EBL and IGMF

Fermi Summer School

Lewes, DE

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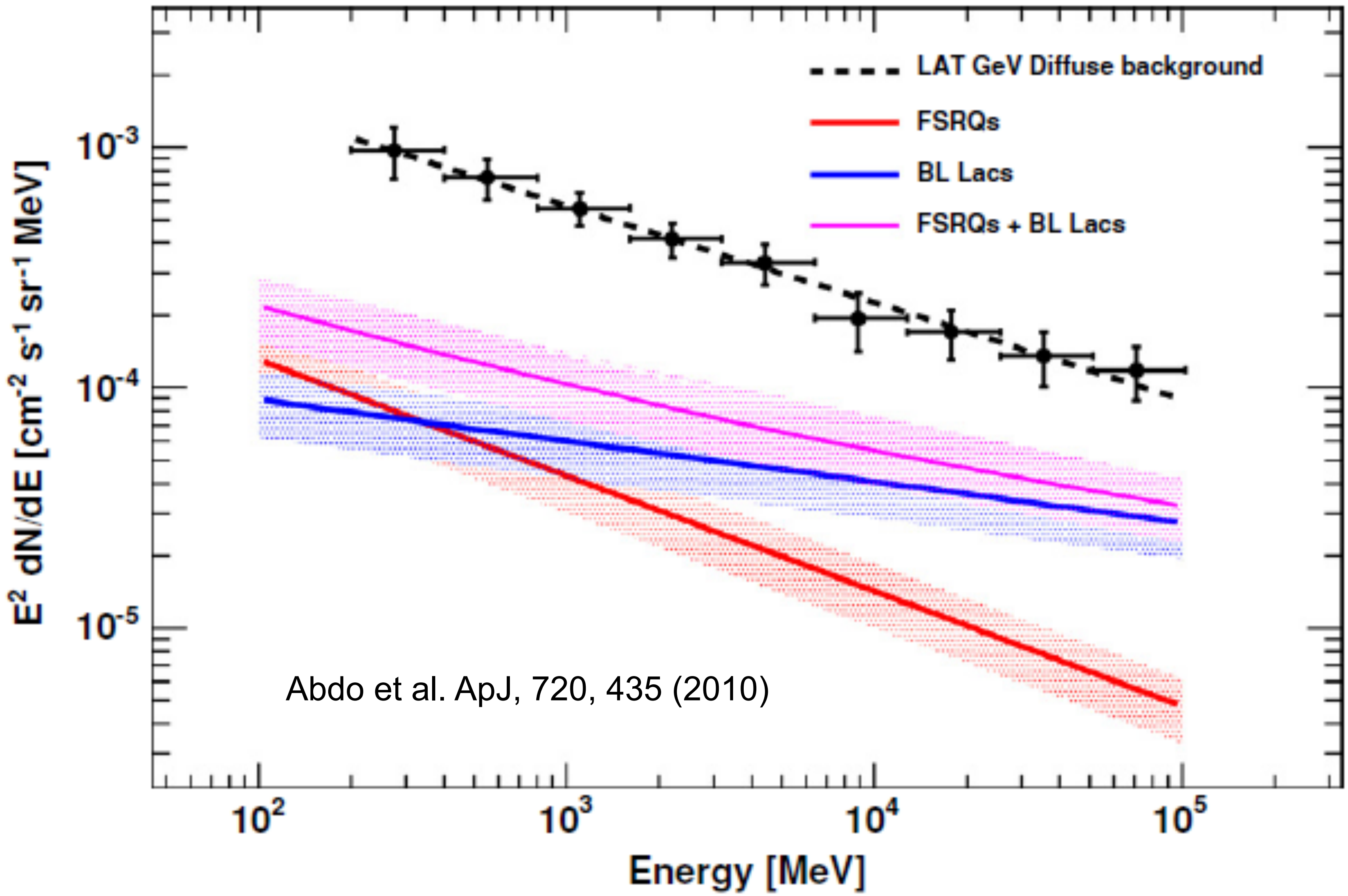
On behalf of the **Fermi Collaboration**

Outline

1. EBL
2. Using Fermi to constrain EBL
3. Measuring the IGMF

1. EBL



LAT GeV Diffuse background
FSRQs
BL Lacs
FSRQs + BL Lacs
10^{-3}
10^{-4}
10^{-5}
E^2 dN/dE [cm^{-2} s^{-1} sr^{-1} MeV]
10^2
10^3
10^4
10^5
Energy [MeV]
Abdo et al. ApJ, 720, 435 (2010)

IR-UV EBL

The Extragalactic Background Light (EBL) at IR/UV frequencies is dominated by the background radiation from all the stars which have ever existed, either directly (UV-optical) or through absorption and re-radiation by dust (IR)

Why is it important?

• Contains information about the evolution of matter in the universe: star formation history, dust extinction, light absorption and re-emission by dust, etc

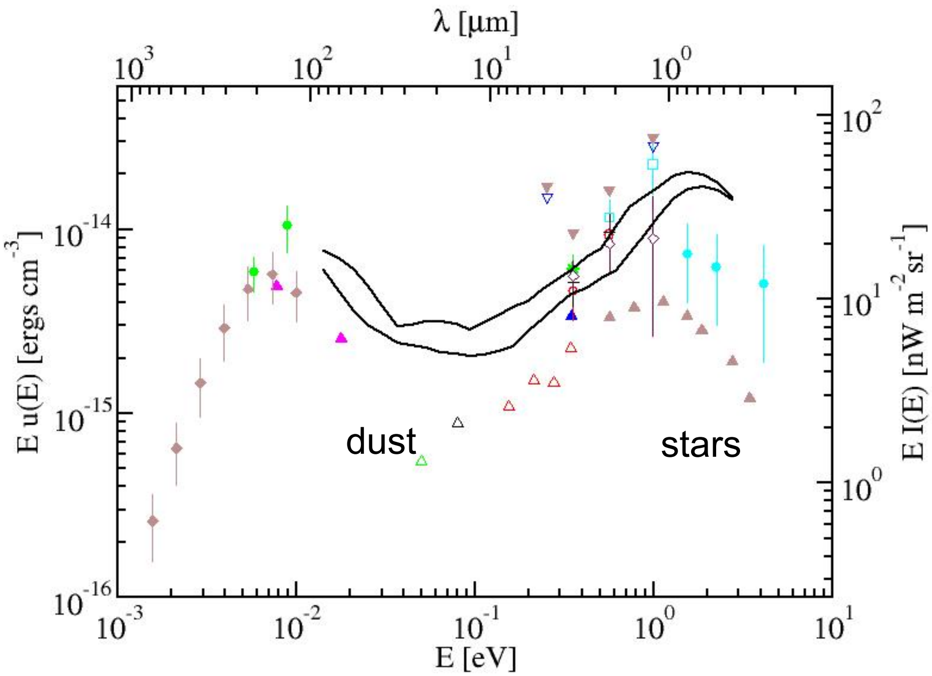
• Knowledge of the absorption effects due to EBL is necessary to infer the intrinsic spectra of extragalactic gamma-ray sources.

Measurement

• Direct measurements difficult because of foreground subtraction: zodiacal light; Galactic synchrotron radiation

• Number counts can give lower limits.

• EBL evolves due to star formation, absorption and re-emission of light by dust



EBL and γ-ray absorption

- EBL photons interact with γ rays via pair production:

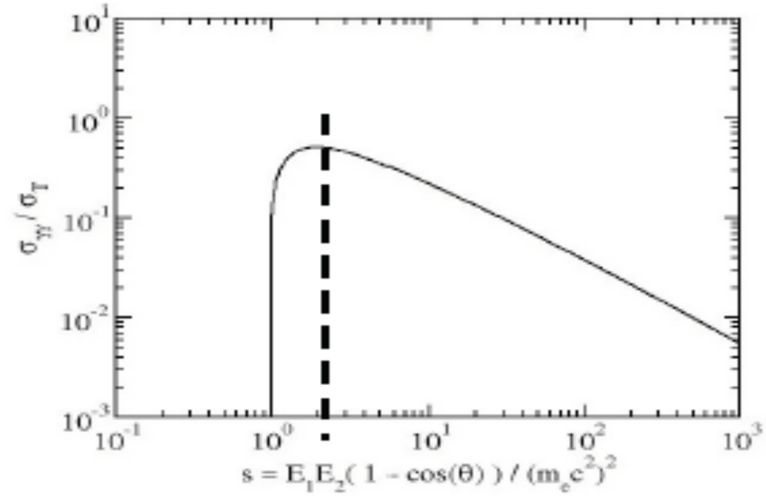
$$\gamma_{ebl} + \gamma_{\gamma\text{-ray}} \rightarrow e^- + e^+$$

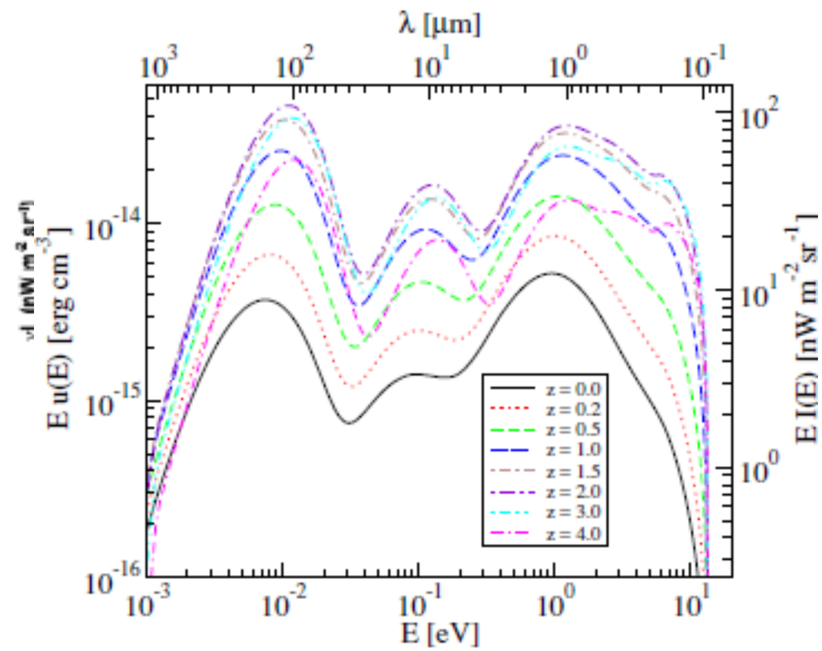
- EBL photons interact with γ-rays primarily at a peak wavelength:

500 GeV γ rays ⇔ 1 eV target photons

- GeV γ-rays interact with primarily UV-optical EBL photons, while TeV γ-rays are absorbed by near/mid IR EBL photons
- The farther away a source is, the greater its optical depth to EBL absorption.
- Nearby sources: TeV sources, sensitive to near-mid IR EBL
- More distant sources: GeV sources, sensitive to UV/optical EBL

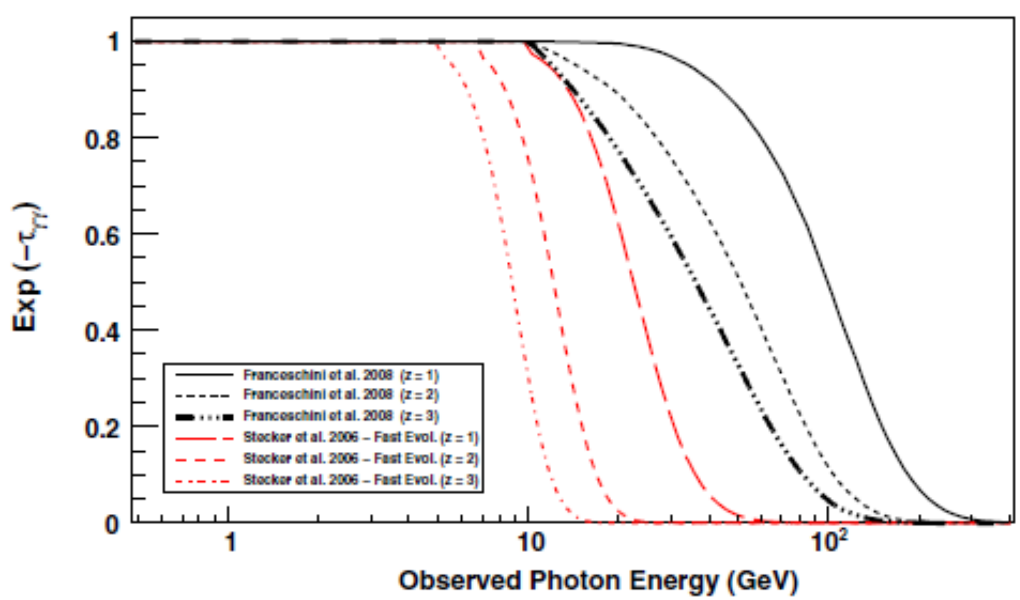
Universe transparent below ~10 GeV

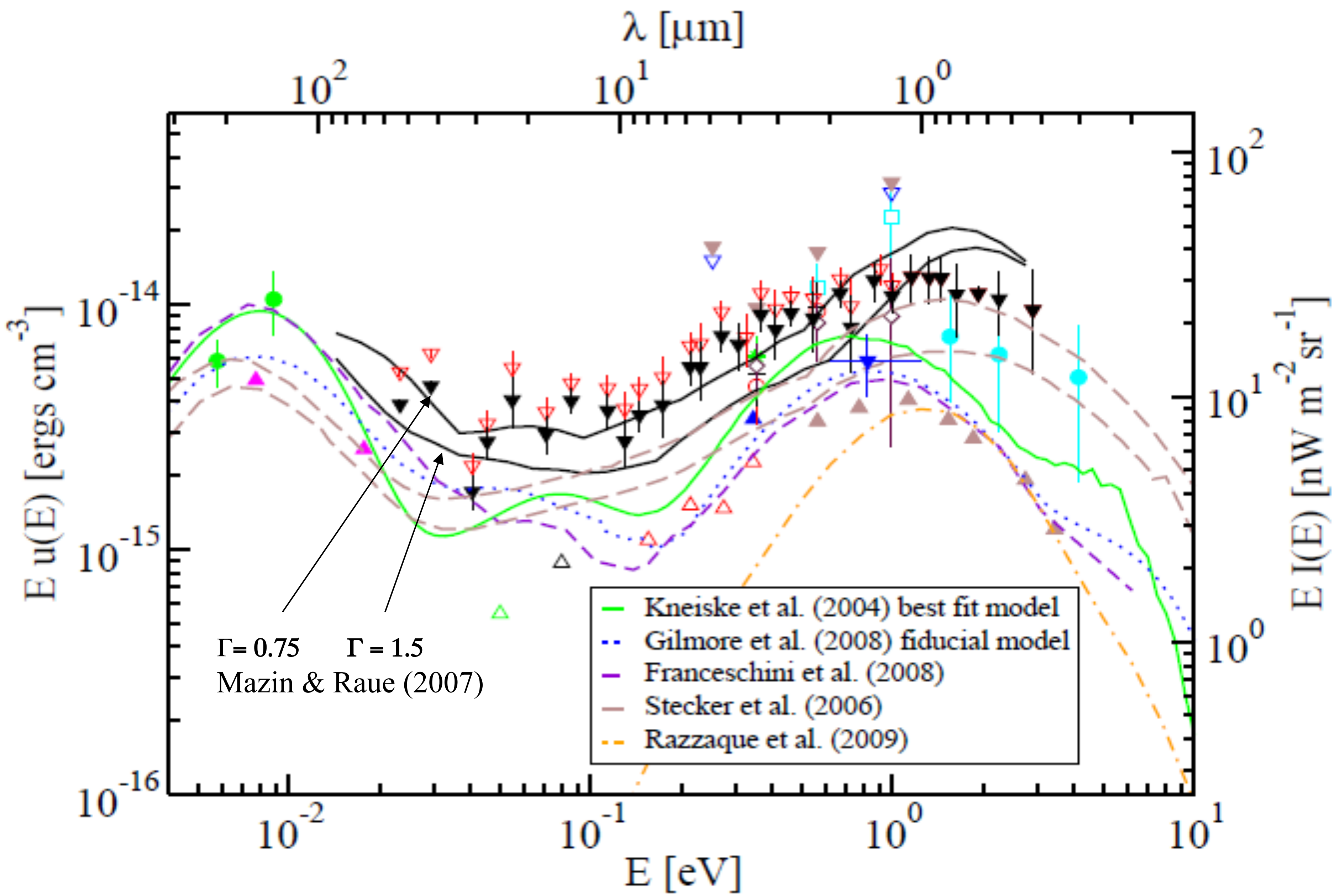




Models of the EBL

- ❑ γ-ray horizon: $\tau_{\gamma\gamma}(E\gamma,z) = 1$ (Stecker-Fazio relation)
- ❑ Empirical method: sum optical/IR emissions from sources at various redshifts using luminosity-dependent galaxy SEDs (Stecker et al., Franceschini et al. 2008)
- ❑ Model of galaxy formation during mergers of dark matter halos, including supernova feedback, dust attenuation, metal production (Primack et al., Gilmore)
- ❑ Inferring EBL spectrum from TeV observations by scanning over a large grid of possible EBL, deabsorbing TeV observations limited by spectral hardness (0.75 and 1.5) (Mazin & Raue 2007)
- ❑ Models based on integrating stellar light with dust absorption absorption (Kneiske, Finke et al.)



