Probing the intergalactic magnetic field through gamma-ray observations with the *Fermi* LAT and H.E.S.S.

Manuel Meyer for the H.E.S.S. and Fermi LAT collaborations
mey@sdu.dk

Cosmic Magnetism in Voids and Filaments Conference, Bologna, January 25, 2023

Indirect detection of the IGMF

Using gamma-ray observations of blazars

See also talk by R. Alves Batista and A. Neronov

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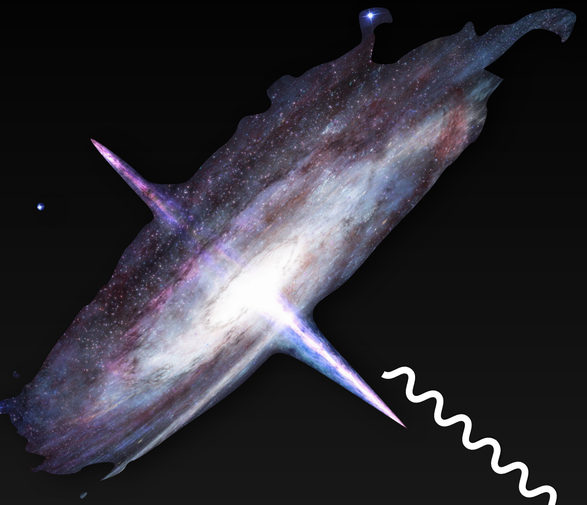

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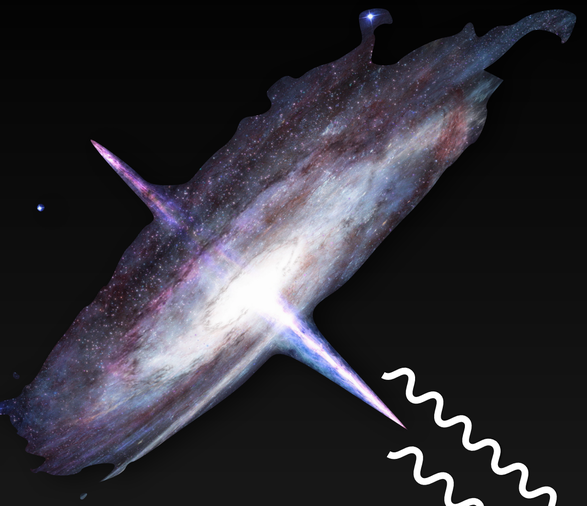

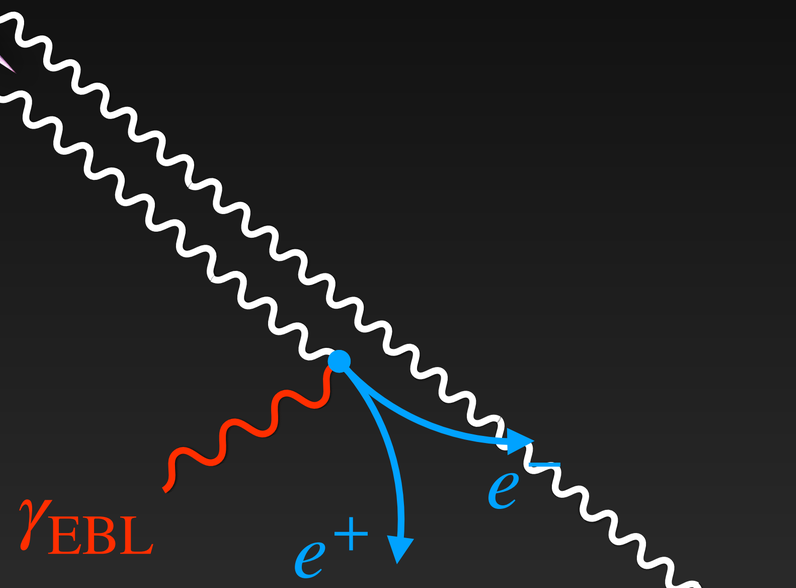

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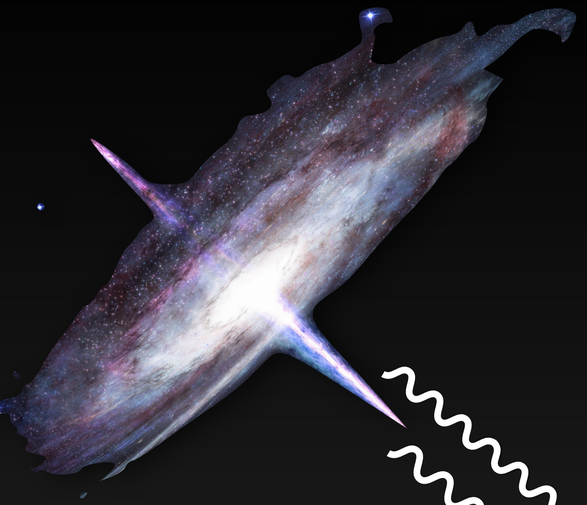

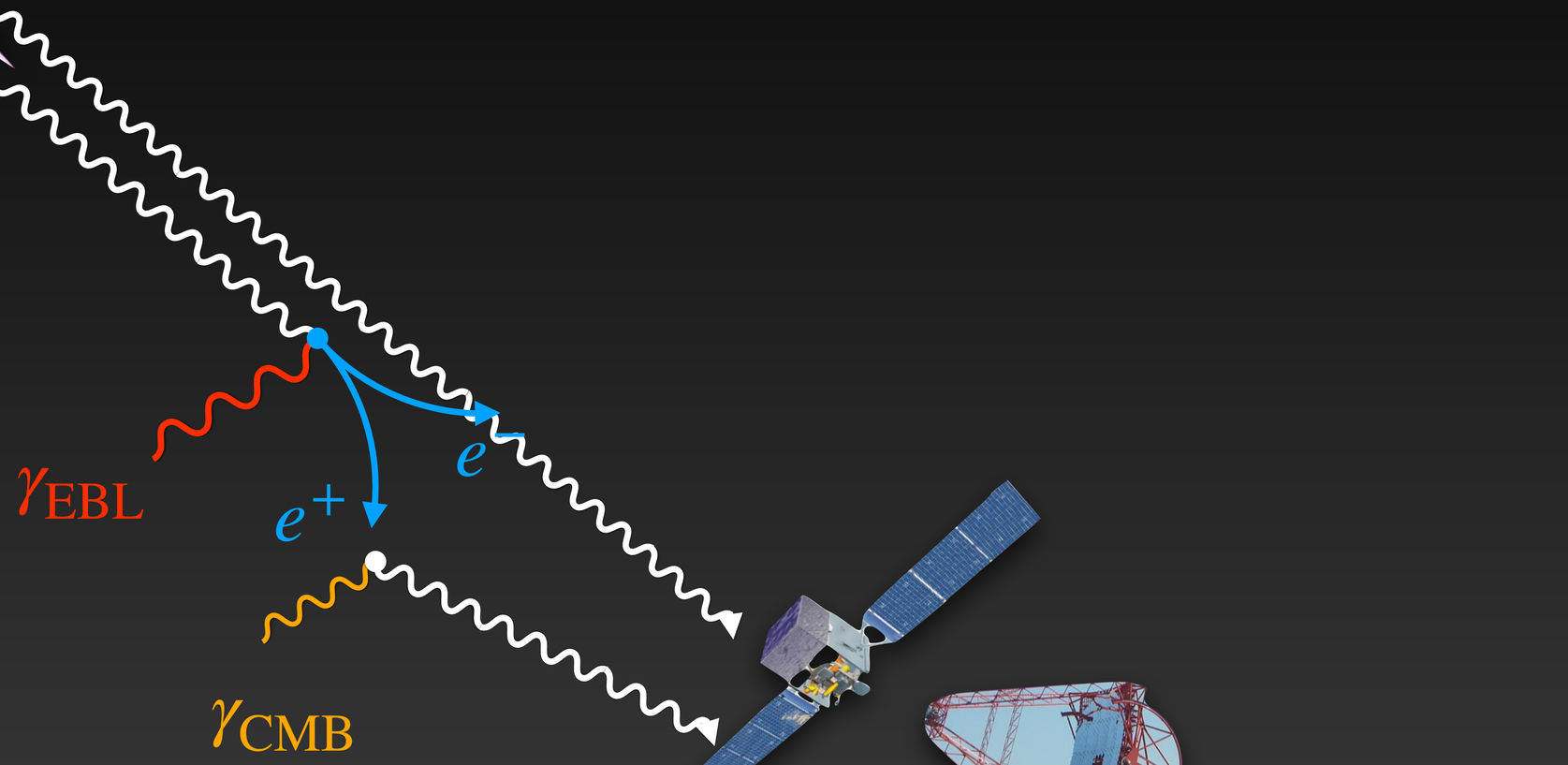

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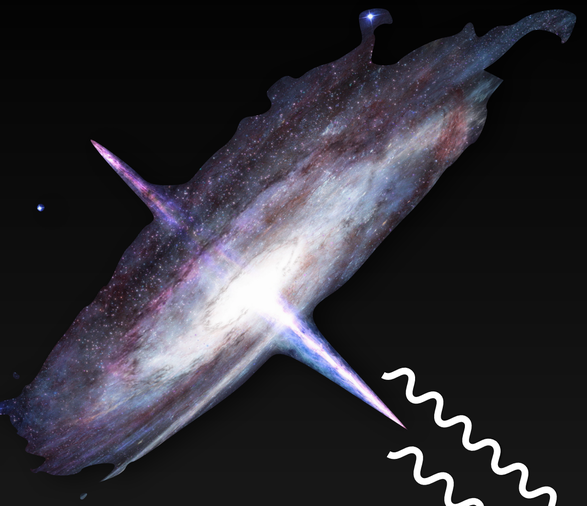

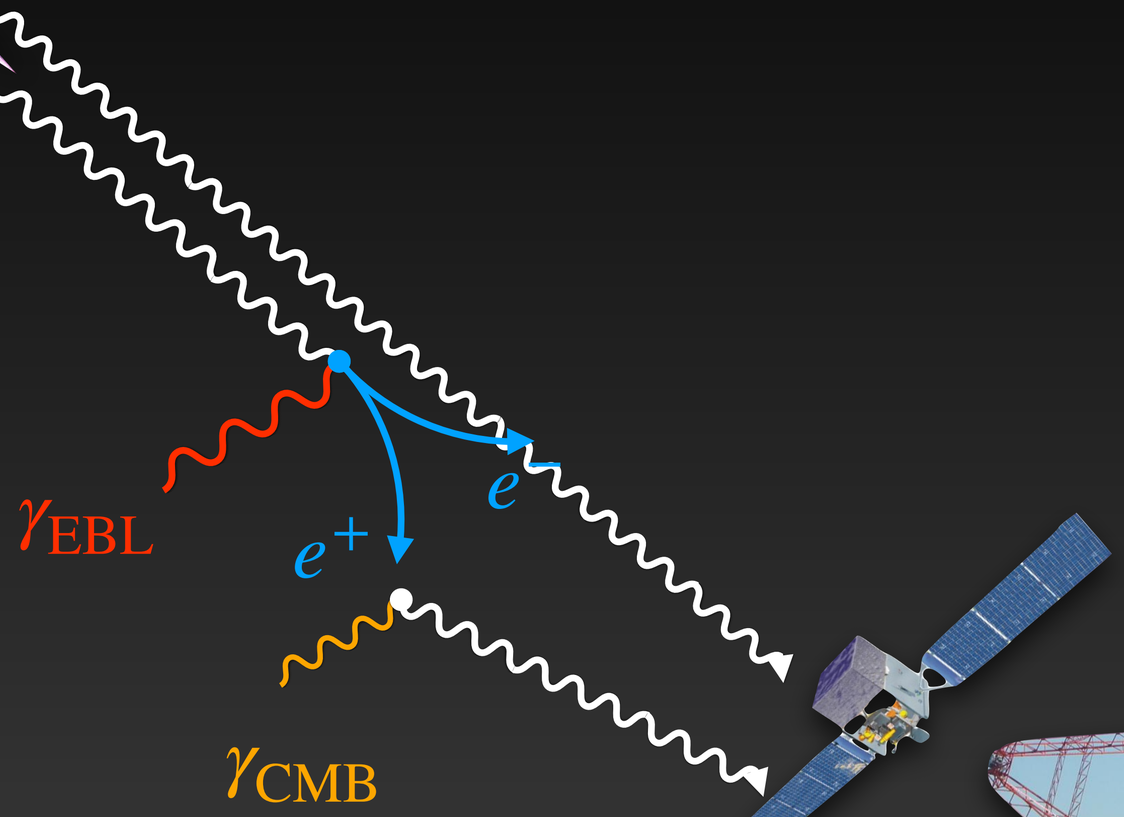

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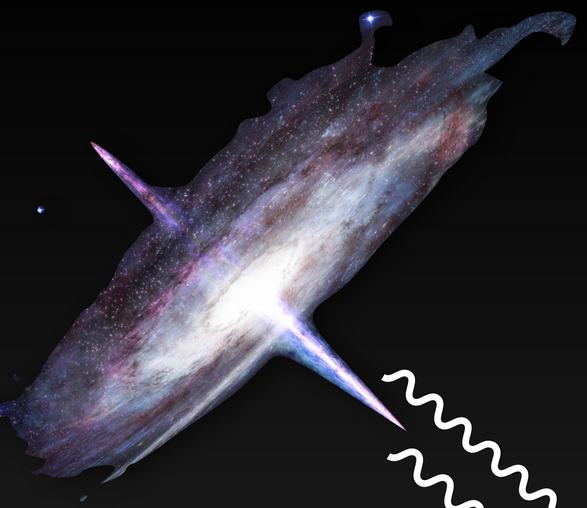

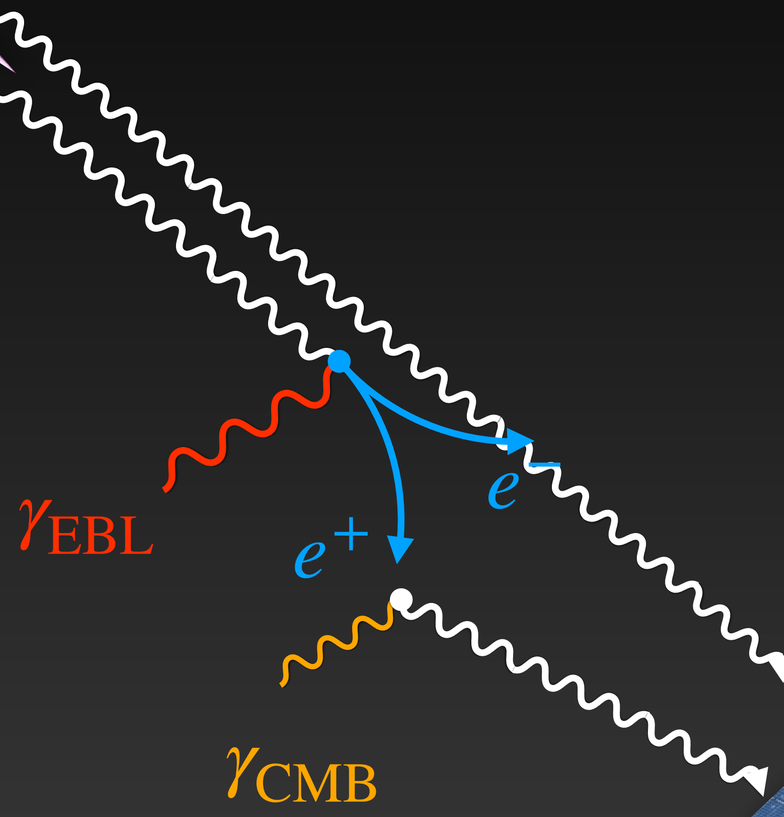

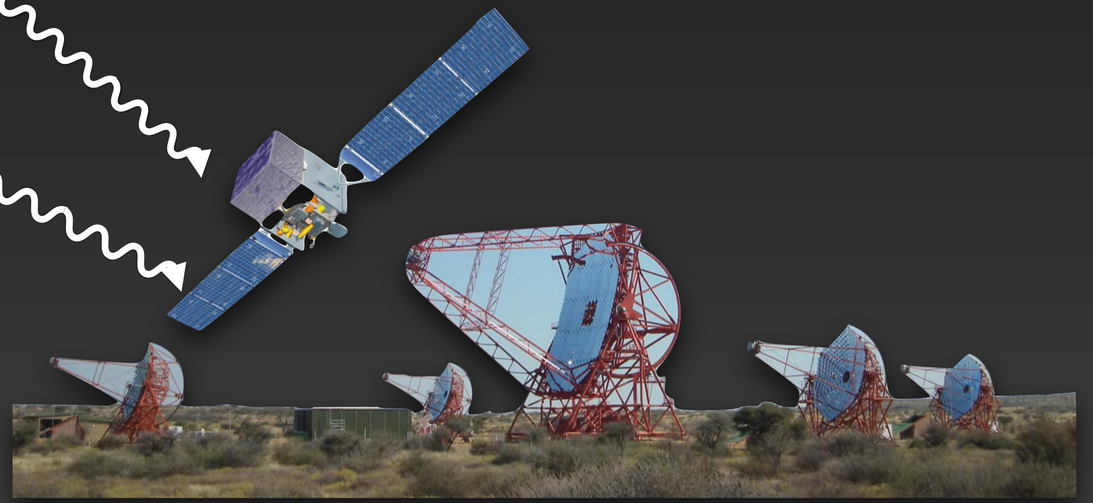

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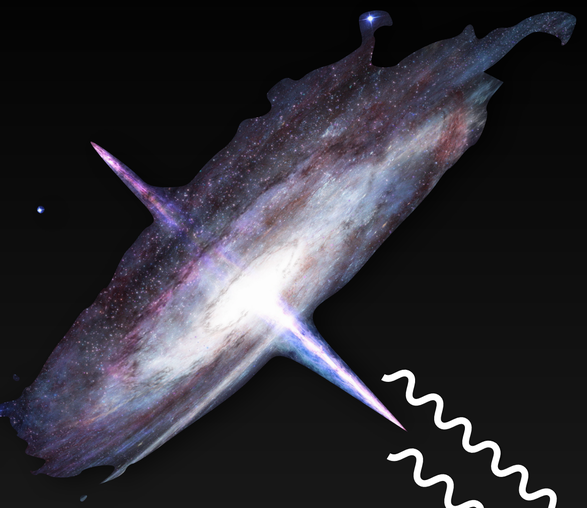

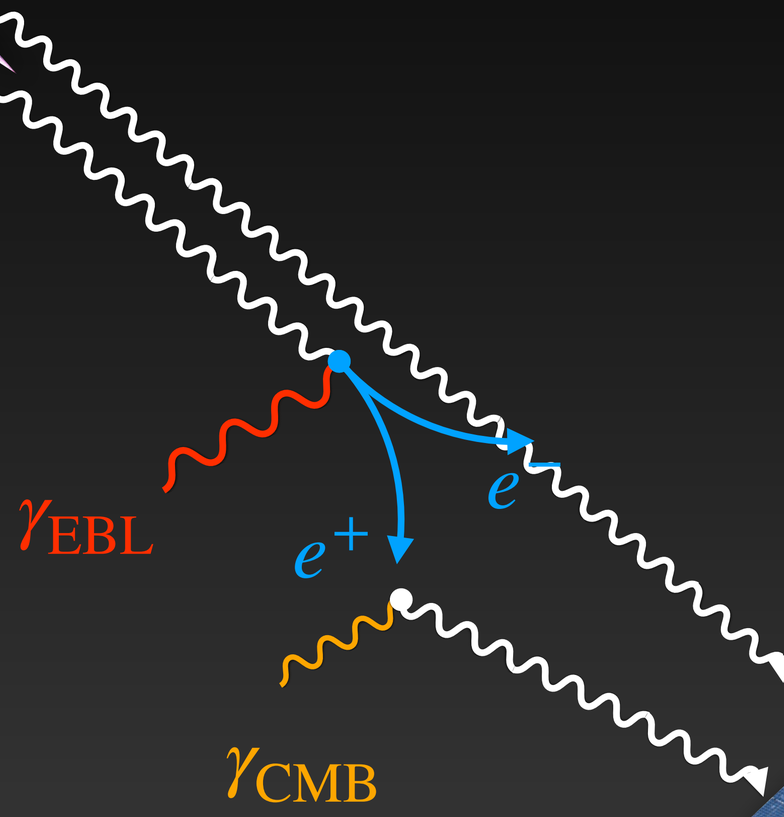

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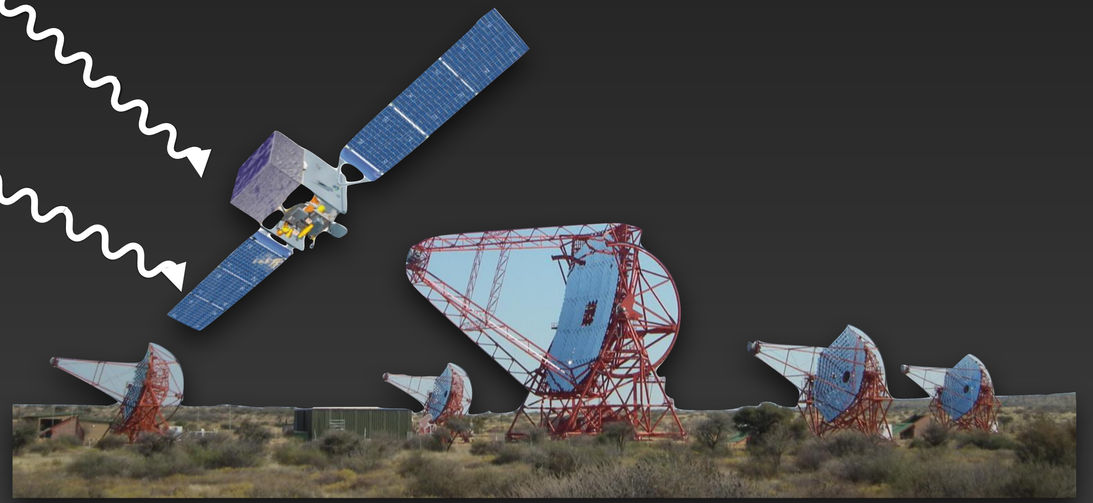

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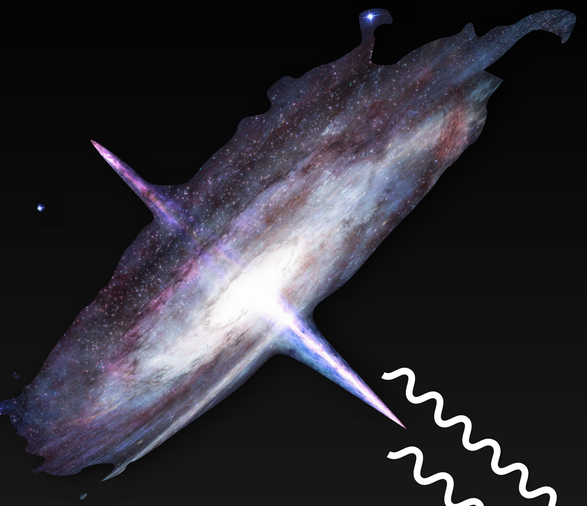

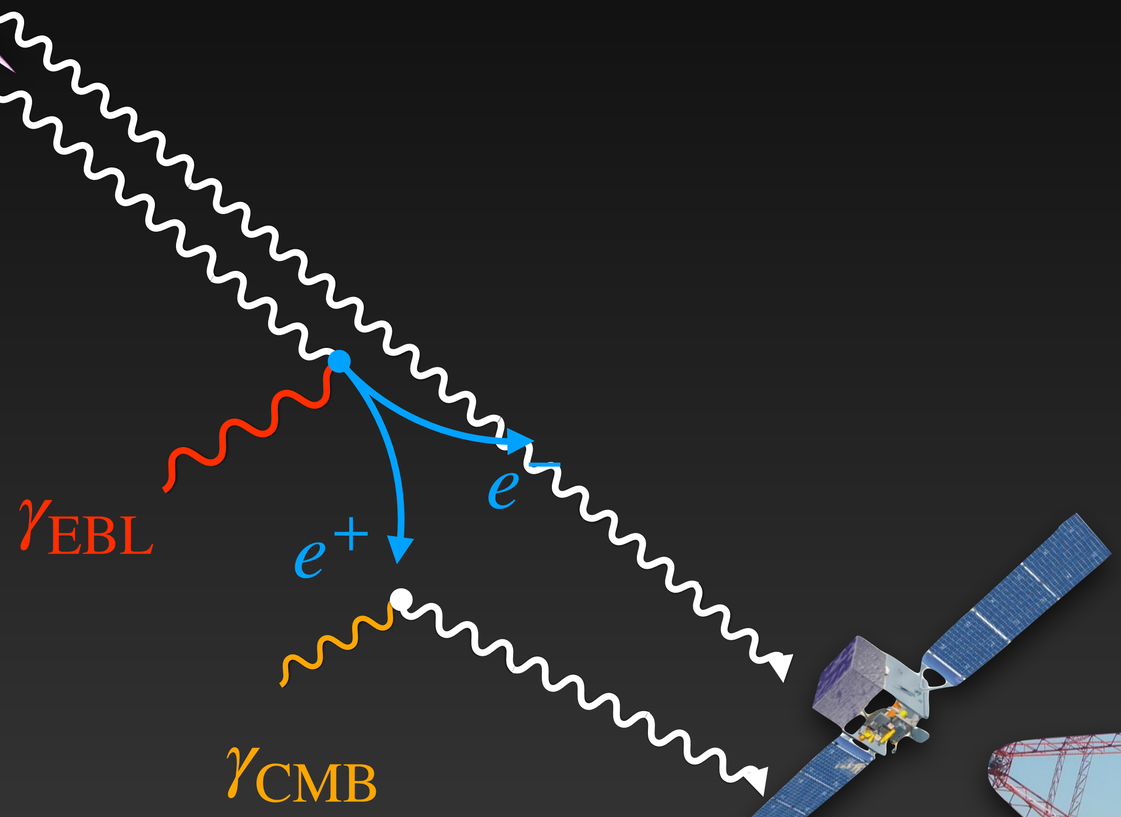

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H.E.S.S.

