A brighter future for TeV astronomy, thanks to the secondary gamma rays and neutrinos

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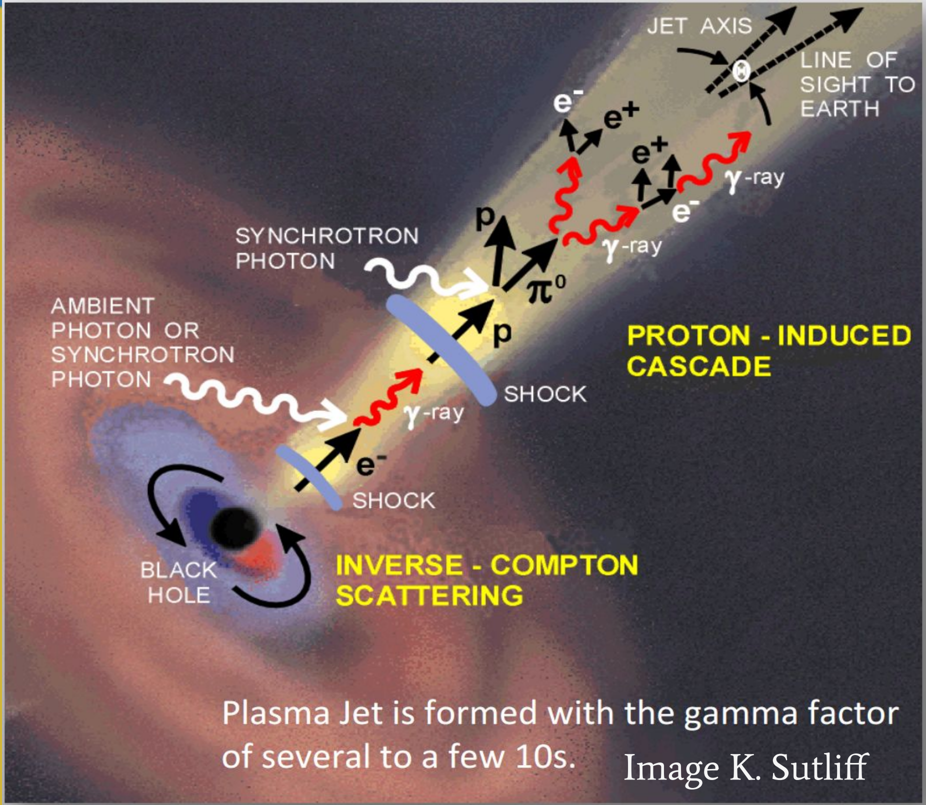
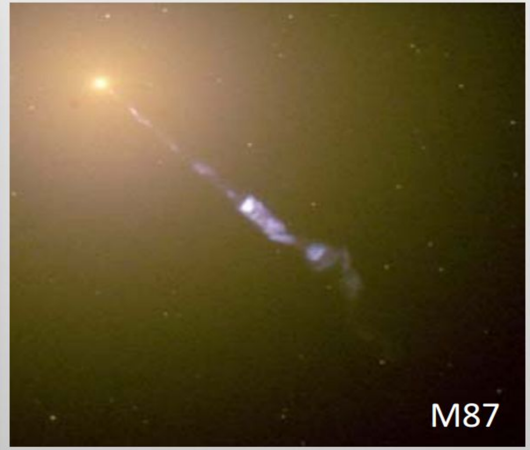
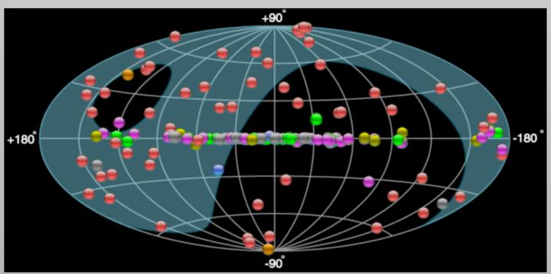
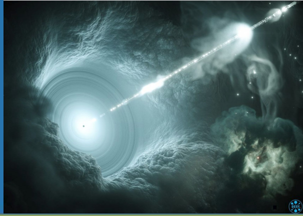
Blazars: supermassive black holes with a jet

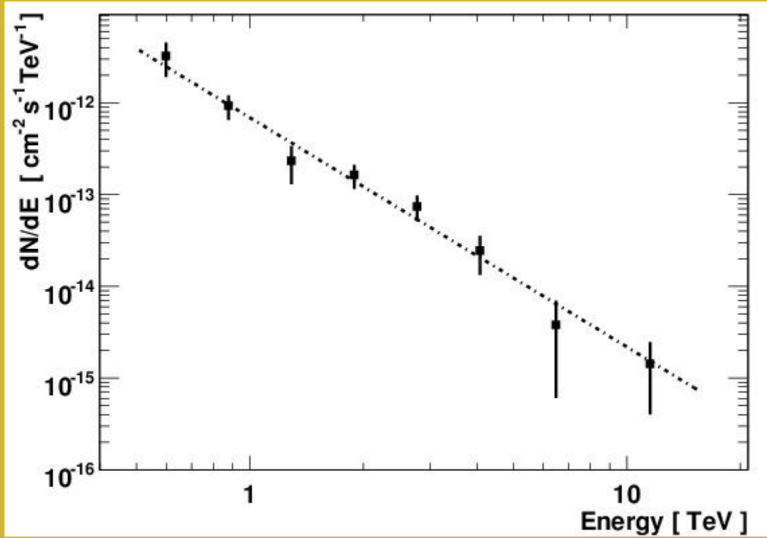


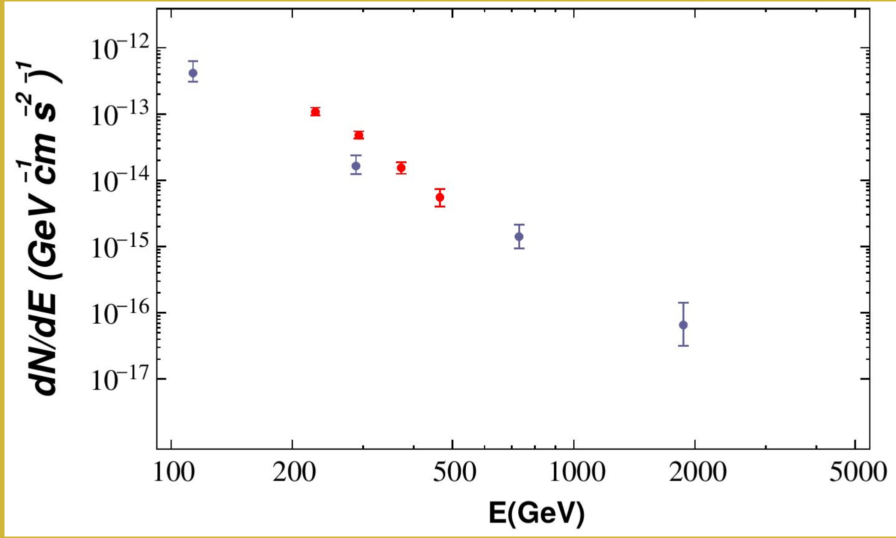




HESS(black), MAGIC (blue), VERITAS (red)



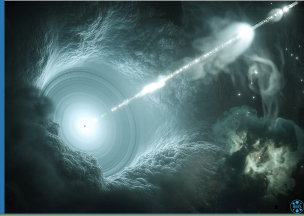


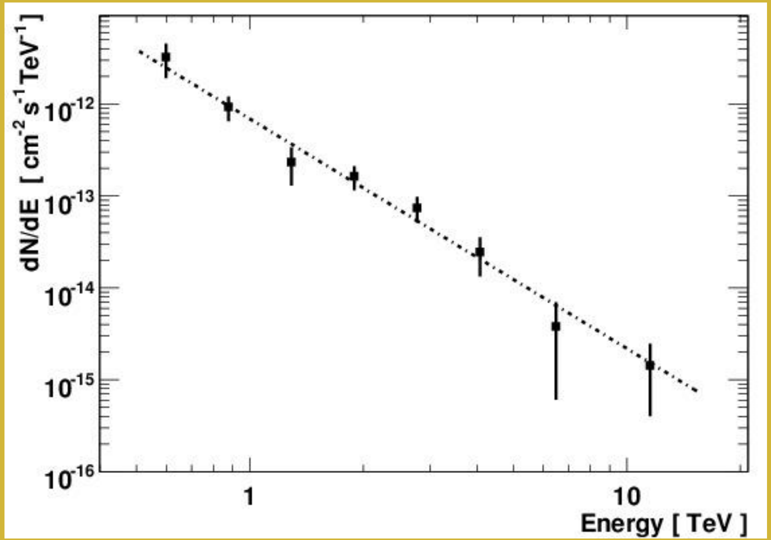


1 ES0229+200 (z=0.14)

3C66A (z=0.44)

HESS(black), MAGIC (blue), VERITAS (red)





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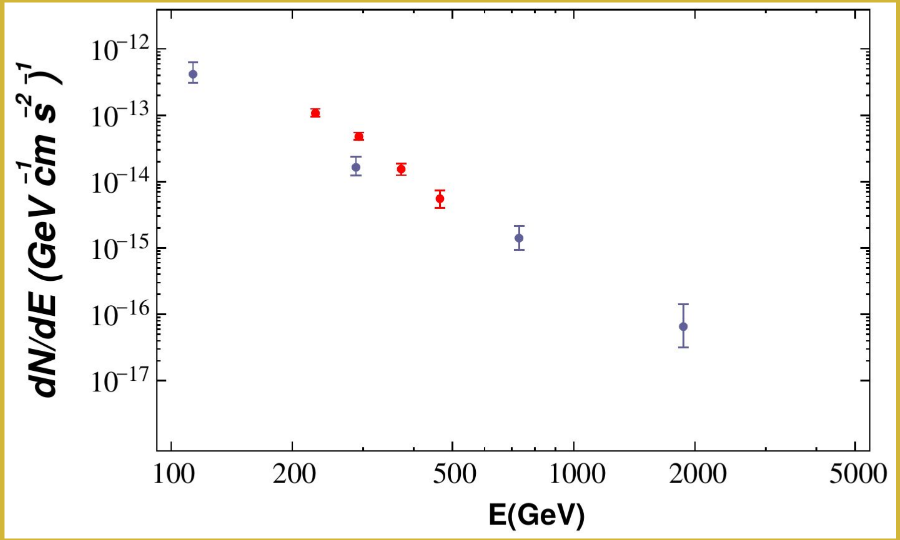
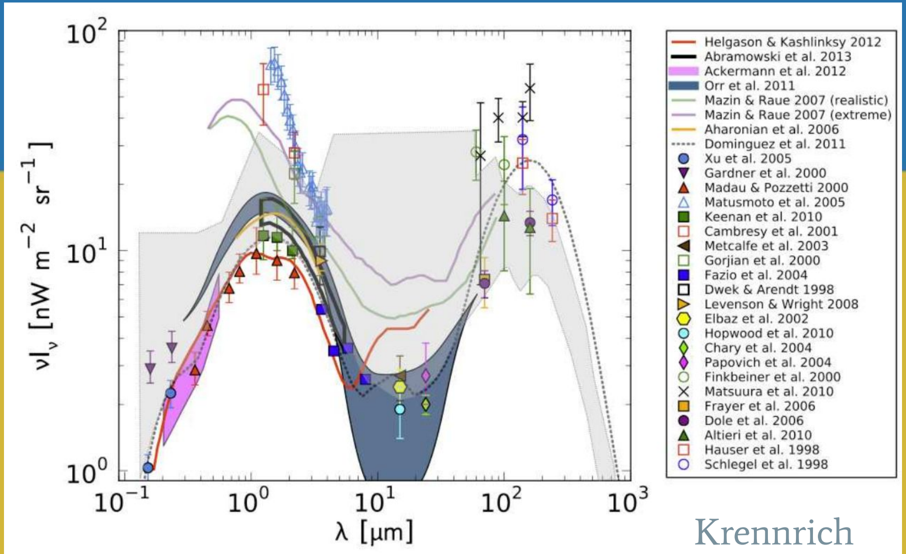