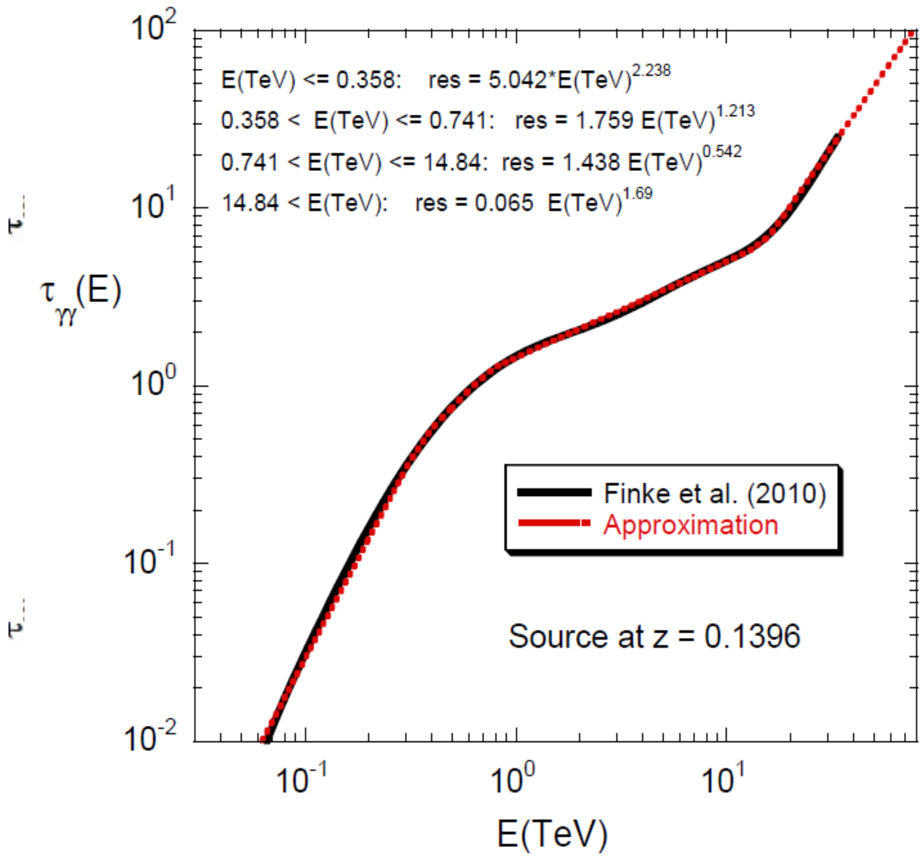


λ [μm]
10^2
10^1
10^0
E u(E) [ergs cm^-3]
10^-14
10^-15
10^-16
E I(E) [nW m^-2 sr^-1]
10^2
10^1
10^0
E [eV]
10^-2
10^-1
10^0
10^1
Γ= 0.75
Γ = 1.5
Mazin & Raue (2007)
Kneiske et al. (2004) best fit model
Gilmore et al. (2008) fiducial model
Franceschini et al. (2008)
Stecker et al. (2006)
Razzaque et al. (2009)

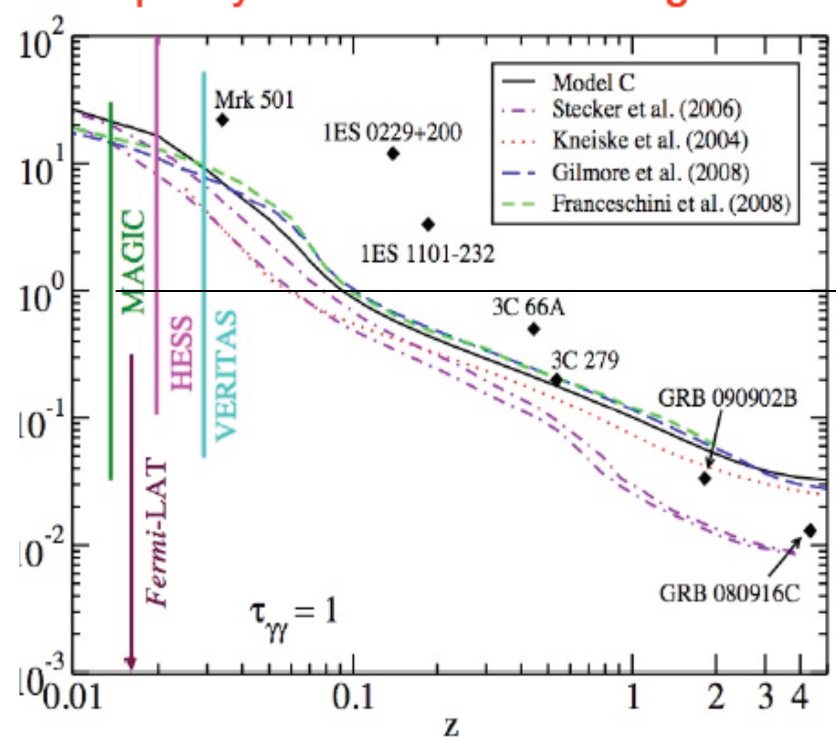
EBL Model Predictions

The opacity of the e^+e^- pair production by HE γ rays with EBL photons depends on the redshift of the source and γ-ray energy

Model opacity predictions

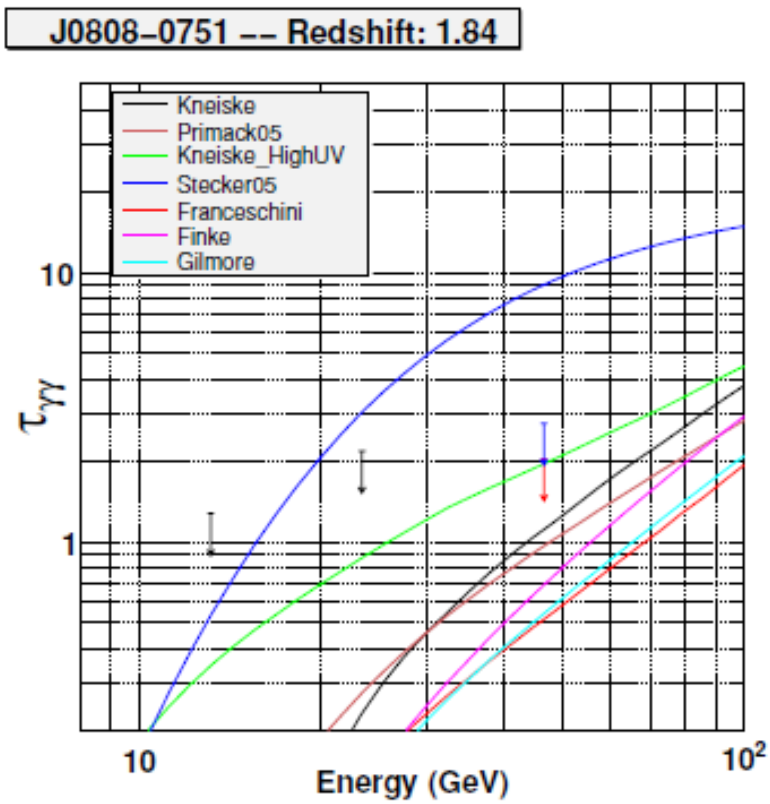


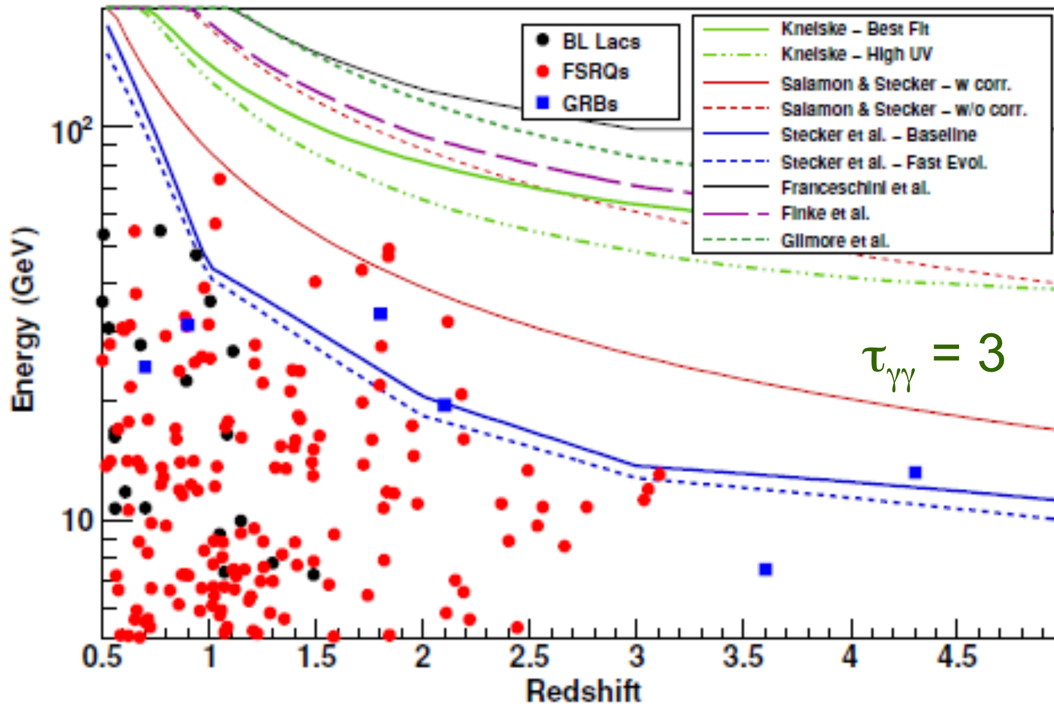
Opacity limit and constraining data



2. EBL Studies with Fermi Data

Highest energy photons from Blazars and GRBs probe EBL models





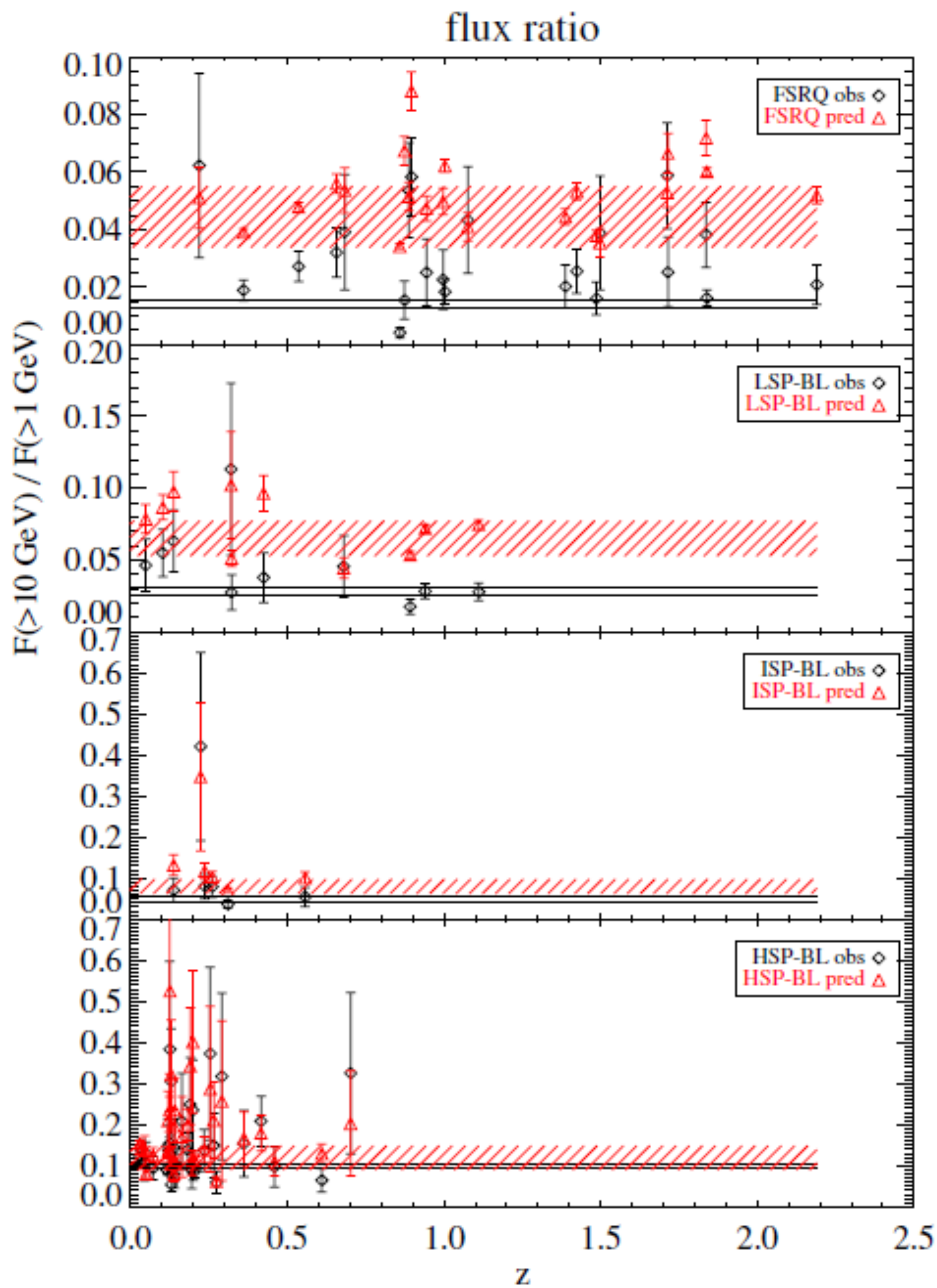
Abdo et al. ApJ, 723, 1082 (2010)

Comparison between expected number of high-energy photons from extrapolation of low energy Fermi GeV spectra constrains EBL model

Flux Ratio Method

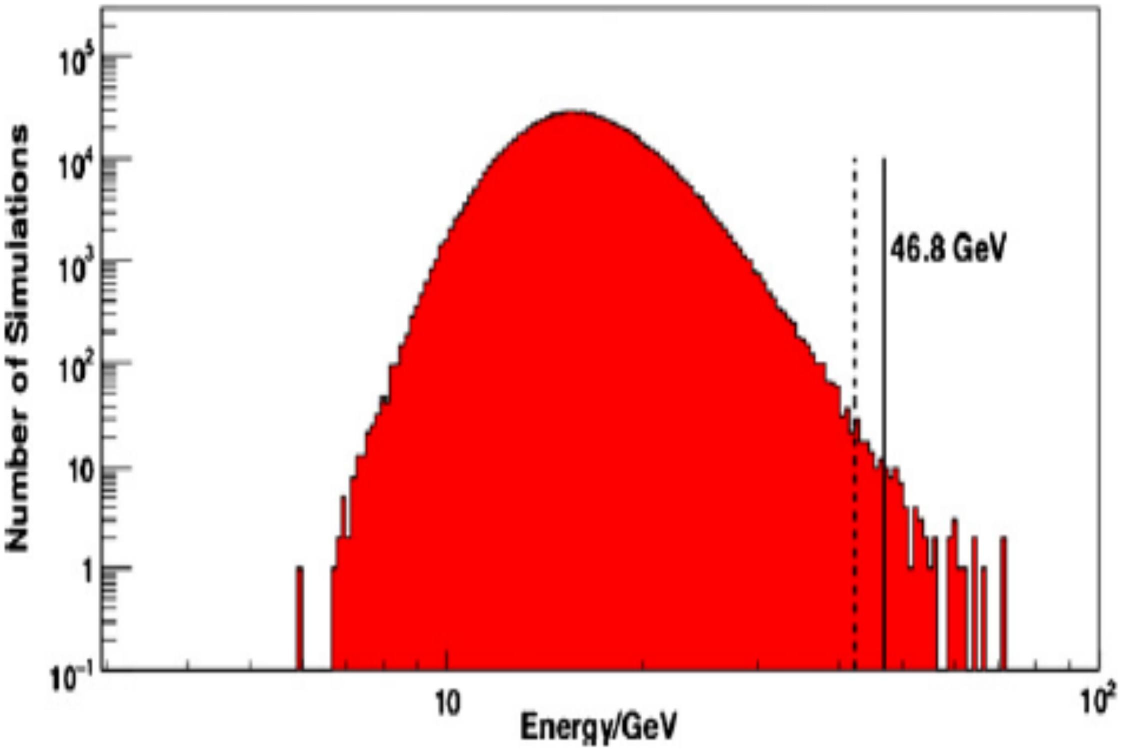
- Assuming intrinsic blazar spectra are z-independent, then ratio of high to low energy fluxes decreases with z

- Must use blazar subclasses because of multi-GeV softenings in FSRQs/LSPs/ISPs that are at higher redshifts than ISPs and HSPs with known redshift



EBL Model Rejection with Fermi Data

1FGL J0808-0750 = PKS 0805-07



Distribution of highest energy photons from MC Simulation:

- Using Stecker et al. 2006 "baseline" EBL model
- Over 11000 simulations
- Mean of distribution = 15.52 GeV
- Mean of distribution with no EBL attenuation effects would be 95.5 GeV (from sims)

Abdo et al. ApJ, 723, 1082 (2010)

For this source and EBL model the probability of having a high energy photon with energy 46.77 GeV or greater is **1.9×10^{-6}** (a **4.6** σ result)

