Secondary TeV gamma rays from distant blazars, and a new measurement of extragalactic background light

- Secondary gamma rays from line-of-sight interactions of cosmic rays produced in blazars:
  - spectra robust, show remarkable agreement with data
  - a broad range of EBL models agree with the data
- Extragalactic magnetic fields, time variability, etc.

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

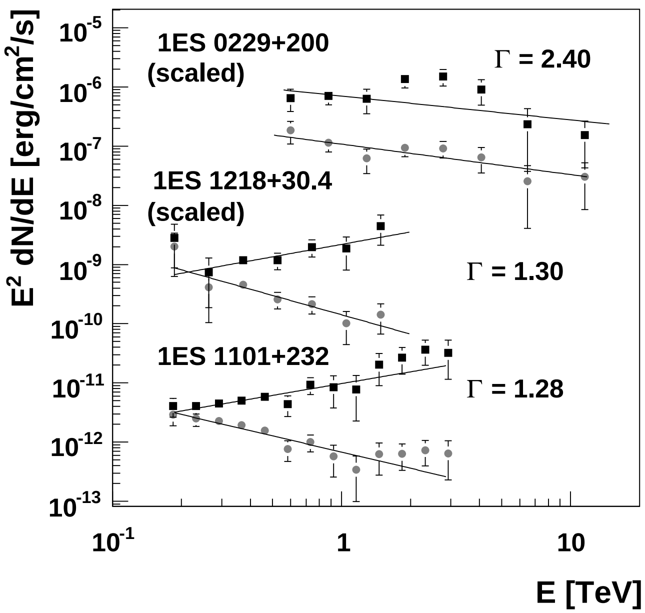
Astropart.Phys. 33 (2010) 81, *ibid.* 35 (2011) 135;

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

ApJ 731 (2011) 51; ApJ Lett. 751 (2012) L11; arXiv:1203.3787

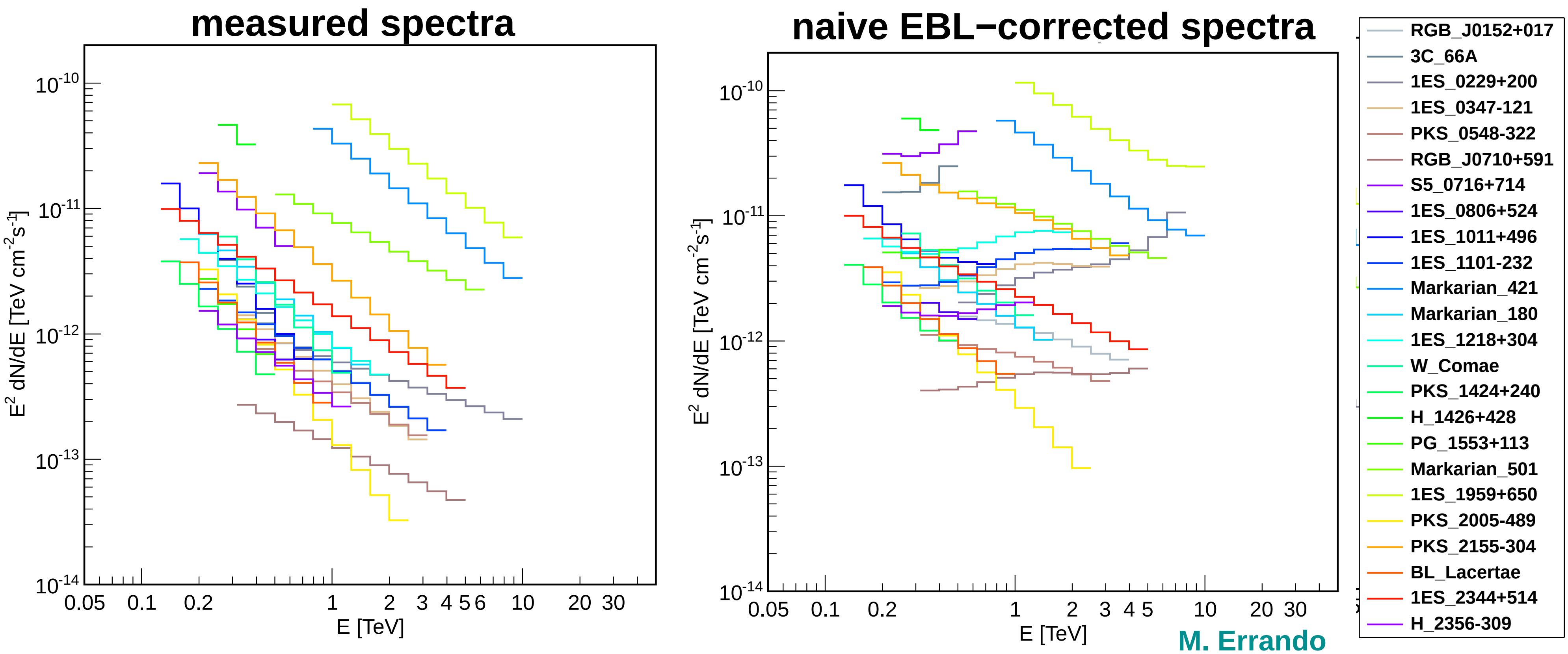
see also related work by **Dermer, Finke, Migliori, Murase, Razzaque, Takami**

