

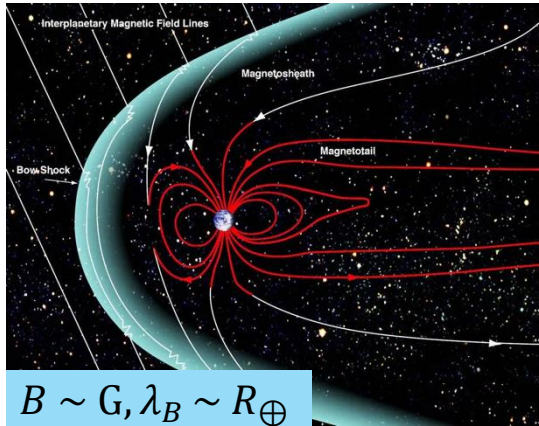
Probing the Intergalactic Magnetic Field with Gamma-Ray Observations

Jeffrey Blunier, Andrii Neronov, Dmitri Semikoz

STEP'UP PhD Congress – 31 March 2026

Intergalactic Magnetic Field (IGMF) : Where is it ?

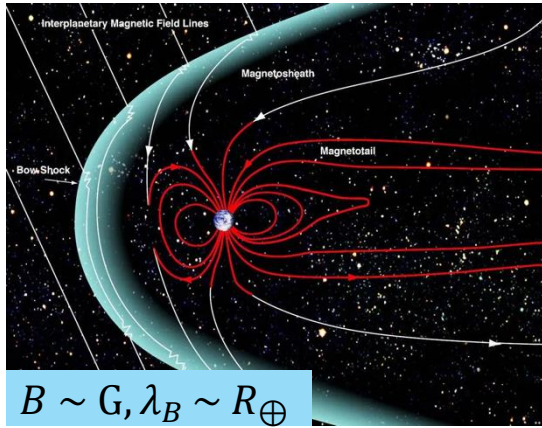
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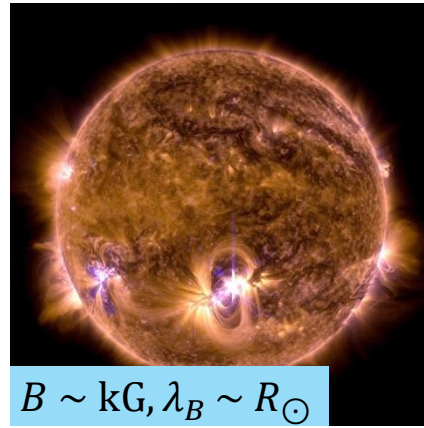
$$B \sim G, \lambda_B \sim R_{\oplus}$$

Credit: NASA

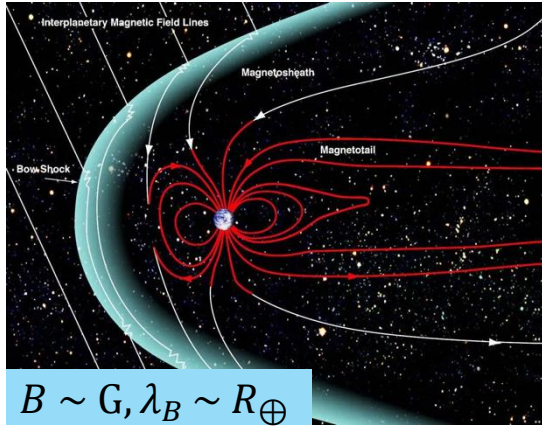
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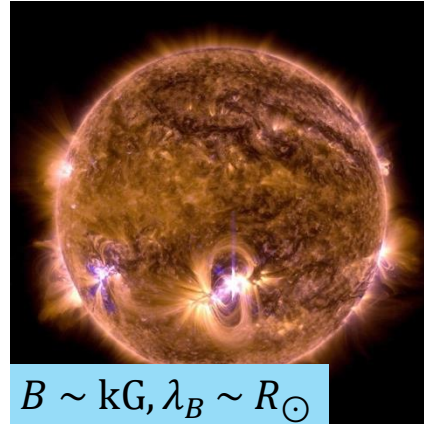


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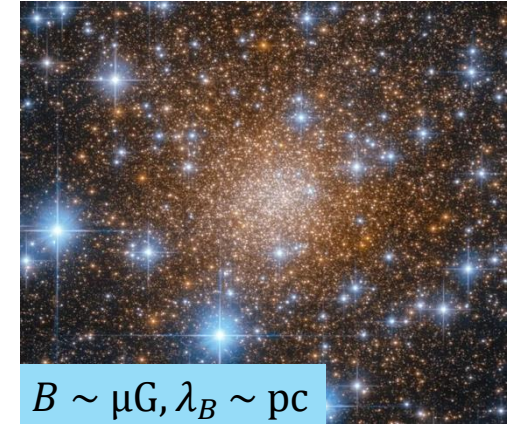


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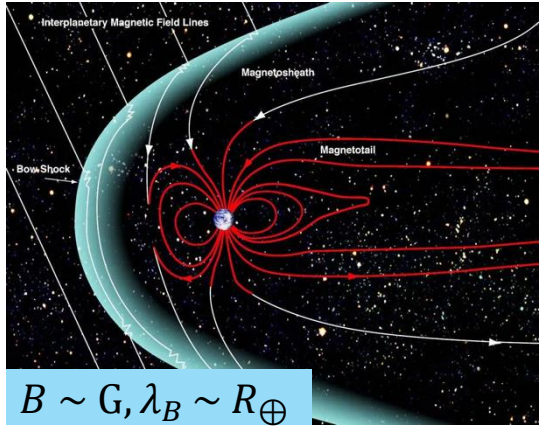


$$B \sim \text{kG}, \lambda_B \sim R_{\odot}$$



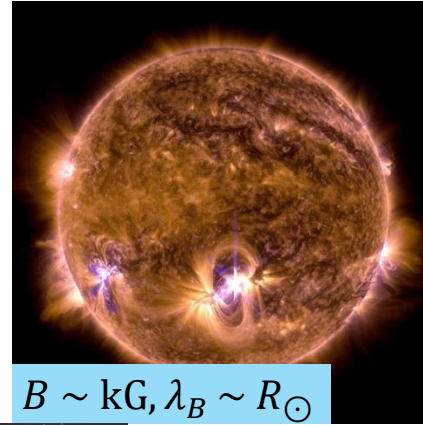
$$B \sim \mu\text{G}, \lambda_B \sim \text{pc}$$

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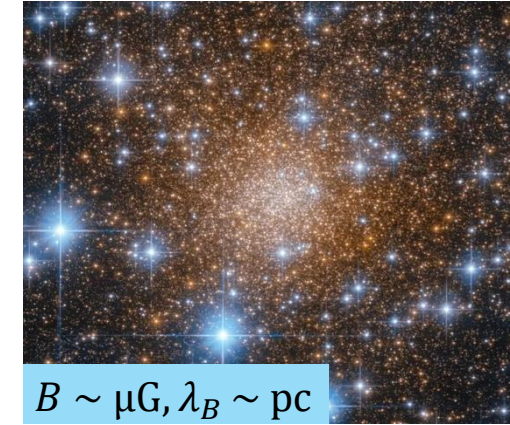


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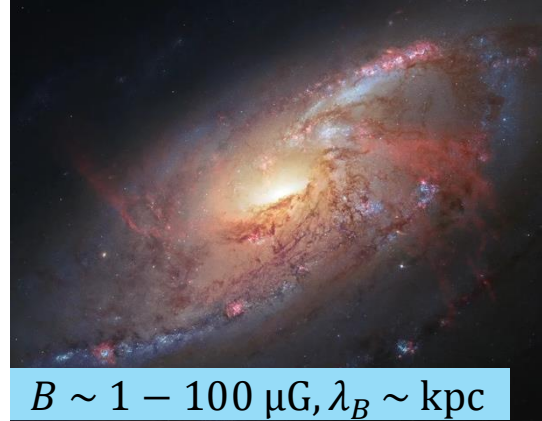
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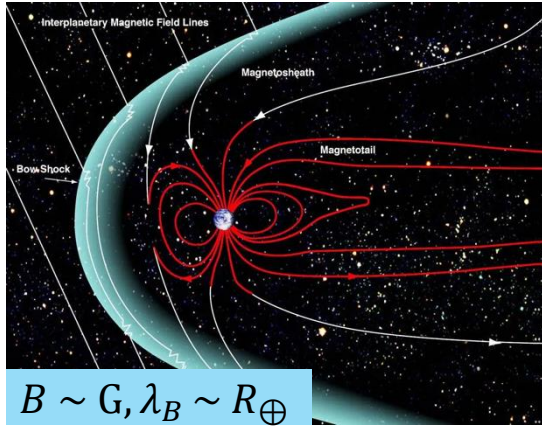


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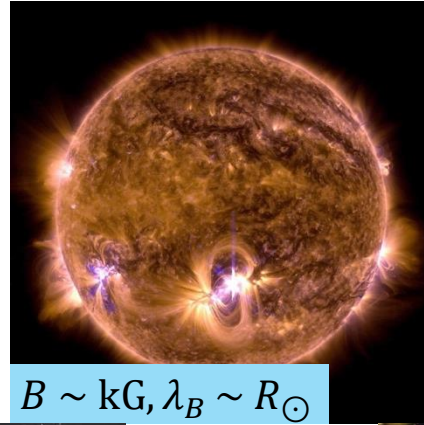
$$B \sim 1 - 100 \mu\text{G}, \lambda_B \sim \text{kpc}$$

IGMF : Where is it ?



$B \sim \text{G}, \lambda_B \sim R_{\oplus}$

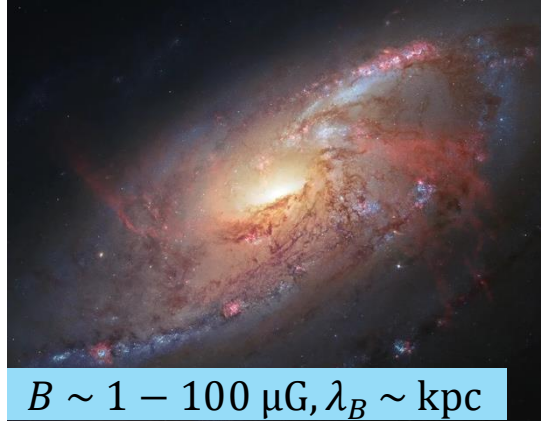
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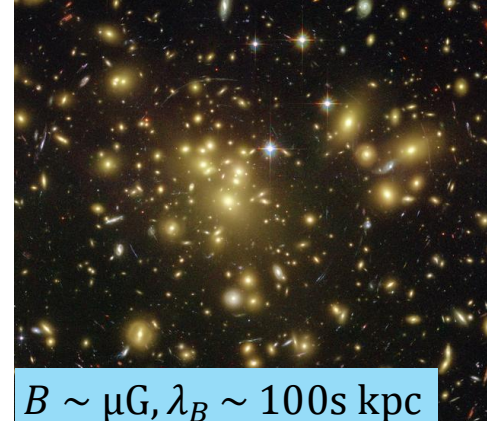
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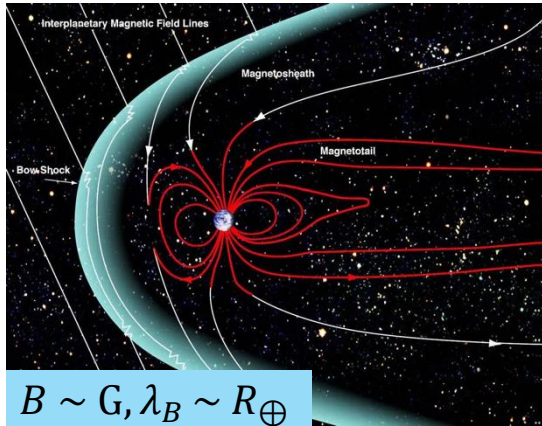


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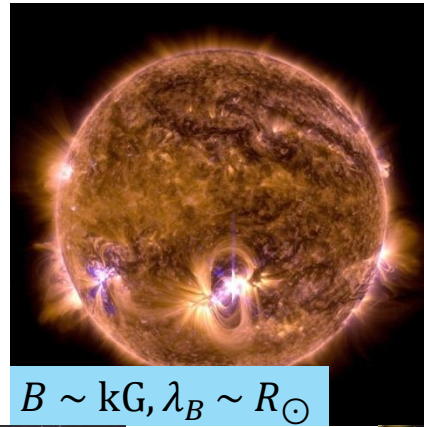
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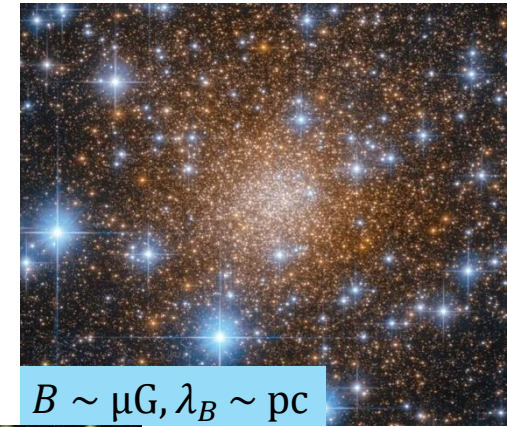


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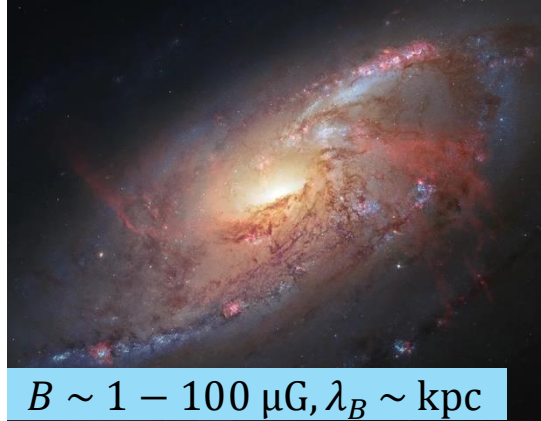
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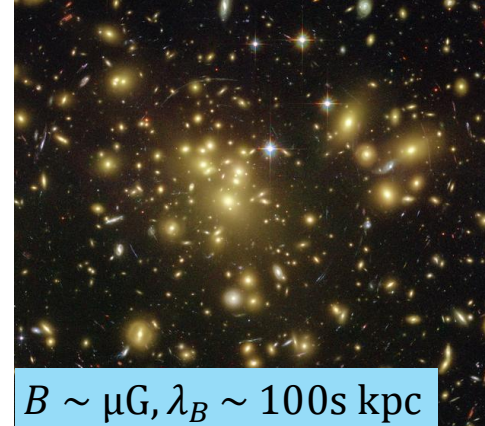
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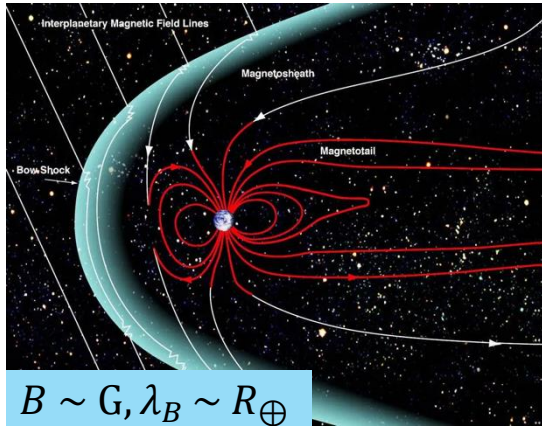
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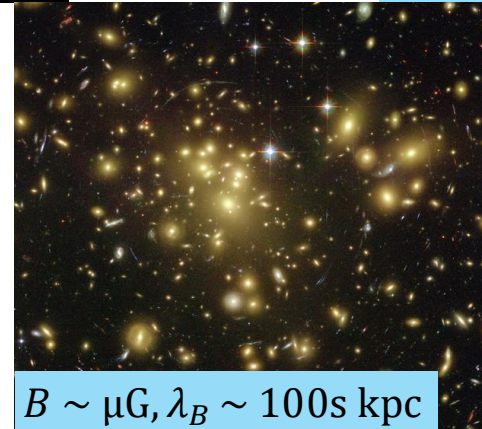
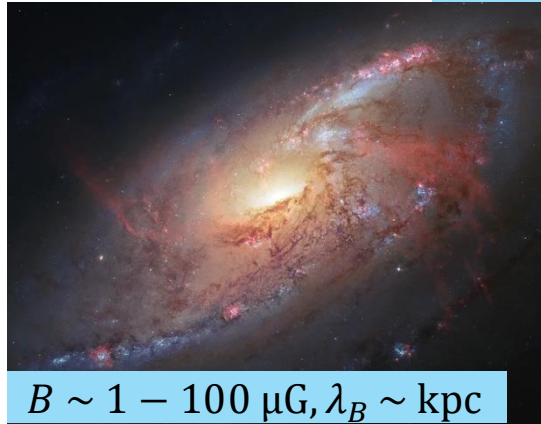
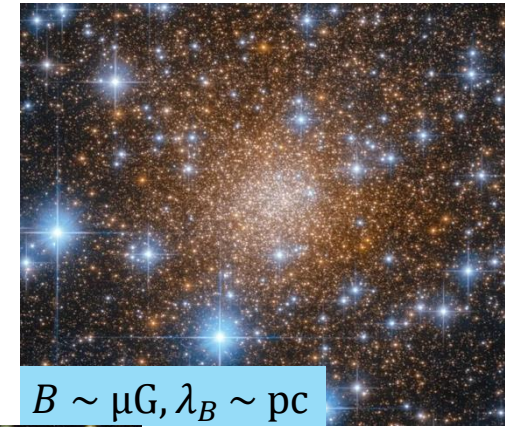
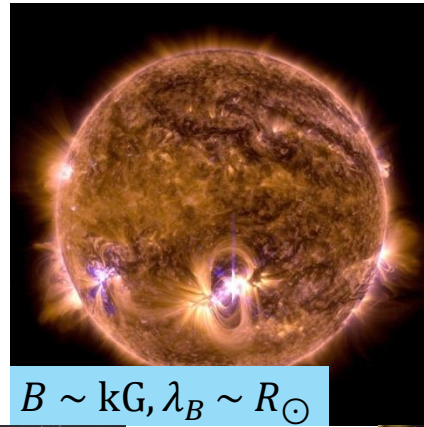
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- Dynamos enhance magnetic fields in structure formation with loss of memory of the original strength (*Garaldi et al. 2021*)

