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MINISTRY OF THE ENVIRONMENT AND SPATIAL PLANNING
SLOVENIAN ENVIRONMENT AGENCY
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Gamma-ray observations and axion-like particles

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BAM! - Axions in the sky
14th of June 2024 | Barolo, Italy

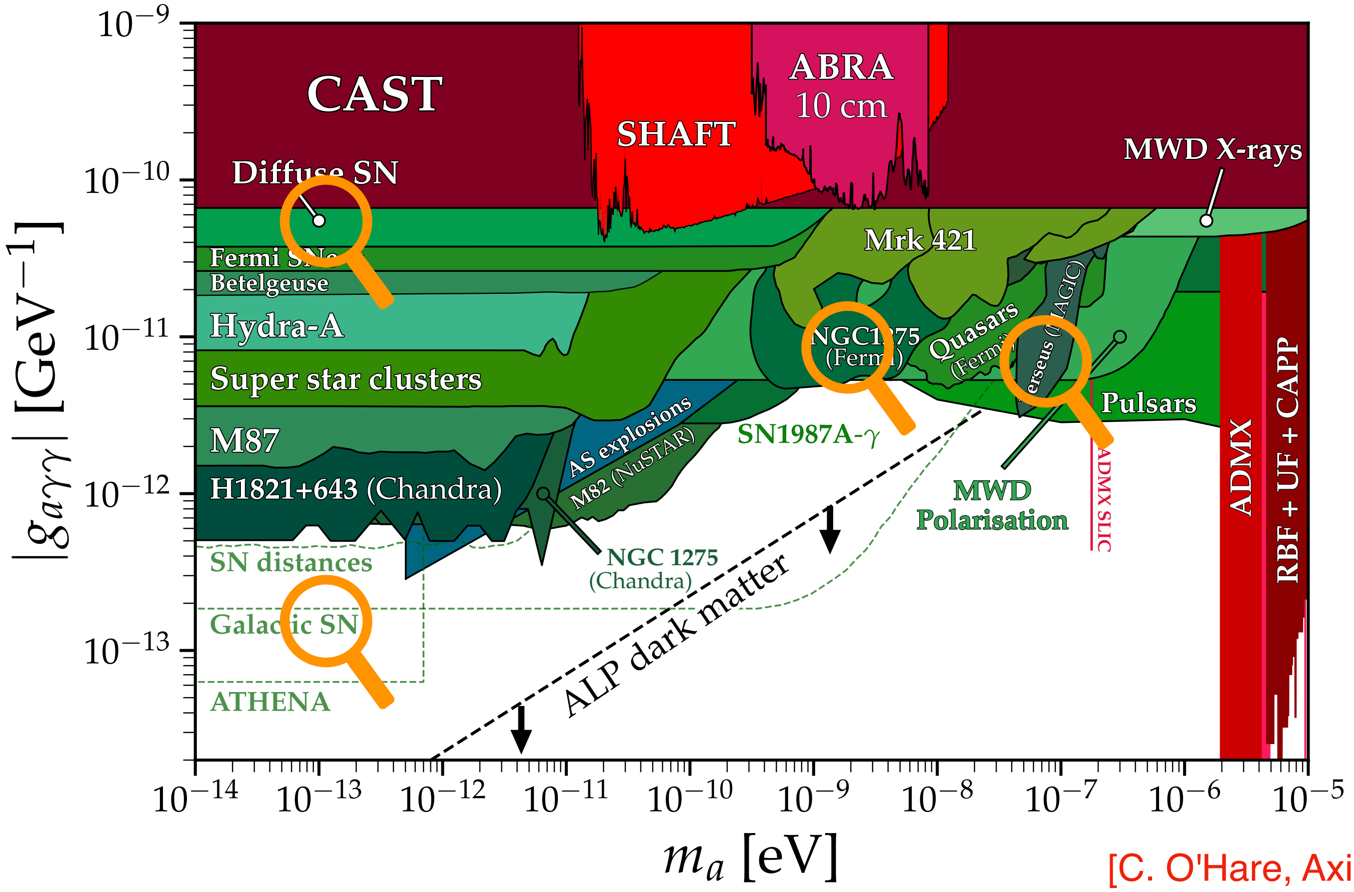
Axions in the sky!
BAM
Barolo Astroparticle Meeting

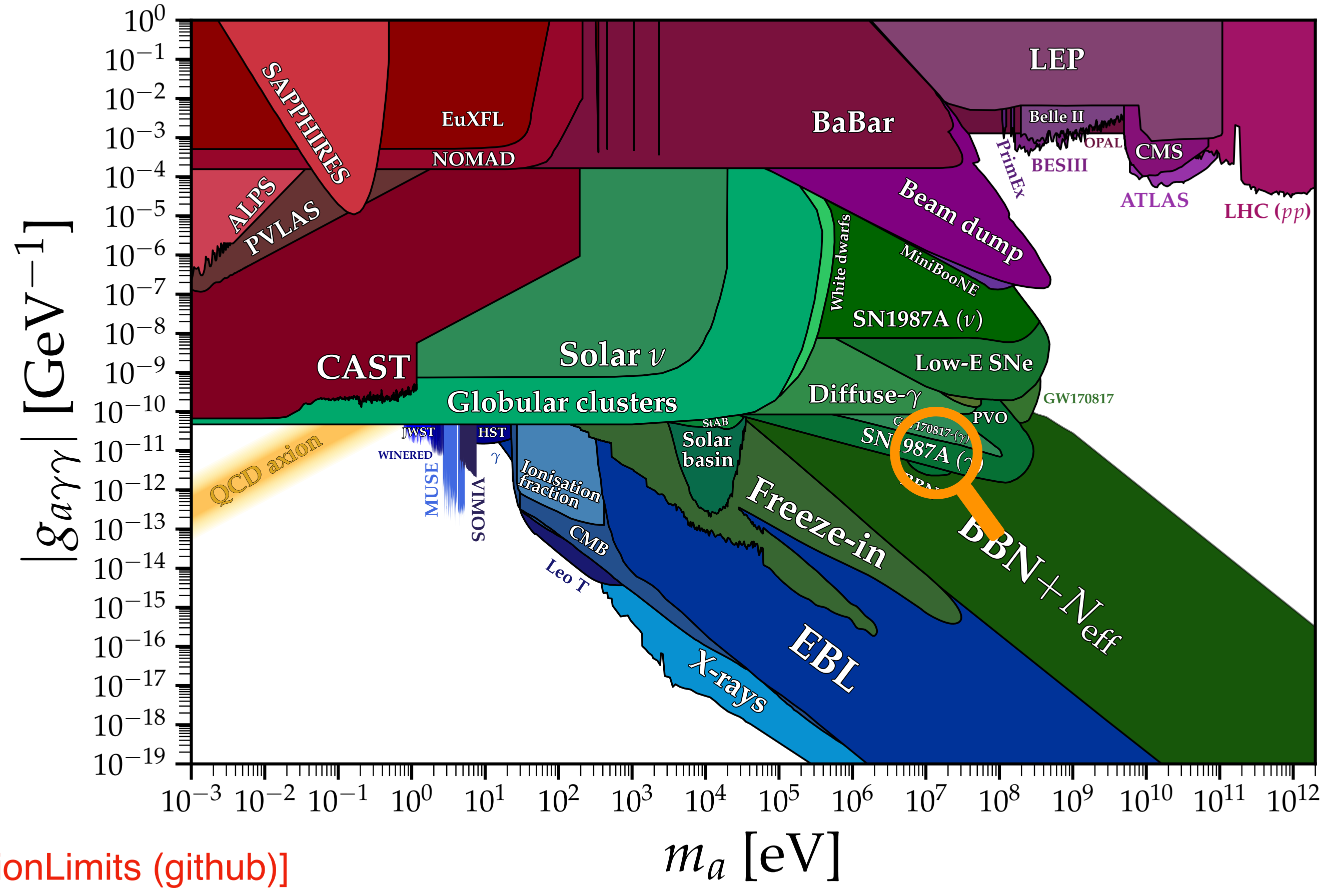
Gamma-ray signatures of ALPs

All relevant phenomenology derives from the minimal Lagrangian

$$\boxed{\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a}$$

Gamma-ray signatures provide competitive search channels with null results (so far):





[C. O'Hare, AxionLimits (github)]

What are promising signatures in the gamma-ray band?

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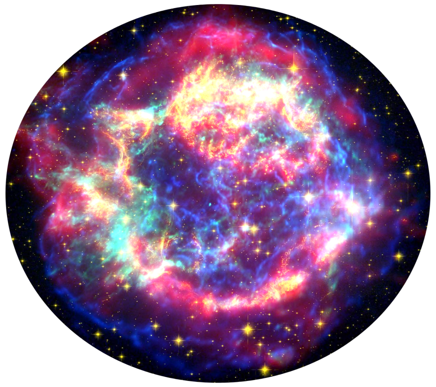
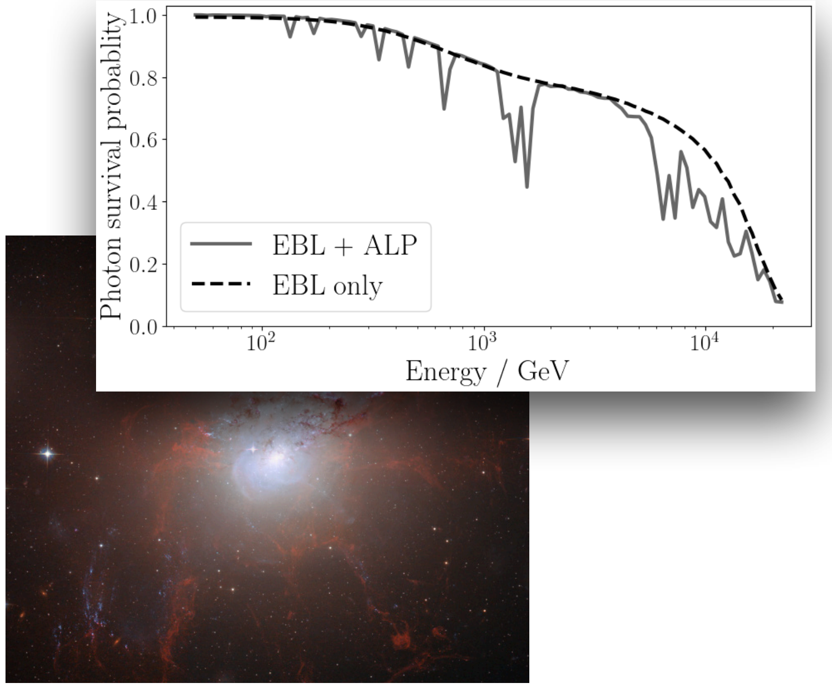
Gamma-ray signatures of ALPs

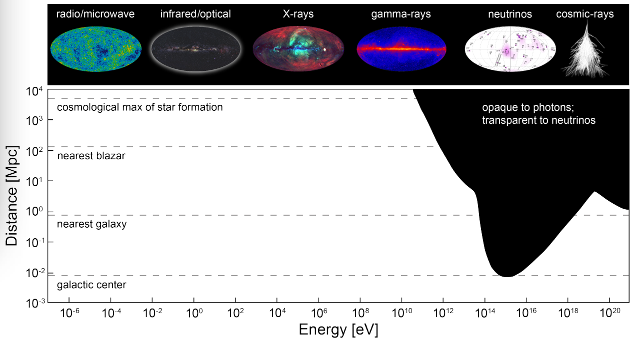
ALP signature



(extra-)galactic Core-collapse supernovae

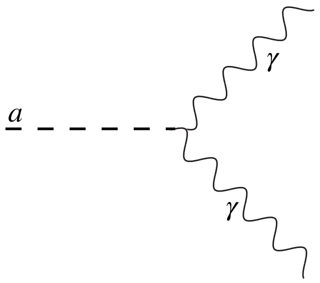


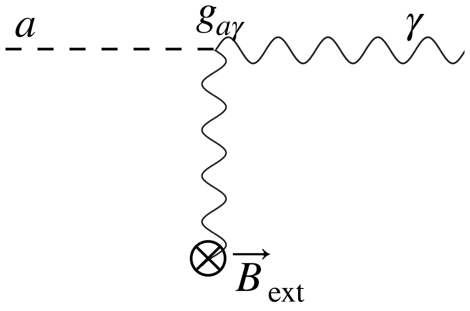
spectral irregularities

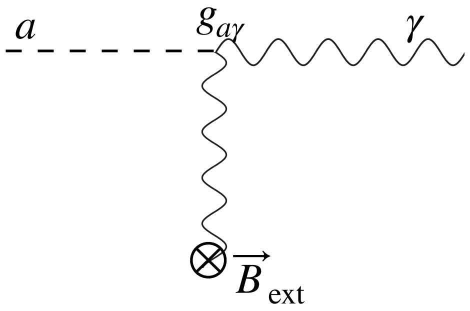


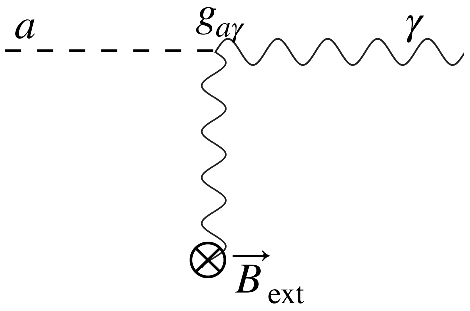
gamma-ray opacity of the universe

Relevant processes









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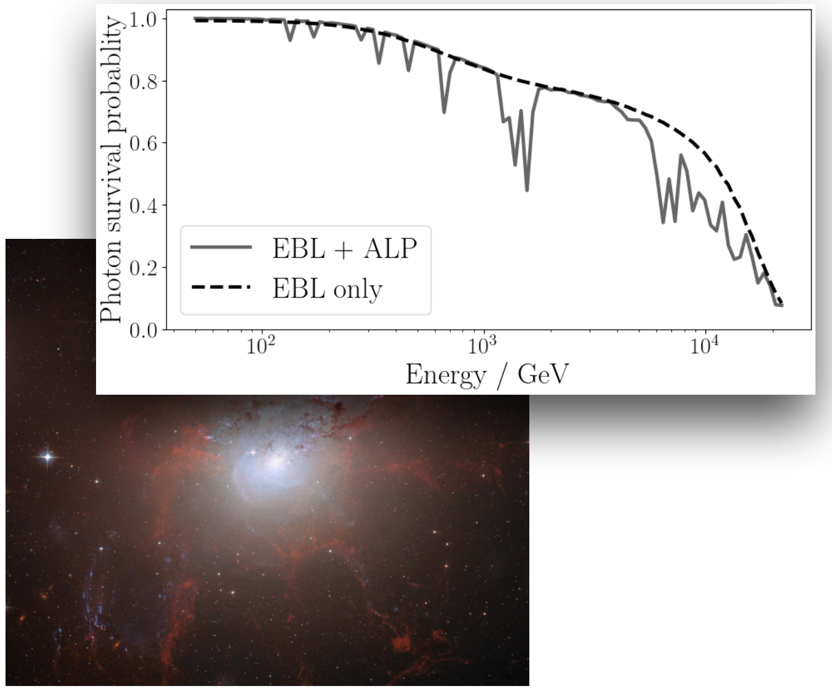
Gamma-ray signatures of ALPs

ALP signature

Relevant processes

(extra-)galactic
Core-collapse
supernovae



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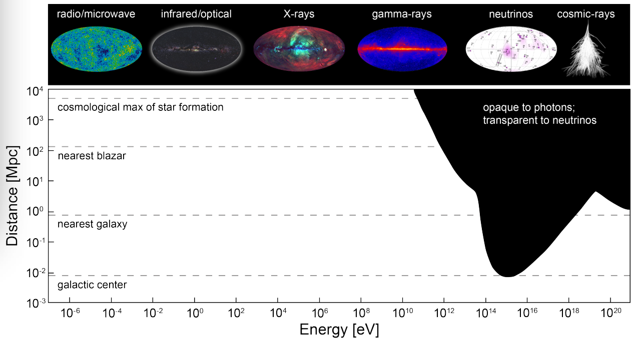
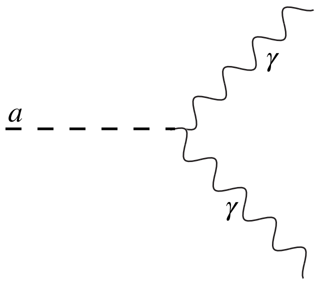
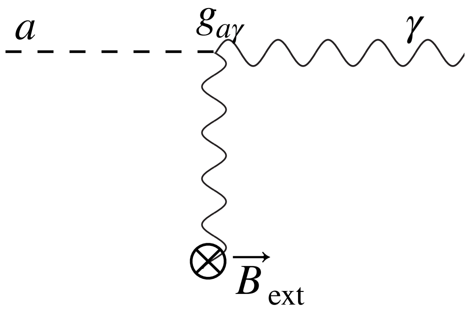
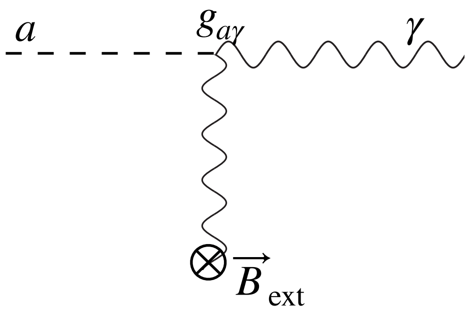
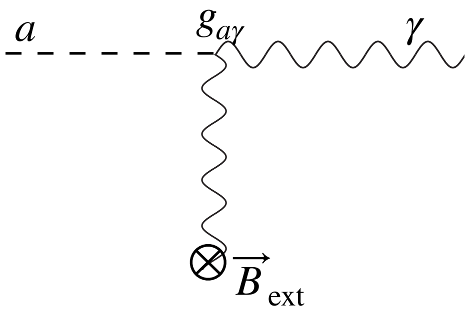


gamma-ray opacity of
the universe









keV **MeV** **GeV** **TeV** **PeV**

γ-ray energies

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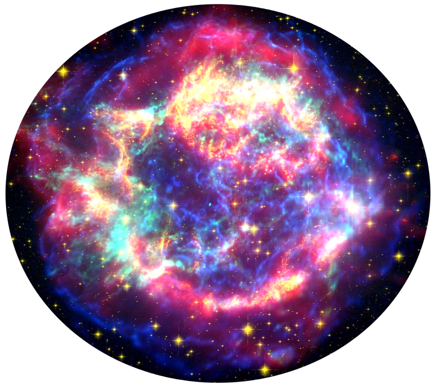
Gamma-ray signatures of ALPs

ALP signature



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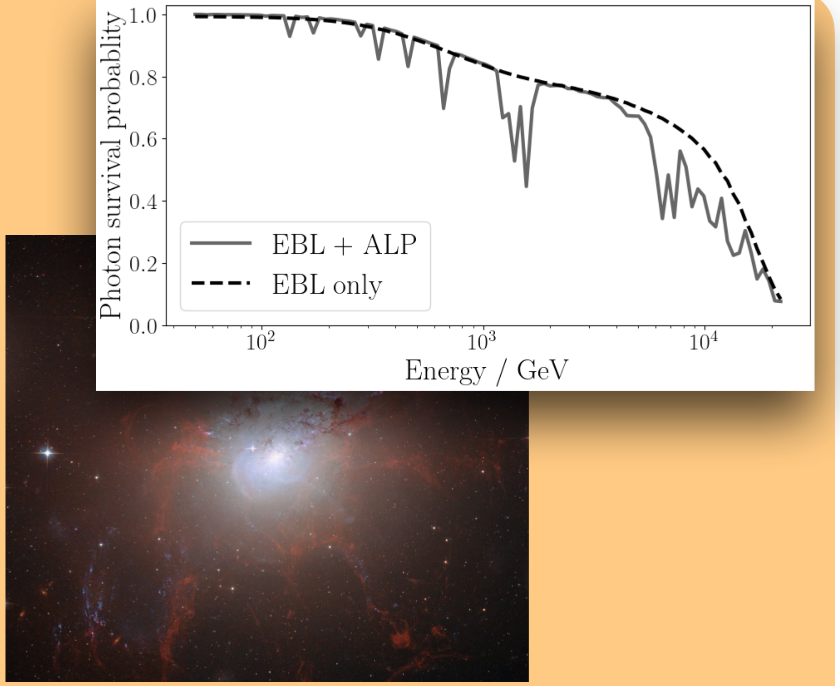
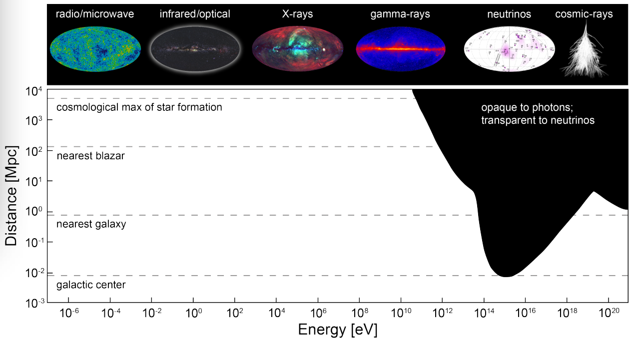
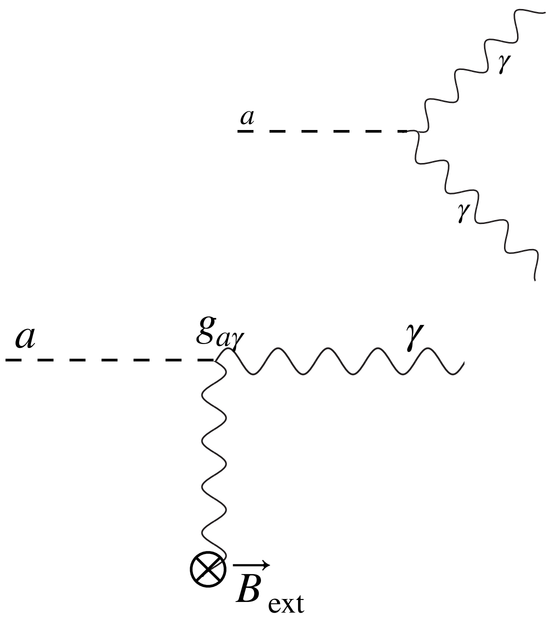


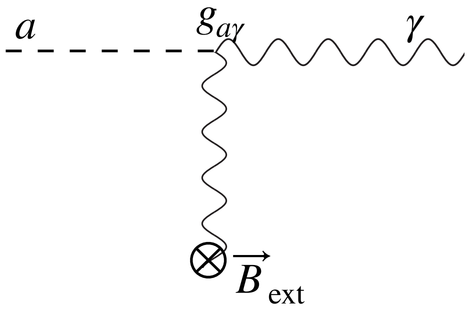
spectral irregularities

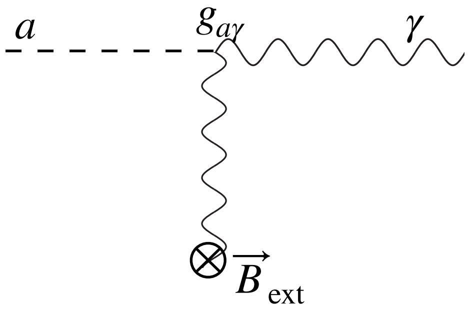


gamma-ray opacity of the universe

Relevant processes







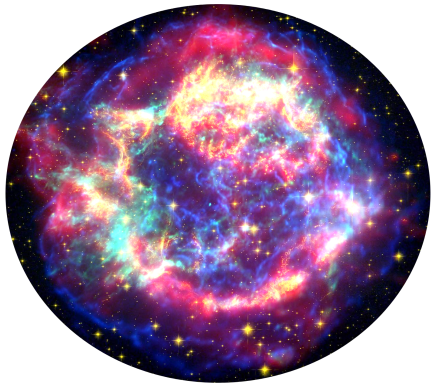
keV **MeV** **GeV** **TeV** **PeV**

γ-ray energies

Gamma-ray signatures of ALPs

ALP signature

Relevant processes



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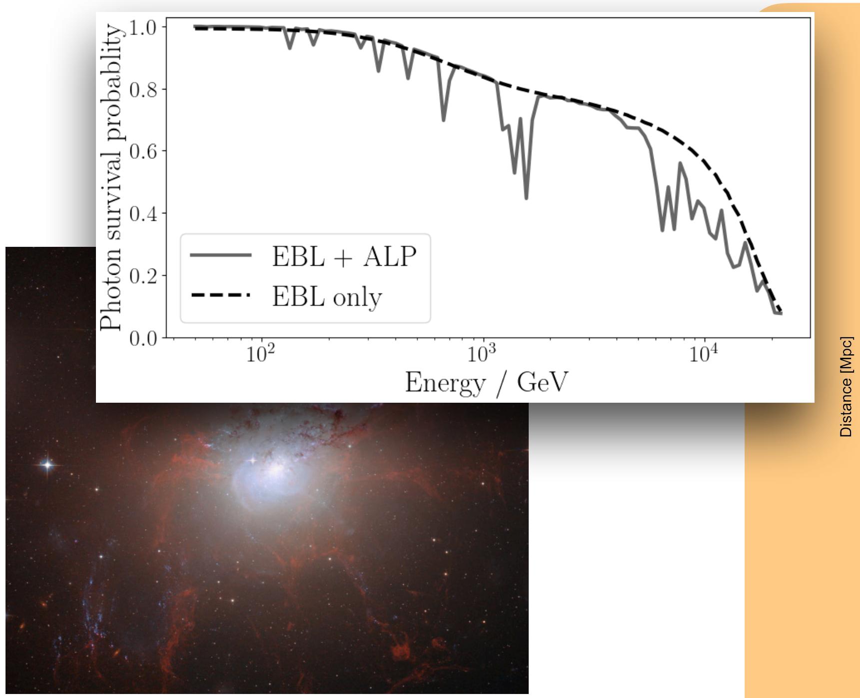

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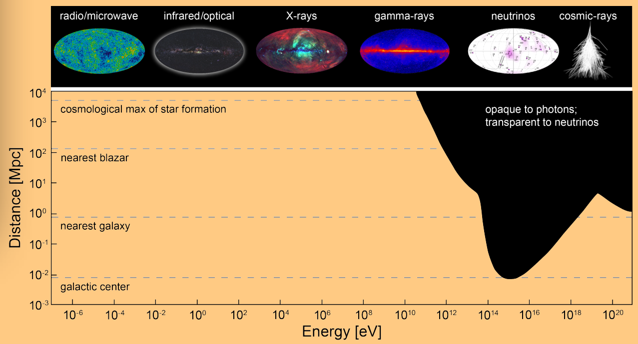
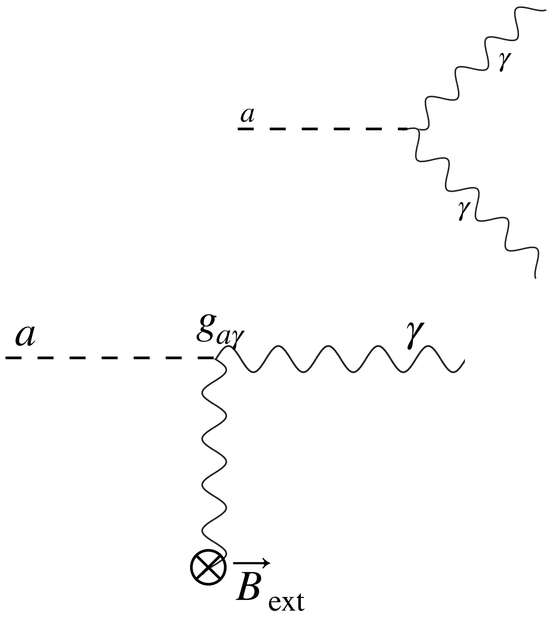
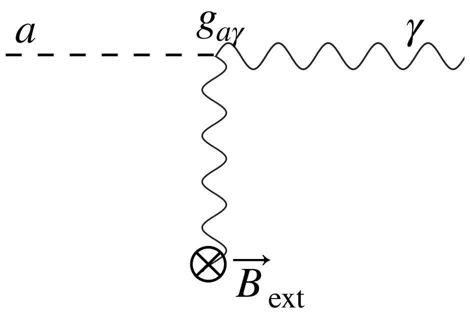
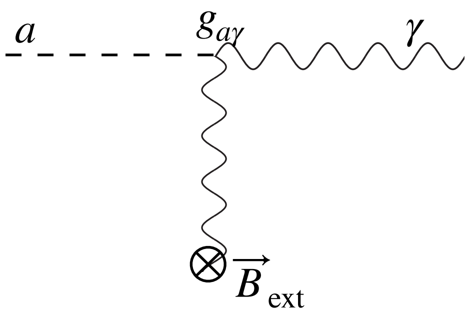


gamma-ray opacity of the universe







keV **MeV** **GeV** **TeV** **PeV**

γ-ray energies

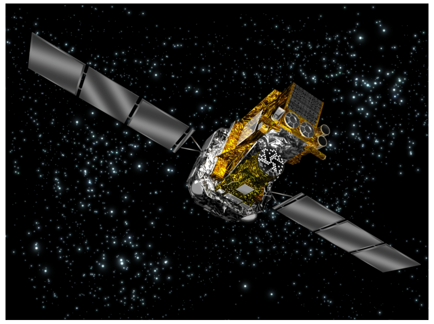
Gamma-ray detection facilities

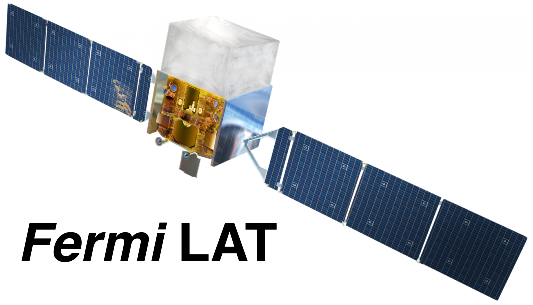
The zoology of gamma-ray instruments currently running (and under construction).

