ULB, May 28, 2010

Detection of the extragalactic magnetic fields with gamma-rays

Dmitri Semikoz

APC , Paris

in collaboration with A.Neronov, A.Elyiv, M.Kachelries and S.Ostapchenko

Overview

1. Existing limits on EGMF

2. Electromagnetic cascade in intergalactic medium
   - the role of Extra Galactic Magnetic Fields (EGMF)

3. Detection of EGMF by gamma-ray telescopes. 3 methods

4. Evidence for existence of non-zero EGMF from Fermi non-detection of the cascade emission

5. Models of the origin of magnetic fields in the Universe and future detection of EGMF by gamma-ray telescopes

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Constraints on the extragalactic magnetic fields

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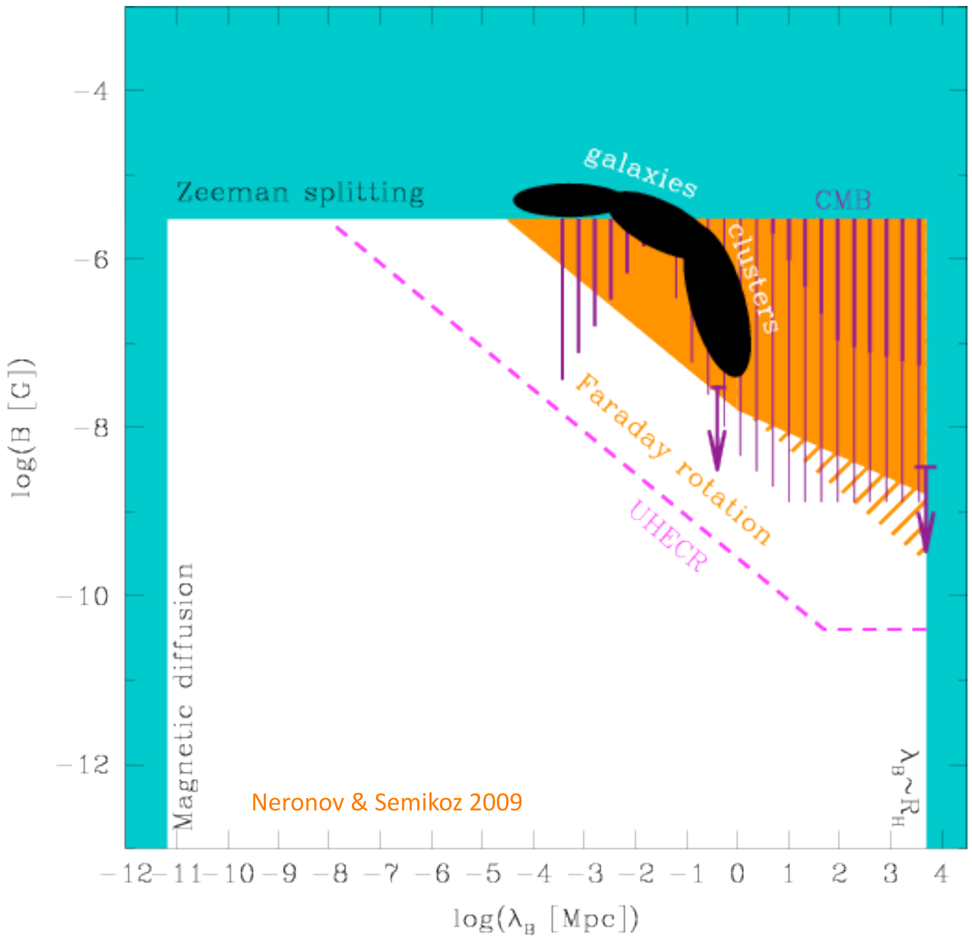
Extragalactic magnetic fields (EGMF)



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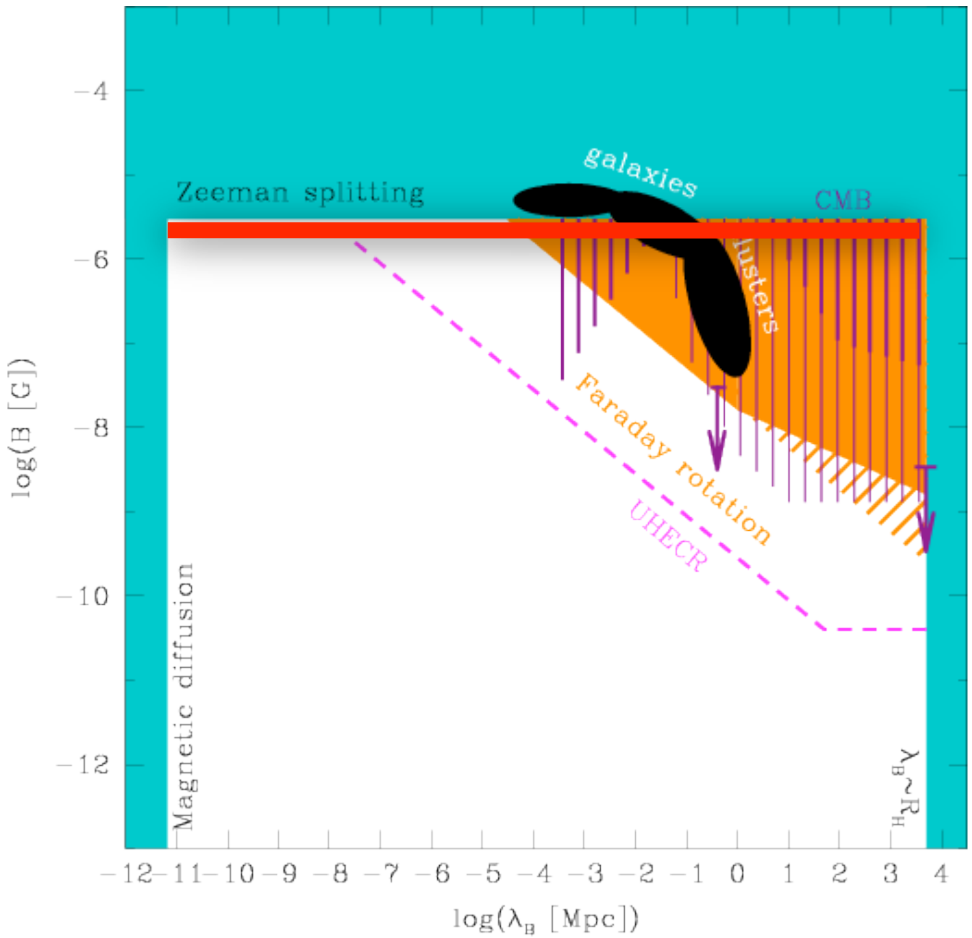

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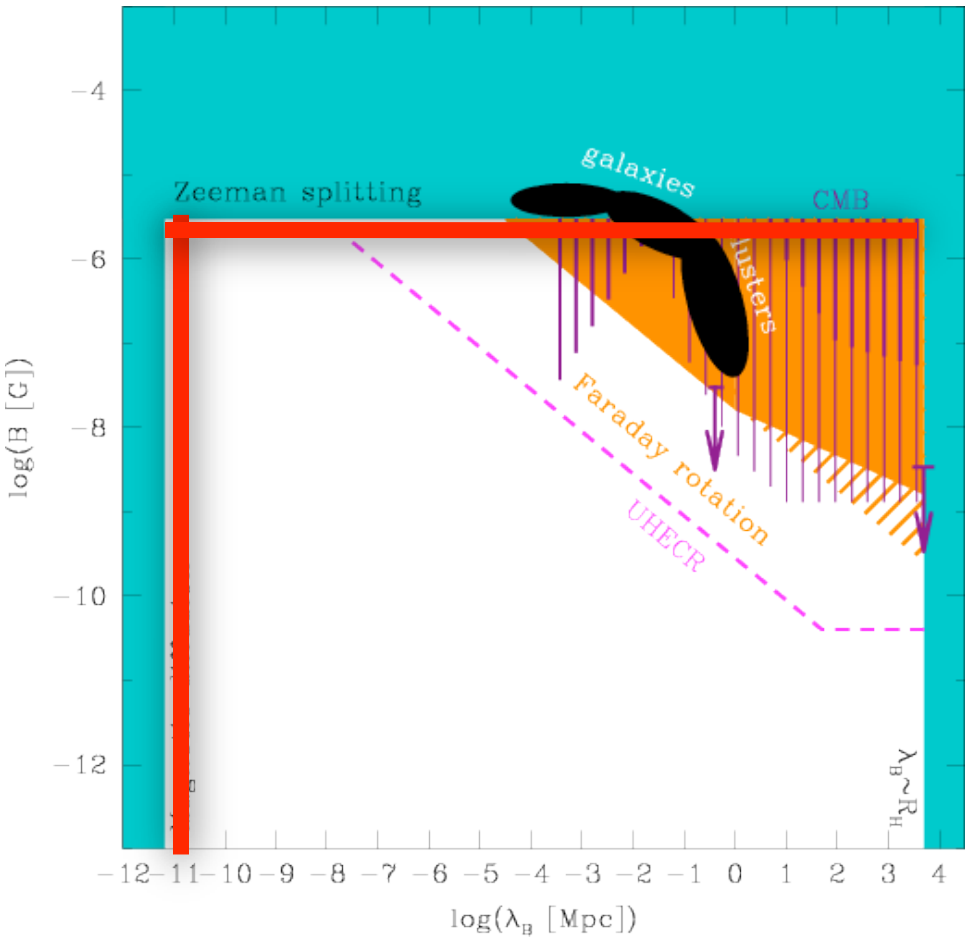

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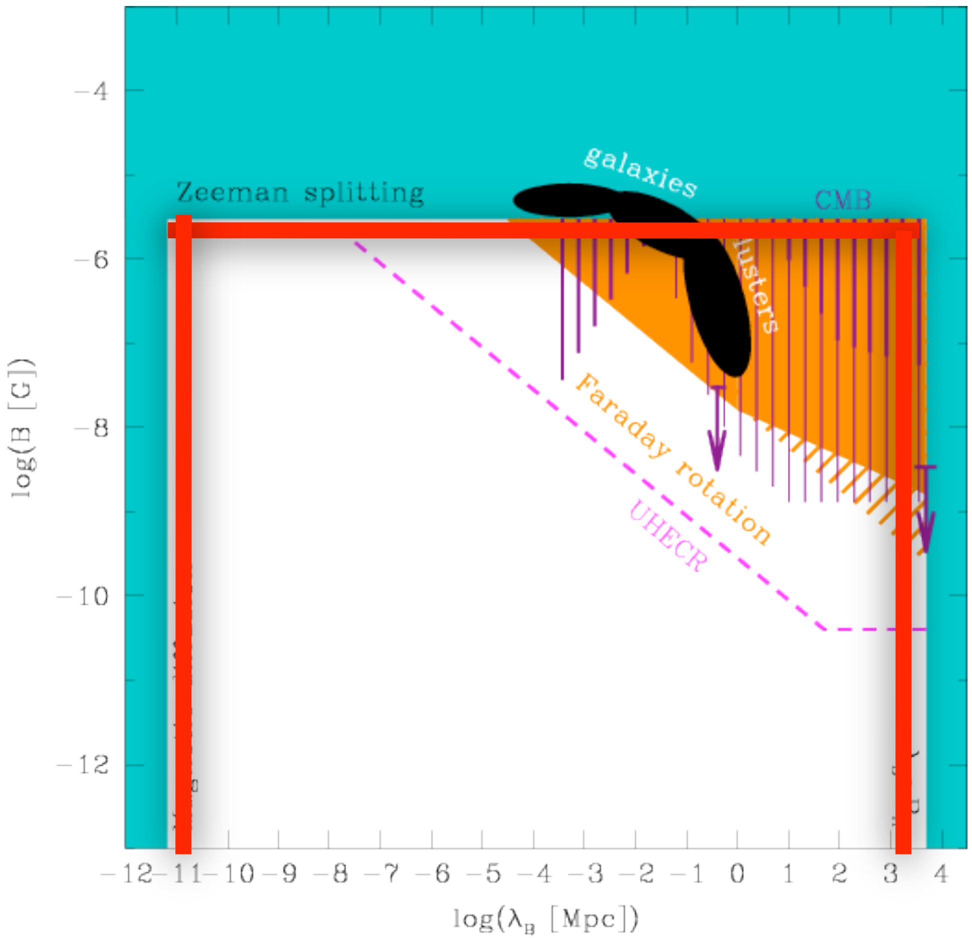

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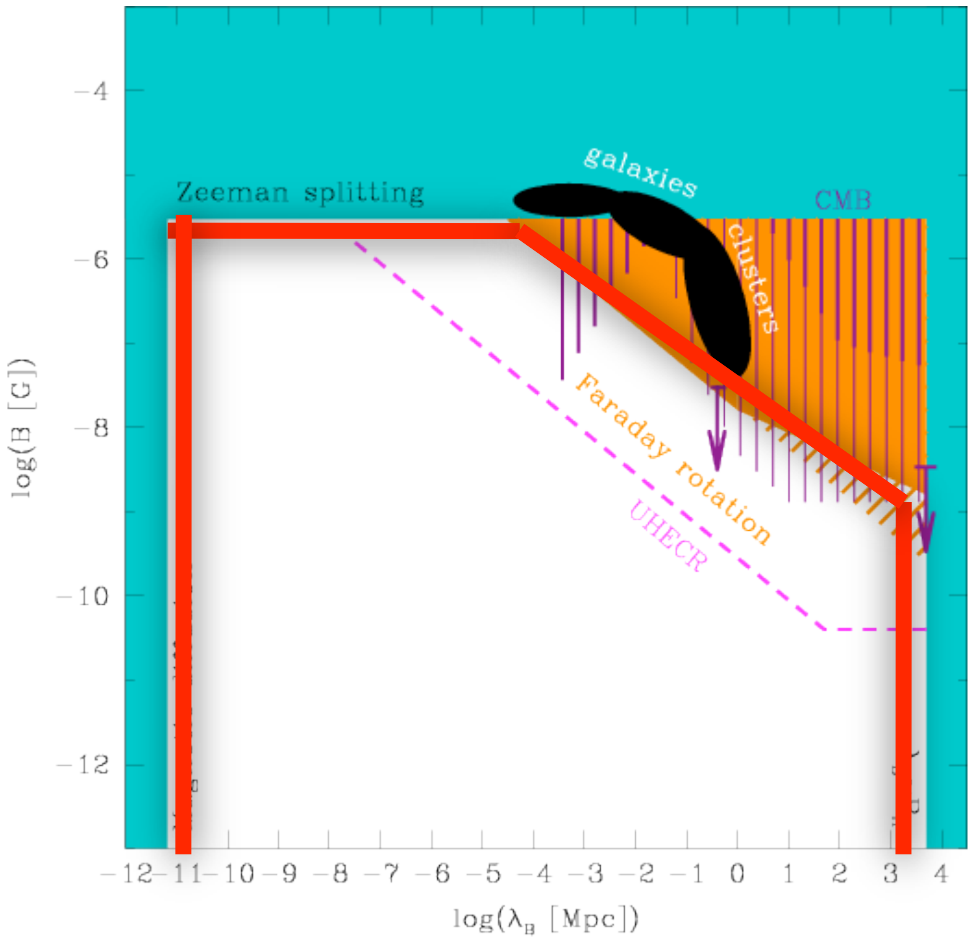

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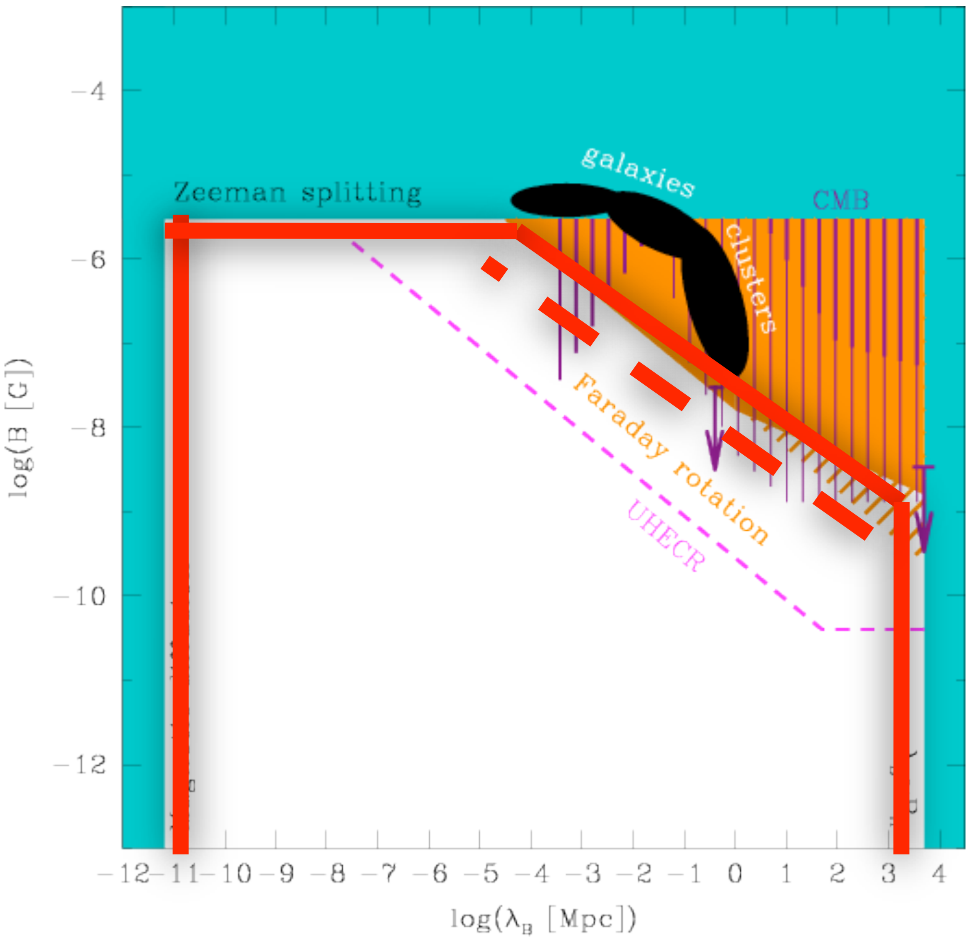

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- EGMF correlation length could be as large as the size of the Universe
- Strong enough EGMF could destroy linear polarization of radio signal from distant quasars
- If strong EGMF were produced before recombination epoch, they would leave imprint on the **CMB anisotropies**.

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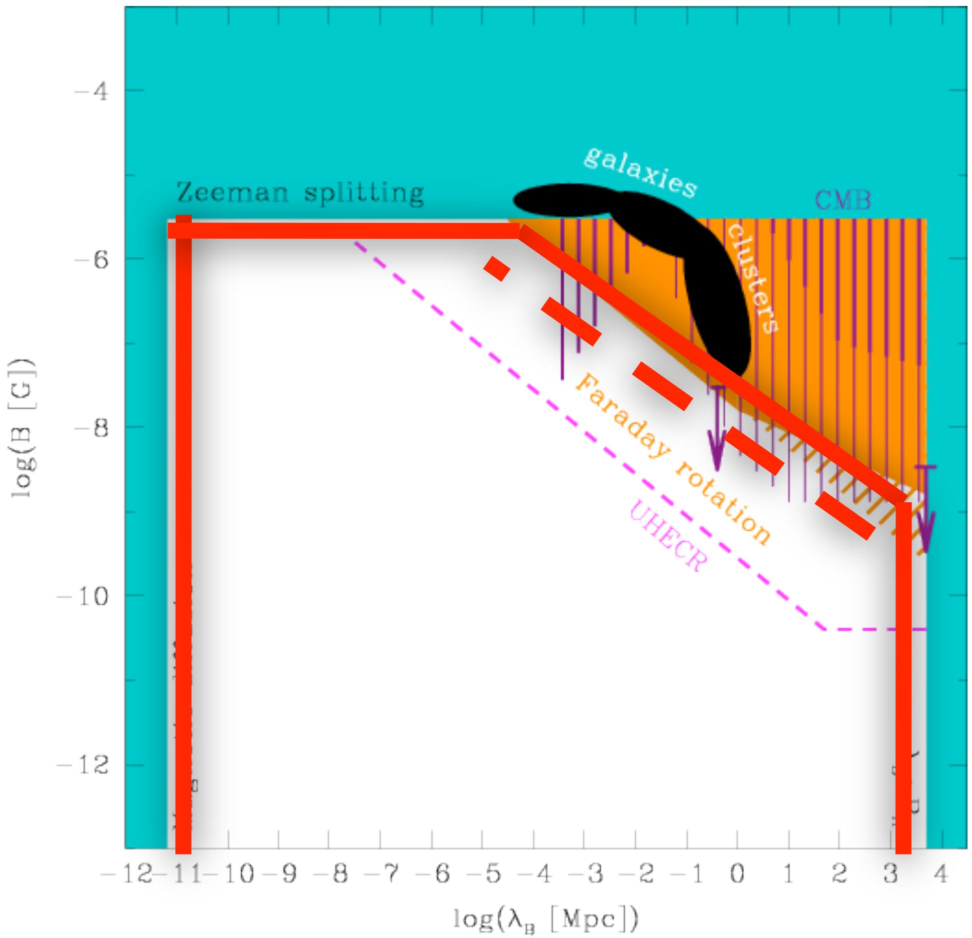
EGMF and the problem of the origin of cosmic magnetic fields



Magnetic fields in spiral and elliptical galaxies reach 1-10 μG.

