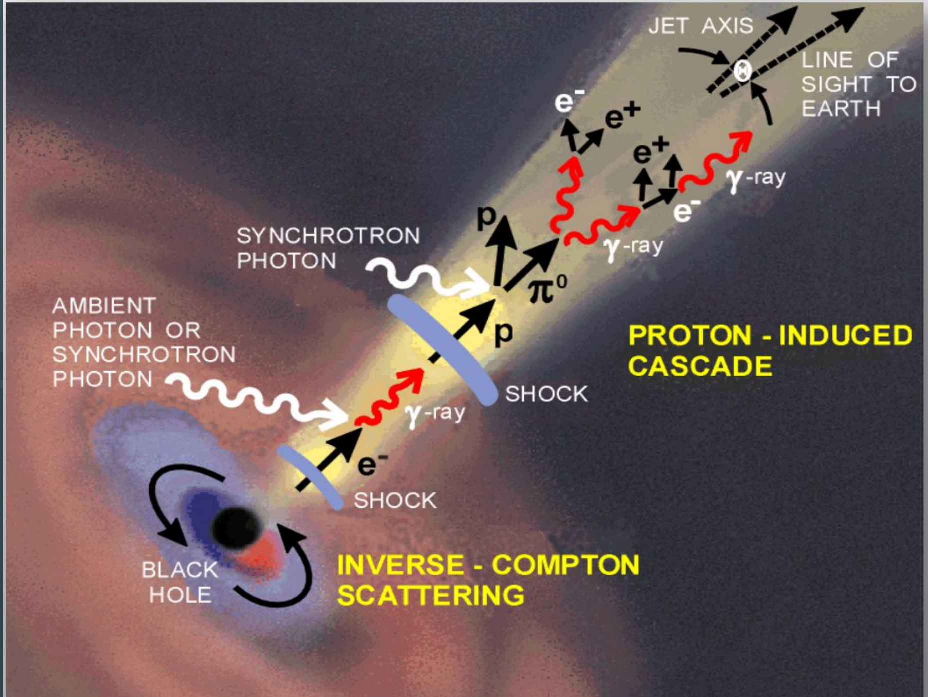
Gamma rays from blazars, and intergalactic magnetic fields

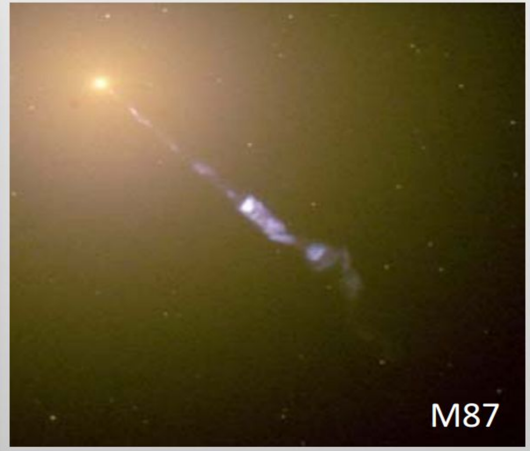
Alexander Kusenko
(UCLA and Kavli IPMU)

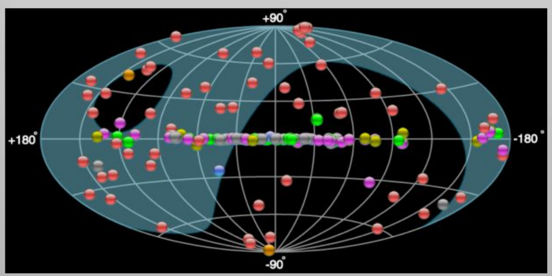
PACIFIC-2016, Moorea, September 14, 2016

Blazars: supermassive black holes with a jet

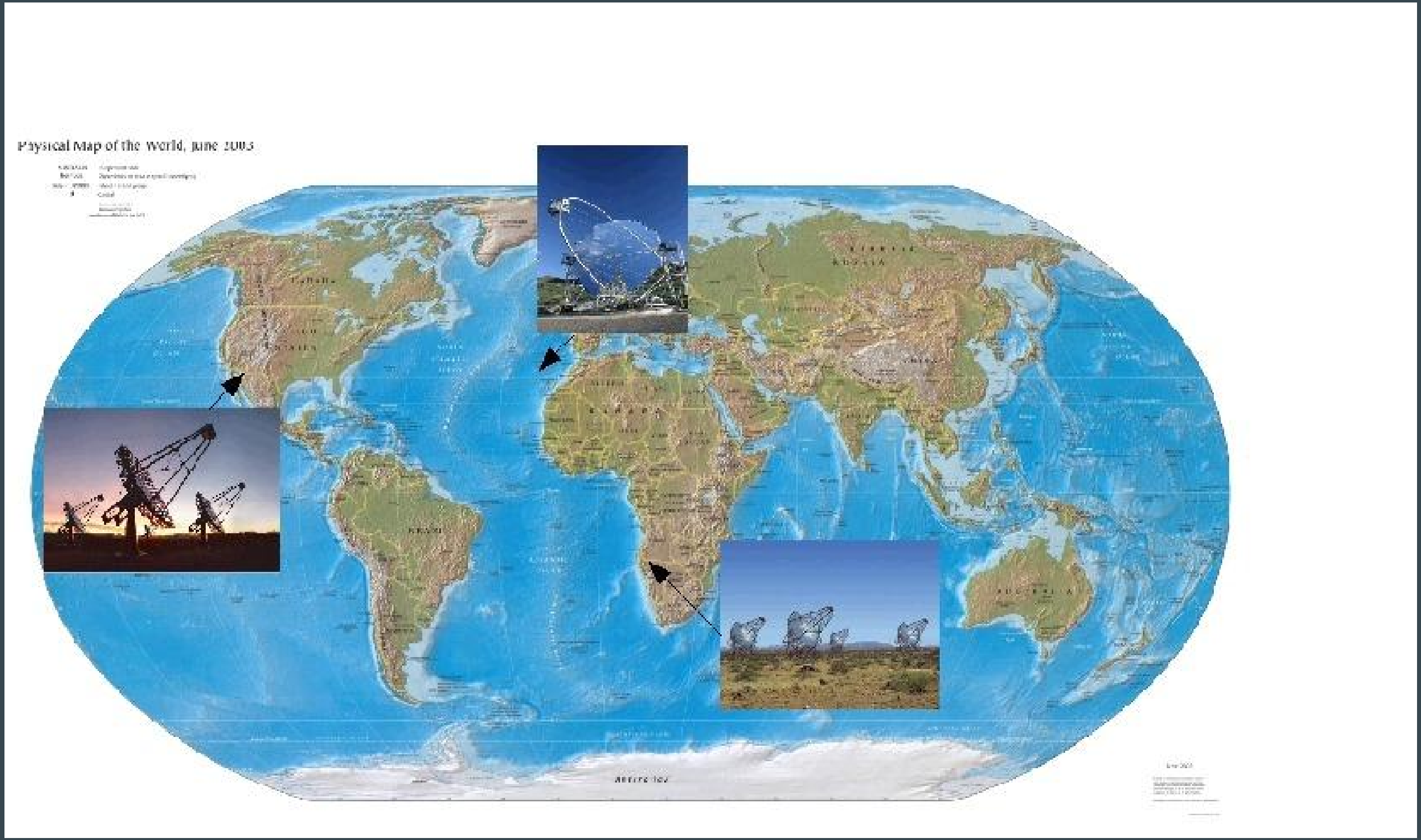


Plasma Jet is formed with the gamma factor of several to a few 10s.

