Multi-messenger Signals from Supermassive Black Holes

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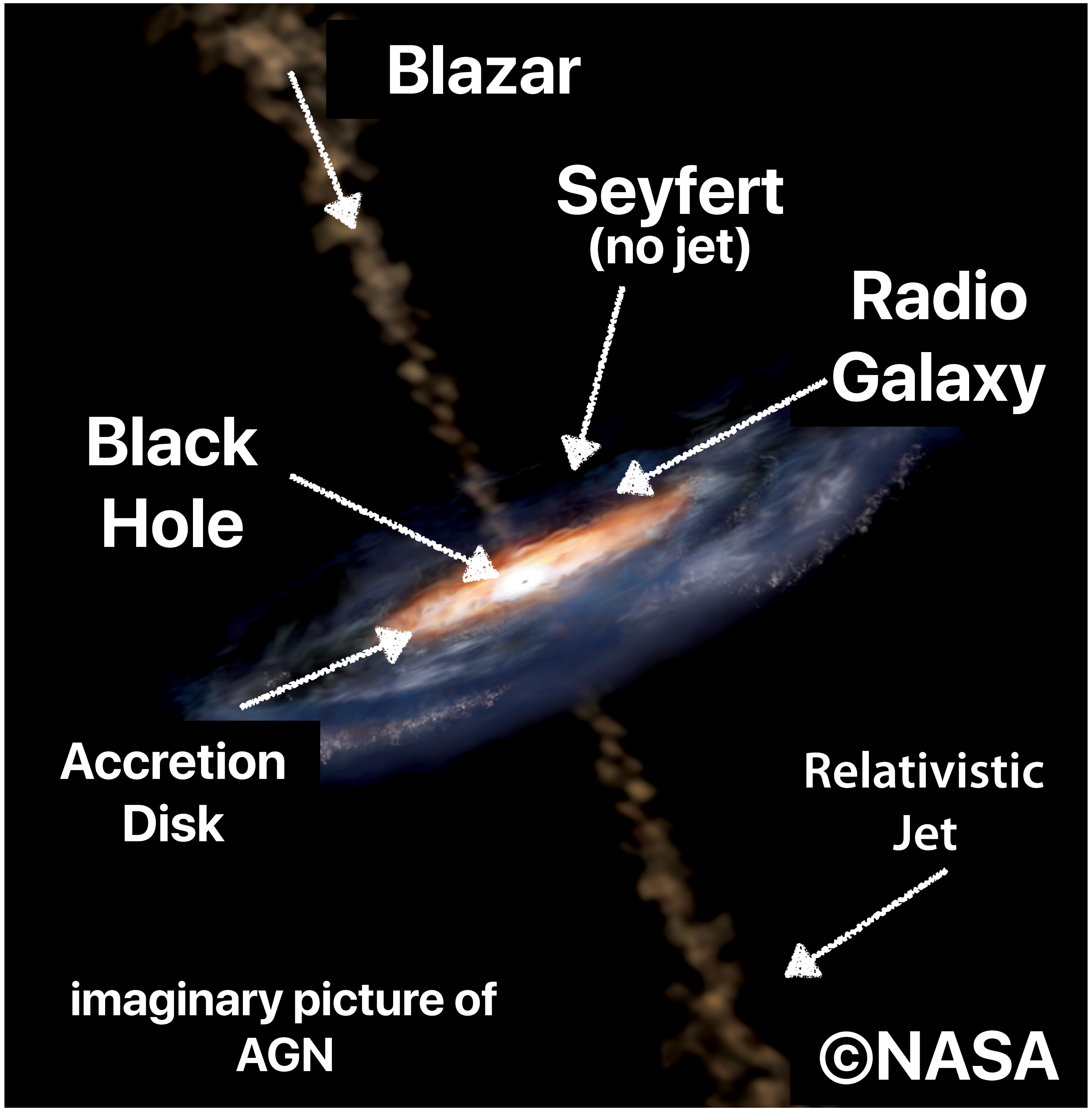
Introduction

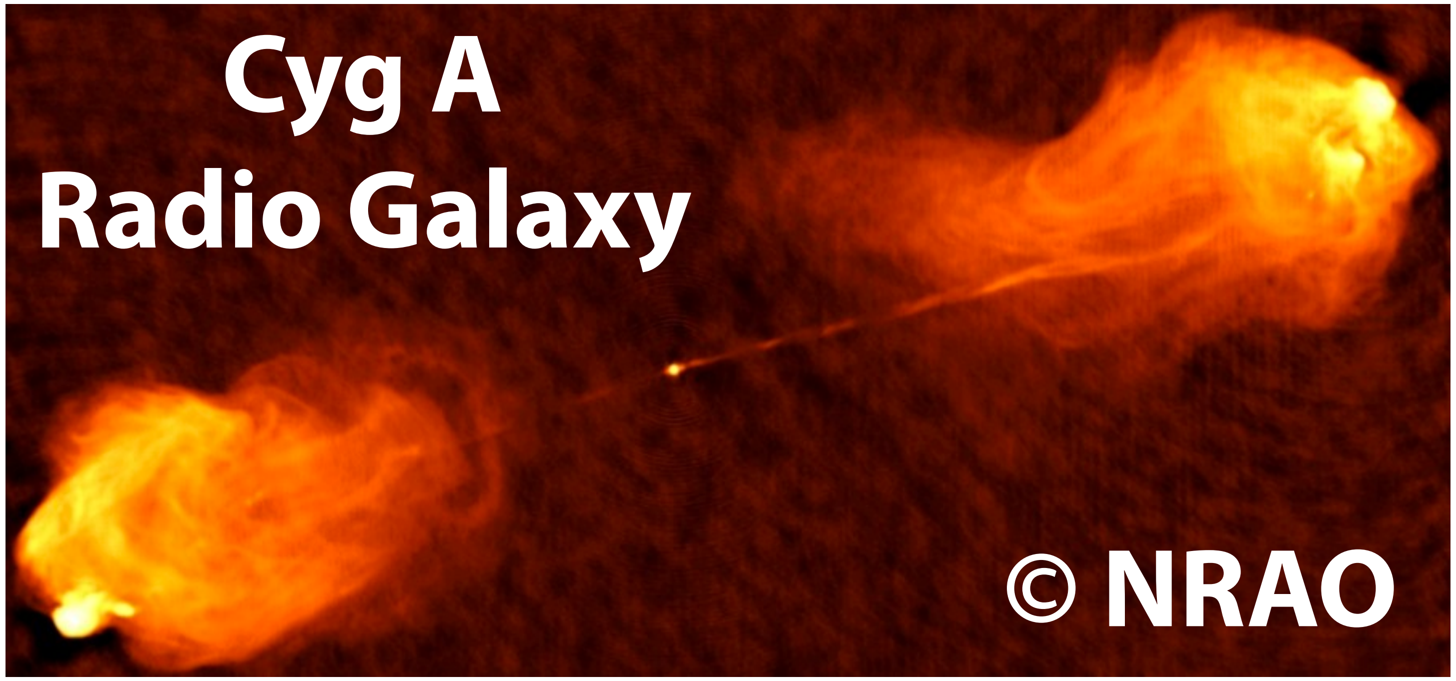
Active Galactic Nuclei (AGNs)

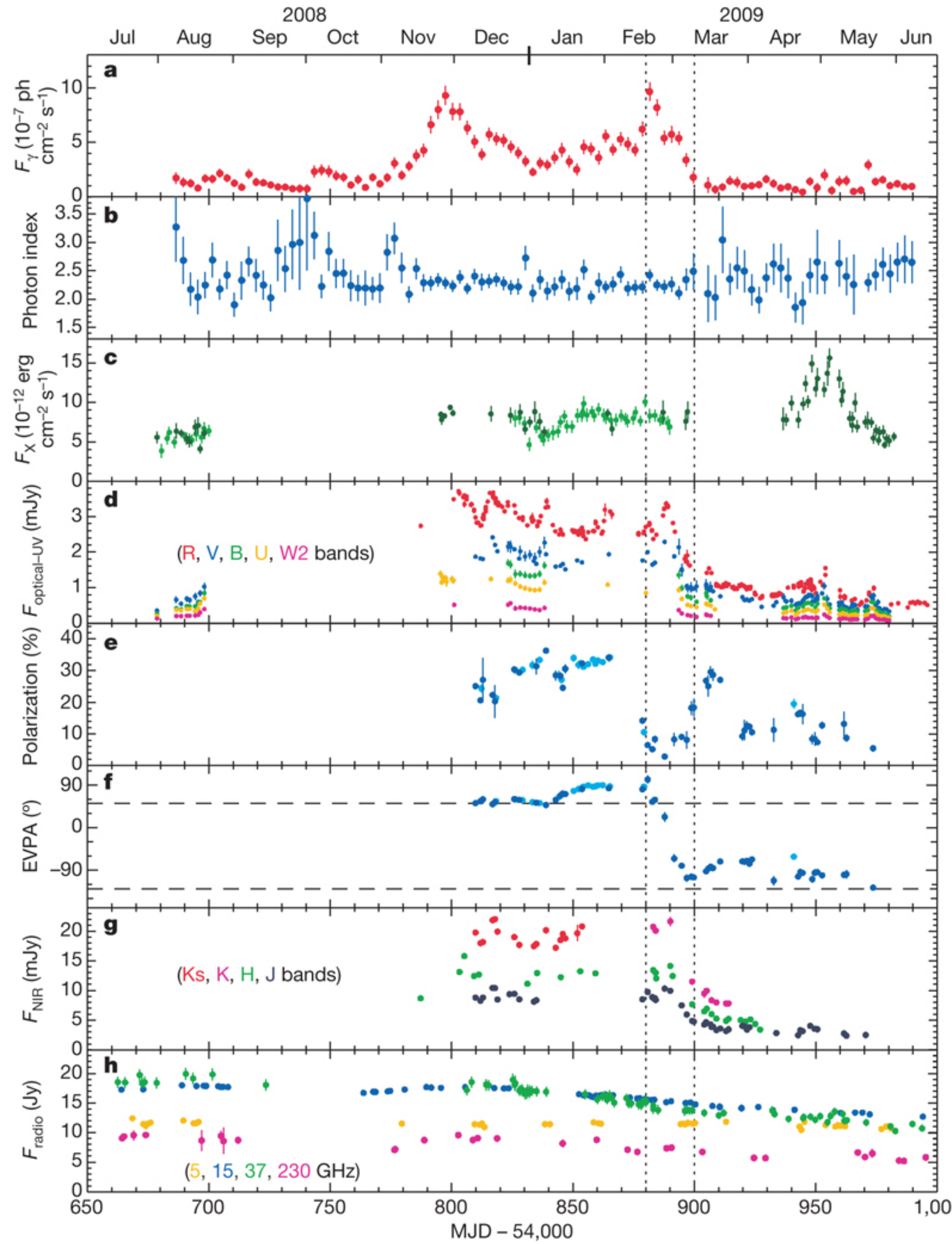


- >10^6 solar mass @ galactic center
  - Correlate with various physical parameters of host galaxies
- Gas accretion
  - brighter than host galaxies (AGNs)
  - Relativistic jets
  - Hot Coronae

AGNs are the most energetic particle accelerators

Blazars





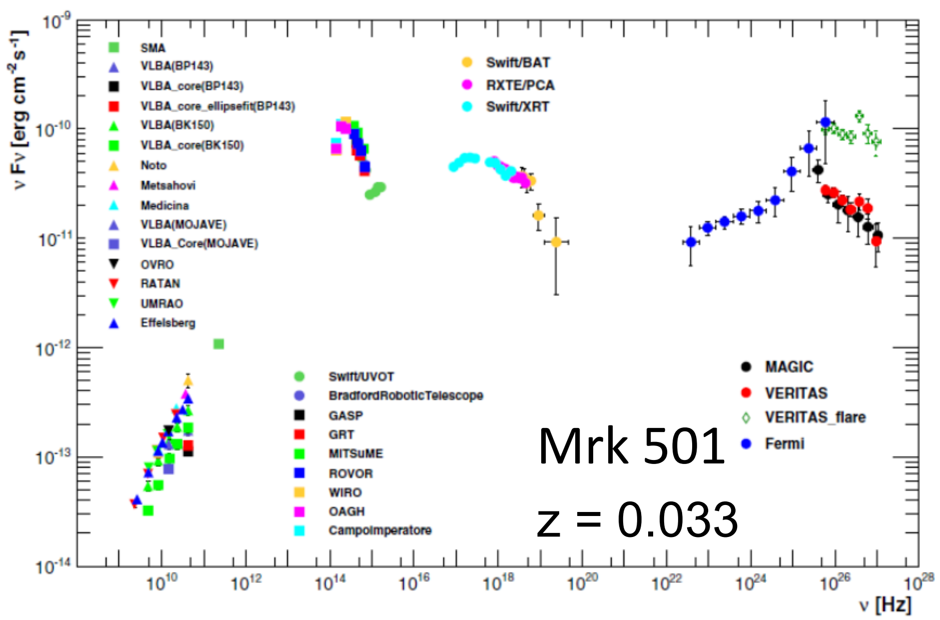
Abdo+'10

- AGNs whose relativistic jets pointing at us.
- Variable (⊿t ~ 1 day)
- ~10% polarization