Galactic magnetic fields are thought to be produced via "α-ω dynamo" amplification of "seed" magnetic fields of the strength $B \gtrsim 10^{-21}$ G.

Magnetic fields in the cores of galaxy clusters reach 1-10 μG.

Cluster magnetic field are thought to be produced via compression and turbulent amplification of **"seed" magnetic fields** of the strength $B \lesssim 10^{-12}$G.

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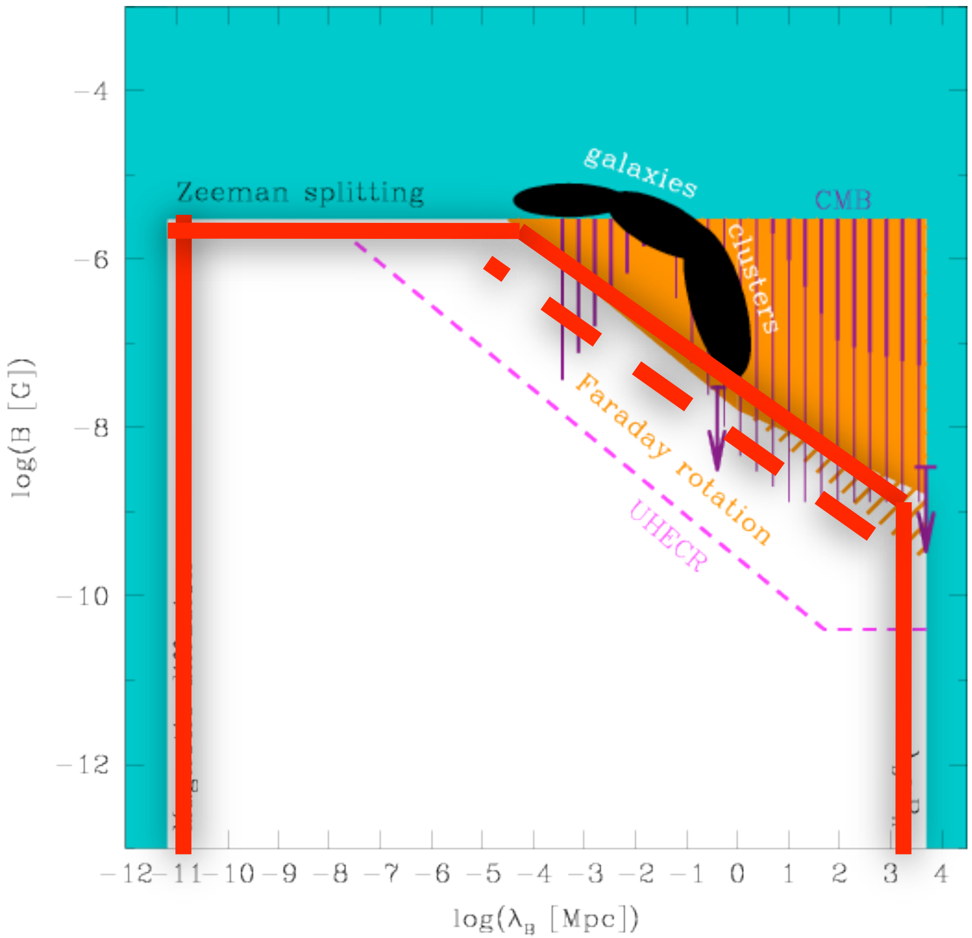

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Magnetic fields in the cores of galaxy clusters reach 1-10 μG.

Cluster magnetic field are thought to be produced via compression and turbulent amplification of "seed" magnetic fields of the strength $B < 10^{-12}$G and/or by AGN's.

The "seed" fields might exist in their initial form as EGMF

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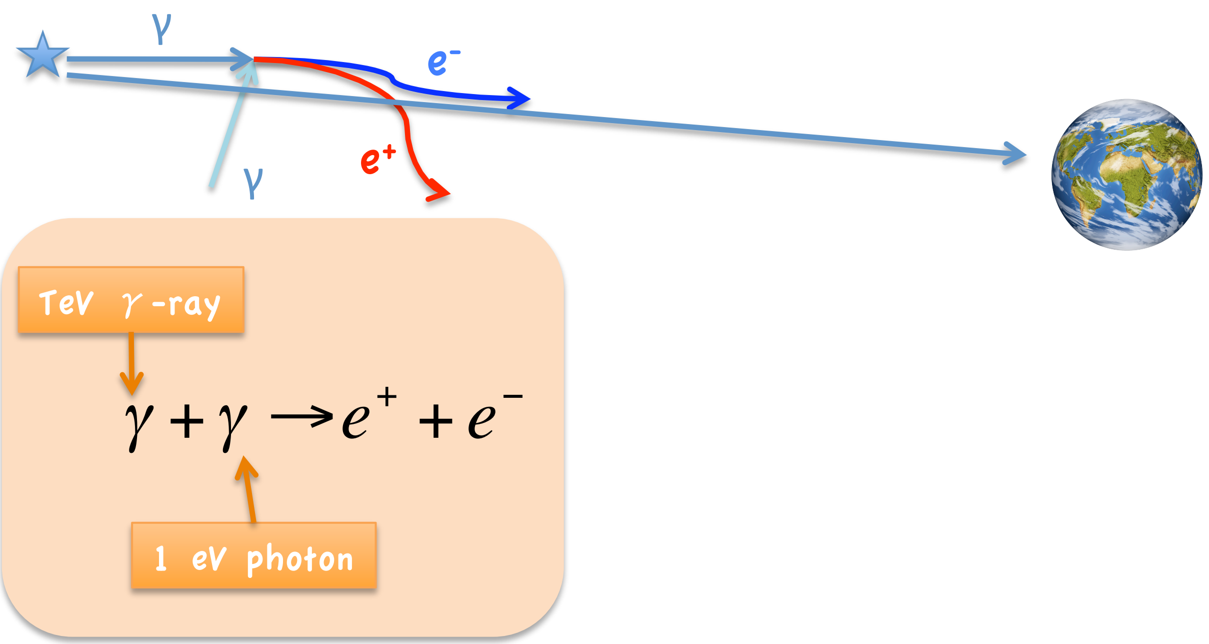
Gamma-ray measurements and electromagnetic cascade

Attenuation of γ–rays via pair production on EBL



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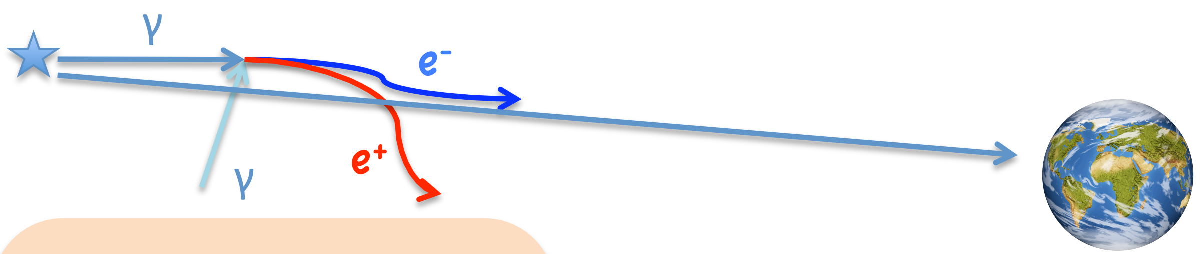
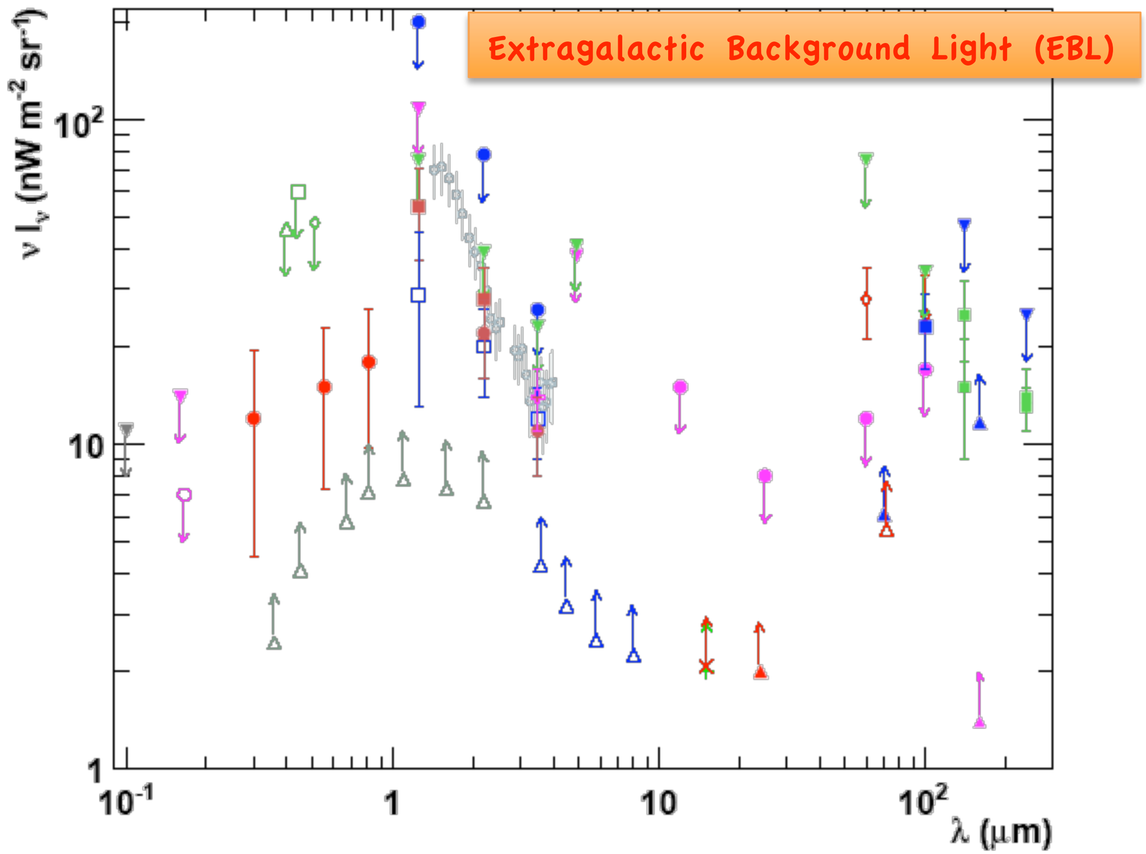


TeV γ-ray

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

1 eV photon



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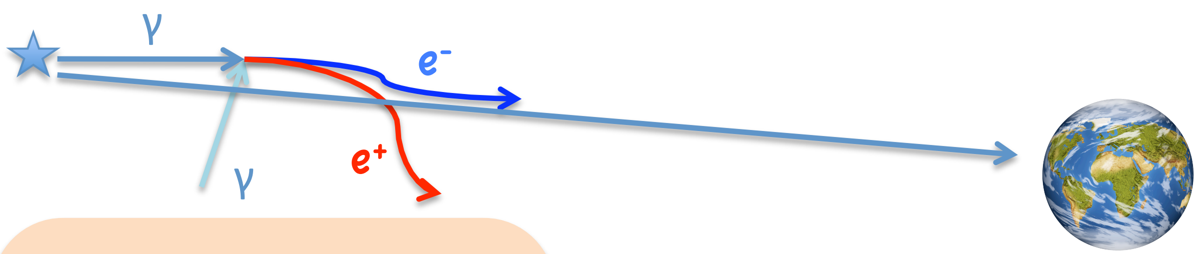

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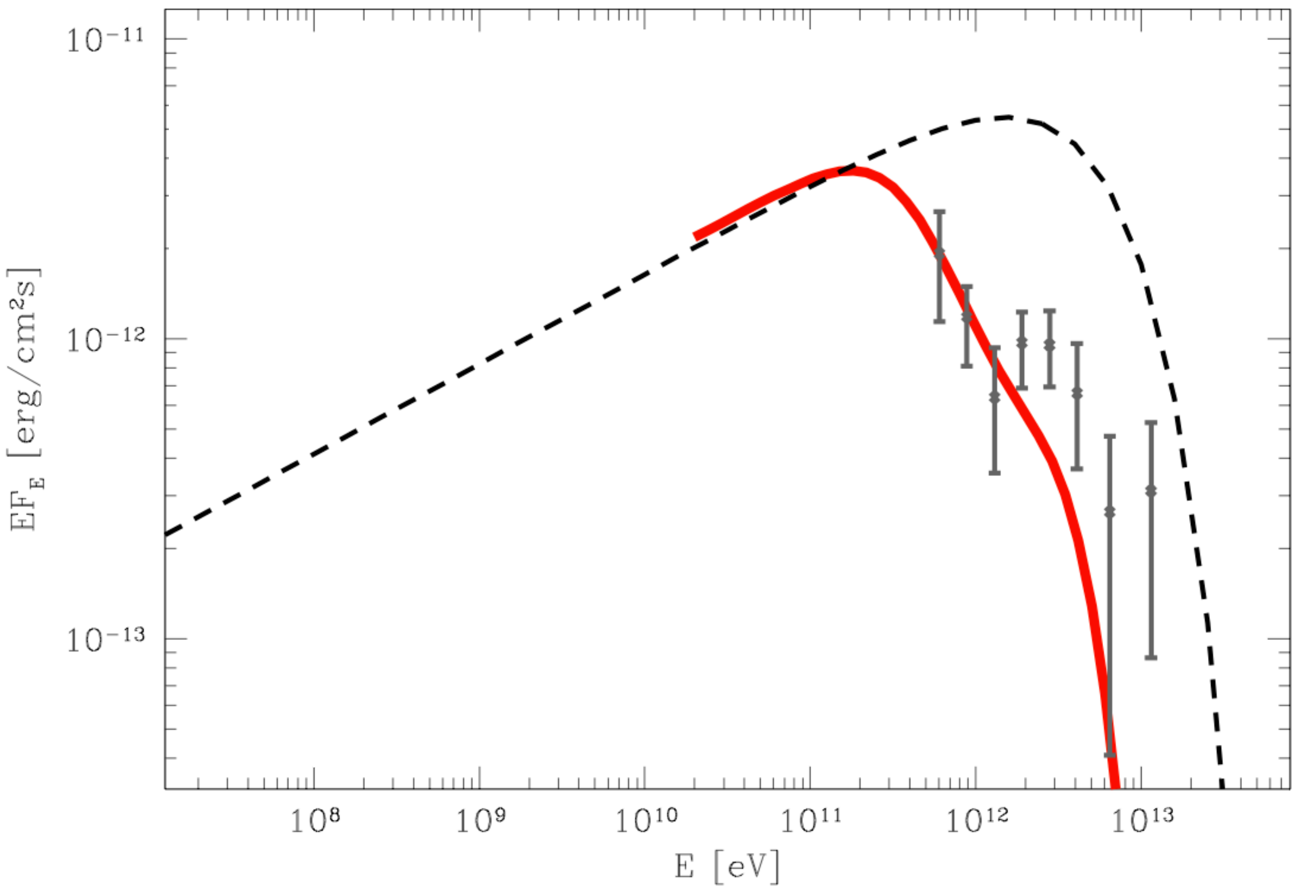
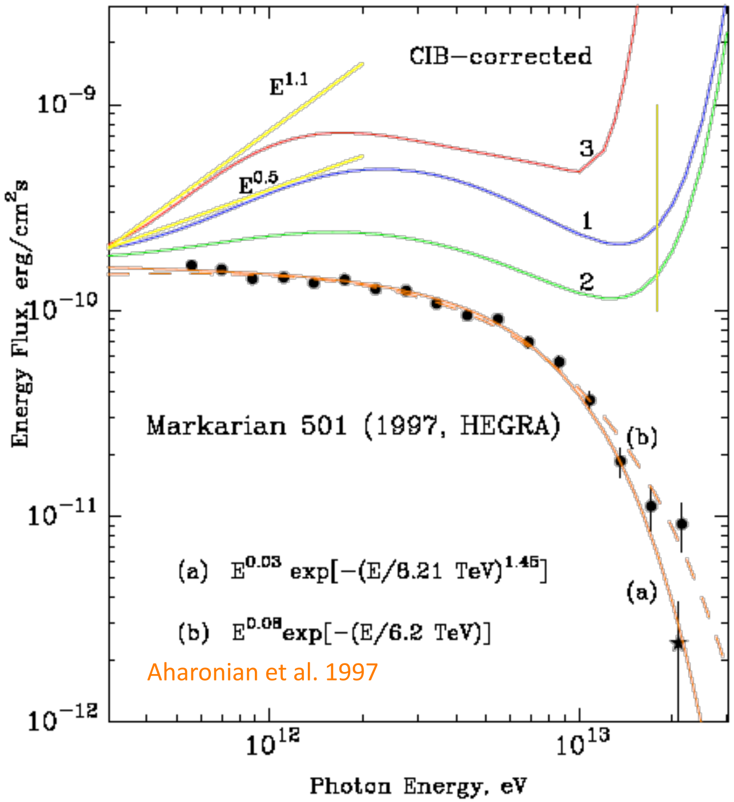


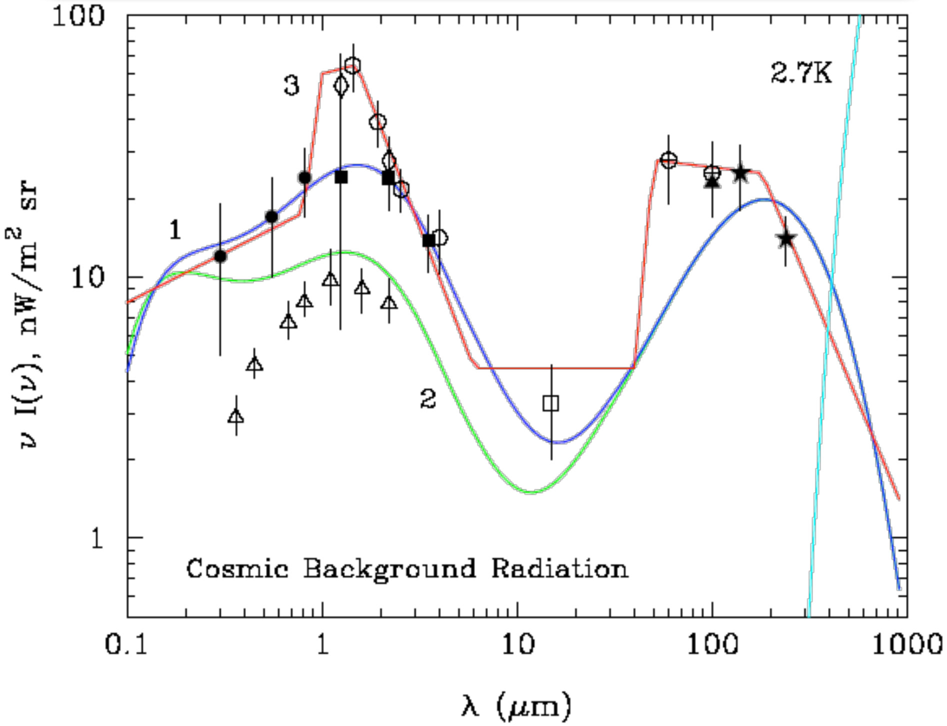
Constraints on EBL from γ-ray observations



Observations of extragalactic TeV γ-ray sources are commonly used to constrain the EBL density

Major uncertainties:

a) unknown intrinsic spectrum of γ-ray source



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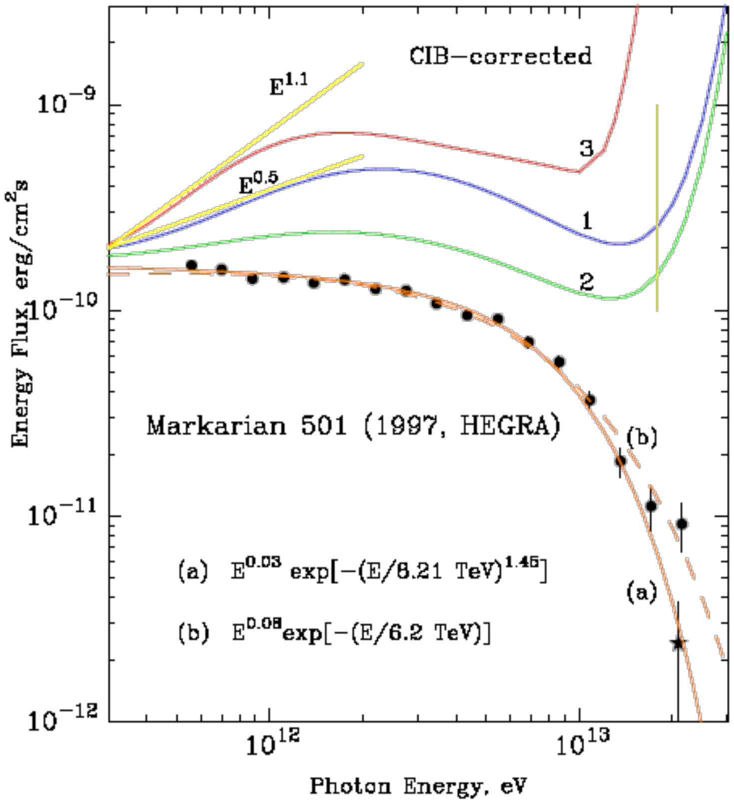