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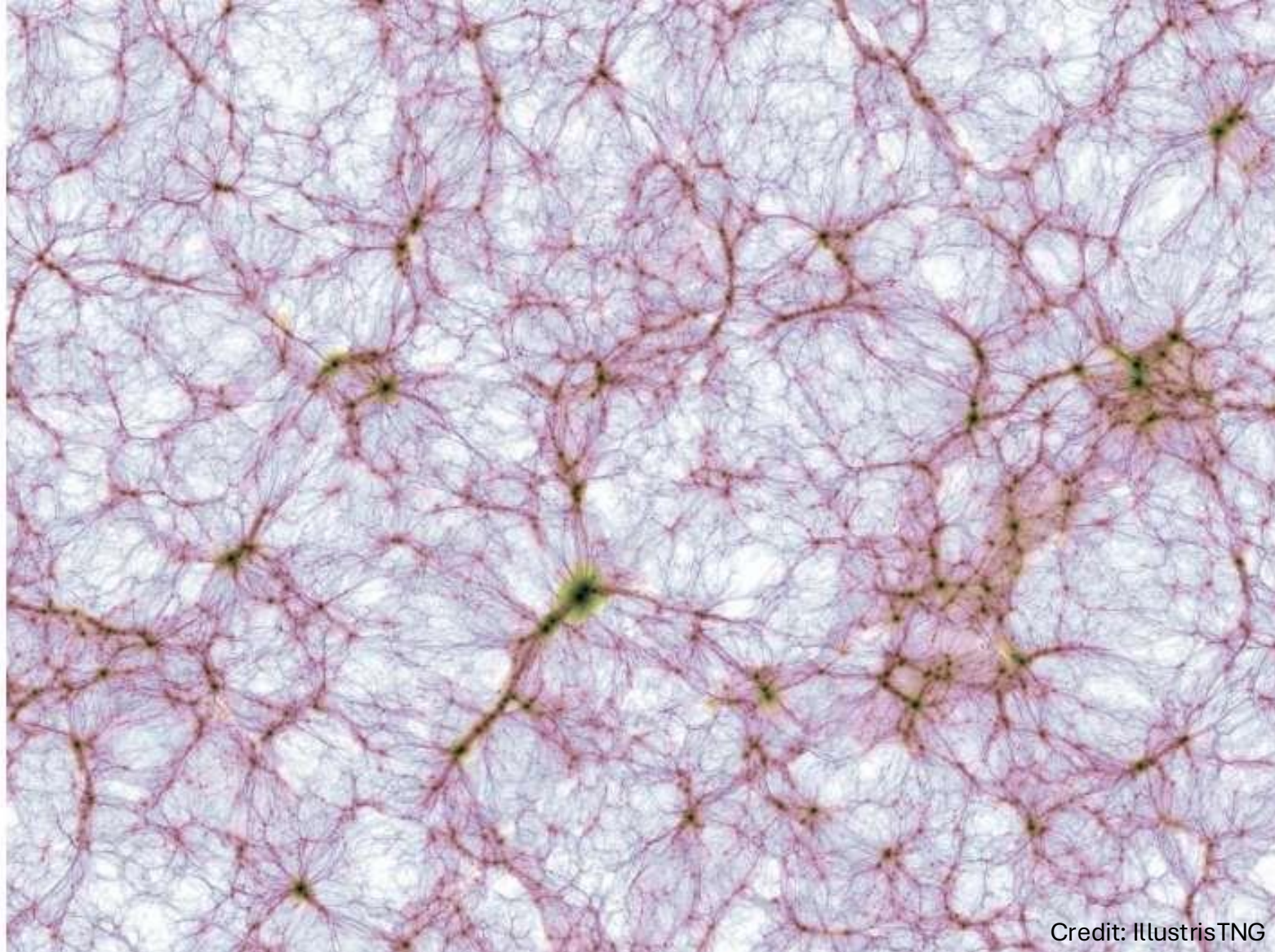


Credit: NASA



- Dynamos enhance magnetic fields in structure formation with loss of memory of the original strength (*Garaldi et al. 2021*)
- Where does the original field comes from ? → Lowest density regions of the Universe = Cosmic voids

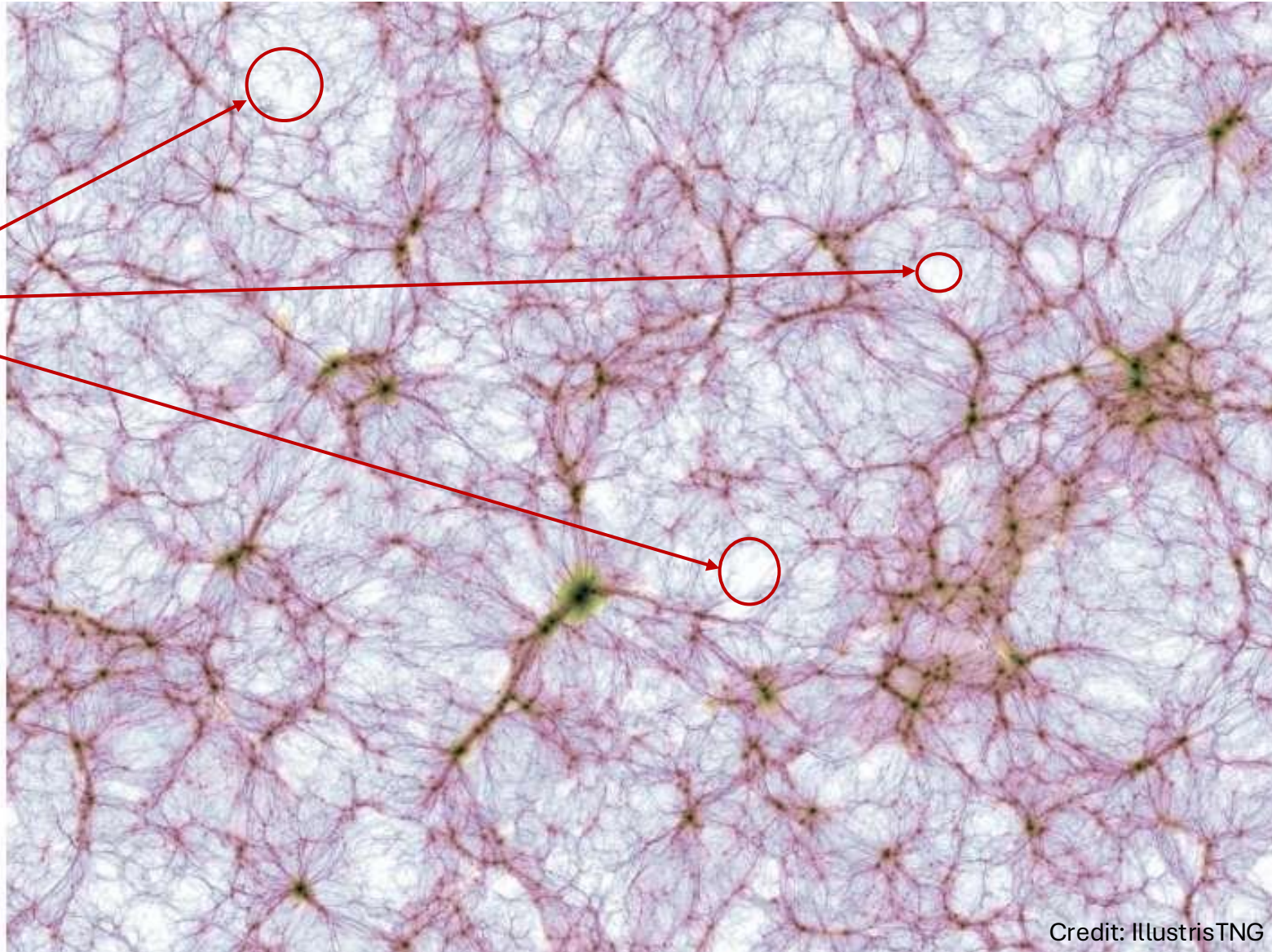
IGMF : Where is it ?



Credit: IllustrisTNG

IGMF : Where is it ?

$B \gtrsim ? G$
 $\lambda_B \sim \text{Mpc}$

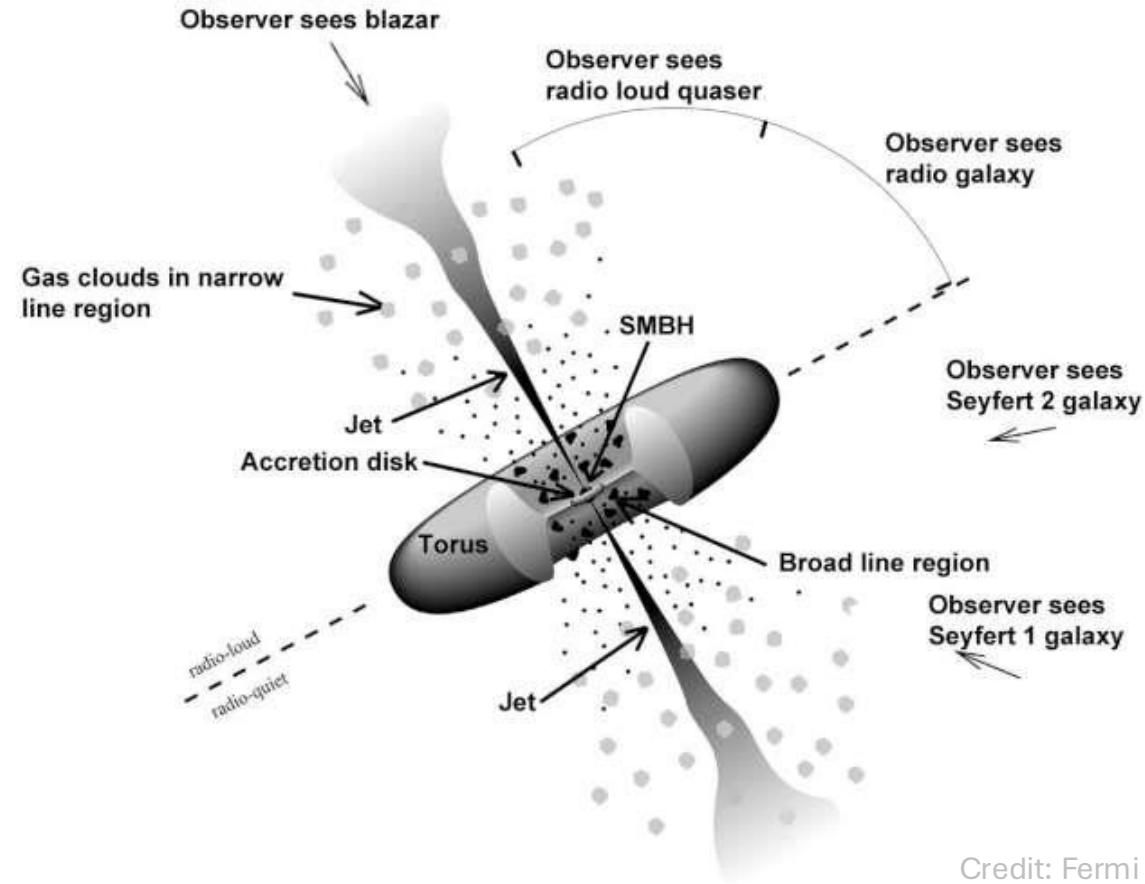


Credit: IllustrisTNG

IGMF : How to constrain it ?

