Axion searches with gamma-ray telescopes

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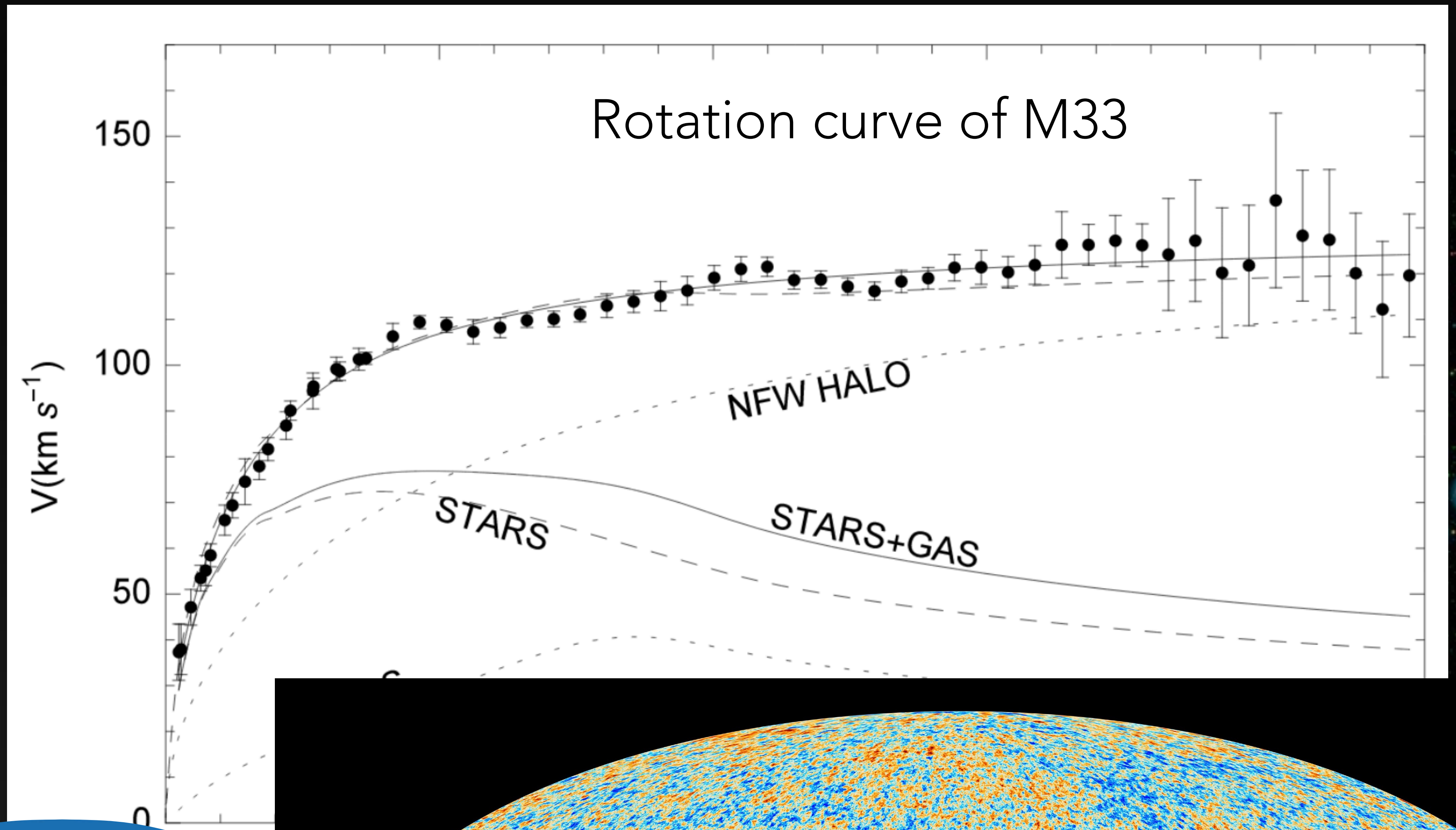
Cosmic WISPers Colloquium
June 24, 2024

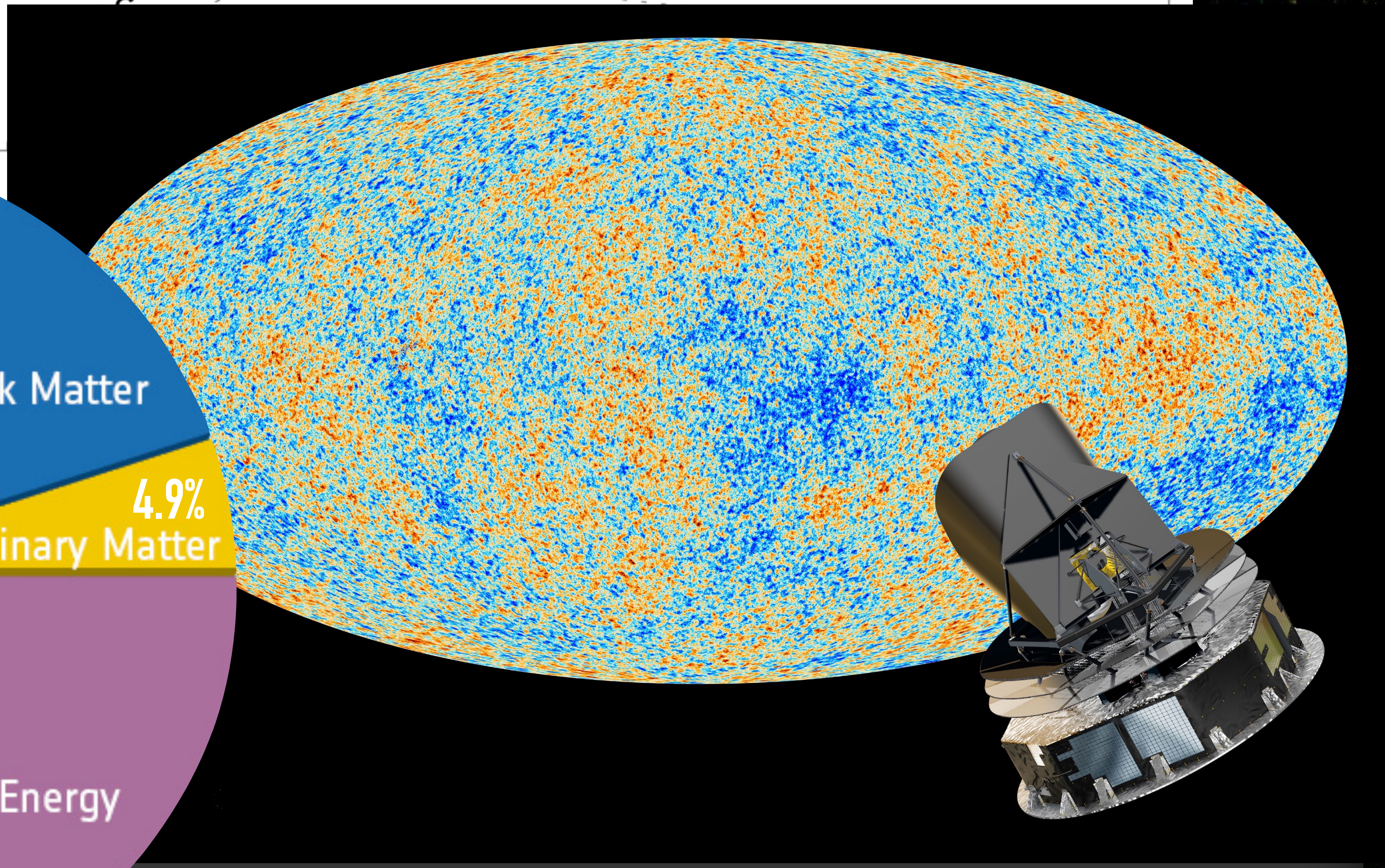
Illustration by Mohammadpour Mir

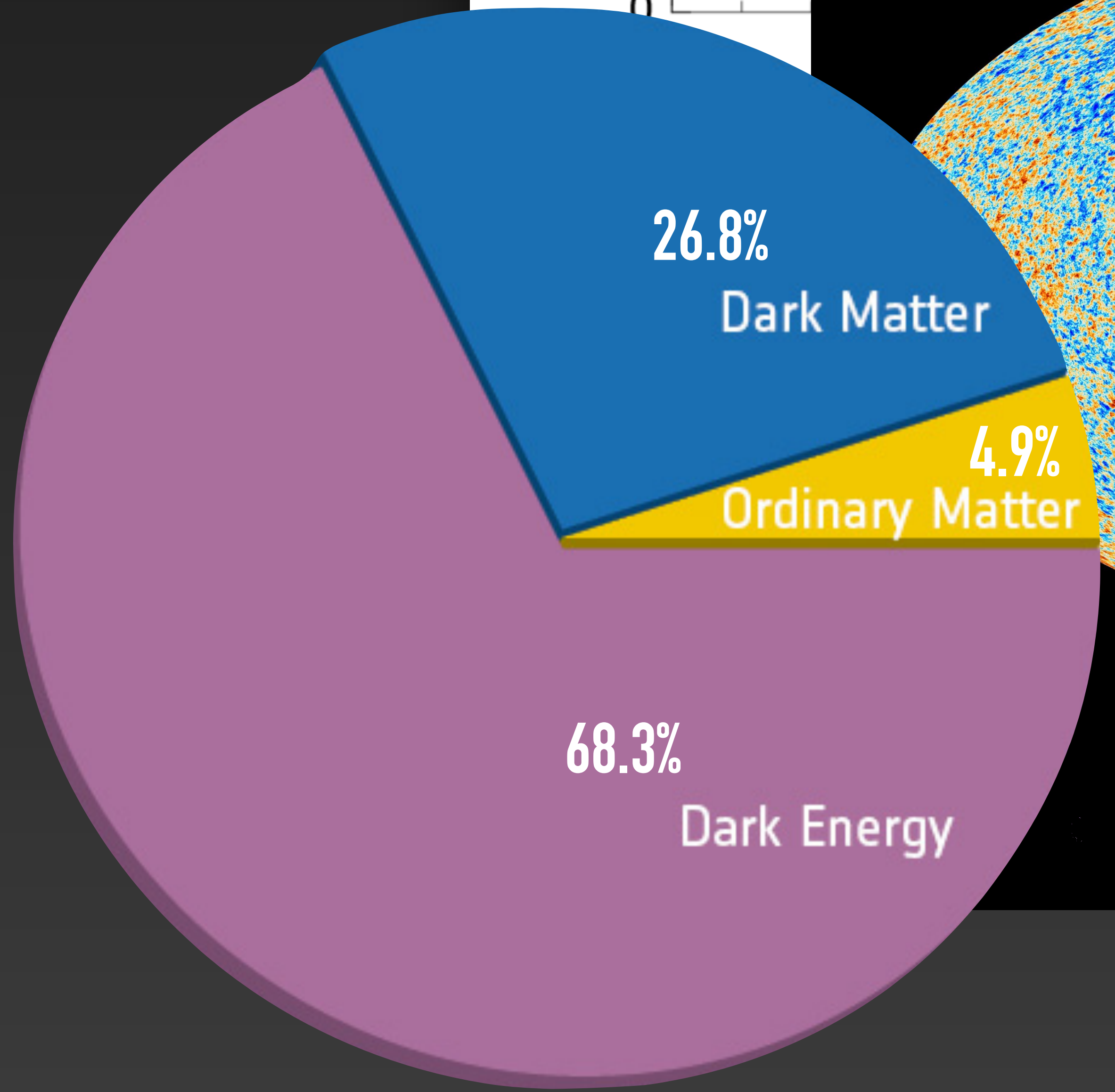
Outline

- Motivation for axions: Solution to dark matter and the strong CP problem
- Photon-axion conversions in astrophysical magnetic fields
- Gamma-ray observations of axion signatures
  - Supernovae
  - Photon dis-/re-appearance
  - ALP decay

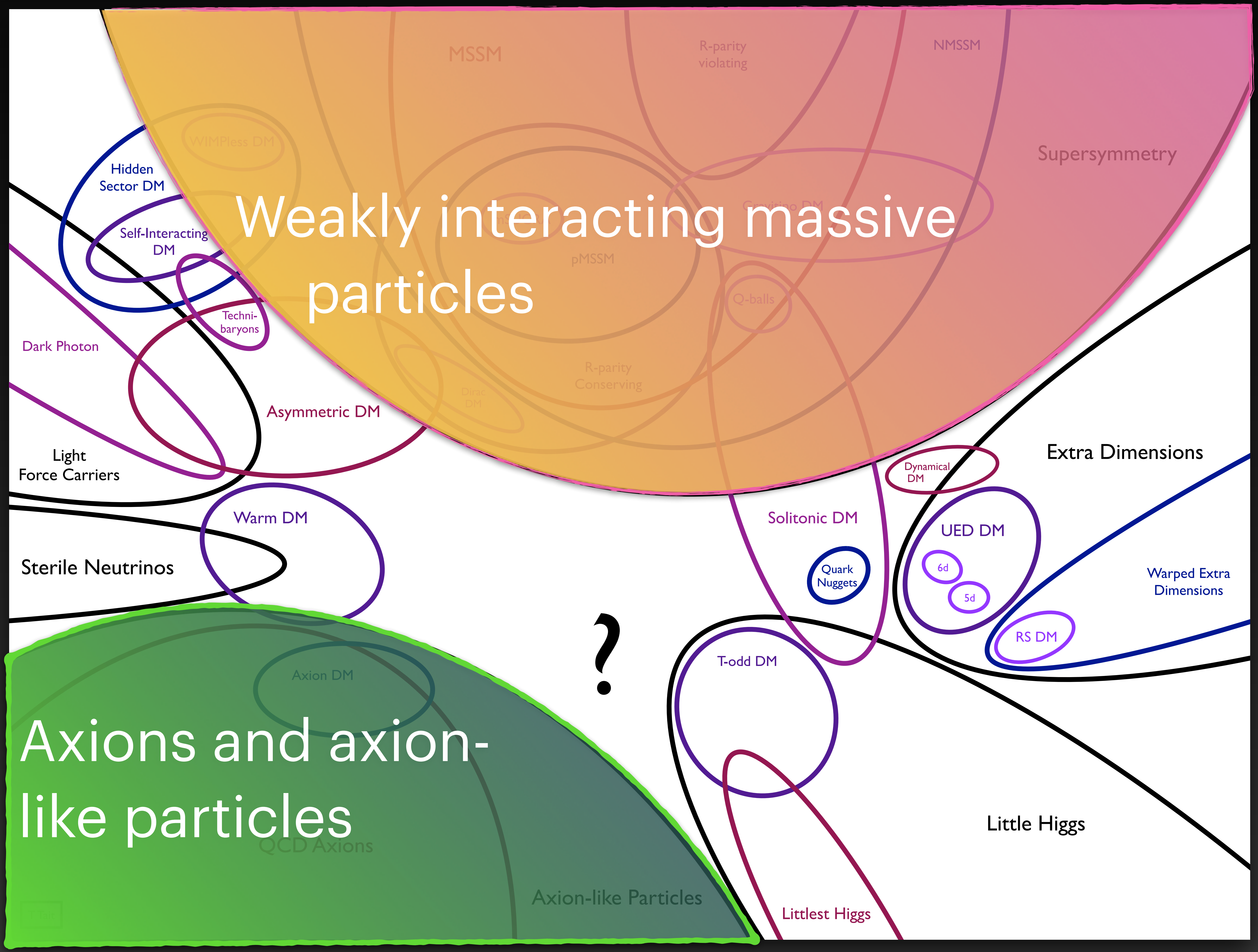
Overwhelming Evidence for the Existence of Dark Matter







Dark matter as a new fundamental particle?



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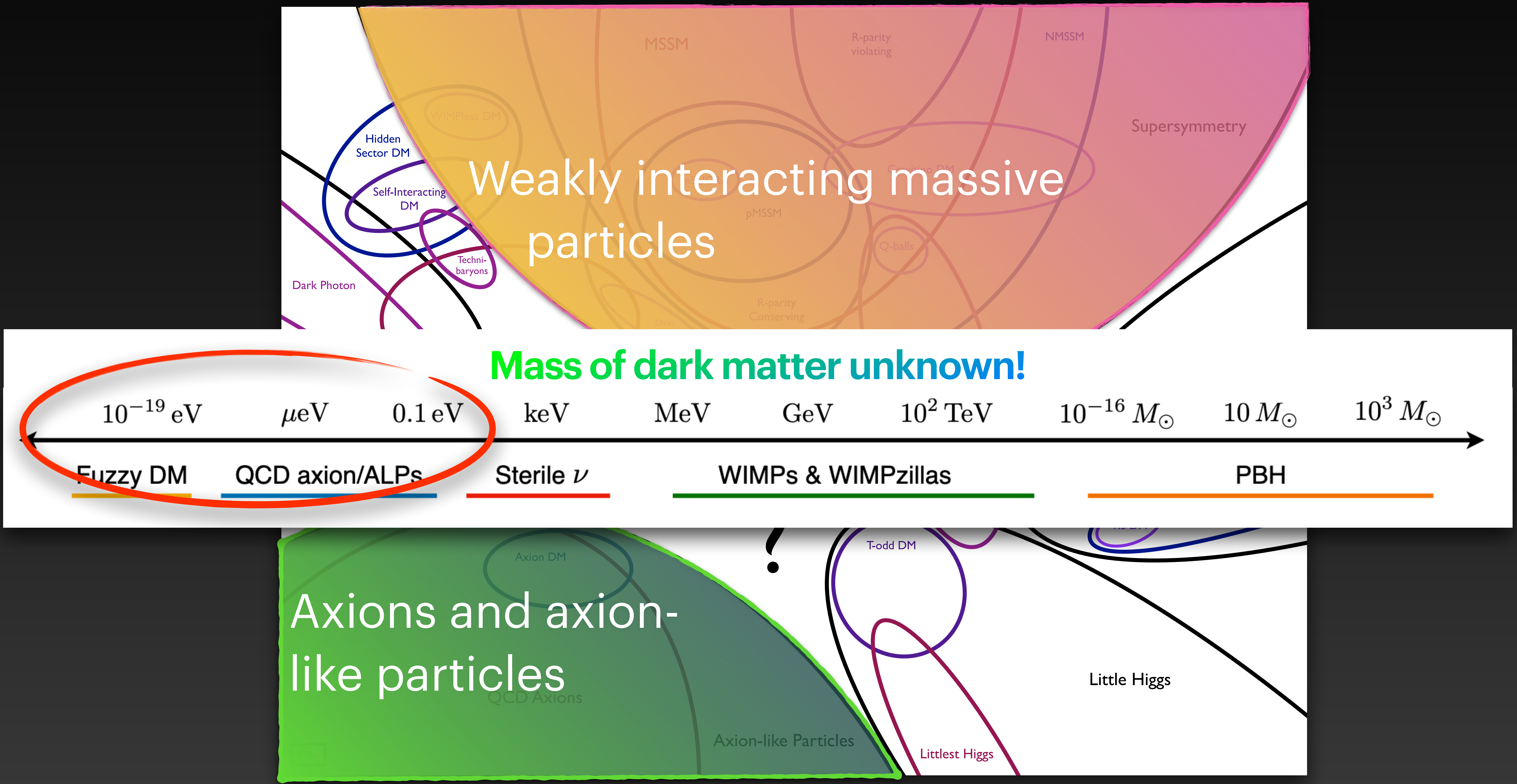
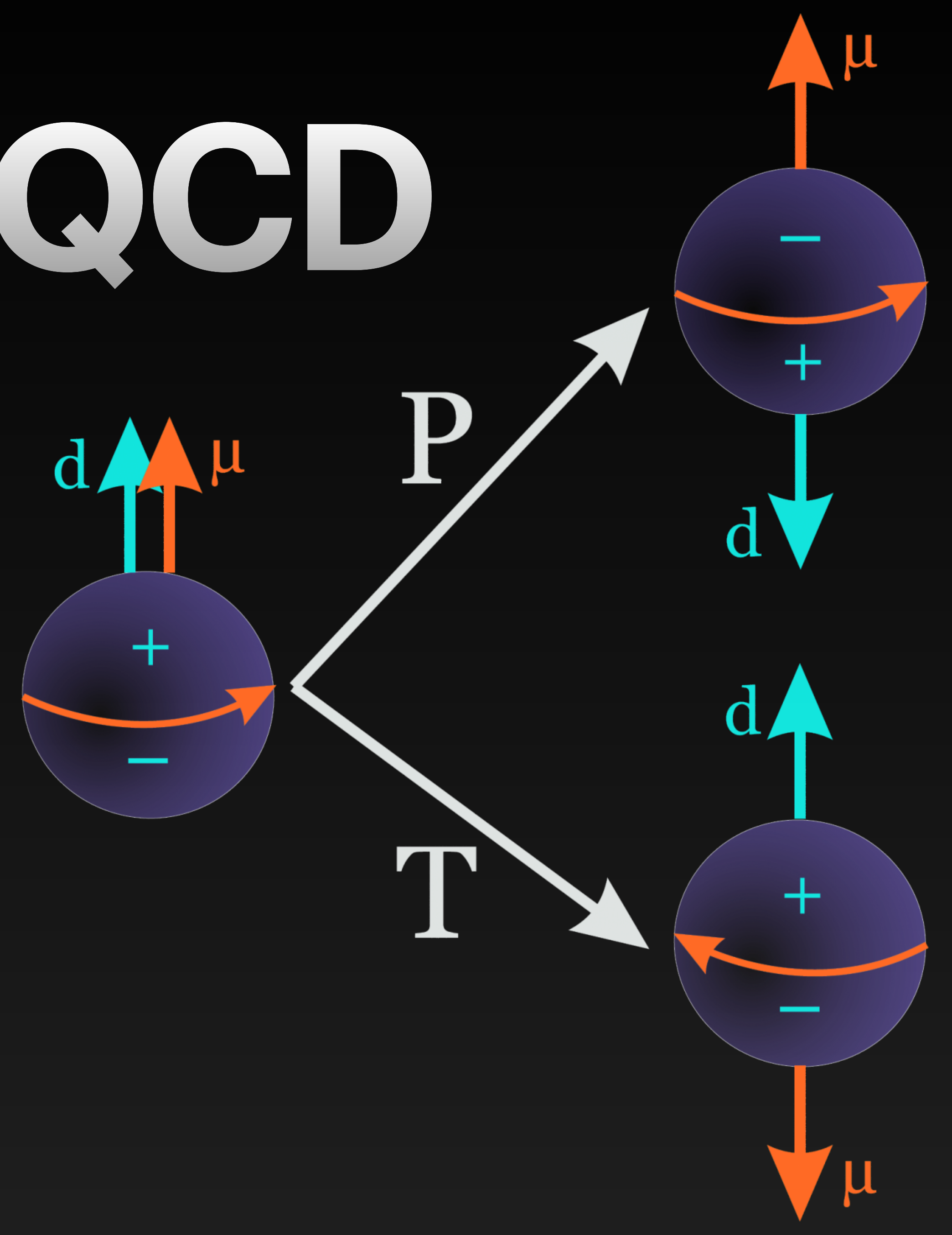


The CP problem in QCD



- QCD Lagrangian includes a term violating **P** and **T** symmetry

$$\mathscr{L}_{\not{CP}} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta_{\mathrm{QCD}}$$

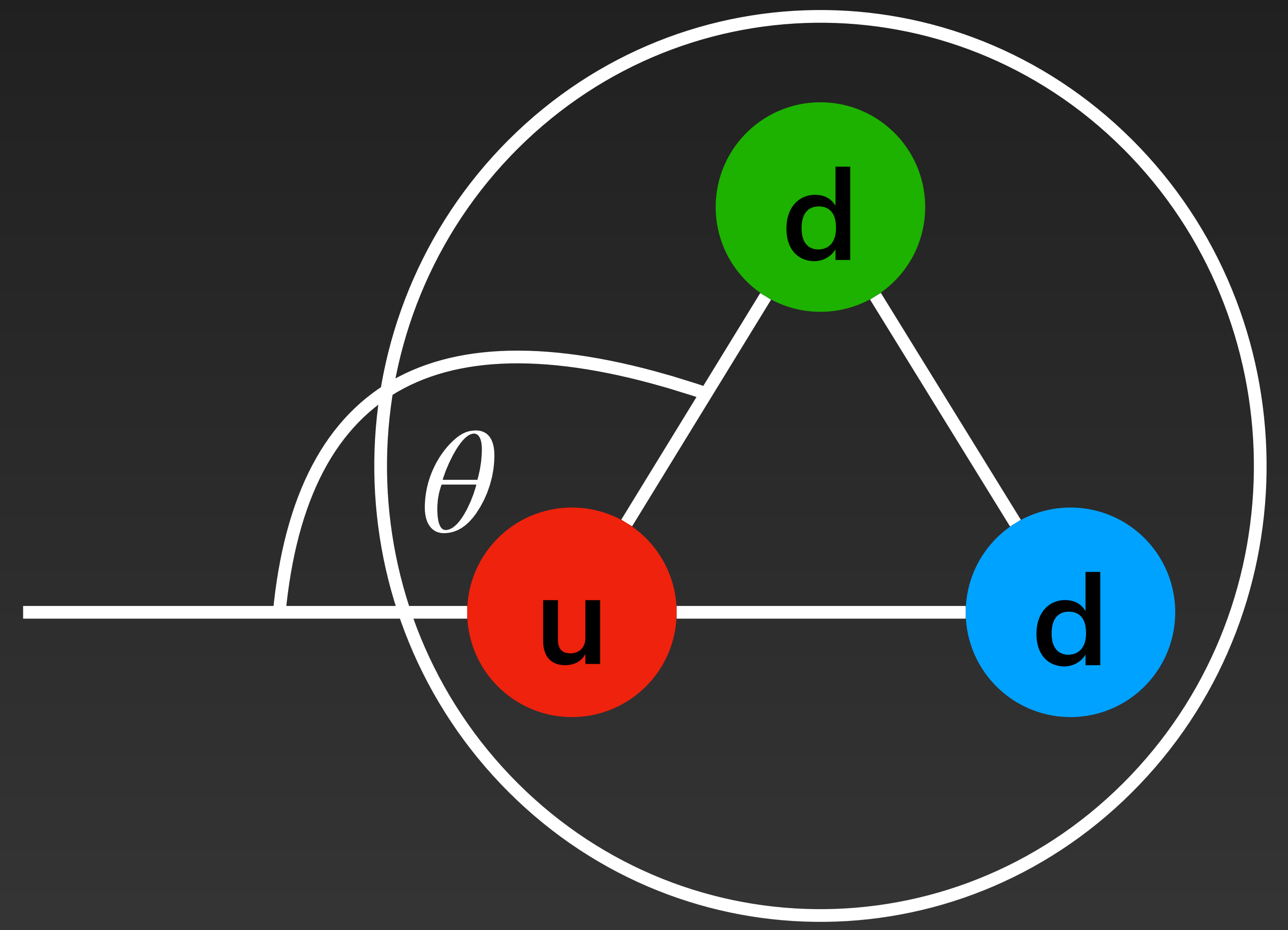
- Leads to EDM term of the neutron

$$\mathscr{L}_{\mathrm{EDM}} = -\frac{d_n}{2} \left(\bar{\psi}_n i \gamma_5 \sigma^{\mu\nu} \psi_n\right) F_{\mu\nu}$$

- Where QCD calculation gives:

$$d_n = (2.4 \pm 1.0) \times 10^{-3}\ \theta\ e\ \mathrm{fm}$$

- Expectation from QCD: $\theta \sim \theta_{\mathrm{QCD}} \sim \mathcal{O}(1)$
- Measurement [Abel et al. 2020]: $|d_n| < 1.8 \times 10^{-26} e$ cm
- $\Rightarrow |\theta| < 0.8 \times 10^{-10}$



[see e.g. Irastorza & Redondo 2018]

[Slide credit: Ben Safdi]

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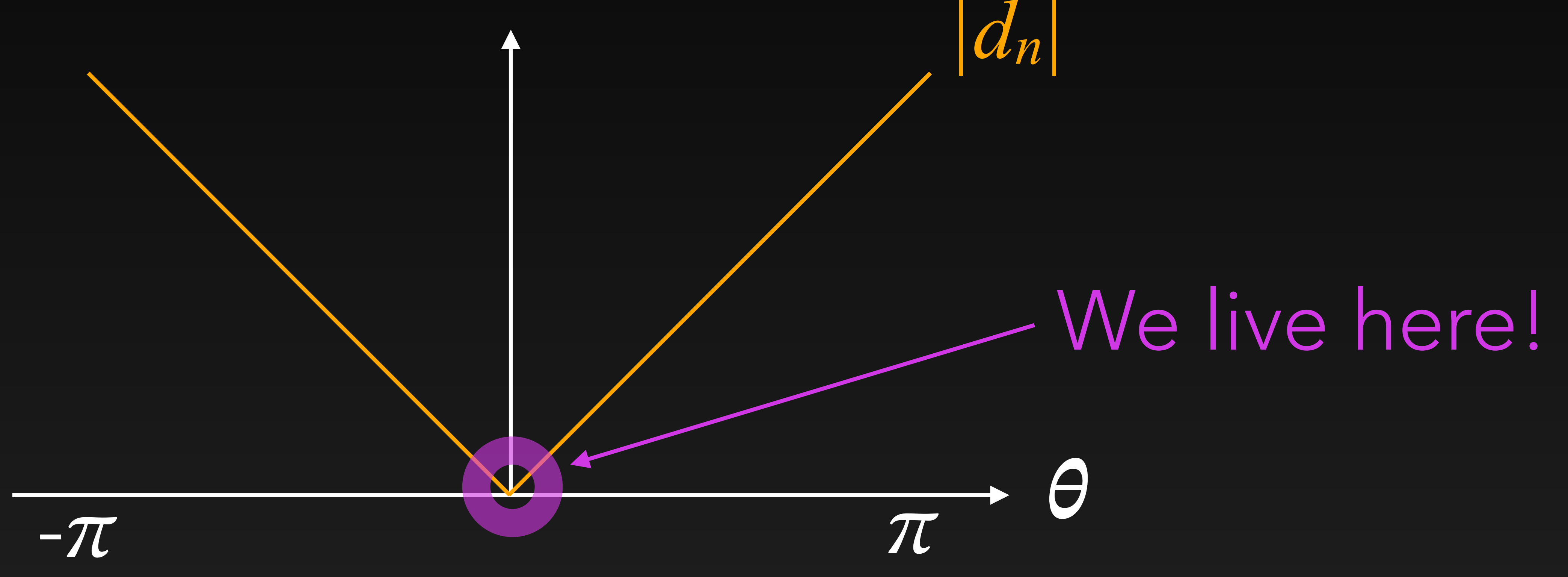
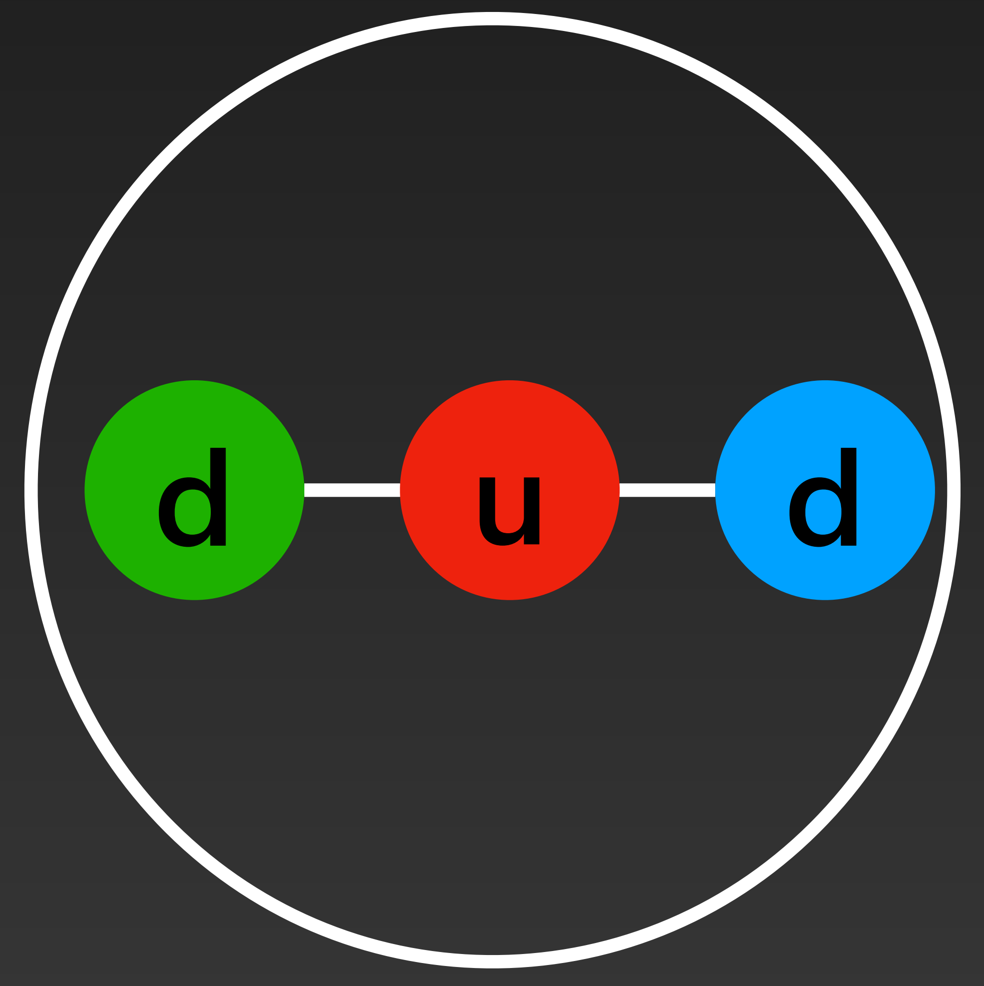




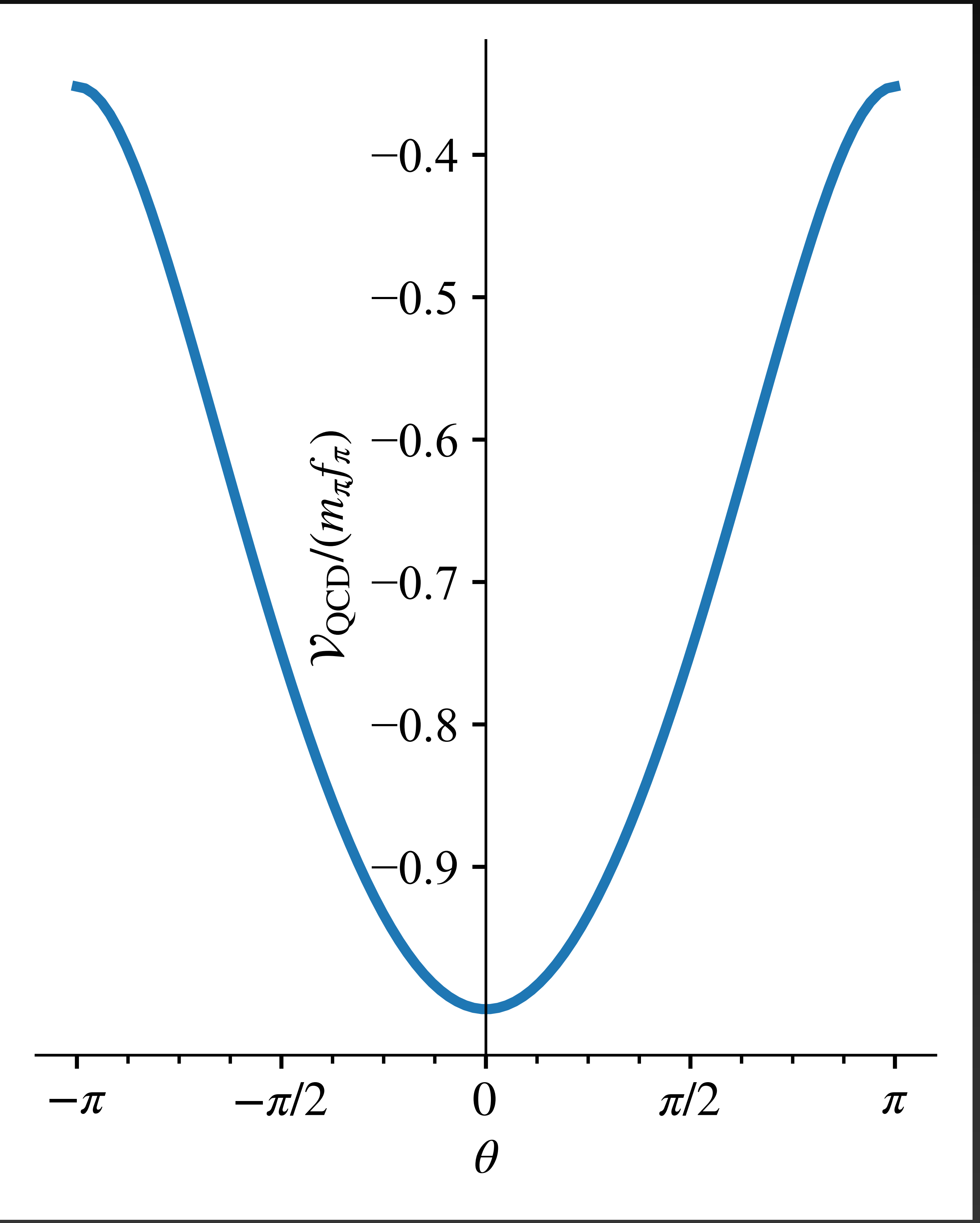
[see e.g. Irastorza & Redondo 2018]

[Hook 2018]

Axion solves the strong CP proble

- $\theta \longrightarrow a\,/\,f_a$ with scalar field a and scale f_a
- Potential $V(a)$ generated by QCD, axion acquires mass

$$m_a = 5.70(7)\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$



[Peccei & Quinn 1977;
Weinberg 1978; Wilczek 1978
see e.g. Irastorza & Redondo 2018]

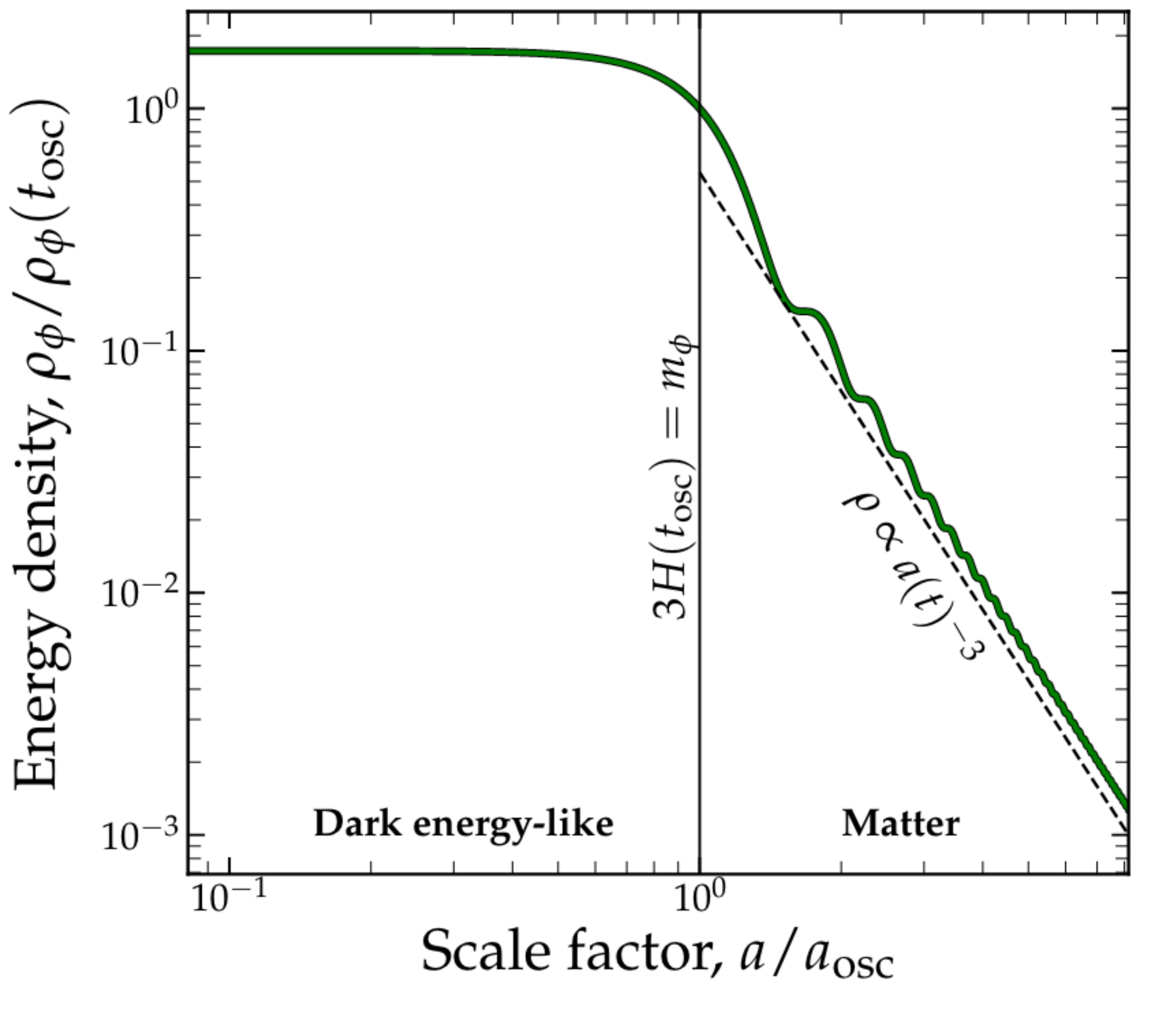
Axions as cold dark matter
Through misalignment mechanism

