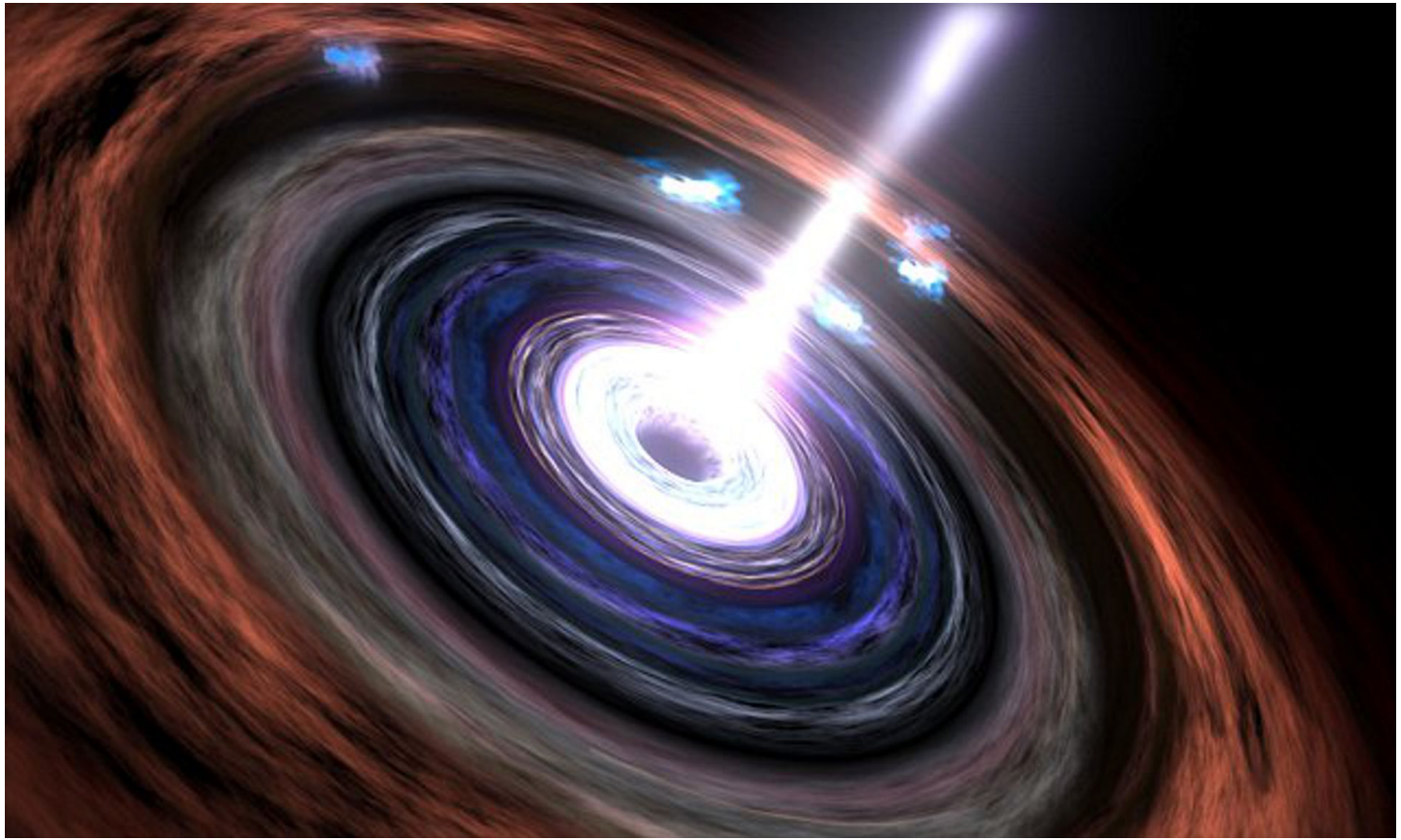
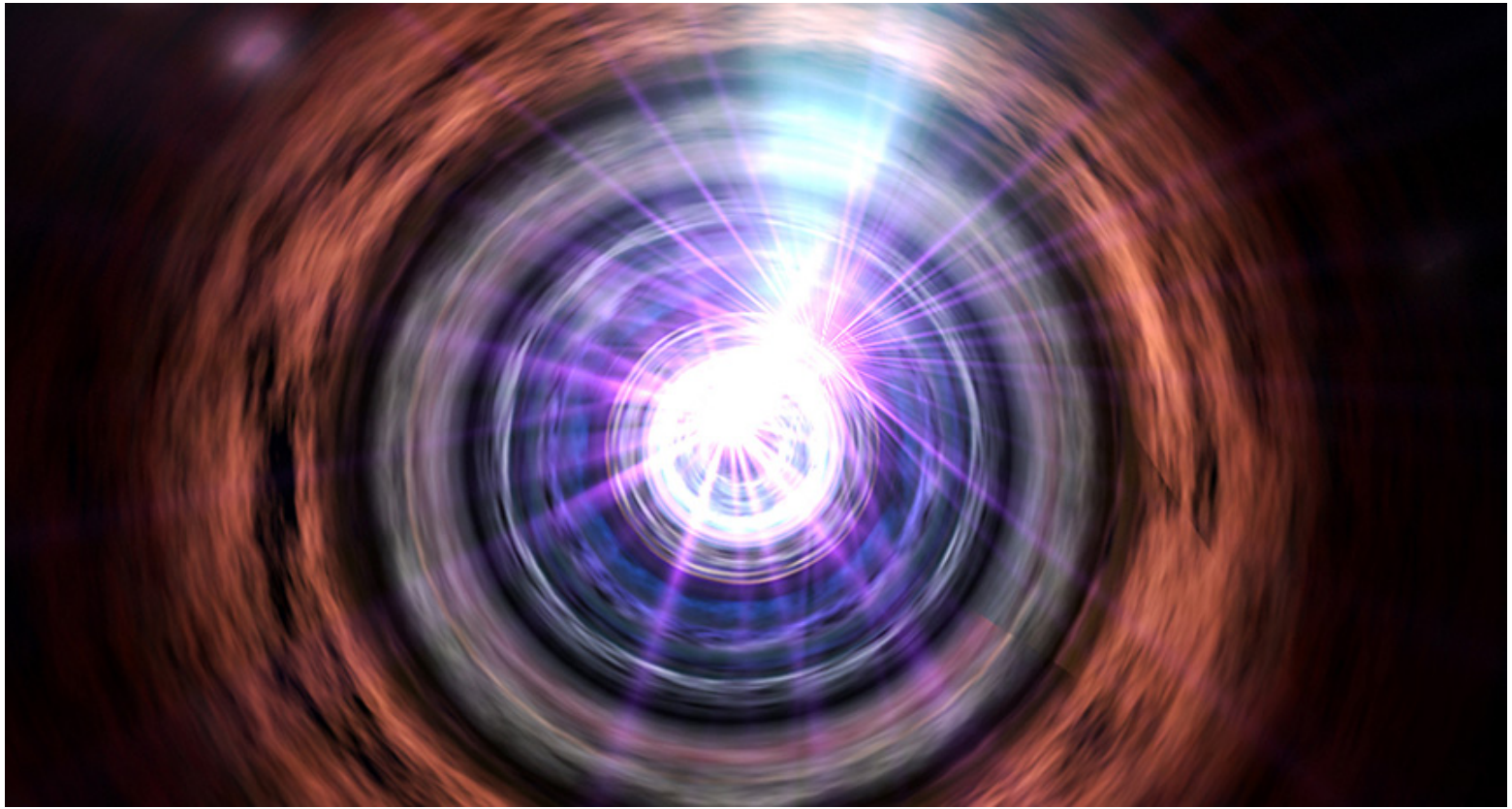
TeV Gamma-Ray Variability in Blazars & more

Qi Feng
Black Hole Flares Workshop: Connecting Theory to Observations
Flatiron Institute

Active Galactic Nuclei (AGNs) – relativistic jets of particles



Blazars – AGN jets pointing toward Earth (dominating the extragalactic gamma-ray sky)



Blazar jets: electrons, protons?

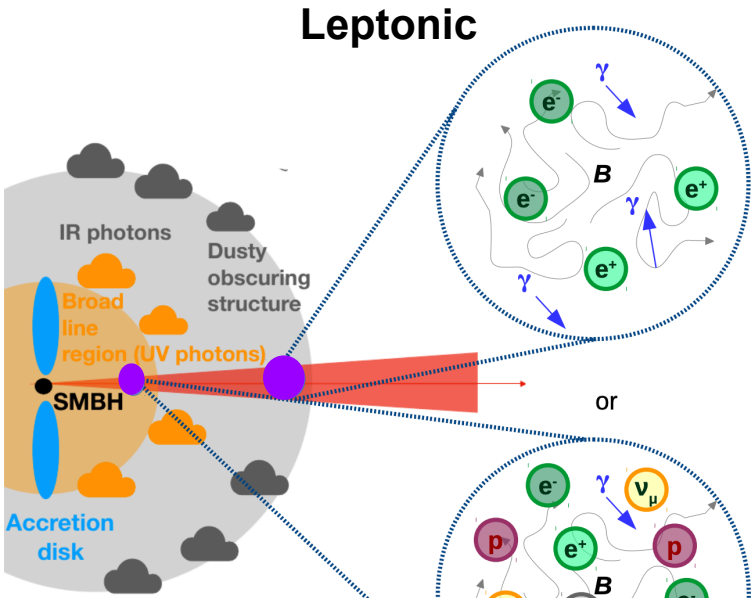
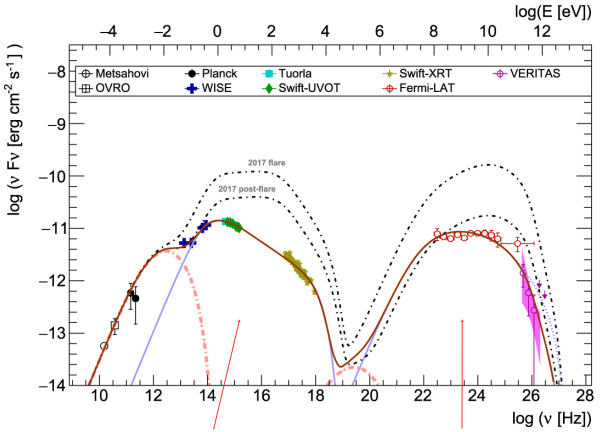


