Cosmic connections: signatures of cosmic rays in gamma ray and neutrino data

Alexander Kusenko
(UCLA and Kavli IPMU)

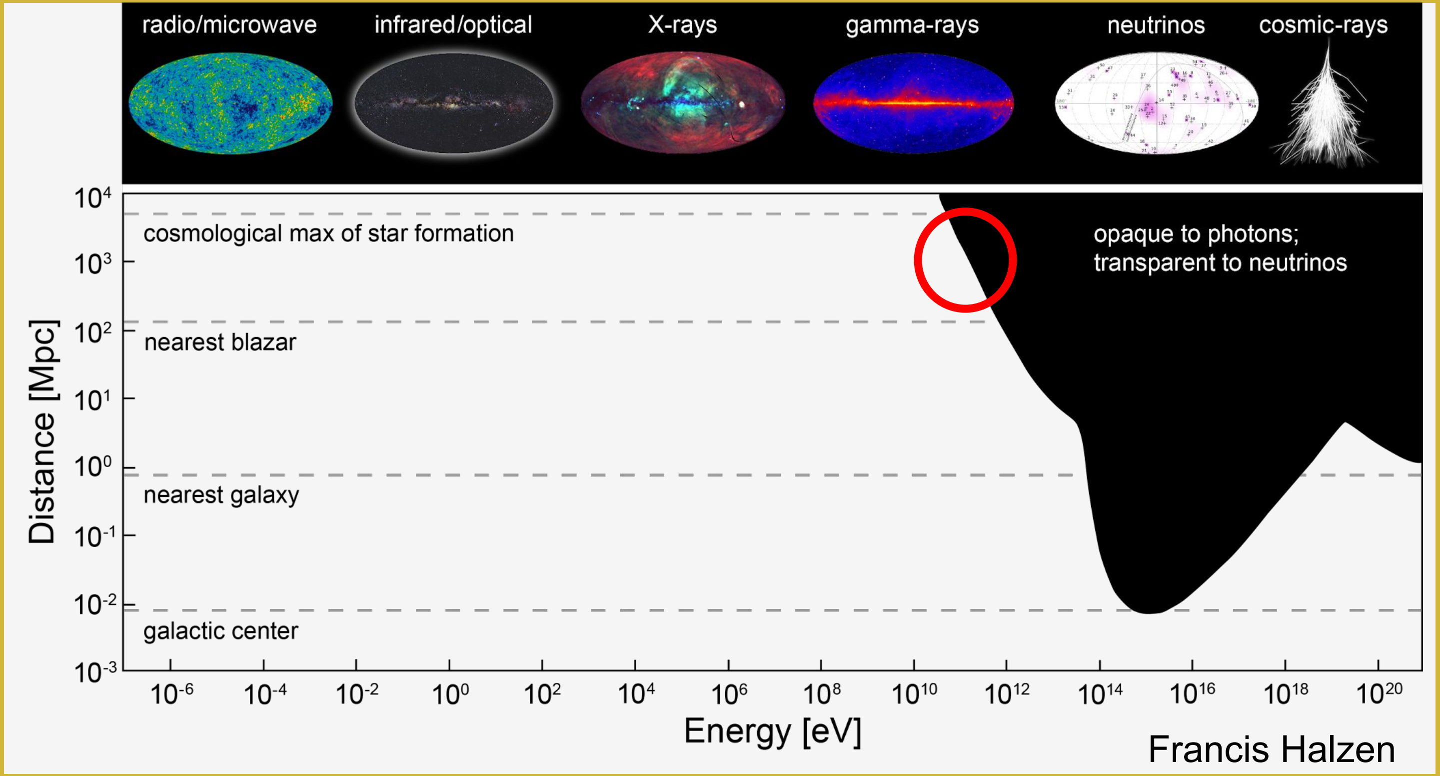
TeVPA 2026
August 31, 2026

Supported by U.S. DOE Office of Science (HEP) and WPI, Japan

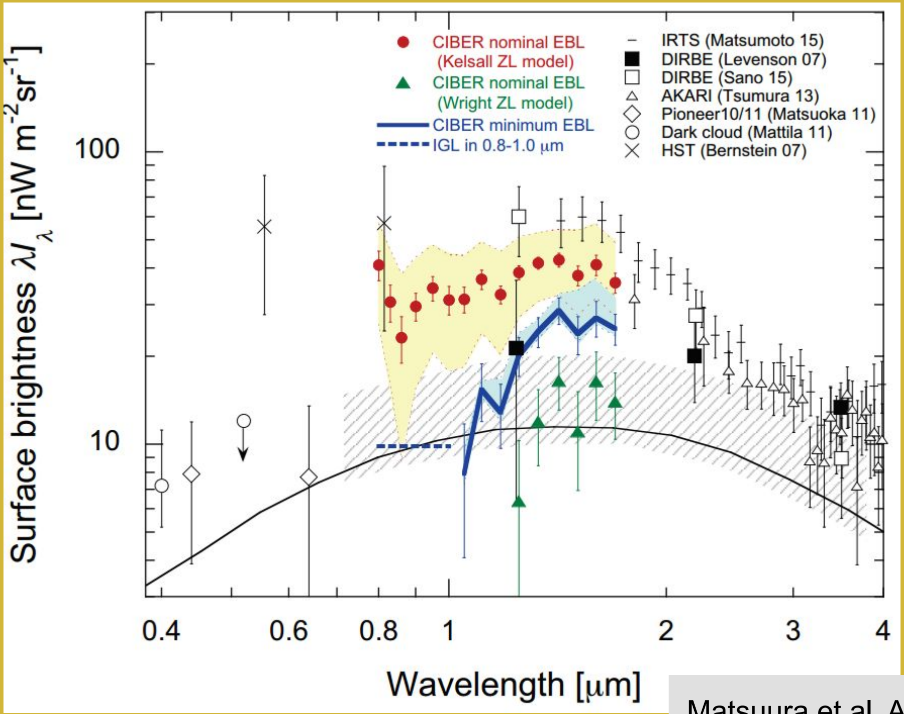
Identifying new connections

- cosmic ray protons in gamma ray and neutrino data
    - extreme EBL obscured outliers provide an opportunity; their spectra are consistent with line-of-sight interactions of cosmic rays accelerated in the source
    - Implications for acceleration models, extragalactic magnetic fields
- cosmic ray nuclei and gamma-ray lines
- cosmic ray nuclei and neutrinos

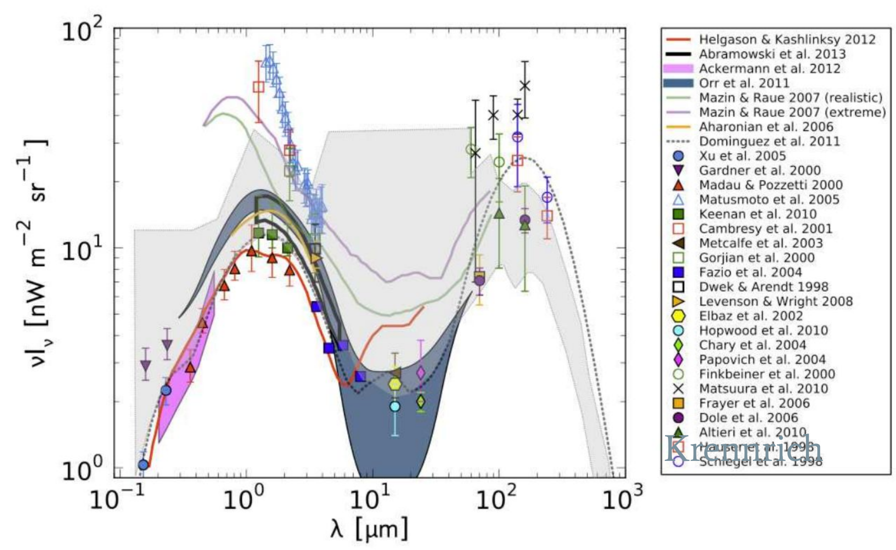
Seeing farther with secondary gamma rays



Extragalactic background light



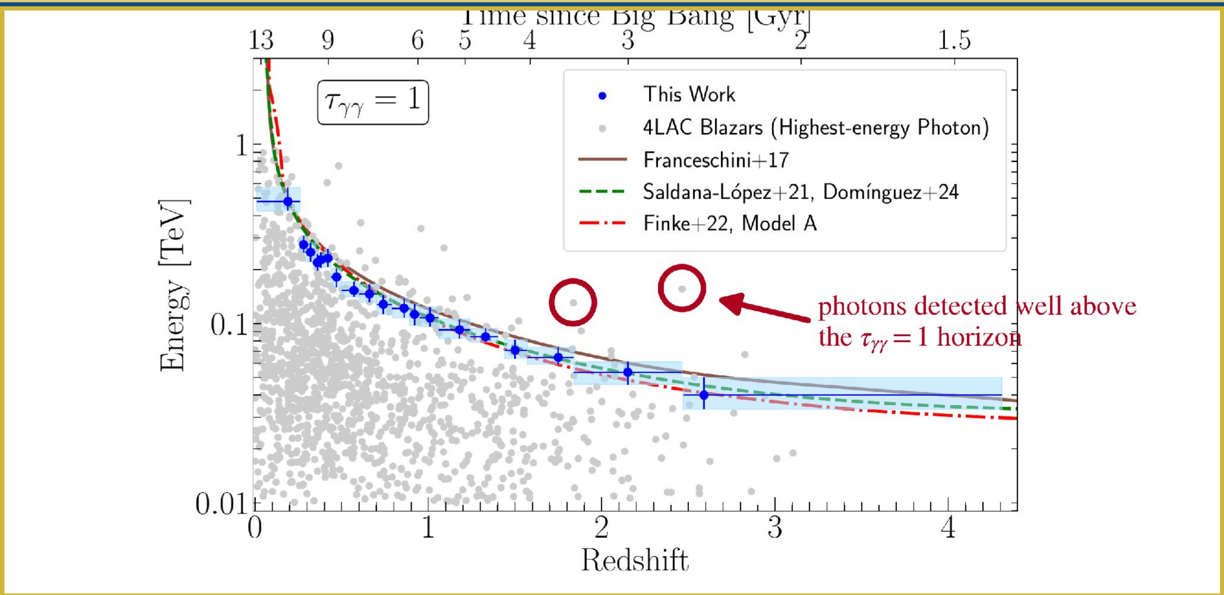
Matsuura et al. ApJ 839,7,2017



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

EBL absorption is the rule — the exceptions are interesting

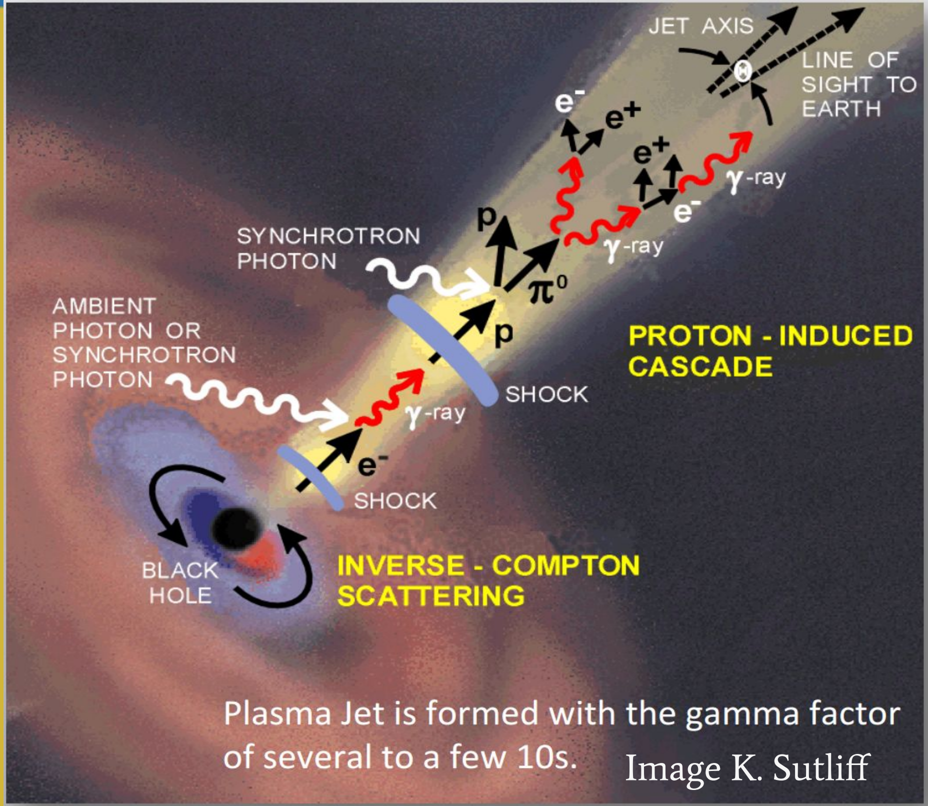
1576 blazars over 0 < z < 4.3
EBL attenuation at ~23σ, and the cosmic gamma-ray horizon measured at 19 epochs.

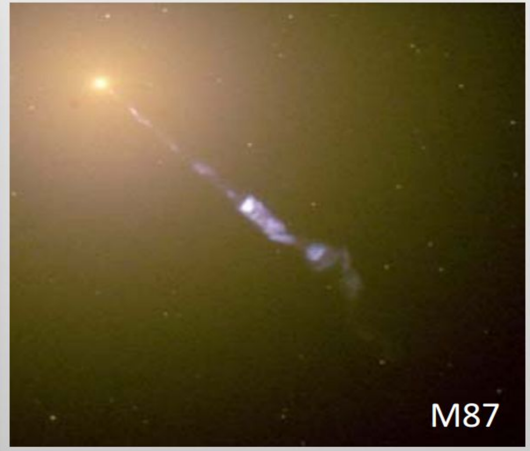


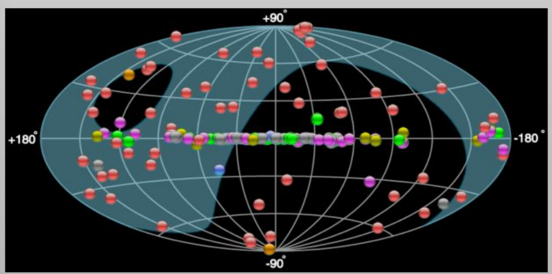
Grey: the single highest-energy photon from each blazar. Banerjee et al. 2026, arXiv:2604.09139, Fig. 6 (annotation added)

The exceptions sit far above the horizon, where the universe should be opaque — efficient cosmic-ray accelerators, and the sources that pin down the EGMF: B > 2.1 × 10^{-17} G from 1ES 0502+675.