- Axion evolution in expanding Universe:

$$\ddot{a} + 3H(t)\dot{a} + m_a^2(t)a = 0$$

- Overdamped in early Universe as long as $3H \gg m_a$, field frozen at its initial value
- Once $3H \sim m_a$ field will start to oscillate
- Oscillations have properties of cold dark matter

[O'hare 2024]



[See e.g. this PhD thesis, Marsh 1510.07633, Arias et al. 1201.5902]

Axion-like particles

- Particles that have similar phenomenology as axions
- Predicted in several **extensions** of the standard model (Majoron, Familon, String Theory …)

  [Chikashige et al. 78; Langacker et al. 86; Wilczek 82, Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli et al. 12, see also Jaeckel & Ringwald 10, Irastorza & Redondo 18 for reviews]
- Generally don't solve strong CP problem
- m_a and f_a are independent parameters
- **Interaction with standard model**:

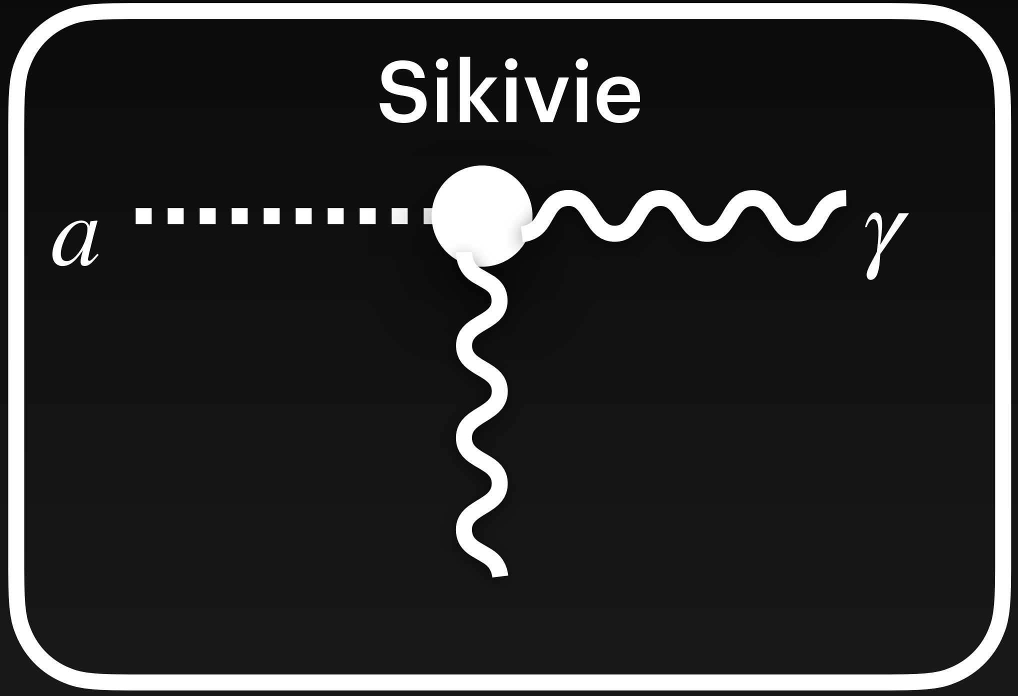
$$\mathcal{L}_\phi \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \frac{\phi}{f_a} - \frac{1}{4} g_{a\gamma}\, \phi\, F_{\mu\nu} \tilde{F}^{\mu\nu} + \partial_\mu \phi \sum_f g_{af} \bar{f} \gamma^\mu \gamma^5 f$$

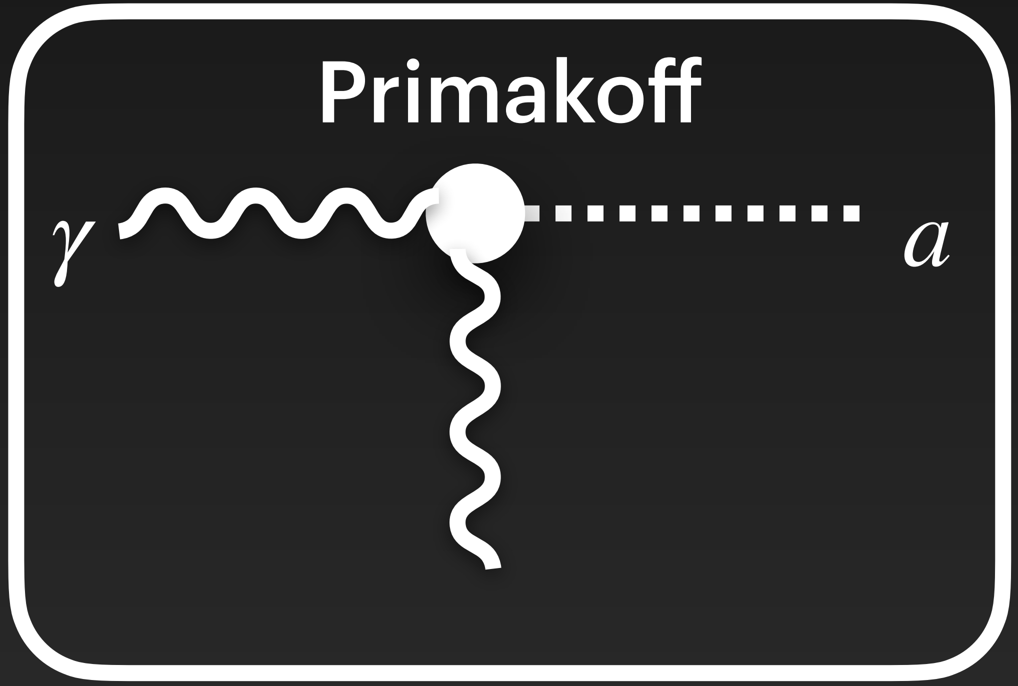
QCD Axion only
Solves CP problem
Gives rise to potential that generates axion mass

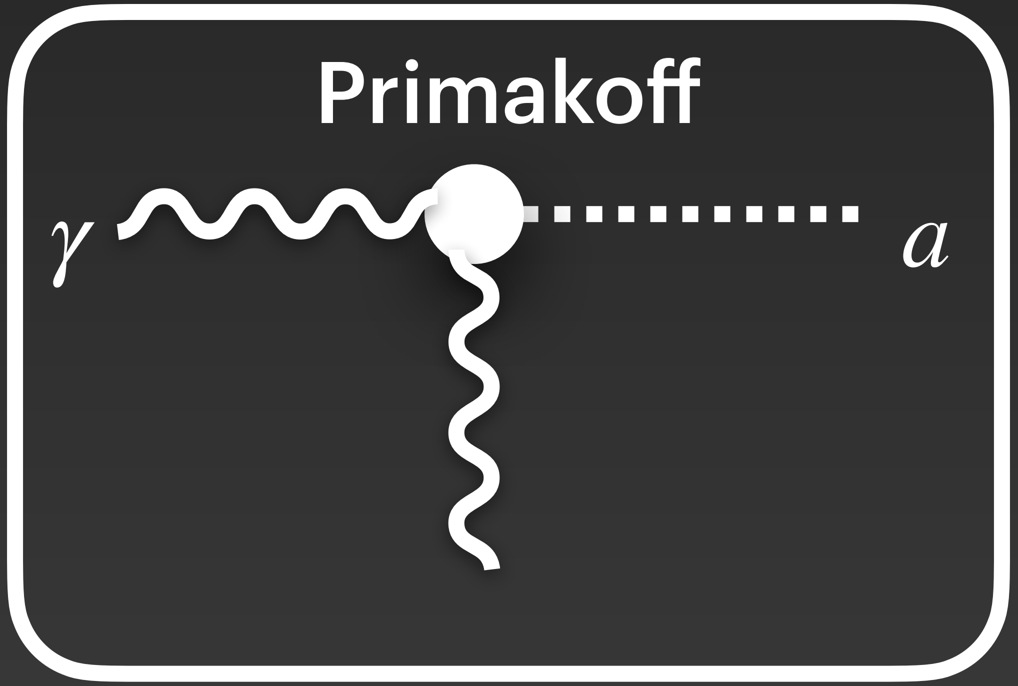
QCD Axion and ALPs

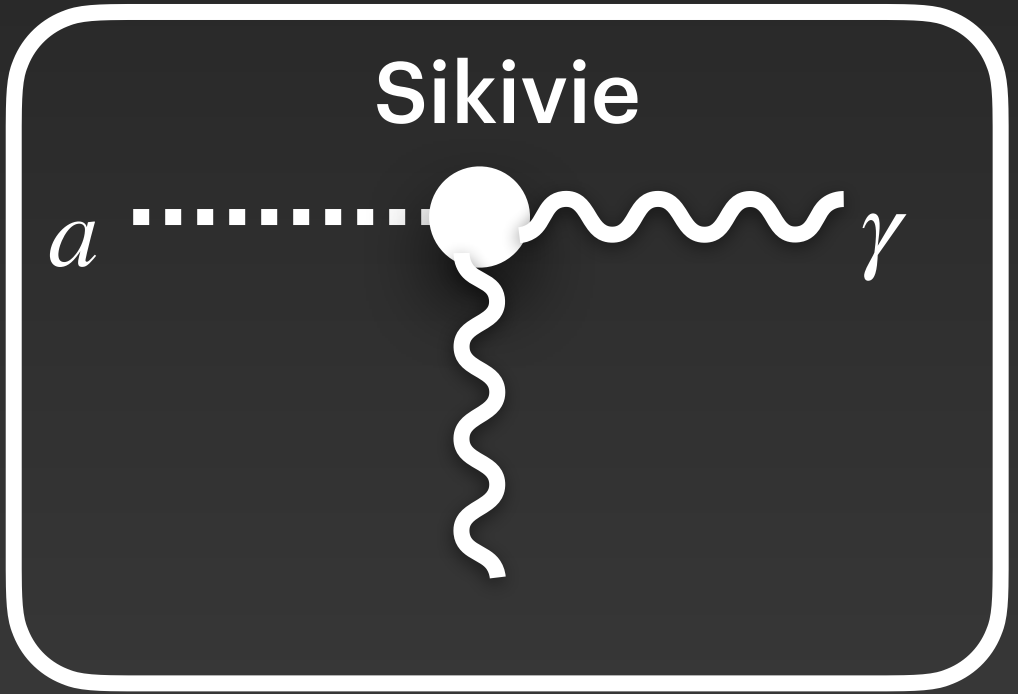
[O'hare 2024]

Axion observables

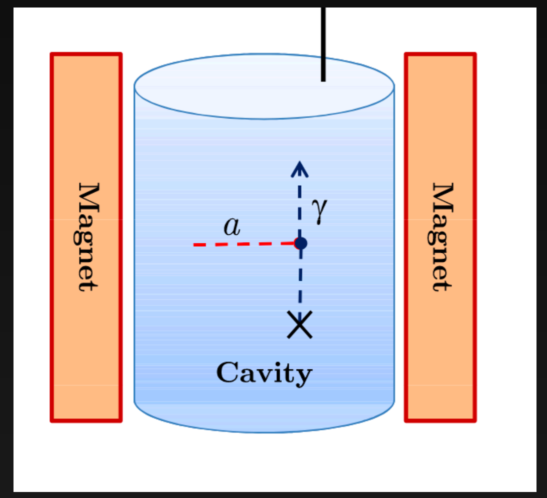




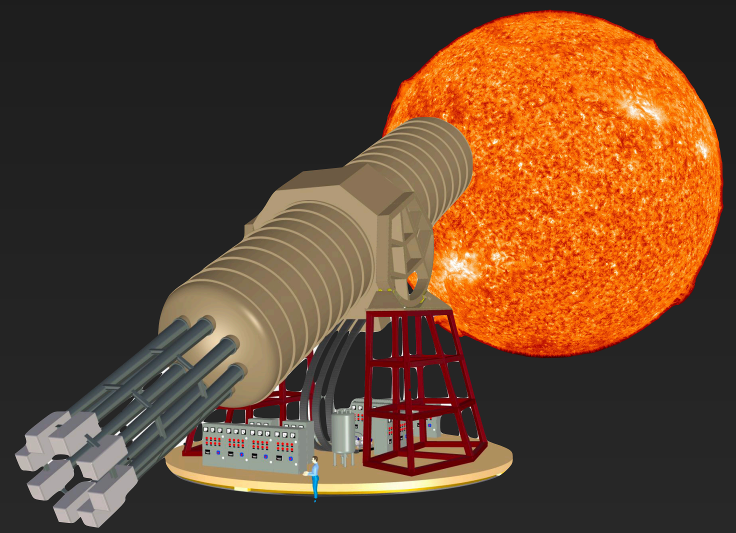




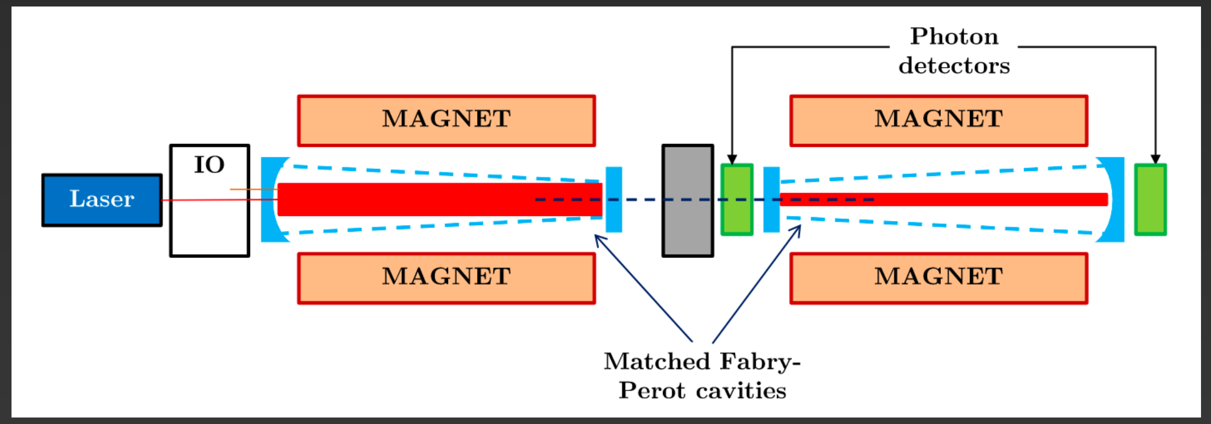
Haloscopes



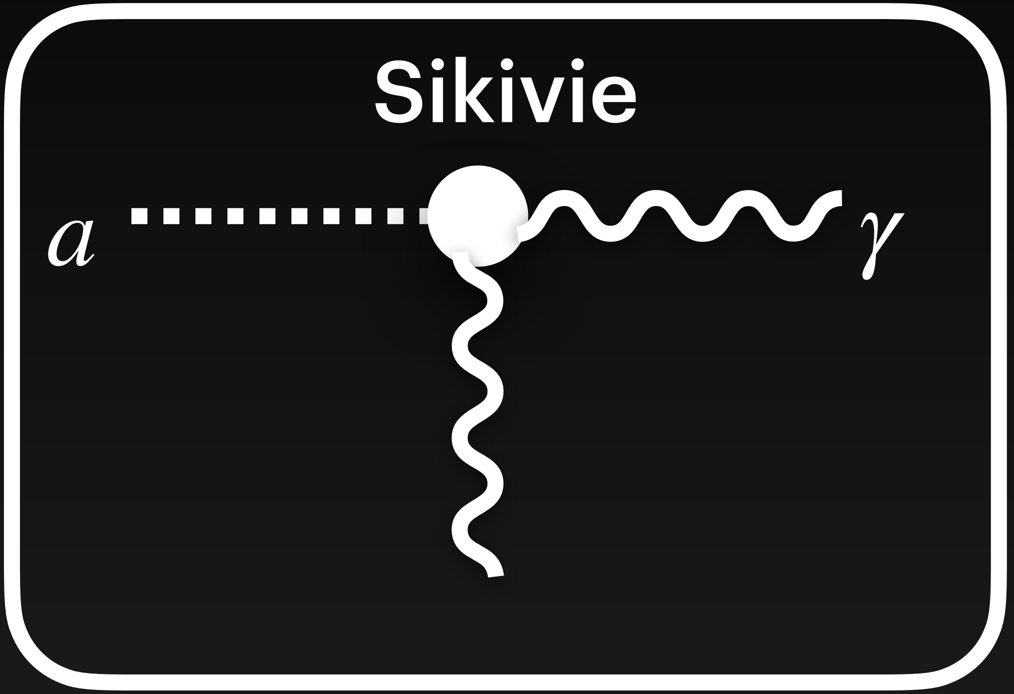
Helioscopes

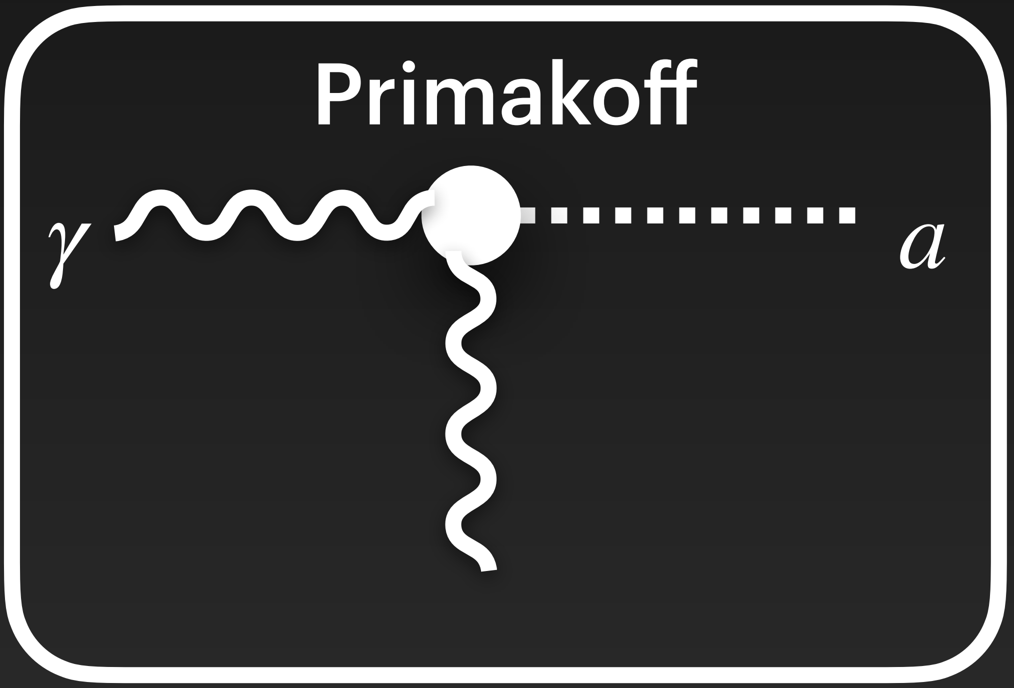


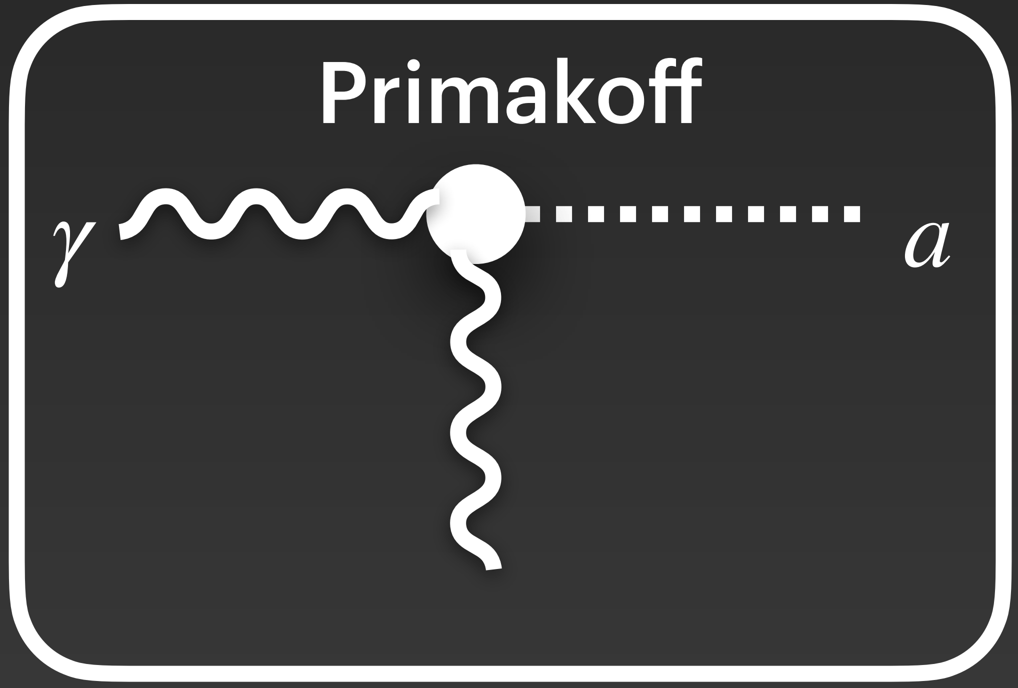
LSW

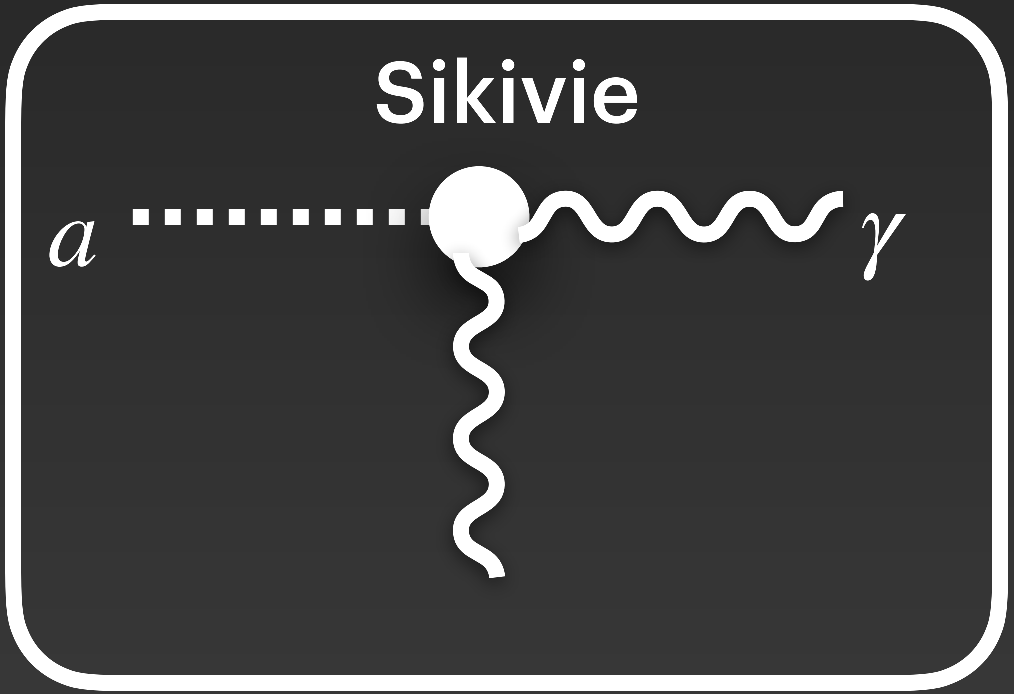


Axion observables — astro counterparts









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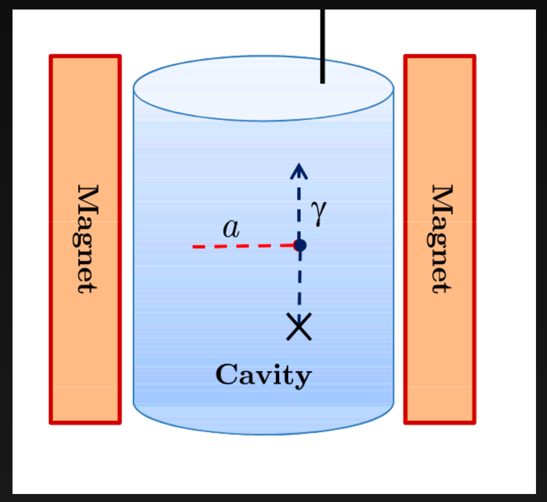

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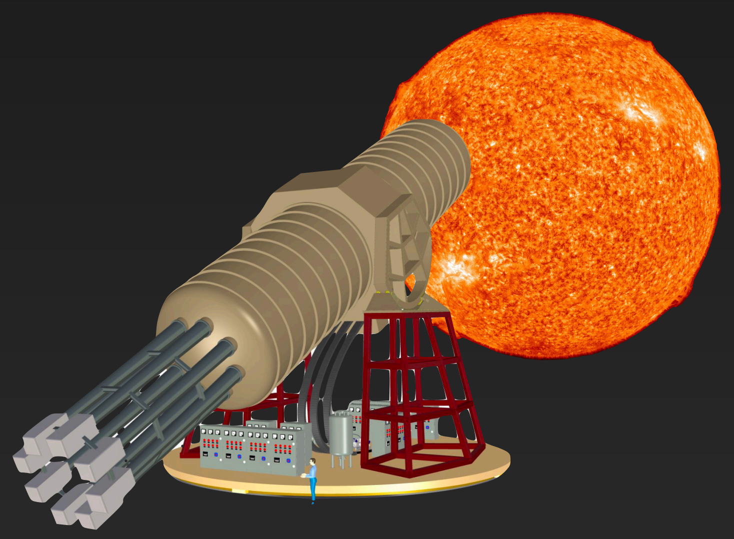

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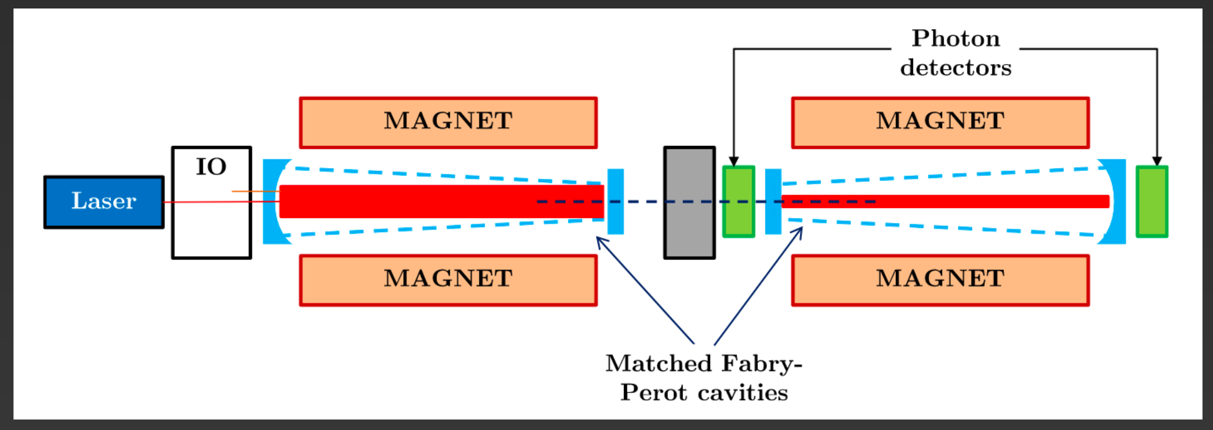
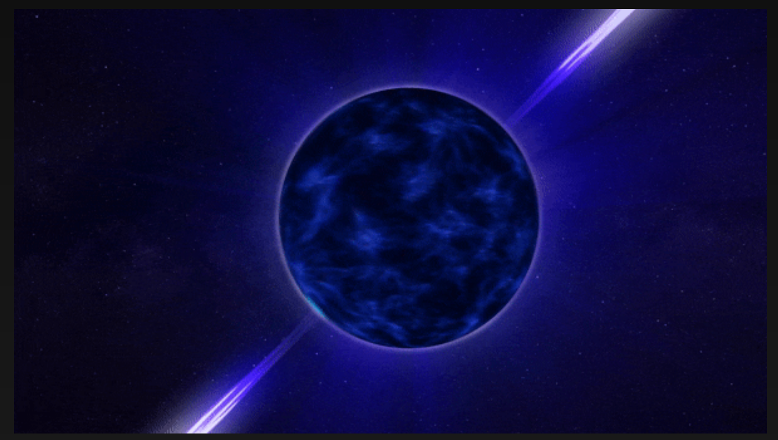
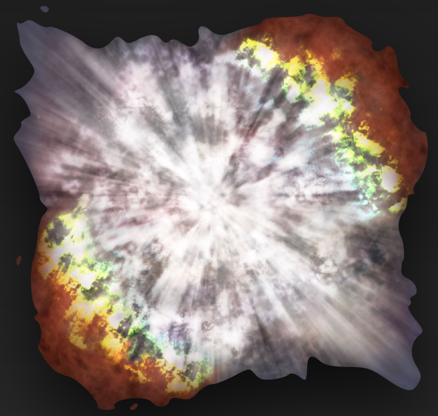


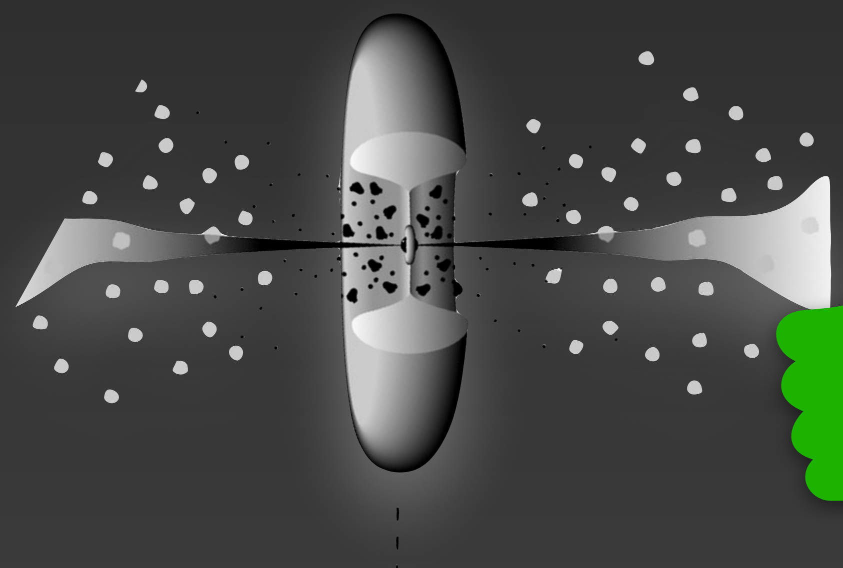
DM conversion in pulsar B fields



Supernovascopes



Photon disappearance / Photon reappearance



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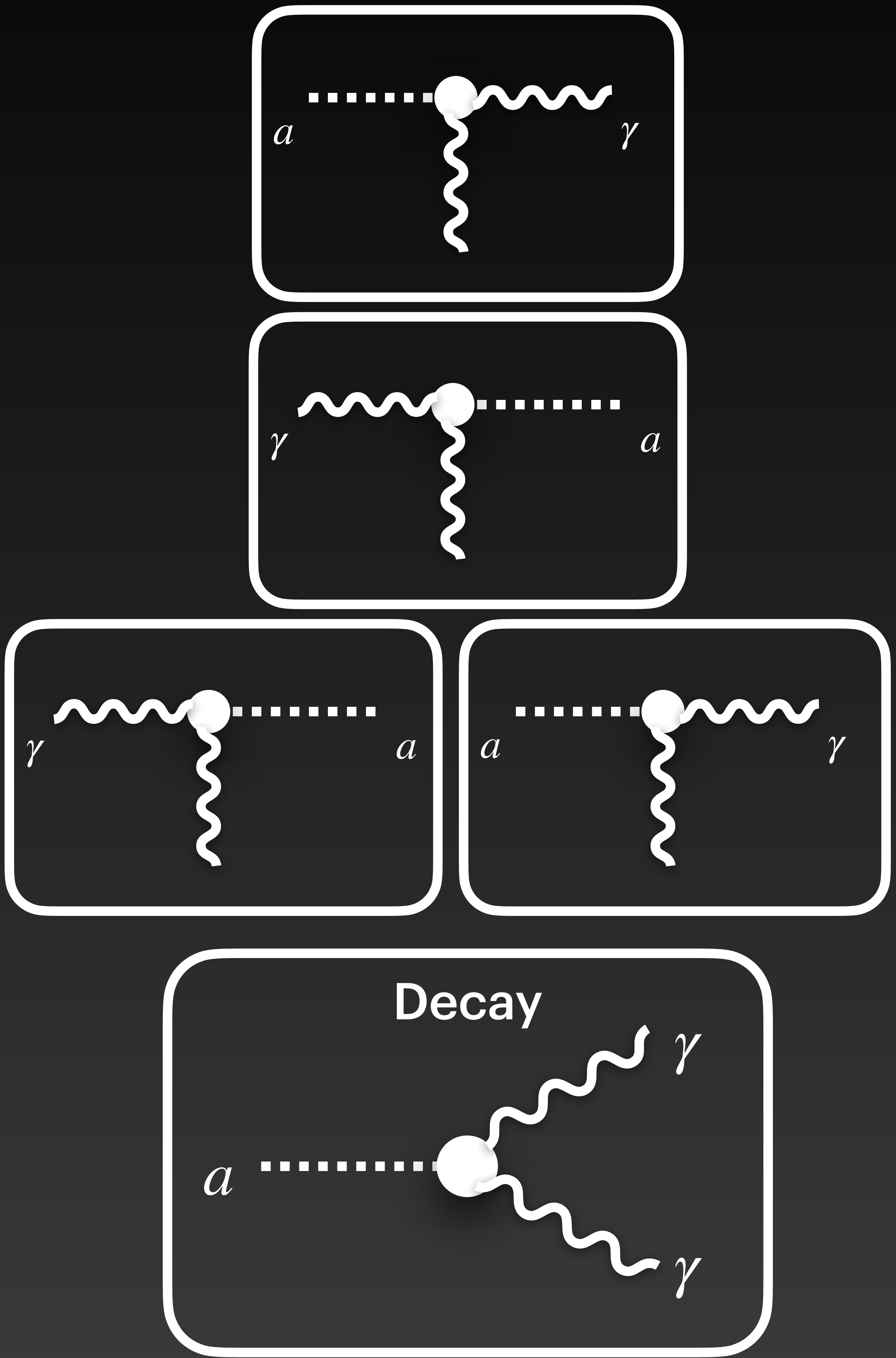

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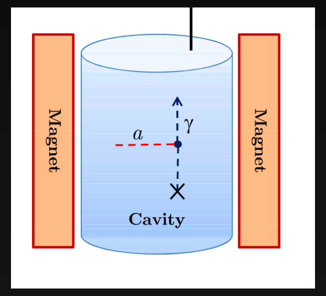

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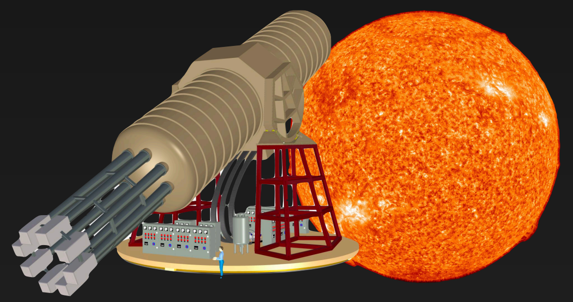

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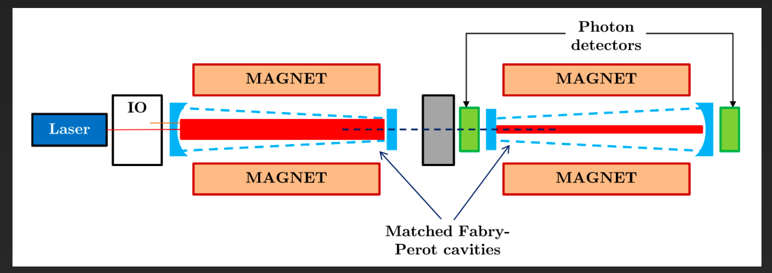
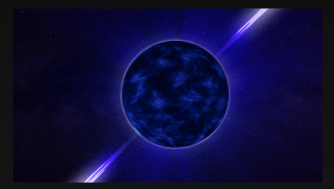


Collider / Beam dump

DM conversion in pulsar B fields

γ rays



Supernovascopes

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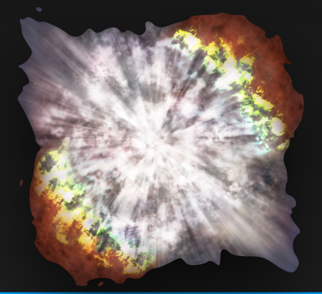

