Magnetic fields in the intergalactic medium

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Overview

What do we know about magnetic fields in the intergalactic medium (voids of the Large scale structure)?

Gamma-ray induced cascades in the intergalactic space

Influence of magnetic fields in the IGM

Observational constraints on IGM magnetic fields from gamma-ray (non) observations of cascade emission by Fermi and ground-based gamma-ray telescopes.

What do we know about IGM magnetic fields?

Weak magnetic fields might exist in IGM. They could be
(a) relic magnetic fields generated in the Early Universe
(b) magnetic fields ejected together with galactic winds

Magnetic fields in IGM have not been detected up to now

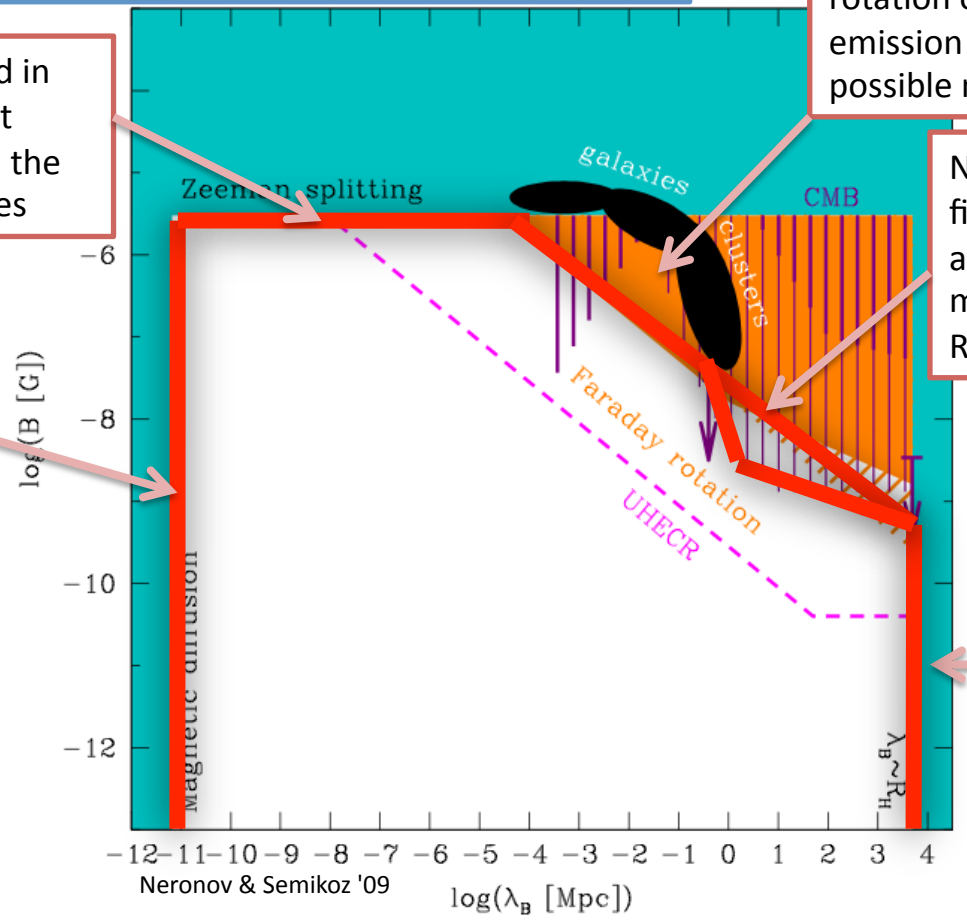
Magnetic field in the IGM is not stronger than the field in galaxies

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

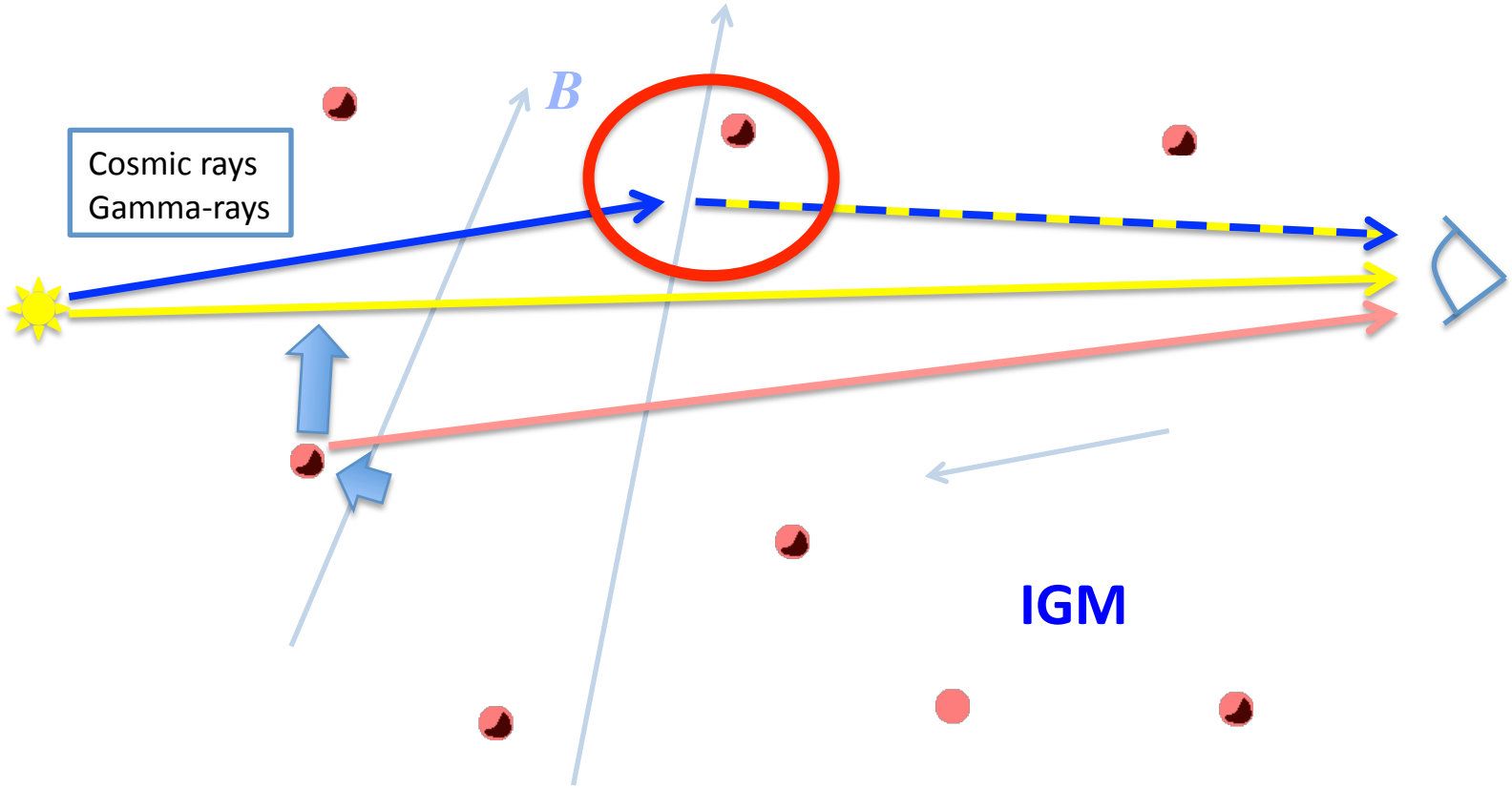
Resistive decay removes short-correlation length fields in T<10 Gyr

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



Neronov & Semikoz '09

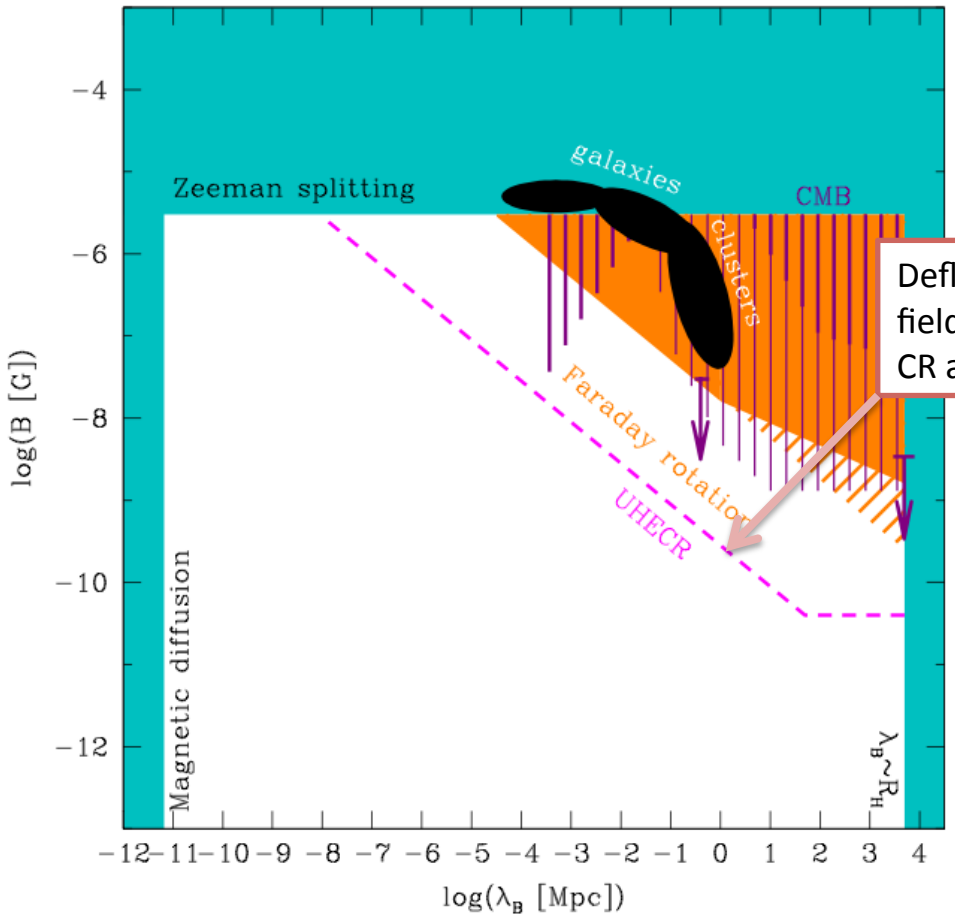
IGM magnetic fields measurement



Extragalactic cosmic rays are deflected by magnetic fields in the IGM:

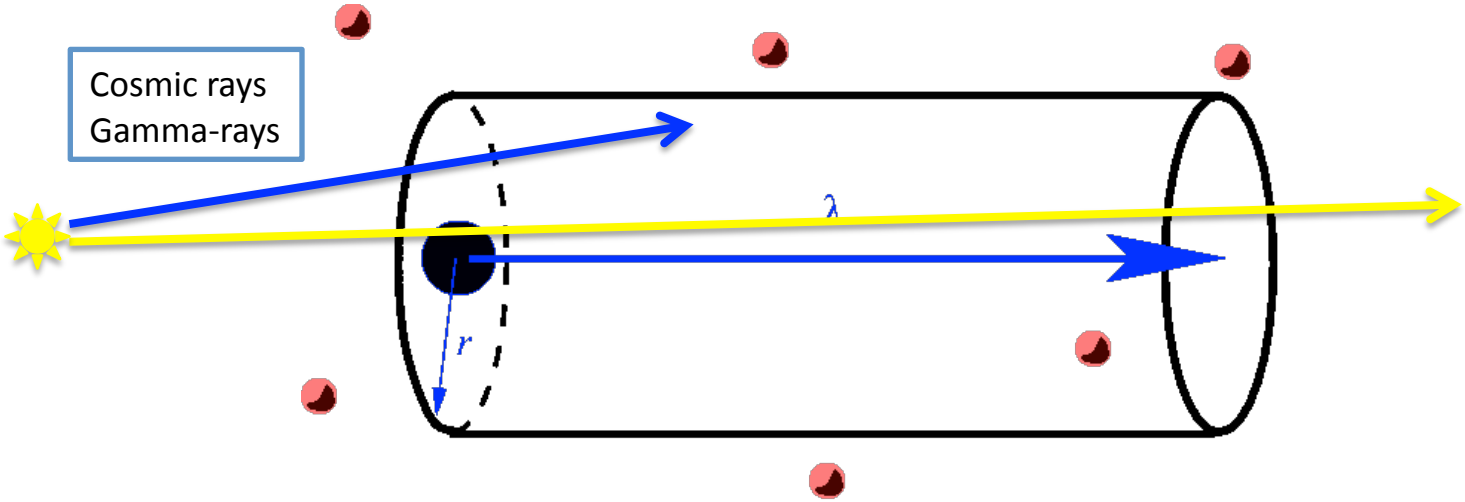
$$R_L = \frac{E_{CR}}{eB} = 1\left[\frac{B}{10^{-9}\,\mathrm{G}}\right]^{-1}\left[\frac{E_{CR}}{10^{18}\ \mathrm{eV}}\right]\ \mathrm{Mpc}$$

What do we know about IGM magnetic fields?



