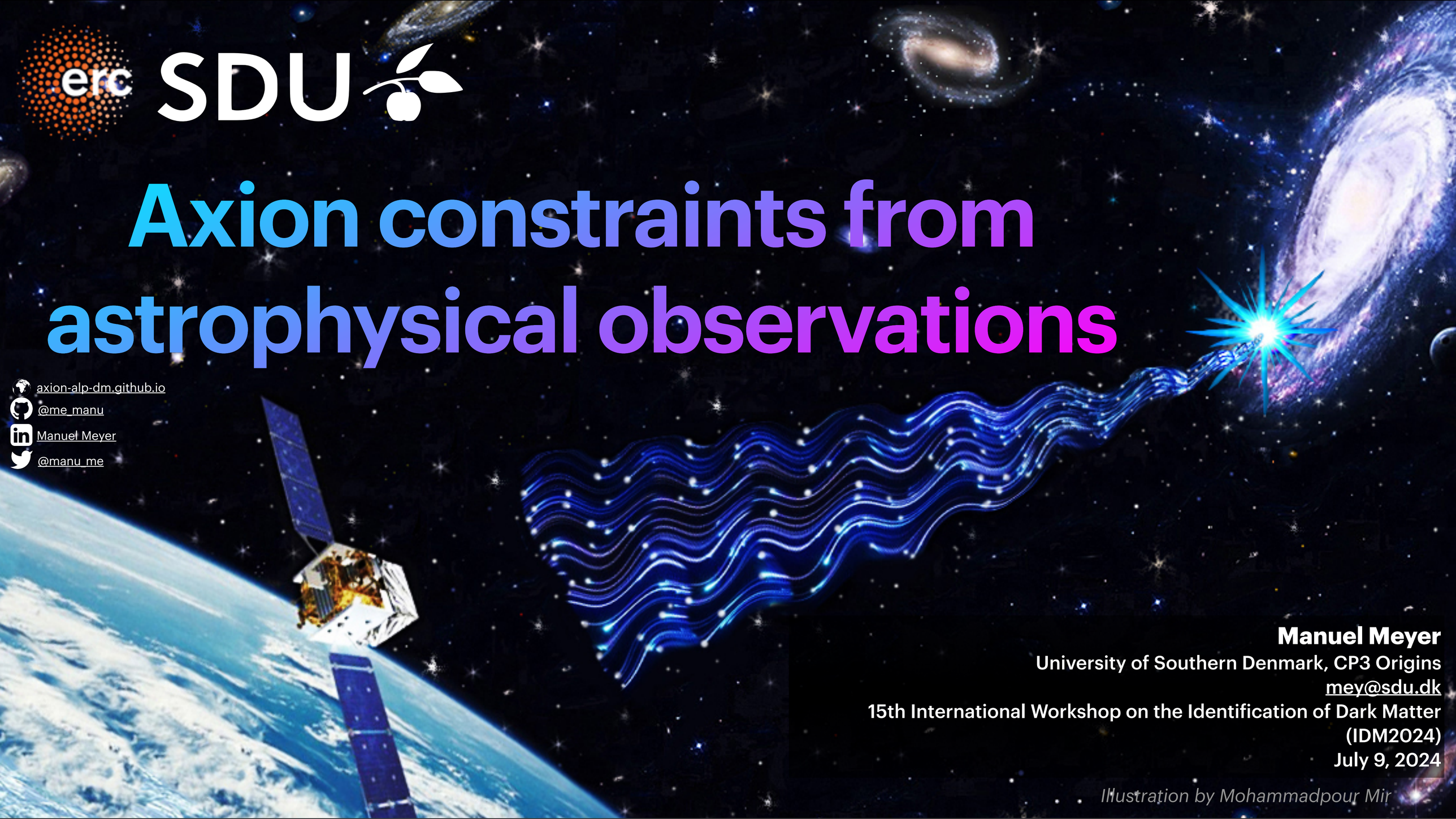


Axion constraints from astrophysical observations

axion-alp-dm.github.io
@me_manu
Manuel Meyer
@manu_me

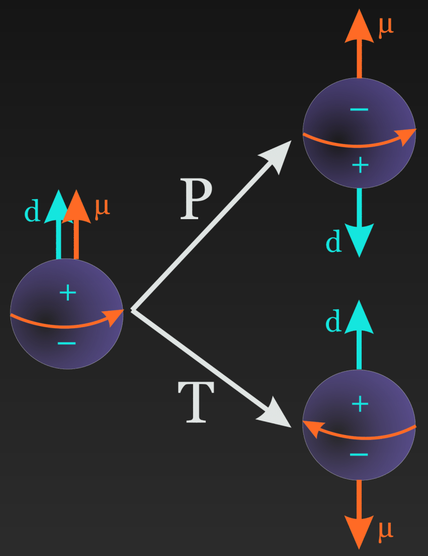
Manuel Meyer
University of Southern Denmark, CP3 Origins
mey@sdu.dk
15th International Workshop on the Identification of Dark Matter (IDM2024)
July 9, 2024

Illustration by Mohammadpour Mir

Motivation to search for axions and axion-like particles

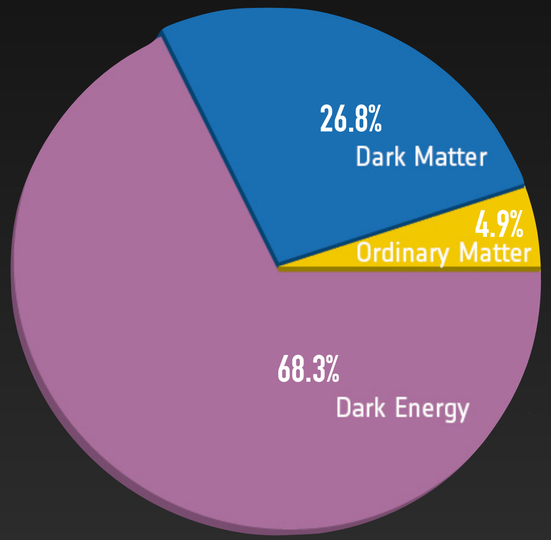
See talks from 1st morning session

Provides solution of the Strong CP problem





Is a particle candidate for cold dark matter

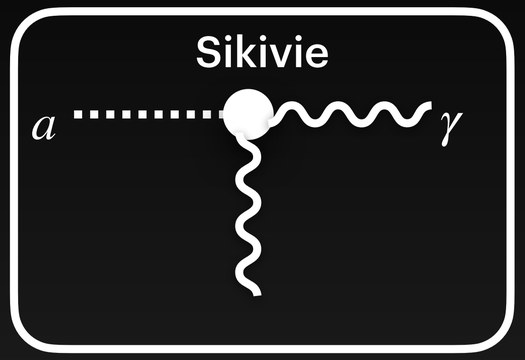


Couplings to the standard model:

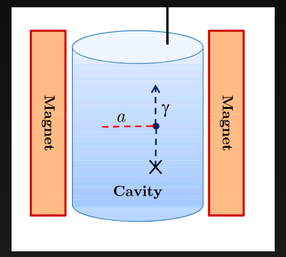
$$\mathscr{L}_a \supset -\frac{\alpha_s}{8\pi} G^c_{\mu\nu} \tilde{G}^{\mu\nu}_c \frac{a}{f_a} - \frac{1}{4} g_{a\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + \partial_\mu a \sum_f g_{af} \bar{f} \gamma^\mu \gamma^5 f$$

Axion observables

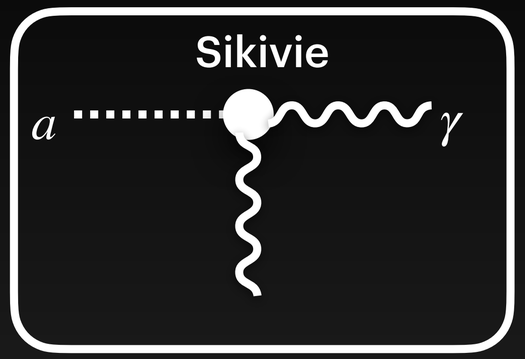
Axion observables

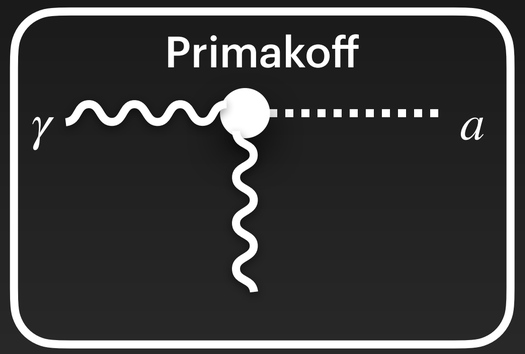


Haloscopes

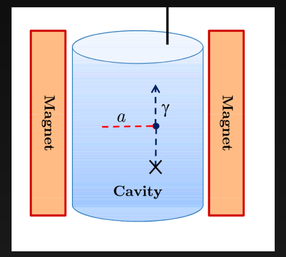


Axion observables

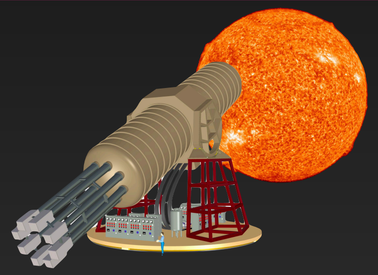




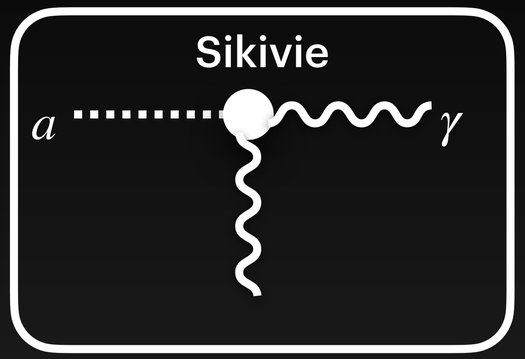
Haloscopes

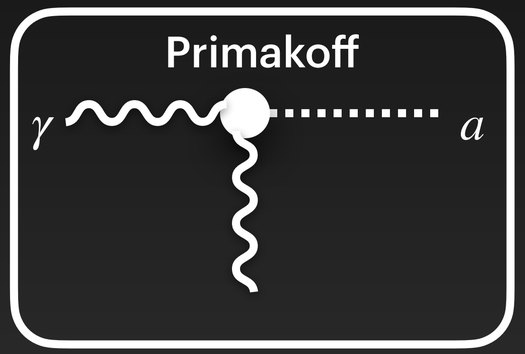


Helioscopes

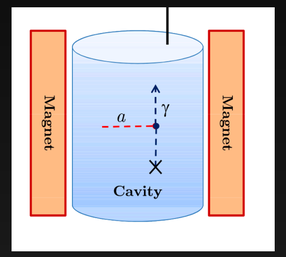


Axion observables



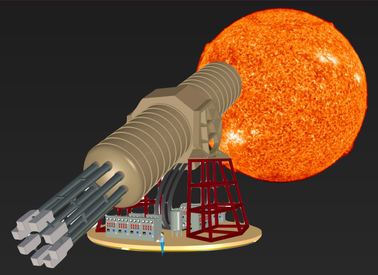


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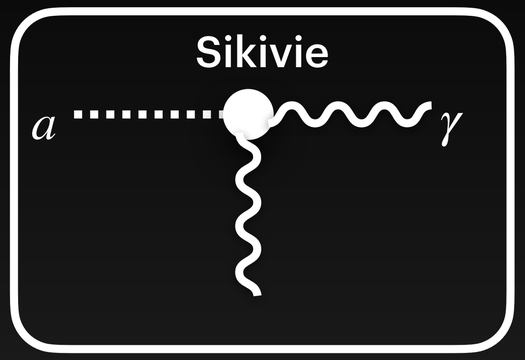


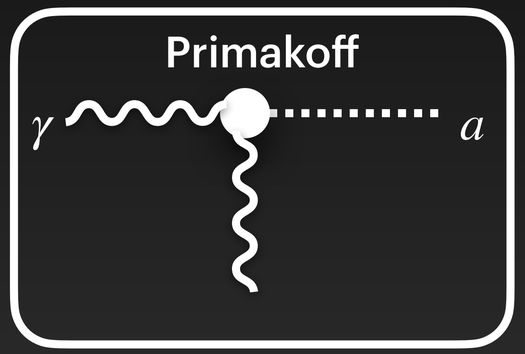
See parallel session on Monday

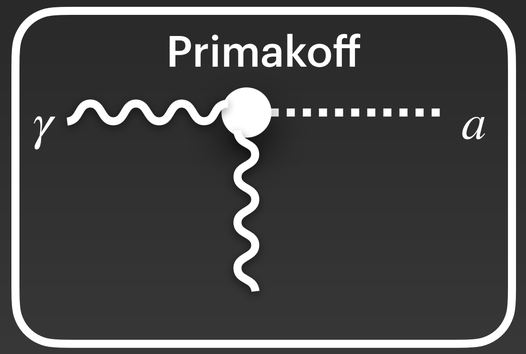
Helioscopes

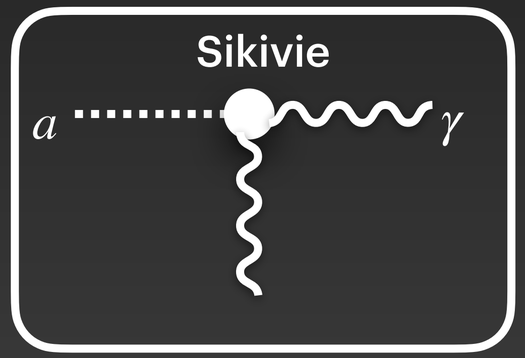


Axion observables

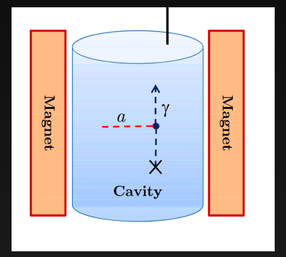






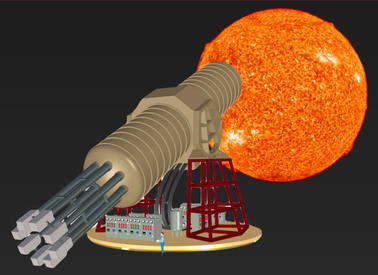


Haloscopes

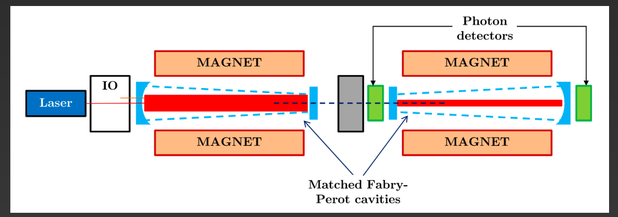


See parallel session on Monday

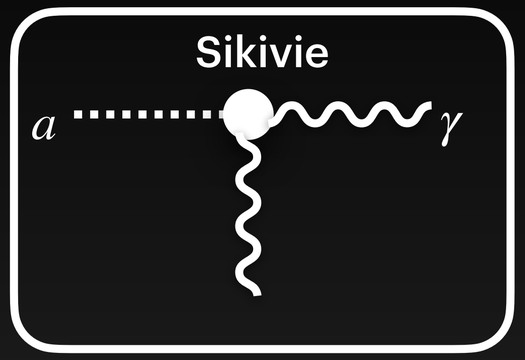
Helioscopes

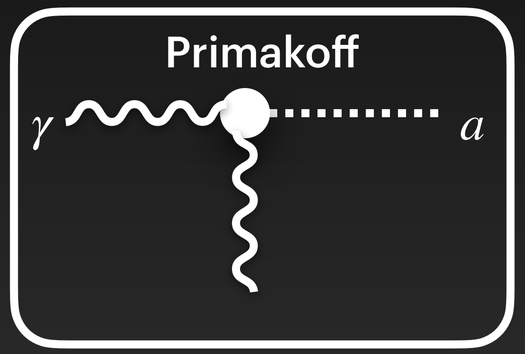


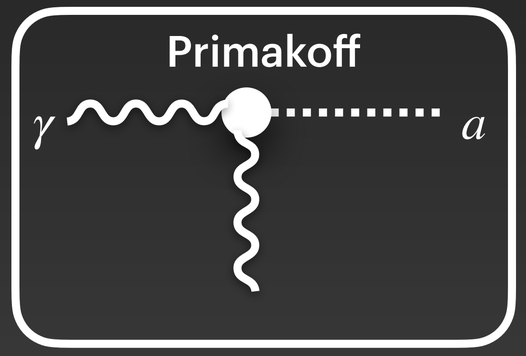
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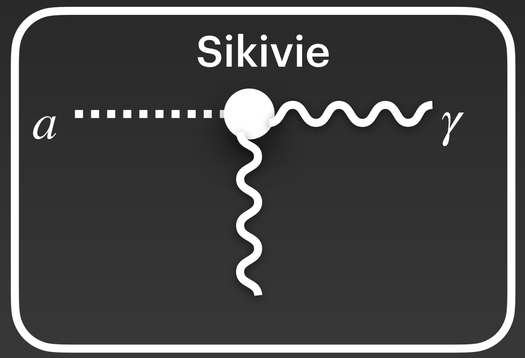


Axion observables

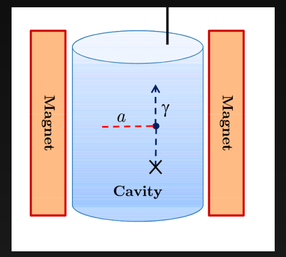






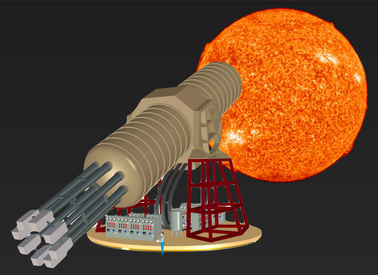


Haloscopes

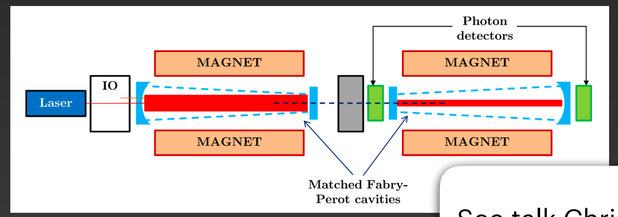


See parallel session on Monday

Helioscopes

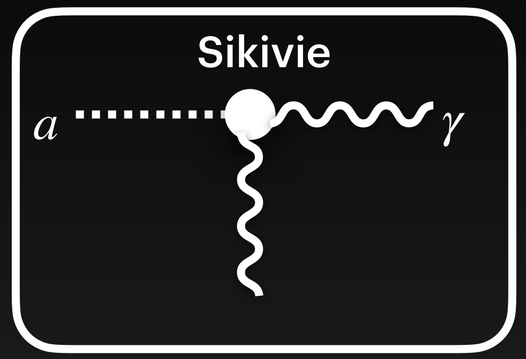


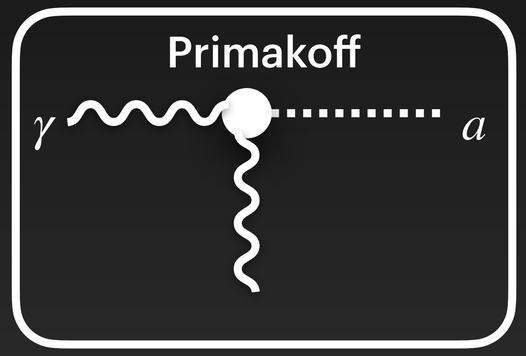
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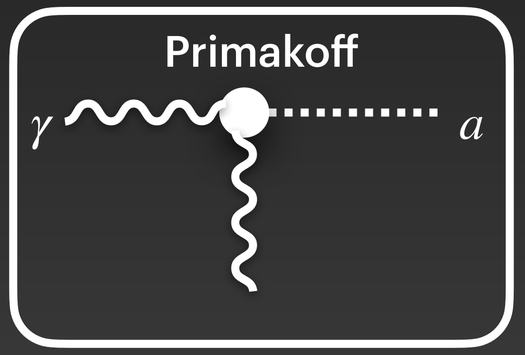


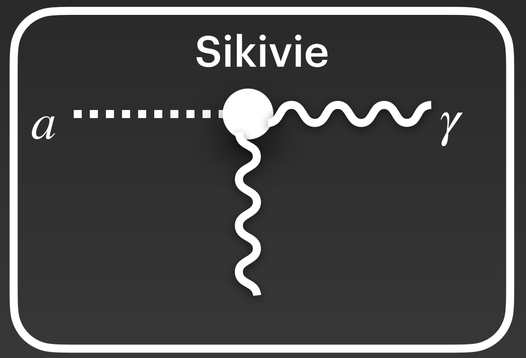
See talk Christina Schwemmbauer Tuesday, 5.10pm

Axion observables — astro counterparts

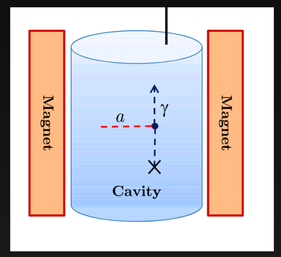




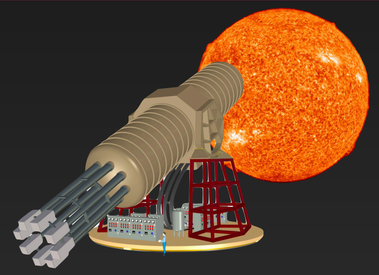




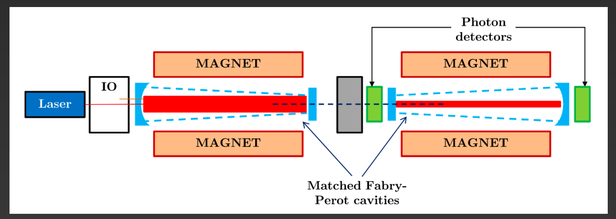
Haloscopes



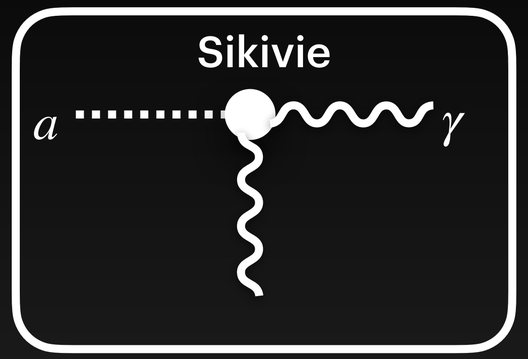
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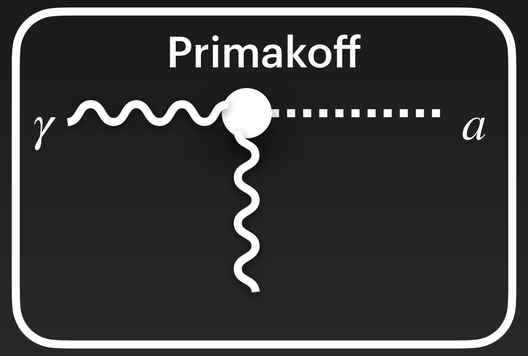


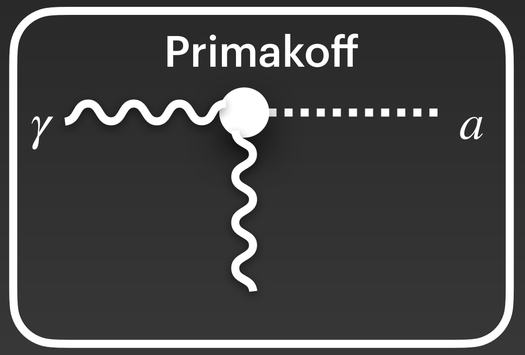
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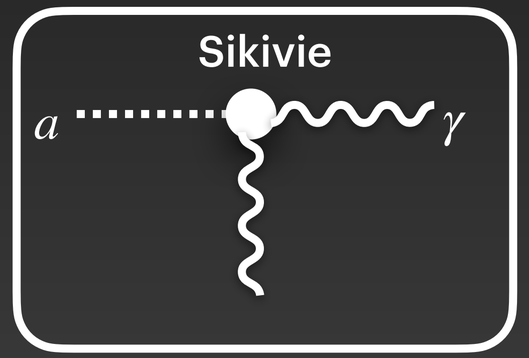


Axion observables — astro counterparts

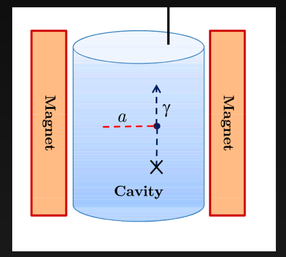




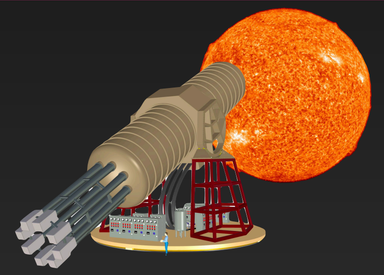




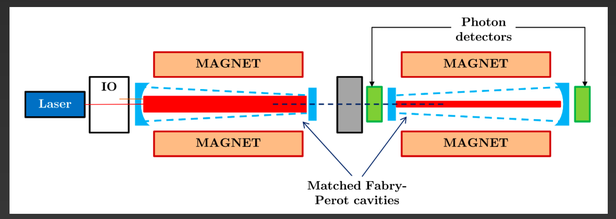
Haloscopes



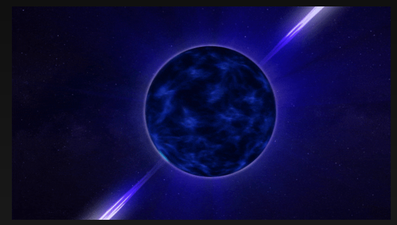
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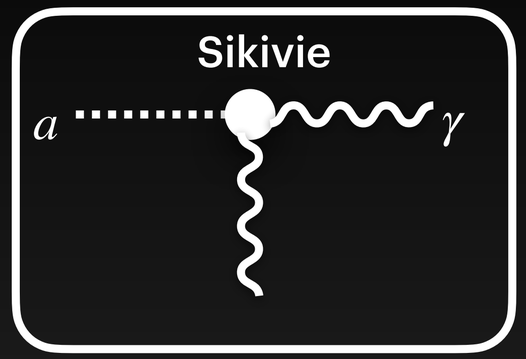
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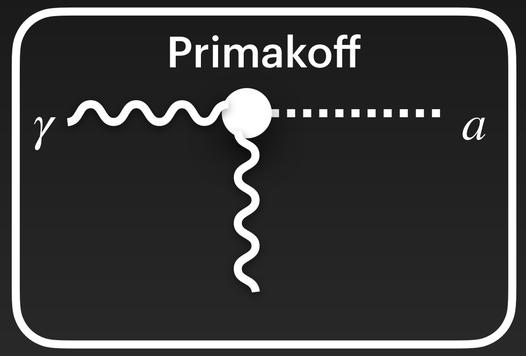


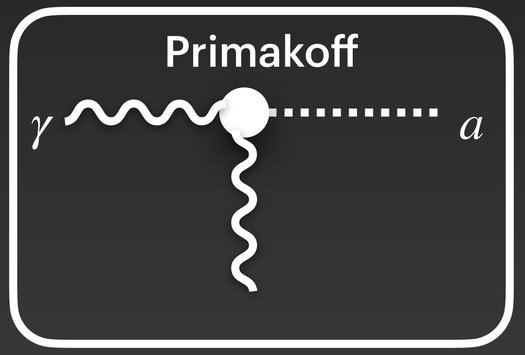
DM conversion in pulsar B fields

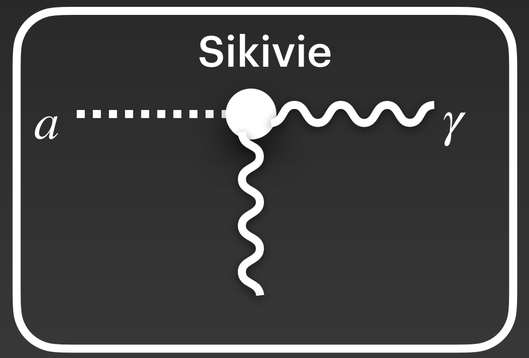


Axion observables — astro counterparts

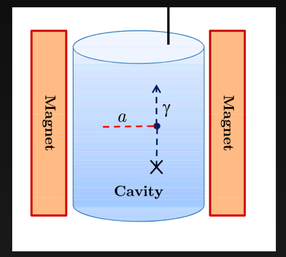




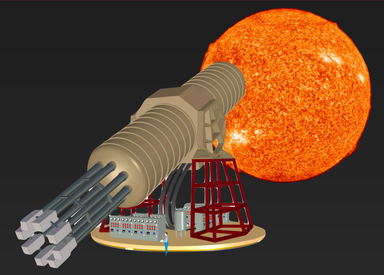




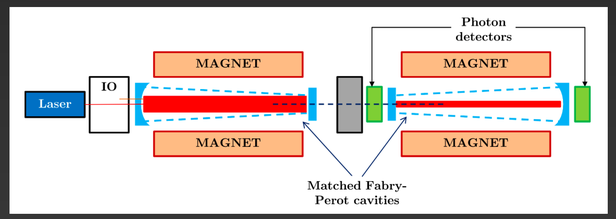
Haloscopes



Helioscopes



LSW

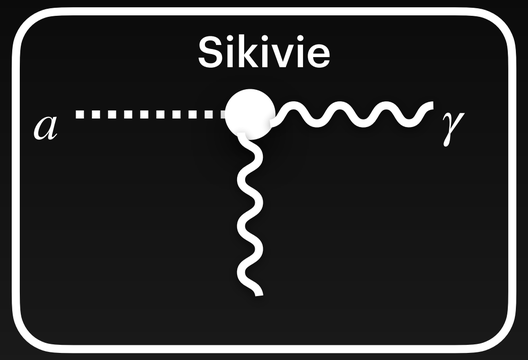


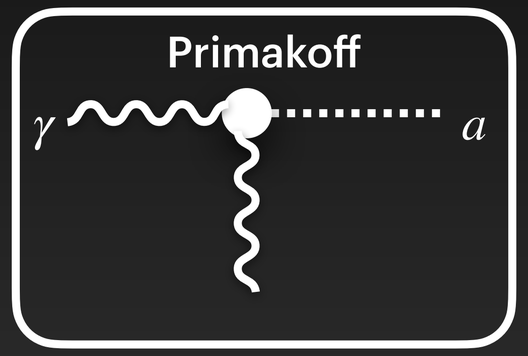
DM conversion in pulsar B fields

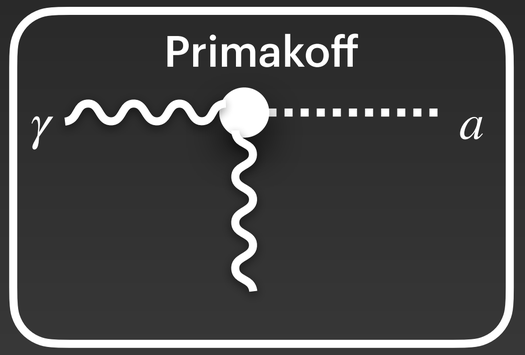


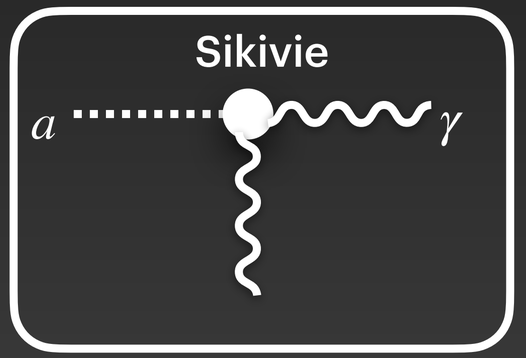
See talk by Luca Visinelli
Wednesday, 2pm

Axion observables — astro counterparts

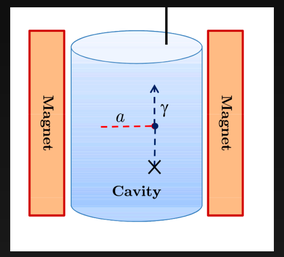




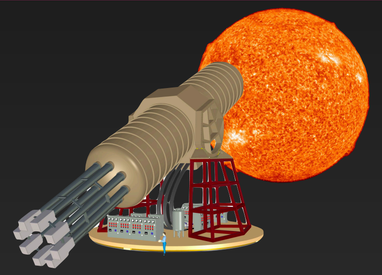




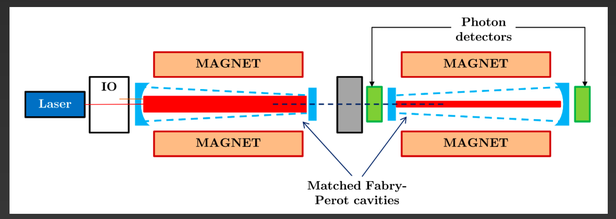
Haloscopes



Helioscopes



LSW

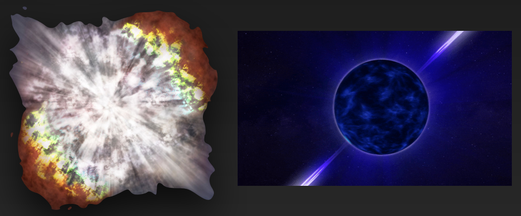


DM conversion in pulsar B fields

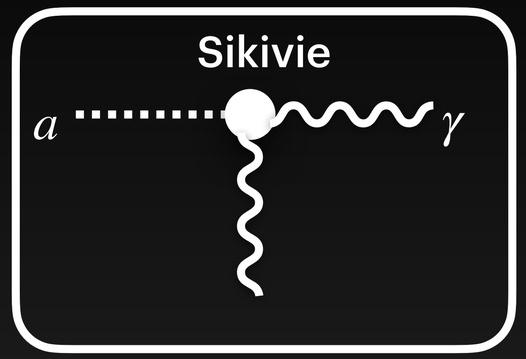


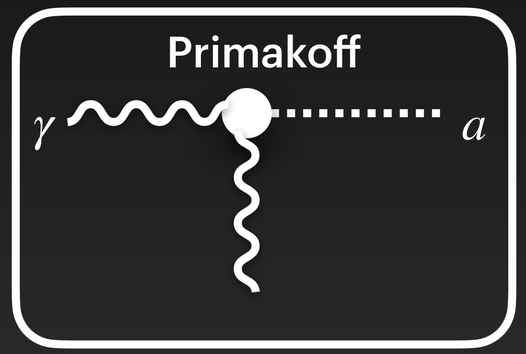
See talk by Luca Visinelli
Wednesday, 2pm

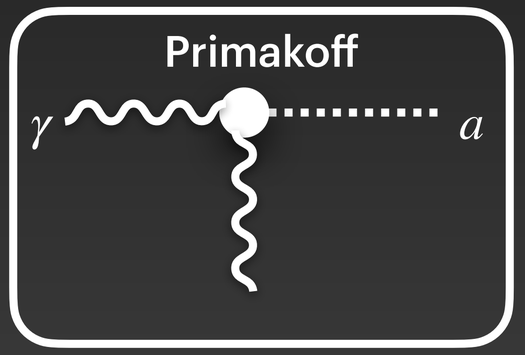
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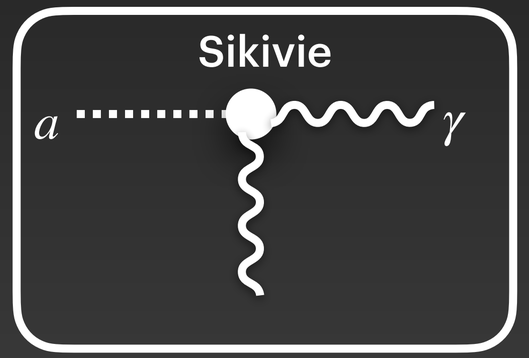


Axion observables — astro counterparts

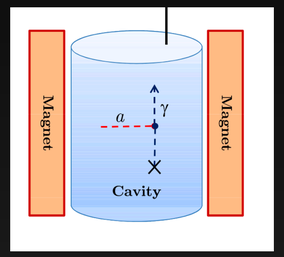




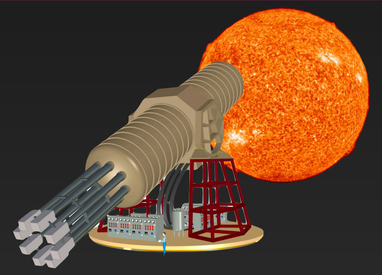




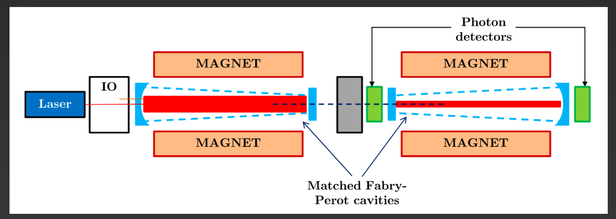
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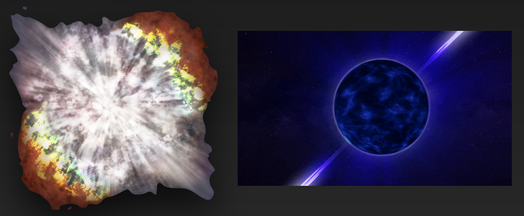


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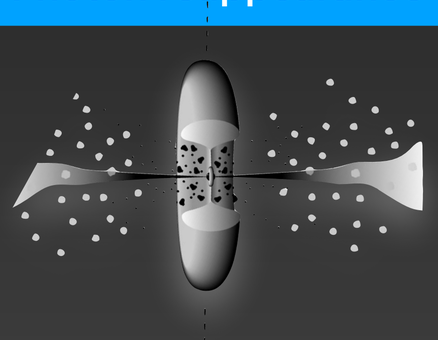


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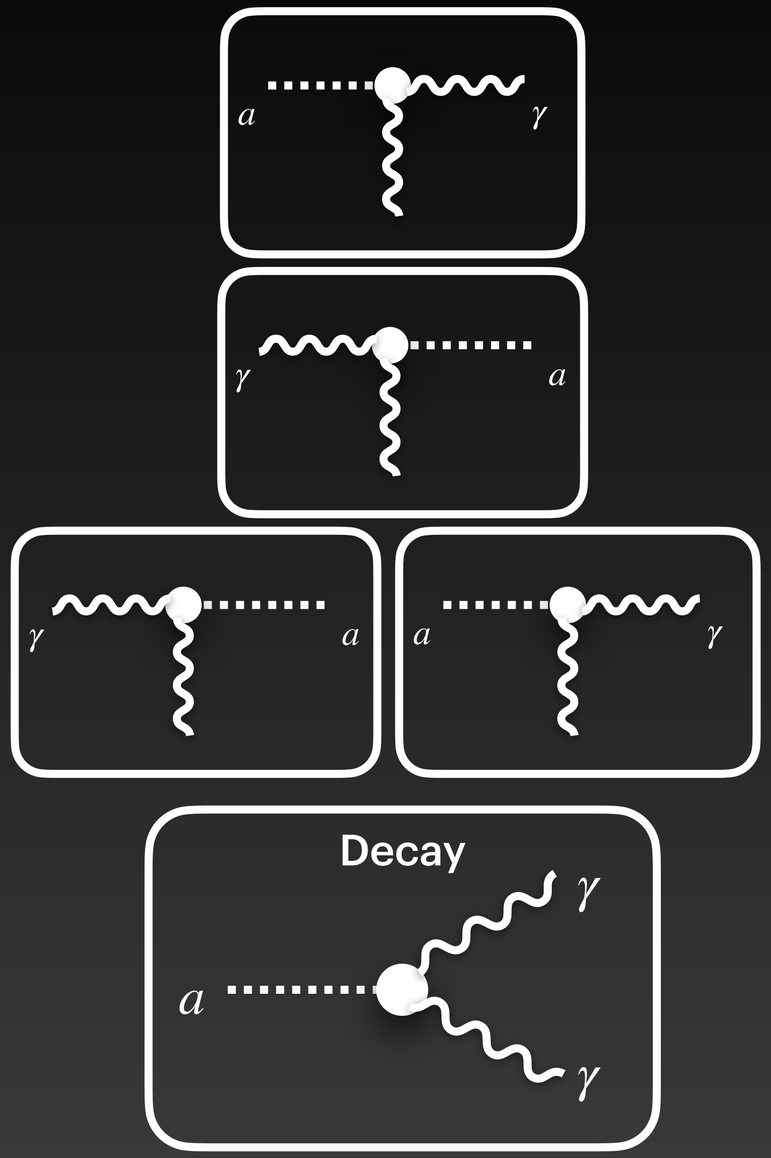
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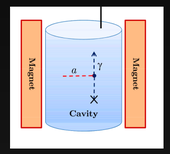
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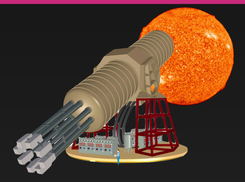
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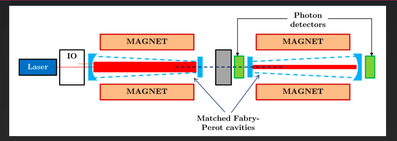
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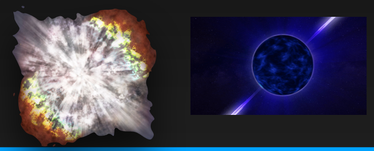
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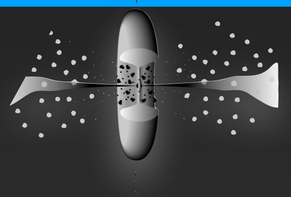
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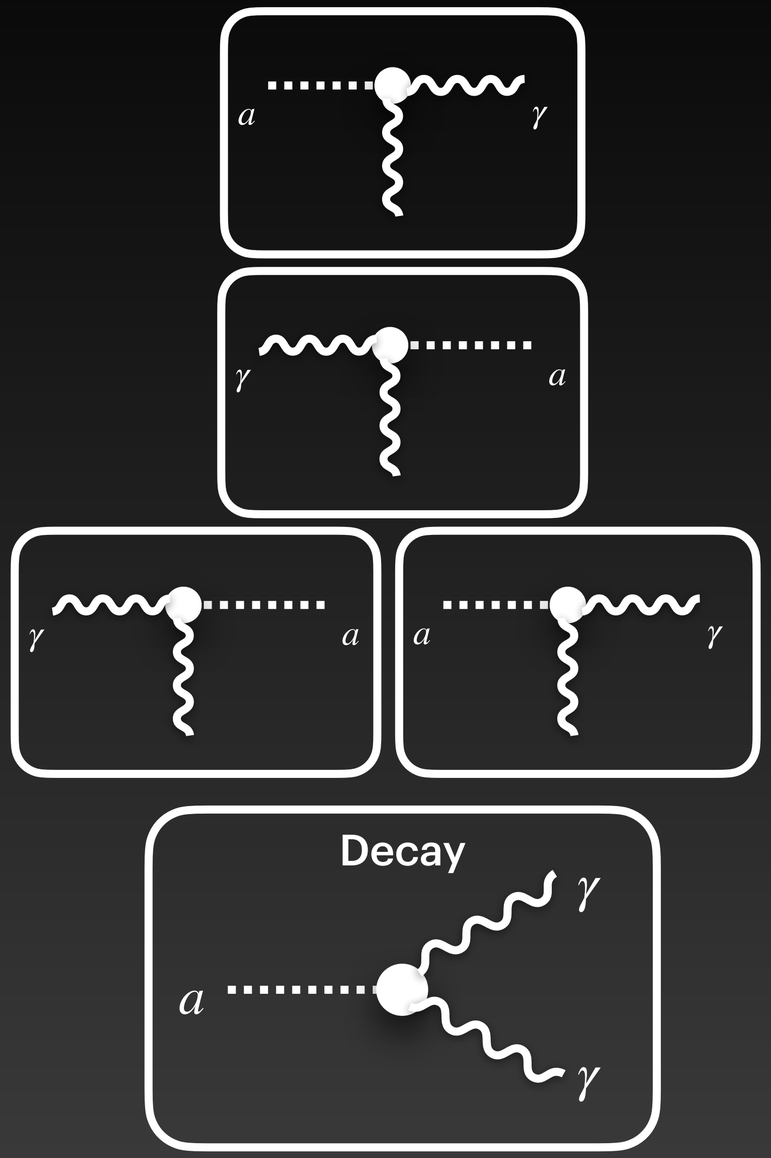
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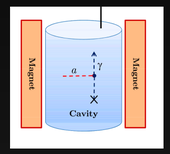
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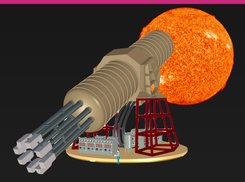
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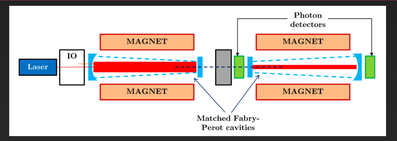
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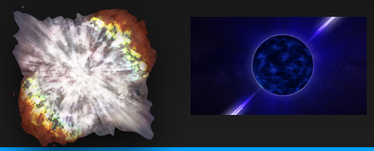
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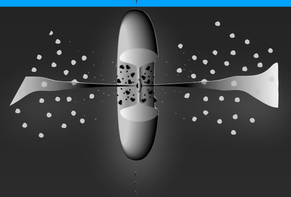
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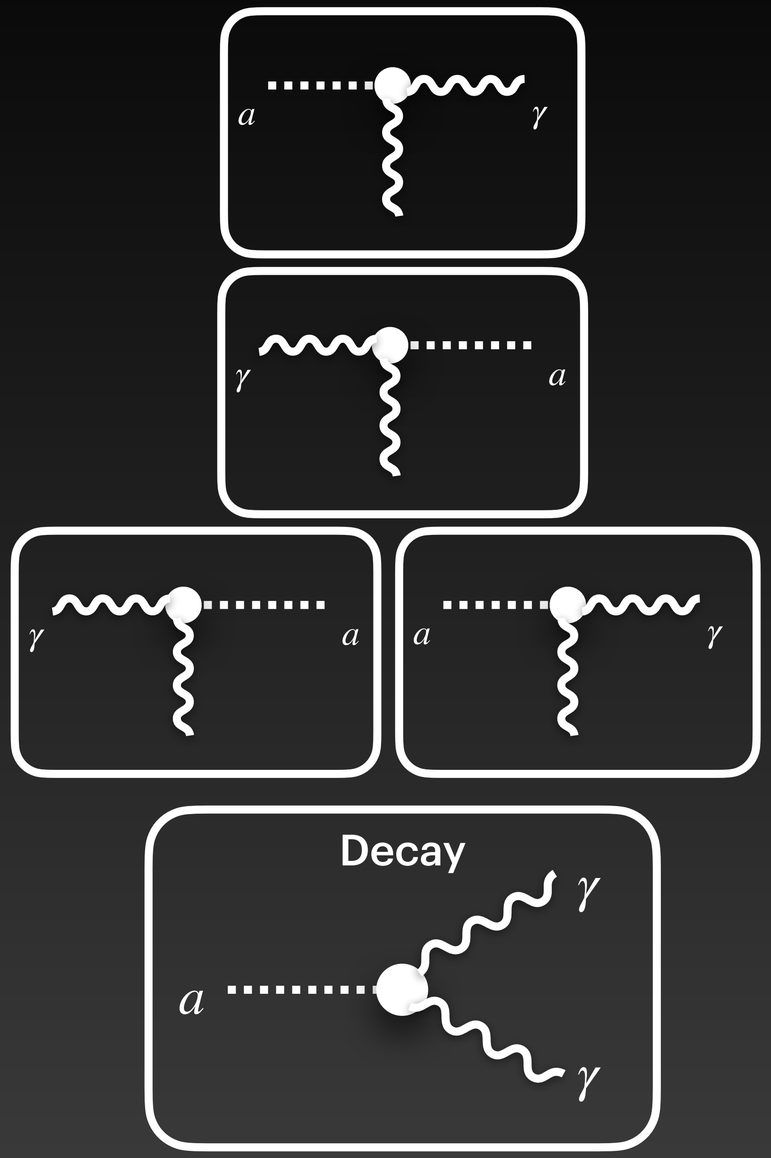
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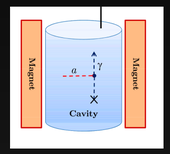
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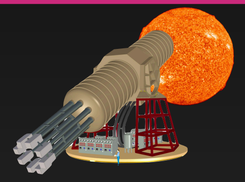
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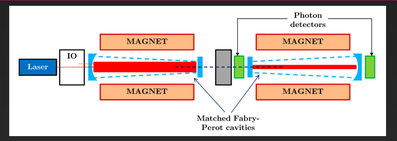
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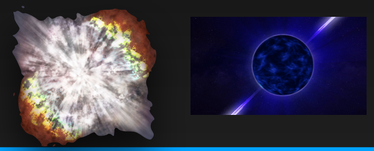
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DM conversion in pulsar B fields



Supernova / pulsarscopes



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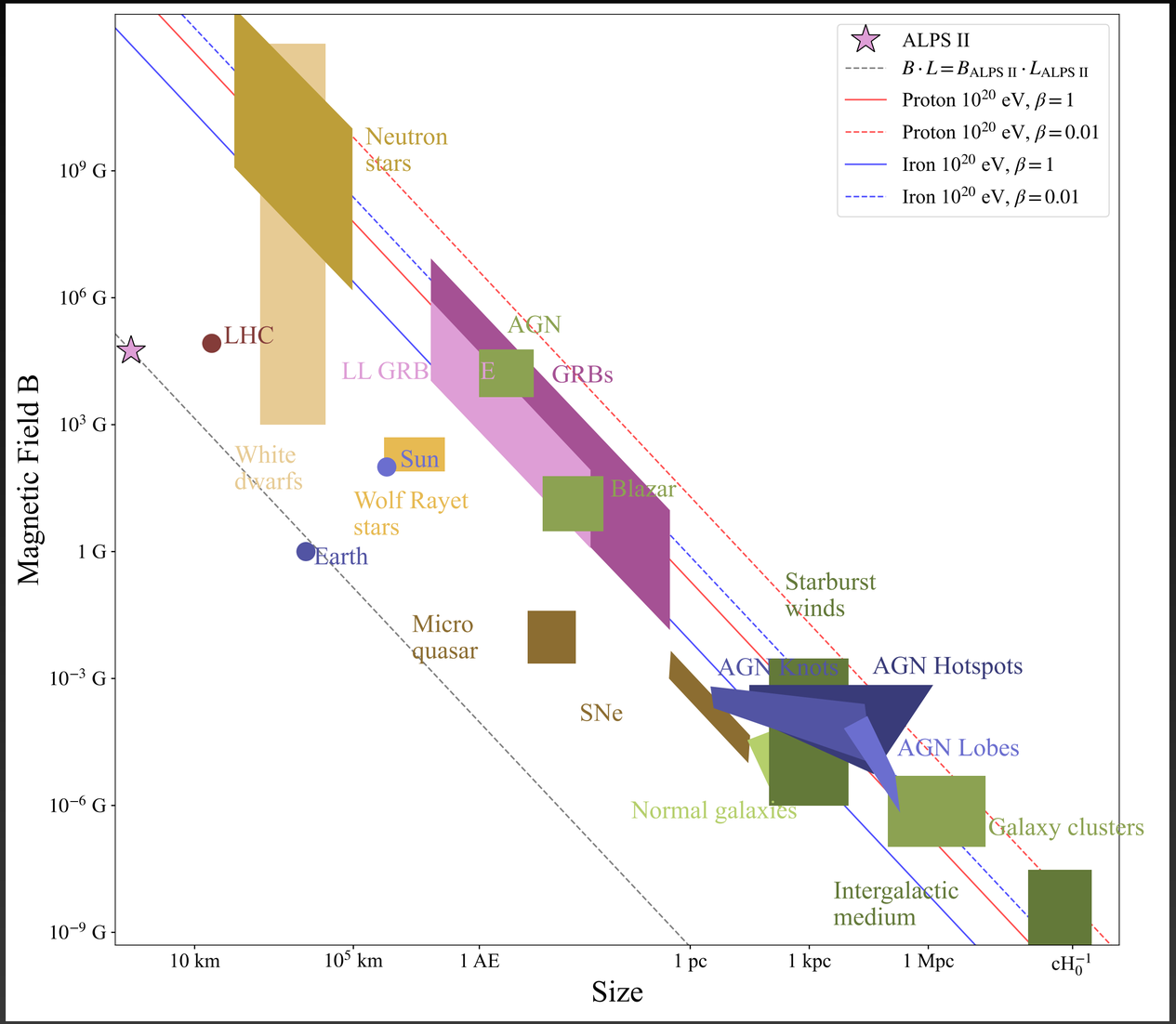
Spectral lines / photon radiation fields



Astrophysical magnetic fields

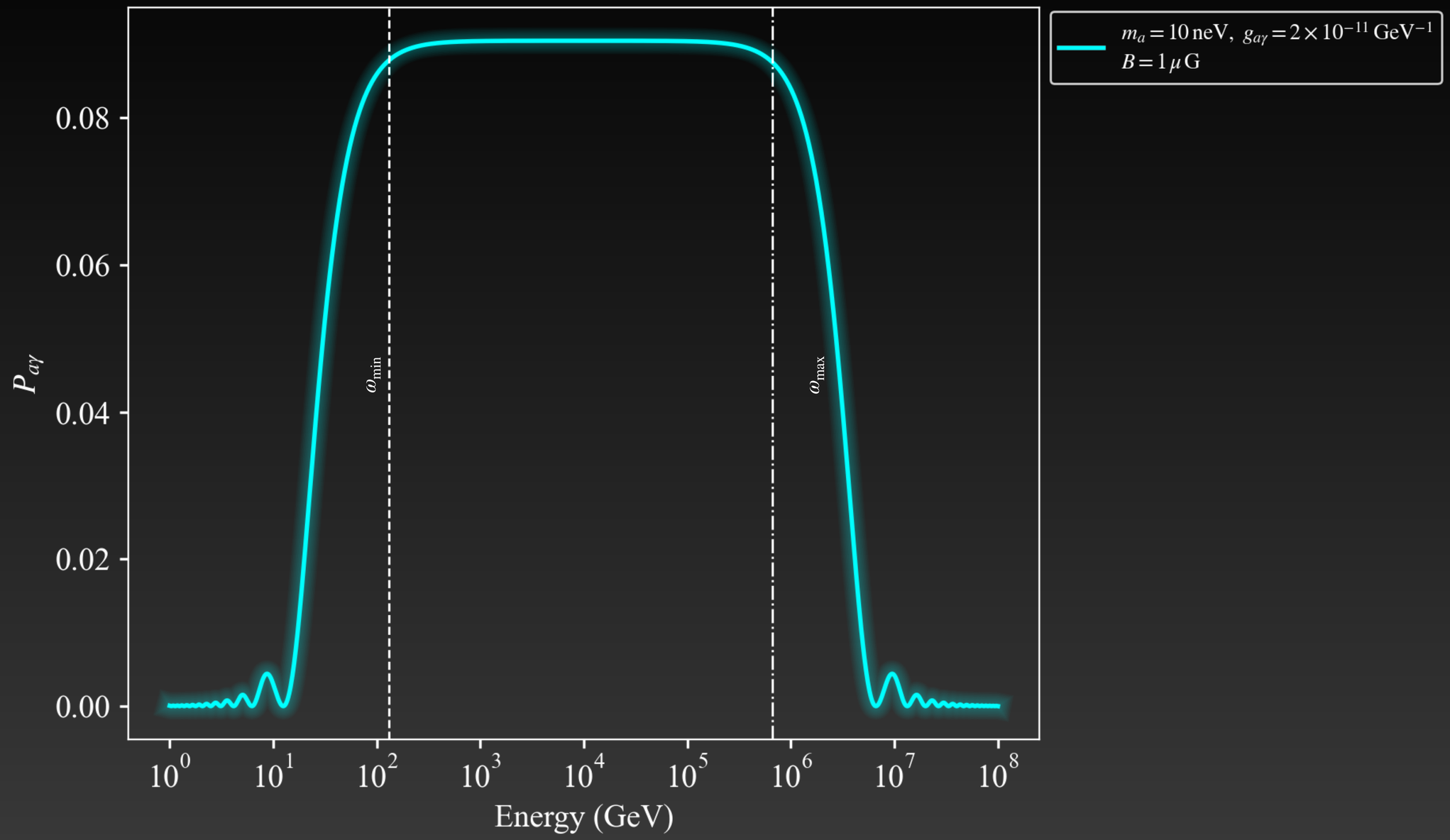


Magnetic fields in the Universe

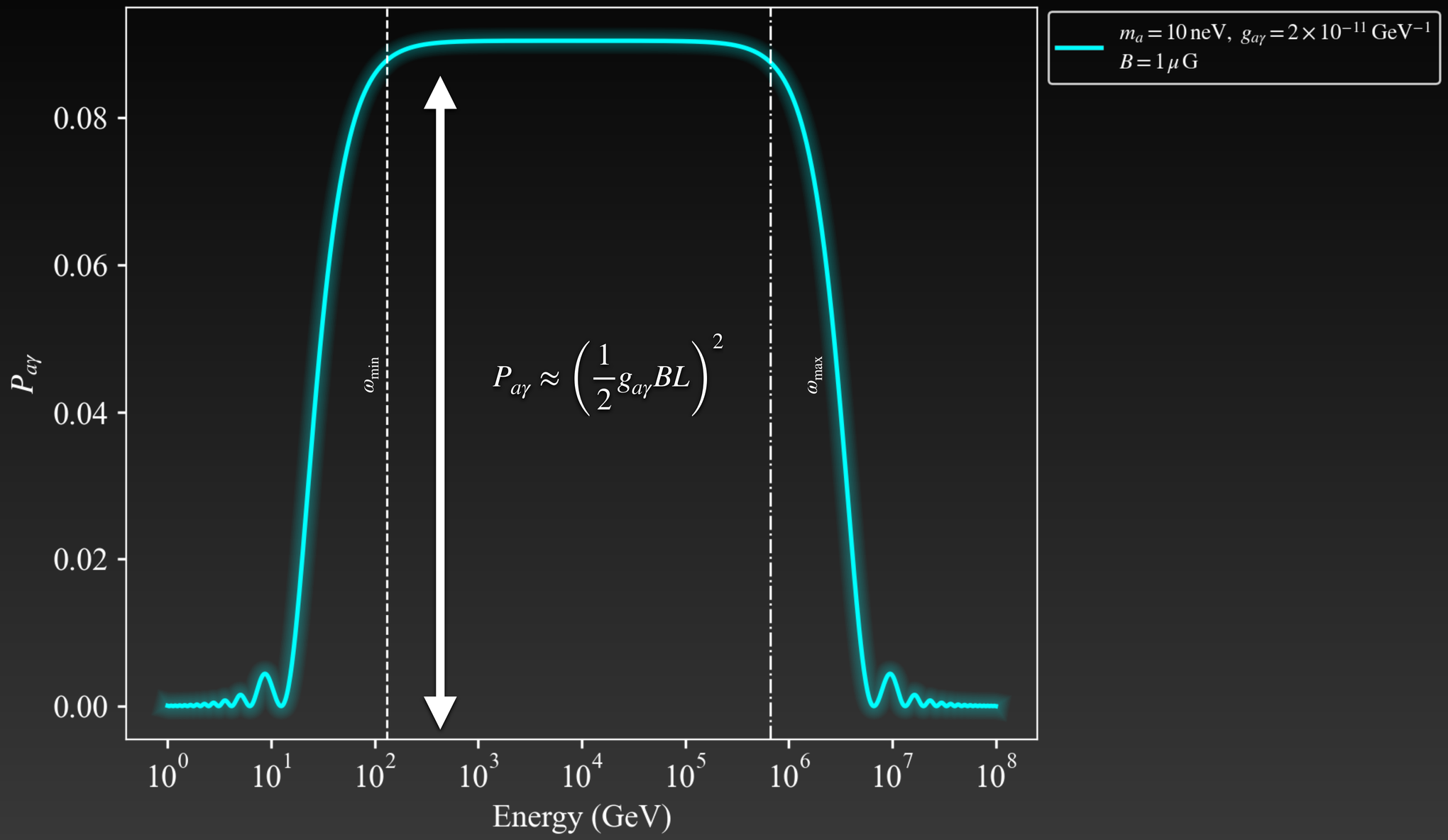


[Hillas 1984,
Pueschel & Maier; Physik Journal 2022
https://github.com/GernotMaier/HillasPlot]

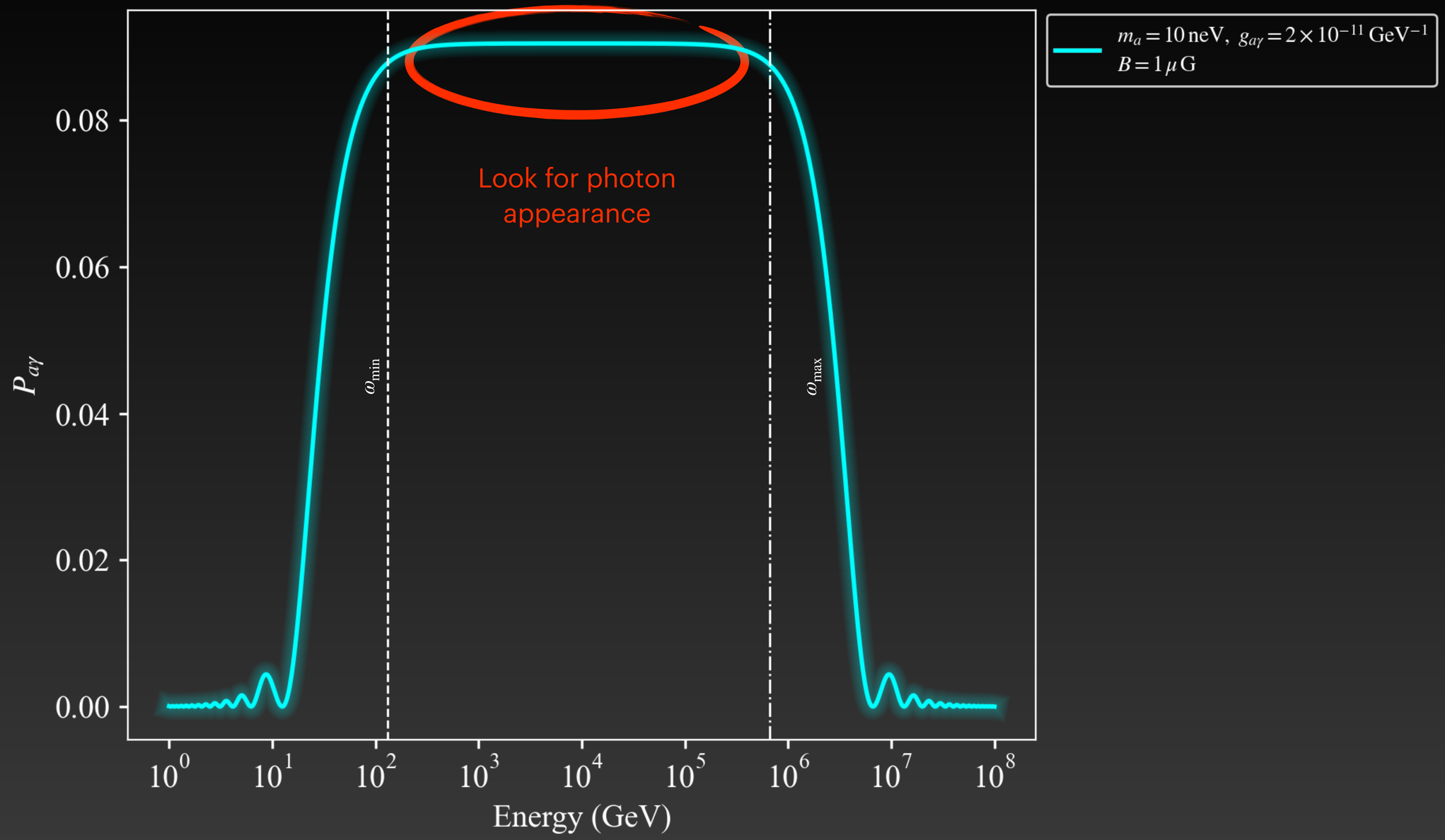
Photon-Axion/ALP Mixing on Galactic scales (10 kpc)



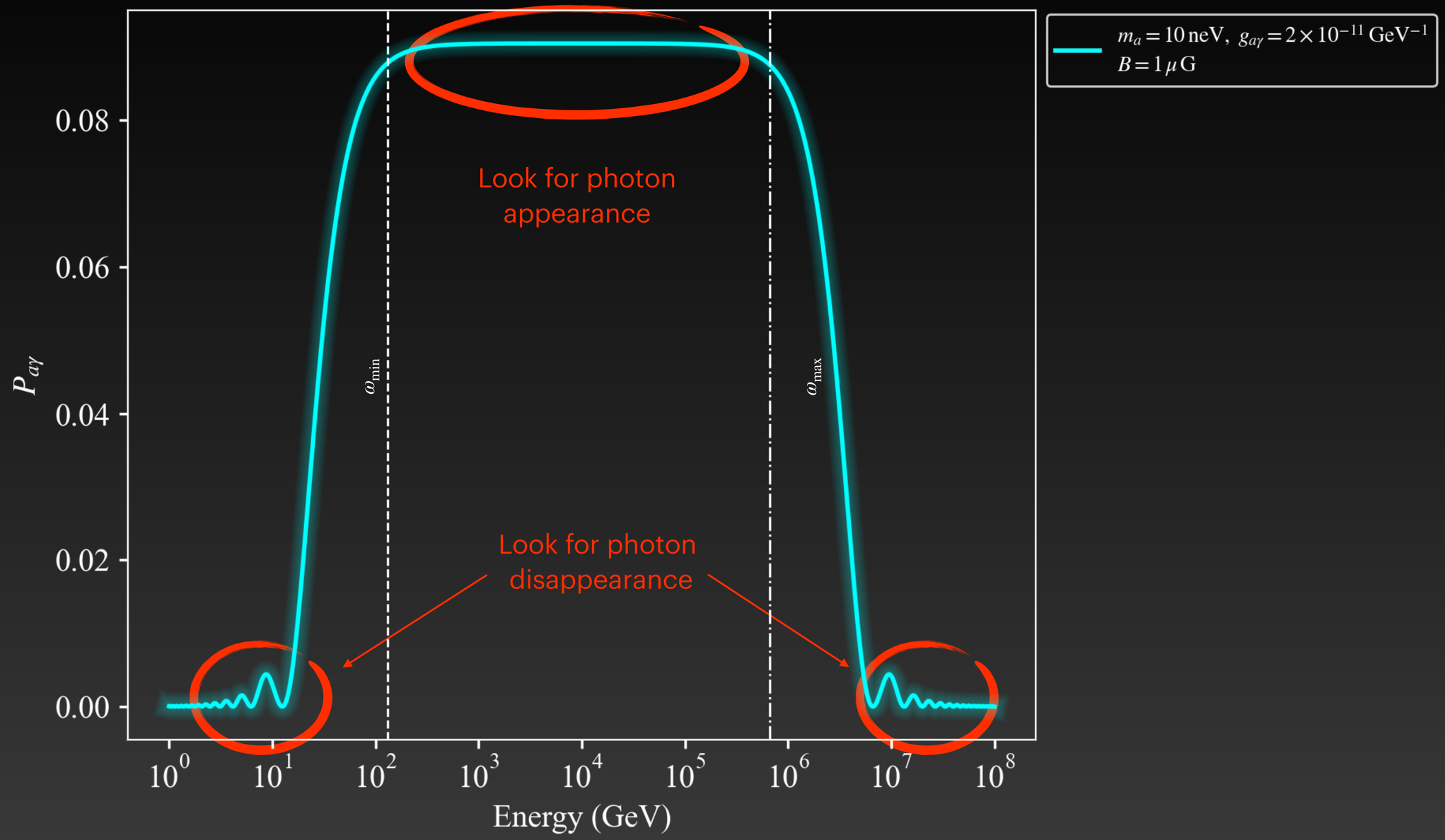
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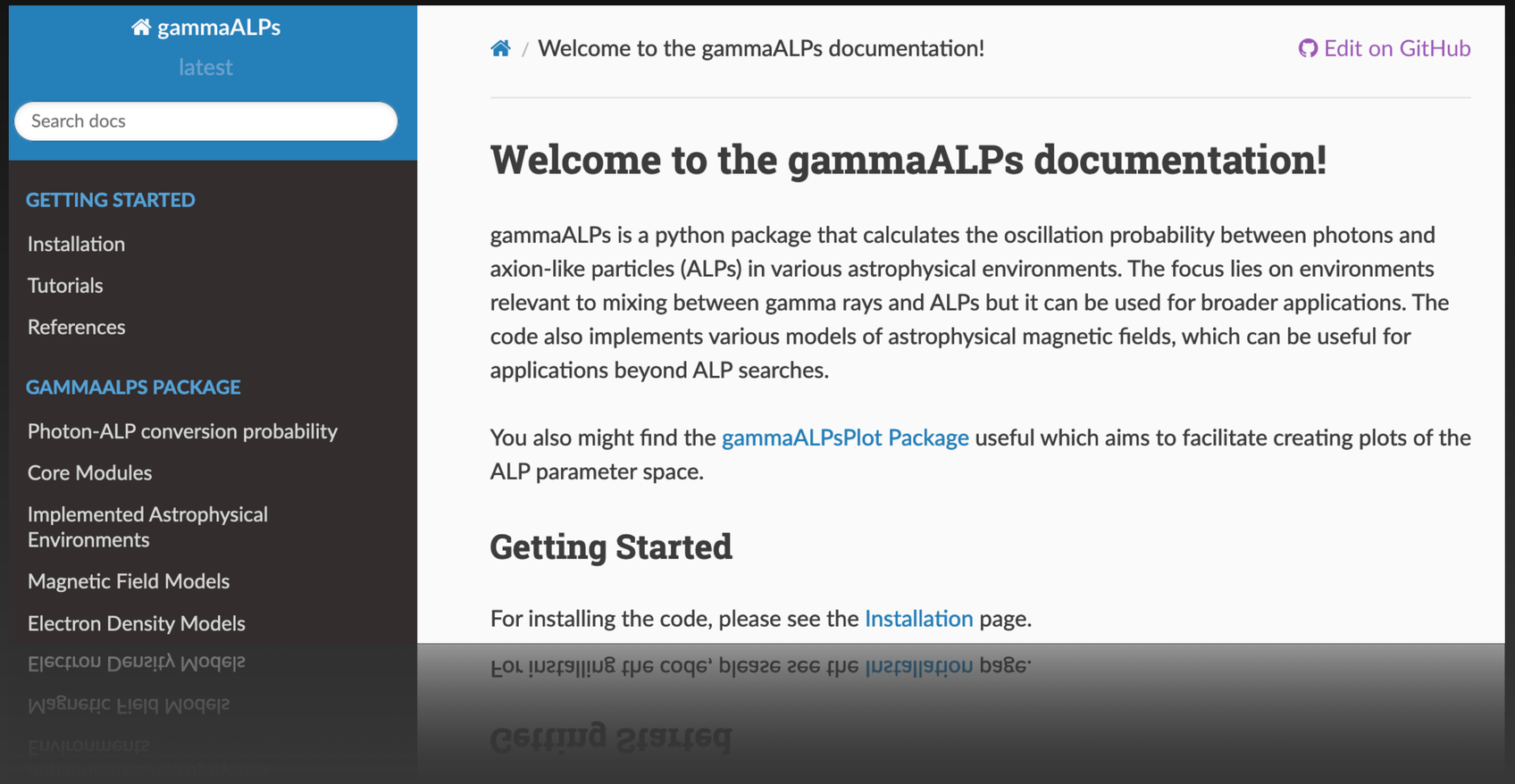


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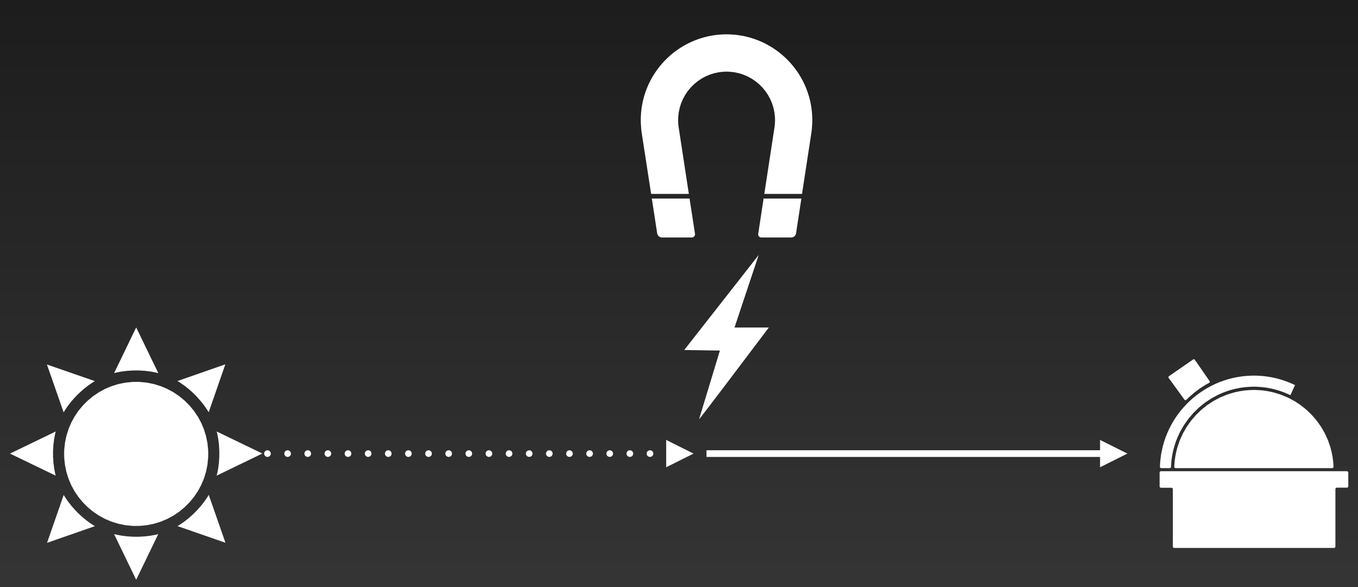
Gamma ALPs

Modular python framework for photon-axion conversion in astrophysical magnetic fields



- Includes models for a plethora of astrophysical environments:
  - AGN jets
  - Galaxy clusters
  - Intergalactic medium
  - Milky Way
- Soon to come:
  - New models for Milky Way [Unger & Farrar, 2024]
  - Intergalactic magnetic field from cosmological MHD simulations [Vazza et al. 2017]

Supernovascopes

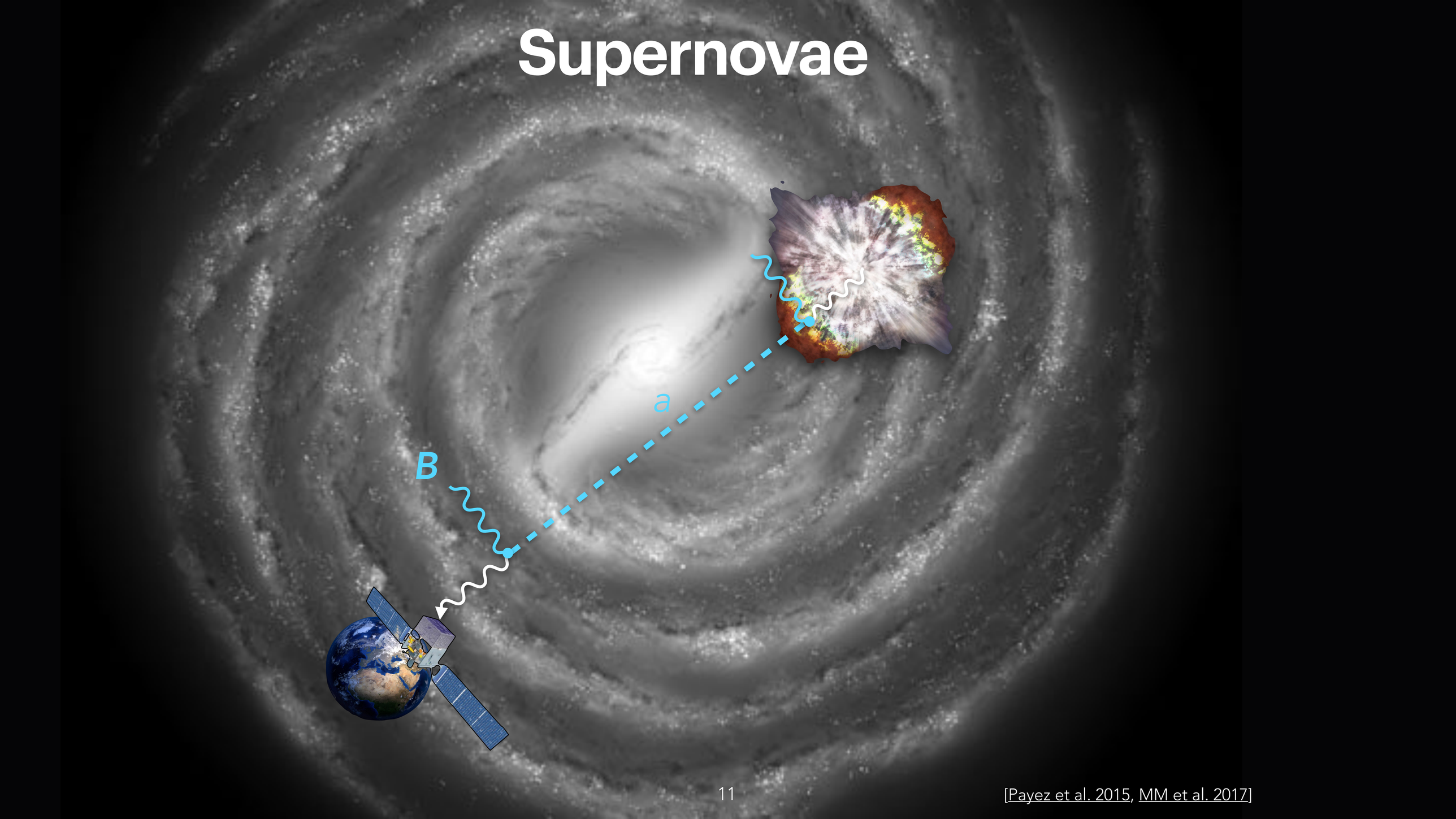


Supernovae



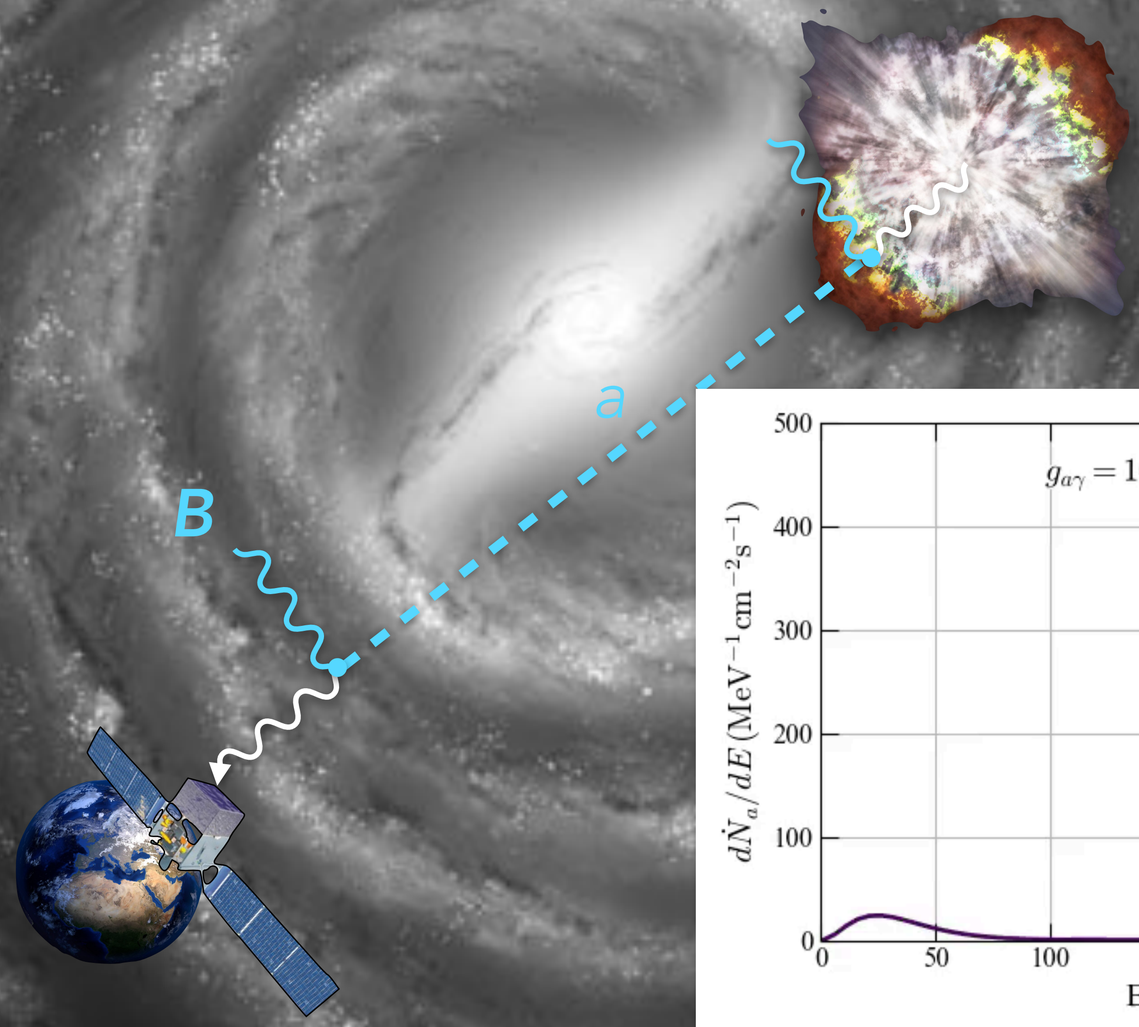
[Payez et al. 2015, MM et al. 2017]

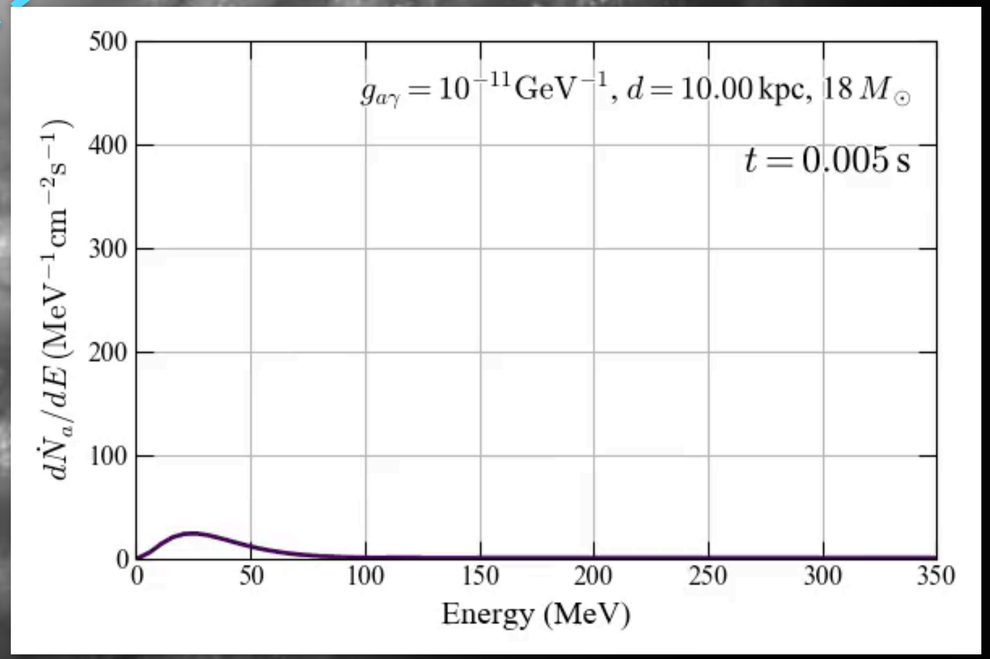
Supernovae



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Supernovae





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Gamma-ray bursts constraints from SN1987A



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- SN1987A was inside field of view (at 90º incidence) of Gamma-ray Spectrometer (GRS) on-board NASA’s solar maximum mission



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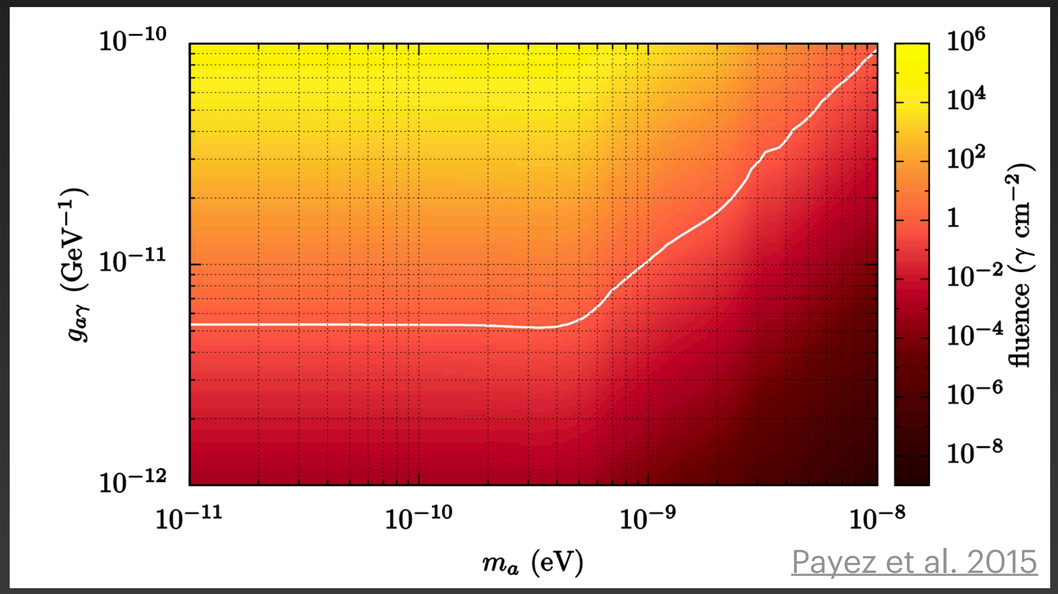
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- Provides limits on photon-ALP coupling $g_{a\gamma} \lesssim 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$ for $m_a \lesssim 4.4 \times 10^{-10}\,\mathrm{eV}$

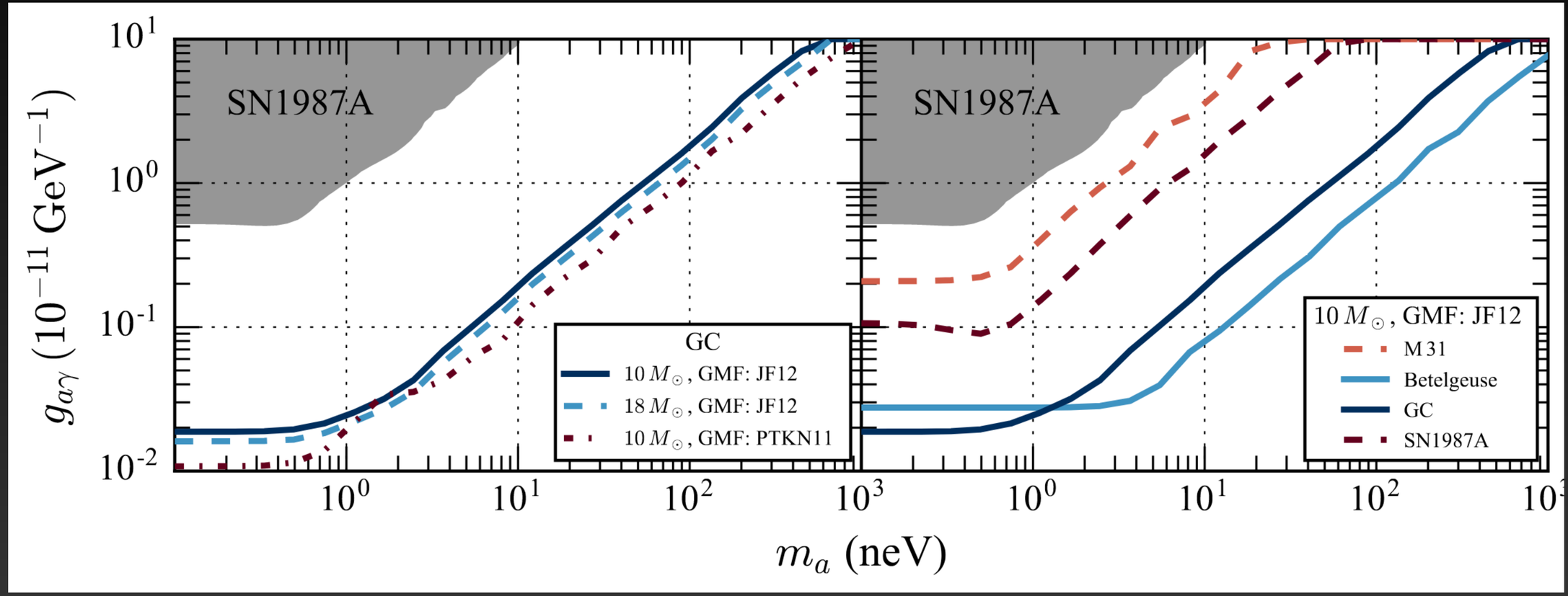

NASA



Payez et al. 2015

What if a core collapse supernova happened now in the Milky Way?

... and was in the field of view of the LAT?