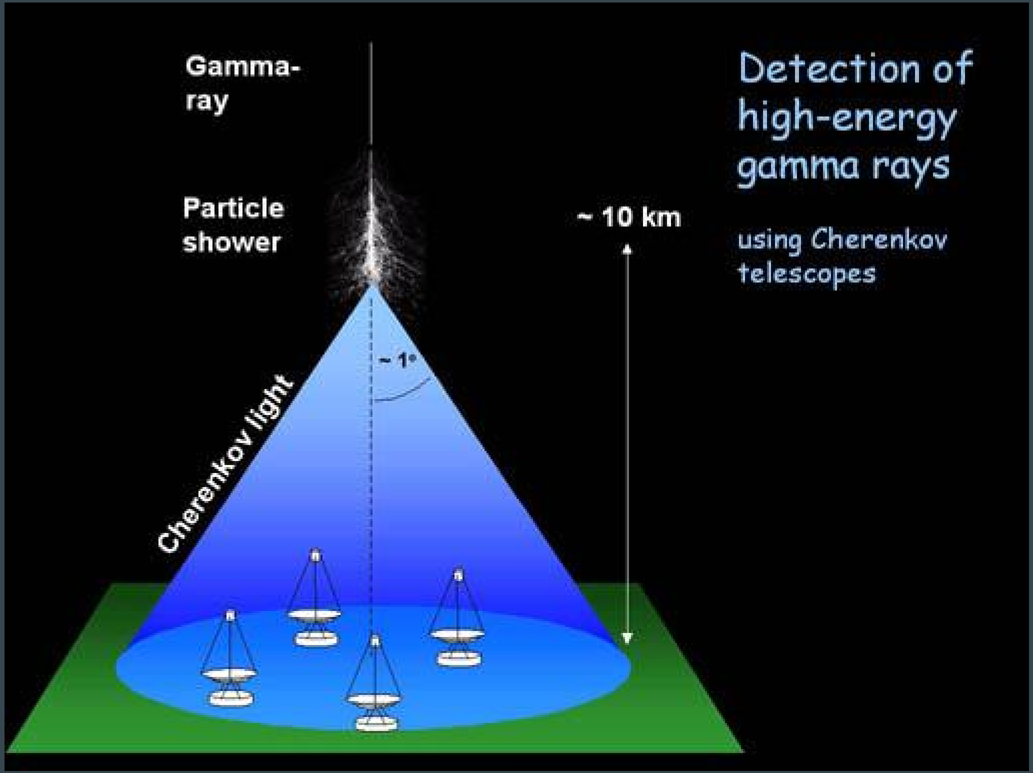




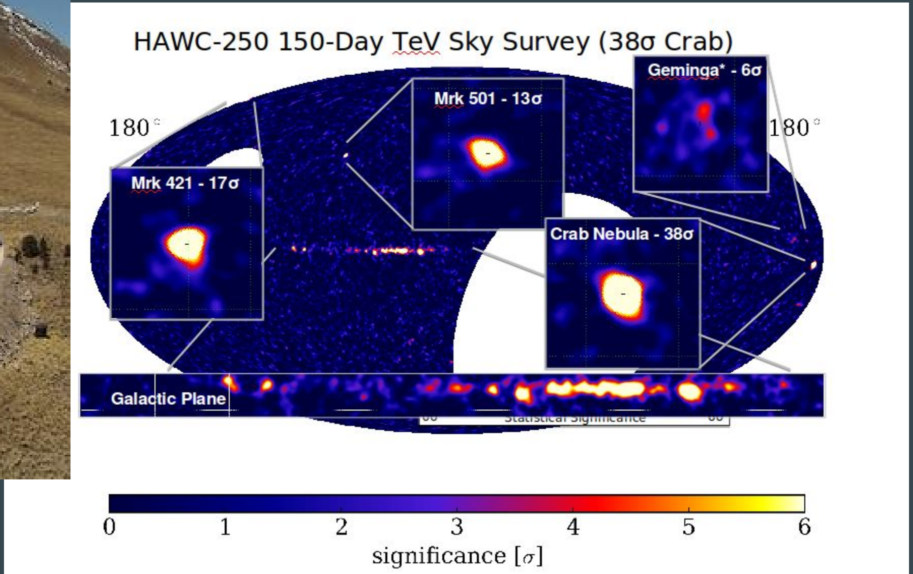
Atmospheric Cherenkov Telescopes



Atmospheric Cherenkov Telescopes

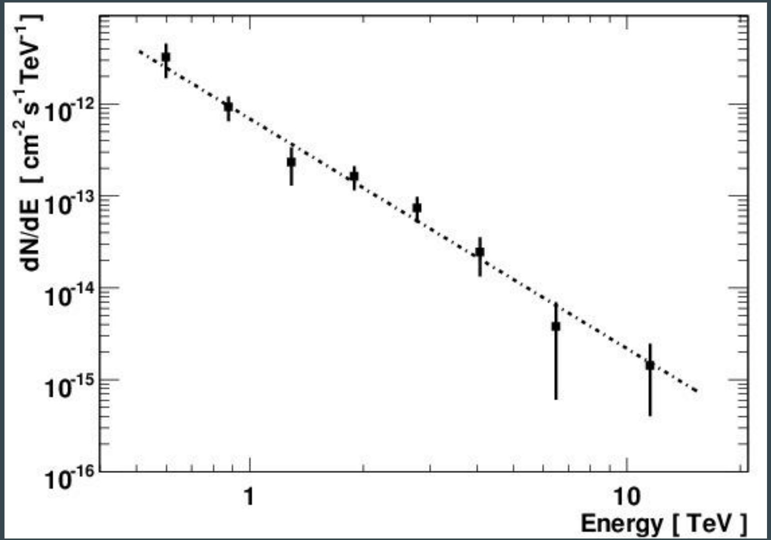


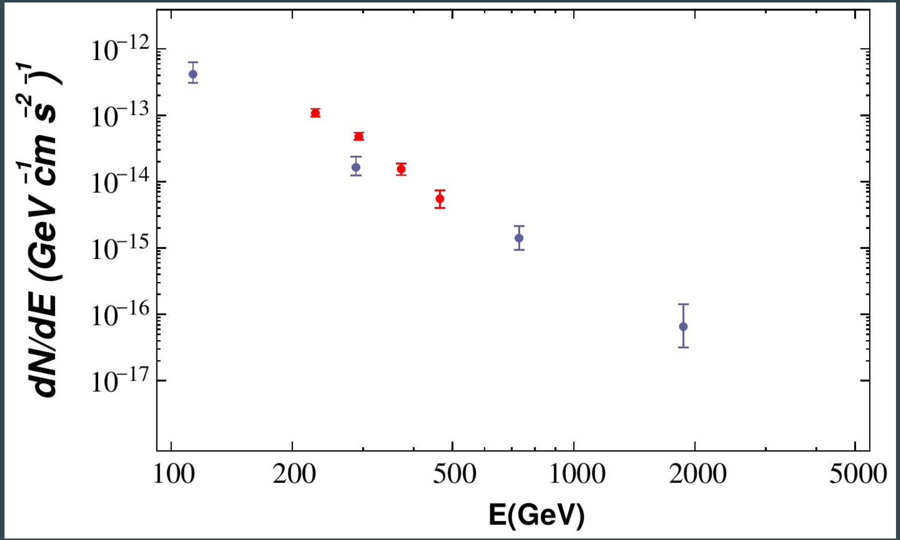
HAWC


HAWC-250 150-Day TeV Sky Survey (38σ Crab)
Geminga* - 6σ
Mrk 501 - 13σ
180°
180°
Mrk 421 - 17σ
Crab Nebula - 38σ
Galactic Plane
0
1
2
3
4
5
6
significance [σ]

Fermi gamma-ray space telescope

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

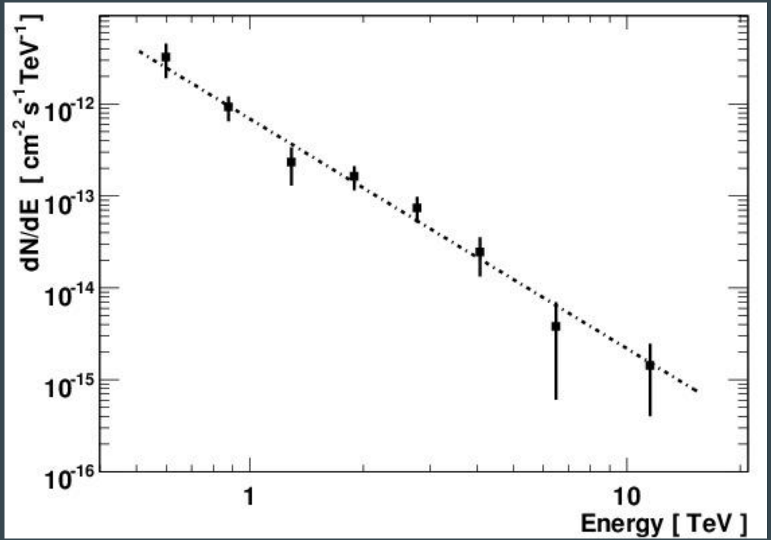


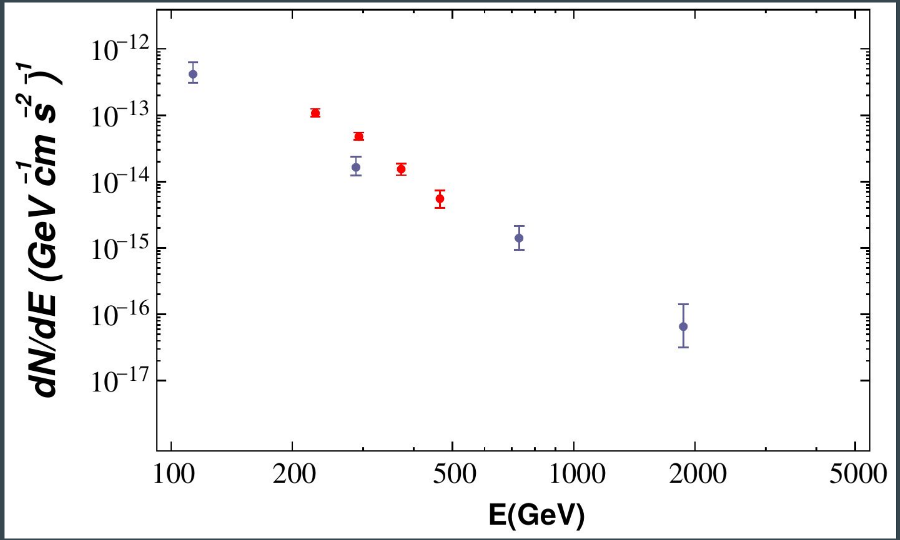


1ES0229+200 (z=0.14)

3C66A (z=0.44)

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





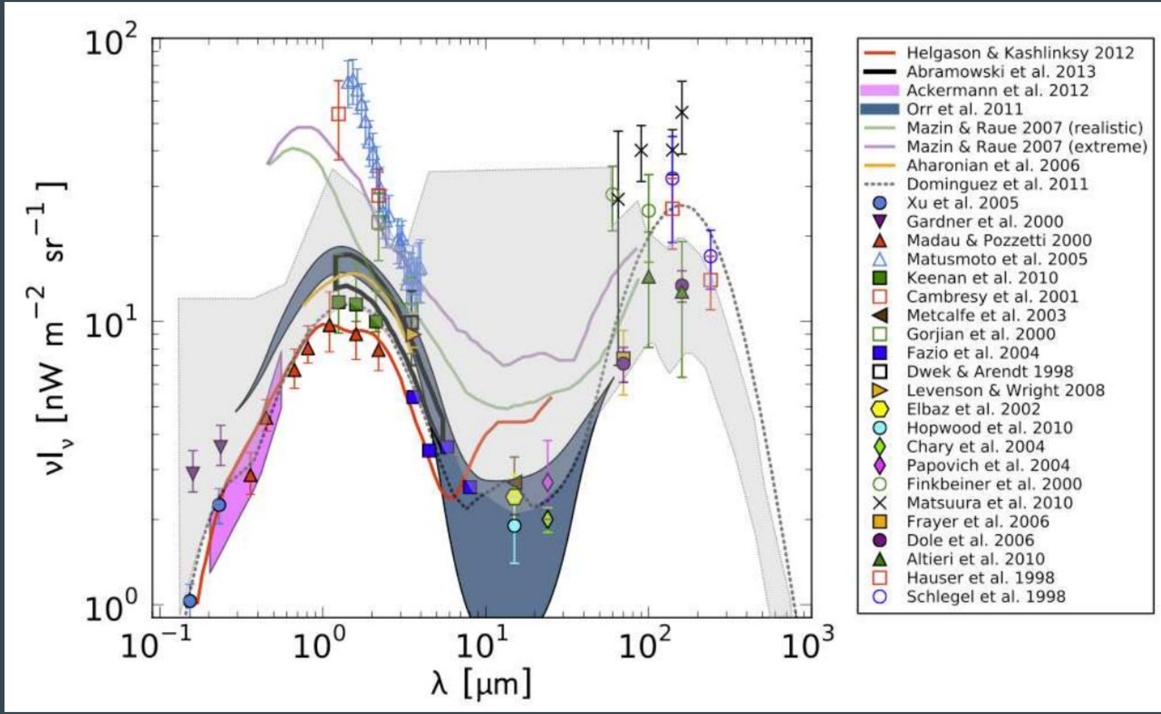
1 ES0229+200 (z=0.14)

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 $\gamma\gamma_{EBL} \rightarrow e^+e^-$

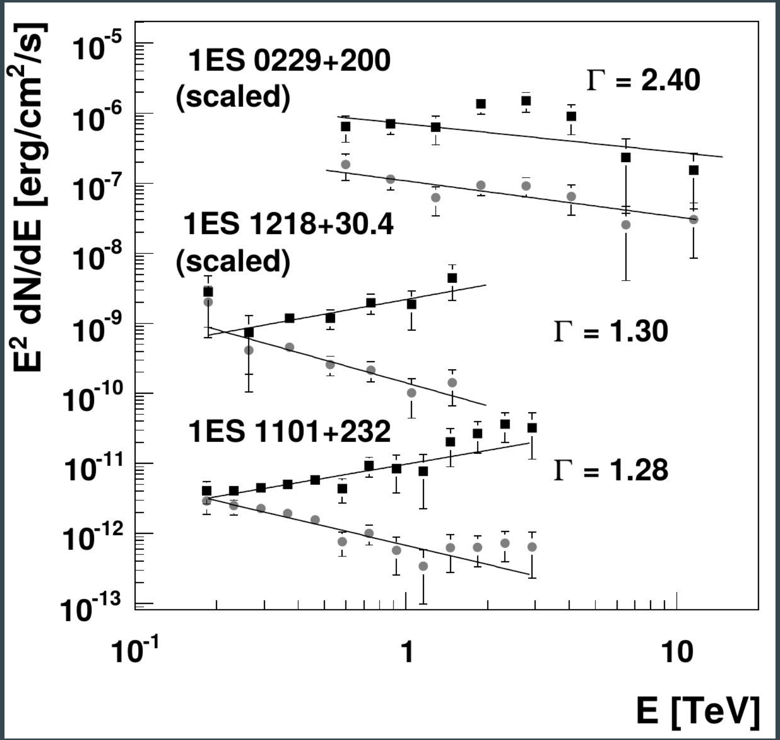
Extragalactic background light



Interactions with EBL must degrade the energies of TeV photons:

$$\gamma\gamma_{EBL} \rightarrow e^+e^-$$

Distant blazars: implausibly hard spectra?