Even the lowest possible level of EBL requires extremely hard spectra

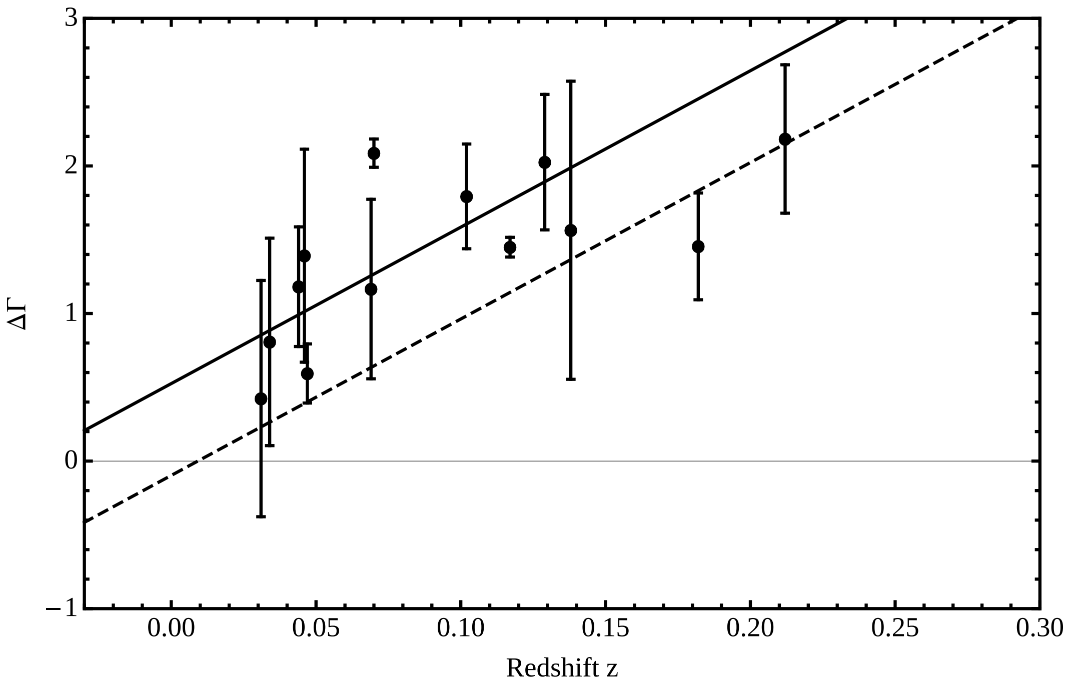


- Models predict $dN/dE \propto E^{-\Gamma}$, where $\Gamma \geq 1.5$ [Aharonian, 2006; Malkov & Drury, 2001].
- Synchrotron-Self-Compton (SSC) in Klein-Nishina regime forces $\Gamma \geq 1.5$ [Böttcher et al, 2008]
- absorption-corrected spectra are extremely hard, $\Gamma < 1.5$, for distant blazars

Cosmic conspiracy



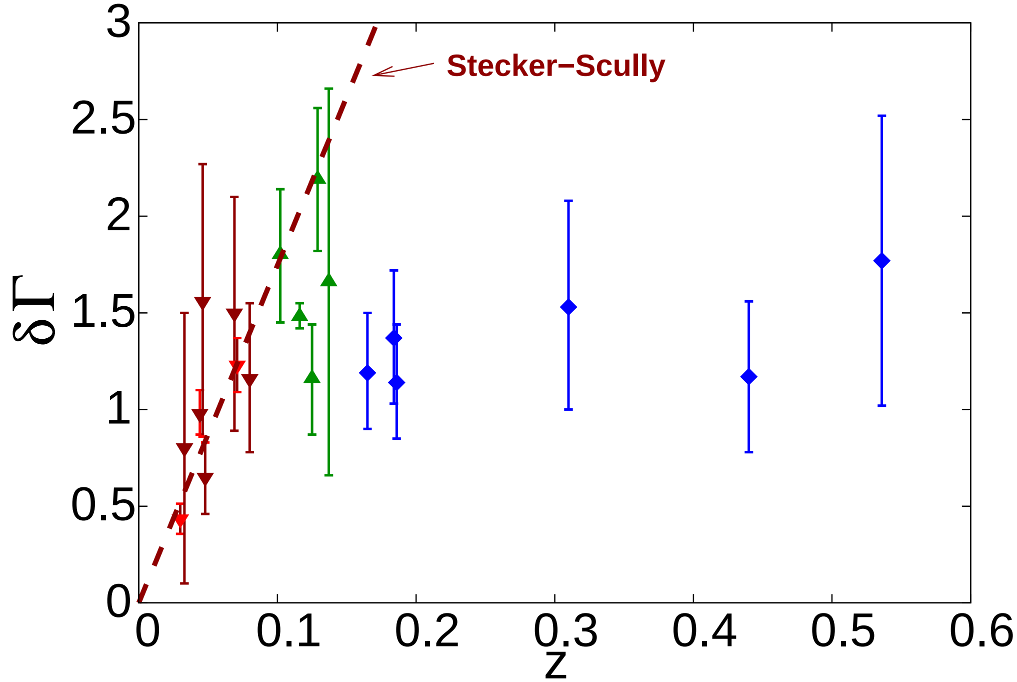
Softening of the spectrum should scale with the redshift