[MM et al. 2017]

core collapse SN rate in Milky Way ~ 3% per year

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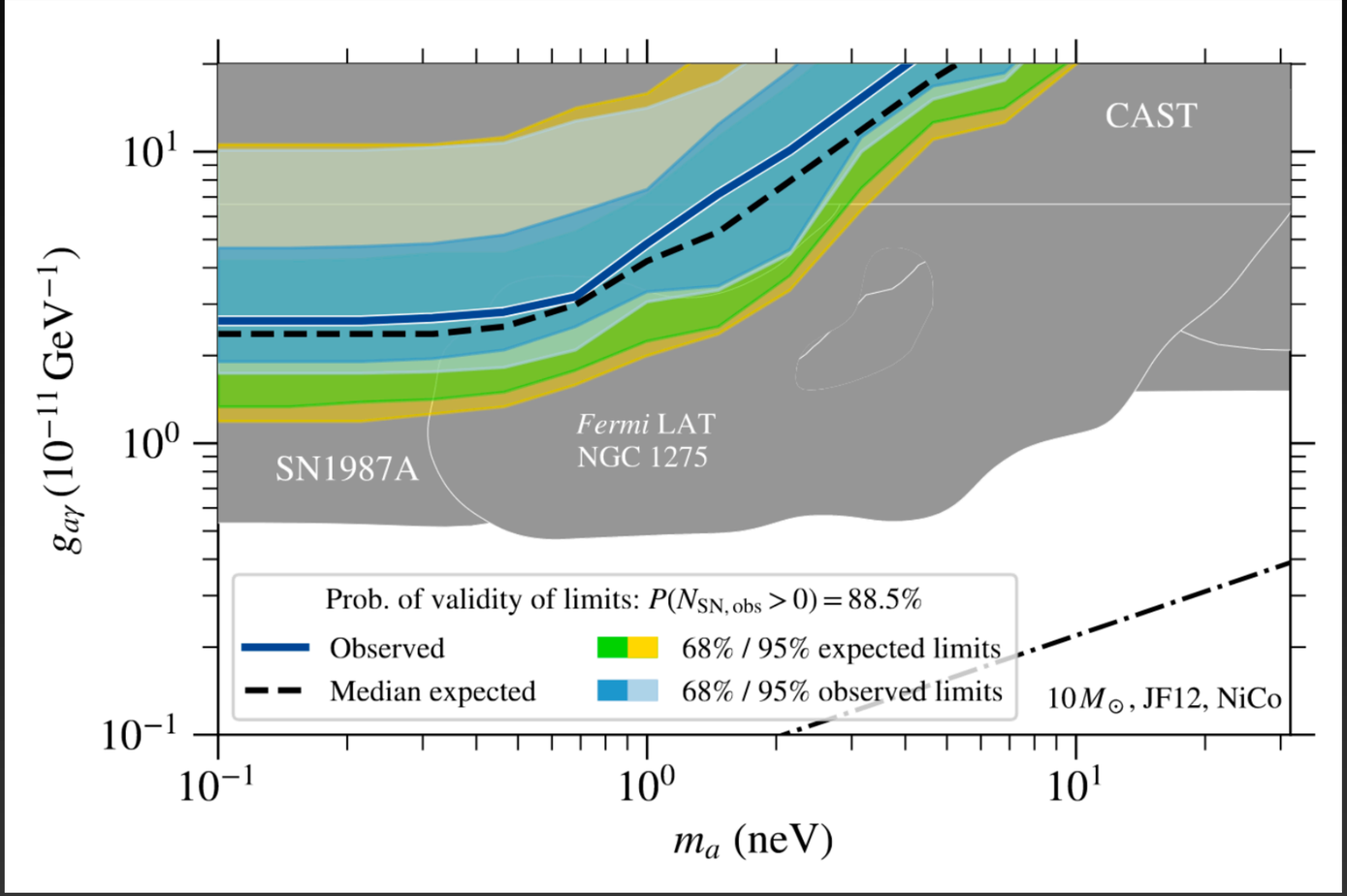
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Look for close by extragalactic supernovae (but no neutrino signal) observed in optical surveys

Combined limits from sample of 20 SNe detected until 2017

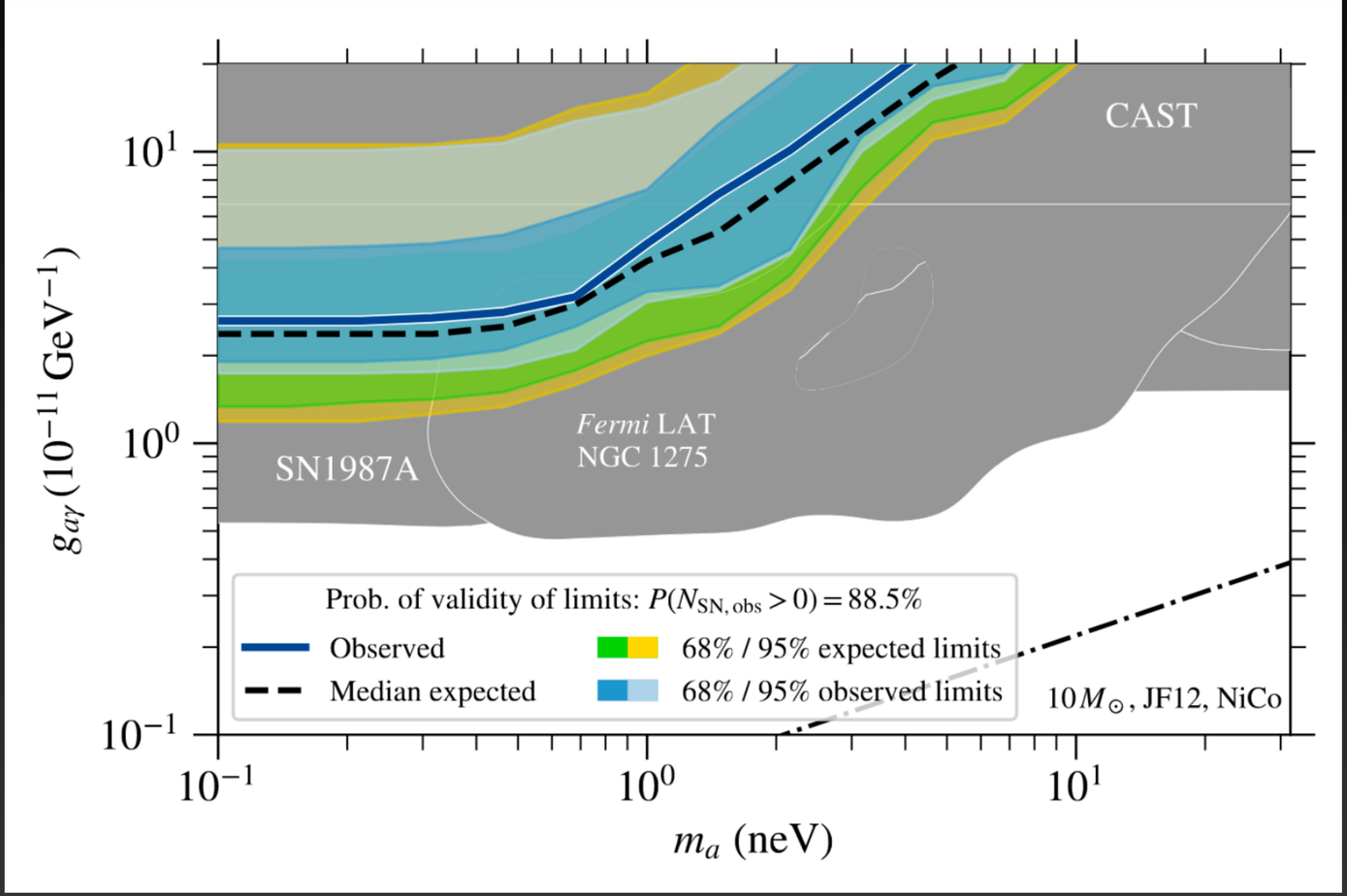


$$P(N_{\mathrm{obs}} \geqslant 1) = 1 - \prod_i \left(1 - p_{\mathrm{obs},i}\right) \approx 89\,\%$$

[MM & Petrushevska 2022]

[MM & Petrushevska 2020]

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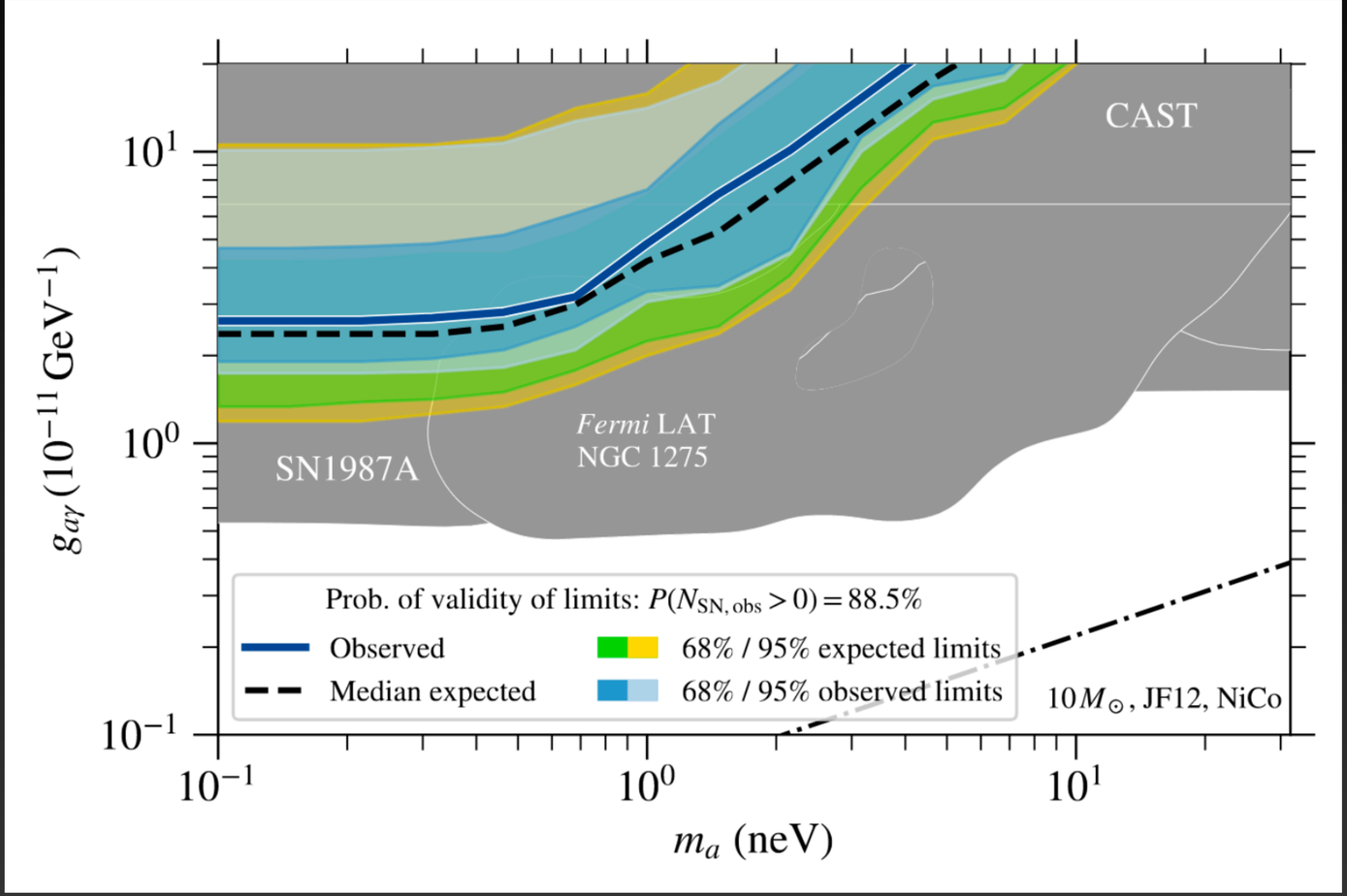
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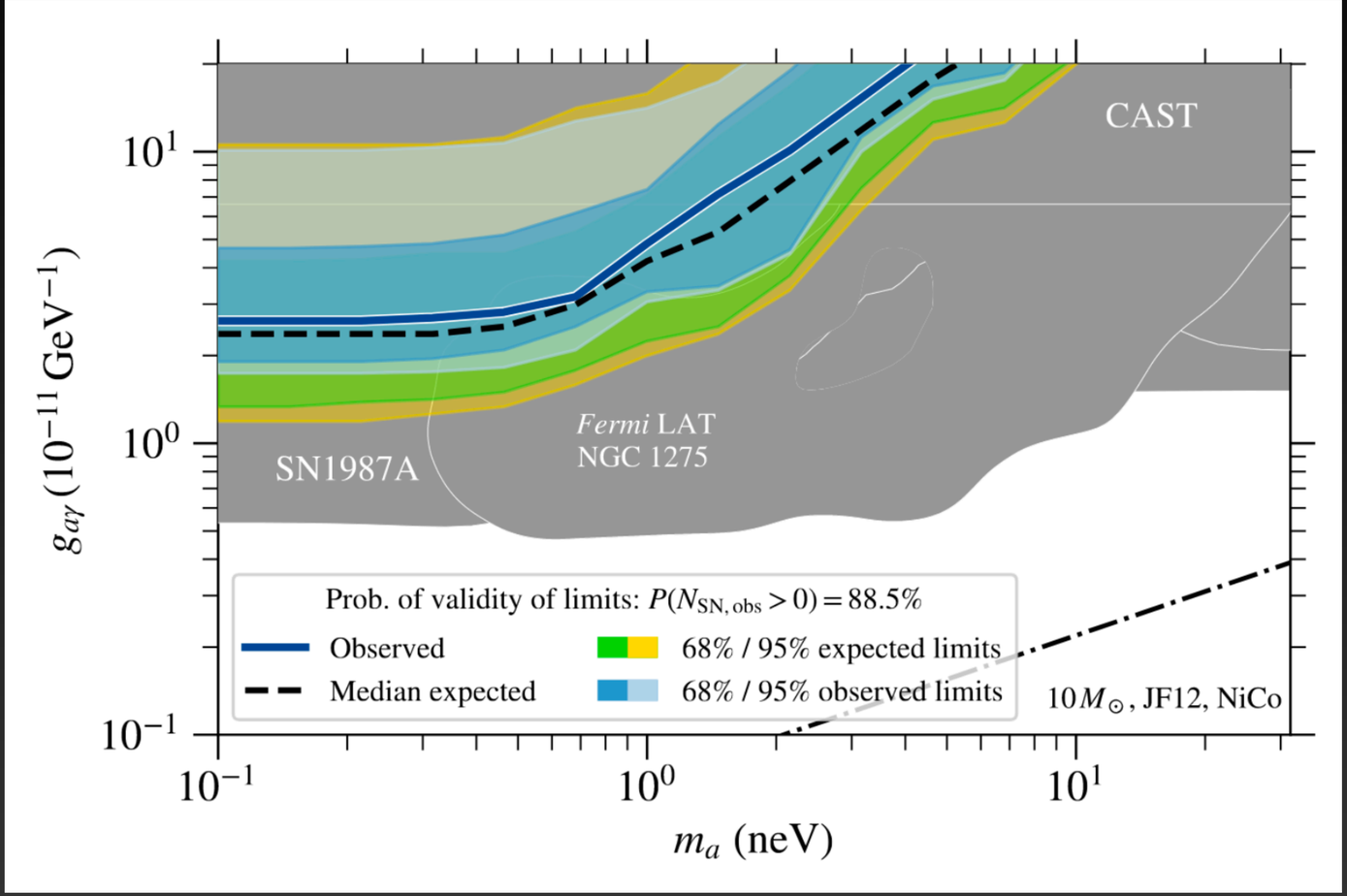
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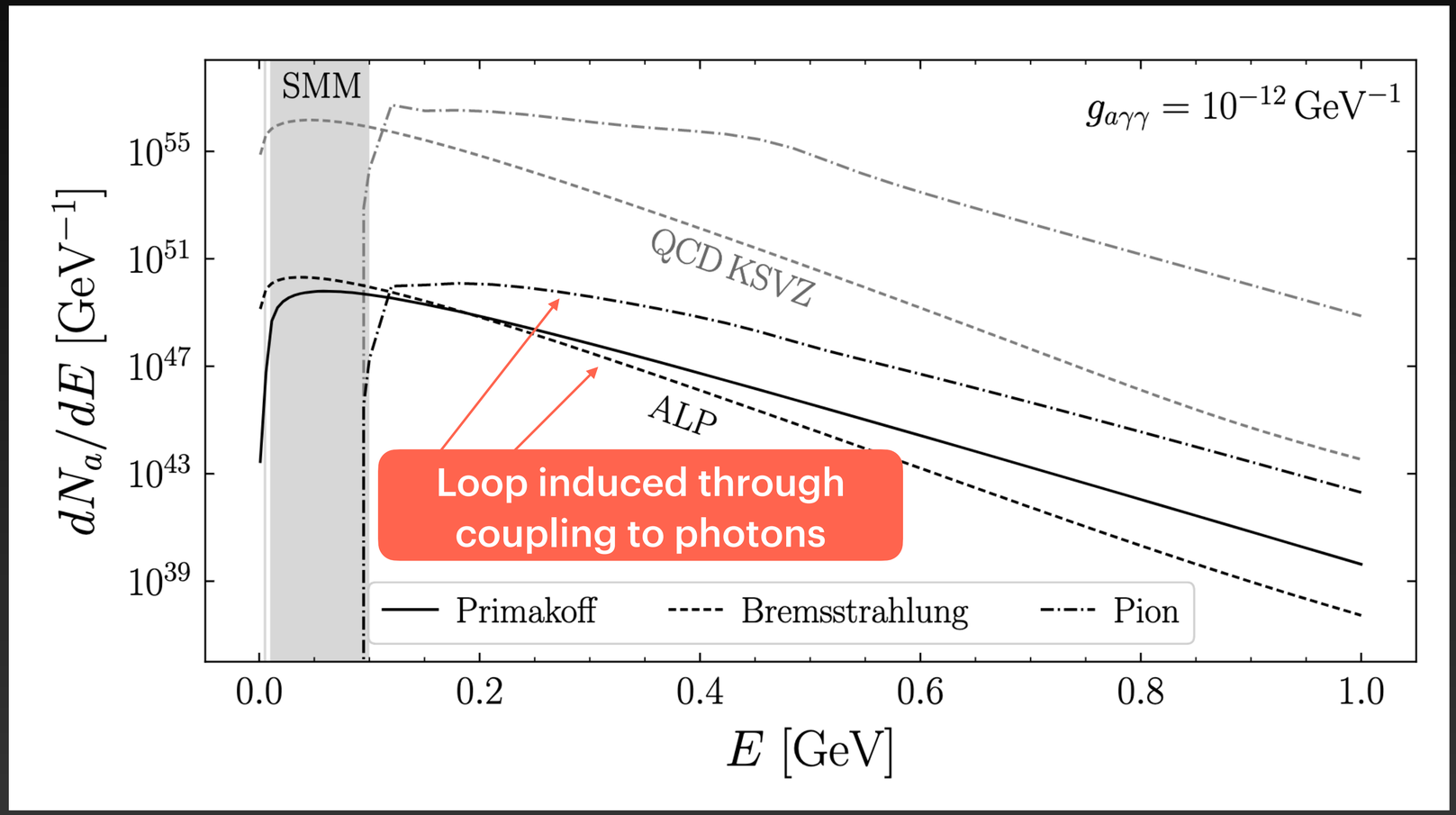
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- Close-by SN2023ixf in already used to search for heavy ALPs [Ravensburg et al. 2024]

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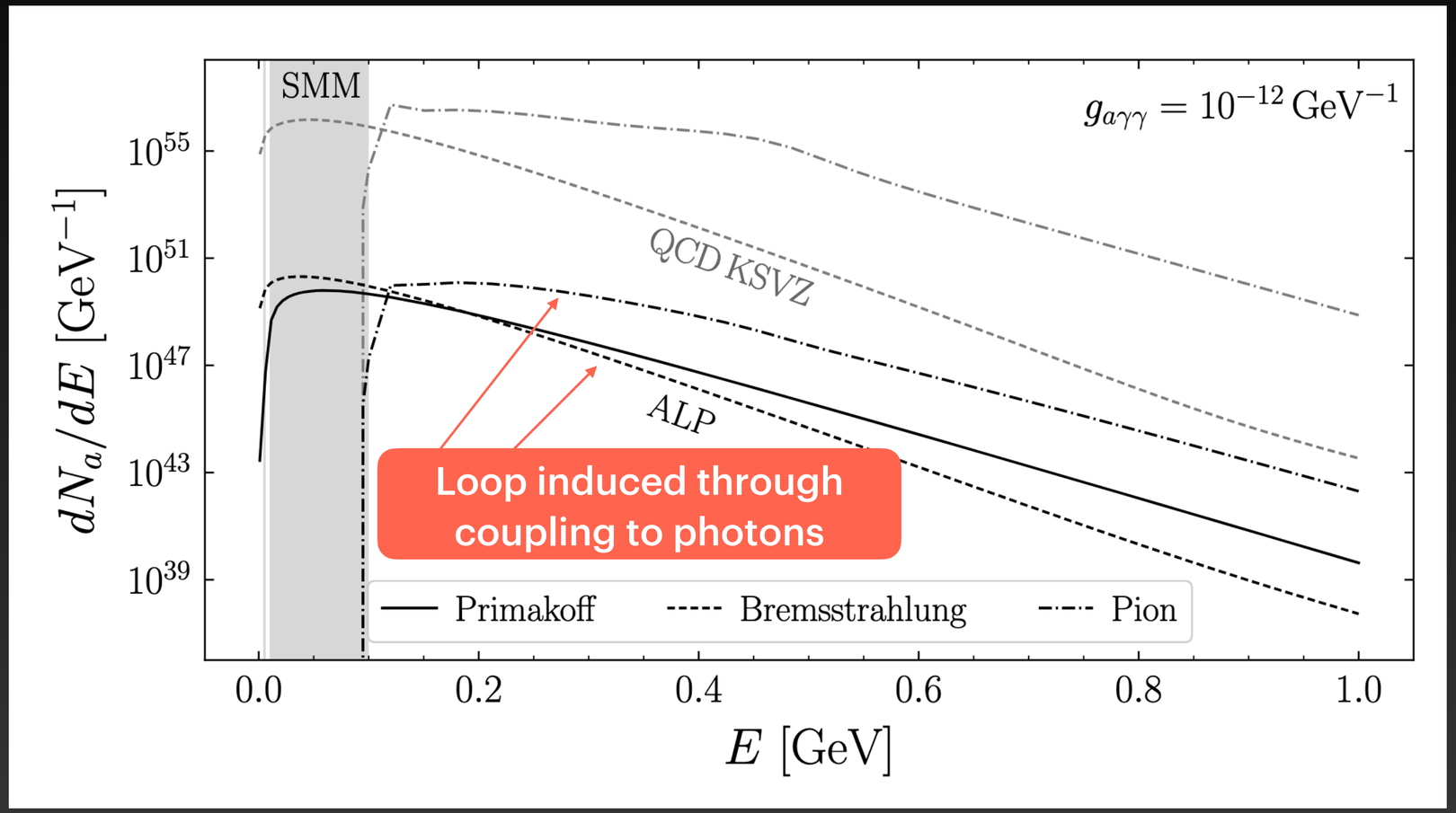
[MM & Petrushevska 2020]

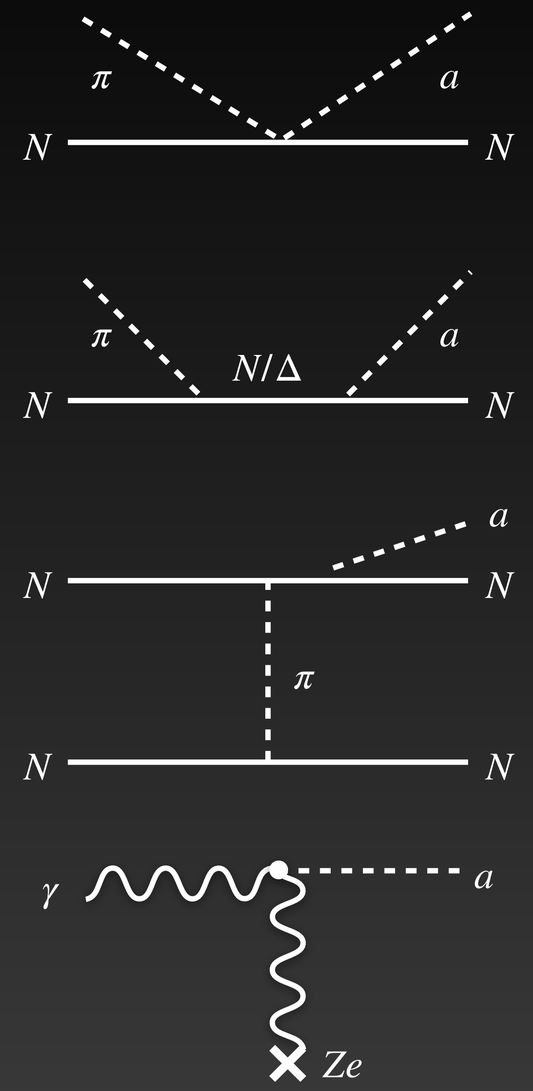
Pion-axion conversion dominating?



[Manzari et al. 2024]

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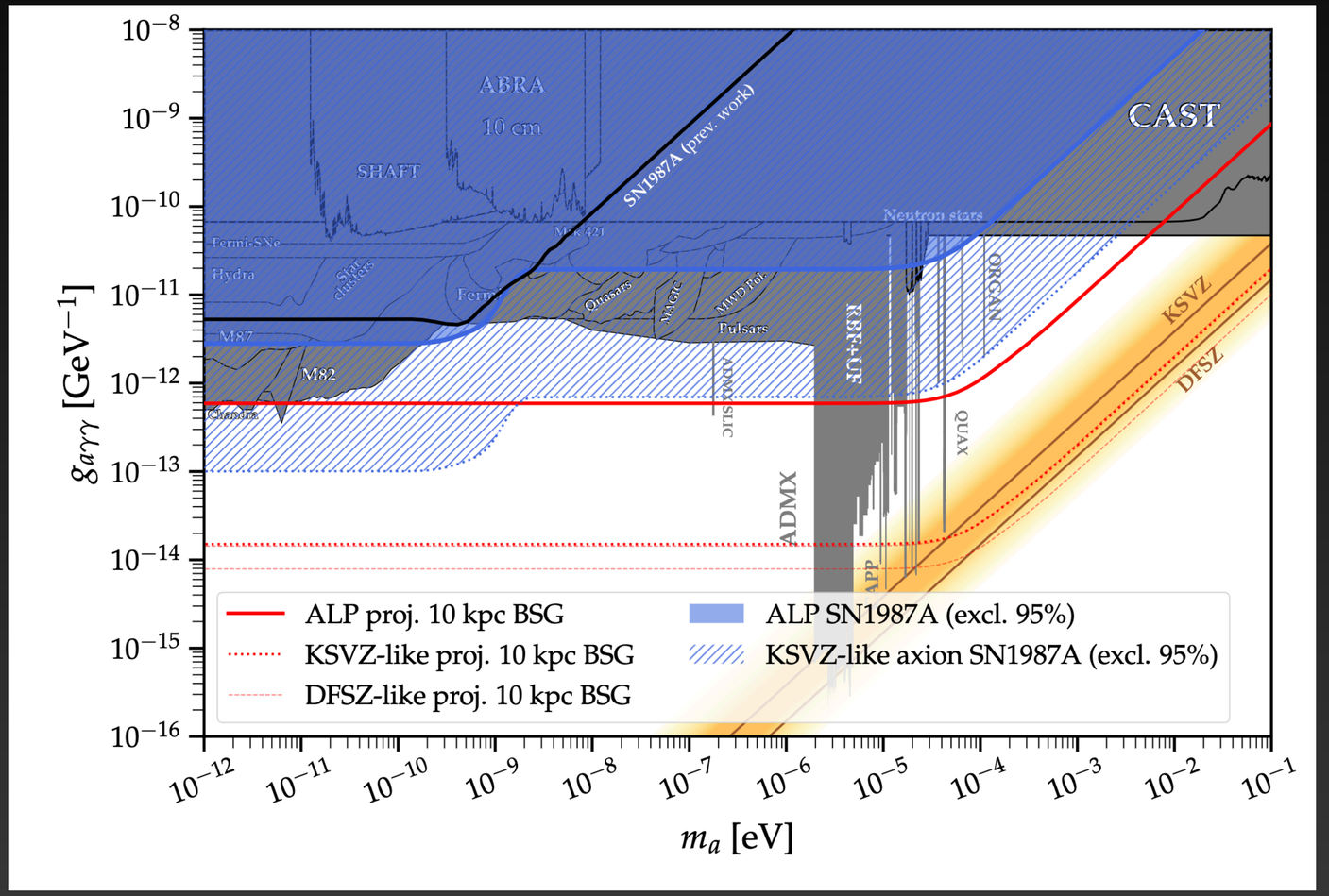




[Manzari et al. 2024]

Revised limits for SN1987A

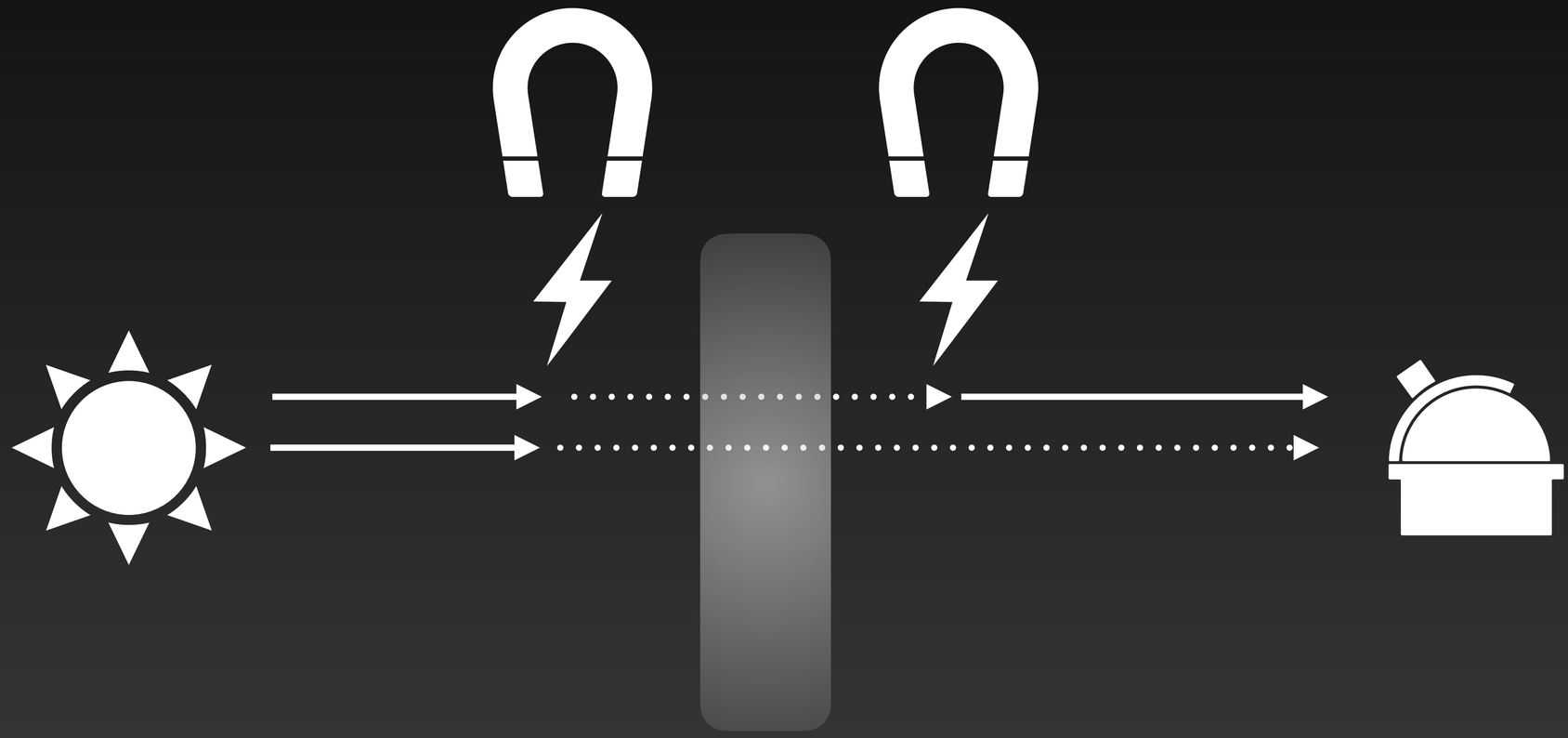
Taking pion-axion conversion and magnetic field of SN progenitor star into account



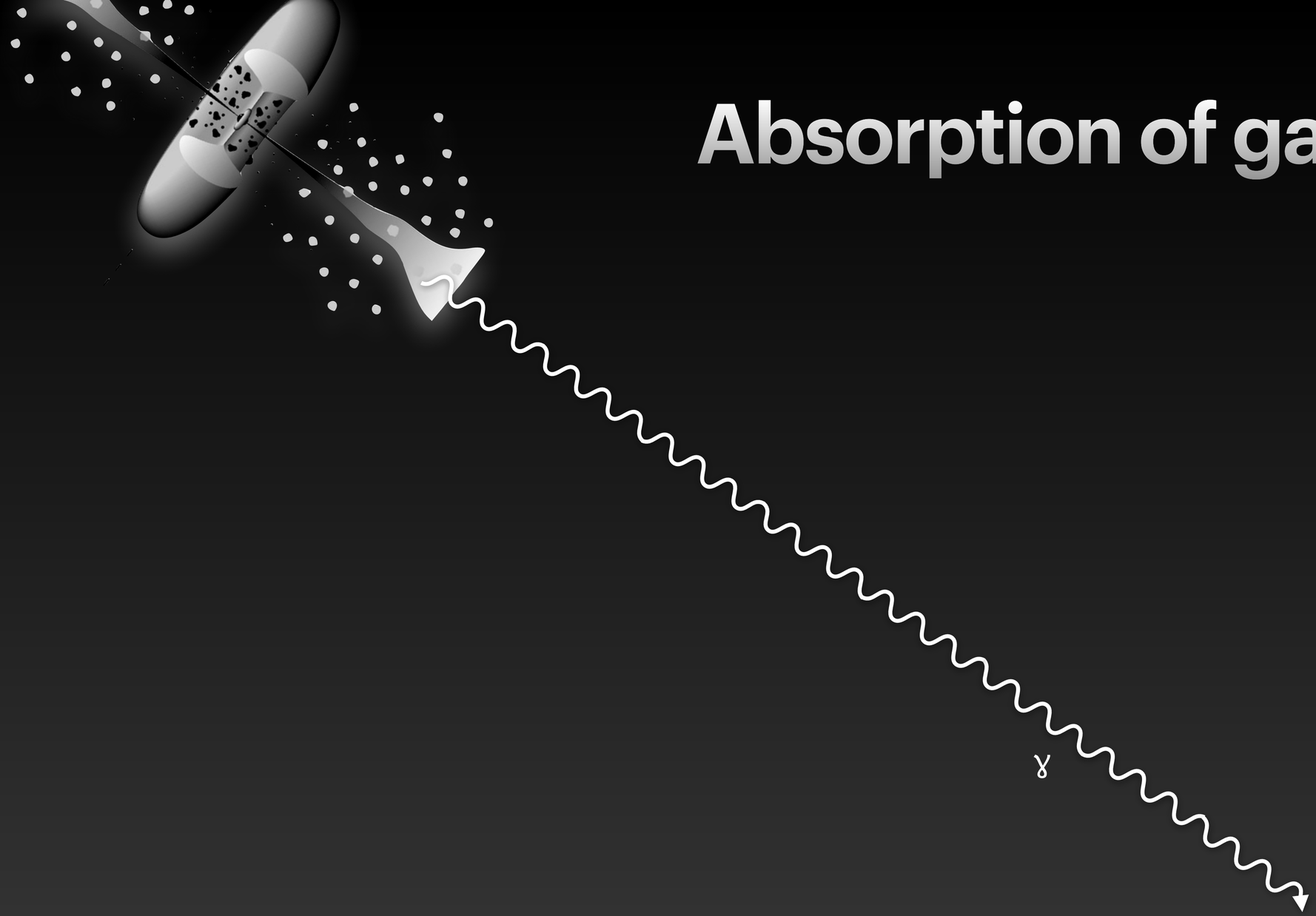
See also the talk by Alessandro Lella, Tuesday 3pm

[Manzari et al. 2024]

Photon disappearance and reappearance

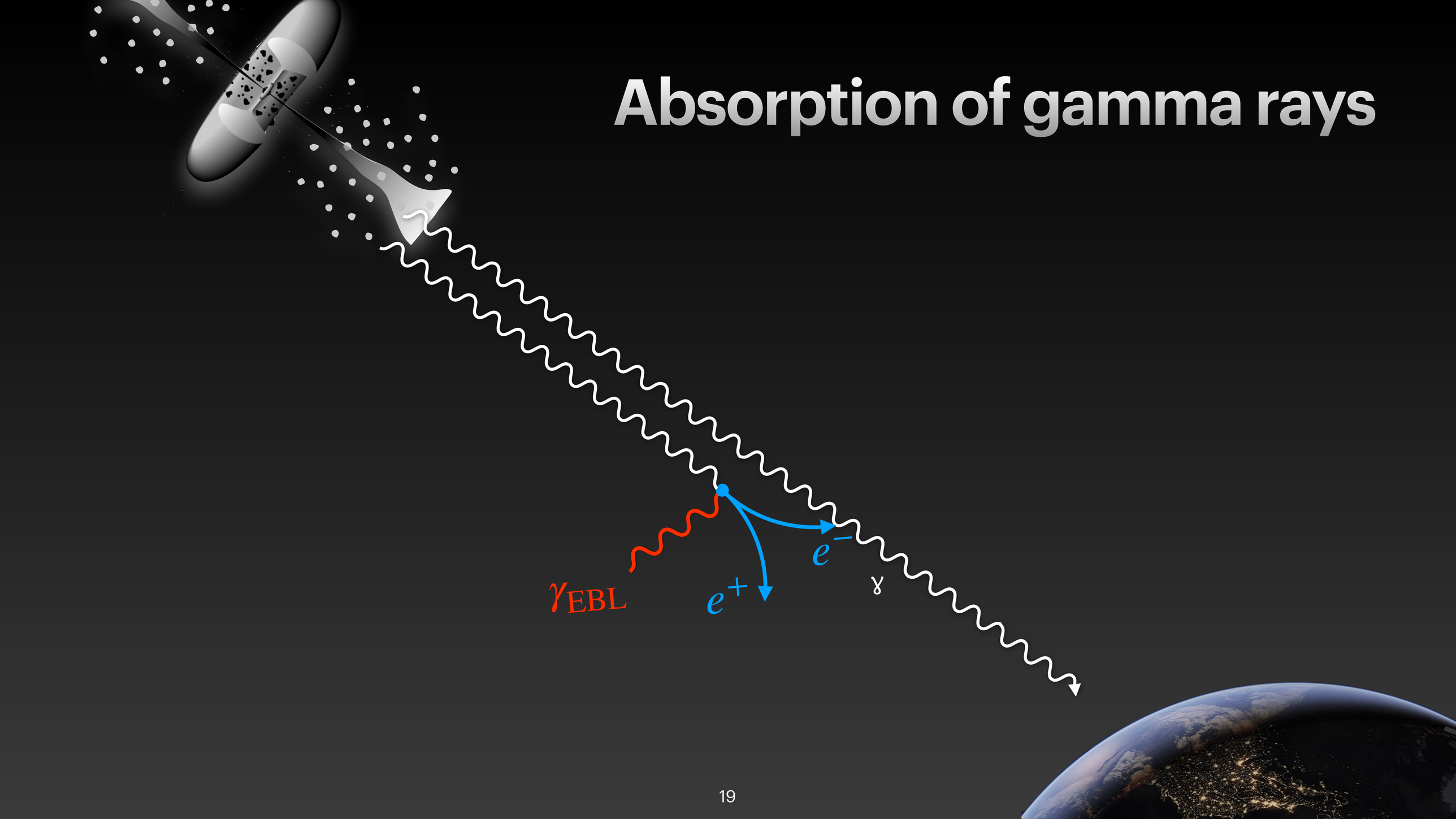


Absorption of gamma rays

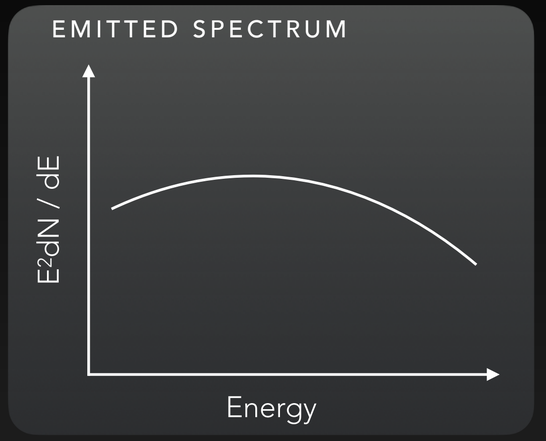


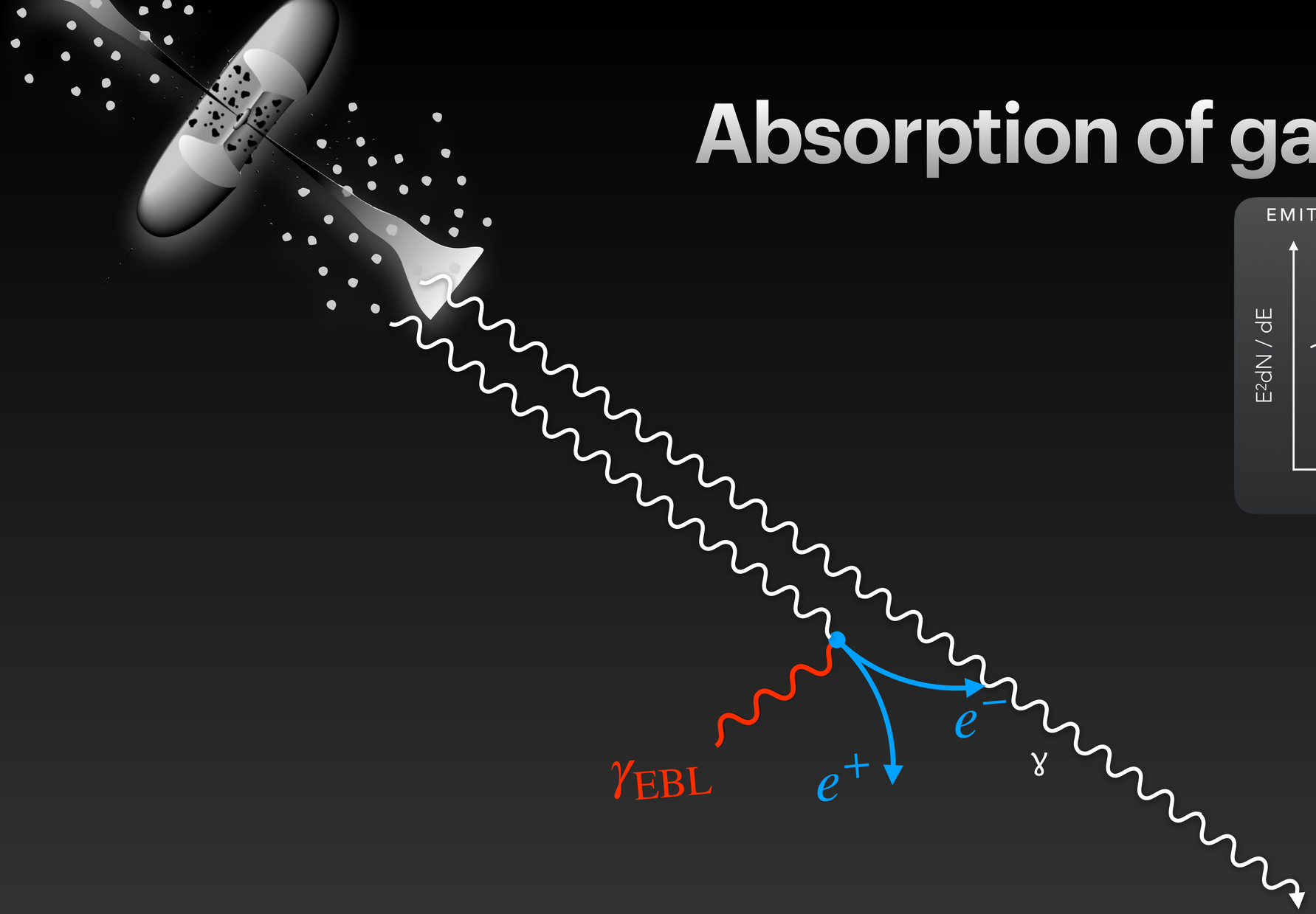


Absorption of gamma rays



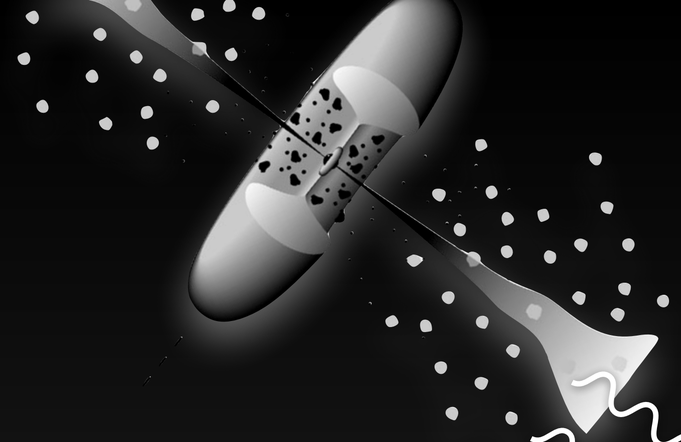
Absorption of gamma rays

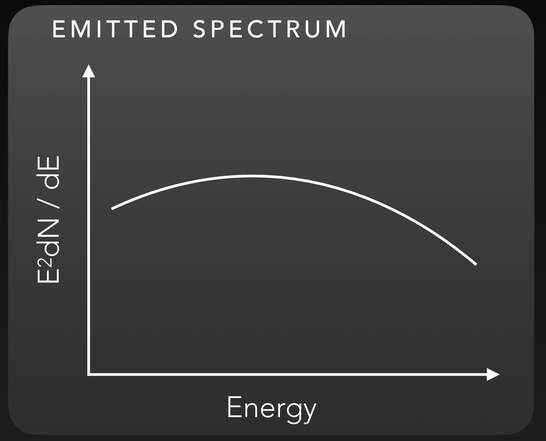






Absorption of gamma rays

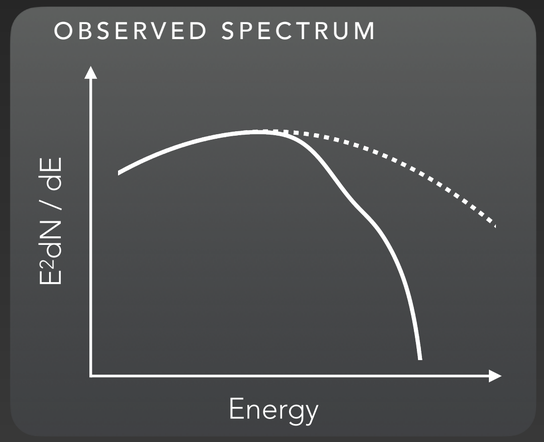




γ_{EBL} e^+ e^- γ

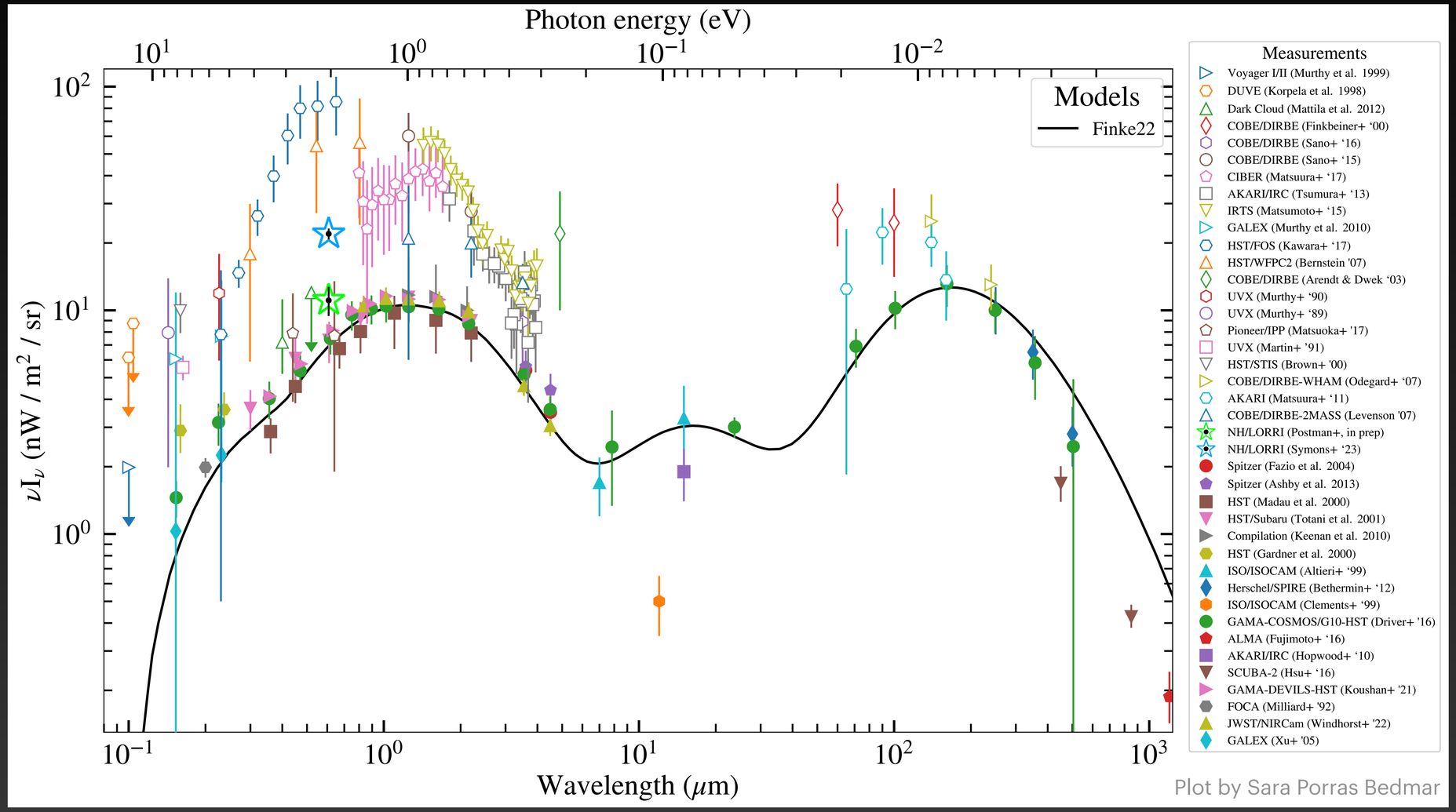
EXPONENTIAL ABSORPTION WITH OPTICAL DEPTH $\tau_{\gamma\gamma}$:

$$\exp\left(-\tau_{\gamma\gamma}(E,z)\right)$$





The extragalactic background light

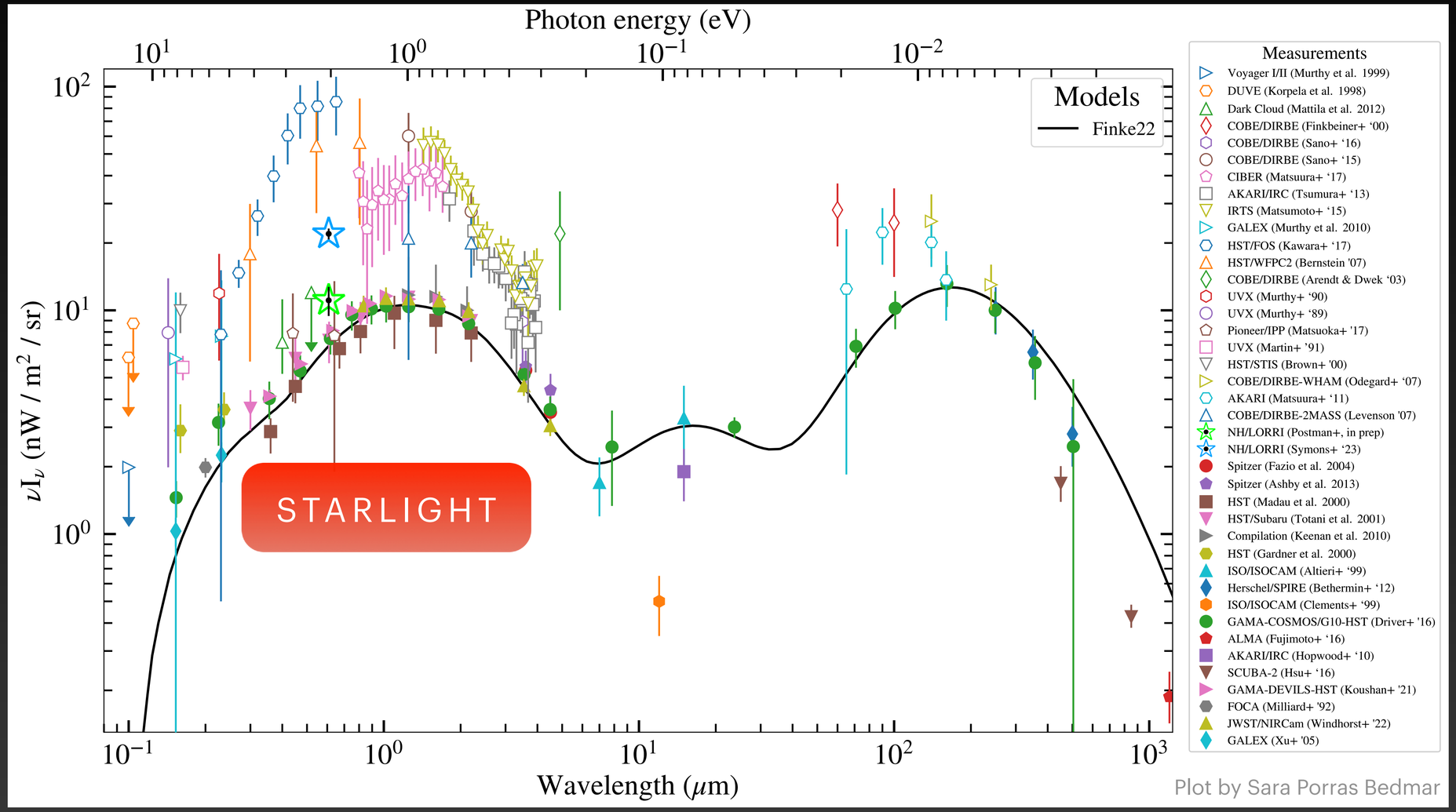


Plot by Sara Porras Bedmar

Biteau (2024), 10.5281/zenodo.7842238

[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013]

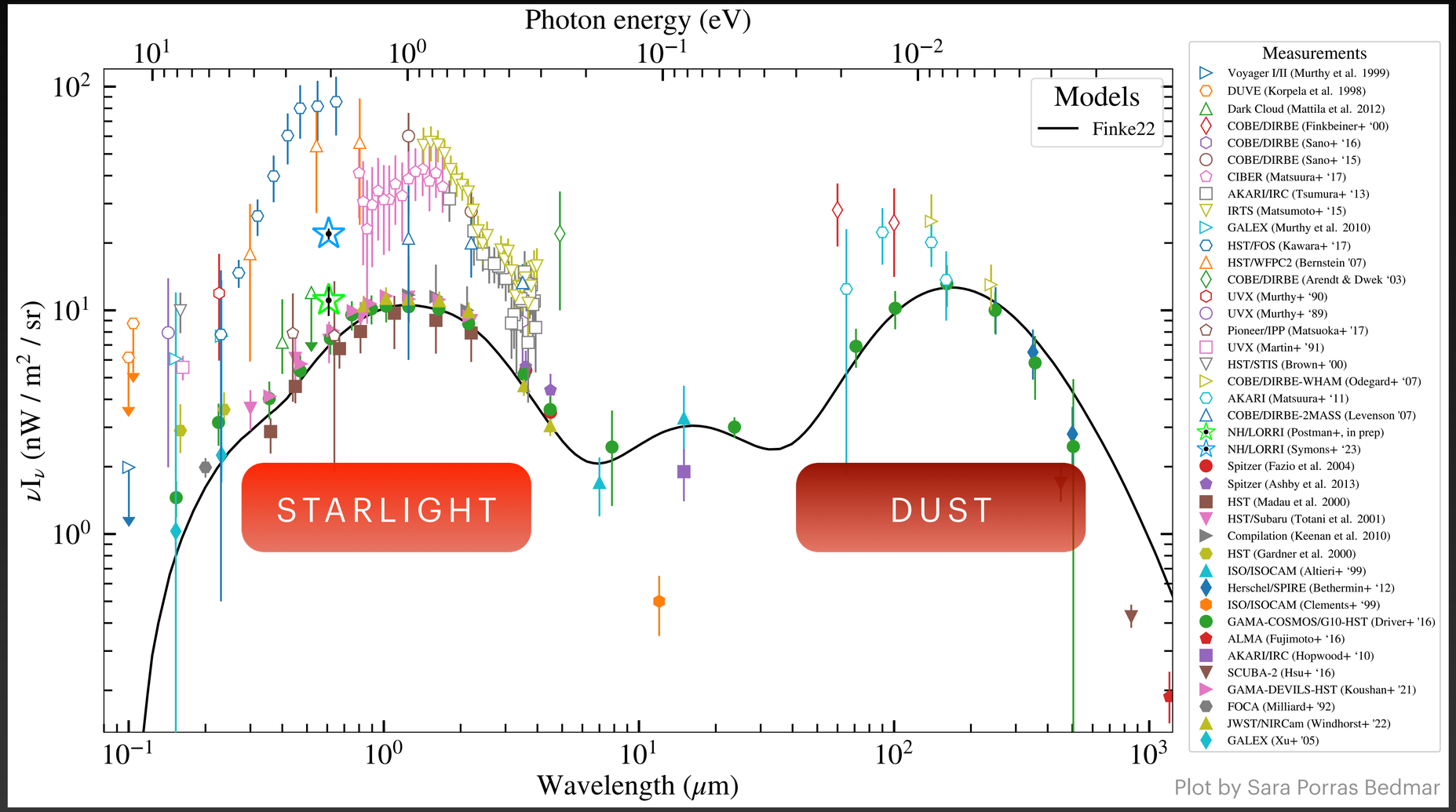
The extragalactic background light



Plot by Sara Porras Bedmar

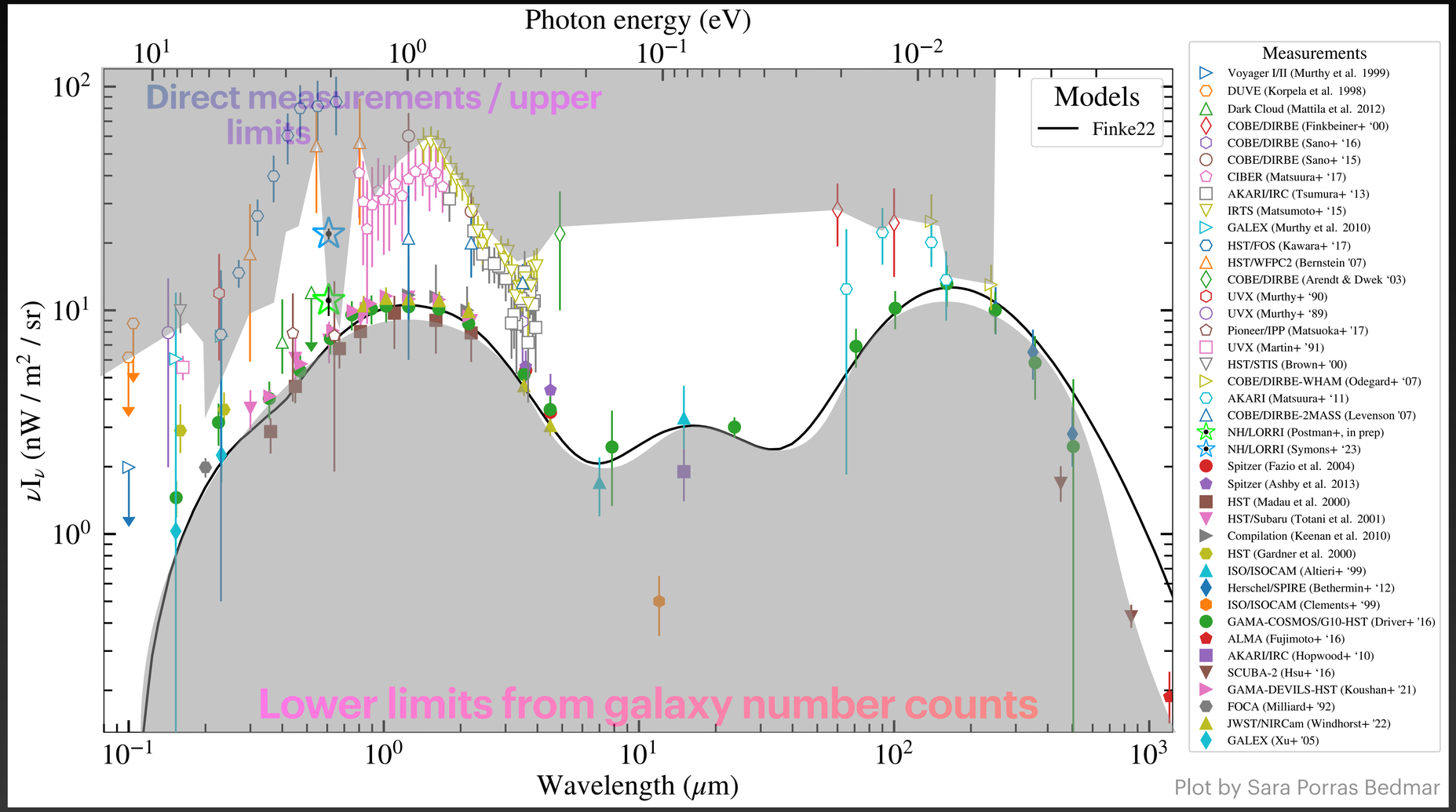
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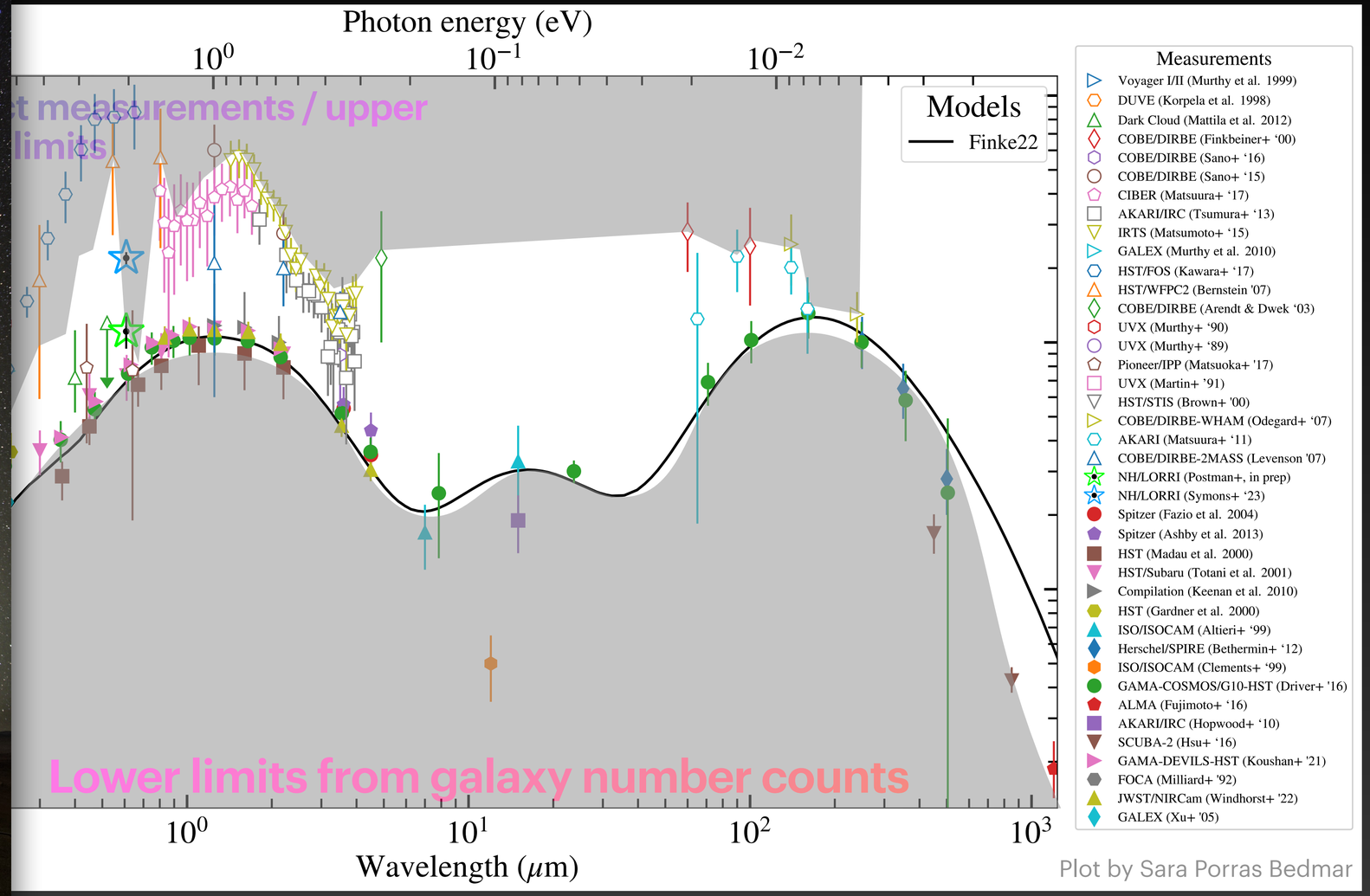
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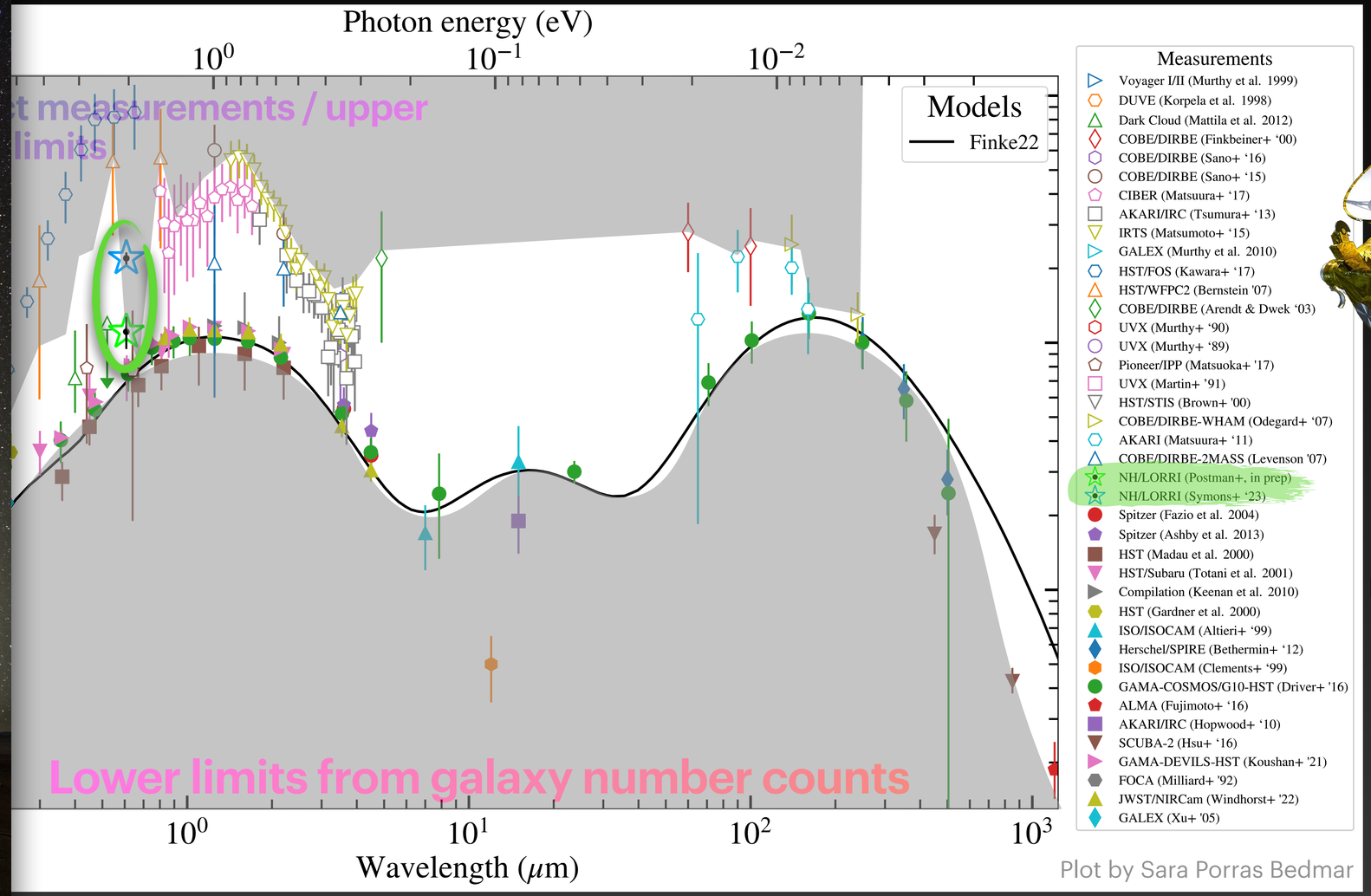
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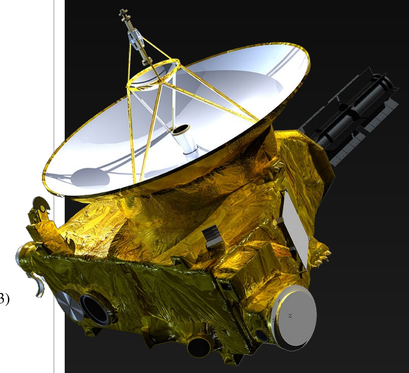
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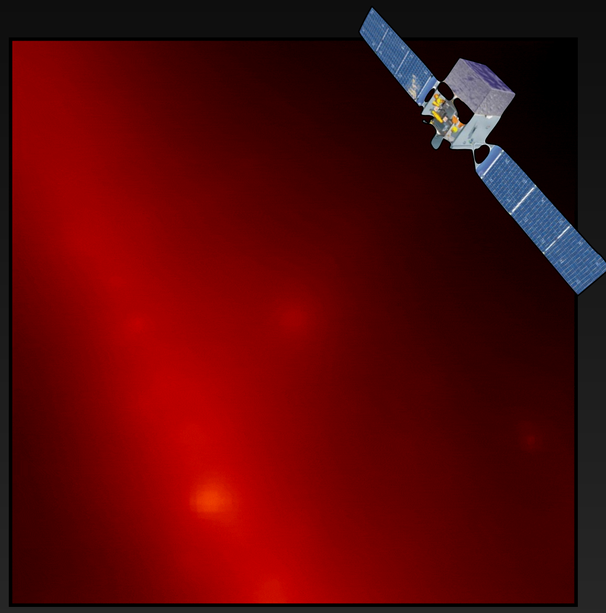


New Horizons Spacecraft / Long Range Reconnaissance Imager (LORRI): EBL measurement at **53 AU!**

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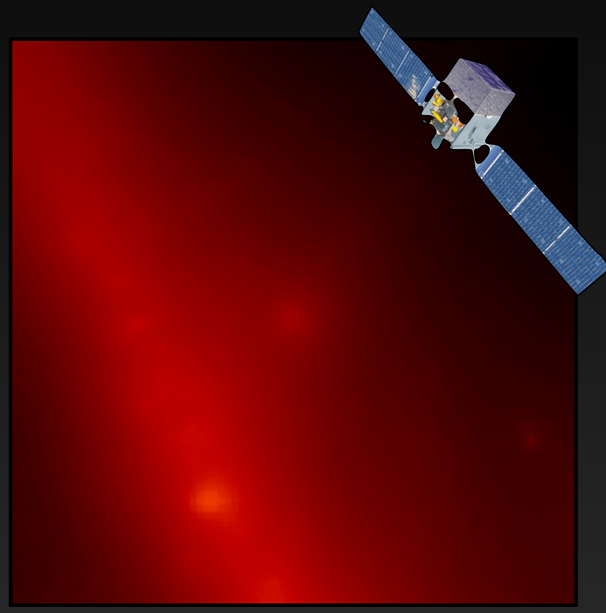
GRB221009A — BOAT



https://gcn.gsfc.nasa.gov/other/221009A.gcn3

GRB221009A — BOAT

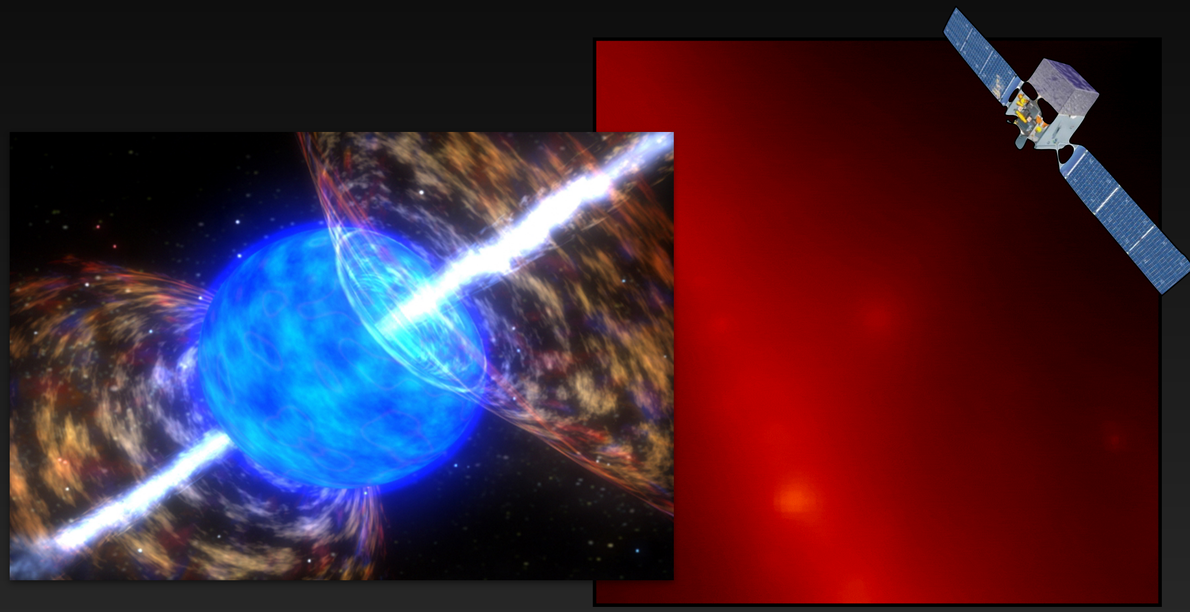
- Brightest GRB ever observed



https://gcn.gsfc.nasa.gov/other/221009A.gcn3

GRB221009A — BOAT

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- Probable precursor: collapsar (massive star collapsing to black hole)



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GRB221009A — BOAT

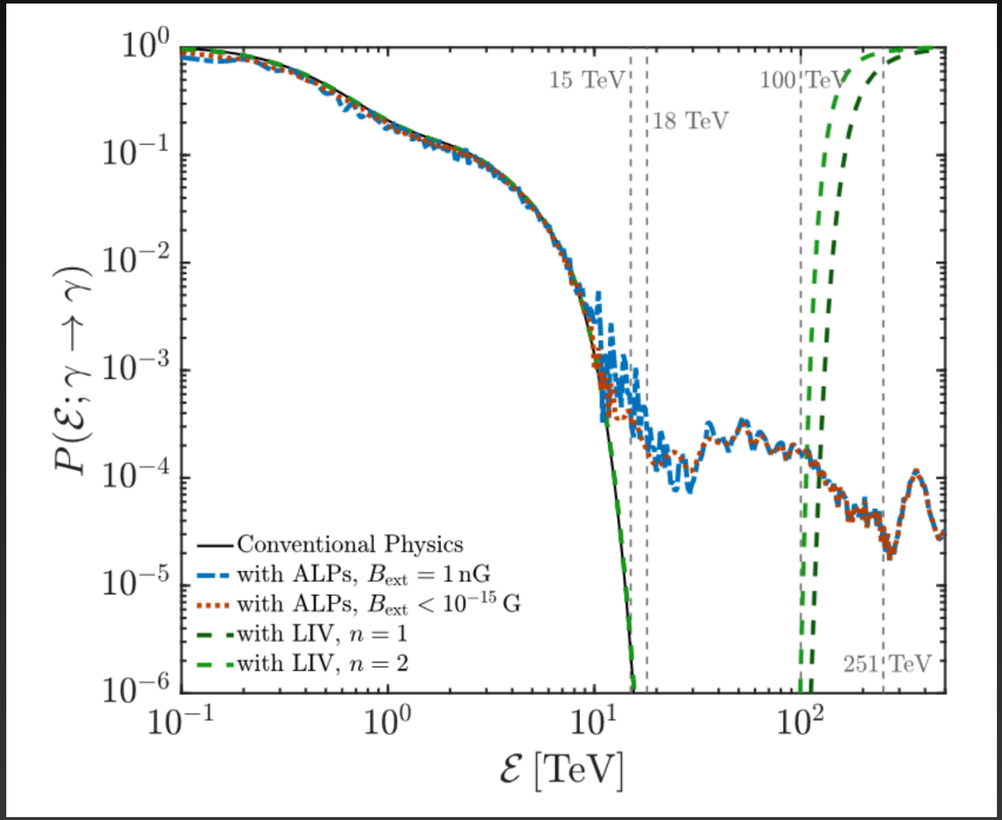
- Brightest GRB ever observed
- Probable precursor: collapsar (massive star collapsing to black hole)
- Redshift $z = 0.1505$ (VLT X-Shooter, GTC) from CaI, II absorption lines
- Detected at very high energies with LHAASO up to 13 TeV



https://gcn.gsfc.nasa.gov/other/221009A.gcn3
[LHAASO Collaboration Science 2023, Sci. Adv. 2023]

ALP interpretation required?

[Galanti et al. 2024]

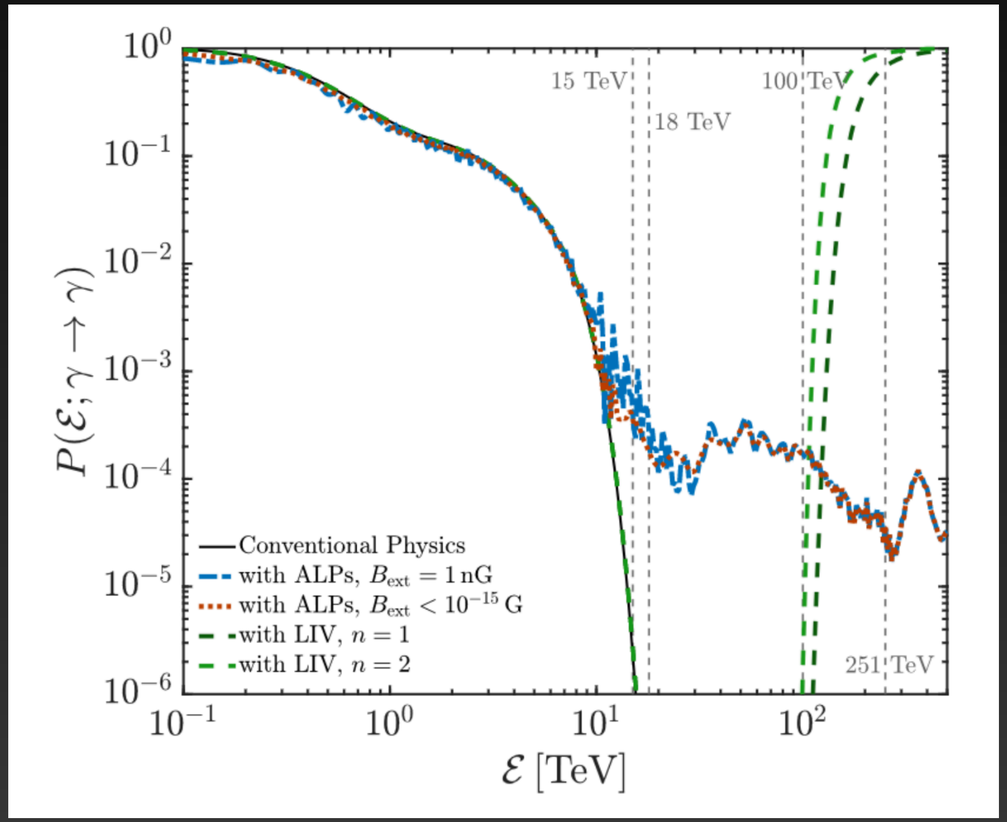


[Galanti et al. 2024 and 10+ other papers]

ALP interpretation required?

- Astrophysical environments considered:

[Galanti et al. 2024]

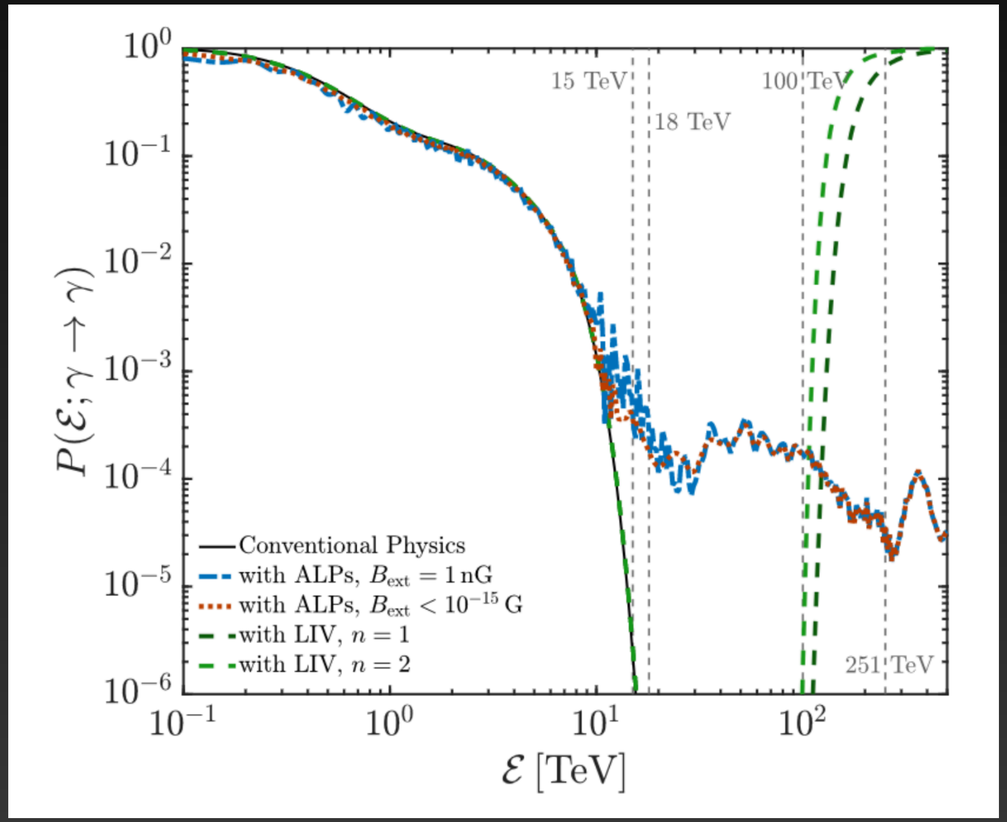


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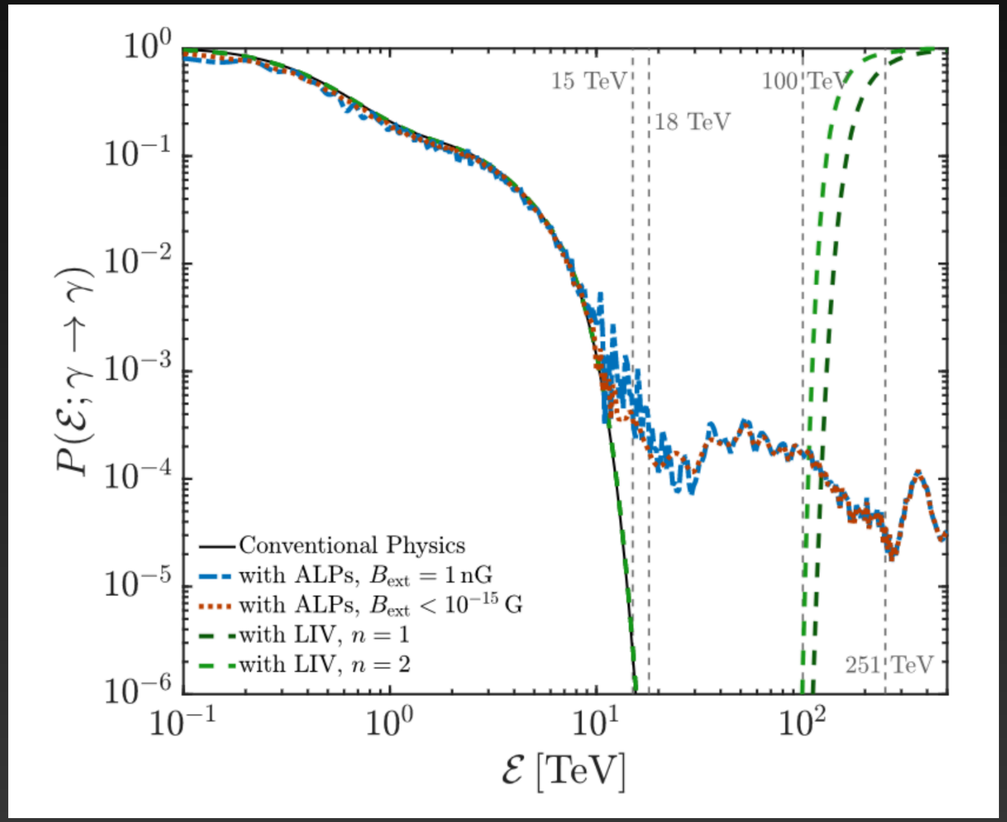


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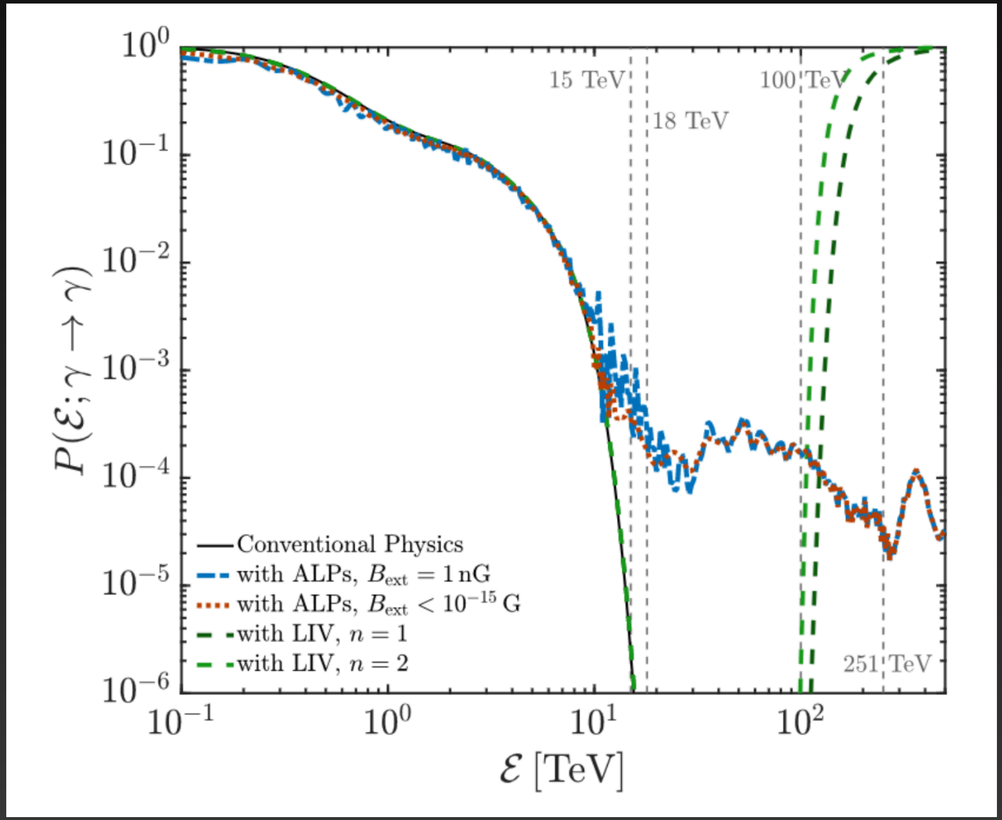


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[Galanti et al. 2024]

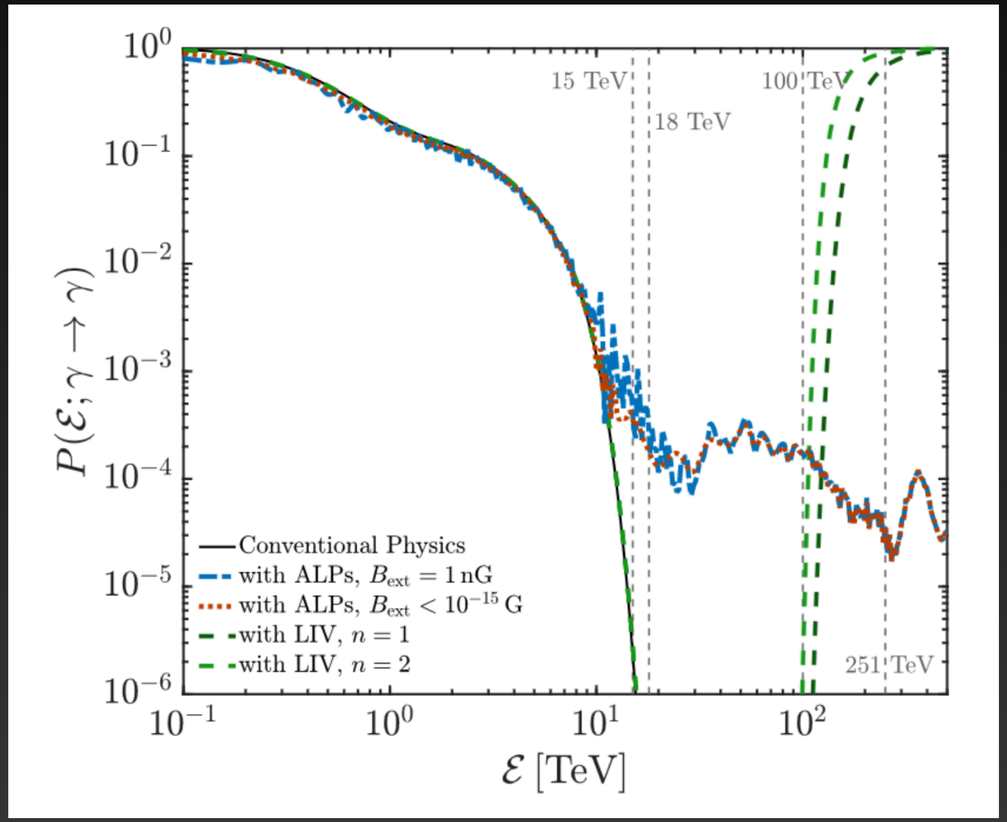


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[Galanti et al. 2024]

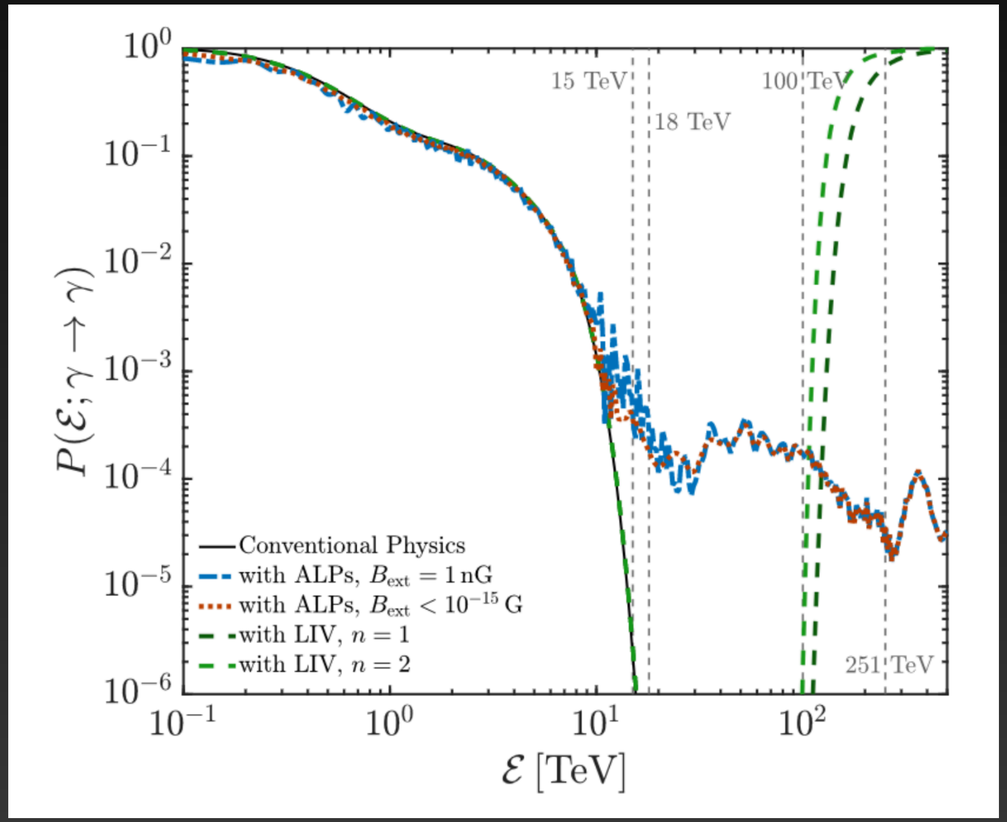


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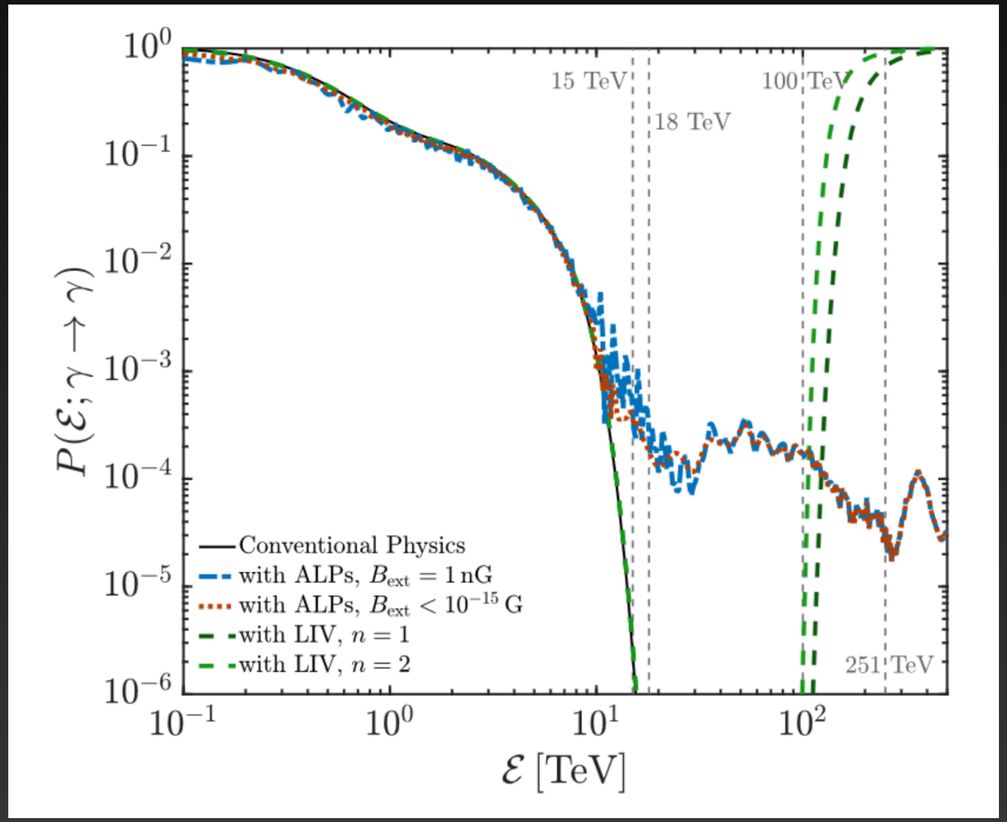


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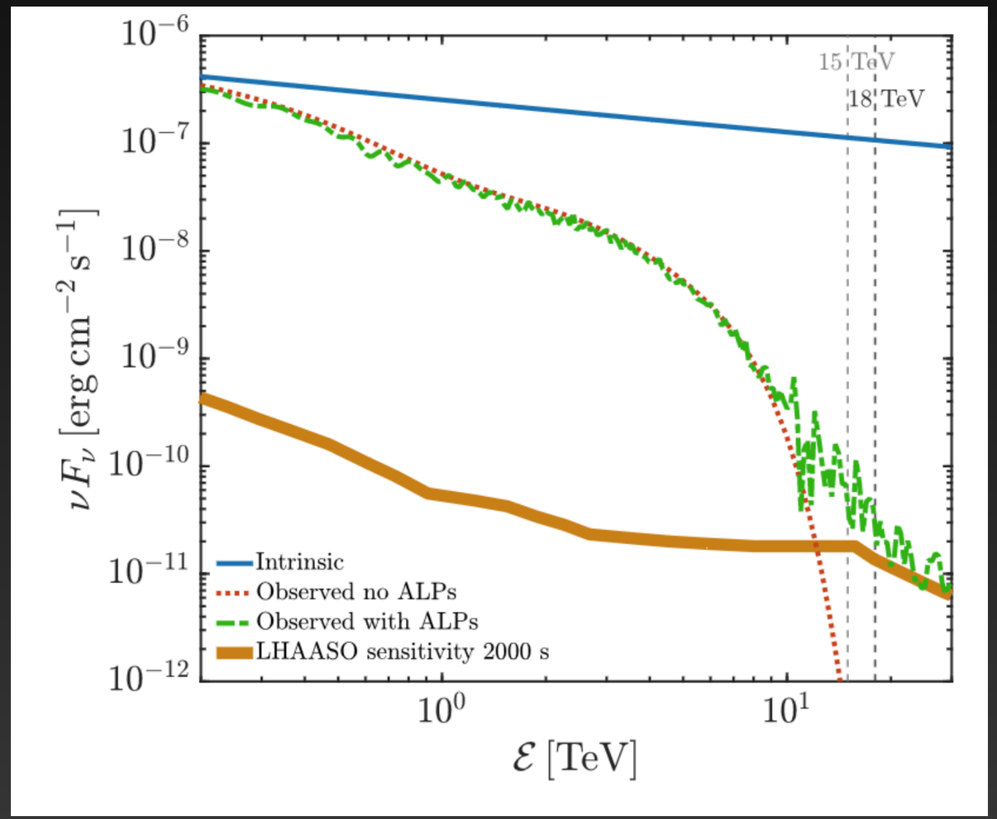


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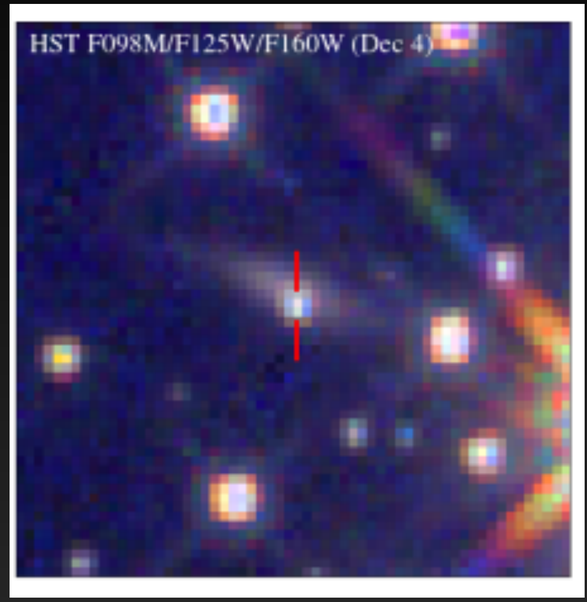


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Caveats

Caveats

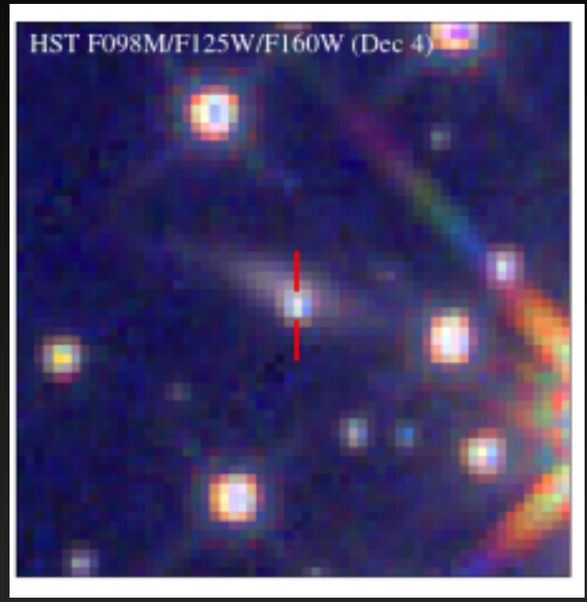
- Host galaxy observed with JWST and HST:



[Levan et al. 2023]

Caveats

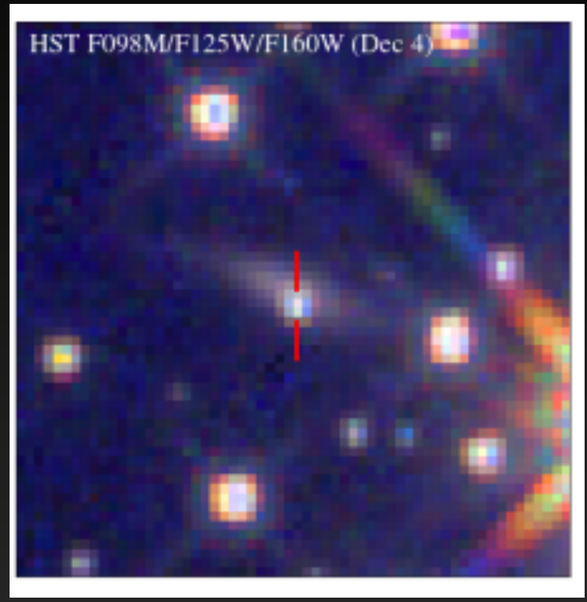
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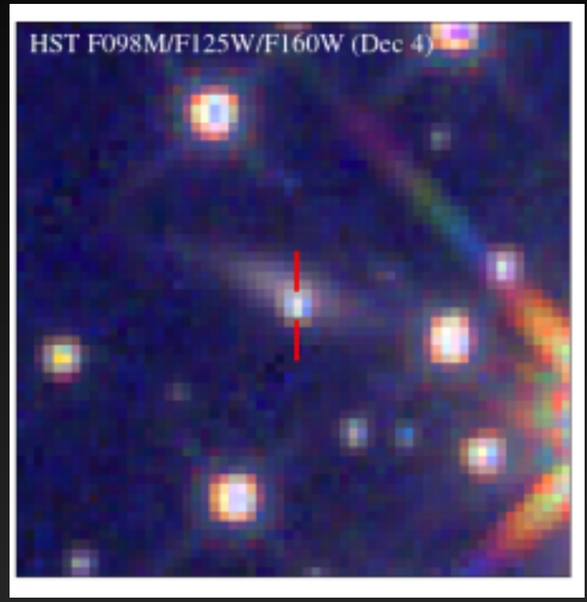
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Caveats

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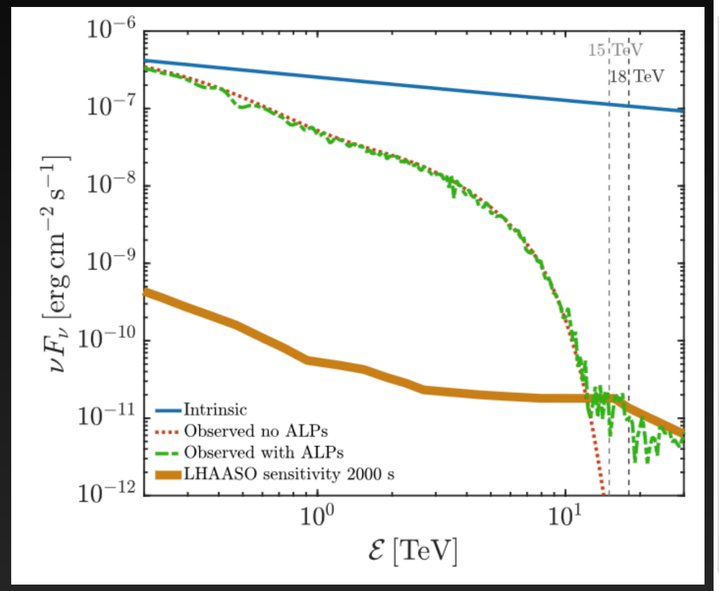


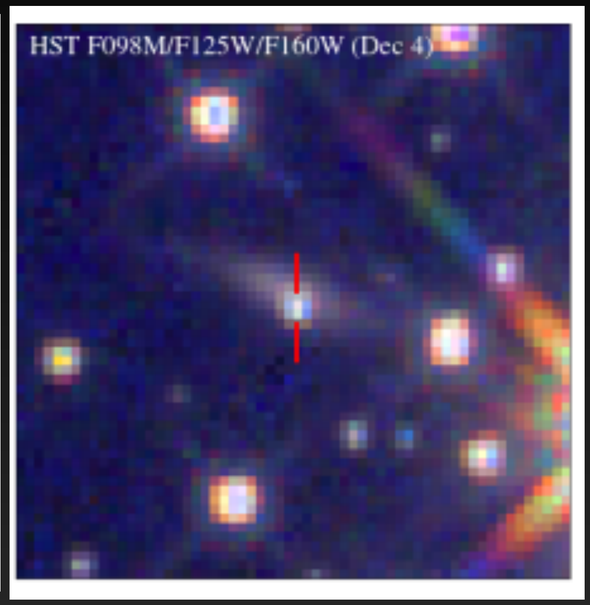
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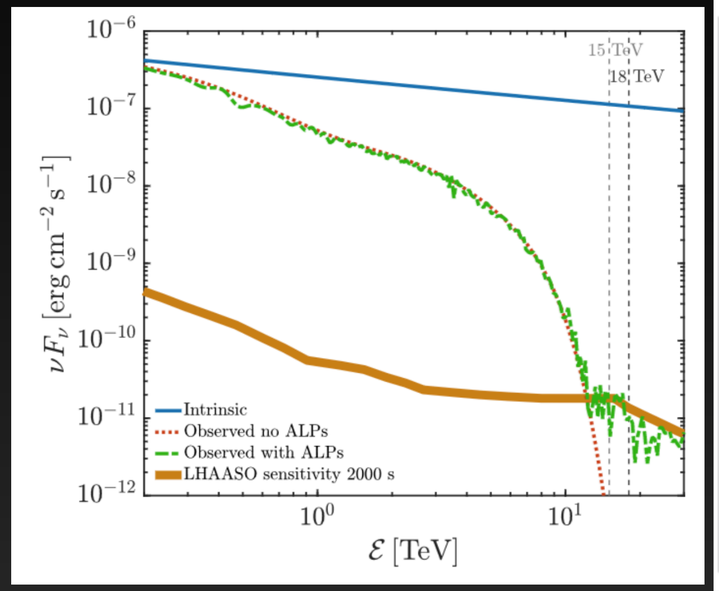


