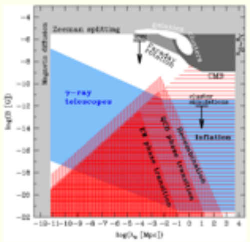
Gamma-ray observations of blazars
And
Extragalactic Magnetic Fields

Andrii Neronov
ISDC Geneva



Theory and observations of extragalactic magnetic fields

APC, Paris - December 13-15, 2010

Overview

1. Problem of the origin of magnetic fields in galaxies and galaxy clusters

2. Attenuation of γ–rays via pair production on Extragalactic Background Light (EBL)

3. Electromagnetic cascade in intergalactic medium
   - the role of ExtraGalactic Magnetic Fields (EGMF)

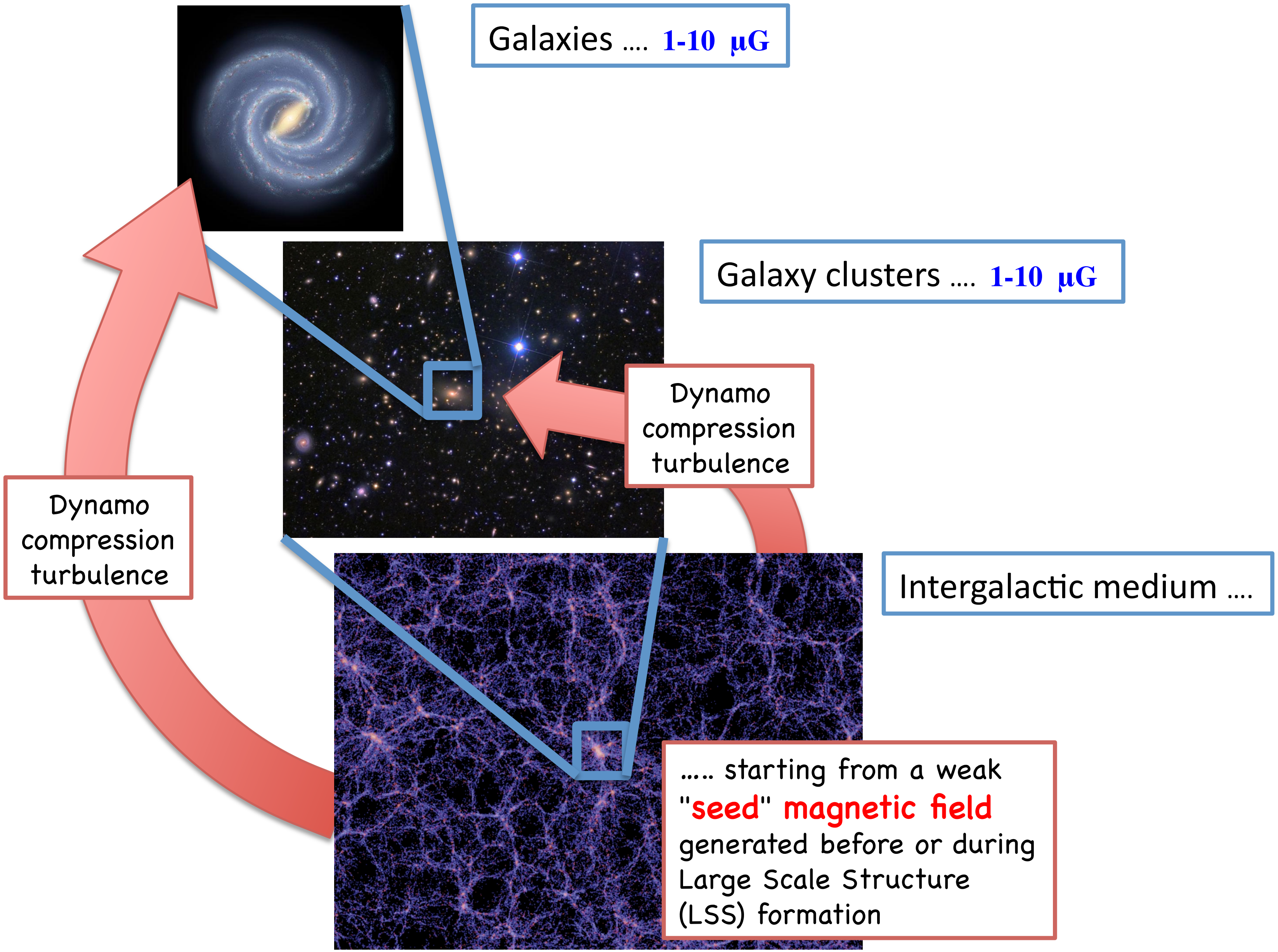
4. EGMF and the problem of the origin of cosmic magnetic fields

5. Search for emission from electromagnetic cascades with Fermi telescope

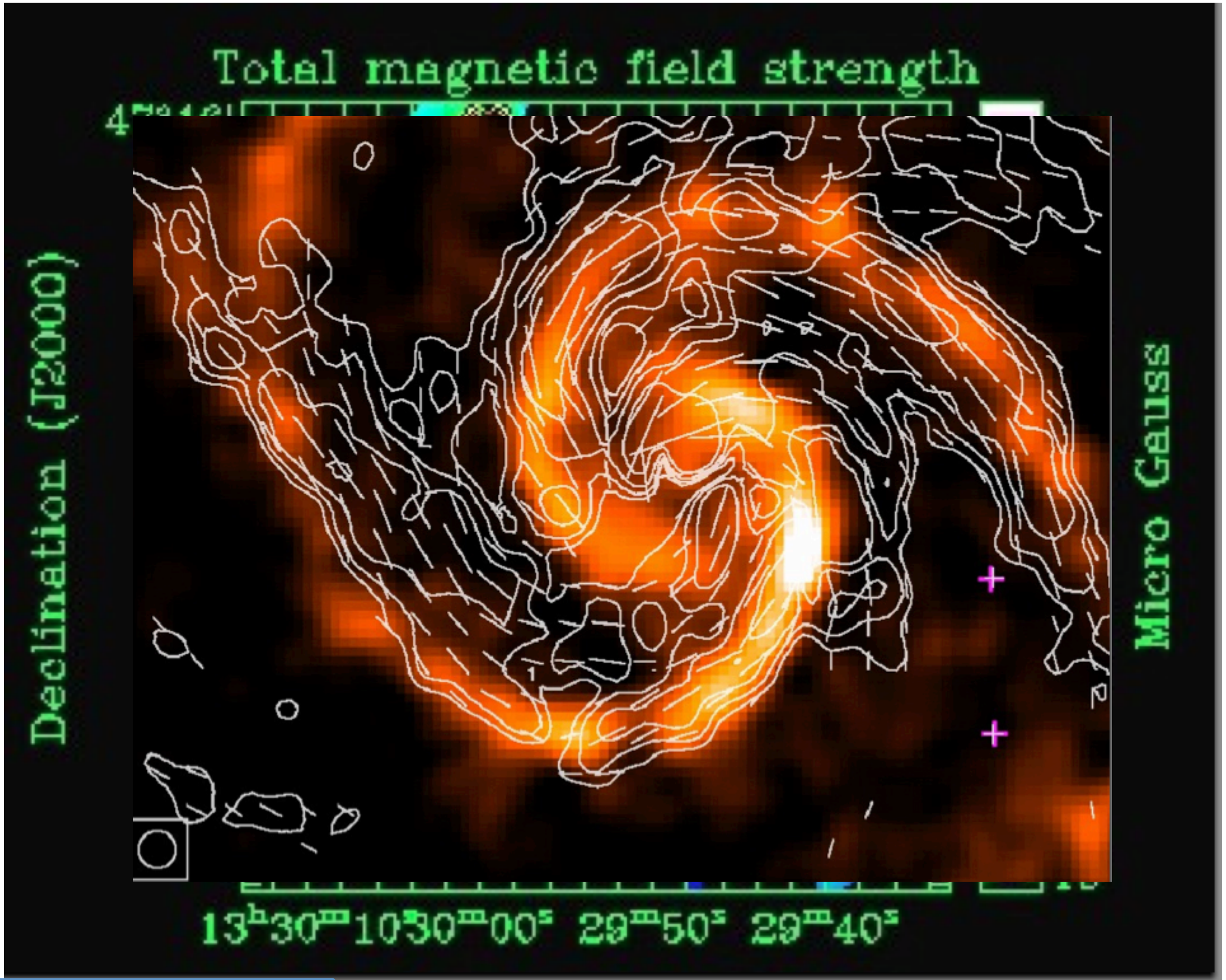
6. Evidence for existence of non-zero EGMF from Fermi non-detection of the cascade emission

7. Implications for the models of the origin of magnetic fields in the Universe

Magnetic fields in the Universe



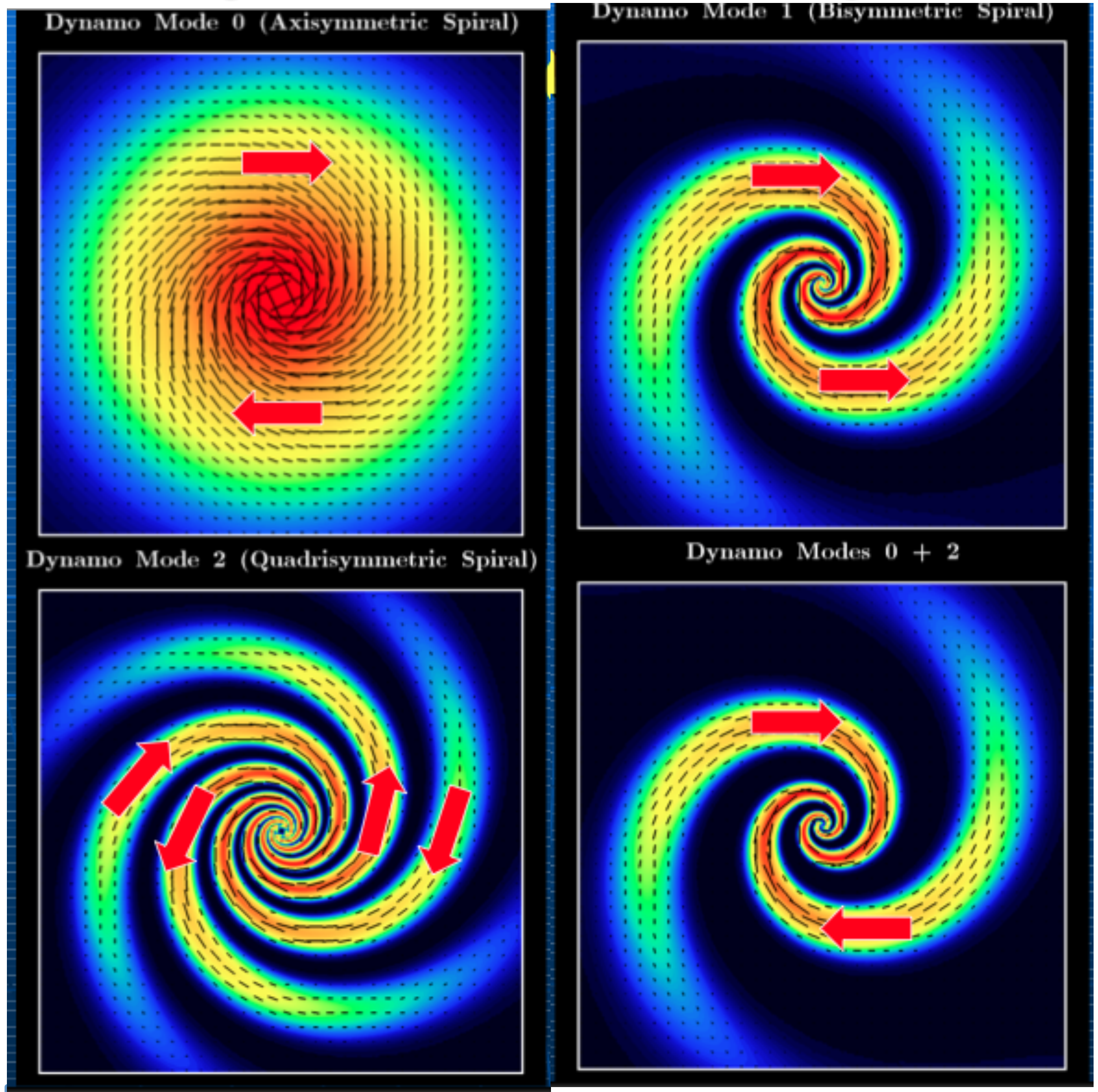
Magnetic fields in galaxies



M51 Fletcher & Beck '08

Ordered magnetic fields ~10 μG are produced via "mean field dynamo" mechanism

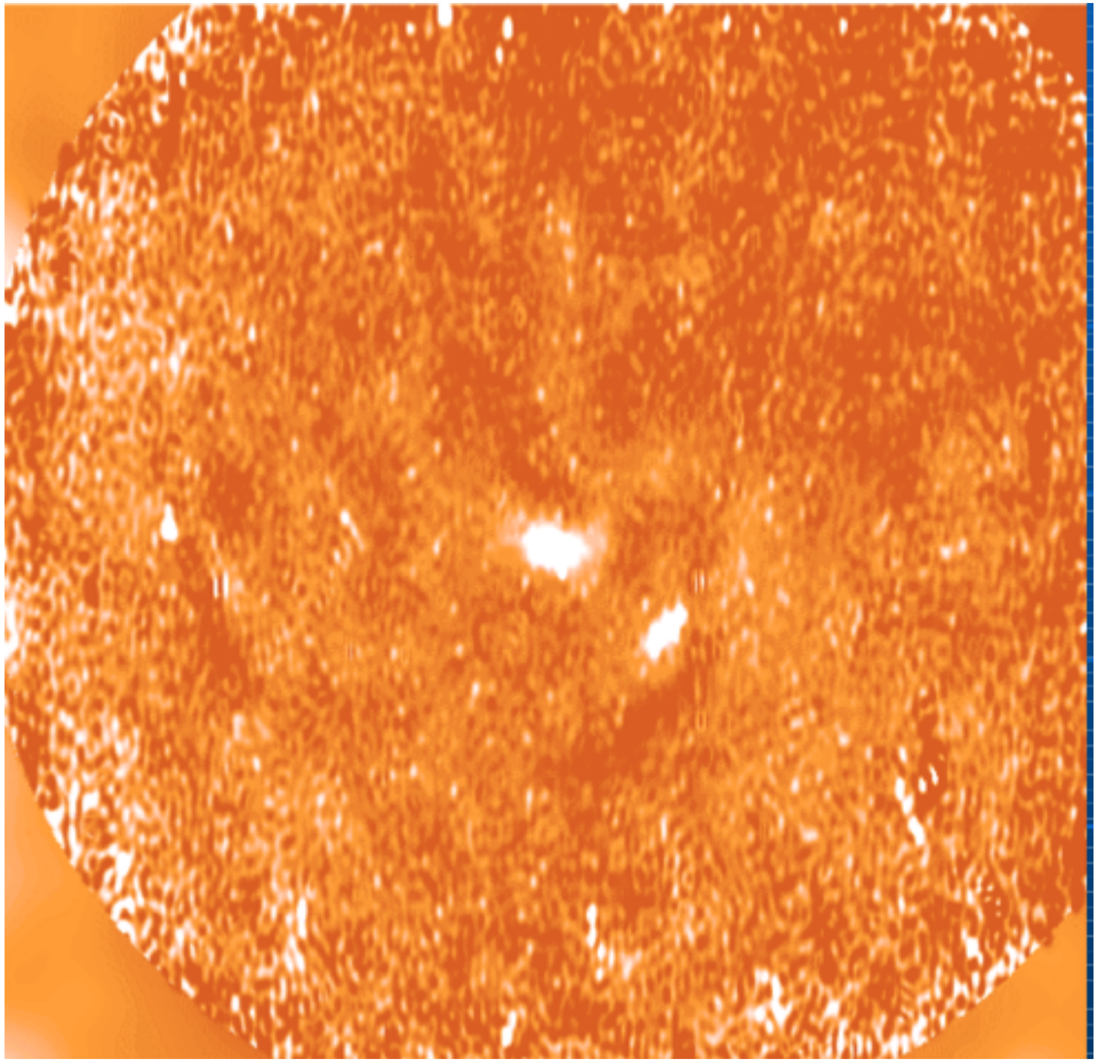
Magnetic fields in galaxies



Berkhujsen et al. '03

Ordered magnetic fields **~10 μG** are produced via "mean field dynamo" mechanism

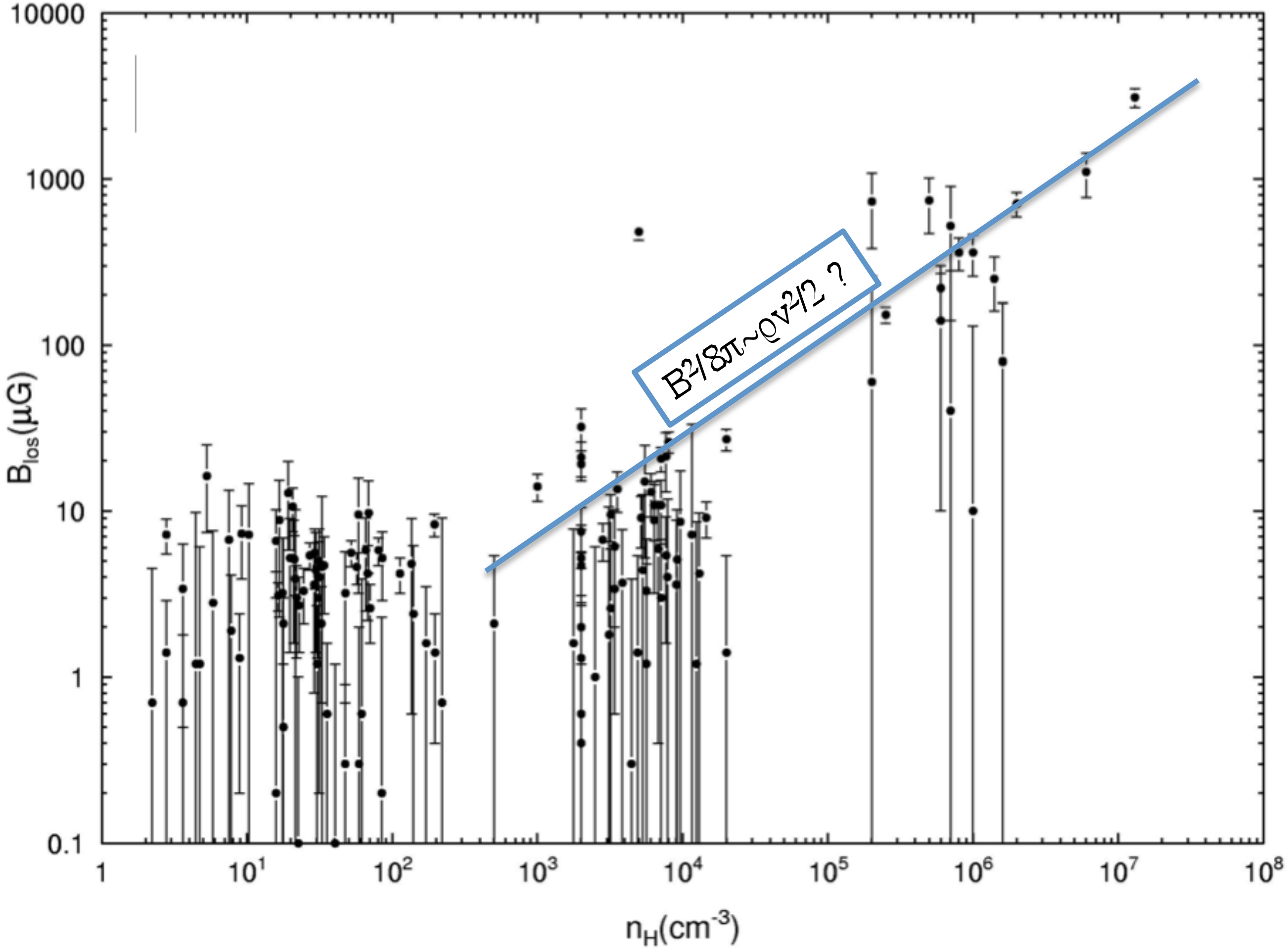
Magnetic fields in galaxy clusters



Coma cluster Kronberg et al. '07

Cluster magnetic fields **~10 μG** also have ordered component on 100 kpc scales
Different type of dynamo mechanism should be at work, efficient at much shorter time scales

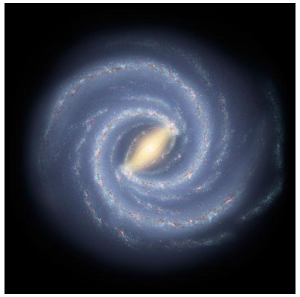
Limiting magnetic field strength

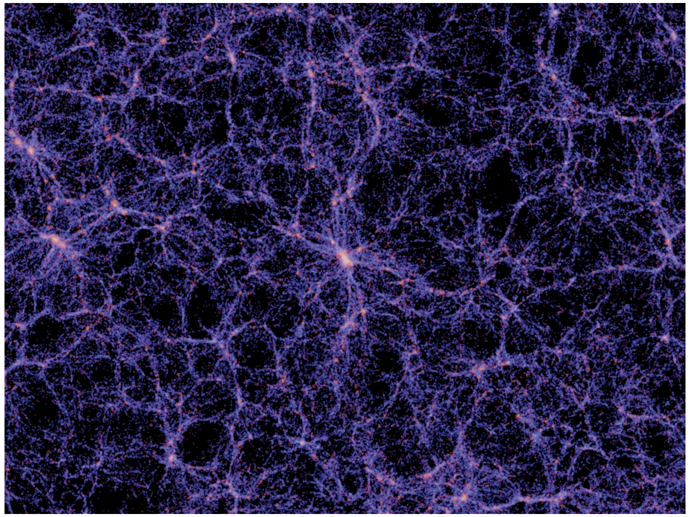


Magnetic fields measurements via Zeeman splitting effect Heiles & Crutcher

Amplification process might end at the point when magnetic field reaches equipartition with turbulent energy

Problem of the origin of magnetic fields





Is compression of pre-existing magnetic fields during LSS formation sufficient to generate the observed cluster magnetic fields?

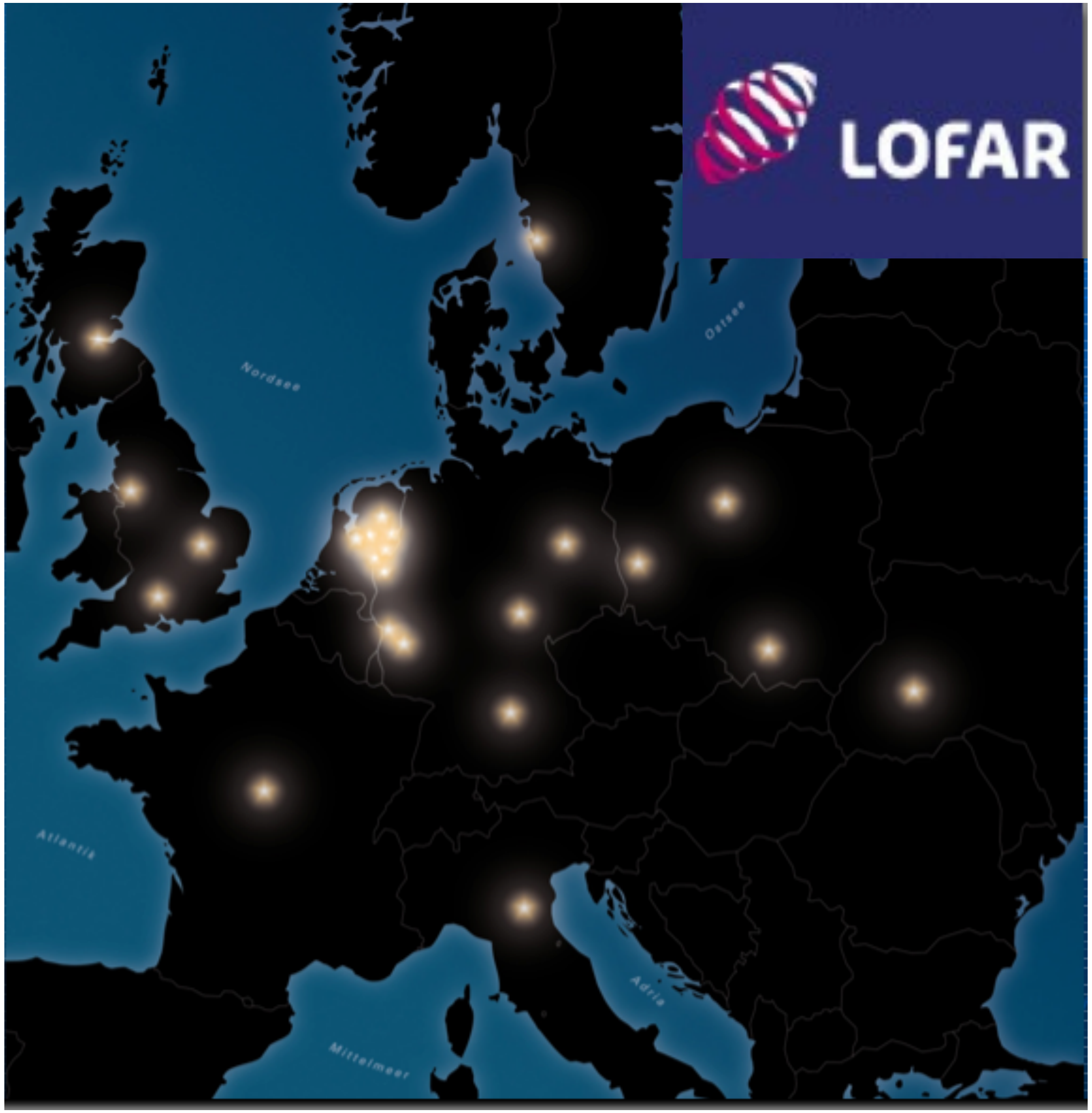
Are the fields in galaxies are produced via dynamo mechanism, in a way different from the cluster magnetic fields?

