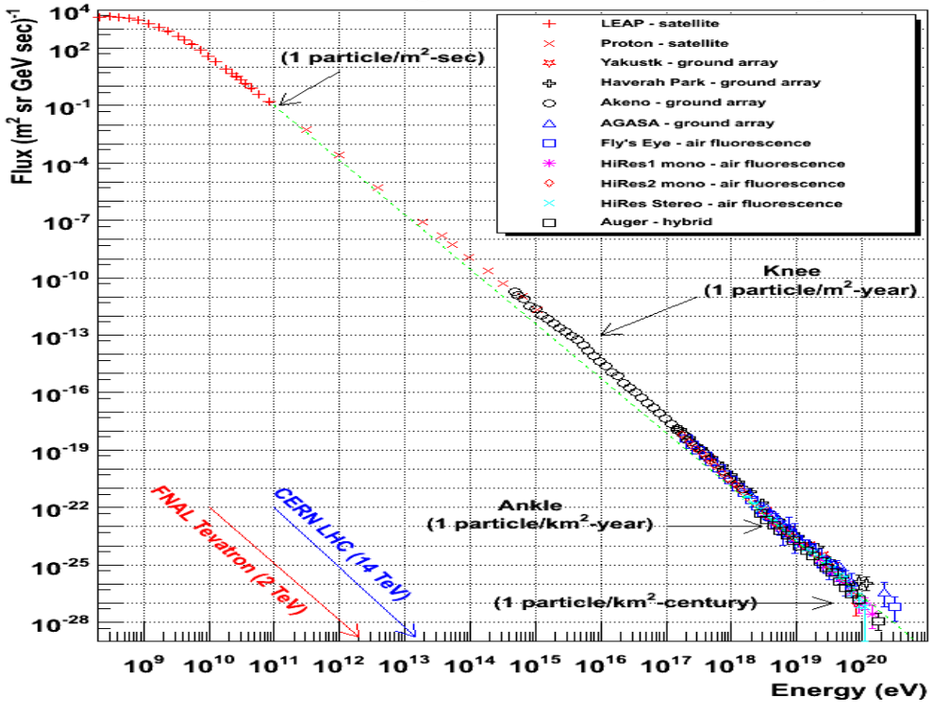
Gamma-ray Astrophysics: Phenomenology

Yoshiyuki Inoue (RIKEN)

Gordon Research Conference, 2019-07-01

Why Gamma-ray Astrophysics?

Unveil the origin of cosmic rays



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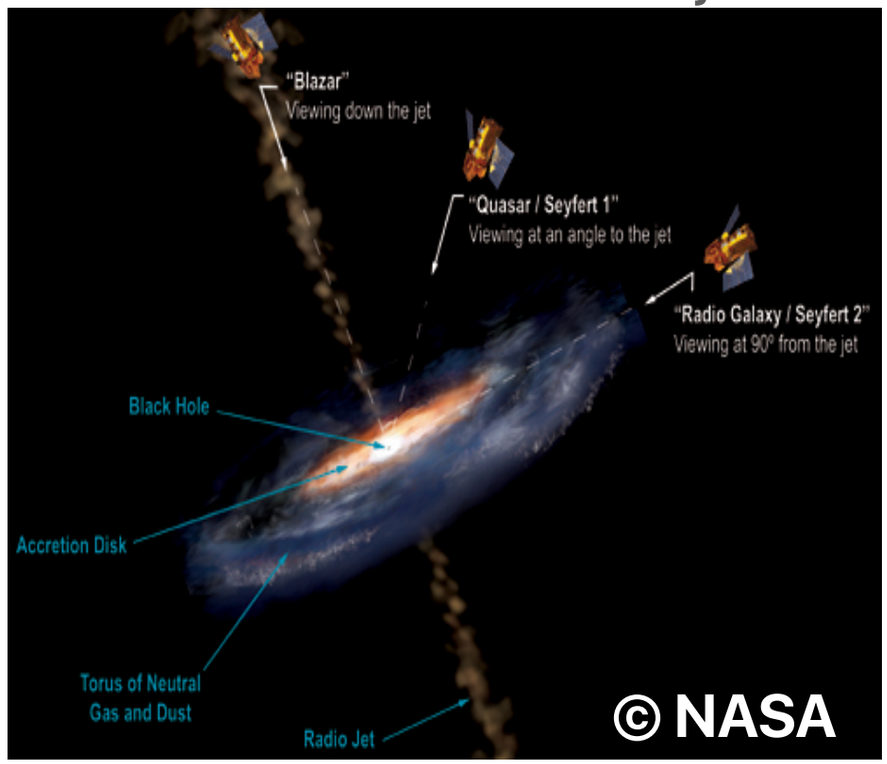
Understand relativistic jets



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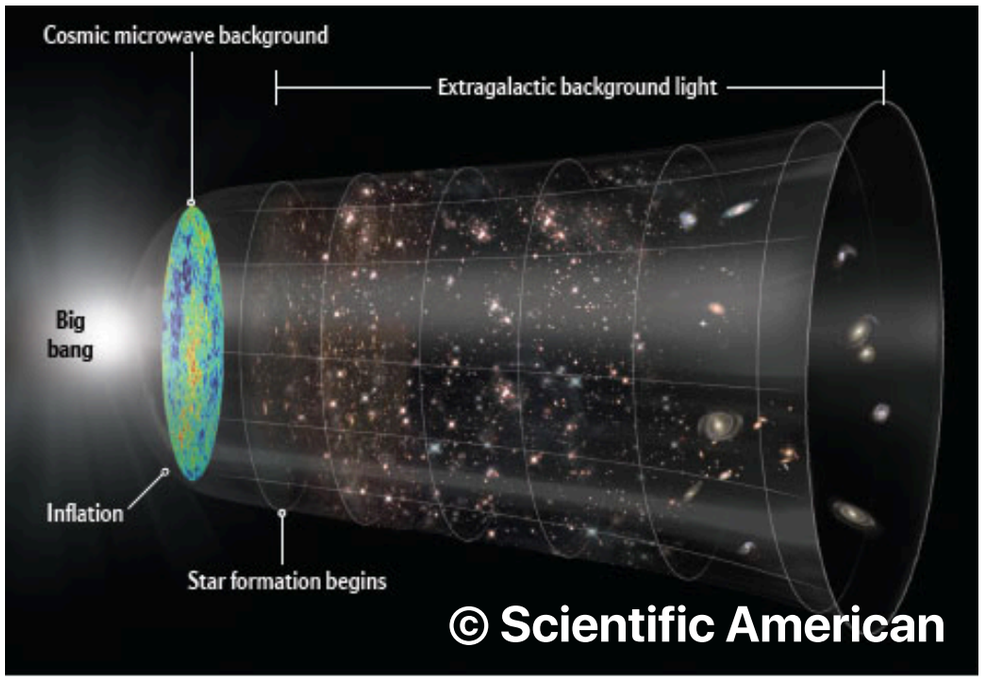
Probe the cosmic history



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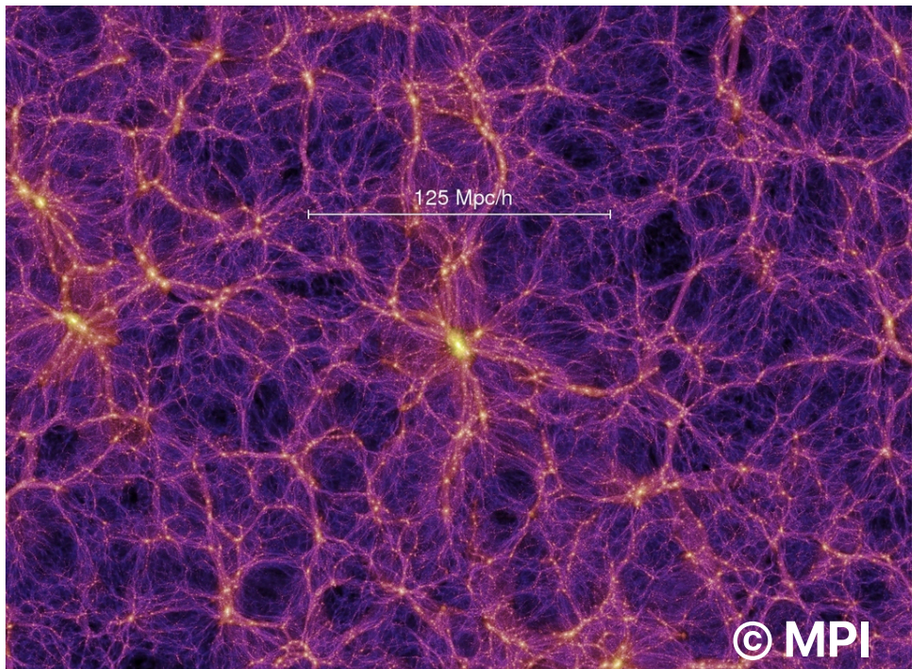
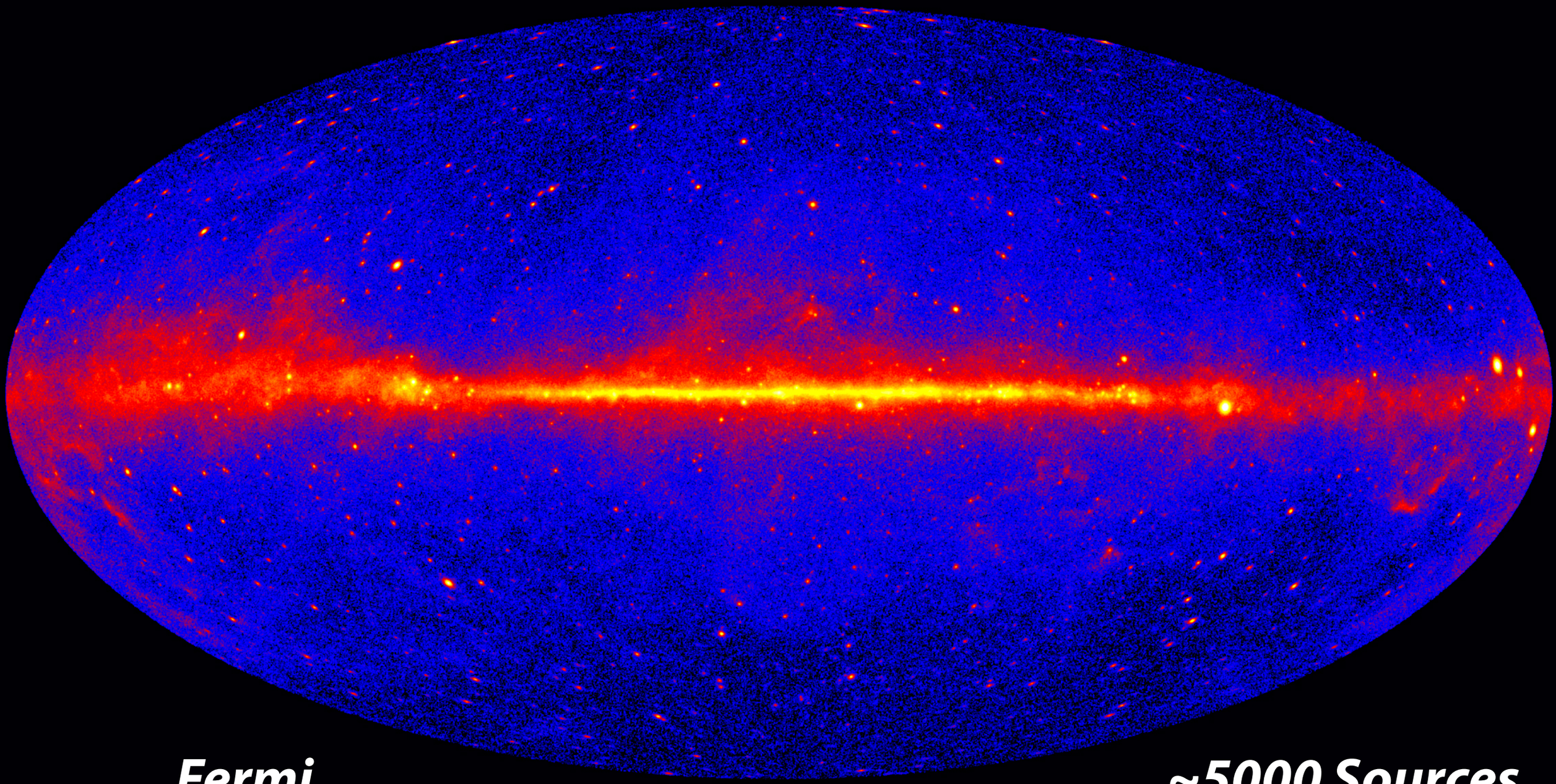
Hunt for dark matter signals