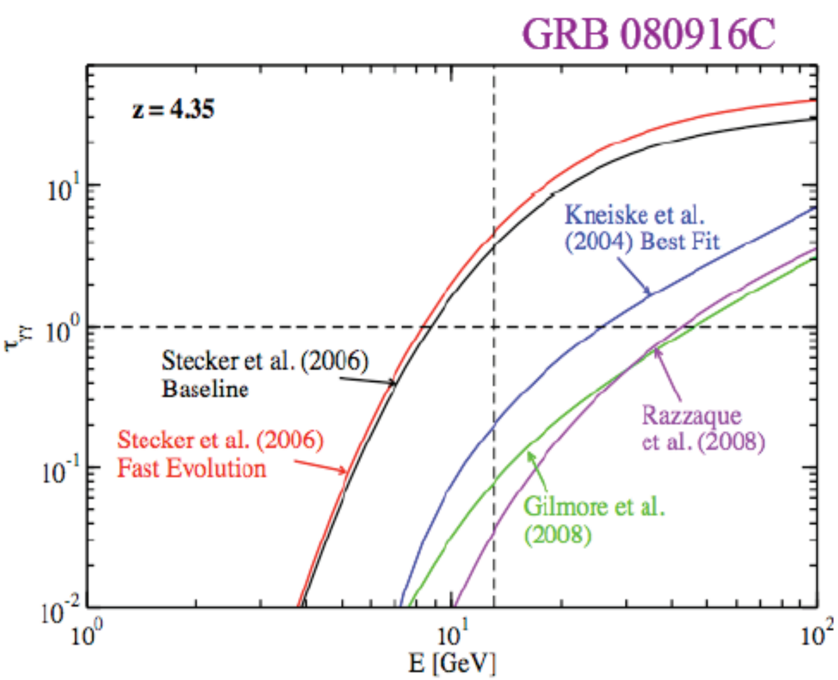
Constraints on EBL Models from GRBs

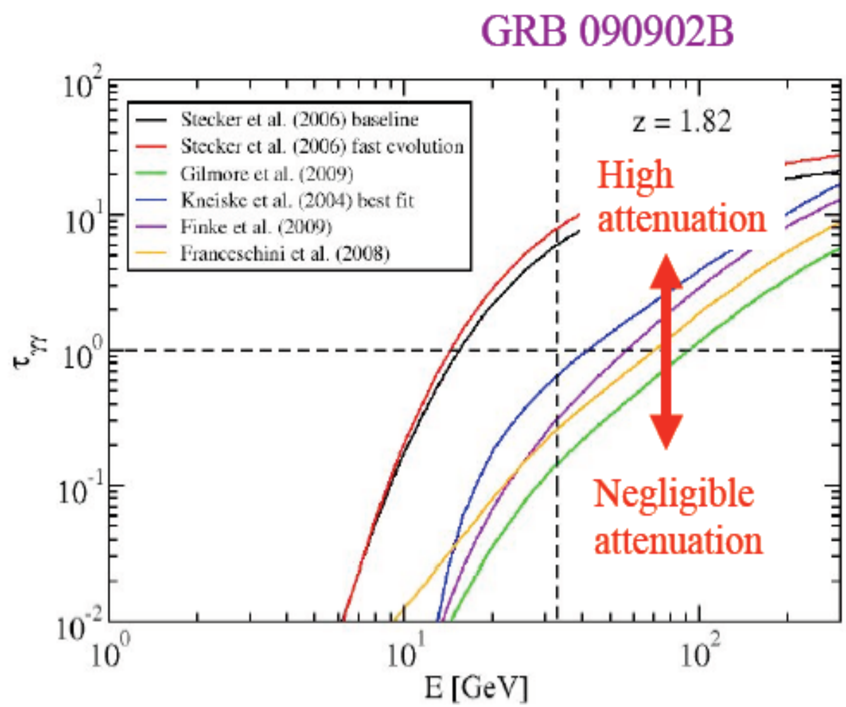
Opacity of $\gamma\gamma \rightarrow e^+e^-$ pair production by the 13.2 GeV (GRB 080916C) and 33.4 GeV (GRB 090902B, highest from a GRB!) γ rays with optical-UV photons of the EBL

For Stecer et al. 2006 fast-evolution/baseline models, the opacity $\tau_{\gamma\gamma} \sim 5.0/3.7$ (GRB 080916C) and $\tau_{\gamma\gamma} \sim 7.7/5.8$ (GRB 090902B)

Both models can be ruled out with >3σ significance

Other models: OK



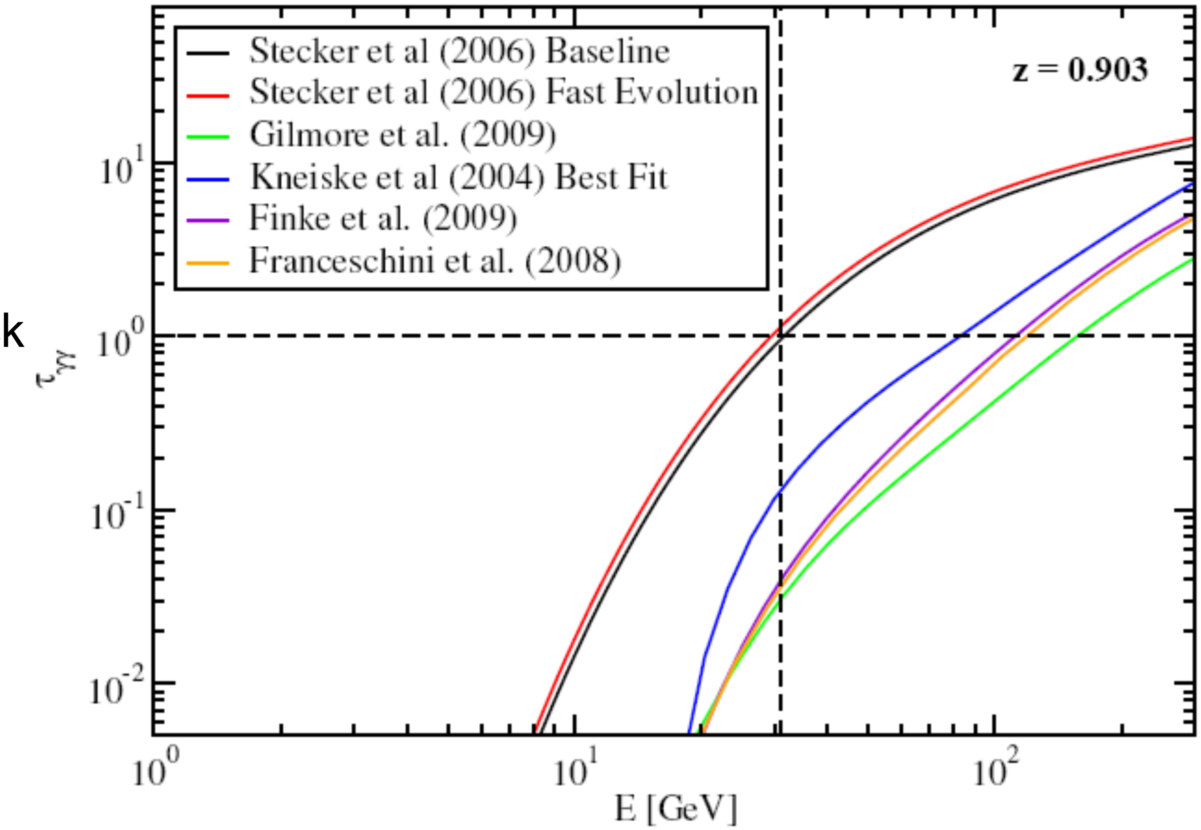


EBL Constraints: GRB 090510

Highest energy photon: $30.5^{+5.8}_{-2.6}$ GeV

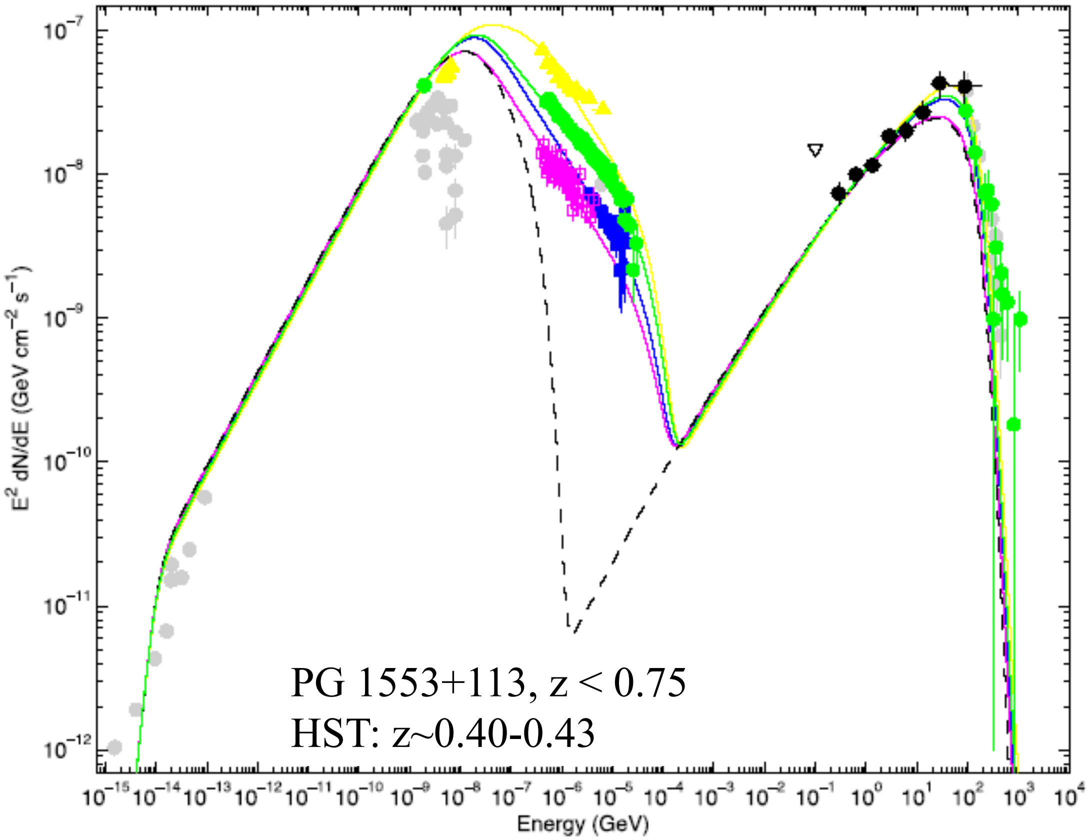
(0.829 s after LAT trigger
in interval c)
z = 0.903
Only Stecker et al. model
is (marginally) optically thick

Compare GRB 080916C:
Highest energy photon:
13 GeV
But z = 4.35



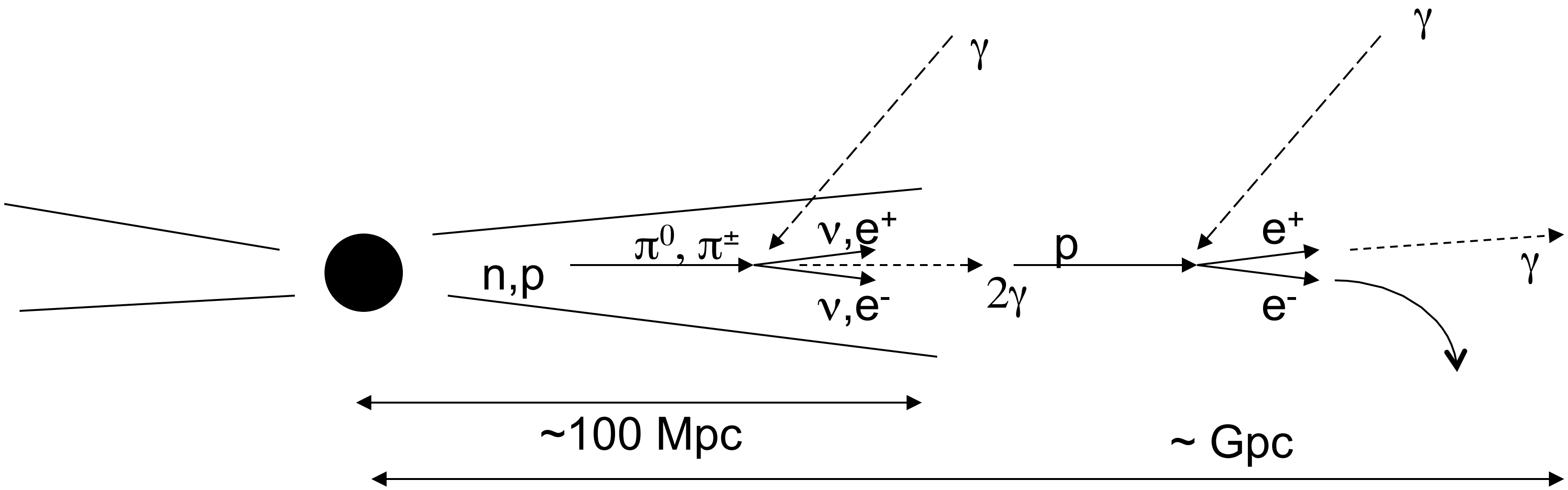
Redshift Constraints on BL Lacs

- Only ~60% of 2LAC BL Lacs have measured redshifts
- VHE γ rays constrain EBL; provides method for determining redshift of BL Lacs



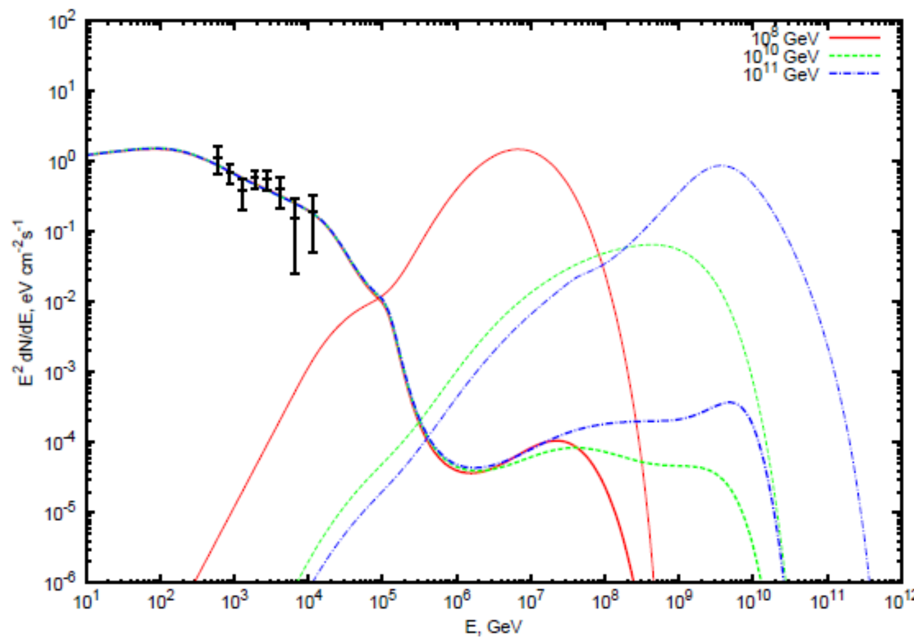
Abdo et al. ApJ, 708, 1310 (2010)

Just one thing…



UHECR protons with energies ~10^{19} eV make ~10^{16} eV $e^{\pm}$ that cascade in transit and Compton-scatter CMBR to TeV energies

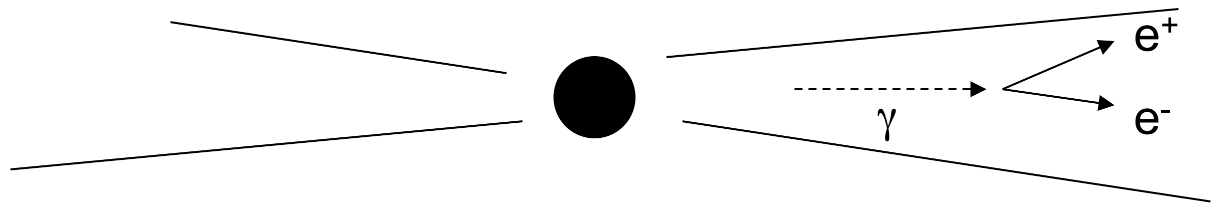
Essey, Kalashev, Kusenko, Beacom (2010, 2011)



3. Cascade Halo Radiation, the EBL and the IGMF

Magnetic obscuration of charged particle trajectories:

UHECR ions; Lepton secondaries of $\gamma\gamma \rightarrow e^+e^-$



Attenuation by the EBL: what happens to the generated pairs?