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

Softening of the spectrum should scale with the redshift

but something goes wrong for distant blazars



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

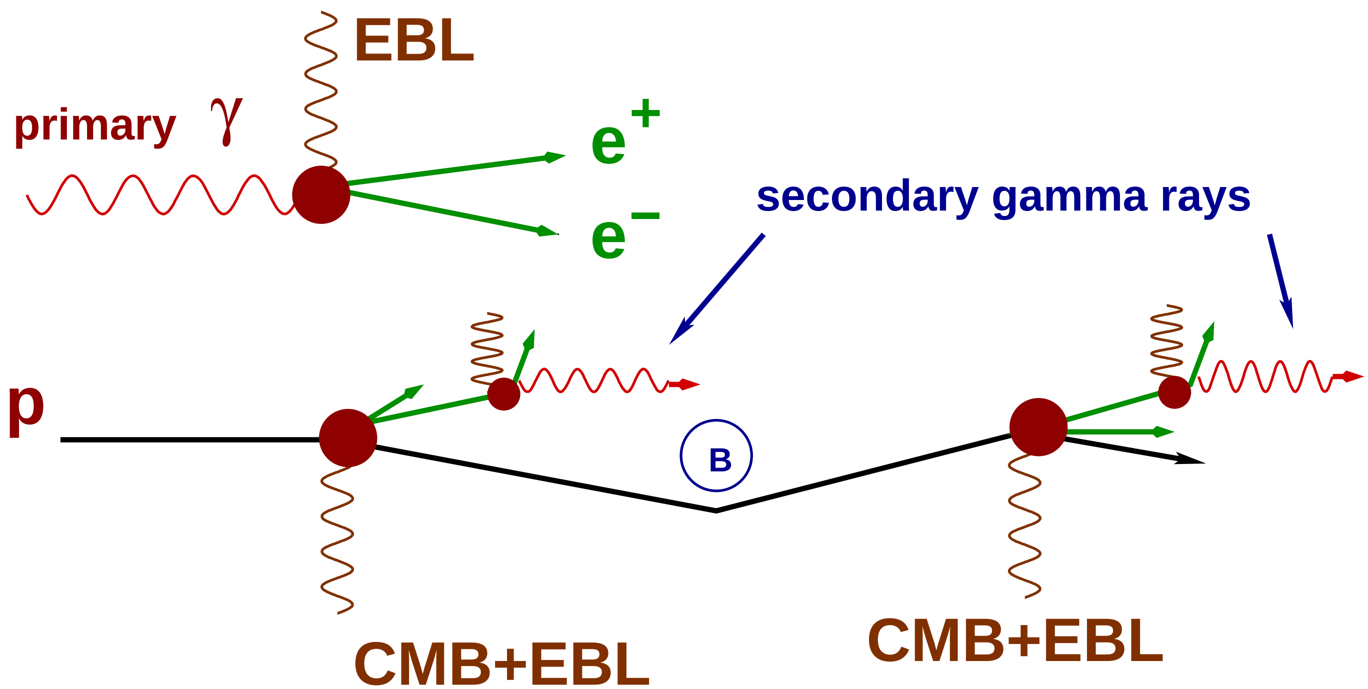
Proposed "new physics" solutions:

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
[talk by Kohri]
- ***Lorentz invariance violation*** for high-velocity particles may prevent pair production
[Protheroe et al.]

Is there a more conventional explanation?

AGN produce both UHECR and gamma rays



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?

Unusual 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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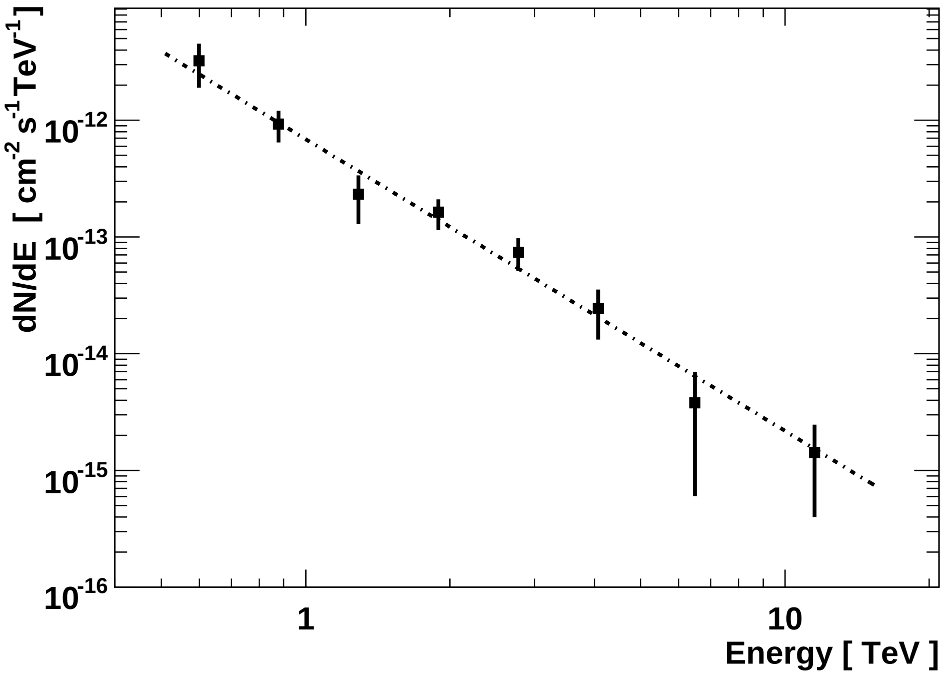
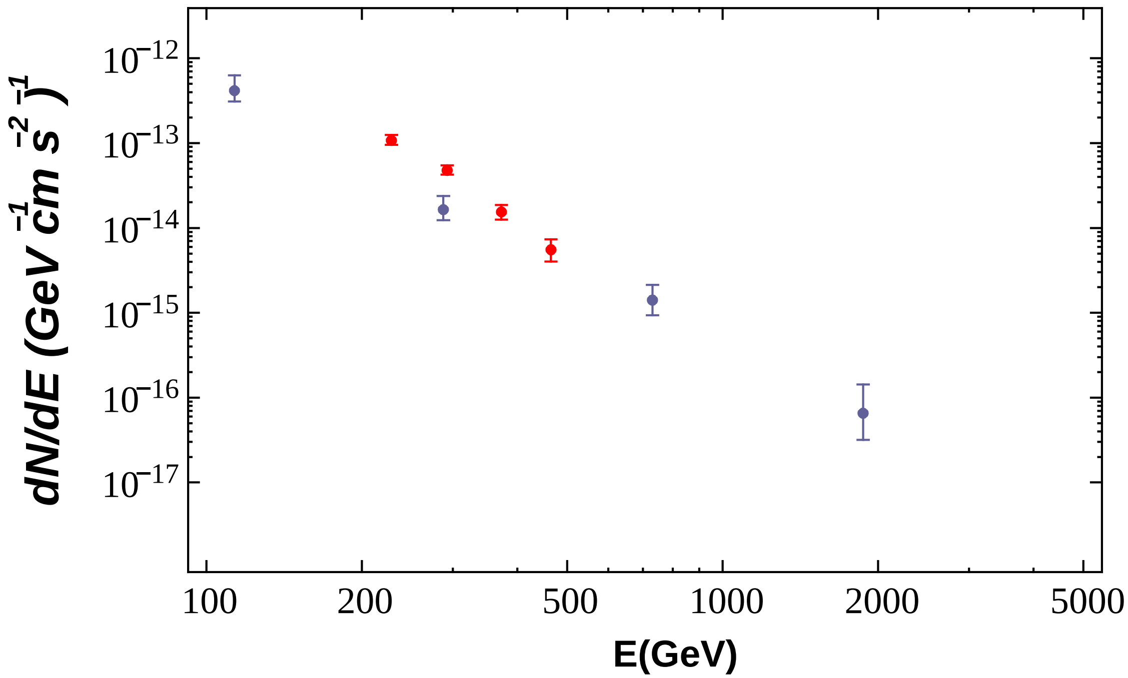
Gamma-ray observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)

