Constraints on the Intergalactic Magnetic Field from Gamma-Ray Observations of Blazars

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Intergalactic Magnetic Field

Two broad categories for generating IGMF:

Astrophysical: Motion of plasma from outflows from first stars, AGN, or galaxies separates electrons and protons, which creates electric and magnetic fields.

Result: IGMF only in galaxy clusters, along filaments, or where matter is found.

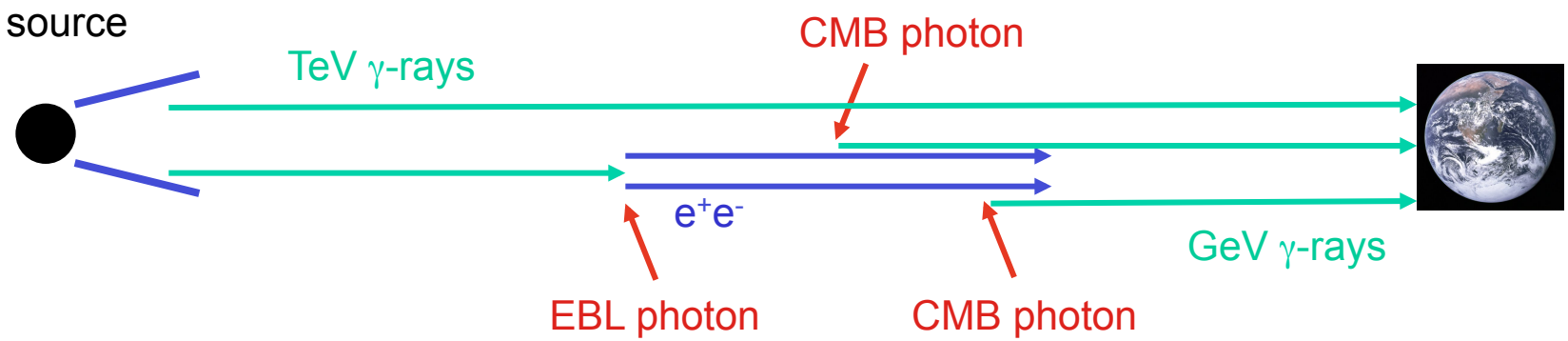
Cosmological: Plasma motion in early universe, during phase transitions or era of inflation

Results: IGMF throughout universe, including in voids.

e.g., Neronov & Semikov (2009, Phys Rev D, 80, 123012)