What is the efficiency of different field amplification mechanisms? Are there saturation effects?

What is the initial strength of the field at the beginning of amplification process?

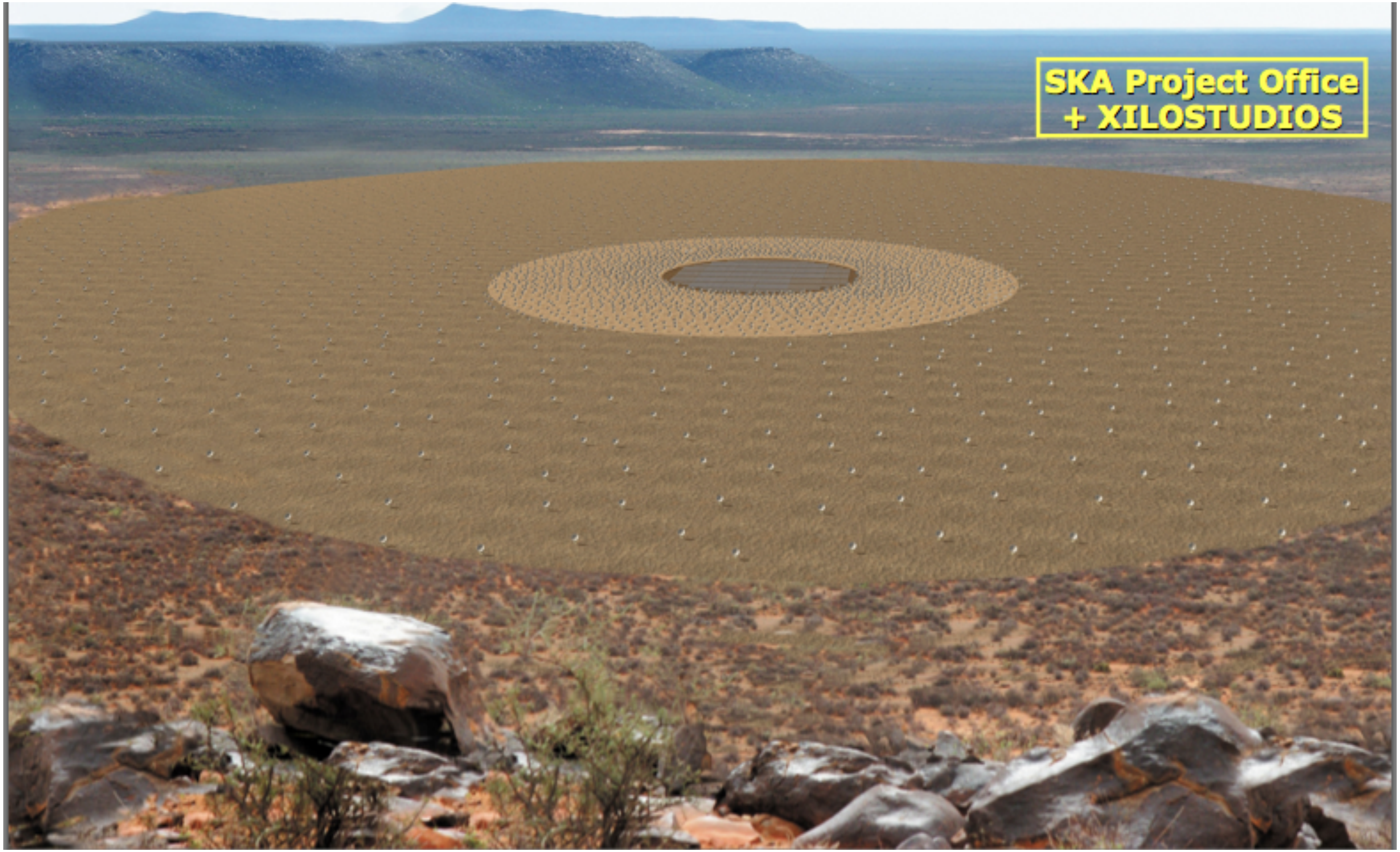
Where do the seed fields for amplification come from?

Problem of the origin of magnetic fields



Problem of the origin of magnetic fields is one of the key science topics of all next-generation radio telescopes (**LOFAR**)

Problem of the origin of magnetic fields



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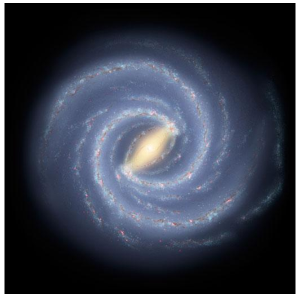
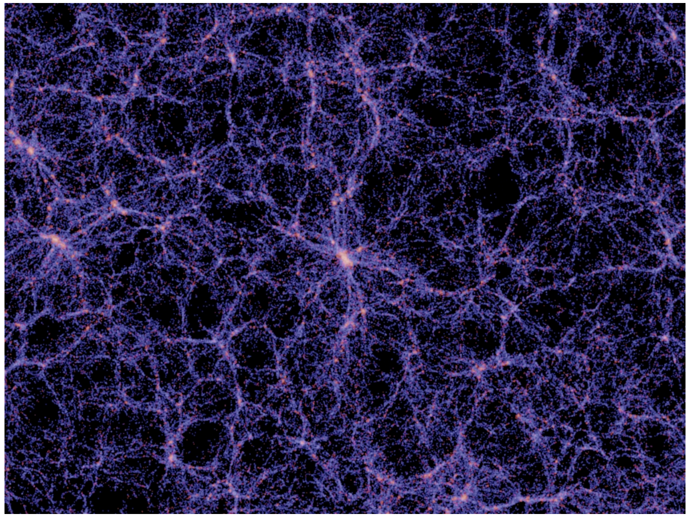
Problem of the origin of magnetic fields
&
high-energy gamma-ray astronomy ?

Problem of the origin of magnetic fields





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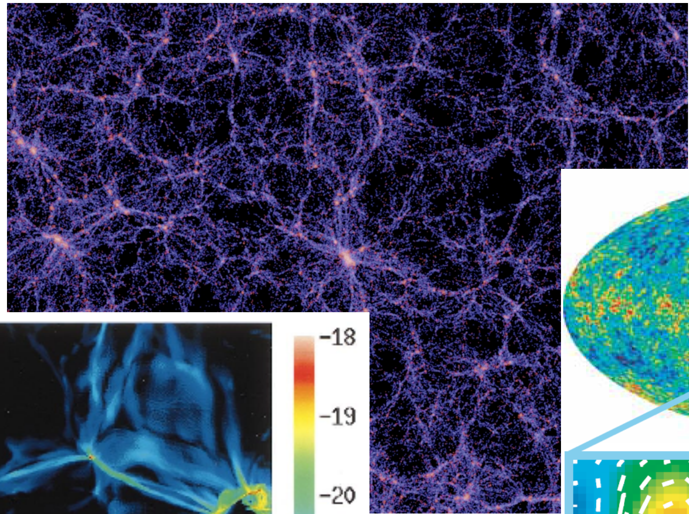
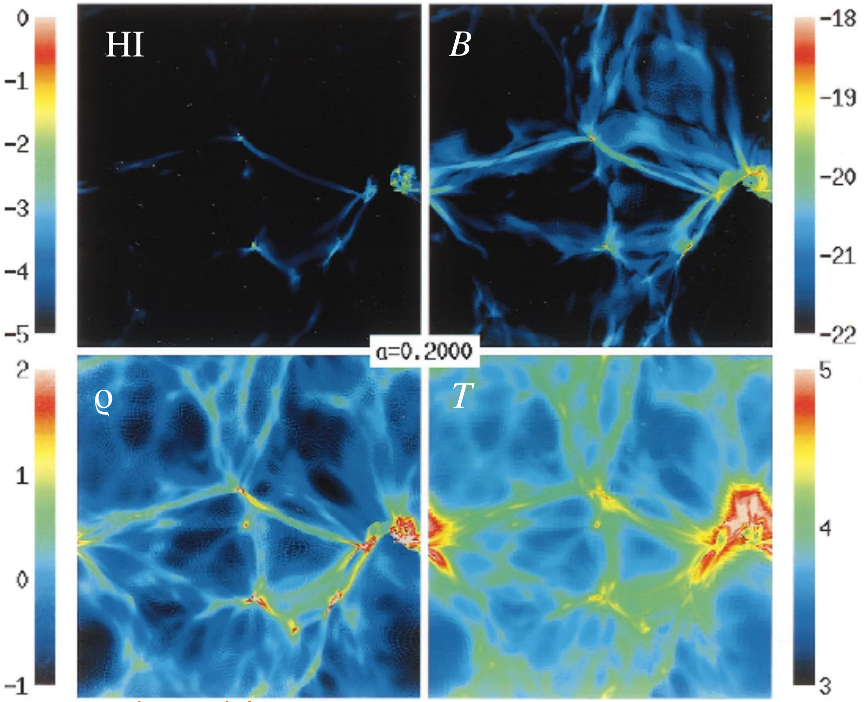
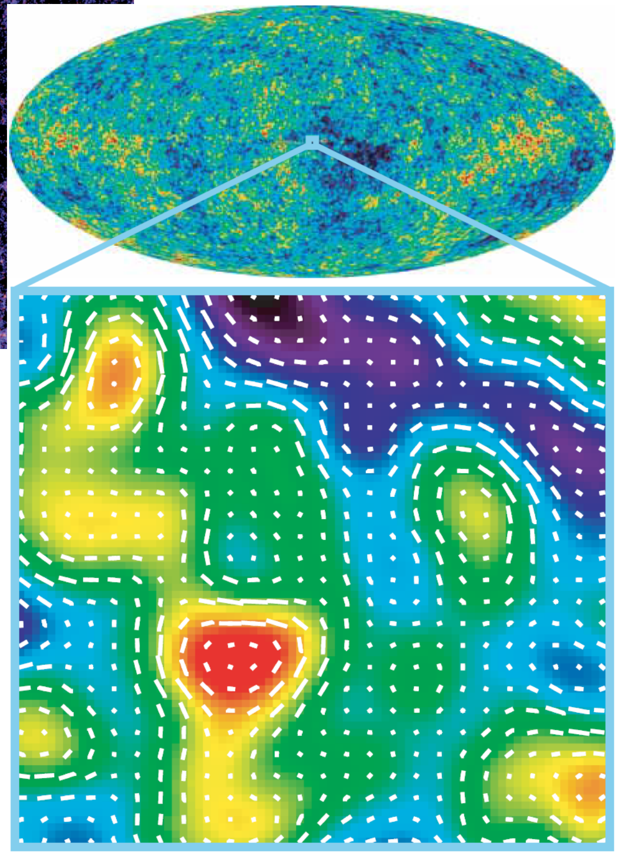
Origin of the large-scale seed fields





Gnedin et al. '00



Takahashi et al. '06

"**Astrophysical**" scenaria: seed magnetic fields are generated via "Bierman battery" mechanism during structure formation

"**Cosmological**" scenaria assume that the same type of mechanism is working at the moments of phase transitions in the Early Universe

Measurement of the large-scale fields?

Weak magnetic fields in the intergalactic medium (IGM) are difficult to measure (not enough matter to trace the fields…)

Magnetic field in the IGM is not stronger than the field in galaxies

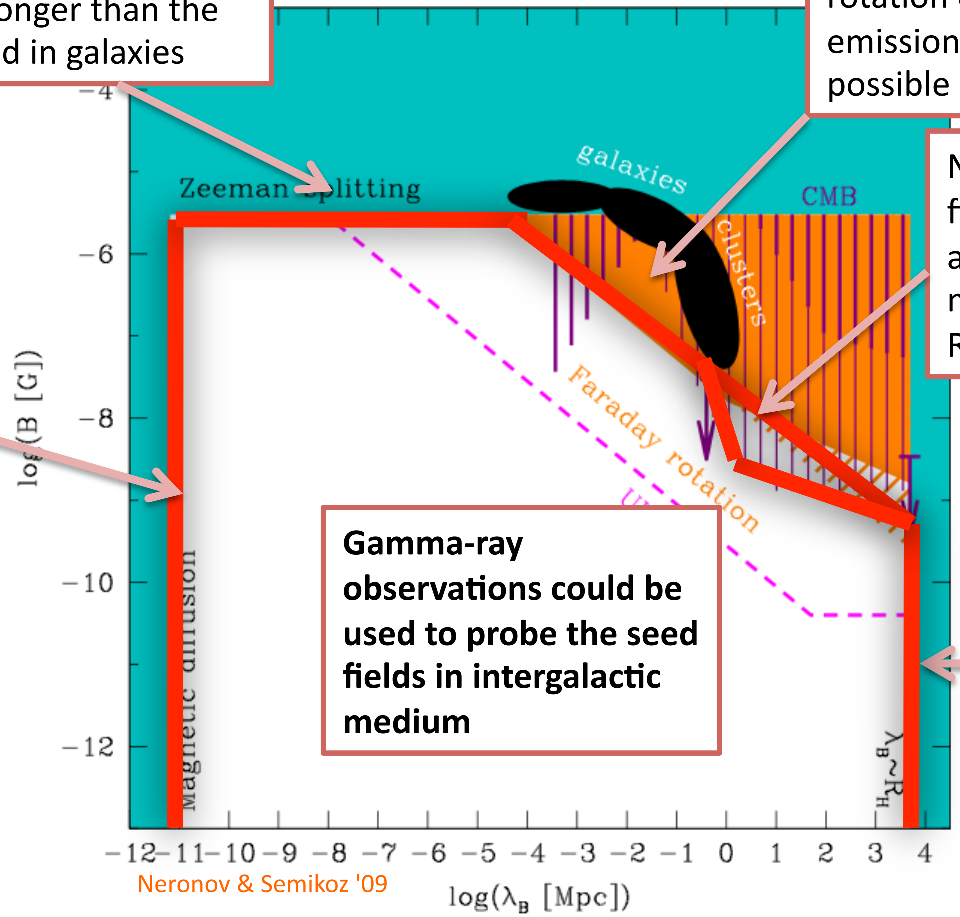
Non-observation of Faraday rotation of polarized radio emission from quasars limits possible magnetic fields in IGM

Non-observation of magnetic field induced features in the anisotropy of CMB limits magnetic fields produced before Recombinaiton

Resistive decay removes short-correlation length fields in T<10 Gyr

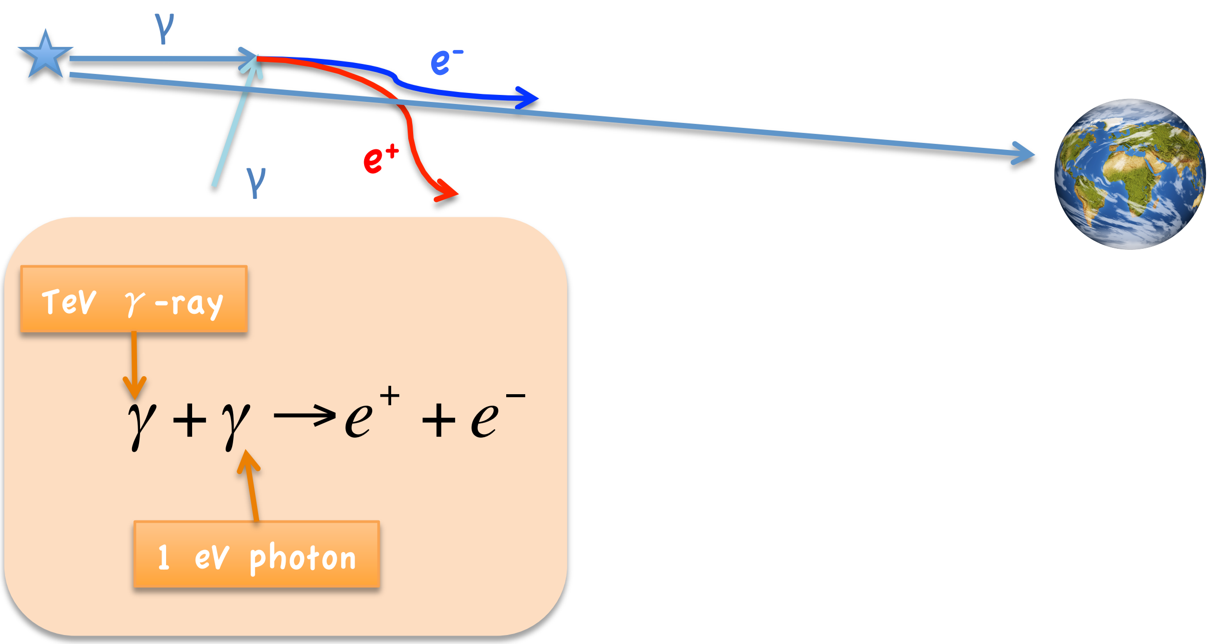
Gamma-ray observations could be used to probe the seed fields in intergalactic medium

Magnetic field homogeneity scale can, in principle, be comparable to the size of the Universe



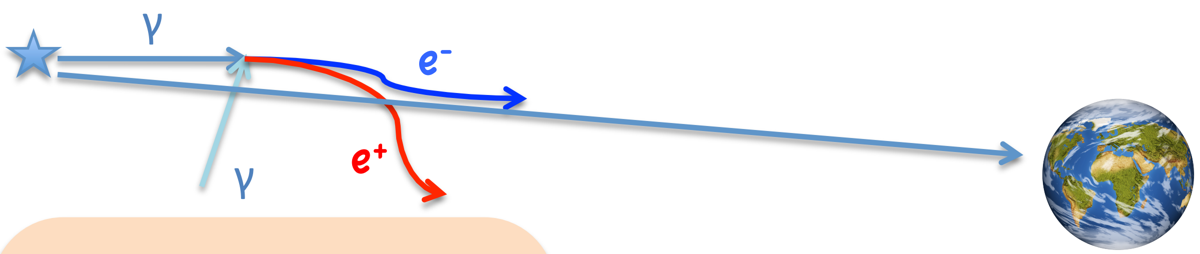
Neronov & Semikoz '09

Attenuation of γ-rays via pair production on EBL



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

Attenuation of γ-rays via pair production on EBL

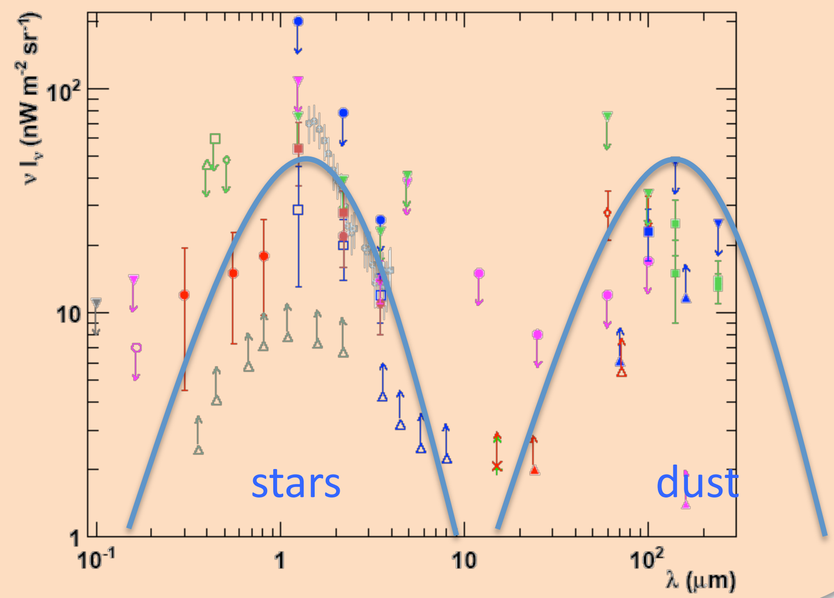


TeV γ-ray

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

1 eV photon

Target photons are from **Extragalactic Background Light (EBL)**: starlight + scattering by dust from all galaxies



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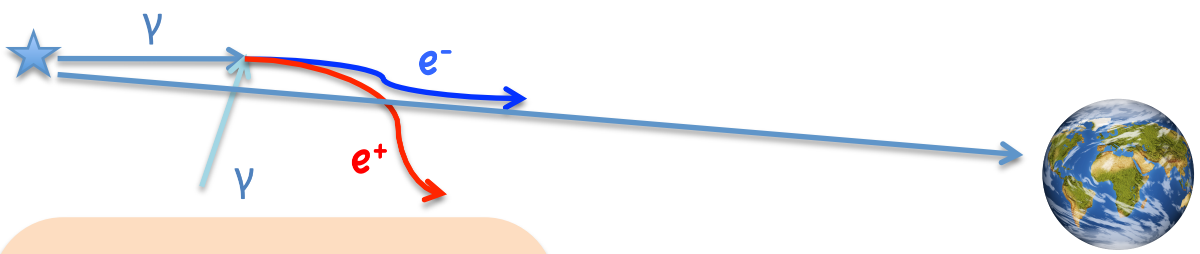

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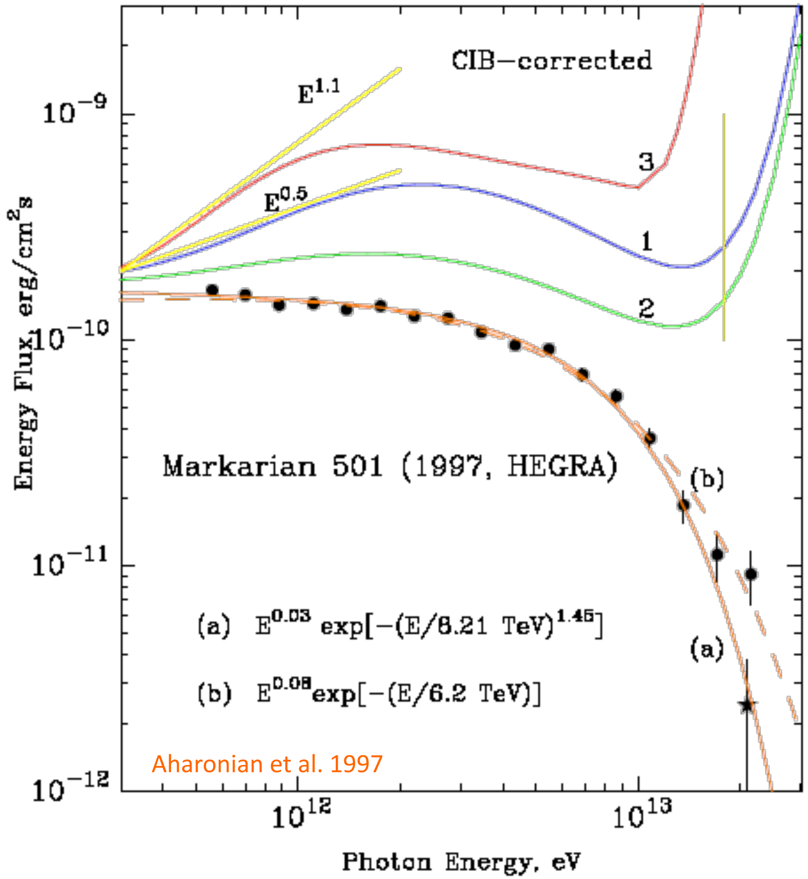