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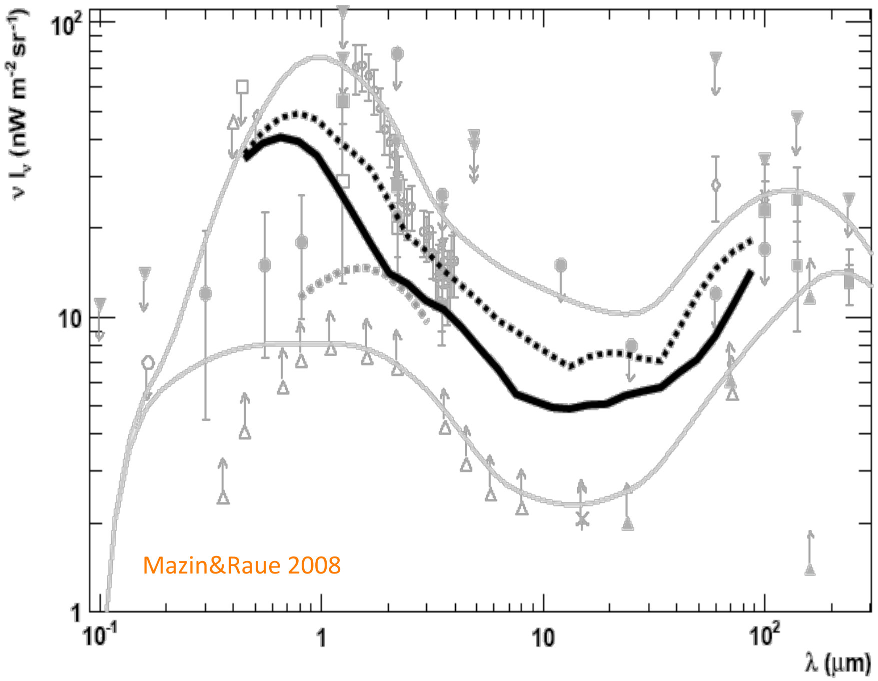

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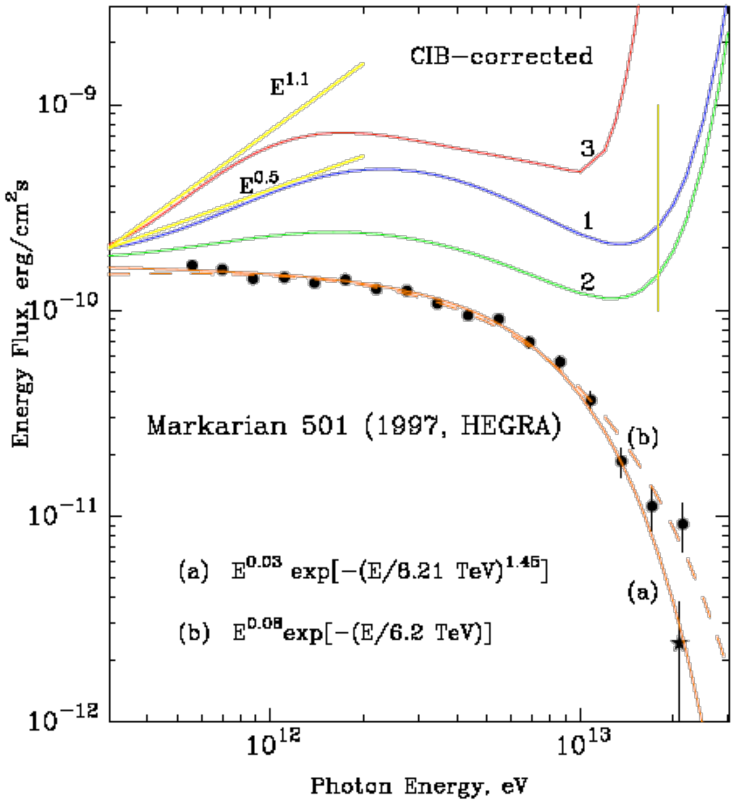

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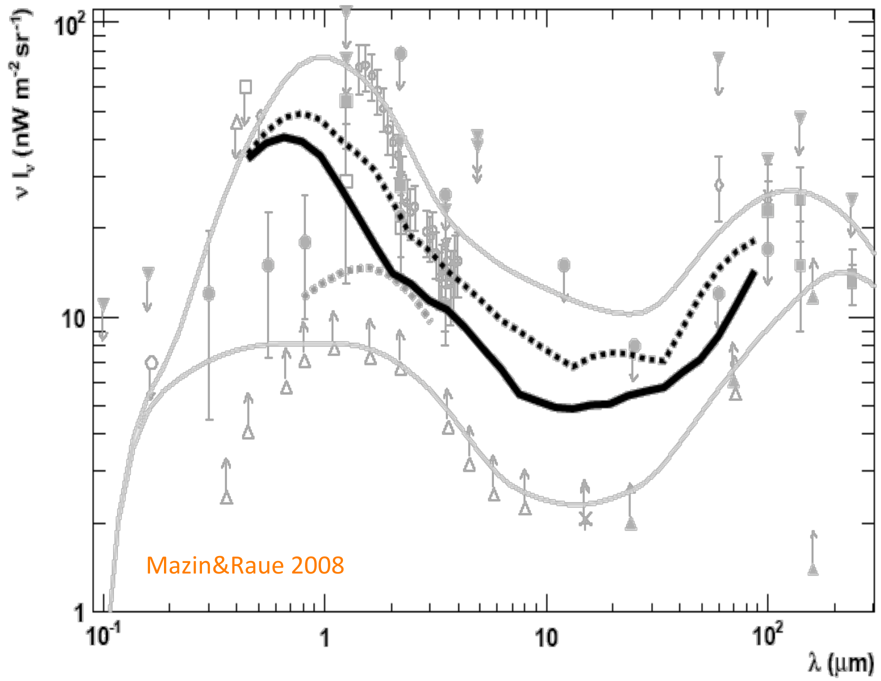

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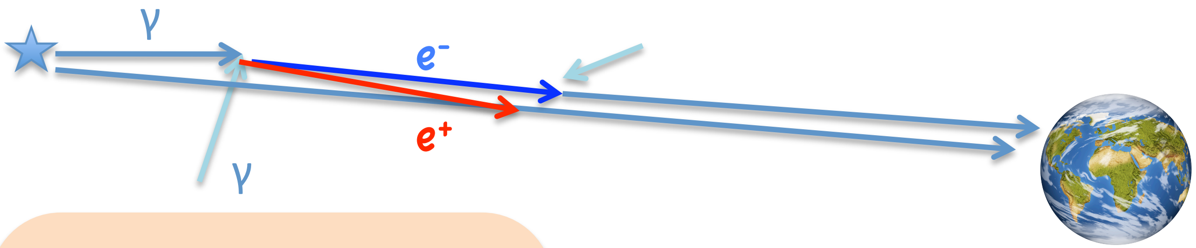
Electromagnetic cascade in intergalactic medium



TeV γ-ray

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

1 eV photon

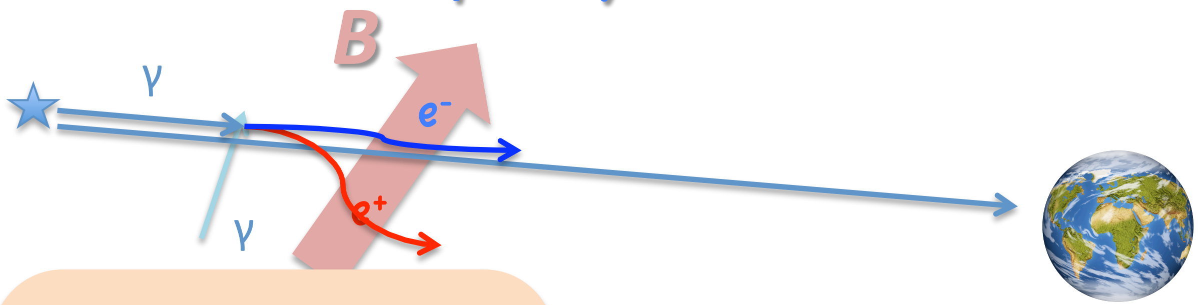
GeV γ-ray

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma$$

CMB photon

$$E_{\gamma} = 0.75\ \mathrm{GeV} \left(\frac{E_e}{0.5\mathrm{TeV}} \right)^2$$

γ-rays from cascade on EBL



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Trajectories of $e^{+}e^{-}$ pairs are deflected by Extragalactic Magnetic Fields (EGMF), if such fields are present in intergalactic medium.

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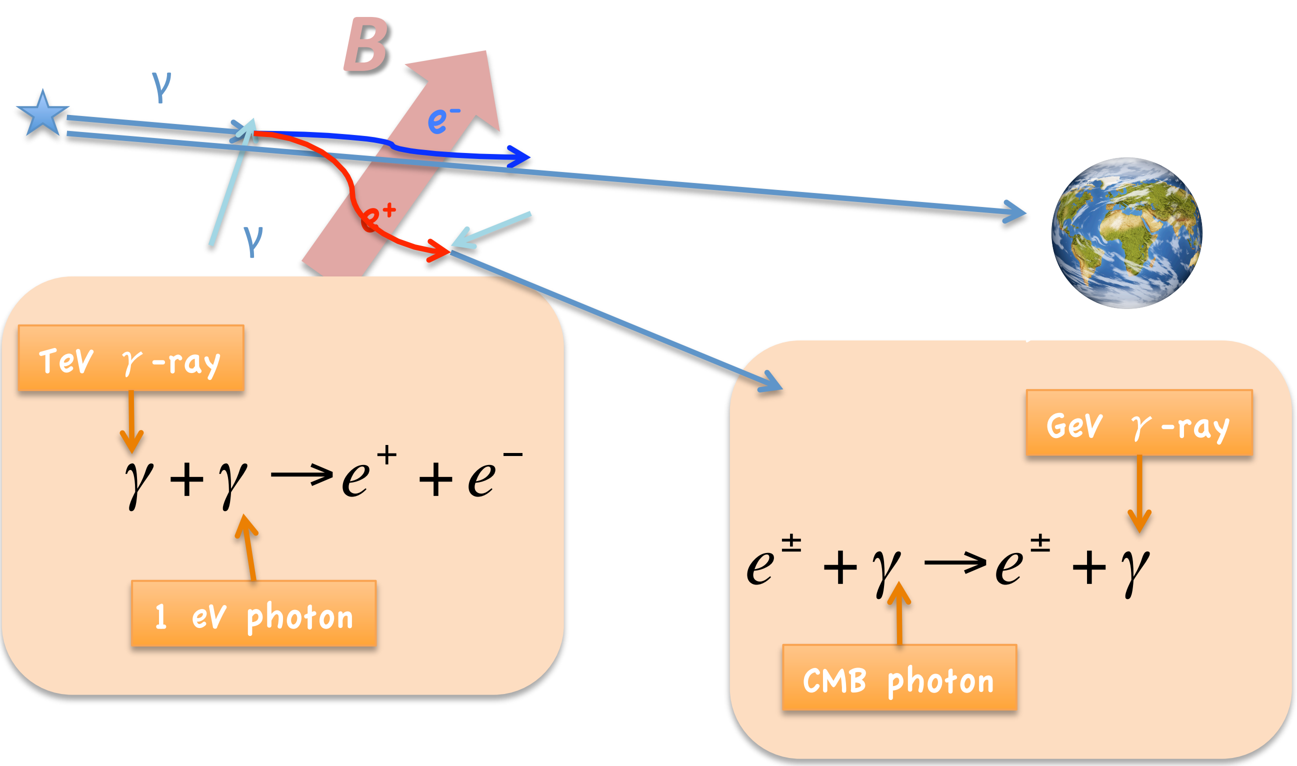
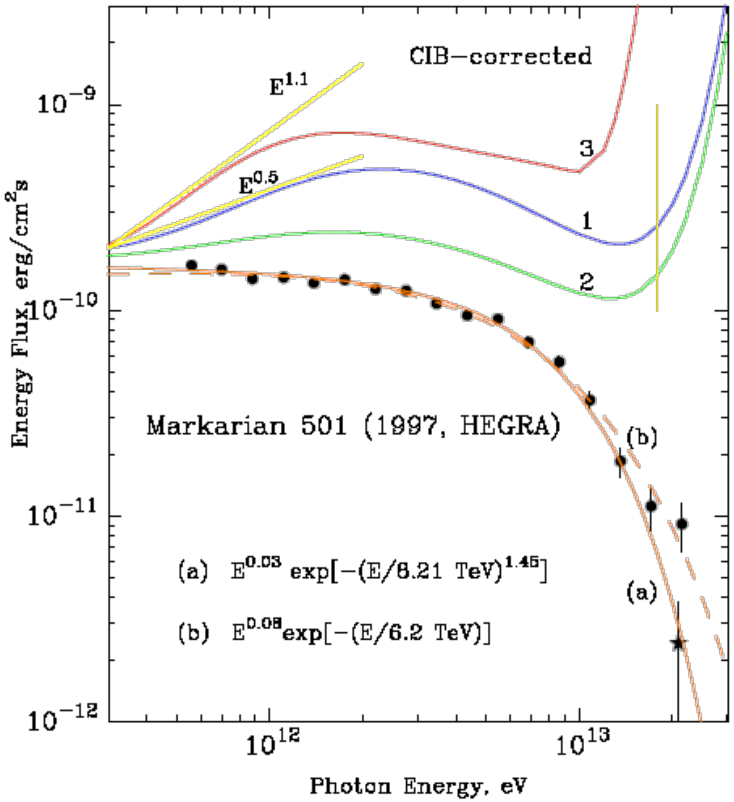


Trajectories of e^+e^- pairs are deflected by Extragalactic Magnetic Fields (EGMF), if such fields are present in intergalactic medium.

If the primary γ-ray was emitted along the line of sight, secondary cascade γ-rays produced by deflected electrons/positrons are not emitted along the line of sight.

Constraints on EBL from γ-ray observations



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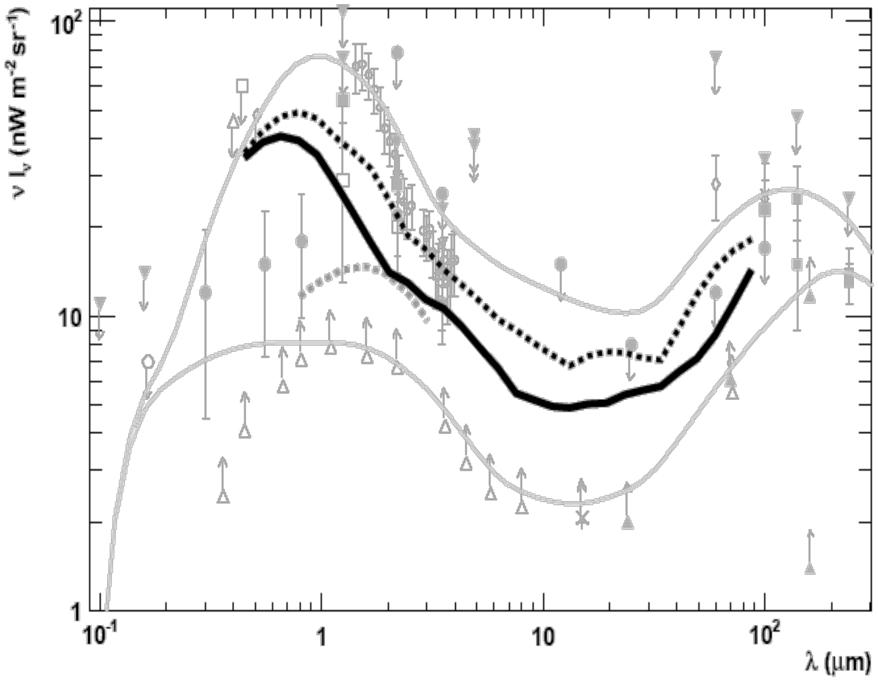
Solution: e+e- pairs are deflected by **strong magnetic fields**



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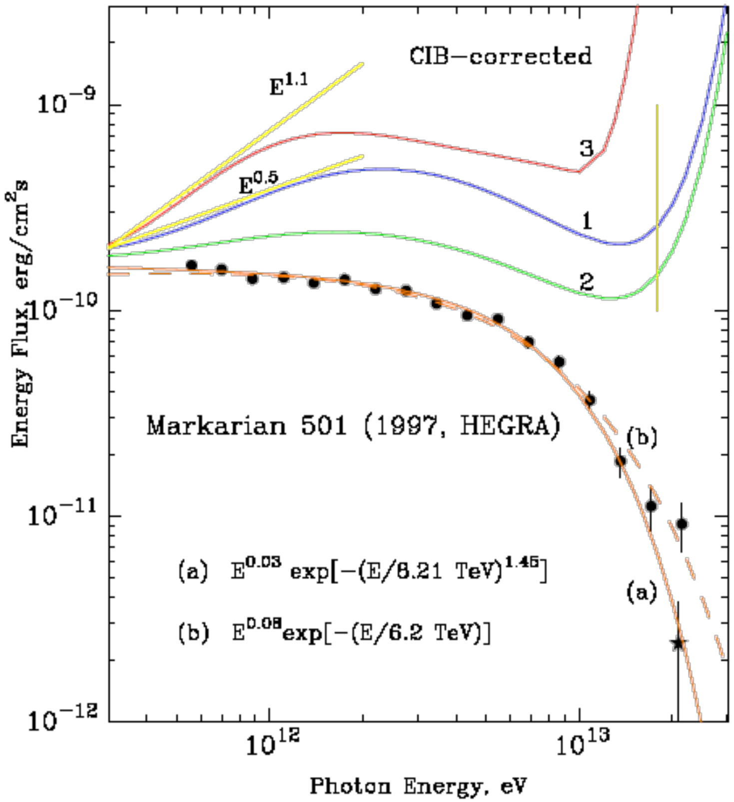

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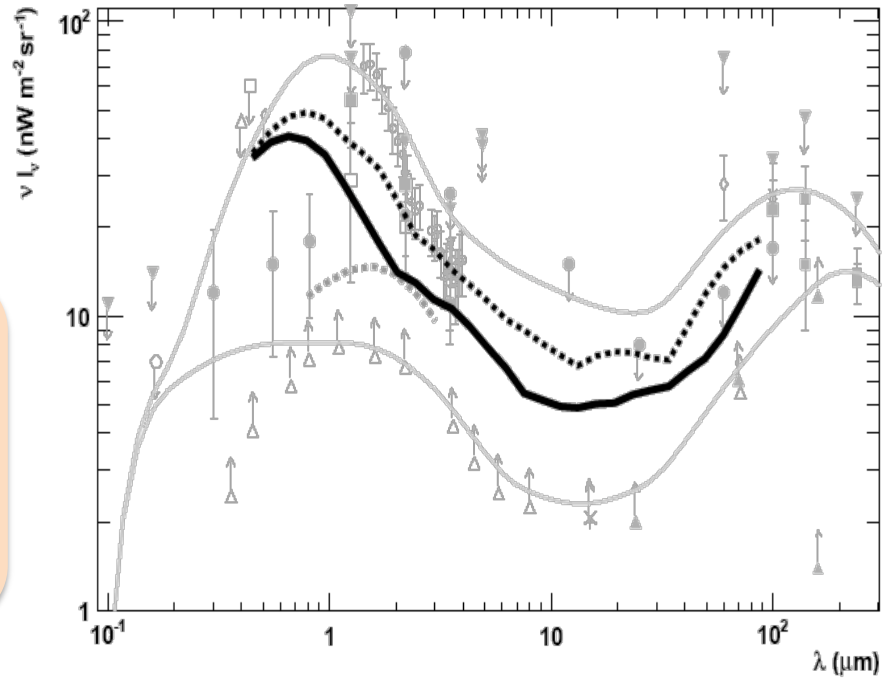

Electron Larmor radius

$$R_L = \frac{E_e}{eB} \approx 3\times10^{23}\left[\frac{B}{10^{-13}\mathrm{G}}\right]\left[\frac{E_e}{10\ \mathrm{TeV}}\right]\mathrm{cm}$$

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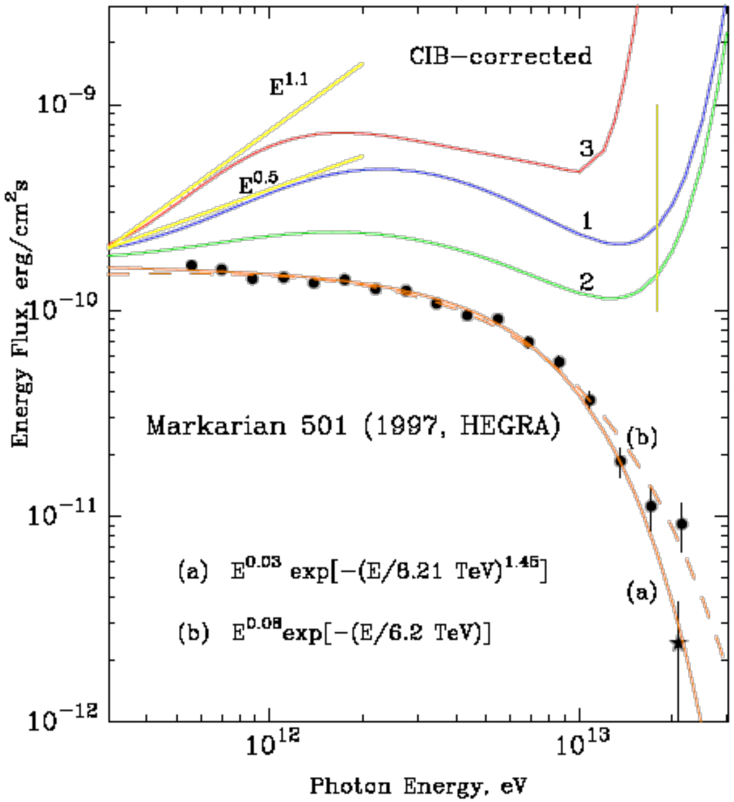

