IGMF measurements from TeV and Fermi data

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Outline:

Introduction: IGMF & TeV Blazars

Propagation of VHE gamma-rays:
EBL and IGMF

Constraining the IGMF

Caveats

Intergalactic magnetic fields

IGMF could provide of the "seed" fields assumed in dynamo amplification models for magnetic fields in galaxies and galaxy clusters (e.g. Kulsrud & Zweibel 2008).

IGMF could be:

★ **primordial** (inflation, e.g. Turner & Widrow 1988 or phase transition era in the Early Universe, e.g. Kahniashvili et al. 2011)

★ **"astrophysical",** i.e. produced during the early stages of protogalaxy formation (e.g. Gnedin et al. 2000).

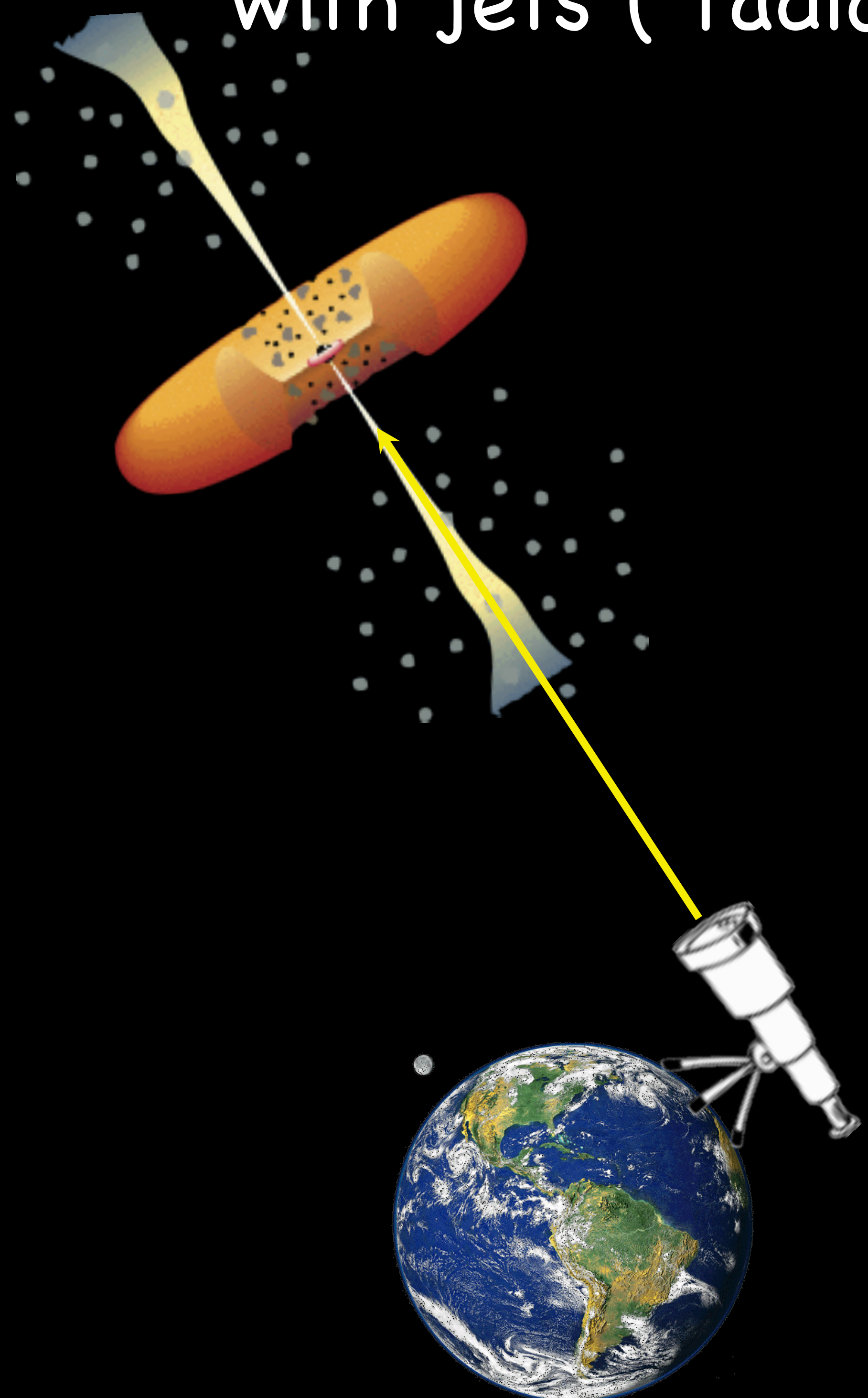
Classical methods allow to derive **upper limits** on IGMF (e.g. Faraday rotation of polarization angle of radio emission of quasars, e.g. Kronberg 2001, or the effects of magnetic fields on the Cosmic Microwave Background, e.g. Durrer et al. 2000).

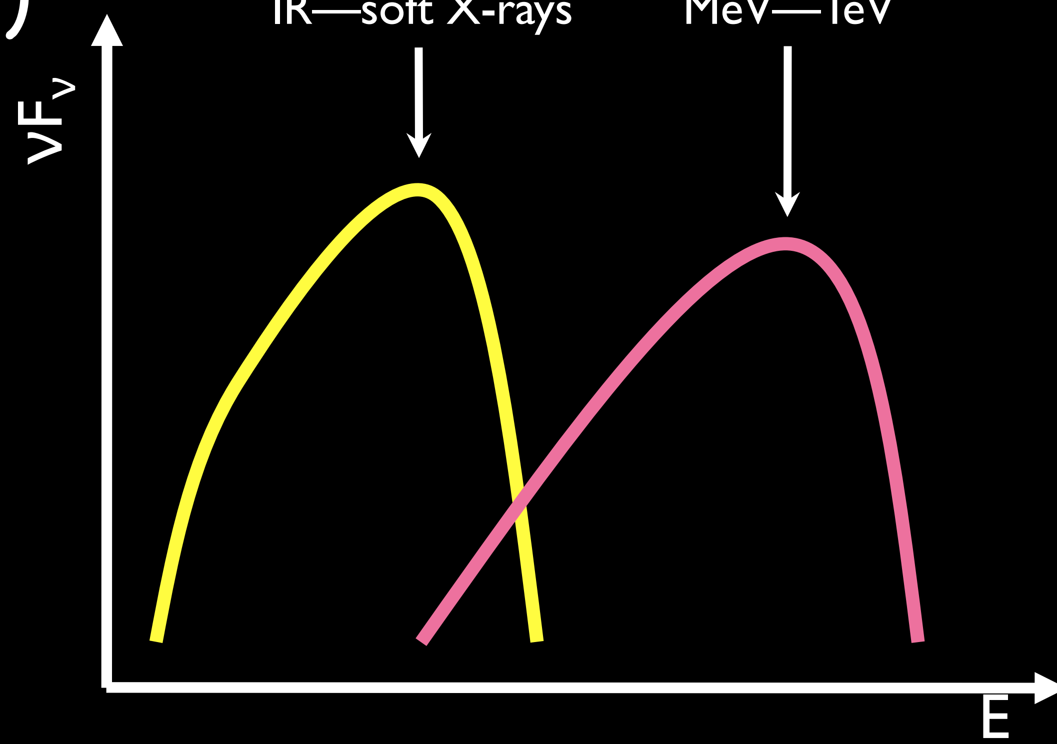
$$B<10^{-9}\ G$$

Lower limits could be obtained through the effects of IGMF on pairs produced by absorbed gamma rays (e.g. Plaga 1995)

The beacons: blazars

Active Galactic Nuclei
with jets ("radio loud")





Blazars

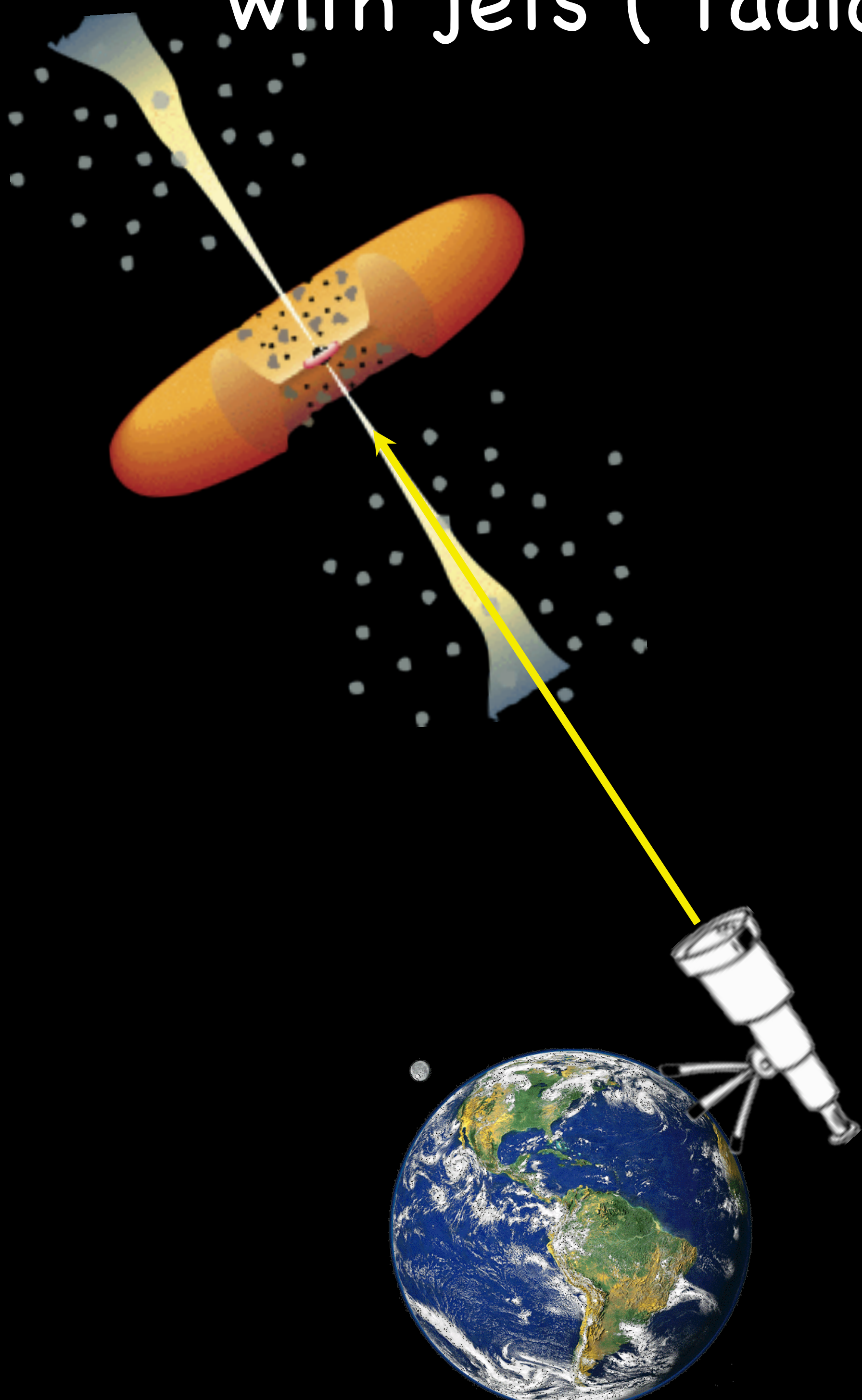
SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

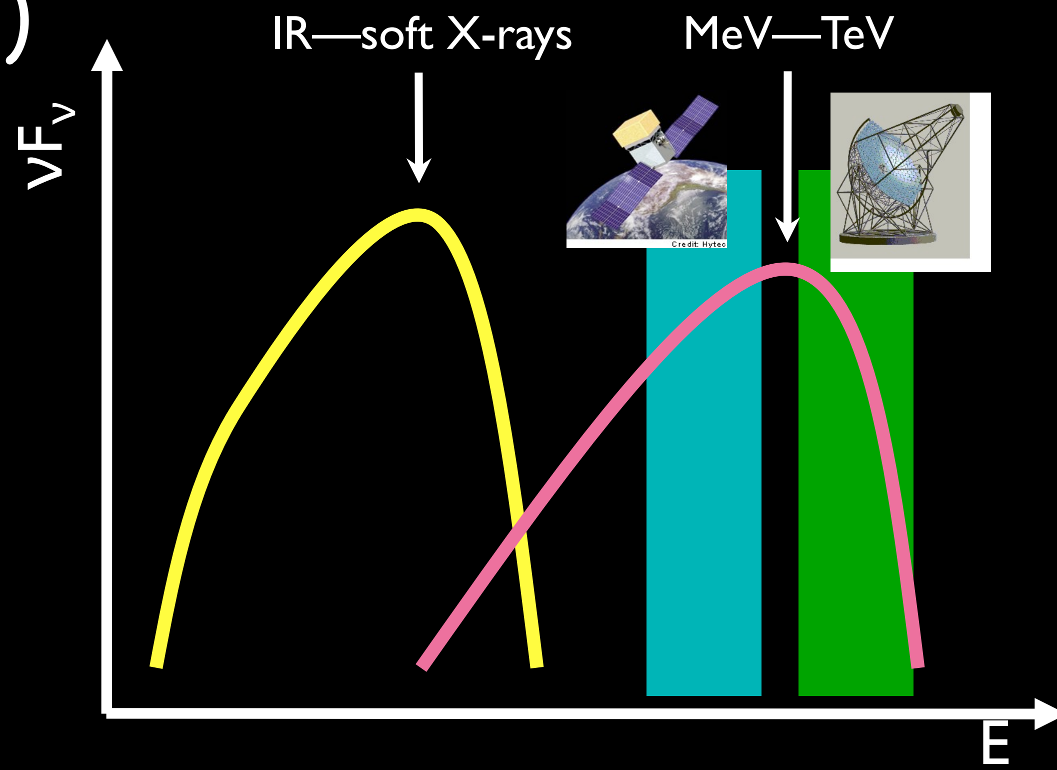
Two broad bumps:

Synchrotron and IC in leptonic models.

