Secondary TeV Gamma Rays from Distant Blazars, and EBL

- 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;

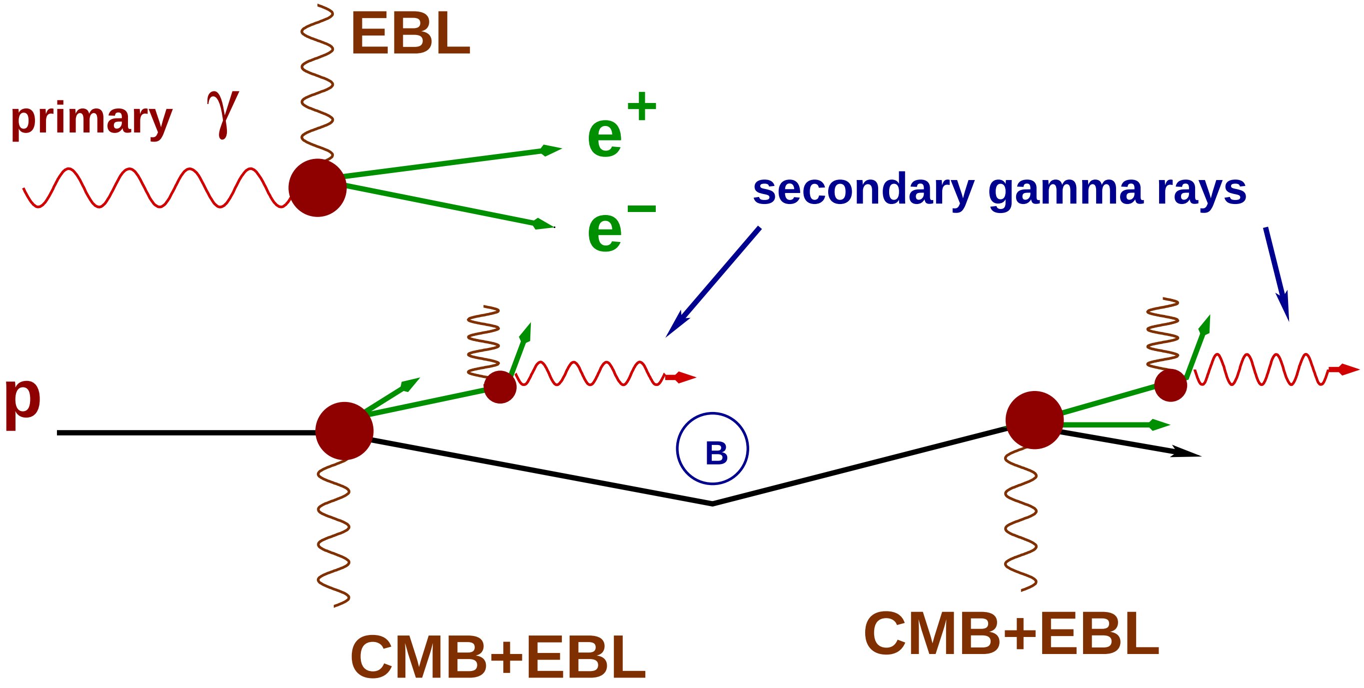
Phys. Rev. Lett. 104 (2010) 141102;

ApJ 731 (2011) 51;

ApJ Lett. 751 (2012) L11; ApJ 757 (2012) 183 ; PR D 87, 063002 (2013)

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

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
$\boldsymbol{p\gamma \rightarrow pe^+e^-,\ p\gamma \rightarrow p\pi^0}$: 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

$$
\begin{aligned}
F_{\mathrm{primary},\gamma}(d) &\propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} && (1)\\
F_{\mathrm{secondary},\gamma}(d) &= \frac{p\lambda_\gamma}{4\pi d^2}\left[1-e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} && (2)\\
F_{\mathrm{secondary},\nu}(d) &\propto (F_{\mathrm{protons}} \times d) \propto \frac{1}{d}. && (3)
\end{aligned}
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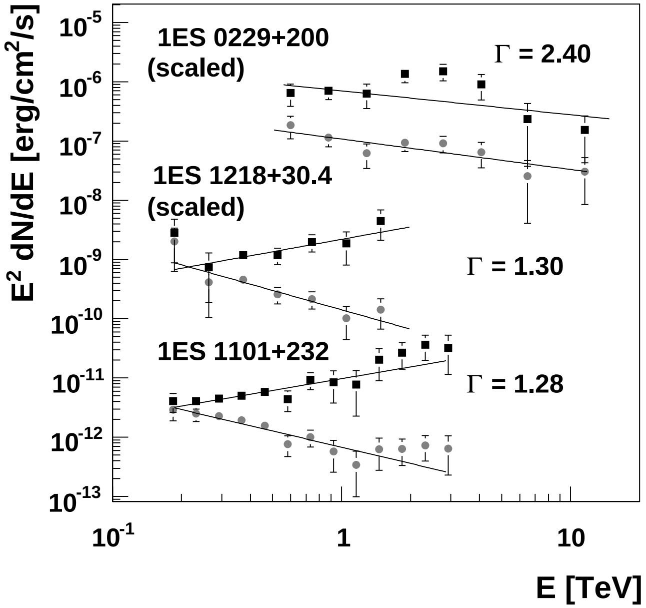
$$