Pair halos (Aharonian, Coppi, & Völk 1994; Roustazadeh & Böttcher 2011)

Temporal delay and Intergalactic Magnetic Field (IGMF) (Plaga 1995)

Temporal delay/echoes from bursting sources (Razzaque et al. 2004; Murase et al. 2008)

Angular extent of halos around blazars (Elyiv et al. 2009, Aharonian et al. 2009)

Halo extent at GeV energies ⇒ measurement of IGMF

Ando & Kusenko (2010): ~30′ halos in stacked data of 170 hard-spectrum Fermi blazars

$\Rightarrow B_{IGMF} \sim 10^{-15}$ G $(\lambda_{coh}/\text{kpc})^{-1/2}$ **Criticisms: Neronov et al. (2011), Fermi statement and paper in preparation**

Spectral TeV/GeV constraints on IGMF (d'Avezac et al. 2007; Neronov & Vovk 2010; Tavecchio et al. 2010)

Nondetection by Fermi of TeV blazar sources ⇒ B_{IGMF} >~ 10^{-16} G

Limits on IGMF and Correlation Length

Origin of the Intergalactic Magnetic Field (B_{IGMF}):

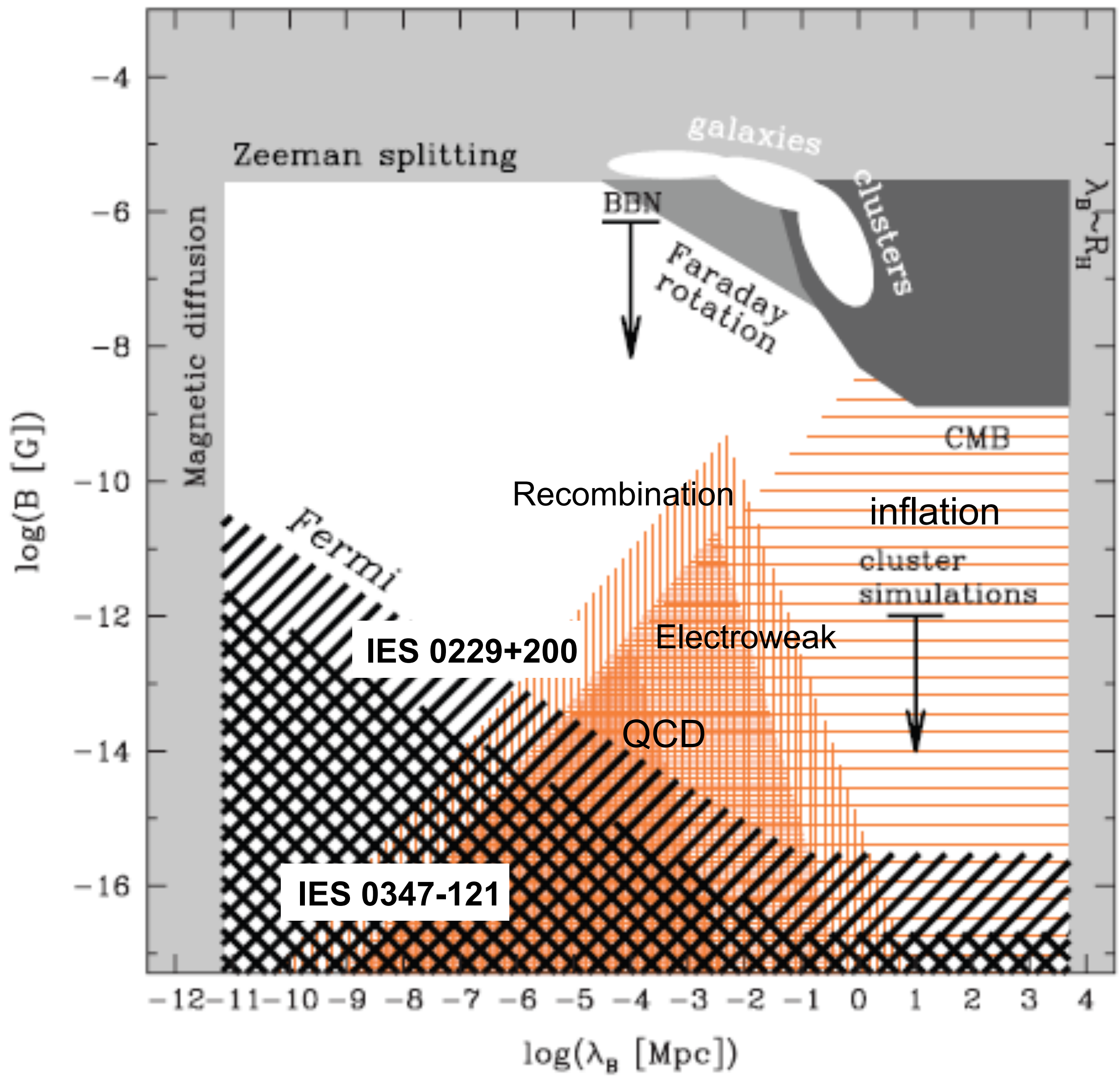
Primordial

Early universe physics

Biermann battery (~10^{-30} G on Mpc scale)

Galaxy dynamo

other



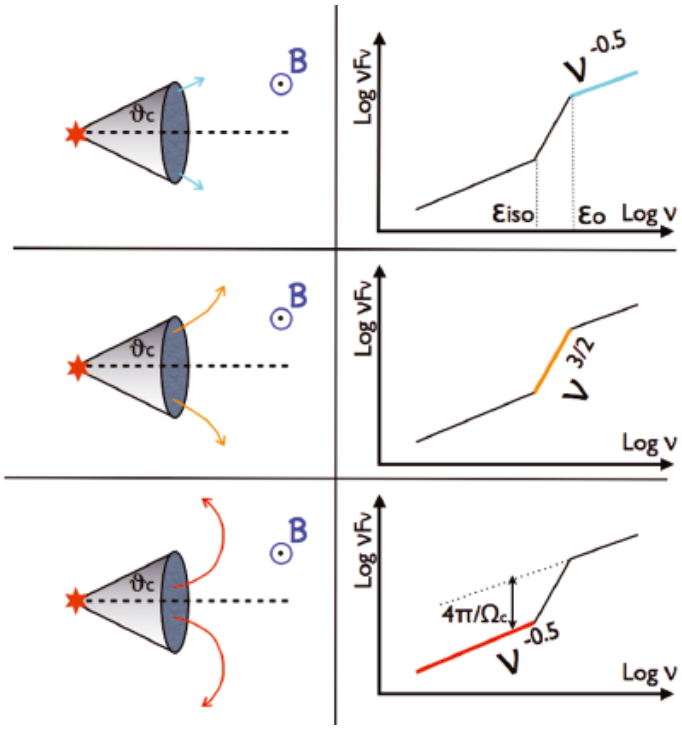
Neronov & Vovk (2010)

Spectral Model of Halo Emission

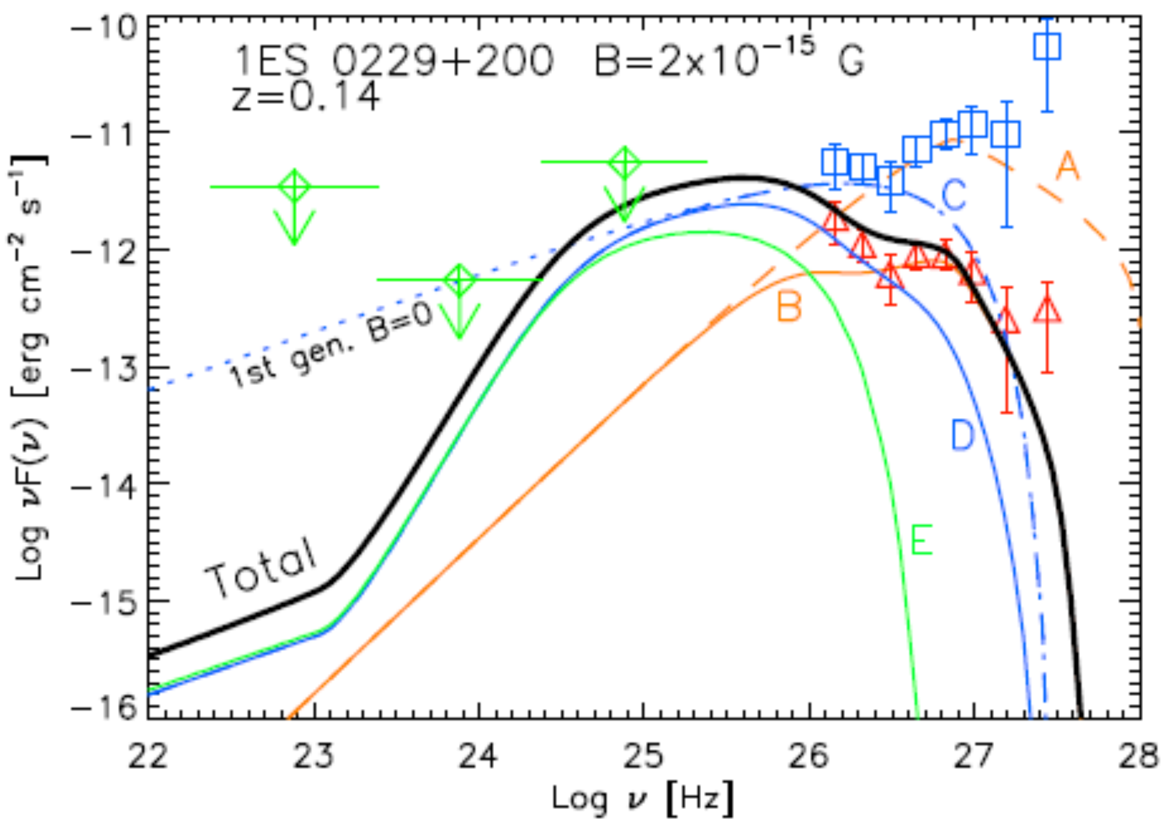
Cooling spectrum $\nu F_\nu \propto \nu^{1/2}$

Compton-scattered spectrum $\nu F_\nu \propto \nu^{3/2}$

Isotropized spectrum $\nu F_\nu \propto \nu^{1/2}$

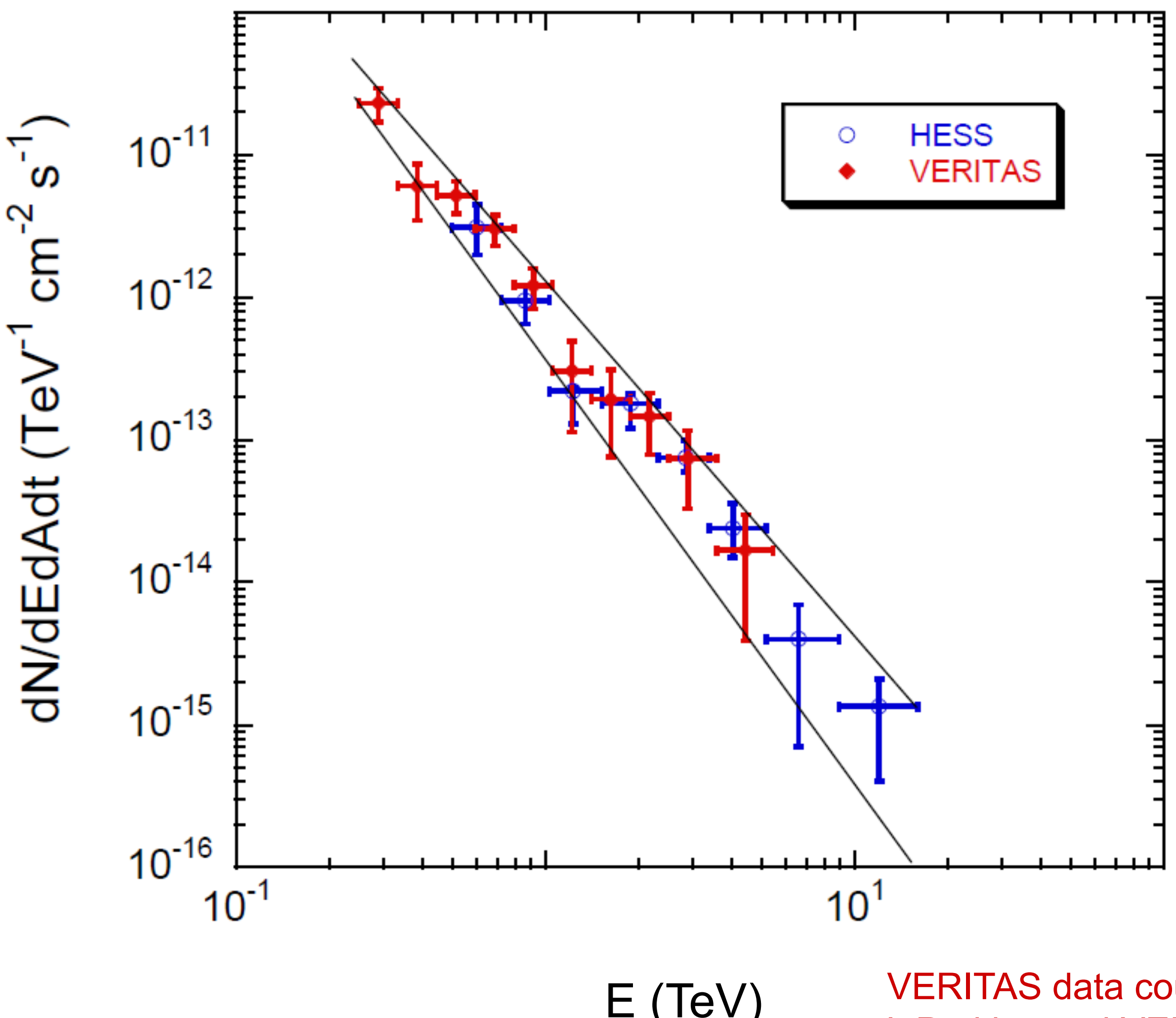


Tavecchio et al. (2010a,b)