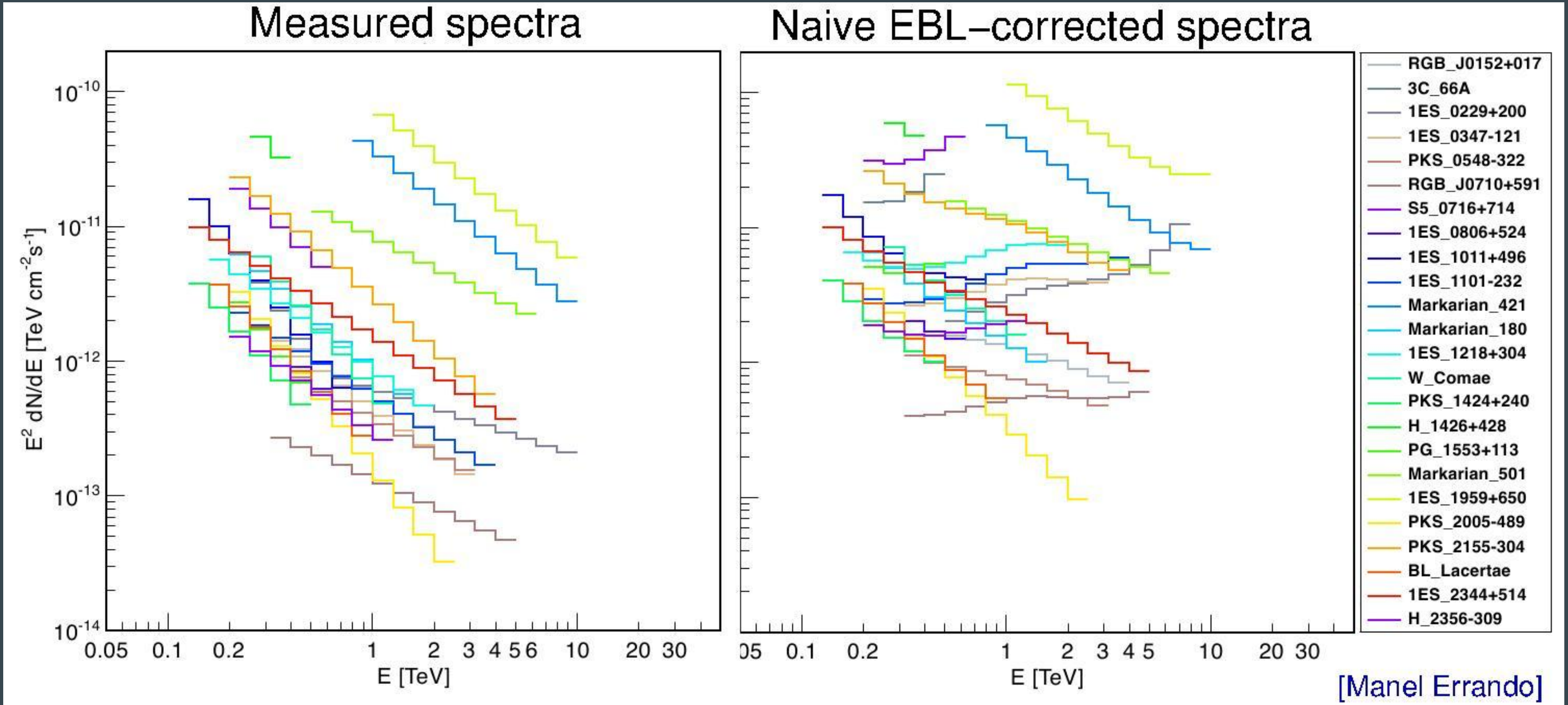


Absorption-corrected spectra would have to be extremely hard for distant blazars:

$$\Gamma < 1.5$$

[Aharonian et al.]

Blazar spectra

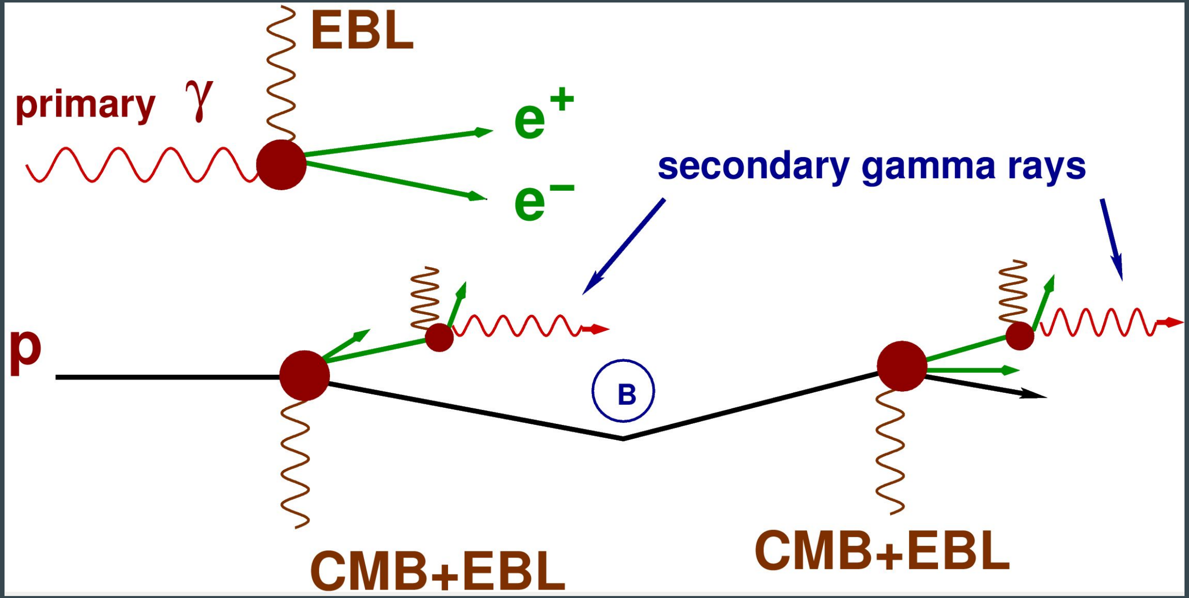


The mysterious transparency of the Universe...

- 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] ~~$\gamma\gamma_{EBL} \rightarrow e^+e^-$~~

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

γ rays and cosmic rays



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

[Essey & AK (2010)]

Different scaling

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

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

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

For distant sources, the secondary signal wins!

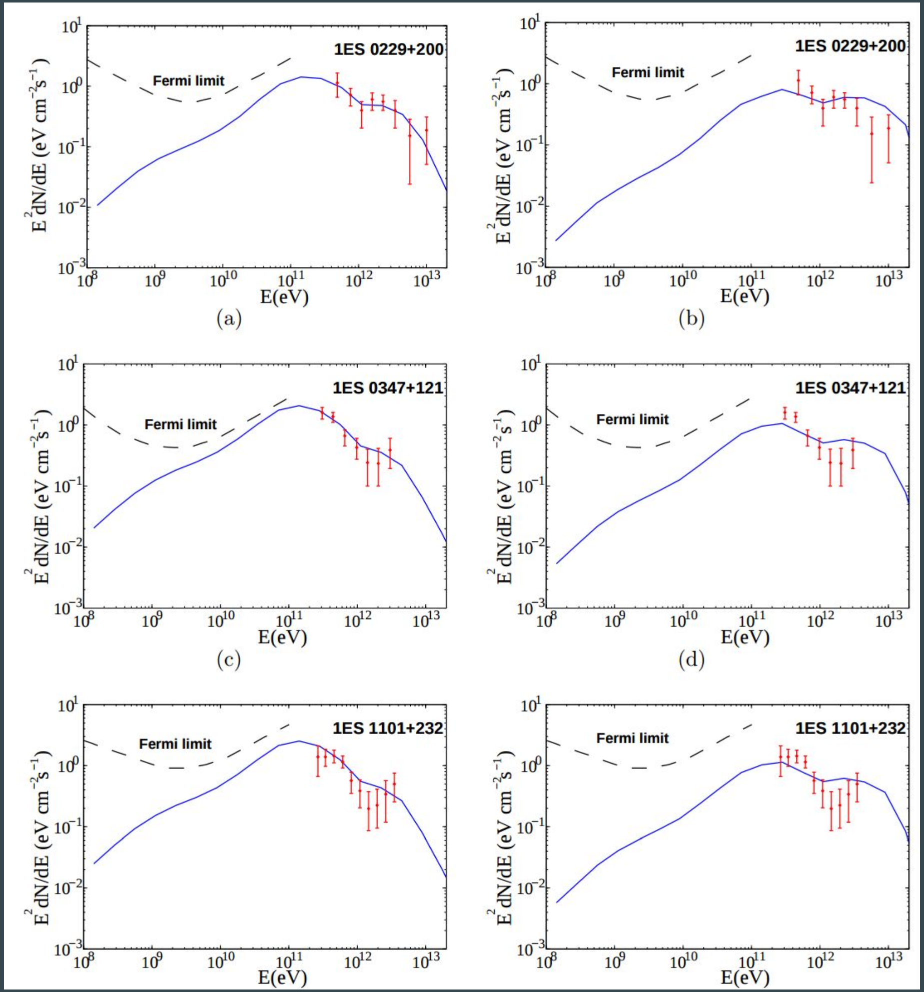
One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

