Extragalactic magnetic fields
and
extended emission around γ-ray sources

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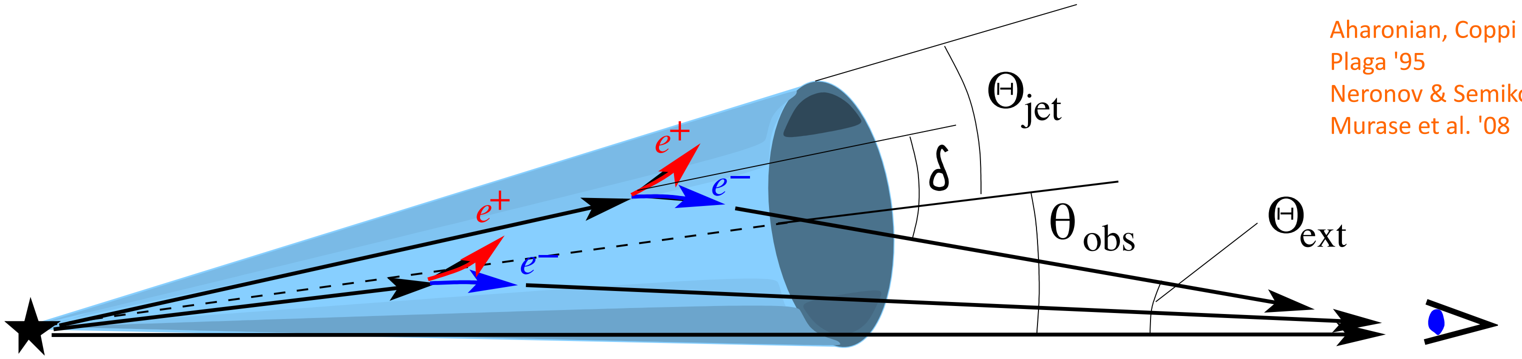
Magnetic fields and gamma-ray induced cascades in the IGM



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

Absorption of Very-High-Energy (VHE, $E \sim 0.1$-10 TeV) gamma-rays on Extragalactic Background Light (EBL, $E \sim 0.1$-10 eV) photons leads to deposition of e^+e^- pairs in the intergalactic medium.

e^+e^- pairs re-emit gamma-rays via inverse Compton scattering of CMB photons. Electromagnetic cascade develops along the gamma-ray beam.

Secondary cascade emission could be detected by gamma-ray telescopes. Deflections of trajectories of e^+e^- pairs by magnetic fields make the cascade emission signal to appear as

- extended and
- time-delayed

emission around the primary extragalactic gamma-ray source.

Magnetic fields and gamma-ray induced cascades in the IGM

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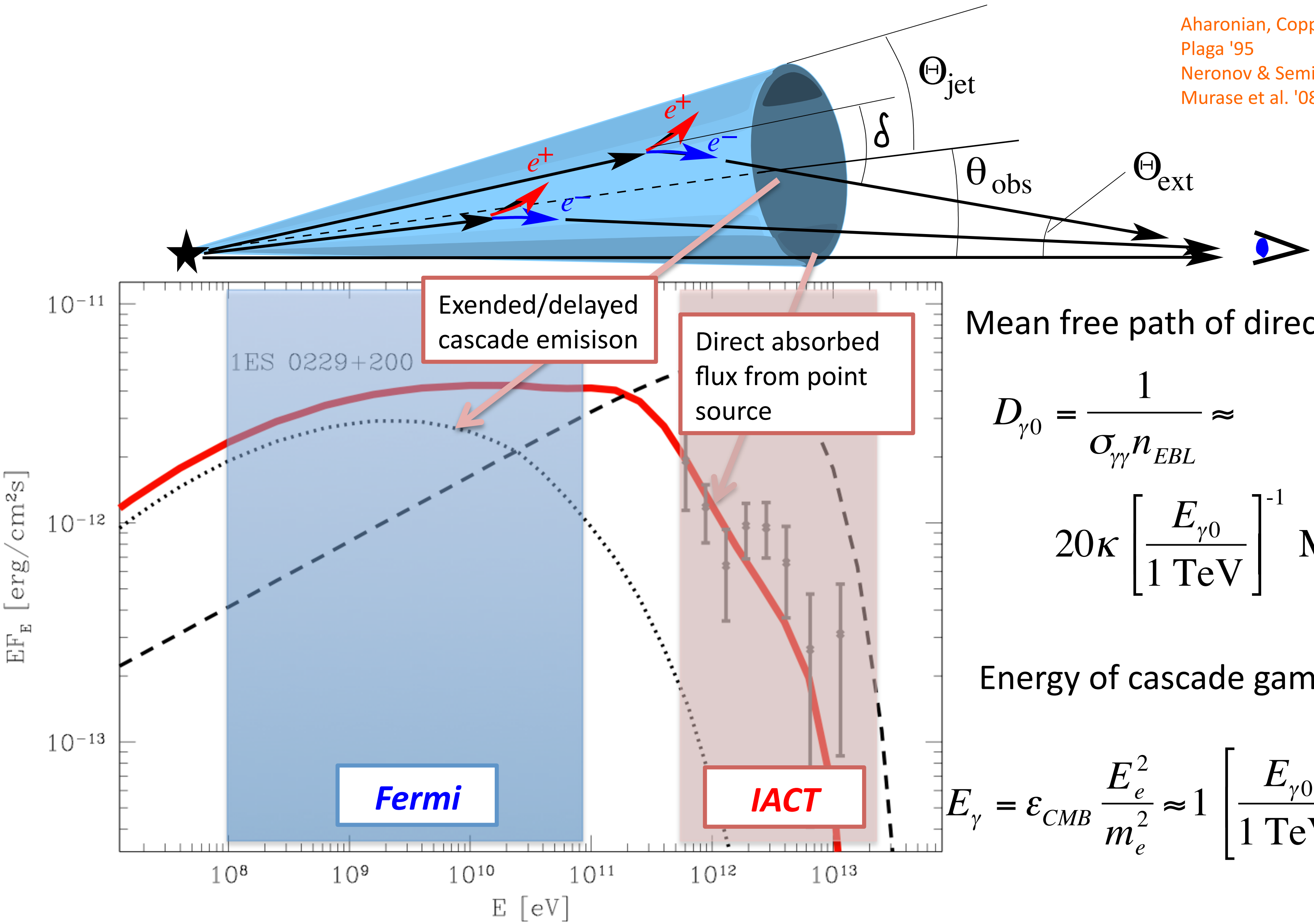

Mean free path of direct γ-rays:

$$D_{\gamma 0} = \frac{1}{\sigma_{\gamma\gamma} n_{EBL}} \approx$$

$$20\kappa \left[\frac{E_{\gamma 0}}{1\ \mathrm{TeV}}\right]^{-1} \mathrm{Mpc}$$

Energy of cascade gamma-rays:

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

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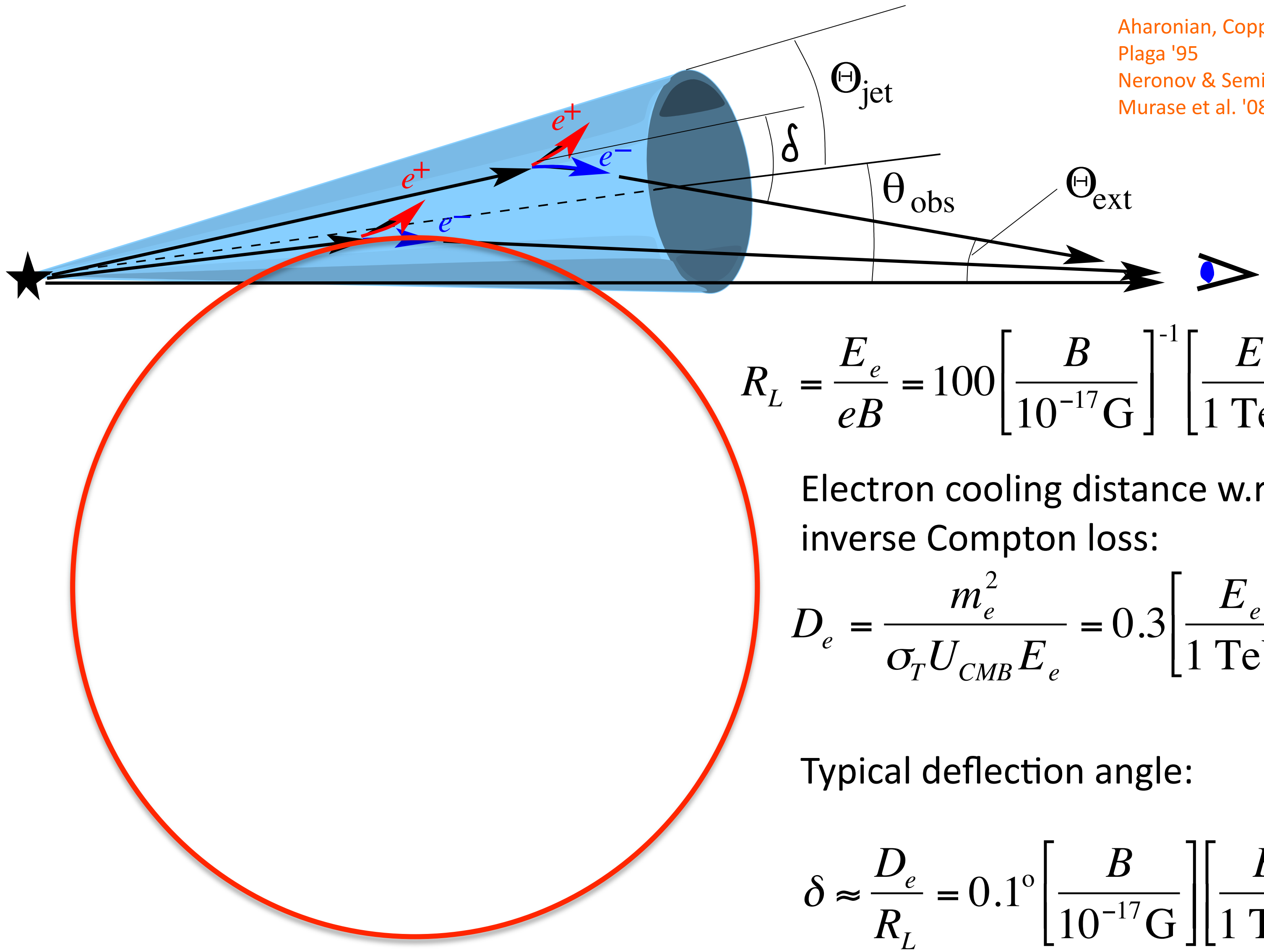


