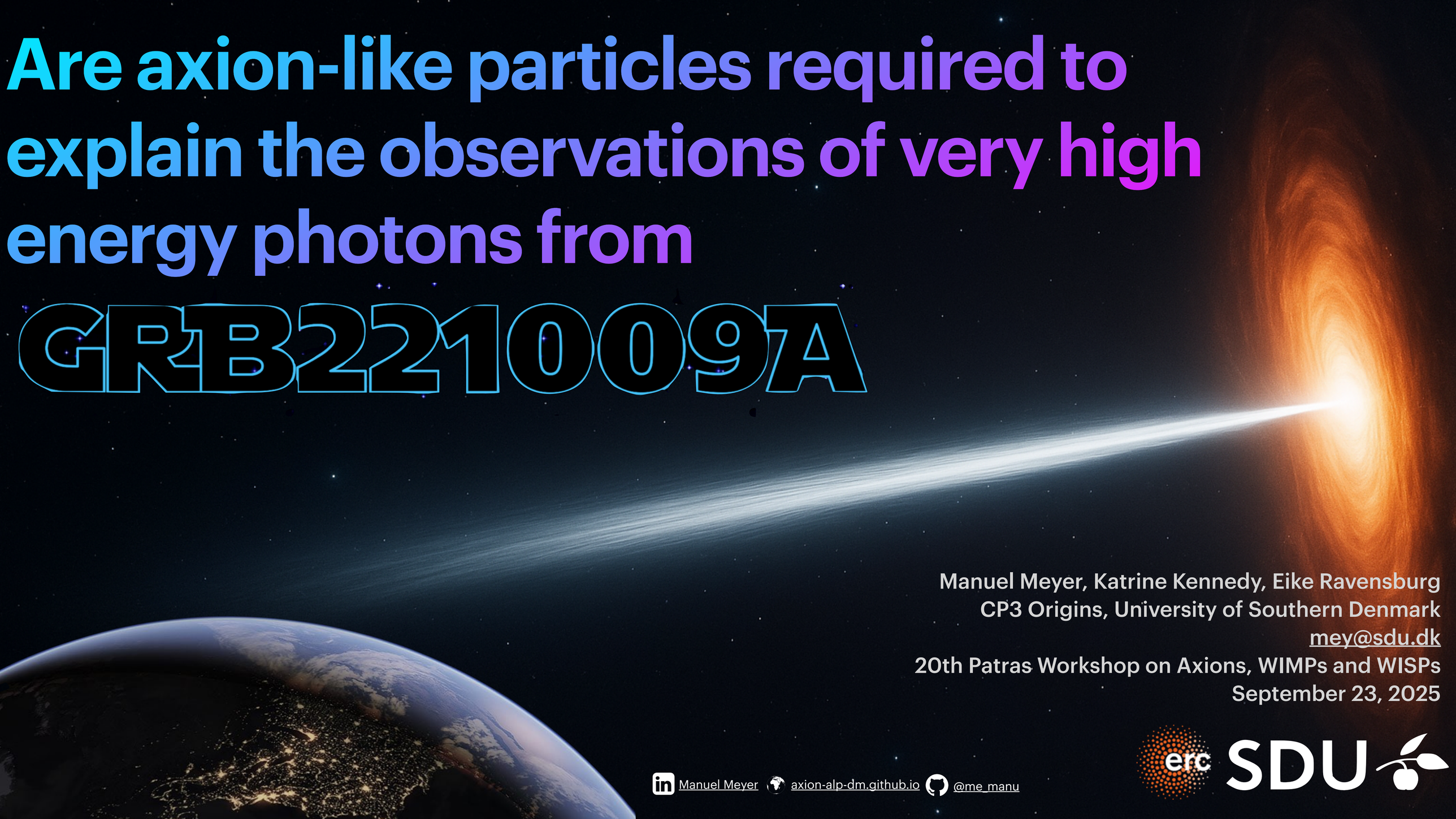
A long time ago in a galaxy far, far away ...

A long time ago (~3 years) in a galaxy far, far away (~2.4×10^9 light years) ...


GRB221009A

Are axion-like particles required to explain the observations of very high energy photons from GRB221009A



Manuel Meyer, Katrine Kennedy, Eike Ravensburg
CP3 Origins, University of Southern Denmark
mey@sdu.dk

20th Patras Workshop on Axions, WIMPs and WISPs
September 23, 2025

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

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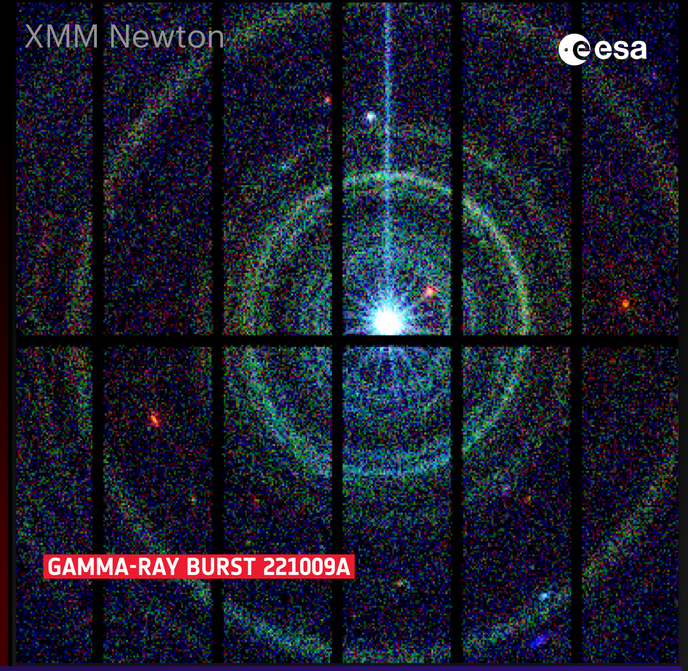
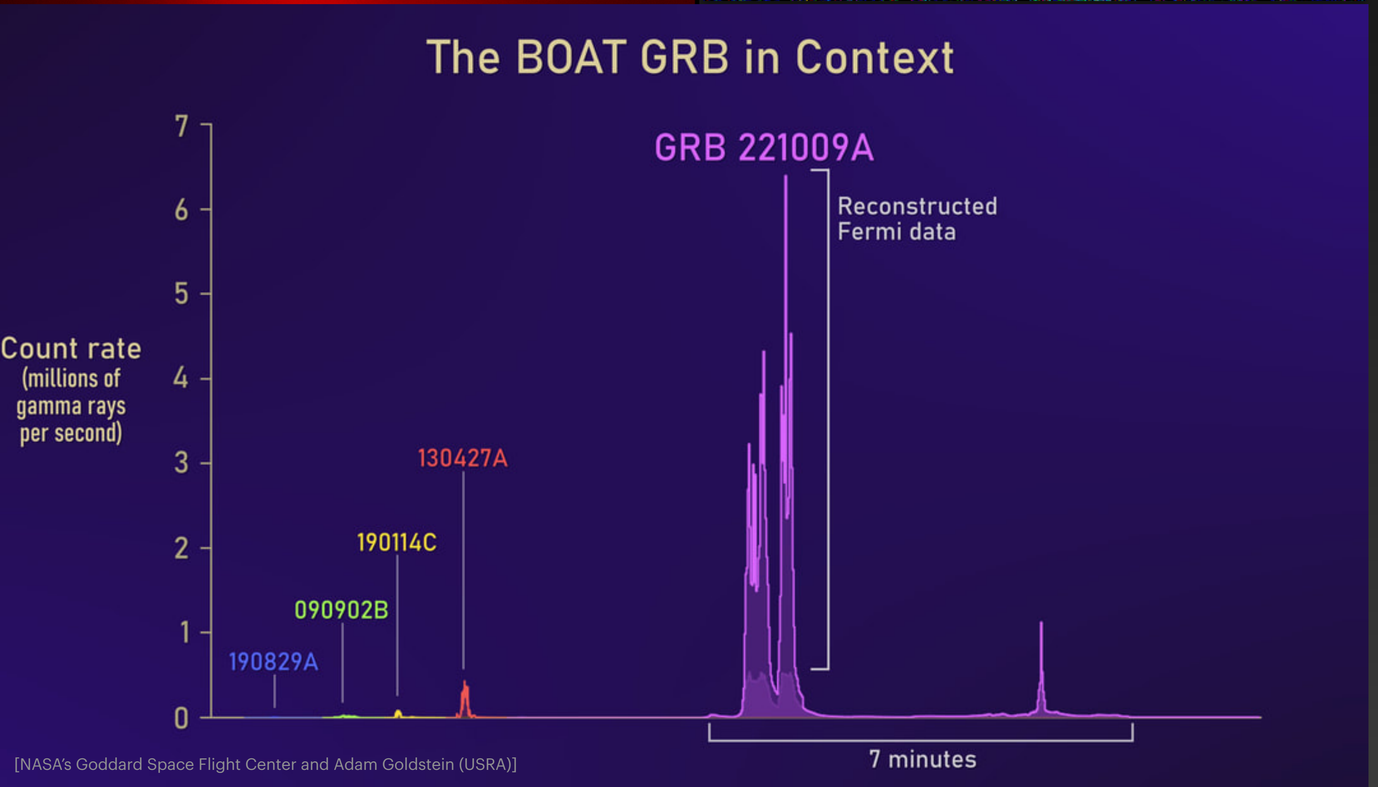
GRB221009A — BOAT

E > 100 MeV
10 hours of observation
20º x 20º
Credit: NASA/DOE/*Fermi* LAT Collaboration





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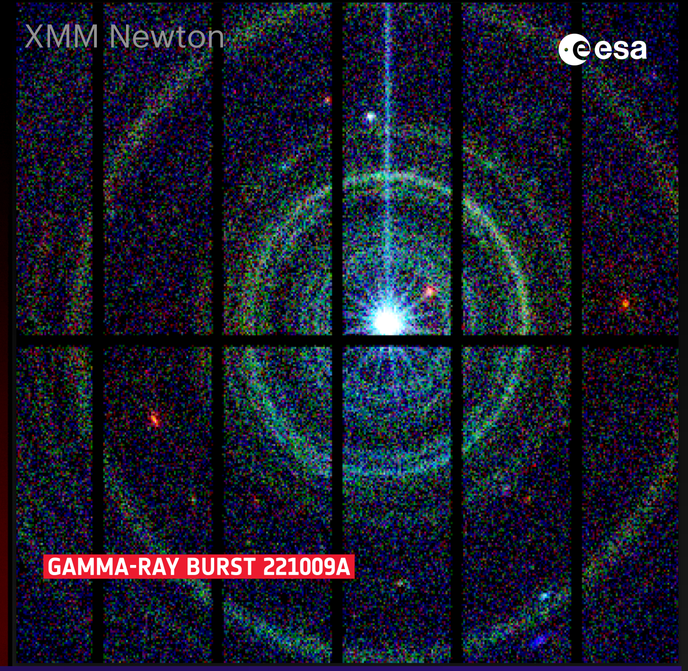

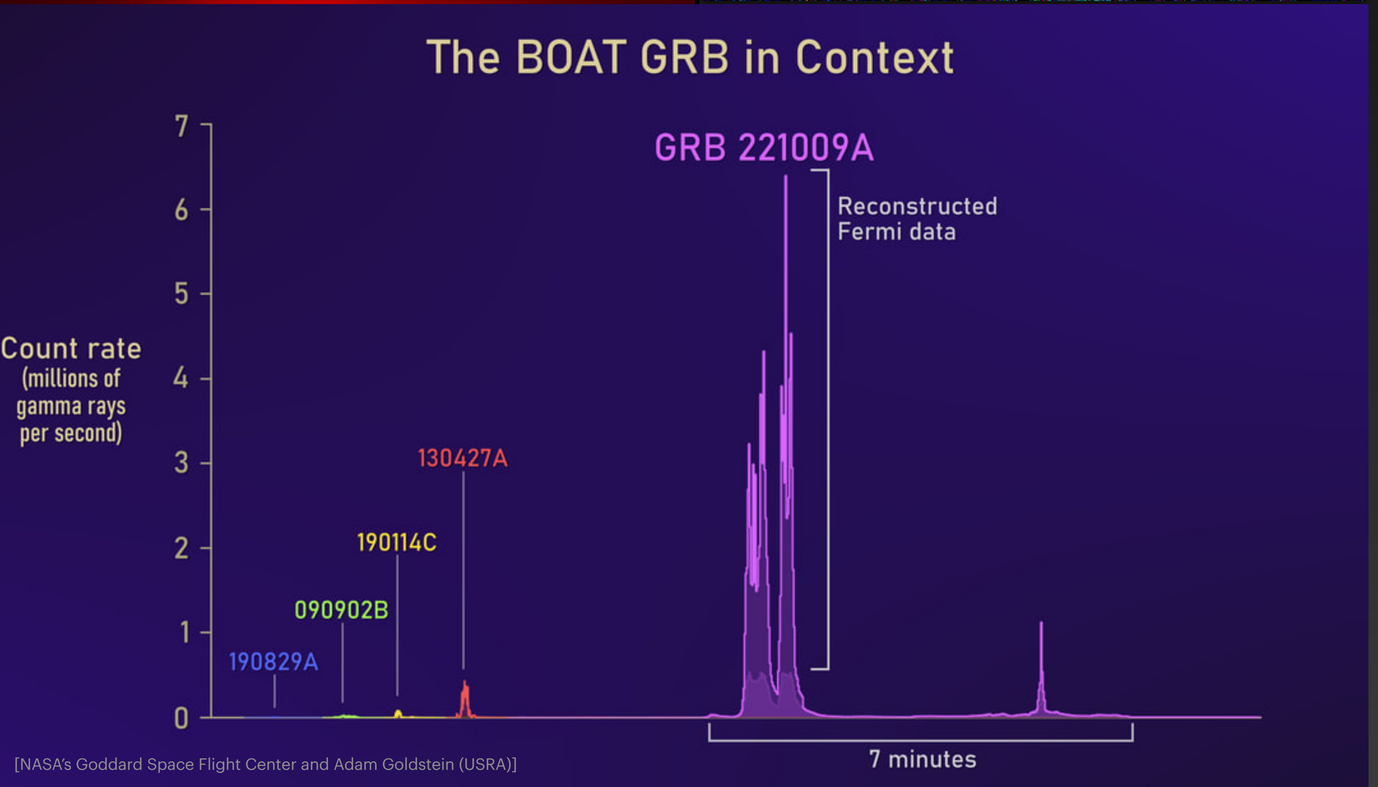

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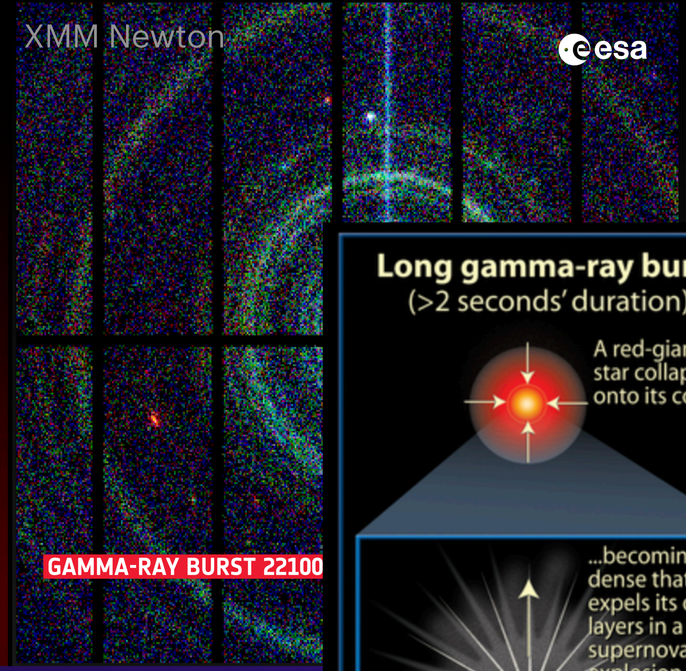

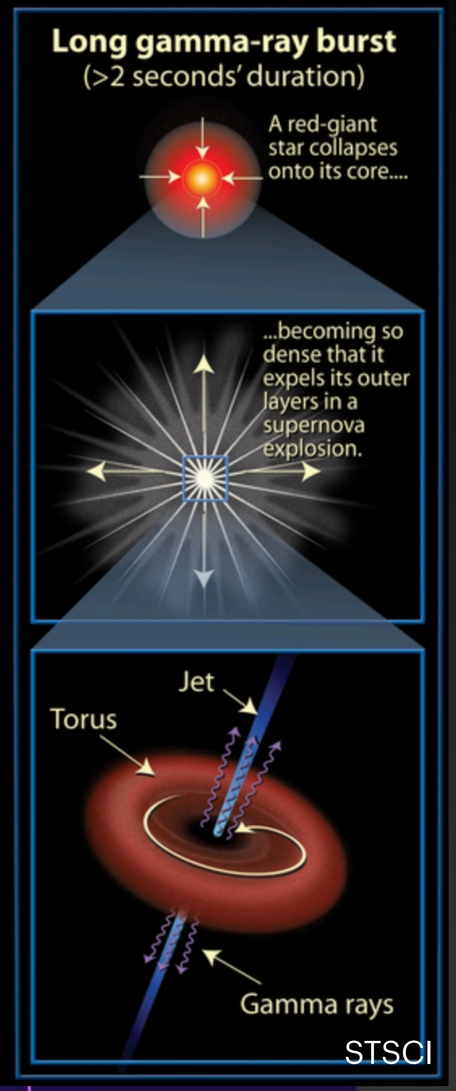

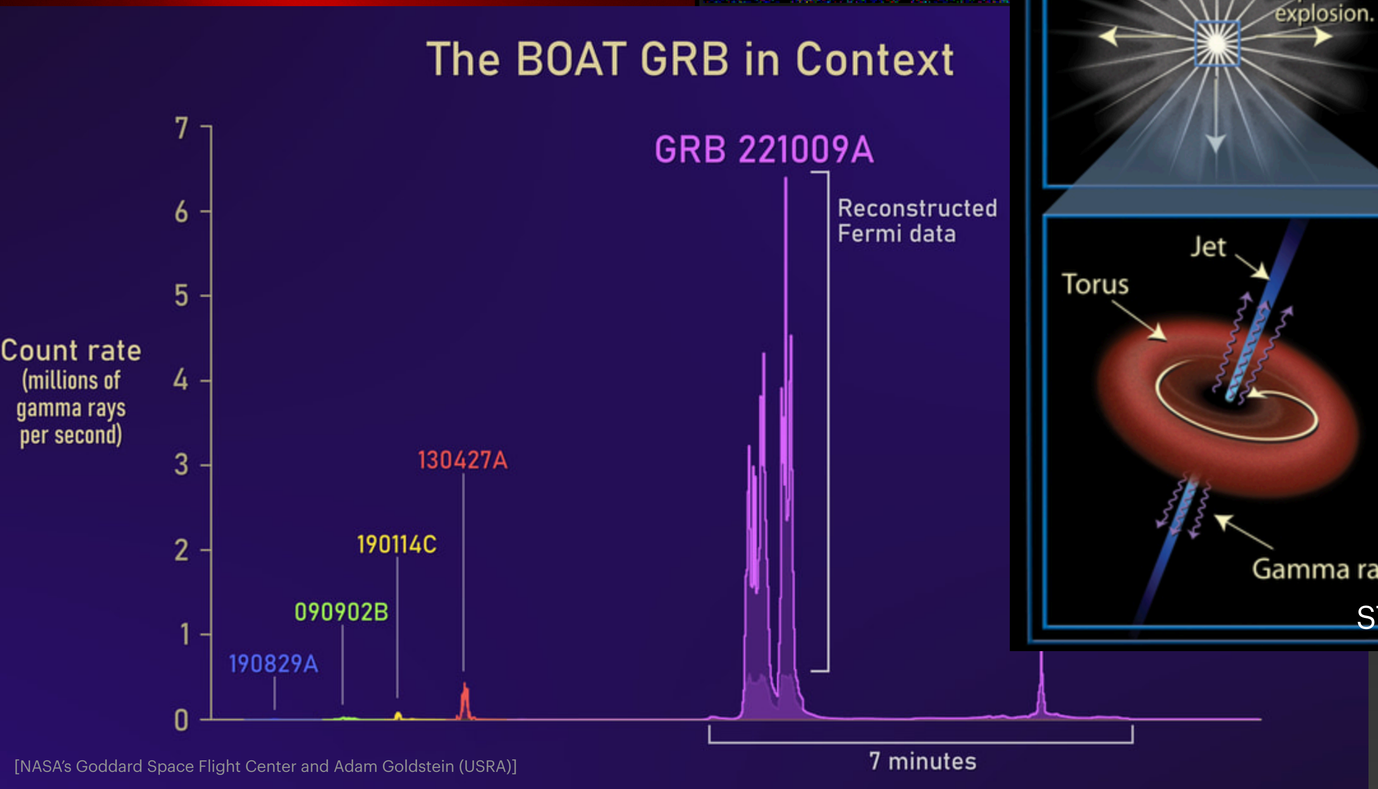

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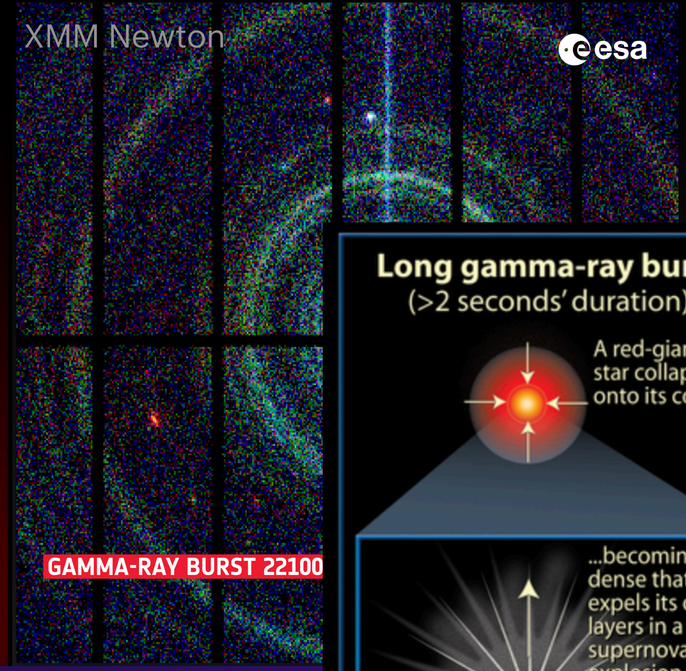

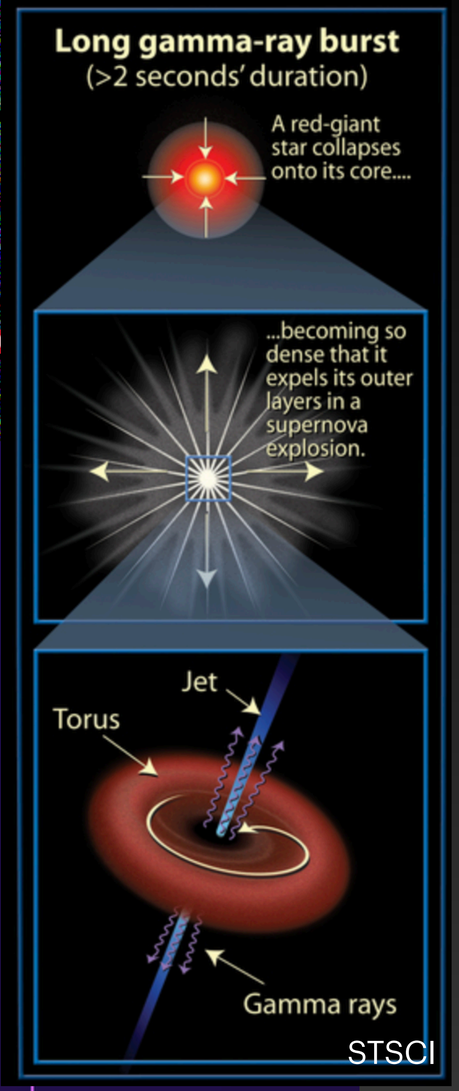

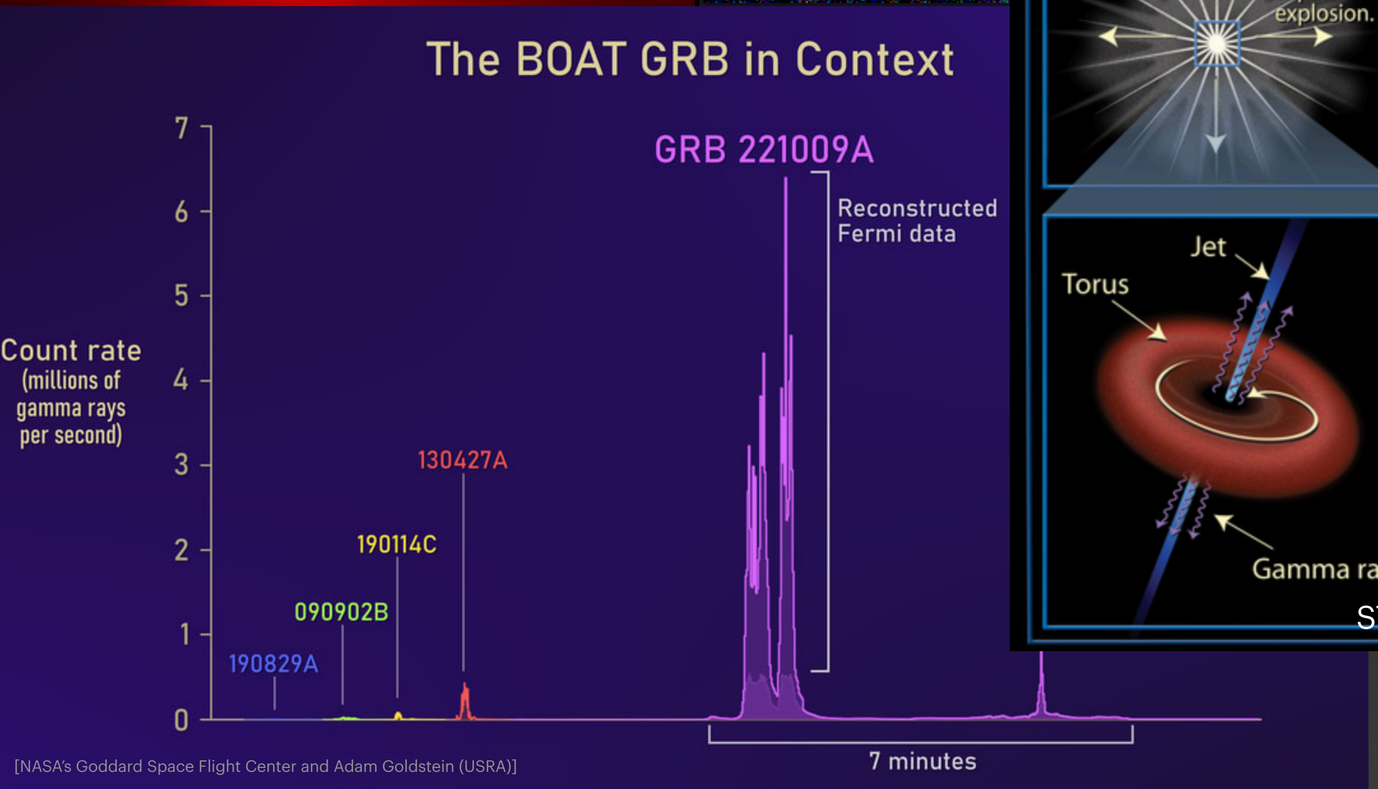

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- Redshift $z = 0.1505$ ($D_L \approx 2.4 \times 10^9$ ly) from CaI, II absorption lines measured with VLT X-Shooter
  [Malesani et al., 2023, arXiv:2302.07891]