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

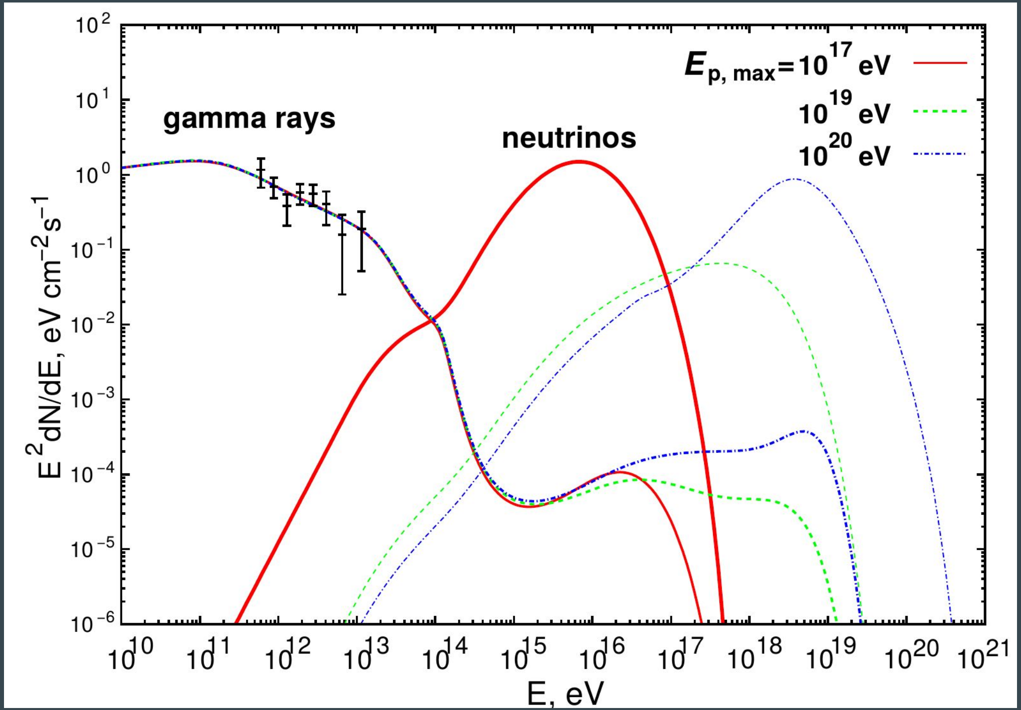
Reasonable CR power for a source up to z~1
[Aharonian, Essey, AK, Prosekin (2013);
Razzaque, Dermer, Finke (2012);
Murase, Dermer, Takami, Migliore (2012)]

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

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



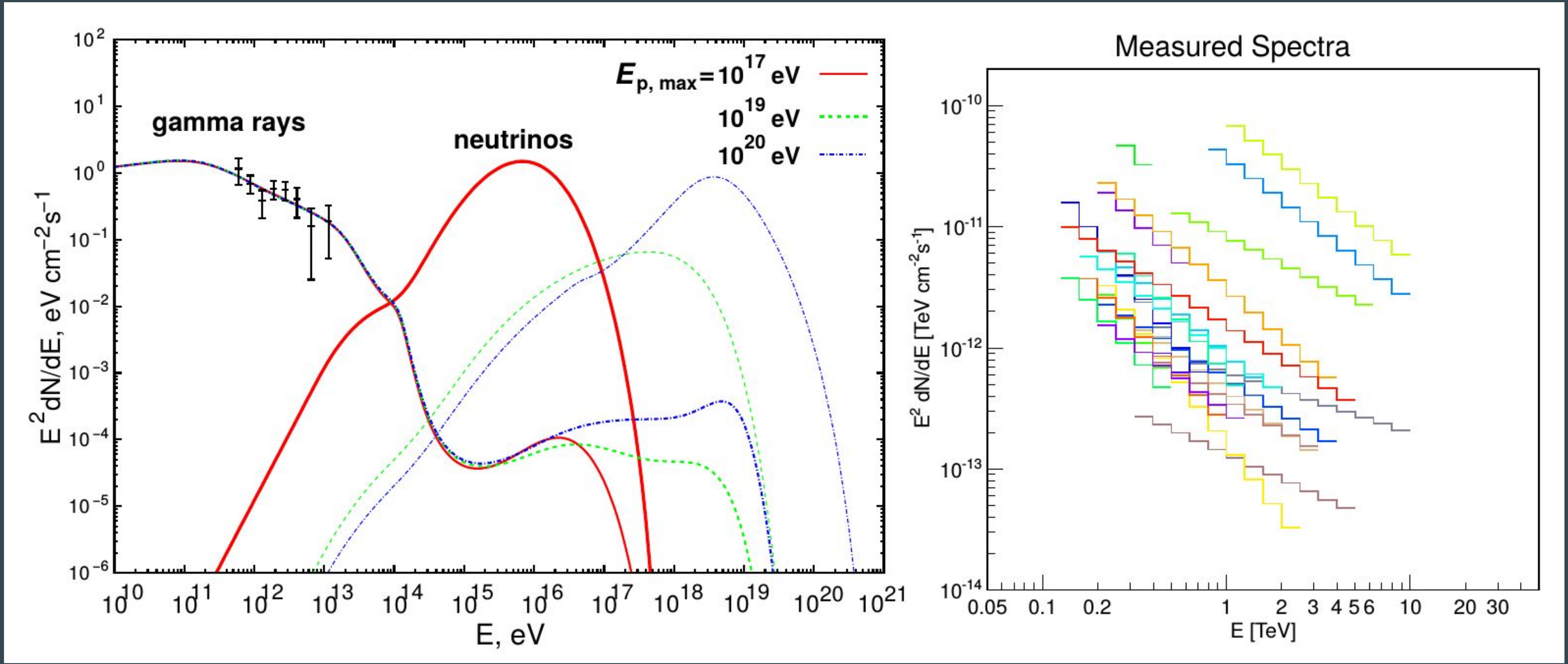
Secondary γ,ν from 1ES0229+200 (z=0.14)



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

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

Robust shapes explain observed universality



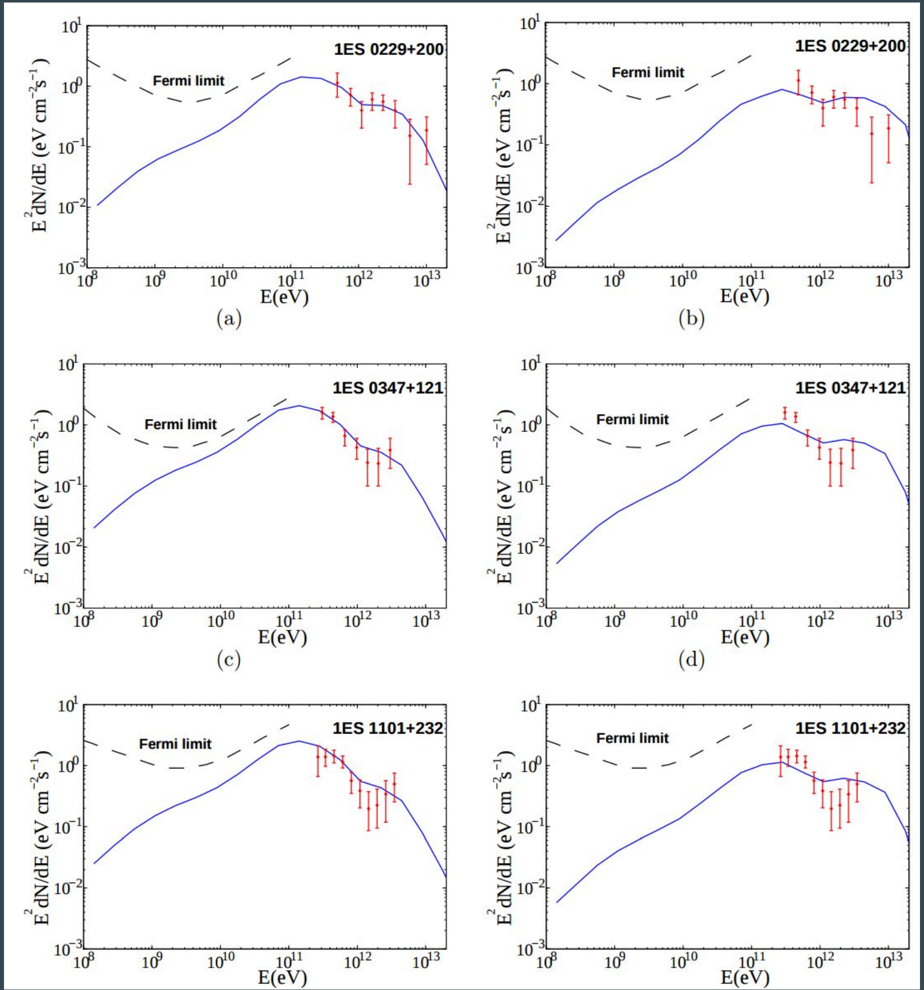
EBL models

"Low EBL" on the left,

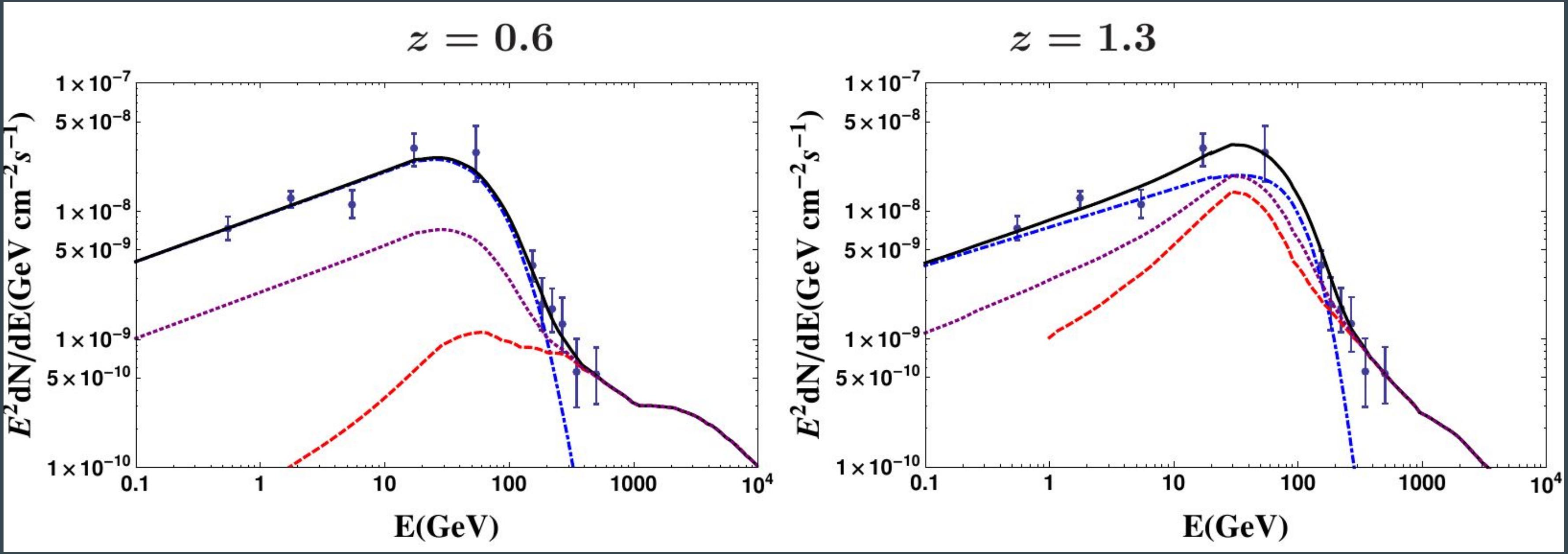
"High EBL" on the right,

Both appear to be consistent. More data needed to distinguish..