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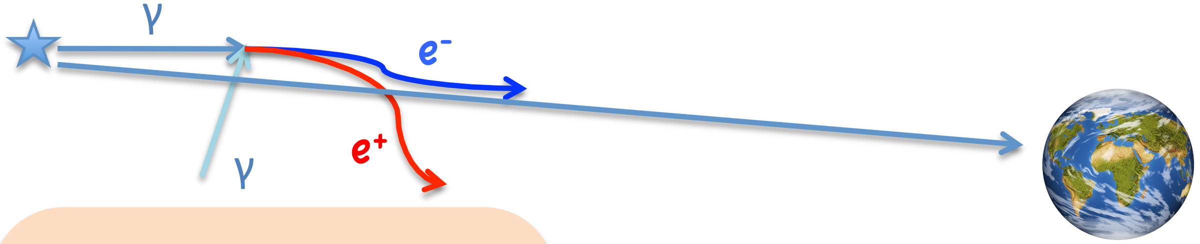

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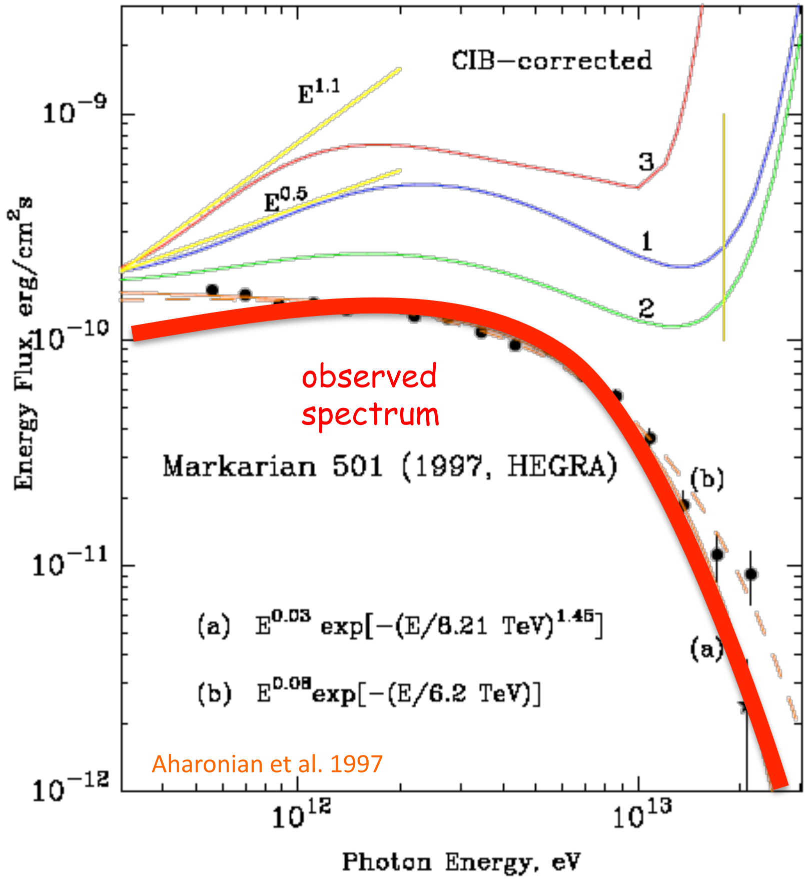

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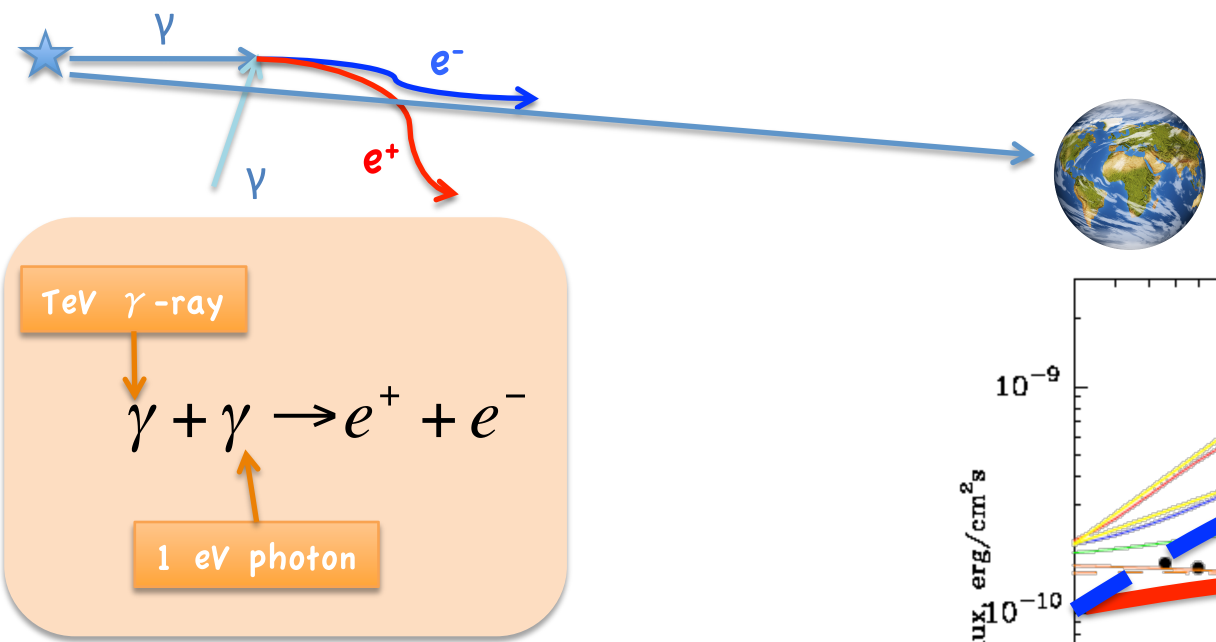
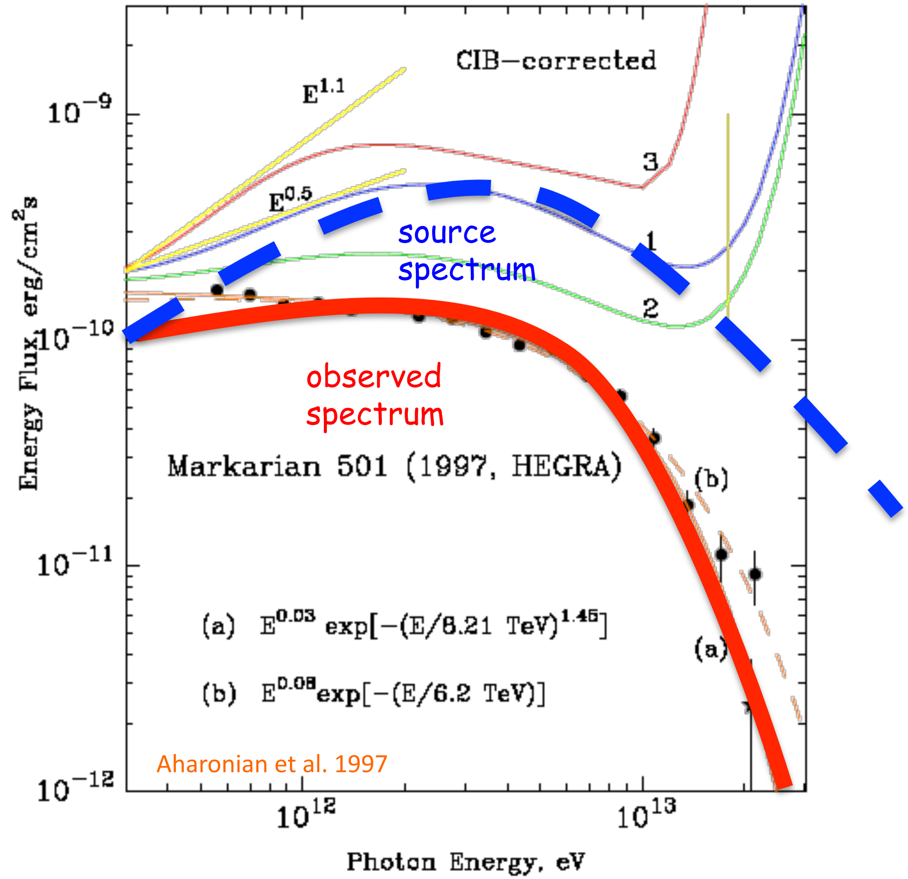
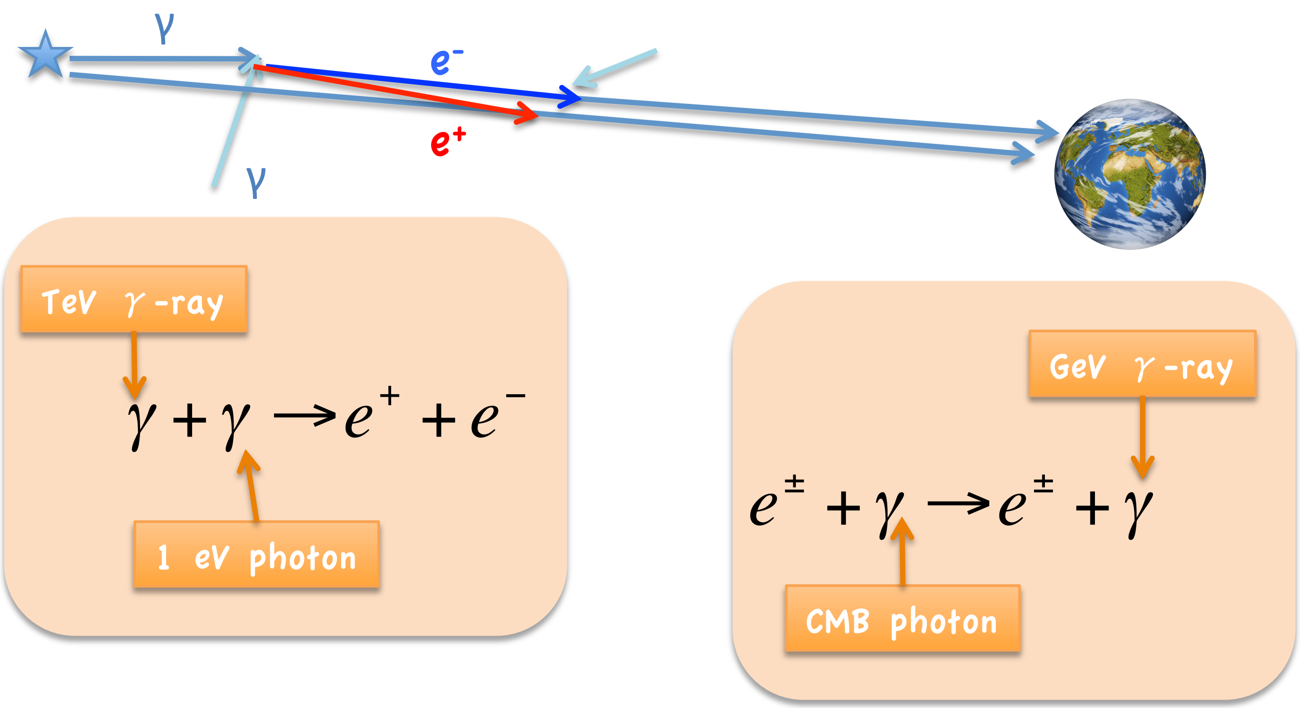
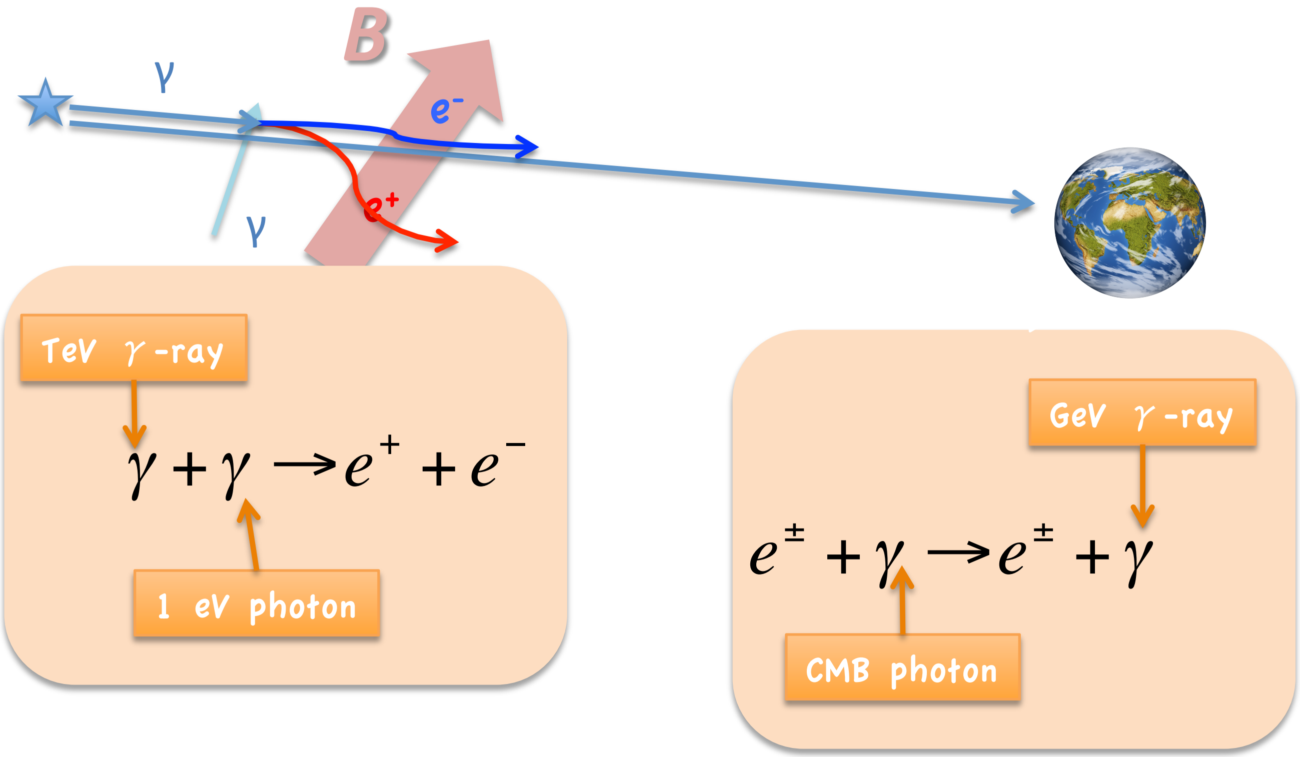




Electromagnetic cascade in intergalactic medium

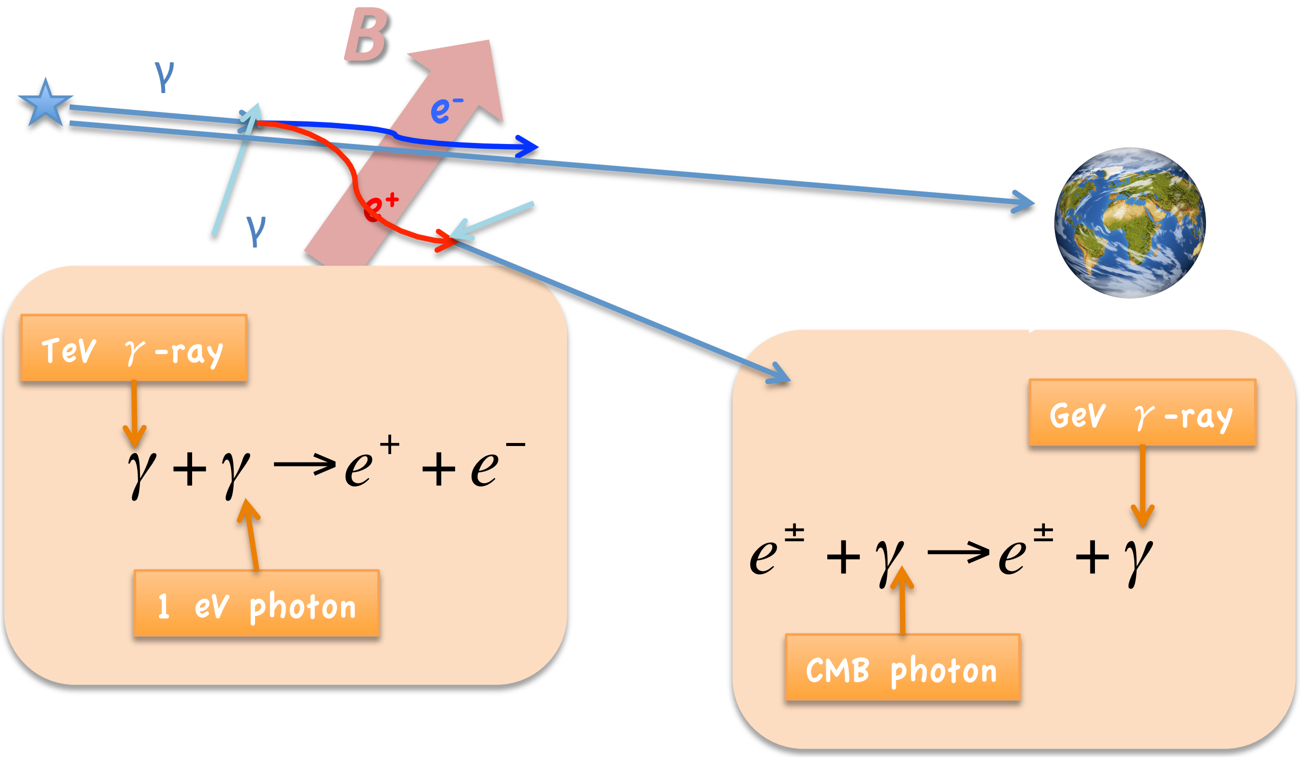


γ-rays from cascade on EBL



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

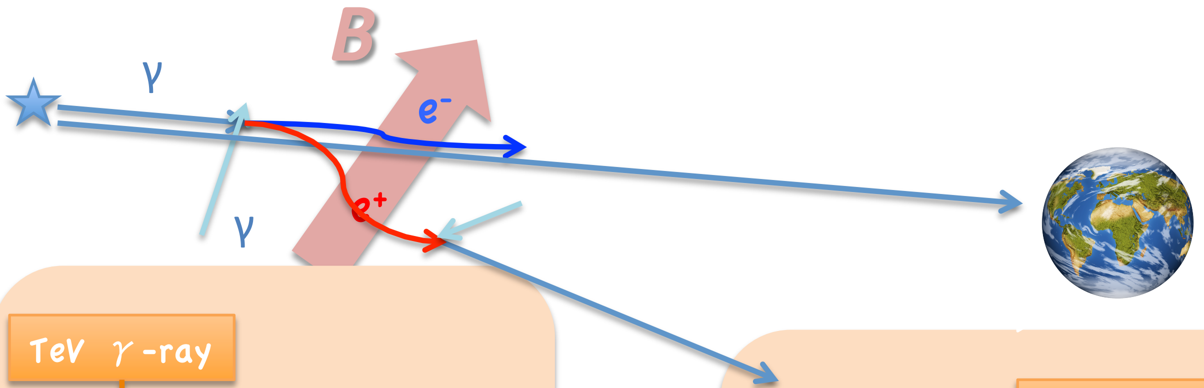
γ-rays from cascade on EBL



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.

γ-rays from cascade on EBL



TeV γ-ray

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

1 eV photon

GeV γ-ray

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

CMB photon

Electron Larmor radius

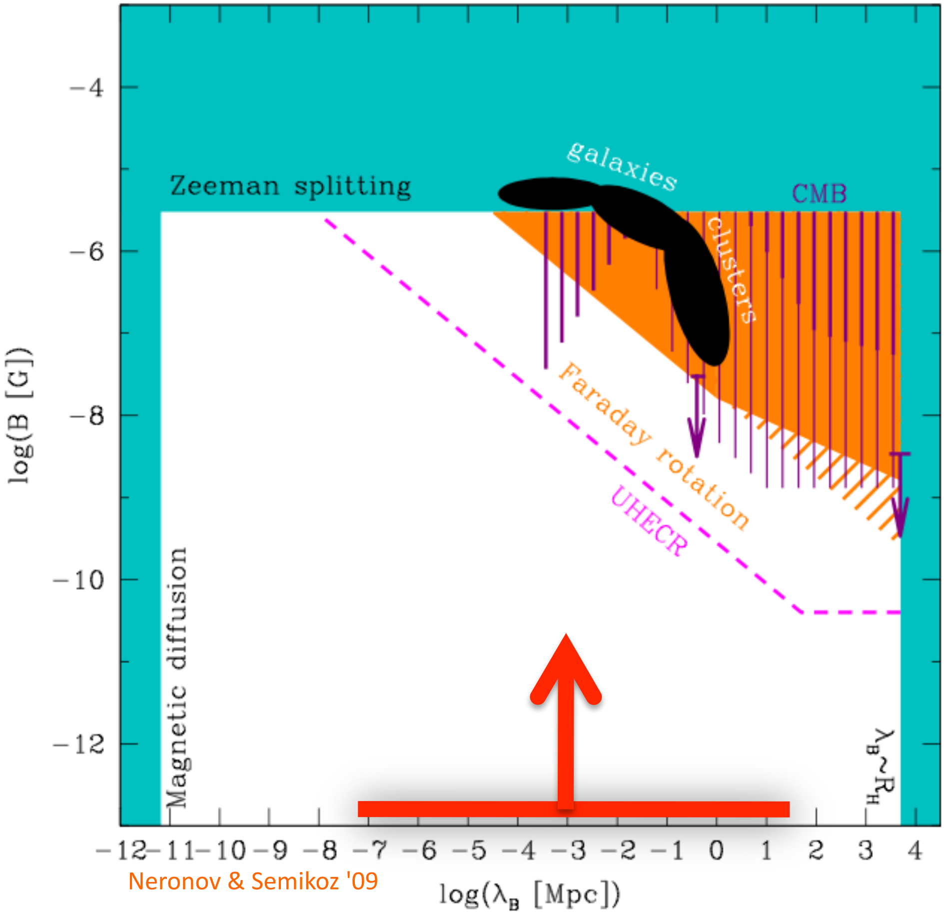
$$R_L = \frac{E_e}{eB} \approx 3\times 10^{28}\left[\frac{B}{10^{-18}\mathrm{G}}\right]\left[\frac{E_e}{10\ \mathrm{TeV}}\right]\ \mathrm{cm}$$

Electron cooling distance

$$D_e = \frac{3m_e^2}{4\sigma_T U_{CMB} E_e} \approx 10^{23}\left[\frac{E_e}{10\ \mathrm{TeV}}\right]^{-1}\ \mathrm{cm}$$

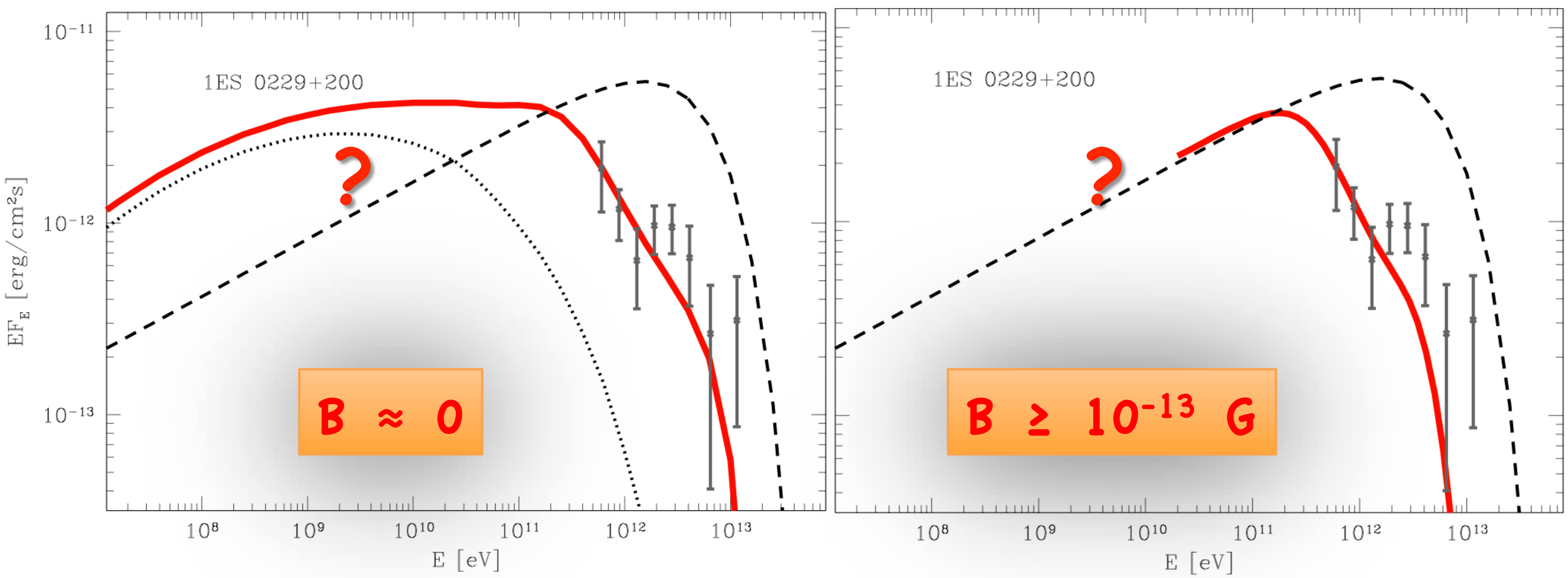
$B \geq 10^{-13}$ G ?