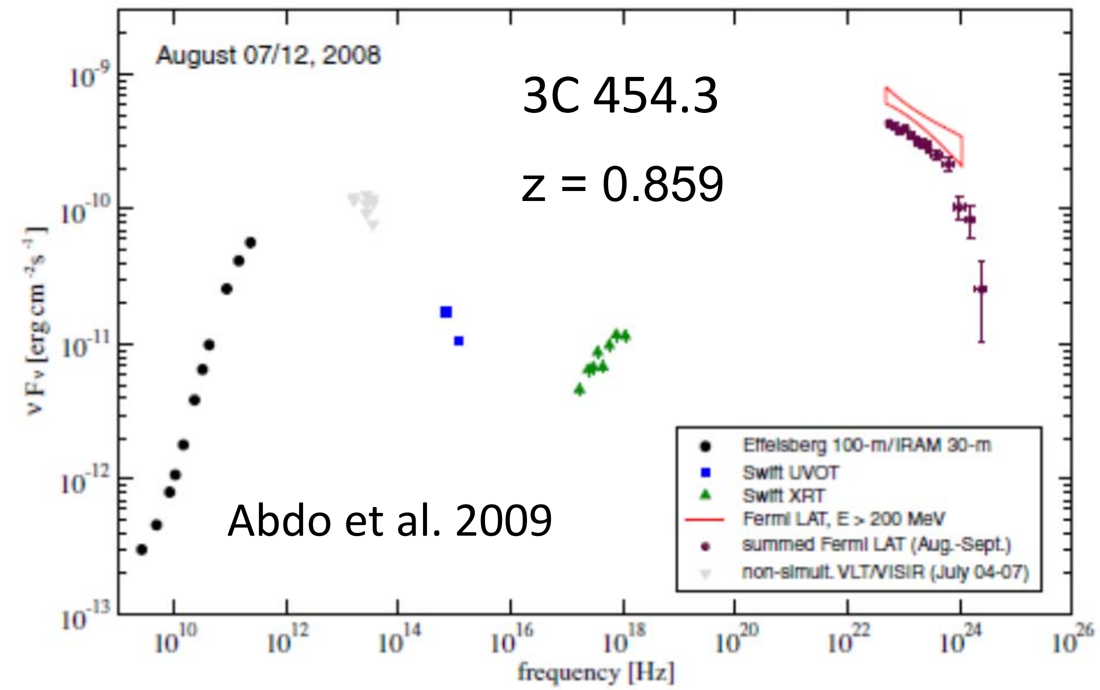
Blazar Spectra

FSRQs: cutoffs at GeV with VHE episodes

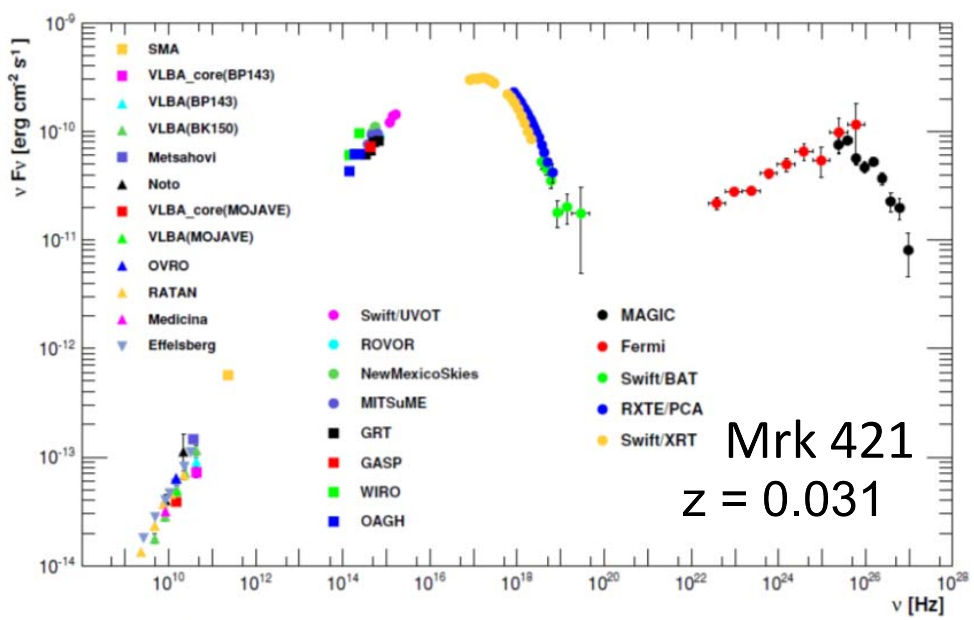
BL Lacs: emission to VHE/TeV energies

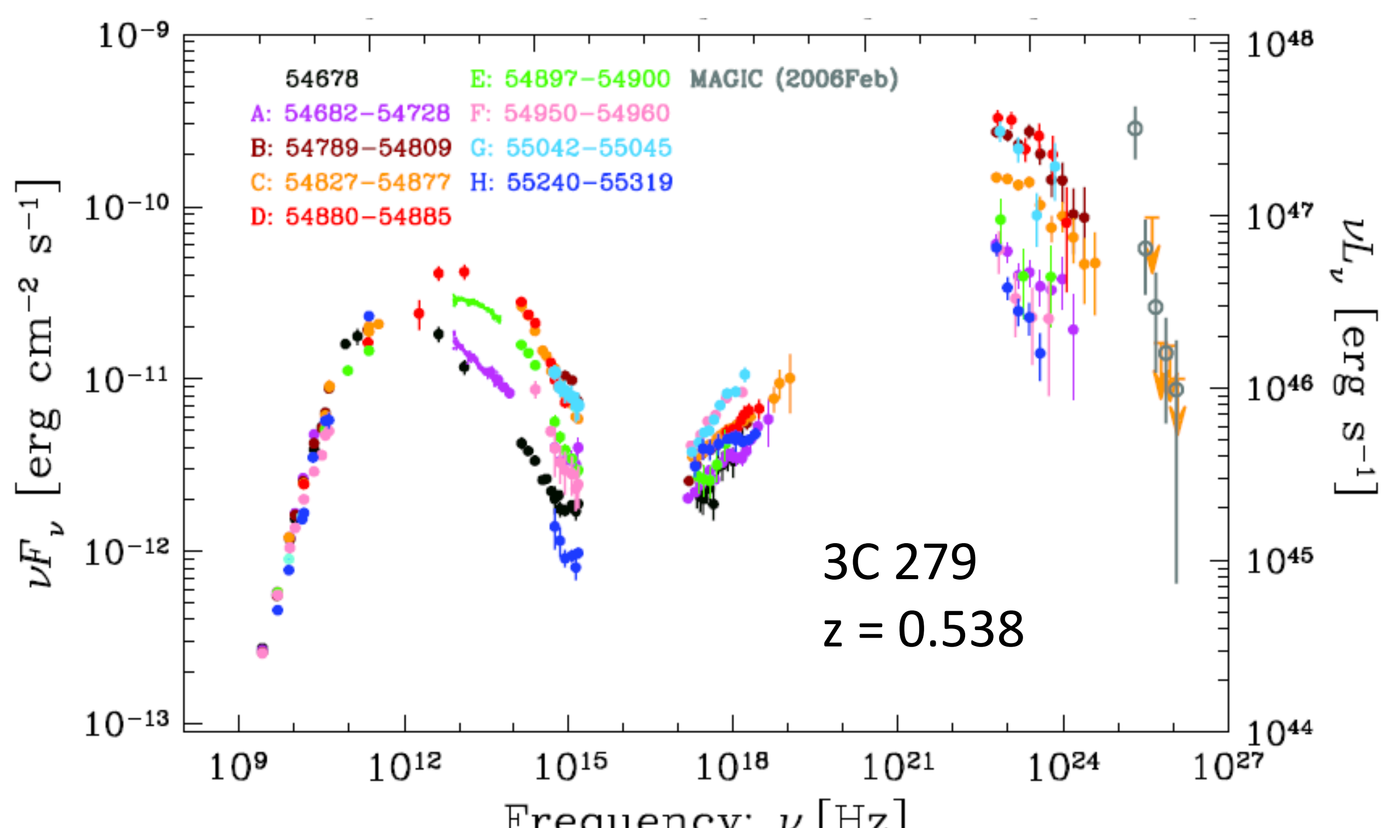


Abdo et al. 2011a



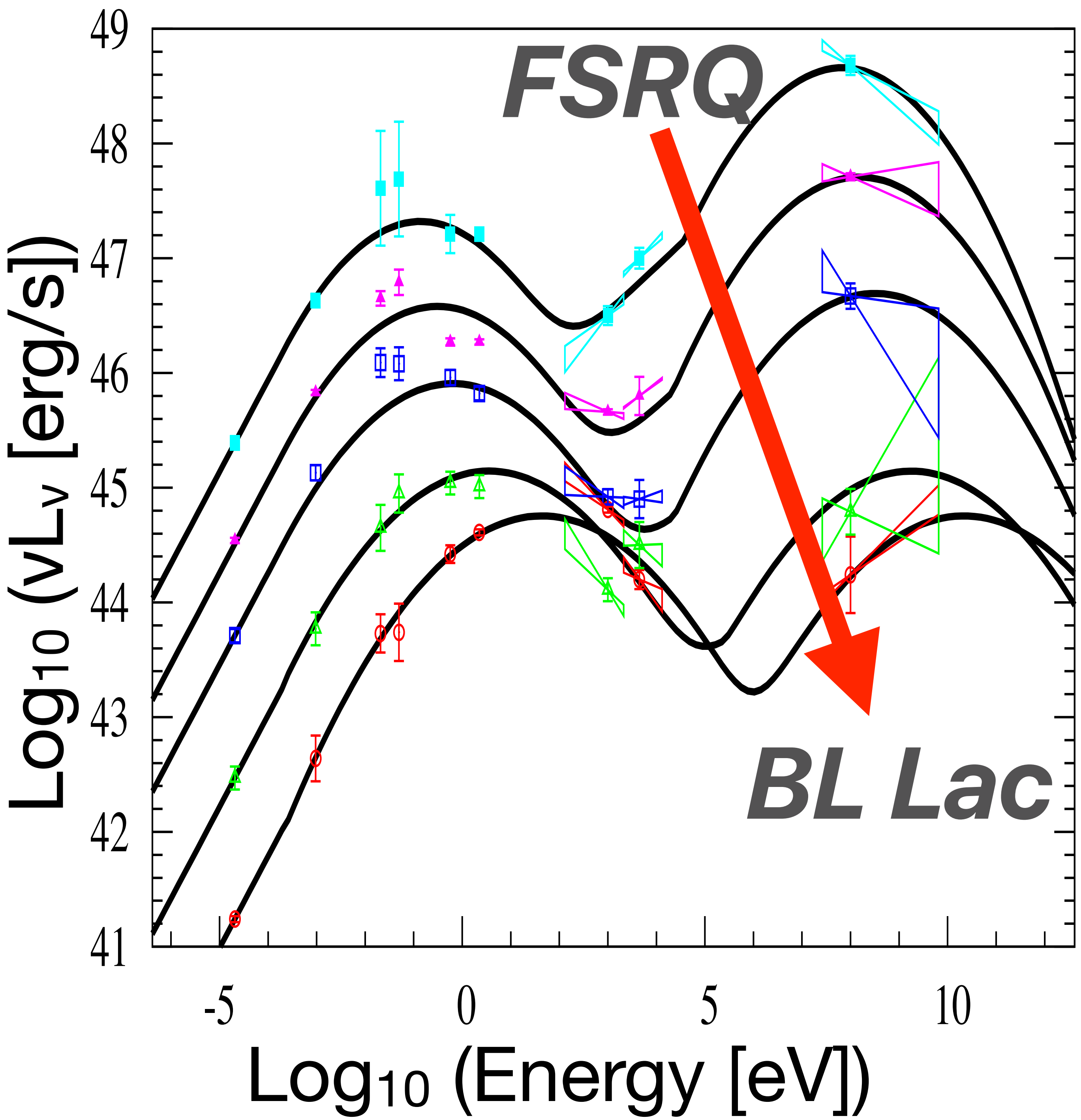
Abdo et al. 2011b





VHE (> 100 GeV)

Typical Spectra of Blazars



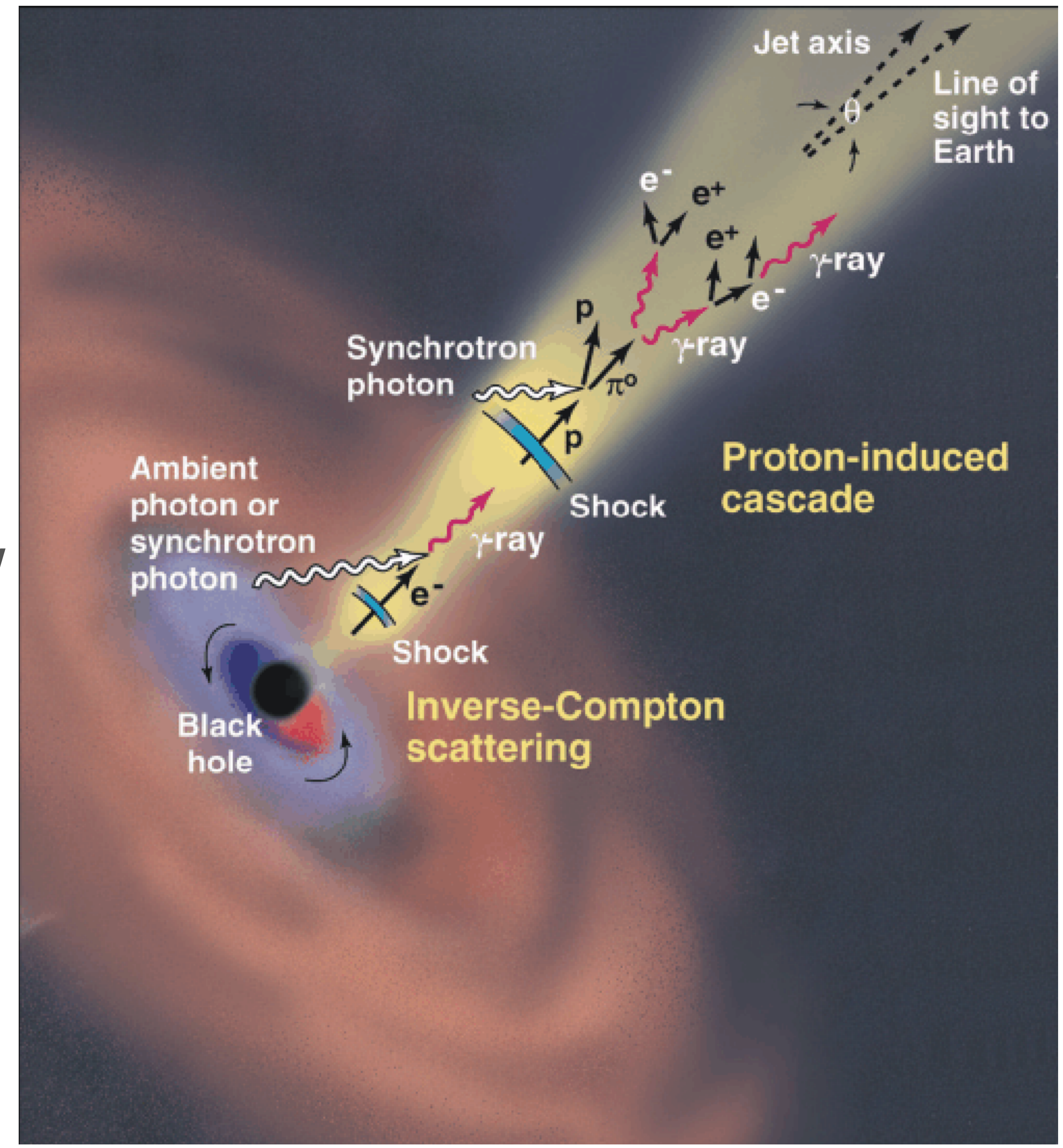
Fossati+'98, Kubo+'98, Ghisellini+'17

- Non-thermal emission from radio to gamma-ray
- Two peaks
  - Synchrotron
  - Inverse Compton
    - Hadronic?
- Luminous blazars (Flat Spectrum Radio Quasars: FSRQs) tend to have lower peak energies (Fossati+'98, Kubo+'98)