Figure from M. Petropoulou

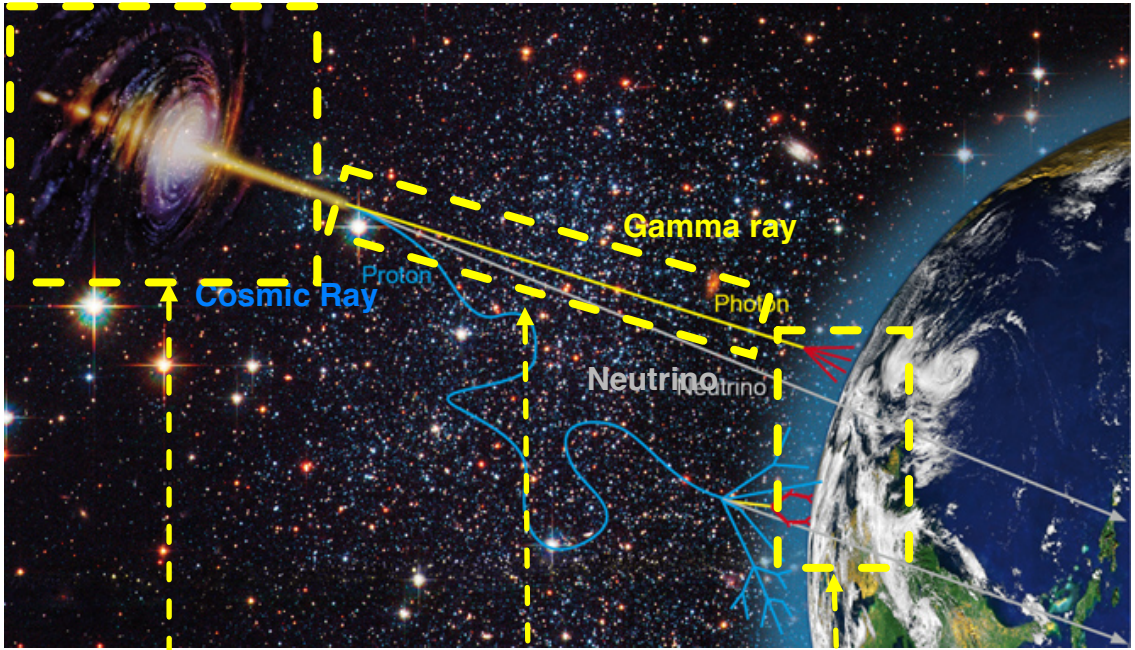


Synchrotron:
$e^{+/-}$ + B

Inverse Compton:
$e^{+/-}$ + γ

Hardronic:
p + γ …

TeV Gamma-Ray Blazar Science Themes

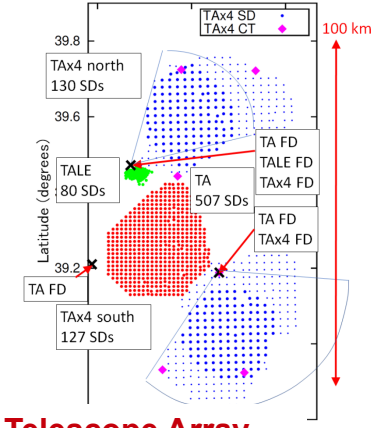


Science Drivers
- Origin of cosmic rays
- Extreme environments
- Frontiers in physics

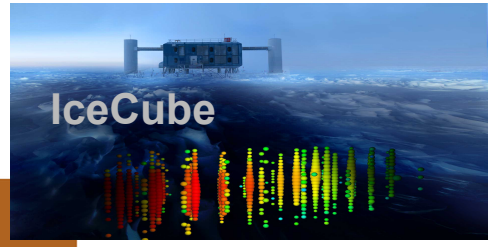
Propagation
- Extragalactic background light
- Axion-like particles?

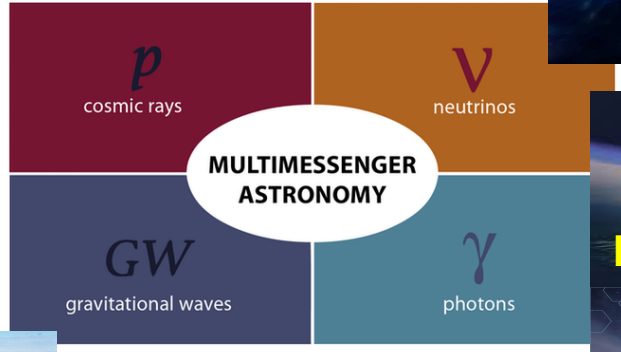
Detectors
- Instrument/data driven

Multi-messenger astrophysics: new windows on the universe

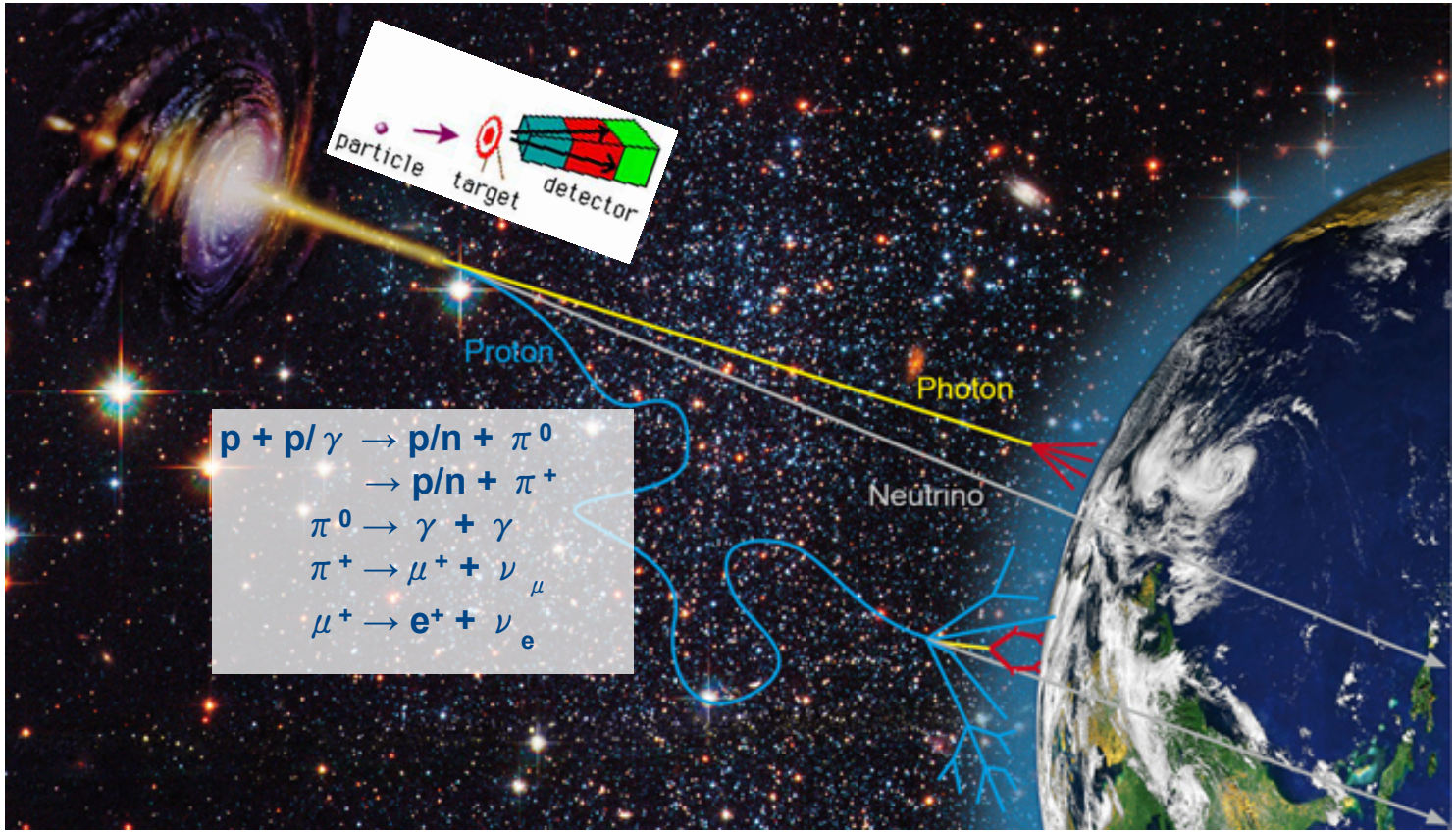


Telescope Array

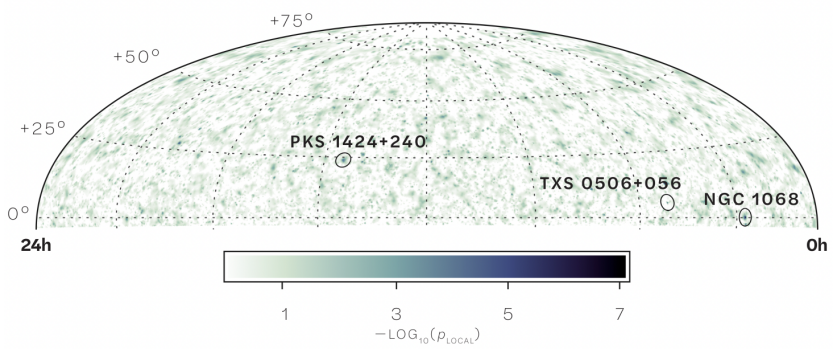




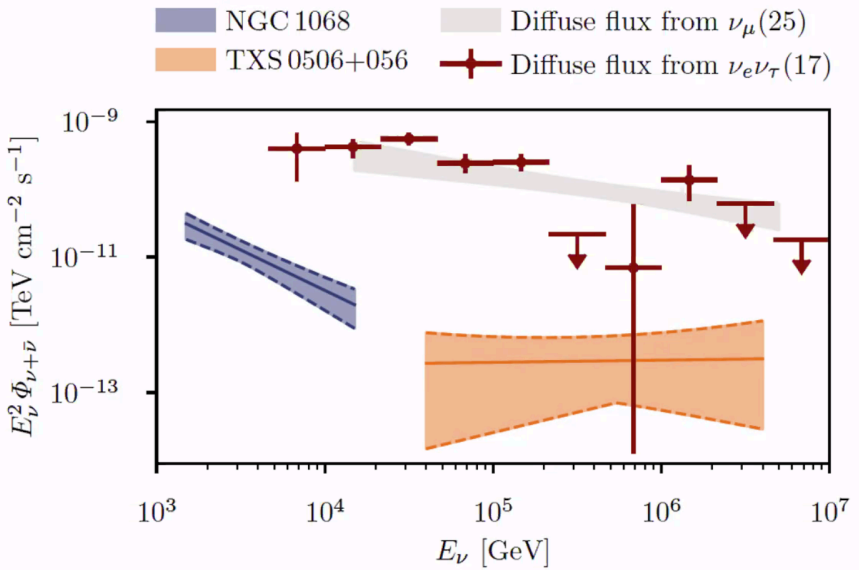
Neutrinos and gamma rays are key to cosmic-ray origin



State-of-the-art neutrino sky



The IceCube Collaboration, Science, 378, 6619, 538-543 (2022)

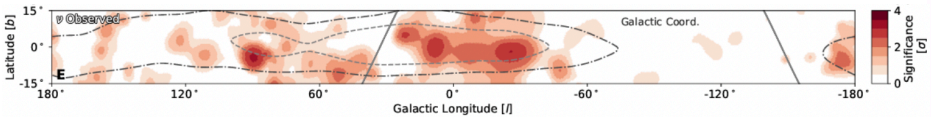


[25] IceCube. ApJ 928, 50 (2020)
[17] IceCube. PRL. 125, 121104 (2020)

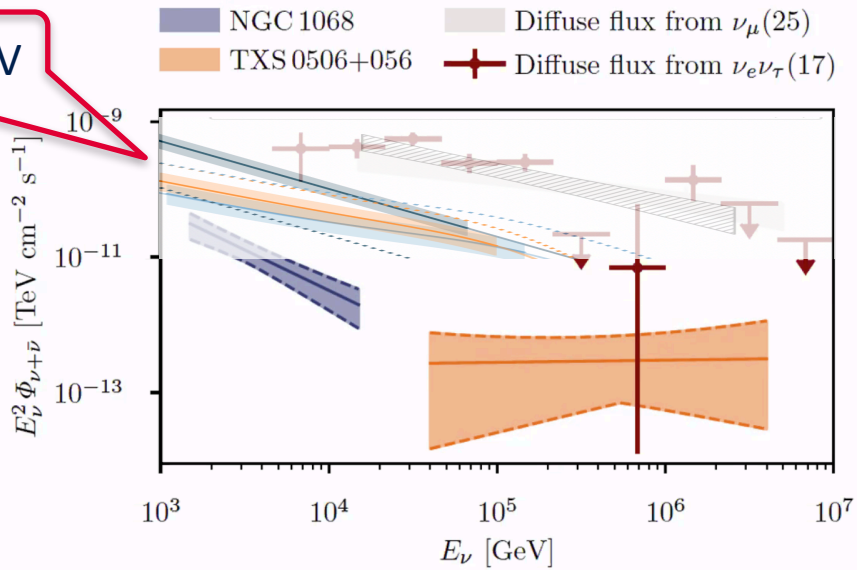
- **Diffuse astrophysical neutrinos & the Galactic plane detected.**
- **High-energy neutrinos are extragalactic.**
- **It is difficult to find astrophysical neutrino sources in IceCube data.**