3C66A (z=0.44)

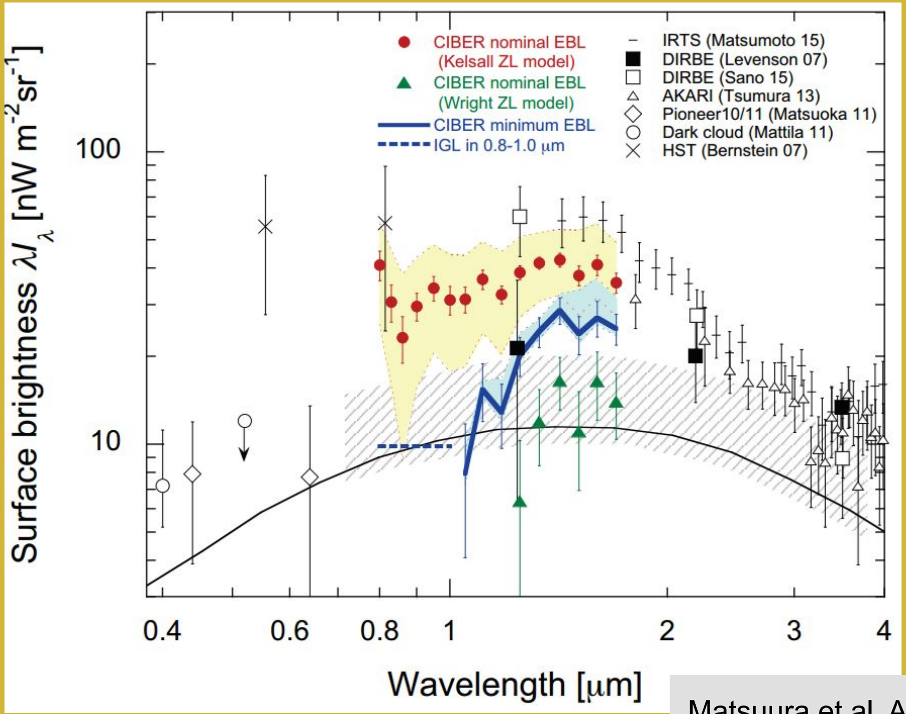
Theory: “we predict a sharp cutoff between 0.1 and 1 TeV” Stecker, et al. (1992)

Data: no sign of absorption due to $\gamma\gamma_{EBL} \rightarrow e^+e^-$

Extragalactic background light



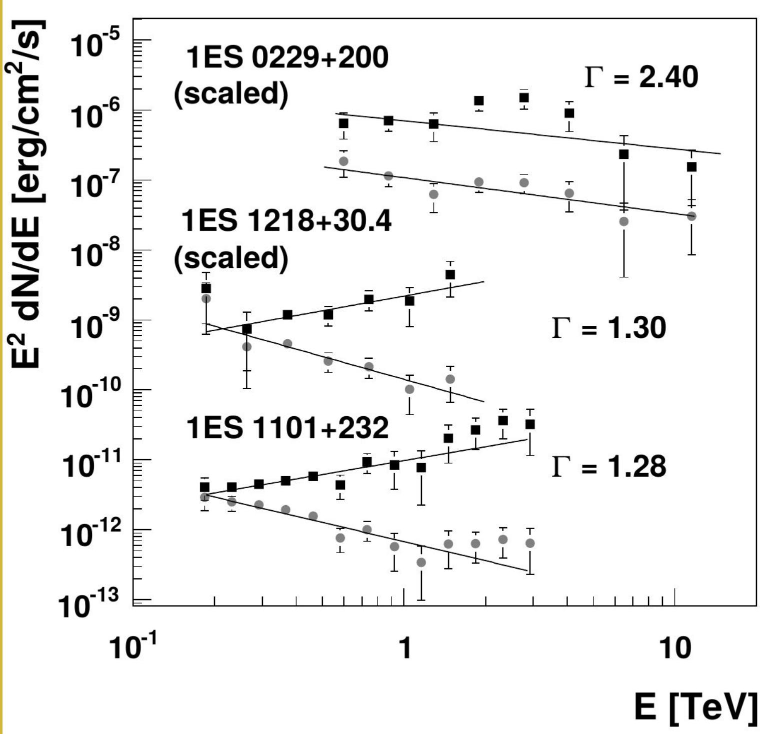
Krennrich



Matsuura et al. ApJ 839,7,2017

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

Distant blazars: implausibly hard spectra?

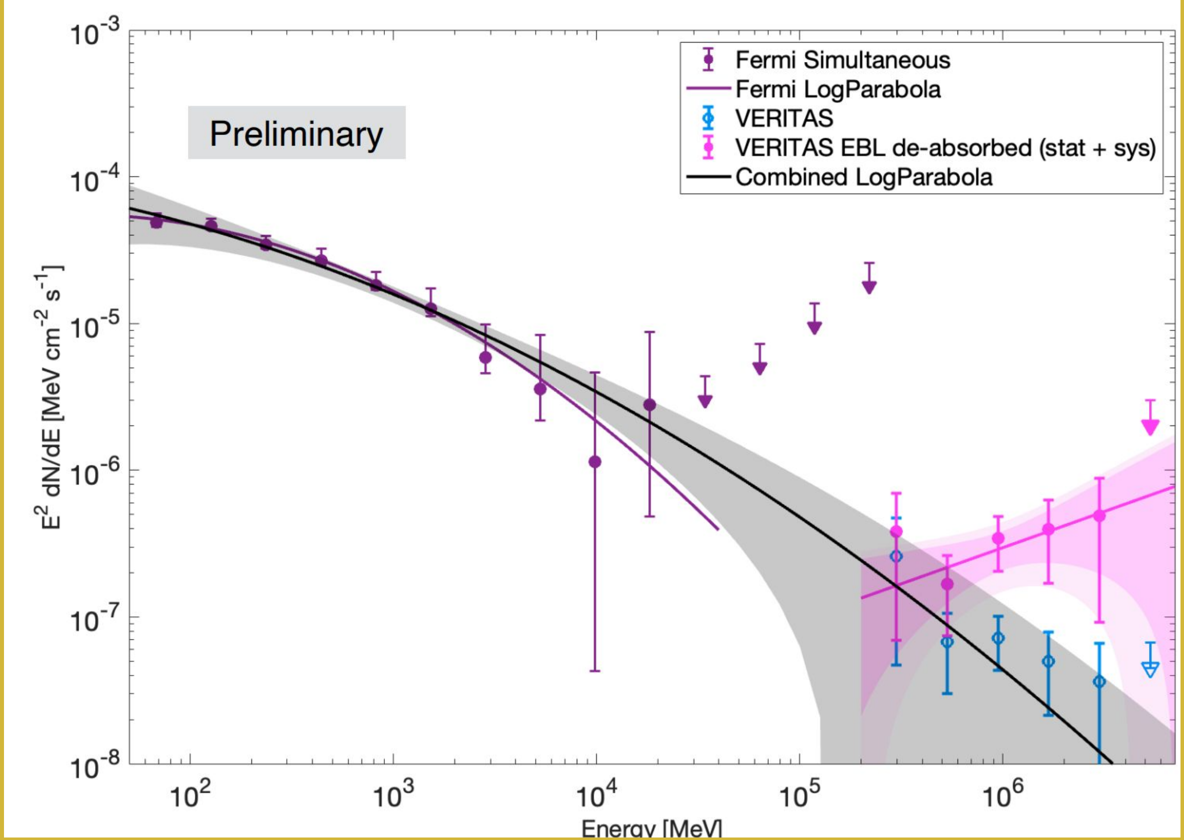


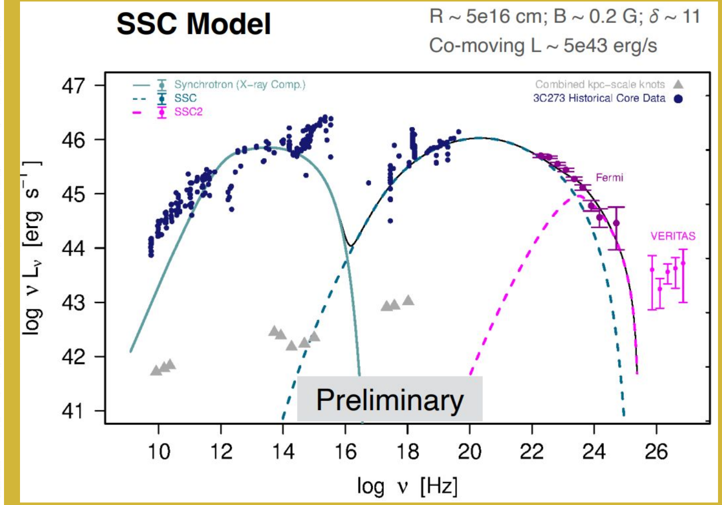
Absorption-corrected spectra would have to be extremely hard for distant blazars:

$$\Gamma < 1.5$$

[Aharonian et al.]