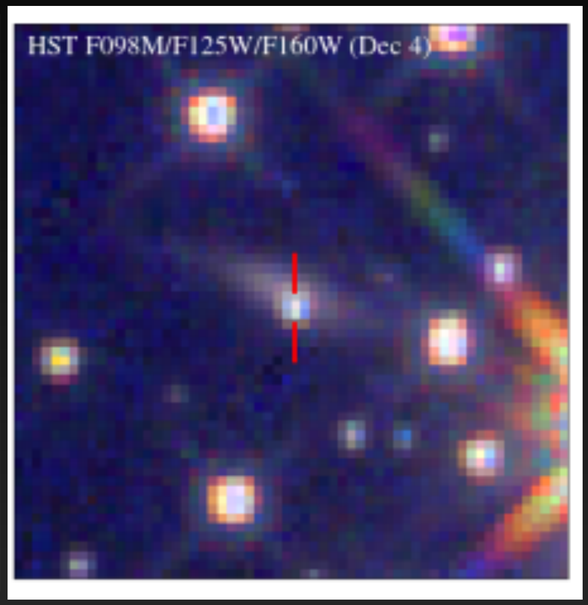
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Caveats

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Galanti et al. 2024



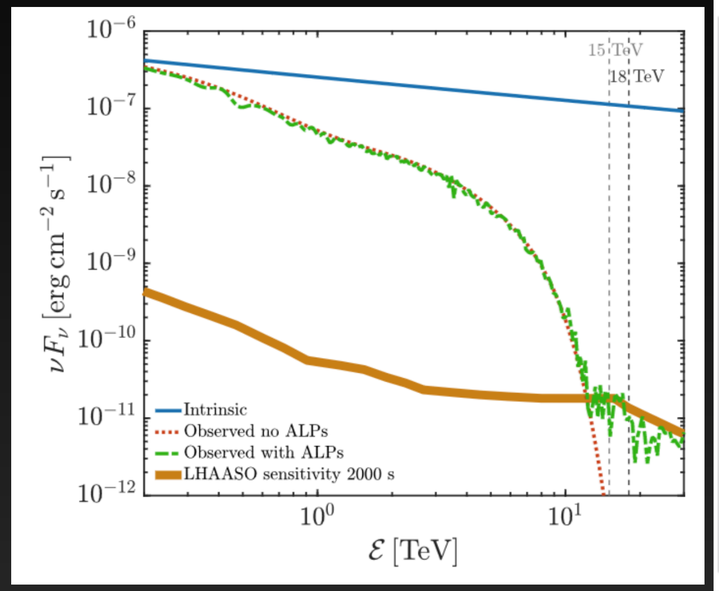


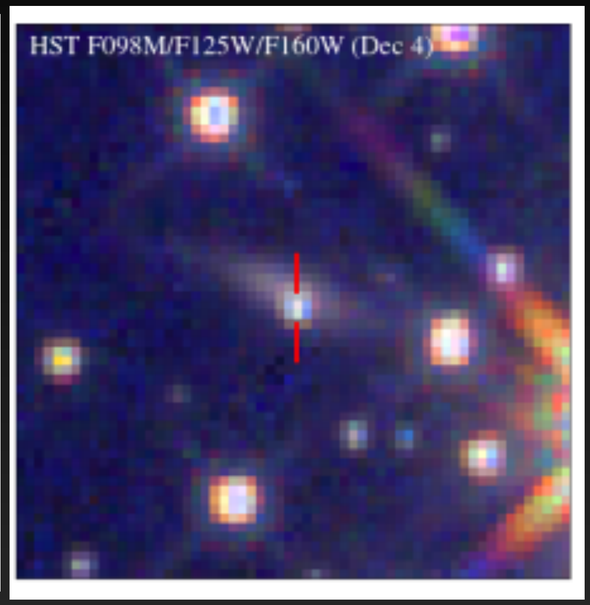
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Caveats

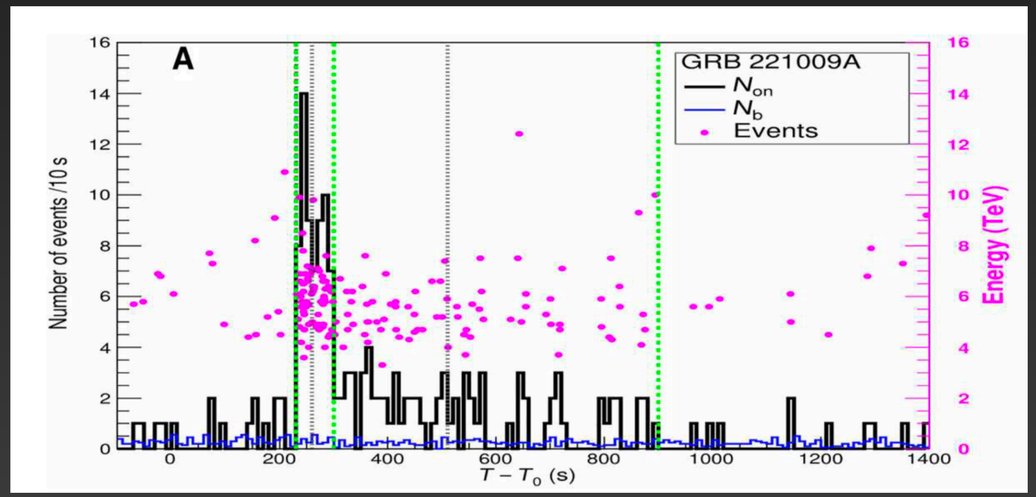
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Galanti et al. 2024





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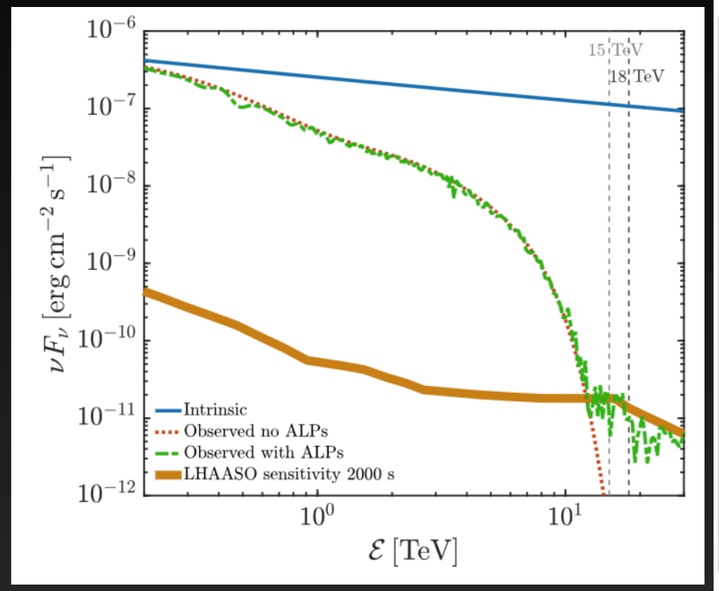


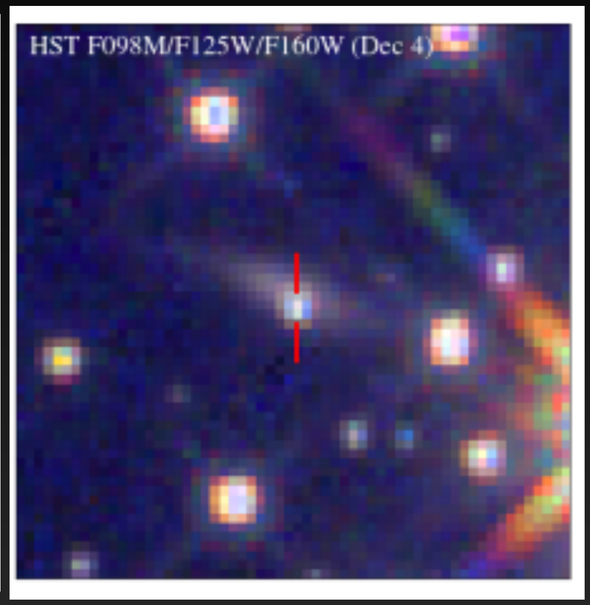
[Cao et al. 2023]

Caveats

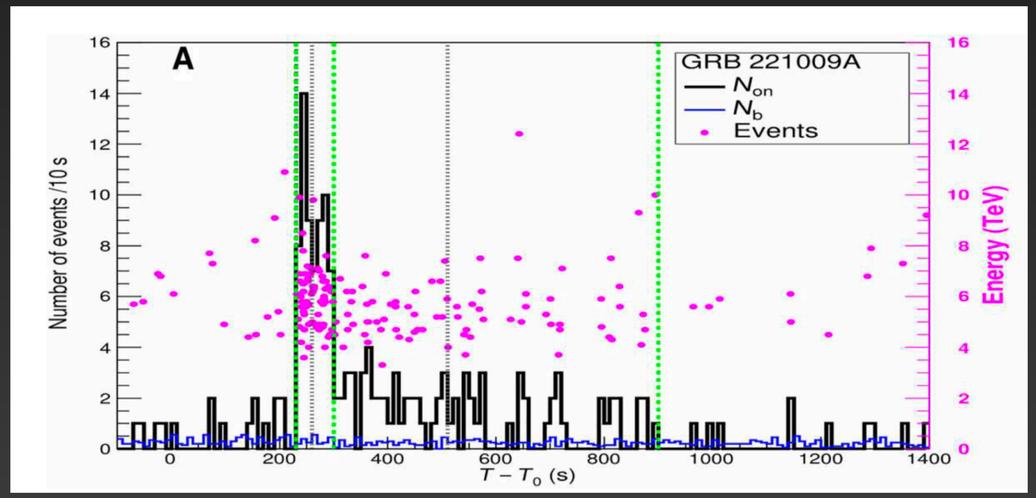
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Galanti et al. 2024





[Levan et al. 2023]



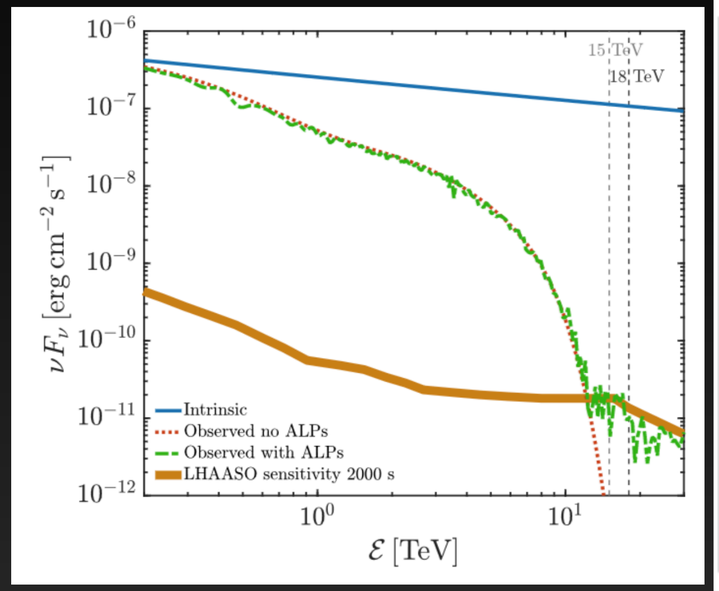
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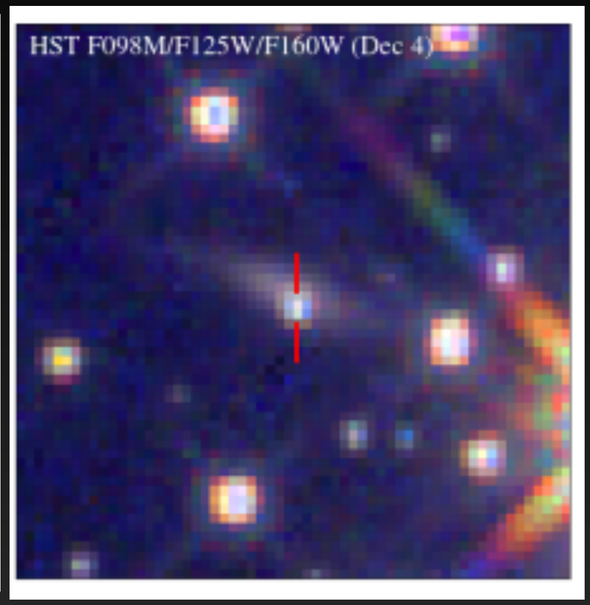
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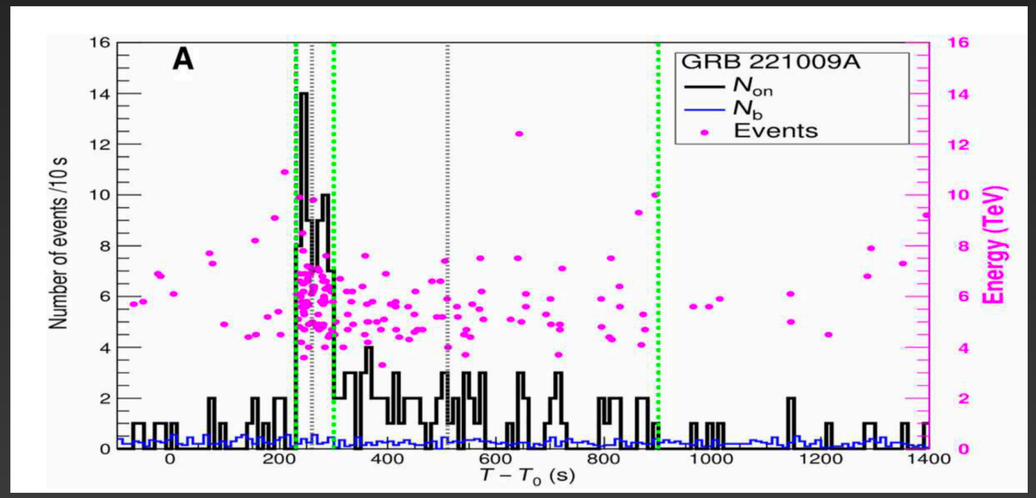
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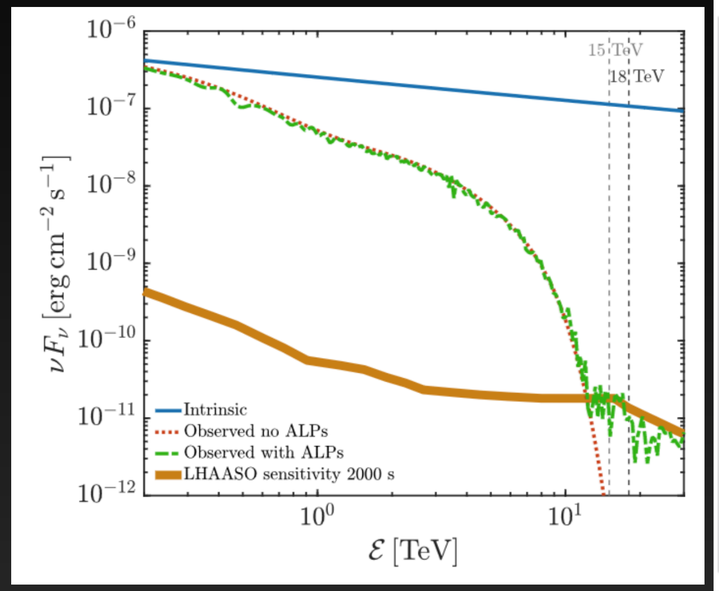
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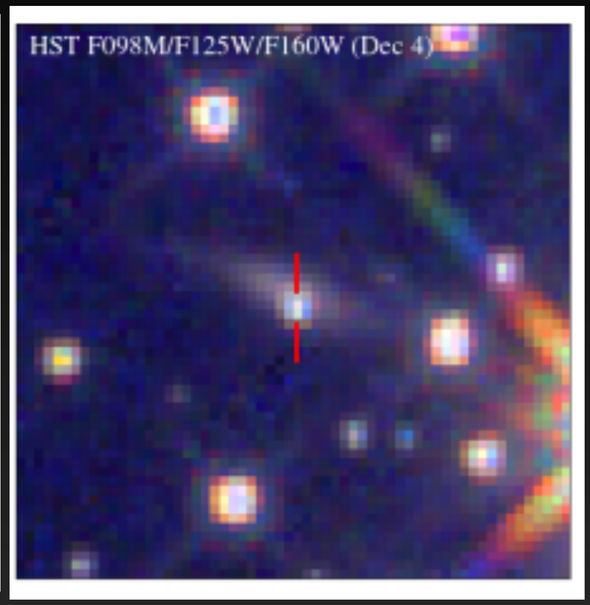
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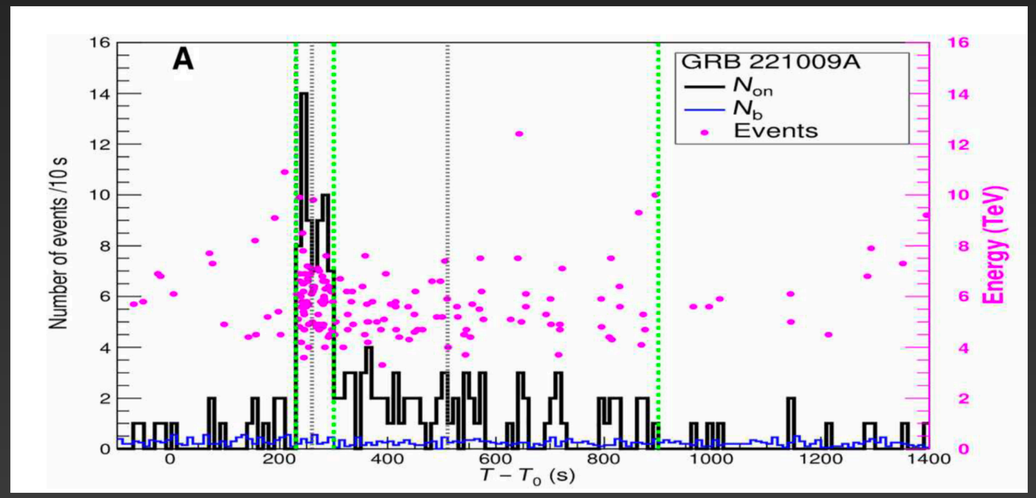
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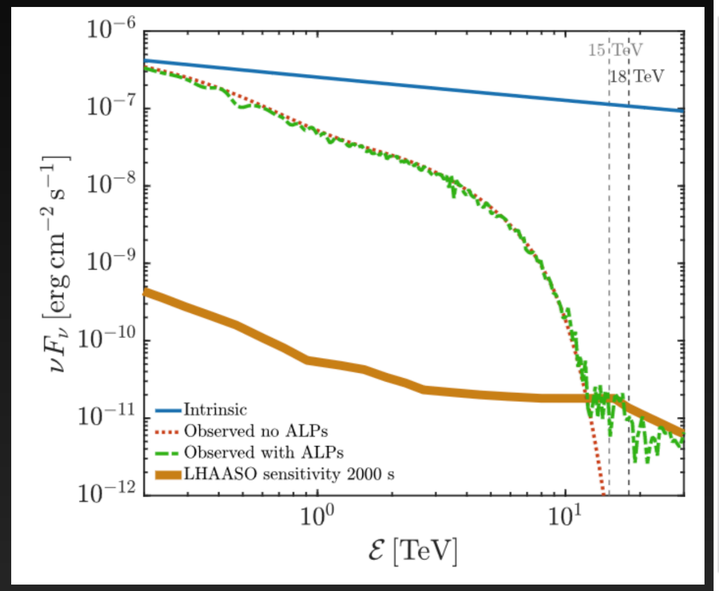
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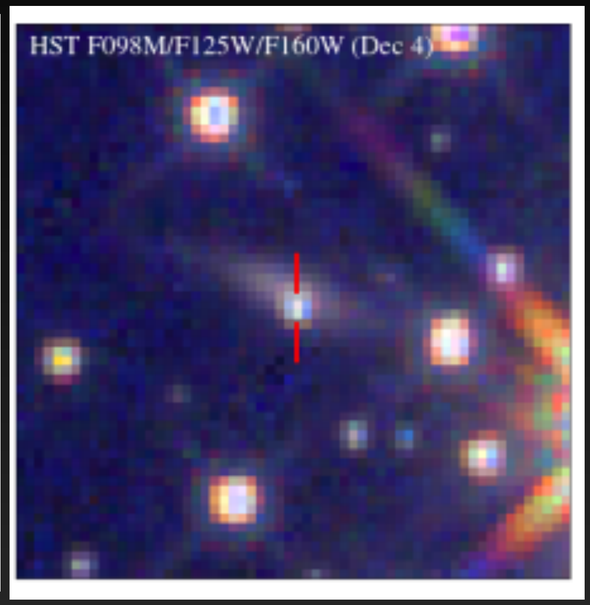
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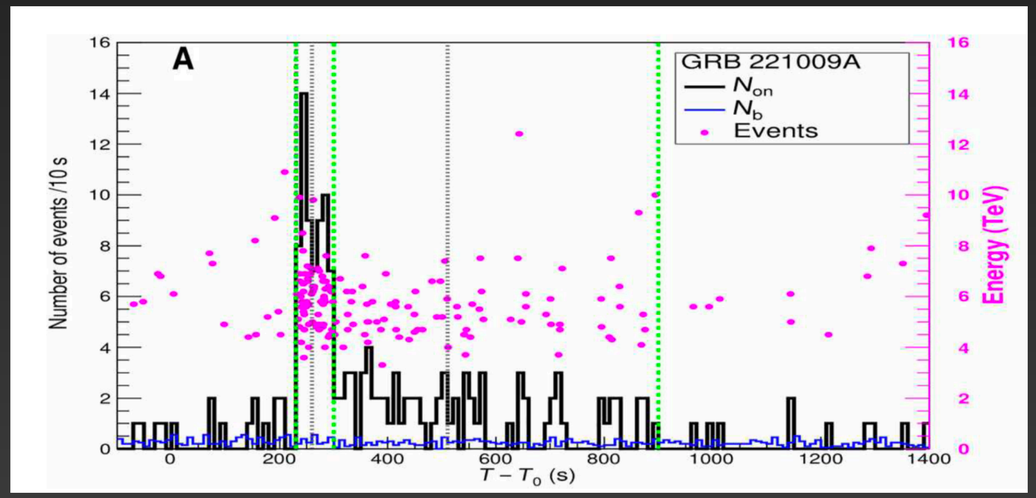
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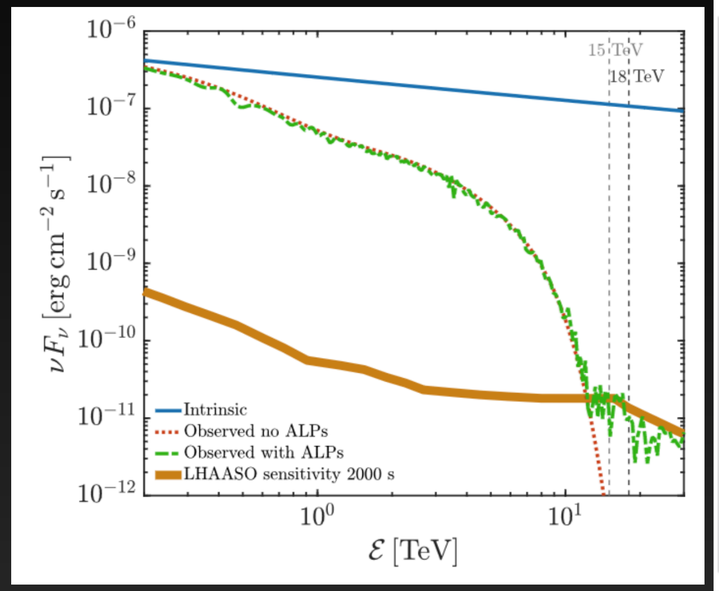
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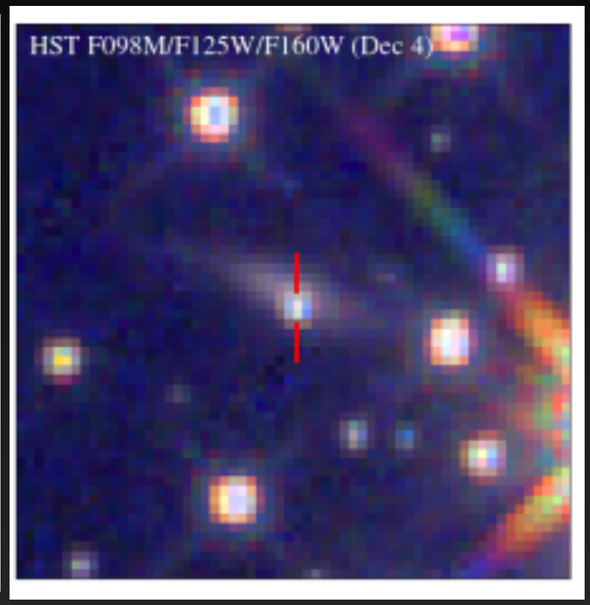
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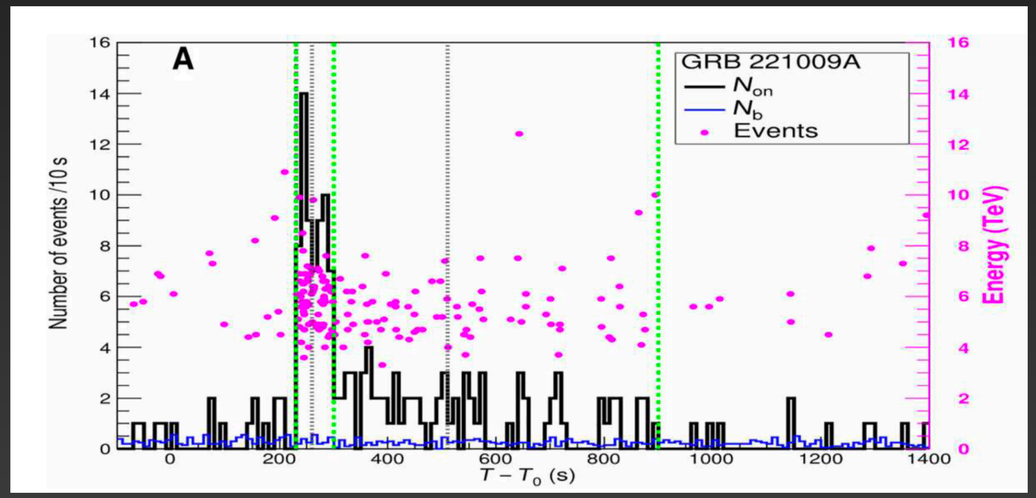
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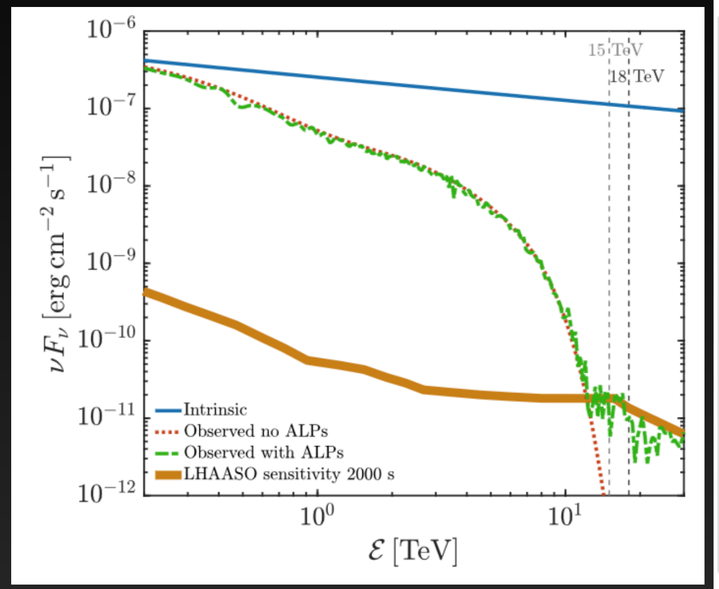
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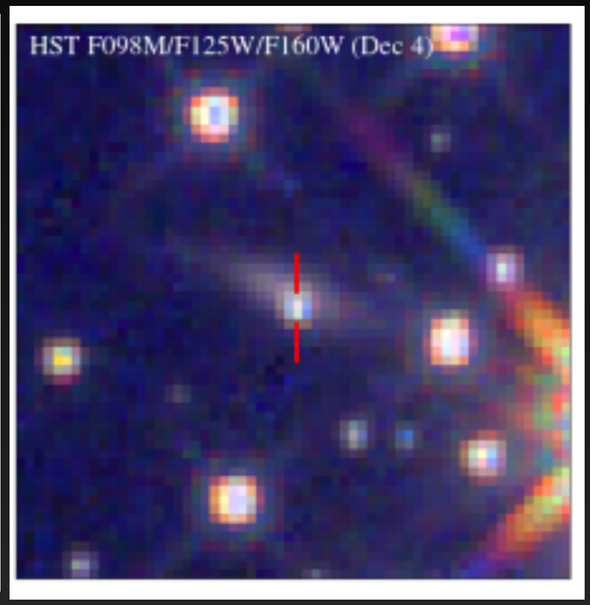
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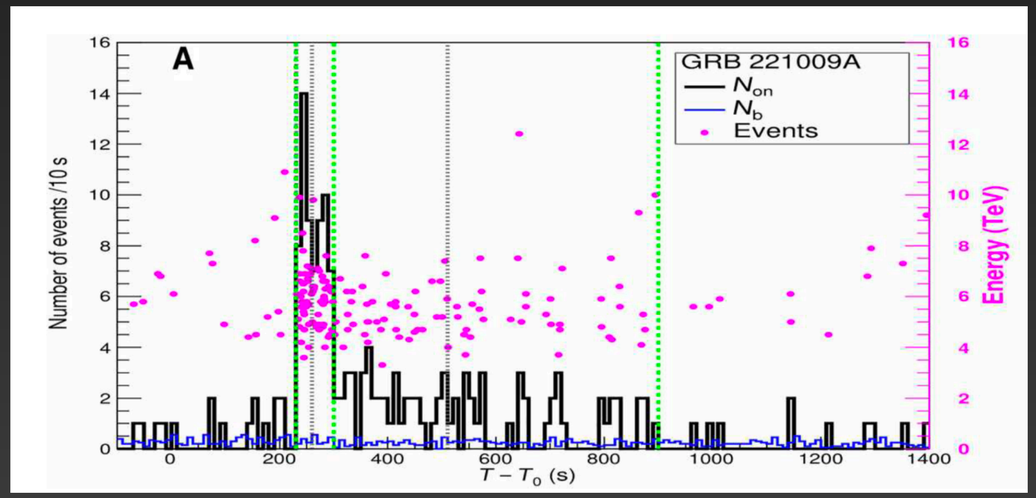
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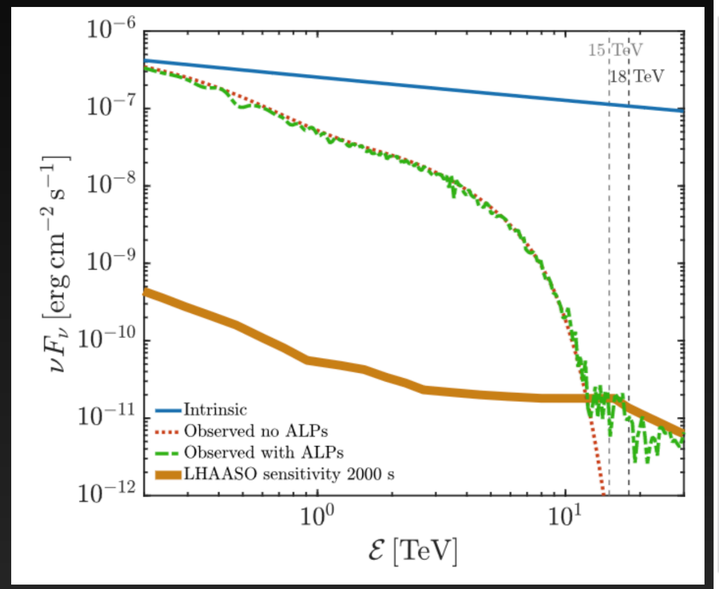
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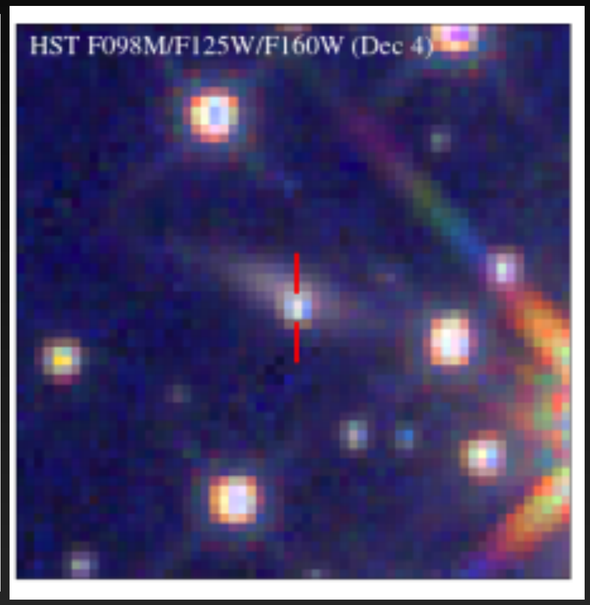
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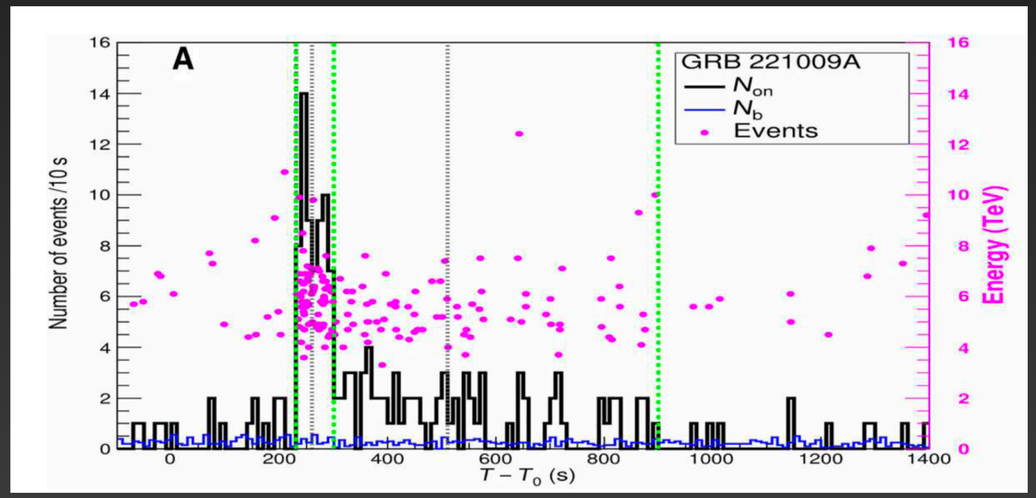
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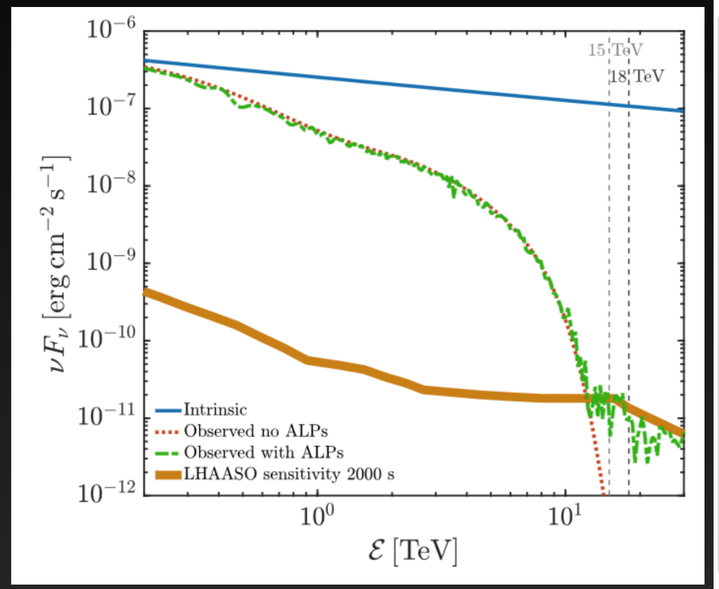
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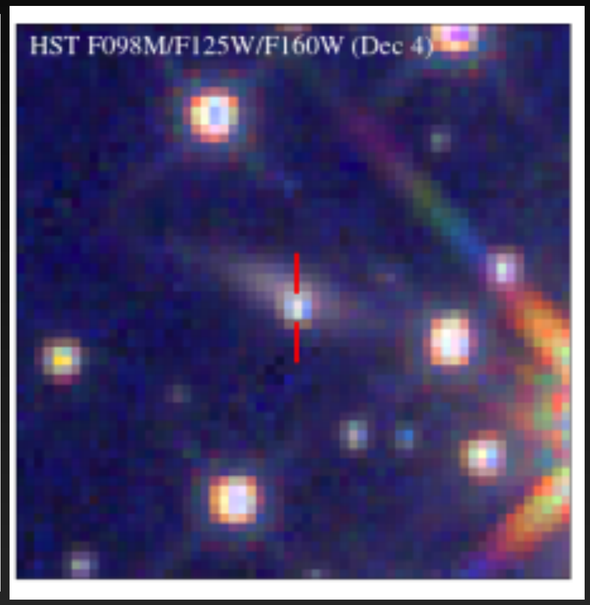
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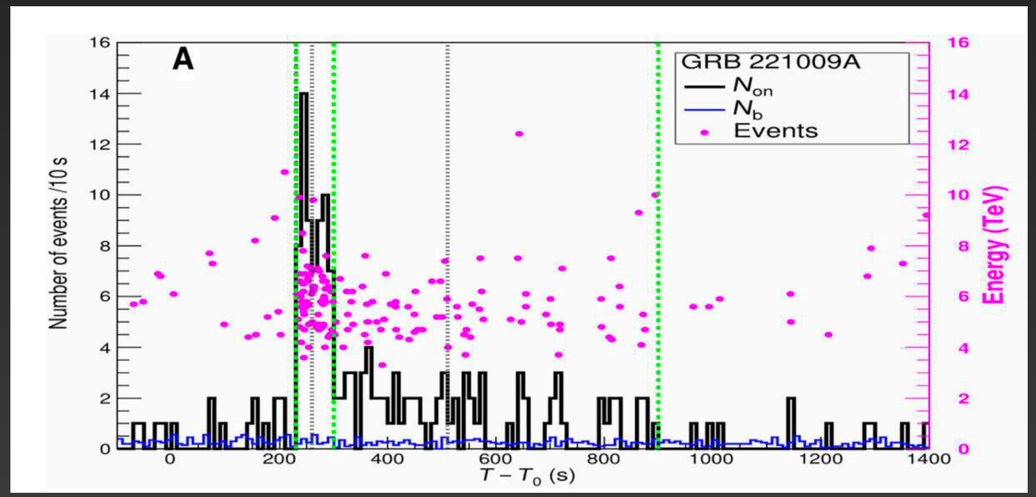
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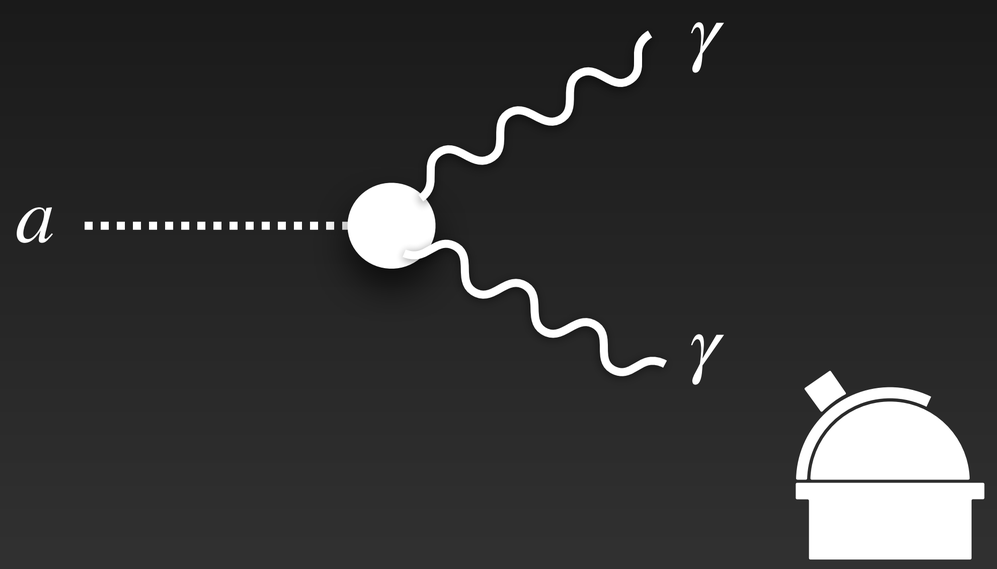


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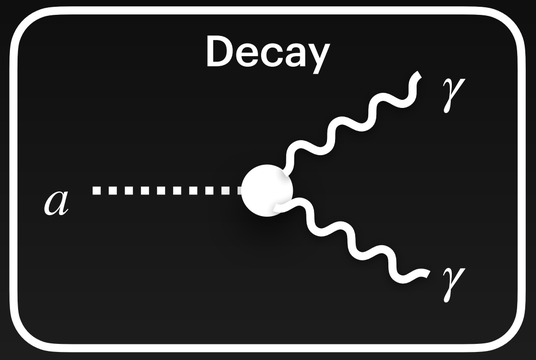


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ALP decay

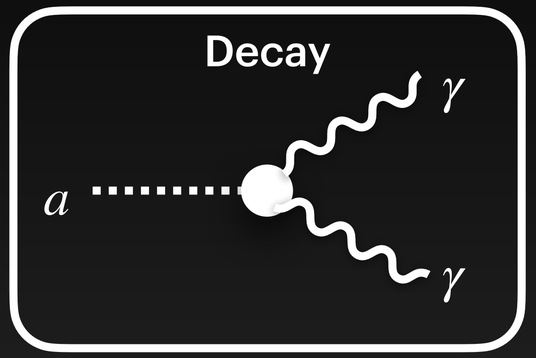


Dark matter Axion decay: Galactic Halo



Overduin 2002,
Cadamuro & Redondo 2012,
Bernal et al. 2023
Porras Bedmar, MM, Horns (in prep.)

Dark matter Axion decay: Galactic Halo



Decay rate:

$$\Gamma_{a\gamma} = \tau_{a\gamma}^{-1} = \frac{m_a^3 g_{a\gamma}^2}{64\pi}$$

Decay time:

$$\tau_{a\gamma} \gtrsim 13.8\,\mathrm{Gyr} \left(\frac{5.5\times10^{-7}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2 \left(\frac{1\,\mathrm{eV}}{m_a}\right)^3$$

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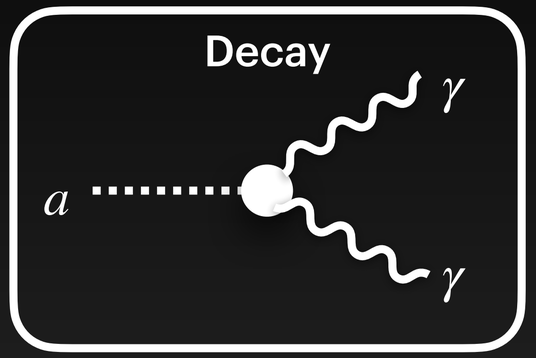
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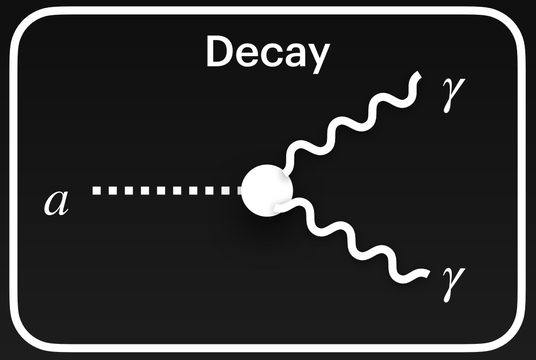
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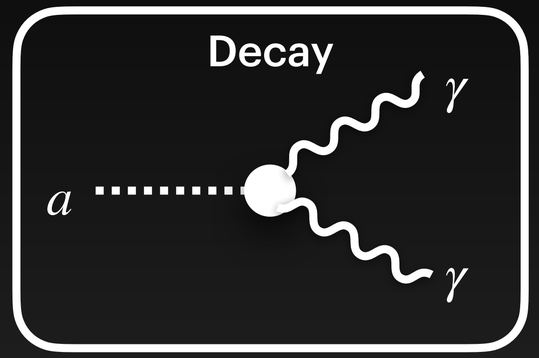
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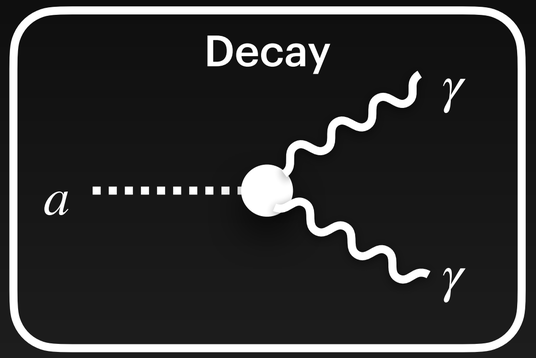
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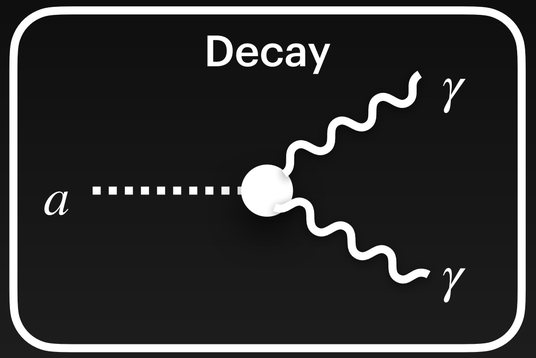
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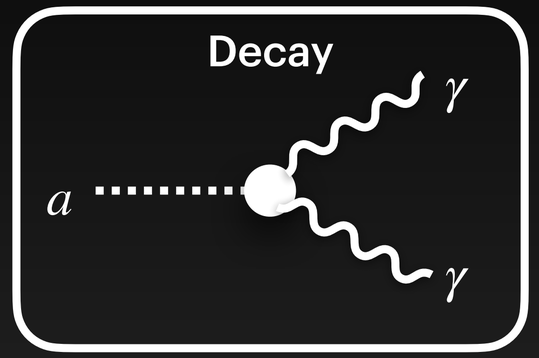
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$$f(\lambda) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{decay}}} e^{-\frac{1}{2}\left(\frac{\lambda-\lambda_{\mathrm{decay}}}{\sigma_{\mathrm{decay}}}\right)^2}$$

- Velocity dispersion: $\sigma_{\mathrm{decay}} = 2\lambda_{\mathrm{decay}}\frac{v_{\mathrm{disp}}}{c}$, $v_{\mathrm{disp}} = 220\,\mathrm{km/s}$
- Very narrow line

Overduin 2002,
Cadamuro & Redondo 2012,
Bernal et al. 2023
Porras Bedmar, MM, Horns (in prep.)

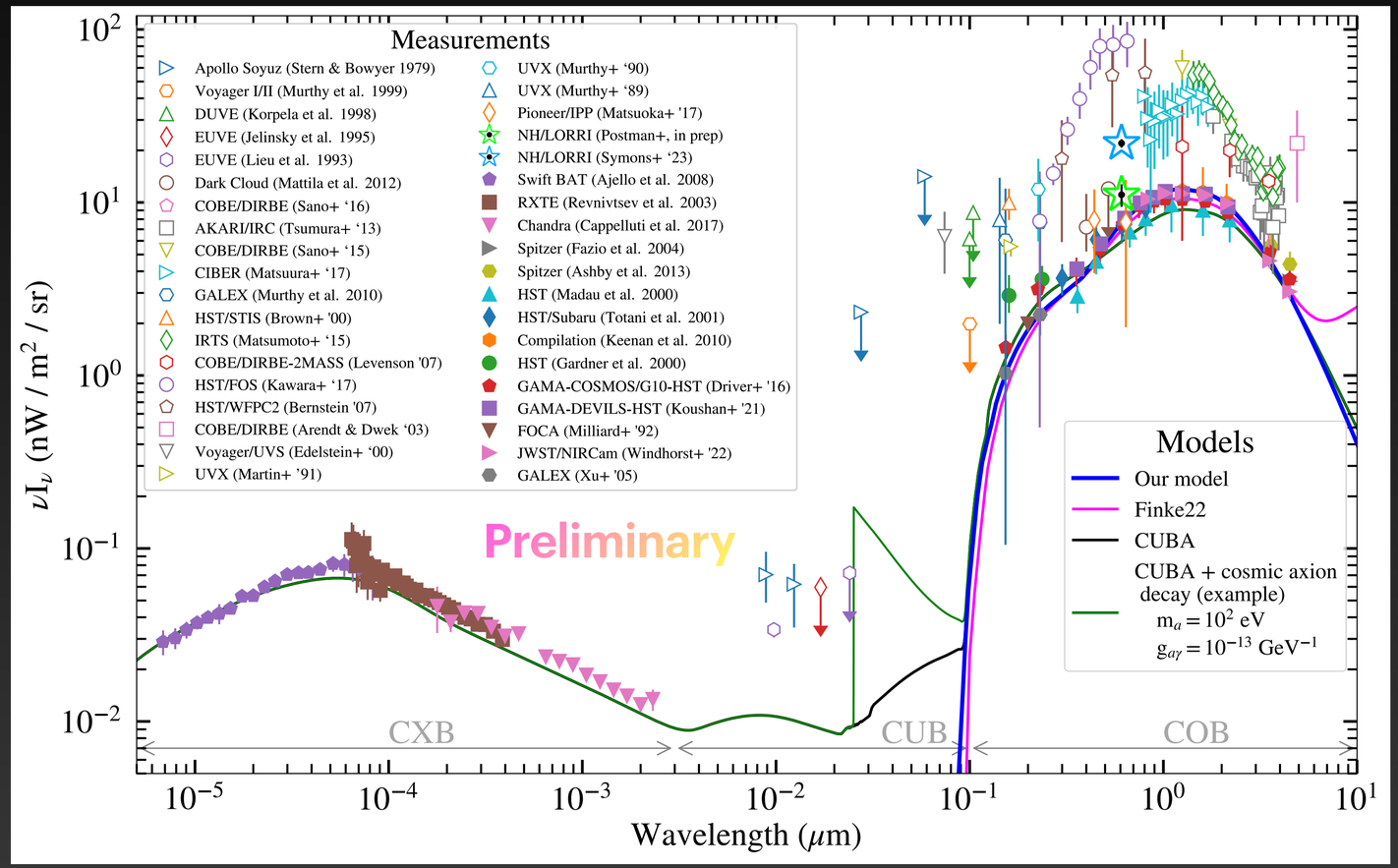
Cosmic axion decay

- Axion dark matter would also decay over the entire history of the universe
- Contributes to isotropic photon backgrounds (see lecture on EBL)

$$\nu I_\nu(\lambda, z) = \frac{\Omega_a \rho_{\mathrm{crit},0}}{64\pi} \frac{m_a^2 g_{a\gamma}^2}{\lambda H(z_*)} \Theta(z_* - z)$$

$$\text{With } z_* = \frac{m_a}{2} \frac{\lambda}{2\pi} (1+z) - 1$$

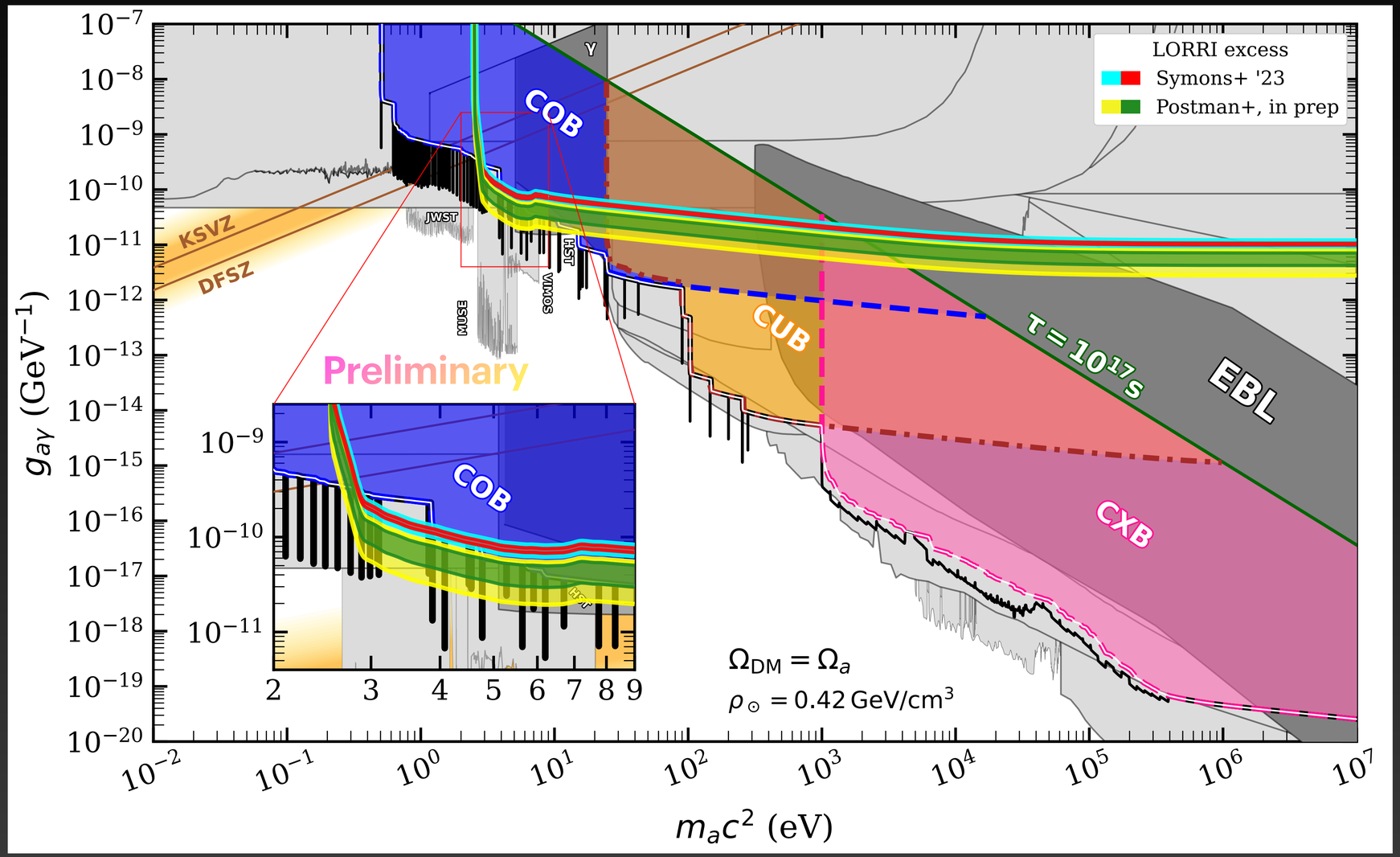
Porras Bedmar, MM, Horns (in prep.)



Overduin 2002,
Cadamuro & Redondo 2012,
Bernal et al. 2023

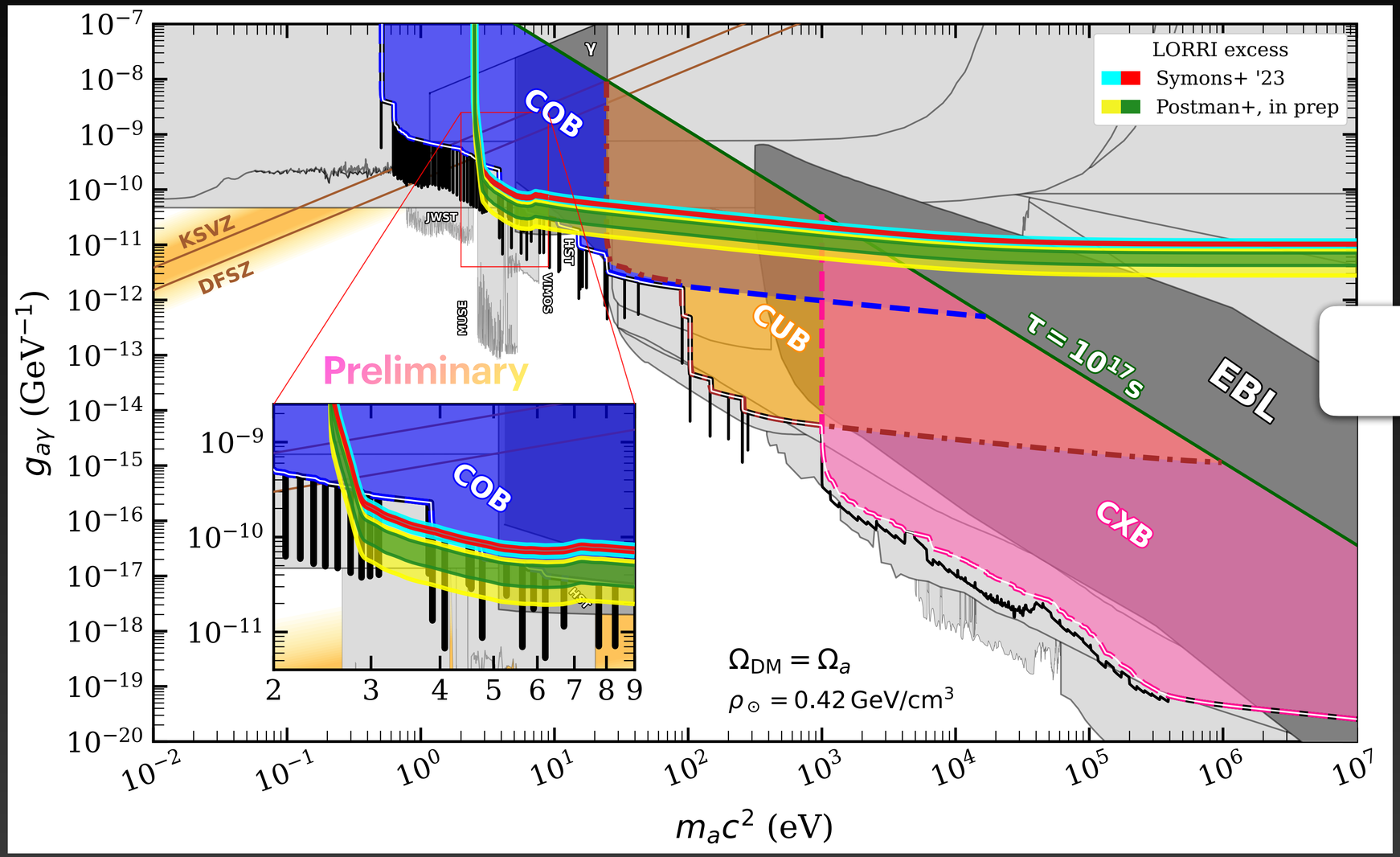
Constraints from ALP decay

Porras Bedmar, MM, Horns (in prep.)



Constraints from ALP decay

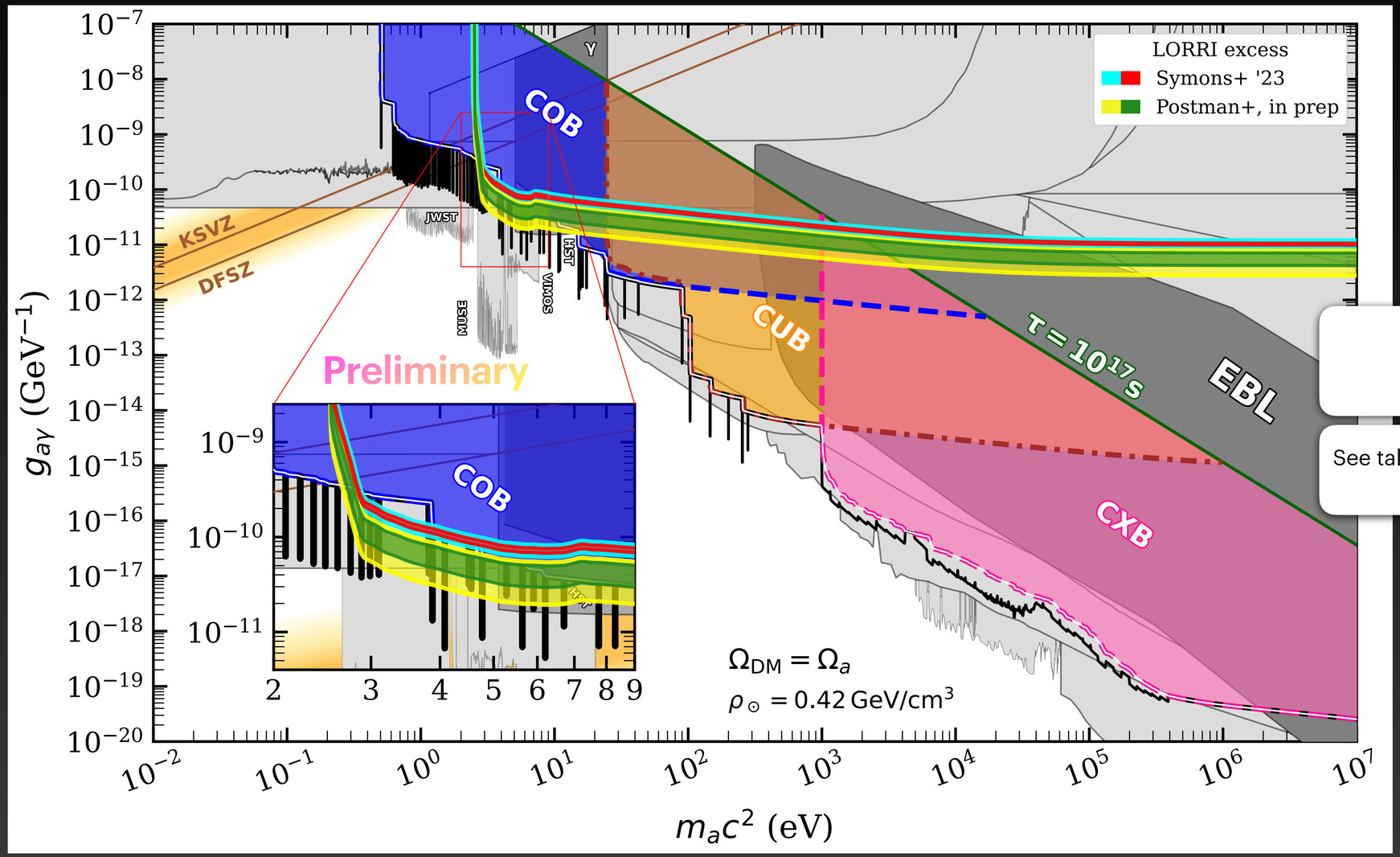
Porras Bedmar, MM, Horns (in prep.)



See talk Marco Taoso
Wednesday, 2.40pm

Constraints from ALP decay

Porras Bedmar, MM, Horns (in prep.)

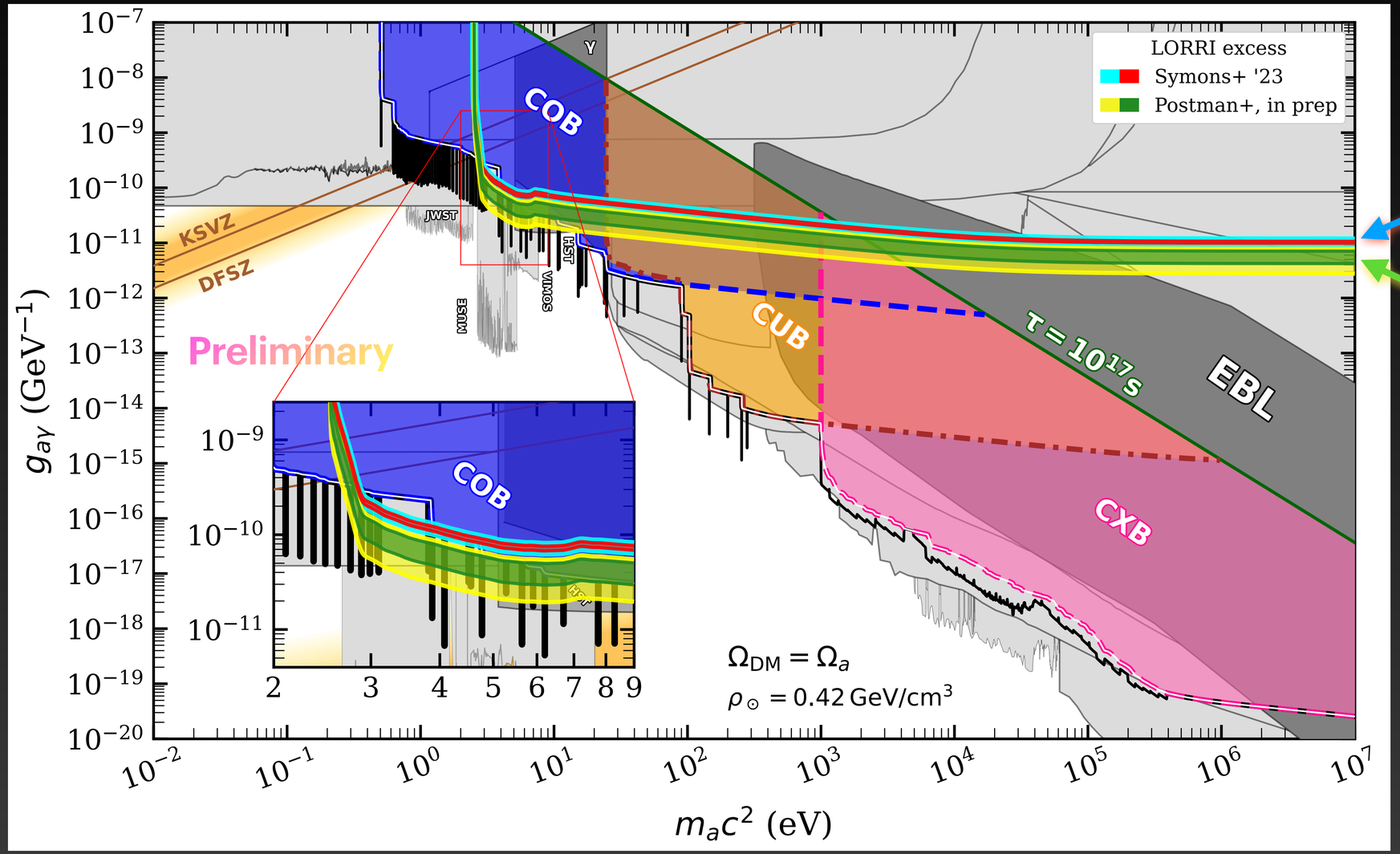


See talk Marco Taoso
Wednesday, 2.40pm

See talk by Giovanni Grilli di Cortona
Wednesday, 2.20pm

Constraints from ALP decay

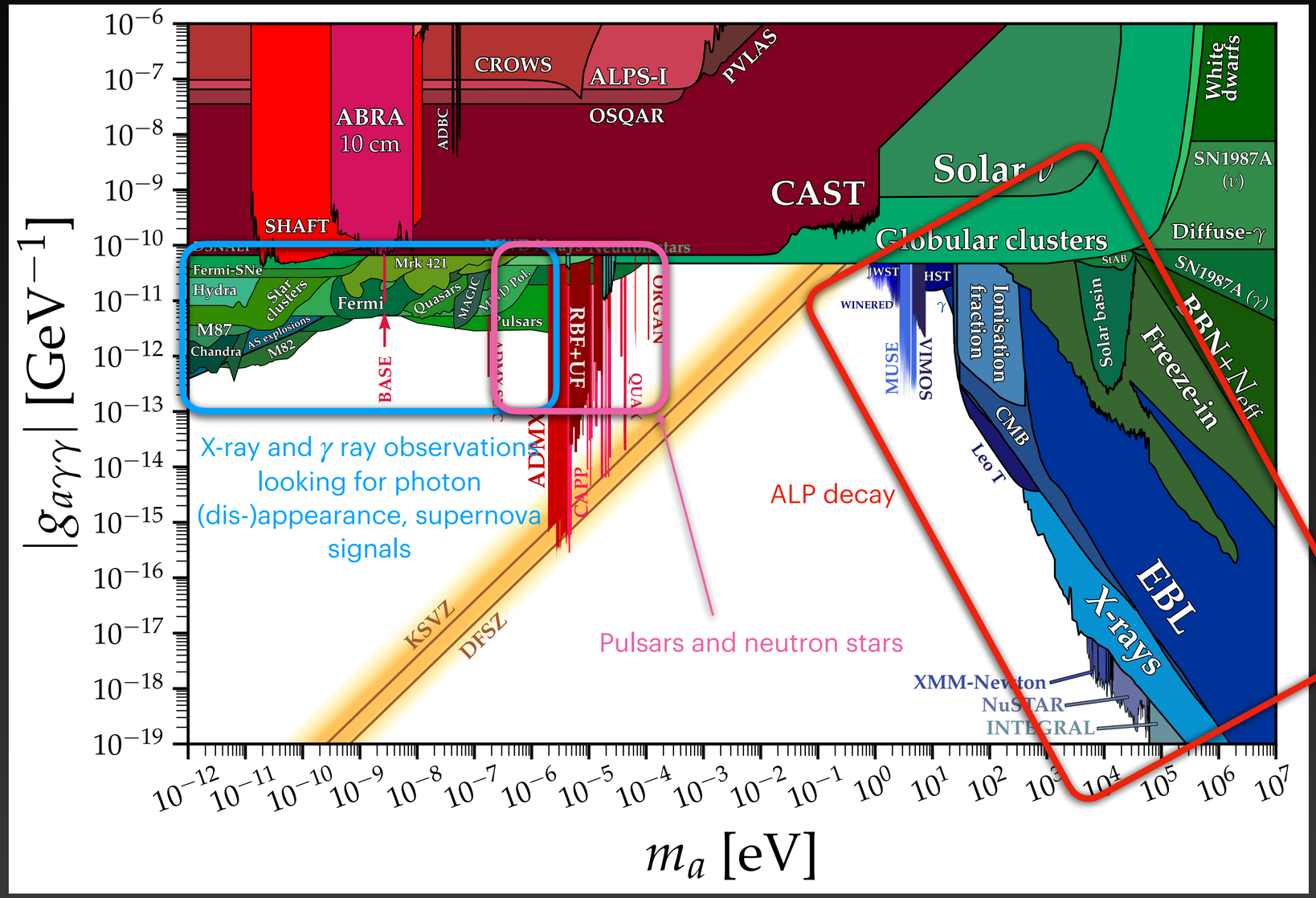
Porras Bedmar, MM, Horns (in prep.)



Parameters that could explain LORRI excess [Symons et al. 2023] Taking all EBL measurements into account

LORRI excess might actually be lower and lower significance [Postman et al. in prep]

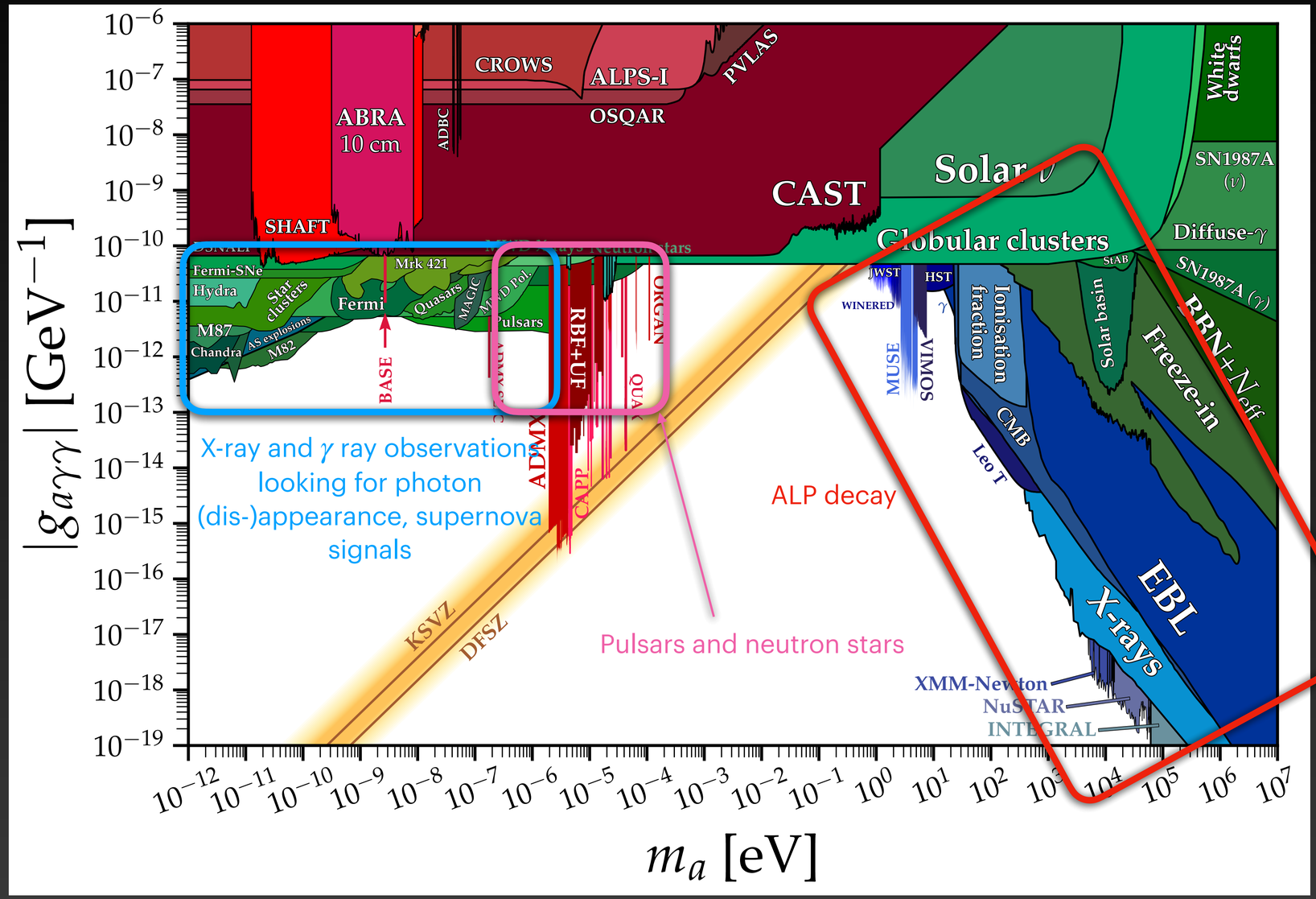
Summary and conclusions



https://doi.org/10.5281/zenodo.3932430

Summary and conclusions

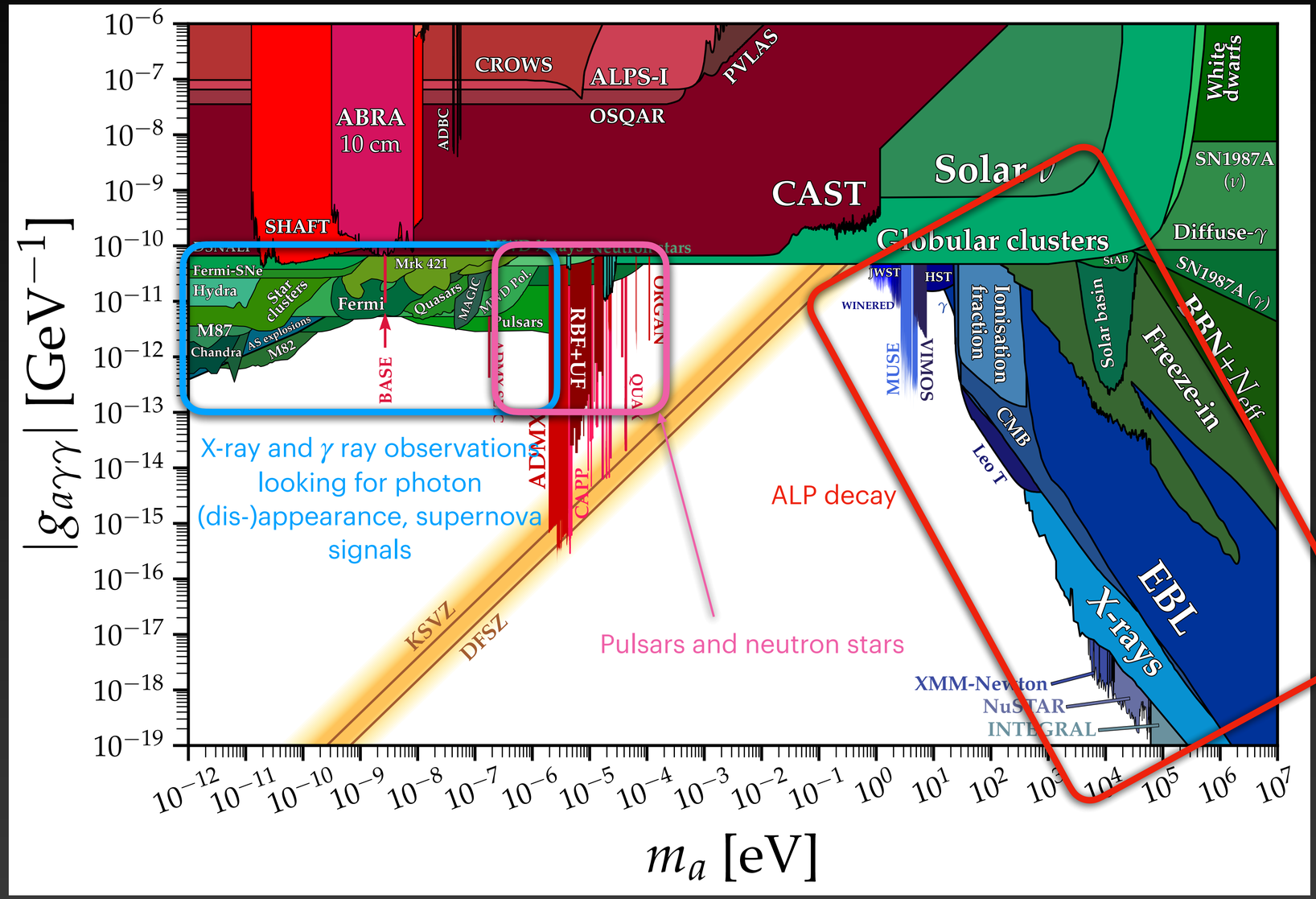
- Astrophysical observations probe a wide range of axion parameters



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Summary and conclusions

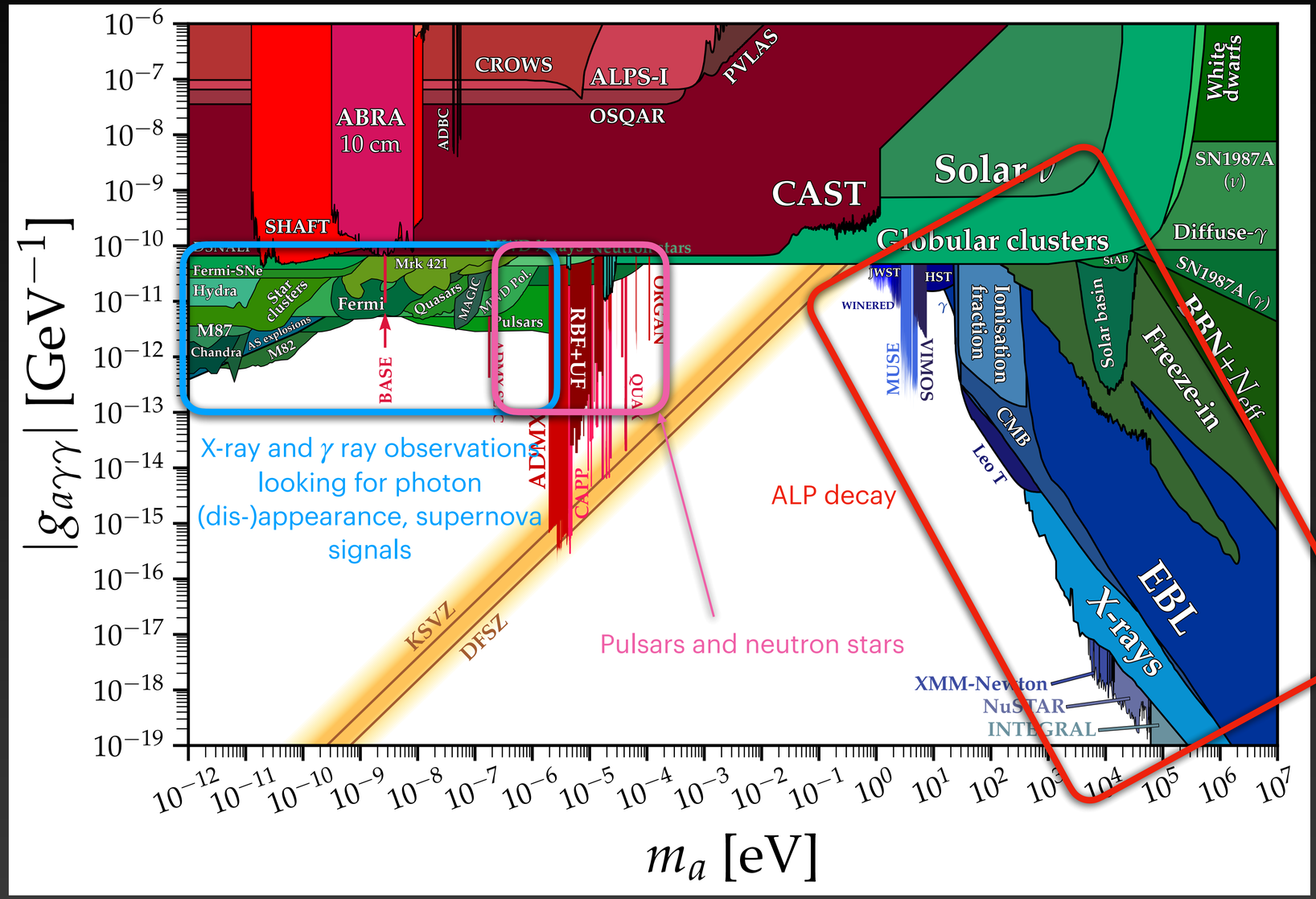
- Astrophysical observations probe a wide range of axion parameters
- Sensitive to many observables



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Summary and conclusions

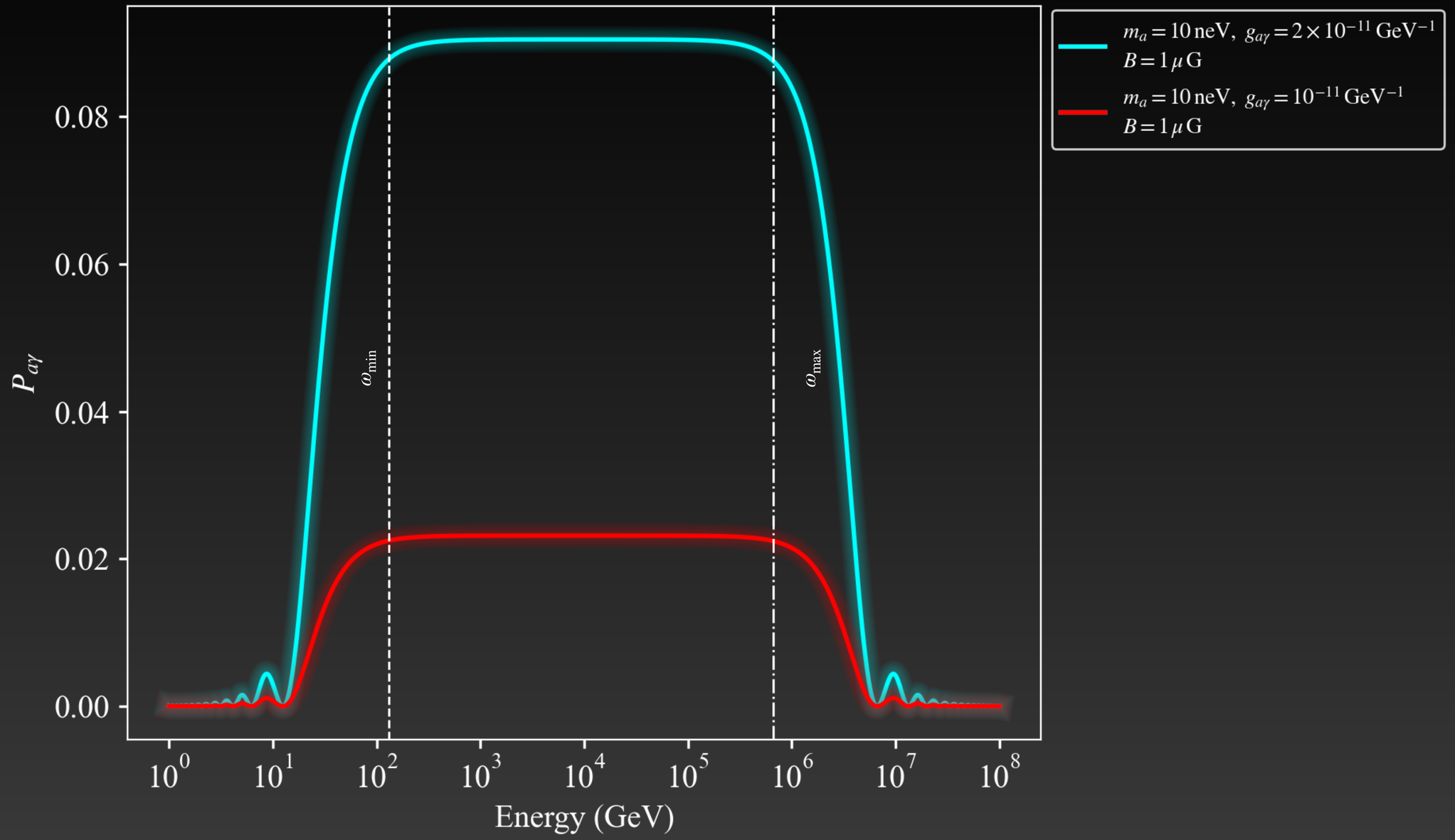
- Astrophysical observations probe a wide range of axion parameters
- Sensitive to many observables
- Provide some of the strongest constraints (but astrophysical B fields remain uncertain)



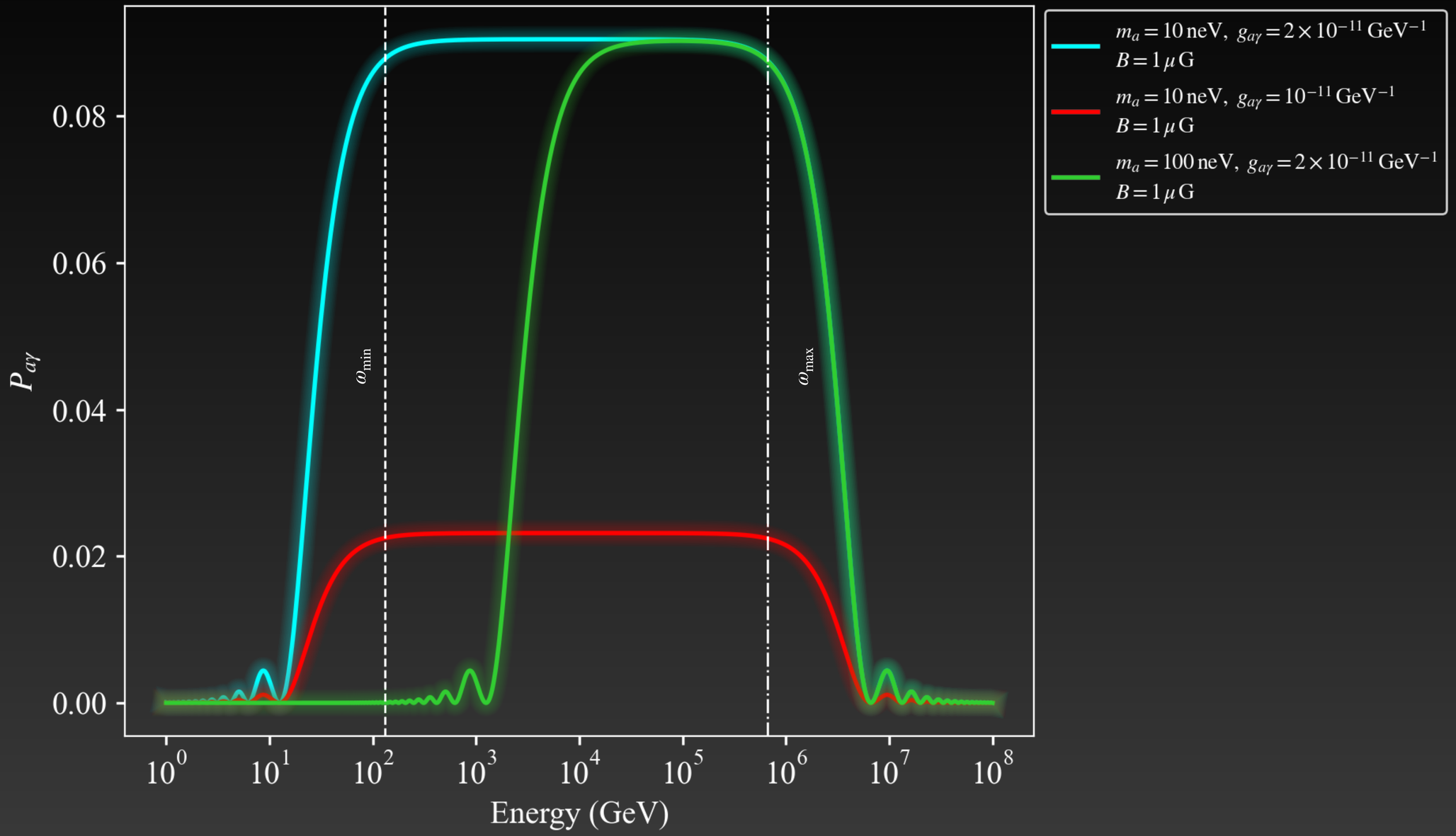
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Back up

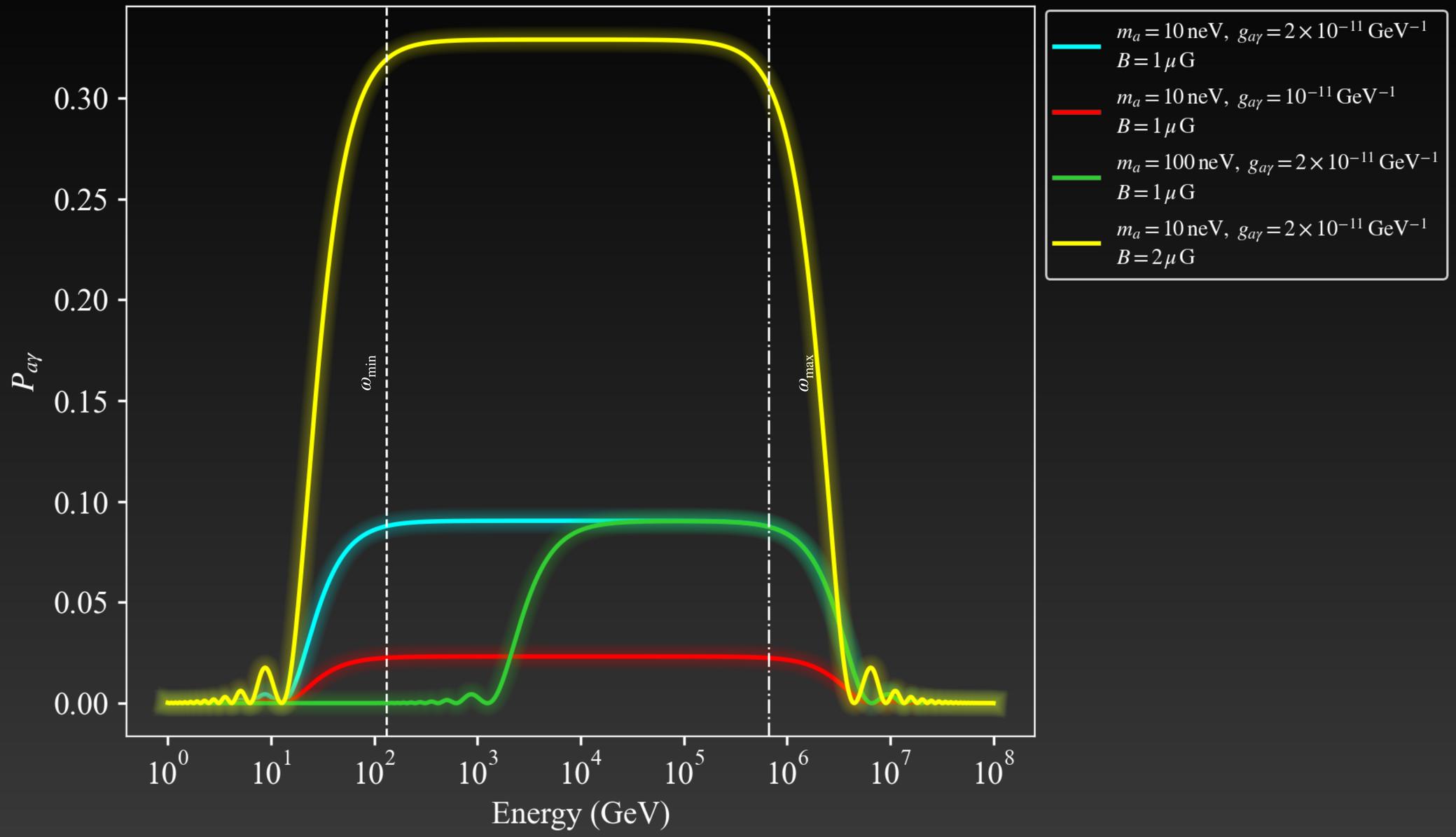
Photon-Axion/ALP Mixing on Galactic scales



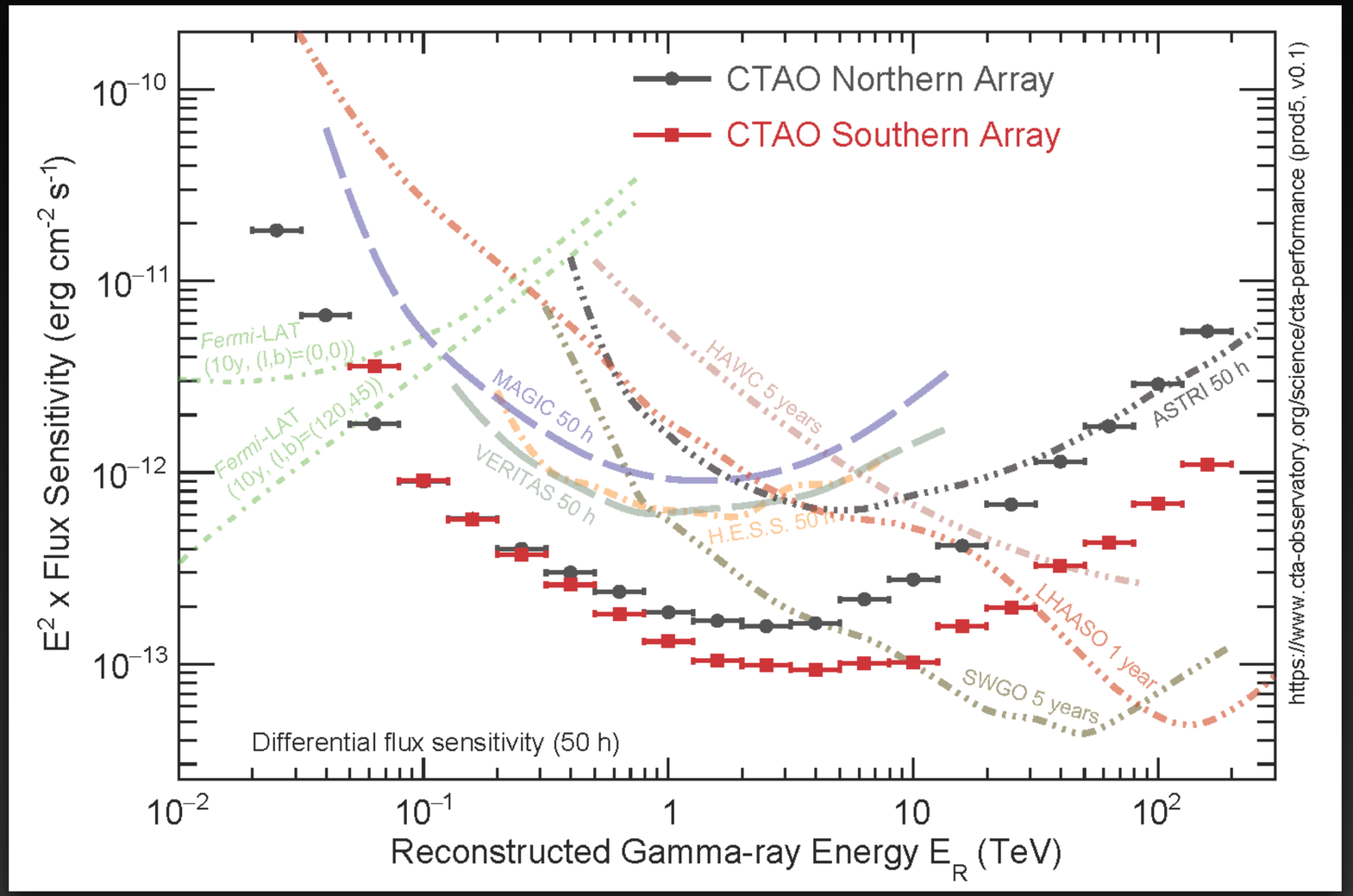
Photon-Axion/ALP Mixing on Galactic scales