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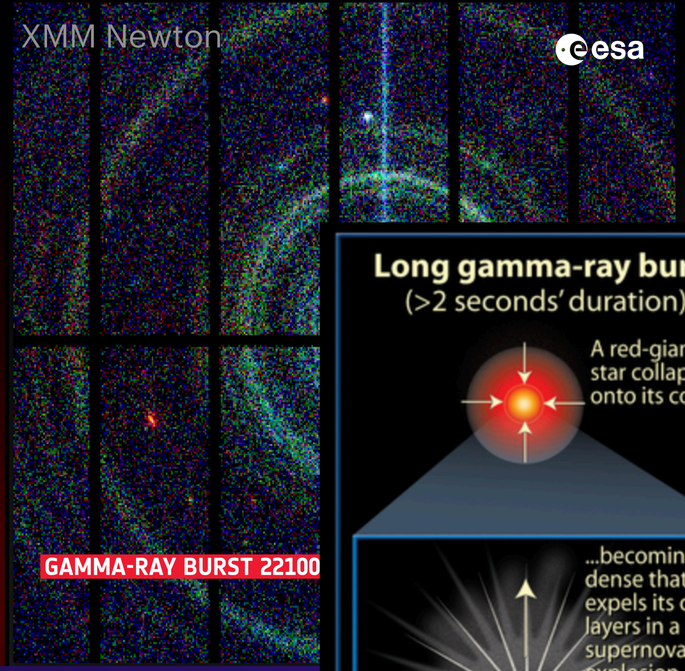

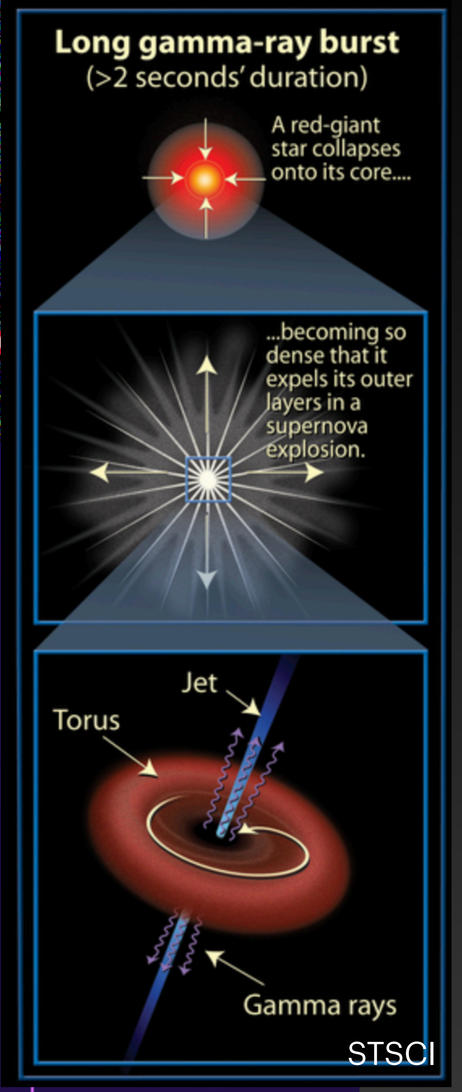

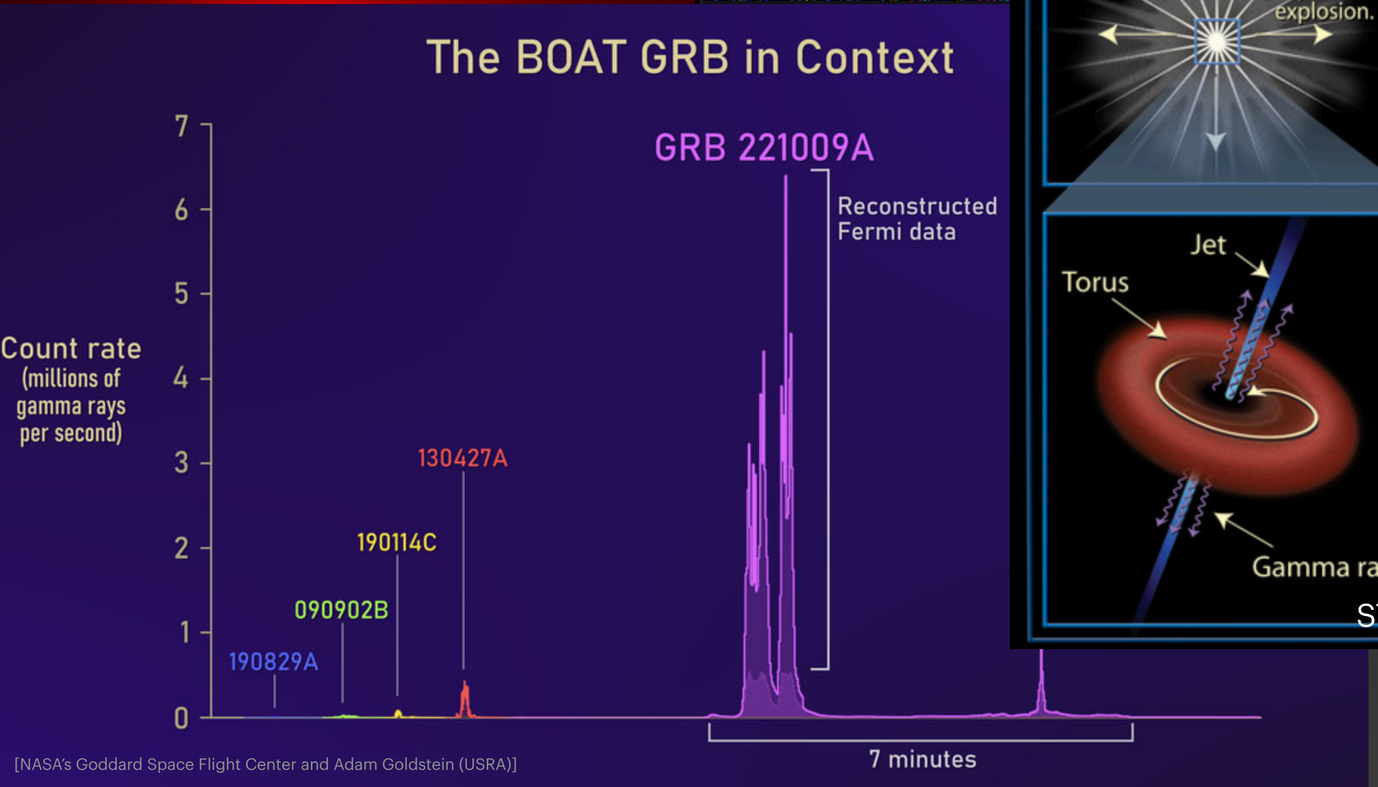

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- *Fermi* LAT detected 99.4 GeV photon (record from GRB) at $T_0 + 240\,\mathrm{s}$
  [Axelsson et al., 2025, arXiv:2409.04580]

Why exciting for axion enthusiasts?

GCN Circular 32677

Subject LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
Event GRB 221009A
Date 2022-10-11T09:21:54Z (3 years ago)
From Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and
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We report the observation of GRB 221009A, which was detected by Swift (Kennea
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GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy
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Very unlikely to observe $E = 18$ TeV photon from source at $z = 0.151$ — need new physics?

VHE photons seen with LHAASO

LHAASO Mt Haizi, Sichuan, China

[LHAASO Collaboration 2023, Science, 380, 6652; 2023, Sci. Adv., 9, 46]

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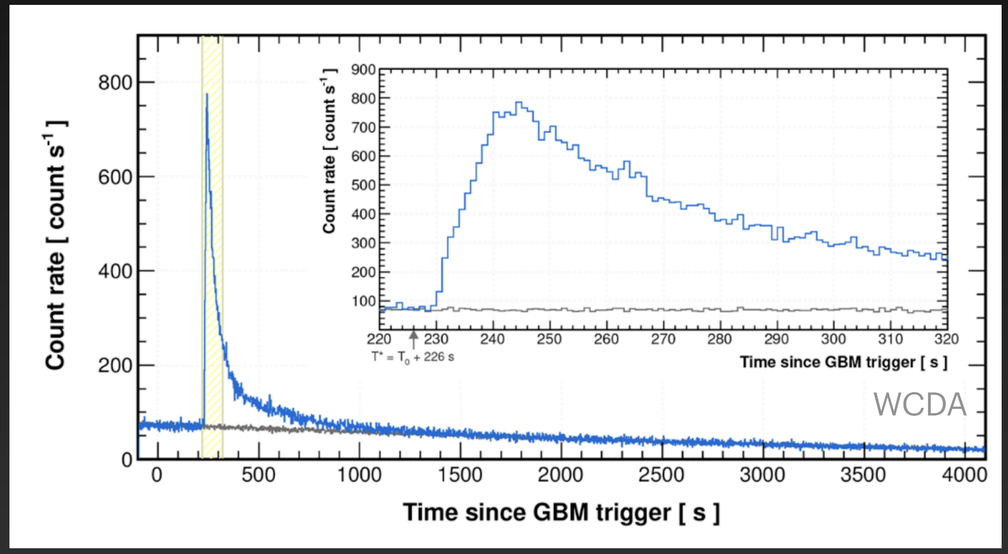
- WCDA: > 64,000 gamma rays between 0.2 TeV and 7 TeV in ~3000s



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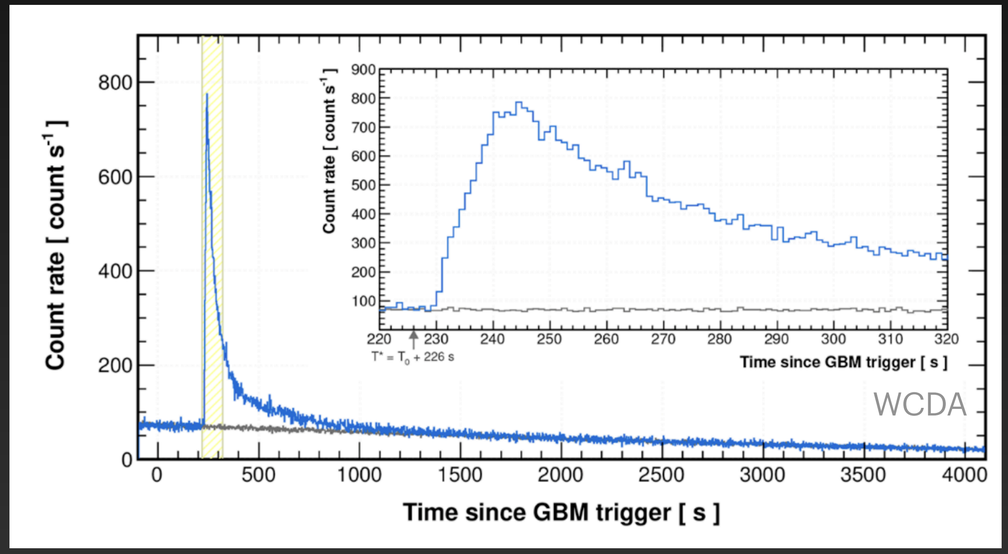

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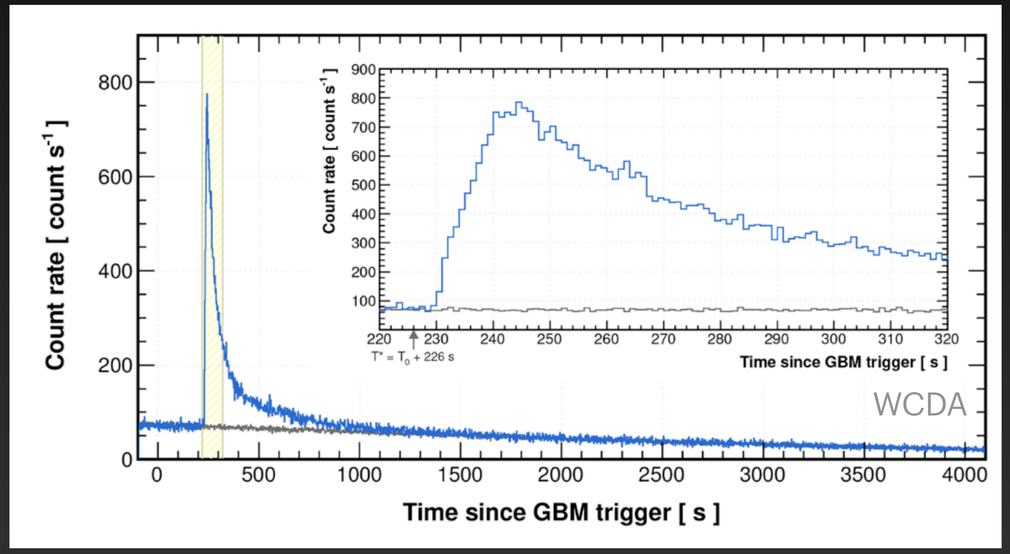
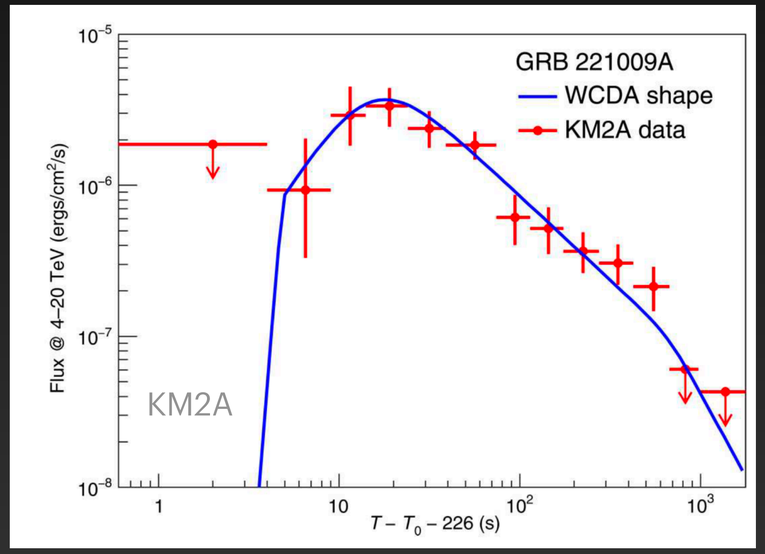
- WCDA: > 64,000 gamma rays between 0.2 TeV and 7 TeV in ~3000s
- Light curve suggests jet opening angle of 1.6°
- KM2A: 140 gamma rays between 3 and $\gtrsim$ 13 TeV in ~900s



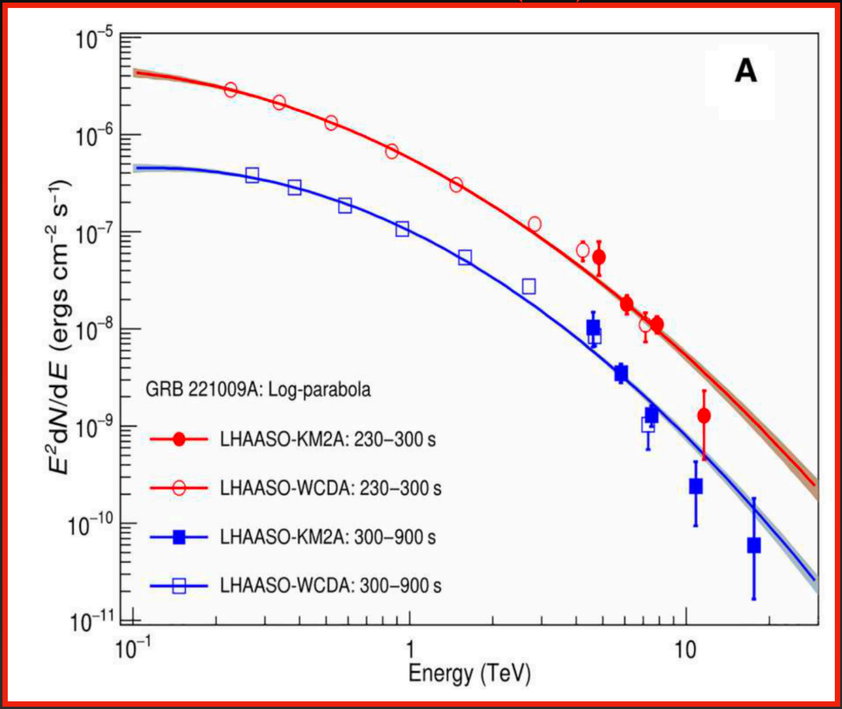


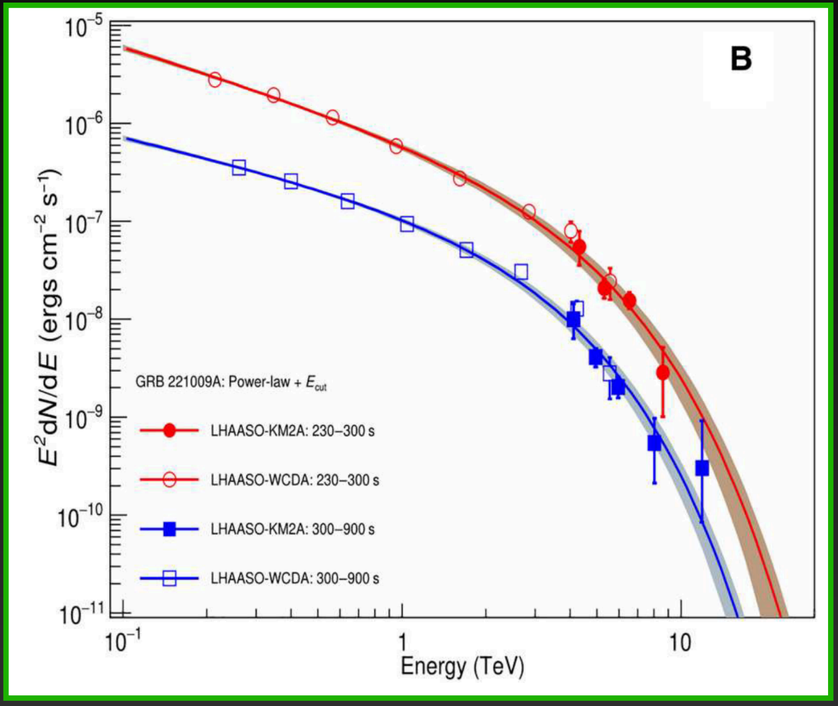
[LHAASO Collaboration 2023, Science, 380, 6652; 2023, Sci. Adv., 9, 46]

Combined WCDA+KM2A spectrum

Log parabola (LP): $\frac{dN}{dE} = N\left(\frac{E}{E_0}\right)^{-\alpha-\beta\ln(E/E_0)}$

Power law with exp. cutoff: $\frac{dN}{dE} = N\left(\frac{E}{E_0}\right)e^{-E/E_{\rm cut}}$





- Reconstruction depends on assumed source spectrum
- Maximum photon energies: $E_{\rm max}^{\rm LP} = 17.8^{+7.4}_{-5.1}$ TeV whereas $E_{\rm max}^{\rm EPL} = 12.2^{+3.5}_{-2.4}$ TeV
- EPL spectrum provides better fit for combined data set

[LHAASO Collaboration, Sci. Adv. 2023]


Absorption of VHE gamma rays

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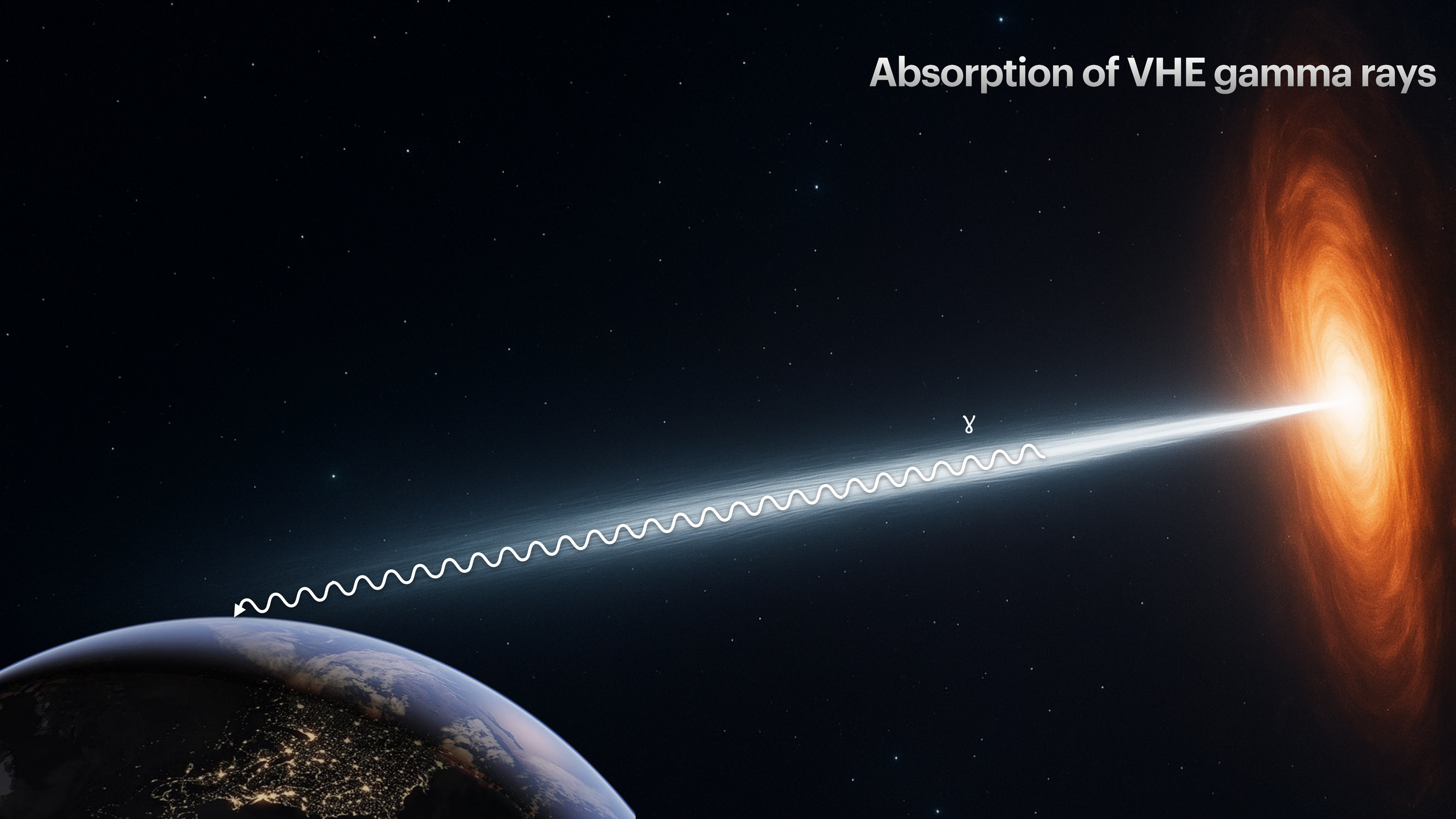

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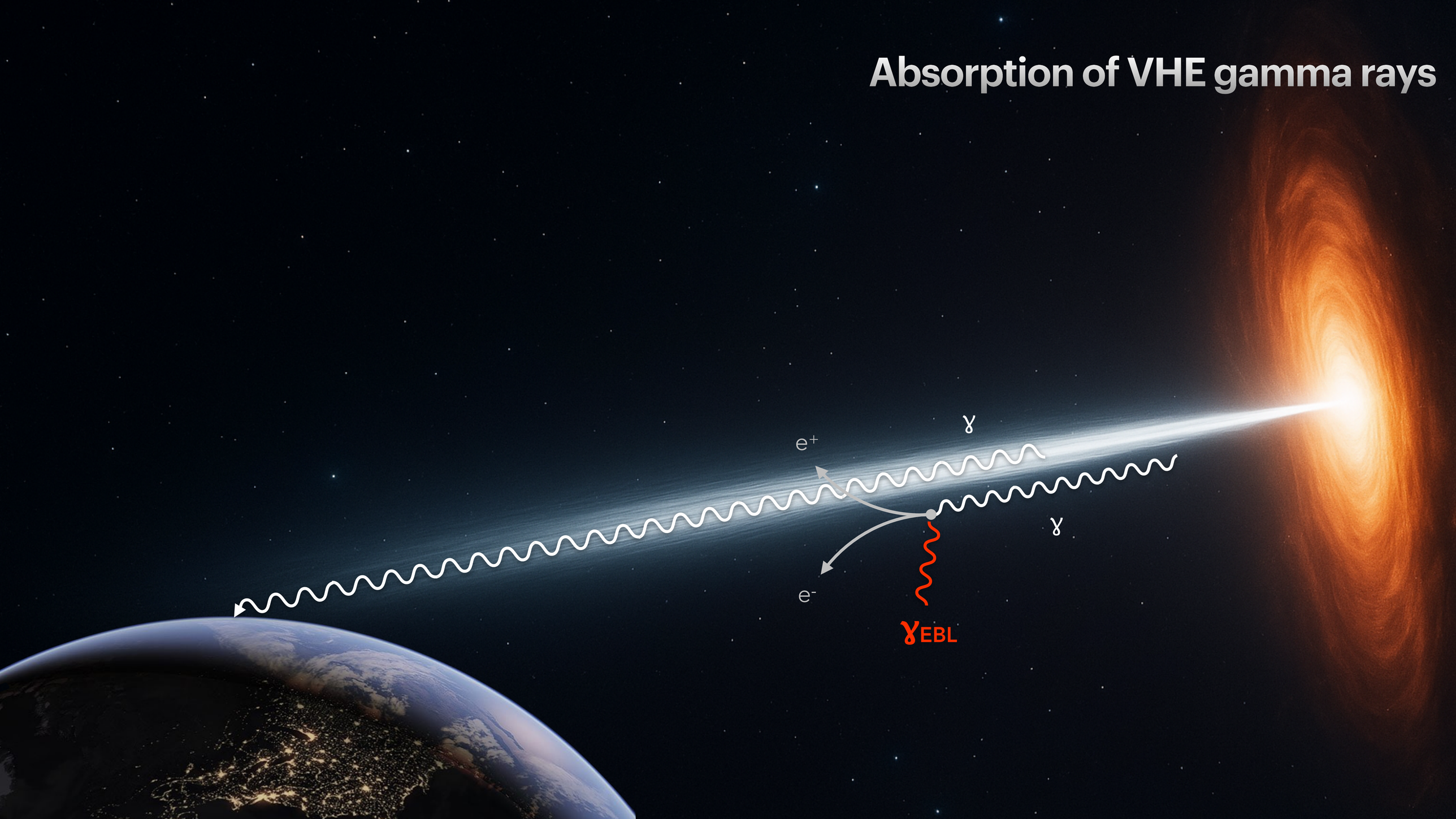
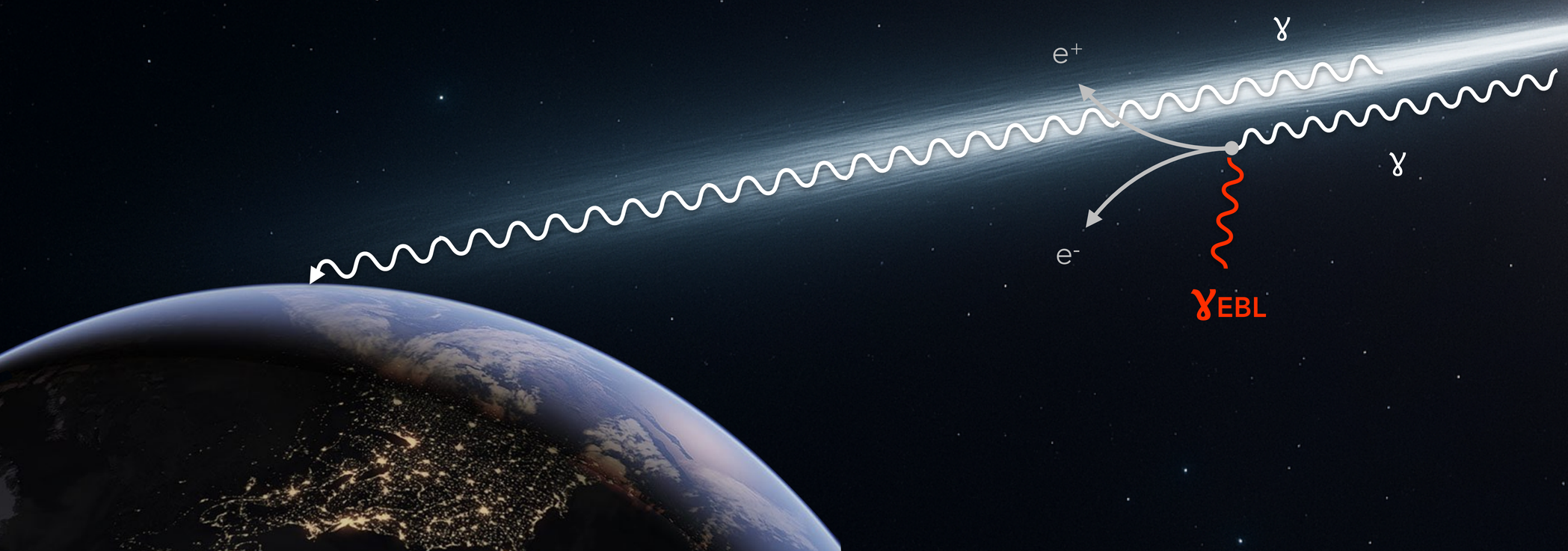