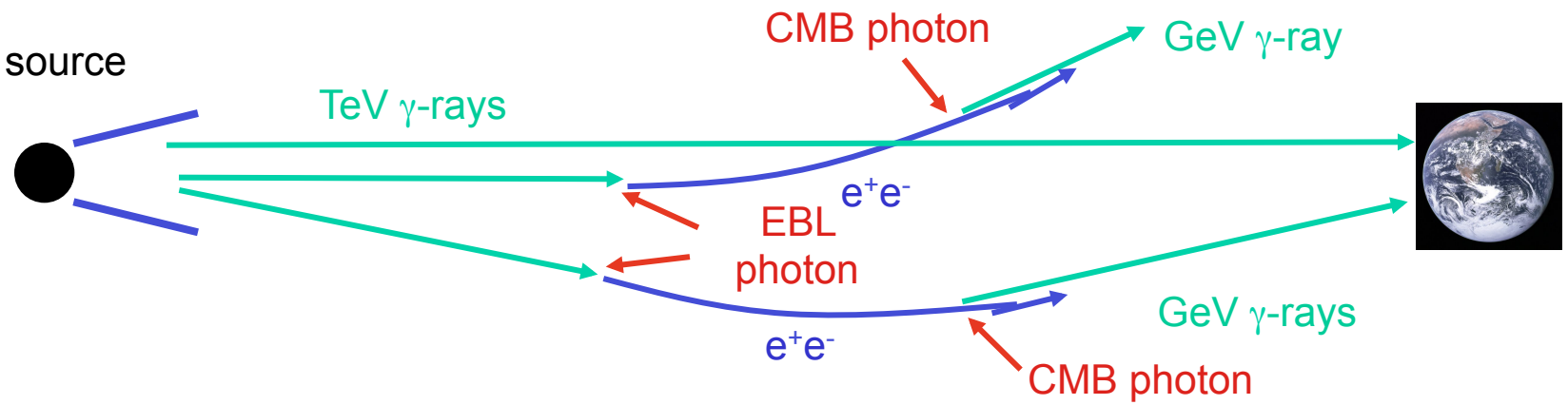
EBL pair cascade

No Intergalactic Magnetic Field



GeV γ-rays delayed due to slower e+e- speed

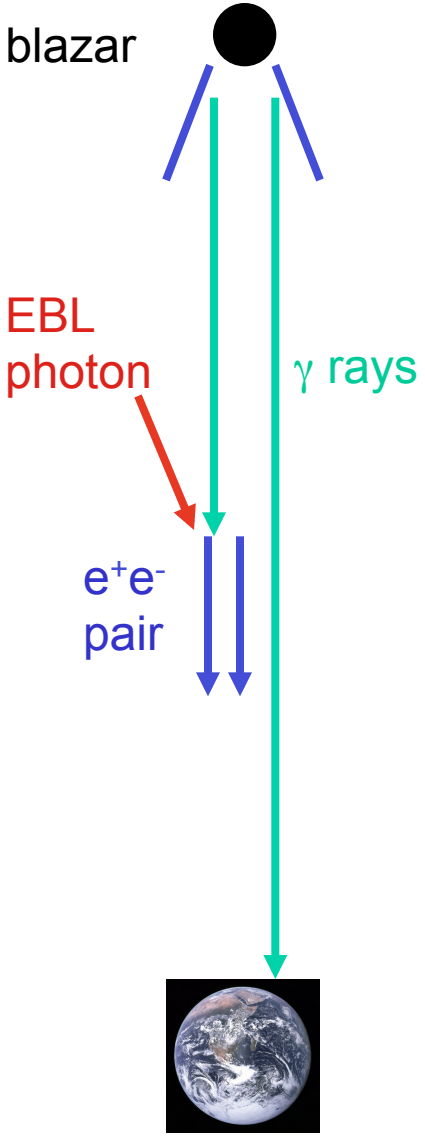
Non-zero Intergalactic Magnetic Field



GeV γ-rays delayed due to slower e+e- speed and greater distance traveled

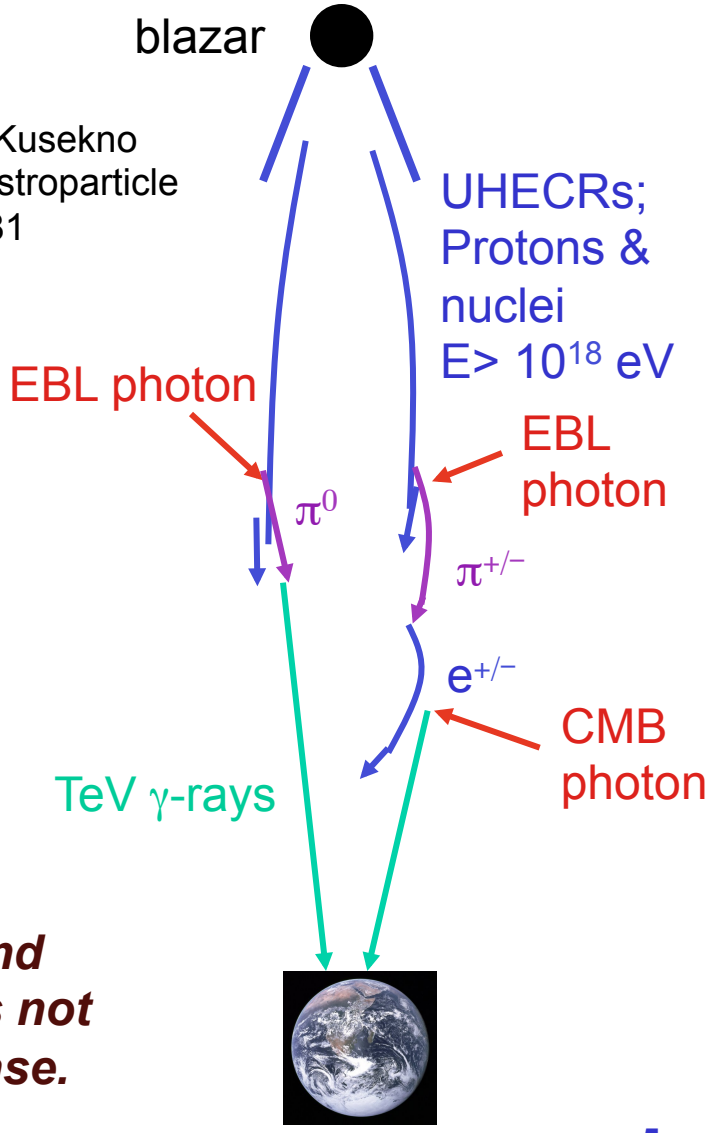
Assumption #1

The gamma rays originate at the source.



We assume this is the case . . .

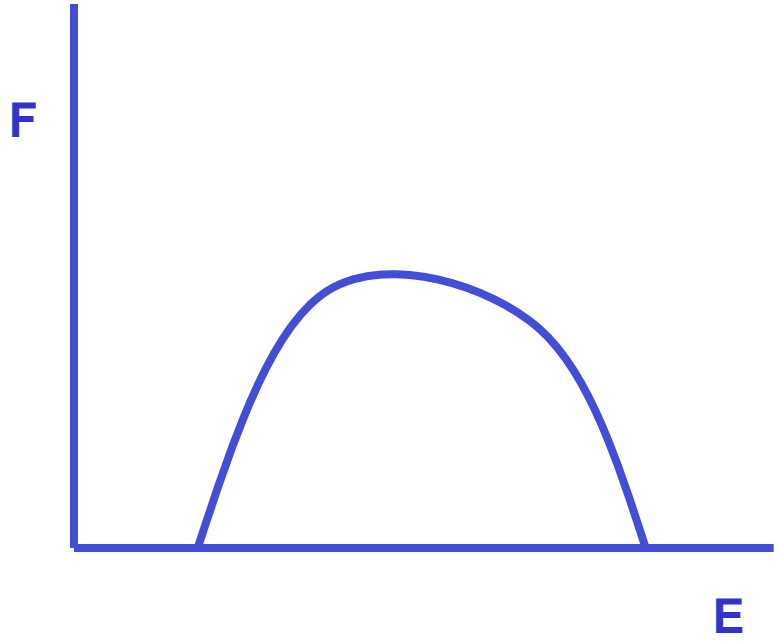
Essey & Kusekno (2010), Astroparticle Ph., 33, 81



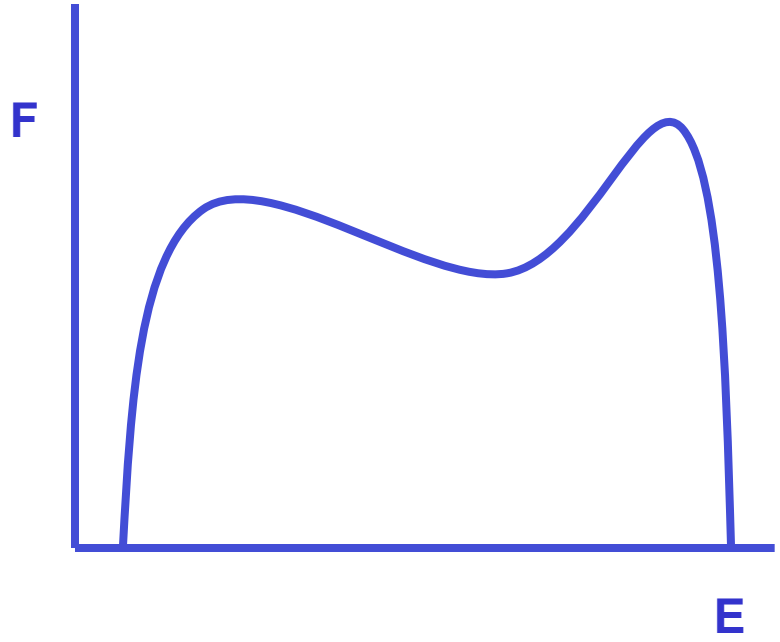
. . . and this is not the case.