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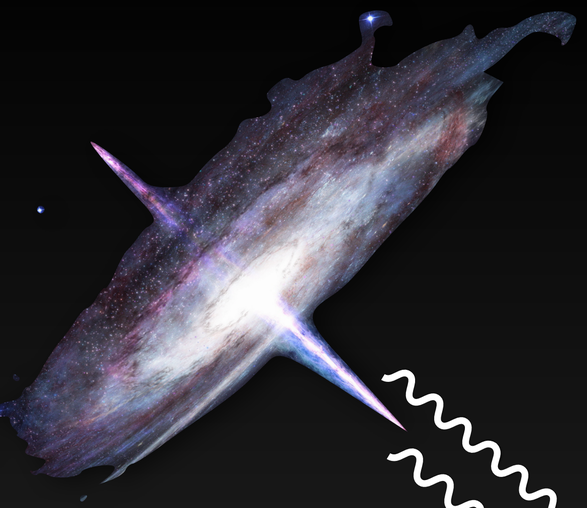
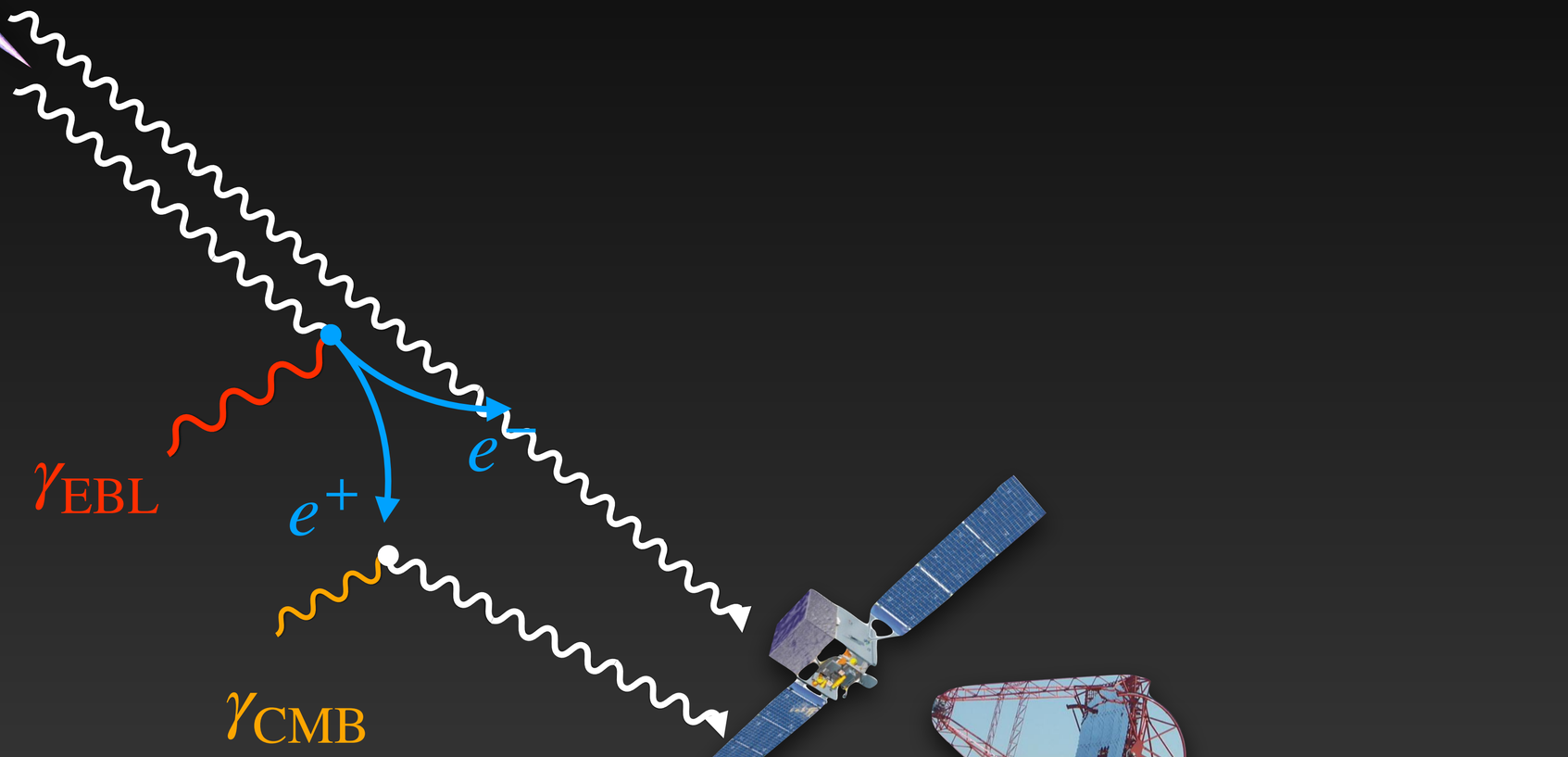
Goal: new constraints on the IGMF

Using a combined maximum likelihood approach of H.E.S.S. and LAT data





H.E.S.S.

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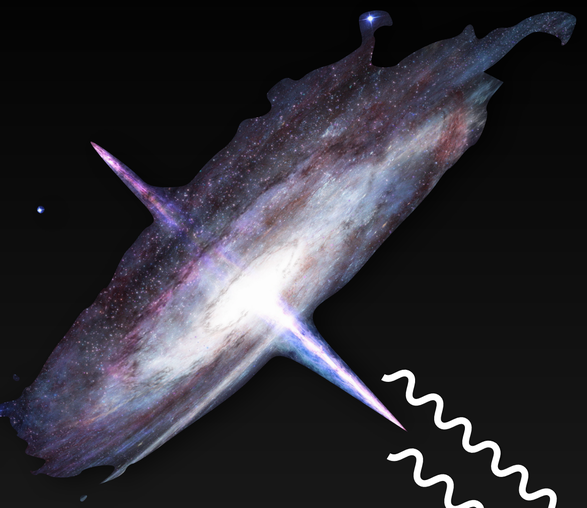

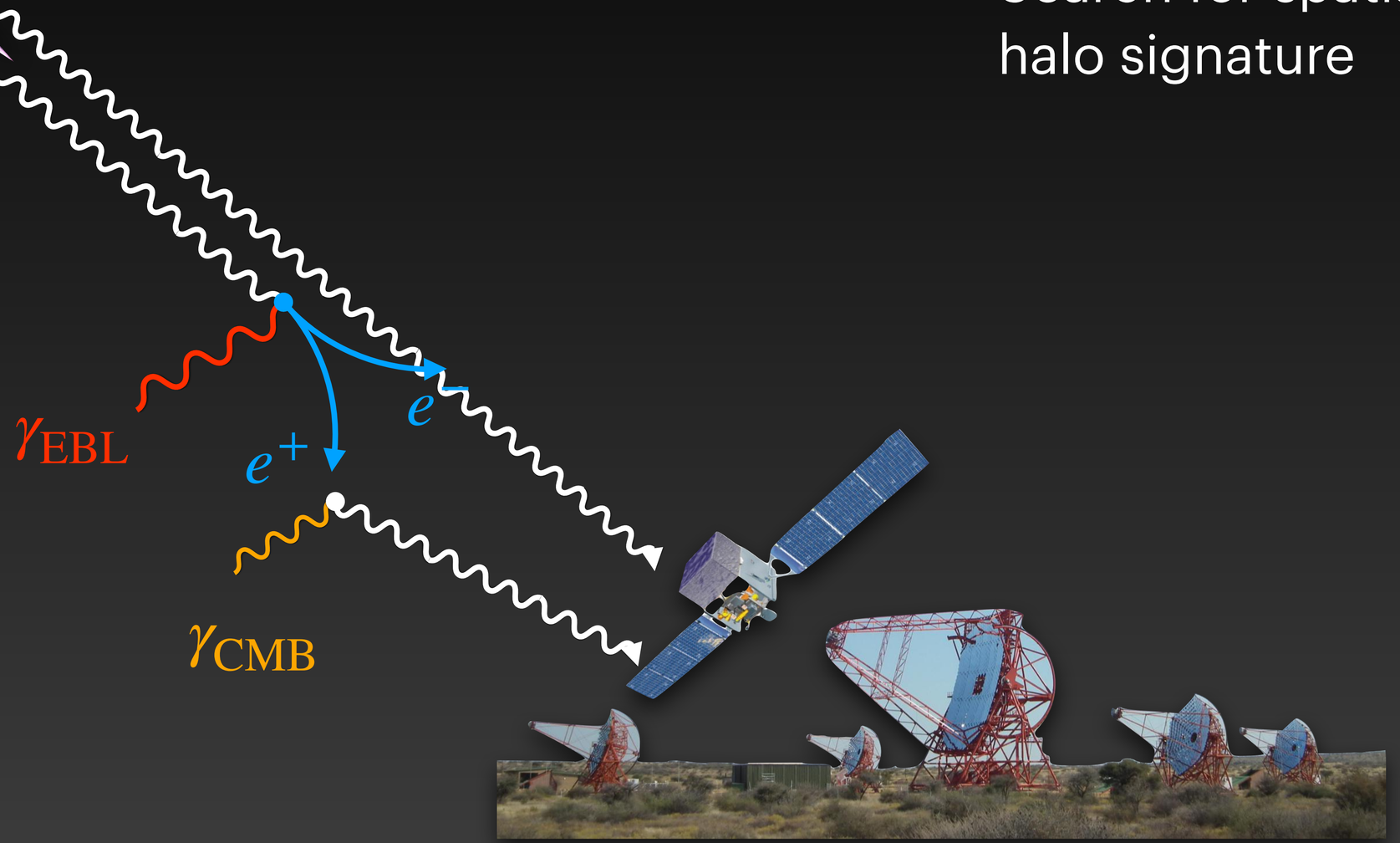

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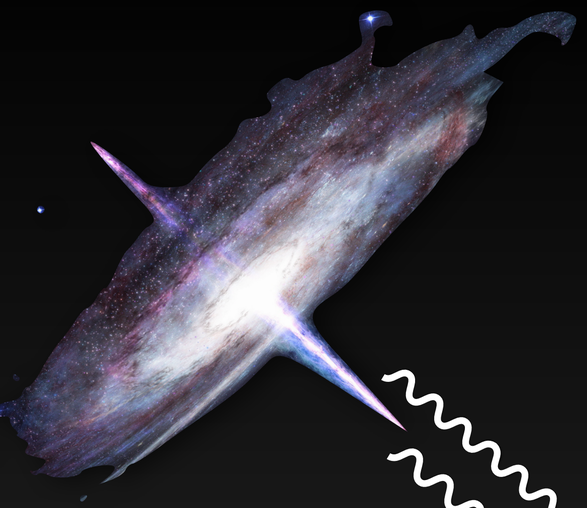

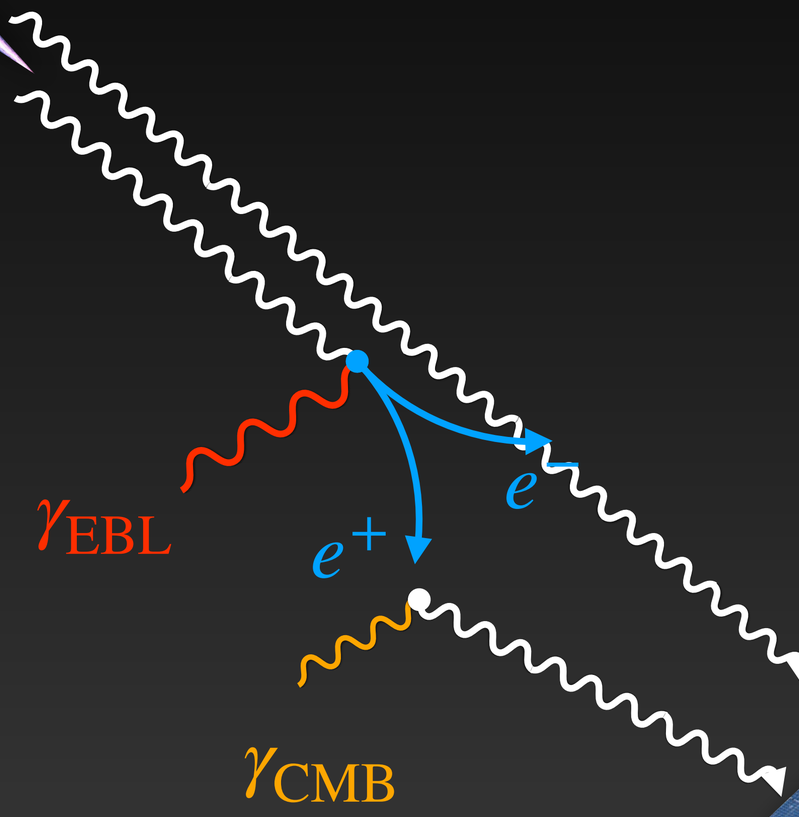

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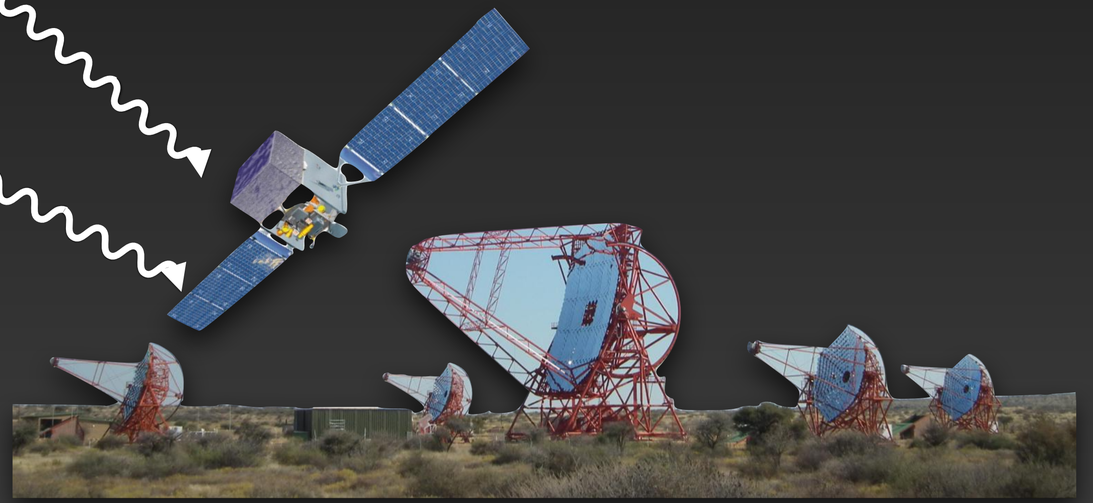

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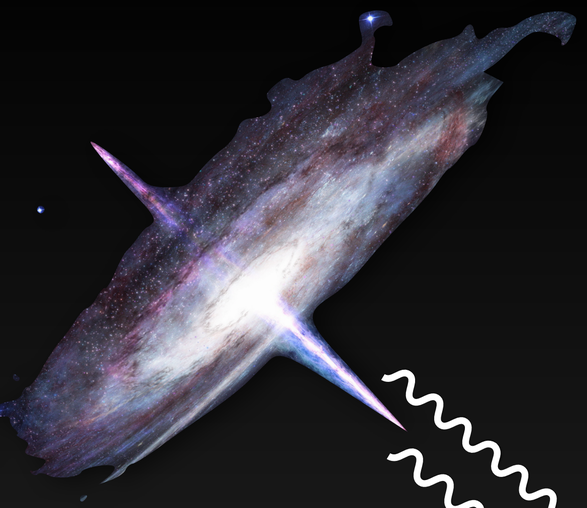

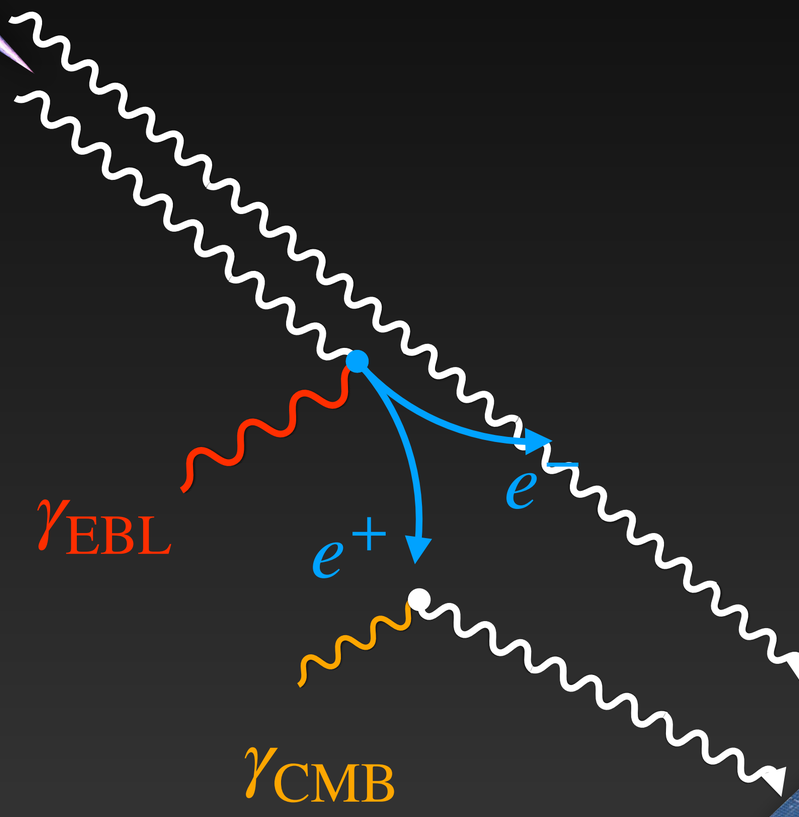

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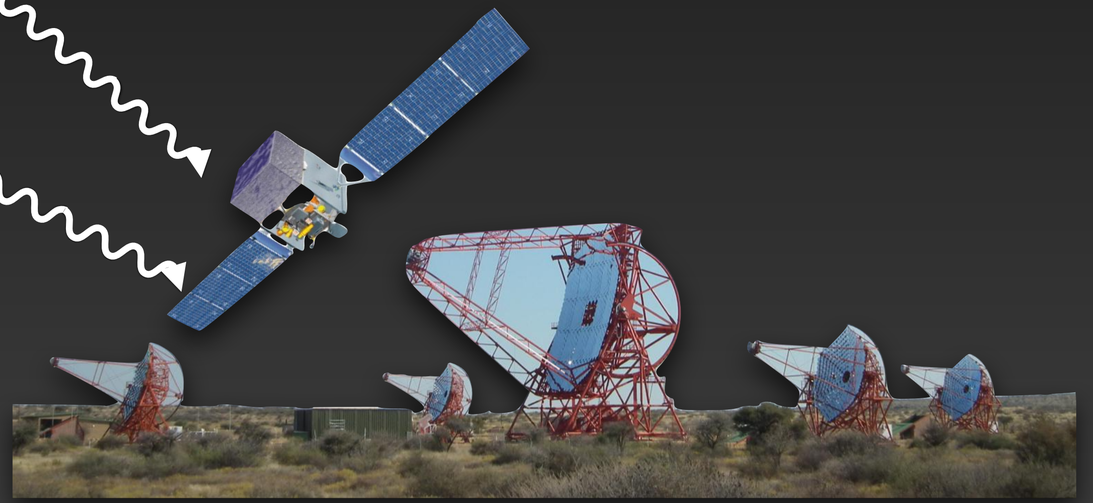
- Realistic predictions for halo from Monte Carlo Simulations
- Combining H.E.S.S. and Fermi-LAT data on the likelihood level



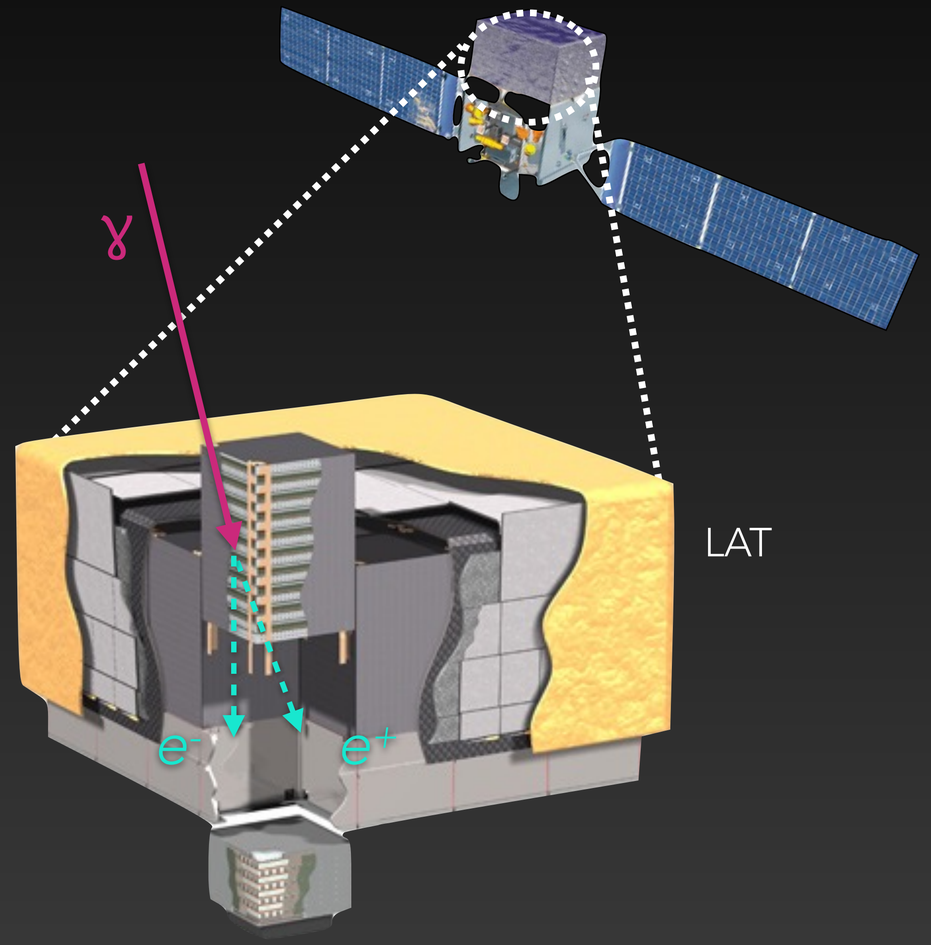
H.E.S.S.

The *Fermi* Large Area Telescope (LAT)

Observing the gamma-ray sky since June 11, 2008

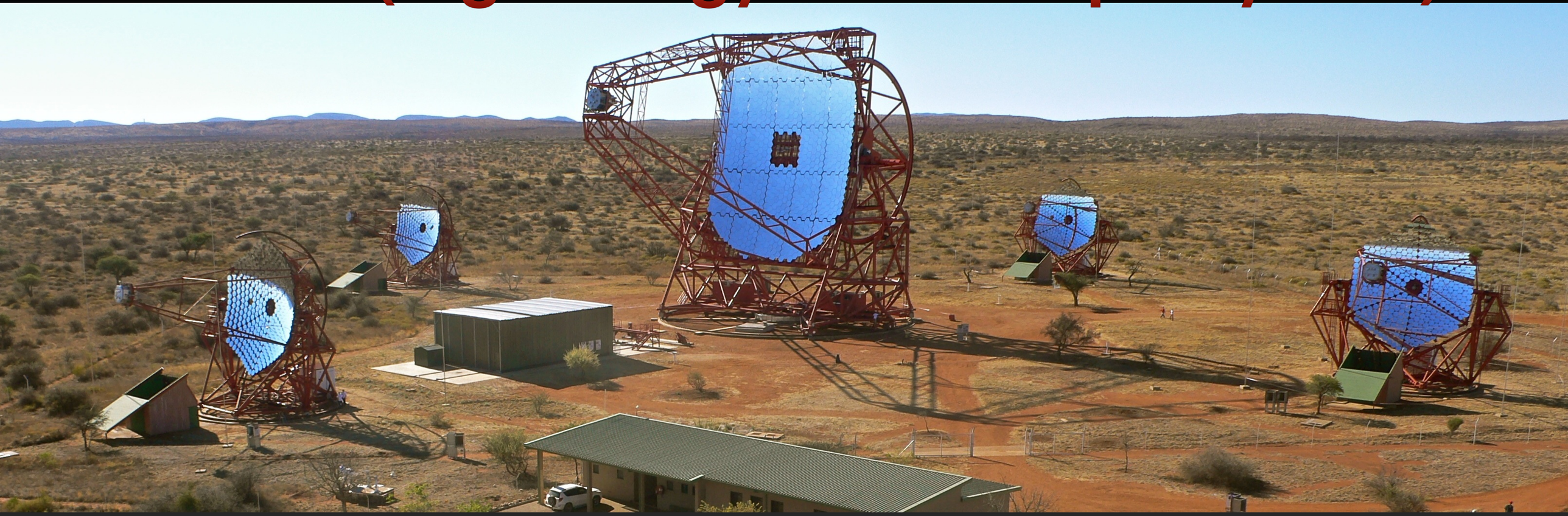
Energy range	20 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	0.8° @ 1 GeV
Field of view	2.4 sr (~20% of the sky)
Orbital period	91 minutes
Altitude	565 km

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



[Atwood et al. 2009]

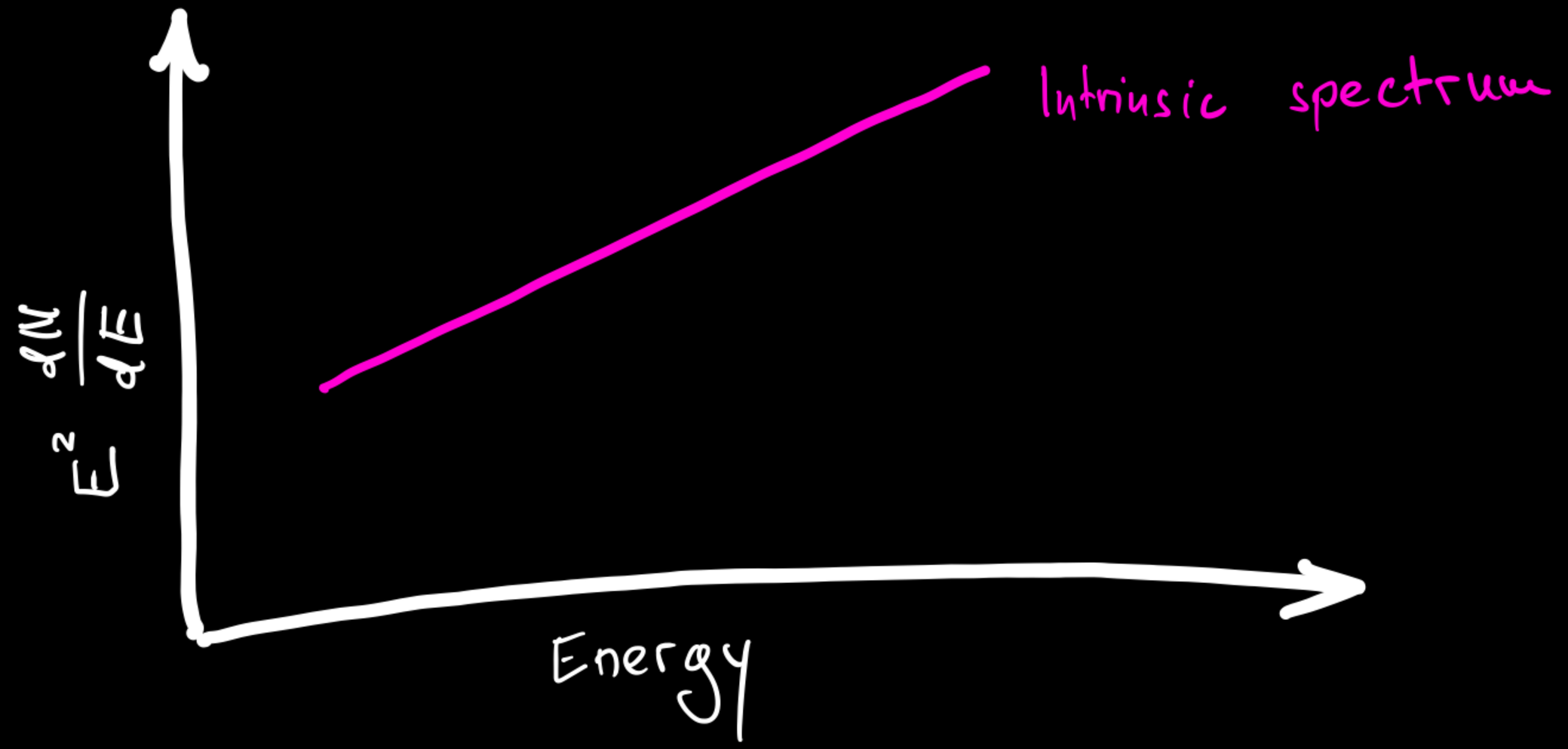
H.E.S.S. (High energy Stereoscopic System)



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

H.E.S.S.