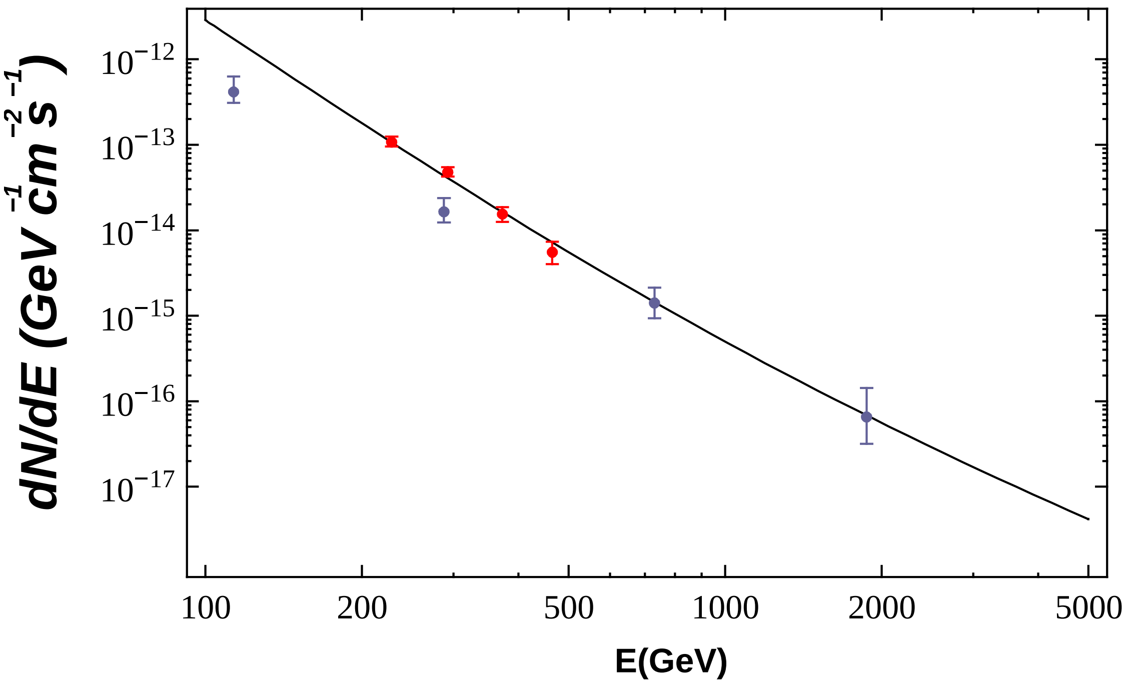




HESS (black), MAGIC (blue) and VERITAS (red) data points

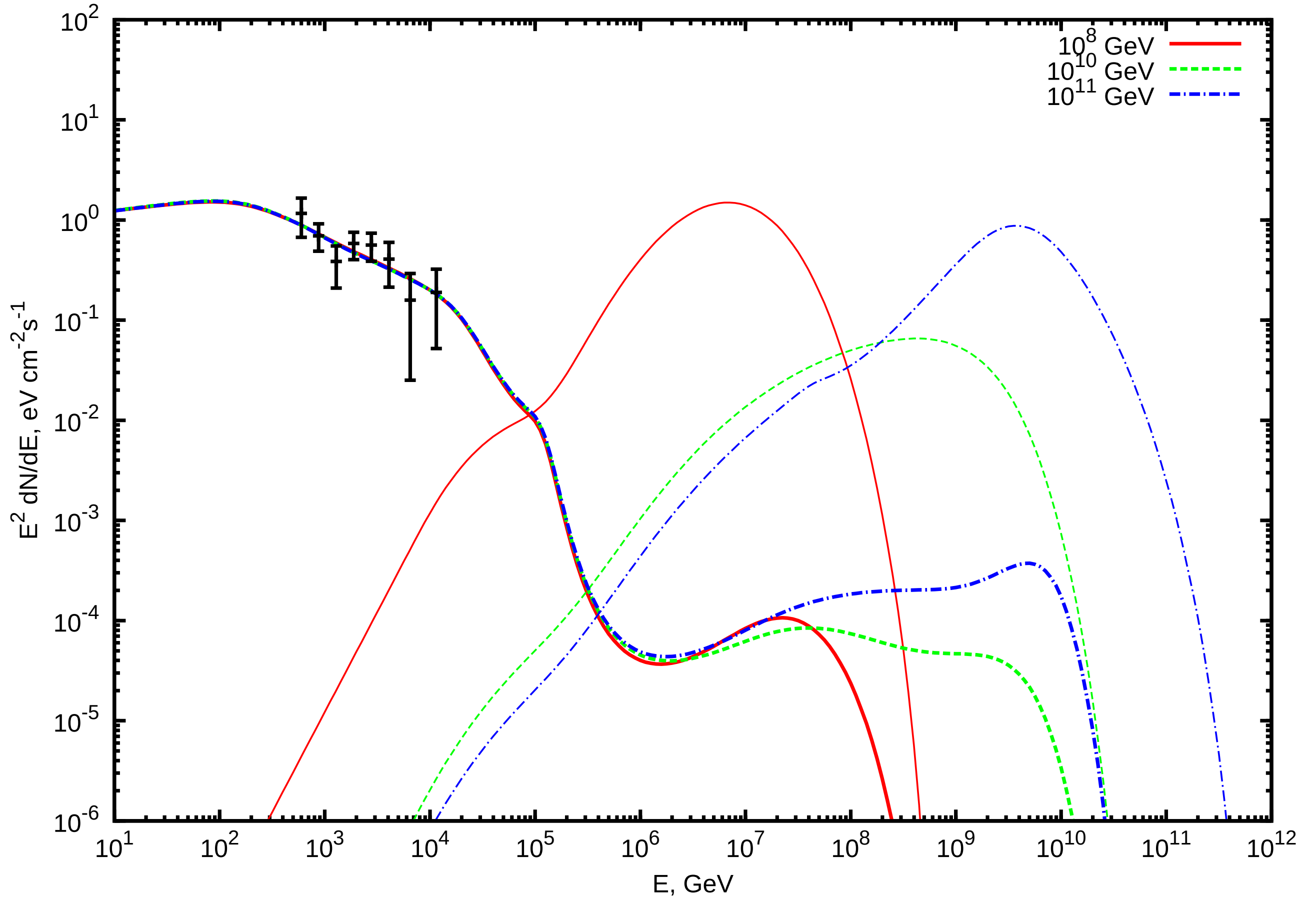
A one parameter fit, 3C66A

(parameter = power emitted in CR, subject to constraints)



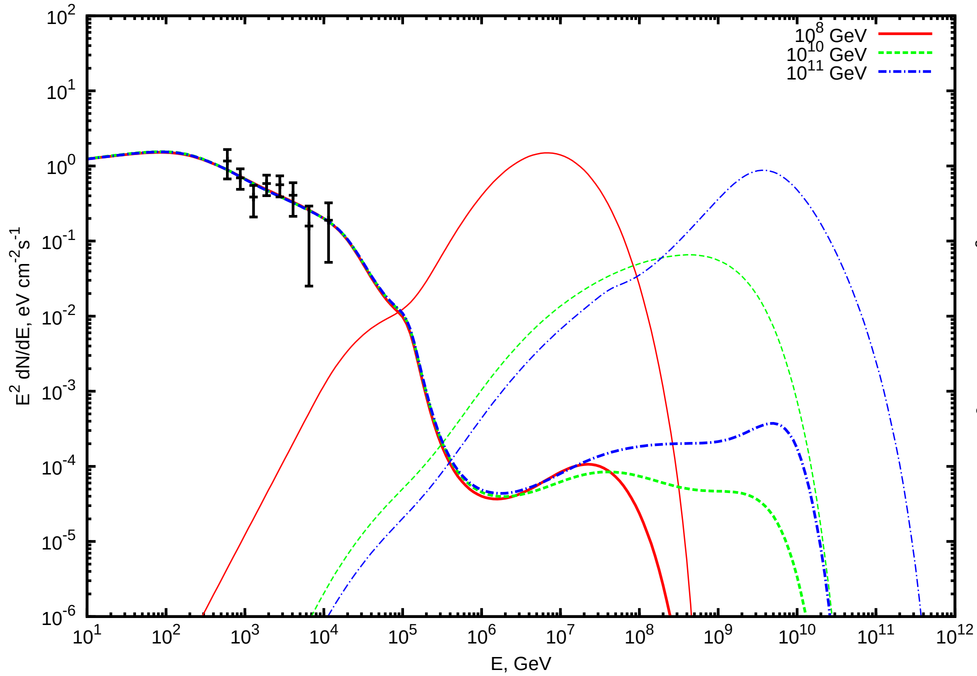