Assumption #2

The gamma-ray spectrum is not curved upwards.

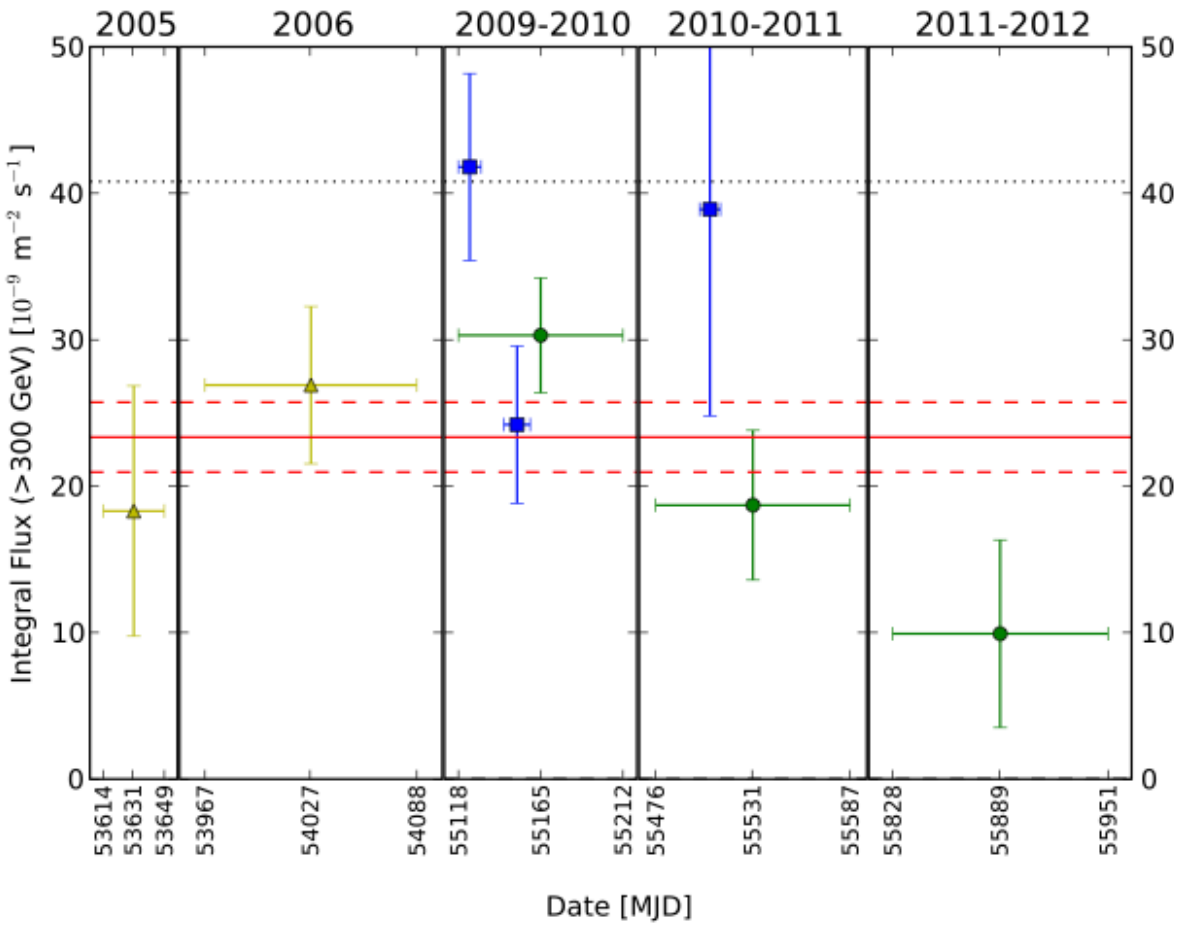


We assume the γ-ray spectrum has this shape . . .



. . . and not this shape.