Deflections of CRs by magnetic fields have significant effect of CR arrival directions

Interactions of high-energy particles in IGM



IGM

– dark matter
$\varrho \sim \varrho_{cr} \sim 10^{-29}$ g/cm^{-3}

– baryons
$\varrho_b \sim 0.05\ \varrho_{cr} \sim 10^{-7}$ cm^{-3}

– radiation
$n_{CMB} \sim 400$ cm^{-3}

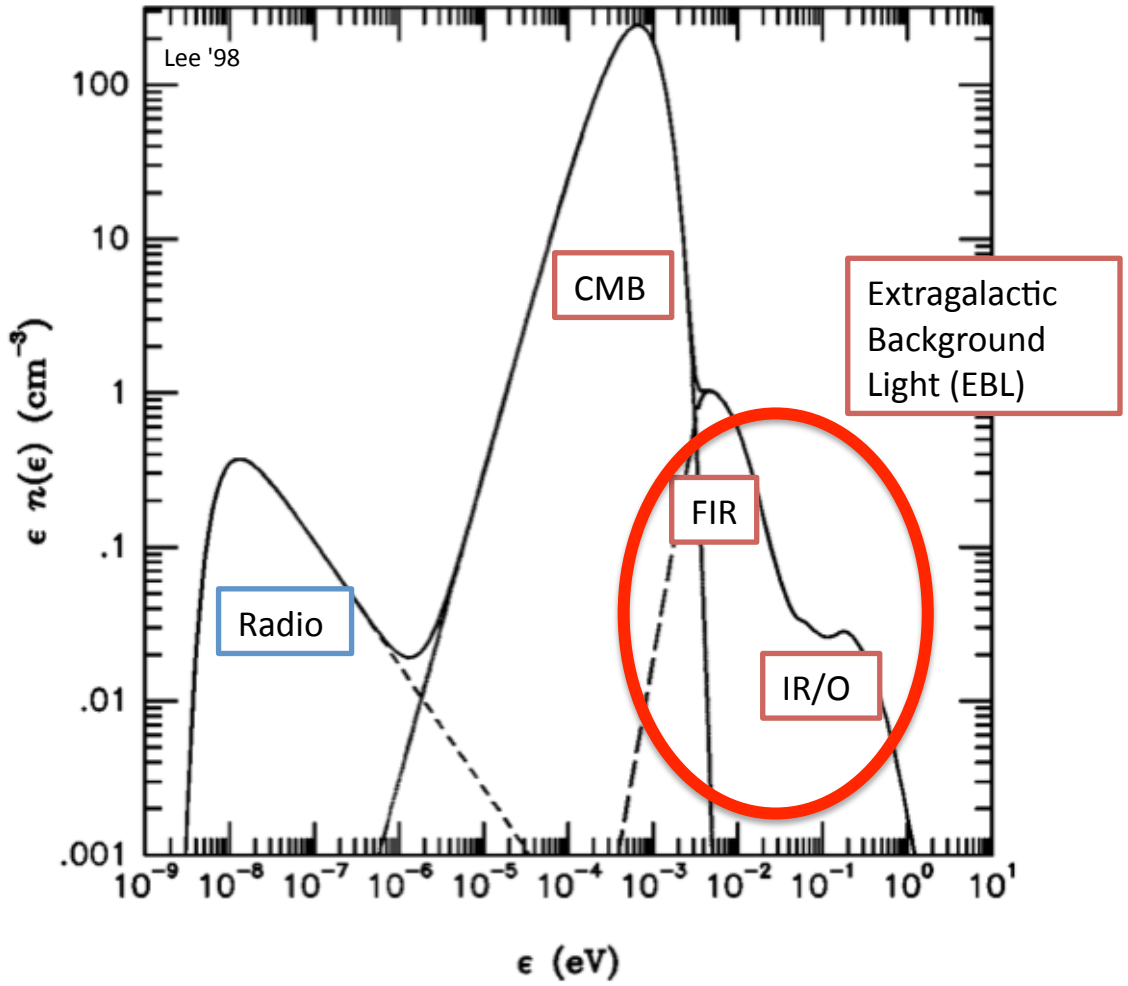
"mean free path" of a particle

$$\lambda = \frac{1}{\sigma_{\text{int}} n}$$

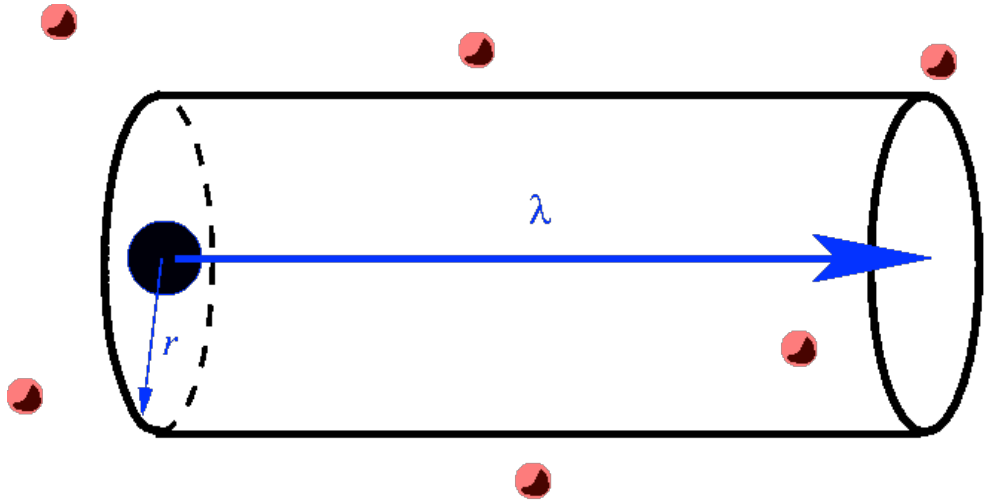
Interaction cross-section $\sigma_{int} \sim r^2$

density of the medium

Radiation background in IGM



Propagation of high-energy particles though IGM



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– EBL $n_{EBL} \sim 0.01\text{-}1$ cm^{-3}

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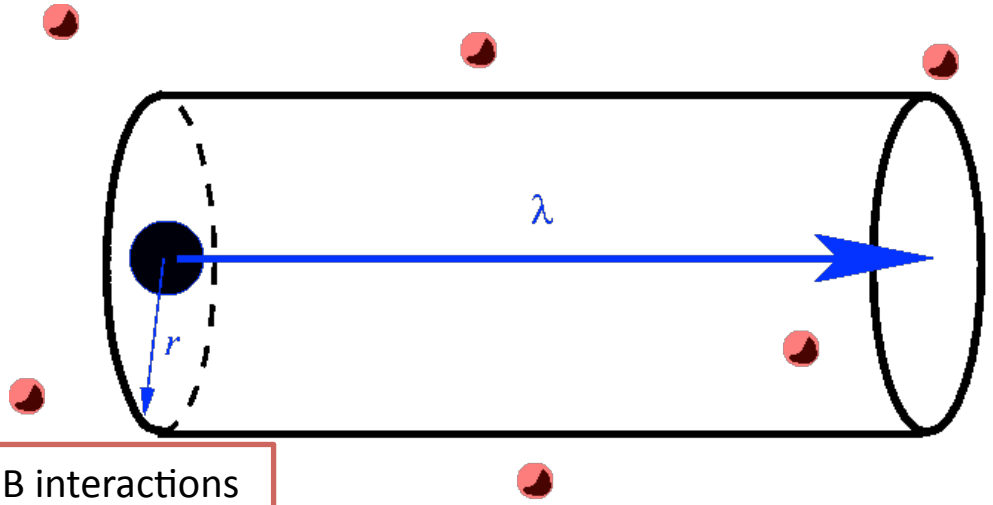

– Cosmic ray + CMB interactions

$n_{CMB} \sim 400\ cm^{-3}$

$\sigma_{int} \sim 10^{-28}\ cm^2$

$\lambda \sim 10$ Mpc

– for cosmic rays with energies above above a threshold for reaction

$$p + \gamma \rightarrow p + \pi$$

$$E_p > \frac{(m_p m_\pi + m_\pi^2/2)c^2}{E_{CMB}}$$

Greisen, Zatsepin, Kuzmin '66

$$\lambda = \frac{1}{\sigma_{\text{int}} n}$$

IGM

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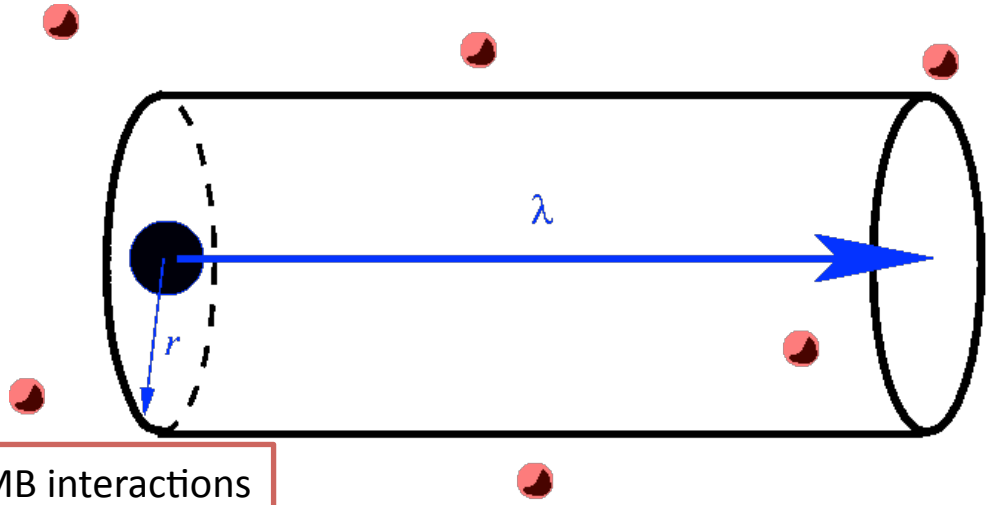
Propagation of high-energy particles though IGM



– Gamma ray + CMB interactions

n_{CMB}~400 cm^{-3}

$\sigma_{int} \sim 10^{-25}$ cm^2

$\lambda \sim 10$ kpc

– for cosmic rays with energies above above a threshold for reaction

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

$$E_\gamma > \frac{(m_e c^2)^2}{E_{CMB}} \sim 3 \times 10^{14} \text{eV}$$

$$\lambda = \frac{1}{\sigma_{\text{int}} n}$$

IGM

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$\varrho \sim \varrho_{cr} \sim 10^{-29}$ g/cm^{-3}