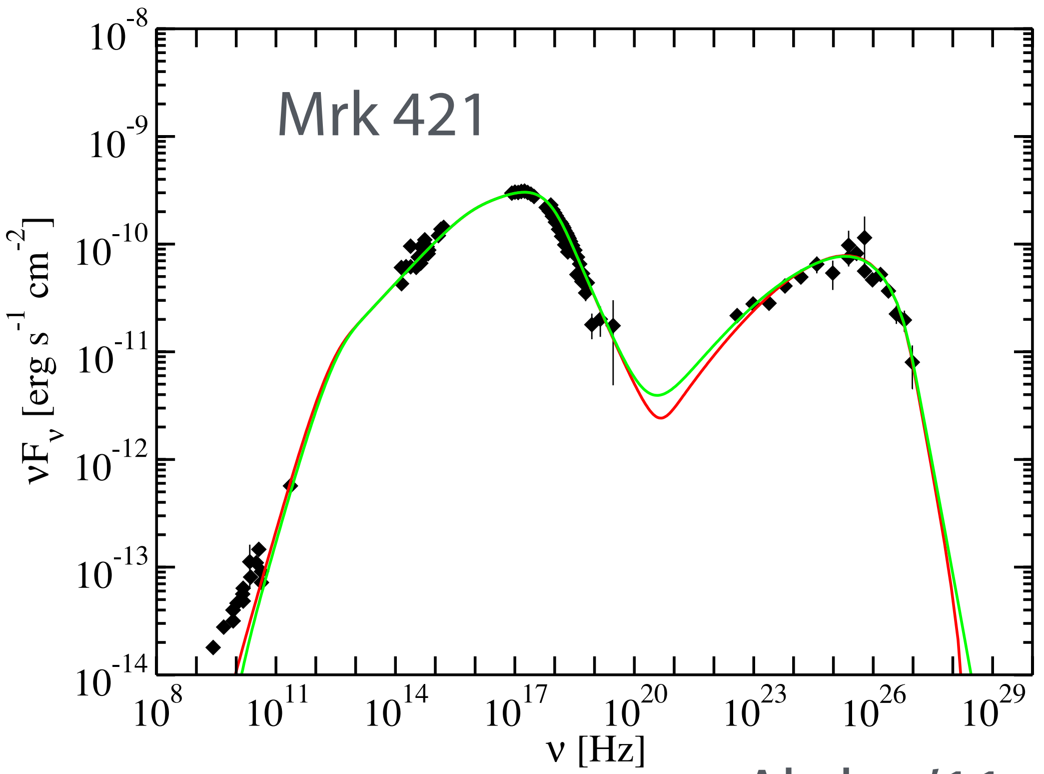
Blazar Emission

Blazar Emission Mechanism

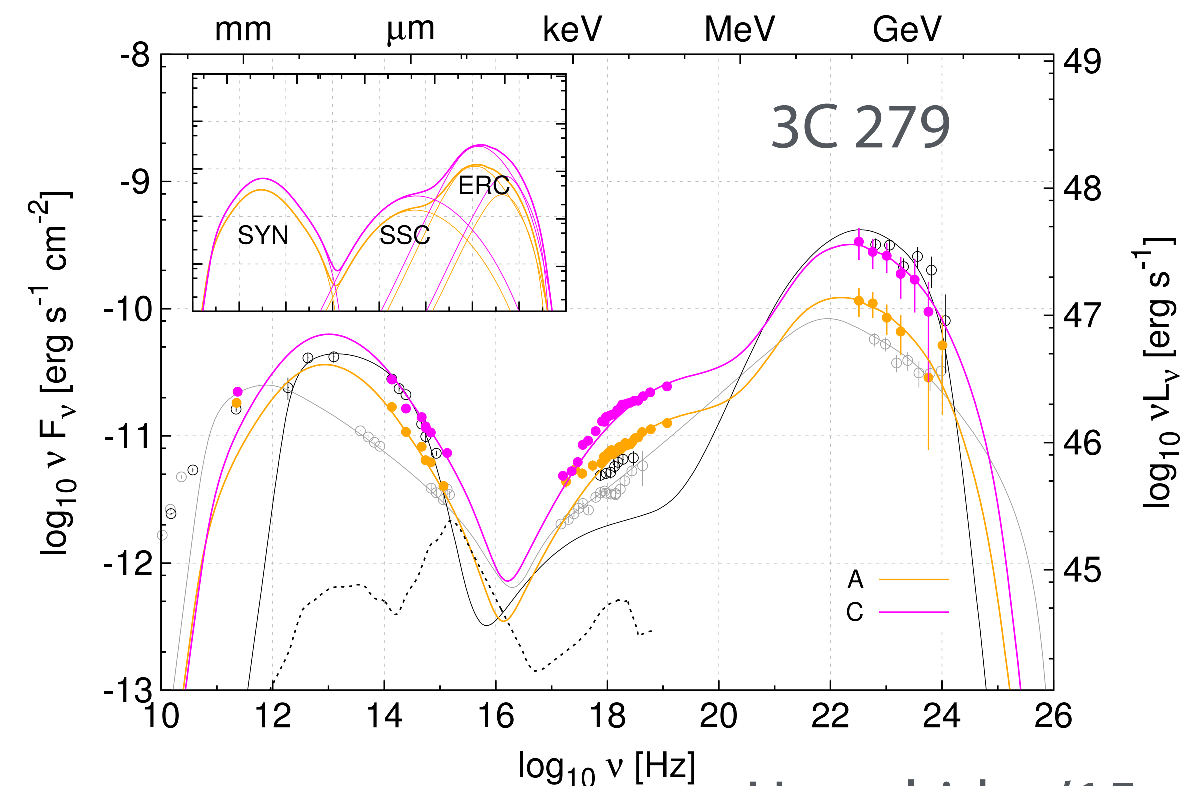
- Non-thermal gamma rays
  - relativistic particles and intense photon fields
- **Leptonic model**
  - non-thermal synchrotron associated w/ Synchrotron-Self-Compton (SSC) or External Compton (EC) components
- **Hadronic model**
  - secondary nuclear production, proton synchrotron, photomeson production



Leptonic Scenario



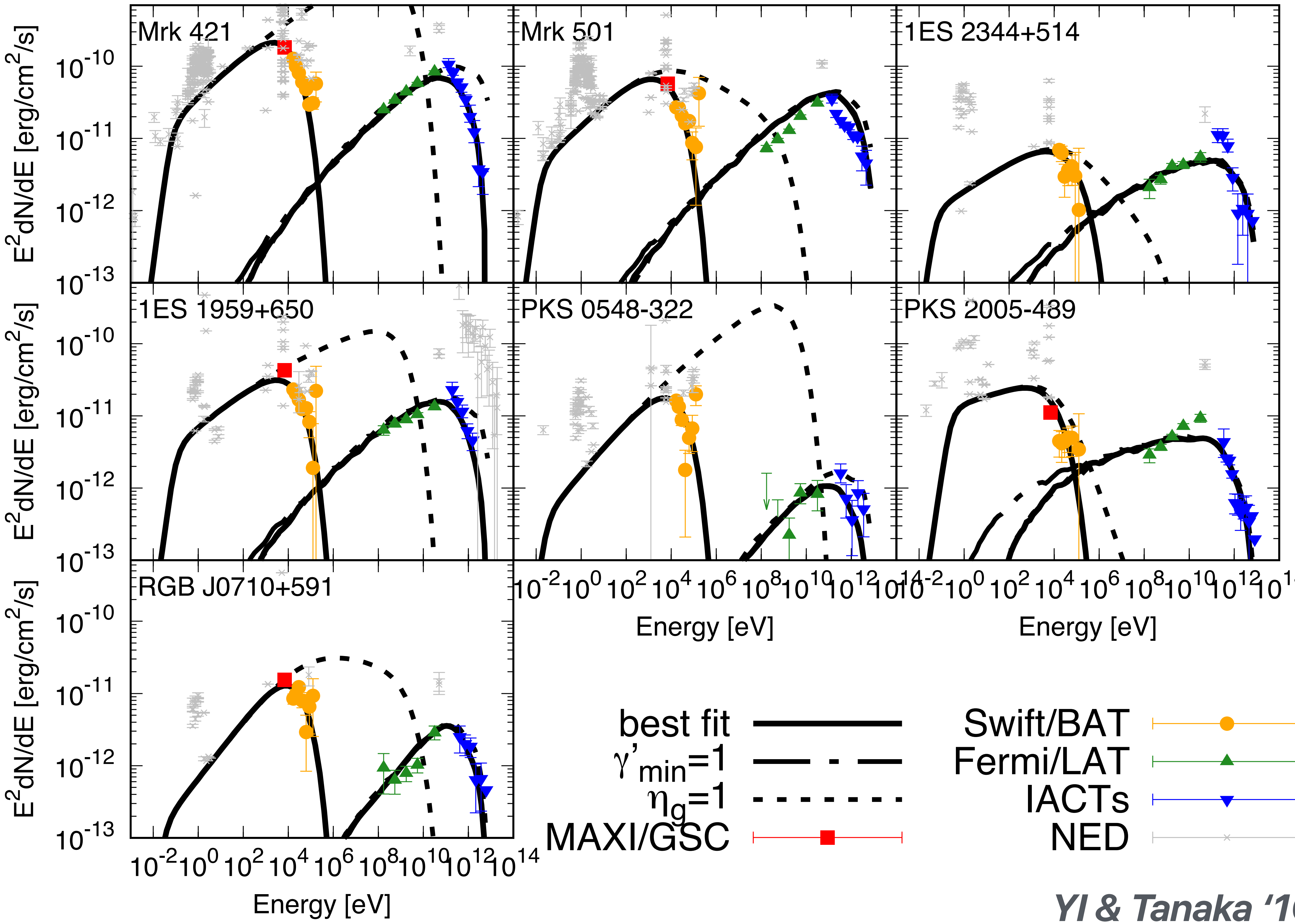
Abdo+'11



Hayashida+'15

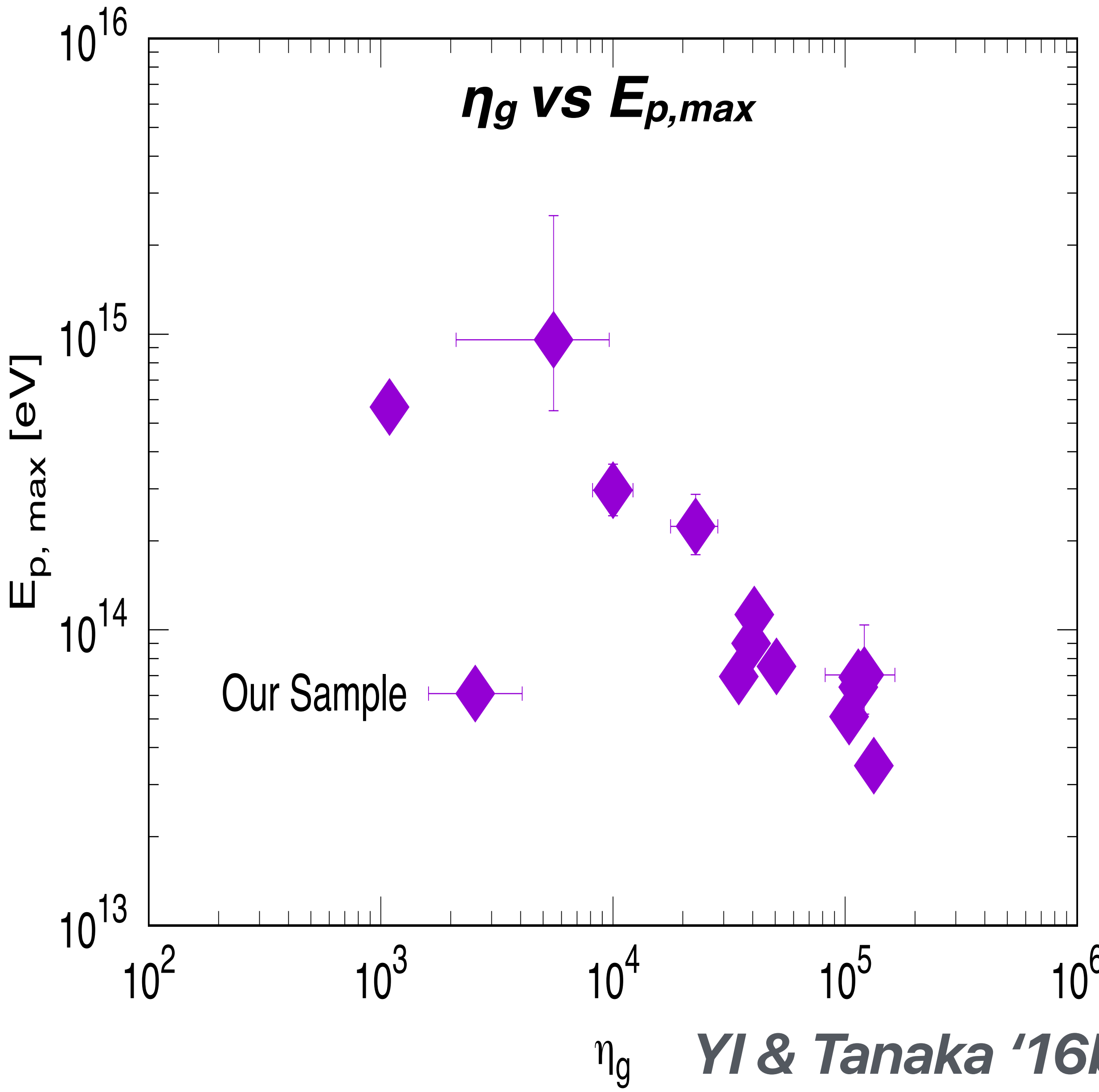
- Radiation from accelerated electrons in inner jets
  - shock? turbulence? reconnection? shear?
- One (multi)-zone synchrotron/SSC/EIC
- target photon: synchrotron, broad line regions (BLRs), dust torus, accretion disk

