Intergalactic cascades, and their implications

- Secondary gamma rays from line-of-sight interactions of cosmic rays can be responsible for hard spectra of distant blazars
- Spectra robust, show remarkable agreement with data
- A broad range of EBL models agree with the data
- Extragalactic magnetic fields

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

Astropart.Phys. 33 (2010) 81, *ibid.* 35 (2011) 135;

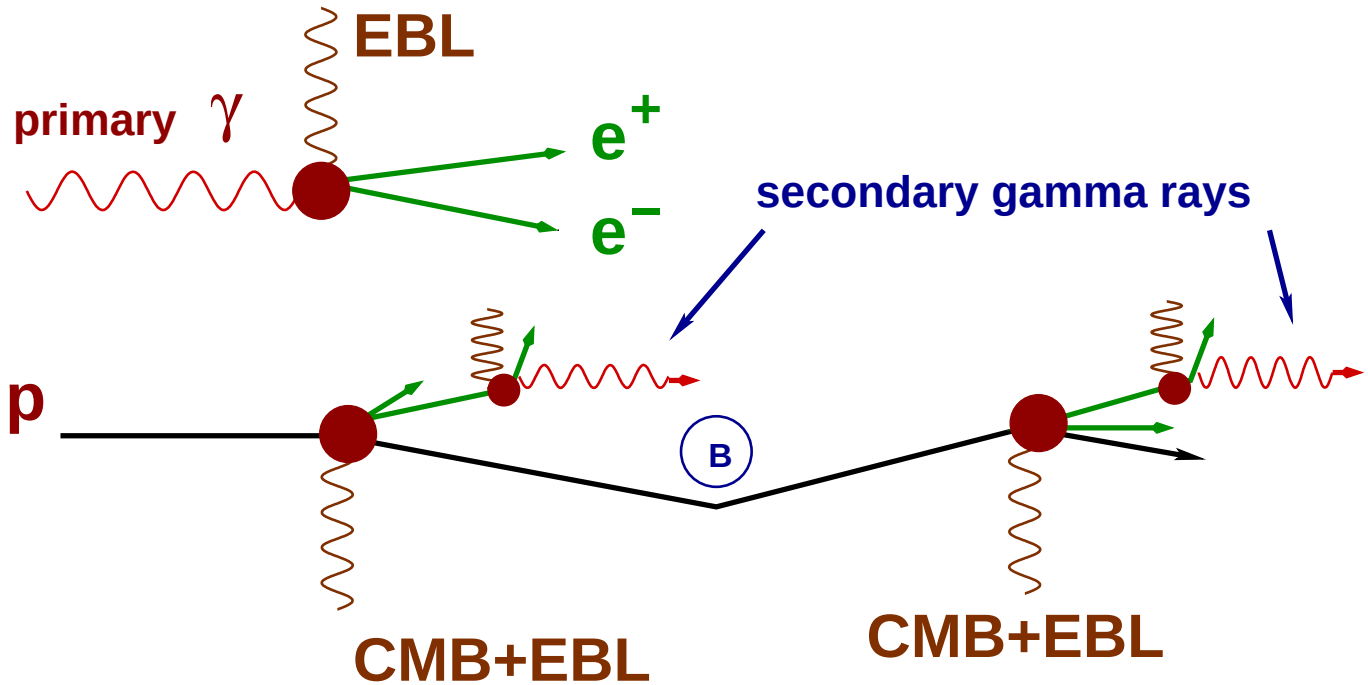
Phys. Rev. Lett. 104 (2010) 141102;

ApJ 731 (2011) 51;

ApJ Lett. 751 (2012) L11; arXiv:1203.3787; arXiv:1206.6715

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

AGN produce both UHECR 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
  $$\Lambda \sim 1/(\pi R^2 n) \sim 3 \times 10^3 \mathrm{Mpc}$$
  The mean MFP for linear propagation is of the order of the size of the observed universe.
- **IGMFs are not known:**
  - upper limits: $B < 10^{-9}$ **G** from non-observation of Faraday rotations
  - lower limits: $B > 10^{-30}$ **G** if one believes the galactic fields are seed fields amplified by dynamo.

  For magnetic fields $B < 10^{-14}$ **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
$p\gamma \to pe^+e^-$, $p\gamma \to p\pi^0$: 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

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

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

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

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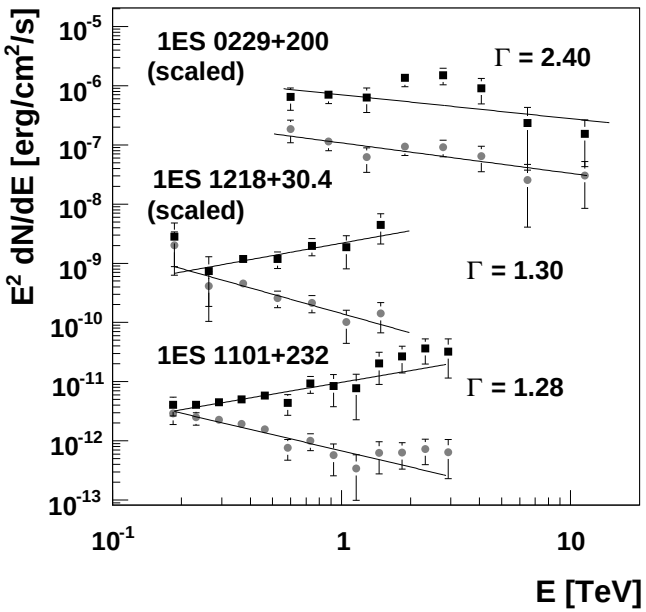
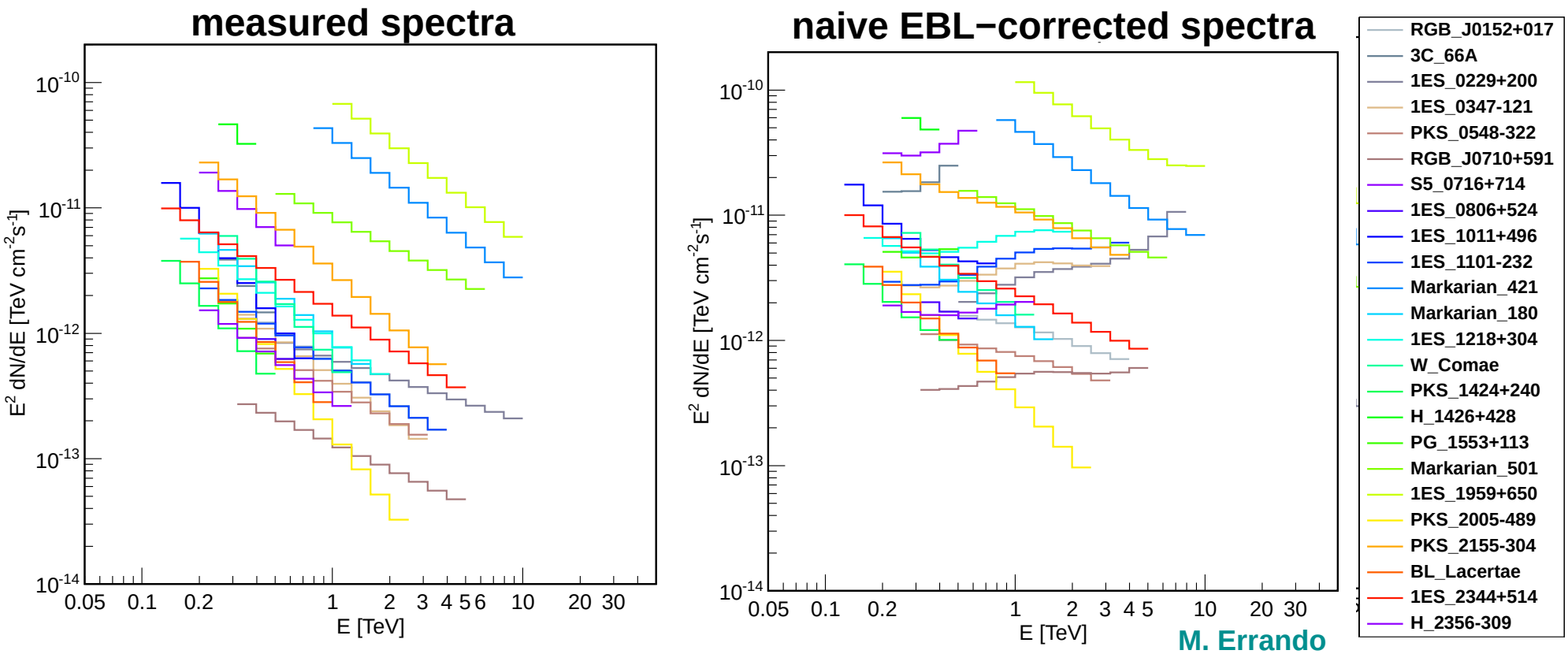
For distant sources, secondary signals win