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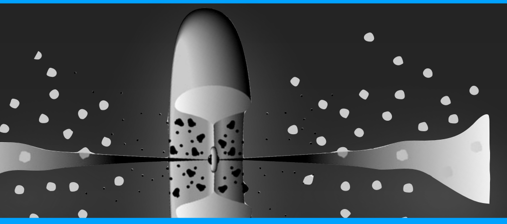
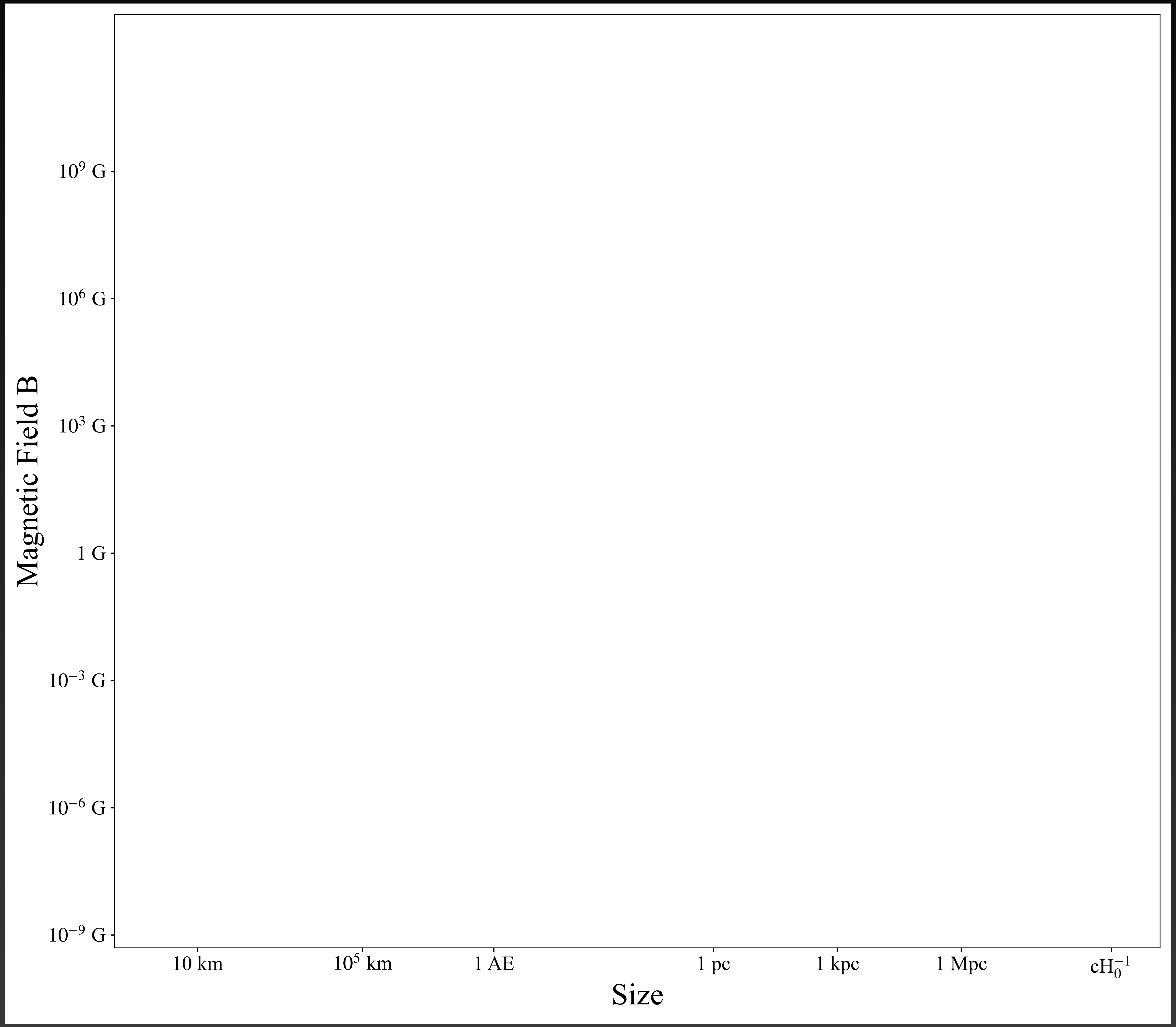


Spectral lines / photon radiation fields

γ rays

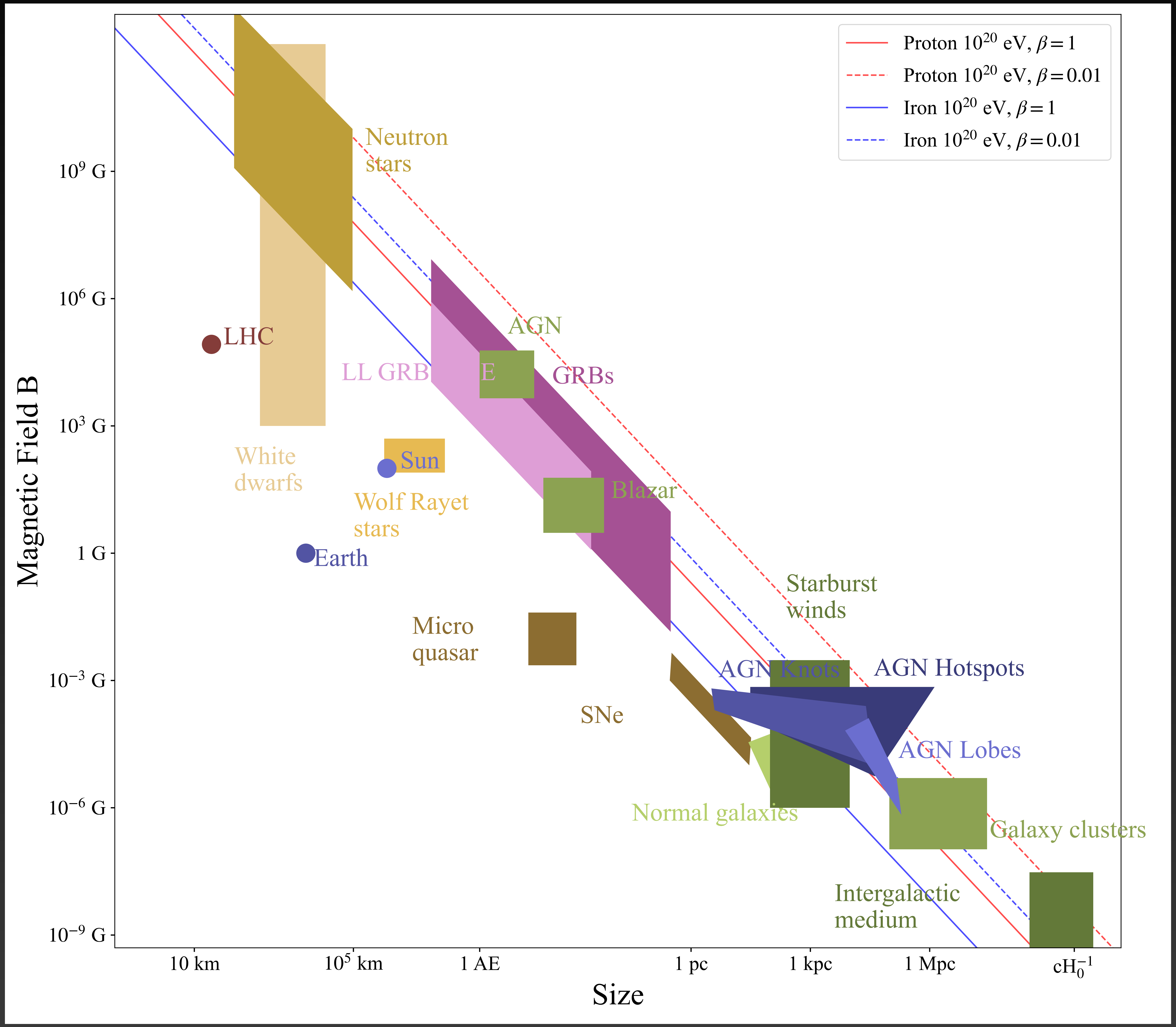
Astrophysical magnetic fields

Magnetic fields in the Universe



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

Magnetic fields in the Universe



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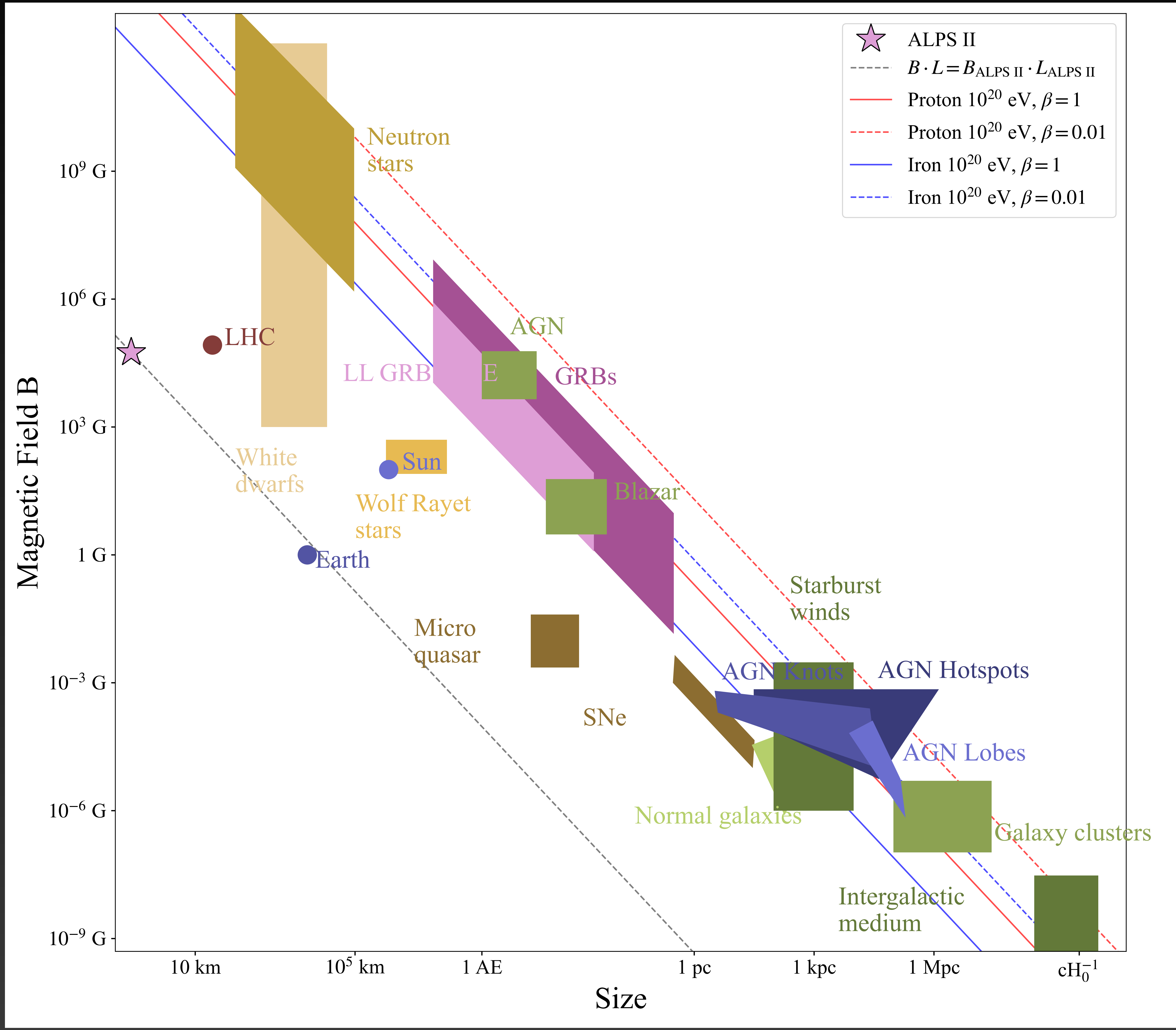

[Hillas 1984,
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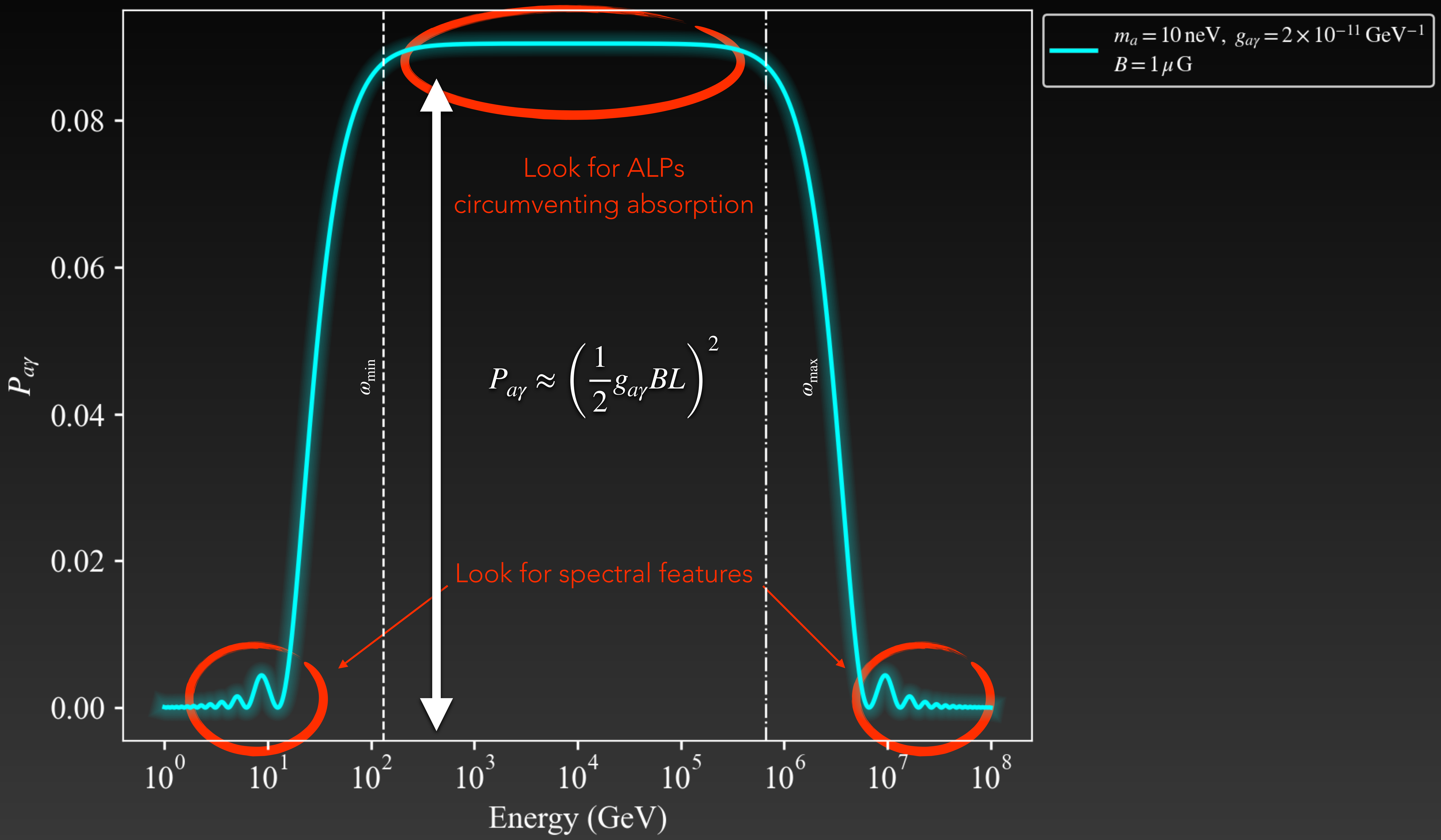
Photon-Axion/ALP Mixing on Galactic scales (10 kpc)



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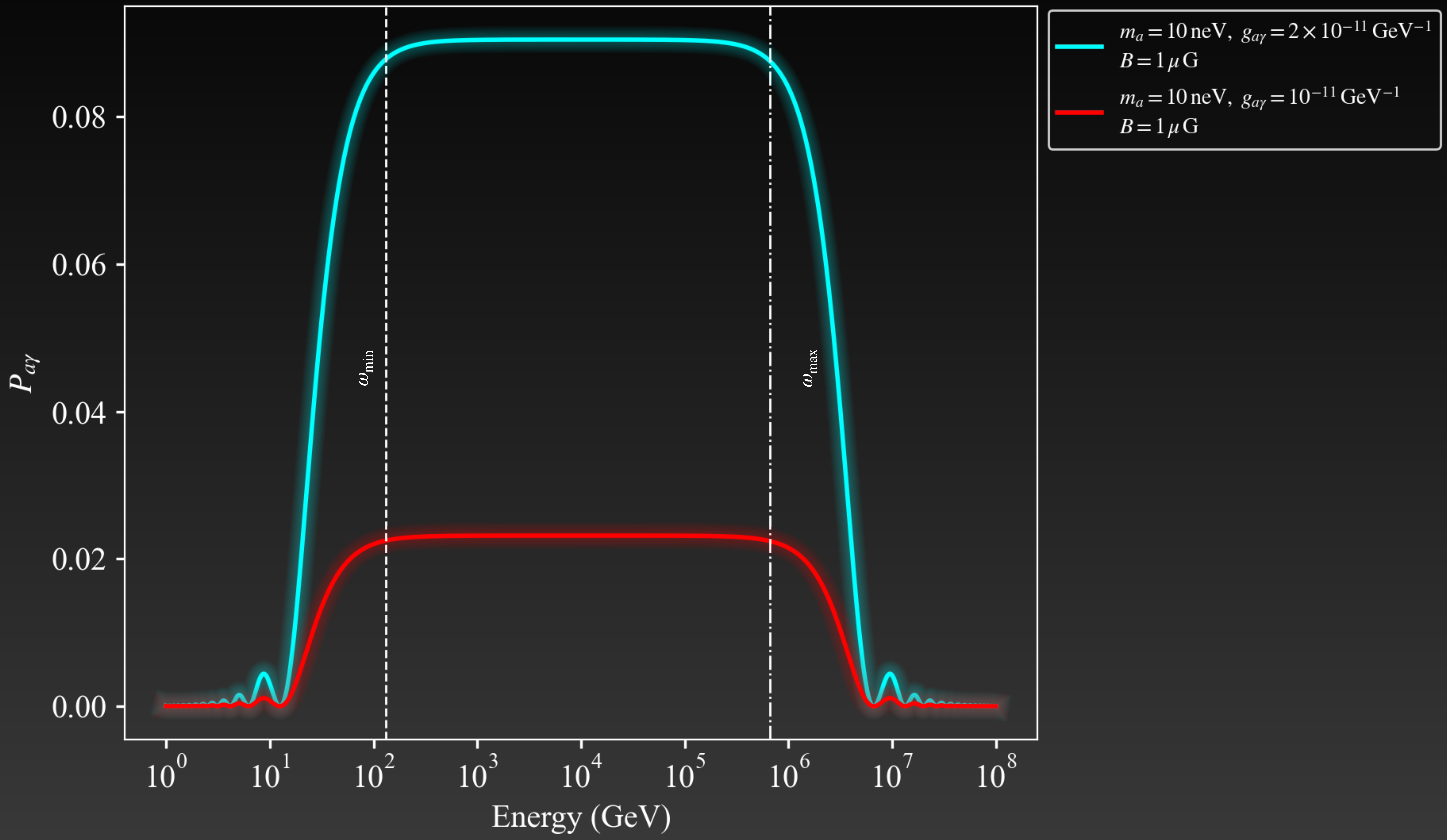

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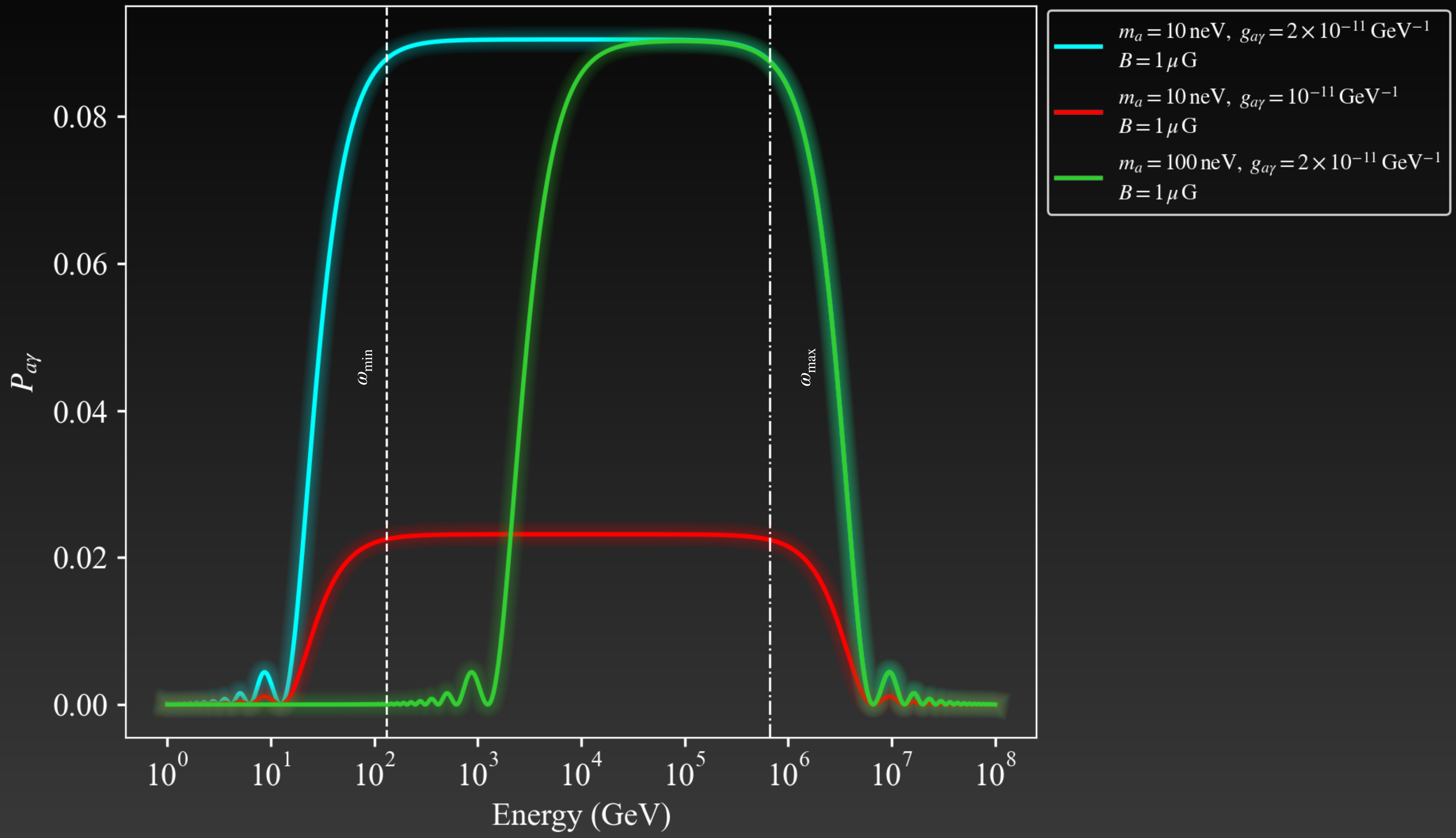

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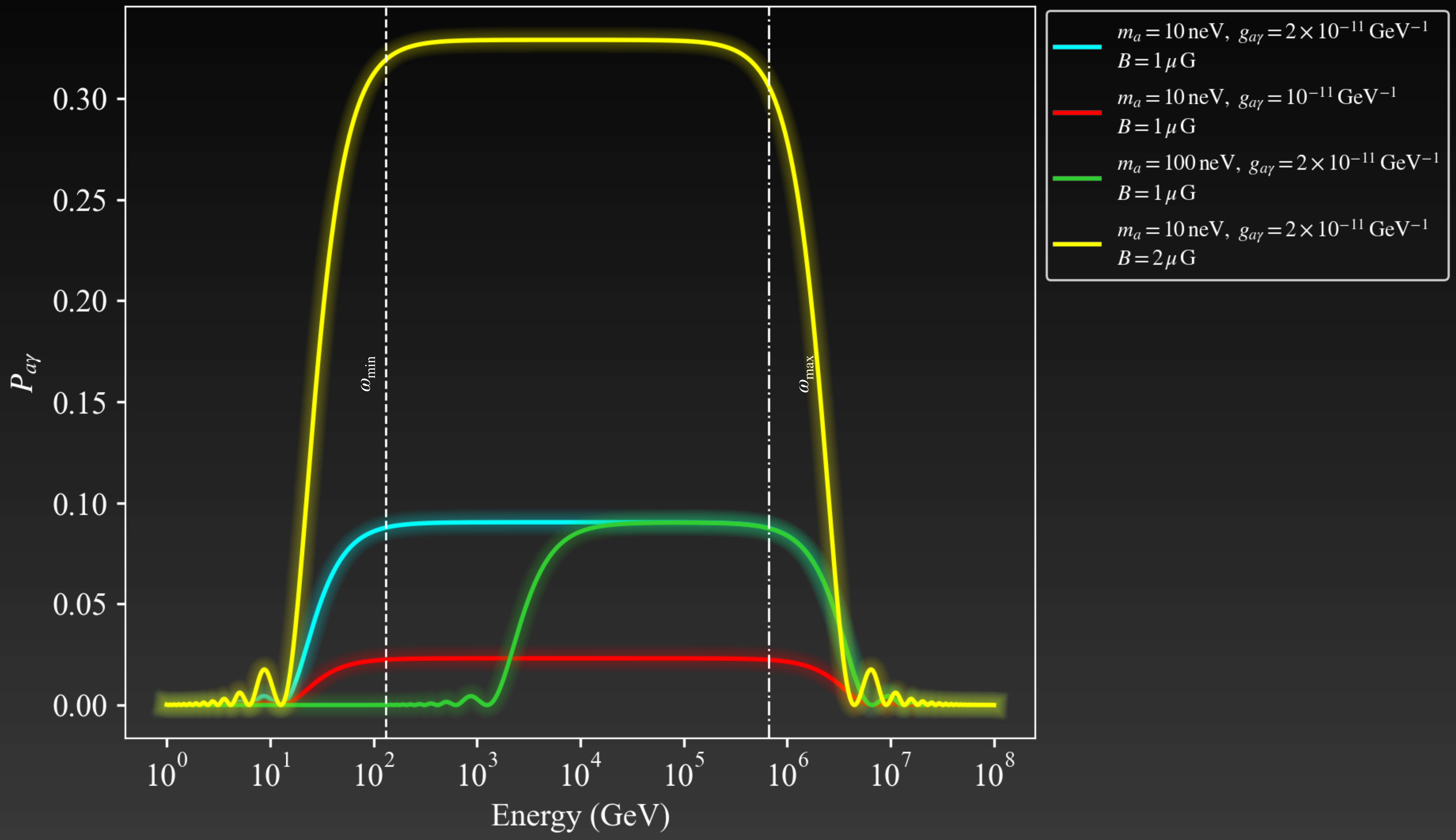
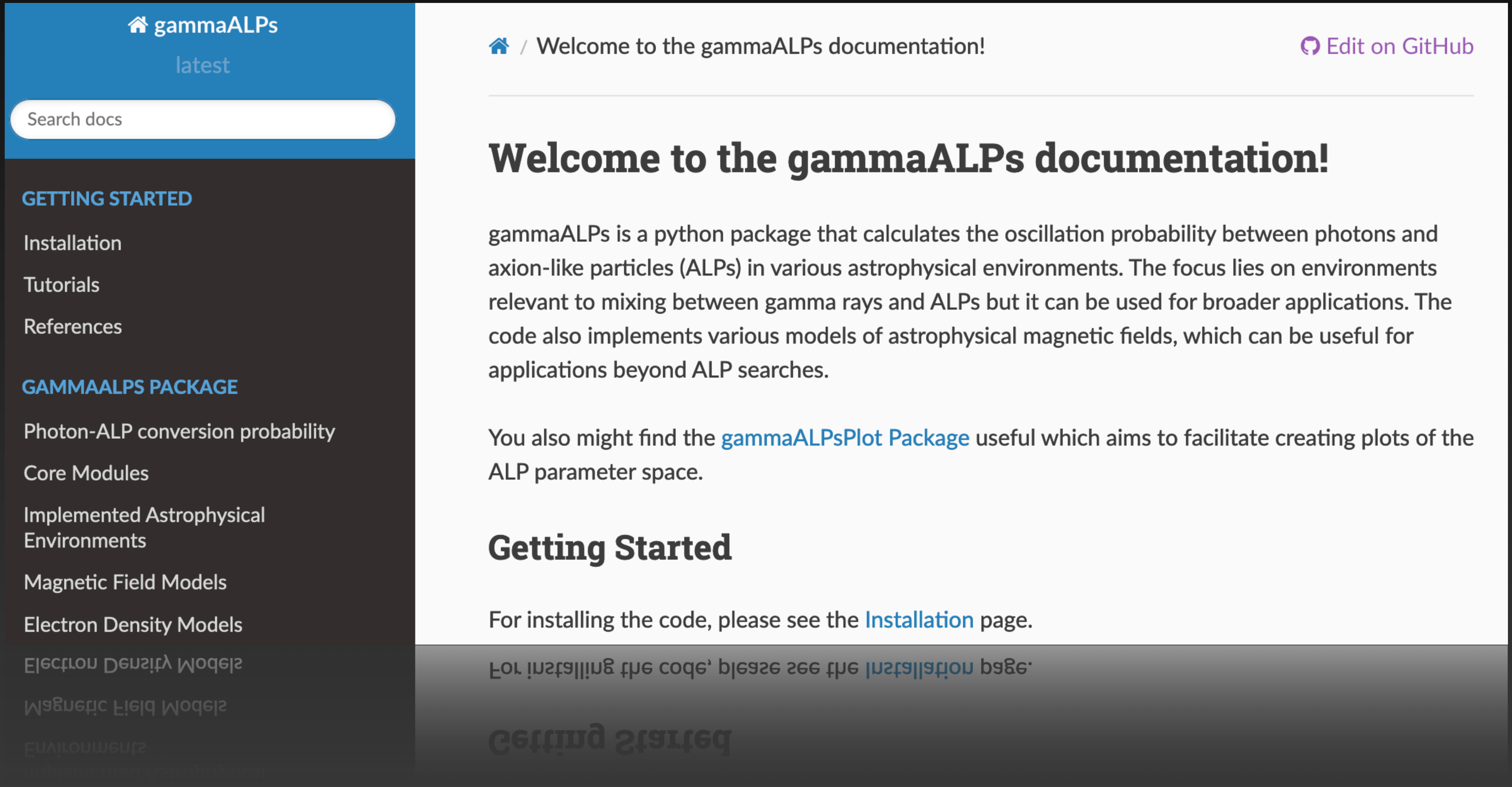


Gamma ALPs

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


gammaALPs
latest
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GETTING STARTED
Installation
Tutorials
References

GAMMAALPS PACKAGE
Photon-ALP conversion probability
Core Modules
Implemented Astrophysical Environments
Magnetic Field Models
Electron Density Models

/ Welcome to the gammaALPs documentation!
Edit on GitHub

Welcome to the gammaALPs documentation!

gammaALPs is a python package that calculates the oscillation probability between photons and axion-like particles (ALPs) in various astrophysical environments. The focus lies on environments relevant to mixing between gamma rays and ALPs but it can be used for broader applications. The code also implements various models of astrophysical magnetic fields, which can be useful for applications beyond ALP searches.

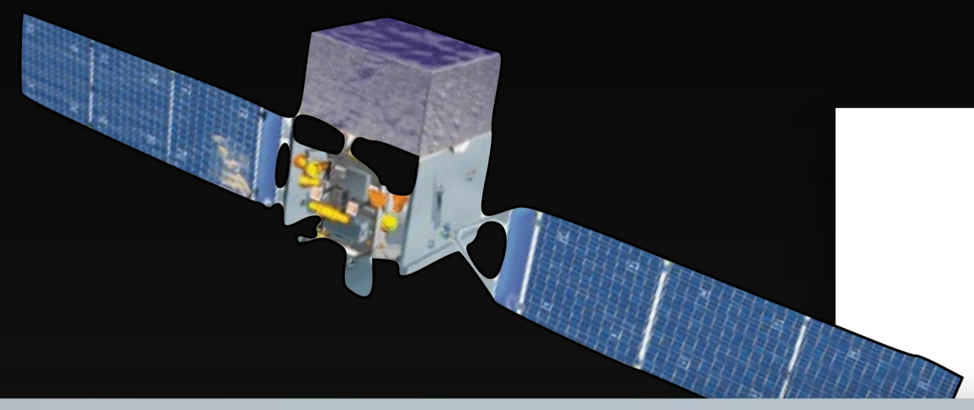
You also might find the gammaALPsPlot Package useful which aims to facilitate creating plots of the ALP parameter space.

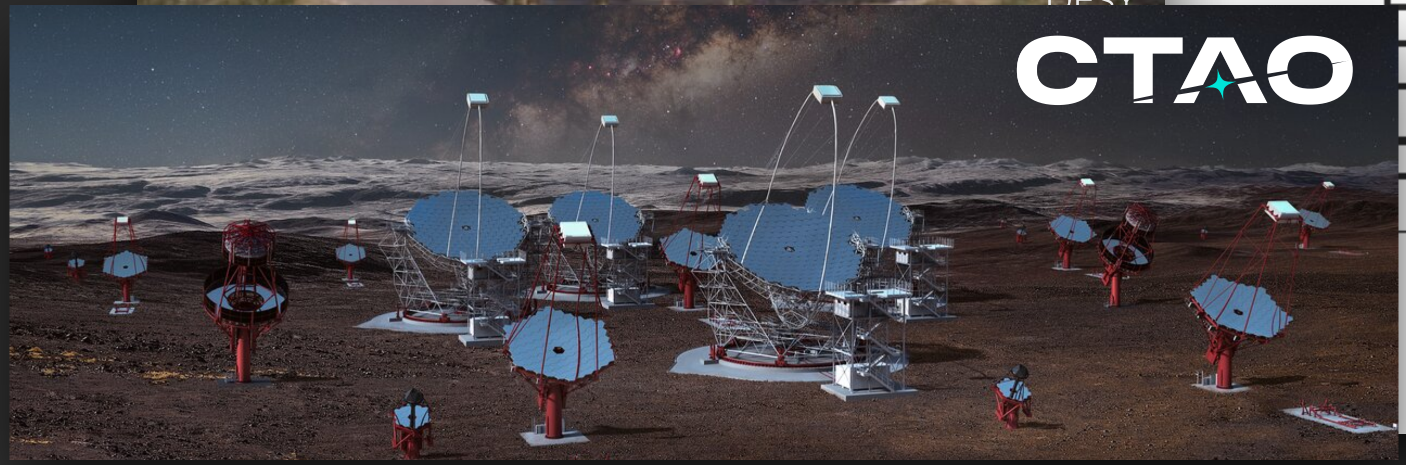
Getting Started

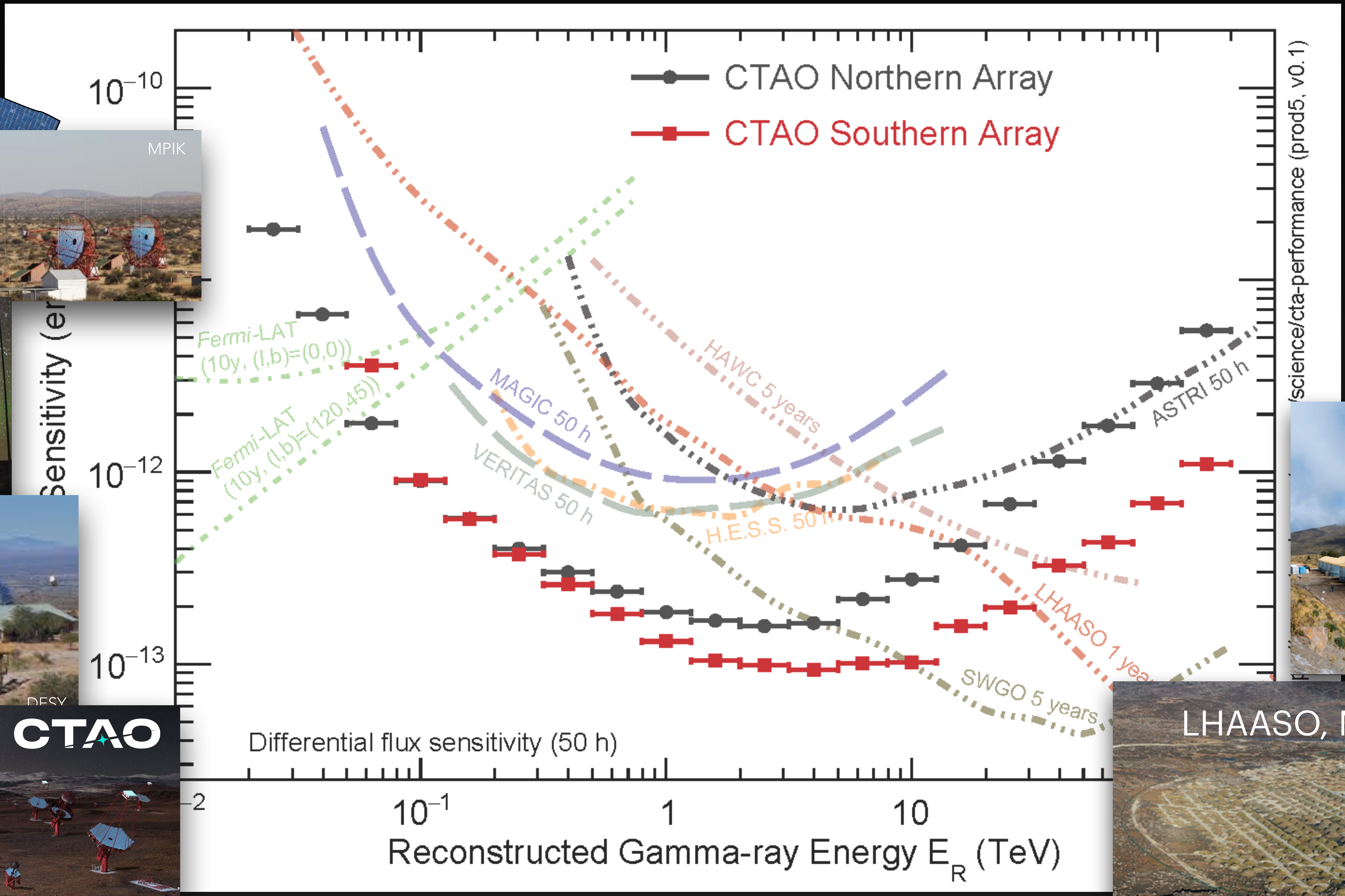
For installing the code, please see the Installation page.