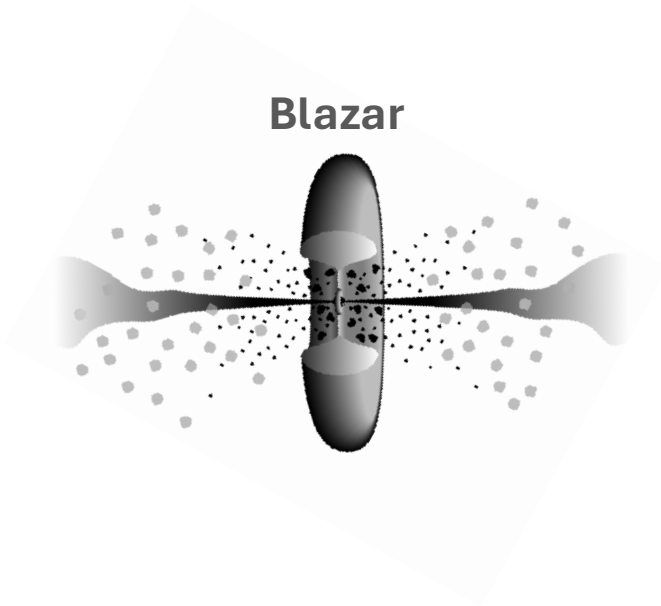
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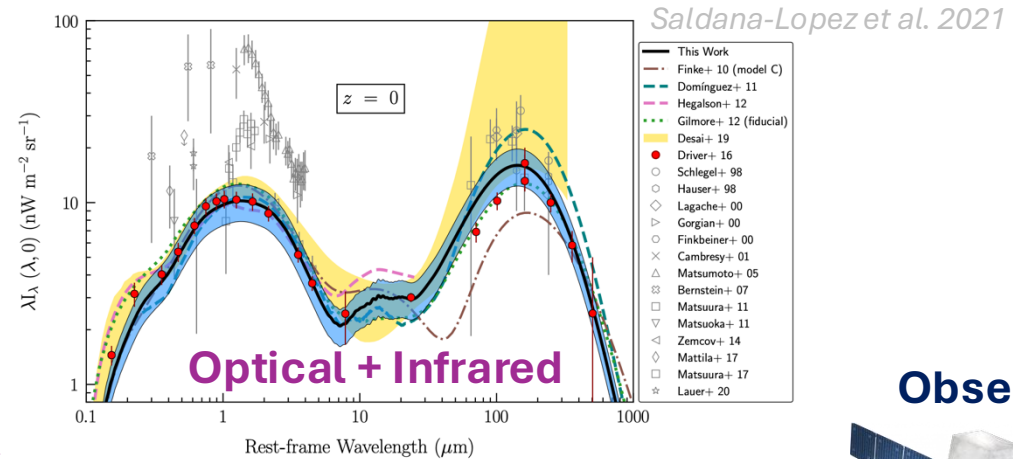
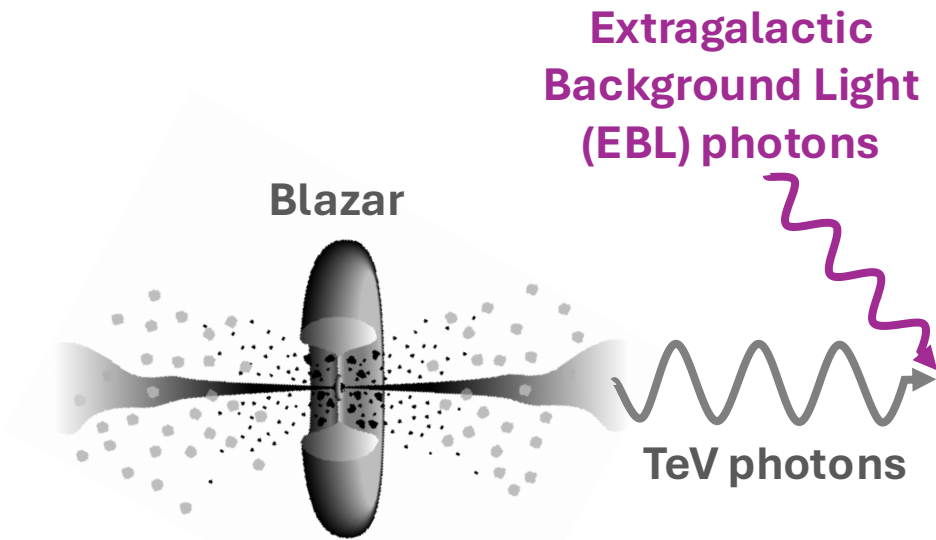
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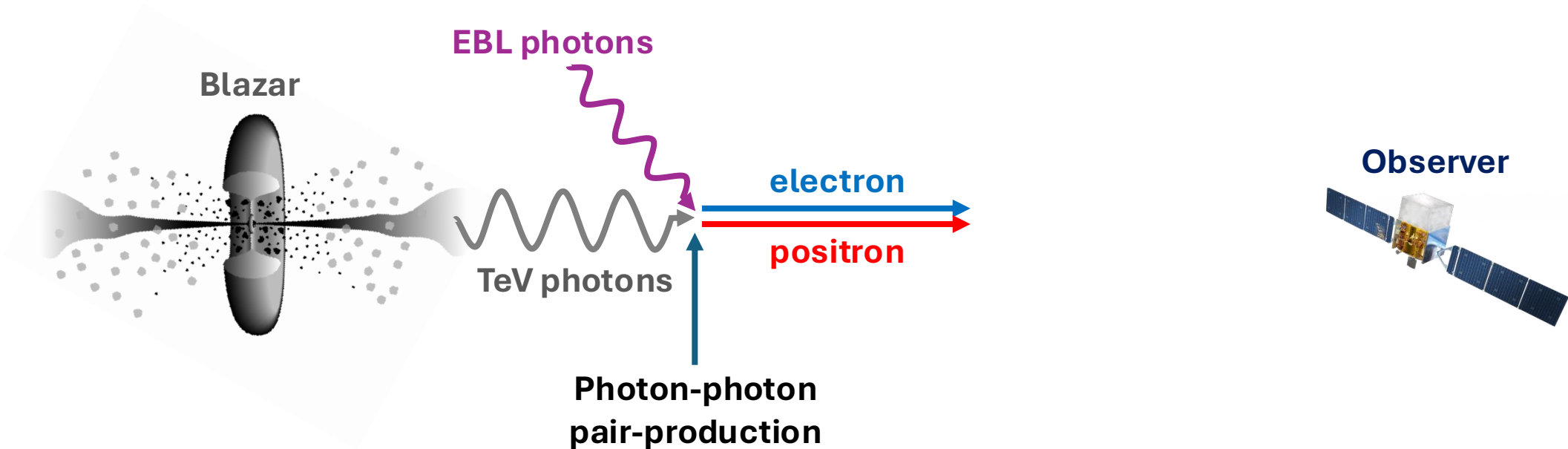
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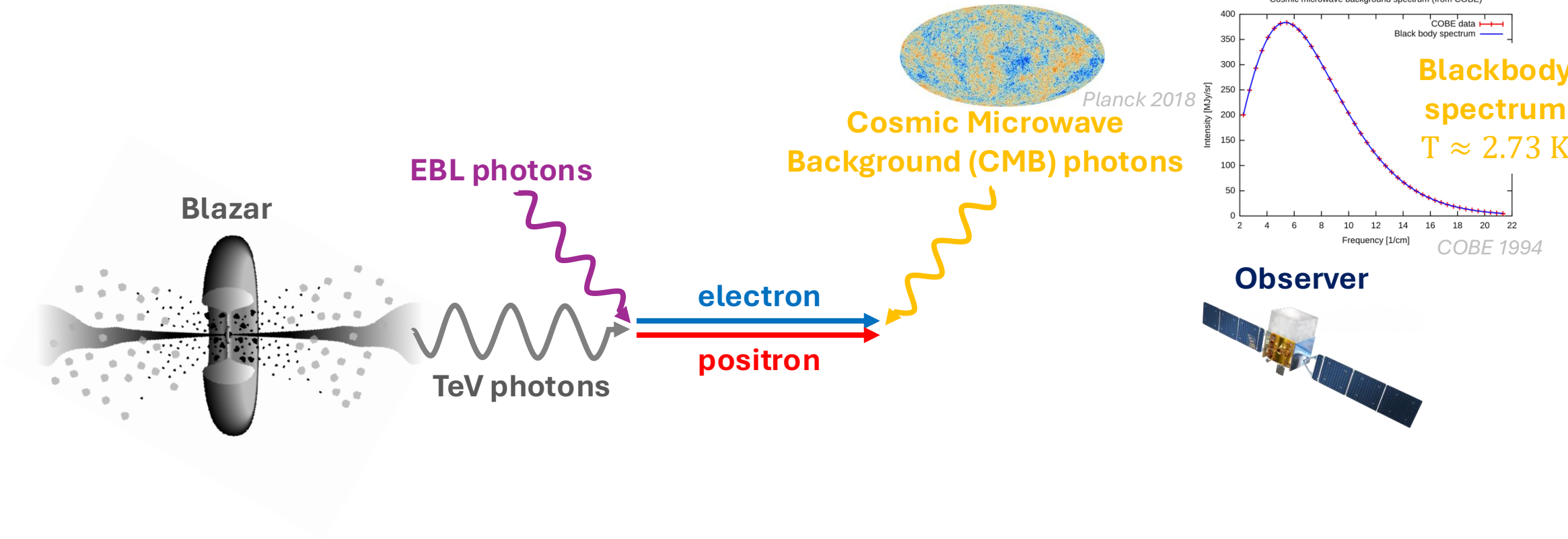
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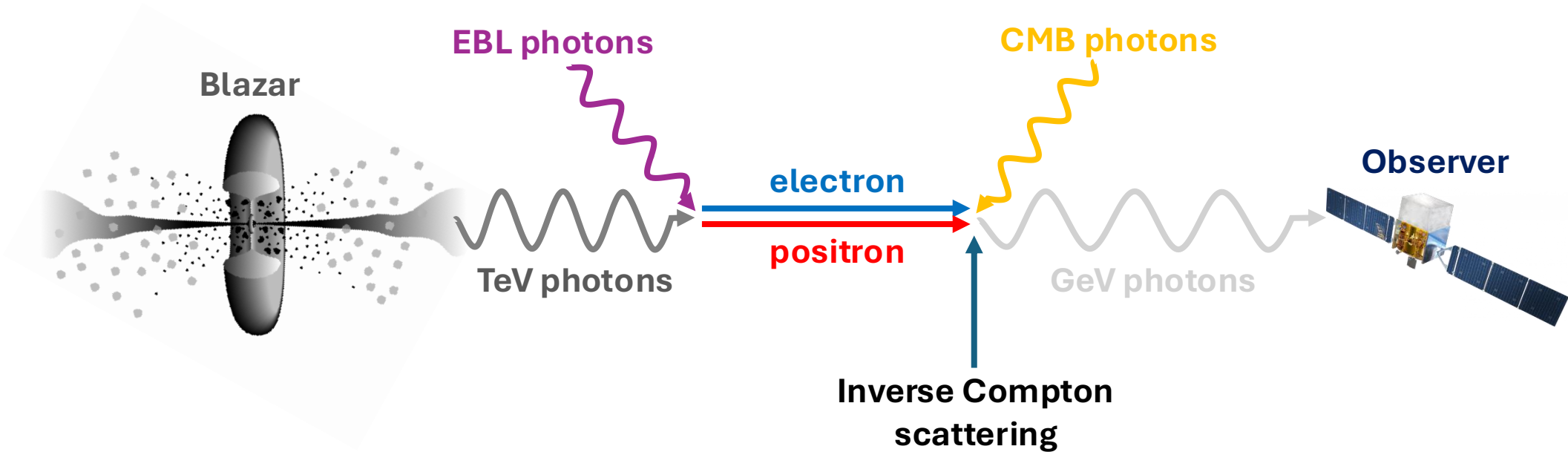
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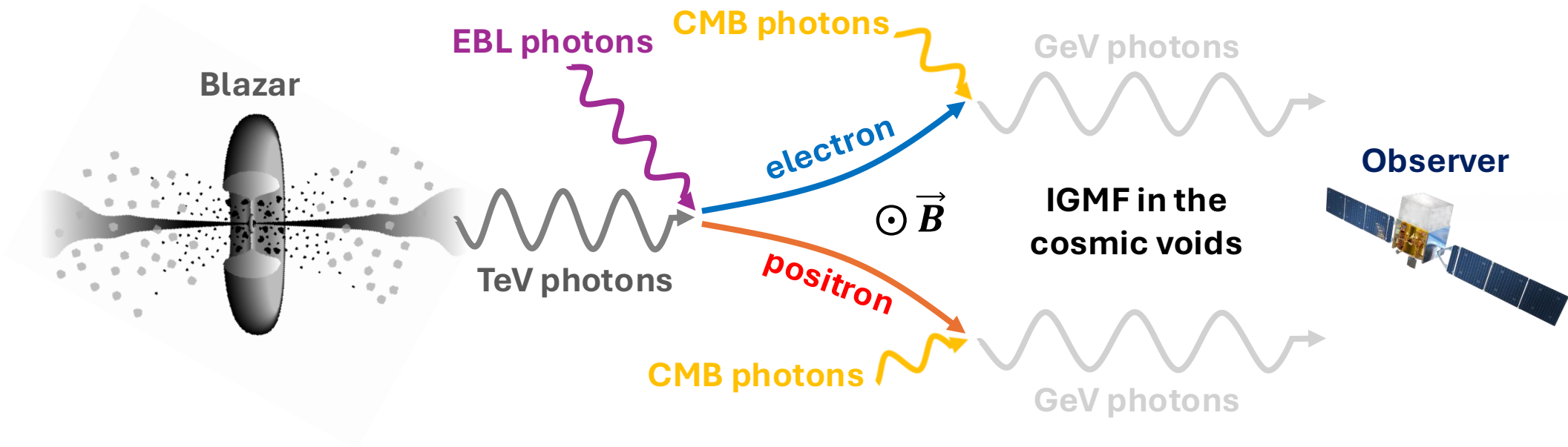
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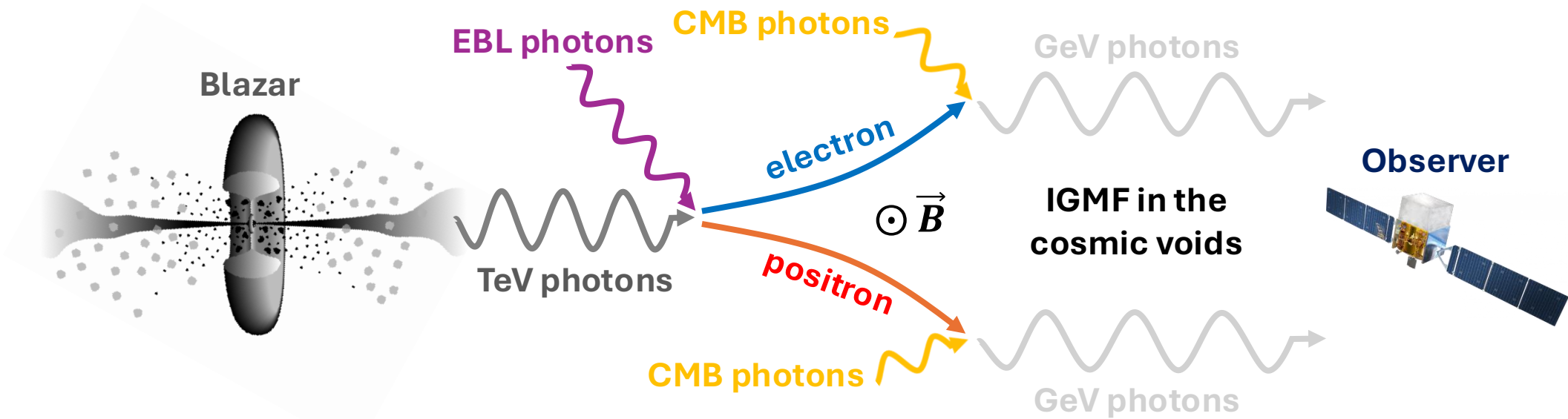
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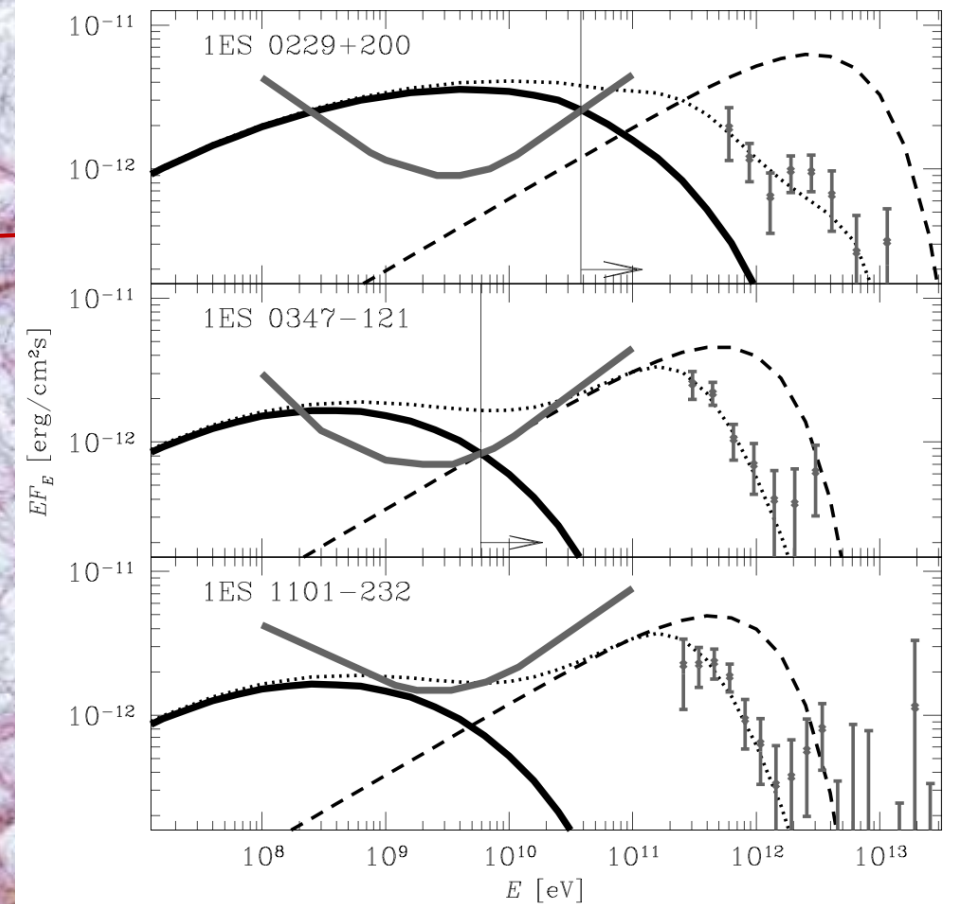
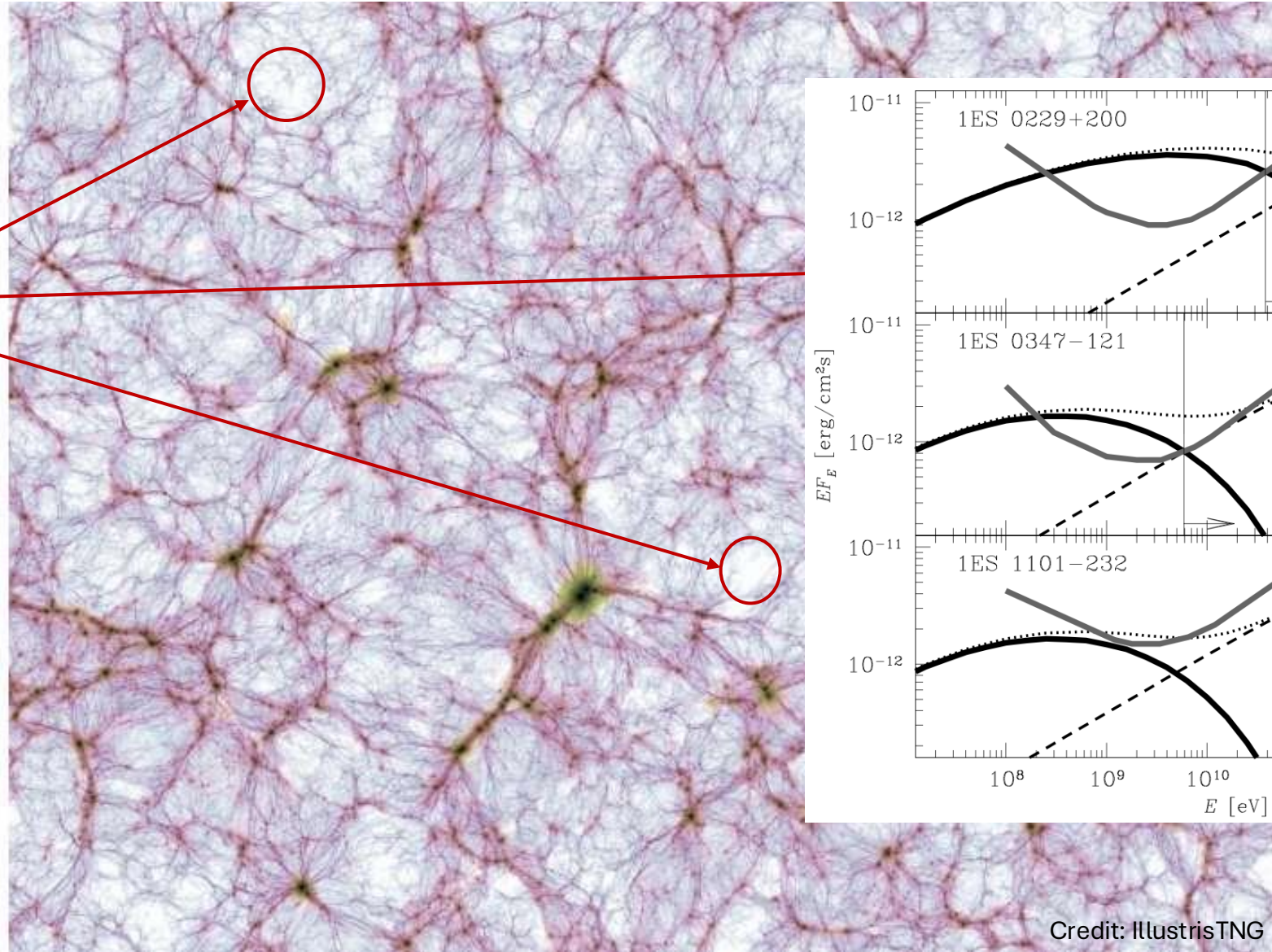
- Possibility to infer lower bound on IGMFs from modeling + observations