Photon-Axion/ALP Mixing on Galactic scales

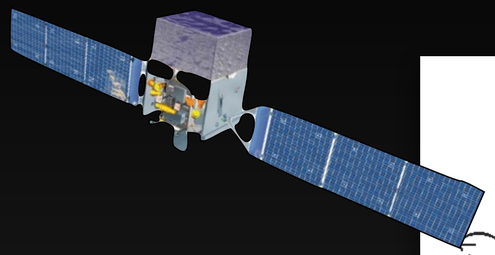


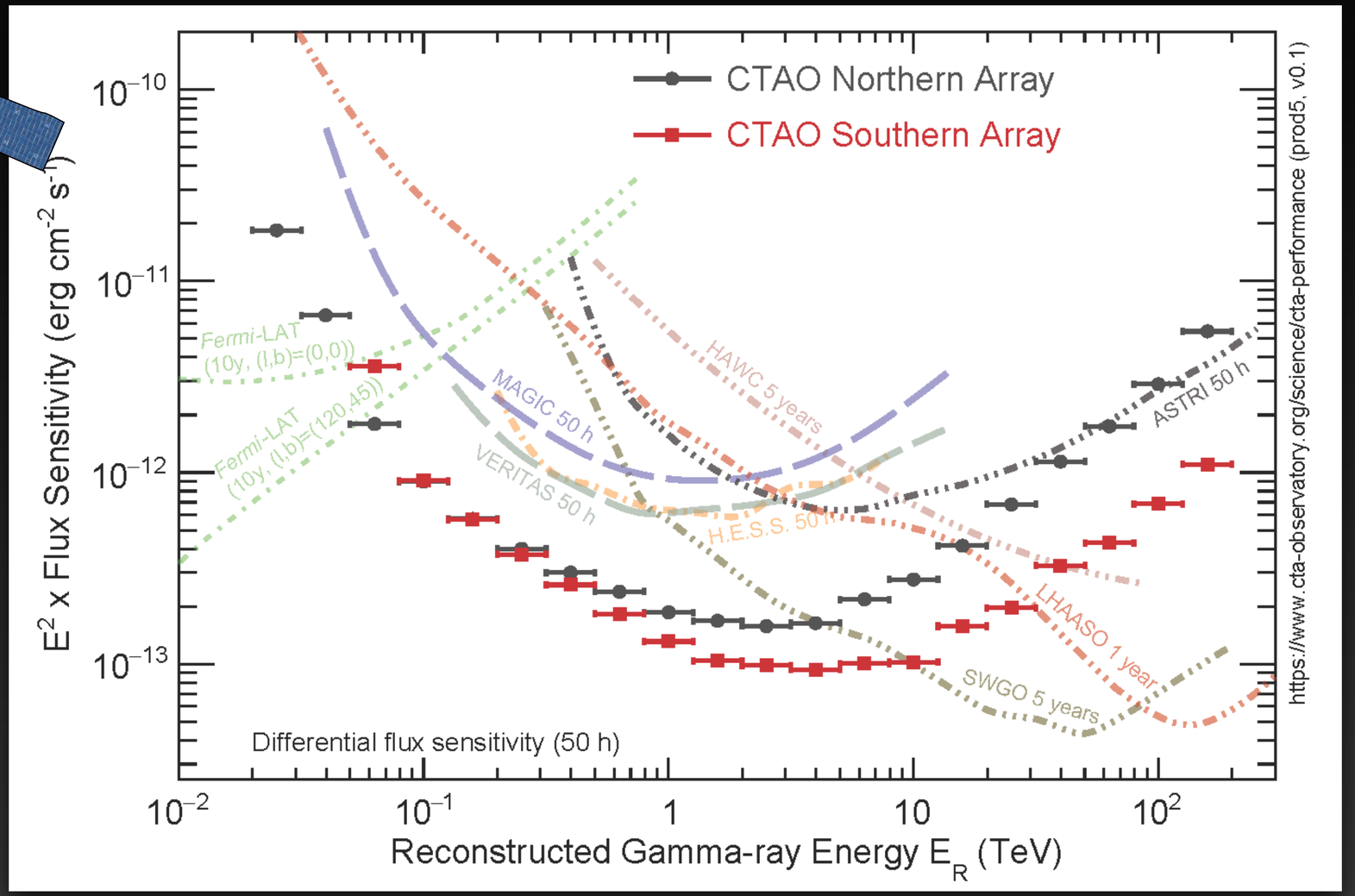
Gamma-ray telescopes



https://www.cta-observatory.org/

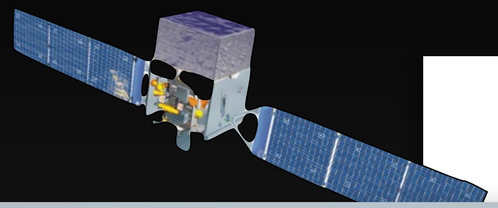
Gamma-ray telescopes



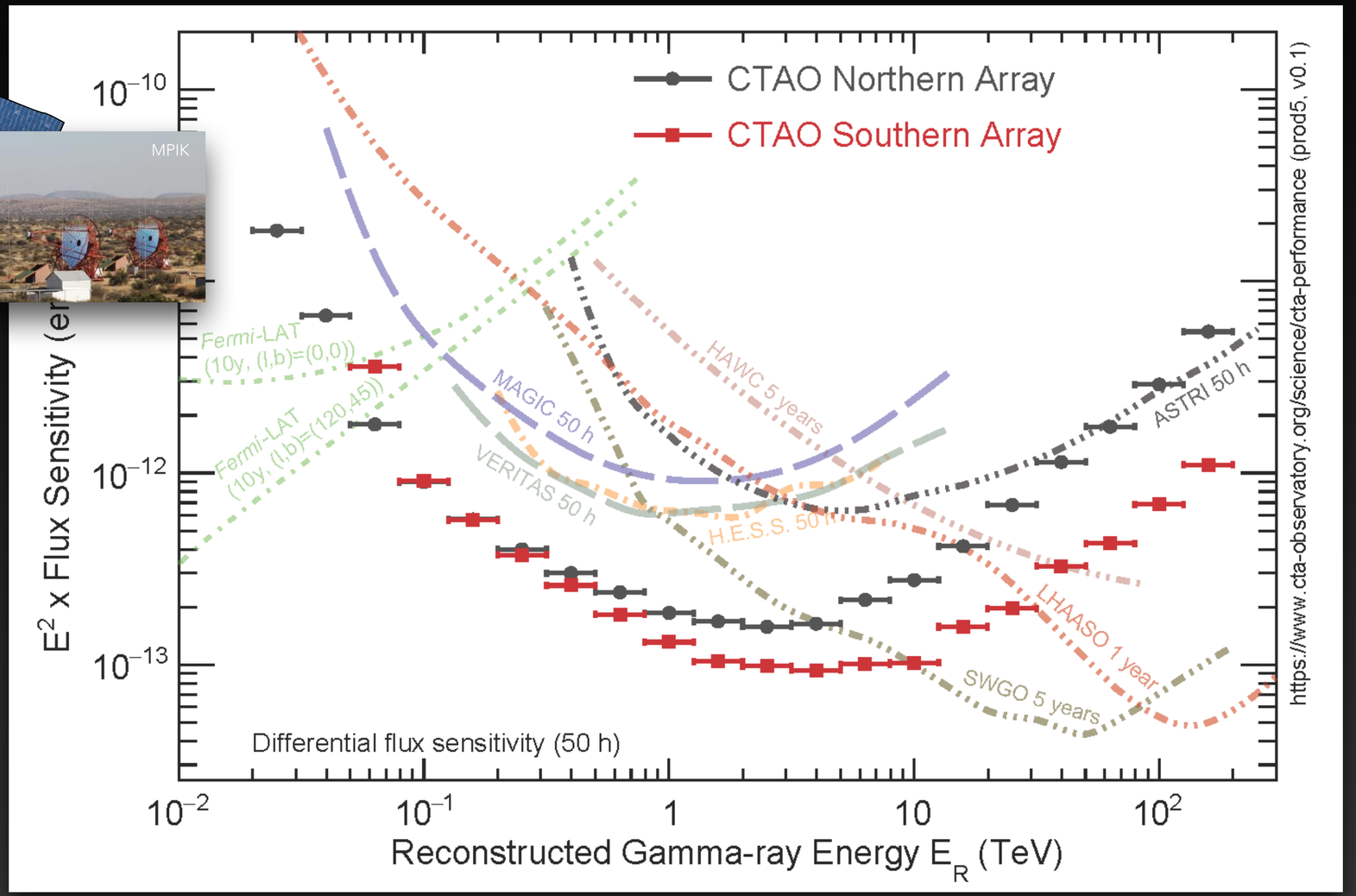


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Gamma-ray telescopes

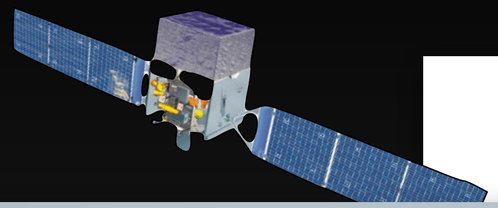






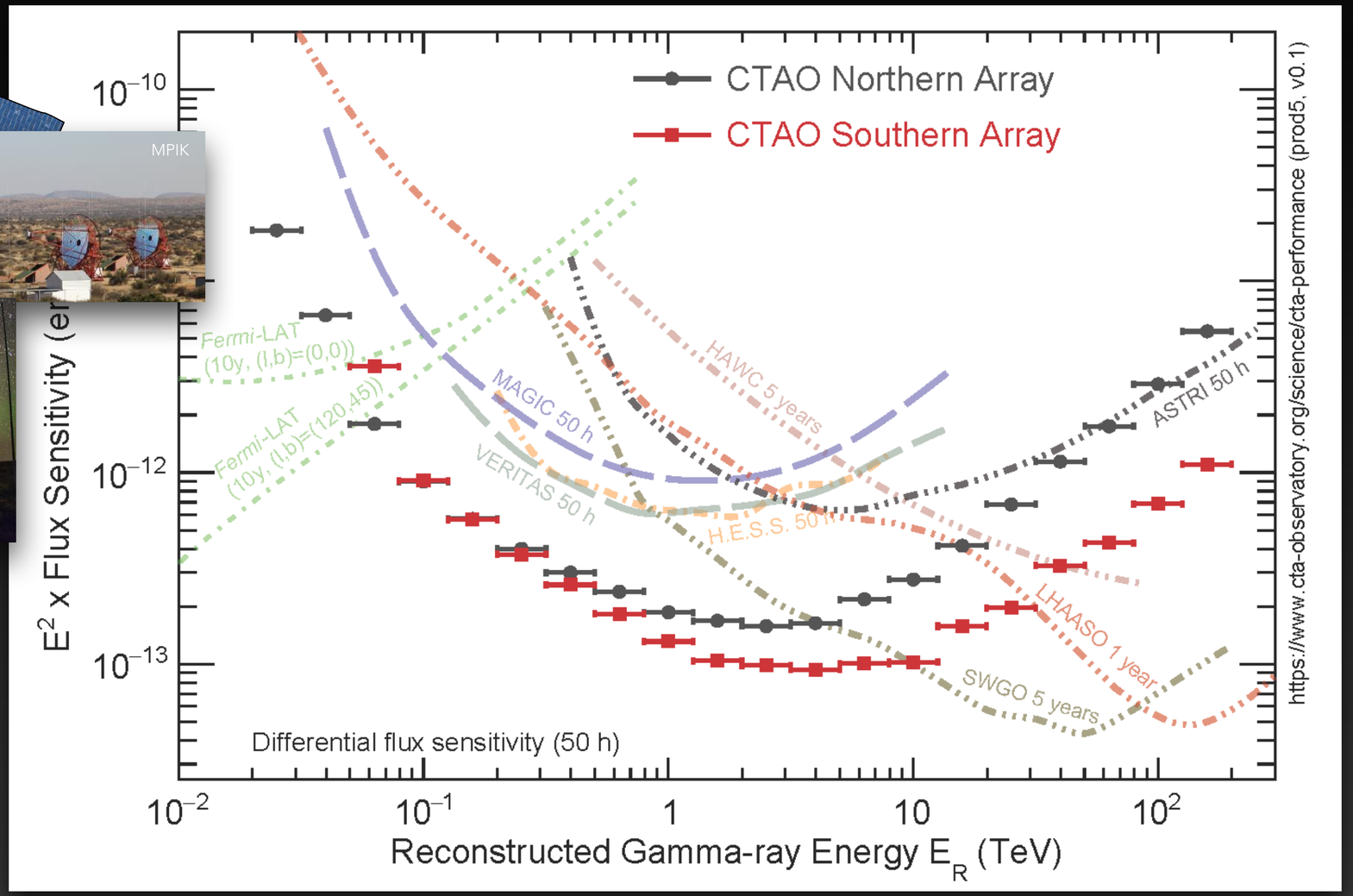
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Gamma-ray telescopes



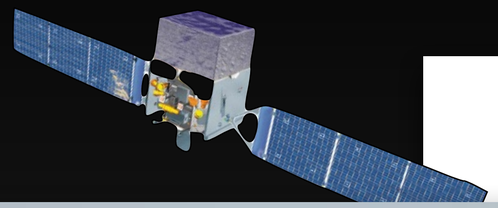






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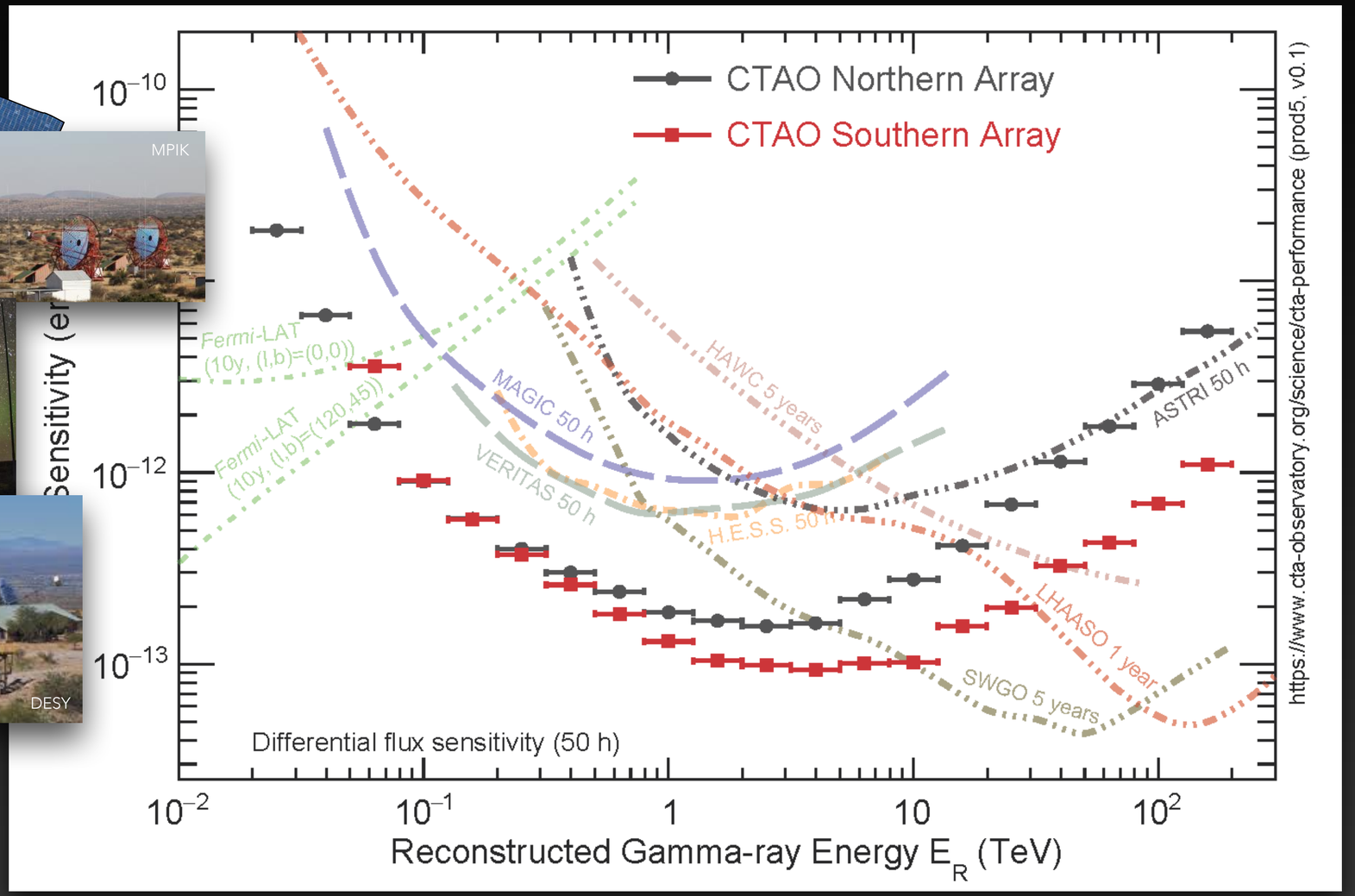
Gamma-ray telescopes





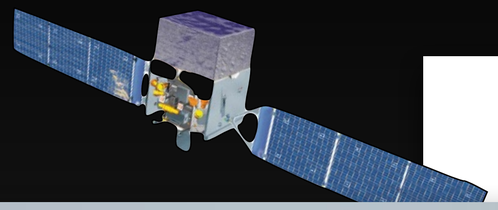






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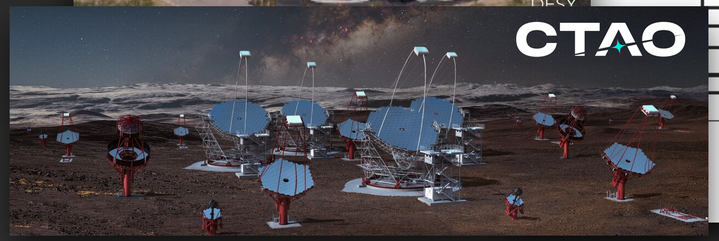
Gamma-ray telescopes

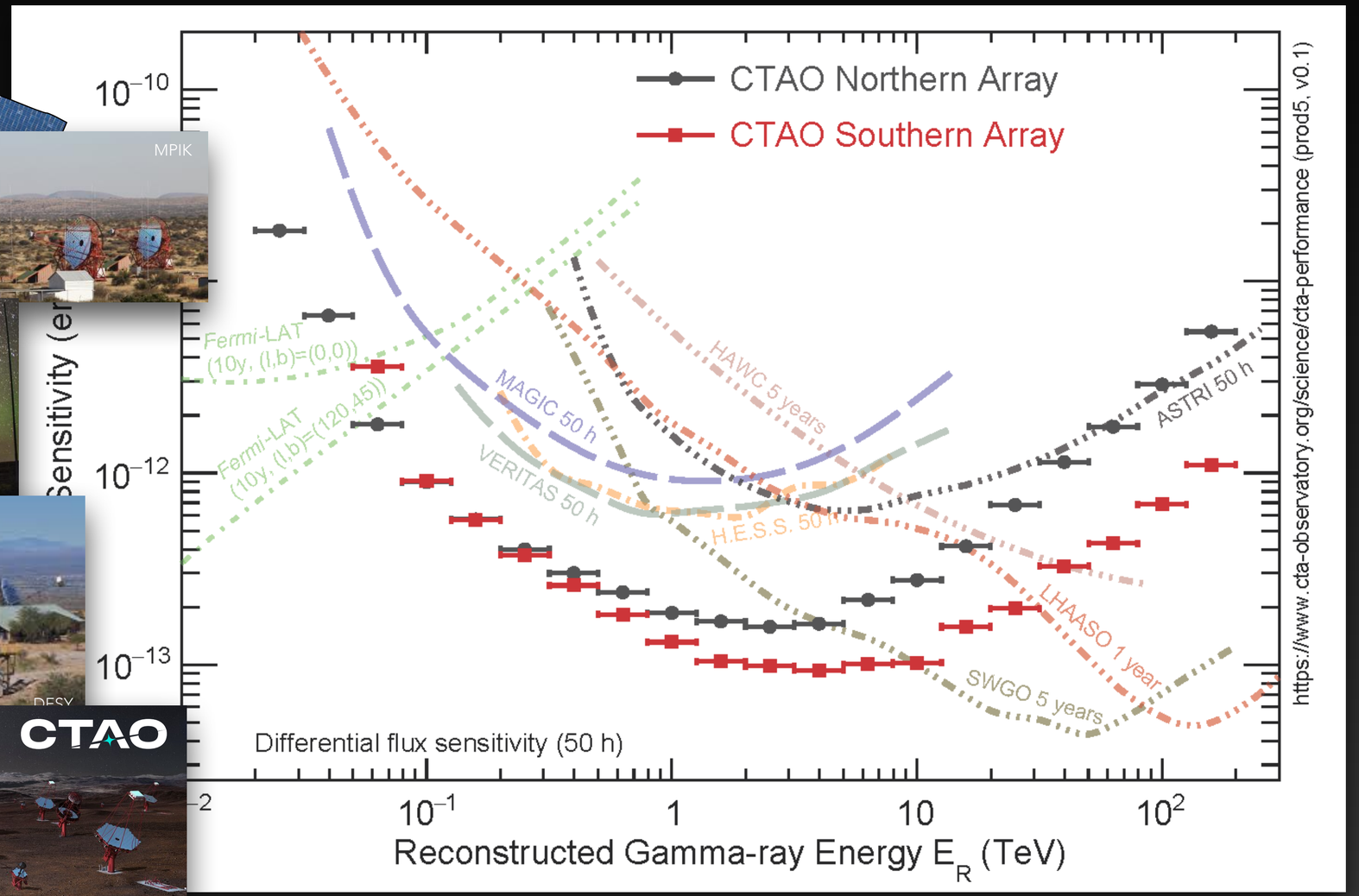






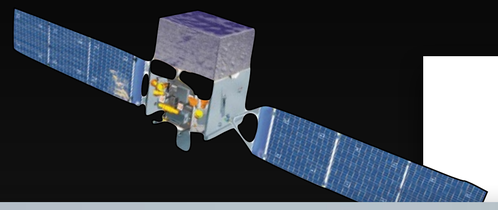






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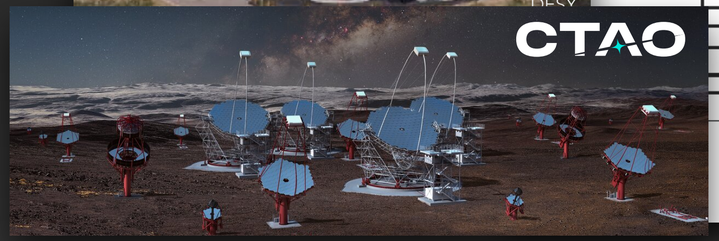
Gamma-ray telescopes

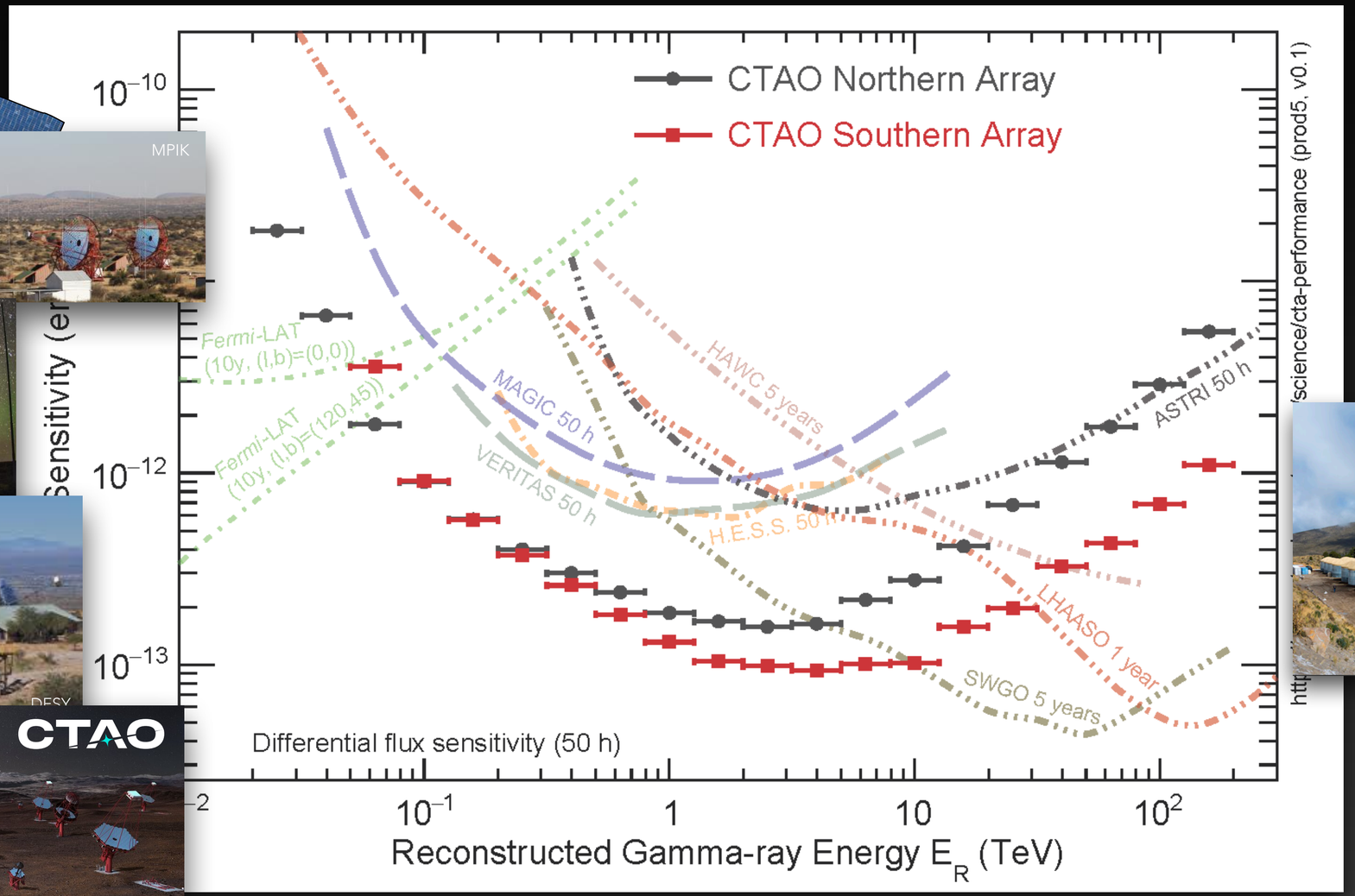








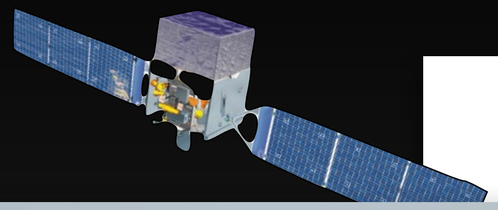






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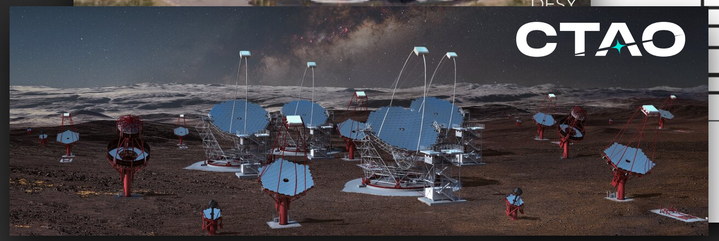
Gamma-ray telescopes

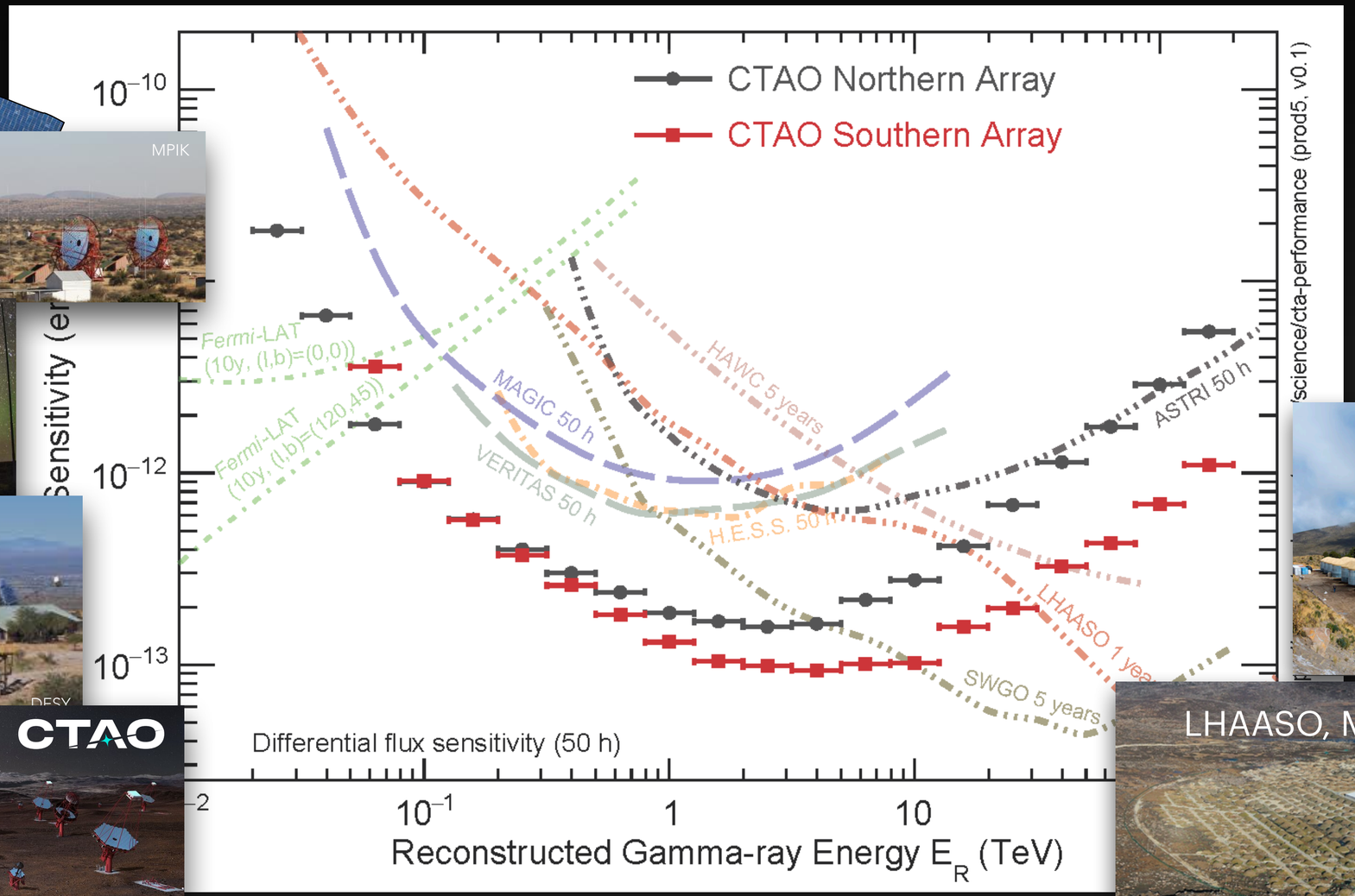










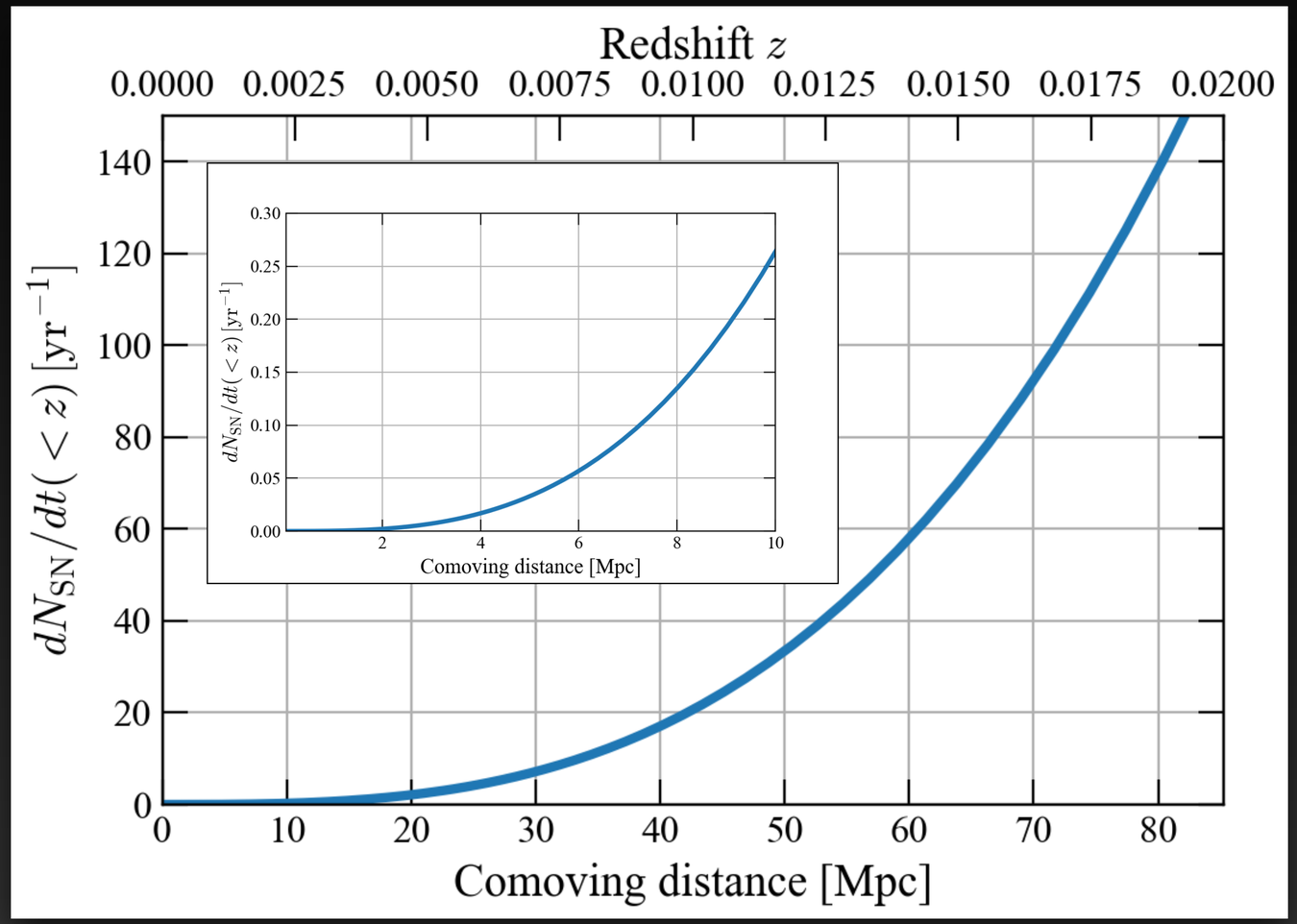






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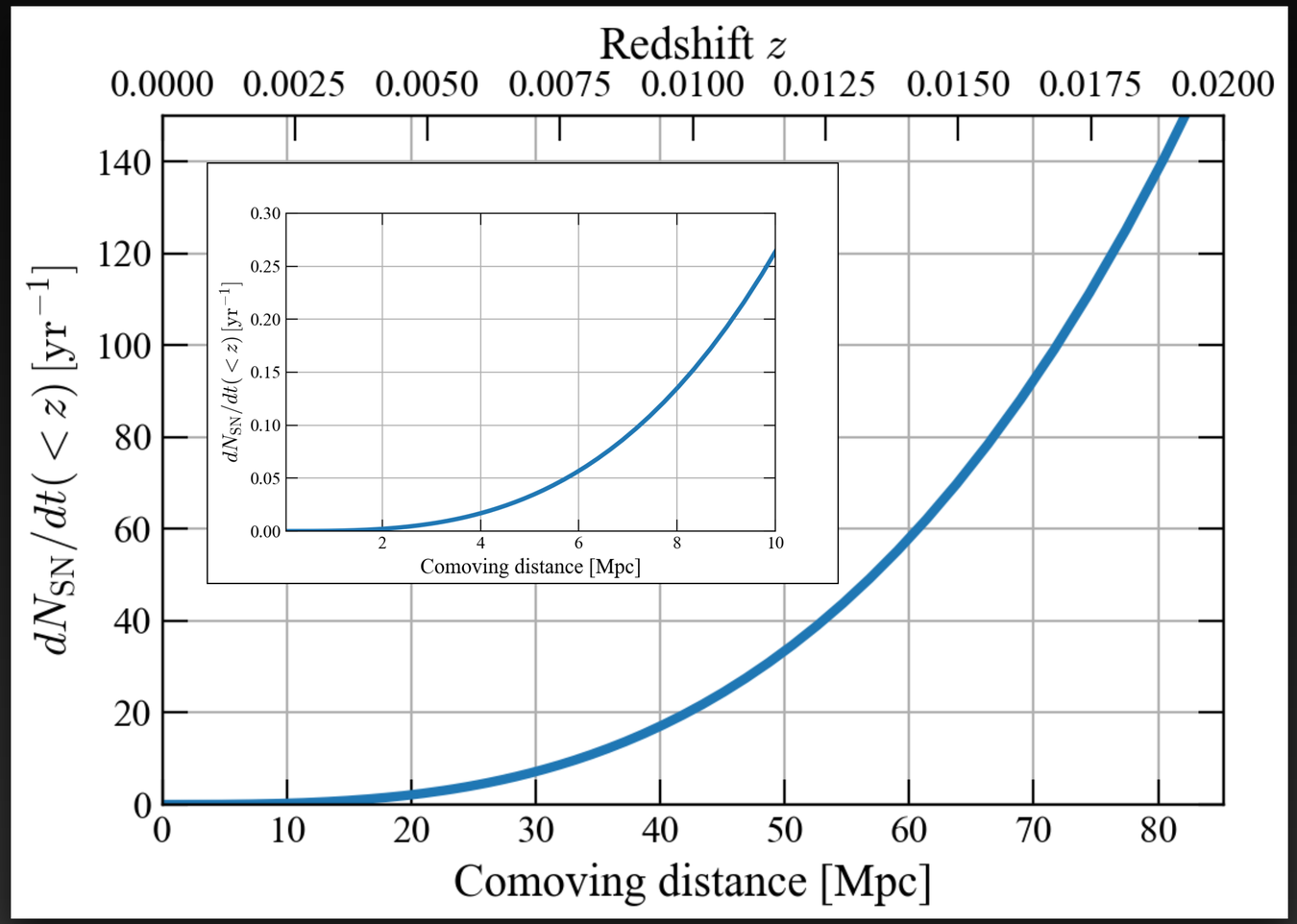
Look for Extragalactic Supernovae instead



Lien & Fields 2009

Look for Extragalactic Supernovae instead

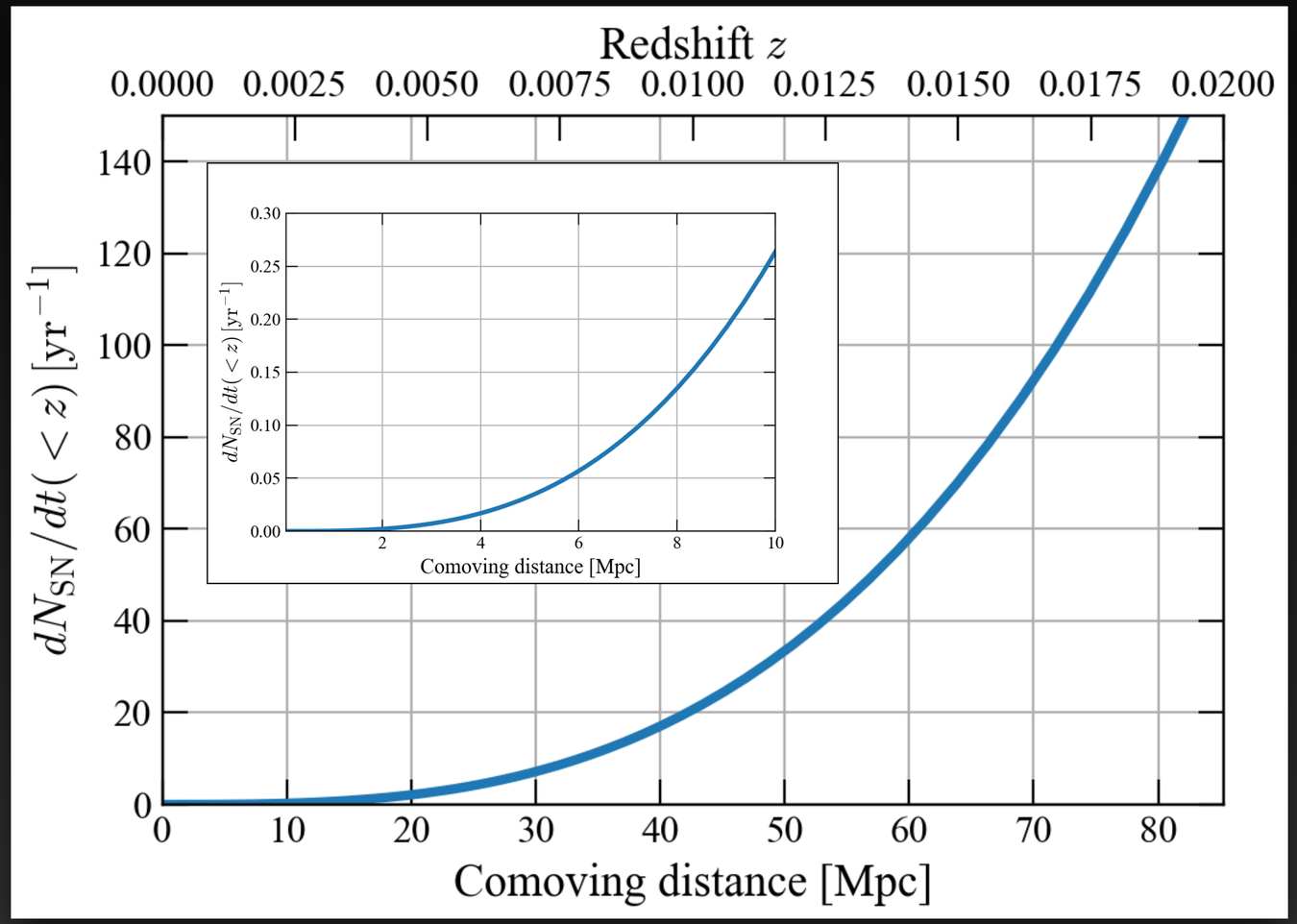
- But **no neutrino signal!**



Lien & Fields 2009

Look for Extragalactic Supernovae instead

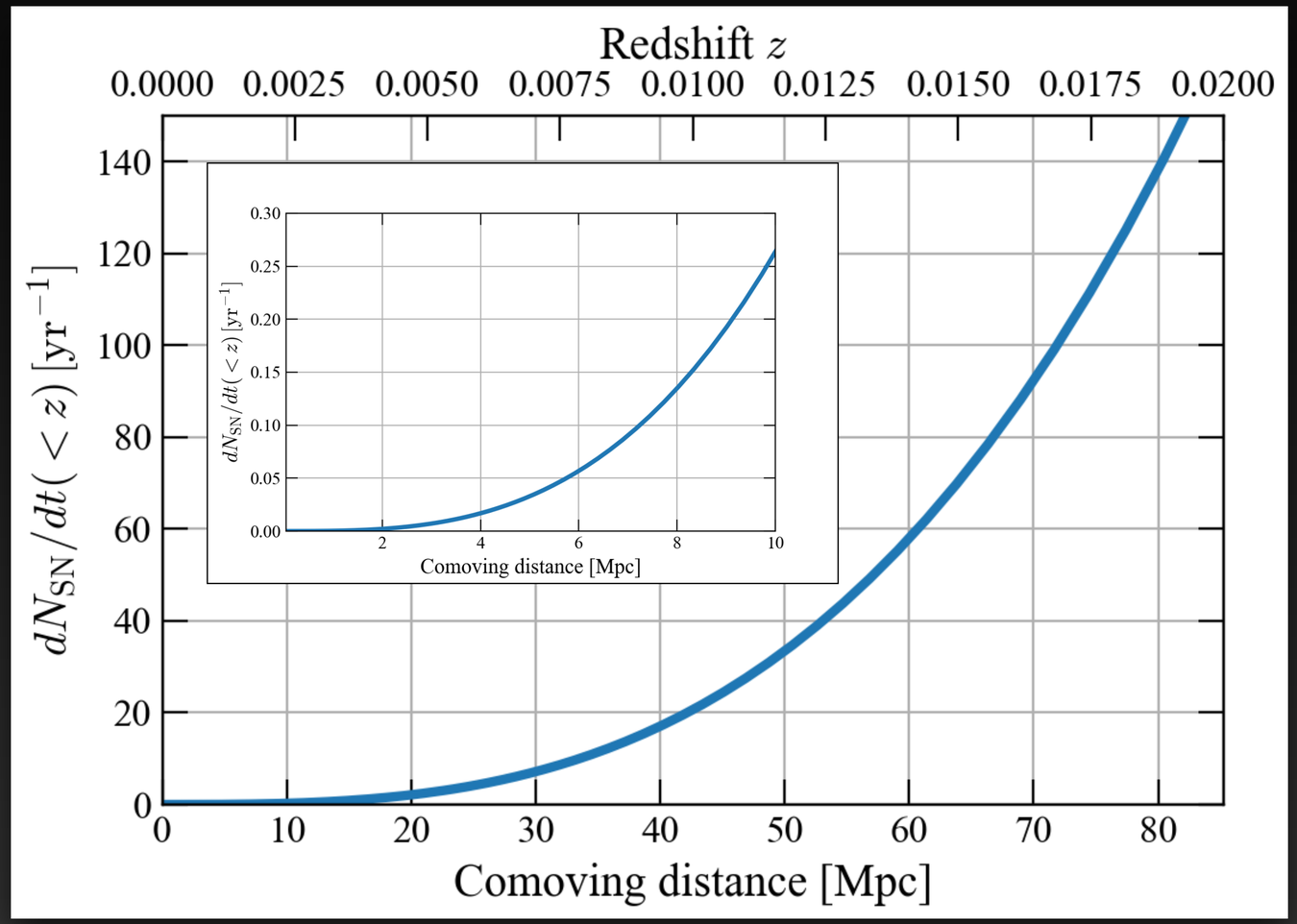
- But **no neutrino signal!**
- Use **optical light** curves to estimate explosion times
  [e.g. Cowen et al. 2010]



Lien & Fields 2009

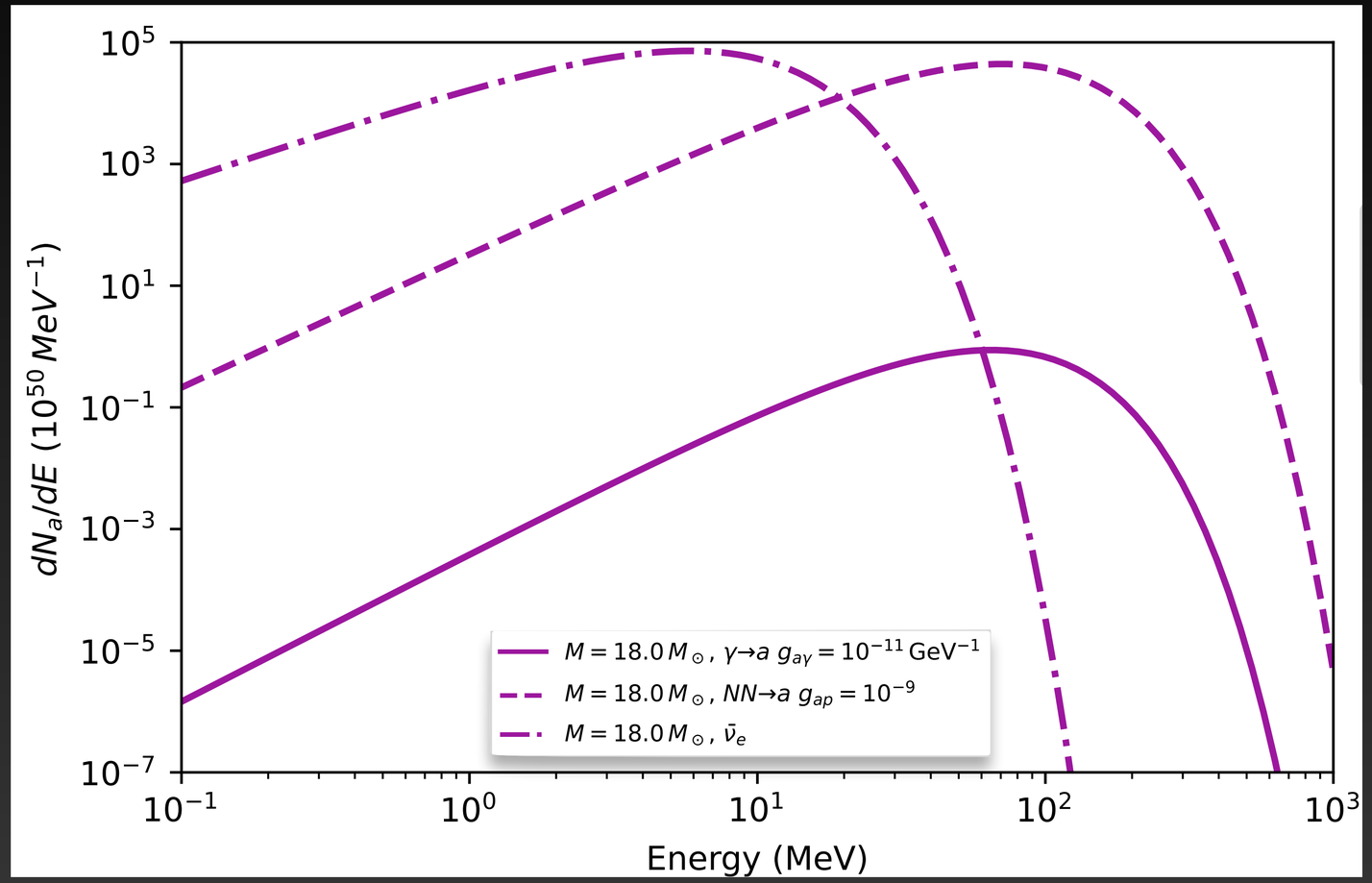
Look for Extragalactic Supernovae instead

- But **no neutrino signal!**
- Use **optical light** curves to estimate explosion times
  [e.g. Cowen et al. 2010]
- Possible with light curves from **surveys** such as **ASAS-SN, iPTF, ZTF, TESS Satellite, Rubin Observatory**



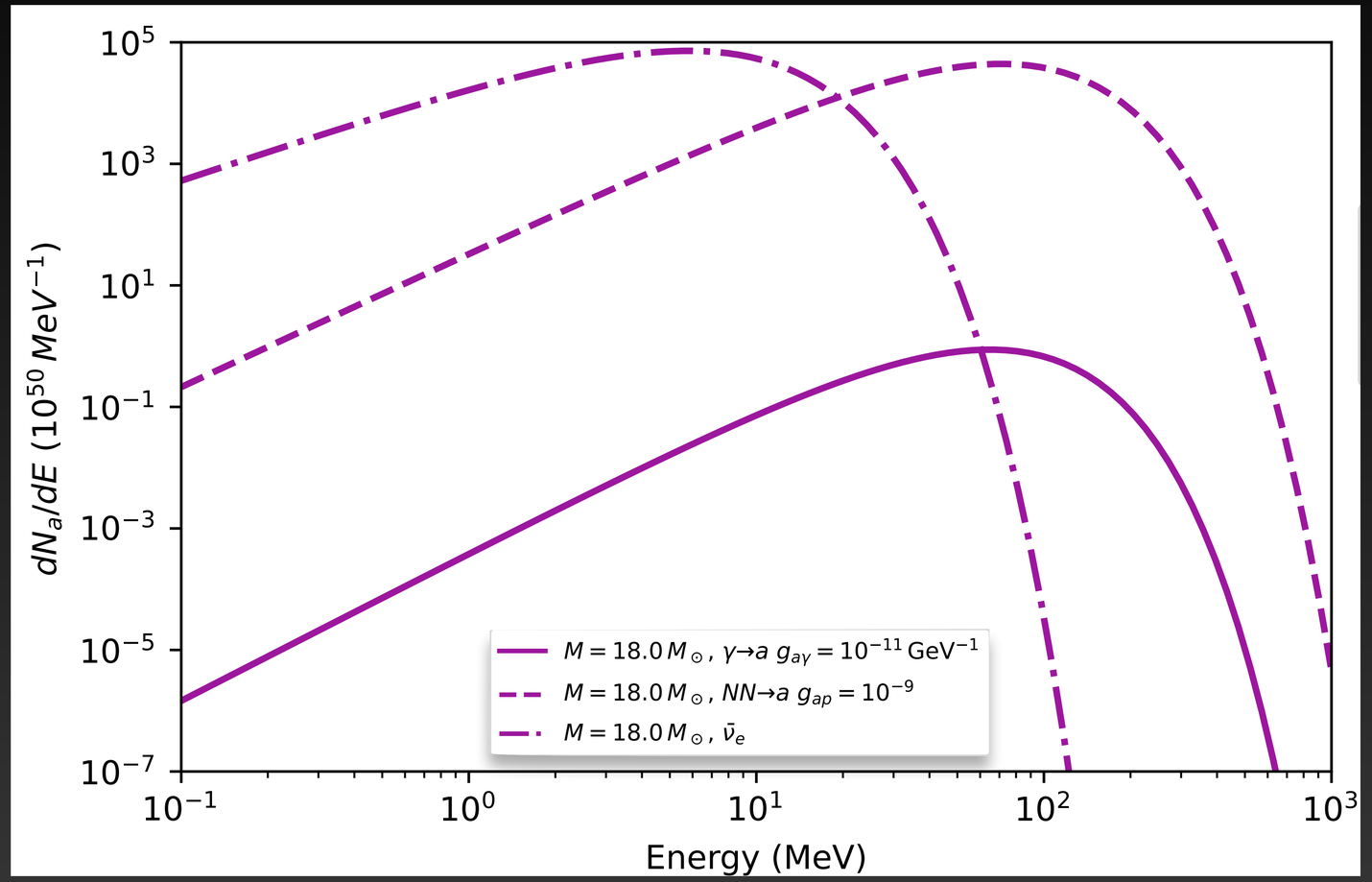
Lien & Fields 2009

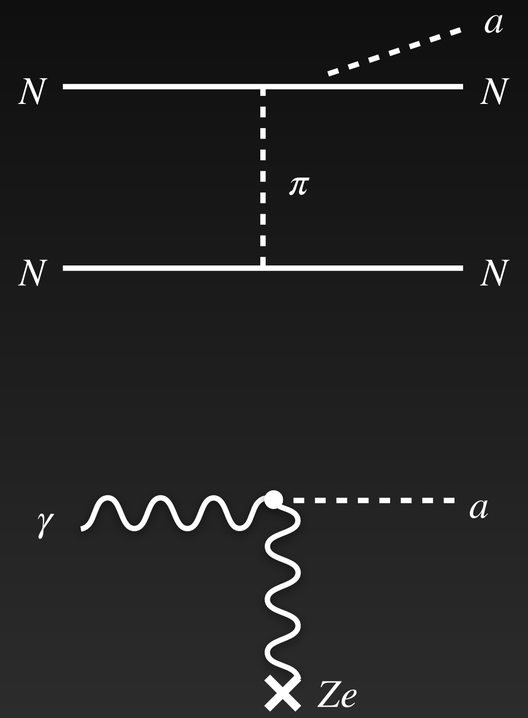
Beyond (tree-level) photon-ALP coupling



[Calore et al. 2020, 2022]

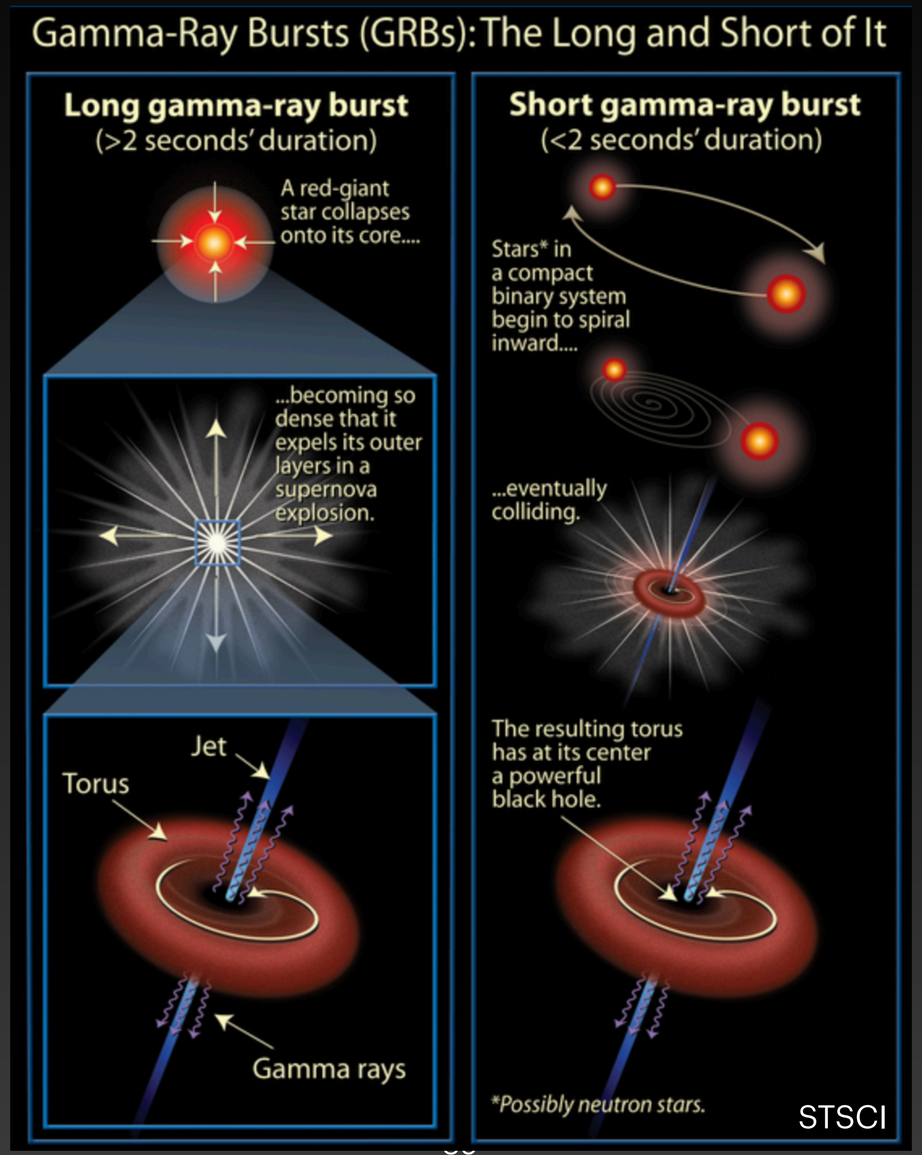
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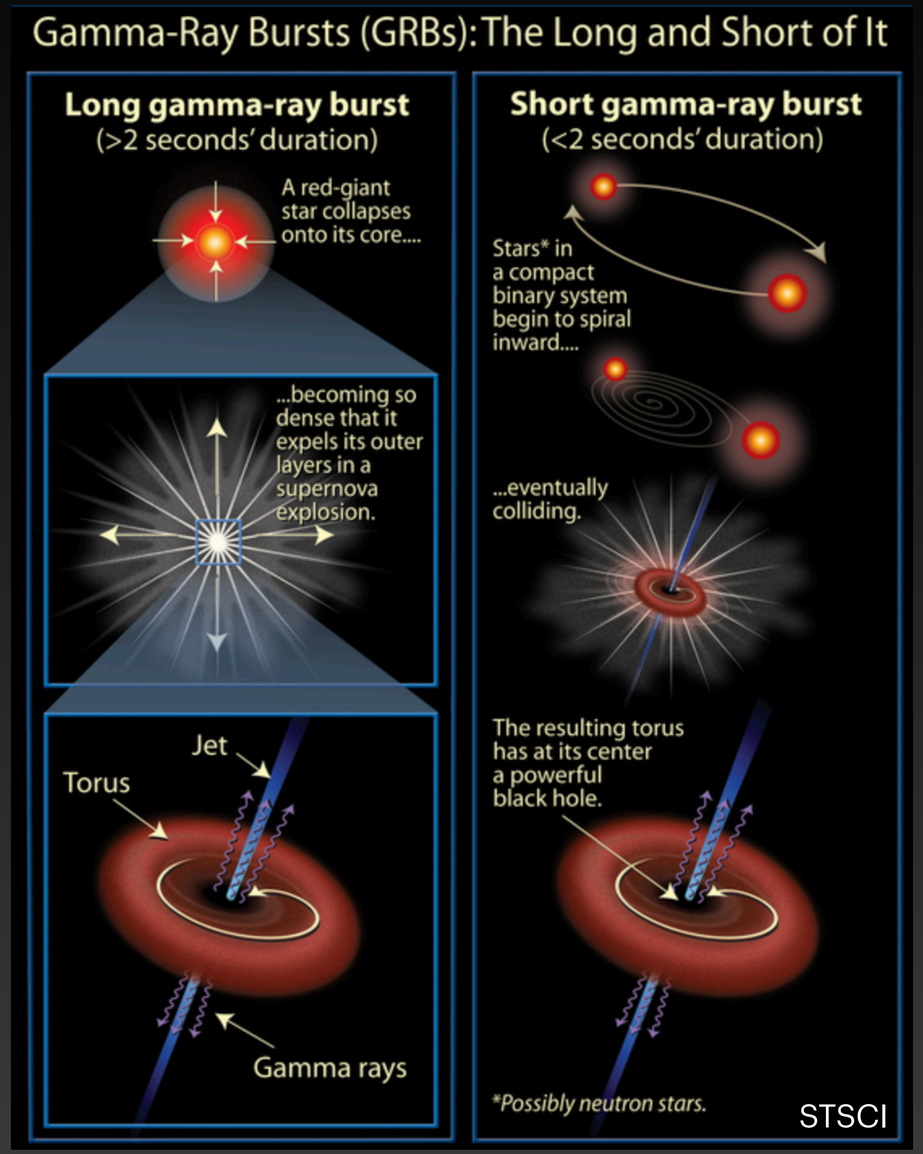


[Calore et al. 2020, 2022]

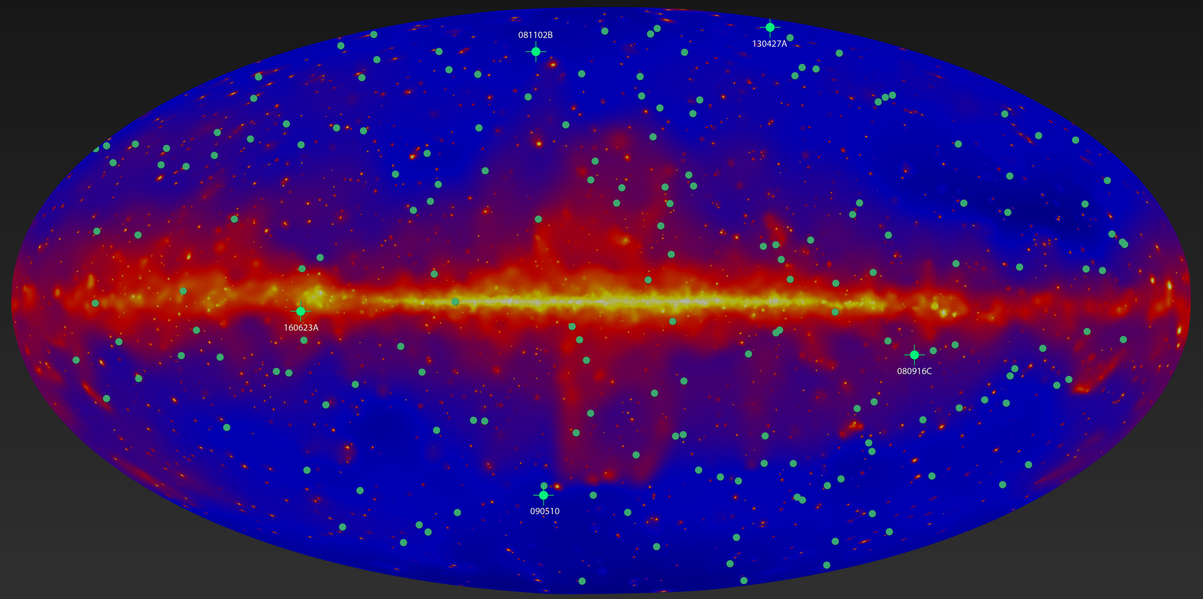
One slide on GRBs



One slide on GRBs

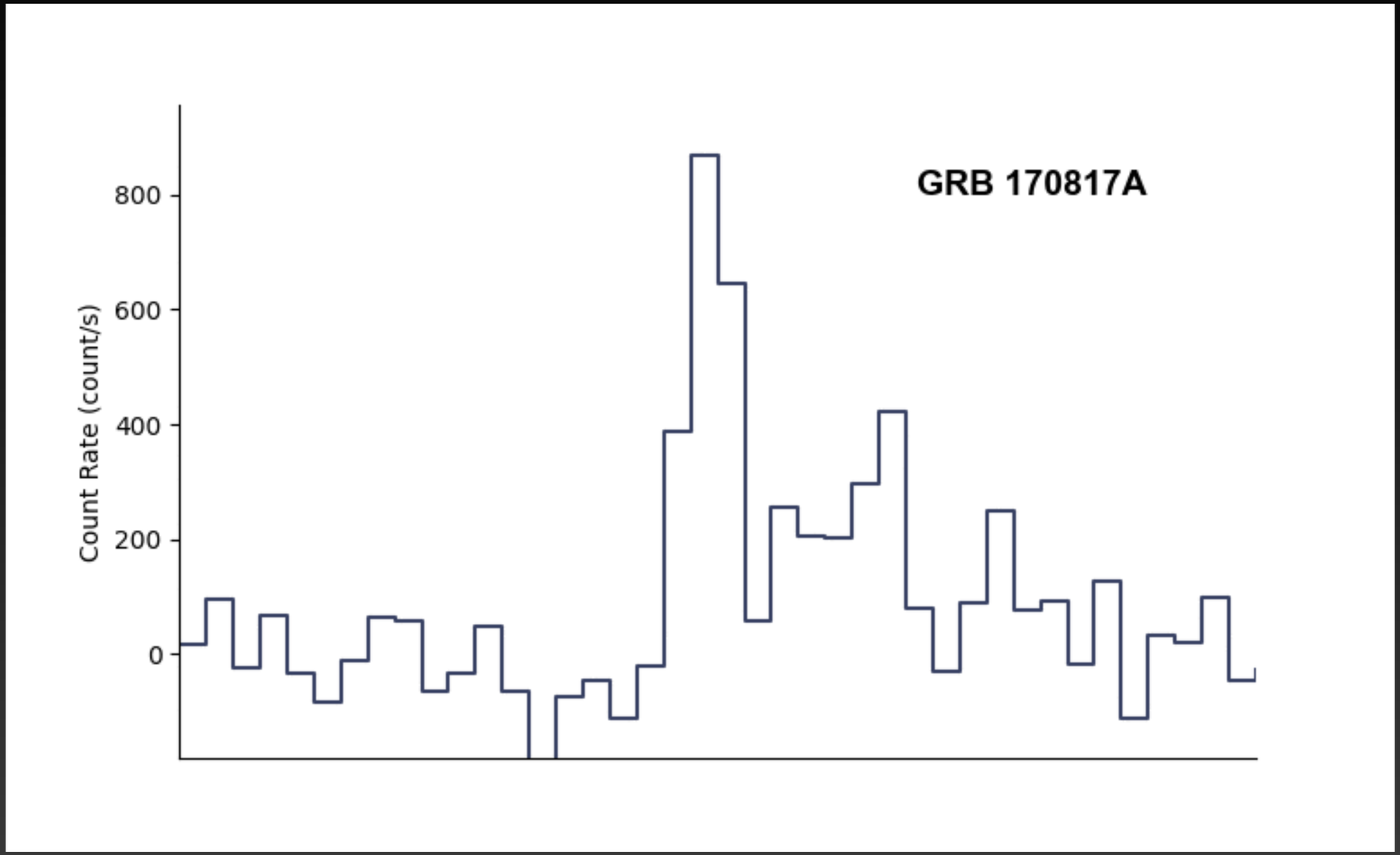


17 short GRBs, 169 long GRBs detected in 10 years with the LAT



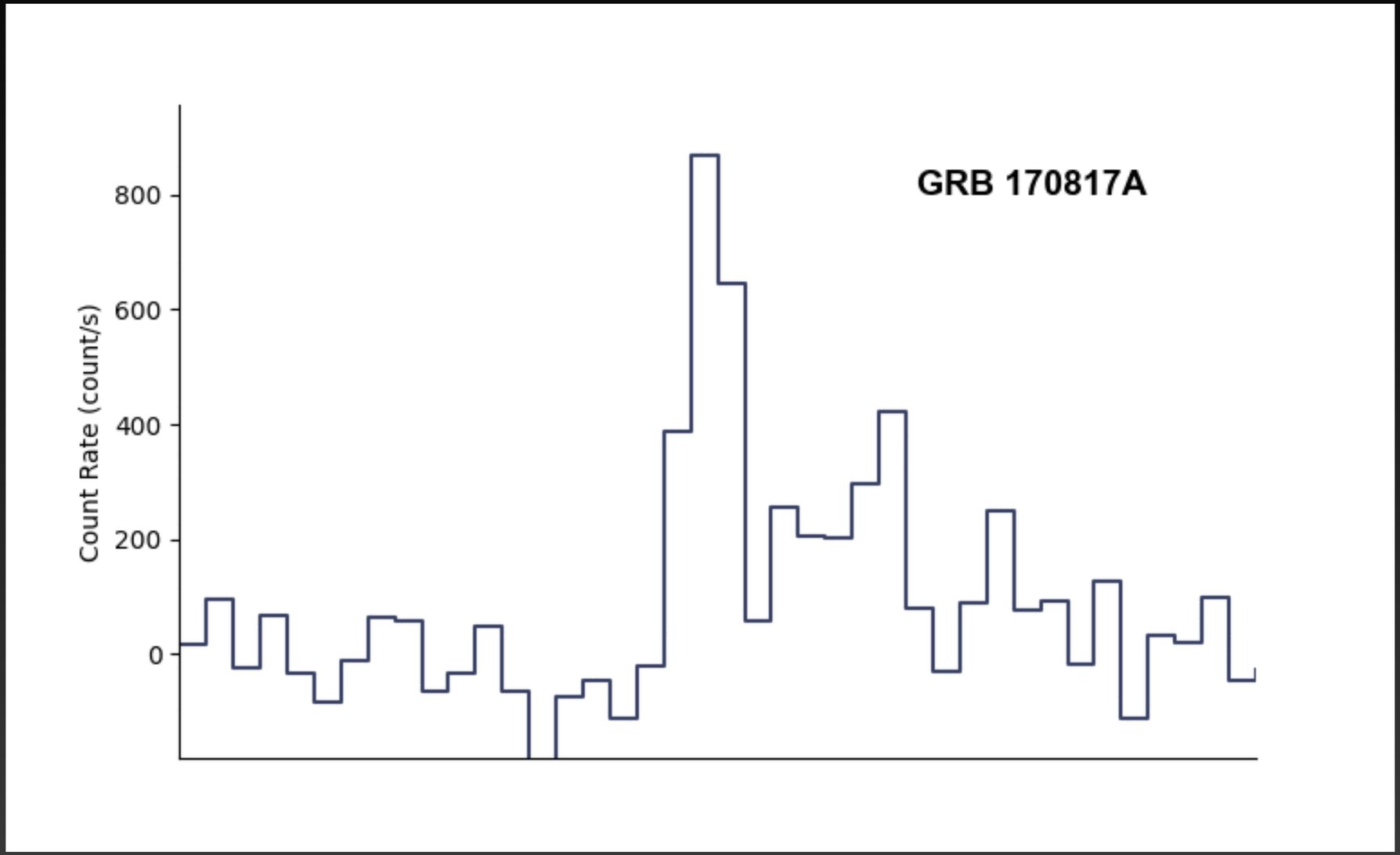
2FLGC, Ajello et al. (2019)

GRB221009A in perspective



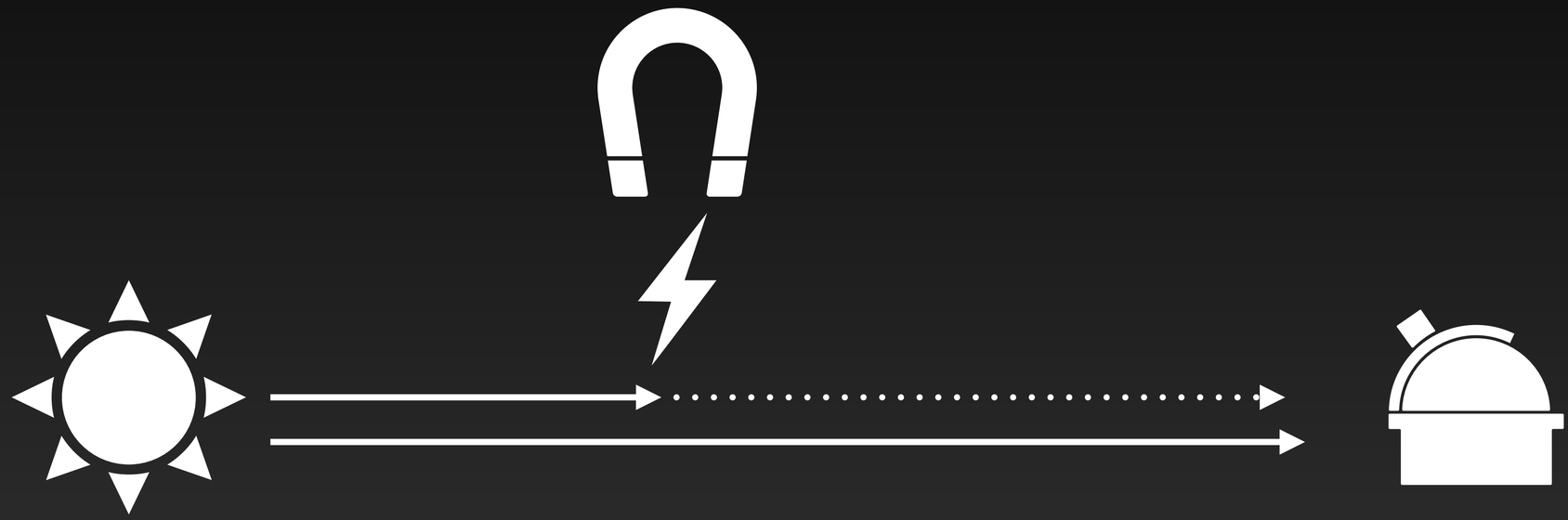
Credit: Adam Goldstein

GRB221009A in perspective

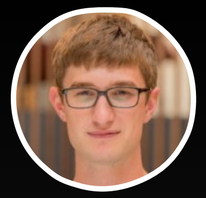


Credit: Adam Goldstein

Searches for axion-induced oscillations in blazar spectra



Search for Oscillations in bright Blazars



Work by Jamie Davies, PhD student at Oxford

[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

[MM, Scargle, Blandford 2019]

PKSB1222+216
Bayesian blocks, $N_{\rm Blocks} = 75$
QB
Average flux

3C273
Bayesian blocks, $N_{\rm Blocks} = 68$
QB
Average flux

3C279
Bayesian blocks, $N_{\rm Blocks} = 106$
QB
Average flux

PKS1510-089
Bayesian blocks, $N_{\rm Blocks} = 118$
QB
Average flux

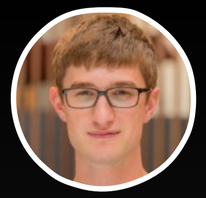
CTA102
Bayesian blocks, $N_{\rm Blocks} = 114$
QB
Average flux

3C454.3
Bayesian blocks, $N_{\rm Blocks} = 156$
QB
Average flux

$F\ [10^{-6}\,{\rm cm}^{-2}\,{\rm s}^{-1}]$

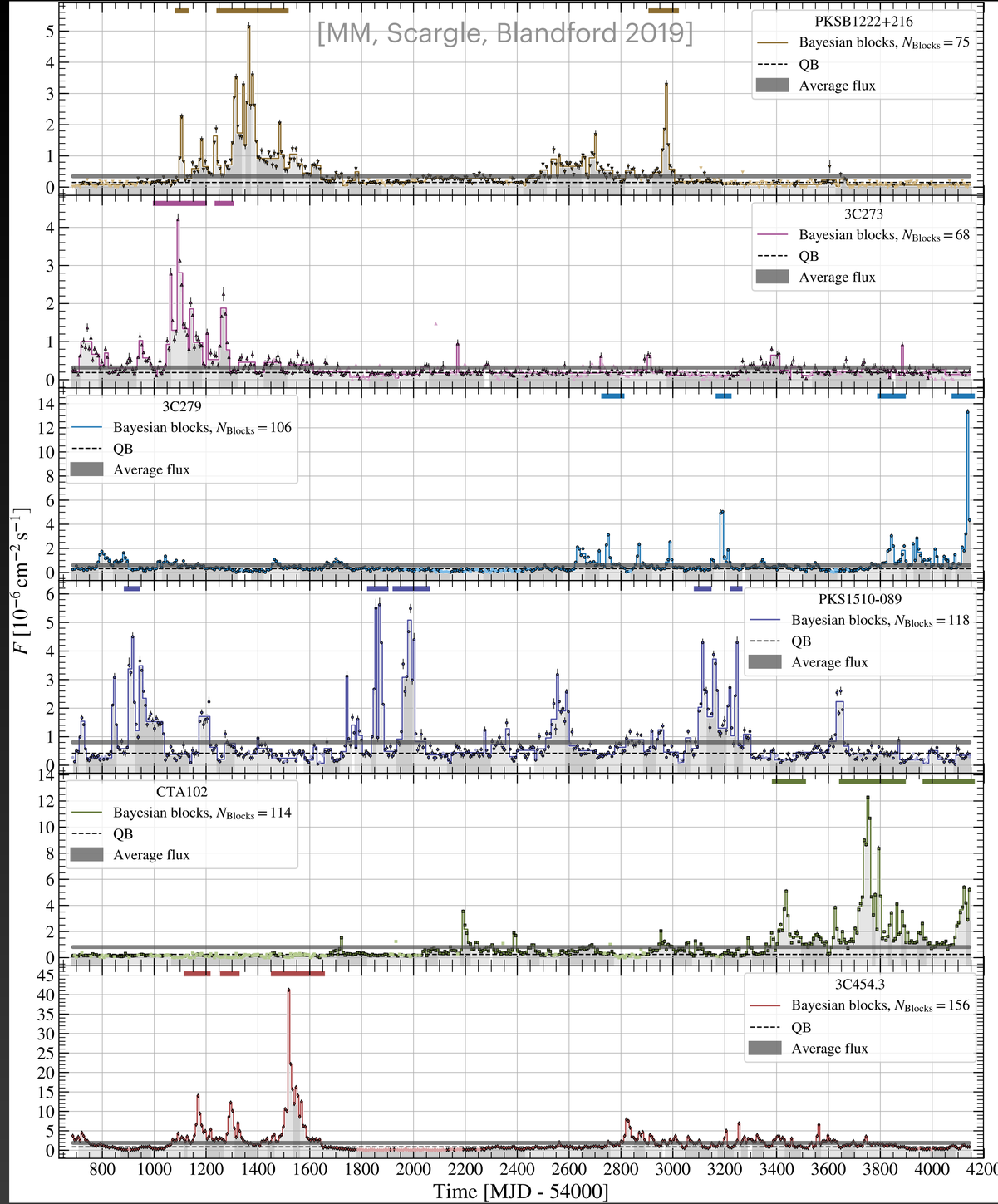
Time [MJD - 54000]

Search for Oscillations in bright Blazars



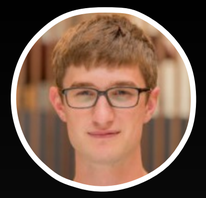
Work by Jamie Davies, PhD student at Oxford

- Requires high photon statistics



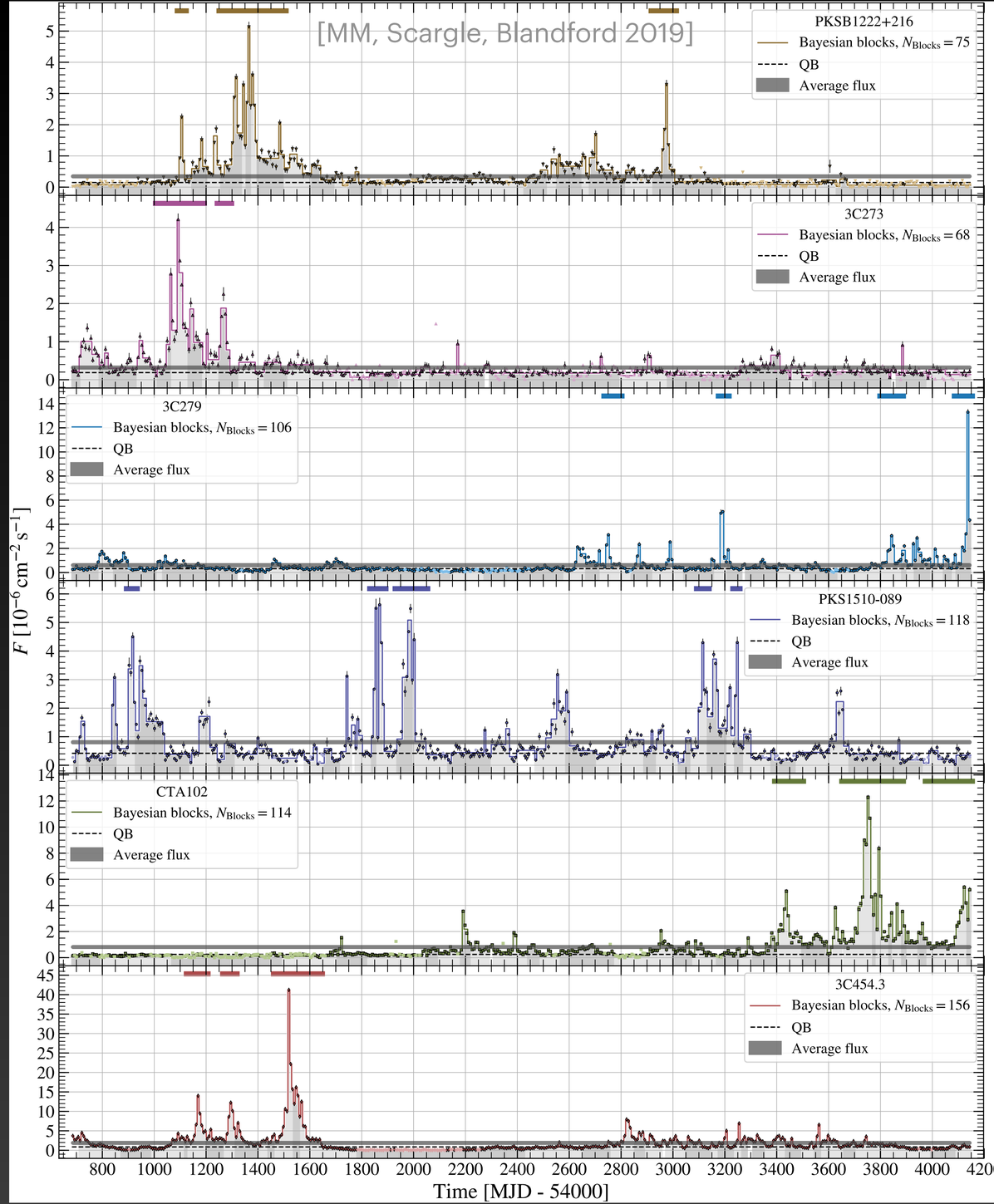
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

Search for Oscillations in bright Blazars



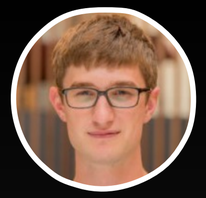
Work by Jamie Davies, PhD student at Oxford

- Requires high photon statistics
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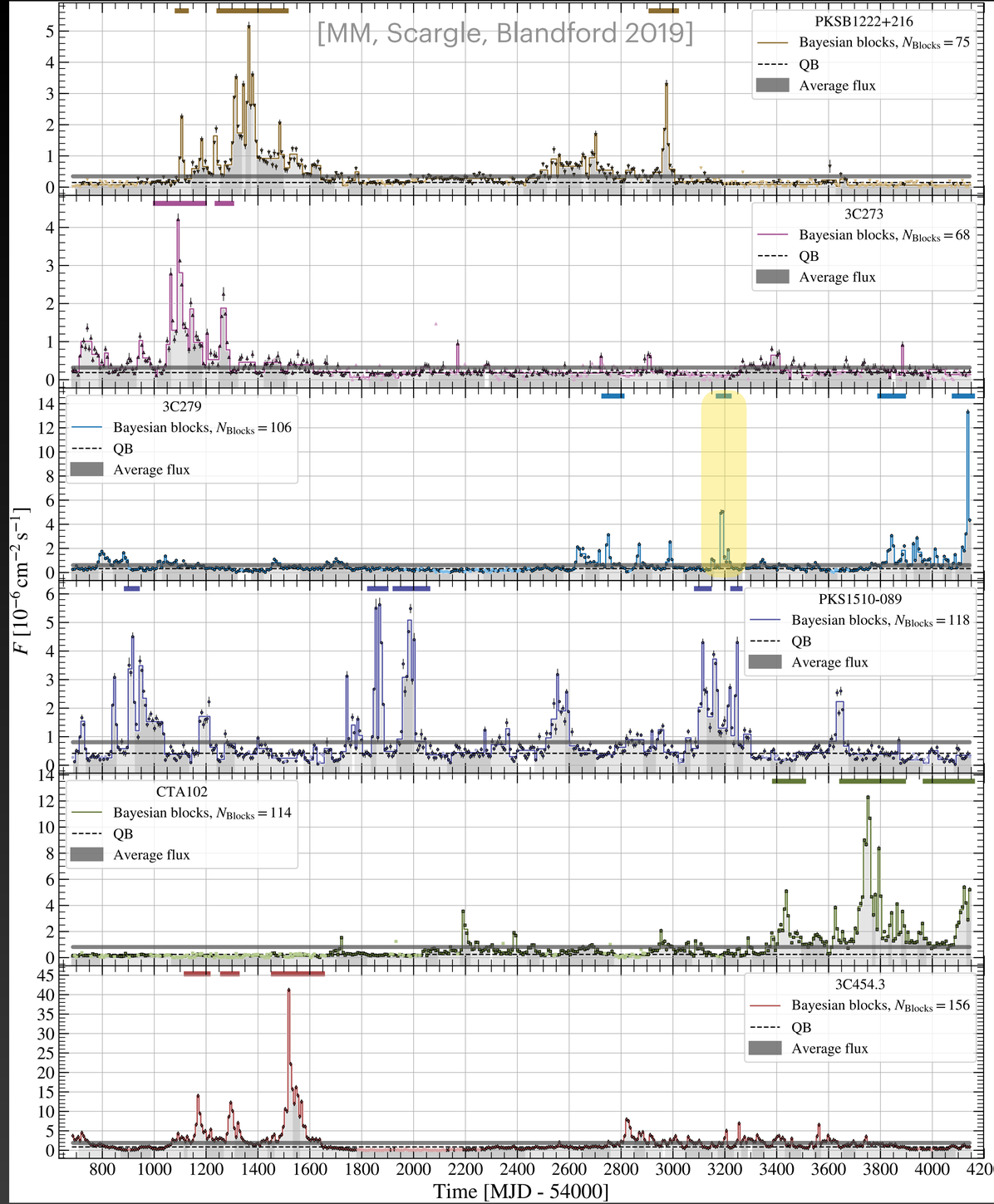
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

Search for Oscillations in bright Blazars



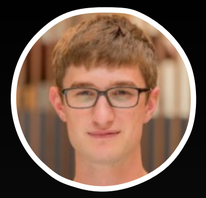
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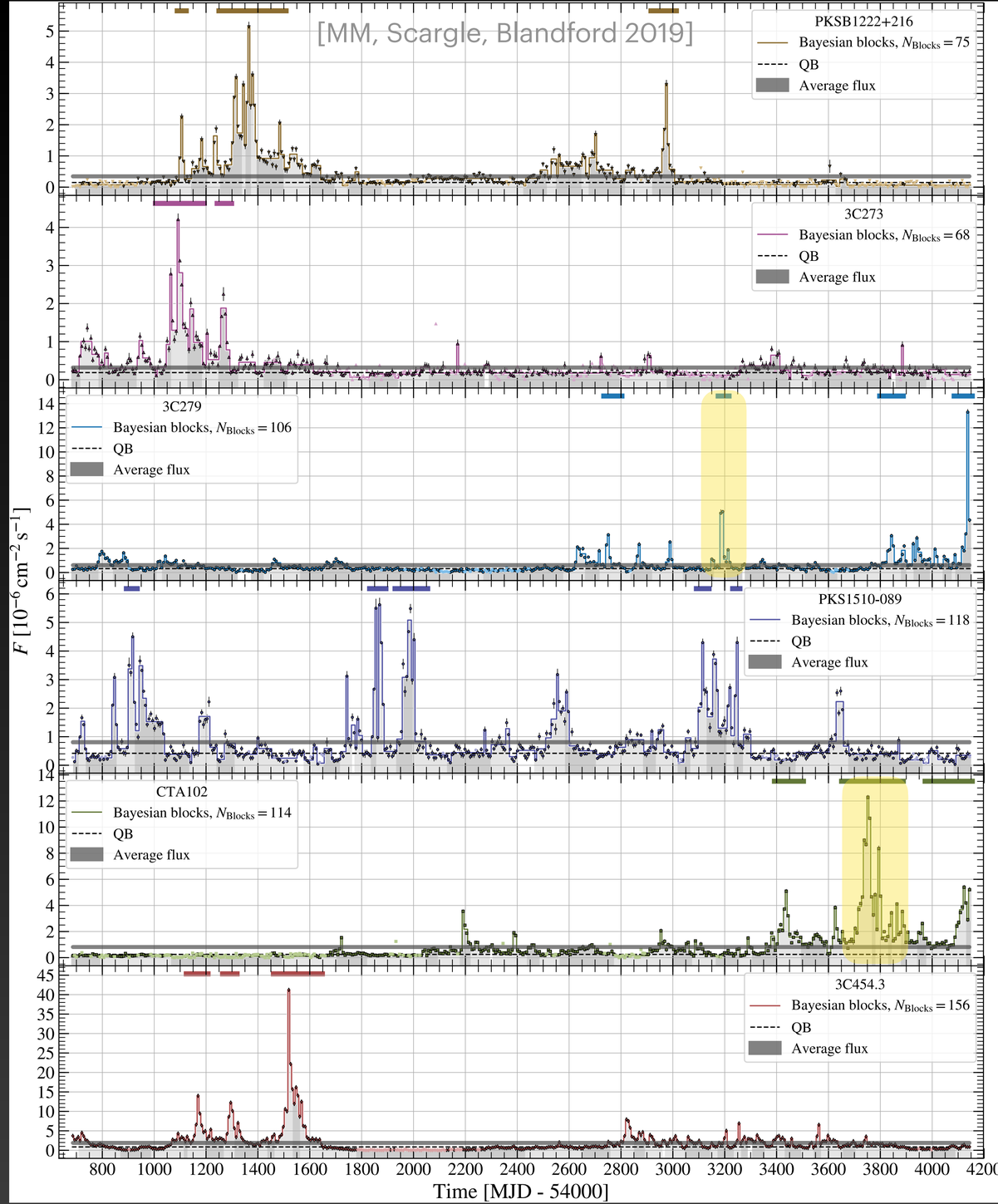
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Search for Oscillations in bright Blazars



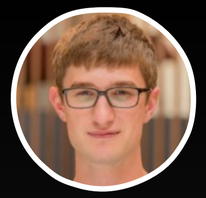
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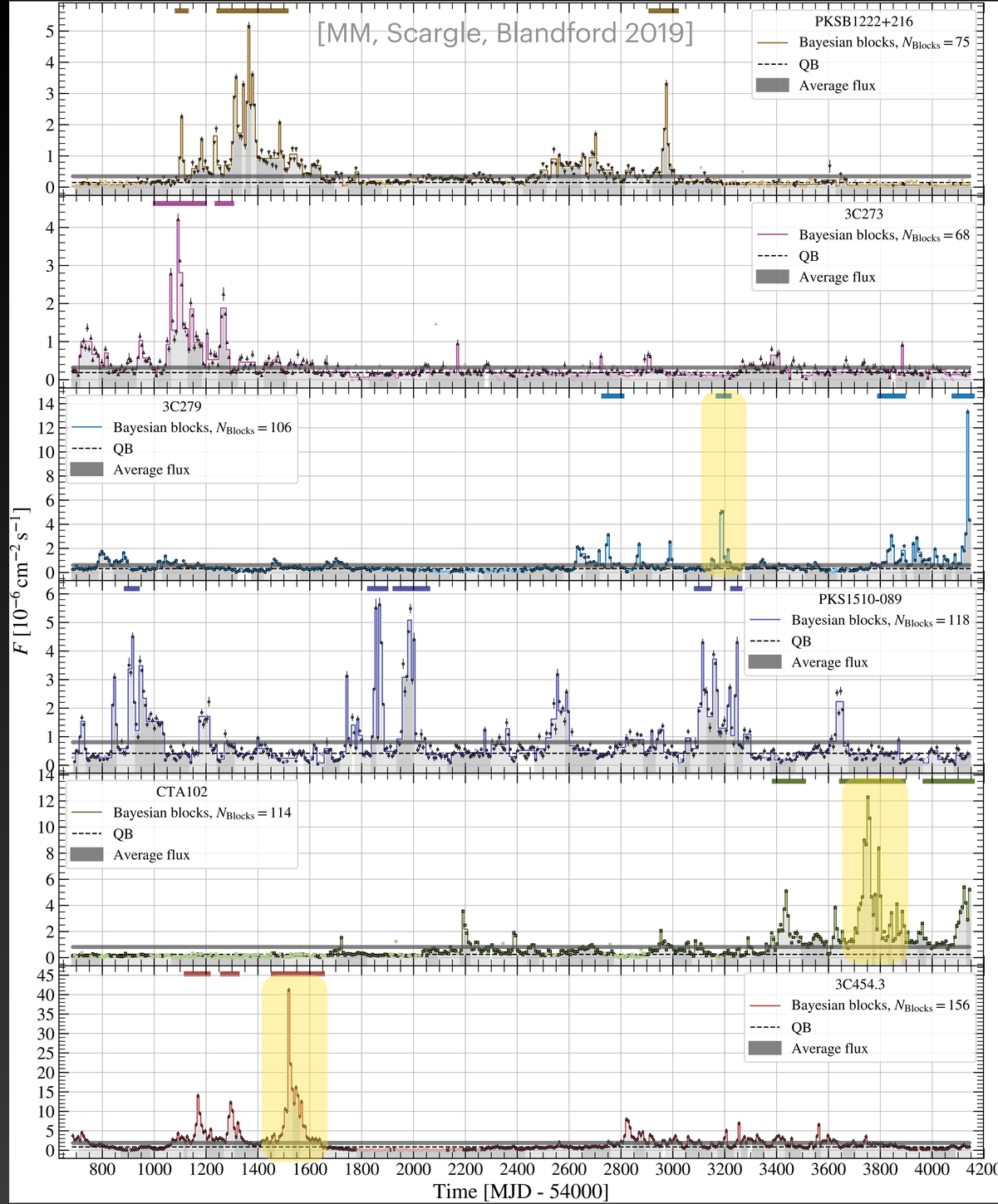
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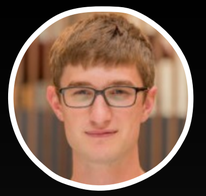
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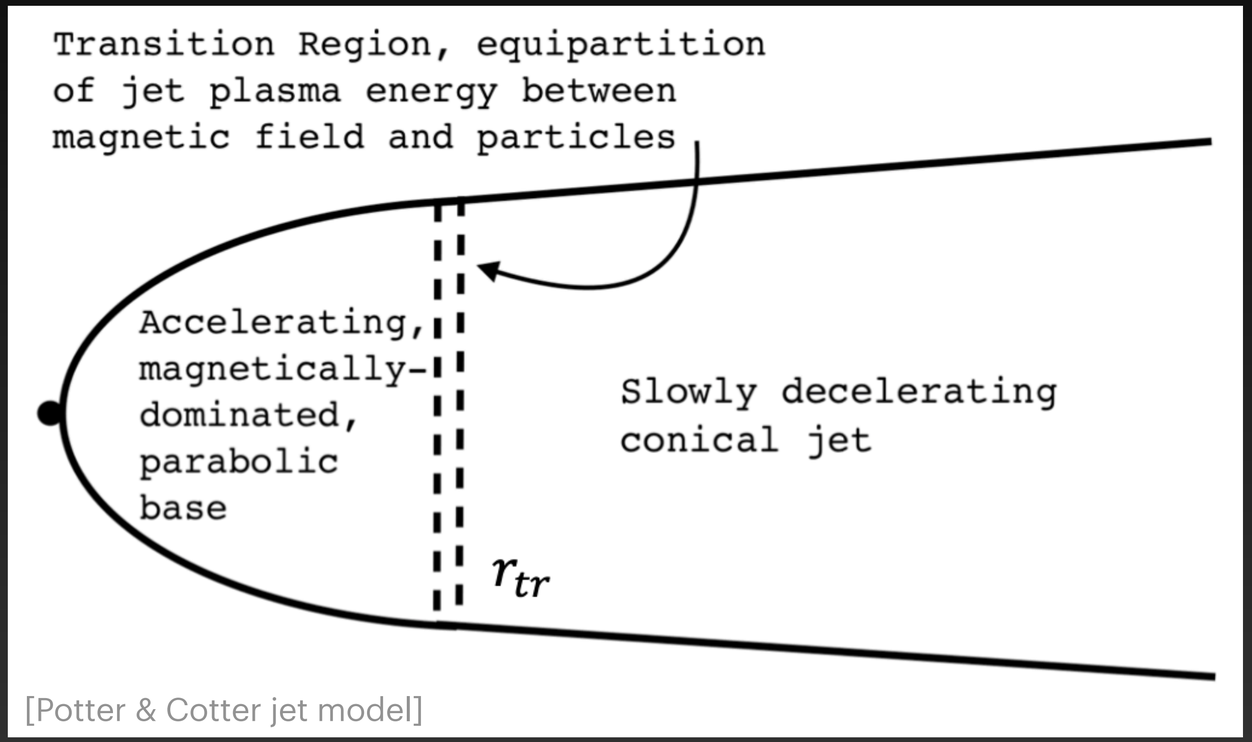