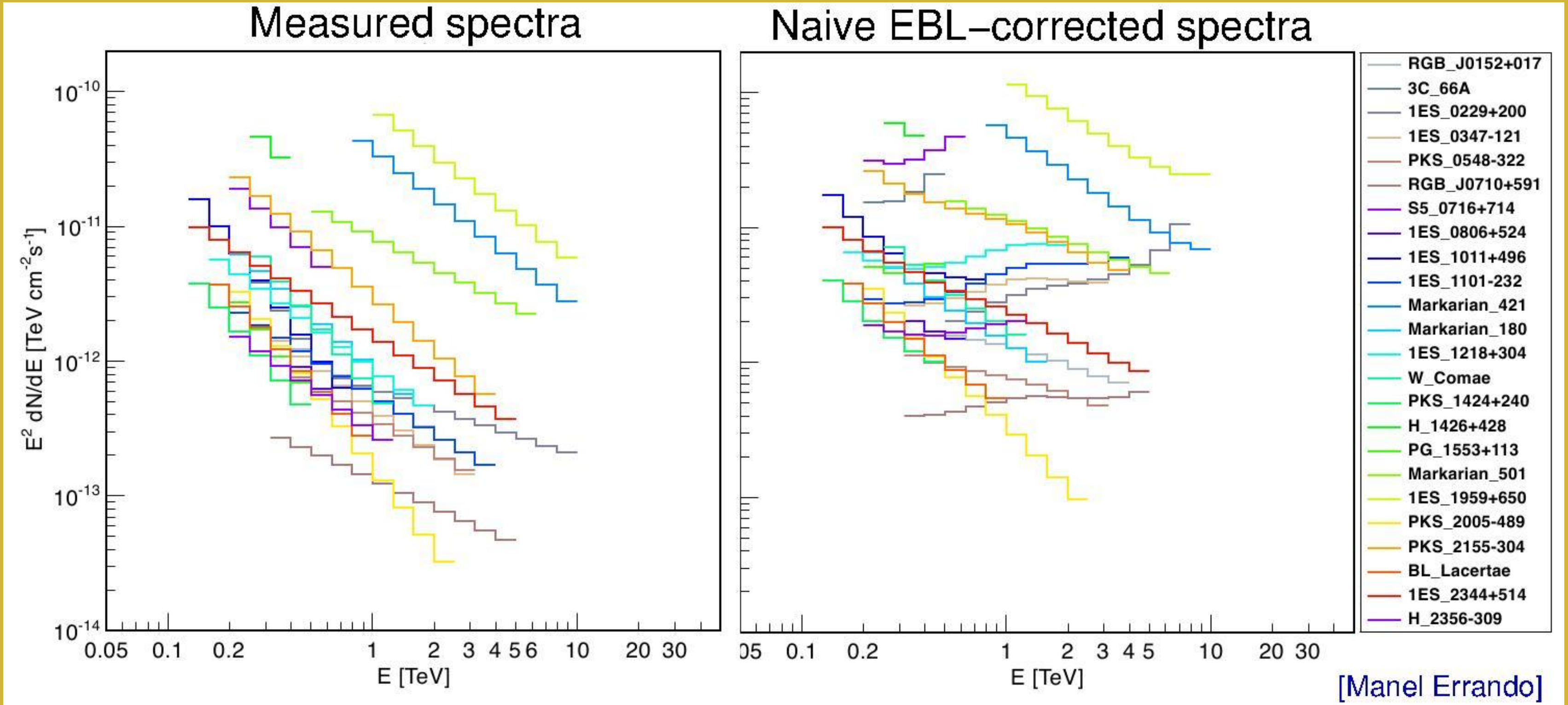
3C 273 (z = 0.159) VERITAS (Benbow, ICRC-2025)



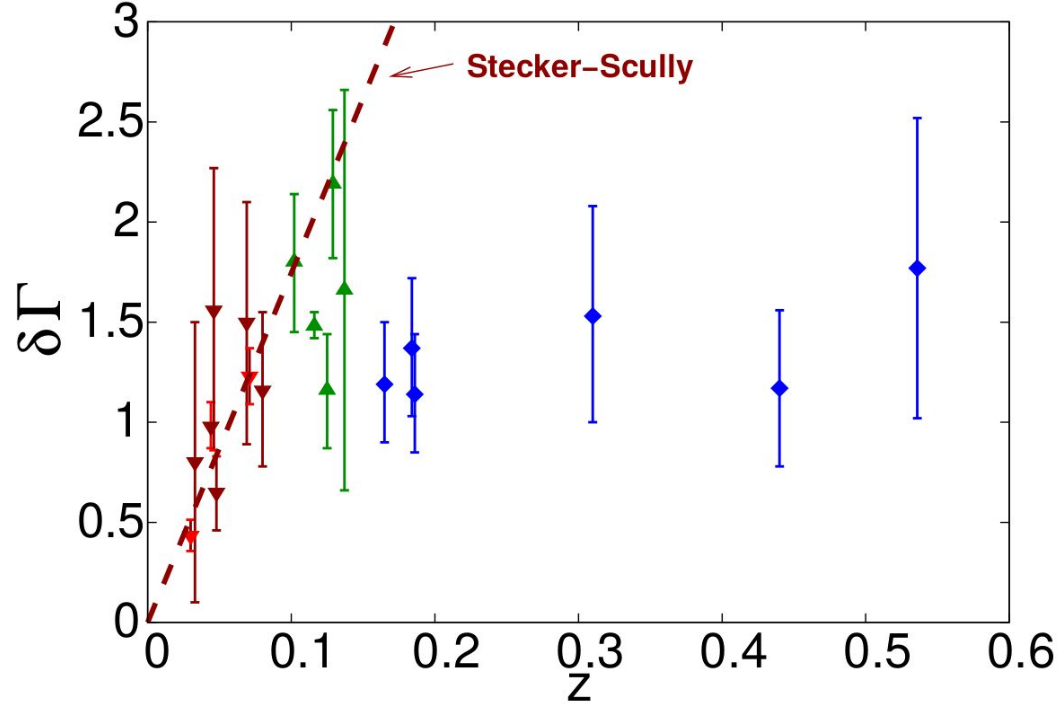


- Inconsistent with acceleration models
- No time variability @TeV

Blazar spectra



Spectral softening: problem with distant blazars



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

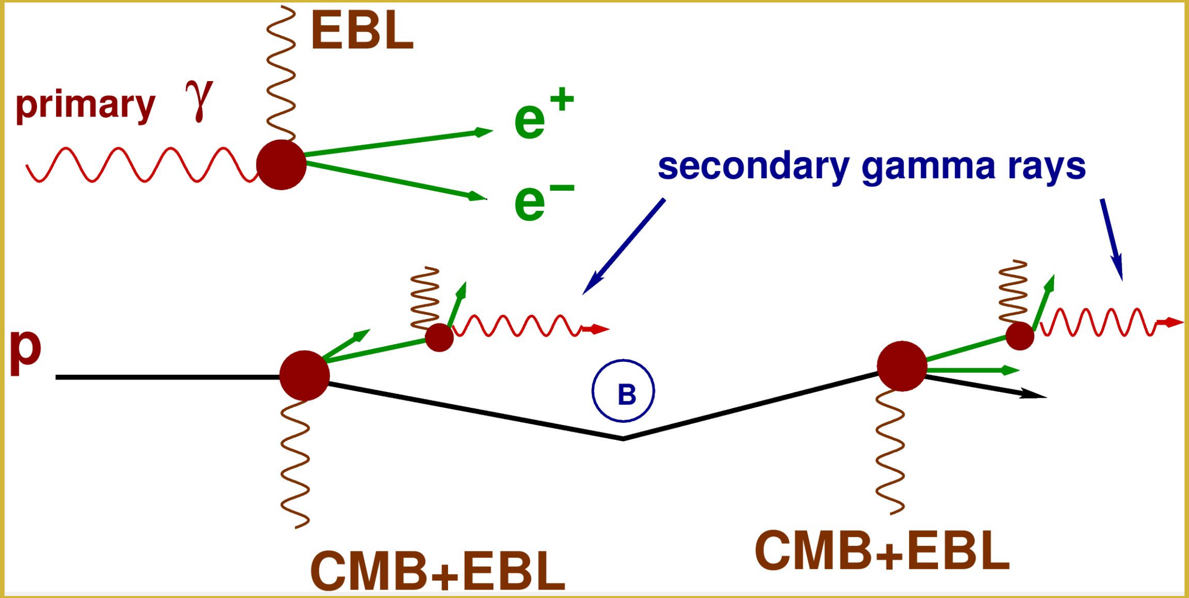
Analytical predictions for the spectral softening
work well for the nearby blazars,
but not for distant blazars

The mysterious transparency of the Universe...

- Hypothetical axion-like particles: photons convert into them in magnetic fields near the source, and they convert back to gamma rays? [de Angelis et al.]
- Violation of the Lorentz invariance suppresses the pair production? [Stecker, Glashow; etc.] $\gamma\gamma_{EBL} \rightarrow e^+e^-$

New physics is an exciting possibility,
but can there be a more conventional explanation?

Gamma rays and cosmic rays



Secondary gamma rays from line-of-sight interactions of CRs

[Essey & AK (2010)]

Different scaling

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

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

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

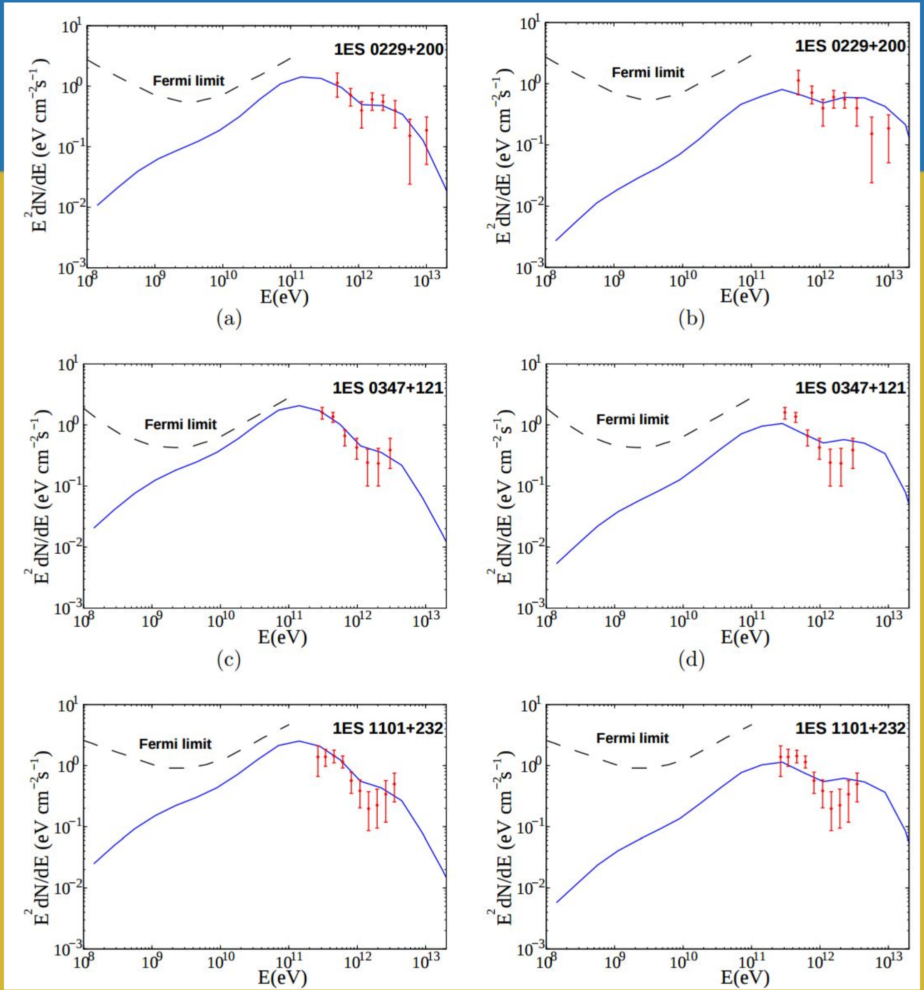
For distant sources, the secondary signal wins!