IGMF : Where is it ?

$$B \gtrsim 10^{-16} \text{ G}$$

$$\lambda_B \sim \text{Mpc}$$

Non-observation
of secondary
emission from
blazars

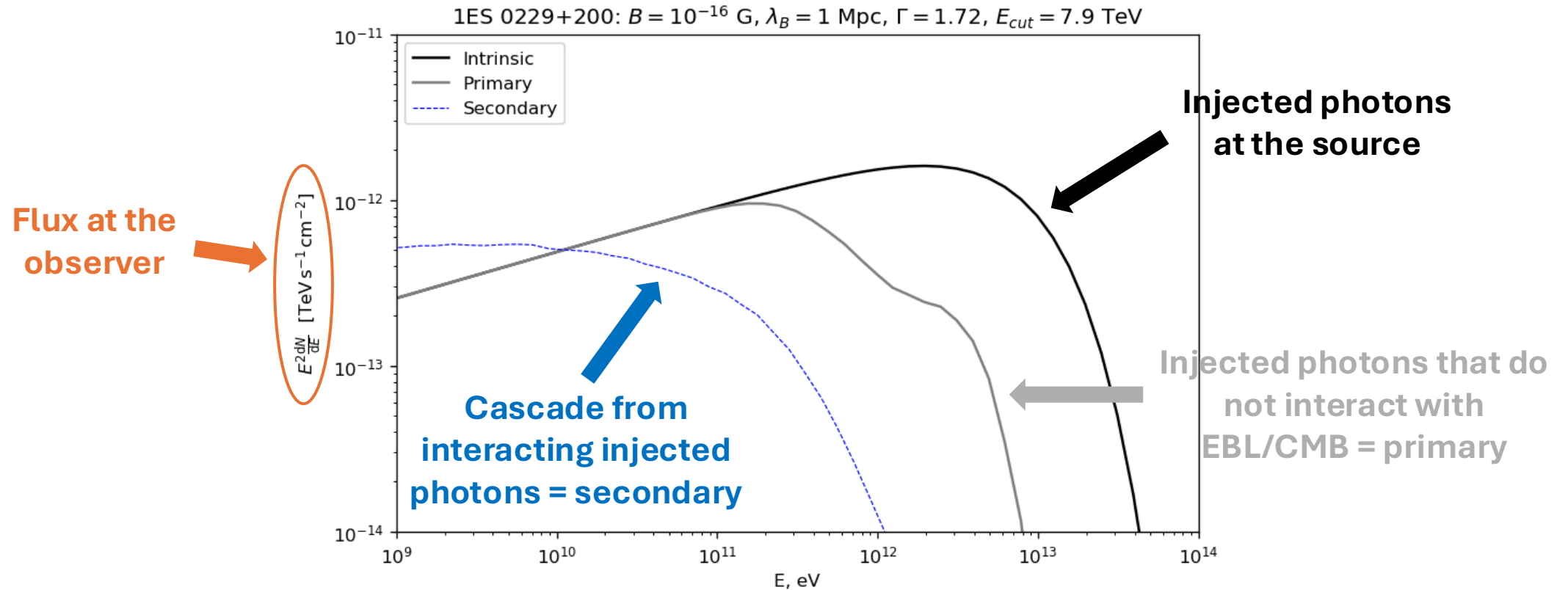


Neronov & Vovk 2010

Credit: IllustrisTNG

Modeling with the CRbeam code

- Monte Carlo code for simulating electromagnetic cascades (Pair production, Inverse Compton) through the intergalactic medium (IGM) (*Berezinsky & Kalashev 2016, Kalashev et al. 2023*)



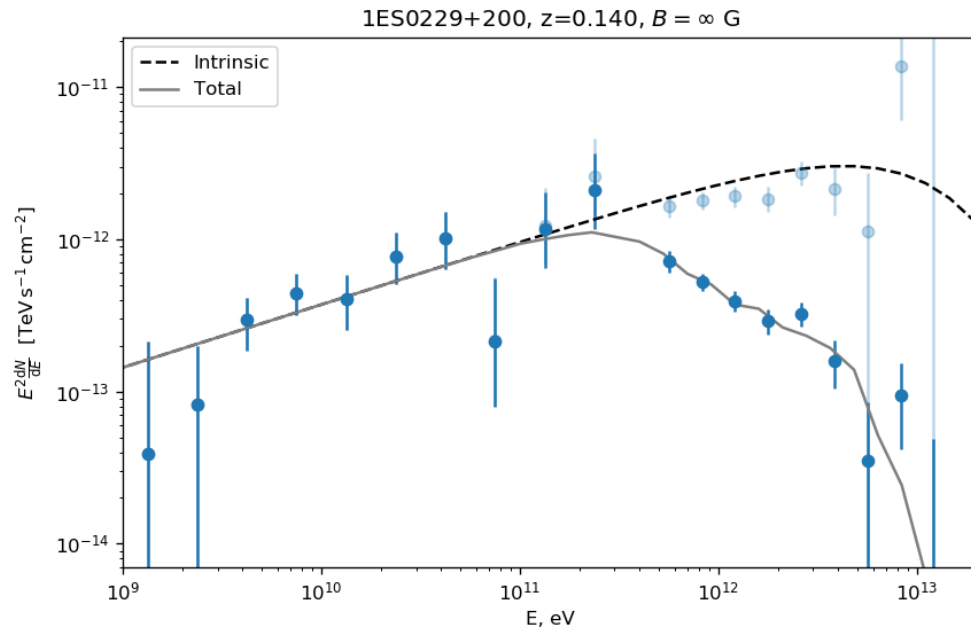
Selection of blazars for IGMF study

Infinite magnetic field

- Total suppression of secondary emission
- Total flux is only primary

Zero magnetic field

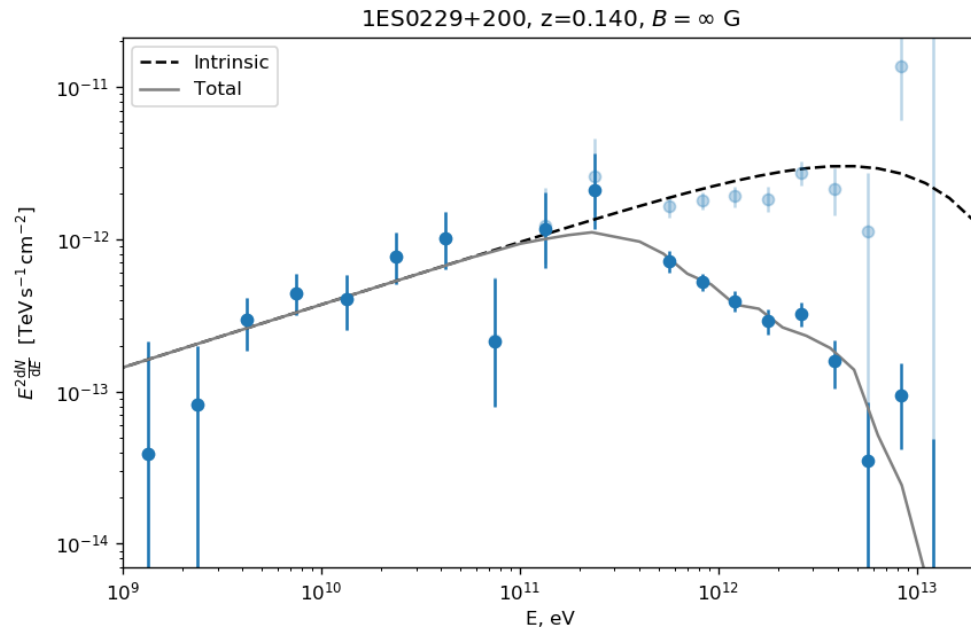
- Total secondary emission coming to the observer
- Total flux is primary + secondary



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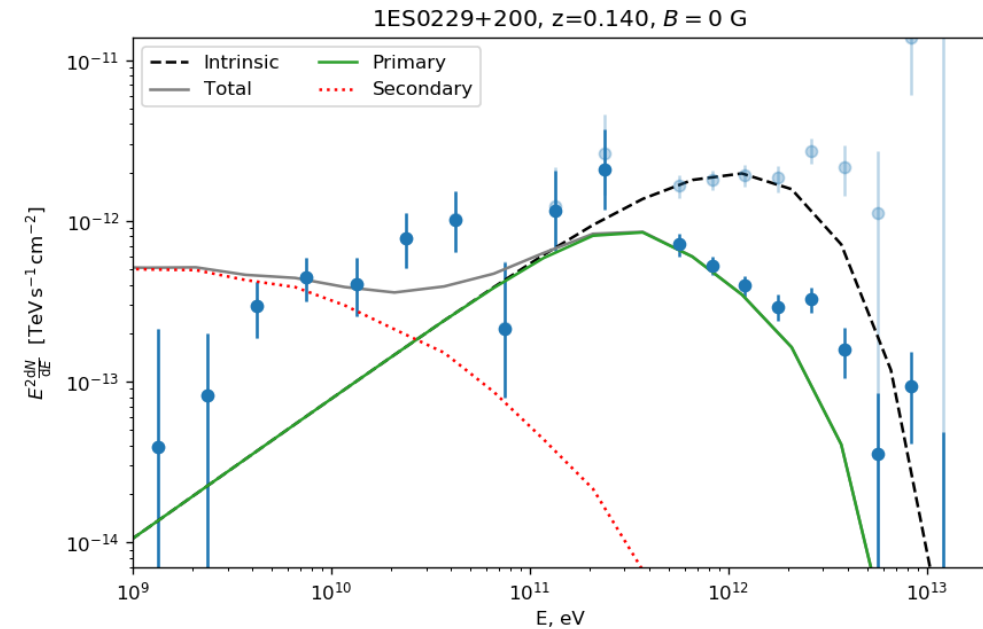
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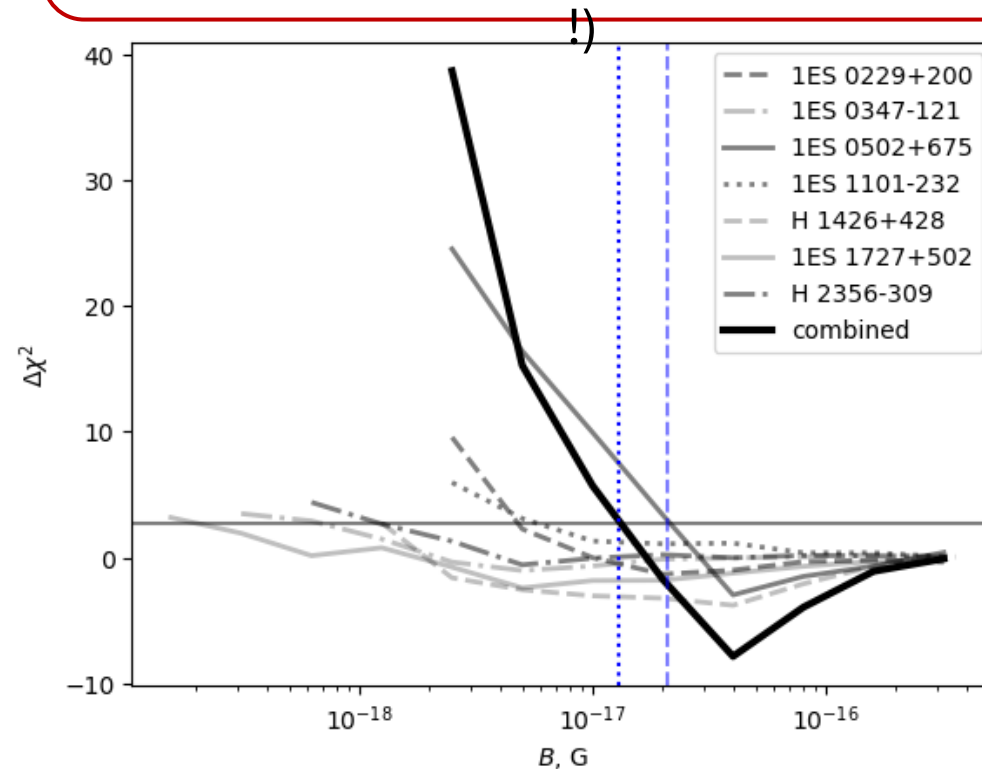


Derivation of lower bound on IGMF

- Define $\Delta\chi^2 = \chi^2(B|E_{cut}, \Gamma, N_0) - \chi^2_\infty \leq 2.71$ (95% CL) to infer lower bound on IGMF (*Blunier, Neronov & Semikoz 2025*)

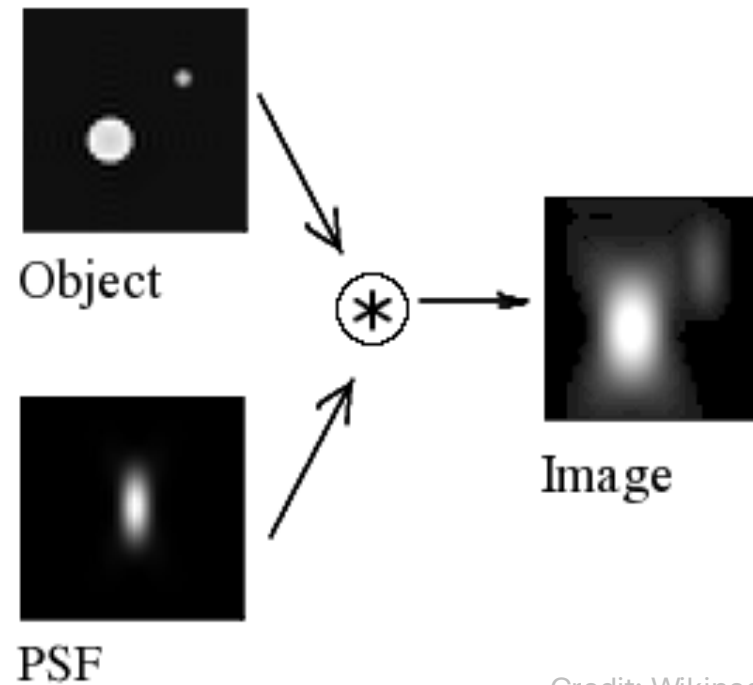
$$\diamond B_{all} > 1.3 \times 10^{-17} \text{ G}$$

$$\diamond B_{0502} > 2.1 \times 10^{-17} \text{ G (new source$$



Point Spread Function (PSF) of Fermi Large Area Telescope (LAT)

- Fermi-LAT response “spreads” the source signal → Convolution with PSF “blurry” the image
- Importance of modeling the PSF when studying extended sources → Point source and potential extended emission can be mixed up