Distant blazars have hard spectra

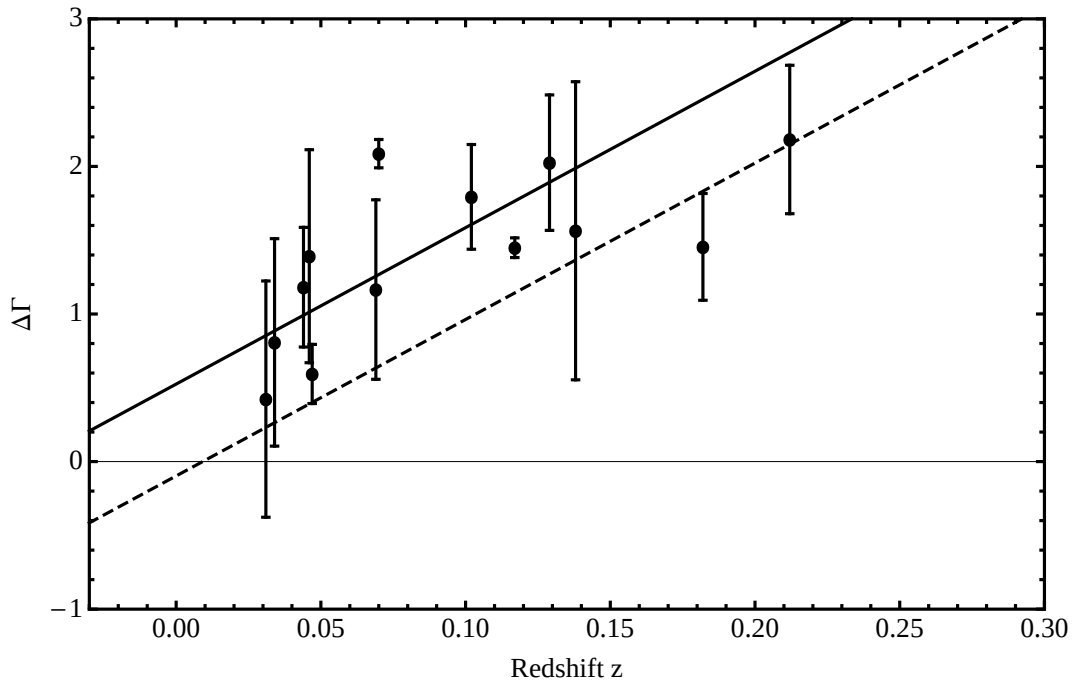


Absorption-corrected spectra are extremely hard, $\Gamma < 1.5$, for distant blazars.