State-of-the-art neutrino sky

The Galactic plane emits neutrinos <100 TeV



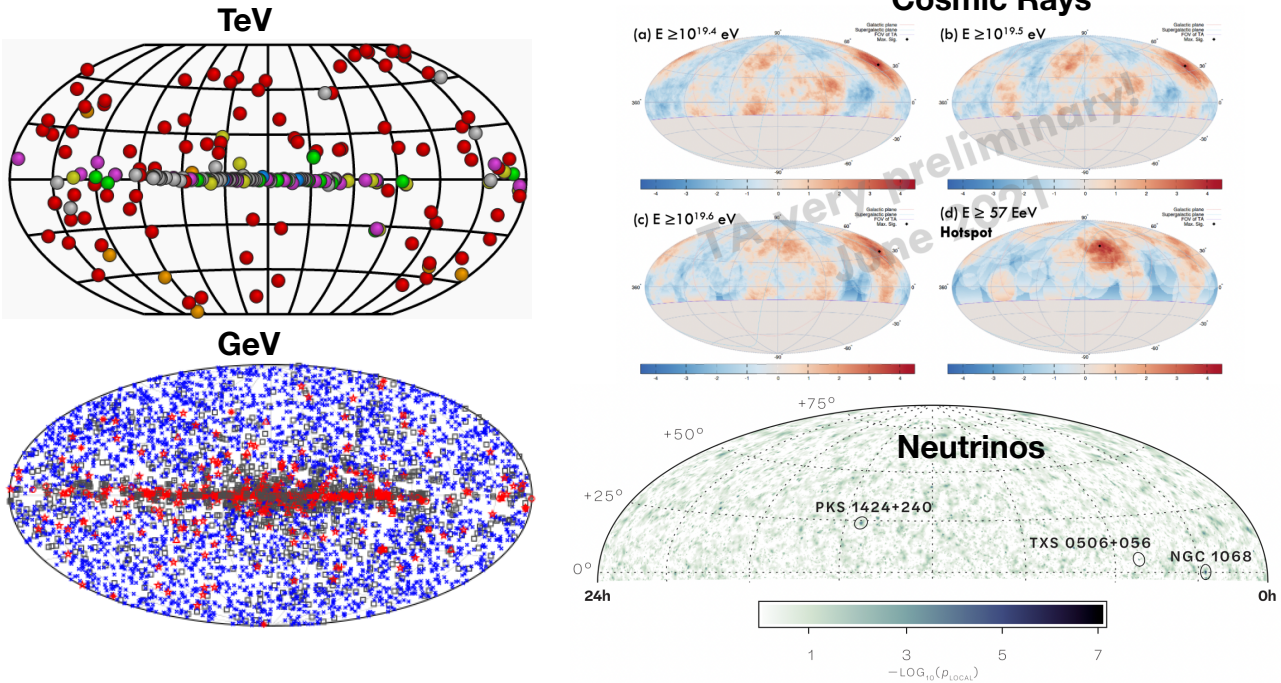
The IceCube Collaboration, Science, 380, 6652, 1338-1343 (2023)



[25] IceCube. ApJ 928, 50 (2020)
[17] IceCube. PRL. 125, 121104 (2020)

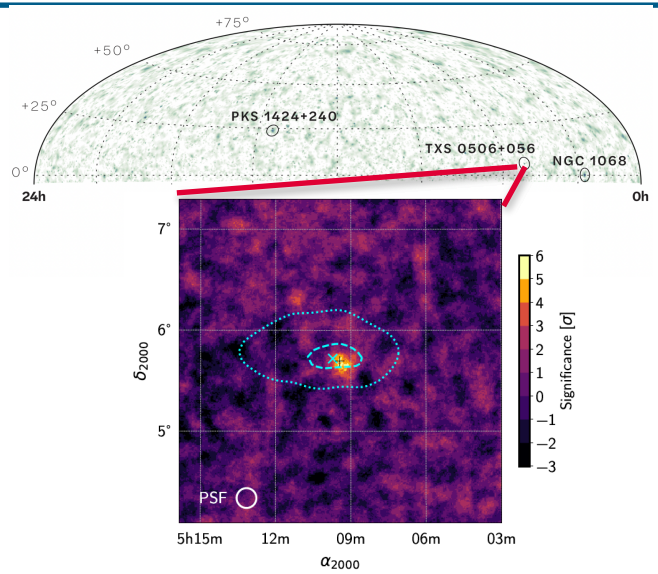
- **At least three different populations of sources**
  → many more sources to be discovered

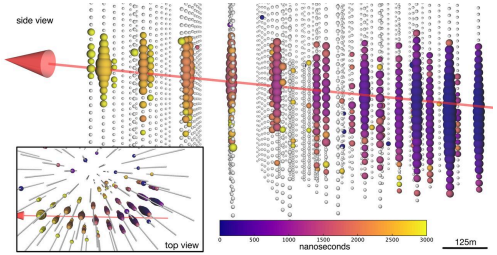
(Some) AGNs are special



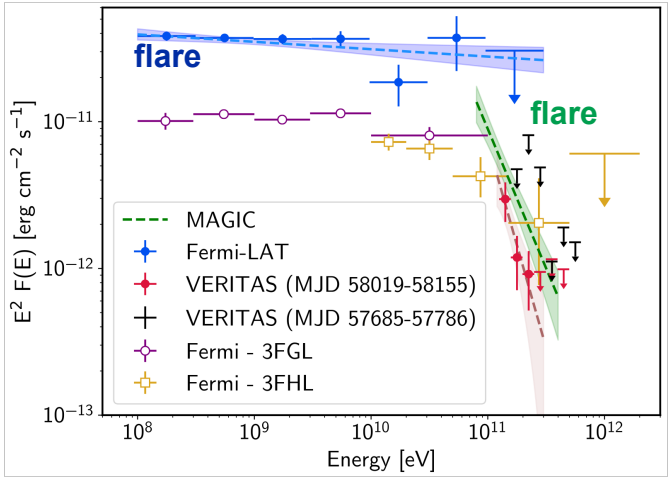
- Cosmic rays > 10^{18} eV and astrophysical neutrinos > 10^{15} eV are **extragalactic**.
- AGNs dominate the **extragalactic** gamma-ray sky.

Searching for neutrino-emitting AGNs





IceCube Collaboration, 2018 Science, 361 eaat1378



VERITAS Collaboration, 2018 ApJL, 861, L20

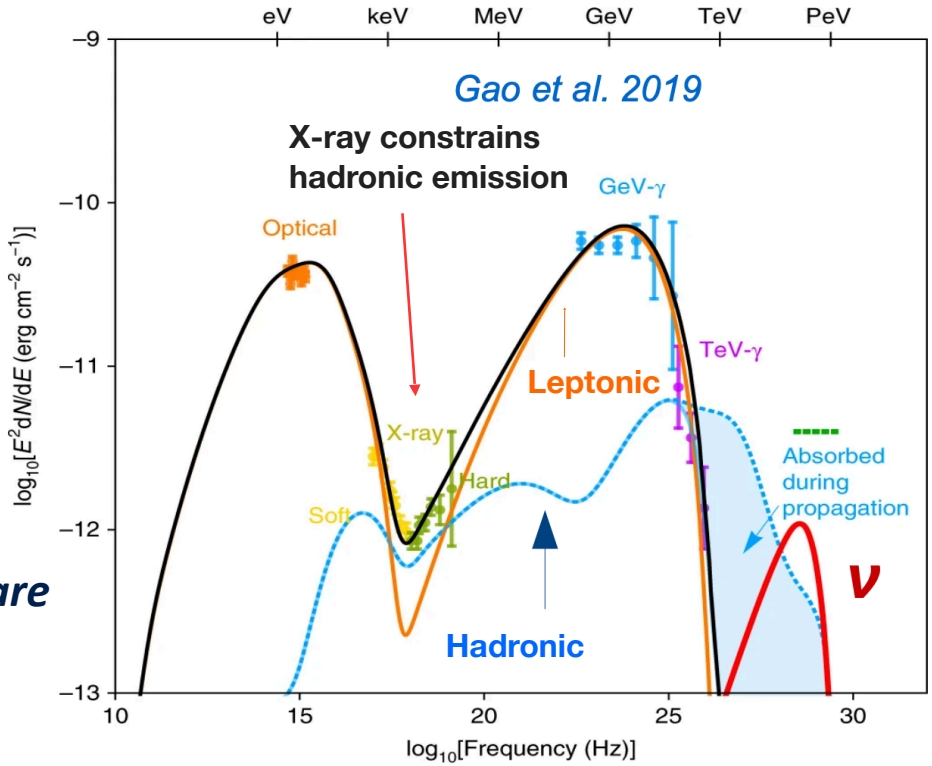
Temporal + Spatial Coincidence

IceCube: ~290 TeV neutrino event IC170922A

TXS 0506+056 flaring in gamma rays

The association is uncertain ~3.5 sigma

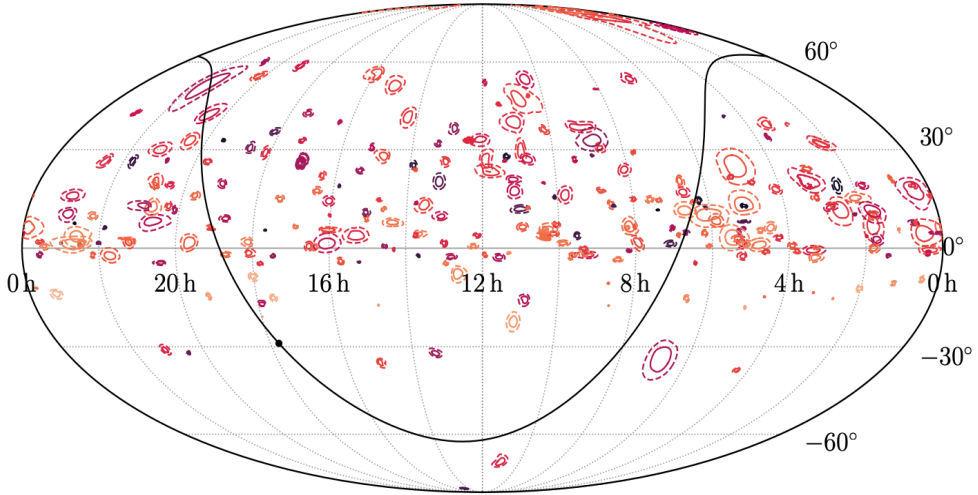
Photons are mostly leptonic



X-ray & gamma-ray are important

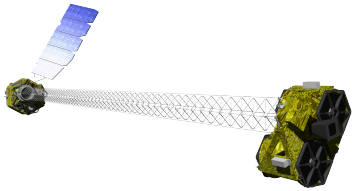
Mild problems in neutrino production: Proton luminosity super Eddington