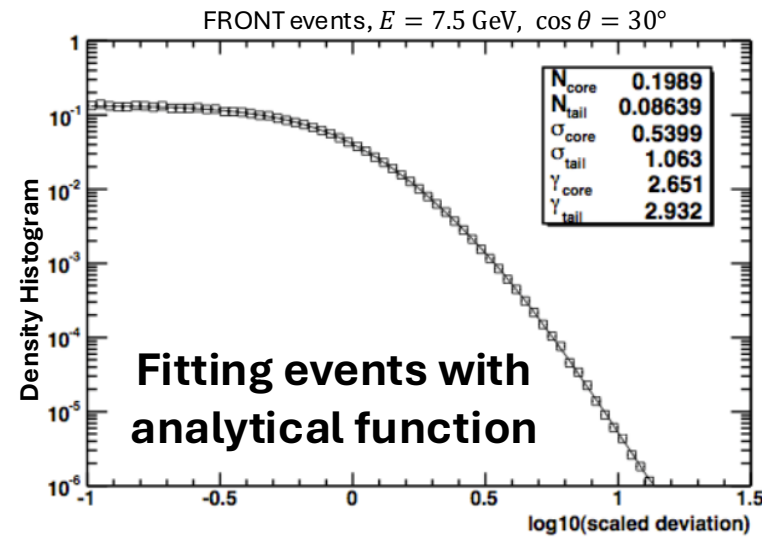
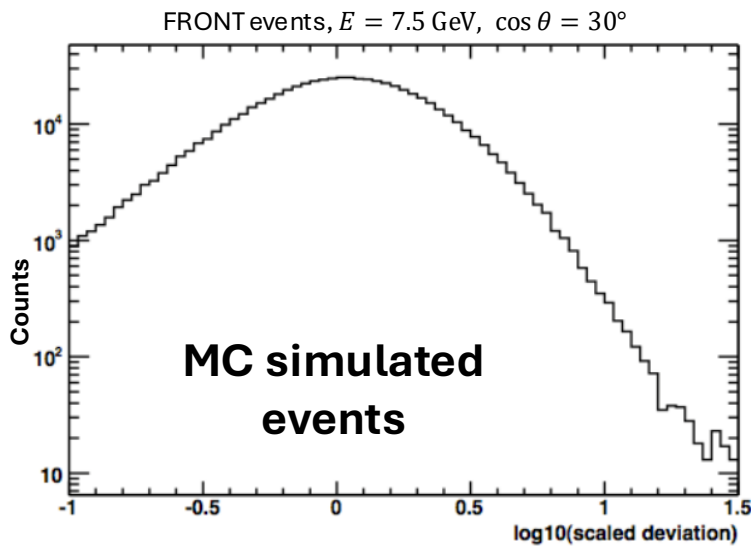
Credit: Wikipedia

PSF of Fermi-LAT

- Different ways to derive the PSF:

PSF of Fermi-LAT

- Different ways to derive the PSF:
 - ❖ Analytical definition by fitting events from Monte-Carlo simulations with different event reconstructions in different energy and inclination angle bins

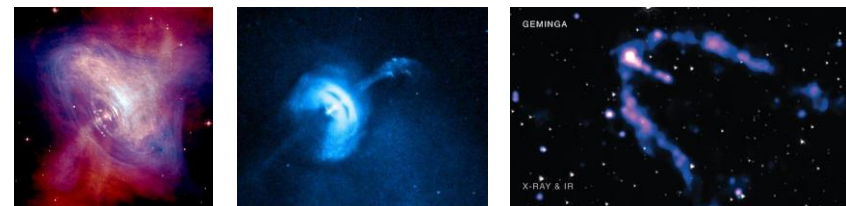


Credit: Fermi-LAT CICERONE documentation

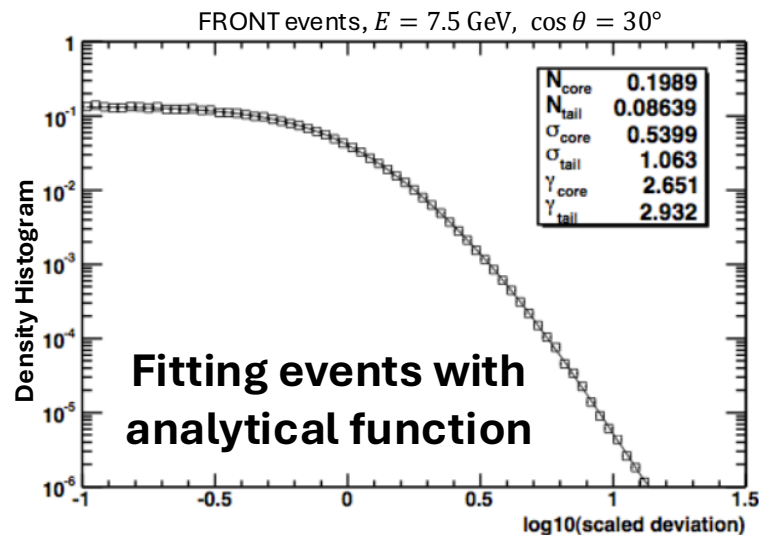
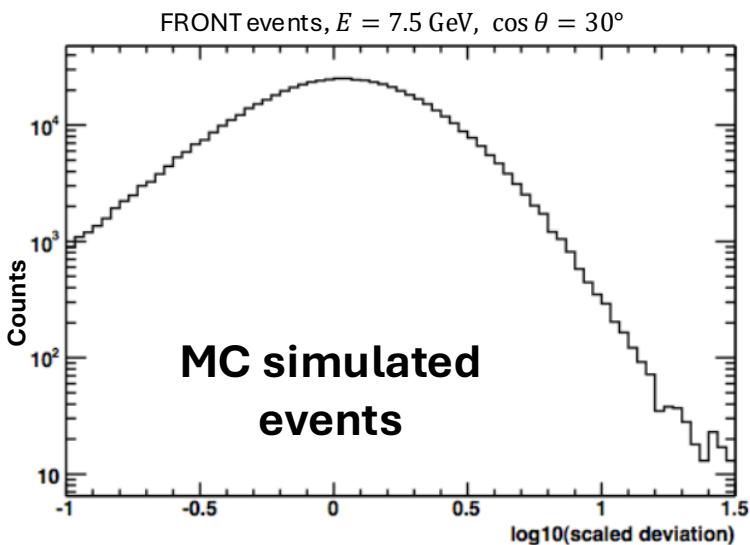
PSF of Fermi-LAT

➤ Different ways to derive the PSF:

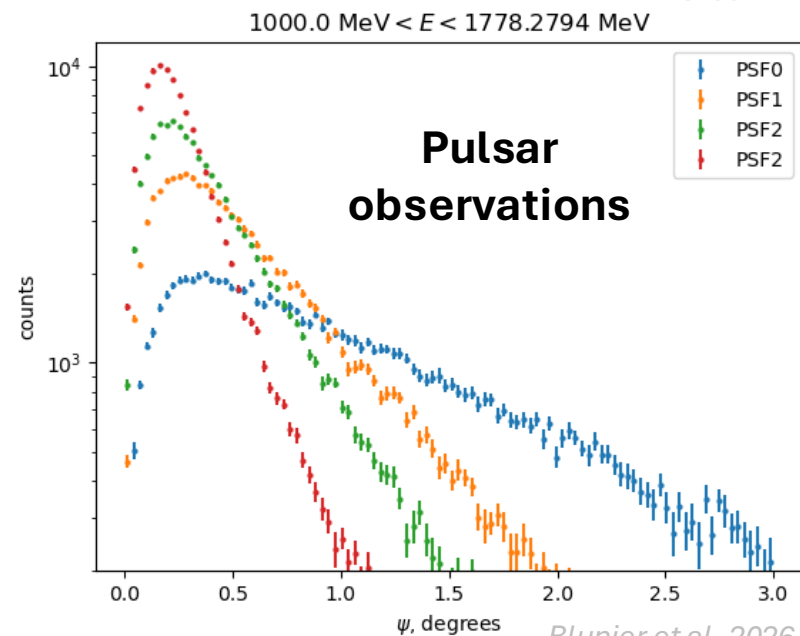
- ❖ Analytical definition by fitting events from Monte-Carlo simulations with different event reconstructions in different energy and inclination angle bins
- ❖ Data-driven from pulsar observations (genuine point sources)



Credit: NASA



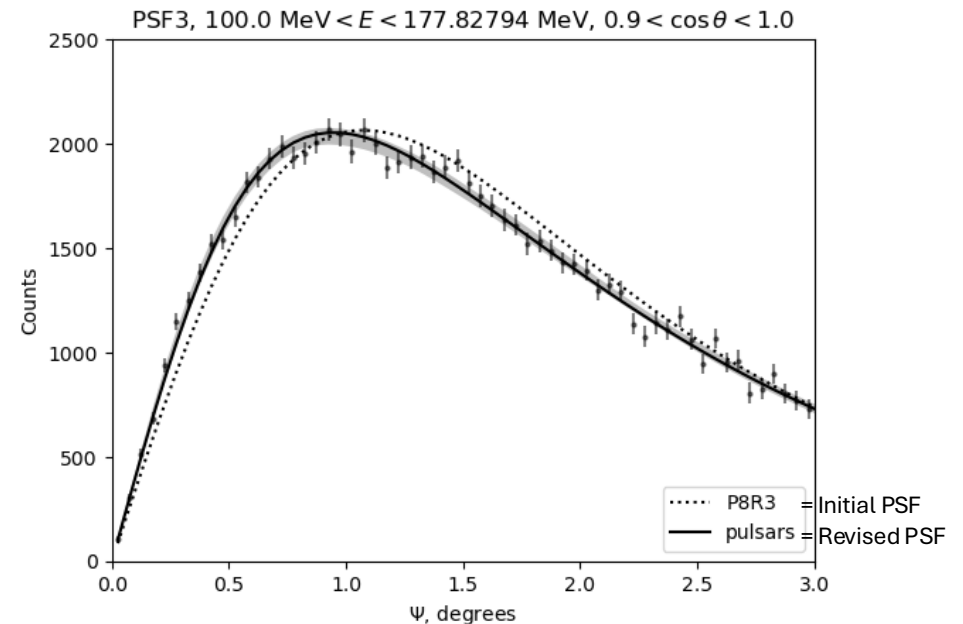
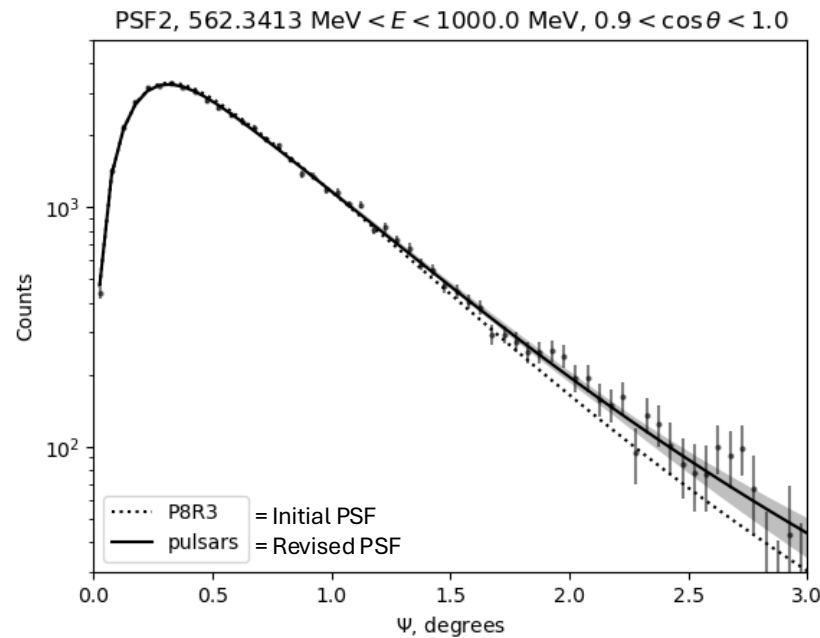
Credit: Fermi-LAT CICERONE documentation



Blunier et al. 2026

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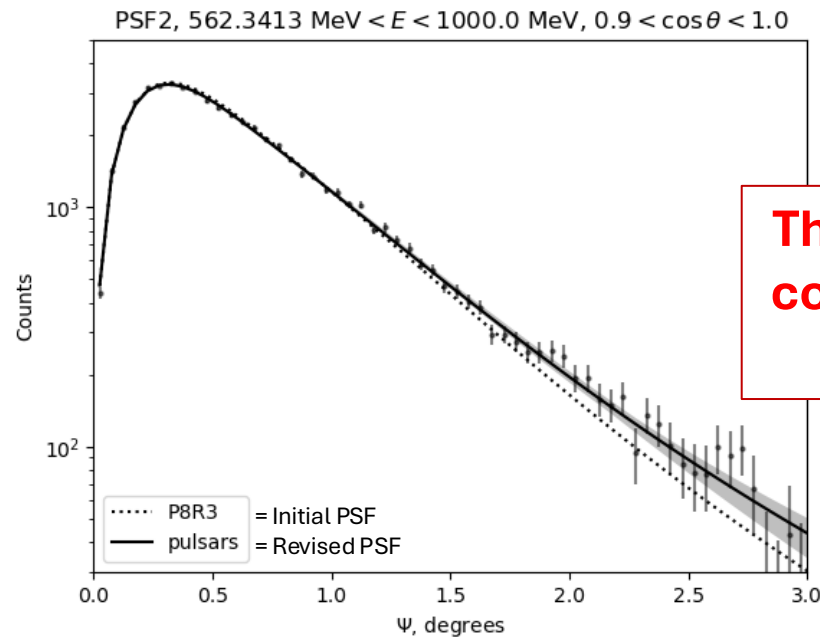
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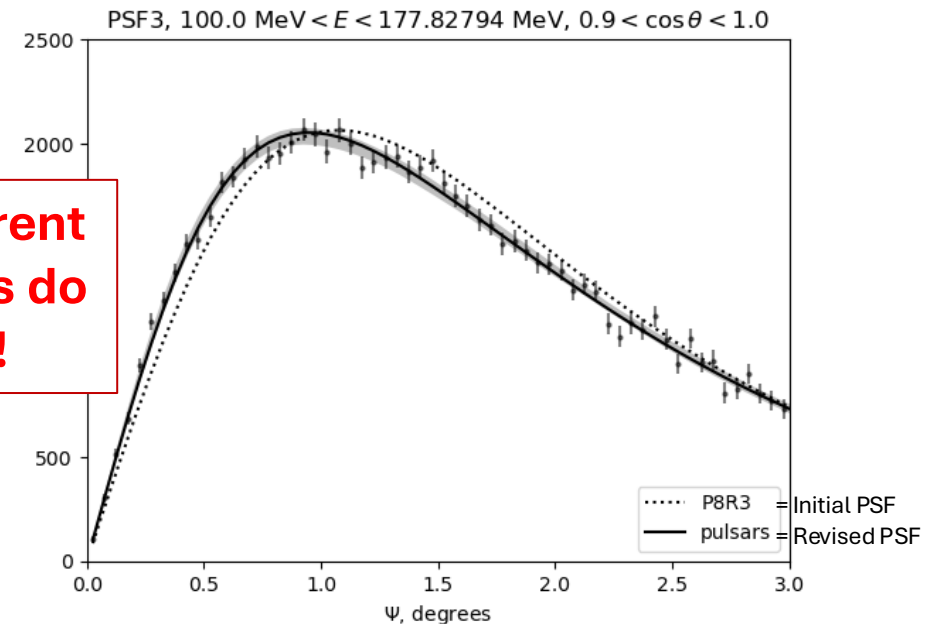
Blunier et al. 2026

PSF of Fermi-LAT

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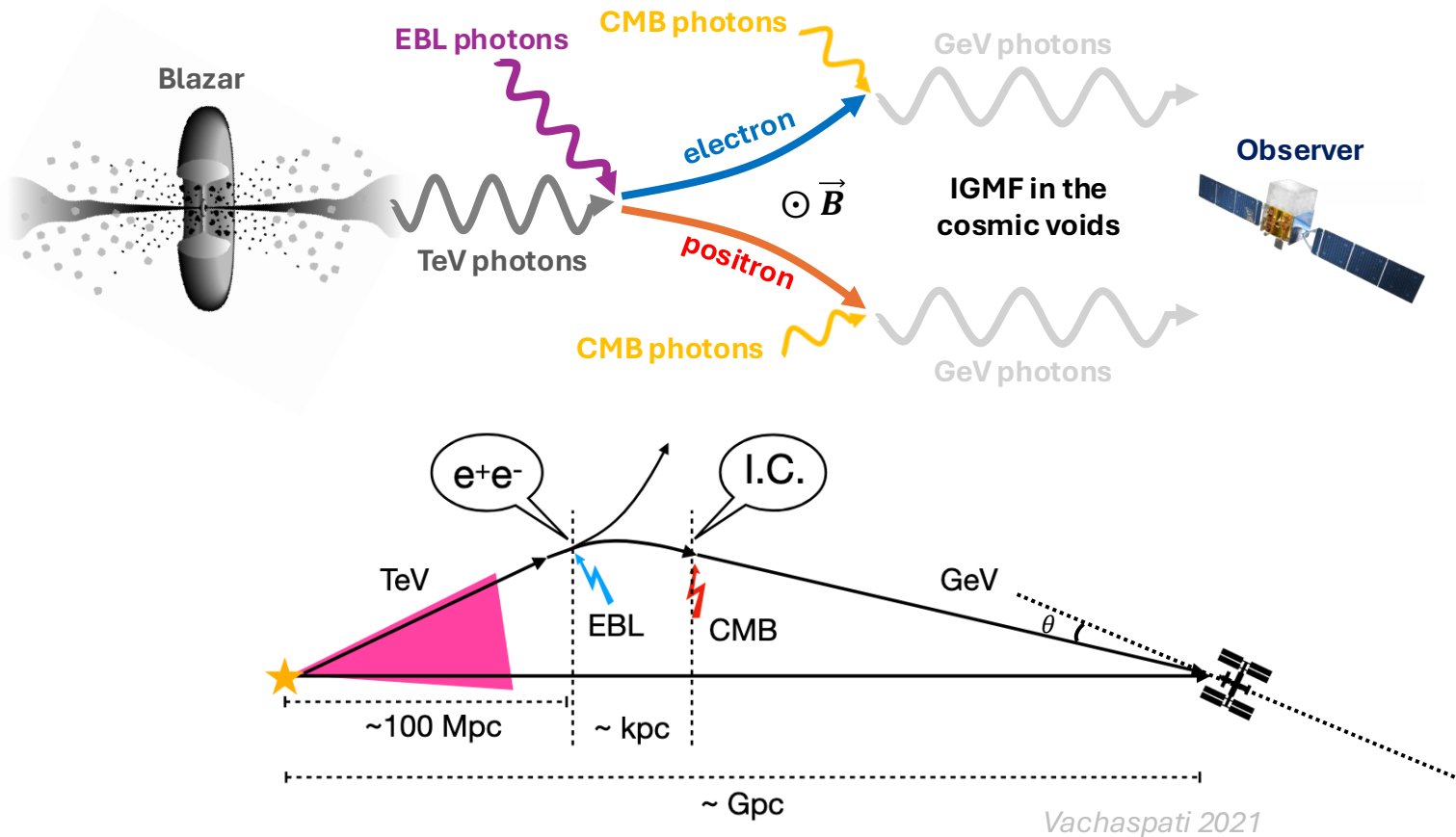
The two different computations do not agree !