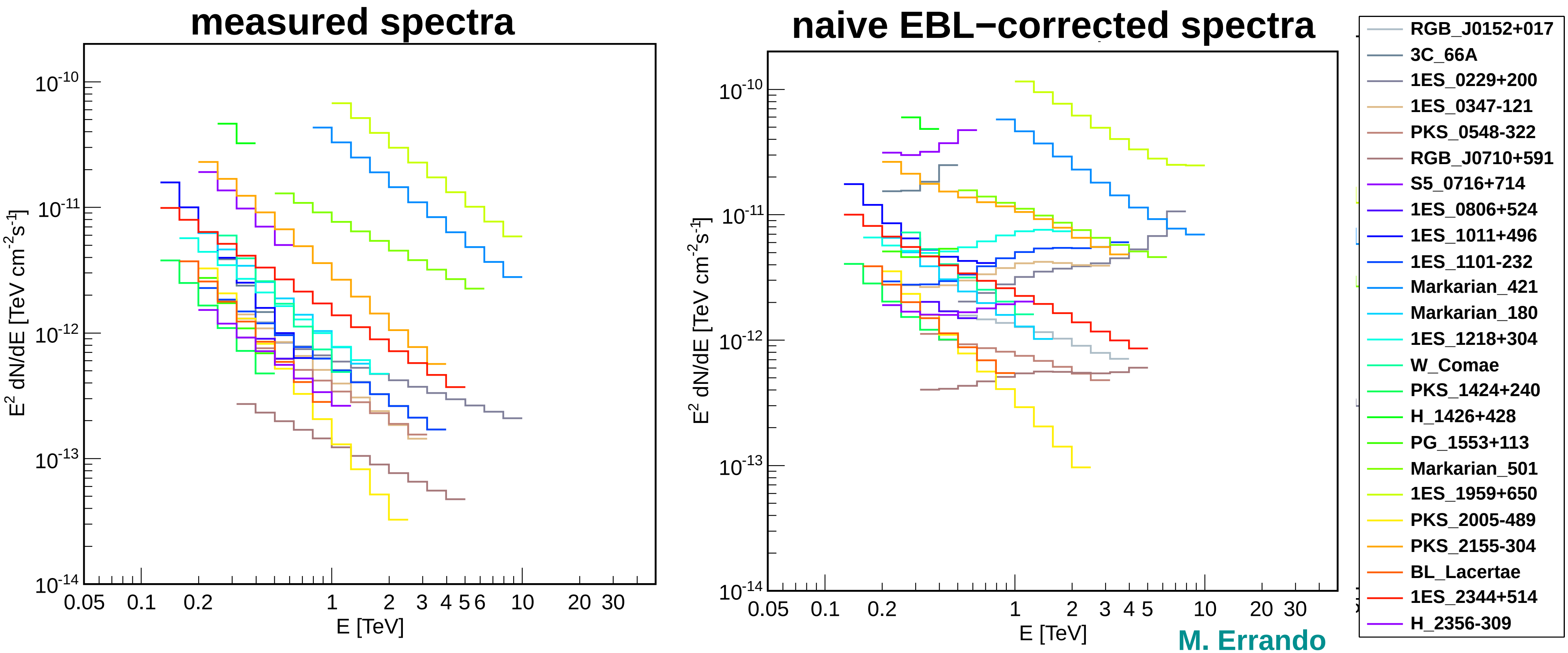
For distant sources, secondary signals win

Distant blazars have hard spectra



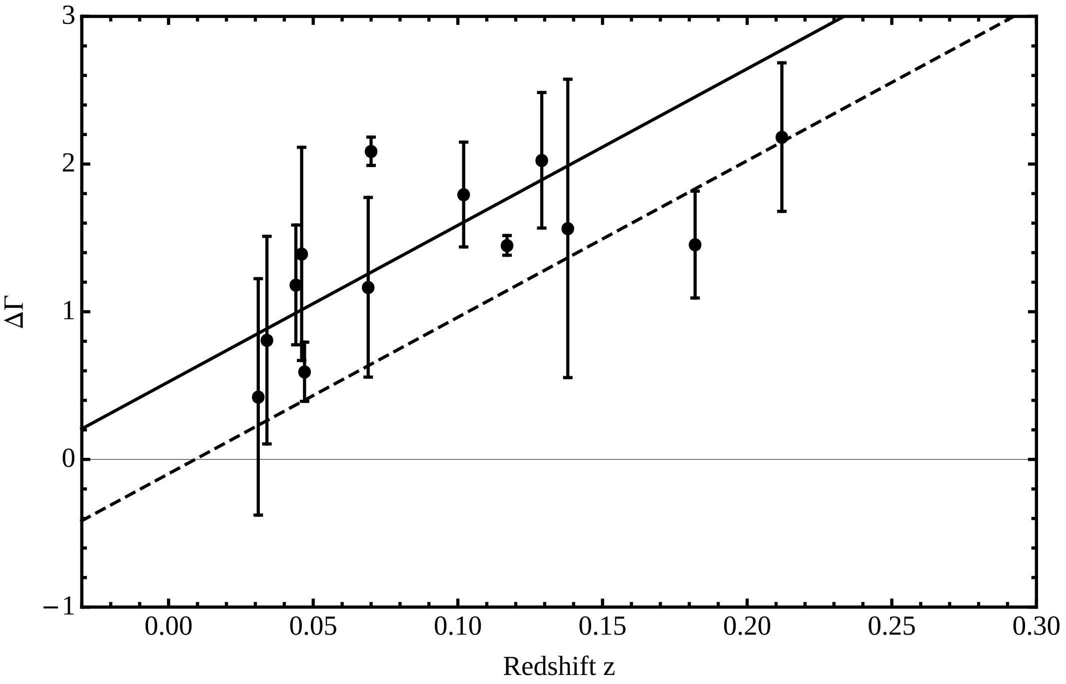
Absorption-corrected spectra are extremely hard, $\Gamma < 1.5$, for distant blazars. [Aharonian et al.]