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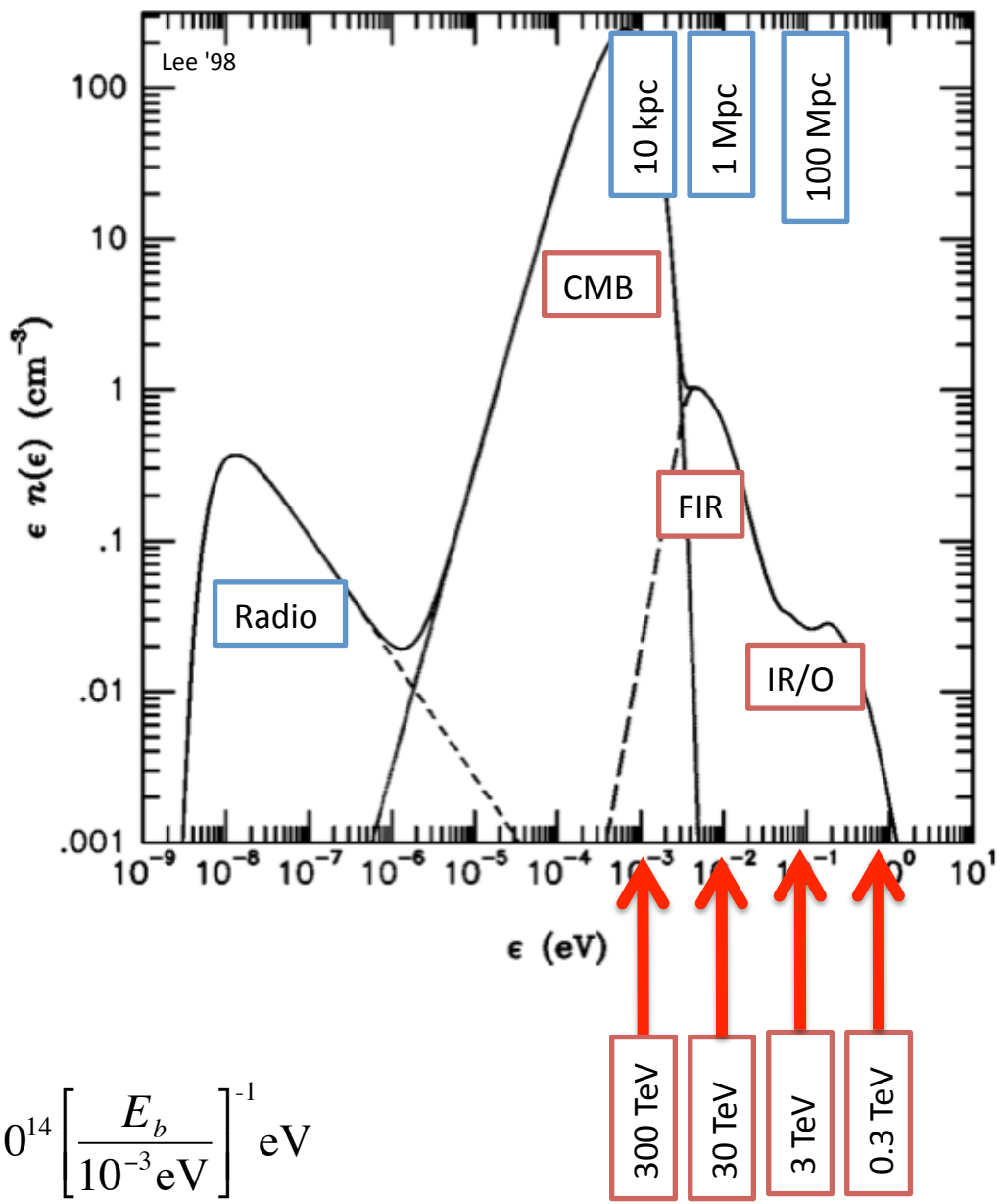
– radiation

n_{CMB}~400 cm^{-3}

– EBL n_{EBL}~0.01-1 cm^{-3}

Radiation background in IGM

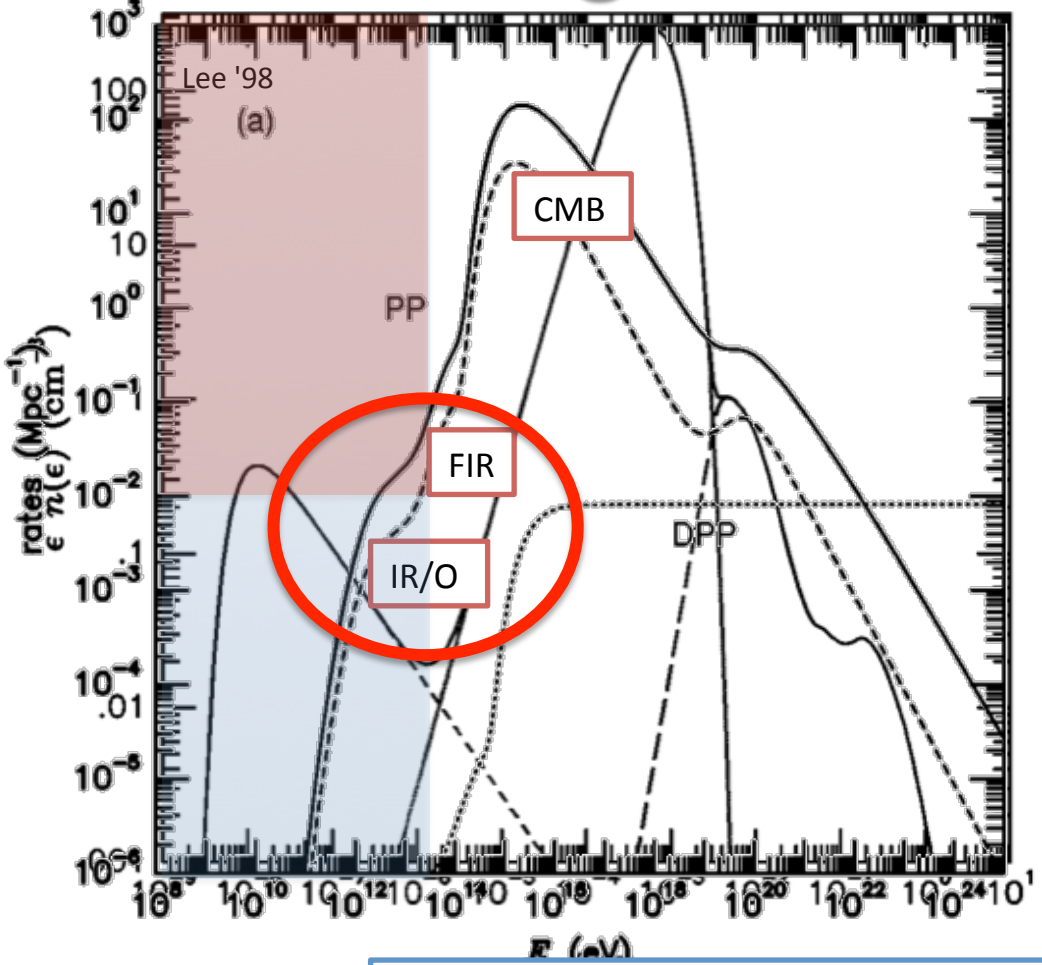


$$\lambda = \frac{1}{\sigma_{\rm int} n}$$

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

$$E_\gamma > \frac{(m_e c^2)^2}{E_b} \sim 3 \times 10^{14} \left[\frac{E_b}{10^{-3}\,\mathrm{eV}}\right]^{-1} \mathrm{eV}$$

Radiation background in IGM



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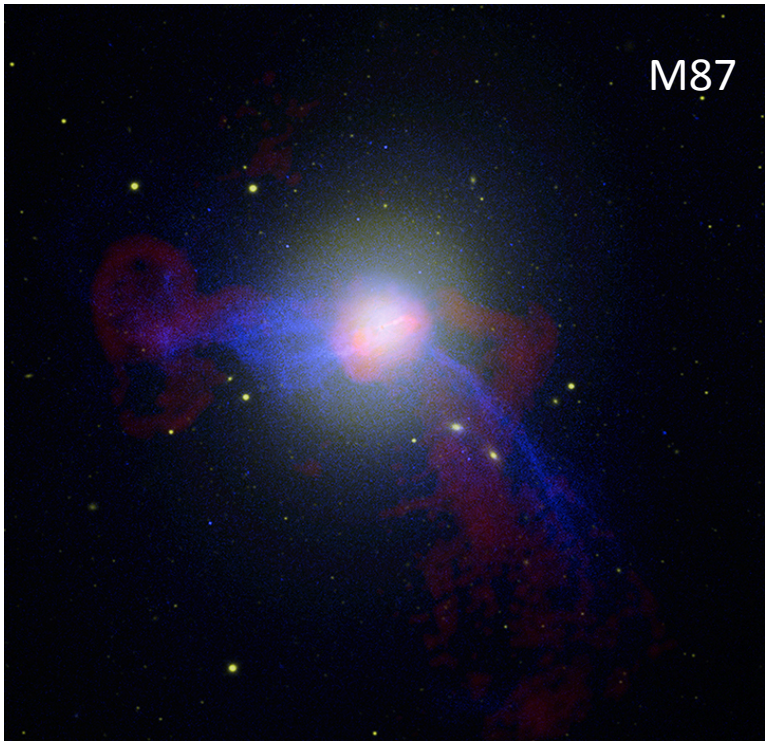
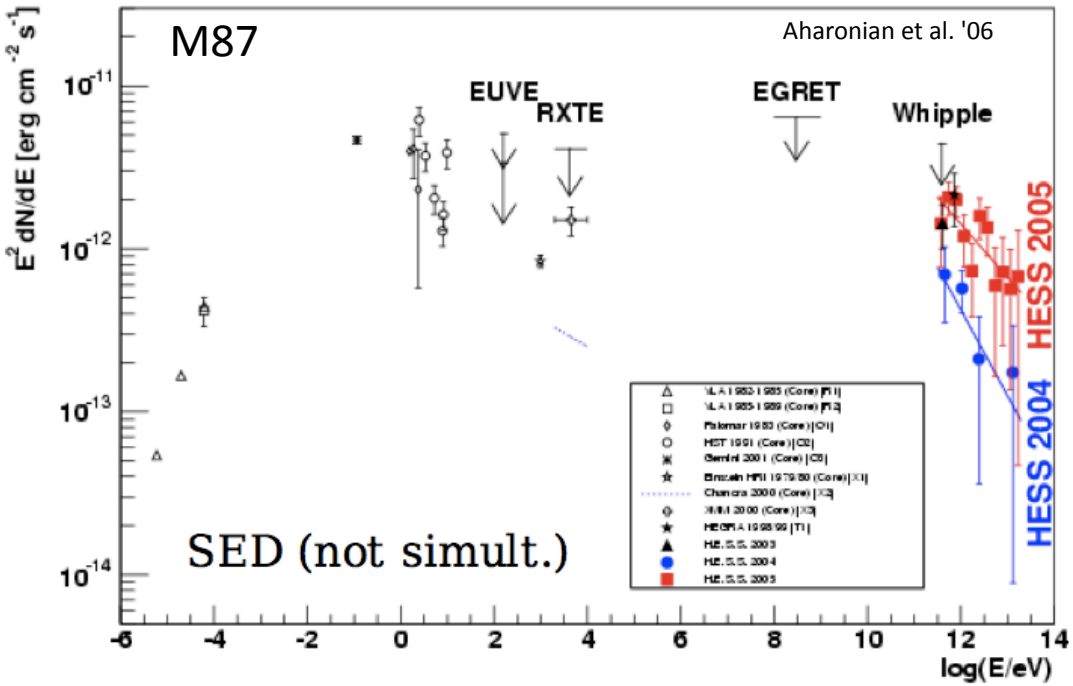
Gamma-ray telescopes observe emission from extragalactic sources up to $E_\gamma \sim 10$ TeV$\sim 10^{13}$ eV.