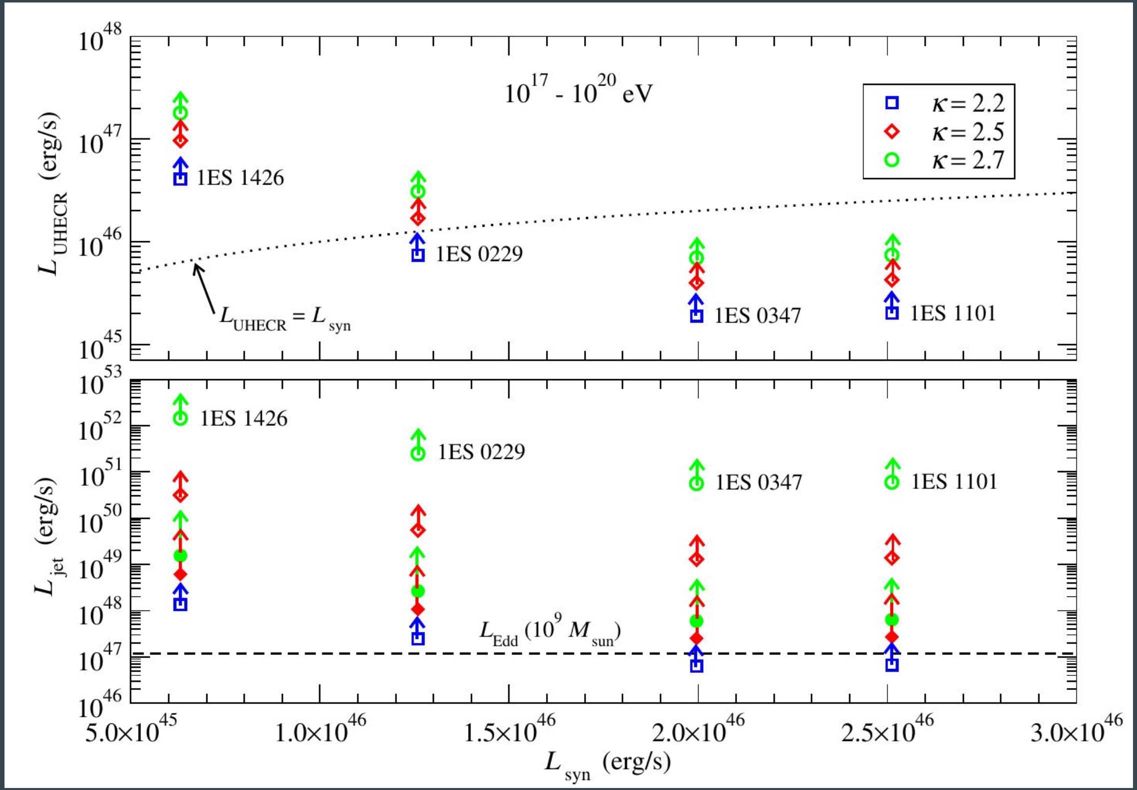
Source	Redshift	EBL Model	L_p , erg/s	$L_{p,\mathrm{iso}}$, erg/s	χ^2	DOF
1ES0229+200	0.14	Low	1.3×10^{43}	4.9×10^{45}	6.4	7
1ES0229+200	0.14	High	3.1×10^{43}	1.1×10^{46}	1.8	7
1ES0347-121	0.188	Low	2.7×10^{43}	1.0×10^{46}	16.1	6
1ES0347-121	0.188	High	5.2×10^{43}	1.9×10^{46}	3.4	6
1ES1101-232	0.186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



PKS 1424+240 at z>0.6 (the most extreme TeV blazar!)



Required power in cosmic rays

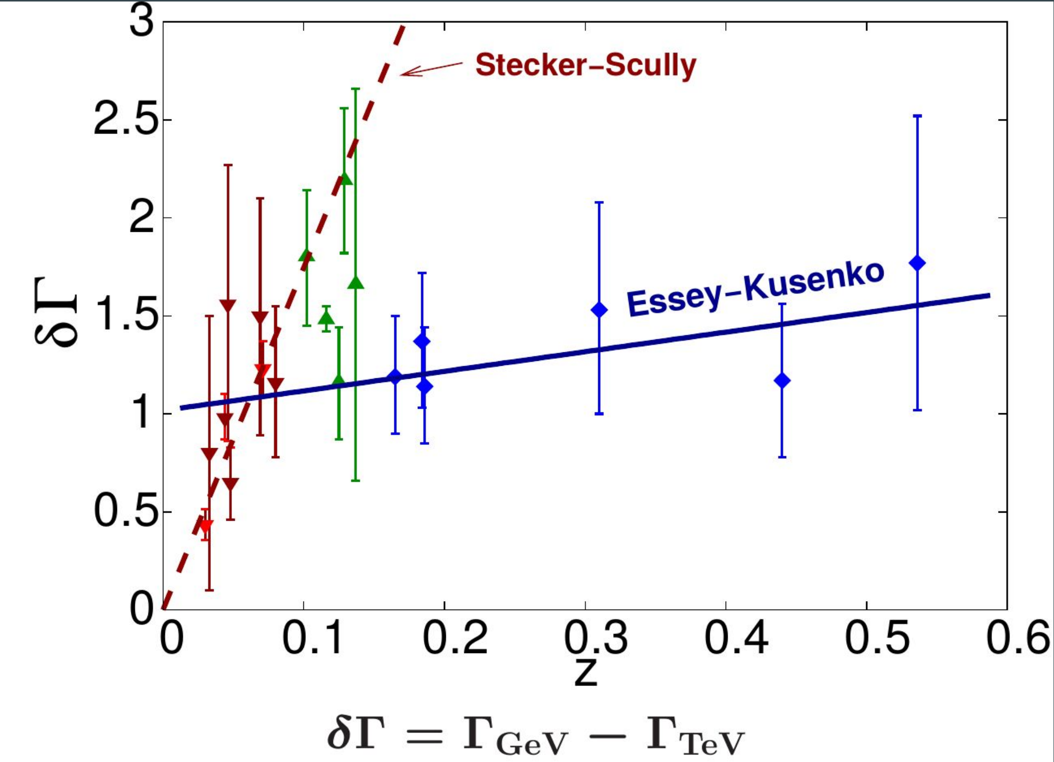


High, but not unreasonable

Consistent with models

[Razzaque et al. (2012)]

Spectral softening



Three populations in red, blue and green are seen in primary, secondary, or mixed components, respectively.

Predictions: no variability for TeV blazars at z>0.15. In good agreement with data.

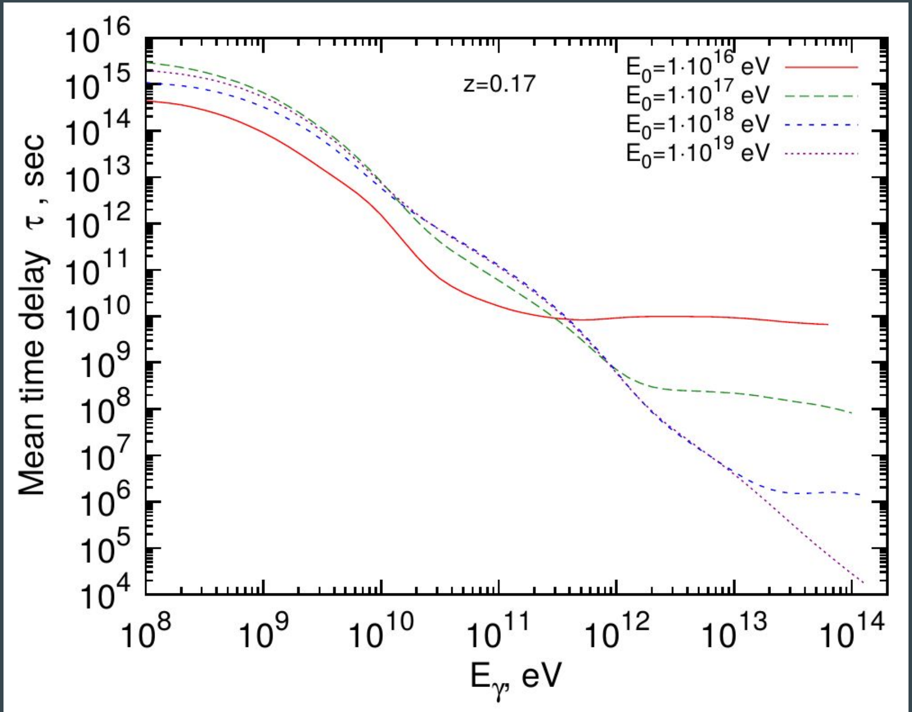
[Prosekin, Essey, AK, Aharonian]

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

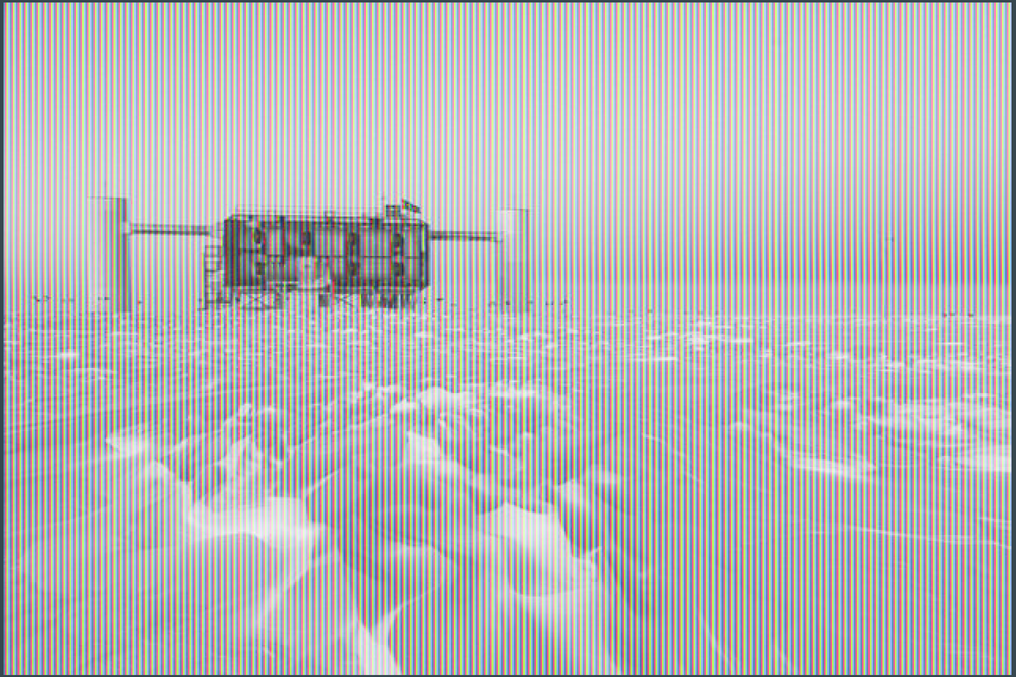
Nearby blazars are variable at all energies. Distant blazars are variable at lower energies, but there is no evidence of variability for, e.g., E>1 TeV, z > 0.15