The beacons: blazars

Active Galactic Nuclei
with jets (“radio loud”)





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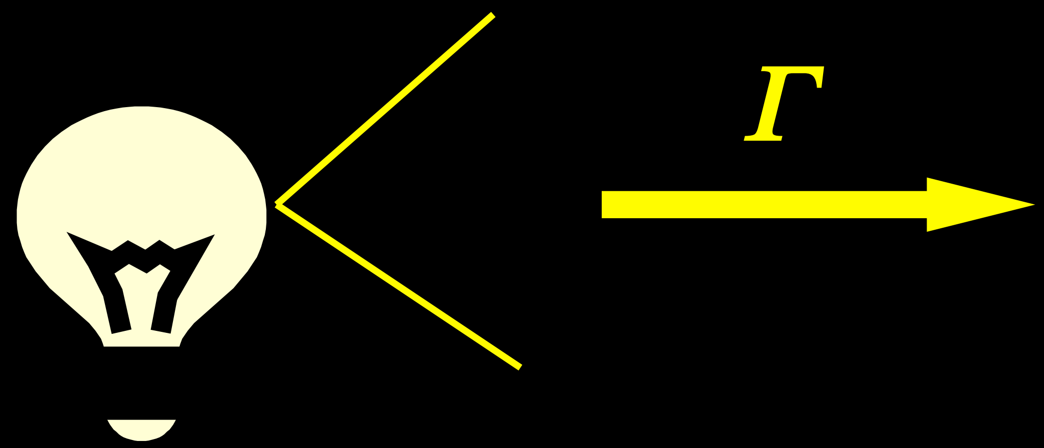
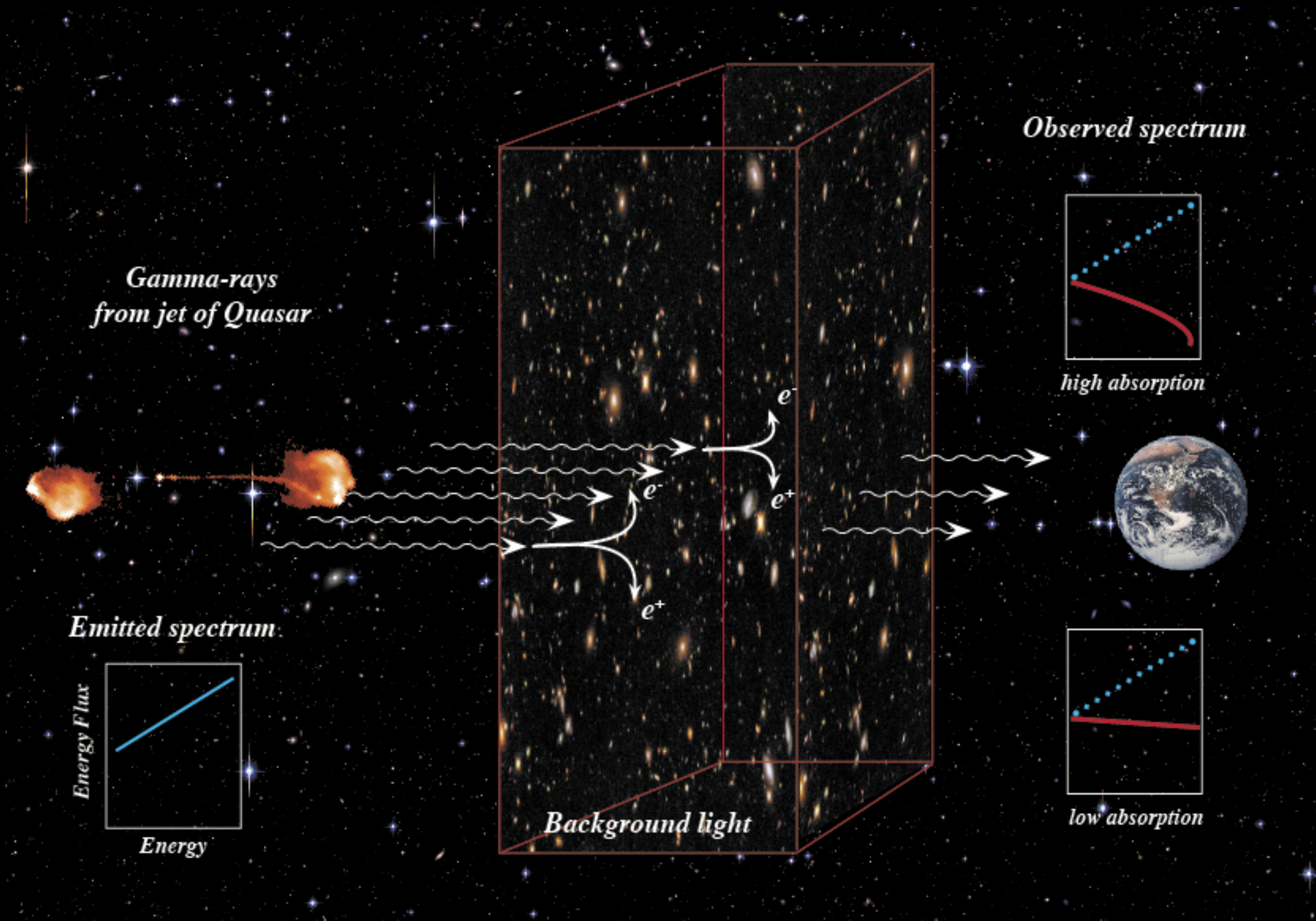
Relativistic beaming



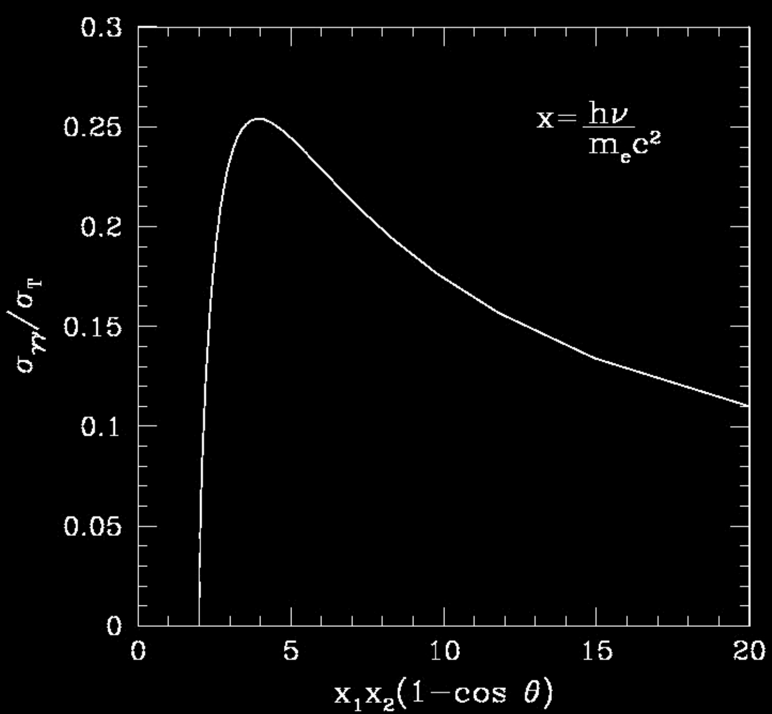
$\Theta \sim 1/\Gamma$ "beaming angle"

Typically Γ=10-20

Propagation of gamma rays



Absorbing gamma rays



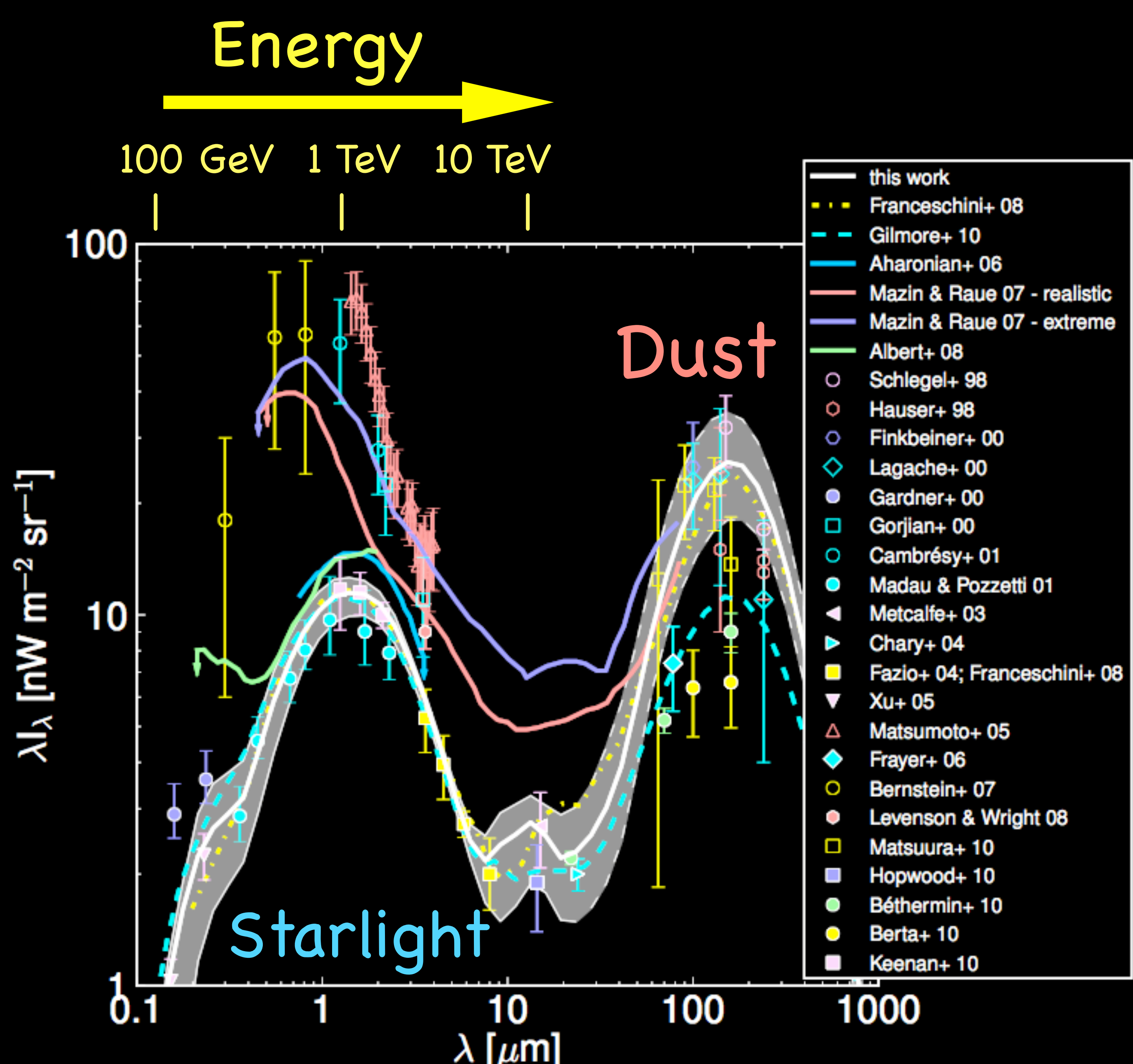
$$\gamma + \gamma \rightarrow e^+ + e^-$$

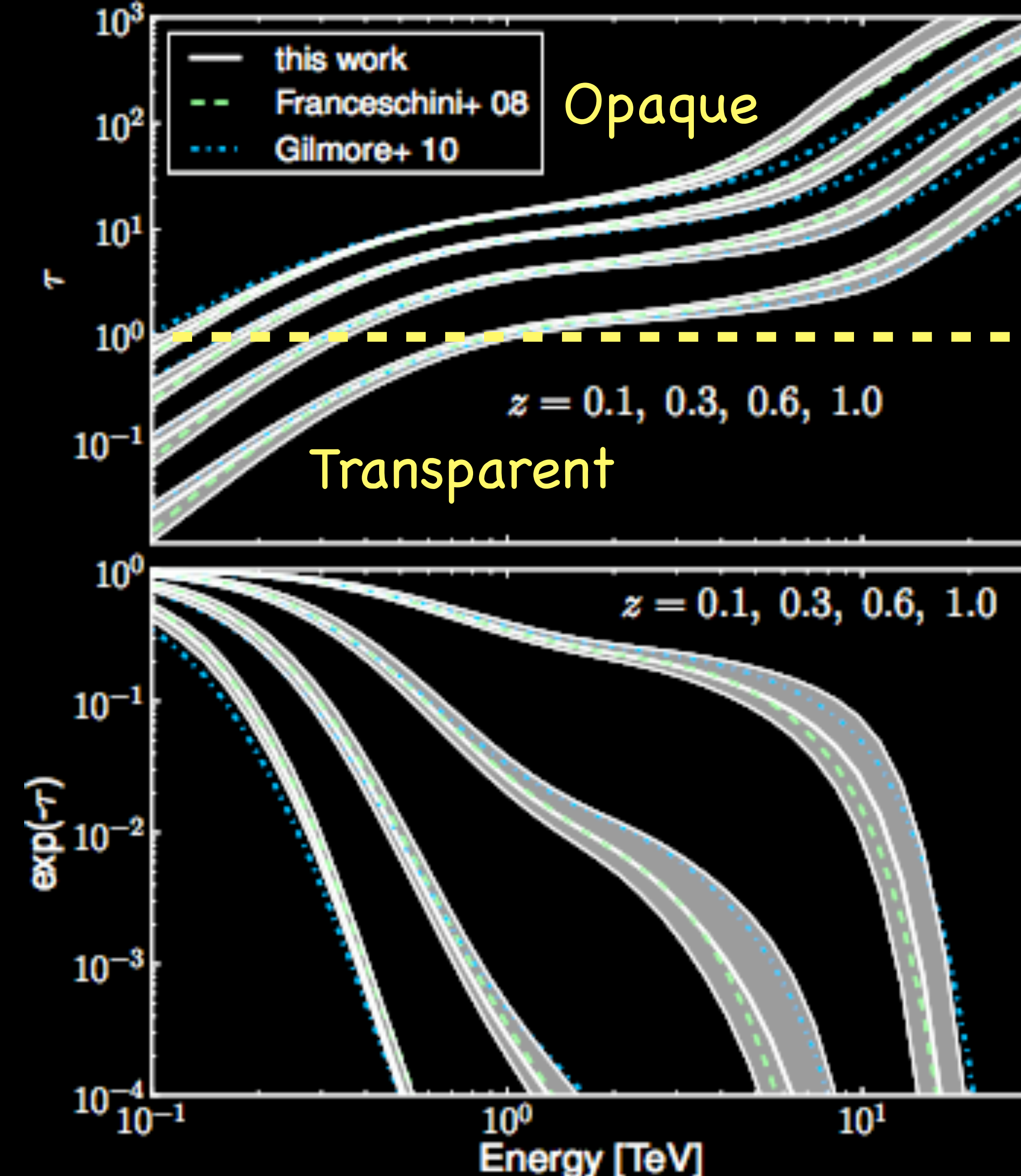
$$\sigma(s) = \frac{3}{16}\sigma_T(1-s^2)\left[(3-s^4)\ln\frac{1+s}{1-s} - 2s(2-s^2)\right]$$

$$s = \left[1 - \frac{2}{x_1 x_2 (1-\mu)}\right]^{1/2}$$

Rule of thumb: $\nu = 2 \times 10^{15}\left(\frac{E}{100\,\mathrm{GeV}}\right)^{-1}$ *Hz*