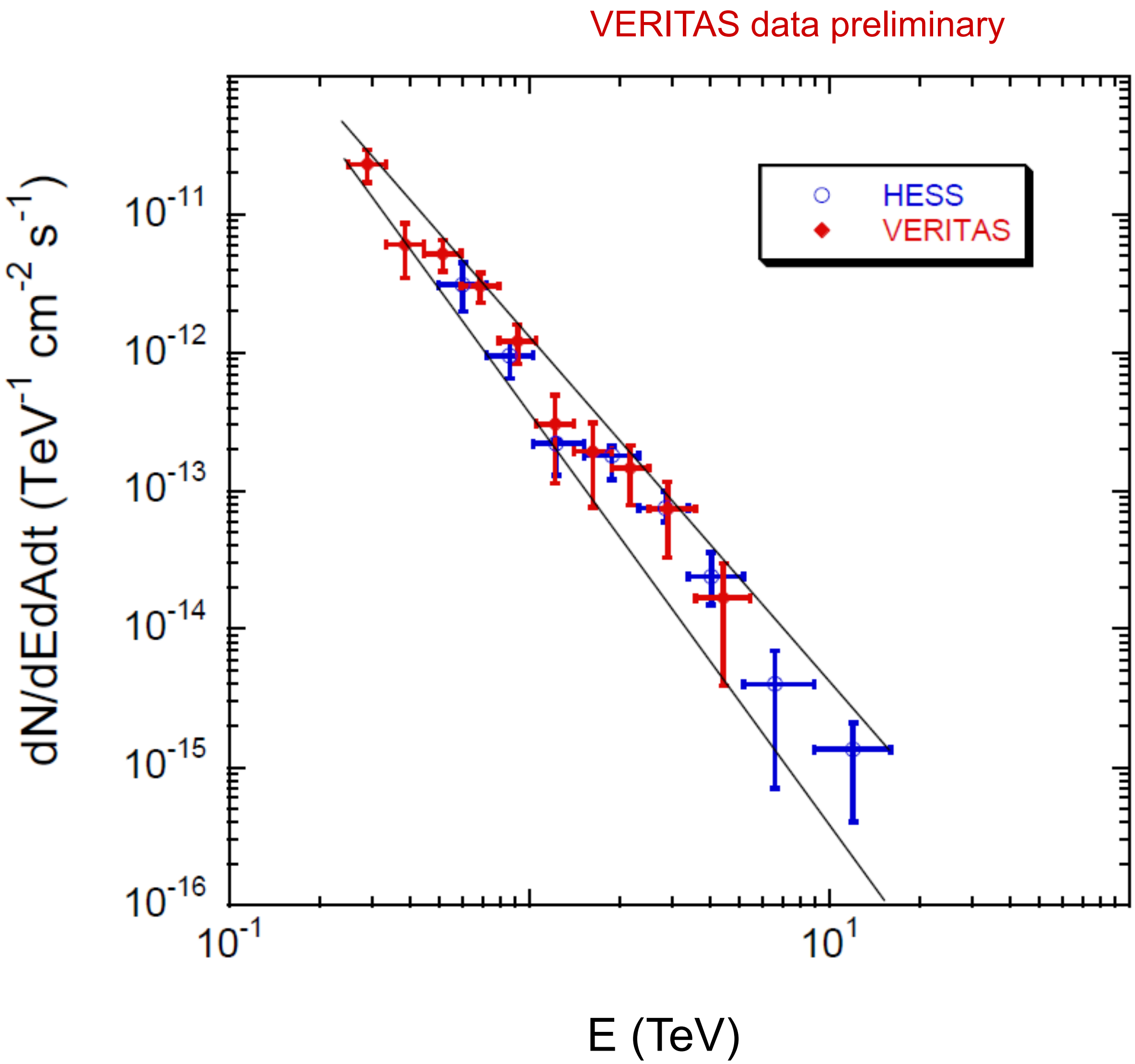
TeV Data

VERITAS data preliminary

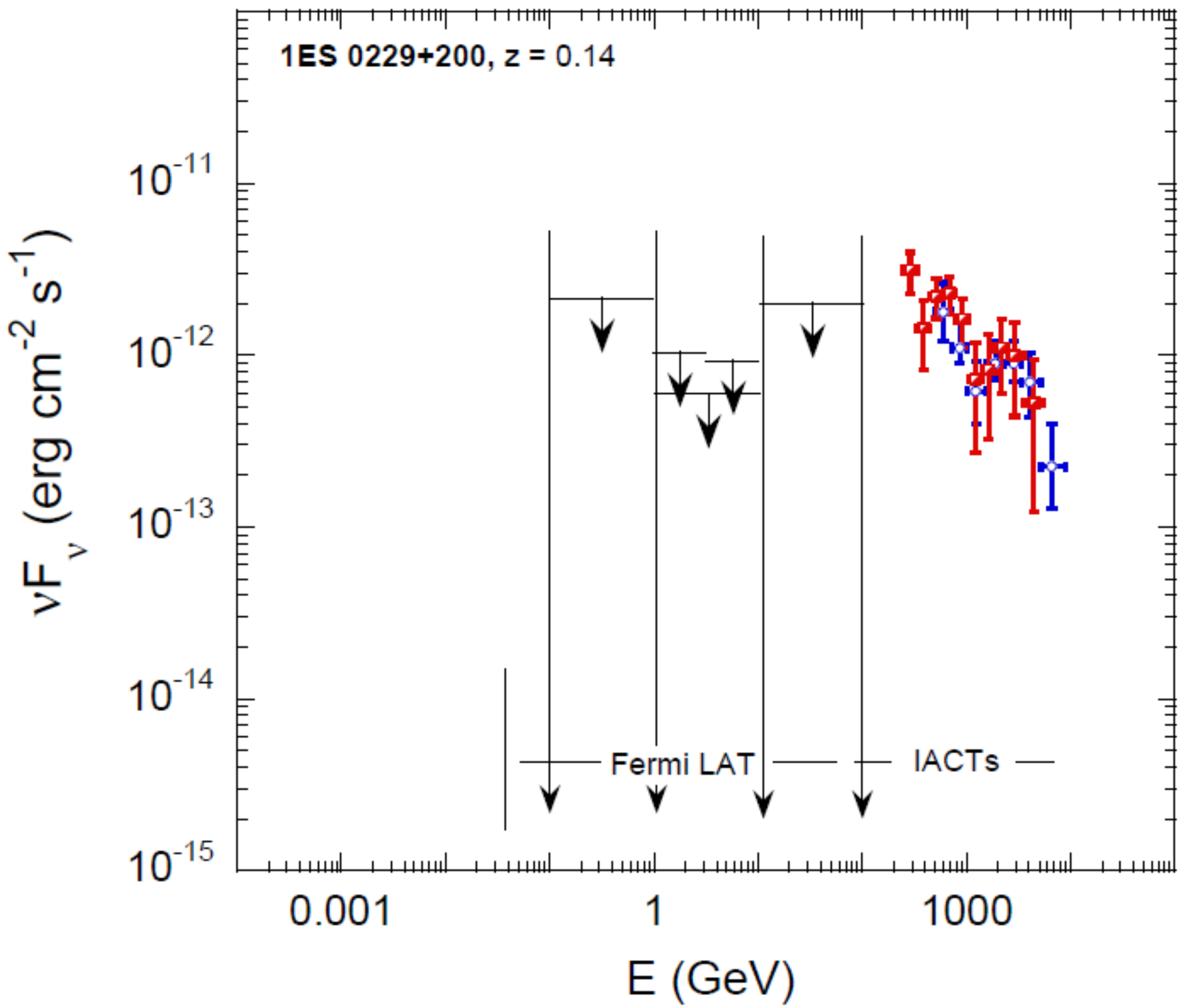


VERITAS data courtesy
J. Perkins and VERITAS team

TeV Data

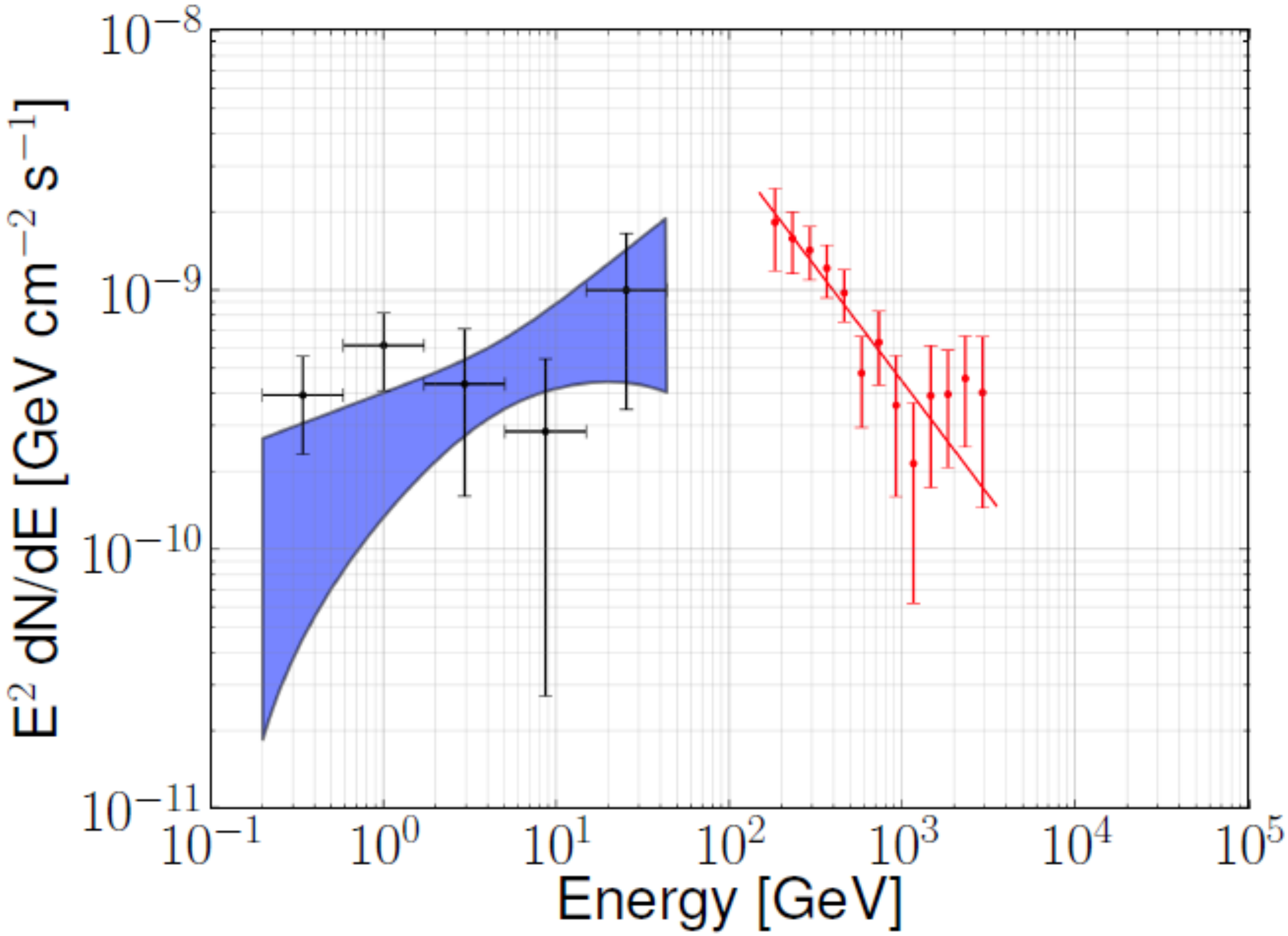

VERITAS data preliminary
HESS
VERITAS
dN/dEdAdt (TeV^{-1} cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-1}
10^{1}
E (TeV)

GeV/TeV Data



1ES 0229+200, z = 0.14
νF_ν (erg cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
Fermi LAT
IACTs
0.001
1
1000
E (GeV)

GeV-TeV Data

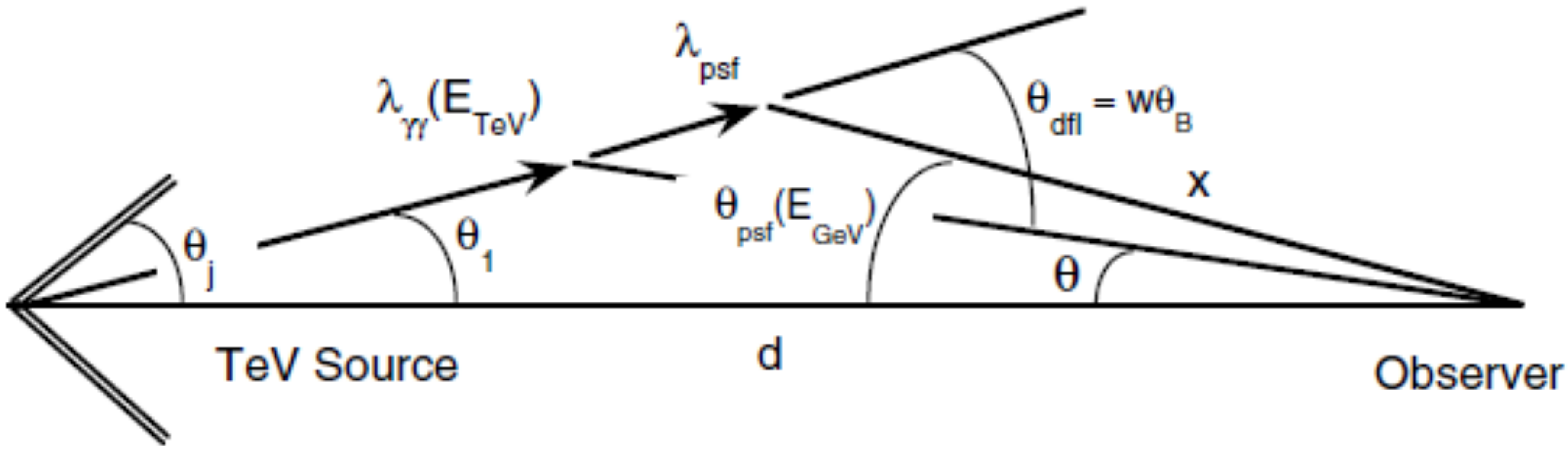


(Orr, Krennrich, Dwek 2011)

Geometry for Compton-γγ Cascade

$$\theta \cong \theta_{\rm dfl}\,\frac{\lambda_{\gamma\gamma}}{d} < \theta_{psf}$$

$$\theta_B = \lambda_T / r_L \cong \frac{B_{IGMF}/10^{-15}\,G}{E_{GeV}}$$



Apply to 1ES 0229+200
$z = 0.1396 \cong 0.14$

Halo photon: $\theta \gtrsim \theta_{psf}$

Semi-analytic Model of Cascade

$$f_\epsilon = \nu F_\nu \ , \ \epsilon = h\nu/m_e c^2$$

Pair injection from EBL absorption

$$f_{\epsilon_s} = \frac{3}{2}\left(\frac{\epsilon_s}{\epsilon_0}\right)^2 \int_{\max[\sqrt{\epsilon_s/4\epsilon_0}, \gamma_{\rm dfl}, \gamma(\Delta t_{eng})]}^{\infty} d\gamma \ \gamma^{-4}\left(1 - \frac{\epsilon_s}{4\gamma^2\epsilon_0}\right) \times$$

kinematic term

$$\int_\gamma^\infty d\gamma_i \ \frac{f_\epsilon\{\exp[\tau_{\gamma\gamma}(\epsilon, z)] - 1\}}{\epsilon^2}$$

cascade

$$\epsilon = 2\gamma_i$$

$$\gamma_{dfl} = \begin{cases} \frac{r_{\rm L}}{c}\ \theta_j \ , & \lambda_{\rm T} < \lambda_{coh} \ \Rightarrow \ \gamma > \frac{c}{\nu_{\rm T}\lambda_{coh}} \\ \frac{r_{\rm L}}{c}\ \theta_j \sqrt{\frac{\lambda_{\rm T}}{\lambda_{coh}}} \ , & \lambda_{\rm T} > \lambda_{coh} \ \Rightarrow \ \gamma < \frac{c}{\nu_{\rm T}\lambda_{coh}} \end{cases}$$

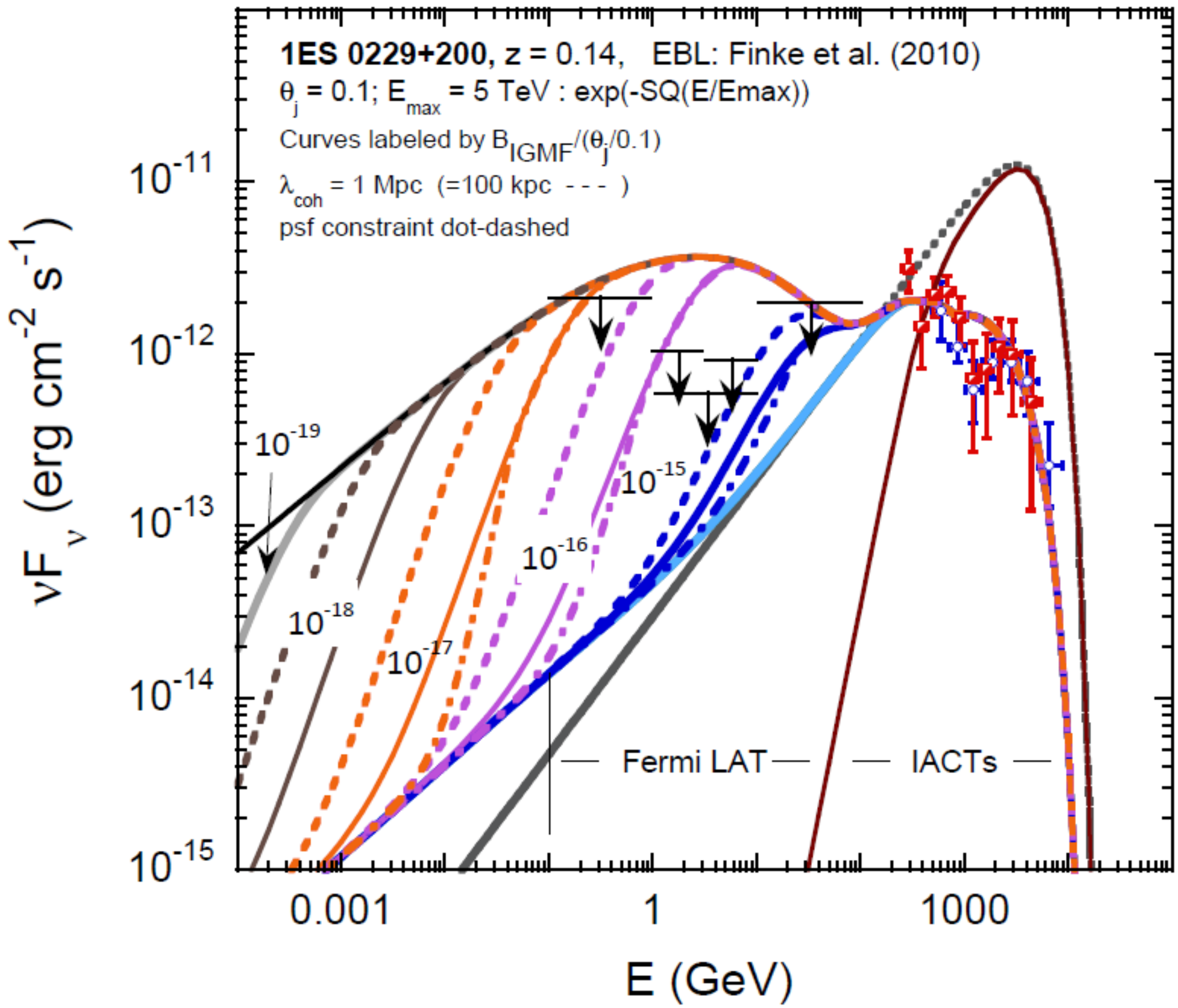
$\gamma(\Delta t_{eng})$: time for electrons to cool to γ during activity time Δt_{eng} of central engine