At the distances >>100 Mpc

Highest energy gamma-rays interact with EBL on the way from the source

Extragalactic TeV gamma-ray sources

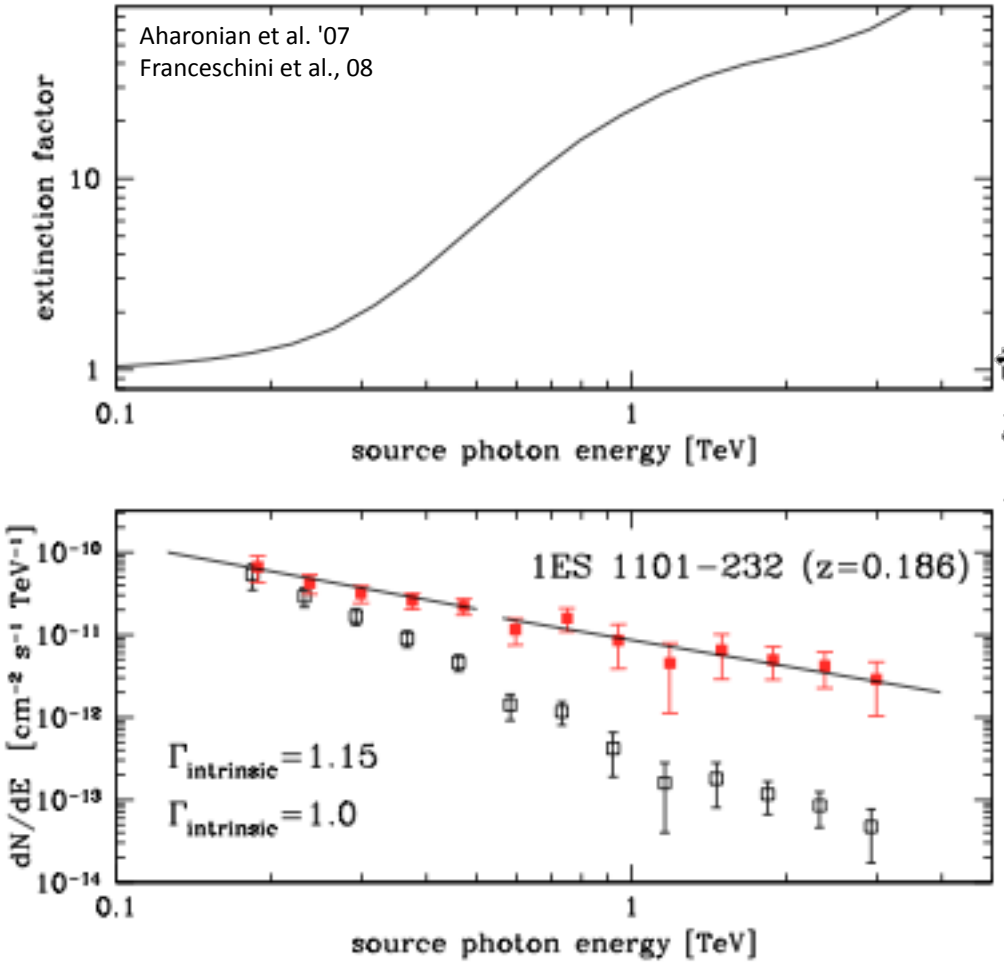


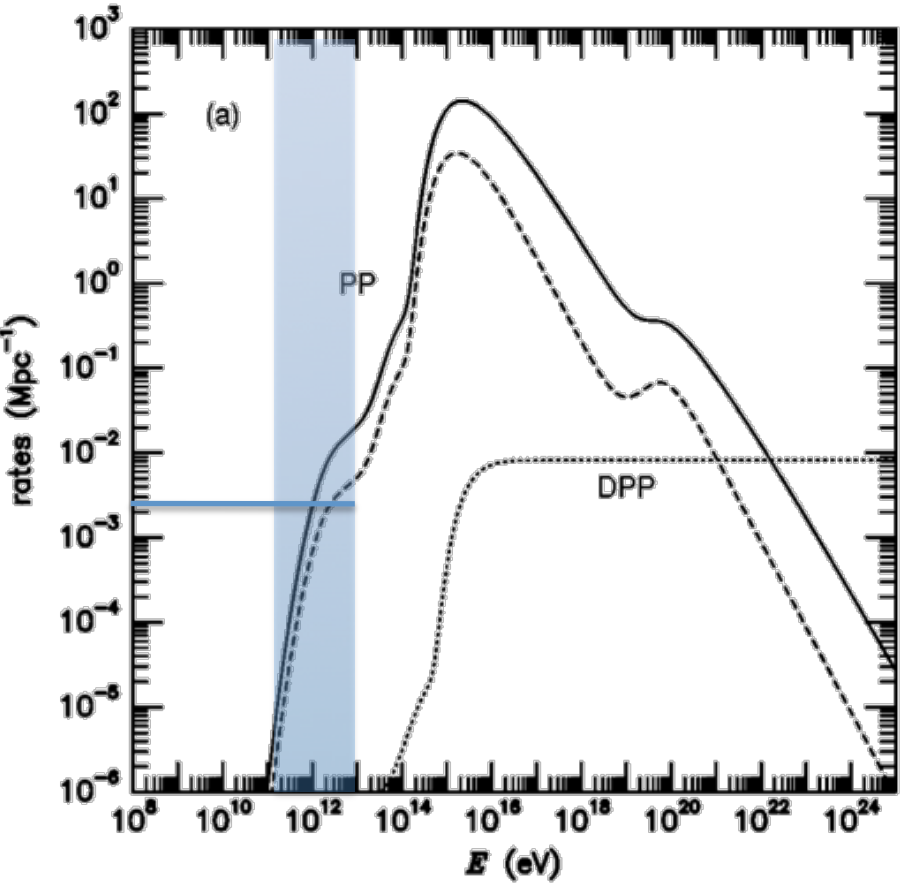


Most of the known extragalactic sources of multi-TeV gamma-rays are BL Lac type objects, which are presumably FR I radio galaxies with jets aligned along the line of sight.

Several nearby FR I galaxies (Cen A, M87, NGC 1275) with jets not aligned along the line of sight are also detected.

Attenuation of gamma-ray flux by pair production on EBL





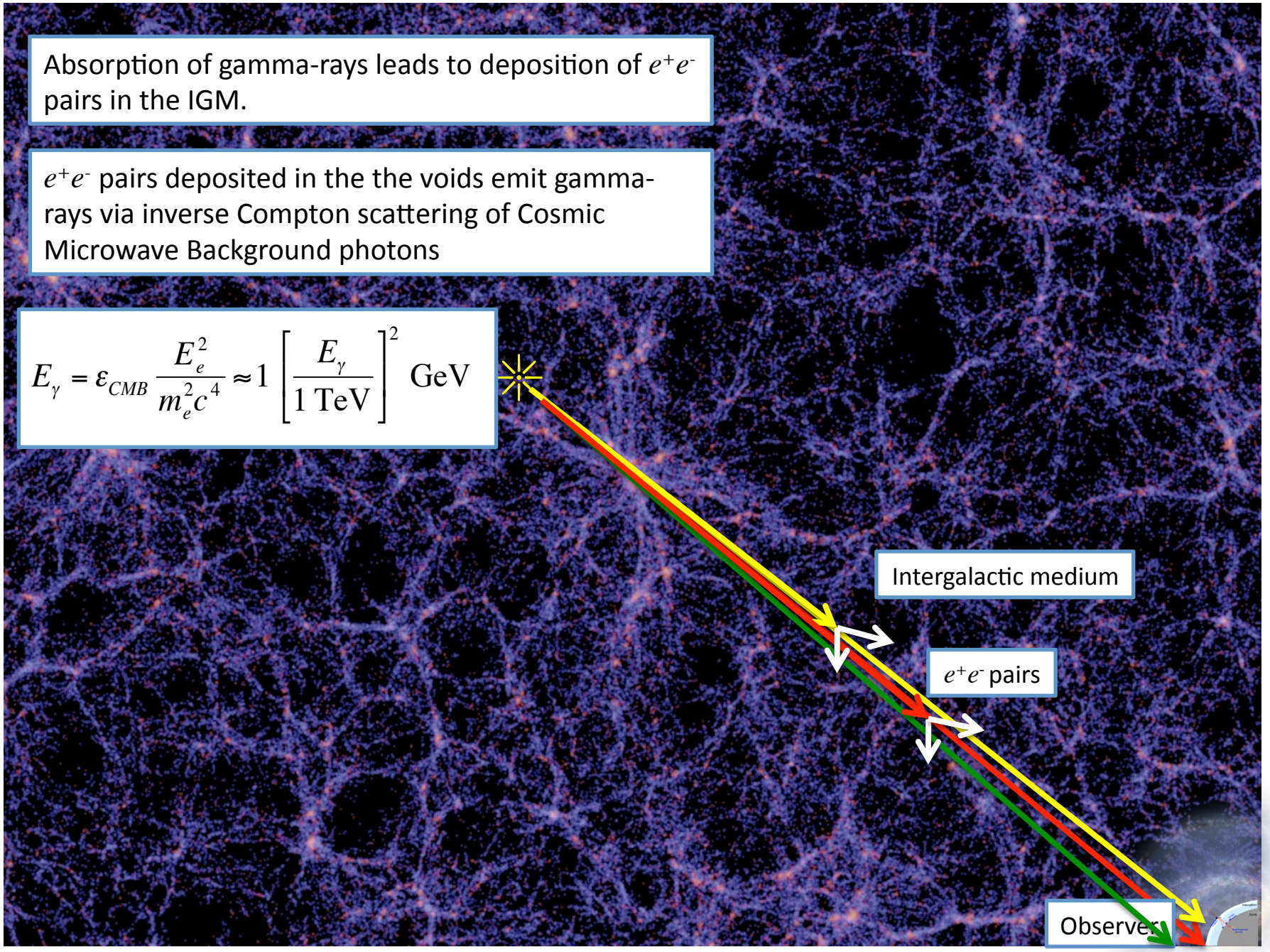
Pair production on EBL significantly suppresses gamma-ray flux from distant sources at the highest energies.