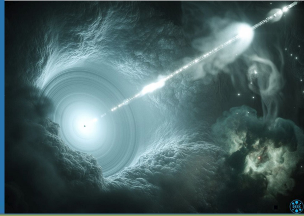
Blazars: supermassive black holes with a jet

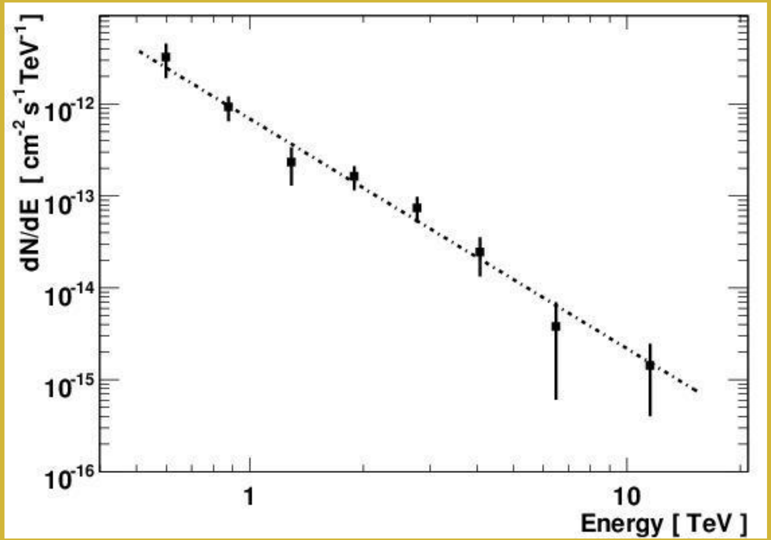




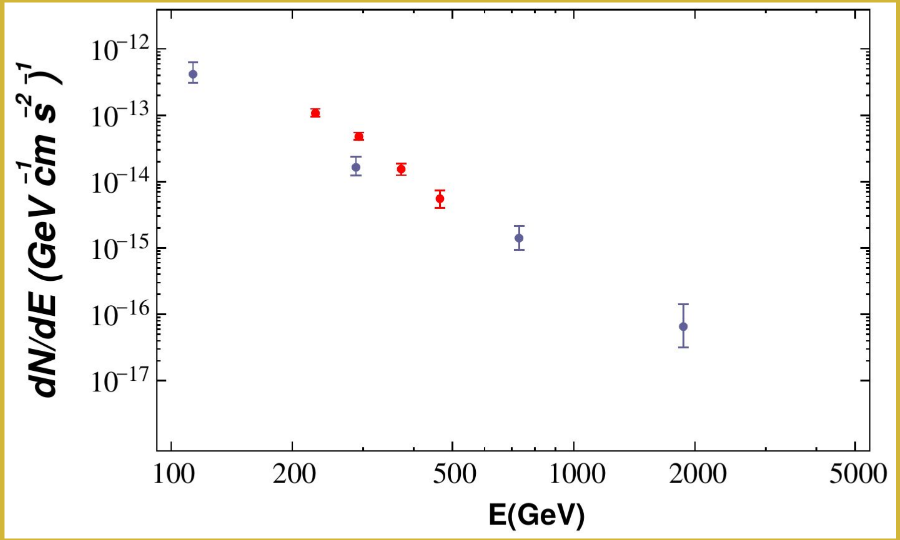


HESS(black), MAGIC (blue), VERITAS (red)



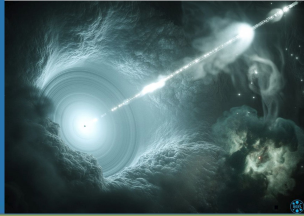


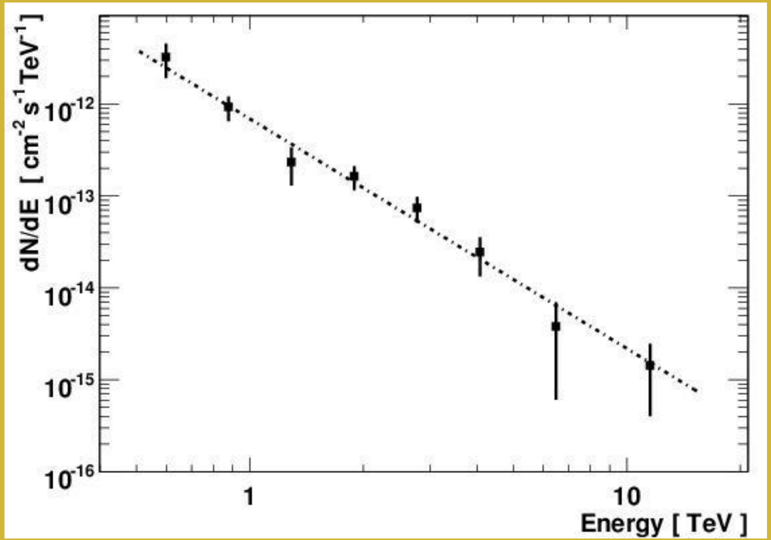
1 ES0229+200 (z=0.14)



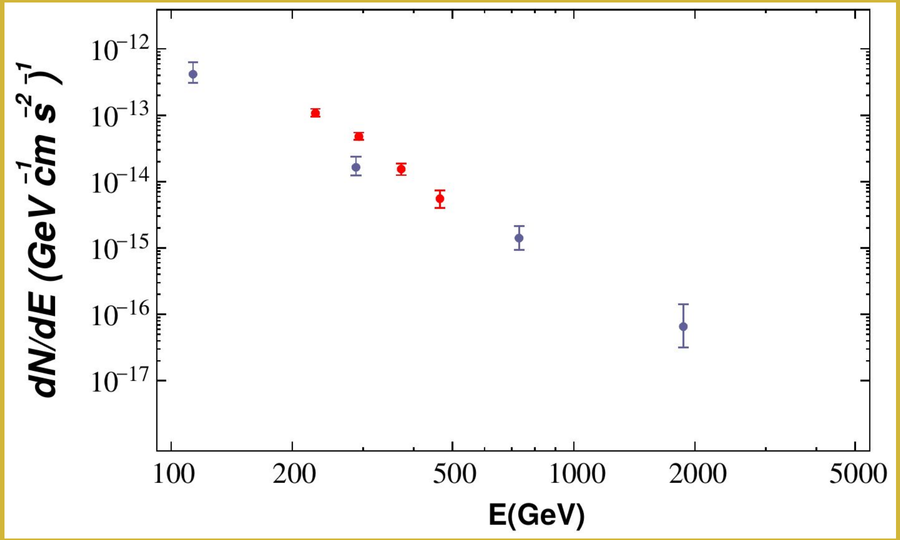
3C66A (z=0.34)

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





1 ES0229+200 (z=0.14)



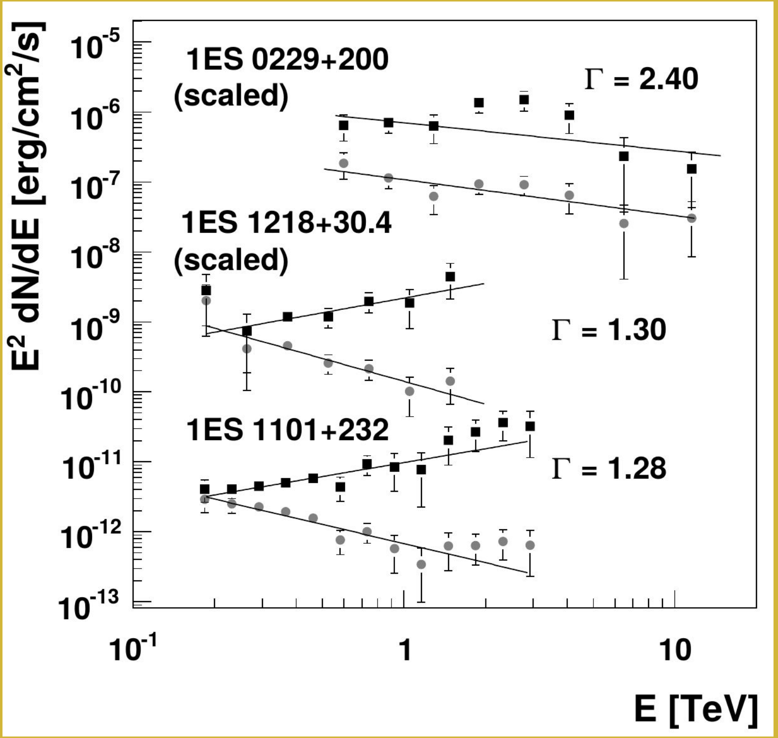
3C66A (z=0.34)

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

Data: no cutoff seen.

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

Distant blazars: outliers with implausibly hard spectra



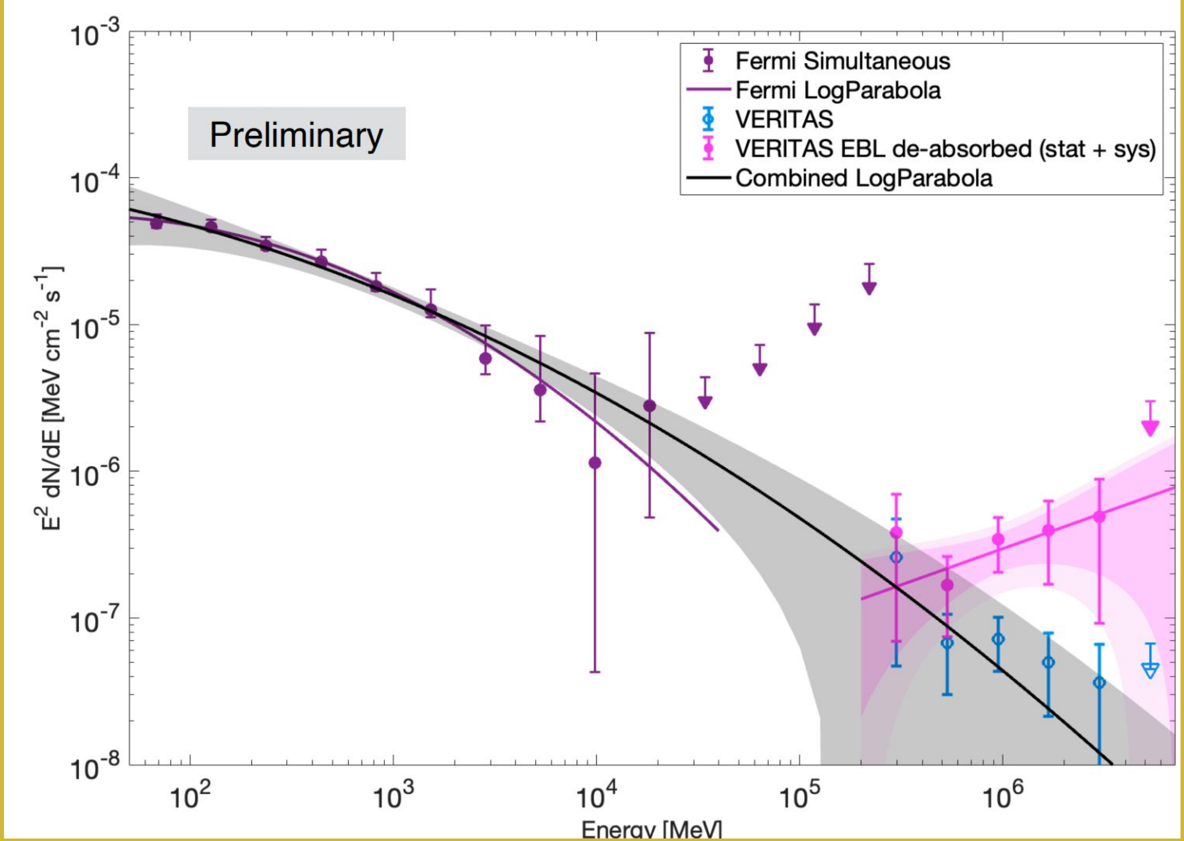
Absorption-corrected spectra would have to be extremely hard for distant blazars:

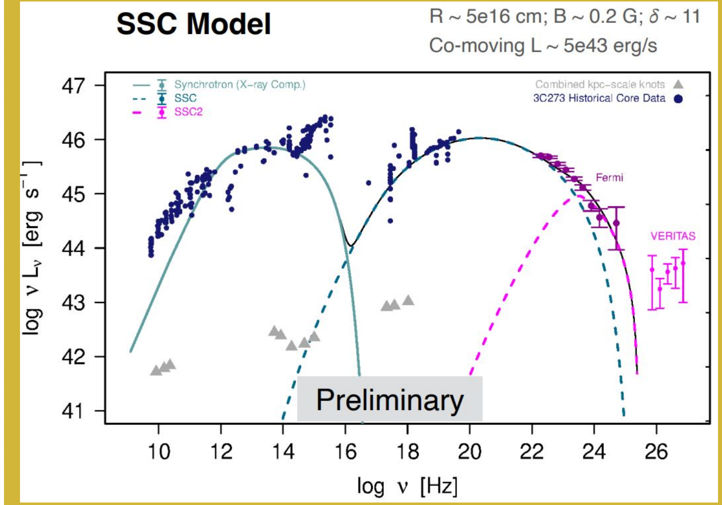
$$\Gamma < 1.5,$$

challenging acceleration models

[Aharonian et al.]