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Electron cooling distance

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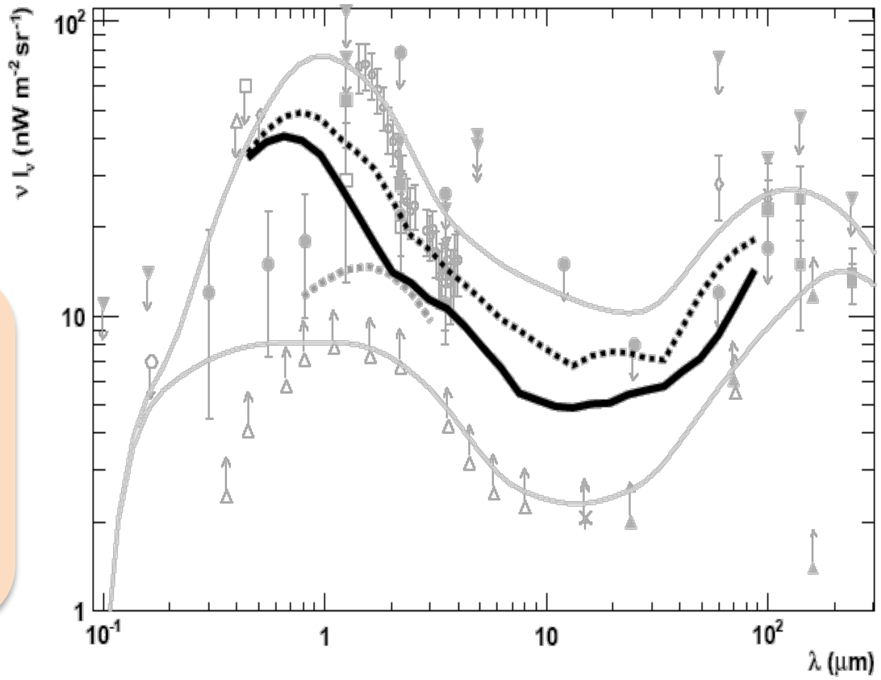

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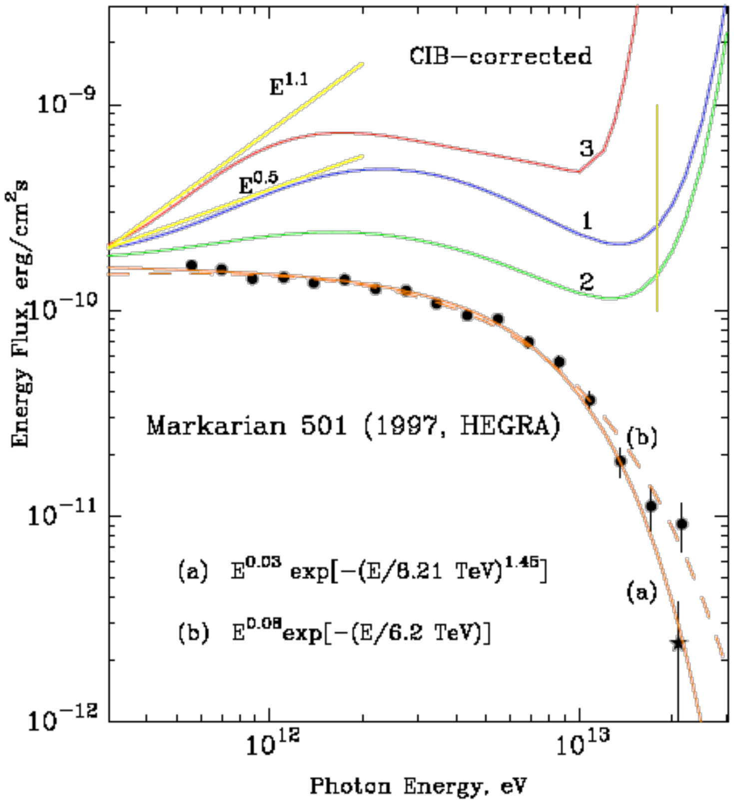

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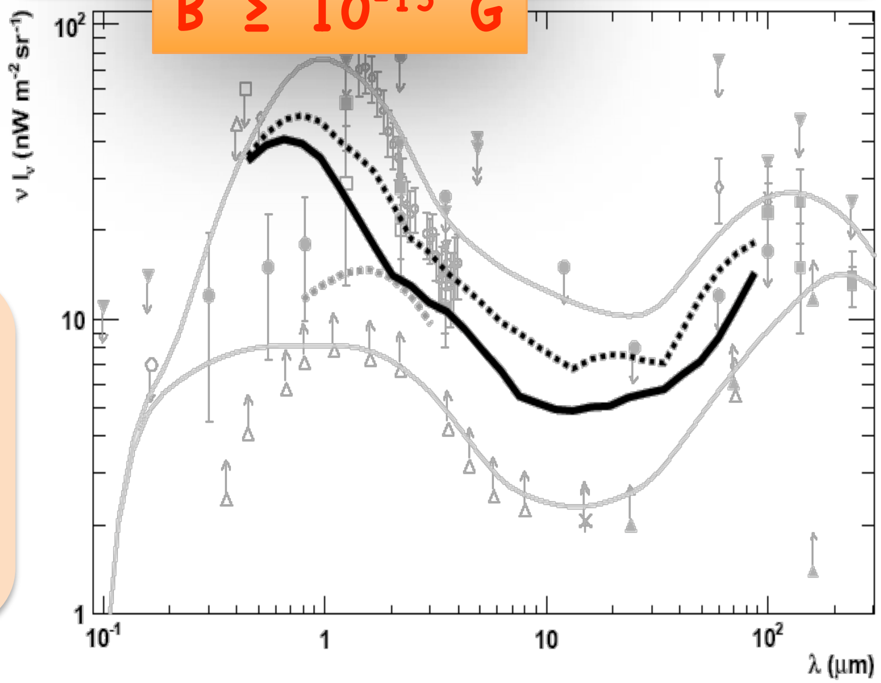

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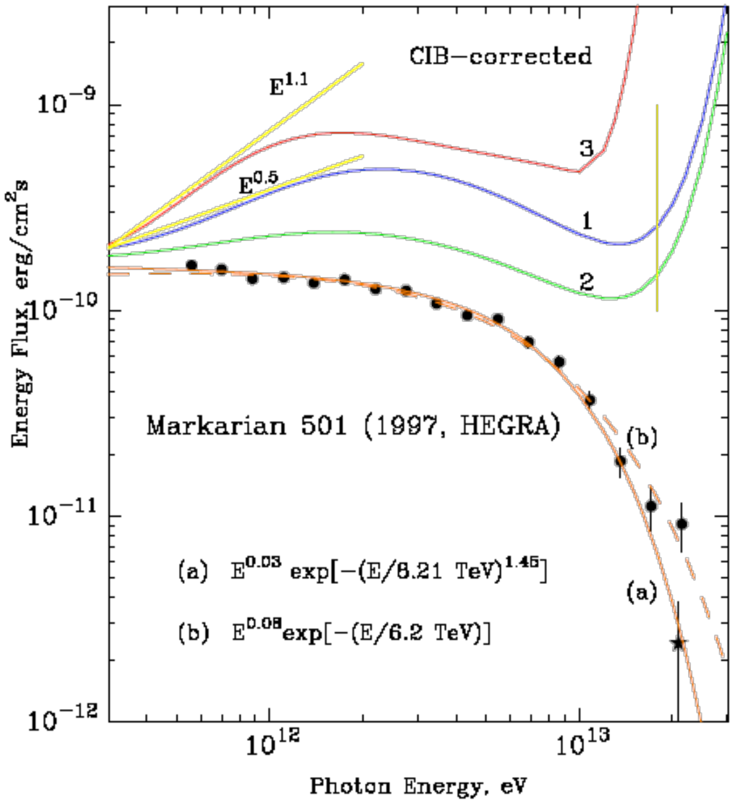

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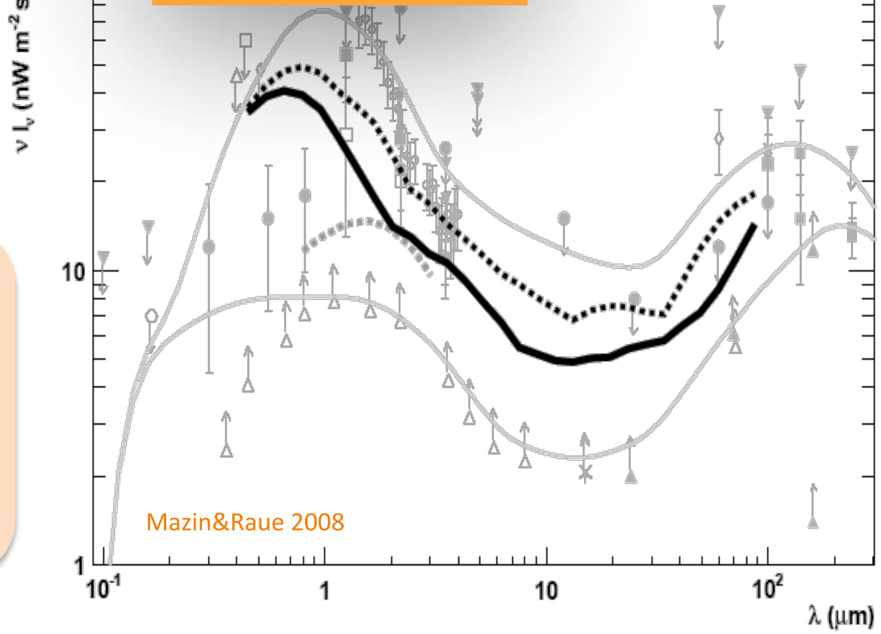

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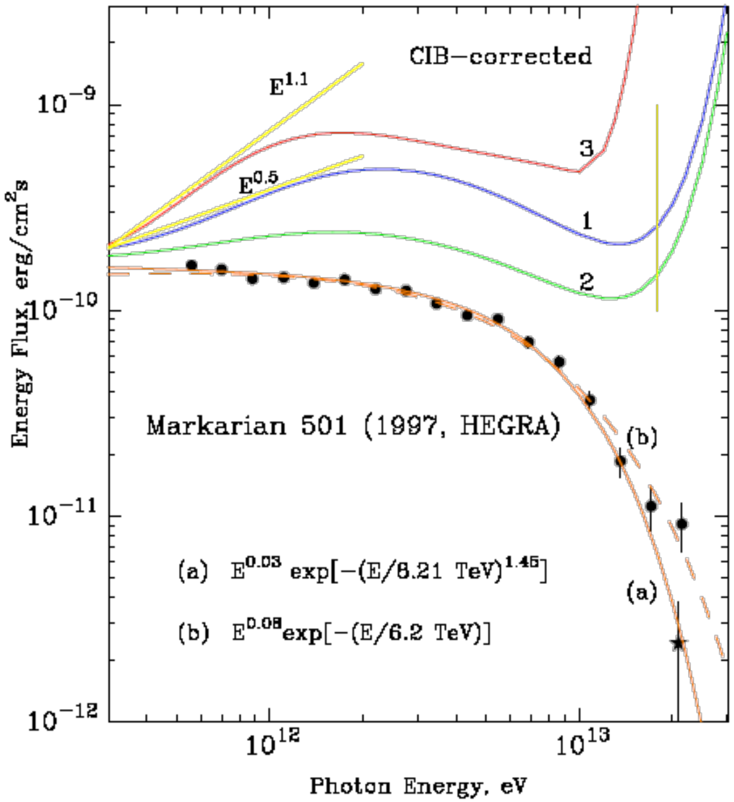

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B ≥ 10^{-13} G ?

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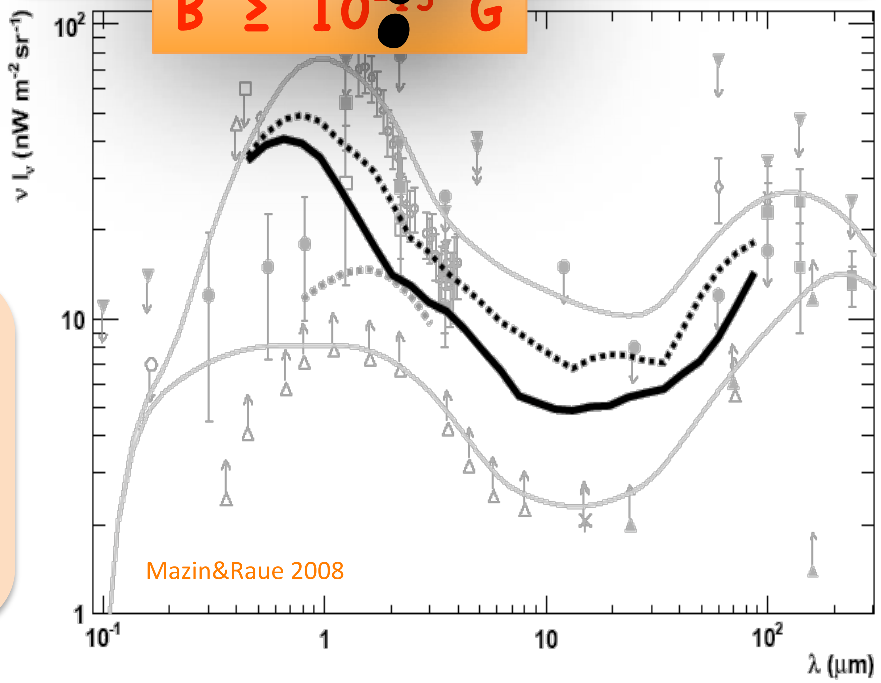

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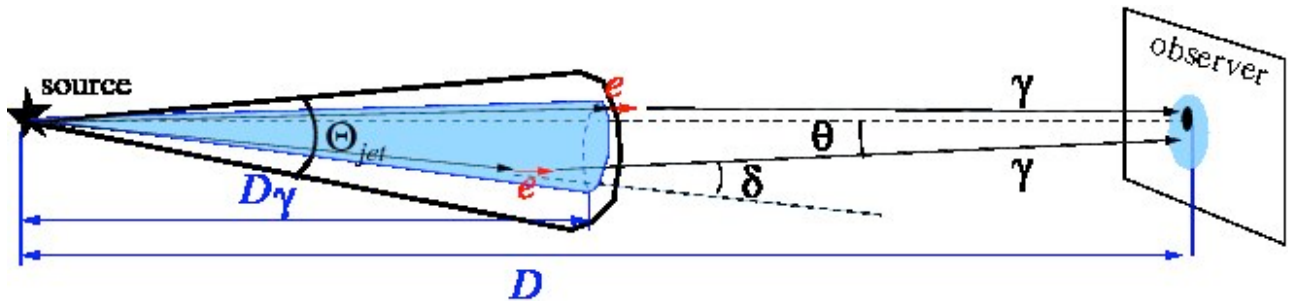
Detection of EGMF with cascade

Production of secondary photons: distances



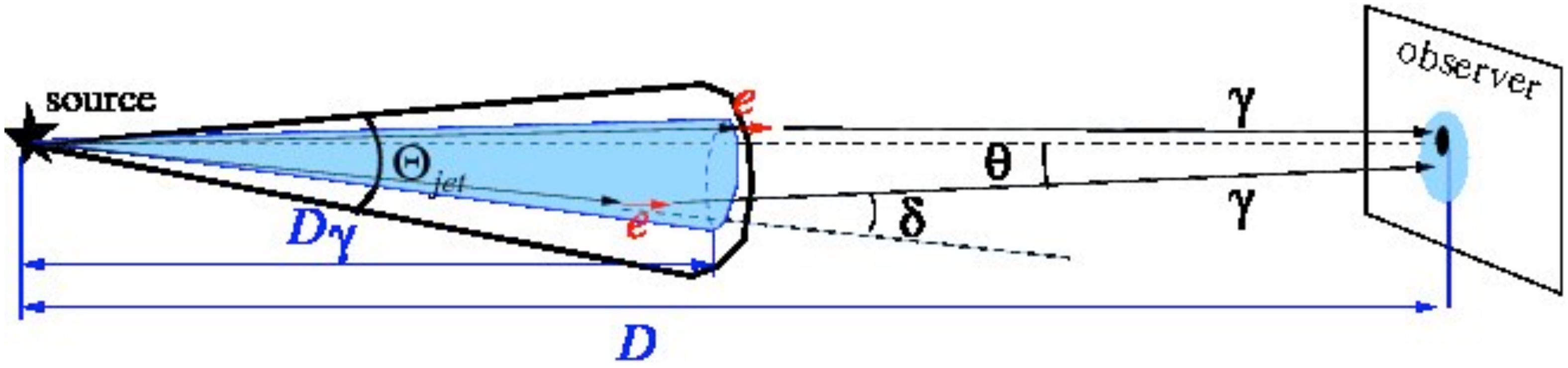
$$D_{\gamma_0} = \frac{1}{n_{\mathrm{IR}}\sigma_{PP}} \propto 15\ \mathrm{Mpc}\ \frac{40\ \mathrm{TeV}}{\mathrm{E}}\ \frac{10nW/(m^2 sr)}{(\nu F(\nu))_{IR}}$$

$$D_{\gamma} = \frac{1}{n_{\mathrm{IR}}\sigma_{PP}} \propto 400\ \mathrm{Mpc}\ \frac{1\ \mathrm{TeV}}{\mathrm{E}}\ \frac{10nW/(m^2 sr)}{(\nu F(\nu))_{IR}}$$

$$\lambda_e = \frac{1}{n_{\mathrm{CMB}}\sigma_{ICS}} \sim 1\ \mathrm{kpc}$$

A.Neronov and D.S., astro-ph/0604607

Production of secondary TeV photons: angles and time delay



$$t_{\mathrm{delay}} = D\delta^2 \frac{\tau - 1}{2\tau^2} \approx 10^5 \text{ years}$$

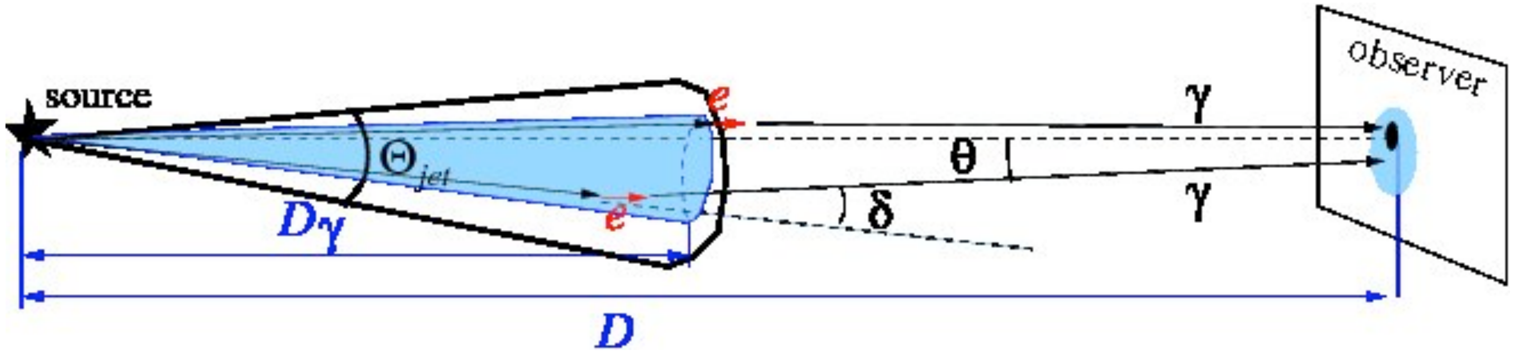
$$\tau = n_{\mathrm{IR}} \sigma_{PP} D_{\gamma_0}$$

$$\delta \leq \Theta_{jet} \frac{\tau}{\tau - 1}$$

$$\theta_{ER} = \frac{\delta}{\tau}$$

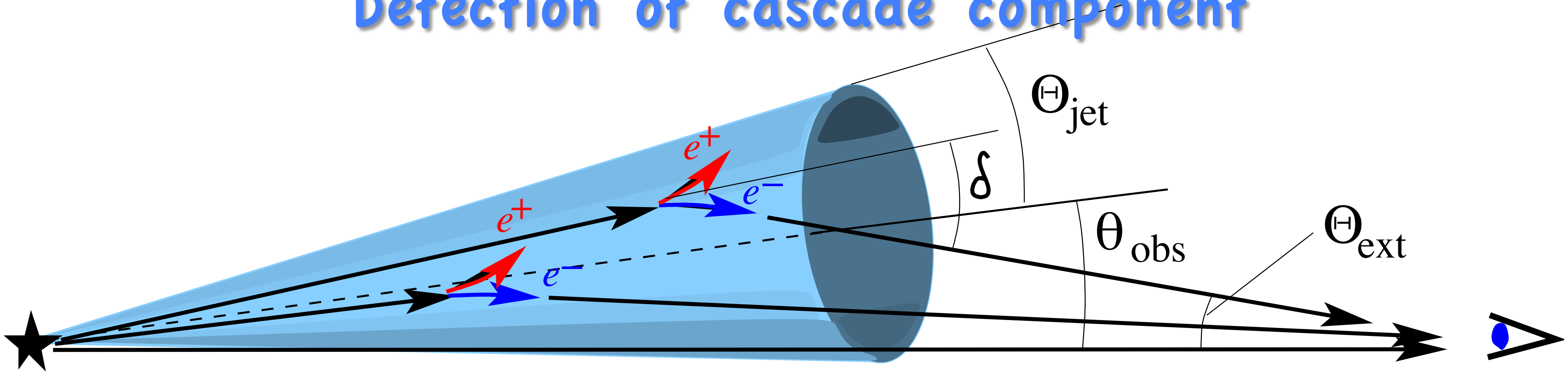
Production of secondary TeV photons:

Energy



$$E_\gamma = 1.2 \text{ TeV} \left(\frac{E_e}{20 \text{TeV}} \right)^2$$

Detection of cascade component



Cascade emission component in the spectra of blazars could be identified and separated from the intrinsic source emission via characteristic

- spectral and/or

- imaging and/or

- timing

properties.