Blazar spectra

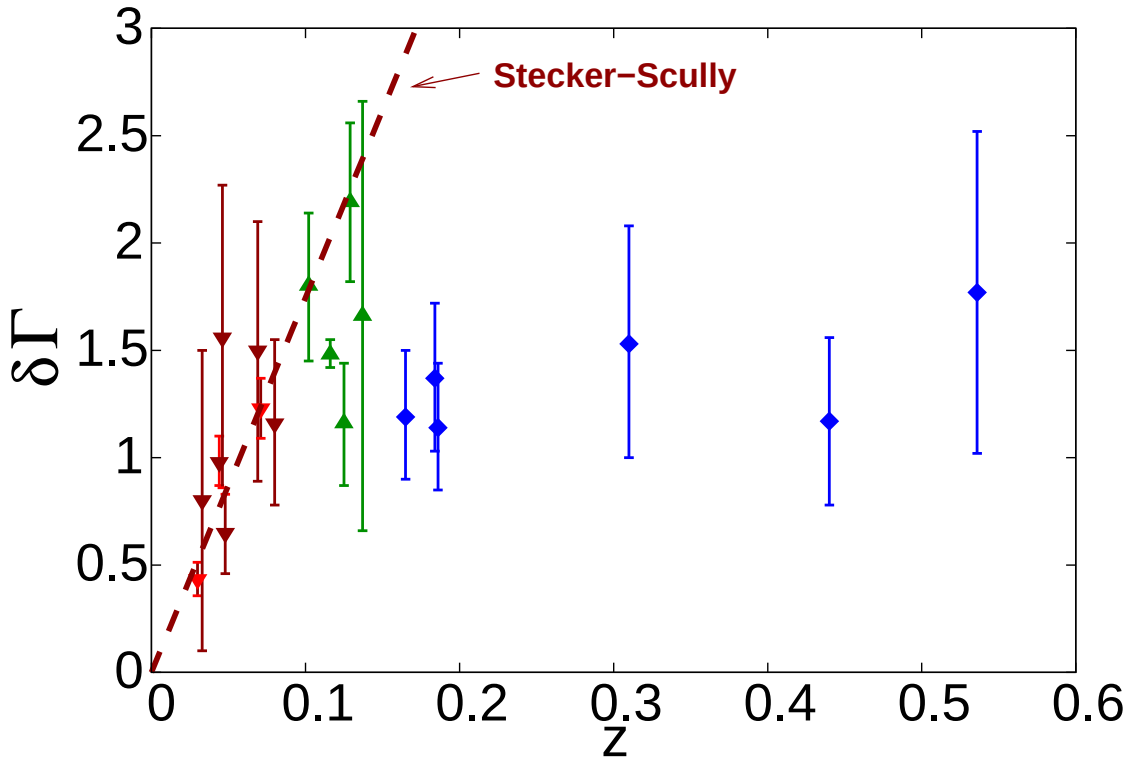


Softening of the spectrum as a function of the redshift



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

Distant blazars are different:



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

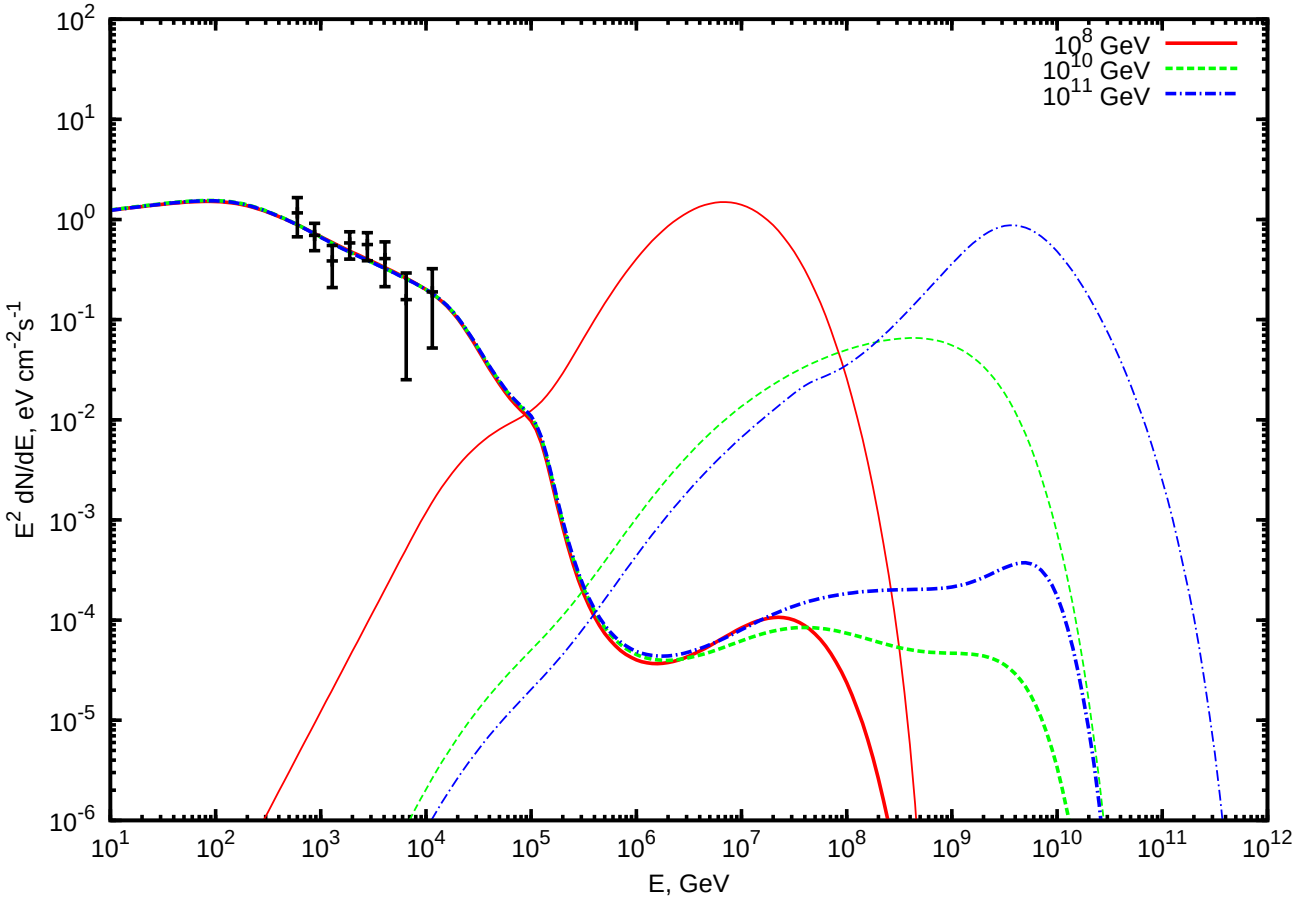
Proposed "new physics" solutions:

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.]

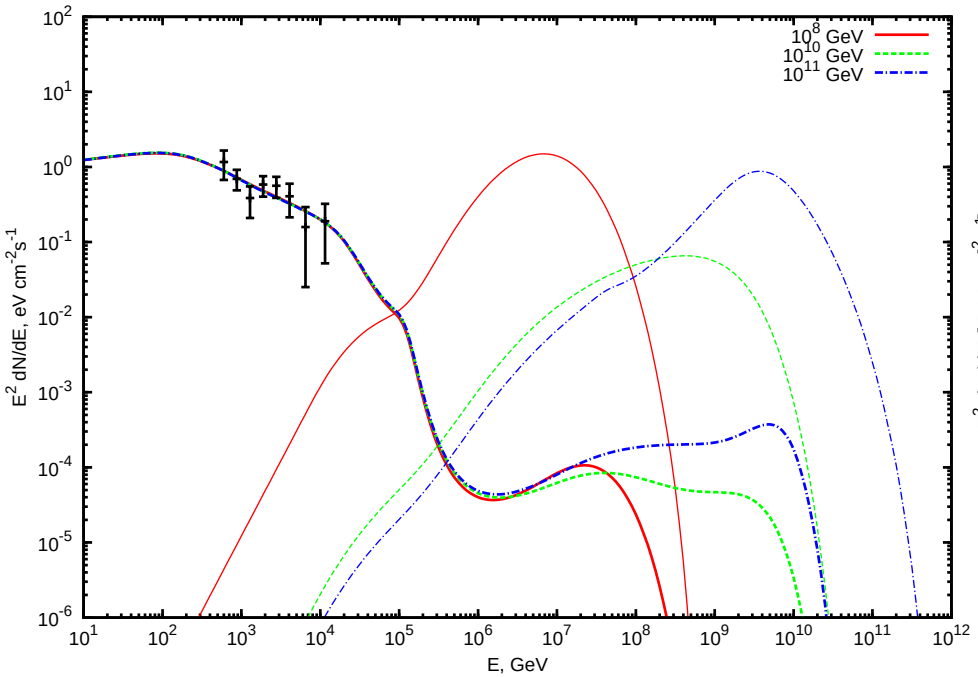
Is there a more conventional explanation?