Blazar spectra



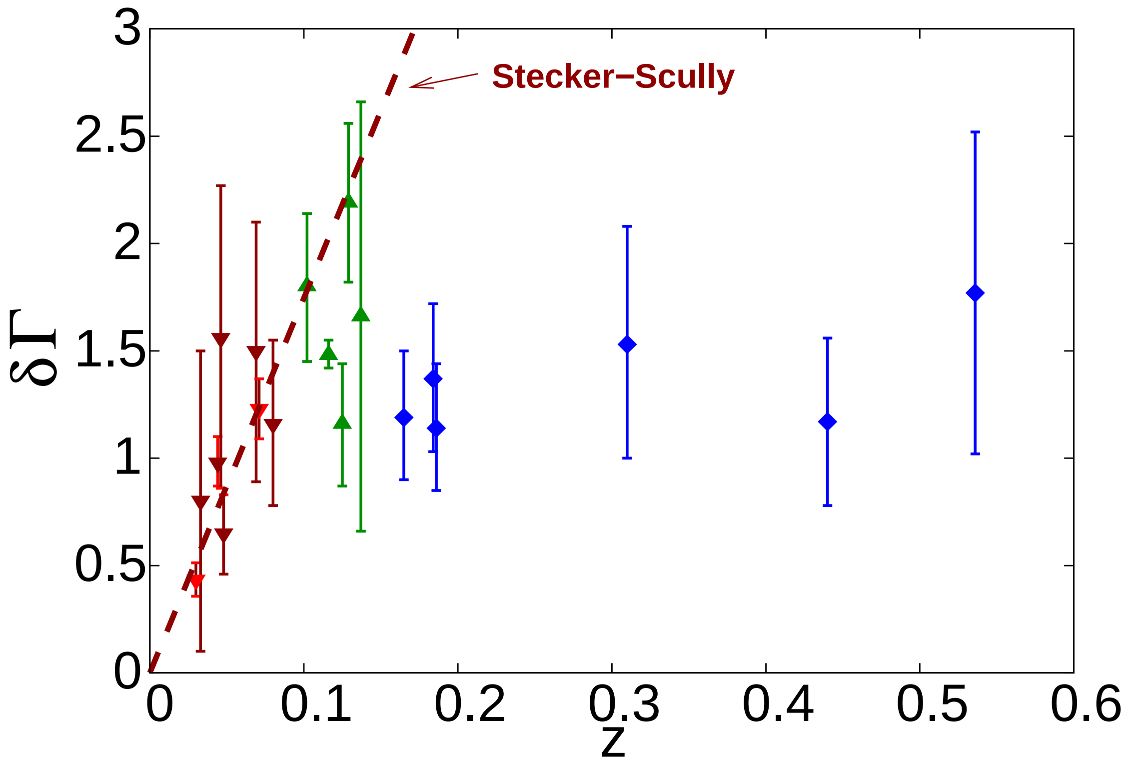
M. Errando

Softening of the spectrum as a function of the redshift



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

Distant blazars are different:



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

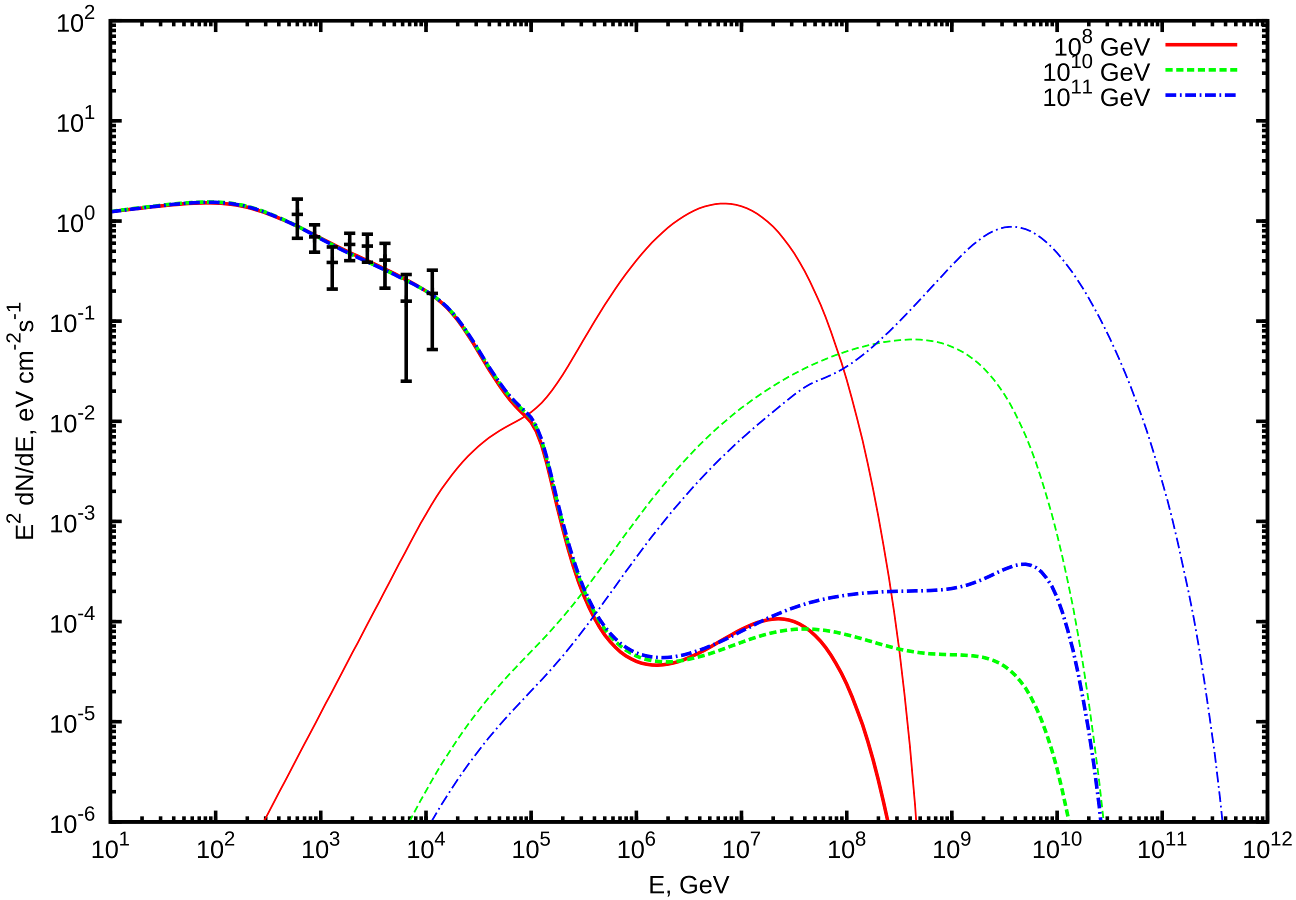
Proposed “new physics” solutions:

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.]

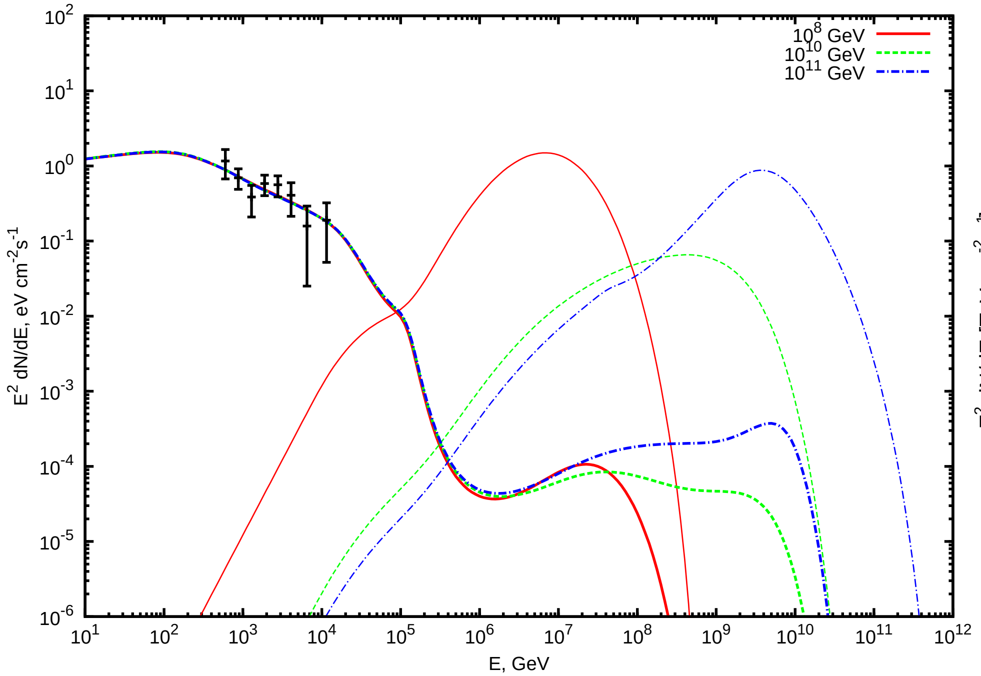
Is there a more conventional explanation?