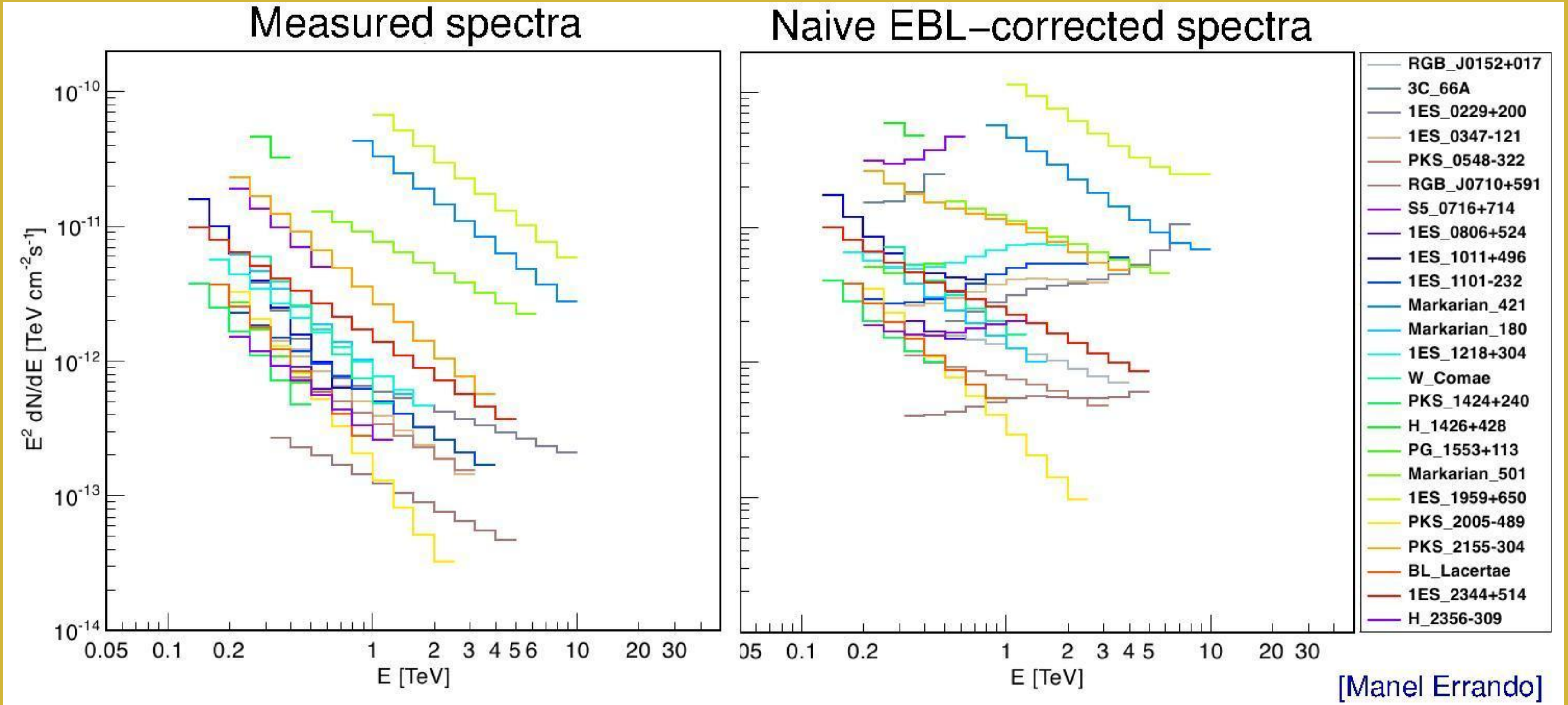
3C 273 (z = 0.158) — VERITAS, preliminary (ICRC 2025)



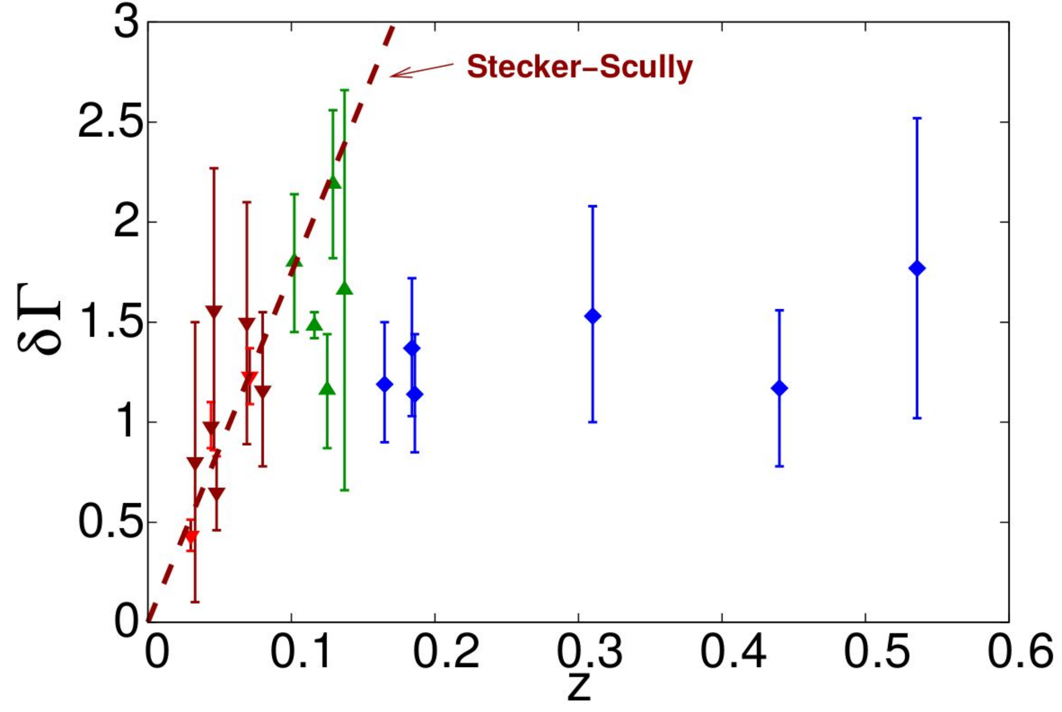


- Inconsistent with acceleration models
- No fast variability; ~3-yr decay time scale

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

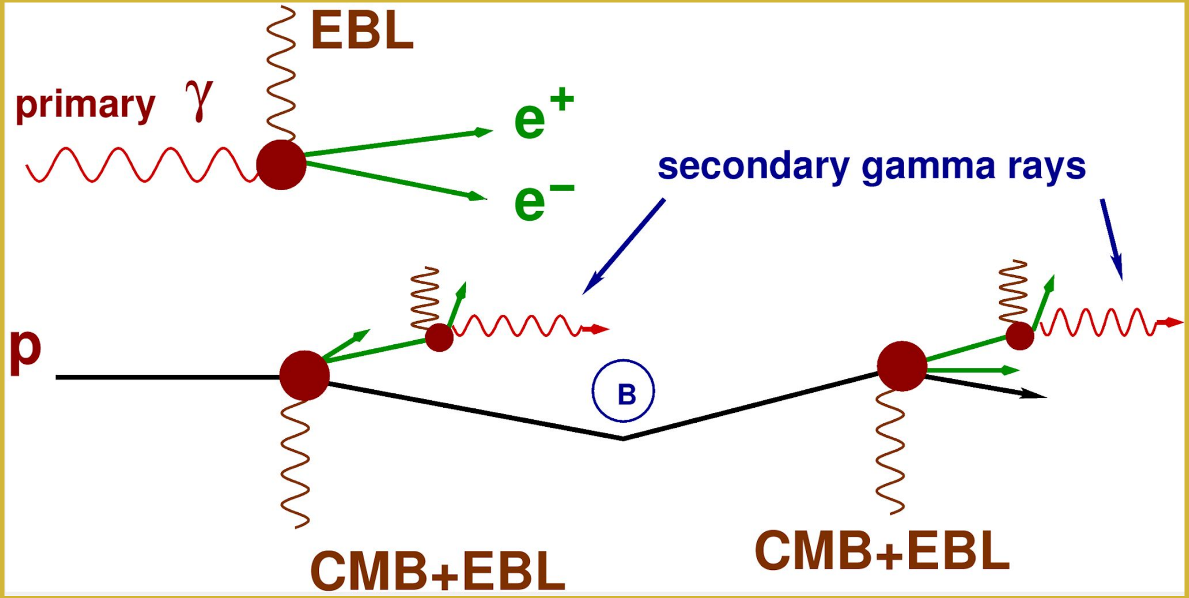
The mysterious transparency of the Universe...

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

Exotic new physics is an exciting possibility,
but EBL absorption is observed in most sources.

Can there be a more conventional explanation of the
EBL defying outliers?

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!

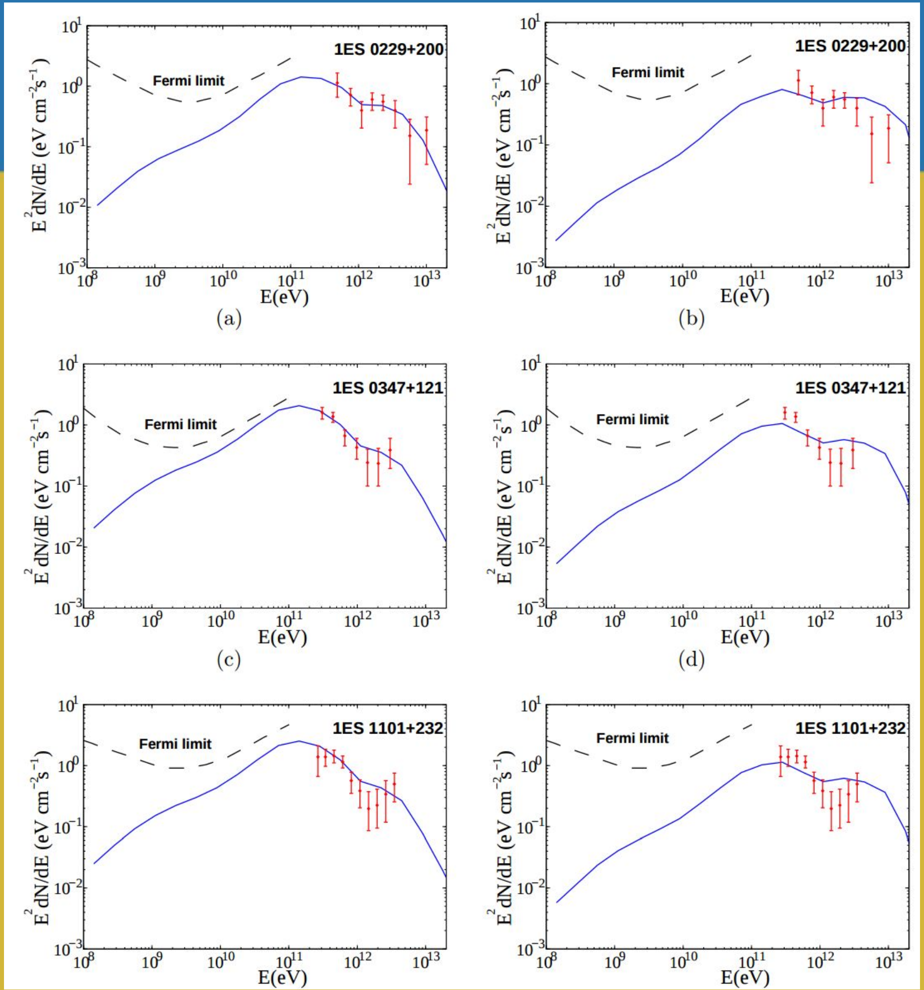
One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

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)