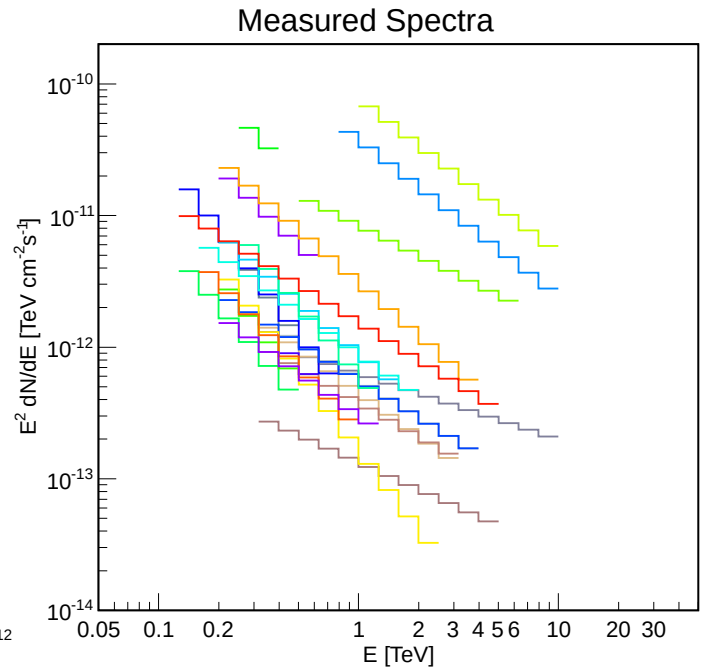
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



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

Robust spectral shapes explain the observed universality





EBL models

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

Models considered:

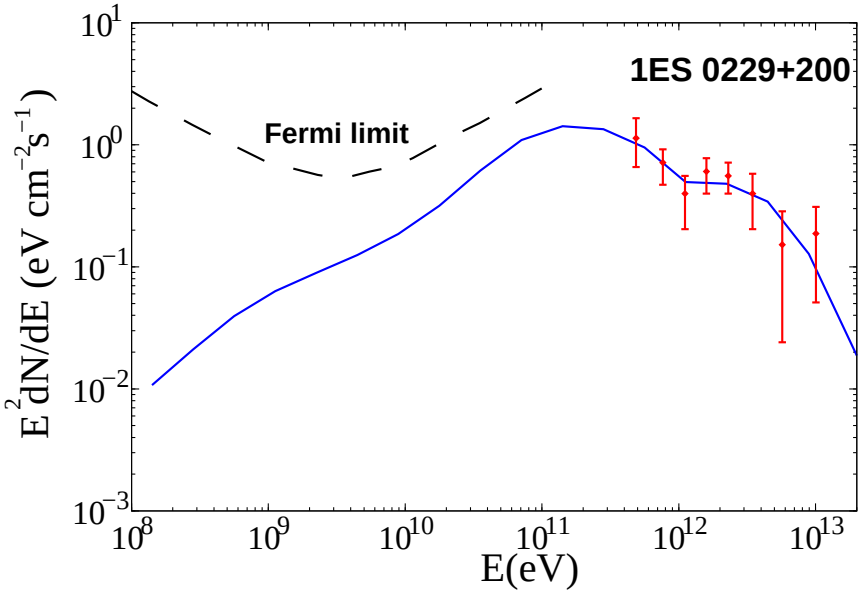
"High" EBL: Stecker et al. (2006) ApJ, 648, 774

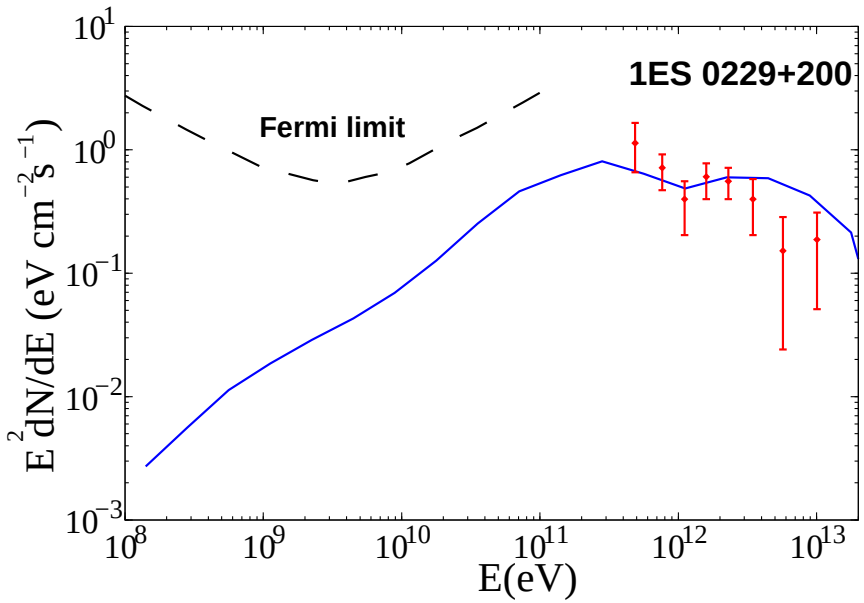
Models between low and high: Salamon & Stecker 1998; Kneiske et al. 2002, 2004; Stecker et al. 2007; Franceschini et al. 2008; Horiuchi et al. 2009; Primack et al. 2009; Gilmore et al. 2009; Razzaque et al. 2009; Finke et al. 2010.