One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

Good agreement with data for high-redshift blazars (both “high” and “low” EBL models).

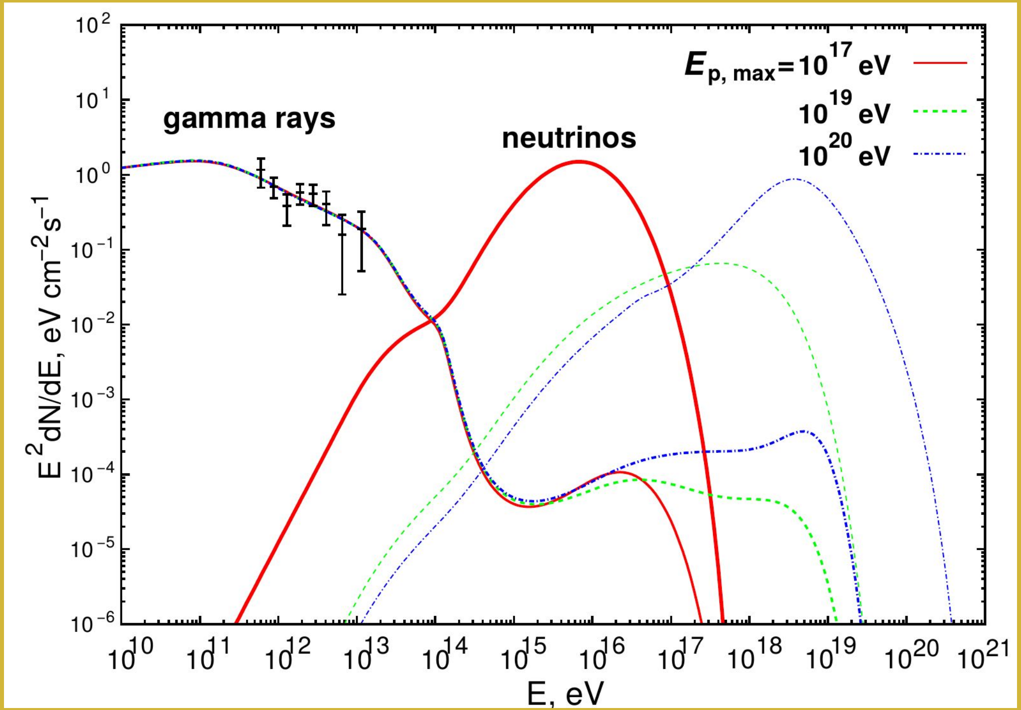
Reasonable CR power for a source up to z~1
[Aharonian, Essey, AK, Prosekin (2013);
Razzaque, Dermer, Finke (2012);
Murase, Dermer, Takami, Migliore (2012)]

Consistent with data on time variability
[Prosekin, Essey, AK, Aharonian (2012)]



Essey, Kalashev, AK, Beacom, ApJ (2011)

Secondary gamma, neutrinos from 1ES0229+200

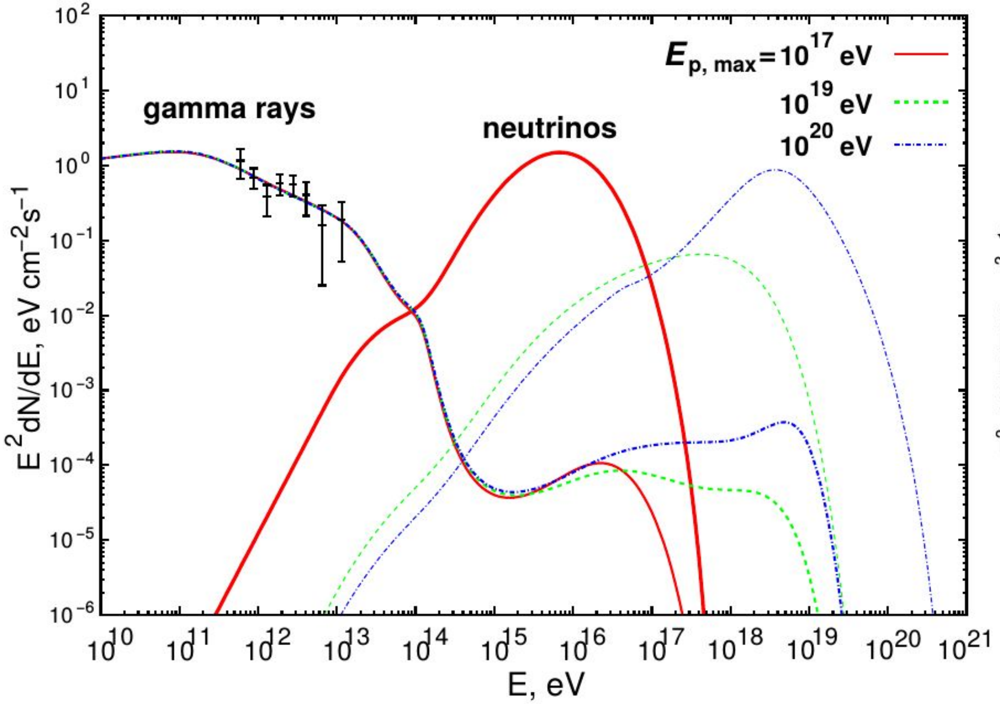


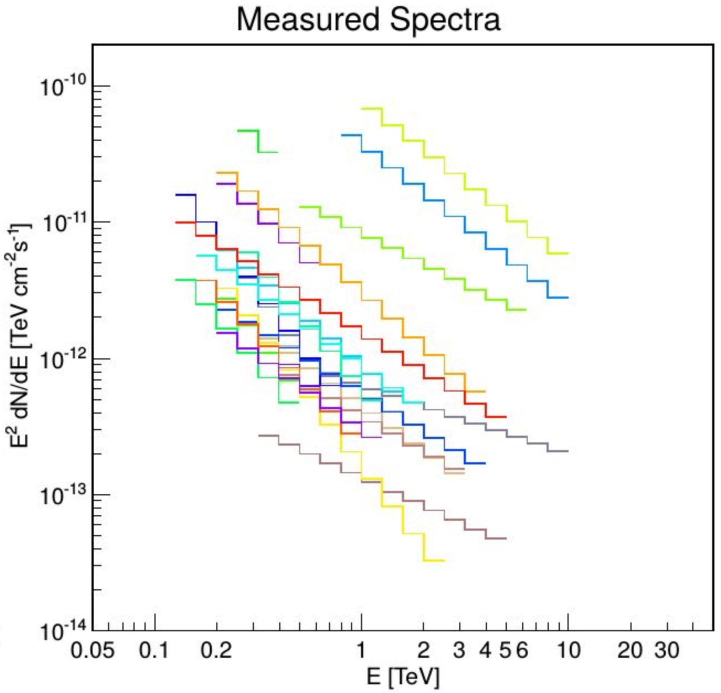
(z=0.14)

- Gamma-ray spectra **robust**
- Neutrino spectra **peaked**

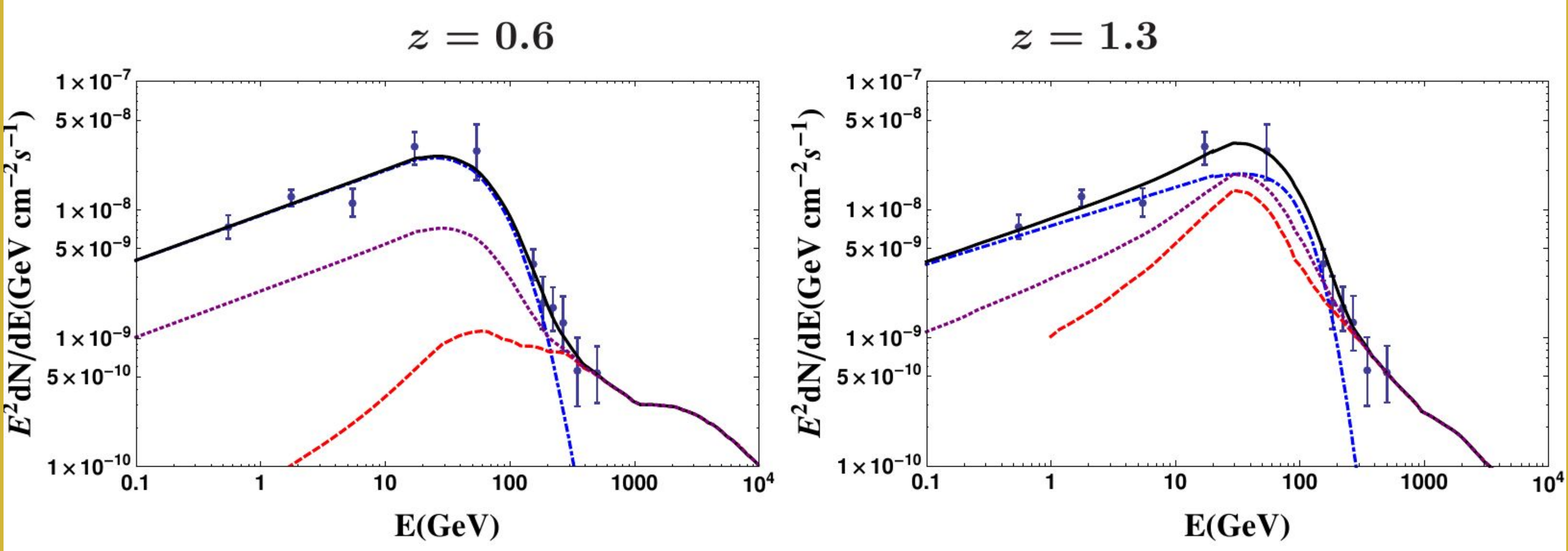
[Essey, Kalashev, AK, Beacom, PRL (2010)]

Robust shapes explain observed universality





PKS 1424+240 at $z > 0.6$ (a very extreme TeV blazar!)