© MPI

GeV Gamma-ray Sky

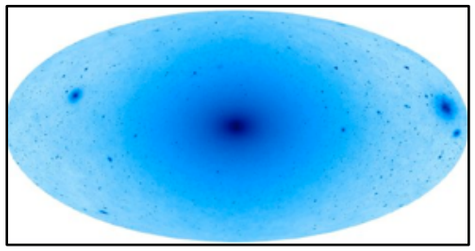


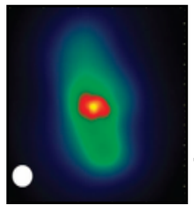
Fermi

~5000 Sources

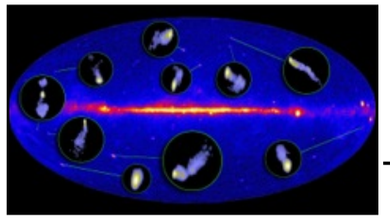
Gamma-ray Objects

Dark Matter searches

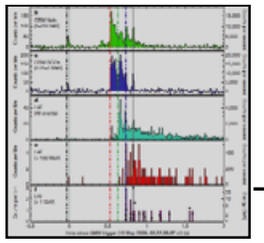




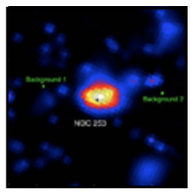
Radio Galaxies



Blazars

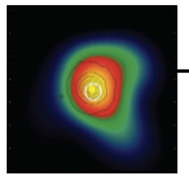


GRBs

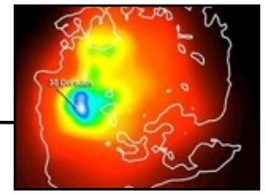


Starburst Galaxies

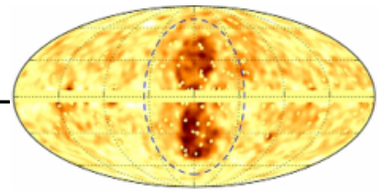
Extragalactic



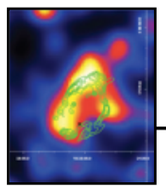
Globular Clusters



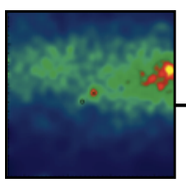
LMC & SMC



Fermi Bubbles

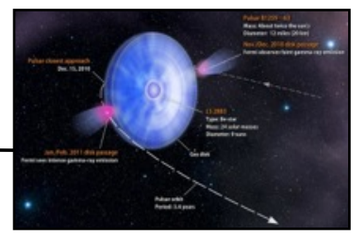


SNRs & PWN

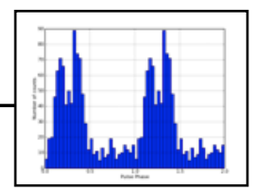


Novae

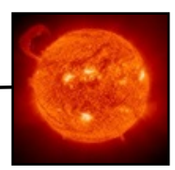
Galactic



γ-ray Binaries

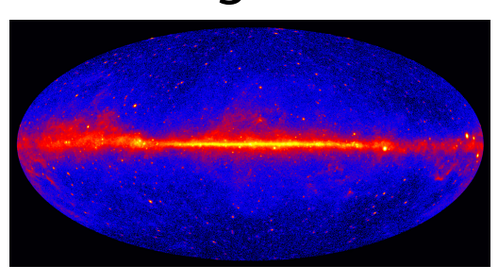


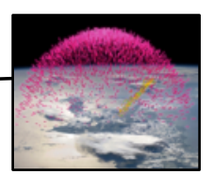
Pulsars: isolated, binaries, & MSPs



Sun: flares & CR interactions

Background

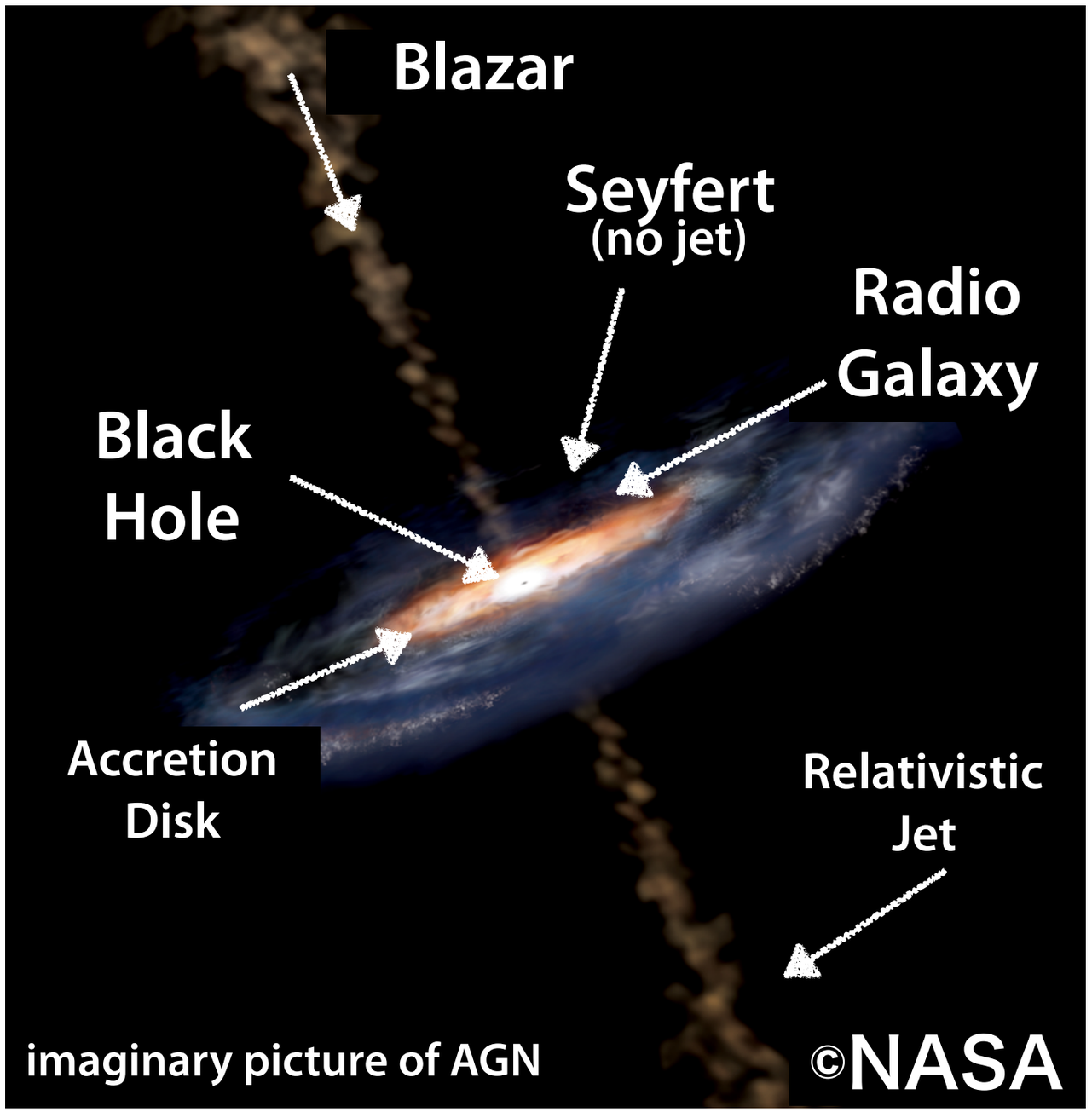




Terrestrial γ-ray Flashes

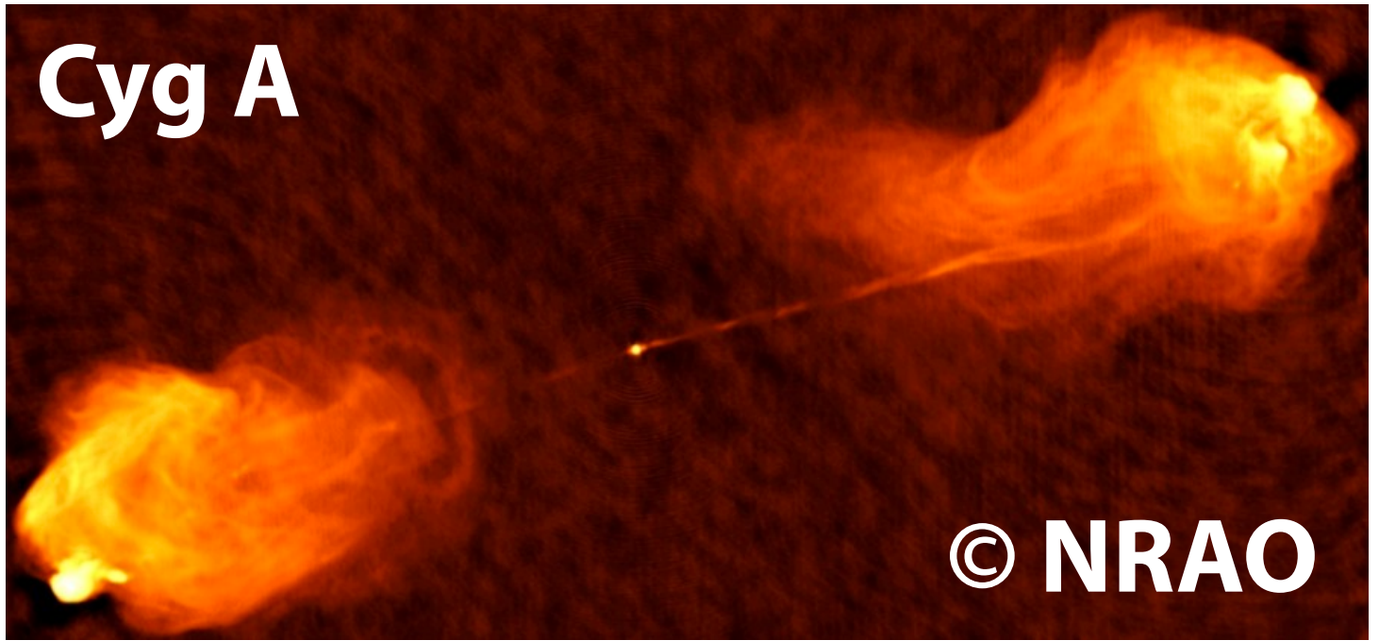
Unidentified Sources

Active Galactic Nuclei (AGNs)

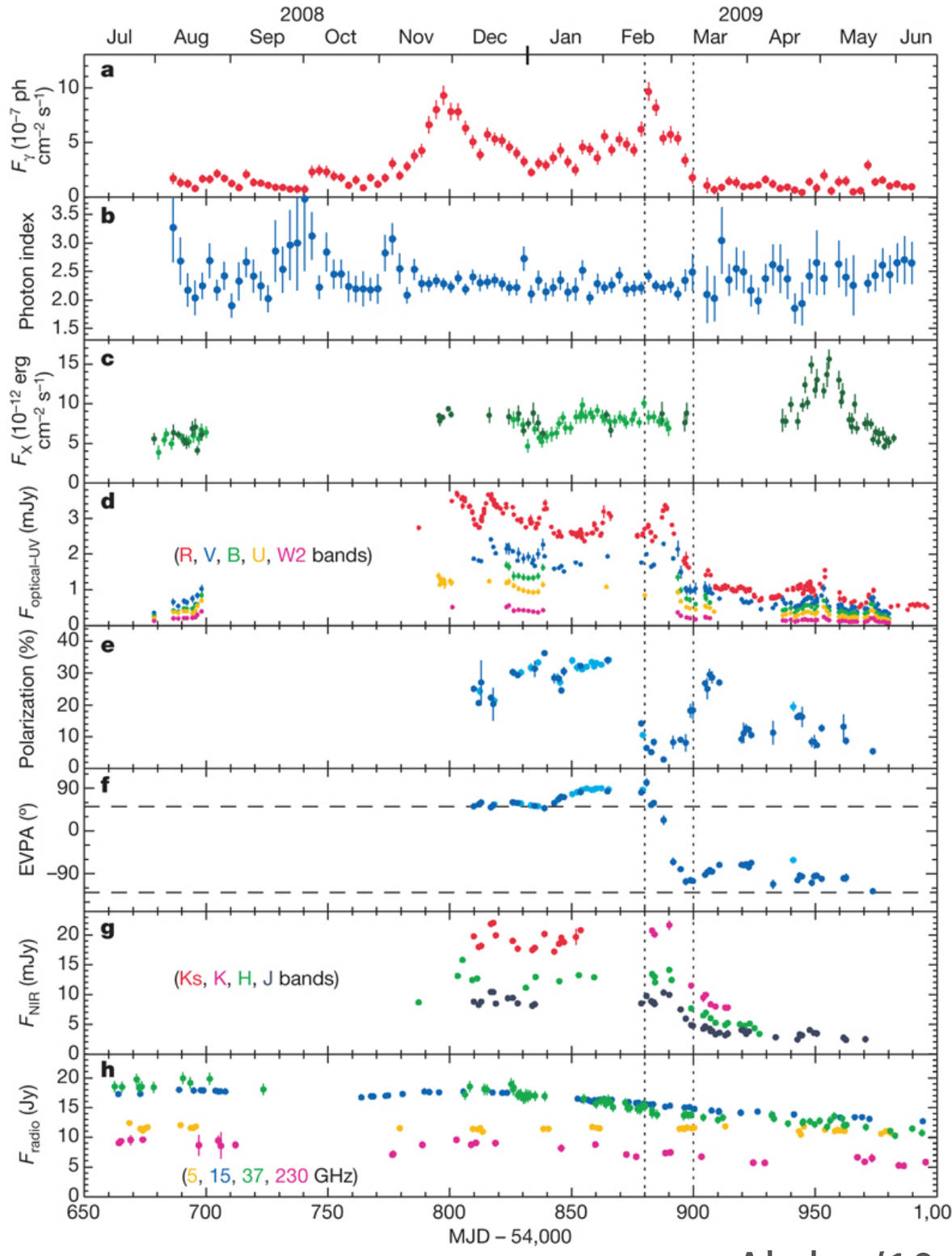


- >10^6 solar mass @ galactic center
  - Correlate with various physical parameters of host galaxies
- Gas accretion -> brighter than the galaxy (AGNs)
  - Various population
  - Relativistic jet
    - Ultra-high-energy cosmic rays / high-energy neutrinos

Blazars



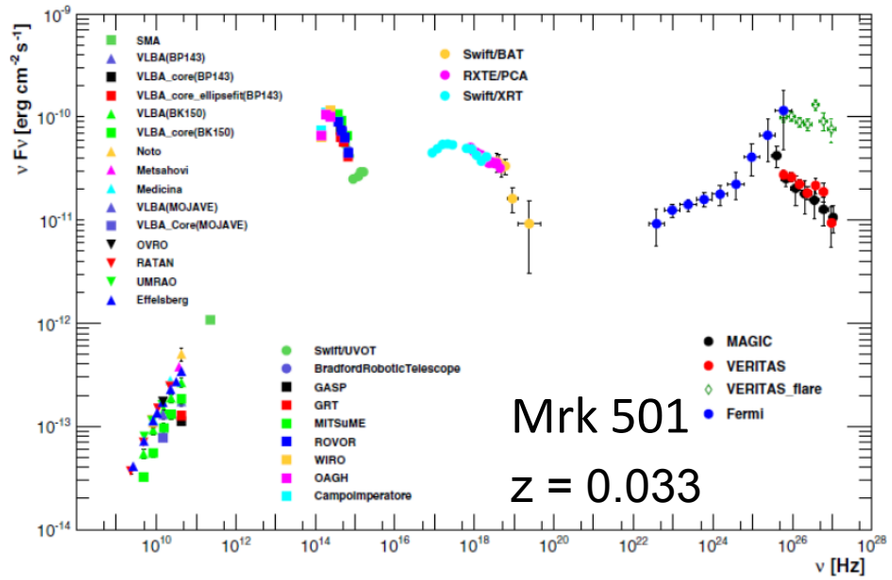
- AGNs whose relativistic jets pointing at us.
- Variable ($\Delta t \sim 1$ day)
- ~10% polarization



Abdo+'10

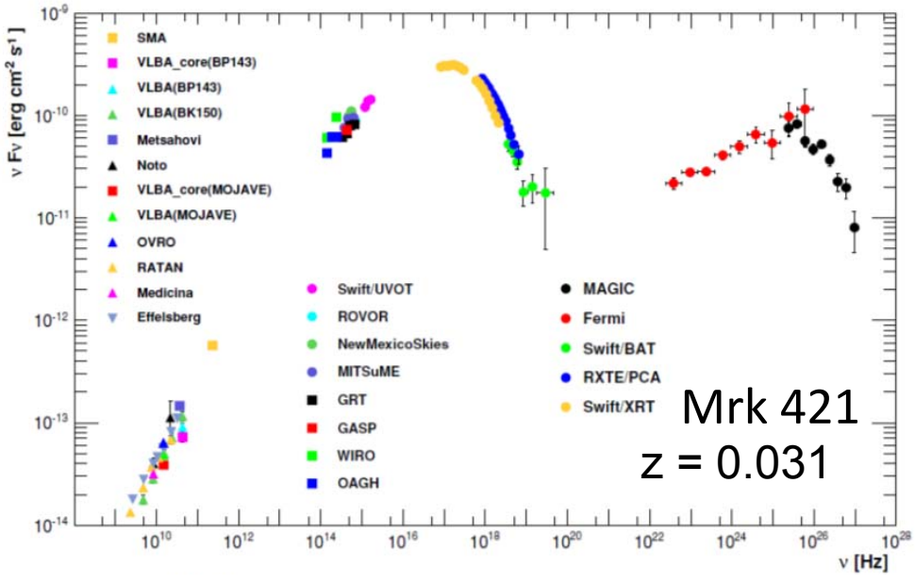
Blazar Spectra

BL Lacs: emission to VHE/TeV energies



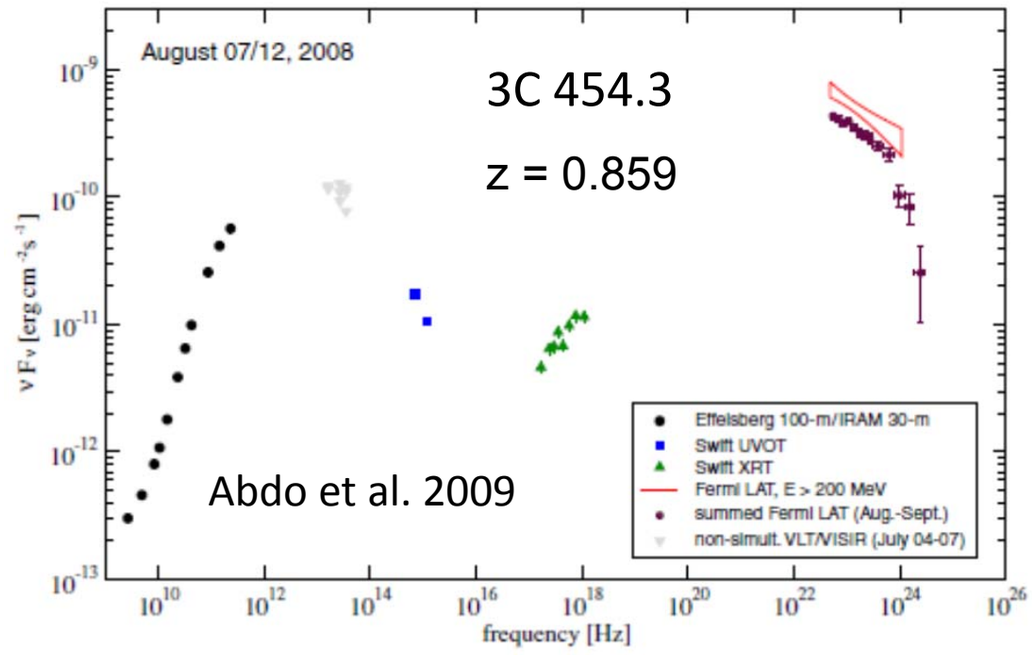
Abdo et al. 2011a

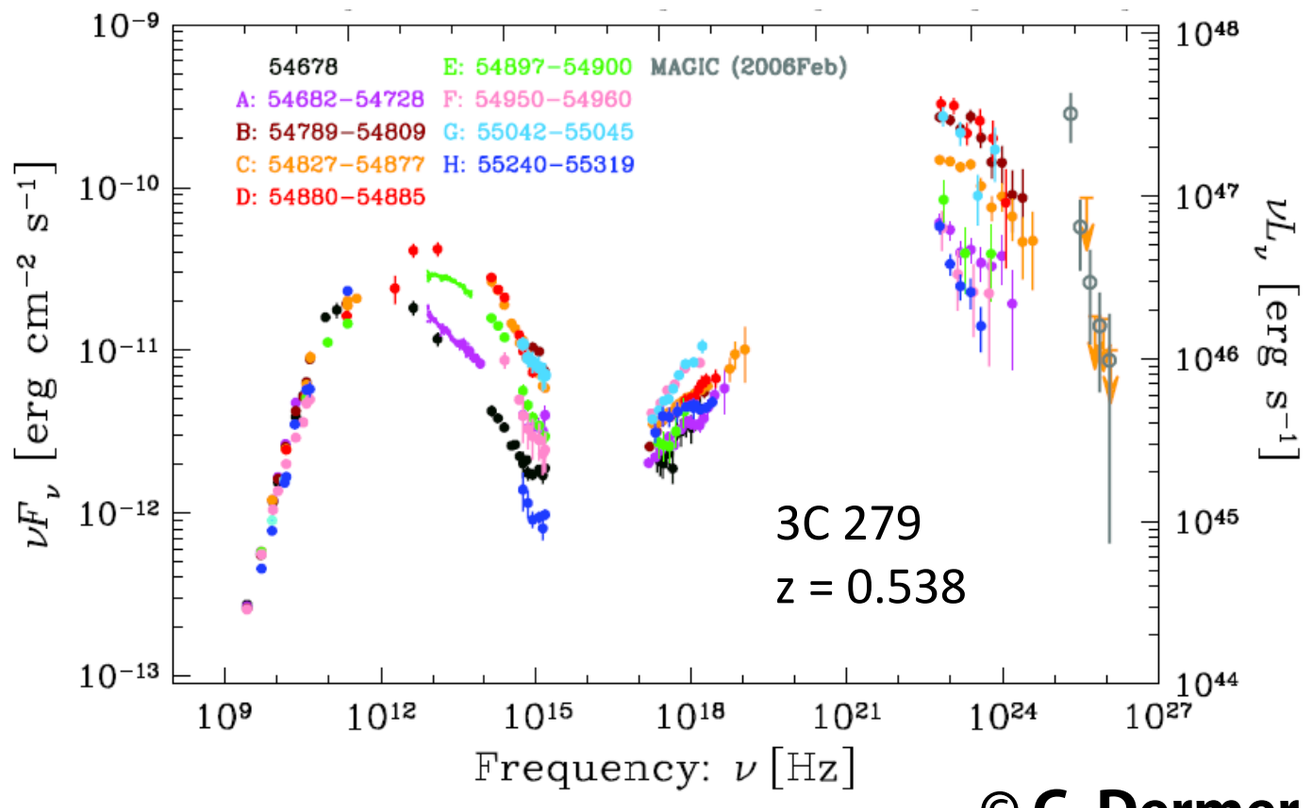
Abdo et al. 2011b



VHE (> 100 GeV)

FSRQs: cutoffs at GeV with VHE episodes





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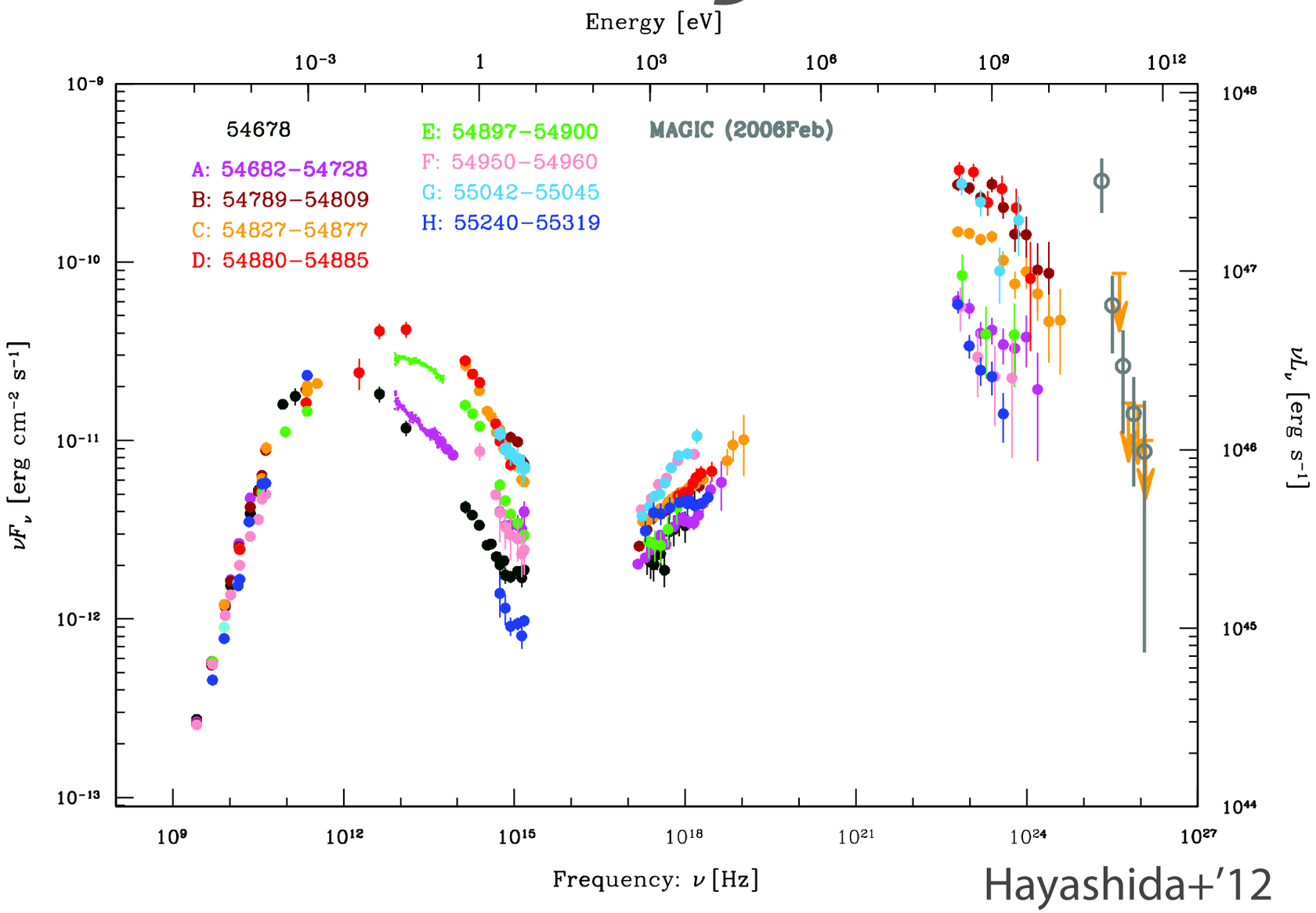
Why Gamma-ray for Blazars?