Present

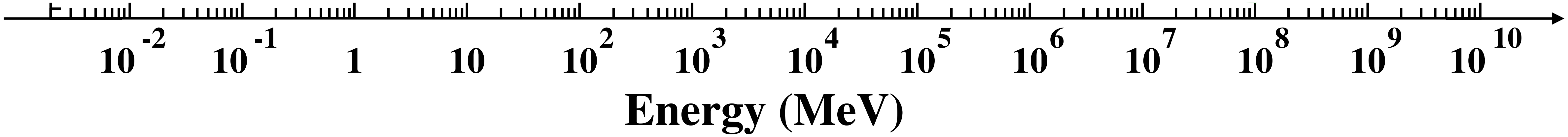
Satellite missions

INTEGRAL





***Fermi* LAT**



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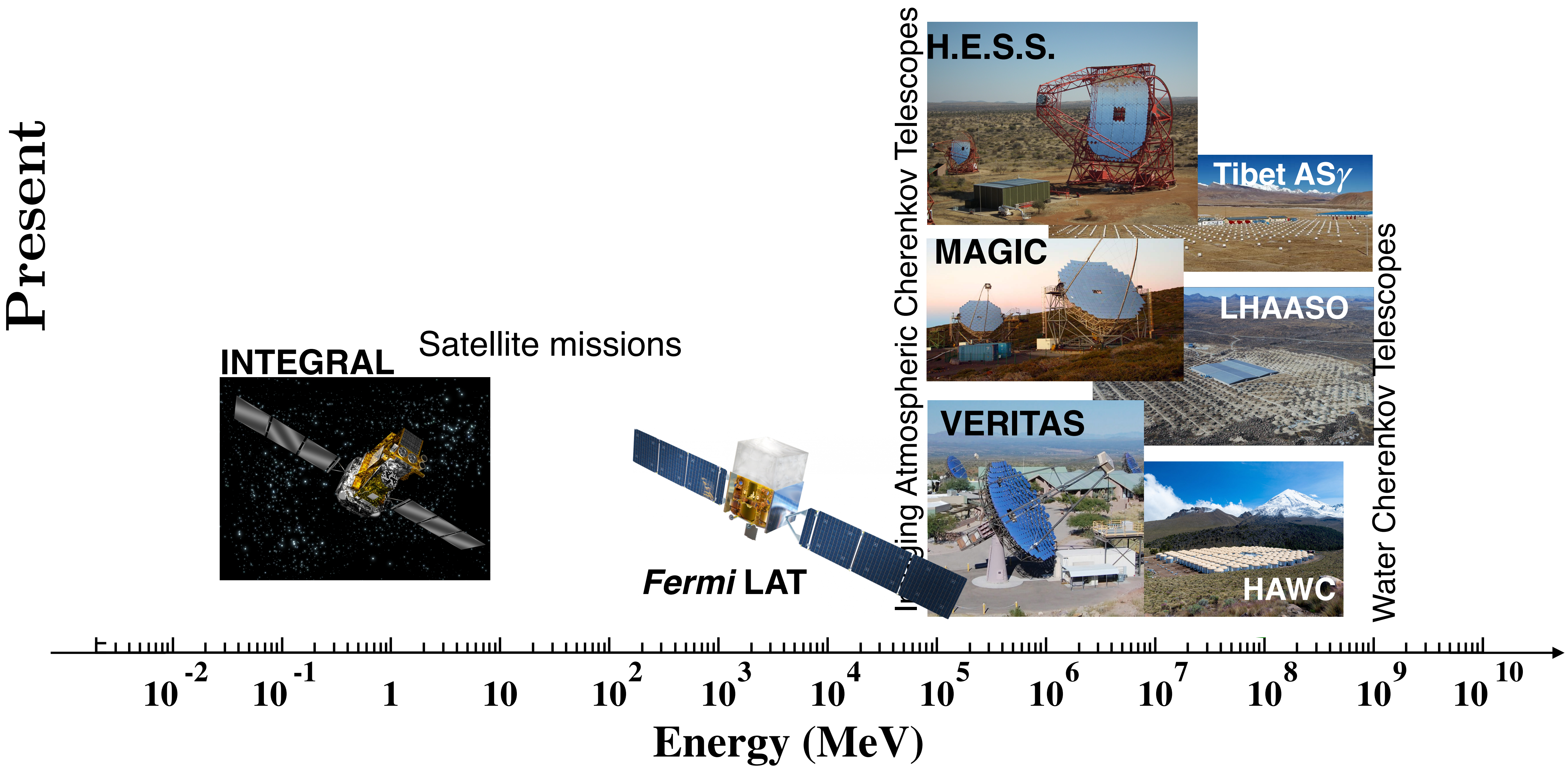

Gamma-ray detection facilities

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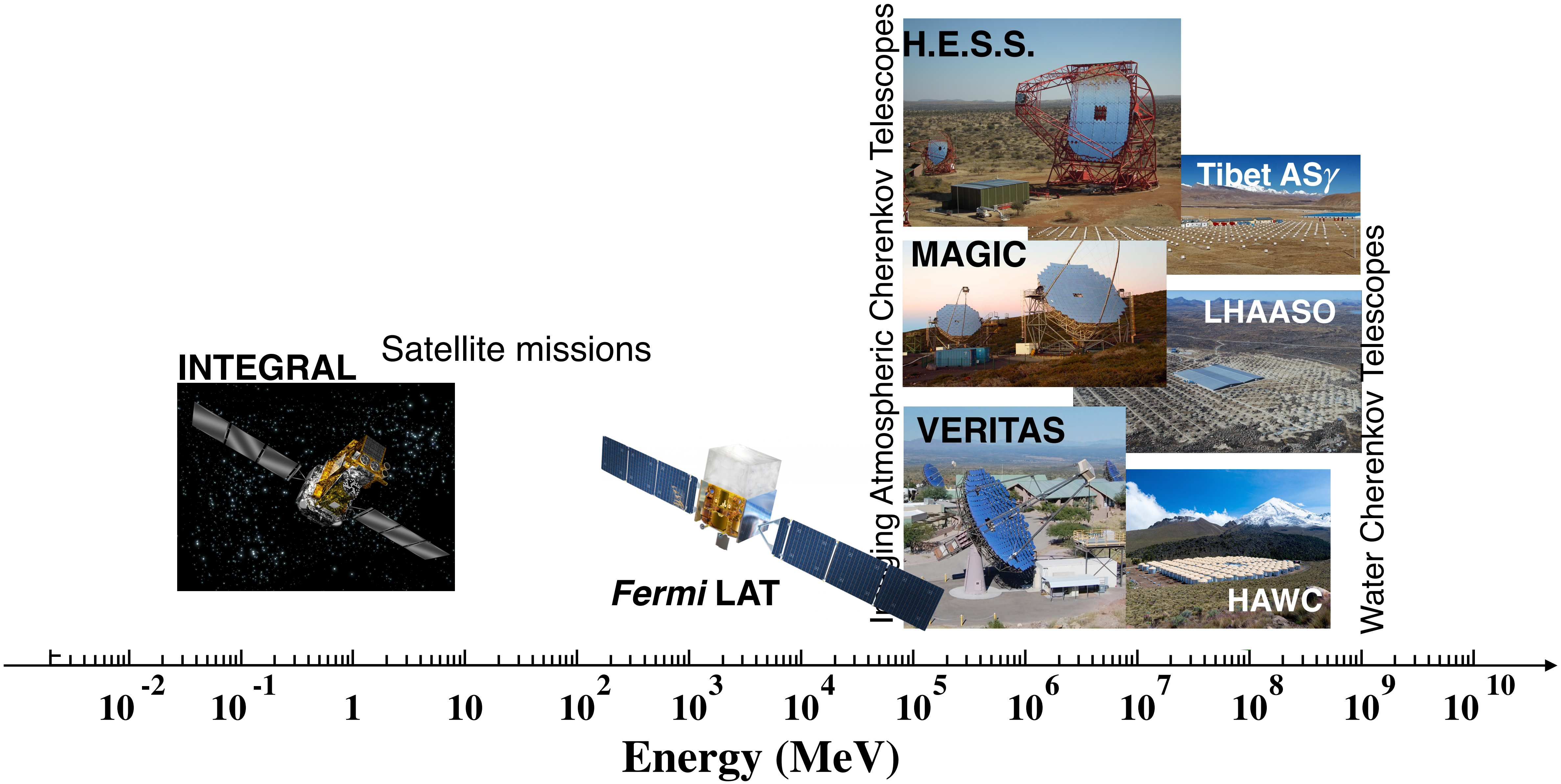
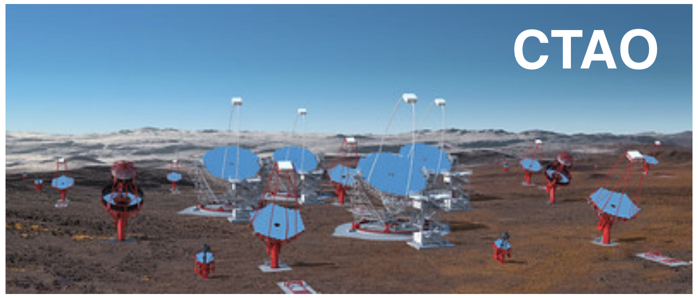
Present



Future

?



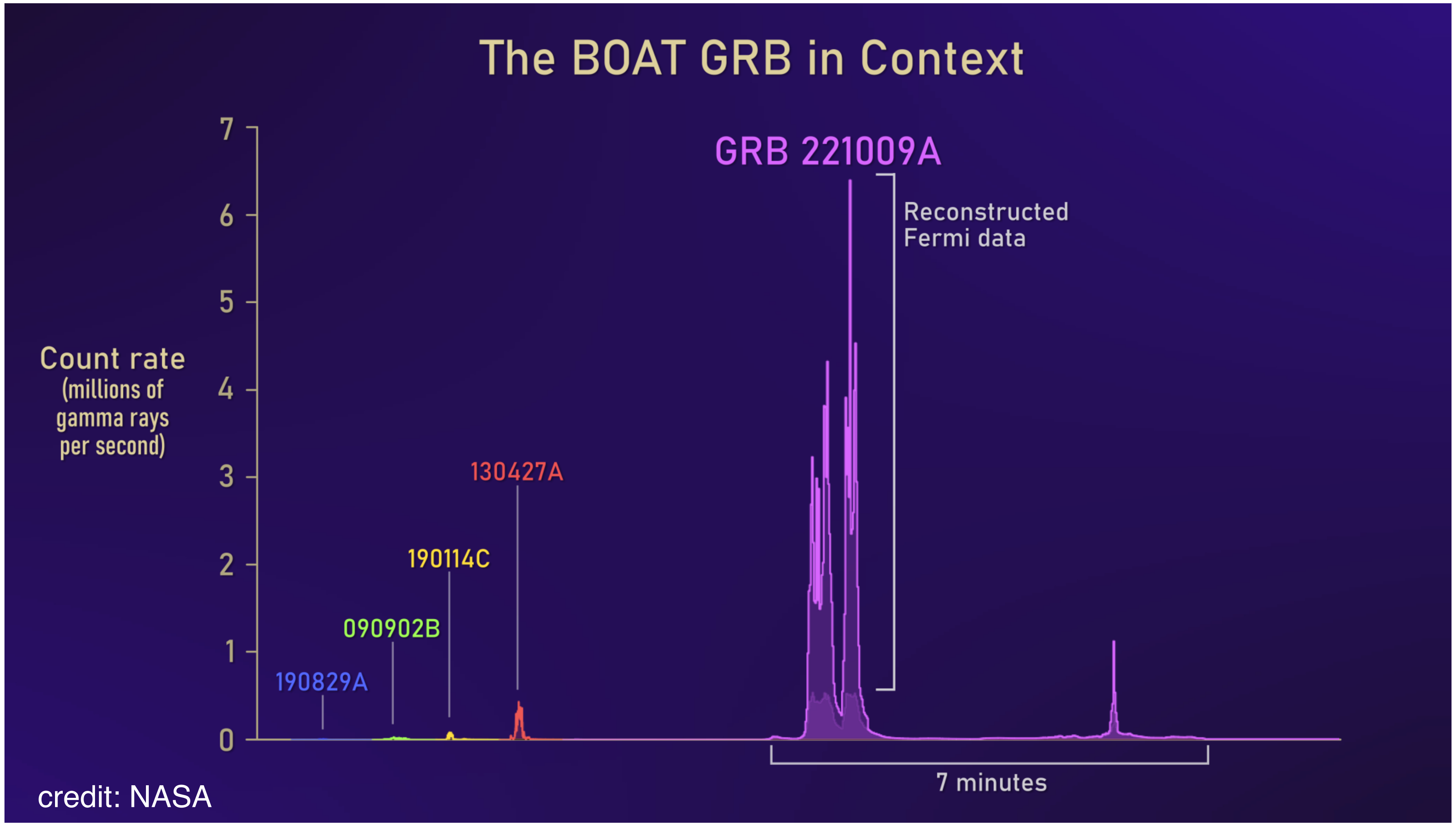
Breeching the opacity of the universe

See also M. C. D. Marsh's talk!

The Brightest Of All Times — GRB 221009A

On the 9th of October 2022 an extremely luminous Gamma Ray Burst (GRB) at redshift $z = 0.151$ *was* observed on Earth and in space by gamma-ray telescopes.

- **1-in-10000 year event**
- **Saturated the GRB monitor on Fermi**
- **It was so bright despite being inside the Galactic plane.**
- **Detected by LHAASO and HAWC (IACTs full moon phase)**



credit: NASA

Important observation: LHAASO detected a gamma-ray event of 18 TeV [LHAASO Collaboration, GCN Circular n. 32677 (2022)] [LHAASO collab., Science 380 (2023)] [LHAASO collab., Sci. Adv. 9, 46 (2023)] (Before that, the most energetic ever-detected GRB particle was 3 TeV [H.E.S.S. collab., Science 372, 1081 (2021)])

→ The claim of a 251 TeV gamma ray detected by Carpet-2 is disputed.

Absorption on the extragalactic background light

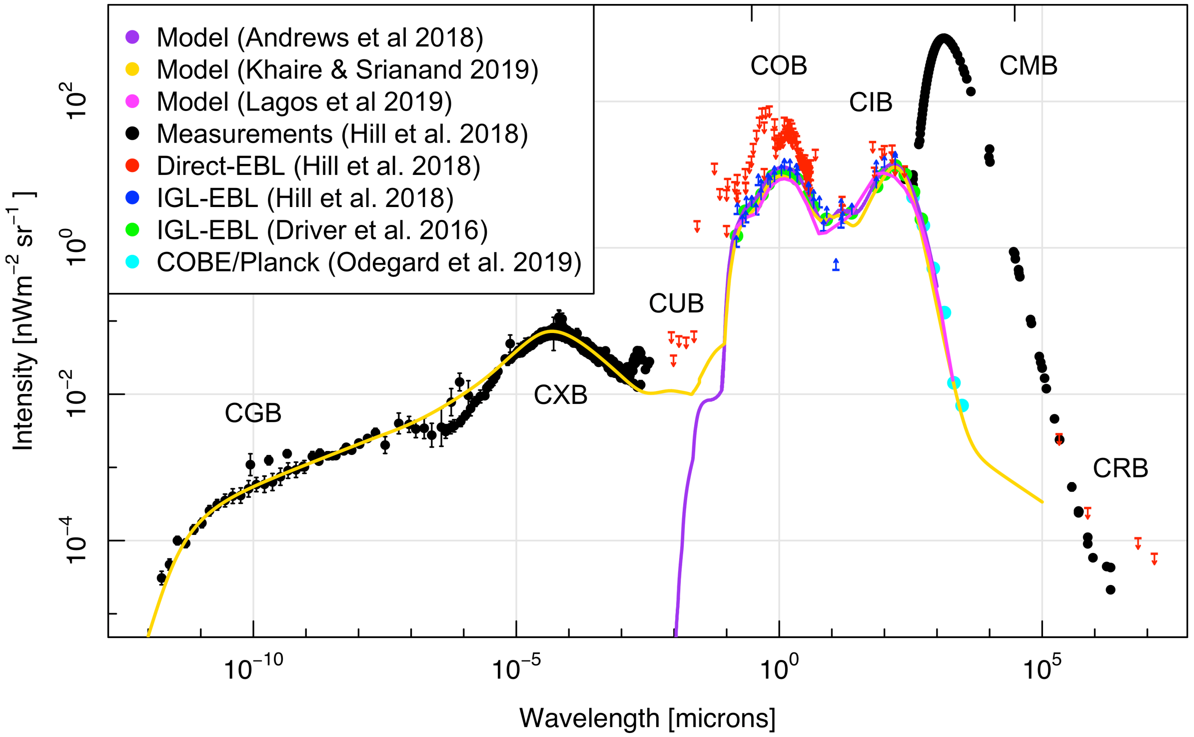
The universe becomes almost opaque to very-high-energy gamma rays above ten TeV.

→ **The reason: attenuation on the extragalactic background light (EBL)**

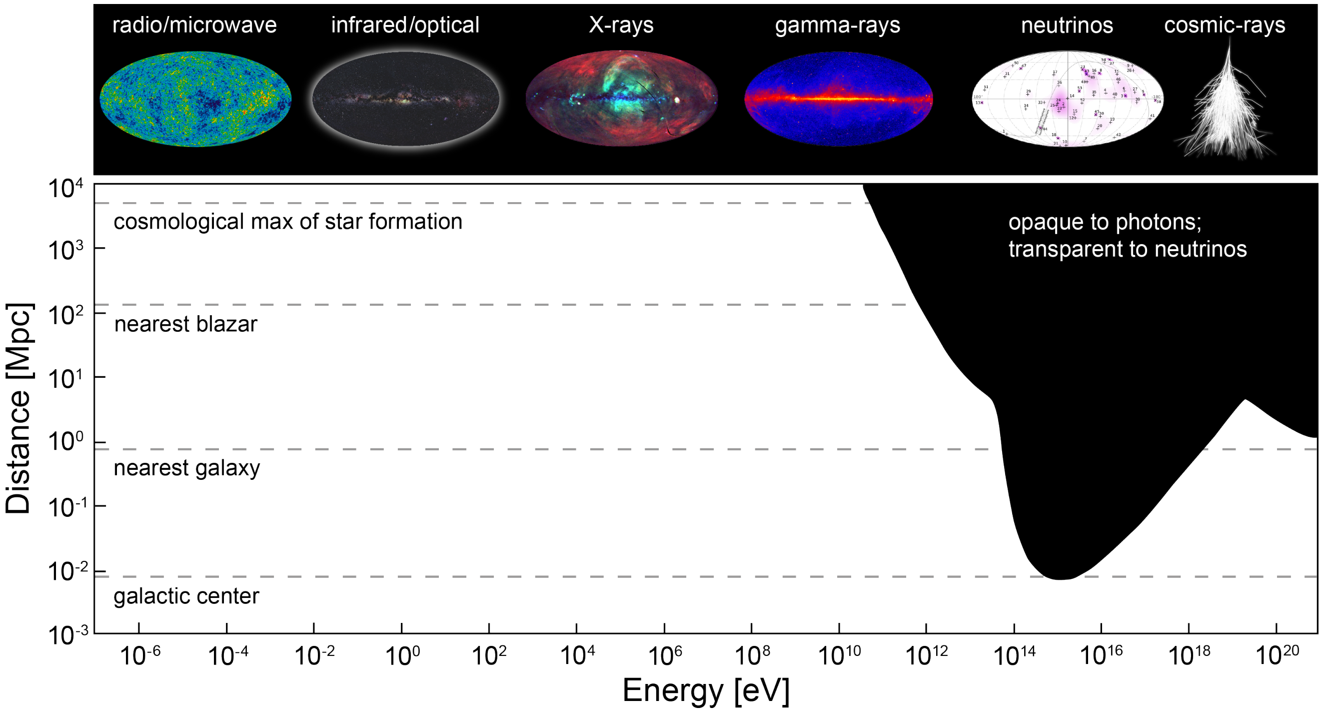
Mixture of radiation fields, e.g.: light from stars/galaxies, light re-radiated after dust absorption

$$\phi_{obs}(E) = \phi_{int}(E) \cdot \exp\left[-\tau(E,z)\right] \qquad \tau = \frac{d}{n(E)\sigma(\gamma\gamma \to e^+e^-)}$$

[Driver, IAU Symposium 355, 2102.12089]

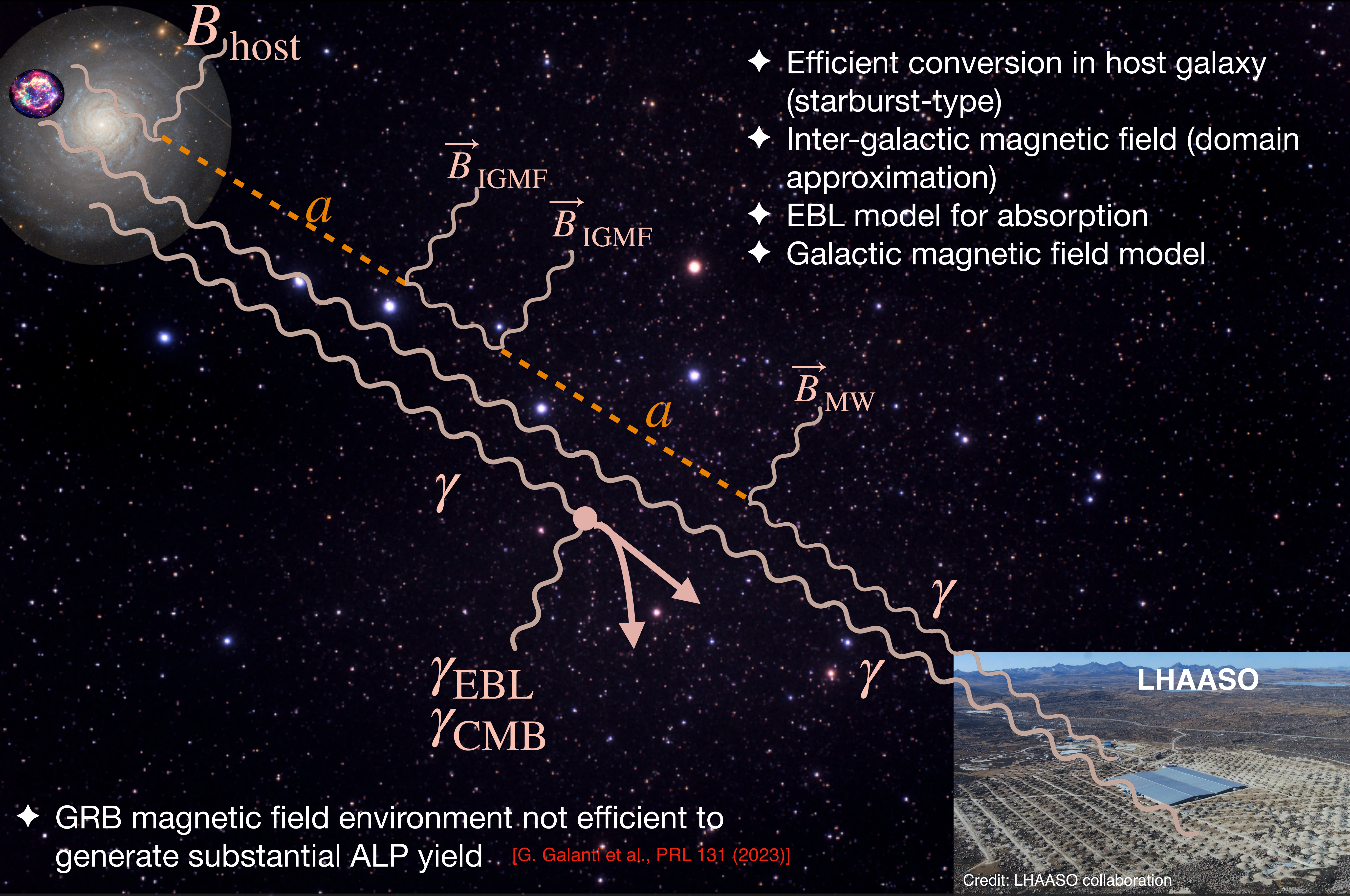


credit: IceCube collab.