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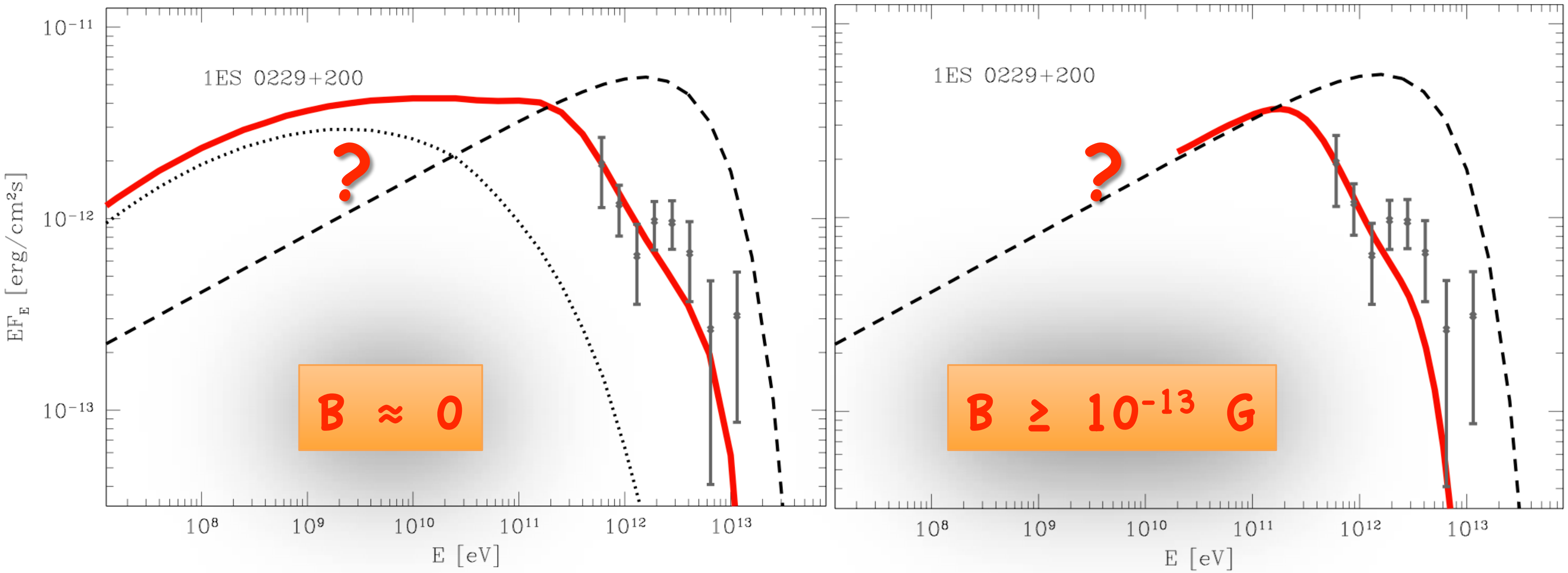
Contribution of cascade to the spectrum



In the absence of measurements of EGMF it is not clear if the observed –ray spectra of blazars emitting in the TeV range are intrinsic to the source or formed in result of development of electromagnetic cascade in the intergalactic space along the line of sight

If intrinsic source spectrum extends to >10 TeV, cascade emission could contribute in the 0.1-1 TeV band spectrum

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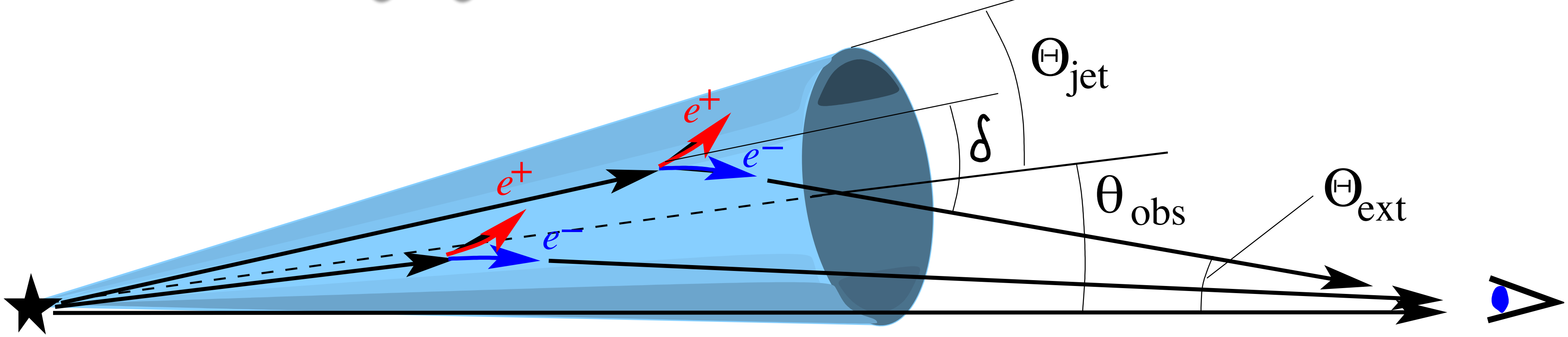
Imaging of cascade: 3-d cascade needed



3-d cascade in turbulent EGMF

A.Neronov, D.Semikoz, M.Kachelriess, S.Ostapchenko and A.Elyev , 2009

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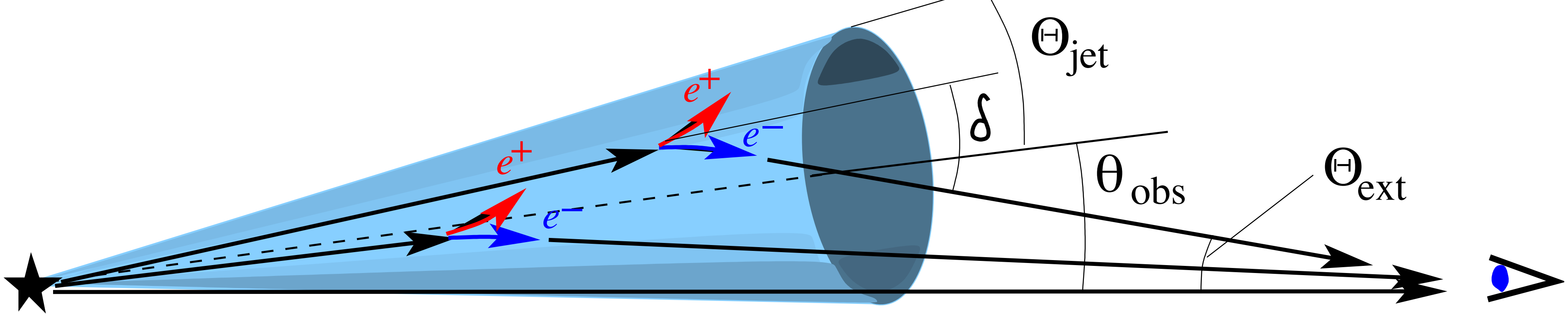
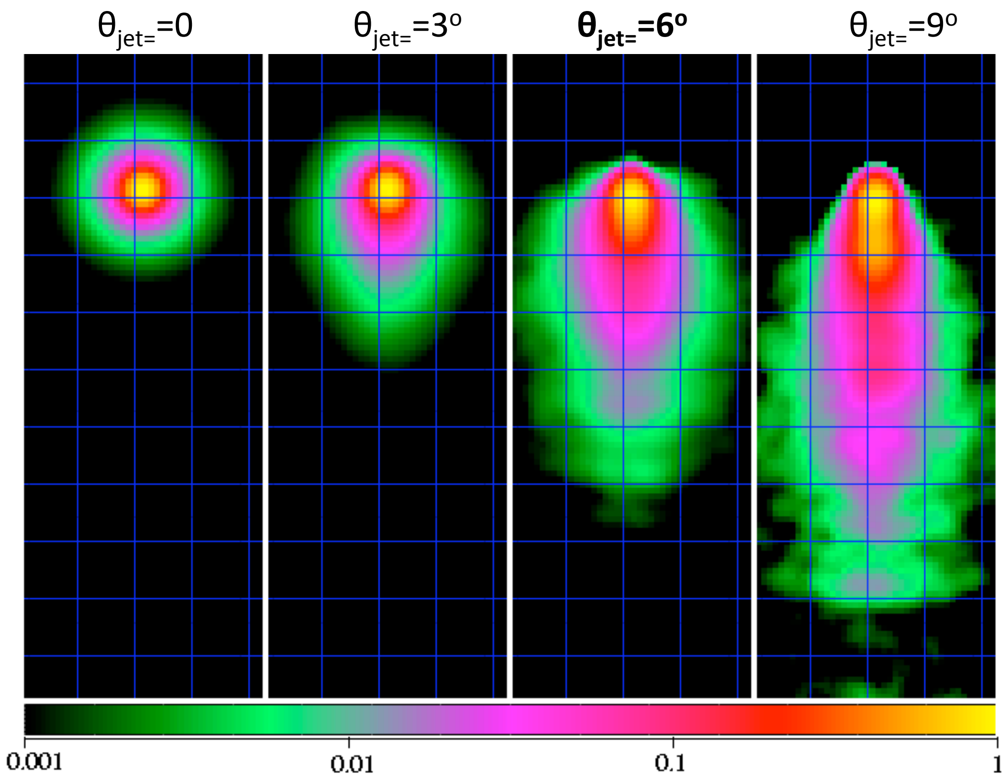
Imaging of cascade: jet opening angle

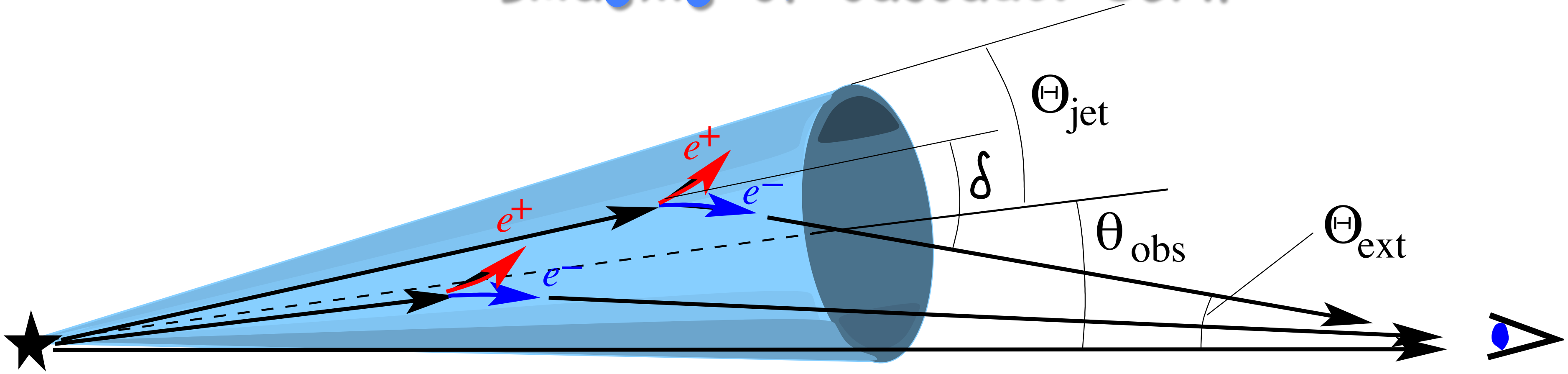


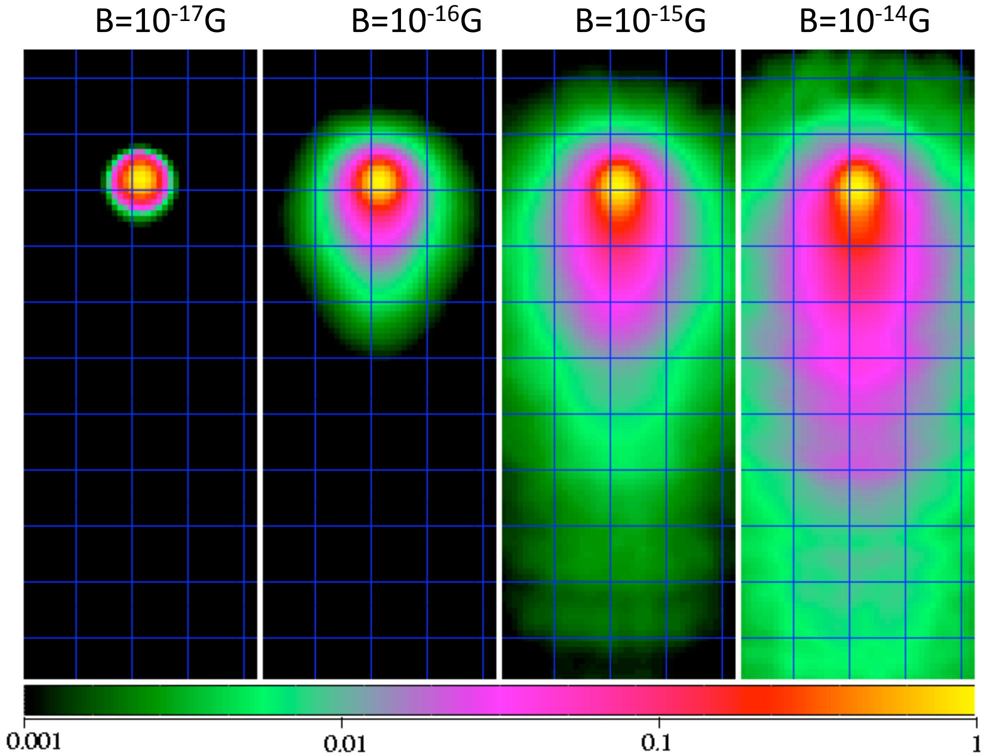
Imaging: cascade component forms an extended emission around initially point source.

- detectability depends on the telesope PSF and on the scale of angular deflections of e+e- pairs



Imaging of cascade: EGMF

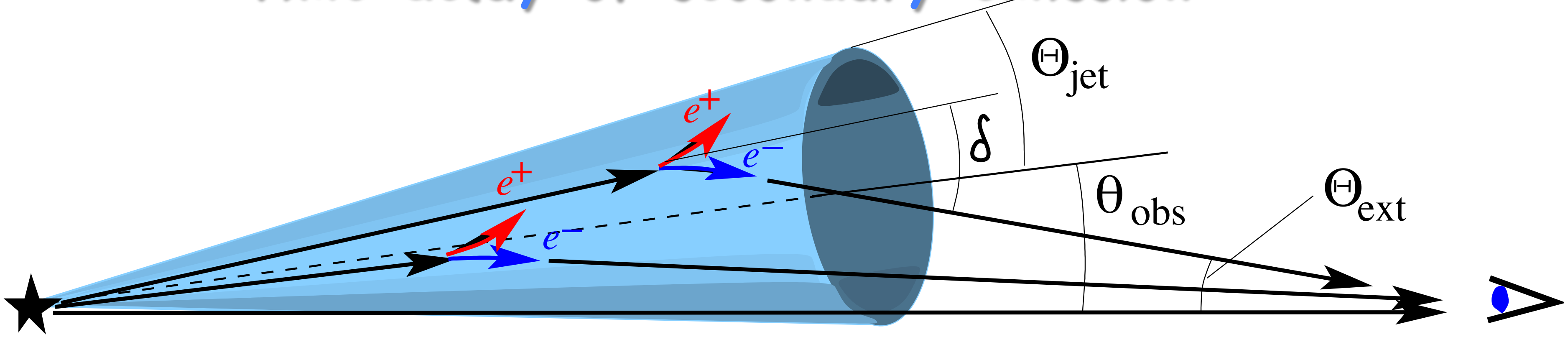


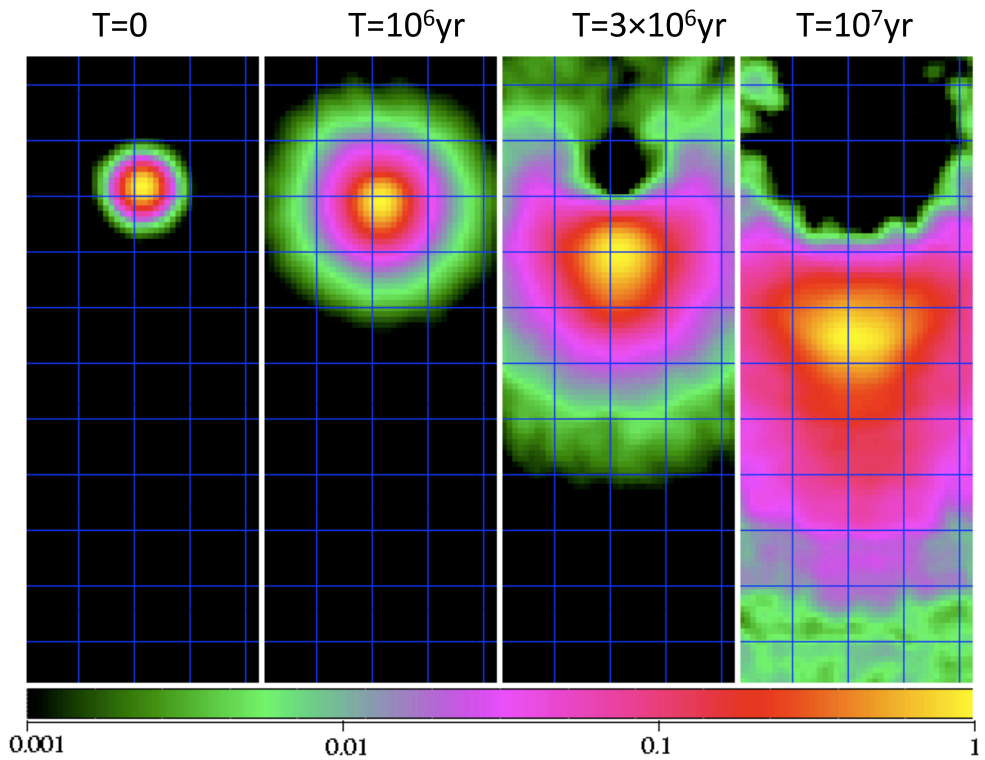


Imaging: cascade component forms an extended emission around initially point source.