$$R_L = \frac{E_e}{eB} = 100\left[\frac{B}{10^{-17}\mathrm{G}}\right]^{-1}\left[\frac{E_e}{1\ \mathrm{TeV}}\right]\mathrm{Mpc}$$

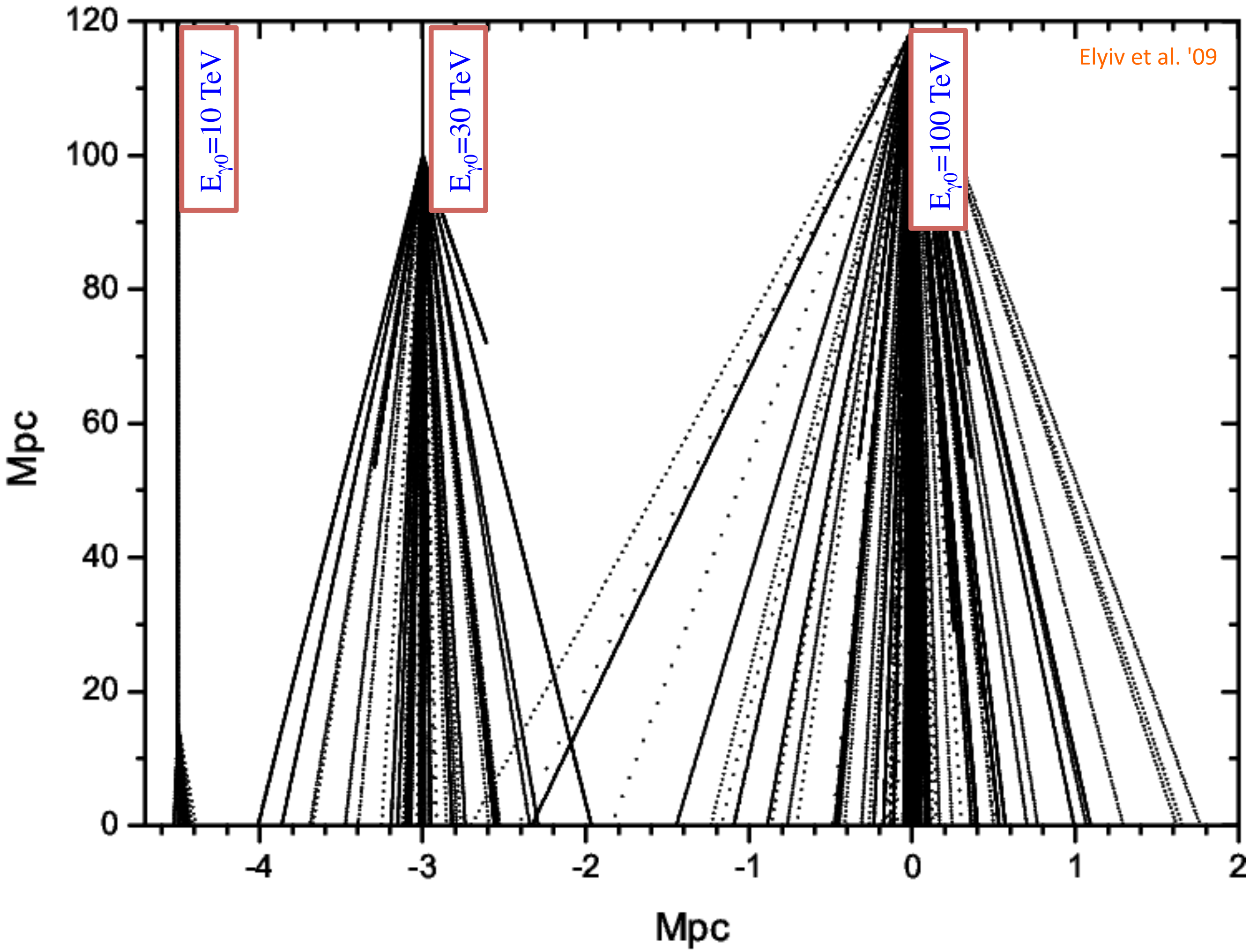
Electron cooling distance w.r.t. the inverse Compton loss:

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

Typical deflection angle:

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

Spatial structure of the cascade



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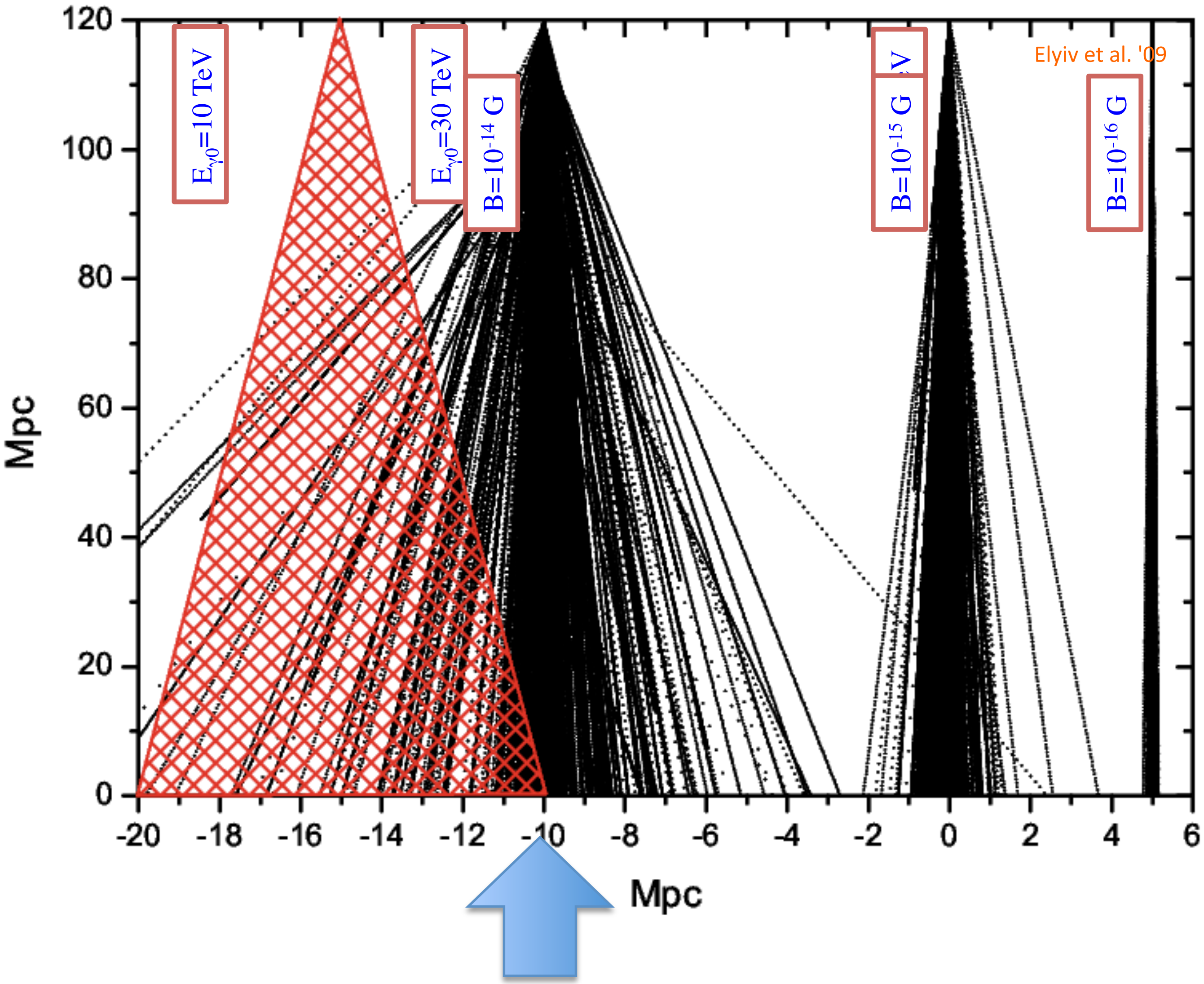