- ✦ At sub-PeV energies, Galactic physics probably only major contributor.
- ✦ Exotic physics, especially feebly interacting particles as ALPs, circumvent EBL absorption.
  → **May give rise to extragalactic gamma-ray contribution by (partially) alleviating the universe's opaqueness.**

Modelling the photon survival probability of a GRB



Credit: LHAASO collaboration

- ✦ Efficient conversion in host galaxy (starburst-type)
- ✦ Inter-galactic magnetic field (domain approximation)
- ✦ EBL model for absorption
- ✦ Galactic magnetic field model

- ✦ GRB magnetic field environment not efficient to generate substantial ALP yield [G. Galanti et al., PRL 131 (2023)]

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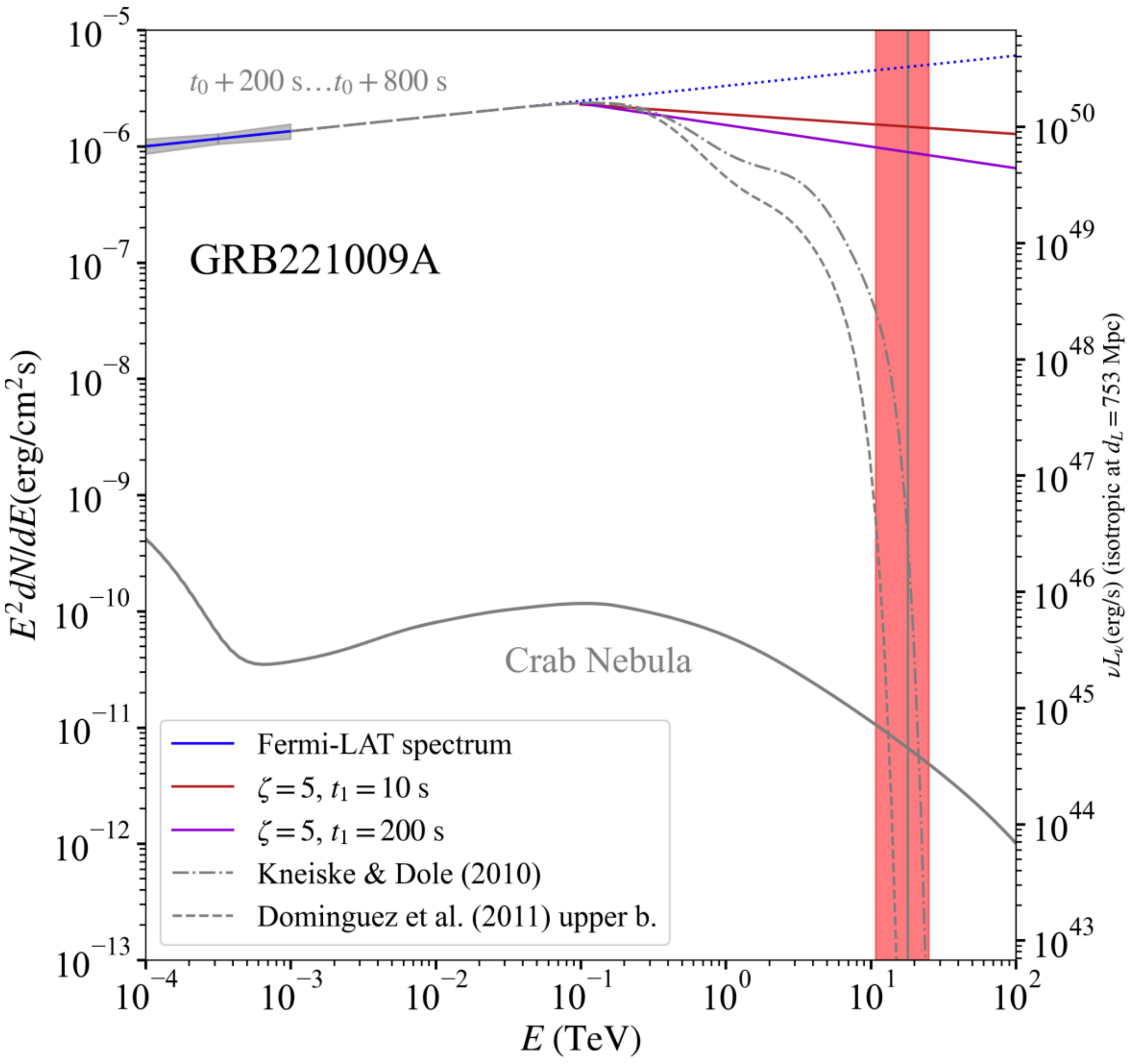
Can ALPs explain GRB 221009A?

What do we know about the origin of GRB 221009A?

— hosted in a disc galaxy

— seen edge-on from Earth [A. J. Levan et al., ApJL 946 (2023) 1]

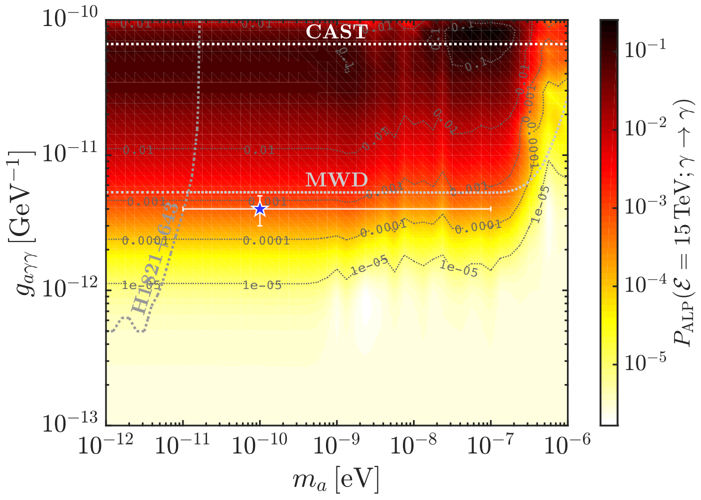
→ GRB propagates through intergalactic medium (potentially strong absorption in host's radiation fields of sub-PeV gamma rays)



[A. Baktash et al., arXiv:2210.07172]

ALP-hypothesis addressed in several works with varying level of detail:

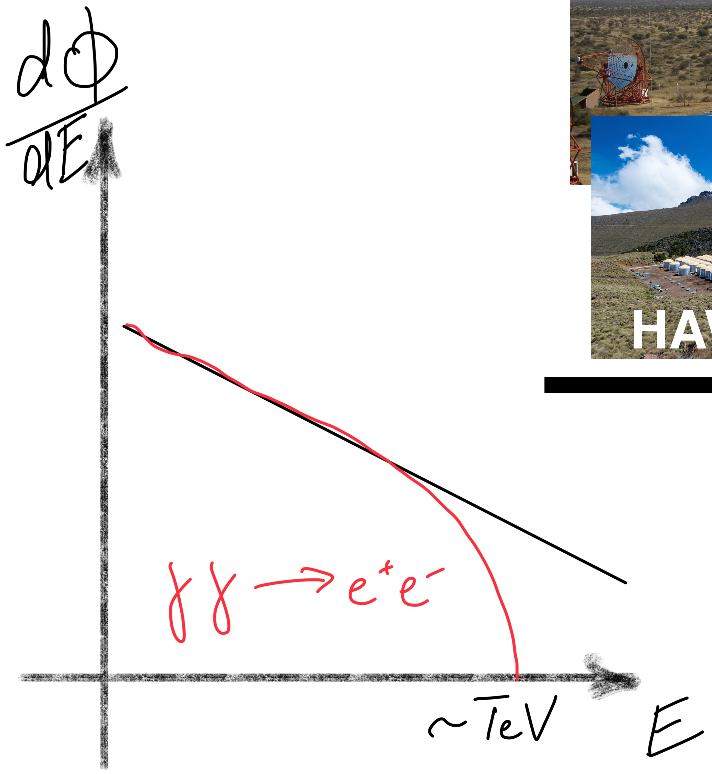
1. ALP hypothesis plausible for 18 TeV event + model for $\gamma\gamma$-attenuation in host galaxy
   [P. Carenza & M.C. D. Marsh, arXiv:2211.02010]
2. ALP solves puzzle about 18 TeV event (only EBL attenuation, starburst/star-forming galaxy distinction)
   [G. Galanti et al., PRL 131, 25

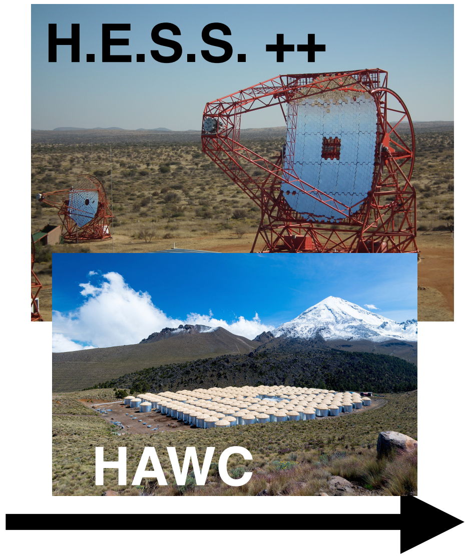


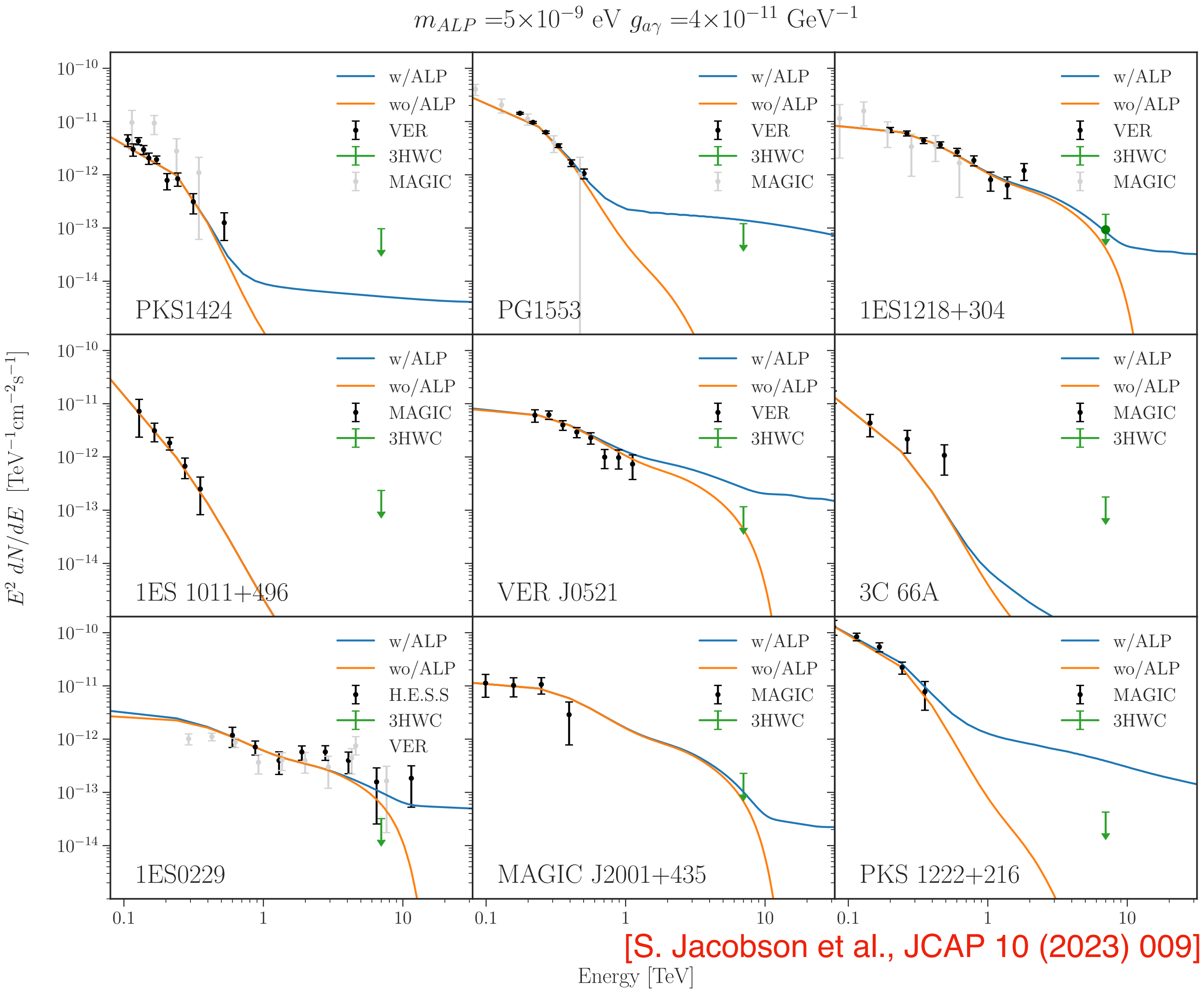
3. ALP hypothesis does not plausibly alleviate the tension
   [A. Baktash et al., arXiv:2210.07172]

Leveraging the universe’s transparency

Test transparency of the universe with a sample of (steady and flaring) high-energy sources.





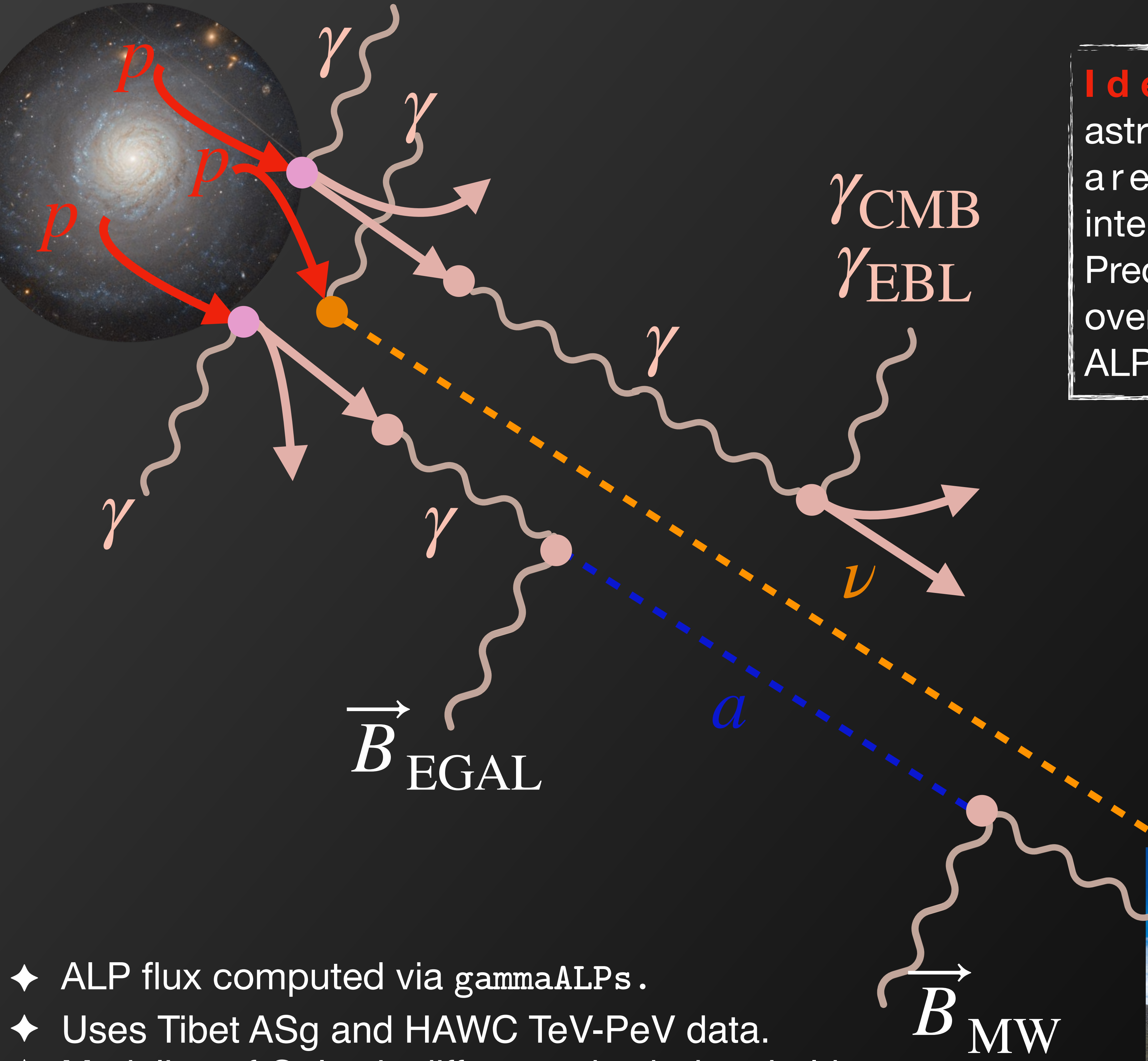


[S. Jacobson et al., JCAP 10 (2023) 009]

General findings so far:

- ✦ No clear signals only upper limits compatible with existing ones from complementary targets.
- ✦ Slightly less constraining limits from analysis of sources on Fermi LAT’s 2FHL catalogue (up to 2 TeV) [R. Buehler et al., JCAP 09 (2020) 027]
- ✦ Magnetic field models of target sources (jets, clusters, etc.) crucial (+ uncertain).

Leveraging the IceCube neutrino flux



Idea: Assume sub-PeV astrophysical neutrinos of IceCube are due to photo-hadronic interactions in star-forming galaxies. Predict concomitant gamma-ray flux over history of the universe incl. ALPs.

- ✦ ALP flux computed via `gammaALPs`.
- ✦ Uses Tibet ASg and HAWC TeV-PeV data.
- ✦ Modeling of Galactic diffuse and sub-threshold point source contribution.

Credit: HAWC collaboration

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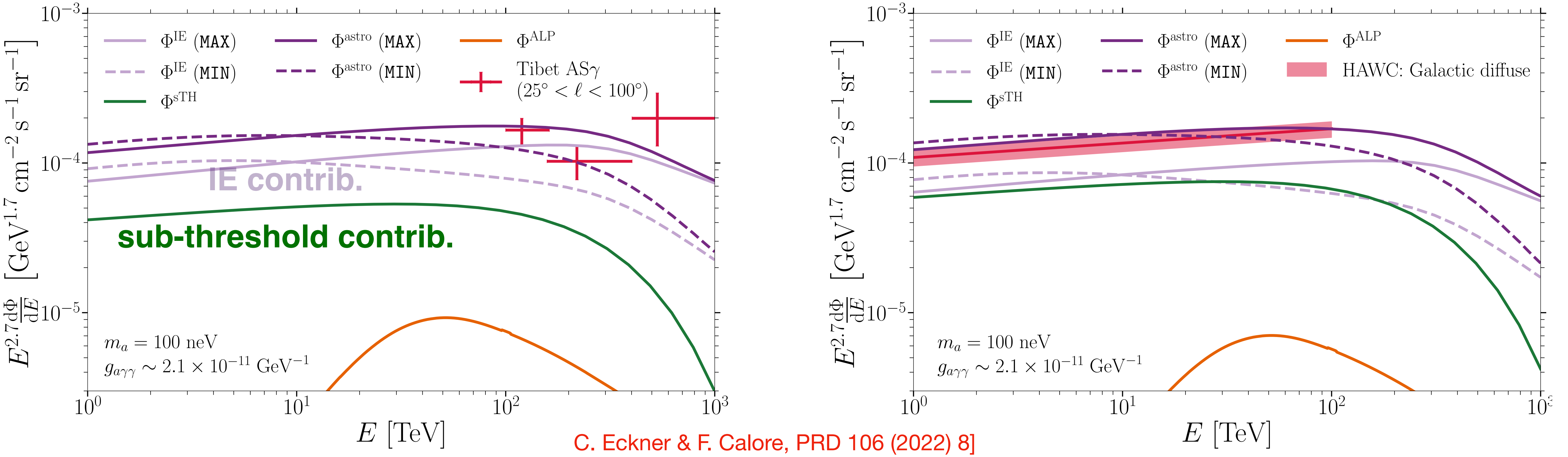
Star-forming galaxies emit at sub-PeV energies via ALPs

- ✦ The astrophysical contribution to the physics probed by both instruments is already sufficient to explain the measurements.
  —> Plotted spectra for $g_{a\gamma\gamma} \equiv 0$.



C. Eckner & F. Calore, PRD 106 (2022) 8]

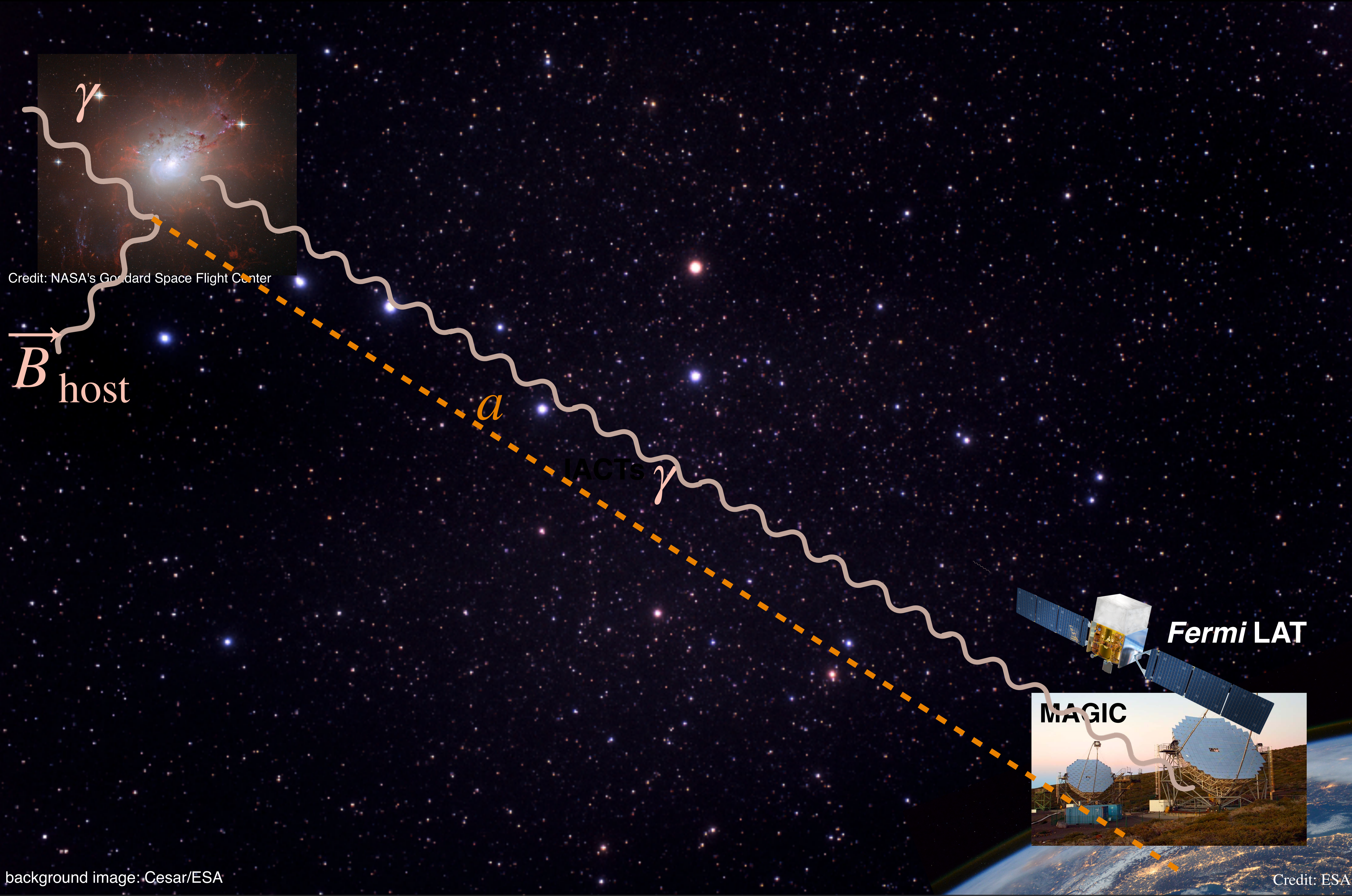
- ✦ Little space for an additional exotic component: For 100 neV axion-like particle this scenario translates to an upper limit on the photon-ALP coupling (at a 95% confidence level) of (using the maximal scenario for IE)

$$g_{a\gamma\gamma} \lesssim 2.1 \times 10^{-11}\ \mathrm{GeV}^{-1}$$

- ✦ A very similar study used the broadband diffuse flux measurement by LHAASO with comparable constraining power. [L. Mastrototaro et al., AEPJ C (2022) 82]

Spectral irregularities in extragalactic sources

Modulation of extragalactic gamma-ray spectra

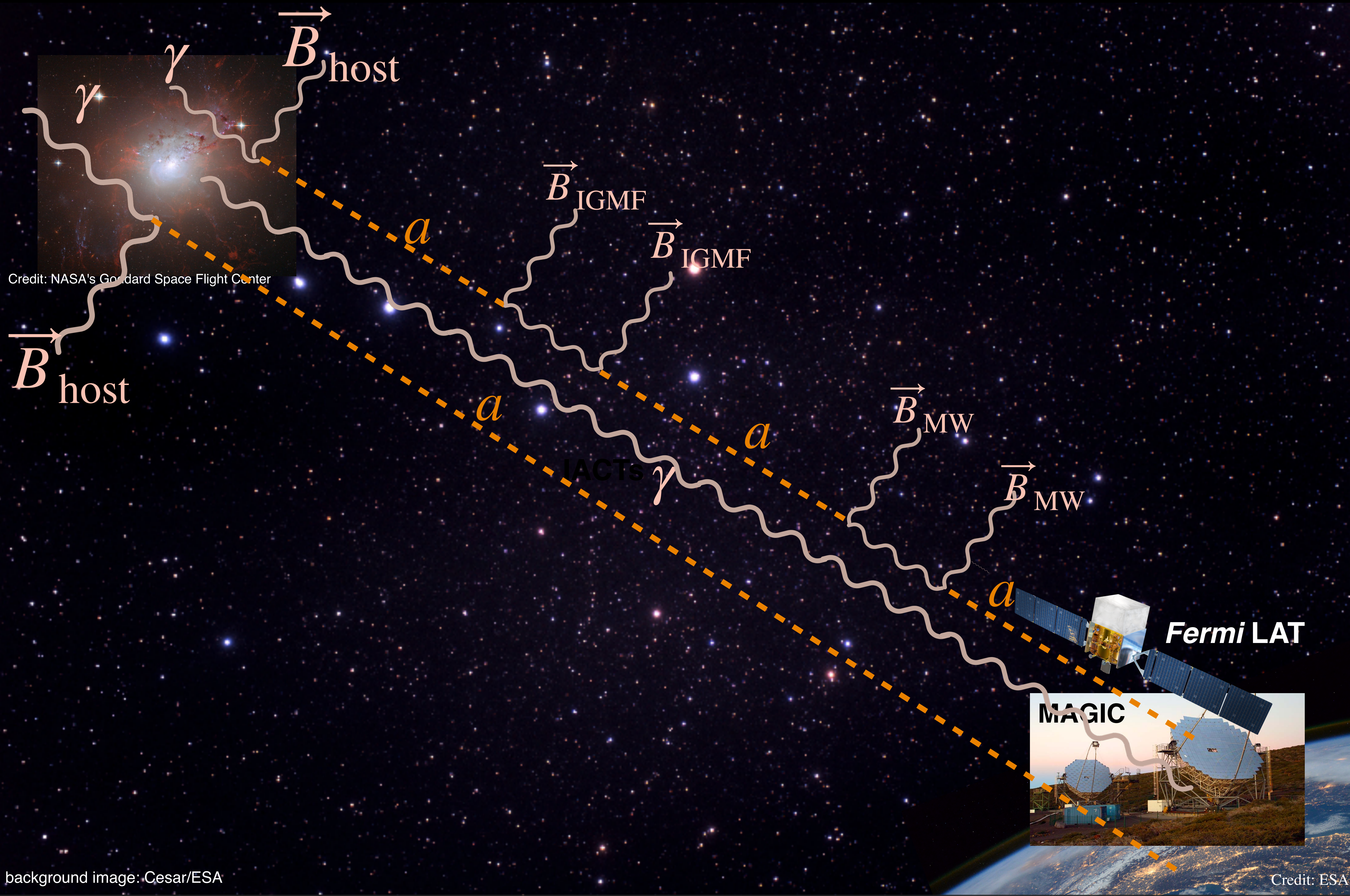


Credit: NASA's Goddard Space Flight Center

background image: Cesar/ESA

Credit: ESA

Modulation of extragalactic gamma-ray spectra



Credit: NASA's Goddard Space Flight Center

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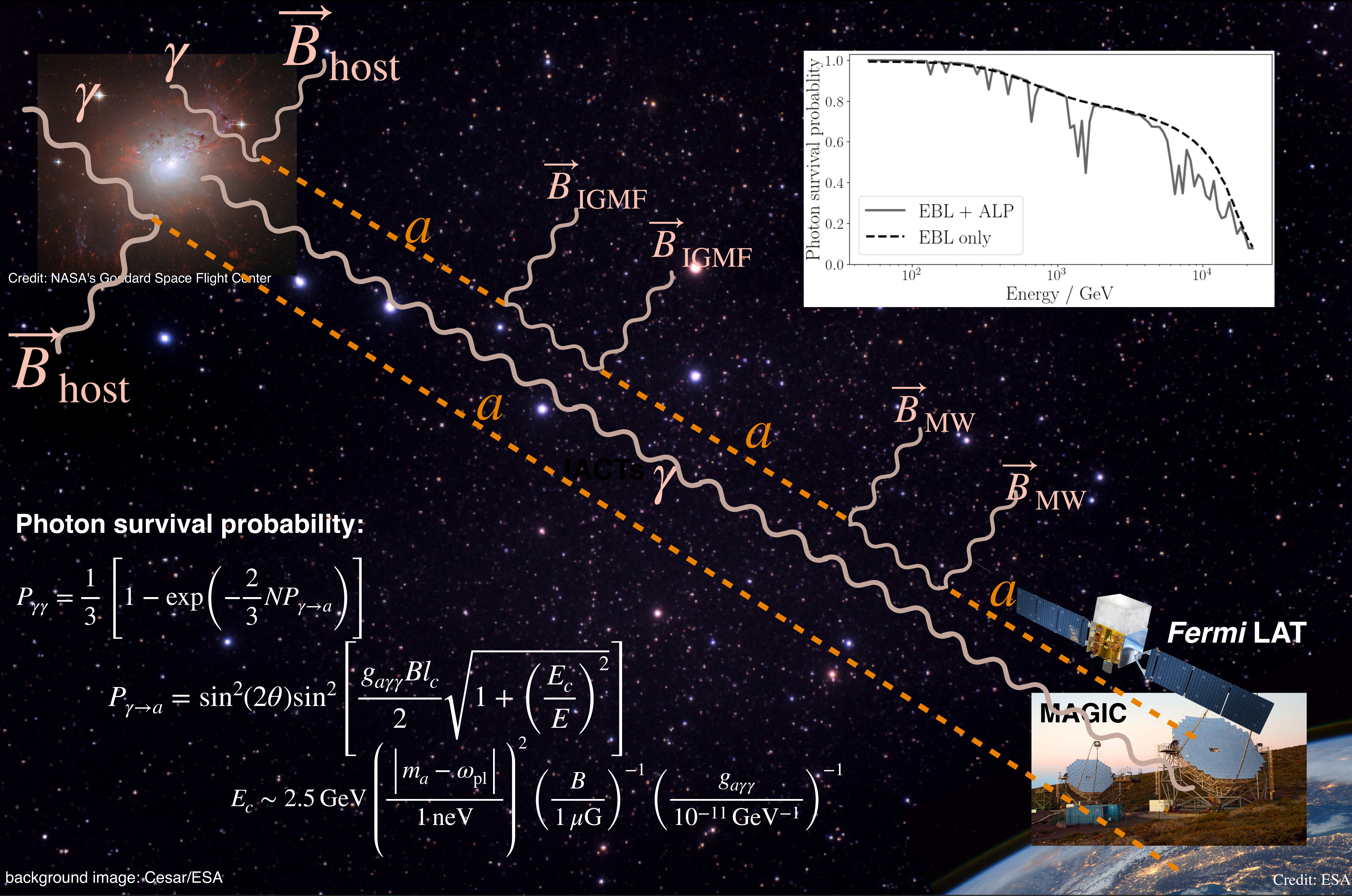
Modulation of extragalactic gamma-ray spectra