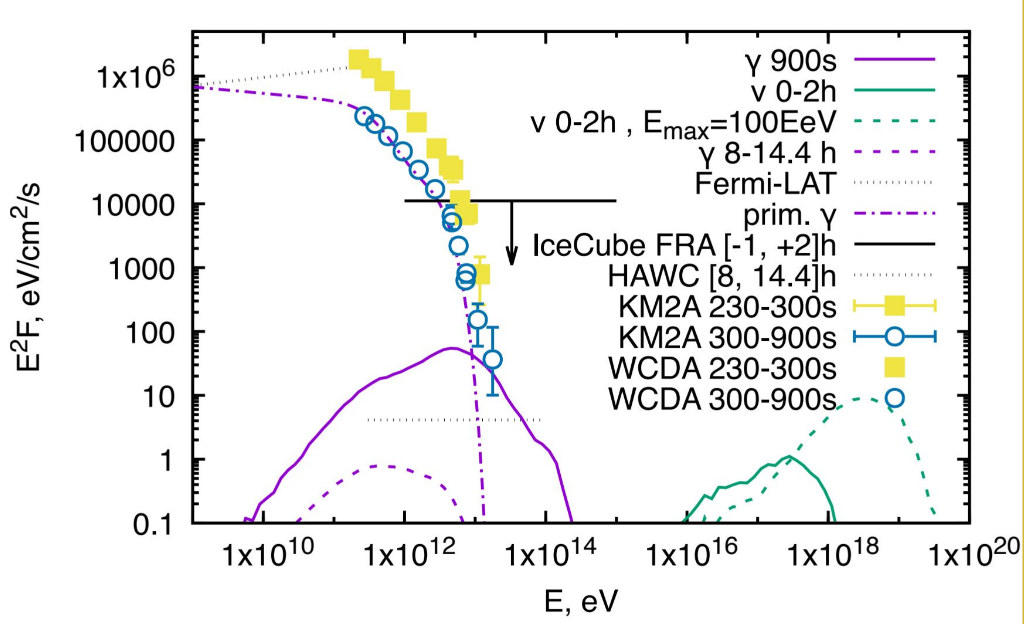
[Essey, AK, Astropart.Phys. 57-58 (2014) 30] data: VERITAS and Fermi

$z > 0.6035$ [Furniss et al., ApJL 768, 2, L31 (2013)]

GRB221009A, the brightest GRB ever observed, E up to **250 TeV**

$$\tau_{\gamma\gamma}(18\ \text{TeV}) \gtrsim 10 \text{ for all recent EBL models}$$

$$\exp[-\tau_{\gamma\gamma}(18\ \text{TeV})] \lesssim 4.5 \times 10^{-5}$$

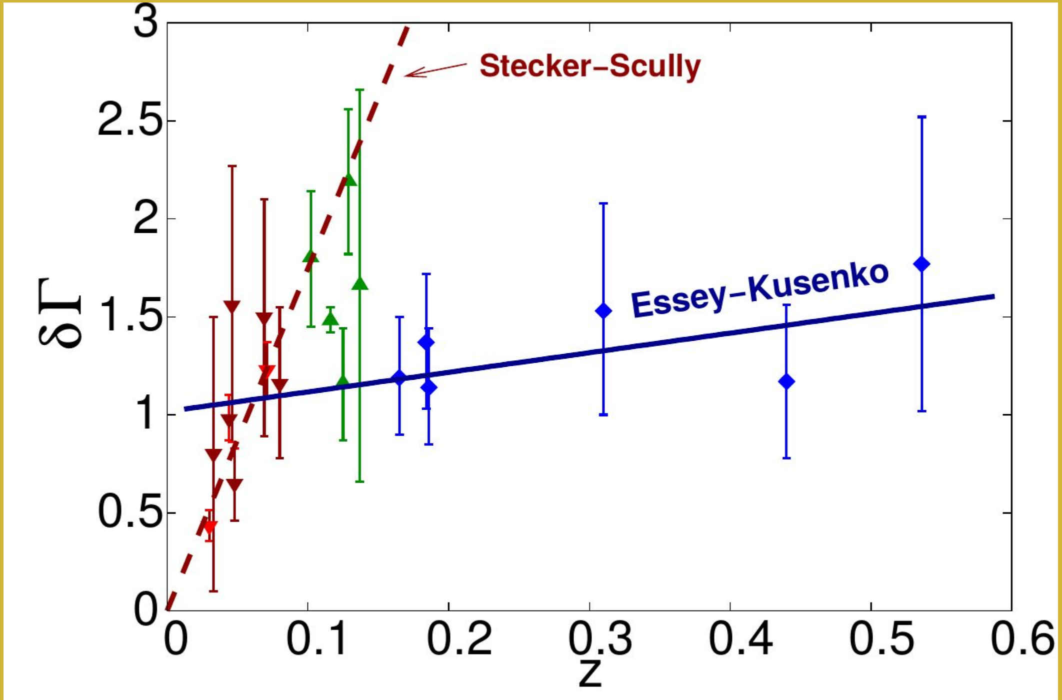


Lorentz invariance violation?
[Finke, Razzaque, 2023 ApJL 942 L21]

Secondary gamma rays explain the last data points well.

[Kalashev, Aharonian, Essey, Inoue, AK, Phys.Rev.D 112 (2025) 2, 023022]

Spectral softening

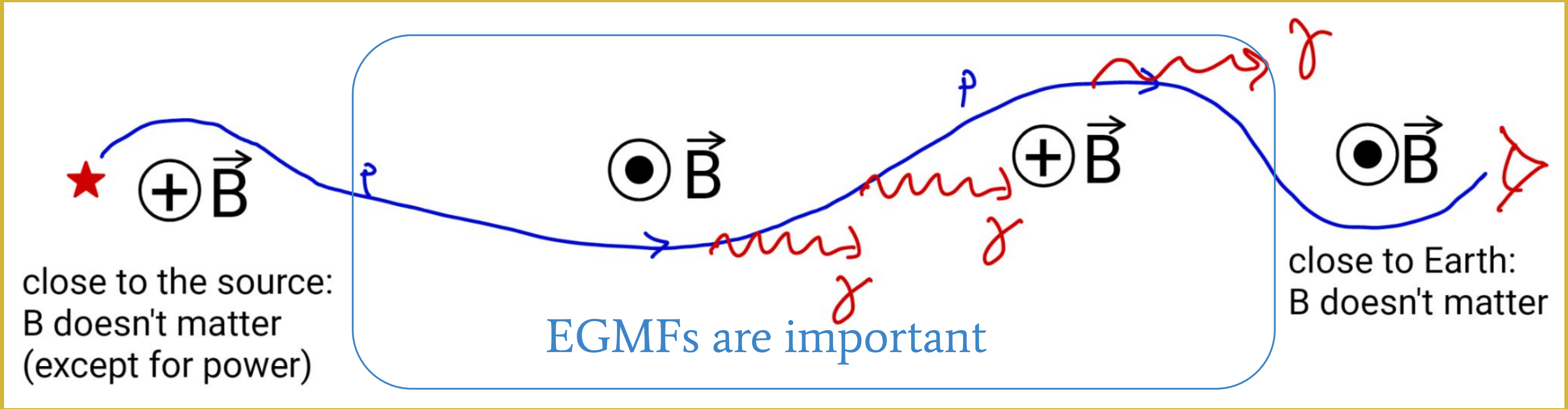


$$\delta\Gamma = \Gamma_{\mathrm{GeV}} - \Gamma_{\mathrm{TeV}}$$

Three populations in red, blue and green are seen in primary, secondary, or mixed components, respectively.
[Essey, AK, ApJ.Lett. 751 (2012)]

Predictions: no variability for TeV blazars at z>0.15. In good agreement with data.
[Prosekin, Essey, AK, Aharonian]

Magnetic fields delay protons (and cascades)



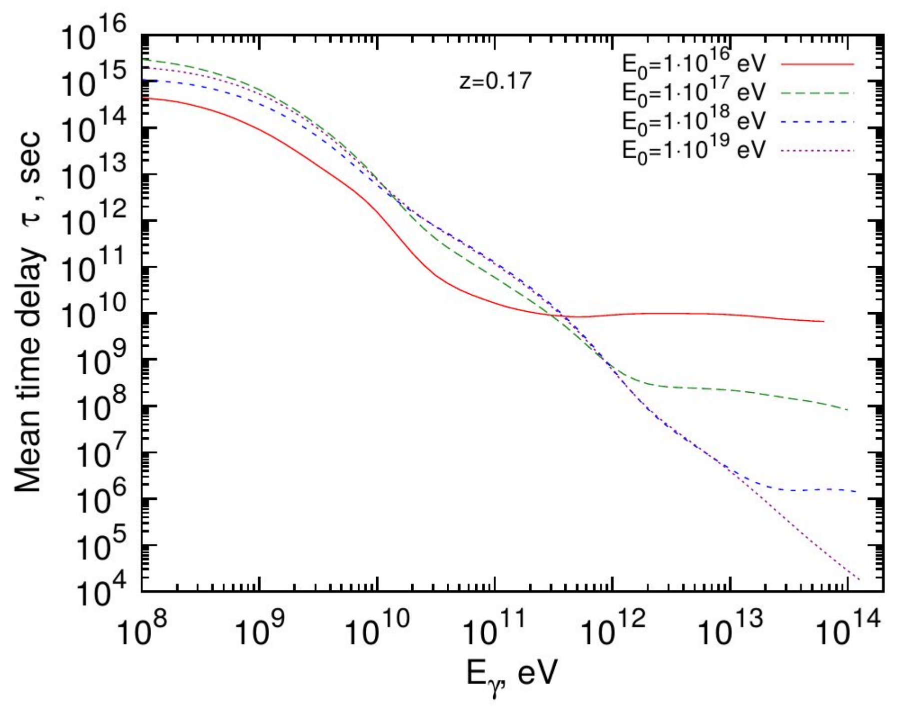
Magnetic fields in voids affect the propagation of protons and the electrons in the cascades. Also important: any filaments that intersect the line of sight. However, with probability ~1 a source at z=1 is not obscured by a filament.

[Aharonian et al., Phys.Rev.D 87 (2013) 6, 063002, 1206.6715]

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

Nearby blazars are variable at all energies. Distant blazars are variable at lower energies, but there is no evidence of variability for, e.g., E>1 TeV, z > 0.15

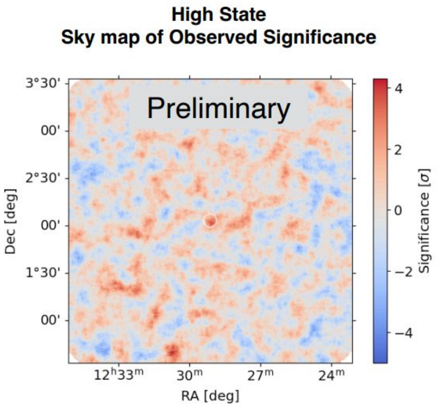
Prediction: stochastic *pedestal* emerges at high energy, high redshifts, for distant blazars above which some flares may rise in a stochastic fashion.