γ-rays from cascade on EBL



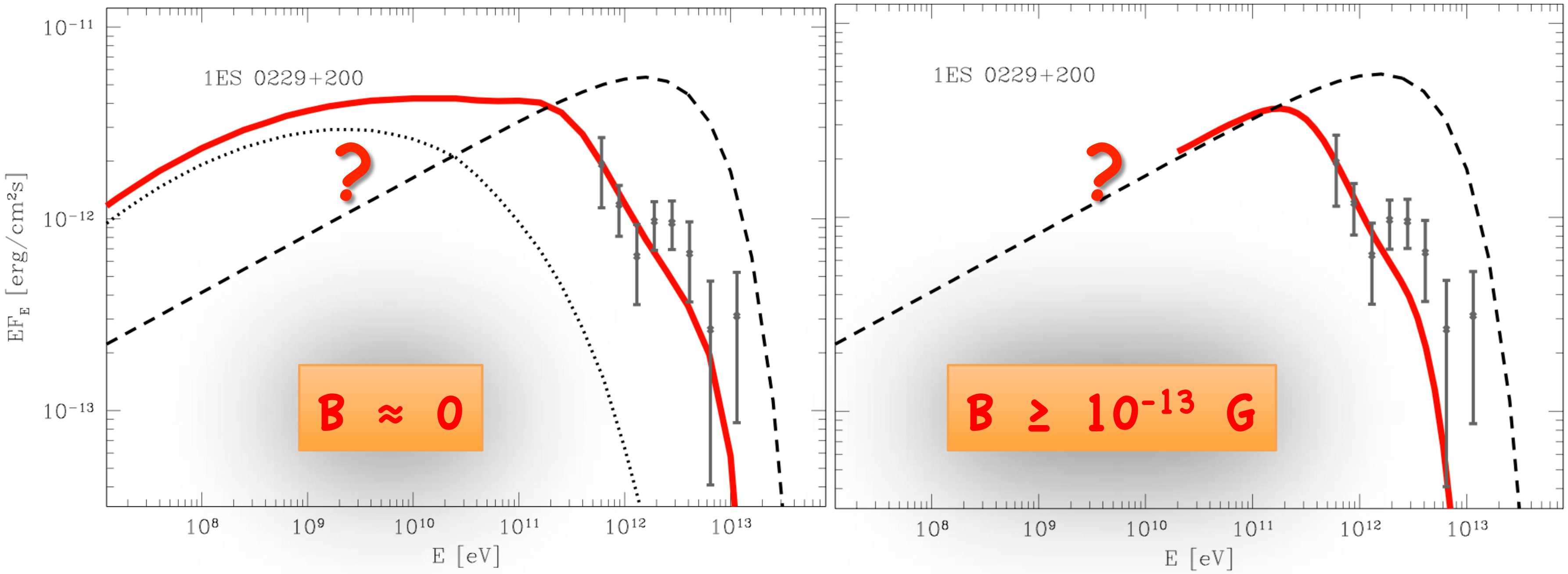
Neronov & Semikoz '09

EGMF-related uncertainty of the observed spectra of blazars



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

Cascade component of γ-ray spectra of blazars

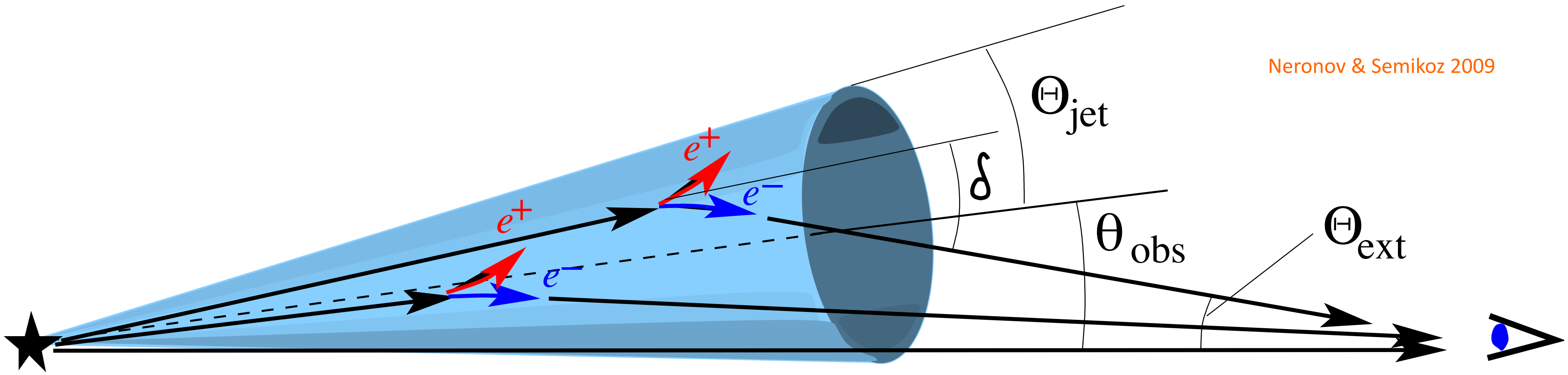


Cascade emission component in the spectra of blazars could be identified and separated from the intrinsic source emission via characteristic

- **imaging** and/or
- **spectral** and/or
- **timing**

properties.

Properties of the cascade component of γ-ray spectra



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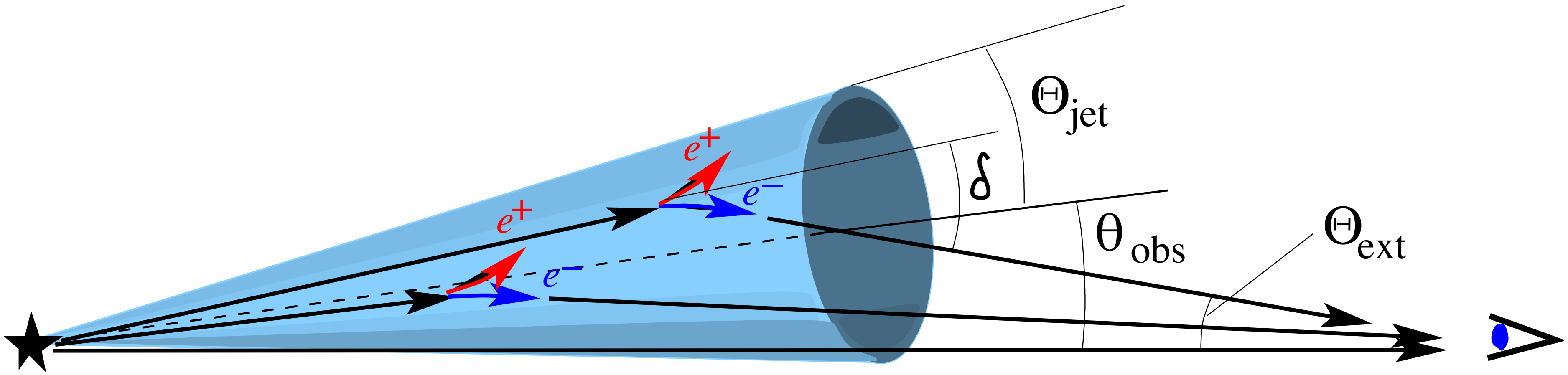
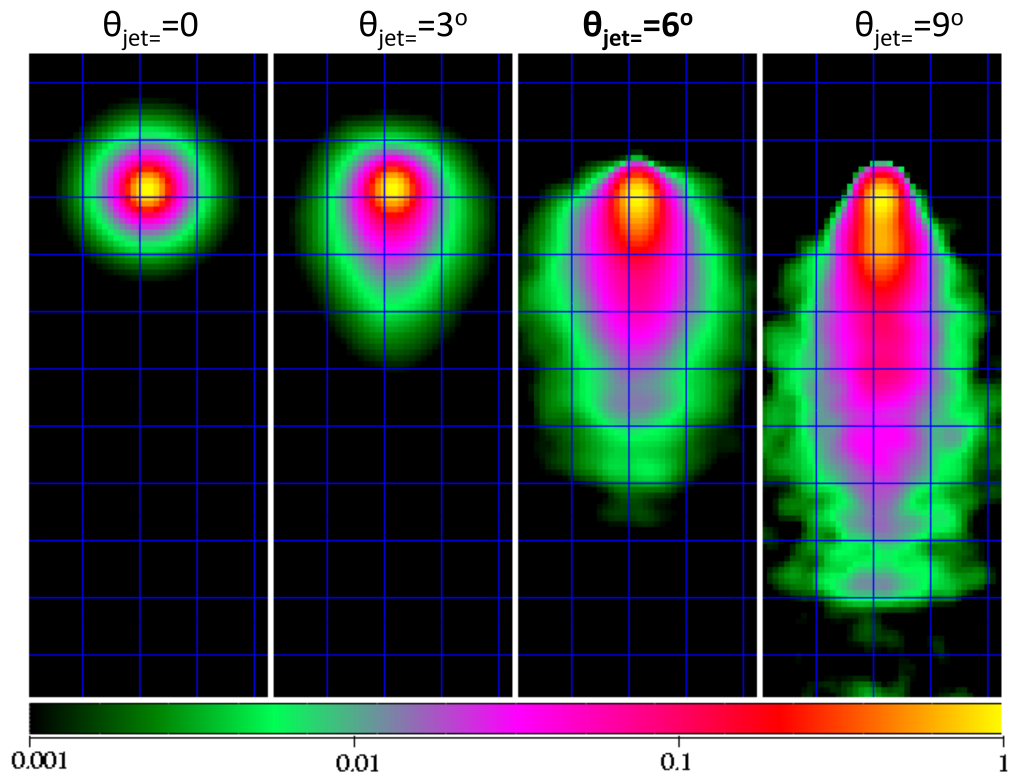


Imaging: cascade component forms an extended emission around initially point source.

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



Neronov et al. 2010

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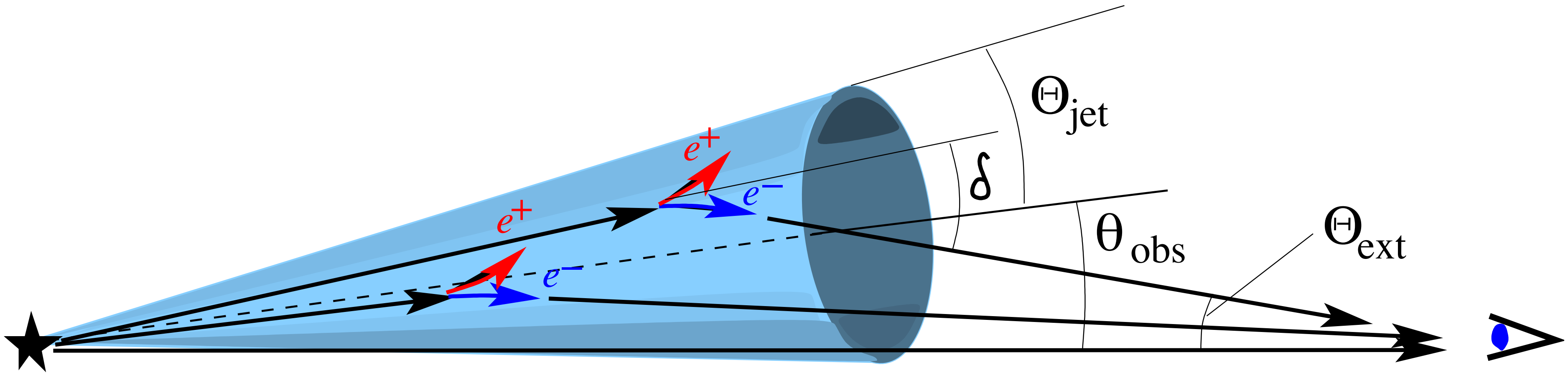

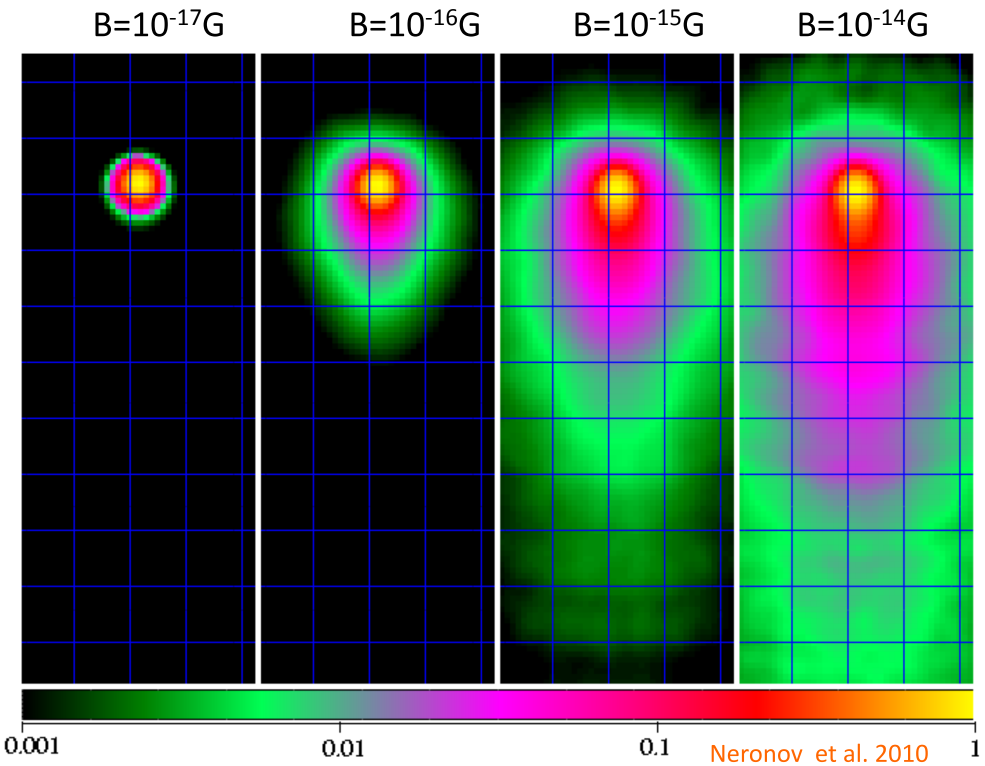

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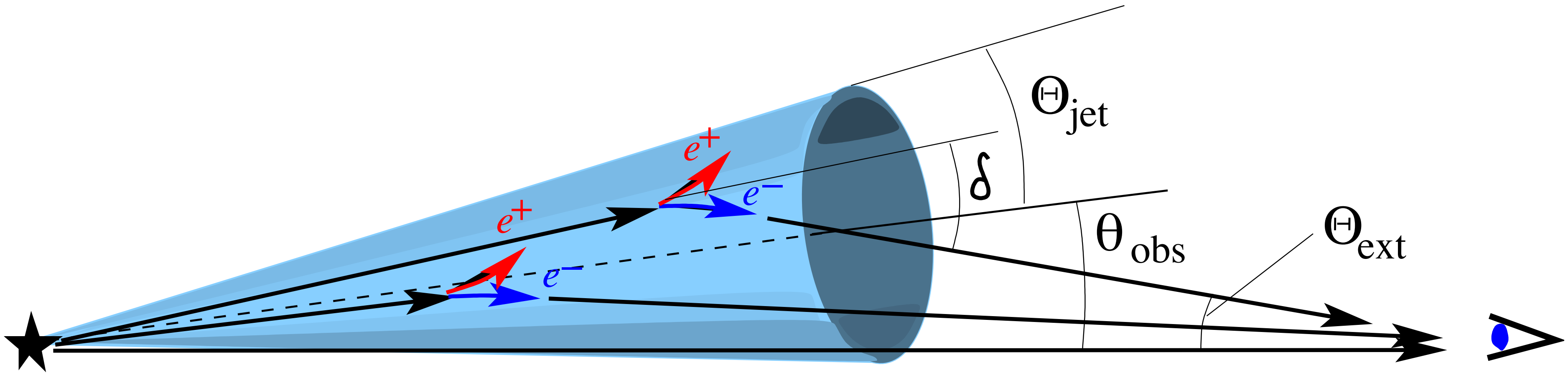
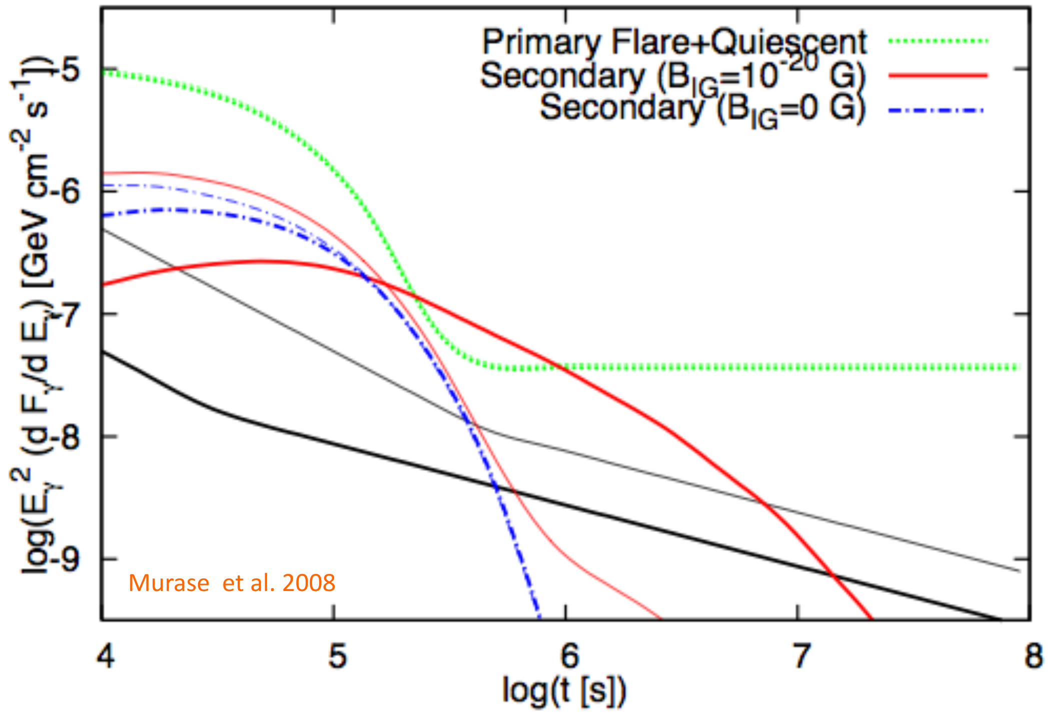


Timing: cascade component emission is delayed, compared to the direct signal from the point source

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



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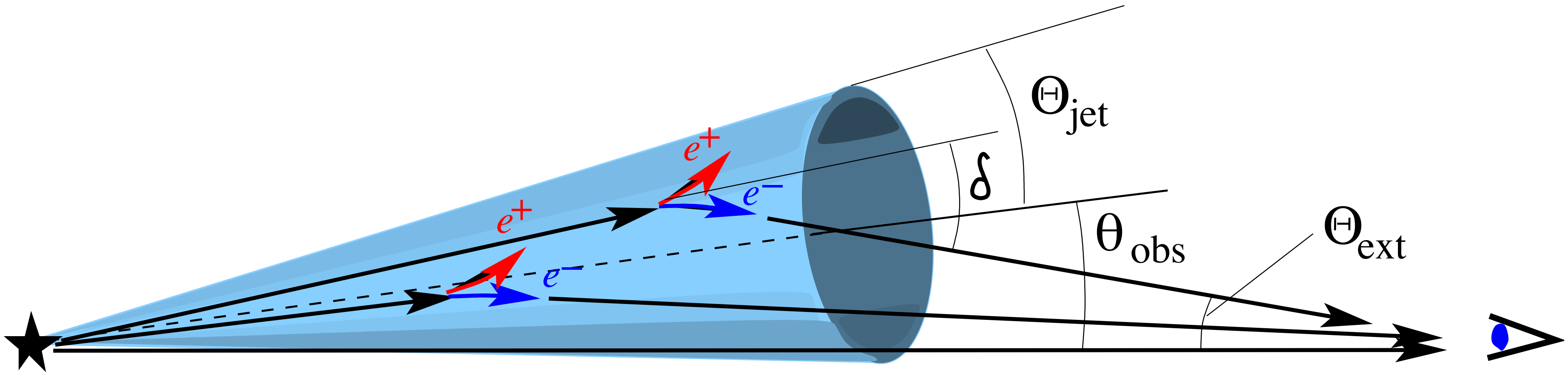

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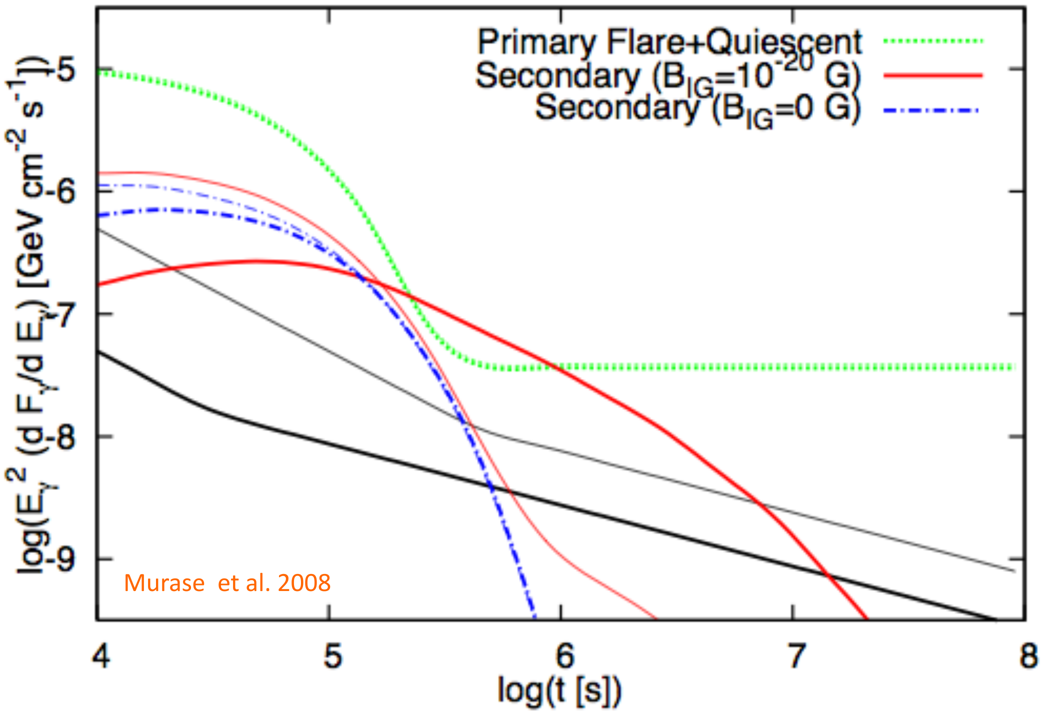

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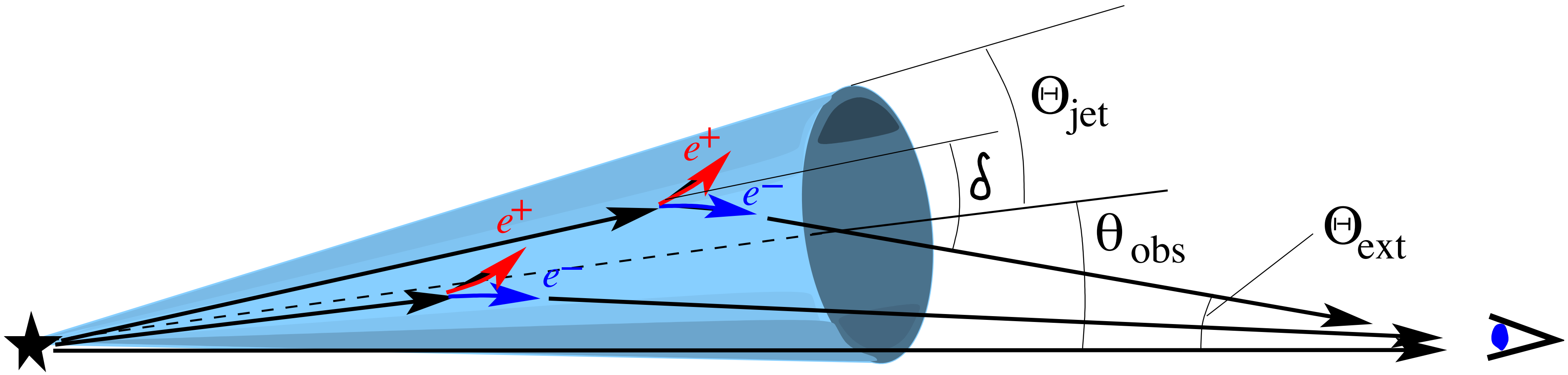