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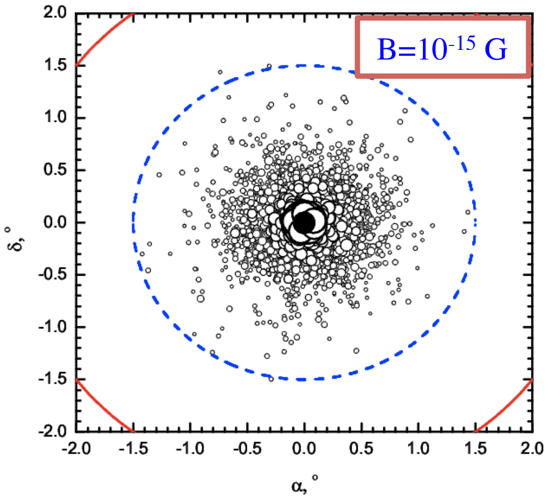
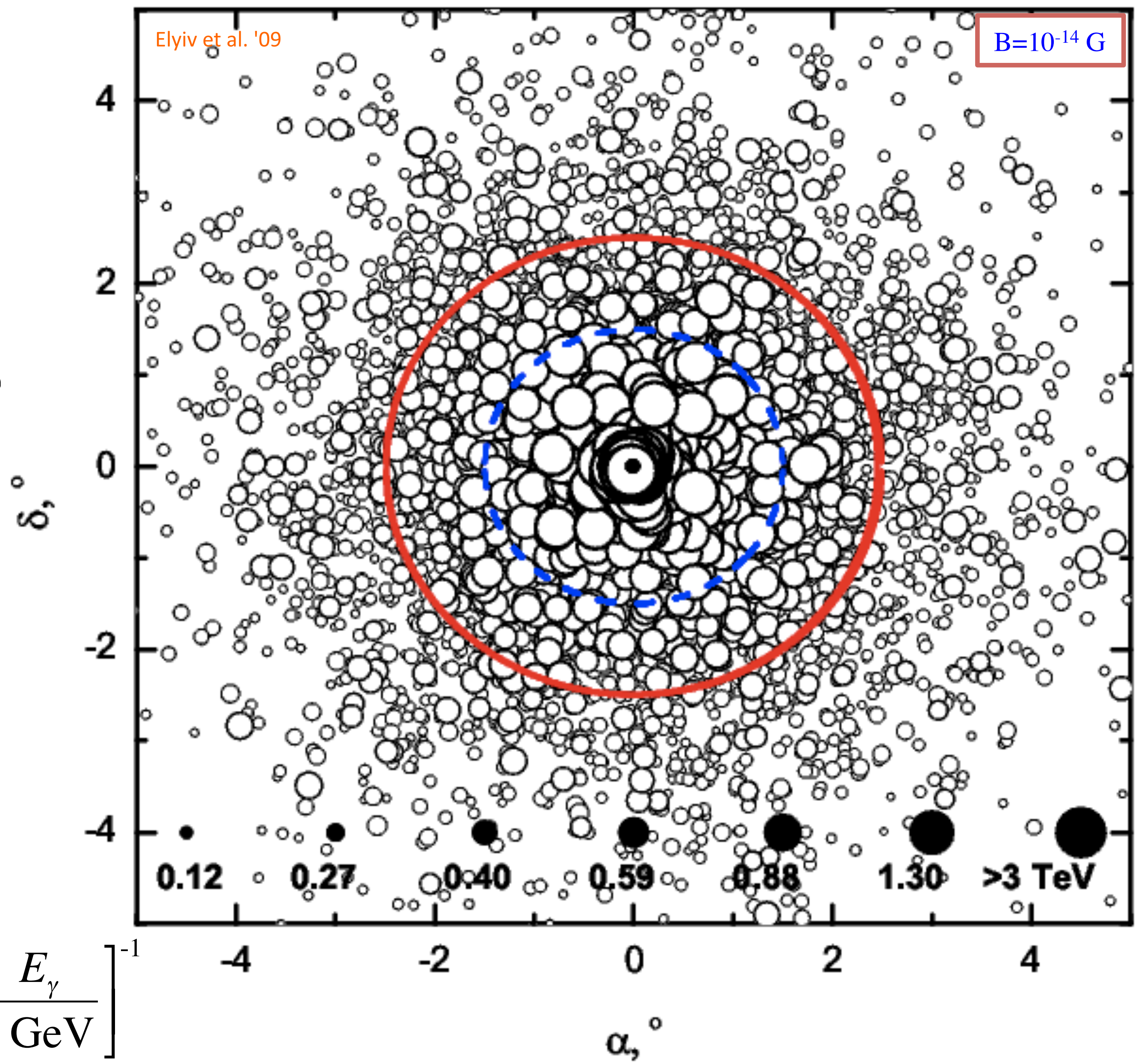
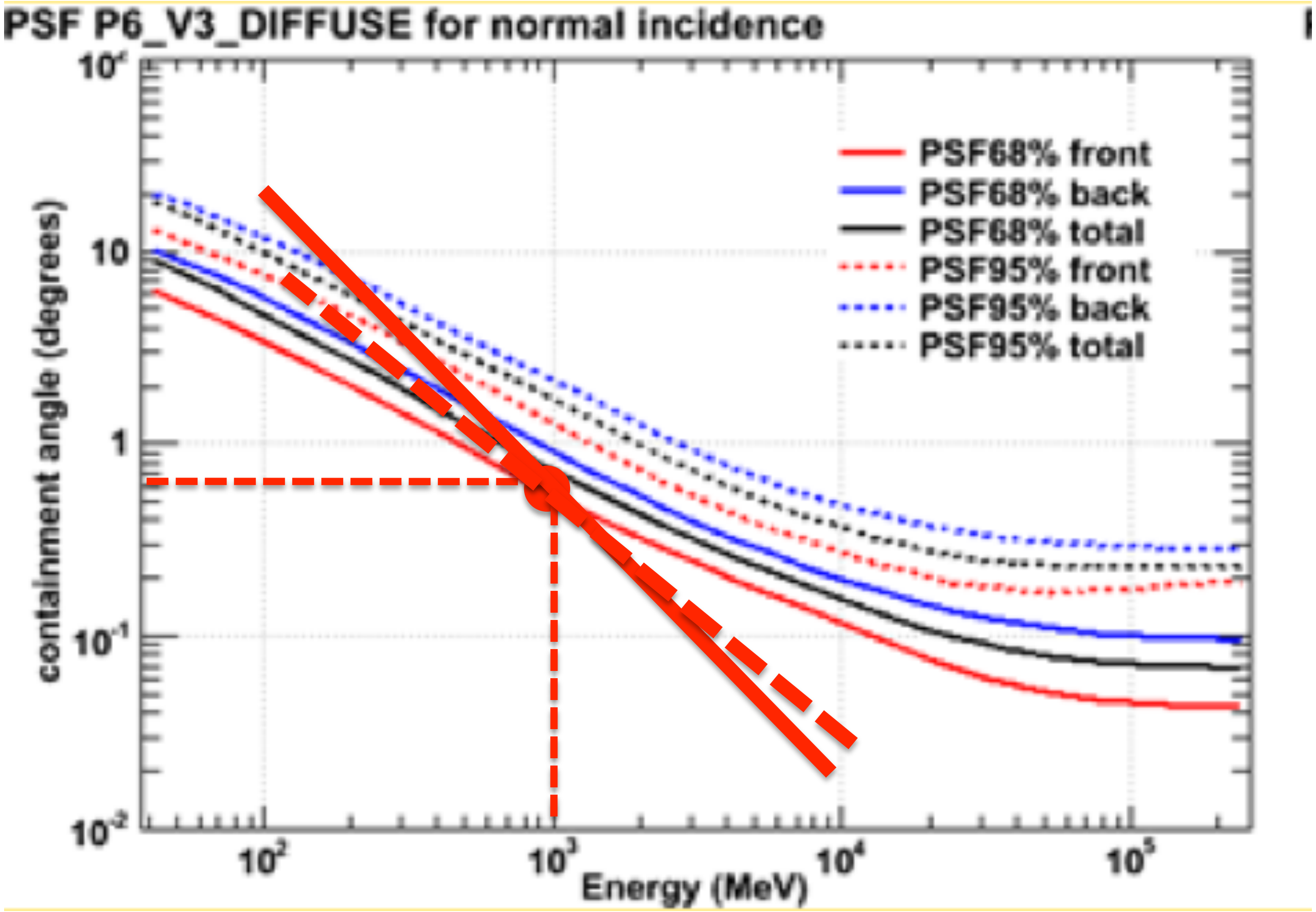




$$\Theta \approx \frac{\delta}{\tau_0} = 0.4^{\circ}\,\frac{1}{\tau}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_\gamma}{1\ \mathrm{GeV}}\right]^{-1}$$