More searches with temporal + spatial coincidence



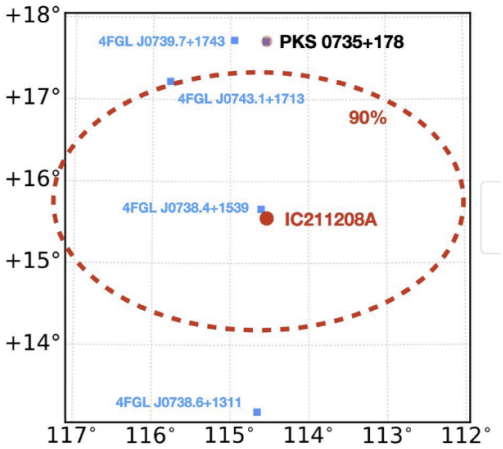
IceCube alerts + flaring blazars

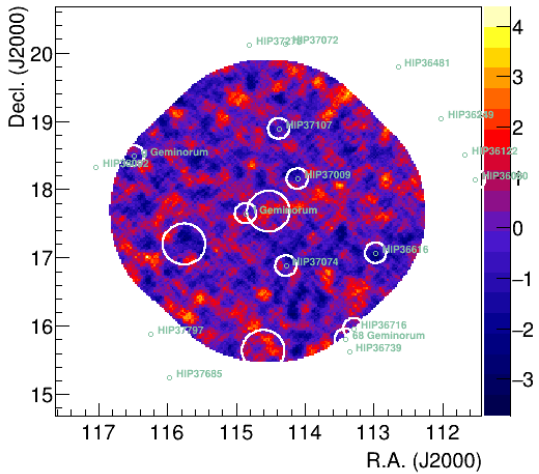
X-ray & gamma-ray are important



PKS 0735+178 / IceCube-211208A

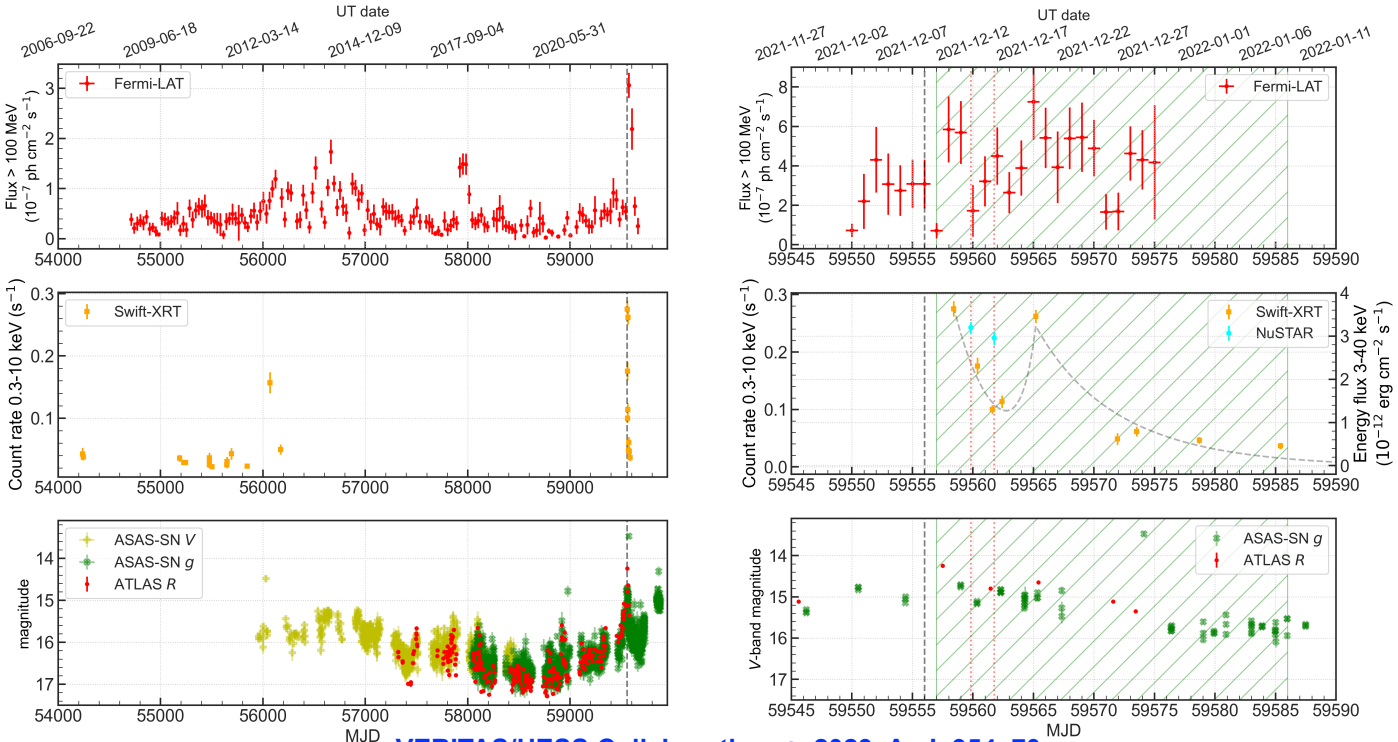
- An IceCube event at 170 TeV on 2021-12-08; 50% probability of being astrophysical.
- A few more neutrinos detected by other detectors.
- A nearby flaring blazar PKS 0735+178:
  - Historic high flux & variable daily in GeV, X-ray, and optical;
  - Triggered observations from Swift, NuSTAR, VERITAS;
  - VERITAS/HESS upper limits above 300 GeV.





PKS 0735+178 / IceCube-211208A: temporal coincidence

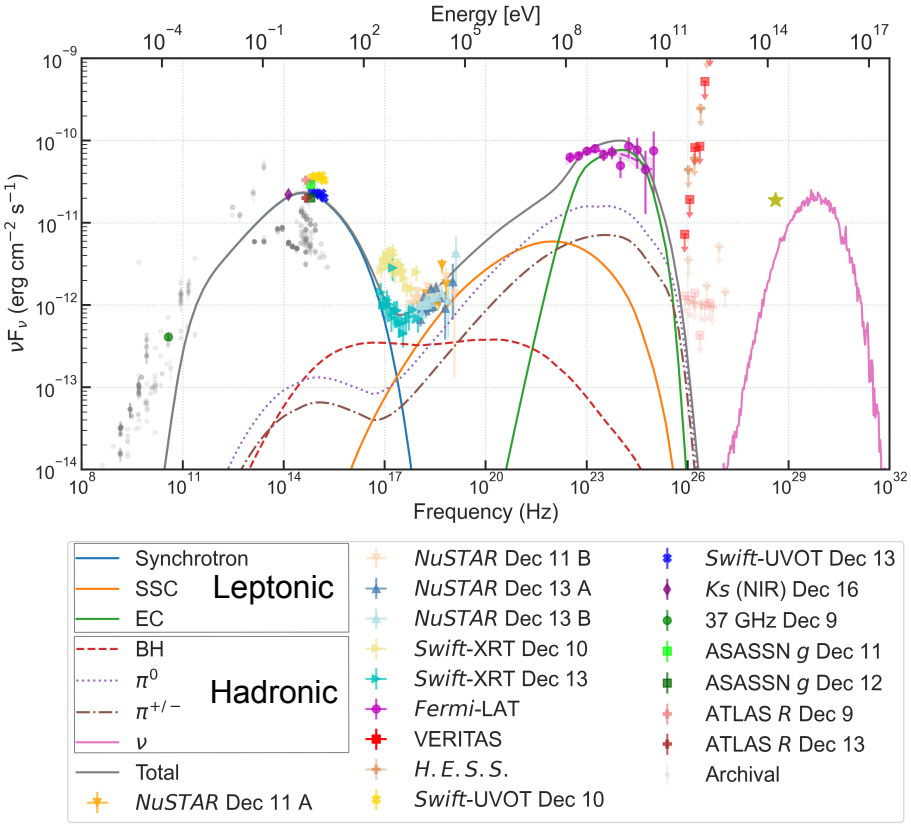
On longer timescales (years): Historic high fluxes coincident with the neutrino
On shorter timescales (days): fast, 1-day soft X-ray variability → R < ~5e16 cm



VERITAS/HESS Collaborations+, 2023, ApJ, 954, 70

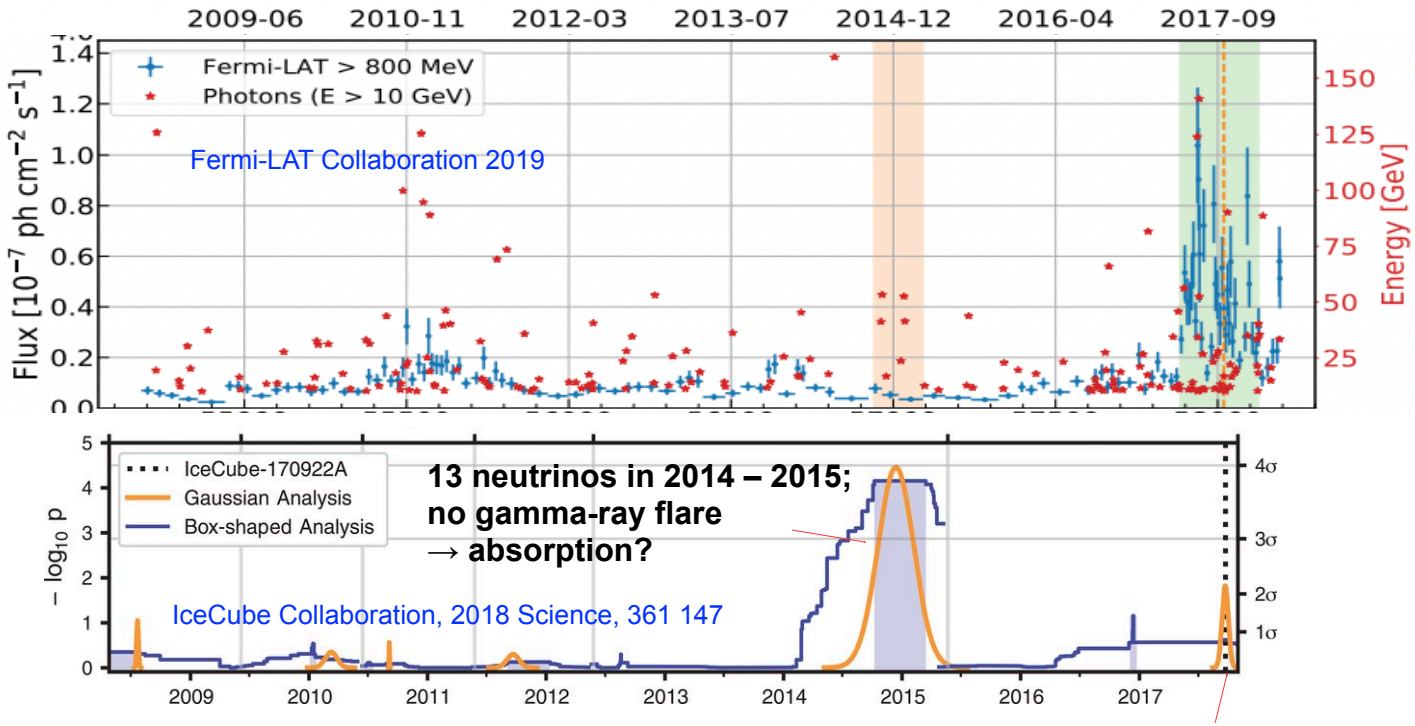
PKS 0735+17 broadband spectrum

- **Gamma-ray spectral cutoff: need external photon field**.
- **Subdominant hadronic** component constrained by X-ray observations. Similar to TXS 0506+056.