- 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]

Gamma-ray telescopes

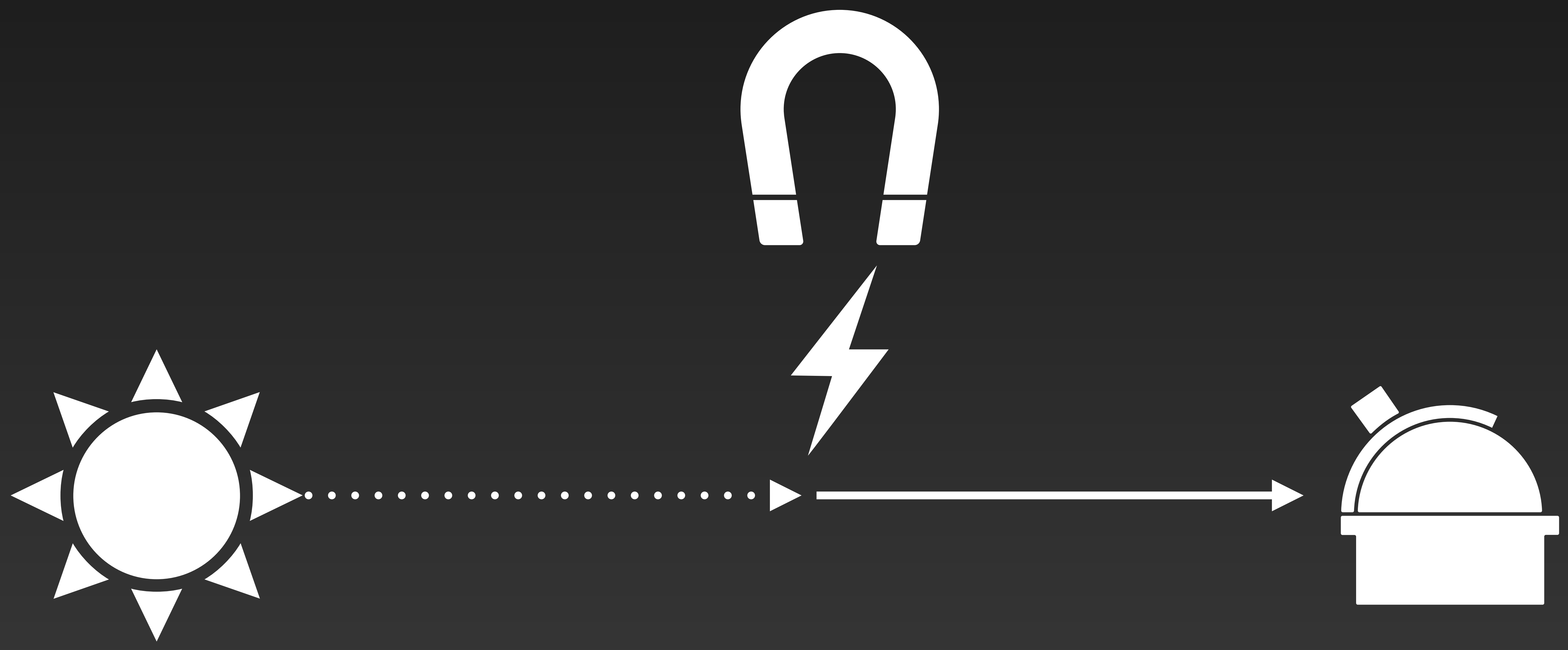






https://www.cta-observatory.org/

Supernovascopes



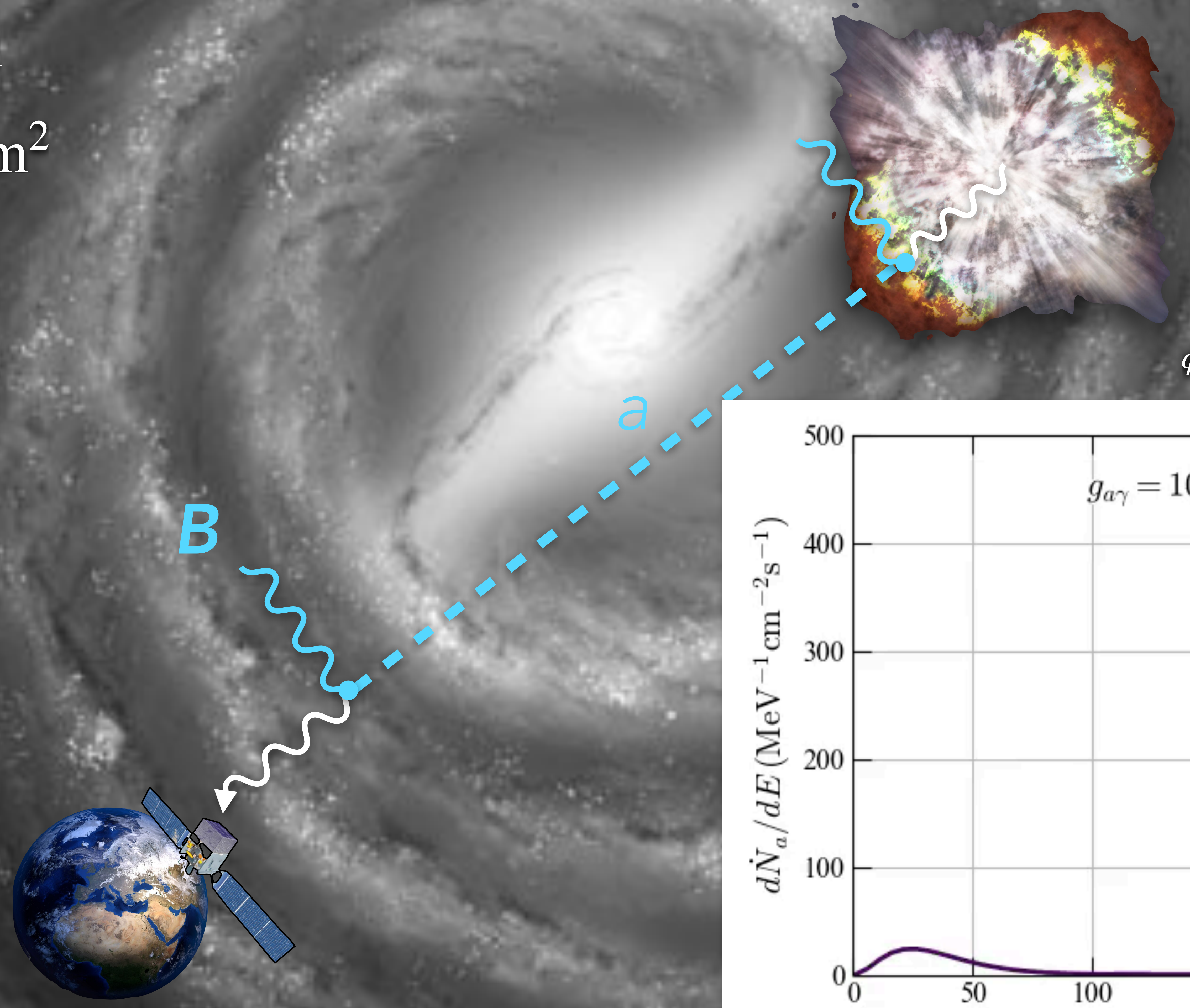
Supernovae

$\langle B_\perp \rangle \approx 1\,\mu\mathrm{G}$

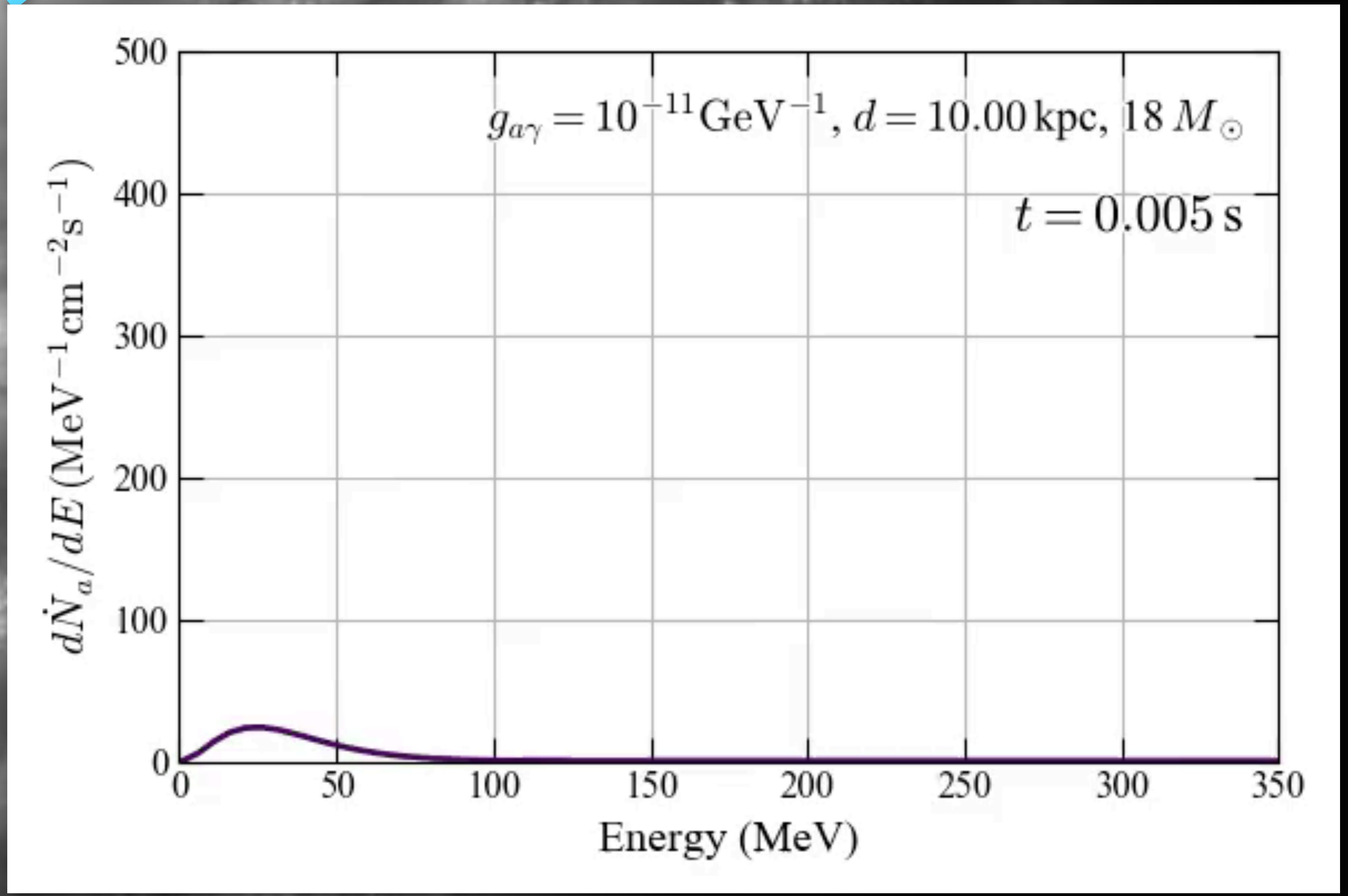
$L = 10\,\mathrm{kpc}$

$P_{a\gamma} \approx 0.1$

$A \approx 0.5\,\mathrm{m}^2$



$\phi_a \approx 10^5\,\mathrm{s}^{-1}\mathrm{cm}^{-2}(g_{a\gamma}/2\times10^{-11}\,\mathrm{GeV}^{-1})^2$



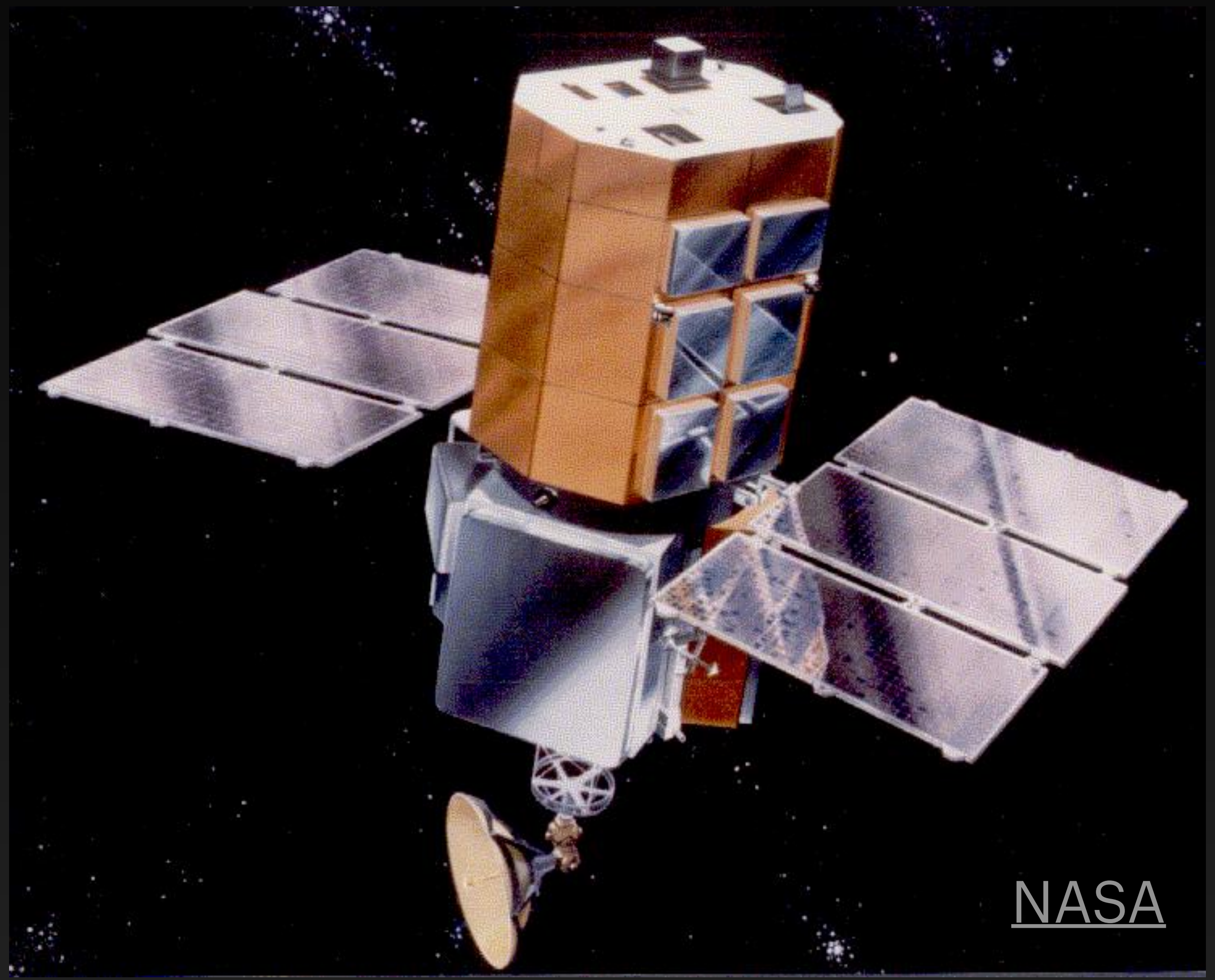
$\phi \approx 4\times10^7$ photons s^{-1}

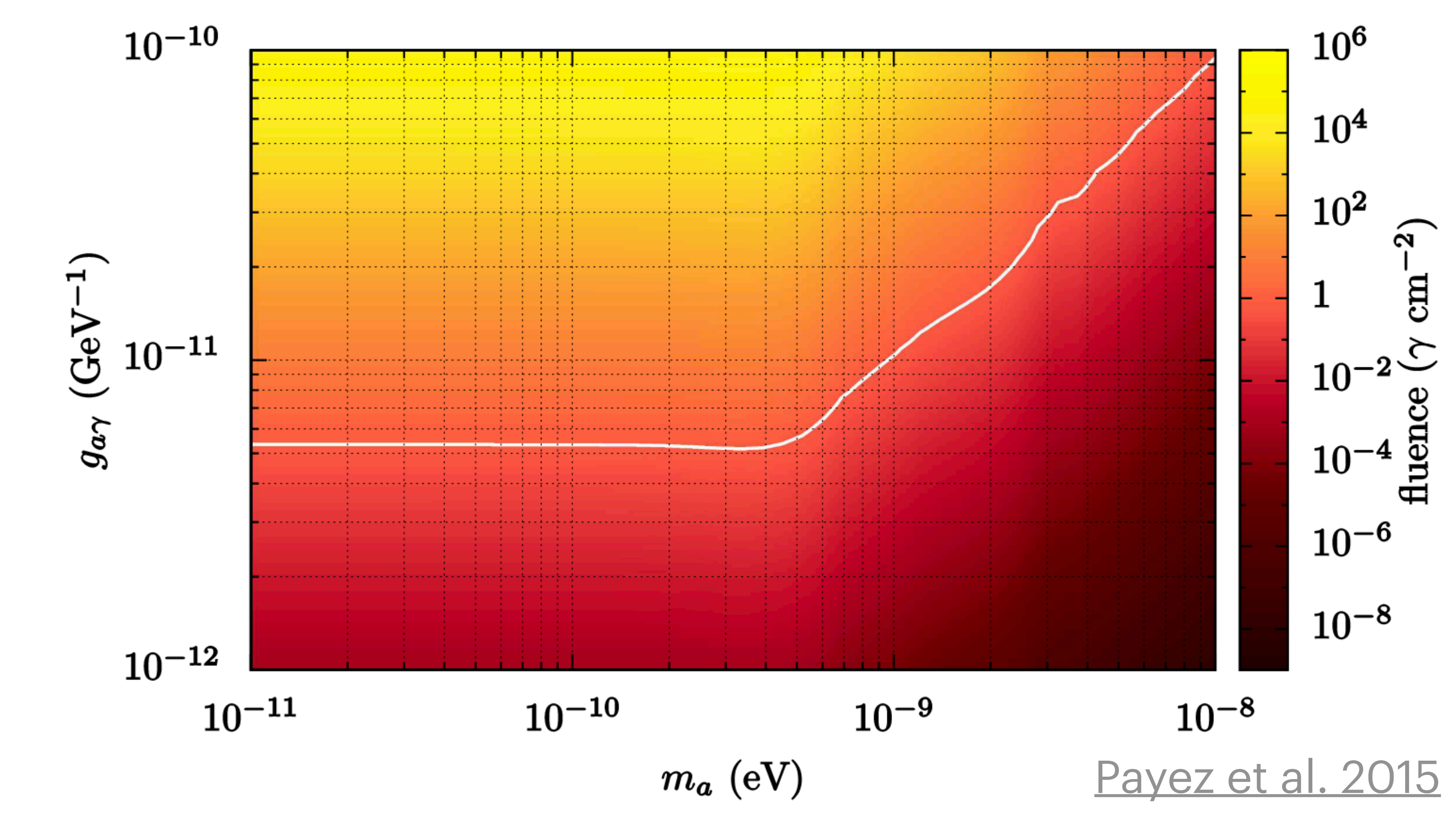
(for 20 seconds, scales as $g_{a\gamma}^4$)

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

Gamma-ray bursts constraints from SN1987A

- SN1987A was inside field of view (at 90º incidence) of Gamma-ray Spectrometer (GRS) on-board NASA's solar maximum mission
- No gamma rays observed
- Gamma-ray fluence (= gamma-ray flux integrated over time) between $25\,\mathrm{MeV} \leqslant E \leqslant 100\,\mathrm{MeV}$ limited to $< 0.6\,\mathrm{cm}^{-2}$ at $3\,\sigma$ C.L.
- Non-observation provides limits on photon-ALP coupling $g_{a\gamma} \lesssim 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$ for $m_a \lesssim 4.4 \times 10^{-10}\,\mathrm{eV}$

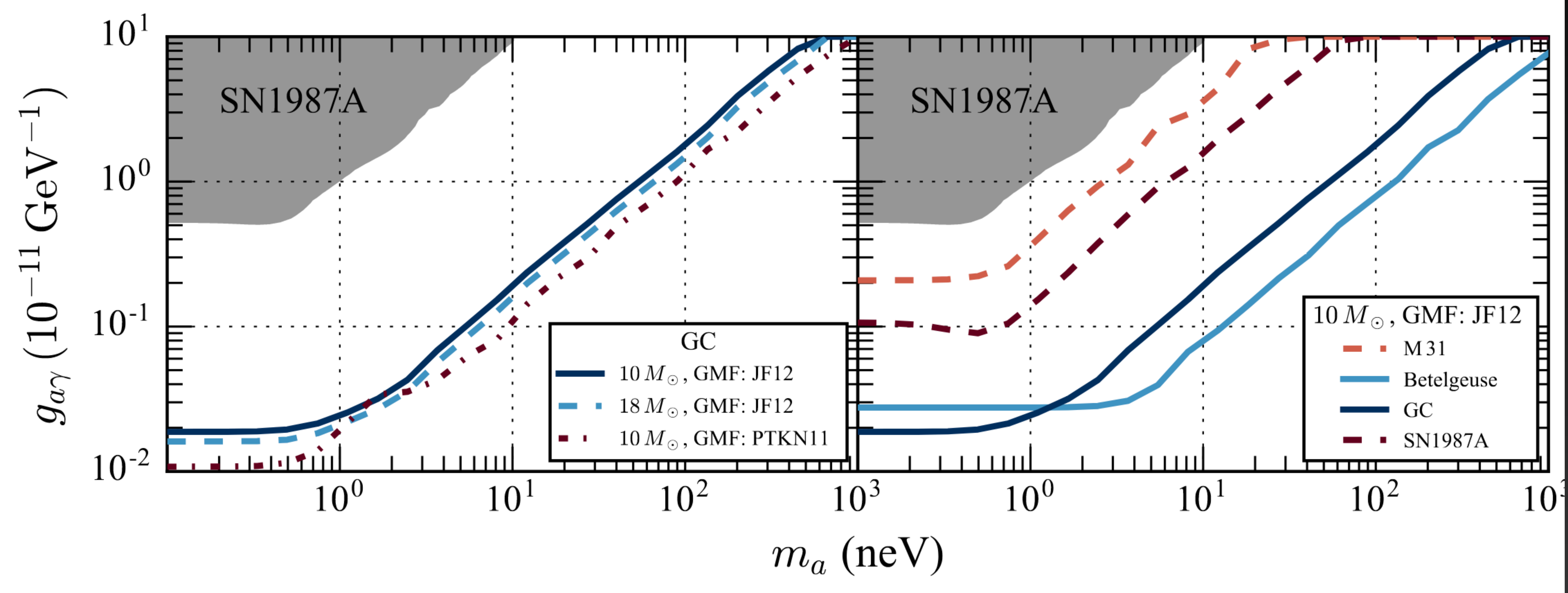




Payez et al. 2015

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]

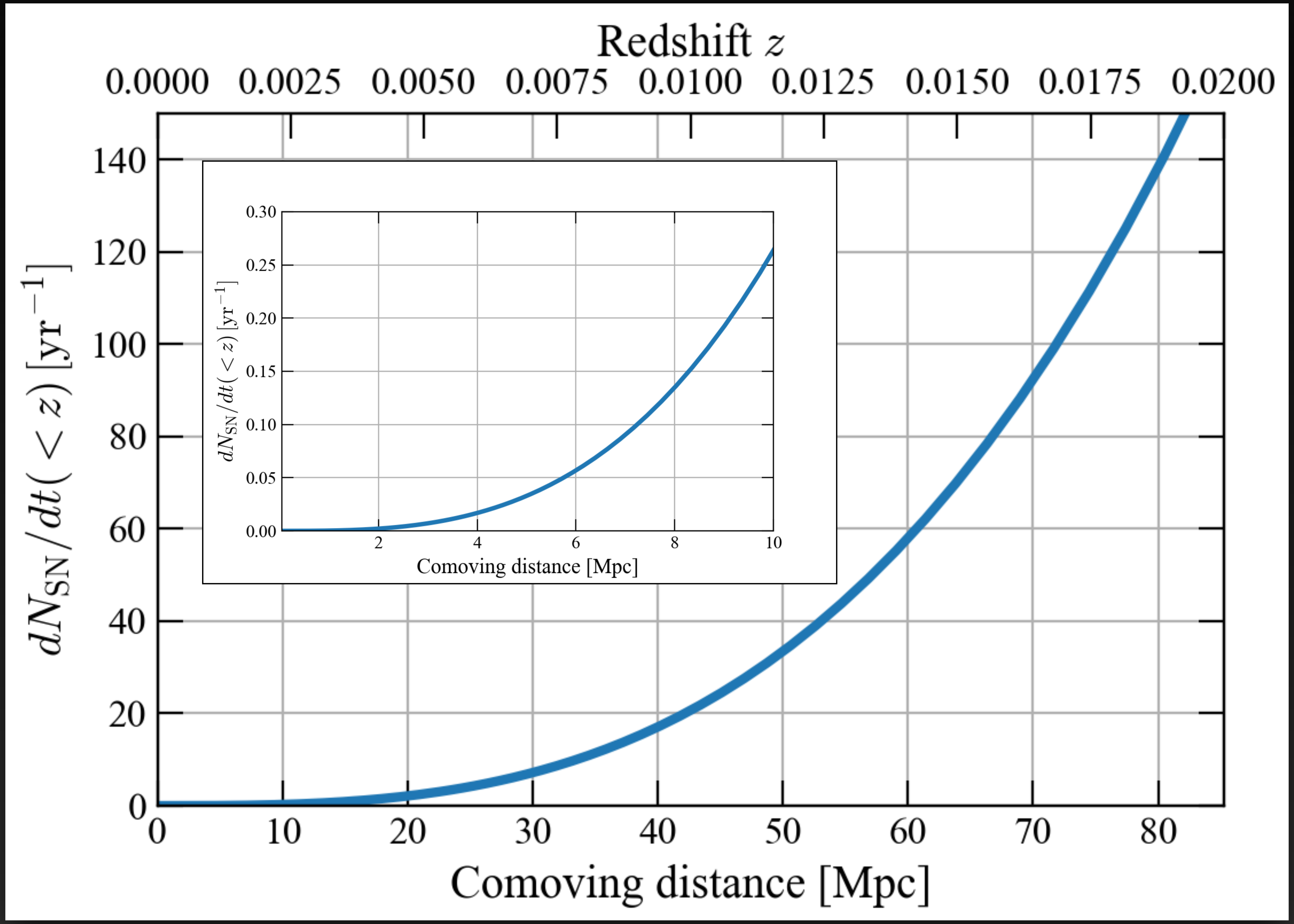
core collapse SN rate in Milky Way ~ 3% per year

LAT observers ~20% of the Sky

→ 2% chance to catch at least one such event if LAT operates for 3 more years

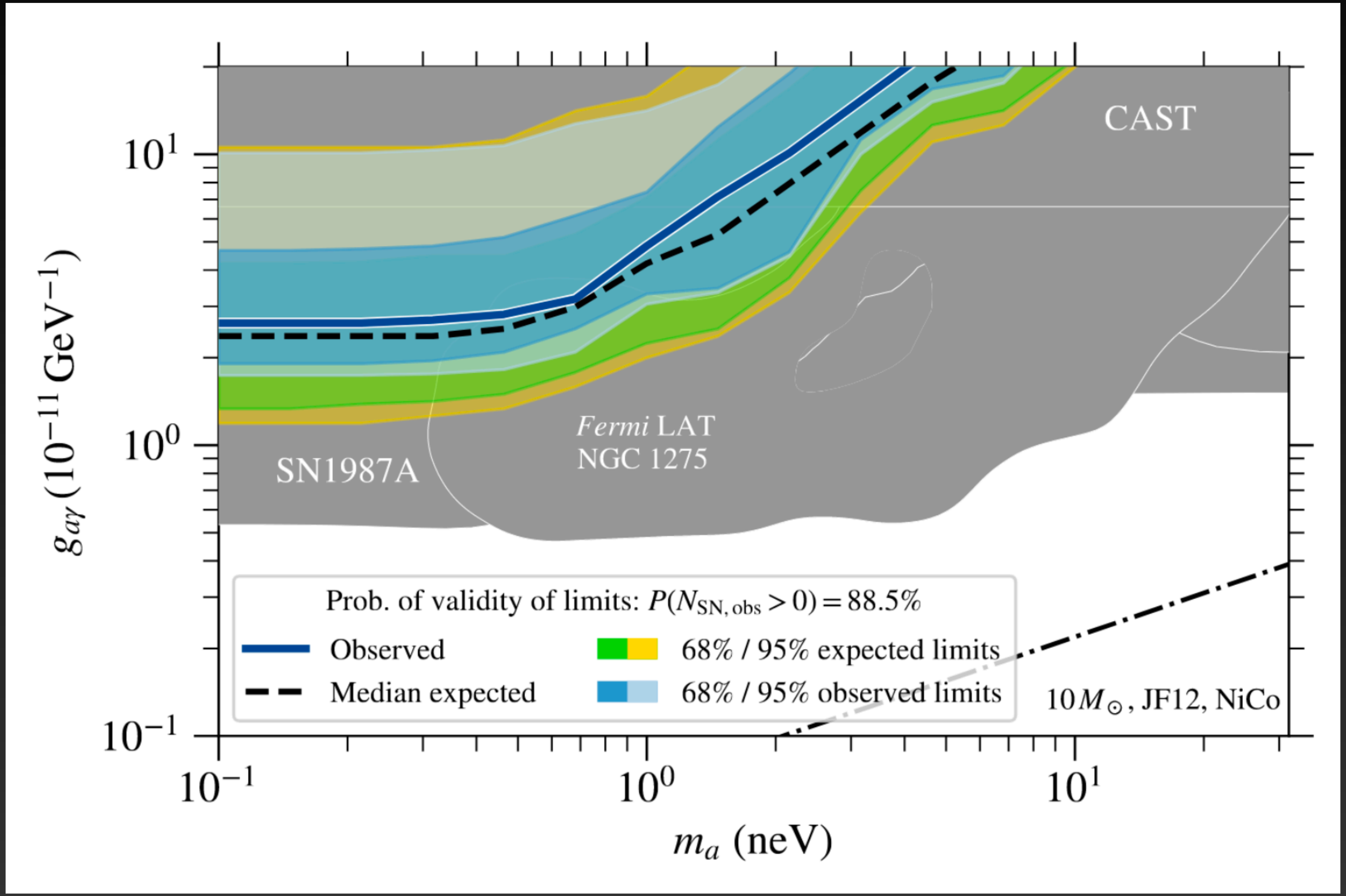
Look for Extragalactic Supernovae instead

- 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

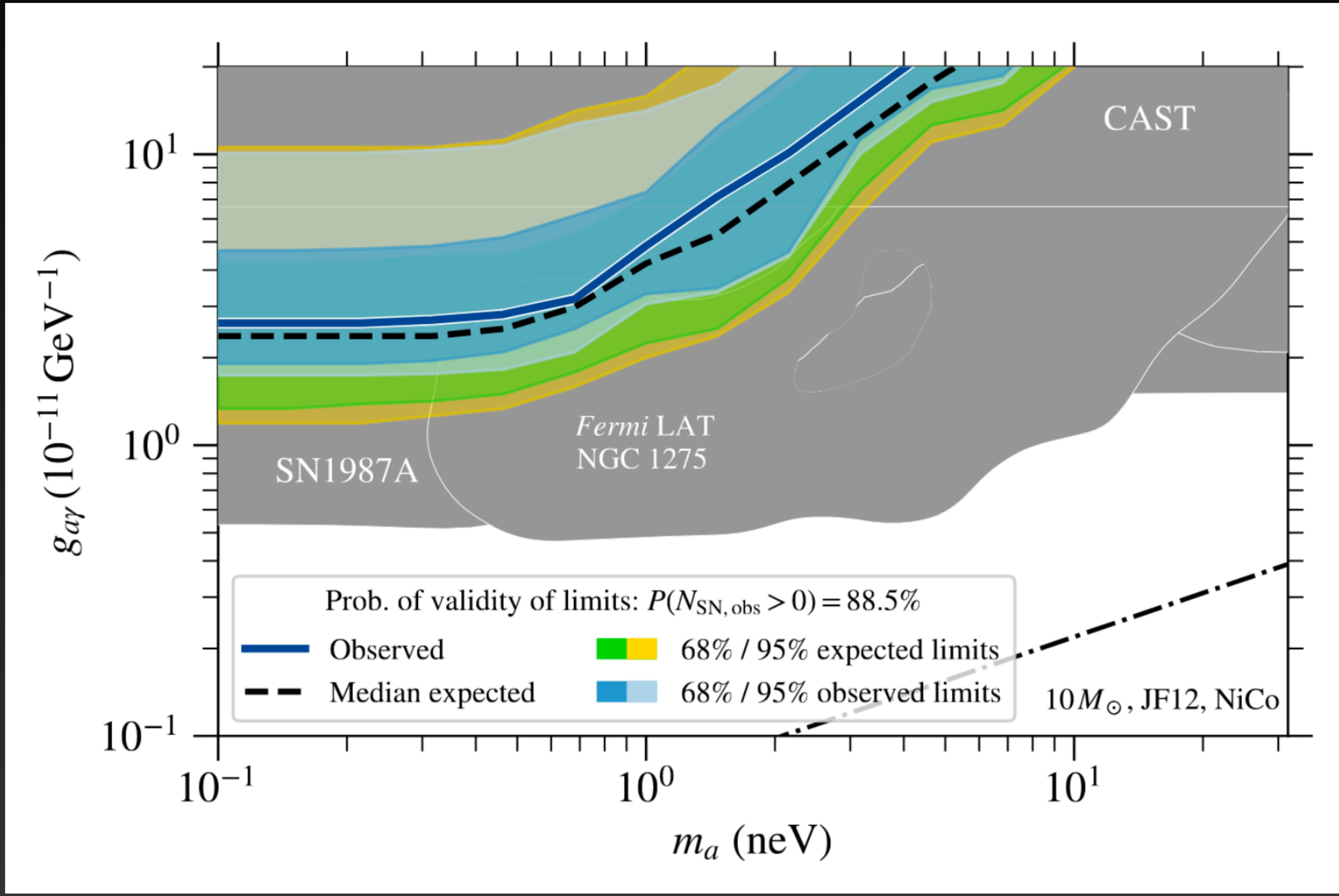
Combined limits from sample of 20 SNe detected until 2017



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

[MM & Petrushevska 2020]

SNe sample is growing

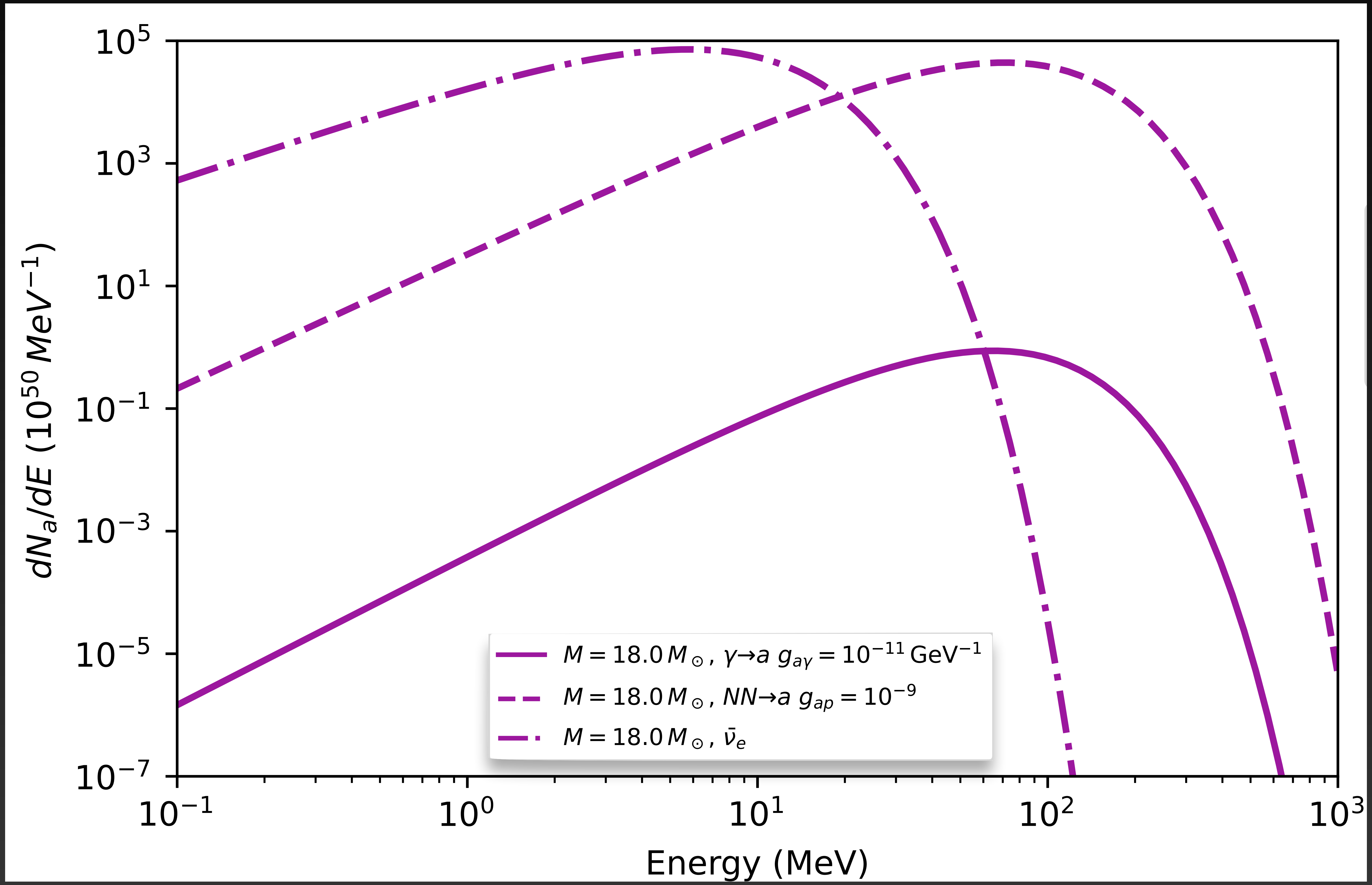


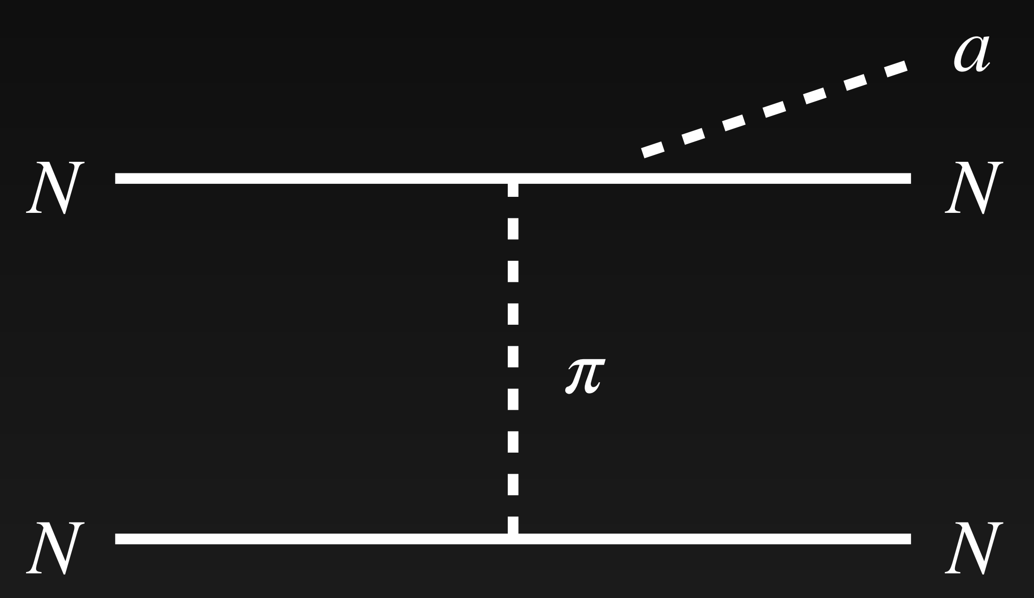
- ZTF, ASAS-SN and other surveys are already observing
- Vera Rubin Observatory will see first light in 2023
- TESS satellite provides high cadence light curves for some SNe
- Close-by SN2023ixf in already used to search for heavy ALPs [Ravensburg et al. 2024]

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

[MM & Petrushevska 2022]
[MM & Petrushevska 2020]

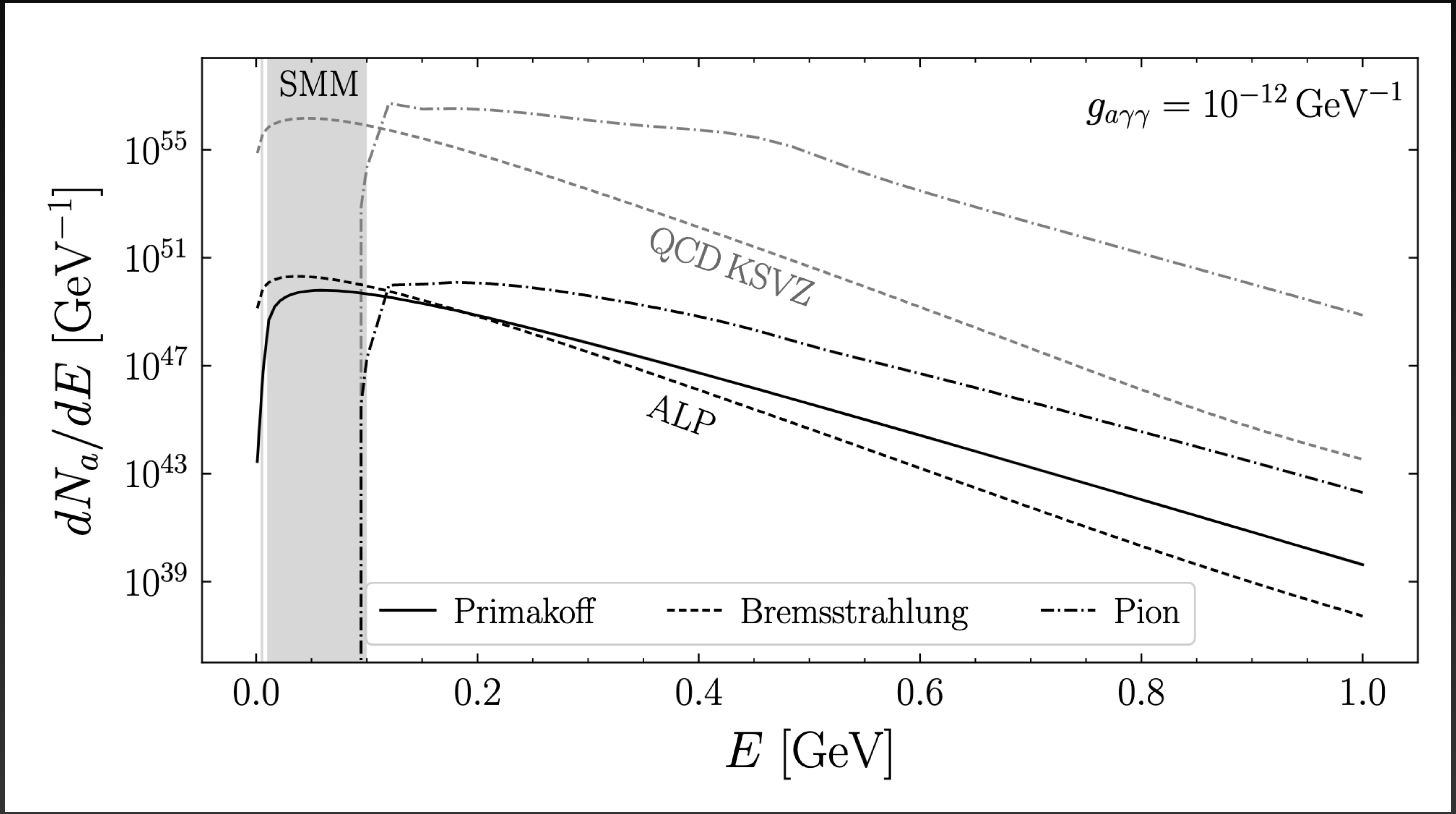
Beyond photon-ALP coupling

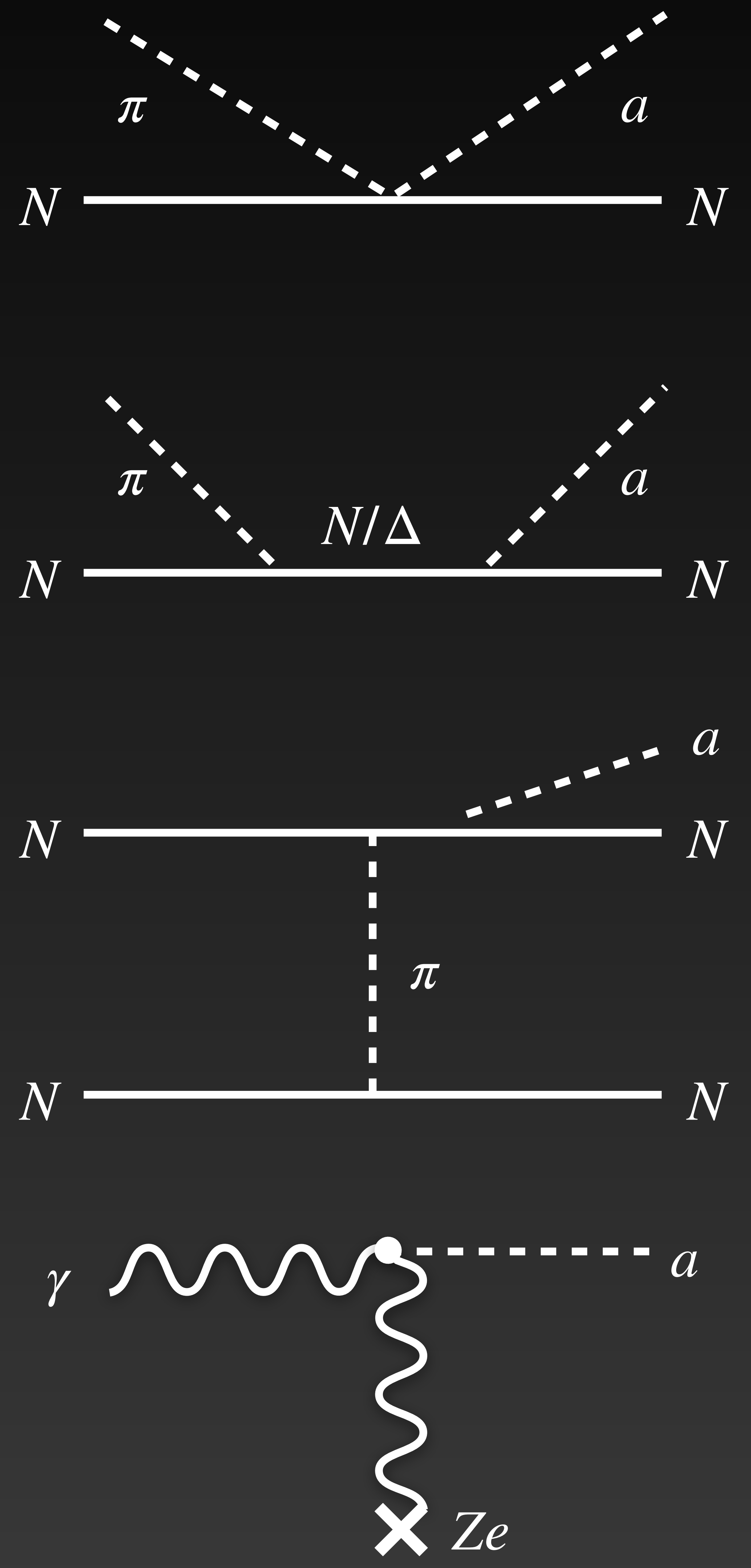




[Calore et al. 2020, 2022]

Pion-axion conversion dominates?