Blunier et al. 2026

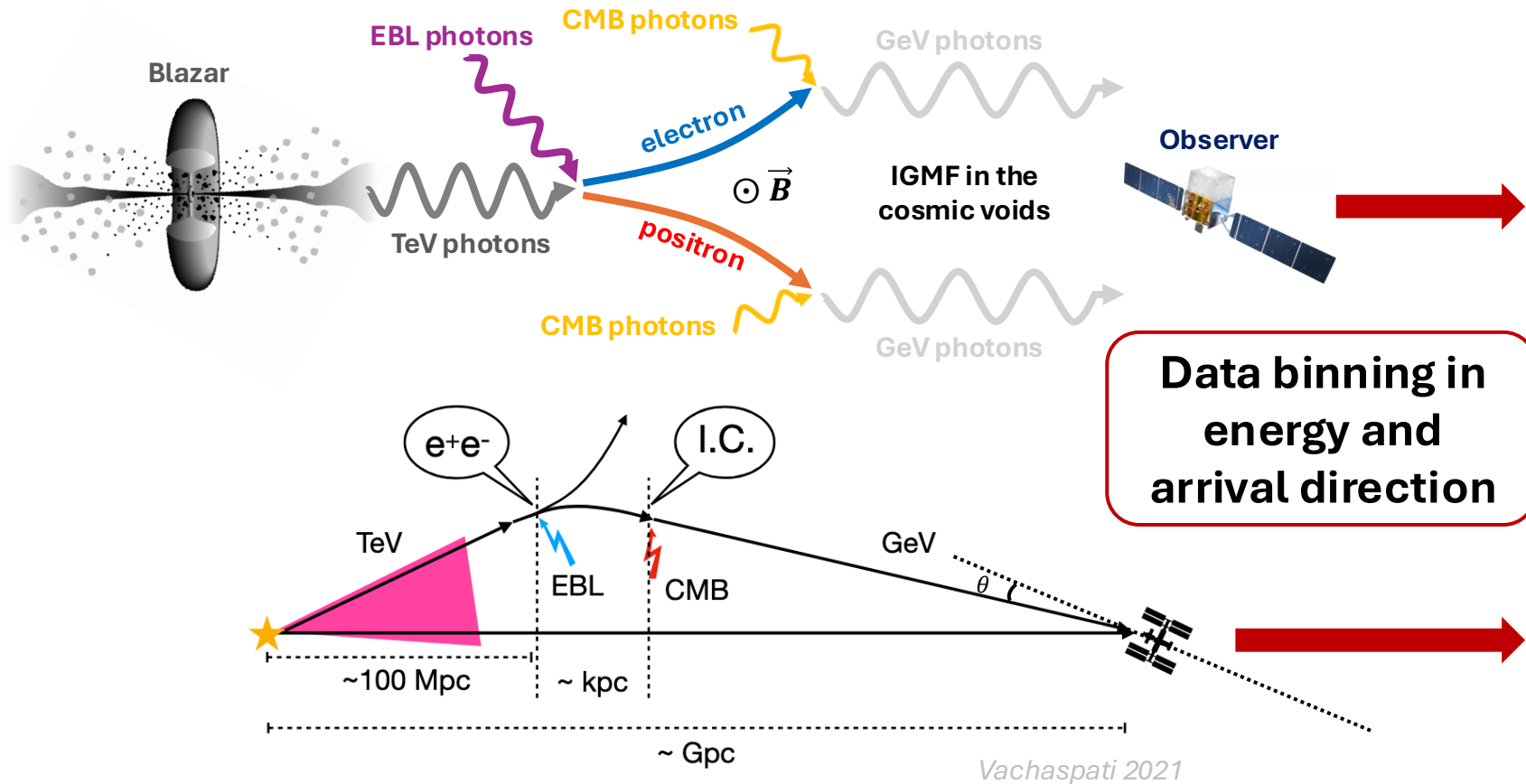
Search for extended emission around Mrk 501

- Secondary emission from blazars can create a halo around the source due to different arrival angles

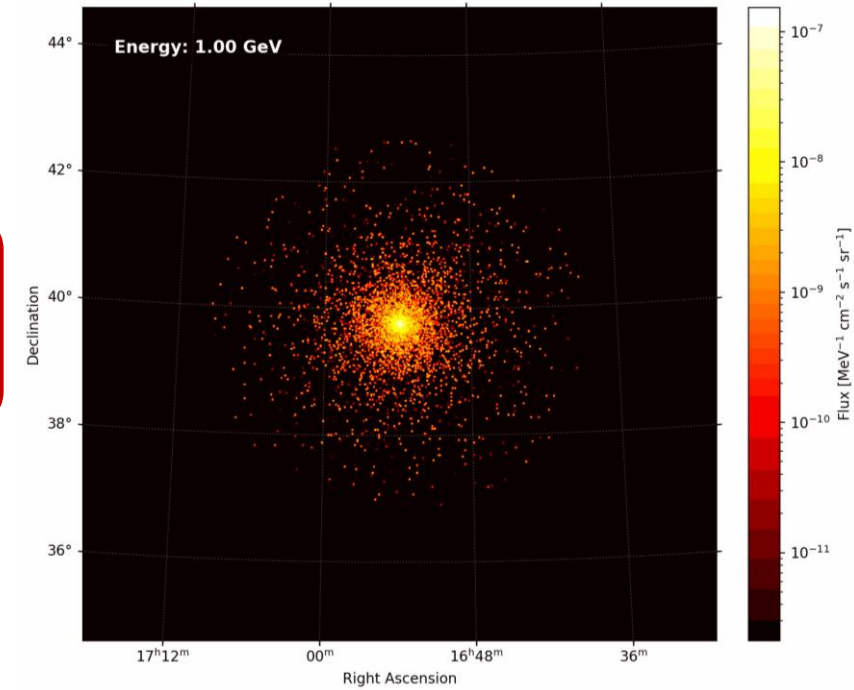


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Astronomical count image



Search for extended emission around Mrk 501

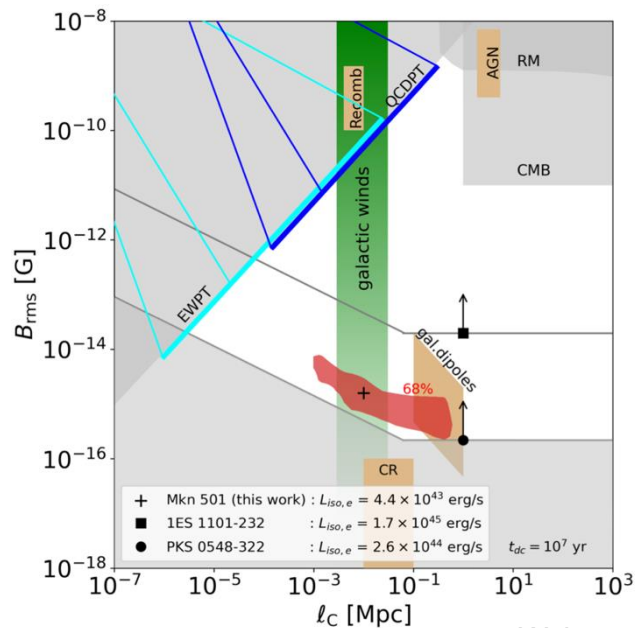
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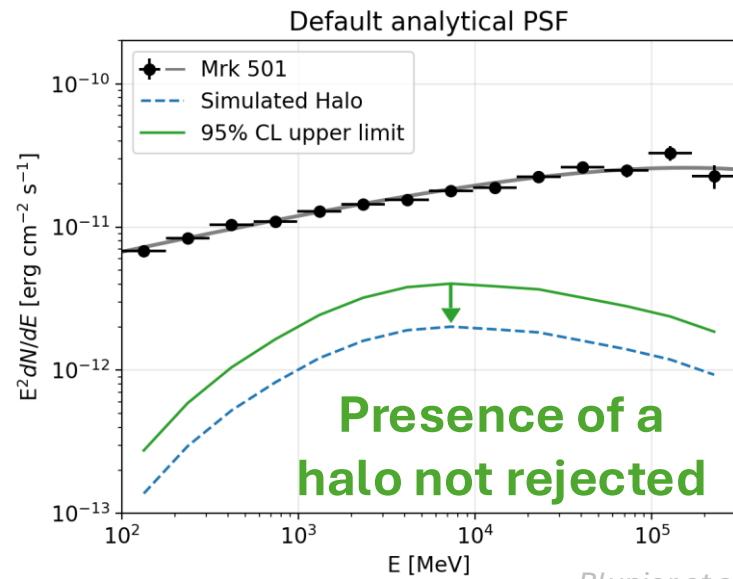
Webar et al. 2025

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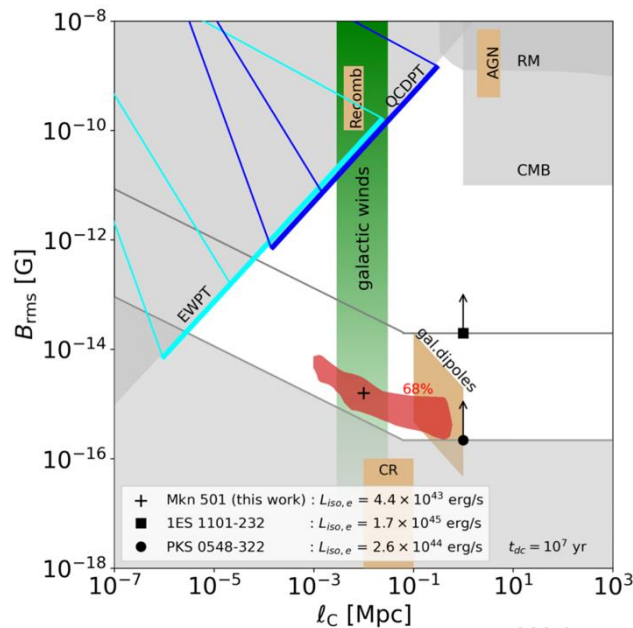
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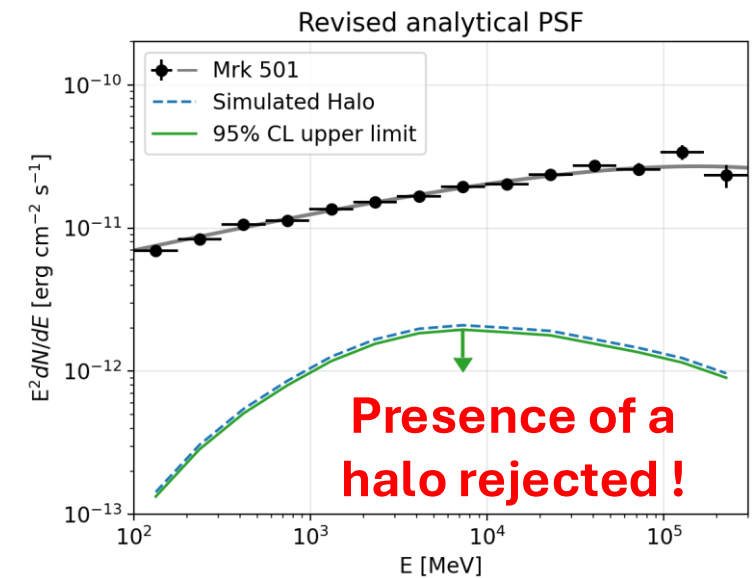
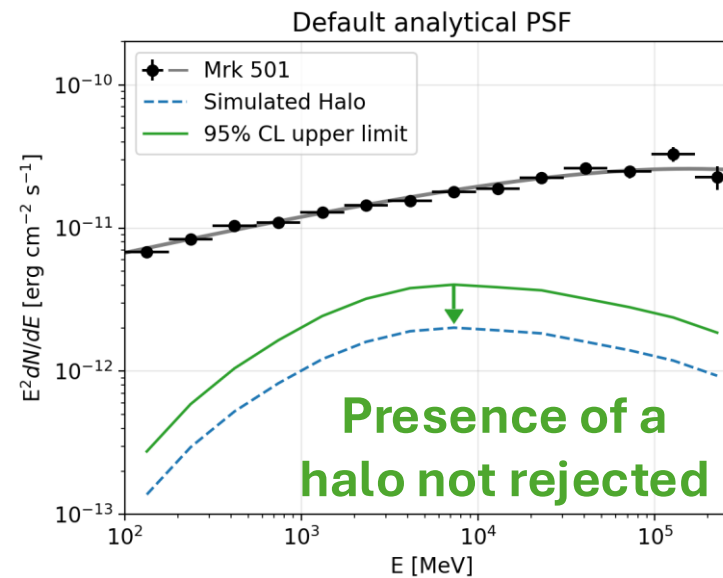
Blunier et al. 2026

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Webar et al. 2025



Blunier et al. 2026

Conclusions

- Probing the IGMF with gamma-ray observations may give us an insight on the origin of the cosmic magnetism of our Universe
- Only lower limits so far: Revision of conservative lower bound on IGMF in the voids of the LSS with a set of sources of interest called blazars

$$\diamond B_{all} > 1.3 \times 10^{-17} \text{ G}$$

- Identification of a new source, 1ES 0502+675, for IGMF study providing a tighter lower bound

$$\diamond B_{0502} > 2.1 \times 10^{-17} \text{ G}$$

- Modelling of PSF of Fermi-LAT is important to probe the measurement of the IGMF that can yield to false positive detection of secondary emission halo
- Need to improve estimation of intrinsic source spectrum parameters (E_{cut}) with next generation IACT (CTAO) and air shower arrays (LHAASO) for potential measurement of this field

Back up slides

Physics of electromagnetic cascade

- Interaction rate per unit path length:

$$R(E, z) = \frac{1}{2} \int_0^\infty dE' n(E', z) \int_{-1}^1 d\mu (1 - \beta\mu) \sigma(s), \quad \beta = \sqrt{(1 - m^2/E^2)}$$

- Breit-Wheeler Pair-Production cross-section:

$$\sigma_{\text{PP}} = \sigma_{\text{T}} \frac{3}{16} (1 - \beta^2) \left[(3 - \beta^4) \ln \frac{1 + \beta}{1 - \beta} - 2\beta(2 - \beta^2) \right], \quad \beta = \sqrt{1 - 4m_e^2/s}, \quad s = 2E_\gamma E_b(1 - \mu) \quad (\mu = \cos \theta)$$

- Inverse Compton scattering cross-section:

$$\sigma_{\text{ICS}} = \sigma_{\text{T}} \frac{3 m_e^2}{8 s \beta} \left[\frac{2}{\beta(1 + \beta)} (2 + 2\beta - \beta^2 - 2\beta^3) - \frac{1}{\beta^2} (2 - 3\beta^2 - \beta^3) \ln \frac{1 + \beta}{1 - \beta} \right], \quad \beta = (s - m_e^2)/(s + m_e^2)$$
$$s = m_e^2 + 2E_e E_b(1 - \mu)$$