[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

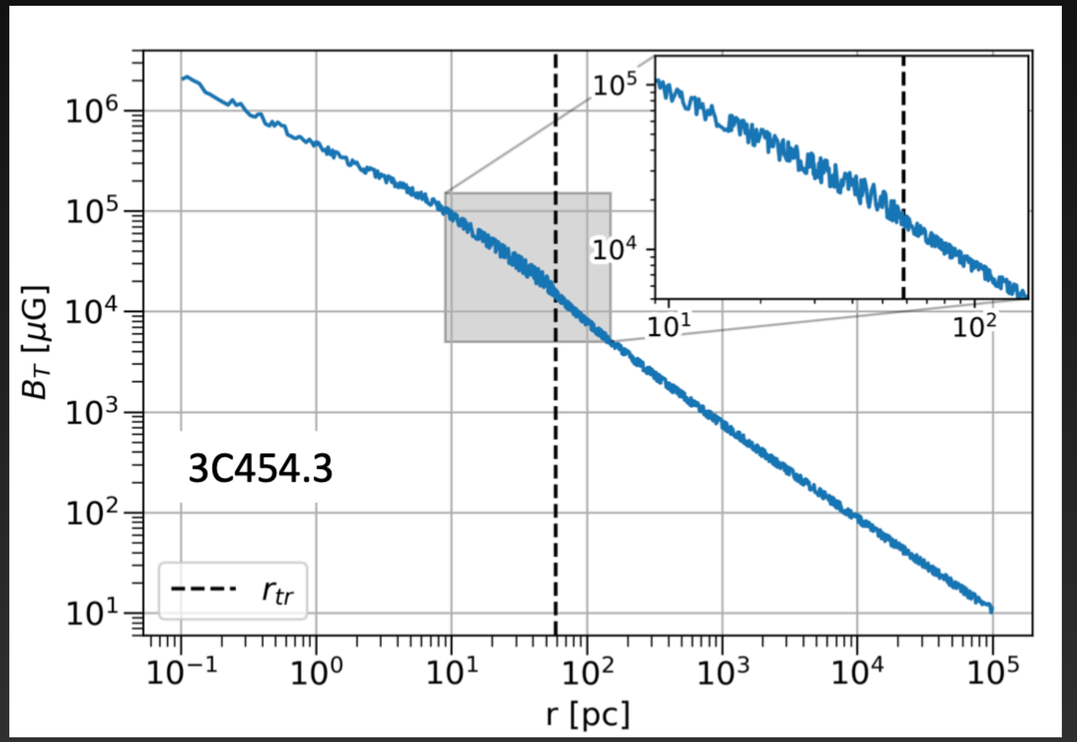
Modeling the jet magnetic field



Work by Jamie Davies,
PhD student at Oxford

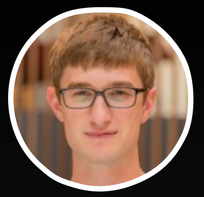


[Potter & Cotter jet model]

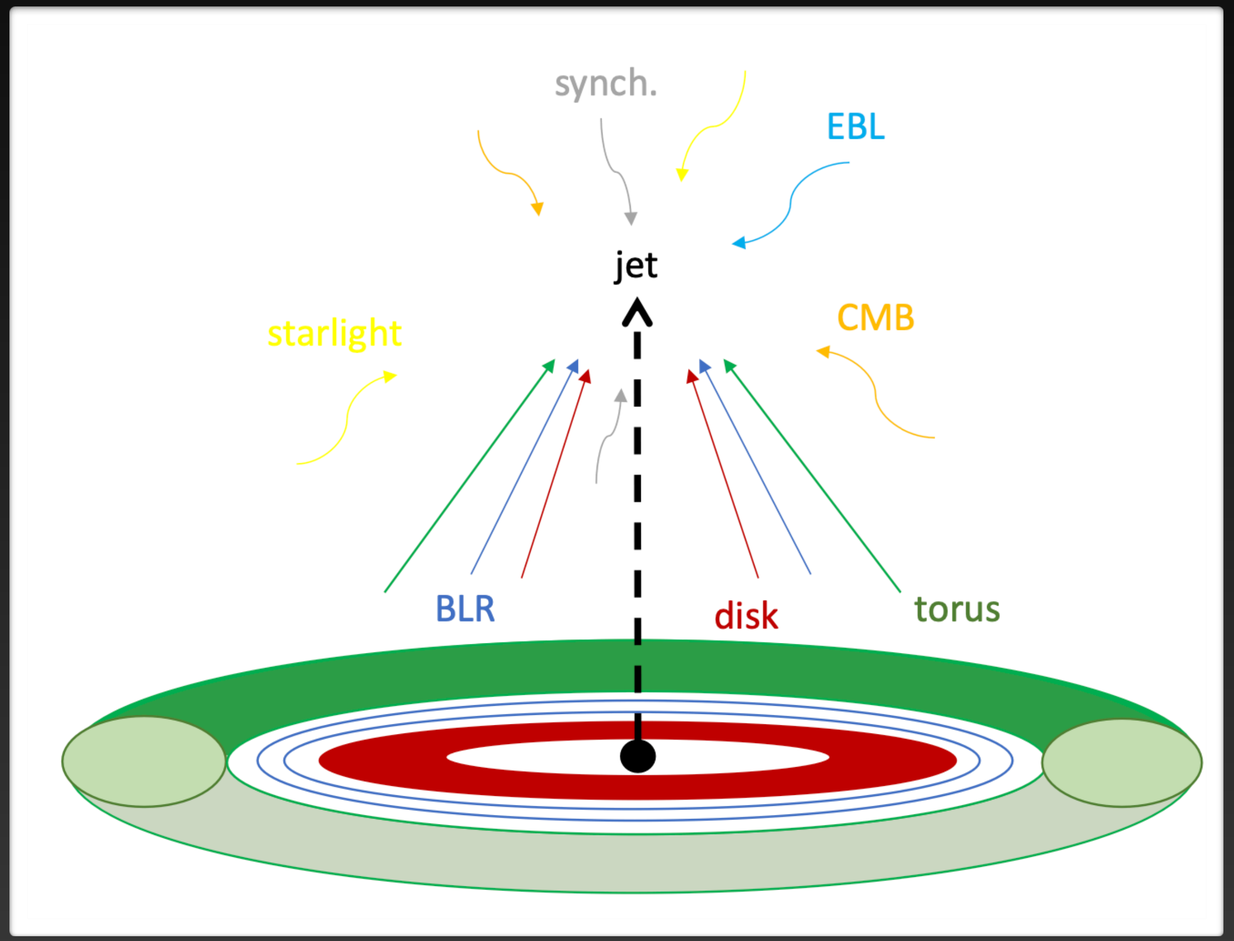


[Davies, MM, Cotter 2022]

Account for photon-photon dispersion

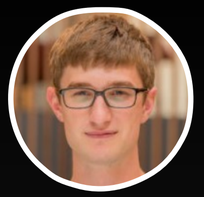


Work by Jamie Davies,
PhD student at Oxford



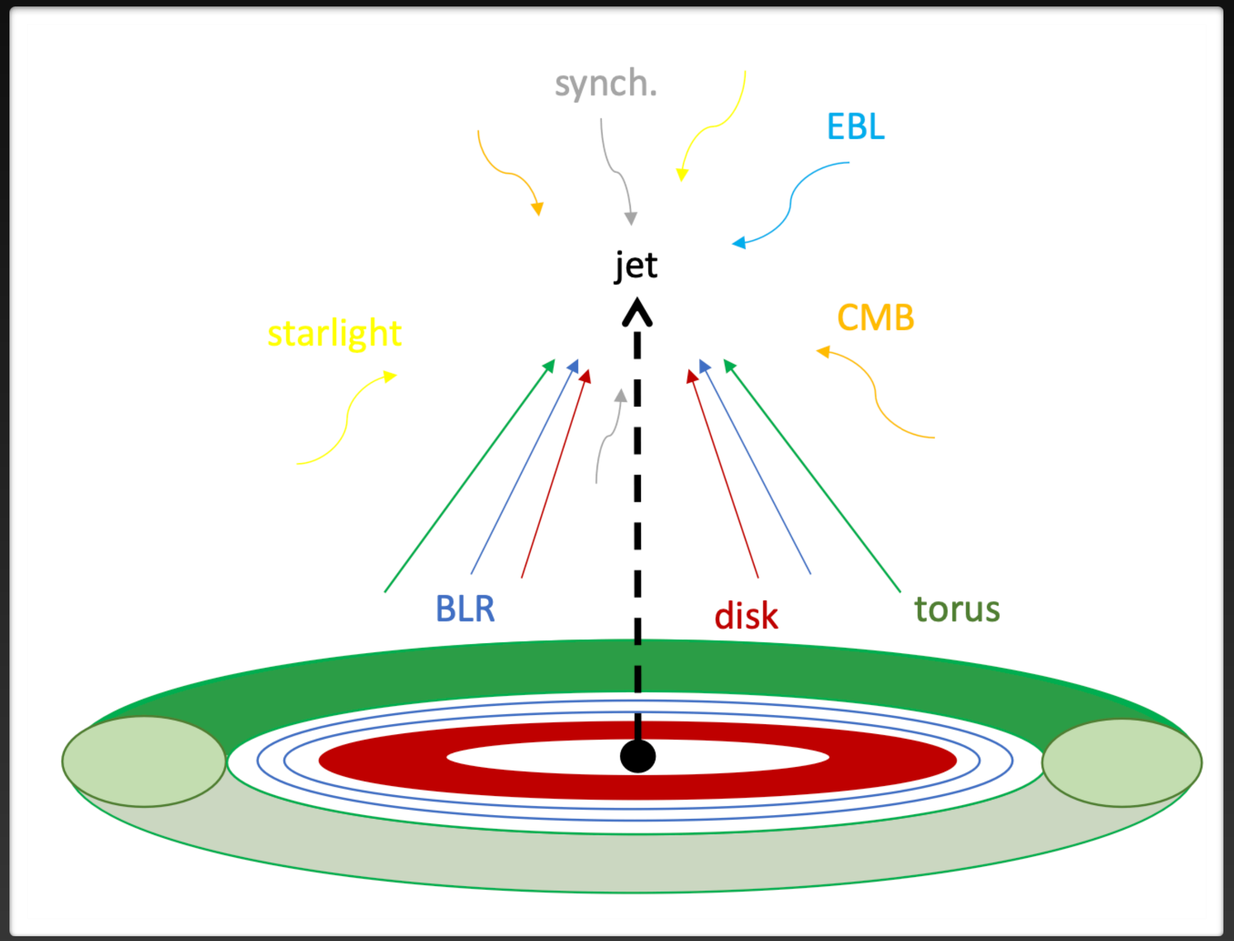
[Davies, MM, Cotter 2022]

Account for photon-photon dispersion



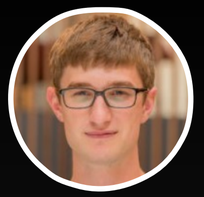
Work by Jamie Davies,
PhD student at Oxford

- Bright photon fields present in FSRQs



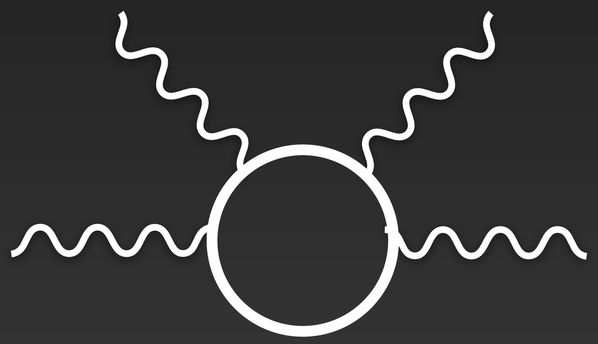
[Davies, MM, Cotter 2022]

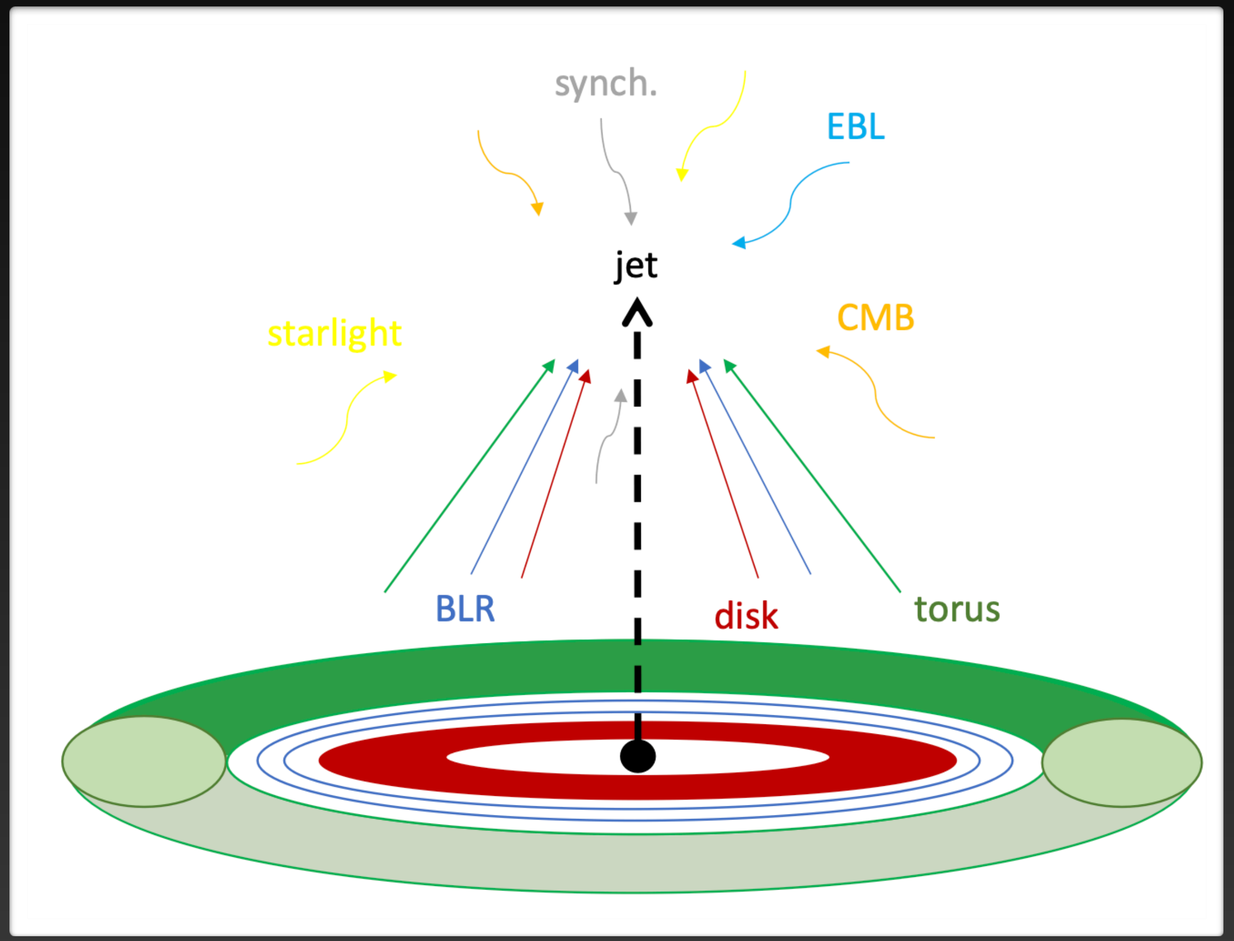
Account for photon-photon dispersion



Work by Jamie Davies,
PhD student at Oxford

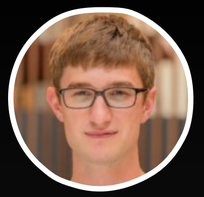
- Bright photon fields present in FSRQs
- Leads to photon-photon dispersion





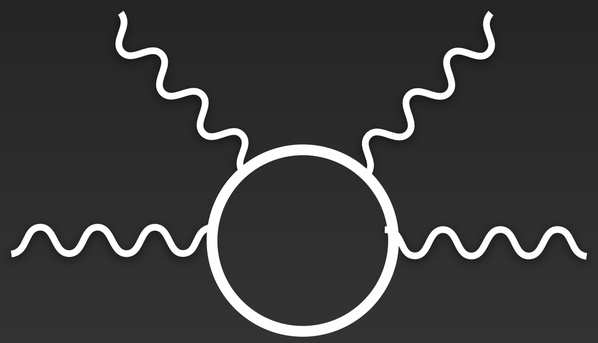
[Davies, MM, Cotter 2022]

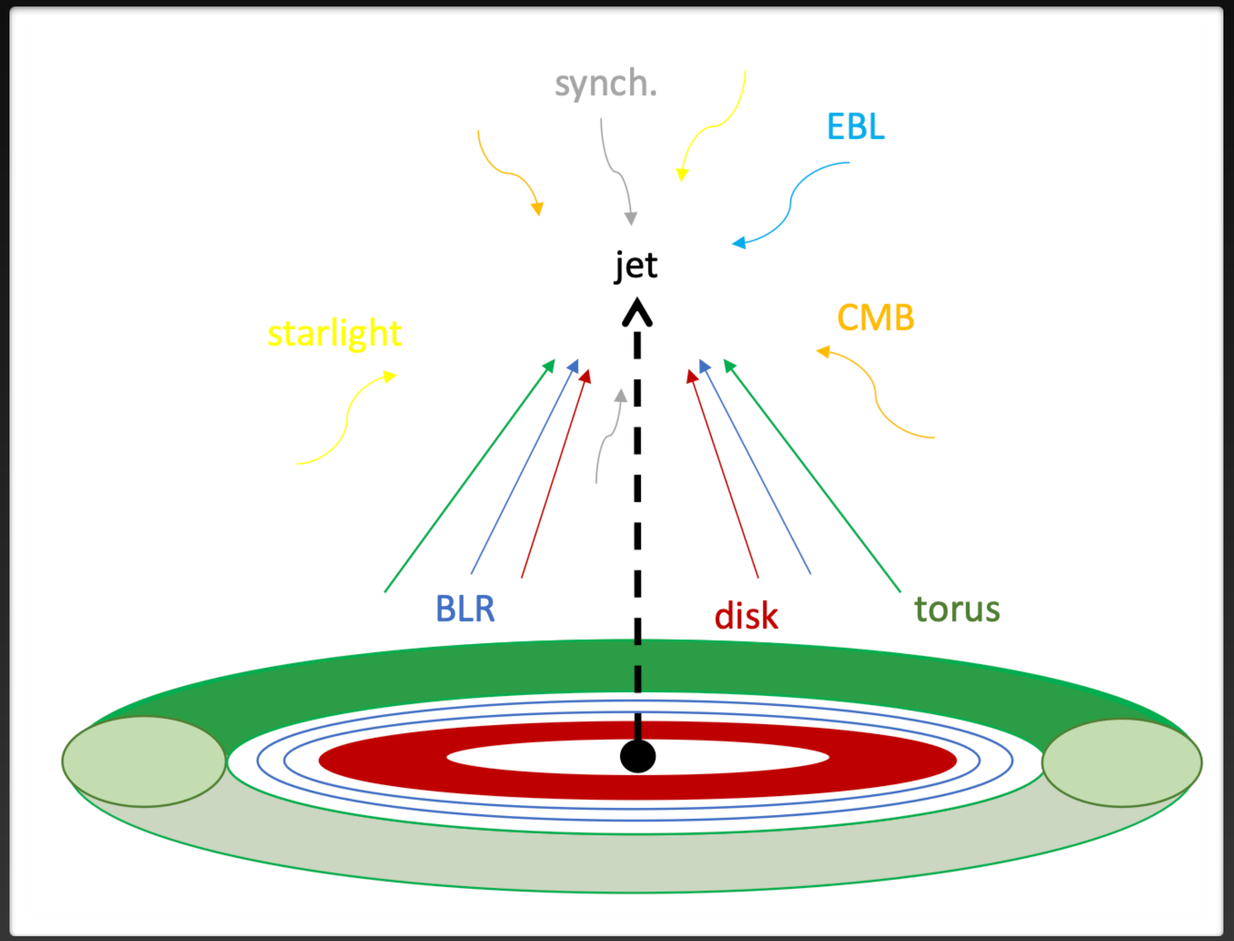
Account for photon-photon dispersion



Work by Jamie Davies,
PhD student at Oxford

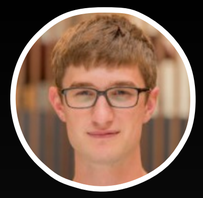
- Bright photon fields present in FSRQs
- Leads to photon-photon dispersion
- Must be taken into account in photon-ALP oscillation calculations





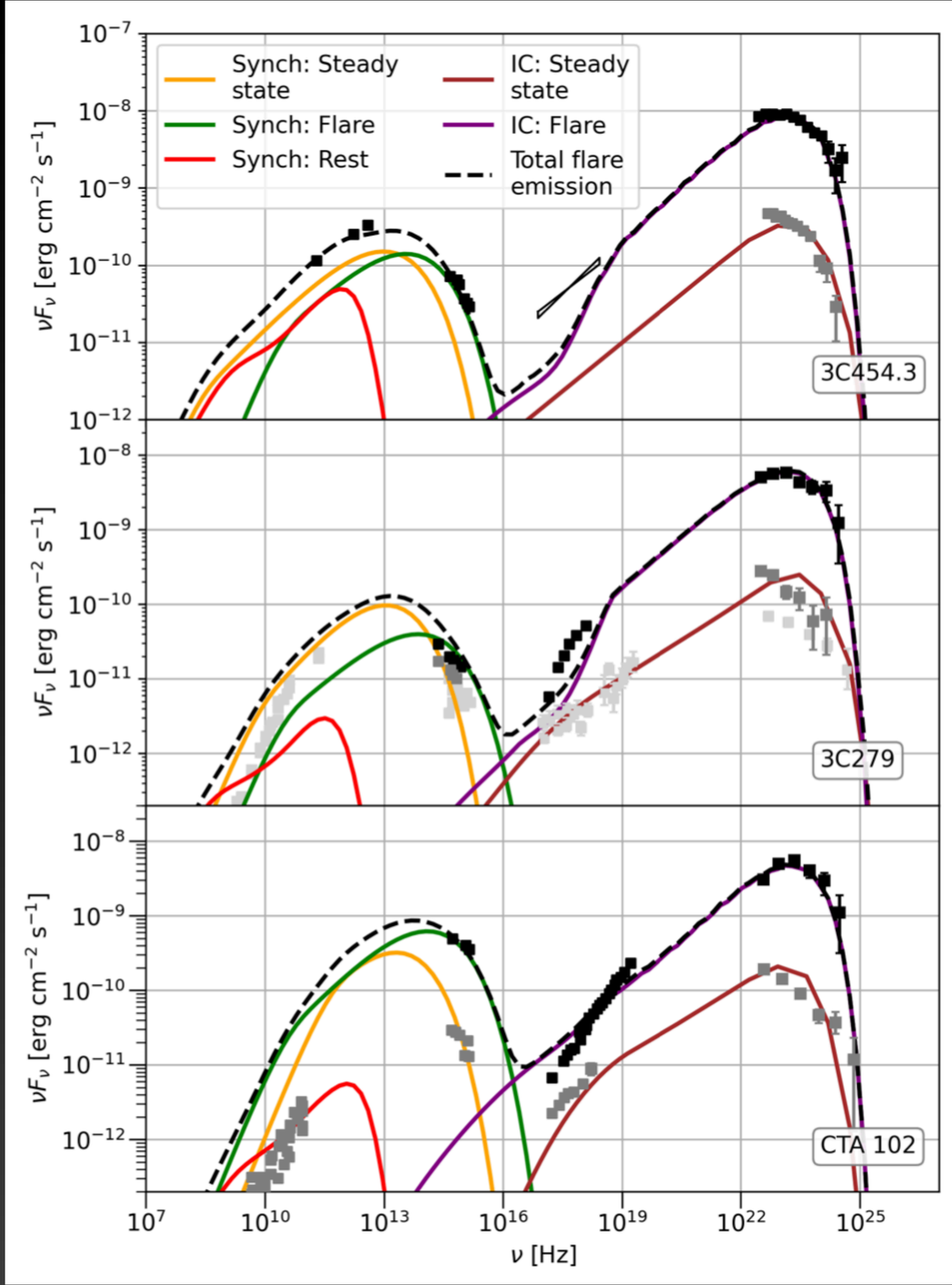
[Davies, MM, Cotter 2022]

Self-consistent modeling



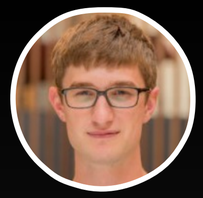
Work by Jamie Davies, PhD student at Oxford

- Assumed B-field needs to reproduce broad band emission



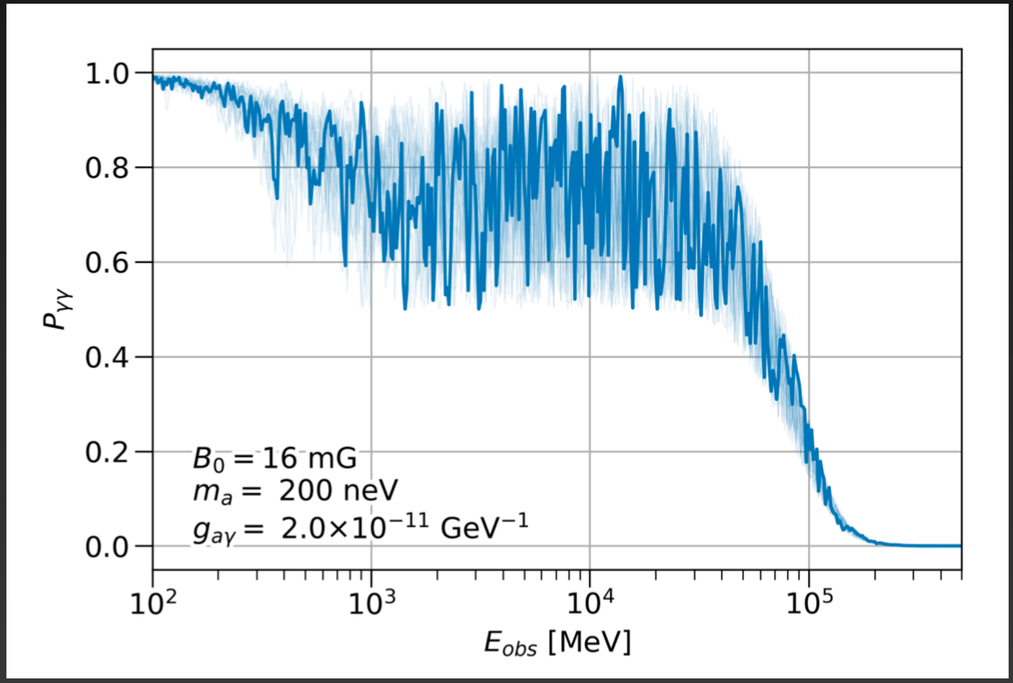
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

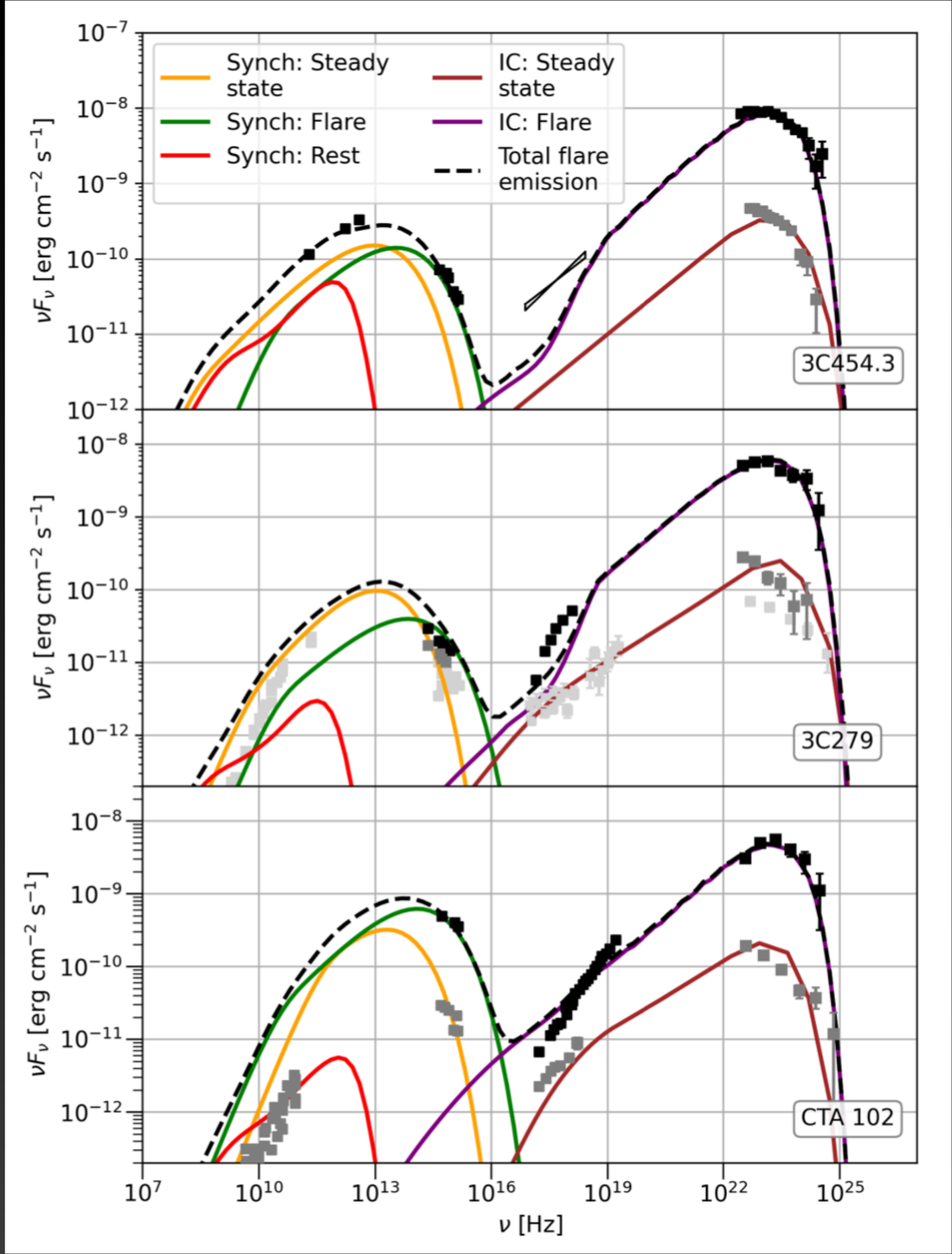
Self-consistent modeling



Work by Jamie Davies, PhD student at Oxford

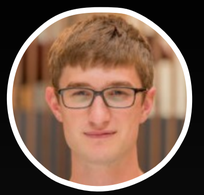
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[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

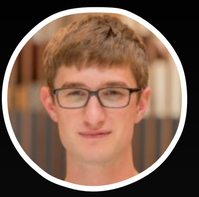
Data analysis



Work by Jamie Davies,
PhD student at Oxford

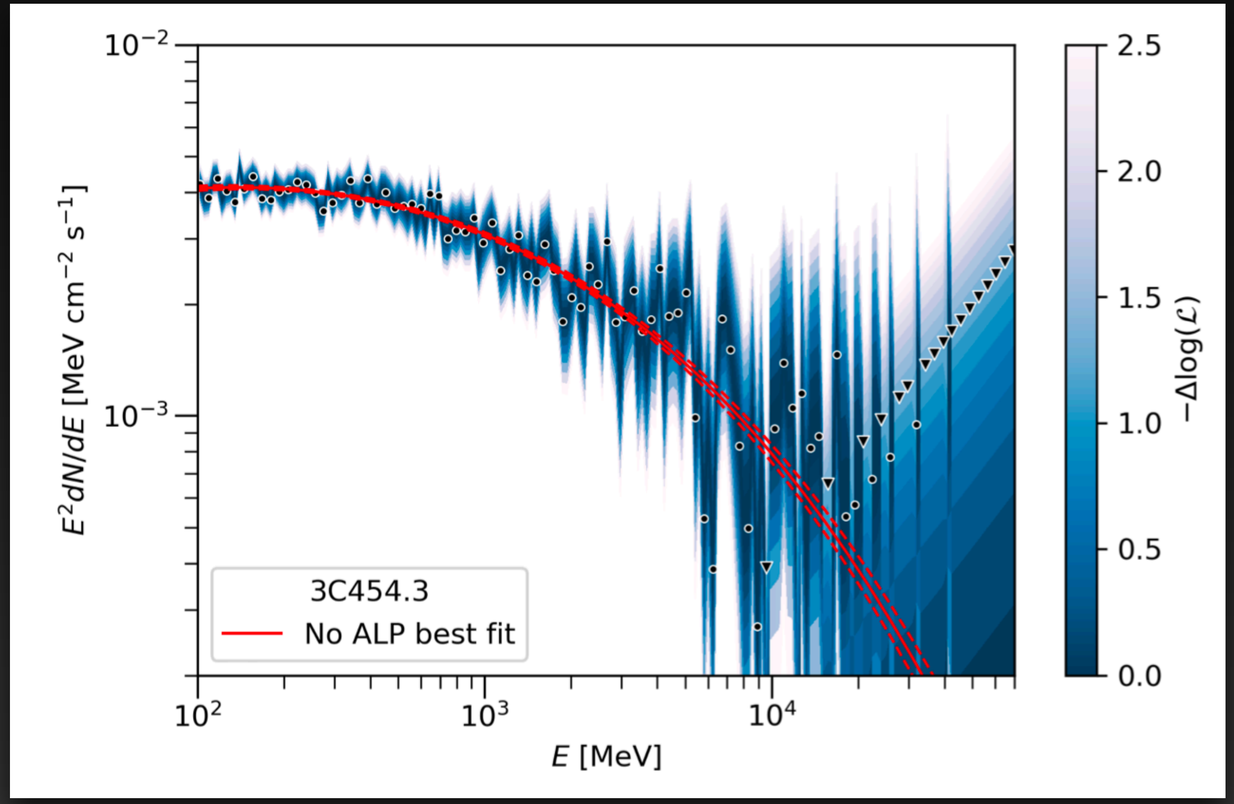
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

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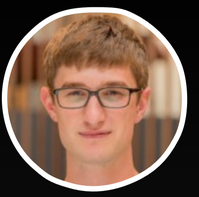
Work by Jamie Davies,
PhD student at Oxford

- Considered flares from 3 bright sources observed with Fermi LAT



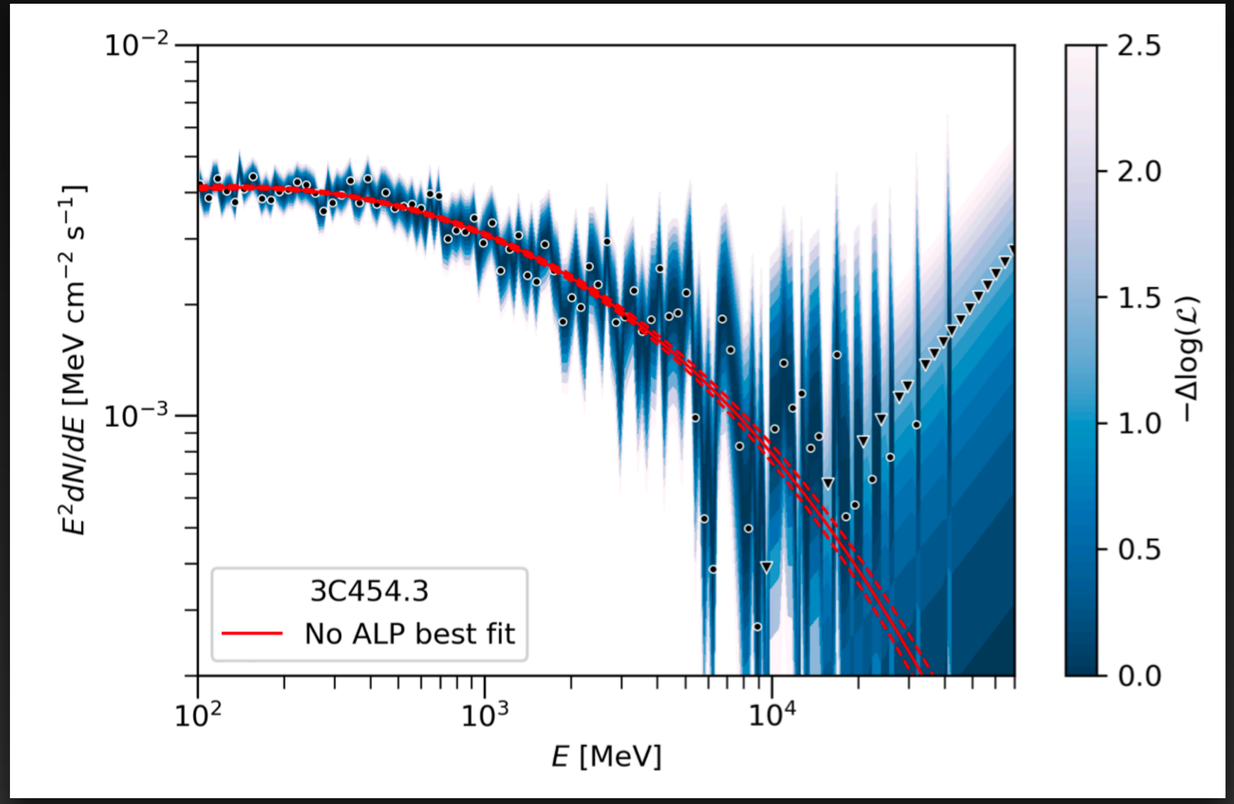
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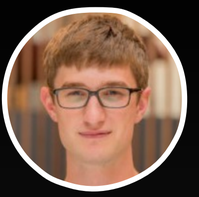
Work by Jamie Davies,
PhD student at Oxford

- Considered flares from 3 bright sources observed with Fermi LAT
- First time:



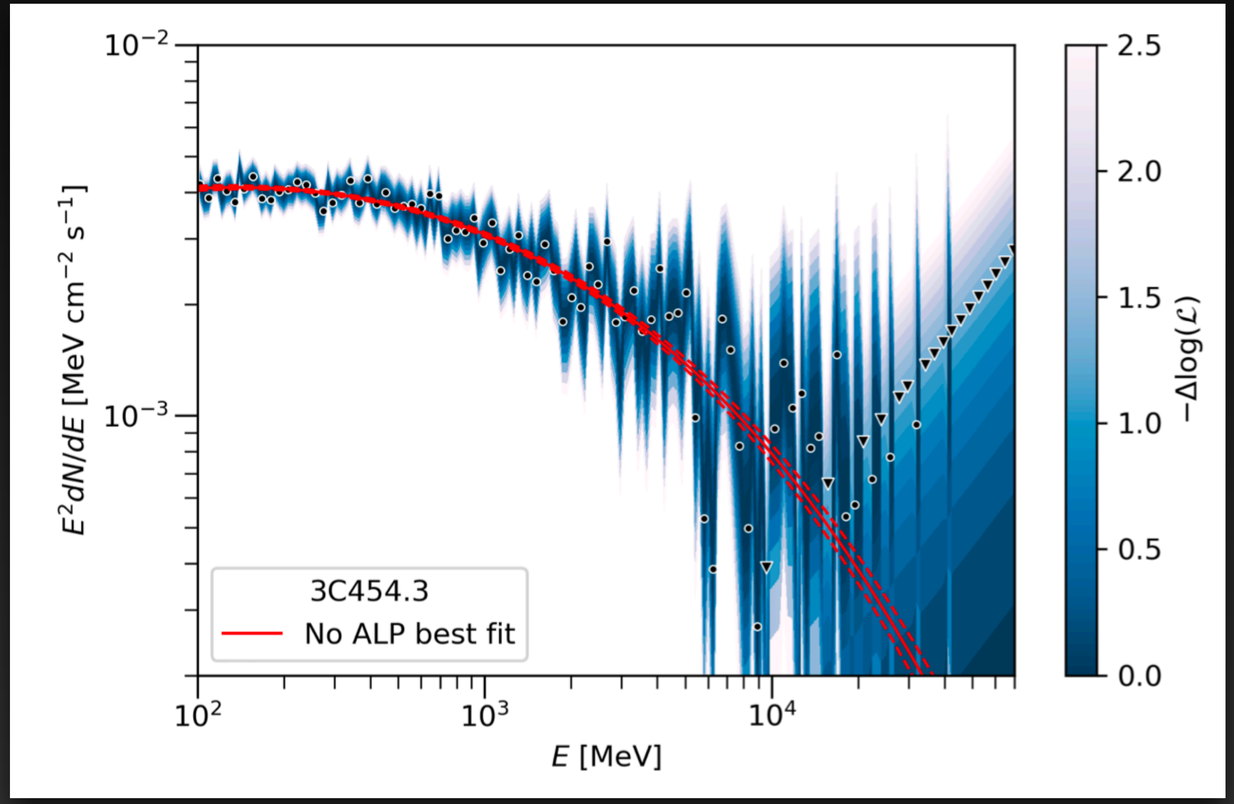
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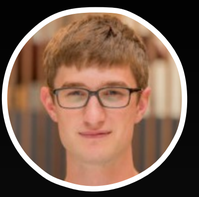
Work by Jamie Davies,
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- Considered flares from 3 bright sources observed with Fermi LAT
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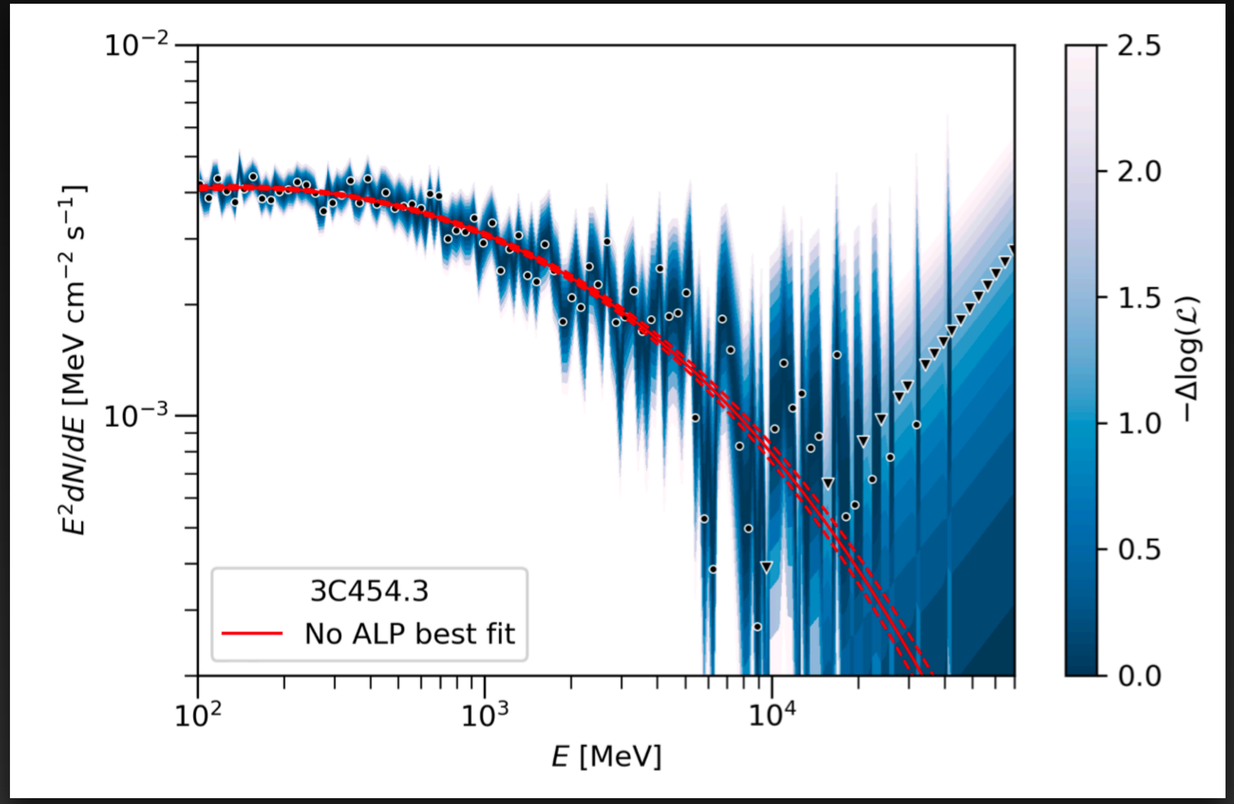
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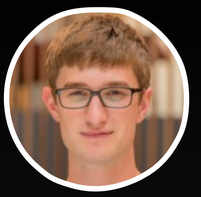
Work by Jamie Davies,
PhD student at Oxford

- Considered flares from 3 bright sources observed with Fermi LAT
- First time:
  - included effect photon-photon dispersion
  - B field strength left free in the fit

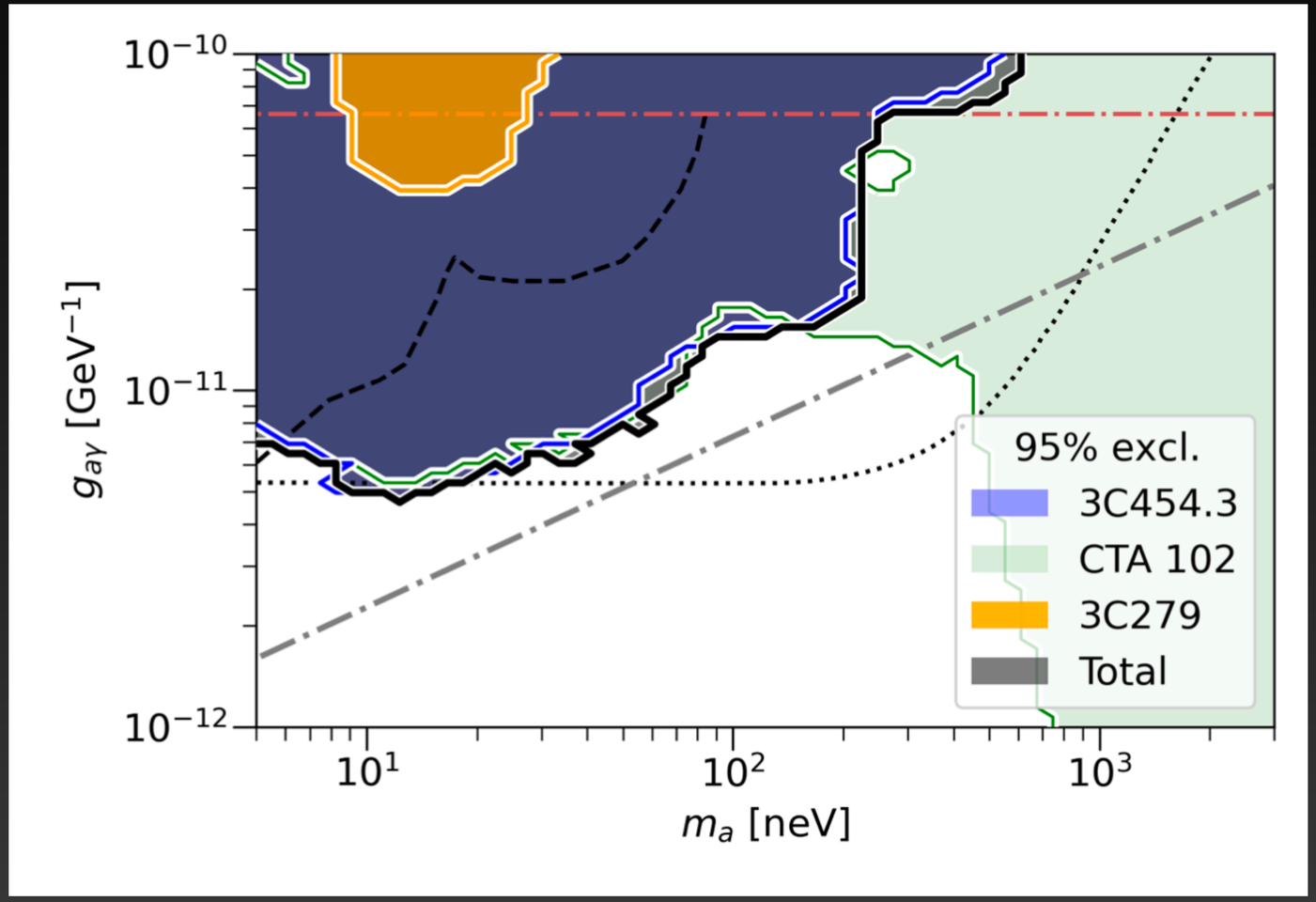


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Constraints

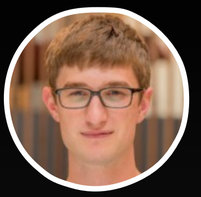


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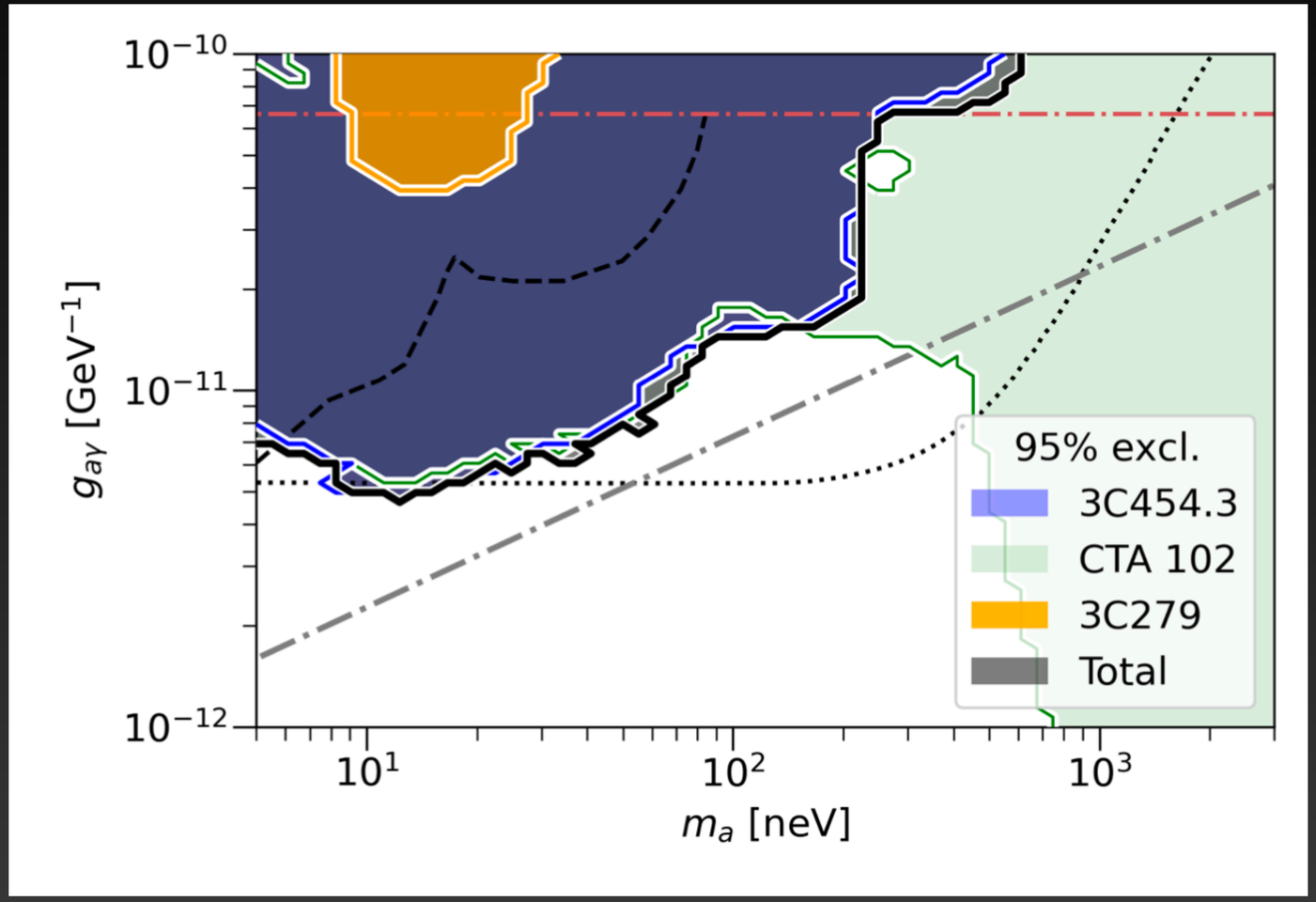
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

Constraints



Work by Jamie Davies,
PhD student at Oxford

- No preference for ALPs found
- Strong constraints on photon-ALP coupling



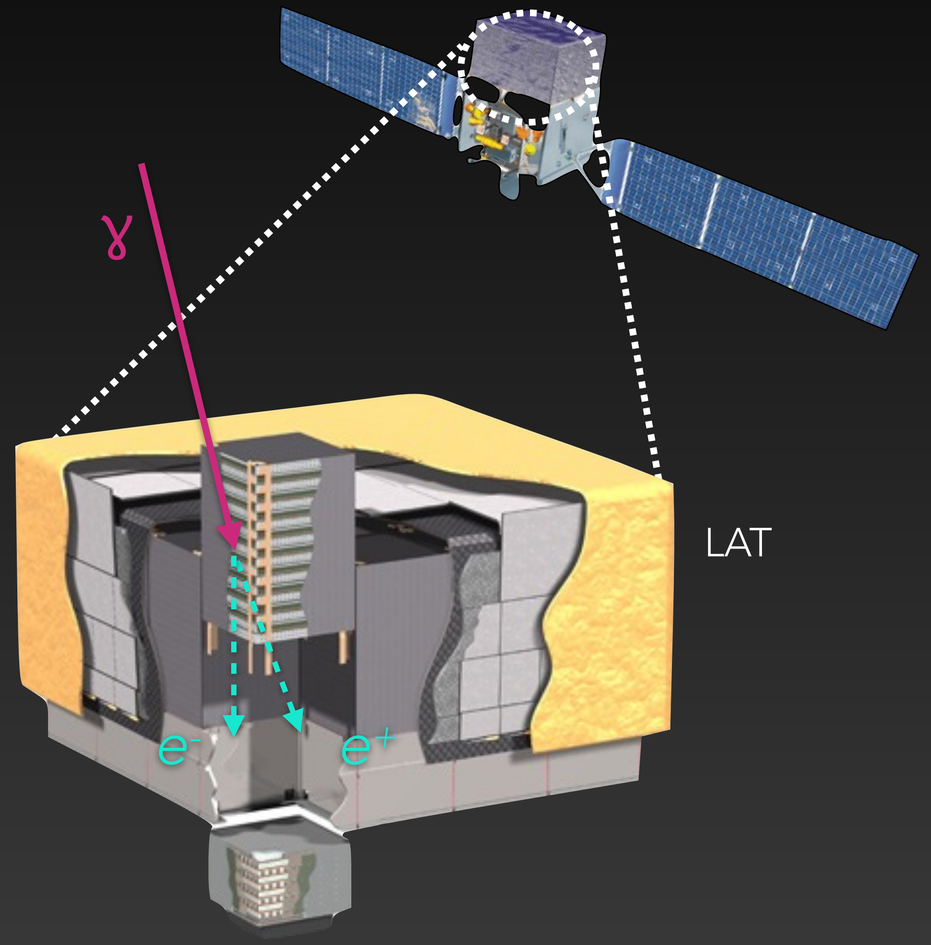
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

The *Fermi* Large Area Telescope (LAT)

Observing the gamma-ray sky since June 11, 2008

Energy range	20 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	0.8° @ 1 GeV
Field of view	2.4 sr (~20% of the sky)
Orbital period	91 minutes
Altitude	565 km

- **Survey mode**: full sky observed every 3 hours
- **Public data**, available within 12 hours



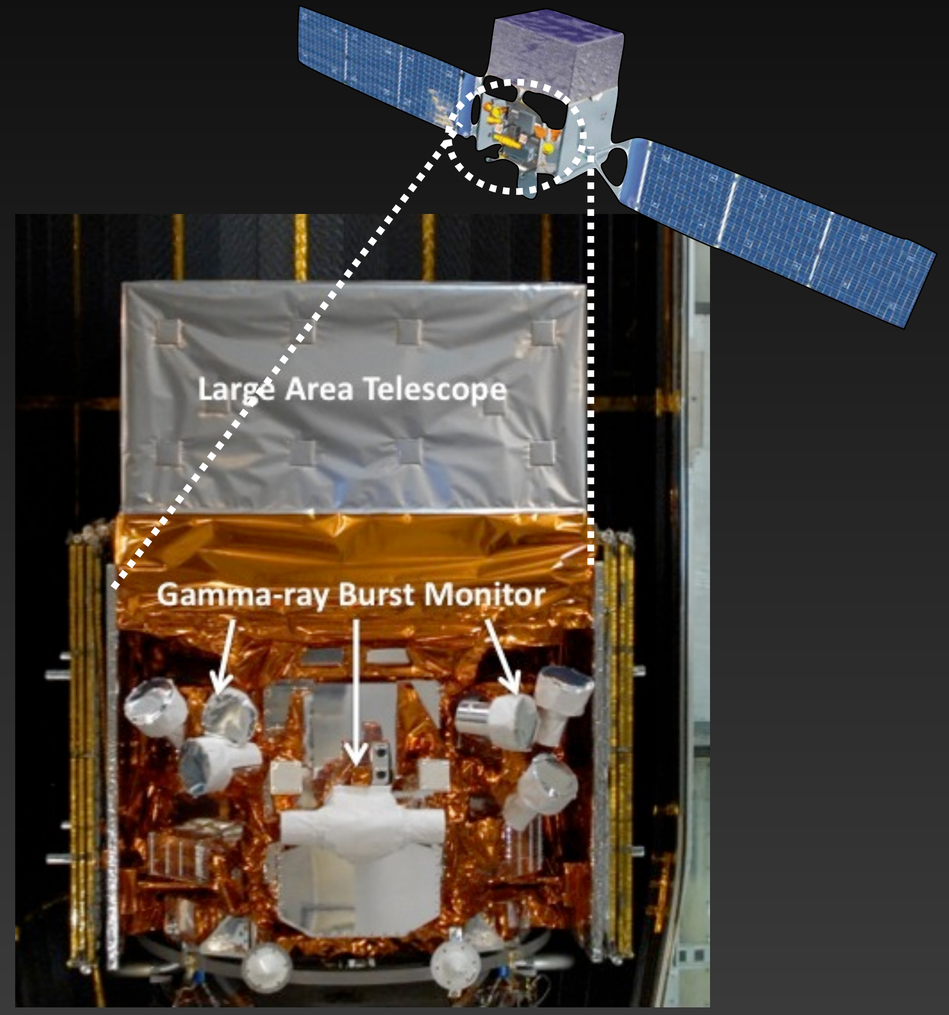
[Atwood et al. 2009]

The *Fermi* Gamma-ray Burst Monitor (GBM)

Observing the gamma-ray sky since June 11, 2008

Energy range	8 keV - 40 MeV
Gamma-rat burst localization	~3˚
Field of view	9.5 sr (~75% of the sky)
Timing accuracy	2 μs

- 12 NaI and 2 BGO Scintillators

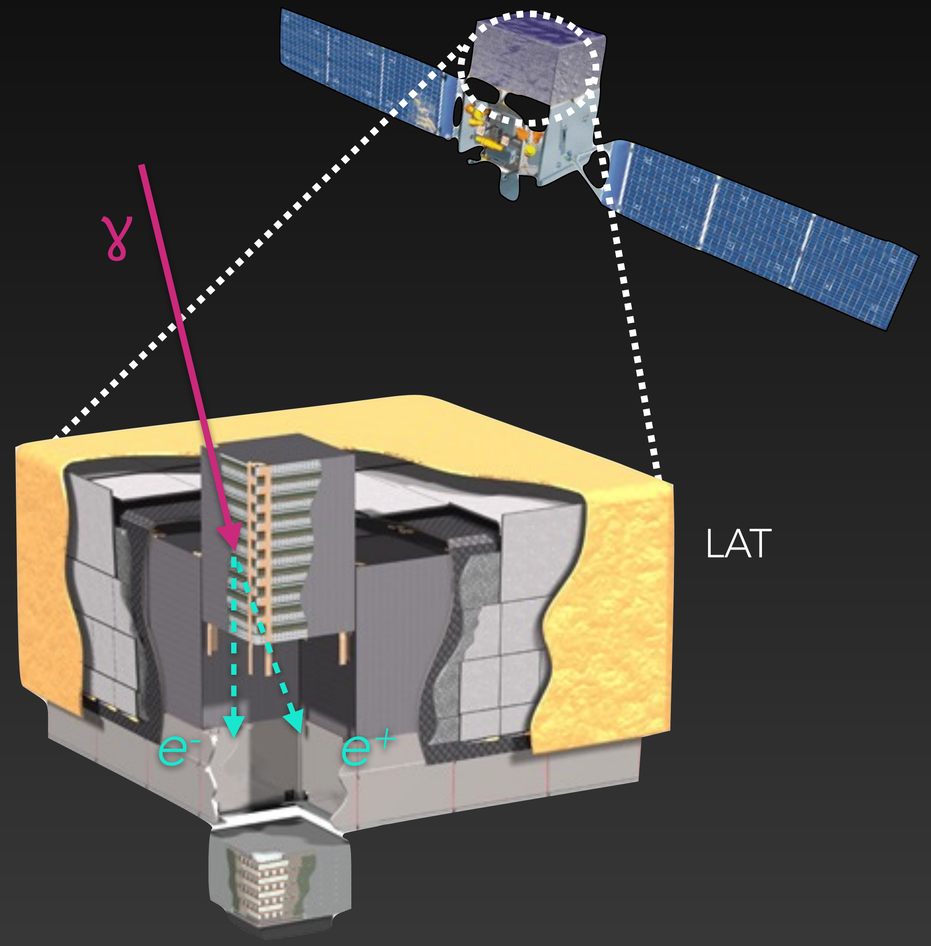


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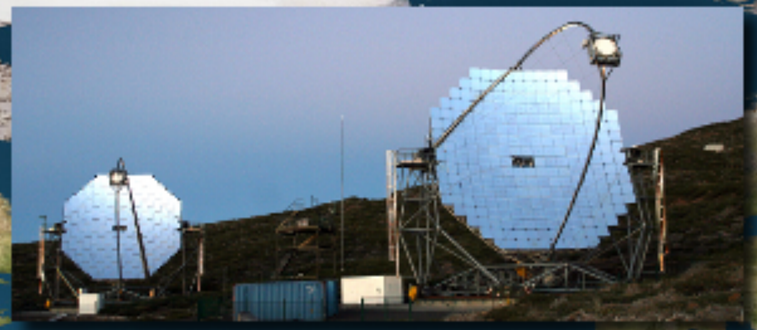
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[Atwood et al. 2009]



MAGIC
2 telescopes
La Palma, Canary Islands



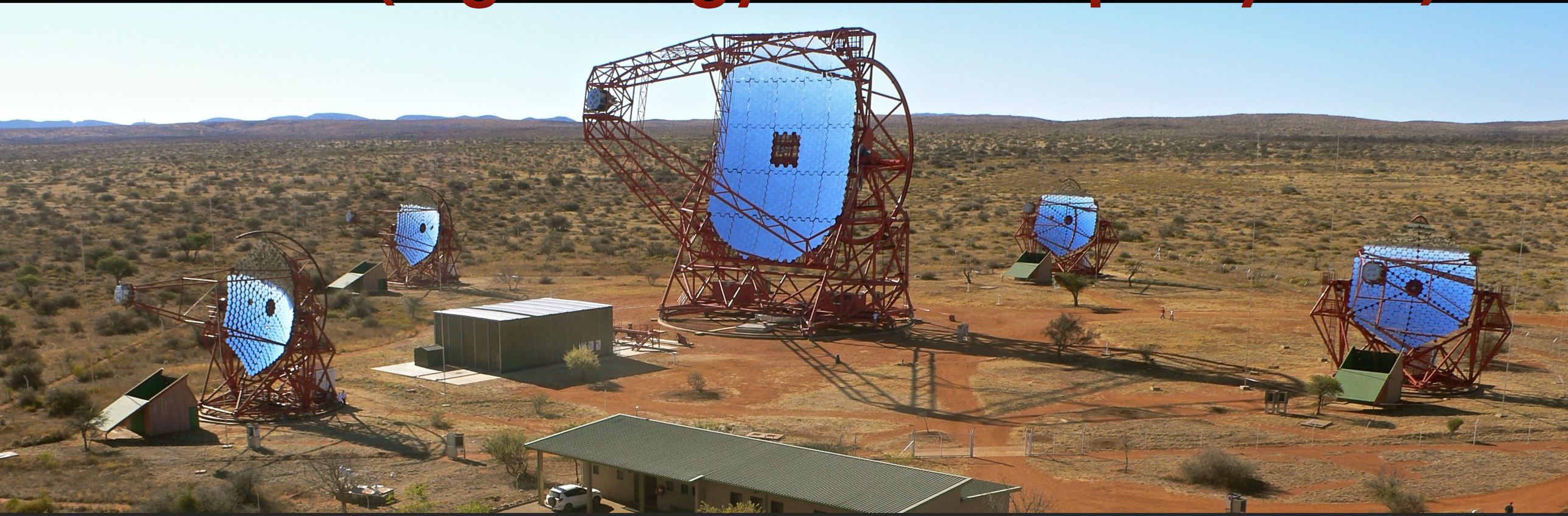
VERITAS
4 telescopes
Mount Hopkins, Arizona, USA



H.E.S.S.
4 + 1 telescopes
Khomas highlands, Namibia

For Energies ≳ 50 GeV: Imaging Air Cherenkov Telescopes (IACTs)

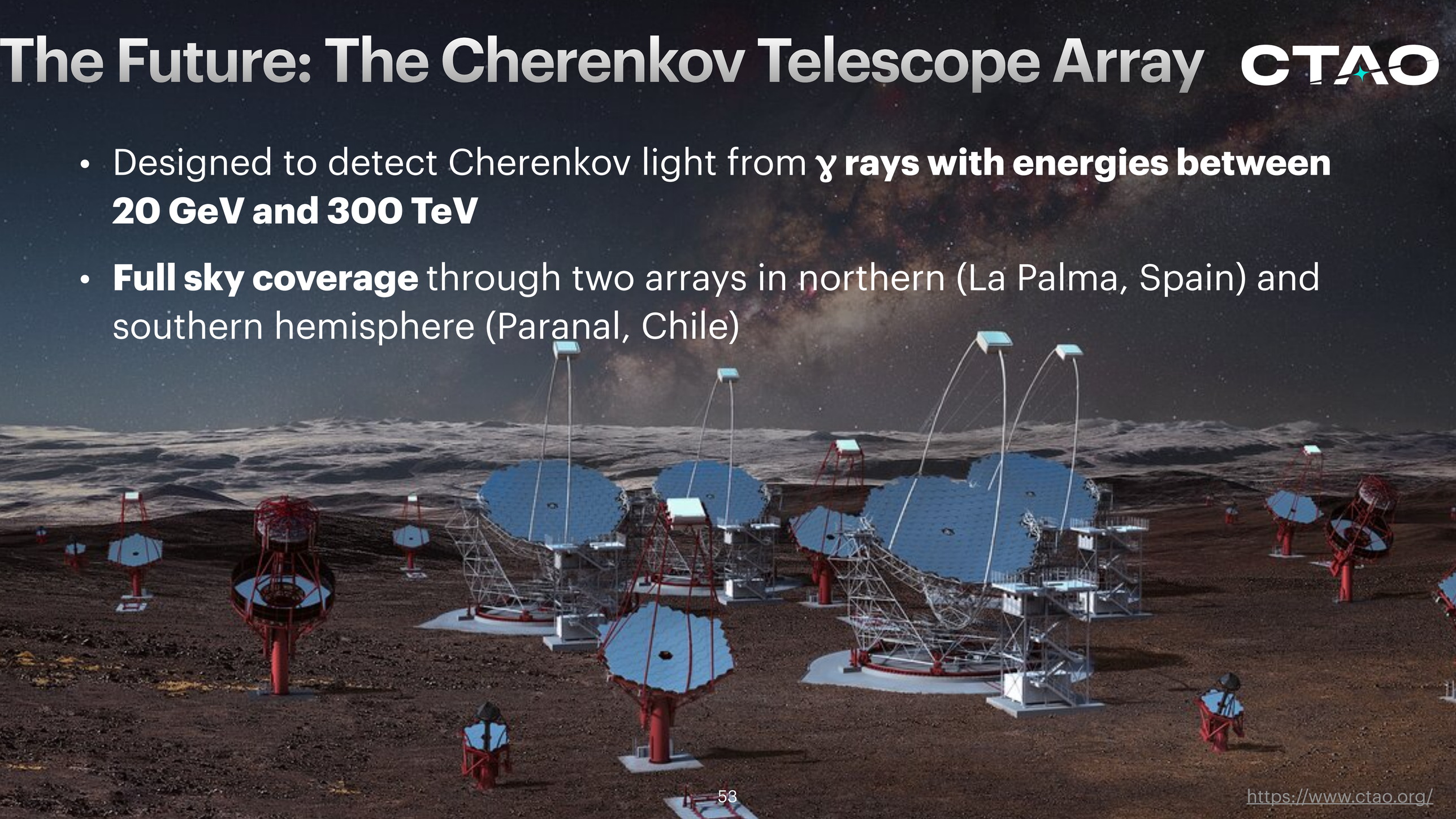
H.E.S.S. (High energy Stereoscopic System)



- Located in Khomas Highland in Namibia (22º S)
- Commenced operations in 2002
- Operations extended at least until 2025
- Energy coverage: above 50 GeV up to 100 TeV
- Field of view: 3º - 5º
- Angular resolution: 3 to 6 arc minutes

The Future: The Cherenkov Telescope Array

- Designed to detect Cherenkov light from **ɣ rays with energies between 20 GeV and 300 TeV**
- **Full sky coverage** through two arrays in northern (La Palma, Spain) and southern hemisphere (Paranal, Chile)

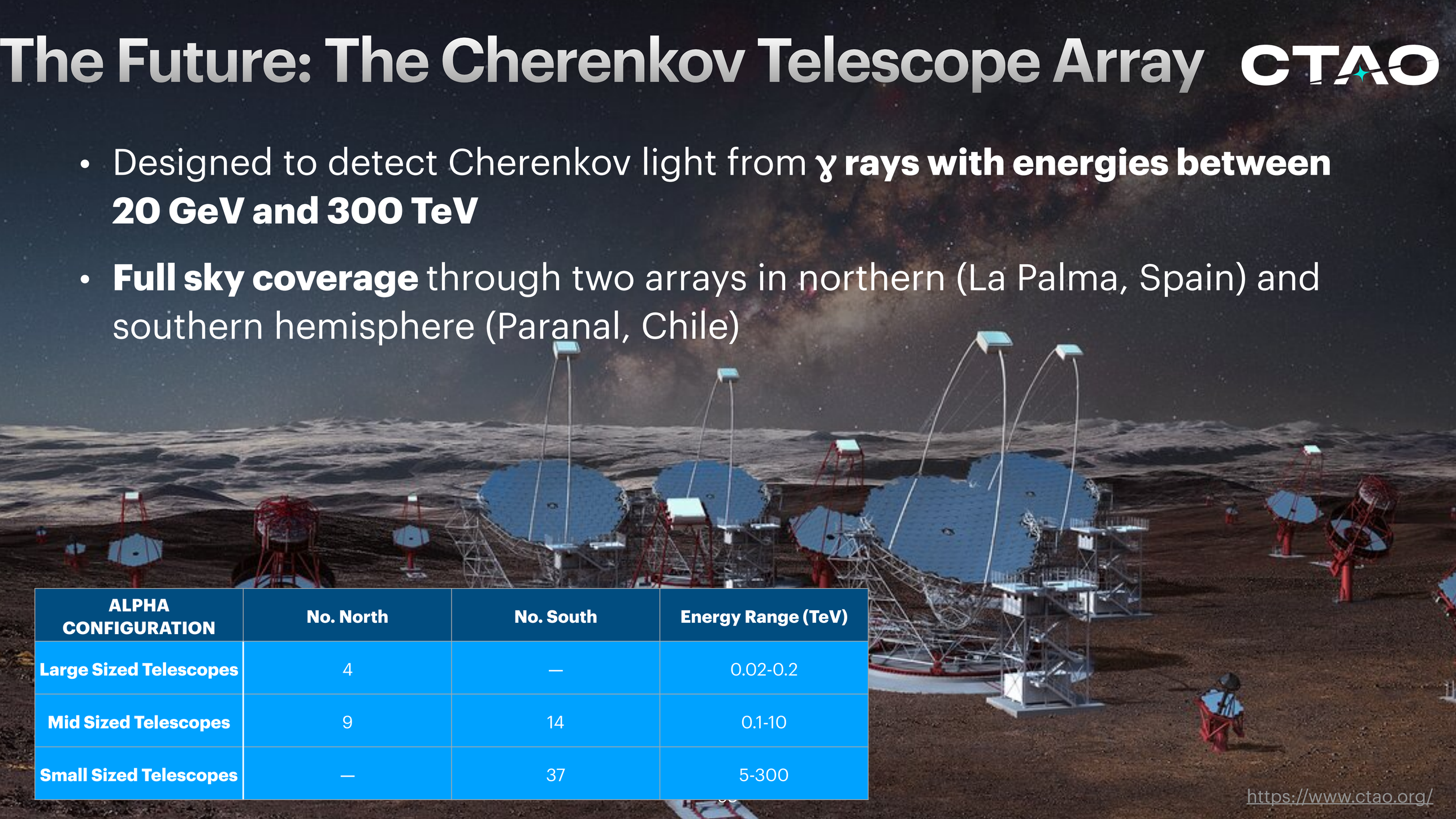


https://www.ctao.org/

The Future: The Cherenkov Telescope Array

CTAO

- Designed to detect Cherenkov light from **ɣ rays with energies between 20 GeV and 300 TeV**
- **Full sky coverage** through two arrays in northern (La Palma, Spain) and southern hemisphere (Paranal, Chile)



ALPHA CONFIGURATION	No. North	No. South	Energy Range (TeV)
Large Sized Telescopes	4	—	0.02-0.2
Mid Sized Telescopes	9	14	0.1-10
Small Sized Telescopes	—	37	5-300

https://www.ctao.org/

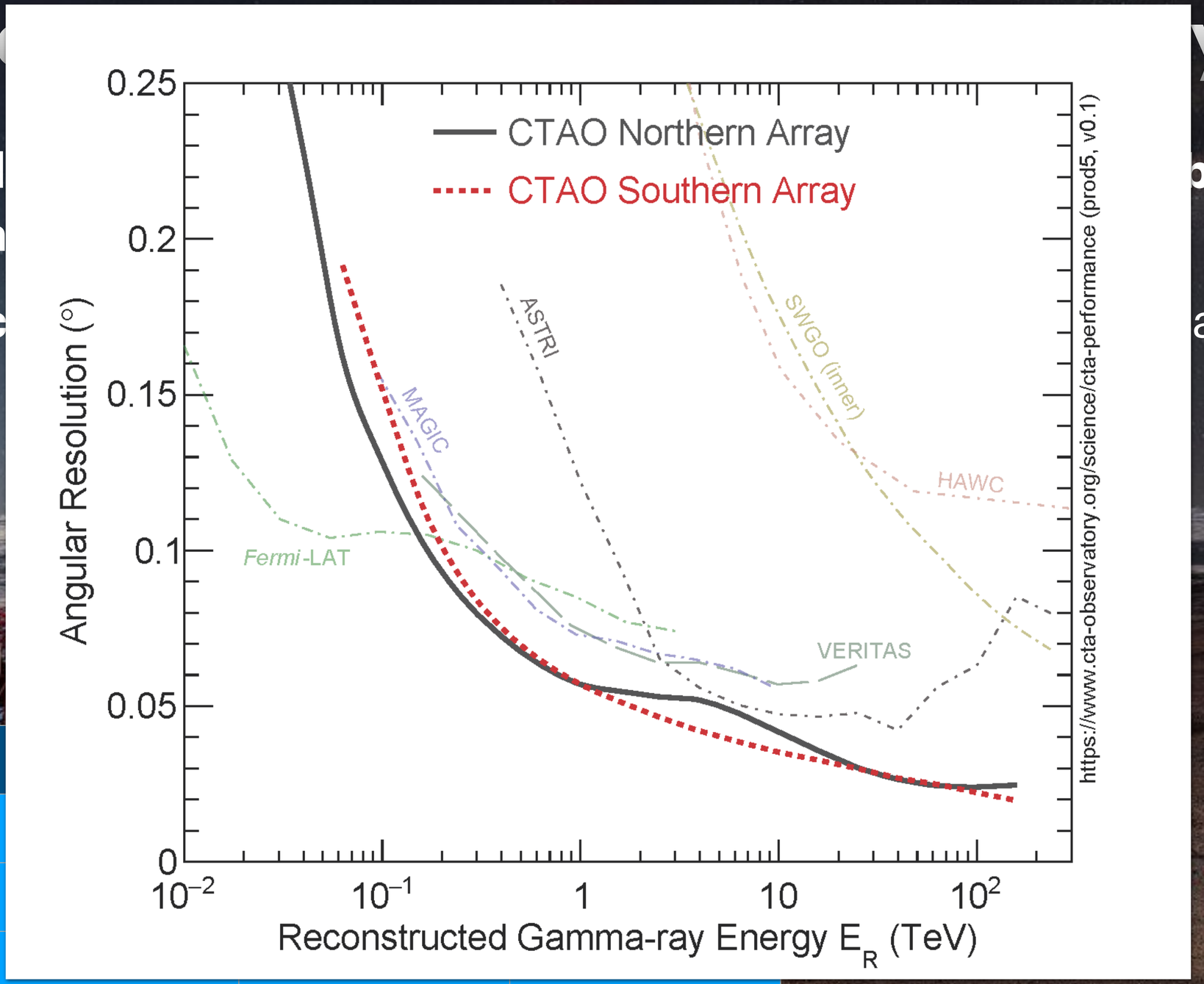
The Futur

y CTAO

- Designed
  20 GeV a
- **Full sky c**
  southern

between

ain) and



ALPHA CONFIGURATION	
Large Sized Telescopes	
Mid Sized Telescopes	
Small Sized Telescopes	

https://www.cta-observatory.org/

Water Cherenkov Detectors





https://www.hawc-observatory.org
http://english.ihep.cas.cn/lhaaso

Water Cherenkov Detectors

- Detect particles in air showers through Cherenkov radiation in water detectors





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http://english.ihep.cas.cn/lhaaso

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http://english.ihep.cas.cn/lhaaso

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https://www.hawc-observatory.org
http://english.ihep.cas.cn/lhaaso

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  - Observations possible 24 hours a day





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http://english.ihep.cas.cn/lhaaso

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- Current detectors:





https://www.hawc-observatory.org
http://english.ihep.cas.cn/lhaaso

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- Current detectors:
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https://www.hawc-observatory.org
http://english.ihep.cas.cn/lhaaso

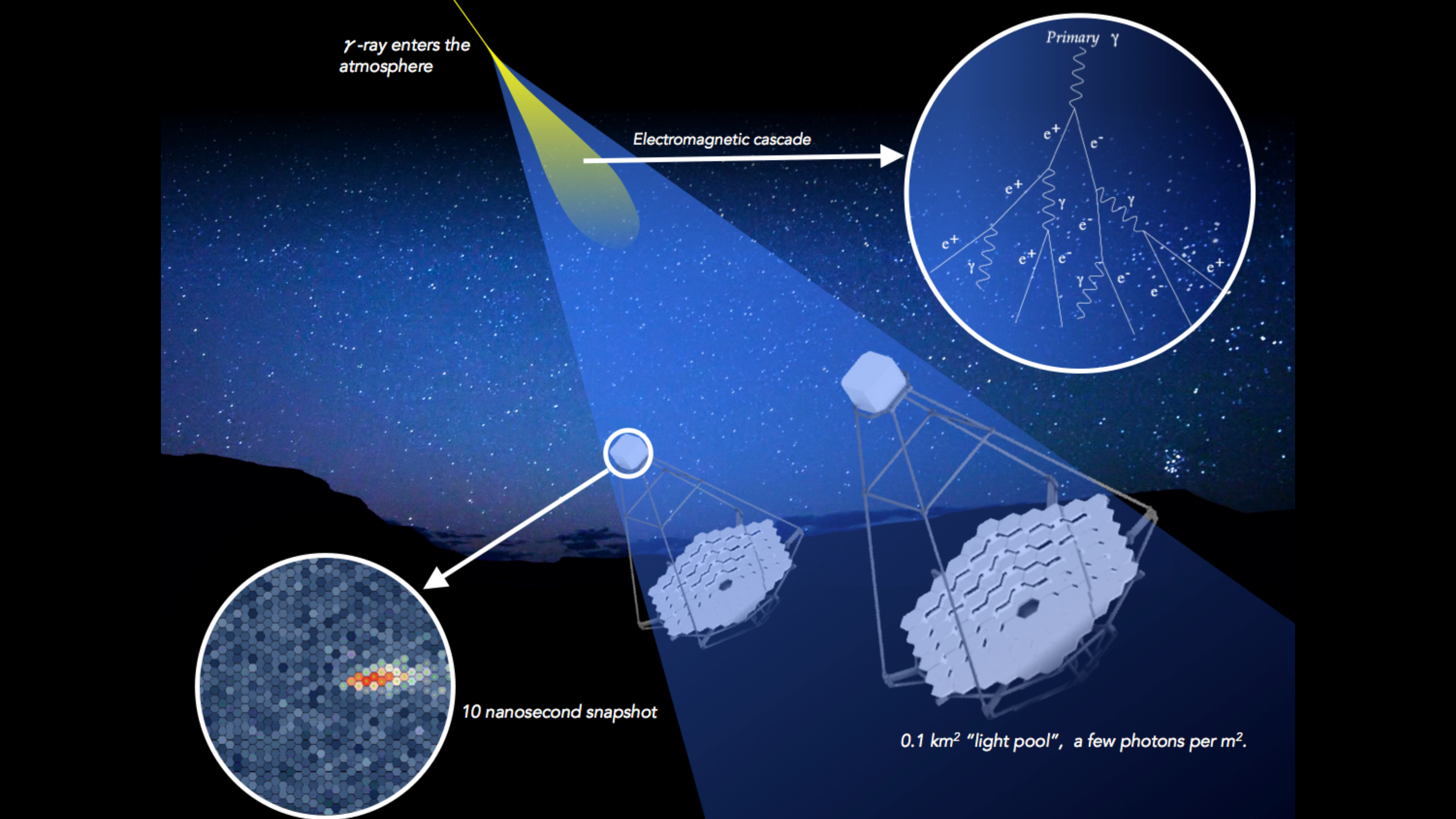
Water Cherenkov Detectors

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  - Observations possible 24 hours a day
- Current detectors:
  - HAWC (High Altitude Water Cherenkov Gamma-ray Observatory)
  - LHAASO (Large High Altitude Air Shower Observatory)





https://www.hawc-observatory.org
http://english.ihep.cas.cn/lhaaso


γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².

LHAASO

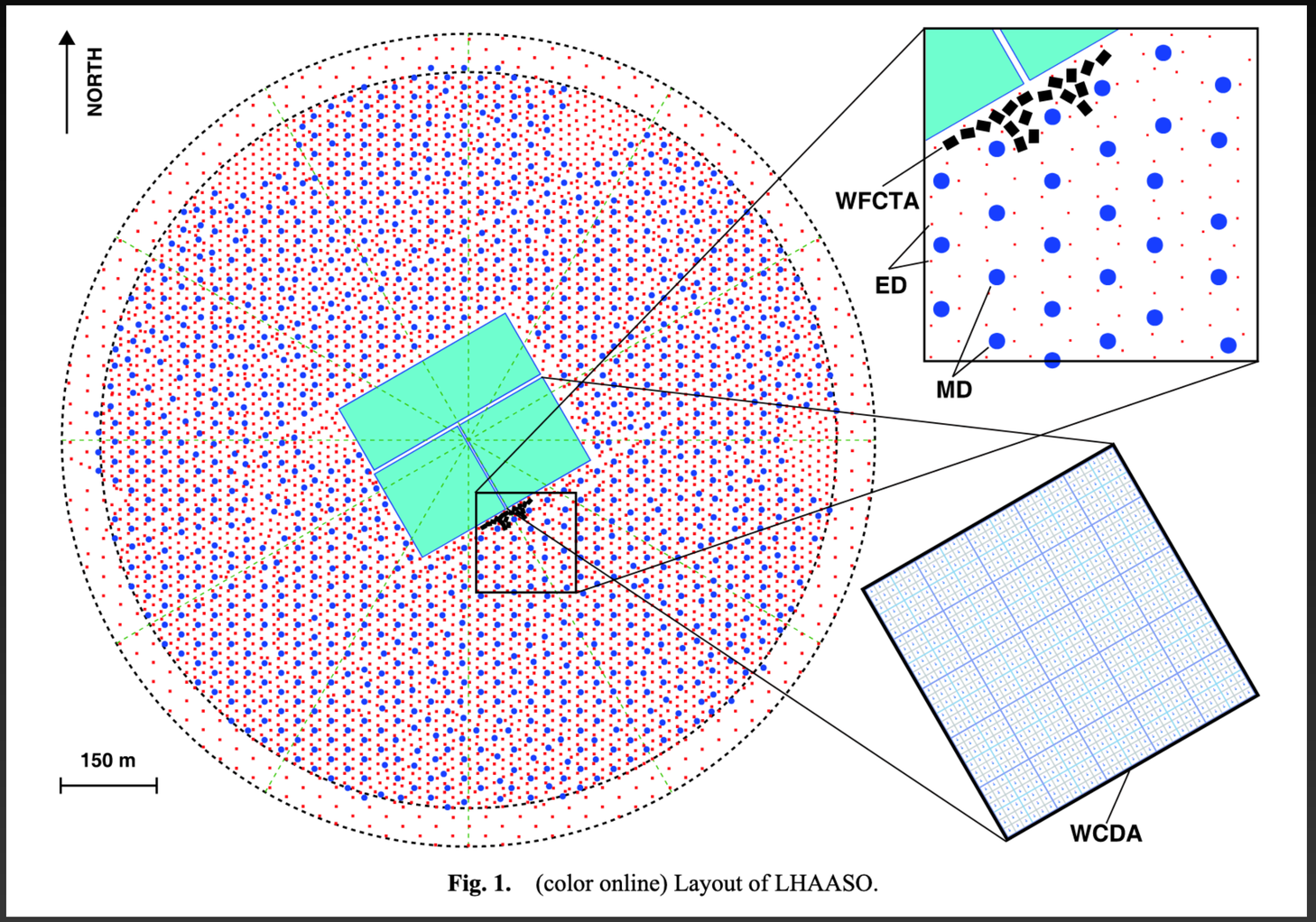


Fig. 1. (color online) Layout of LHAASO.

[Ma et al. 2022]

LHAASO

- **KM2A**: square kilometer array with EM and muon detectors

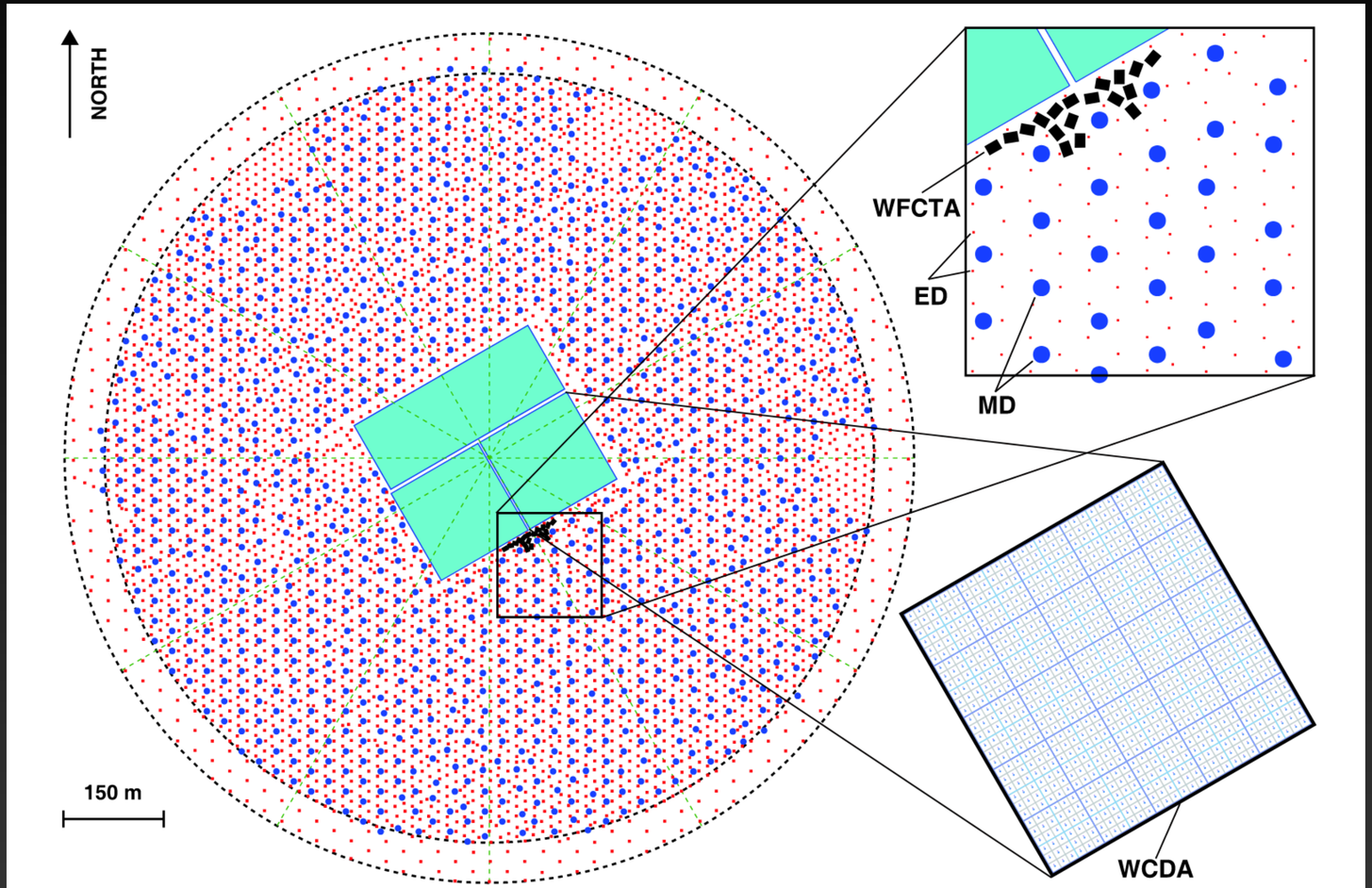


Fig. 1. (color online) Layout of LHAASO.