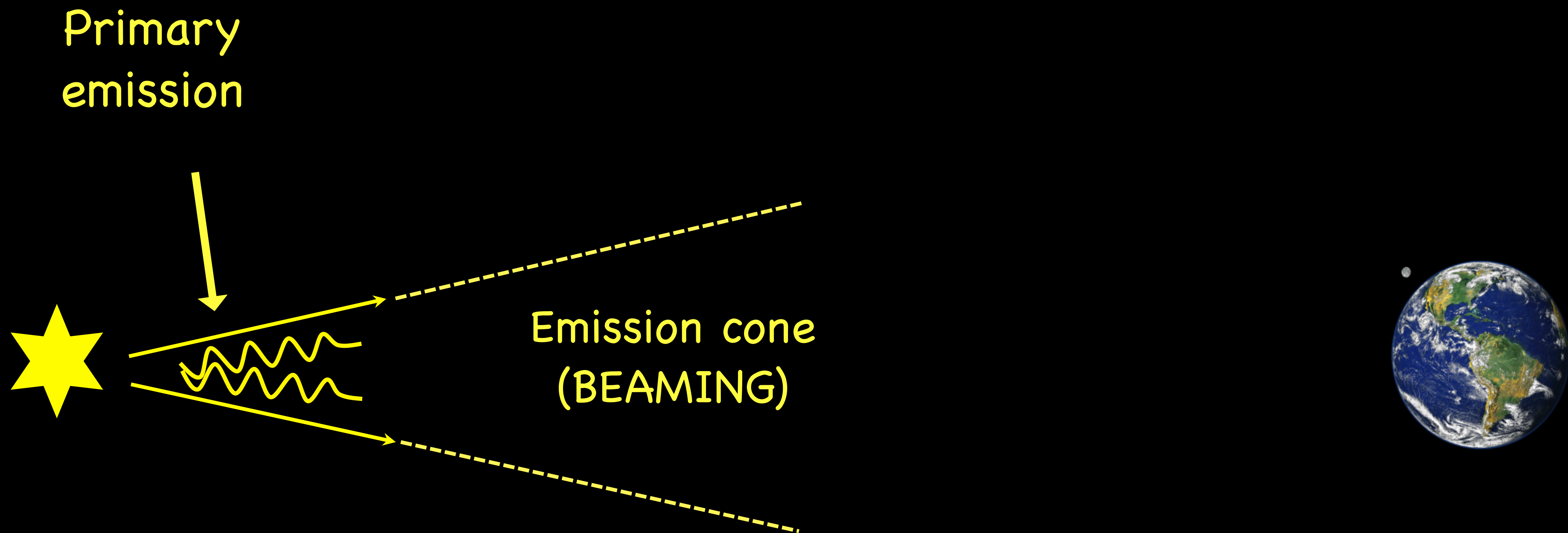
Extragalactic background light



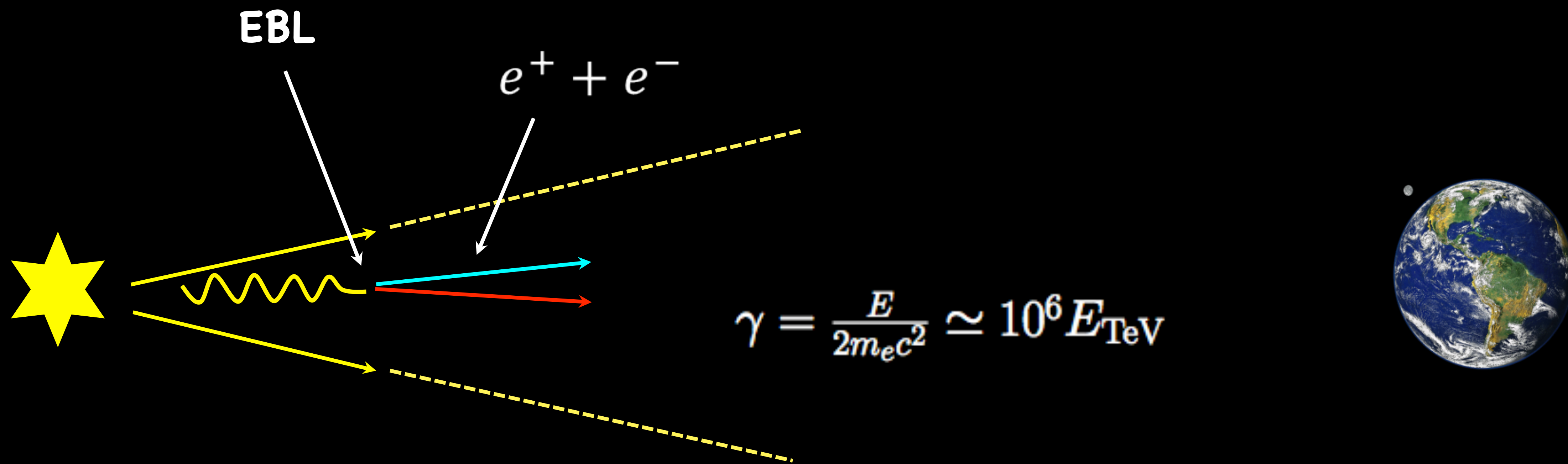


Dominguez-Diaz et al. 2010

Effect of IGMF

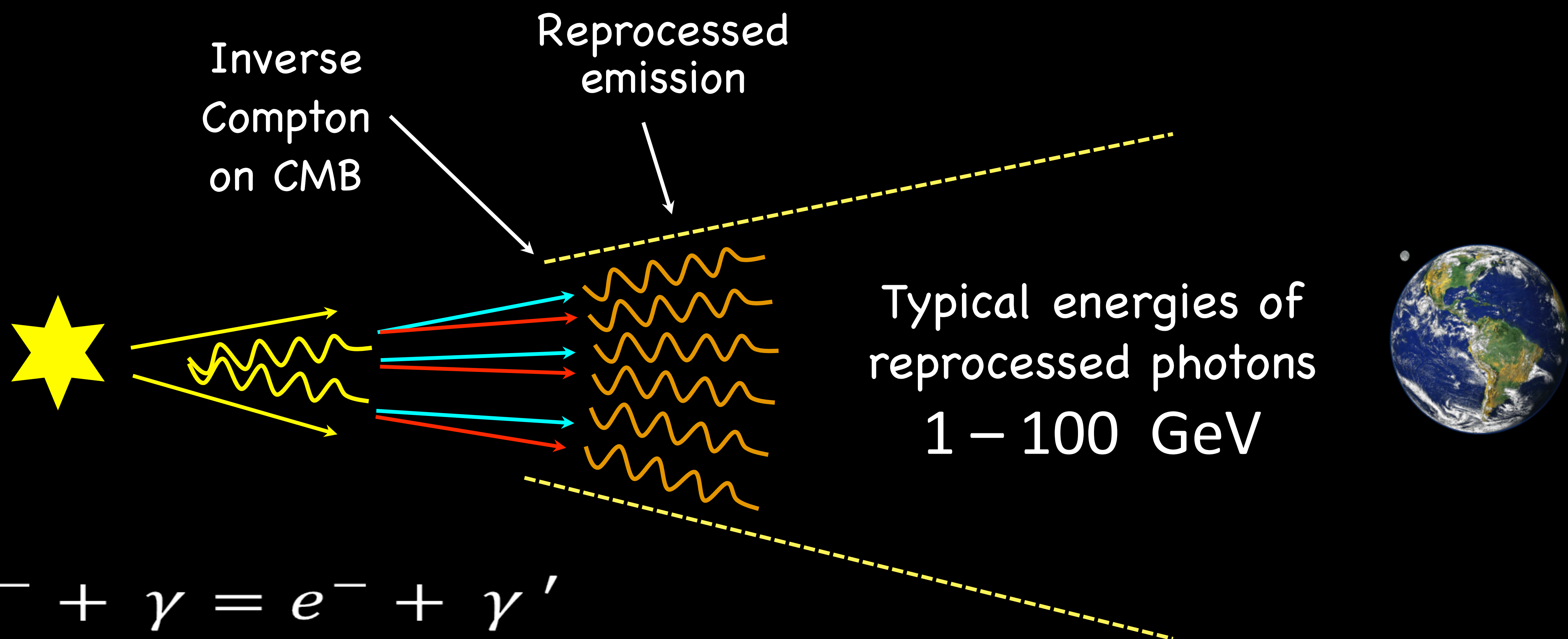


Effect of IGMF



$$\gamma_1 + \gamma_2 = e^- + e^+$$

Effect of IGMF



$$e^- + \gamma = e^- + \gamma'$$

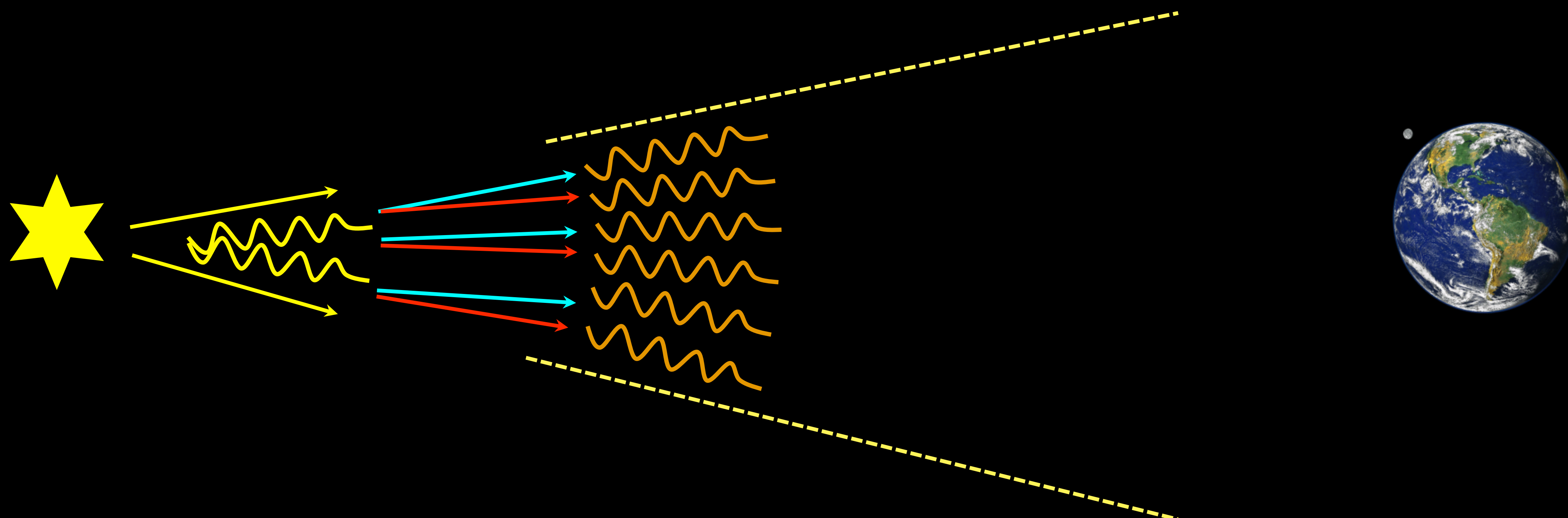
$$\epsilon = \gamma^2 h\nu_{\rm CMB} \simeq 2.8\, kT_{\rm CMB}\, \gamma^2 = 0.63\, E_{\rm TeV}^2\ {\rm GeV}$$

$$ct_{\rm cool} = \frac{3m_e c^2}{4\gamma U_{\rm CMB,0}(1+z_r)^4} \simeq 2\times 10^{24} \gamma_6^{-1} (1+z_r)^{-4}\ {\rm cm}$$

$$N(\gamma) = k\gamma^{-2}$$

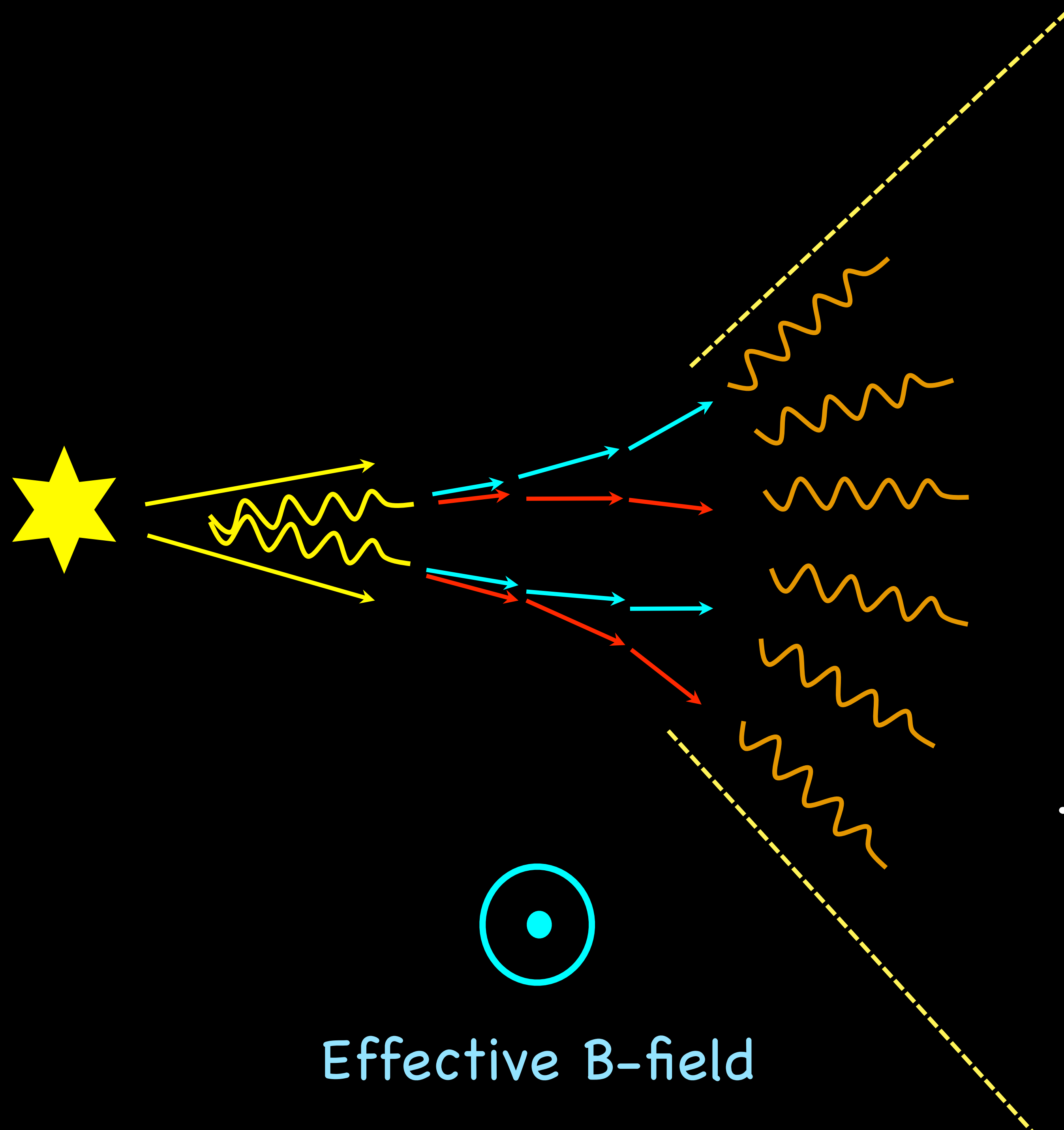
“cooled “ distribution

B=0



The reprocessed emission is contained within the primary beaming cone

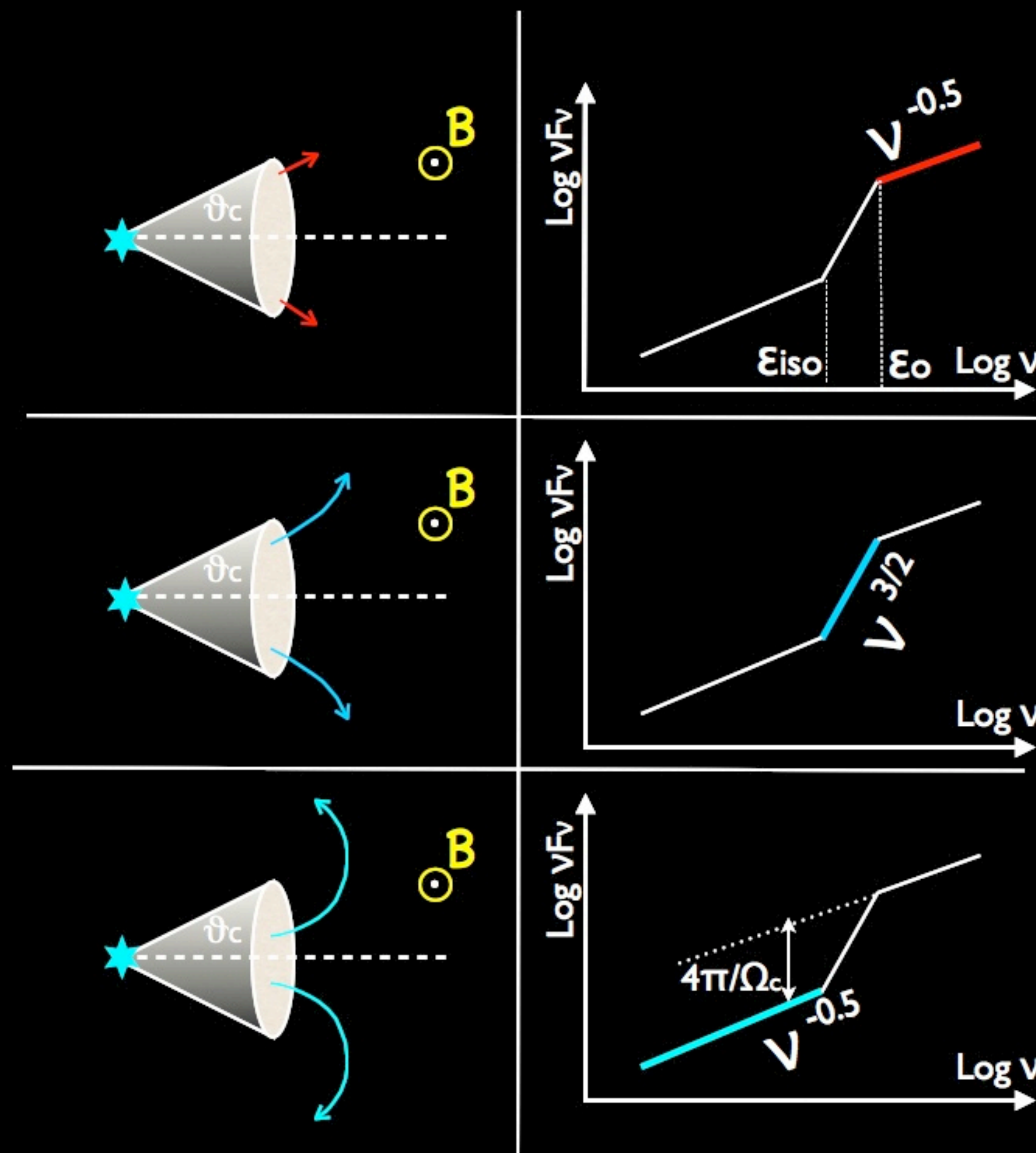
B>0



$$\theta_\gamma = \frac{ct_{\rm cool}}{r_{\rm L}} = 1.17\, B_{-15}\, \gamma_6^{-2}\ \mathrm{rad}$$