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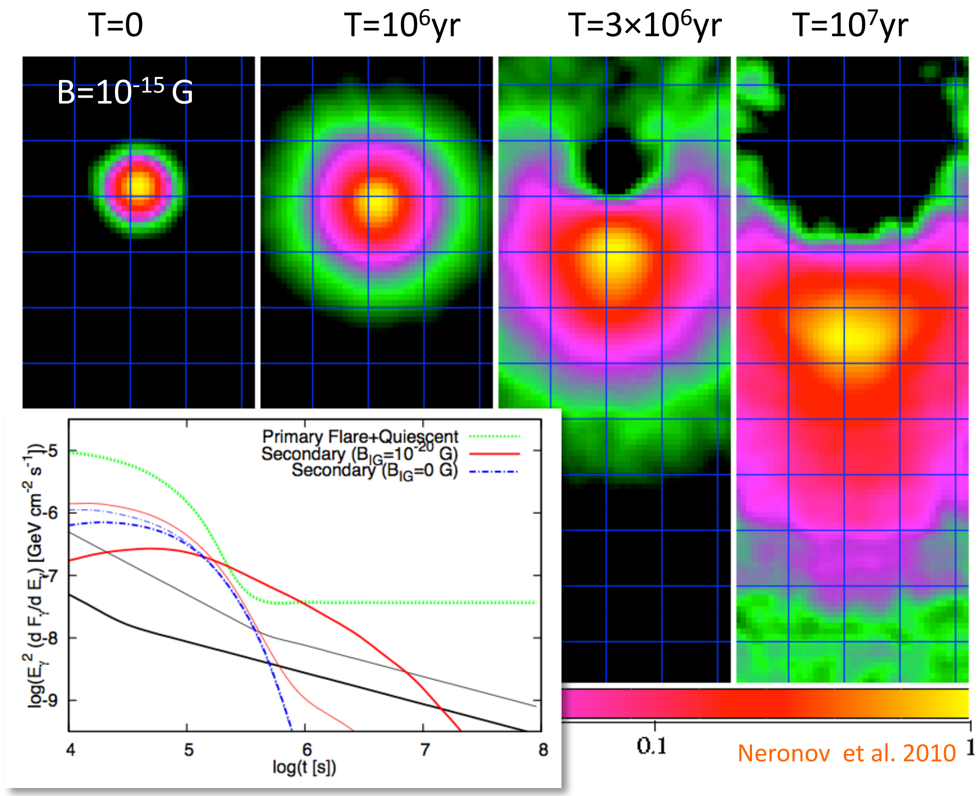
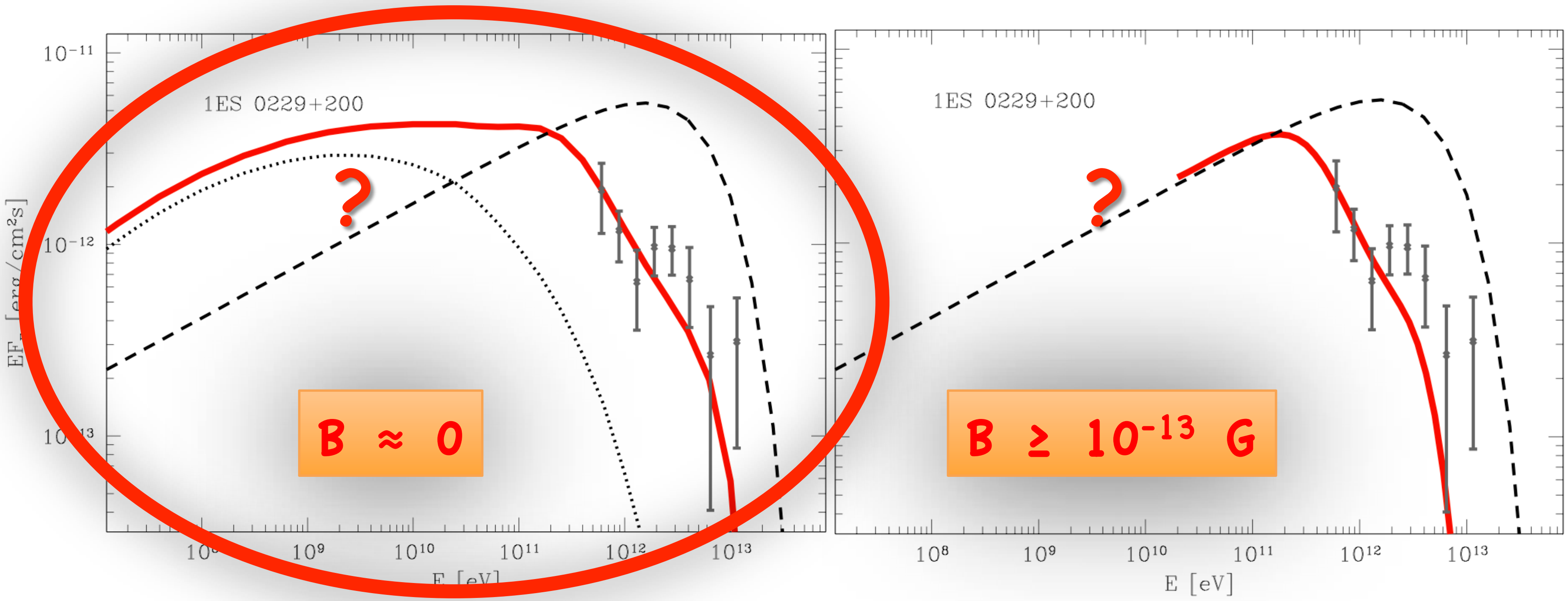


Could EGMF be B≈0?



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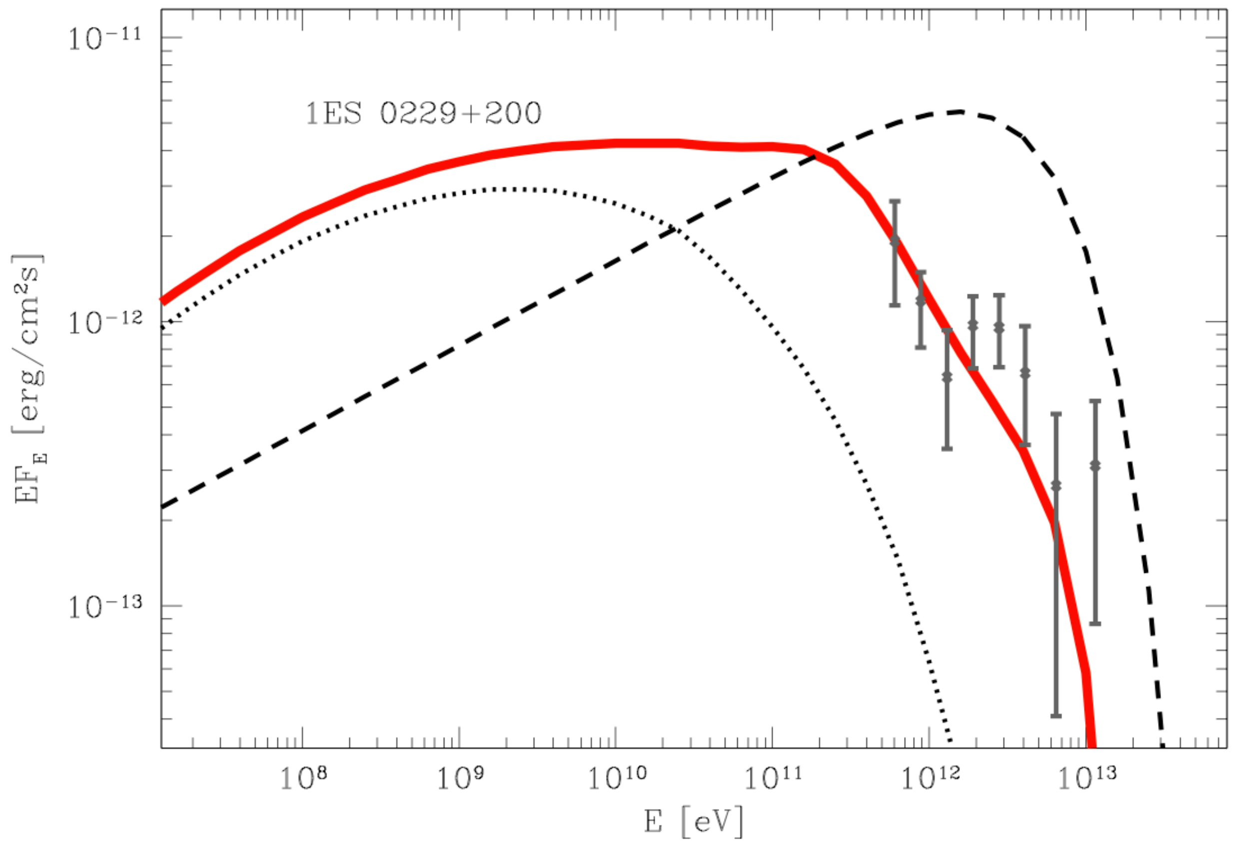

If EGMF is negligible, cascade emission component should be commonly present in the spectra of TeV γ-ray loud blazars.

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

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

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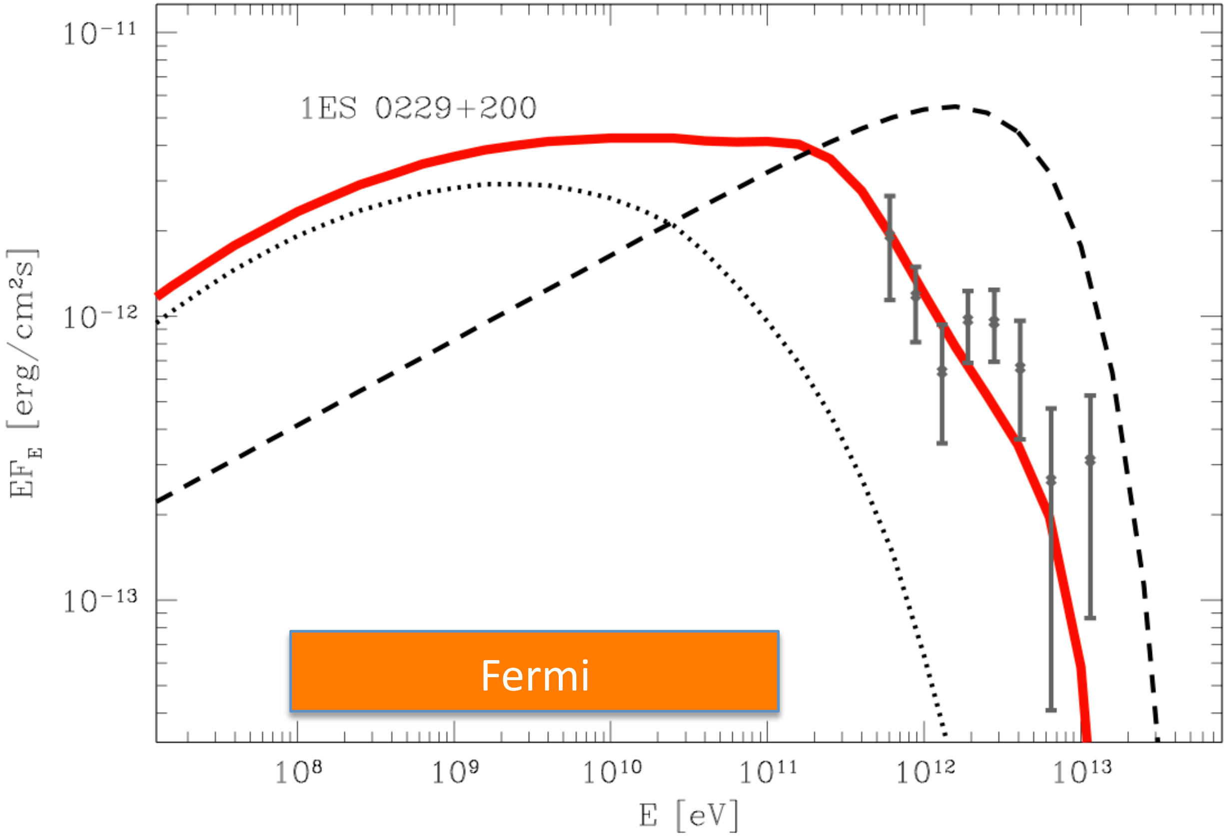

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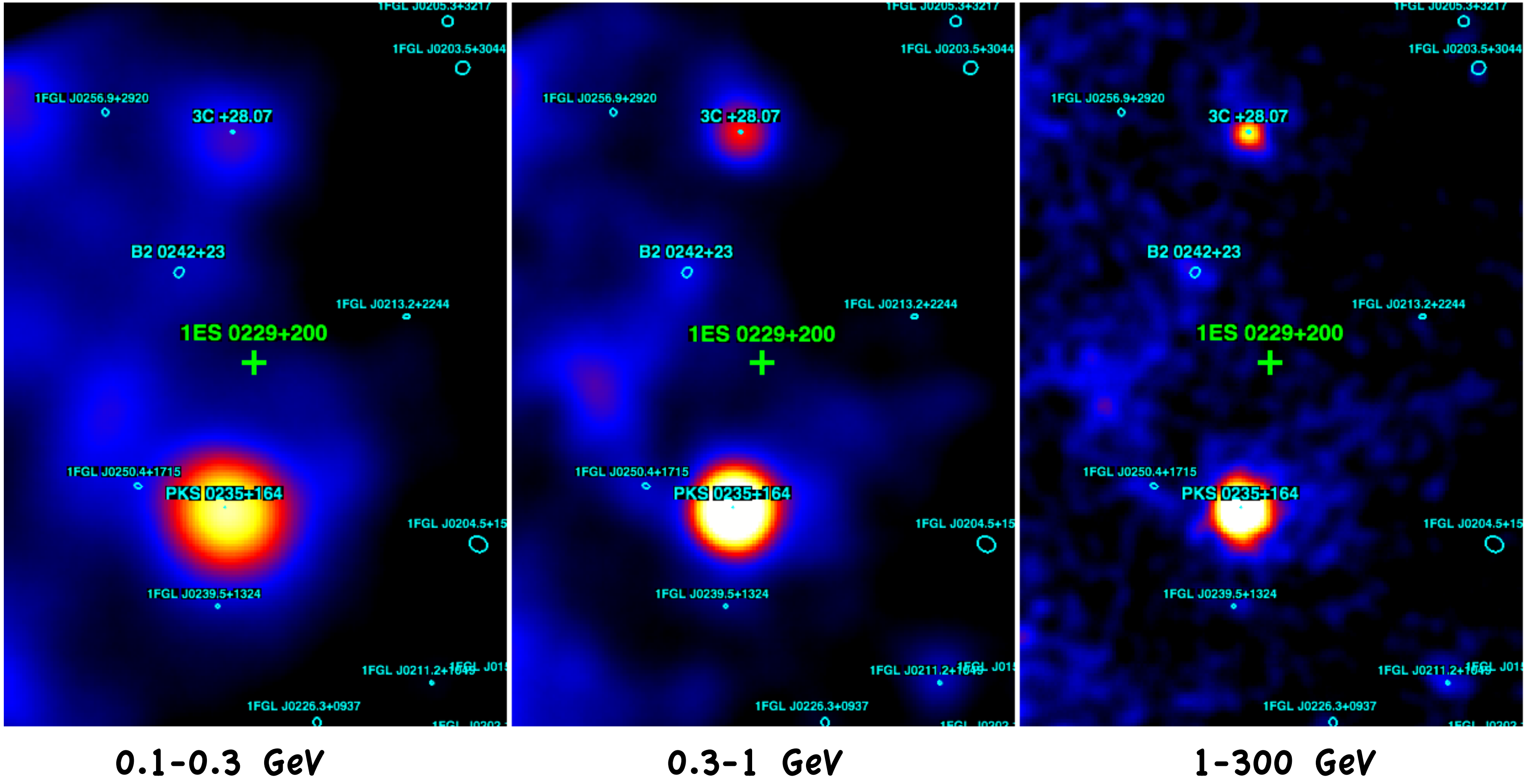

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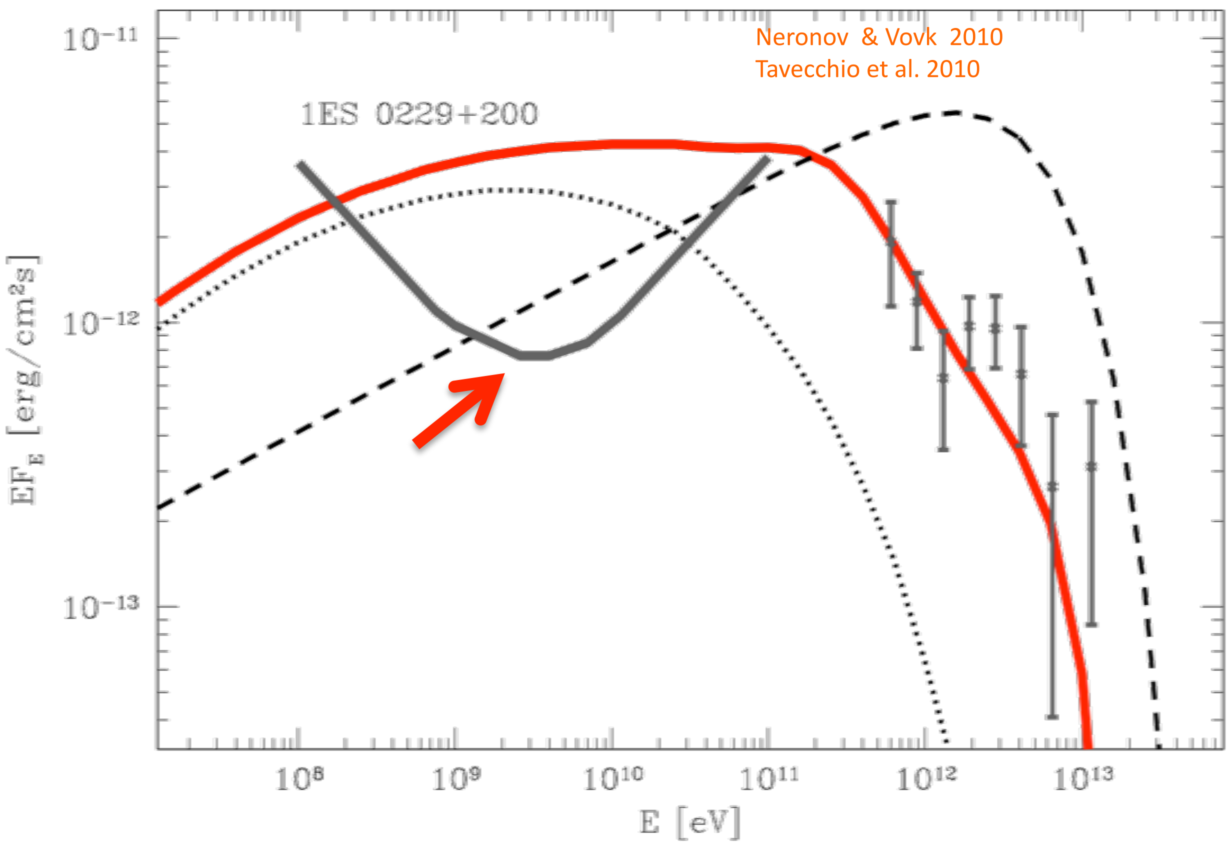

Fermi upper limits on the steady state flux from **high-redshift / hard intrinsic spectra blazars** are below the expected level of the cascade emission

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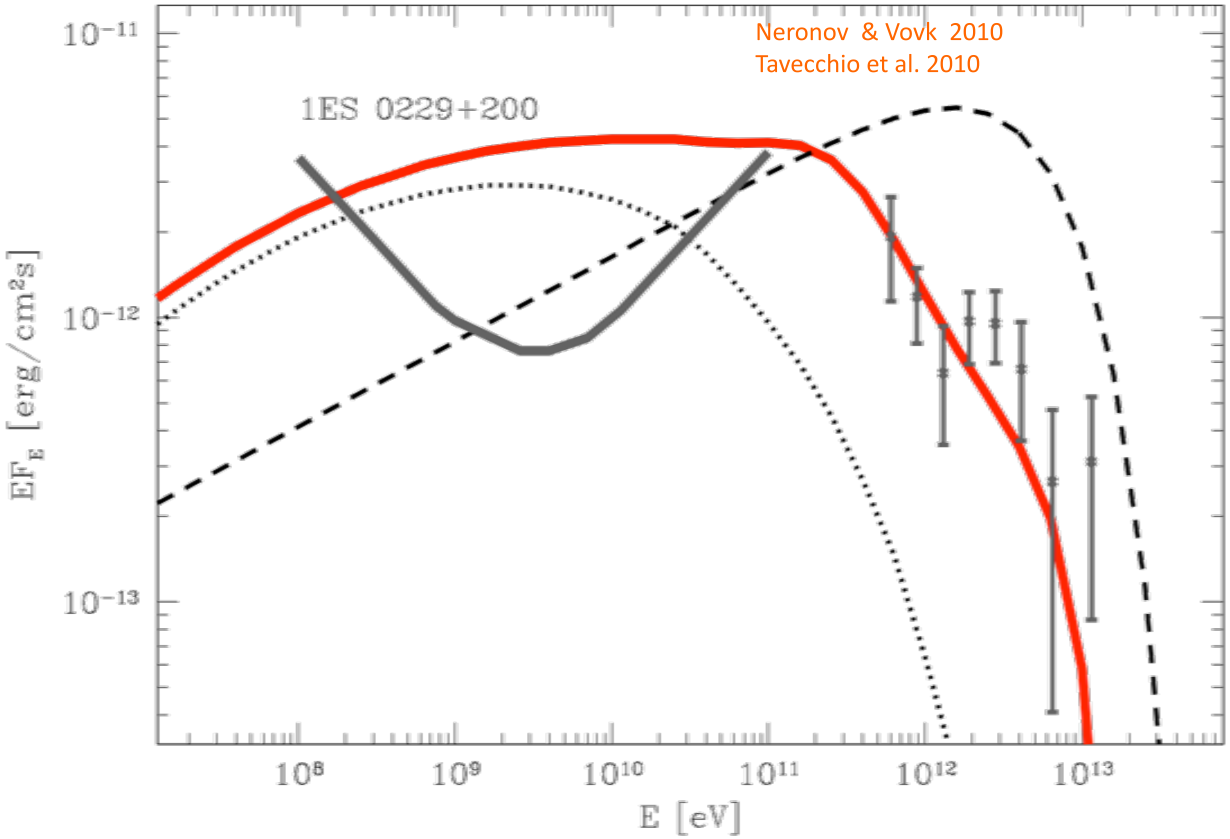

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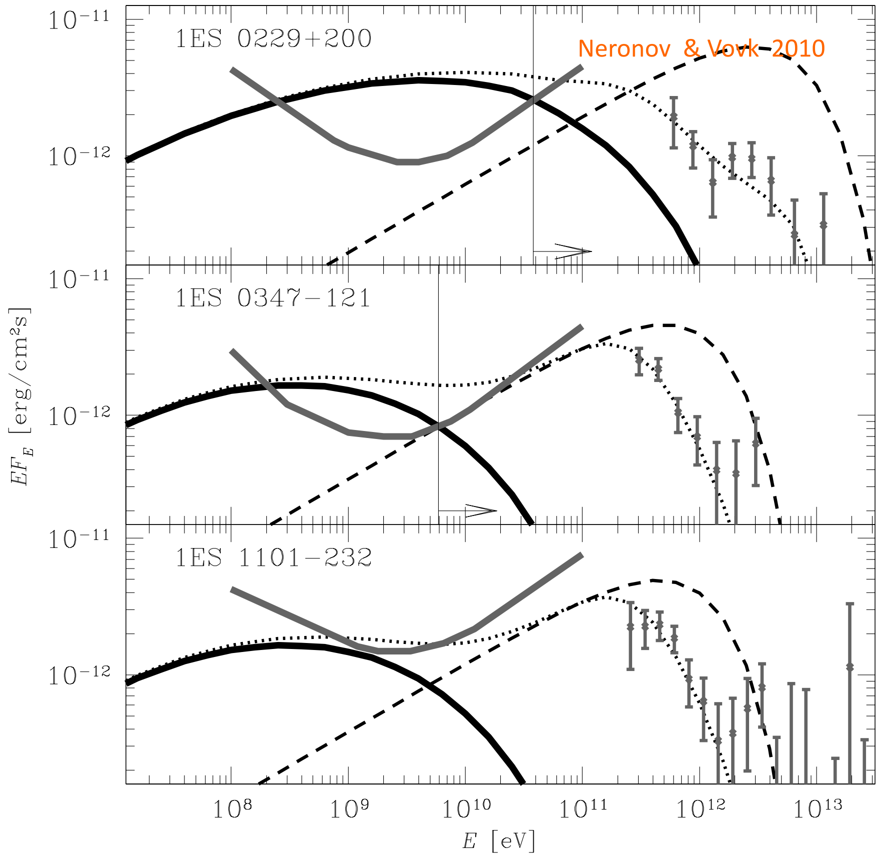