[Ma et al. 2022]

LHAASO

- **KM2A**: square kilometer array with EM and muon detectors
- **WCDA**: Water Cherenkov Detector 78,000 m^2

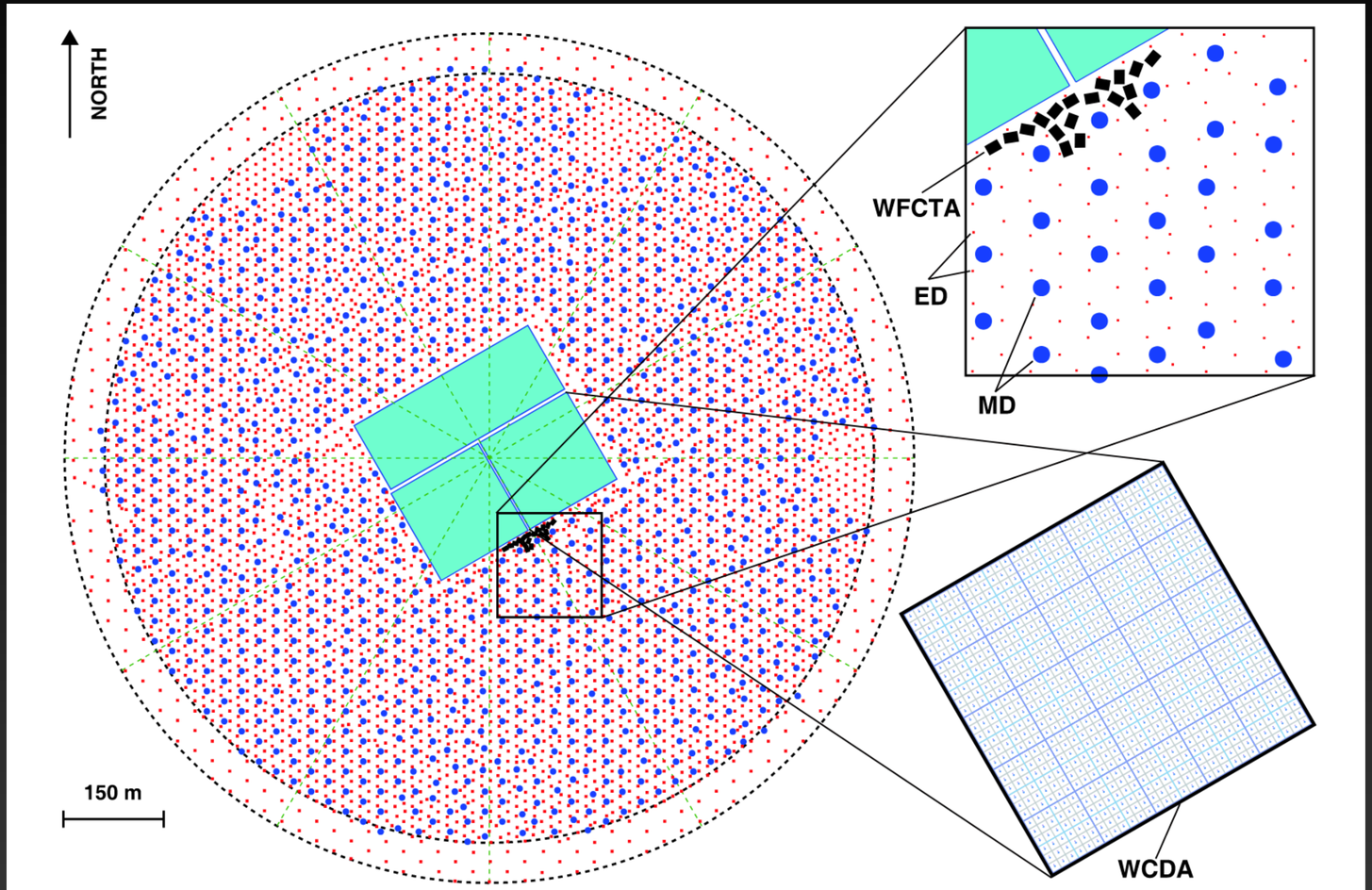


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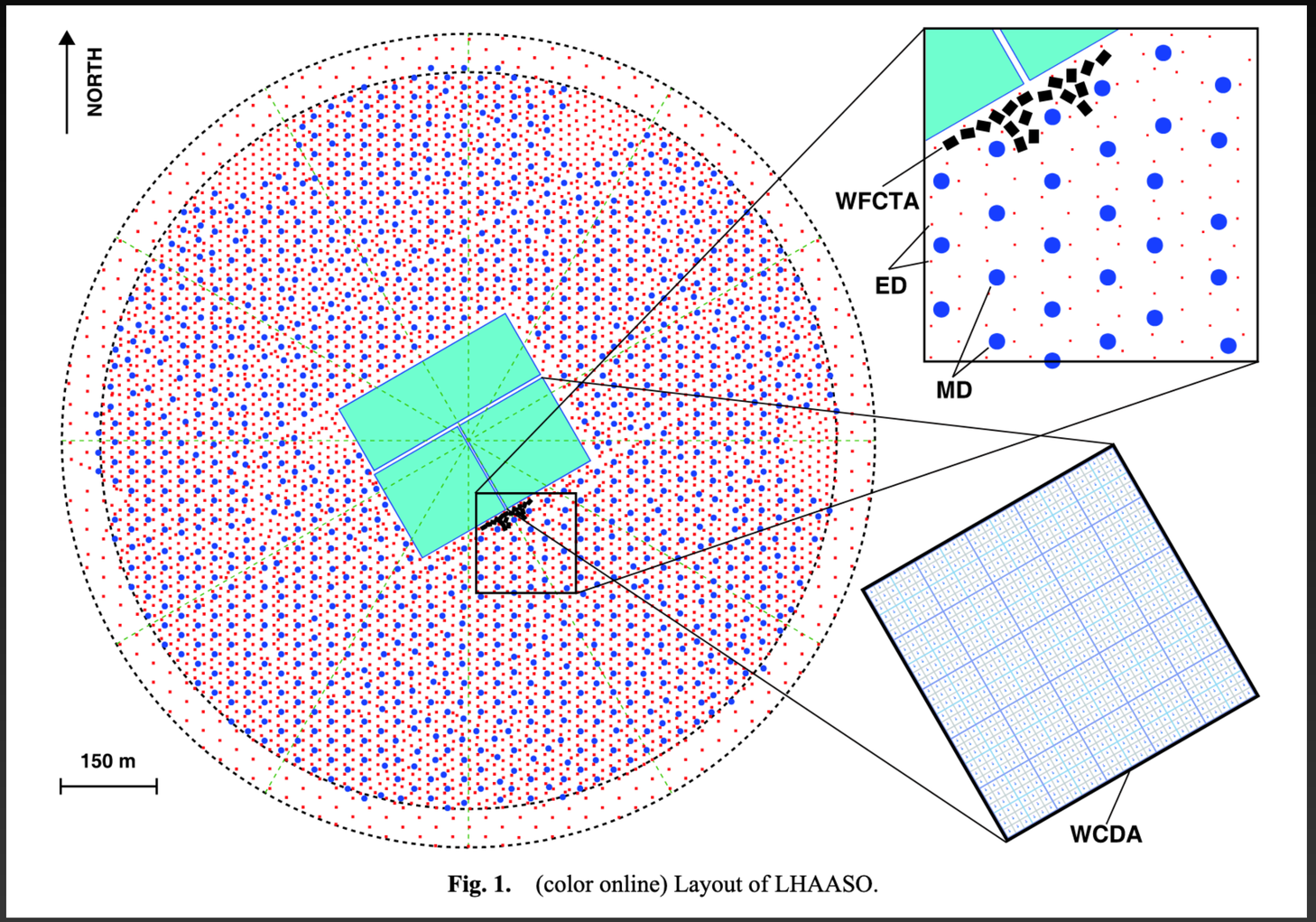


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- **WCDA**: Water Cherenkov Detector 78,000 m^2
- **WFCTA**: 18 wield field Cherenkov Telescopes
- **ENDA**: Electron Neutron detector, 10,000m^2

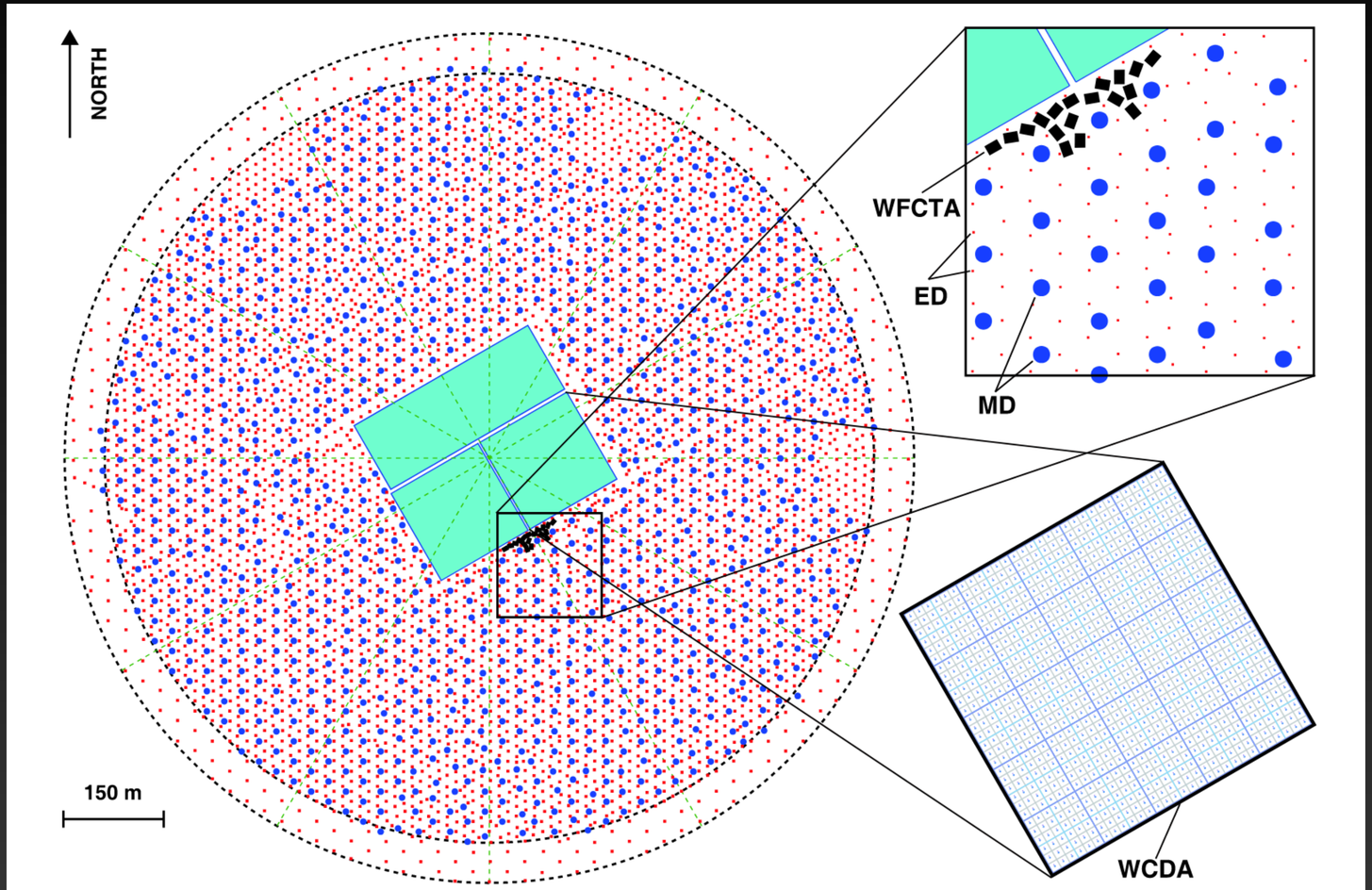
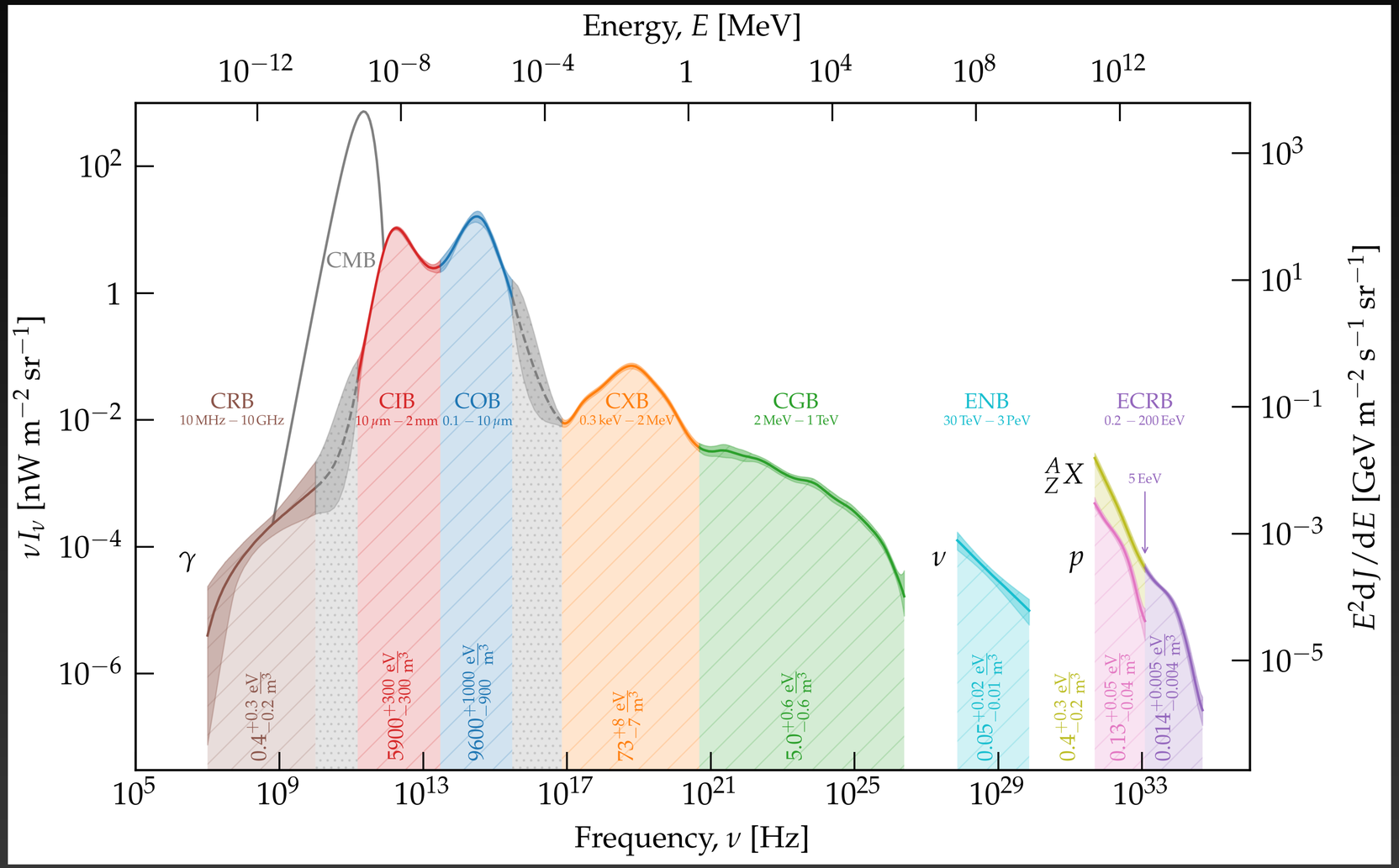


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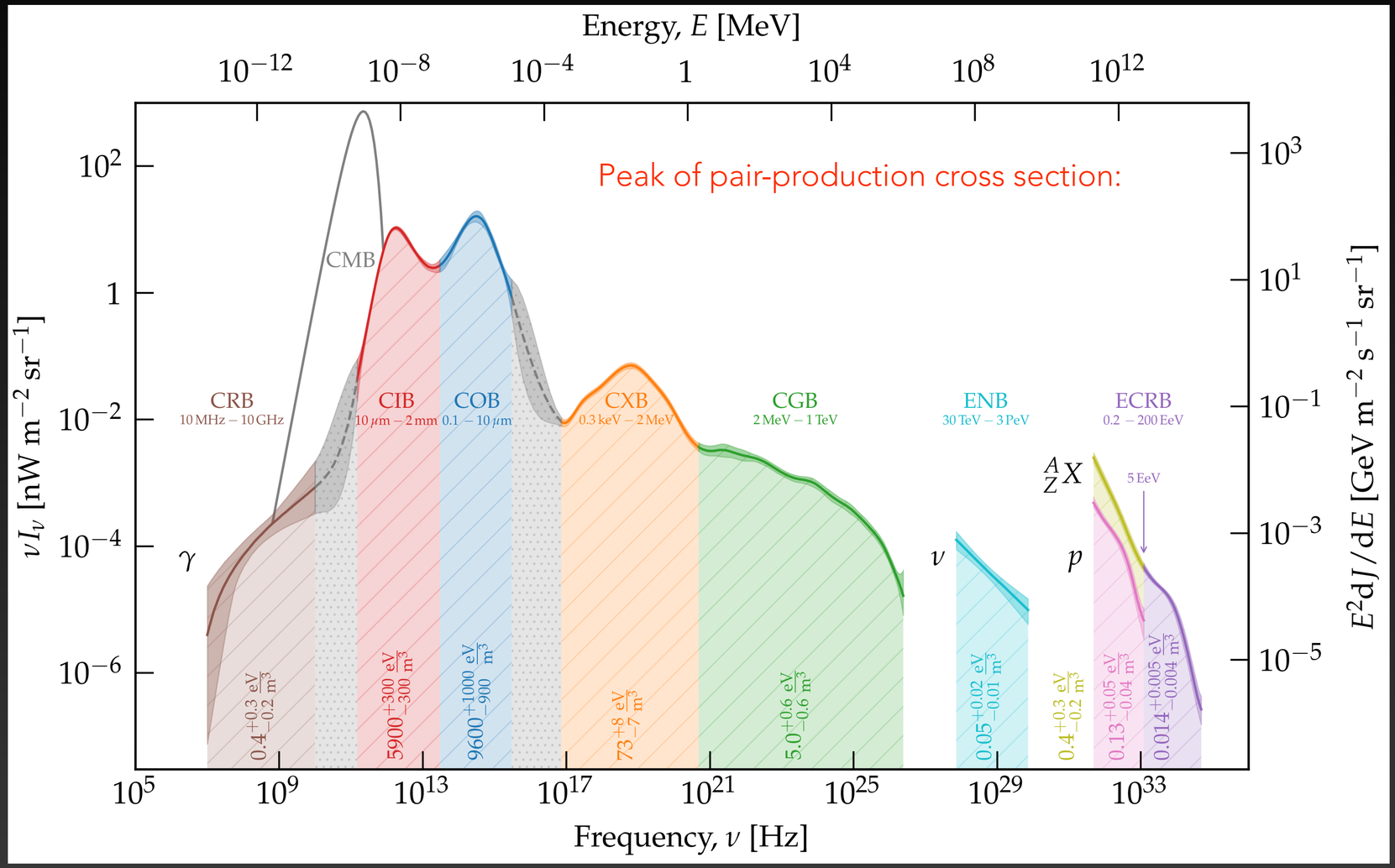
[Ma et al. 2022]

Background radiation fields



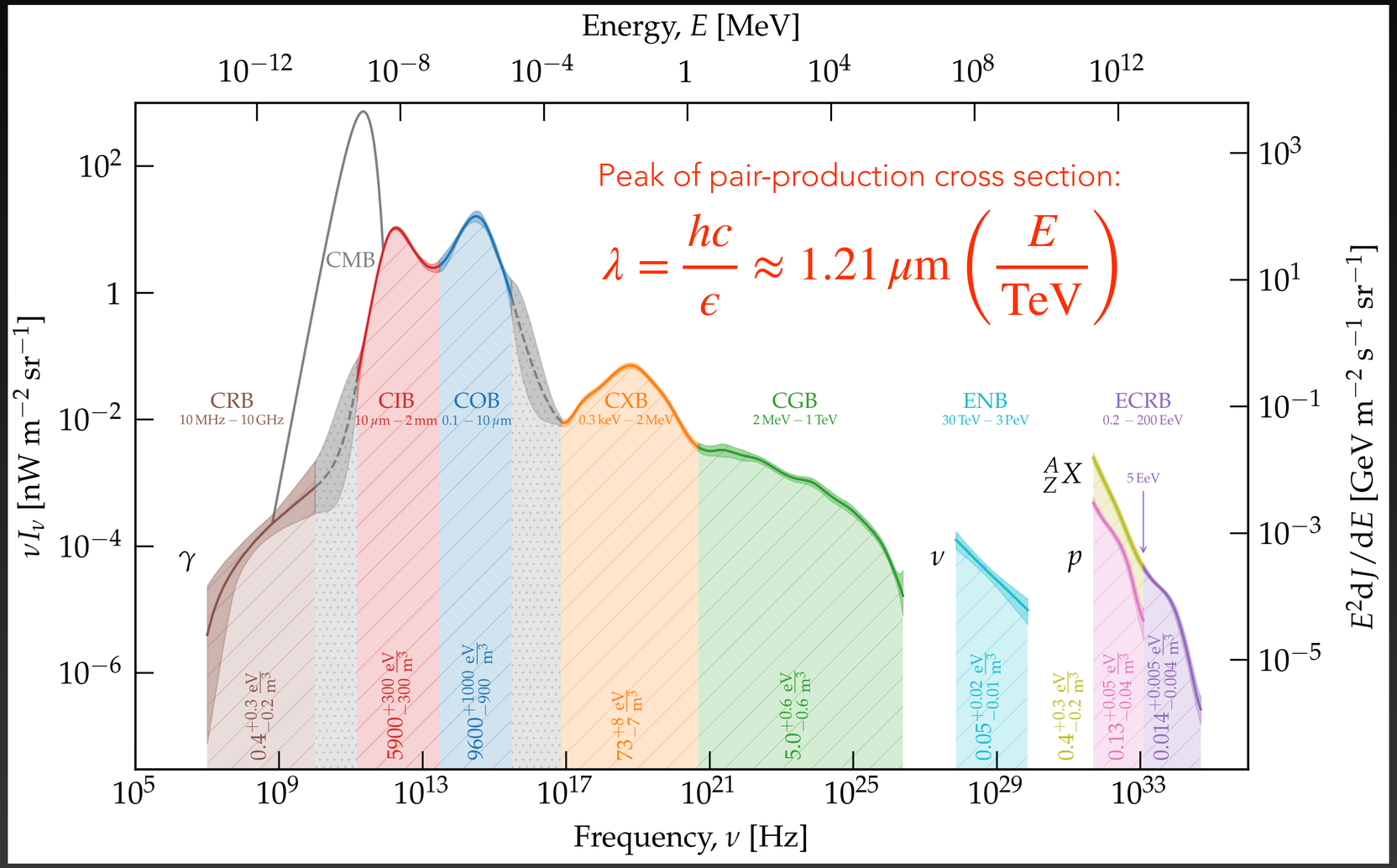
Biteau (2024), 10.5281/zenodo.7842238

Background radiation fields



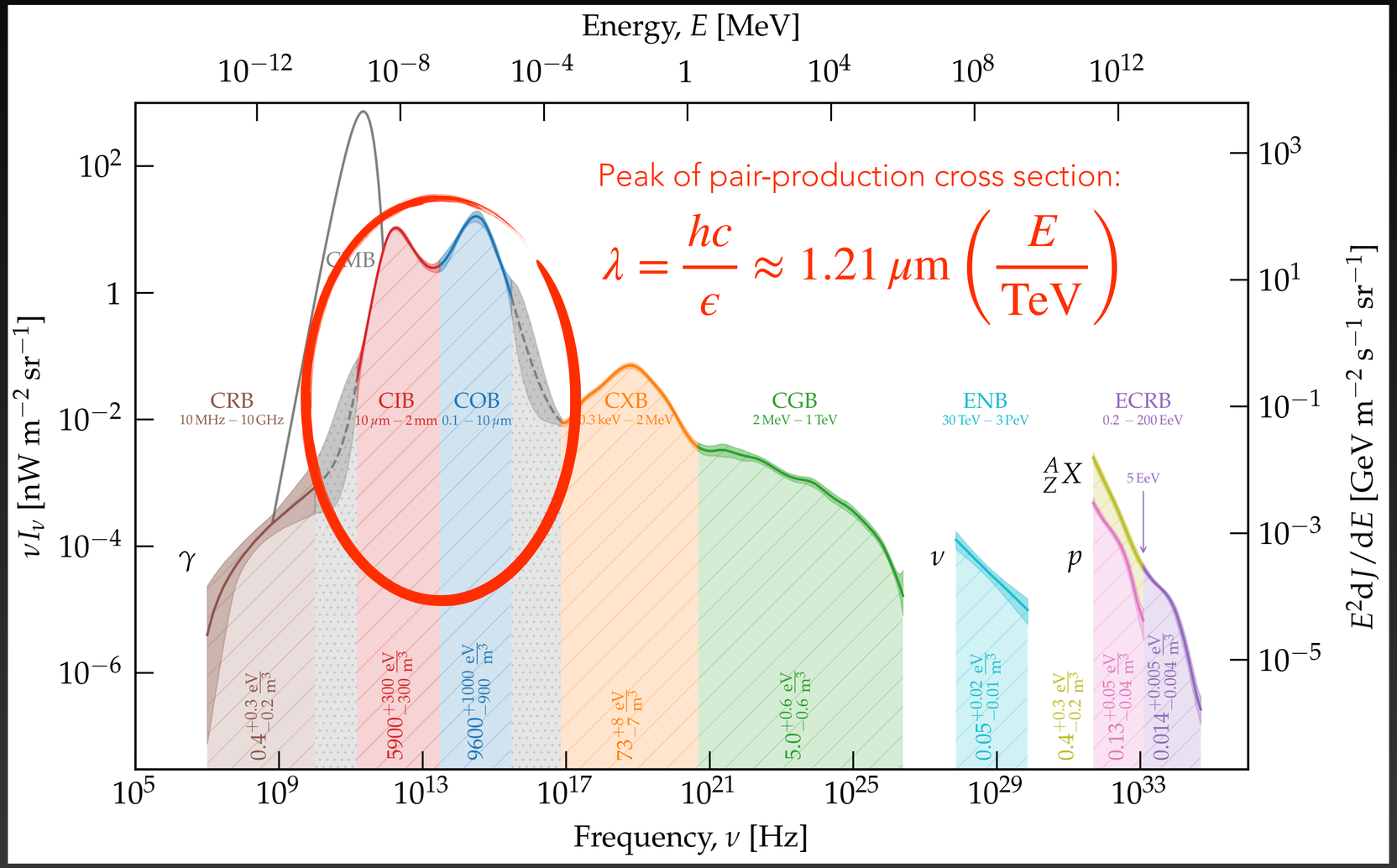
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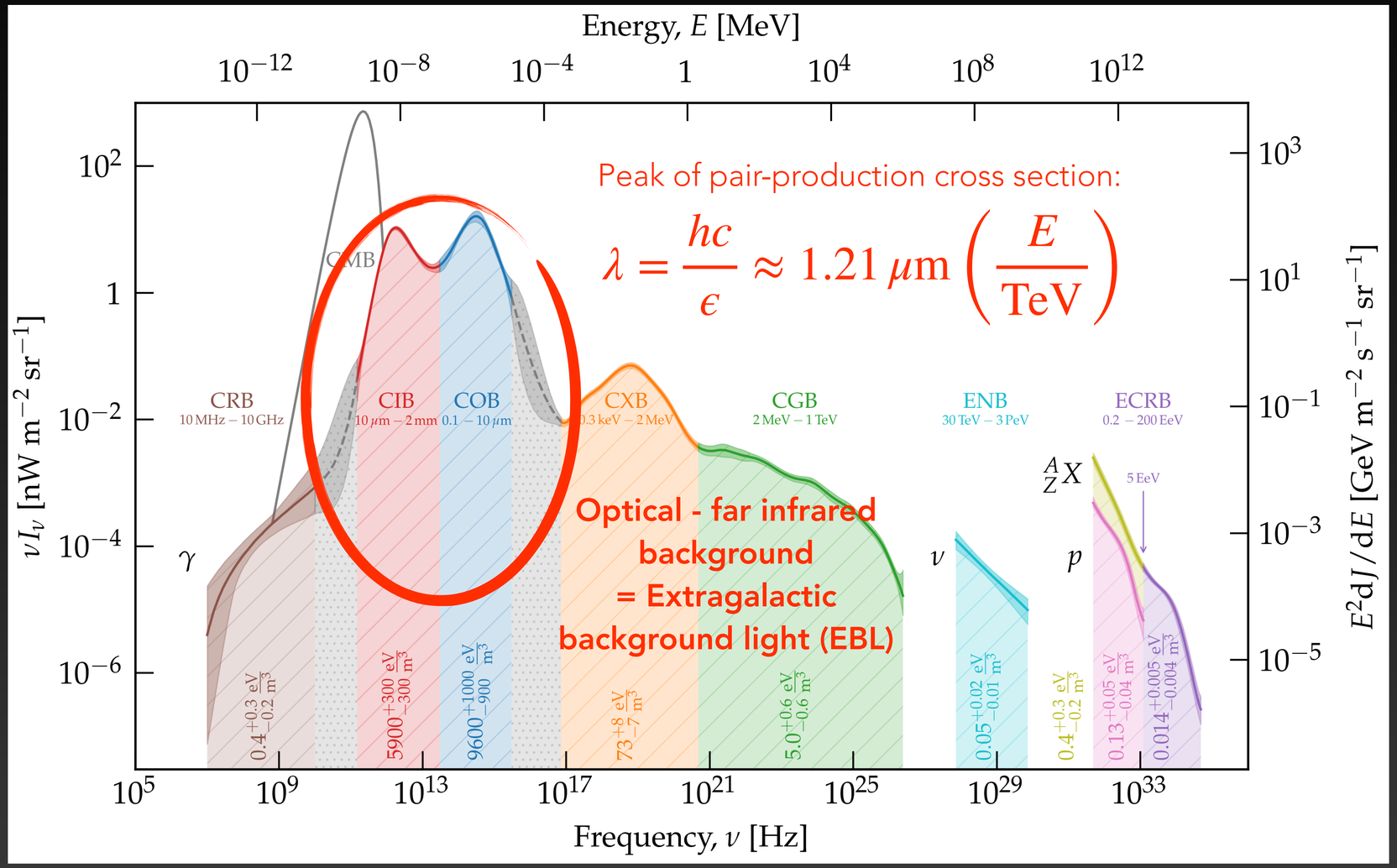
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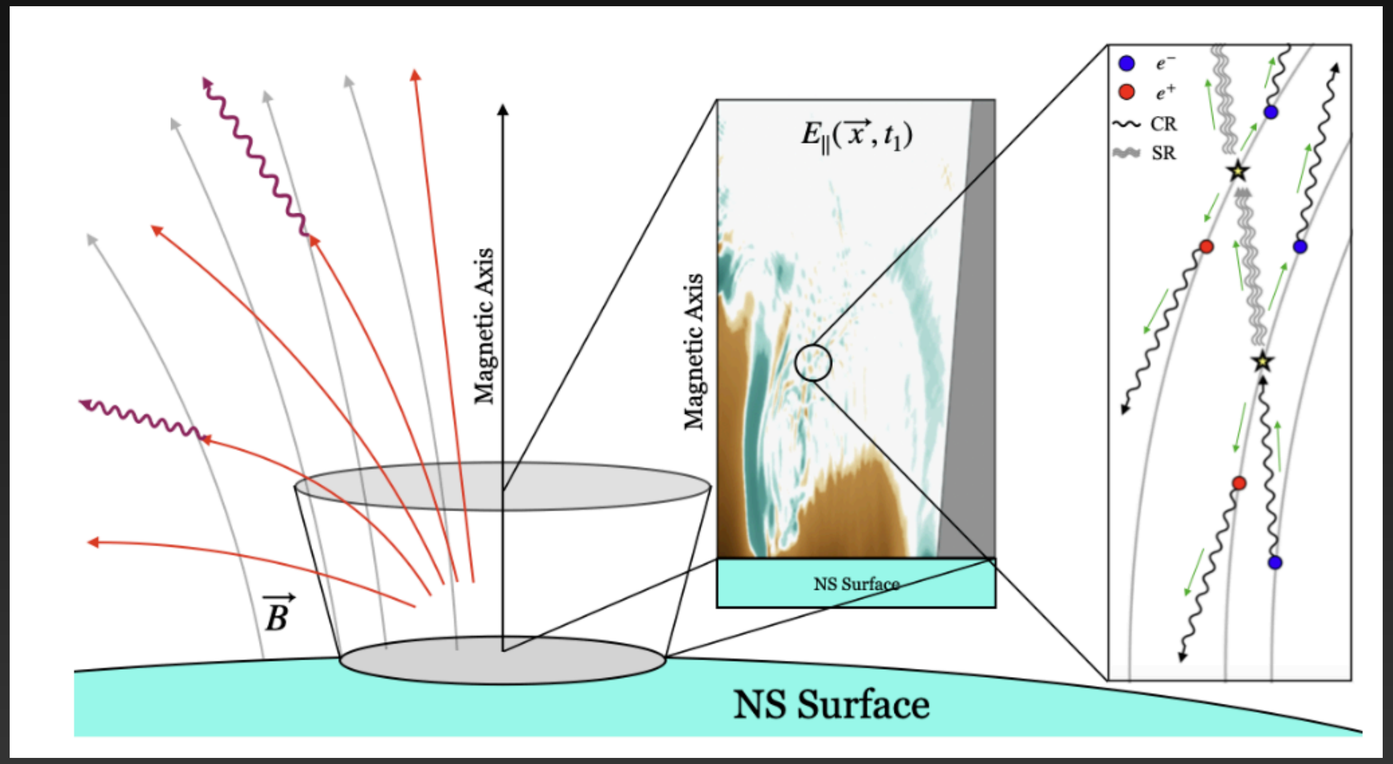
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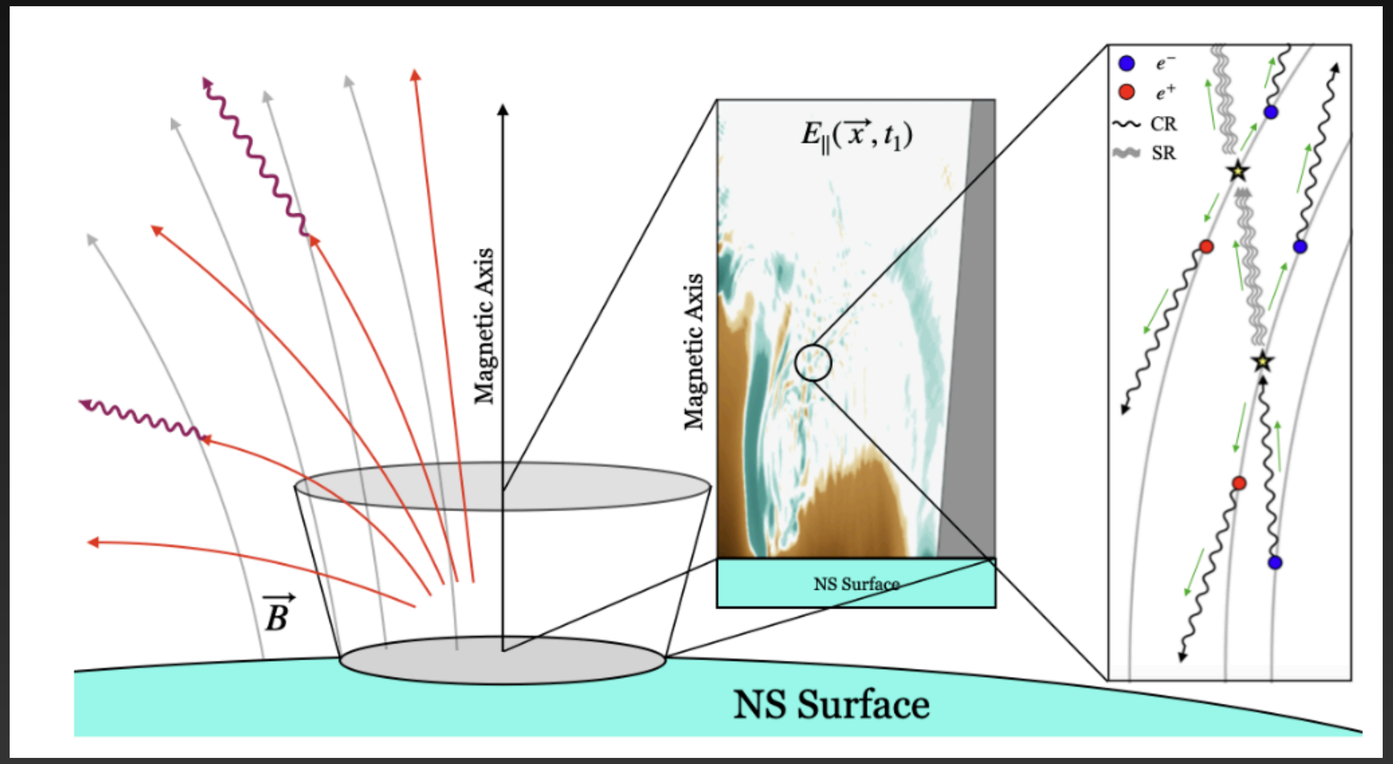
Axion pulsar scopes



[Noordhuis et al. 2023]

Axion pulsar scopes

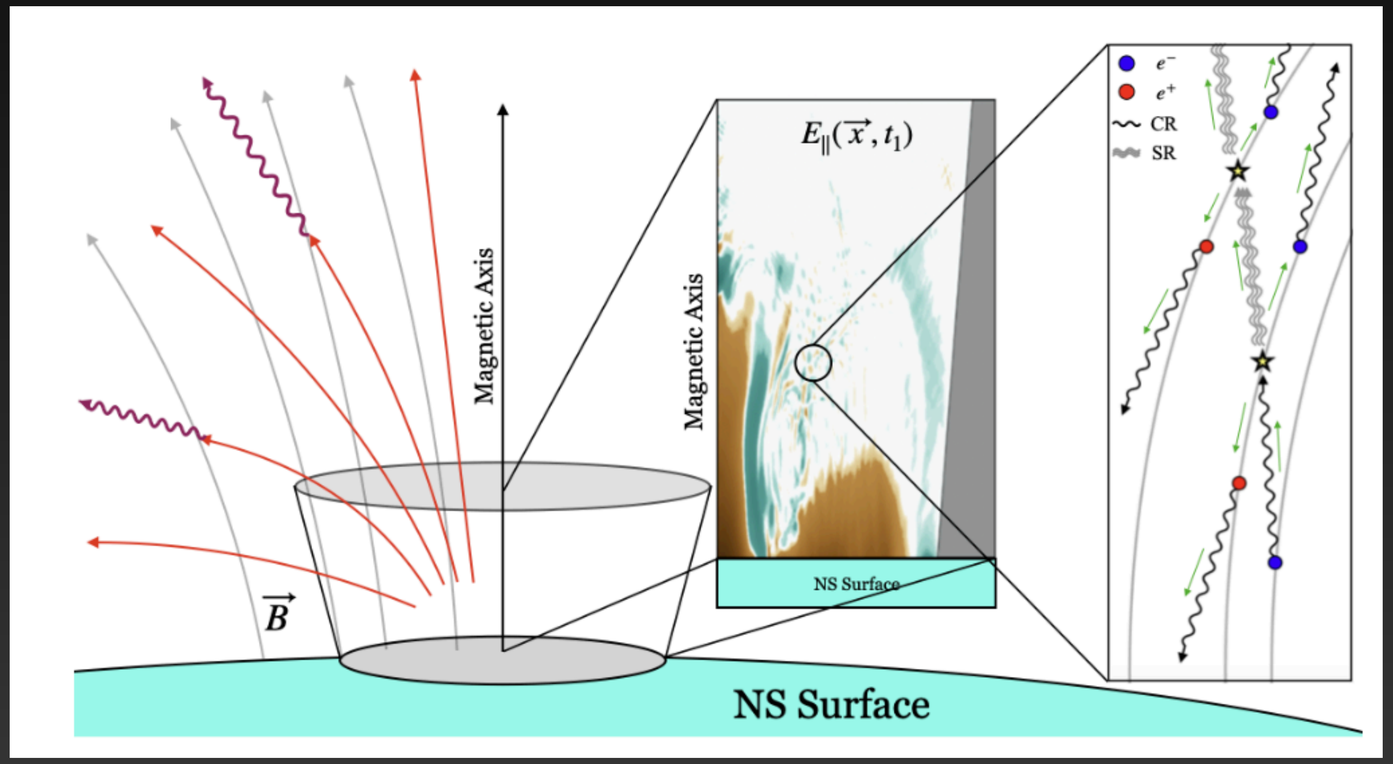
- Idea: axions produced from electric field in pulsar magnetosphere



[Noordhuis et al. 2023]

Axion pulsar scopes

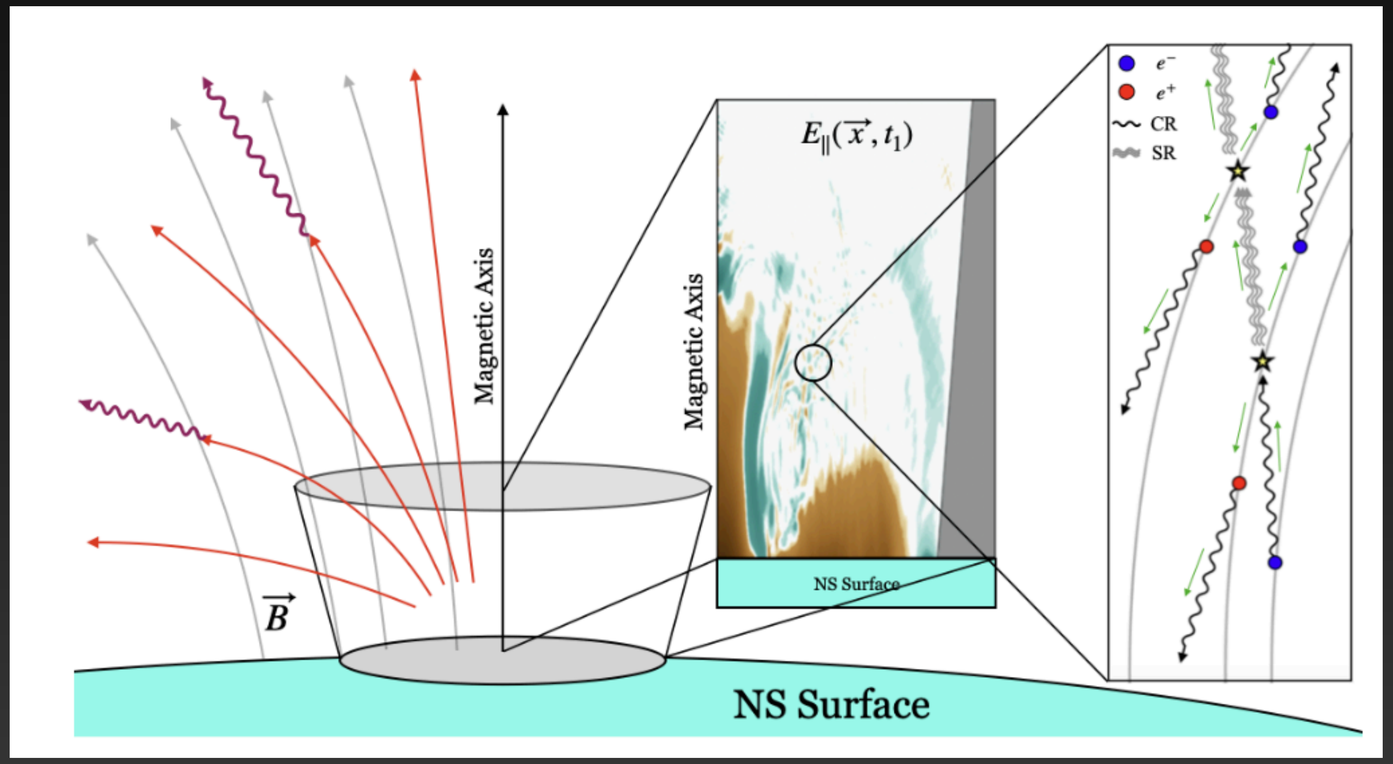
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[Noordhuis et al. 2023]

Axion pulsar scopes

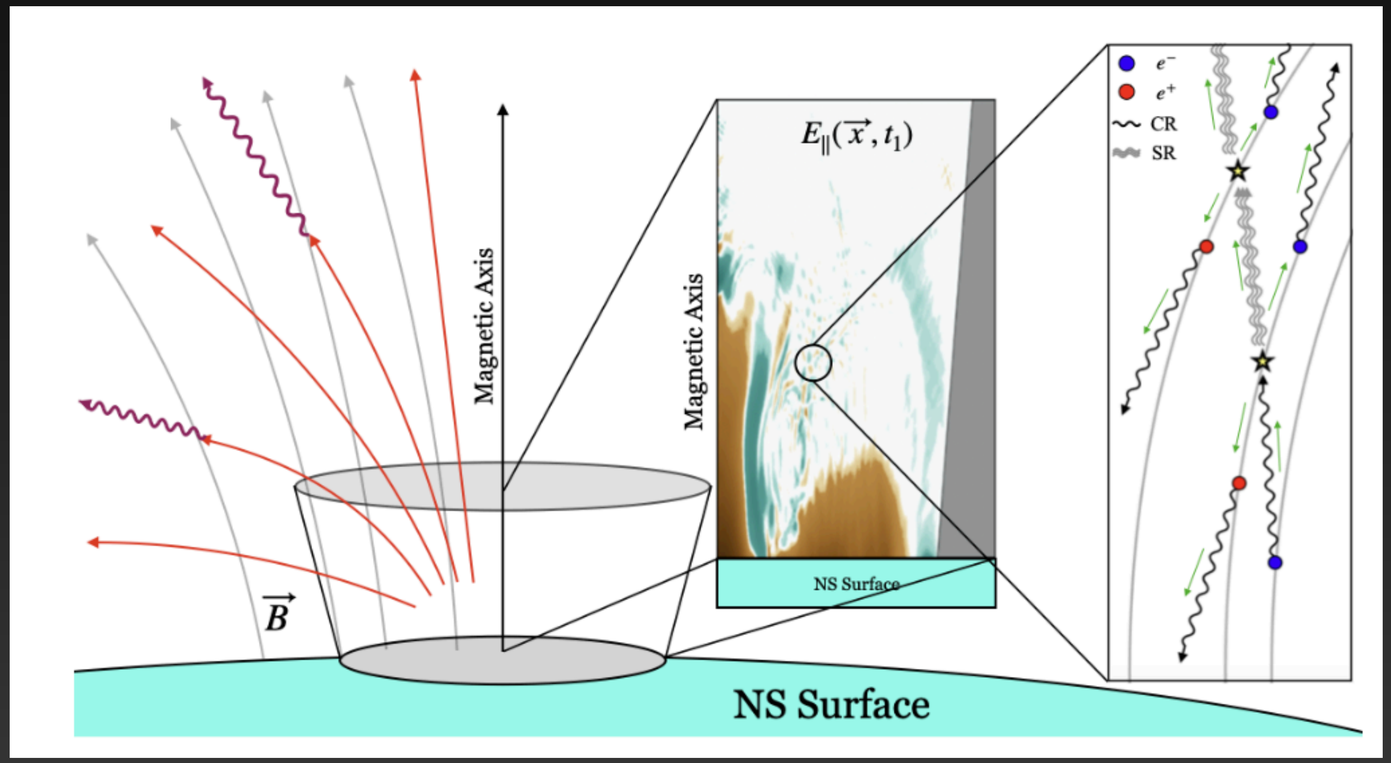
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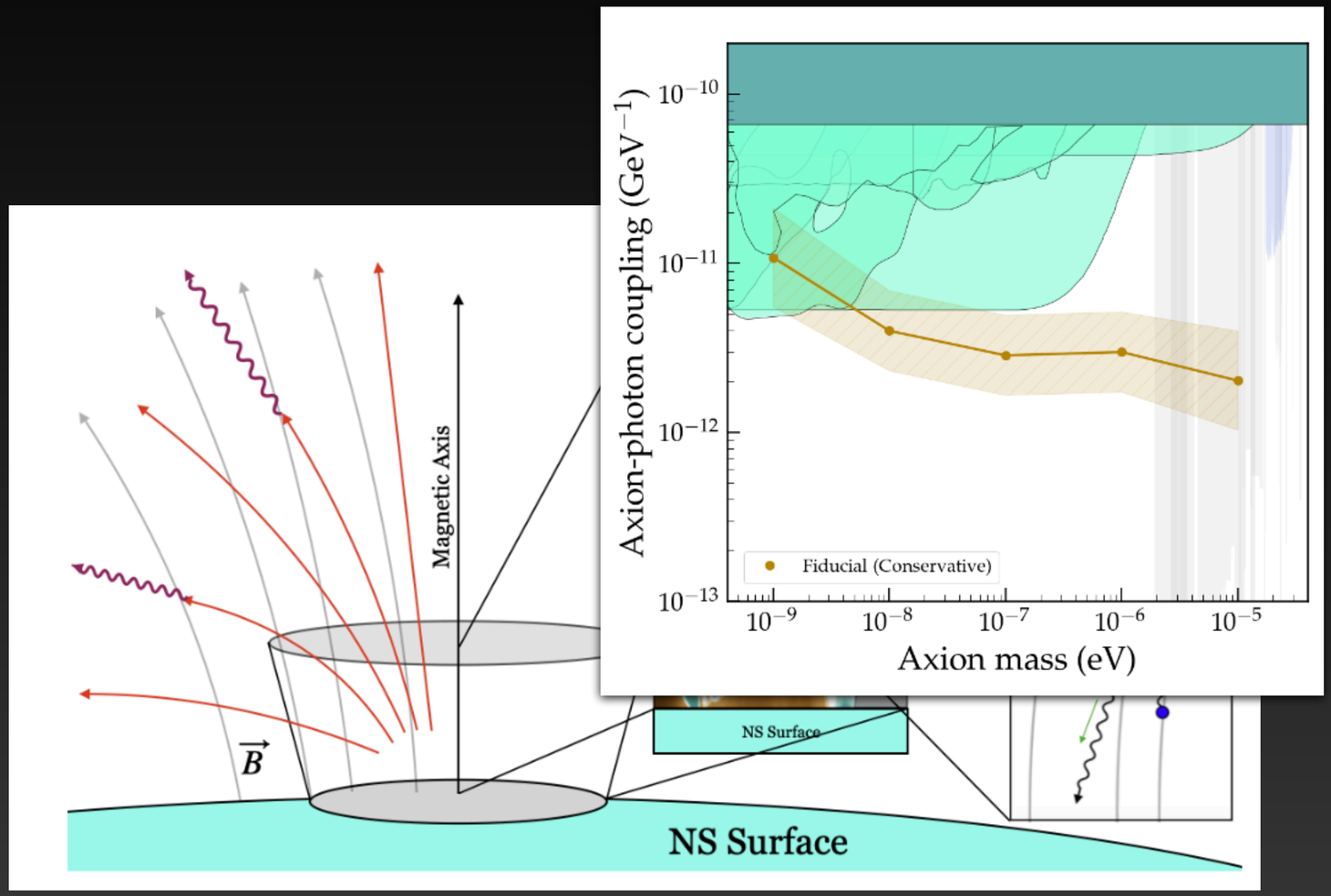
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[Noordhuis et al. 2023]

Axion pulsar scopes

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[Noordhuis et al. 2023]

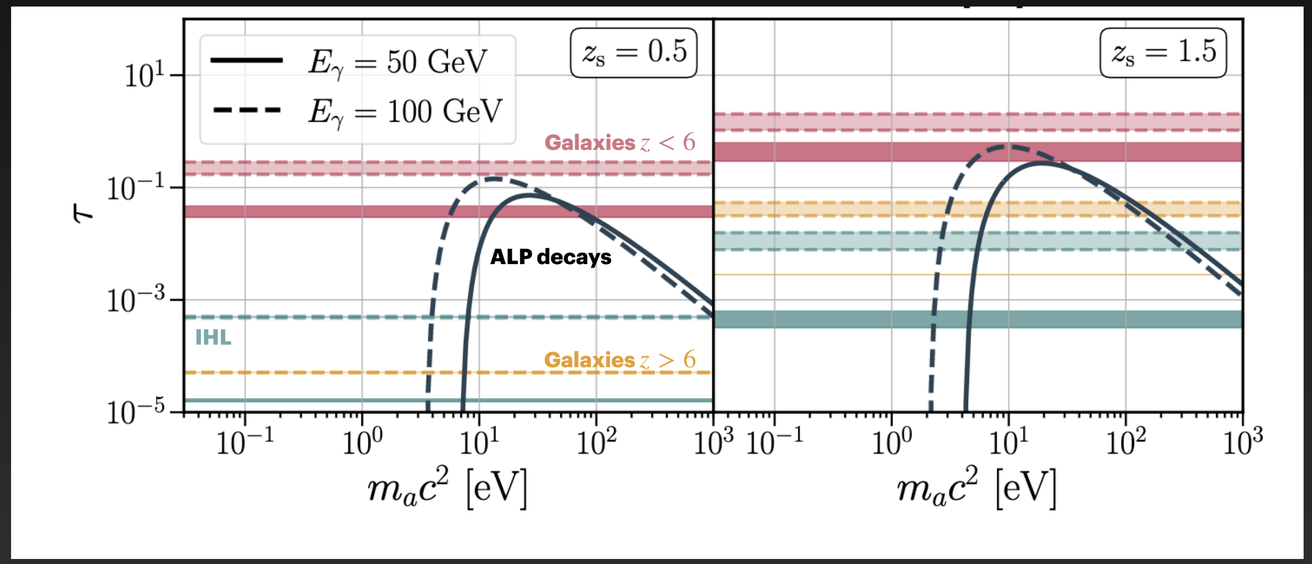
Cosmological ALP decay would contribute to the EBL

Would increase the optical depth of the Universe

- Enables constraints on axion decay from gamma-ray observations of distant sources

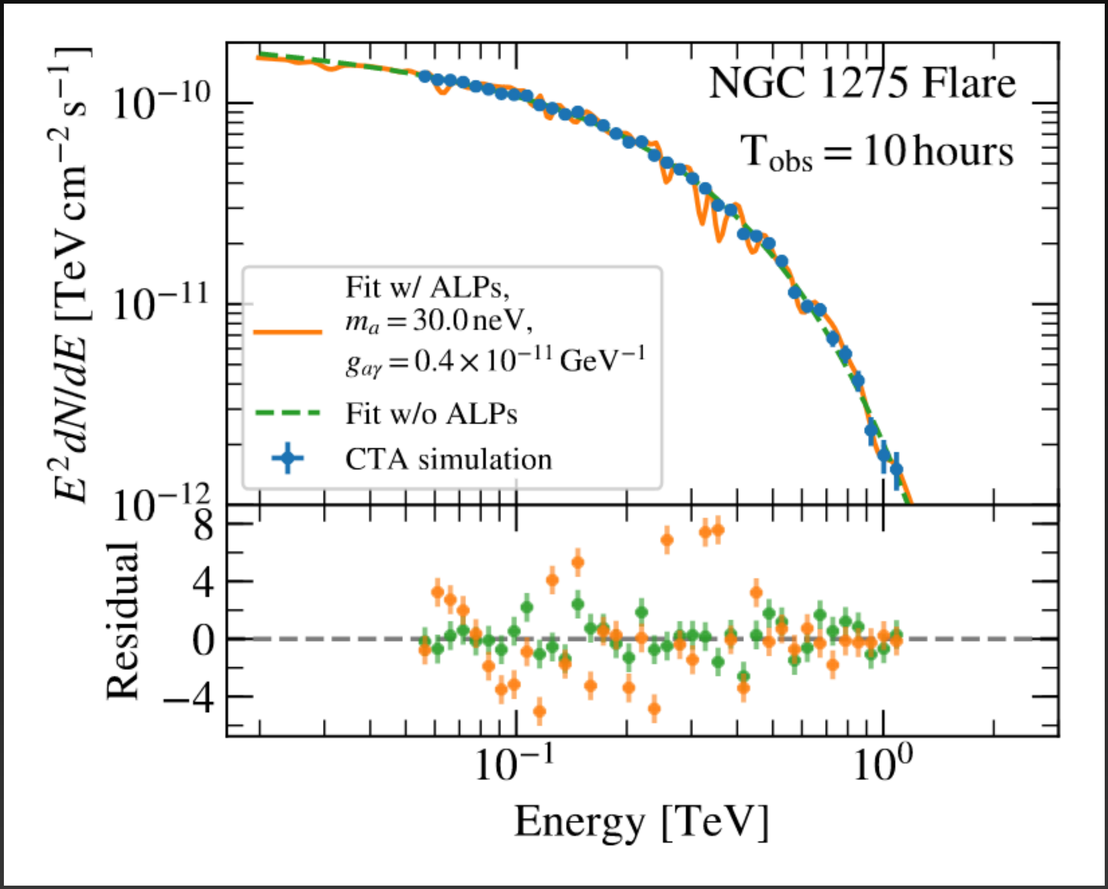
- Could be probed with current and future gamma-ray observations

[Bernal et al. 2023]



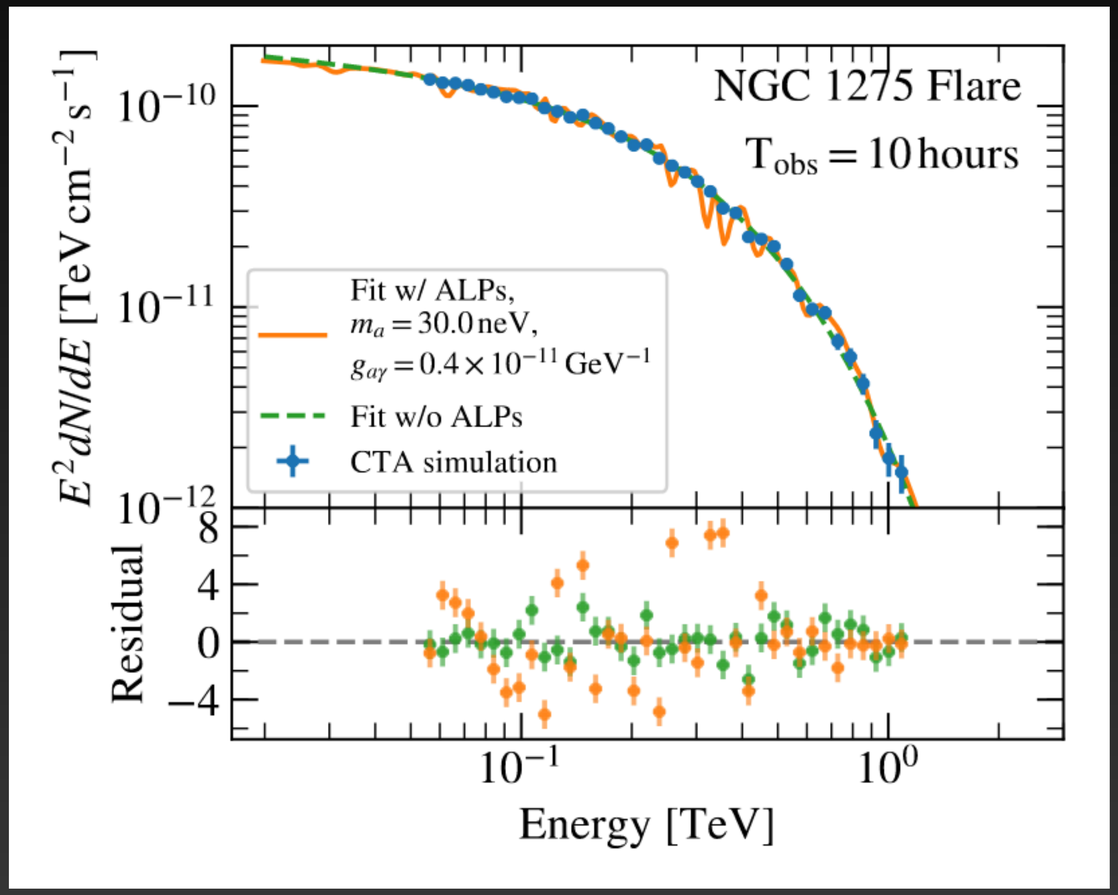
[Korochkin et al. 2020, Bernal et al. 2023]

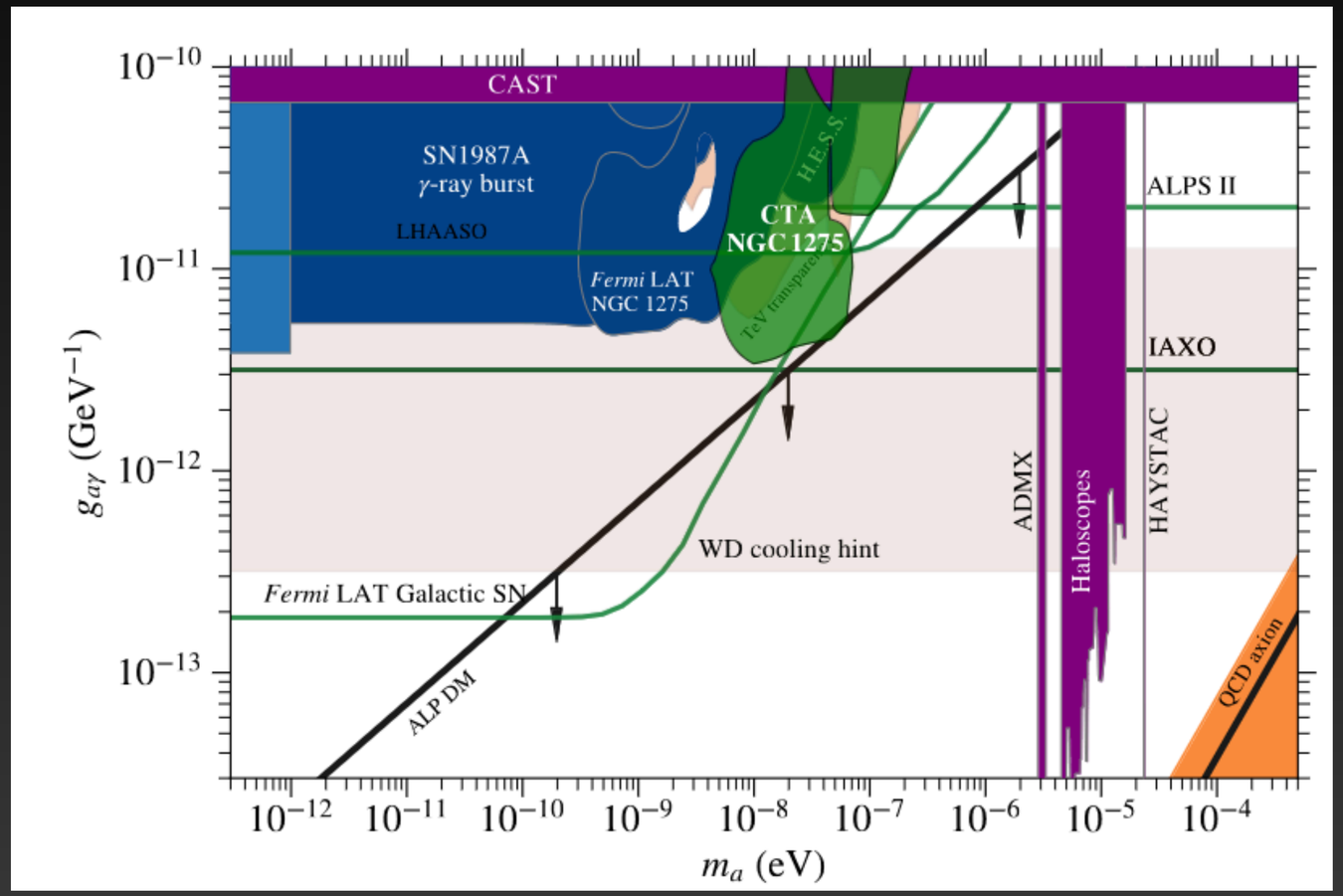
CTAO will probe photon re- and disappearance



[CTA consortium: Abdalla et al. 2021]

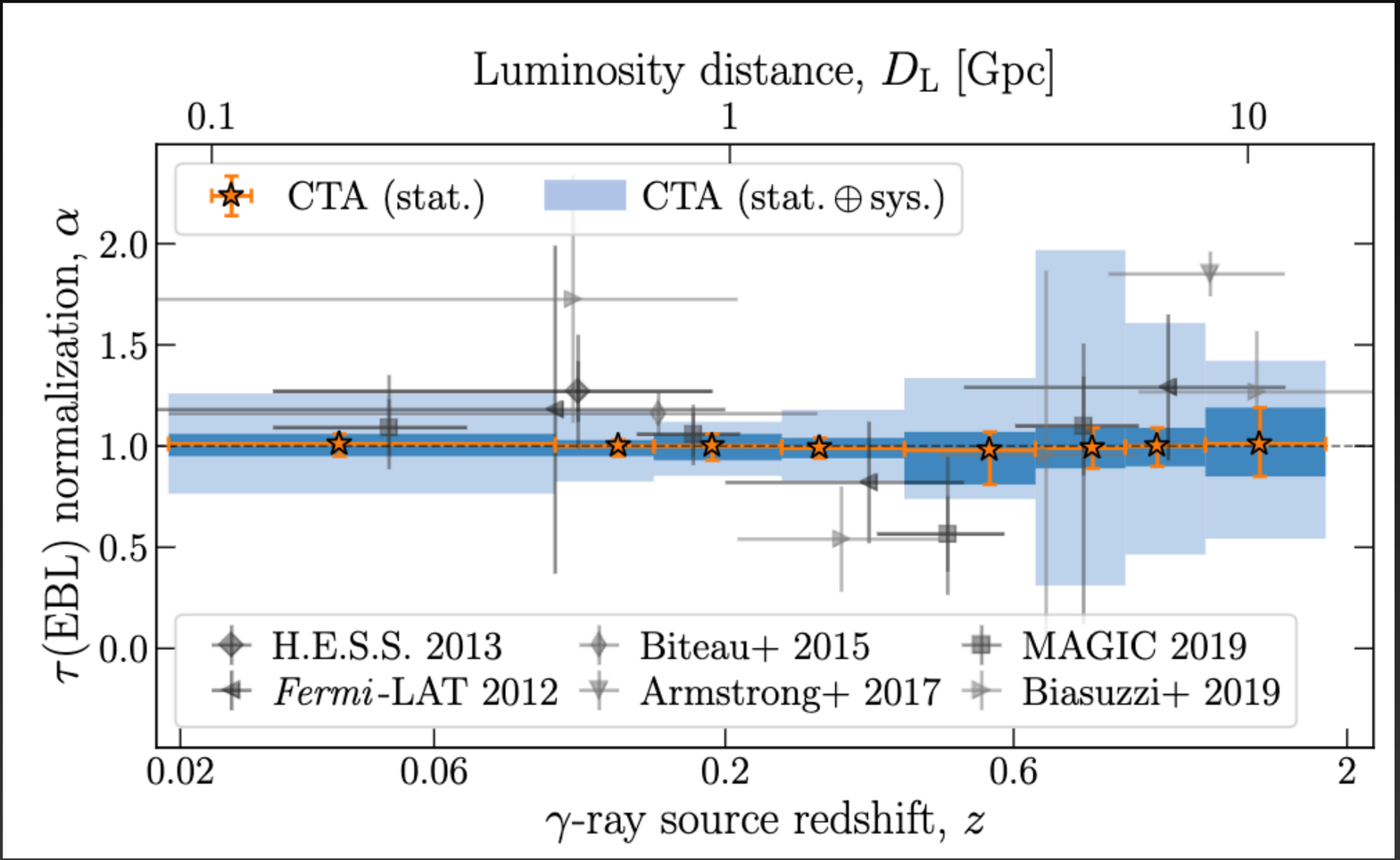
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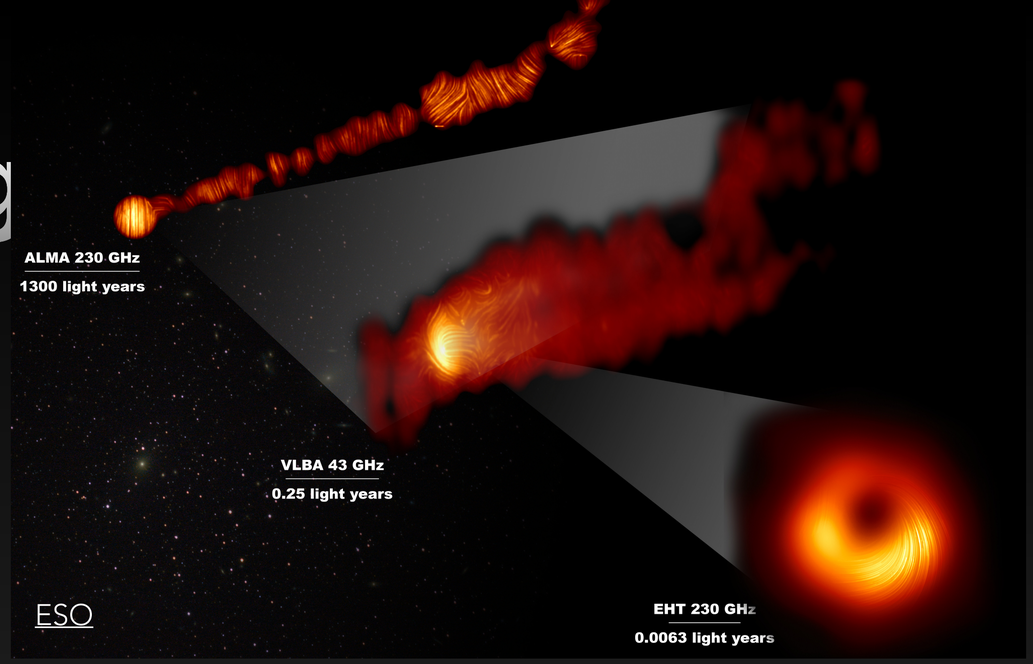
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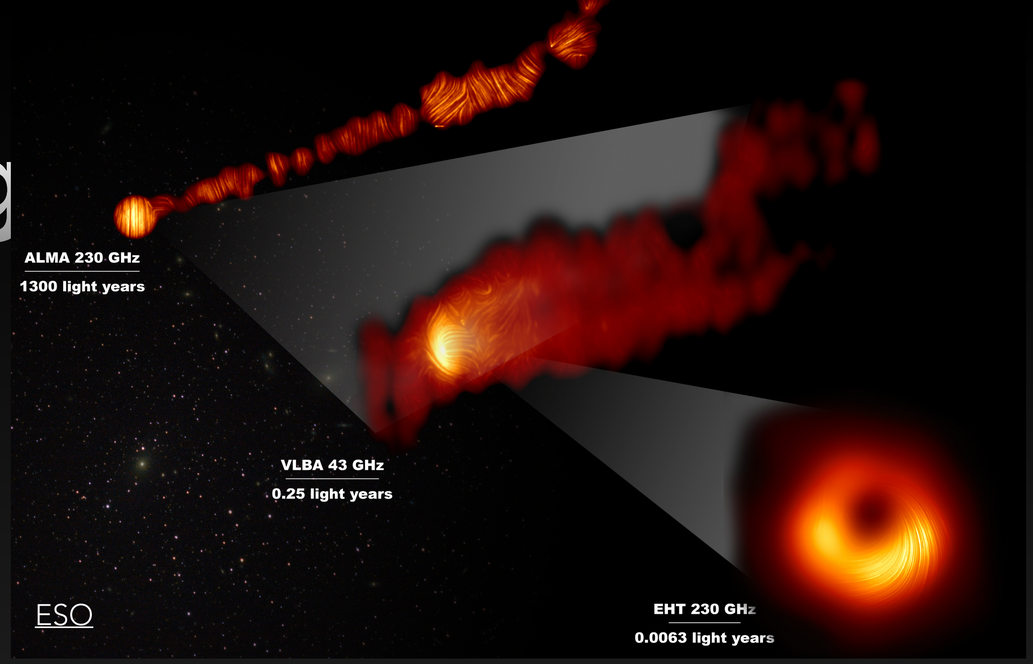
Jet Mag



[see Pudritz et al. 2012, for a review]

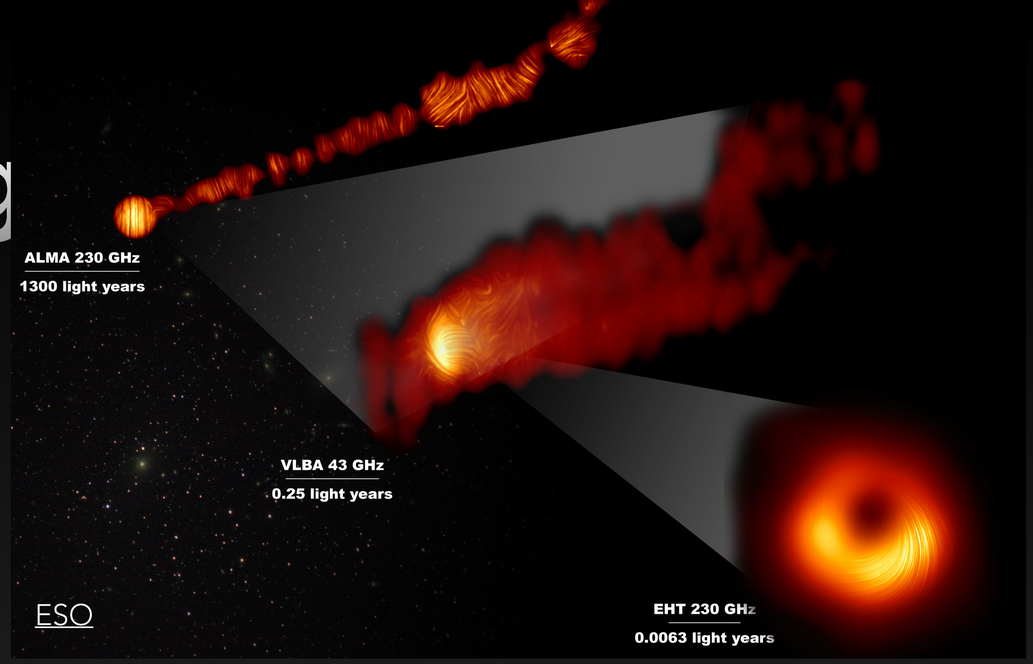
Jet Mag

- Presence of fields inferred from:



[see Pudritz et al. 2012, for a review]

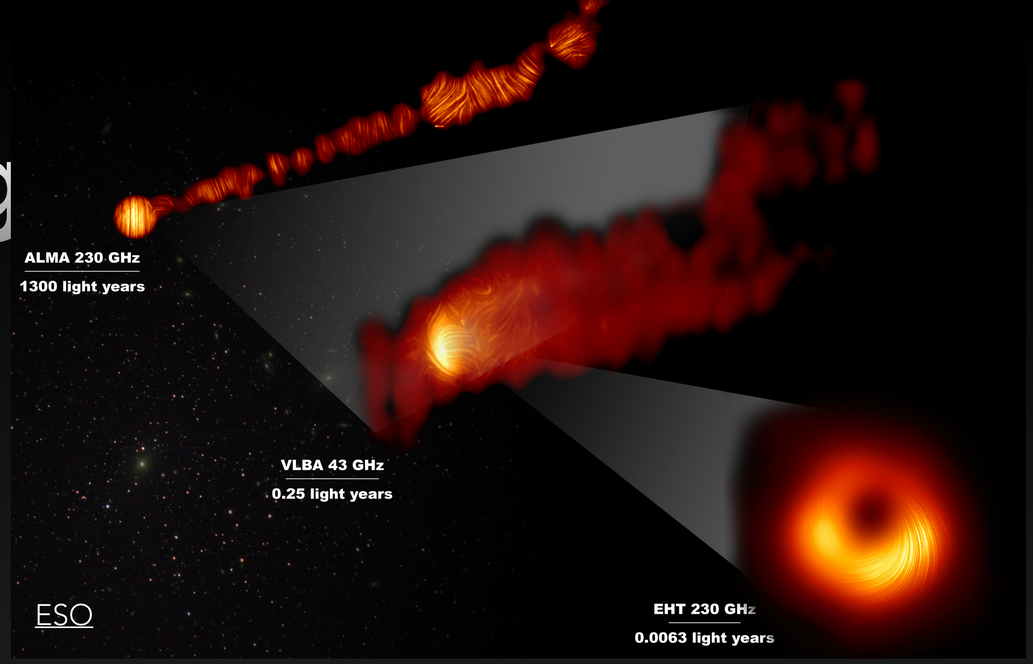
Jet Mag



- Presence of fields inferred from:
  - Synchrotron emission

[see Pudritz et al. 2012, for a review]

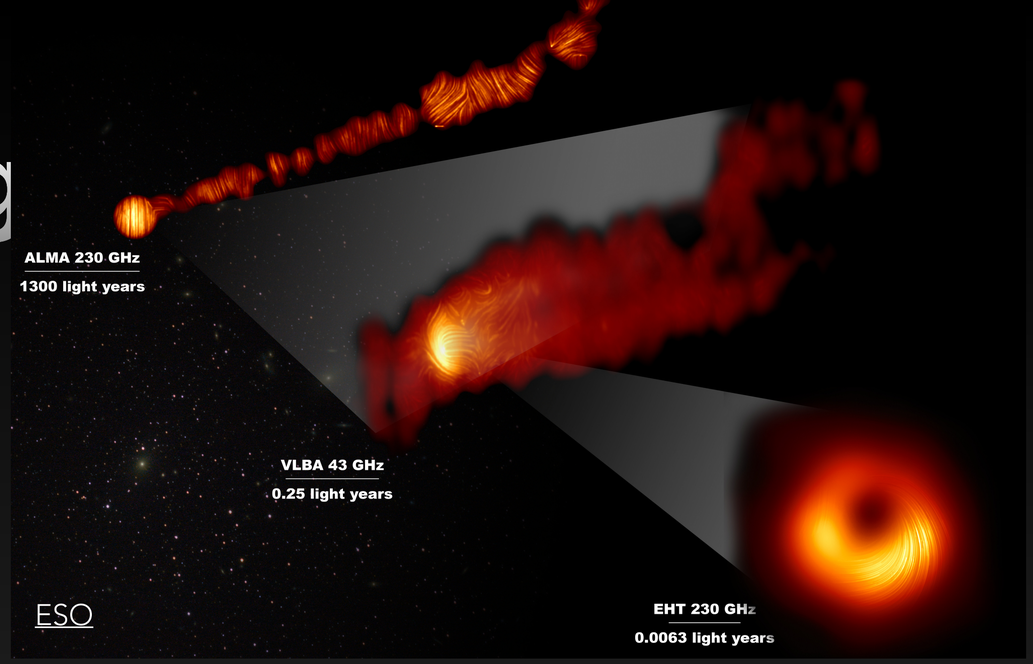
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- Presence of fields inferred from:
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  - Polarization

[see Pudritz et al. 2012, for a review]

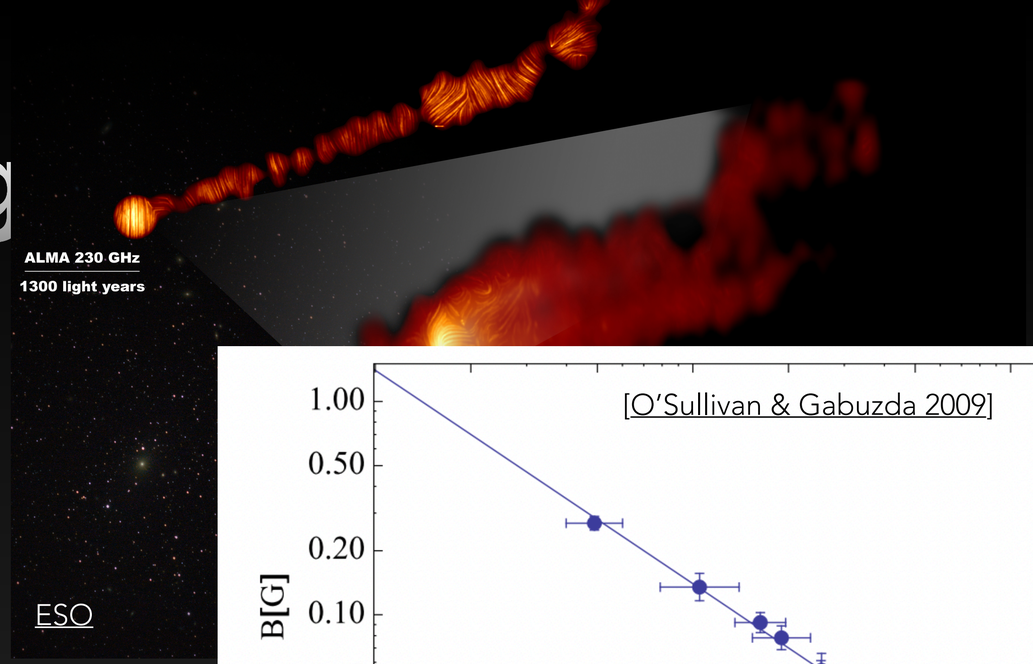
Jet Mag



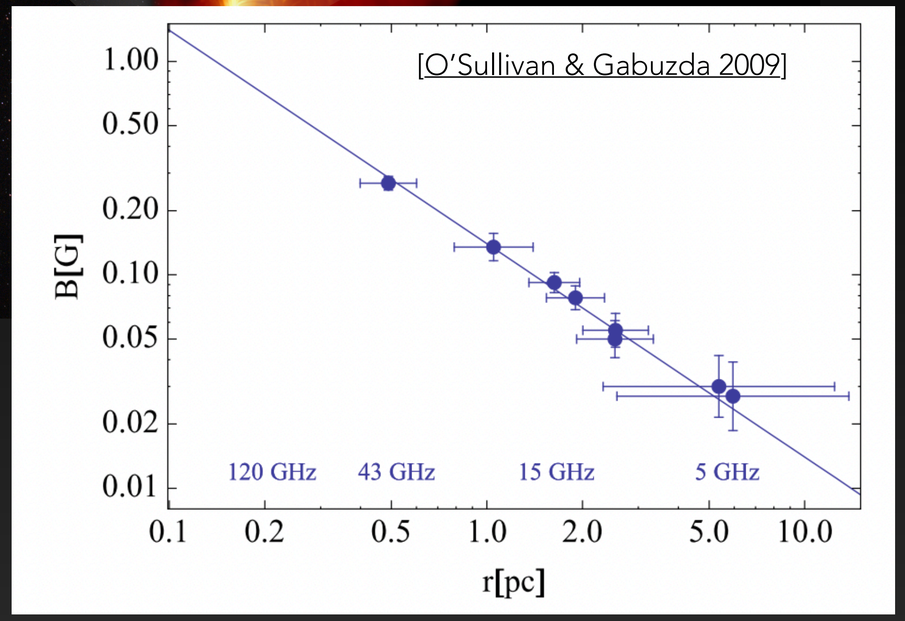
- Presence of fields inferred from:
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  - Polarization
  - Rotation measures (rotation of polarization)

[see Pudritz et al. 2012, for a review]

Jet Mag

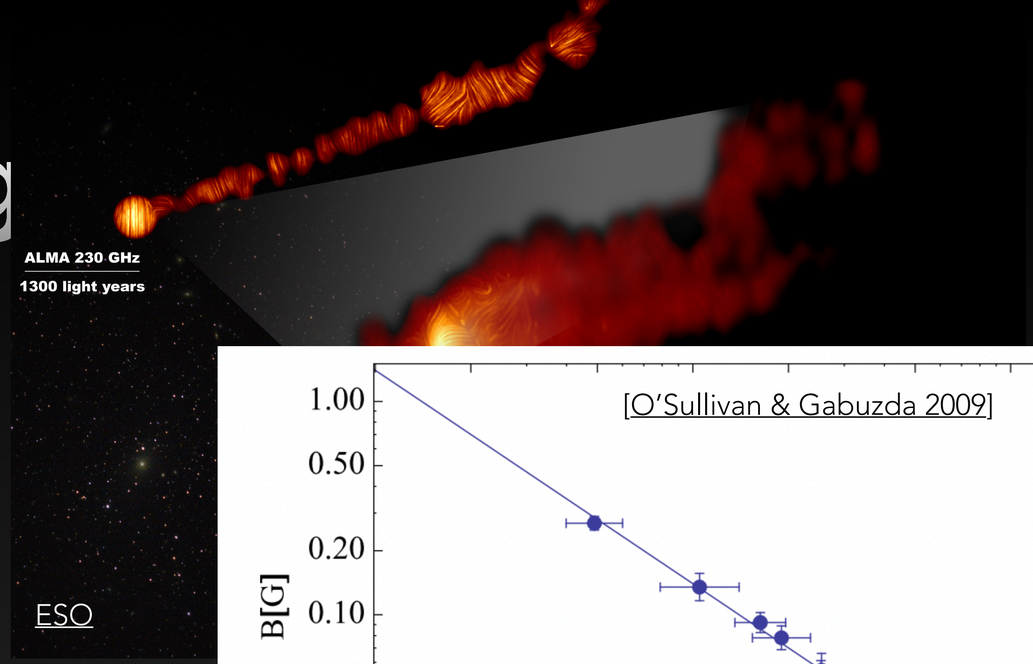


- Presence of fields inferred from:
  - Synchrotron emission
  - Polarization
  - Rotation measures (rotation of polarization)
  - Core shift

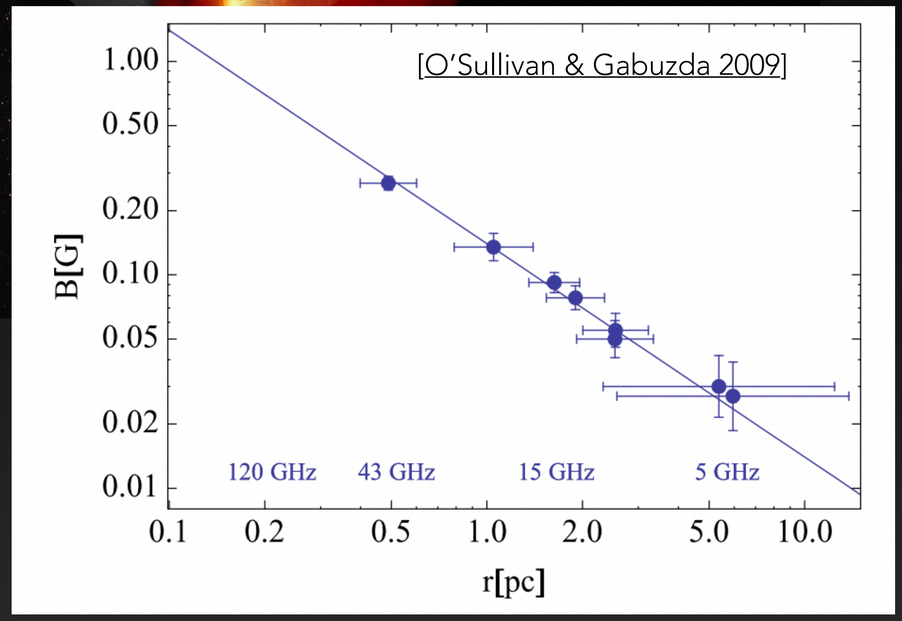


[see Pudritz et al. 2012, for a review]

Jet Mag

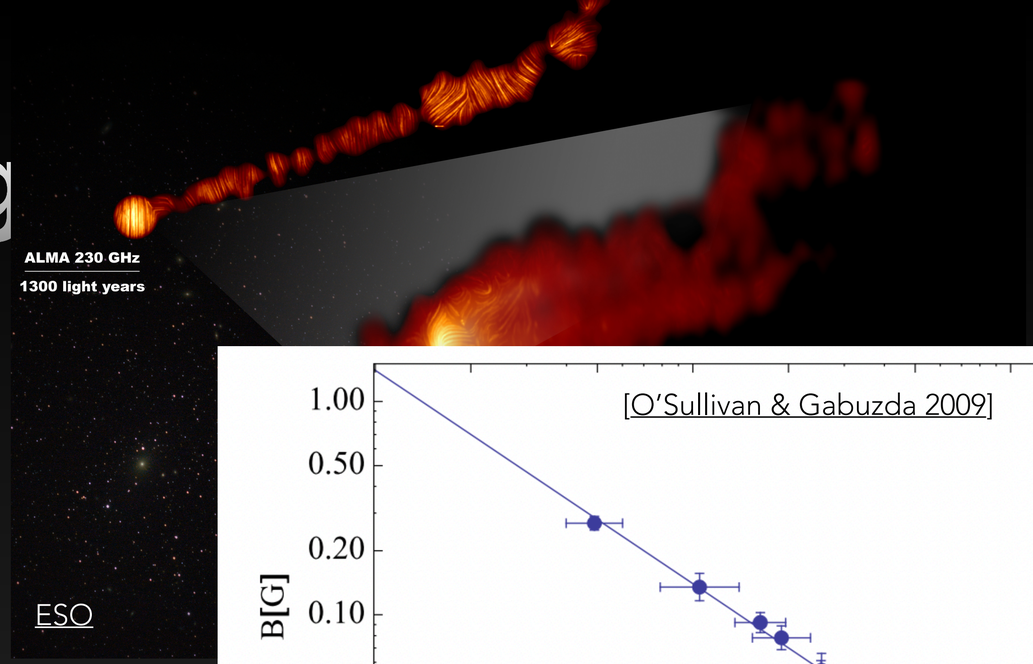


- Presence of fields inferred from:
  - Synchrotron emission
  - Polarization
  - Rotation measures (rotation of polarization)
  - Core shift
- Structure:

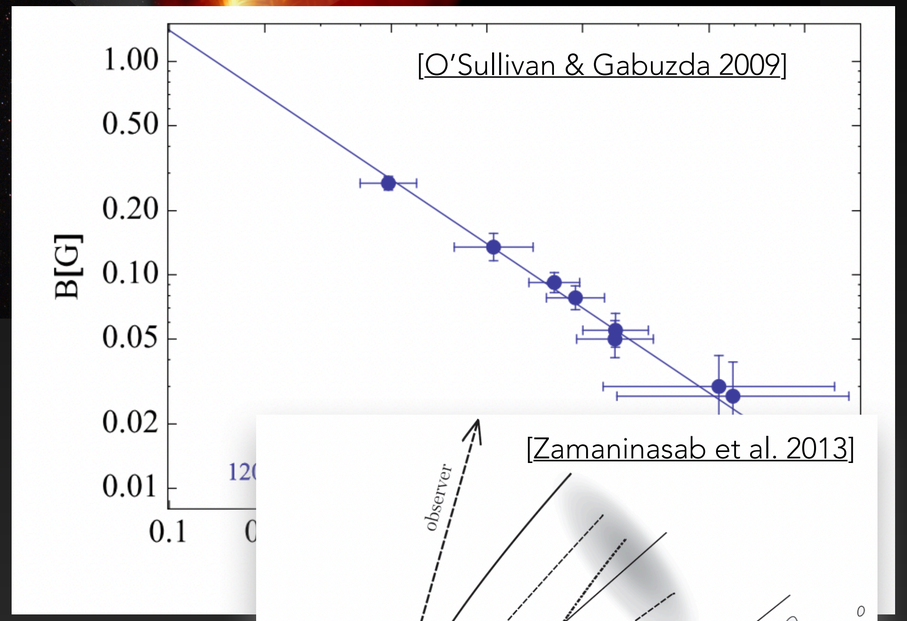


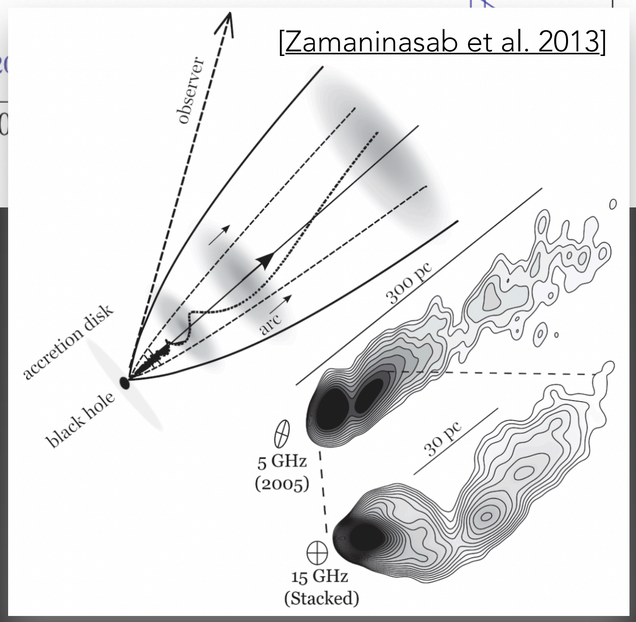
[see Pudritz et al. 2012, for a review]

Jet Mag



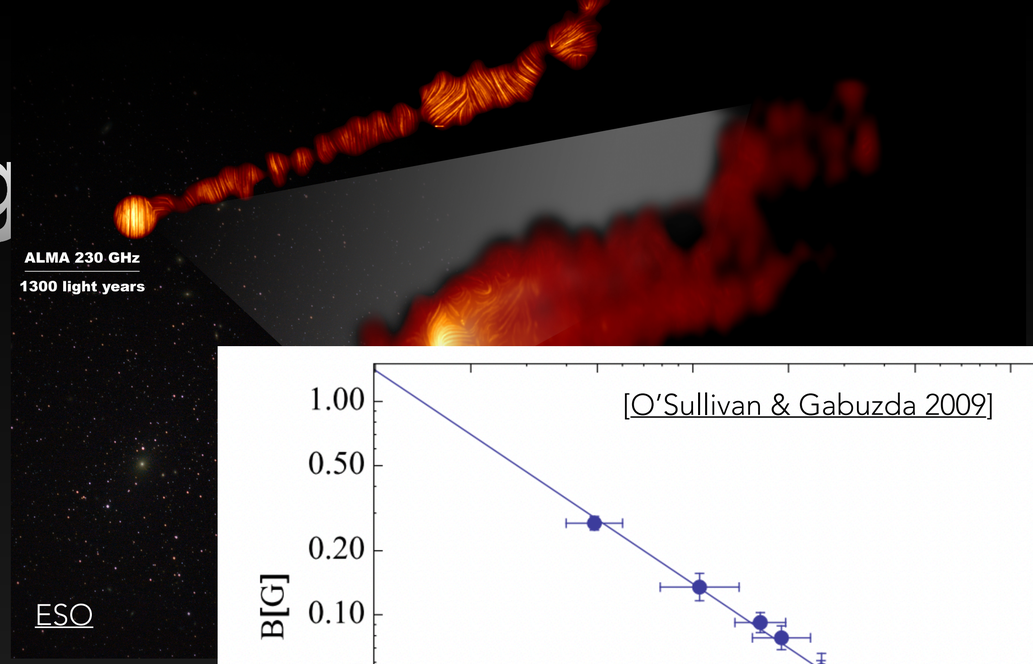
- Presence of fields inferred from:
  - Synchrotron emission
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  - Rotation measures (rotation of polarization)
  - Core shift
- Structure:
  - Helical shape



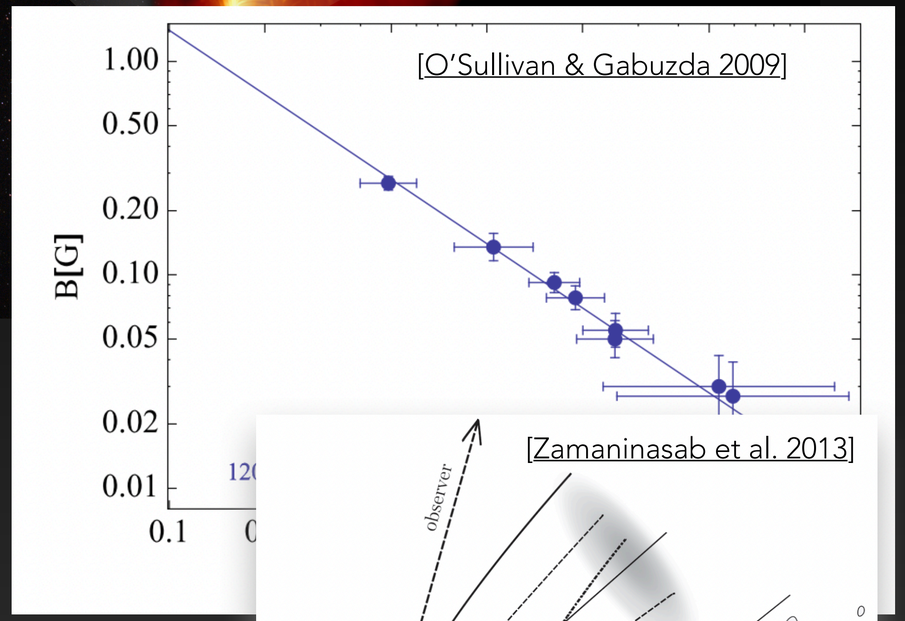


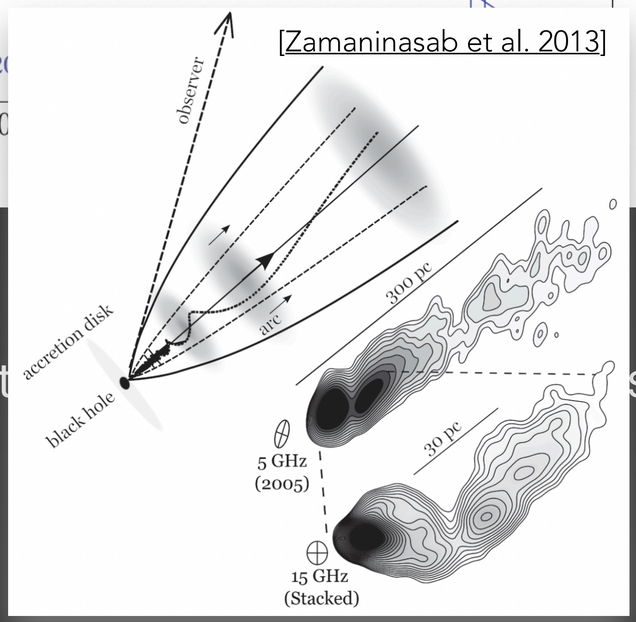
[see Pudritz et al. 2012, for a review]

Jet Mag



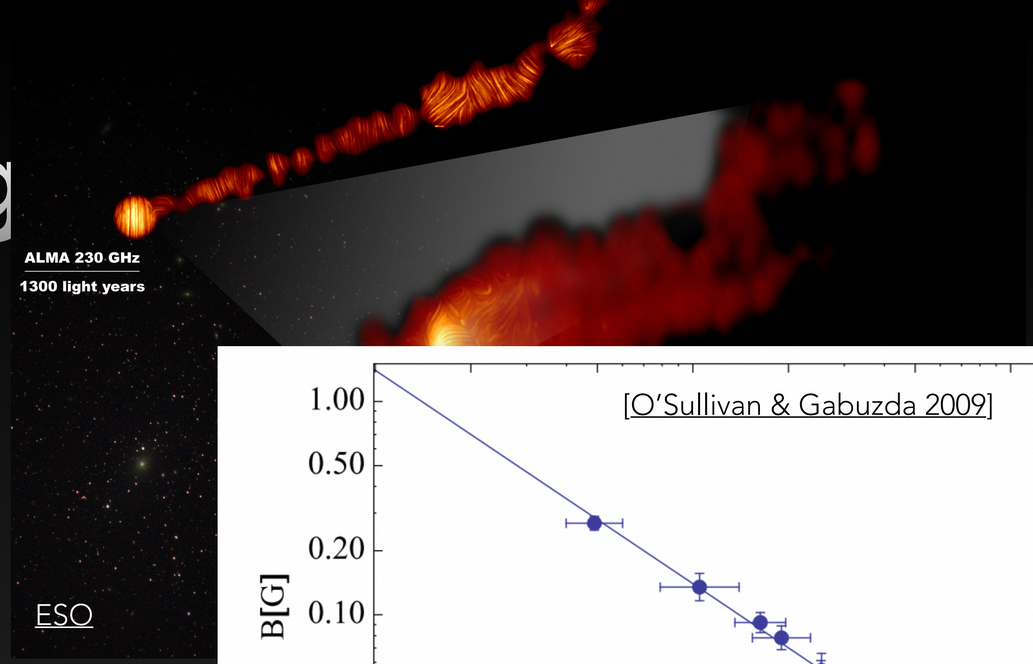
- Presence of fields inferred from:
  - Synchrotron emission
  - Polarization
  - Rotation measures (rotation of polarization)
  - Core shift
- Structure:
  - Helical shape
  - Poloidal component dominates at base, toroidal component



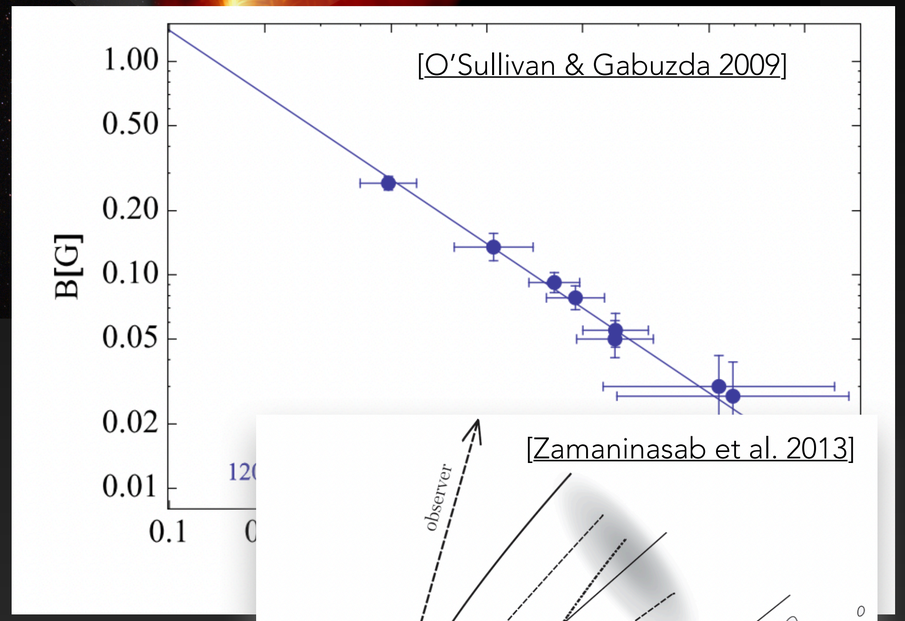


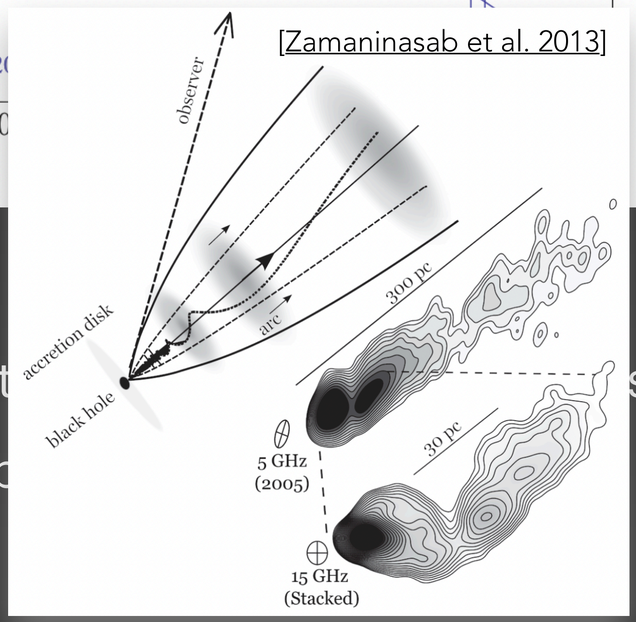
[see Pudritz et al. 2012, for a review]

Jet Mag



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  - Synchrotron emission
  - Polarization
  - Rotation measures (rotation of polarization)
  - Core shift
- Structure:
  - Helical shape
  - Poloidal component dominates at base, toroidal component
  - Coherent on large scales but with additional turbulent comp