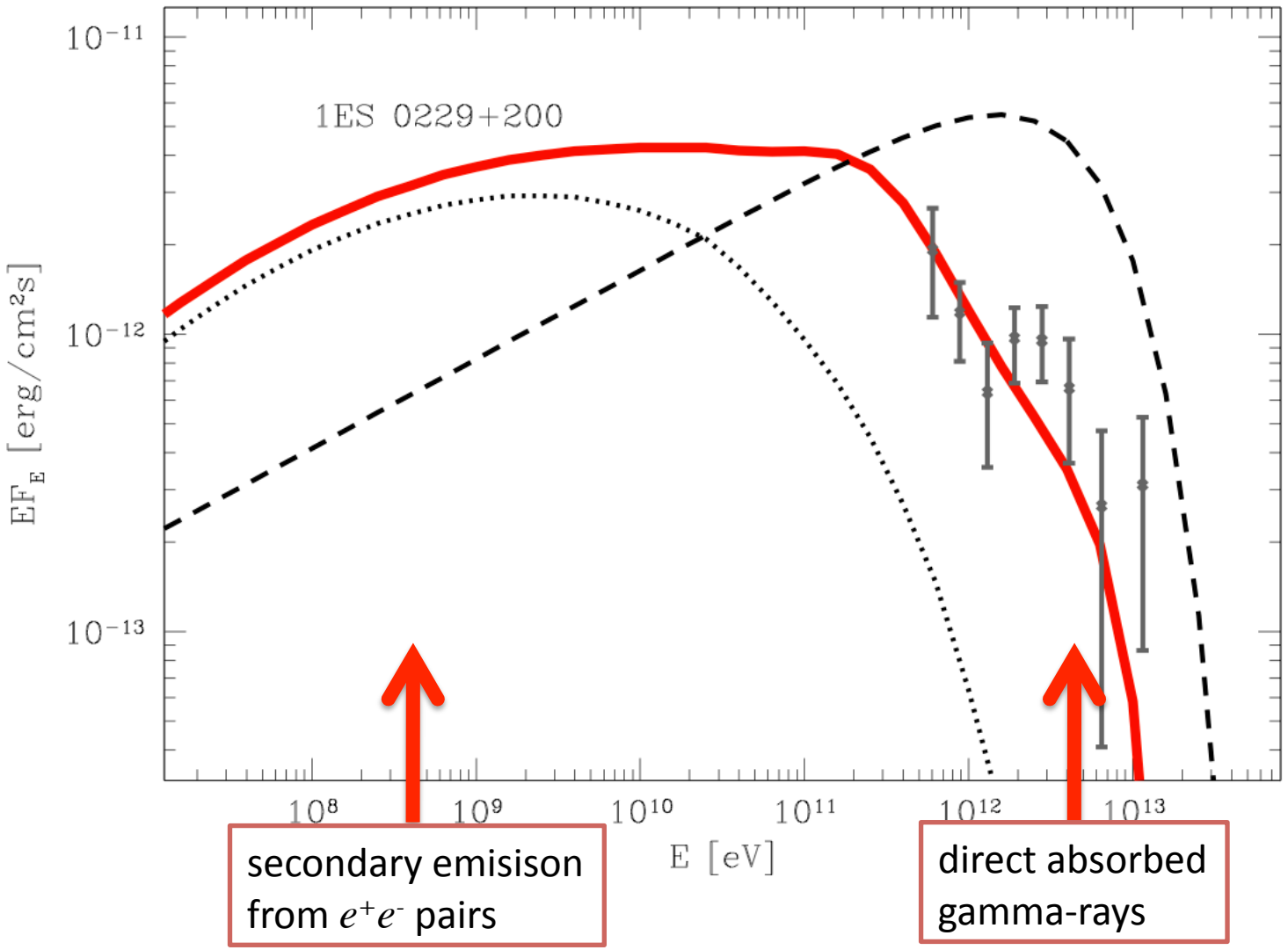
Electromagnetic cascade in IGM

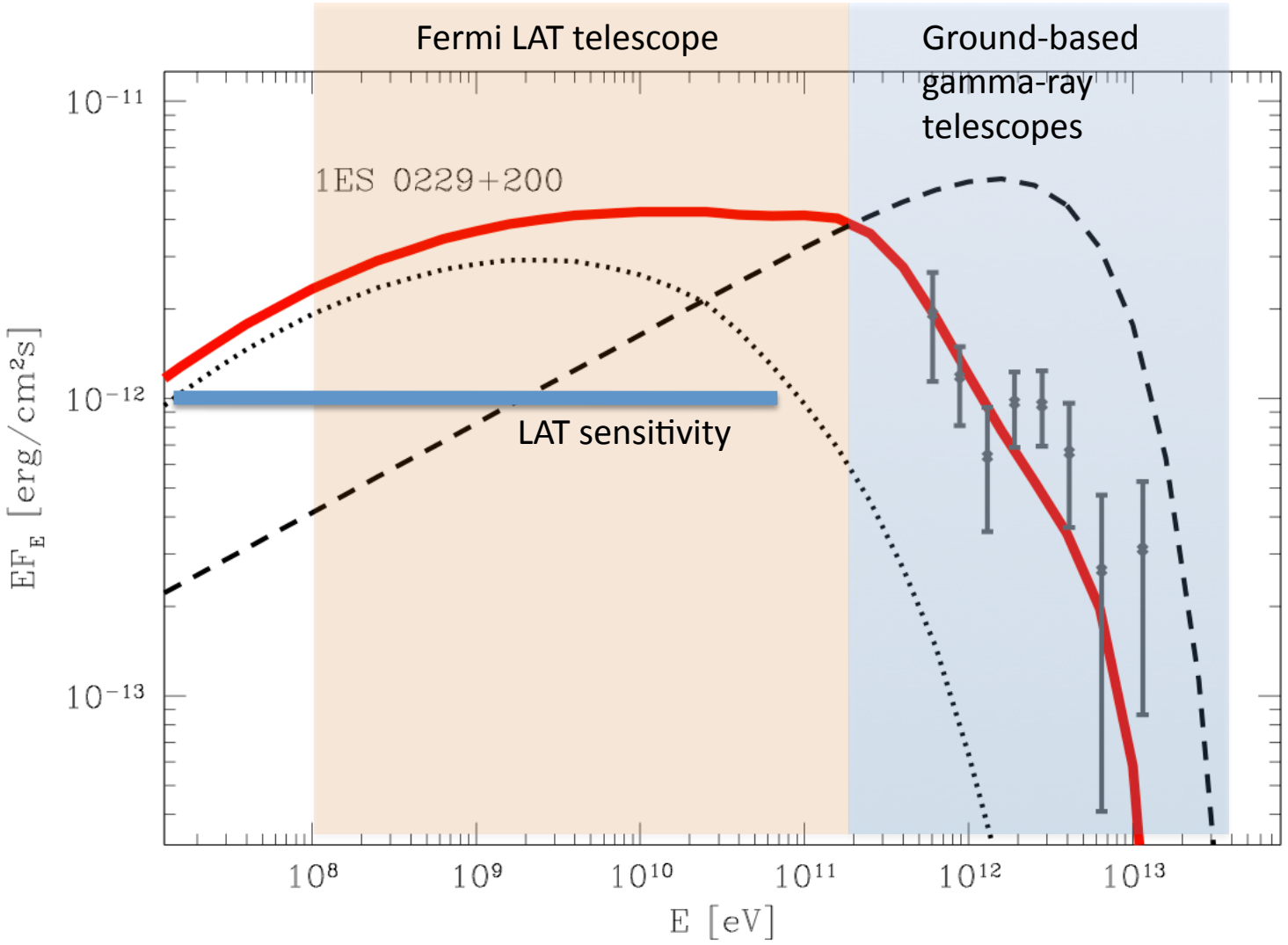
Absorption of gamma-rays leads to deposition of e^+e^- pairs in the IGM.

e^+e^- pairs deposited in the the voids emit gamma-rays via inverse Compton scattering of Cosmic Microwave Background photons

$$E_\gamma = \varepsilon_{CMB} \frac{E_e^2}{m_e^2 c^4} \approx 1 \left[\frac{E_\gamma}{1\ \mathrm{TeV}} \right]^2 \ \mathrm{GeV}$$

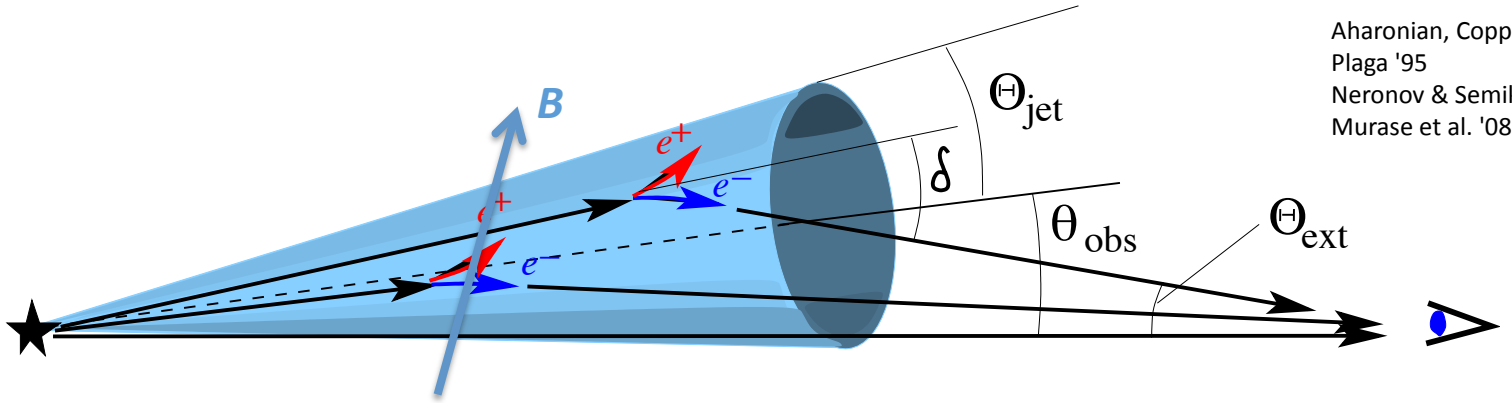



1ES 0229+200
10^{-11}
10^{-12}
10^{-13}
EF_E [erg/cm²s]
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
E [eV]
secondary emisison from e^+e^- pairs
direct absorbed gamma-rays



Gamma-ray emission from e^+e^- pairs in the voids of Large Scale Structure is potentially observable, either as a "secondary" component of spectra of individual sources, or as a component of extragalactic diffuse gamma-ray emission.

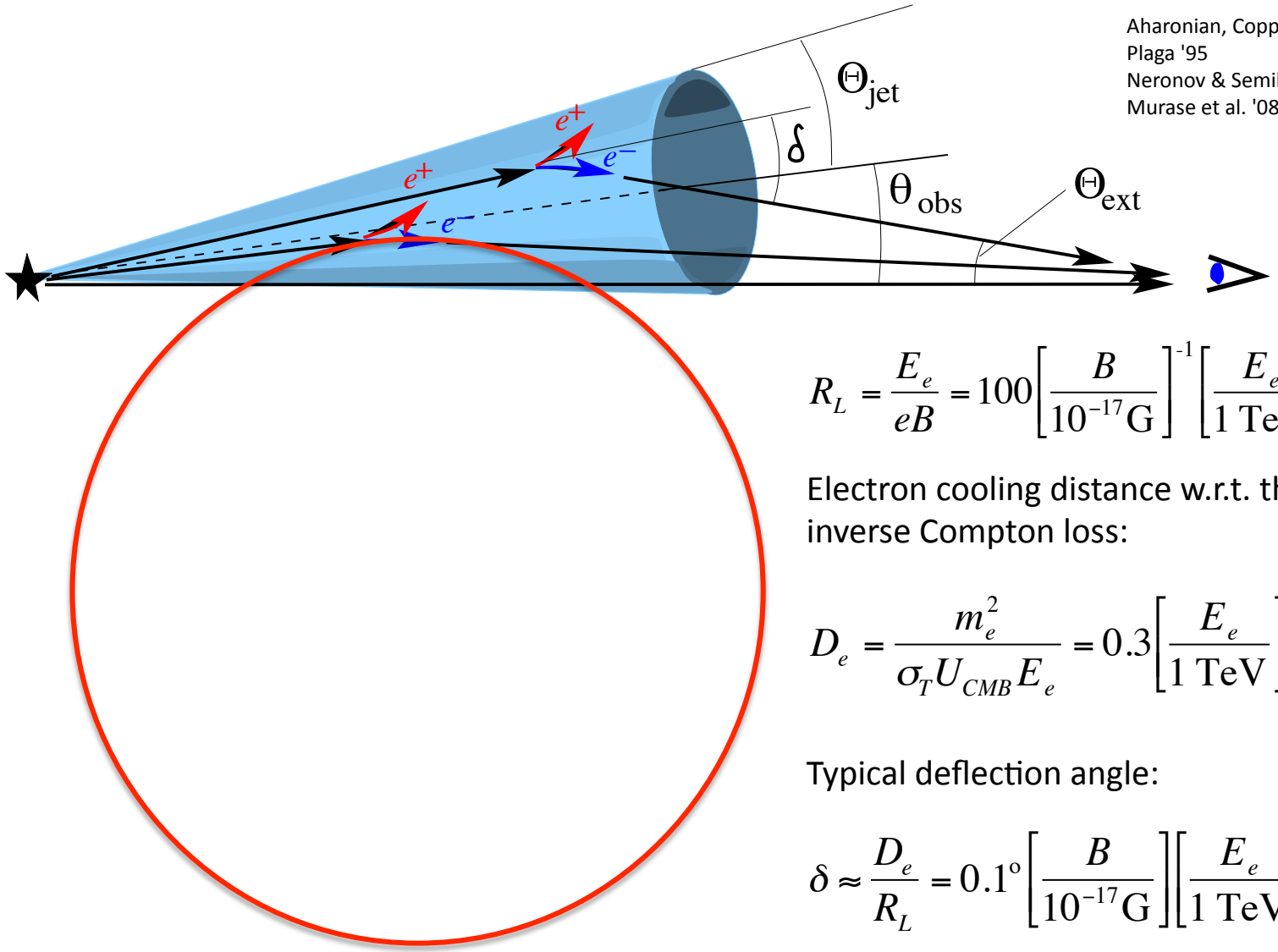
Magnetic fields in intergalactic medium



Aharonian, Coppi & Voelk '94
Plaga '95
Neronov & Semikoz '07, '09
Murase et al. '08

Magnetic field, if present in the voids of Large Scale Structure, deflects e^+e^- pairs so that secondary gamma-rays do not come from the same direction as the primary gamma-rays

Magnetic fields in intergalactic medium



Aharonian, Coppi & Voelk '94
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$$R_L = \frac{E_e}{eB} = 100\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]^{-1}\left[\frac{E_e}{1\ \mathrm{TeV}}\right]\ \mathrm{Mpc}$$

