Observed blazar spectra, and implications for EBL

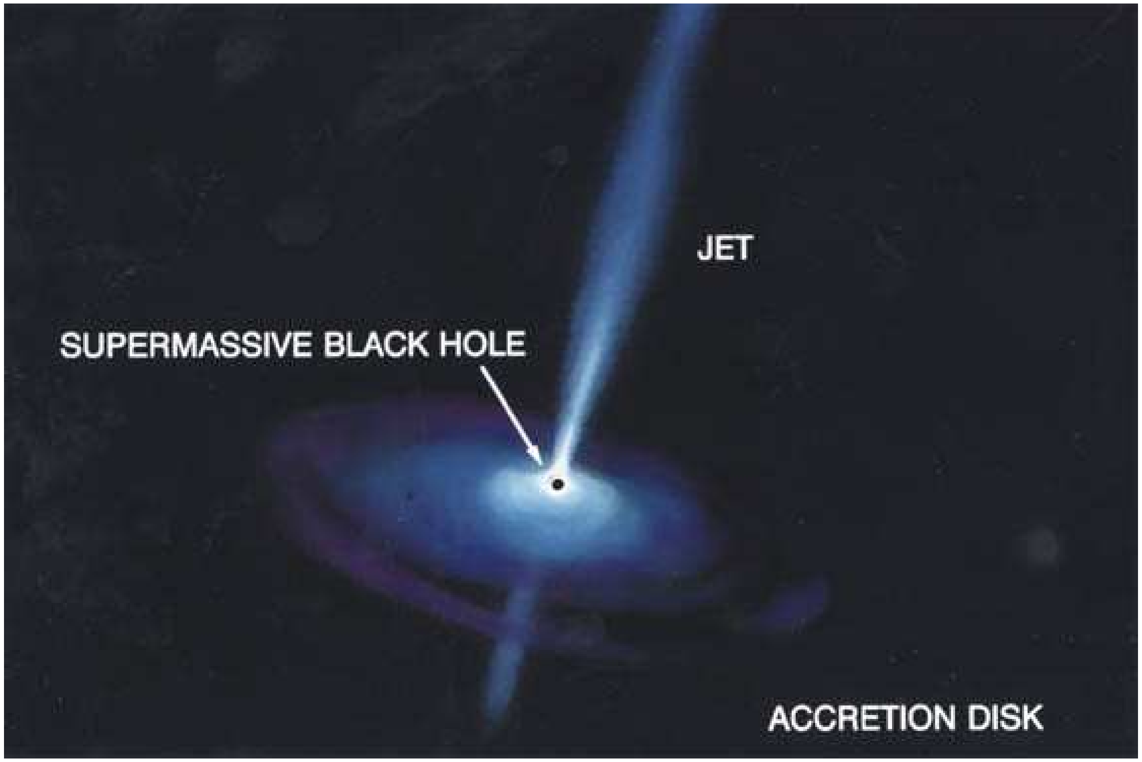
- The spectra of distant blazars
- Secondary gamma rays: spectra robust, agreement with data
- Astrophysical neutrinos from blazars – and the IceCube discovery
- Implications for EBL: no reliable upper limits from gamma-ray data

Based on work in collaboration with **Felix Aharonian, Shin'ichiro Ando, John Beacom, Warren Essey, Yoshiyuki Inoue, Oleg Kalashev, Anton Prosekin**

Astropart.Phys. 33 (2010) 81, *ibid.* 35 (2011) 135; Phys. Rev. Lett. 104 (2010) 141102; ApJ 731 (2011) 51; ApJ Lett. 751 (2012) L11; ApJ 757 (2012) 183 ; PR D 87, 063002 (2013); Phys.Rev.Lett. 111 (2013) 041103; Astropart.Phys. 54 (2014) 118; ibid., 57-58 (2014) 30

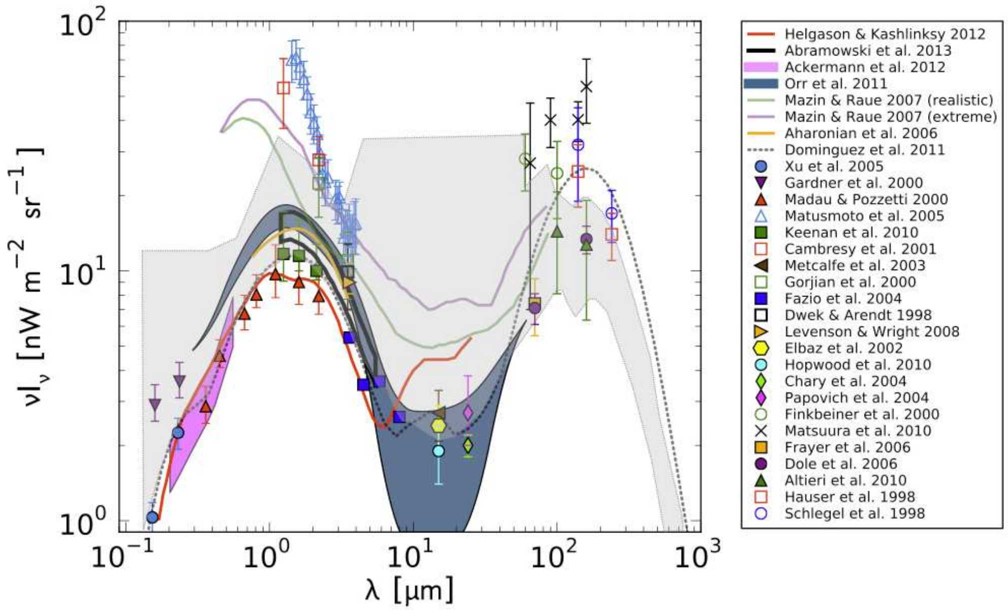
see also related work by **Dermer, Finke, Migliori, Murase, Razzaque, Takami,...**

Active galactic nuclei: blazars



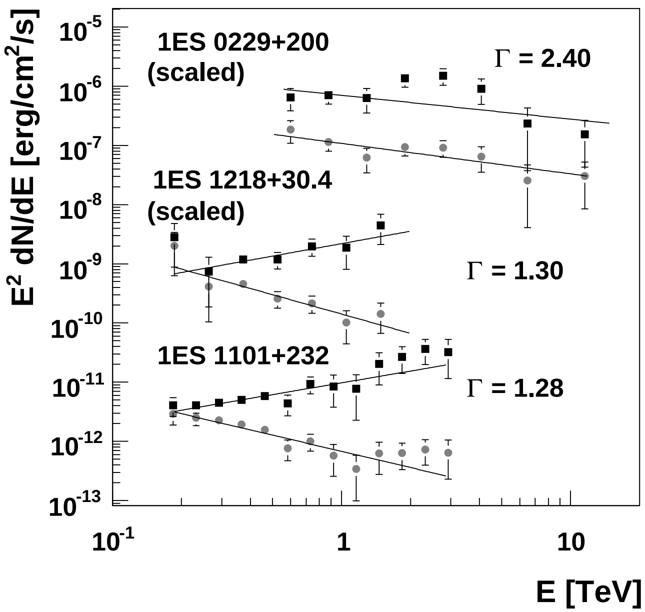
when AGN jet points at Earth, called *blazar*

Extragalactic background light (EBL)
(direct and processed starlight)



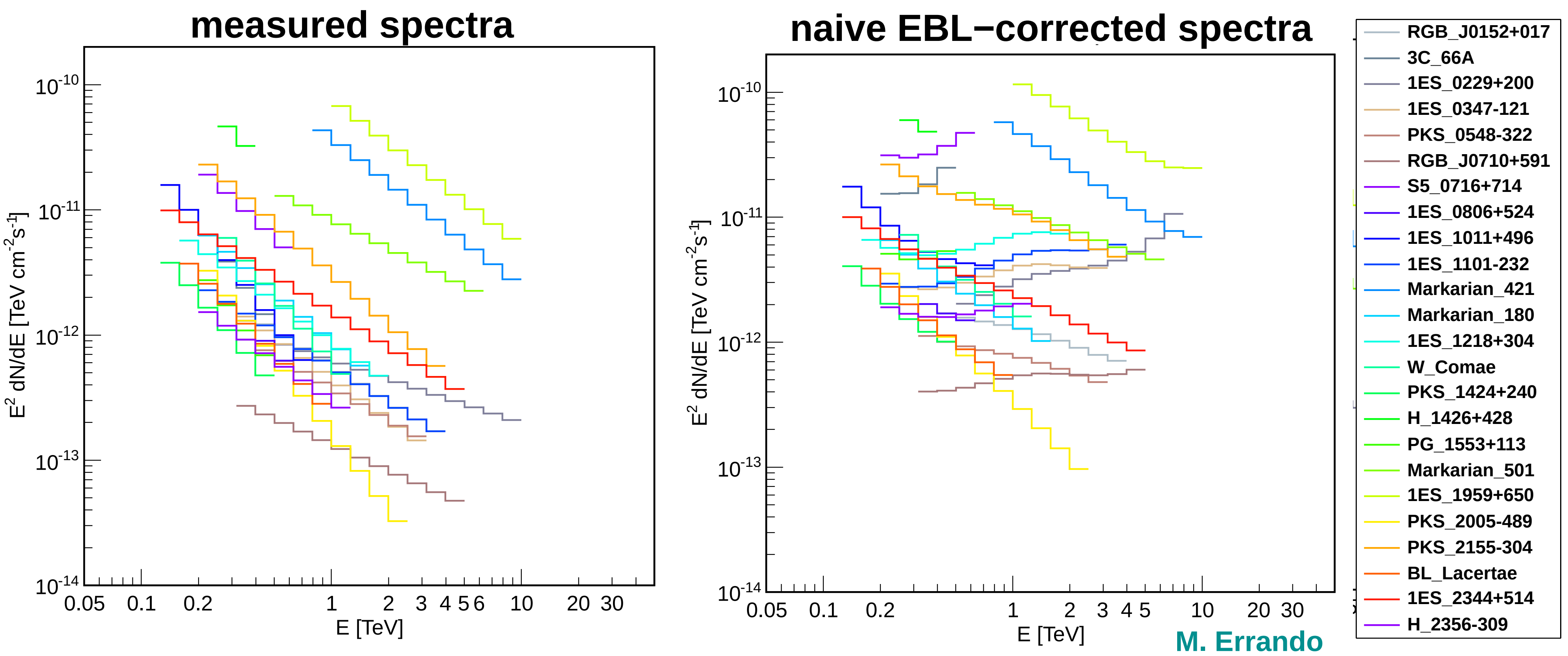
interactions $\gamma\gamma_{EBL} \rightarrow e^+e^-$
must degrade the energies of TeV photons

Distant blazars have implausibly hard spectra

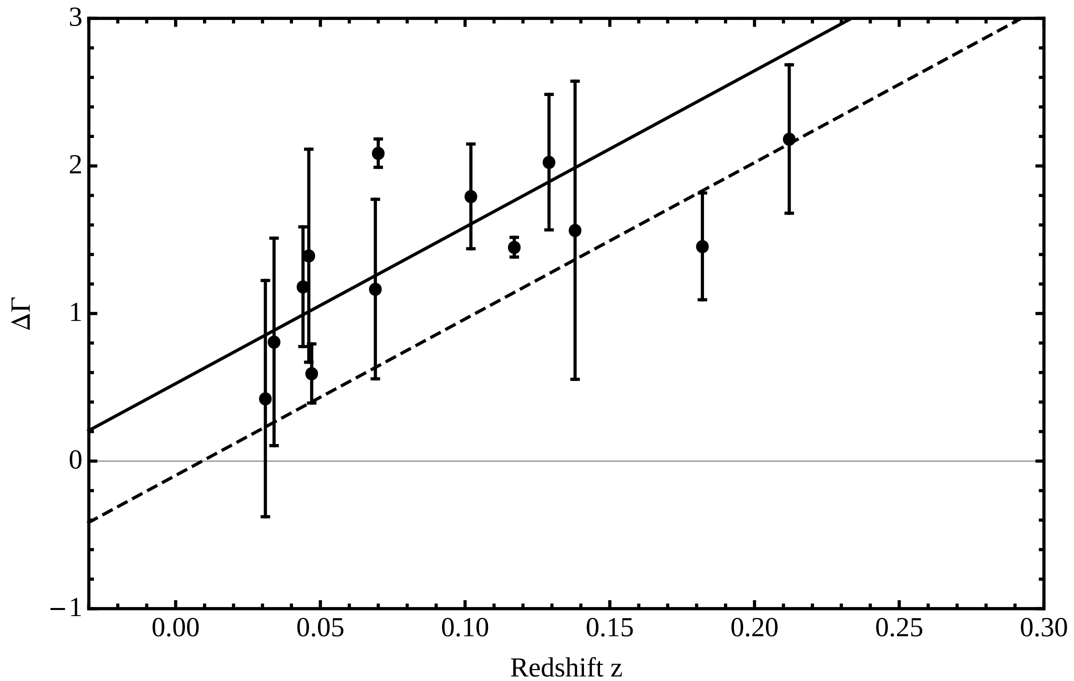


Absorption-corrected spectra are extremely hard, $\Gamma < 1.5$, for distant blazars. [Aharonian et al.]