"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)

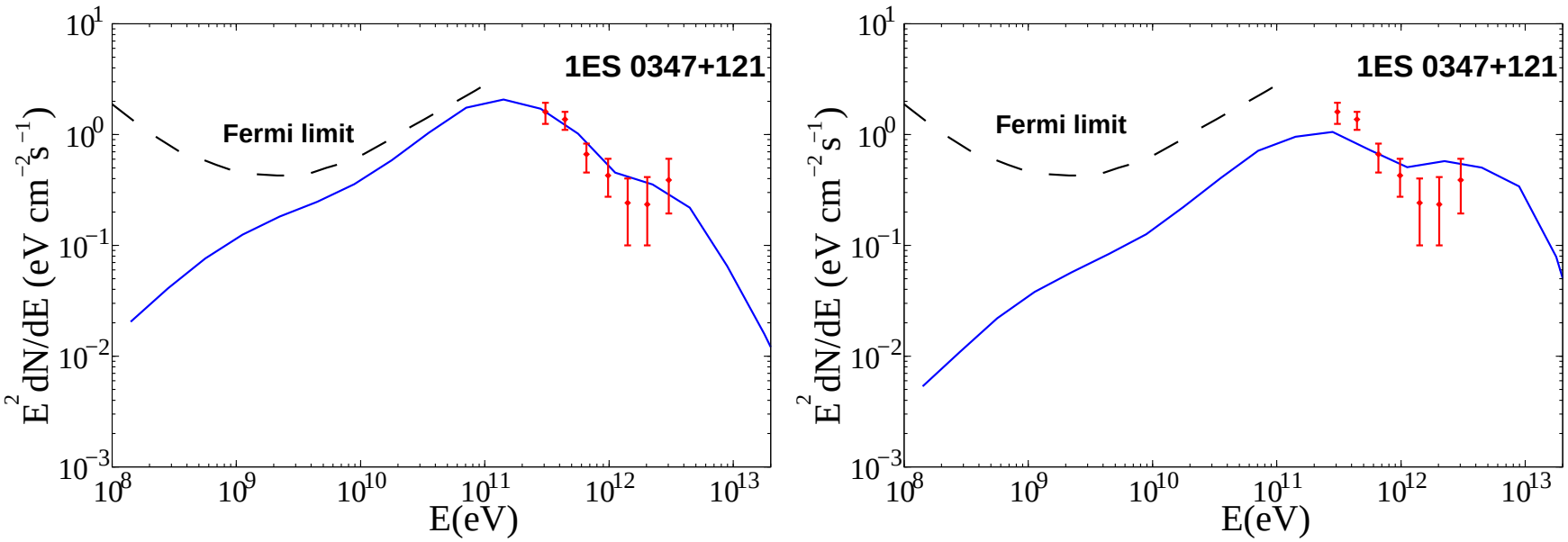




Both fit the data.

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

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



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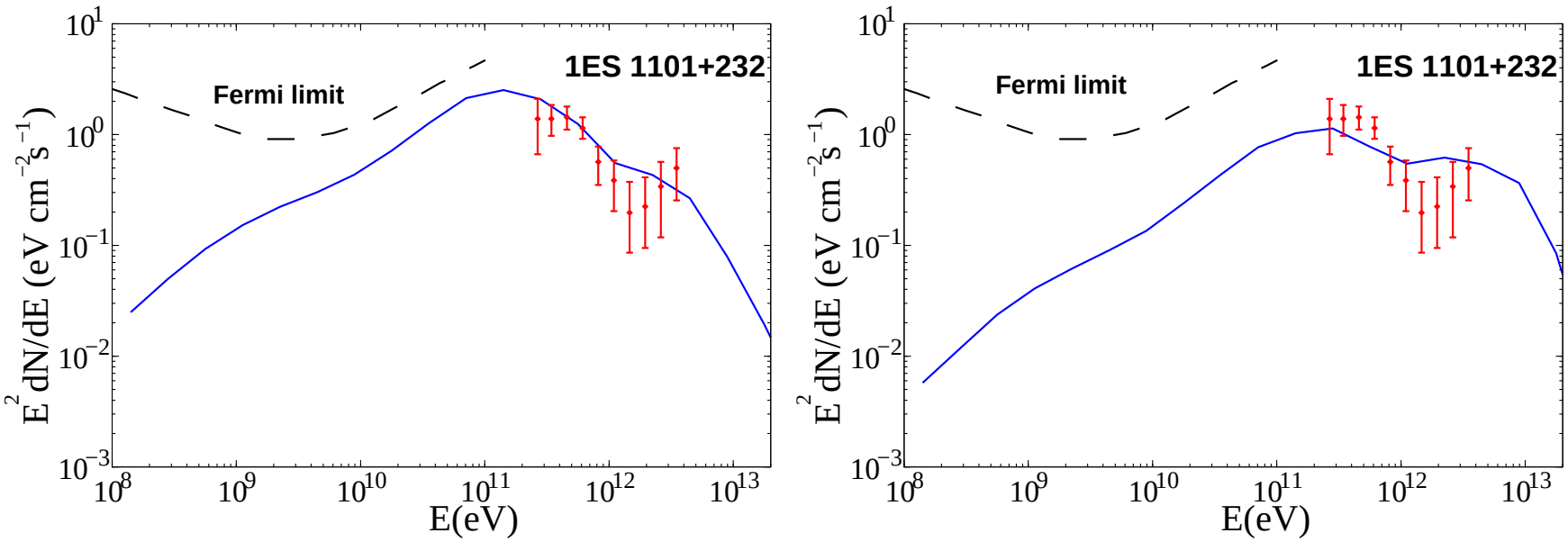
"Low" EBL (left), "high" EBL (right)



Both fit the data.

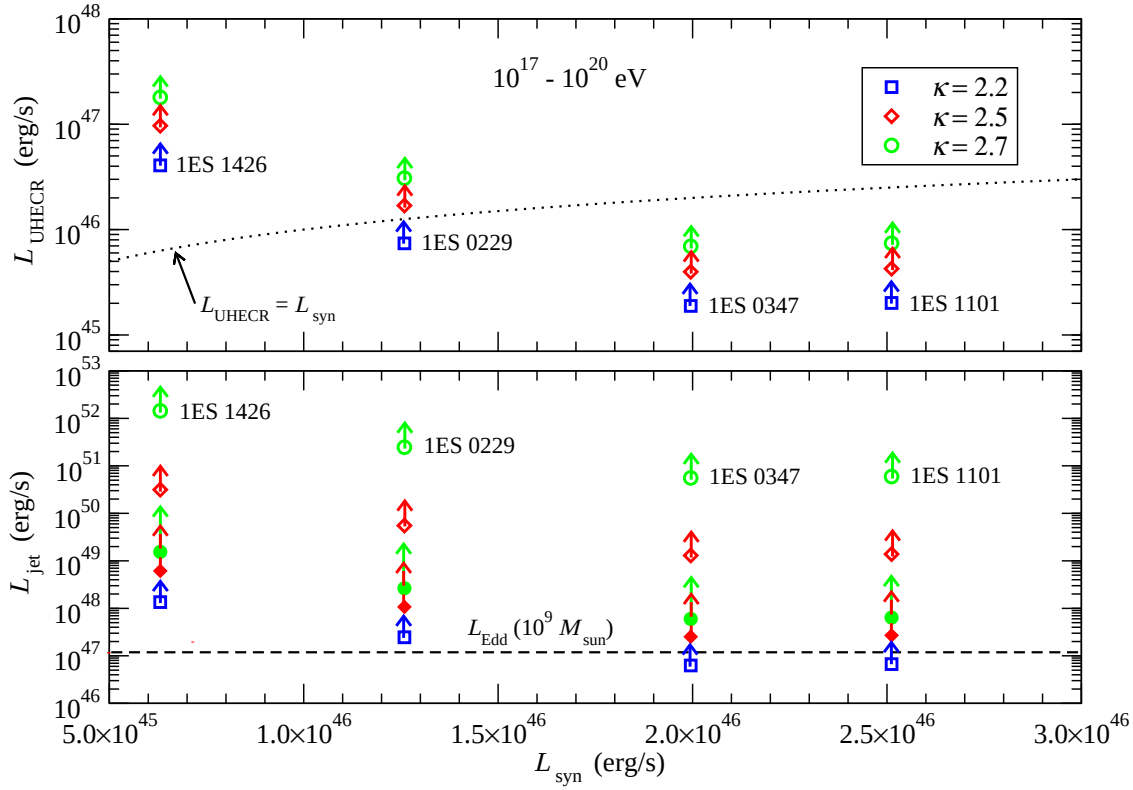
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL vs "high" EBL