Assumption #3



1ES 0229+200
Aliu et al. (2014), ApJ, 782, 13

We assume the source variability is minimal

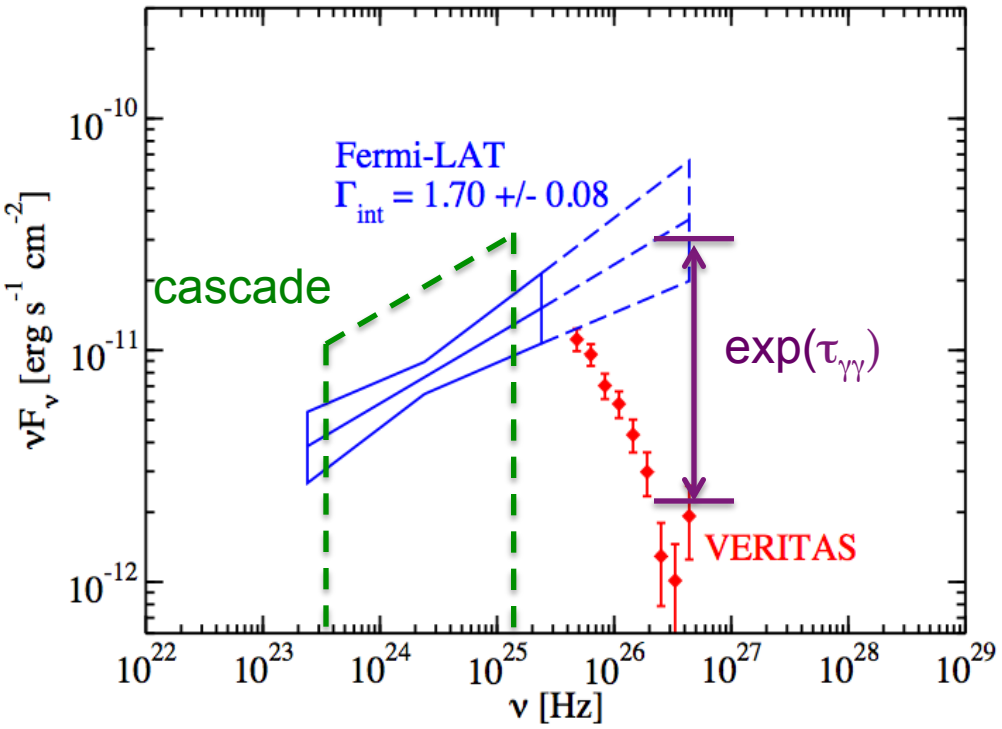
Assumption #4

We assume photons don't convert to axions (e.g., Sanchez-Conde et al. 2009)

We assume plasma beam instabilities are not important (e.g., Broderick et al. 2012)

Rule out low B fields

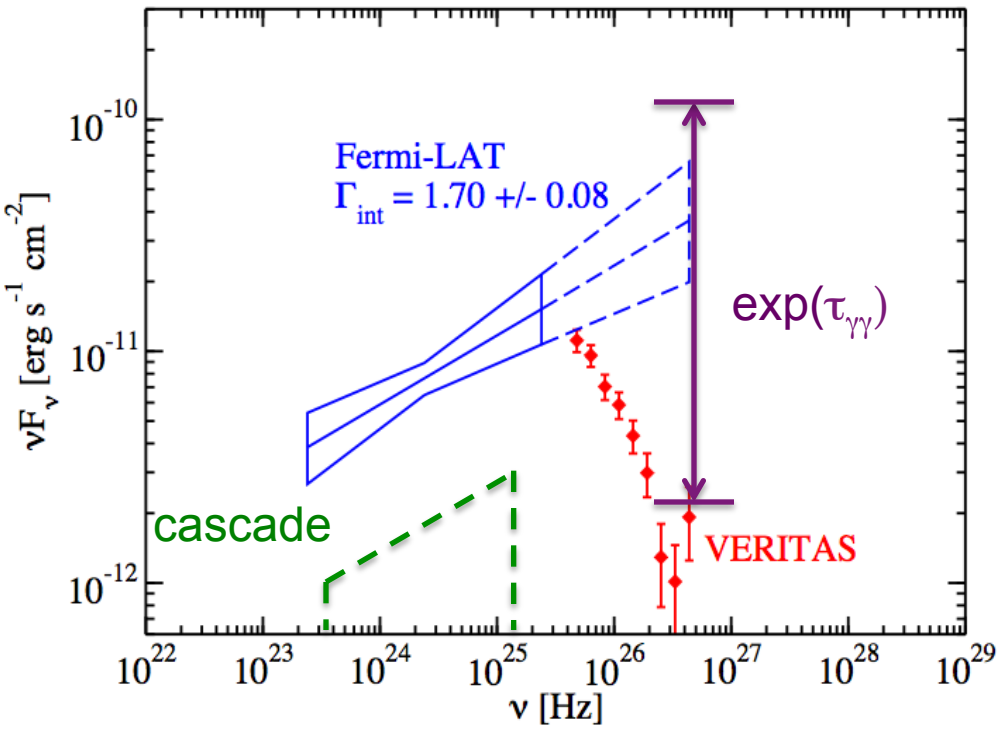
- If B-field is ***low***, cascade will be ***large***.
- Cascade can't be above observed LAT flux