Absorption of VHE gamma rays

$$F_{\mathrm{obs}} = F_{\mathrm{int}} \exp\left(-\tau_{\gamma\gamma}(E, z) \right)$$



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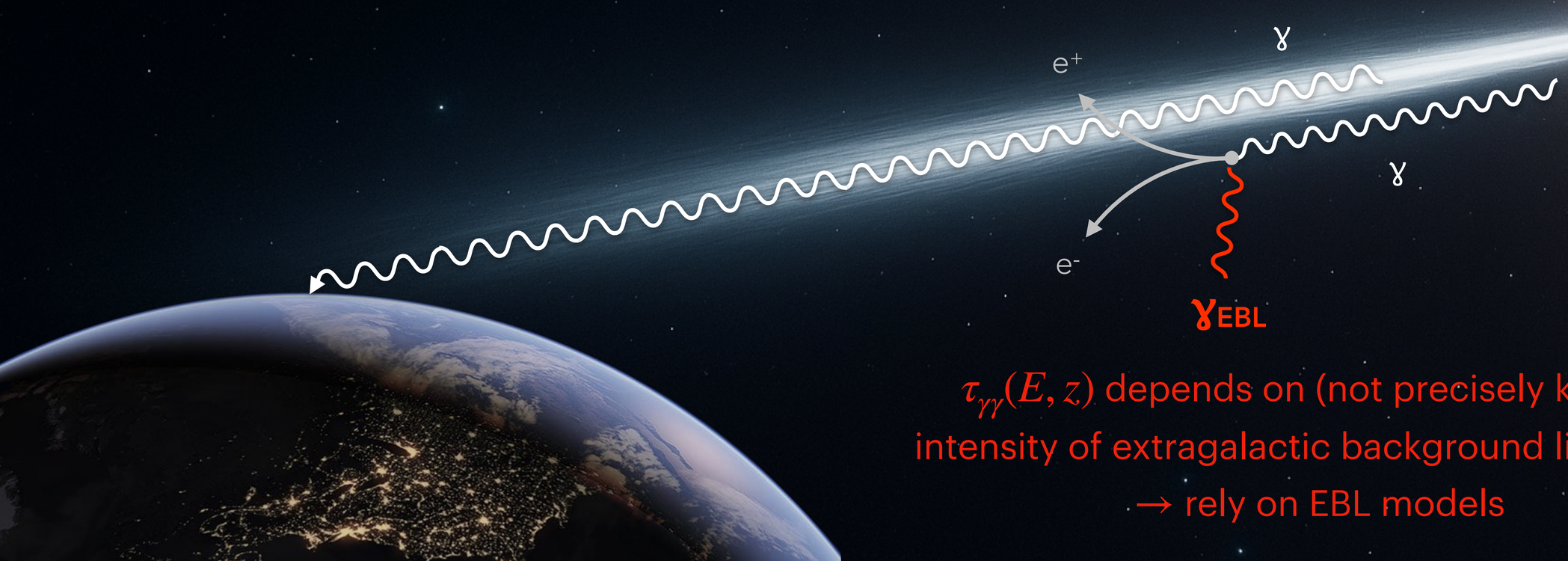
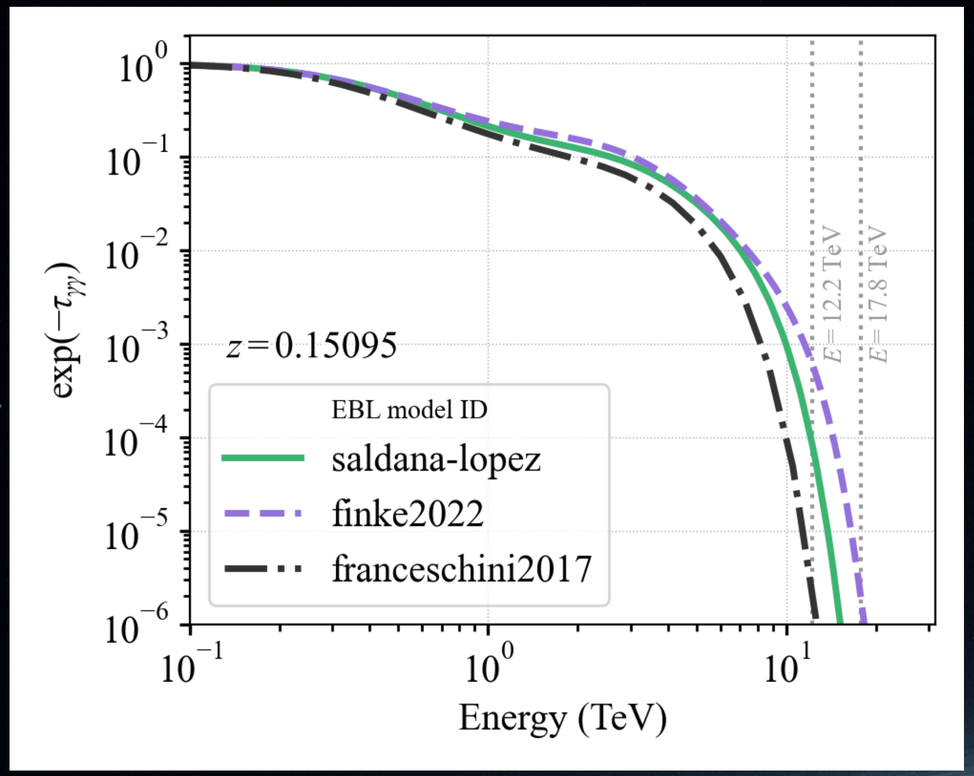


$\tau_{\gamma\gamma}(E, z)$ depends on (not precisely known)
intensity of extragalactic background light (EBL)
→ rely on EBL models

Absorption of VHE gamma rays

Transmission for selection of recent EBL models



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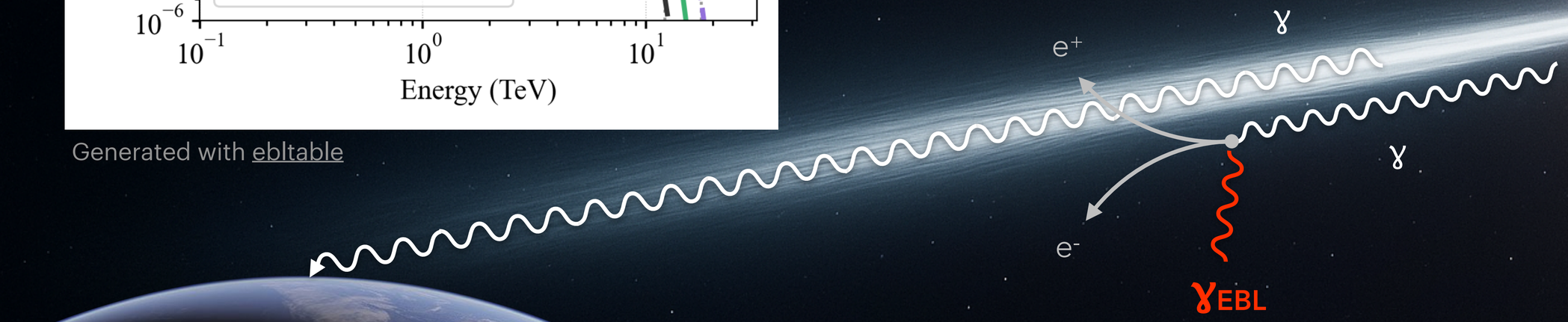

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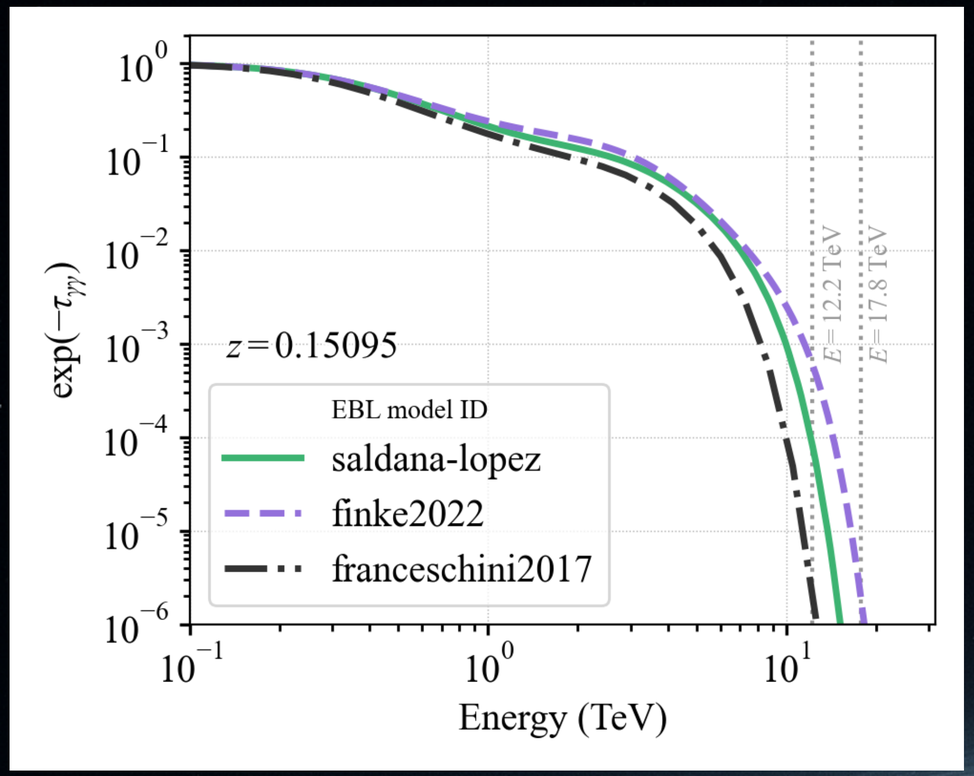
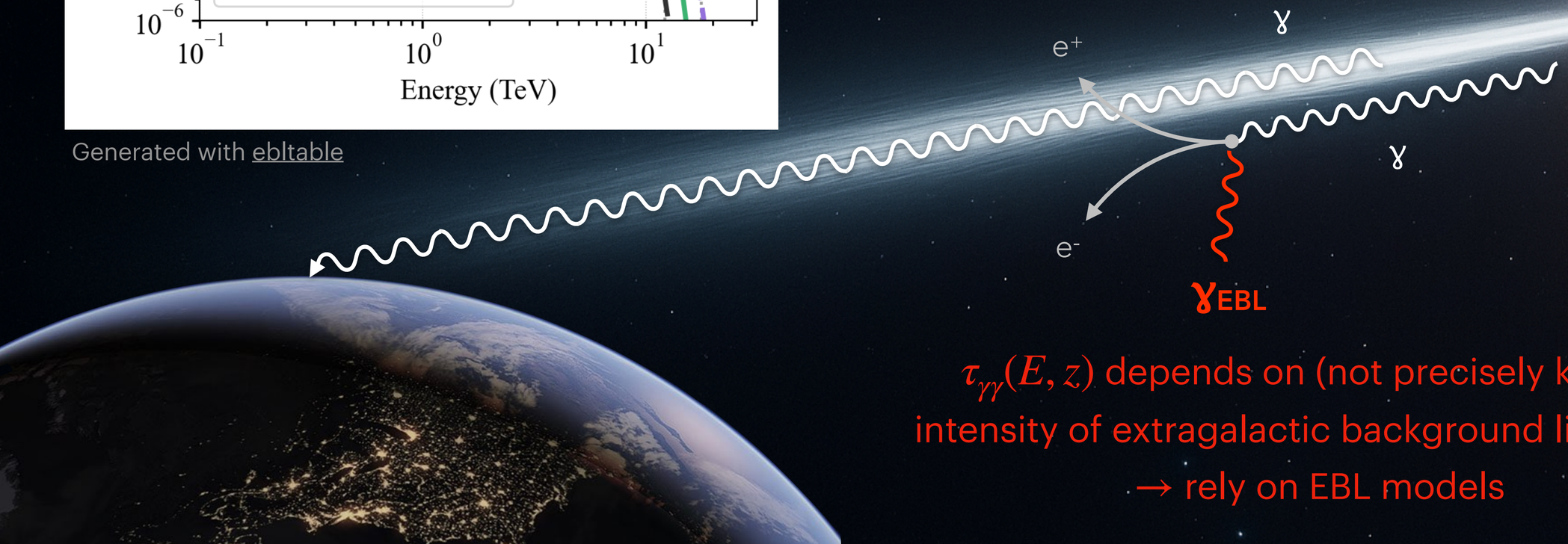


Generated with ebltable

Depending on energy and EBL model:

$$8 \times 10^{-13} \lesssim e^{-\tau_{\gamma\gamma}} \lesssim 6 \times 10^{-4}$$

$$F_{\mathrm{obs}} = F_{\mathrm{int}} \exp\left(-\tau_{\gamma\gamma}(E, z)\right)$$



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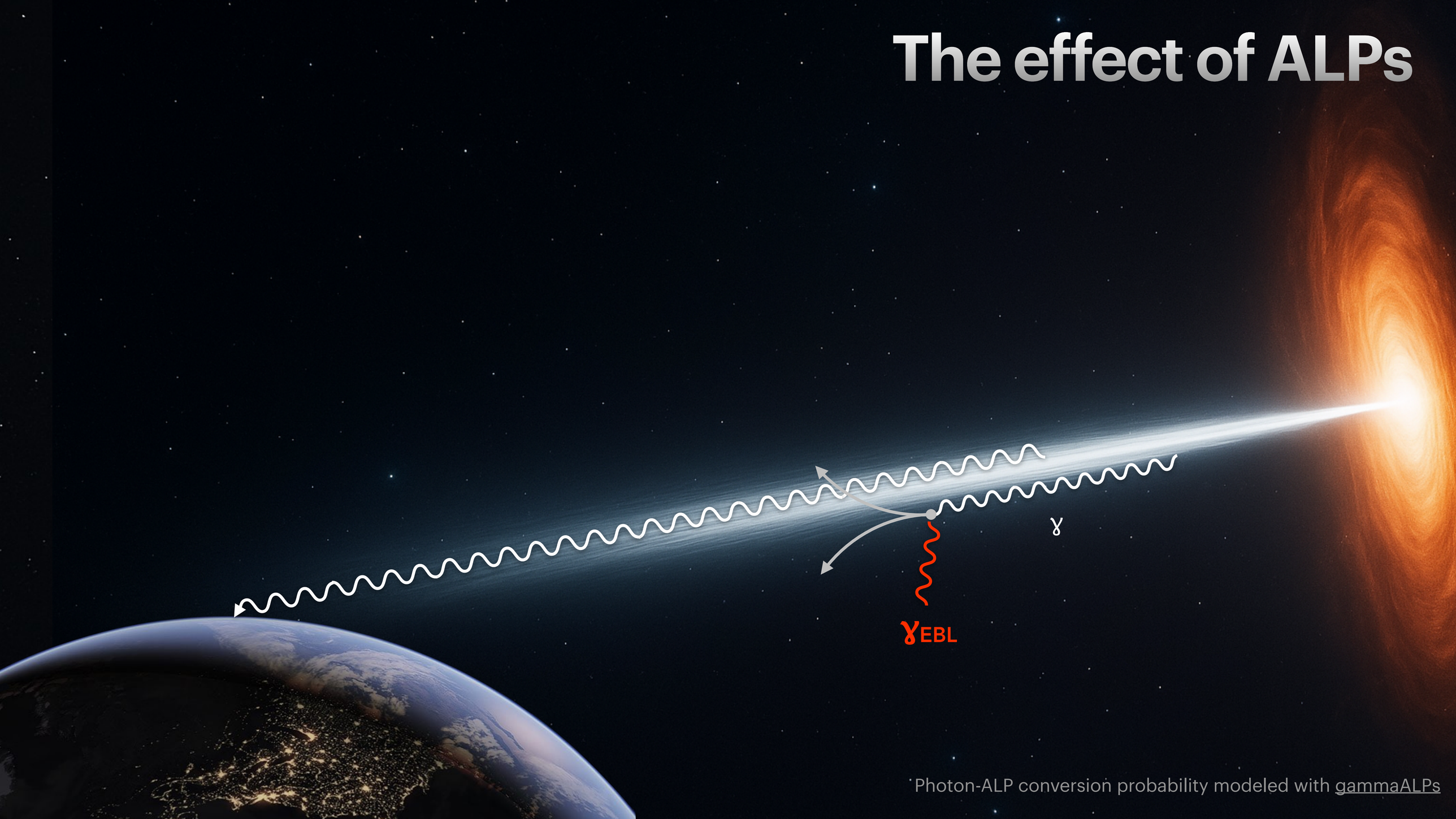
The effect of ALPs



* Photon-ALP conversion probability modeled with gammaALPs

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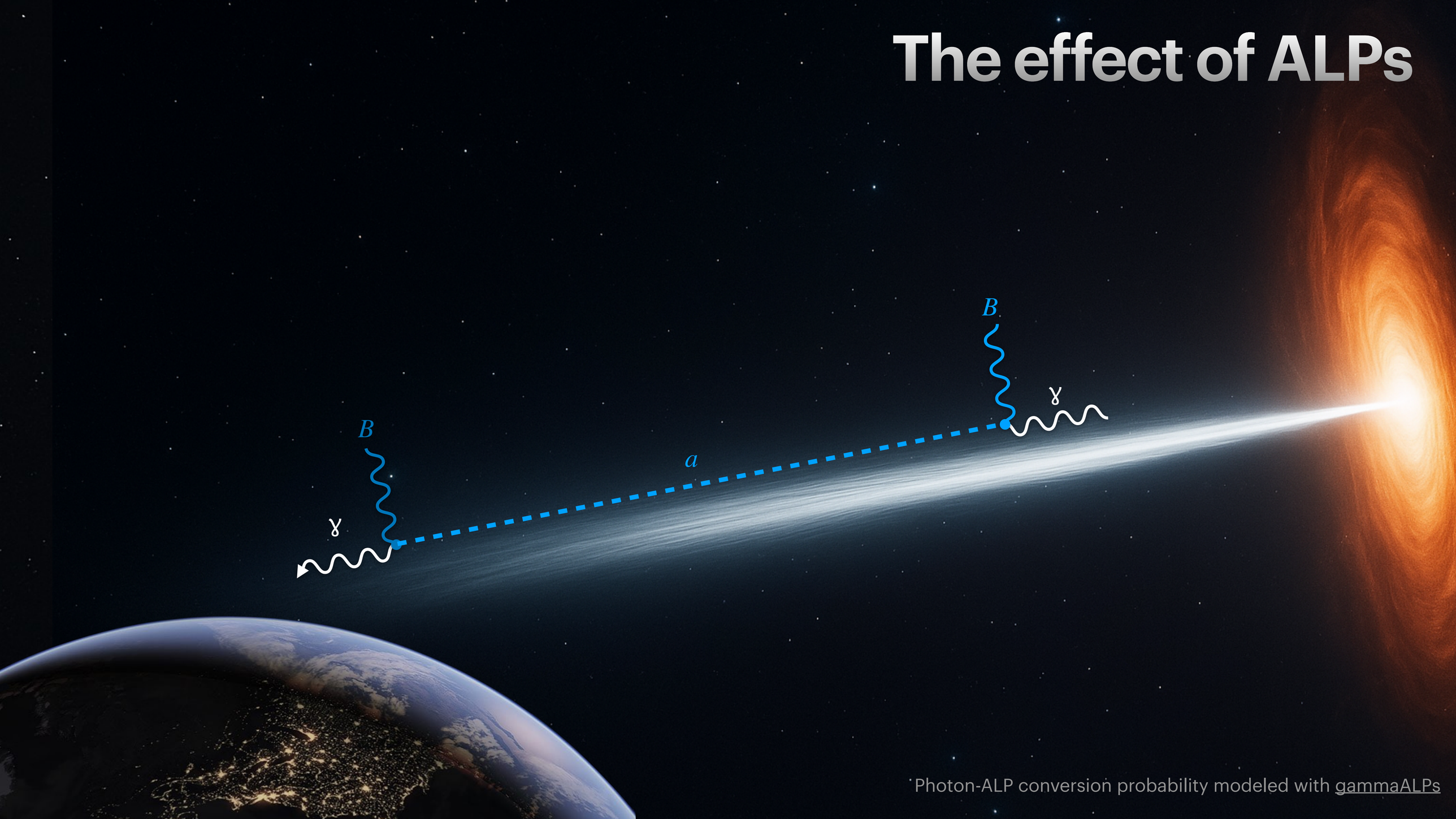

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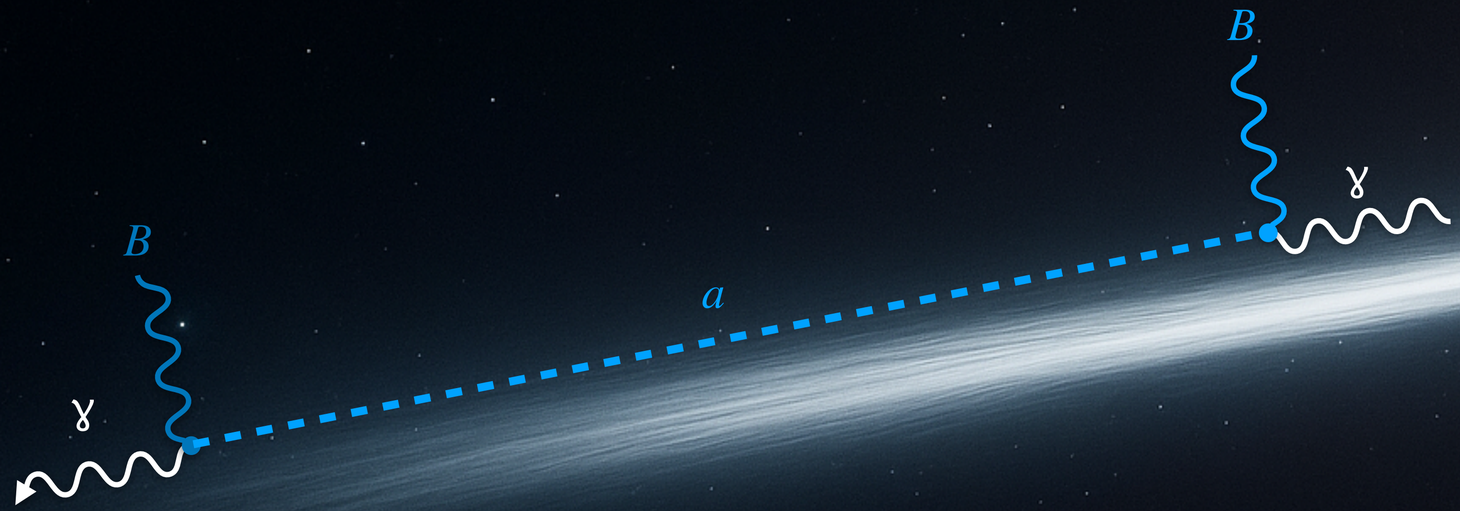
The effect of ALPs

ALP production in B field of host galaxy

(Inside GRB, photon-ALP conversion negligible,
see, e.g., Baktash, Horns, MM (2022), Galanti et al. (2023))



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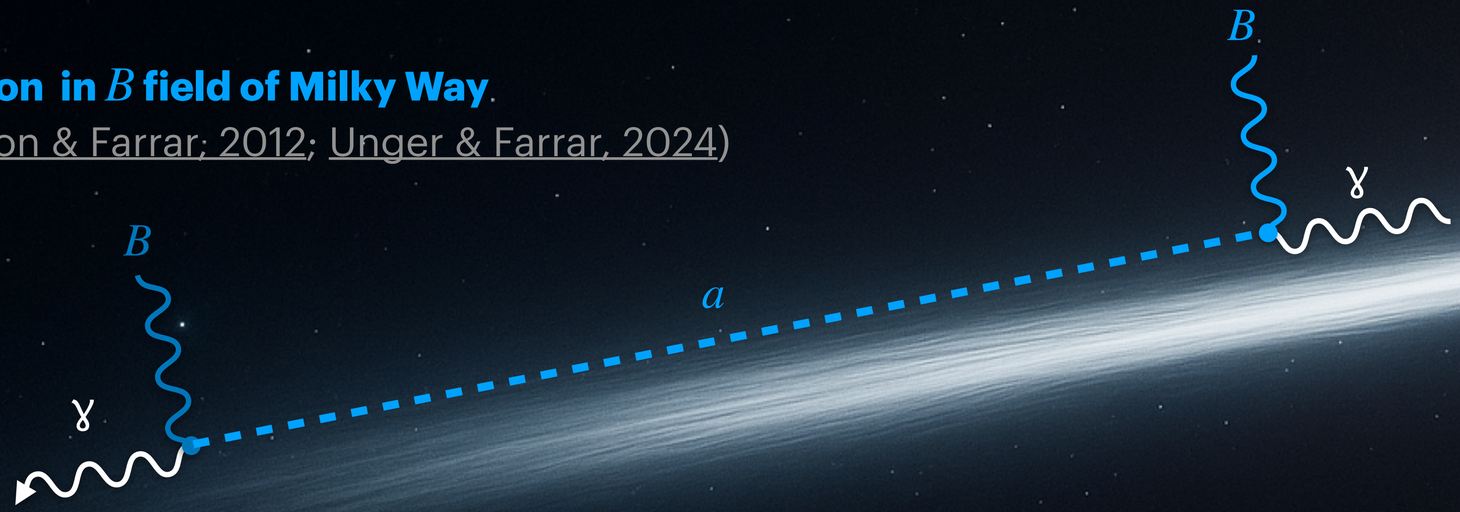
Reconversion in B field of Milky Way

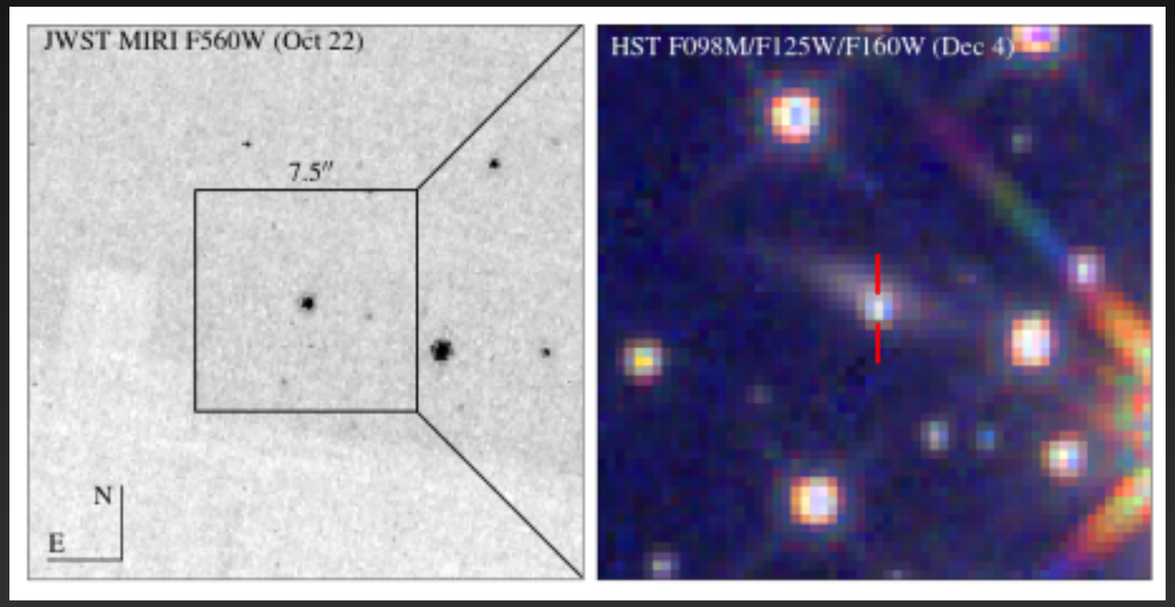
(Assumed models: Jansson & Farrar; 2012; Unger & Farrar, 2024)



* Photon-ALP conversion probability modeled with gammaALPs

What do we know about the host galaxy of GRB221009A?