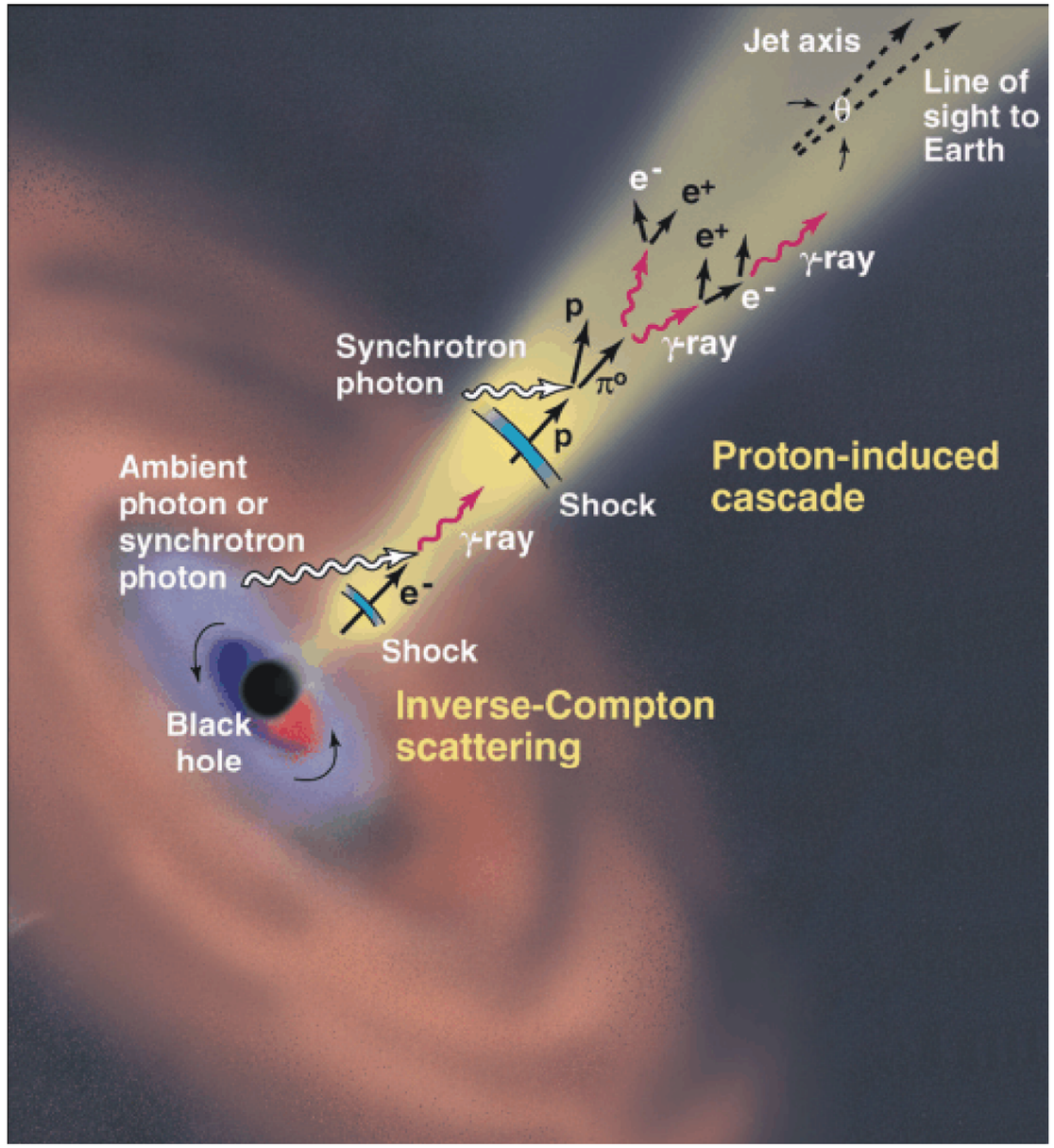


Hayashida+'12

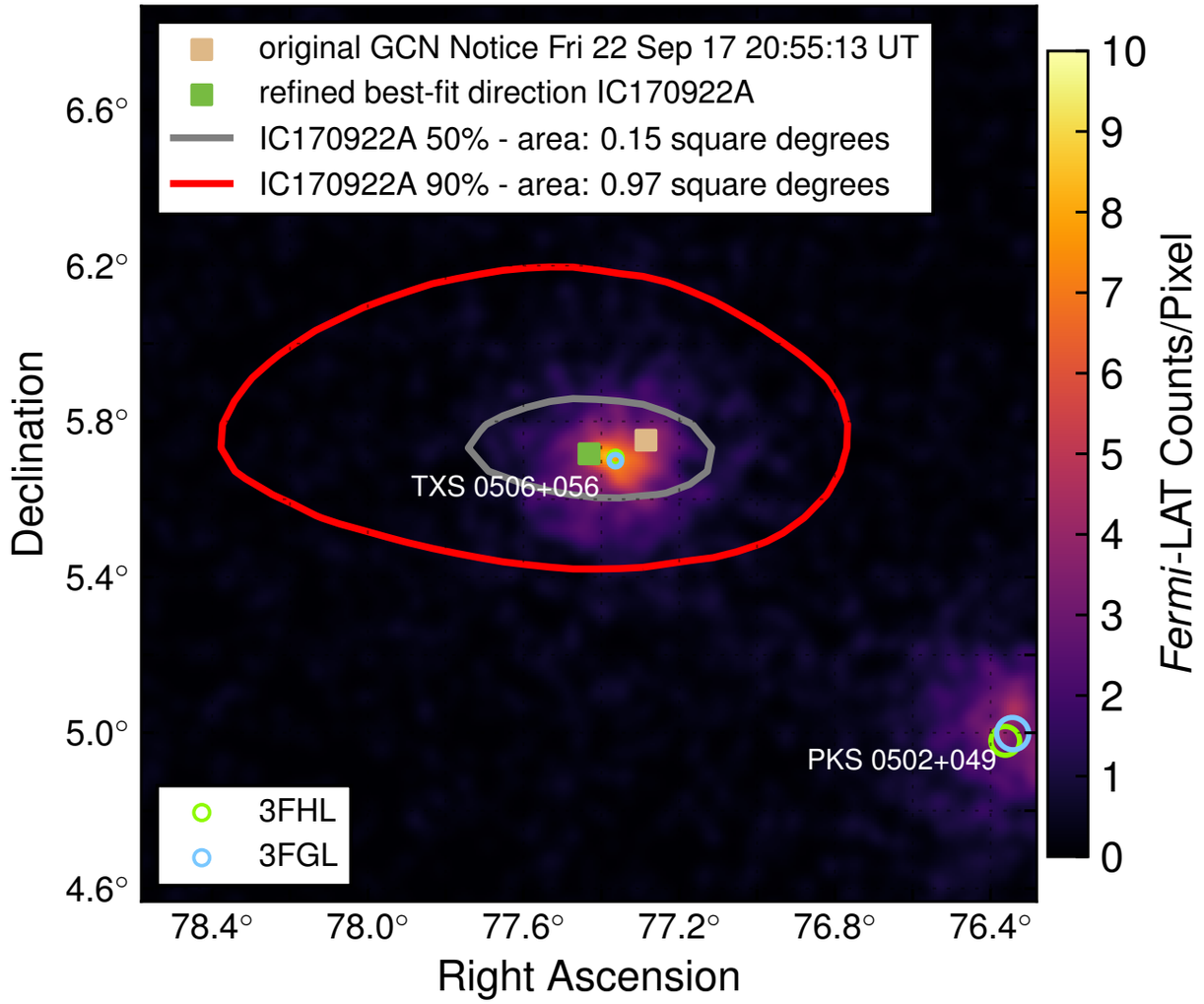
- Spectral energy distribution of a blazar 3C279
- Jet radiative power is dominated by gamma-ray.

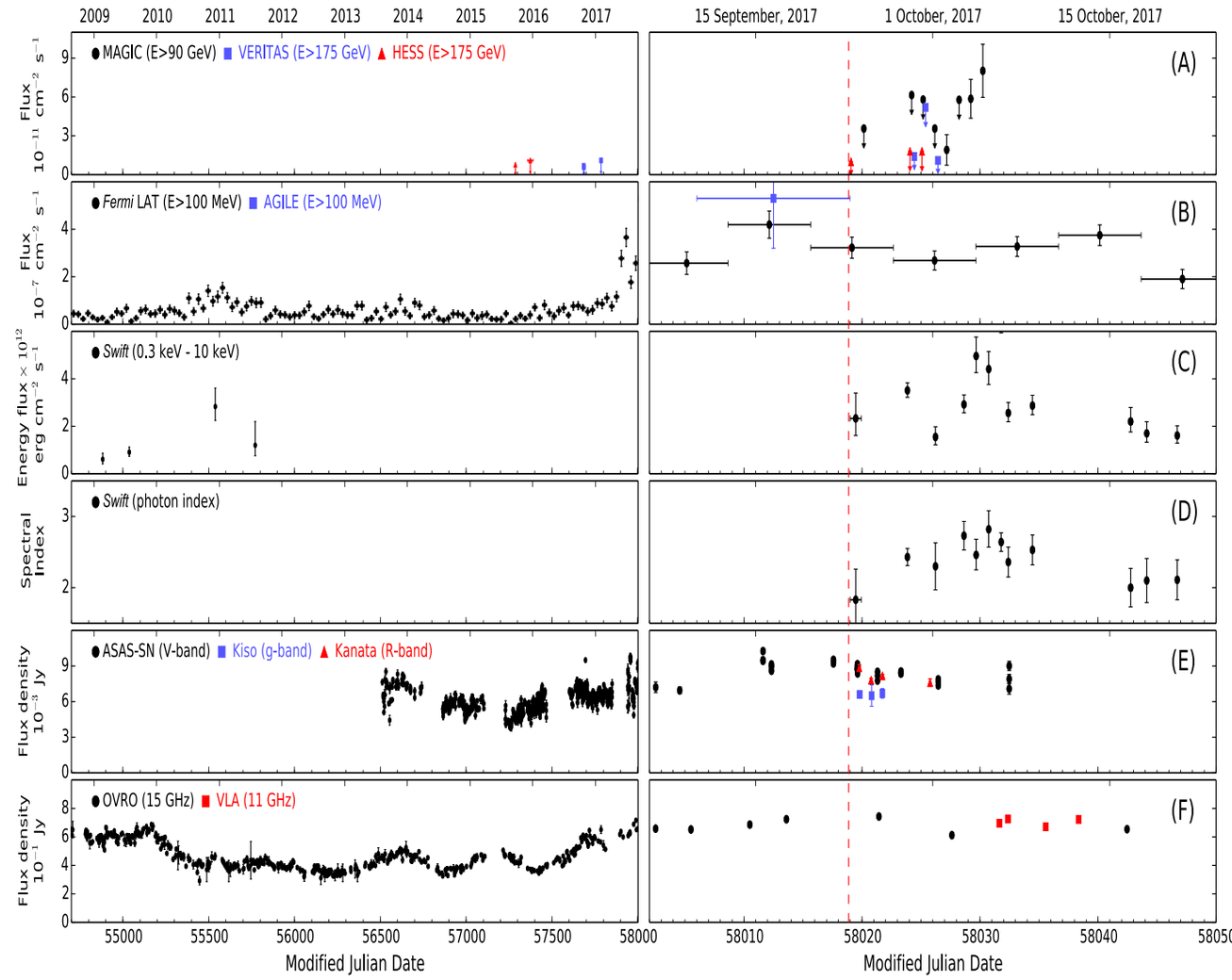
Blazar Emission Mechanism

- Non-thermal gamma rays
  - relativistic particles and intense photon fields
- **Leptonic model**
  - non-thermal synchrotron associated w/ Synchrotron-Self-Compton (SSC) or External Compton (EC) components
- **Hadronic model**
  - secondary nuclear production, proton synchrotron, photomeson production



IceCube 170922A (TXS 0506+056)

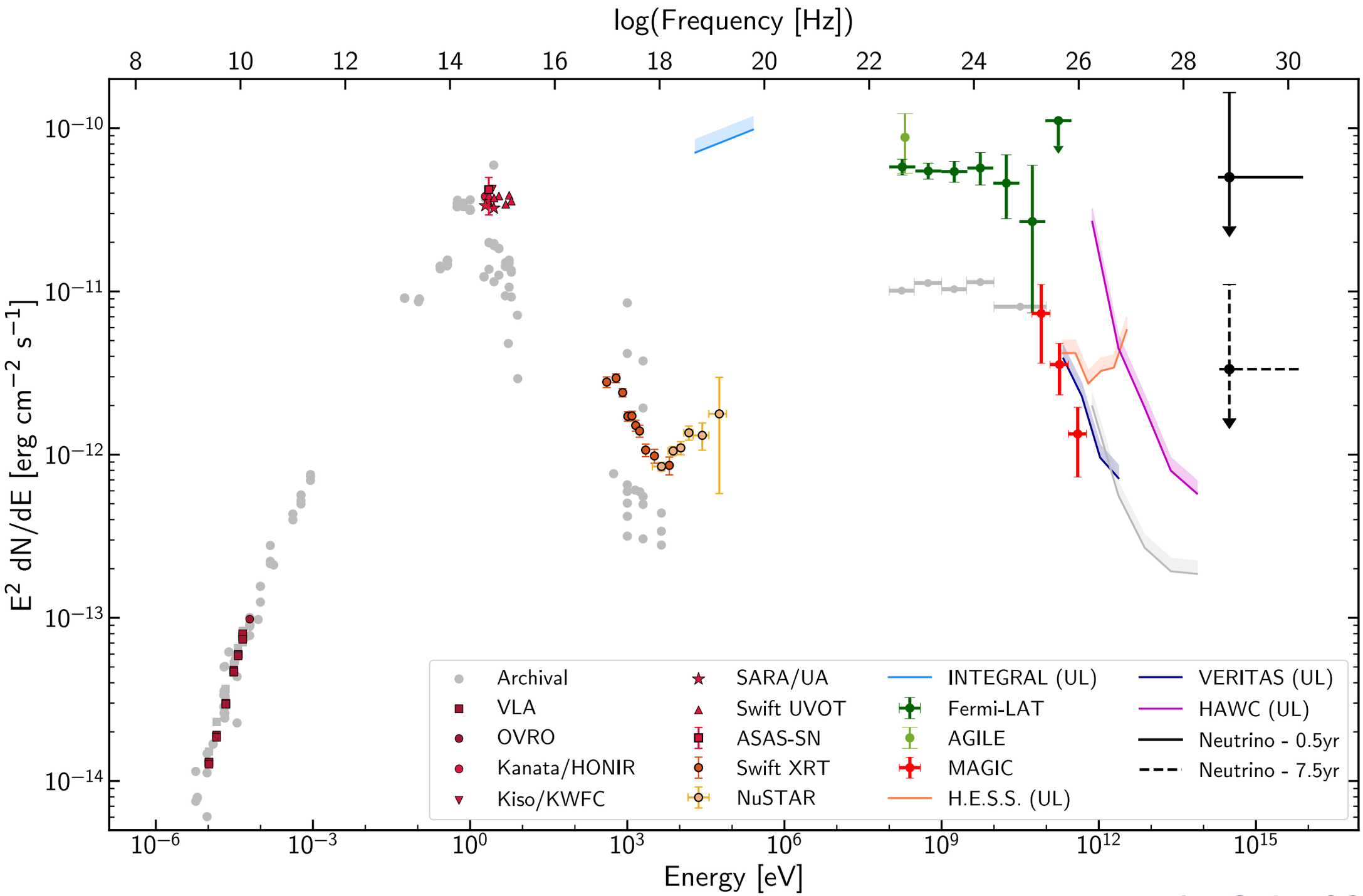




IceCube 2018

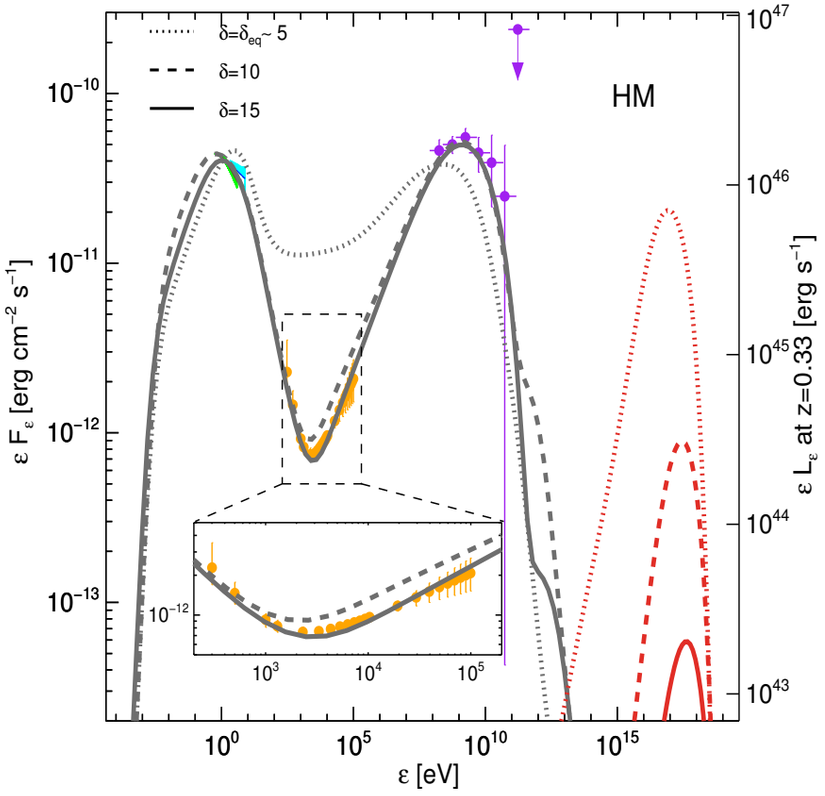
- A ~300 TeV neutrino from TXS 0506+056 (blazar)
  - 3-sigma association