Georganopoulos, JF, & Reyes (2010), ApJ, 714, 157

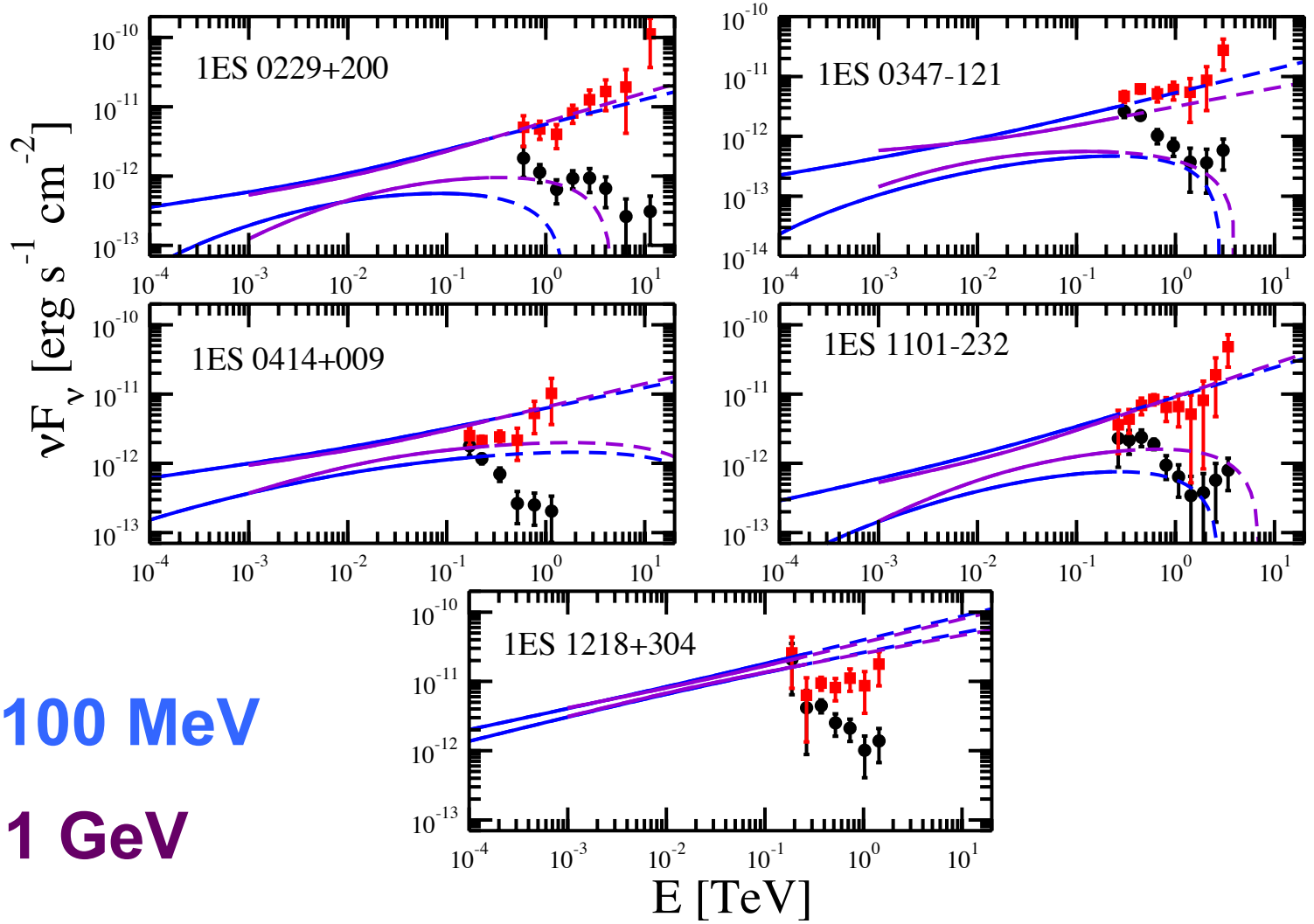
Rule out High B fields

- If B-field is ***high***, cascade will be ***small***.
- If deabsorbed TeV points are above extrapolated LAT spectrum, the model is ruled out ***unless*** the cascade is significant fraction of the LAT flux.



Georganopoulos, JF, & Reyes (2010), ApJ, 714, 157

Source Selection

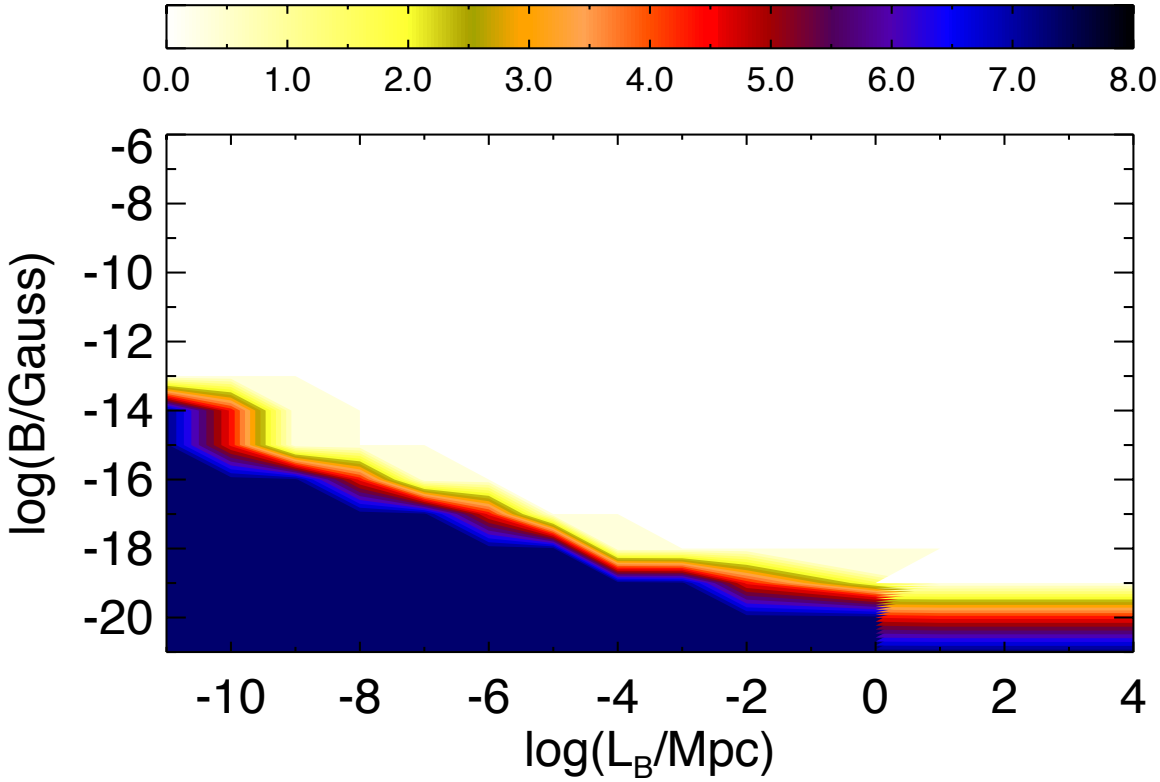


> 100 MeV

> 1 GeV

Results

- Combined results for all sources
- Conservative results: assumes sources have been creating TeV γ-rays for 3 years
- Use JF et al. (2010) EBL model
- Low ***B*** ruled out at 7.2σ
- High ***B*** not ruled out