VERITAS/HESS Collaborations+, 2023, ApJ, 954, 70

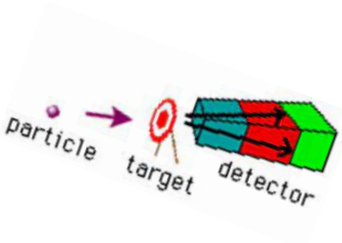
TXS 0506+056: a “masquerading” blazar?



IceCube: ~290 TeV neutrino event IC170922A

“Hidden/masquerading” blazars as neutrino sources?

- Gamma-ray absorption features?
- Temporal coincidence between gamma-ray “suppressed” state and neutrino production?
- Gamma-ray emitting location?



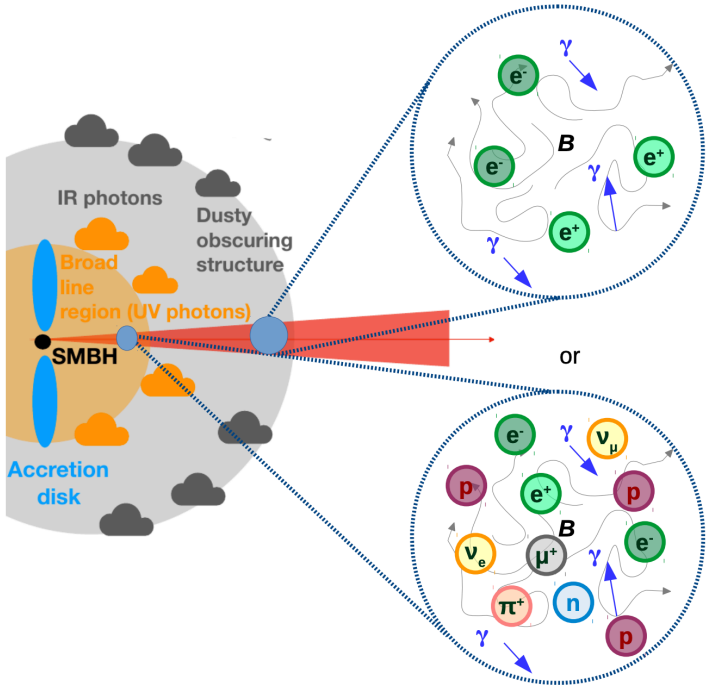
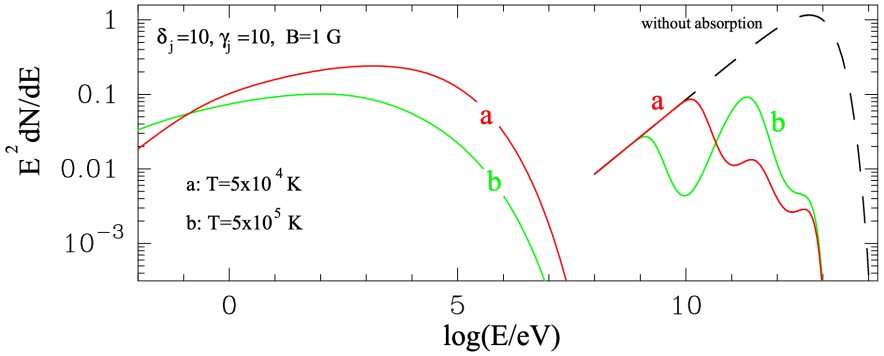


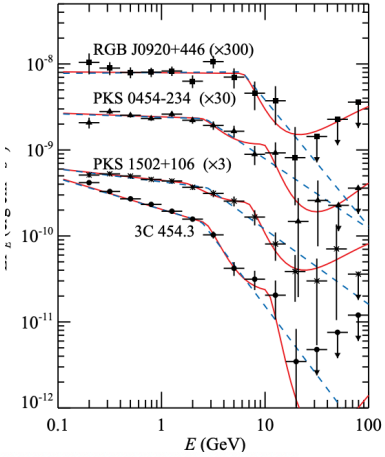
Figure adapted from M. Petropoulou

Gamma-ray absorption features & gamma suppressed states?

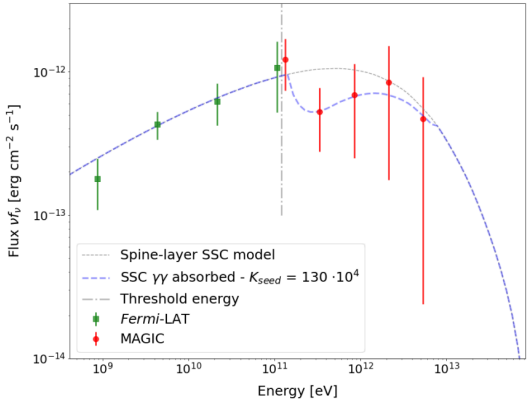
Aharonian+ 2008

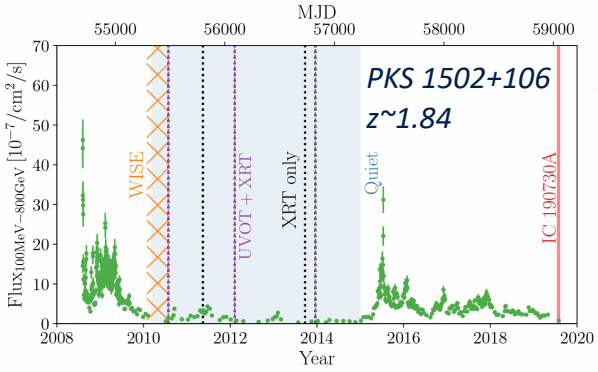


Poutanen & Stern 2010

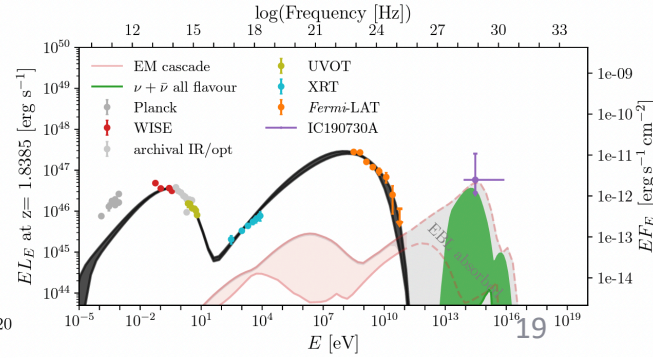


Foffano+ 2022





Oikonomou+ 2021



Where do gamma rays come from? (are hadronic pγ processes important?)

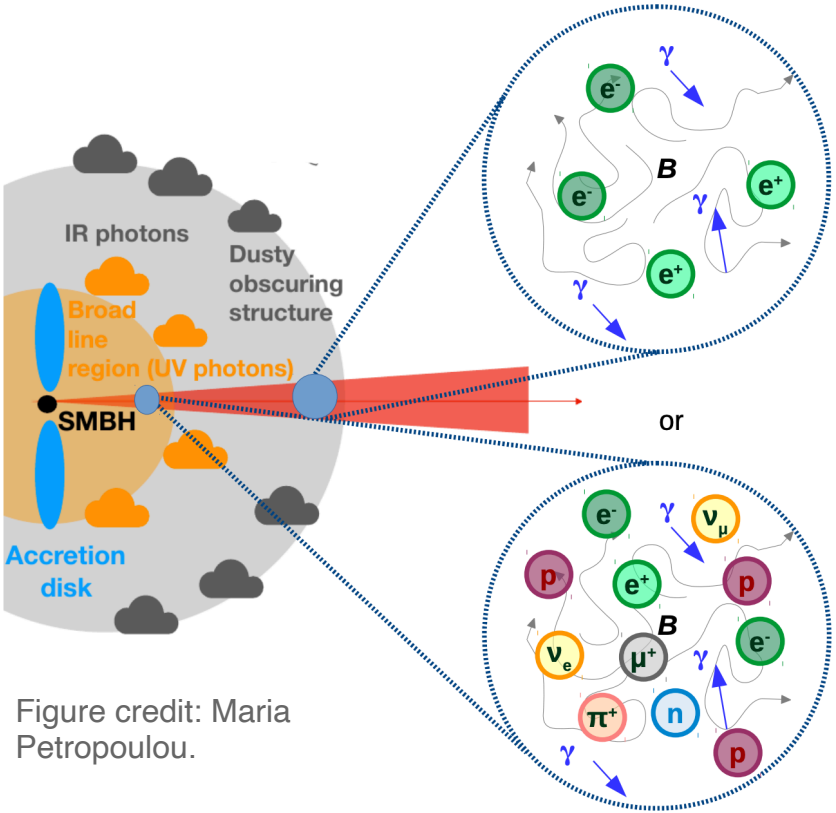
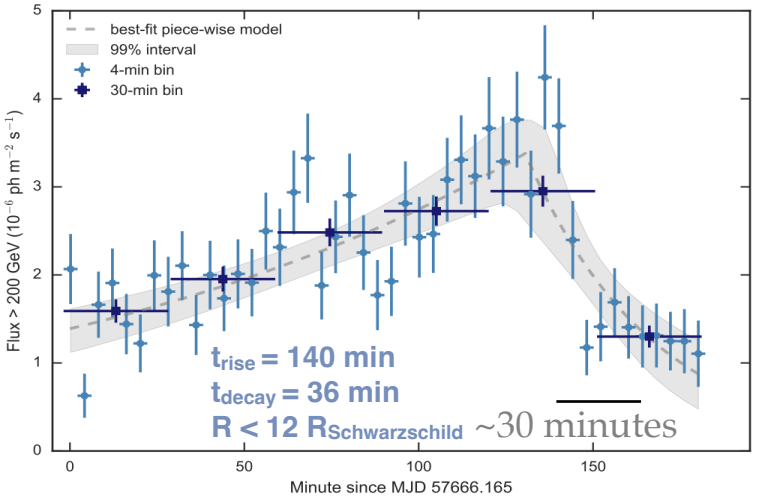


Figure credit: Maria Petropoulou.