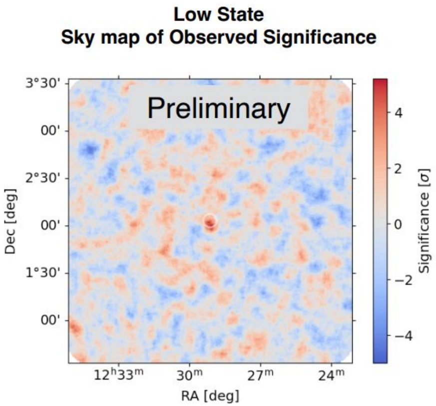


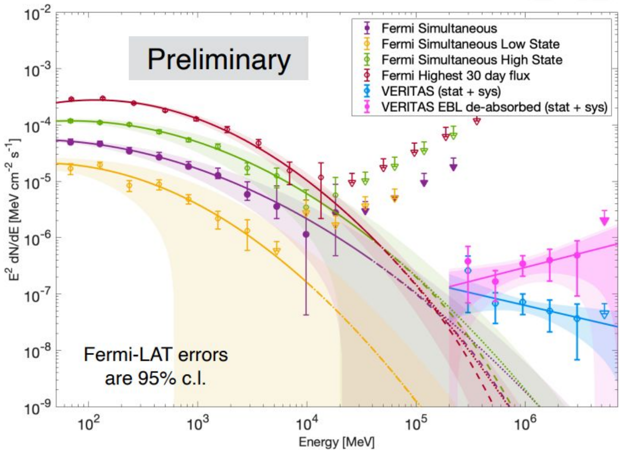
[Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183]

3C273: no time variability at the highest energies

Variability is not Dominant

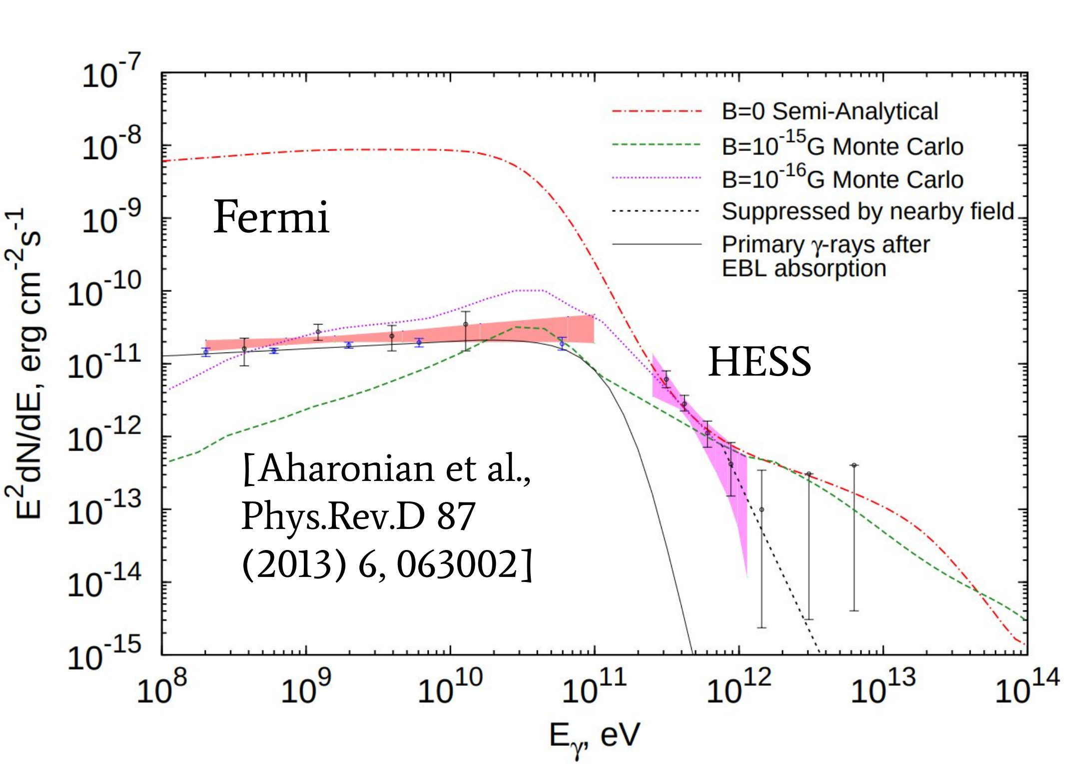






- VERITAS sees VHE emission from 3C 373 during both the high & low Fermi epochs
  - All high-state data: t = ~86 h (37% of data); 76 γ; 3.1σ; F(>350 GeV) = (2.3 ± 0.8) x 10^{-13} cm^{-2} s^{-1}
  - All low-state data: t = ~136 h (59% of data); 117 γ; 3.7σ; F(>350 GeV) = (2.1 ± 0.6) x 10^{-13} cm^{-2} s^{-1}
  - Pre-Fermi data: t = ~9 h (4% of data); 21 γ; 2.4σ; F(>350 GeV) = (9.0 ± 4.1) x 10^{-13} cm^{-2} s^{-1}
- VERITAS emission incompatible with all Fermi states, including SED from highest 30-day flux

Case study: PKS 0447-439, assuming z=1.3



TeV observations from z=1.3 aer consistent with EBL if secondary gamma rays are included
Aharonian et al. Phys.Rev.D 87 (2013) 6, 063002

Redshift uncertain: z> 1.2 [H. Landt, MNRAS, 423, L84 (2012)], but disputed by Pita et al., arXiv:1208.1785 and Fumagalli et al. arXiv:1207.3592.

CTAO extragalactic survey discovery potential

Cherenkov Telescope Array Observatory (CTAO) extragalactic survey will see an enhancement in the number of distant TeV sources, thanks to secondary gamma rays.

[De Franco, Inoue, Sanchez-Conde, Cotter Astropart. Phys. 93 (2017) 8 arXiv:1707.00250]

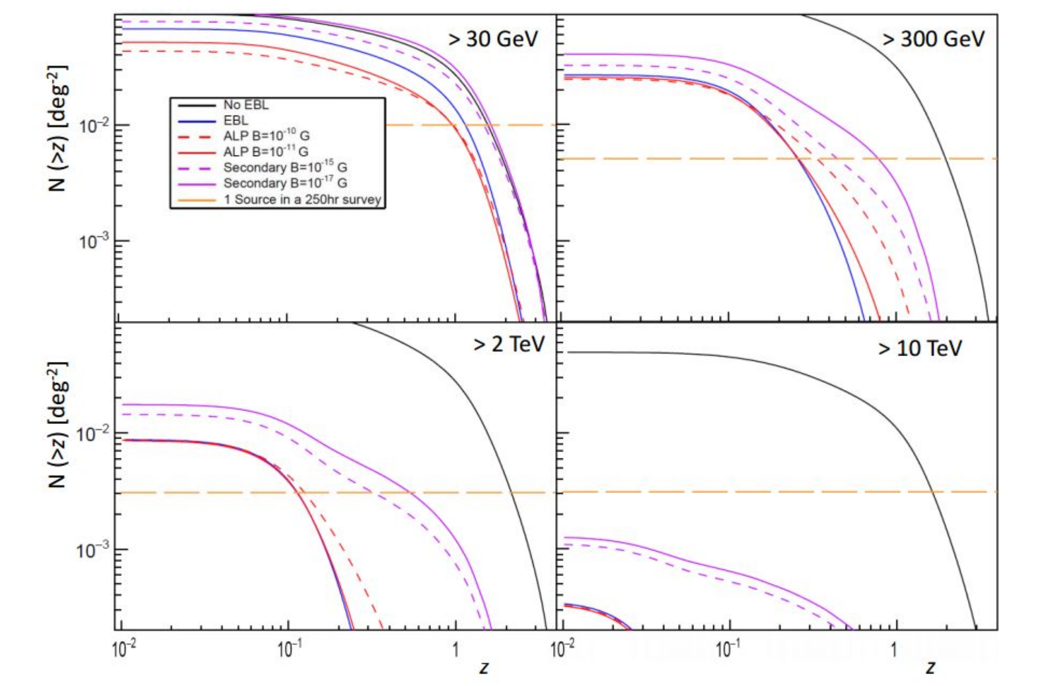
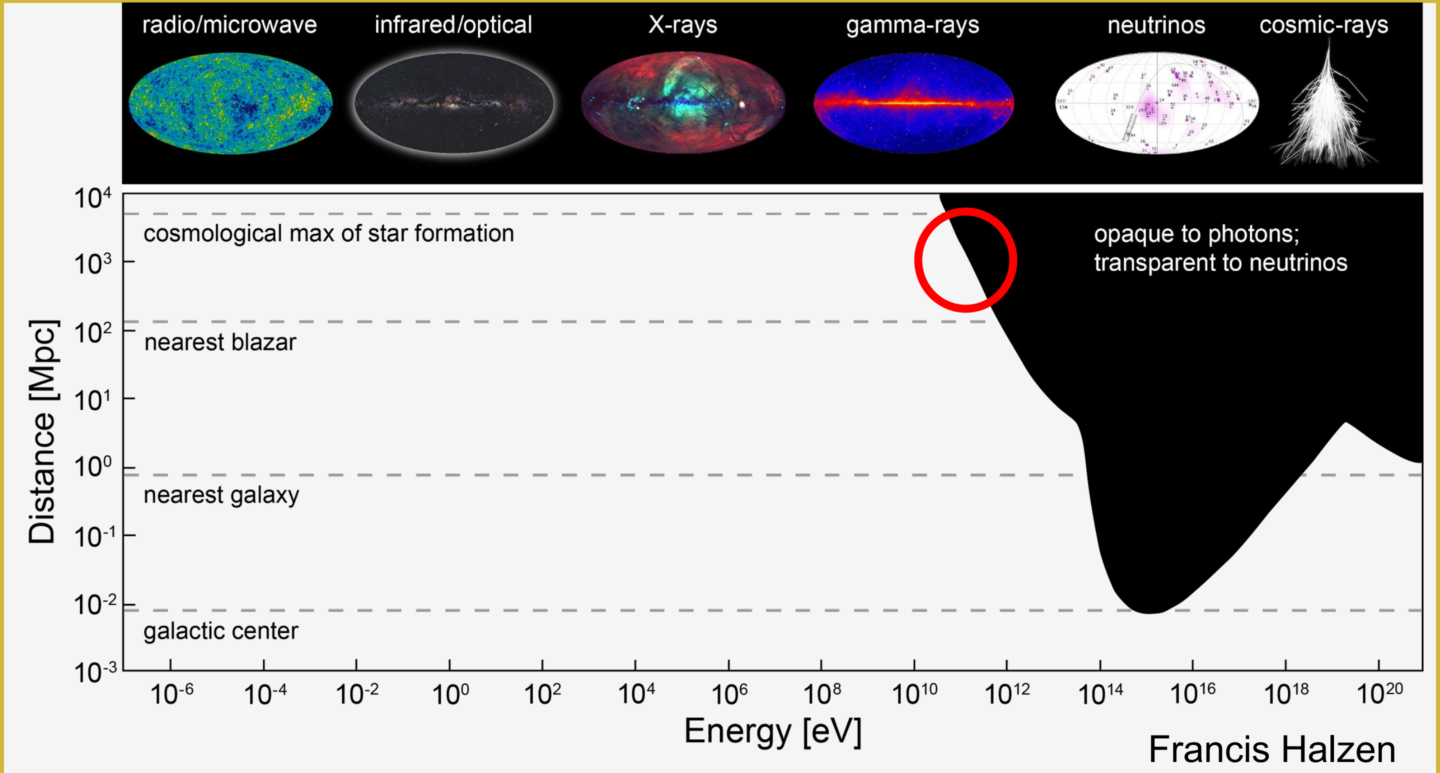