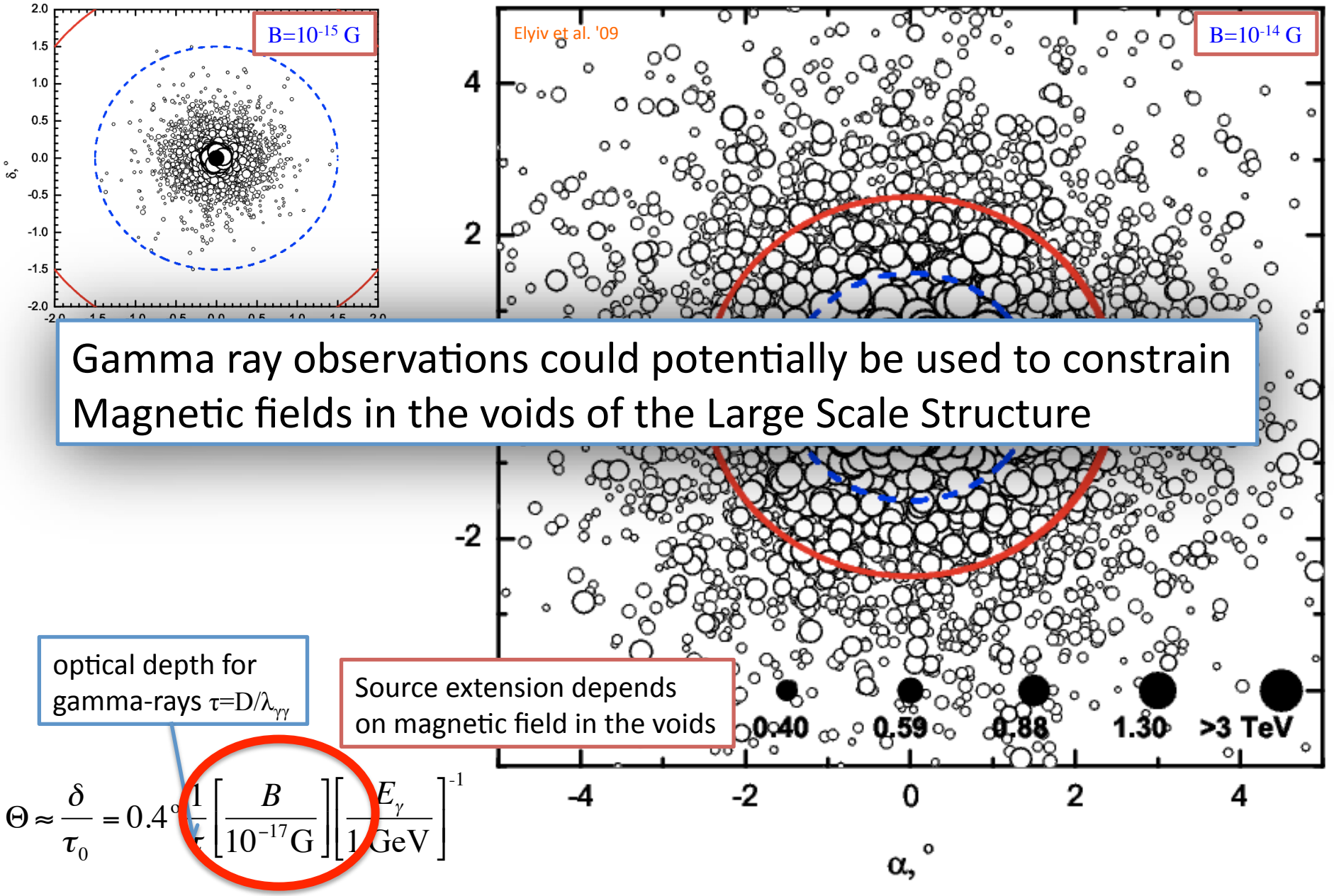
Electron cooling distance w.r.t. the inverse Compton loss:

$$D_e = \frac{m_e^2}{\sigma_T U_{CMB} E_e} = 0.3\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-1}\ \mathrm{Mpc}$$

Typical deflection angle:

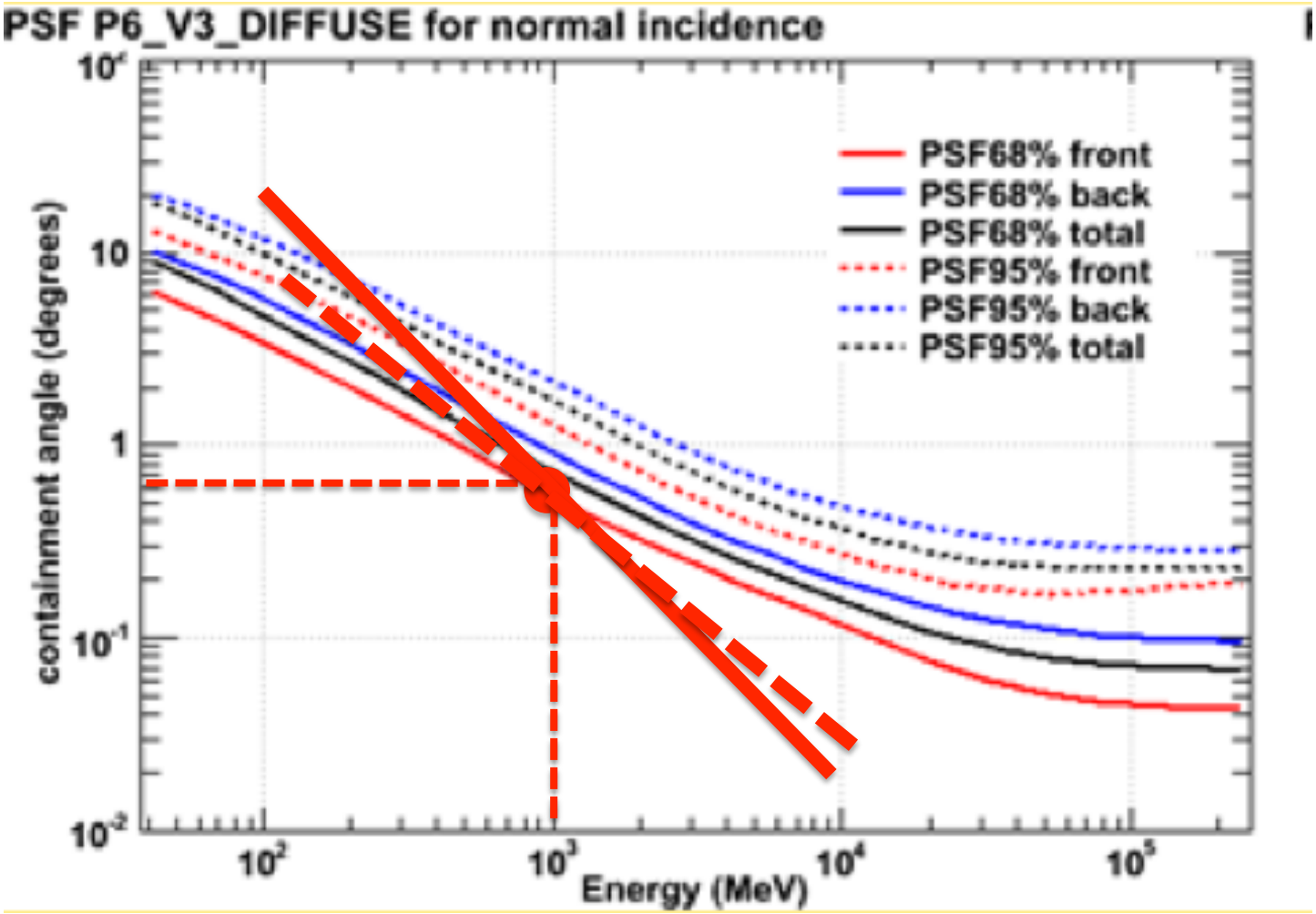
$$\delta \approx \frac{D_e}{R_L} = 0.1^{\circ}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-2}$$

Spatial structure of secondary emission



$$\Theta \approx \frac{\delta}{\tau_0} = 0.4^\circ \frac{1}{\tau}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_\gamma}{1\,\mathrm{GeV}}\right]^{-1}$$

Measurement of magnetic fields with Fermi



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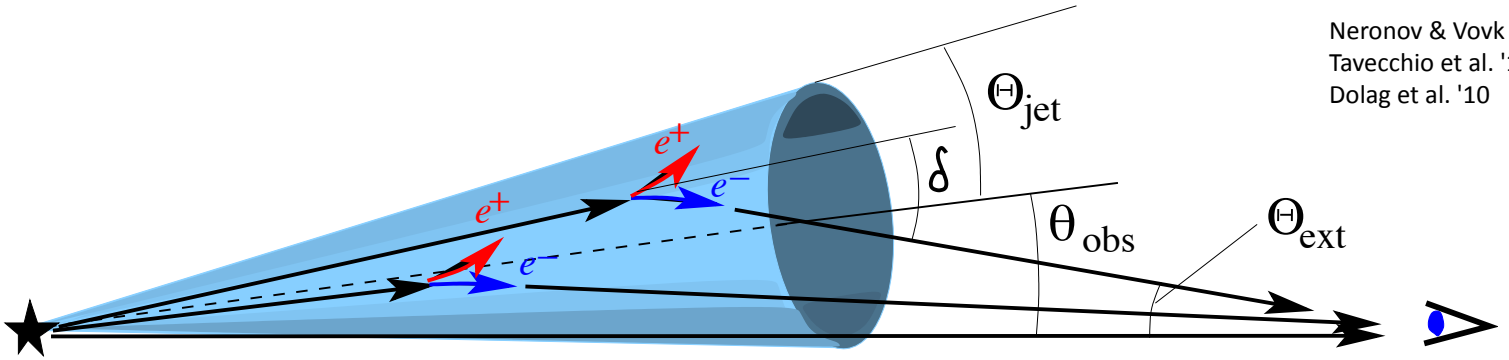
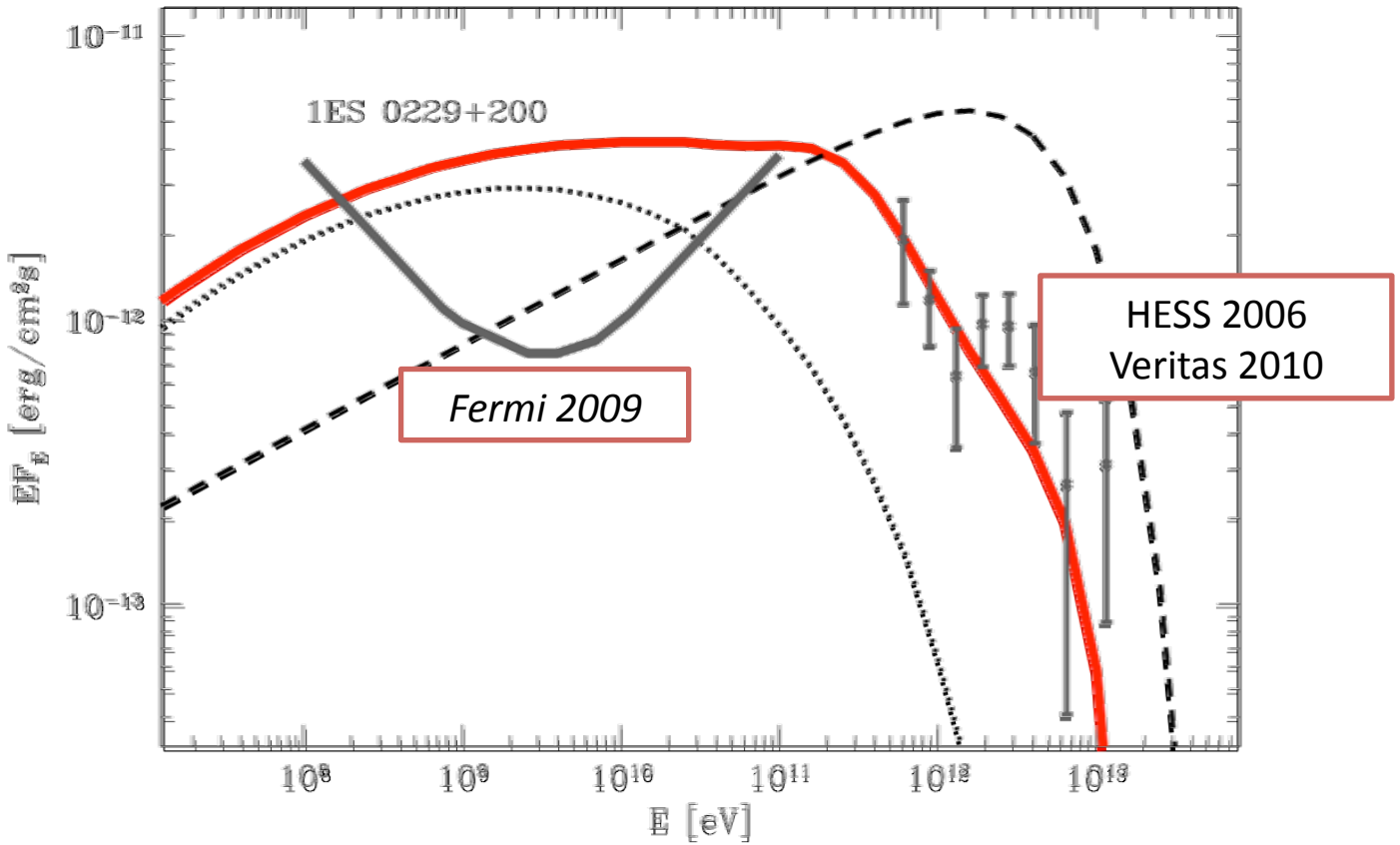
Fermi observations of extended emission from the cascade emission are sensitive to magnetic fields in the range $B \geq 10^{-17}$ G