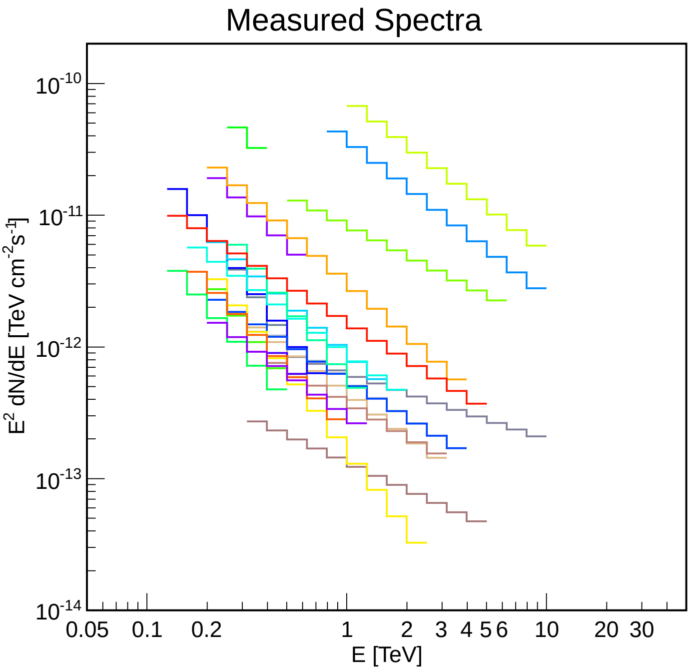
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



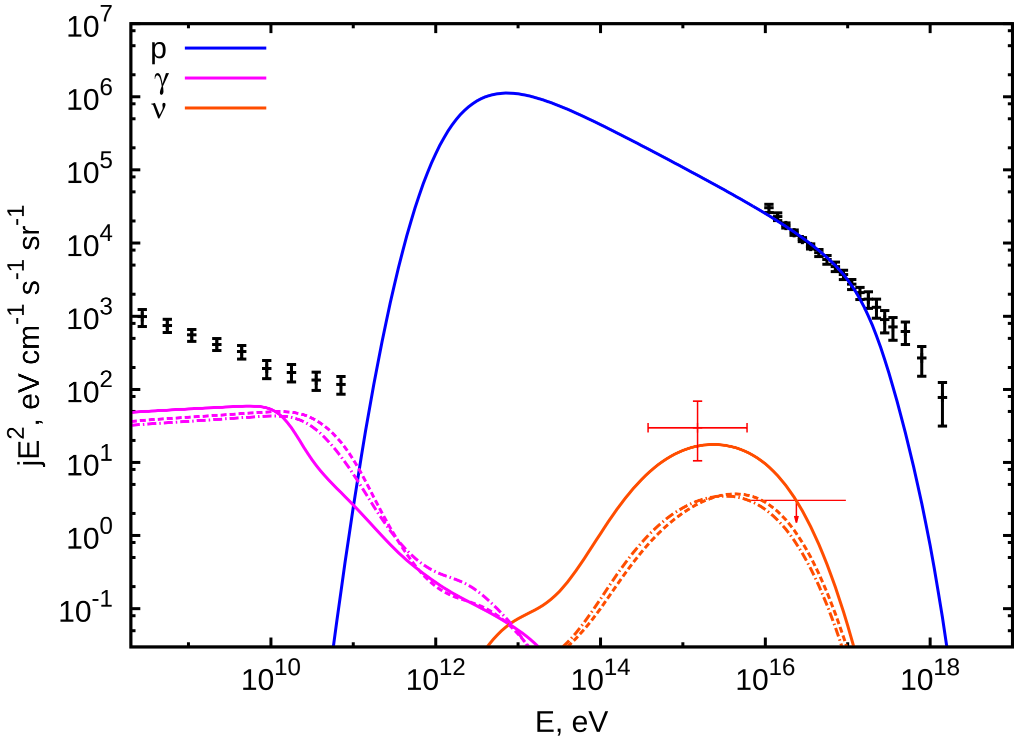
[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]

Robust spectral shapes explain the observed universality





Neutrinos discovered by IceCube consistent with secondary spectrum



EBL models

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

Models considered:

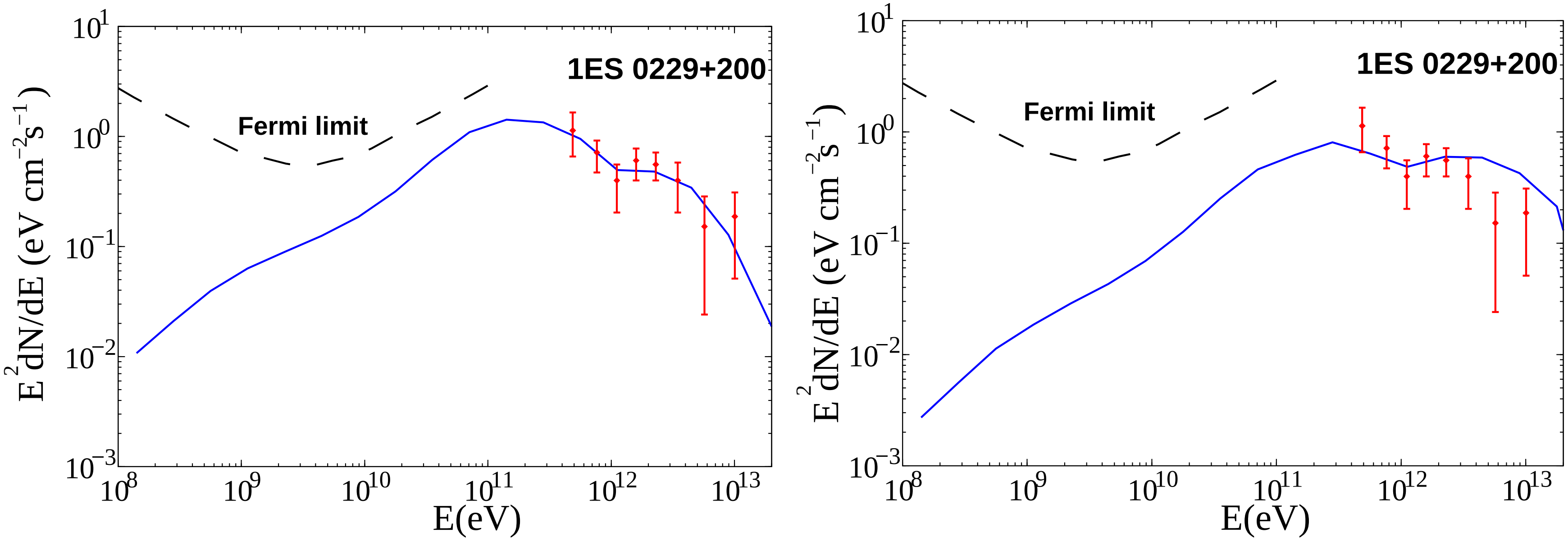
"High" EBL: Stecker et al. (2006) ApJ, 648, 774

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.

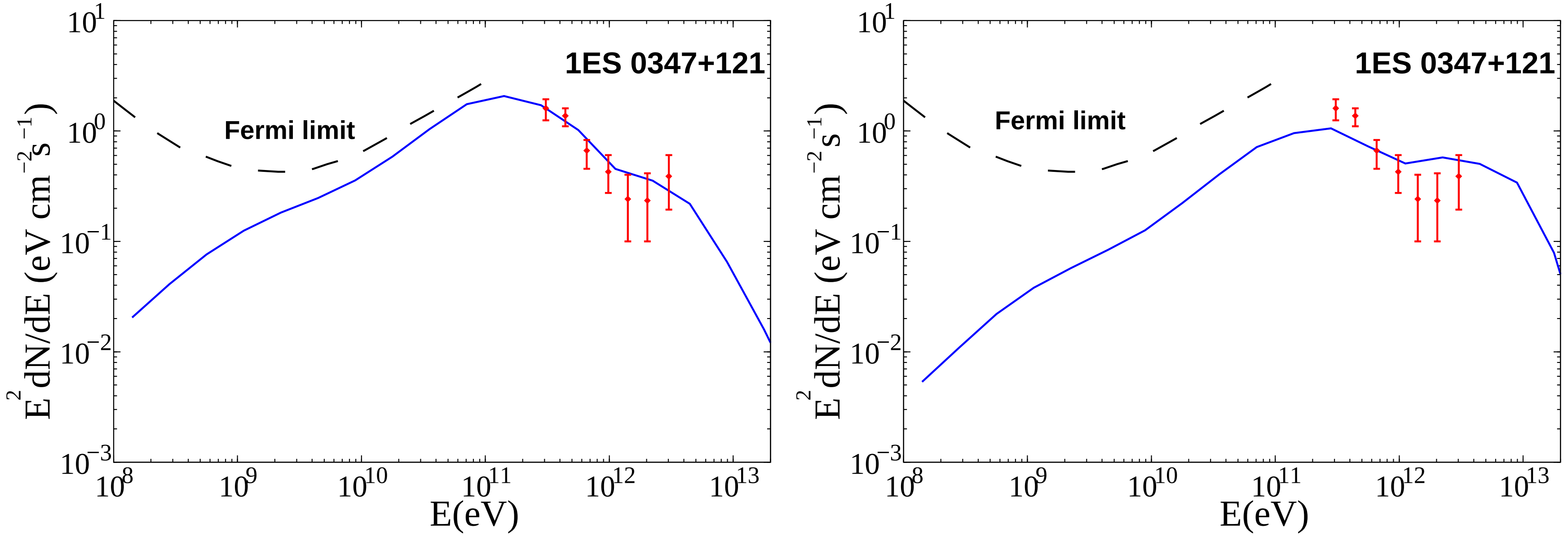
“Low“ EBL (left), ”high“ EBL (right)



Both fit the data.