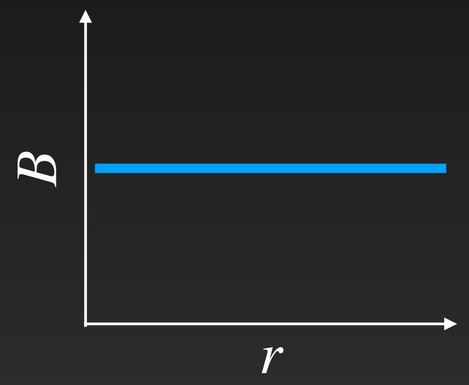
- Observed with JWST and HST
- Appears to be disc galaxy
- Observed edge-on
- Half-light radius $R_e = (2.45 \pm 0.20)$kpc
- GRB (projected) offset from center by 0.65 kpc
- Mass $\log(M/M_\odot) = 9.00^{+0.23}_{-0.47}$



Levan et al. (2023), 2302.07761

Modeling the B field of the host galaxy

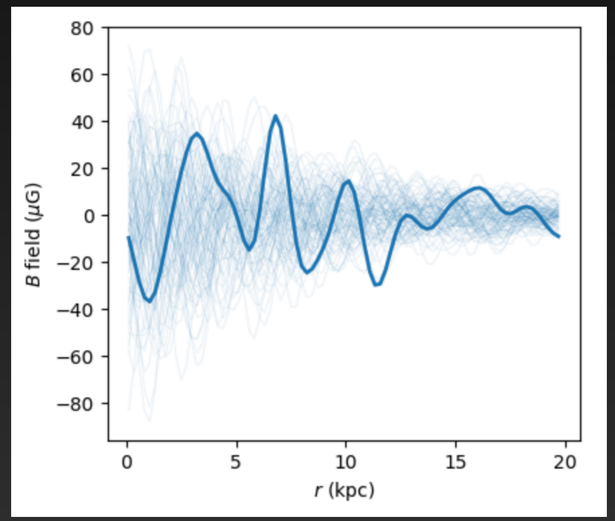
Constant B field
[e.g. LHAASO Collaboration 2023, Sci. Adv., 9, 46]



$B_0 = 5\mu\mathrm{G}$

$L_0 = 2R_e$

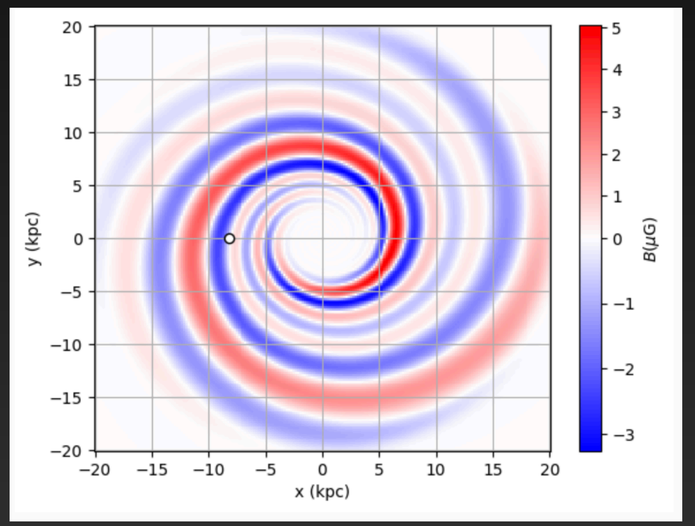
Turbulent B fields (spiral and starburst)
[Galanti et al. (2023)]



$B_0 = (20,50)\mu\mathrm{G} \times \exp(-r/r_0)$

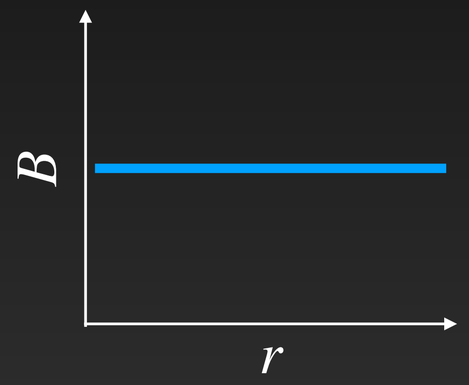
$r_0 = (15,10)\,\mathrm{kpc}$

Spiral-like galaxy
[e.g. Carenza & Marsh (2022), Troitsky (2024)]



Modeling the B field of the host galaxy

Constant B field
[e.g. LHAASO Collaboration 2023, Sci. Adv., 9, 46]



$B_0 = 5\mu\mathrm{G}$

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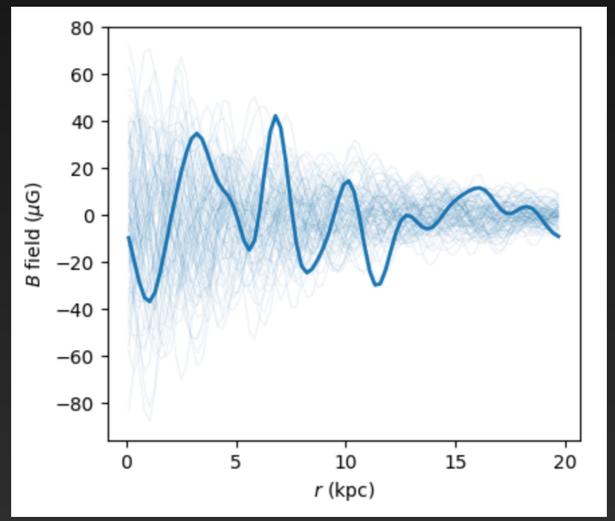
Turbulent B fields (spiral and starburst)
[Galanti et al. (2023)]



$B_0 = (20,50)\mu\mathrm{G} \times \exp(-r/r_0)$

$r_0 = (15,10)\,\mathrm{kpc}$

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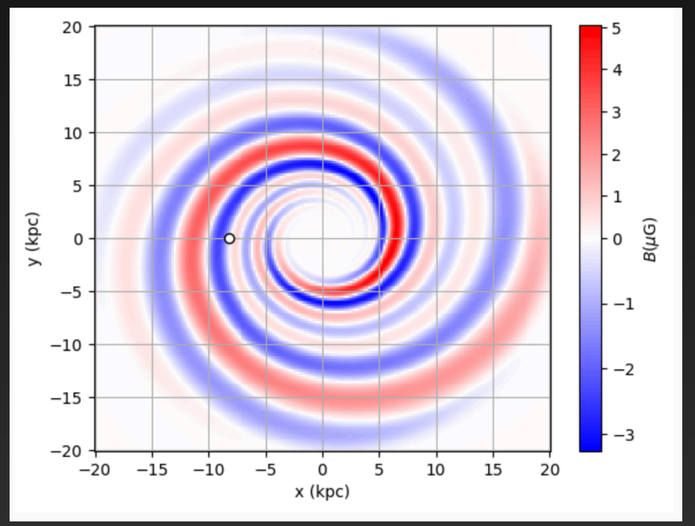

We test all 4 scenarios

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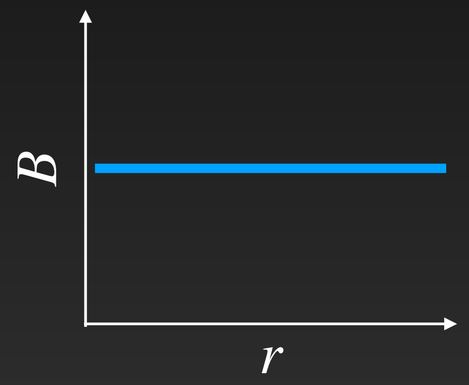

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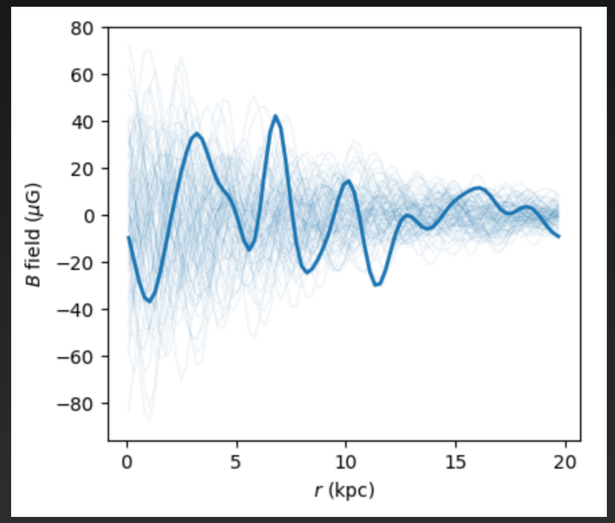

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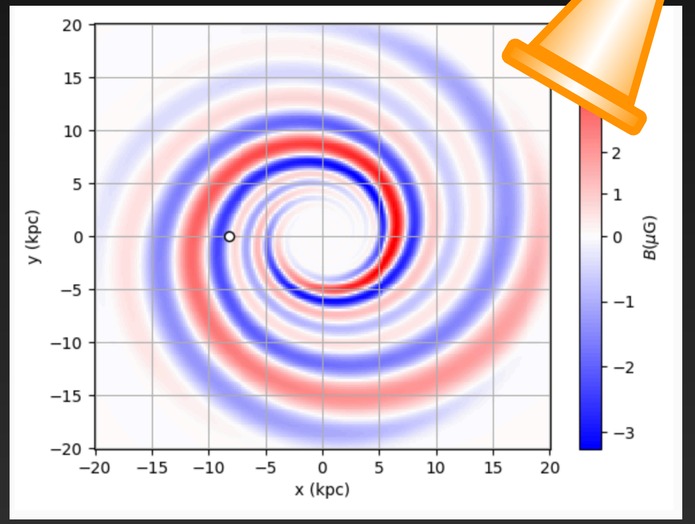
Work in progress



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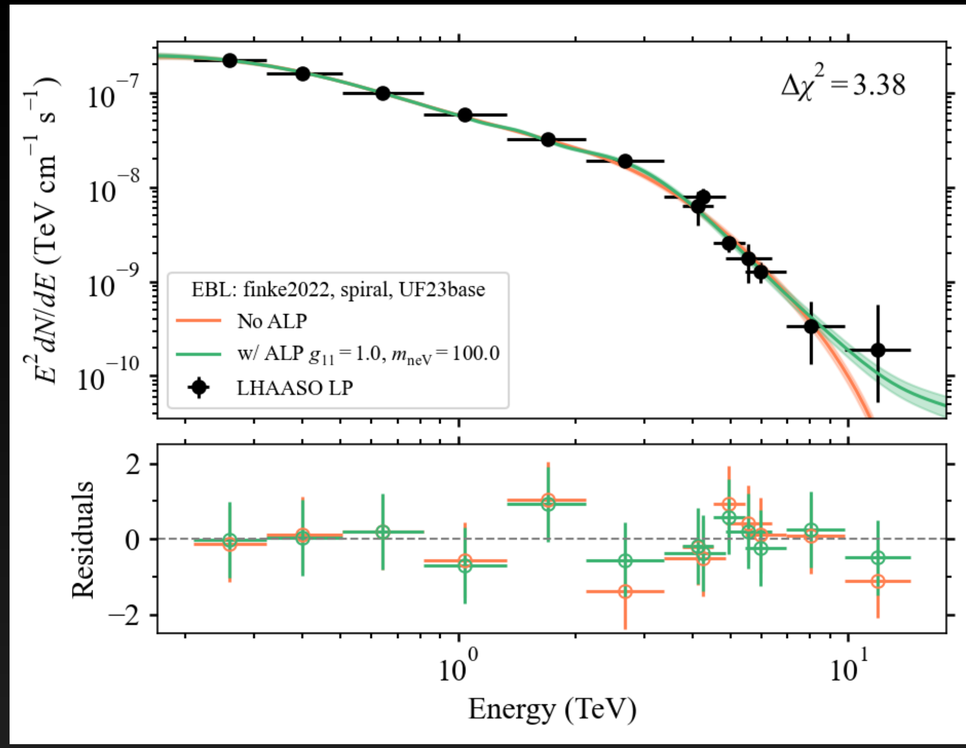
Results - General trends



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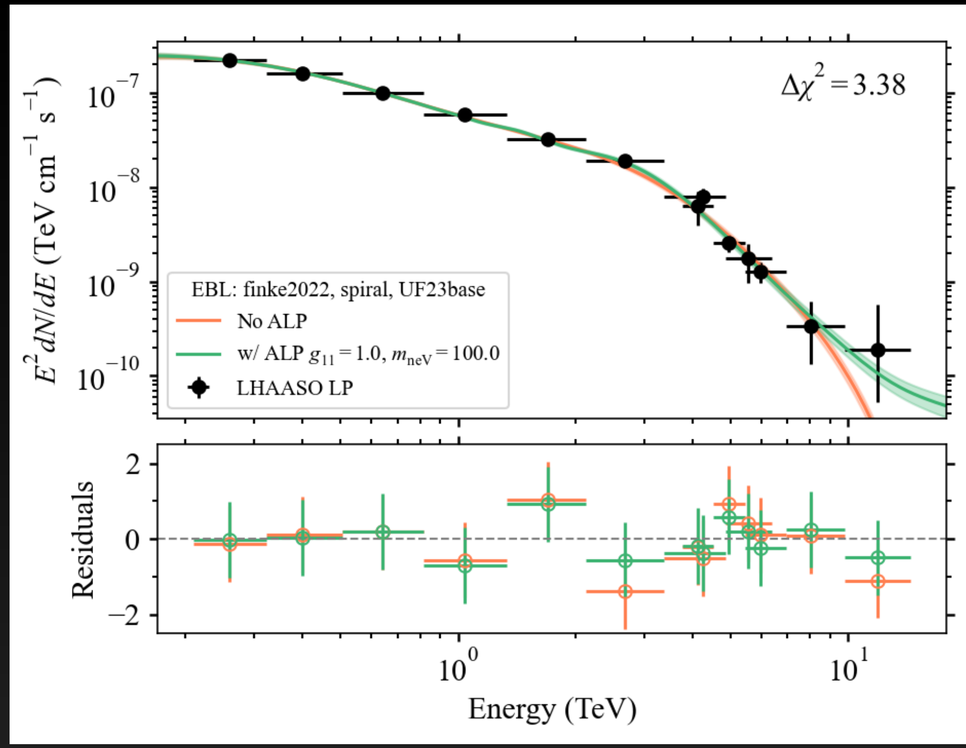

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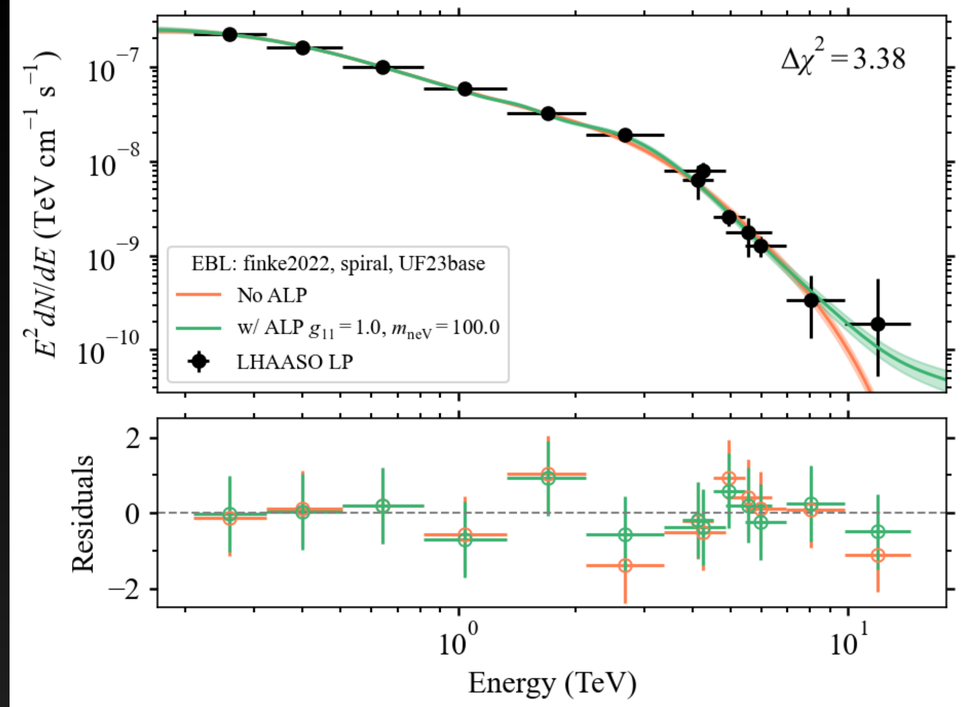

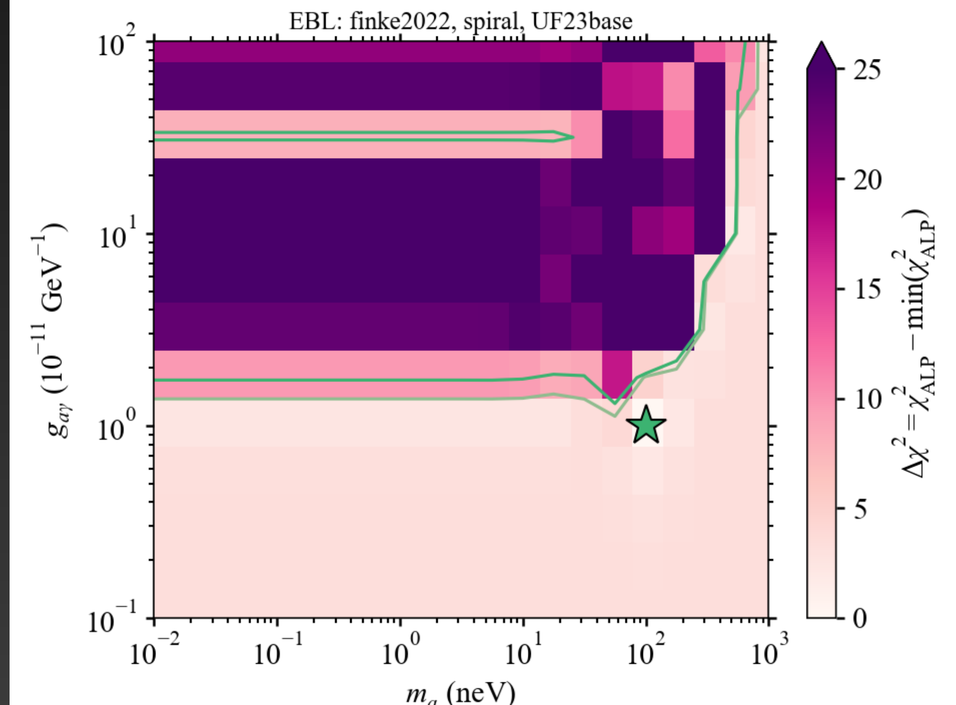

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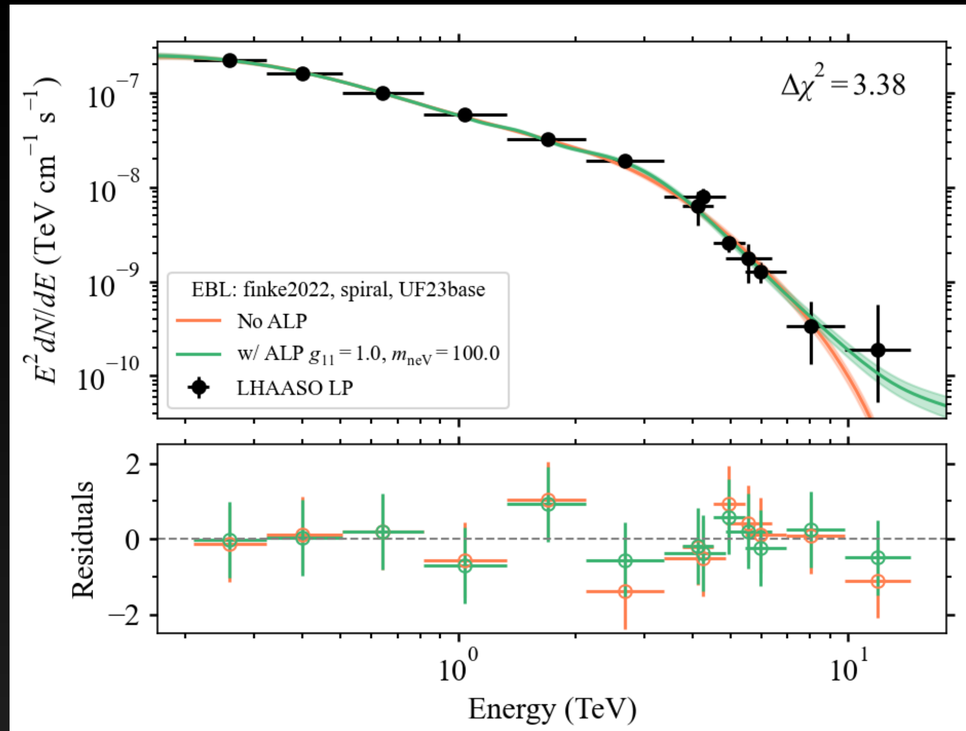

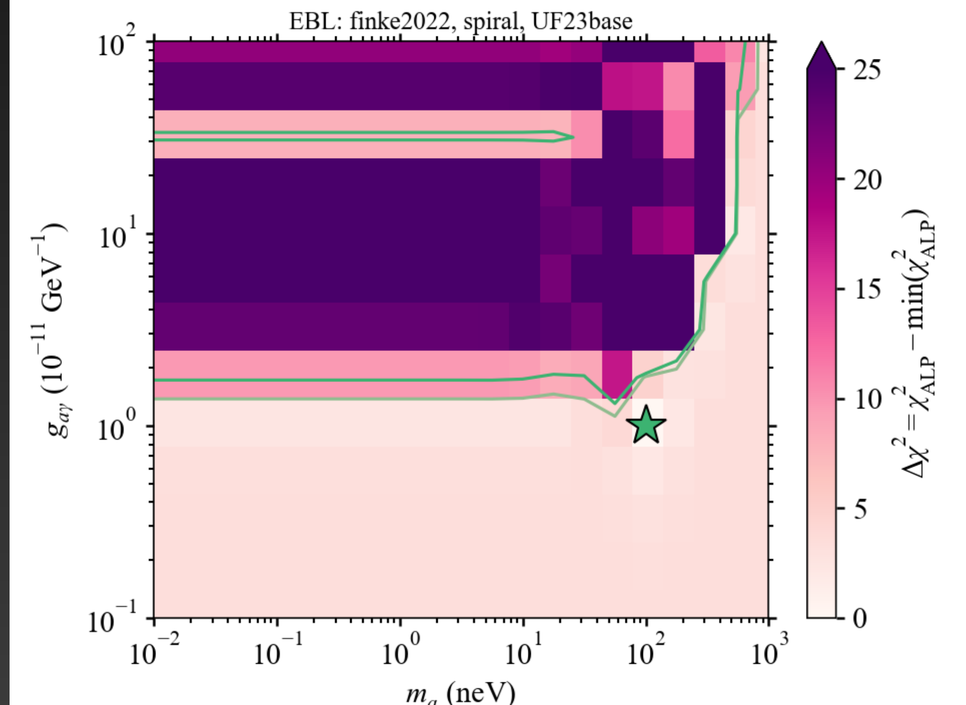

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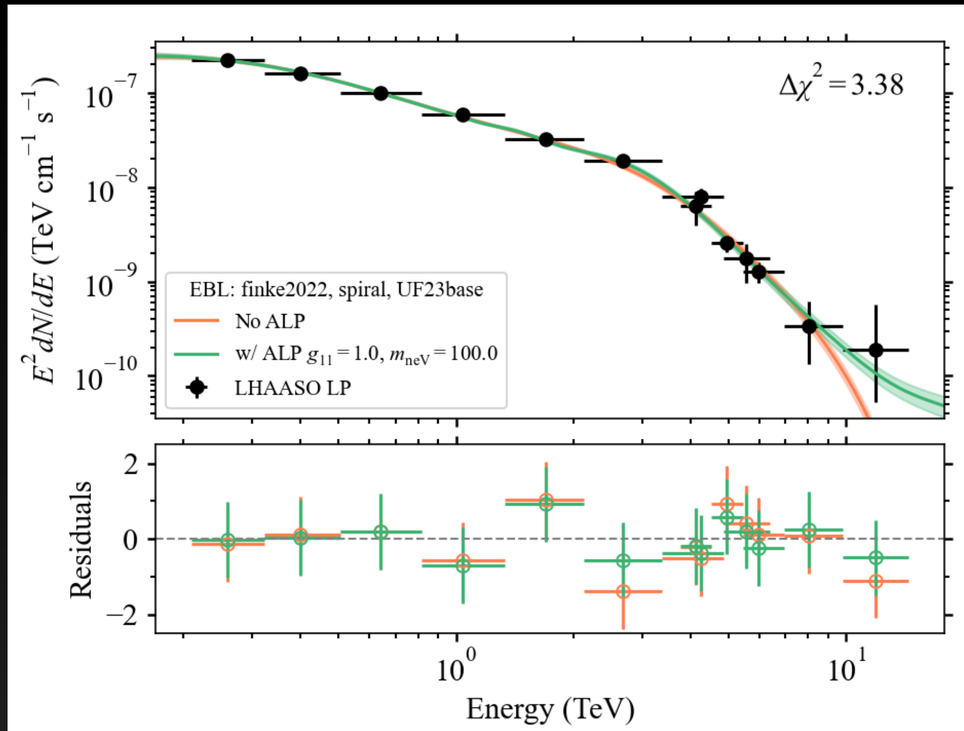