Basic idea



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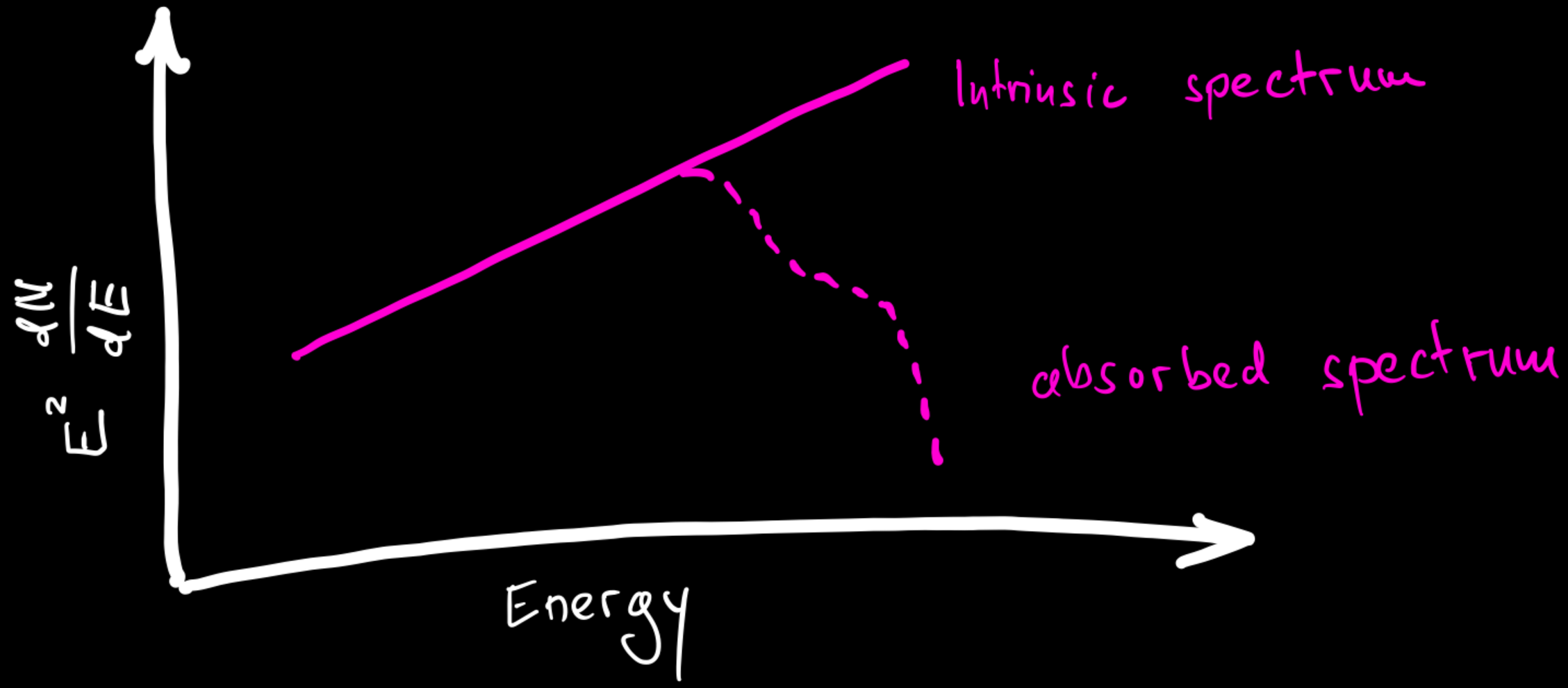

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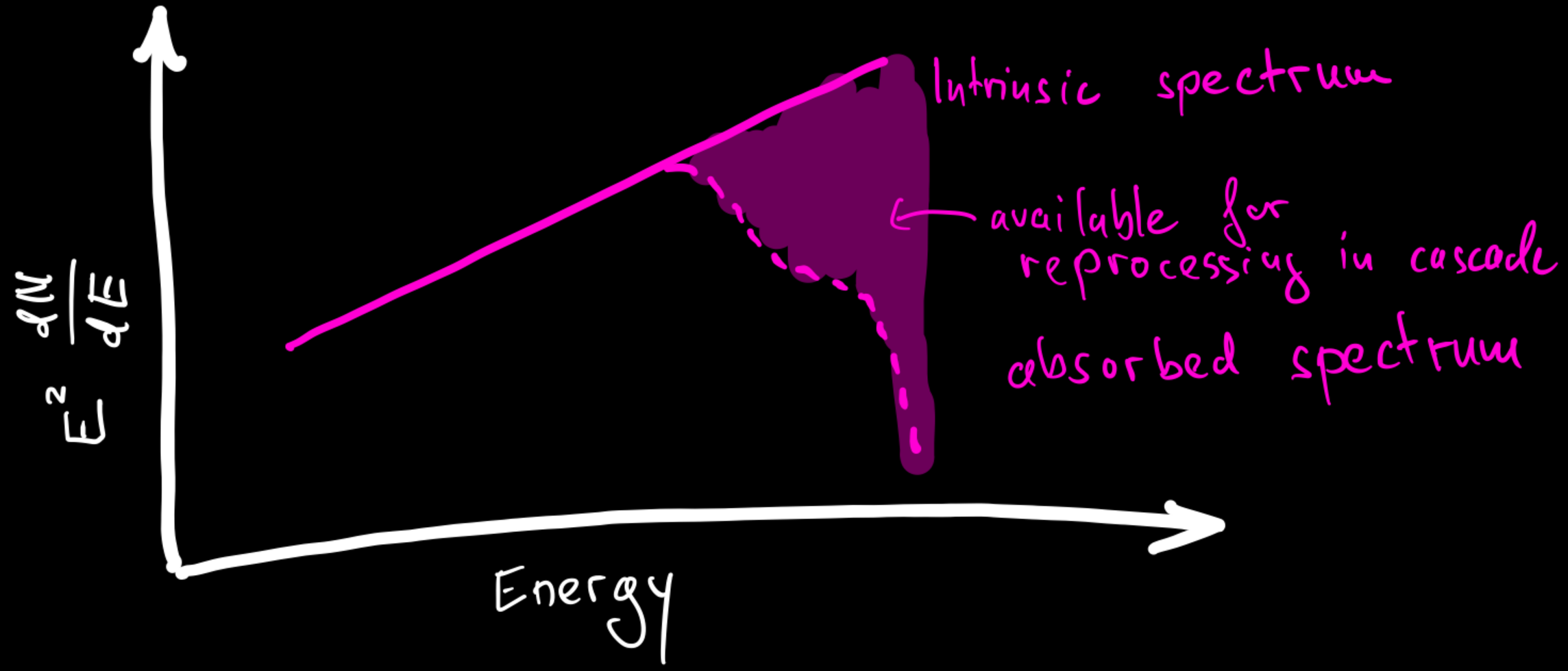
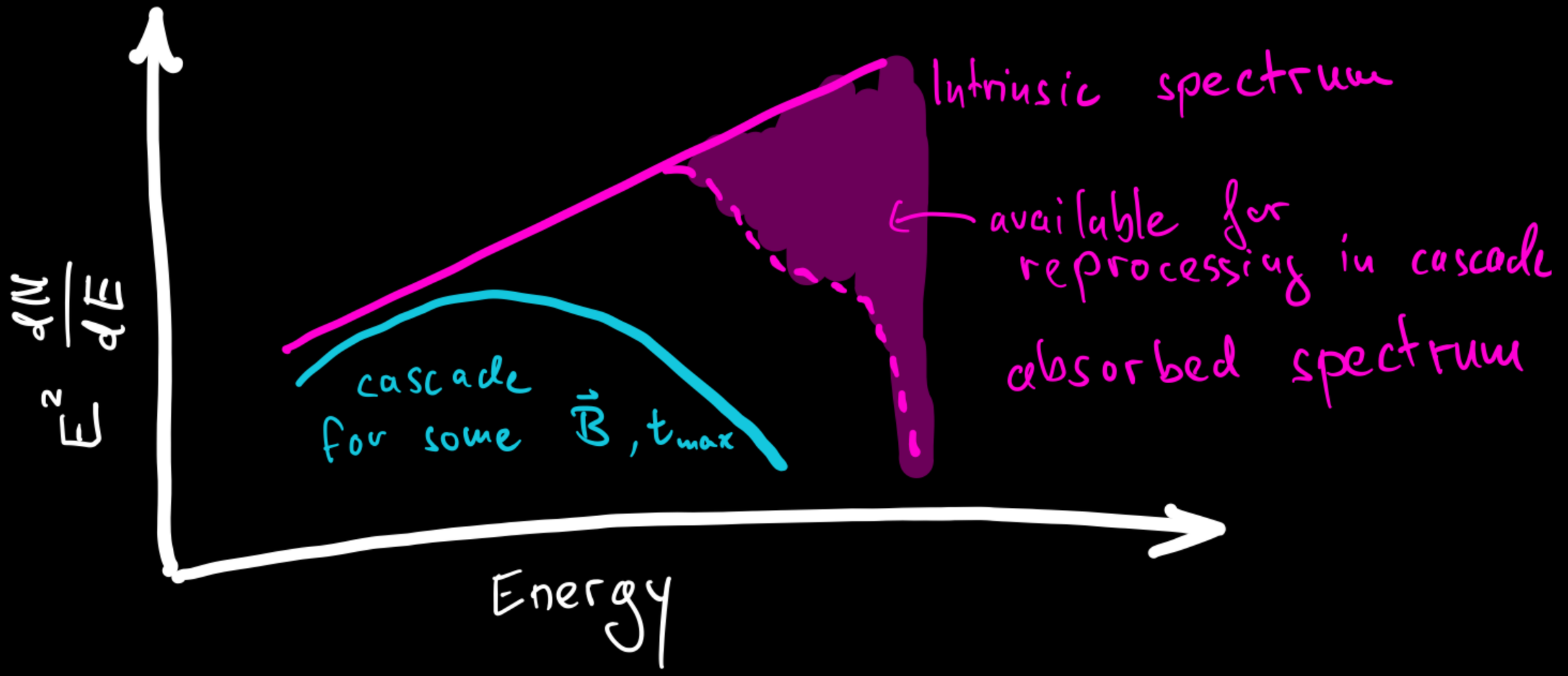

$E^2 \frac{dN}{dE}$
Energy
Intrinsic spectrum
available for reprocessing in cascade
absorbed spectrum

Basic idea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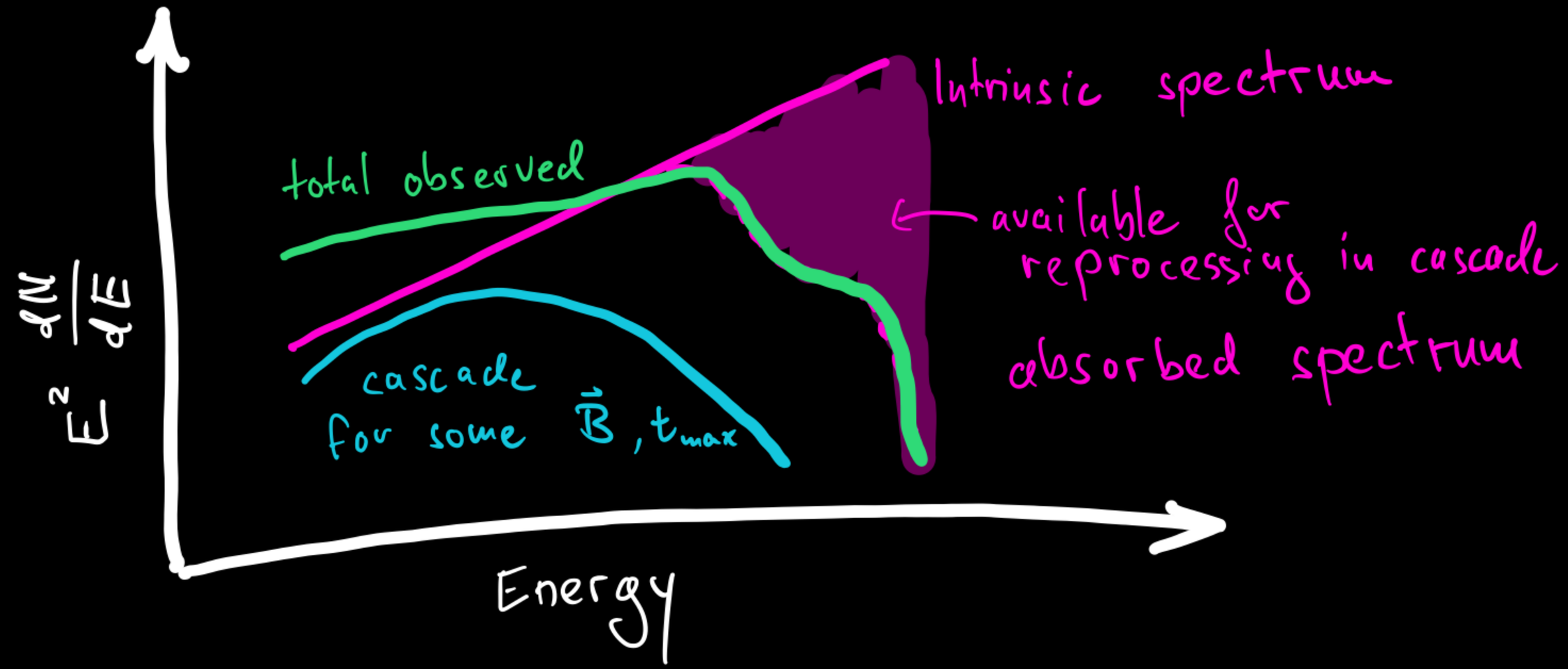
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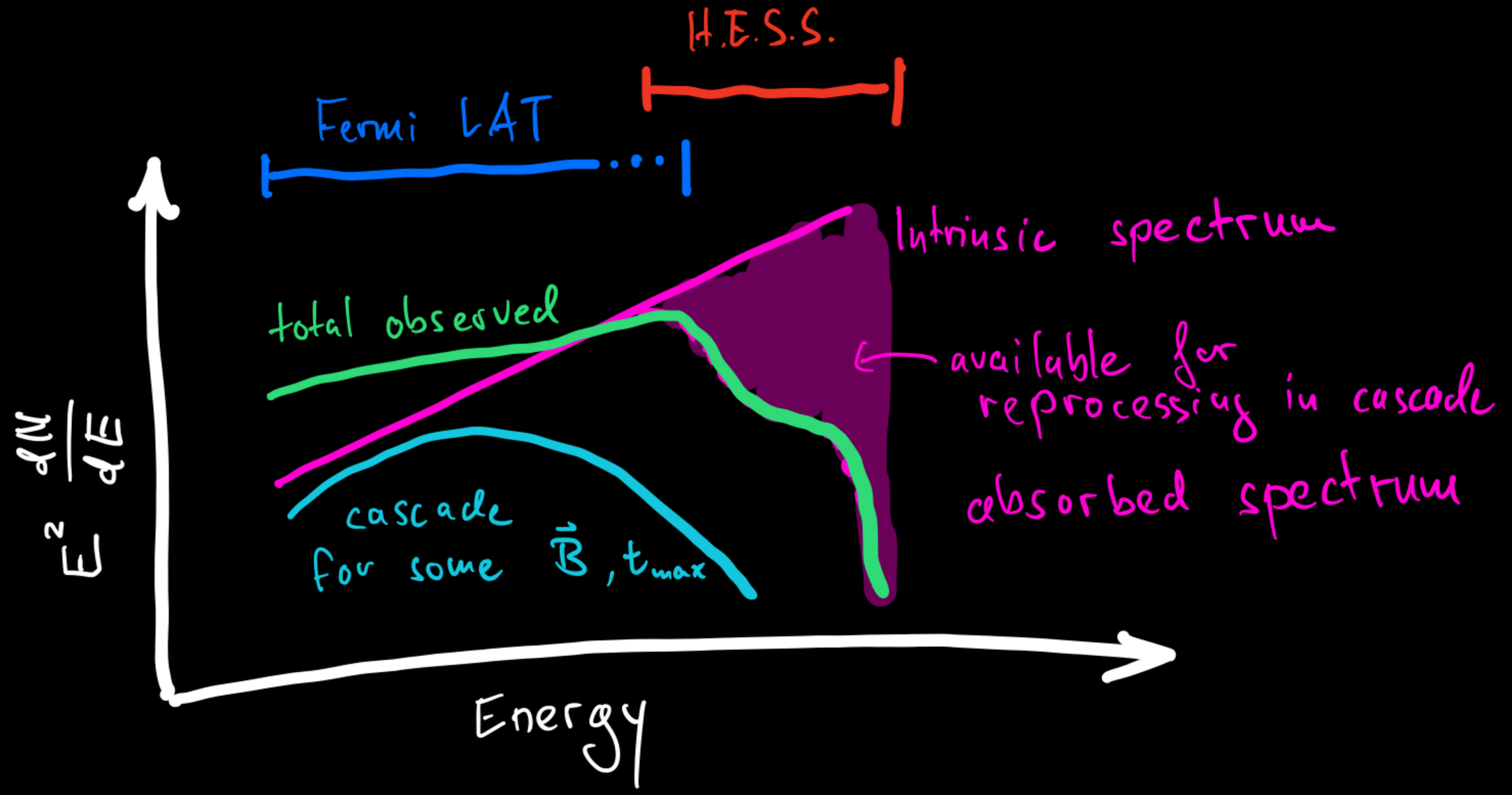
H.E.S.S.
Fermi LAT
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Energy

Source Selection

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H.E.S.S.

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Resulting sources:

Source Name	Redshift
1ES 0229+200	0,139
1ES 0347-121	0,188
PKS 0548-322	0,069
1ES 1101-232	0,186
H 2356-309	0,165

H.E.S.S.

Modeling the halo with CRPropa3

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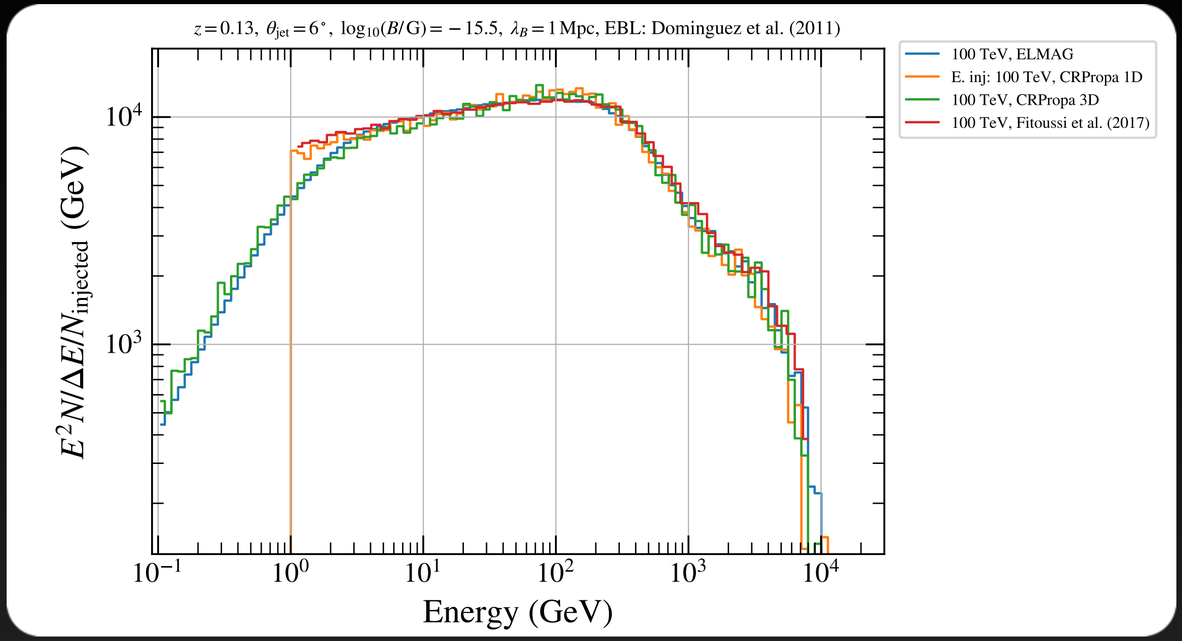

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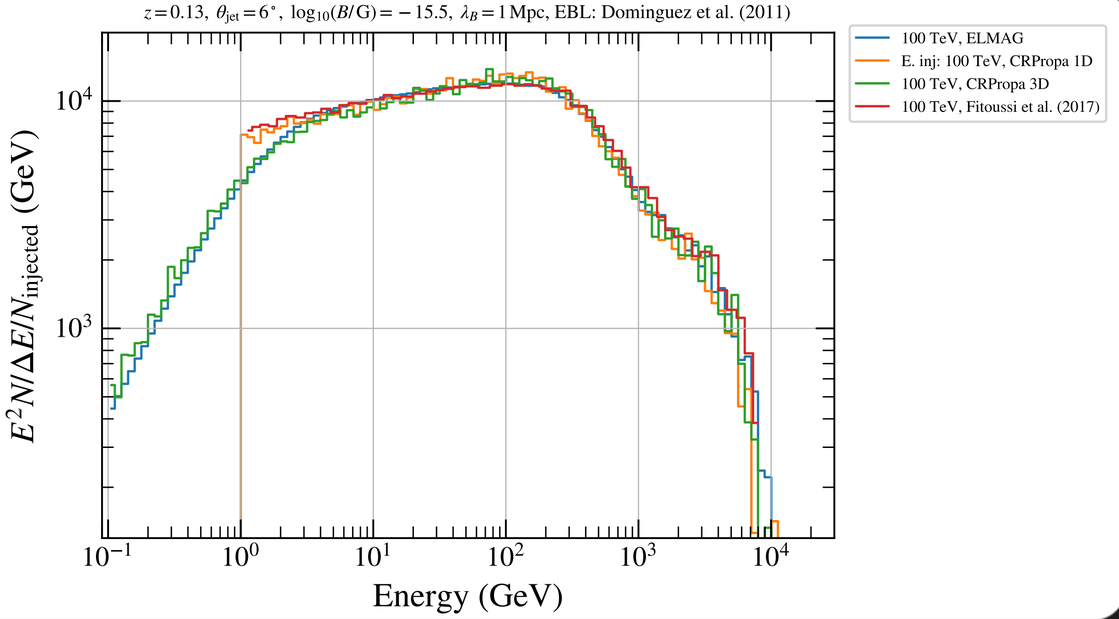