Detection of extended emission with Fermi



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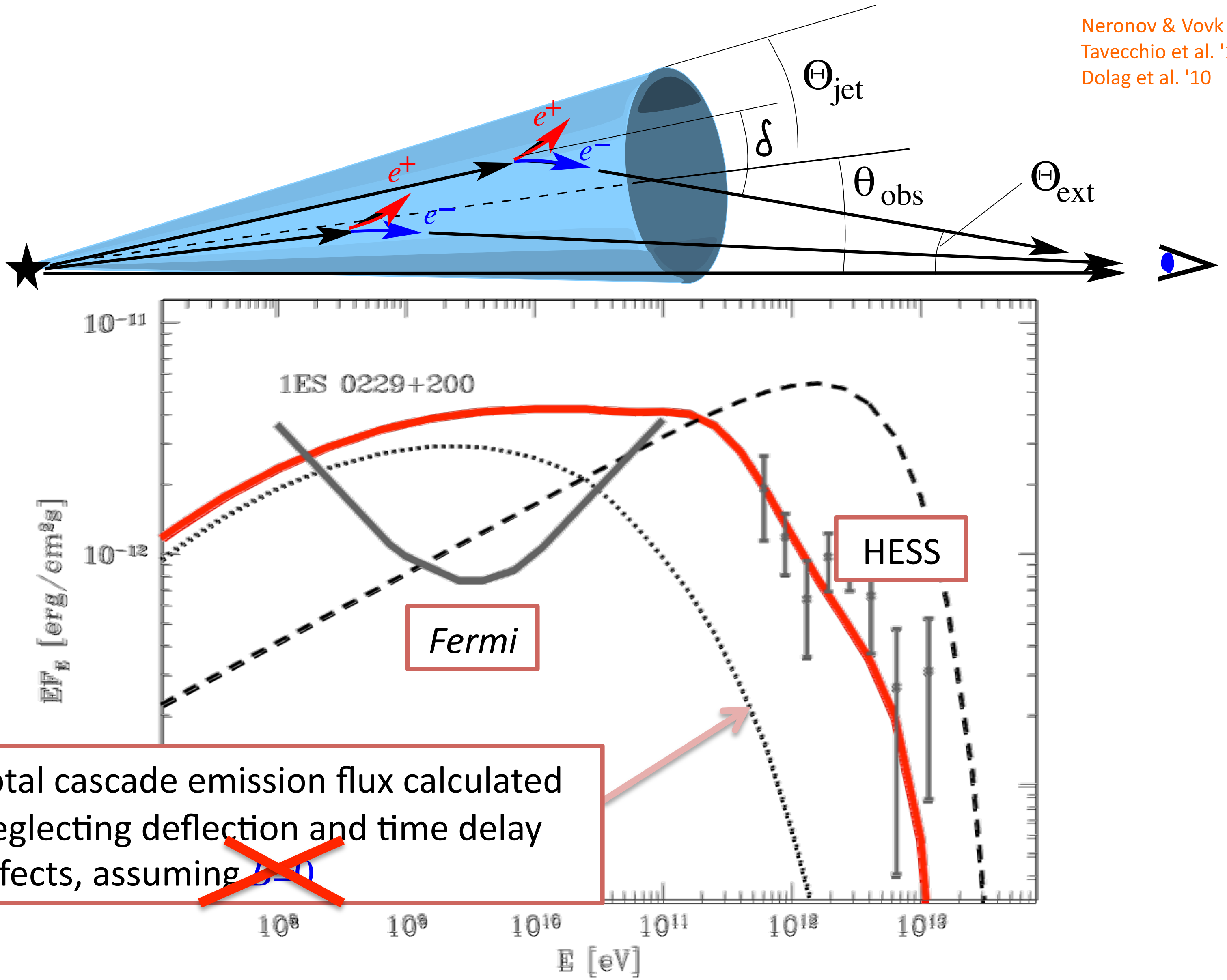
Fermi observations of extended emission from the cascade emission are sensitive to magnetic fields in the range $B \geq 10^{-17}$ G

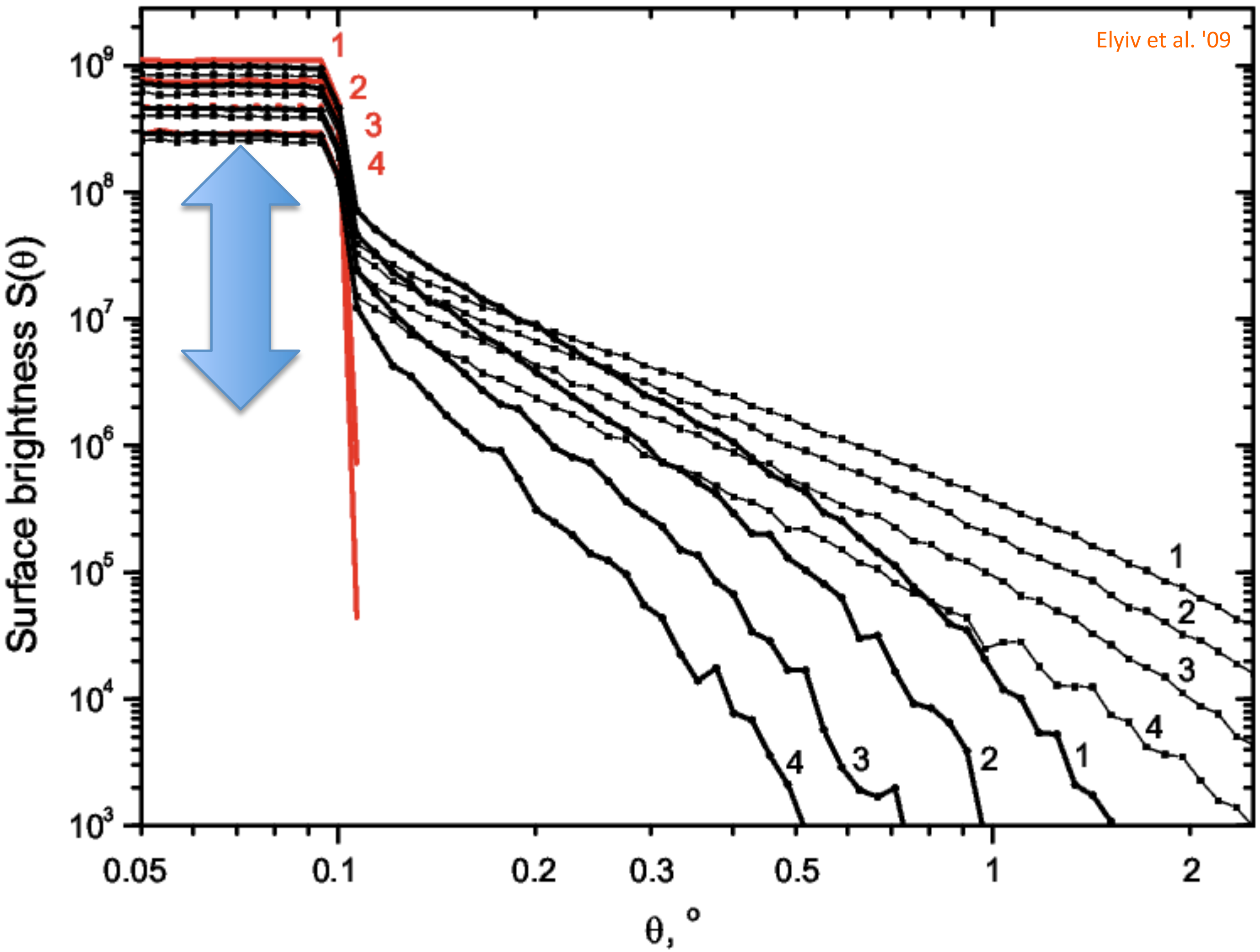
Detection of extended emission with Fermi

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



Total cascade emission flux calculated neglecting deflection and time delay effects, assuming ~~$\delta=0$~~

Halos around Fermi blazars?