Measurement of magnetic fields with Fermi

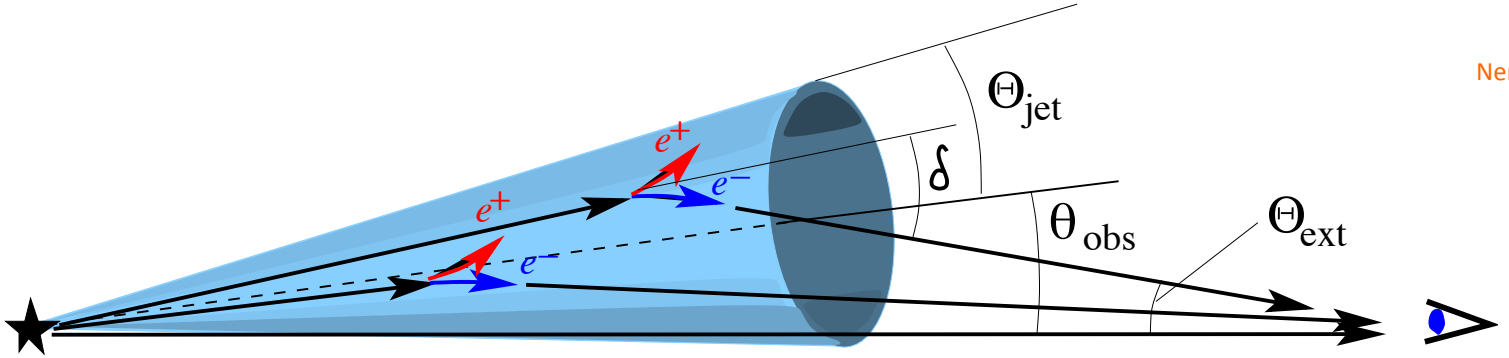
Neronov & Vovk '10
Tavecchio et al. '10
Dolag et al. '10

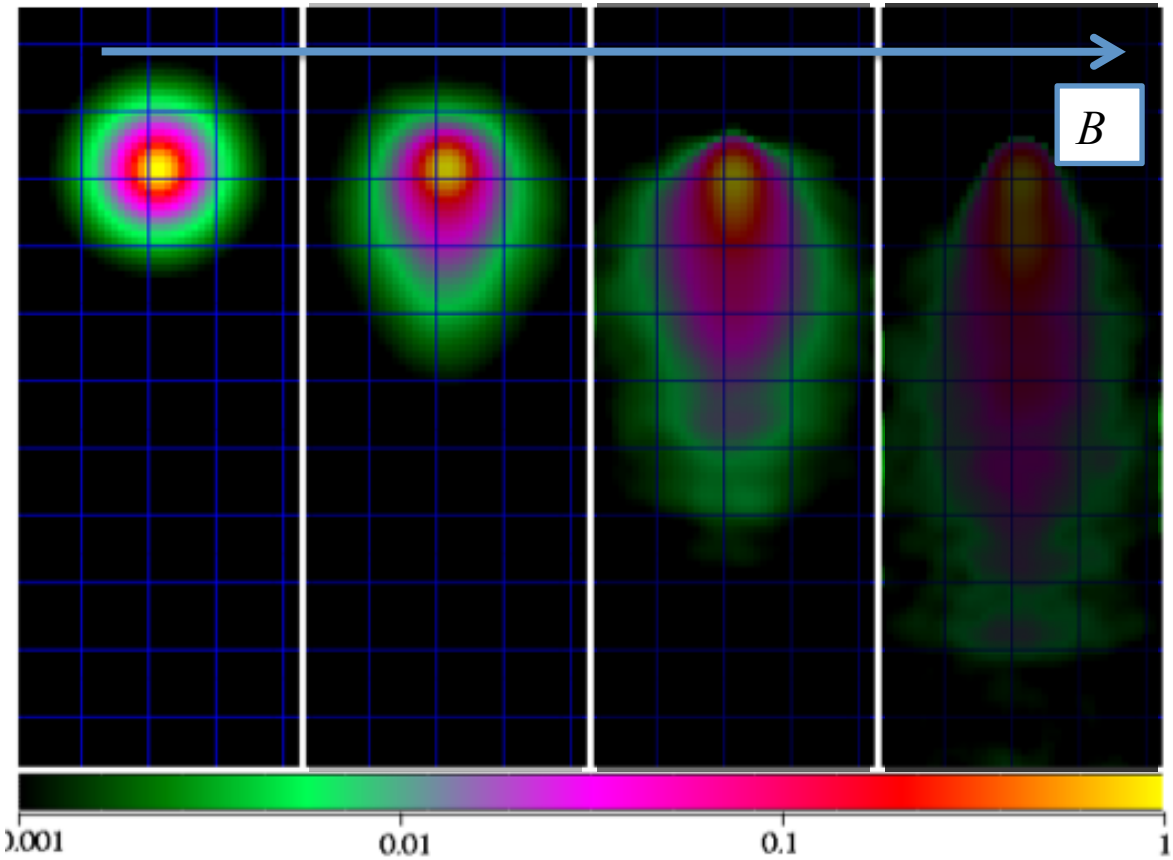




Suppression of cascade emission

Neronov et al. '10





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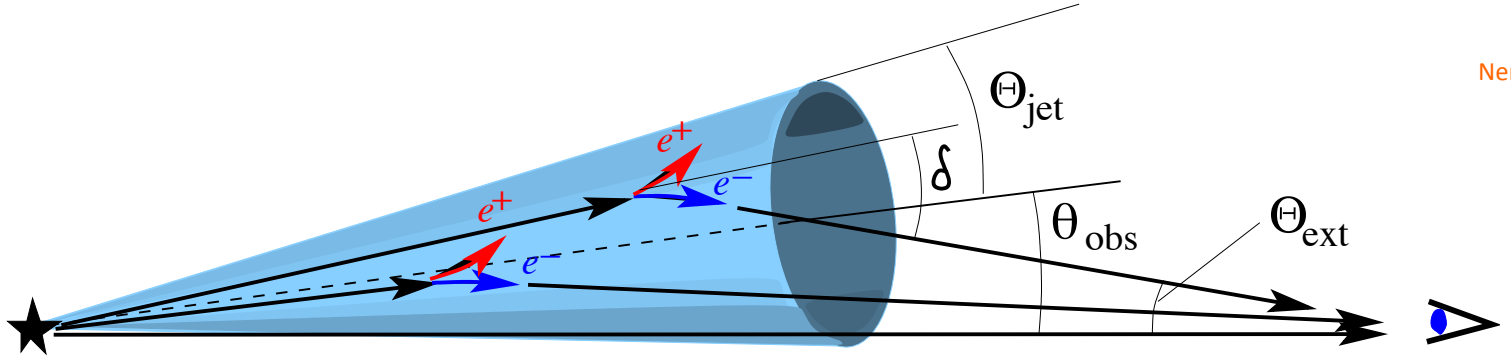
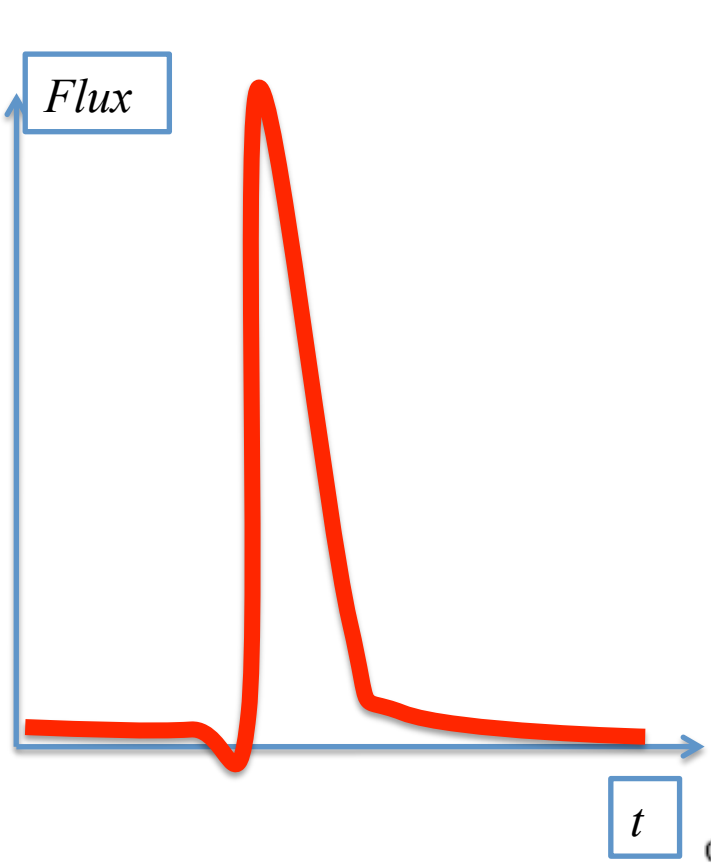
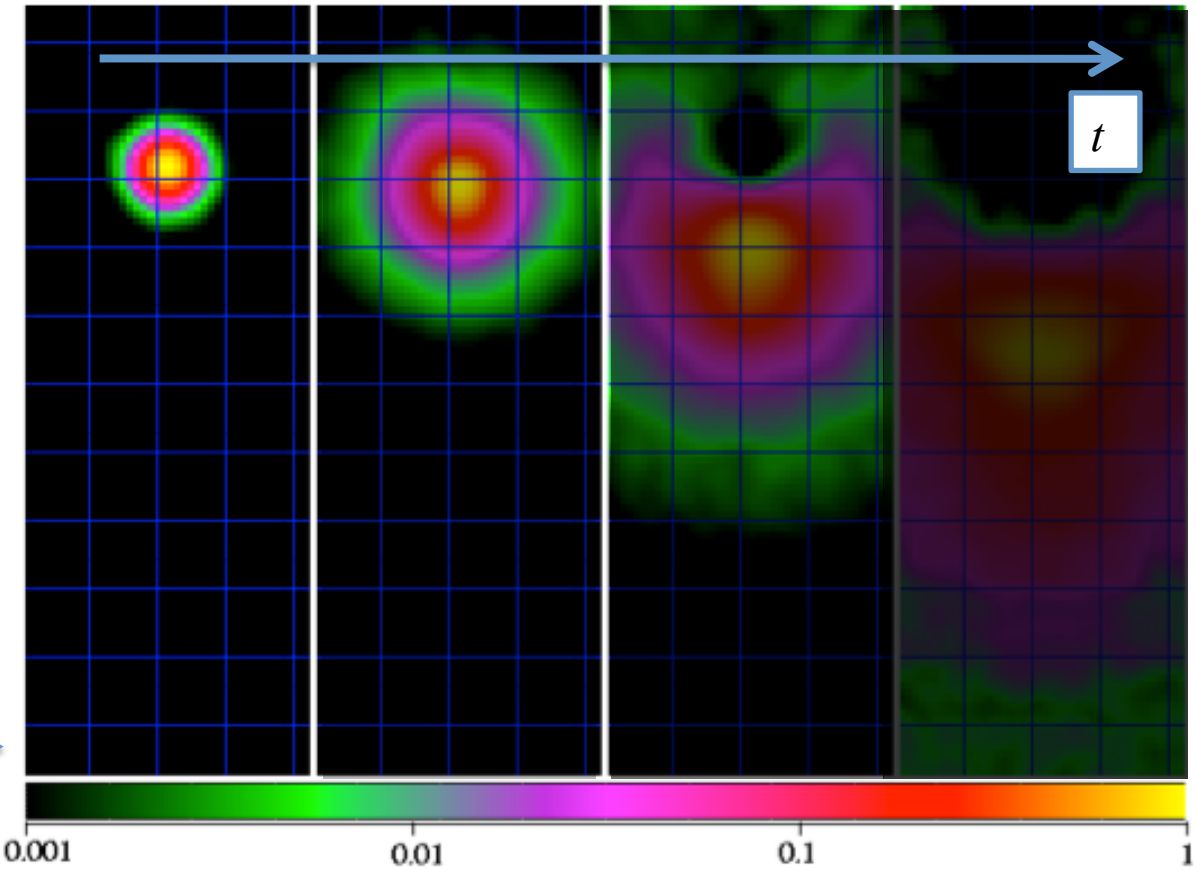