- detectability depends on the telesope PSF and on the scale of angular deflections of e+e- pairs (i.e. on the strength of EGMF)

Time delay of secondary emission





Timing: cascade component emission is delayed, compared to the direct signal from the point source

- detectability depends on the telesope sensitivity and on the scale of time delay

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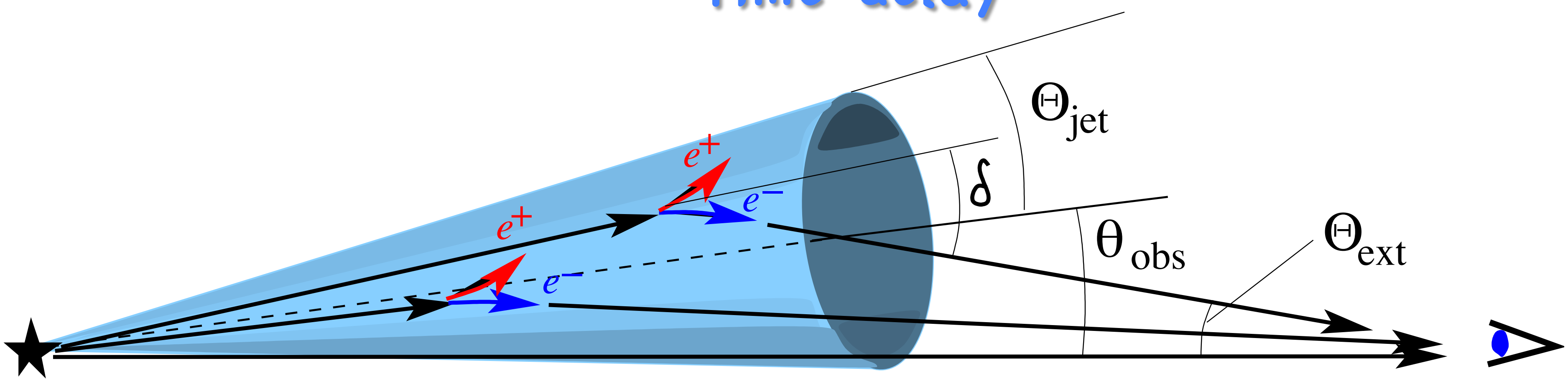
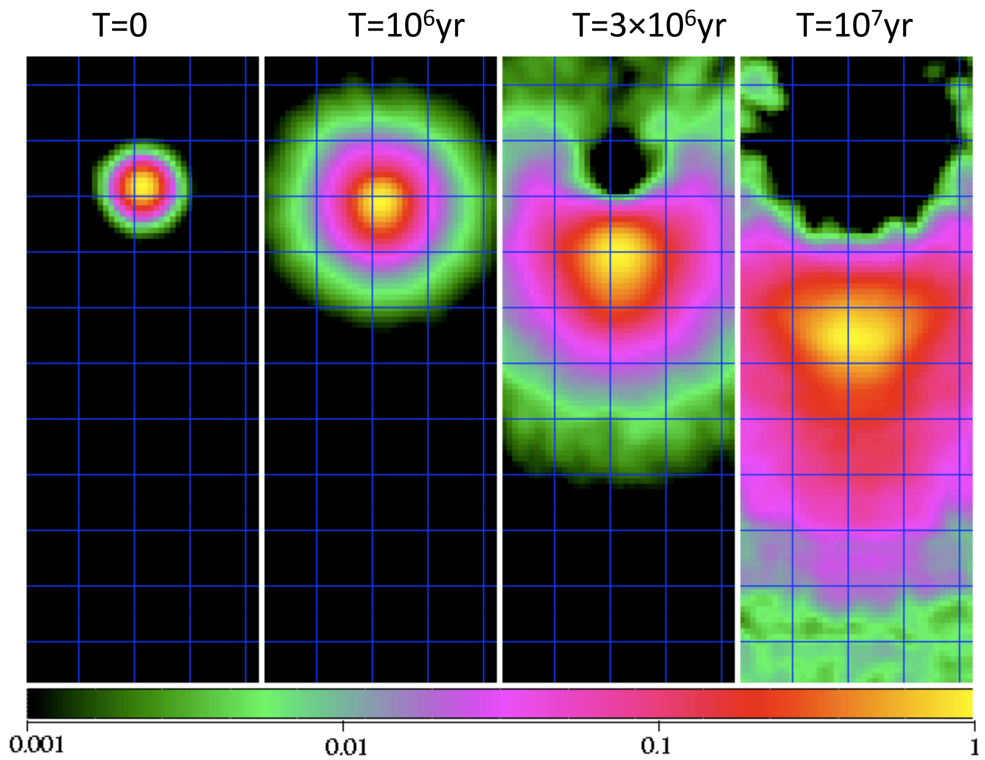
Time delay





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Evidence of non-zero EGMF in the voids

Neronov & Vovk 2010

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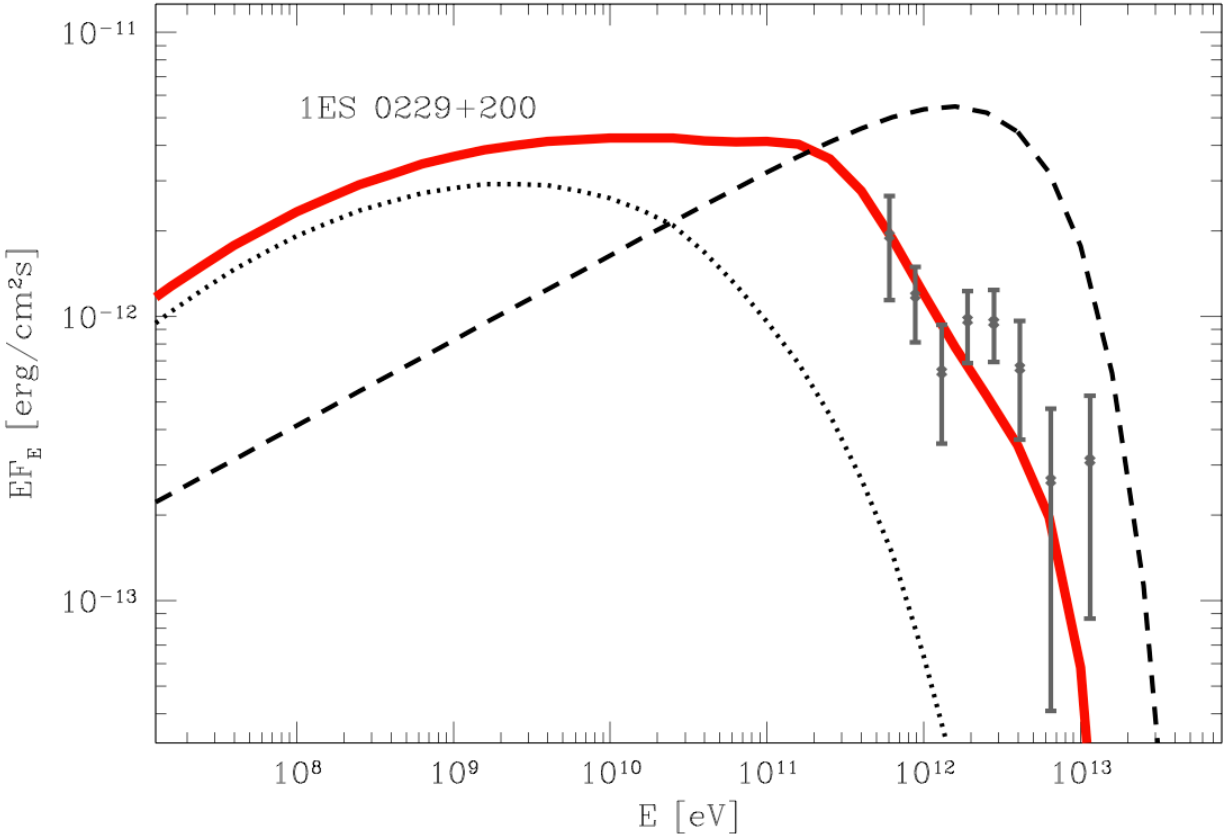
Could EGMF be B≈0?



If EGMF is negligible, cascade emission component should be commonly present in the spectra of TeV γ-ray loud blazars.

$$E_\gamma = \varepsilon_{CMB} \frac{E_e^2}{m_e^2} \approx 0.75 \left[\frac{E_{\gamma 0}}{1\ \mathrm{TeV}}\right]^2 \ \mathrm{GeV}$$

Electromagnetic cascade emission initiated by TeV photons is peaked in the GeV energy band.

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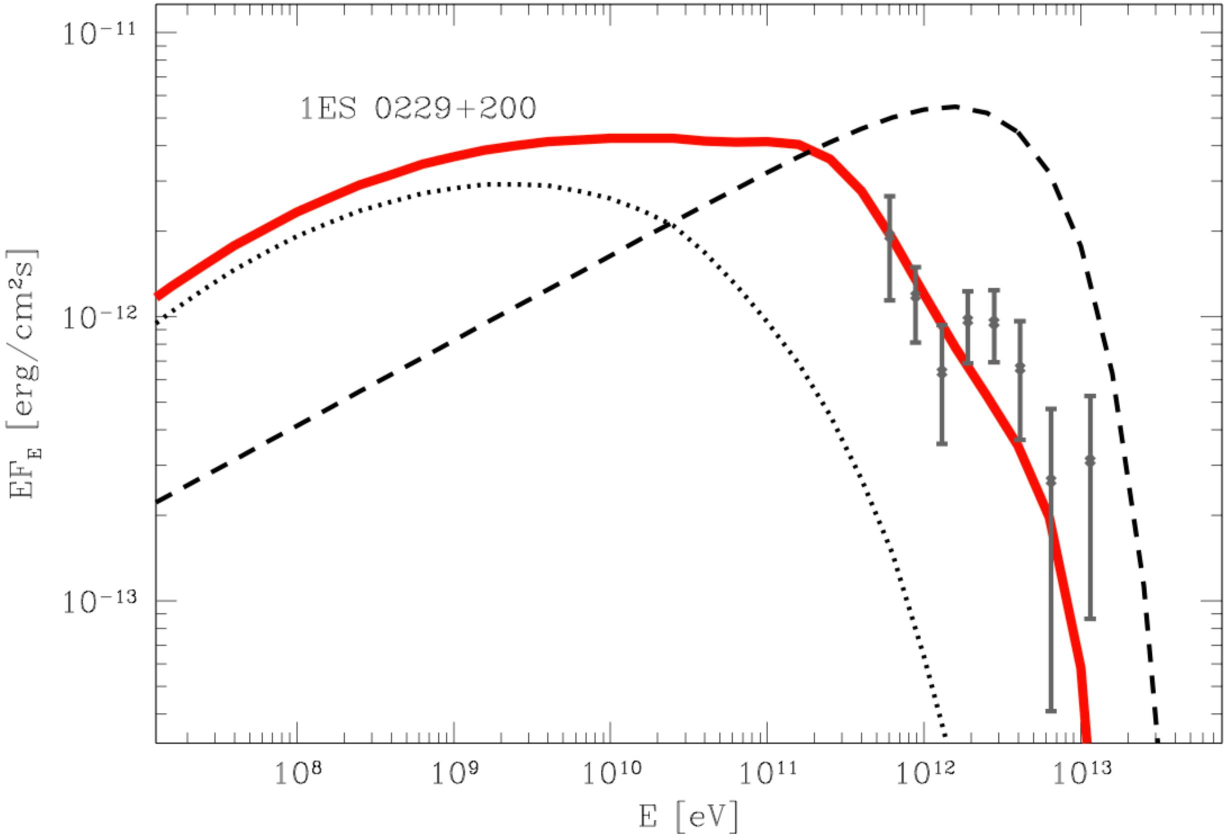

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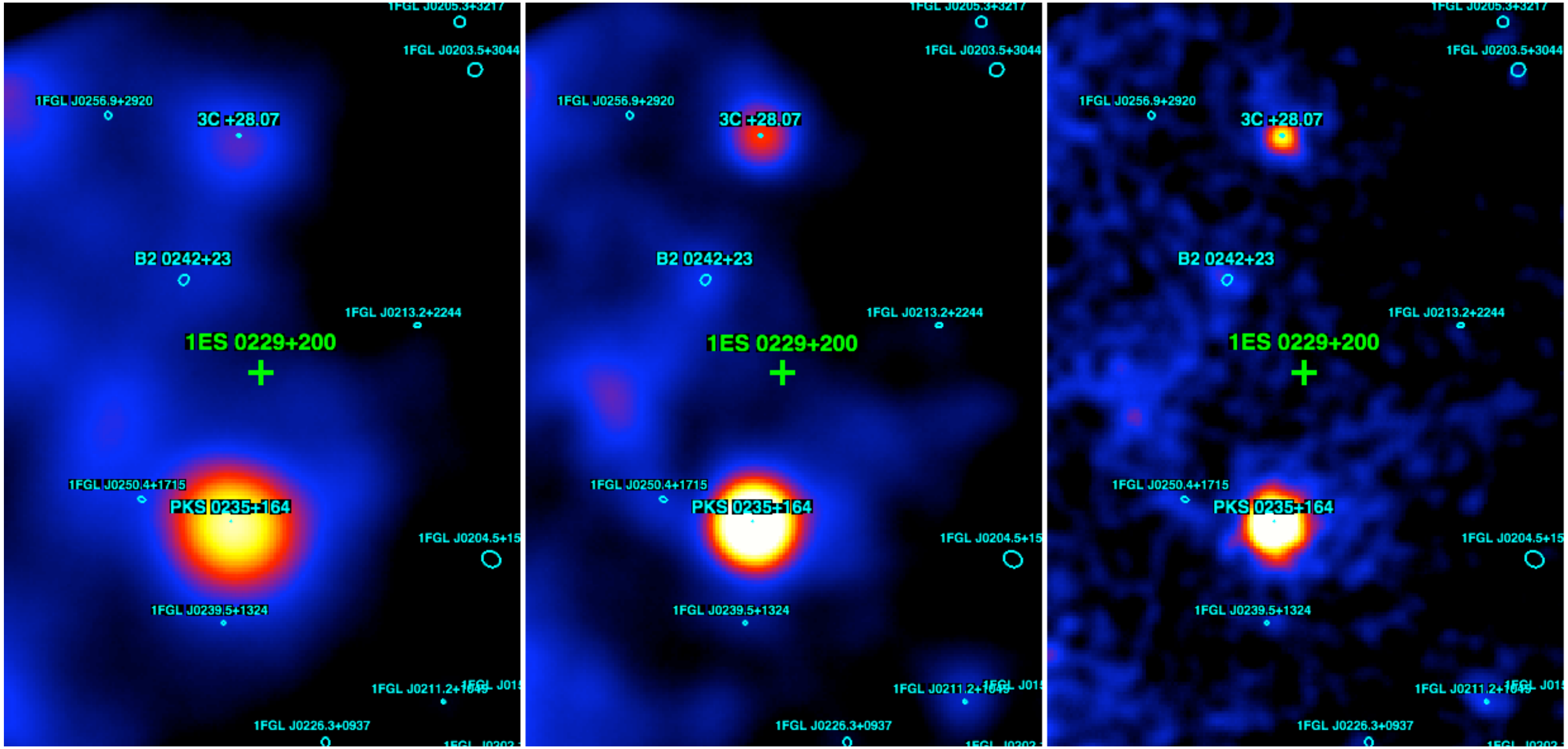

0.1-0.3 GeV 0.3-1 GeV 1-300 GeV

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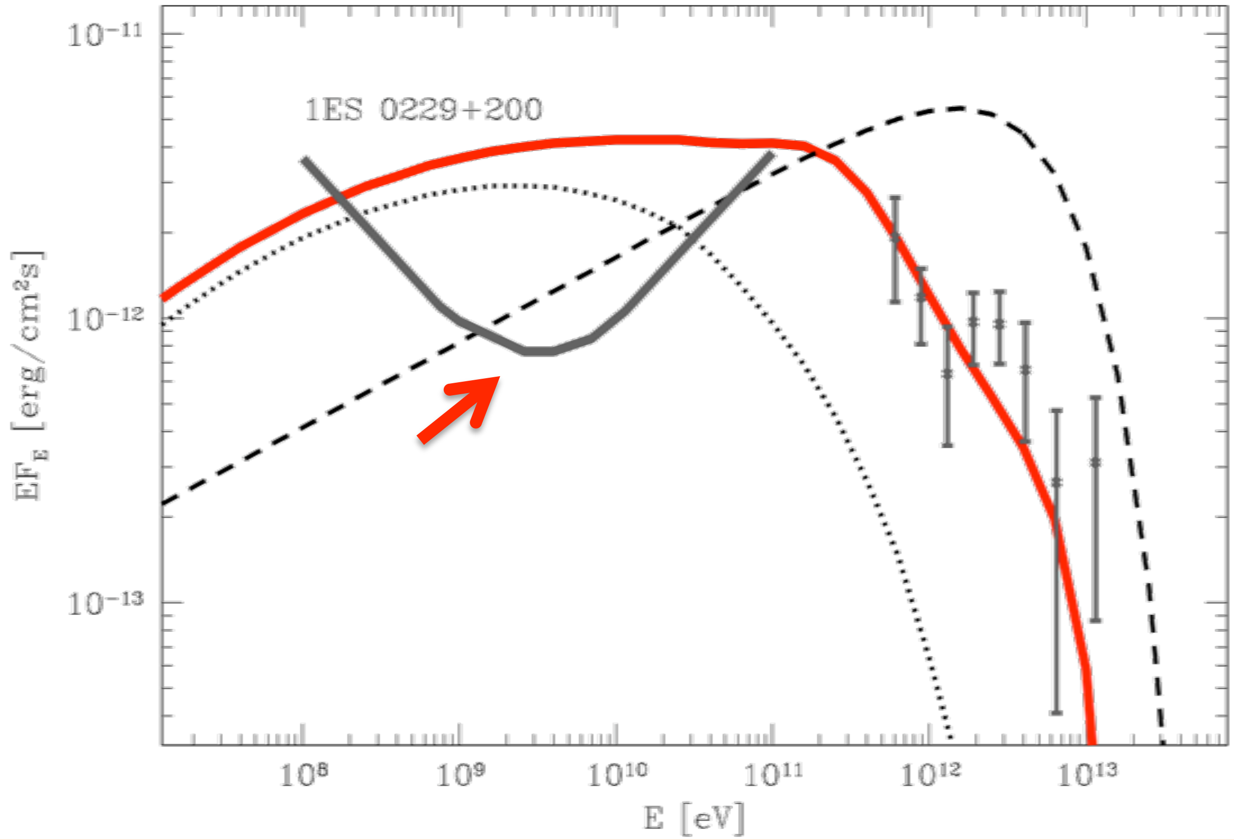

Fermi upper limits on the steady state flux from high-redshift / hard intrinsic spectra blazars are below the expected level of the cascade emission

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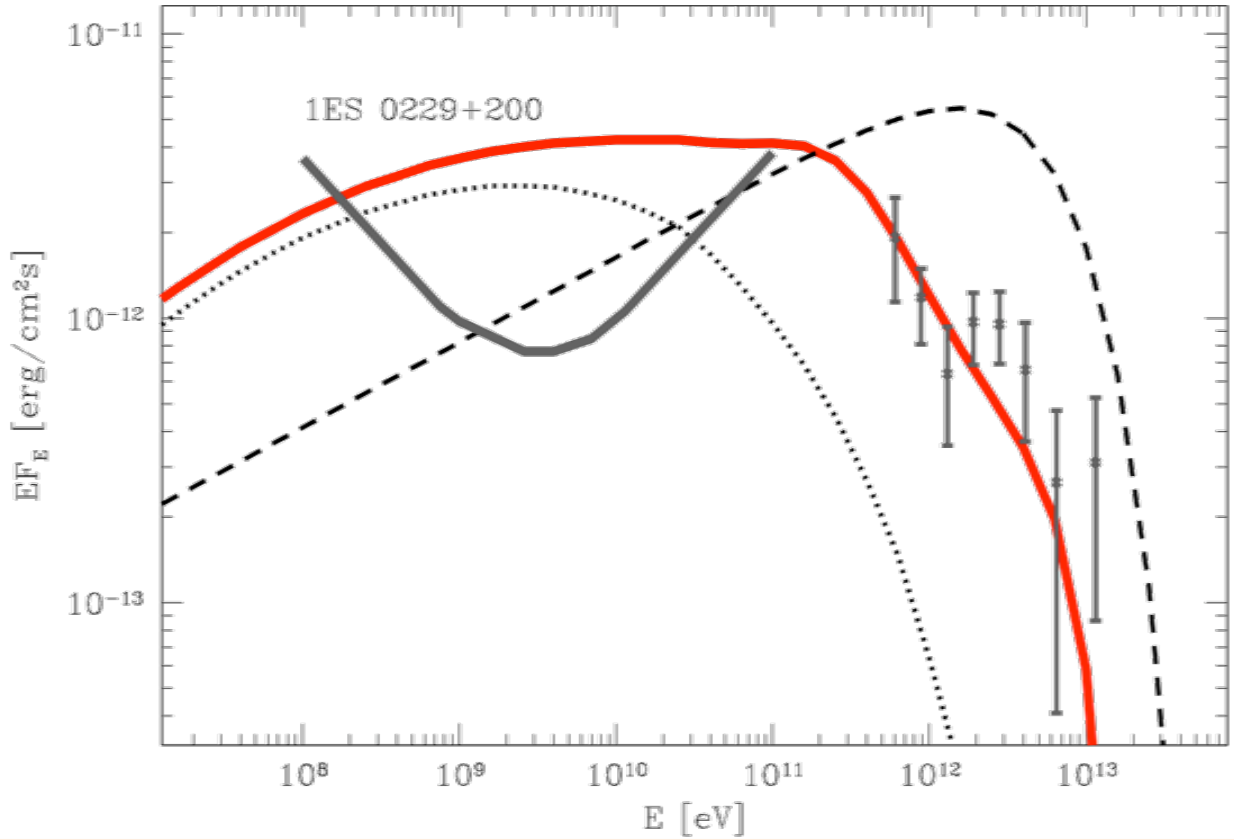

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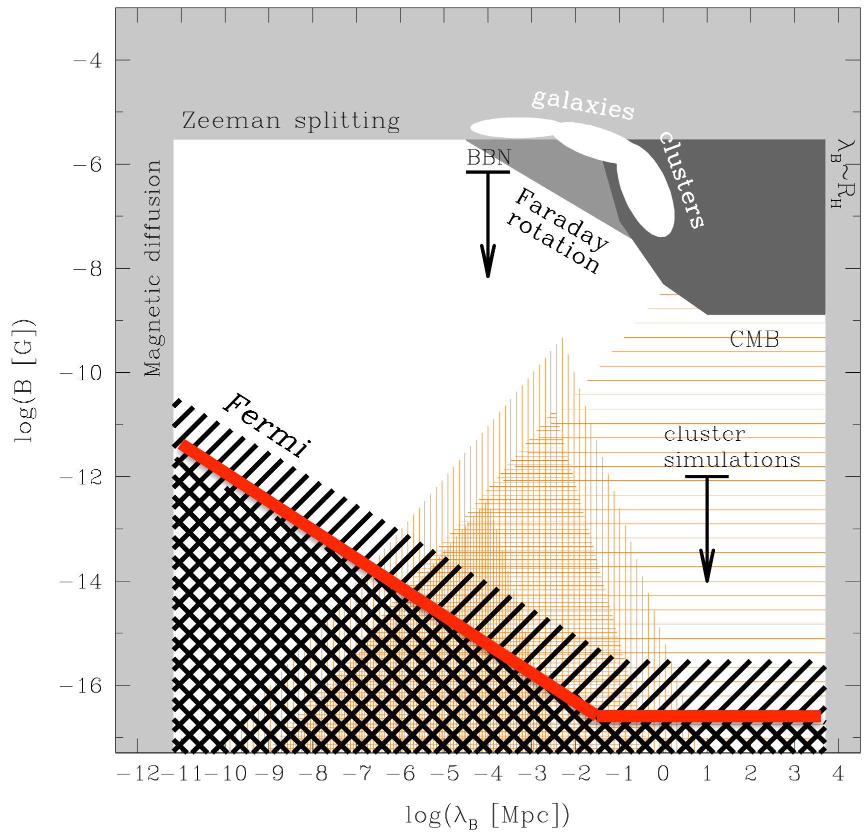