The reprocessed flux is diluted within a larger solid angle

A simplified model for the spectrum



Stationary VHE flux!

$$F(\epsilon) = k\epsilon^{-0.5}\frac{1}{\Omega_c+\Omega_\gamma}$$

$$\Omega_\gamma = 2\pi(1-\cos\theta_\gamma) \sim \pi\theta_\gamma^2$$

$$\Omega_c = 2\pi(1-\cos\theta_c) \sim \frac{\pi}{\Gamma^2}$$

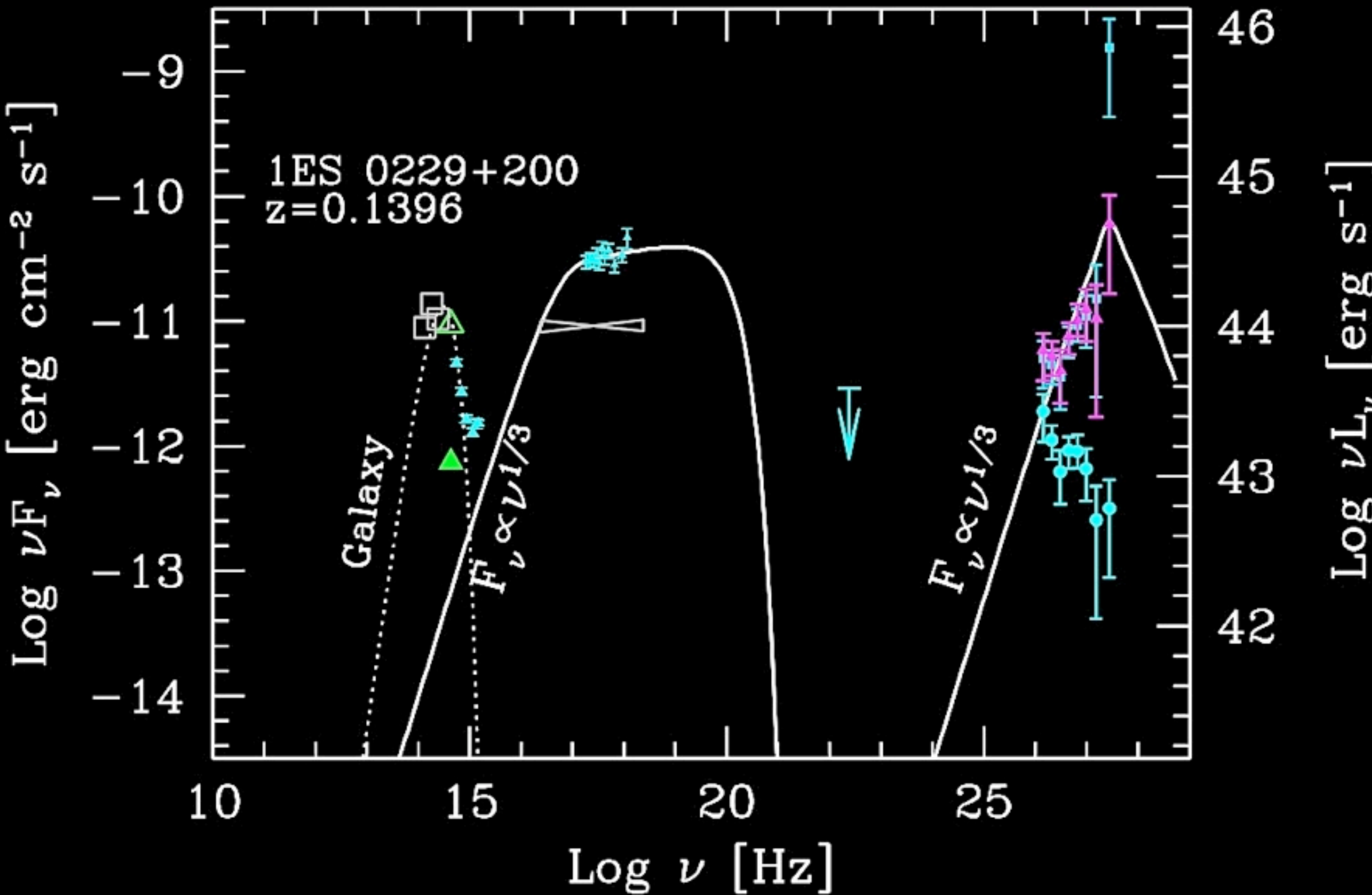
FT et al. 2010

Basic requirements

- ✓ *Hard and powerful TeV spectrum*
- ✓ *Large distance (high absorption)*
- ✓ *Low intrinsic GeV flux*

1ES 0229+200: the source of desires

FT et al. 2009



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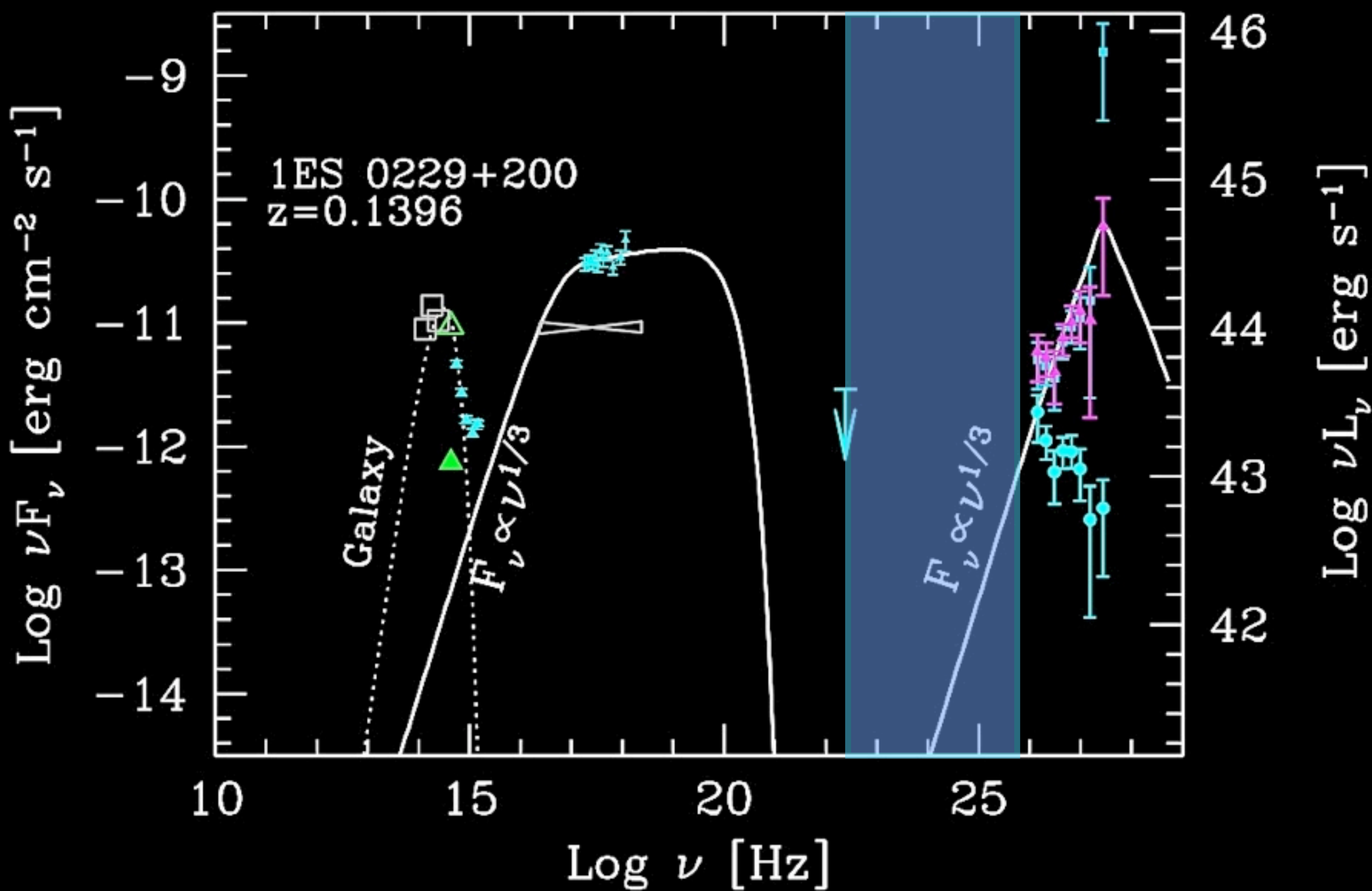
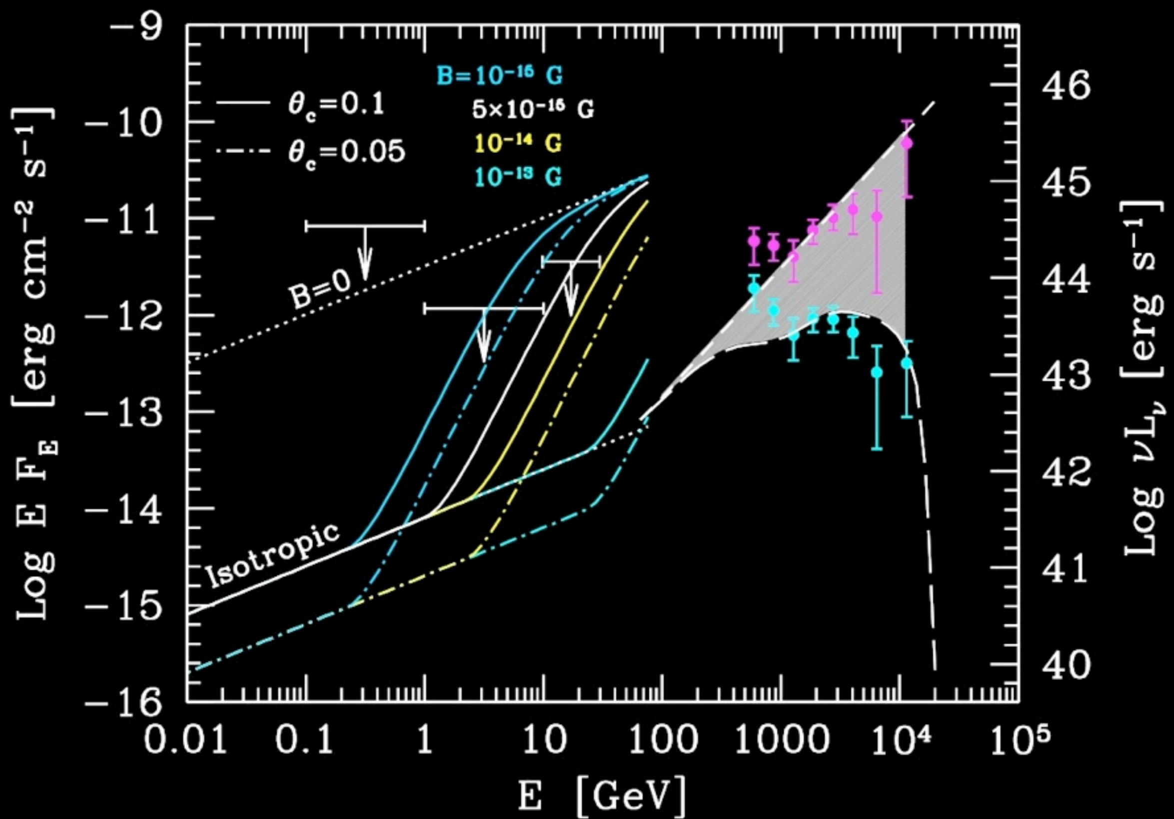
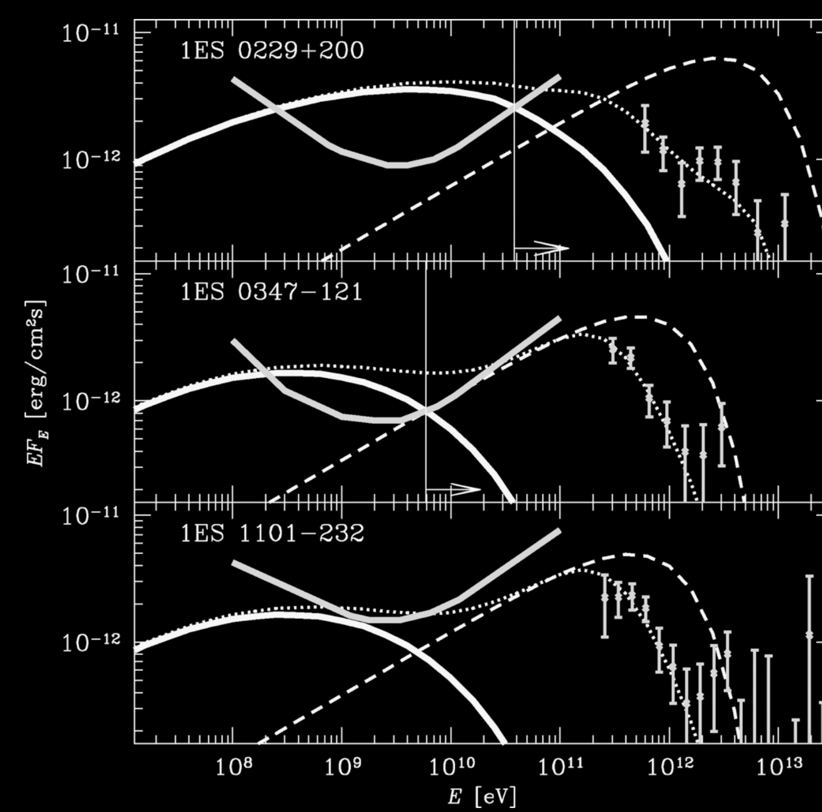


B>0!