Multi-messenger SED: TXS 0506+056

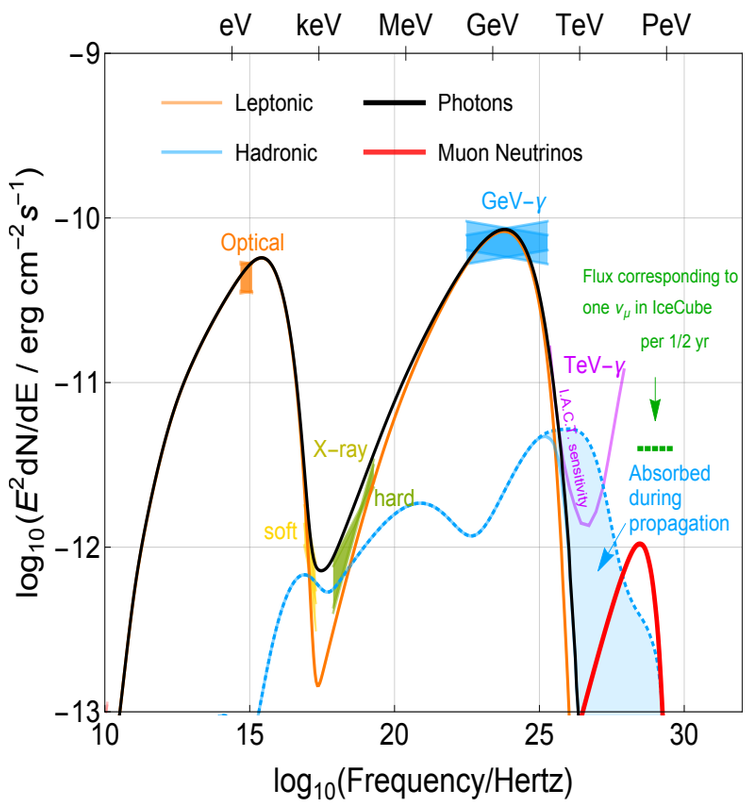


IceCube 2018

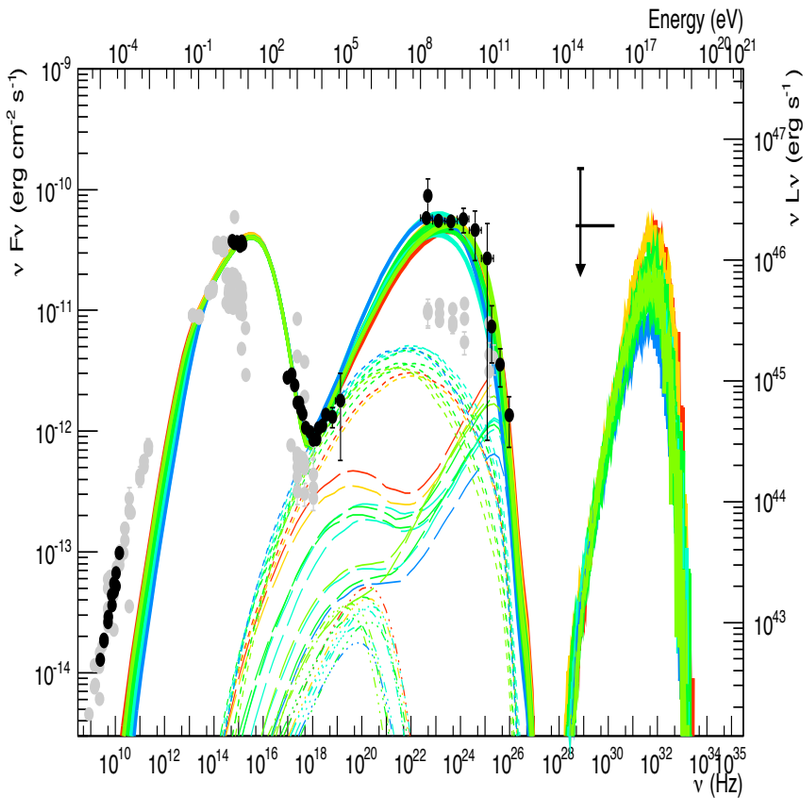
Theoretical Interpretation



Keivani+'18



Gao+'18

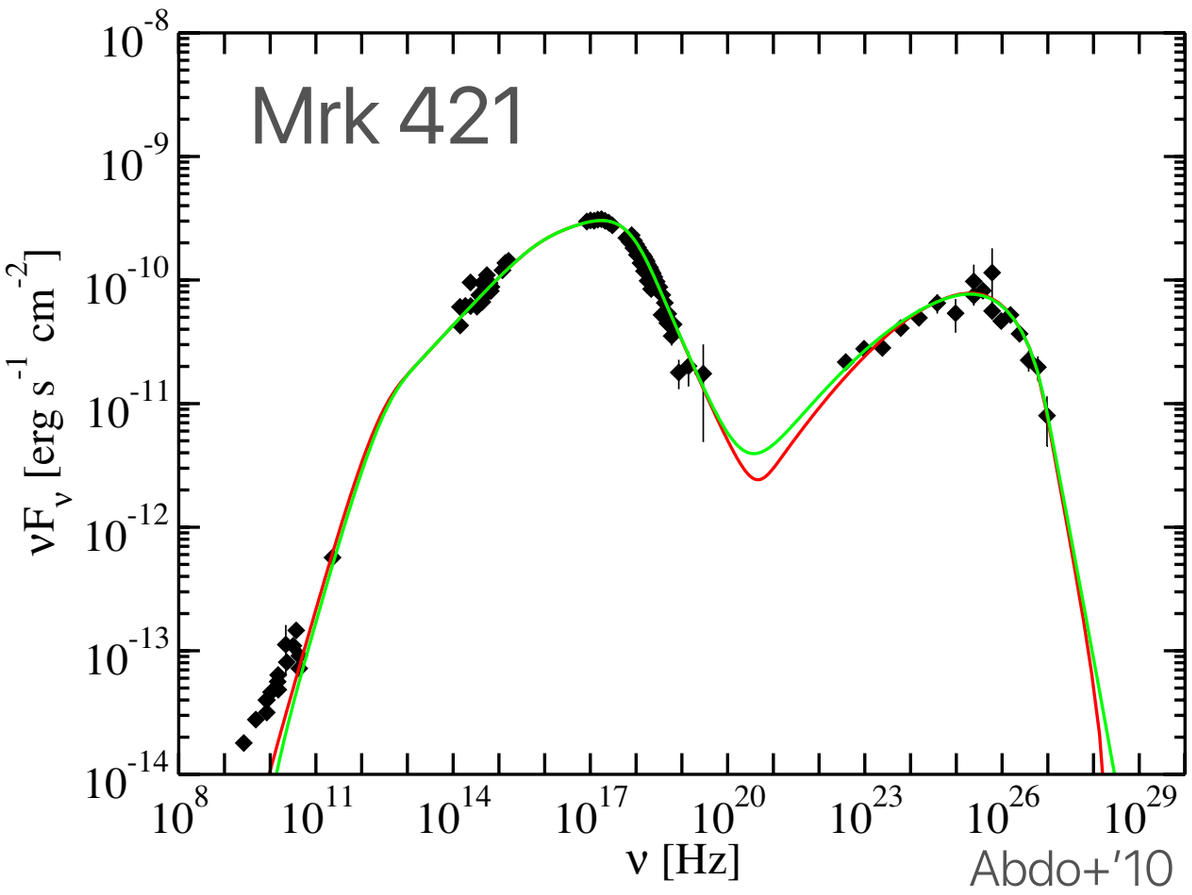


Cerruti+'18

- **<u>Pure hadronic model is ruled out</u>** because too much X-rays
- Lepto-hadronic model is favored (e.g., Keivani+'18;Cerruti+'18;Gao+'18,,,,).
  - Required jet power is comparable to Eddington luminosity.

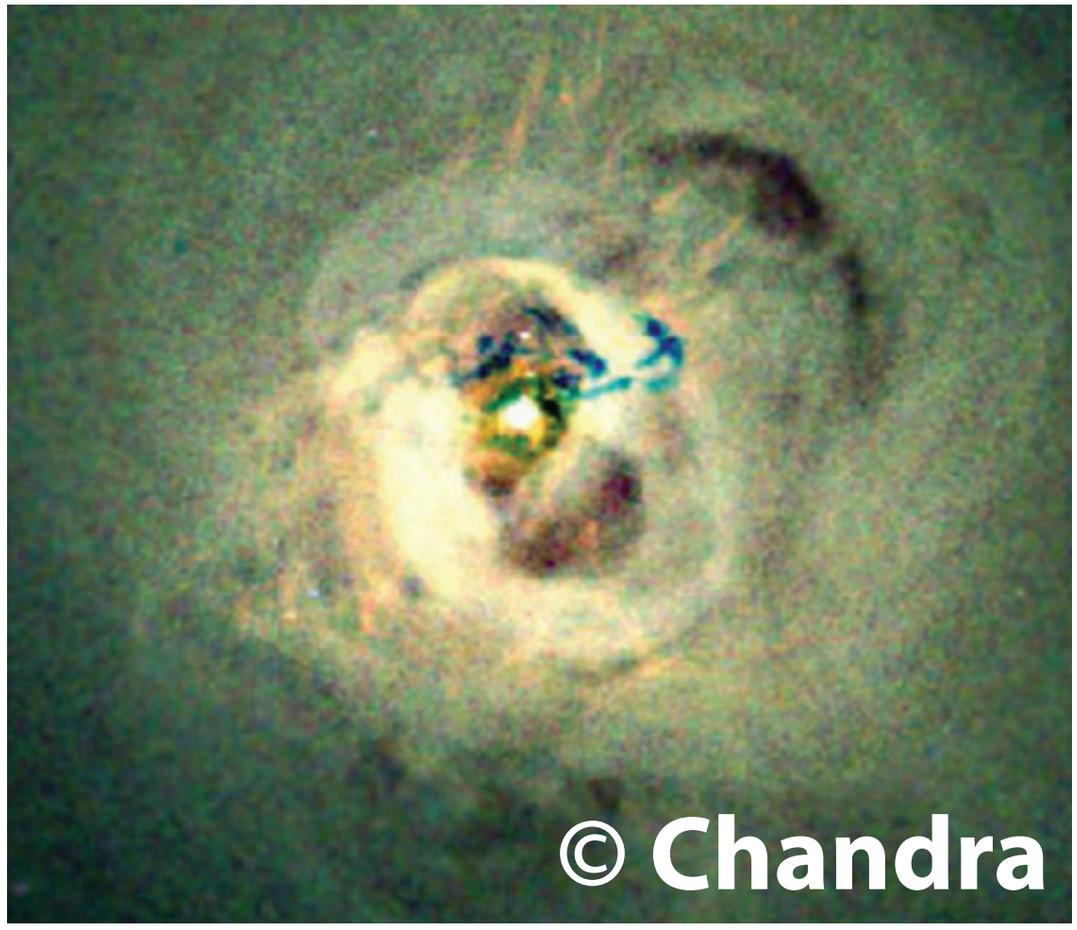
Estimating Jet Power

Blazar SED Fitting



- Particle distribution functions from data (e.g., Ghisellini+'15; YI & Tanaka'16)
  - assume e.g., cold protons

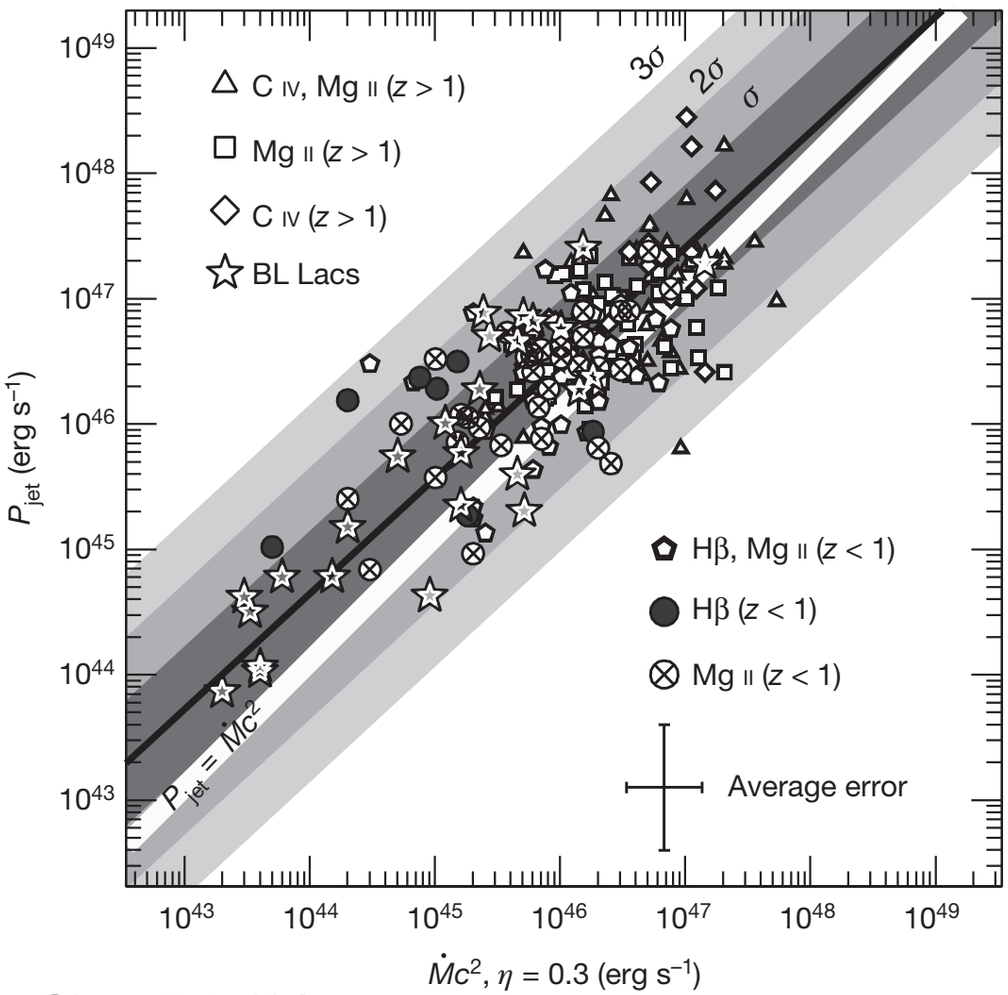
Large-scale Jet



- Empirical relation between radio luminosity and jet power (e.g., Willott+'99)
  - calibrated by X-ray cavity

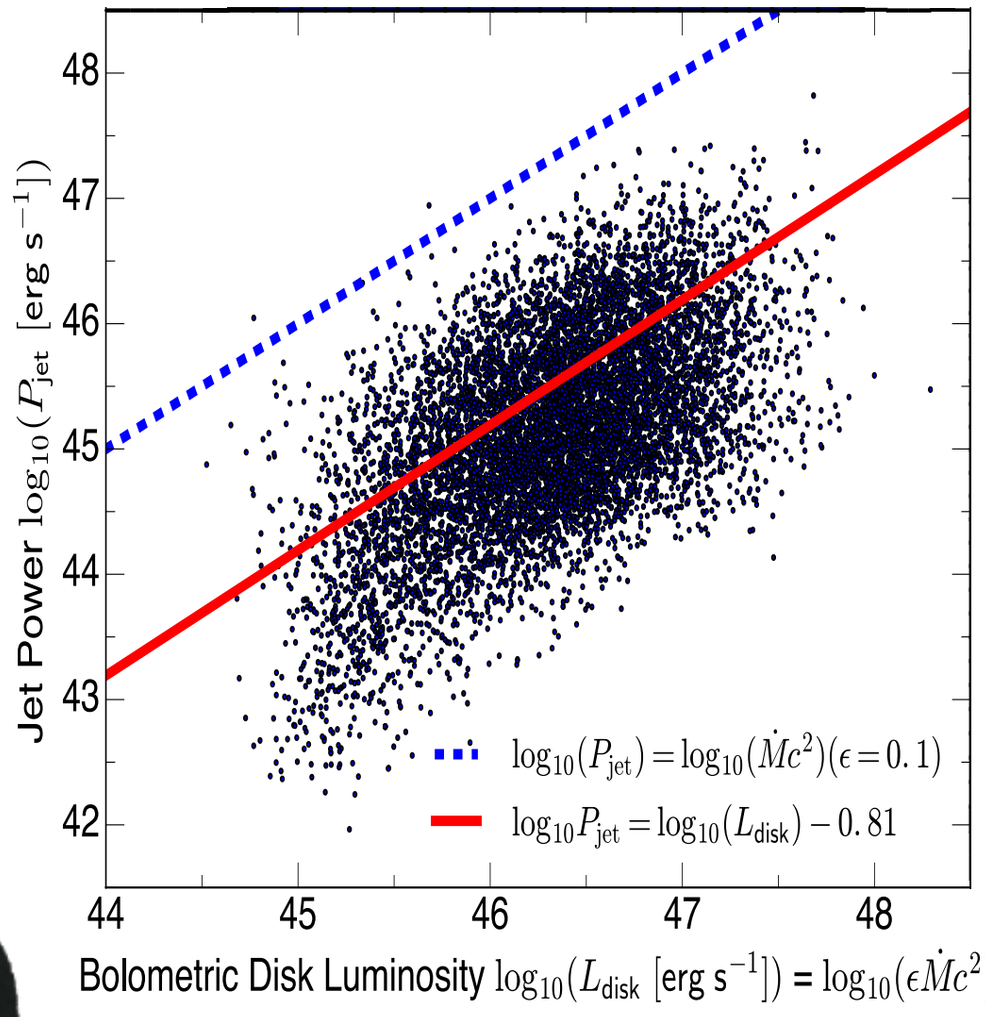
AGN Jet Power?