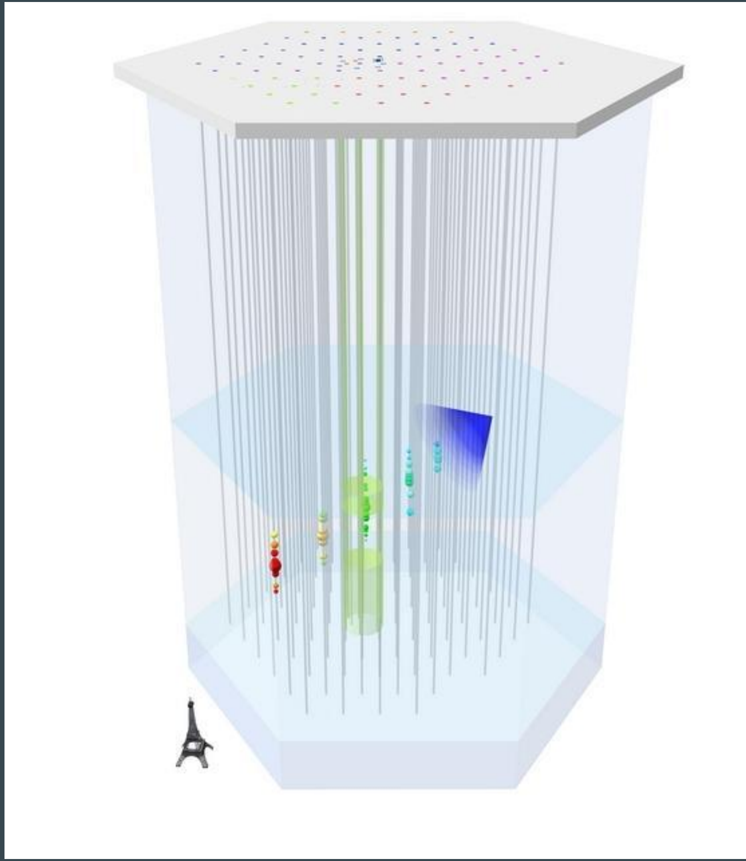
Prediction: stochastic *pedestal* emerges at high energy, high redshifts, for distant blazars above which some flares may rise in a stochastic fashion.

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



IceCube detector

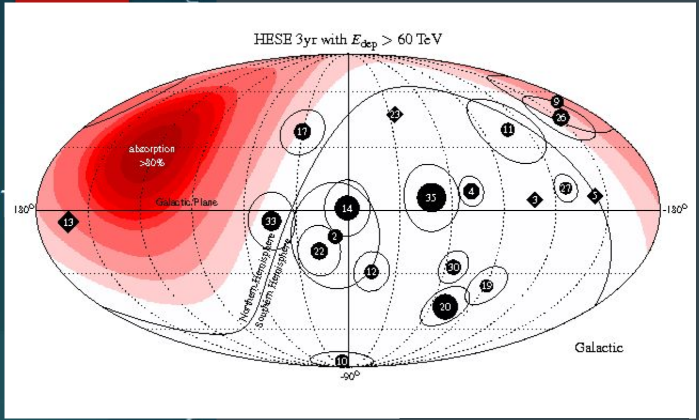




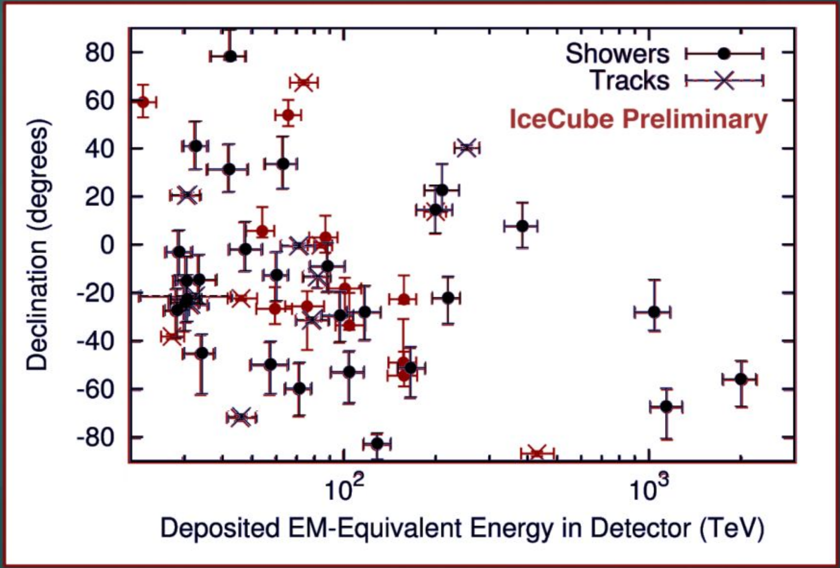
Starting event channel

- Use outer layer of IceCube detector as muon veto
  - Updated from previous publication (3 year sample, PRL 1
    101101) with additional one year of data

• Glowing significance: $4.1\sigma(2y) \rightarrow 5.7\sigma(3y) \rightarrow 6.5\sigma(4y)$
• Increasing number of events: 28(2y) →36+1(3y) →53+1(4y)
• No new over PeV event



Ahlers et al.

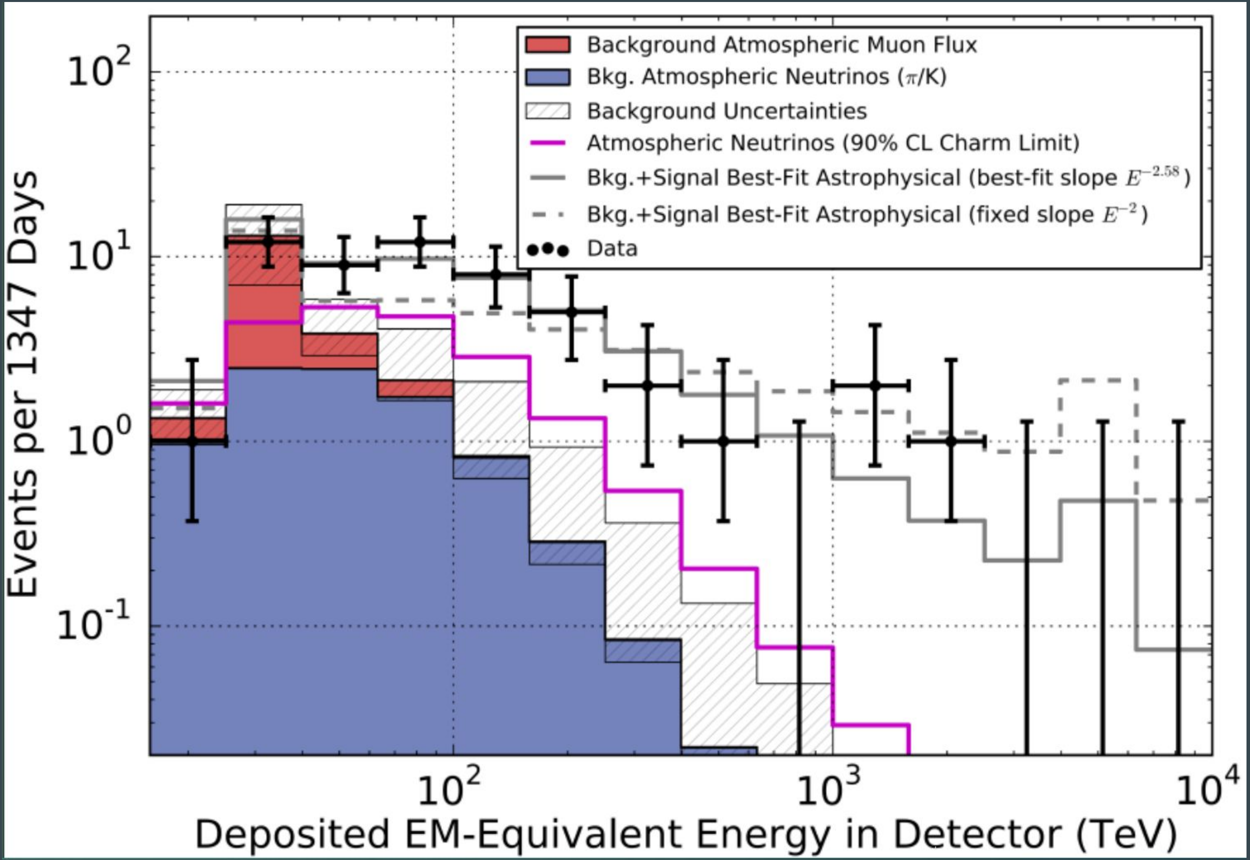


Ishihara

High significance; small backgrounds: atmospheric neutrino backgrounds would appear primarily in the northern sky (top), also at low energies and predominantly as tracks.

The attenuation of high-energy neutrinos in the Earth is visible in the top right of the figure

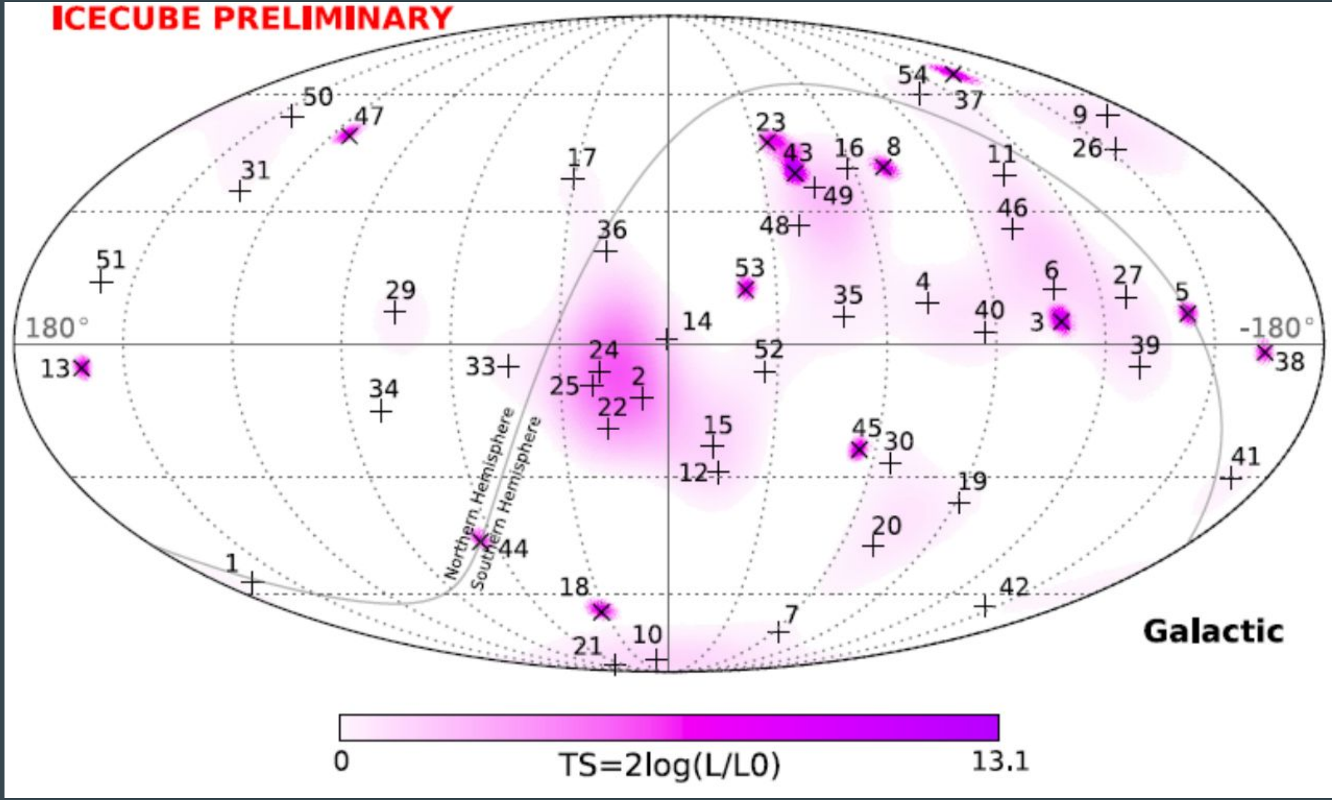
IceCube neutrinos: the spectrum



Power law with a cutoff?