Spectral Fitting w/ a Leptonic Model



YI & Tanaka '16b

Maximum Proton Energy from HBLs

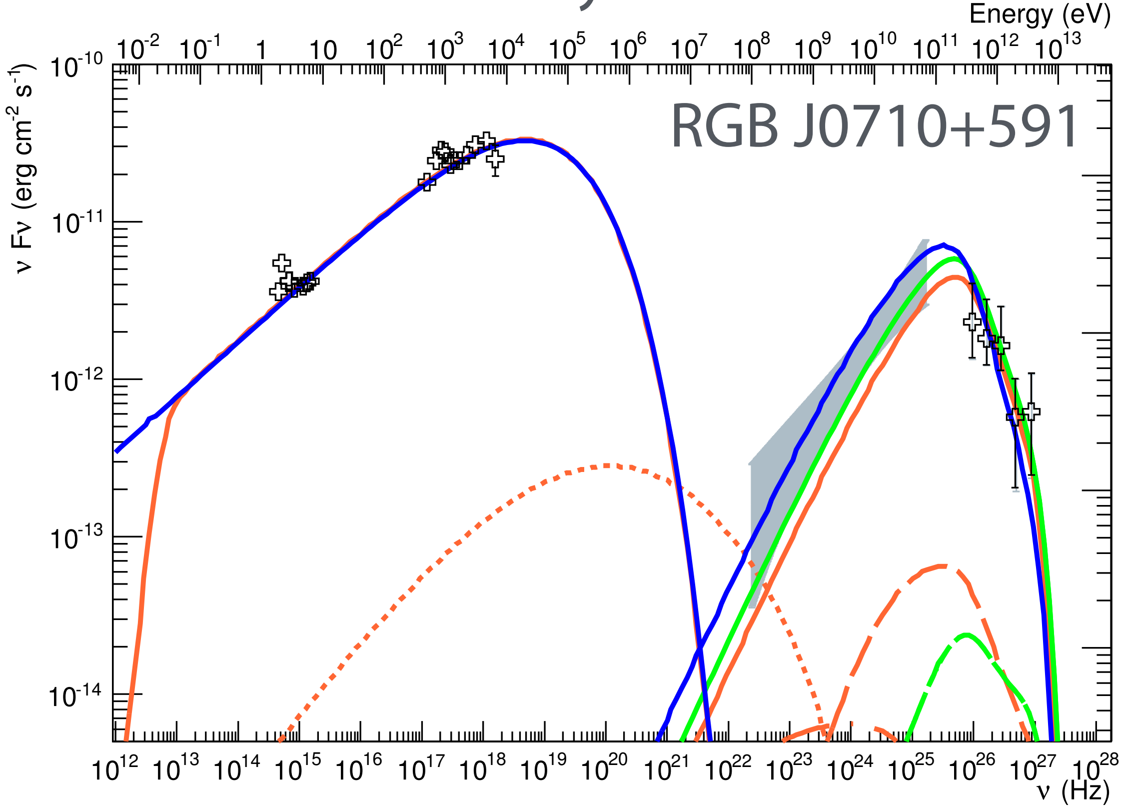


YI & Tanaka '16b

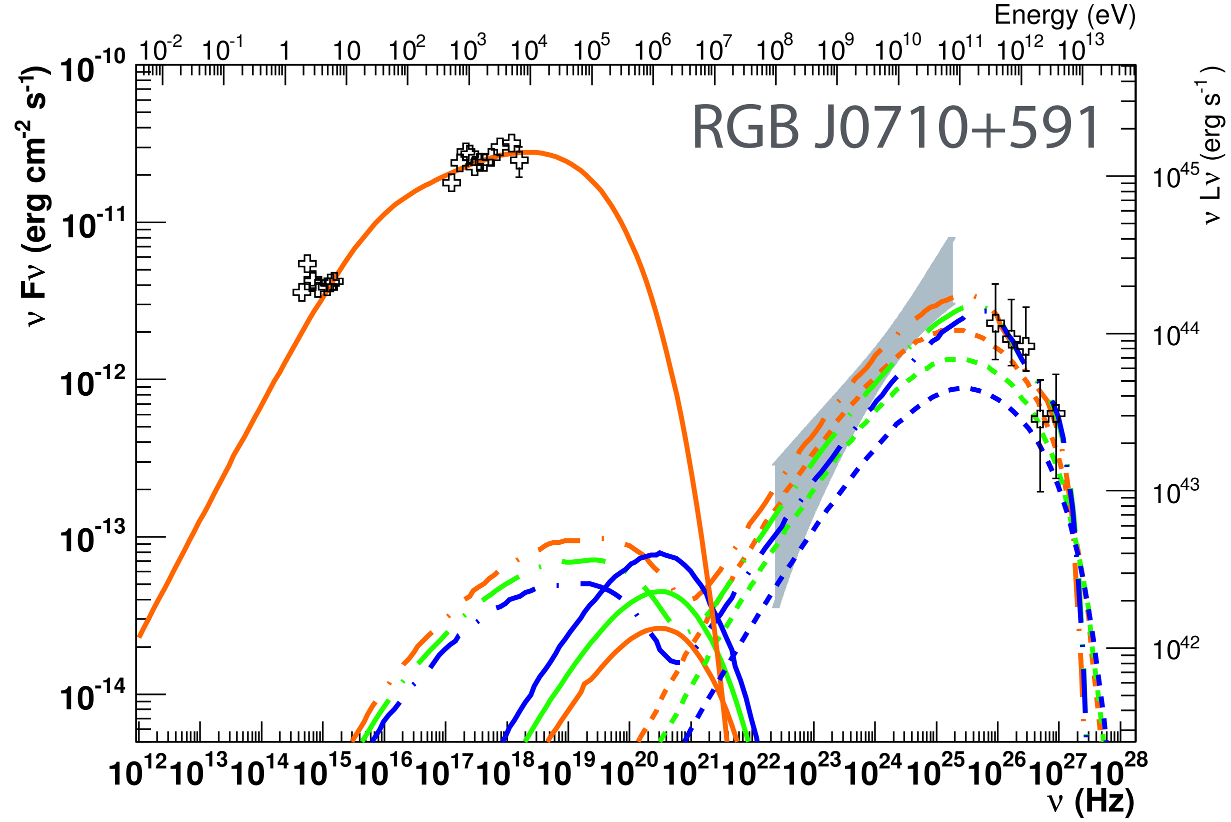
- HBLs are not efficient accelerators having η_g ~ 5x10^4.
  - consistent with previous individual source studies (Inoue & Takahara '96, Sato+'08, Finke+'08)
- the maximum proton energy from HBLs is <10^{15} eV.

Lepto-Hadronic Scenario

Proton-Synchrotron



Photomeson cascade

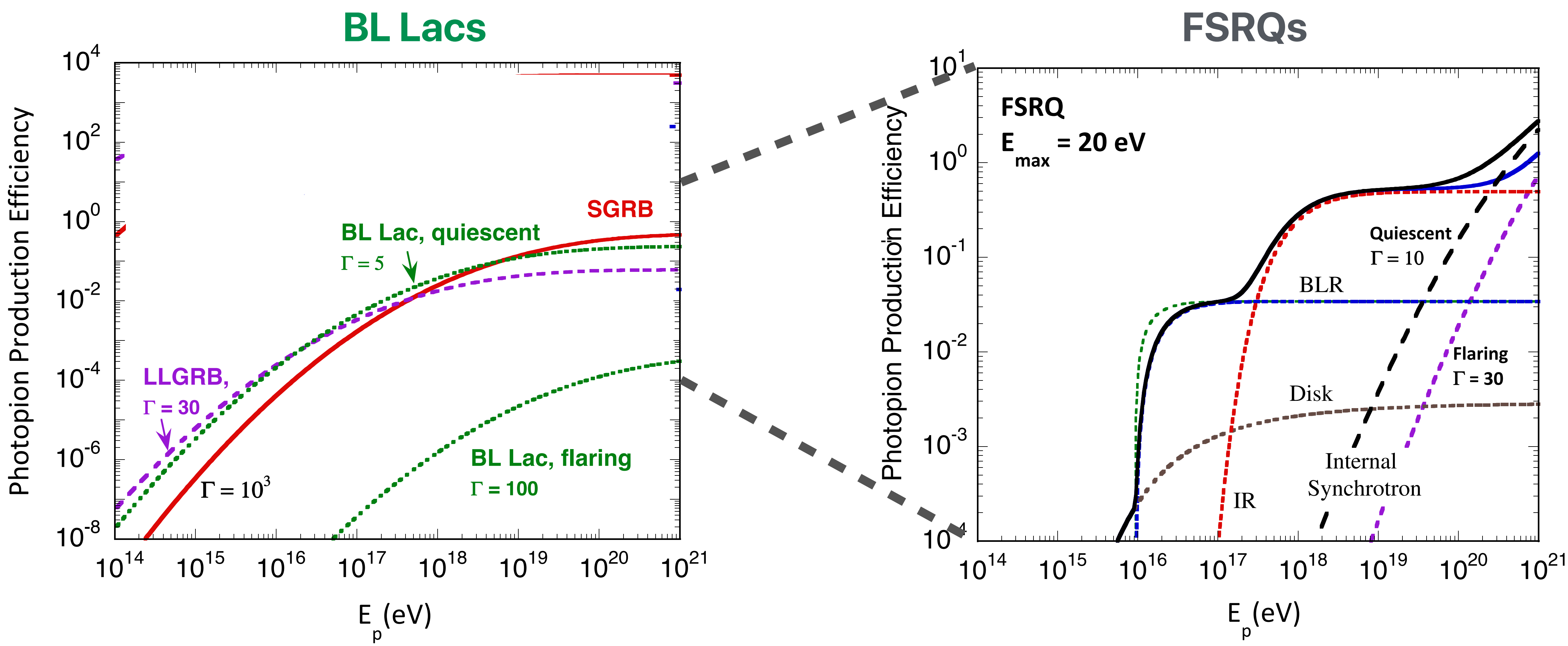


Cerruti+'14

- Proton (Ion) Synchrotron
  - p + B -> p + γ
- Photomeson interaction (cascade)
  - p+γ -> p/n, π -> p/n, ν, γ, e

Photomeson Production Efficiency

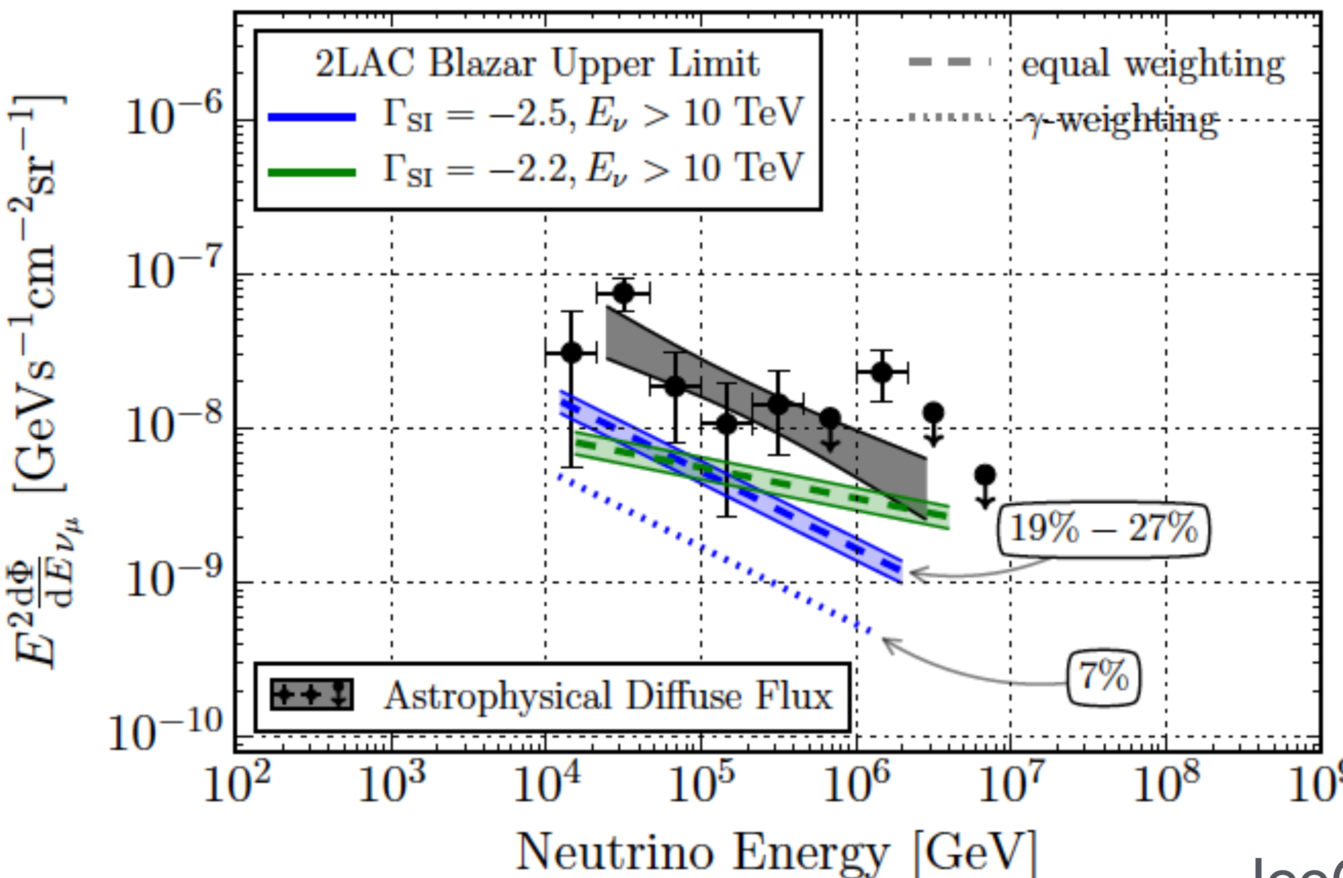
Dermer, Murase, & YI ’14



- BL Lacs are inefficient neutrino factories, but UHECRs can survive
- FSRQs are efficient because of external photon field
  - have a ν spectral peak at ~PeV due to BLR photons