Blazar SED Fitting



Ghisellini+'14

Large-scale Jet

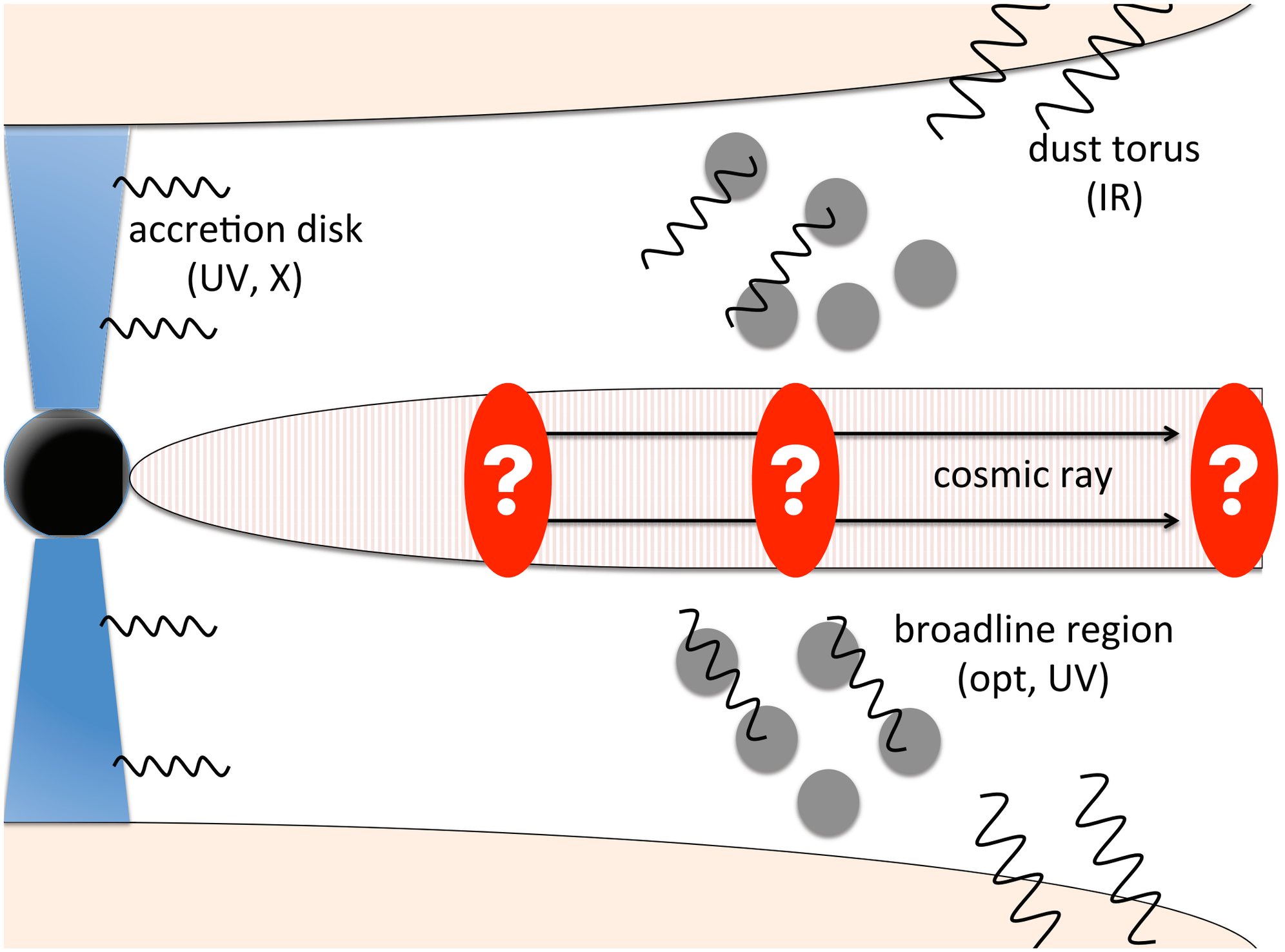


YI+'17

$$P_{\rm jet} \gtrsim \dot{M}_{\rm in} c^2$$

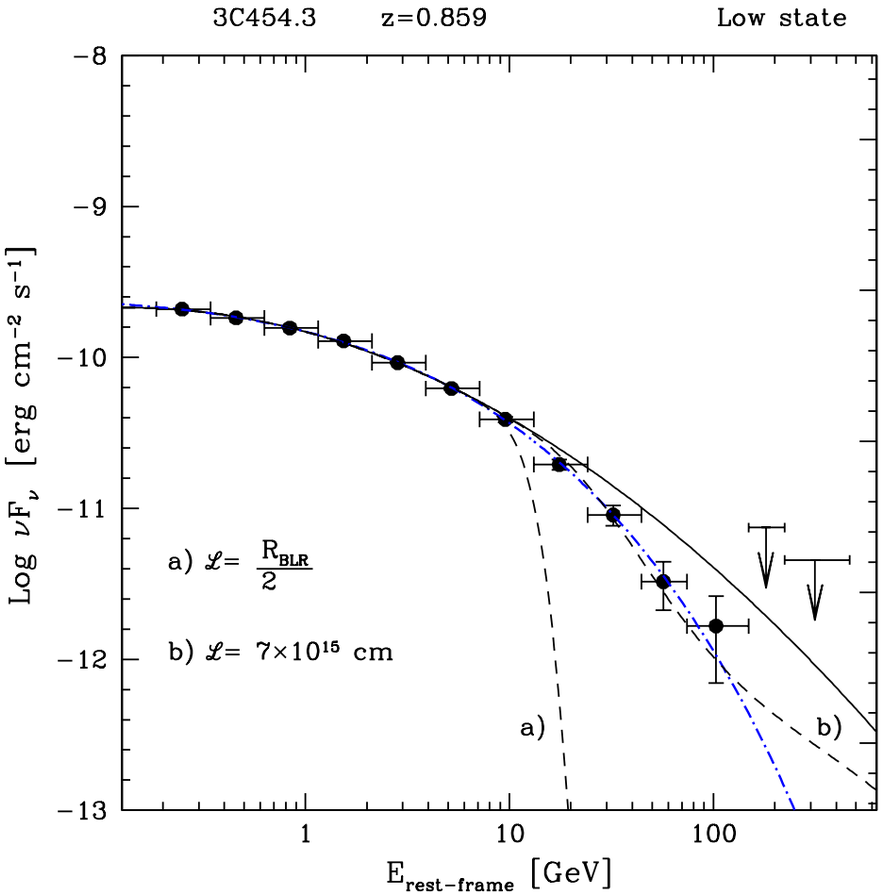
$$P_{\rm jet} \sim 7 \times 10^{-3} \dot{M}_{\rm in} c^2$$

Blazar Emission Zone

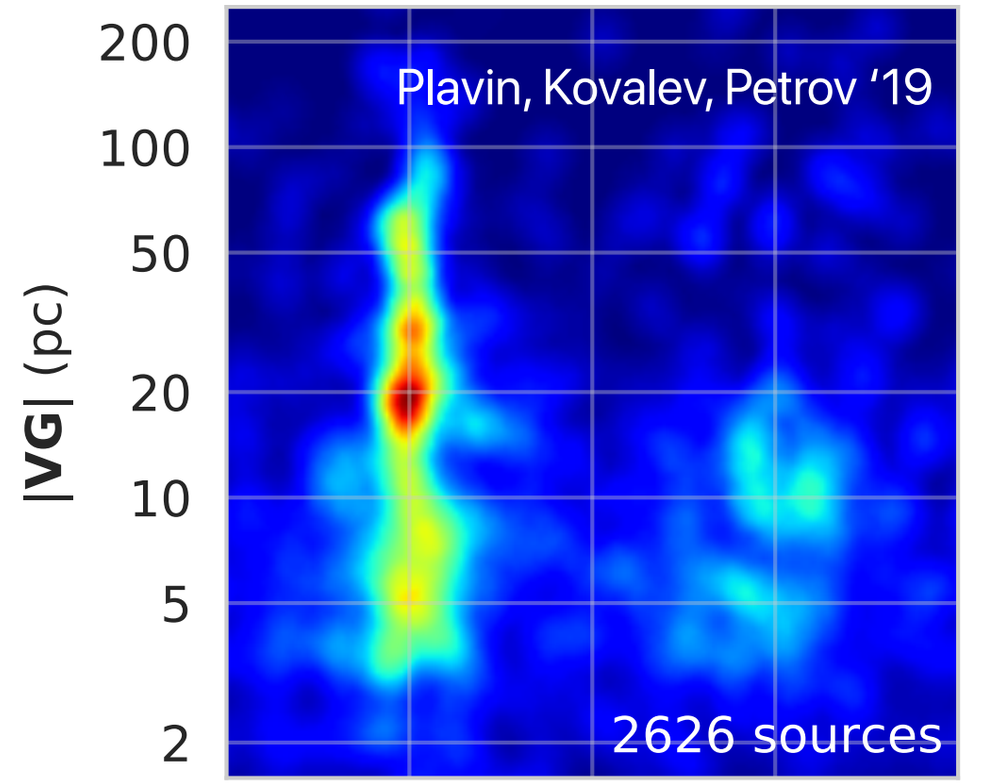


Murase, YI, & Dermer '14

Location of Blazar Emission



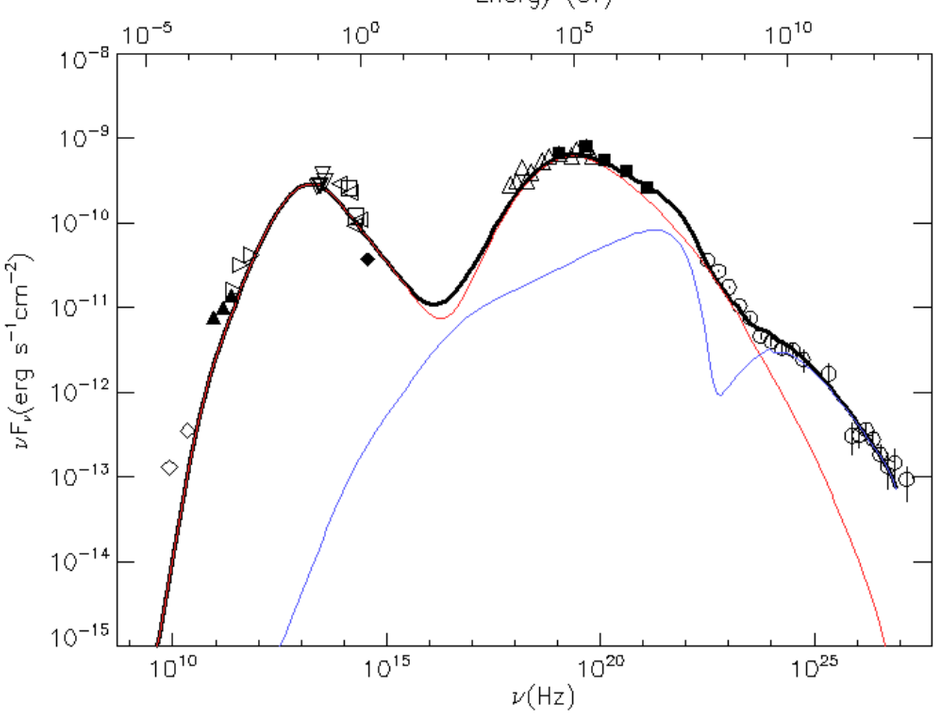
Costamante+'18



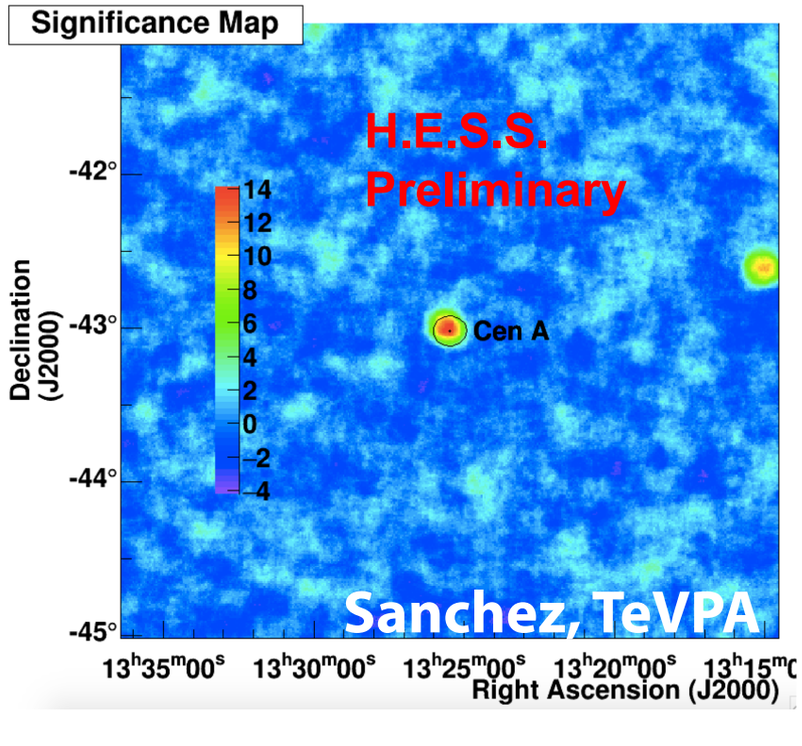
Offset relative to jet

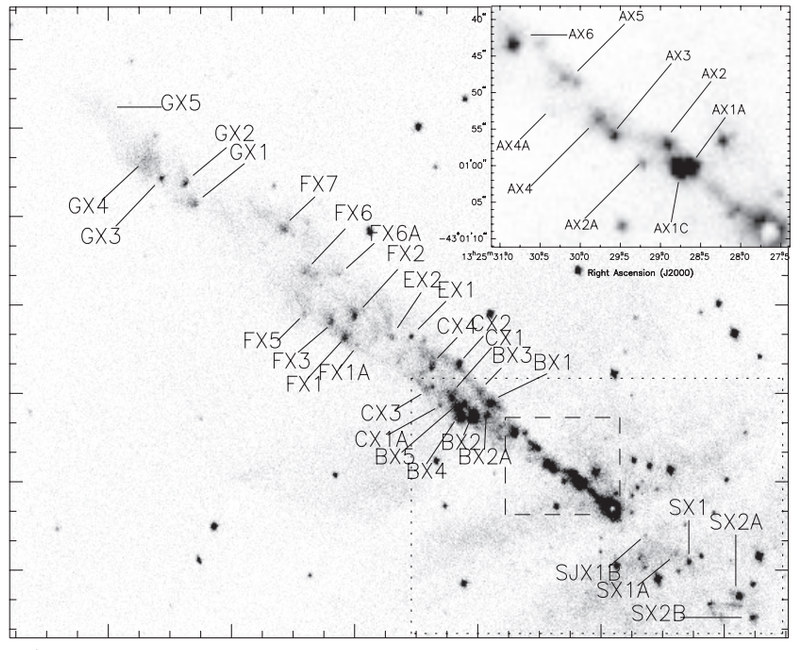
- Lack of significant broad-line region photon attenuation signature in Fermi (GeV) data (Costamante+'18)
- Gaia (optical) emission locates ~20–50 pc away from the VLBI (radio) core (Plavin, Kovalev, Petrov '19)

Centaurus A: evidence of kpc jet?



HESS/Fermi+'18

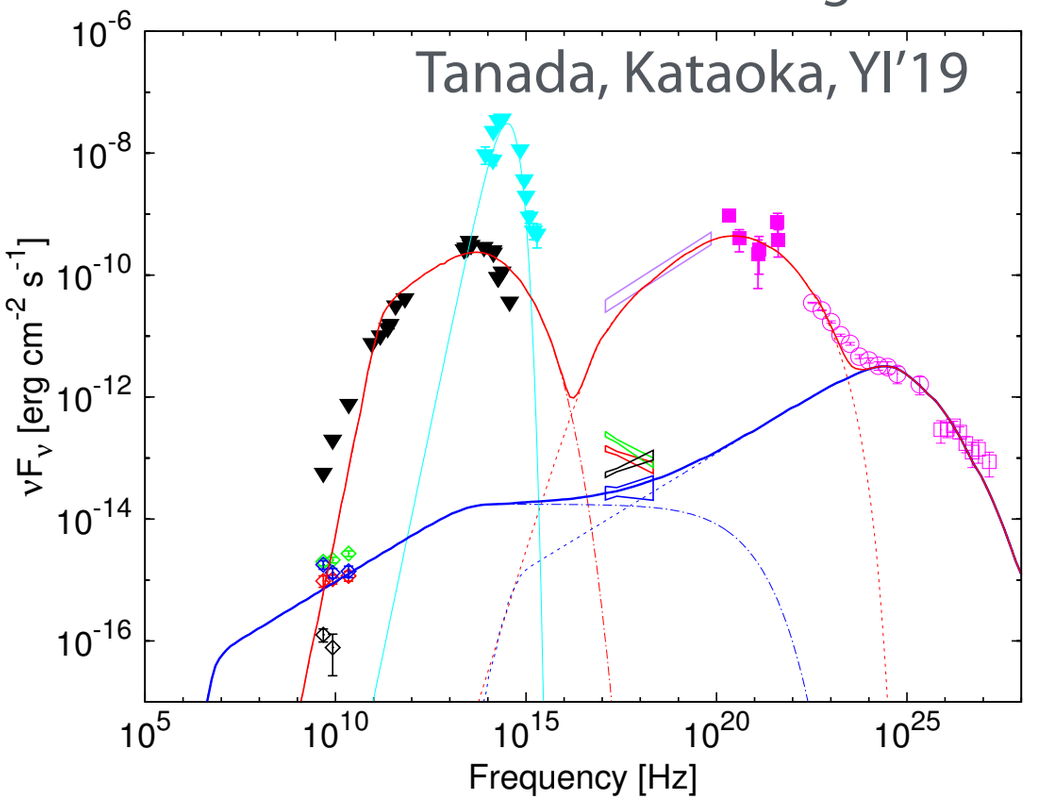




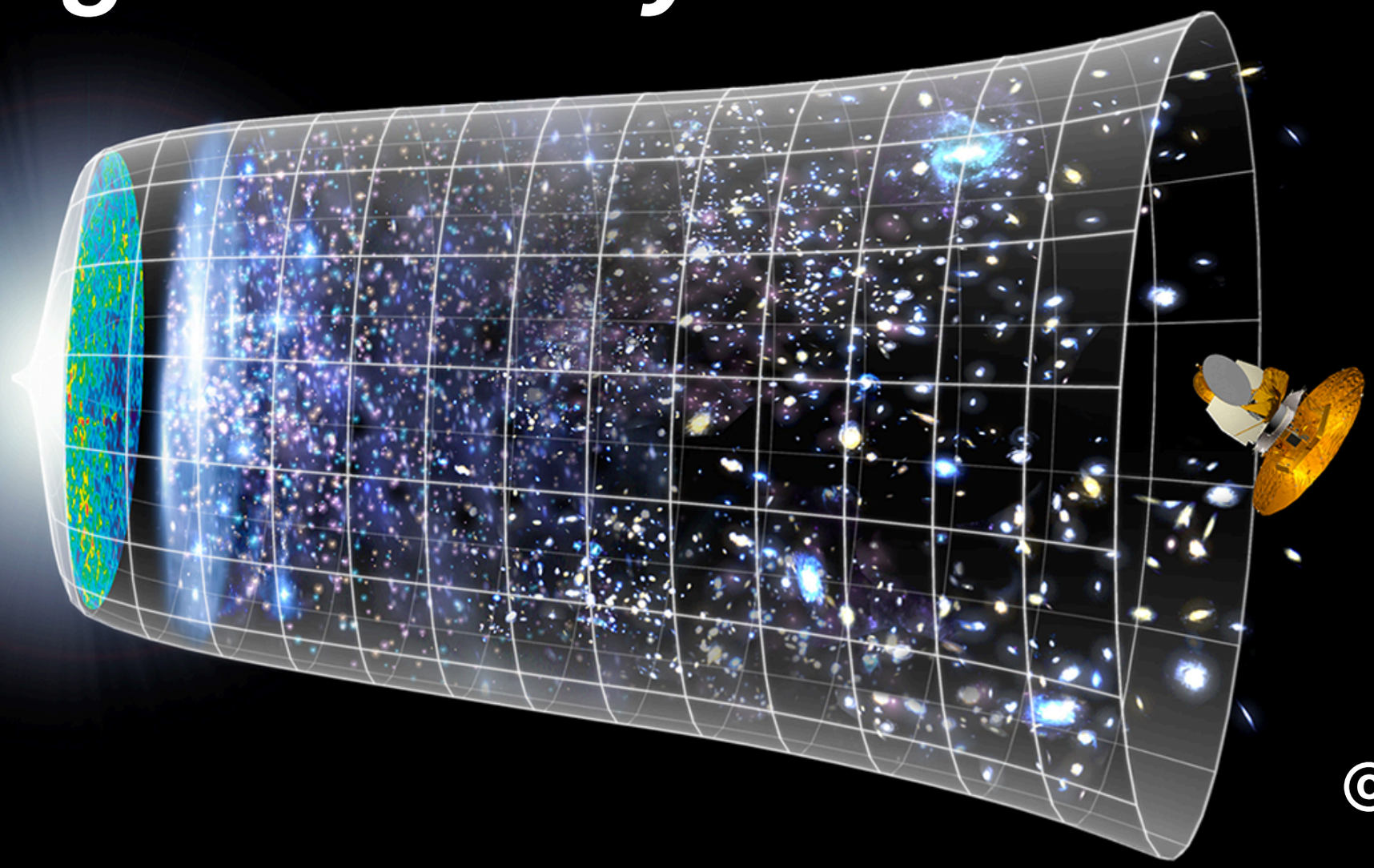
Right Ascension (J2000)

Goodger+'10

- Spectral hardening from ~4 GeV (Sahakyan+'13).
- HESS reports spatial extension along the jet axis .
- Chandra sees many knots (Goodger+'10).
  - Can be interpreted by IC scattering of starlight in knots (Tanada, Kataoka, YI'19).