Computation of Fermi-LAT spectra

- September 2008 – March 2025, *P8R3_SOURCEVETO_V3* class → lowest residual CR background
- Suppressed diffuse emission background at high galactic latitude $|b| > 10^\circ$
- Fermi Science Tools tool chain *gtselect-gtmktime-gtlcube-gtexpmap*
- Aperture photometry method for photon counts S with 68% / 95% containment radii R_{68}^2 / R_{95}^2 of the PSF (*Neronov & Semikoz 2025*):

$$S = (R_{95}^2 C_{68} - R_{68}^2 C_{95}) / (0.68 R_{95}^2 - 0.95 R_{68}^2) \text{ for } E < 50 \text{ GeV}$$

$$S = C_{95} / 0.95 \text{ for } E > 50 \text{ GeV (background free)}$$

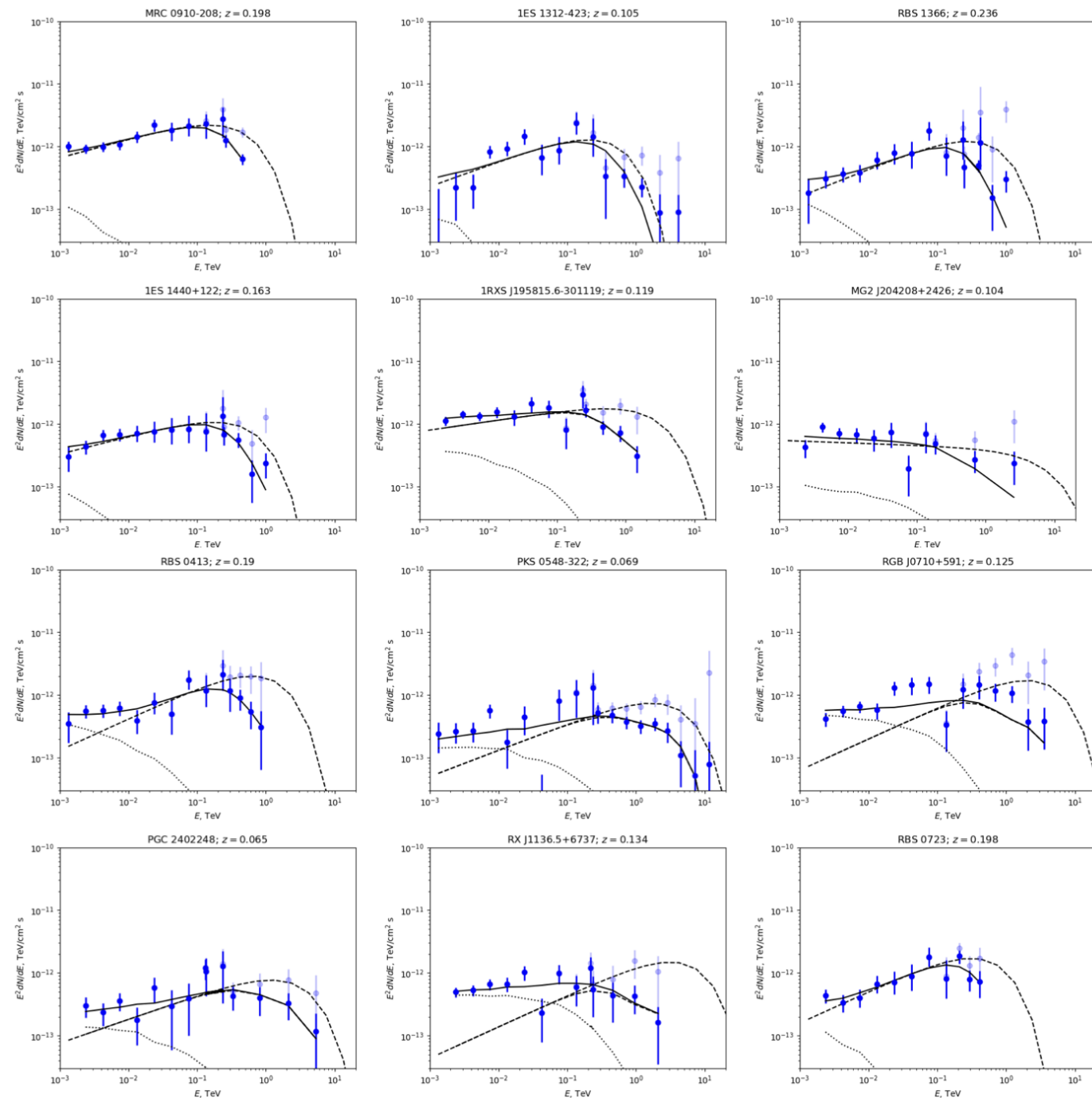
- 4σ detection for sources having ≥ 3 photons with $E > 100 \text{ GeV}$ in R_{68}

Selection of extreme blazars for IGMF study

- Catalog of Very High Energy ($E > 100$ GeV) AGNs at high galactic latitude $|b| > 10^\circ$ from Fermi-LAT telescope (*Neronov & Semikoz 2025*) cross-checked with available Imaging Atmospheric Cherenkov Telescopes (HESS, VERITAS, MAGIC)
- 7 extreme blazars extracted with incompatible zero magnetic field fit

Name	RA	Dec	Time	Γ	E_{cut}	z	χ_∞^2/dof	χ_0^2/dof
1 SHBL J001355.9-185406	3.48	-18.912	41.5h H(1)	$1.68^{+0.08}_{-0.12}$	$0.8^{+0.5}_{-0.3}$	0.095	2.86/10	3.3/10
2 1ES 0229+200	38.214	20.316	144.1h H(2)	$1.63^{+0.03}_{-0.05}$	> 3.6	0.14	13.9/16	50.1/16
			54h V(3)					
			145.5h M(4)					
3 RBS 0413	49.972	18.753	48h V(5)	$1.72^{+0.15}_{-0.17}$	> 0.8	0.19	8.4/11	6.3/11
4 1ES 0347-121	57.354	-11.994	59.2h H(2)	$1.62^{+0.05}_{-0.06}$	> 0.9	0.188	29.1/16	37.1/16
5 1ES 0502+675	76.996	67.622	13h V(6)	$1.50^{+0.03}_{-0.06}$	> 1.0	0.314	17.7/14	85.3/14
6 PKS 0548-322	87.625	-32.277	53.9h H(2)	$1.80^{+0.03}_{-0.03}$	> 3.7	0.069	26.3/16	24.7/16
7 RGB J0710+591	107.623	59.135	22.1h V(7)	$1.76^{+0.05}_{-0.05}$	> 3.2	0.125	26.3/11	26.8/11
8 PGC 2402248	113.362	51.88	50h M(8)	$1.78^{+0.03}_{-0.02}$	> 1.3	0.065	9.2/11	9.7/11
9 RBS 0723	131.812	11.569	45.3h M(9)	$1.57^{+0.12}_{-0.15}$	> 0.2	0.198	6.2/8	5.2/8
10 MRC 0910-208	138.227	-21.045	17h H(10)	$1.75^{+0.05}_{-0.08}$	$0.6^{+0.5}_{-0.2}$	0.198	5.6/9	5.0/9
11 1ES 1101-232	165.909	-23.496	71.9h H(2)	$1.58^{+0.04}_{-0.04}$	> 2.0	0.186	10.3/15	44.2/15
12 RX J1136.5+6737	174.118	67.613	30h M(11)	$1.86^{+0.06}_{-0.06}$	> 1.0	0.134	7.9/10	7.7/10
13 1ES 1312-423	198.768	-42.611	150h H(12)	$1.69^{+0.09}_{-0.12}$	$0.8^{+0.6}_{-0.4}$	0.105	23.6/12	25.6/12
14 RBS 1366	214.494	25.724	56h V(13)	$1.71^{+0.05}_{-0.09}$	> 0.4	0.236	12.7/12	14.7/12
15 H 1426+428	217.129	42.678	73.5h V(14)	$1.795^{+0.015}_{-0.015}$	> 3.2	0.129	22.1/17	26.9/17
16 1ES 1440+122	220.698	12.013	53h V(15)	$1.77^{+0.09}_{-0.08}$	> 0.3	0.163	5.8/11	6.6/11
17 1ES 1727+502	262.078	50.227	508d L(16)	$1.83^{+0.08}_{-0.06}$	$2.0^{+1.3}_{-0.4}$	0.055	17.2/12	20.0/12
18 1ES 1741+196	266.008	19.596	30h V(17)	$1.96^{+0.06}_{-0.06}$	> 0.4	0.08	7.0/10	6.9/10
19 1RXS J195815.6-301119	299.581	-30.181	7.3h H(10)	$1.90^{+0.03}_{-0.05}$	> 0.9	0.119	5.5/11	5.7/11
20 MG2 J204208+2426	310.536	24.458	52.5h M(9)	$1.95^{+0.05}_{-0.05}$	> 0.6	0.104	14.1/9	13.7/9
21 H 2356-309	359.772	-30.637	150.5h H(2)	$1.63^{+0.03}_{-0.05}$	$1.5^{+1.3}_{-0.5}$	0.165	20.4/16	26.1/16

Sources that do not yield IGMF constraint



Sources that do yield IGMF constraint

Name	$B_{min}/10^{-17} \text{ G}$
1ES 0229+200	0.5
1ES 0347-121	0.07
1ES 0502+675	2.1
1ES 1101-232	0.6
H 1426+428	0.13
1ES 1727+502	0.02
H 2356-309	0.12

Table 2: Limits on IGMF from individual sources.

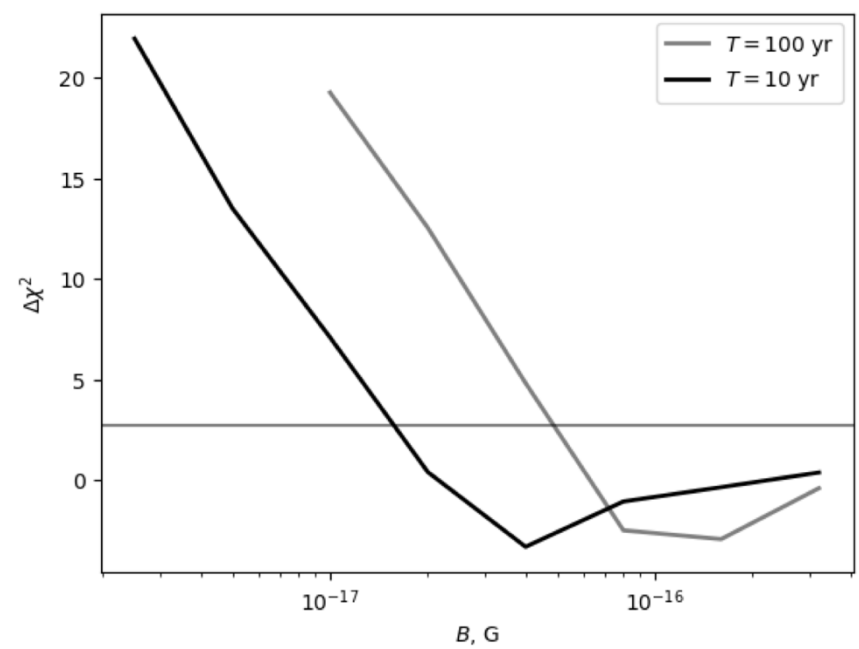
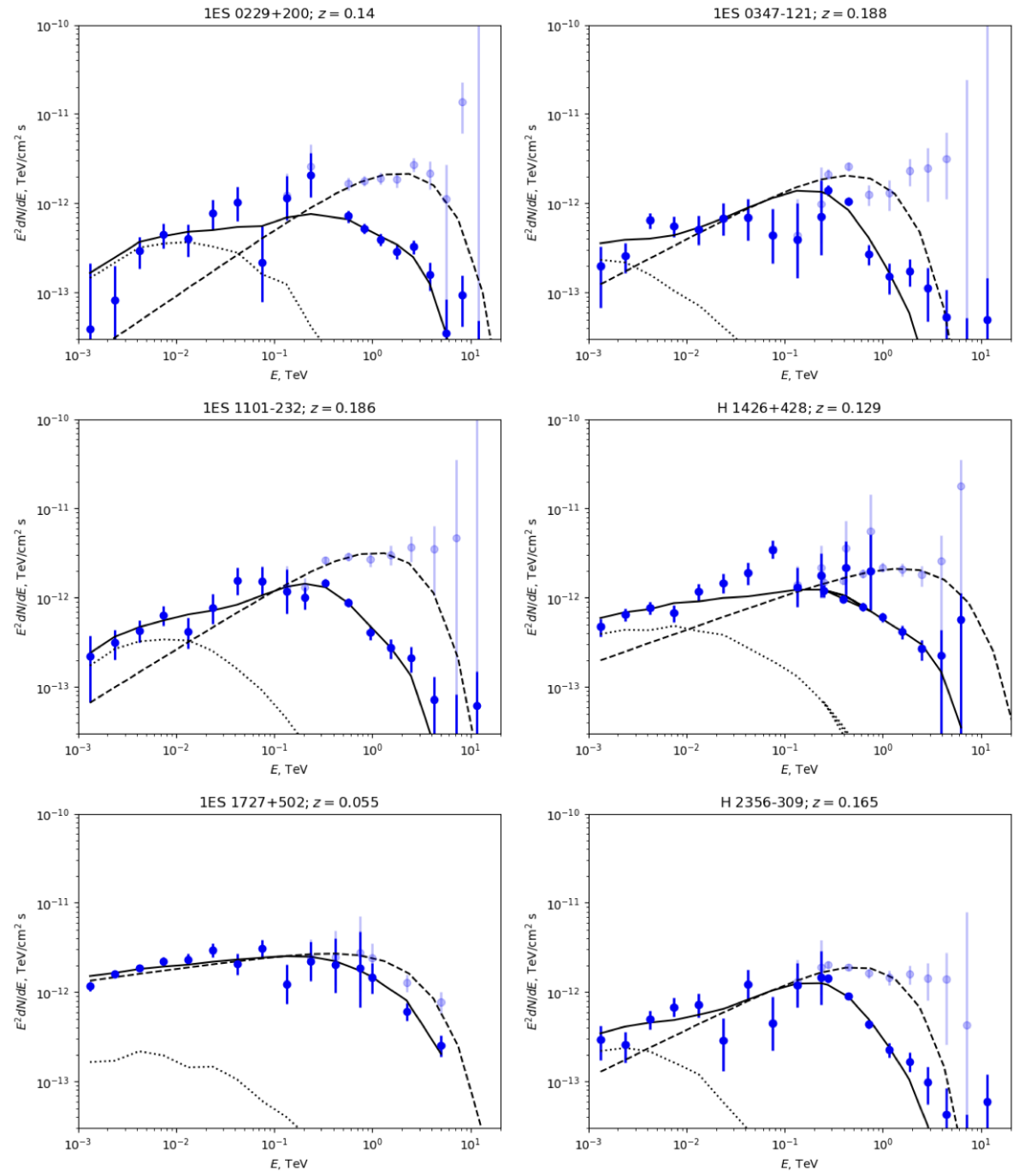


Fig. 5: Comparison of $\Delta\chi^2(B)$ profiles for 1ES 0502+675 for two different assumptions about source activity period.