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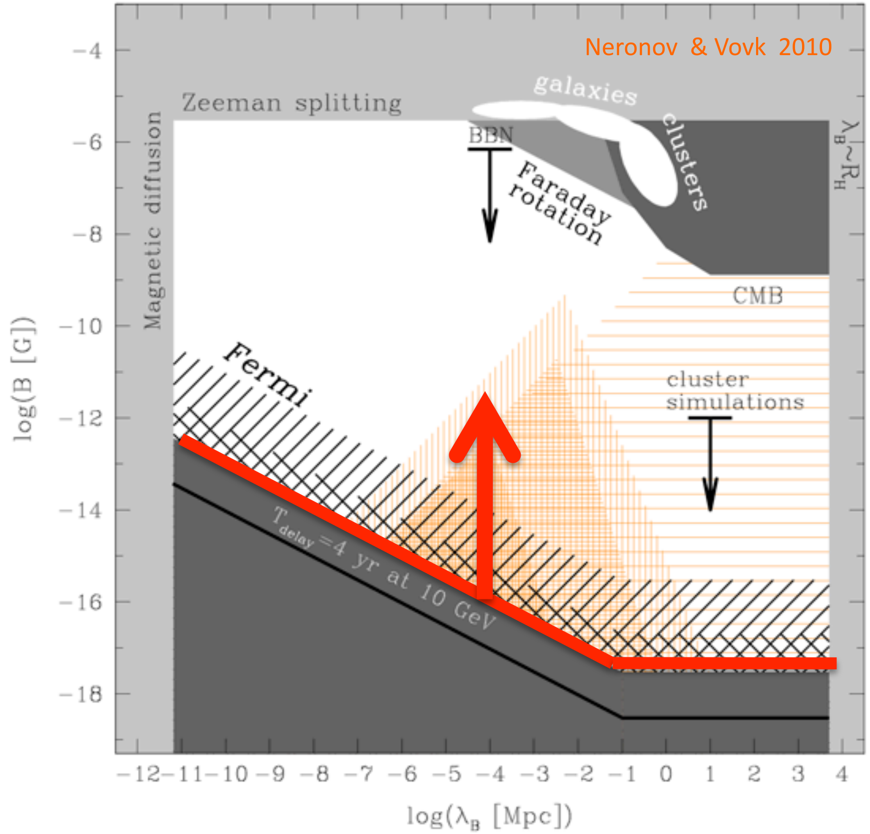

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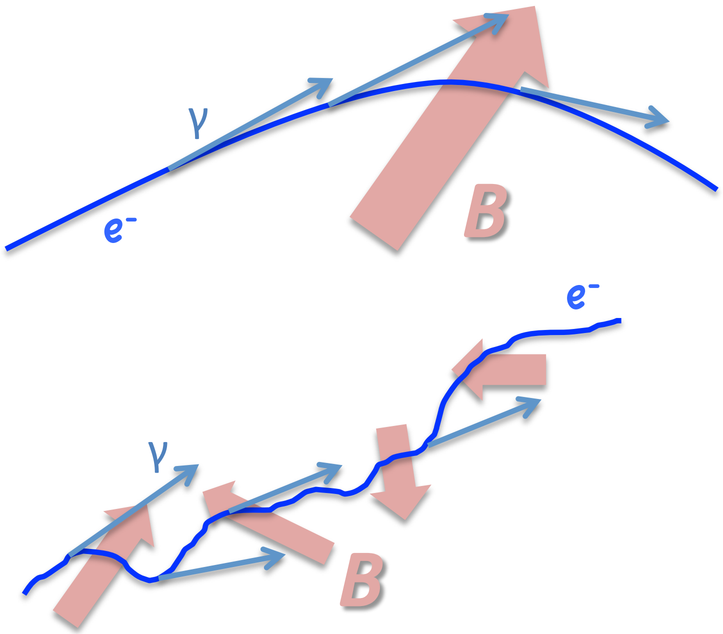
Dependence of the limit on EGMF correlation length



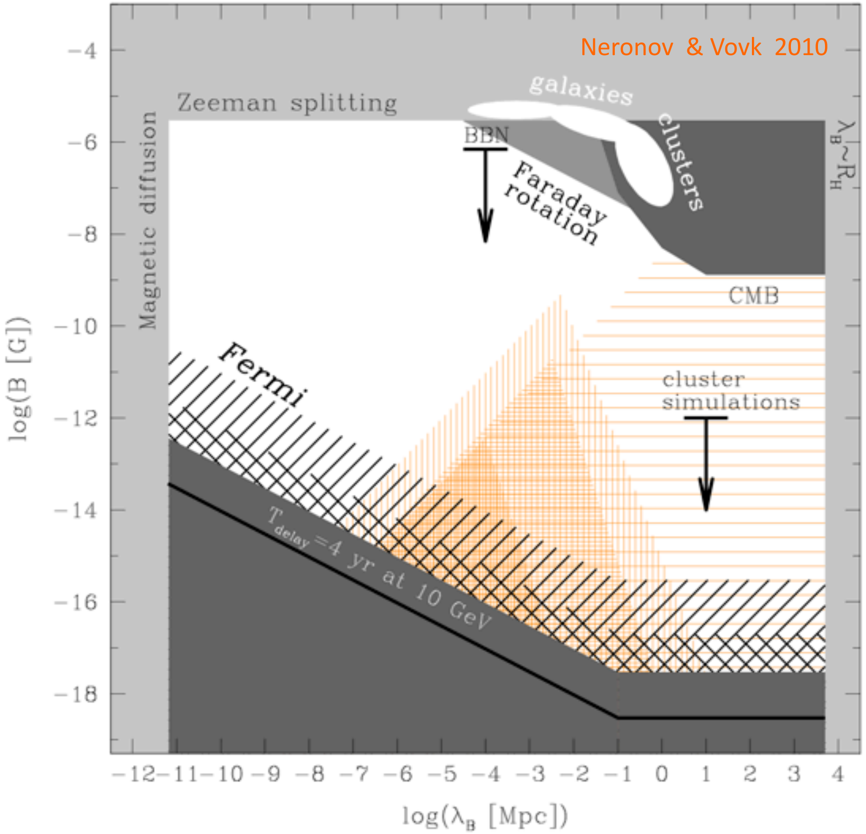
If the correlation length of EGMF is large, deflection angle is

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

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

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

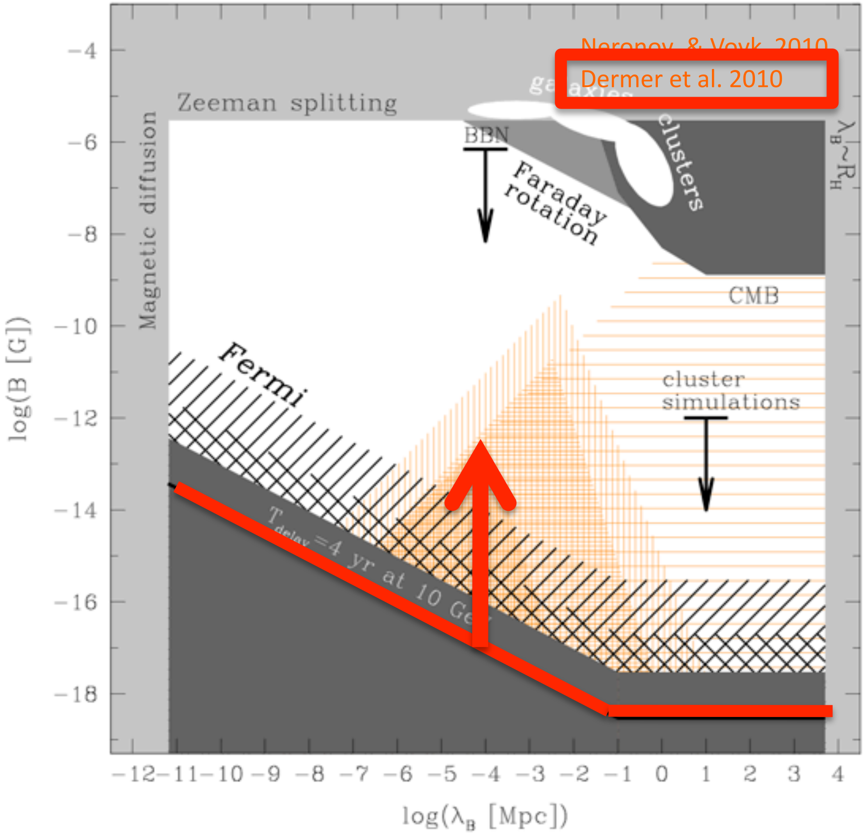
Uncertainties of the lower bound on EGMF



– 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.

EGMF bound from simultaneous GeV-TeV observations



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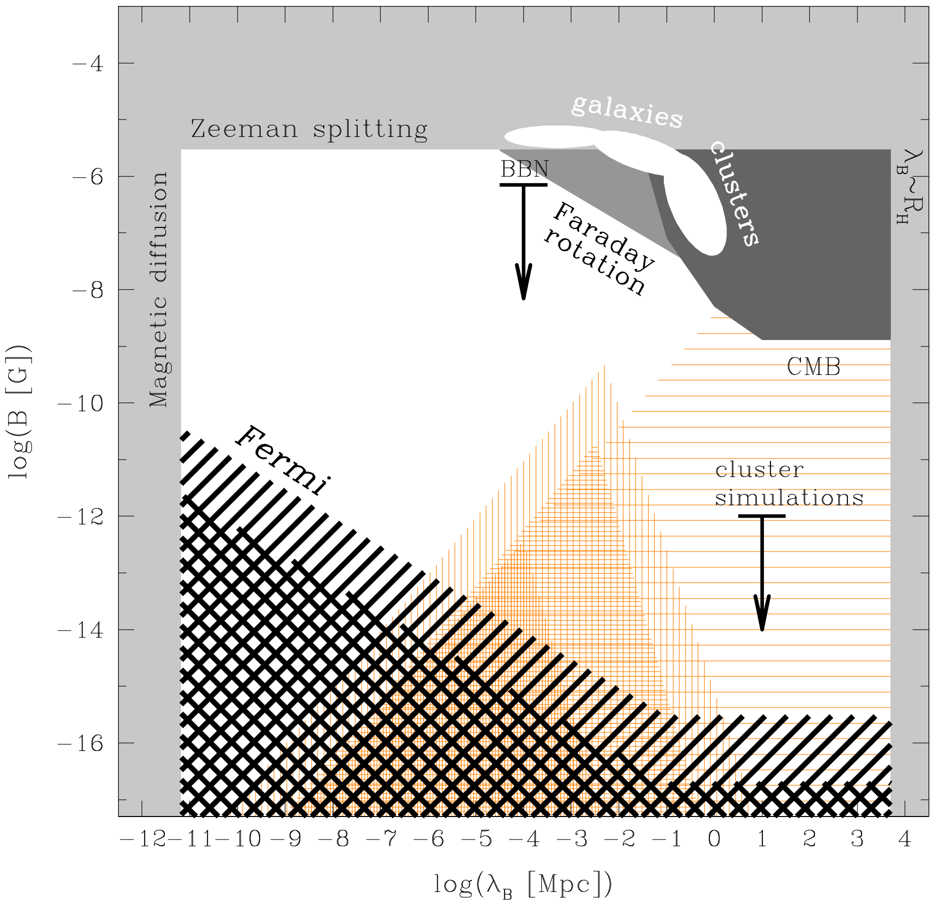
EGMF and the problem of the origin of cosmic magnetic fields



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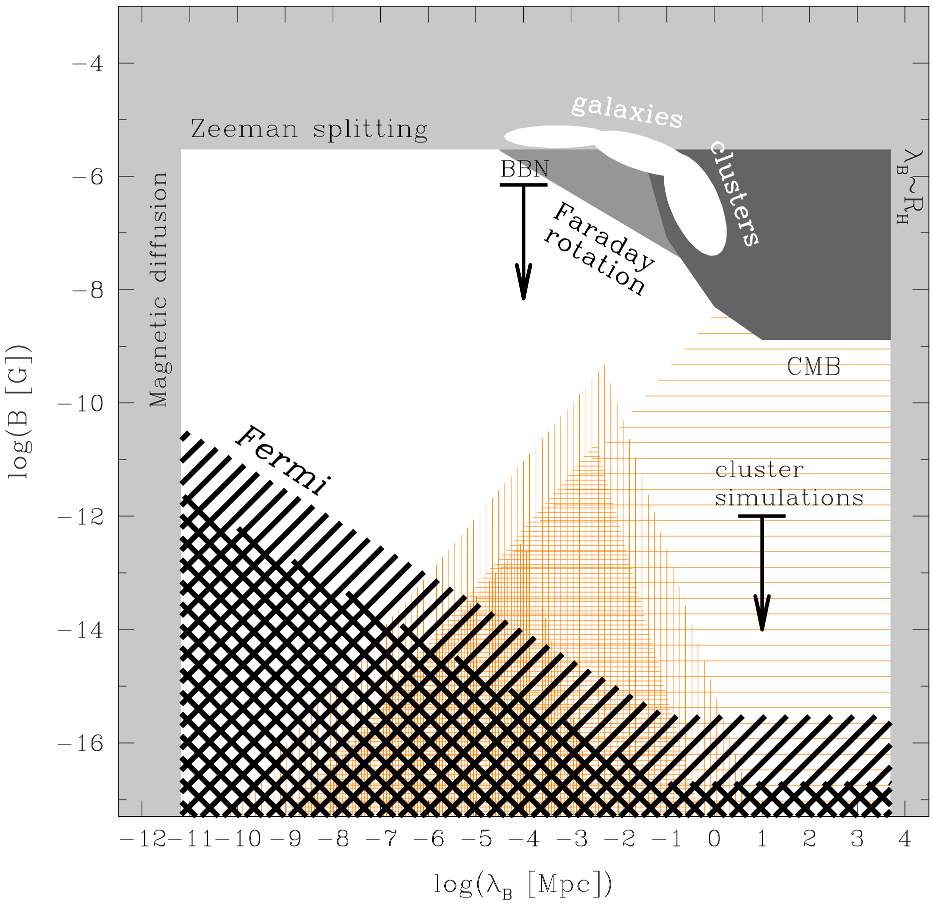

Existing models of the “seed” fields:

– astrophysical seed fields

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

– cosmological seed fields

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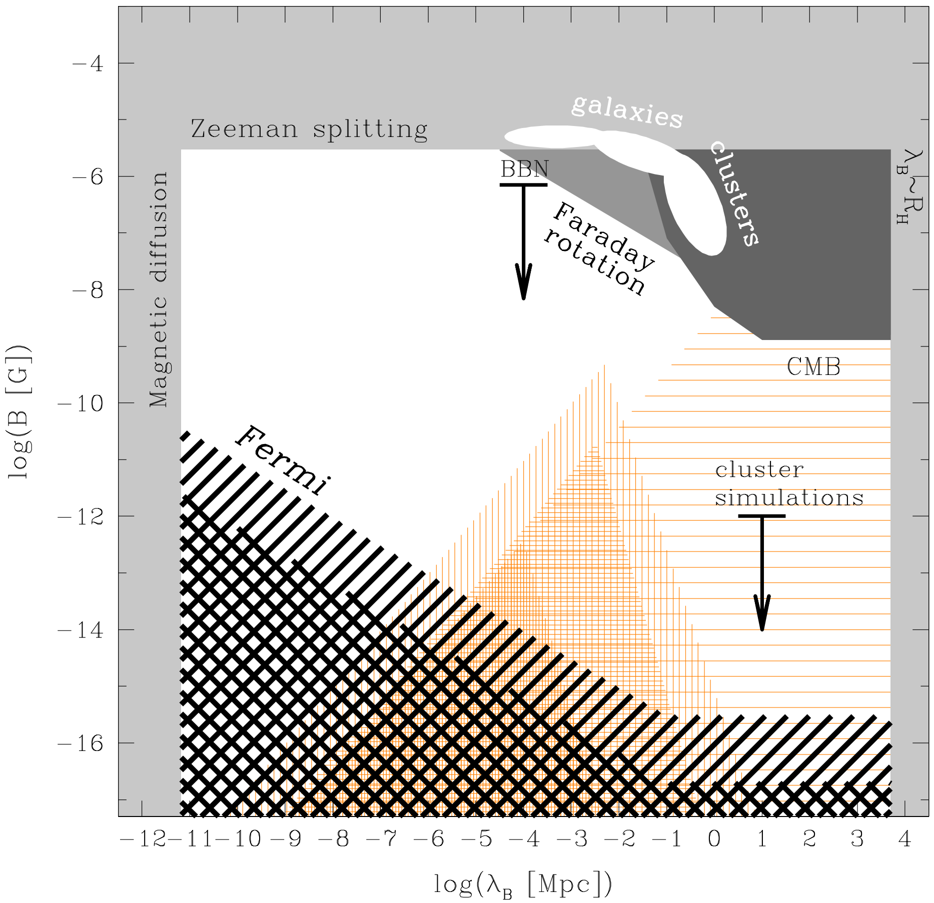

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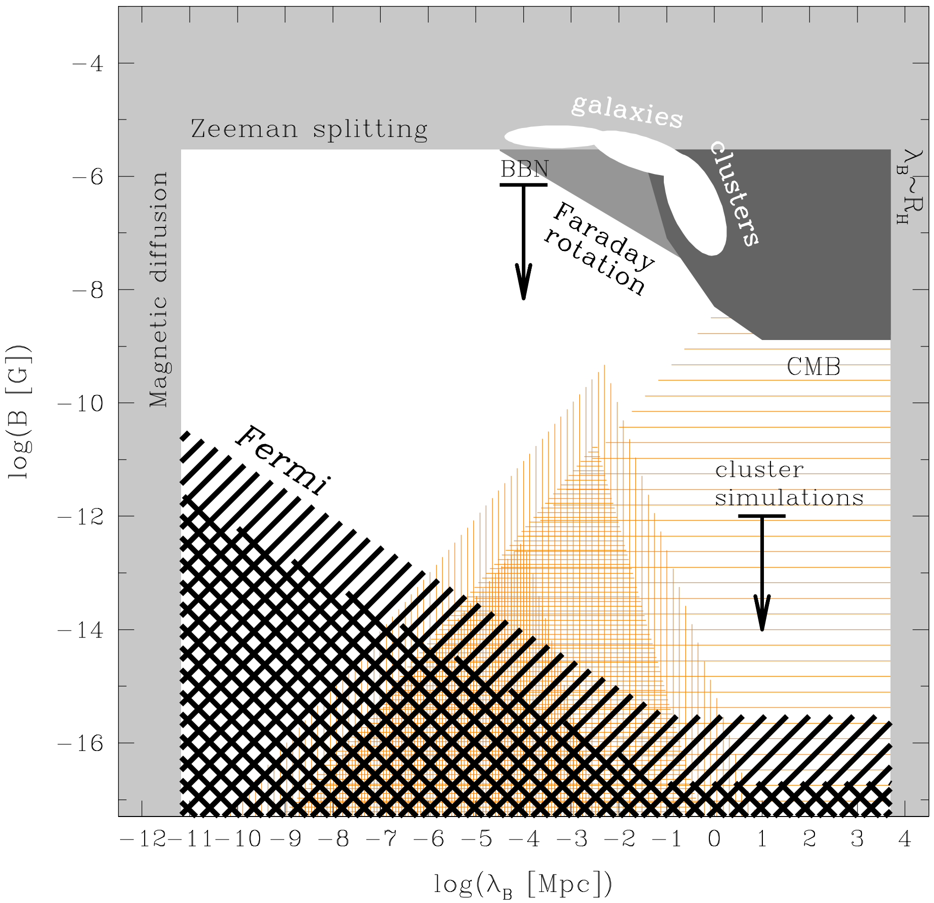

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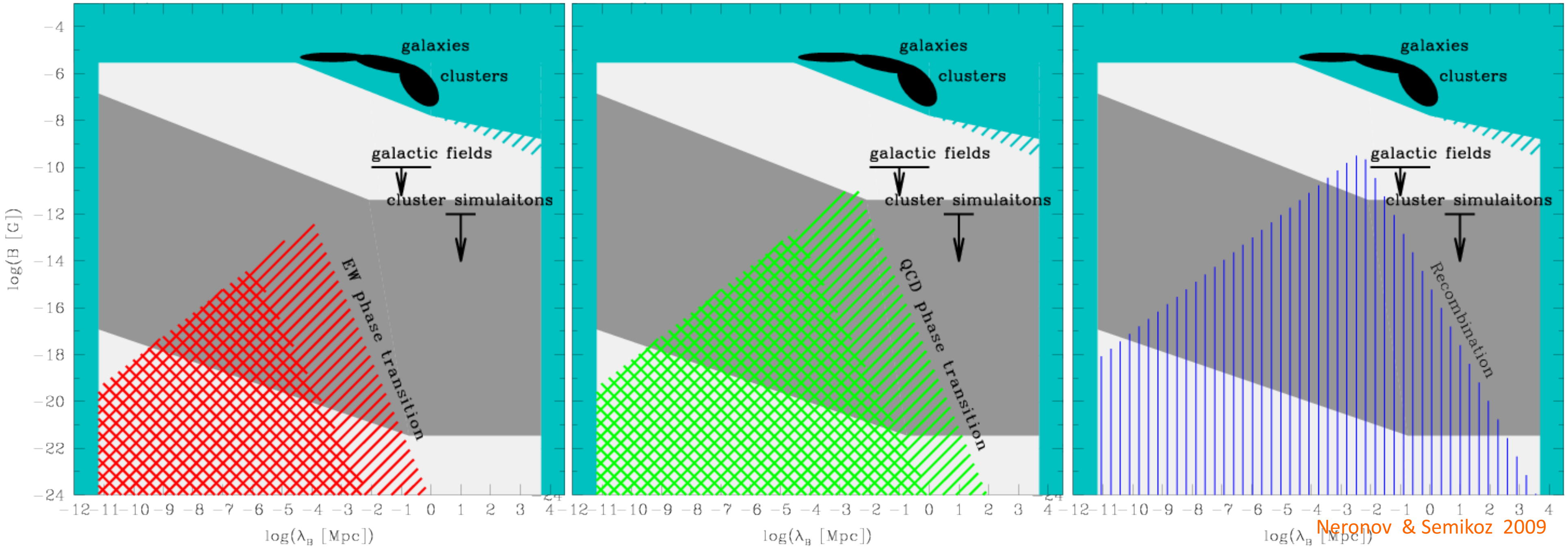
- Inflation
- Electroweak phase transition
- QCD phase transitions
- Recombination