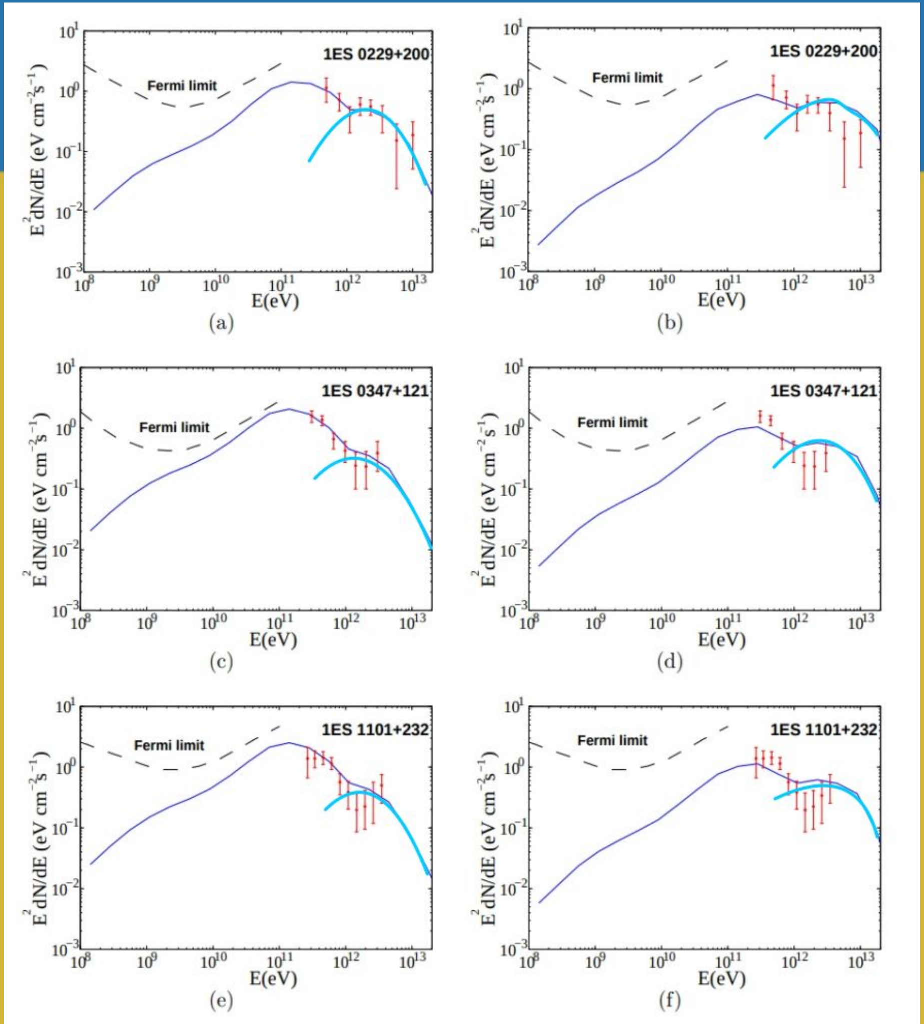


One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

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

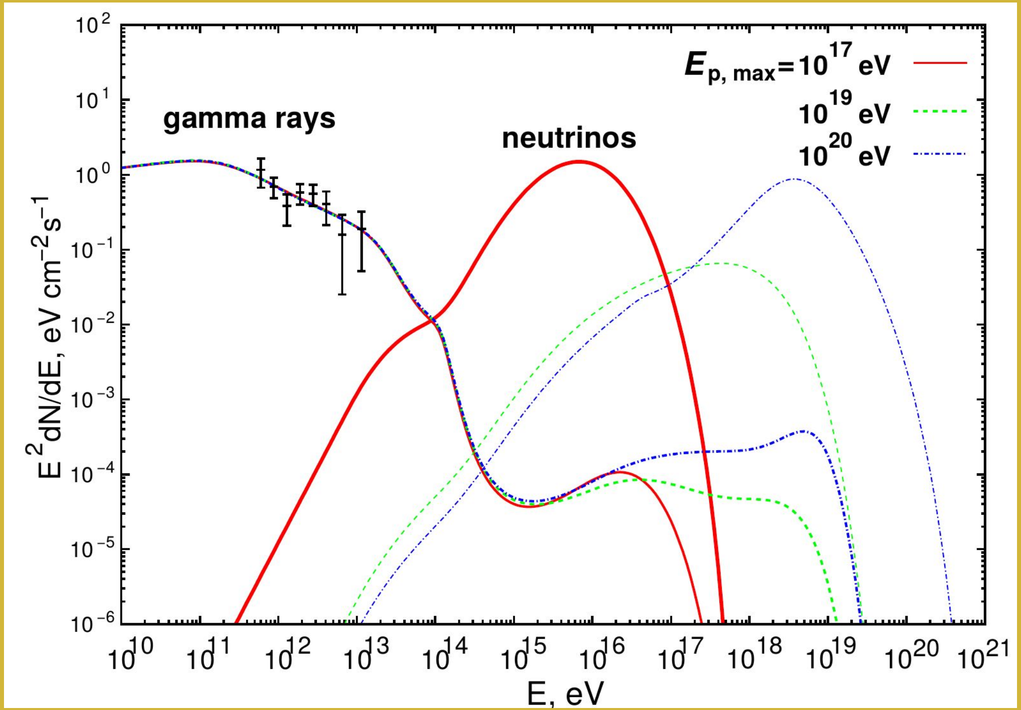
Reasonable CR power for a source up to z~1
[Aharonian, Essey, AK, Prosekin (2013);
Razzaque, Dermer, Finke (2012);
Murase, Dermer, Takami, Migliore (2012)]

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



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

Secondary gamma rays, neutrinos from 1ES0229+200

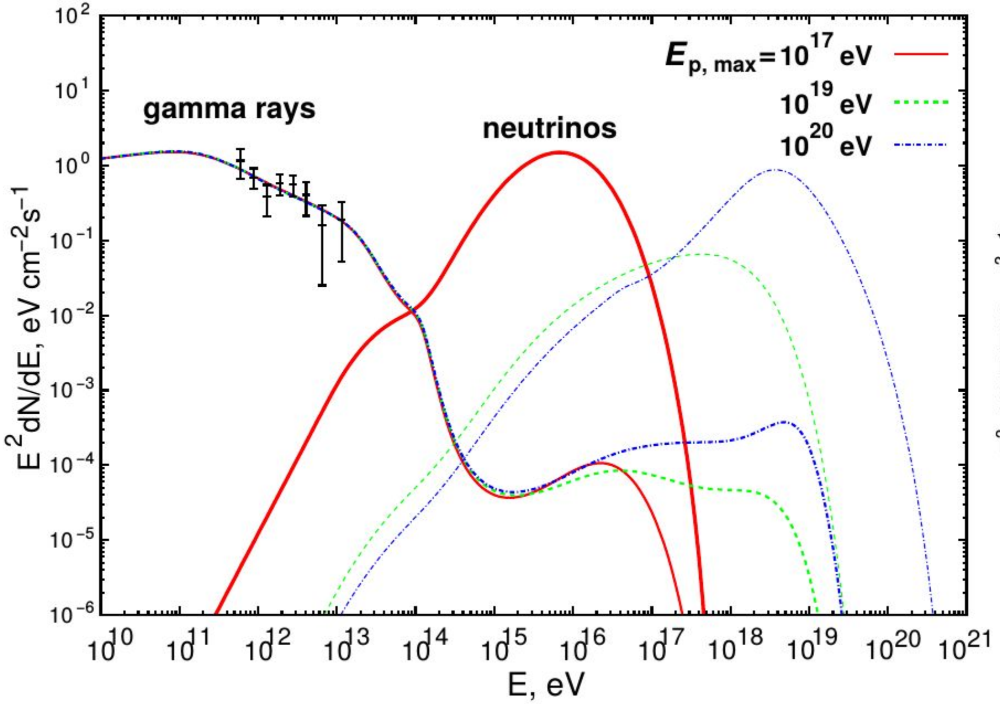


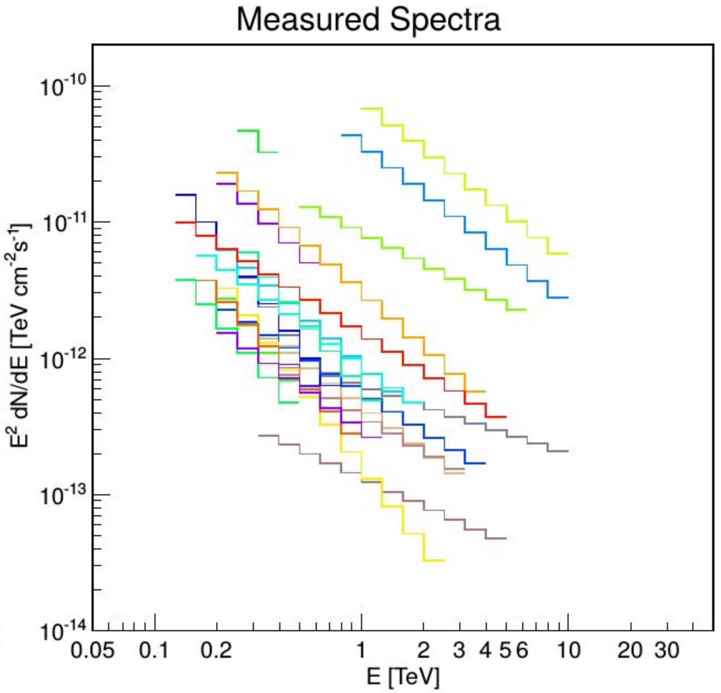
(z=0.14)

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

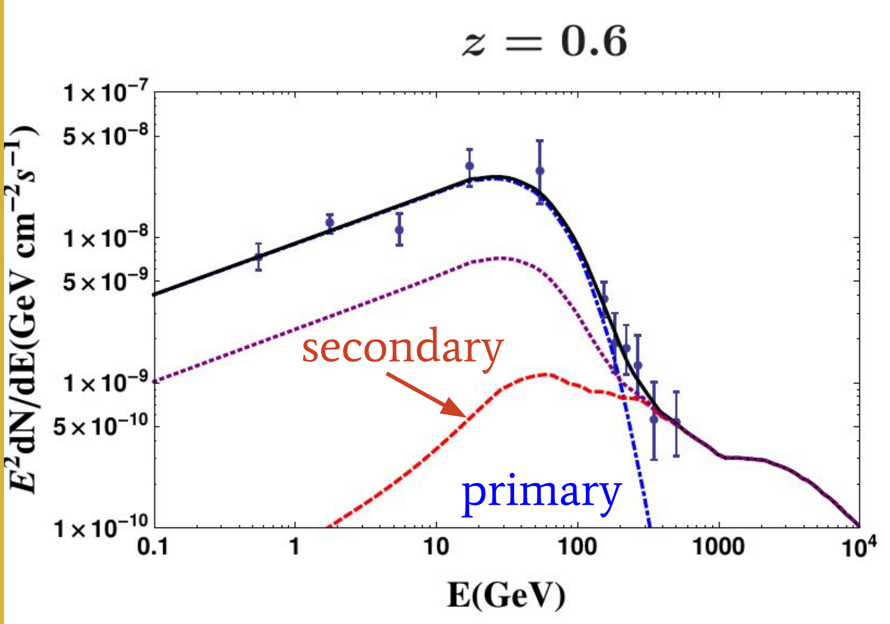
[Essey, Kalashev, AK, Beacom, PRL (2010)]

Robust shapes explain observed universality





PKS 1424+240 at $z > 0.6$ (EBL obscured TeV blazar)



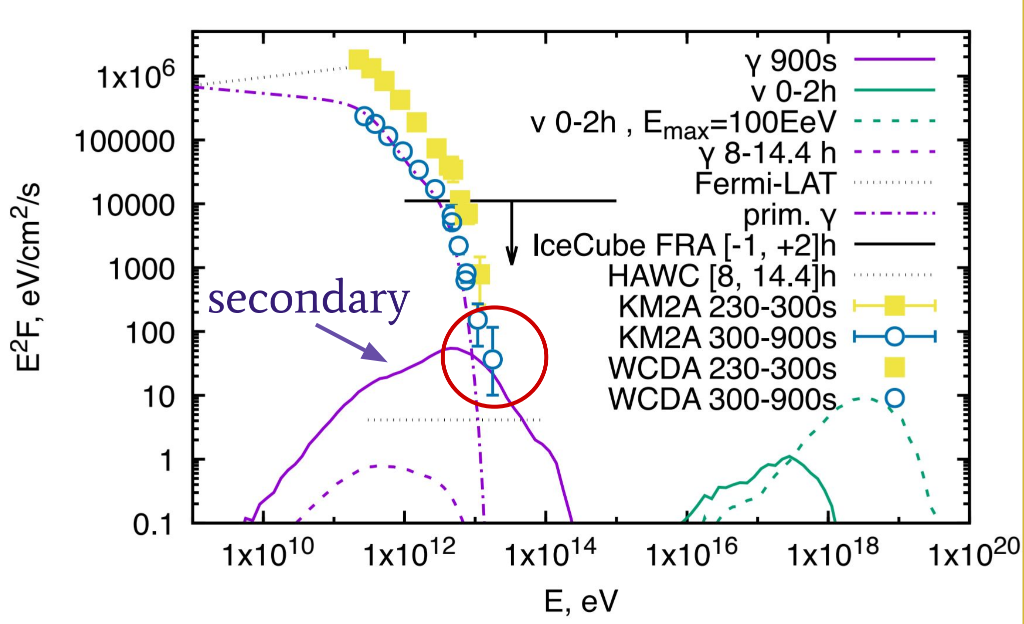
Secondary component improves the fit dramatically.

[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 **~13 TeV**

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

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

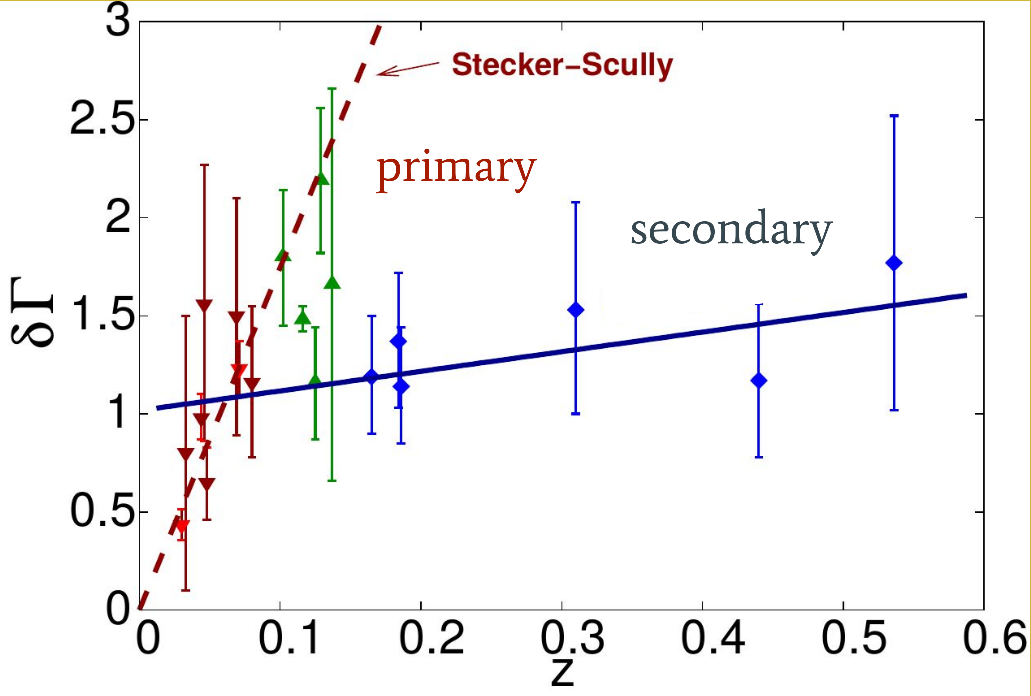


Lorentz invariance violation?
[Finke, Razzaque, 2023 ApJL 942 L21]

Secondary gamma rays explain the last data points well.