[Essey, AK, Astropart Phys. 33, 81 (2010)]

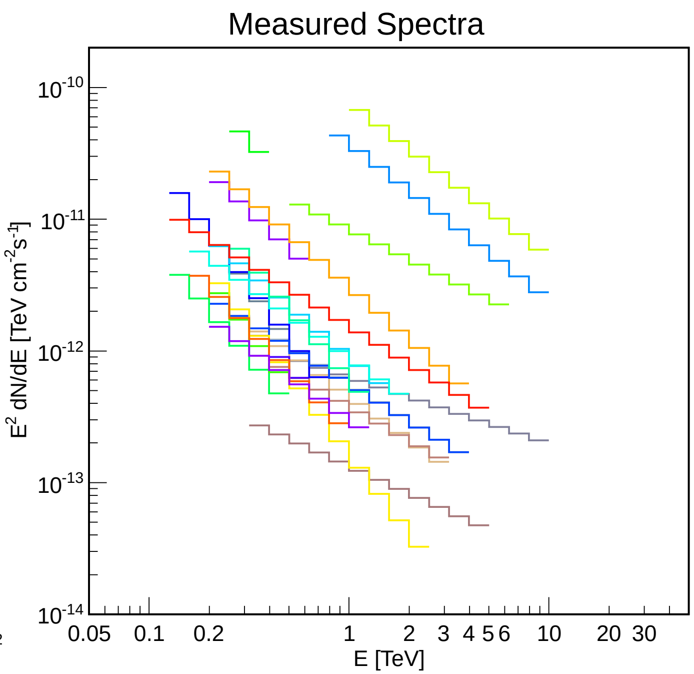
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



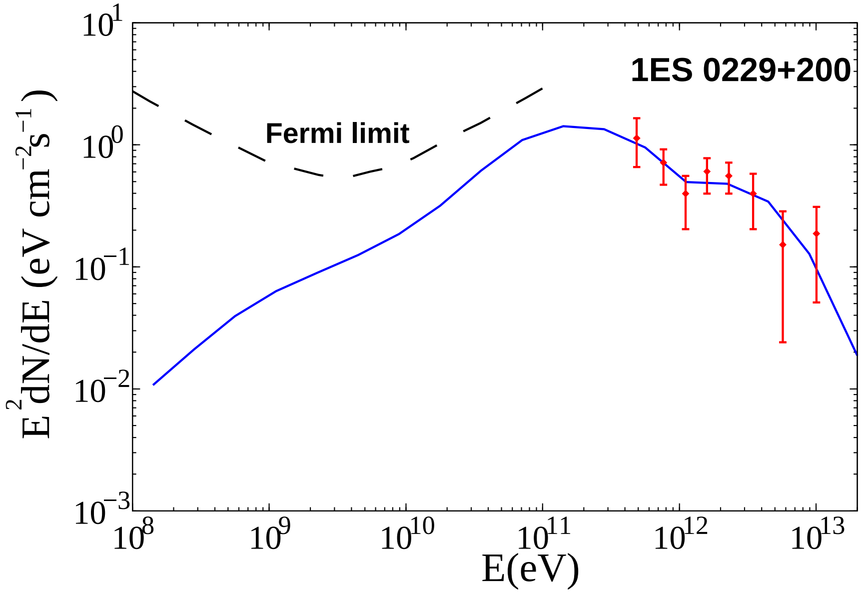
[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]