Blazar spectra

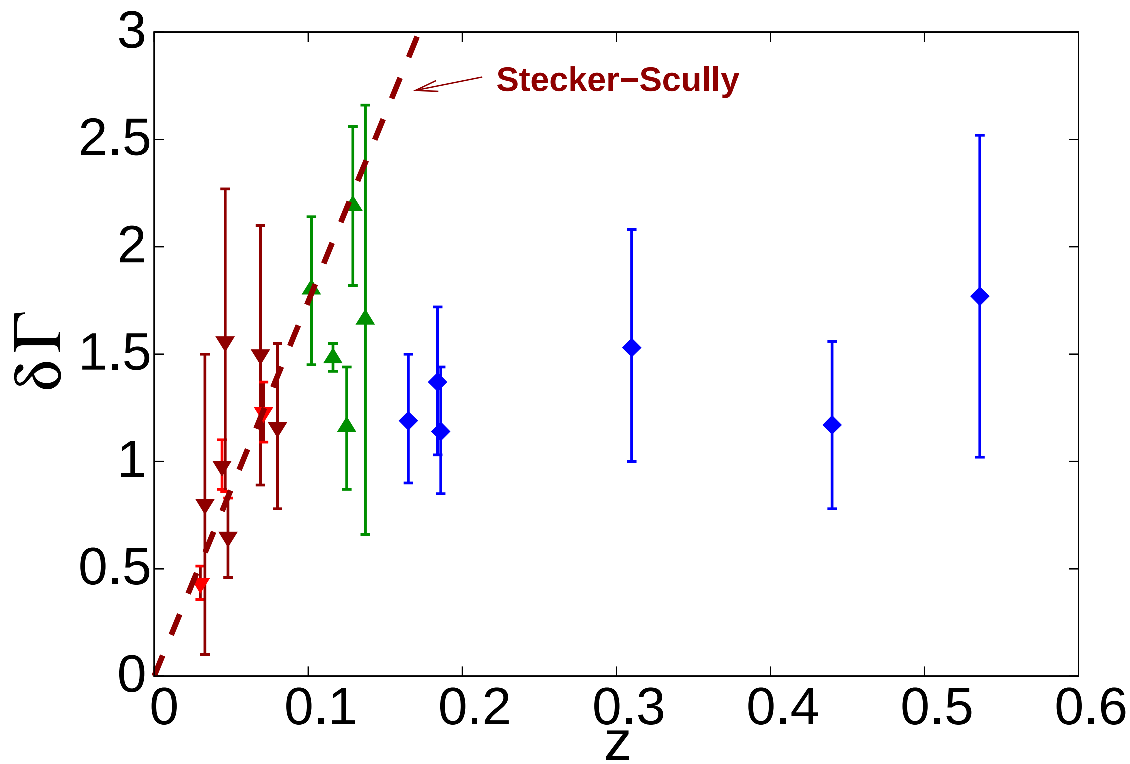


Softening of the spectrum as a function of the redshift



$$\Delta\Gamma = \Gamma_{\rm GeV} - \Gamma_{\rm TeV}$$ [Stecker, Scully]

Distant blazars are different:



$\delta\Gamma = \Gamma_{\rm GeV} - \Gamma_{\rm TeV}$ [Stecker, Scully]

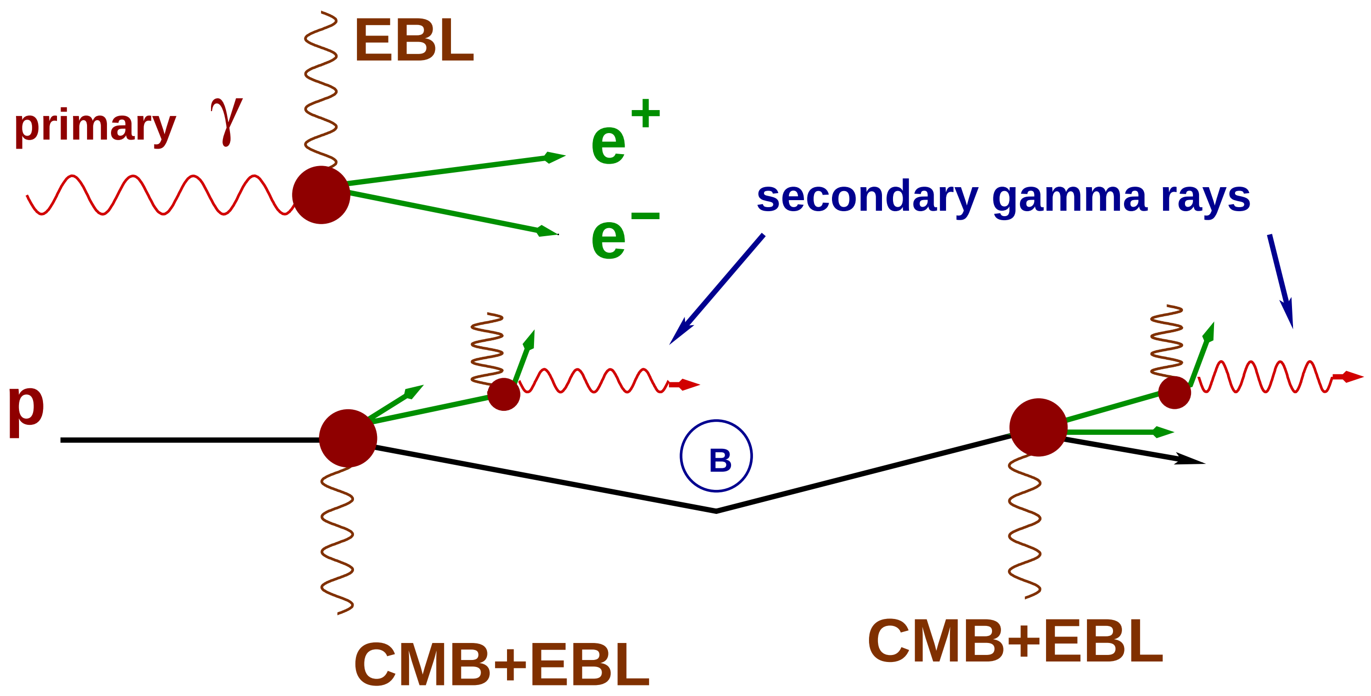
Proposed "new physics" solutions:

The lack of absorption prompted some exotic solutions:

- photons may convert into some hypothetical ***axion-like particles*** that convert back into photons in the galactic magnetic fields
  [Hooper et al.; de Angelis et al.; Simet et al.]
- ***Lorentz invariance violation*** for high-velocity particles may prevent pair production
  [Protheroe et al.]

Is there a more conventional explanation?

AGN produce both cosmic rays and gamma rays



Cosmic rays from AGN

- **No significant attenuation** below GZK cutoff.
  Propagate cosmological distances for $E \lesssim 10^{18}$ eV.
- **Rectilinear propagation** affected only by IGMFs.
  Clusters of galaxies (size R, density n) cause large deflections, but the mean free path of a proton

$$\boldsymbol{\Lambda \sim 1/(\pi R^2 n) \sim 3 \times 10^3 \mathrm{Mpc}}$$

  The mean MFP for linear propagation is of the order of the size of the observed universe.
- **IGMFs are not known:**
  - upper limits: $\boldsymbol{B < 10^{-9}}$ **G** from non-observation of Faraday rotations
  - lower limits: $\boldsymbol{B > 10^{-30}}$ **G** if one believes the galactic fields are seed fields amplified by dynamo.

  For magnetic fields $\boldsymbol{B < 10^{-14}}$ **G**, deflections are smaller than the angular resolution of ACTs.

Secondary gamma rays from cosmic rays along the line of sight?

Gamma-rays produced at the source can attenuate via pair production on EBL for TeV energies: expect **attenuation of TeV γ rays**.

Protons below GZK cutoff interact with EBL, CMB and produce γ rays via
$p\gamma \rightarrow pe^+e^-$, $p\gamma \rightarrow p\pi^0$: expect **regeneration of TeV γ rays**
Photon backgrounds provide opacity/sink for the former, source for the latter.

What is the scaling of these effects with distance?

Different scaling

$$F_{\rm primary,\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} \tag{1}$$

$$F_{\rm secondary,\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1-e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \tag{2}$$

$$F_{\rm secondary,\nu}(d) \propto (F_{\rm protons} \times d) \propto \frac{1}{d}. \tag{3}$$

Different scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} \quad (1)$$

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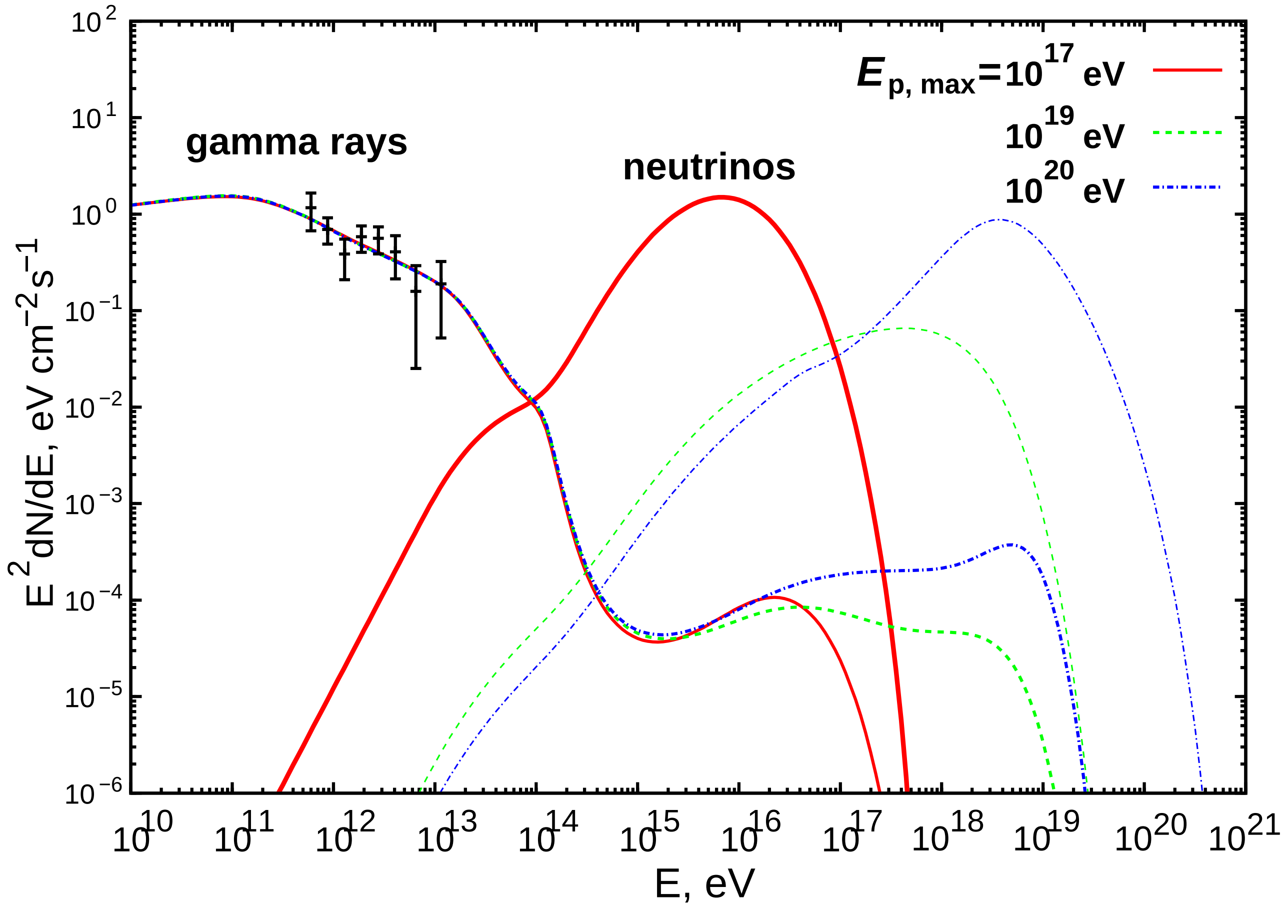
$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}. \quad (3)$$