Two components?

IceCube neutrinos: the arrival directions



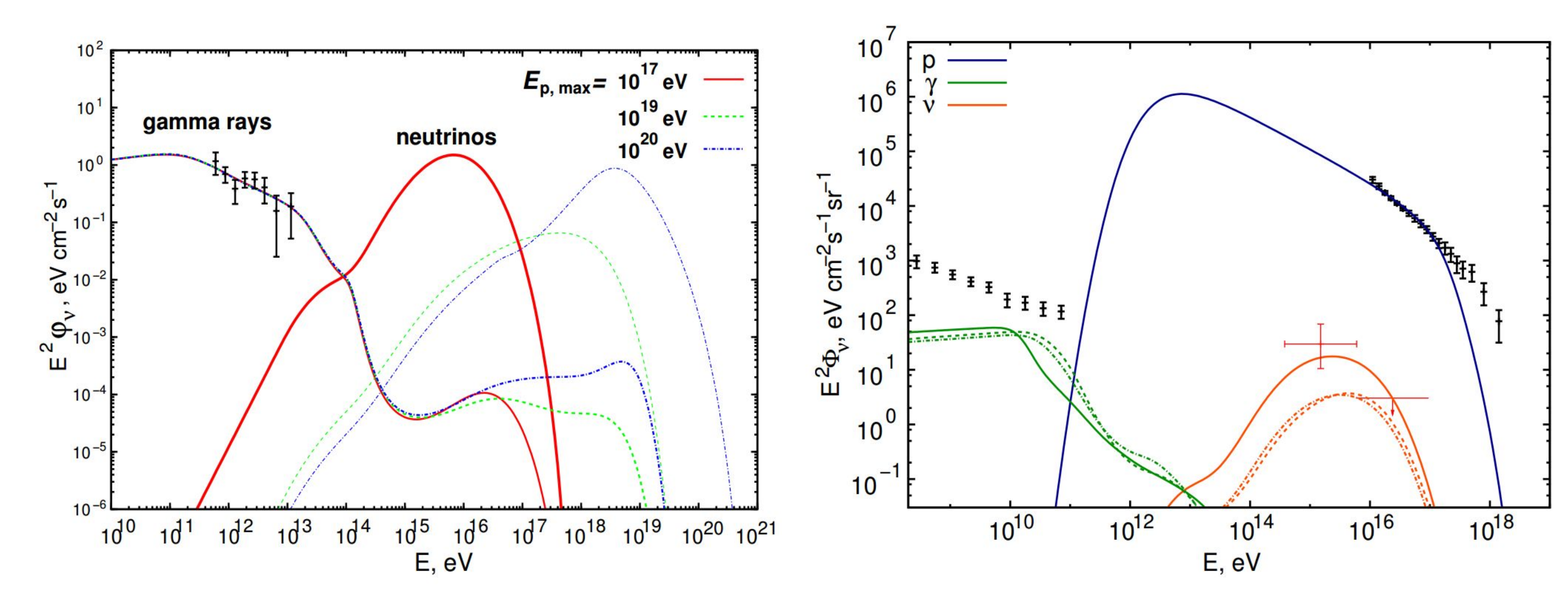
Anisotropy is key to identifying the sources, and also the production mechanism (in some cases).

Consistent with isotropy.

Small anisotropy possible

Two components?

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

A peaked spectrum at 1 PeV can result from cosmic rays accelerated in AGN and interacting with photon backgrounds, assuming that secondary photons explain the observations of TeV blazars.

prediction: PRL 104, 141102 (2010)
consistency with IceCube: PRL 111, 041103 (2013)

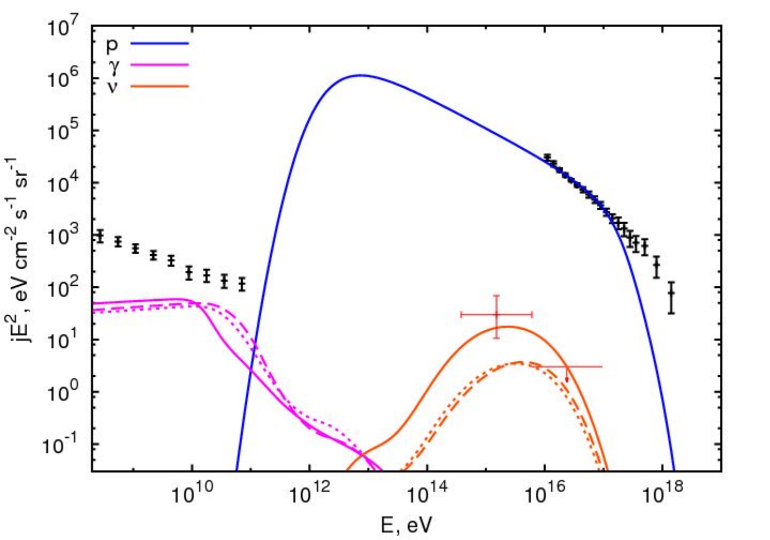
PRL **104**, 141102 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Secondary Photons and Neutrinos from Cosmic Rays Produced by Distant Blazars

Warren Essey,[1] Oleg E. Kalashev,[2] Alexander Kusenko,[1,3] and John F. Beacom[4,5,6]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095-1547, USA*
[2]*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312 Russia*
[3]*IPMU, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
[4]*Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, Ohio 43210, USA*
[5]*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
[6]*Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*
(Received 27 December 2009; revised manuscript received 22 February 2010; published 8 April 2010)

Secondary photons and neutrinos produced in the interactions of cosmic ray protons emitted by distant active galactic nuclei (AGN) with the photon background along the line of sight can reveal a wealth of new information about the intergalactic magnetic fields, extragalactic background light, and the acceleration mechanisms of cosmic rays. The secondary photons may have already been observed by gamma-ray telescopes. We show that the secondary neutrinos improve the prospects of discovering distant blazars by IceCube, and we discuss the ramifications for the cosmic backgrounds, magnetic fields, and AGN models.

DOI: 10.1103/PhysRevLett.104.141102 PACS numbers: 95.85.Pw, 98.54.Cm, 98.70.Sa, 95.85.Ry



PRL **111**, 041103 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei

Oleg E. Kalashev,[1] Alexander Kusenko,[2,3] and Warren Essey[2]
[1]*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312, Russia*
[2]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095-1547, USA*
[3]*Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
(Received 28 February 2013; revised manuscript received 14 June 2013; published 24 July 2013)

The observed very high energy spectra of *distant* blazars are well described by secondary gamma rays produced in line-of-sight interactions of cosmic rays with background photons. In the absence of the cosmic-ray contribution, one would not expect to observe very hard spectra from distant sources, but the cosmic ray interactions generate very high energy gamma rays relatively close to the observer, and they are not attenuated significantly. The same interactions of cosmic rays are expected to produce a flux of neutrinos with energies peaked around 1 PeV. We show that the diffuse isotropic neutrino background from many distant sources can be consistent with the neutrino events recently detected by the IceCube experiment. We also find that the flux from any individual nearby source is insufficient to account for these events. The narrow spectrum around 1 PeV implies that some active galactic nuclei can accelerate protons to EeV energies.

DOI: 10.1103/PhysRevLett.111.041103 PACS numbers: 95.85.Ry, 98.54.Cm, 98.70.Sa

Implications for intergalactic magnetic fields

Magnetic fields along the line of sight:

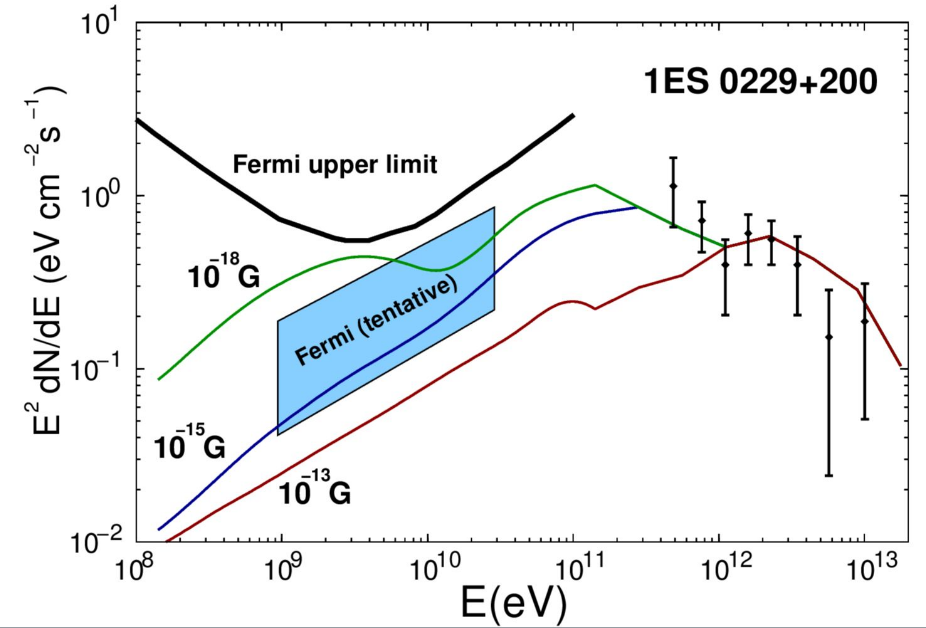
$$1 \times 10^{-17}\ \mathrm{G} < B < 3 \times 10^{-14}\ \mathrm{G}$$

Essey, Ando, AK (2011)

Lower limits: see also Finke et al. (2015)

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]



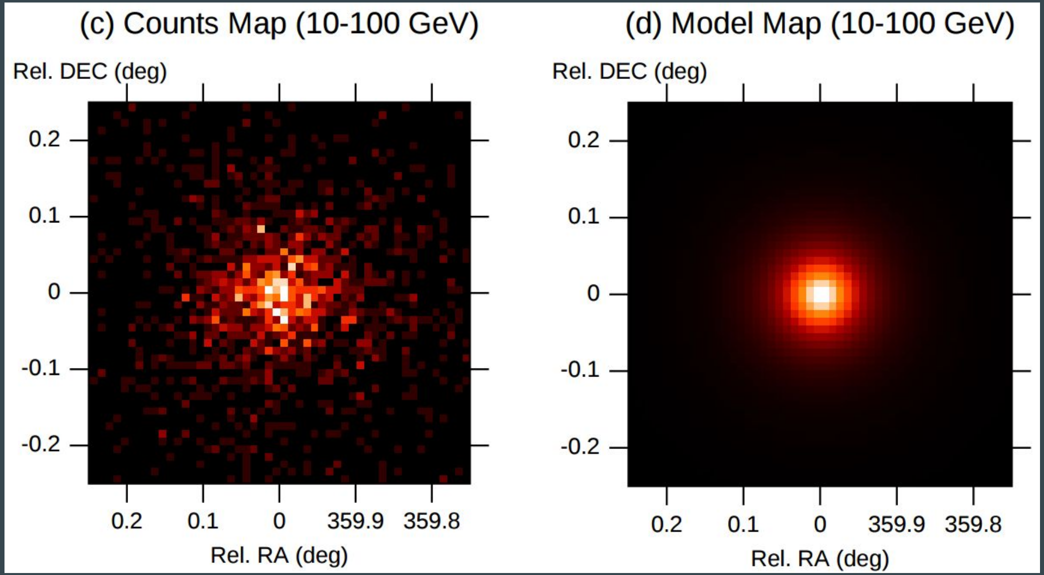
Essey, Ando, AK (2011)

Blazar halos: an independent measurement of IGMFs

Halos around stacked images of blazars implying

$B \sim 10^{-15}$ G

were reported (3.5σ) in 1st year Fermi data [Ando & AK, ApJL 722 (2010) L39].