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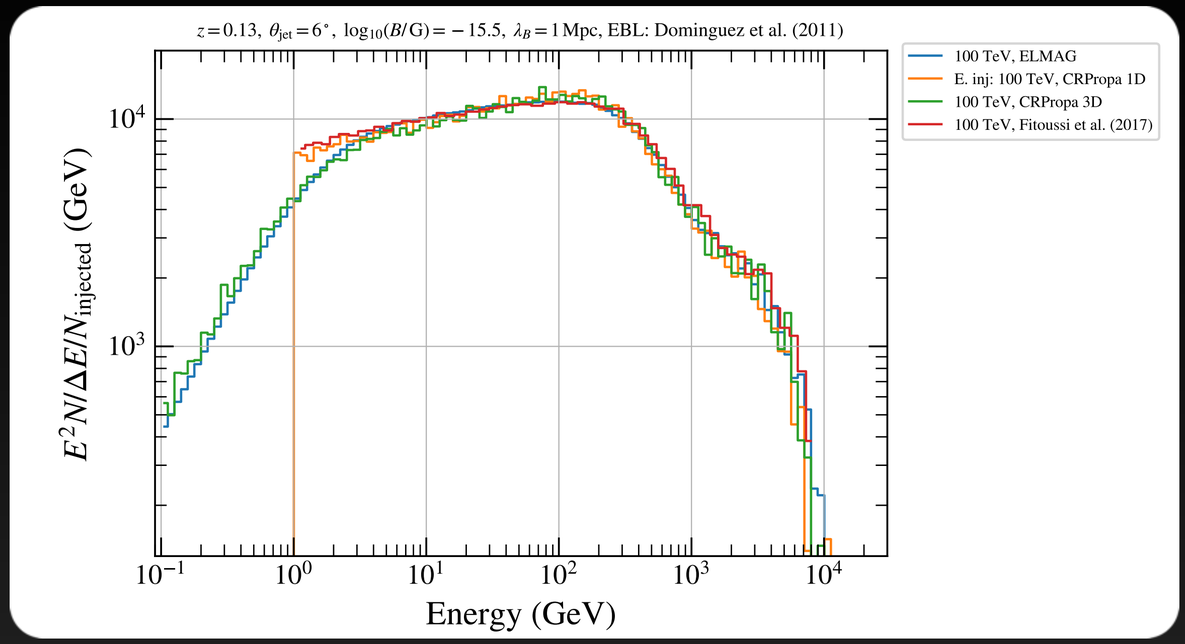
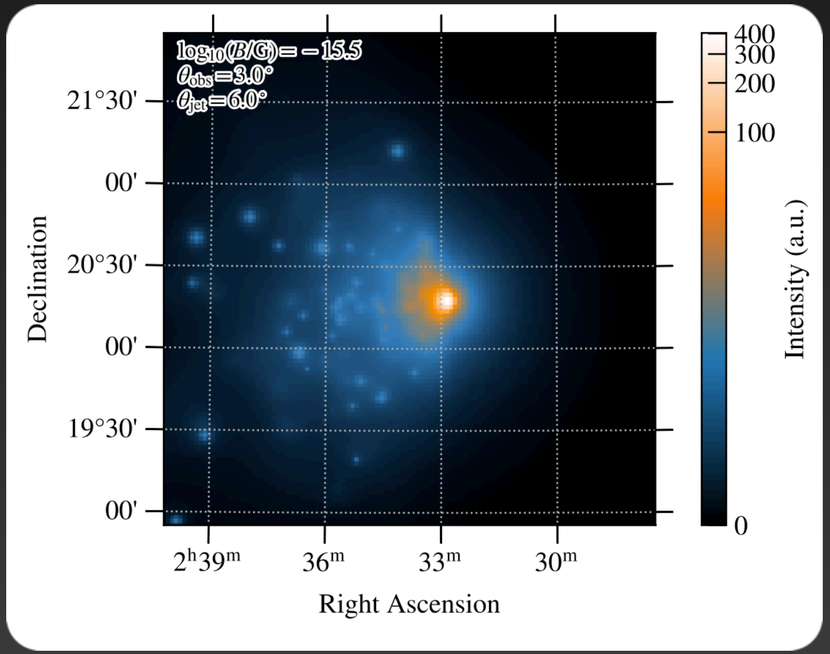




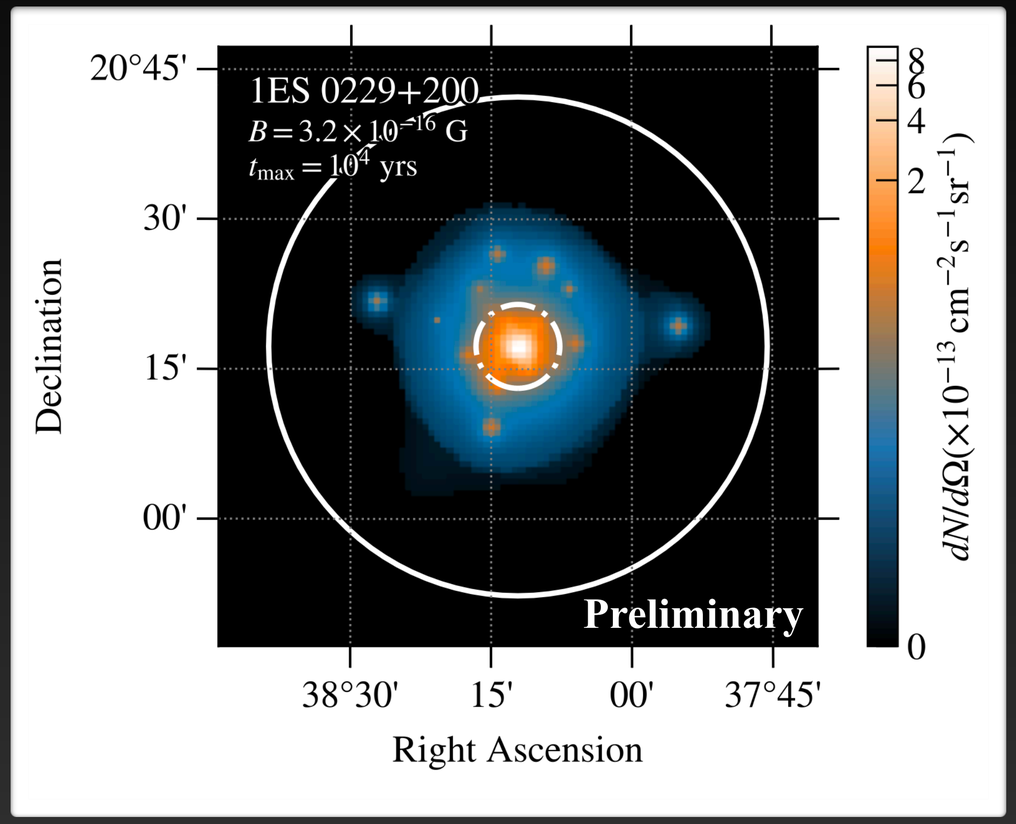
Fermi-LAT data selection

Parameter	Selection
Time range	11.5 years
Energy Range	> 1 GeV
ROI size	6º x 6º
Max. Zenith angle	100º
Filter	DATA_QUAL>0 && LAT_CONFIG==1
Spatial binning	0.025º / pixel
Energy binning	8 bins per decade
Event Class / IRFs	P8R3_SOURCE_V3, inflight PSF
Event types	PSF0-2, PSF3

H.E.S.S.

Searching for cascade emission in LAT data

Model expectation



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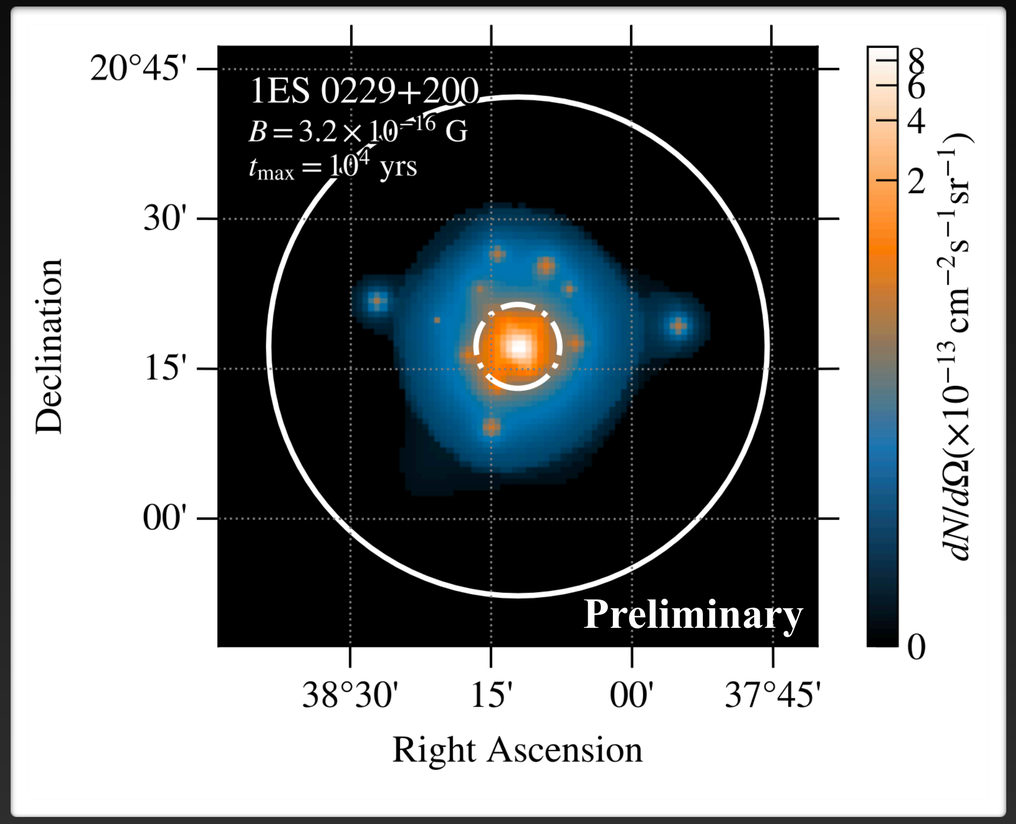
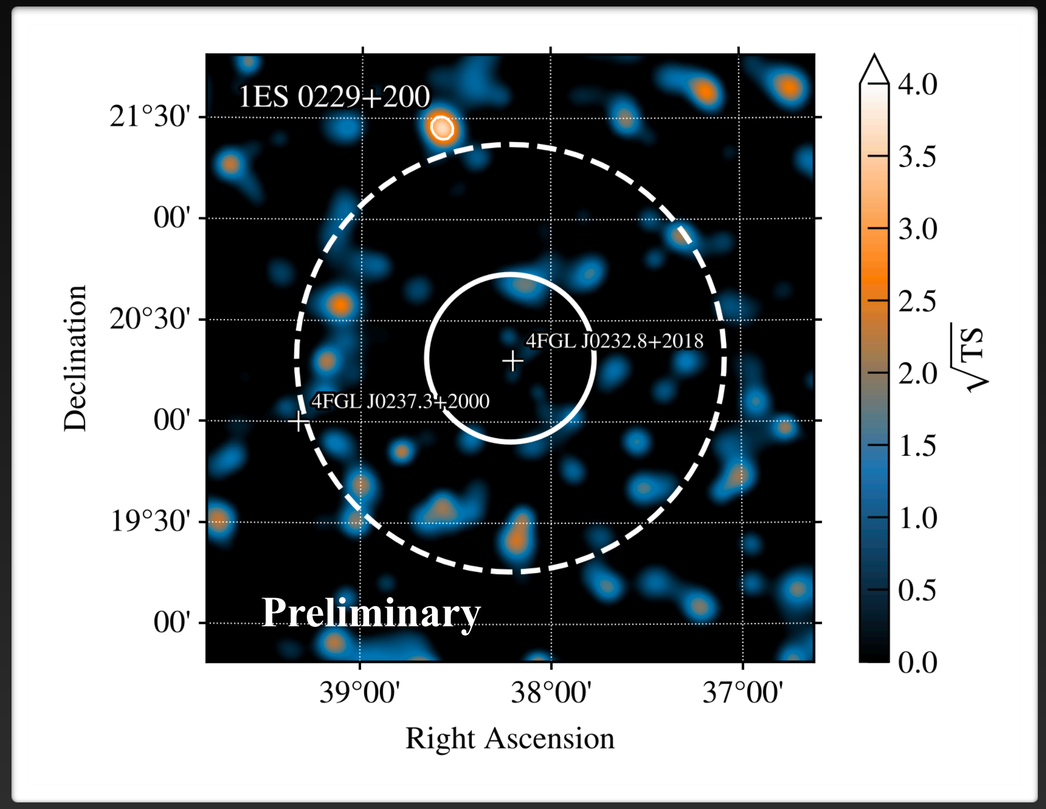


TS map from data



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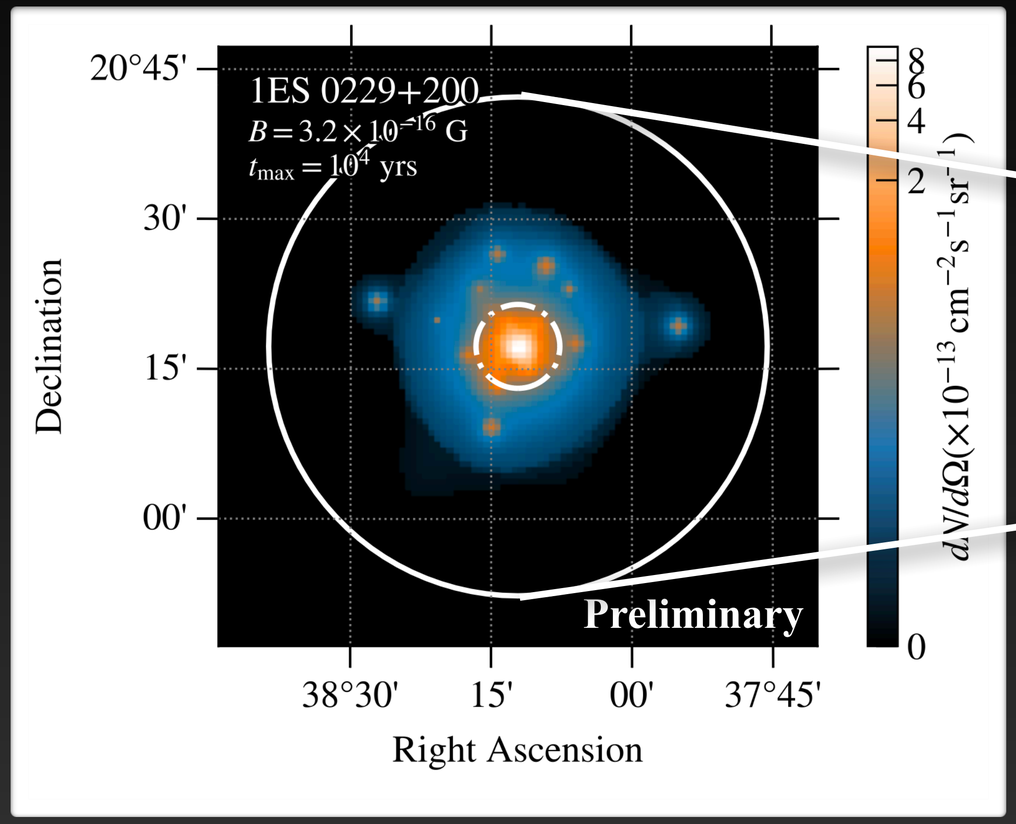

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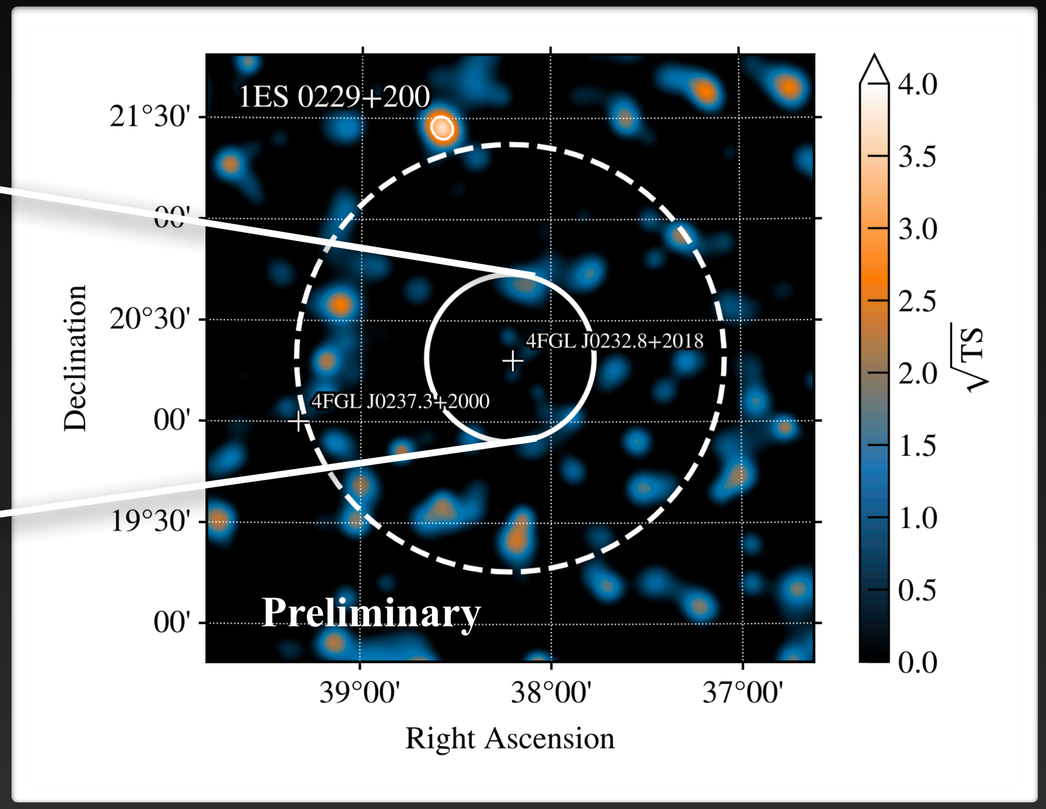

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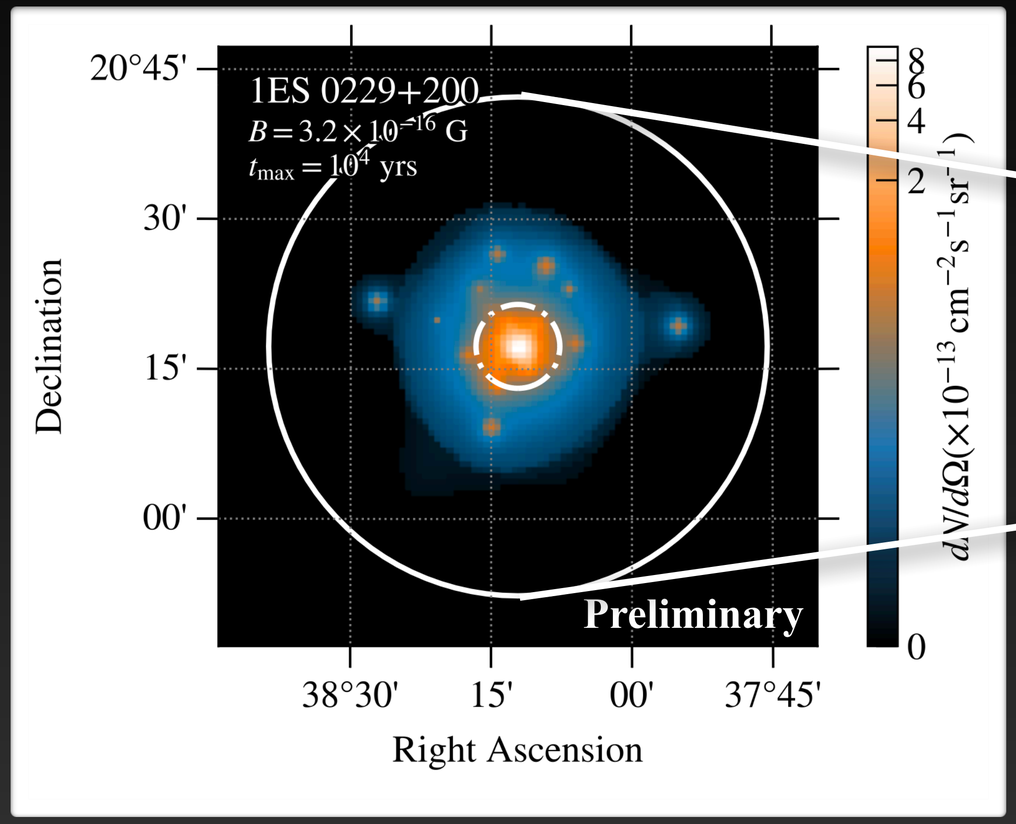

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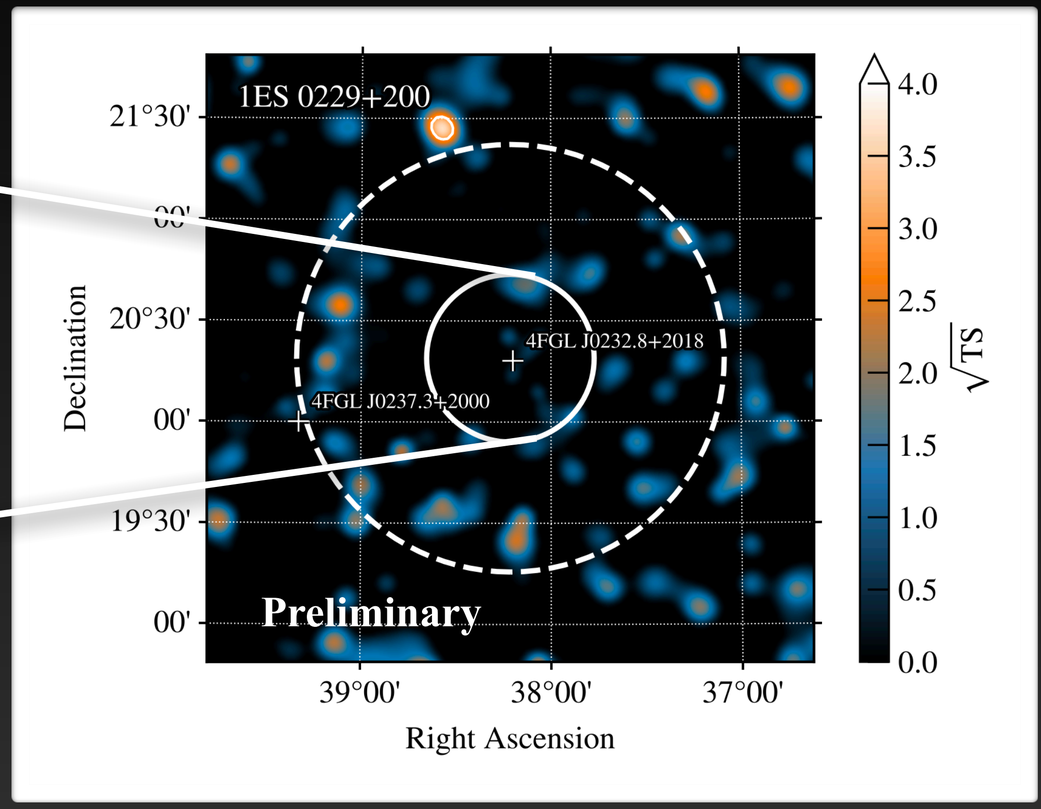

- TS map tests at each pixel if additional emission is present
- No un-modeled excess emission in vicinity of sources observed

Extracting LAT likelihoods in the presence of a halo

Some technical details

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  - Loop over spectral parameters, add corresponding halo template, extract likelihood of fit, $\ln \mathscr{L}_{\mathrm{LAT}}$

H.E.S.S. Data sets

- Data taken with small telescopes up to 2018 considered here
- Analysis performed using gammapy [Deil et al. 2017]
- Source spectra ϕ_{obs} well described by power law including EBL absorption,
  $\phi_{\mathrm{obs}} = N(E/E_0)^{-\Gamma}\exp(-\tau)$

Preliminary

Source	Life time (hours)	Detection significance	Power law index Γ
1ES 0229+200	144,1	16.5σ	1.76 ± 0.12
1ES 0347-121	59,2	16.1σ	2.12 ± 0.15
PKS 0548-322	53,9	10.2σ	1.92 ± 0.12
1ES 1101-232	71,9	18.7σ	1.66 ± 0.09
H 2356-309	150,5	23.4σ	2.10 ± 0.09

H.E.S.S.