Murase-san’s talk

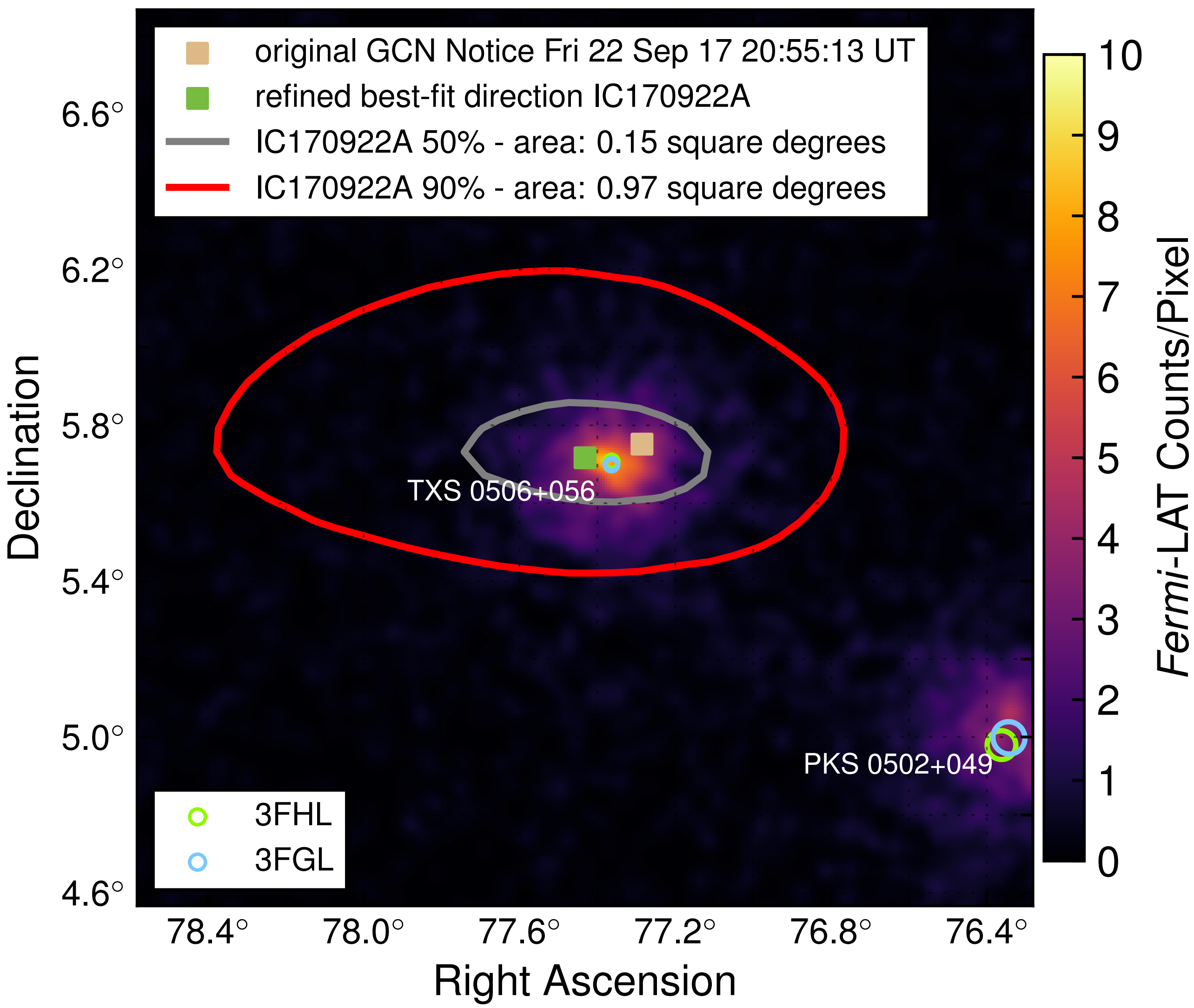
Fermi Blazars Contribution

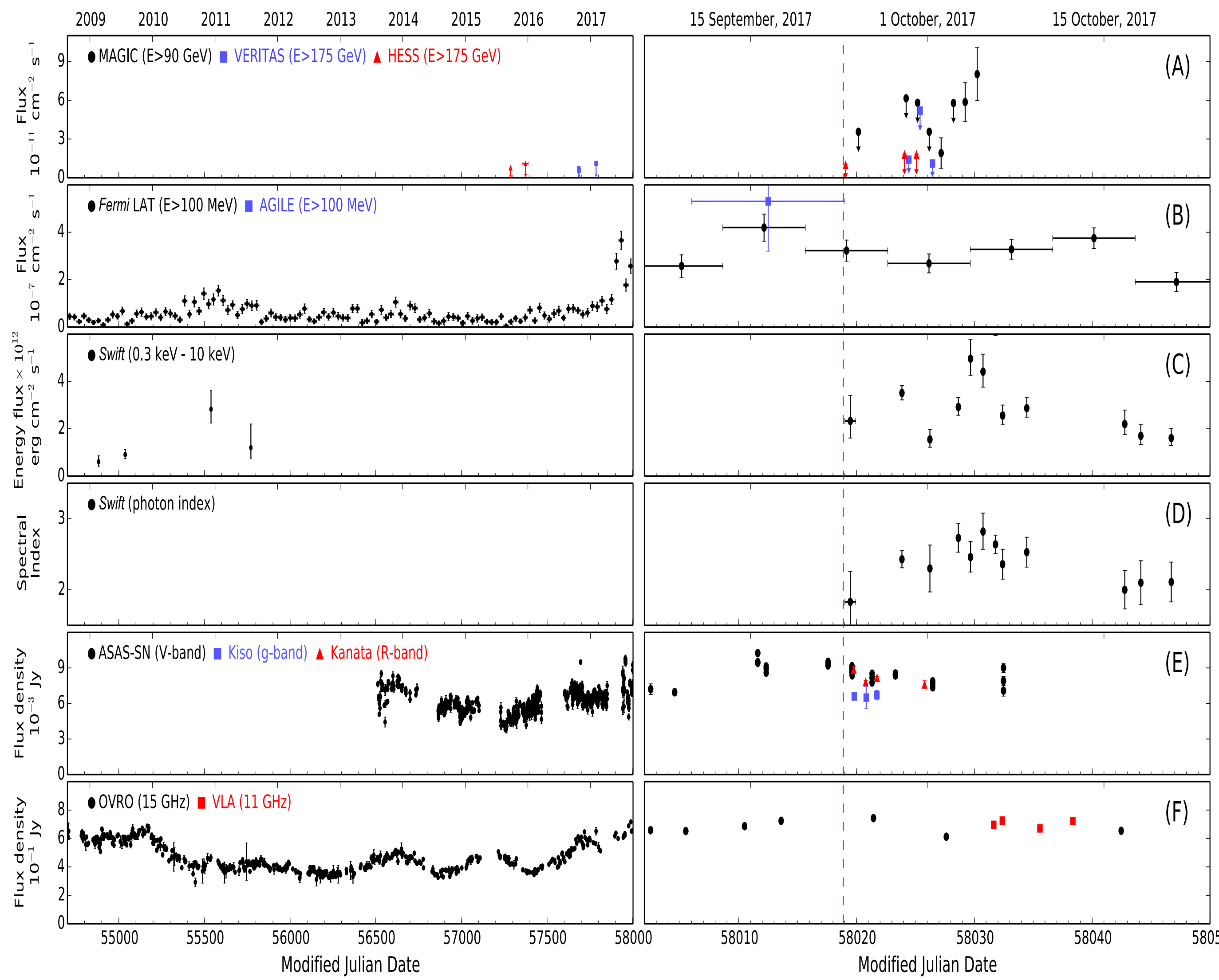


IceCube '17

- Blazars are rare (~1-10 deg^{-2})
- Fermi/LAT blazars can explain <7-27 % of the IceCube flux
  - Note: Fermi/LAT is not sensitive to MeV blazars (most powerful blazars) and extreme HBLs (highest energy blazars)

IceCube 170922A (TXS 0506+056)

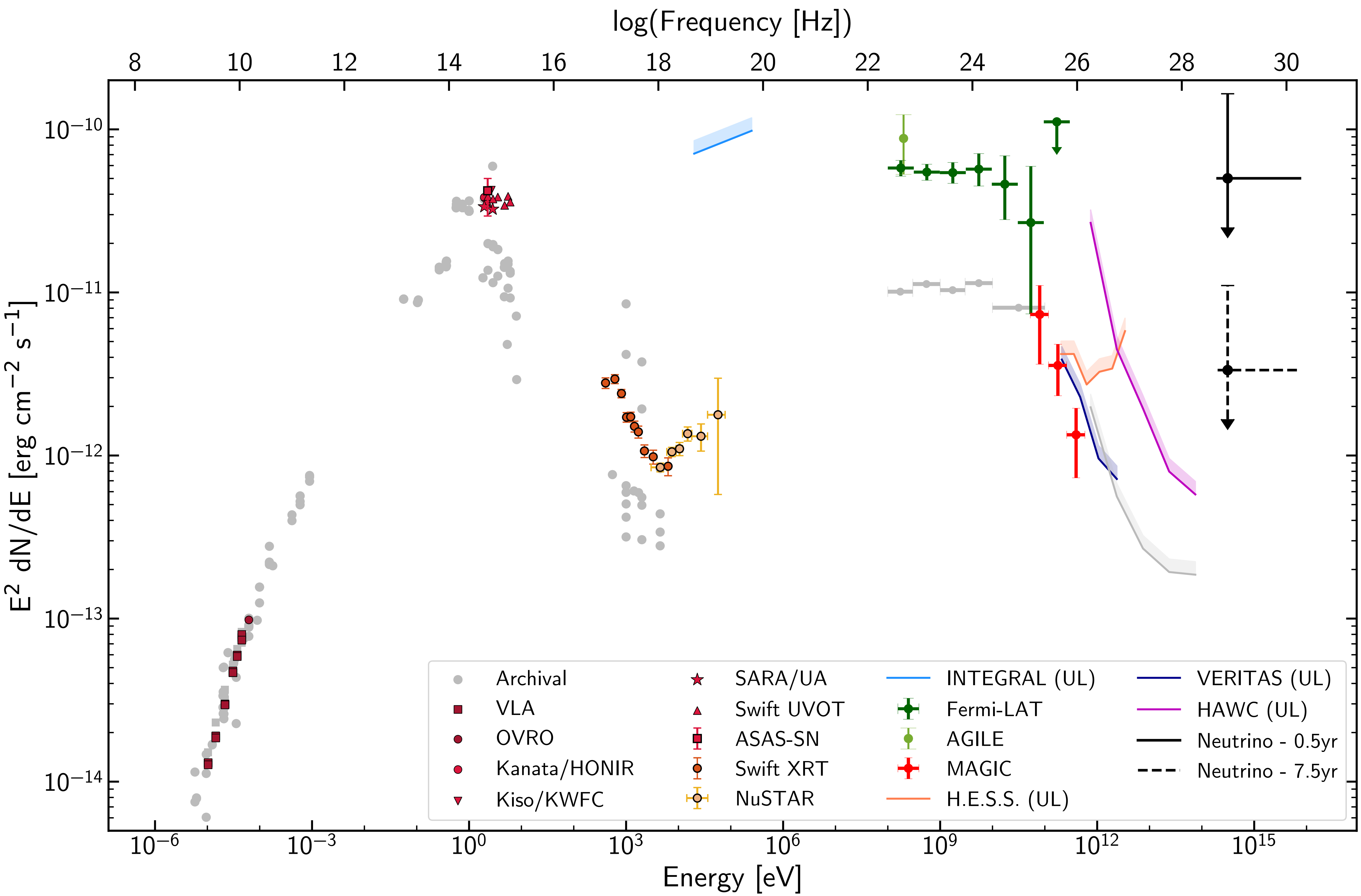




IceCube 2018

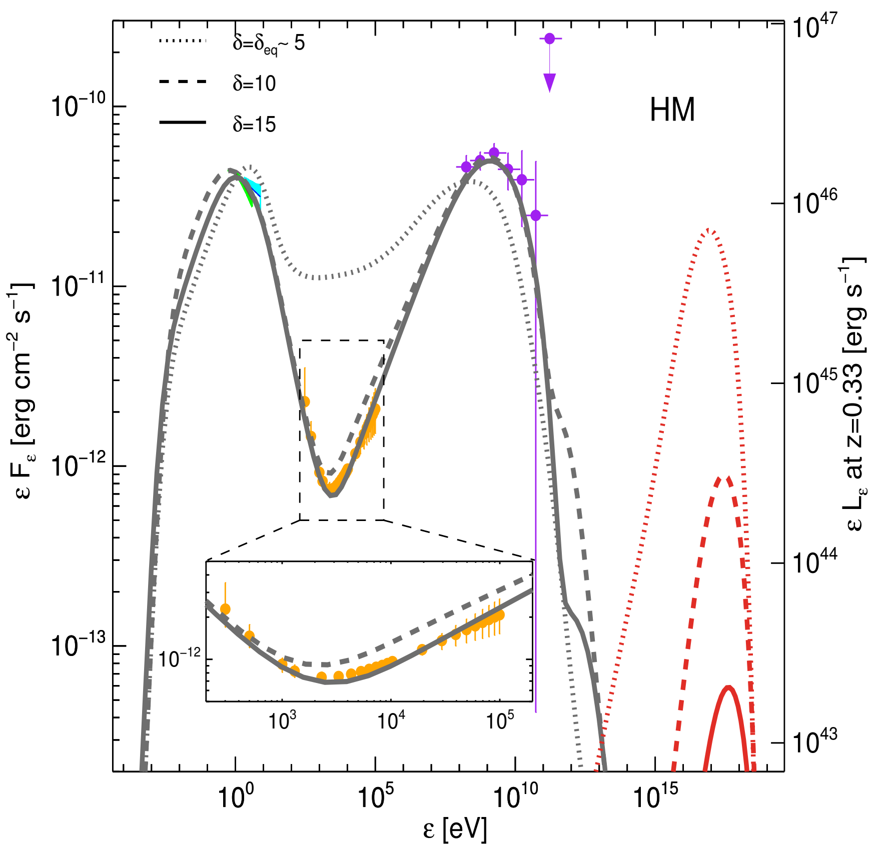
- A ~300 TeV neutrino from TXS 0506+056 (blazar)
  - 3-sigma association