Size of the emitting region – from time to space

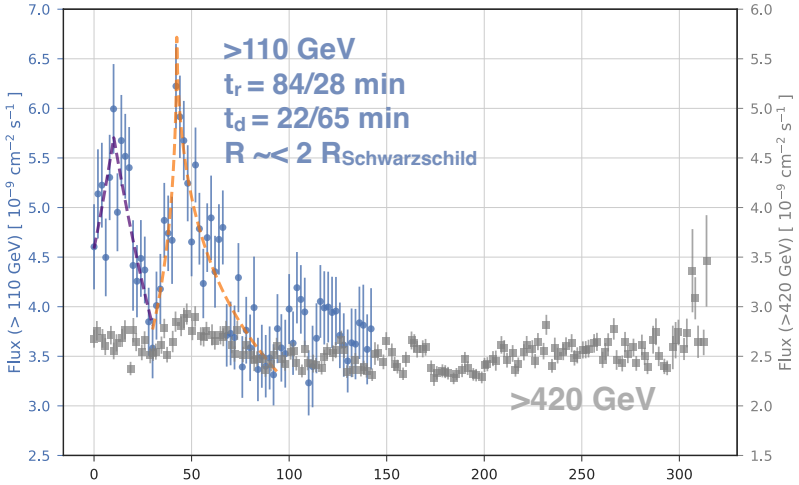
BL Lacertae
Fast TeV gamma-ray flares in 2011, 2015, and 2016

VERITAS Collaboration, 2018, ApJ, 856, 95



Mrk 421
Fast TeV gamma-ray flares in 2010

VERITAS Collaboration, 2020, ApJ, 890, 97



Extremely compact emitting zone!
- smaller than the Event Horizon Telescope angular resolution (by ~300x)

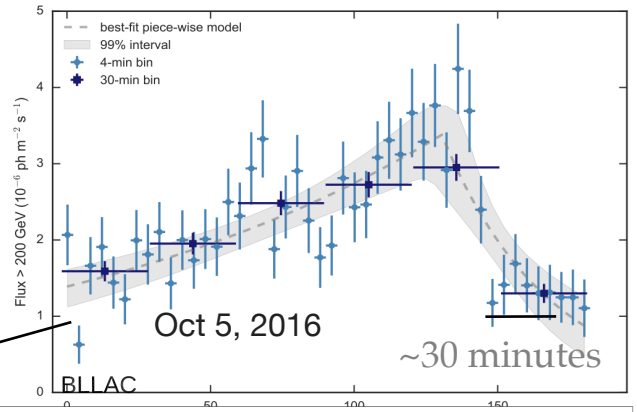
Localizing Emitting Region with Rapid TeV Flares

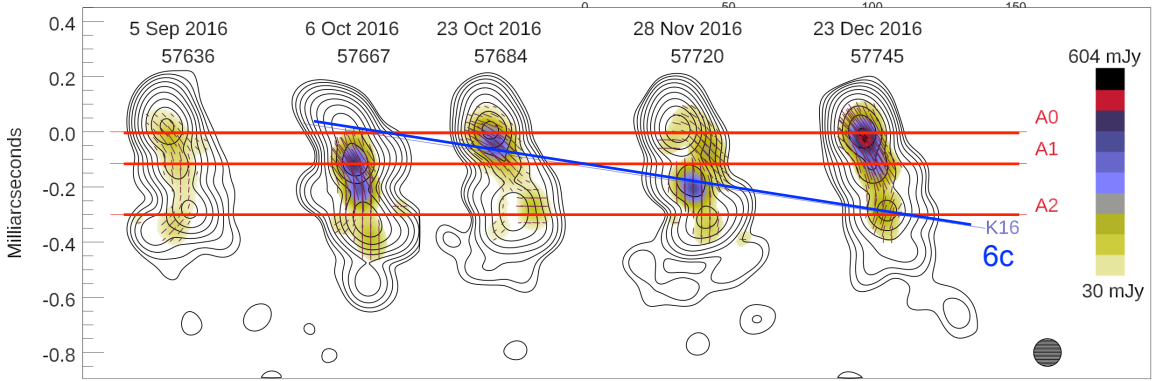
BL Lacertae – Fast TeV flares **coincident** with superluminal radio knots.

- **TeV emitting region** could be at the radio core (~1 pc) near the central black hole; outside of the BLR (~0.025 pc).

- Need large Doppler factor to escape (>13).

VERITAS Collaboration, 2018, ApJ, 856, 95





A candidate superluminal knot appears

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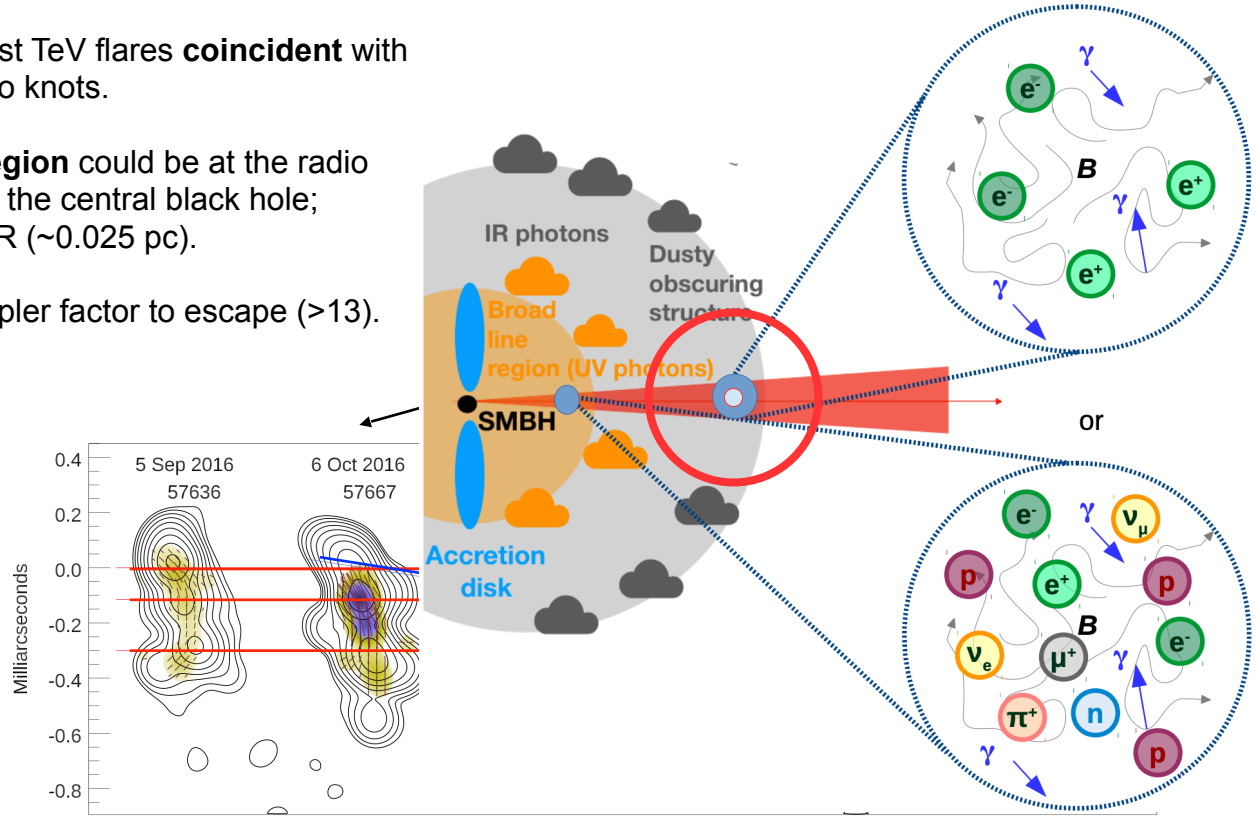
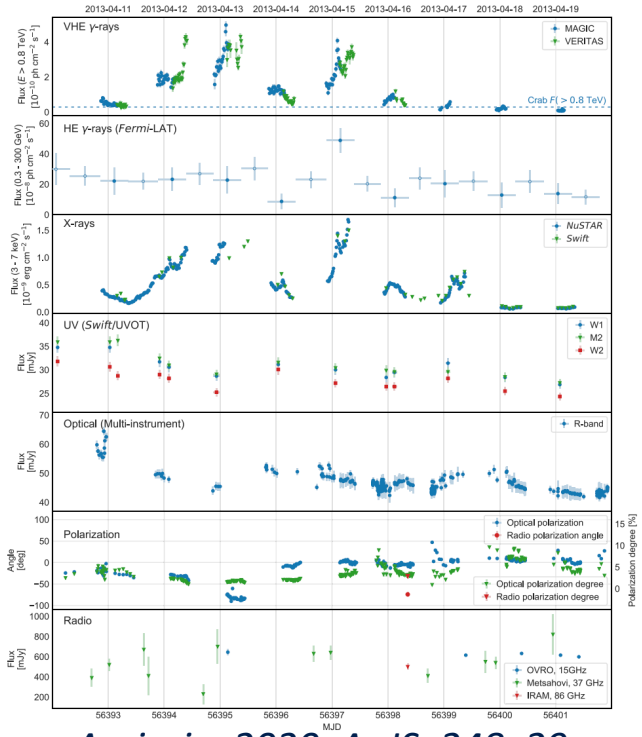


A candidate superluminal knot appears

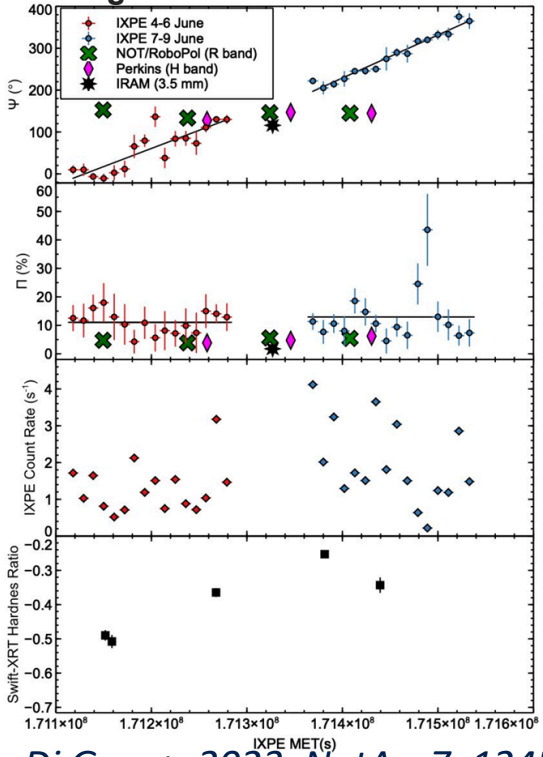
Fast TeV flares vs X-ray

Fast TeV gamma-ray flares correlated with X-ray flares in Mrk 421 in 2013



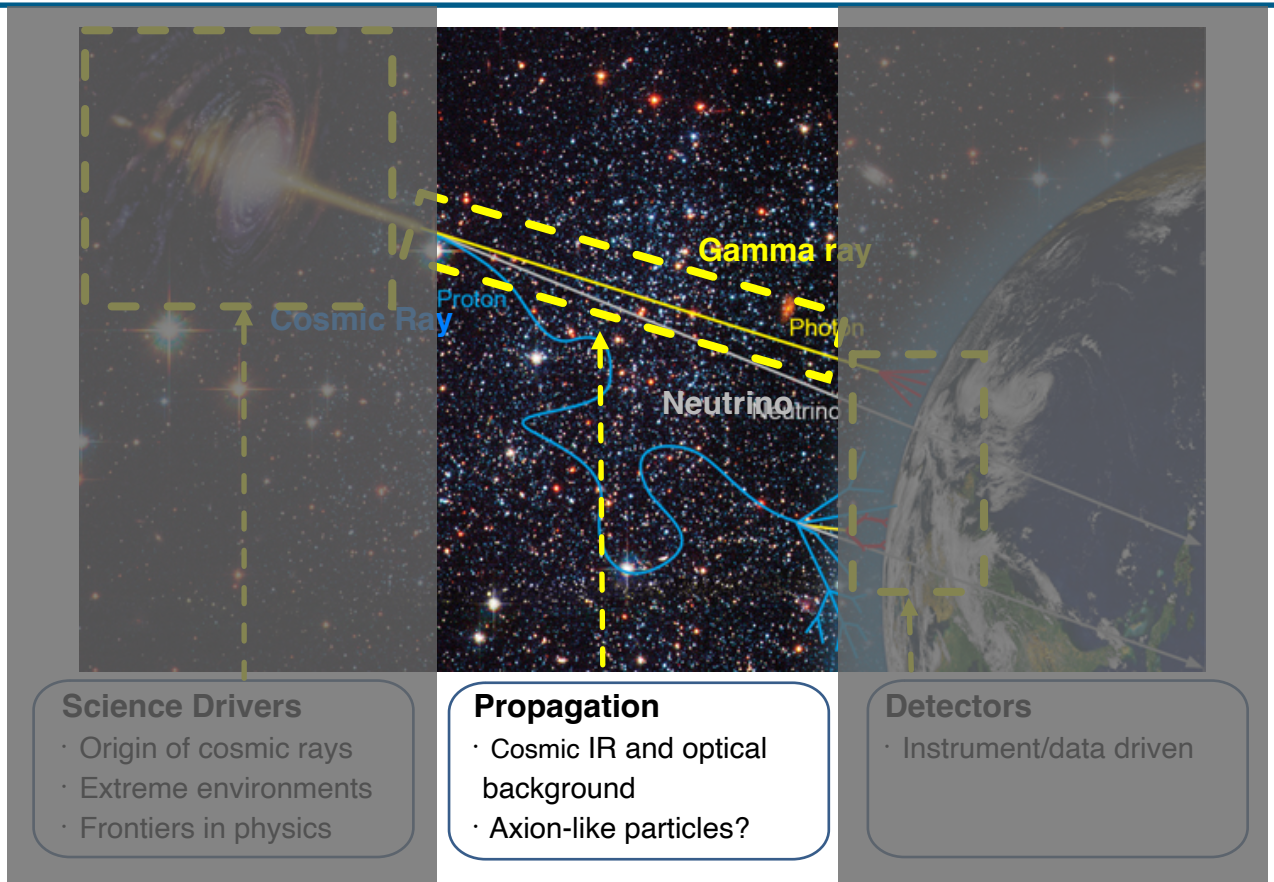
Acciari+, 2020, ApJS, 248, 29

IXPE X-ray polarization rotation in Mrk 421
Shock? Magnetic reconnection? Turbulence?