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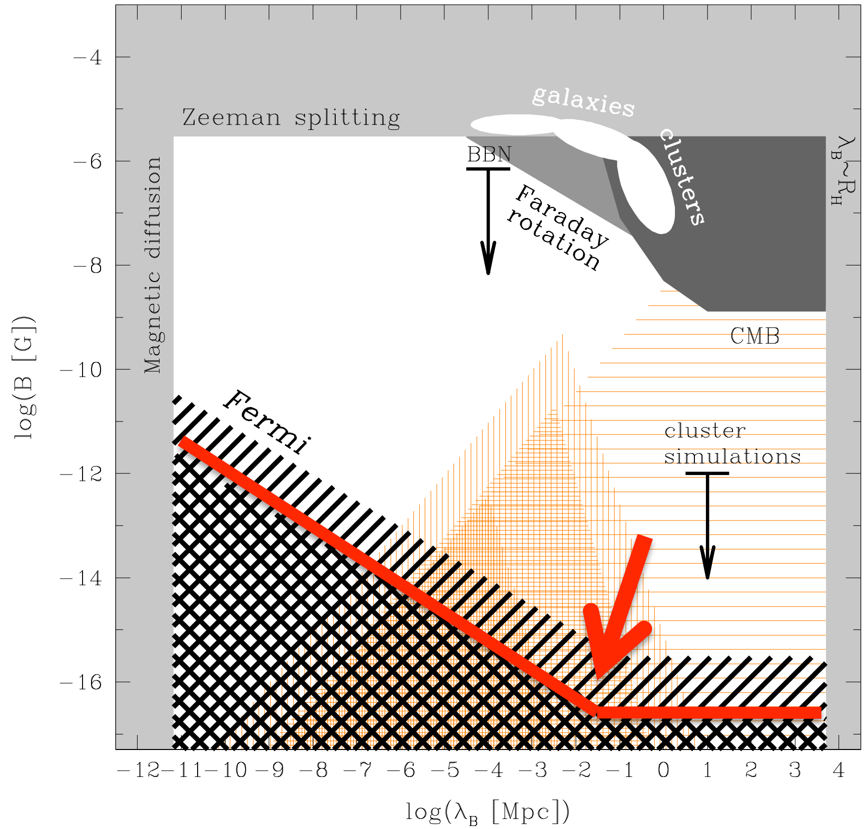

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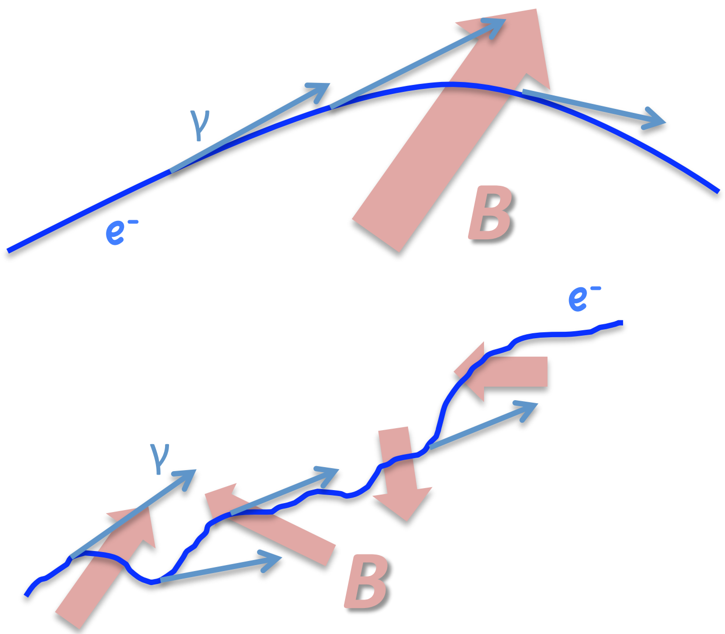
Dependence of the limit on EGMF correlation length



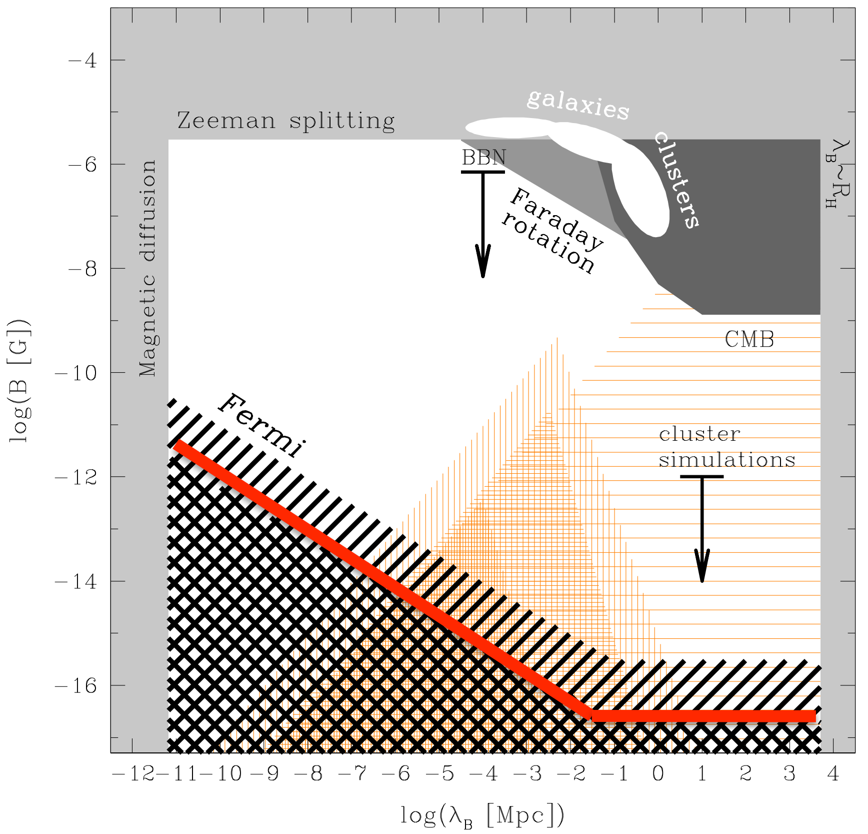
If the correlation length of EGMF is large, deflection angle is

$$\delta = \frac{D_e}{R_L} = 2^O \left[\frac{B}{10^{-16}\mathrm{G}}\right]\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-2}$$

If the correlation length of EGMF is small, ($\lambda_B \ll D_e$) deflection angle is

$$\delta = \frac{\sqrt{D_e \lambda_B}}{R_L} = 1^O \left[\frac{B}{10^{-16}\mathrm{G}}\right]\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-3/2}\left[\frac{\lambda_B}{10\ \mathrm{kpc}}\right]^{1/2}$$

Uncertainties of the lower bound on EGMF



- Strength and spectrum of the cascade component of the spectra is derived assuming a particular EBL spectrum. The bound depends on the (uncertain) normalization of the EBL spectrum.

- GeV and TeV band observations are not simultaneous. The bound depends on the (unknown) variability time scale of the direct source flux.

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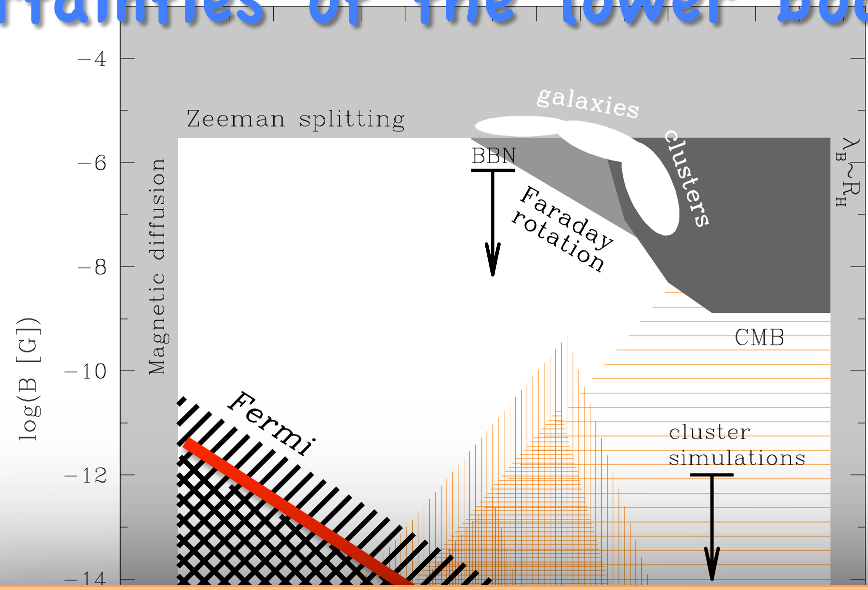

The bound has to be verified with dedicated simultaneous GeV-TeV observations of hard-spectra / high-redshift TeV blazars

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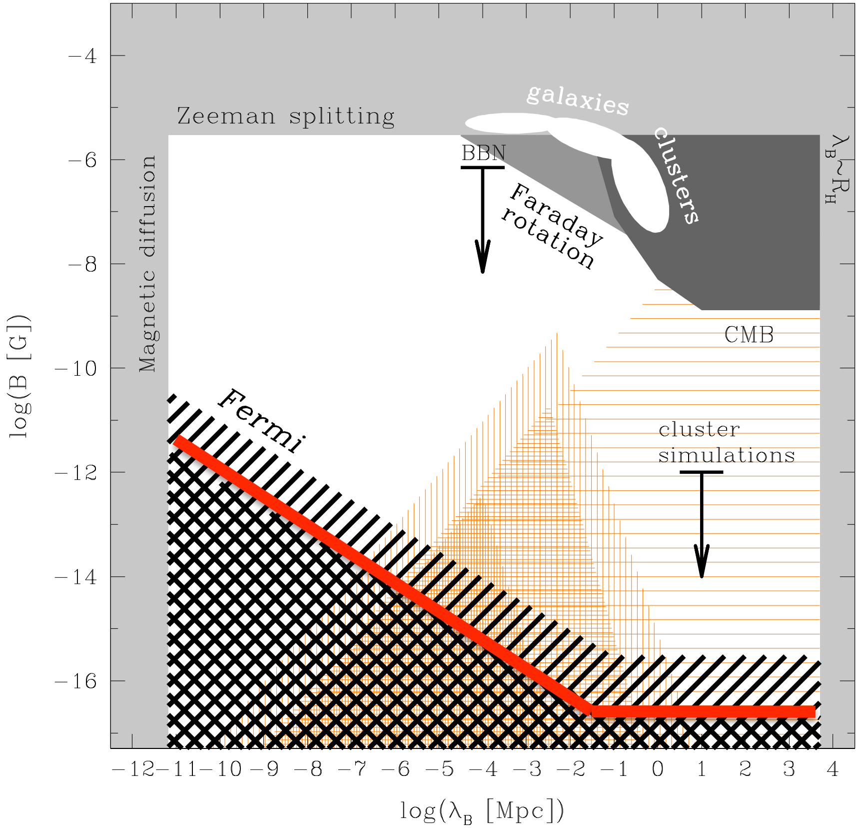
Sensitivity of gamma-ray telescopes to “seed” fields

Seed fields



Existing models of the "seed" fields:

- astrophysical seed fields
- cosmological seed fields

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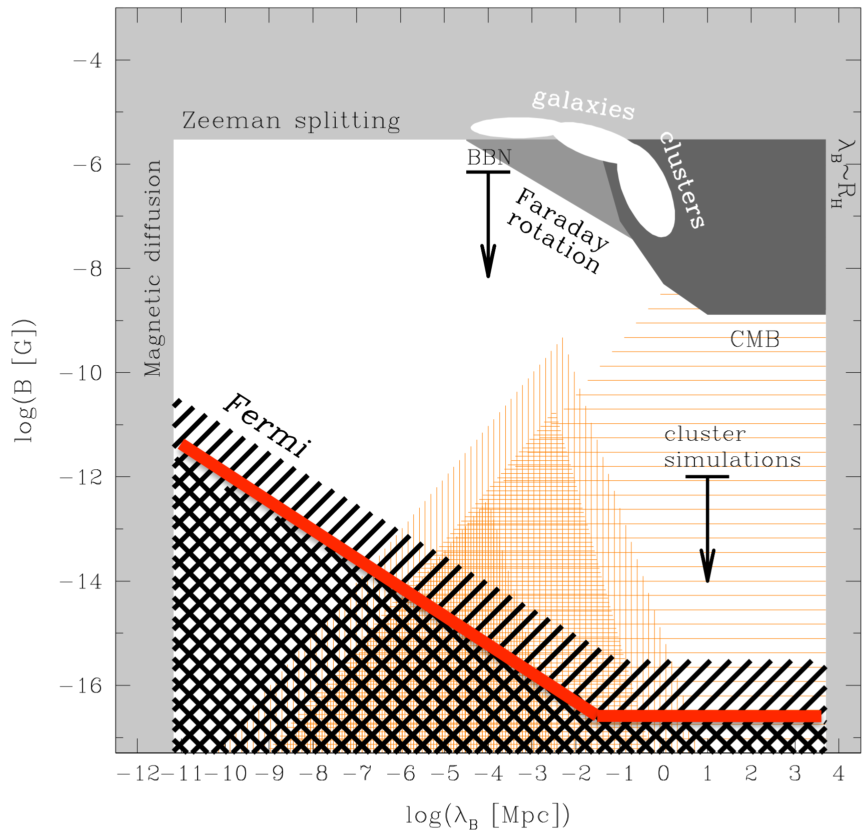
Seed fields



Existing models of the "seed" fields:

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  - LSS formation: gravitational collapse of proto-galaxies
  - Ejections from the first supernovae
  - Ejections from AGN (100 kpc-scale jets)

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- cosmological seed fields

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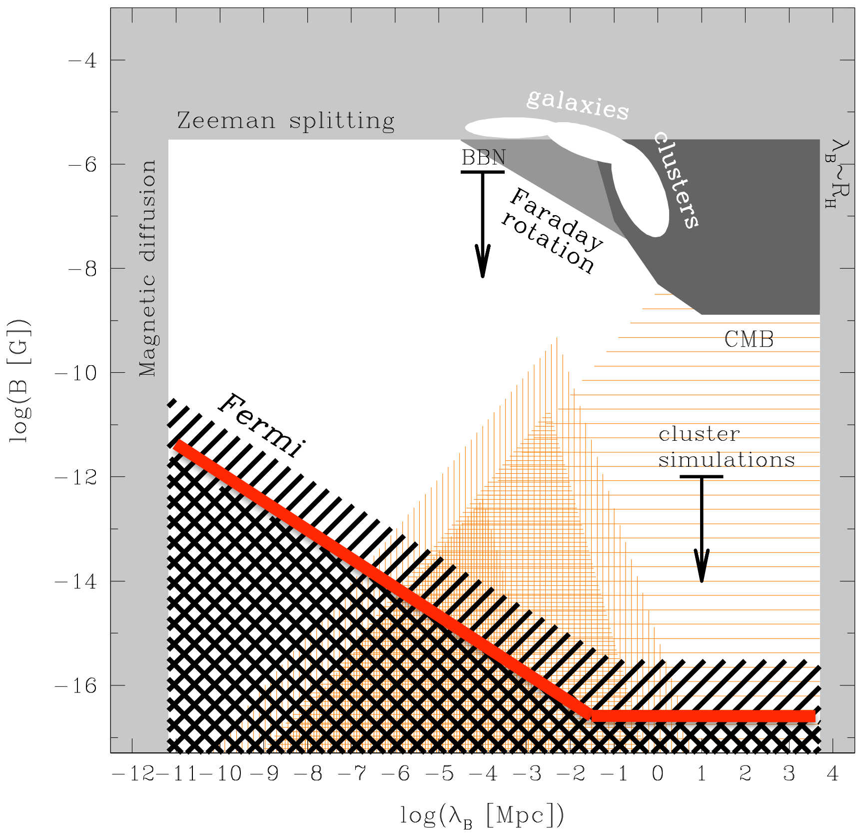

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  - Phase transitions in the Early Universe

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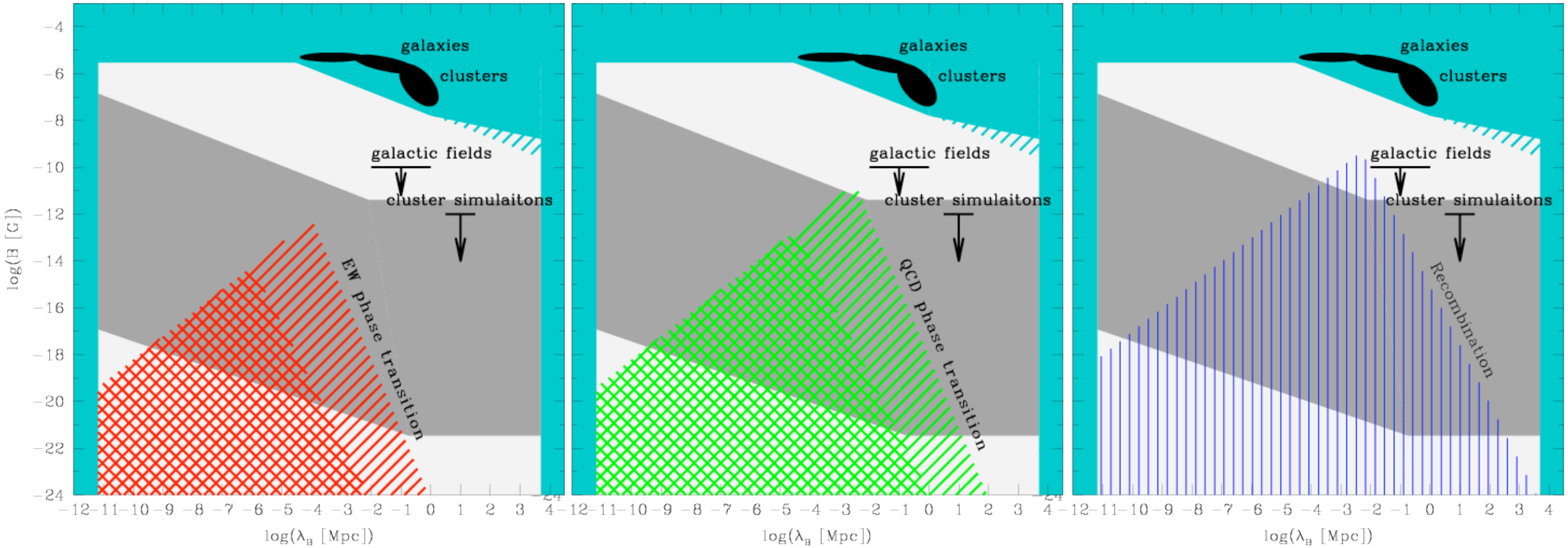
Seed fields



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  - Electroweak phase transition
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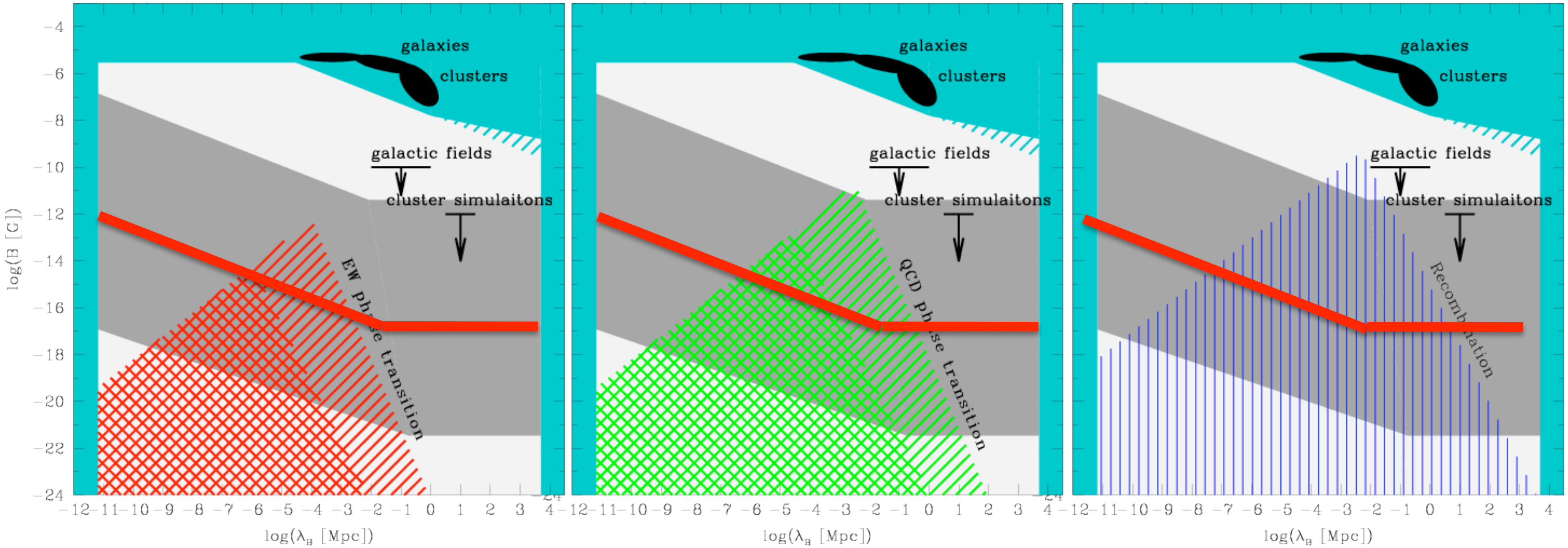
Implications of the lower bound on EGMF