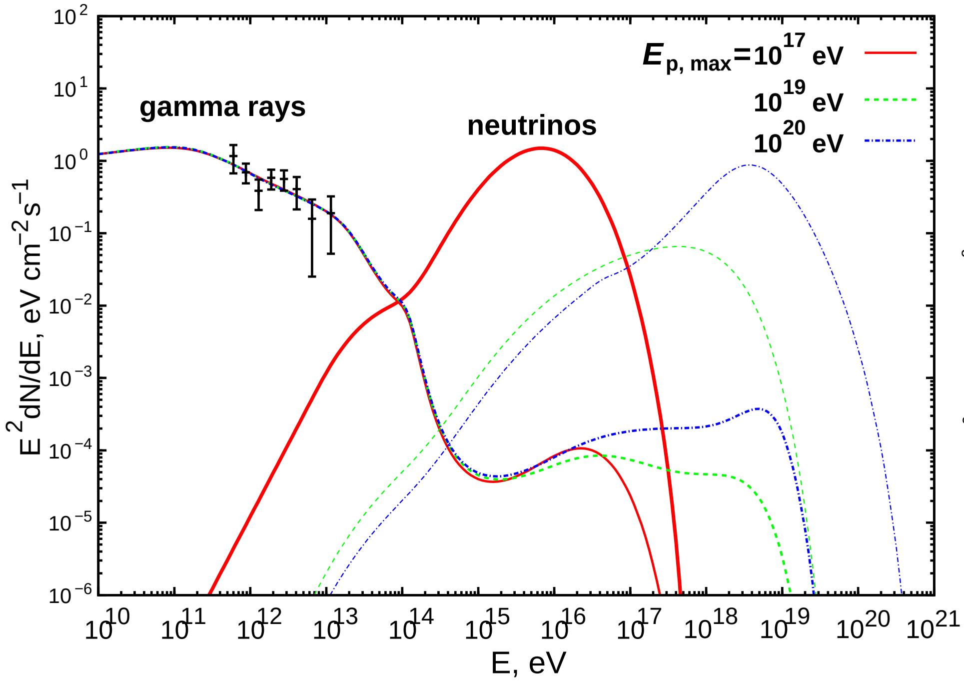
For distant sources, secondary signals win

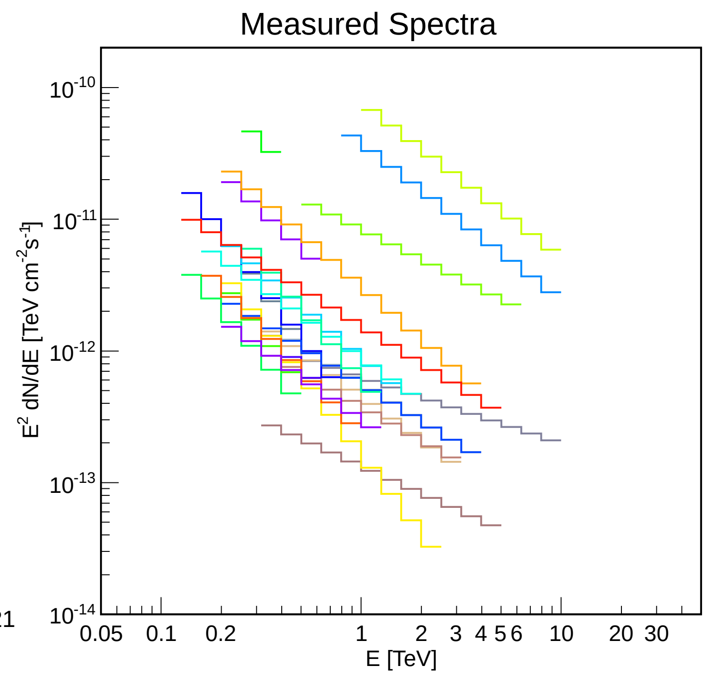
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



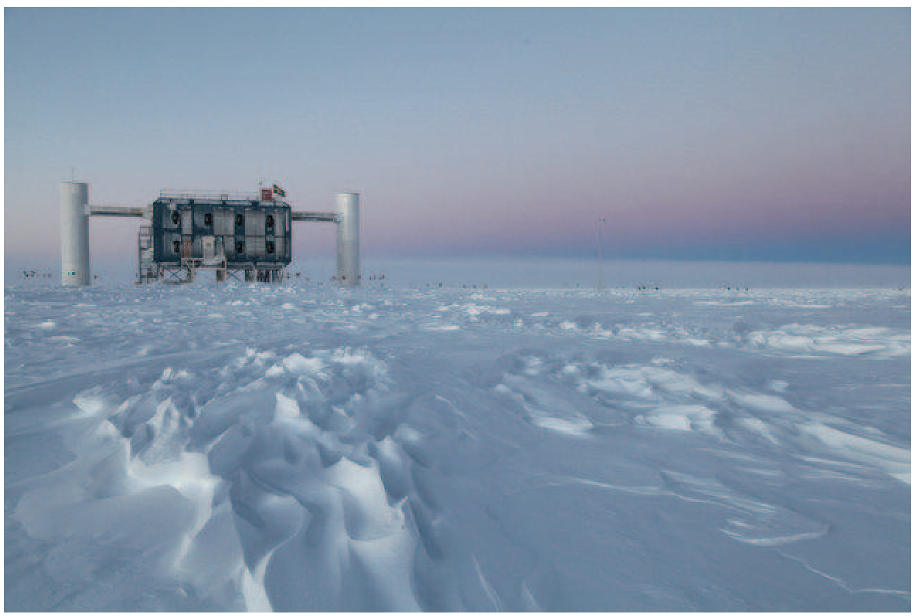
[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]

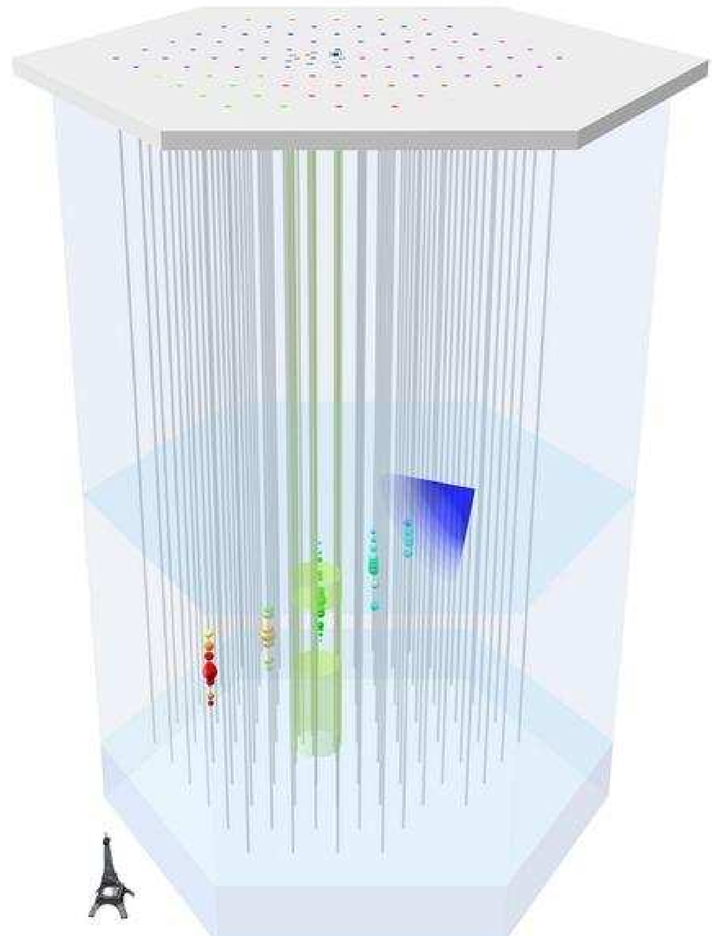
Robust spectral shapes explain the observed universality