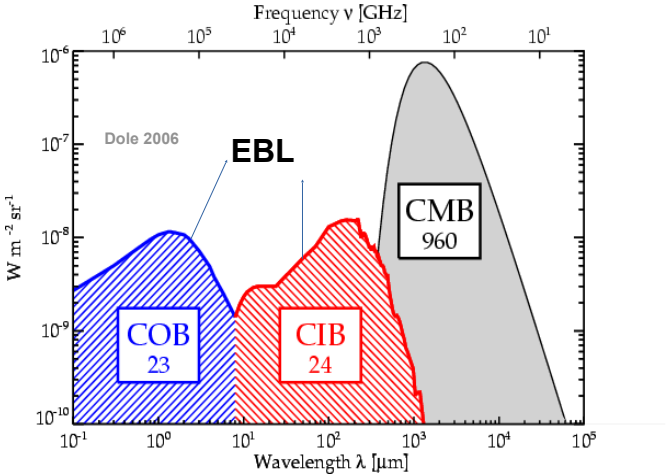


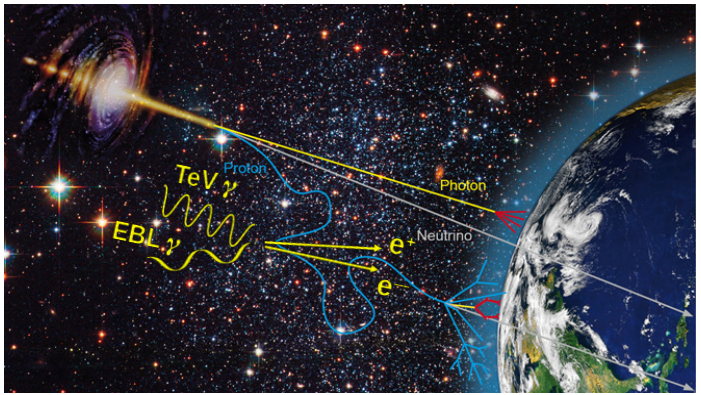
Di Gesu+, 2023, NatAs, 7, 1245

Gamma-ray propagation



Interactions between Extragalactic Background Light (EBL) and TeV gamma-ray photons results in attenuation above ~100 GeV



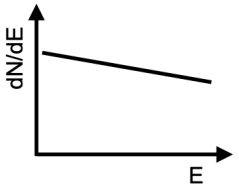


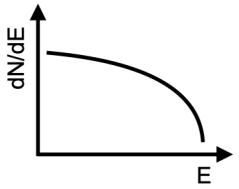
Intrinsic spectrum:

$$\frac{dN}{dE} \propto E^{-\Gamma}, \frac{dN}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_C}\right), \ldots?$$

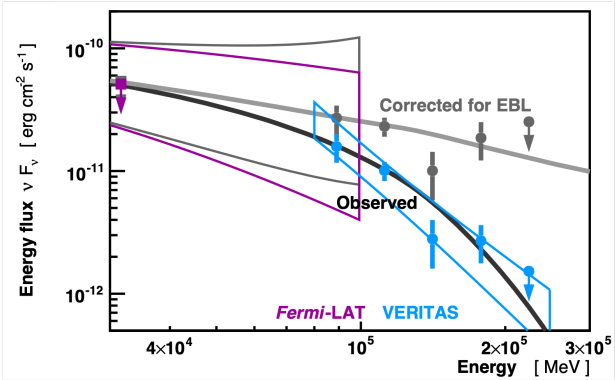
Observed spectrum:

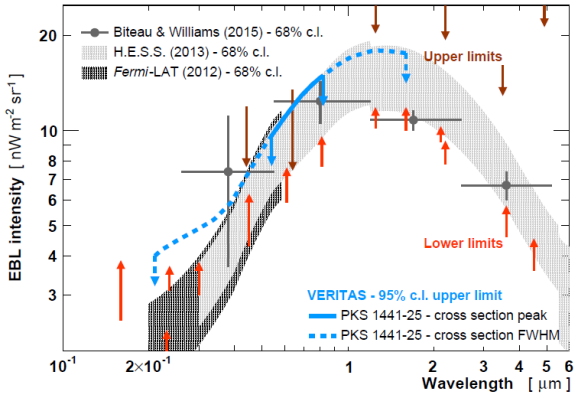
$$\frac{dN}{dE} \propto \left(\frac{dN}{dE}_{int}\right) \exp(-\tau_{\gamma\gamma})$$





Constraints on EBL from a flaring TeV blazar





VERITAS Collaboration, 2015, ApJ, 815, 22A

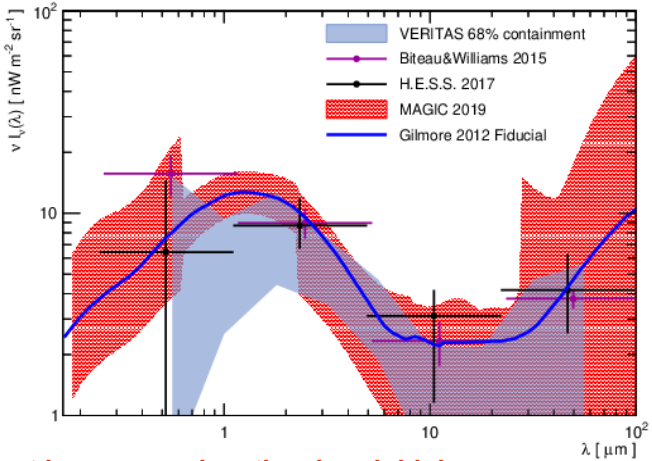
- Interaction of EBL-VHE photons results in attenuation above 100 GeV
- Minimal assumptions on intrinsic spectral properties

(cannot exceed Fermi extrapolation)

- Single source constraints on EBL intensity:
- A quasar half a Universe away:
- PKS 1441+25 @ z = 0.939

Combined constraints on EBL from bright TeV blazars

VERITAS Collaboration, 2019, ApJ, 885, 150

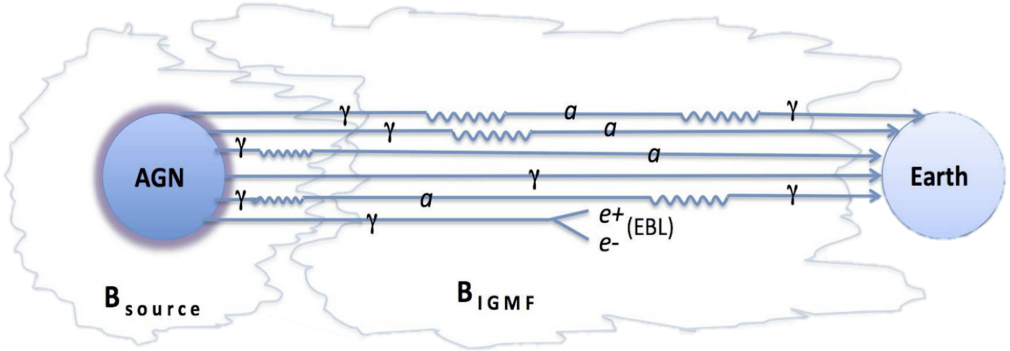


Photons at longer wavelengths absorb higher-energy gamma rays

VERITAS observations on 14 hard-spectrum blazars:

- The **strongest constraints** so far on EBL intensity at IR wavelengths.
- Galaxy surveys have resolved most of the sources of the EBL at these wavelengths.
- The highest intrinsic gamma-ray energy depends on the knowledge of EBL:
  - no evidence for spectral cutoffs between 0.1 and 20 TeV in 8 blazars

Is the universe more transparent than we thought? (photon coupling to axion-like particles)

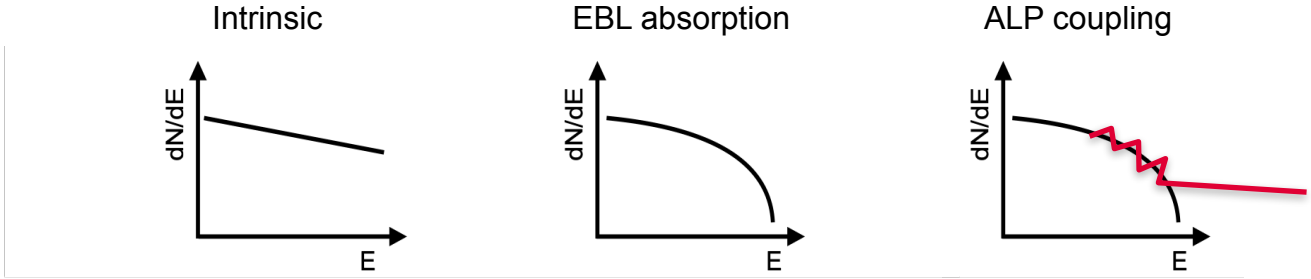


Sánchez-Conde et al. 2009

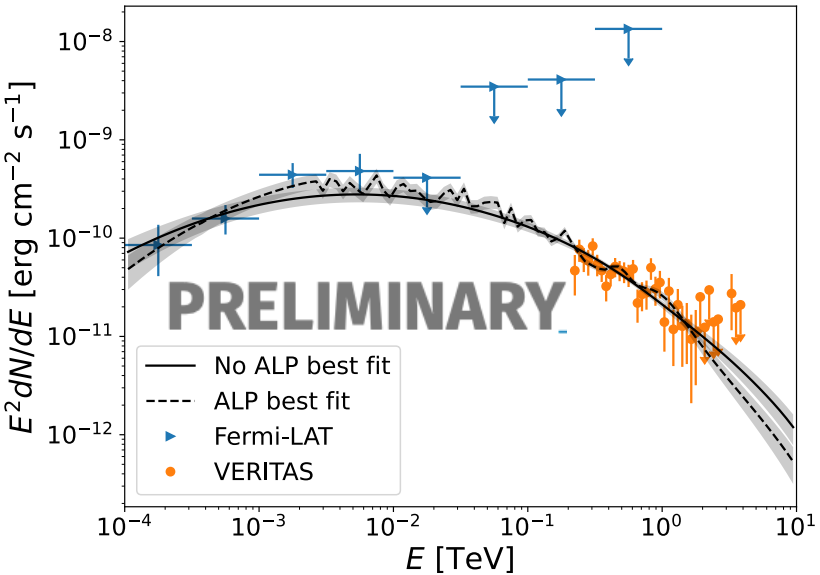
Axion-like particles (ALPs):