Credit: NASA's Goddard Space Flight Center

Credit: ESA

background image: Cesar/ESA

Photon survival probability:

$$P_{\gamma\gamma} = \frac{1}{3}\left[1 - \exp\left(-\frac{2}{3}NP_{\gamma\to a}\right)\right]$$

$$P_{\gamma\to a} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma\gamma}Bl_c}{2}\sqrt{1+\left(\frac{E_c}{E}\right)^2}\right]$$

$$E_c \sim 2.5\,\mathrm{GeV}\left(\frac{\left|m_a-\omega_{\mathrm{pl}}\right|}{1\,\mathrm{neV}}\right)^2\left(\frac{B}{1\,\mu\mathrm{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\,\mathrm{GeV}^{-1}}\right)^{-1}$$

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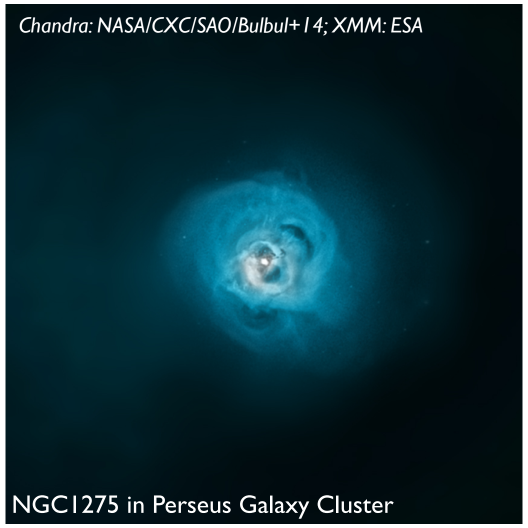
A suitable target: The Perseus Cluster



Properties:

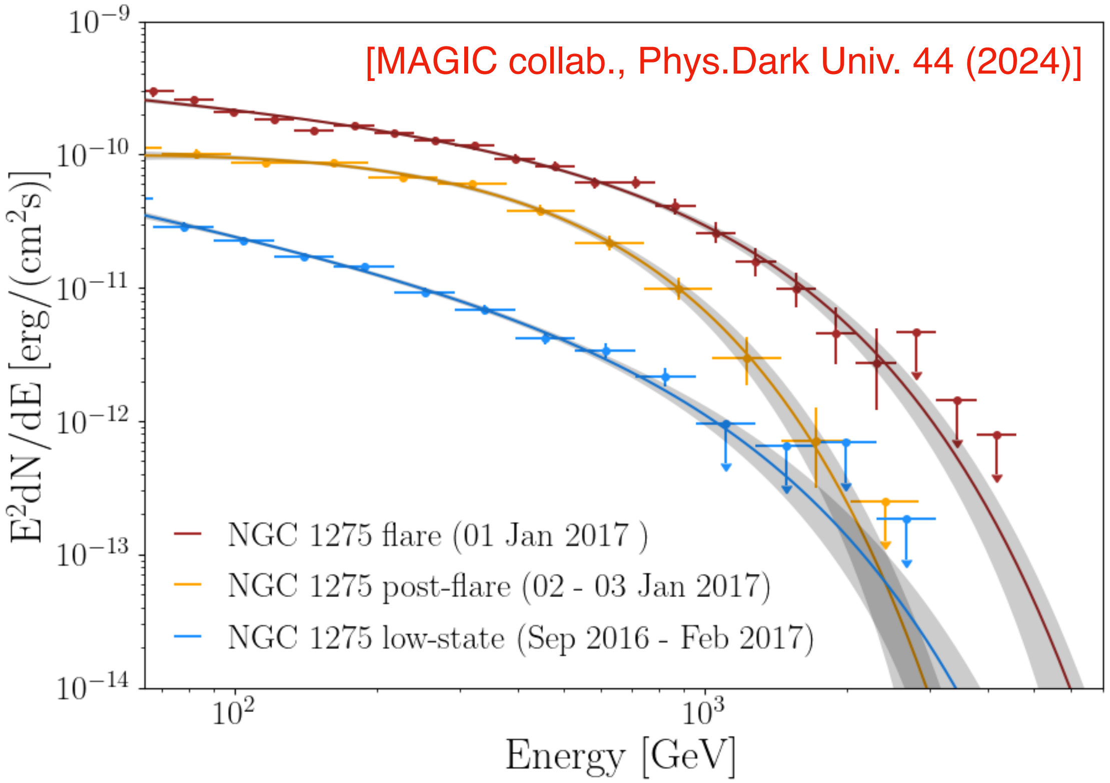
— very massive $\mathcal{O}(10^{14} - 10^{15} M_{\odot})$ at 75 Mpc distance ($z = 0.01756$)

— dynamically relaxed and cool-cored

— **hosts two known AGNs among which NGC 1275**

Ingredients

intrinsic γ-ray spectrum of NGC 1275



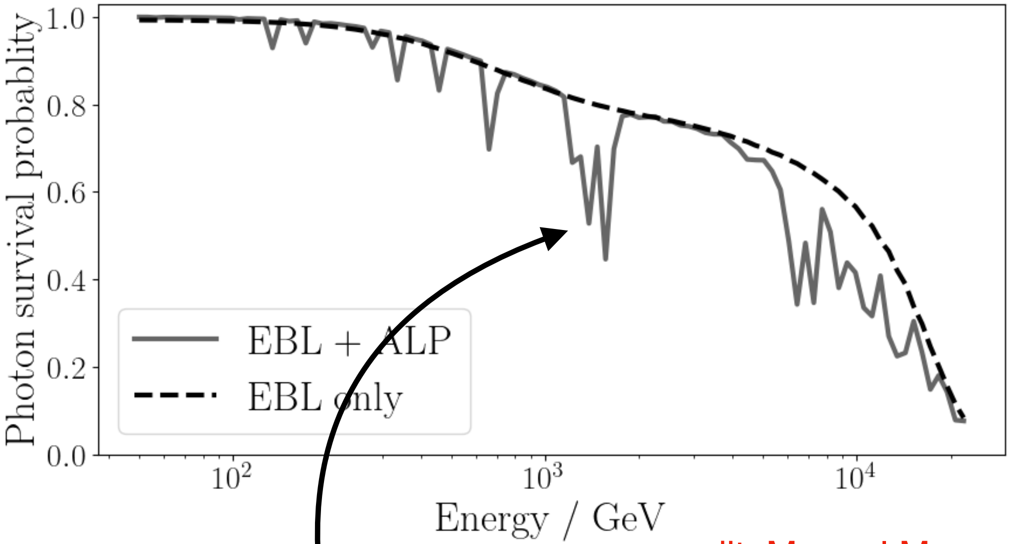
+ model for $\gamma\gamma$-absorption on extragalactic background light **(see next topic)**

magnetic field models:

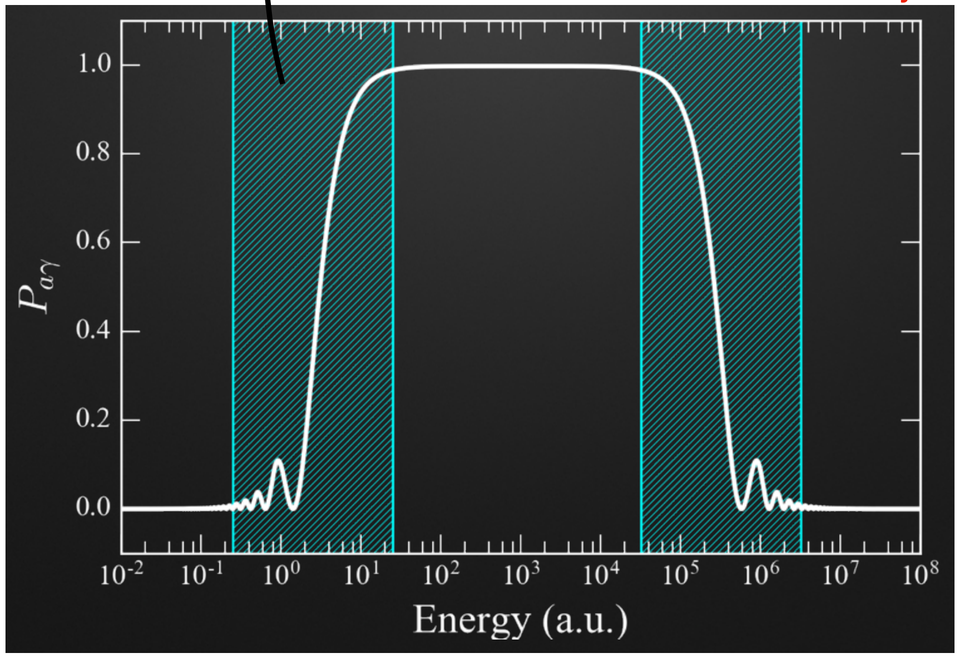
1. Perseus cluster intrinsic magnetic field (**random field with Gaussian turbulence**)
2. Magnetic field of AGN's jets (negligible due to viewing angle)
3. Intergalatic magnetic field (negligible in strength)
4. Milky Way magnetic field

ALP limits from NGC 1275 and MAGIC

Expectation: When $E \simeq E_c$, oscillatory behaviour of photon survival probability
→ “wiggles” in the observed energy spectrum of NGC 1275

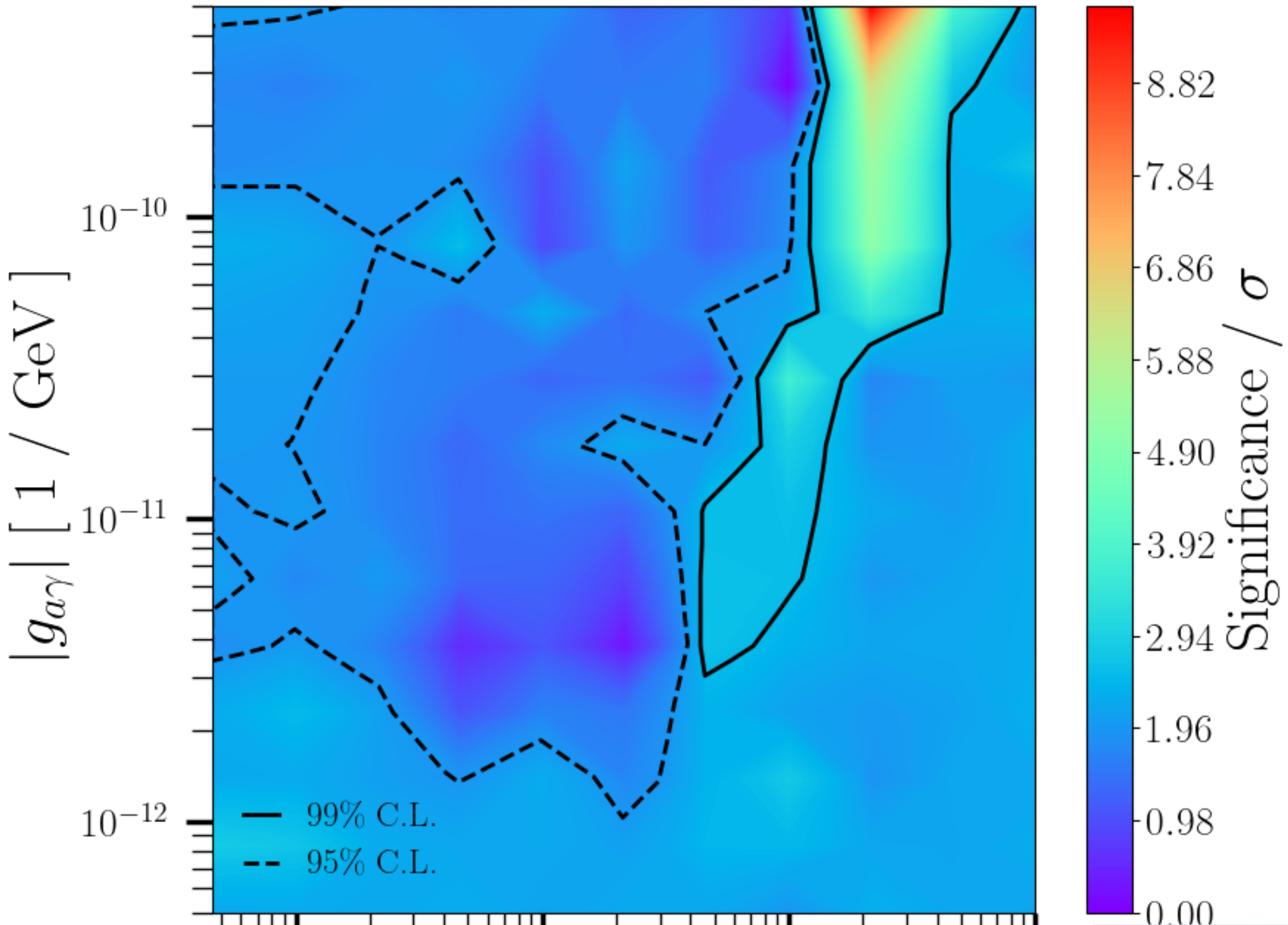


credit: Manuel Meyer



Rejection significance of a “wiggles” scenario

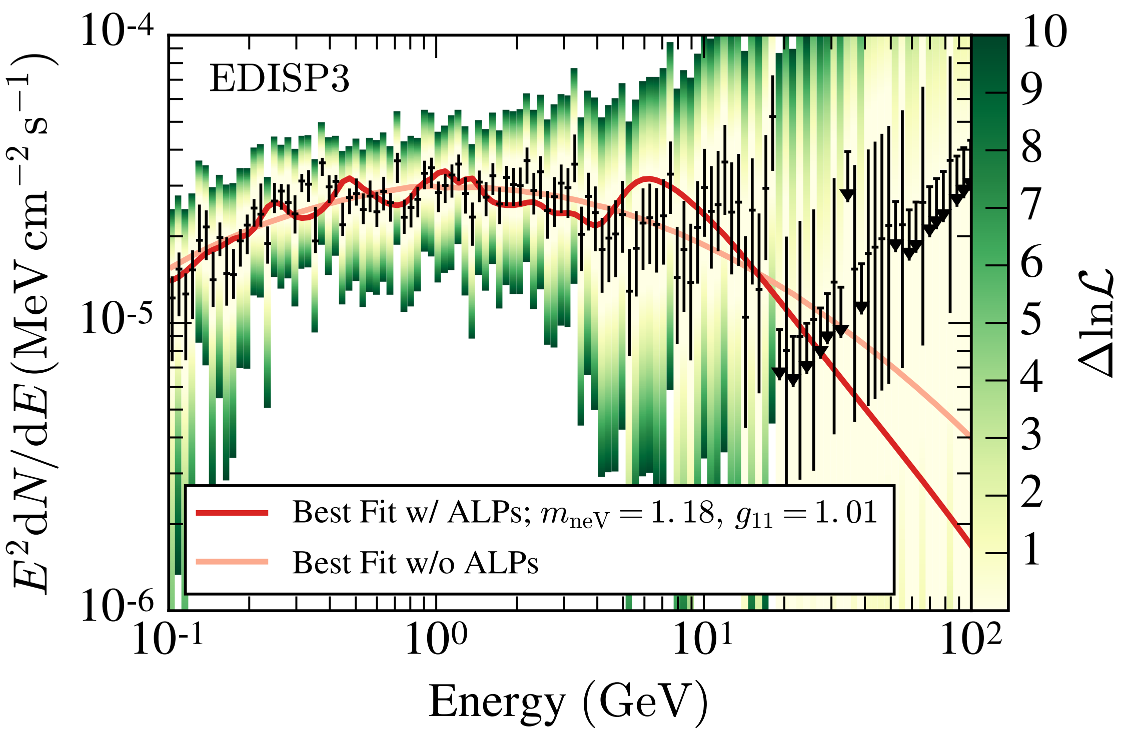
[MAGIC collab., Phys.Dark Univ. 44 (2024)]



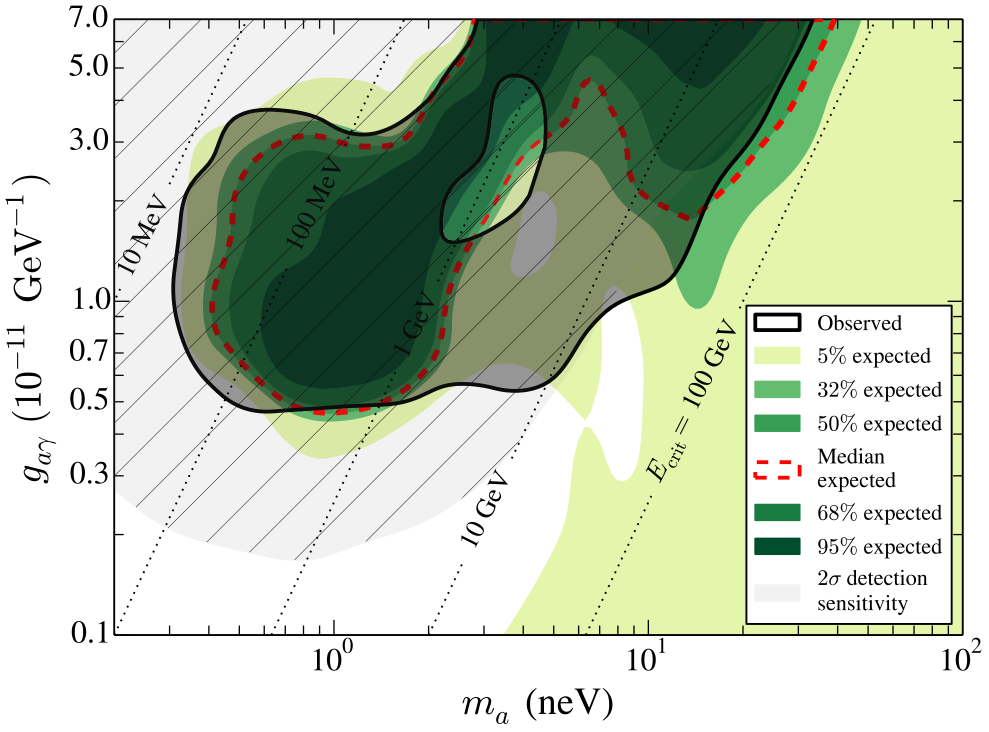
Strongest constraints on ALP parameter space between 40 to 90 neV!

ALP limits from NGC 1275 and *Fermi* LAT

A similar study was performed with data from *Fermi* LAT → requires lower ALP masses to be compatible with energies < 100 GeV accessible for the LAT!



[Fermi-LAT collab., PRL 116 (2016) 16]



Null hypothesis: $\dfrac{\mathrm{d}N}{\mathrm{d}E}\exp(-\tau)$

Intrinsic spectrum
+ EBL absorption

Alternative hypothesis: $\dfrac{\mathrm{d}N}{\mathrm{d}E}P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \vec{B})$

Intrinsic spectrum
+ photon survival probability: EBL + ALP conversion

→ Hypothesis testing based on log-likelihood

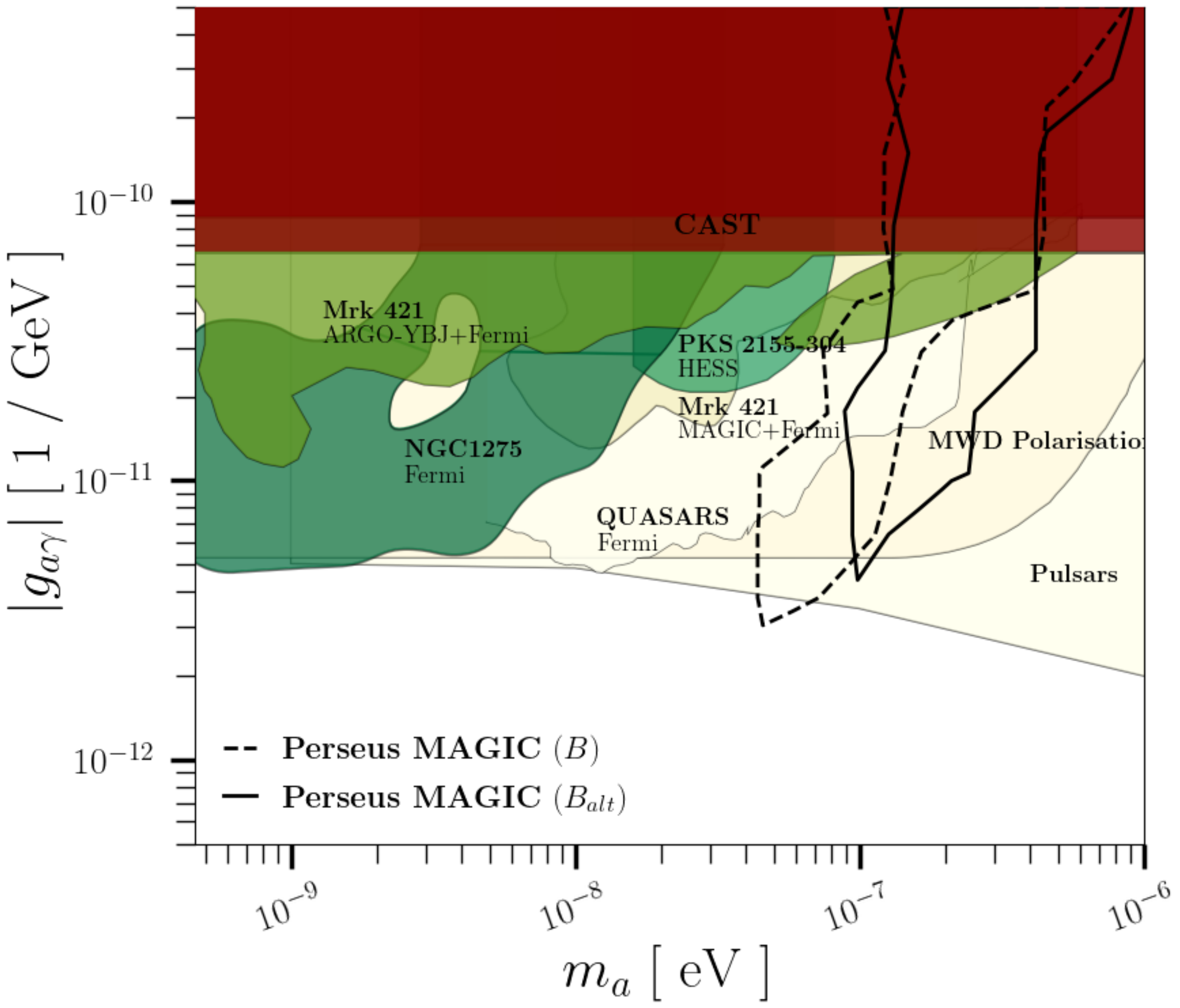
→ Calibrated against Monte Carlo data of the gamma-ray observations (under null hypothesis)

See also similar studies with different targets and instruments:

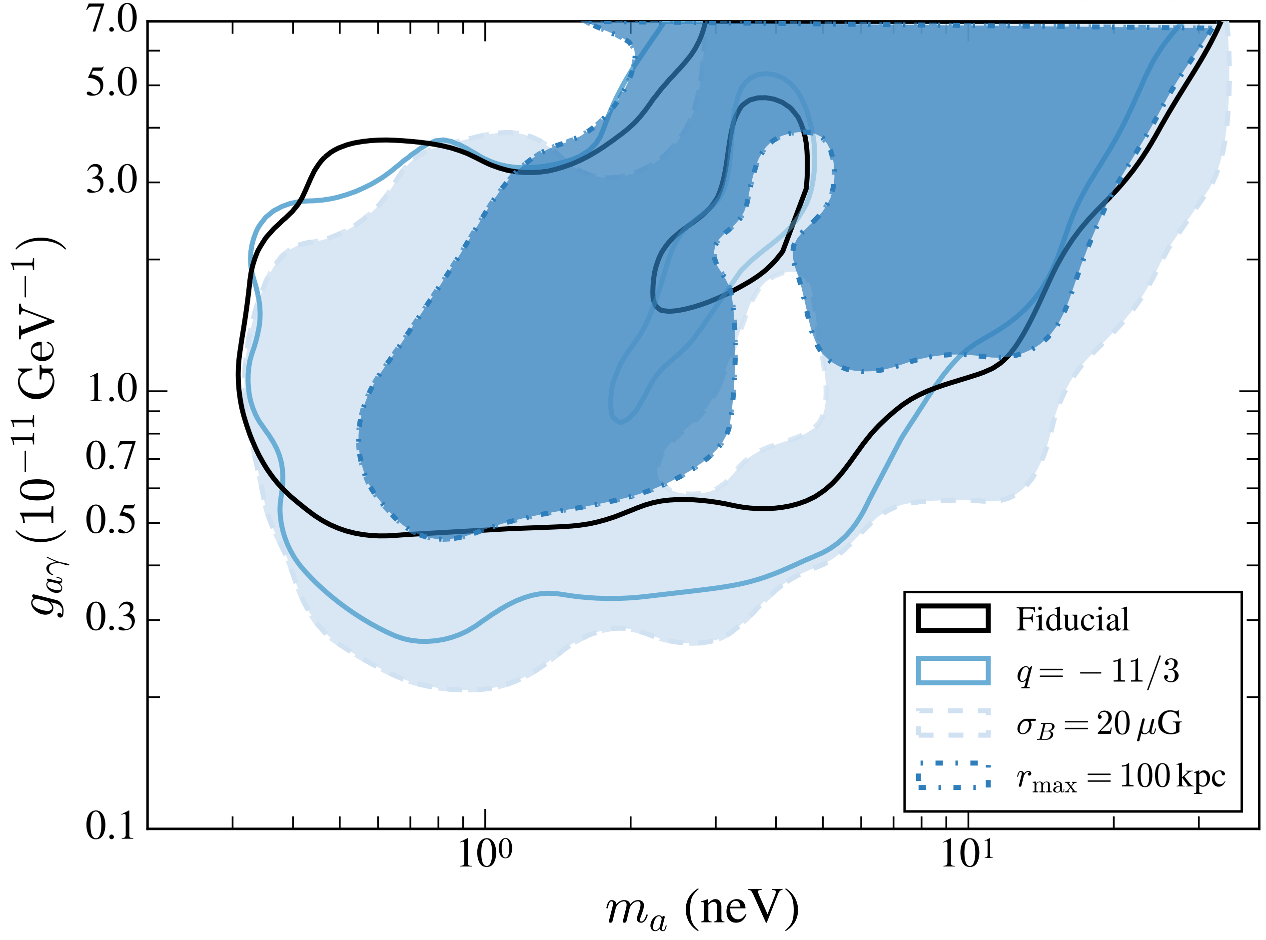
- [H.E.S.S. collab., PRD 88, 102003 (2013) 2] (blazar),
- [Z. Q. Xia et al., PRD 100 (2019) 12] (SNRs),
- [J. Majumdar et al., JCAP 04 (2018) 048] (pulsars),
- [J. Davies et al., PRD 107 (2023)] 8] (jet emission of flaring quasars).