FT et al. 2010

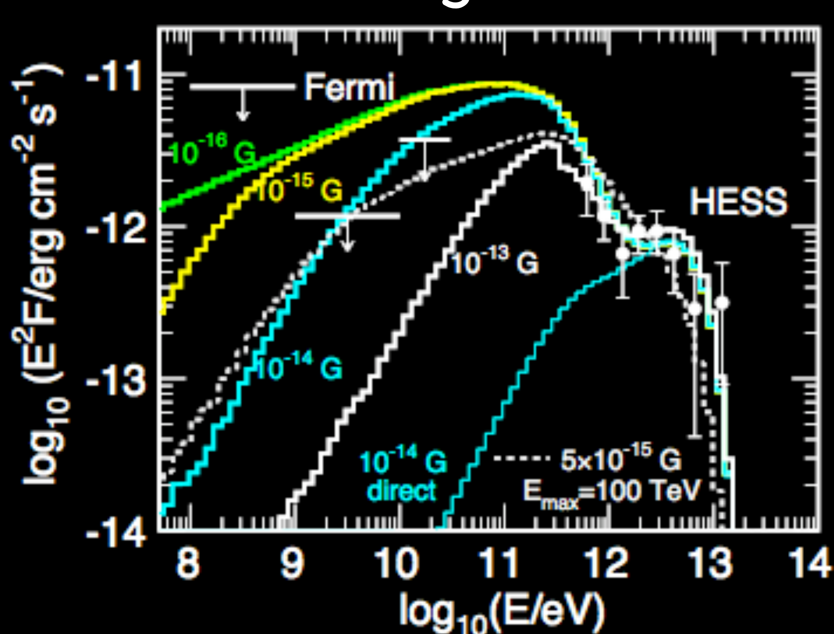


Neronov & Vovk 2010



Stationary VHE flux!

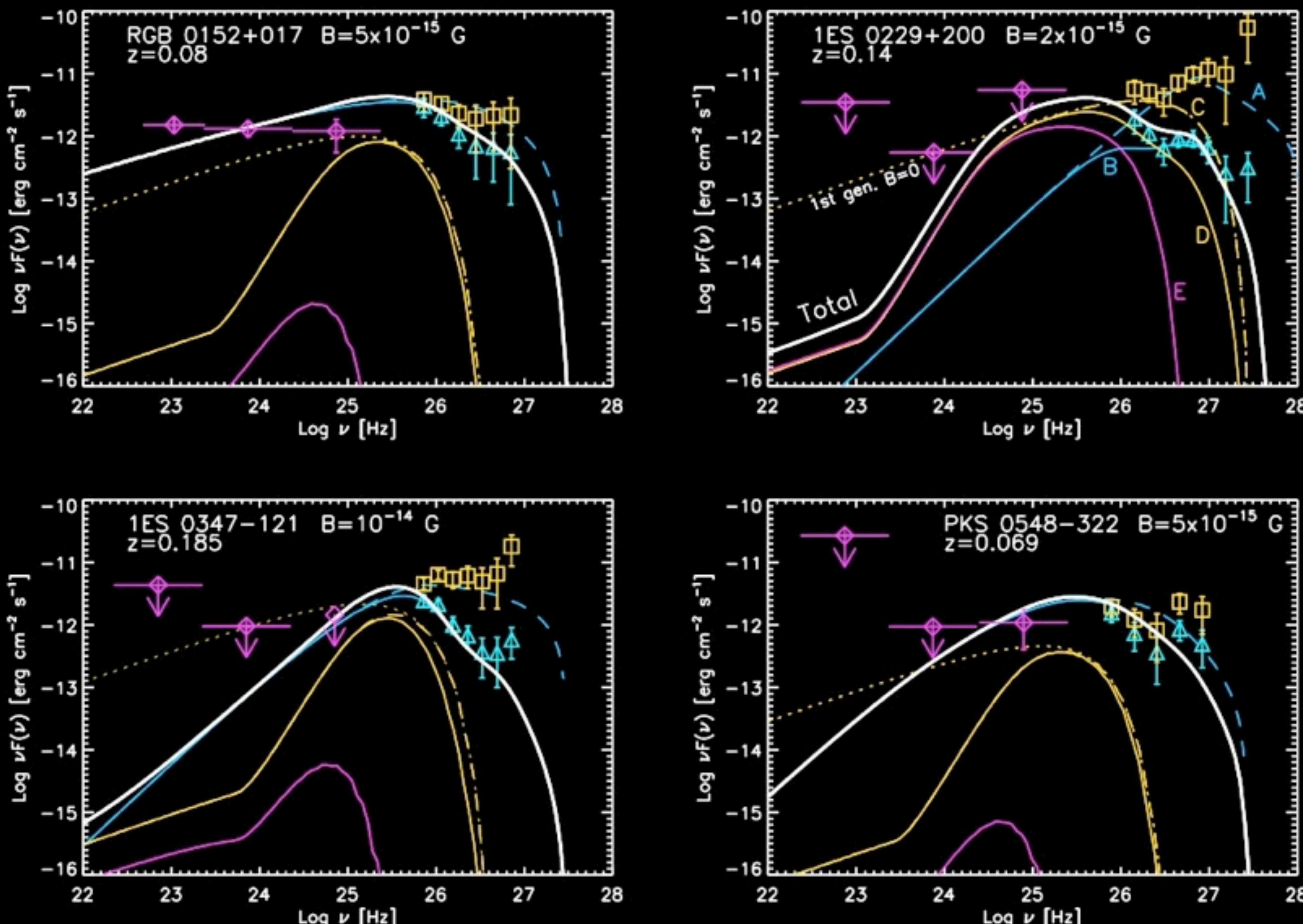
Dolag et al. 2011



B=10^{-16}-10^{-15} G

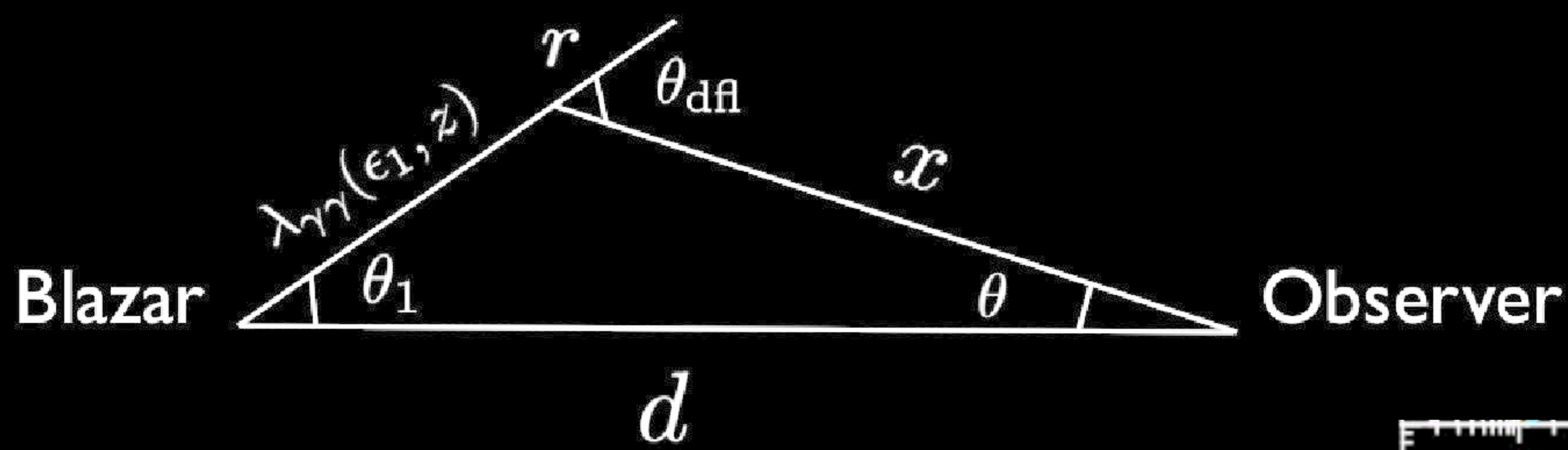
See also:
Taylor et al. 2011
Huan et al. 2011