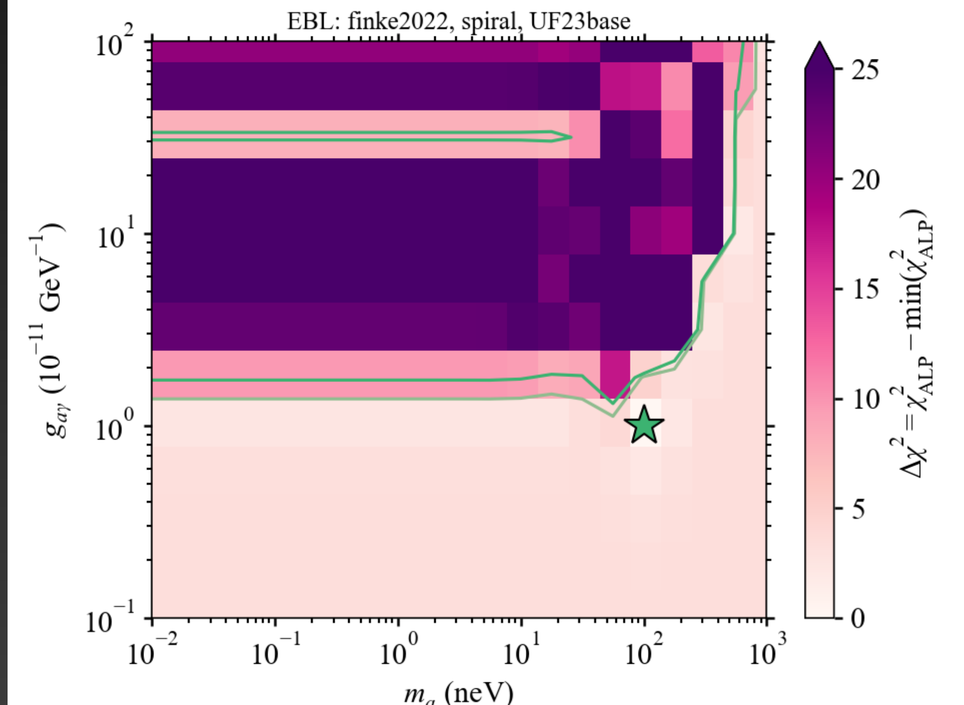

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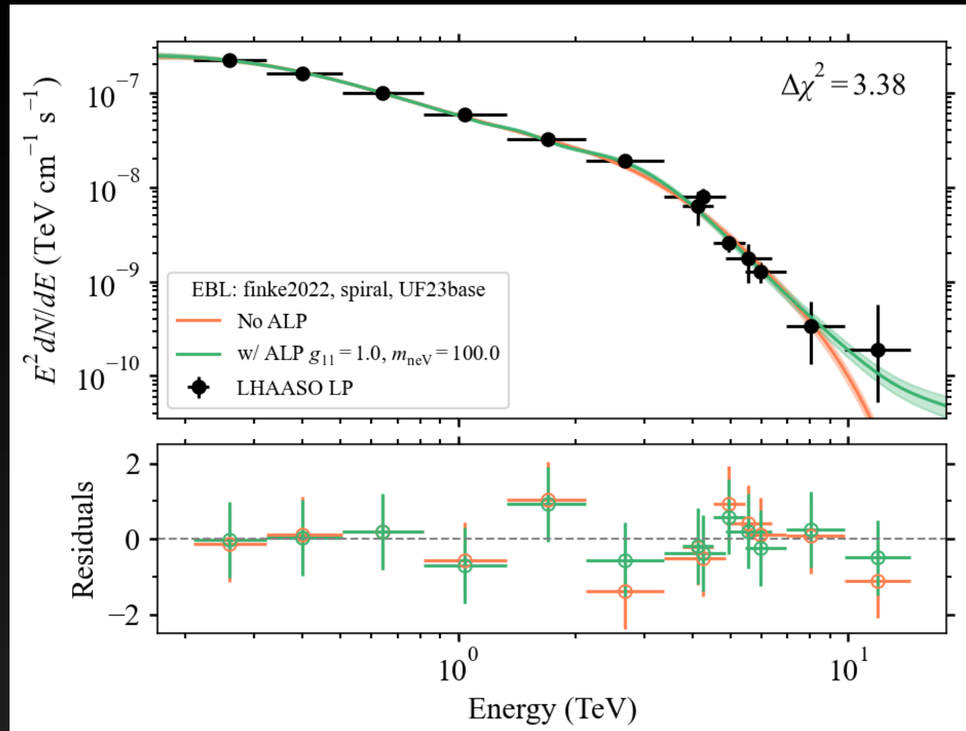
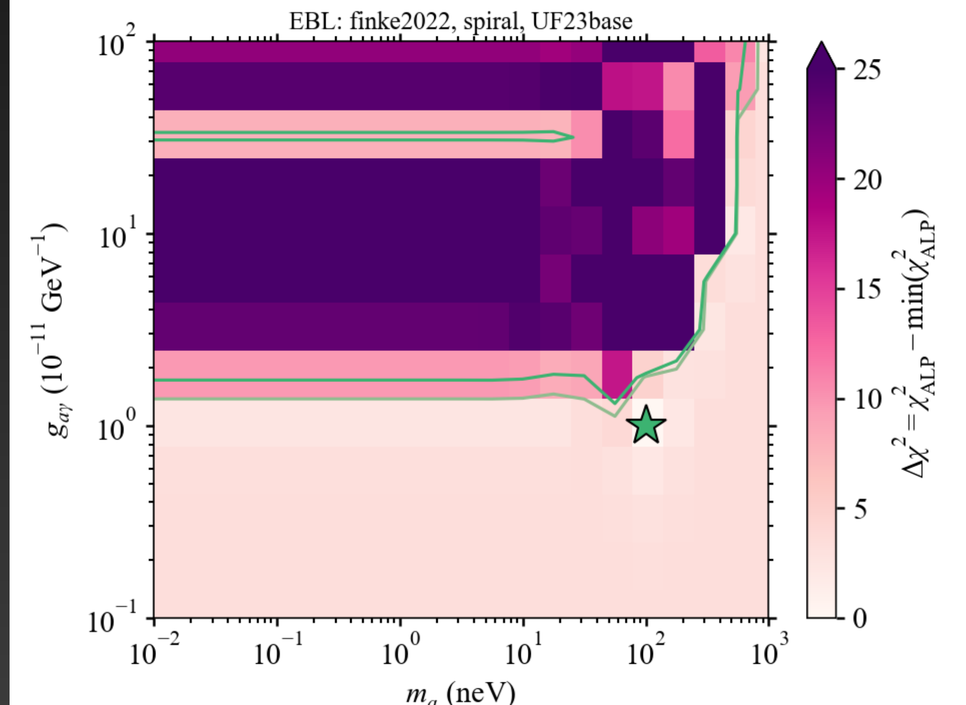
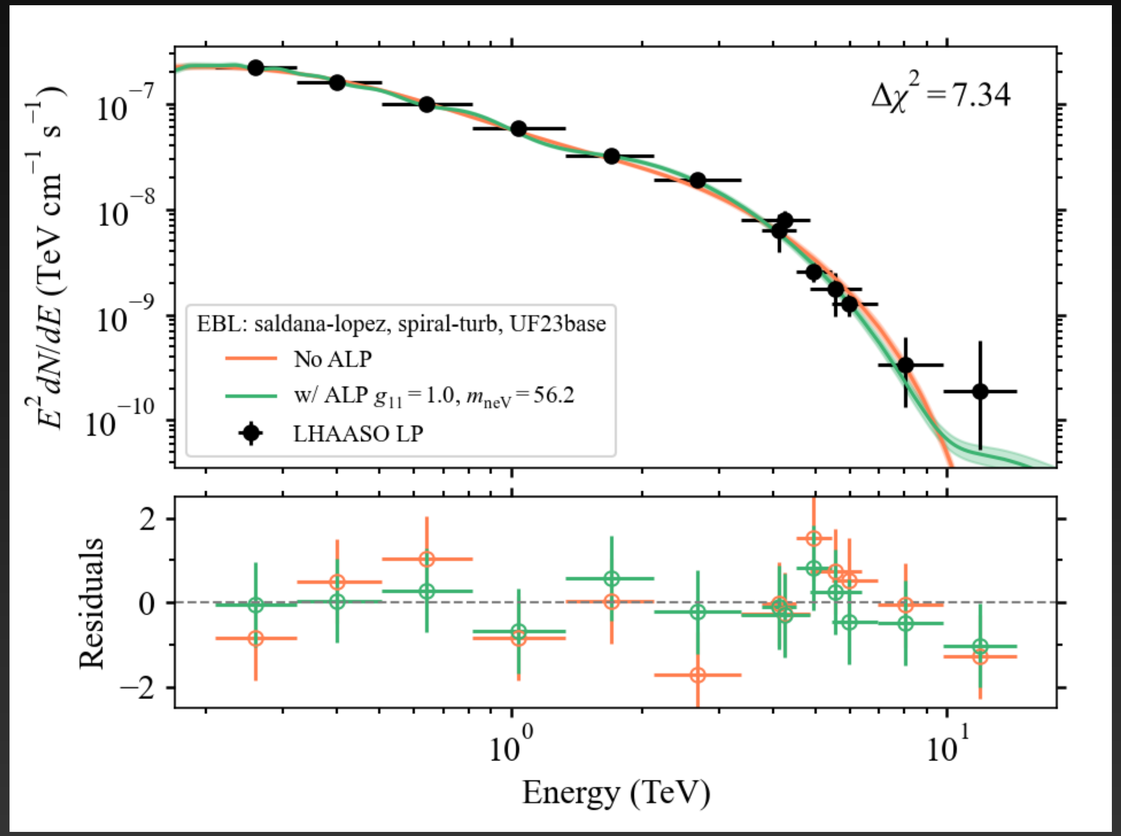




EPL data: Model combination with highest preference for ALPs

$p_{local} = 2.23\sigma$

(Not corrected for trials!)



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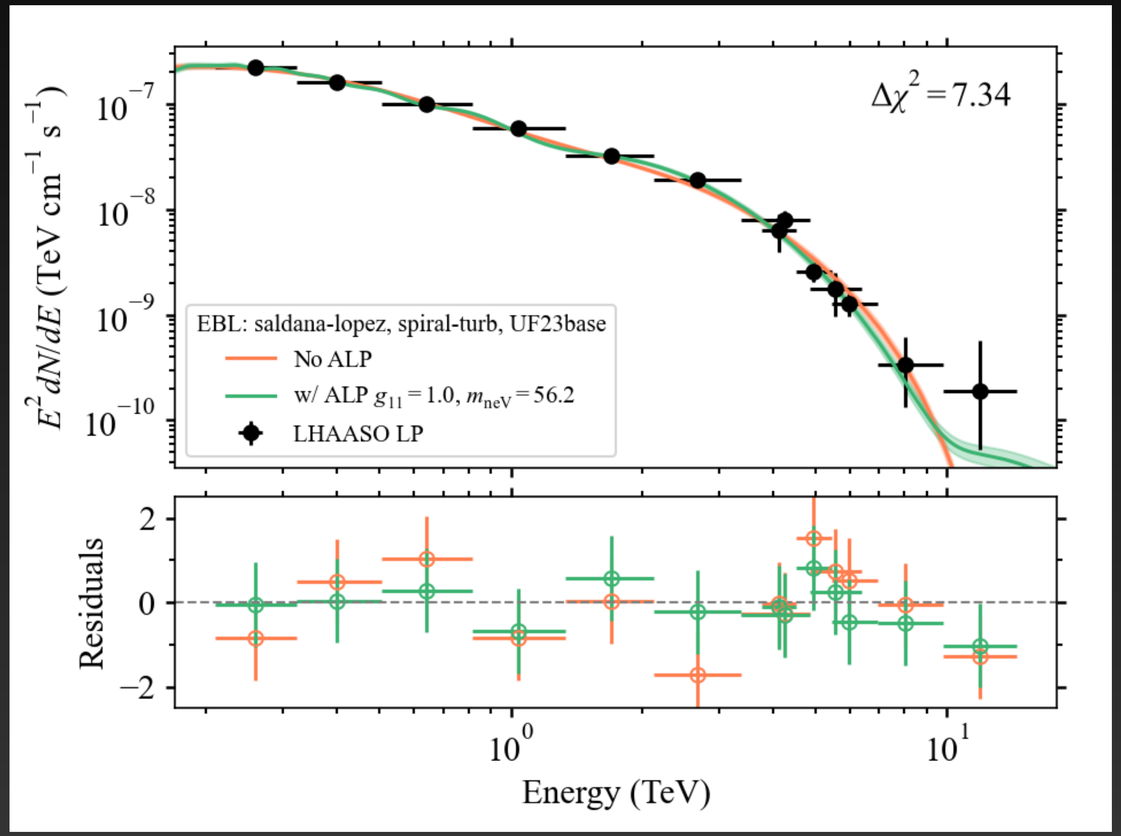

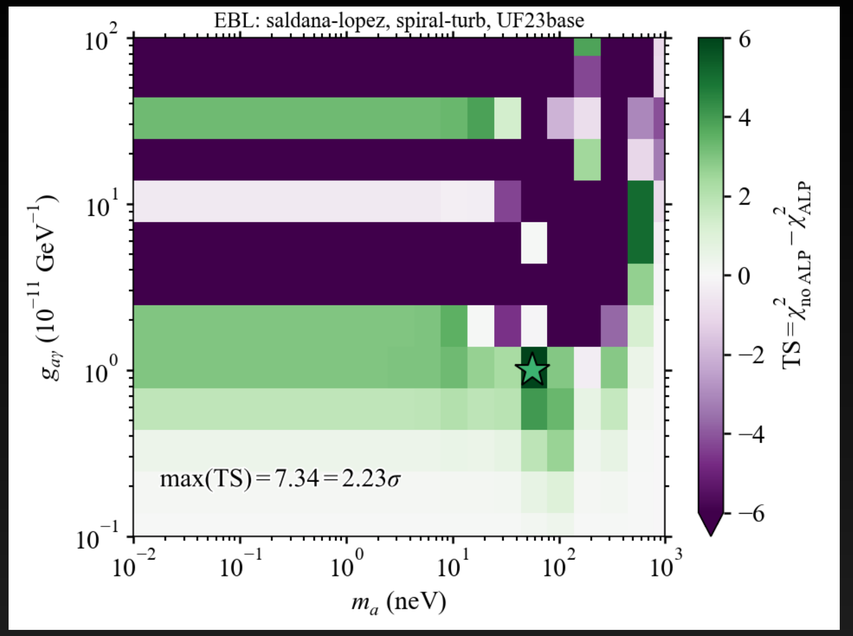

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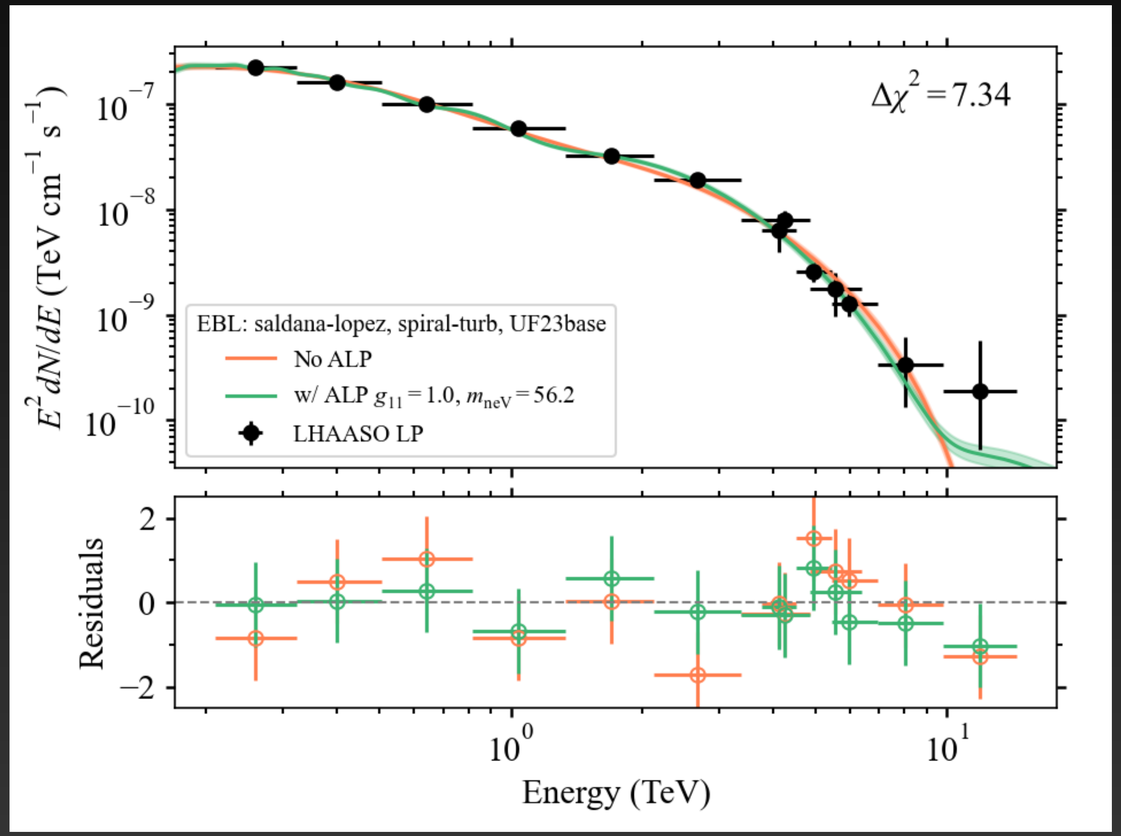