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

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



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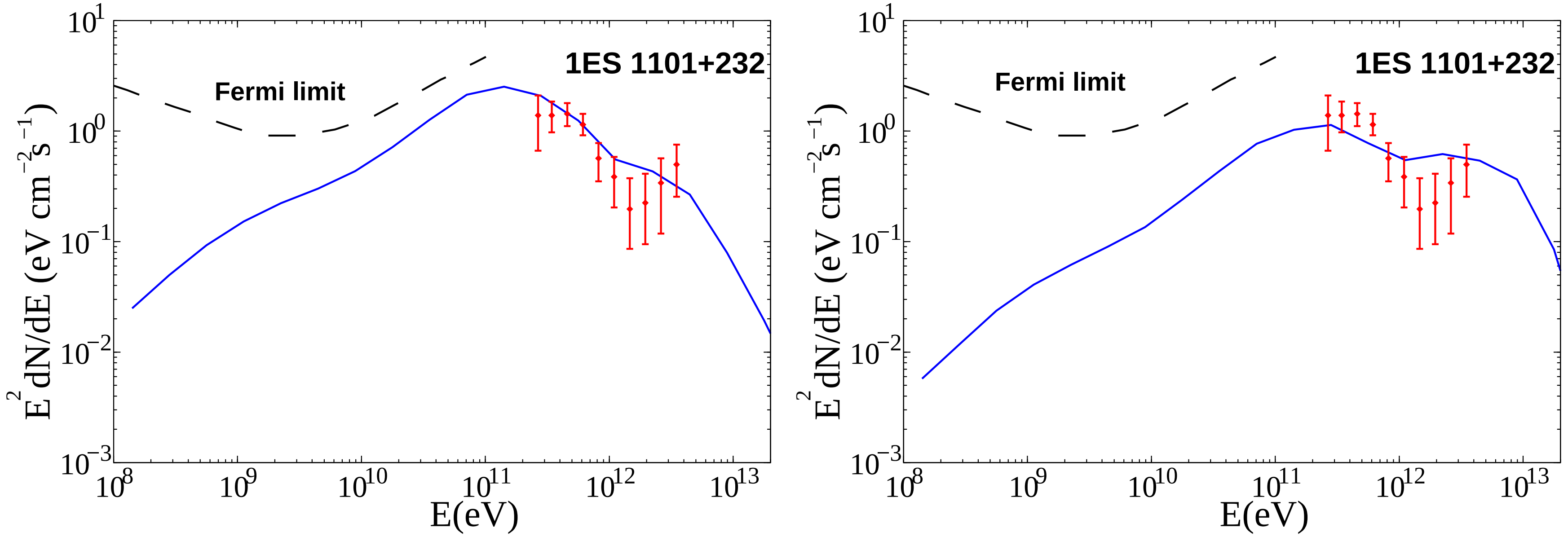


Both fit the data.

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

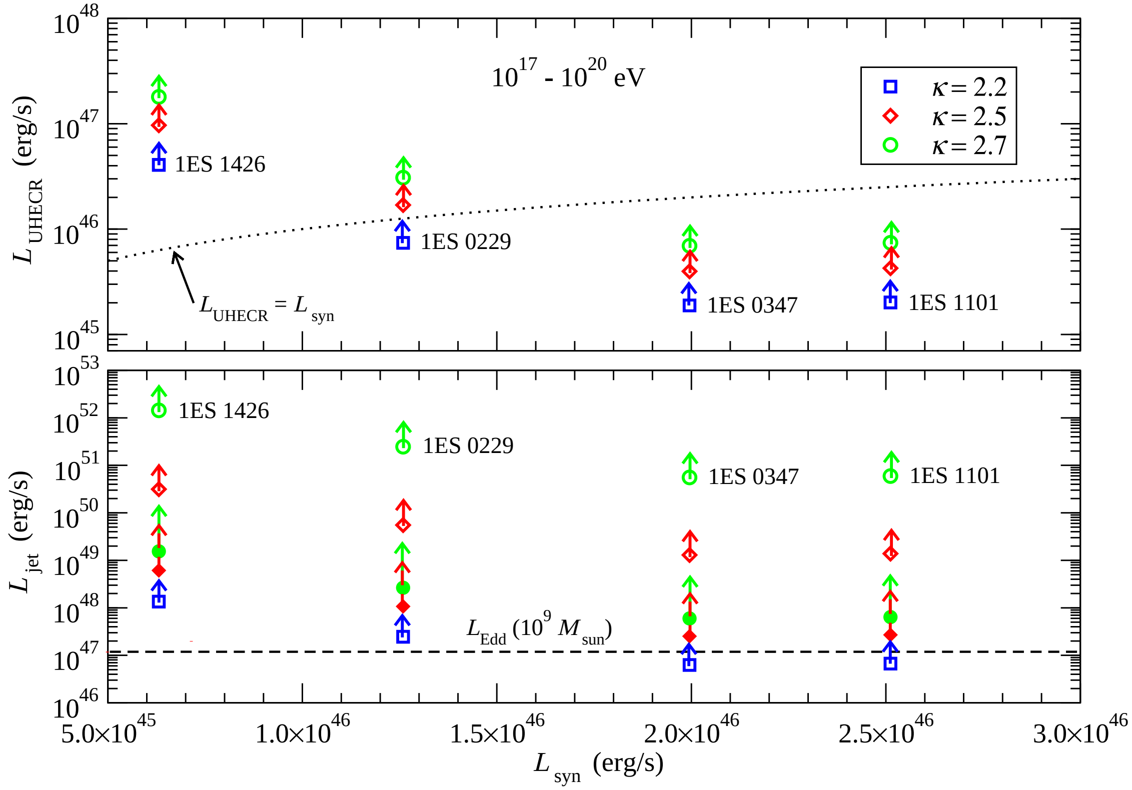
“Low“ EBL vs ”high“ EBL

Source	Redshift	EBL Model	L_p , erg/s	$L_{p,\mathrm{iso}}$, 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, $\alpha = 2.$)