Combined H.E.S.S. and LAT analysis

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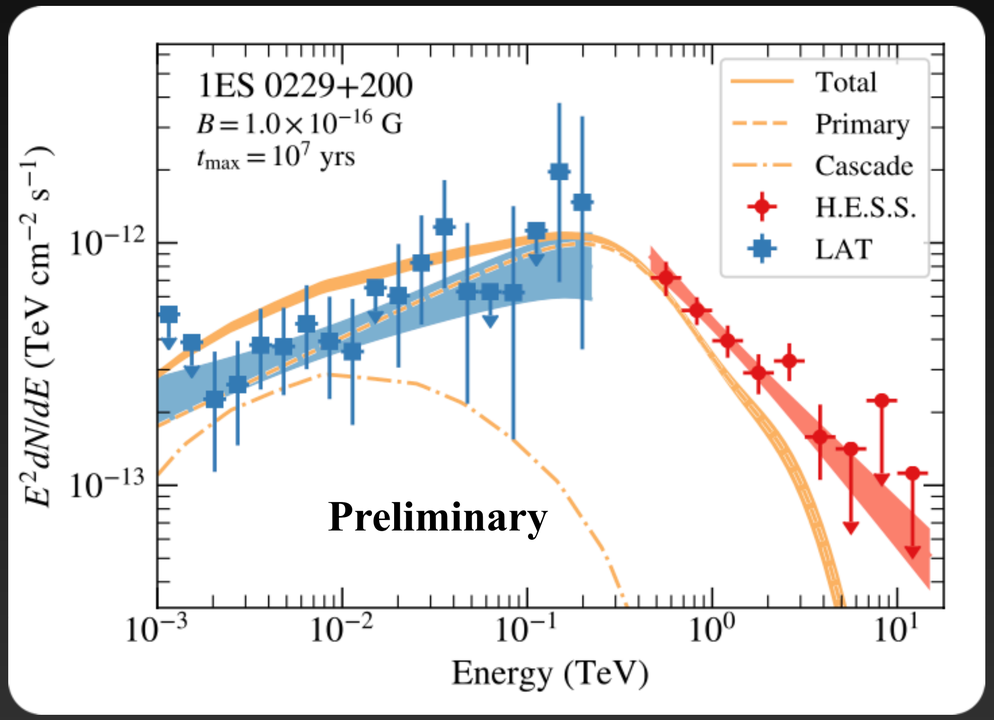

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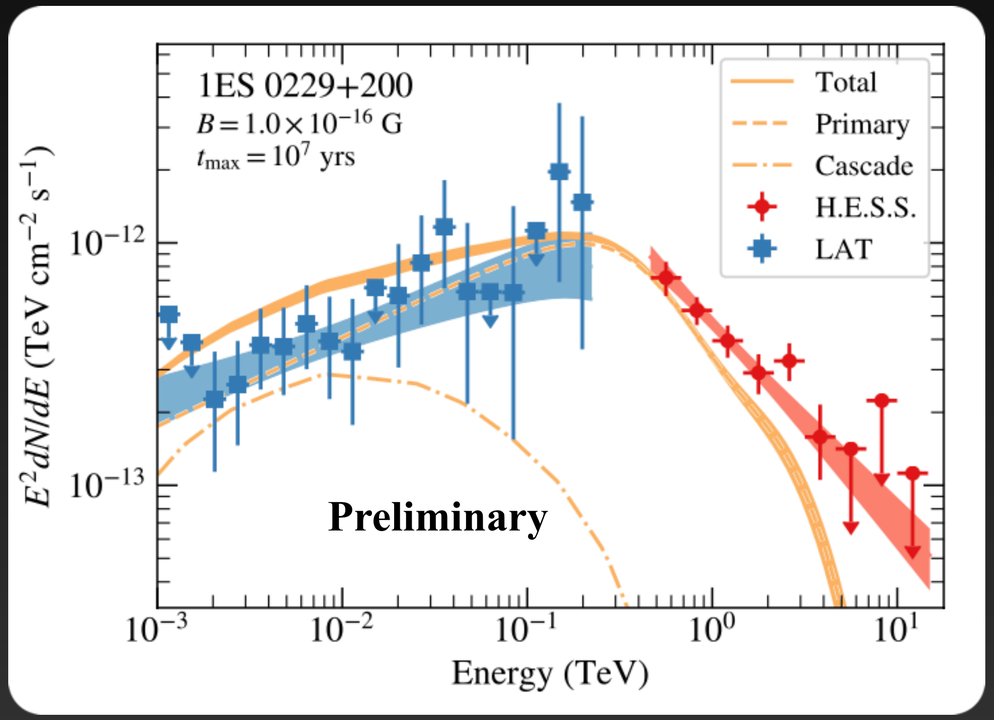

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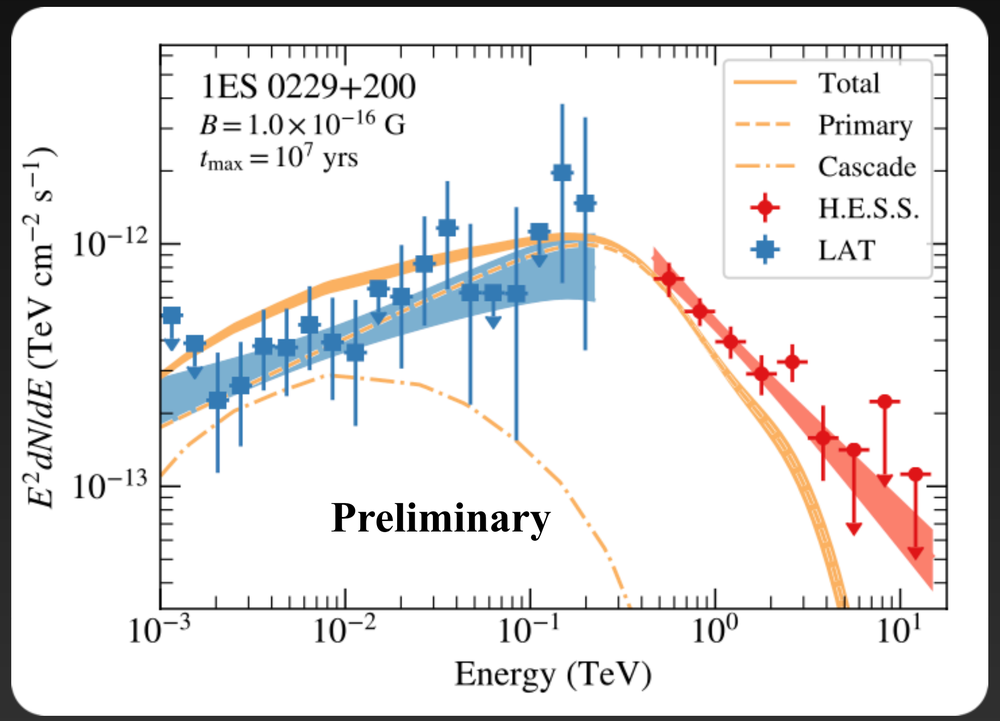

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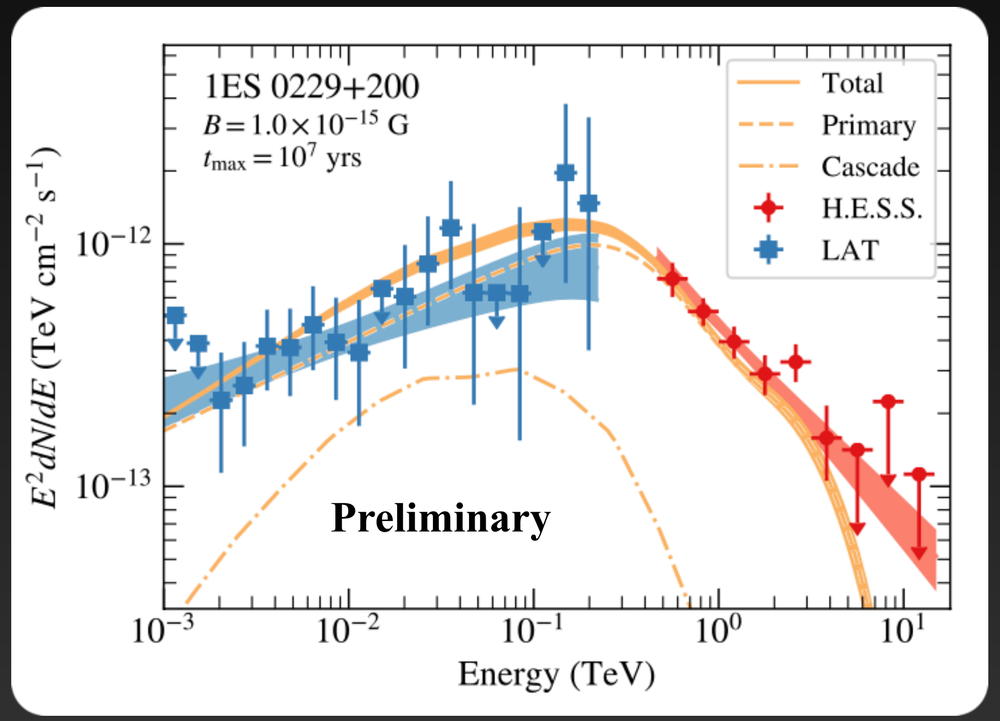

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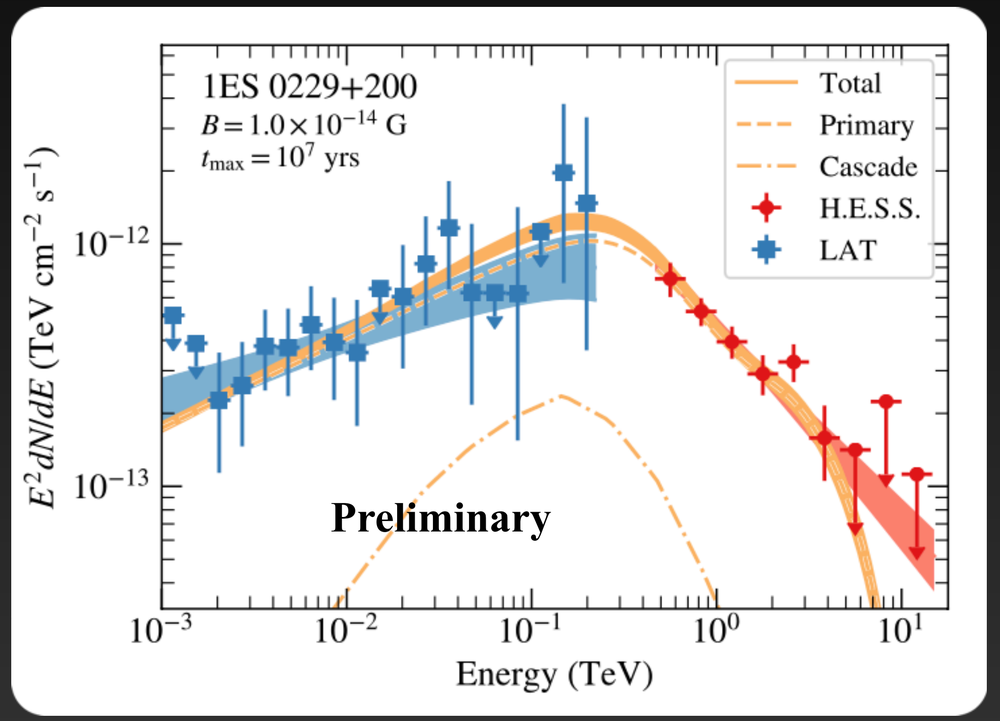

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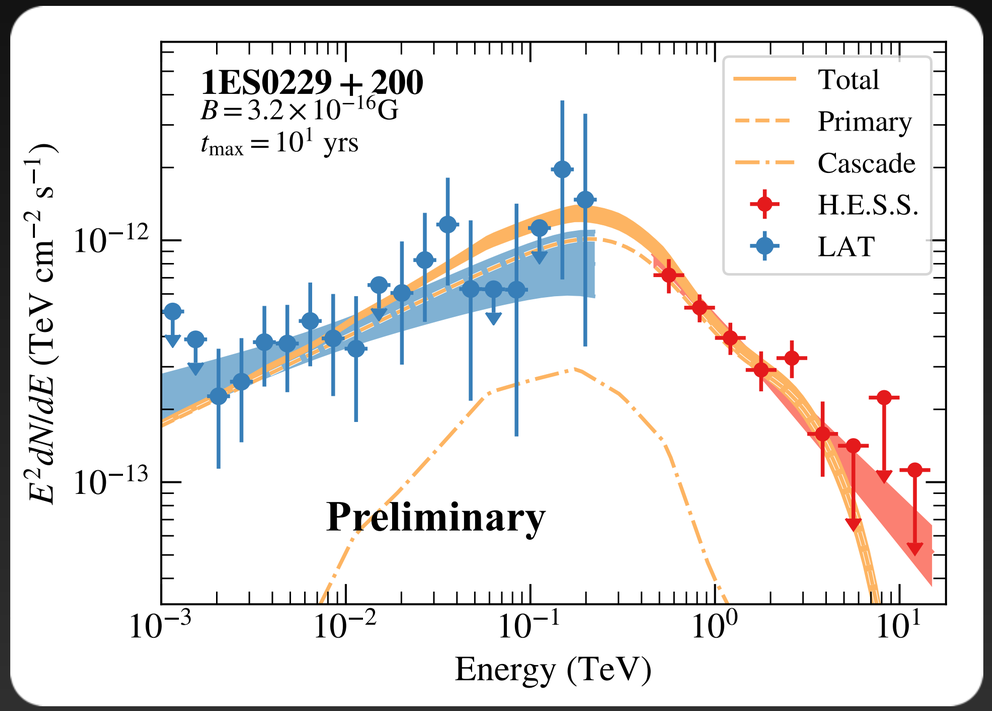

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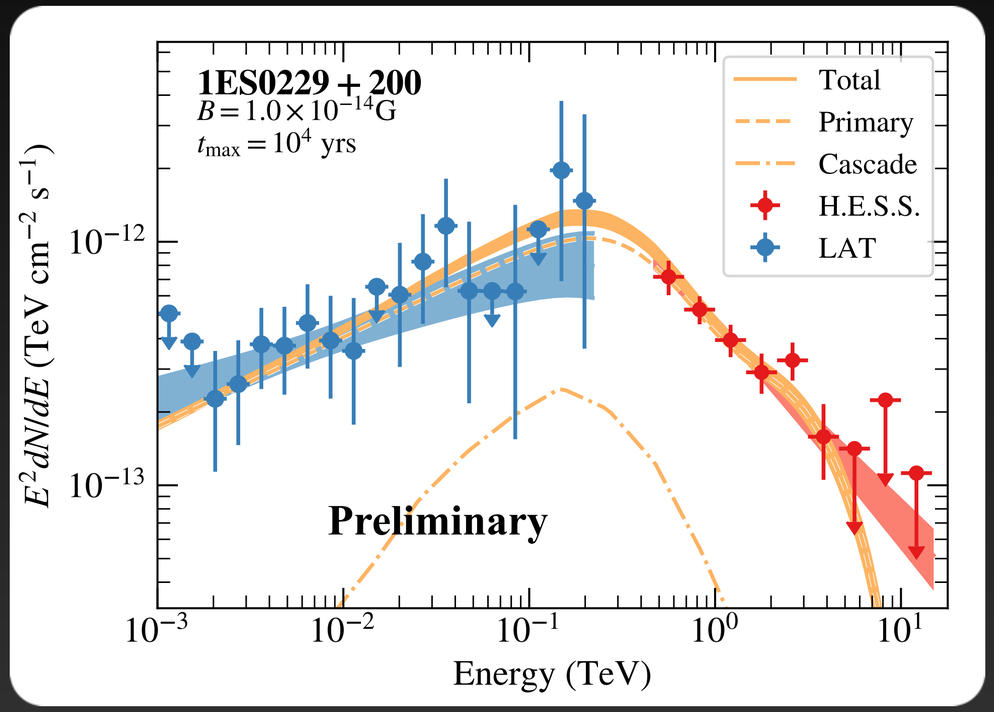
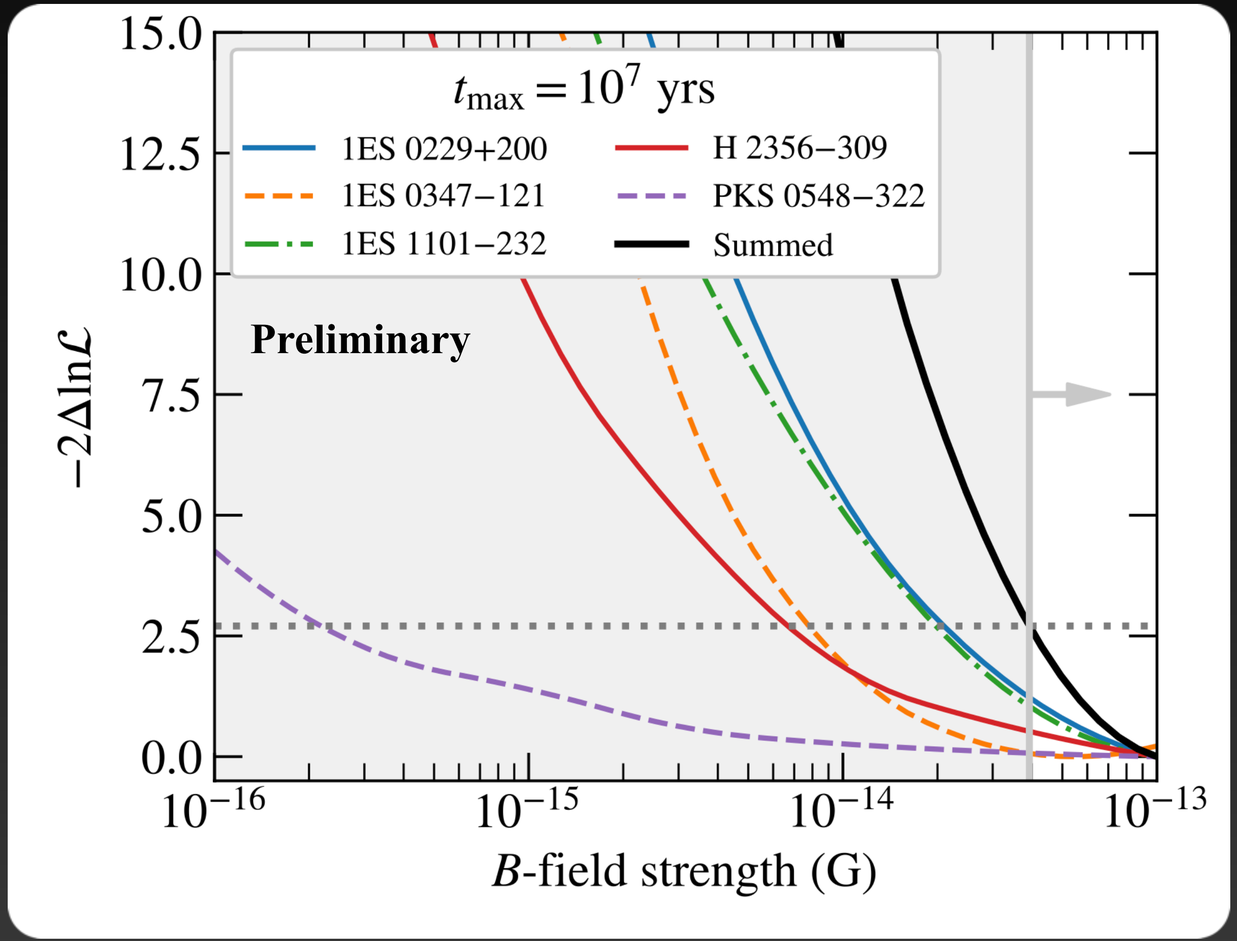


Results: lower limits on IGMF

Data does not prefer presence of halo



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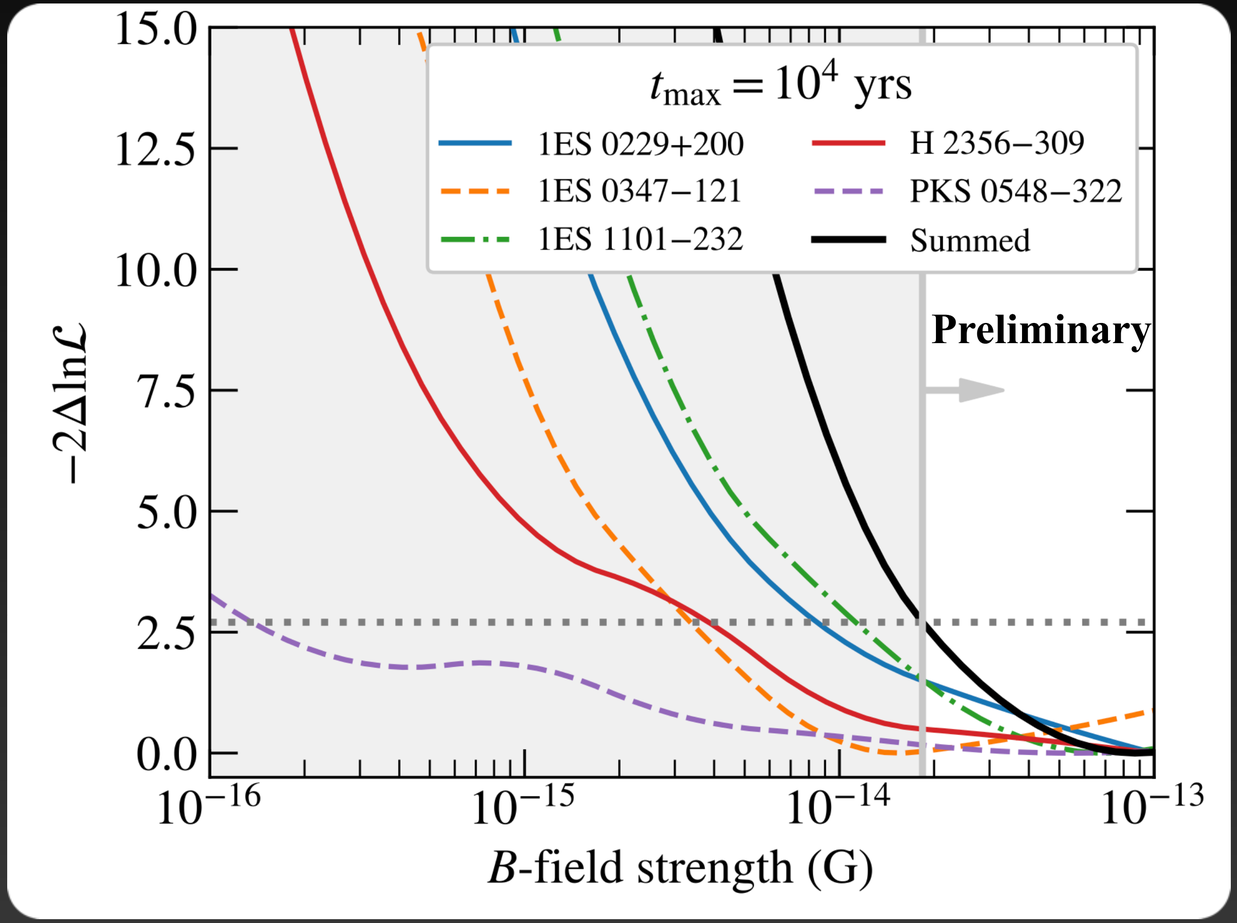

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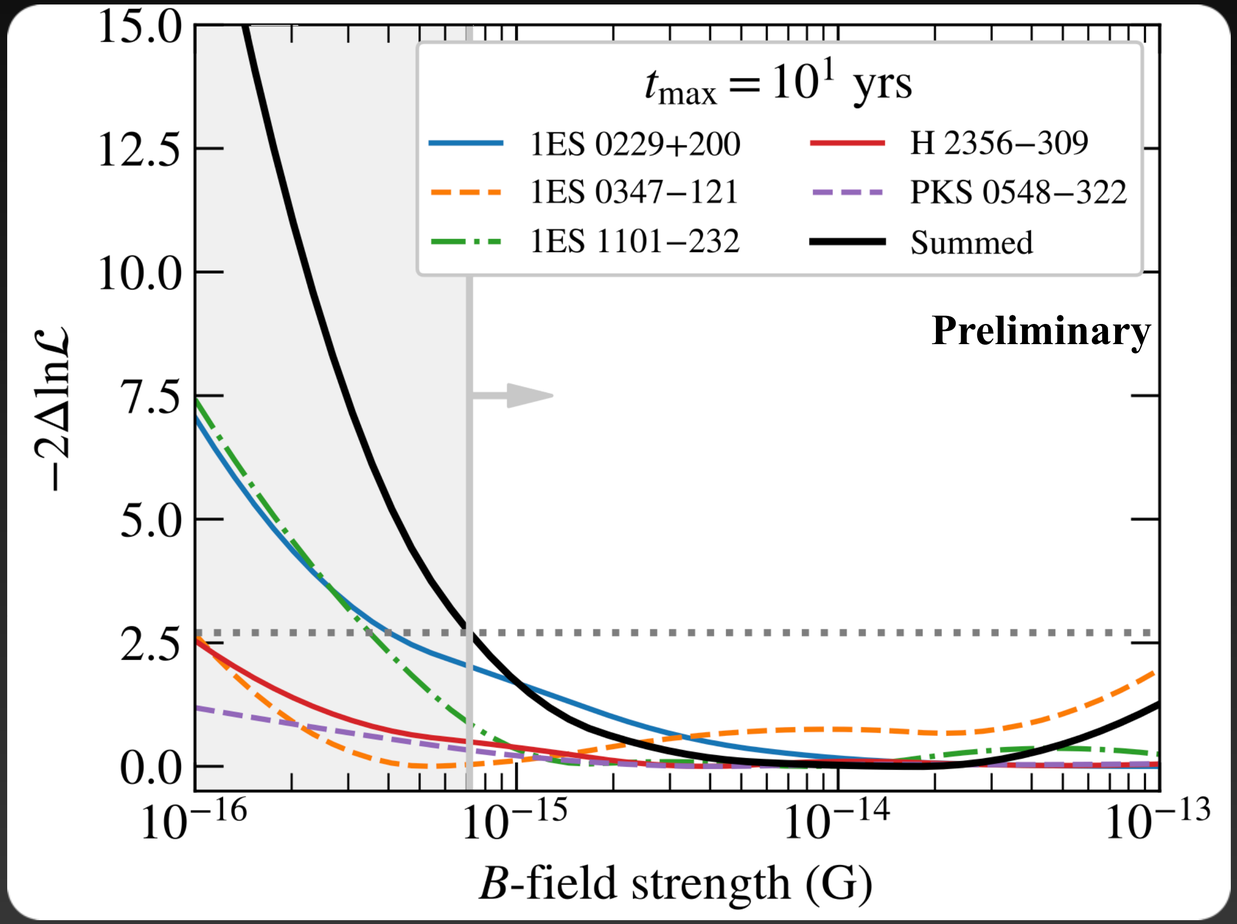