Multi-messenger SED: TXS

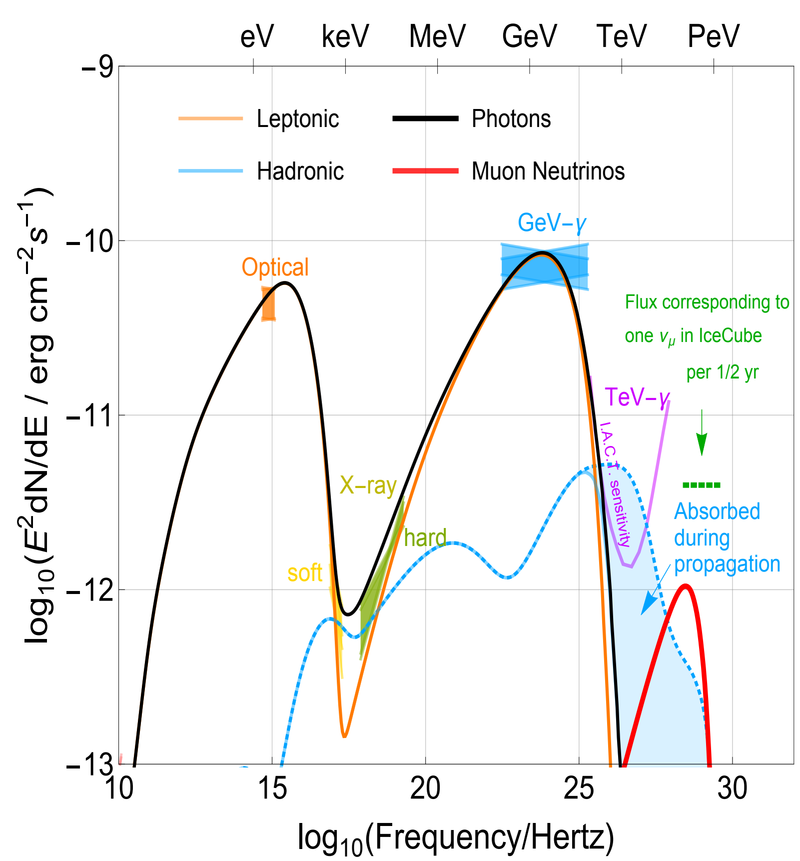


IceCube 2018

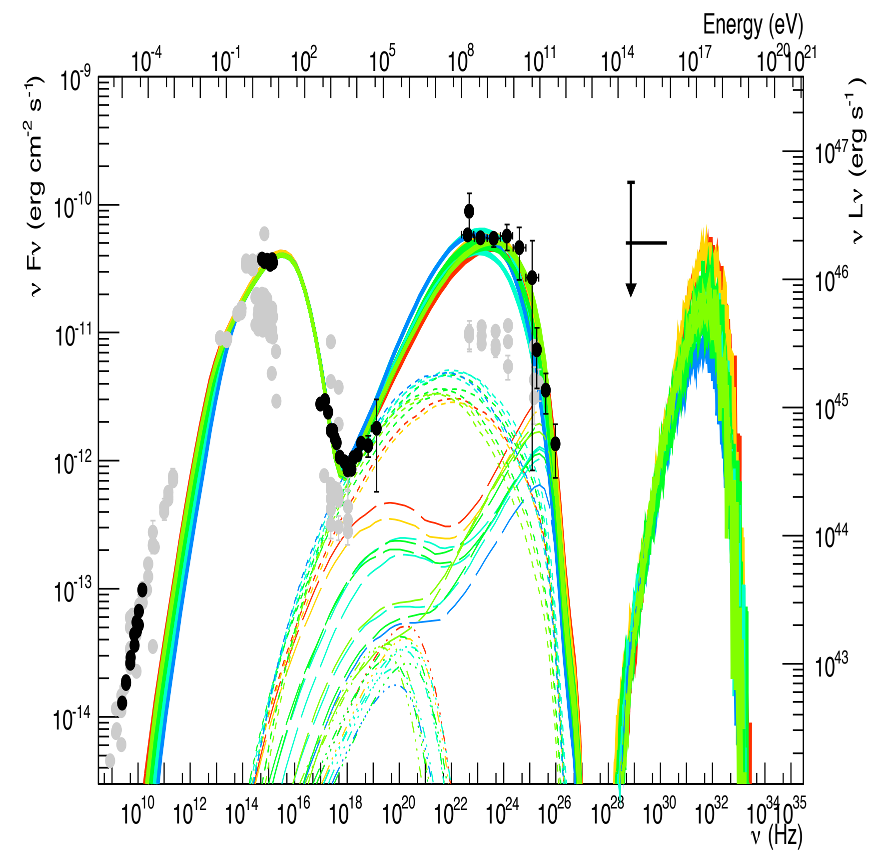
Theoretical Interpretation



Keivani+’18



Gao+’18



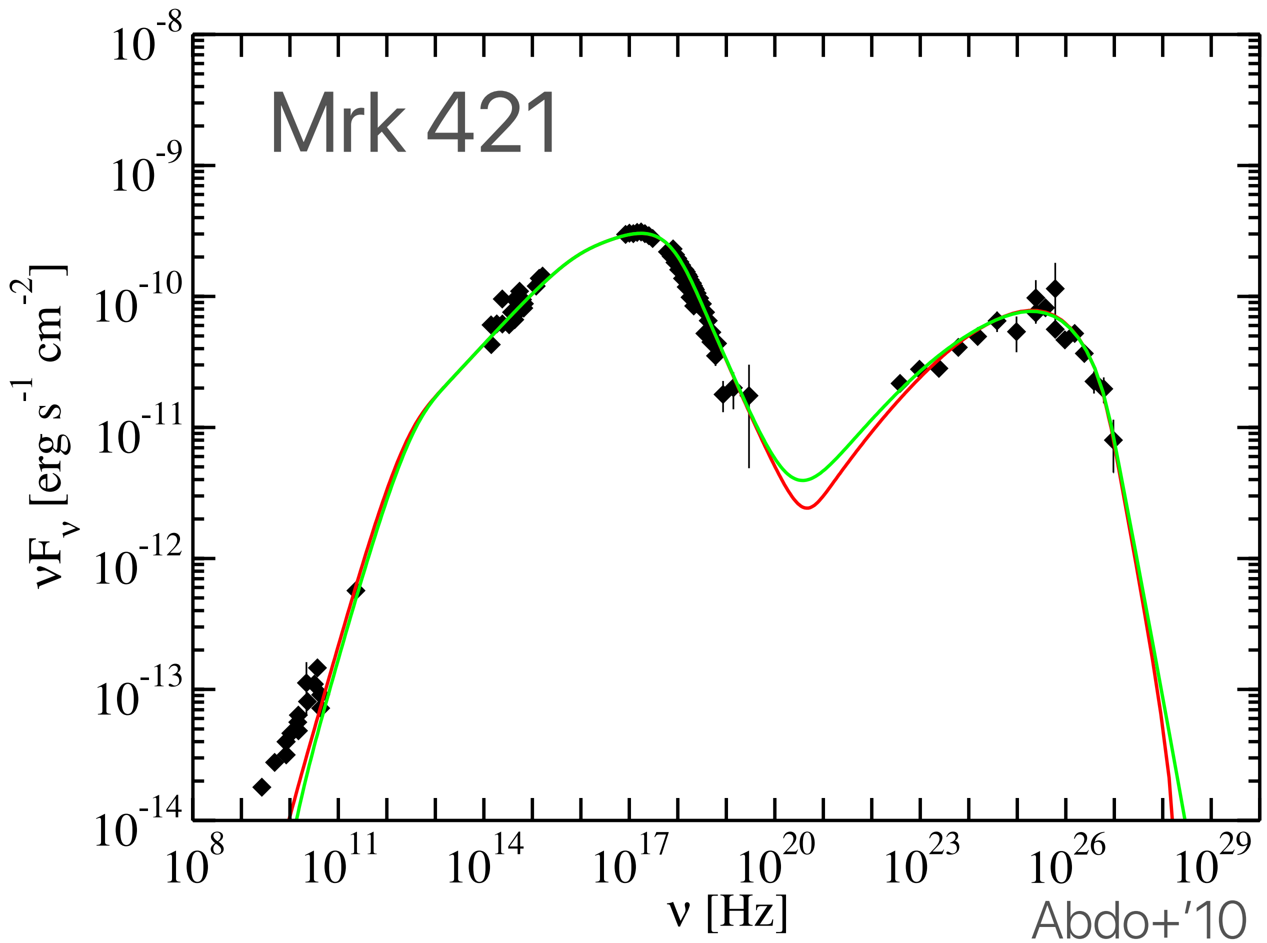
Cerruti+’18

- Pure hadronic model is ruled out because Too much X-ray fluxes
- Lepto-hadronic model is favored (e.g., Keivani+’18;Cerruti+’18;Gao+’18,,,,).
  - Required jet power is comparable to Eddington luminosity.

Power of AGN Jets

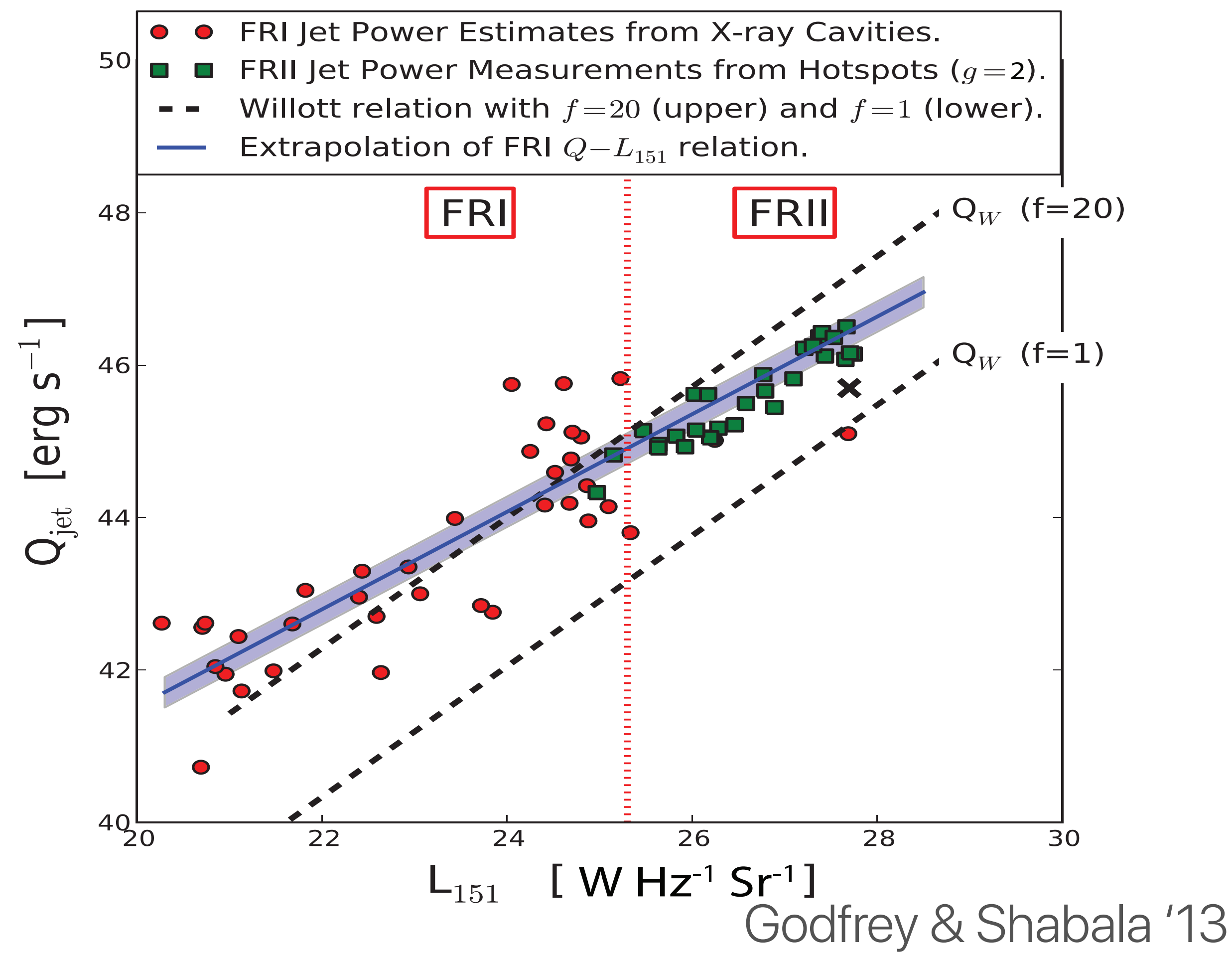
Estimating Jet Power

Blazar SED Fitting



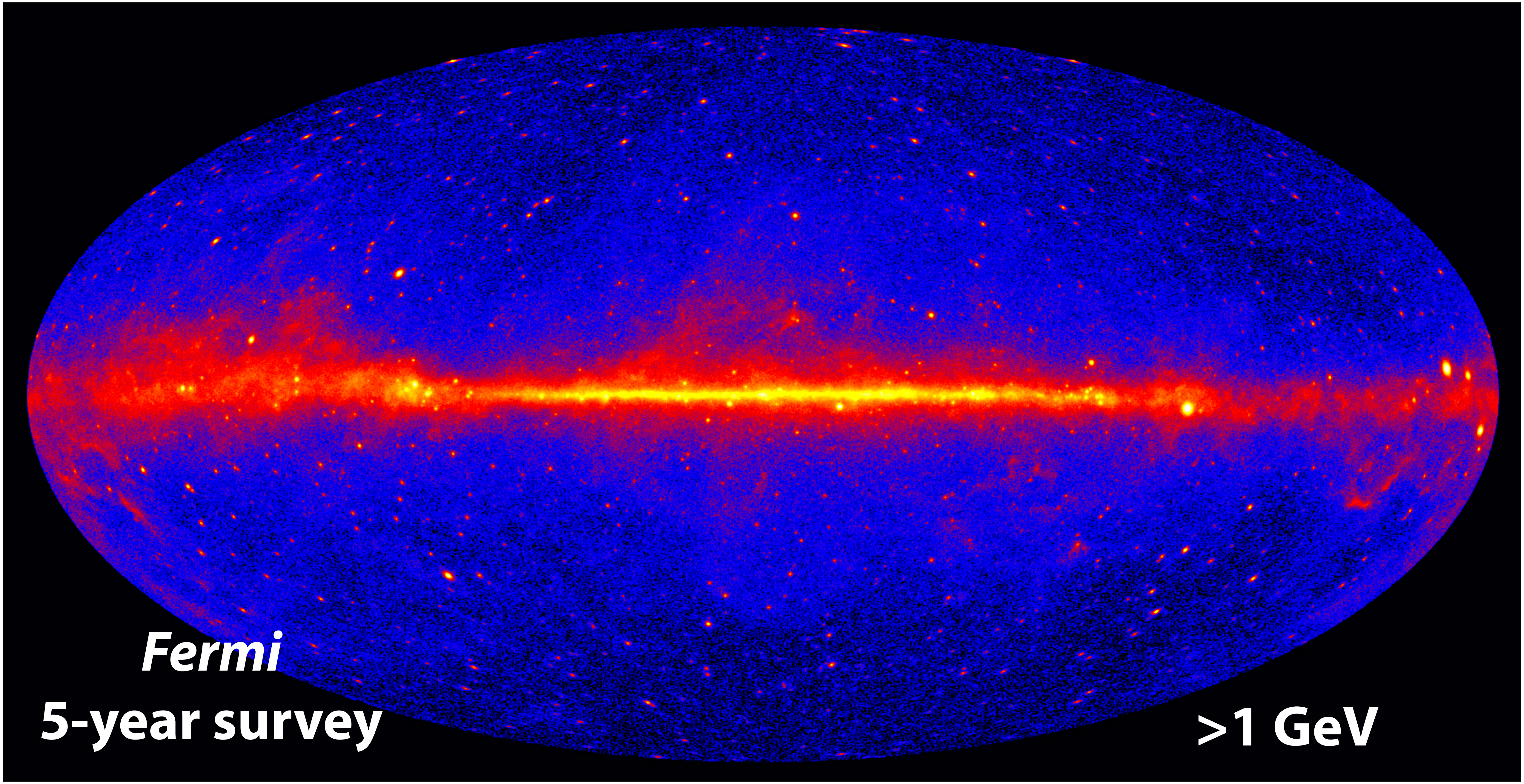
- Particle distribution functions from data (e.g., Ghisellini+'15; YI & Tanaka'16)
  - assume e.g., cold protons