A word on the impact of astrophysical uncertainties

Either for Fermi LAT or MAGIC, modelling the astrophysical environment of the Perseus cluster is critical to derive robust bounds. Especially the intra-cluster magnetic field configuration impacts the results.



[MAGIC collab., Phys.Dark Univ. 44 (2024)]



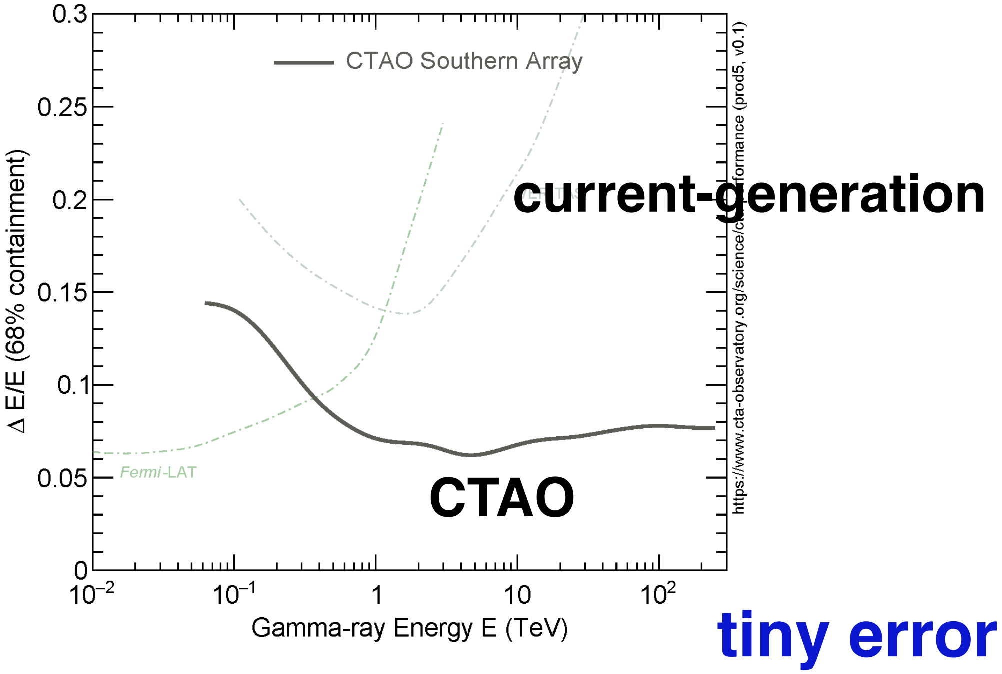
[Fermi-LAT collab., PRL 116 (2016) 16]

Exact exclusion shapes are subject to modelling uncertainties while the exclusion power is definitely given.

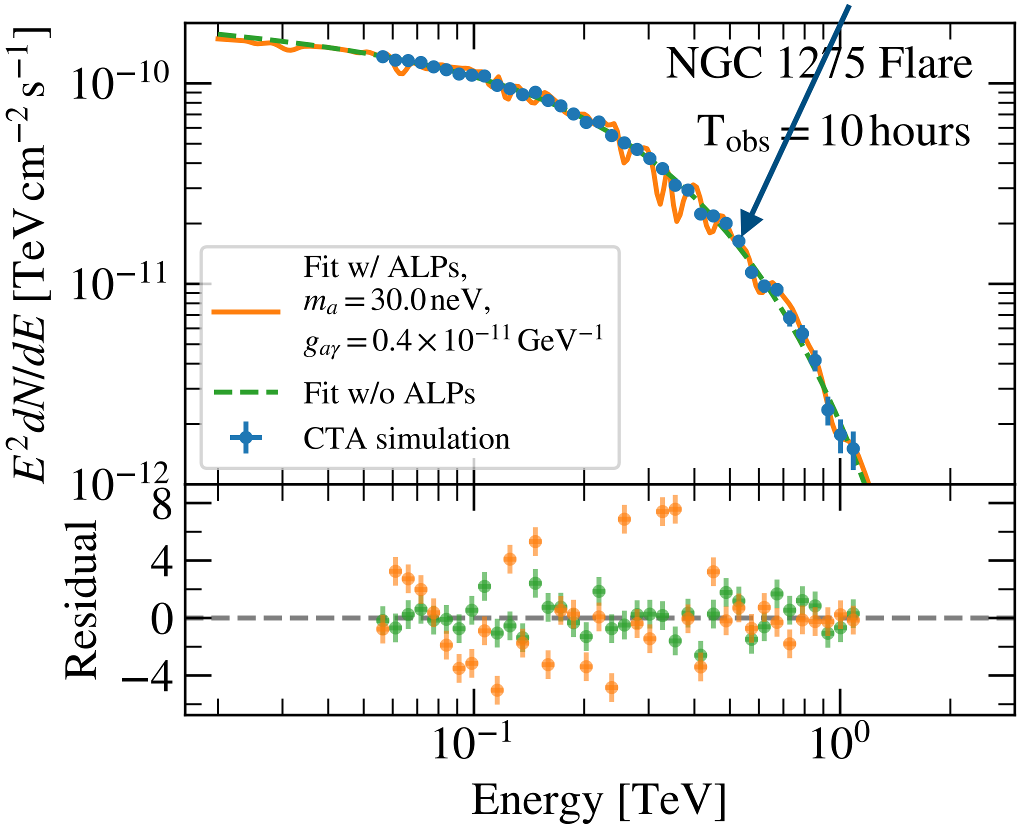
→ A Gaussian turbulence model is robust for single line-of-sight studies although magnetohydrodynamical simulations exhibit large non-Gaussian tails of the turbulence. spectrum [P. Carenza et al., PRD 108 (2023) 10]**.**

Future prospects of CTAO

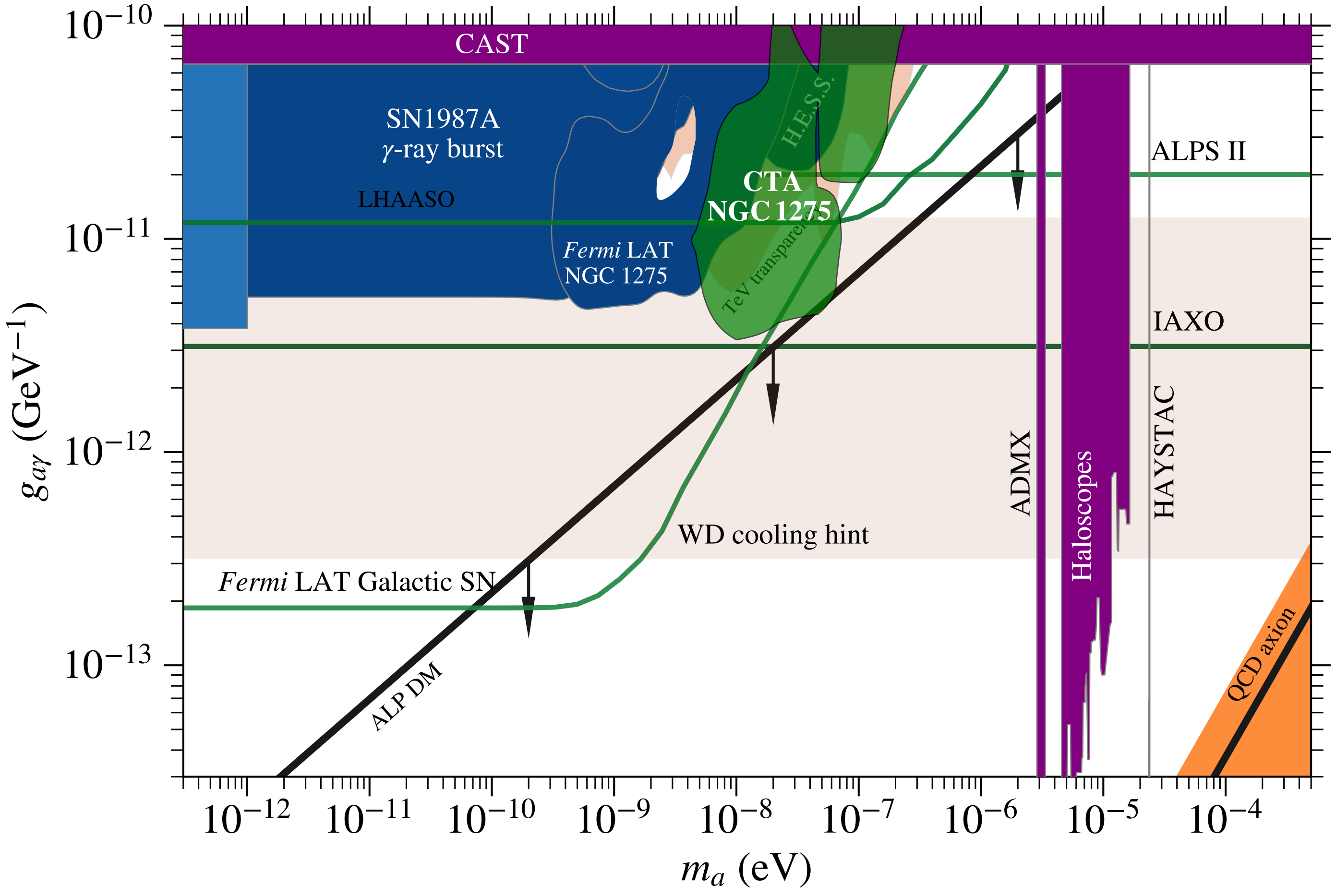
The big leap forward that CTAO will provide is an exquisite energy resolution (and sensitivity) at TeV energies!



tiny error bars



[The CTA Consortium; JCAP 02 (2021) 048]



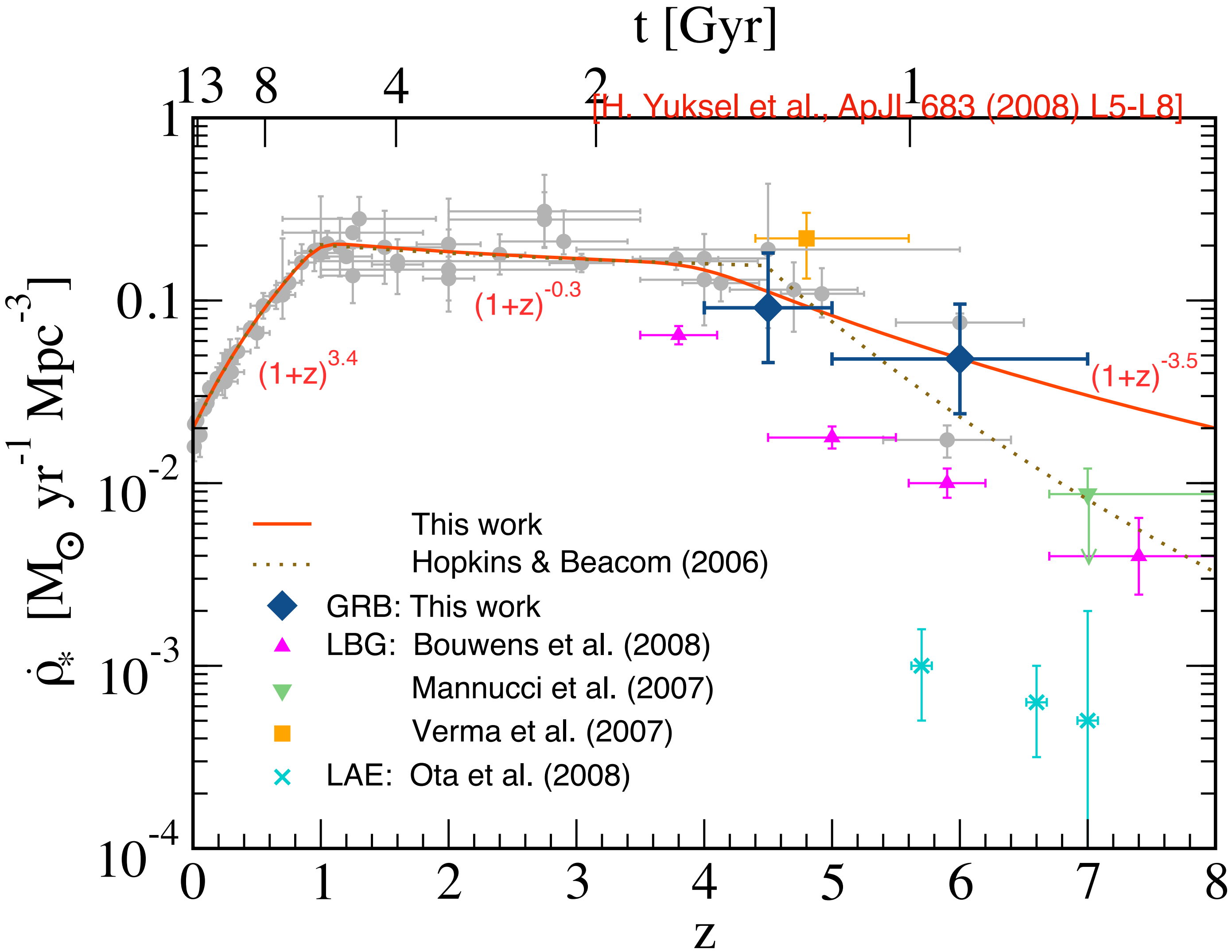
→ **Broader coverage than MAGIC.**
→ **Maximal sensitivity comparable.**
→ **See also talk of G. Kluge at TeVPA 2023 about the applicability of machine learning tools like simulation-based inference.**

Extragalactic supernovae

See also G. Lucente's talk!

Using extragalactic supernova explosions

Since our last chance in 1987, we had no Galactic supernova.
→ **Supernovae are not that rare on larger scales; their rates scales with the star formation rate in the universe.**

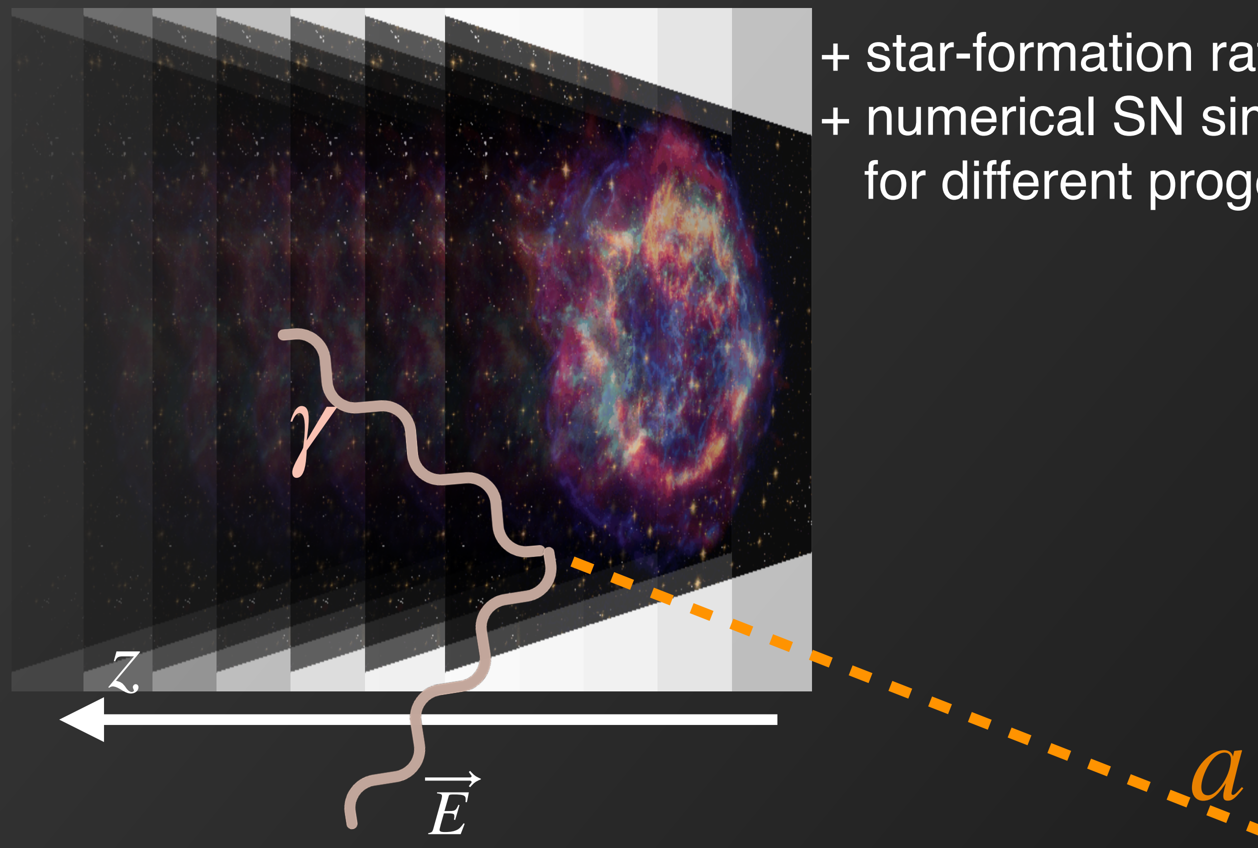


Observables:

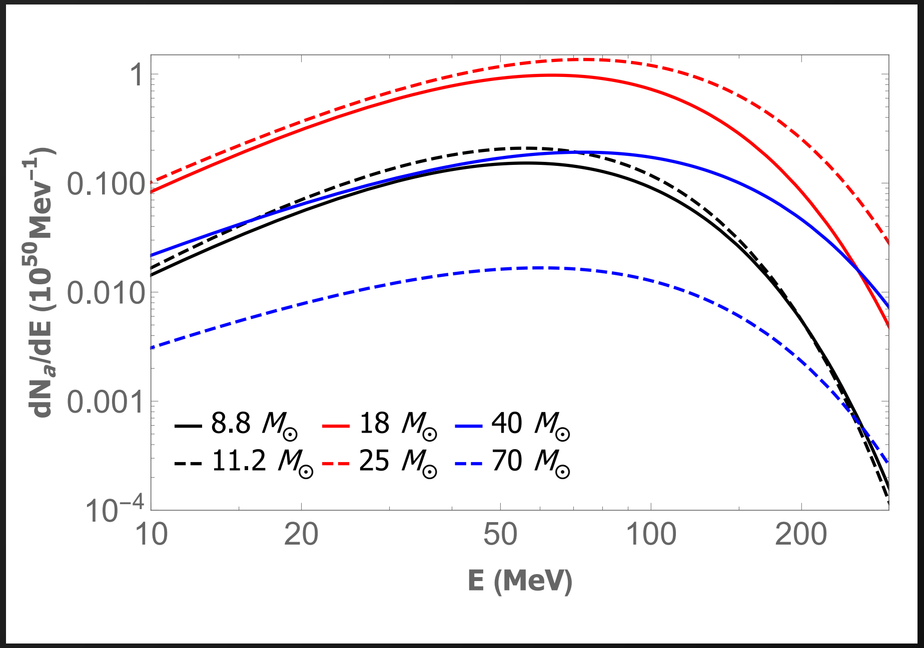
→ **The diffuse axion-like particle background ($m_a \sim \mathcal{O}(10^{-9}\ \mathrm{eV})$),**
→ **individual events: SN 2023ixf ($m_a \sim \mathcal{O}(\mathrm{MeV})$).**

The Diffuse Supernova ALP Background

Cumulative cosmological SN flux

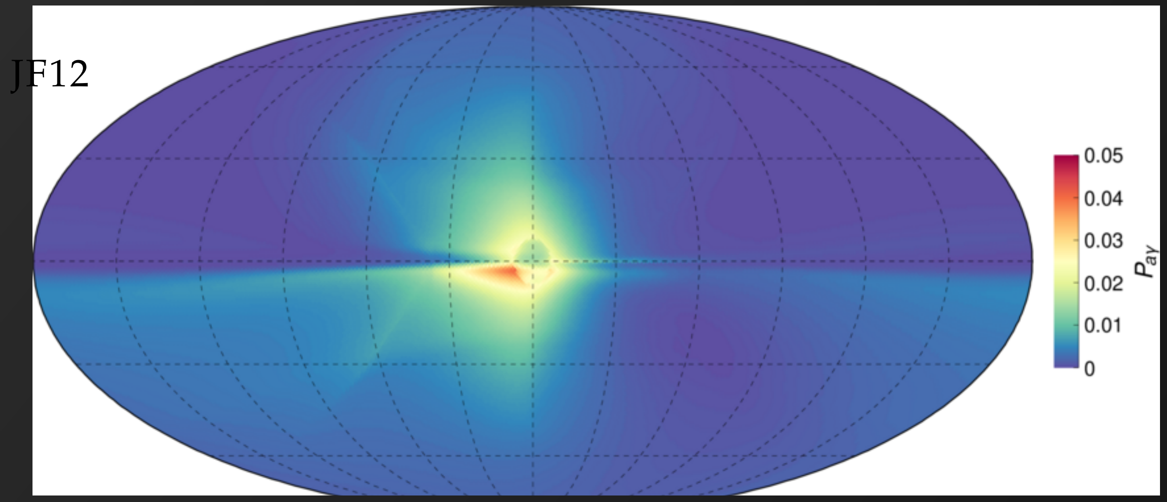


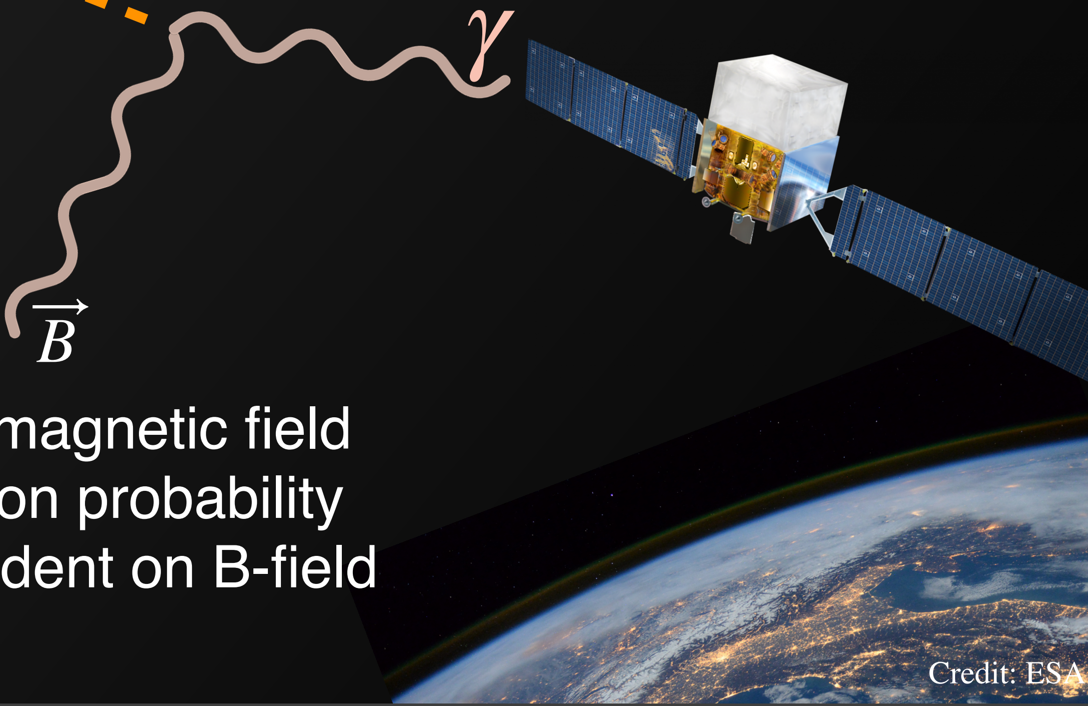
+ star-formation rate
+ numerical SN simulations
for different progenitors masses



[F. Calore, **CE** et al., PRD 105 (2022) 6]

electrostatic field of ions, electrons and protons

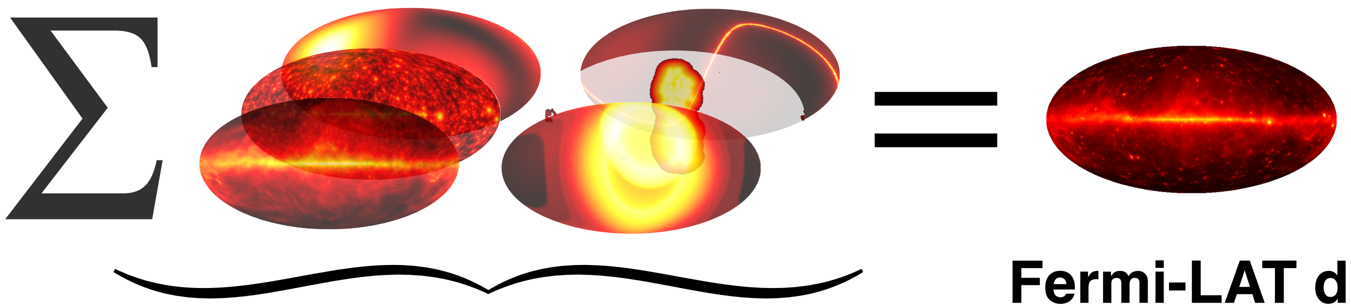




Milky Way’s magnetic field —> conversion probability highly dependent on B-field structure

Credit: ESA

The bound on the ALP parameter space

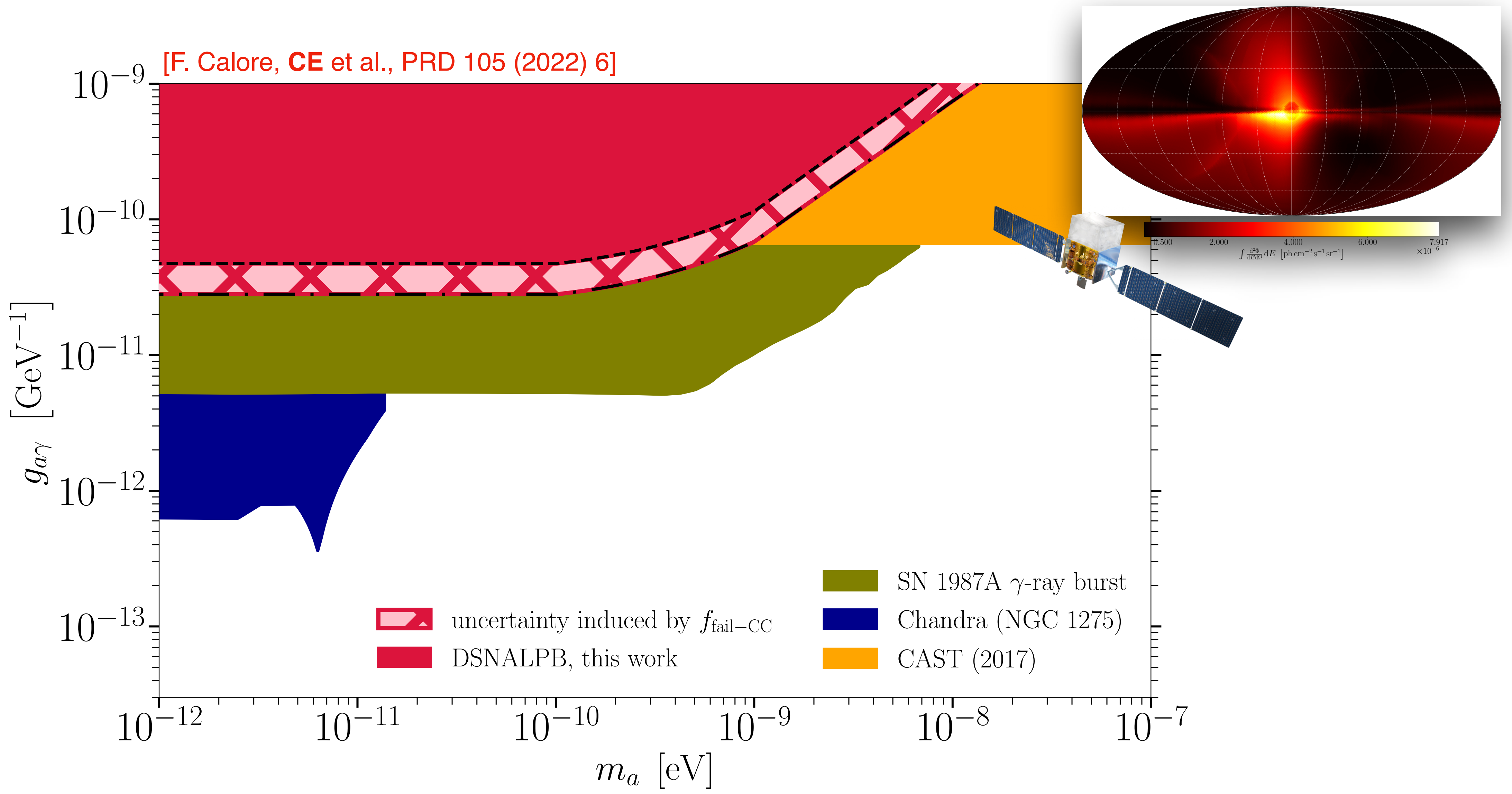


model templates

Fermi-LAT data

No detection: How much space is their to accommodate an additional signal?