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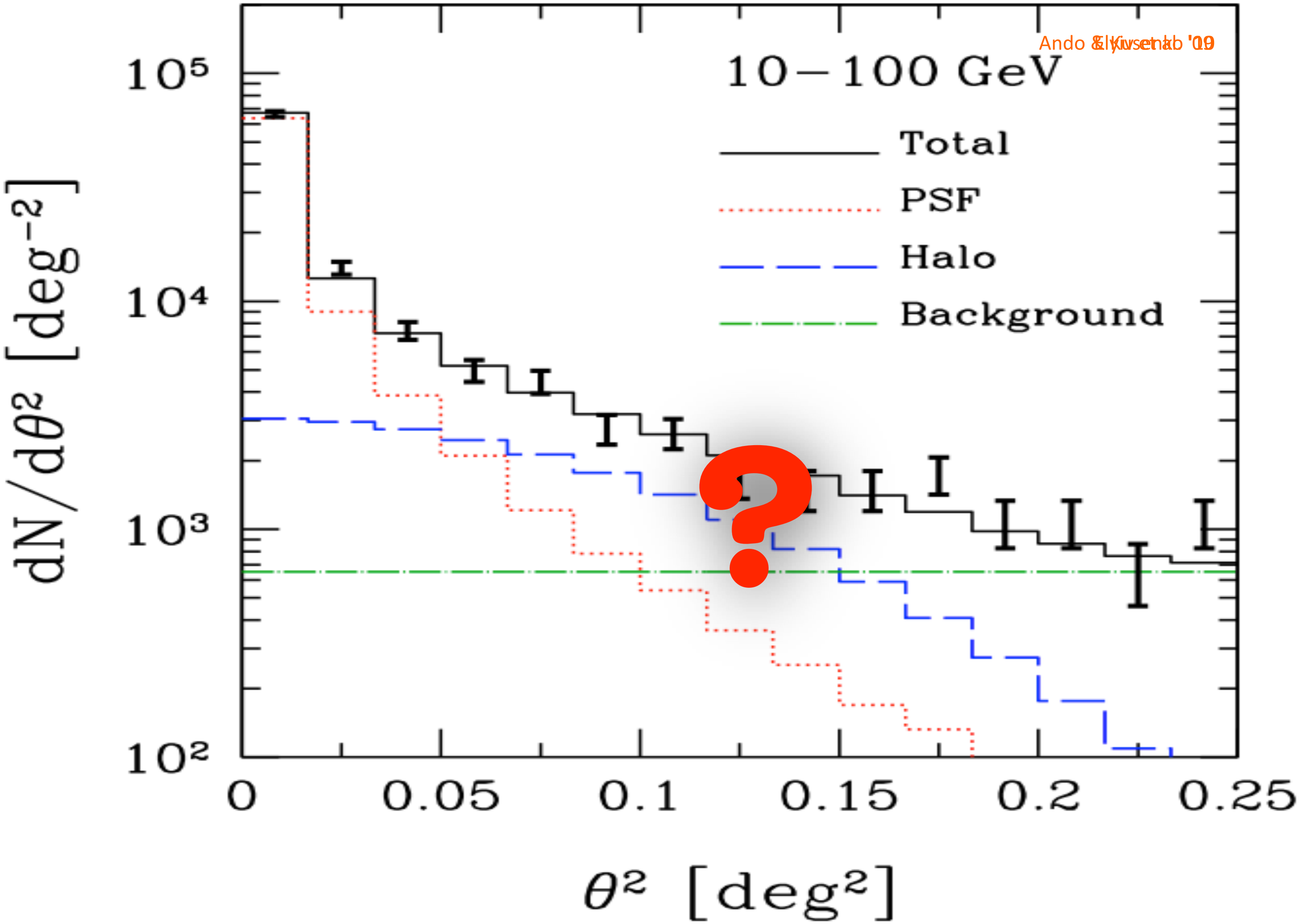

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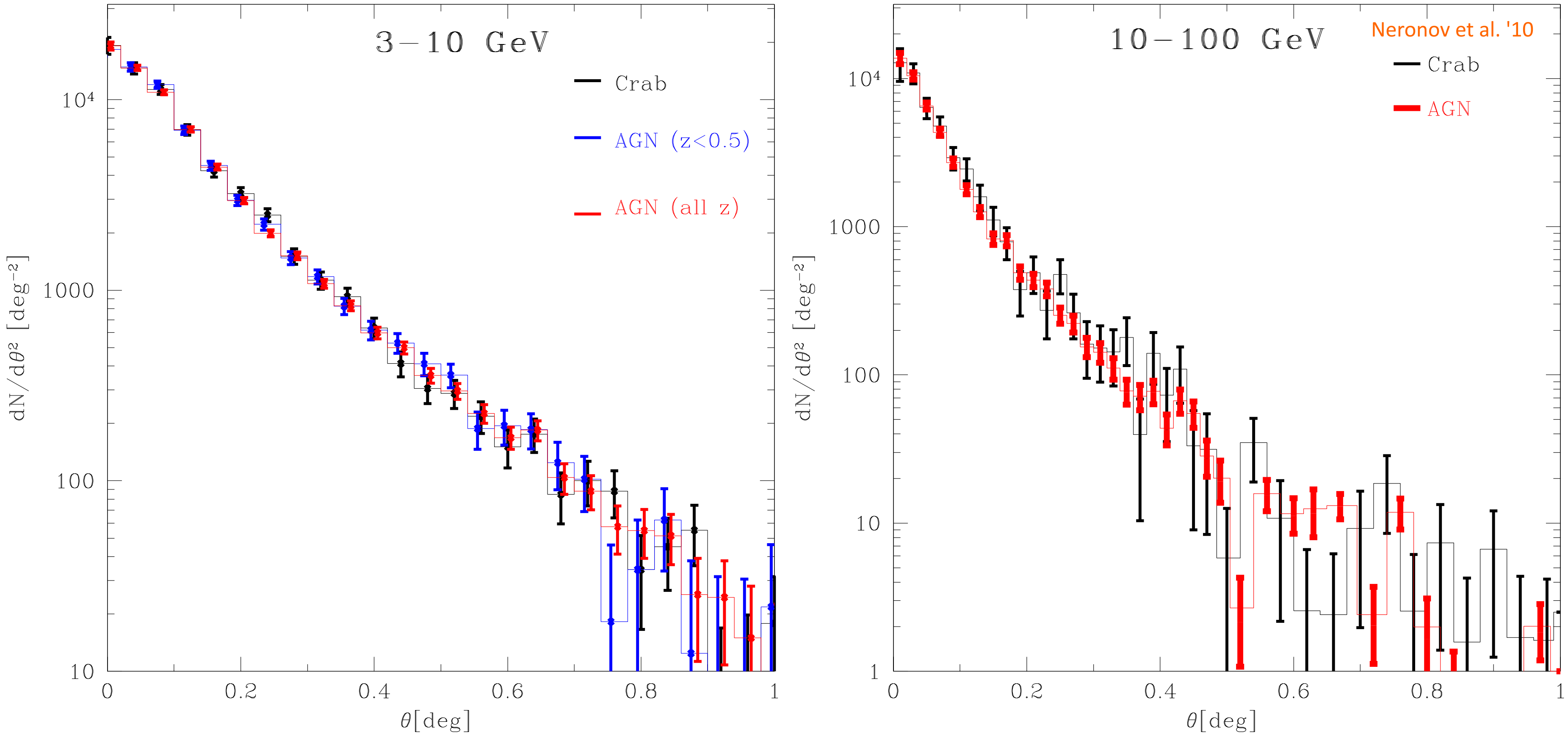
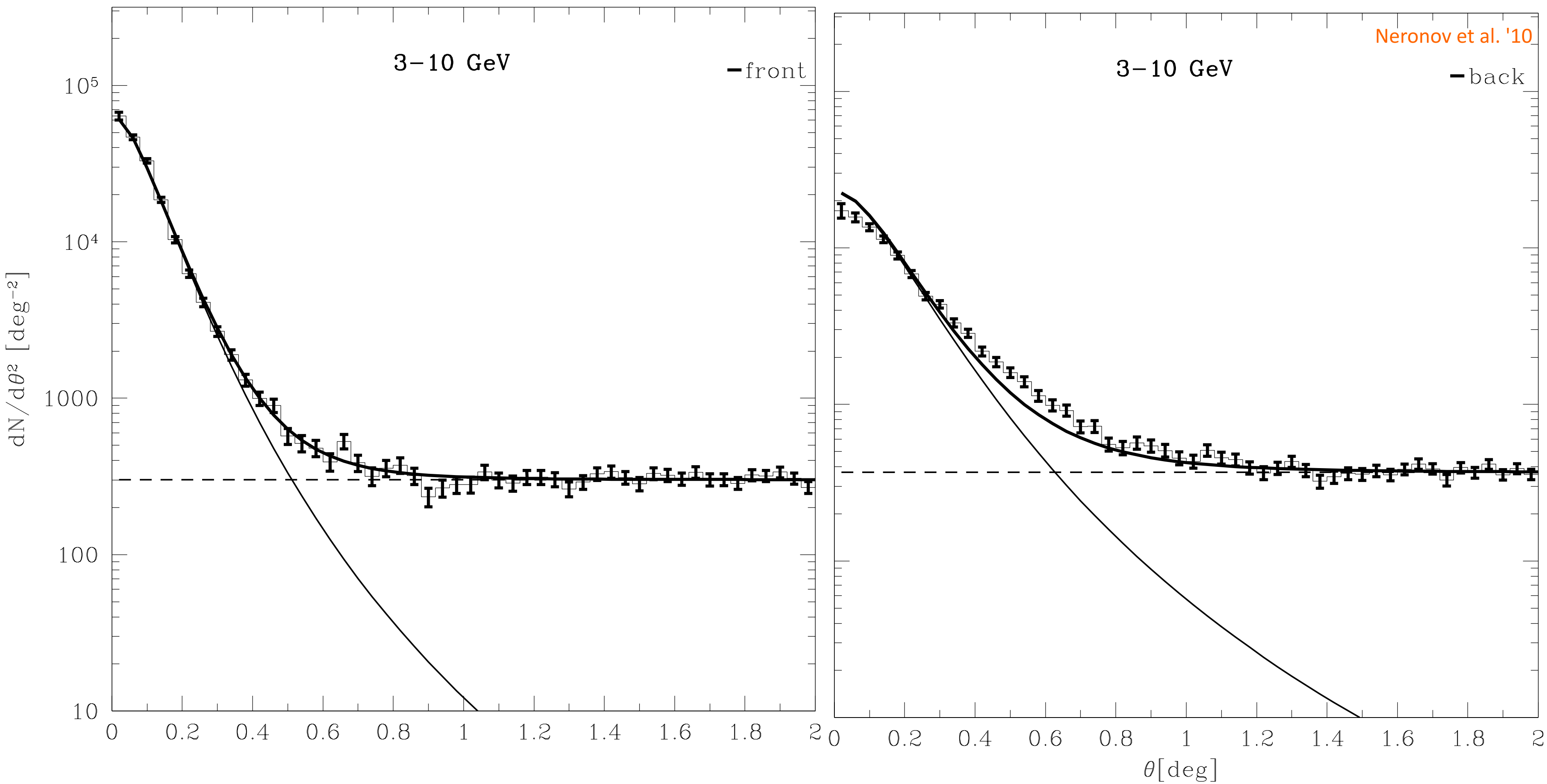