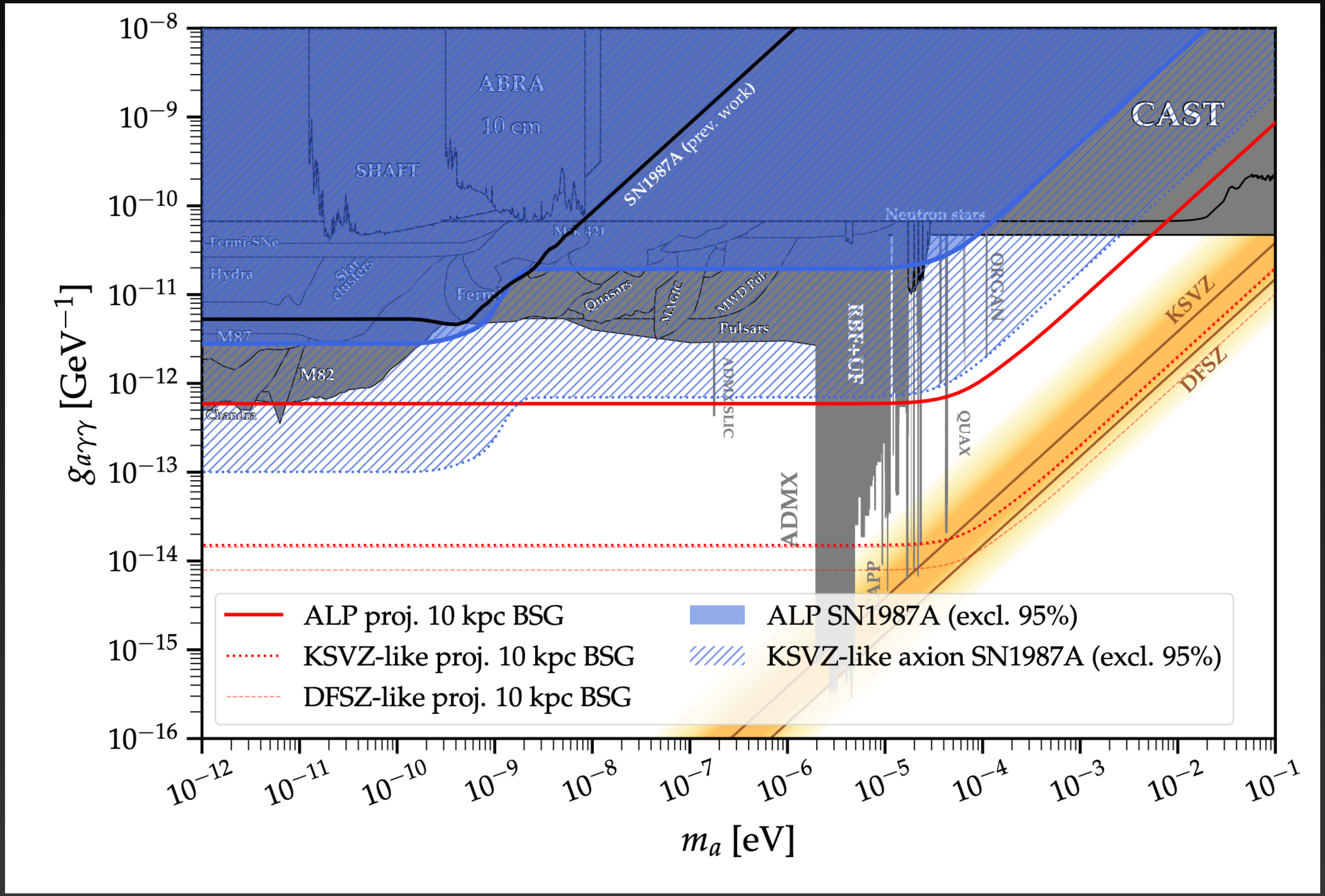




[Manzari et al. 2024]

Revised limits for SN1987A

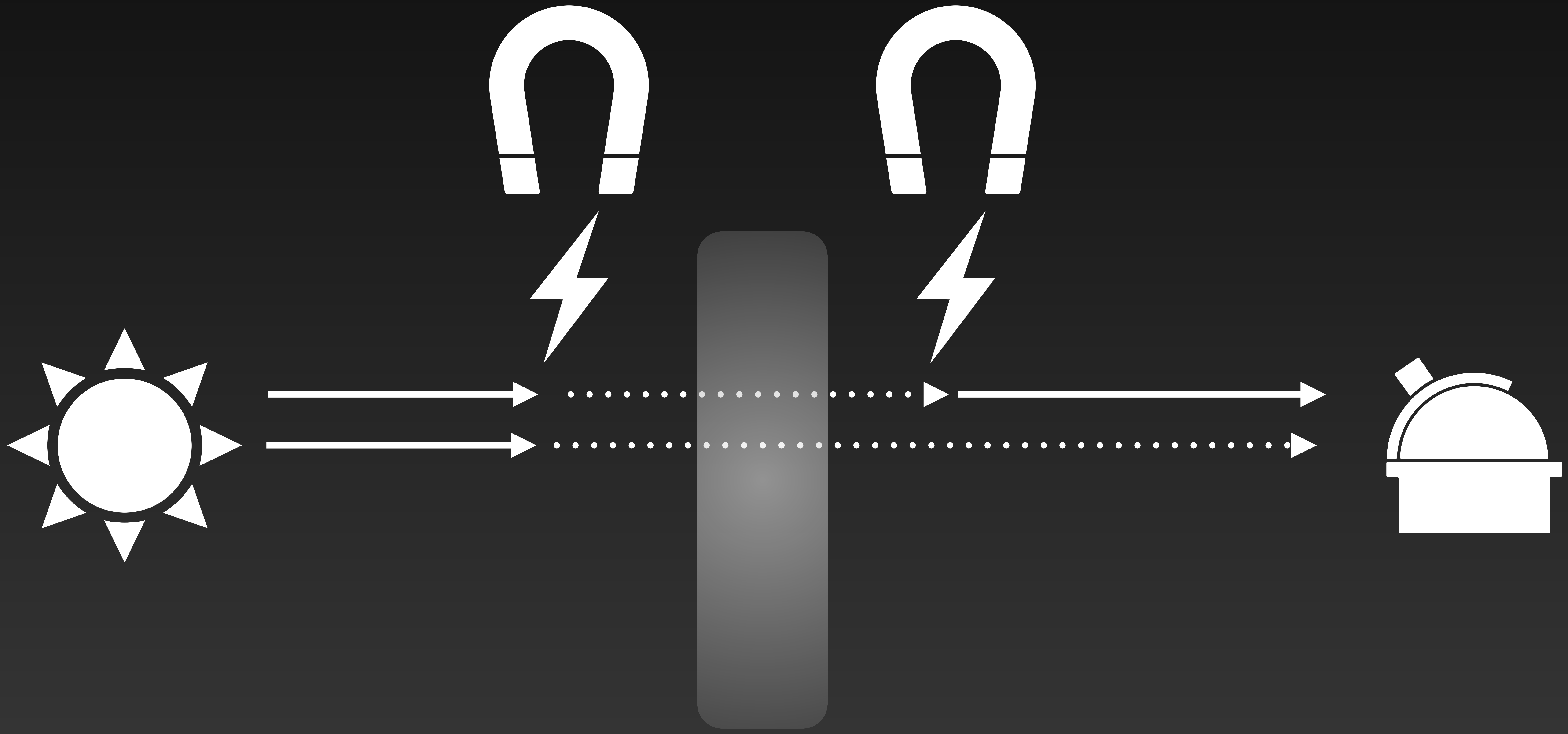
Taking pion-axion conversion and magnetic field of SN progenitor star into account



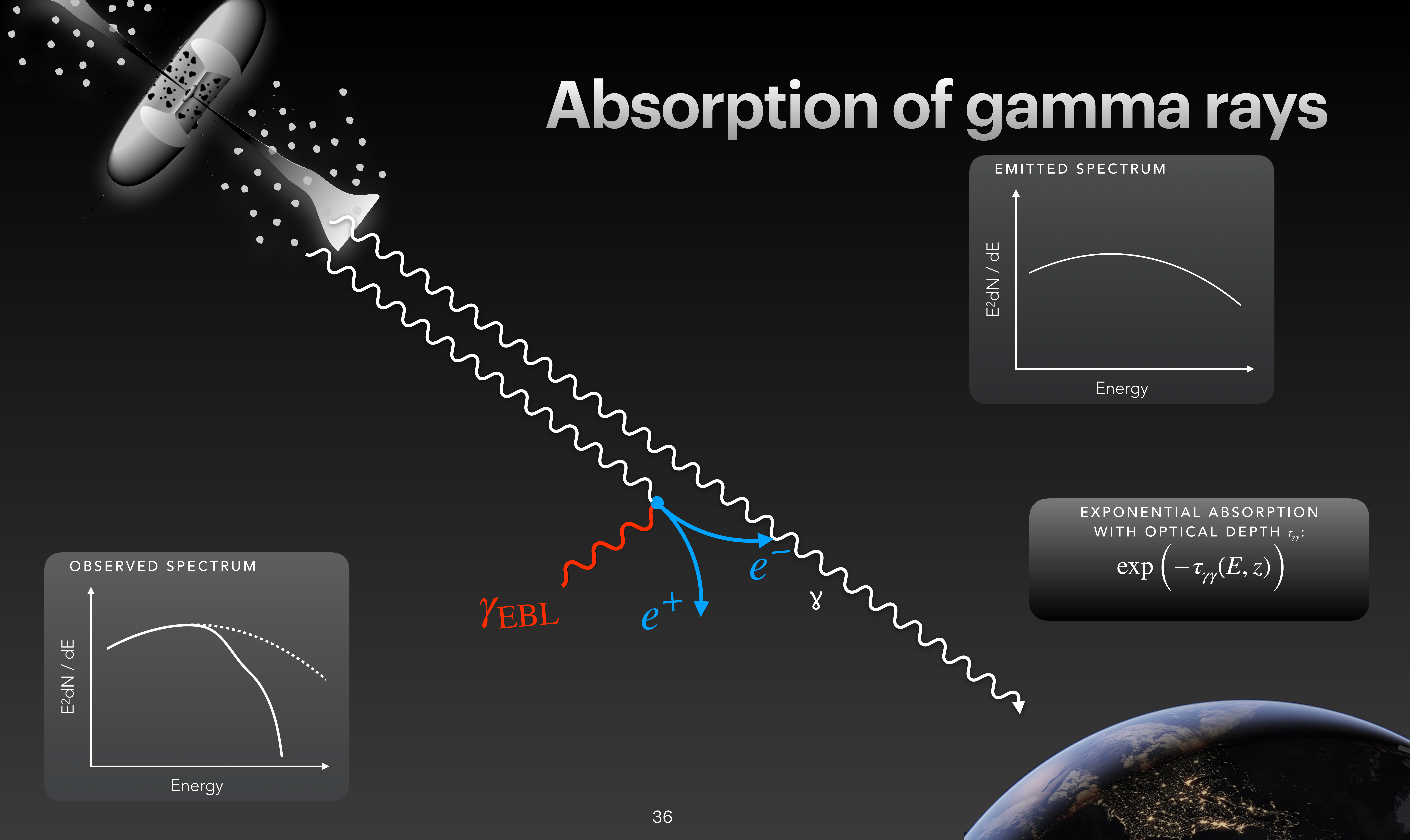
- Requires axion coupling to nucleons
- Magnetic fields of progenitor stars not well constrained

[Manzari et al. 2024]

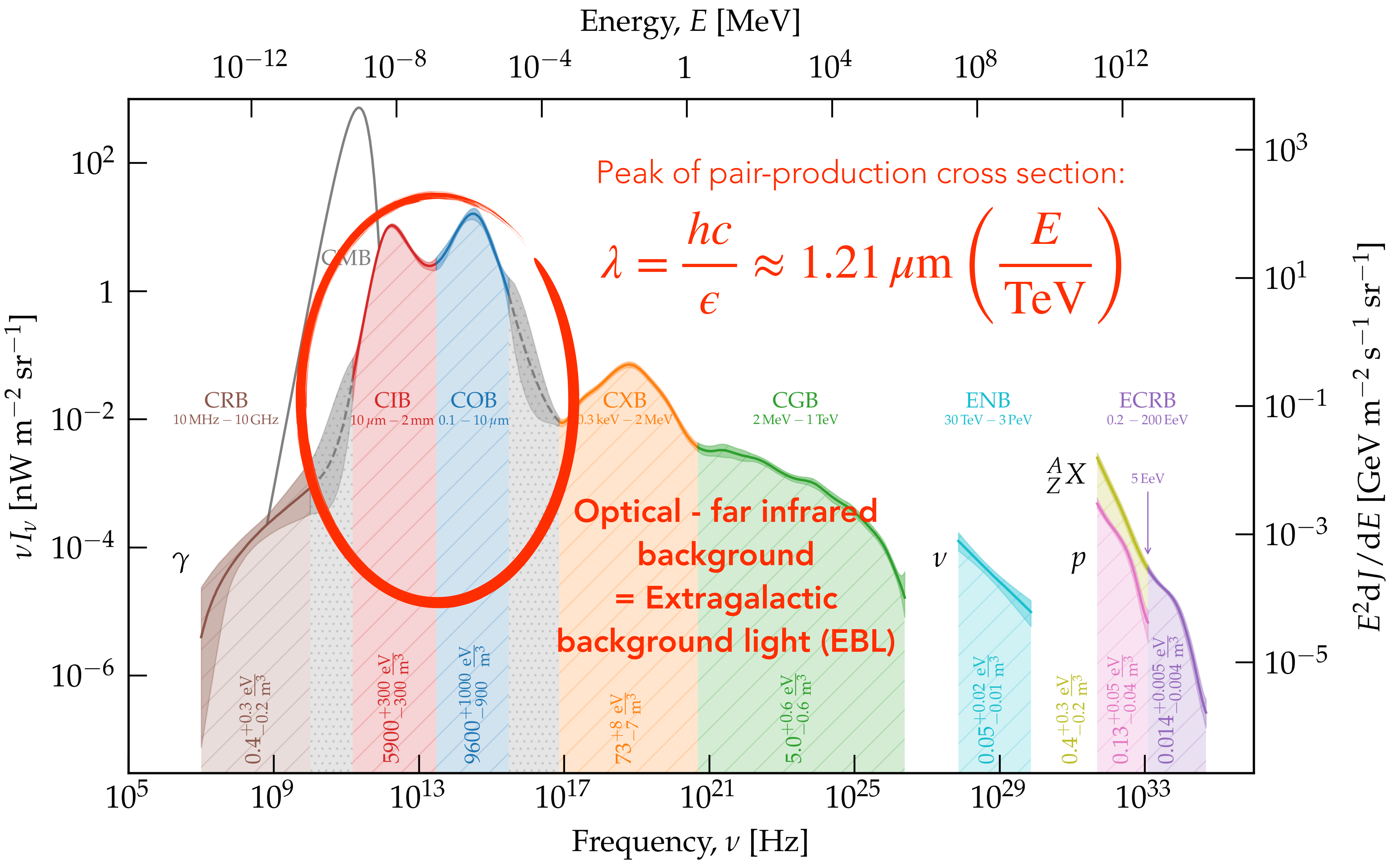
Photon disappearance and reappearance



Absorption of gamma rays

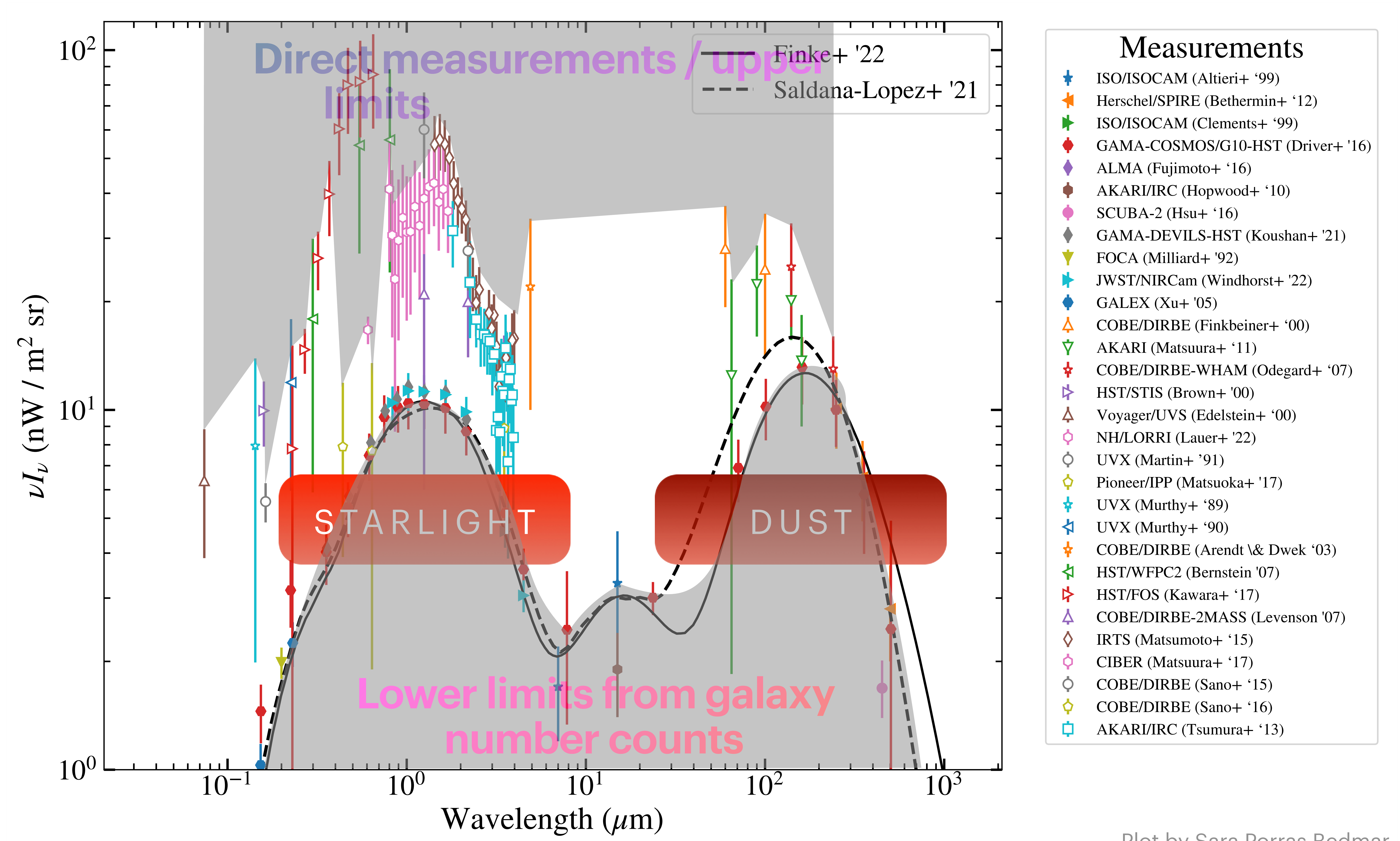


Background radiation fields



Biteau (2024), 10.5281/zenodo.7842238

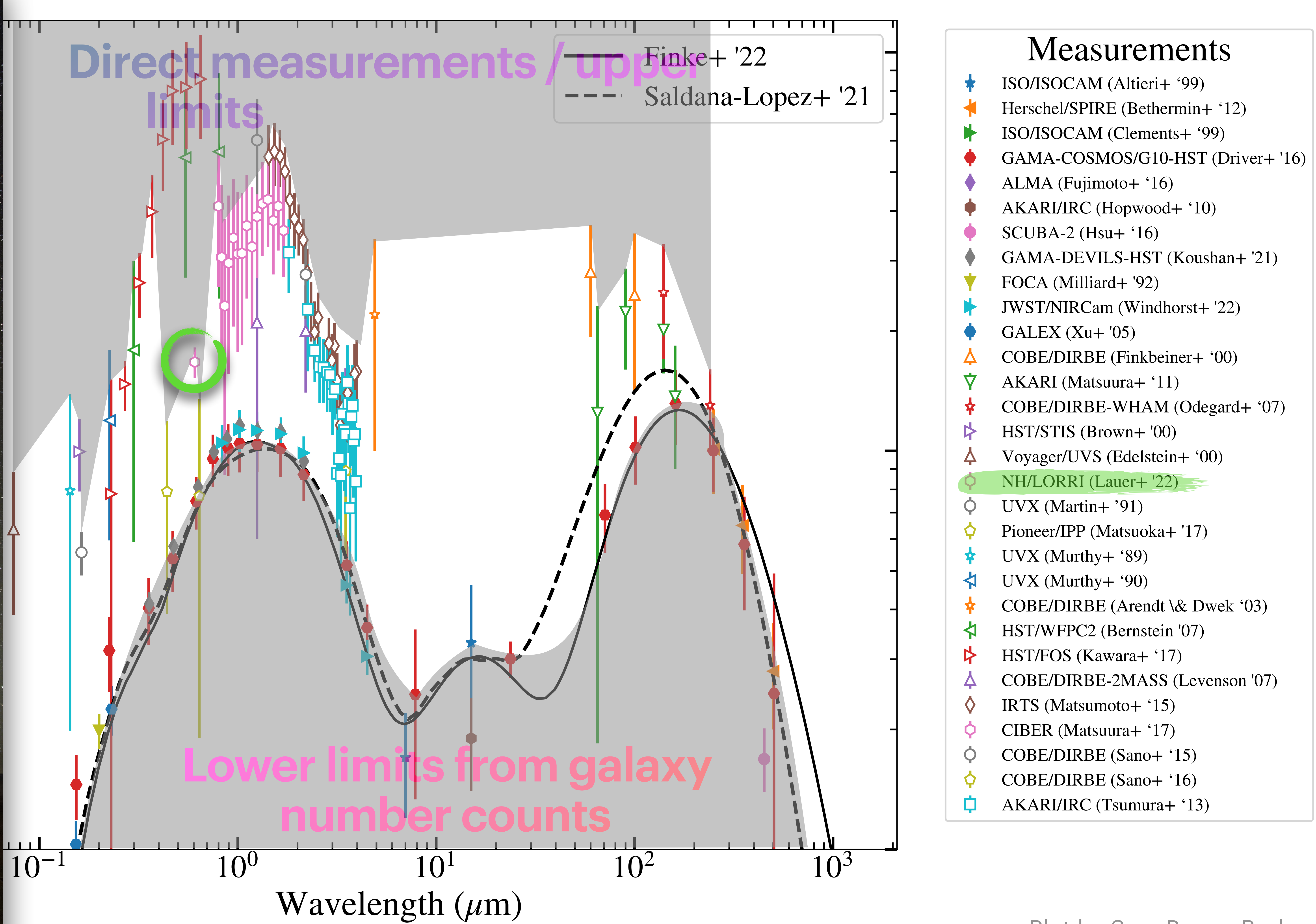
EBL Measurements



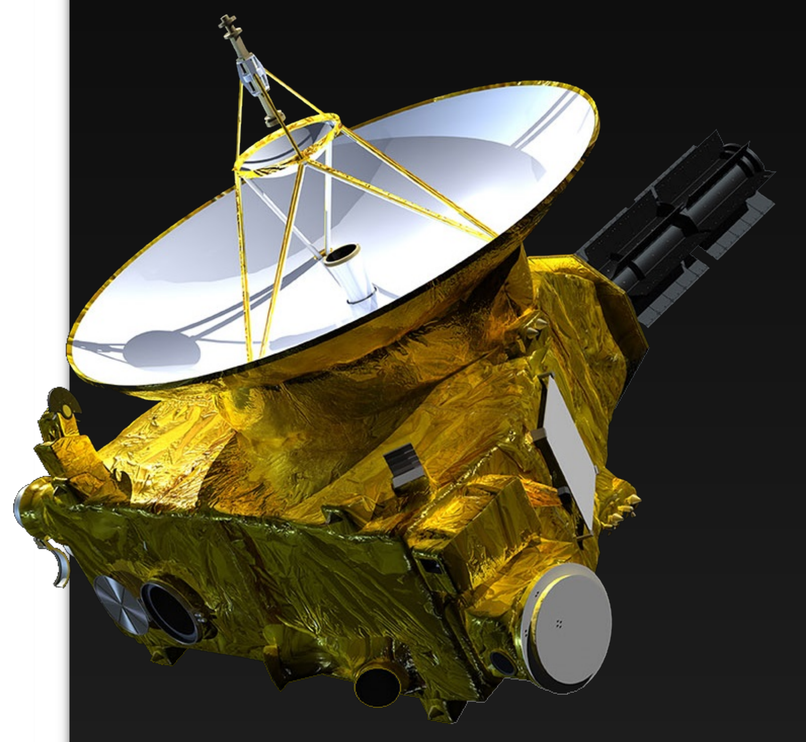
Plot by Sara Porras Bedmar

Biteau (2024), 10.5281/zenodo.7842238
[e.g., Hauser & Dwek 2001, Dwek & Krennrich 2013]

EBL Measurements



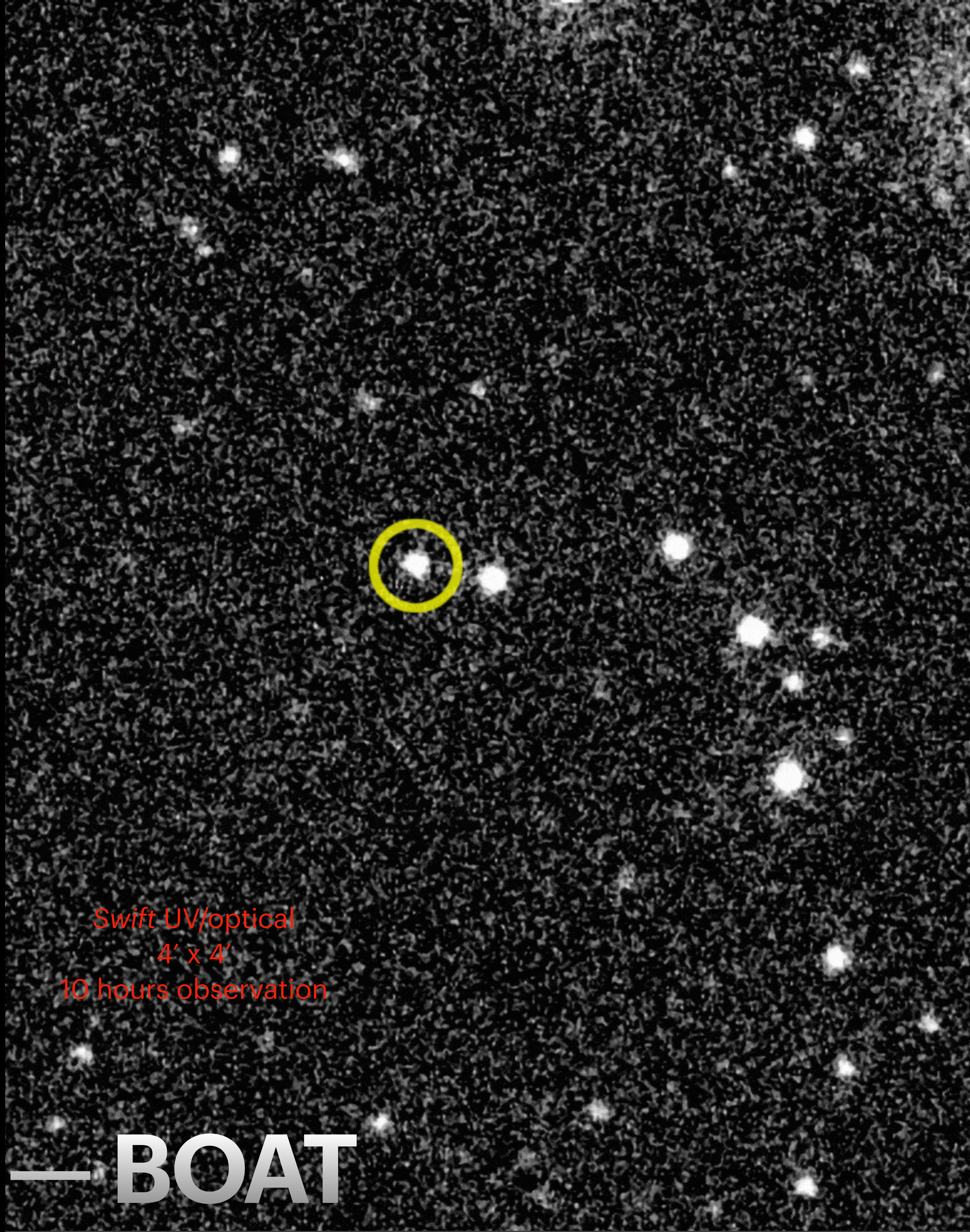
Plot by Sara Porras Bedmar



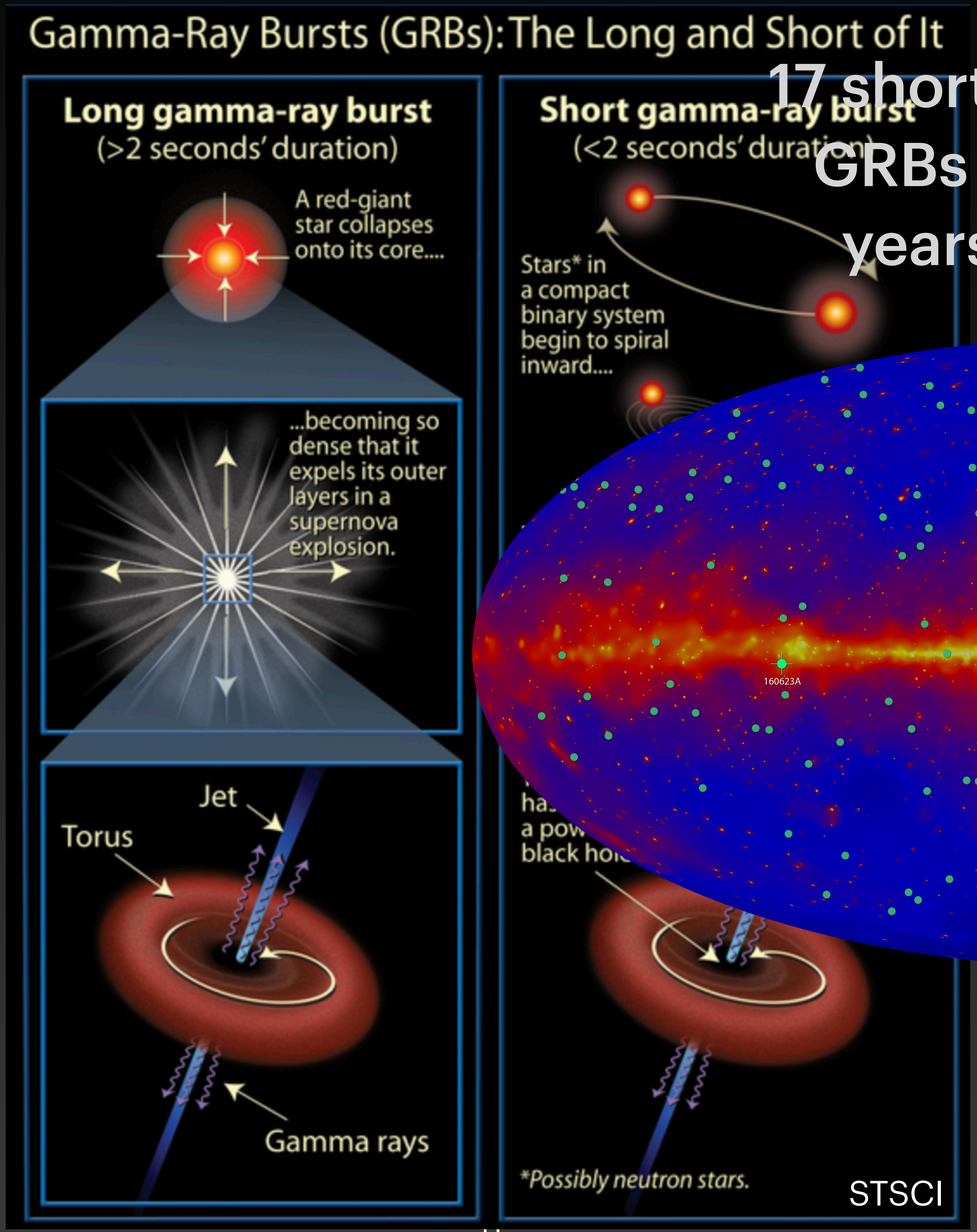
New Horizons Spacecraft / Long Range Reconnaissance Imager (LORRI): EBL measurement at **53 AU!**