Source	Redshift	EBL Model	L_p , erg/s	$L_{p,\mathrm{iso}}$, 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

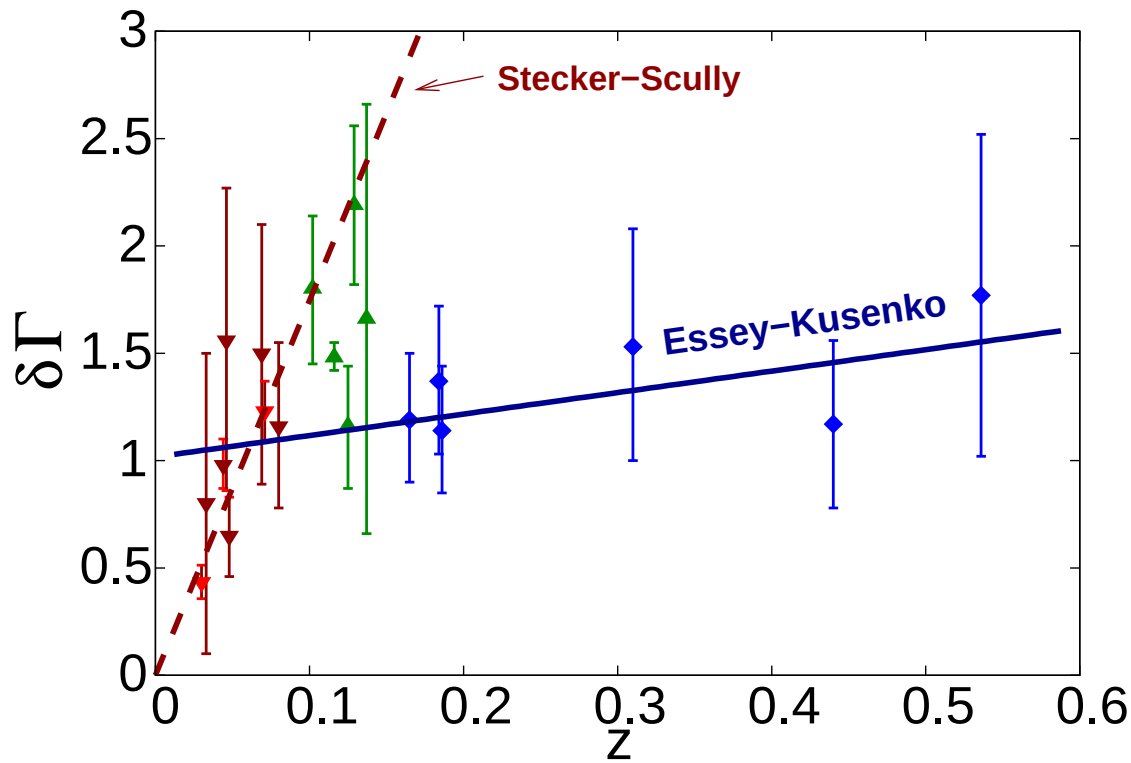
Here we have assumed $\theta_{jet} = 6^\circ$ (and $E_{\max} = 10^{11}$ GeV, $\alpha = 2$.)
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

Lower limits on UHECR and jet powers of TeV blazars



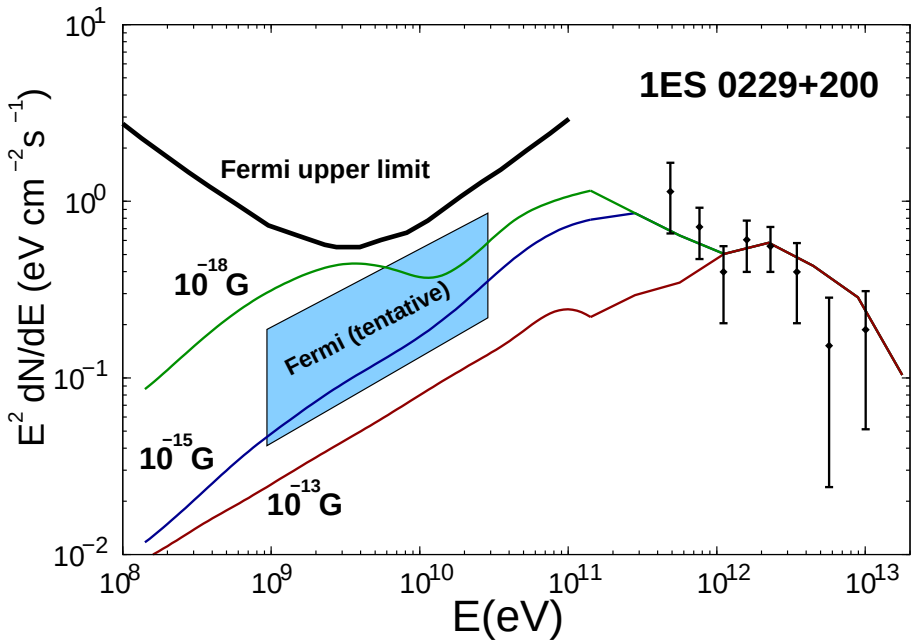
[Razzaque, Dermer, Finke, ApJ, 745, 196 (2012)]

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



$\delta\Gamma = \Gamma_{\rm GeV} - \Gamma_{\rm TeV}$ [Essey, AK]