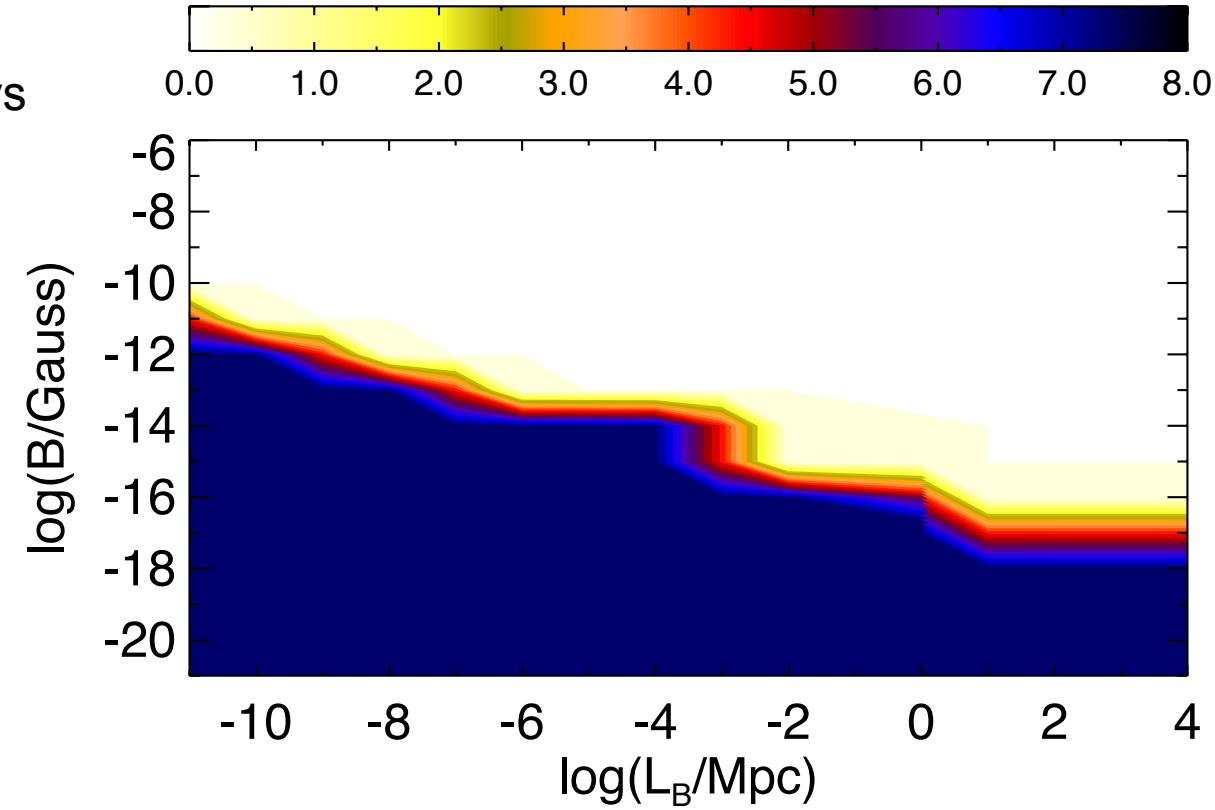


Robustness

- Using very low EBL model (Kneiske & Dole 2010):
  - Low ***B*** ruled out at 5.5σ
- Excluding variable BL Lacs (1218 and 0229)
  - Low ***B*** ruled out at 6.4σ
- Using > 1 GeV spectra
  - Low B ruled out at 6.2σ
- Excluding highest two VHE energy bins
  - Low ***B*** ruled out at 5.9σ
- Using > 1 GeV spectra ***and*** Kneiske & Dole (2010) EBL model:
  - Low ***B*** ruled out at 2.6σ
  - cf. Arlen et al. (2014)

Results with Less Conservative Assumptions

- Assumes sources have been creating TeV γ-rays for the Hubble time
- Low ***B*** ruled out at 7.2σ
- High ***B*** not ruled out



Implications

Evidence for cosmological generation of the IGMF.

If the IGMF originates from inflationary magnetogenesis, and ***if*** the conservative constraints are correct and $B > 10^{-15}$ G, then this is in conflict with the detection of gravitational waves by BICEP2/Keck Array (Ade et al. 2014). See Fujita & Mukohyama (2012, 2014); Ferreira et al. (2014).

But this claimed detection seems to be in error based on a recent analysis by the BICEP2/Keck and Planck collaborations (Ade et al. 2015).

Summary

- Low ***B*** values are ruled out at >5σ:
  - for all EBL models tested
  - regardless of whether variable sources were excluded
  - regardless of whether highest VHE points were excluded
  - ***except*** for lowest EBL model and > 1 GeV spectra

- Consistent with previous results (e.g. Neronov & Vovk 2010)