Large-scale Jet



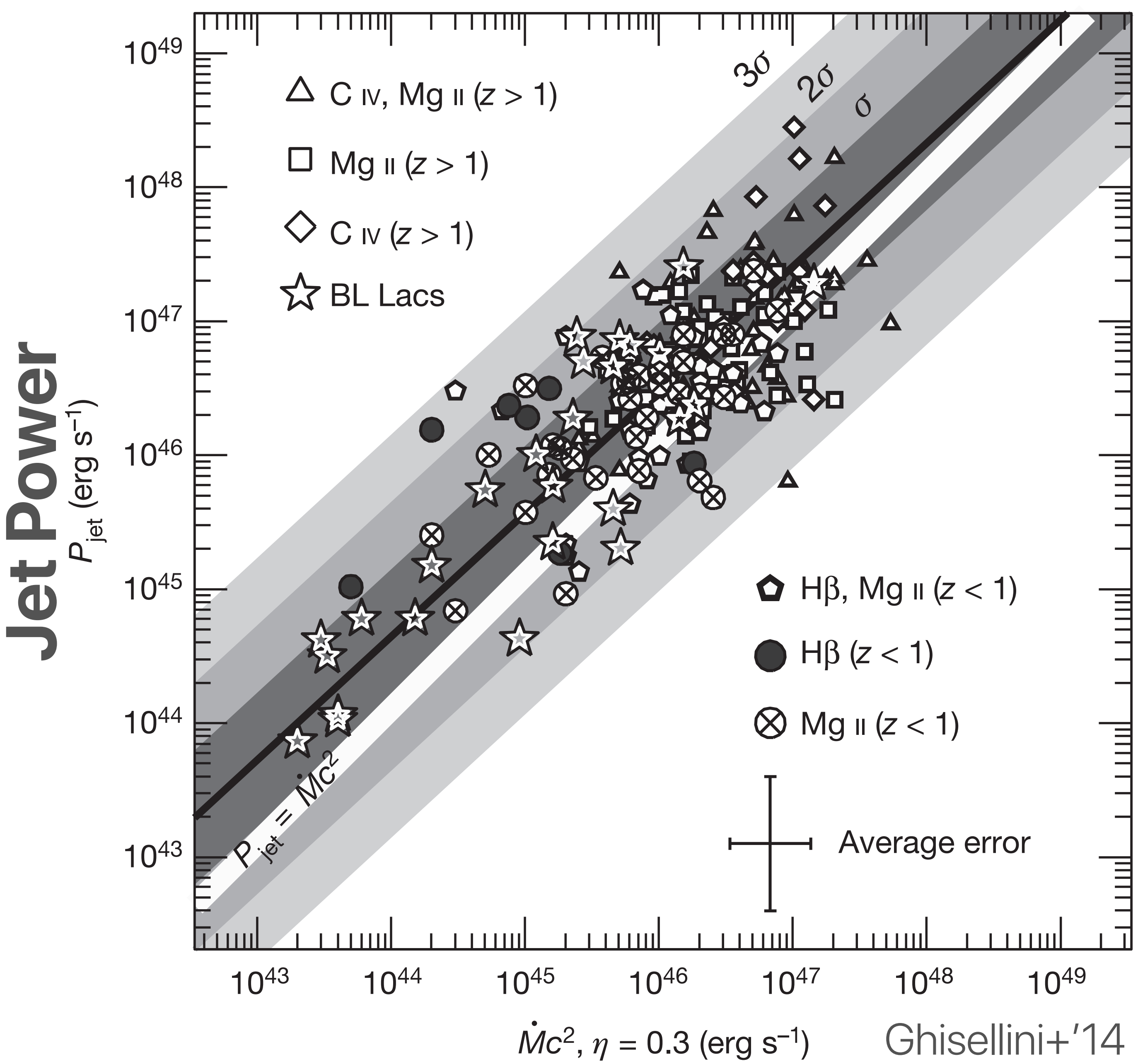
- Empirical relation between radio luminosity and jet power (e.g., Willott+'99)
  - calibrated by X-ray cavity

Fermi has seen many blazars



- ~1700 blazars are detected in GeV

Blazar Jet Power



- One-zone leptonic model
- Assume cold protons
- Accretion rate from lines
- 217 Fermi Blazars
  - Correlation between jet power and accretion rate (Ghisellini+'14)

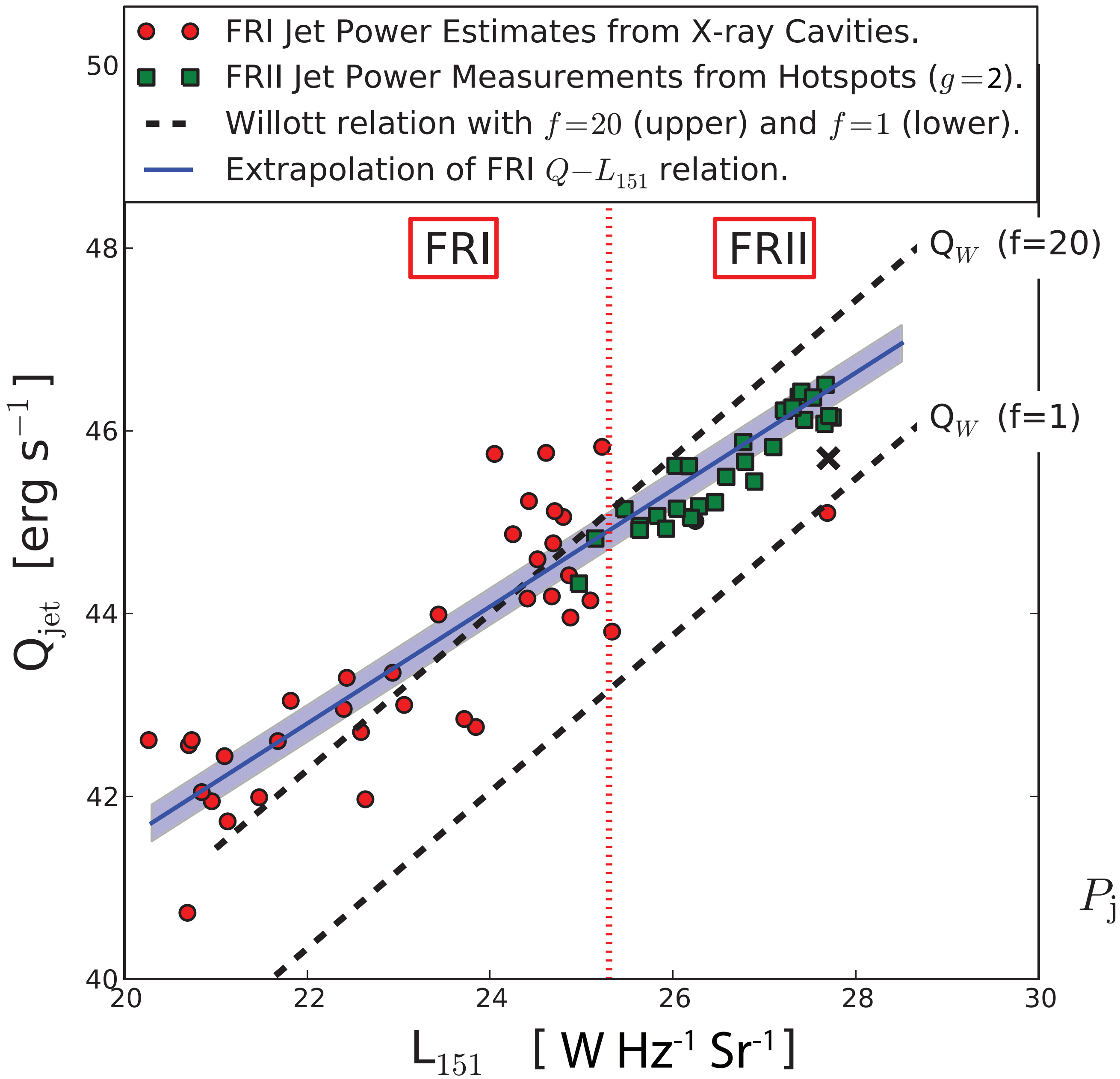
$$P_{\rm jet} \gtrsim \dot{M}_{\rm in} c^2$$

- Similar results for TeV blazars (YI & Tanaka'16)

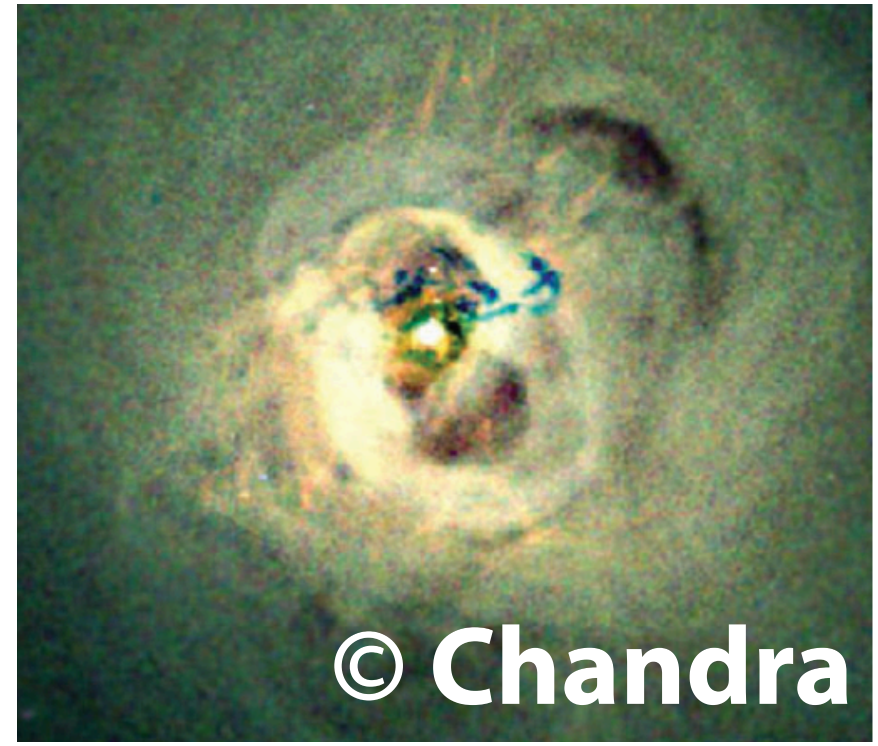
Multi-wavelength Sky Survey

- Various sky survey data in various wavelengths are now available.
- e.g., SDSS has identified >5x10^5 quasars with spectroscopy
    - Mass of SMBH & bolometric luminosity are available.

Estimating Jet Power by X-ray Cavity



Godfrey & Shabala '13

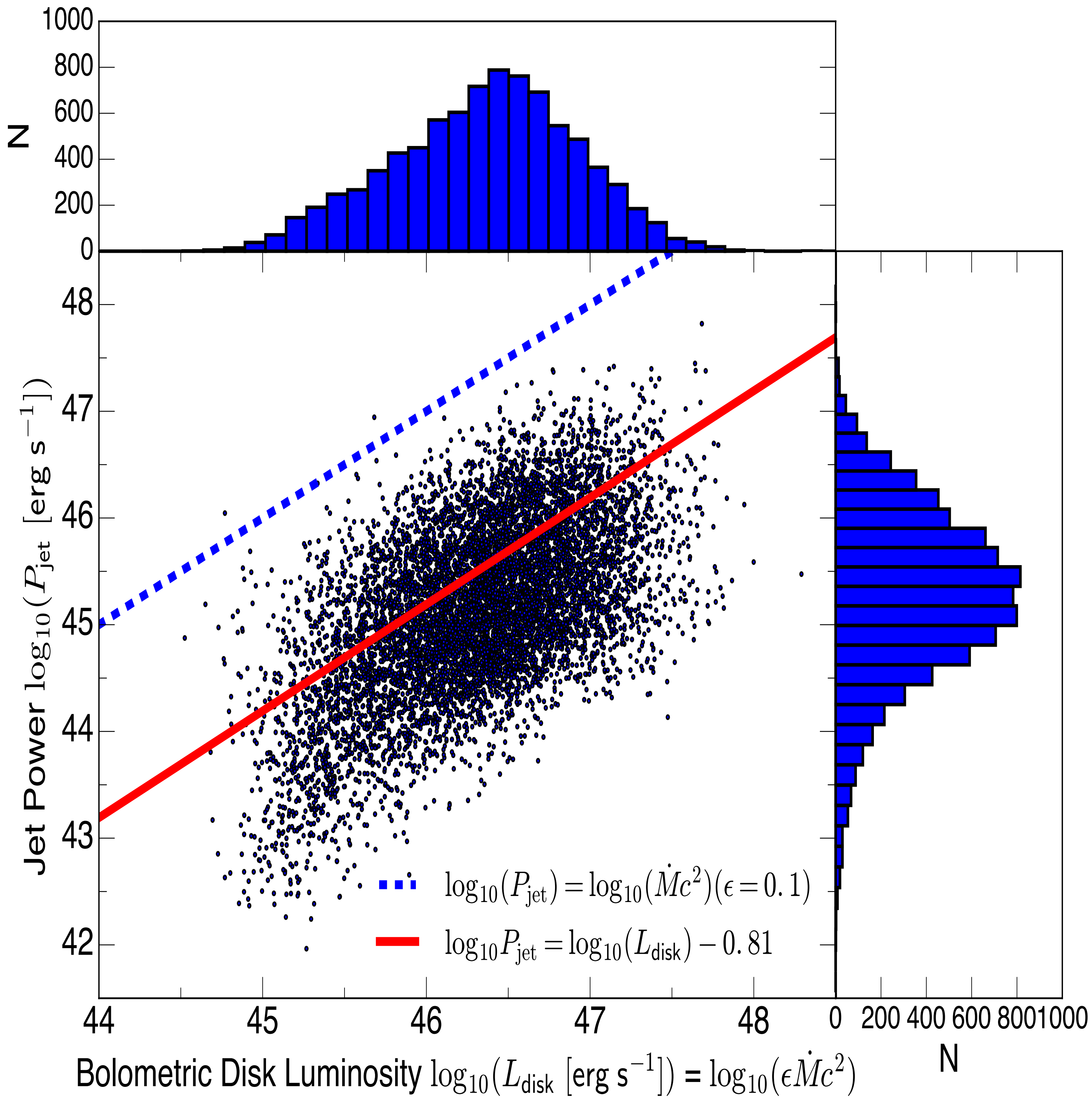


- an empirical relation between radio luminosity and jet power (Willott+'99)

$$P_{\rm jet} = 9.5 \times 10^{46} \left(\frac{f}{10}\right)^{3/2} \left(\frac{L_{151\ \rm MHz}}{10^{28}\ \rm W\ Hz^{-1}\ sr^{-1}}\right)^{6/7} \ [\rm erg\ s^{-1}],$$