ALP signal



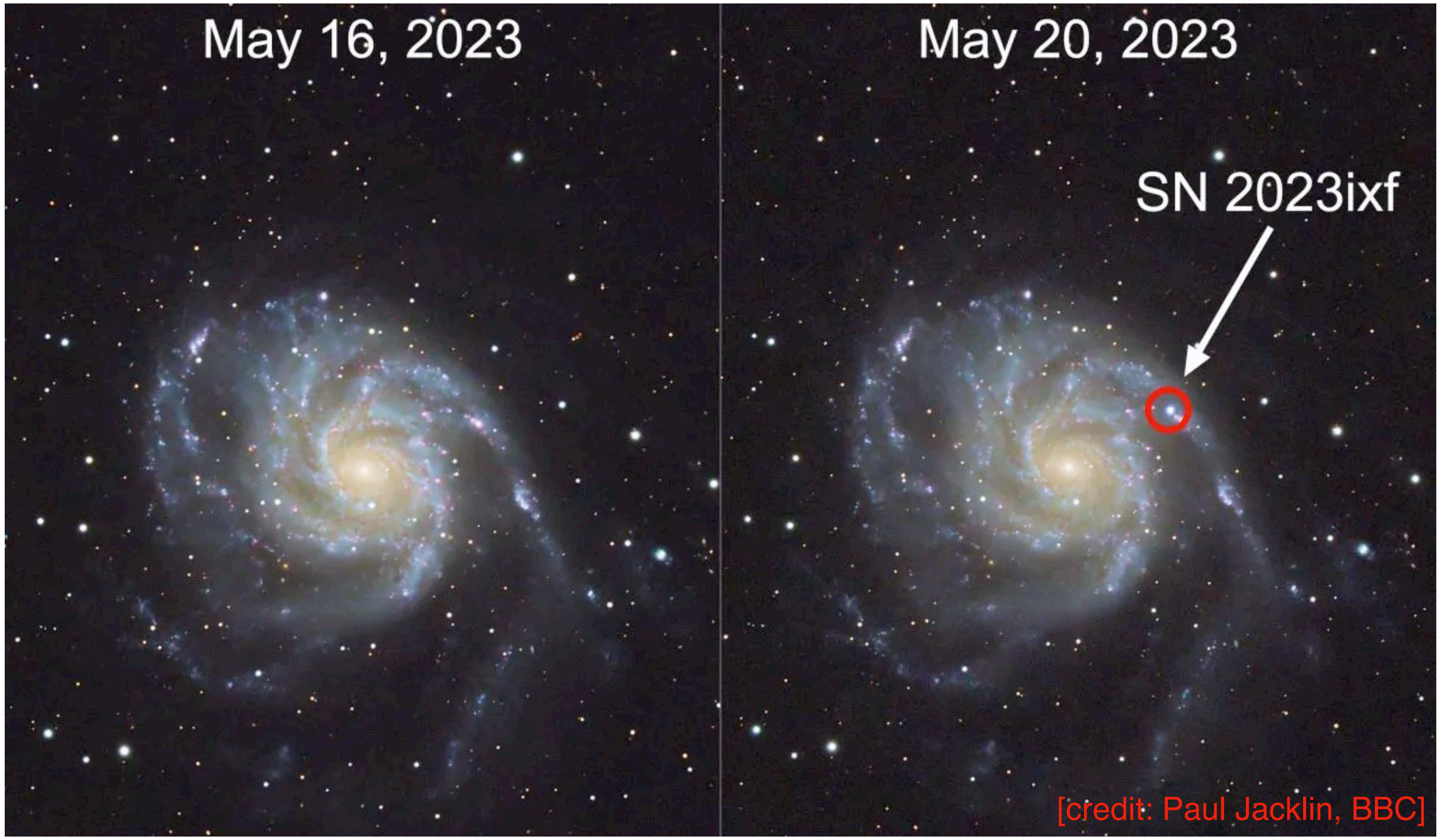
[F. Calore, **CE** et al., PRD 105 (2022) 6]

Constraints stronger than CAST (solar axion bounds) and can be improved with future gamma-ray measurements (MeV mission).

The decay of MeV-scale ALPs and SN 2023ixf

What about individual extragalactic SN events?

A recent type II supernova was optically detected in the Pinwheel galaxy (M 101, distance ~ 7 Mpc) on the 18th of May 2023 with a progenitor mass from 9 to 22 $M_{\odot}$.



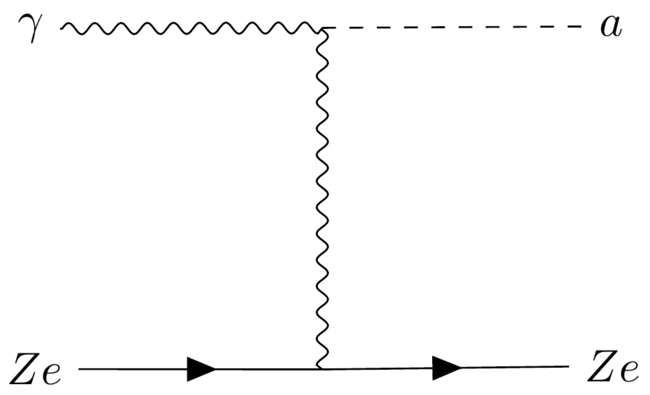
[credit: Paul Jacklin, BBC]

→ Large scientific and publication attention, e.g. [C. D. Kilpatrick et al., ApJL 952 (2023) 1], [L. A. Sgro et al., Res. Notes AAS 7 (2023), 141]

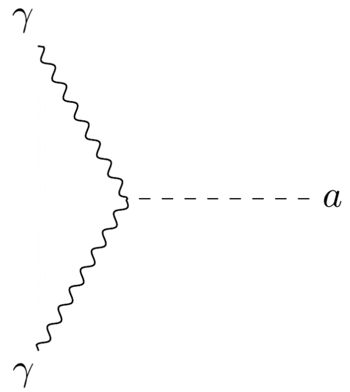
→ As individual event too faint to detect signal of light ALPs, but **MeV-scale ALPs are accessible via ALP decay**!

The decay of MeV-scale ALPs and SN 2023ixf

ALP production:
(environmental properties via numerical simulation results of 11 $M_\odot$ progenitor)



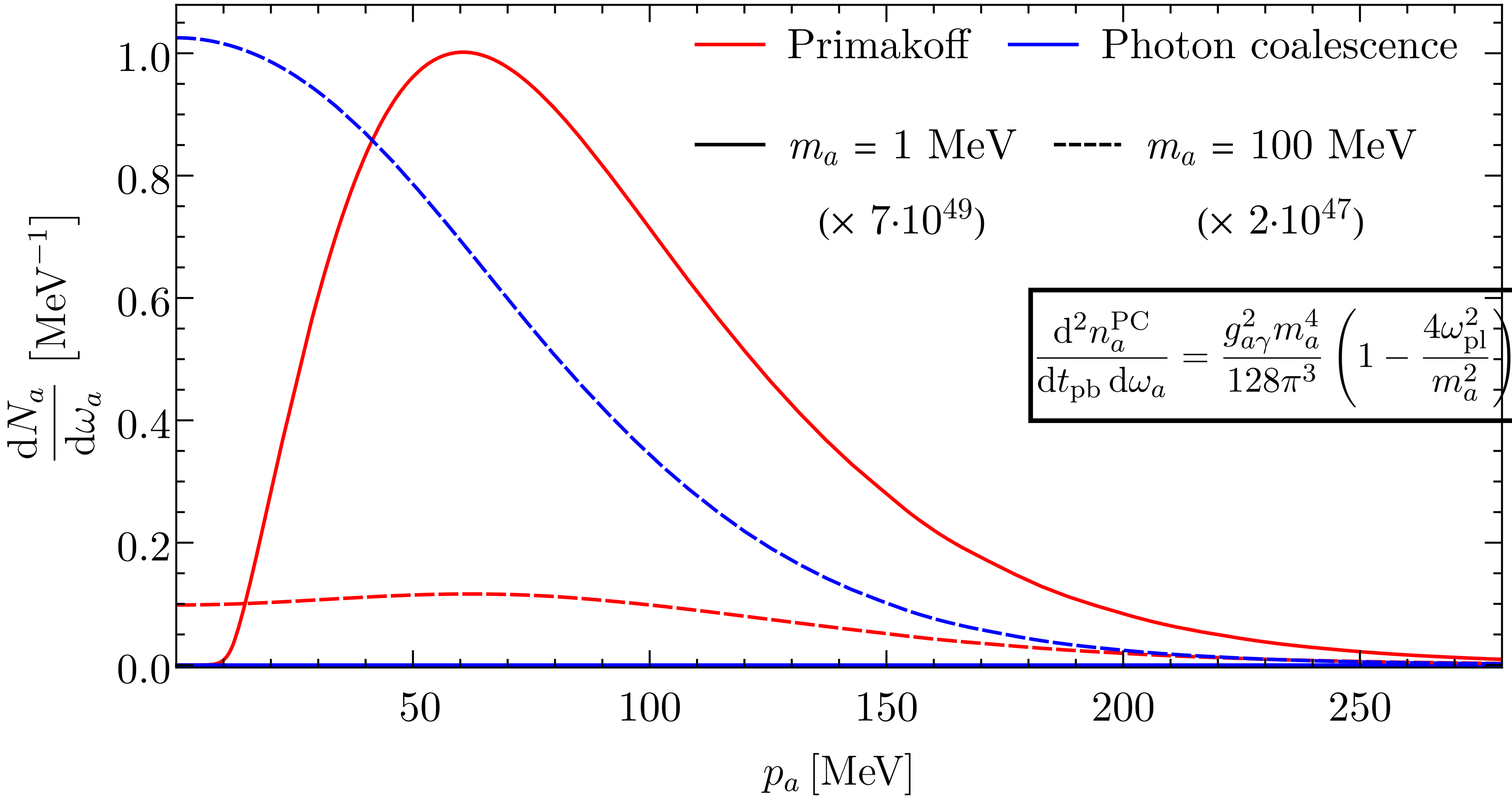
Primakoff process



inverse decay/ photon coalescence

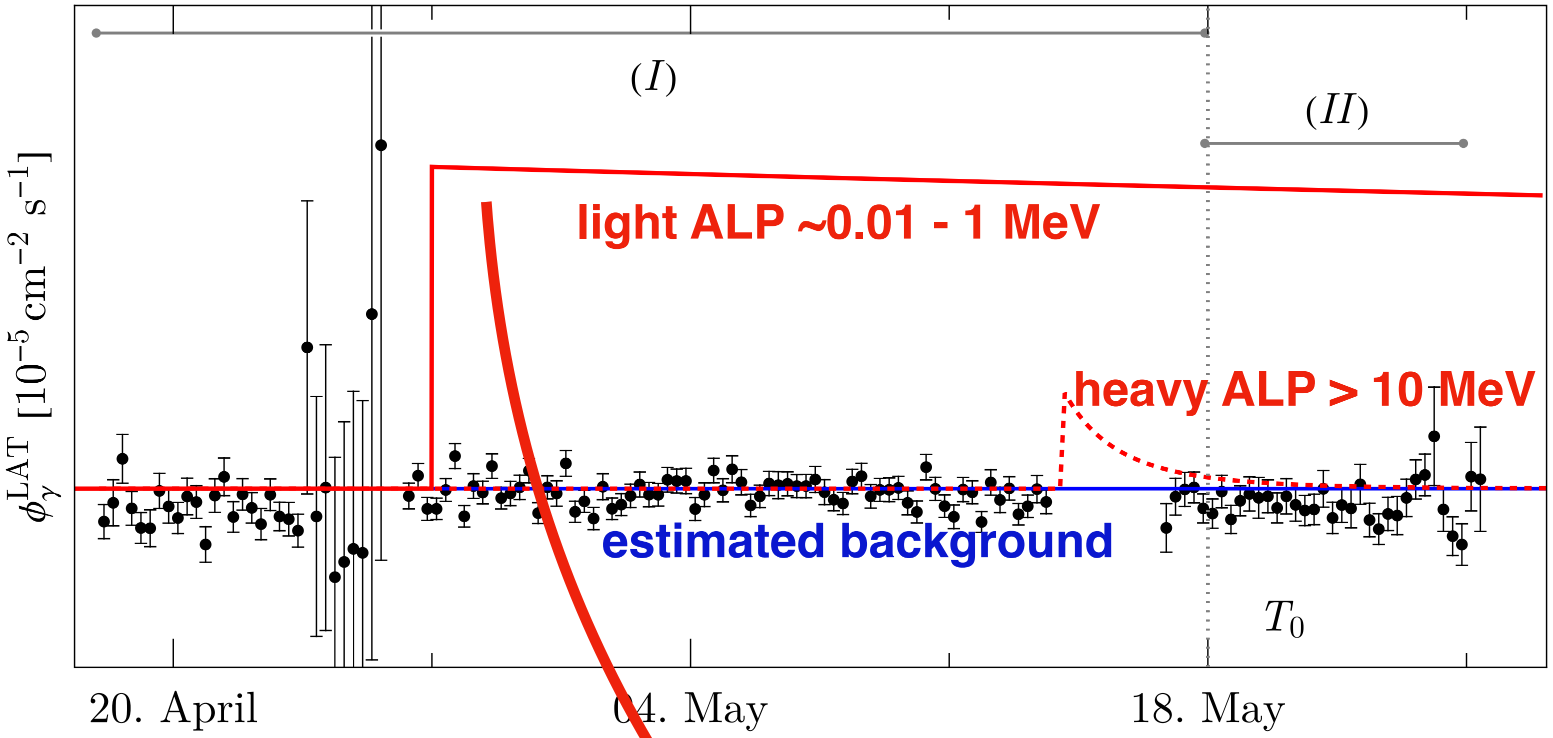
We accounted for photon coalescence was ignored in previous studies since it only becomes relevant above the MeV scale!

[E. Müller, **CE** et al., JCAP 07 (2023) 056]



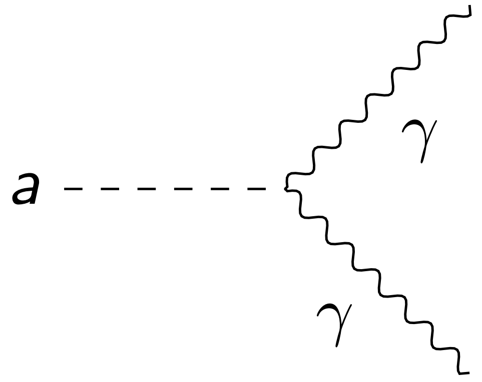
$$\frac{d^2 n_a^{\mathrm{PC}}}{dt_{\mathrm{pb}}\, d\omega_a} = \frac{g_{a\gamma}^2 m_a^4}{128\pi^3}\left(1-\frac{4\omega_{\mathrm{pl}}^2}{m_a^2}\right)\int_{\omega_{\min}}^{\omega_{\max}} d\omega_\gamma \left[\left(e^{\omega_\gamma/T}-1\right)\left(e^{(\omega_a-\omega_\gamma)/T}-1\right)\right]^{-1}$$

The decay of MeV-scale ALPs and SN 2023ixf

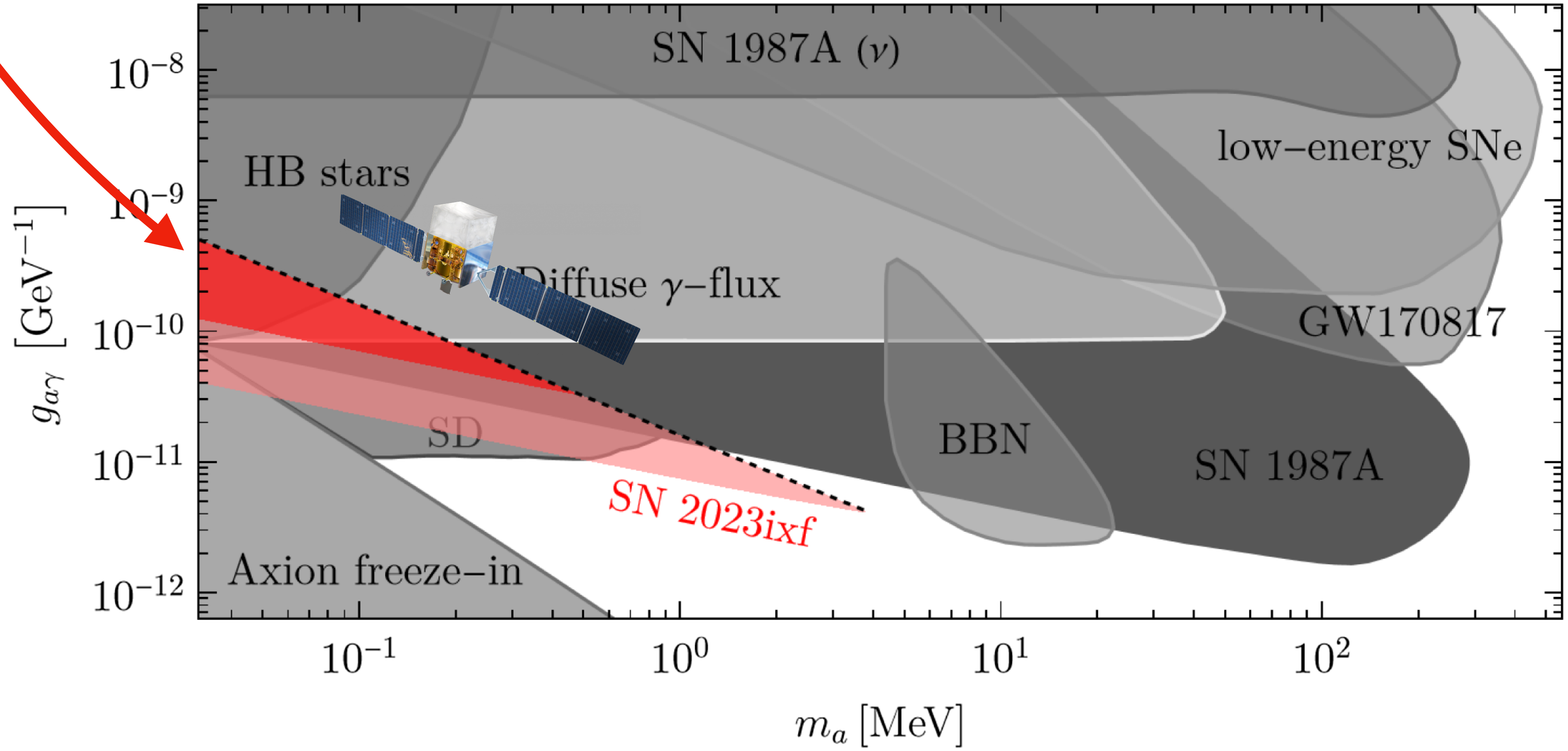


The Fermi-LAT data towards SN 2023ixf around the optical onset.

signal:
ALP decay



[E. Müller, **CE** et al., PRD 109 (2024) 2]



SN 2023ixf can probe unexplored parts of MeV-scale ALPs via ALP decay (within uncertainties: progenitor mass, distance and volume of the SN).

Impatiently awaited and already anticipated: a Galactic supernova

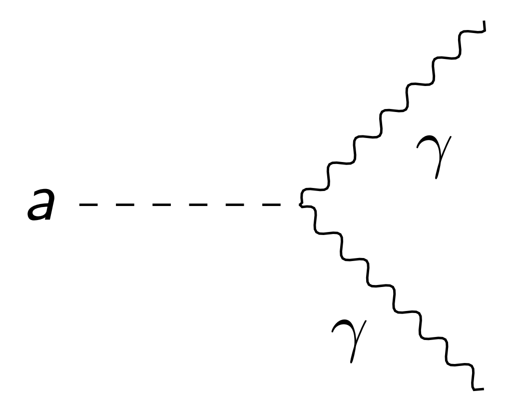
See also G. Lucente’s talk!

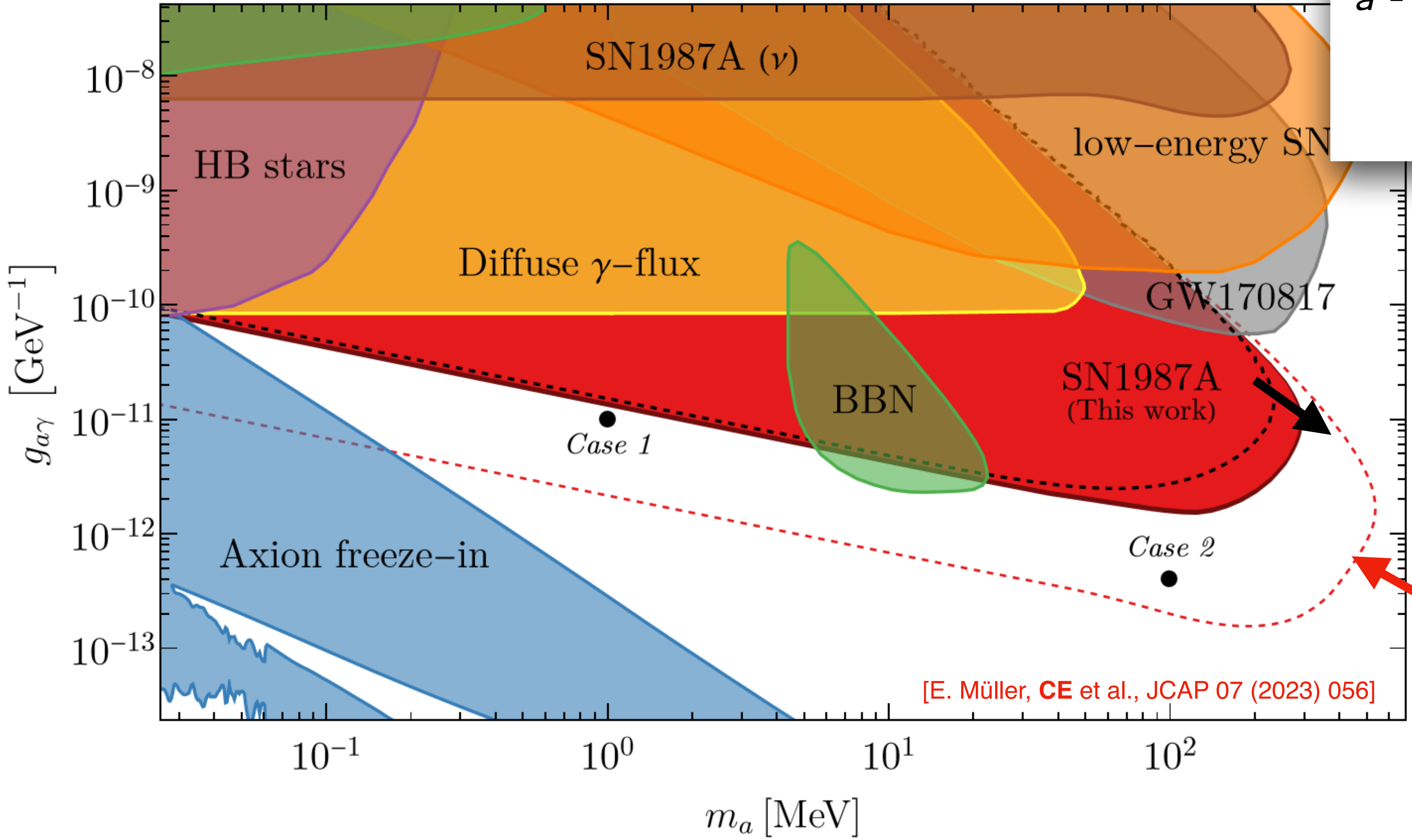
What if there where a Galactic supernova like 1987?