- High ***B*** values are still unconstrained

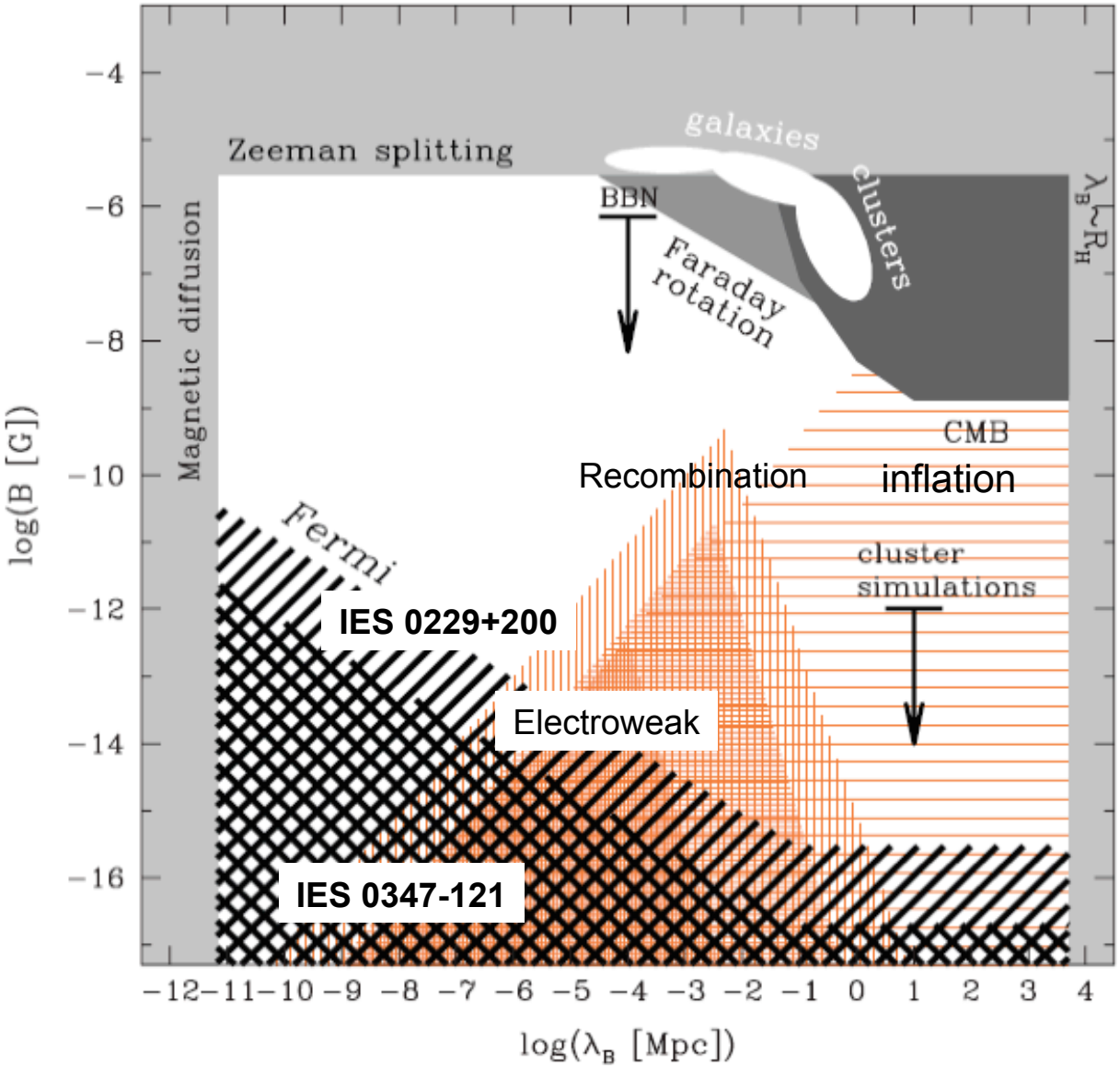
- No evidence for cascade in LAT spectrum

- Cosmological models for IGMF generation favored over astrophysical models

- If IGMF originates from inflationary magnetogenesis, some tension with BICEP2/Keck result if $B>10^{-15}$ G (Fujita & Mukohyama 2012, 2014; Ferreira et al. 2014)

Extra Slides

Intergalactic Magnetic Field



Orange: Allowed by a variety of ways of generating the IGMF.

More interesting ways: phase transitions in the early universe, or inflationary magnetogenesis

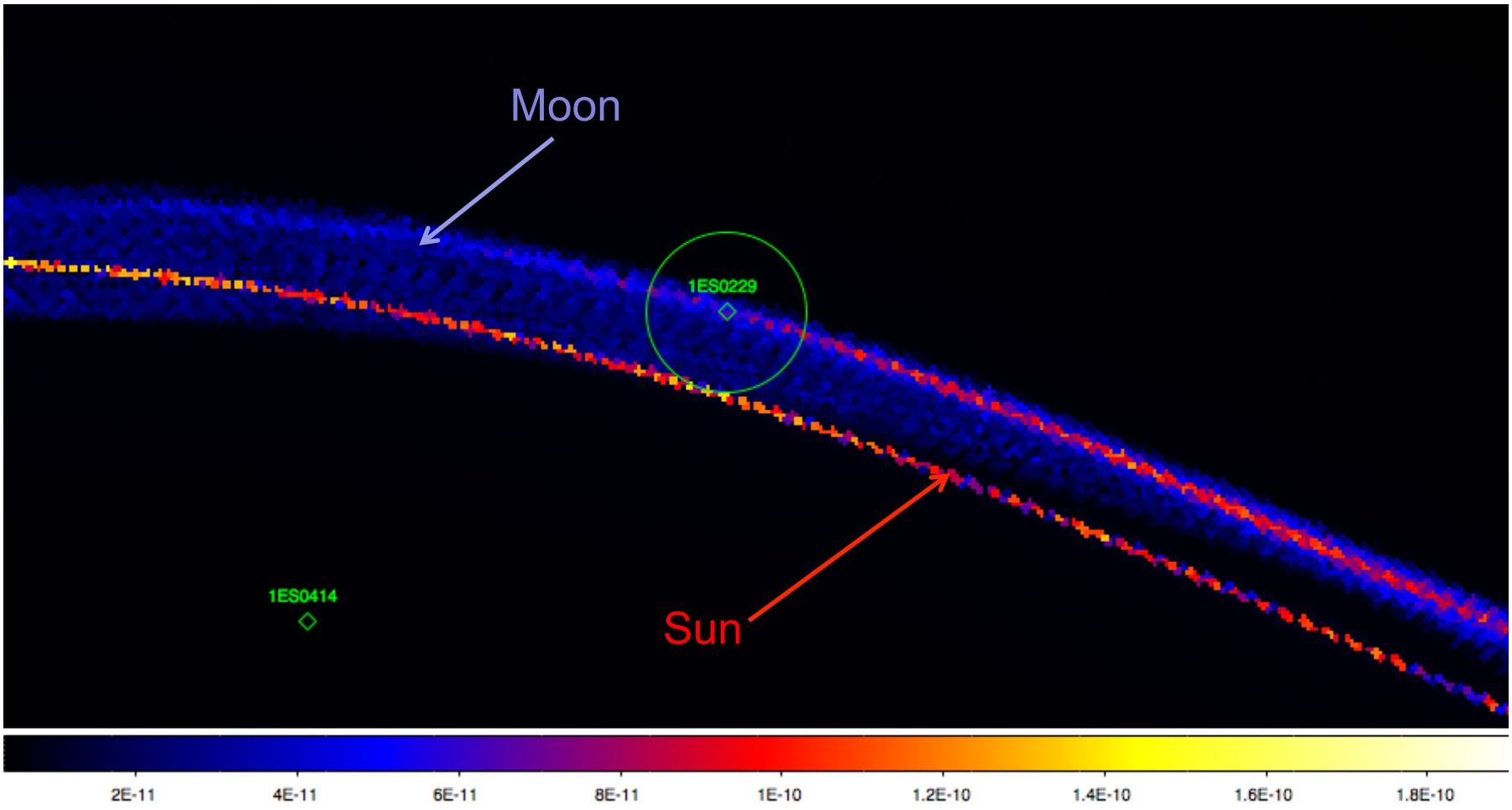
Black/gray: ruled out.