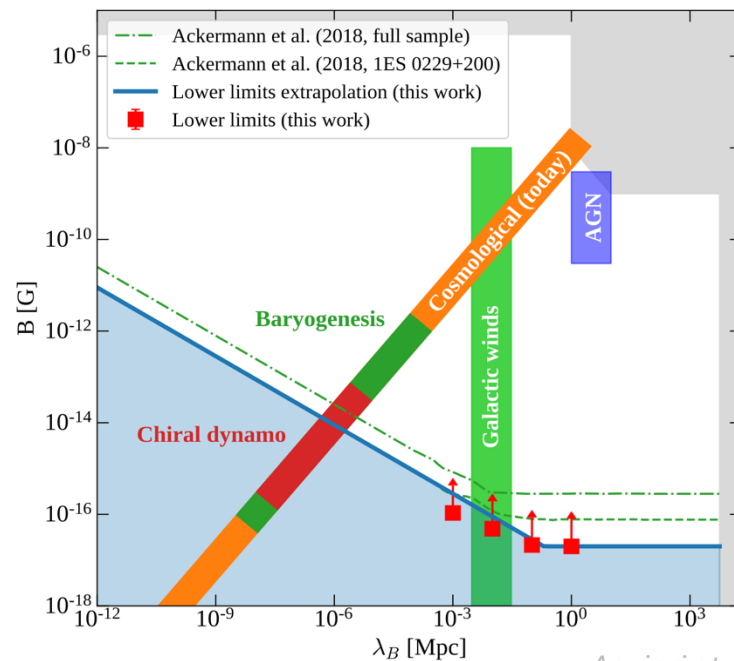
Comparison to previous conservative bounds

➤ *Acciari et al. 2023* : Study of blazar 1ES 0229+200 with Fermi-LAT + IACTs observations over $T \sim 10$ yr

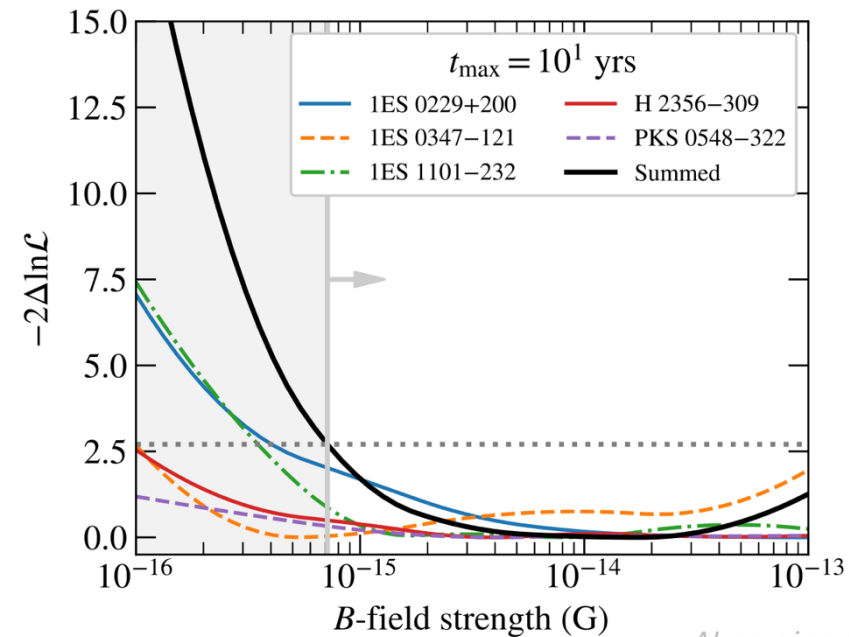
$$\diamond B_{0229} > 1.8 \times 10^{-17} \text{ G}$$

➤ *Aharonian et al. 2023* : Study of 5 blazars with Fermi-LAT + HESS observations over $T \sim 10$ yr

$$\diamond B_{all} > 7.1 \times 10^{-16} \text{ G}, B_{0229} > 4.0 \times 10^{-16} \text{ G}$$



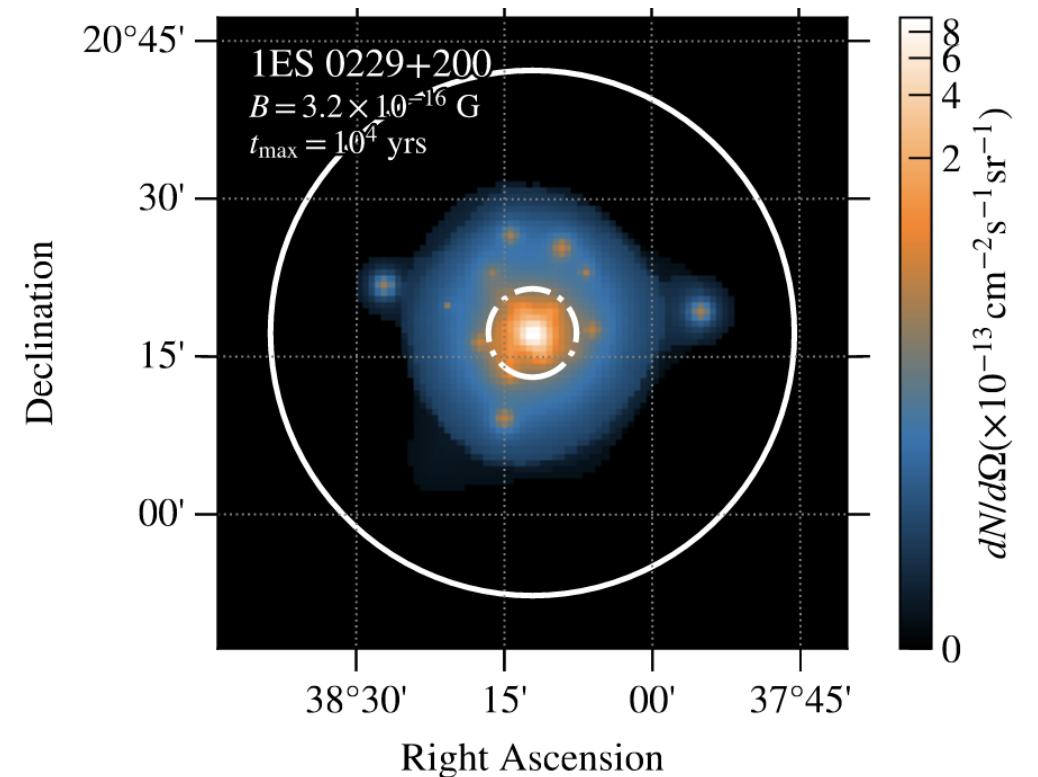
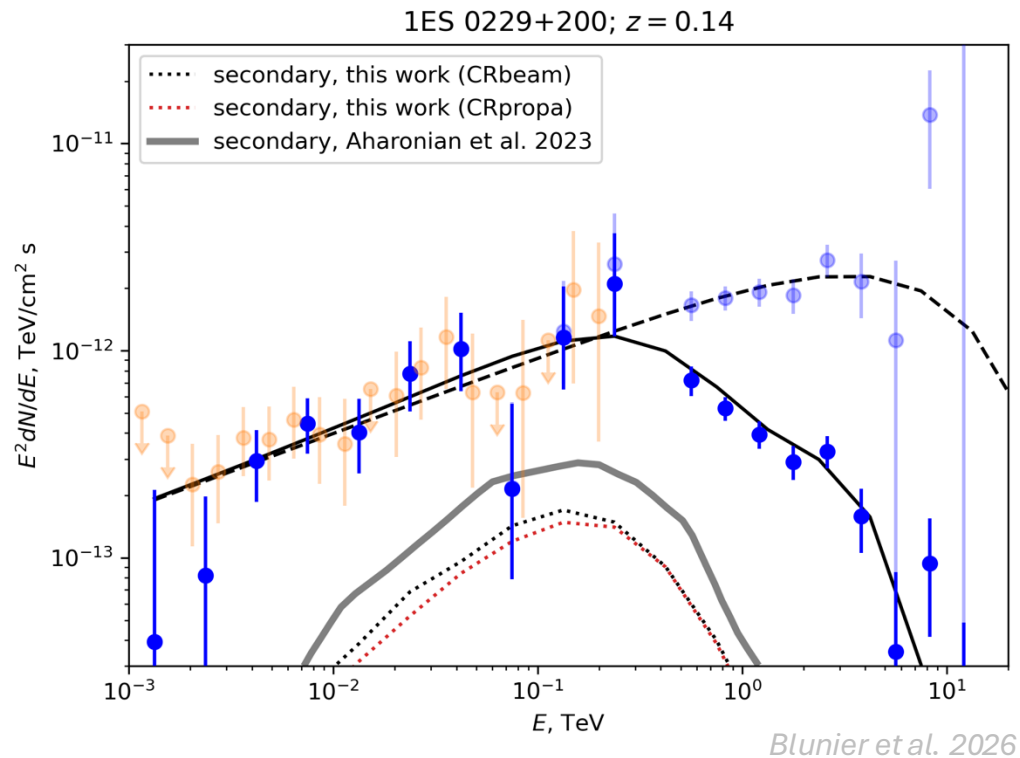
Acciari et al. 2023



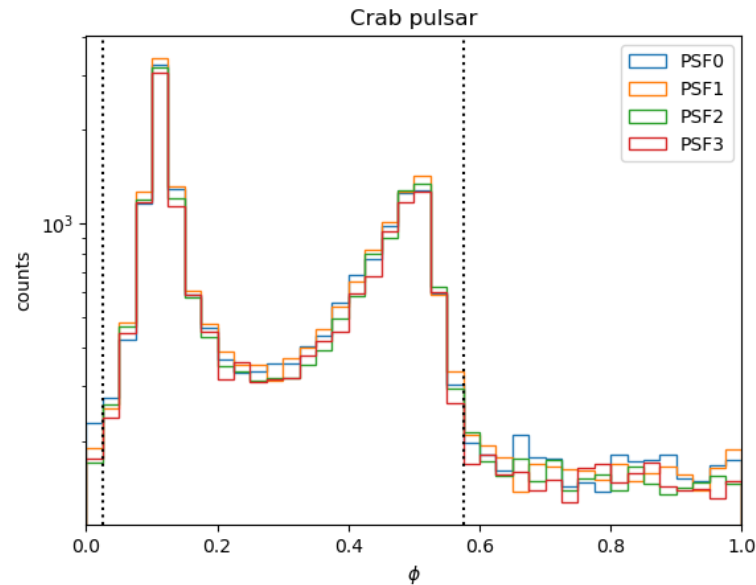
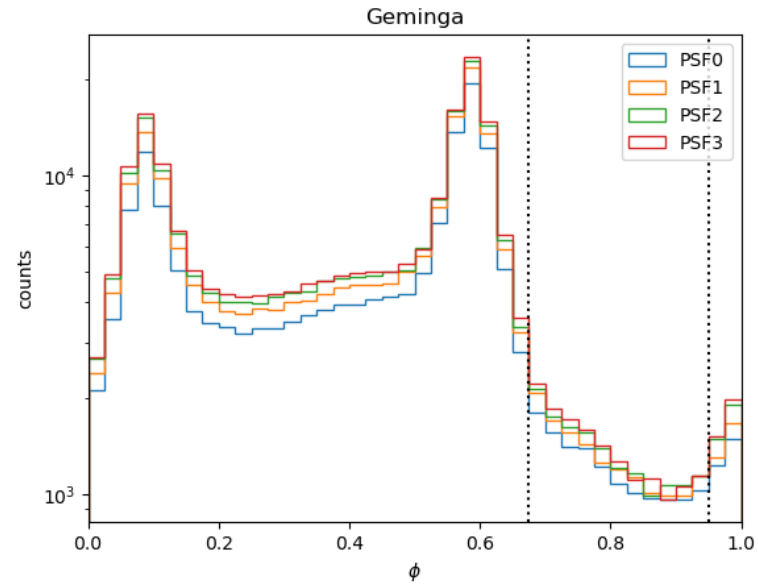
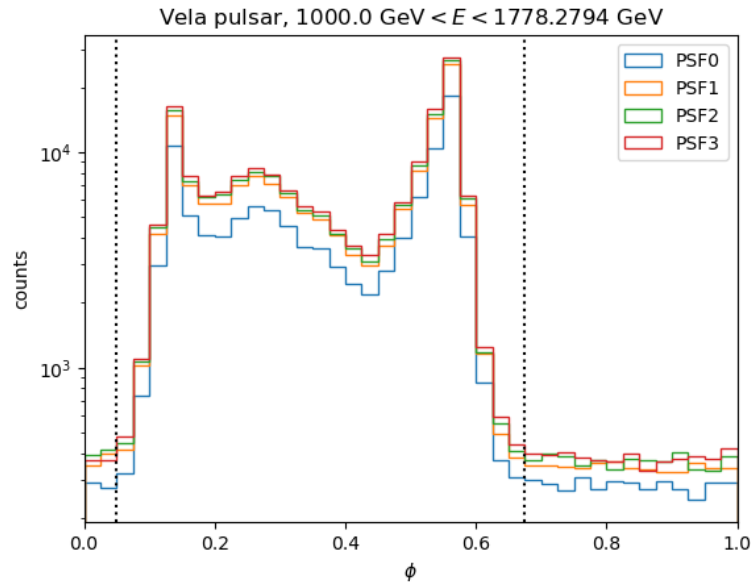
Aharonian et al. 2023

Comparison with Aharonian et al. 2023

- Resolution needed to observe secondary emission with $T \sim 10$ yr: $\theta \sim 10''$
- Difference in secondary flux modelling for 10 yr activity time



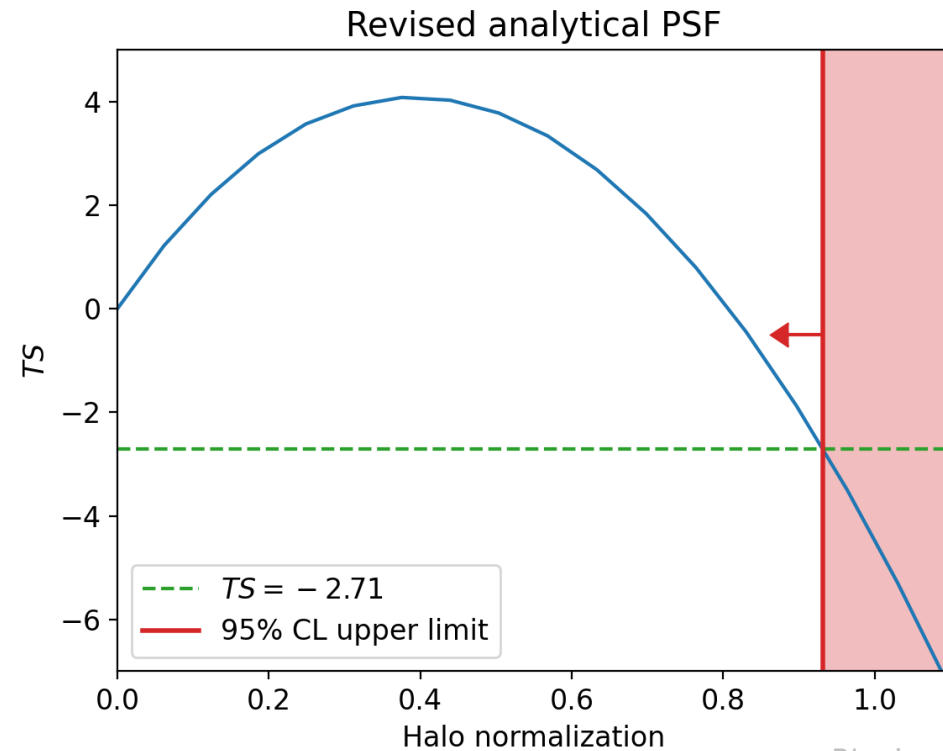
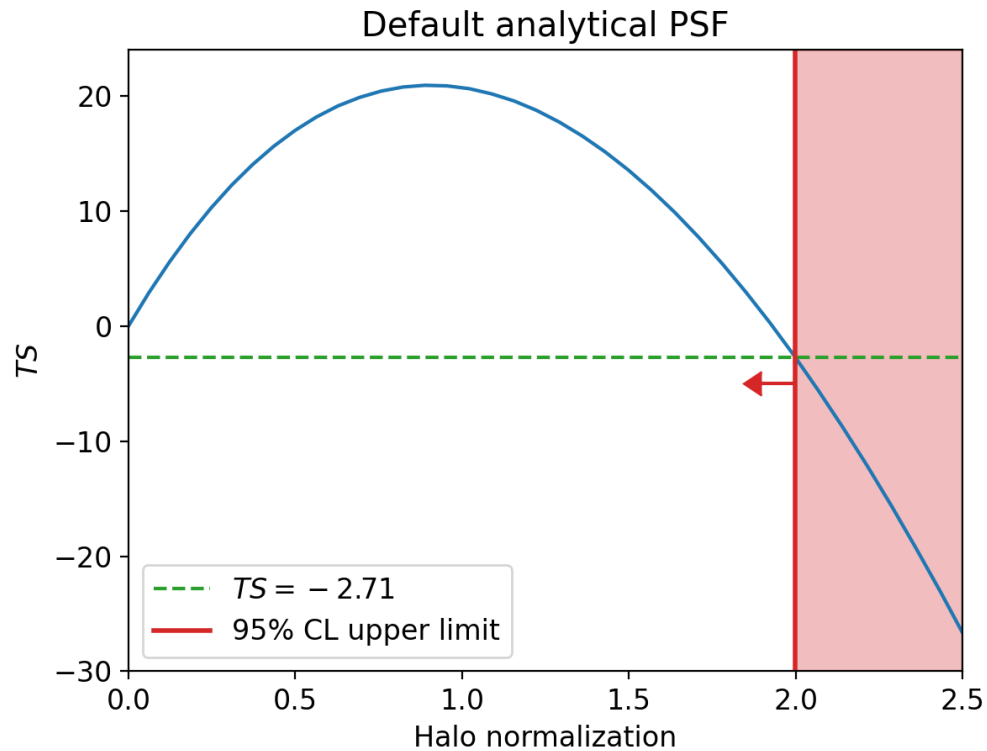
Data-driven PSF from Pulsar observations



Blunier et al. 2026

Likelihood scan of halo normalization

- Scan of the normalization parameter space of the halo up to the worse possible accepted upper limit at a 95% confidence level for the analytical and revised PSF of Fermi-LAT



Blunier et al. 2026