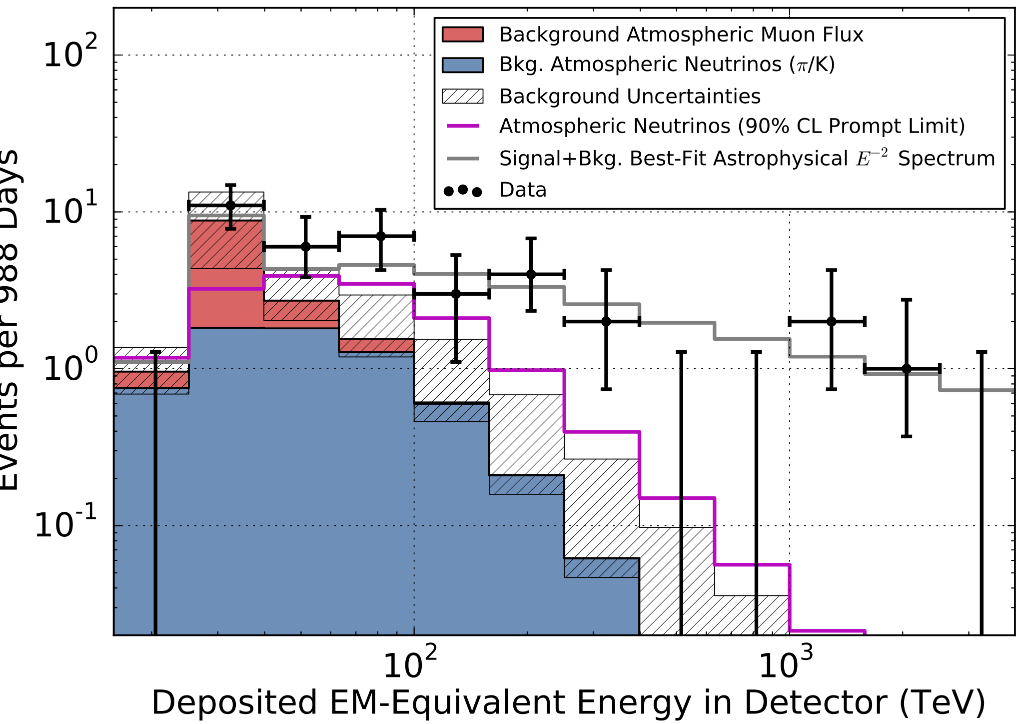


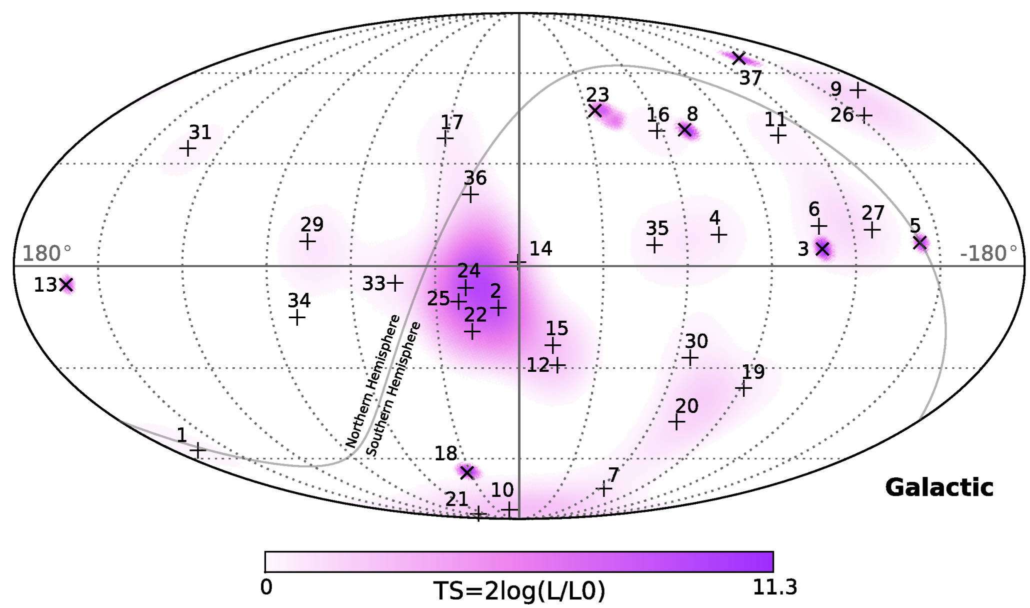
IceCube detector



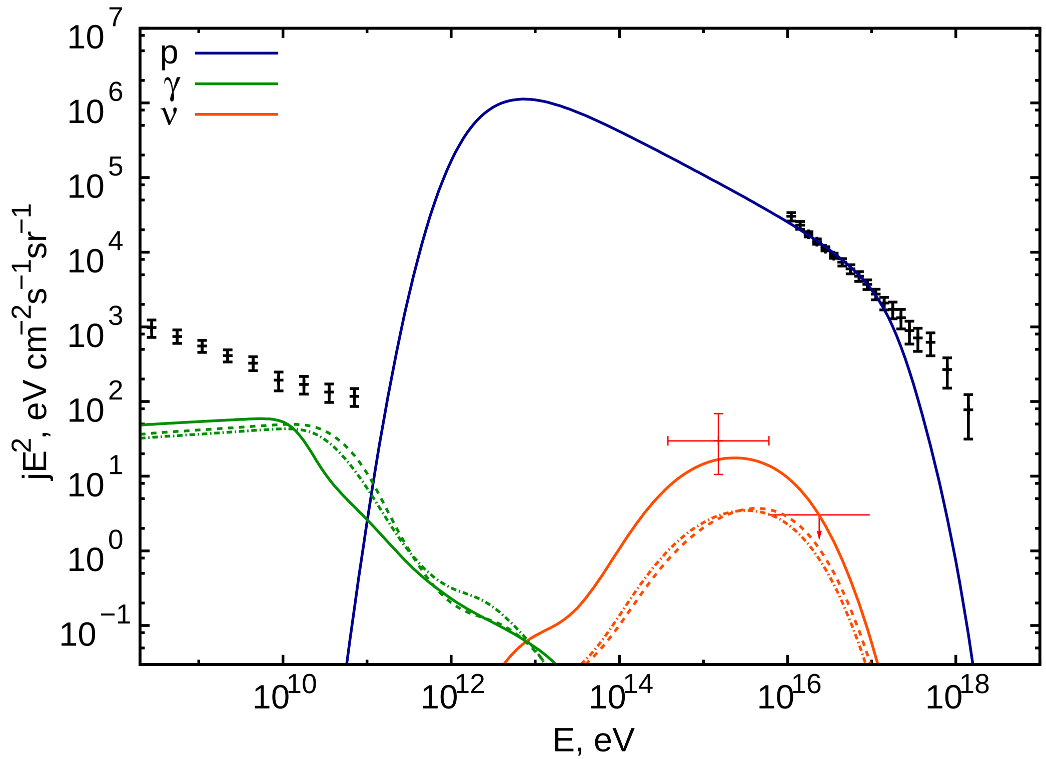


PeV neutrinos discovered by IceCube





PeV neutrinos discovered by IceCube consistent with secondary spectrum



[Kalashev, Kusenko, Essey, Phys.Rev.Lett. 111 (2013) 041103]

EBL models

Once the contribution from cosmic rays is included, the spectra are not very sensitive to the level of EBL.

Models considered:

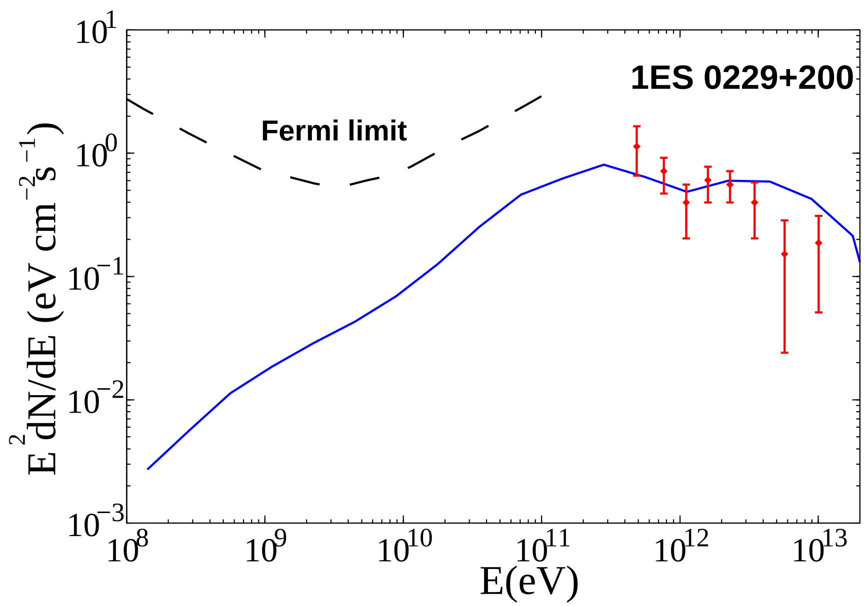
"High" EBL: Stecker et al. (2006) ApJ, 648, 774

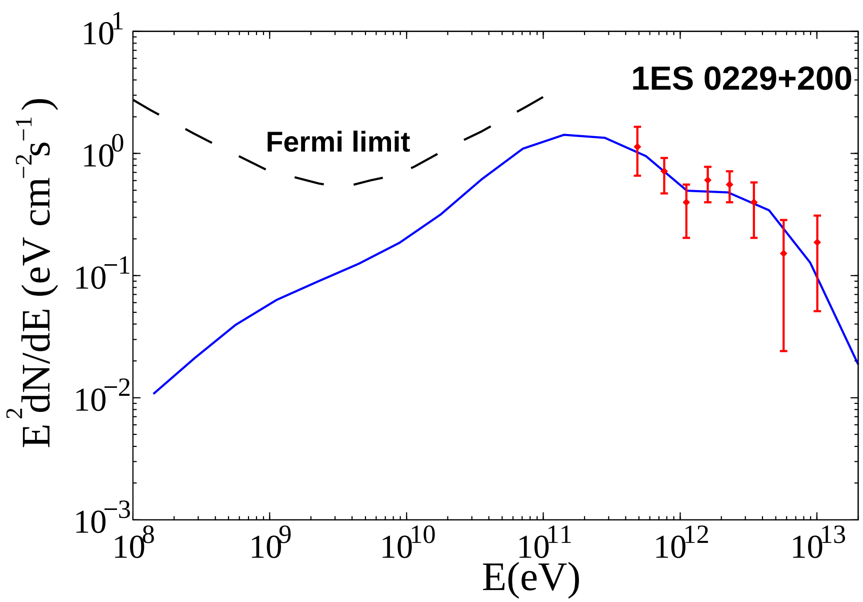
Models between low and high: Salamon & Stecker 1998; Kneiske et al. 2002, 2004; Stecker et al. 2007; Franceschini et al. 2008; Horiuchi et al. 2009; Primack et al. 2009; Gilmore et al. 2009; Razzaque et al. 2009; Finke et al. 2010.

"Low" EBL: Shaped as "high", but at the level of 40% lower.

The range between "high" and "low" encompasses all models.

"Low" EBL (left), "high" EBL (right)

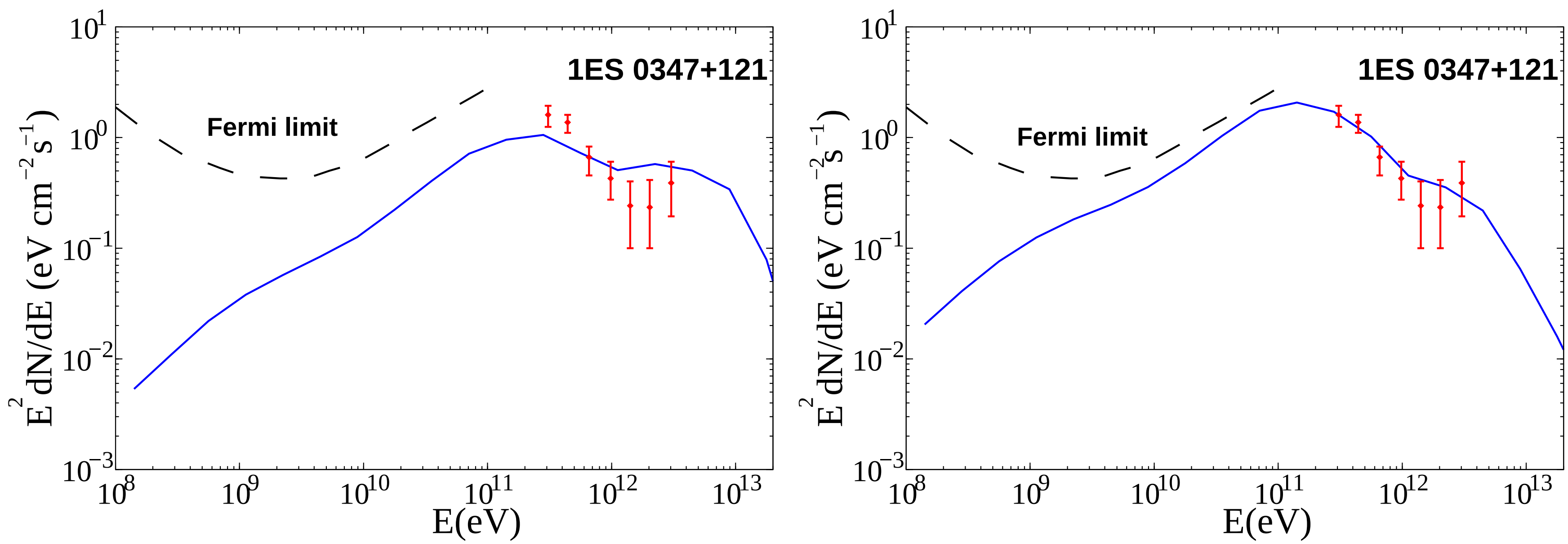




Both fit the data.