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

Spectral softening

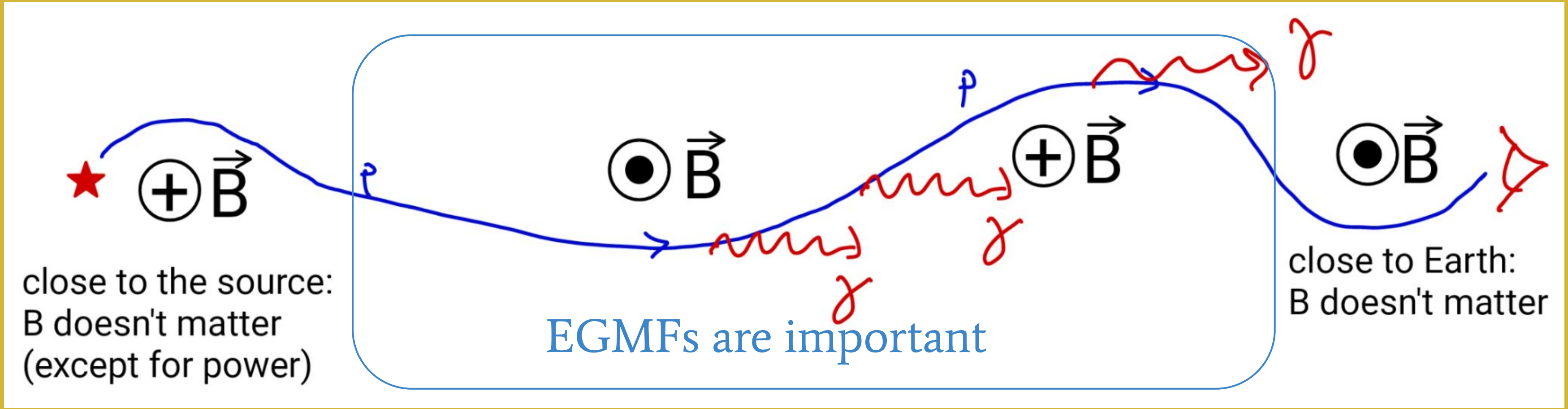


$\delta\Gamma = \Gamma_{GeV} - \Gamma_{TeV}$

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

Prediction: no fast variability for TeV blazars at z>0.15. Consistent 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.

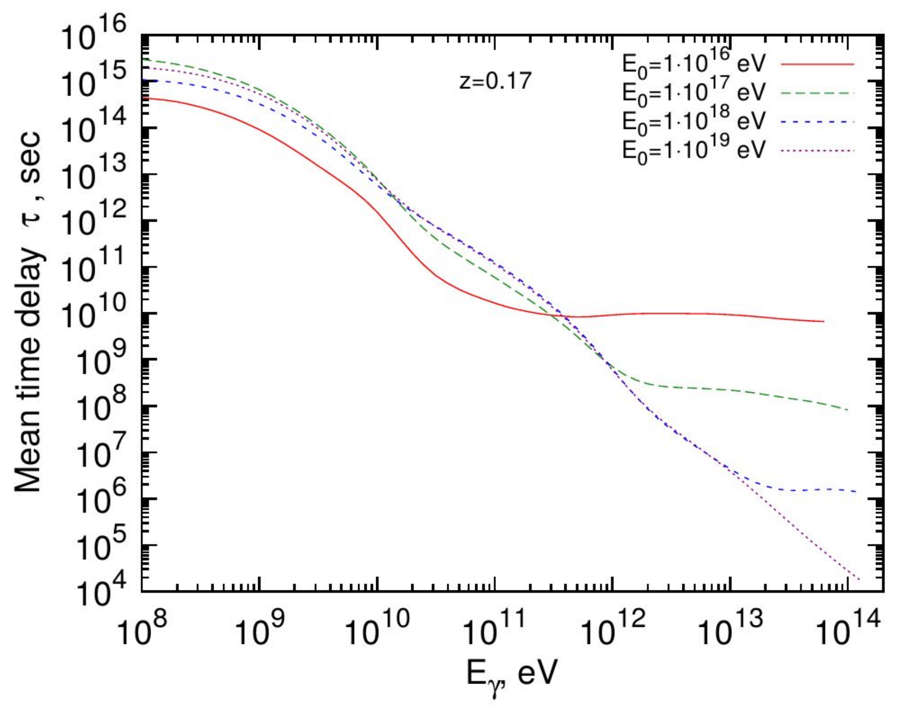
[Aharonian et al., Phys.Rev.D 87 (2013) 6, 063002, 1206.6715]

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 no fast (minute–day) variability is seen at E>1 TeV, z > 0.15

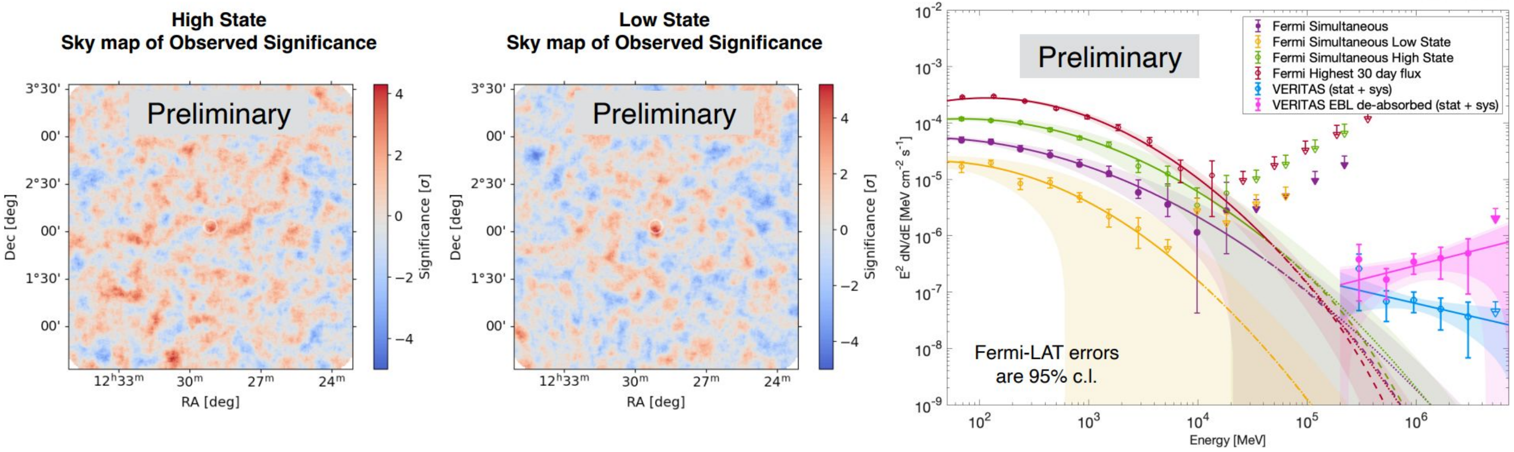
Prediction: stochastic *pedestal* emerges at high energy, high redshifts, for distant blazars above which some flares may rise in a stochastic fashion.

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



3C 273: no fast 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

Brighter future: 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]

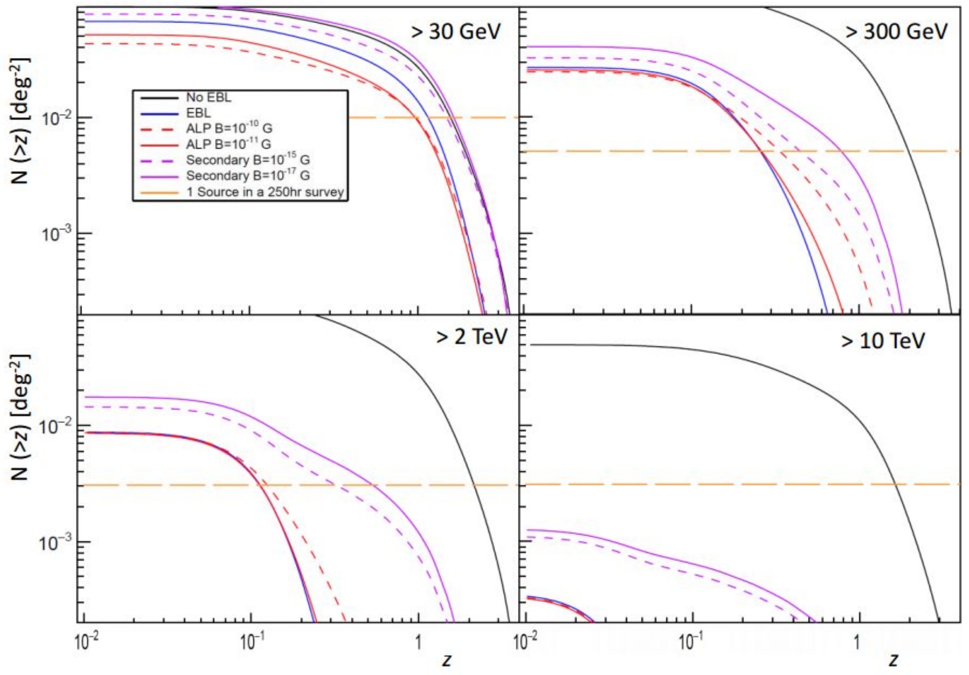


Figure 3: Cumulative source count as a function of redshift for CTA-South, assuming a 5σ integral flux sensitivity and 50 hr exposure observation. Dashed horizontal line represents 1 source detected in a 250 hr survey.

Implications for intergalactic magnetic fields

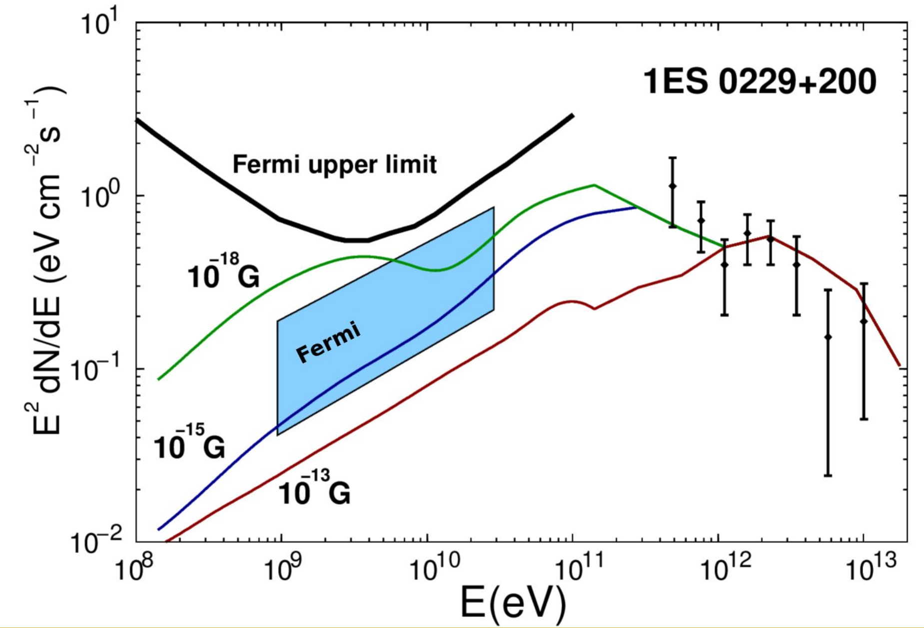
Magnetic fields along the line of sight:

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

Lower limits: talk by Vovk

Upper limits: Essey, Ando, AK (2011)

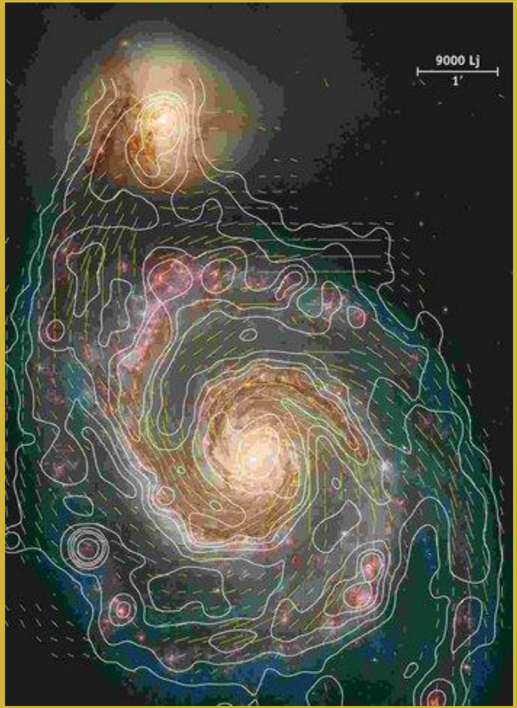
If an intervening filament deflects protons, then no secondary component is expected. However, even a source at z~1 has an order-one probability to be unobscured by magnetic fields, and can be seen in secondary gamma rays
[Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]



Essey, Ando, AK (2011)

Magnetic fields and matter-antimatter asymmetry

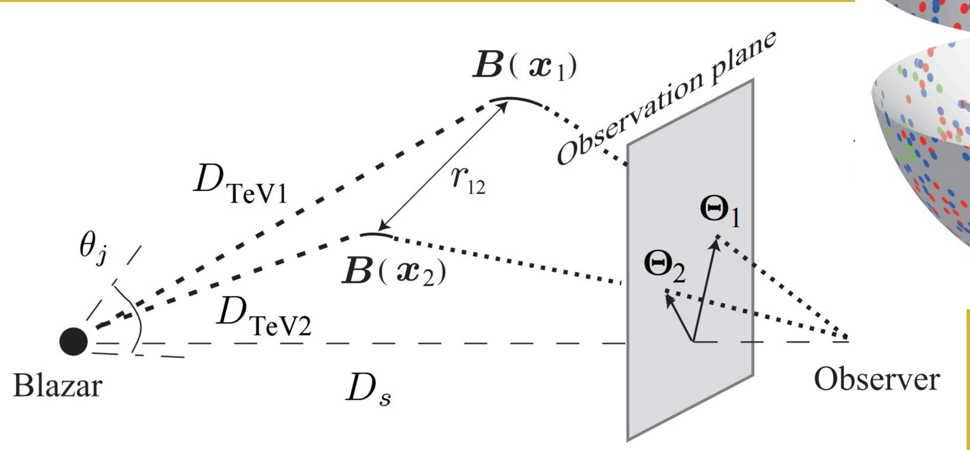
Intergalactic magnetic fields away from galaxies may be representative of primordial seed fields.