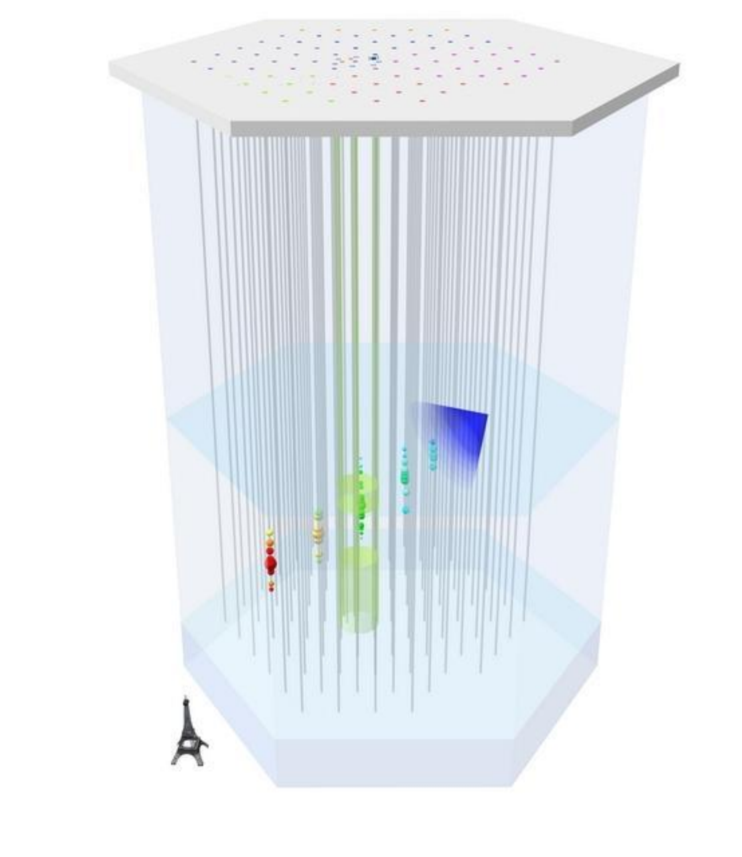
Figure 3: Cumulative source count as a function of redshift for CTA-South, assuming a 5σ integral flux sensitivity and 50 hr exposure observation. Dashed horizontal line represents 1 source detected in a 250 hr survey.

Seeing farther with secondary gamma rays

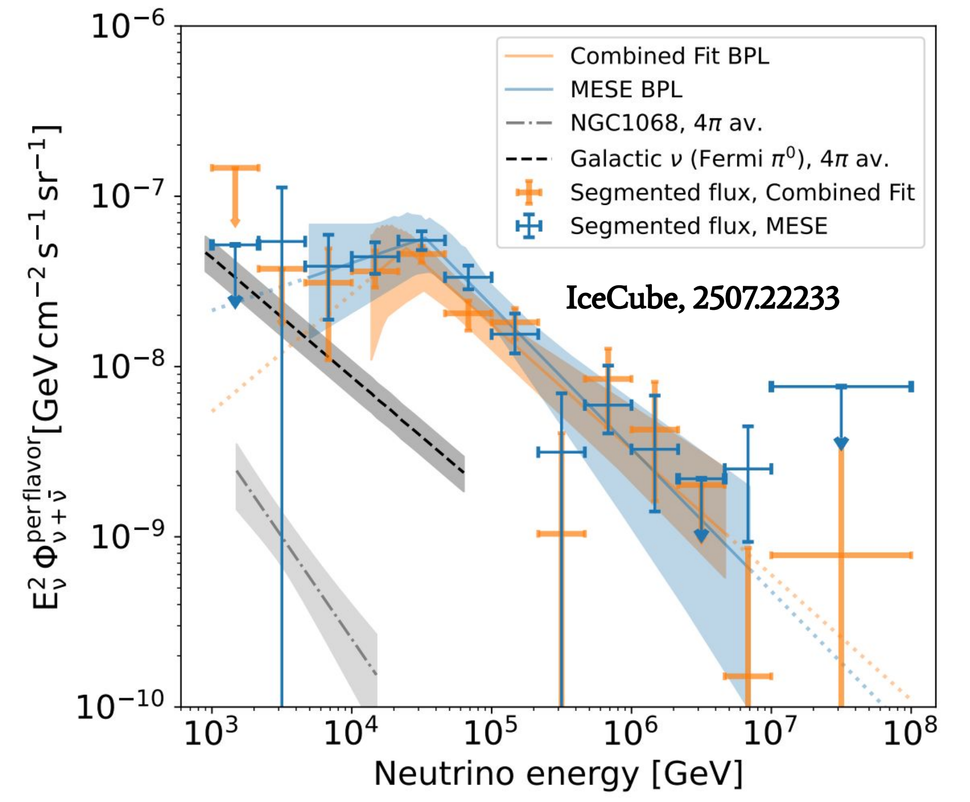


IceCube detector

Talk by Yoshida



IceCube neutrinos: the spectrum



Not a single power law

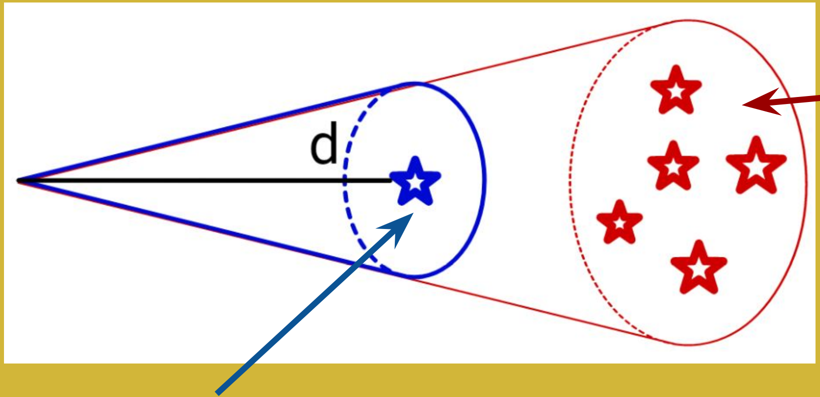
Multiple components?

A peak at a few PeV?

Neutrino scaling ⇒ no point sources

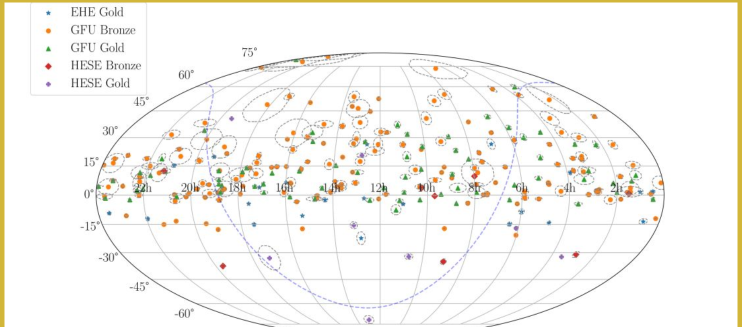
$$F_{\text{secondary},\nu}(d) \quad \propto \quad (F_{\text{protons}} \times d) \propto \frac{1}{d}.$$