[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL (left), "high" EBL (right)



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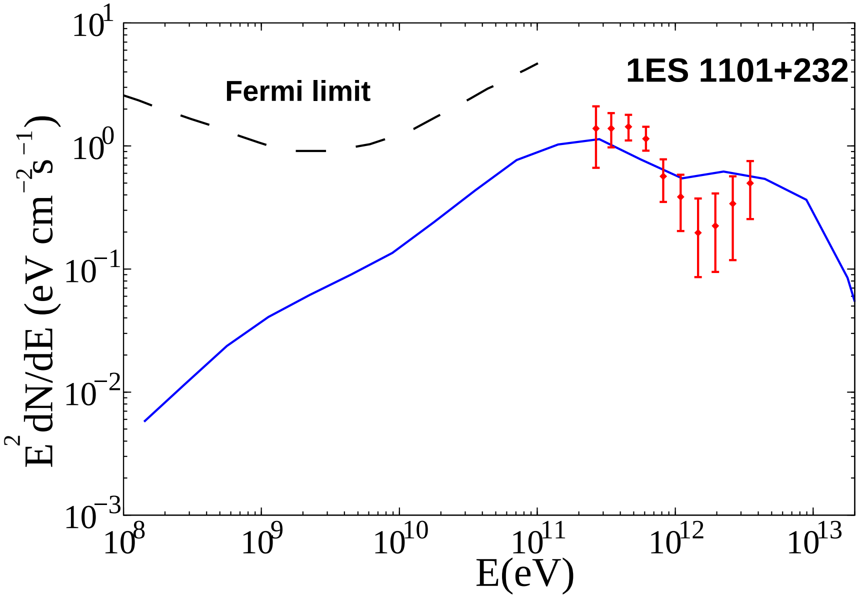
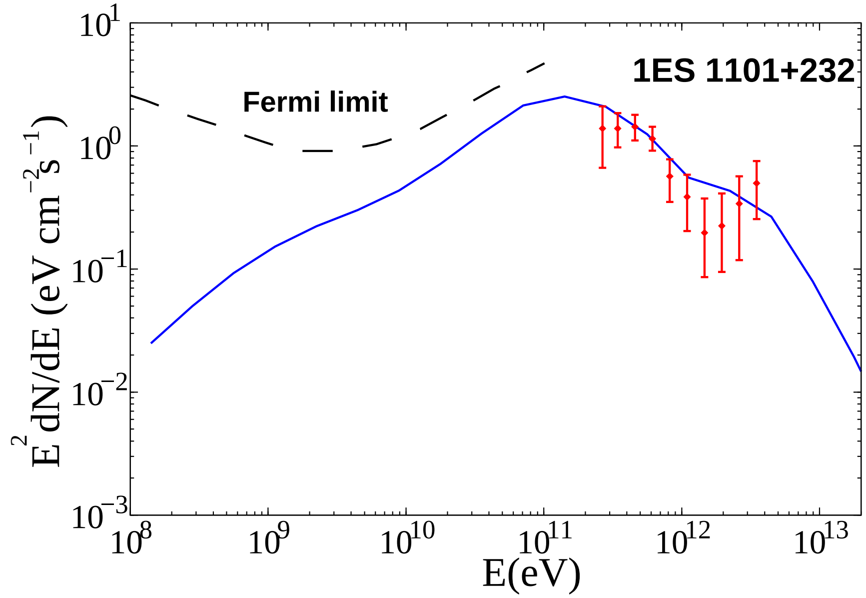




Both fit the data.

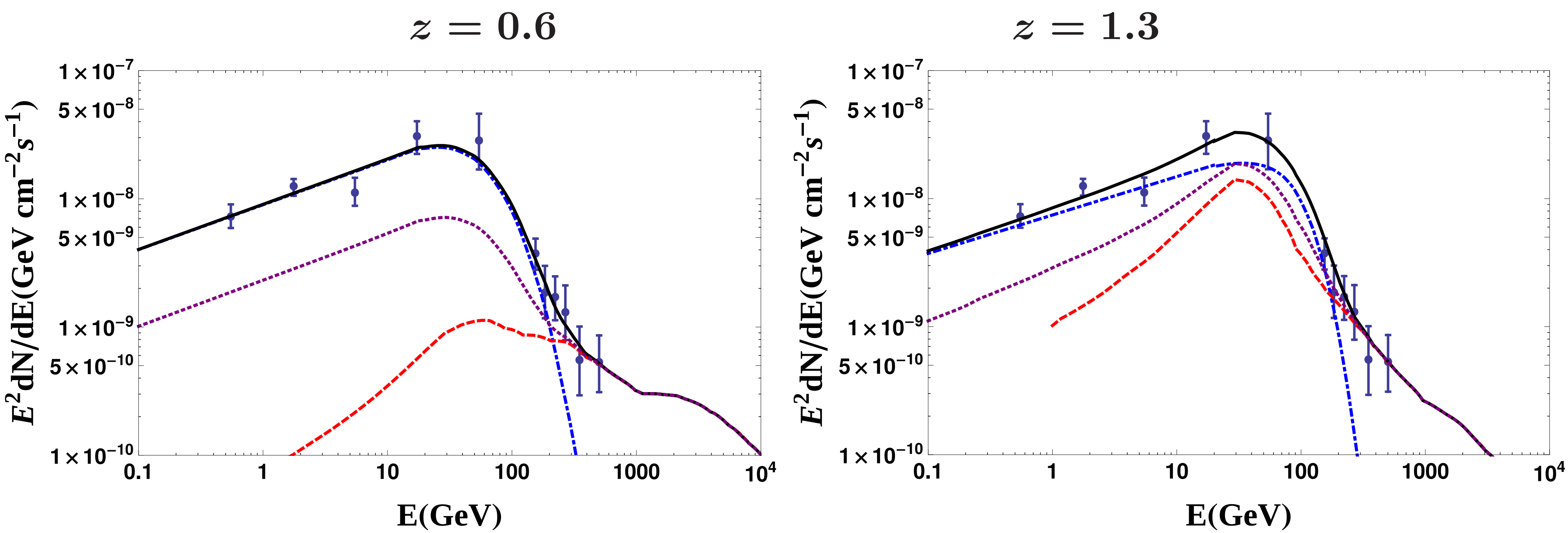
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL vs "high" EBL

Source	Redshift	EBL Model	L_p , erg/s	$L_{p,\text{iso}}$, erg/s	χ^2	DOF
1ES0229+200	0.14	Low	1.3×10^{43}	4.9×10^{45}	6.4	7
1ES0229+200	0.14	High	3.1×10^{43}	1.1×10^{46}	1.8	7
1ES0347-121	0.188	Low	2.7×10^{43}	1.0×10^{46}	16.1	6
1ES0347-121	0.188	High	5.2×10^{43}	1.9×10^{46}	3.4	6
1ES1101-232	0.186	Low	3.0×10^{43}	1.1×10^{46}	16.1	9
1ES1101-232	0.186	High	6.3×10^{43}	2.3×10^{46}	4.9	9

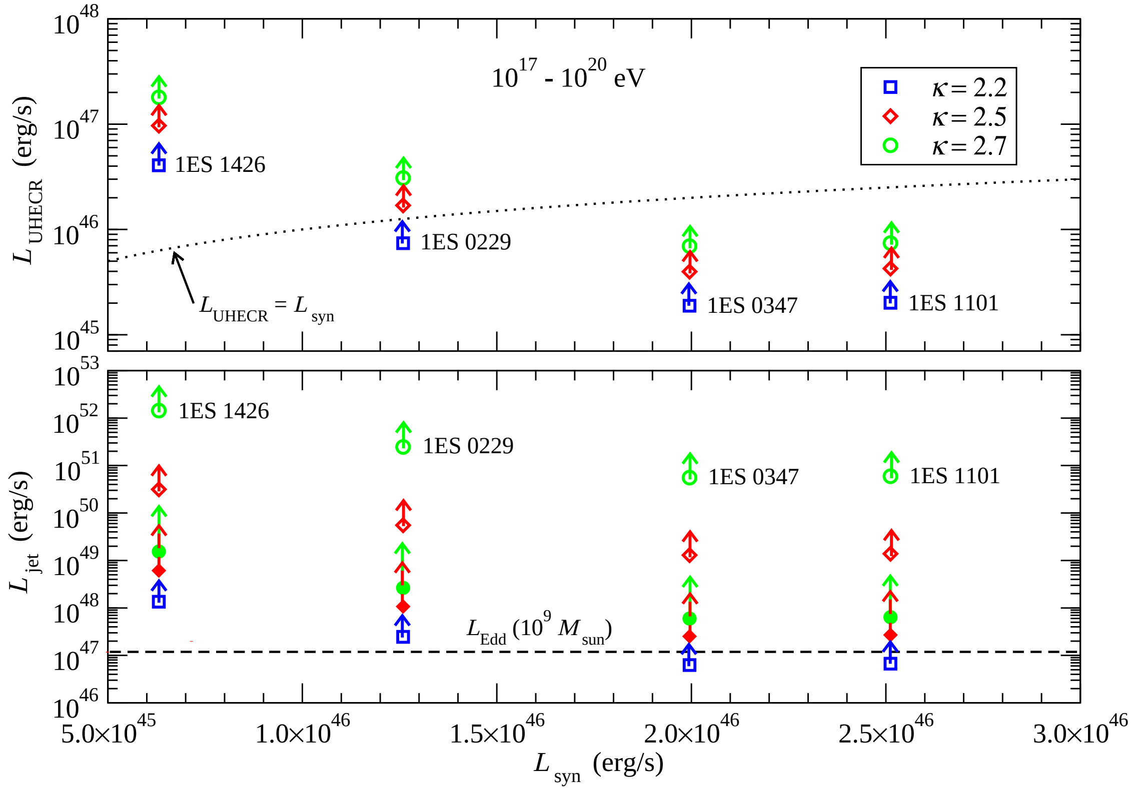
Here we have assumed $\theta_{jet} = 6^\circ$ (and $E_{\max} = 10^{11}$ GeV, $\alpha = 2$.)
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

PKS 1424+240 at $z > 0.6$



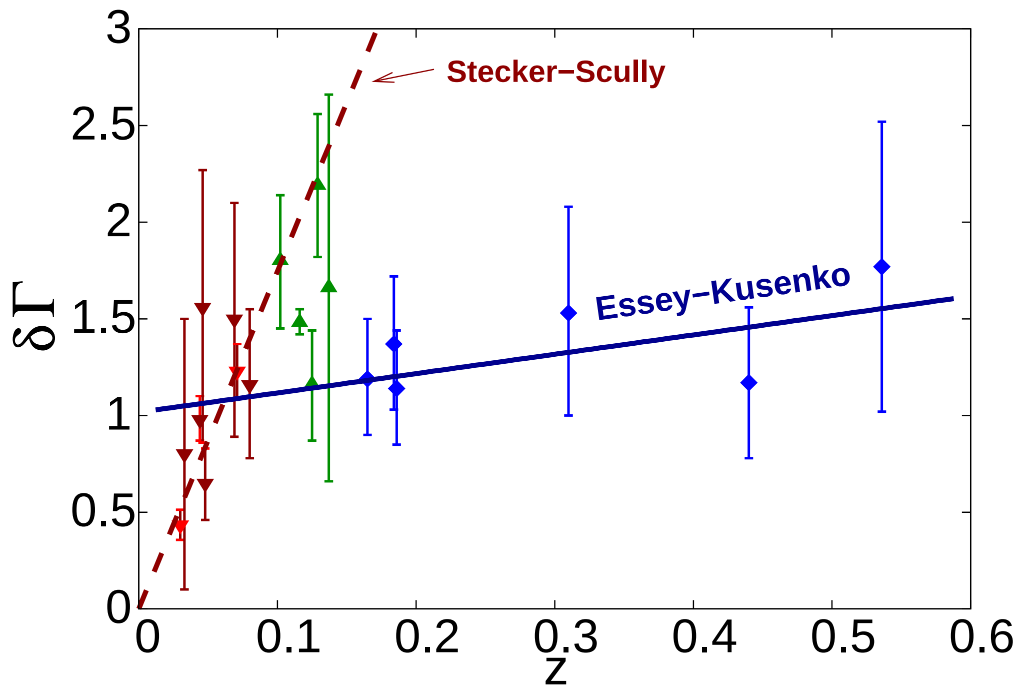
[Essey, AK]

Lower limits on UHECR and jet powers of TeV blazars



[Razzaque, Dermer, Finke, ApJ, 745, 196 (2012)]

Softening of the spectrum reflects the transition from primary to secondary gamma rays



$$\delta\Gamma = \Gamma_{\mathrm{GeV}} - \Gamma_{\mathrm{TeV}}$$

Observations: blazars at $z > 0.15$ show no variability for $E > 1$ TeV

Erosion of time variability for $E > 1$ TeV, $z > 0.15$

Crucial test of the above explanation is the prediction of a slow erosion of time variability for $\boldsymbol{E > 1}$ **TeV**, $\boldsymbol{z > 0.15}$.