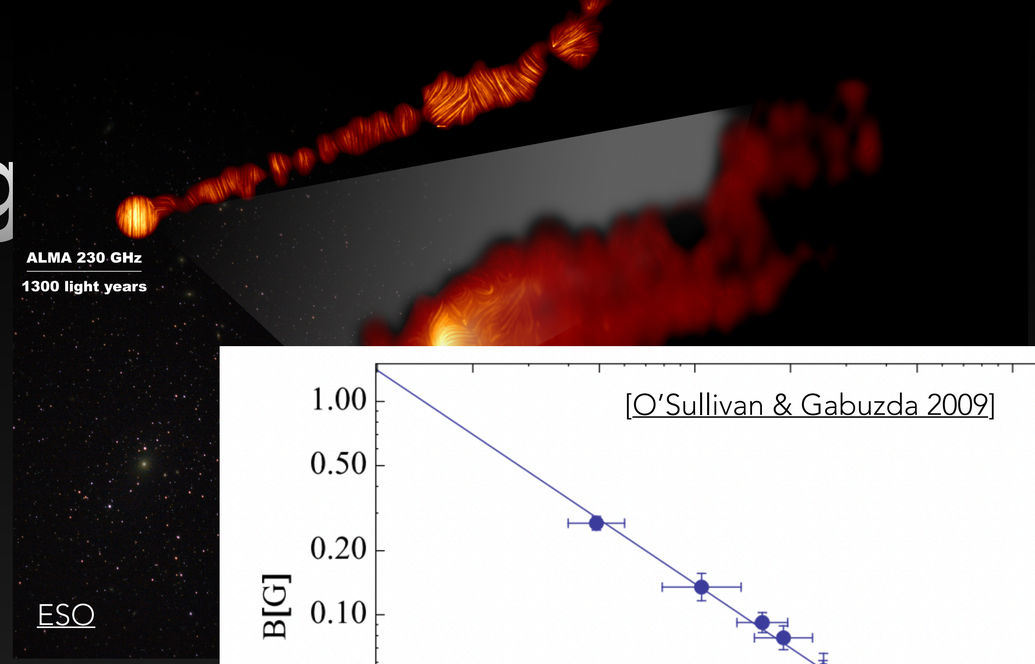


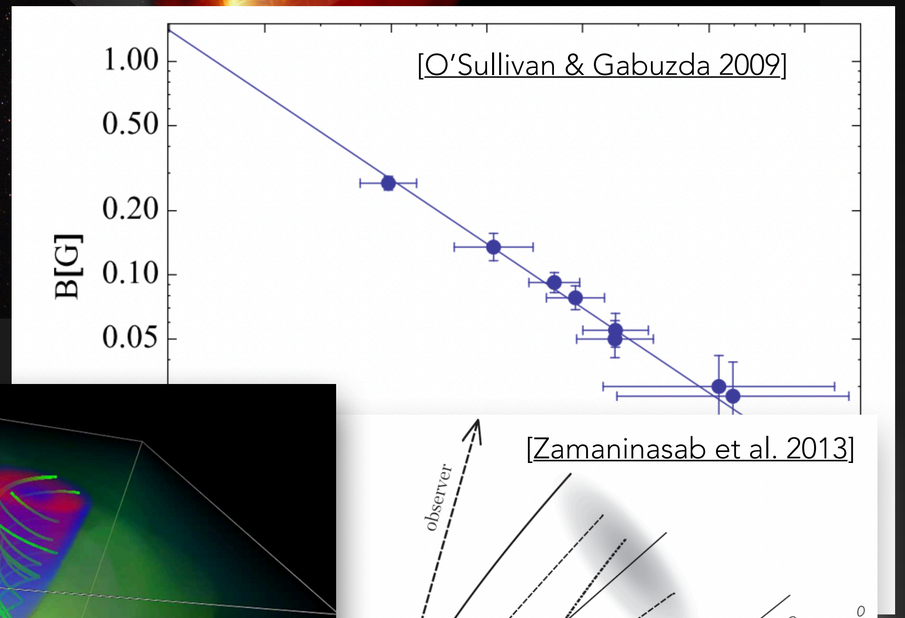


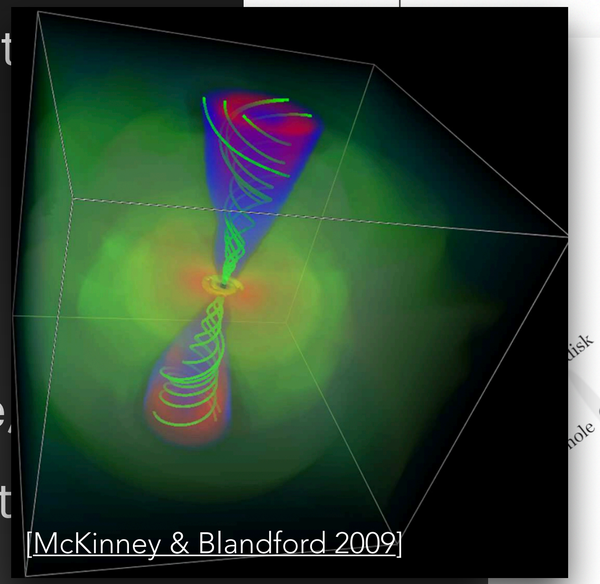
[see Pudritz et al. 2012, for a review]

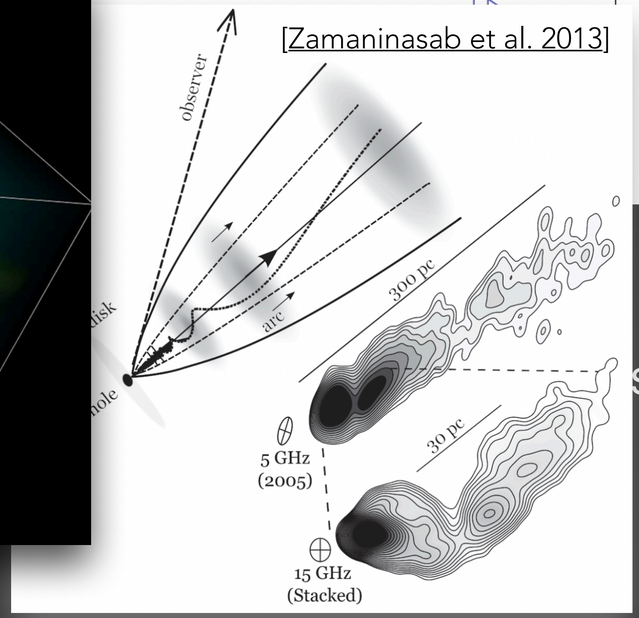
Jet Mag

- Presence of fields inferred from:
  - Synchrotron emission
  - Polarization
  - Rotation measures (rotation of polarizat
  - Core shift
- Structure:
  - Helical shape
  - Poloidal component dominates at base,
  - Coherent on large scales but with addit
- Supported by GMHD simulations





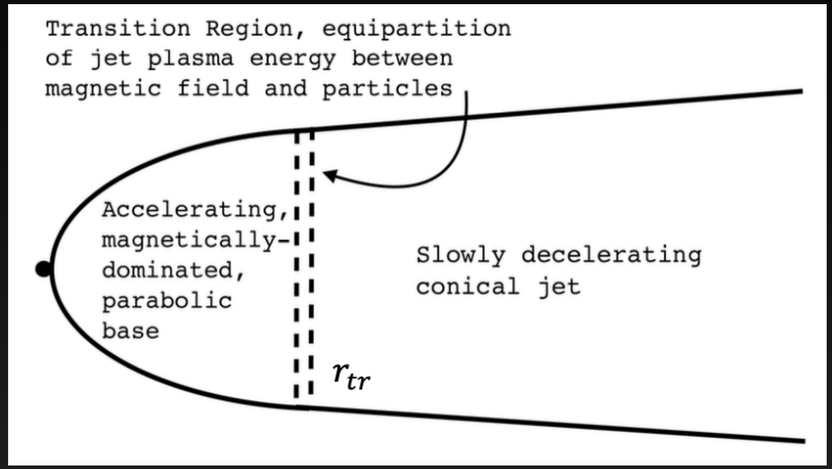


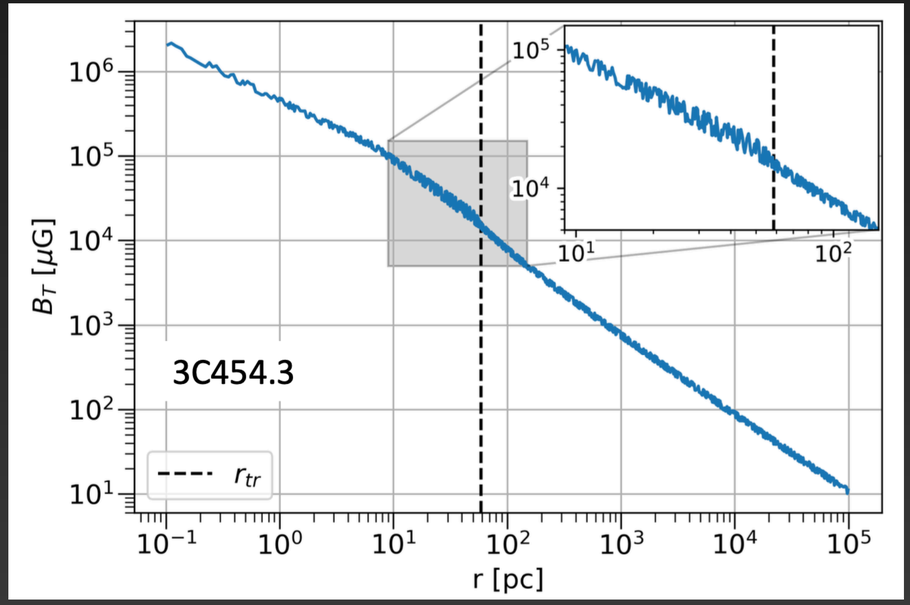


[see Pudritz et al. 2012, for a review]

Jet modeling

- Potter & Cotter jet framework (fits to broadband steady-state observations) for global jet properties (Potter & Cotter 2015; Davies et al 2021)
- Need both field strength and orientation (ALPs only care about the transverse component of the field $B_{\perp}$)
- Use lower-limits of Meyer et al. 2019 for the position of the flare emission regions
- Include photon-photon dispersion from all relevant photon fields (as in Davies et al. 2022)





Magnetic fields in galaxy clusters

[Figure from Bonafede et al., 2010;
see, e.g., Feretti et al., 2012, for a review]

Magnetic fields in galaxy clusters

- Observational evidence:

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$$\Delta\Psi = \Psi - \Psi_0 = \lambda^2(\mathrm{RM})$$

Change of polarization angle

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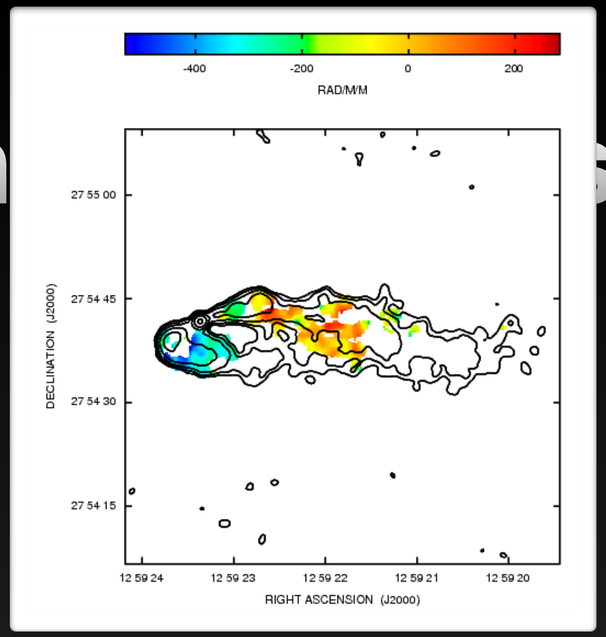
Rotation measure

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Rotation measure map with 5 GHz contours of galaxy NGC 4869 in the Coma cluster

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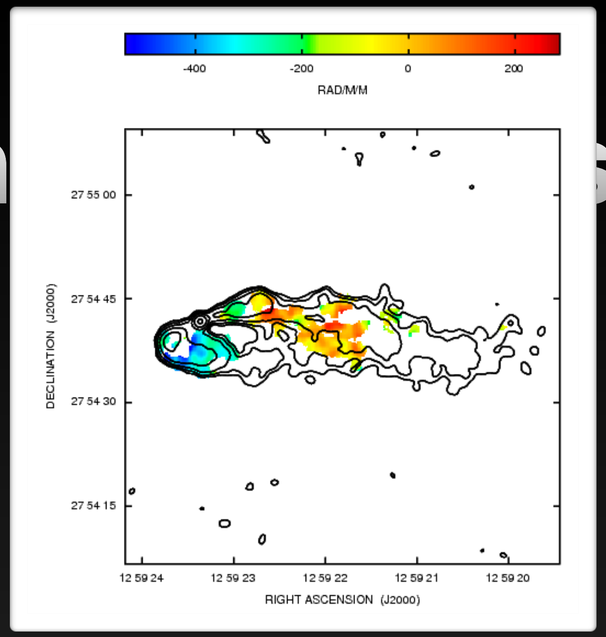
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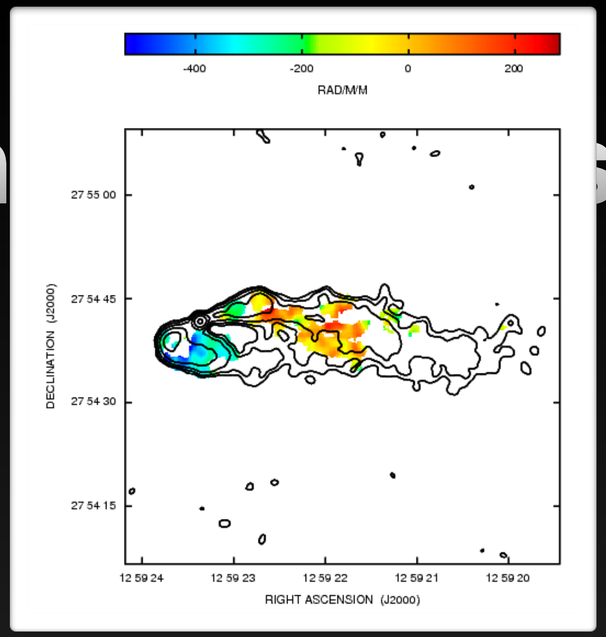
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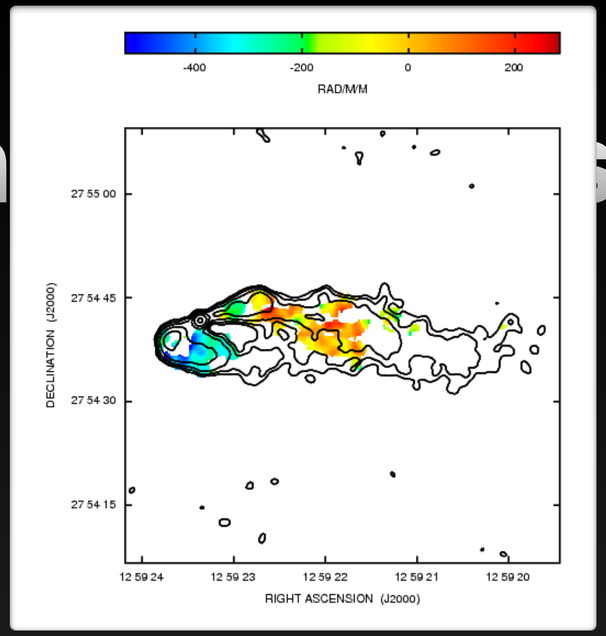
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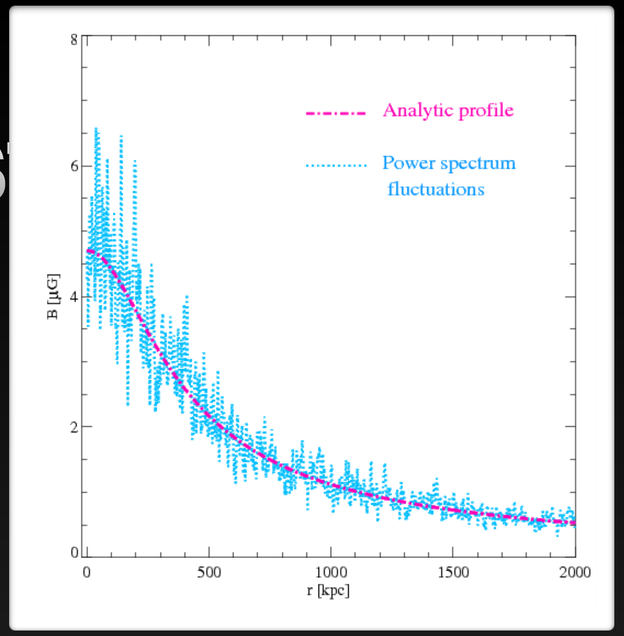
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Simulated B field (blue) and analytical profile (magenta) of the Coma cluster

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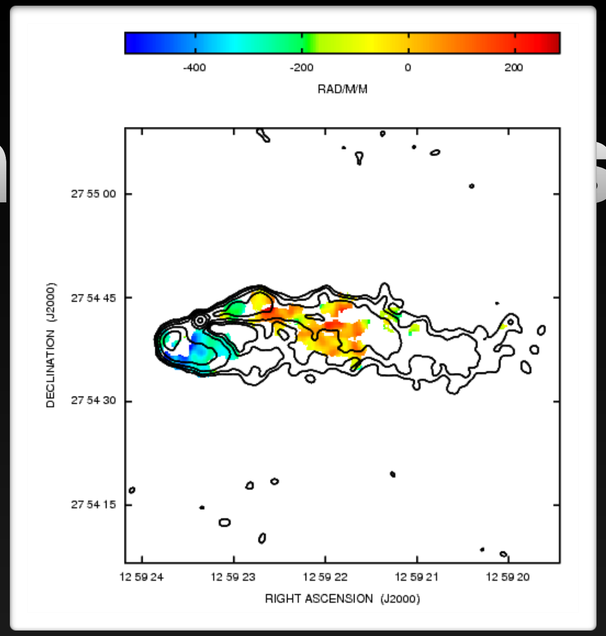
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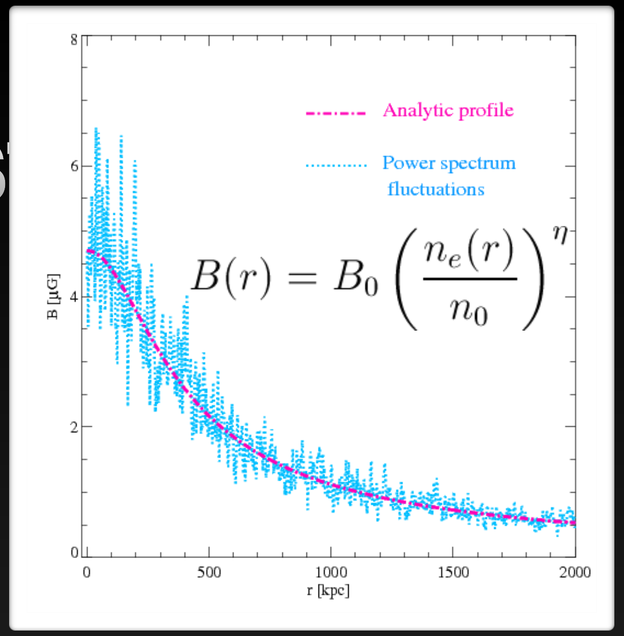
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- Magnetic field follows electron distribution $n_e(r)$



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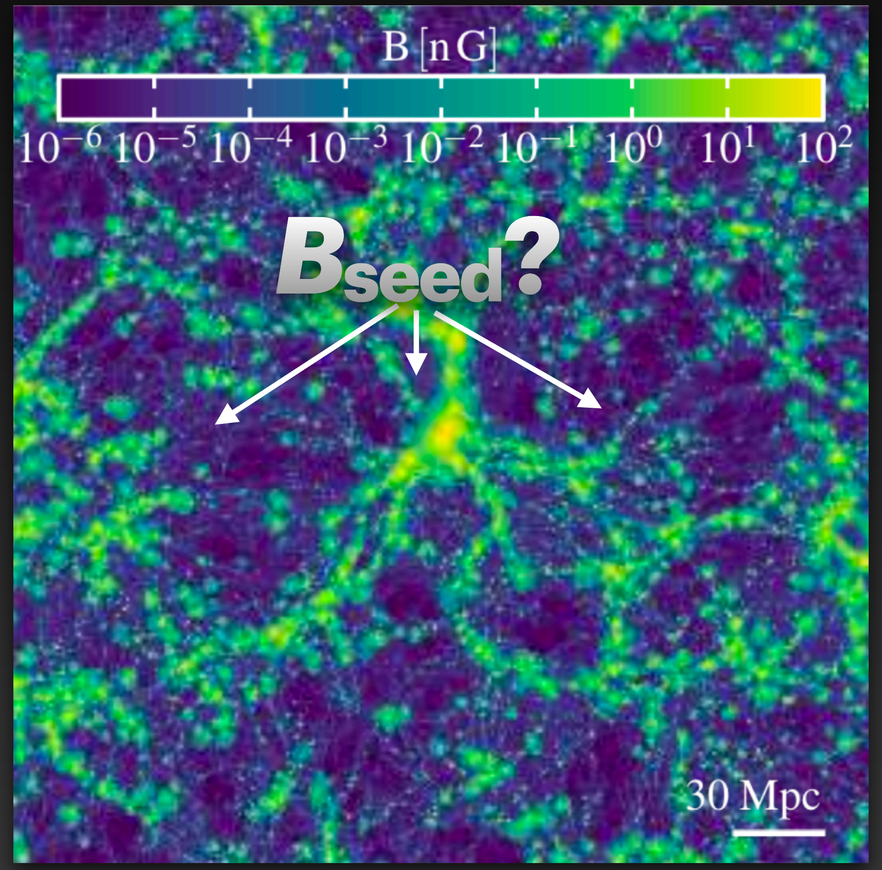
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The Intergalactic magnetic field

- Seed field for magnetic fields in galaxies and galaxy clusters
- Origin, strength, orientation of seed fields unknown
- Only upper limits from direct observations (rotation measures), $B \lesssim 10^{-9}\,\mathrm{G}$
- Indirect measurements from gamma-ray observations suggest $B \gtrsim 10^{-15}\,\mathrm{G}$

IllustrisTNG simulation — Marinacci et al. (2018)



[e.g., Alves Batista & Saveliev 2021]

Magnetic Field of the Milky Way

[Jansson & Farrar 2012; Planck Collaboration 2016]

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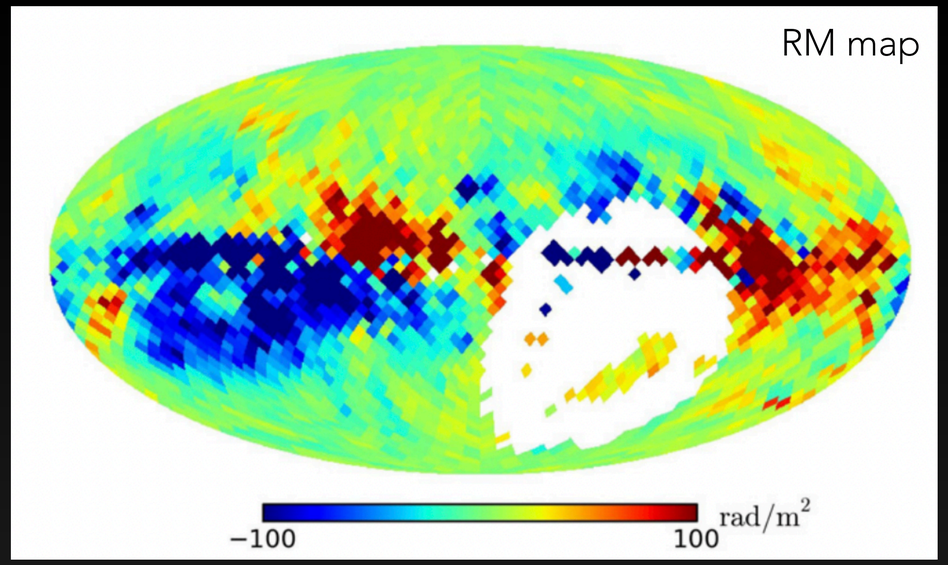
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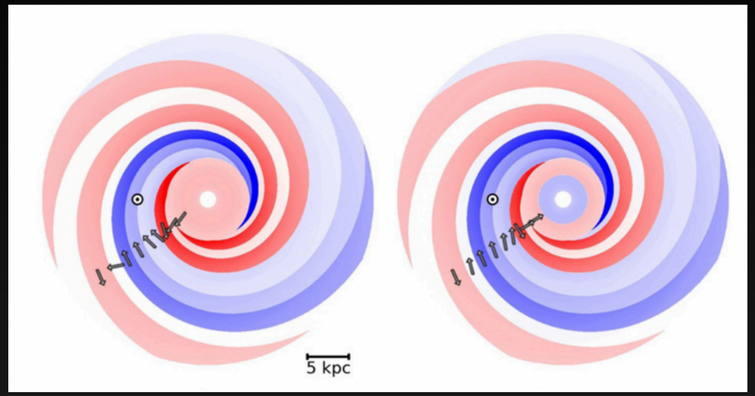


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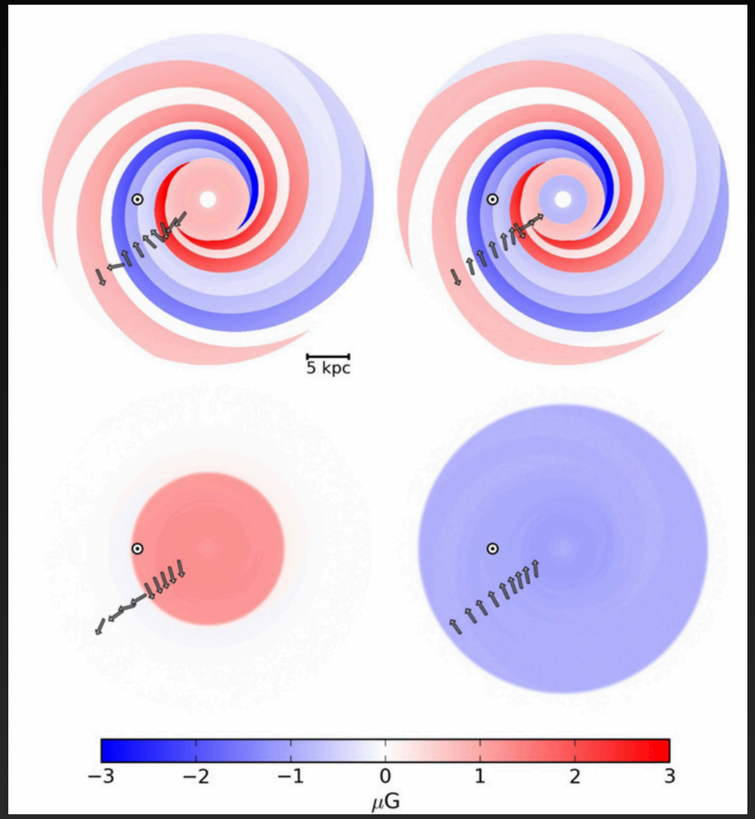
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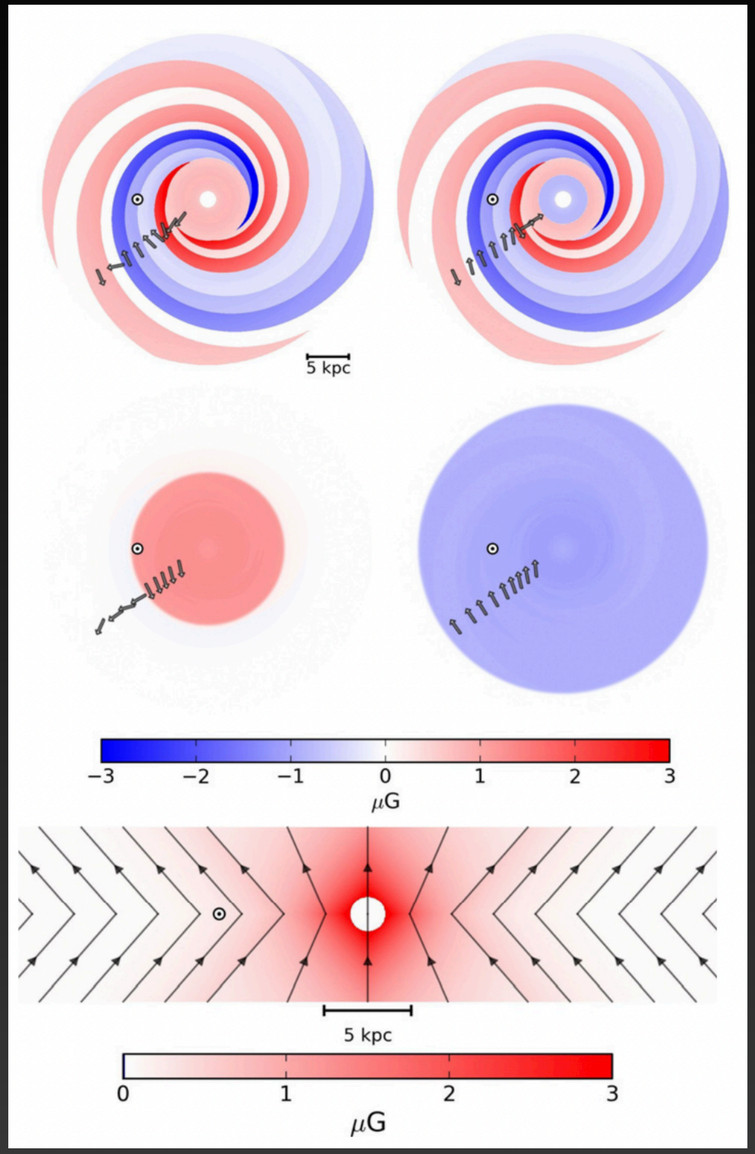
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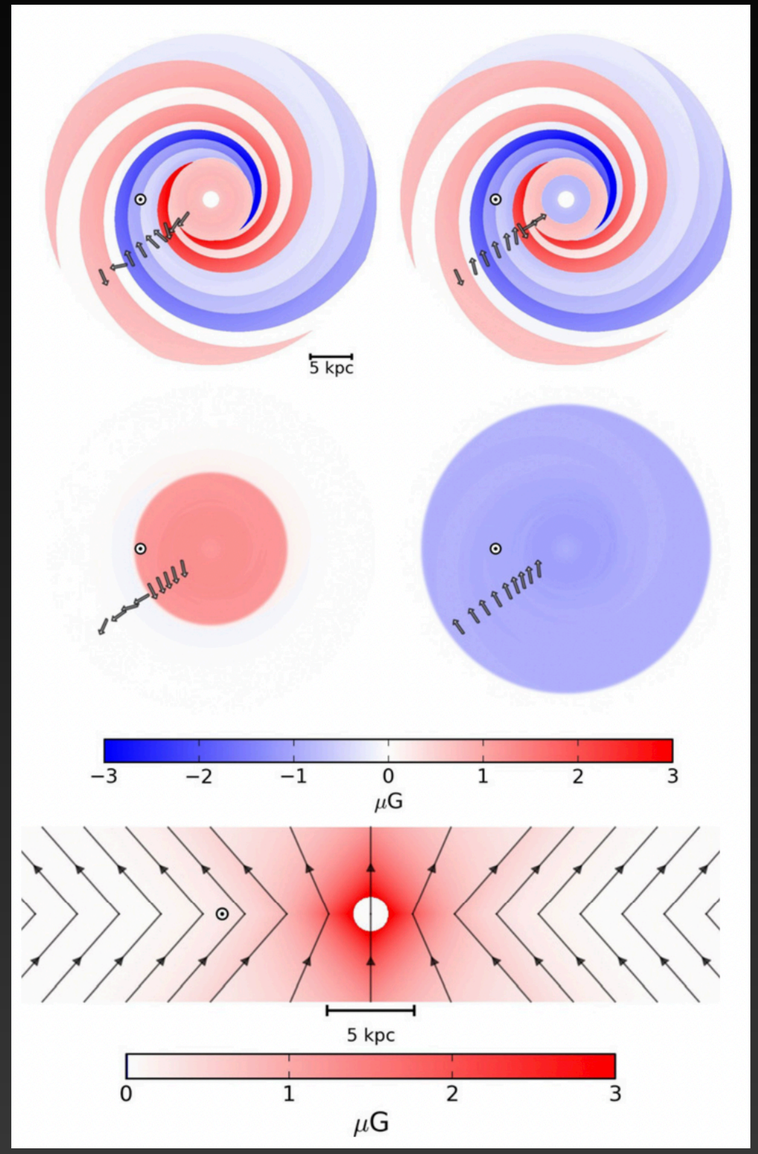
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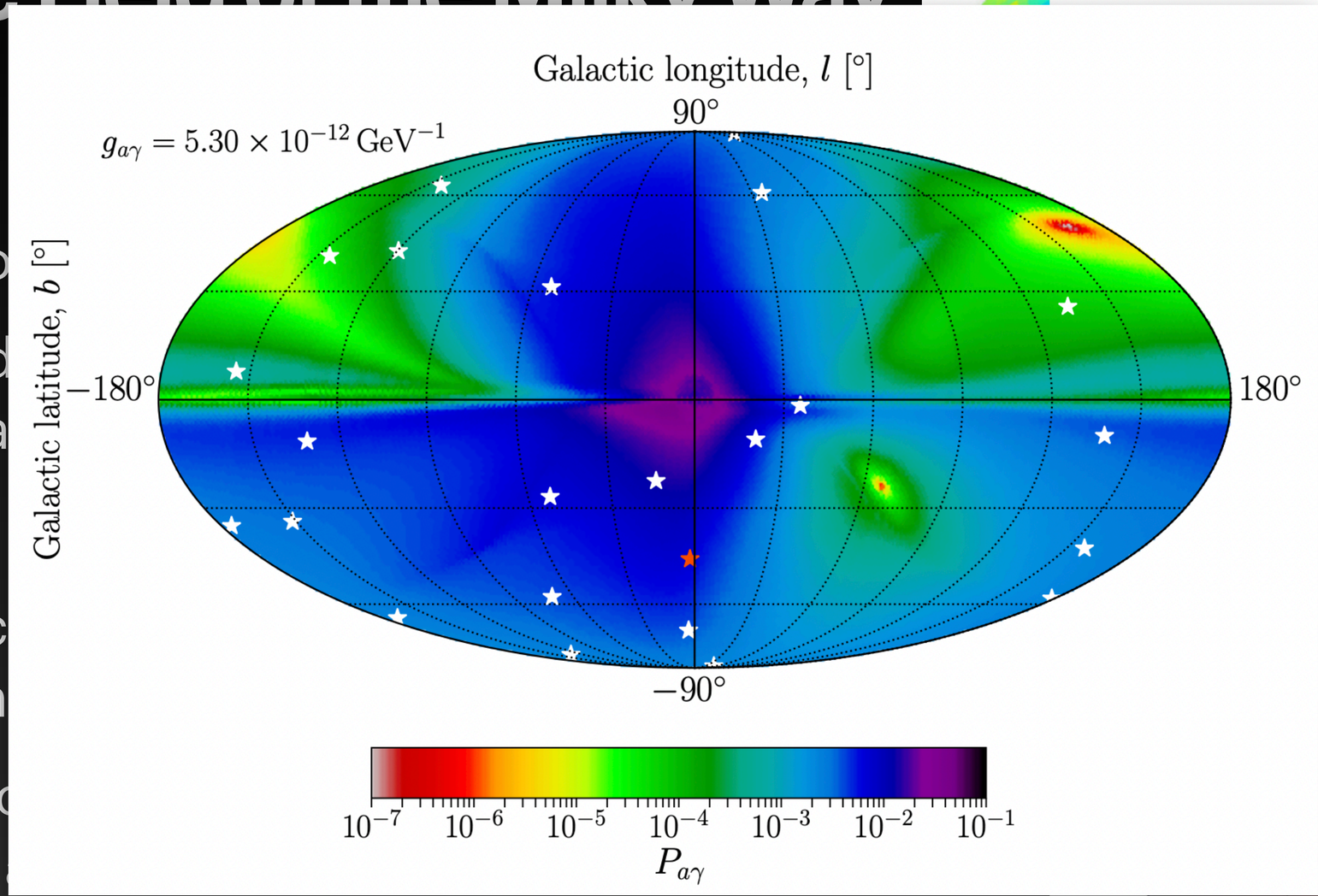
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- Models include various components
- B-field is coherent on large scales but also has turbulent component

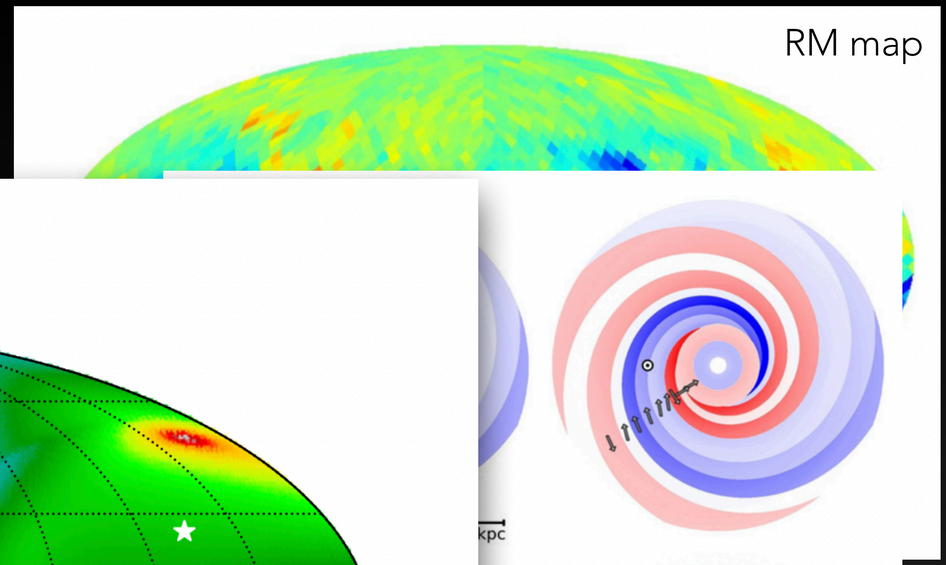


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[Crnogorcevic et al. 2021]

Modeling the EBL

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- EBL usually reported in specific intensity multiplied with frequency, νI_ν, in units of $\mathrm{nW\,m^{-2}\,sr^{-1}}$ which can be converted to a photon density $dn/d\epsilon$ (in units of $\mathrm{eV^{-1}cm^{-3}}$) through

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- $$\left| \frac{dt}{dz} \right| = \frac{1}{H_0(1+z)\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}$$

Optical Depth

$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} dz \left| \frac{dL}{dz} \right|$$

[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013, Biteau & MM 2022]

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Line of sight integral to source

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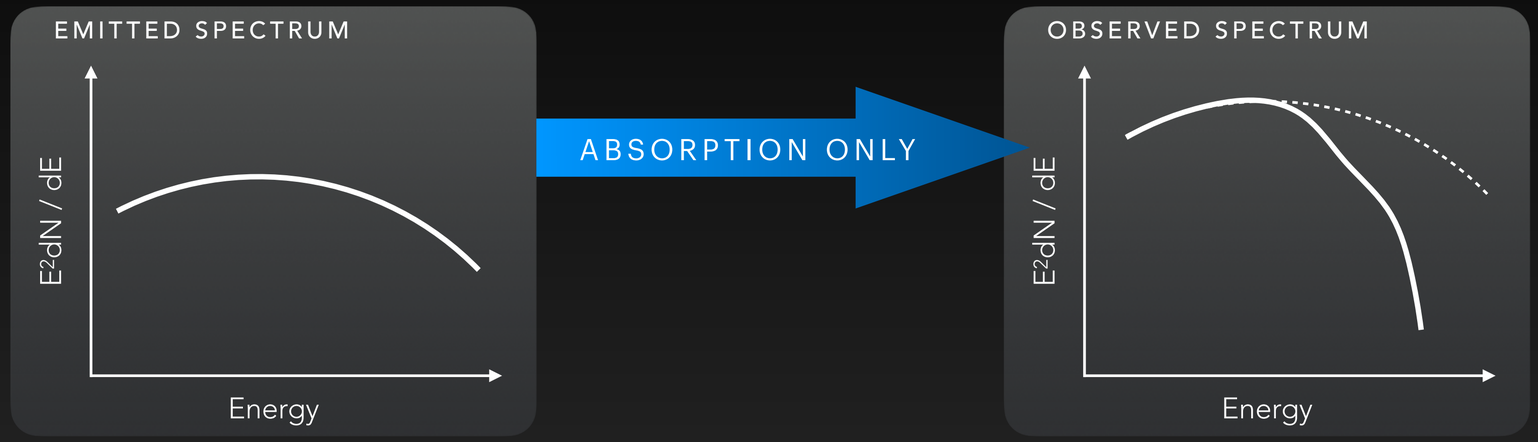
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Universe more transparent to gamma rays

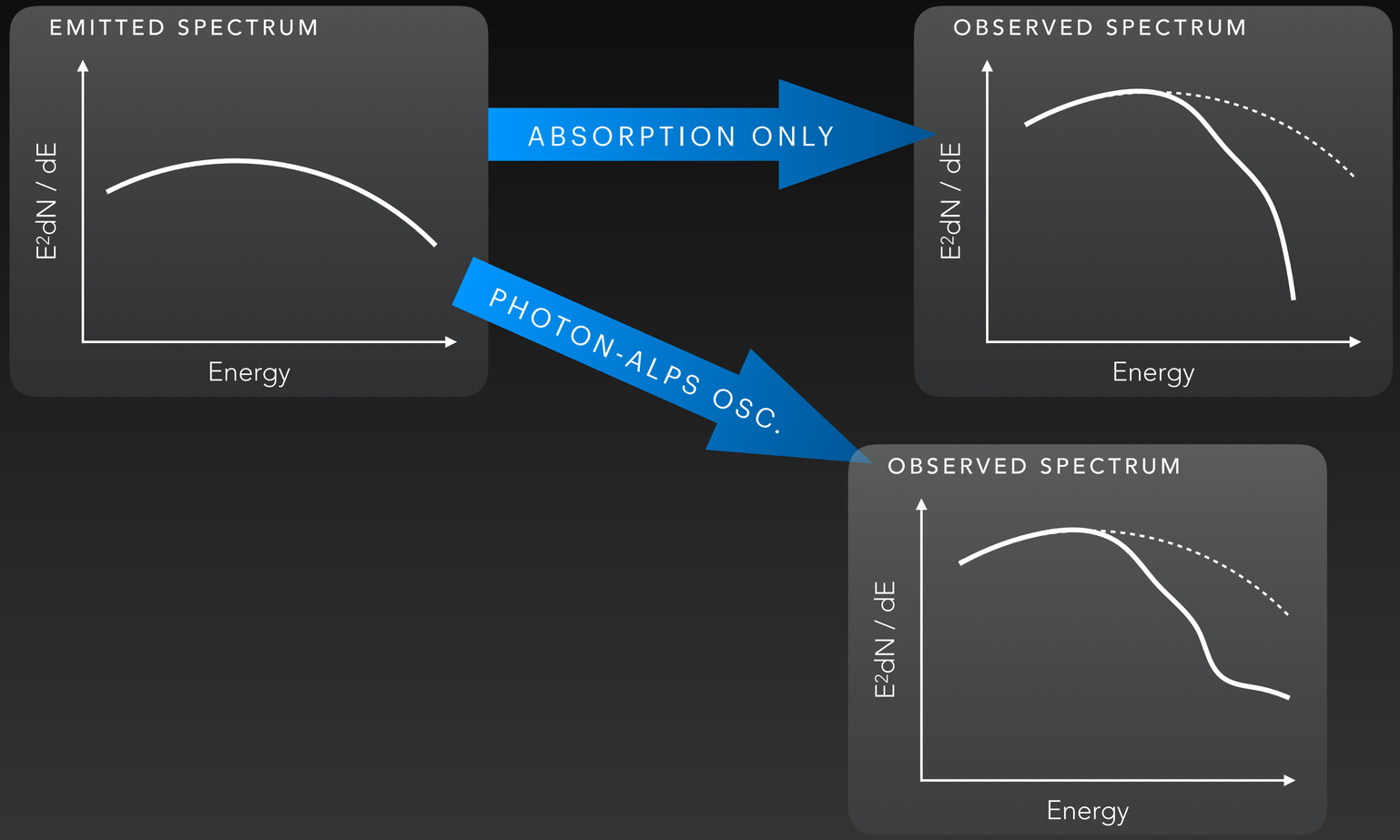
Evidence from AGN observations? — On going discussion



[e.g., Biteau & MM 2022, 2202.0052]

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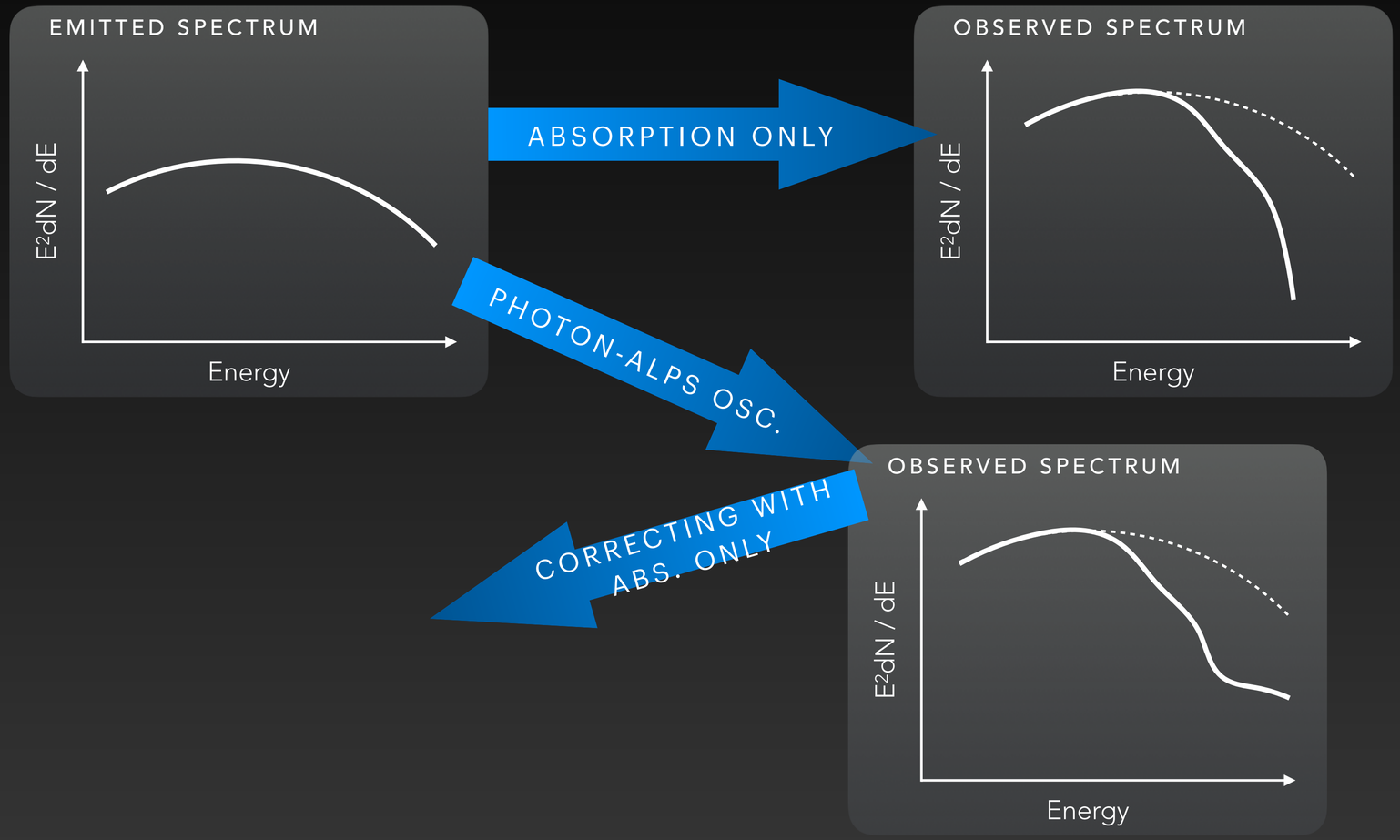
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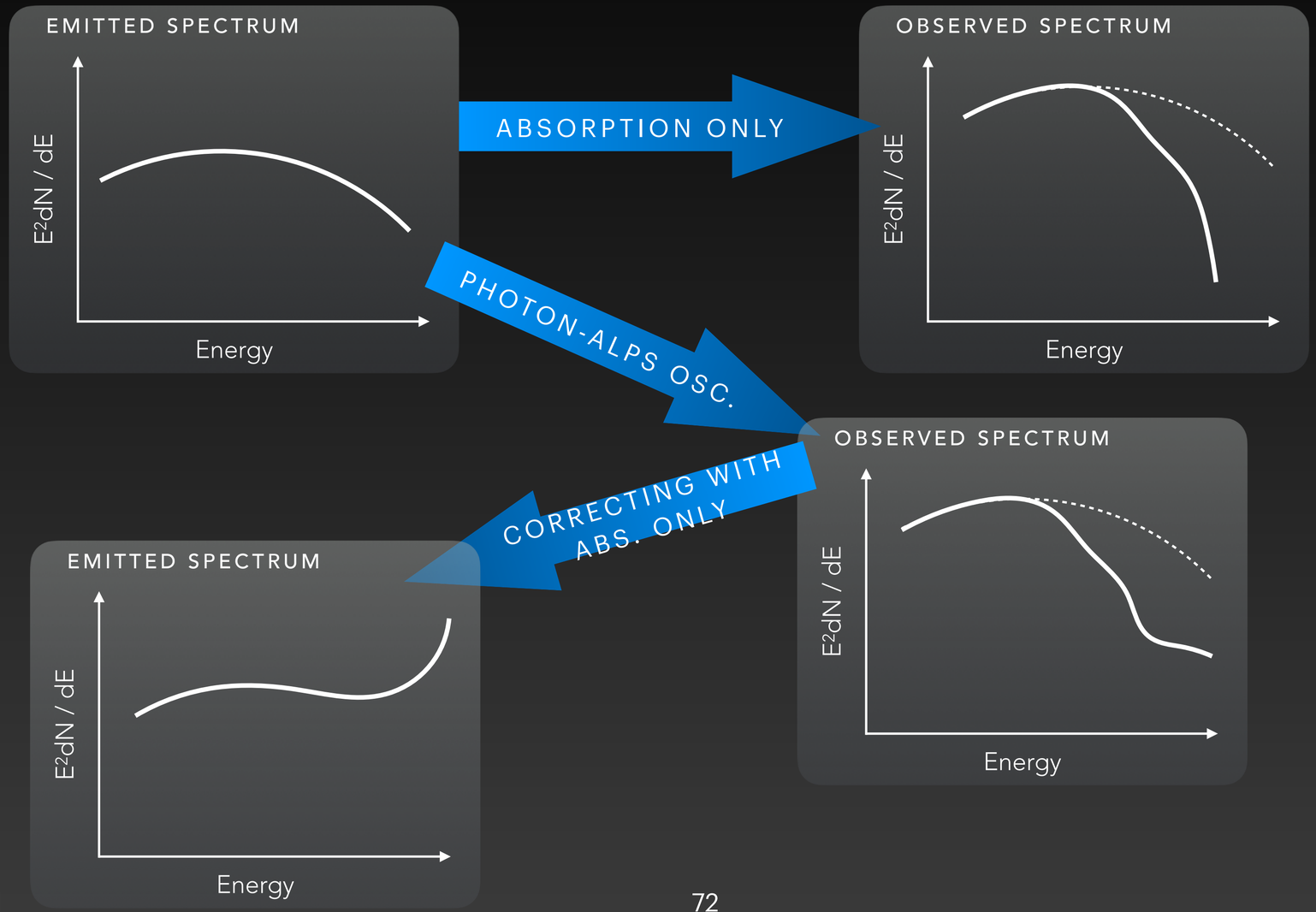
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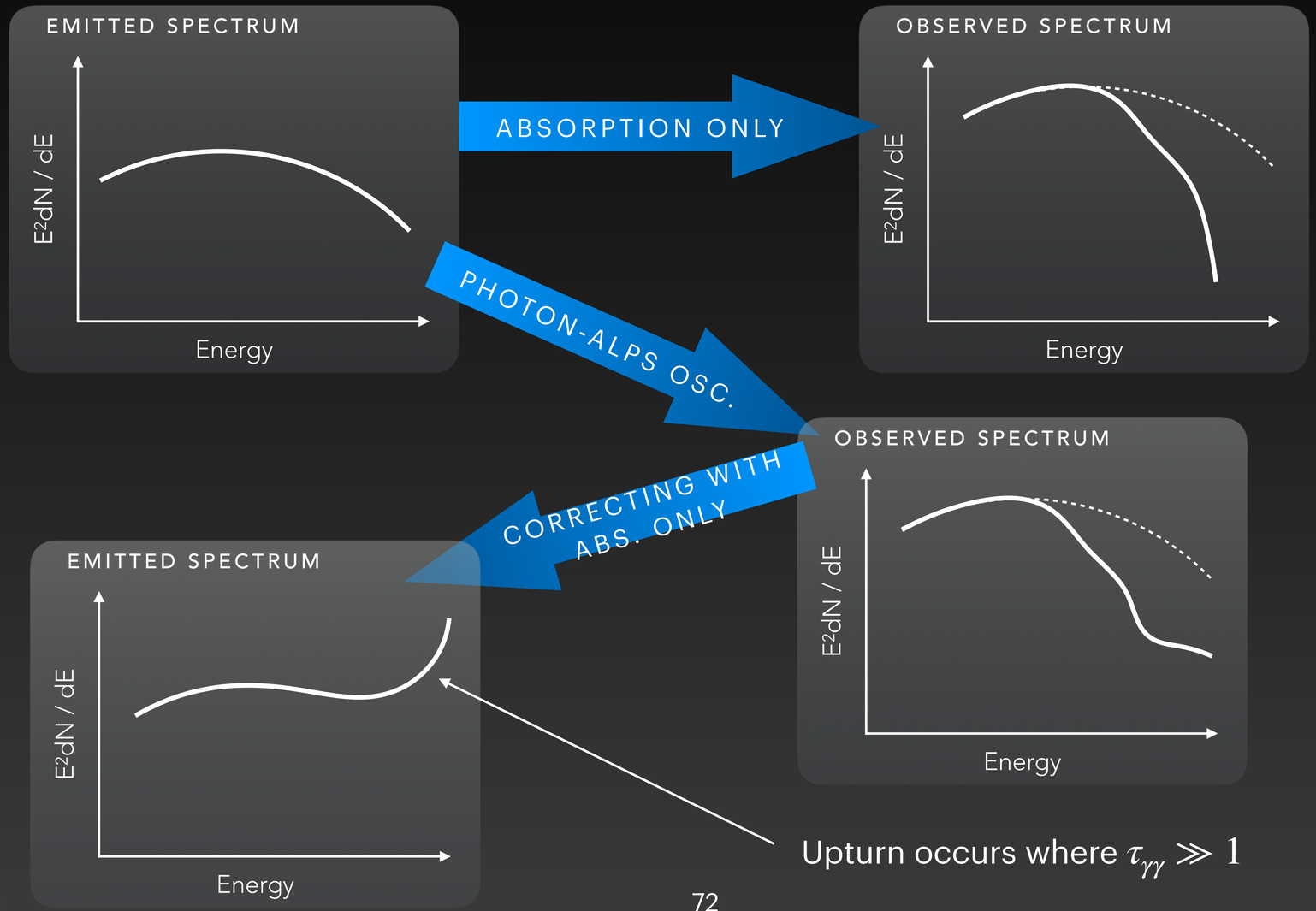
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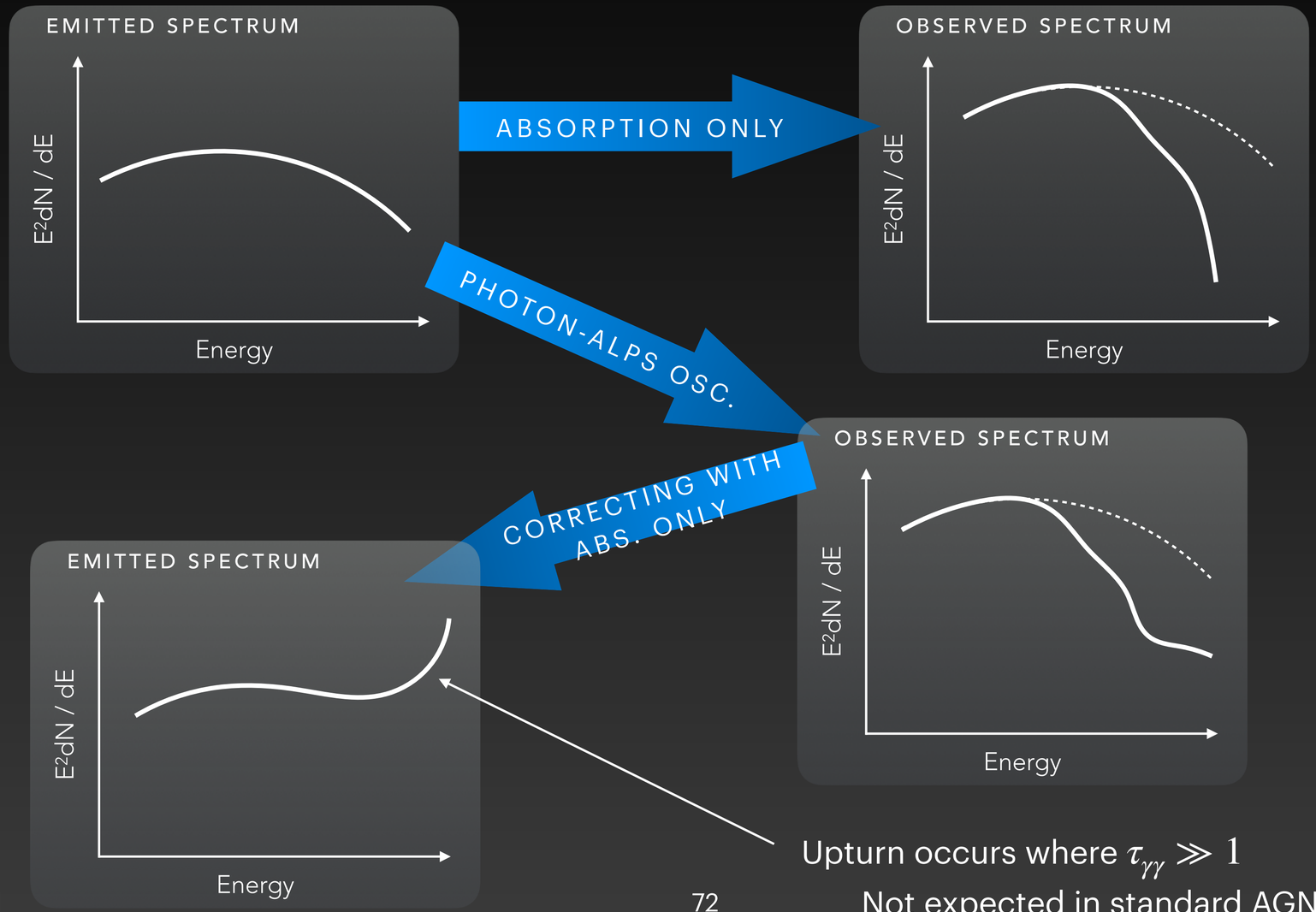
Evidence from AGN observations? — On going discussion



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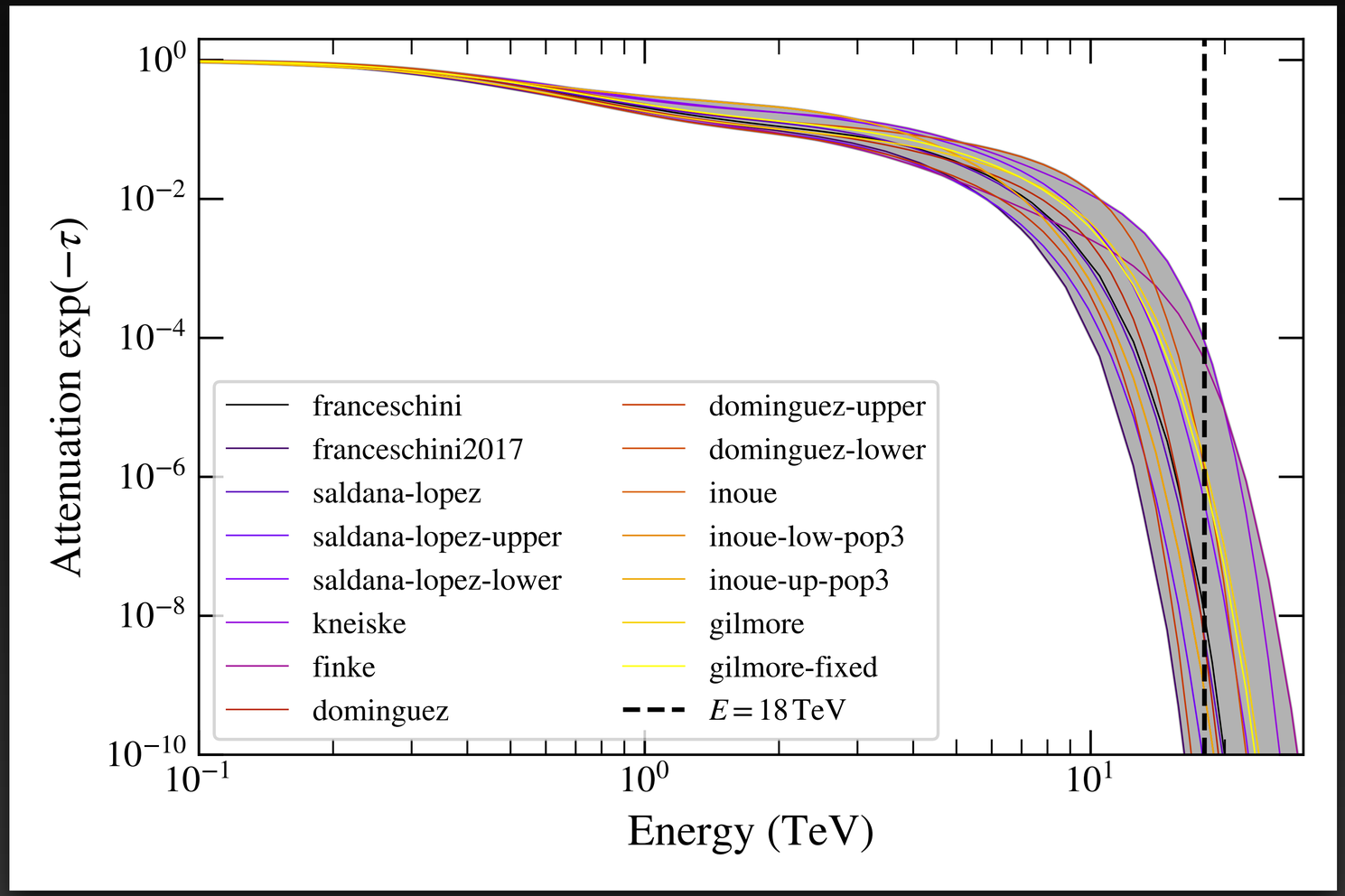
Upturn occurs where $\tau_{\gamma\gamma} \gg 1$

Not expected in standard AGN emission scenarios

[e.g., Biteau & MM 2022, 2202.0052]

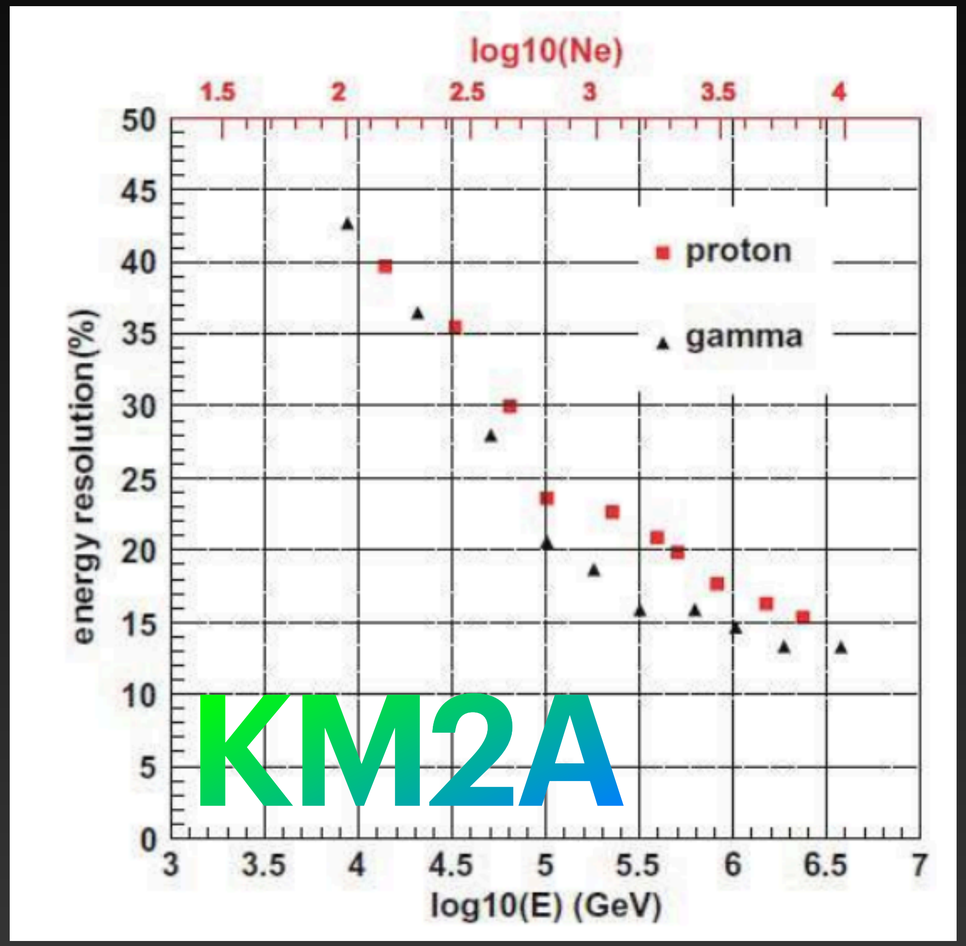
18 TeV photon exceptional!?

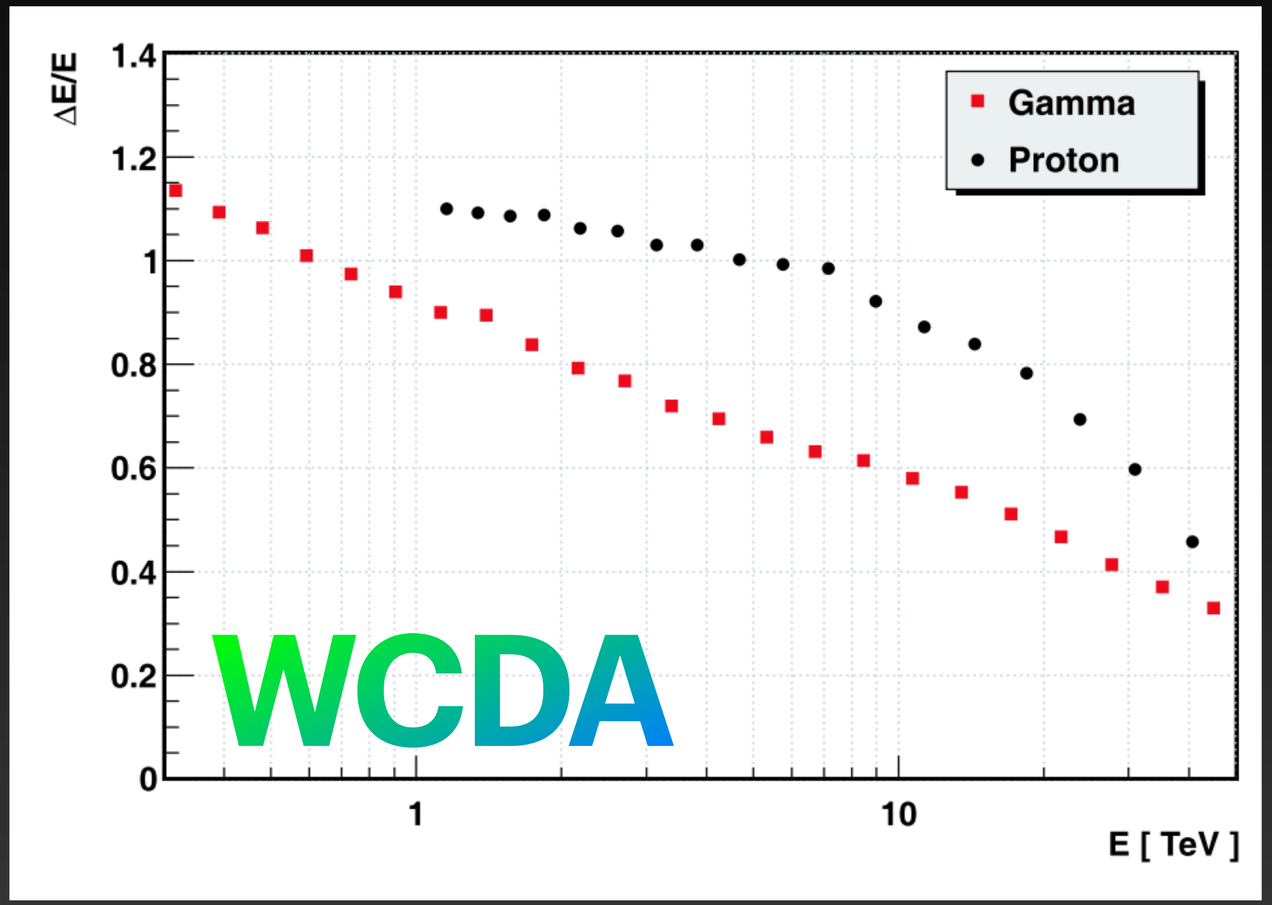
(Considering $z = 0.1505$)



Generated with https://github.com/me-manu/ebltable/

LHAASO Energy resolution

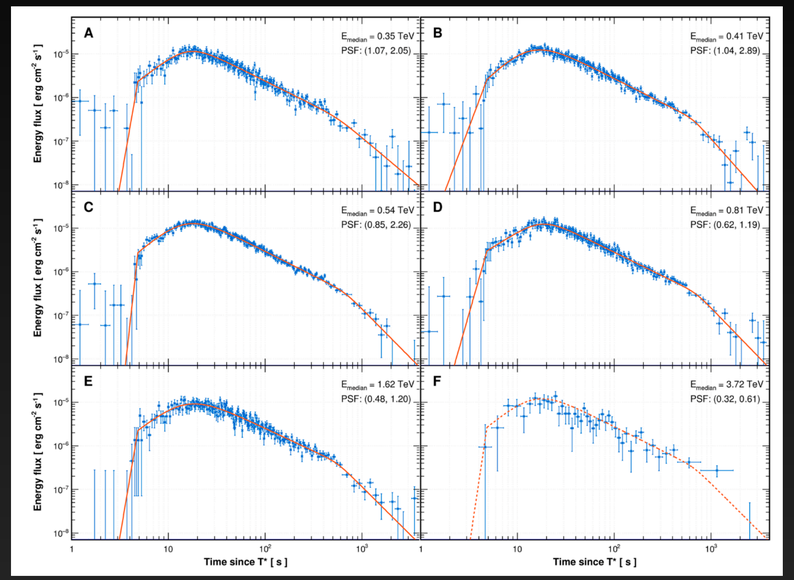


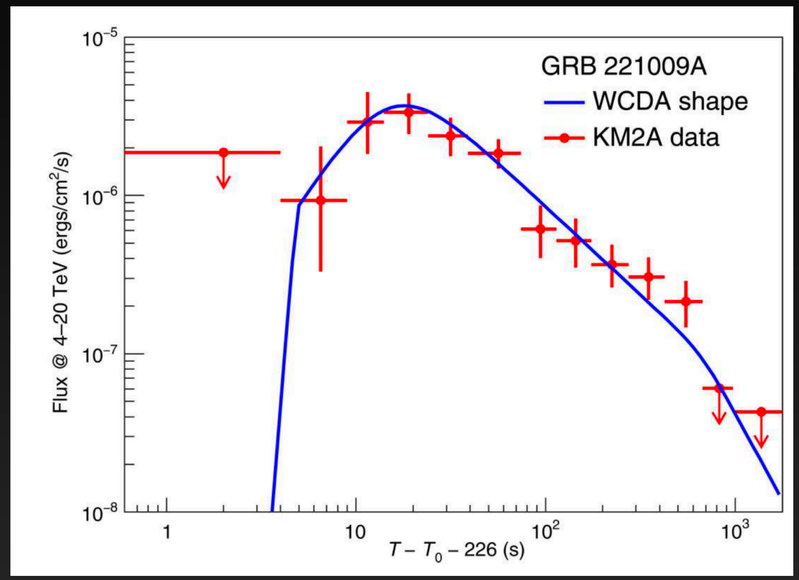


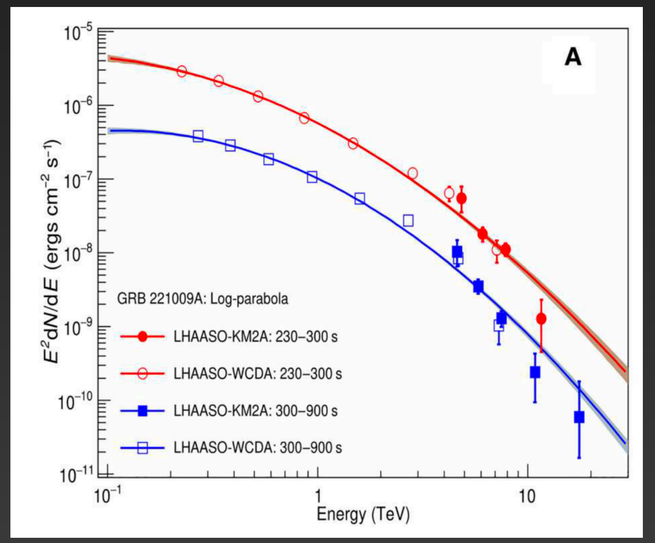
[Ma et al. 2022]

GRB221009A: VHE photons seen with LHAASO

- WCDA: > 64,000 gamma rays above 0.2 TeV
- KM2A: 140 gamma rays between 3 and 13 TeV (first announcement was 18 TeV)







[LHAASO Collaboration Science 2023, Sci. Adv. 2023]

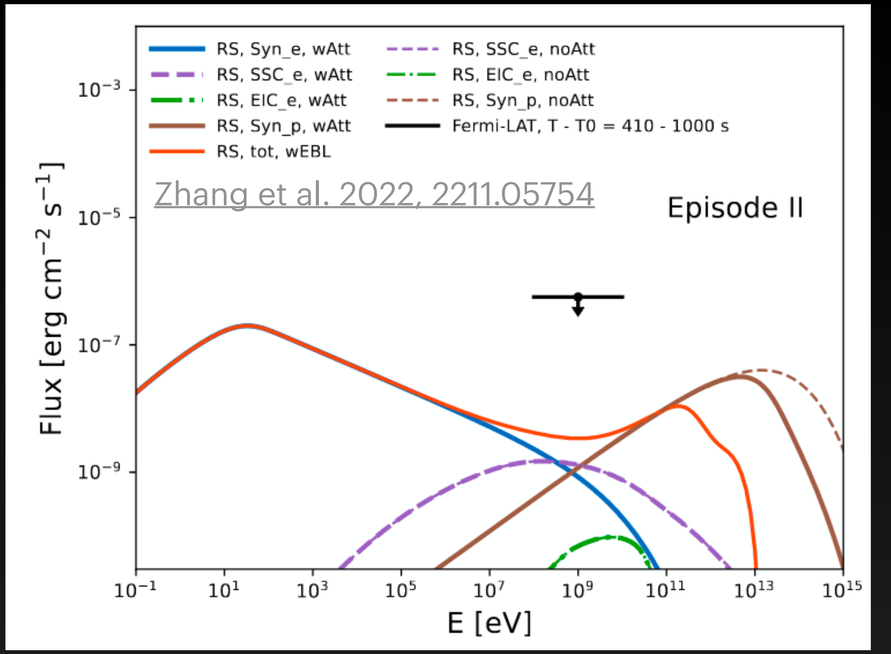
Astrophysical interpretations

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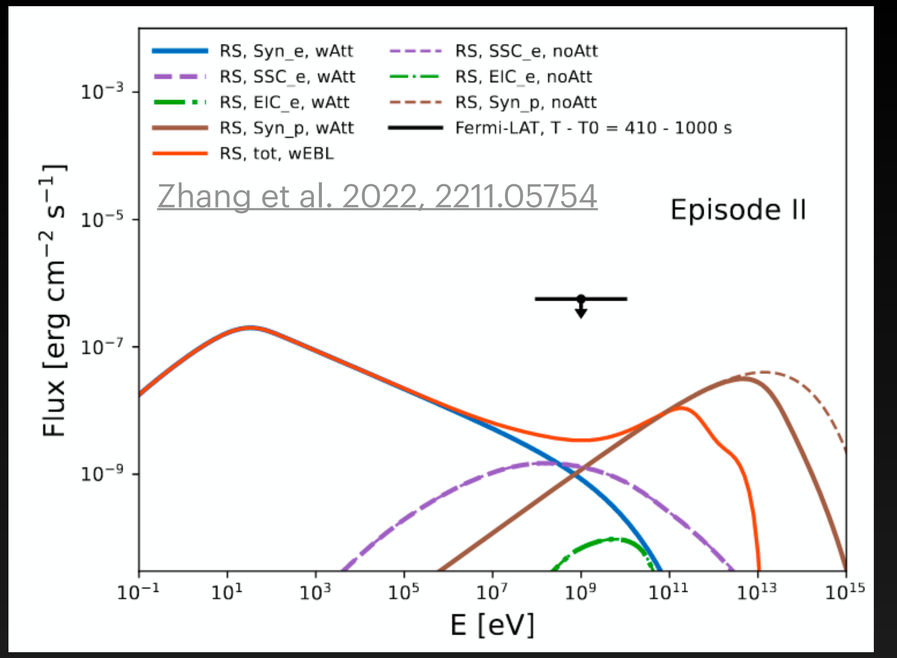
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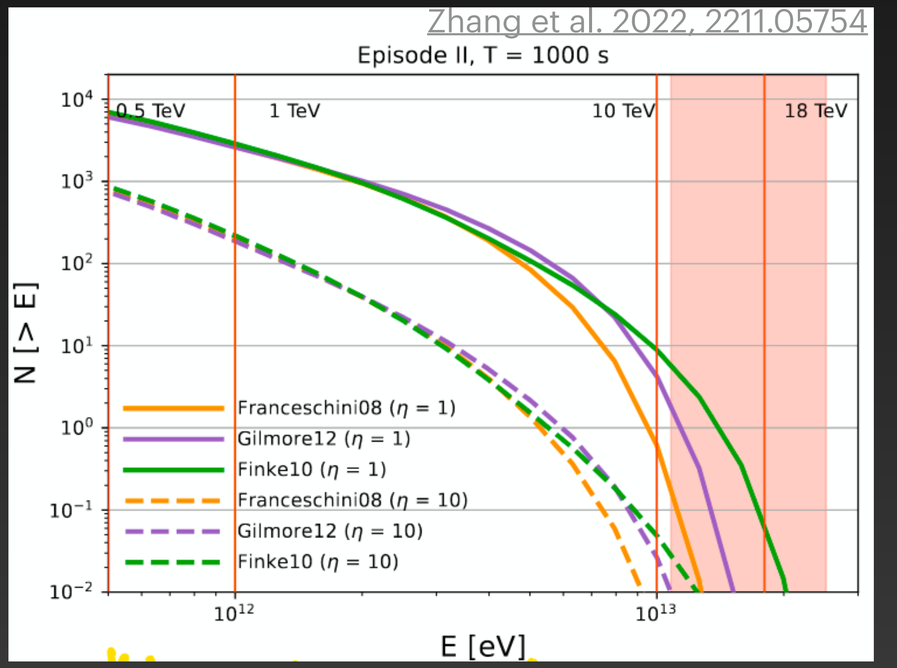
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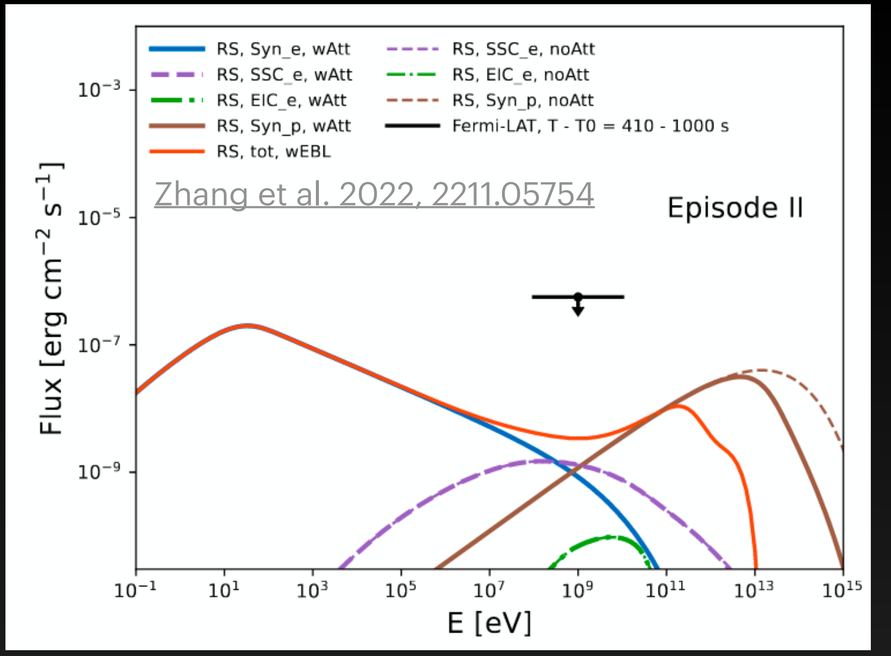
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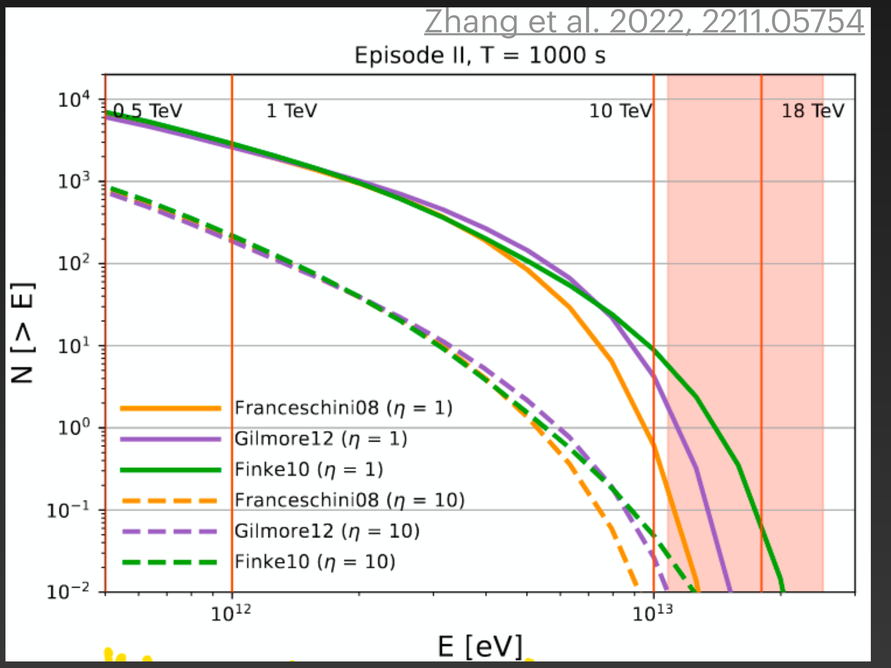




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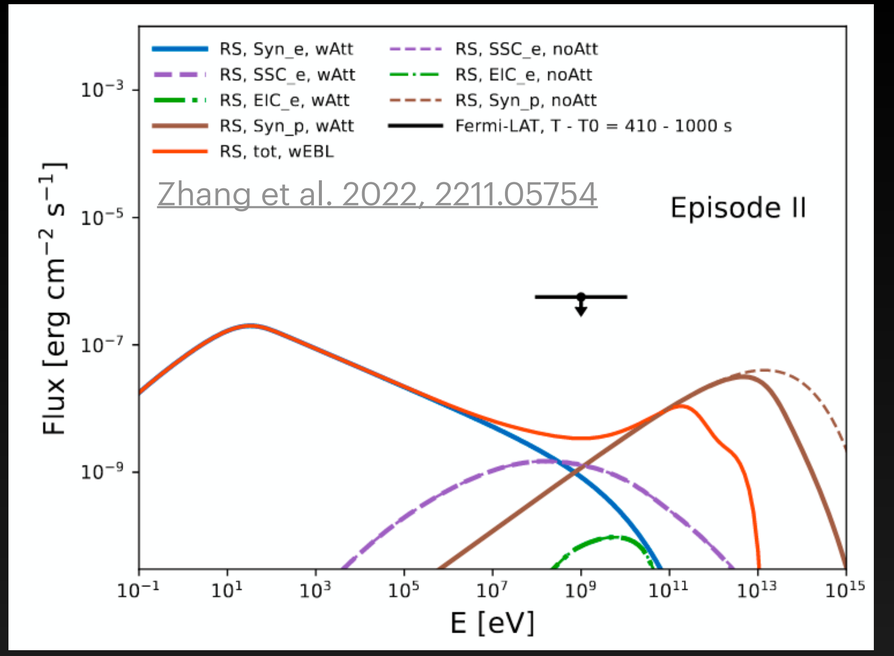
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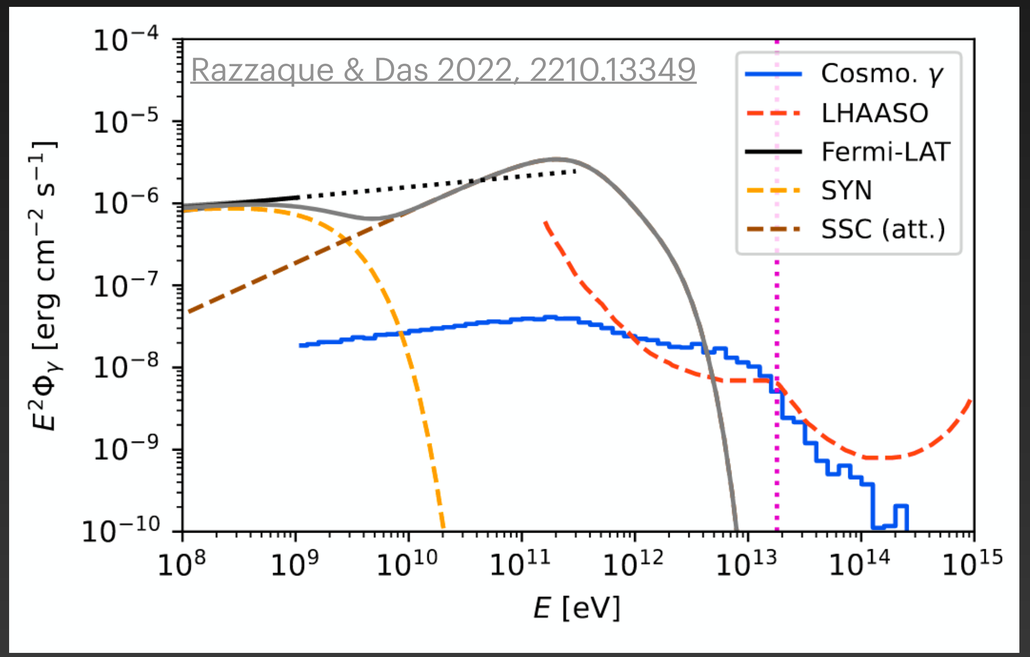




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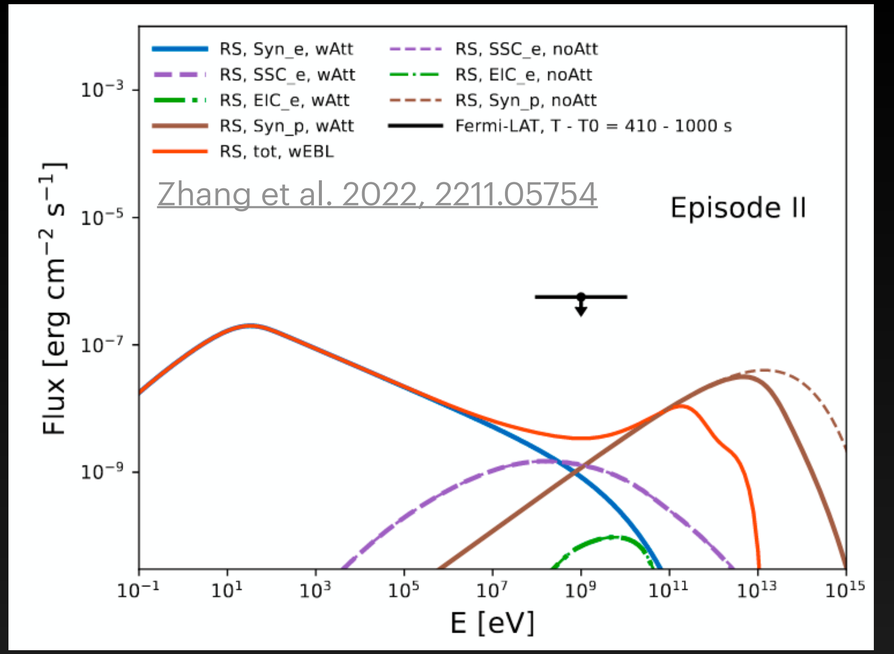
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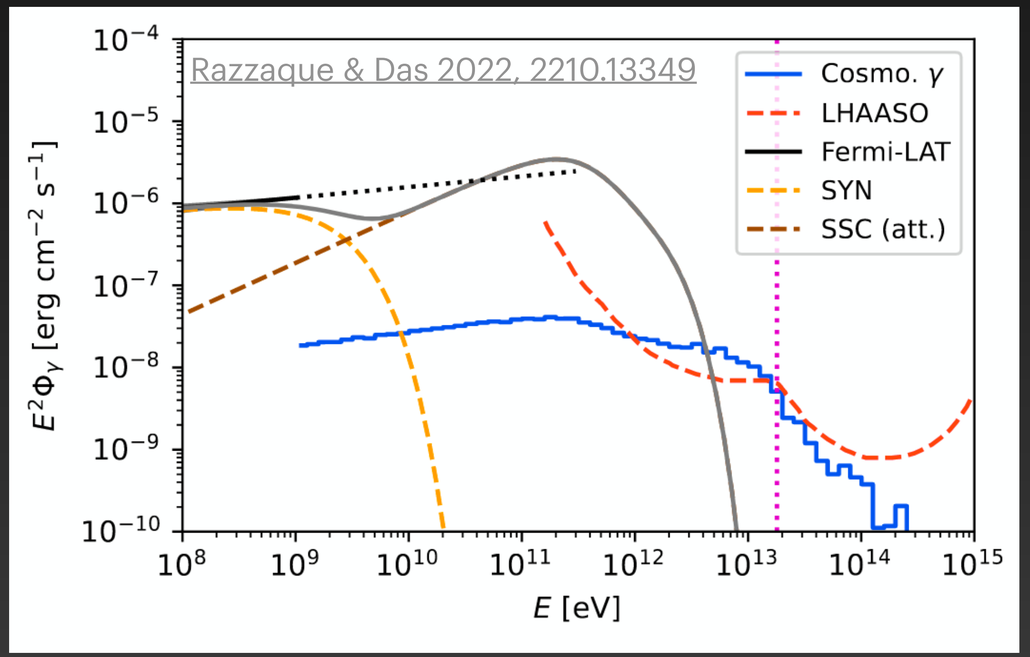




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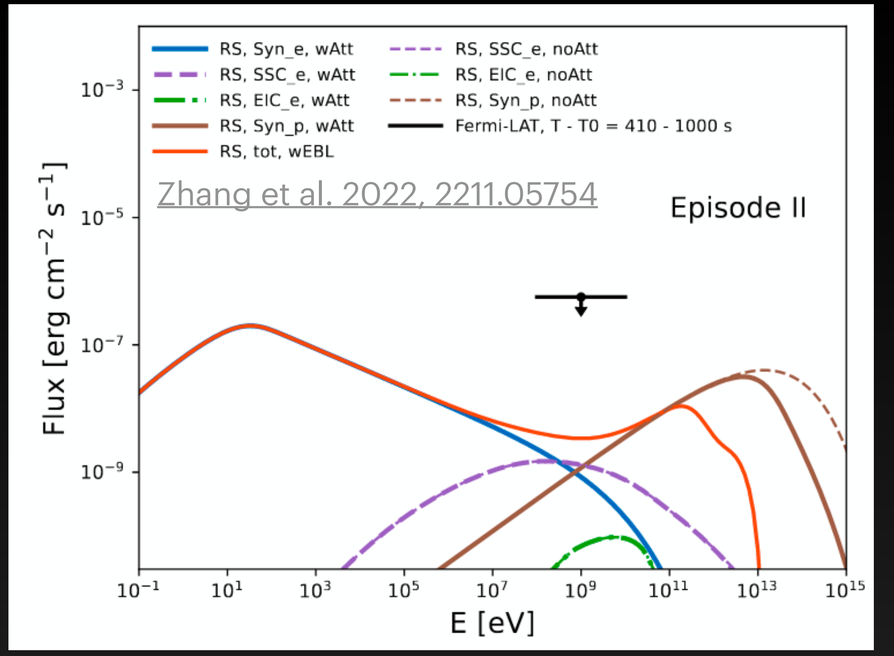
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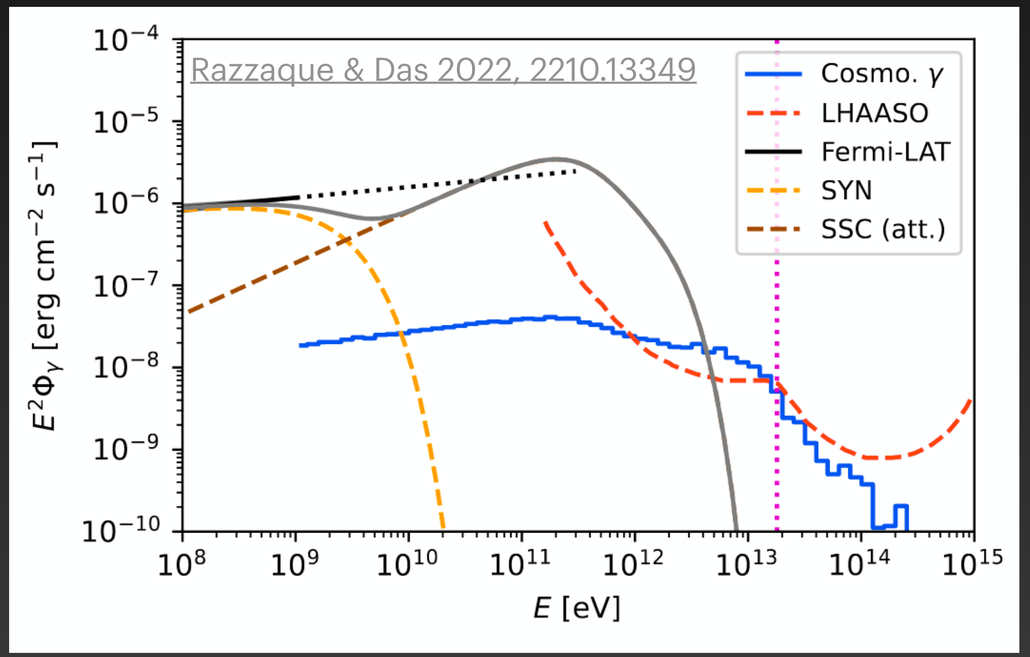




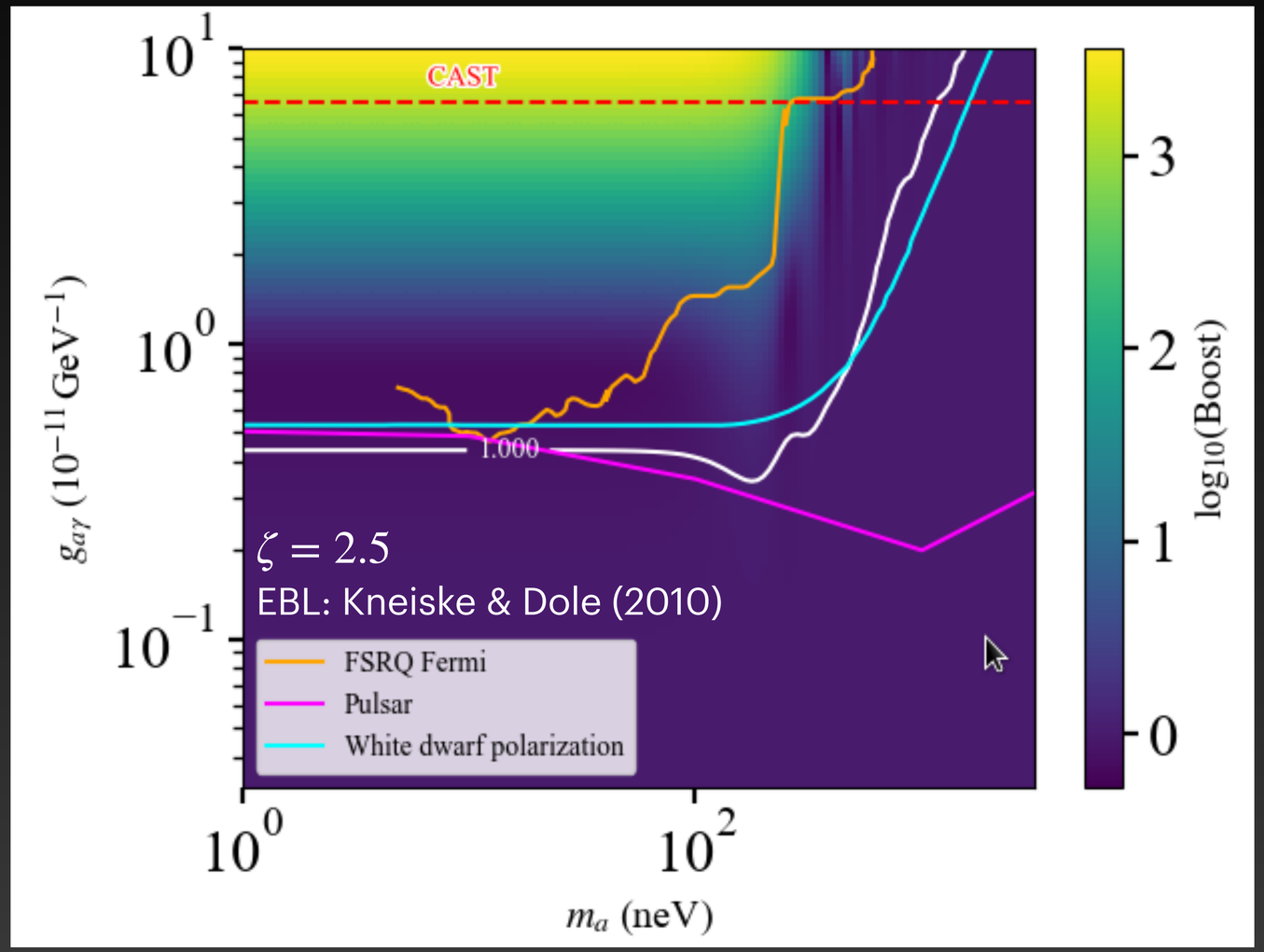
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- Both scenarios consistent with non-detection of neutrinos with IceCube