Verification of the result of Ando & Kusenko (2010) via a direct comparison of photon distribution around AGN with that around Crab pulsar shows that the the result of Ando & Kusenko is **wrong**.

(note that in the published version of Ando & Kusenko paper, there is a new mistake in the estimate of background level in 3-10 GeV band, where they find a halo when comparing AGN photon distribution with the PSF derived from Crab.)

Uncertainty of Fermi PSF



Fermi "instrument characteristics" files used in standard analysis use a 5-parameter analytical approximation for PSF (values of parameters are tabulated). The approximation is not precise enough for back photons

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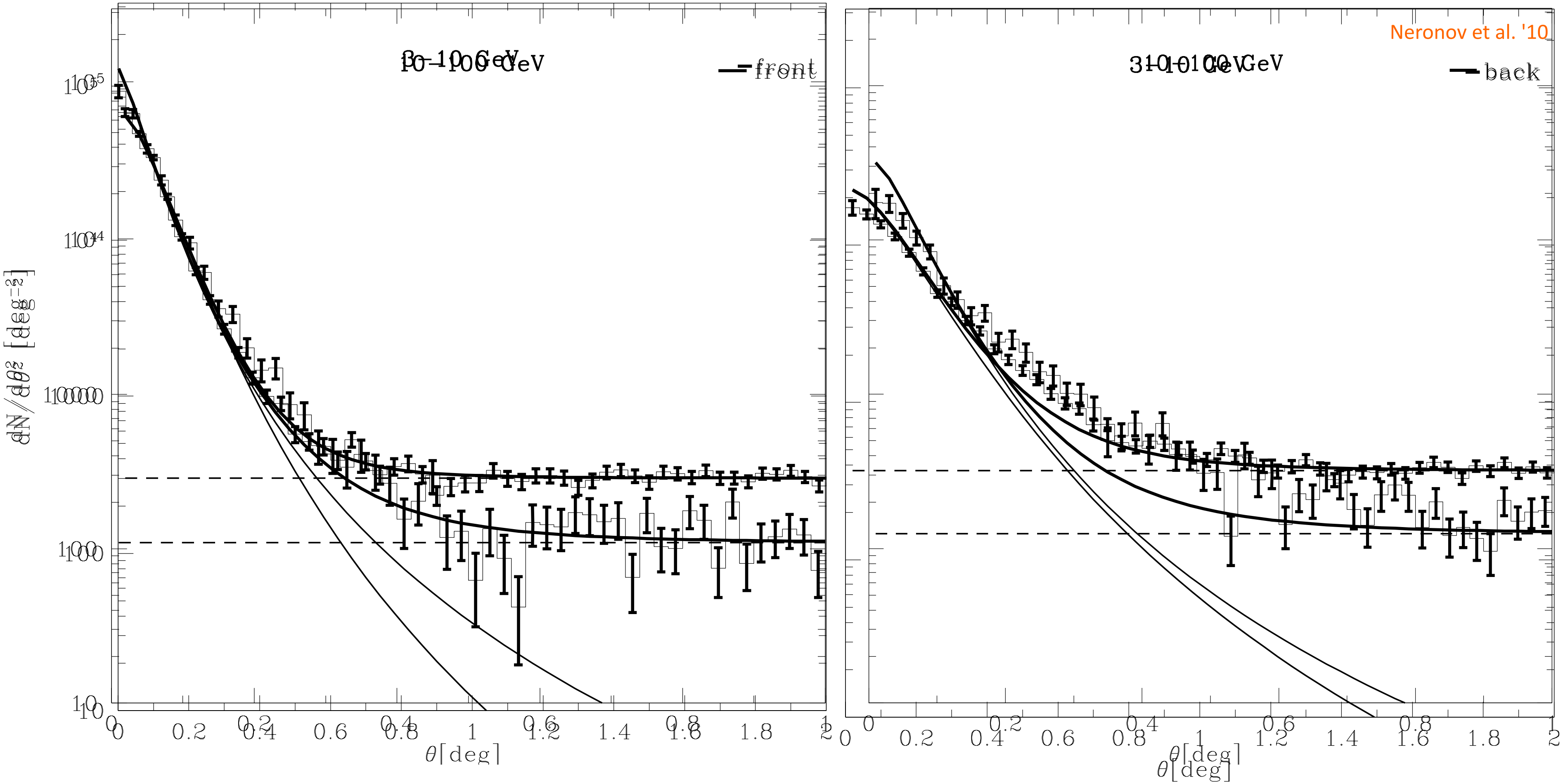

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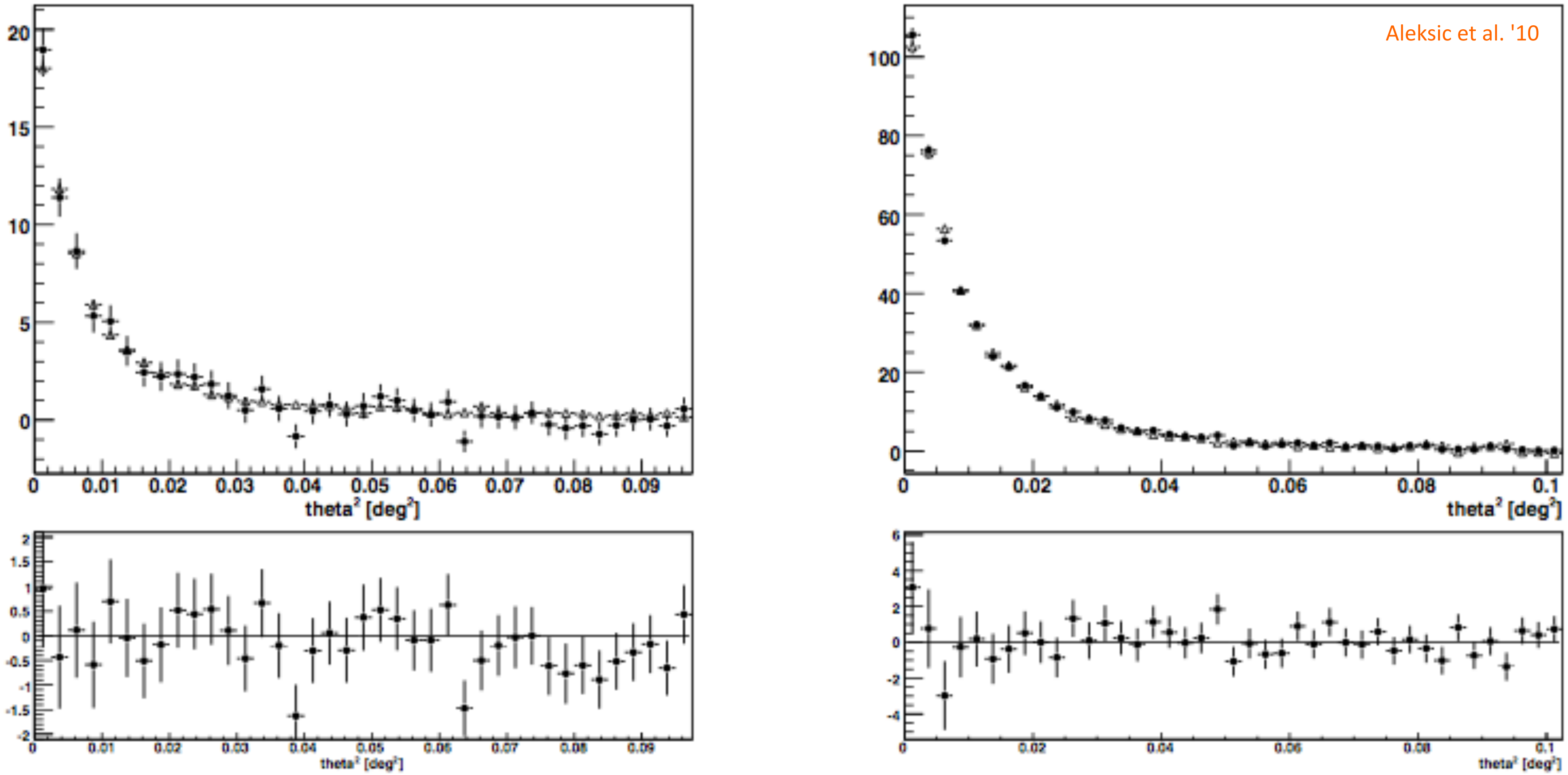
Extended halo vs. jet-like emission