Current data: variability below TeV for distant blazars, above TeV for nearby blazars.

Prediction: stochastic *pedestal* emerges at high energy, high redshifts, for distant blazars above which some flares may rise

Time structure details: **Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183**

Proton delays due to random walk in magnetic fields:

$$\tau_p \propto \frac{B^2}{E_p^2} \propto \frac{B^2}{E_\gamma^{1/2}}.$$

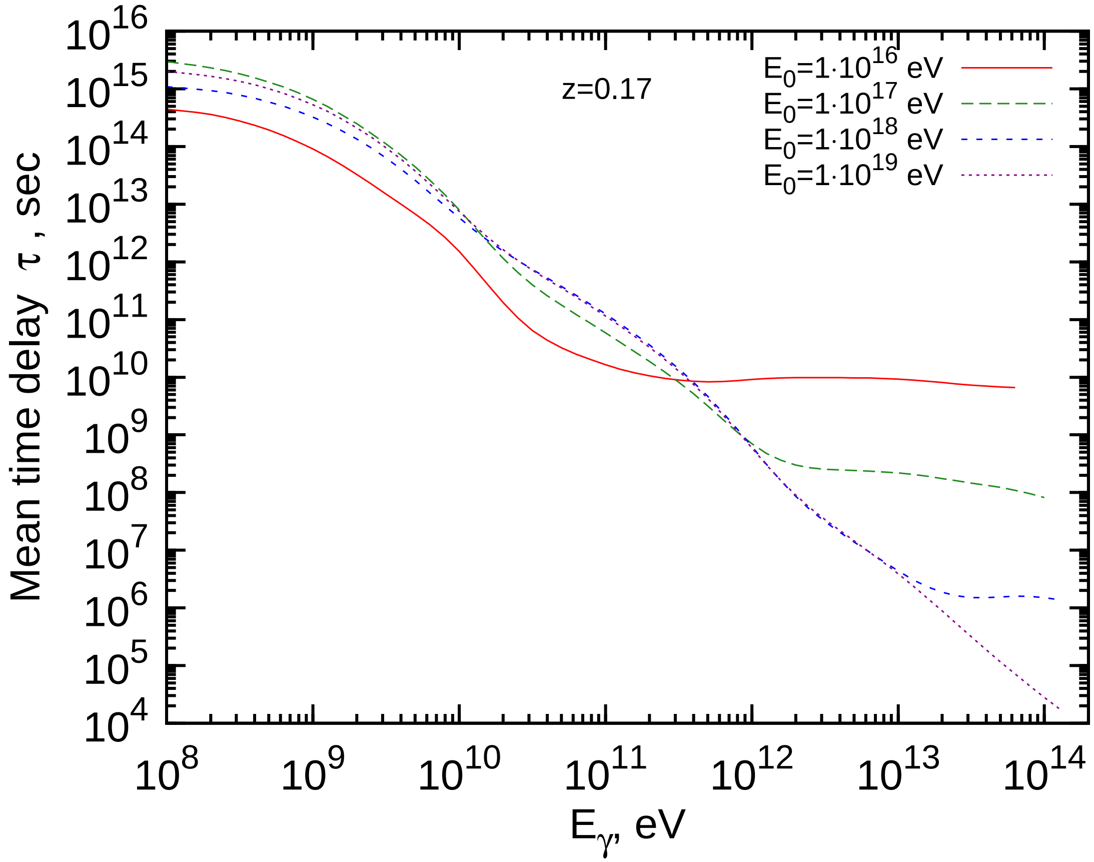
EM cascade delays:

$$\tau_\gamma \approx \tau_e = D_e^3 \frac{e^2 B^2}{c E_e^2} \propto \frac{B^2}{E_e^5} \propto \frac{B^2}{E_\gamma^{5/2}}$$

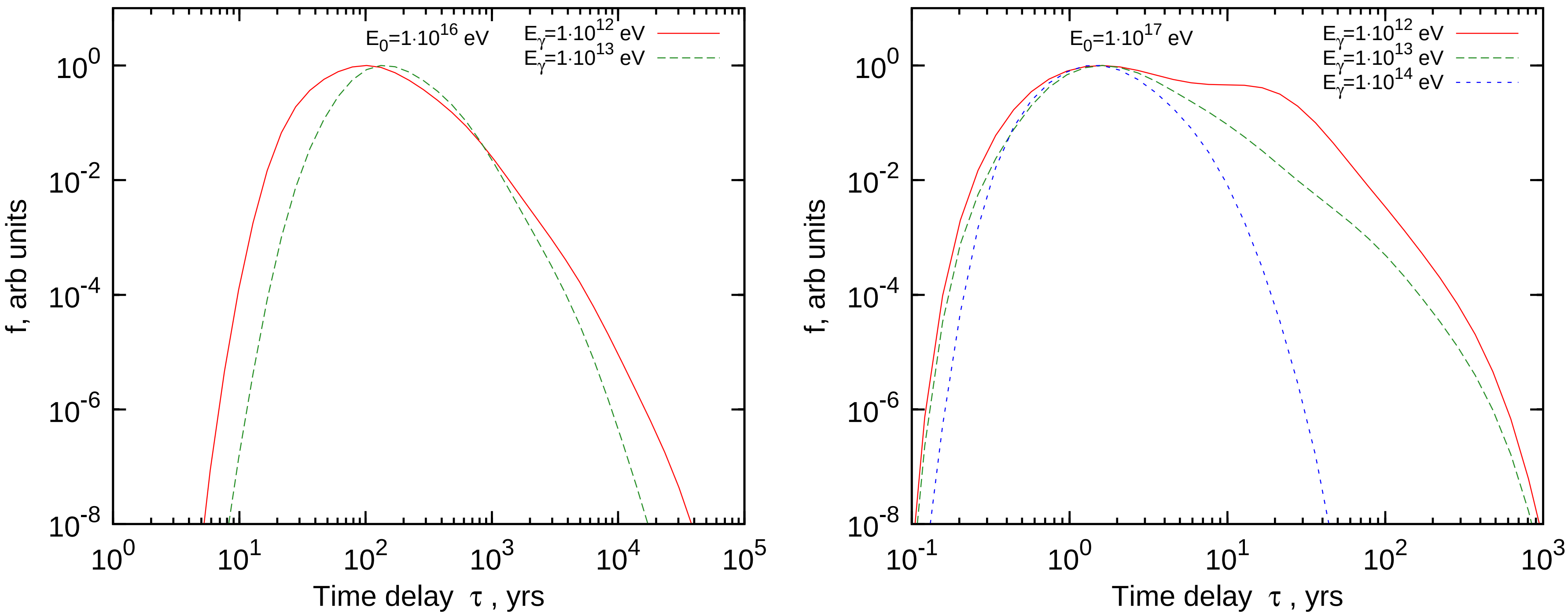
The total time delay of an observed photon is the sum of τ_p and τ_γ:

$$\tau_{\rm tot} = \tau_p + \tau_\gamma = C_1 \frac{B^2}{E_\gamma^{5/2}} + C_2 \frac{B^2}{E_\gamma^{1/2}},$$

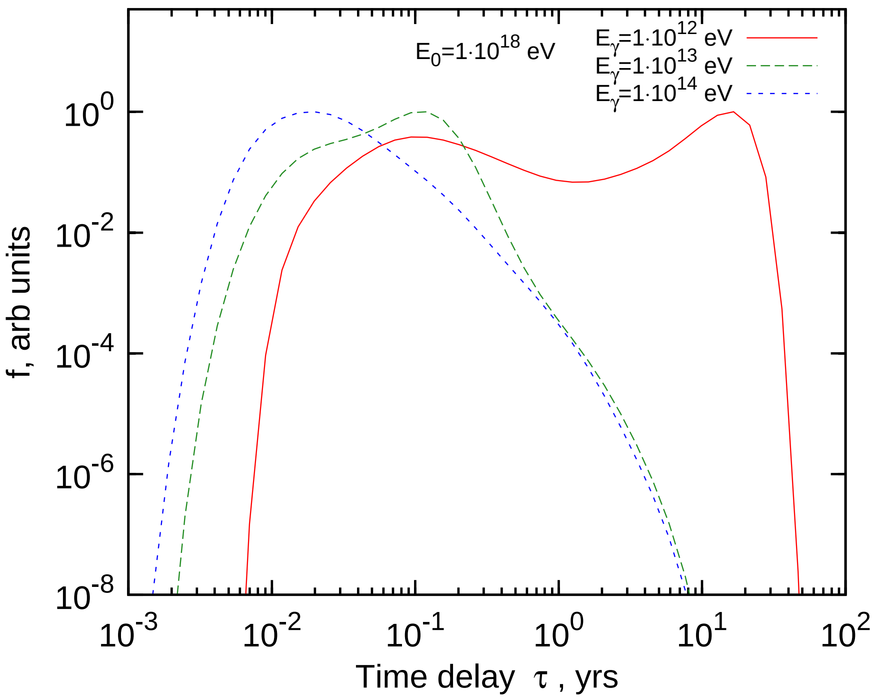
Broken power law.