Neronov & Vovk (2010, Science, 328, 73)

Source Selection

- Blazars in 3FGL and TeV Cat with published VHE spectra and known redshift
- Sources in 3FGL with significance < 4.8σ that it is variable
- Sources with z < 0.3
- Sources with deabsorbed VHE spectra above or near extrapolated LAT spectra
- LAT data analysis:
  - Pass 7 Reprocessed
  - LAT data: August 4, 2008 to June 30, 2014 (~ 6 years)

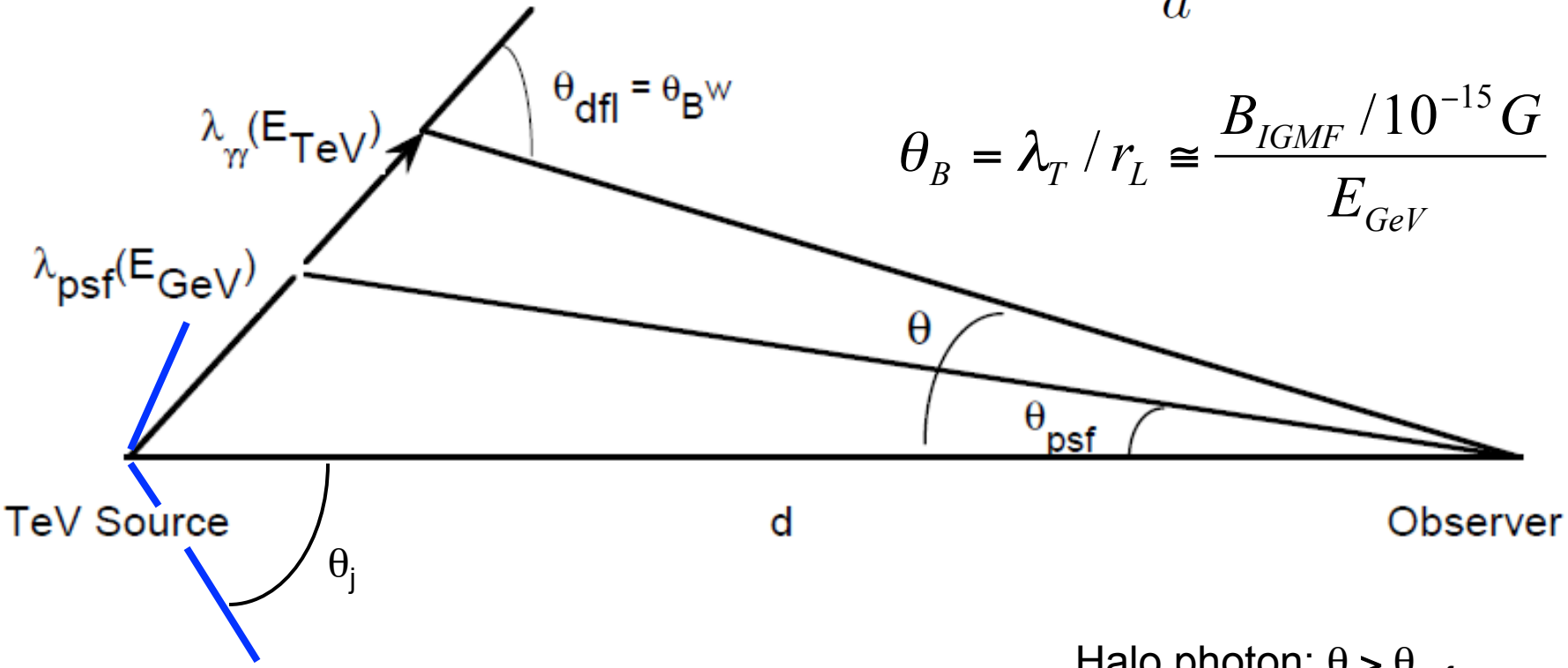
LAT data analysis



Geometry for Compton-γγ Cascade

$$\theta \cong \theta_{\rm dfl} \frac{\lambda_{\gamma\gamma}}{d} < \theta_{psf}$$

$$\theta_B = \lambda_T / r_L \cong \frac{B_{IGMF} / 10^{-15} G}{E_{GeV}}$$



Halo photon: $\theta \gtrsim \theta_{psf}$

Apply to 1ES 0229+200
z = 0.1396

Dermer et al. (2011)