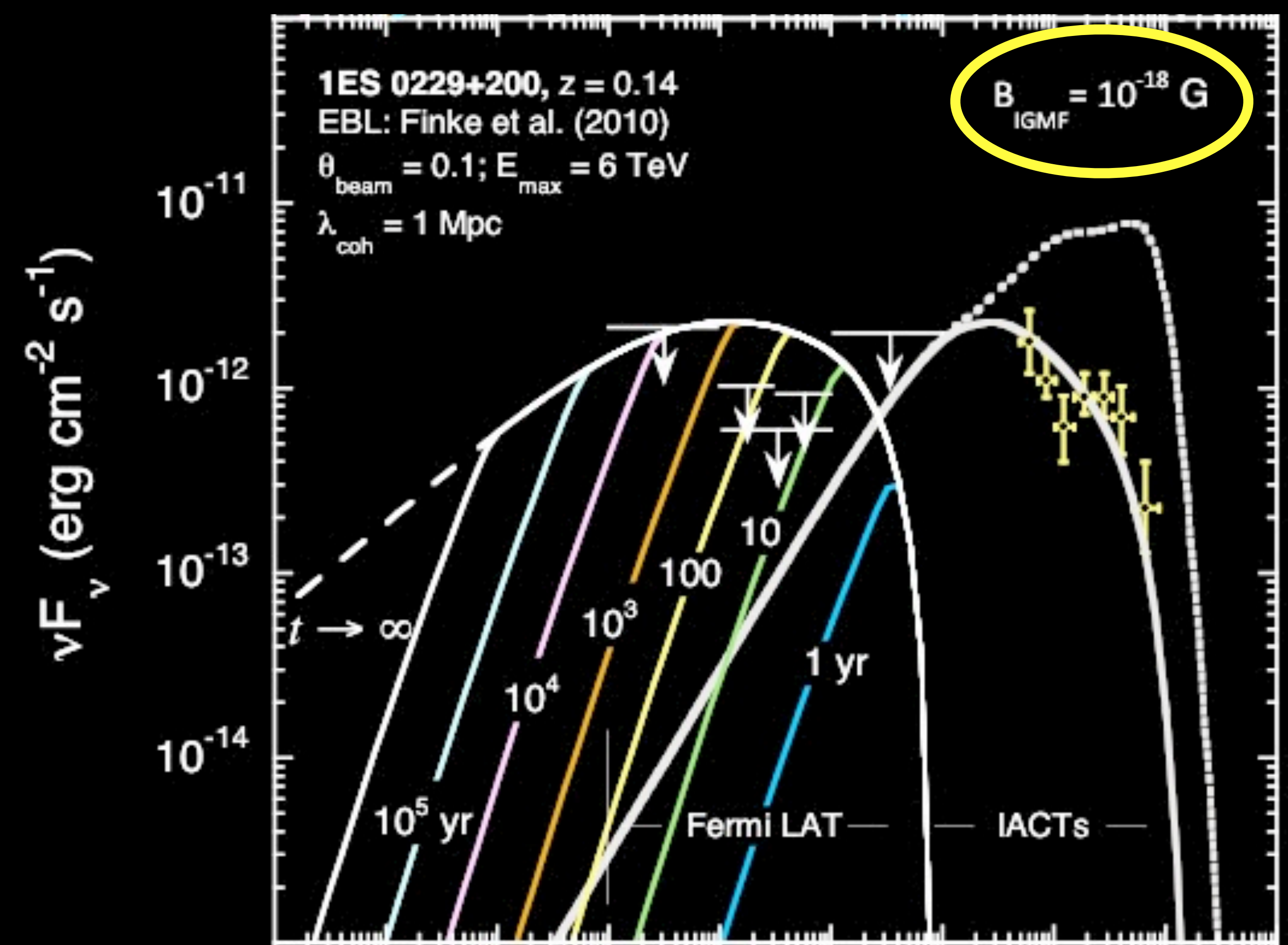
Primary continuum



FT et al. 2011

Source variability and delays

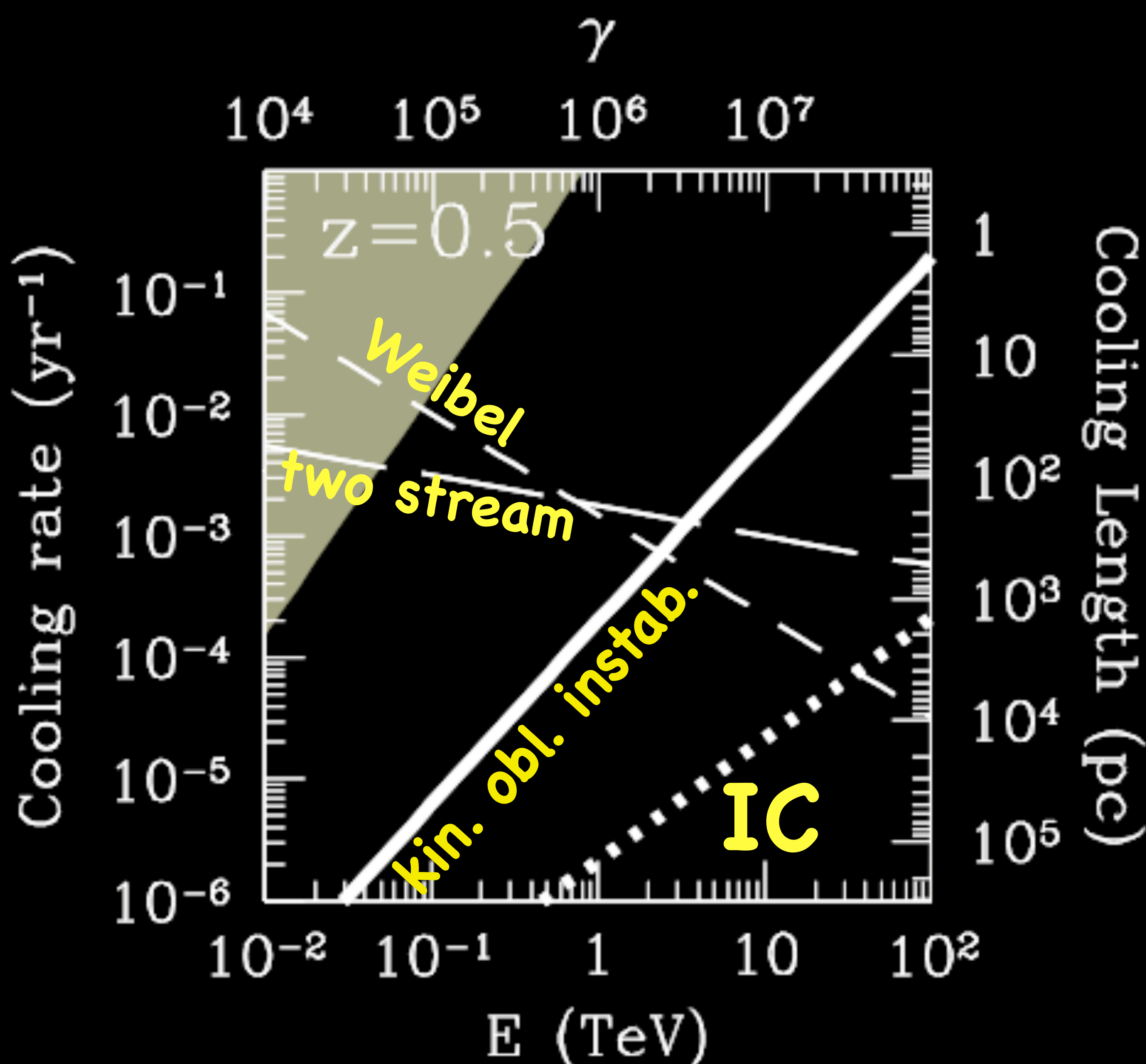




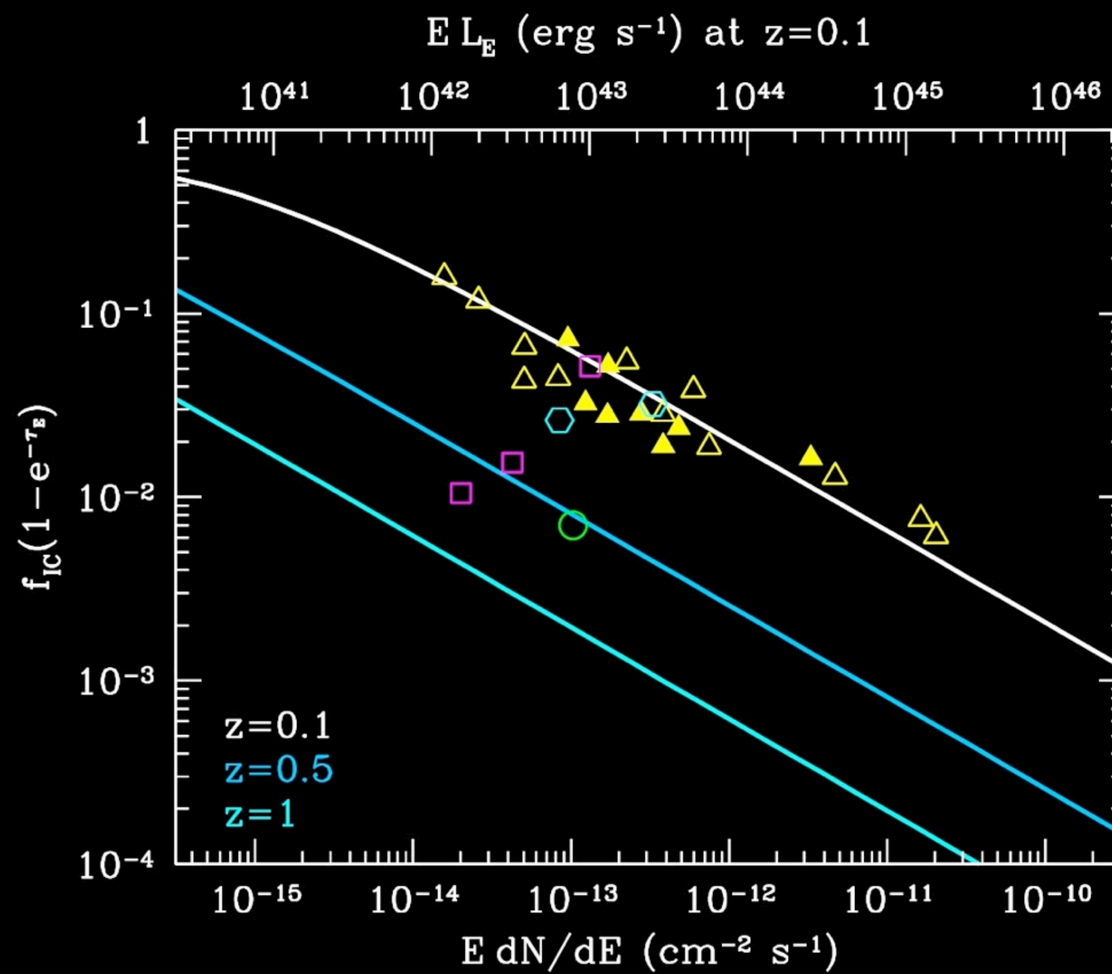
Dermer et al. 2011

Energy losses through plasma instability?

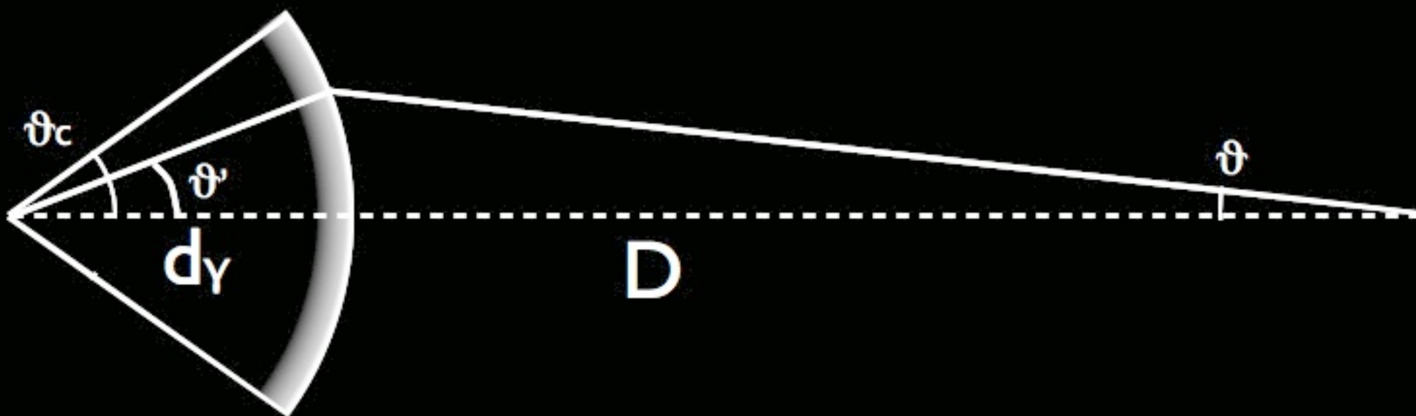
Broderick et al. 2011
arXiv:11065494

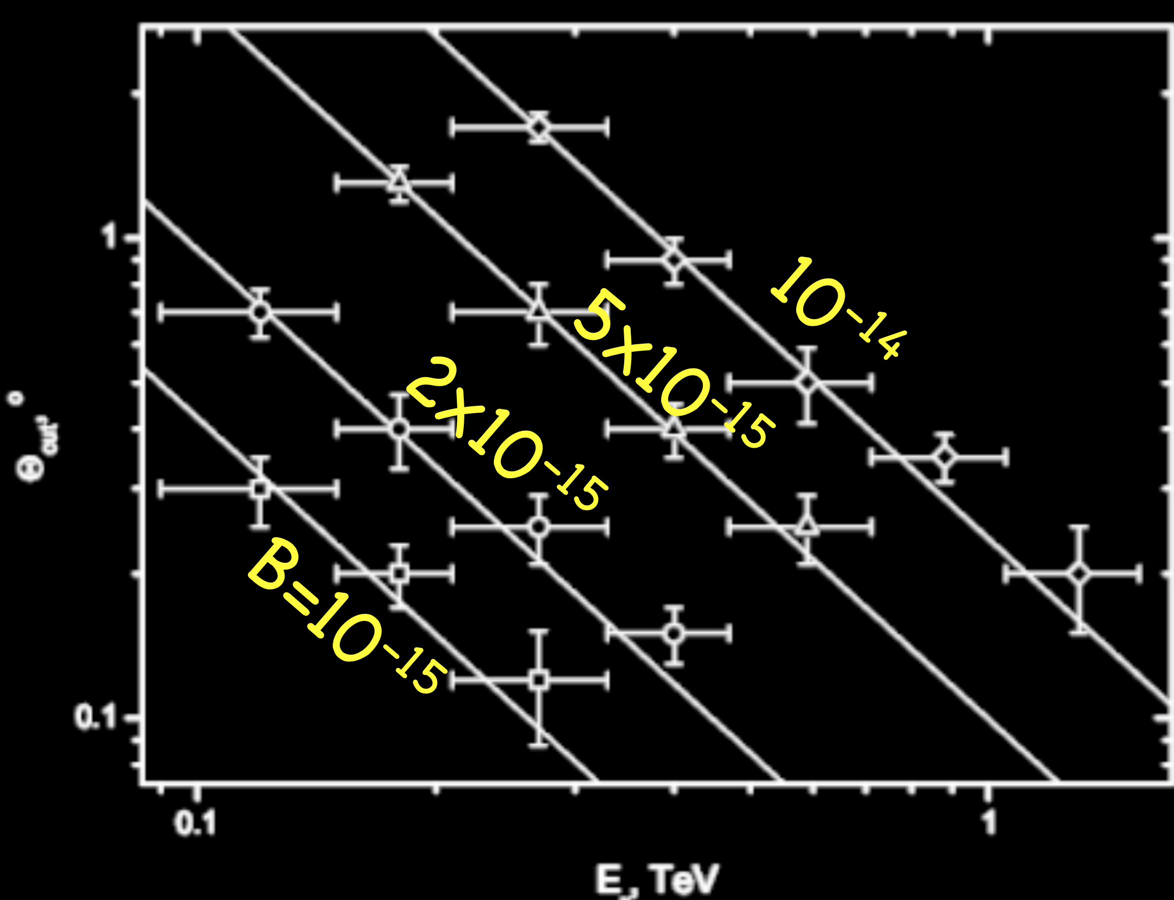


Fraction of energy lost via IC



Angular size: pair "halo"





Elyiv et al. 2009

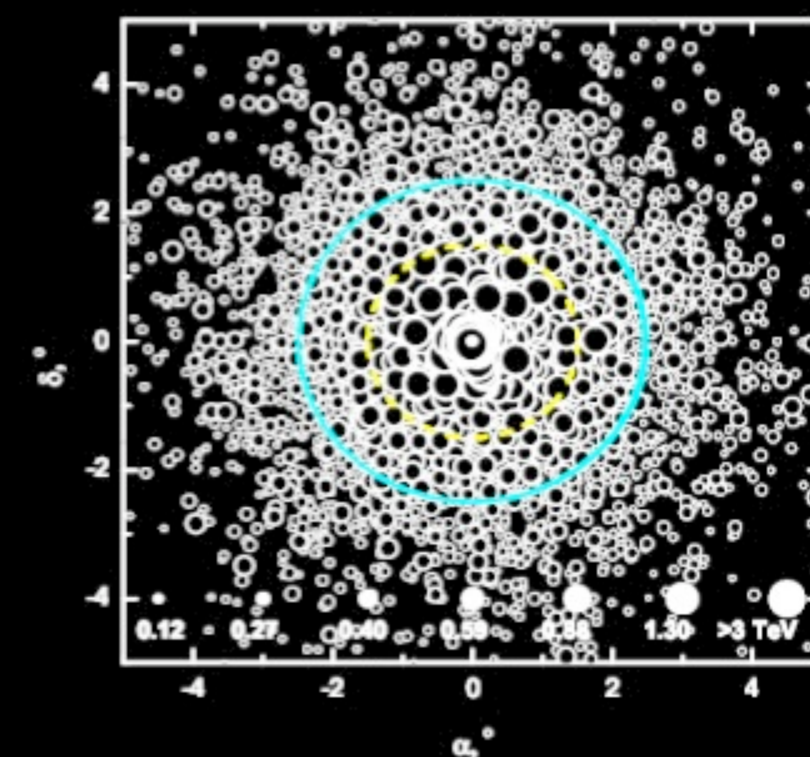
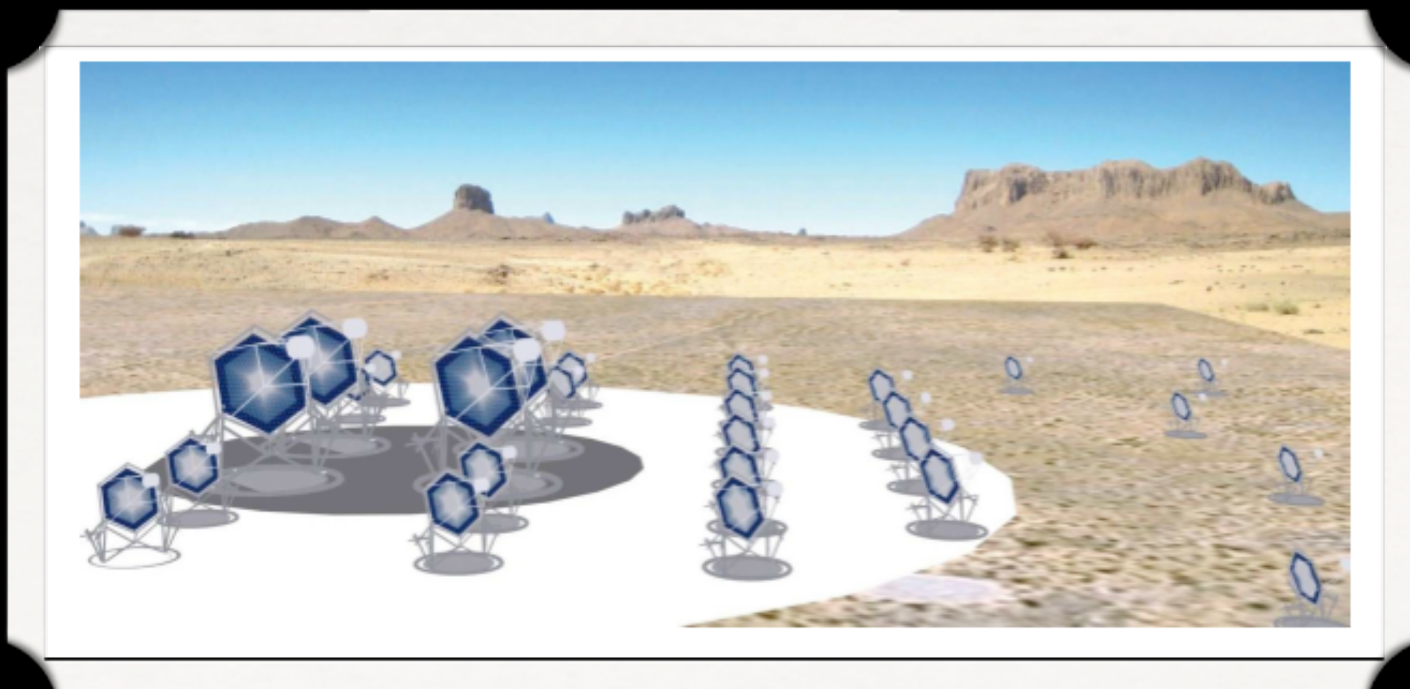
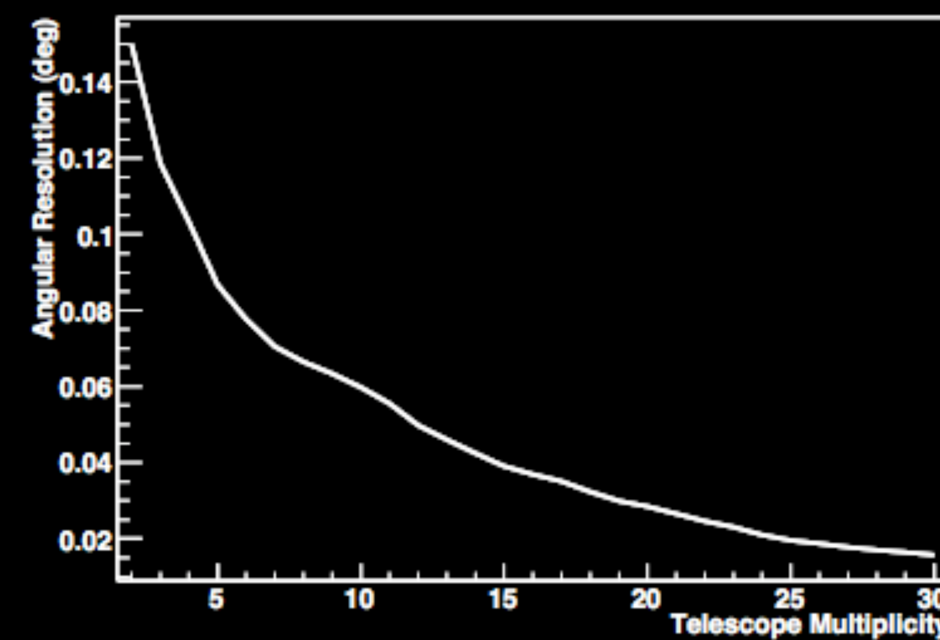