Photon coalescence was previously not accounted for when probing the parameter space of MeV-scale ALPs? Impact on constraints from ALP decay:

→ **SN 1987A**

→ **A future Galactic supernova (same distance as SN 1987A)**

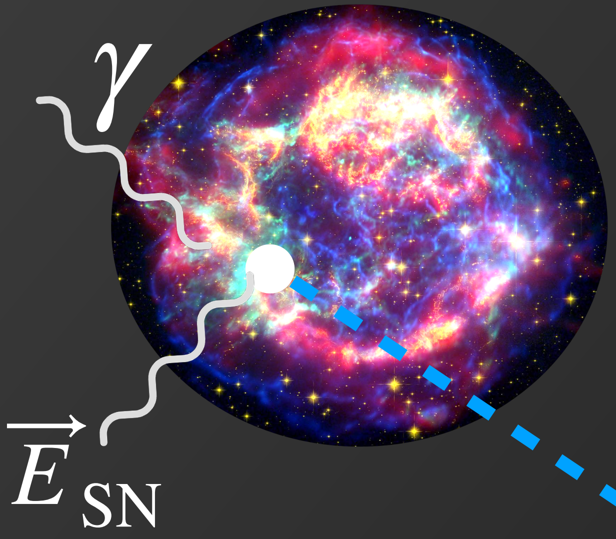




[E. Müller, **CE** et al., JCAP 07 (2023) 056]

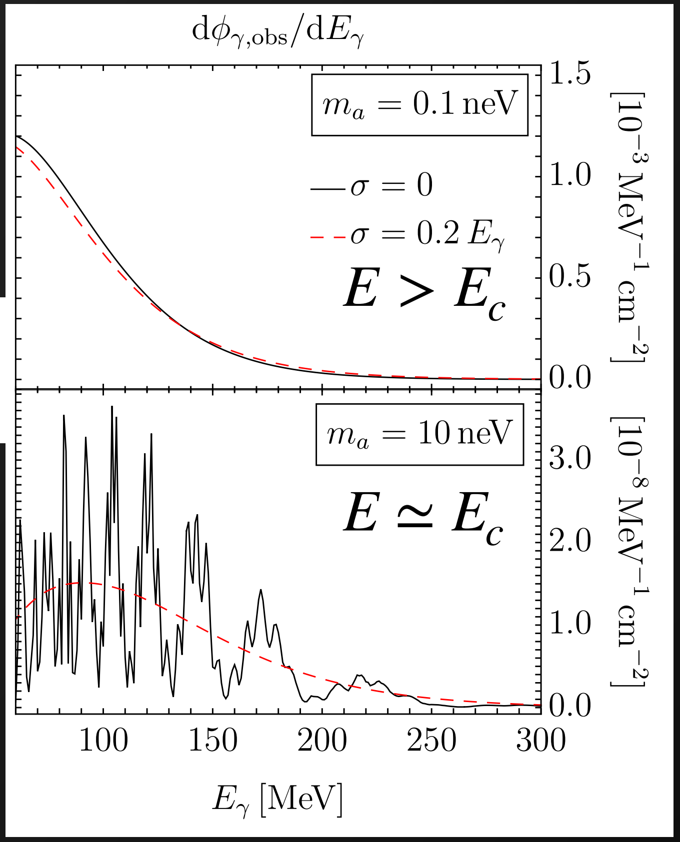
Sensitivity of Fermi-LAT to a future SN at 50 kpc (Fluence 5σ over background)

Searching for ALPs in a future Galactic supernova



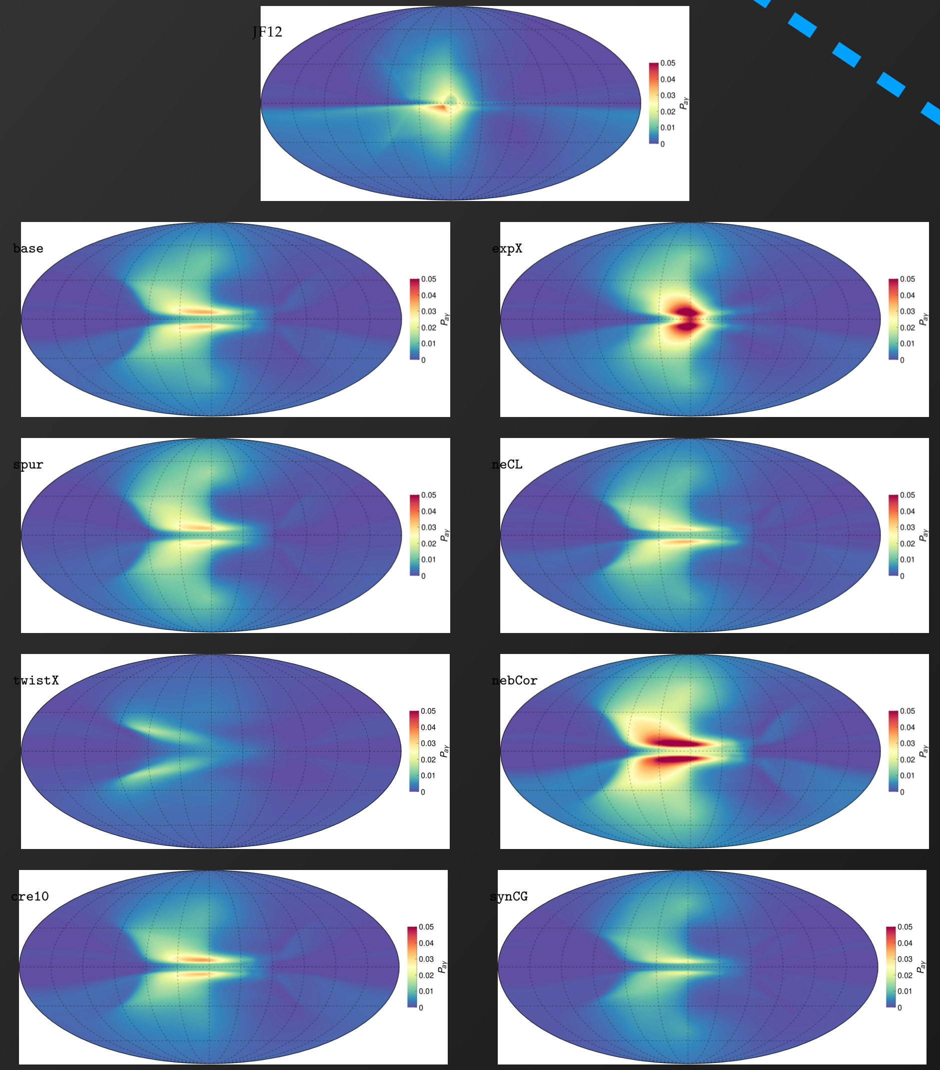
ALP production from Primakoff conversion in supernova core

$$\frac{d\phi_{\gamma,\mathrm{obs}}}{dE_\gamma} = C_{\mathrm{obs}} \left(\frac{E_\gamma}{\epsilon_0}\right)^{\alpha} \exp\left(-\frac{(\alpha+1)E_\gamma}{\epsilon_0}\right)$$



[F. Calore, CE et al., PRD 109 (2024) 4]

a

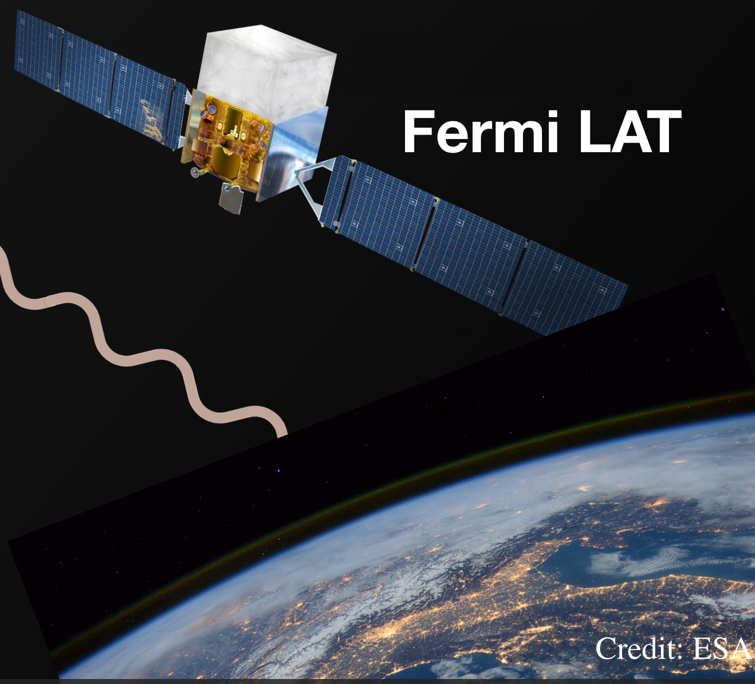


$\vec{B}_{\mathrm{MW}}$

γ

Magnetic field uncertainty!

[M. Unger & G. Farrar, arXiv:2311.12120]

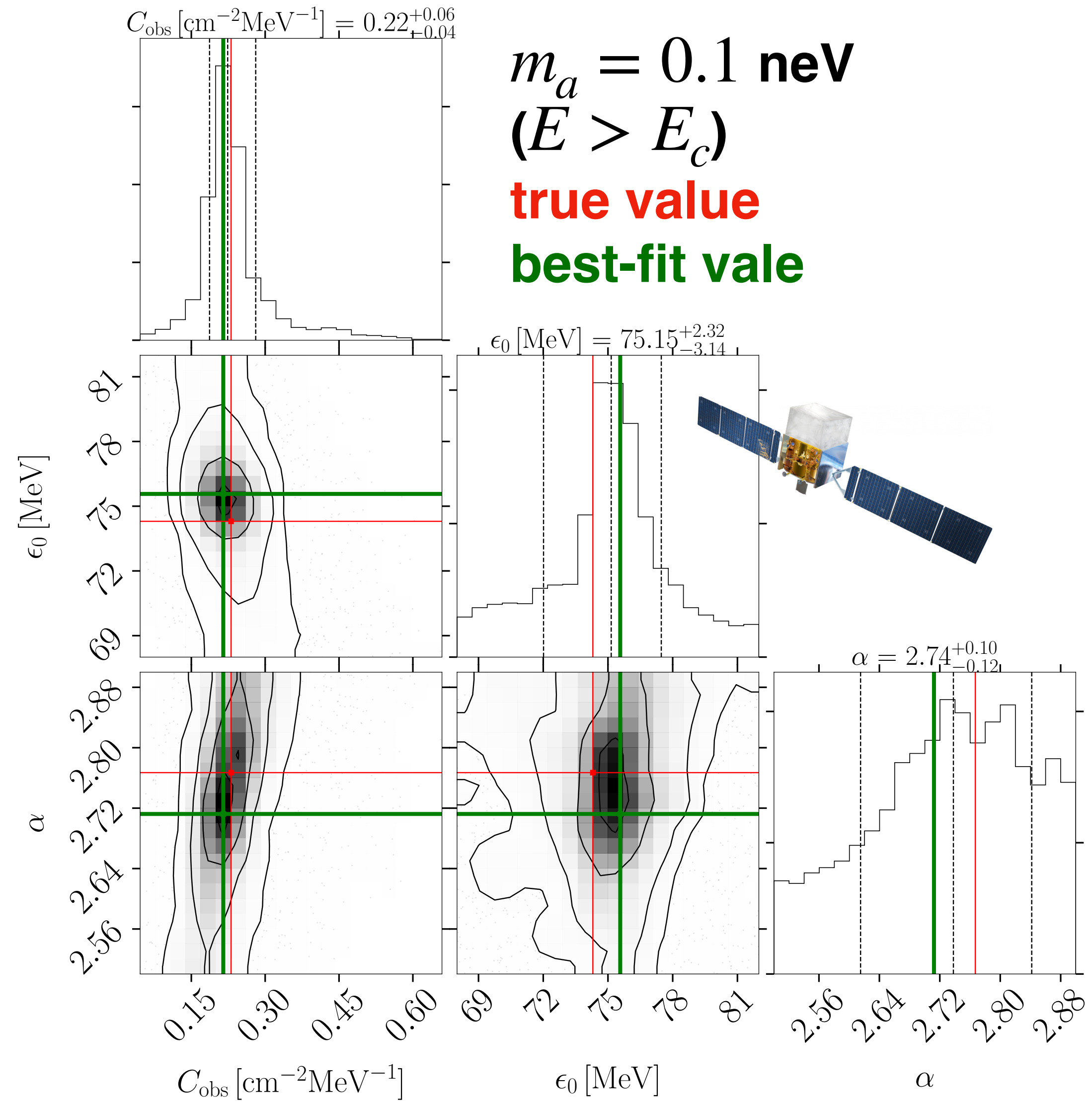


Fermi LAT

Credit: ESA

Searching for ALPs in a future Galactic supernova

What can we learn from a close Galactic supernova (~10 kpc) with a progenitor resembling Betelgeuse (~11 $M_\odot$) regarding ALPs with $m_a \sim \mathcal{O}(1\ \mathrm{neV})$, i.e. Primakoff production?



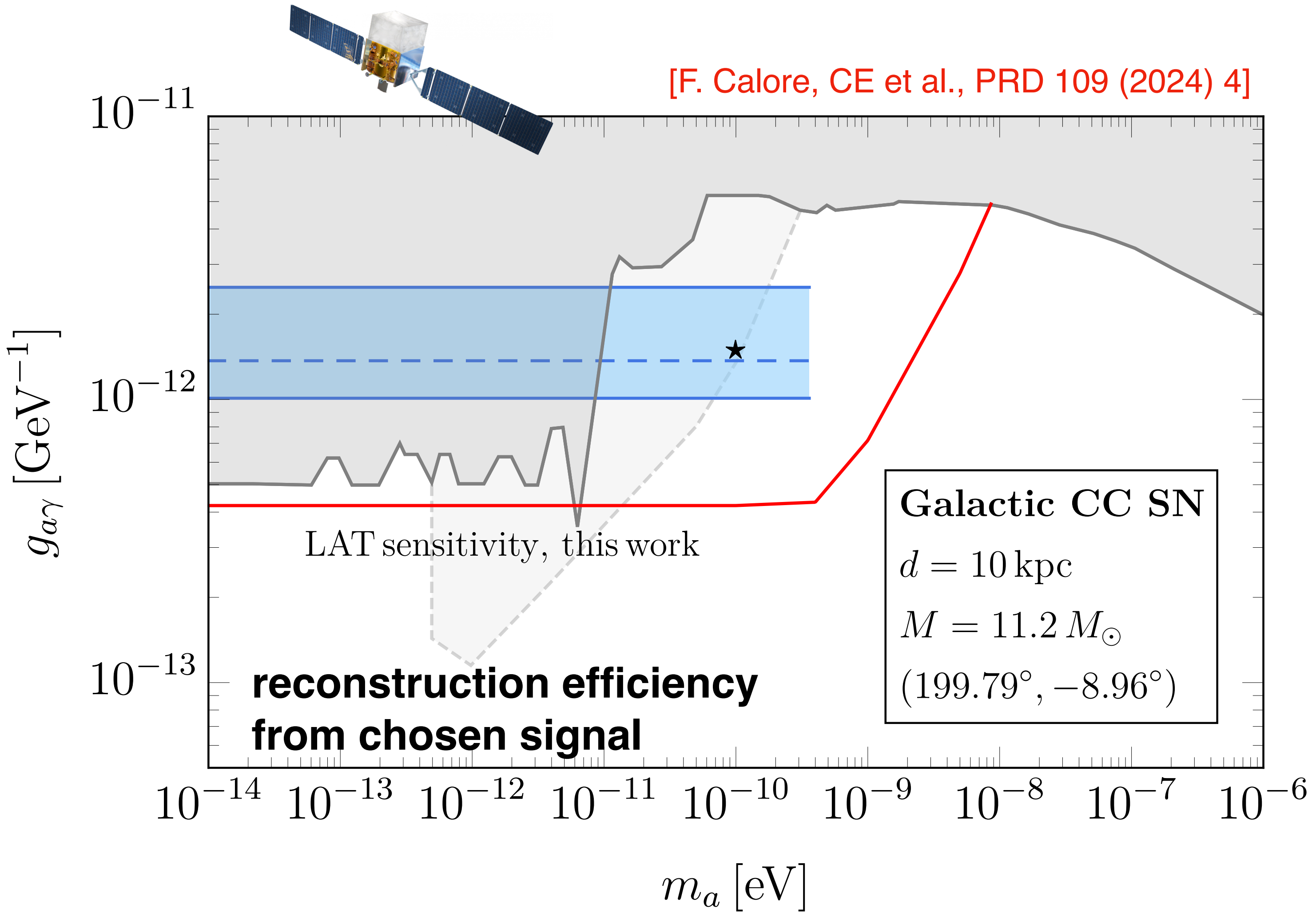
$m_a = 0.1$ **neV**

($E > E_c$)

true value

best-fit vale

[F. Calore, CE et al., PRD 109 (2024) 4]



reconstruction efficiency from chosen signal

Take-home messages and outlook:

1. Prompt gamma-ray emission from a future Galactic supernova event yields stringent bounds on uncharted ALP parameter space.
2. Considering the residual magnetic field of the progenitor star may even enhance the expected ALP production. [C. A Manzari et al., arXiv:2405.19393]

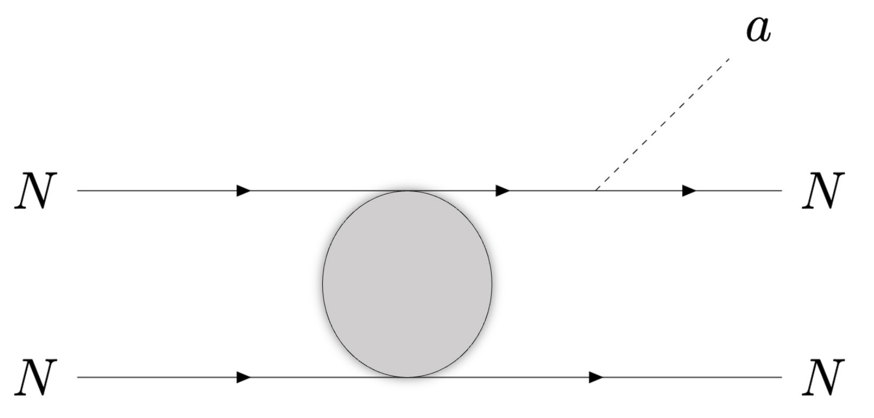
SN prospects for light ALPs with nucleon couplings

Introduction ALP couplings to mesons and hadrons introduces a rich phenomenology:

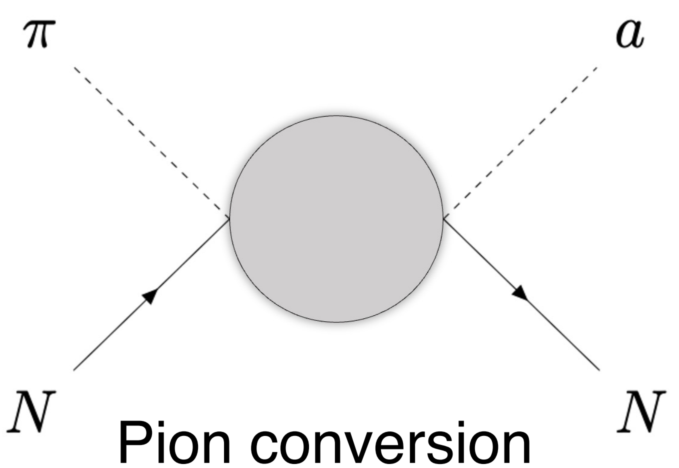
$$\mathcal{L}_{\rm int} = g_a \frac{\partial_\mu a}{2m_N}\left[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \frac{C_{a\pi N}}{f_\pi}\left(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p\right) + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\right]$$

See G. Lucente's talk!

ALP production in SN cores:



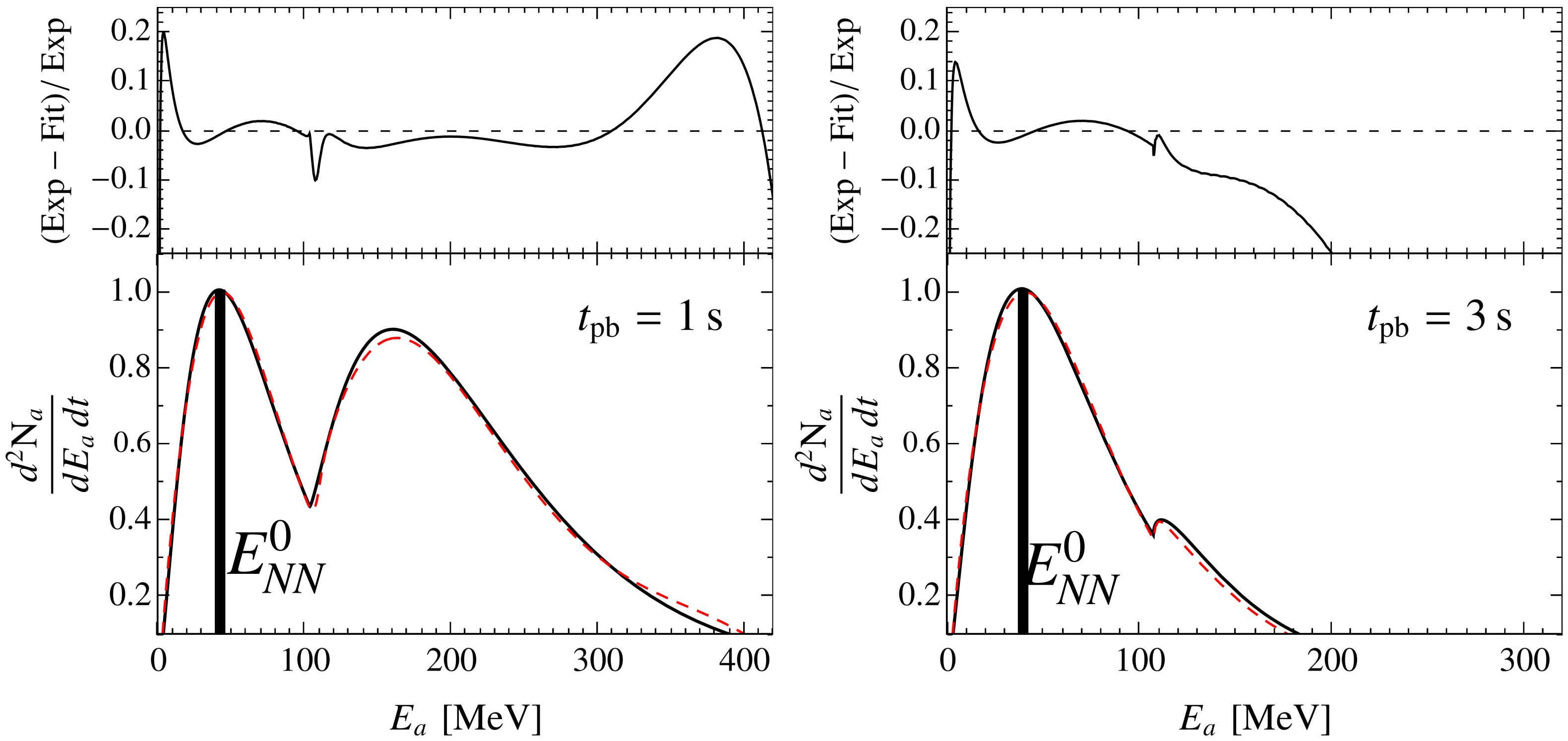
Nucleon-nucleon bremsstrahlung



Pion conversion

Protoneutron star temperature correlates with average energy of Bremsstrahlung ALPs

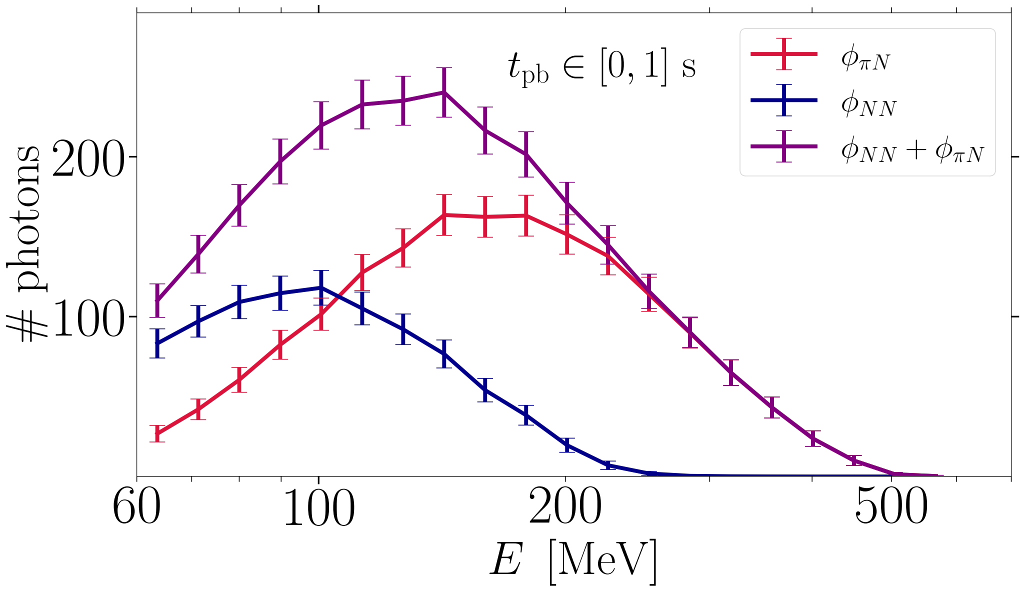
$$\frac{T}{\rm MeV} \simeq -6.93 + \frac{0.45}{\alpha}\left(\frac{E^0_{NN}}{\rm MeV}\right)_{\rm obs}$$

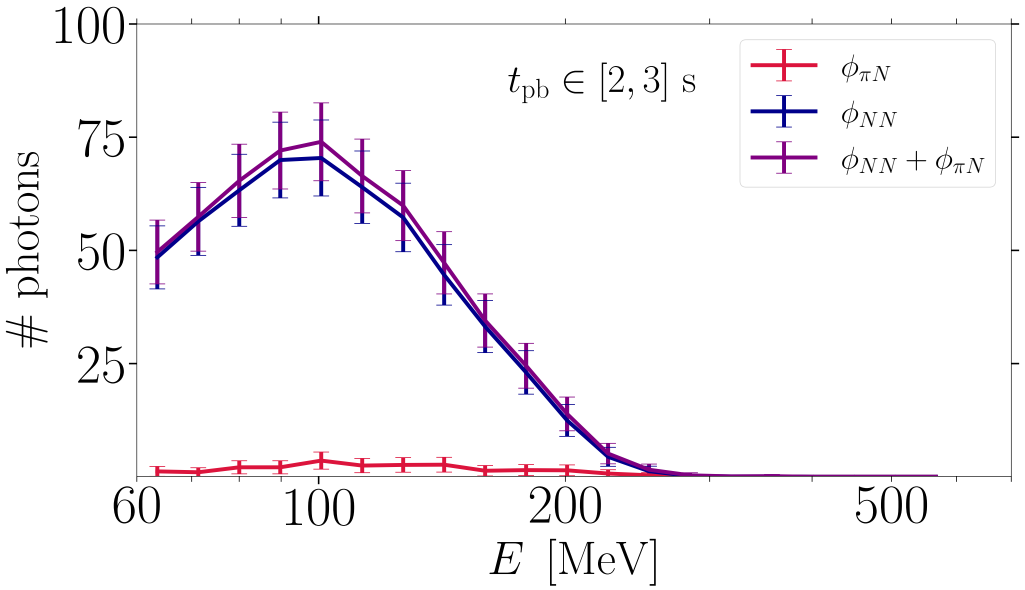


[A. Lella, **CE** et al., arXiv:2405.02395]