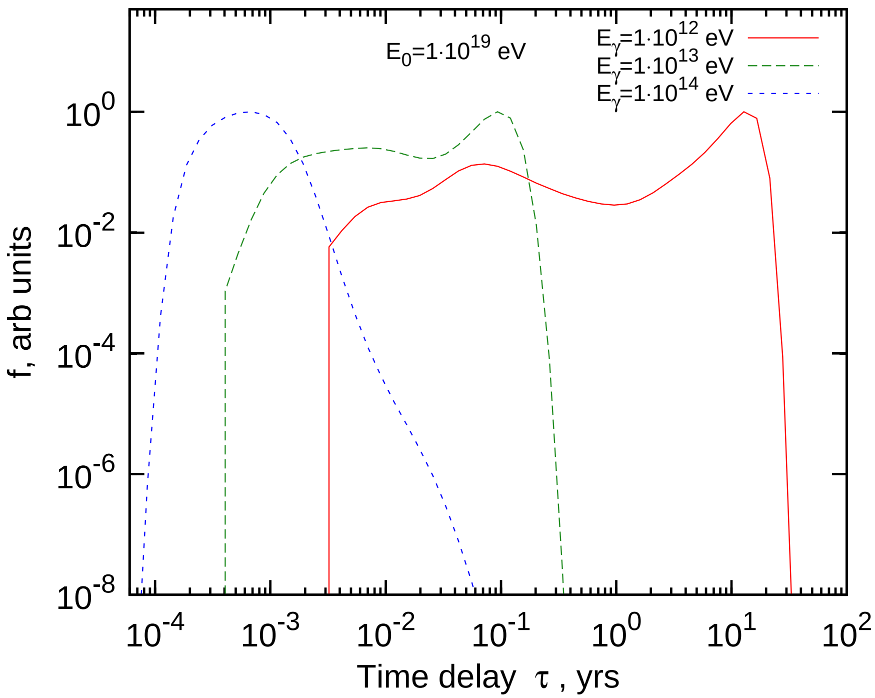


[Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183]



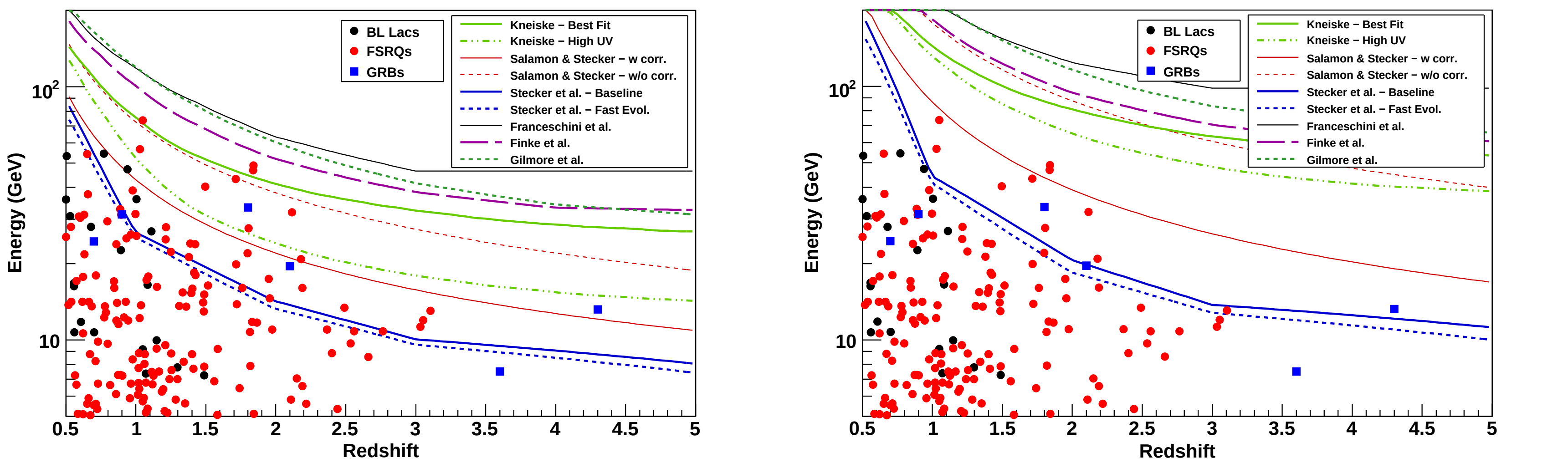
[Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183]



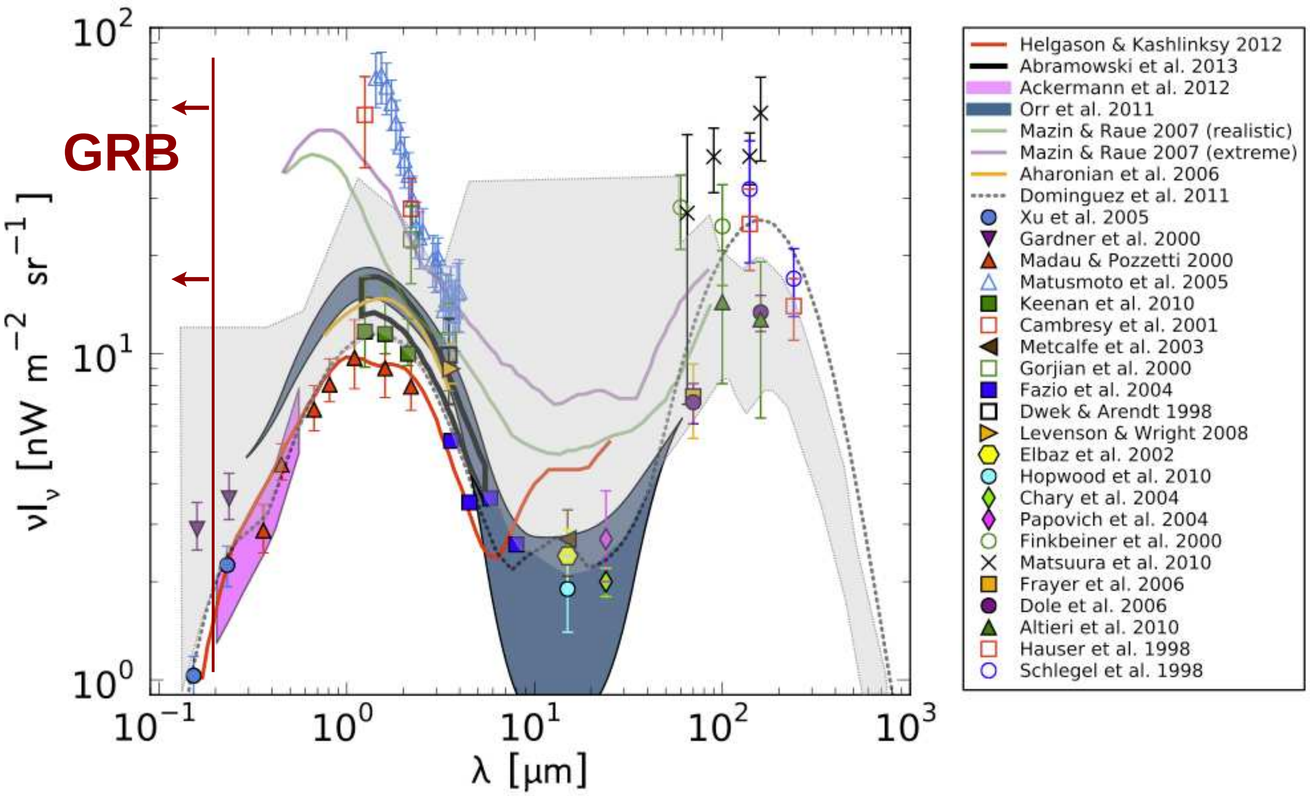


[Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183]

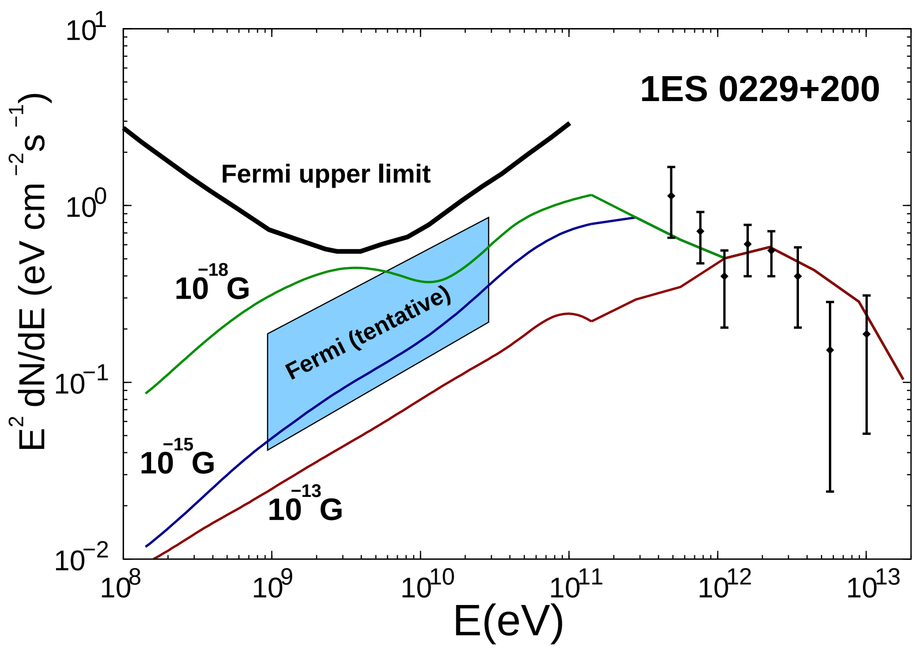
GRB constraints on EBL: shape of EBl spectrum is assumed



GRB constraints on EBL: no constrain at large wavelengths



Spectra $\Rightarrow B \sim 10^{-15}$ Gauss



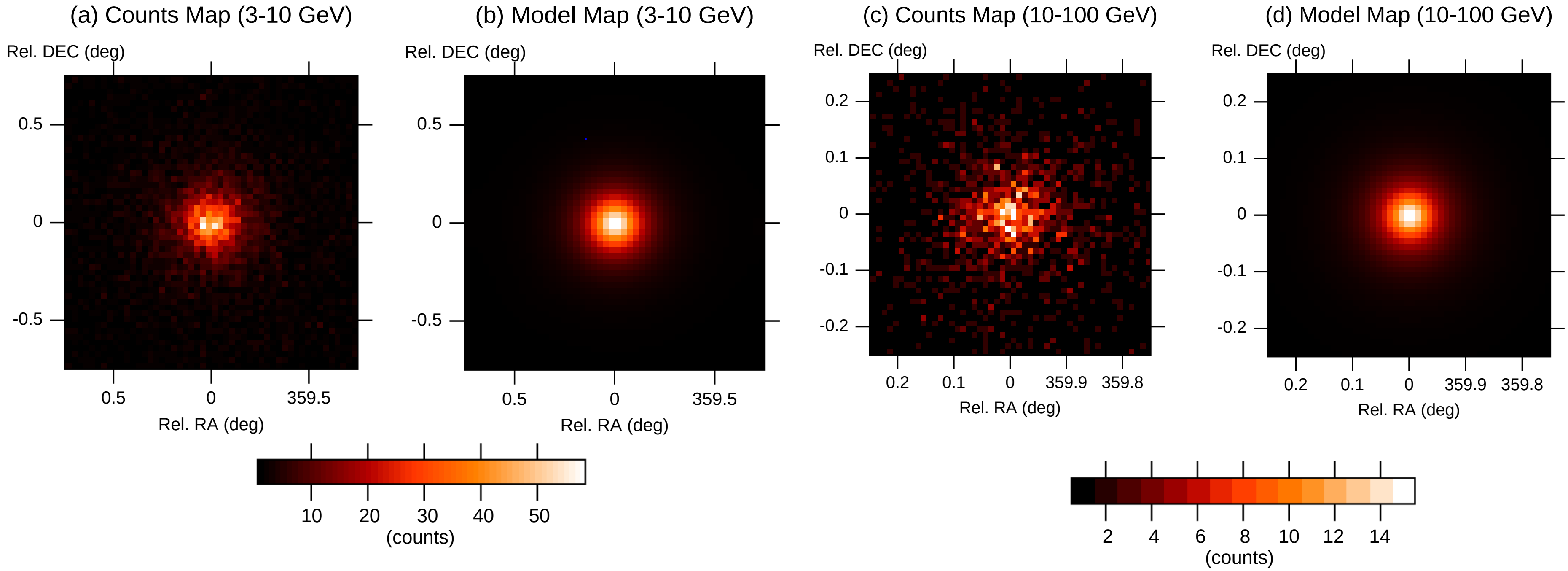
For line-of-sight interactions to explain the point sources, the IGMFs must be in the range:

$$1 \times 10^{-17}\ \mathrm{G} < B < 3 \times 10^{-14}\ \mathrm{G}$$

[Essey, Ando, AK (2011)]

Extended images ⇒ IGMF ∼ 10^{-15} Gauss

Intergalactic magnetic fields make the images of blazars diffuse. The halos around blazars imply 10^{-15} Gauss magnetic fields.