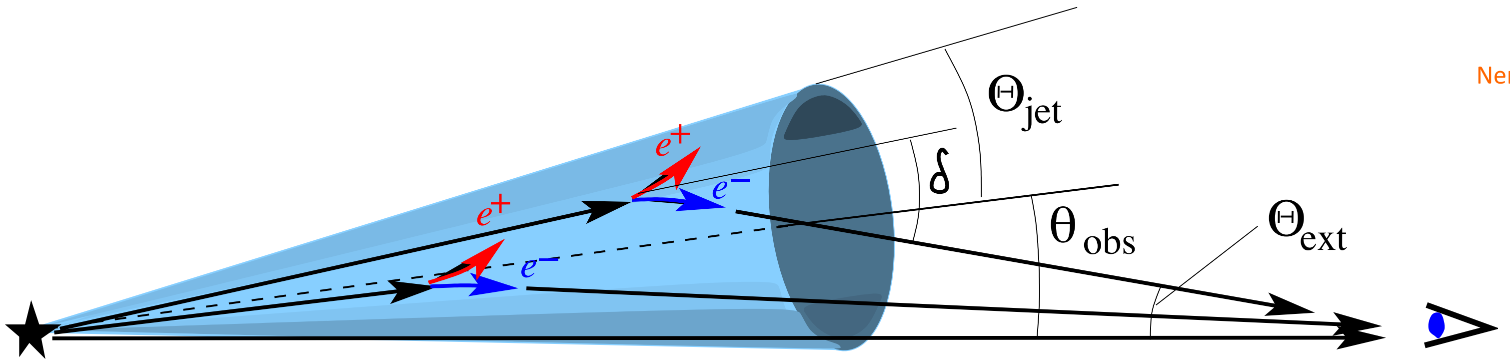


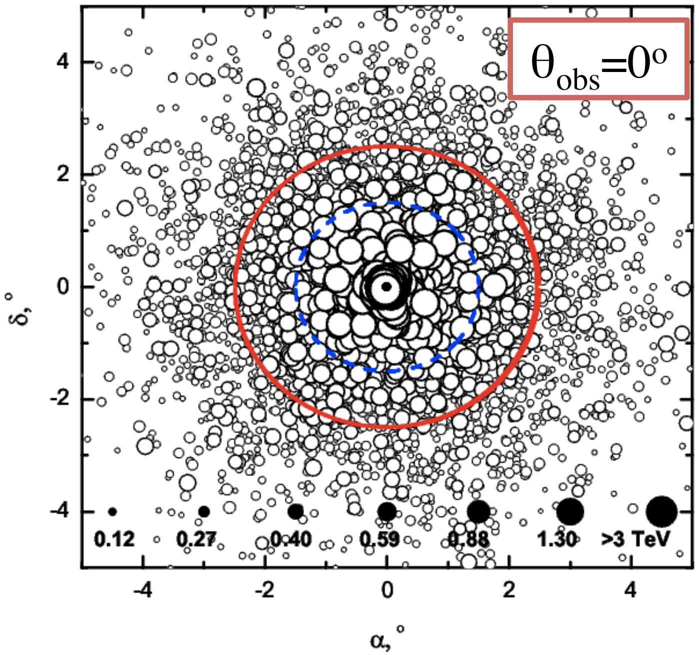
Photon distribution around Mrk 501 (left) and Mrk 421 (right) above 300 GeV observed by MAGIC telescope is also consistent with that around Crab.

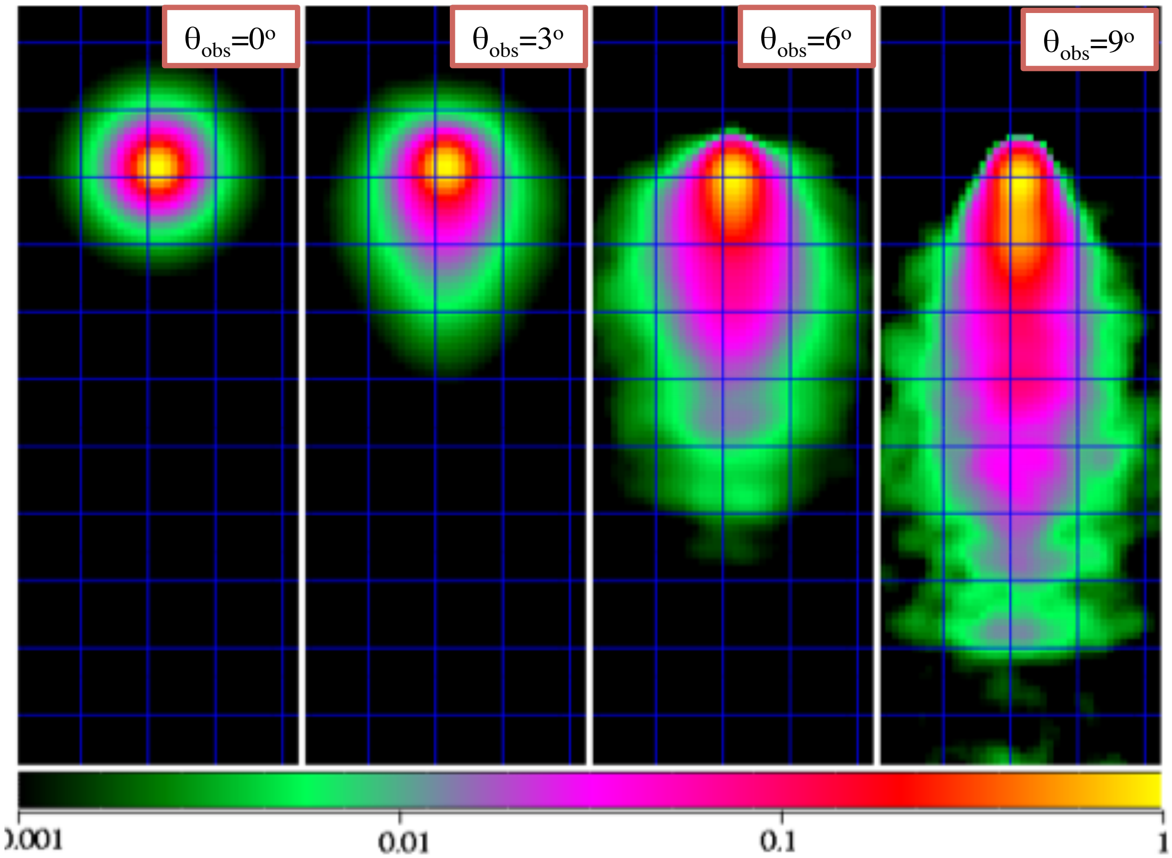
Additional uncertainty: $E_\gamma = \varepsilon_{CMB} \frac{E_e^2}{m_e^2} \approx 300 \left[\frac{E_{\gamma 0}}{17\ \mathrm{TeV}} \right]^2 \ \mathrm{GeV}$