ALP parameters to boost photon flux



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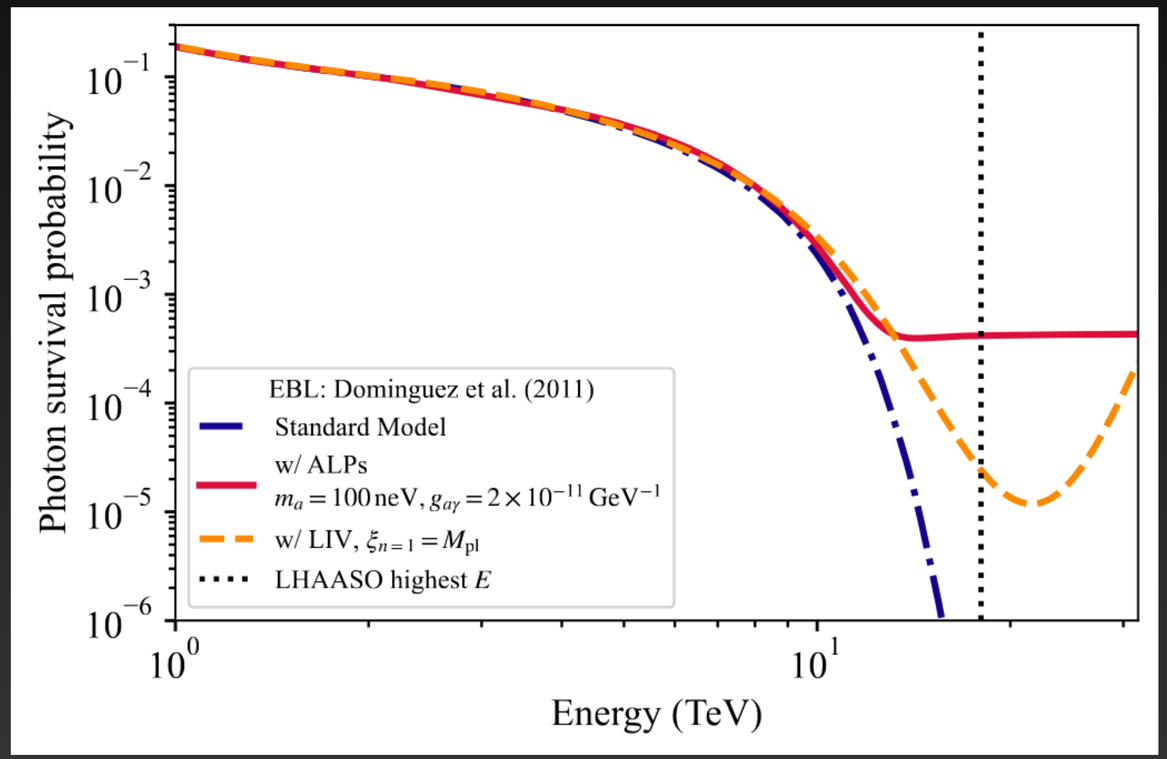
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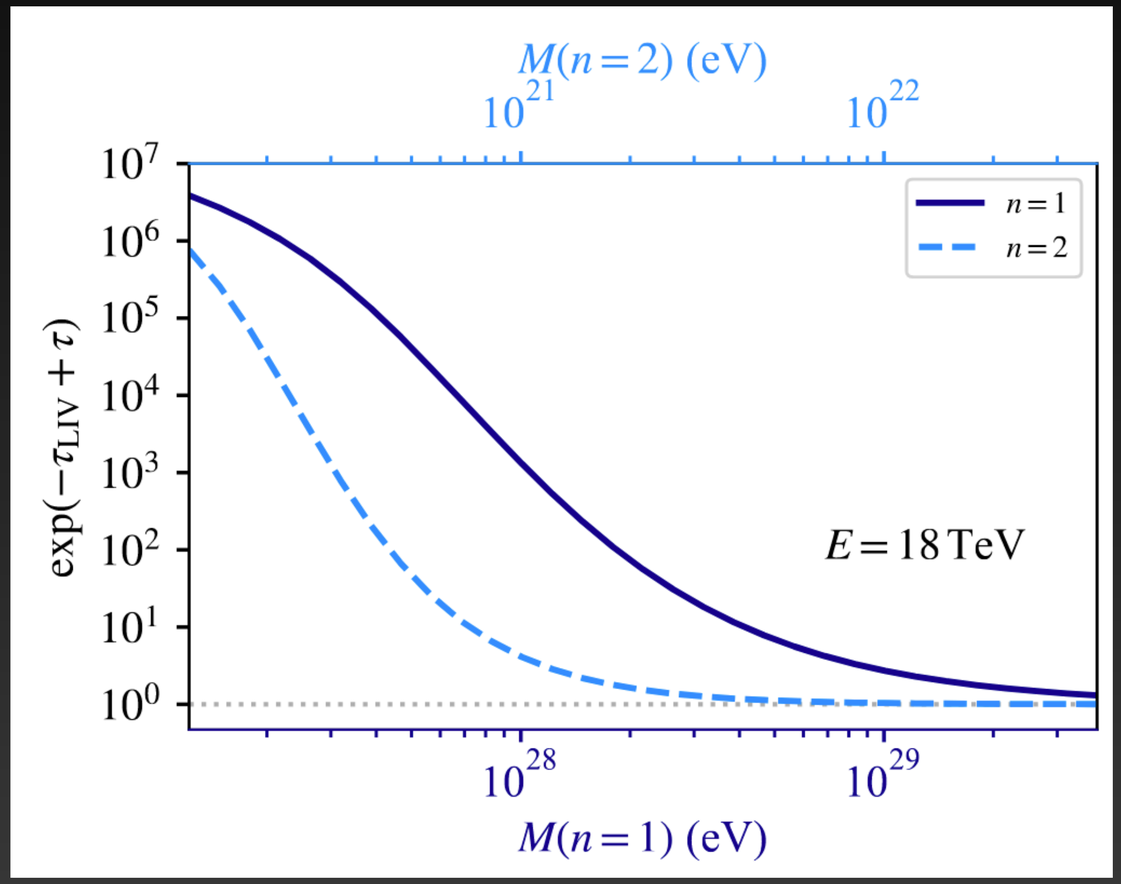


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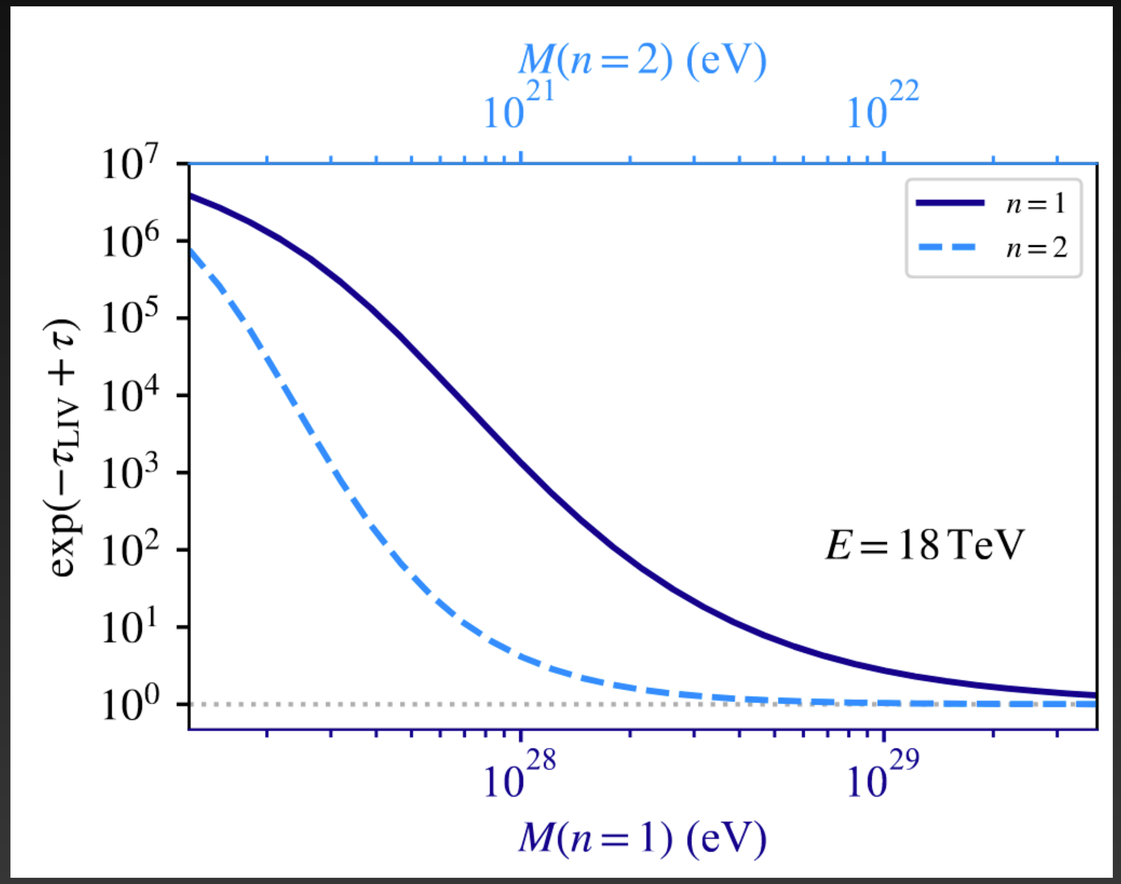


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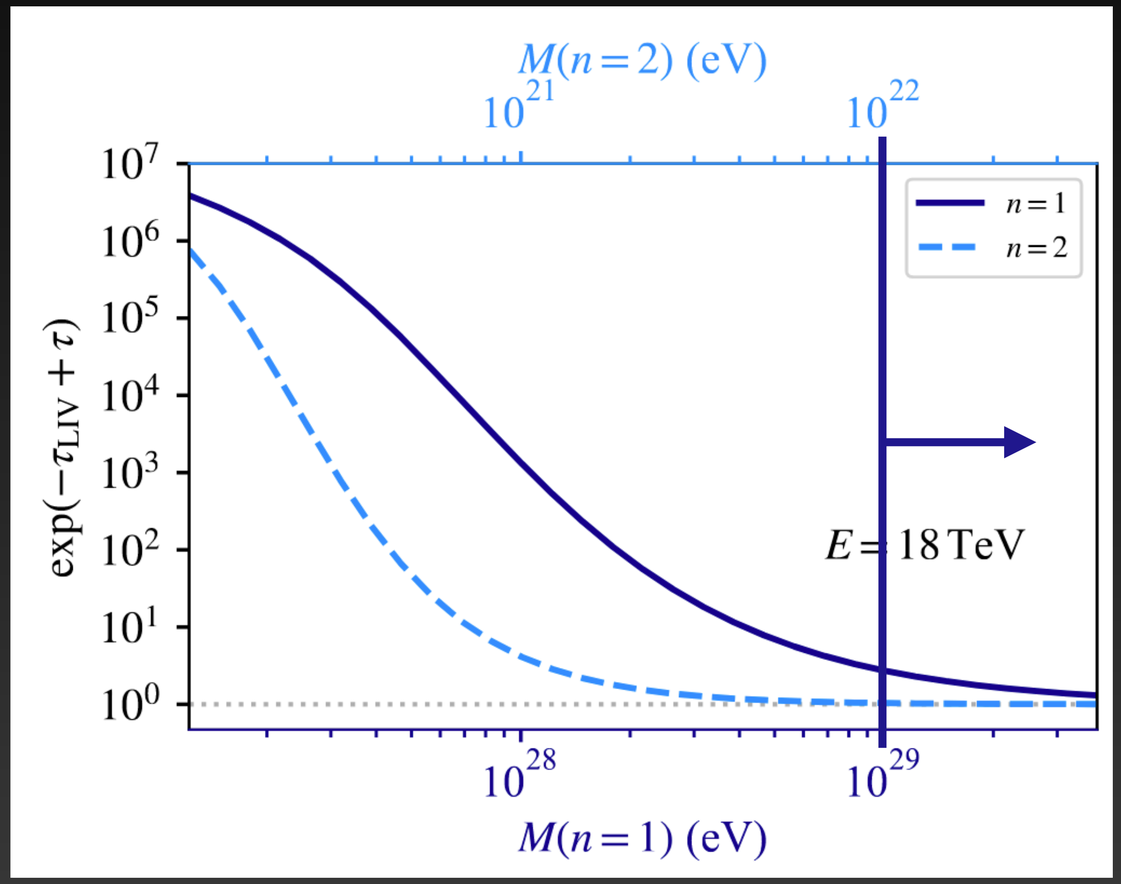


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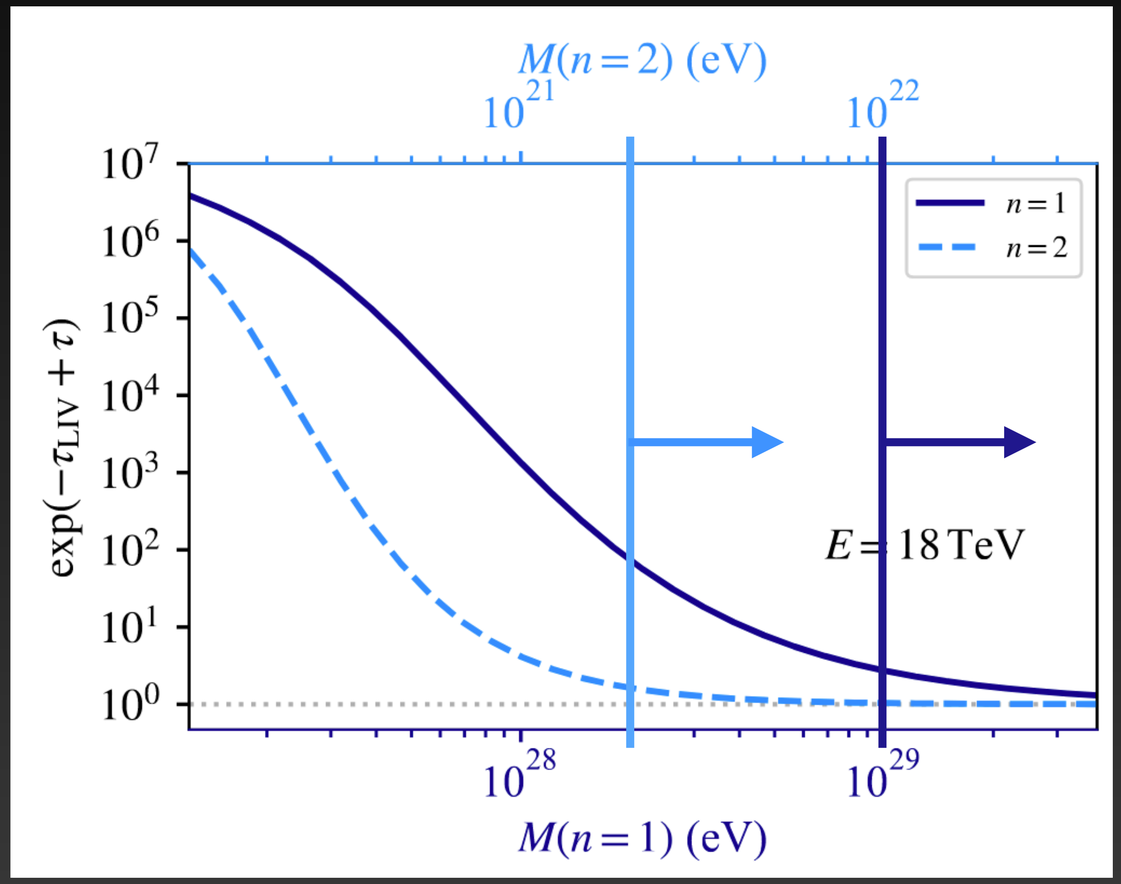


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Fi2010	10.0	6.0	0.9	- (-)	-
Gi2012	13.3	5.4	2×10^{-2}	10.4 (2.6×10^{-7})	12.5 (2.9×10^{-7})
Do2011-	13.5	4.4	1×10^{-2}	11.3 (2.8×10^{-7})	12.9(3.0×10^{-7})
Gi2012f	13.9	5.6	1×10^{-2}	10.1 (2.6×10^{-7})	11.9(2.8×10^{-7})
Fr2008	18.3	6.8	9×10^{-5}	8.4 (2.4×10^{-7})	9.8(2.6×10^{-7})
SL2021	19.1	6.9	4×10^{-5}	8.4 (2.4×10^{-7})	9.7(2.6×10^{-7})
Do2011	19.2	6.1	3×10^{-5}	9.1 (2.5×10^{-7})	10.3(2.7×10^{-7})
Do2011+	27.1	7.8	7×10^{-9}	7.5 (2.1×10^{-7})	8.6(2.4×10^{-7})

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Optimistic scenario

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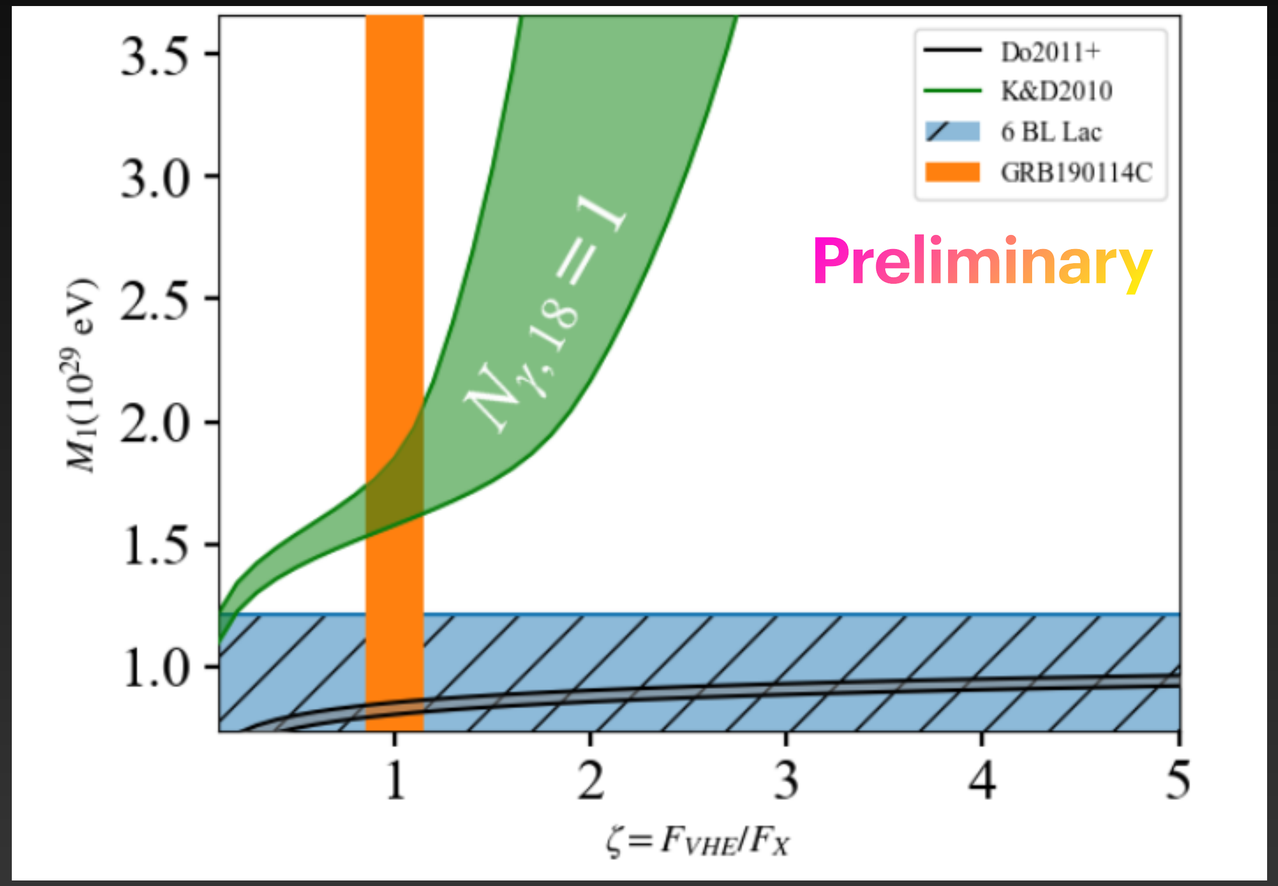
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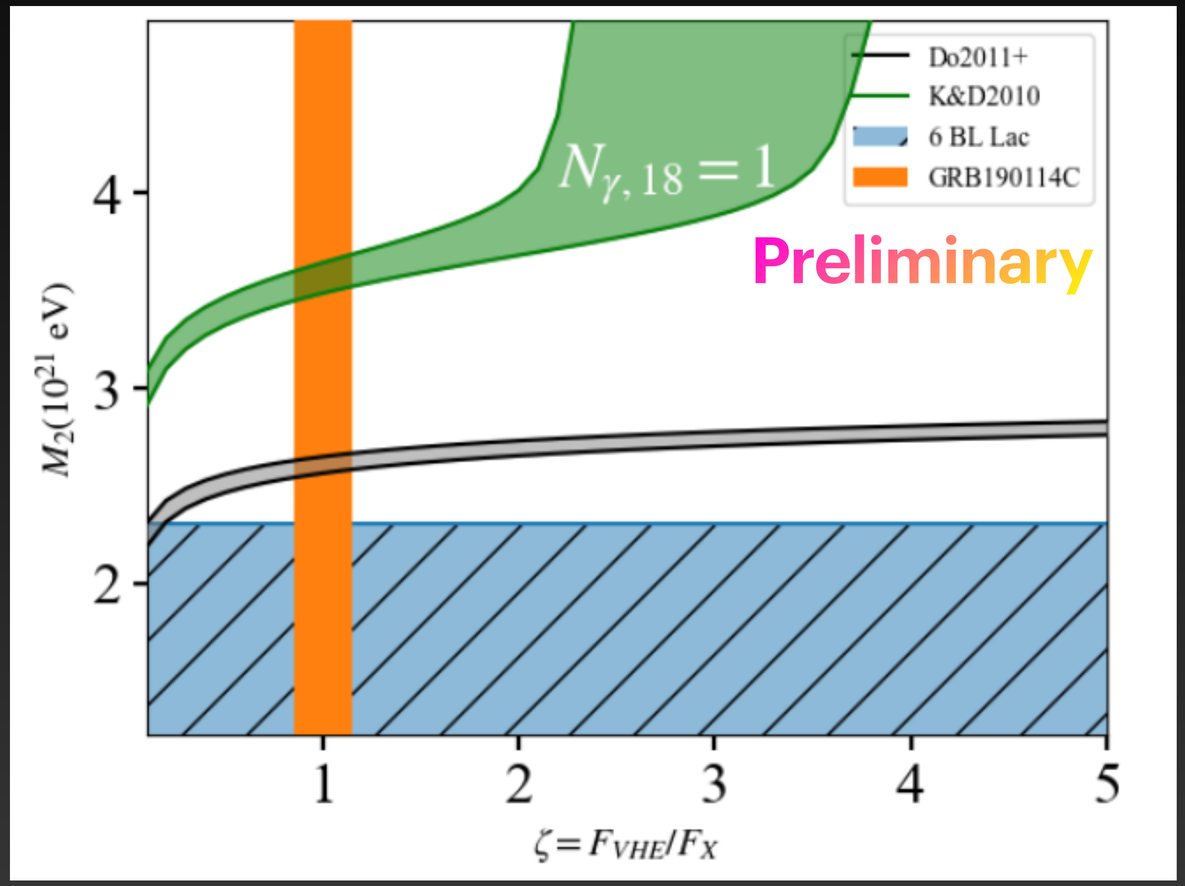
- But strongly suppressed by QED birefringence!

LIV interpretation

Linear

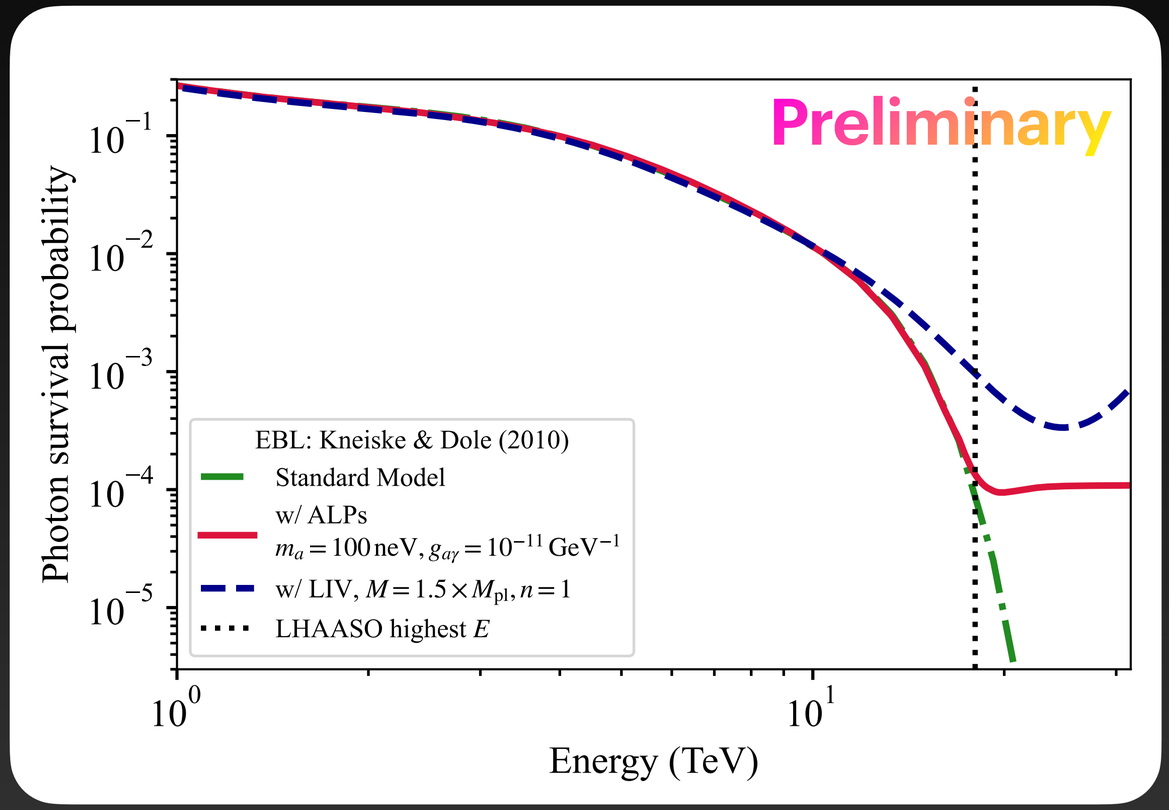


Quadratic



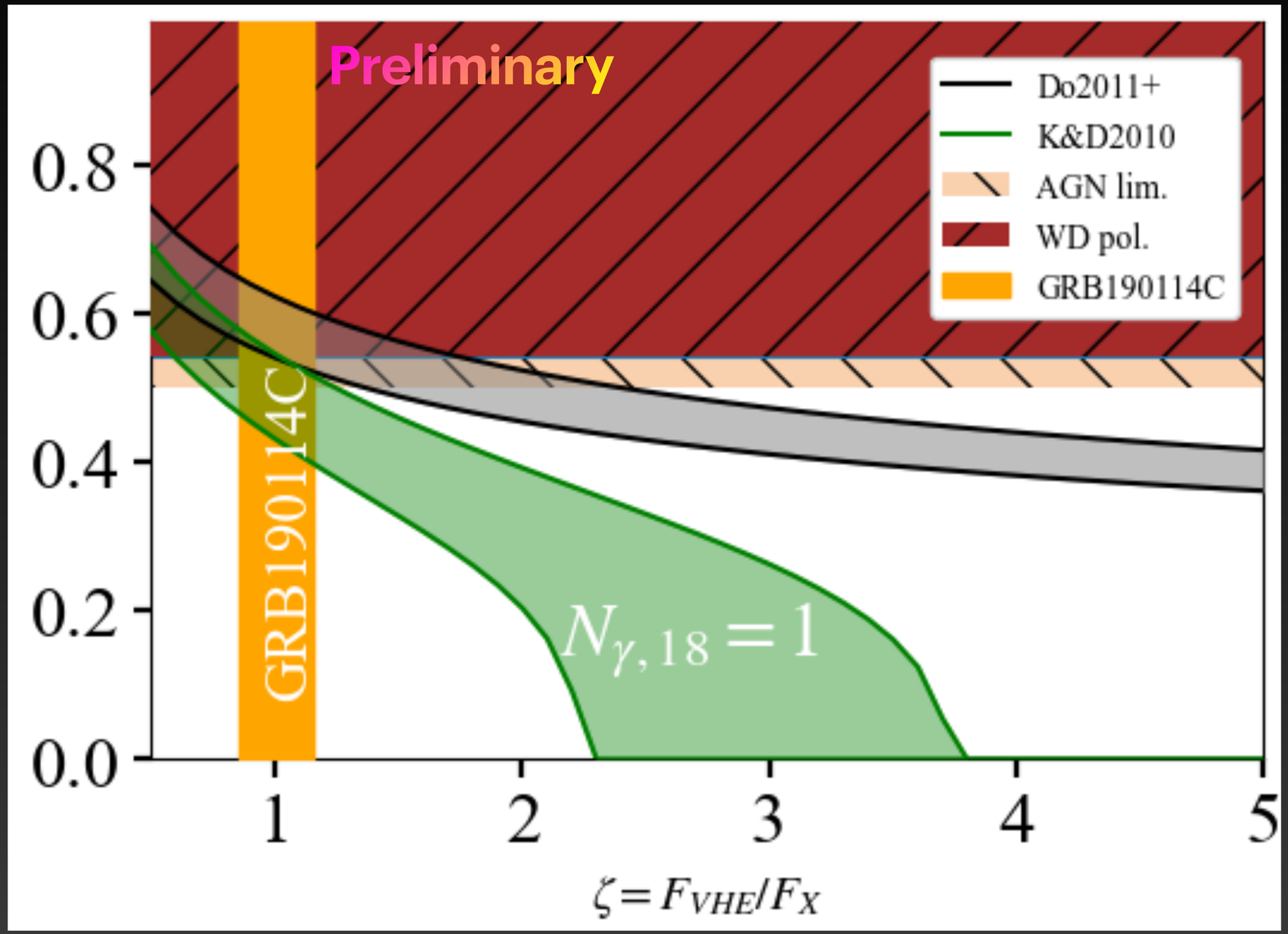
ALP interpretation

- Assumption: photon-ALP conversion in host galaxy & in Milky Way
- Host galaxy: B = 1μG coherent over 10kpc

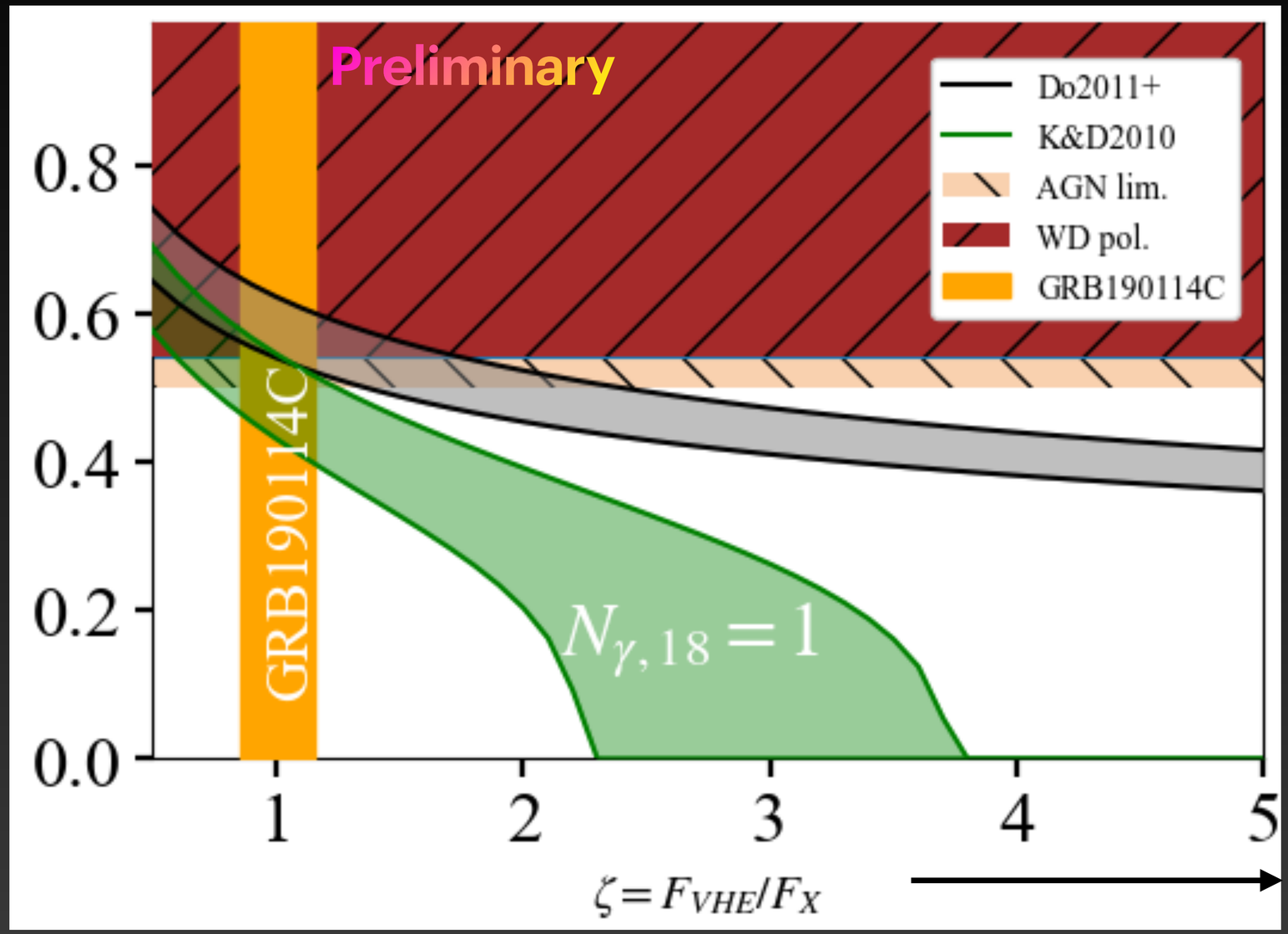


[Baktash, Horns, MM 2022, 2210.07172; Troitsky 2022, 2210.09250; Galanti et al. 2022, 2211.06935 2210.05659; Carenza & Marsh 2022, 2211.02010; Zhang & Ma 2022, 2210.13120

ALP scenario still viable?

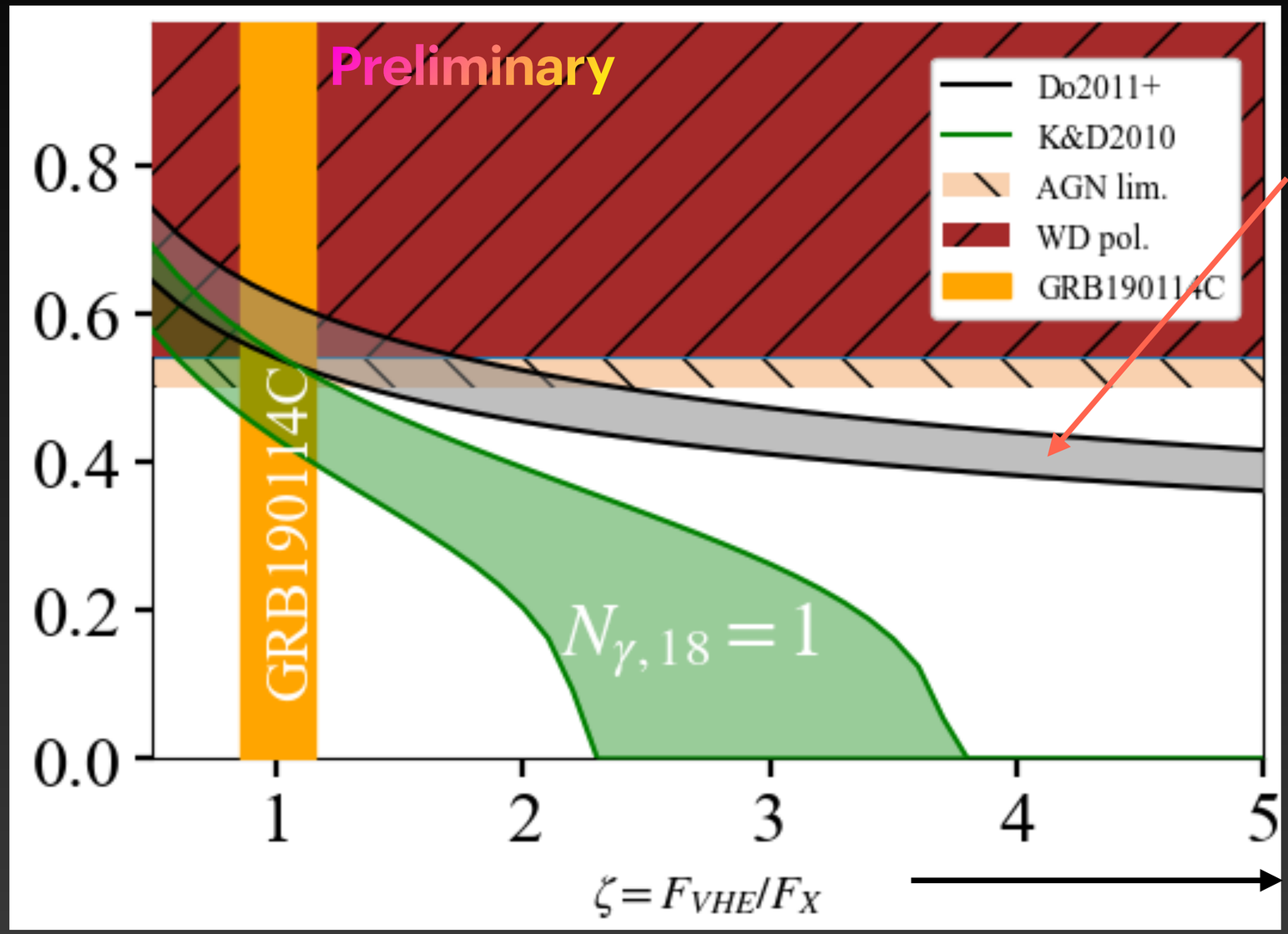


ALP scenario still viable?



More gamma-ray flux
(but $\zeta > 1$ very hard
to achieve in models)

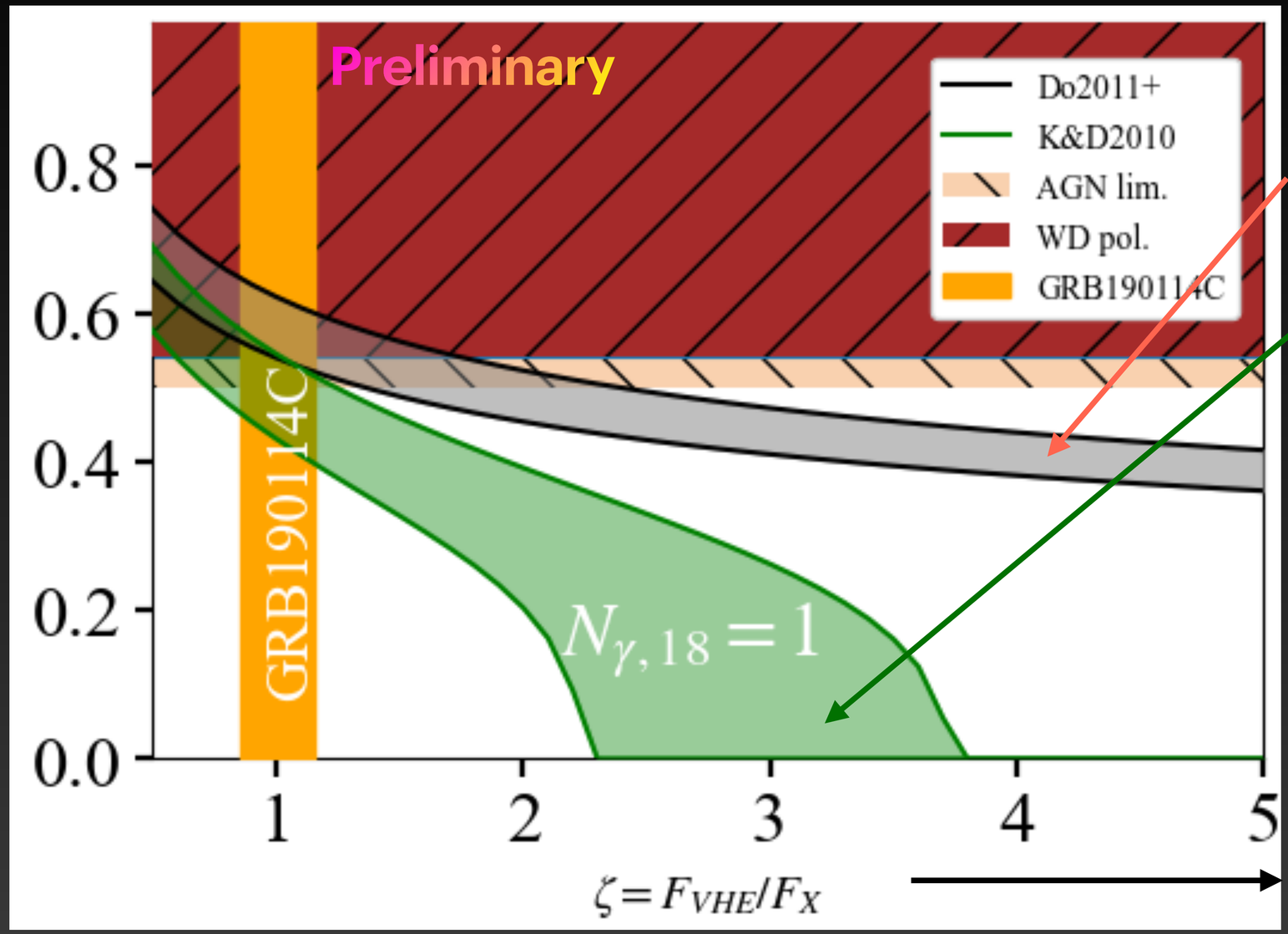
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Max absorption

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ALP scenario still viable?



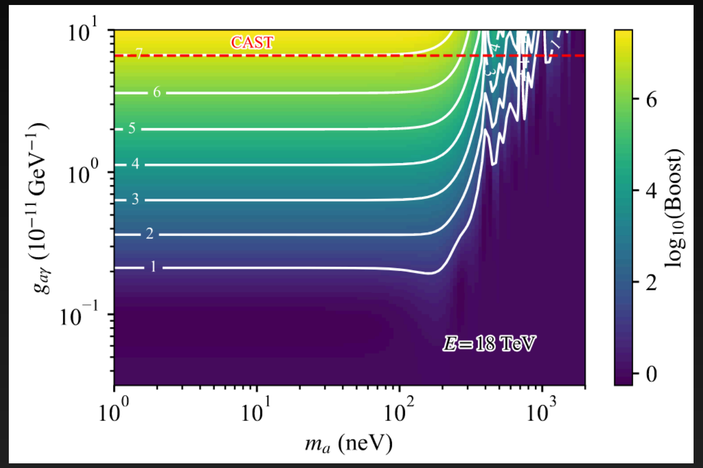
Max absorption

Min absorption

More gamma-ray flux

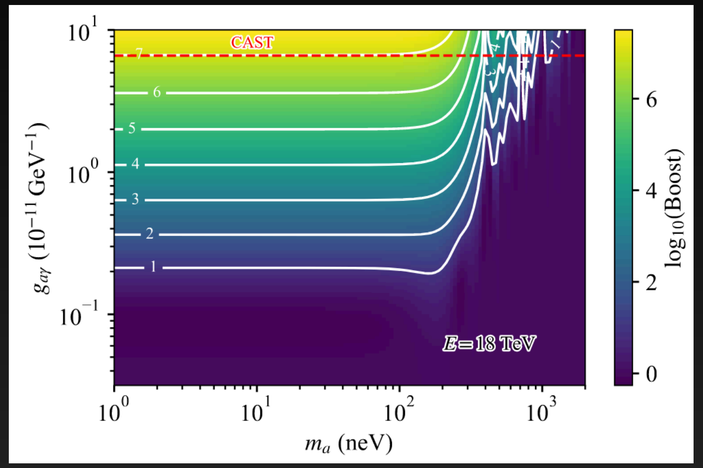
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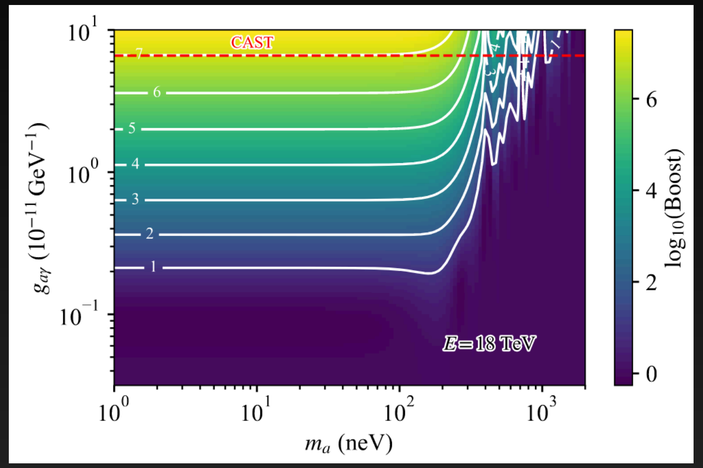
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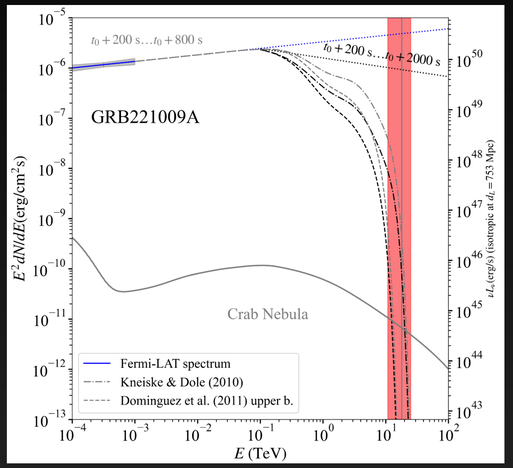
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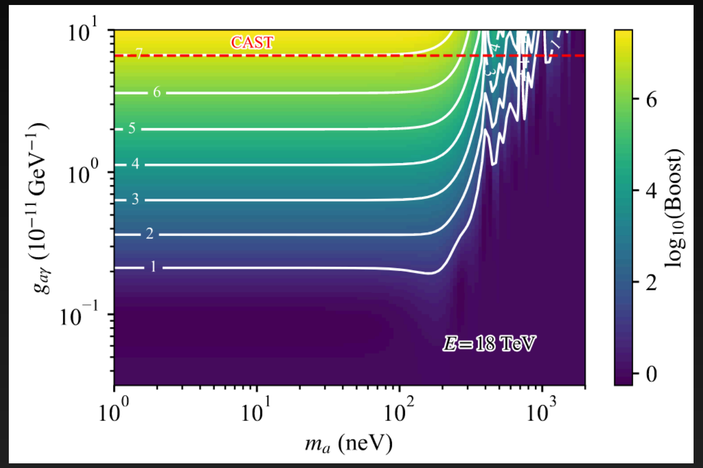
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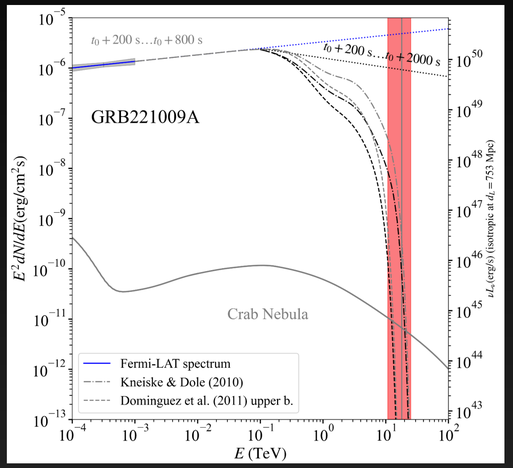




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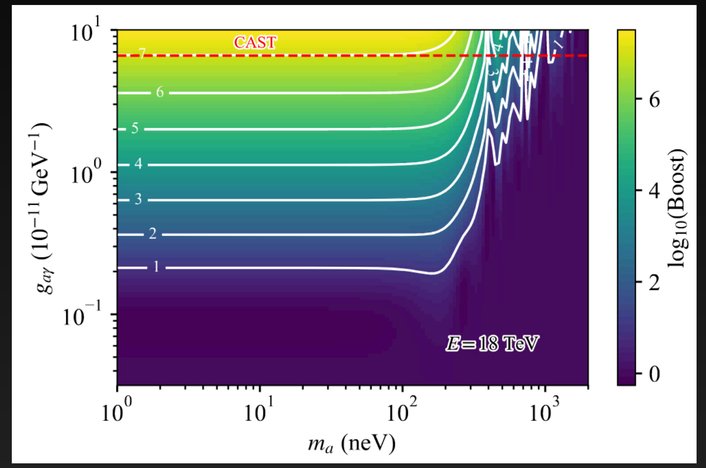


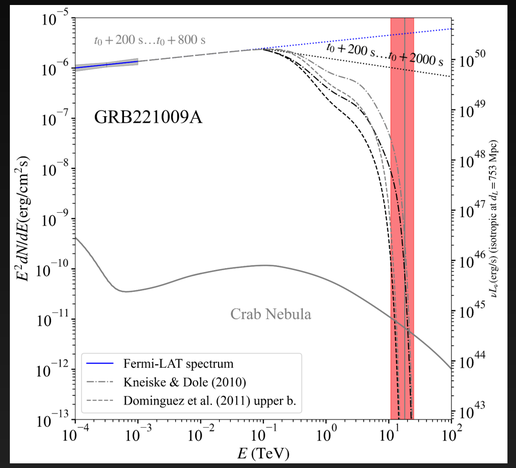
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EBL Model	τ_{18}	τ_{10}	$N_{\gamma,18}$	$g_{a\gamma}$
K&D2010	9.4	4.5	1	-
Fi2010	10.0	6.0	0.9	-
Gi2012	13.3	5.4	2×10^{-2}	0.58
Do2011-	13.5	4.4	1×10^{-2}	0.58
Gi2012f	13.9	5.6	1×10^{-2}	0.58
Fr2008	18.3	6.8	9×10^{-5}	0.59
SL2021	19.1	6.9	4×10^{-5}	0.59
Do2011	19.2	6.1	3×10^{-5}	0.59
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[Baktash, Horns, MM 2022, 2210.07172]

ALP interpretation





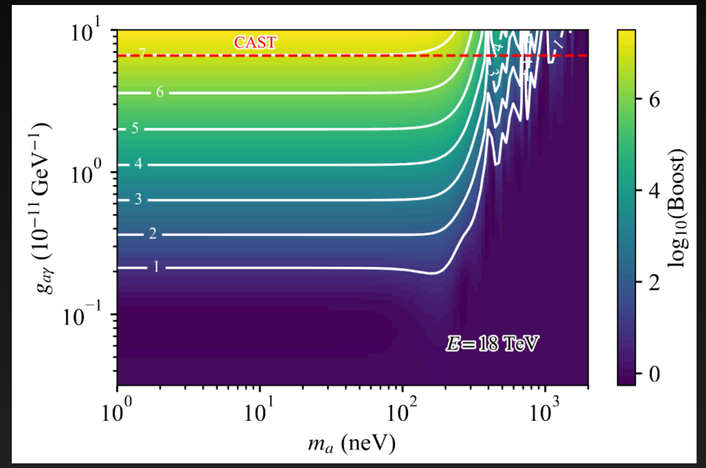
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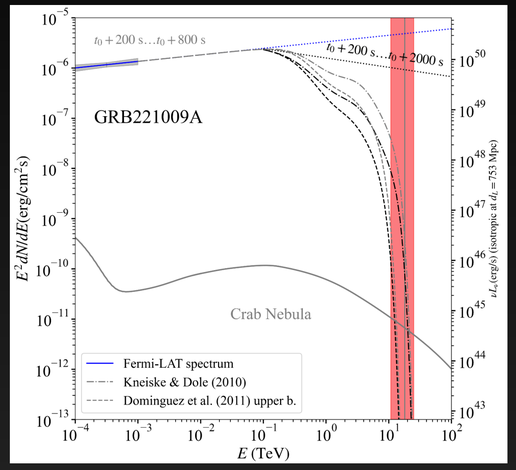
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Realistic scenario

[Baktash, Horns, MM 2022, 2210.07172]

ALP interpretation





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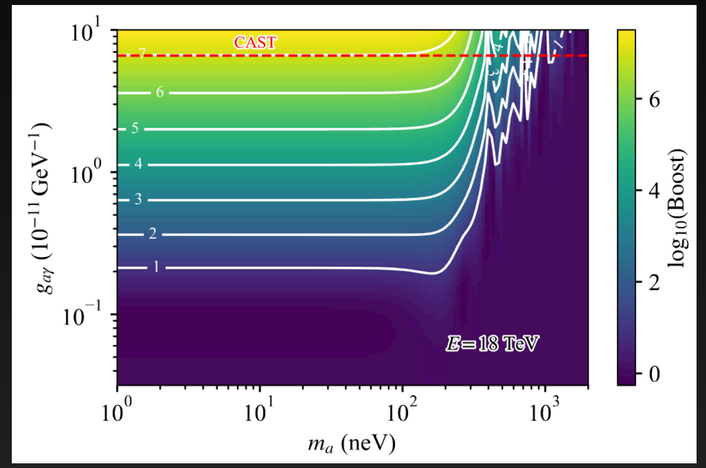
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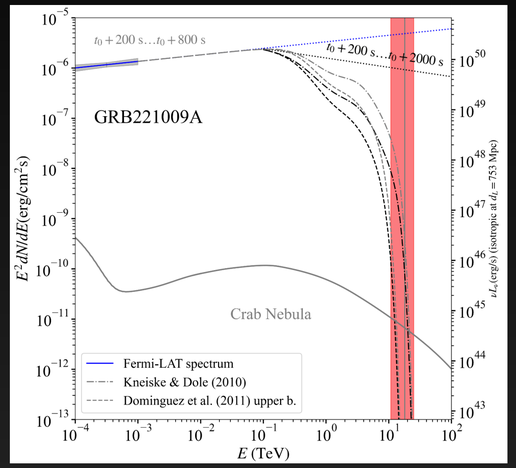
Optimistic scenario

[Baktash, Horns, MM 2022, 2210.07172]

ALP interpretation

- Required $m_a, g_{a\gamma}$ values in ~tension with current constraints





=

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Ingredients to the EBL: stars



$$\mathscr{E}_\nu(z) = f_{\rm esc}(\lambda, z) \int_z^{z_{\rm max}} L_\nu(t_\star(z, z')) \; \psi(z') \left| \frac{dt}{dz'} \right| dz'$$

-

[e.g. Finke et al. 2022]

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Photons escaping dust absorption

Luminosity of stellar population of age $t_\star$

-

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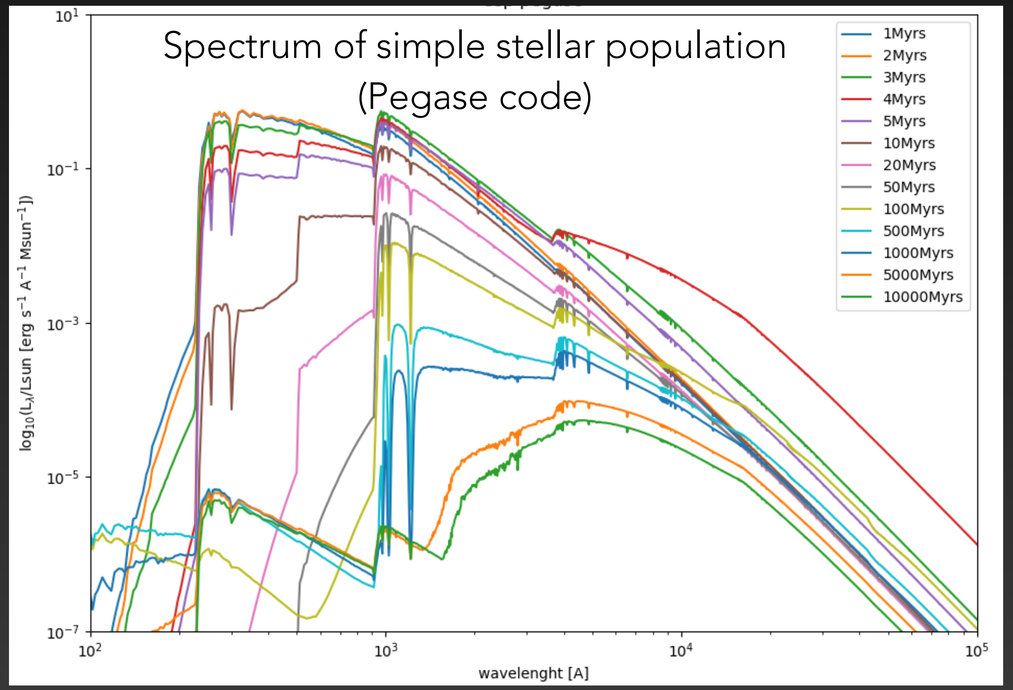


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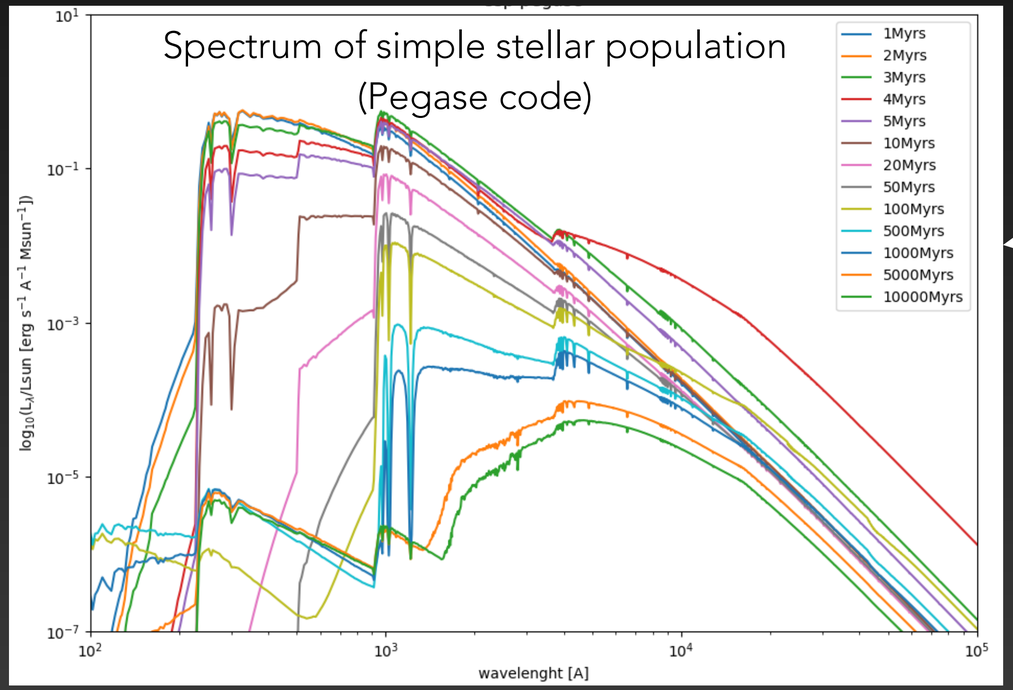


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Initial mass function

[e.g. Finke et al. 2022]

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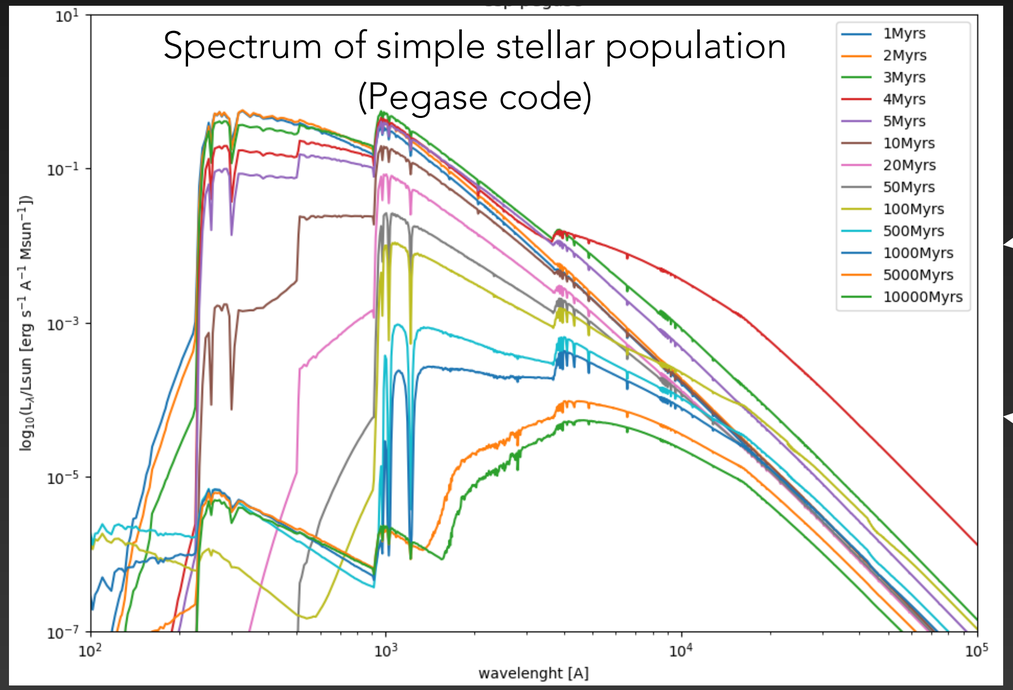


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Photons escaping dust absorption

Luminosity of stellar population of age $t_\star$

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Initial mass function

Stellar metallicity

[e.g. Finke et al. 2022]

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Photons escaping dust absorption

Luminosity of stellar population of age $t_\star$

-

$$t_\star(z, z') = \int_z^{z'} \left| \frac{dt}{dz''} \right| dz''$$

Age of stellar population

[e.g. Finke et al. 2022]

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Photons escaping dust absorption

Luminosity of stellar population of age $t_\star$

Cosmic star formation rate density

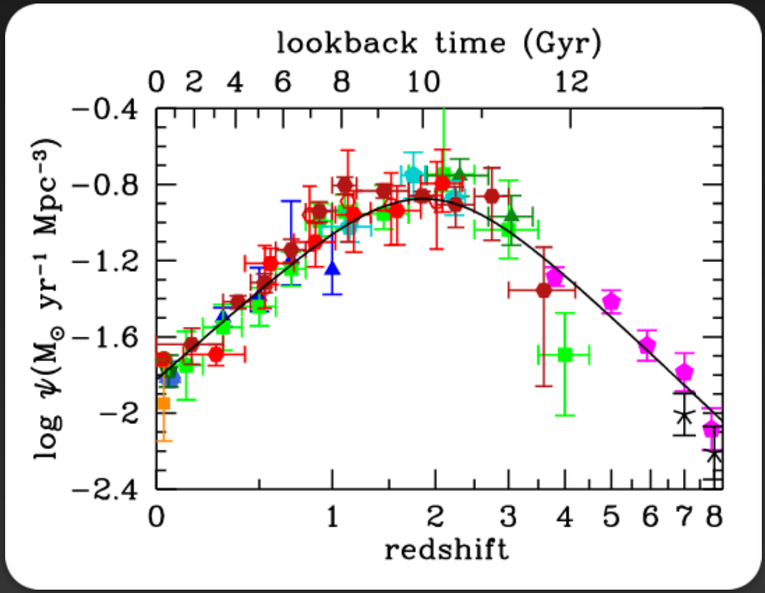
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[Madau & Dickinson 2014]

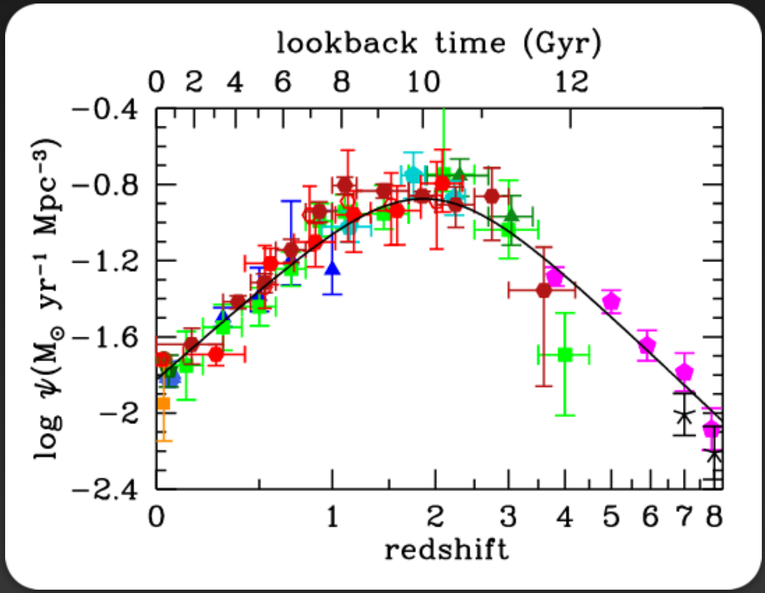
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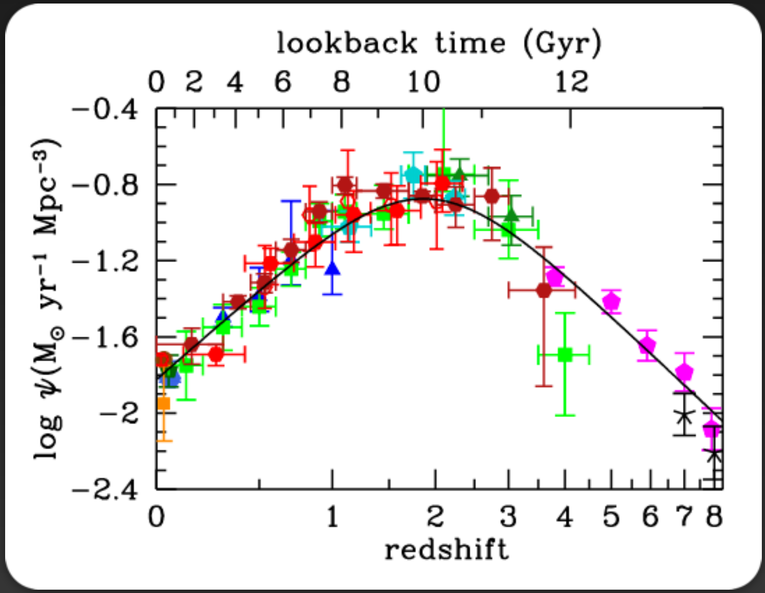
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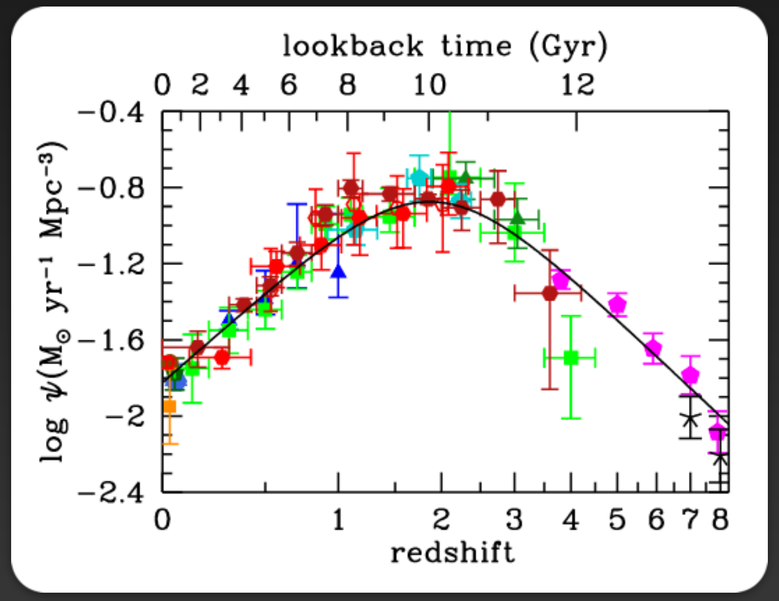
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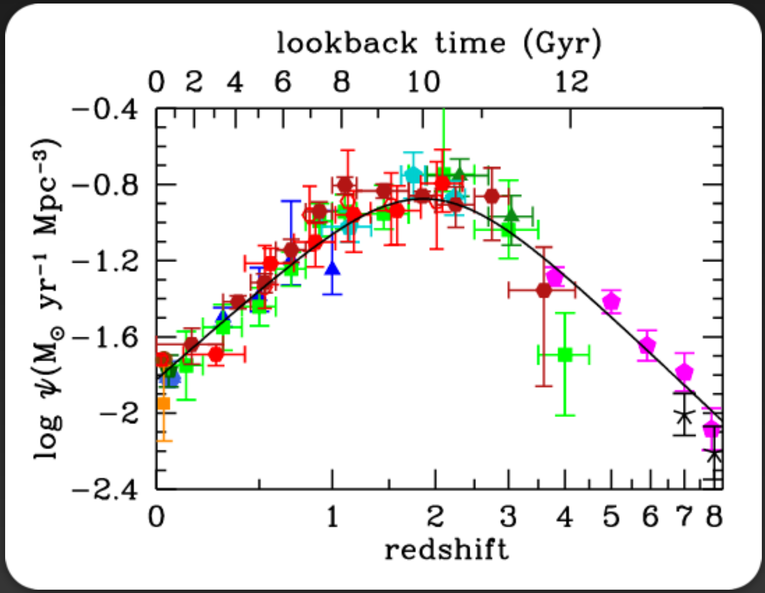
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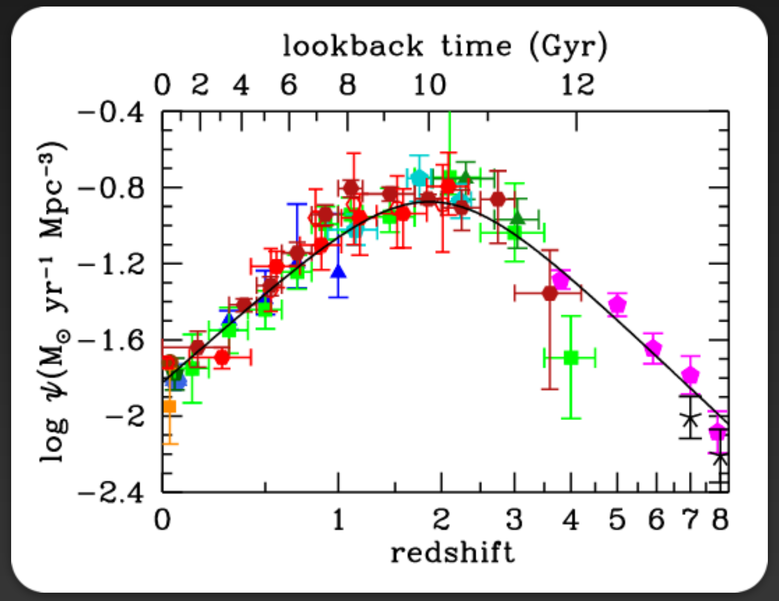
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Axion electrodynamics

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Axion electrodynamics

- Including the axion-photon interaction and axion kinetic terms in the Lagrangian for electromagnetism yields

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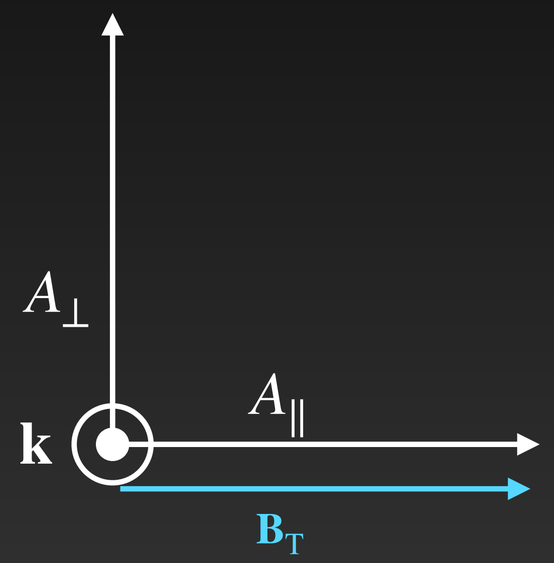
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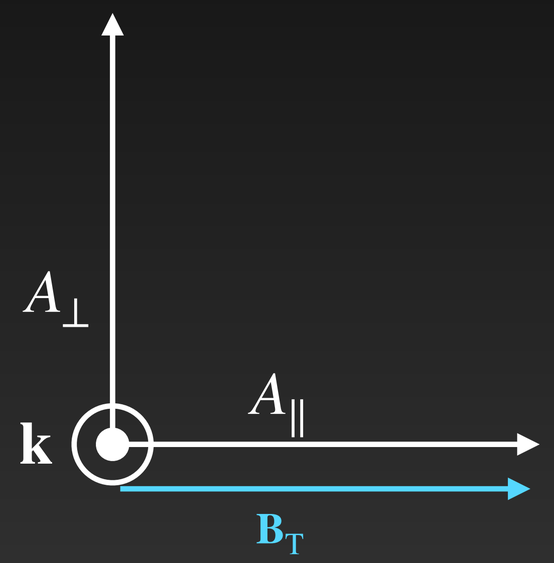
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- Assuming propagation of plane waves along positive $+z$ direction: $\Box = \partial_t^2 - \nabla^2 = -\,\omega^2 - \partial_z^2$



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- Using further that $k = n\omega$, one finds $\omega^2 + \partial_z^2 \approx \omega(n+1)(\omega + i\partial_z) \approx 2\omega(\omega + i\partial_z)$ we arrive at Schrödinger-like equation

Photon-axion Mixing equation

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- Schrödinger-like mixing equation for photon polarization states and axion where z coordinate takes function of time:

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ALP kinetic term	$\Delta_a = -\frac{m_a^2}{2\omega}$

Photon-axion Mixing equation

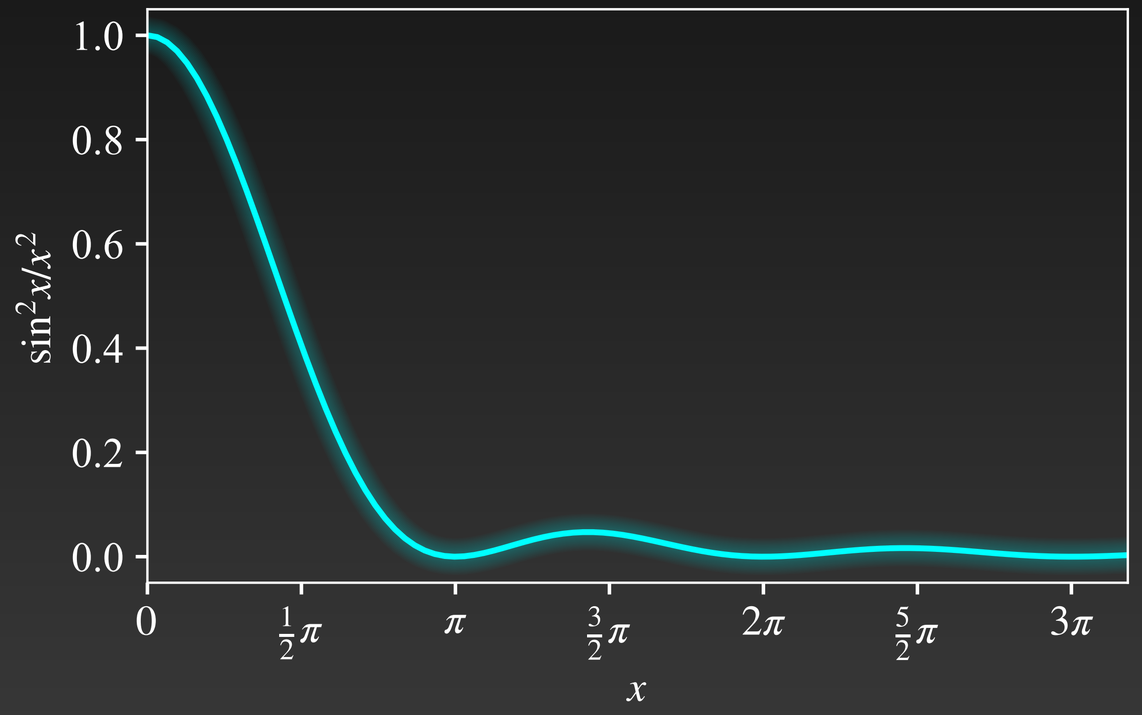
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Effects on A||	$\Delta_{||} = \Delta_{\mathrm{pl}} + \frac{7}{2}\Delta_{\mathrm{QED}} + \Delta_{\gamma\gamma}$
Plasma Frequency	$\Delta_{\mathrm{pl}} = -\frac{\omega_{\mathrm{pl}}^2}{2\omega}$ with $\omega_{\mathrm{pl}}^2 = \frac{4\pi n_{\mathrm{el}} e^2}{m_e}$ the plasma frequency and n_{el} the electron density
QED Birefringence	$\Delta_{\mathrm{QED}} = \frac{\alpha\omega}{45\pi}\left(\frac{B}{B_{\mathrm{cr}}}\right)^2$ with the critical magnetic field $B_{\mathrm{cr}} = \frac{m_e^2}{e} \approx 4.4 \times 10^{13}\,\mathrm{G}$
Photon-photon dispersion	$\Delta_{\gamma\gamma} = \chi_{\mathrm{CMB}}\omega,\ \chi_{\mathrm{CMB}} = \frac{44\alpha^2}{135}\frac{\rho_{\mathrm{CMB}}}{m_e^4} \approx 5.1 \times 10^{-43}$, ρ_{CMB} is the energy density of the CMB
ALP kinetic term	$\Delta_a = -\frac{m_a^2}{2\omega}$
Mixing term	$\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma} B$

Solution the photon-axion mixing equation

- Oscillation probability obtained similar to Rabi oscillations in quantum mechanics

$$P_{\gamma\leftrightarrow a}(z) = |\langle A_{\parallel}|T|a\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta_{\rm osc}z}{2}\right) = (\Delta_{a\gamma}z)^2\frac{\sin^2(\Delta_{\rm osc}z/2)}{(\Delta_{\rm osc}z/2)^2}$$

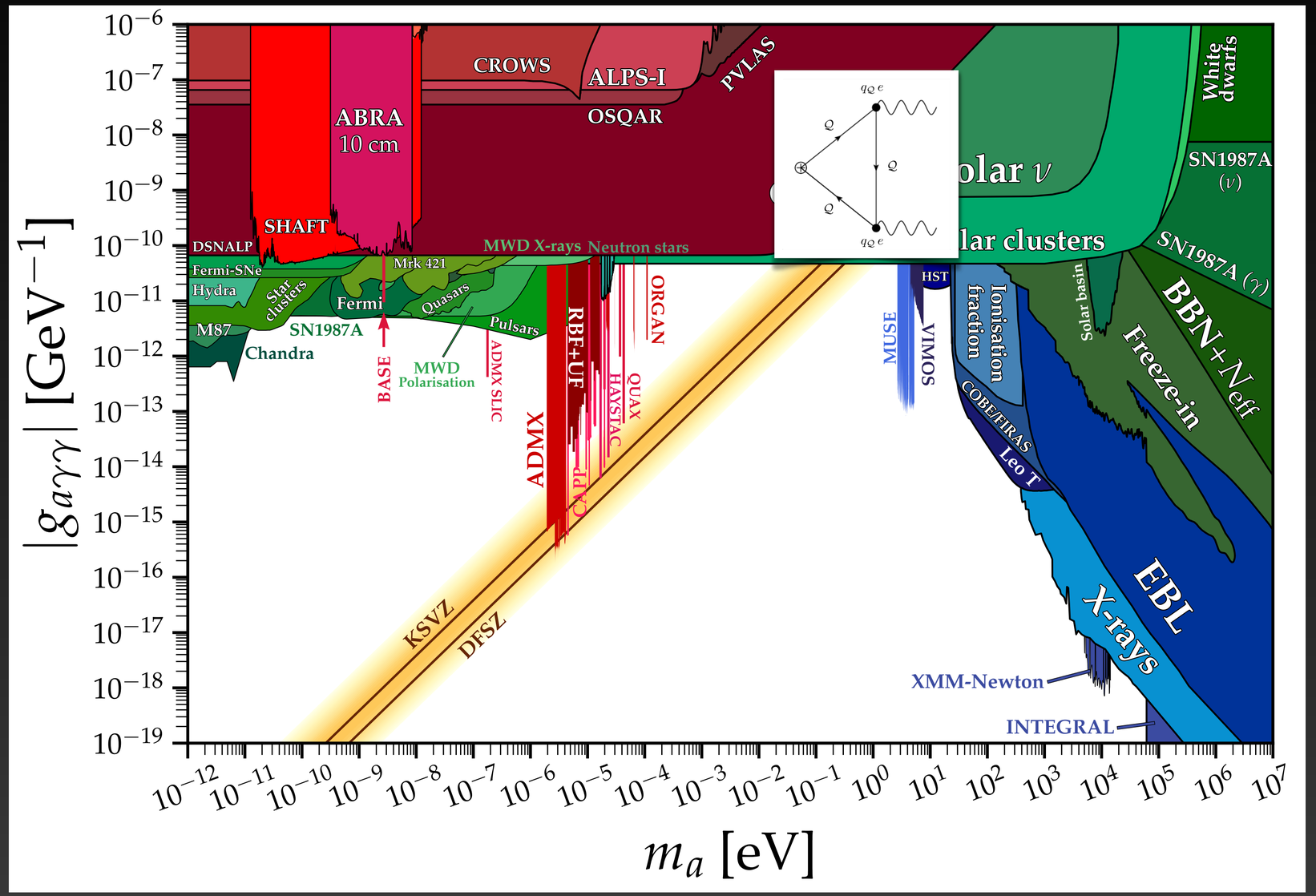


$$\Delta_{\rm osc} = \left(\left(\Delta_a - \Delta_{\parallel})^2 + 4\Delta_{a\gamma}^2\right)\right)^{1/2}$$

inverse of the oscillation length

$$L_{\rm osc} = \frac{2\pi}{\Delta_{\rm osc}}$$

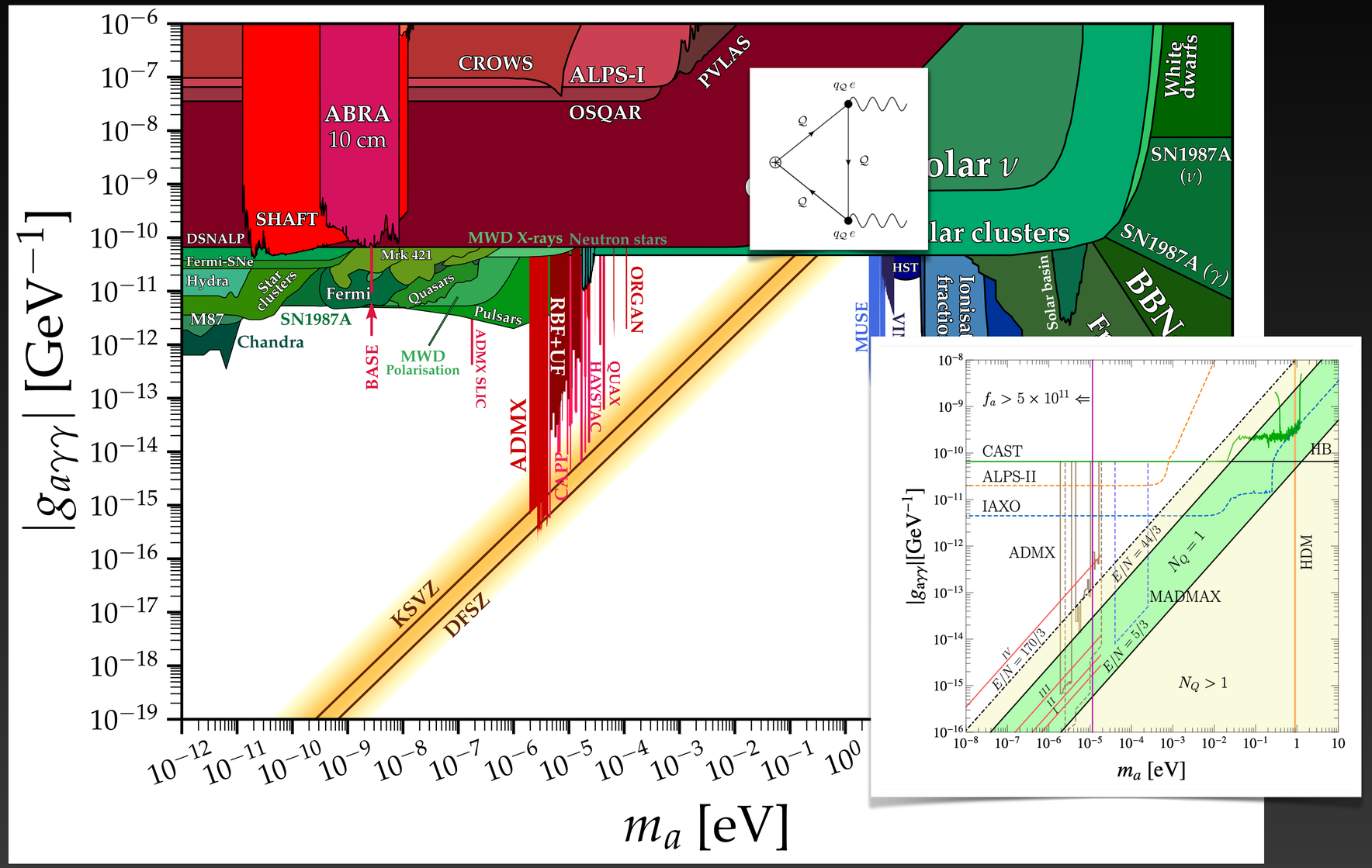
Beyond vanilla axion models



[Di Luzio et al. 2018, Farina et al. 2017, Sokolov & Ringwald 2021]

https://doi.org/10.5281/zenodo.3932430

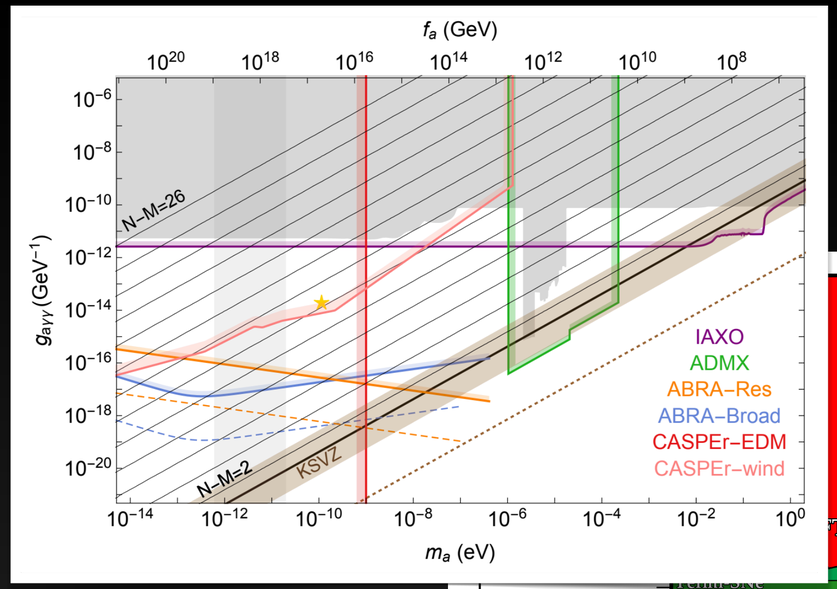
Beyond vanilla axion models

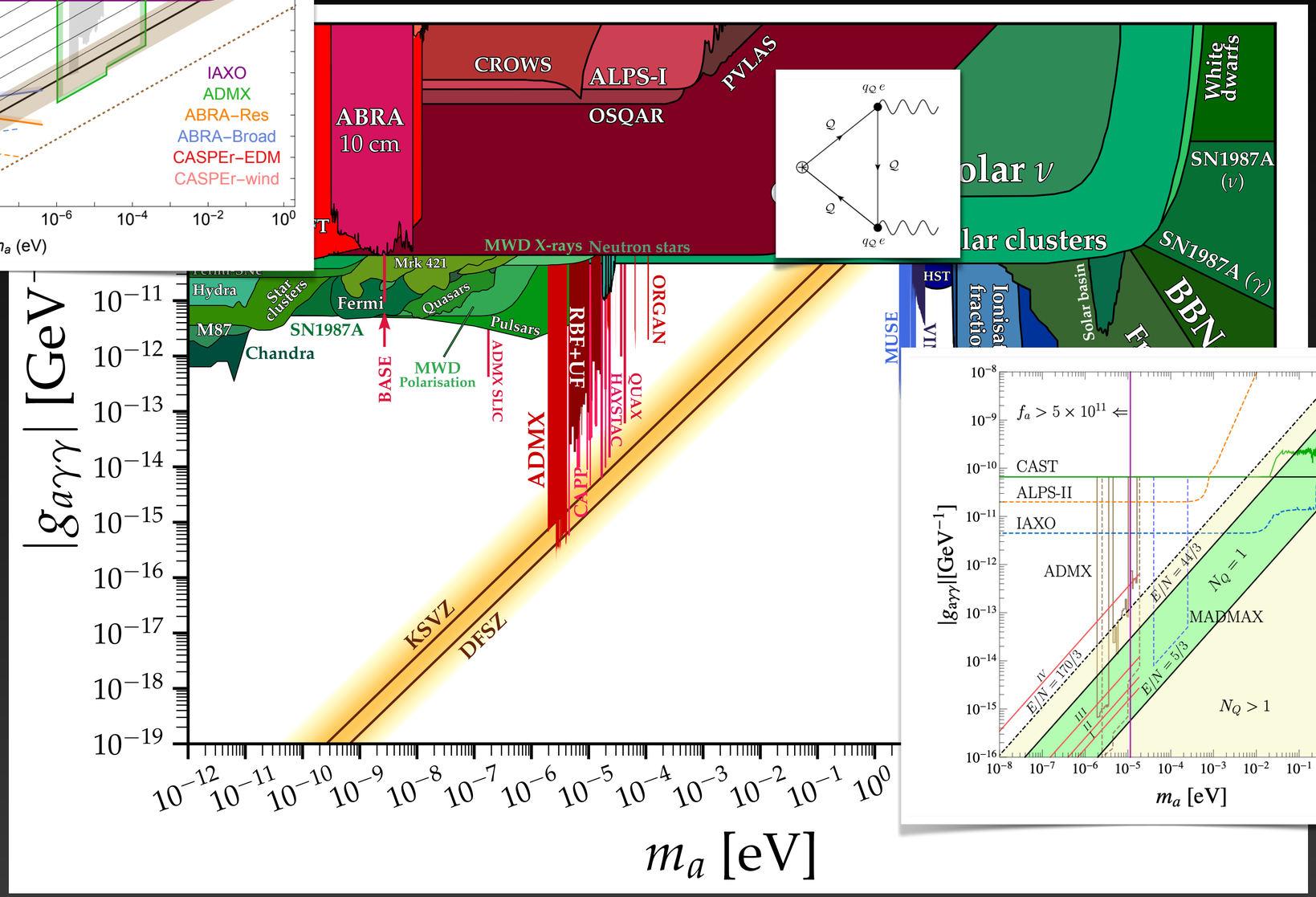


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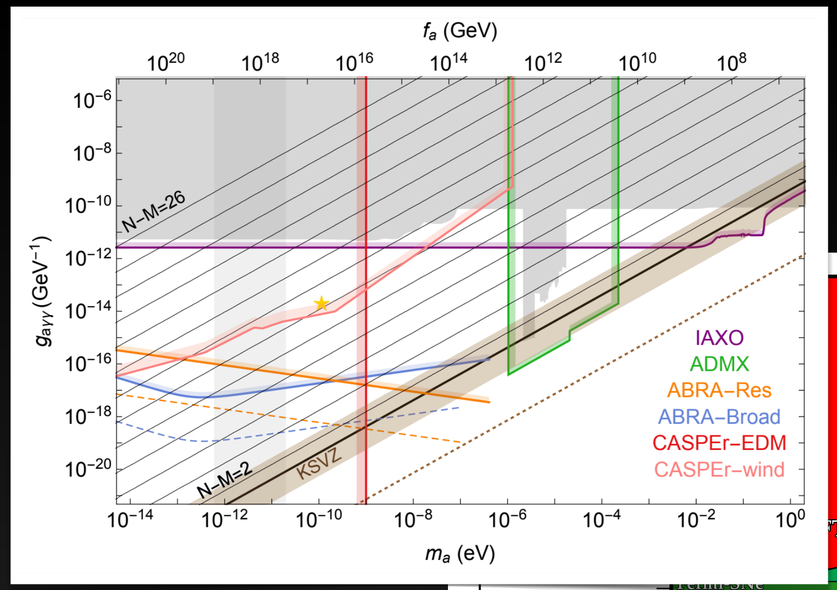


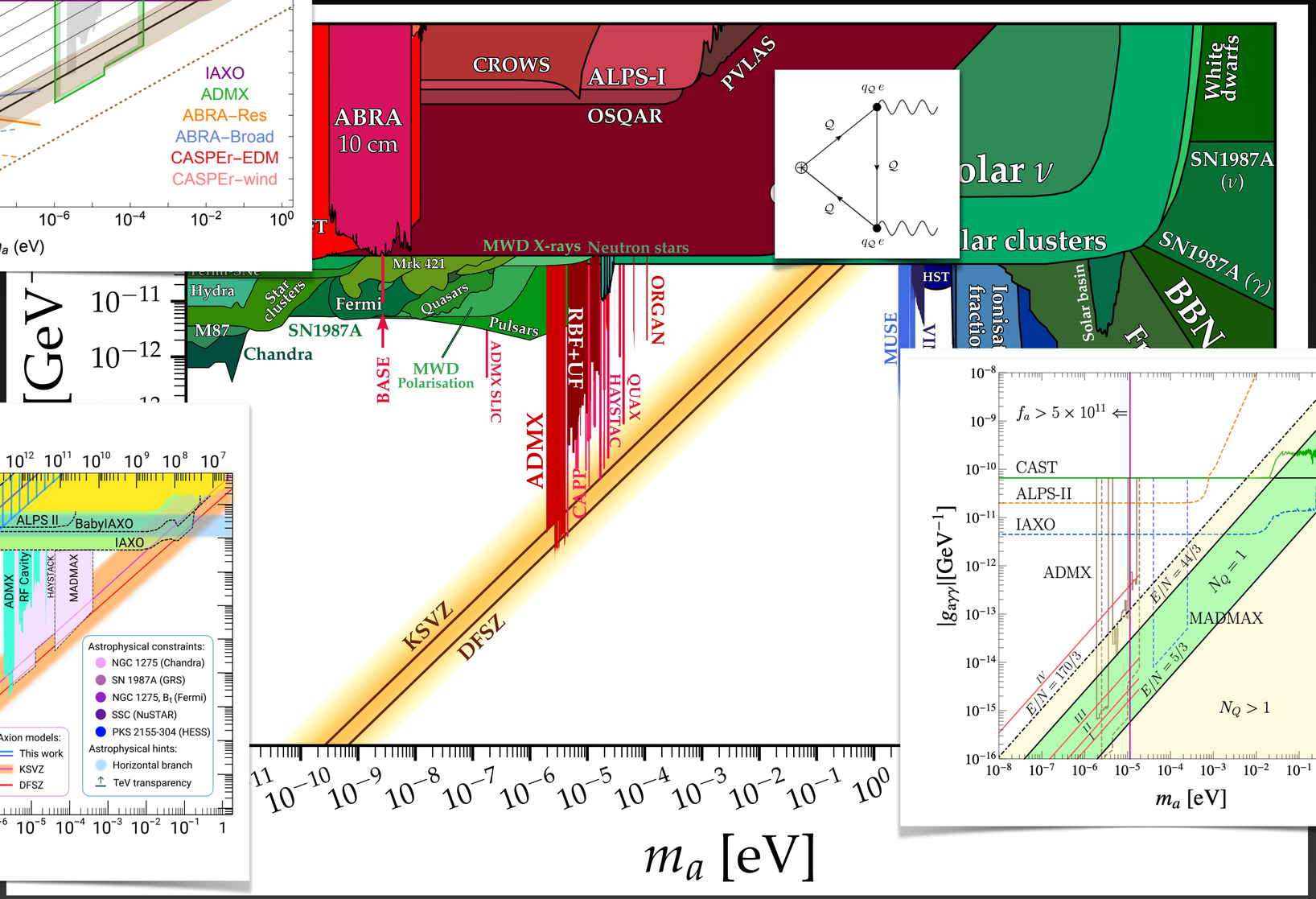


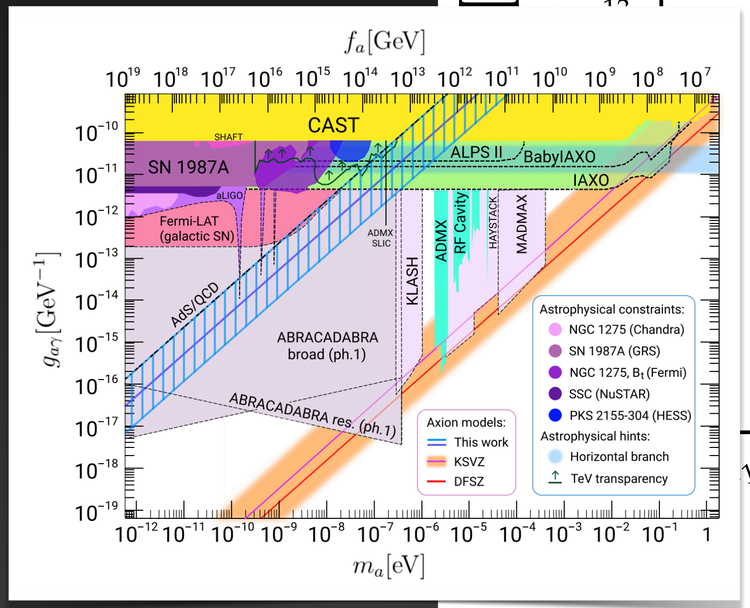
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Axion-like particles

$$\mathscr{L}_\phi \supset \underbrace{-\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \frac{\phi}{f_a}}_{\text{QCD Axion only}} \underbrace{- \frac{1}{4} g_{a\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \partial_\mu \phi \sum_f g_{af} \bar{f} \gamma^\mu \gamma^5 f}_{\text{QCD Axion and ALPs}}$$

QCD Axion only
Solves CP problem
Gives rise to potential that generates axion mass

Connection between coupling and energy scale of broken symmetry f_a:

$$g_{a\gamma} = C_{a\gamma} \frac{\alpha}{2\pi f_a} \qquad g_{af} = C_{af} \frac{m_f}{f_a}$$

$C_{a\gamma}, C_{af}$ depend on UV completion of theory, for QCD axion: $g_{a\gamma}, g_{af} \propto m_a$

[O'hare 2024]