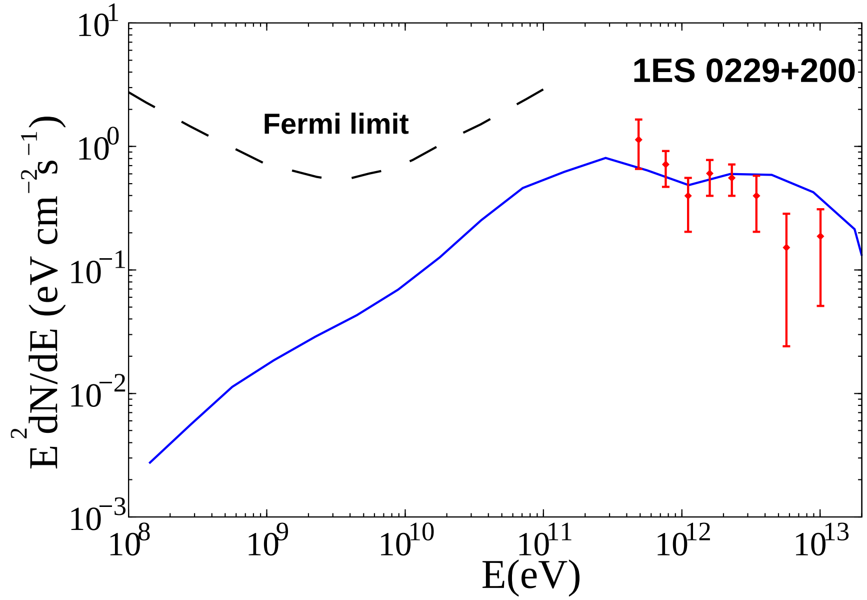
Cosmic conspiracy resolved: robust spectral shapes





“Low“ EBL (left), ”high“ EBL (right)





Both fit the data.

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

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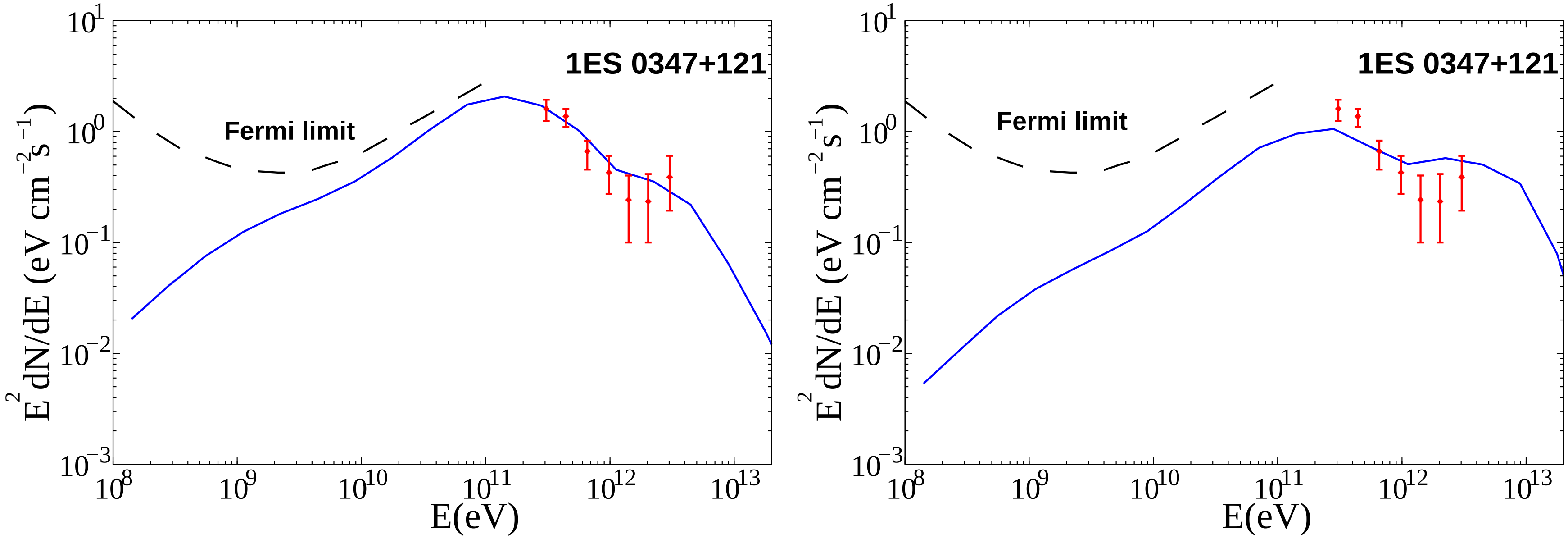