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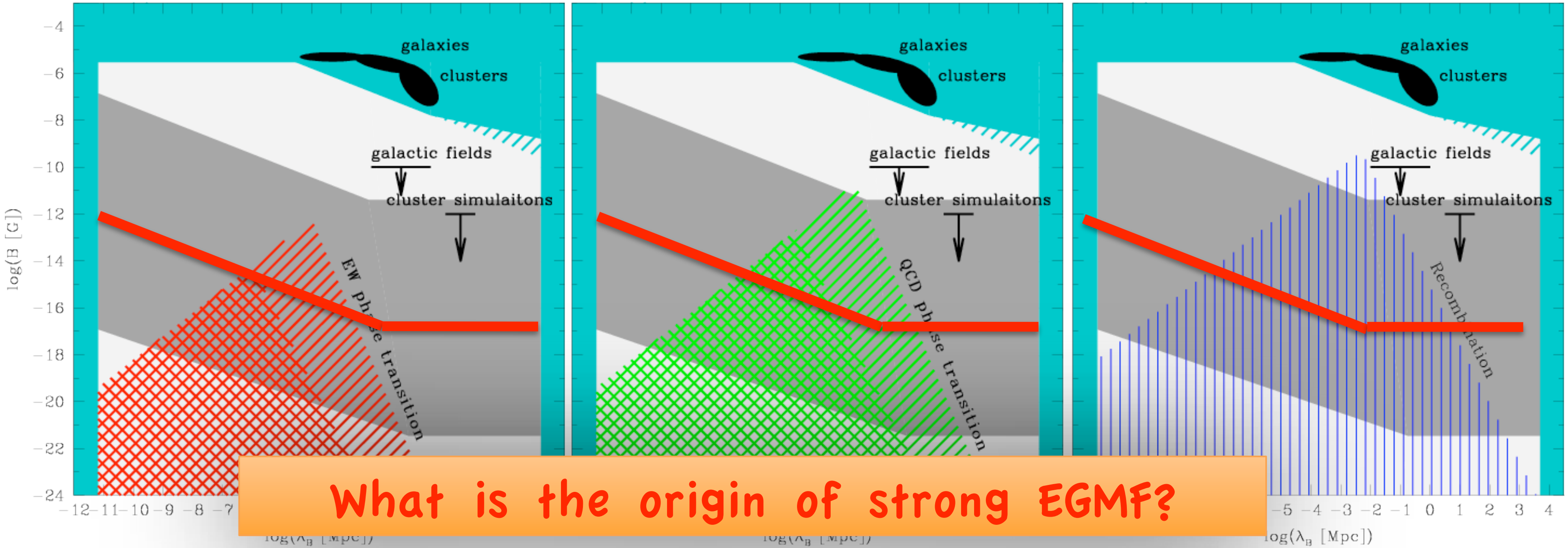

What is the origin of strong EGMF?

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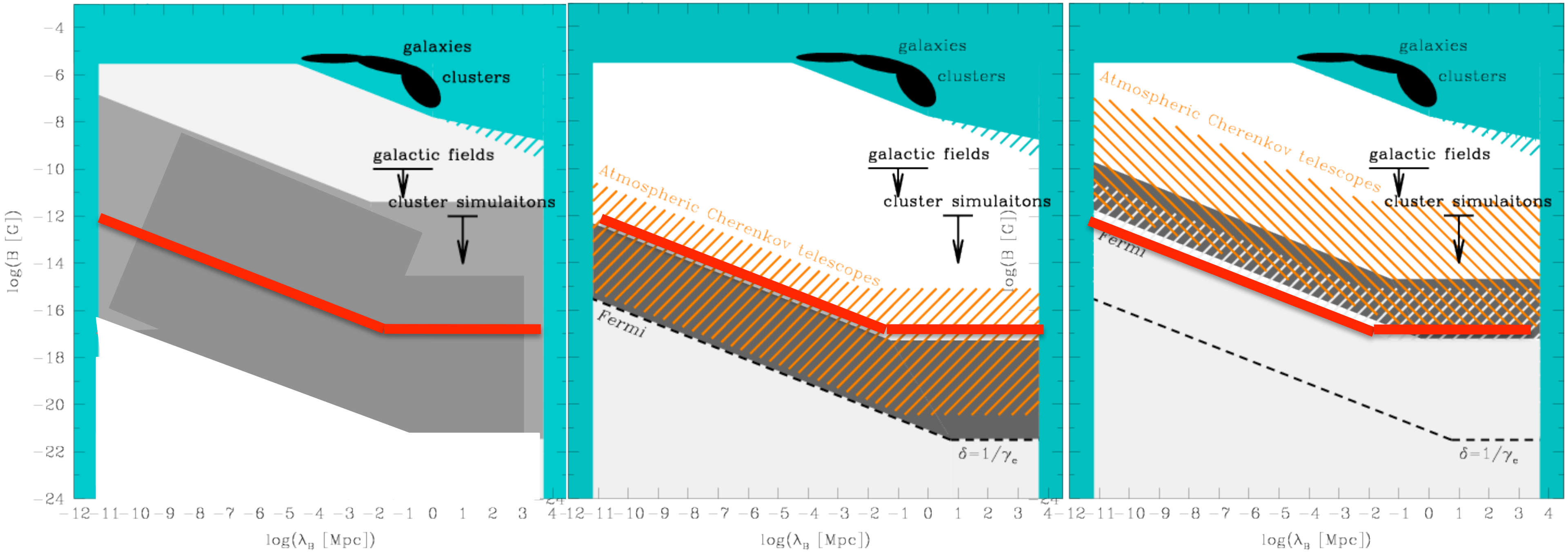
Detection of the seed fields with γ-ray telescopes



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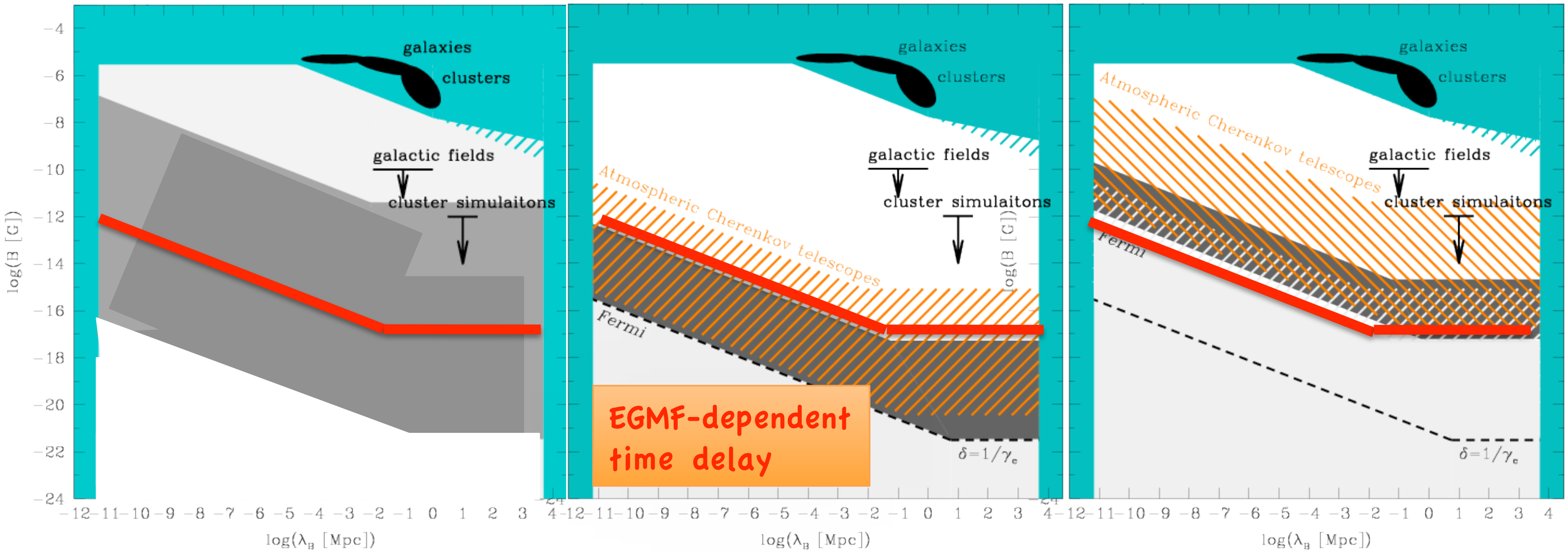

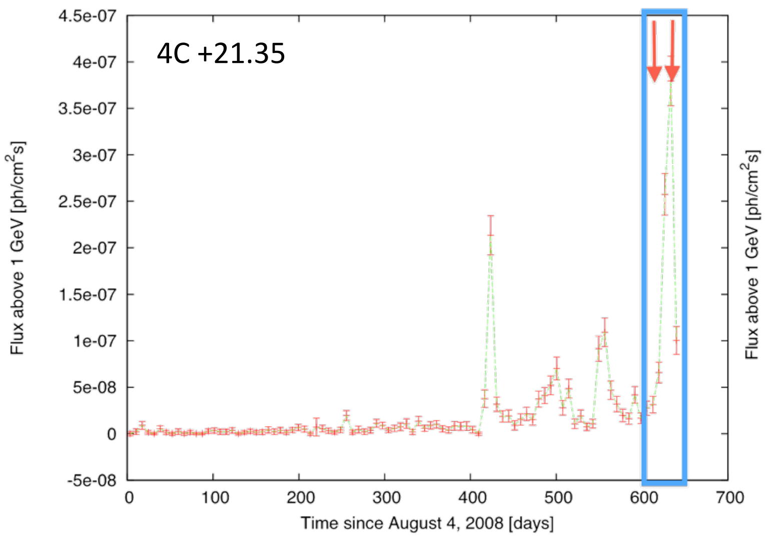

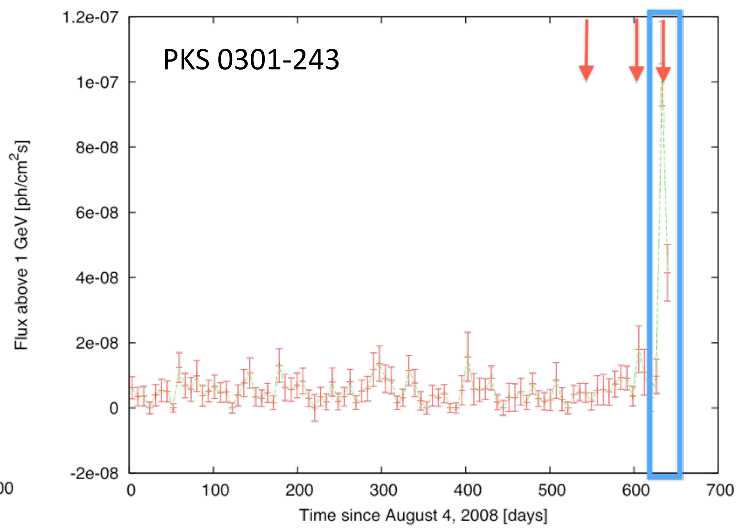

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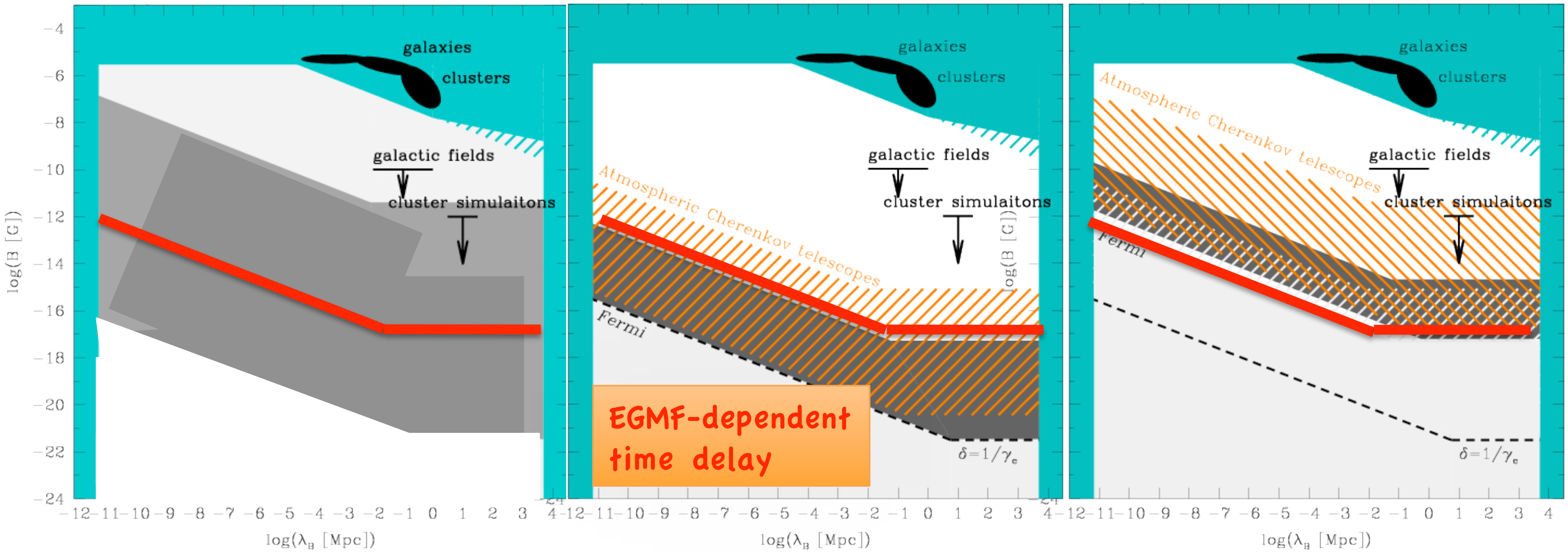

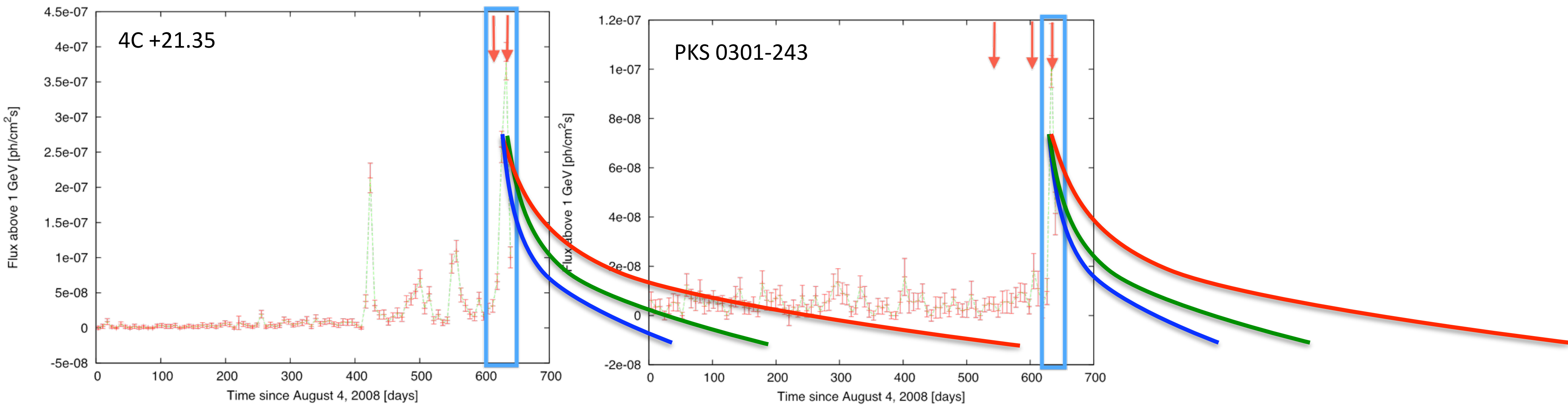

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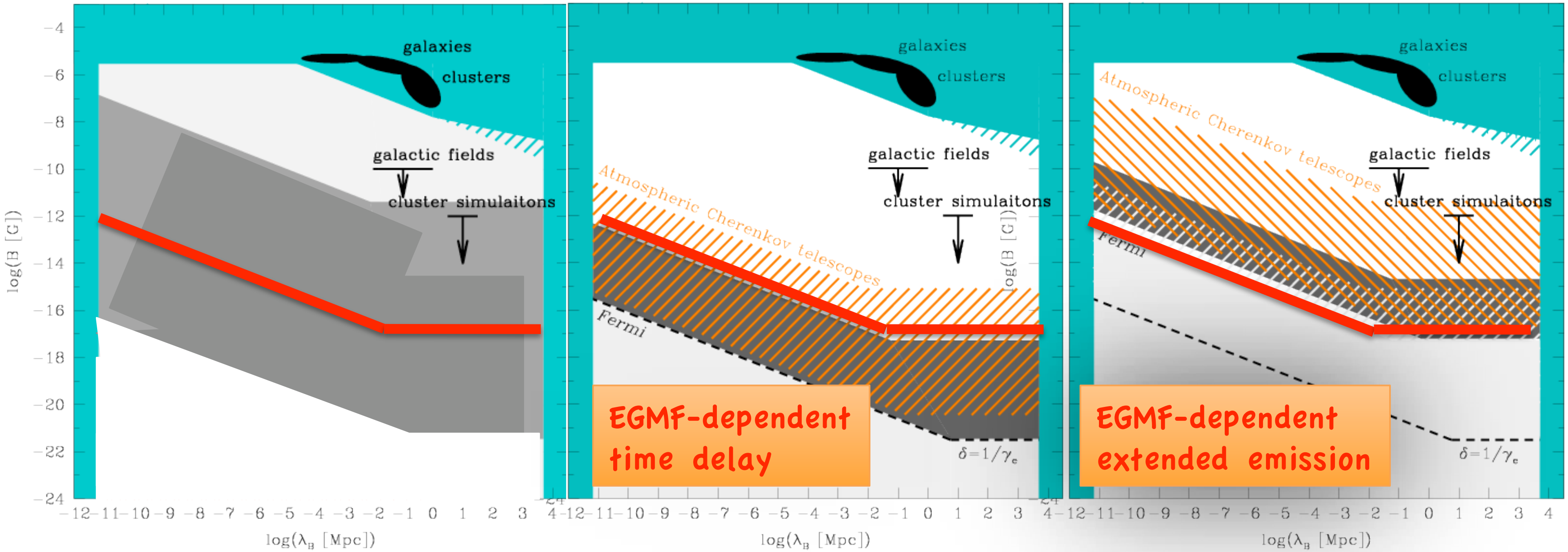

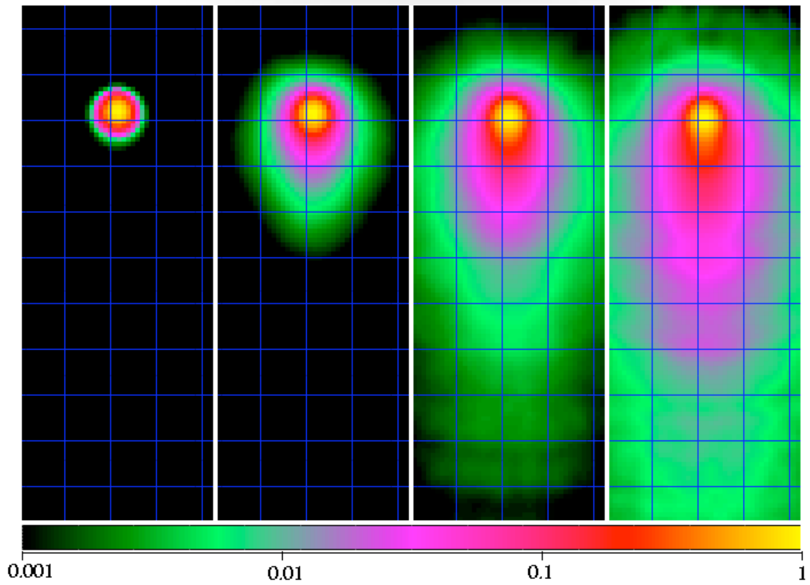

Summary

TeV γ-rays from extragalactic sources (blazars) initiate **electromagnetic cascades in intergalactic space**

Cascade γ-ray emission is in the GeV band and can be detected by **Fermi telescope**

Observational **properties of the cascade** emission strongly **depend on EGMF** strength and correlation length

In the absence of EGMF cascade emission should give contribution into the primary point source flux

Non-detection of this contribution to the flux of TeV blazars by Fermi rules out the possibility of EGMF with the strength below **$\sim 10^{-17}$–10^{-16} G**

Evidence for existense of EGMF with the strength above $\sim 10^{-17}$–10^{-16} G indicates the seed fields at the origin of magnetic fields in galaxies and galaxy clusters are of **cosmological origin**

Future measurement by gamma-ray telescopes will probe EGMF parameter space in the range 10^{-17}–10^{-12} G

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