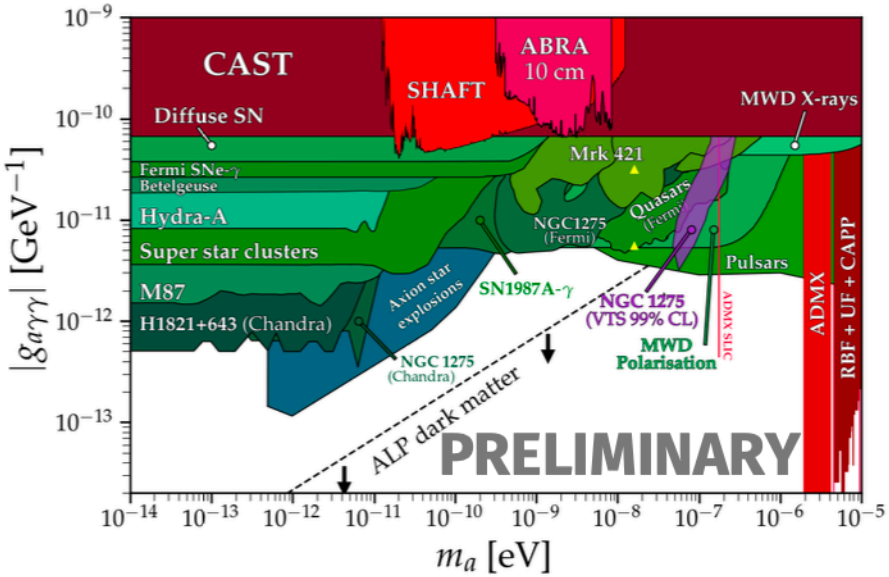
- Hypothetical, beyond Standard Model
- Low mass (<eV), long lifetime
- Weakly interacting
- Coupling to photons in B field
- Dark matter candidate

"Light shining through a wall"



ALP constraints using a flare from NGC 1275
Flare gives good statistics

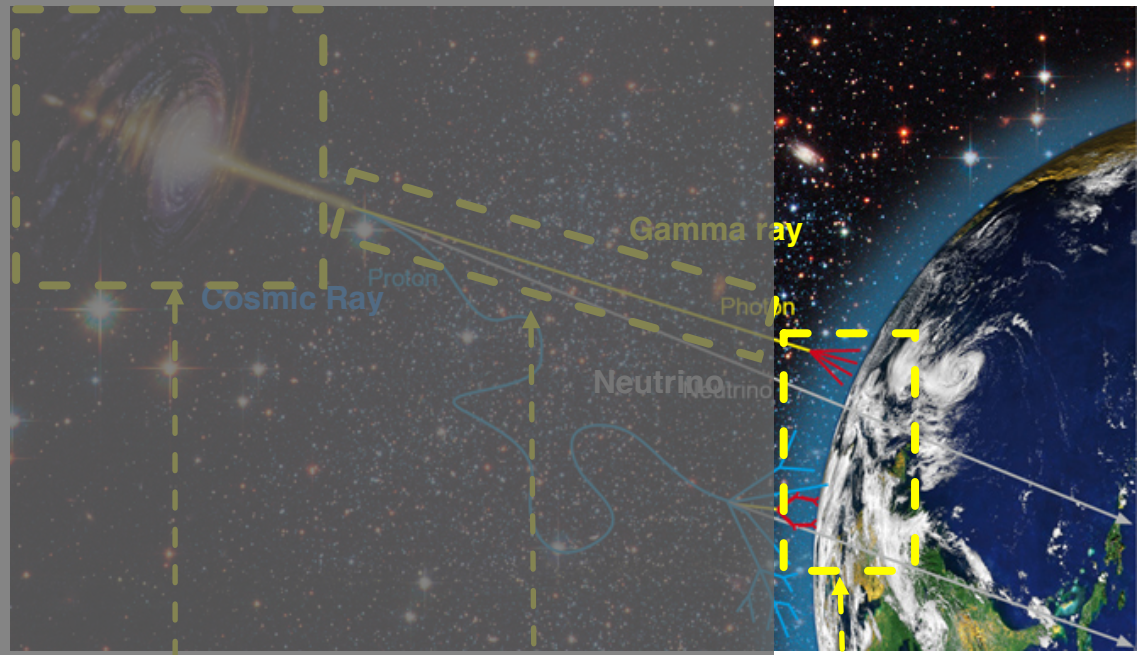




(Ongoing work with Columbia student Colin Adams)

Good opportunity to combine gamma-ray data on blazars from Fermi, VERITAS, and HAWC to test fundamental physics.

Future experiments



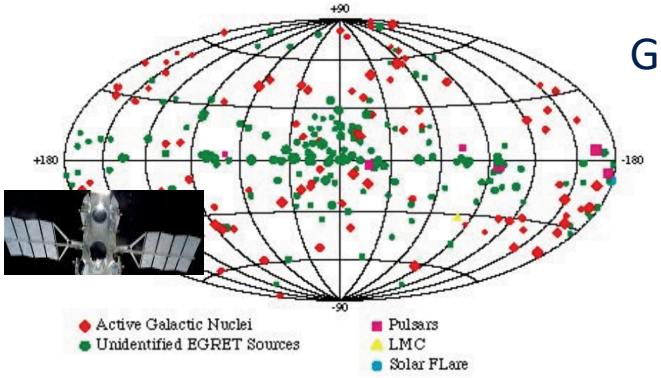
Science Drivers
- Origin of cosmic rays
- Extreme environments
- Frontiers in physics

Propagation
- Cosmic IR and optical background
- Axion-like particles?

Detectors
- Instrument/data driven

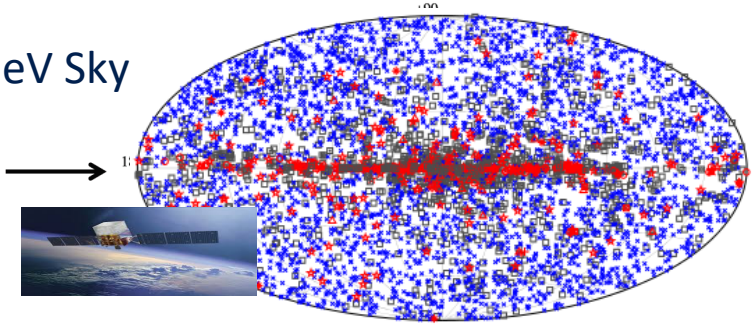
Instrument-driven

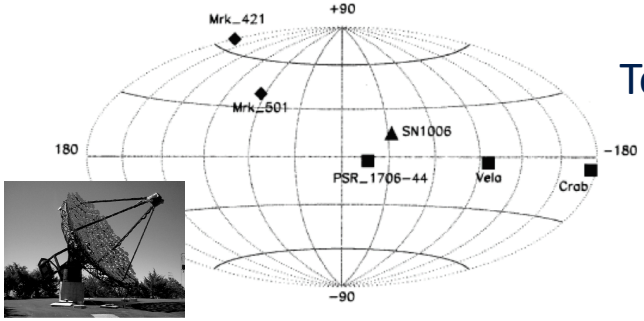
3rd EGRET Catalog (1999)



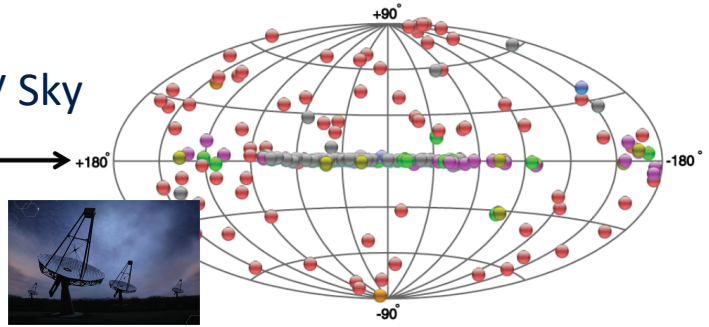
4th Fermi-LAT Catalog (2019)

GeV Sky





TeV Sky

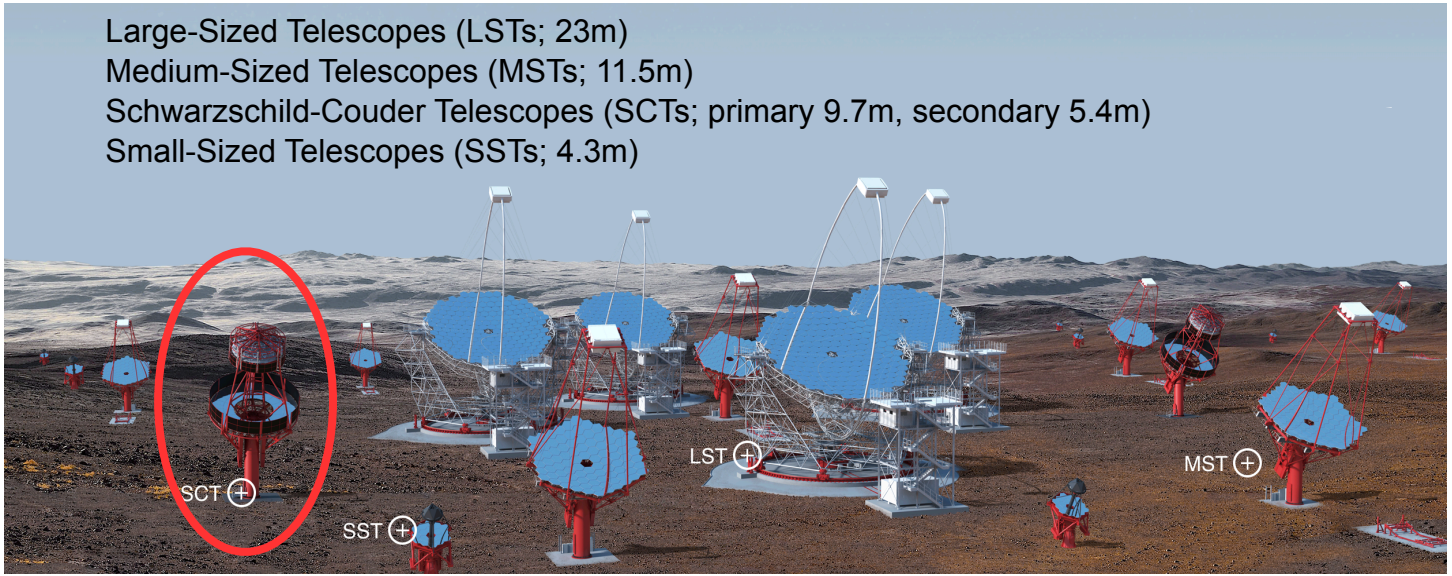


TeV Skymap c. 1998

TeV Skymap c. 2019

Next-generation gamma-ray telescopes: Cherenkov Telescope Array (CTA)

- Two **large** arrays (North 13 / South 50 telescopes)
- **10 fold increase in sensitivity** from current instruments
- 3 telescope sizes → 4 decades of energy (to >100 TeV)
- **Improved angular resolution** and energy resolution



Summary

- Exciting questions in multi-messenger astronomy to be answered in the coming years
  - Some blazars are likely key: Which? How and when are they associated with neutrinos?
- TeV gamma-ray flares from blazars probe
  - The size of the emitting region
  - (With MWL data) The location and particle acceleration
  - Along the path of propagation EBL and ALP
- New instruments on the horizon to advance the field