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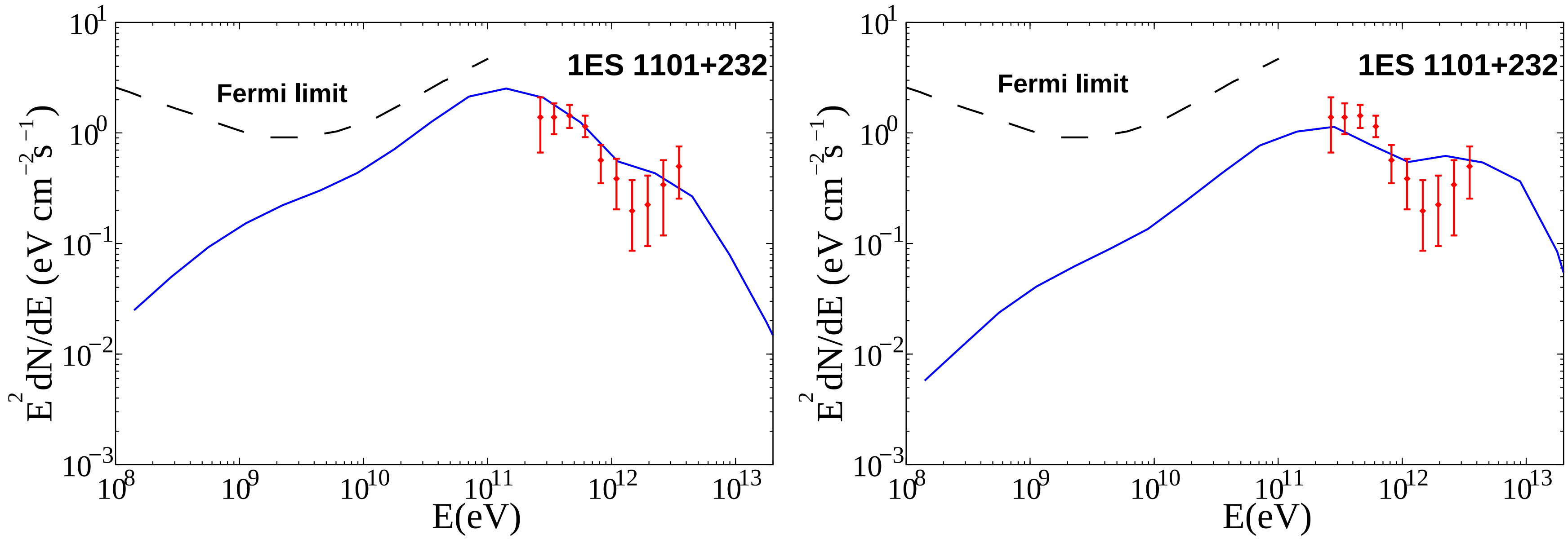

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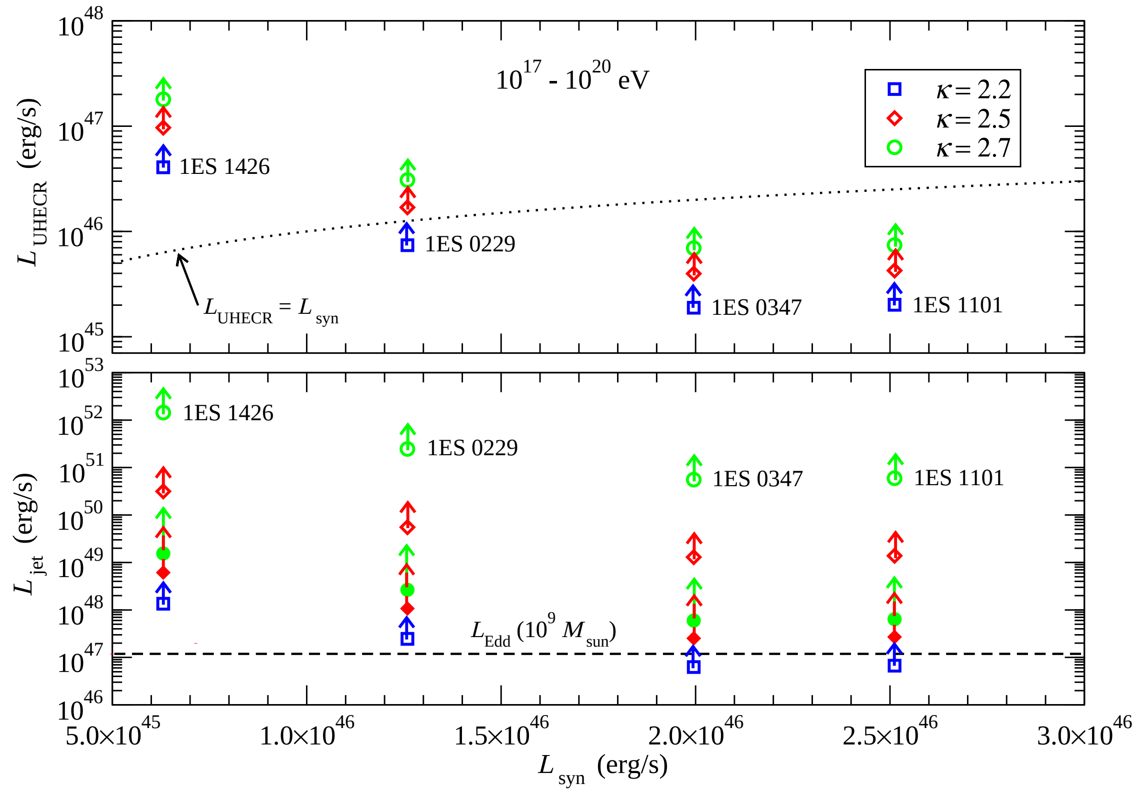
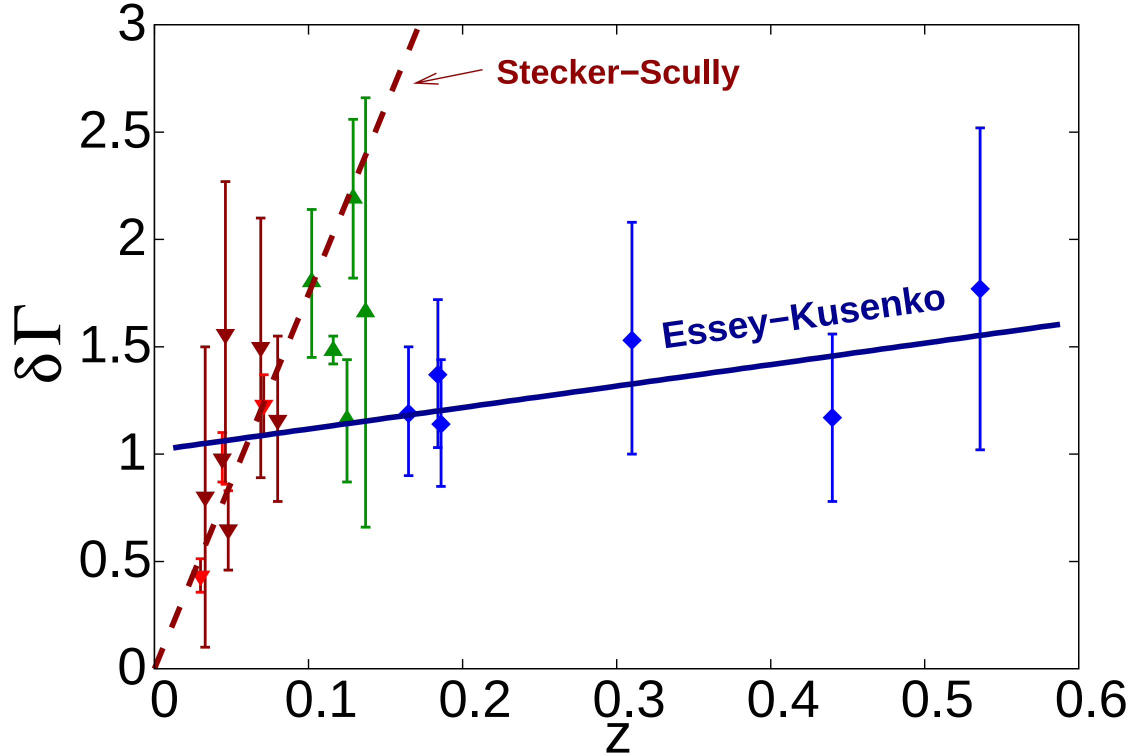
Lower limits on UHECR and jet powers of TeV blazars