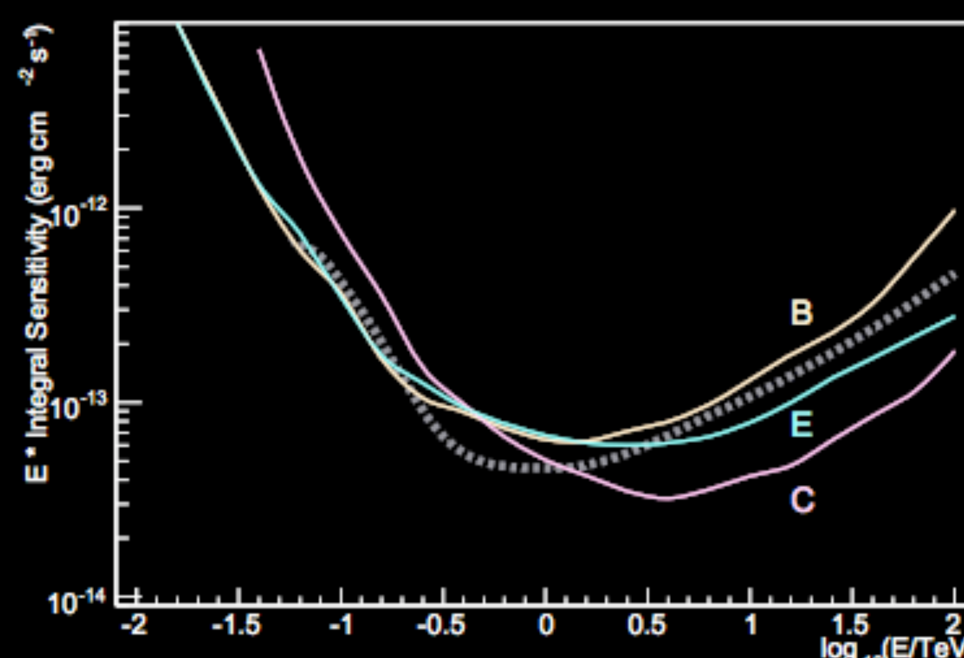
FIG. 4: The arrival directions of the primary and secondary cascade γ-rays (circles) from a source at a distance D = 120 Mpc. The EGMF strength is 10^{-14} G. The sizes of the circles representing each photon are proportional to the photon energies. The blue dashed circle has radius 1.5°, equal to the radius of the FoV or MAGIC telescope. The radius of the blue solid circle is 2.5°, which corresponds to the size of the FoV of HESS telescope.

The future: Cherenkov Telescope Array





http://www.cta-observatory.org/

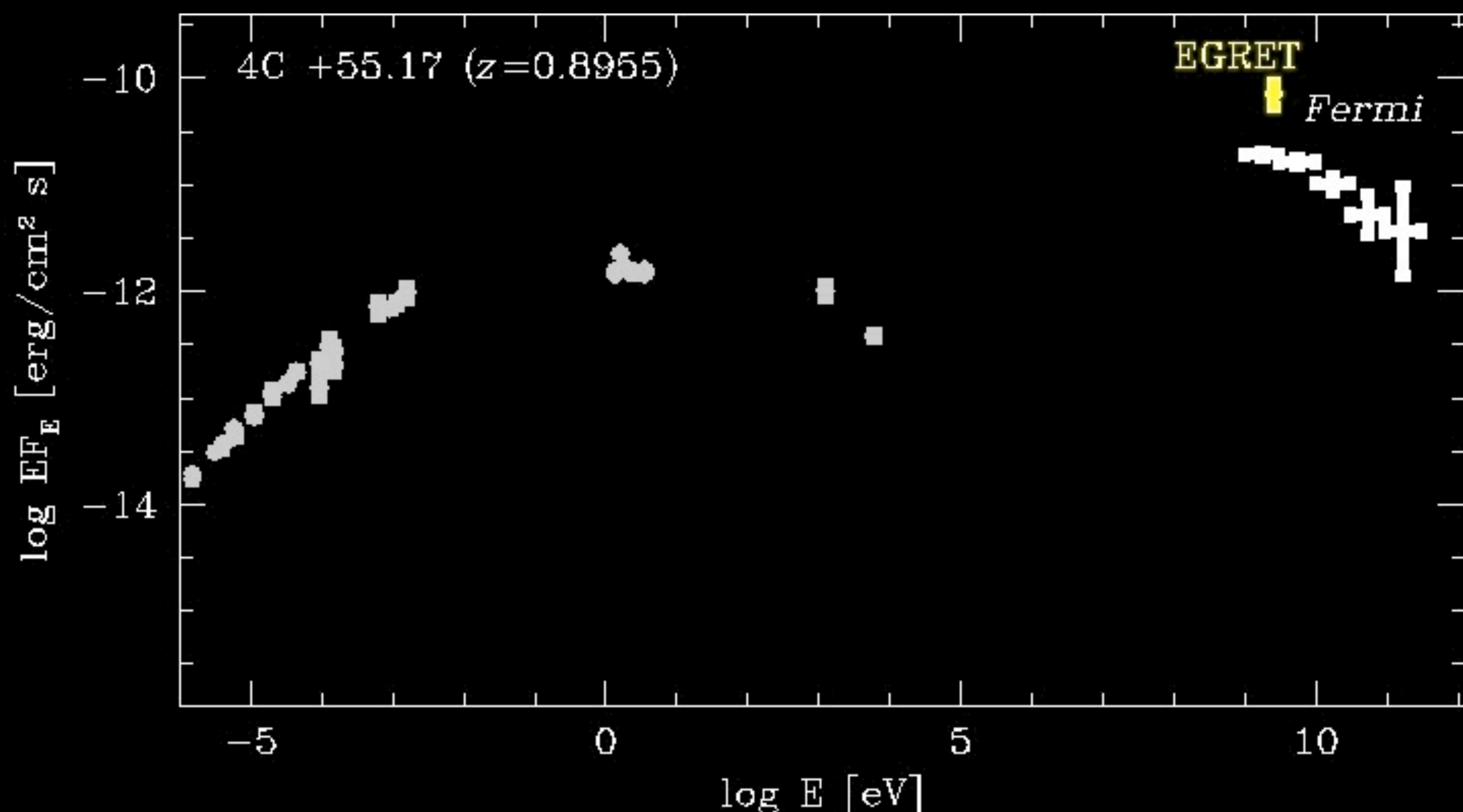


Thank you!

Possible next steps

- ✓ *More extreme TeV sources*
- ✓ *High redshift sources*
- ✓ *Halos (CTA)*

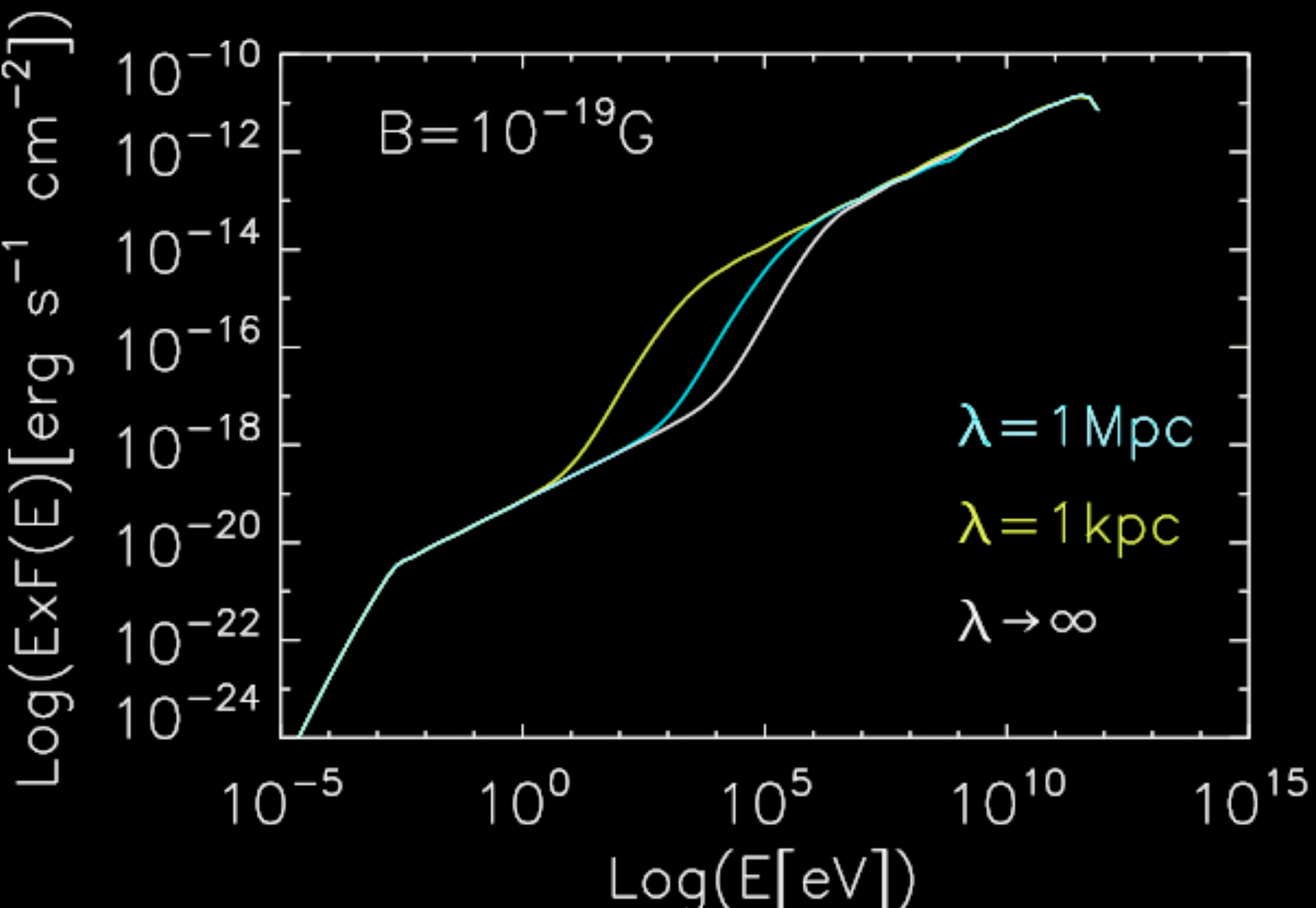
High(er) redshift blazars?



Neronov et al. 2010

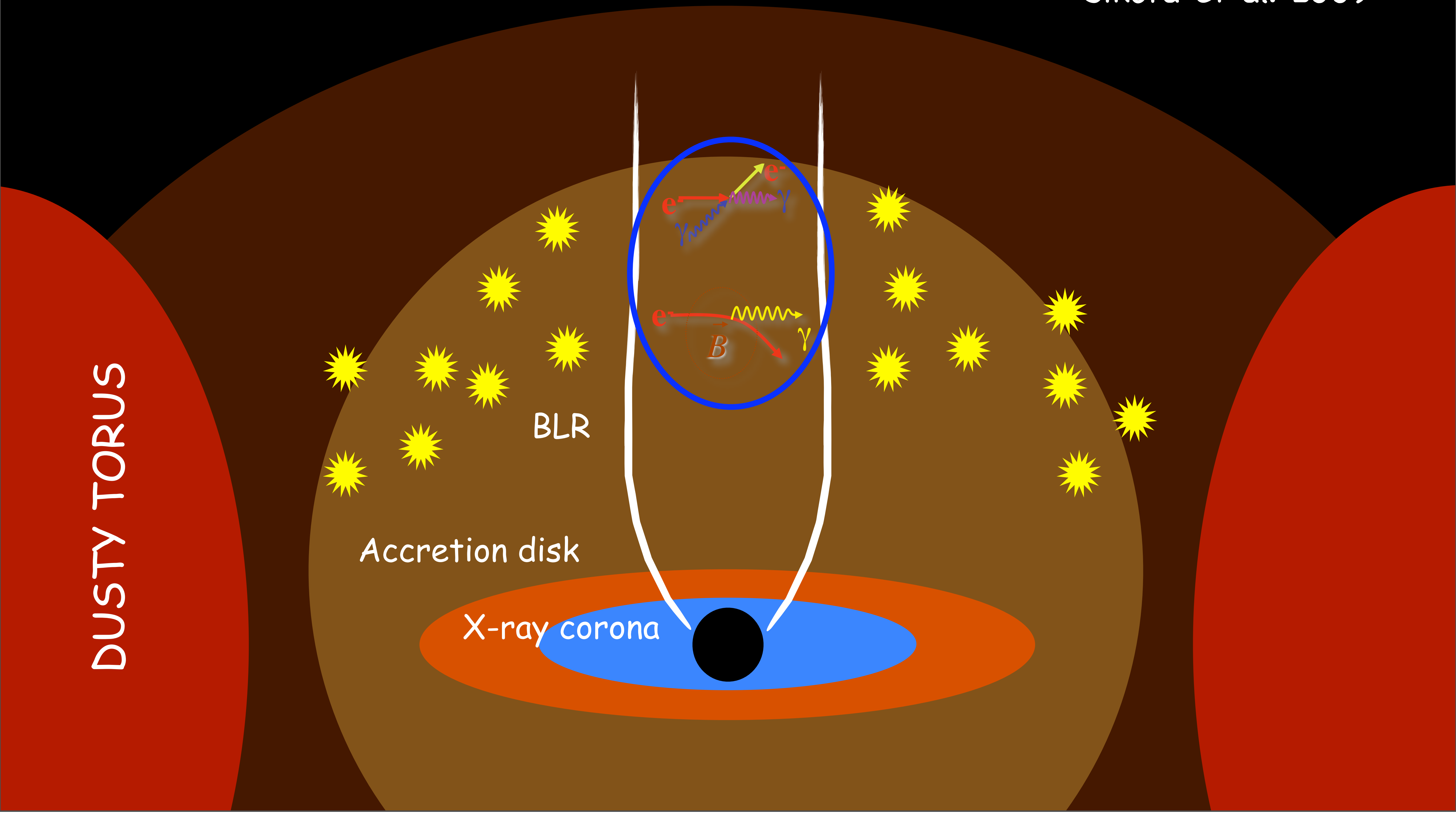
Effect of the correlation length

It reduces the effective deviation angle ("random walk")