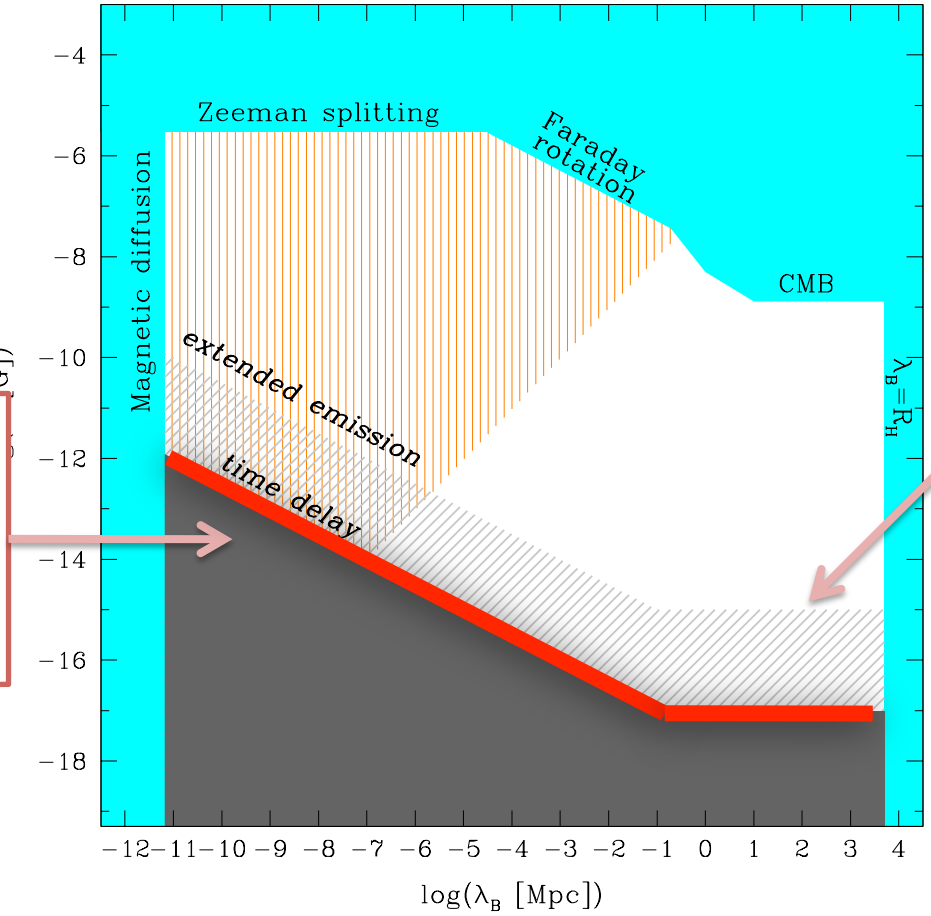




Lower bound on magnetic fields in IGM

Non-detection of cascade emission from several bright TeV extragalactic sources implies existence of non-zero magnetic field in the IGM

Gamma-ray data could be used to derive a **lower bound** on magnetic field in the intergalactic medium



Time delay of the cascade source is larger than assumed source activity period (= several years of gamma-ray observations)

Dermer et al. '10
Taylor, Vovk, Neronov '10

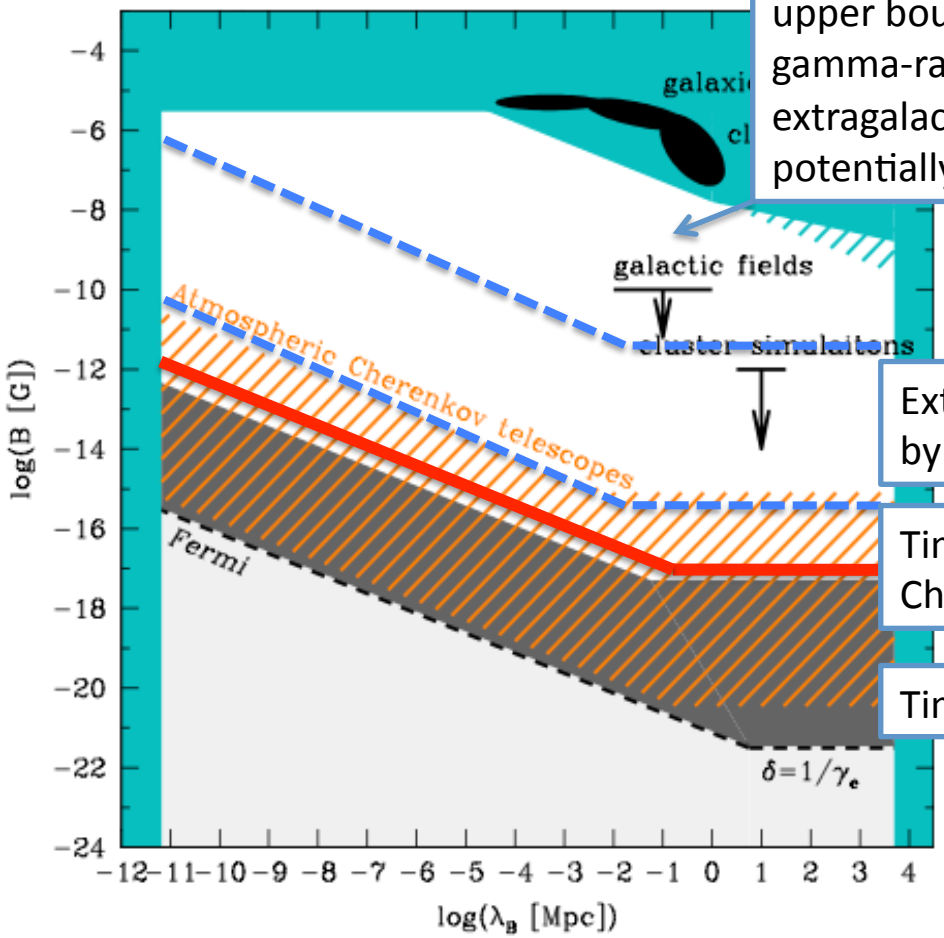
Extension of the cascade source is larger than point-spread function of Fermi telescope

Neronov & Vovk '10
Tavecchio et al. '10
Dolag et al. '10

Measurement of magnetic fields in IGM?

Deeper exposure with Fermi might finally lead to detection of extended emission around extragalactic TeV sources, if magnetic field in IGM is close to the derived lower bound.

Stronger magnetic fields could be probed by ground-based gamma-ray telescopes, able to search for time delayed and/or extended cascade emission at higher energies.



Magnetic fields close to the existing upper bounds lead to isotropized gamma-ray halos around extragalactic sources. This effect is potentially also detectable.

Extended emission measurable by Cherenkov telescopes

Time delay measurable by Cherenkov telescopes

Time delay measurable by LAT

Summary

Absorption of TeV gamma-rays in intergalactic space and subsequent re-emission of gamma-rays by e^+e^- pairs leads to appearance of extended and time delayed gamma-ray emission around extragalactic very-high-energy gamma-ray sources.

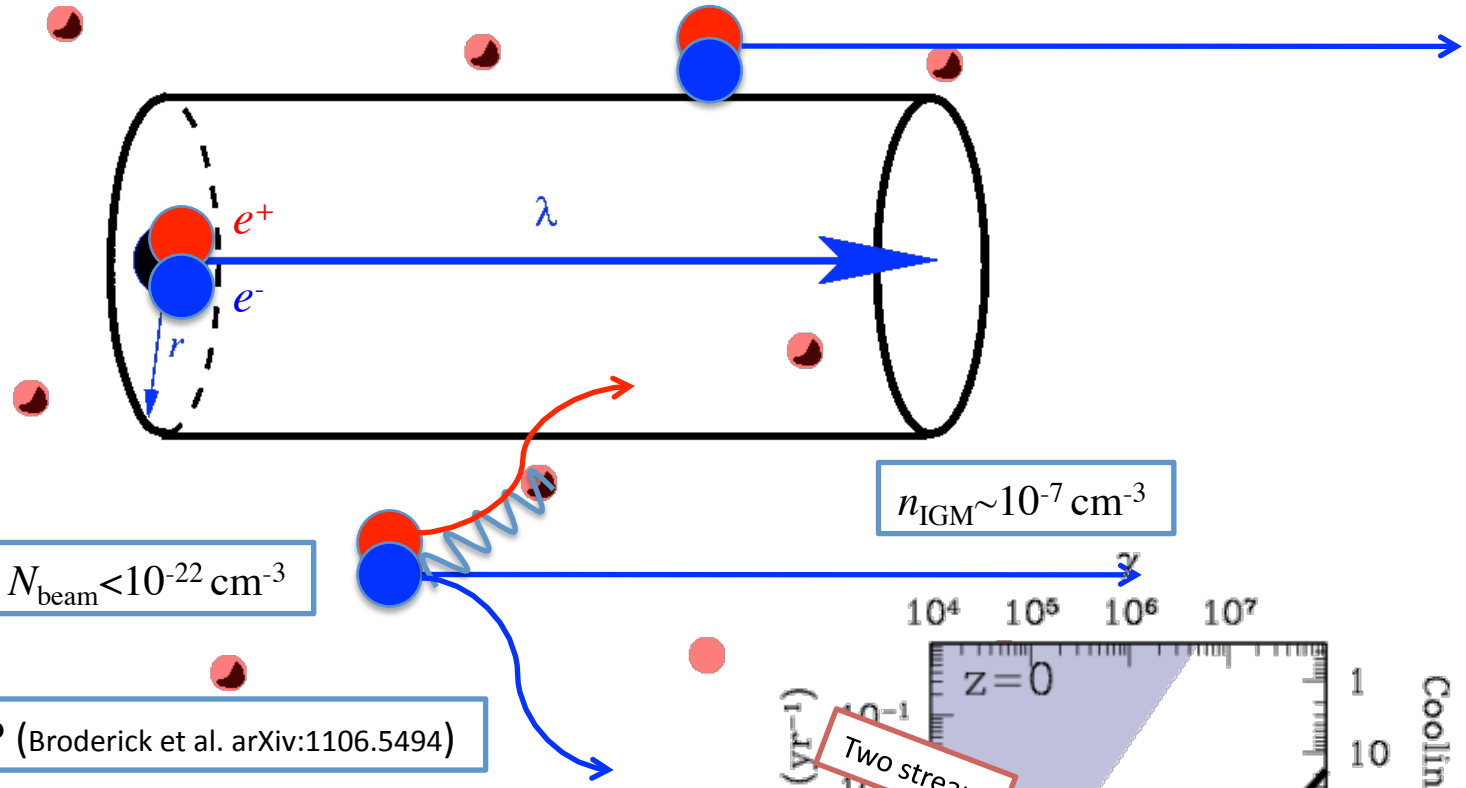
This emission could be detectable by Fermi and/or ground-based Cherenkov gamma-ray telescopes.

Detection of inverse Compton emission from e^+e^- pairs deposited in the intergalactic medium would provide information on the strength of magnetic field in the voids of Large Scale structure.

Non-detection of secondary emission from e^+e^- pairs by Fermi imposes a lower bound on the strength of magnetic field in the intergalactic medium at the level of $\sim 10^{-17}$ G if the signal is suppressed because of the time delay of the secondary emission and $\sim 10^{-16}$ G if suppression is due to the large extension of the secondary source.

Future observations (deeper exposures or more sensitive telescopes) will probe most of the range of possible magnetic field strengths in the intergalactic medium.

Alternative ways to suppress cascade emission?



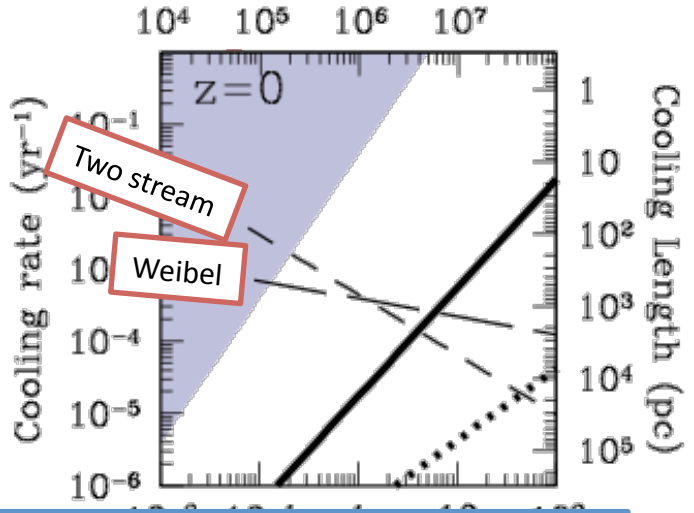
Plasma instabilities? (Broderick et al. arXiv:1106.5494)

Condition for growth of e.g. Weibel instability

$$\theta_{beam} < \gamma_e^{1/3}\left(\frac{n_{beam}}{n_{IGM}}\right)^{2/3} \sim 10^{-9}\left[\frac{\gamma_e}{10^6}\right]^{-2/3} << \frac{1}{\gamma_e}$$

is not satisfied…

Broderick et al. '11
Rabinak et al. '09



Similarly for "two stream" and/or "oblique" instabilities…

reference to numerical simulaitons…