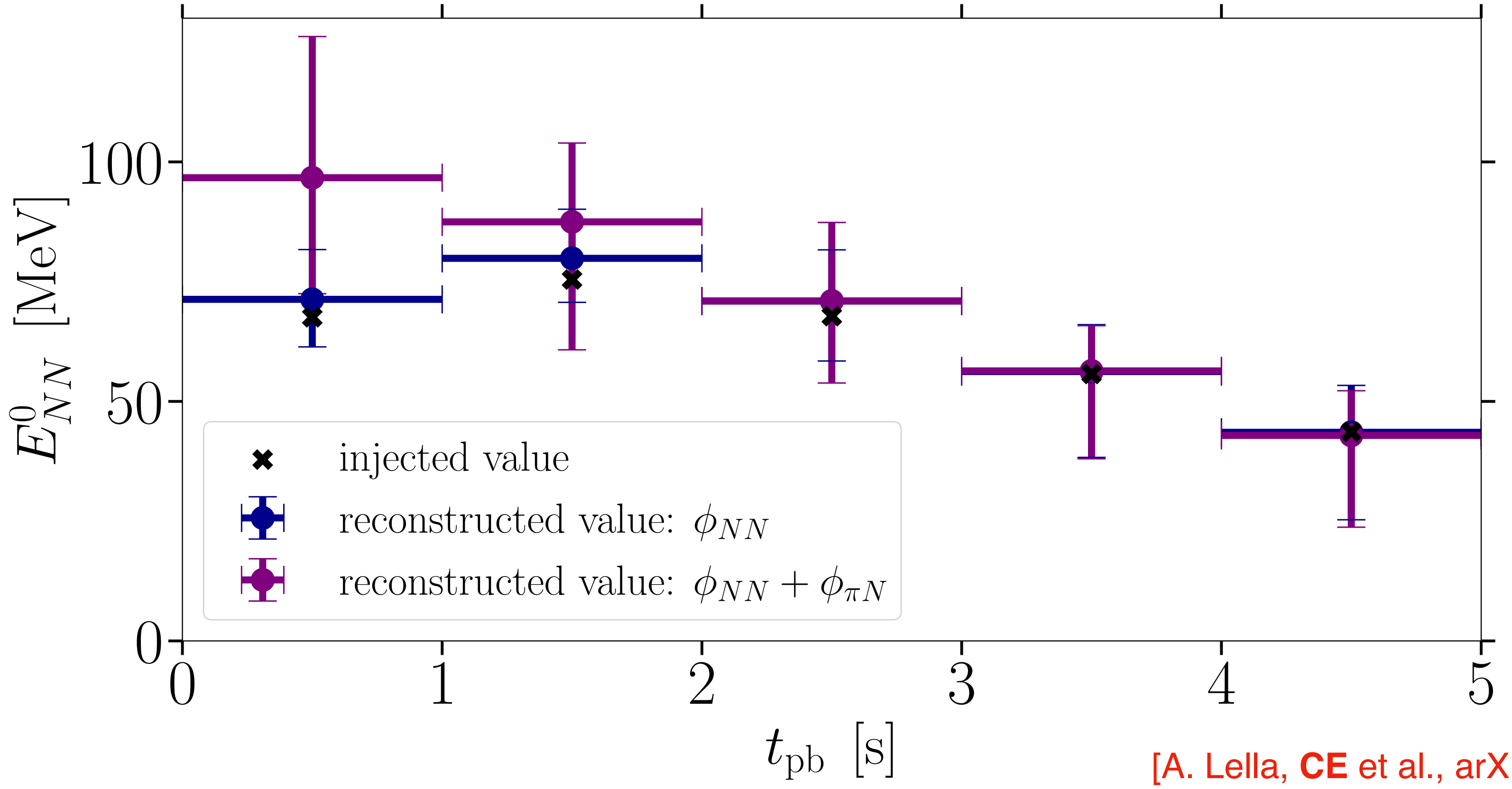
SN prospects for light ALPs with nucleon couplings

While the double peak ALP spectrum is washed out by the LAT’s energy resolution …





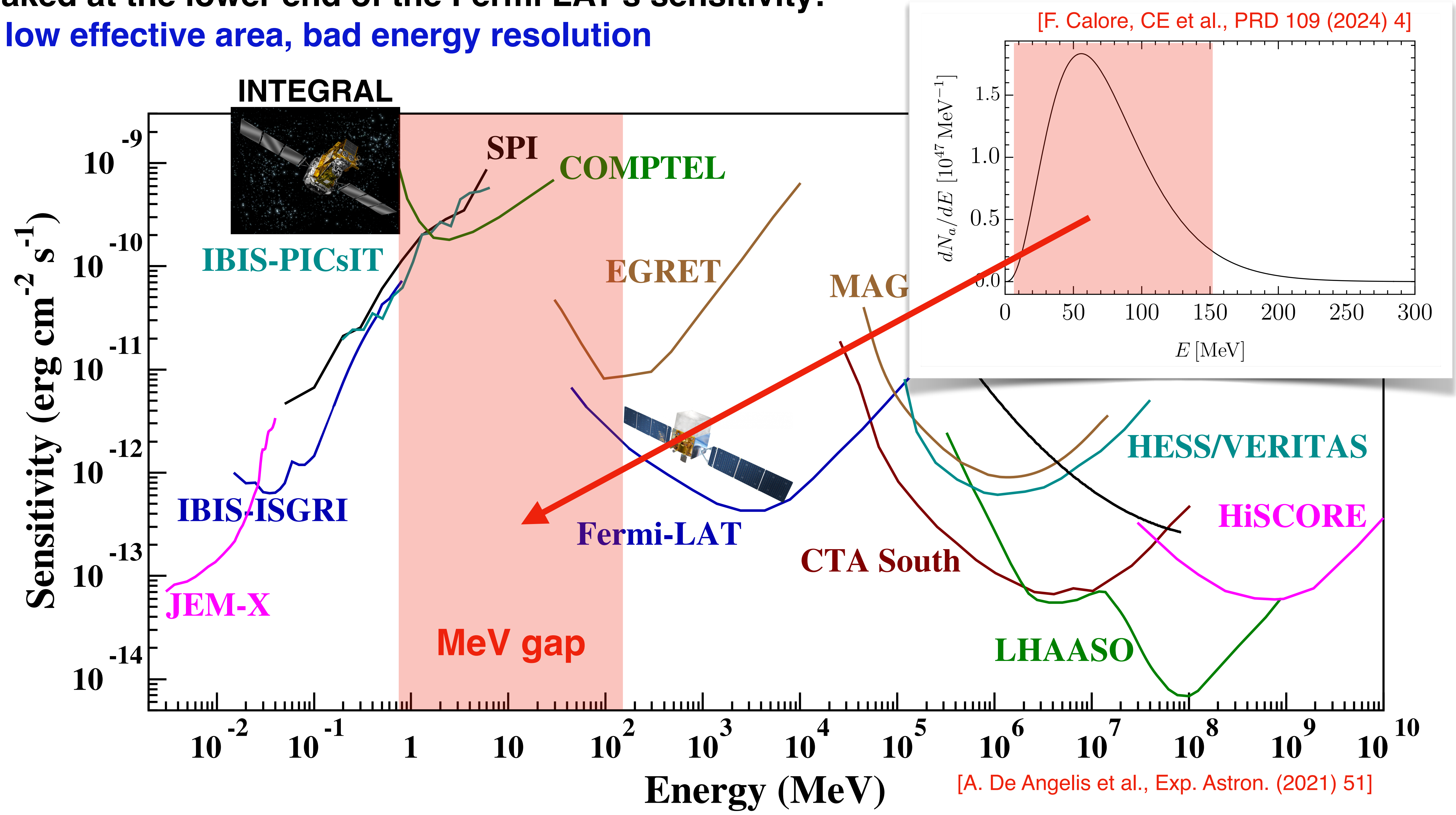
… we can still reconstruct the average energy of the Bremsstrahlung component reasonably well.



[A. Lella, **CE** et al., arXiv:2405.02395]

The MeV gap impacts supernova ALP searches

ALP-induced gamma-ray bursts produce a spectrum peaked at the lower end of the Fermi LAT's sensitivity:
→ **low effective area, bad energy resolution**



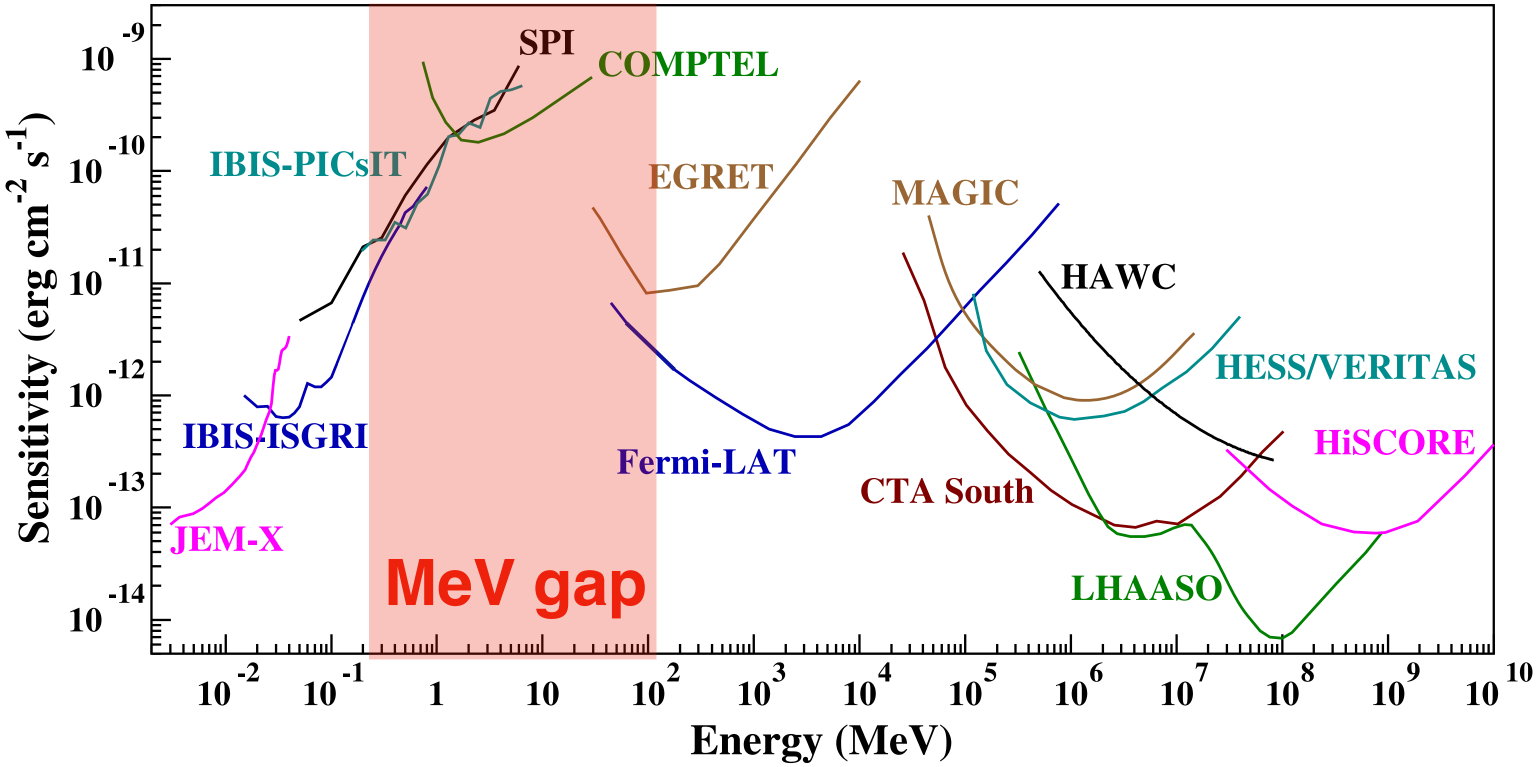
[F. Calore, CE et al., PRD 109 (2024) 4]

[A. De Angelis et al., Exp. Astron. (2021) 51]

An instrument closing this gap greatly enhances our sensitivity to new physics for the next Galactic supernova!

Conclusions

- Gamma-ray signatures of axions and axion-like particles are diverse and can already be tested with current-generation instruments.
- The future is bright with next-generation instruments like the Cherenkov Telescope Array Observatory, updates of LHAASO (and SWGO ?)
- The search directions are clear:
  → Towards the very-high energy end of the gamma-ray spectrum (PeV frontier) [spectral modulations, opacity of the universe]
  → The sensitivity frontier at MeV energies [supernovae]
- Closing the MeV gap also greatly advances astrophysics and searches for dark matter in general.



Backup slides

Deriving the *in situ* gamma-ray spectrum

- Gamma rays and neutrinos generated by $p\gamma$-interactions are linked via:

$$E_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\left(E_\nu = \frac{E_\gamma}{2}\right) = \frac{3}{2} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$

- Adopt best-fitting power law for IceCube neutrino flux + break at low energies:

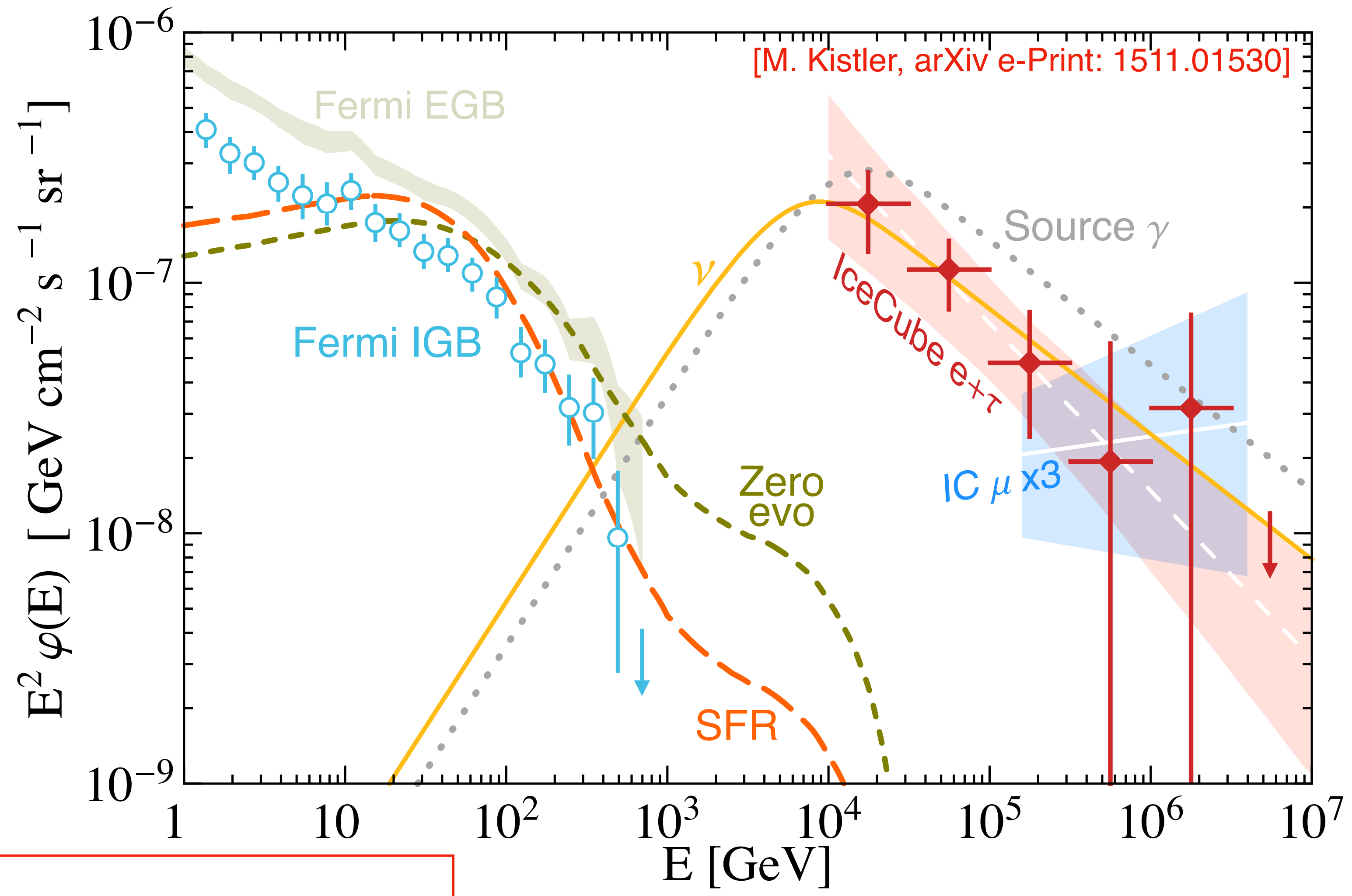
$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = N_0 \left[\left(\frac{E_\nu}{E_b}\right)^2 + \left(\frac{E_\nu}{E_b}\right)^{2\alpha}\right]^{-\frac{1}{2}} \qquad \alpha = 2.87$$

[IceCube collab., PRD 104 (2021) 022002]

- Fix breaking energy at $E_b = 25$ TeV; consistent with IceCube HESE and Cascade data + *Fermi*-LAT IGB.

- In situ neutrino spectrum normalisation N_0 via matching with IceCube measurement:

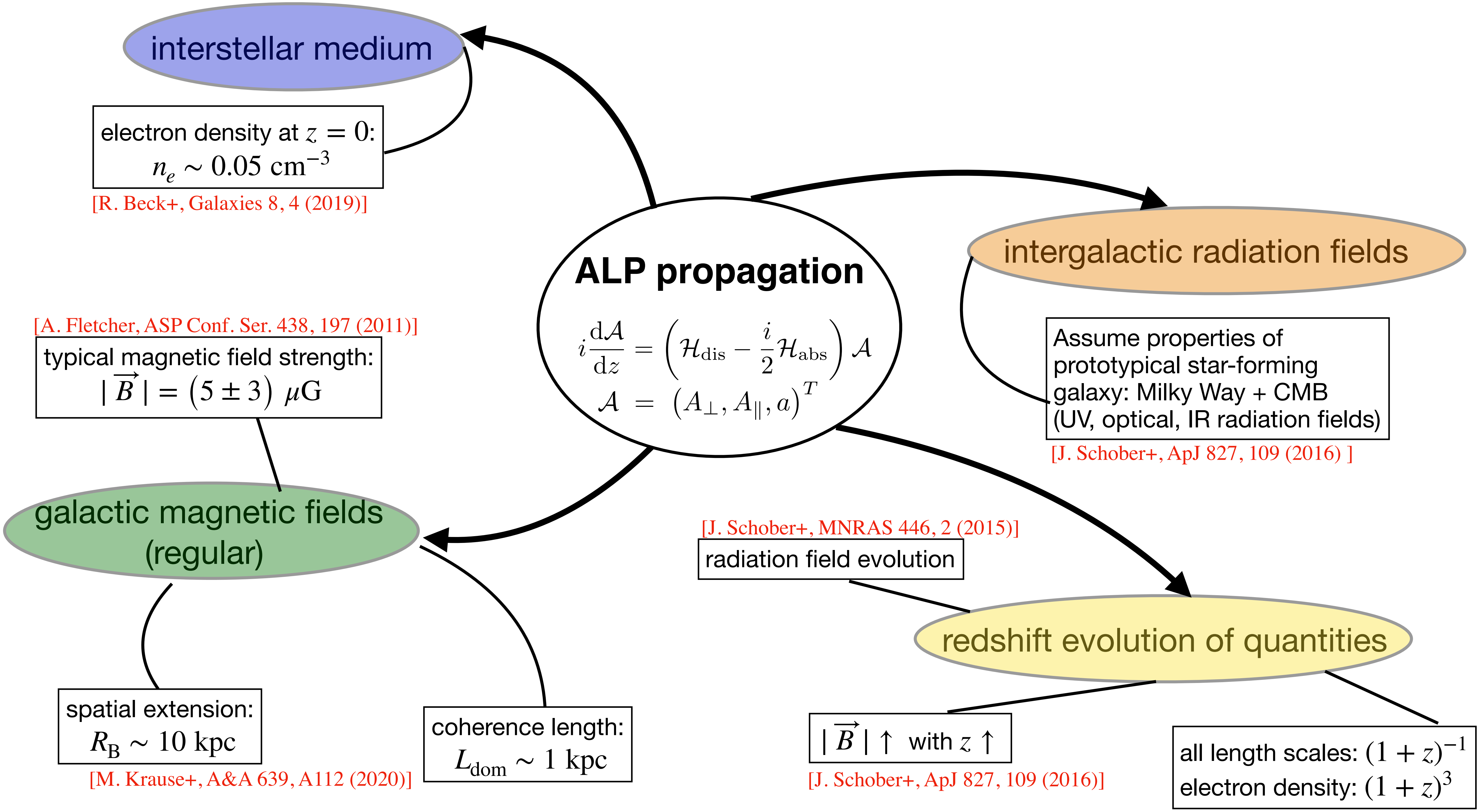
$$\boxed{\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{c}{4\pi}\int_0^\infty \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu'}(1+z)\boxed{\dot{\rho}_*(z)}\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right|\mathrm{d}z}$$



star formation rate density taken from [H. Yuksel, APJ L. 683 (2008)]

Deriving the axion-like particle contribution

- ✦ Photon-ALP mixing in star-forming galaxies according to transfer matrix method implemented in gammaALPs. [M. Meyer+, "gammaALPs" (2021)]
- ✦ Average over multiple realisations of galaxies at given redshift z. [H. Vogel+, arXiv:1712.01839 (2017)]



ALP propagation

$$i\frac{\mathrm{d}\mathcal{A}}{\mathrm{d}z} = \left(\mathcal{H}_{\rm dis} - \frac{i}{2}\mathcal{H}_{\rm abs}\right)\mathcal{A}$$

$$\mathcal{A} = \left(A_\perp, A_\parallel, a\right)^T$$

interstellar medium

electron density at $z = 0$: $n_e \sim 0.05\ \mathrm{cm}^{-3}$

[R. Beck+, Galaxies 8, 4 (2019)]

intergalactic radiation fields

Assume properties of prototypical star-forming galaxy: Milky Way + CMB (UV, optical, IR radiation fields)

[J. Schober+, ApJ 827, 109 (2016)]

galactic magnetic fields (regular)

[A. Fletcher, ASP Conf. Ser. 438, 197 (2011)]

typical magnetic field strength: $|\vec{B}| = (5 \pm 3)\ \mu\mathrm{G}$

spatial extension: $R_{\rm B} \sim 10\ \mathrm{kpc}$

[M. Krause+, A&A 639, A112 (2020)]

coherence length: $L_{\rm dom} \sim 1\ \mathrm{kpc}$

redshift evolution of quantities

[J. Schober+, MNRAS 446, 2 (2015)]

radiation field evolution

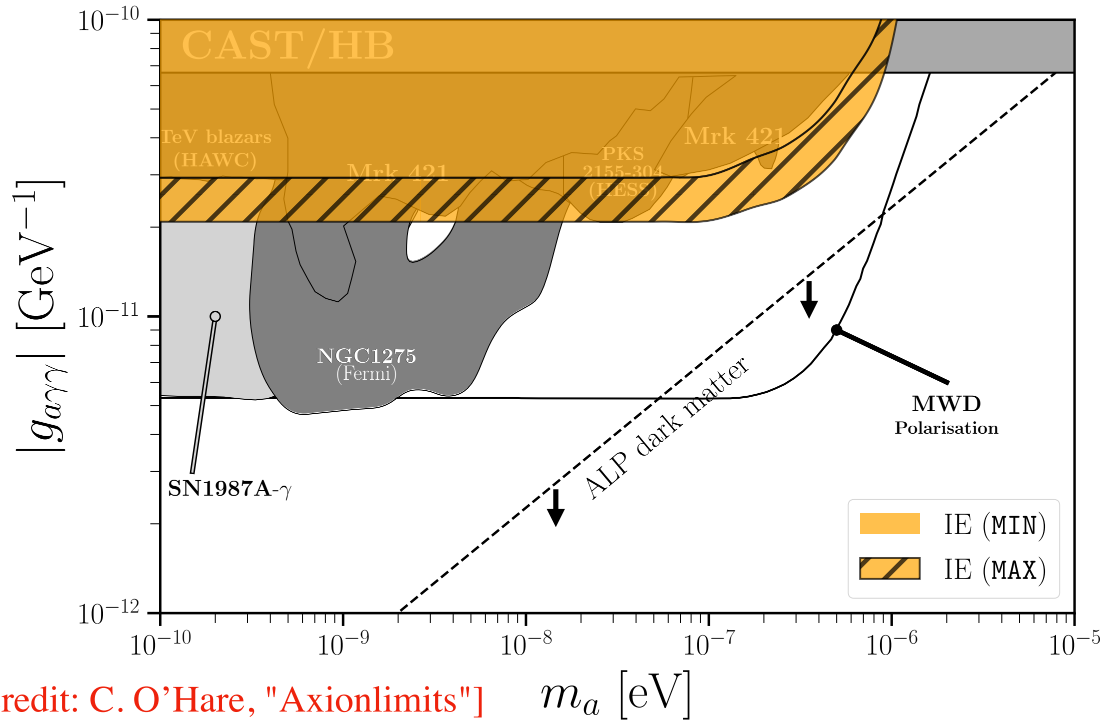
$|\vec{B}| \uparrow$ with $z \uparrow$

[J. Schober+, ApJ 827, 109 (2016)]

all length scales: $(1+z)^{-1}$
electron density: $(1+z)^3$

Discussion

✦ Uncertainty due to modelling of interstellar emission:



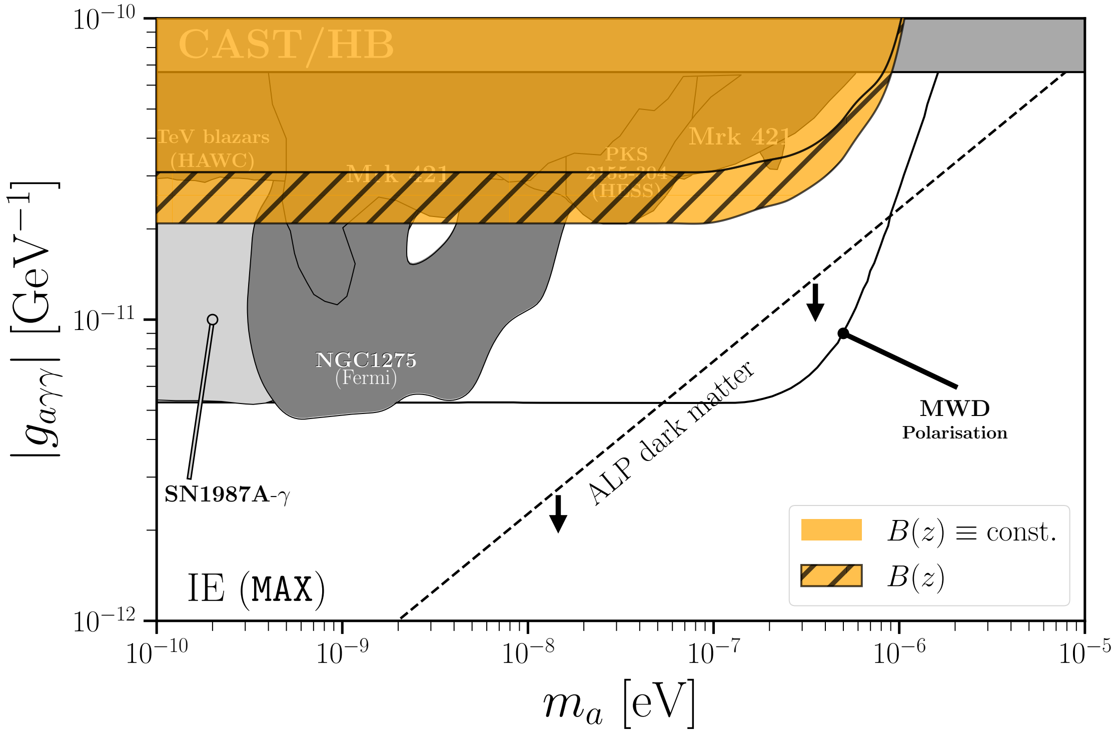
[credit: C. O’Hare, "Axionlimits"]

—> Uncertainty between minimal and maximal IE around a factor of 1.5

—> Even in minimal scenario, competitive constraints.

—> ALPs-only constraints worse by a factor of 3.

✦ Uncertainty due to redshift-dependence of magnetic fields in star-forming galaxies:



—> Formation and evolution of galactic magnetic fields is a subject of ongoing theoretical and experimental research [T. G. Arshakian+, A&A 494, 21 (2009)]

—> Increase of field strength with redshift by no means necessary.

—> What happens if it stays constant? Factor of ~1.5 deterioration of limits (since we are not very sensitive to the high-z sky).