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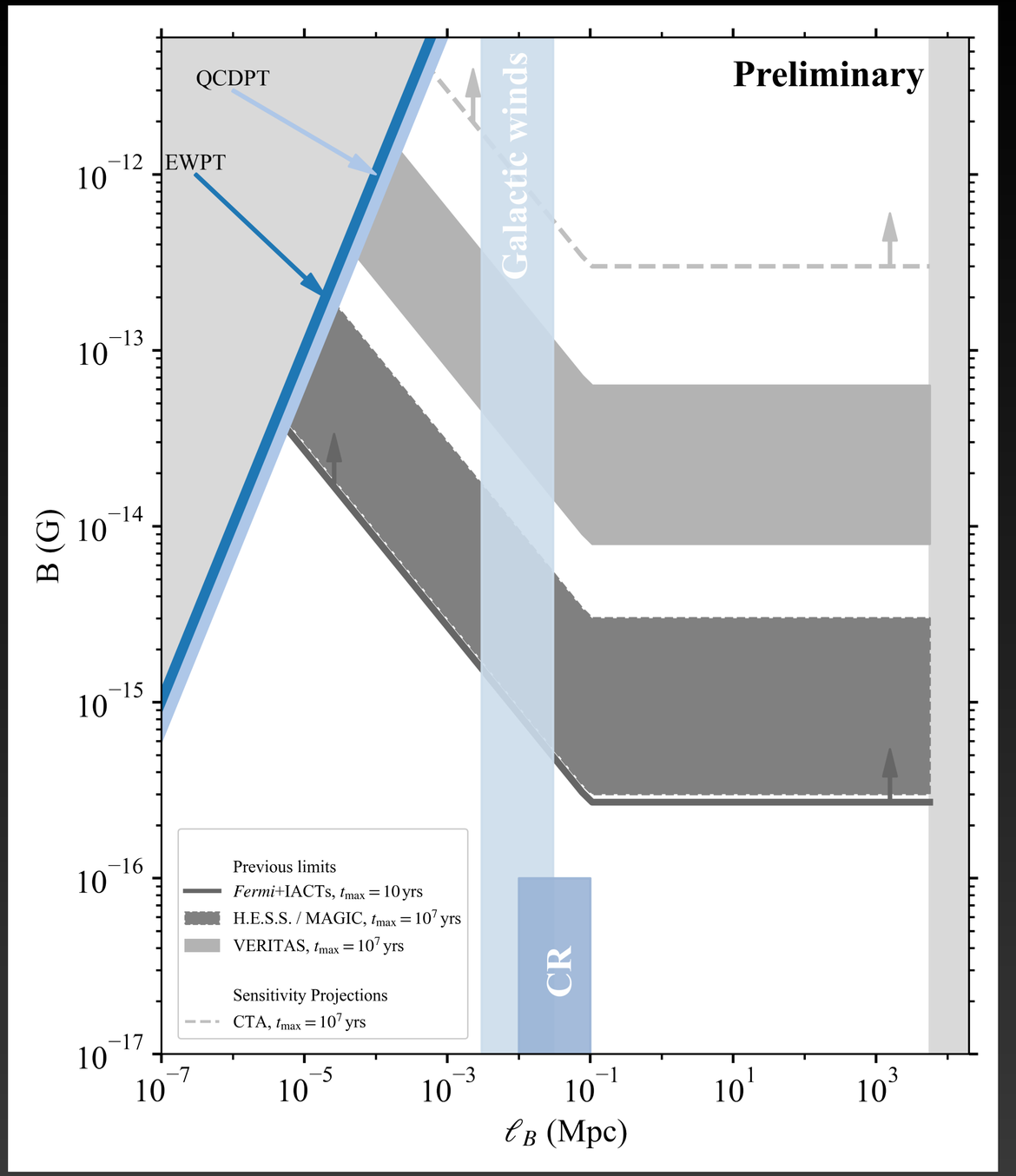

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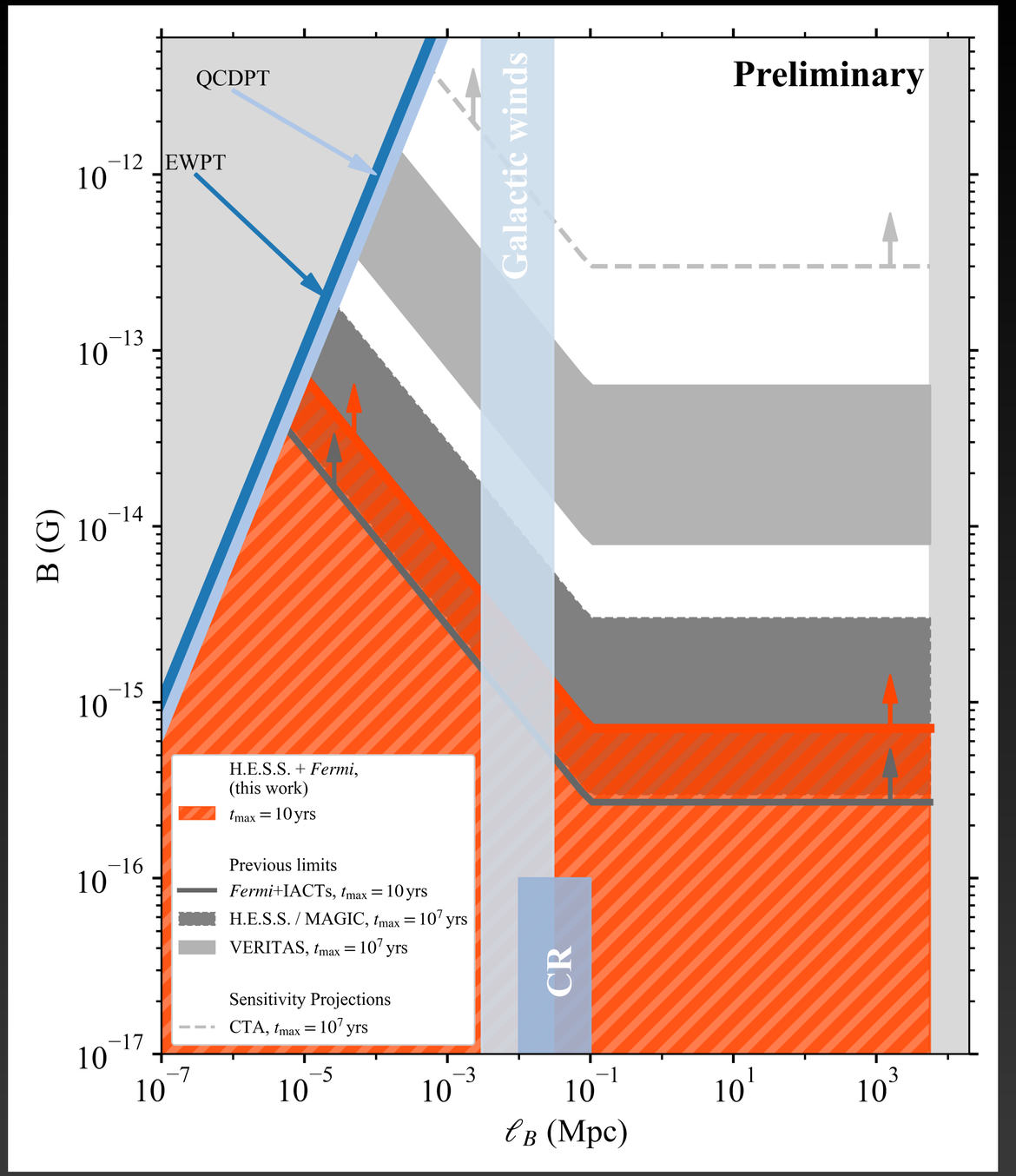

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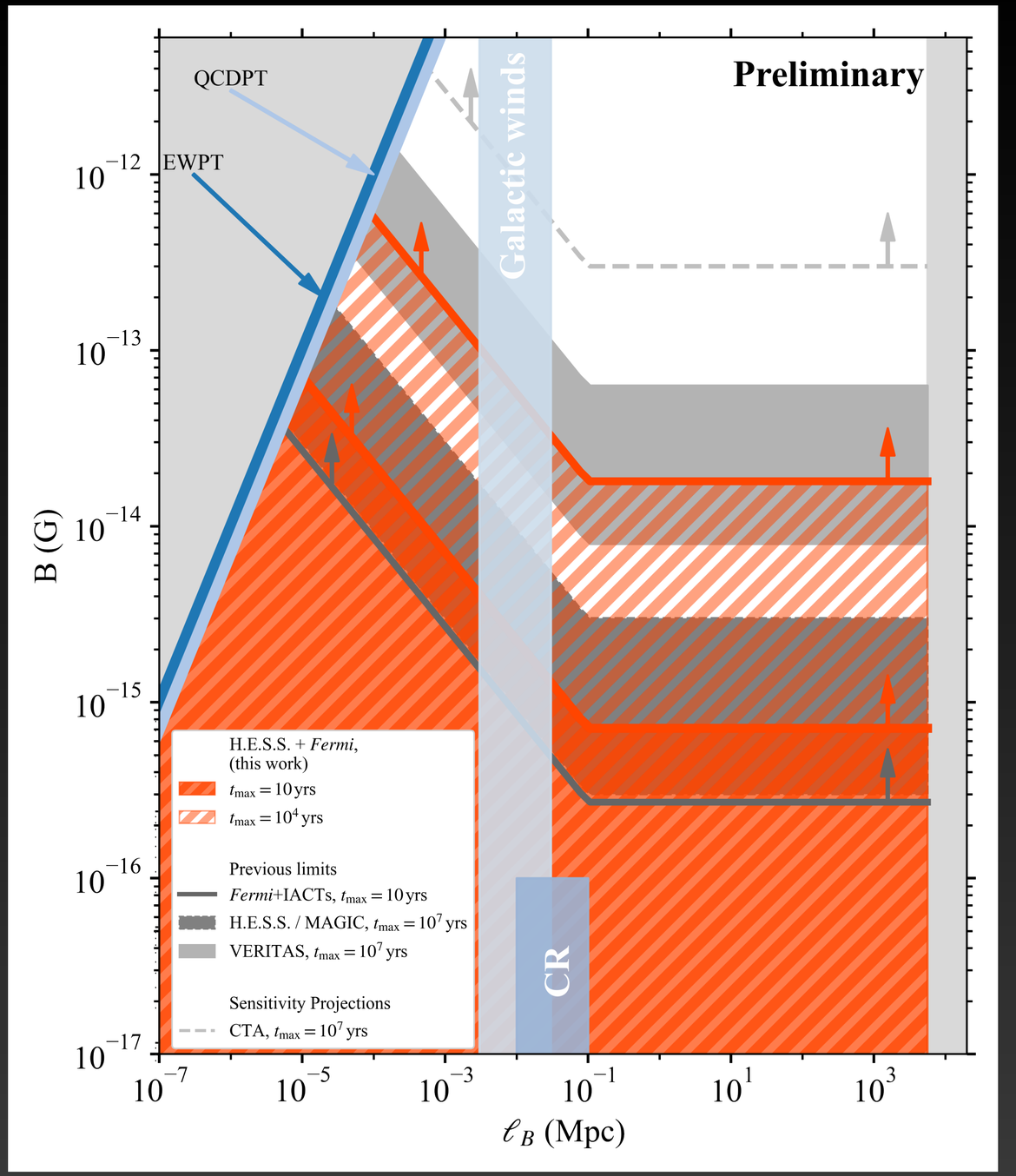

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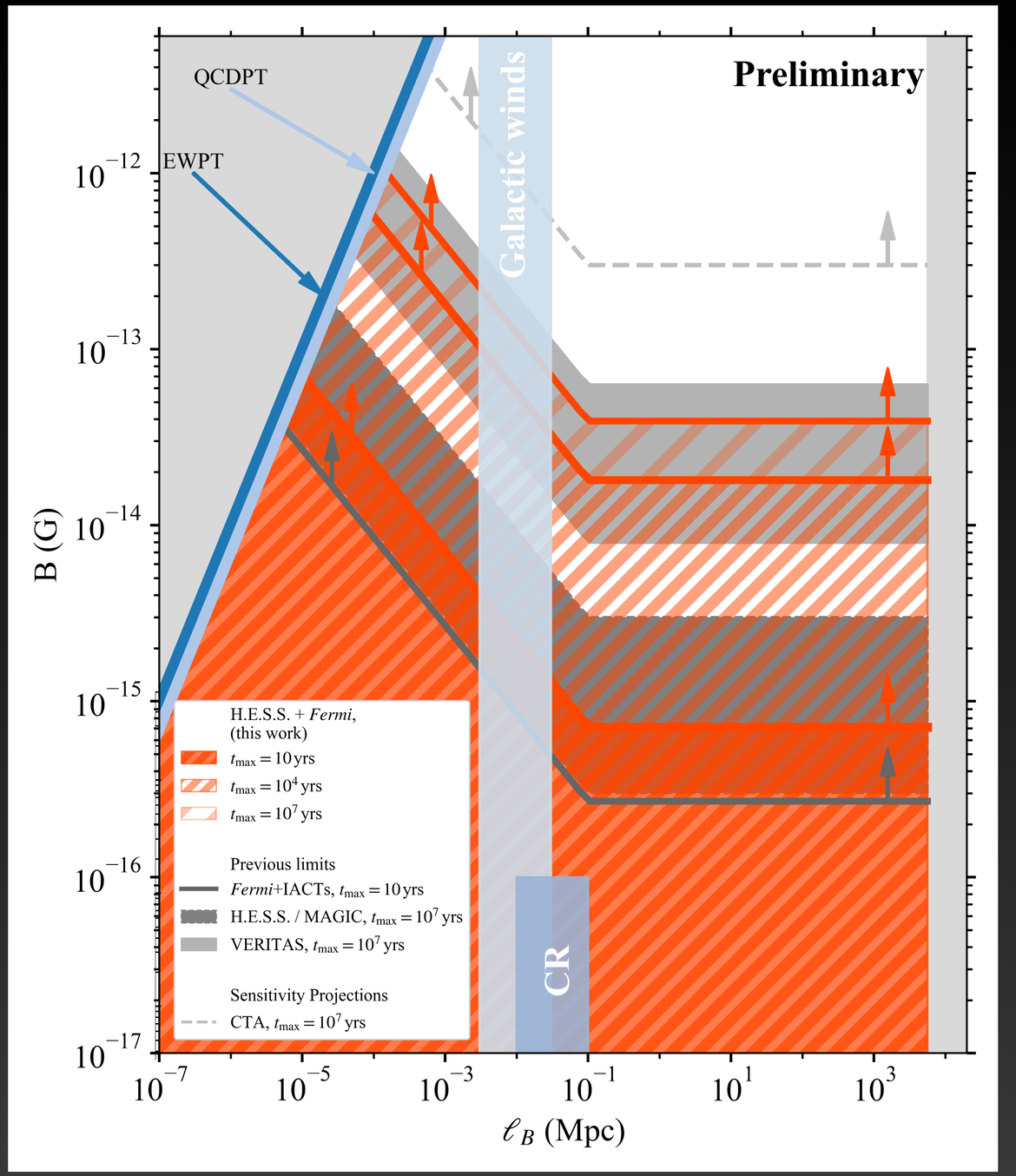

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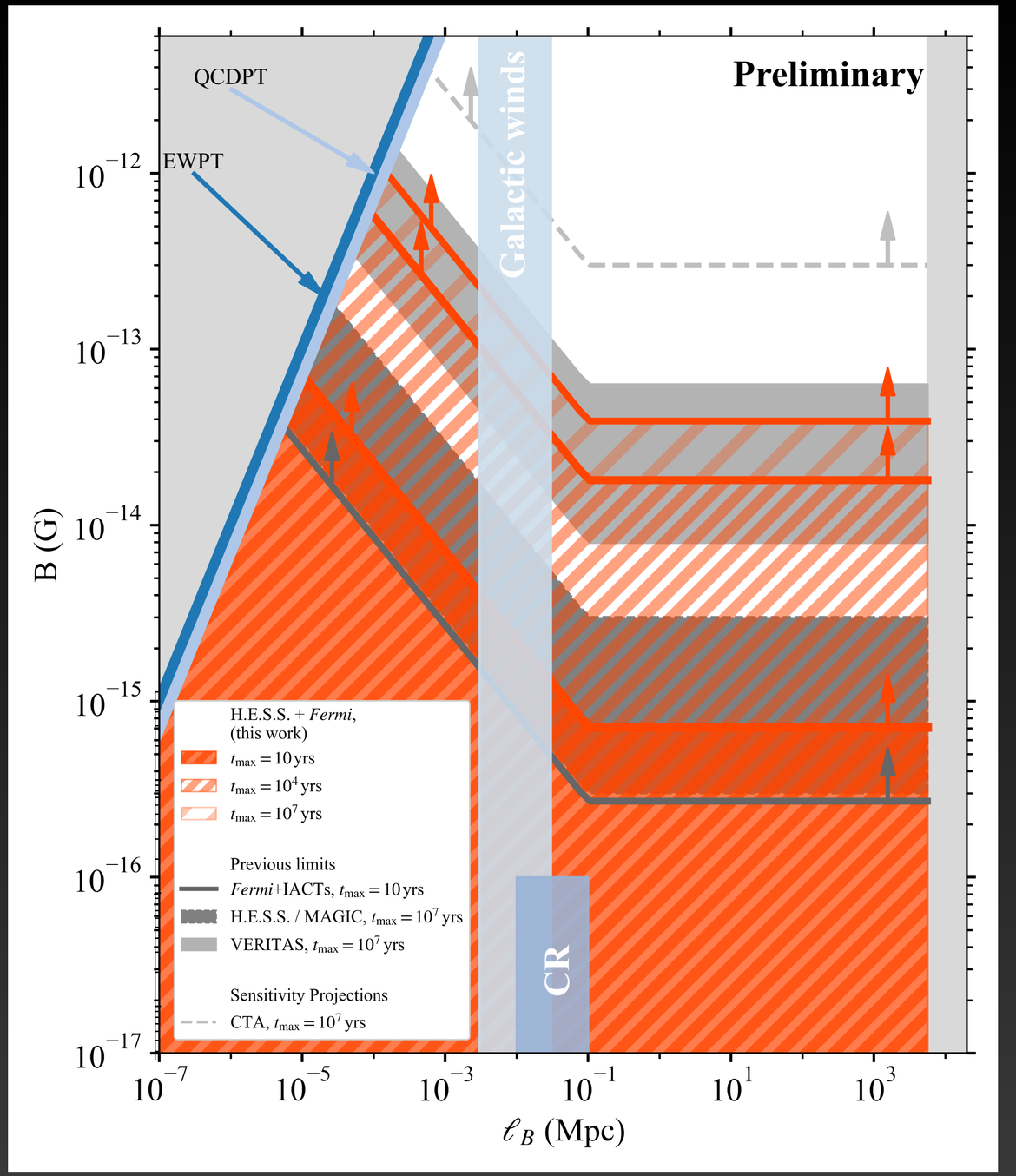

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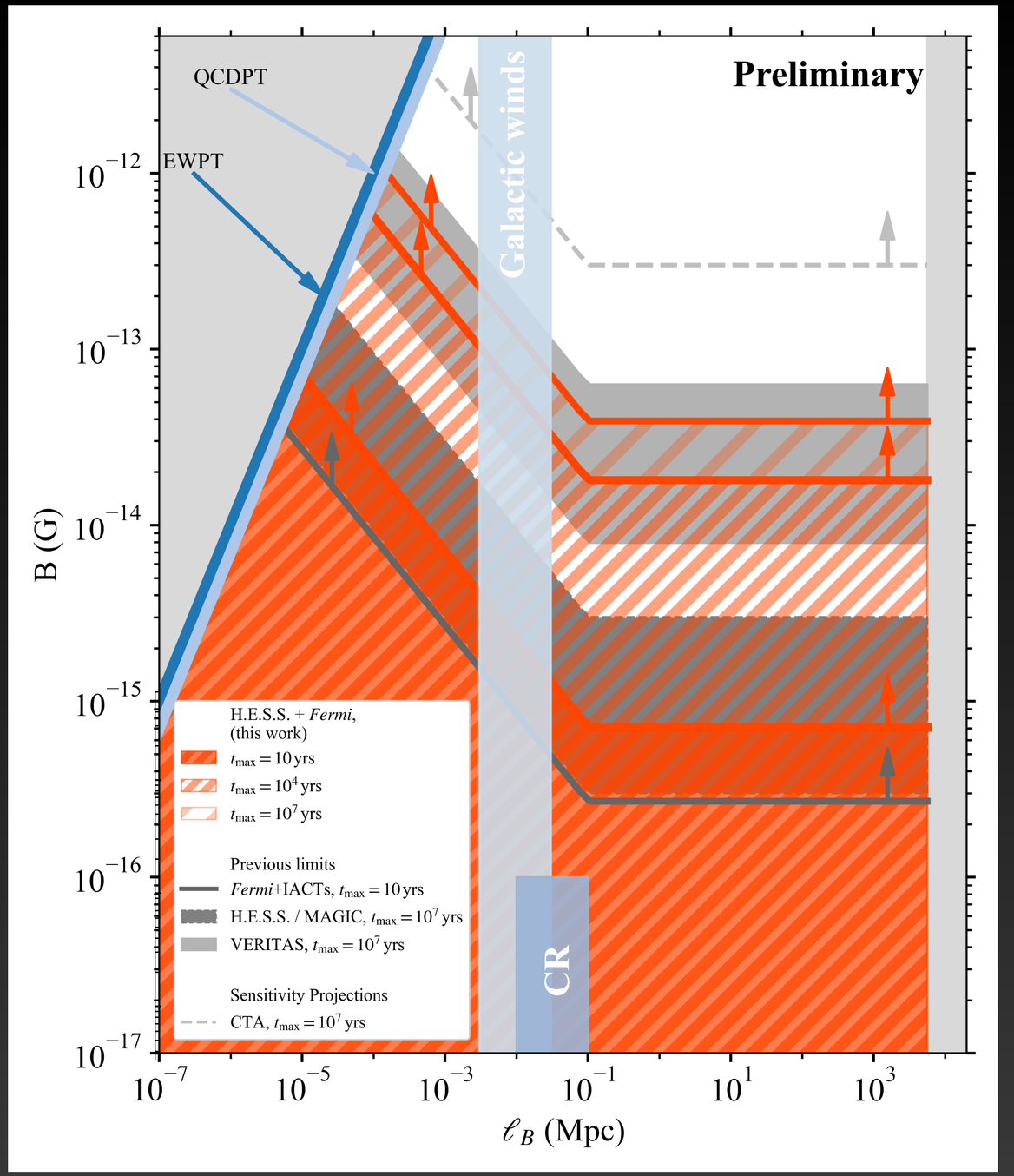

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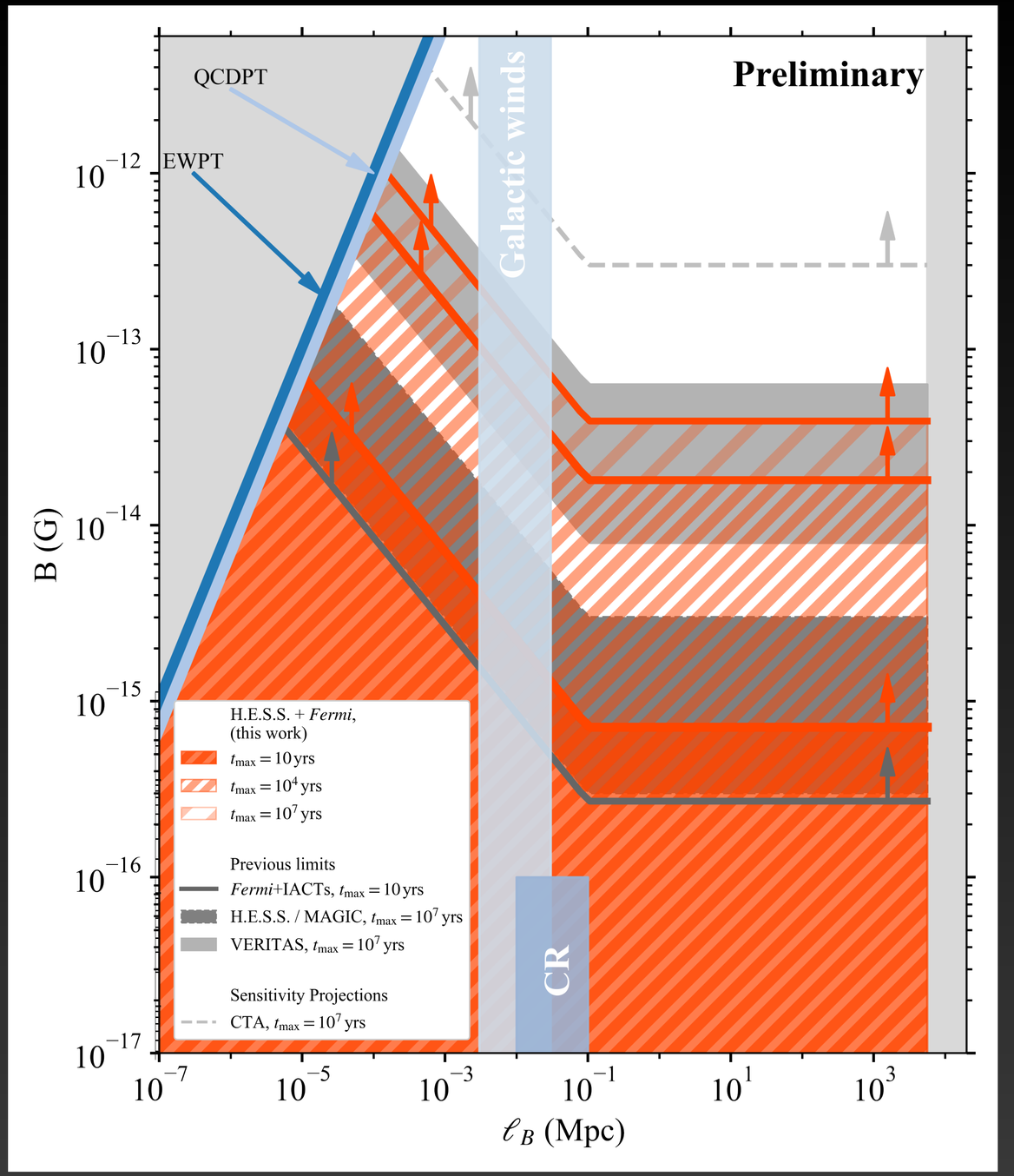