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

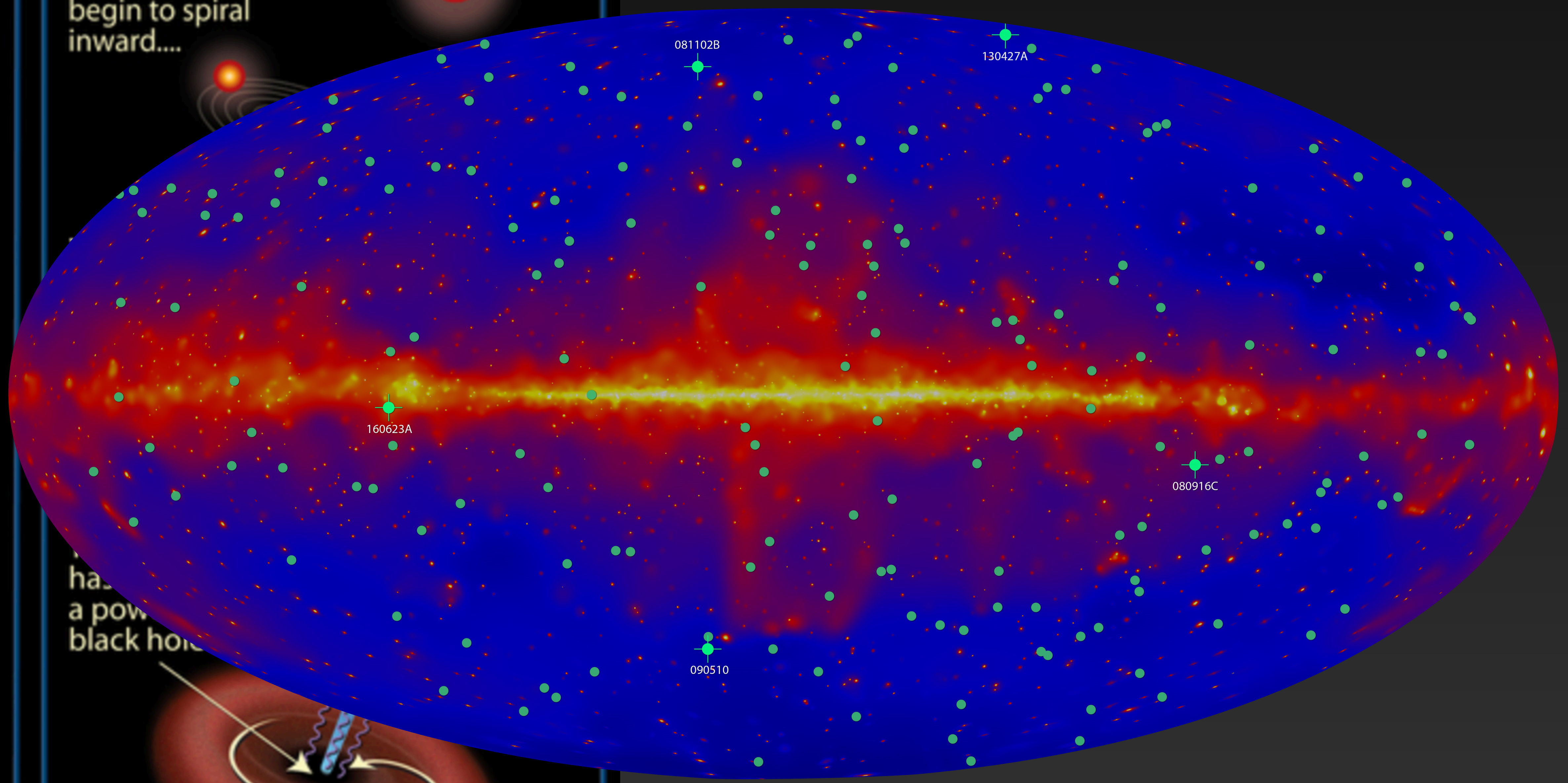
GRB221009A — BOAT



One slide on GRBs

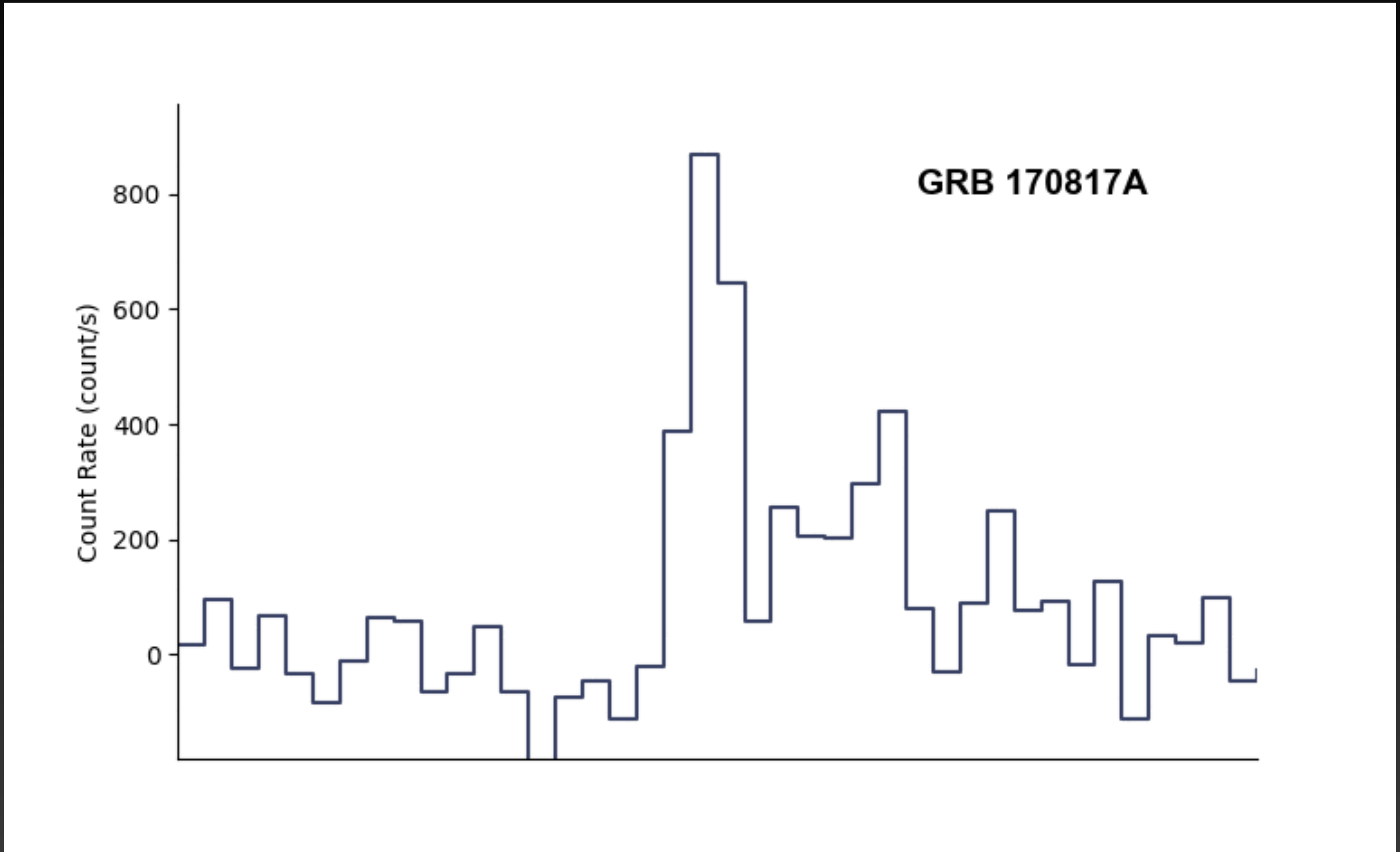


17 short GRBs, 169 long GRBs detected in 10 years with the LAT



2FLGC, Ajello et al. (2019)

GRB221009A in perspective



Credit: Adam Goldstein

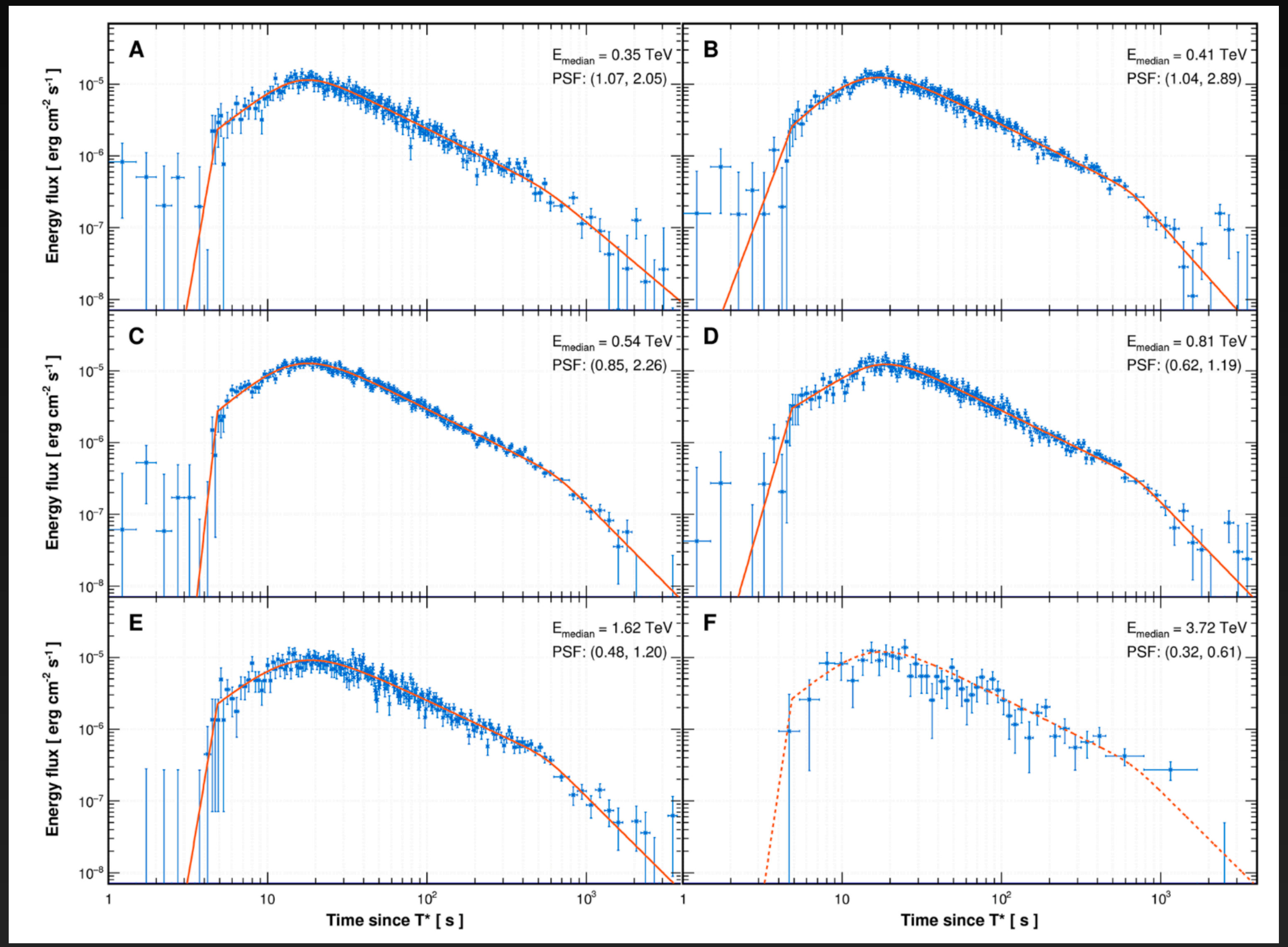
GRB221009A: some facts

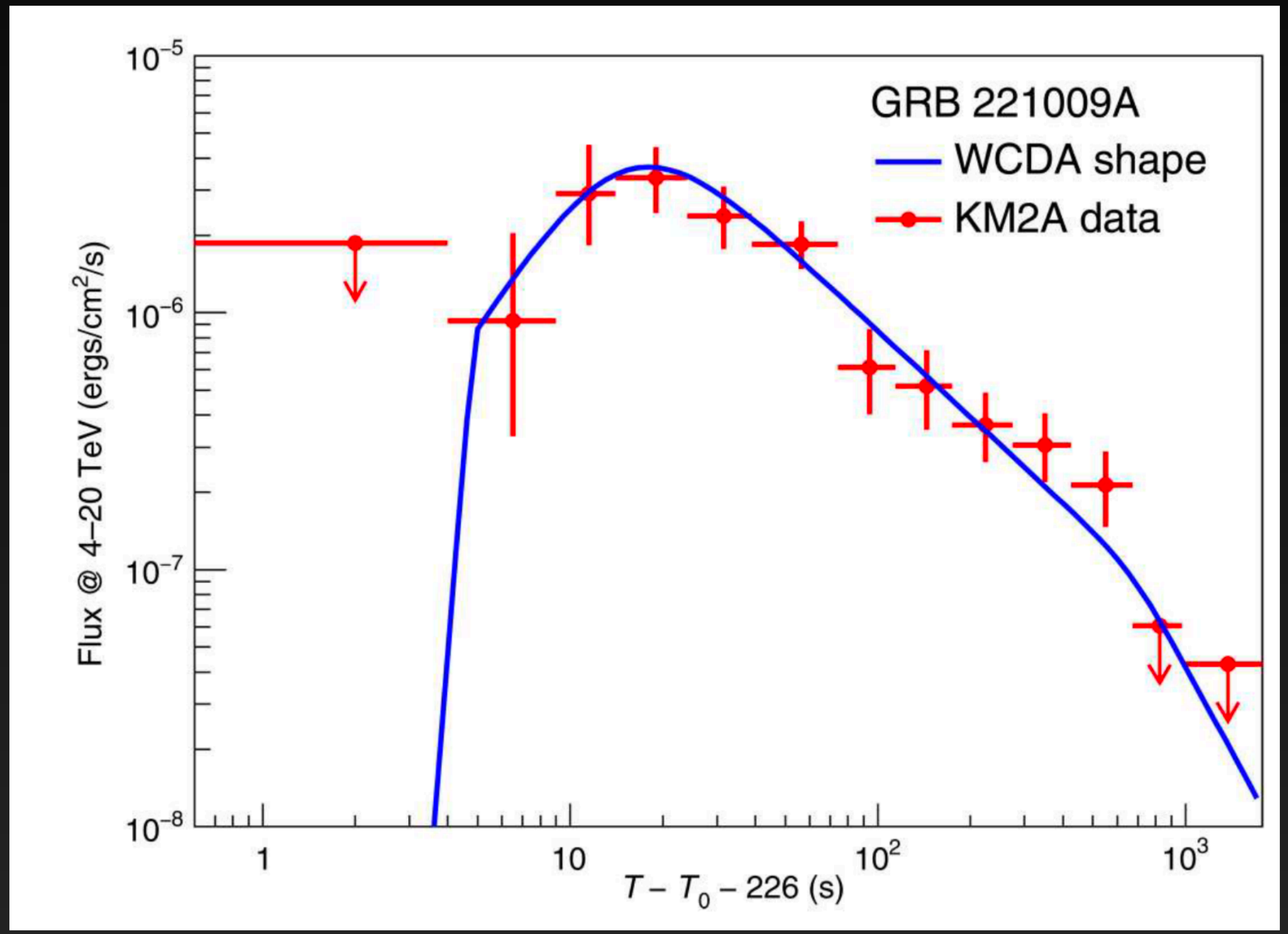
- Brightest GRB observed
- Probable precursor: collapsar (massive star collapsing to black hole)
- Redshift $z = 0.1505$ (VLT X-Shooter, GTC) from CaI, II absorption lines
- *Fermi* LAT detected 99.4 GeV photon (new record from GRB) at $t_0 + 240\,\mathrm{s}$
- LAT and GBM saturated and no simple Fermi analysis recommended at this time, see here
- Detected at very high energies with LHAASO

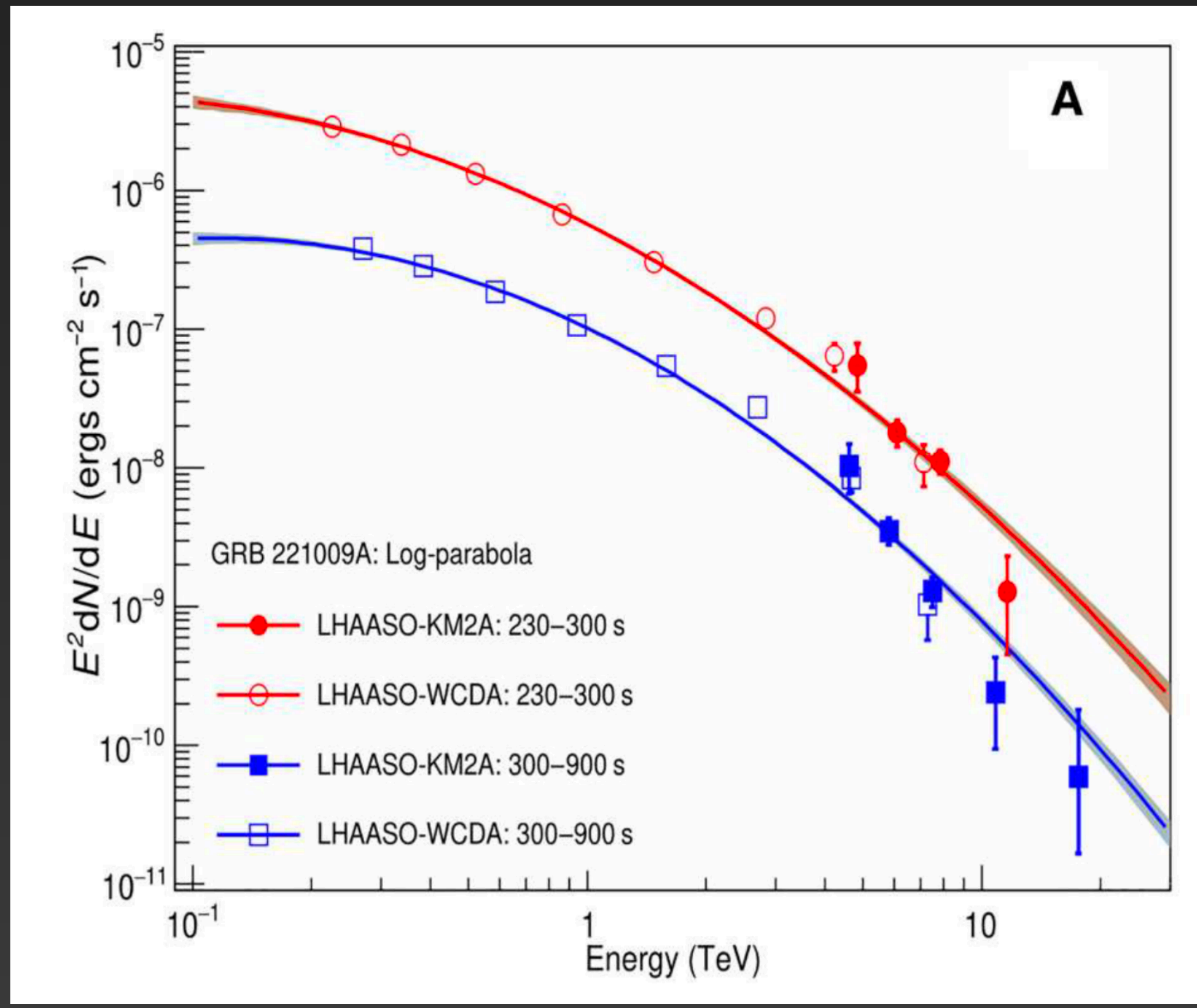
https://gcn.gsfc.nasa.gov/other/221009A.gcn3

GRB221009A: VHE photons seen with LHAASO

- WCDA: > 64,000 gamma rays above 0.2 TeV
- Light curve suggests jet opening angle of 1.6º
- KM2A: 140 gamma rays between 3 and 13 TeV (first announcement was 18 TeV)



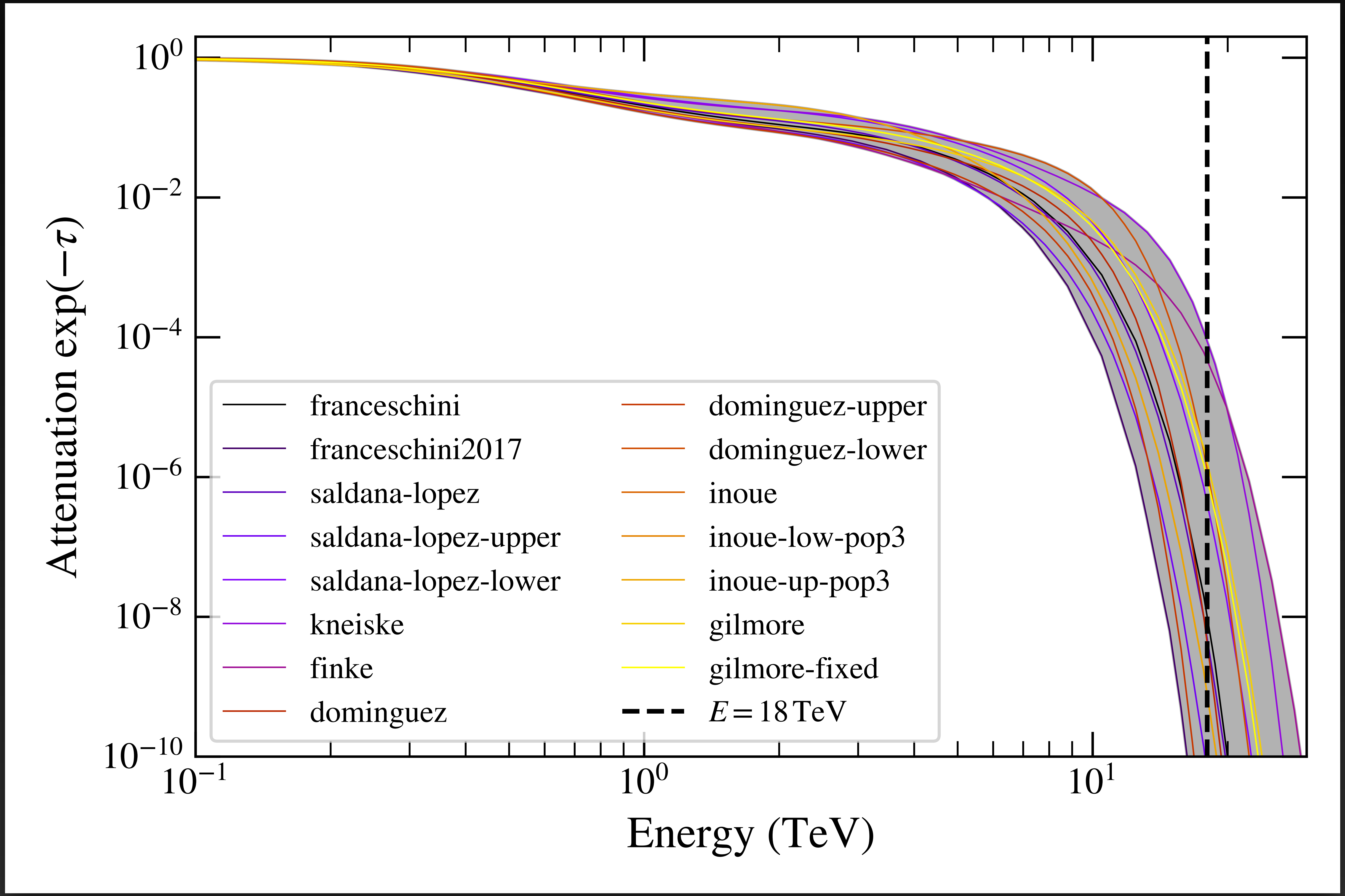




[LHAASO Collaboration Science 2023, Sci. Adv. 2023]

18 TeV photon exceptional!?

(Considering $z = 0.1505$)

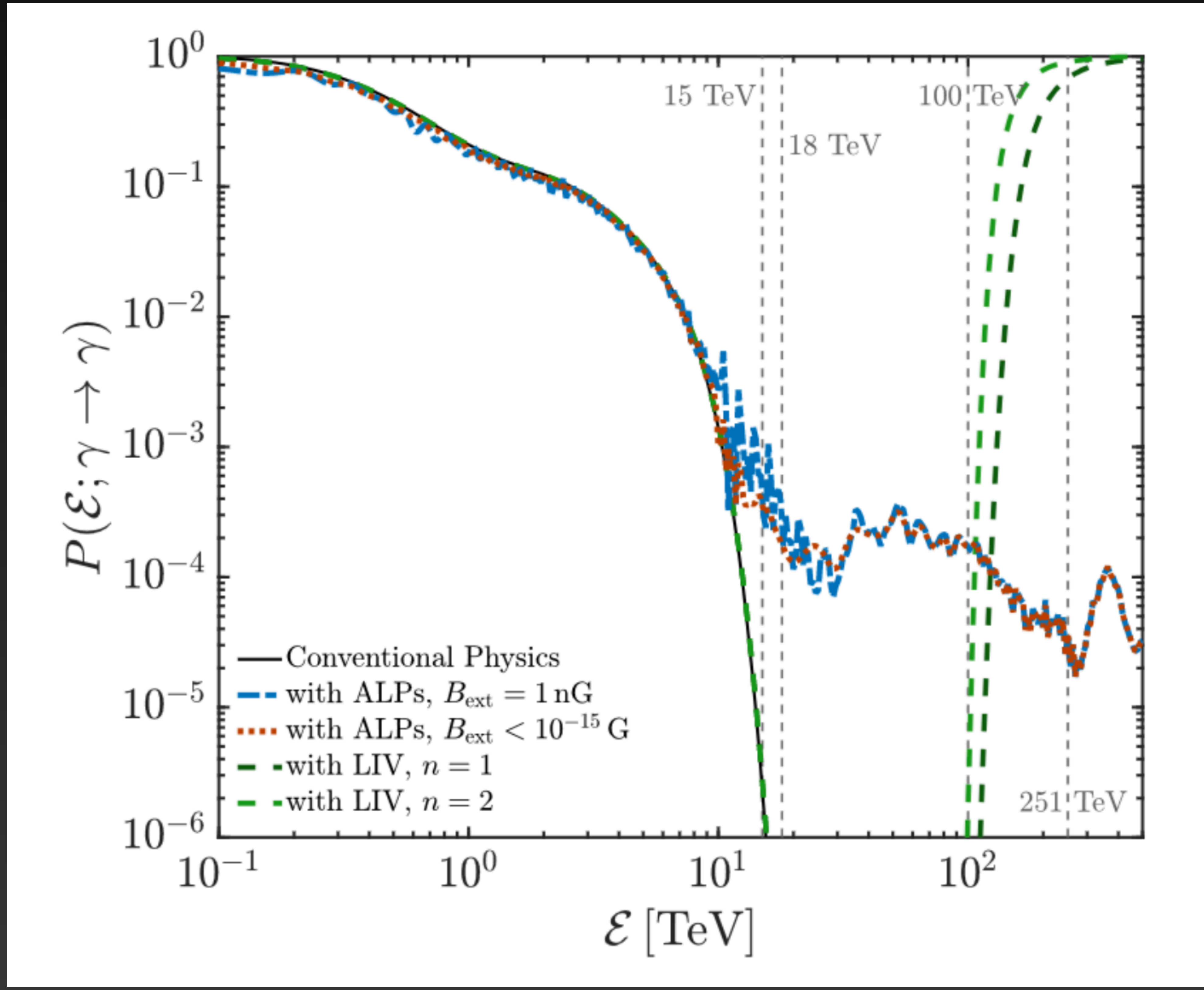


Generated with https://github.com/me-manu/ebltable/

ALP interpretation required?

- Astrophysical environments considered:
  - Mixing in GRB
  - Host galaxy (starburst with high B field or spiral)
  - IGMF
  - Milky Way
- EBL model: Saldana Lopez et al. 2021
- Photon flux considerably boosted at 18 TeV

[Galanti et al. 2024]



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

ALP interpretation required?

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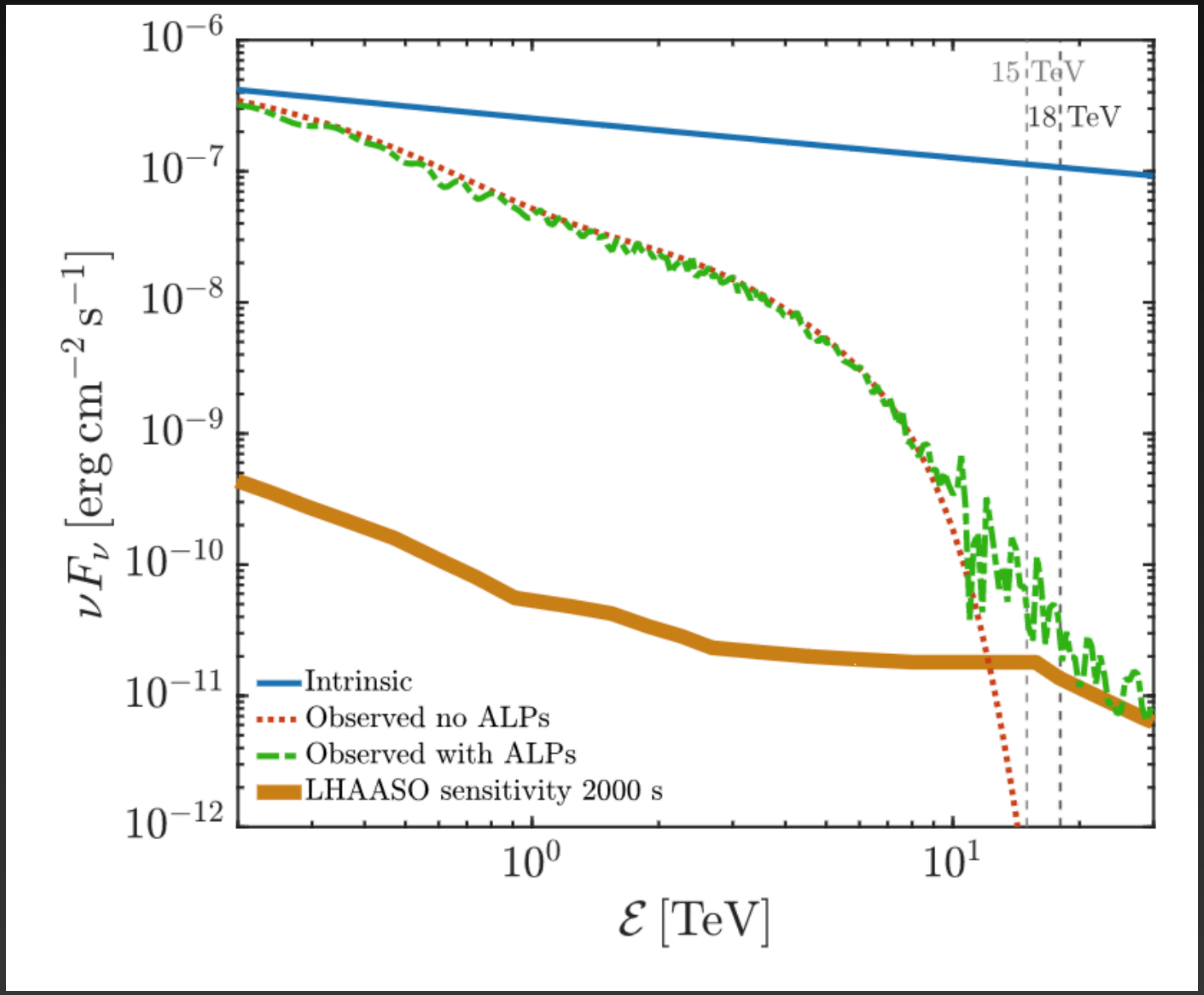
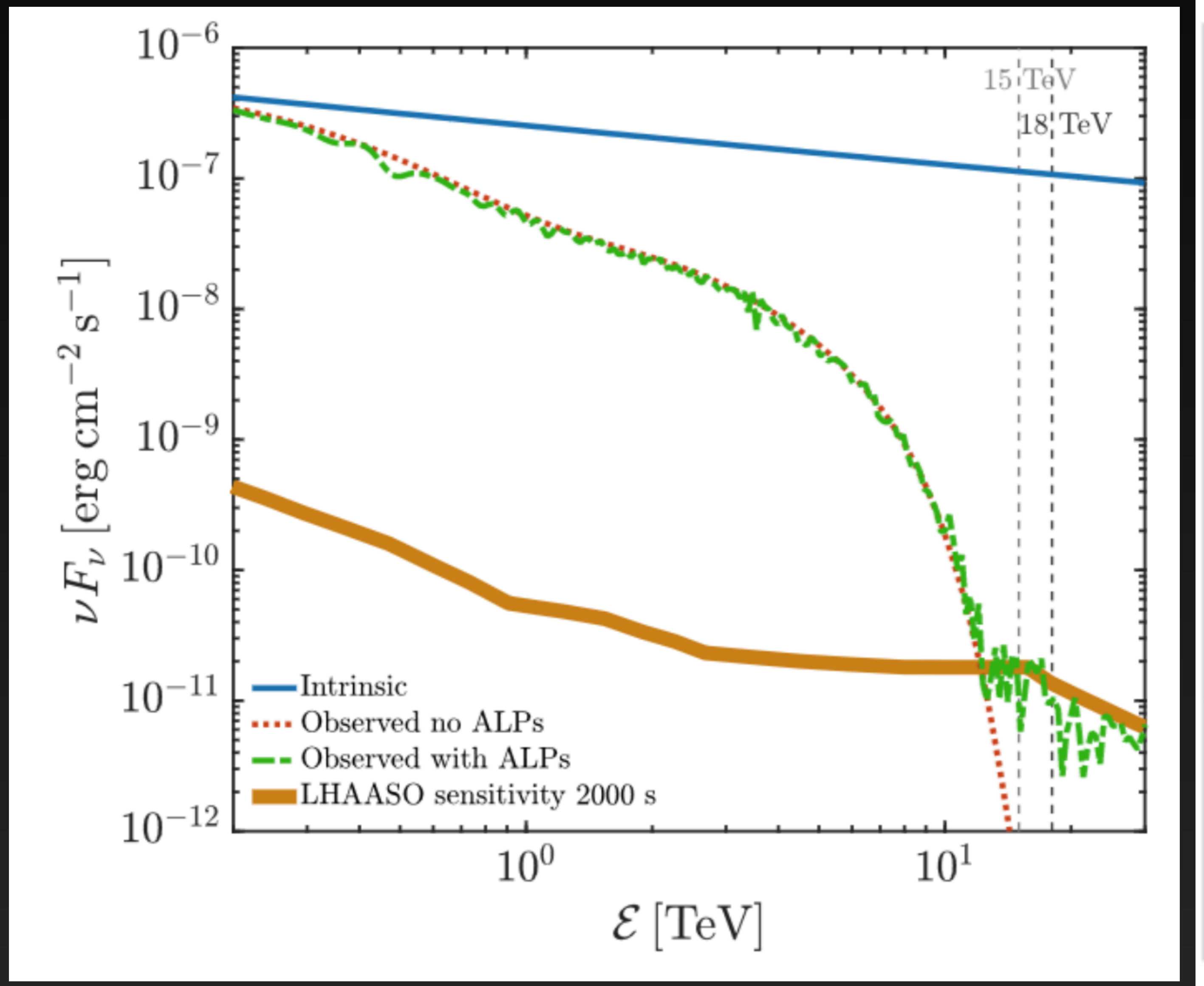


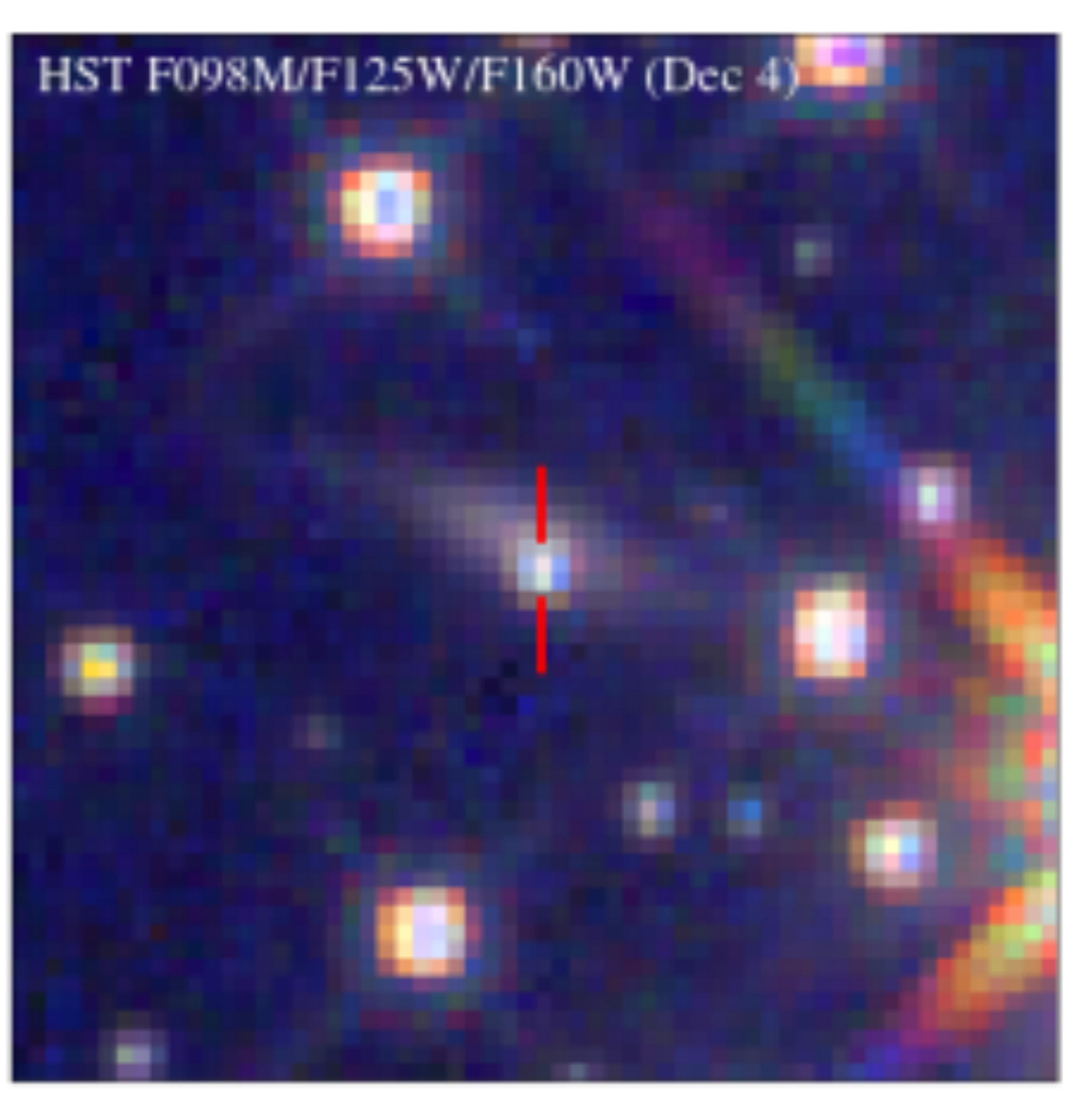
Caveats

- Host galaxy observed with JWST and HST:
  - Appears to be ordinary spiral galaxy
  - Observed edge-on
  - Strong B field unlikely
- LHAASO observations:
  - Highest energy photon at 13 (not 18 TeV)
- EBL uncertainties at 13 TeV:

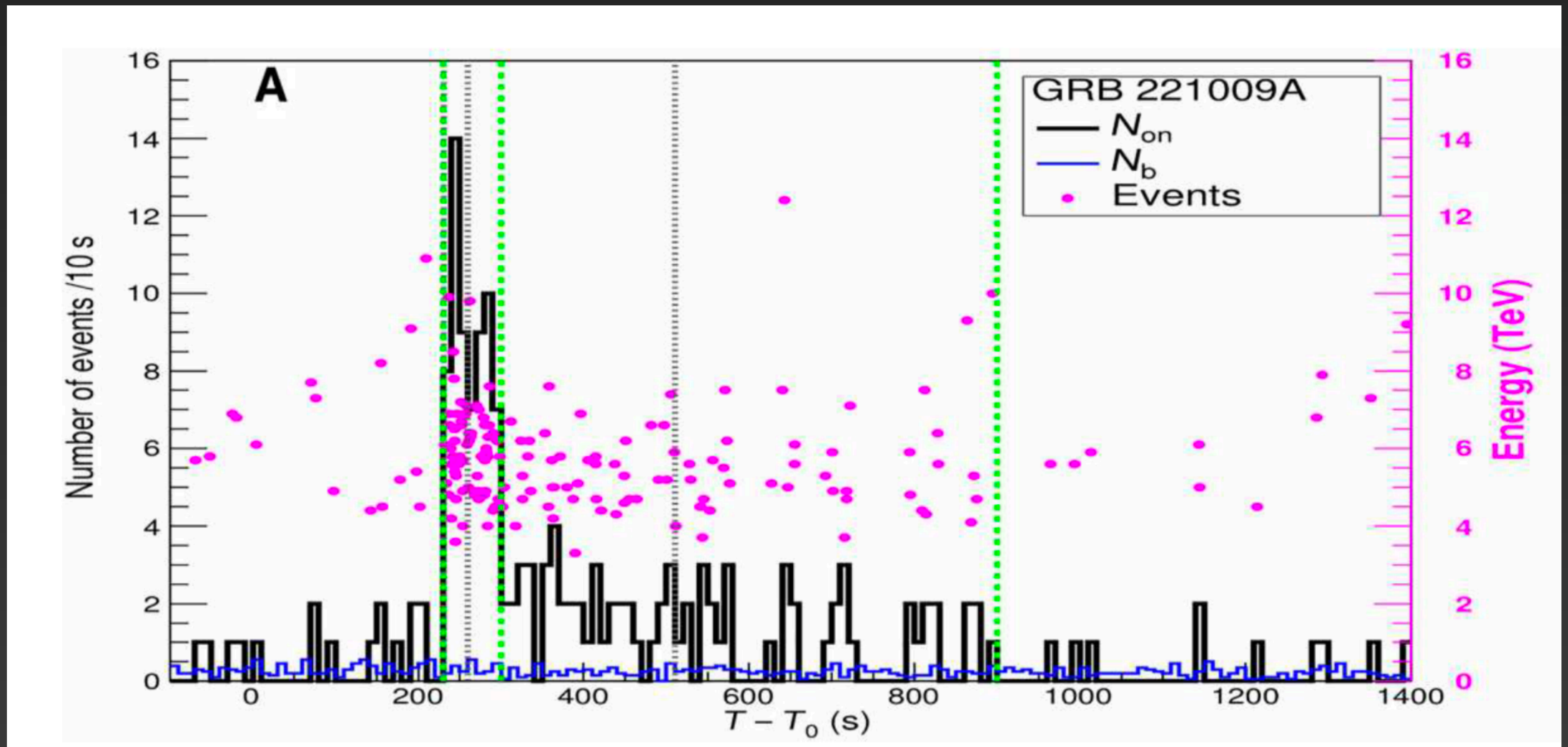
EBL model	Optical depth τ	exp(-τ)
Franceschini+ 2017	14.7	4.3×10^{-7}
Saldana Lopez+ 2021	10.4	3.0×10^{-5}
Dominguez+ 2011	9.3	8.9×10^{-5}
Finke+ 2022	8.0	3.4×10^{-4}
Gilmore+ 2012	7.6	4.8×10^{-4}
Kneiske & Dole 2010	5.7	3.5×10^{-3}

Galanti et al. 2024



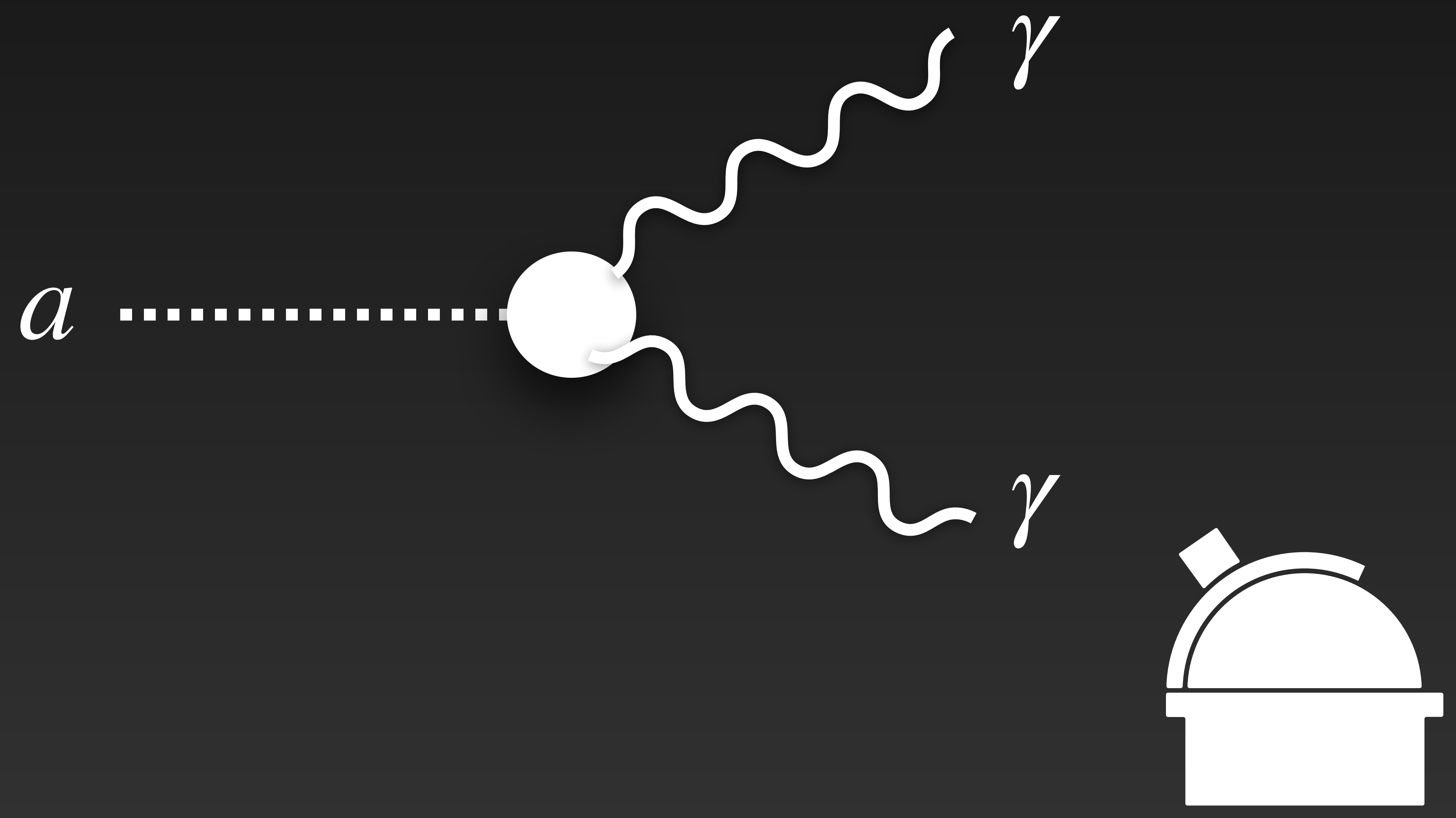


[Levan et al. 2023]

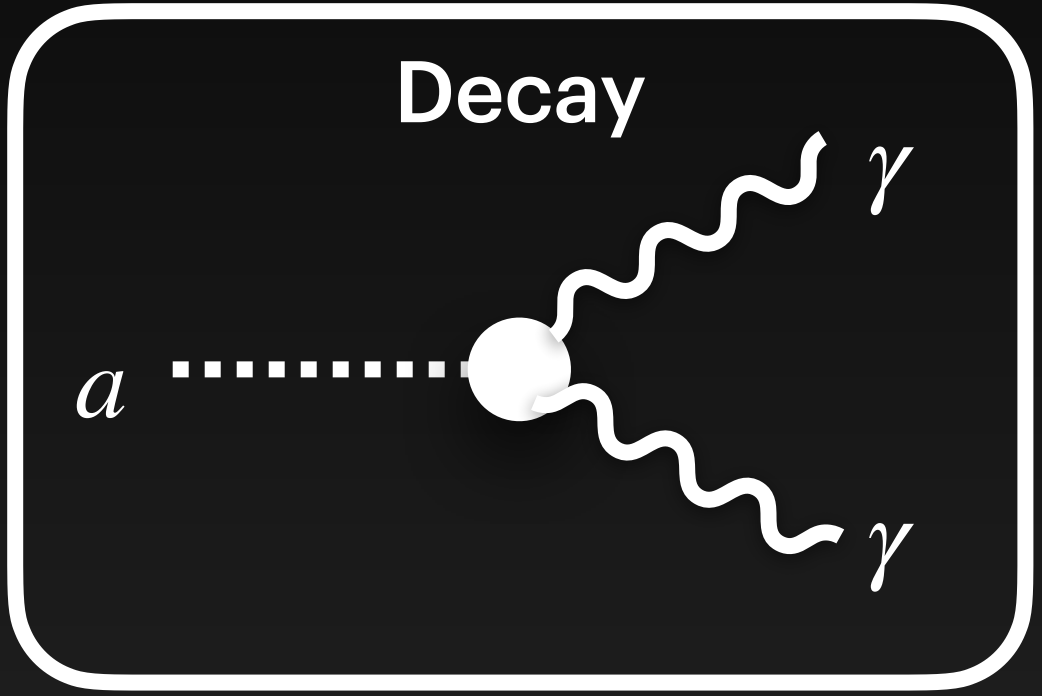


[Cao et al. 2023]

ALP decay



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:

$$\tau_{a\gamma} \gtrsim 13.8\,\mathrm{Gyr}\left(\frac{5.5\times 10^{-7}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2\left(\frac{1\,\mathrm{eV}}{m_a}\right)^3$$

Decay wavelength:

$$\lambda_a = \frac{4\pi}{m_a} = 2.48\,\mu\mathrm{m}\left(\frac{1\,\mathrm{eV}}{m_a}\right)$$

Decay spectrum:

$$\frac{dN_\gamma}{dE_\gamma} \propto \delta\left(\lambda - \frac{4\pi}{m_a}\right)$$

- **Expected photon flux:**

$$\frac{d\Phi}{dE d\Omega} = \underbrace{\left(\frac{1}{4\pi}\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\mathbf{r})d\ell\right)}_{=dD/d\Omega\ (\mathrm{diff.}\ D-\mathrm{factor})} \frac{2\pi\Gamma_a}{m_a} f(\lambda)$$

- **Velocity distribution** (assumed to be independent of $\mathbf{r}$):

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

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

Porras Bedmar, MM, Horns (in prep.)

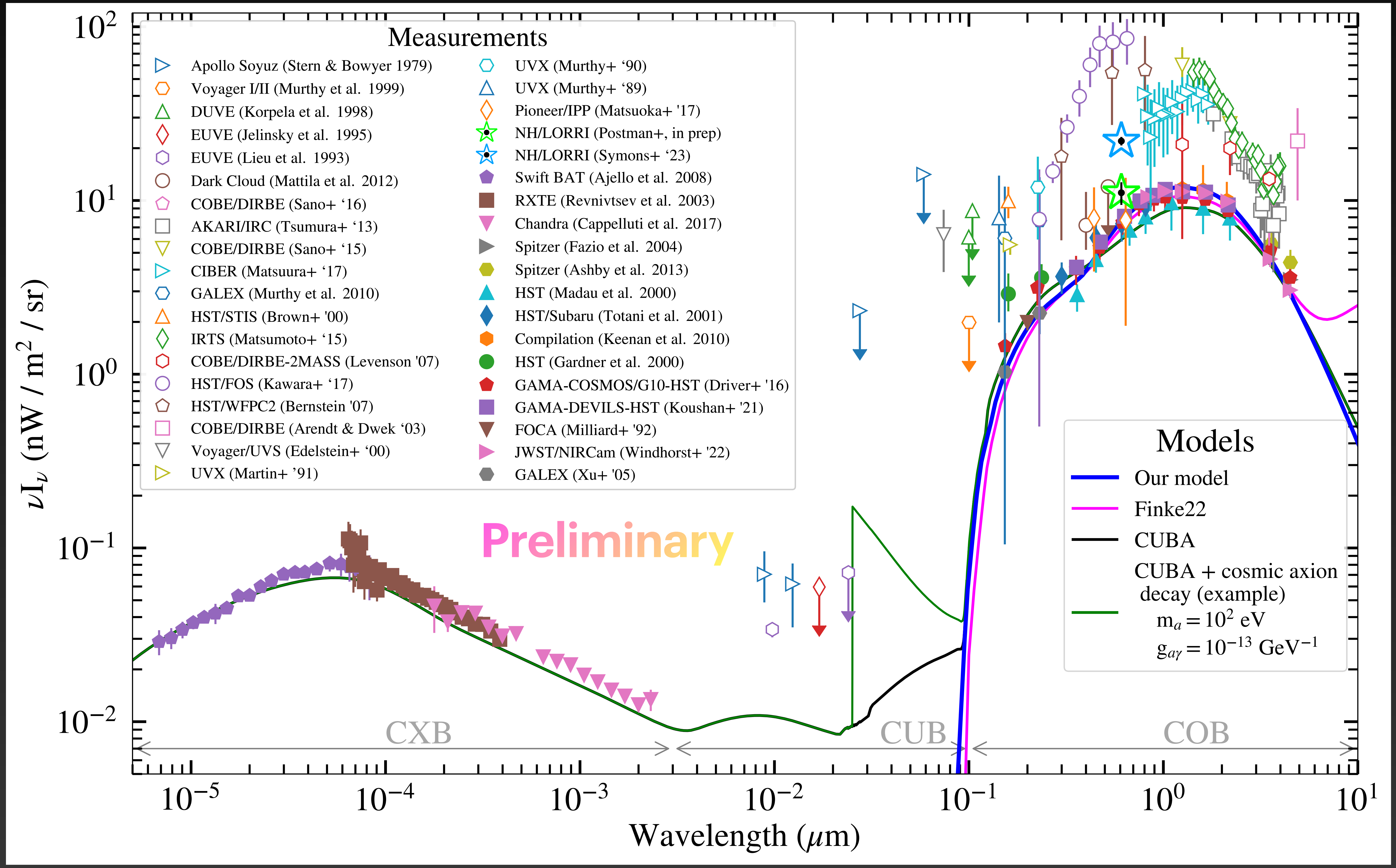
Cosmic axion decay

Porras Bedmar, MM, Horns (in prep.)

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

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

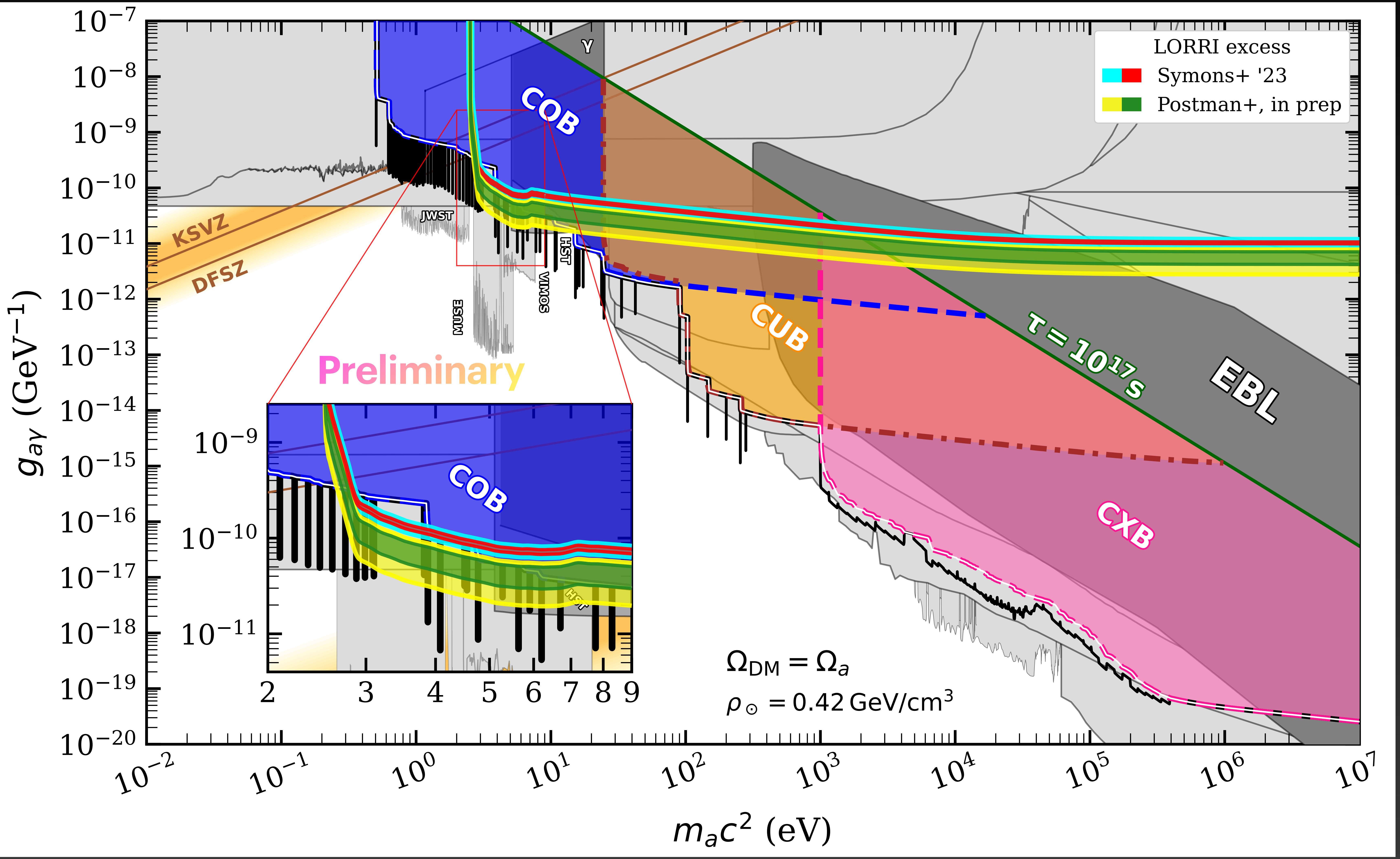
With $z_* = \frac{m_a}{2} \frac{\lambda}{2\pi}(1 + z) - 1$



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

Constraints from ALP decay

Porras Bedmar, MM, Horns (in prep.)



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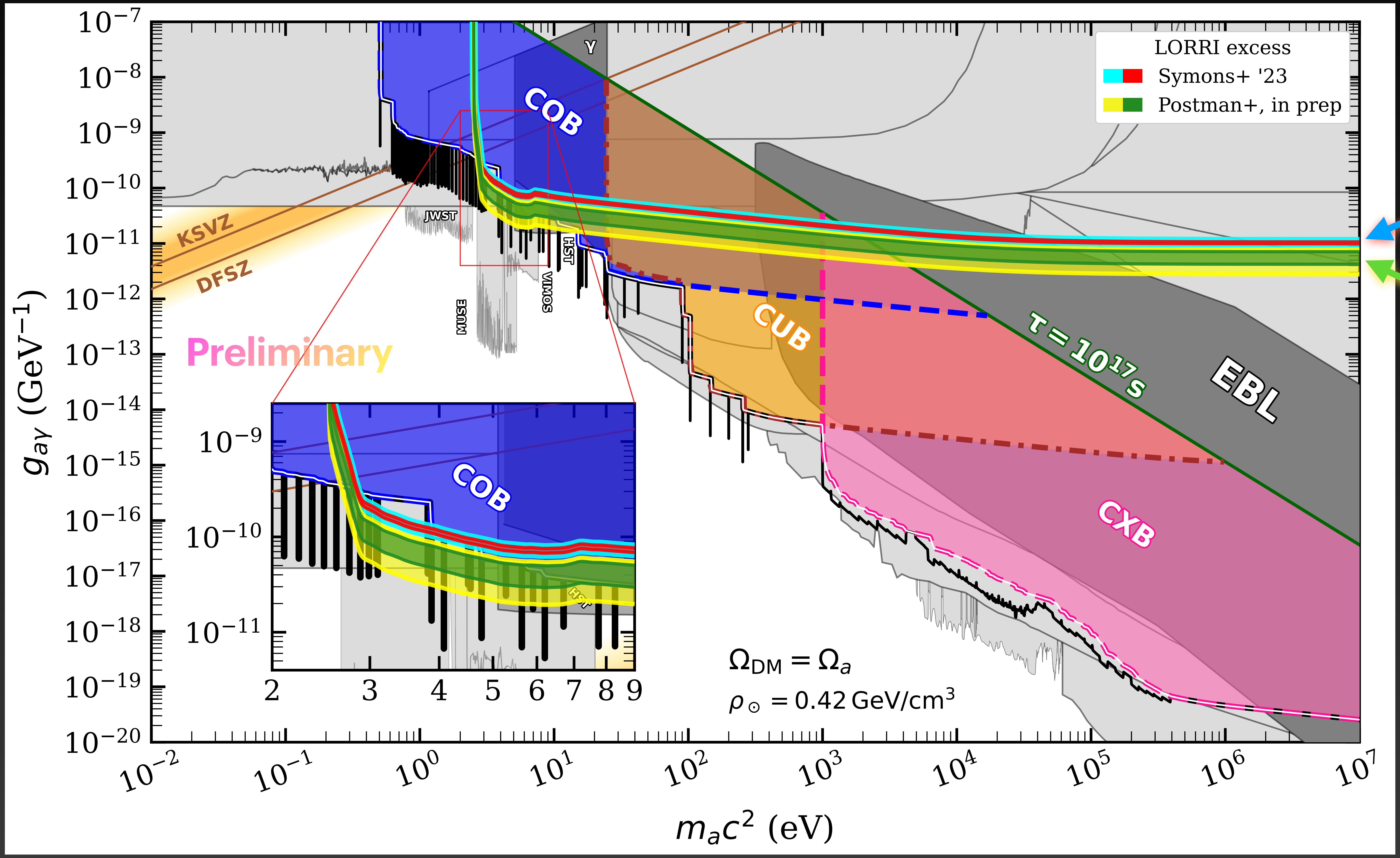


Parameters that could explain LORRI excess [Symons et al. 2023] Taking all EBL measurements into account

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

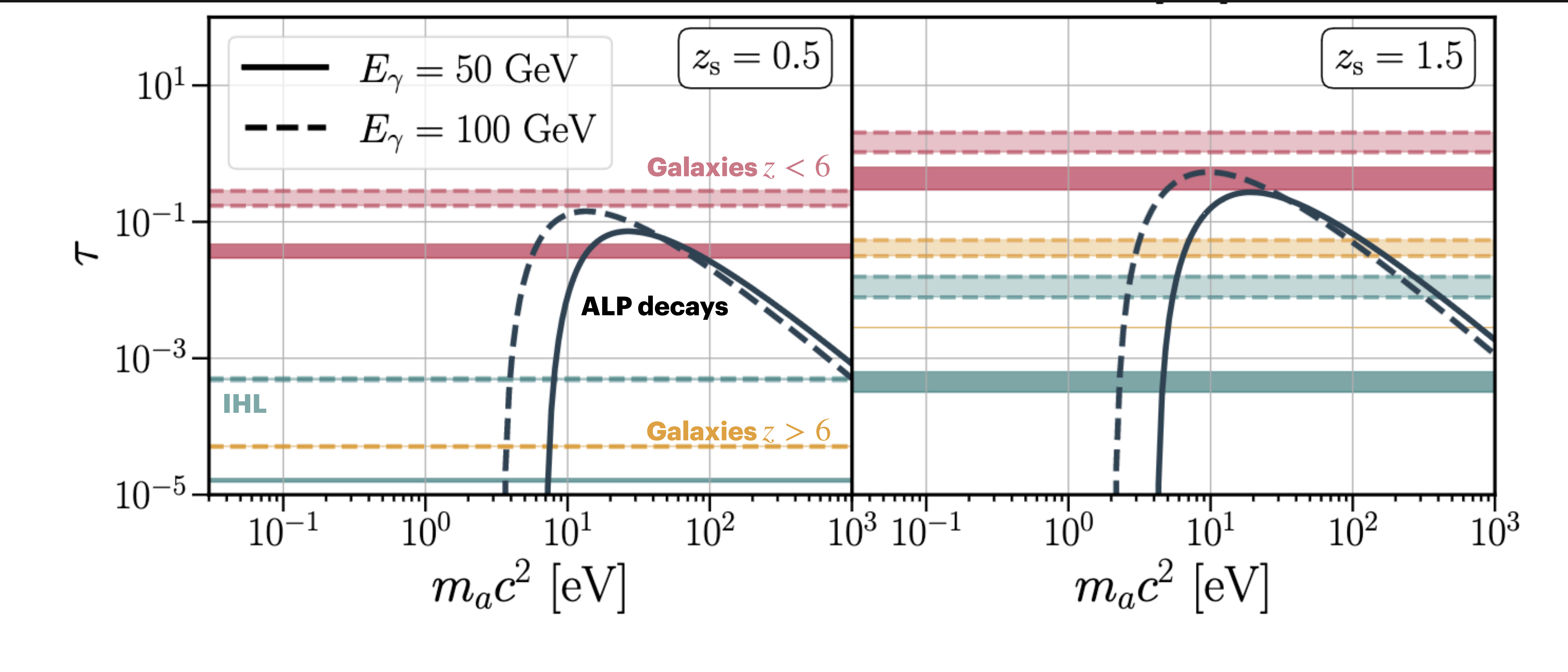
Cosmological ALP decay would contribute to the EBL

Would increase the optical depth of the Universe

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

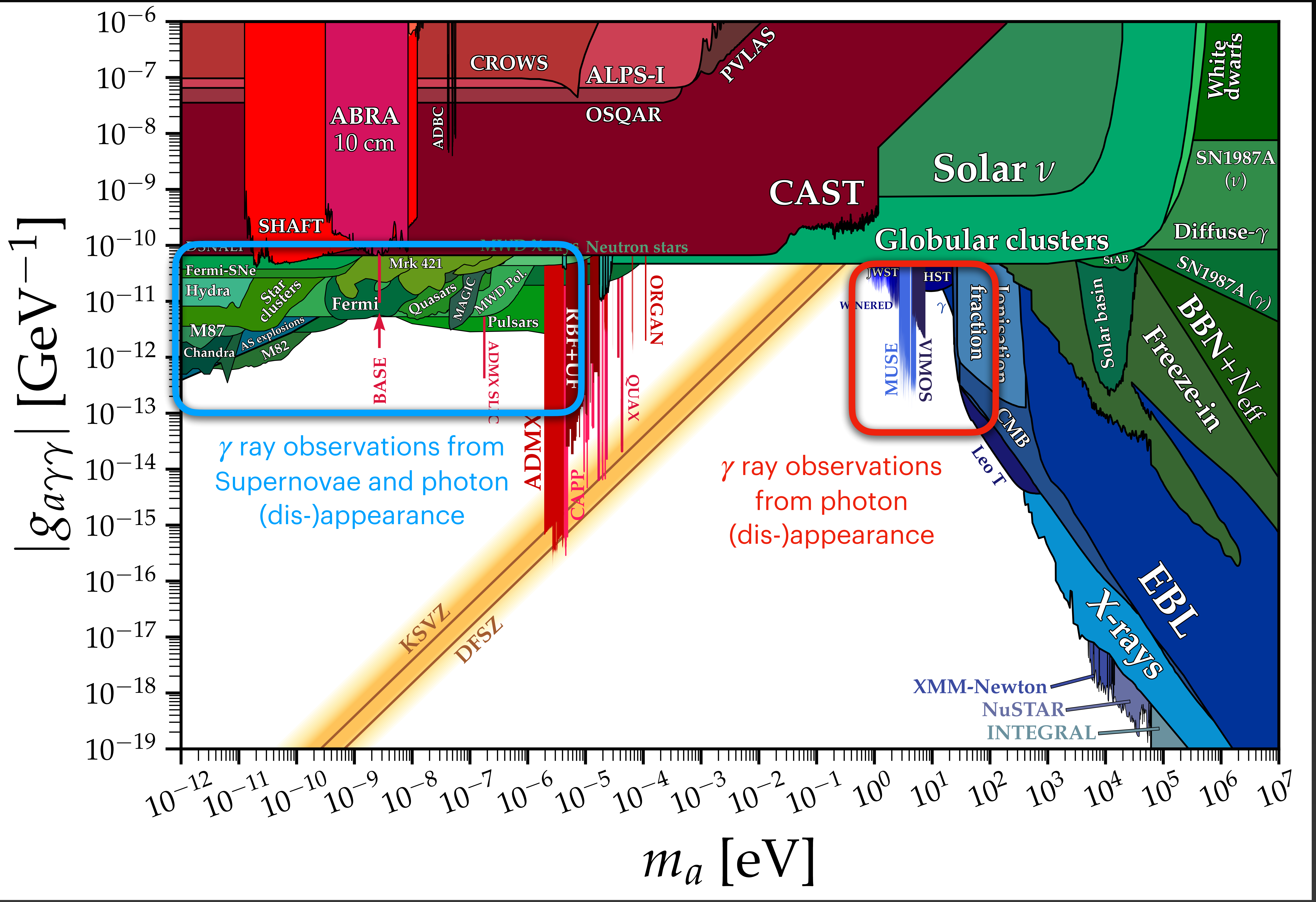
- Could be probed with current and future gamma-ray observations

[Bernal et al. 2023]



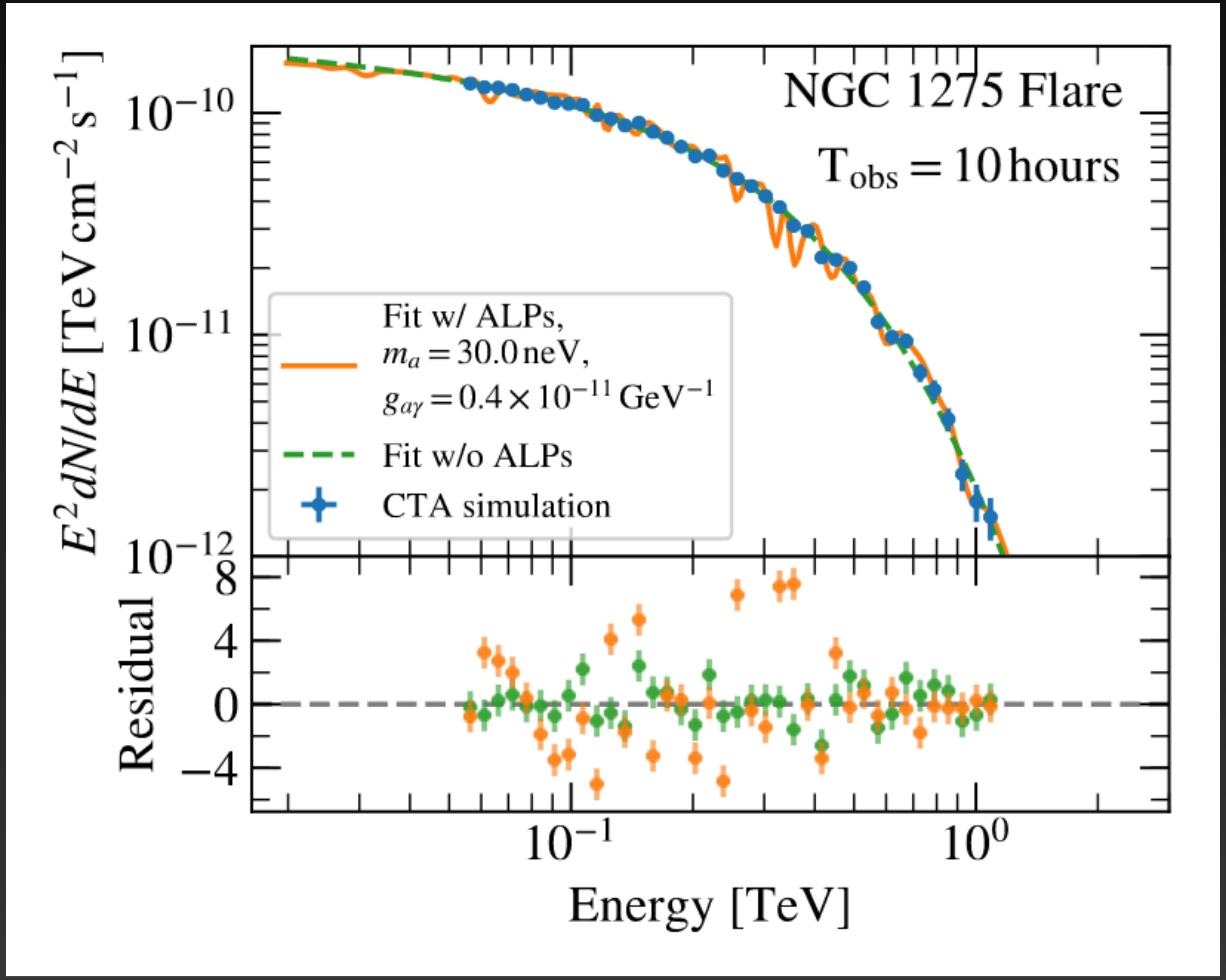
[Korochkin et al. 2020, Bernal et al. 2023]

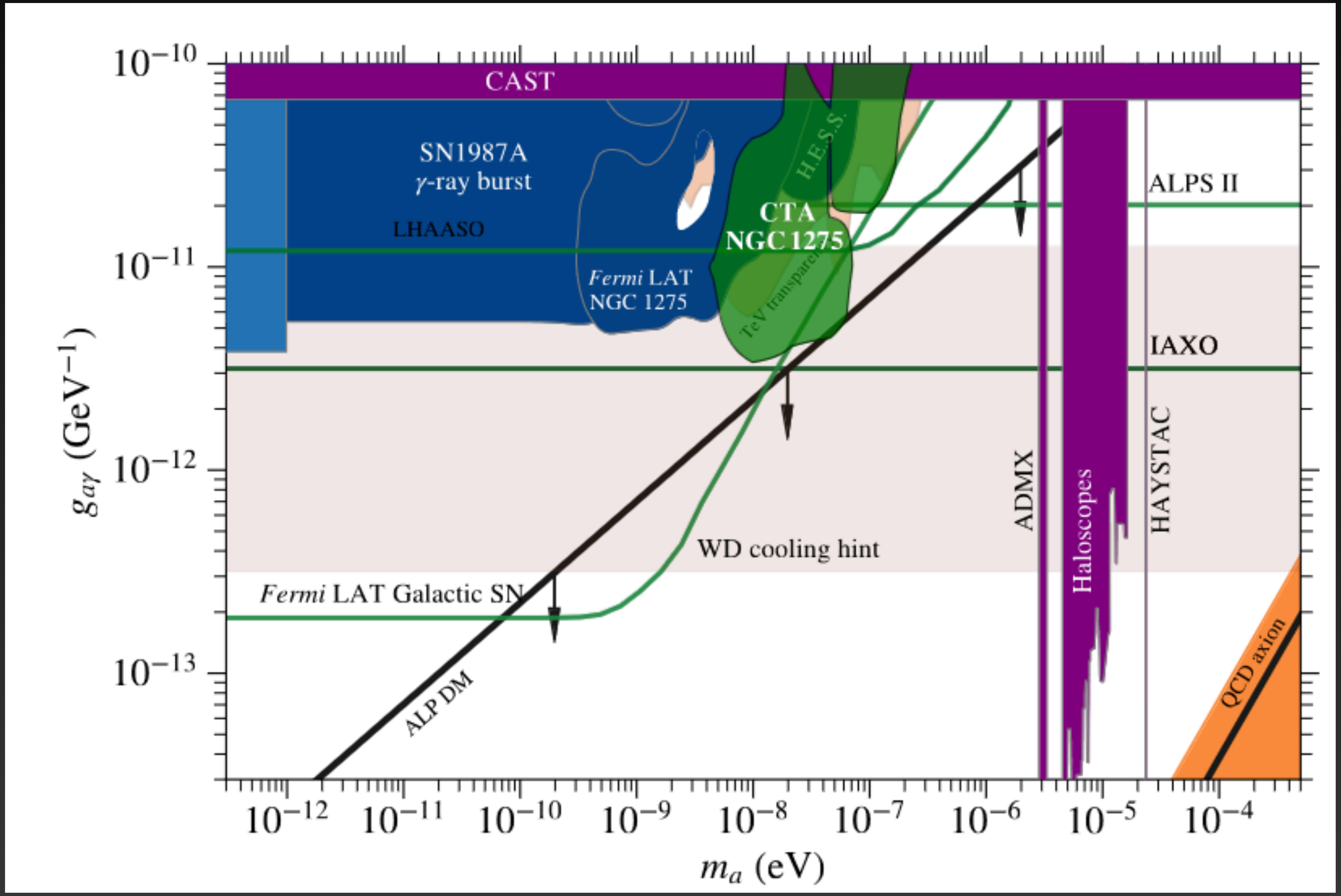
Parameter space for photon-ALP coupling



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

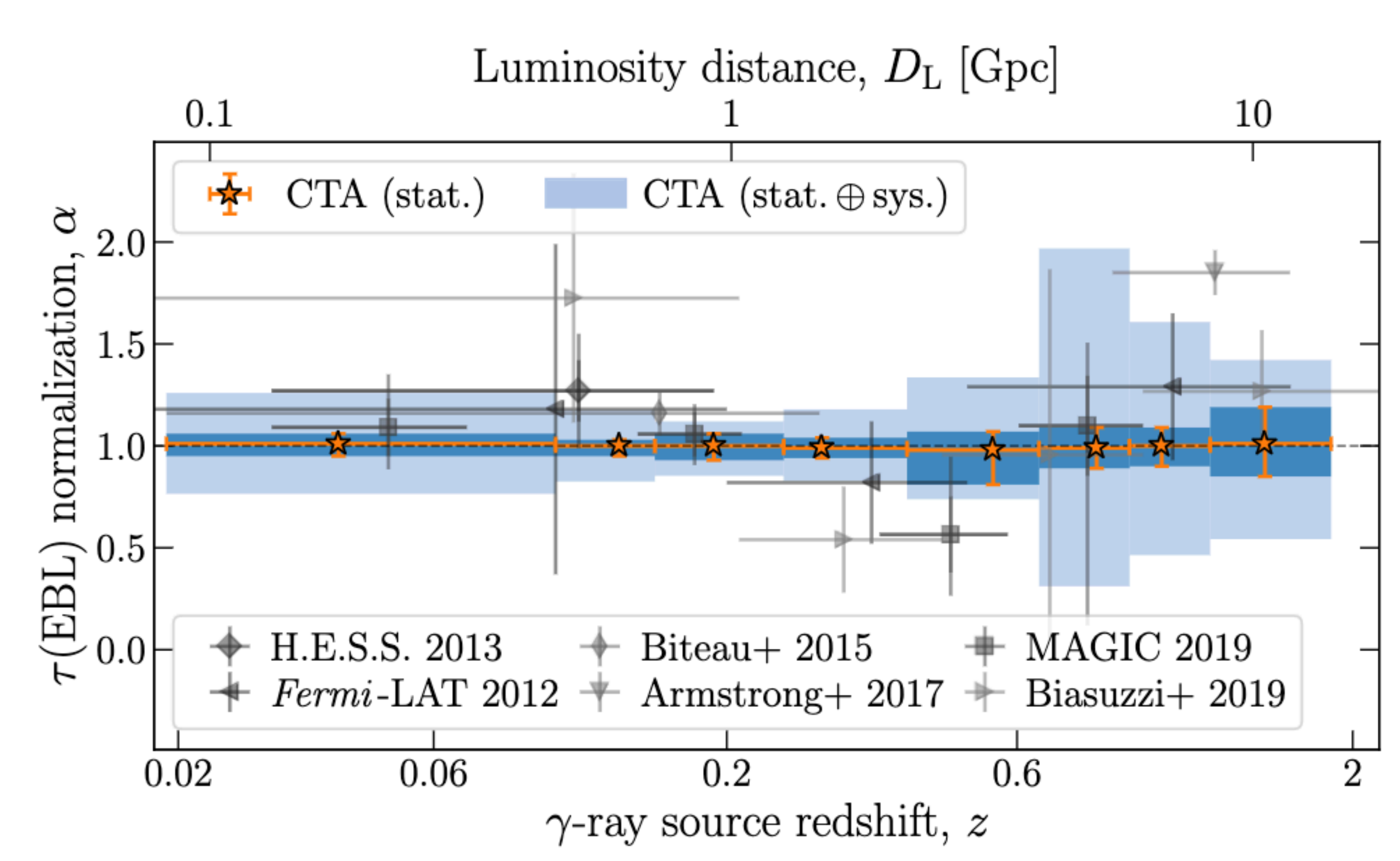
CTAO will probe photon re- and disappearance





[CTA consortium: Abdalla et al. 2021]