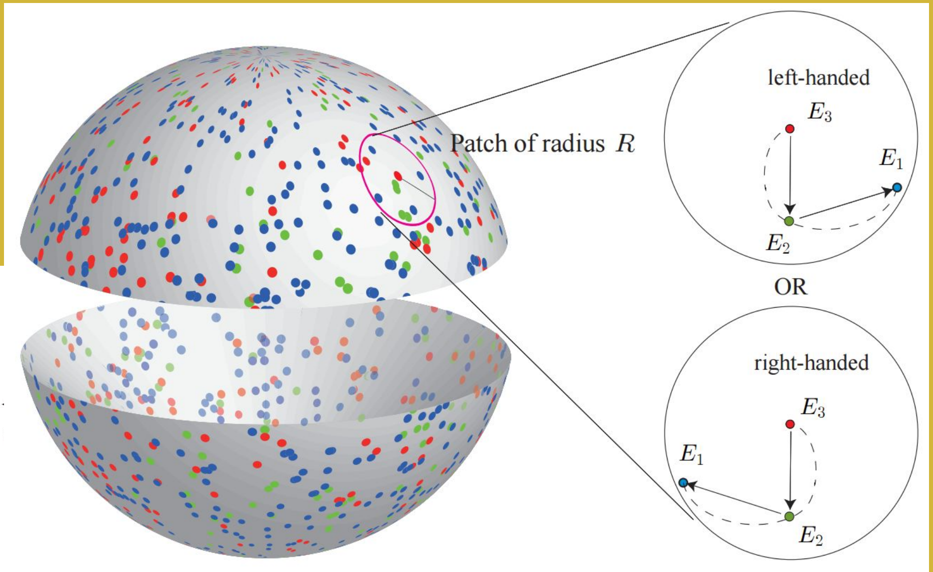


Magnetic helicity (~ Chern-Simons term for the U(1) of hypercharge) can break the symmetry between matter and antimatter and possibly explain the matter-antimatter asymmetry of the universe [Cornwall; Vachaspati et al.]

Magnetic helicity may be observable

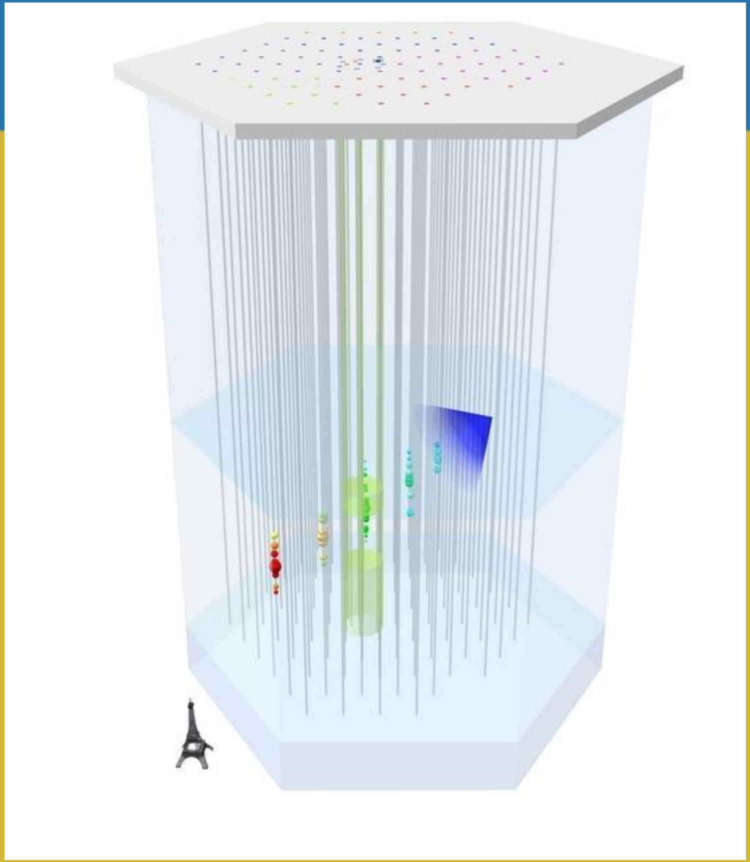
[Vachaspati et al.] reported 3σ evidence of non-zero helicity, with the *correct sign*



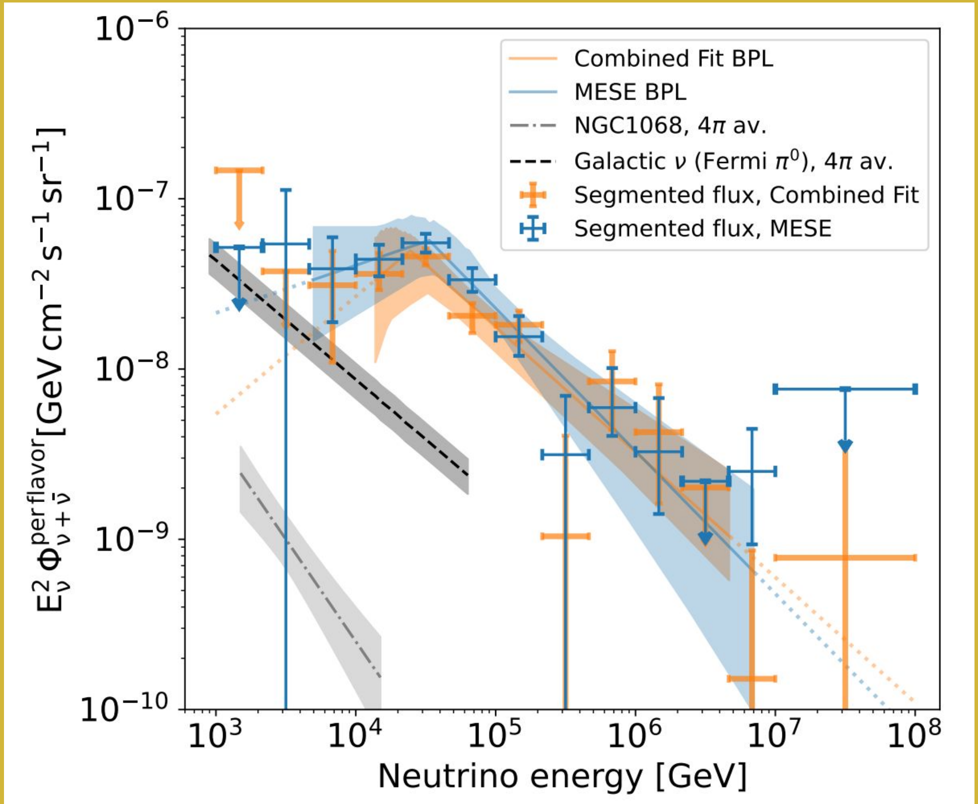


Tashiro, Chen, Ferrer, Vachaspati (2014); not independently confirmed since

IceCube neutrino detector



IceCube neutrinos: the spectrum



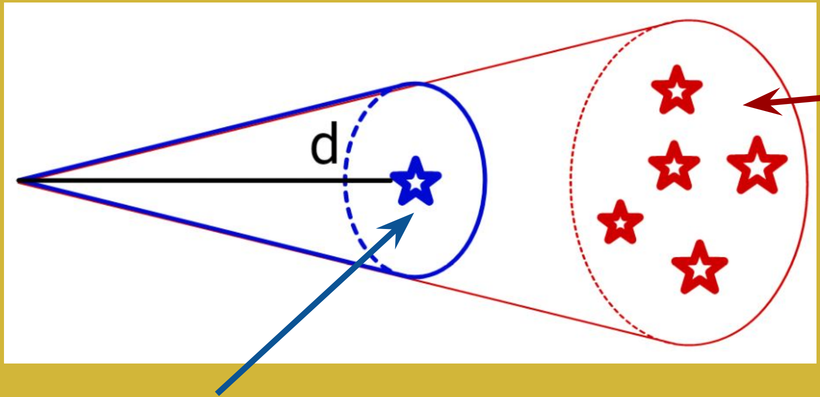
Not a single power law

Multiple components?

Neutrino scaling ⇒ no point sources

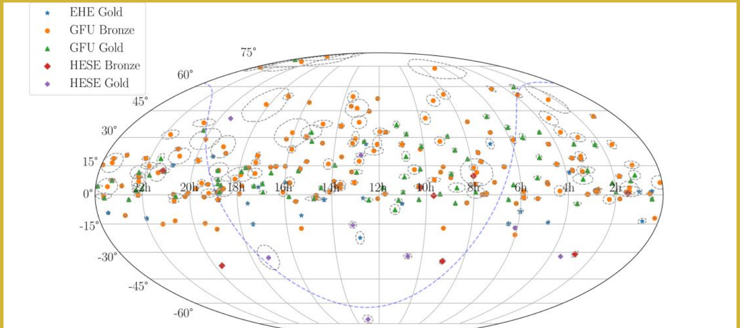
$$F_{\mathrm{secondary},\nu}(d) \quad \propto \quad (F_{\mathrm{protons}} \times d) \propto \frac{1}{d}.$$

Distant (uniformly distributed) sources dominate the signal



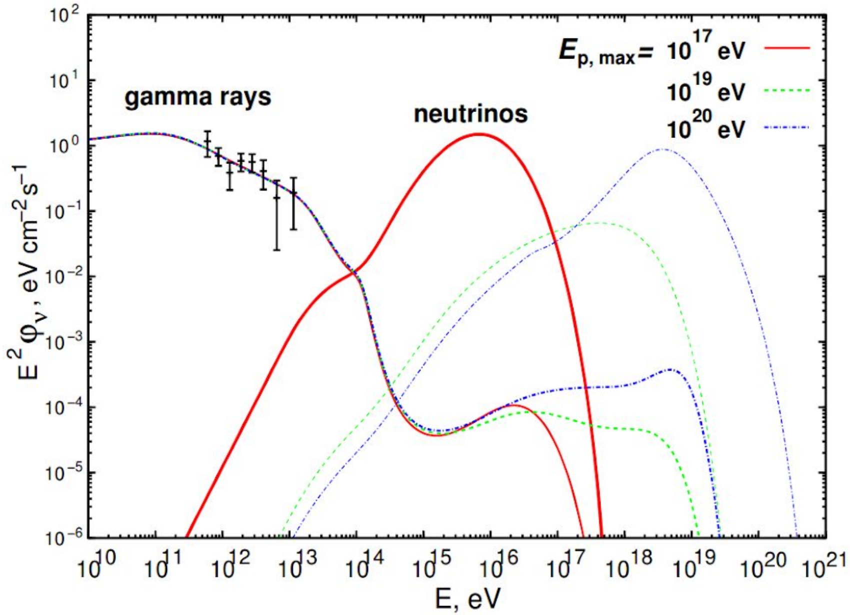
Distant sources dominate for F ∝ 1/d

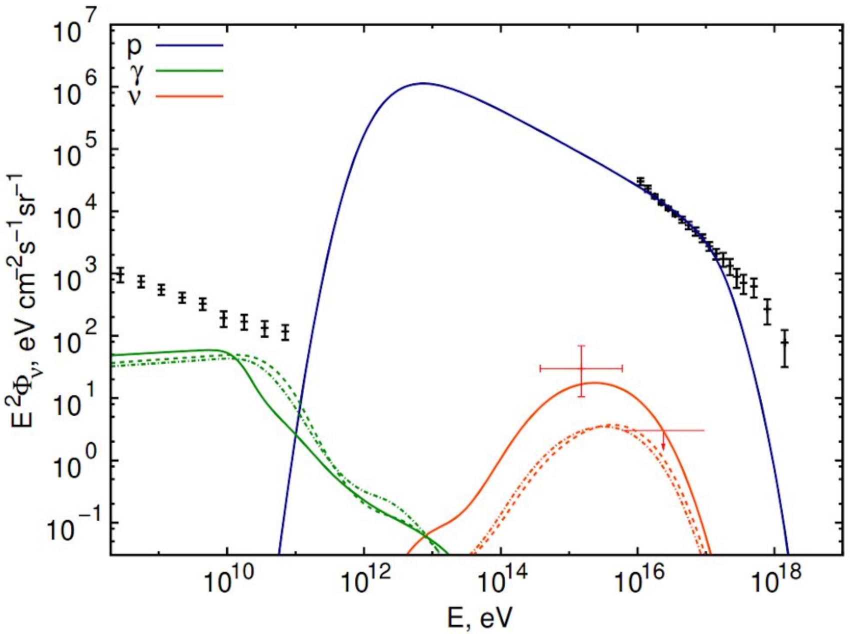
Nearby sources dominate for F ∝ 1/d²



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

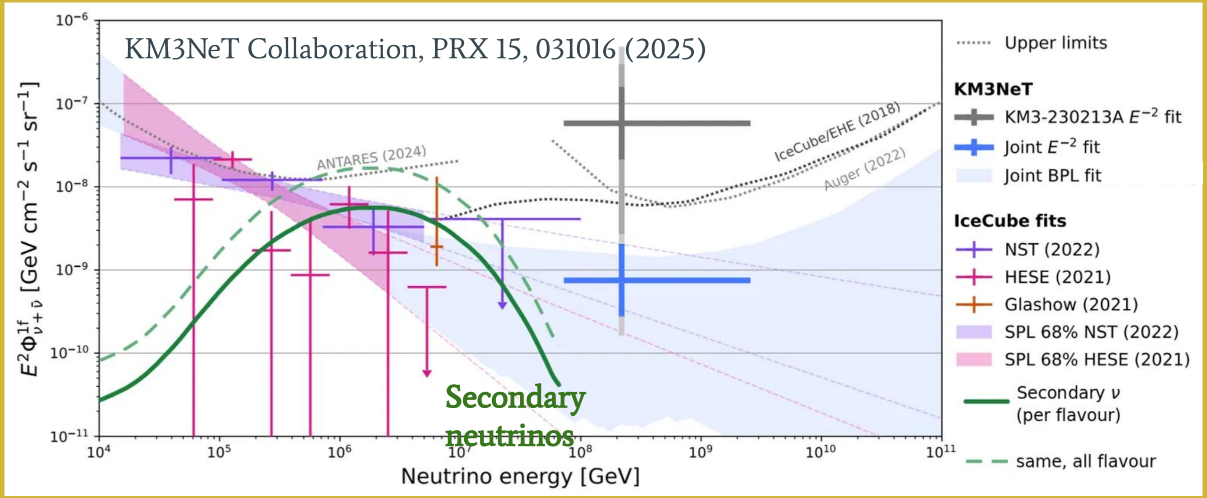
Line-of-sight interactions of CRs from blazars





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

Secondary neutrinos



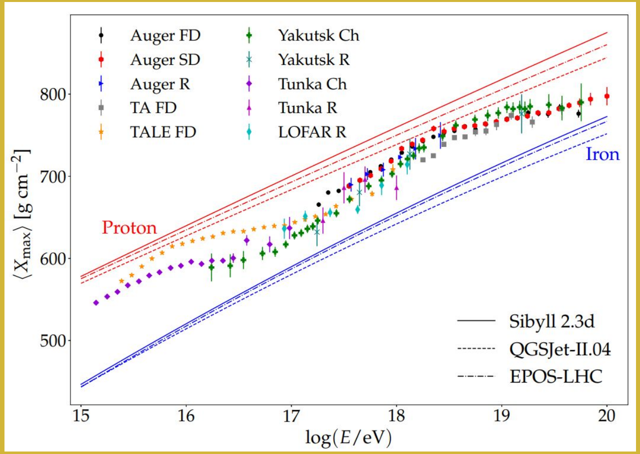
A peaked spectrum at a few PeV can result from cosmic rays accelerated in AGN and interacting with photon backgrounds, assuming that secondary photons explain the observations of TeV blazars.