γ at which electrons are deflected out of beam

Compton (Thomson) spectrum from cooling electrons

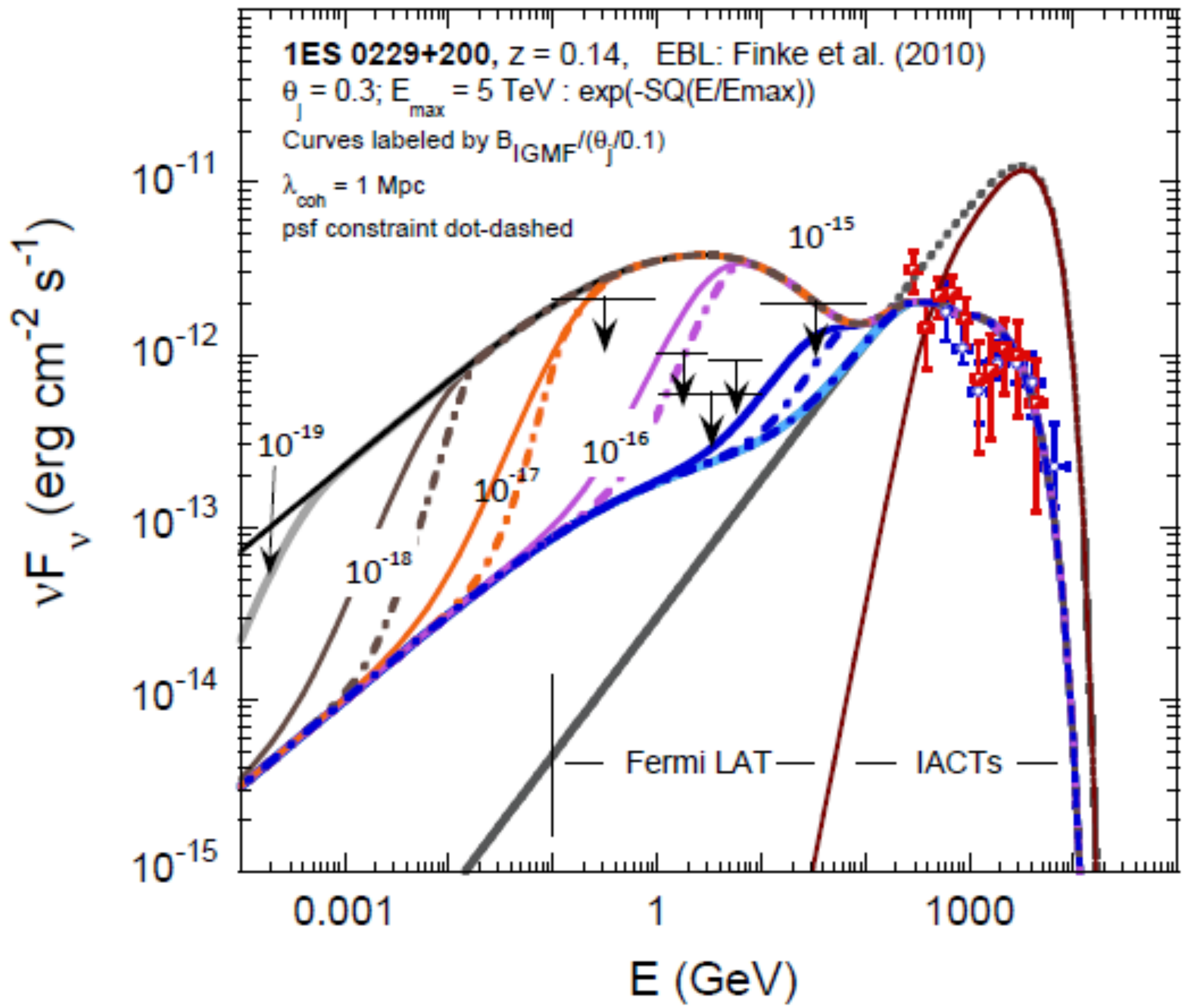
Integration over blackbody spectrum

$\theta_j = 0.1$



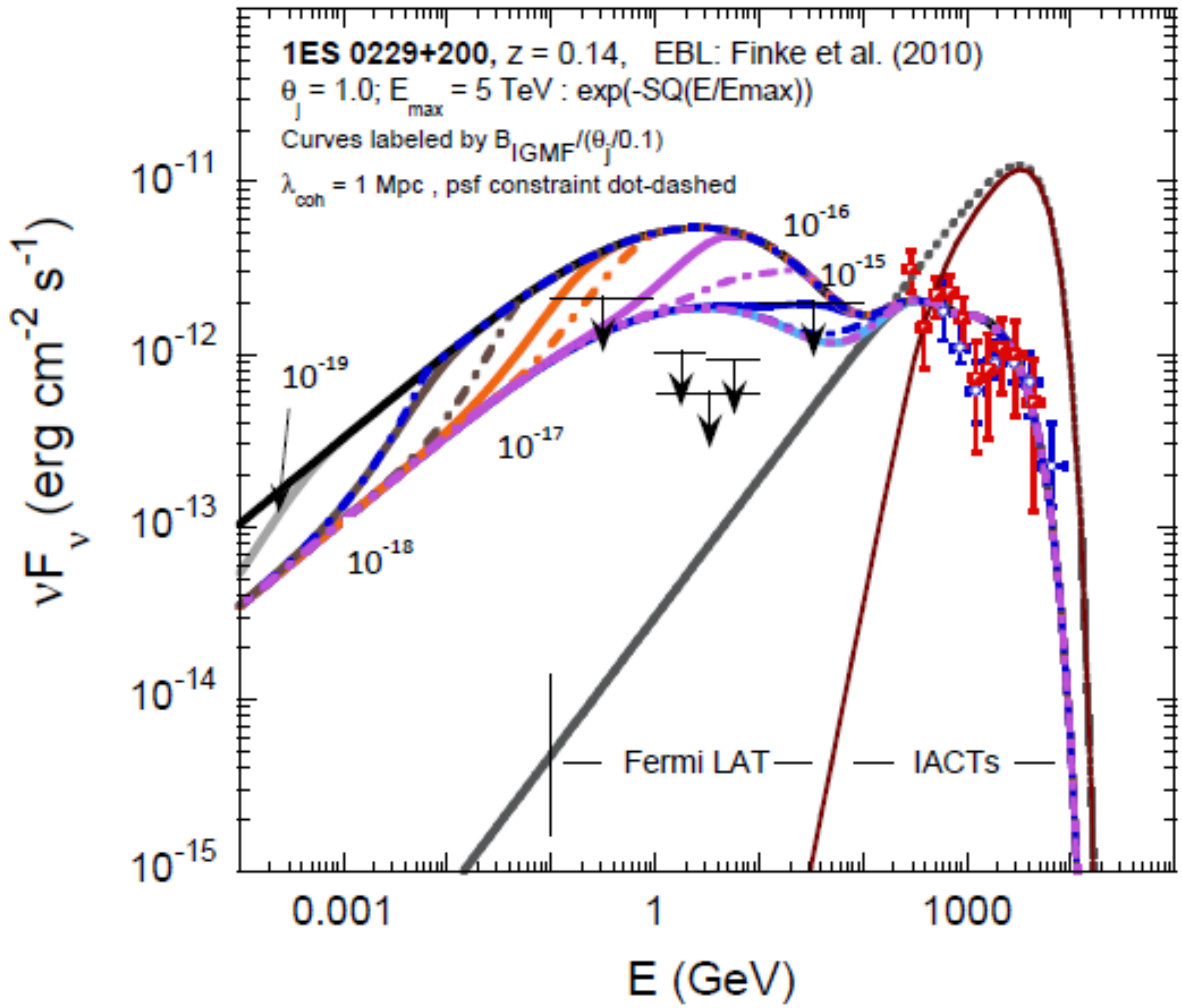
1ES 0229+200, z = 0.14, EBL: Finke et al. (2010)
θj = 0.1; Emax = 5 TeV : exp(-SQ(E/Emax))
Curves labeled by BIGMF/(θj/0.1)
λcoh = 1 Mpc (=100 kpc - - -)
psf constraint dot-dashed
10-19
10-18
10-17
10-16
10-15
Fermi LAT
IACTs
νFν (erg cm-2 s-1)
E (GeV)
10-11
10-12
10-13
10-14
10-15
0.001
1
1000

θ_j = 0. 3



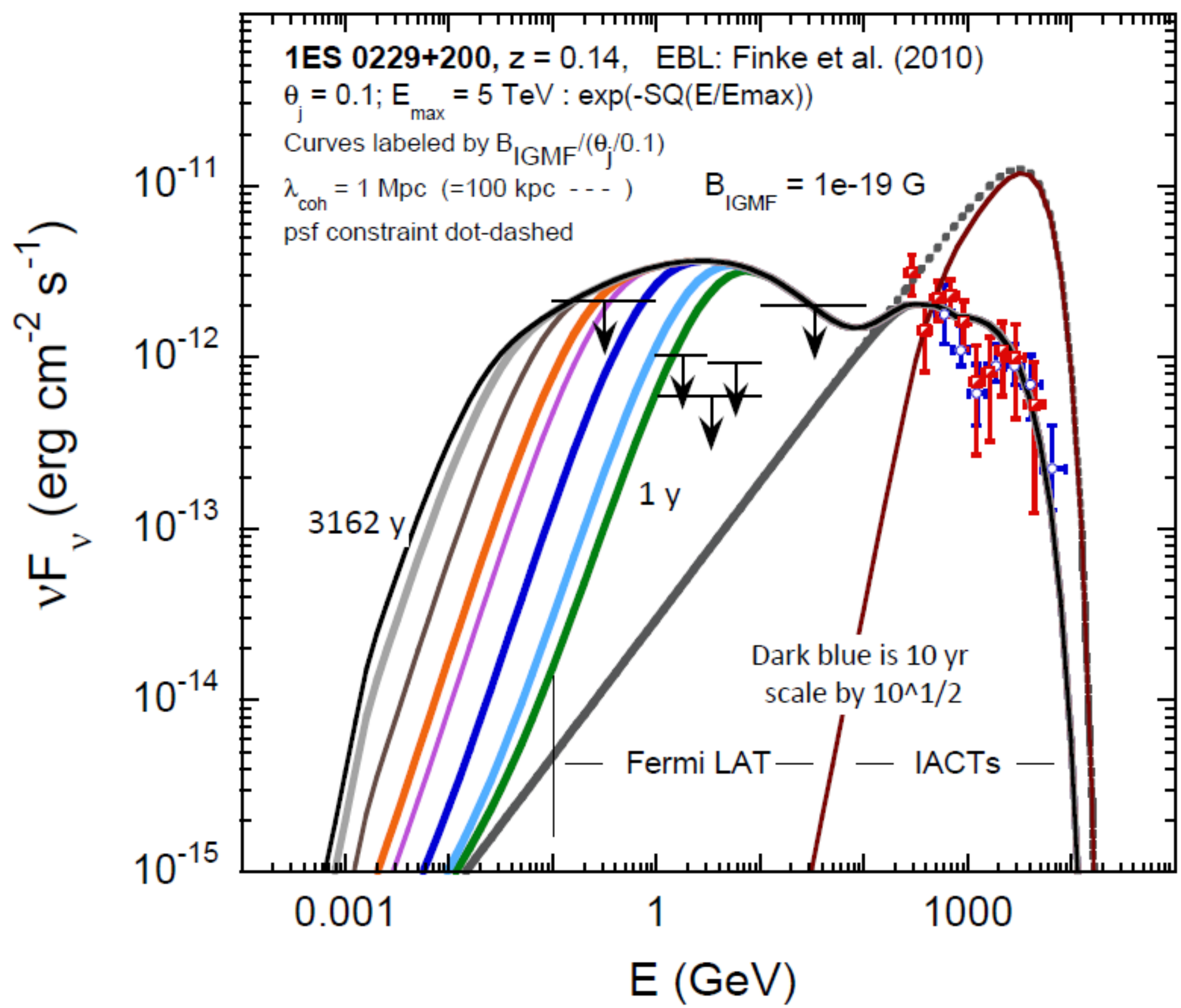
1ES 0229+200, z = 0.14, EBL: Finke et al. (2010)
θj = 0.3; Emax = 5 TeV : exp(-SQ(E/Emax))
Curves labeled by BIGMF/(θj/0.1)
λcoh = 1 Mpc
psf constraint dot-dashed
10-15
10-16
10-17
10-18
10-19
Fermi LAT
IACTs
νFν (erg cm-2 s-1)
E (GeV)
0.001
1
1000
10-11
10-12
10-13
10-14
10-15

θ_j = 1.0



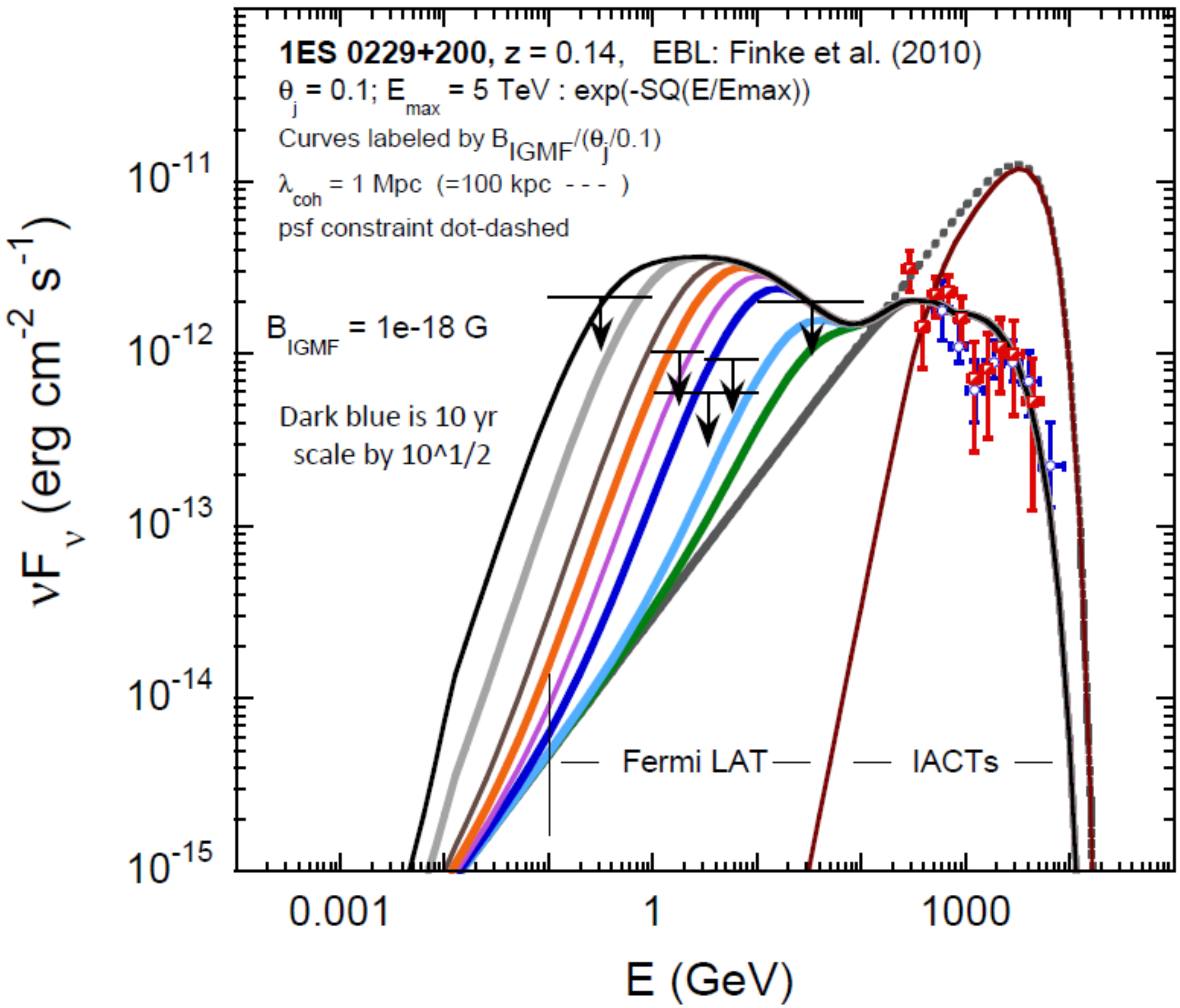
1ES 0229+200, z = 0.14, EBL: Finke et al. (2010)
θj = 1.0; Emax = 5 TeV : exp(-SQ(E/Emax))
Curves labeled by BIGMF/(θj/0.1)
λcoh = 1 Mpc , psf constraint dot-dashed
10-16
10-15
10-19
10-17
10-18
Fermi LAT
IACTs
νFν (erg cm-2 s-1)
E (GeV)
10-11
10-12
10-13
10-14
10-15
0.001
1
1000

$B_{IGMF} = 10^{-19}$ G

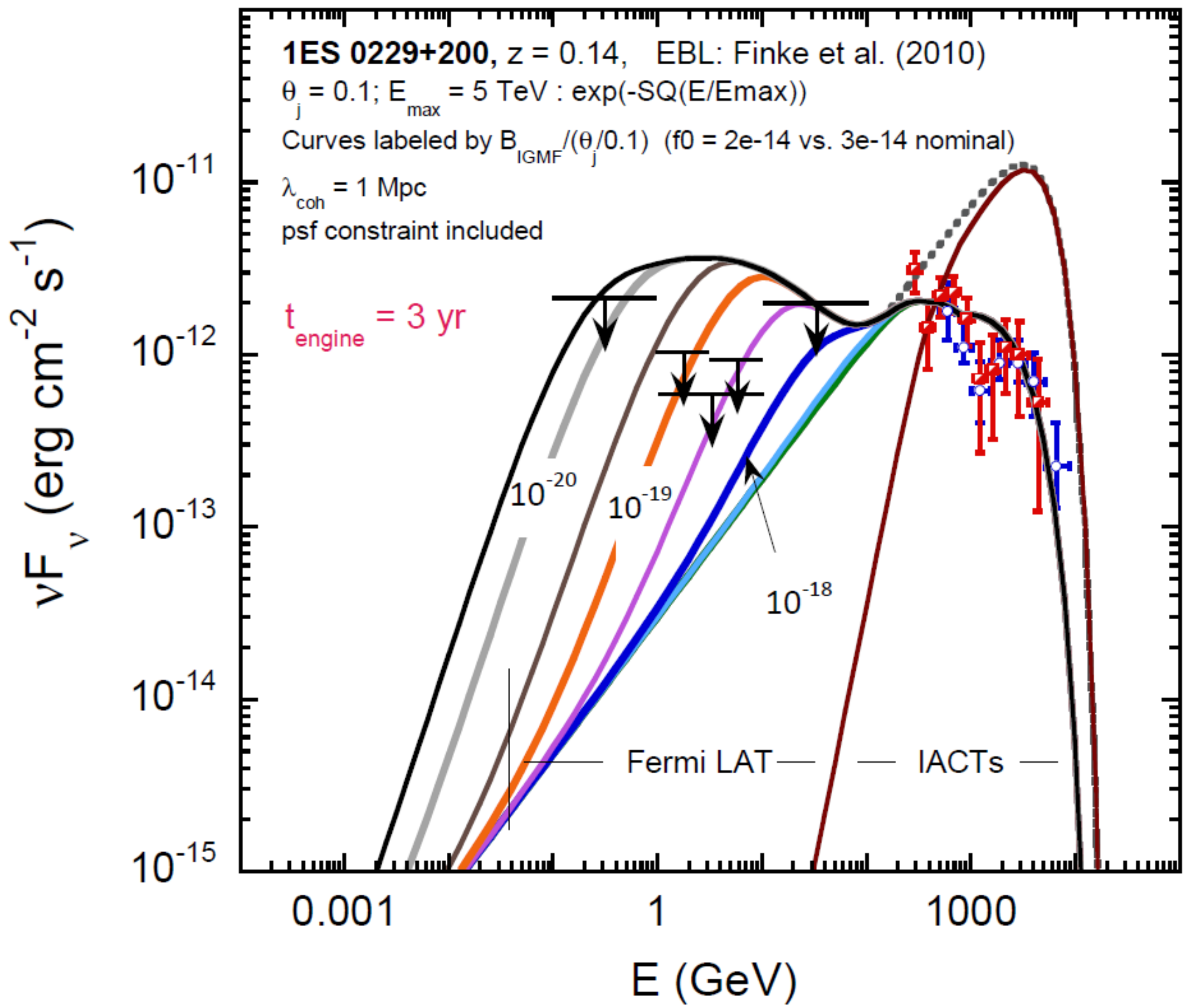


1ES 0229+200, z = 0.14, EBL: Finke et al. (2010)
θj = 0.1; Emax = 5 TeV : exp(-SQ(E/Emax))
Curves labeled by BIGMF/(θj/0.1)
λcoh = 1 Mpc (=100 kpc - - -)
psf constraint dot-dashed
BIGMF = 1e-19 G
3162 y
1 y
Dark blue is 10 yr
scale by 10^1/2
Fermi LAT
IACTs
νFν (erg cm-2 s-1)
E (GeV)
10-11
10-12
10-13
10-14
10-15
0.001
1
1000