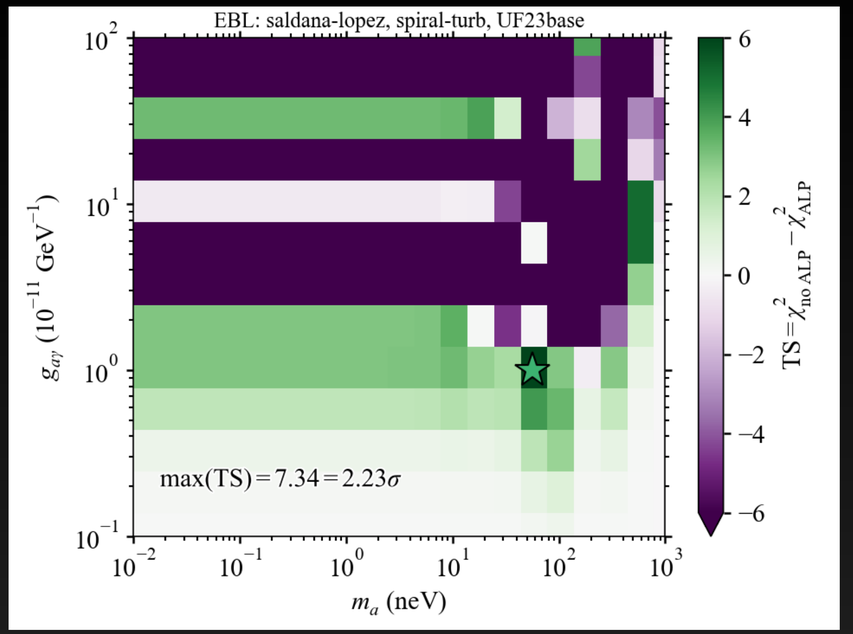

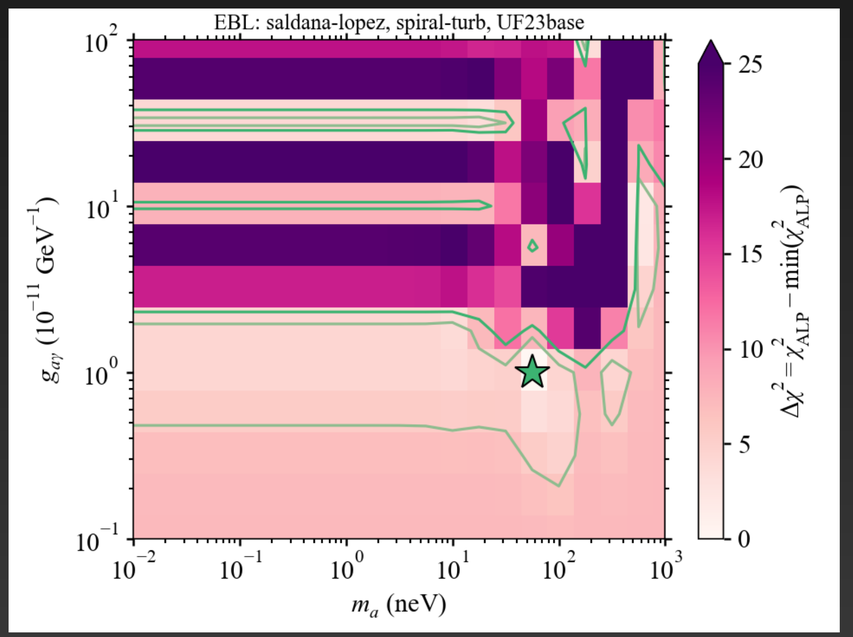

LP data: Model combination with highest preference for ALPs

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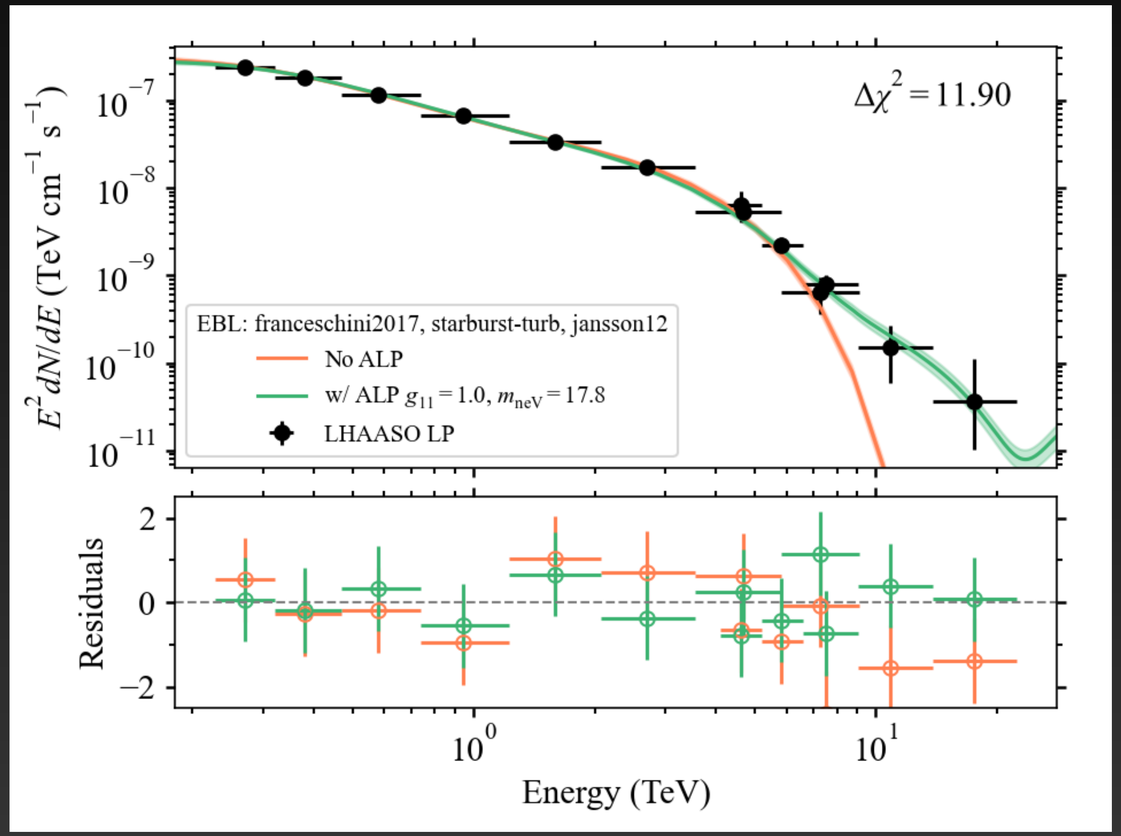
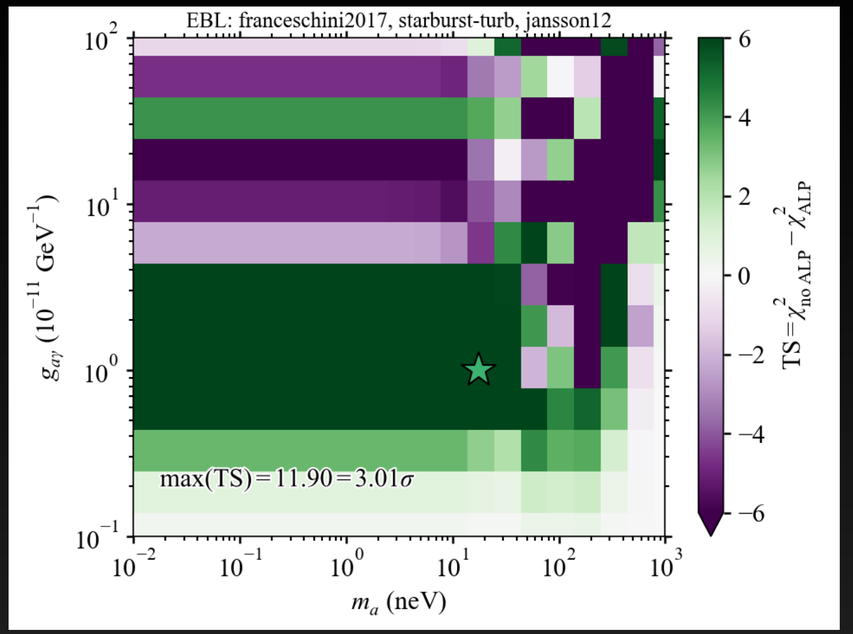
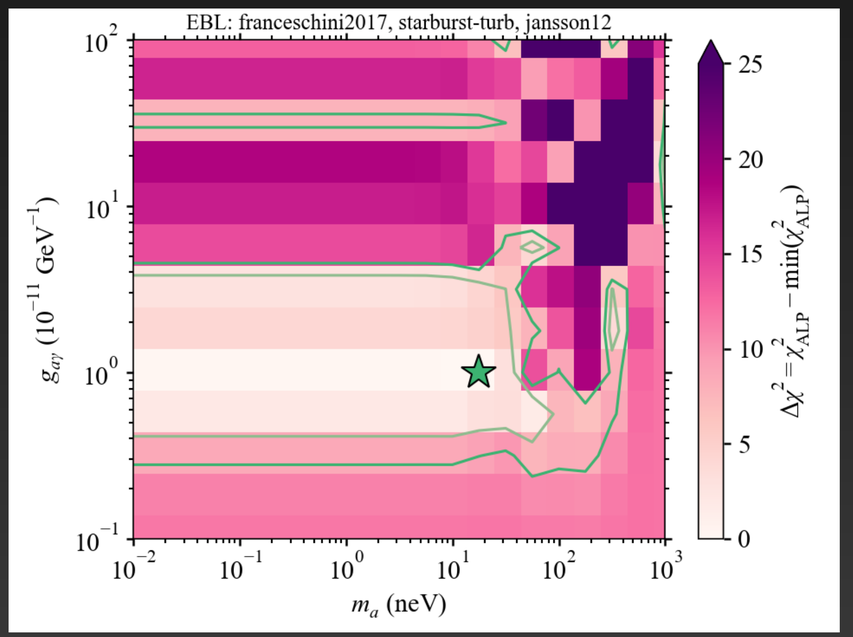
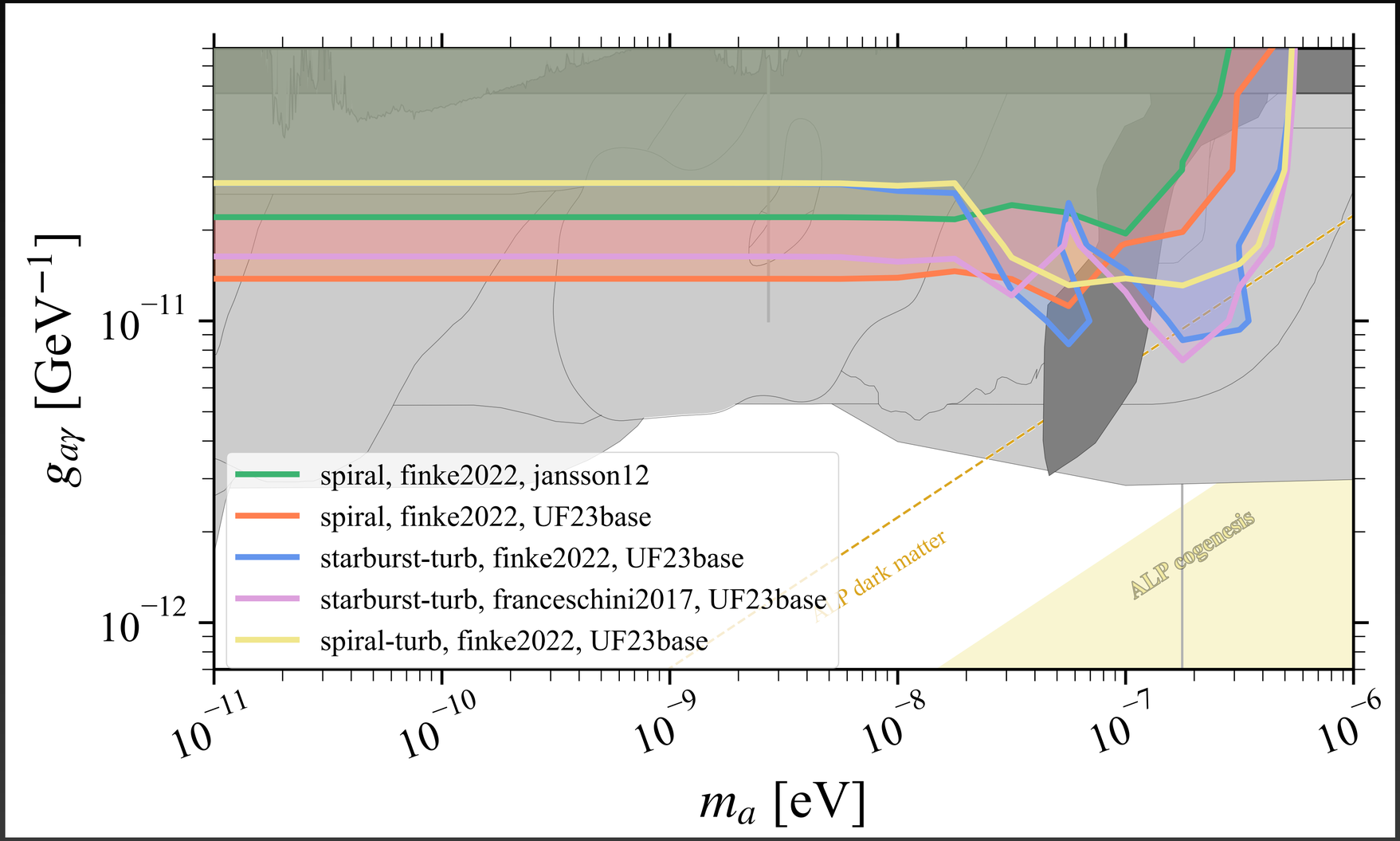






Constraints from GRB221009A in perspective

(Model combinations with $p_{local} < 2\sigma$)



10.5281/zenodo.3932430

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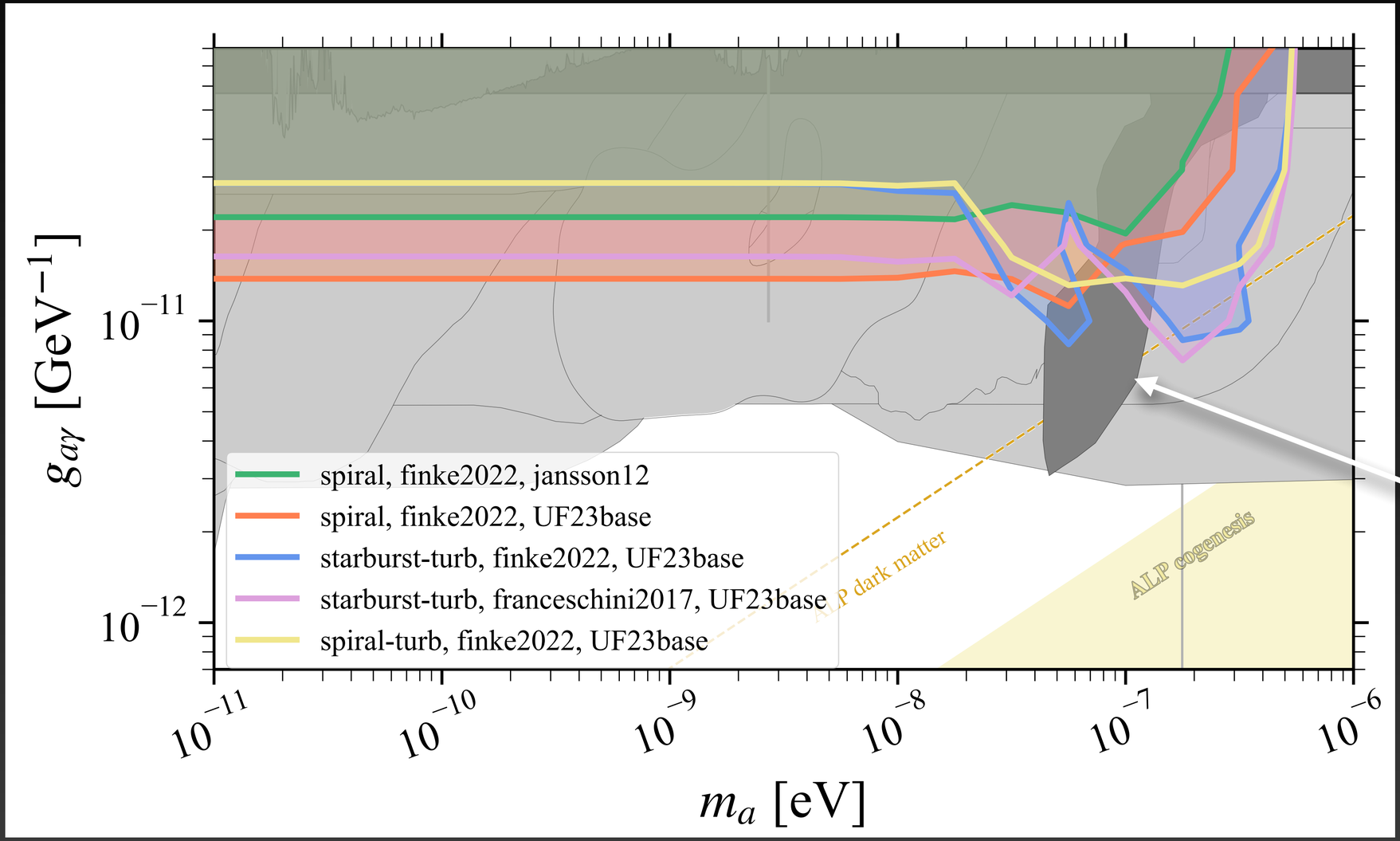

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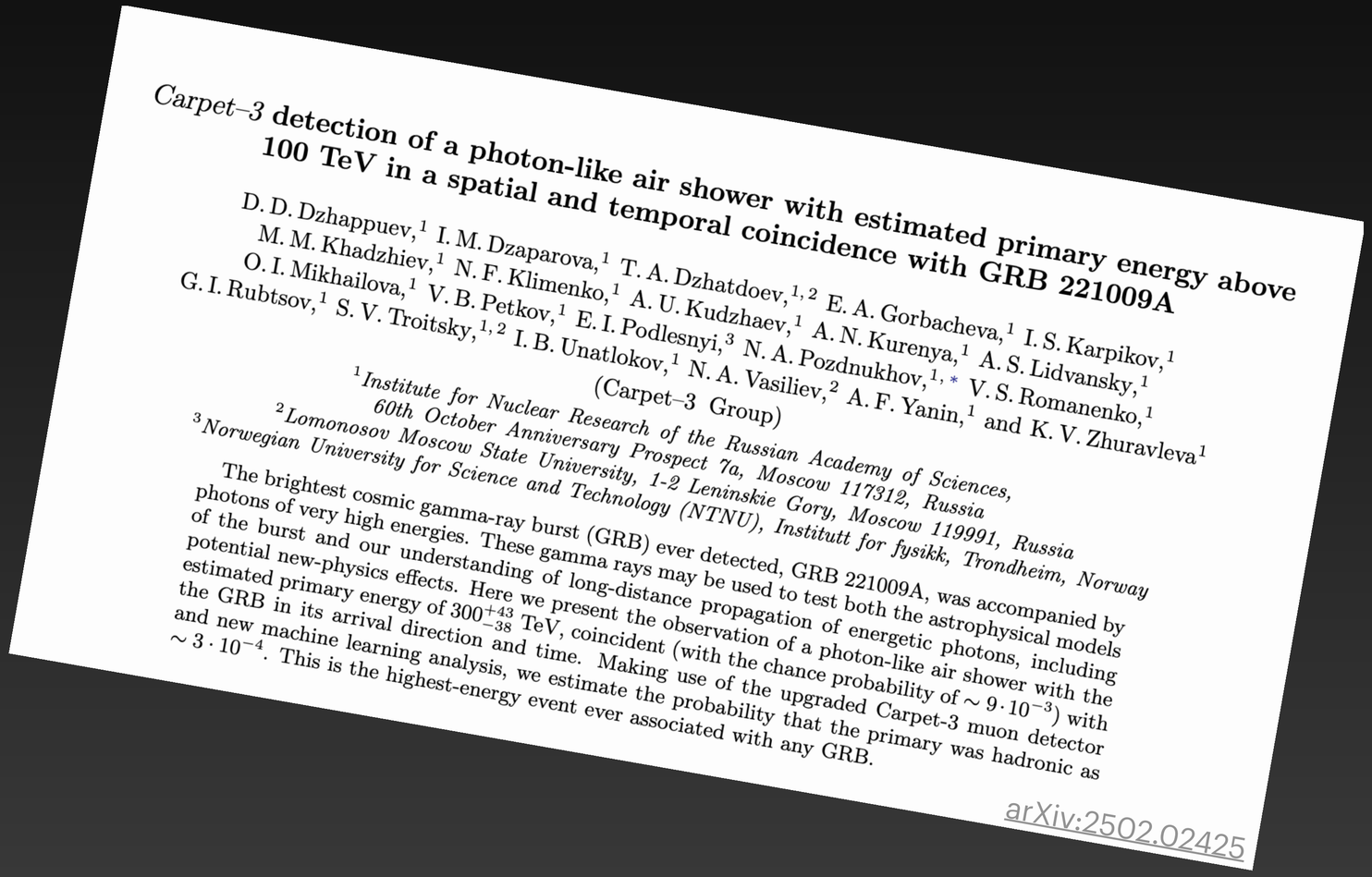
More surprises…?

- Potential detection of photon with 300 TeV in spatial and temporal coincidence with GRB
- Detection with Carpet Air shower array
- If indeed photon from GRB, photon-ALP conversion would not suffice as explanation
- Lorentz invariance violation?



Carpet–3 **detection of a photon-like air shower with estimated primary energy above 100 TeV in a spatial and temporal coincidence with GRB 221009A**

D. D. Dzhappuev,[1] I. M. Dzaparova,[1] T. A. Dzhatdoev,[1,2] E. A. Gorbacheva,[1] I. S. Karpikov,[1] M. M. Khadzhiev,[1] N. F. Klimenko,[1] A. U. Kudzhaev,[1] A. N. Kurenya,[1] A. S. Lidvansky,[1] O. I. Mikhailova,[1] V. B. Petkov,[1] E. I. Podlesnyi,[3] N. A. Pozdnukhov,[1,*] V. S. Romanenko,[1] G. I. Rubtsov,[1] S. V. Troitsky,[1,2] I. B. Unatlokov,[1] N. A. Vasiliev,[2] A. F. Yanin,[1] and K. V. Zhuravleva[1]

(Carpet–3 Group)

[1]*Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, Moscow 117312, Russia*

[2]*Lomonosov Moscow State University, 1-2 Leninskie Gory, Moscow 119991, Russia*

[3]*Norwegian University for Science and Technology (NTNU), Institutt for fysikk, Trondheim, Norway*

The brightest cosmic gamma-ray burst (GRB) ever detected, GRB 221009A, was accompanied by photons of very high energies. These gamma rays may be used to test both the astrophysical models of the burst and our understanding of long-distance propagation of energetic photons, including potential new-physics effects. Here we present the observation of a photon-like air shower with the estimated primary energy of 300^{+43}_{-38} TeV, coincident (with the chance probability of $\sim 9 \cdot 10^{-3}$) with the GRB in its arrival direction and time. Making use of the upgraded Carpet-3 muon detector and new machine learning analysis, we estimate the probability that the primary was hadronic as $\sim 3 \cdot 10^{-4}$. This is the highest-energy event ever associated with any GRB.

arXiv:2502.02425

arXiv:2502.03453 arXiv:2508.09948

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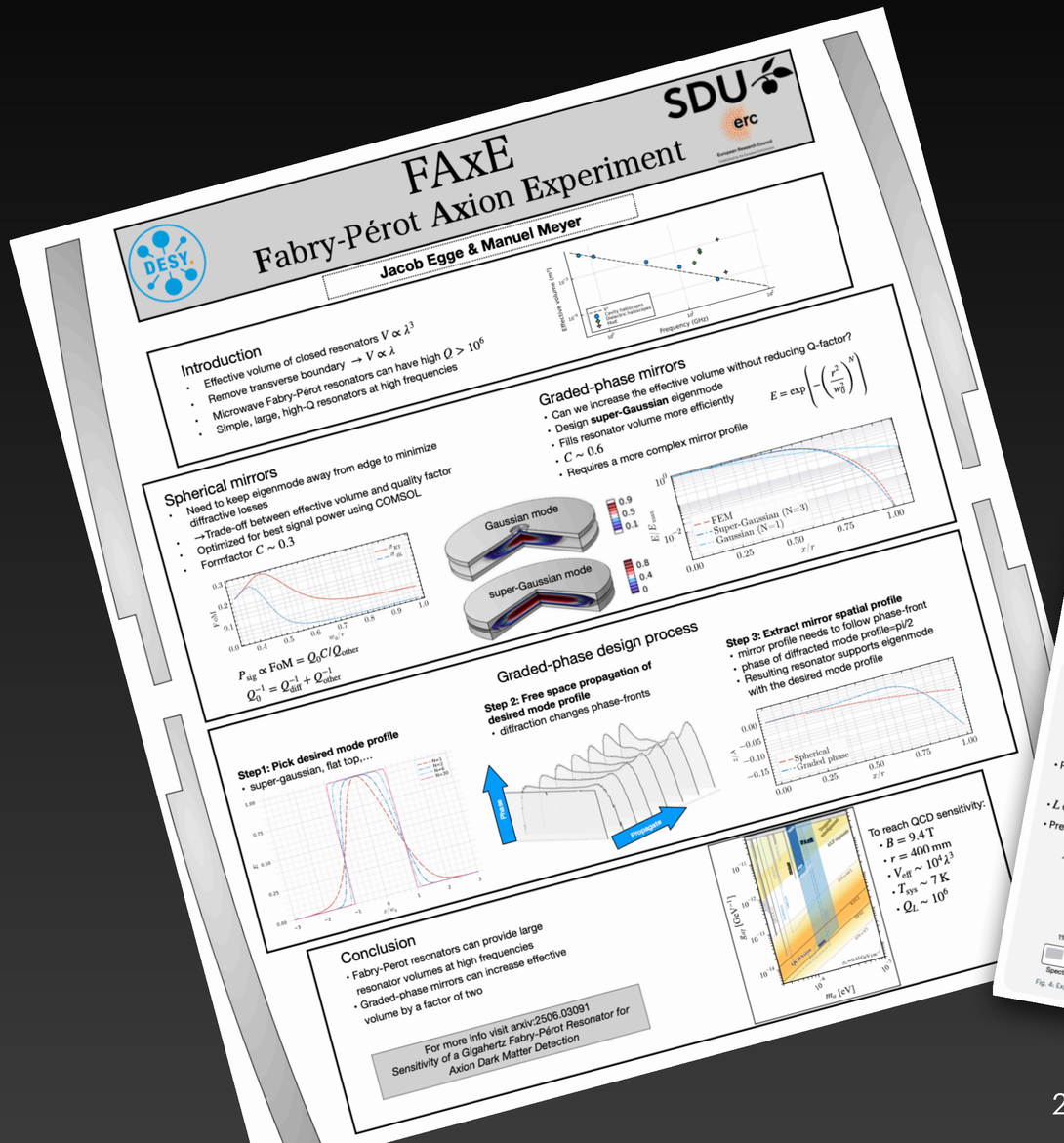
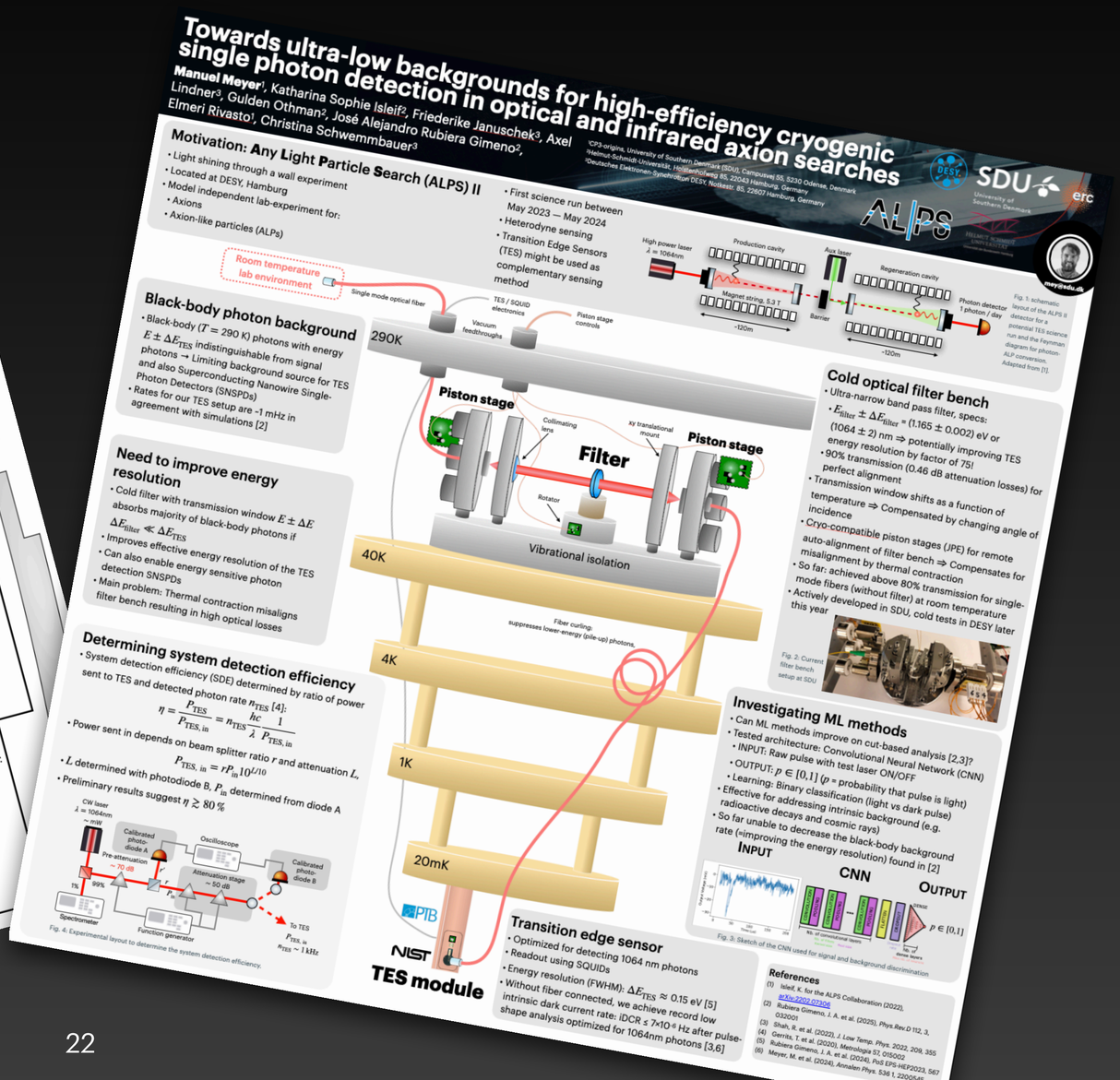
- All tested model combinations yield at most a $p_{local} \sim 3\sigma$ preference for ALPs, however, not corrected for trials

Conclusions

- GRB221009A was an exceptional event
- Allows to probe photon propagation at high optical depth
- Observations can be reconciled with EBL models with lower photon density
- Photon-ALP oscillations generally not necessary to explain observations
- All tested model combinations yield at most a $p_{local} \sim 3\sigma$ preference for ALPs, however, not corrected for trials
- Limits on photon-ALP coupling $g_{a\gamma} \gtrsim 2 \times 10^{-11}\,\mathrm{GeV}^{-1}$ (95% confidence) for $m_a \lesssim 2 \times 10^{-7}\,\mathrm{eV}$

In case you’re fed up with astrophysical uncertainties…





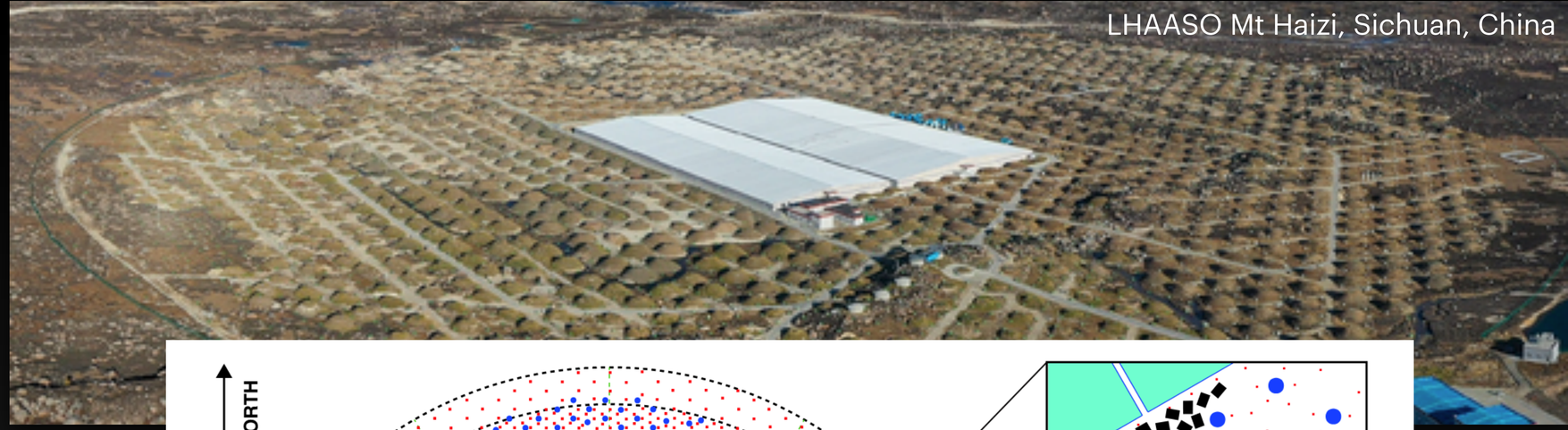
Back up

VHE photons seen with LHAASO

LHAASO Mt Haizi, Sichuan, China

[Ma et al. 2022]