Implications of the lower bound on EGMF



Neronov & Semikoz 2009

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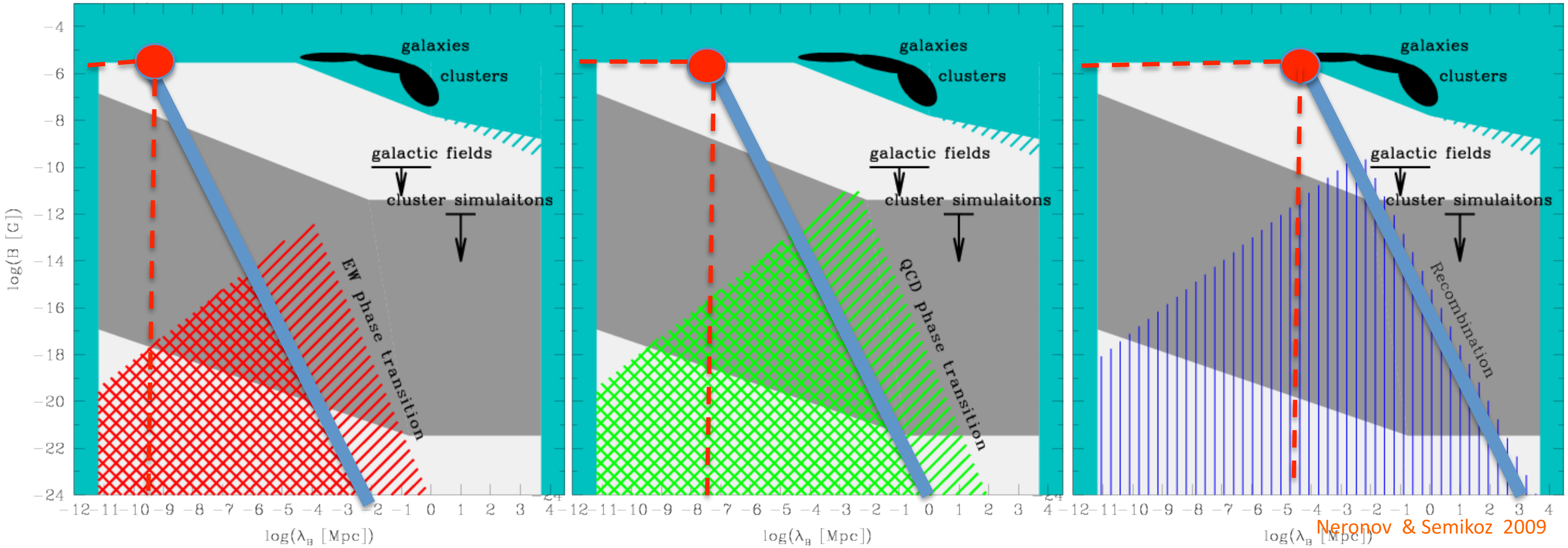

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– Initial magnetic field energy density is smaller than the **critical density** of the Universe

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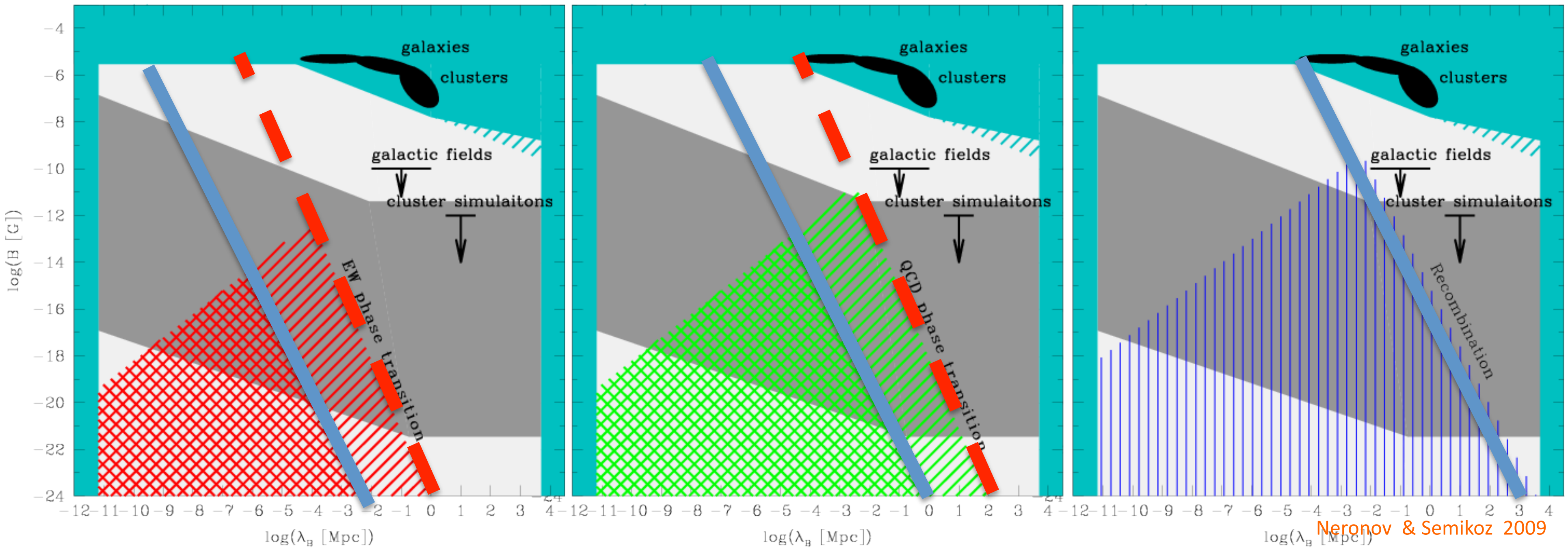

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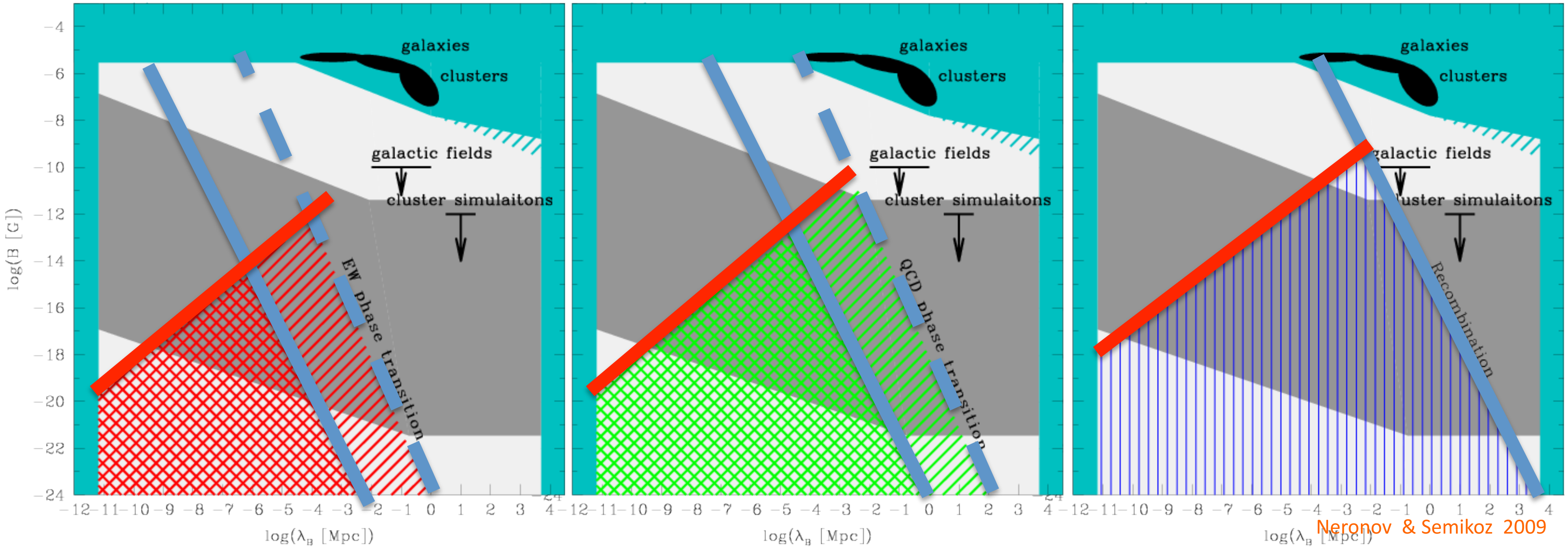

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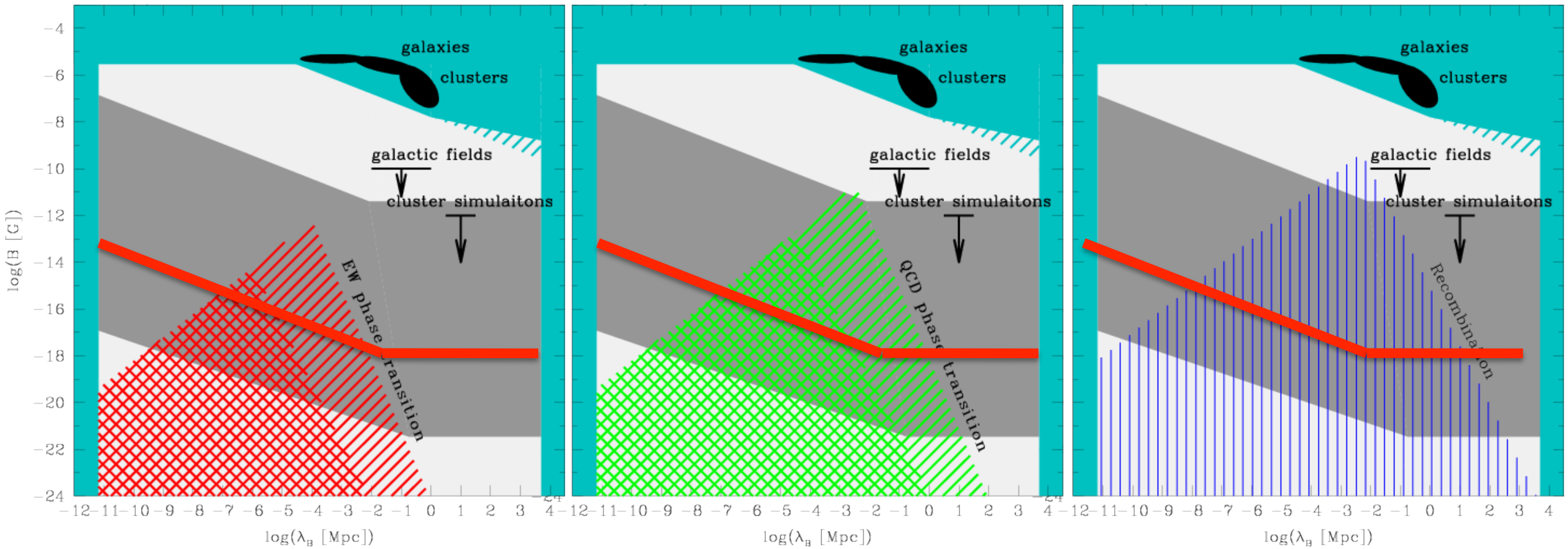
  – energy of short-correlation-length magnetic fields is **dissipated** via turbulence in the course of cosmological evolution

Implications of the lower bound on EGMF



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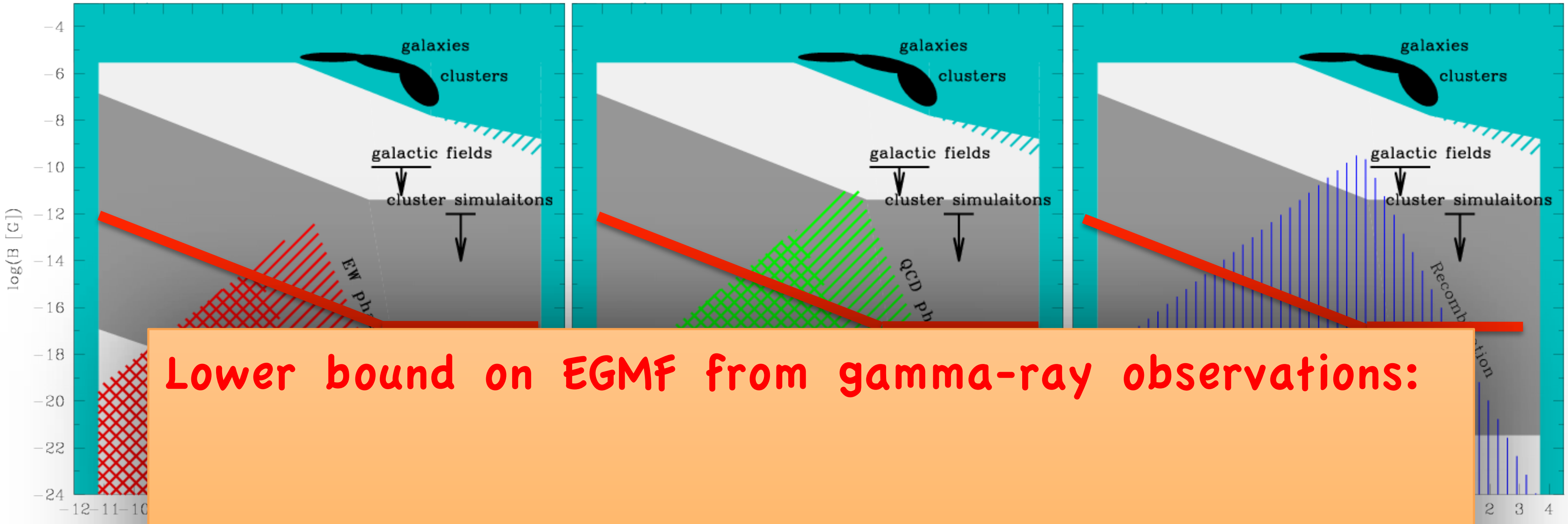
Most of the existing cosmological magnetogenesis models predict fields much weaker than the lower bound from γ–ray observations

Implications of the lower bound on EGMF



Lower bound on EGMF from gamma-ray observations:

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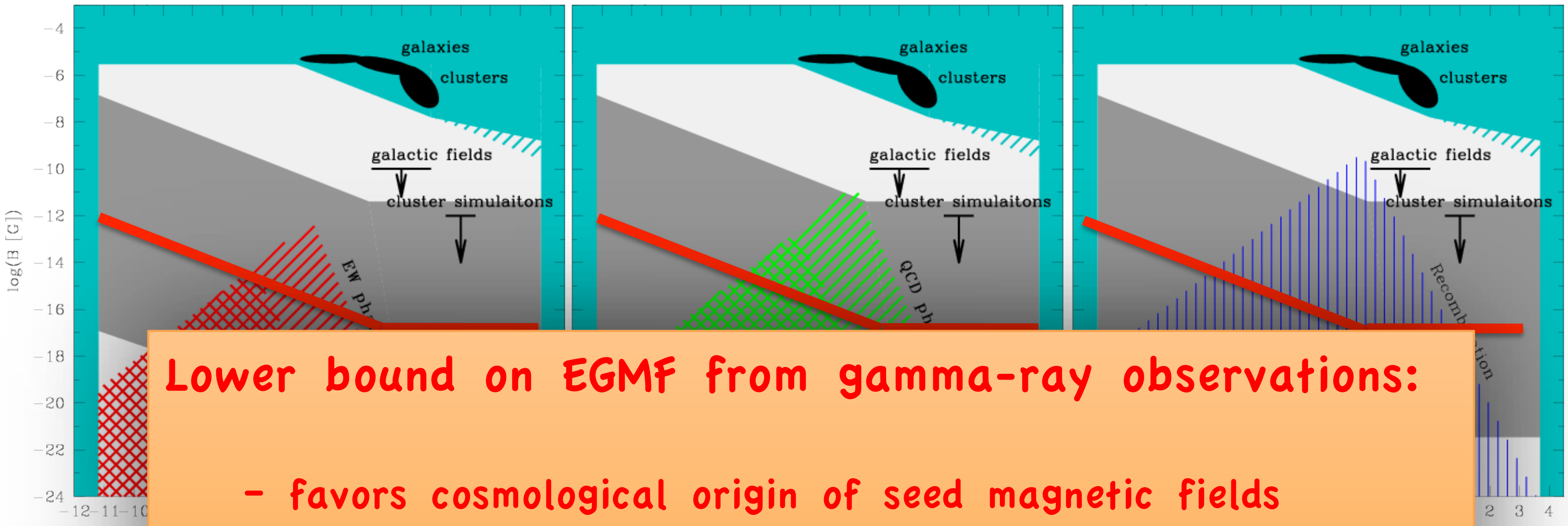

Lower bound on EGMF from gamma-ray observations:

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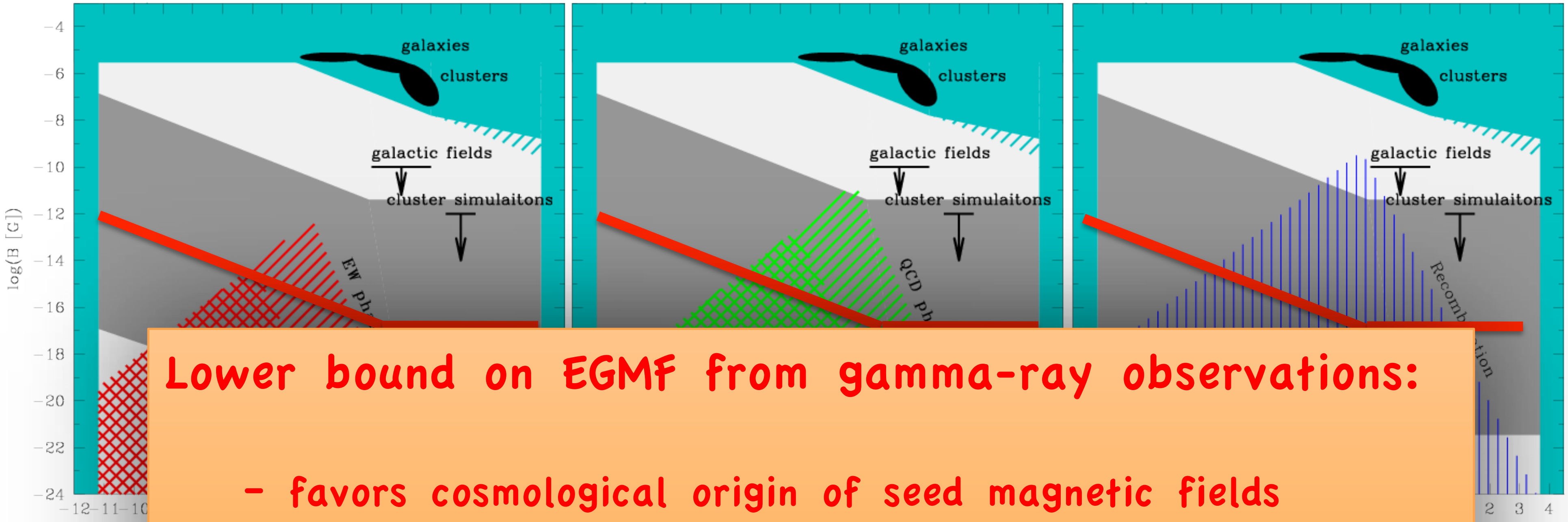
Implications of the lower bound on EGMF



Lower bound on EGMF from gamma-ray observations:

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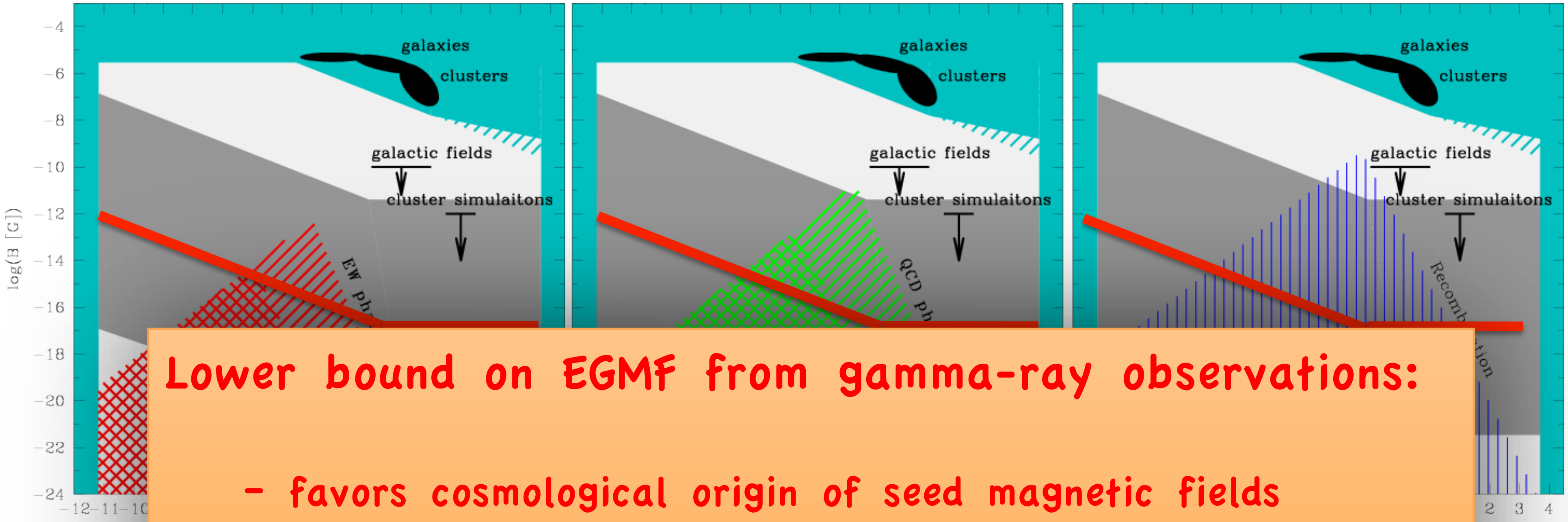
Implications of the lower bound on EGMF

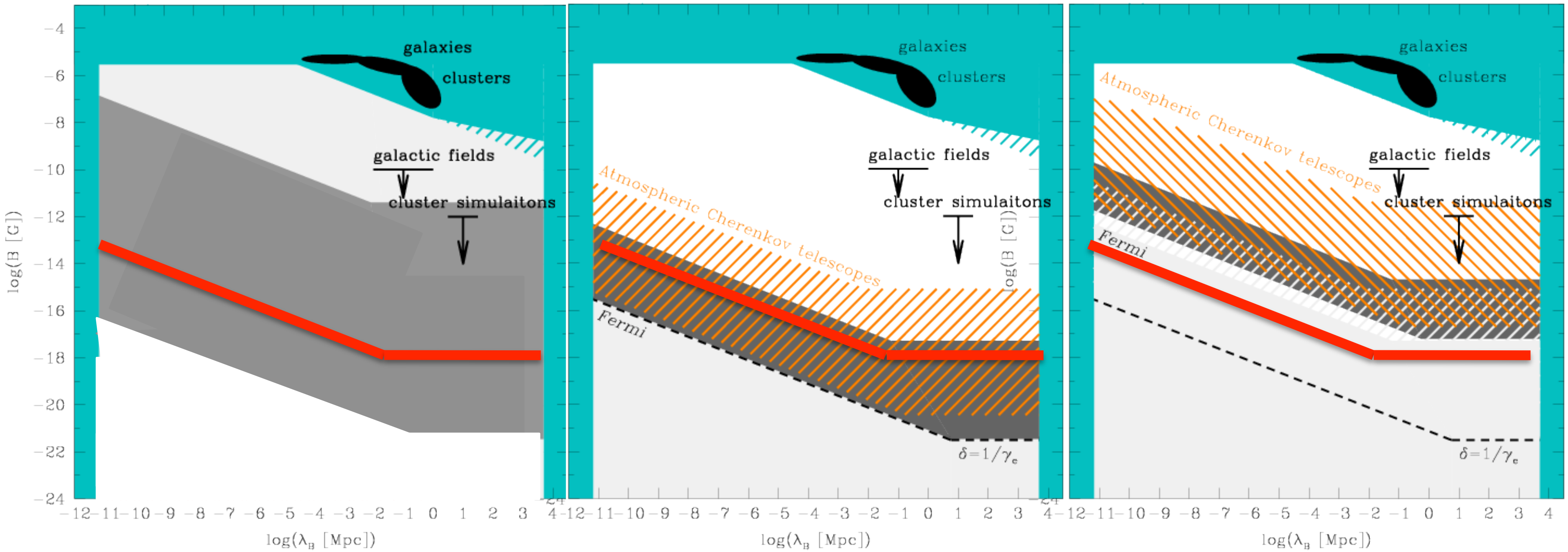


Lower bound on EGMF from gamma-ray observations:

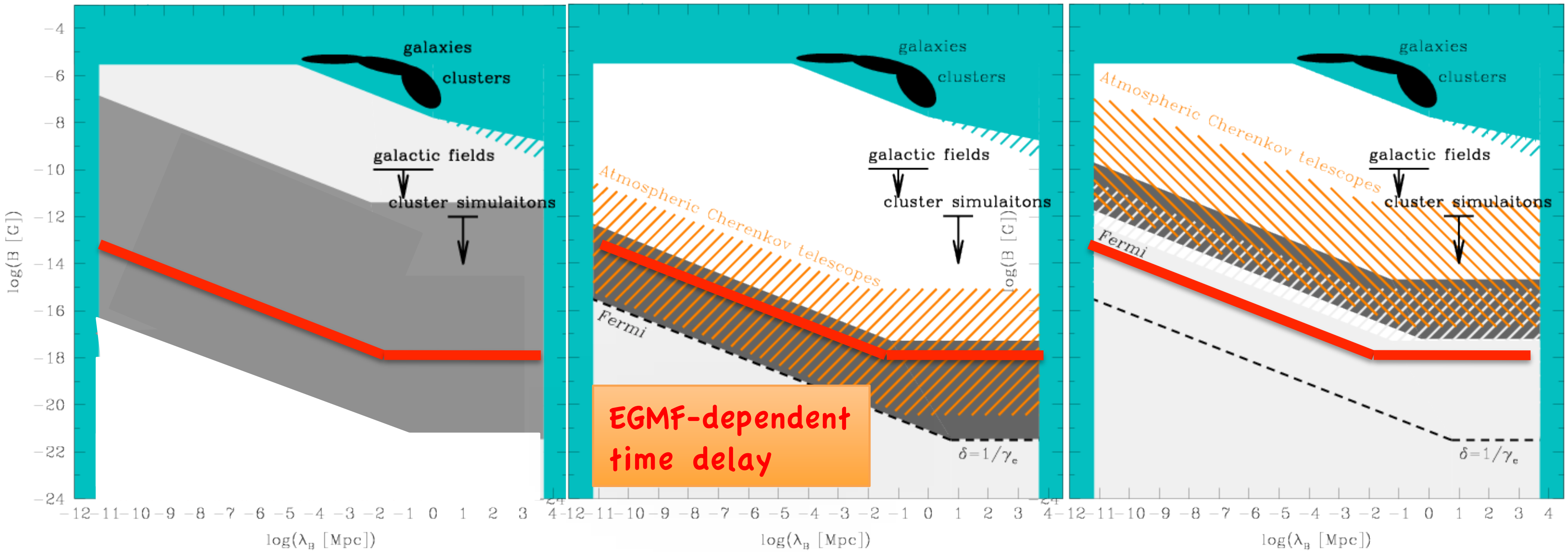
- favors cosmological origin of seed magnetic fields
- rules out the possibility that these fields are non-helical magnetic fields produced at Electroweak phase transition
- Several cosmological magnetogenesis models are not ruled out and could be tested with gamma-ray observations

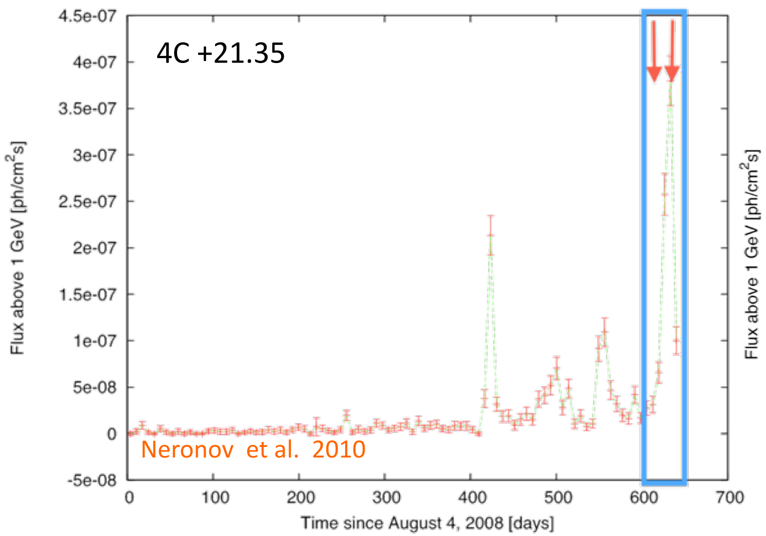
Most of the existing cosmological magnetogenesis models predict fields much weaker than the lower bound from γ–ray observations

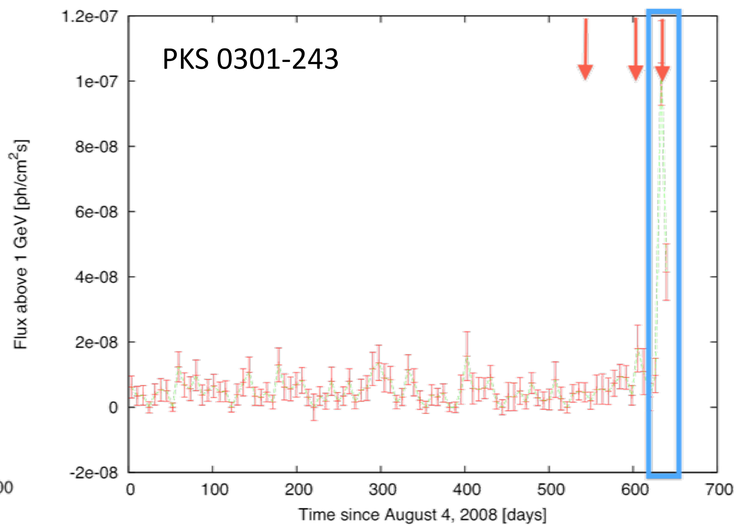
Detection of the seed fields with γ-ray telescopes



EGMF-dependent time delays in Fermi







http://www.isdc.unige.ch/vhe/index.html

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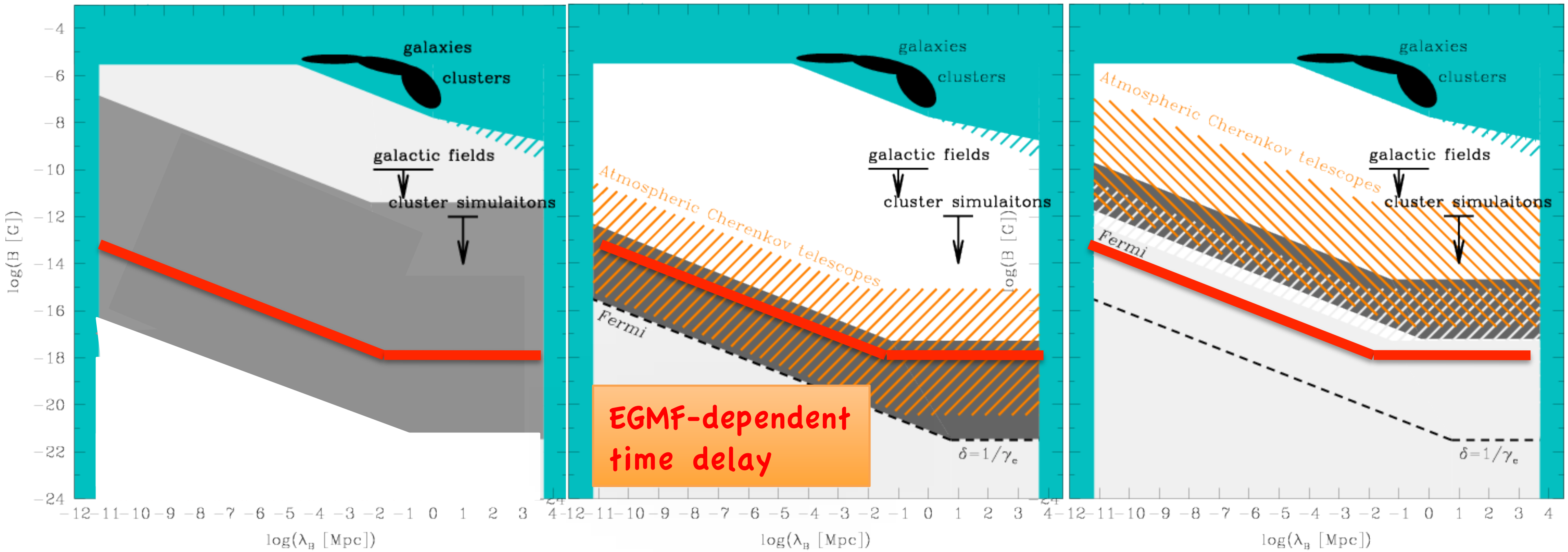

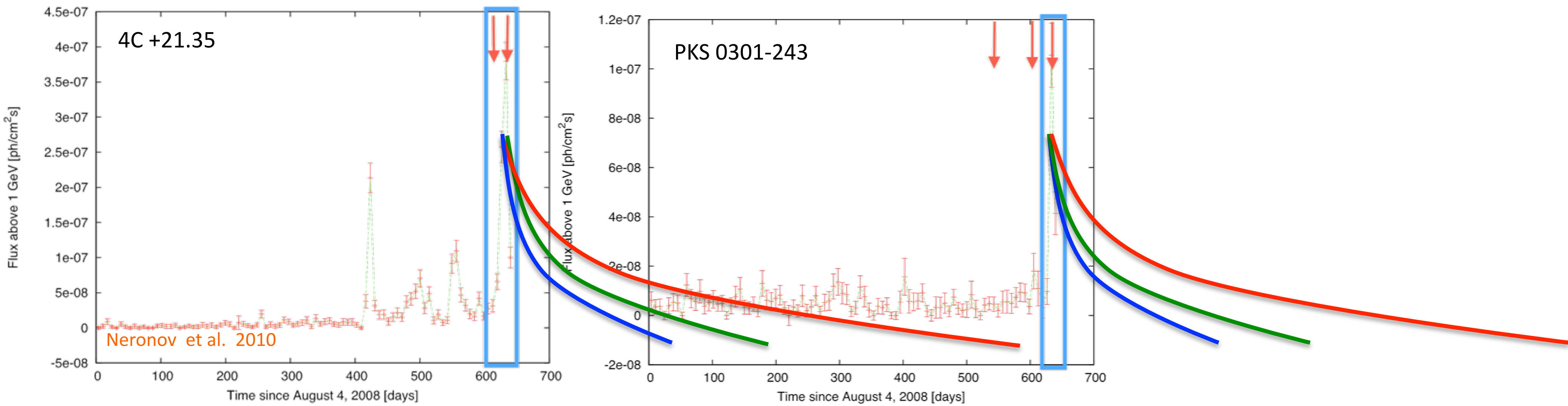

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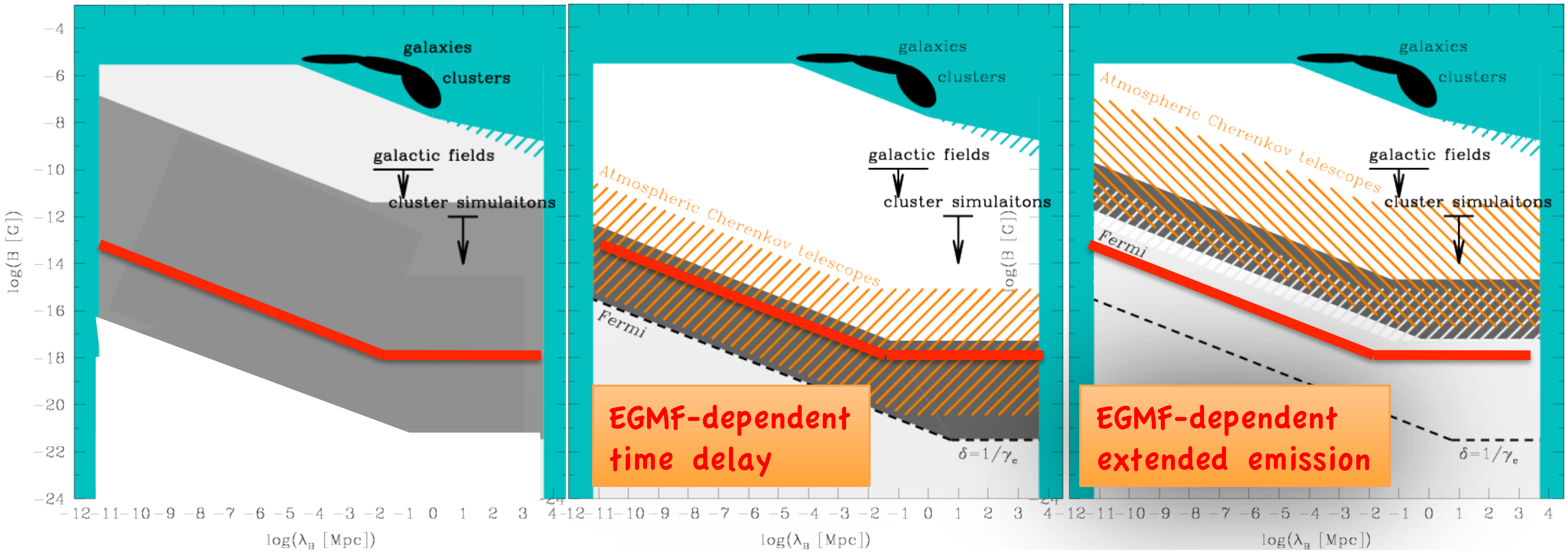
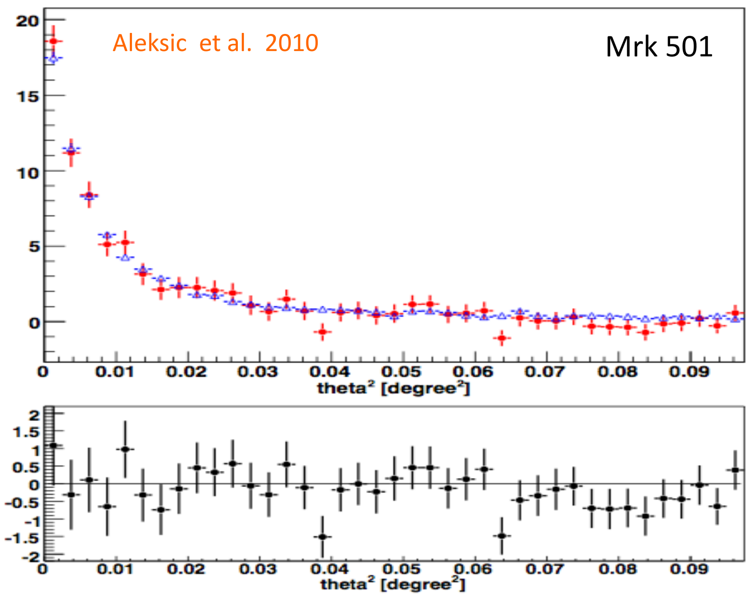
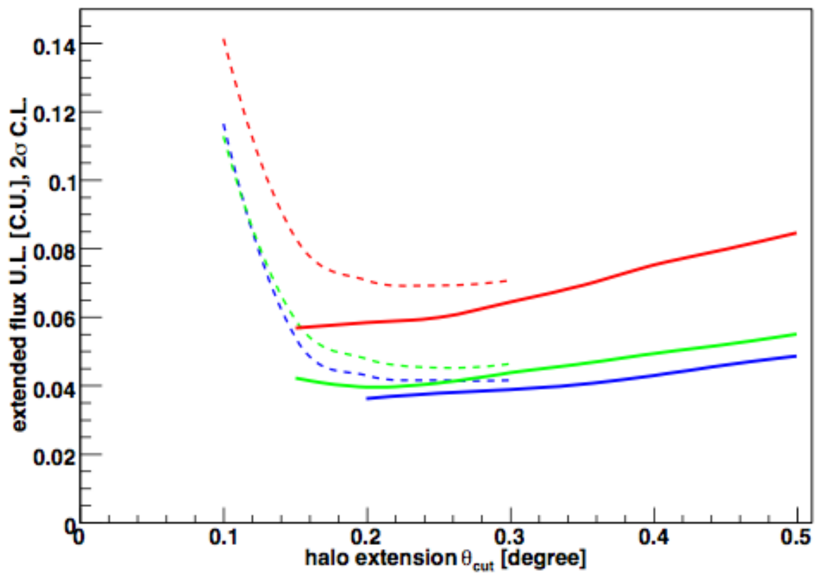
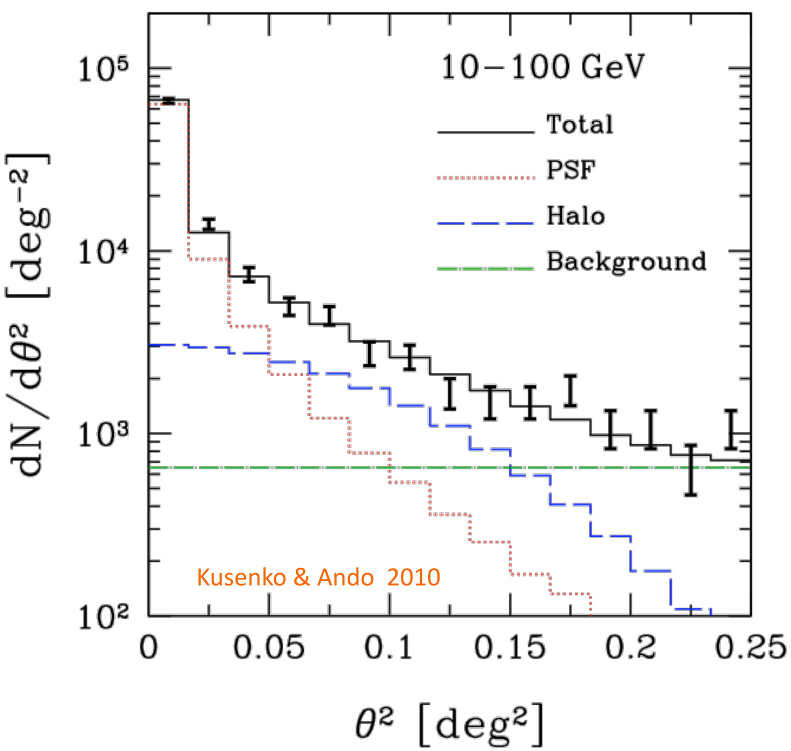
EGMF-dependent extended emission in MAGIC (300 GeV)







EGMF-dependent extended emission in Fermi (10 GeV)



Detection of EGMF-dependent extended emission in the stacked signal from 170 AGN in Fermi was recently claimed by Kusenko & Ando (2010).

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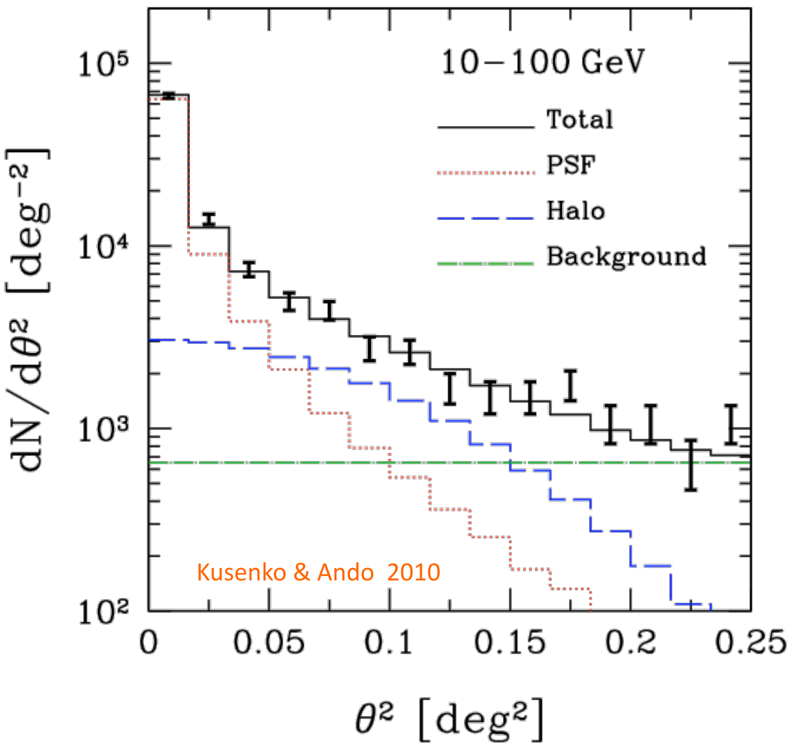

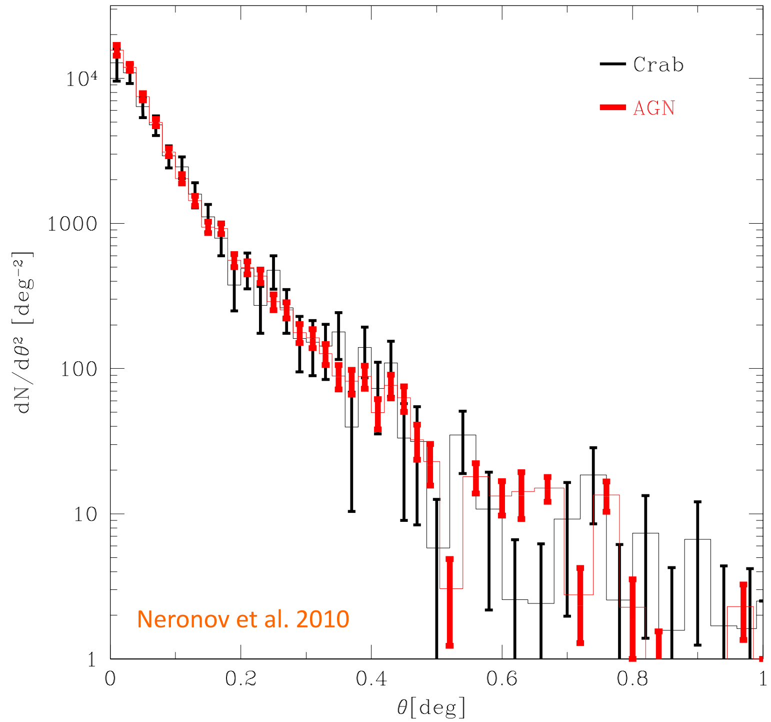

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We do not confirm this result based on:

(a) comparison of the angular distribution of AGN photons with that of the Crab photons

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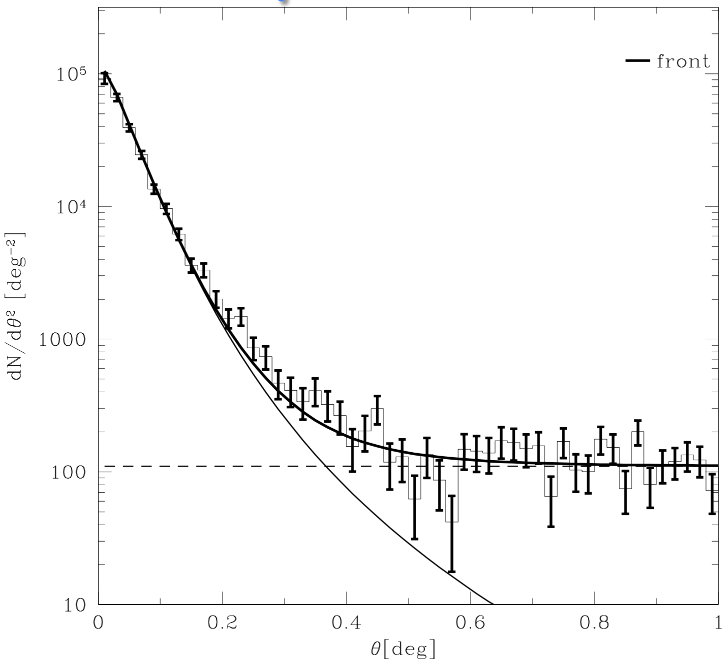

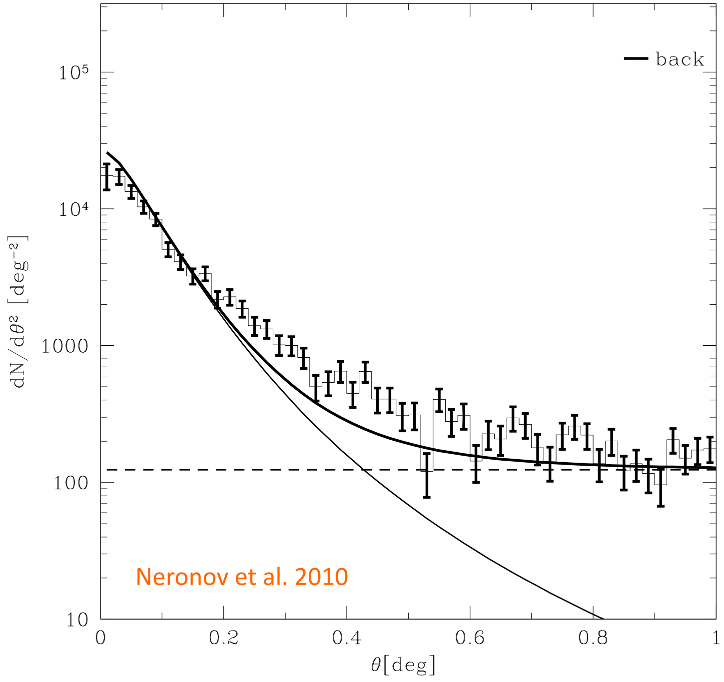

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(b) difference of the excess over PSF in front- and back- converted photons.

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 **$\sim 10^{-18}$–10^{-16} G,** depending on the assumption of the mechanism of suppression of cascade emission

Evidence for existence of magnetic fields in the intergalactic medium provides a new step for understanding of the origin of magnetic fields in the Universe