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

Spectral change reflects the transition from primary to secondary gamma rays



$\delta\Gamma = \Gamma_{\mathrm{GeV}} - \Gamma_{\mathrm{TeV}}$ **[Essey, AK, ApJ Letter, 751, L11 (2012)]**

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, arXiv:1203.3787]**

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.

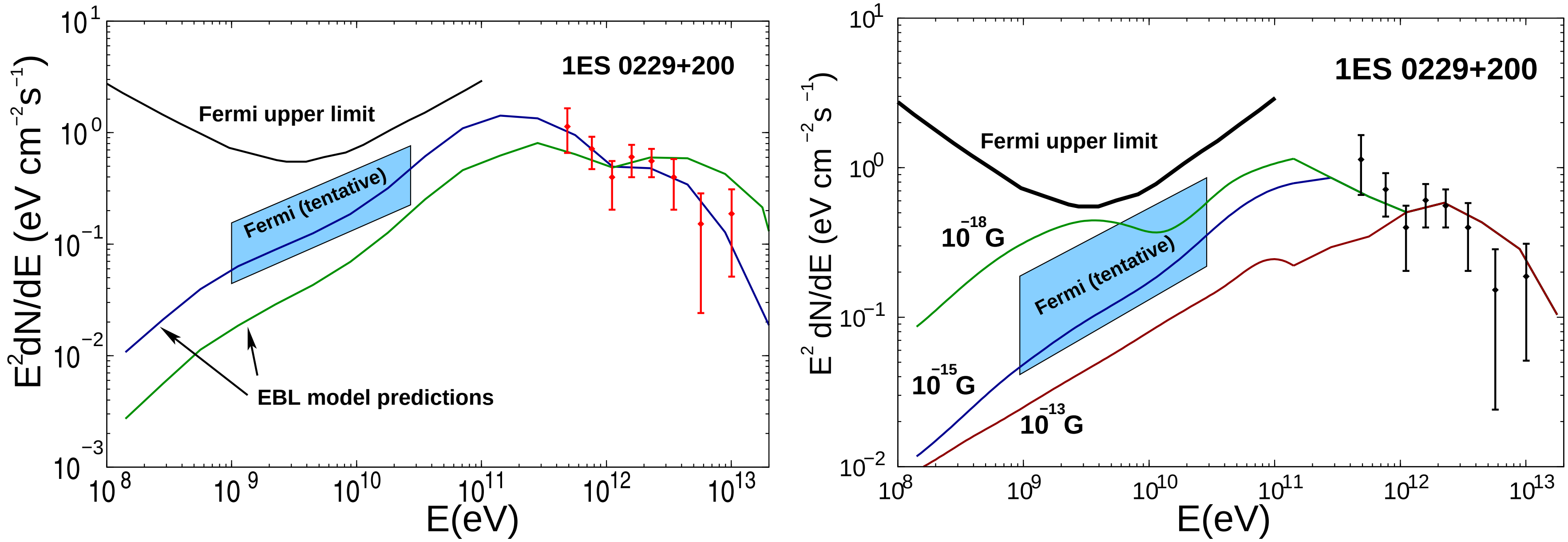
The range between "high" and "low" encompasses all models.

“Low“ EBL 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]

EGMFs: spectra imply *femtogauss fields*



Left: EBL models. Right: Spectra for $B = 10^{-18}$ G (upper line), $B = 10^{-15}$ G (middle line), and B $= 10^{-13}$ G Spectral fits imply EGMF in the range of $\sim 10^{-15}$ G.
[Essey, Ando, AK]

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

For line-of-sight interactions to explain the point sources, the EGMFs 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 $\Longrightarrow$ secondary gamma rays are produced in line-of-sight interactions of cosmic rays
- unusual scaling of sources with distance $\Longrightarrow$ secondary gamma rays dominate the signals of distant sources
- inclusion of cosmic-ray contribution brings the blazar spectra in agreement with observations
- there is no tension between a measurement based on gamma rays and those based on direct optical/IR observations