VHE photons seen with LHAASO


LHAASO Mt Haizi, Sichuan, China

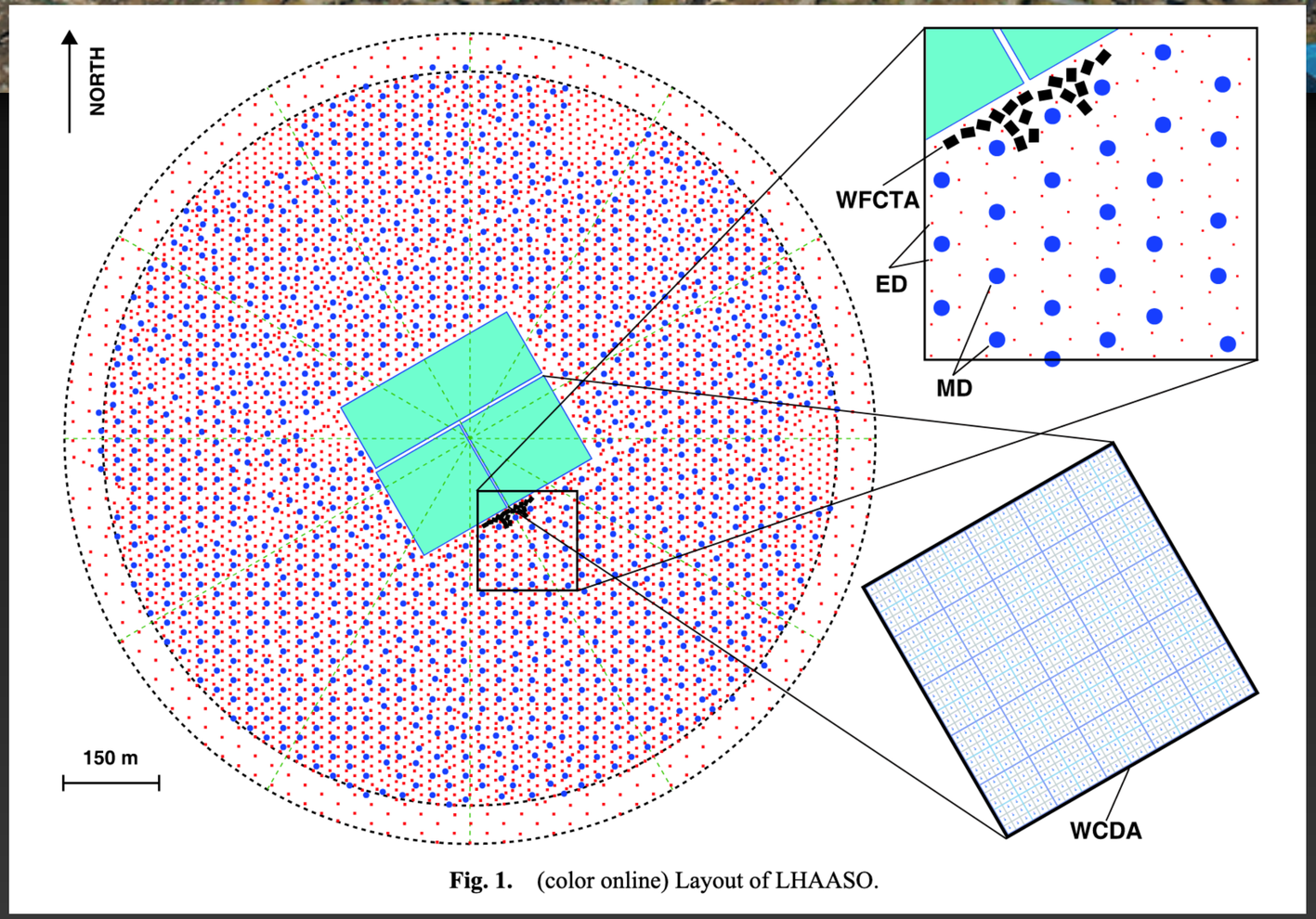
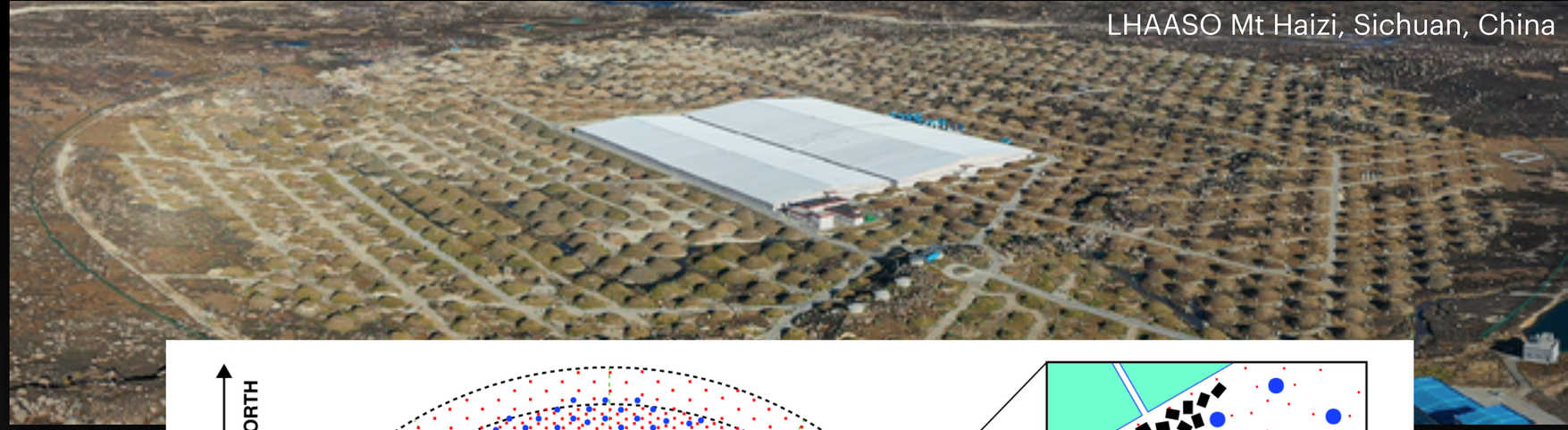


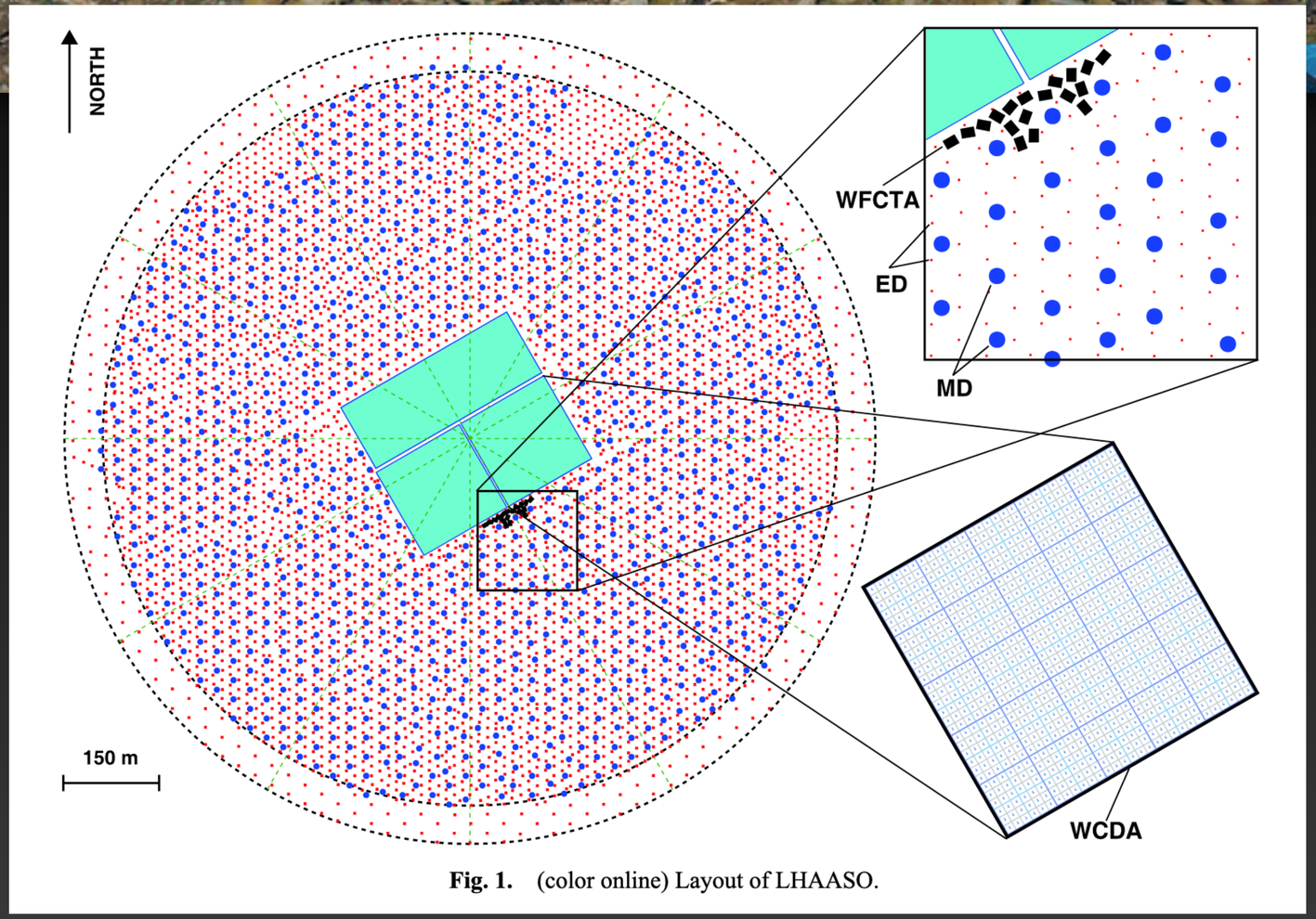
Fig. 1. (color online) Layout of LHAASO.

[Ma et al. 2022]

VHE photons seen with LHAASO


LHAASO Mt Haizi, Sichuan, China

- **WCDA**: Water Cherenkov Detector 78,000 m^2



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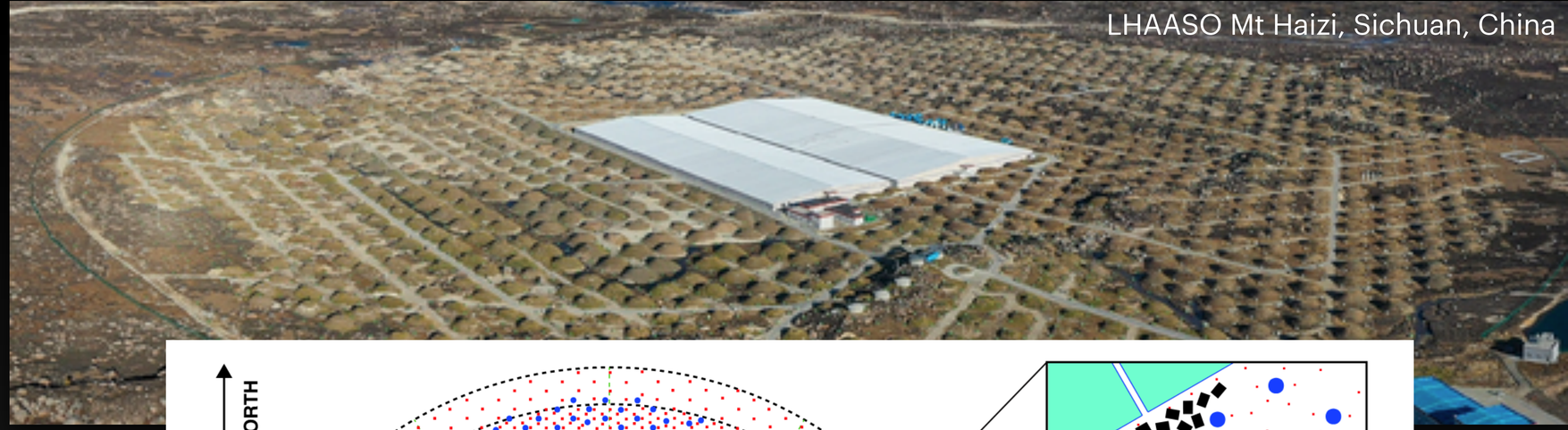
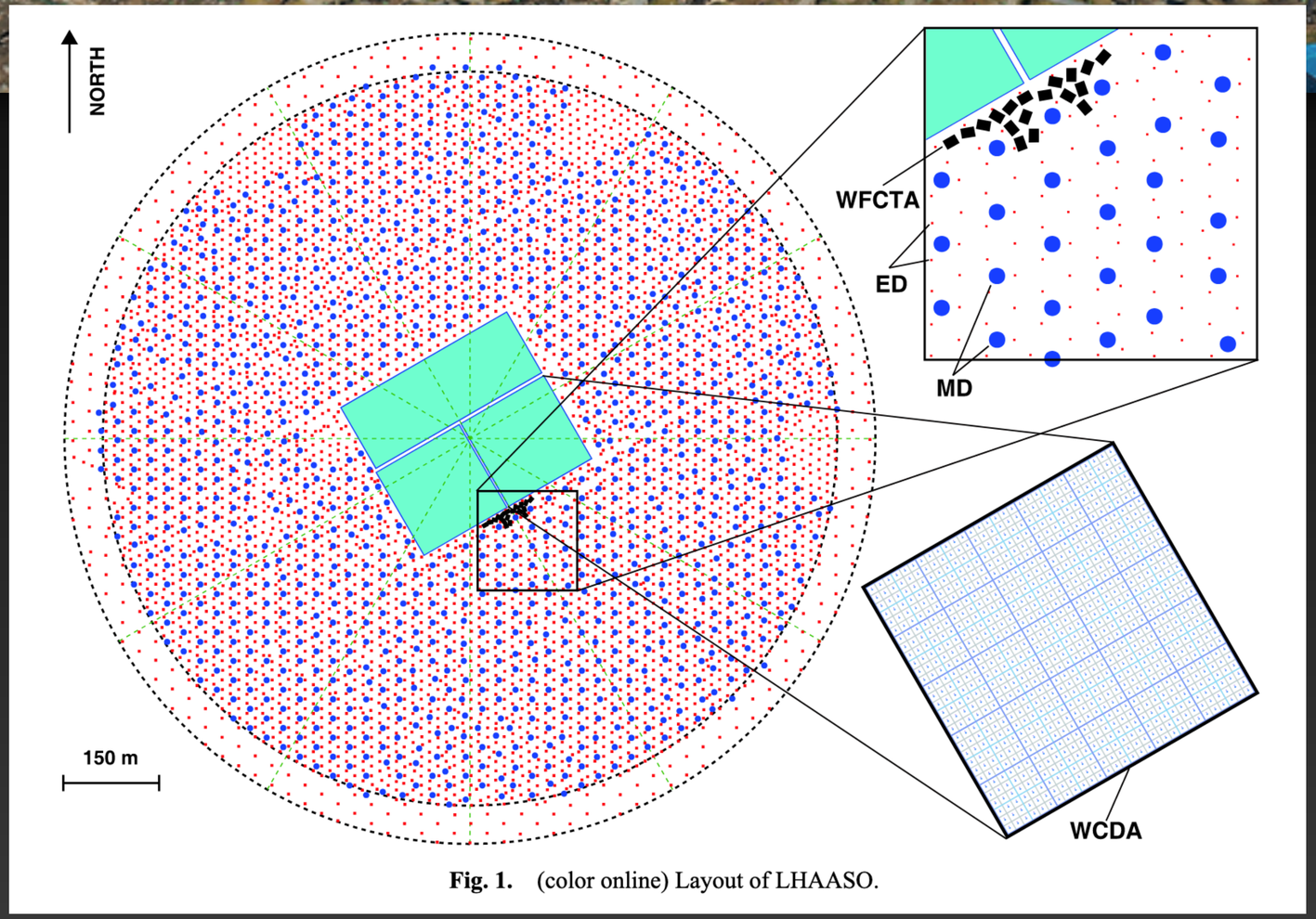

LHAASO Mt Haizi, Sichuan, China

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



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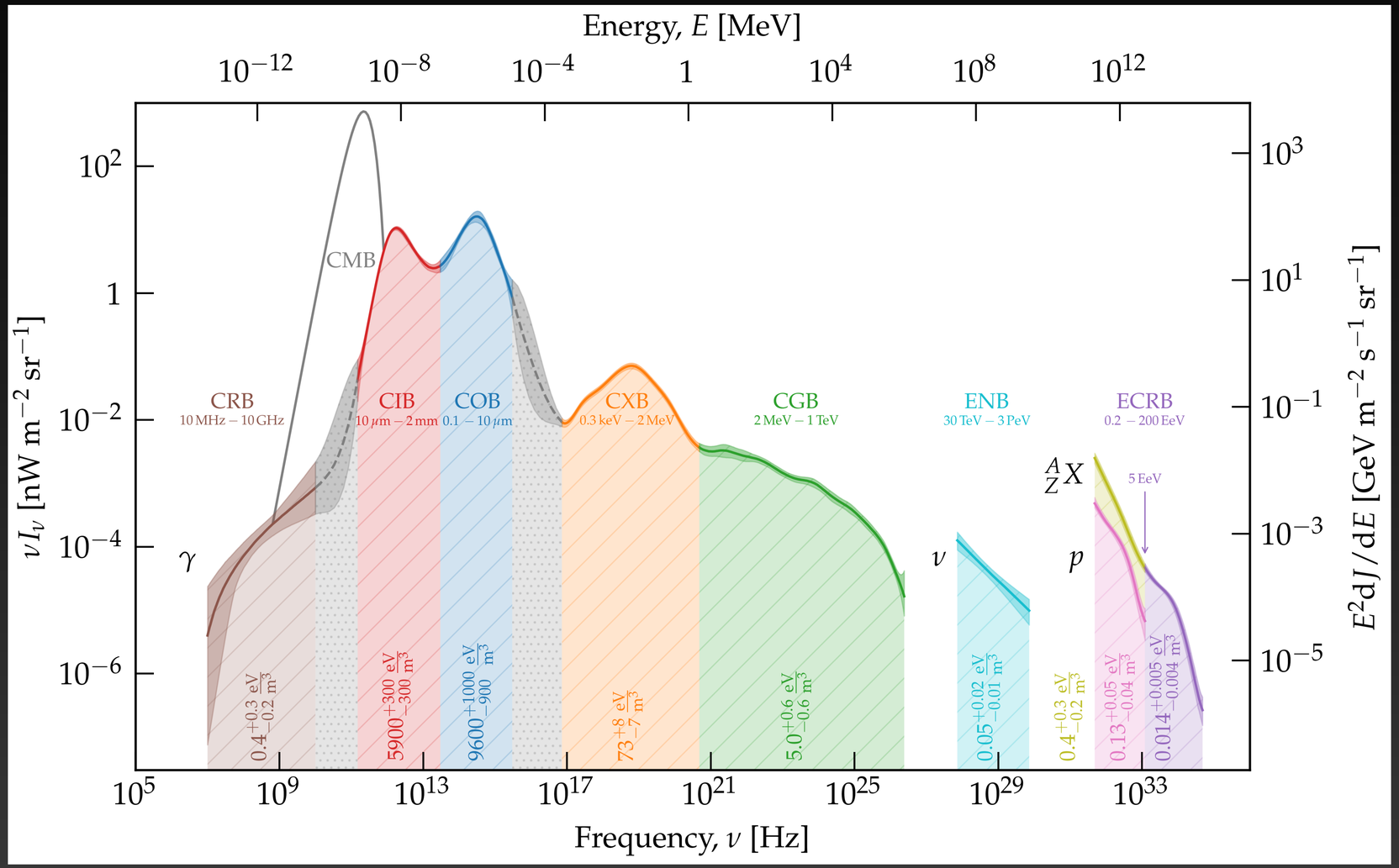
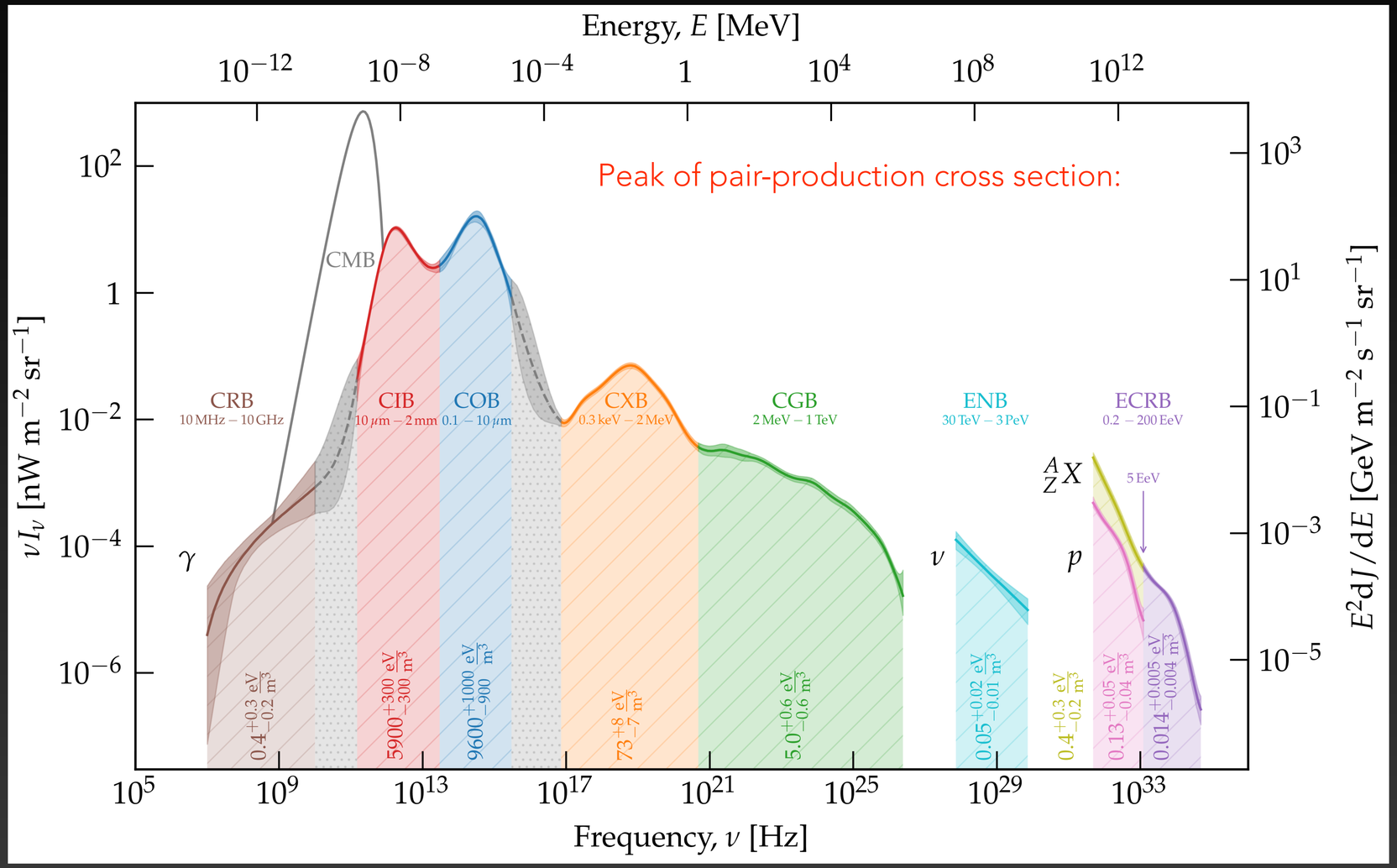
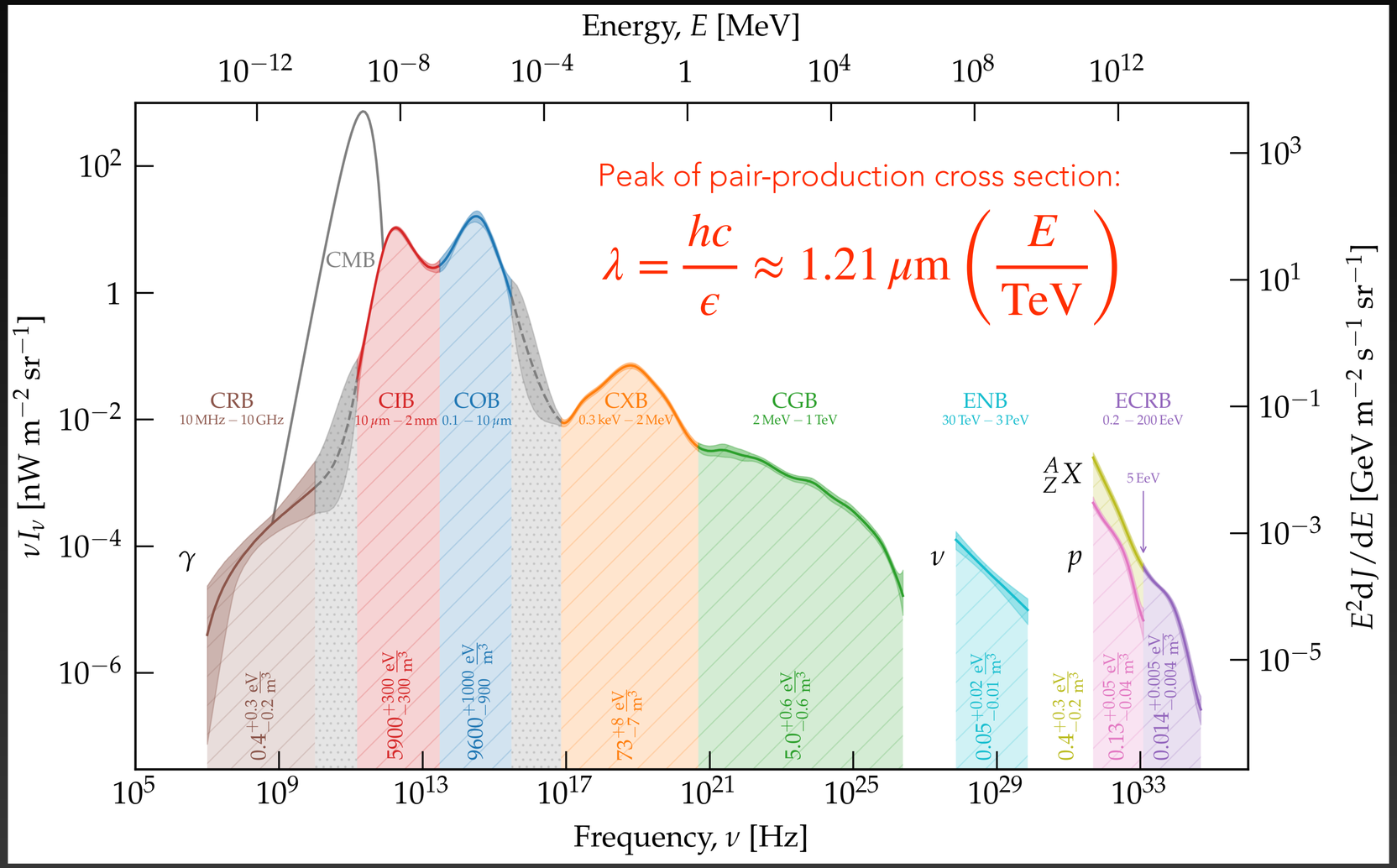
Background radiation fields