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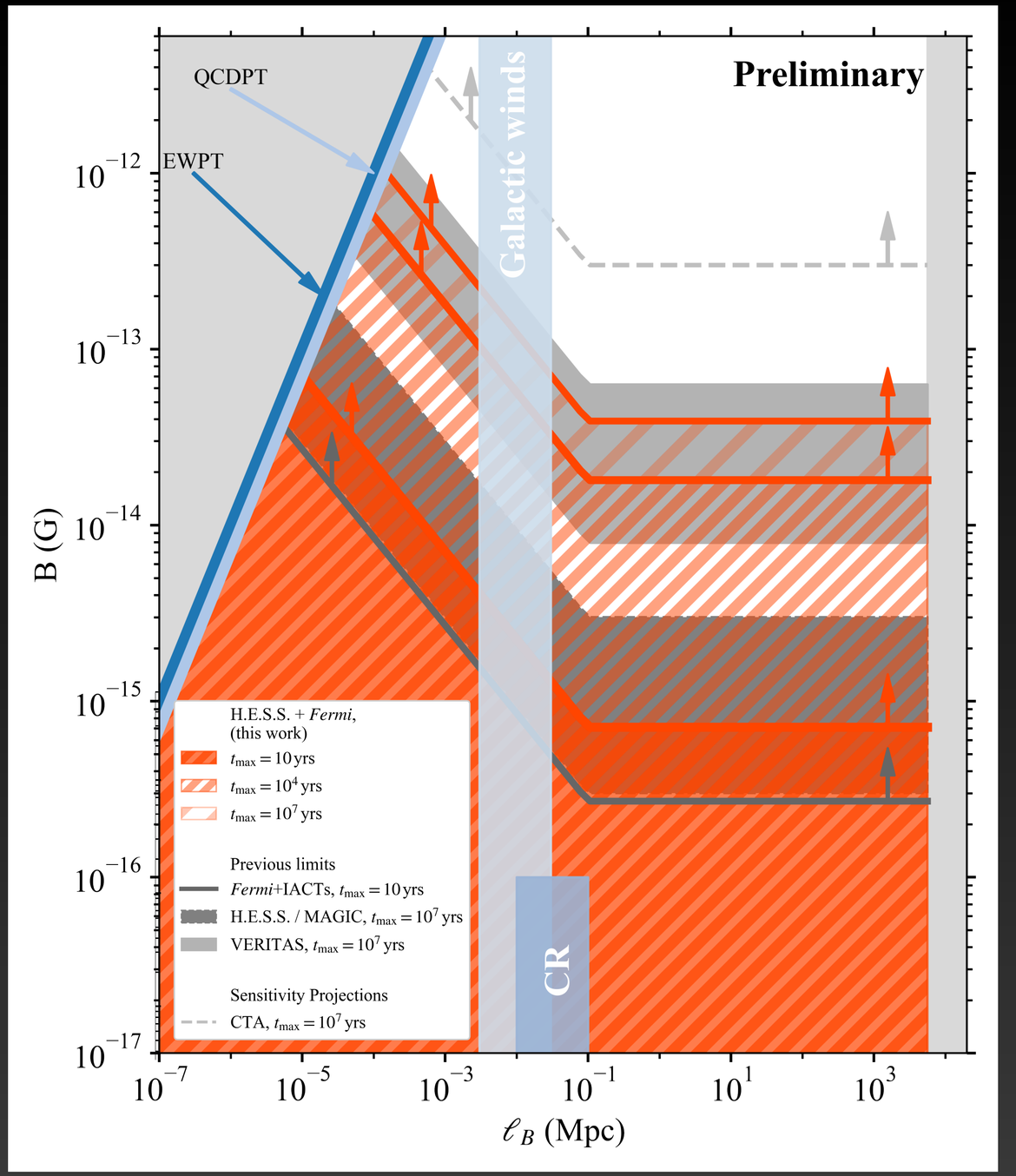

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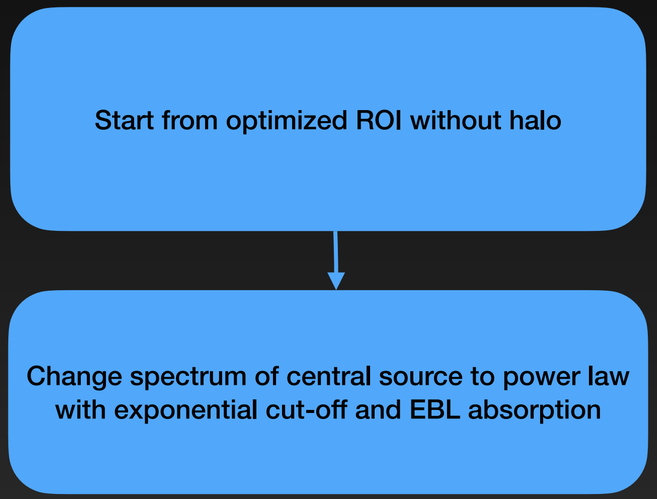
Back up

Fermi-LAT analysis with halo component

Start from optimized ROI without halo

Fermi-LAT analysis with halo component



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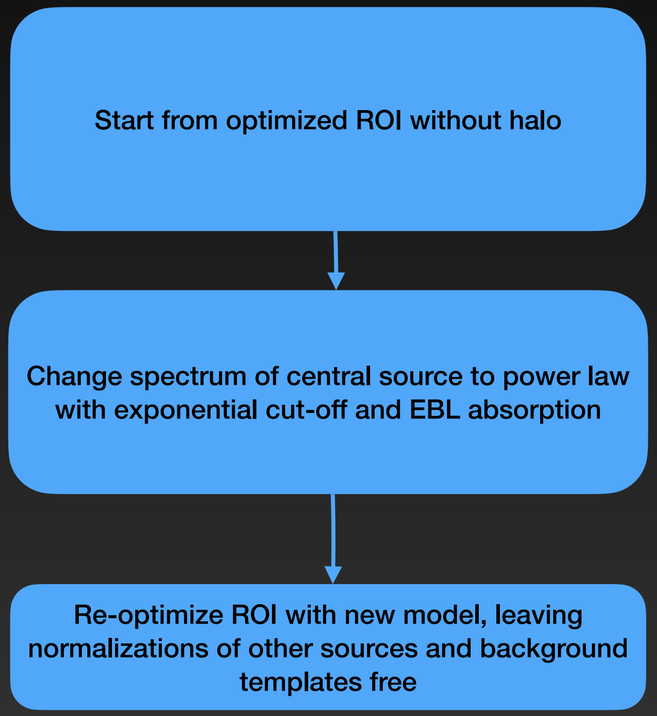

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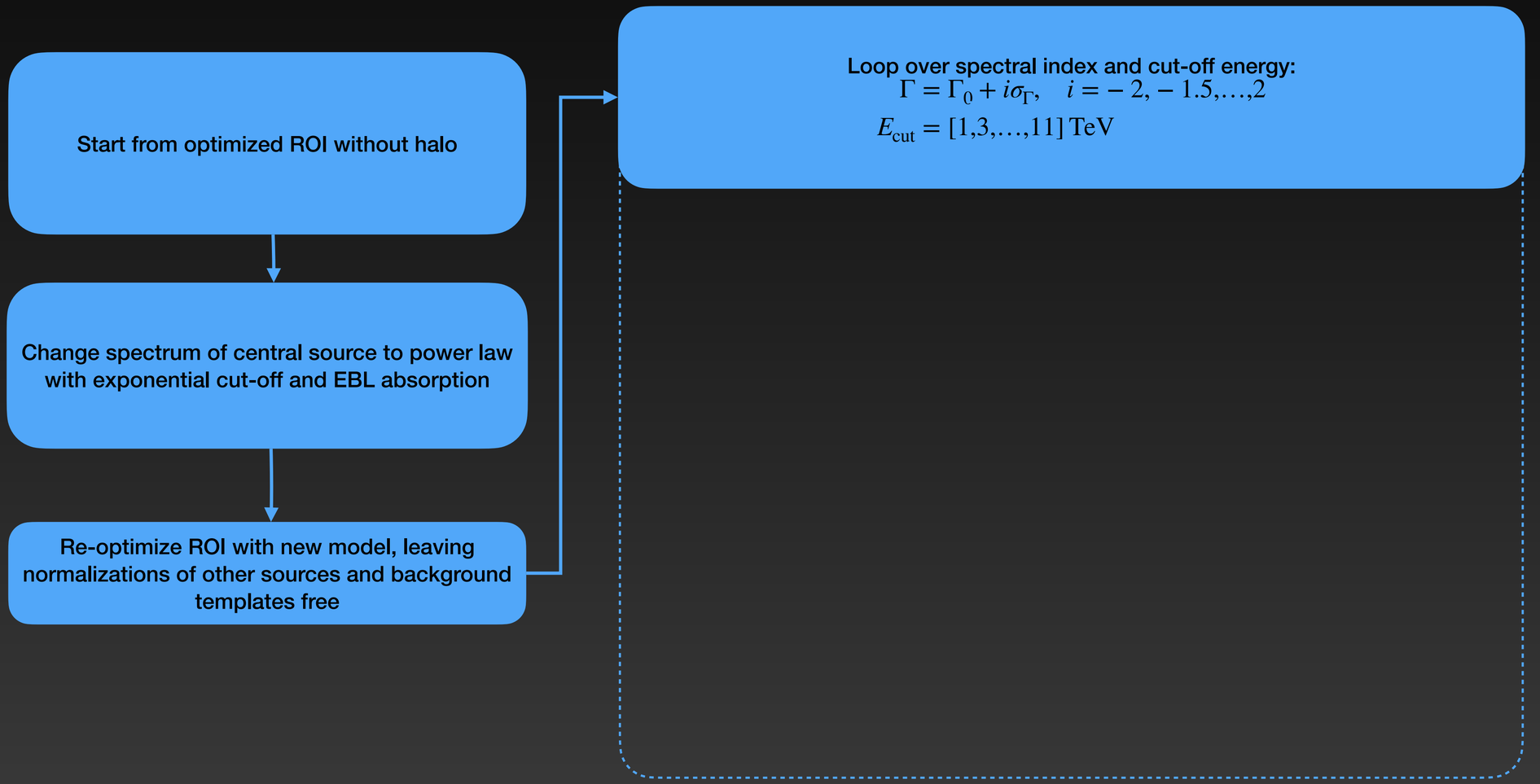

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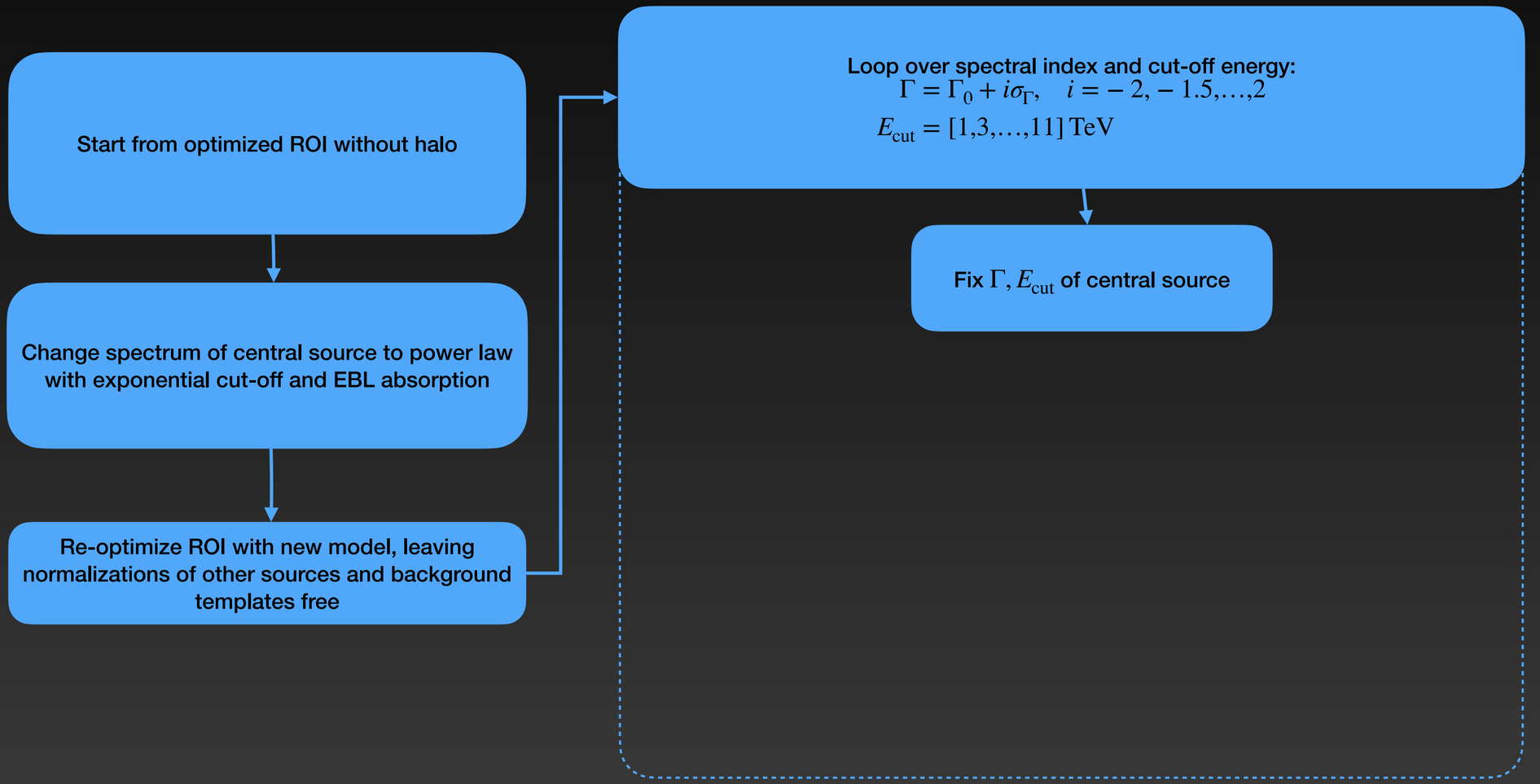

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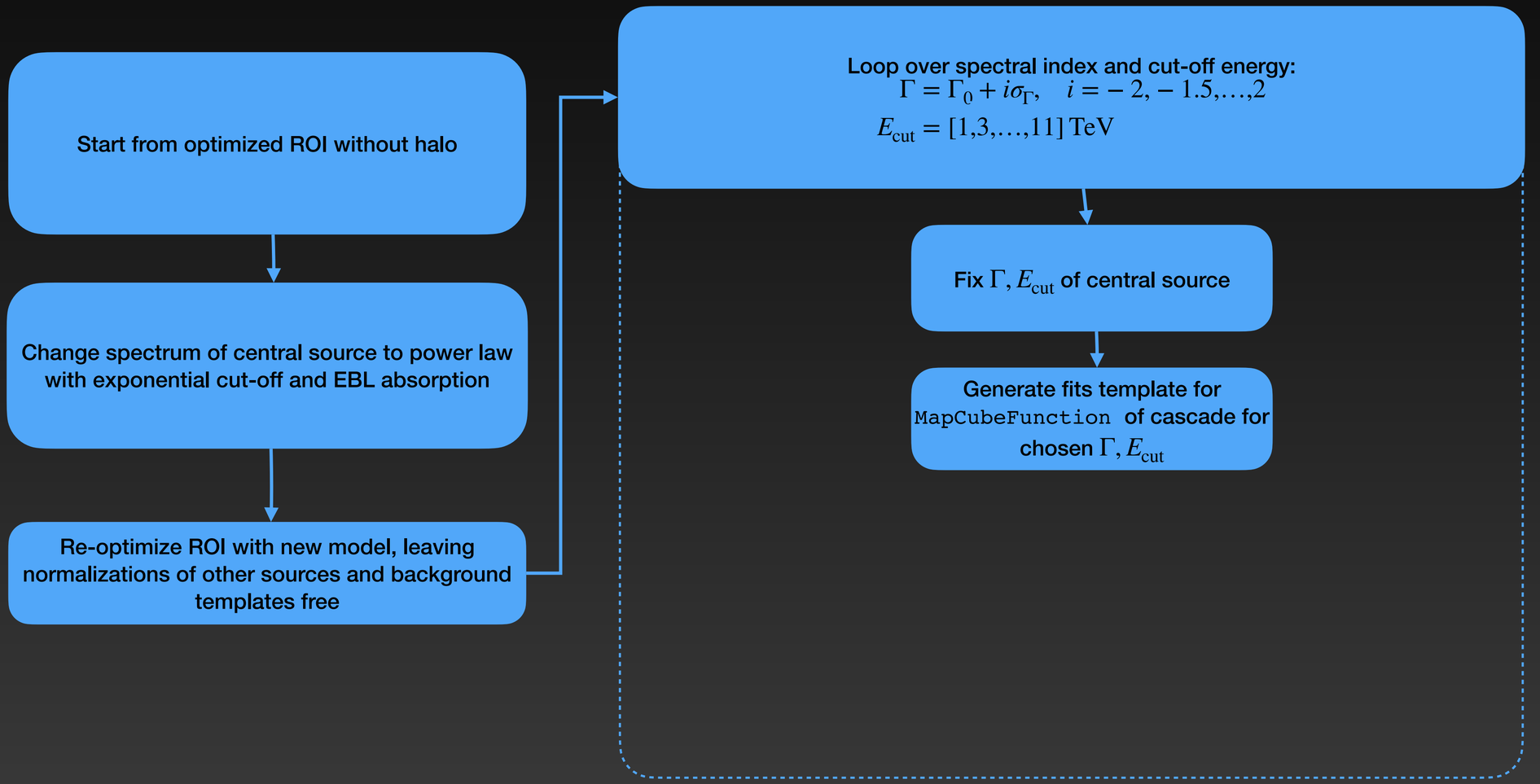

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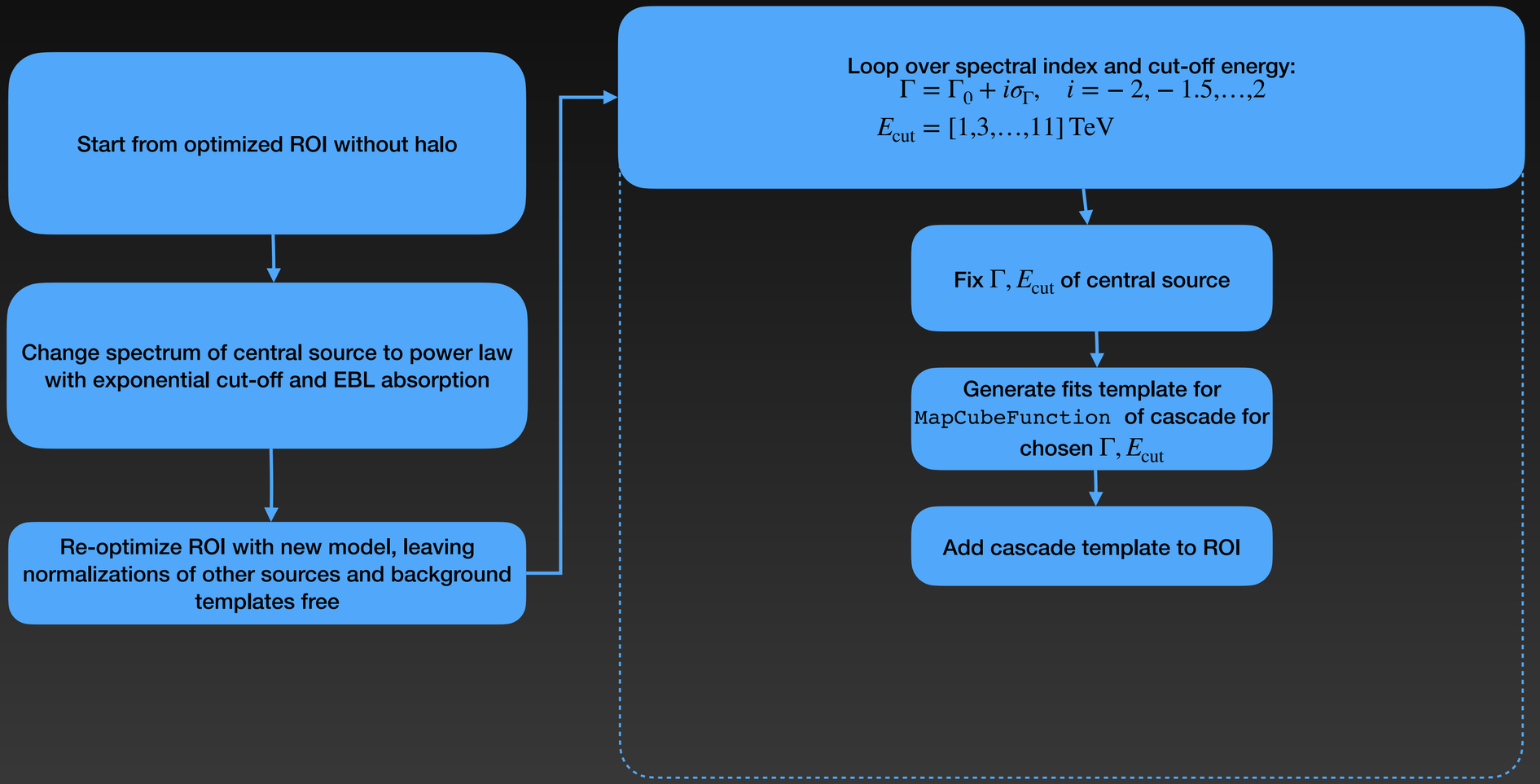

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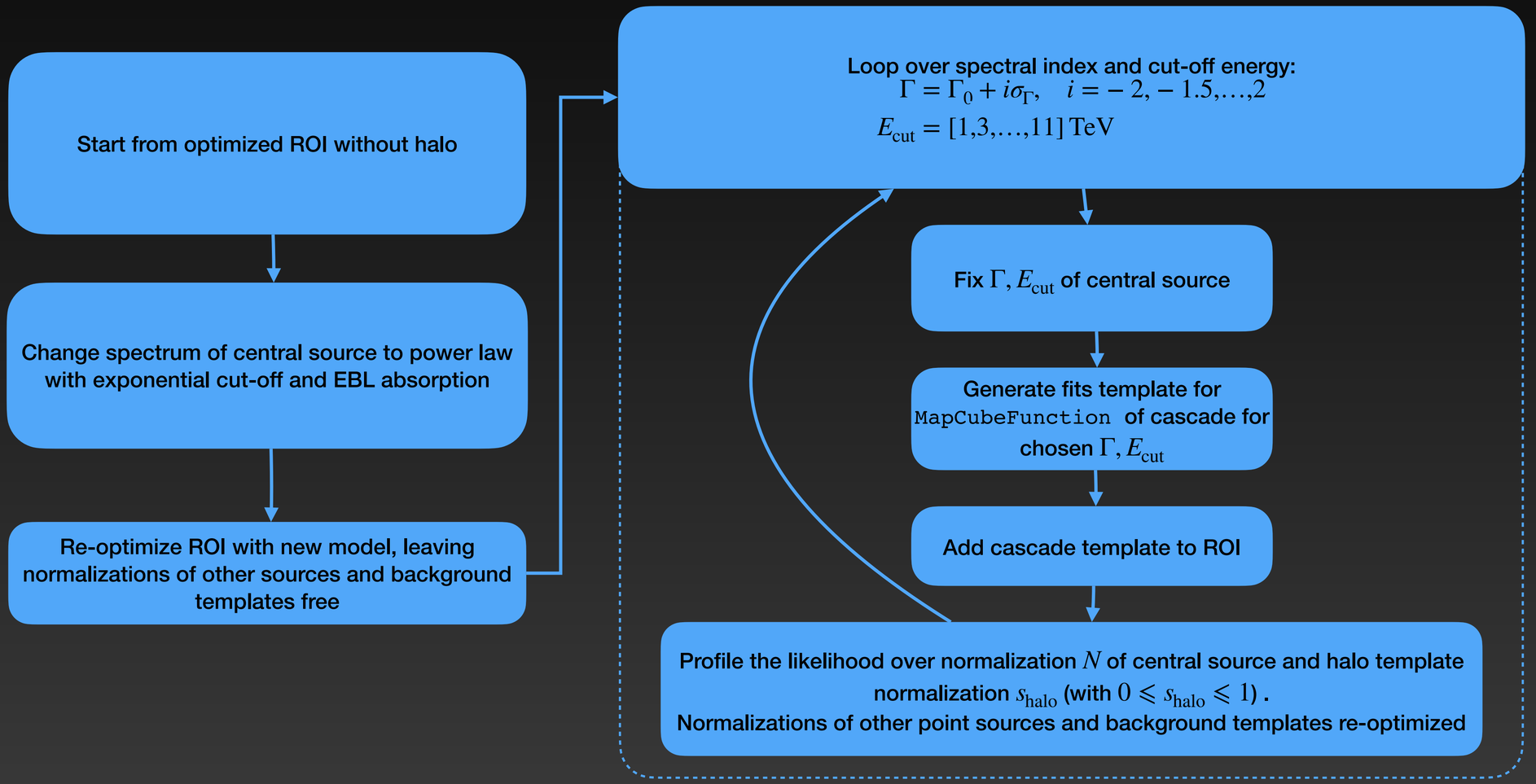

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$$\frac{d\mathcal{N}}{dE d\Omega} = \int_0^\infty d\epsilon \int_0^\infty d\epsilon' \frac{dN}{d\epsilon'} \int_0^{\tau_{\mathrm{max}}} d\tau \frac{d\mathcal{N}}{d\epsilon' dE d\tau d\Omega} \approx \sum_i \sum_j \Delta\epsilon_i \Delta\tau_j w_i \left(\frac{d\mathcal{N}}{d\epsilon dE d\tau d\Omega} \right)_{ij}$$

Building cascade templates

- From the simulated events we build the intensity as function of injected gamma-ray energy ϵ, observed energy E, solid Ω, and delay time τ:

$$\frac{d\mathcal{N}}{d\epsilon dE d\tau d\Omega} = \frac{1}{N_{\rm inj}(\Delta\epsilon)} \frac{\mathcal{N}}{\Delta E \Delta\epsilon \Delta\tau \Delta\Omega}$$

- Simulation done for discrete injection energies ϵ_i
- From this, we can re-weight the cascade histogram for an arbitrary source spectra $dN/d\epsilon$ (e.g., a power law), by computing weights for bins of injected energy:

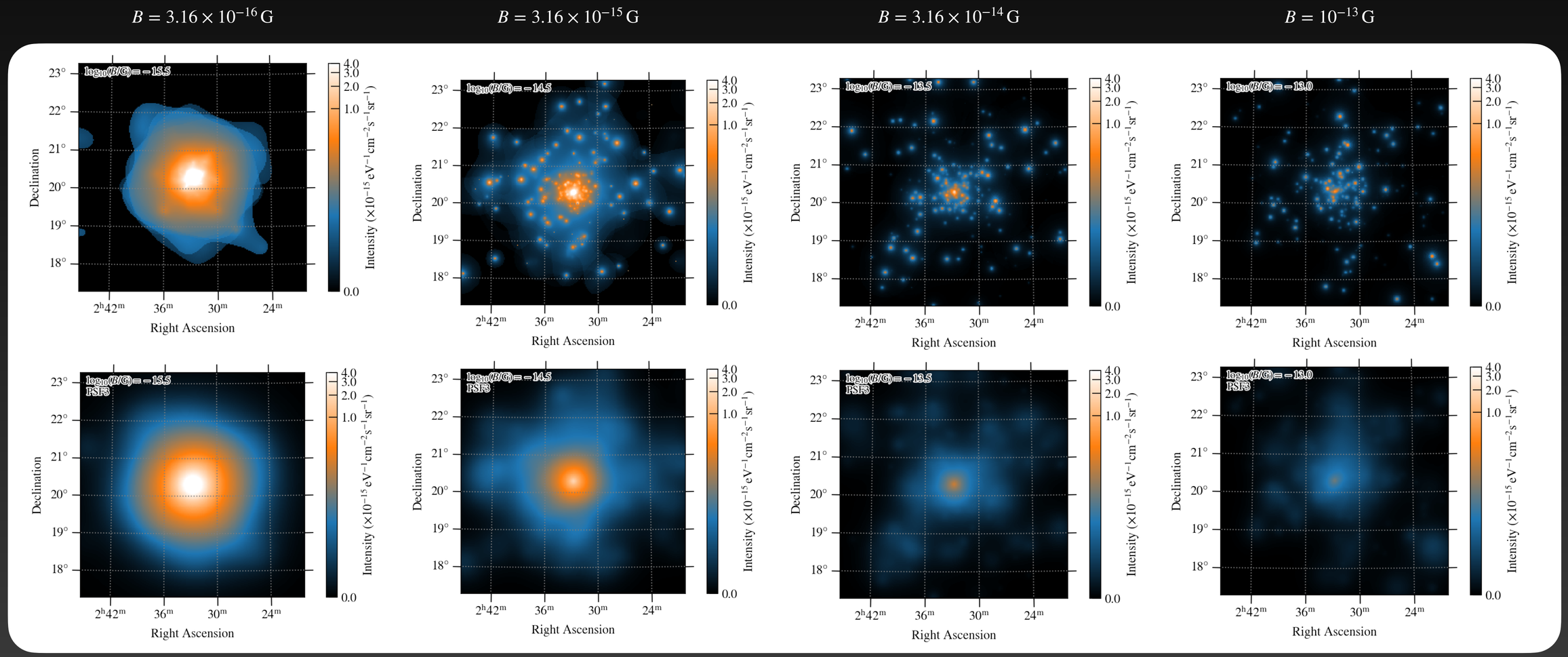
$$w_i = \int_{\Delta\epsilon_i} \frac{dN}{d\epsilon} d\epsilon$$

- With the spectral weights, we obtain the expected cascade flux that arrives within some maximum time delay (assuming constant emission with time)

$$\frac{d\mathcal{N}}{dE d\Omega} = \int_0^\infty d\epsilon \int_0^\infty d\epsilon' \frac{dN}{d\epsilon'} \int_0^{\tau_{\rm max}} d\tau \frac{d\mathcal{N}}{d\epsilon' dE d\tau d\Omega} \approx \sum_i \sum_j \Delta\epsilon_i \Delta\tau_j w_i \left(\frac{d\mathcal{N}}{d\epsilon dE d\tau d\Omega} \right)_{ij}$$

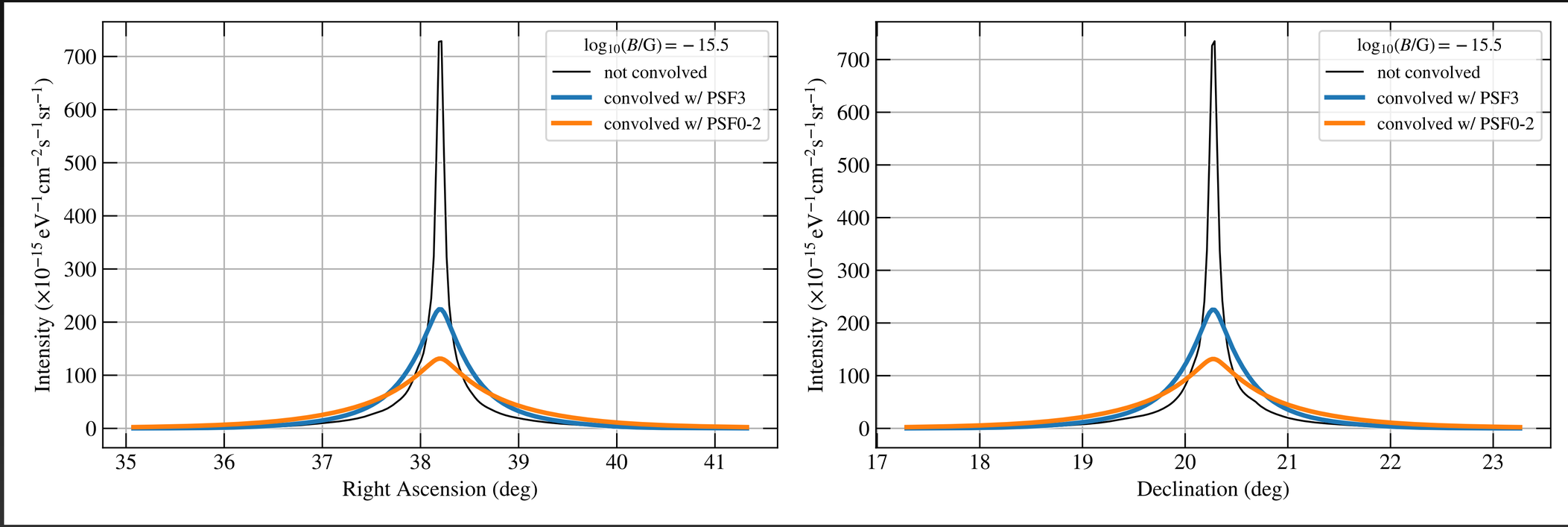
- Cascade flux will depend on IGMF strength B and coherence length λ, injection spectrum, maximum activity time of the source $t_{\rm max}$, as well as $\theta_{\rm jet}, \theta_{\rm obs}$ and source redshift z

Cascade templates as function of IGMF strength: sky maps



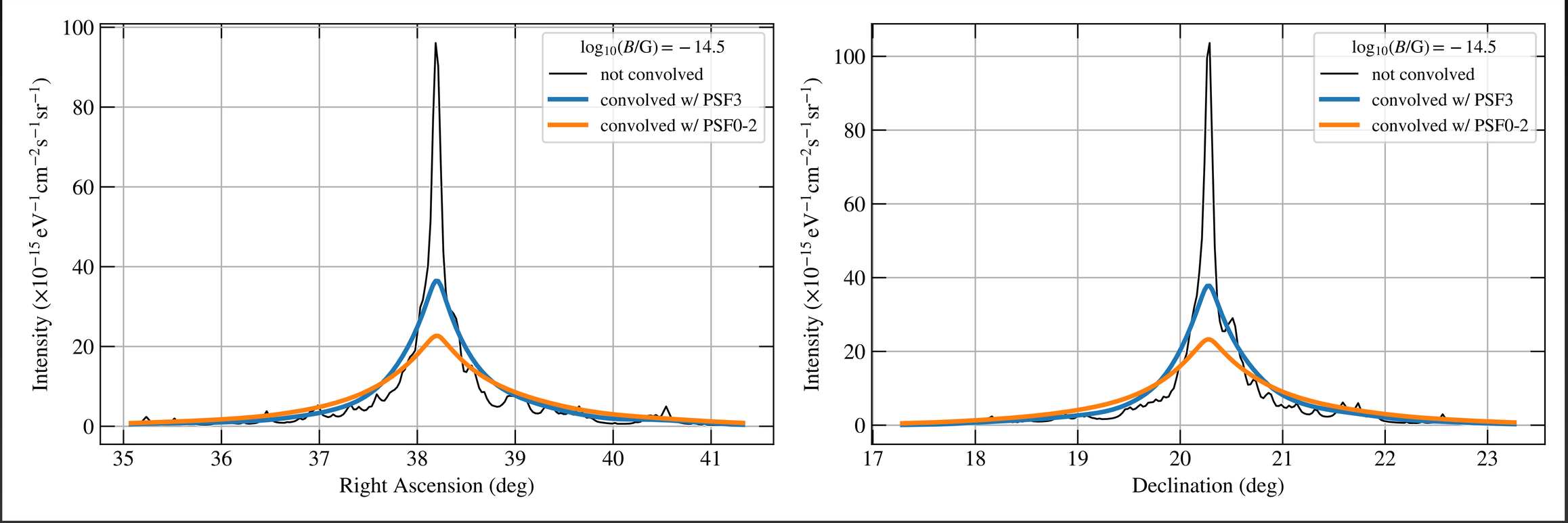
Cascade templates as function of IGMF strength: lon/lat profiles

$B = 3.16 \times 10^{-16}\,\mathrm{G}$, sky map summed over lon/lat and energy



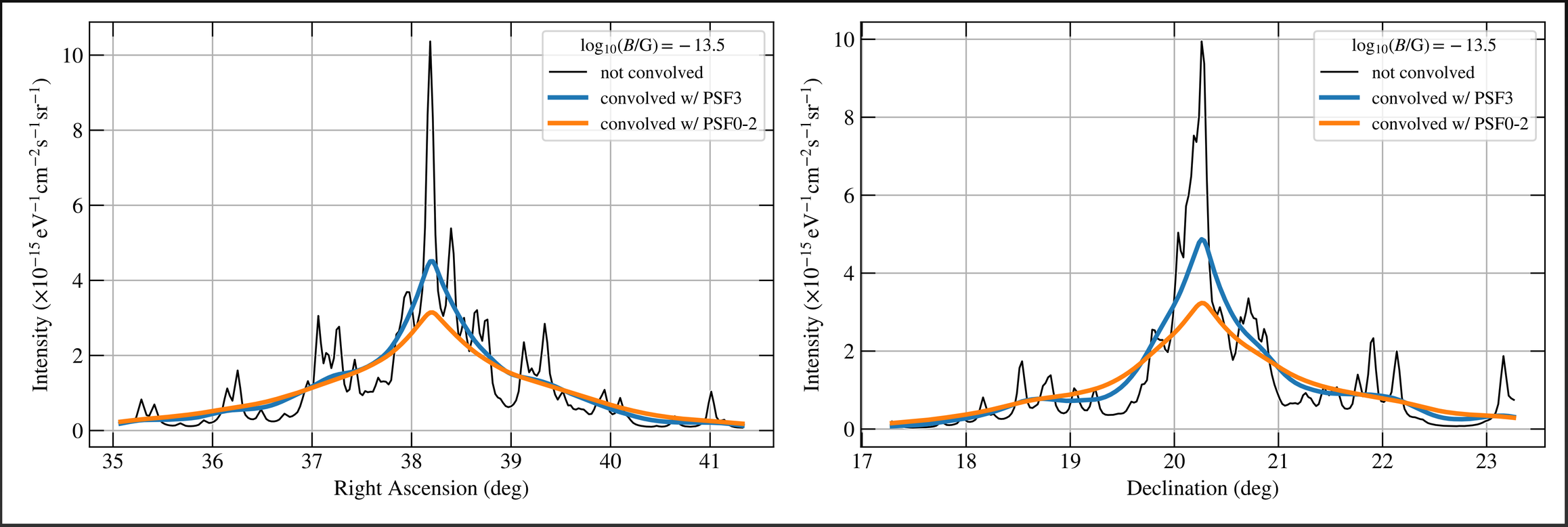
Cascade templates as function of IGMF strength: lon/lat profiles

$B = 3.16 \times 10^{-15}\,\mathrm{G}$, sky map summed over lon/lat and energy



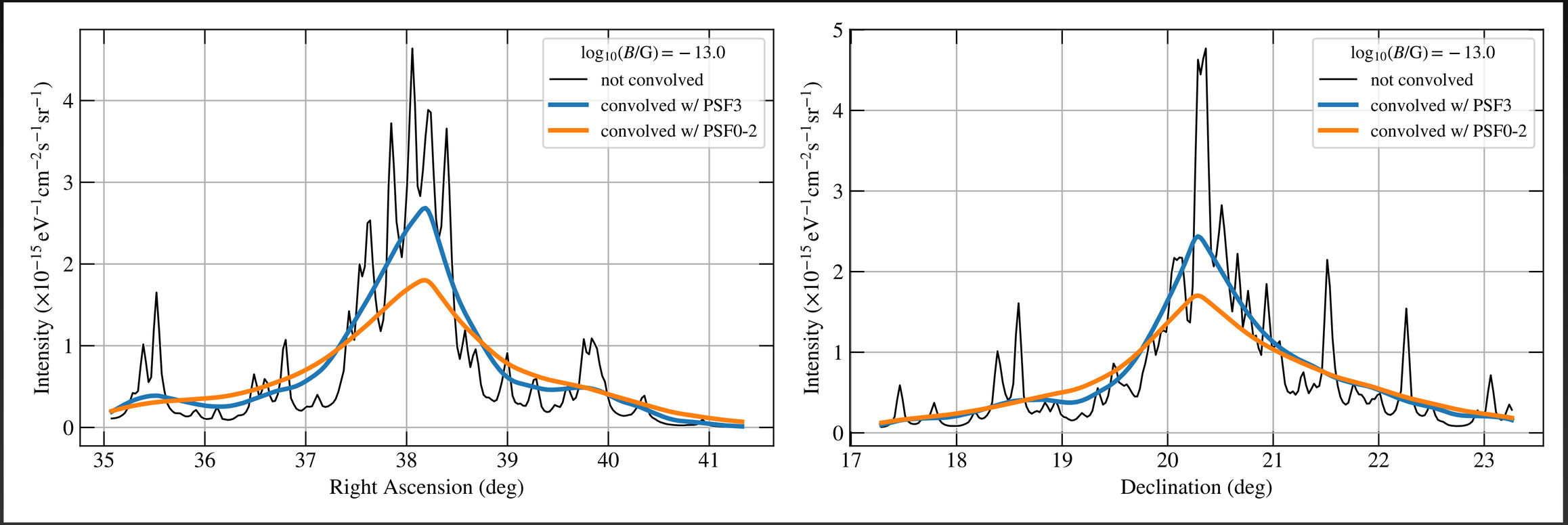
Cascade templates as function of IGMF strength: lon/lat profiles

$B = 3.16 \times 10^{-14}\,\mathrm{G}$, sky map summed over lon/lat and energy

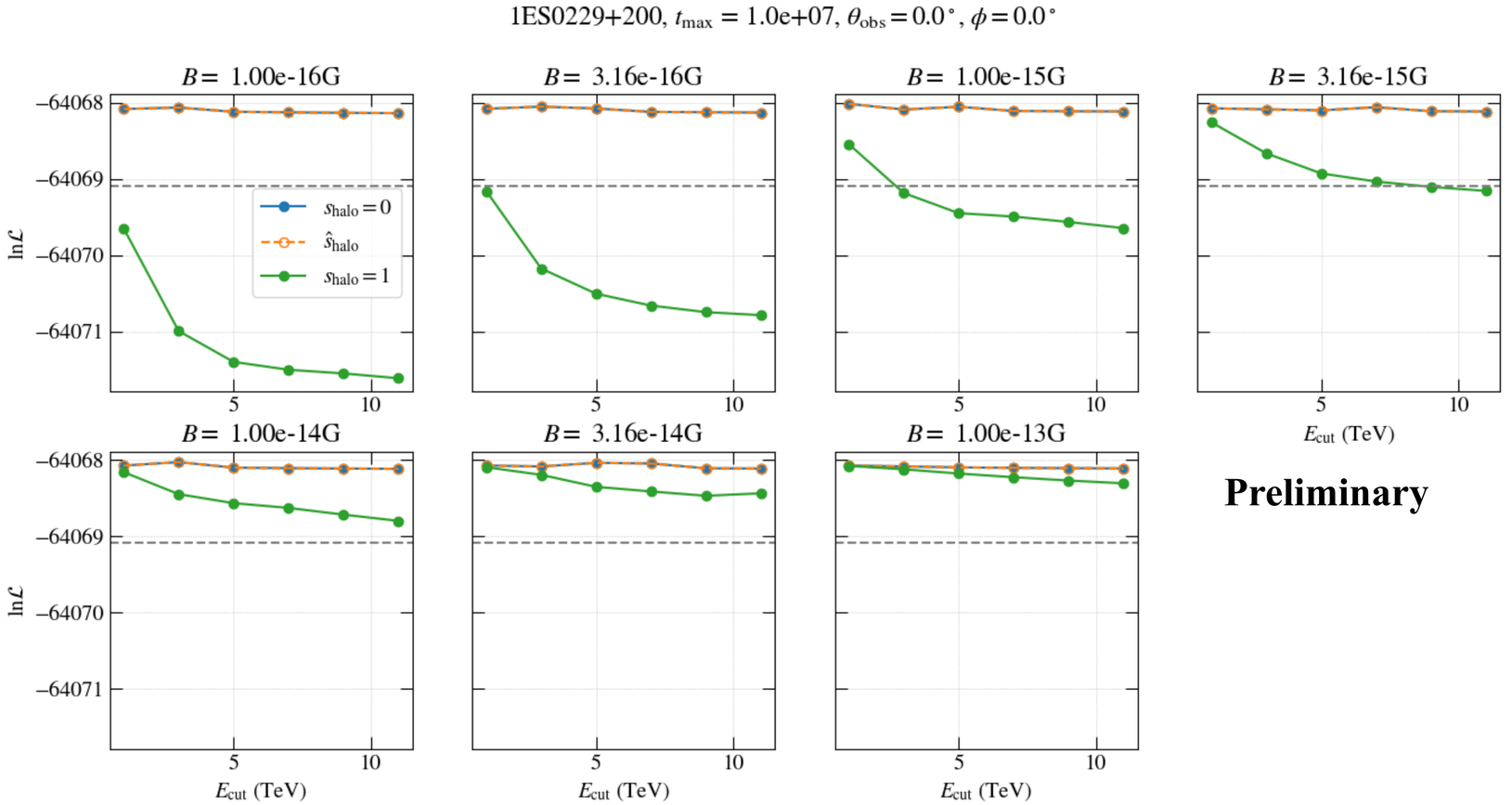


Cascade templates as function of IGMF strength: lon/lat profiles

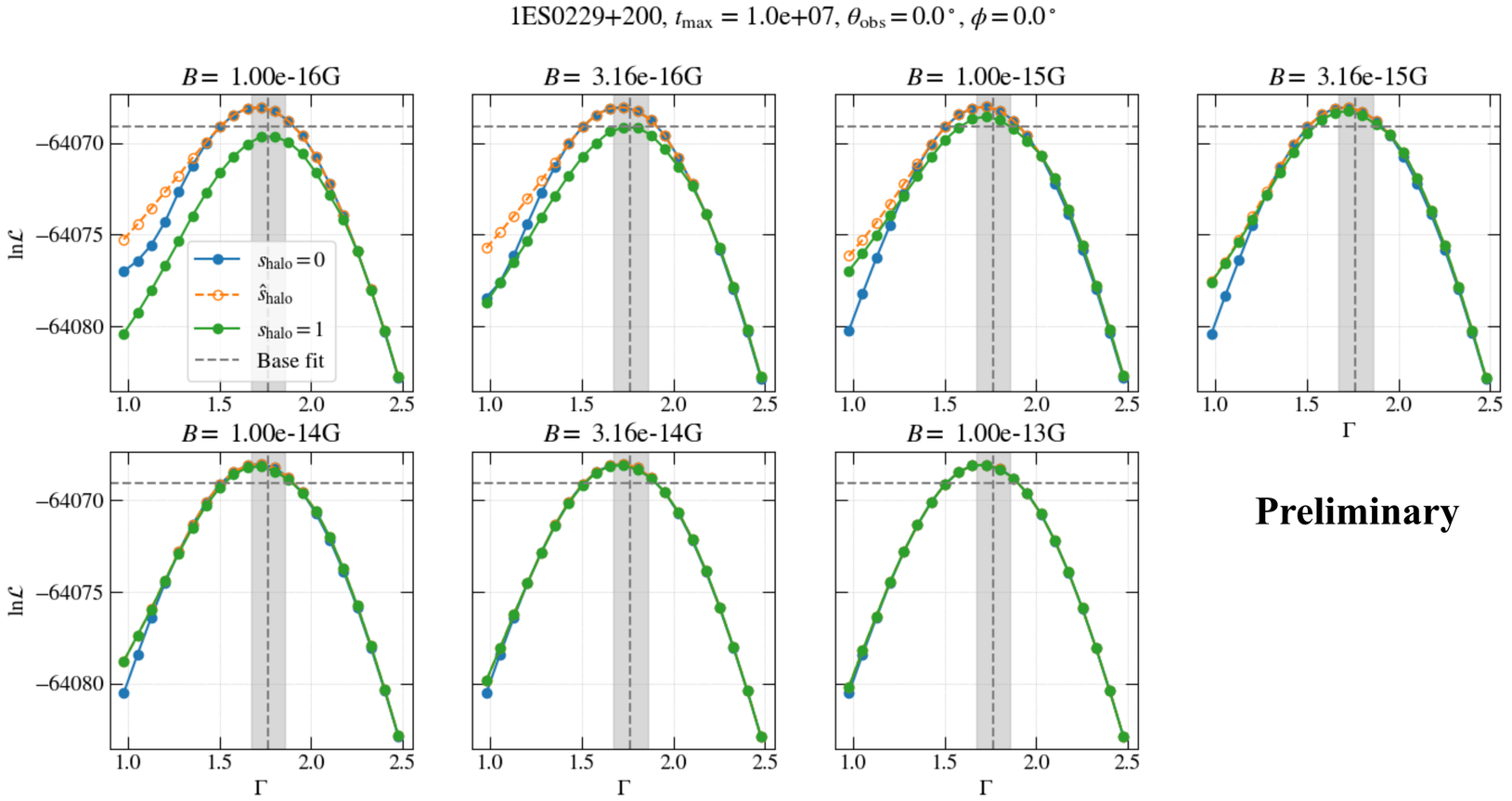
$B = 10^{-13}$ G, sky map summed over lon/lat and energy



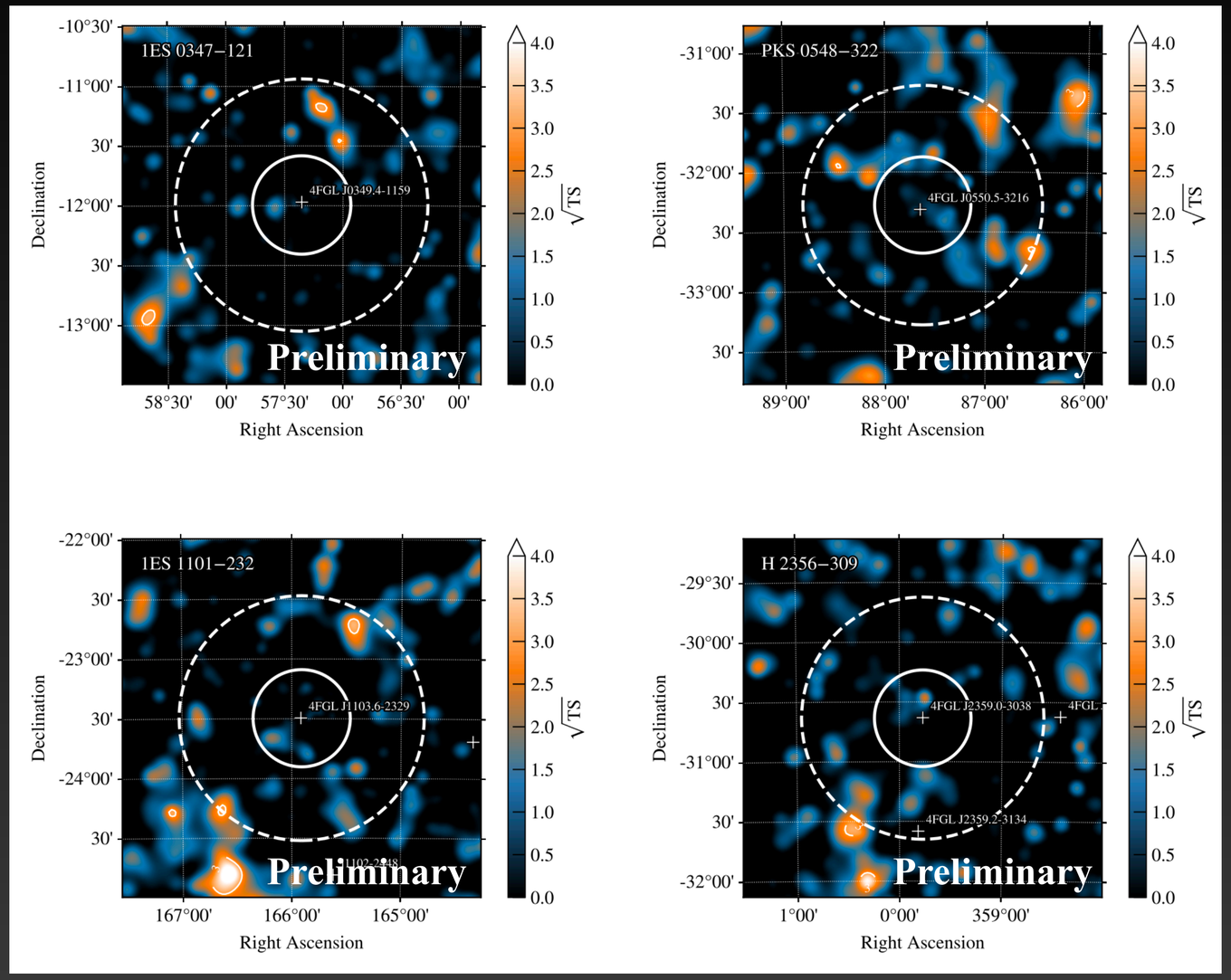
Fermi-LAT Analysis with halo component — Examples of likelihood profile with E_{cut}



Fermi-LAT Analysis with halo component — Examples of likelihood profile with Γ



TS maps for all sources



Source Spectra

1ES0229+200

1ES0347-121

PKS0548-322

1ES1101-232

H2356-309