[Ando, AK, ApJL (2010)]

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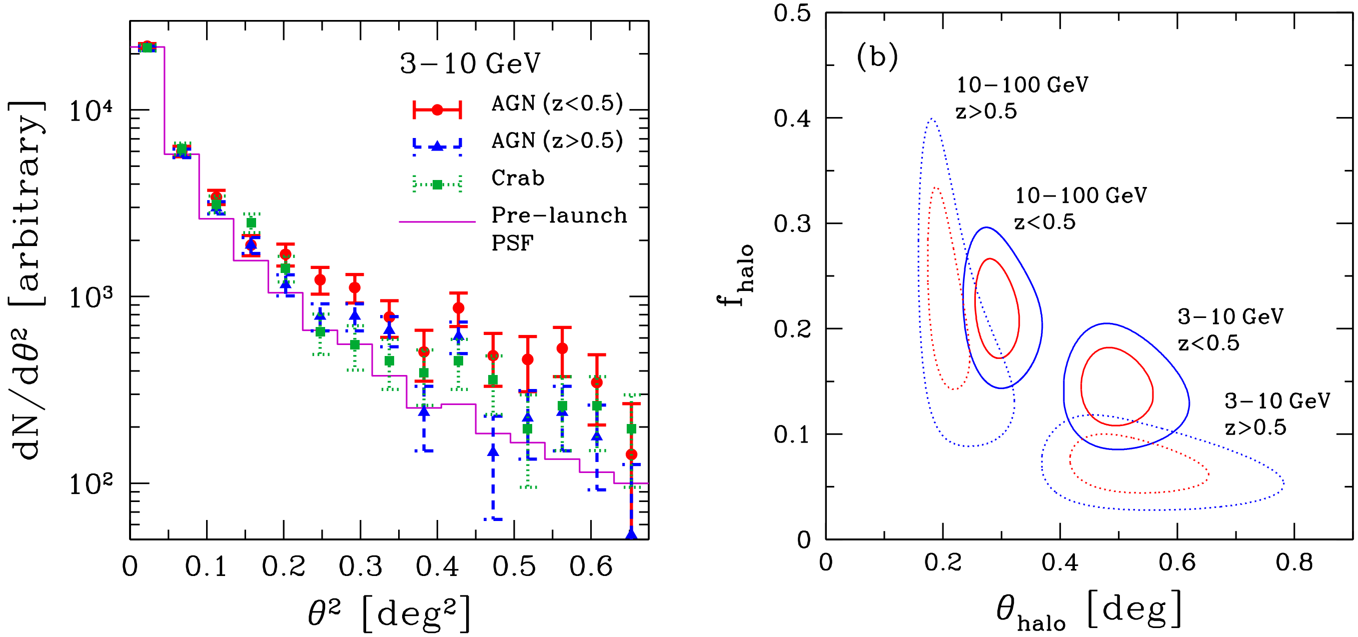
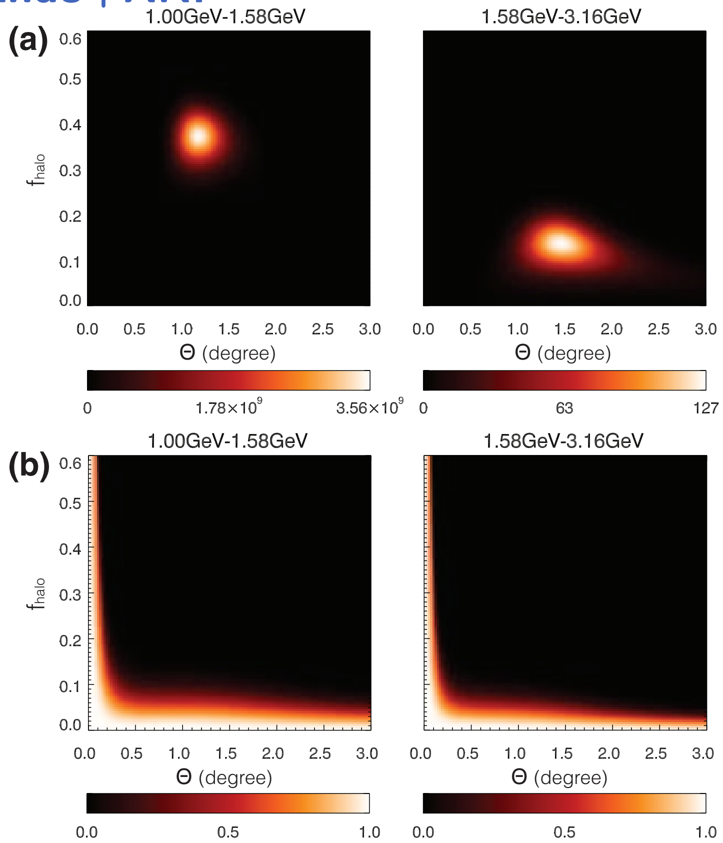


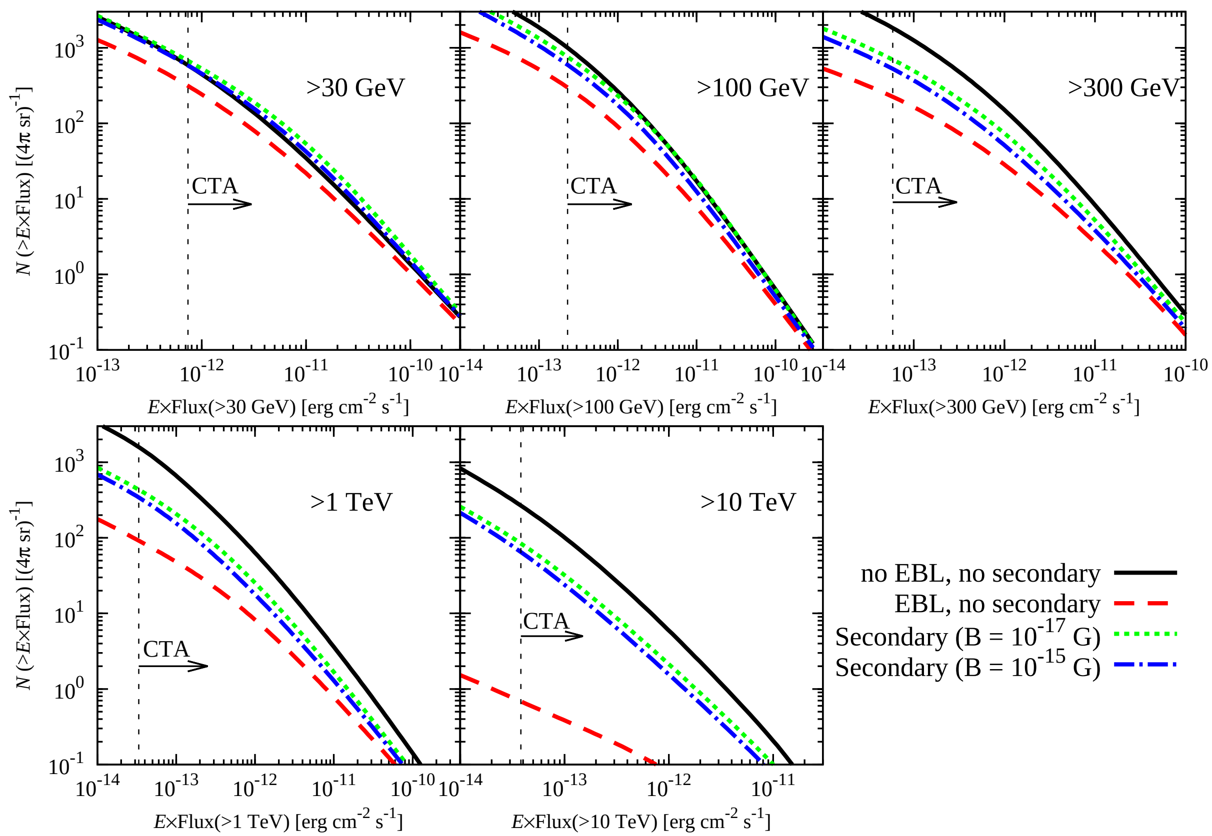
[Ando, AK, ApJL (2010)]

Extended images ⇒ IGMF $\sim 10^{-15}$ Gauss

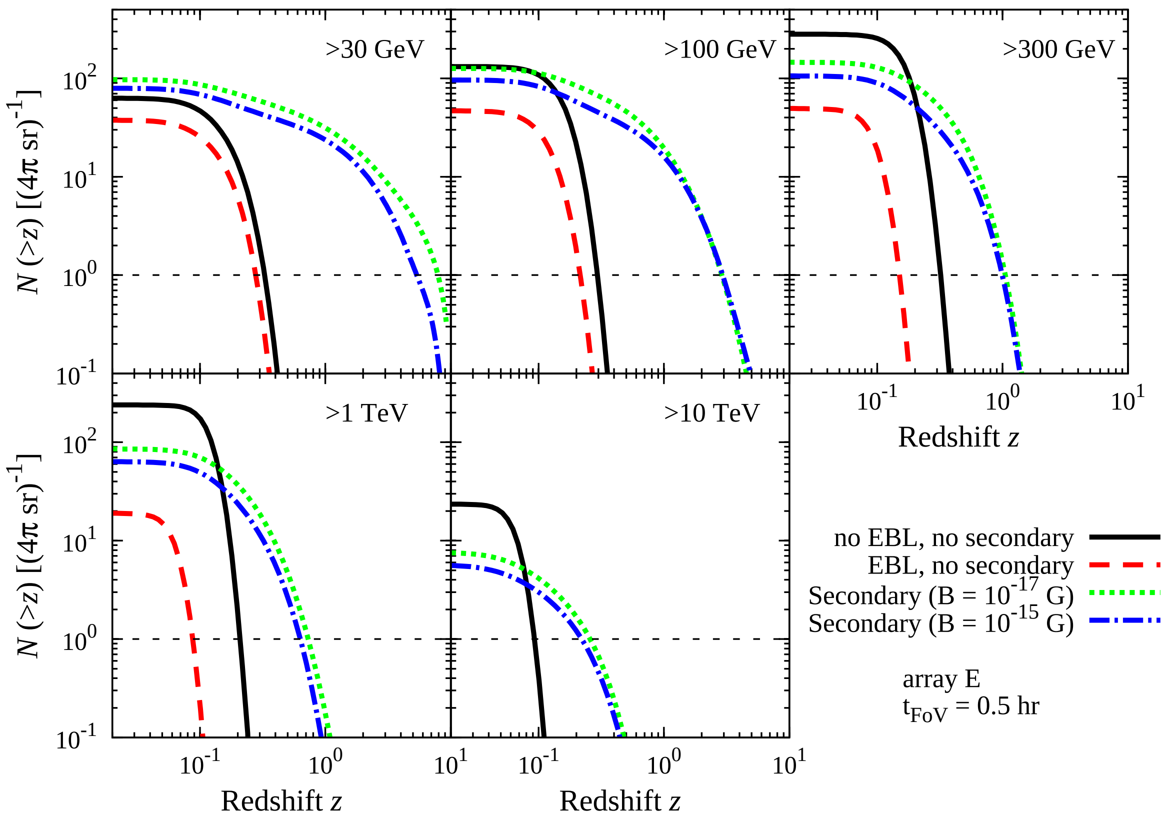
New independent analysis [Chen, Buckley, Ferrer (2014)]: in agreement with Ando+AK and Essey+Ando+AK.



CTA will see more distant, high energy sources



CTA sky survey



Conclusions

- AGN produce both cosmic rays and gamma rays $\Rightarrow$ secondary gamma rays should dominate the signals of distant sources for IGMFs of the order of a femtogauss or smaller.
- Secondary photons from distant blazars produce robust predictions for the spectra, in excellent agreement with the data.
- First evidence that AGN accelerate cosmic rays at least to 10^{17}eV.
- Spectra fit for both high and low EBL. Previously set limits do not hold, except under the assumption of large IGMFs.
- IGMFs in the range $10^{-17} - 10^{-14}$ G are consistent with the secondary interpretation (and with everything else), opening a window for a broad range of EBL models.
- Implications for future ACT detectors, such as CTA: more sources, distant sources.