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

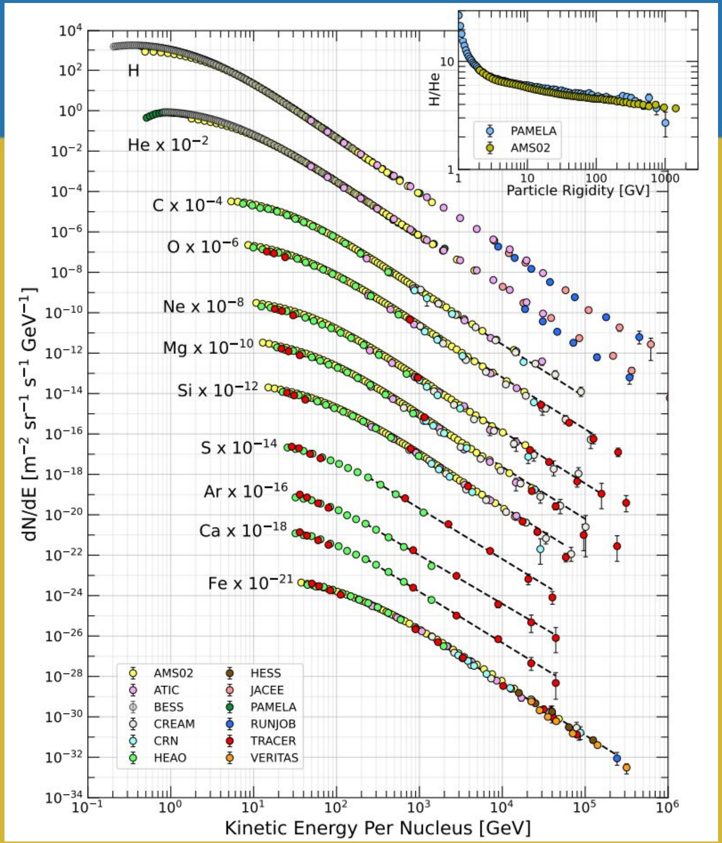
Neutrino at IceCube and KM3NeT:
Not a single power law. Multiple components?
A peak at a few PeV?

Cosmic ray nuclei

Nuclei are observed in cosmic rays, but their sources are obscured by the magnetic fields, even at the highest energies.

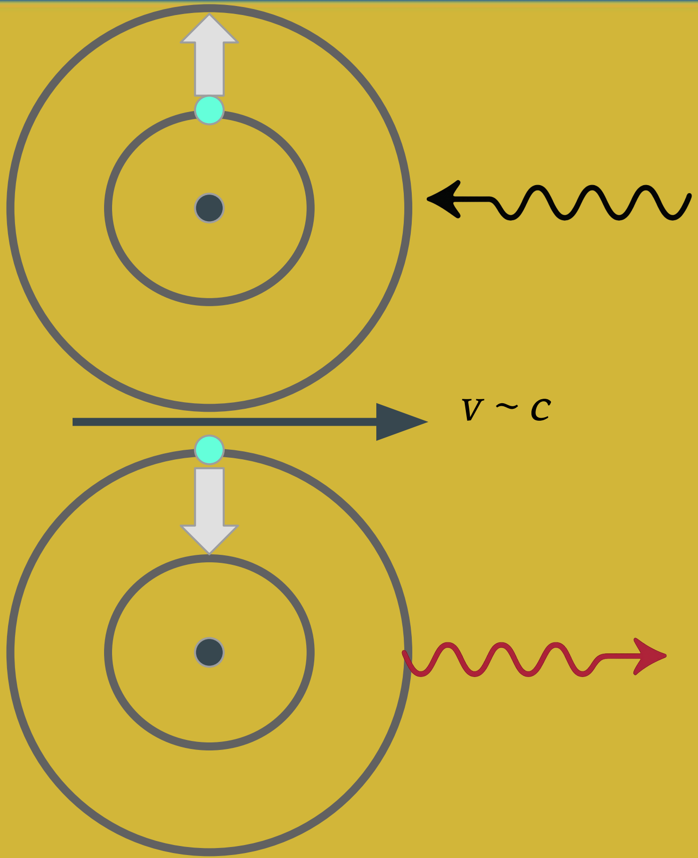


[Supanitsky, arXiv:2212.11695]



[Particle data group]

An atomic line from relativistic ions



Bound-state β decay leaves a hydrogen-like ion.
A CMB photon of energy ε~10^{-4}eV appears as a ~keV photon in the ion frame and excites the bound electron.

$$\gamma = E/M$$

De-excitation emits ΔE = ¾Z^2Ry ≈ 6.9 keV (Fe) in the ion frame, boosted in the lab:

$$E_{\gamma,\mathrm{lab}} \sim \gamma E_{\gamma,\mathrm{i}}$$

The cycle repeats ~10^3 times per ion, until photo-ionisation ends it.
[AK & Voloshin, Phys. Lett. B 707 (2012) 255]

The energy of the target photons sets γ — and therefore where the line lands.

A line, repeated ~10^3 times per ion

The signal is a line

Every de-excitation returns the same single atomic transition, so every photon leaves the ion with the same energy:

$$\Delta E = \frac{3}{8}\alpha^2 m_e c^2 Z^2 \simeq 6.9\left(\frac{Z}{26}\right)^2 \text{ keV}$$

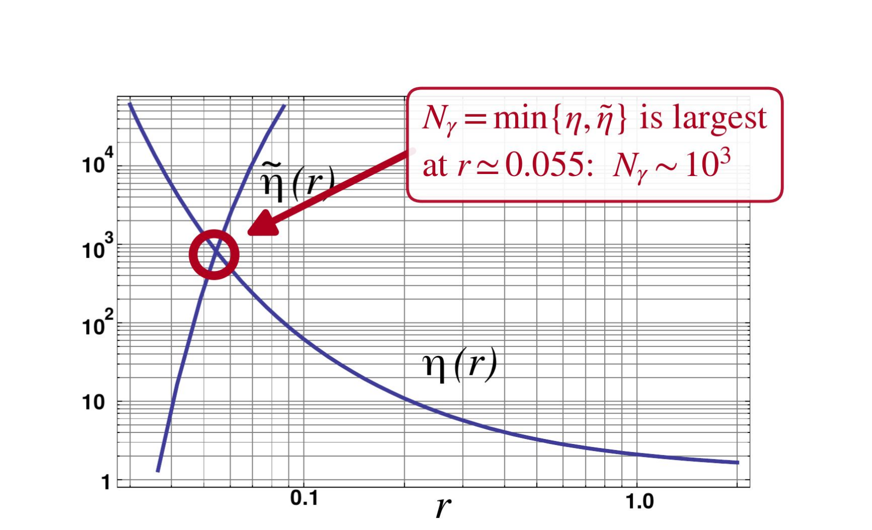
No continuum to smear it out — the width comes only from the spread in γ.

~10^3 photons per ion

Two rates compete: CMB photons excite the bound electron (Γ_e); CMB or EBL photons strip it away for good (Γ_i). Their ratio gives the photons per ion:

$$N_\gamma = \frac{\Gamma_e}{\Gamma_i} = \frac{X(r)}{Y(r)} \equiv \eta(r), \qquad r = \frac{\gamma}{\gamma_Z}$$

$\gamma_Z = \alpha^2 m_e c^2 Z^2 / 4T = 1.96 \times 10^7 (Z/26)^2$ is the γ at which a typical CMB photon reaches the transition energy; $T = T_{CMB} = 2.7$ K



[Kusenko & Voloshin, Phys. Lett. B 707 (2012) 255, Fig. 2 (annotation added)]

One ion at 10^{17} eV lights up about a thousand times before losing the electron.

CMB photons: a GeV shoulder

Kusenko & Voloshin considered ions excited by the CMB.

CMB, T = 2.7 K:

$\gamma_Z = \varepsilon_Z / 2T = 2 \times 10^7$

Photon yield peaks at $\gamma/\gamma_Z = 0.055$

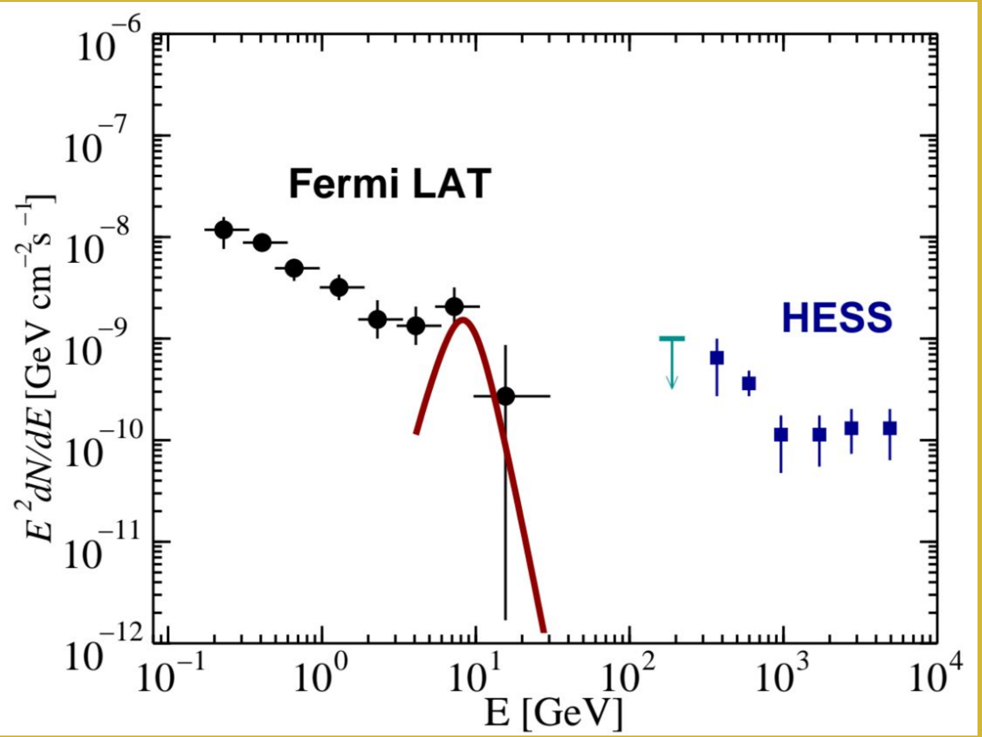
$\Rightarrow \gamma \approx 1.1 \times 10^6$

$\Rightarrow E_{Fe} \sim 10^{17}$ eV (0.1 EeV)

$$E_{line} = \gamma\, \Delta E \approx 8\ \text{GeV}$$

A 5–10 GeV "iron shoulder" might be present in Cen A

[AK & Voloshin, Phys. Lett. B 707 (2012) 255; arXiv:1109.0565]



UV photons: an MeV line of similar origin in some GRBs

Wei et al. applied the same mechanism with a far hotter target: UV photons instead of the CMB.

Circumburst blackbody, T ≳ 9000 K:
⟨ε⟩ ≳ 2 eV — some 10^4 times the CMB

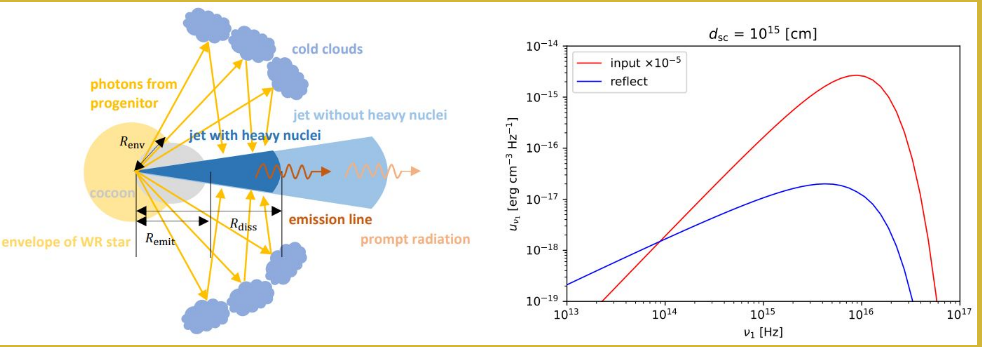
H-like Cu (Z = 29): ΔE ≈ 8.6 keV

γ is now the jet's bulk Lorentz factor,
γ_{bulk} ≈ 820 – 1700 — set by jet dynamics, not by the photon field.

$$E_{line} = \gamma\,\Delta E / (1+z) \approx 5 - 10\ \text{MeV}$$

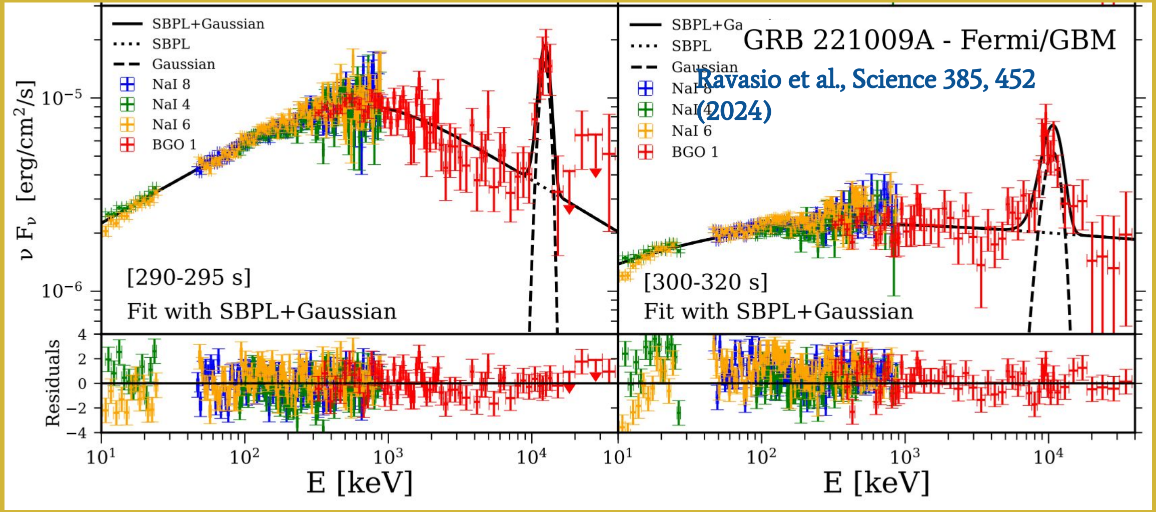
Just where GRB 221009A shows a line.