Distant (uniformly distributed) sources dominate the signal



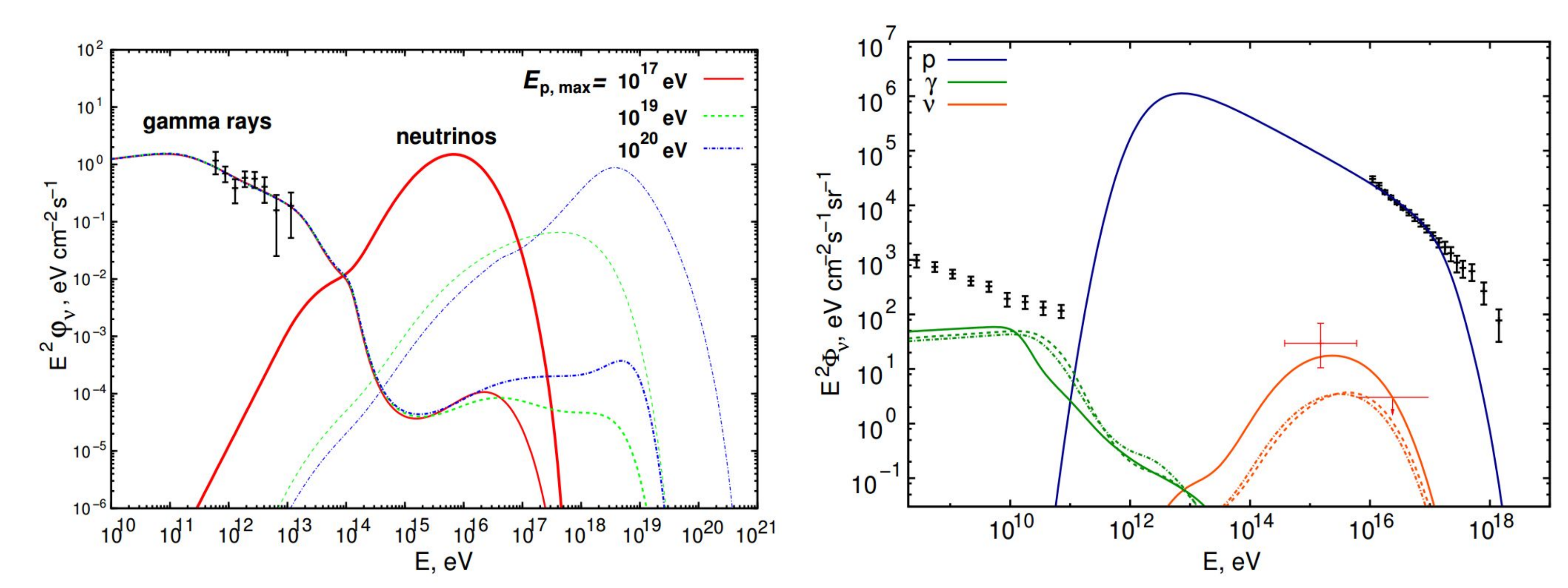
Distant sources dominate for F ∝ 1/d

Nearby sources dominate for F ∝ $1/d^2$



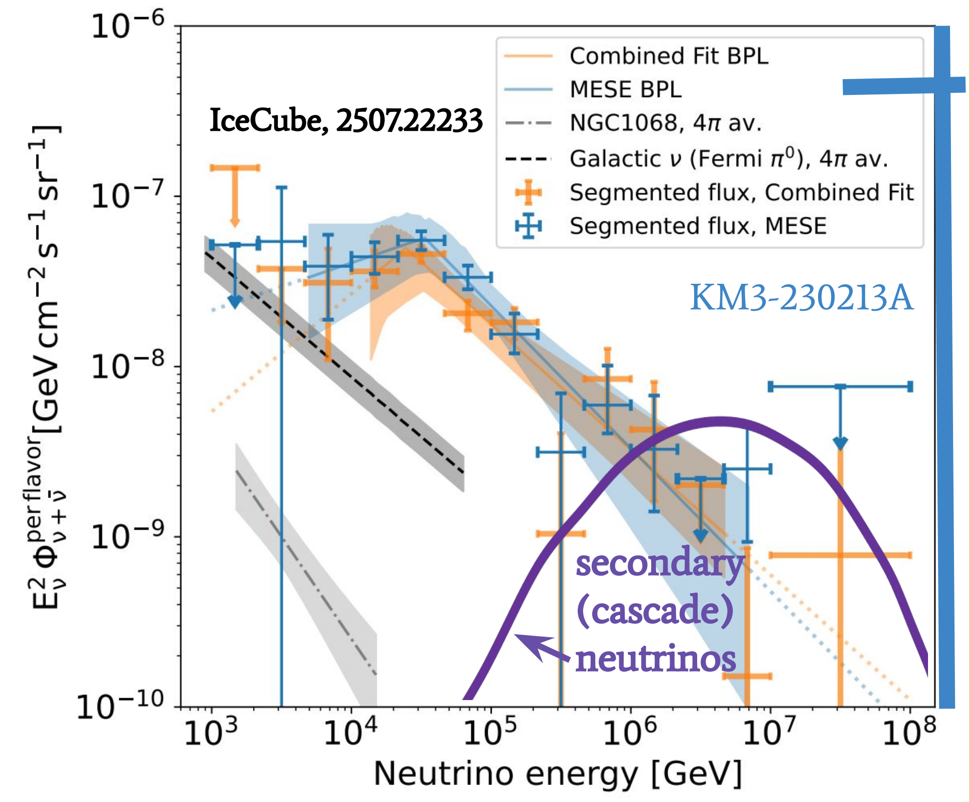
IceCube, ApJ.Suppl. 269 (2023) 1, 25

Line-of-sight interactions of CRs from blazars



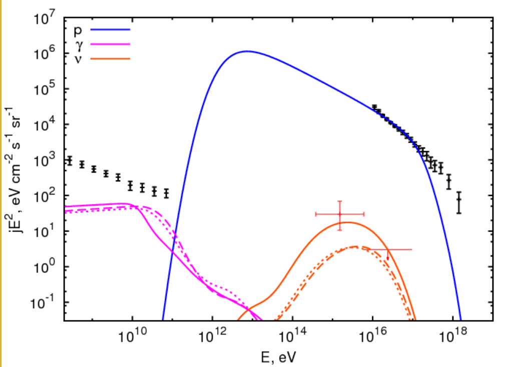
Essey et al. Phys.Rev.Lett. 104 (2010) 141102; Kalashev et al., Phys.Rev.Lett. 111 (2013) 4, 041103

Secondary neutrinos



A peaked spectrum at a few PeV can result from cosmic rays accelerated in AGN and interacting with photon backgrounds, assuming that secondary photons explain the observations of TeV blazars.

Essey et al., PRL 104, 141102 (2010)
Kalashev et al. PRL 111, 041103 (2013)



Implications for intergalactic magnetic fields

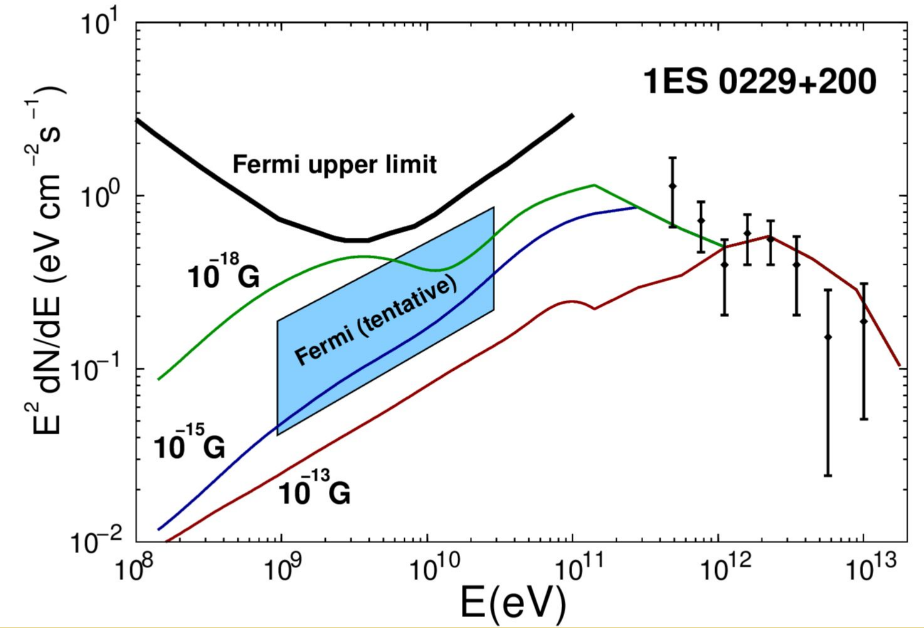
Magnetic fields along the line of sight:

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

Lower limits: Neronov and Vovk (2010) Finke et al. (2015)

Upper limits: Essey, Ando, AK (2011)

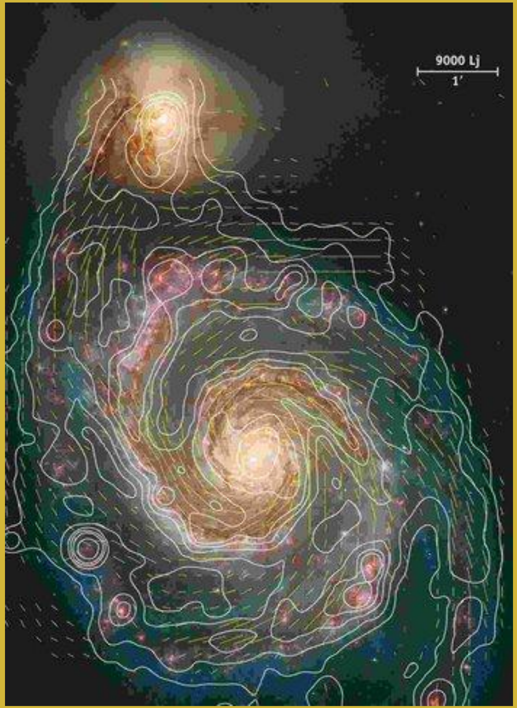
If an intervening filament deflects protons, then no secondary component is expected. However, even a source at z~1 has an order-one probability to be unobscured by magnetic fields, and can be seen in secondary gamma rays
[Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]



Essey, Ando, AK (2011)

Magnetic fields and matter-antimatter asymmetry

Intergalactic magnetic fields away from galaxies may be representative of primordial seed fields.



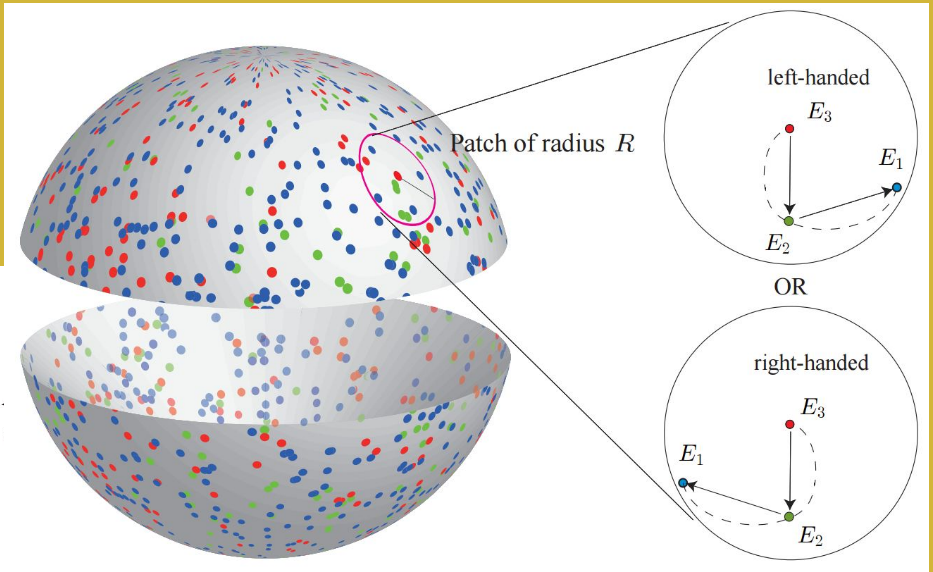
Magnetic helicity

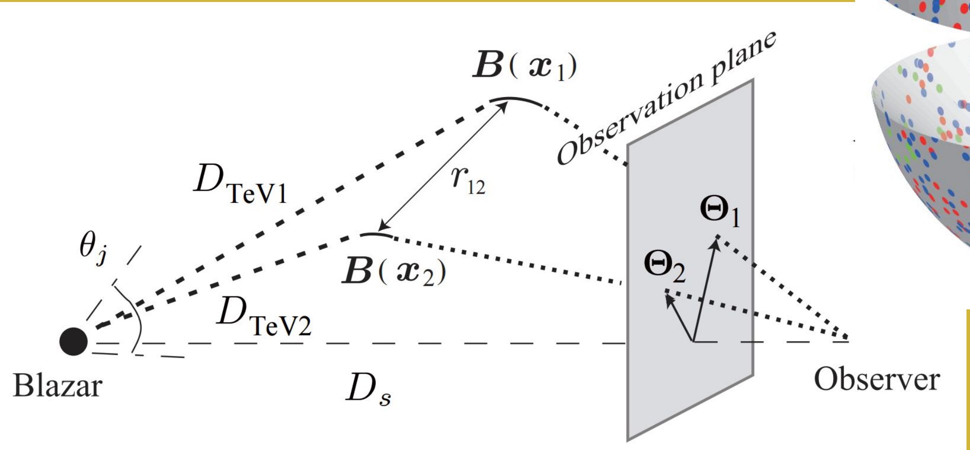
(~ Chern-Simons term for the U(1) of hypercharge)

can break the symmetry between matter and antimatter and possibly explain the **matter-antimatter asymmetry** of the universe [Cornwall; Vachaspati et al.]

Magnetic helicity may be observable

[Vachaspati et al.] reported 3σ evidence of non-zero helicity, with the *correct sign*





Tashiro, Chen, Ferrer, Vachaspati (2014)

Conclusions

- Treating gamma rays and cosmic rays consistently leqasd to excellent agreement of gamma-ray spectra with observations of distant blazars
(and very little model dependence)
- Neutrinos are an interesting probe (but predictions are model-dependent)
- IceCube neutrinos show arrival directions consistent with production on the background, not in sources that trace matter distribution.
The spectrum is model dependent, but is consistent.
- Now as we understand the “beam”, we can use it to test the cosmic photon backgrounds (EBL) and magnetic fields