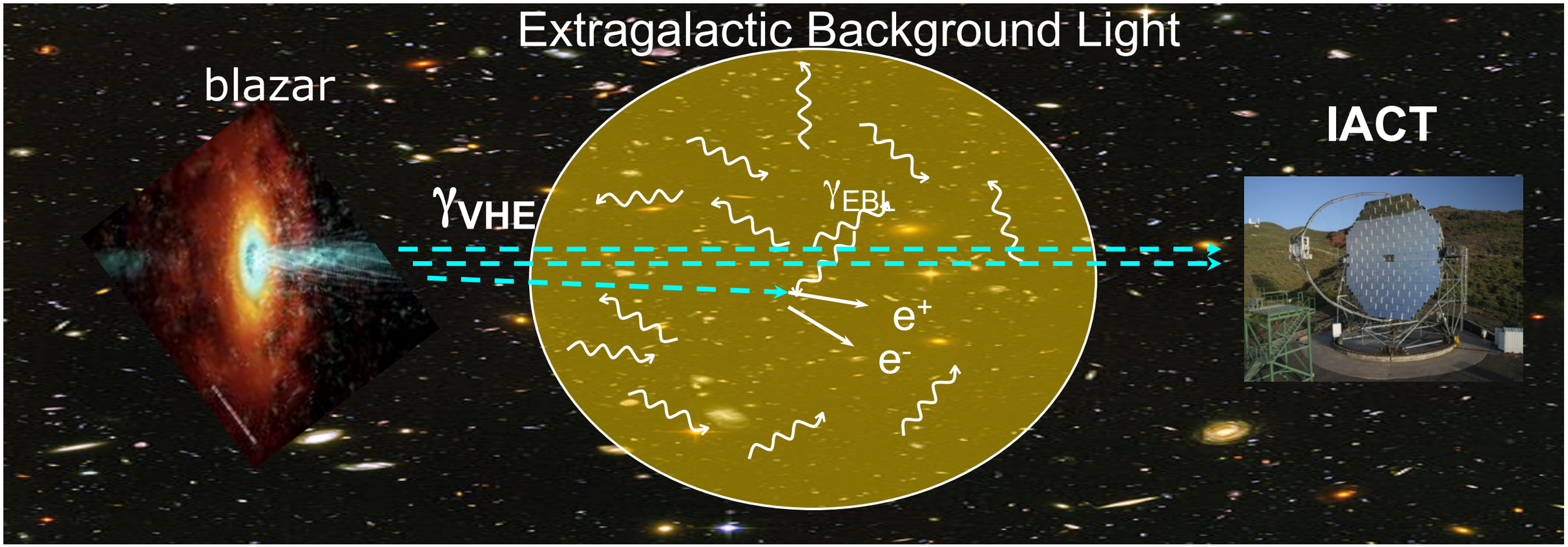


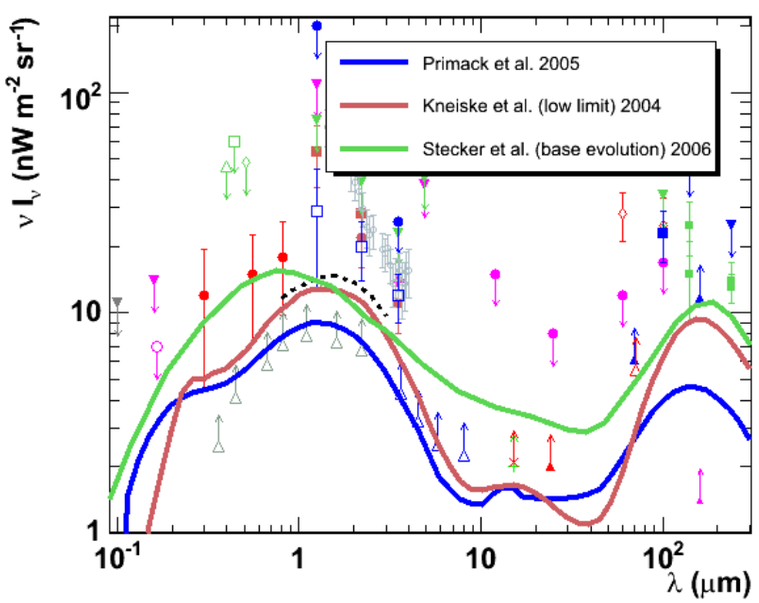
Probing the History of the Universe

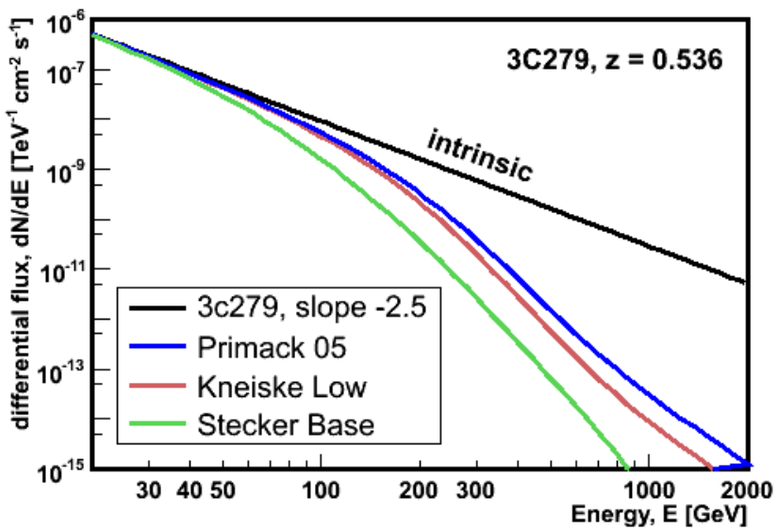


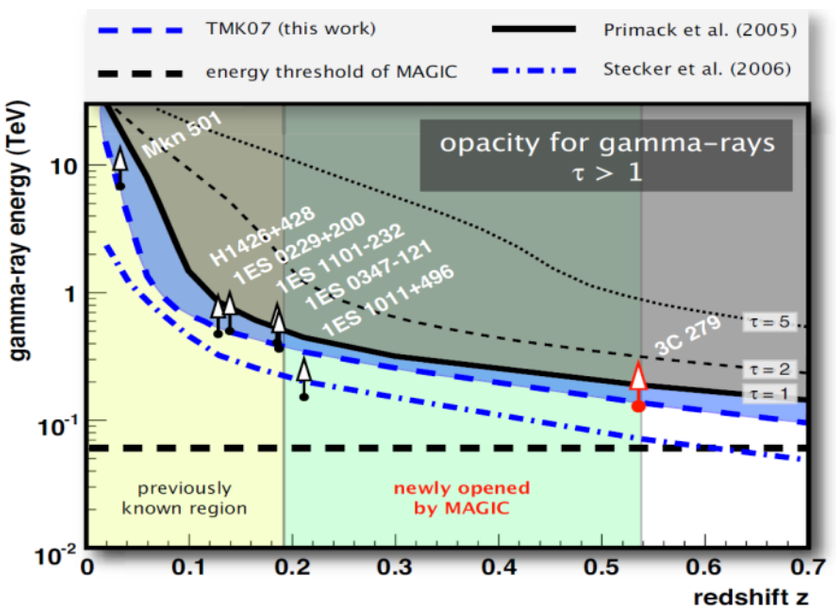
- **<u>Cosmic background radiation</u>**
  - Integrated history of the universe

Gamma-ray Attenuation by Cosmic Optical & Infrared Background

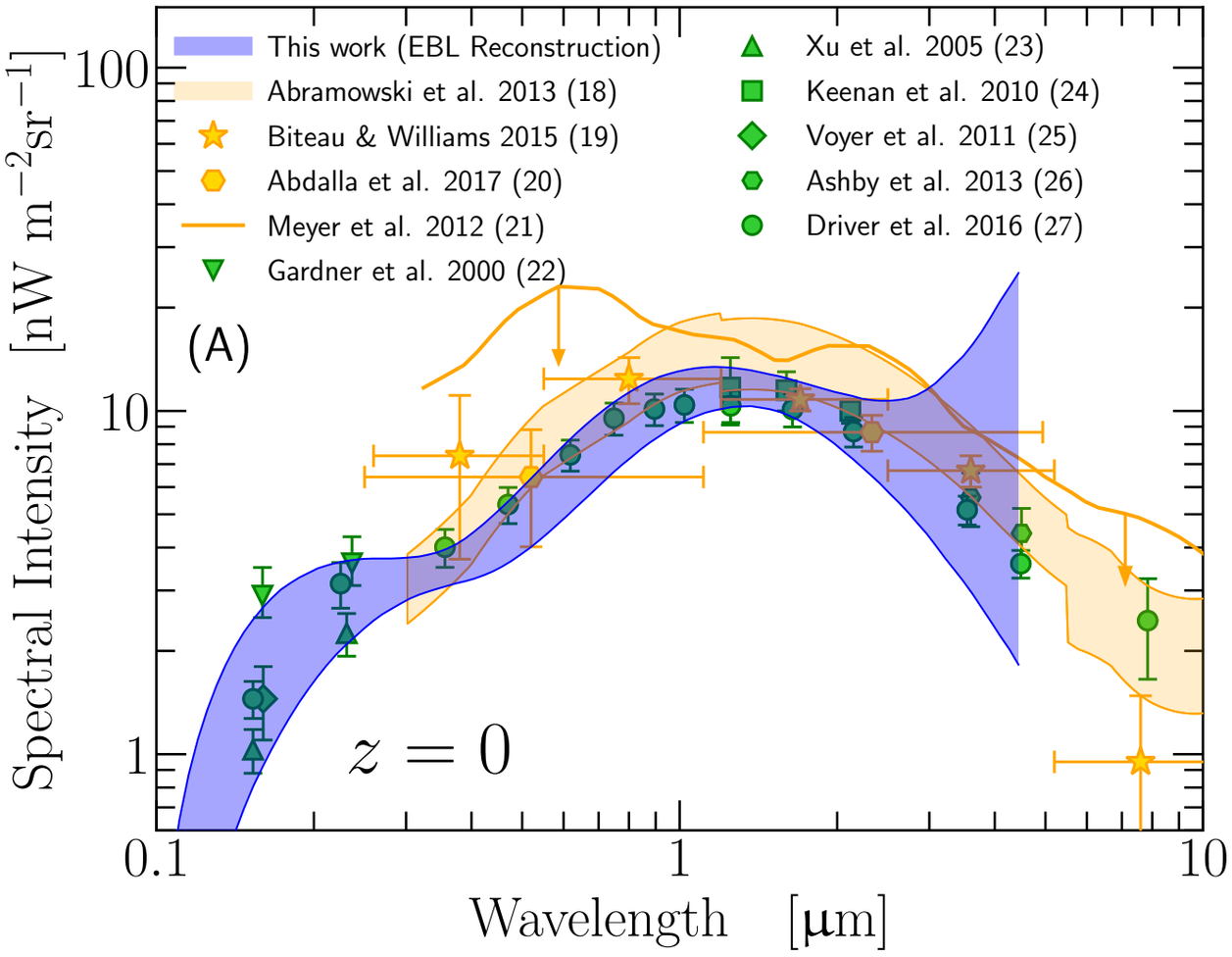


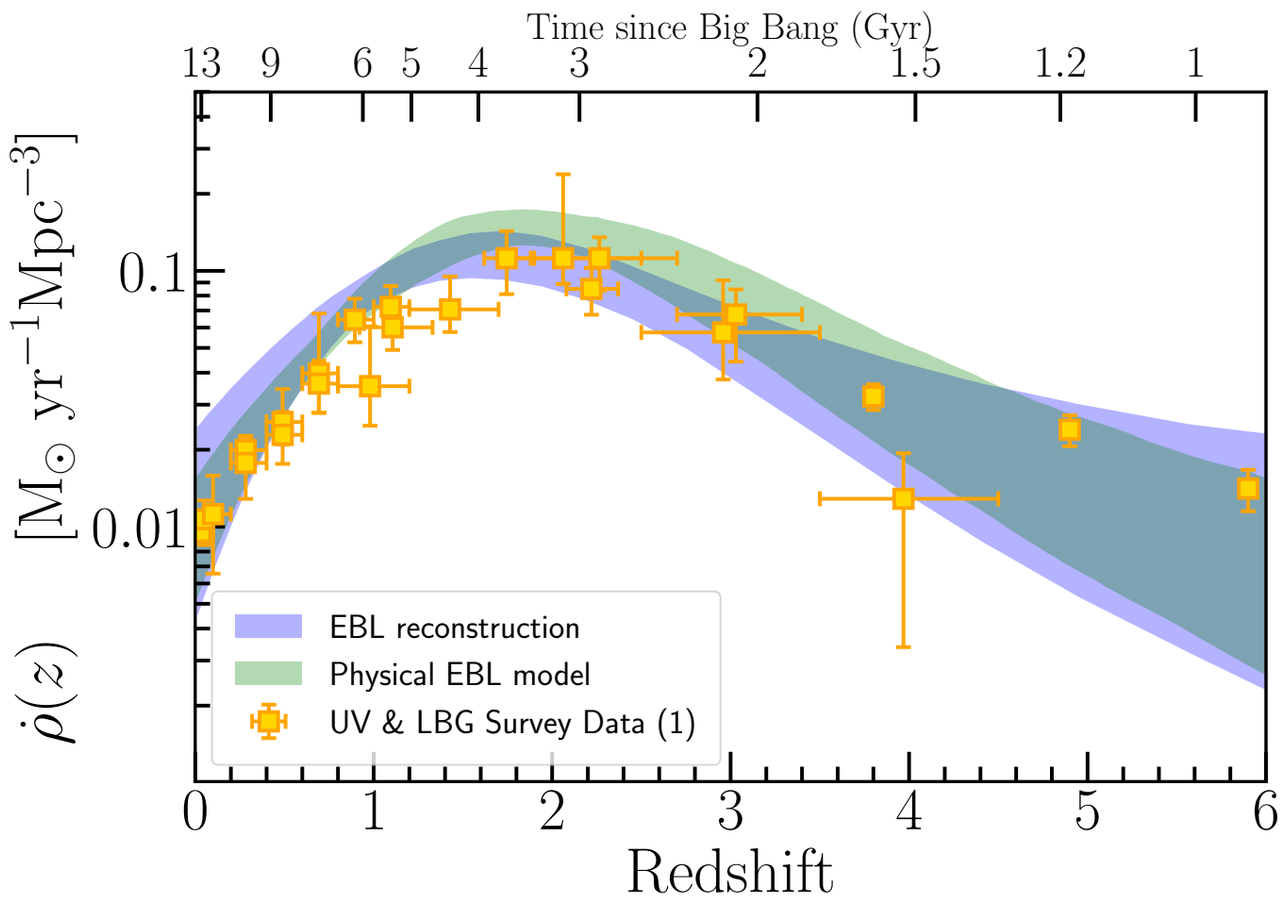






Cosmic Optical & Infrared Background

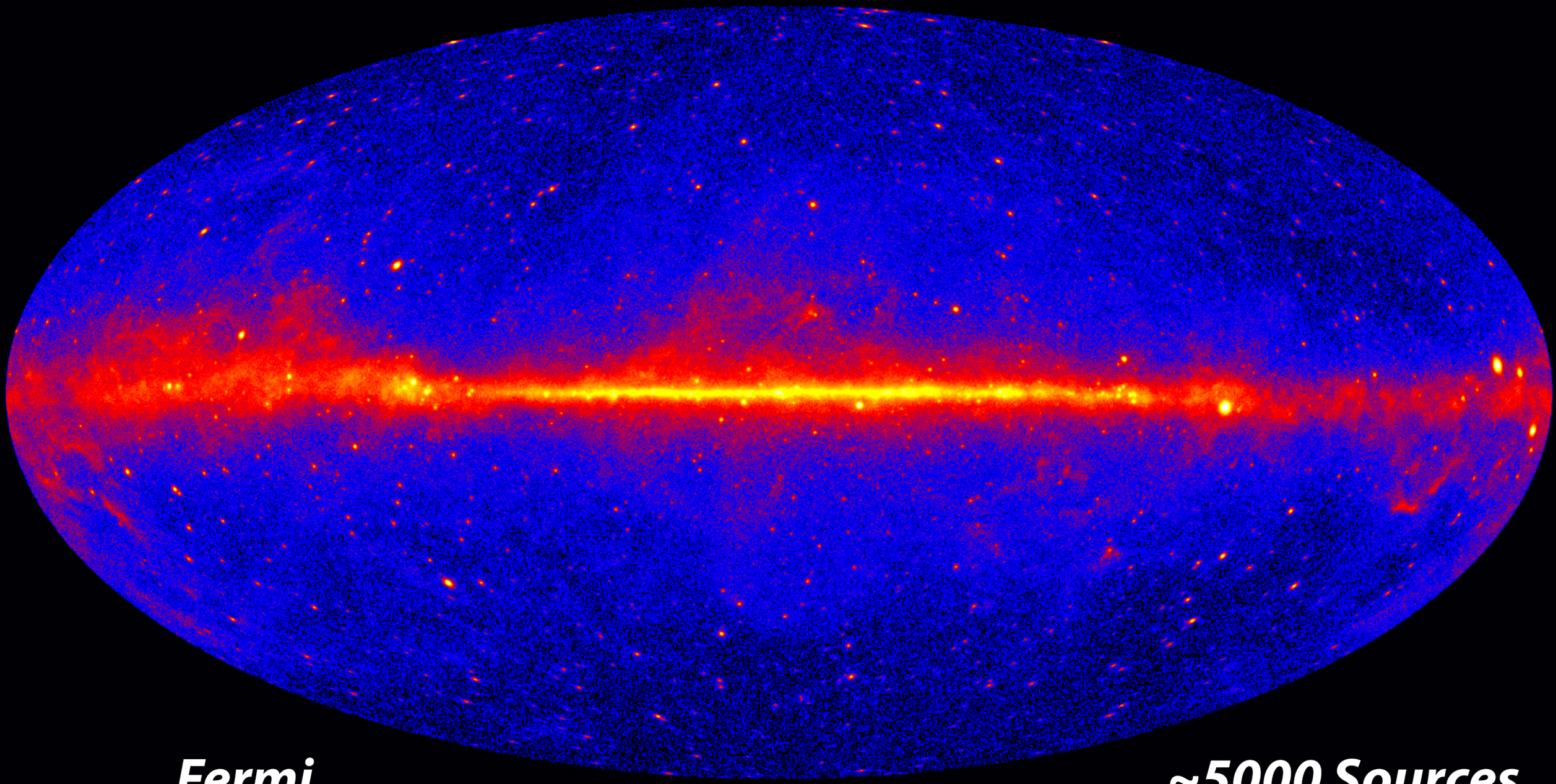




Abdollahi+'18

- Gamma rays can probe the cosmic star formation history.