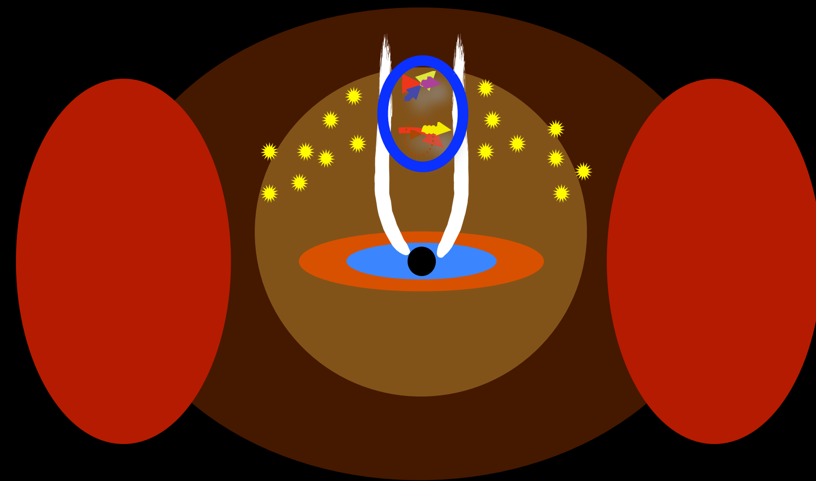


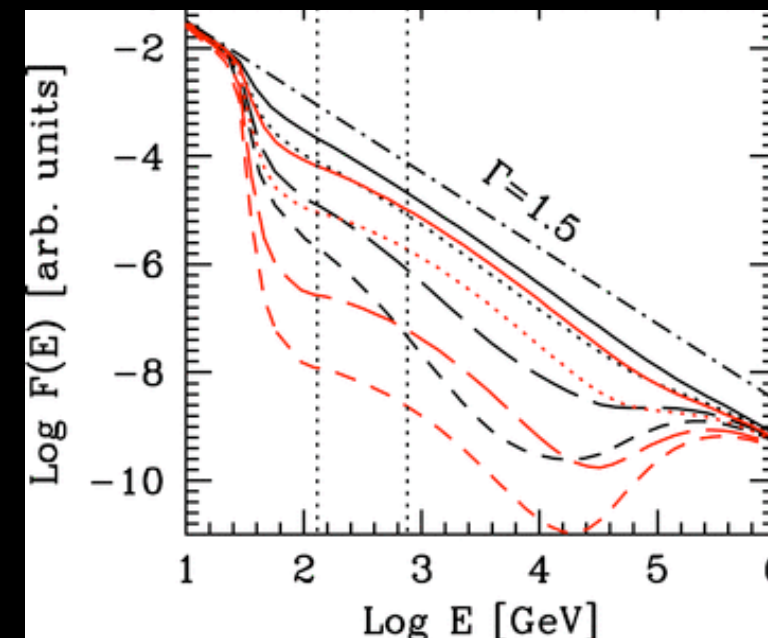
FSRQs: the "canonical" scenario

Dermer et al. 2009
Ghisellini, FT 2009
Sikora et al. 2009



TeV emission from FSRQs? Difficult!



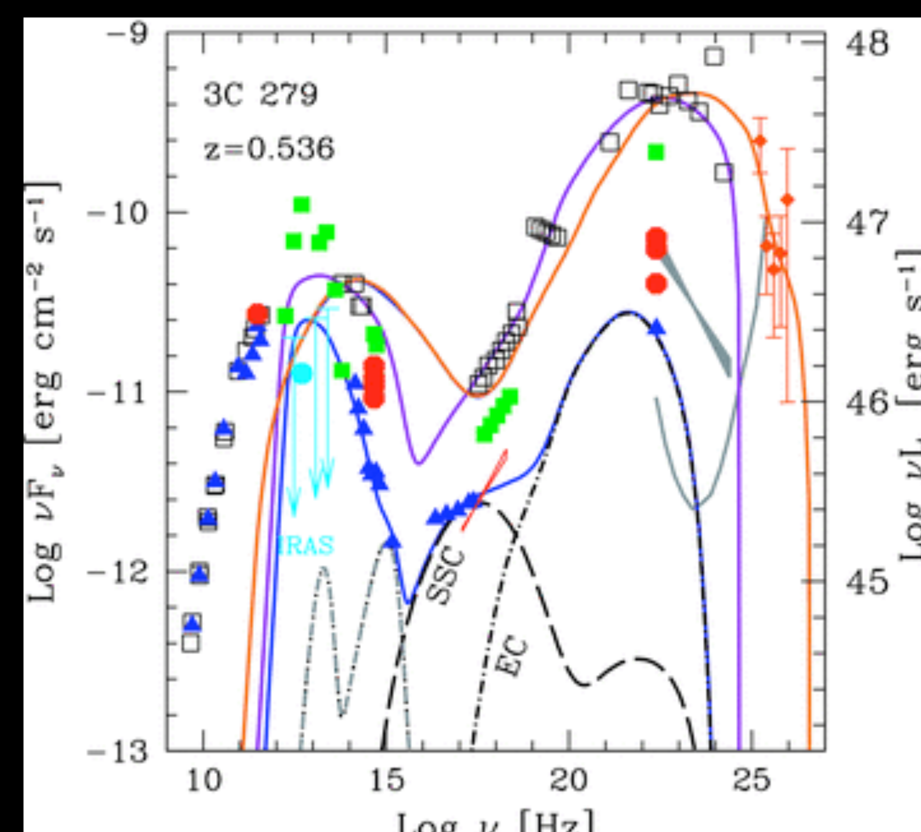


Strong absorption

(E>30 GeV within BLR, E>1 TeV outside)

(e.g. Liu et al. 2008, Reimer 2007, FT & Mazin 2009)

INDEPENDENT ON THE EMISSION MECHANISM!



Decline of the scattering efficiency

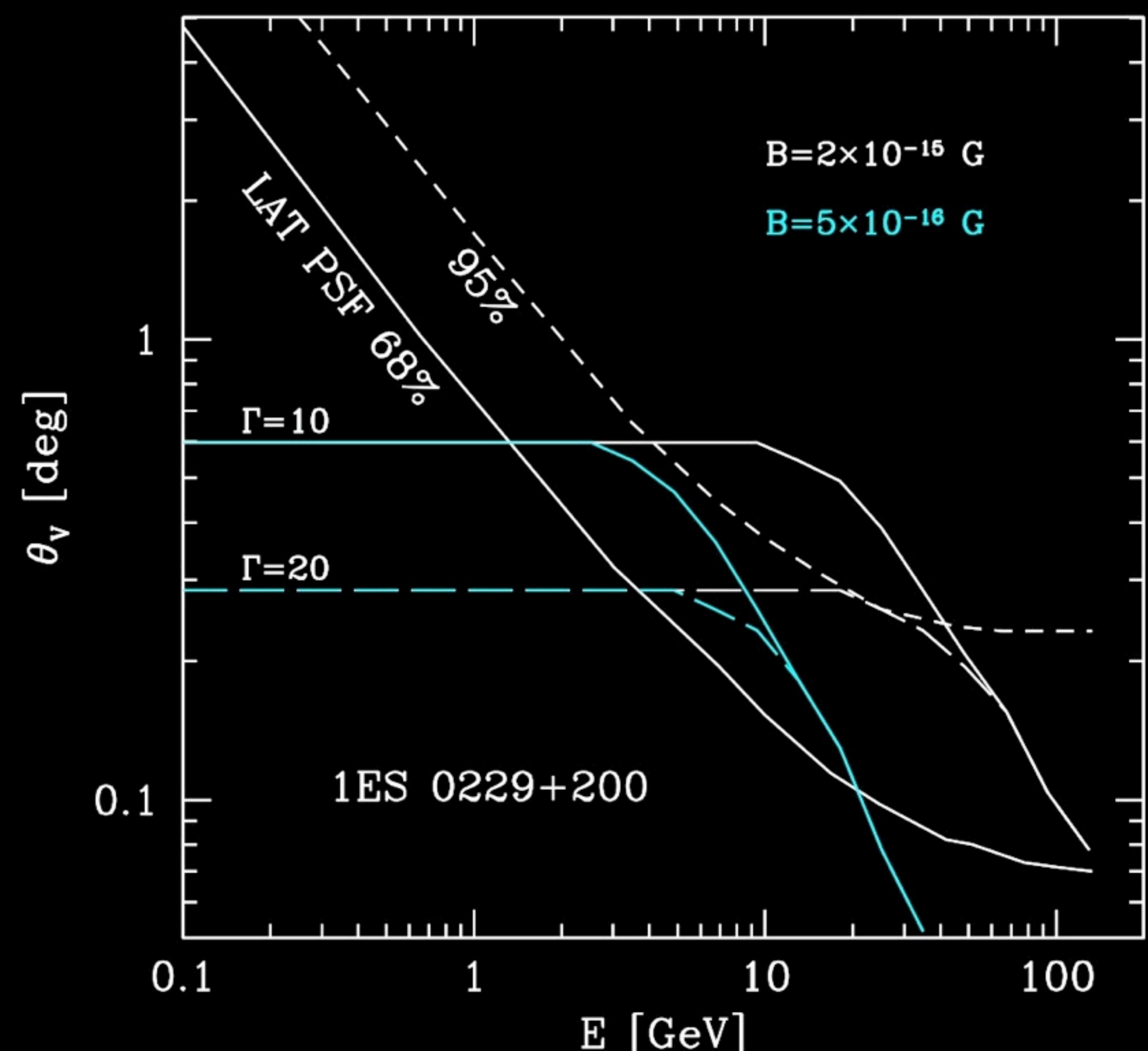
(e.g. Albert et al. 2008, FT & Ghisellini 2008)

$$2\Gamma h\nu_{\mathrm{L}\alpha} < \frac{m_e c^2}{\gamma}$$

$$\nu_{\mathrm{KN}} = \frac{4}{3}\gamma^2\nu_{\mathrm{L}\alpha}\frac{2\Gamma\delta}{1+z} = 15\,\frac{\delta}{\Gamma(1+z)}\ \mathrm{GeV}$$

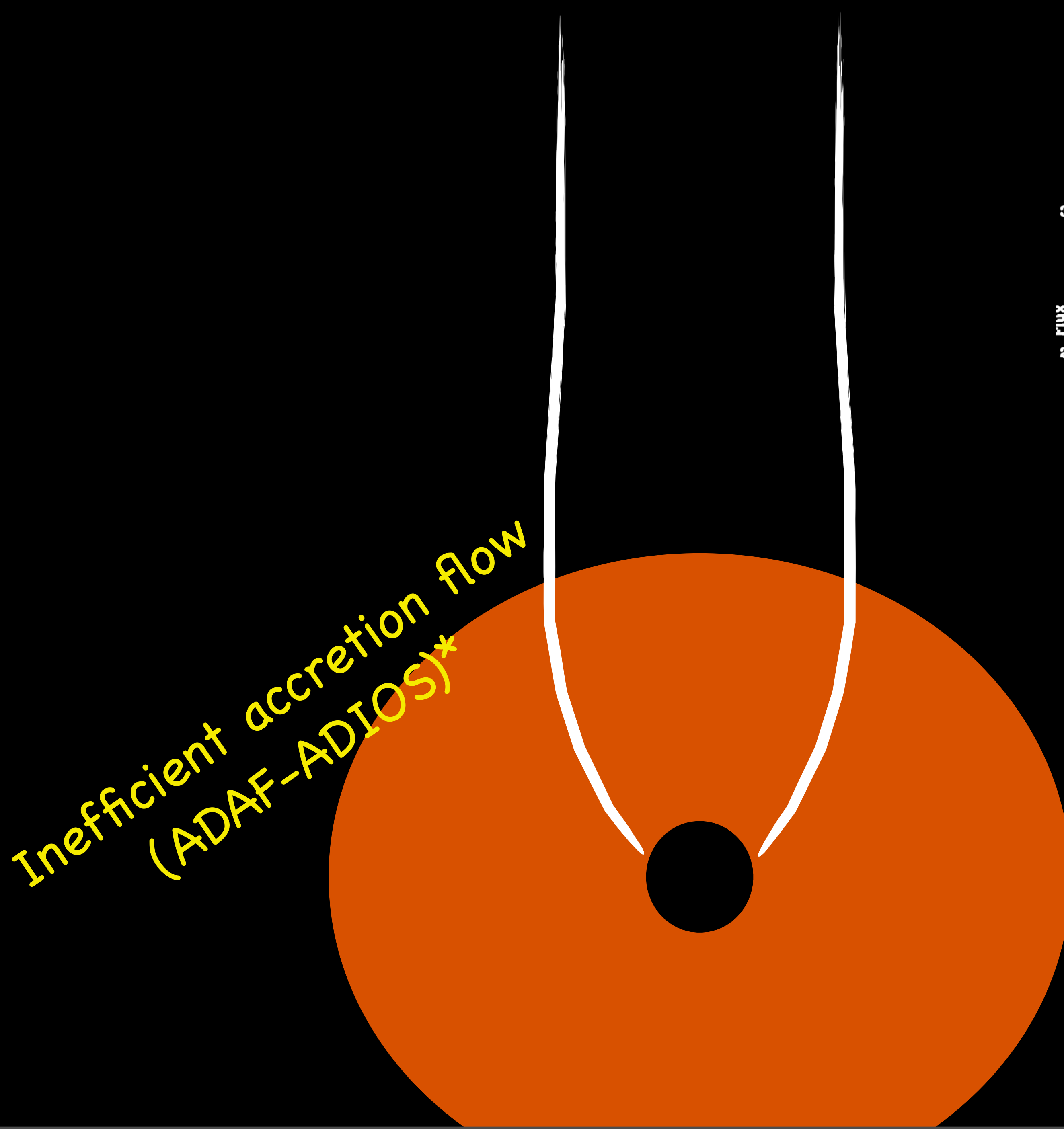
$$\nu_{\mathrm{KN}} = \frac{4}{3}\gamma^2\nu_{\mathrm{IR}}\frac{2\Gamma\delta}{1+z} = 1.2\,\frac{\delta}{\Gamma(1+z)}\ \mathrm{TeV}$$

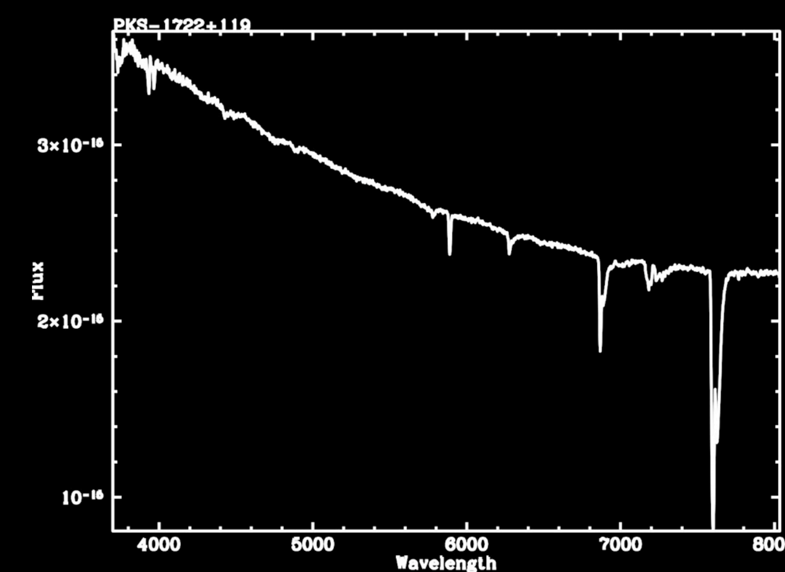
Angular size



FT et al. 2011

BL Lacs: "clean" jets





*but see Raiteri et al. 2009
Capetti et al. 2010 for BL Lac itself

Pair “echo”: a better approach?

Mkn 501: a small z, soft TeV spectrum, variable BL Lac

Takahashi et al. 2011