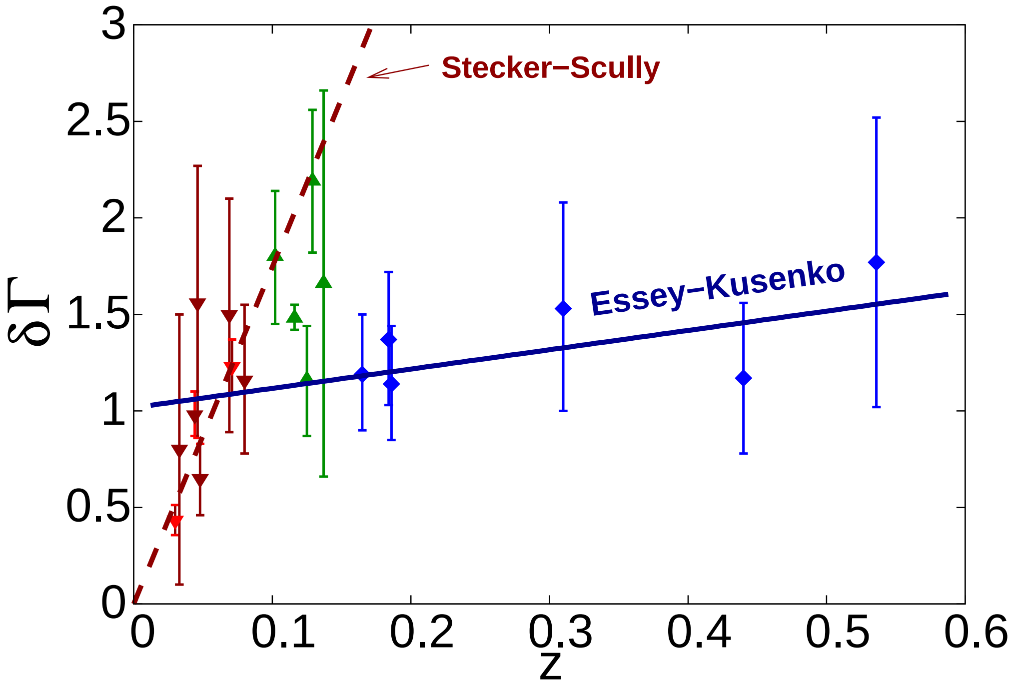
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

Lower limits on UHECR and jet powers of TeV blazars



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

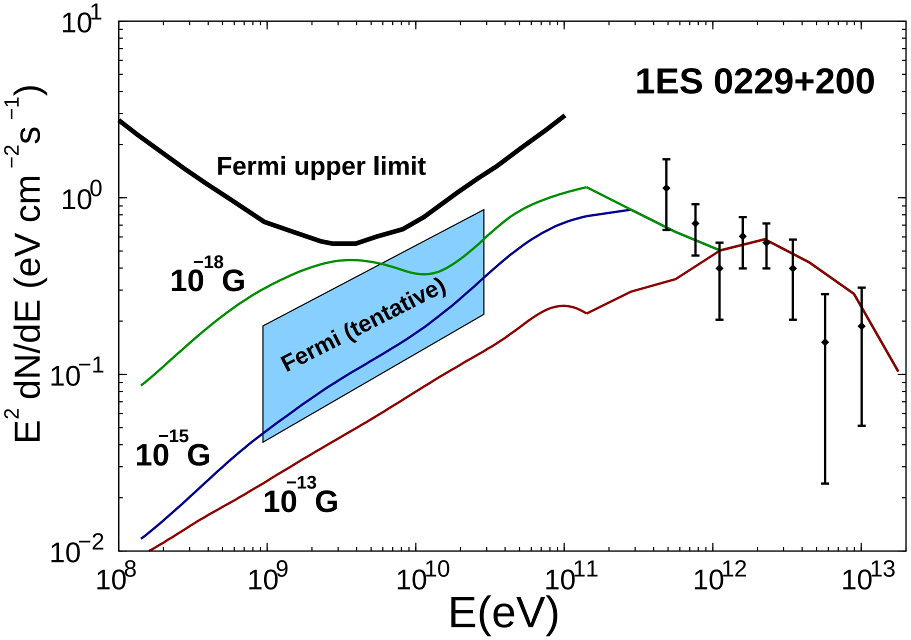
Softening of the spectrum reflects the transition from primary to secondary gamma rays



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

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

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



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

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

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.
- IGMFs in the range $10^{-17} - 10^{-14}$ G are consistent with secondary interpretation (and with everything else), opening a window for a broad range of EBL models.