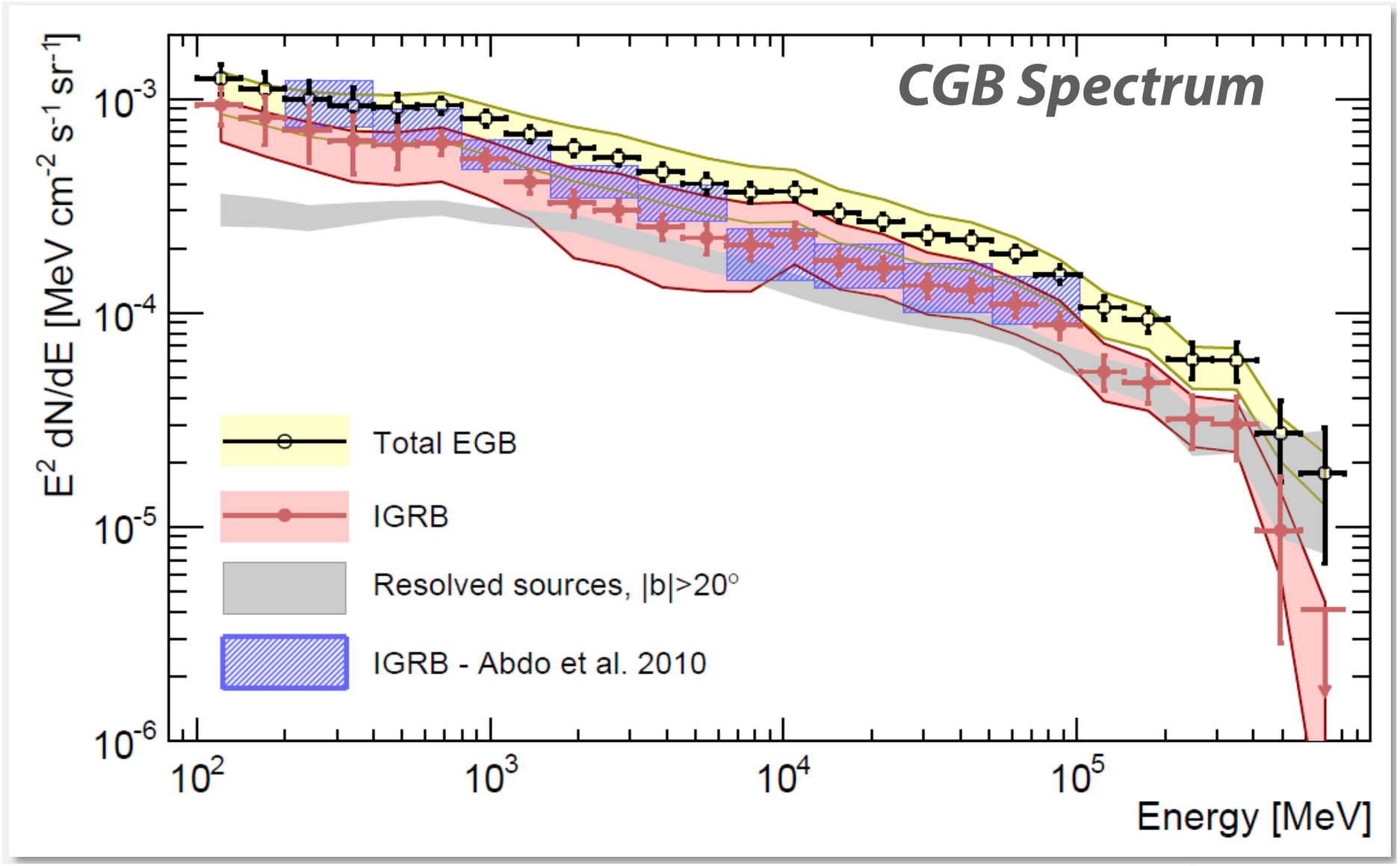
GeV Gamma-ray Sky



Fermi

~5000 Sources

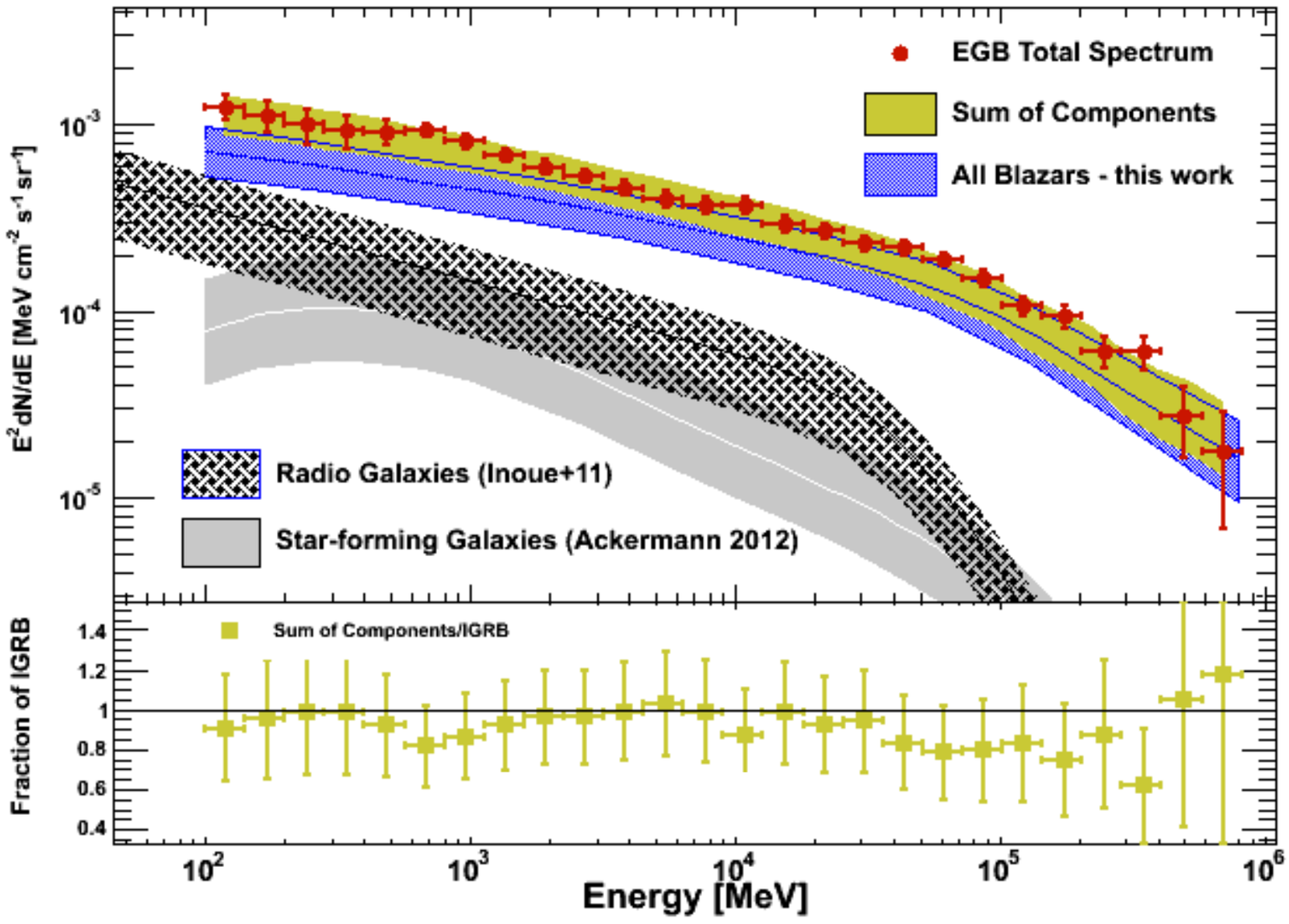
Cosmic Gamma-ray Background Spectrum (>0.1 GeV)



Ackerman+'15

- Fermi has resolved 30% of the CGB at ~1 GeV and more at higher energies.

Components of Cosmic Gamma-ray Background



Ajello, YI +'15

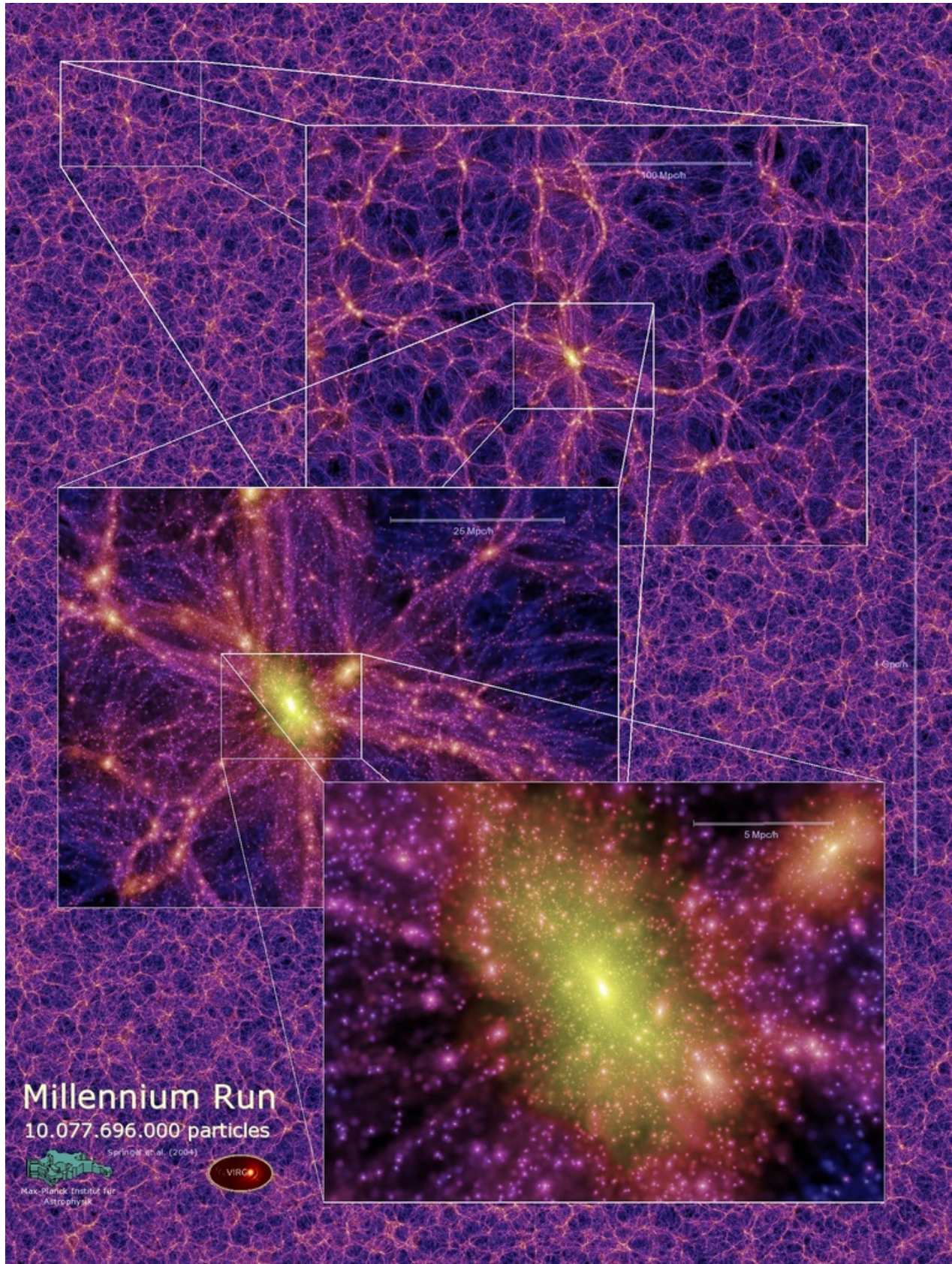
- Blazars (Ajello, YI+'15), Radio gals. (YI'11), & Star-forming gals. (Ackermann+'12) makes almost 100% of CGB from 0.1–1000 GeV.

Dark Matter Contribution to the CGB

- Dark matter particles should have been annihilating/ decaying since the beginning of the universe.

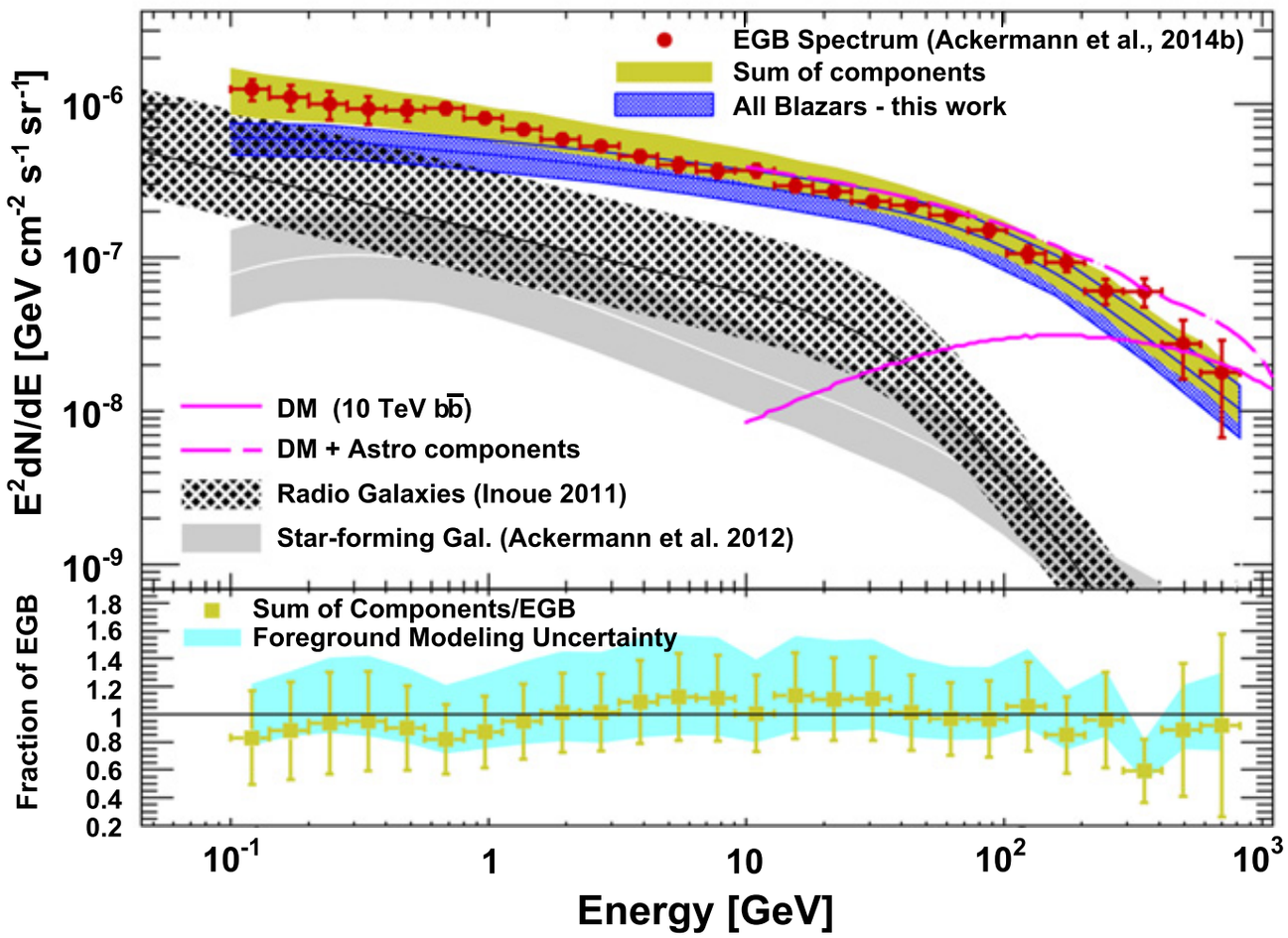
- The annihilation flux depends on the square of density.

$$I_\gamma(\hat{n}) \propto \frac{\langle \sigma v \rangle}{m_\chi^2} \int d\chi \; \rho_\chi^2(\chi \hat{n})$$