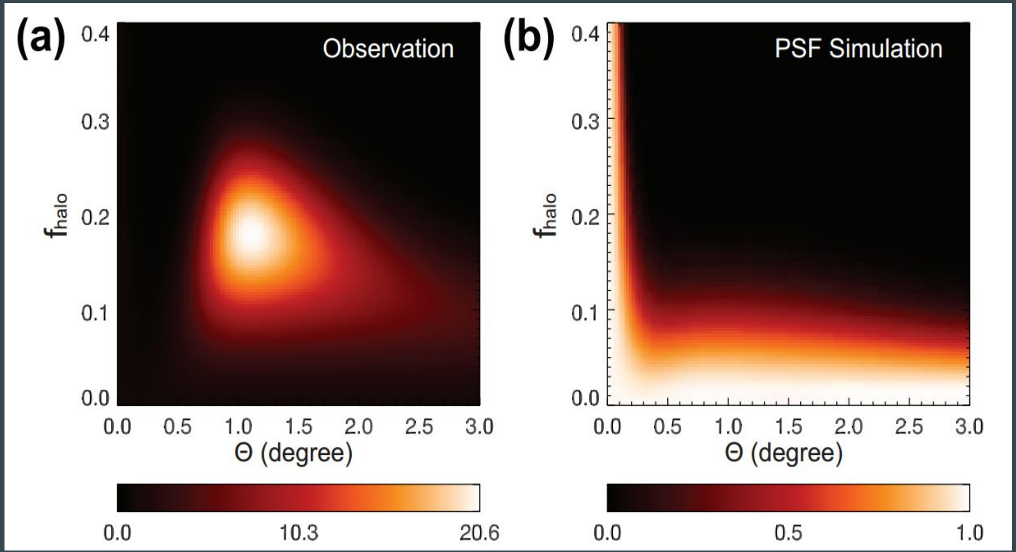
Ando & AK, ApJL 722 (2010)

Blazar halos: an independent measurement of IGMFs

Halos around stacked images of blazars implying **B~10^{-15} G** were reported (3.5σ) in 1st year Fermi data [Ando & AK, ApJL 722 (2010) L39].

Now the same technique was applied to the much larger Fermi data set, detecting lower energy halos of z< 0.5 blazars. The results, **B~10^{-17} -- 10^{-15} G** [Chen, et al. (2015)], confirm earlier results of Ando & AK, arXiv:1005.1924.

Consistent with independent measurement based on the gamma-ray spectra of blazars [Essey, Ando, AK, arXiv:1012.5313]



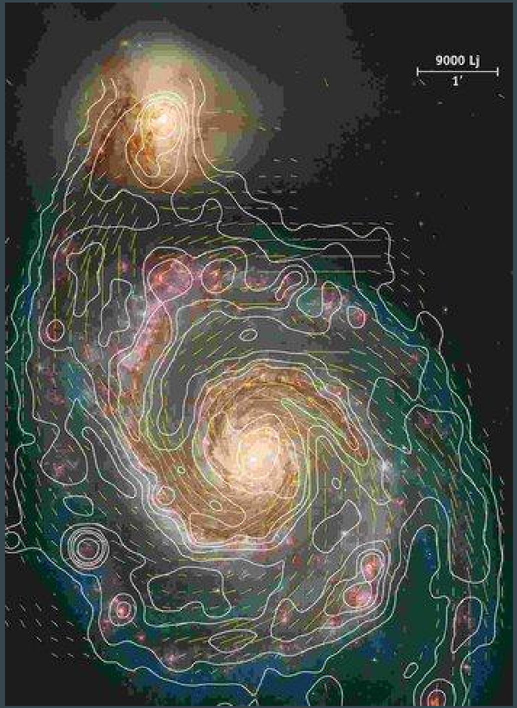
Chen, Buckley, Ferrer, Phys. Rev. Lett. (2015) confirm halos, IGMFs in the **B~10^{-17} -- 10^{-15} G** range

Extragalactic magnetic fields: a new window on the early universe?

Baryogenesis and intergalactic magnetic fields

Magnetic fields in galaxies can arise from dynamo action if there are primordial seeds. Alternatively, they can be generated by Biermann battery or another mechanism.

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



Magnetic fields and the matter-antimatter asymmetry

Matter-antimatter asymmetry of the universe is well measure, but the origin is not known.

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \times 10^{-10} (\text{CMB, nucleosynthesis, etc.})$$

Sakharov's conditions for baryogenesis:

- Baryon number nonconservation
- C, CP violation
- Departure from thermal equilibrium

Leptogenesis

It turns out that it might be easier to generate the lepton asymmetry first, because the existence of the neutrino masses implies non-conservation of L.

At high temperature, the Standard Model interactions preserve (B-L)=const,
but not B,L separately, and (B+L) is driven toward zero.

As a result, a non-zero lepton asymmetry leads to a baryon asymmetry, that is,
to matter- antimatter asymmetry of the universe

(B+L) asymmetry and the primordial magnetic helicity

Magnetic helicity or Chern-Simons term for the U(1) of hypercharge:

$$h_Y(t) \equiv \lim_{V\to\infty} \frac{1}{V} \int_V d^3x \, \mathbf{Y} \cdot \mathbf{B}_Y$$

$$\partial_\mu j^\mu_{e_R} = -\frac{g'^2}{16\pi^2} Y_{\mu\nu} \tilde{Y}^{\mu\nu}$$

$$n_{e_R} - n_{e^c_R} = \lim_{V\to\infty} \frac{1}{V} \int_V d^3x \, j^0_{e_R}$$

$$h_Y = -\frac{2\pi}{\alpha_Y} \left(n_{e_R} - n_{e^c_R} \right)$$

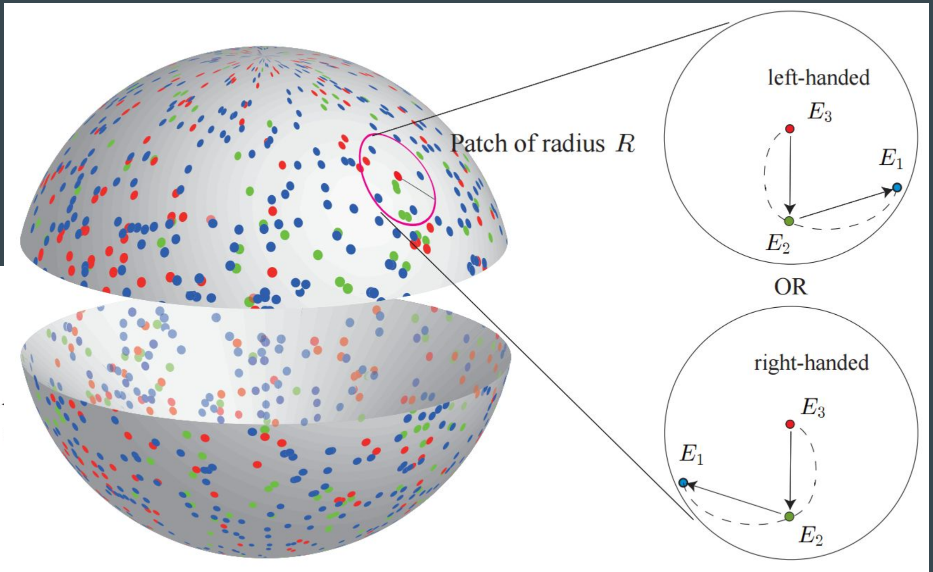
$$h_Y = -\frac{2\pi}{\alpha_Y} \left(n_{e_R} - n_{e^c_R} \right)$$

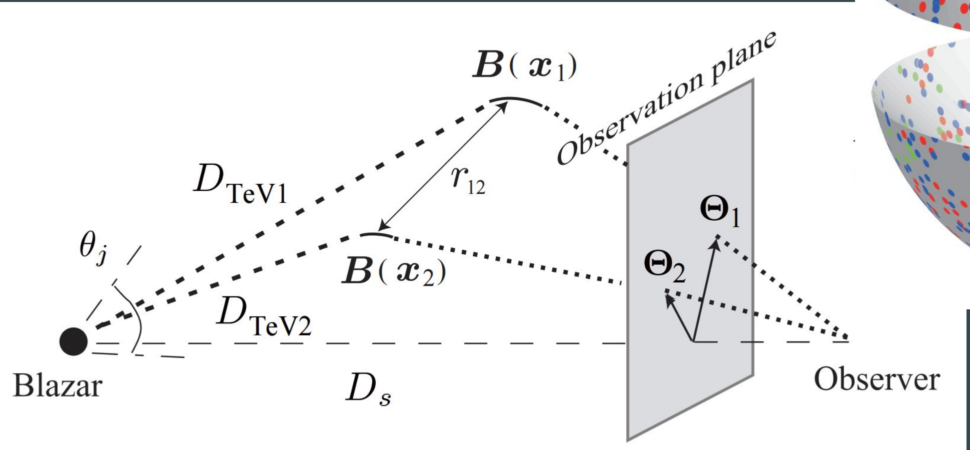
[Cornwall; Vachaspati et al.]

Can the helicity be observed?

Magnetic helicity may be observable

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





Tashiro, Chen, Ferrer, Vachaspati (2014)

Conclusion

- We have learned a lot from treating gamma rays and cosmic rays consistently
- 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)
- Now as we understand the “beam”, we can use it to test the cosmic photon backgrounds (EBL) and magnetic fields
- The first measurements of the magnetic fields are exciting:
possibly, a new window on the universe
- If helicity measurement is confirmed, there may be an additional handle on the origin of the matter-antimatter asymmetry of the universe