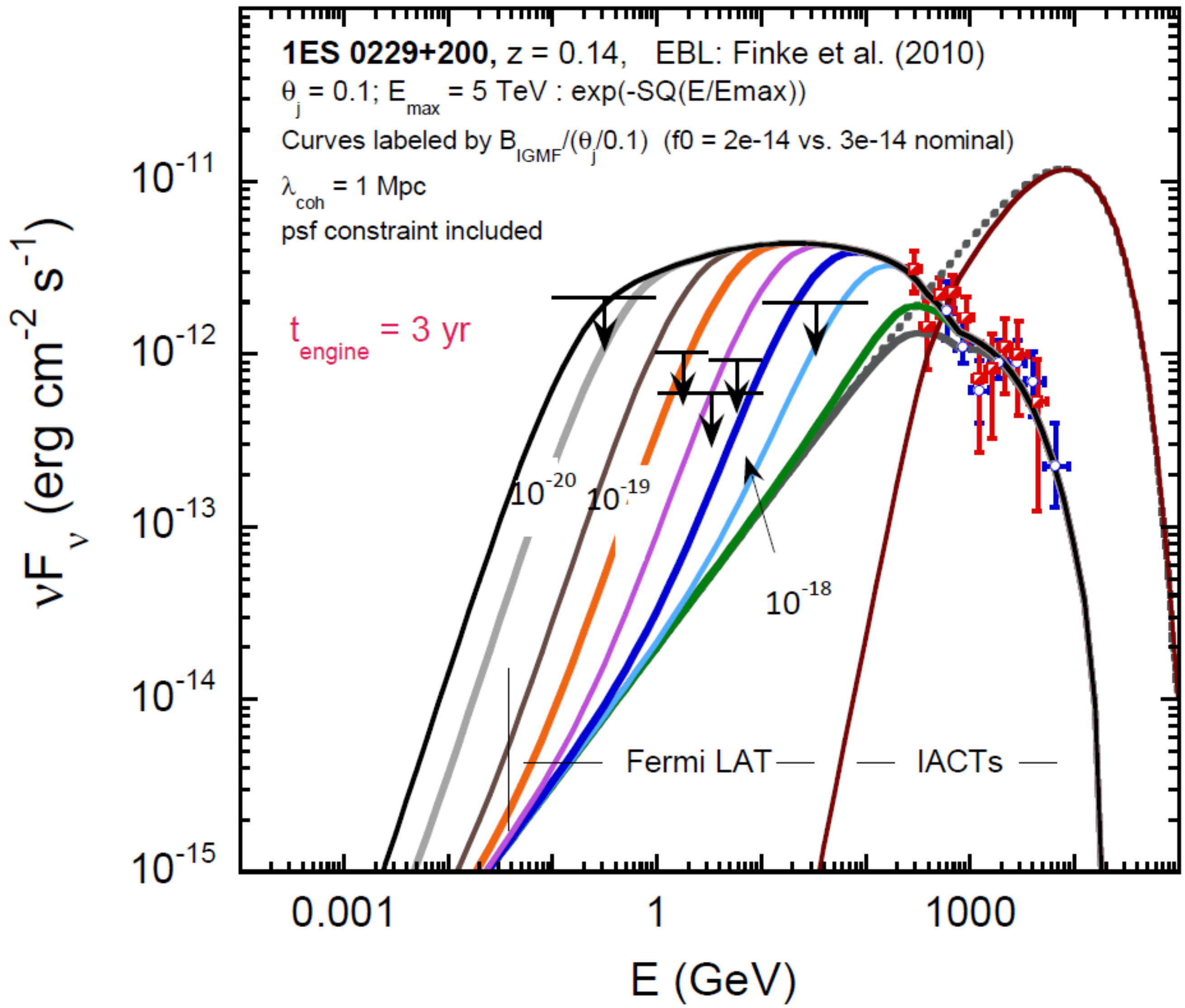
$B_{IGMF} = 10^{-18}$ G


1ES 0229+200, z = 0.14, EBL: Finke et al. (2010)
θj = 0.1; Emax = 5 TeV : exp(-SQ(E/Emax))
Curves labeled by BIGMF/(θj/0.1)
λcoh = 1 Mpc (=100 kpc - - -)
psf constraint dot-dashed
BIGMF = 1e-18 G
Dark blue is 10 yr
scale by 10^1/2
Fermi LAT
IACTs
10-11
10-12
10-13
10-14
10-15
0.001
1
1000
νFν (erg cm-2 s-1)
E (GeV)

Range of B_{IGMF}; t_{engine} = 3 yr

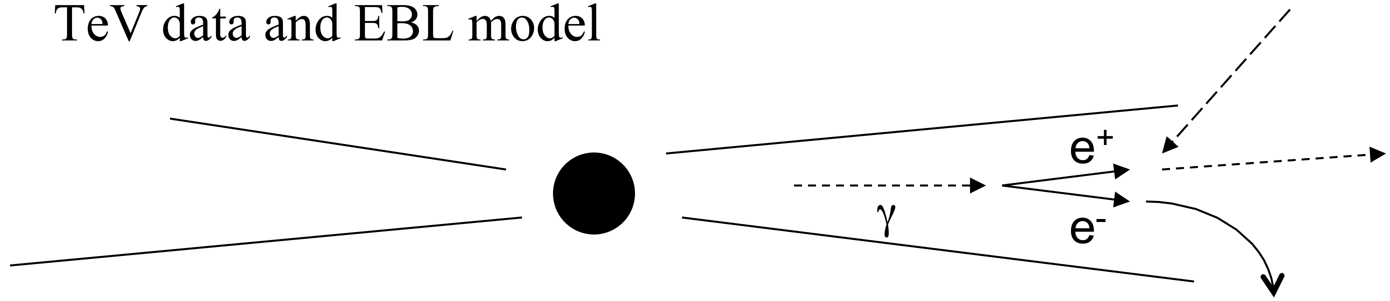


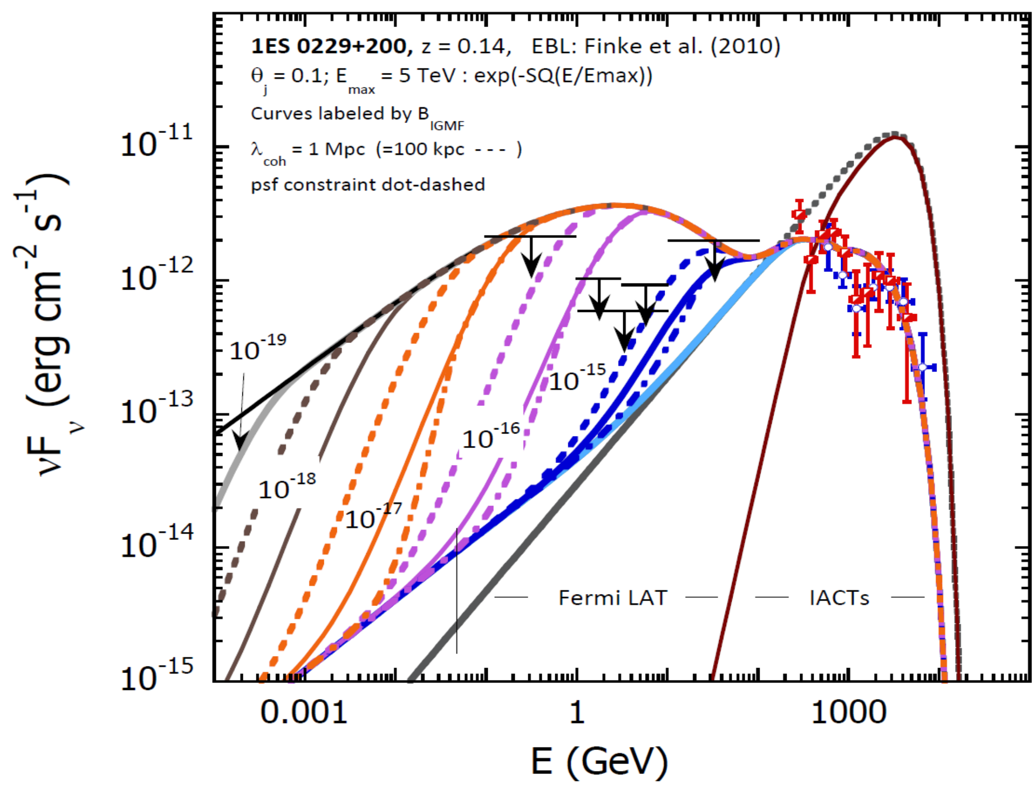
Range of B_{IGMF}; Different Source Spectrum



Lower Limits on the Intergalactic Magnetic Field

- Use Fermi upper limits or detections at GeV energies to limit B_{IGMF} given TeV data and EBL model





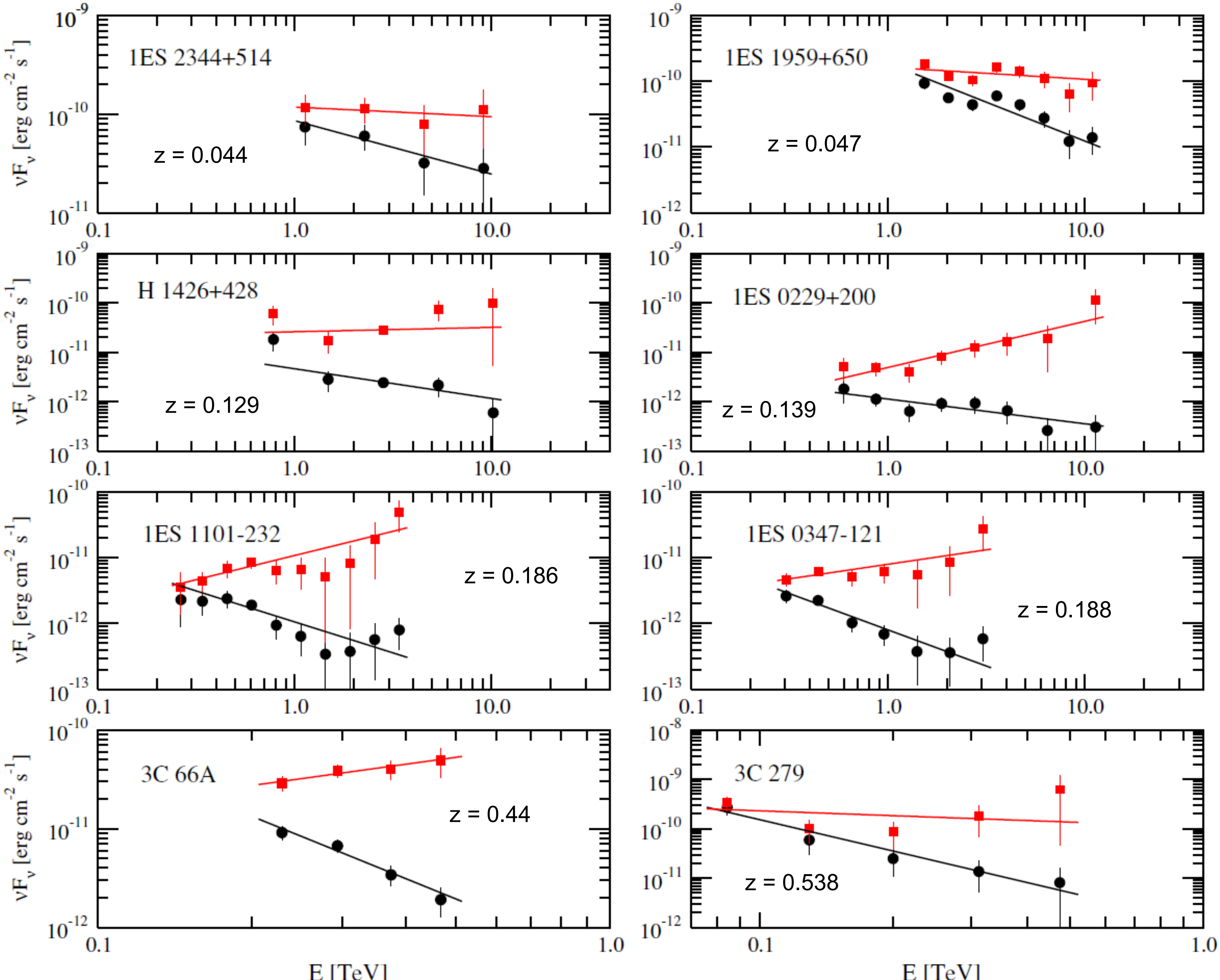
$\stackrel{?}{\Rightarrow} B_{IGMF} \gtrsim 10^{-15}$ G

(Neronov & Vovk 2010; Tavecchio et al. 2010)

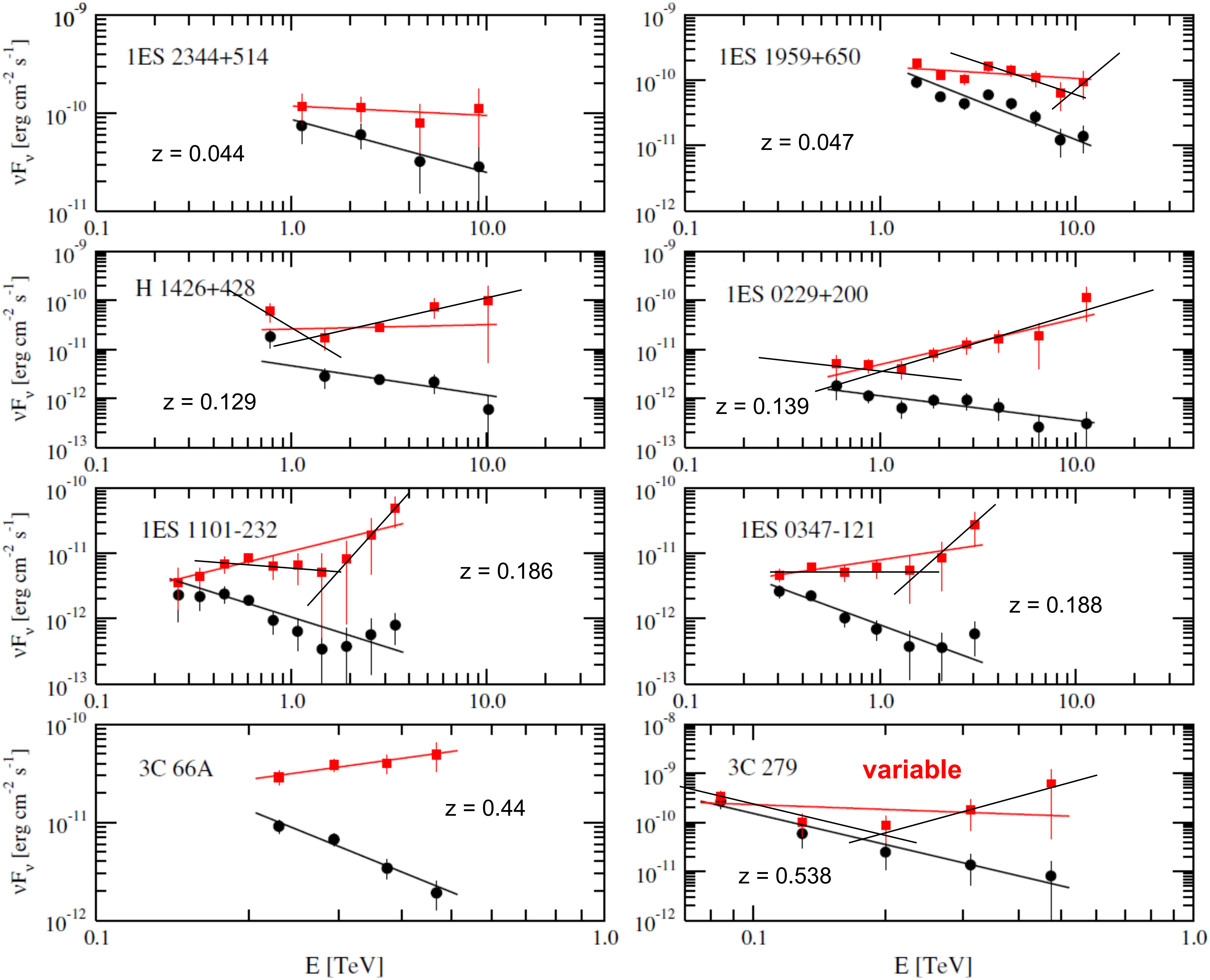
$\Rightarrow B_{IGMF} \gtrsim 10^{-18}$ G