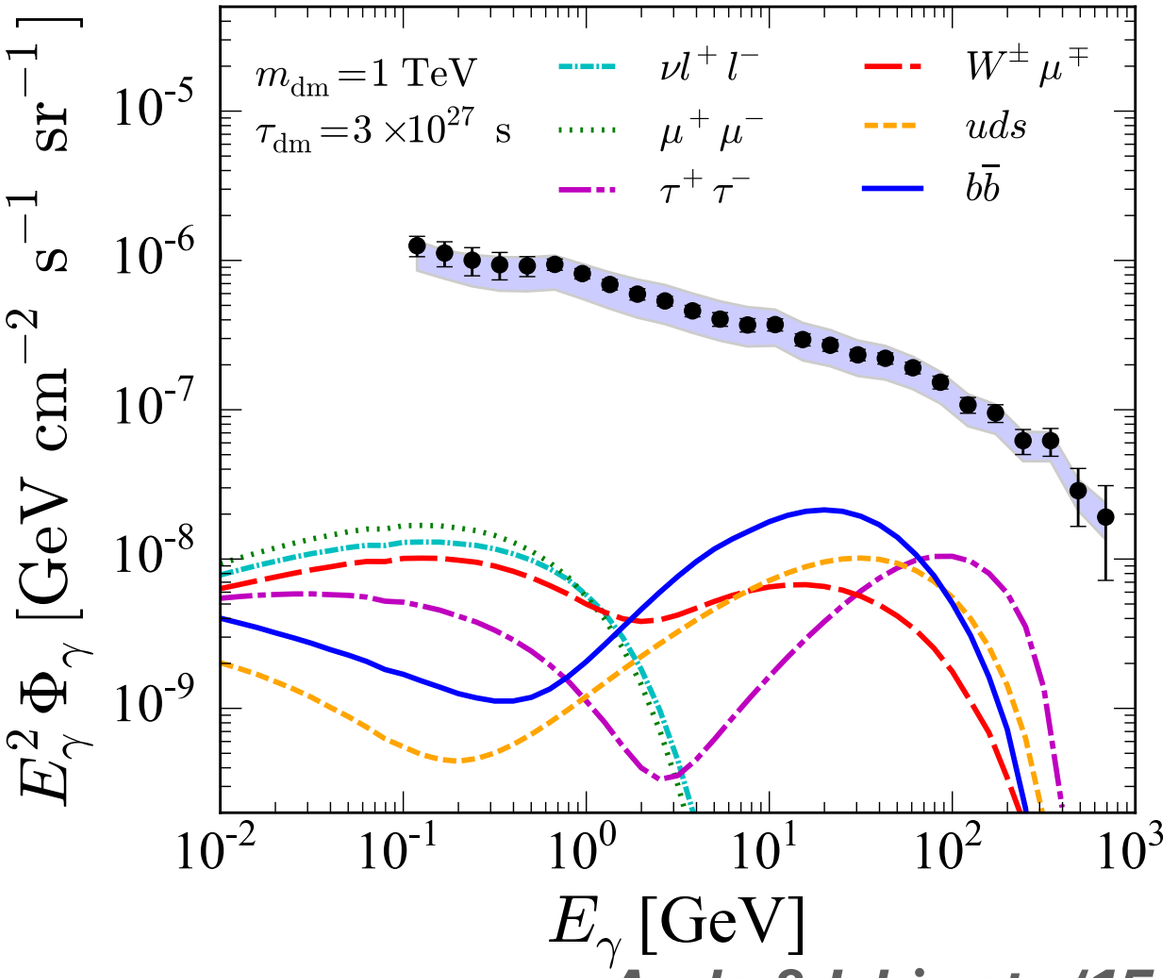
CGB from DM particles

Annihilation



Ajello, YI +'15

Decay

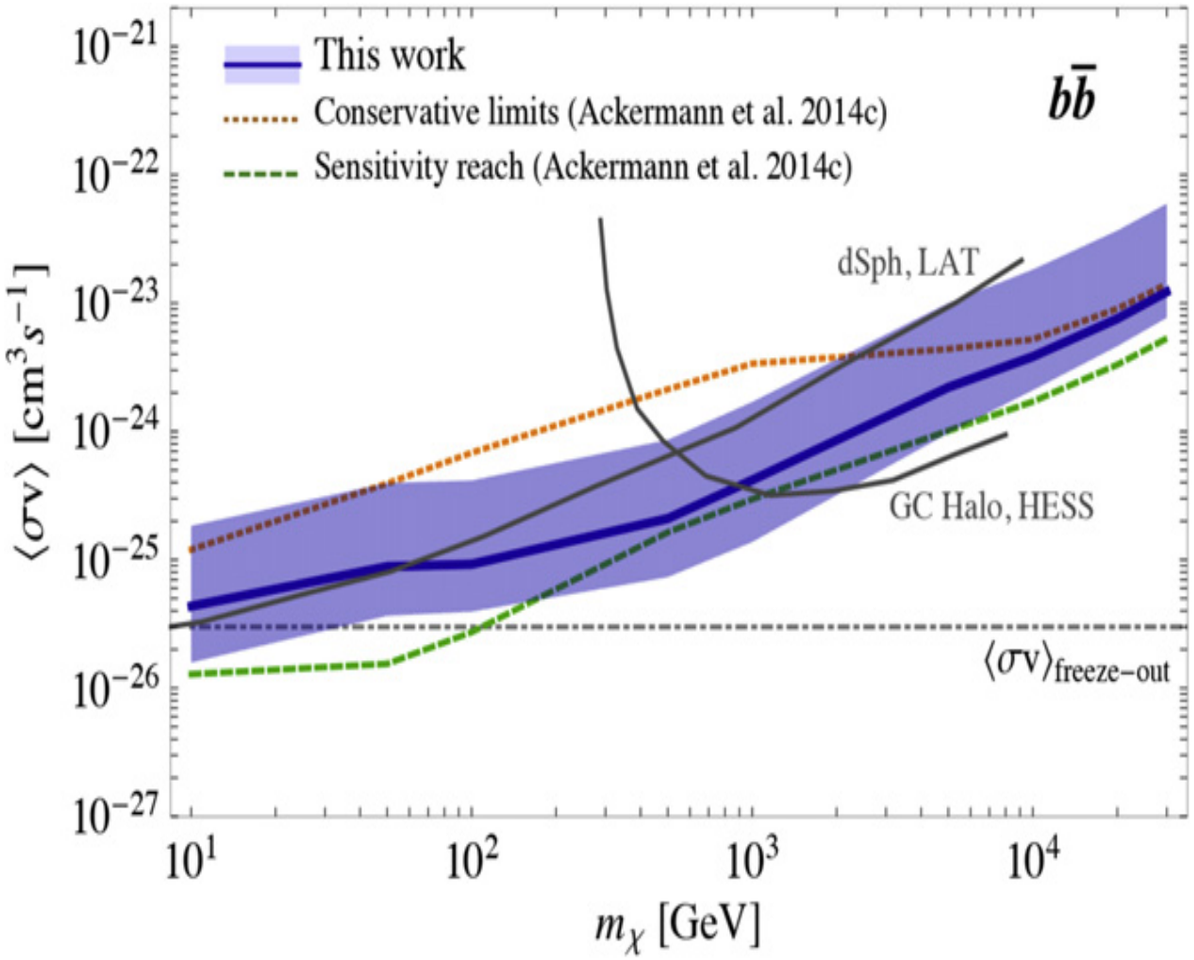


Ando & Ishiwata '15

- DM annihilation/decay creates a feature in the spectrum.

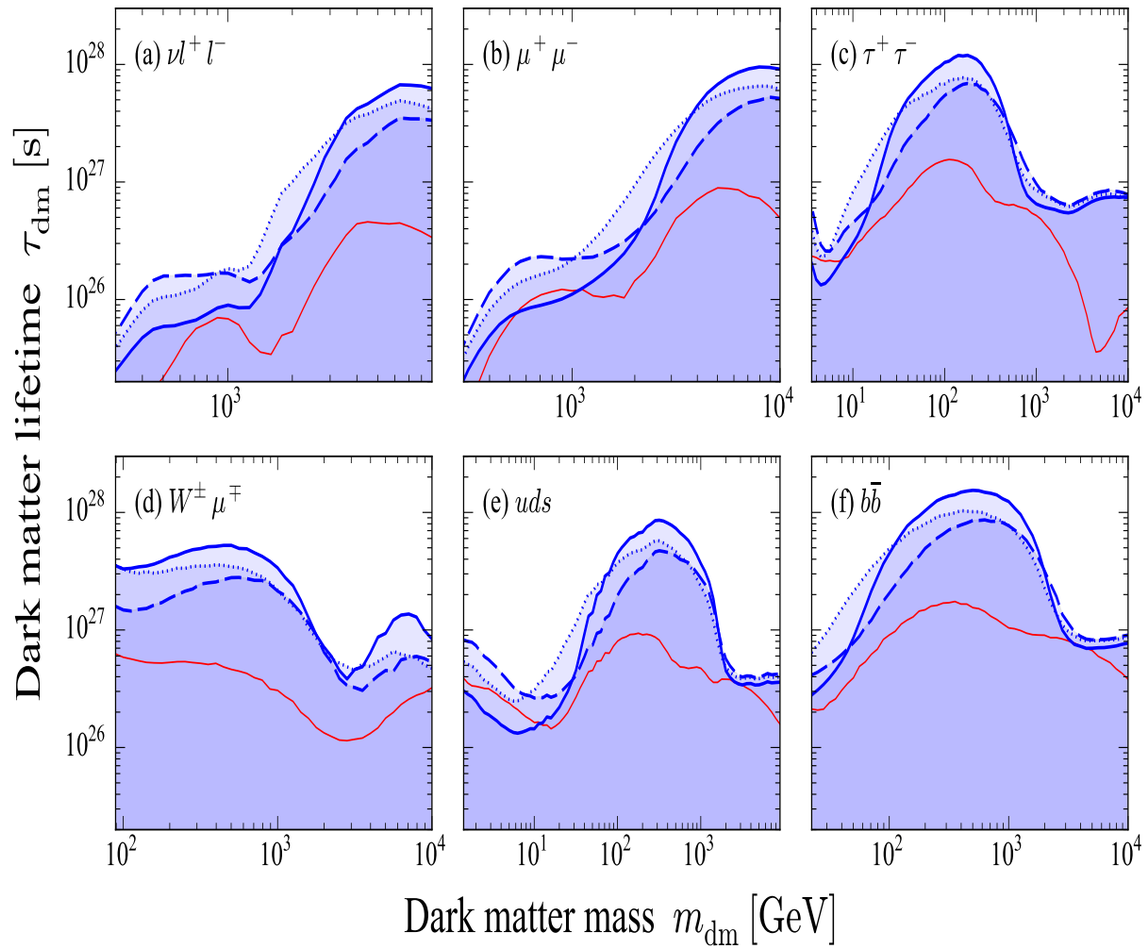
Constraints on DM parameters

Annihilation



Ajello, YI +'15

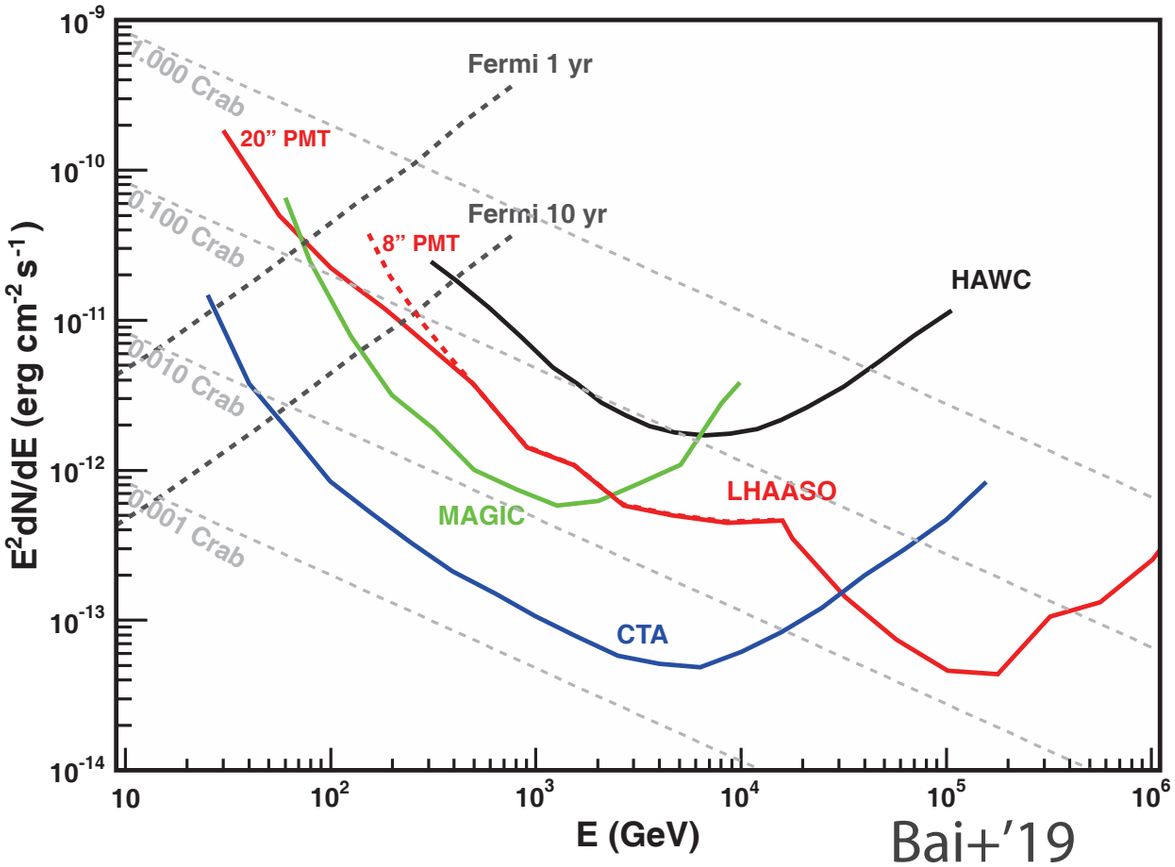
Decay



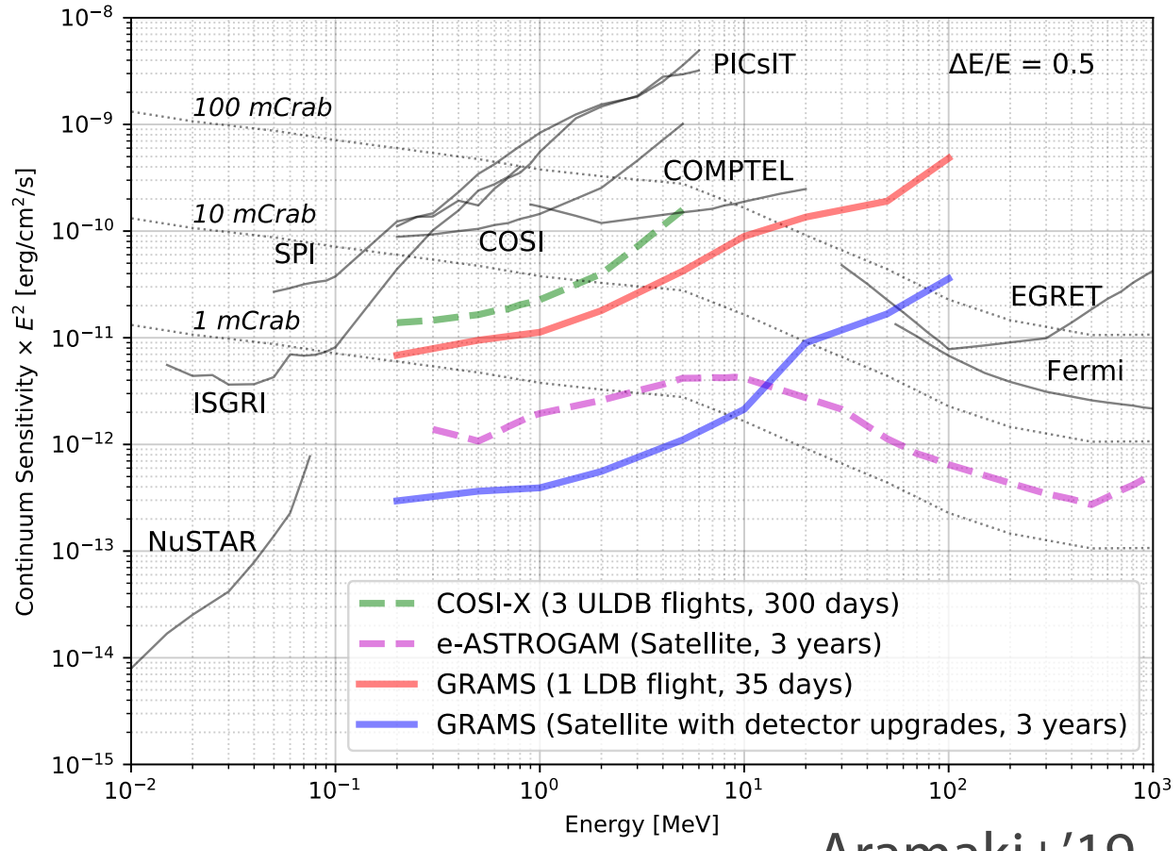
Ando & Ishiwata '15

- Annihilation: comparable to constraints from dwarfs by Fermi
- Decay: > 10^{27}s

Gamma-ray Astrophysics in 2020s



Bai+'19

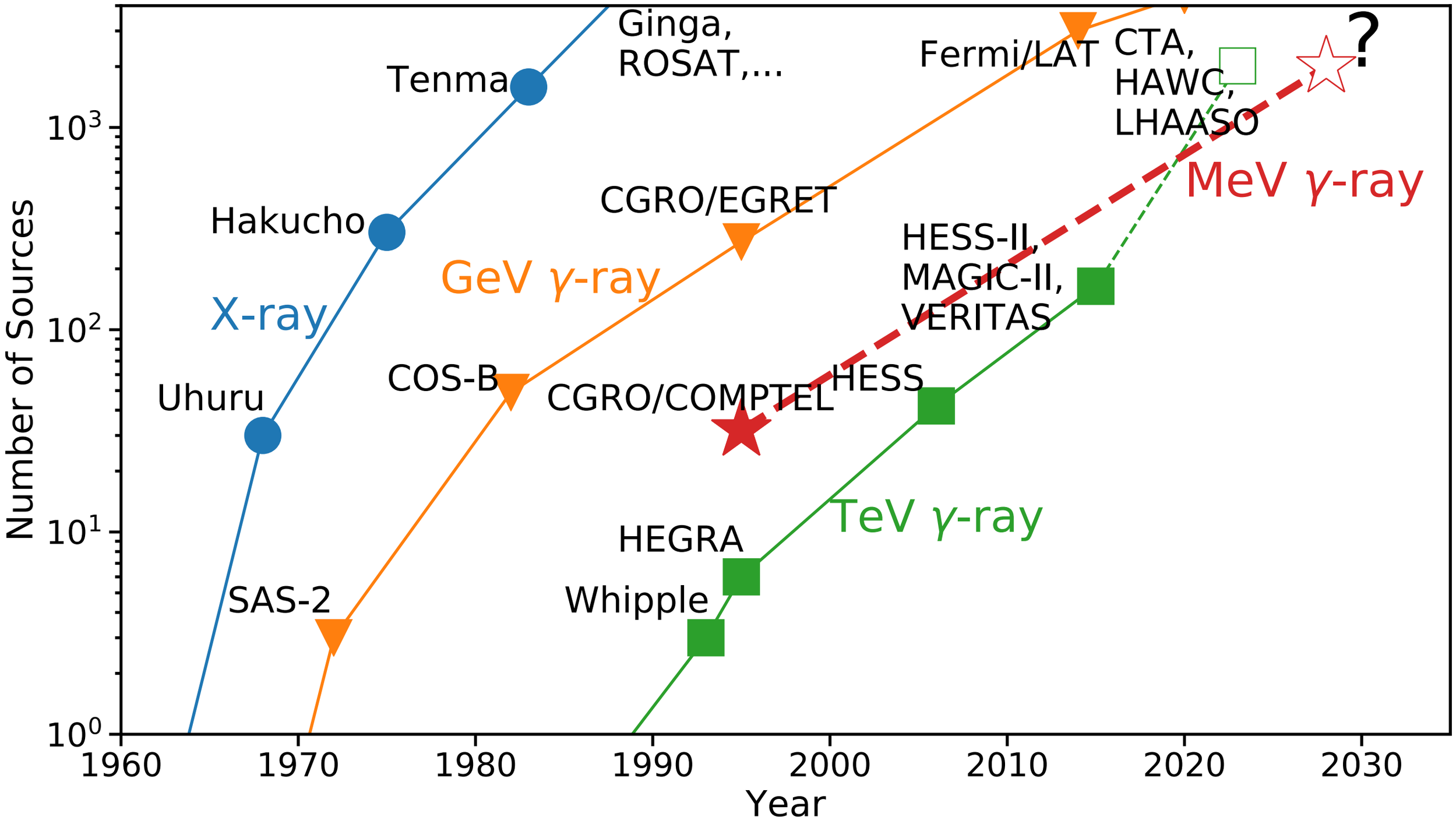


Aramaki+'19

- At >20 GeV, CTA and LHAASO enable us to observe >10 times fainter sources.

- In the MeV band, various projects are on-going.

Number of Gamma-ray Objects



Kifune plot (modified by YI)

Summary

- ~5000 gamma-ray sources.
- Pure hadronic scenario is ruled out for TXS 0506+056.
  - Blazar emission regions are further than BLR.
- Gamma rays can probe the cosmic star formation history.
- Cosmic gamma-ray background radiation is made of blazars, radio galaxies, and star-forming galaxies.