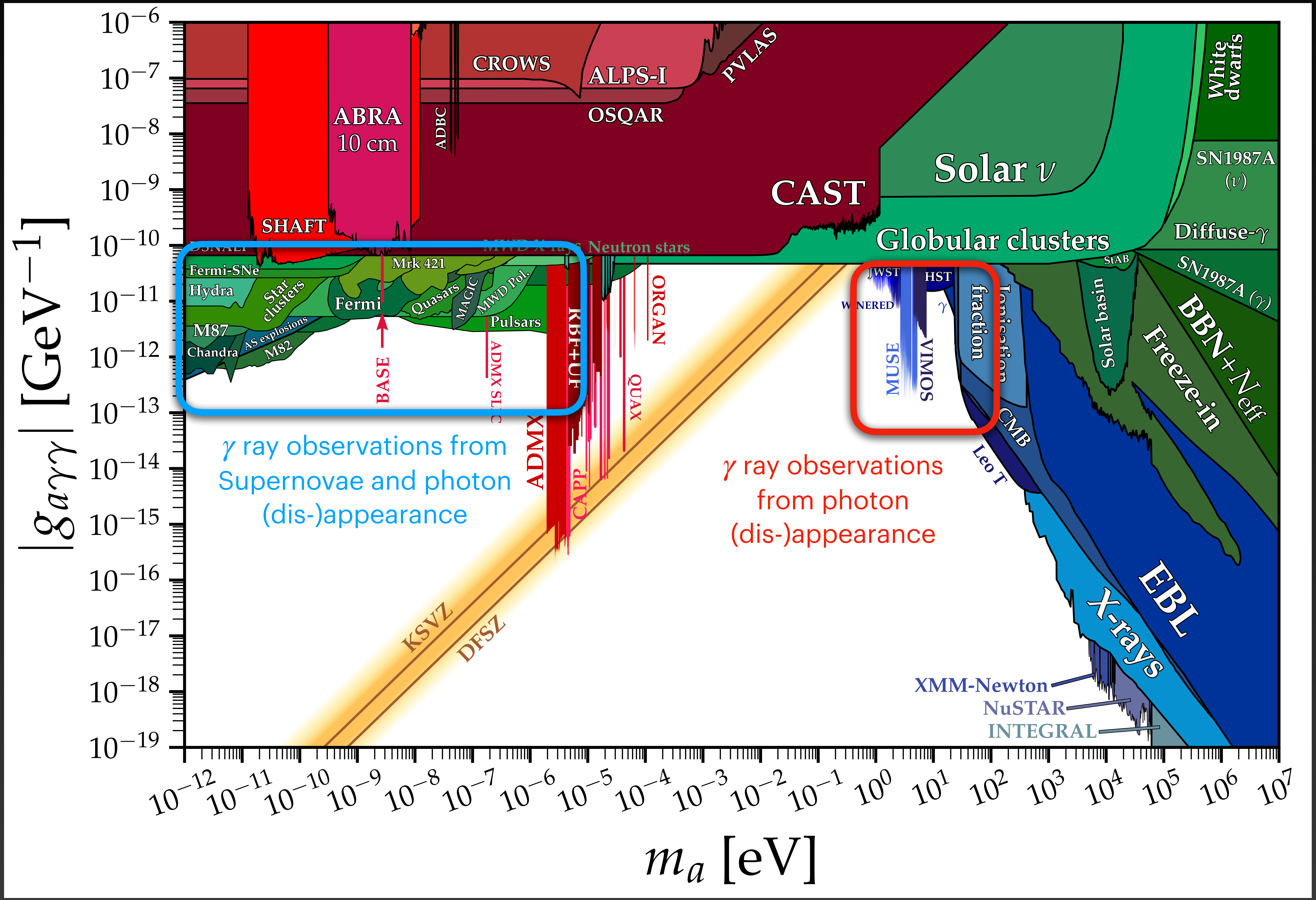
CTAO will probe photon re- and disappearance



[CTA consortium: Abdalla et al. 2021]

Summary and conclusions

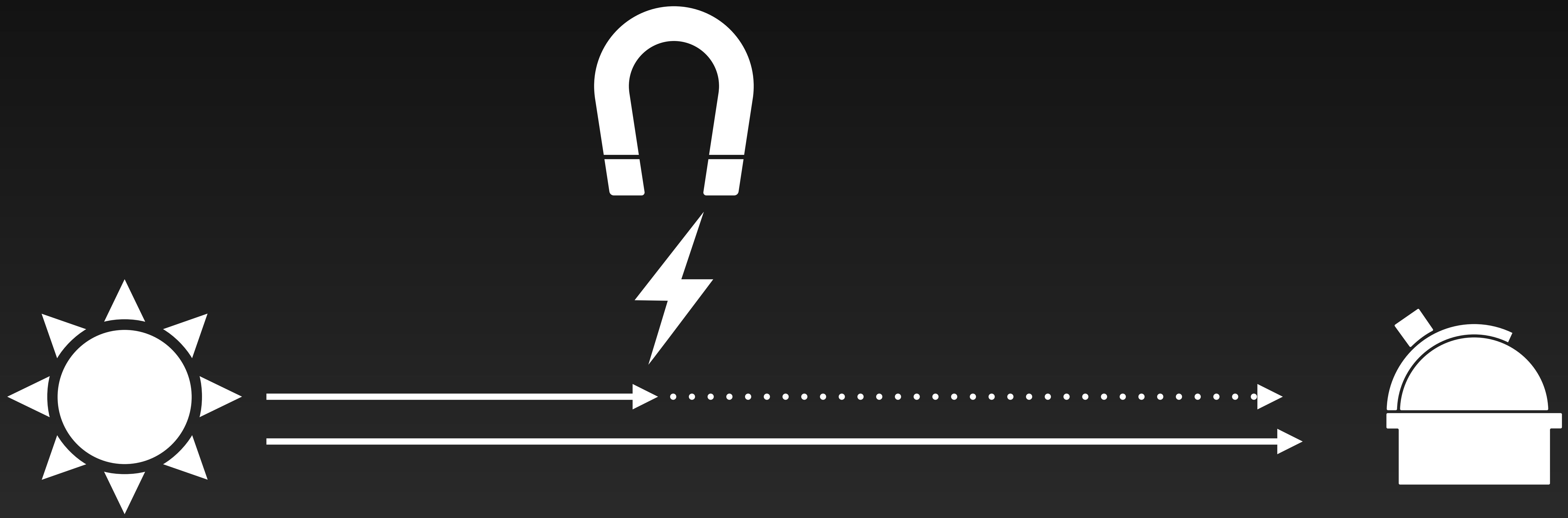
- Gamma-ray observations probe a wide range of axion parameters
- Sensitive to many observables
- Provide some of the strongest constraints (but astrophysical B fields remain uncertain)
- Fermi LAT will (hopefully) continue operations beyond 2025
- New observations with CTAO are commencing this decade



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

Back up

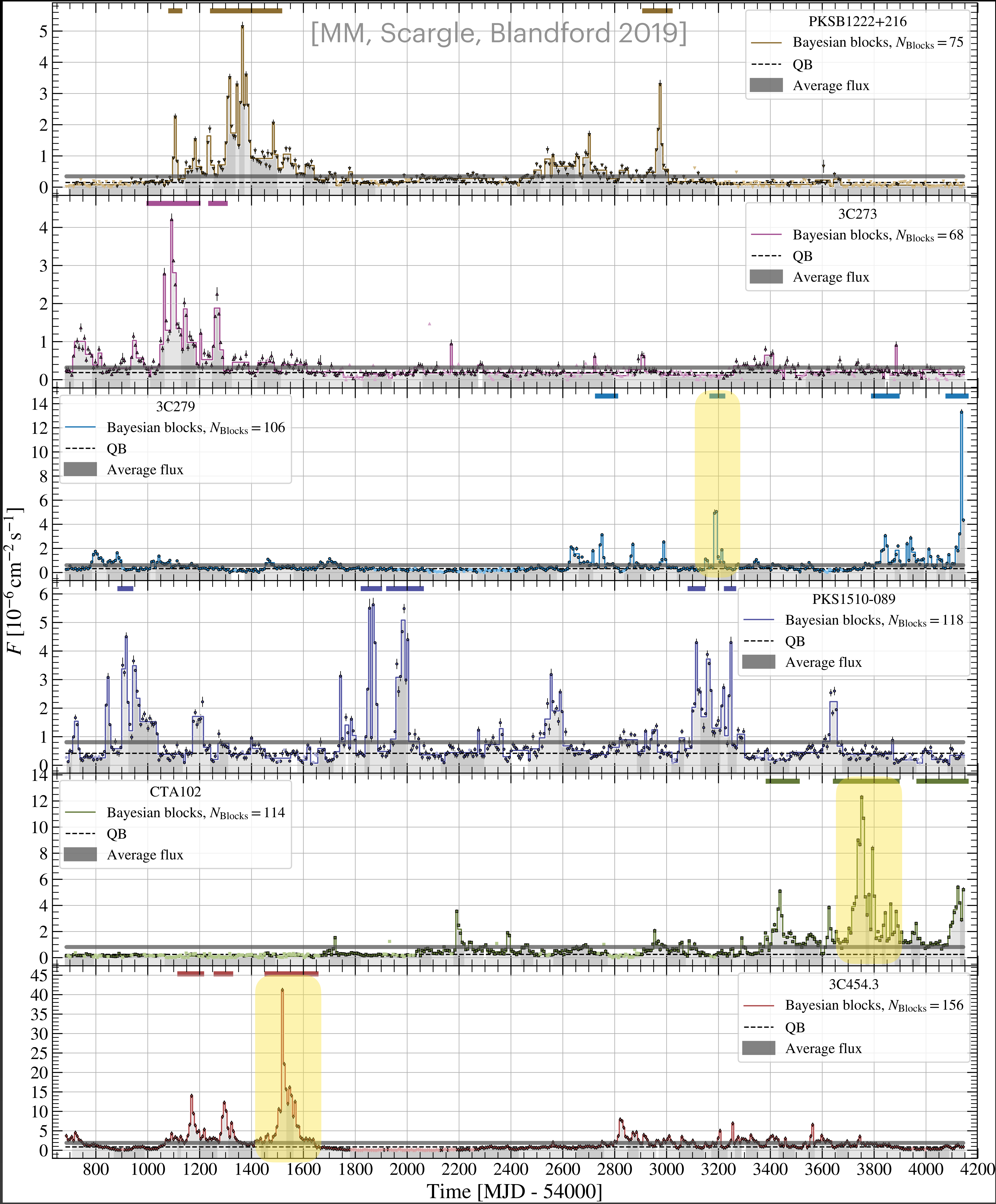
Searches for axion-induced oscillations in blazar spectra



Search for Oscillations in bright Blazars

Work by Jamie Davies, PhD student at Oxford

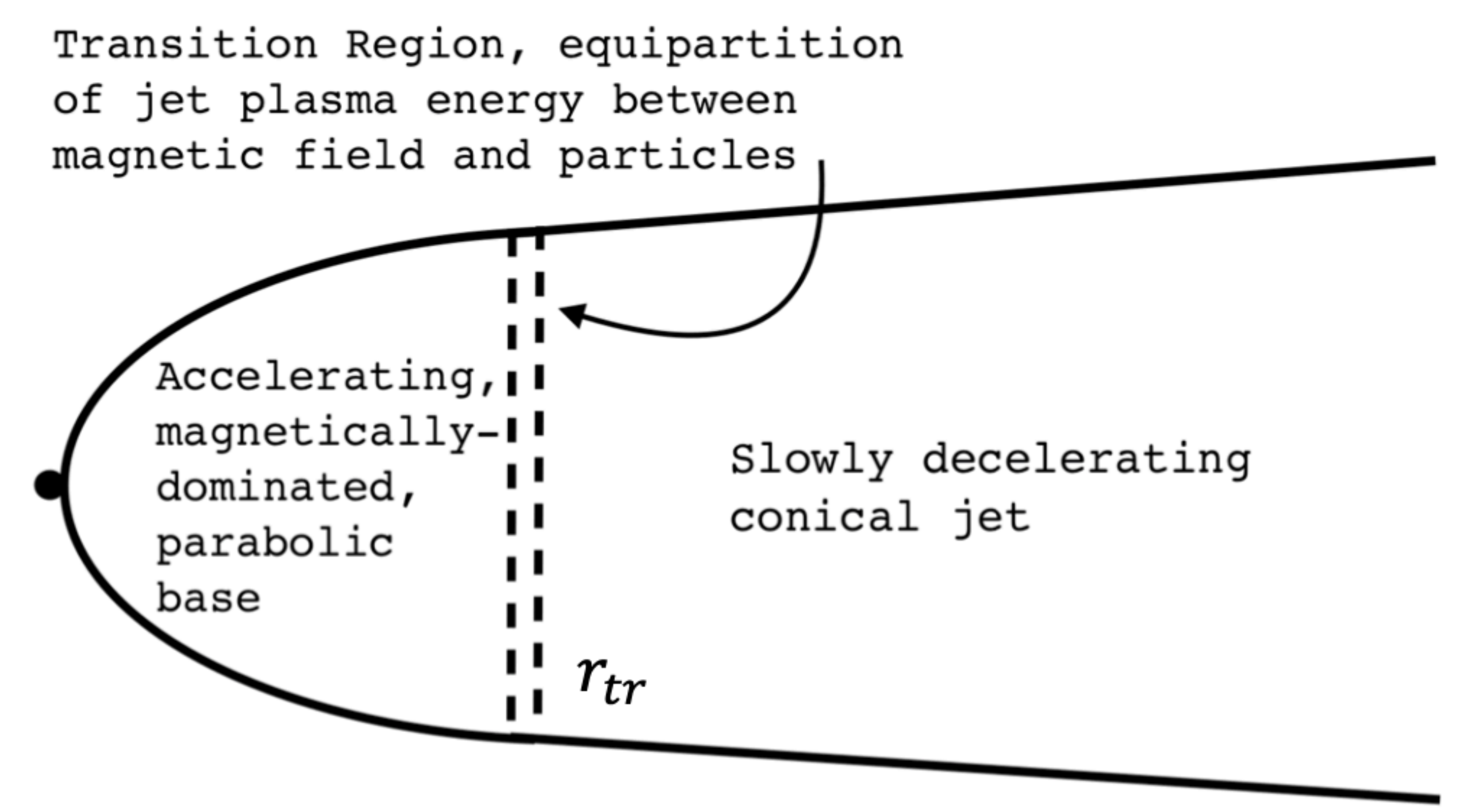
- Requires high photon statistics
- Selected the brightest flares ever observed with *Fermi* LAT from flat spectrum radio quasars



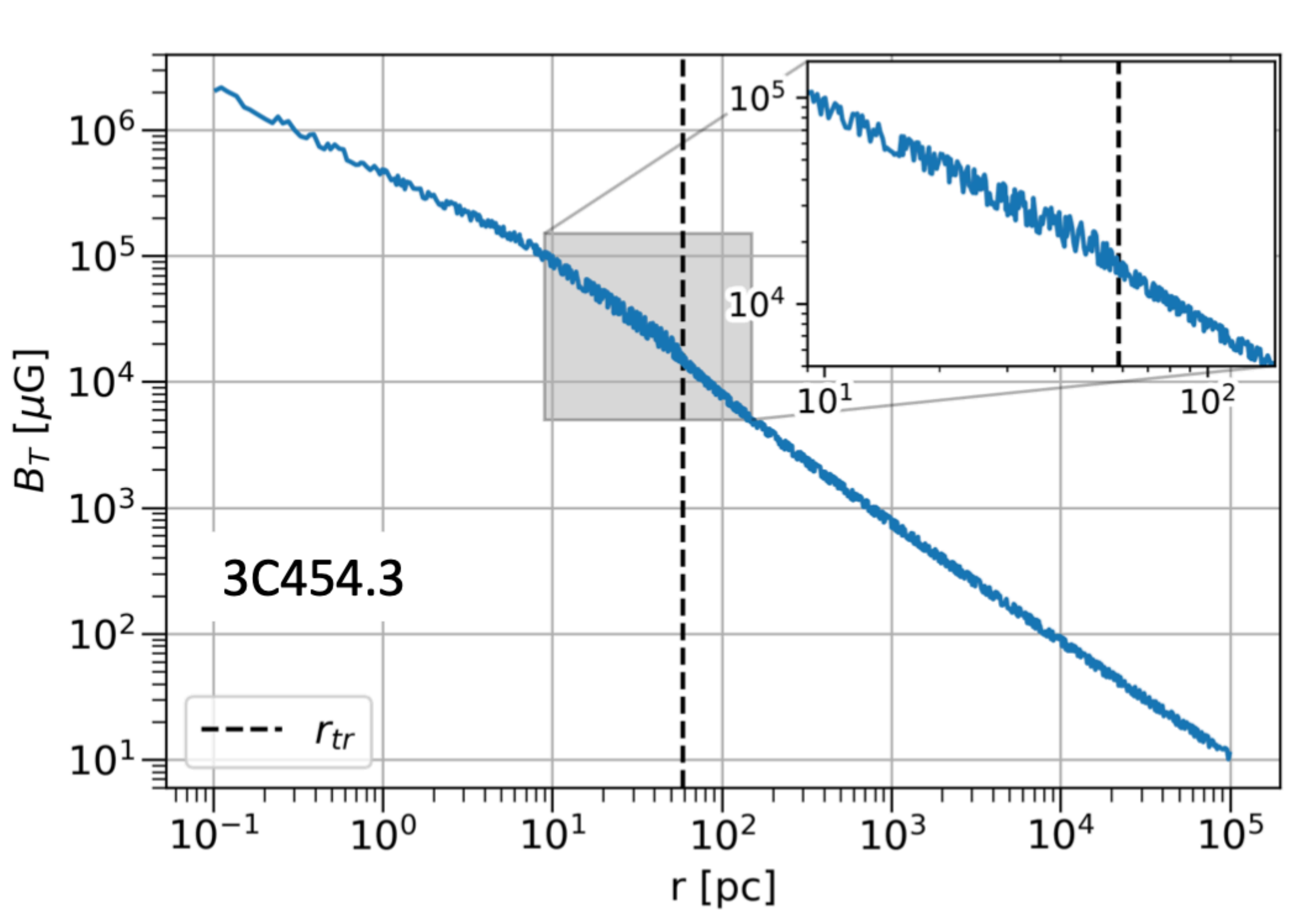
[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

Modeling the jet magnetic field

Work by Jamie Davies, PhD student at Oxford



[Potter & Cotter jet model]

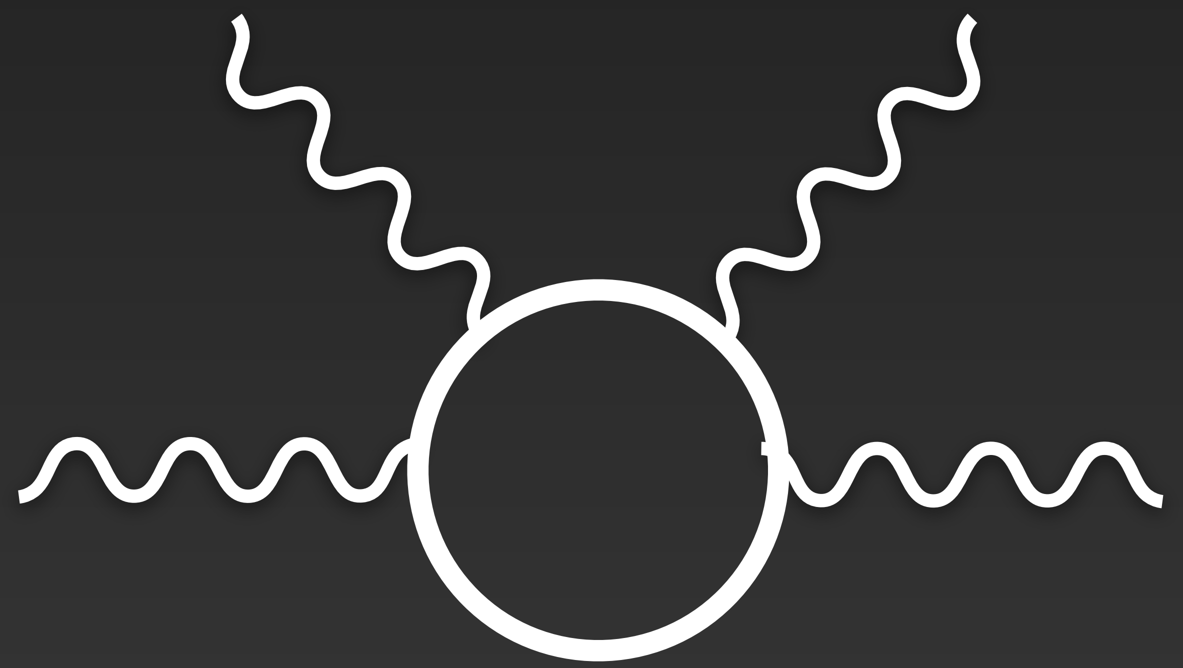


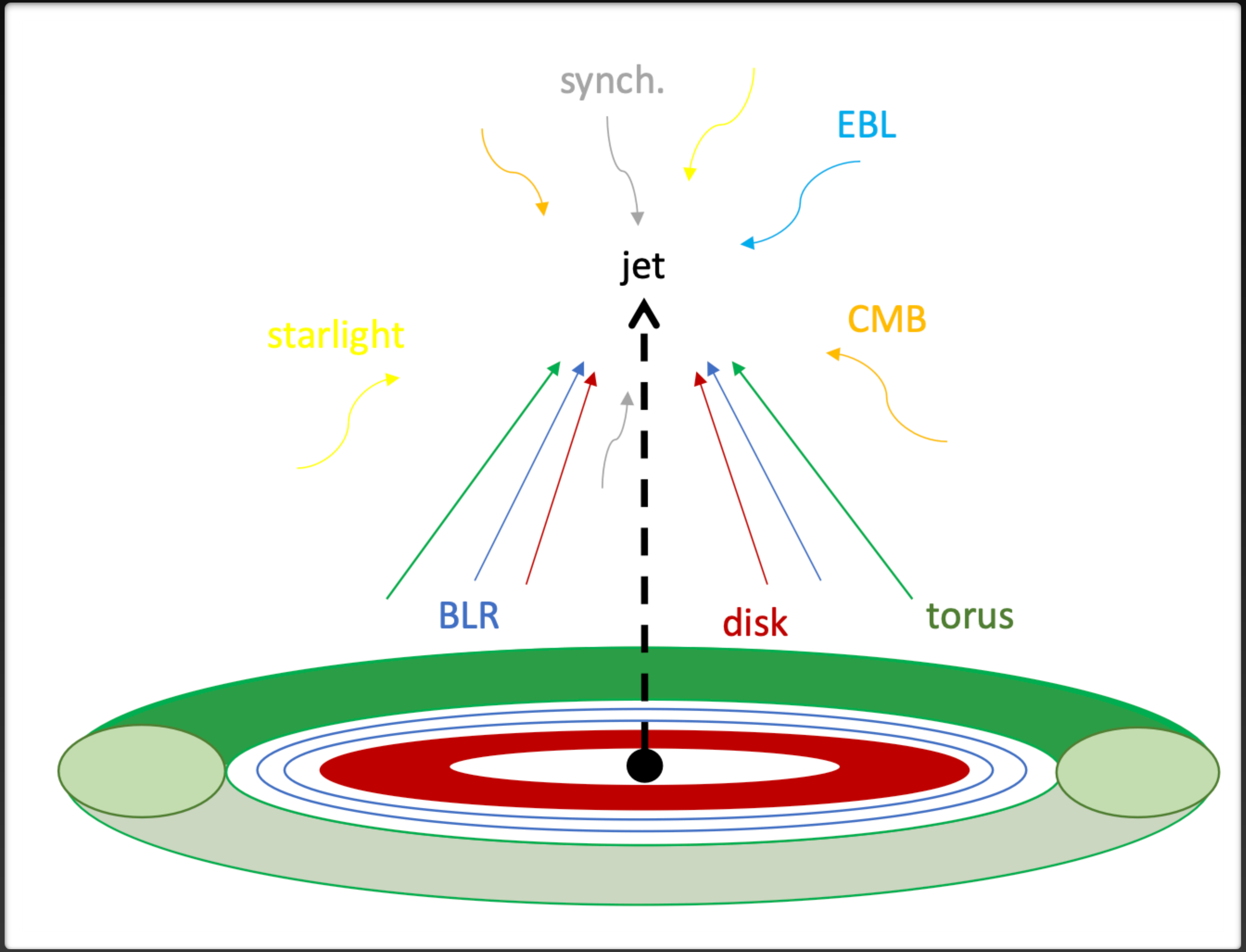
[Davies, MM, Cotter 2022]

Account for photon-photon dispersion

Work by Jamie Davies, PhD student at Oxford

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



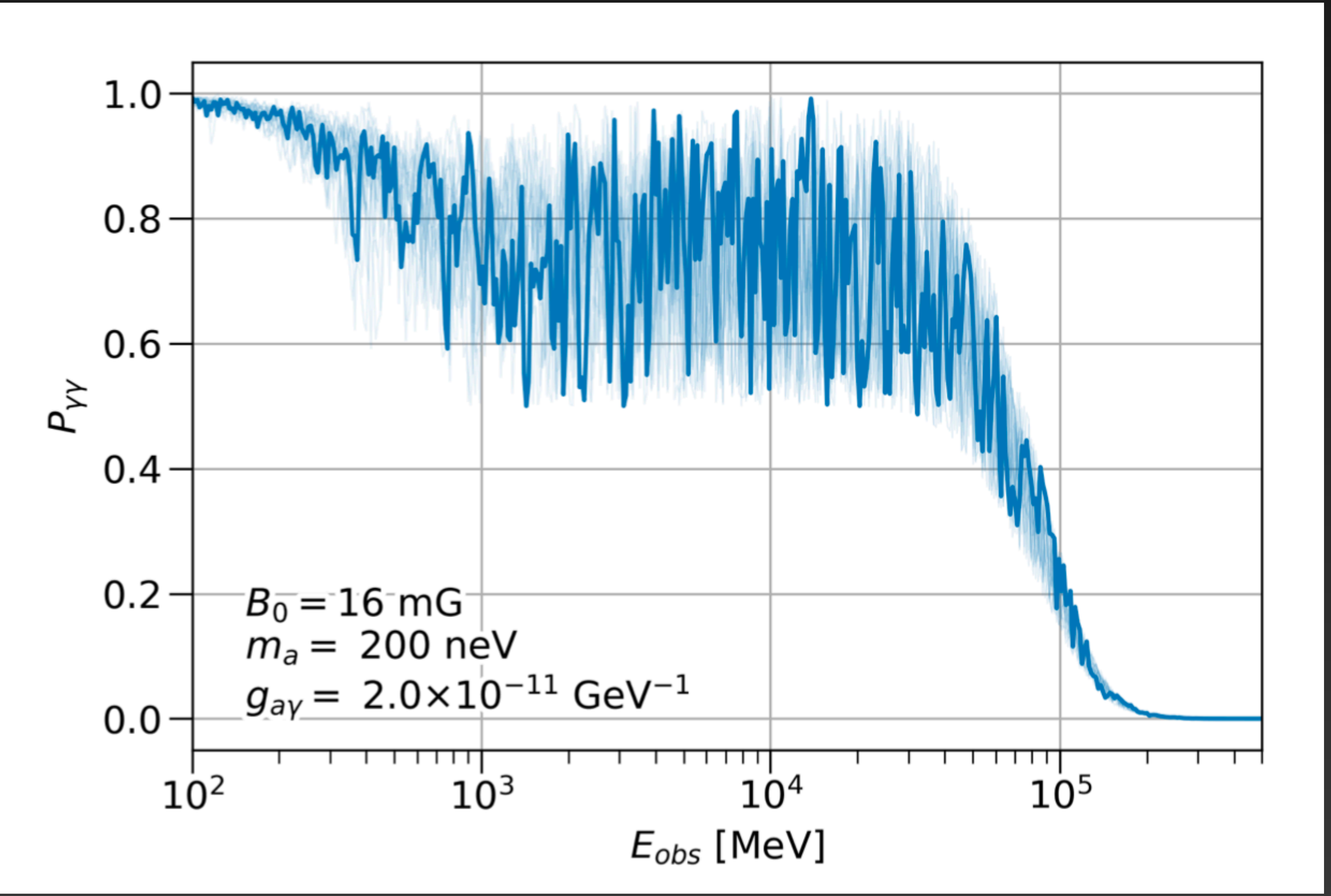


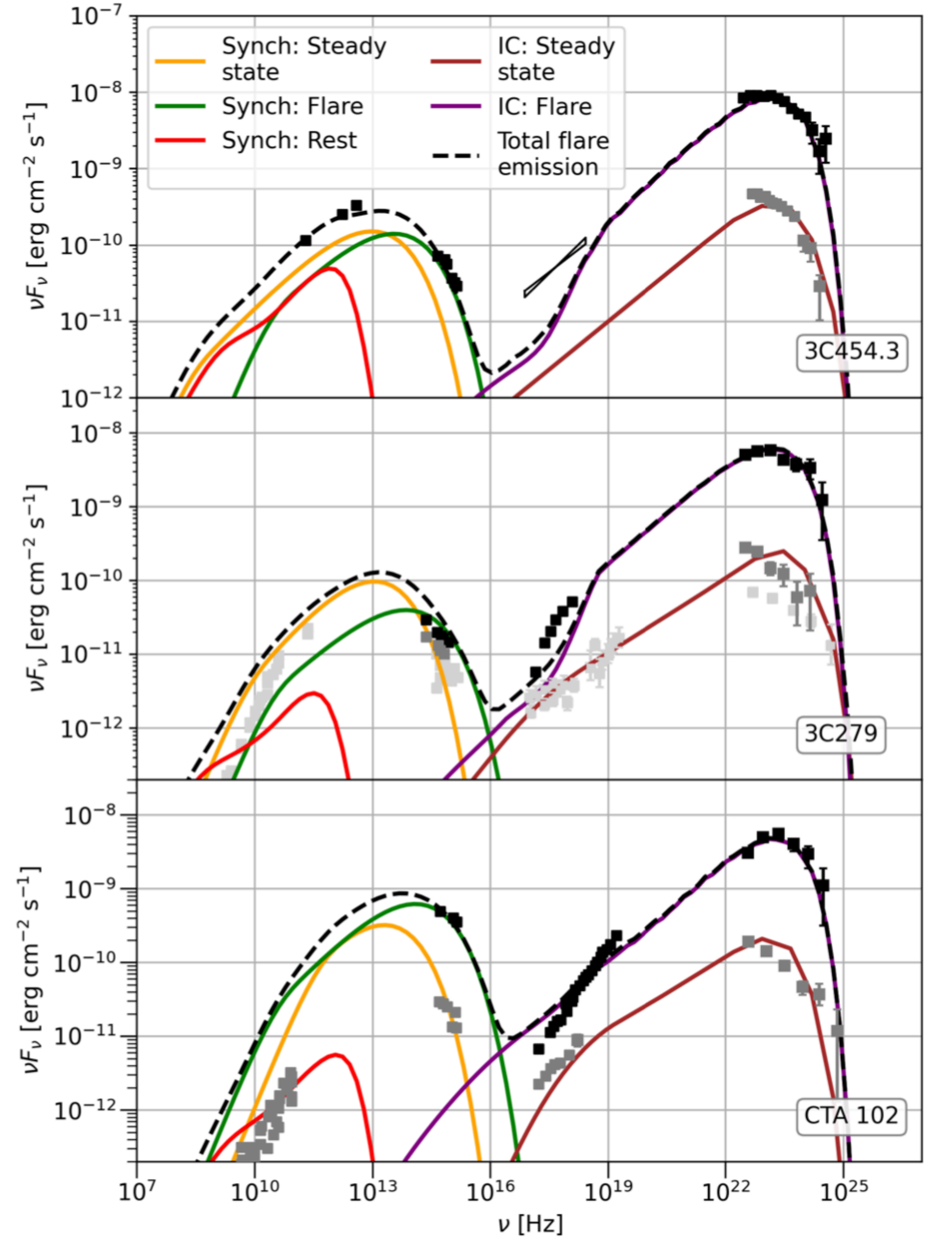
[Davies, MM, Cotter 2022]

Self-consistent modeling

Work by Jamie Davies, PhD student at Oxford

- Assumed B-field needs to reproduce broad band emission



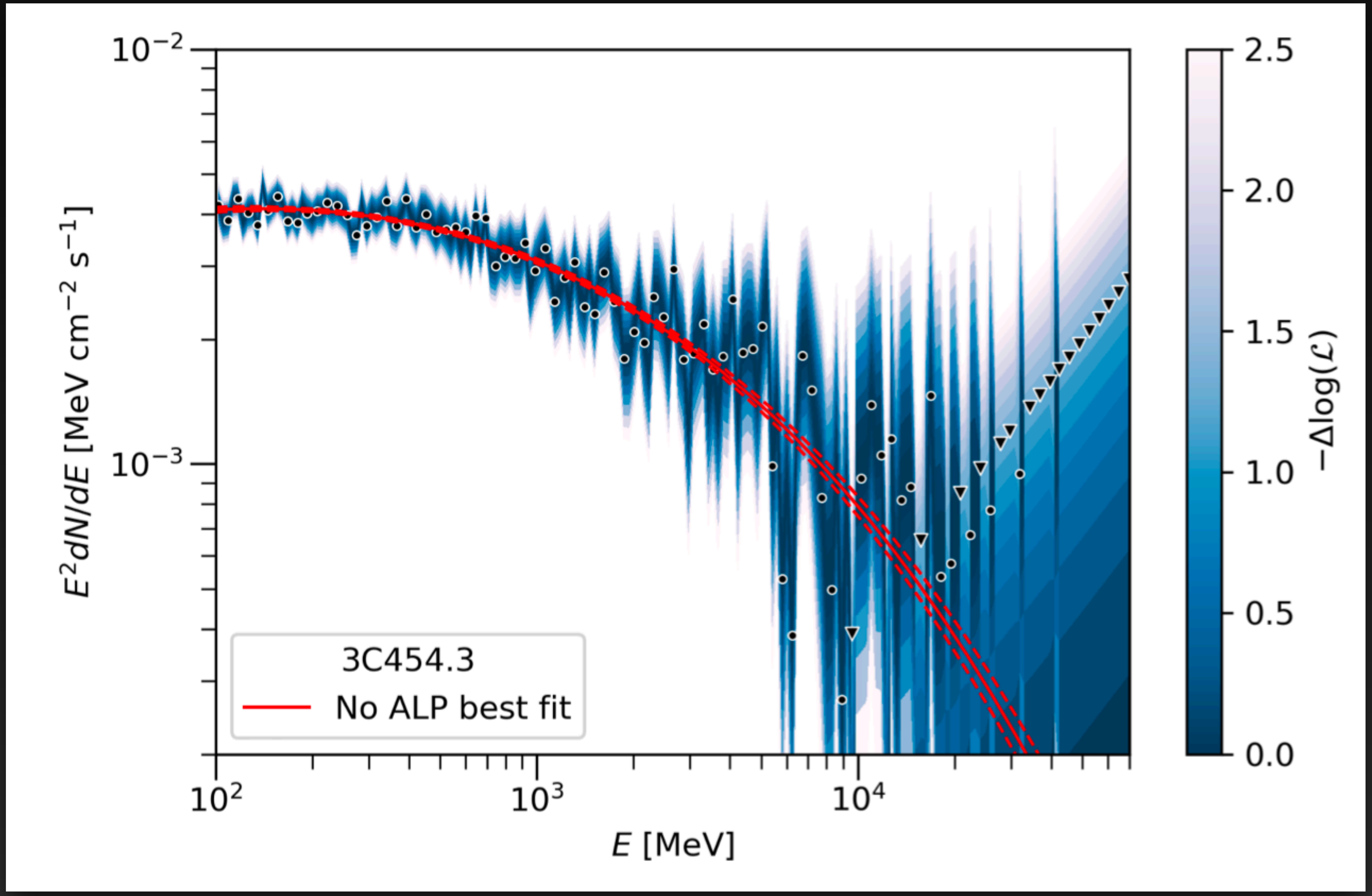


[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

Data analysis

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

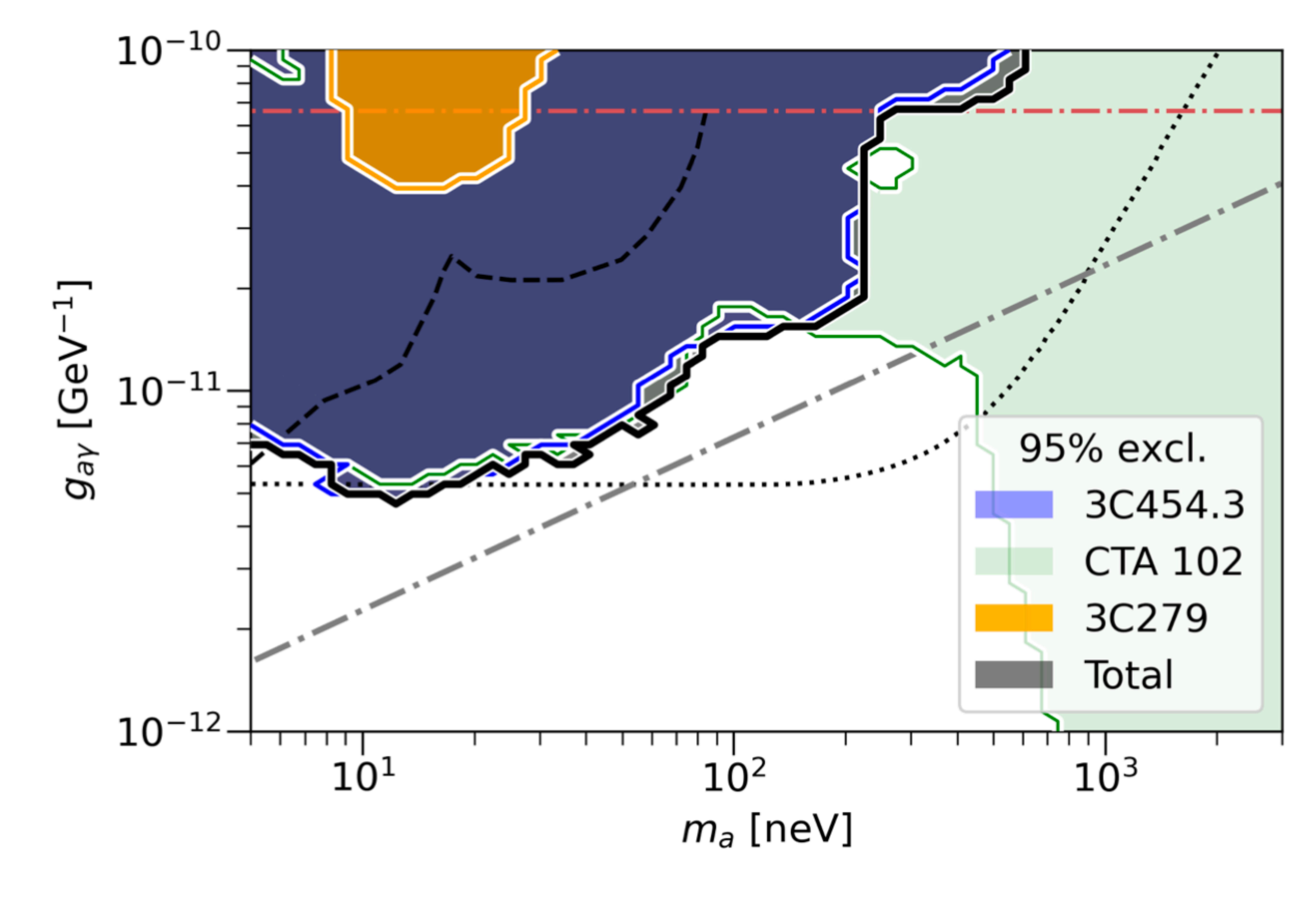


[Davies, MM, Cotter, 2022, 2211.03414, accepted in PRD]

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]