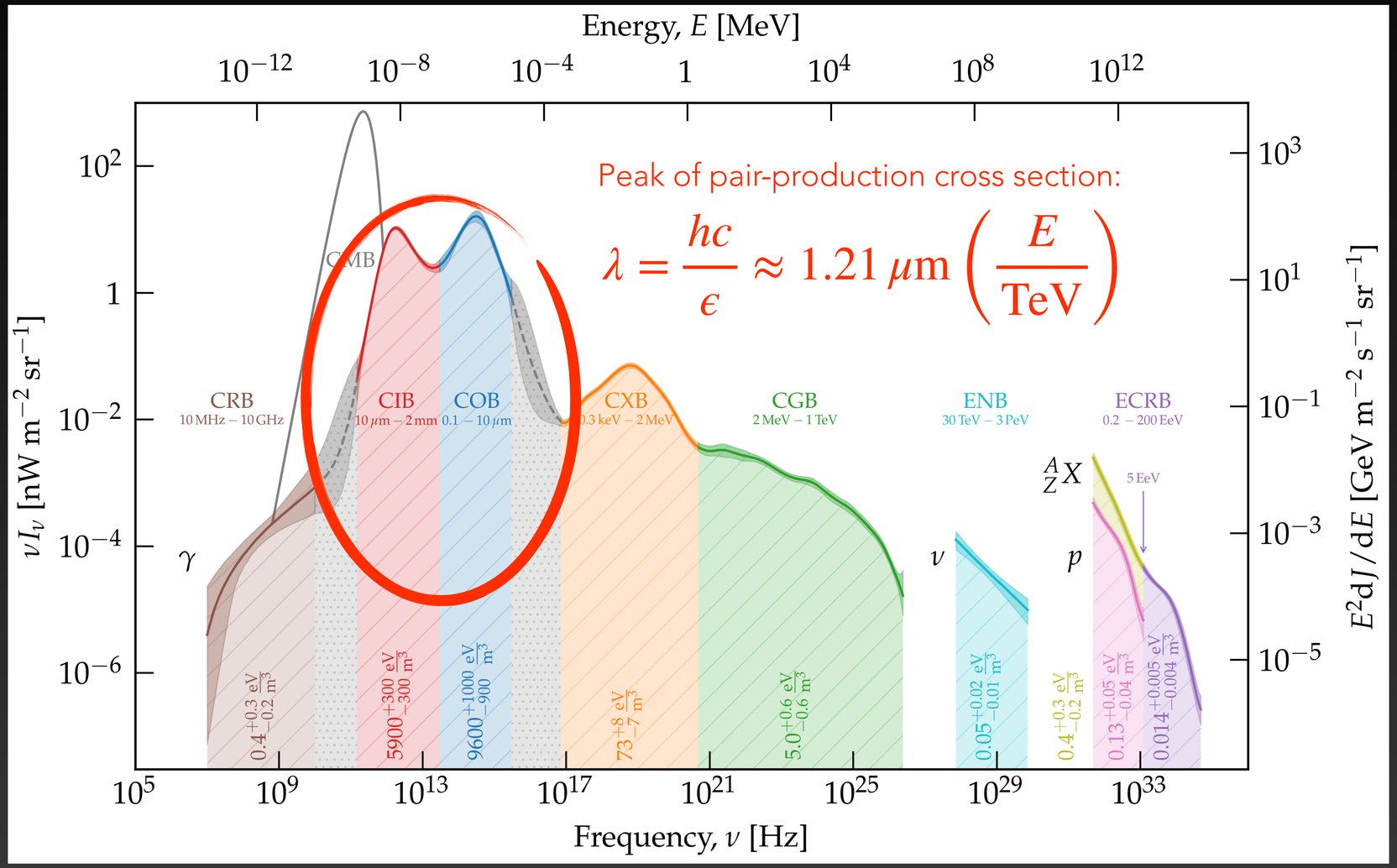
Background radiation fields



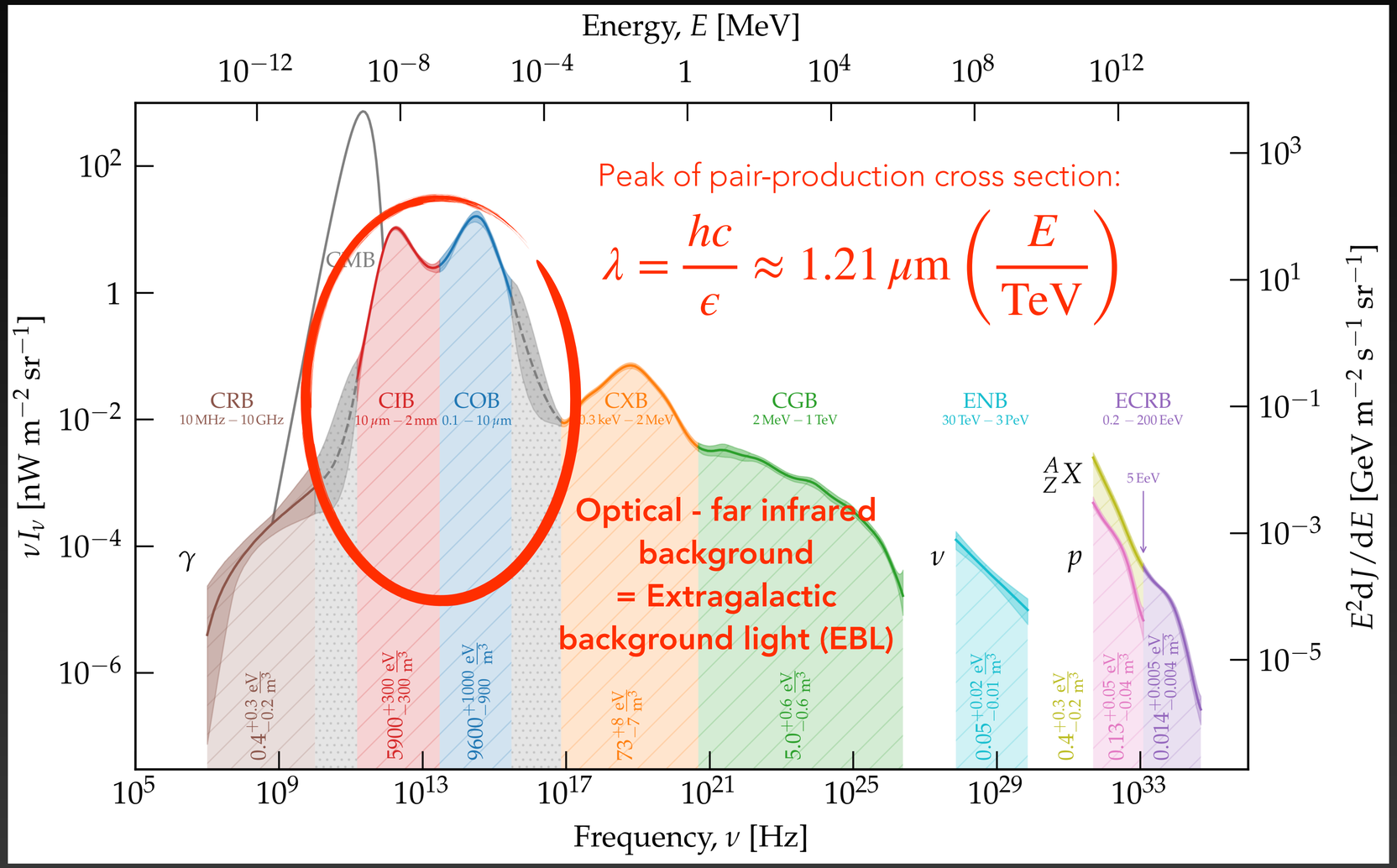
Background radiation fields



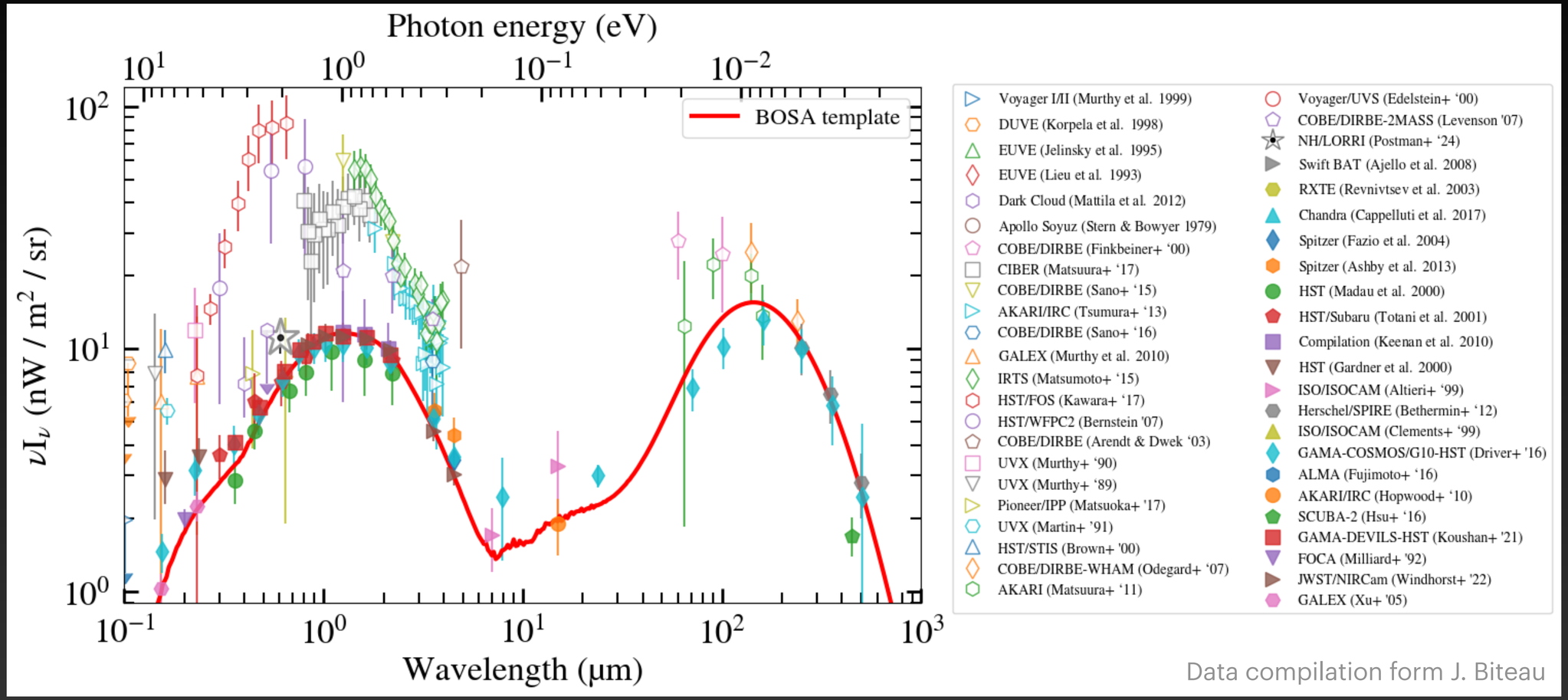
Background radiation fields



Background radiation fields



EBL Measurements



Data compilation form J. Biteau

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

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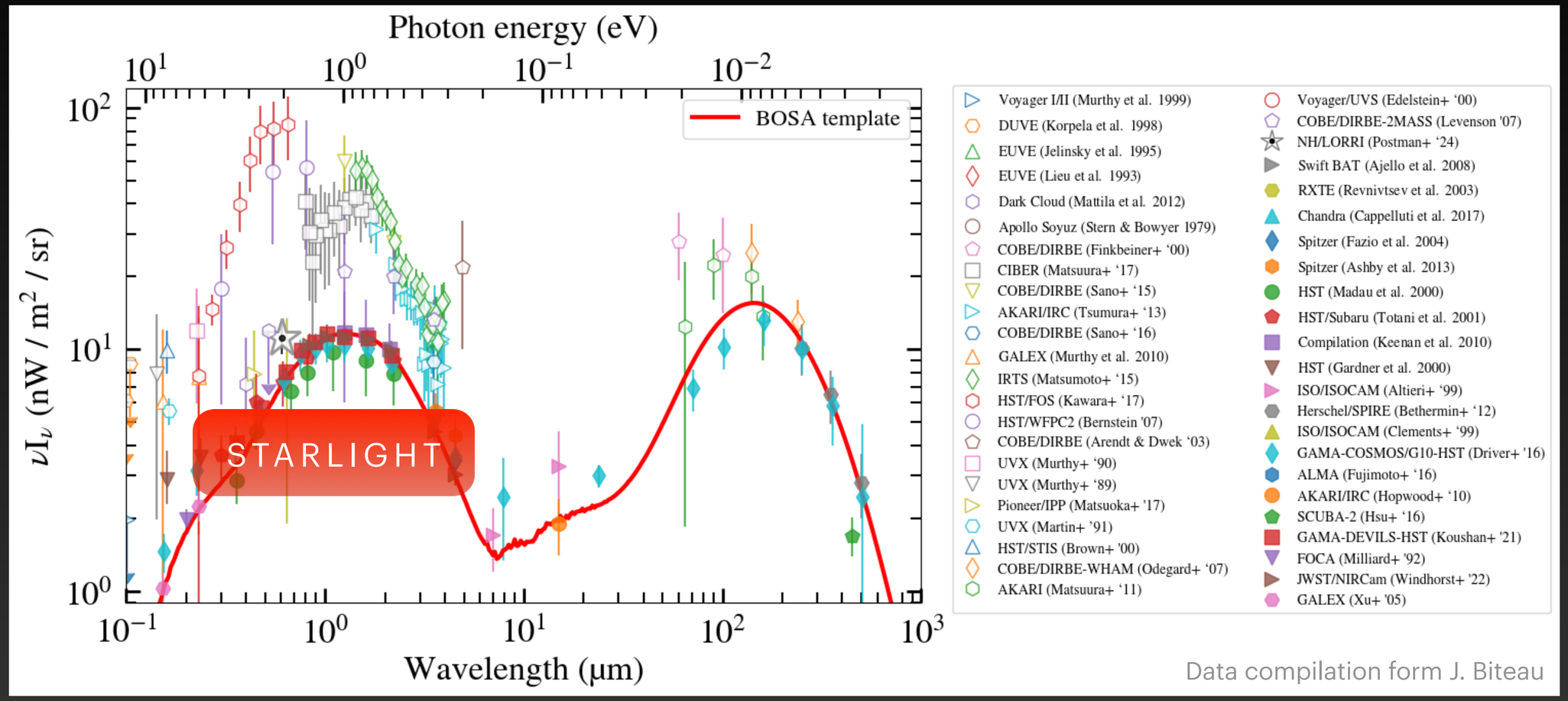

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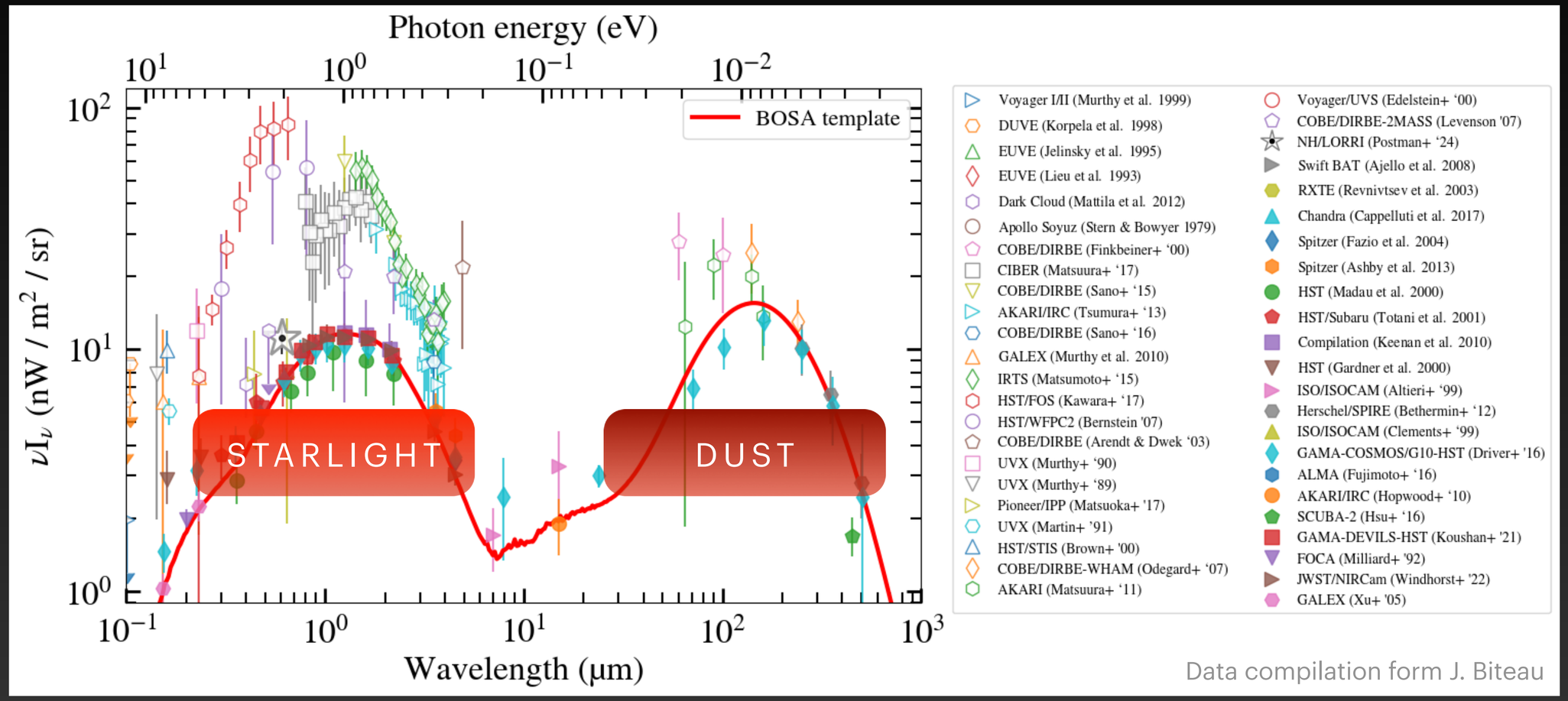

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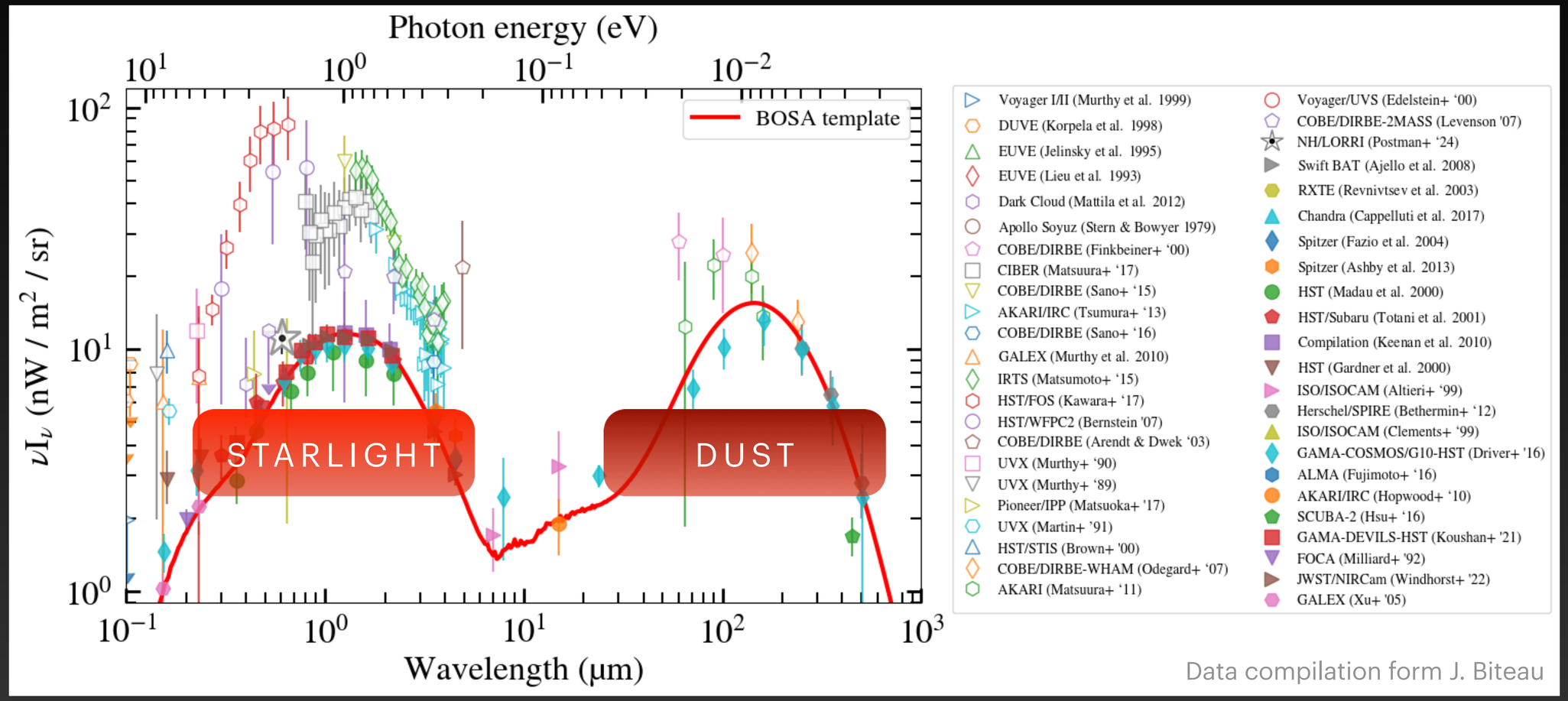

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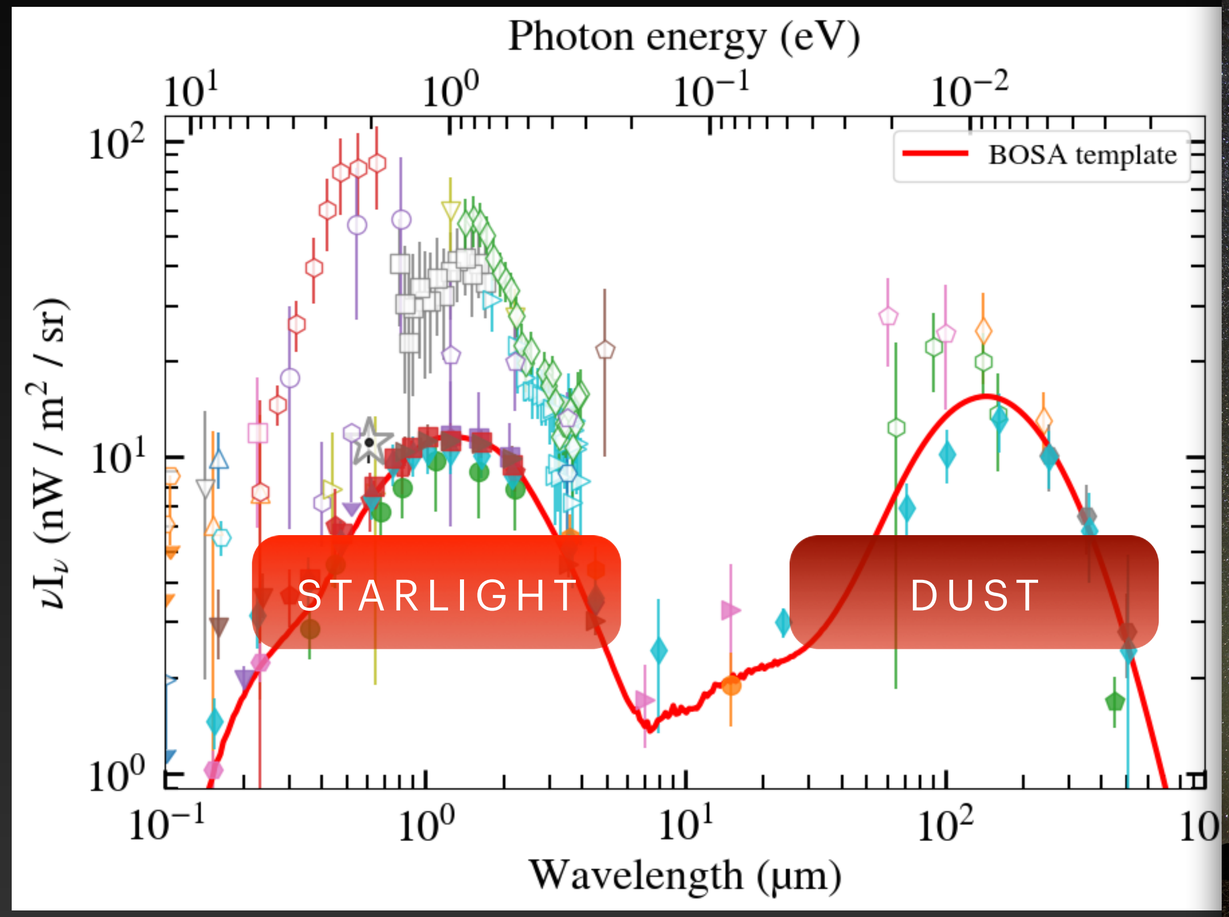

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ood+ '10)
6)
ST (Koushan+ '21)
2)
ndhorst+ '22)

rm J. Biteau

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

Optical Depth

$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} dz \left| \frac{dL}{dz} \right| \int_0^{\infty} d\epsilon \frac{dn}{d\epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(\beta)$$

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

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Line of sight integral to source

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

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Line of sight integral to source

Integral over energy over photon density of background radiation field

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

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Line of sight integral to source

Integral over energy over photon density of background radiation field

Integral over angle $\mu = \cos\theta$ between photon momenta over pair-production cross section

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

Data	GMF	EBL	Host	p_{local}
EPL	Jansson12	Saldana-Lopez	Constant	1.26σ
EPL	UF23, base	Saldana-Lopez	Constant	1.79σ
EPL	Jansson12	Finke	Constant	0.97σ
EPL	UF23, base	Finke	Constant	1.33σ
EPL	Jansson12	Franceschini	Constant	1.17σ
EPL	UF23, base	Franceschini	Constant	1.68σ

Data	GMF	EBL	Host	p_{local}
EPL	Jansson12	Saldana-Lopez	Turbulent, spiral	2.01σ
EPL	UF23, base	Saldana-Lopez	Turbulent, spiral	2.23σ
EPL	Jansson12	Finke	Turbulent, spiral	1.36σ
EPL	UF23, base	Finke	Turbulent, spiral	0.83σ
EPL	Jansson12	Franceschini	Turbulent, spiral	1.19σ
EPL	UF23, base	Franceschini	Turbulent, spiral	1.22σ

Data	GMF	EBL	Host	p_{local}
EPL	Jansson12	Saldana-Lopez	Turbulent, starburst	1.84σ
EPL	UF23, base	Saldana-Lopez	Turbulent, starburst	2.02σ
EPL	Jansson12	Finke	Turbulent, starburst	0.86σ
EPL	UF23, base	Finke	Turbulent, starburst	0.86σ
EPL	Jansson12	Franceschini	Turbulent, starburst	1.20σ
EPL	UF23, base	Franceschini	Turbulent, starburst	1.15σ

Data	GMF	EBL	Host	p_{local}
LP	Jansson12	Saldana-Lopez	Constant	1.46σ
LP	UF23, base	Saldana-Lopez	Constant	1.74σ
LP	Jansson12	Finke	Constant	1.71σ
LP	UF23, base	Finke	Constant	1.90σ
LP	Jansson12	Franceschini	Constant	2.75σ
LP	UF23, base	Franceschini	Constant	2.85σ

Data	GMF	EBL	Host	p_{local}
LP	Jansson12	Saldana-Lopez	Turbulent, spiral	1.54σ
LP	UF23, base	Saldana-Lopez	Turbulent, spiral	1.62σ
LP	Jansson12	Finke	Turbulent, spiral	1.68σ
LP	UF23, base	Finke	Turbulent, spiral	1.70σ
LP	Jansson12	Franceschini	Turbulent, spiral	2.88σ
LP	UF23, base	Franceschini	Turbulent, spiral	2.92σ

Data	GMF	EBL	Host	p_{local}
LP	Jansson12	Saldana-Lopez	Turbulent, starburst	1.59σ
LP	UF23, base	Saldana-Lopez	Turbulent, starburst	1.74σ
LP	Jansson12	Finke	Turbulent, starburst	1.82σ
LP	UF23, base	Finke	Turbulent, starburst	1.89σ
LP	Jansson12	Franceschini	Turbulent, starburst	3.01σ
LP	UF23, base	Franceschini	Turbulent, starburst	2.89σ