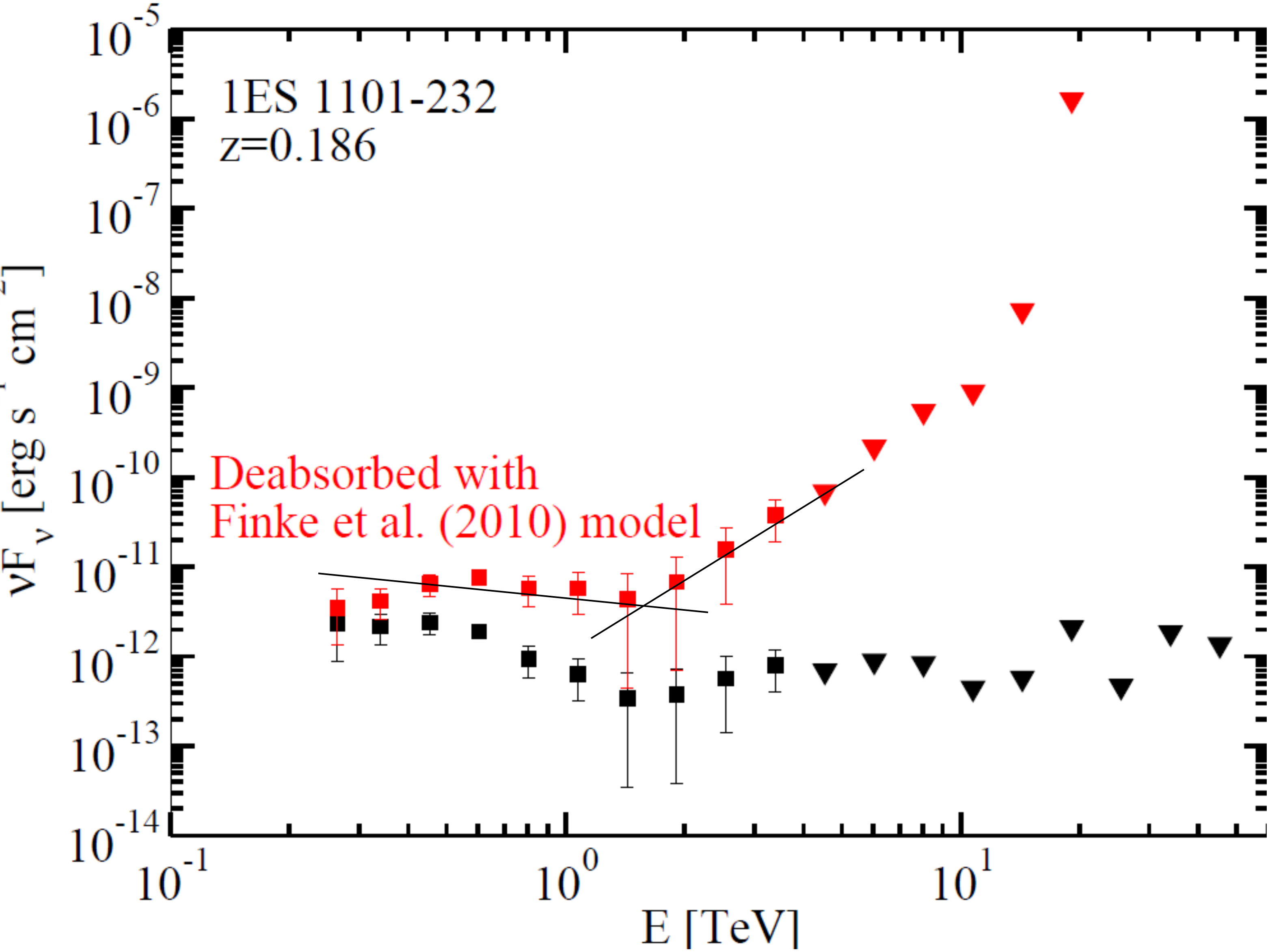
(relaxing assumption of extended TeV emission)

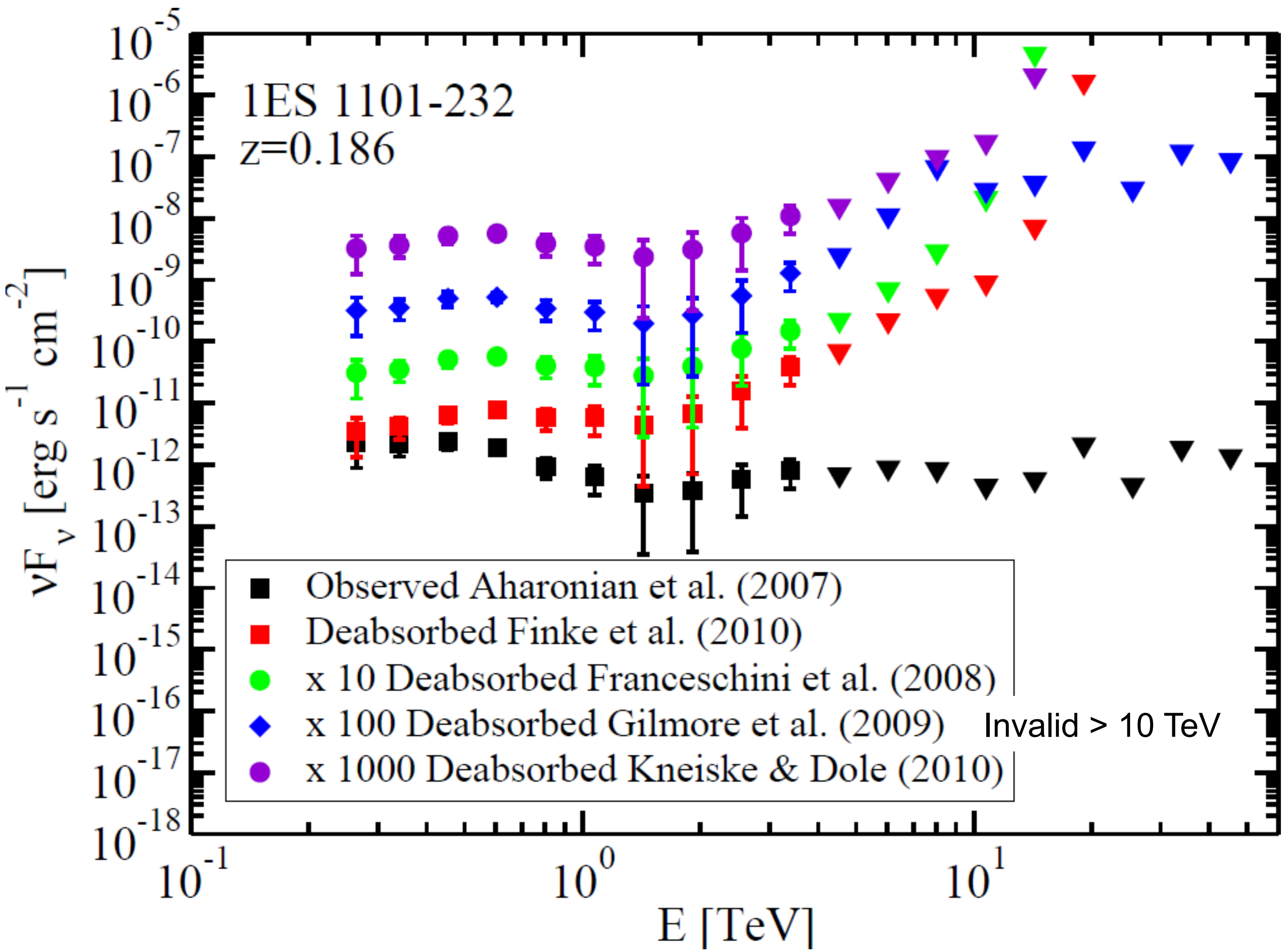
(CD, Cavadini, Razzaque, Finke, Chiang, Lott, 2011)



Finke et al. (2010)


1ES 2344+514
z = 0.044
1ES 1959+650
z = 0.047
H 1426+428
z = 0.129
1ES 0229+200
z = 0.139
1ES 1101-232
z = 0.186
1ES 0347-121
z = 0.188
3C 66A
z = 0.44
3C 279
variable
z = 0.538
νFν [erg cm^-2 s^-1]
E [TeV]

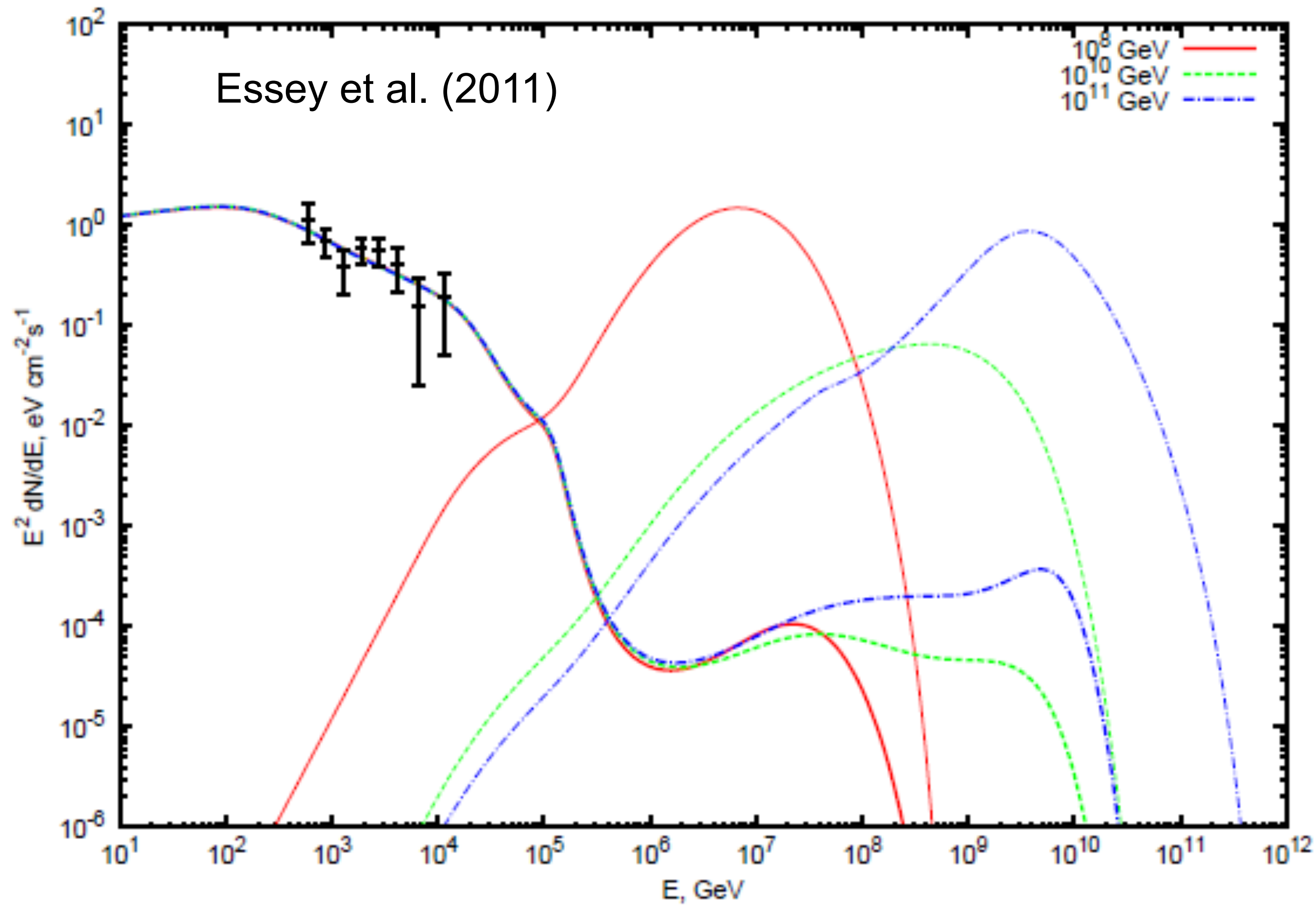

1ES 1101-232
z=0.186
Deabsorbed with
Finke et al. (2010) model
νF_ν [erg s^{-1} cm^{-2}]
E [TeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
10^{0}
10^{1}



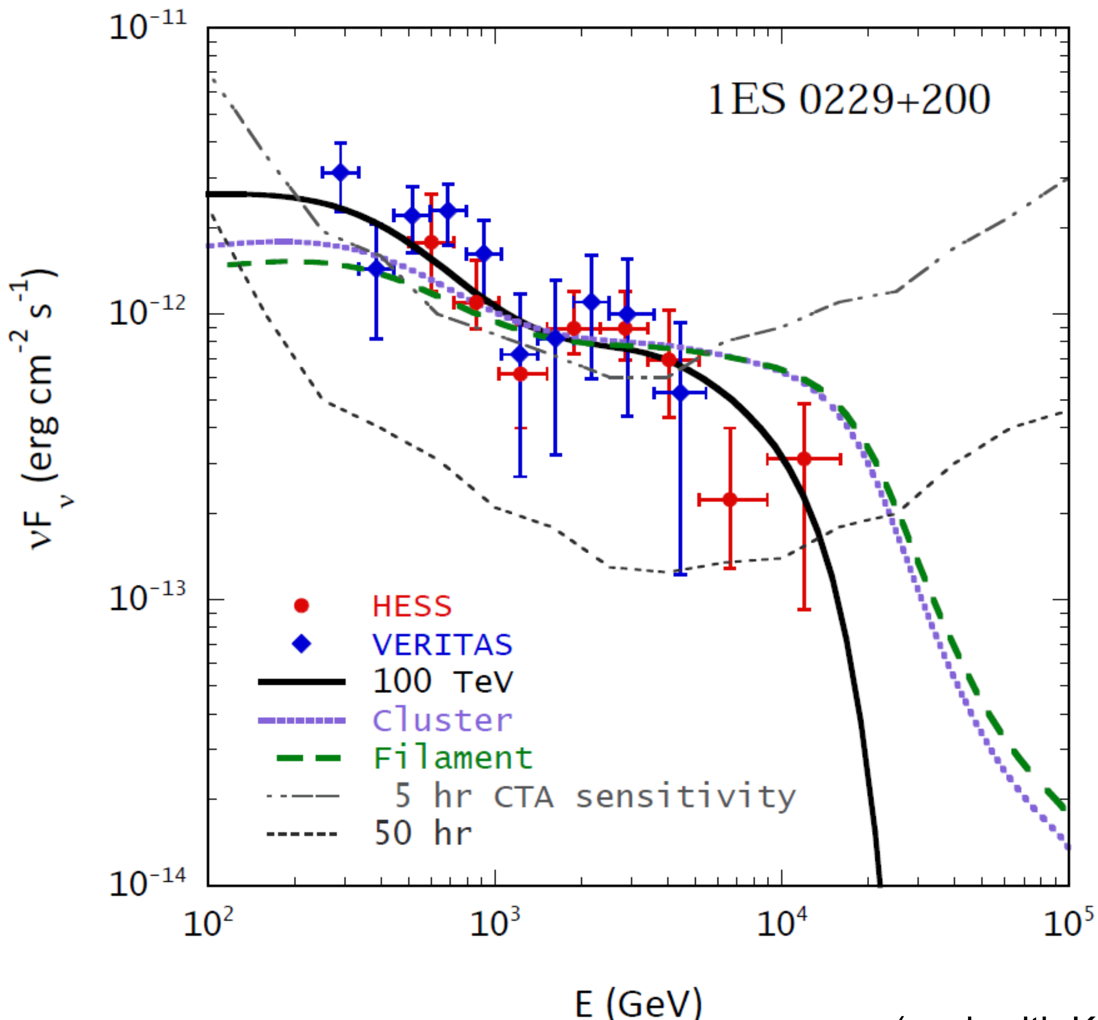
1ES 1101-232
z=0.186
νF_ν [erg s^-1 cm^-2]
E [TeV]
Observed Aharonian et al. (2007)
Deabsorbed Finke et al. (2010)
x 10 Deabsorbed Franceschini et al. (2008)
x 100 Deabsorbed Gilmore et al. (2009)
x 1000 Deabsorbed Kneiske & Dole (2010)
Invalid > 10 TeV

Origin of Hard TeV Emission Component?

- New component could be leptonic or hadronic
- Must explain dependence of break energy on z



Test for Source Photons or UHECR Production of TeV Emission Component



(work with K. Murase, H. Takami)

Conclusions

- EBL model constraints from GeV-TeV analysis of blazars and GRBs
- High EBL models ruled out--provided photons are made at the source
- Deconvolved emission spectra reveal hard TeV component for most EBL models

- Halo emission likely for large opening angle, persistent TeV jet sources
- Large range of primary source spectra match data
- All require an emission component with νF_ν peak >~ 5 TeV
- Minimalist model implies B_{IGMF} >~ 10^{-18} G
- Discriminate flux of >>10 TeV source emission from spectrum near 1 TeV-- Spectral shoulder at 1 TeV implies hard primary emission

- Question: Origin of this spectral component?
- Leptonic or hadronic (UHECR?)
- Use next generation CTA experiment to discriminate

Final Thoughts

- Annie Jump Cannon is from Delaware
- Lewes: first “town” in the first state
- Crab cakes
- ppt version of my talks will be at my website
- book
- Future of γ-ray astronomy is bright