[Wei et al., ApJ Lett. 968 (2024) 1, L5; arXiv:2405.10775]

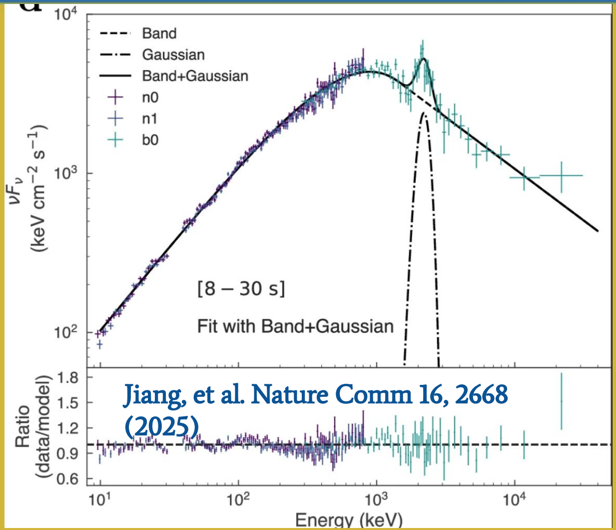


Reflected light from the Wolf–Rayet progenitor is one candidate origin; the jet's own photons are disfavoured.

MeV emission lines in GRB 221009A and GRB 221023A: an iron shoulder?



Ravasio et al., Science 385, 452 (2024)



Jiang, et al. Nature Comm 16, 2668 (2025)

Would be difficult to explain by, e.g., a blue-shifted e^+e^- line, because it would require a bulk Lorentz factor $\Gamma \sim 12$, too low to be consistent with the models. Also, the e^+e^- line would be much broader.

The "iron shoulder" explanation works well [Wei et al., ApJ Lett. 968 (2024) 1, L5; arXiv:2405.10775]

COSI can search for nuclear accelerators!

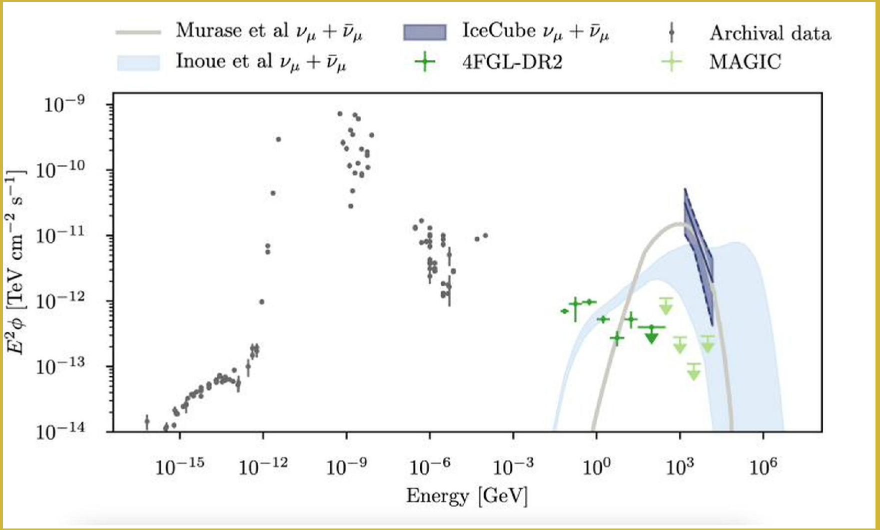
NGC 1068: TeV neutrinos unaccompanied by gamma rays

IceCube detects TeV neutrinos from NGC 1068 — 79 events, 4.2σ.

[Abbasi et al., Science 378, 538 (2022)]

In an AGN, neutrinos are normally made by photopion production (pγ), which leaves a gamma-ray flux comparable to the neutrino flux.

But Fermi and MAGIC see far less than that: at TeV energies the accompanying gamma rays are simply not there.



IceCube Collaboration, Abbasi et al., Science 378, 538 (2022)

So the neutrinos are not coming from photopion production in a region transparent to gamma rays. Something has to hide the gamma rays or make the neutrinos another way.

One explanation: a corona

A two-zone picture: the gamma rays come from a gamma-thin region — star formation, or an AGN disk wind — while the neutrinos are made in the gamma-opaque hot plasma right around the black hole, the corona.

[Ajello, Murase & McDaniel 2023; Eichmann et al. 2022; Peretti et al. 2023; Inoue, Khangulyan & Doi 2020; Murase, Kimura & Mészáros 2020; Neronov et al. 2023; Blanco et al. 2023; Mbarek et al. 2023; Fiorillo et al. 2024]

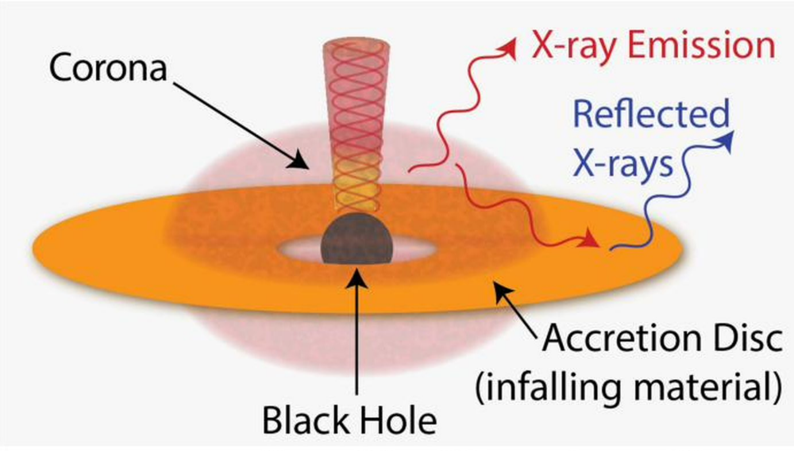


Image: danwilkins.net/research

We do not know whether the corona is there.

It is inferred from X-ray spectra, not resolved. Questions remain about the acceleration mechanism, energy budget.

[Inoue, Takasao & Khangulyan, PASJ (2024), arXiv:2401.07580]

An alternative: β decay of photodisintegrated nuclei

Jets accelerate nuclei, not only protons.

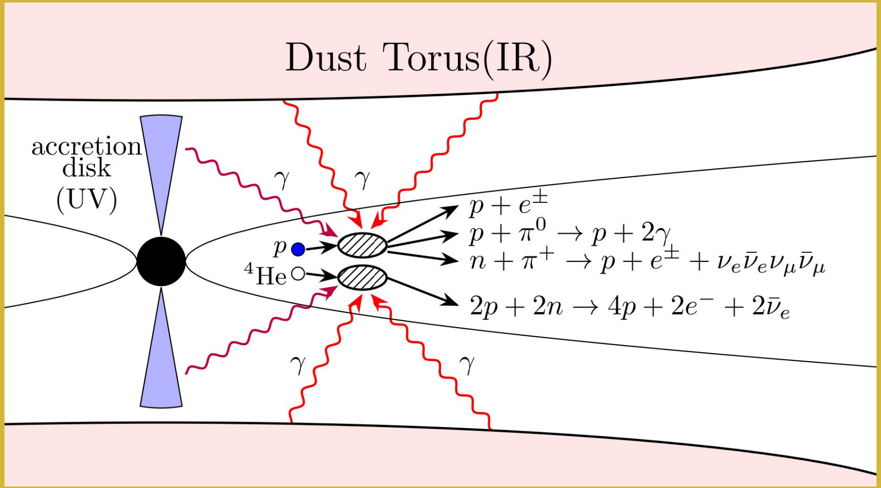
⁴He photodisintegrates on the disk UV field, releasing free neutrons:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

The energy goes into the neutrino and the electron, and the electrons cool by synchrotron — so the neutrinos arrive with no matching gamma rays. The deficit is intrinsic, not absorption.

No corona is required: the site is the jet, at ~0.8 pc.

[Yasuda, Sakai, Inoue & AK, Phys. Rev. Lett. 134, 151005 (2025); arXiv:2405.05247]



The neutrino energy is naturally predicted by the UV background

For beta decaying nuclei, the UV photons set the neutrino energy

Inputs: disk "big blue bump" $\varepsilon_{UV} \approx 10$ eV **^{4}He photodisintegration threshold $E_{thr} = 20.6$ MeV**
(cross section peaks at 25 MeV, σ ≈ 1.5 mb)

1. $$\gamma_N = \frac{E_{\rm thr}}{\varepsilon_{\rm UV}} \simeq \frac{20.6\ \mathrm{MeV}}{10\ \mathrm{eV}} \simeq 2.1 \times 10^6 \quad \Longrightarrow \quad E_{^4\mathrm{He}} = \gamma_N\,(4 m_p c^2) \simeq 8\ \mathrm{PeV}$$

2. $$E_n = \gamma_N m_n c^2 \sim 1\ \mathrm{PeV} \quad \Longrightarrow \quad n \to p + e^- + \bar{\nu}_e, \qquad \langle E_\nu \rangle_{\rm rest} \sim \mathrm{MeV}$$

3. $$E_\nu \simeq \gamma_N \langle E_\nu \rangle_{\rm rest} = \langle E_\nu \rangle_{\rm rest} \frac{E_{\rm thr}}{\varepsilon_{\rm UV}} \simeq 1\ \mathrm{TeV}$$

The TeV scale of the IceCube neutrinos is fixed by the ^{4}He photodisintegration threshold divided by the disk UV photon energy, times the β-decay neutrino energy.

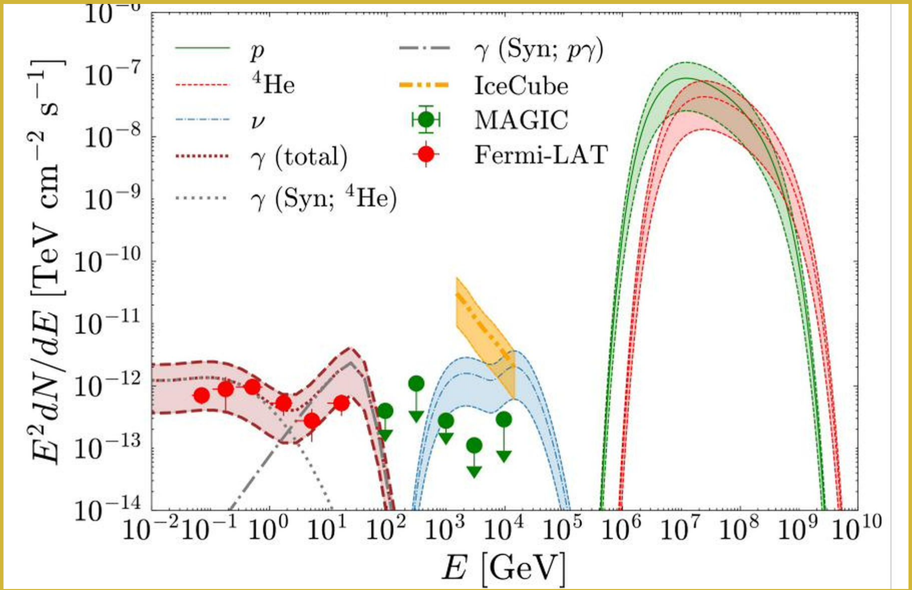
What the β-decay origin predicts

Peaked spectrum, not a power law — the threshold imposes a low-energy cutoff on ν production. IceCube's published fit assumes an unbroken power law.

Gamma-ray deficit is intrinsic, not absorption. β decay puts the energy into ν and e^-, and the electrons cool by synchrotron at B ~ 0.01–10 G.

Flavor (1:0:0) at the source → ≈(3:1:1) at Earth, versus (1:1:1) for pions.

NB: IceCube's 2026 all-sky flavor fit excludes pure neutron decay for the diffuse flux [PRL 137, 081002]. That constrains the diffuse flux, not NGC 1068 — a per-source analysis with the peaked template is the real test.



Conclusions

- Treating gamma rays and cosmic rays consistently leads to excellent agreement of gamma-ray spectra with observations of “outlier” distant blazars (and very little model dependence)
- Neutrinos are an interesting probe
- IceCube diffuse neutrinos: arrival directions consistent with production on the background, not in sources that trace matter distribution.
- Now as we understand the “beam”, we can use it to test the cosmic photon backgrounds (EBL) and magnetic fields, potentially opening a new window on the early universe
- MeV lines, GeV lines may help identify nuclear accelerators
  COSI may be able to search for them soon!
- Beta decay neutrinos may account for some sources of neutrinos unaccompanied by gamma rays