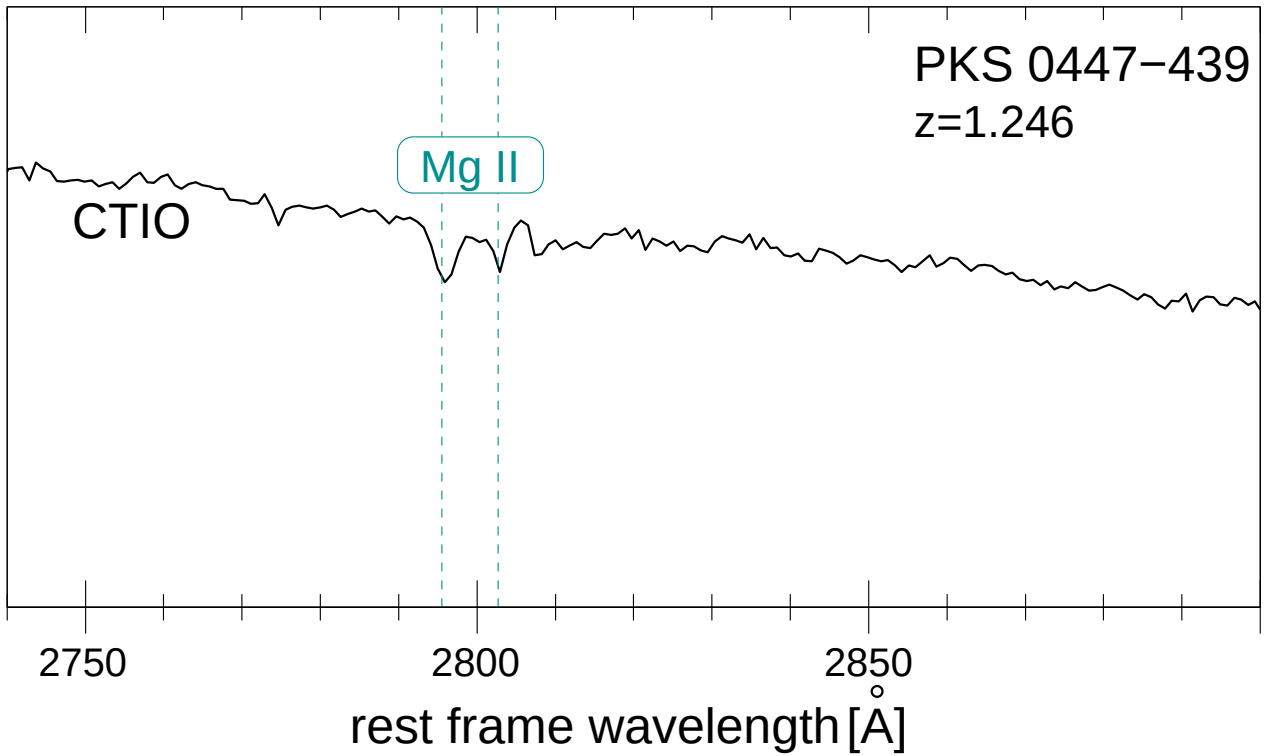
Spectra $\Rightarrow B \sim 10^{-15}$ Gauss



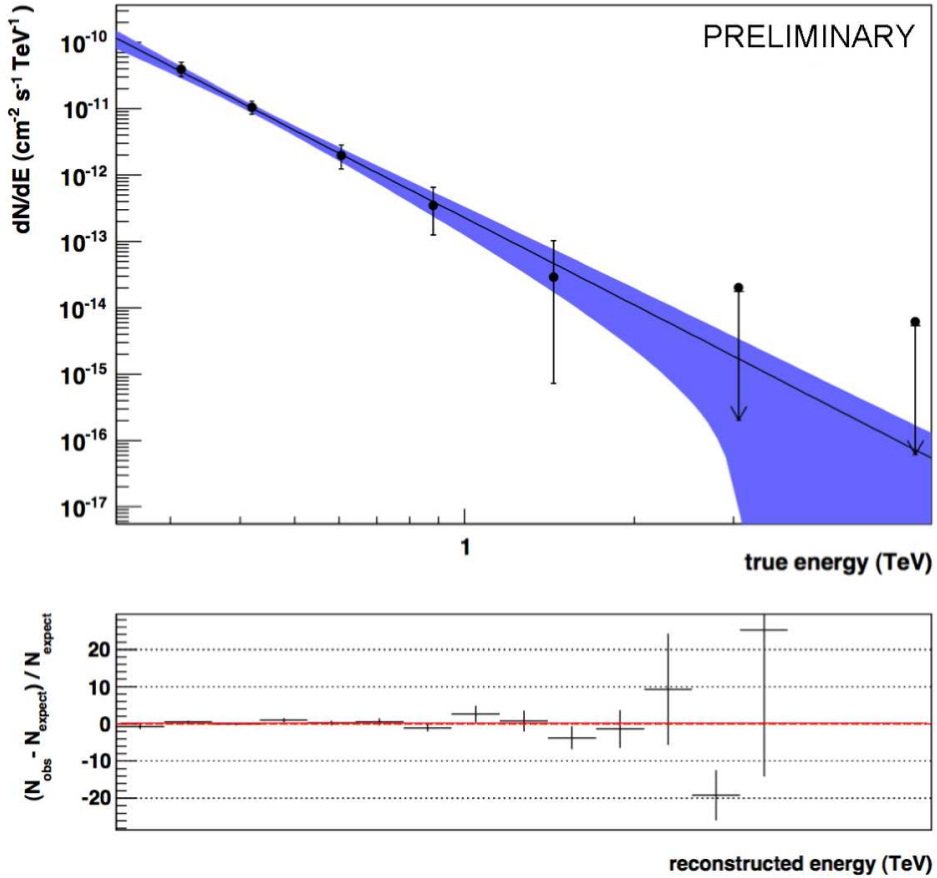
For line-of-sight interactions to explain the point sources, the IGMFs must be in the range:

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

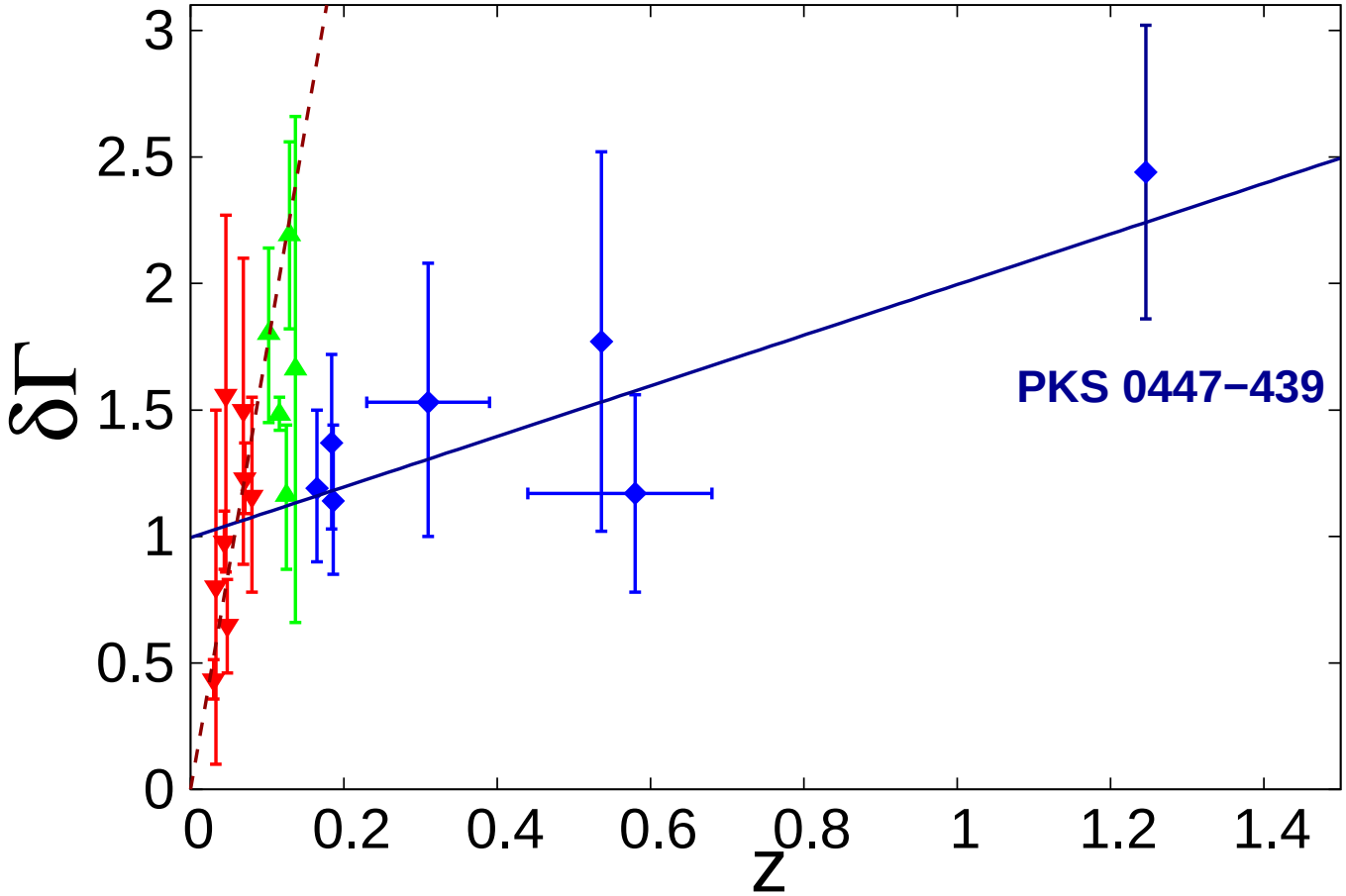
PKS 0447-439: $z \geq 1.248$



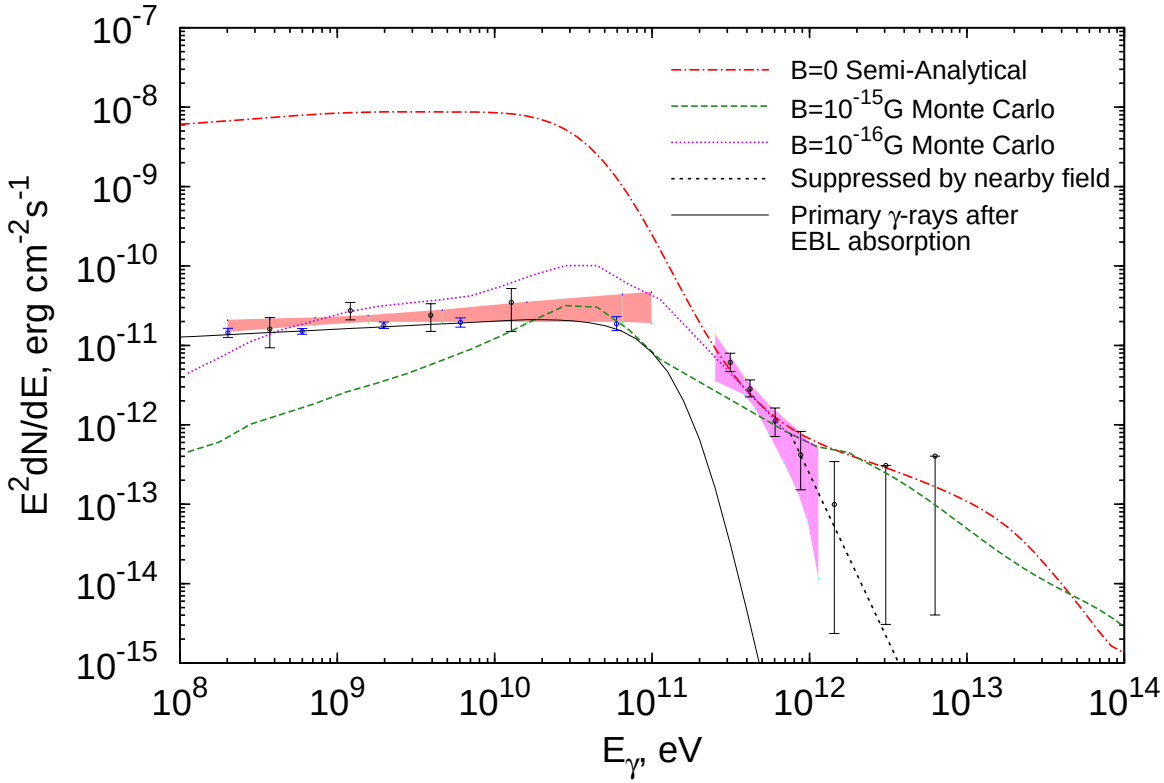
[Landt, MNRAS 423, L84 (2012)]



[Zech et al. (HESS collaboration), *PoS* TEXAS2010, 200 (2010)]


δΓ
z
PKS 0447−439
0
0.5
1
1.5
2
2.5
3
0
0.2
0.4
0.6
0.8
1
1.2
1.4

Secondary spectrum from a source at $z = 1.3$



Isotropic luminosity in protons: $L_{\rm p,iso} \sim 10^{50}{\rm erg/s}$.

For $\theta = 3^\circ$, $\boldsymbol{L_p \sim L_{\rm Edd}(M = 10^9 M_\odot)}$

[Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]

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.
- Spectra fit for both high and low EBL. Previously set limits hold only under the assumption of large IGMFs.
- Some exceptional sources can be seen in secondary gamma rays even from cosmological distances. PKS 0447-439 may be the first example, but more can be expected.
- IGMFs in the range $10^{-17} - 10^{-14}$ G are consistent with secondary interpretation (and with everything else)