Extended halo vs. jet-like emission

Neronov et al. '10







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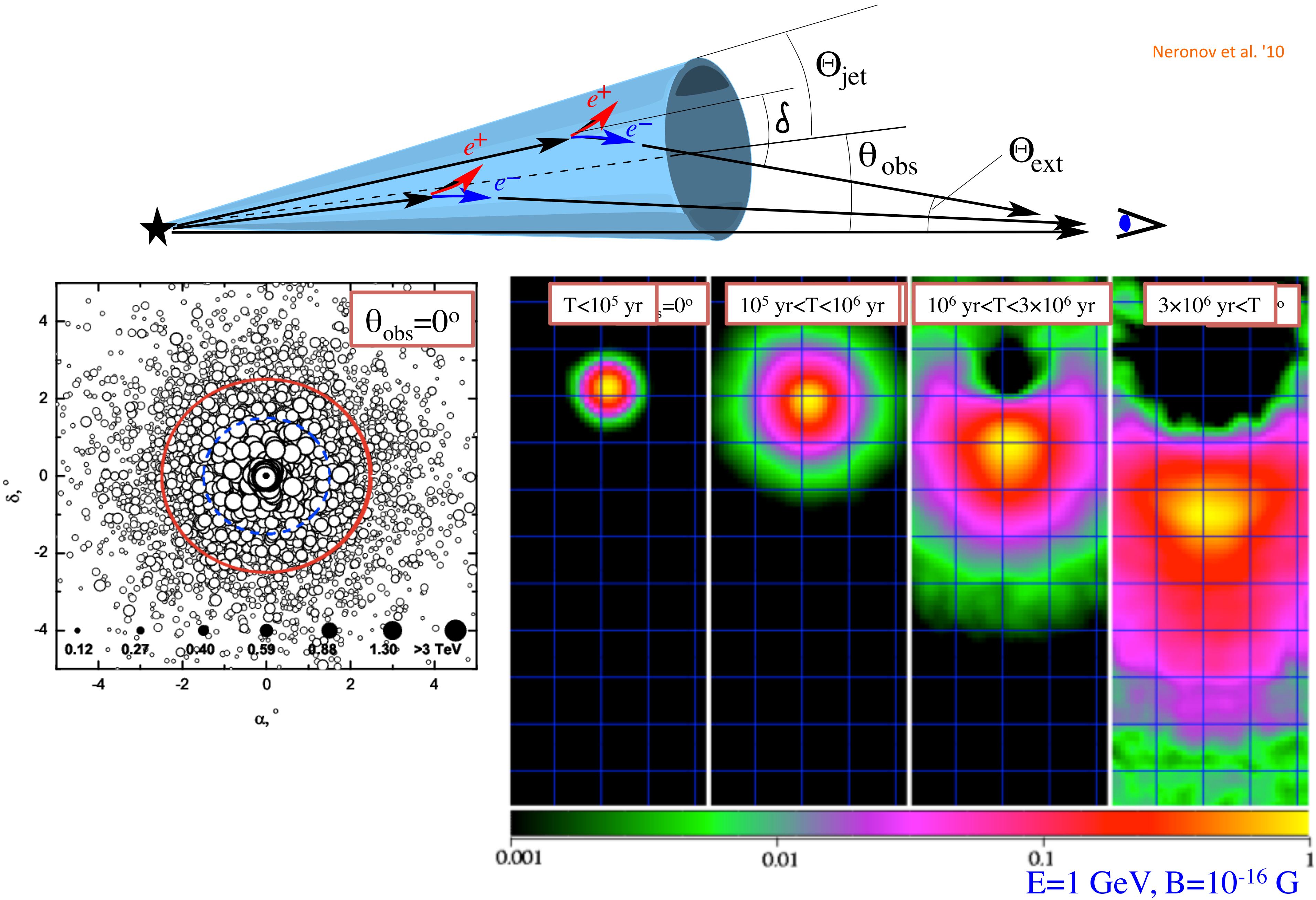
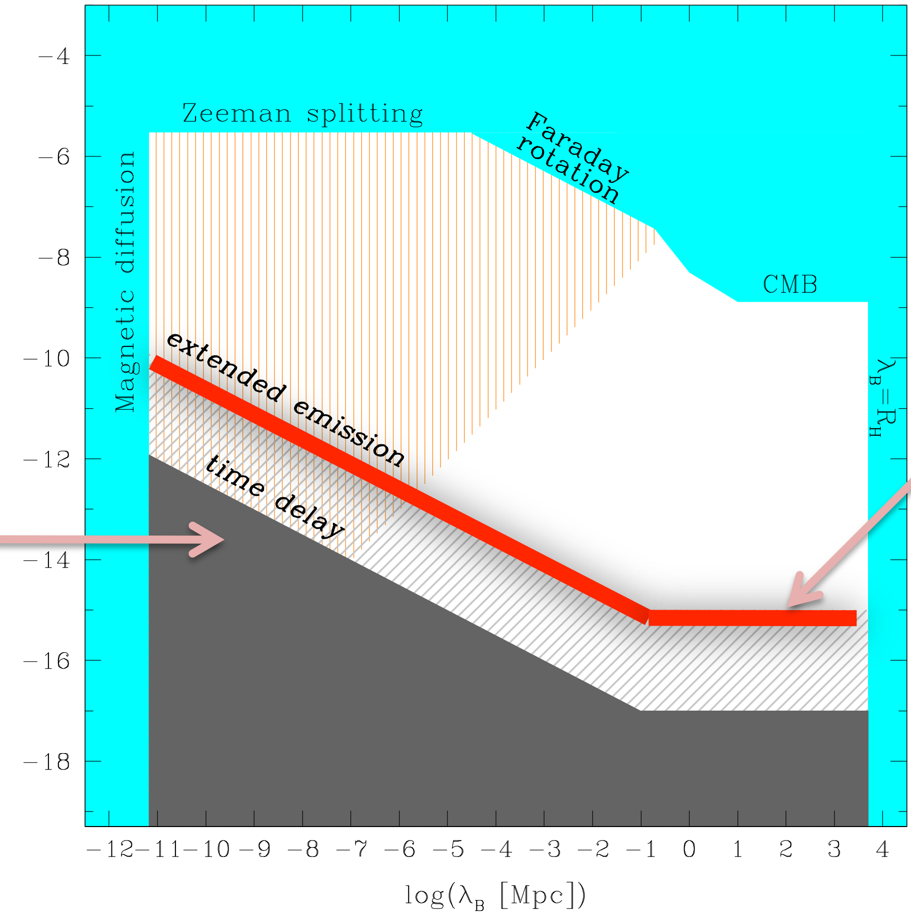


Lower bound on magnetic fields in IGM

Fermi upper bound on the cascade flux is inconsistent with assumption of negligible magnetic fields along the line of sight

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 (in prep)

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

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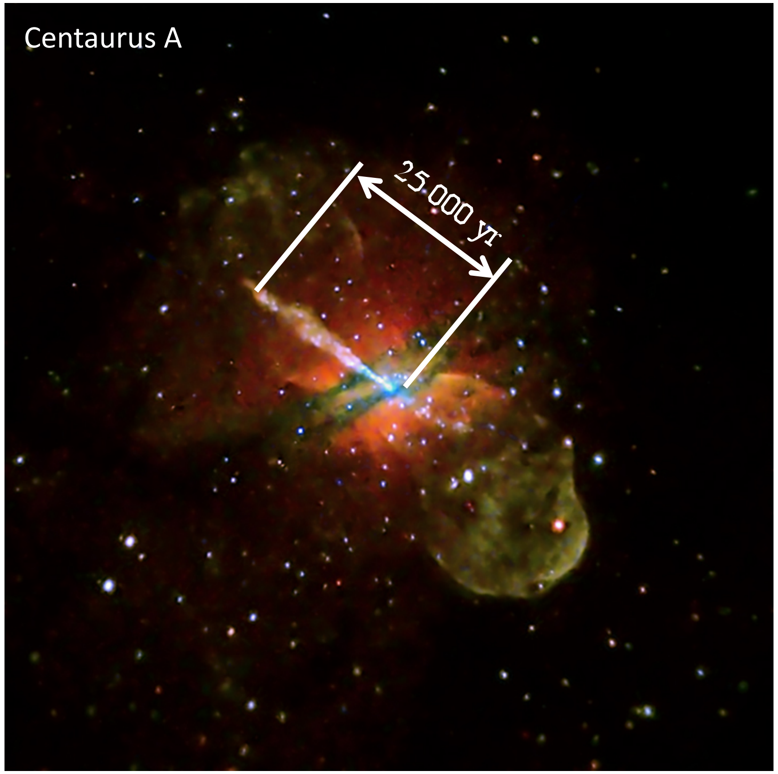

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Summary

Absorption of TeV gamma-rays from distant blazars and subsequent re-emission of gamma-rays from electromagnetic cascade could lead to appearance of extended gamma-ray emission around extragalactic sources.

This emission could be detectable by Fermi is magnetic field is strong enough ($B>10^{-17}$ G for large correlation length)

Extended emission could appear either in the form of an extended halo or as a jet-like extension of the source.

Up to now, 0.1-100 GeV extended emission around blazars is not detected

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Non-detection of extended emission from most promising candidates imposes a lower bound on the strength of magnetic field in the intergalactic medium at the level of $\sim 10^{-15}$ G if suppression of the cascade emission due to extended nature of the cascade source is assumed.