- calibrated by X-ray cavity & hot spot measurements (Godfrey & Shabala '13).

Radio Quasar Jet Power



YI +’17

- SDSS-DR7 (Shen+’11)
- NVSS @ 1.4 GHz (Condon+’98)

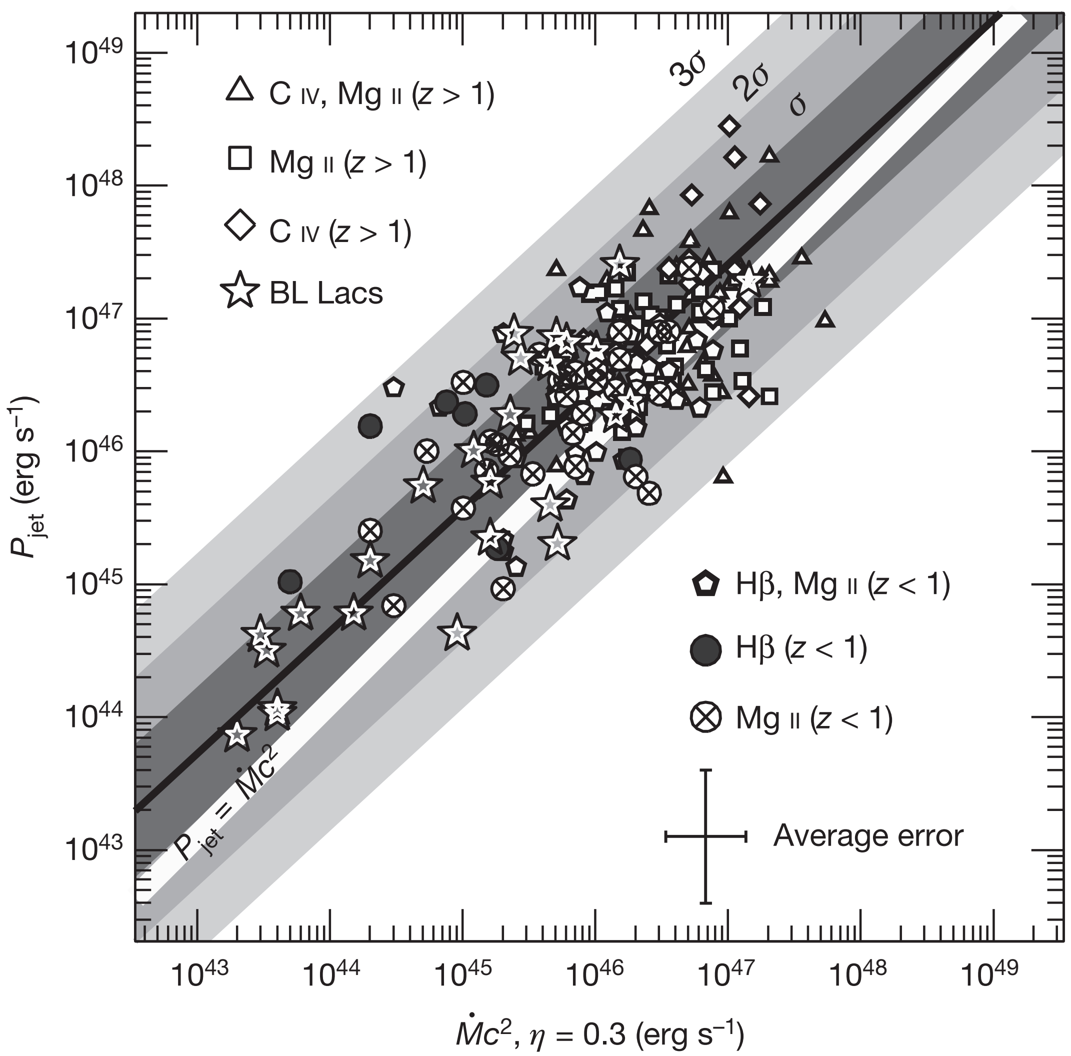
  ➡~8000 radio quasars

- Estimate jet power using the empirical relation
- Accretion rate from bolometric disk luminosity
  - disk radiative efficiency ε = 0.1
- Jet power moderately correlates with disk luminosity (YI+’17, see also Shankar+’08; Velzen & Falcke’13 using different sample)

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

AGN Jet Power

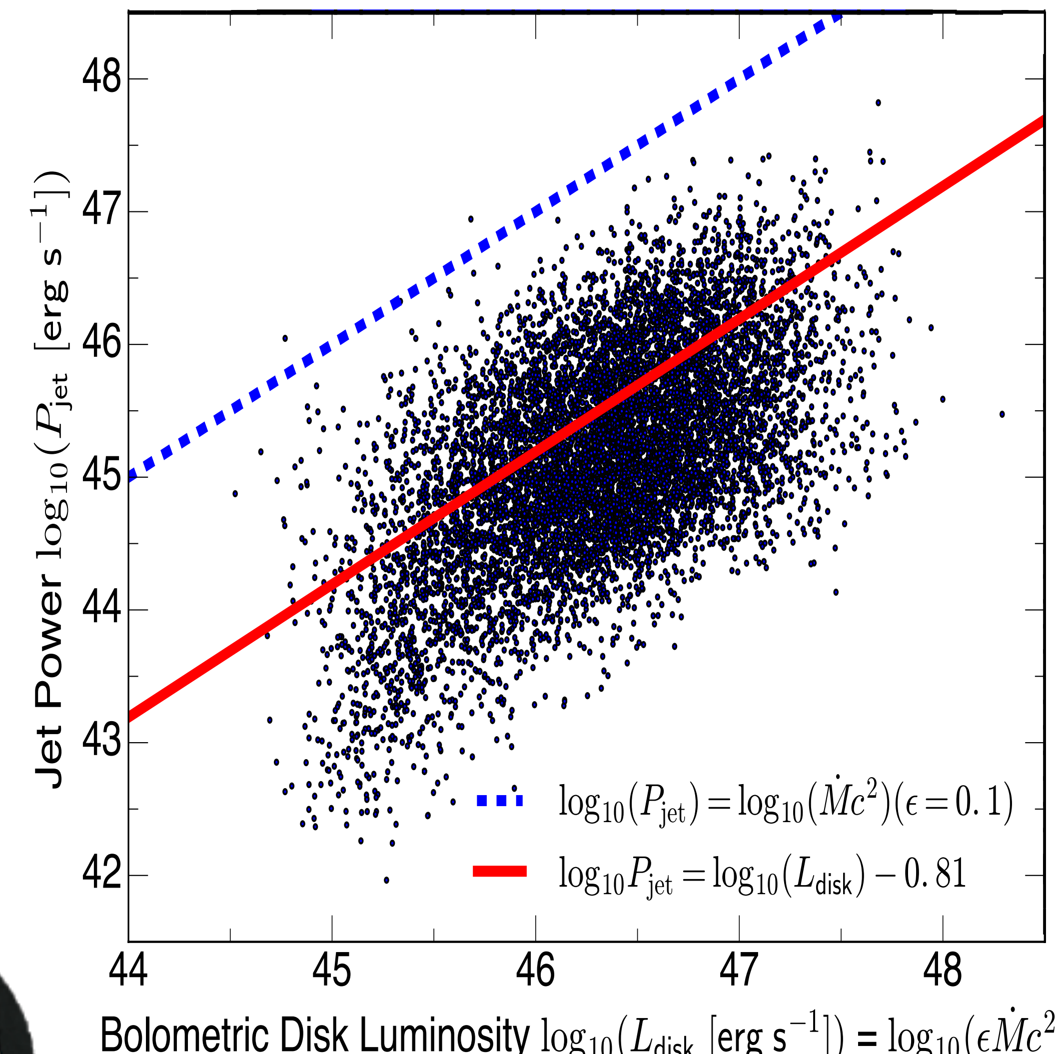
Blazar SED Fitting



Ghisellini+'14

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

Large-scale Jet



YI+'17

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

Causes of Discrepancy

Blazar SED Fitting

- Minimum electron Lorentz factor γ_{min} ~1
  - Observationally, γ_{min} <100~1000 (Kataoka & Stawarz'16)
- Jet composition
  - Pairs?
- Leptohadronic emission
  - More power?

Large-scale Jet

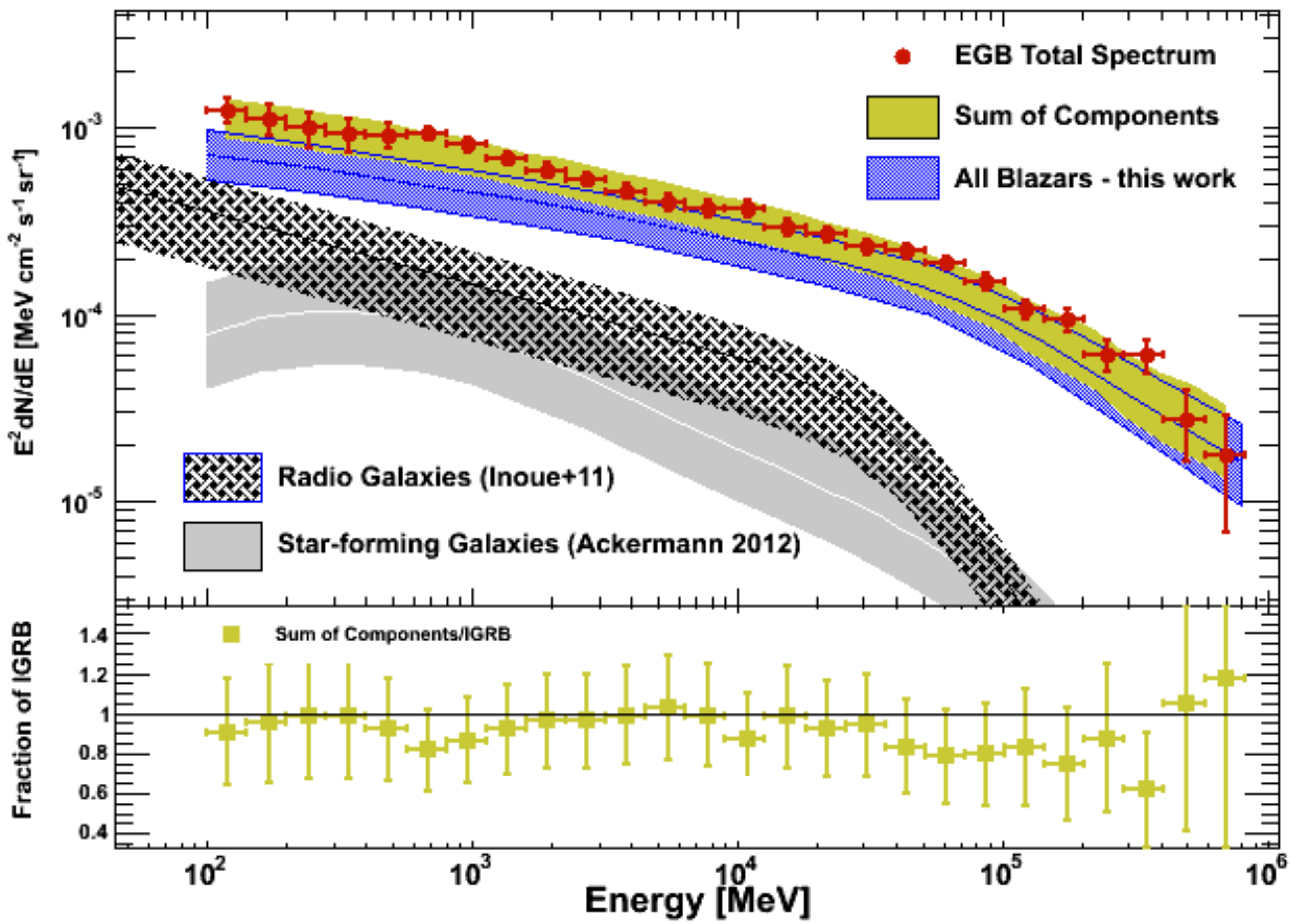
- Different timescales
- Empirical relation?

$$P_{\rm jet} = 9.5 \times 10^{46} \left(\frac{f}{10}\right)^{3/2} \times \left(\frac{L_{151\ \rm MHz}}{10^{28}\ \rm W\ Hz^{-1}\ sr^{-1}}\right)^{6/7}\ [\rm erg\ s^{-1}]$$

- Calibrated by Cavity?
  - role of shock?

Evolution of Blazars

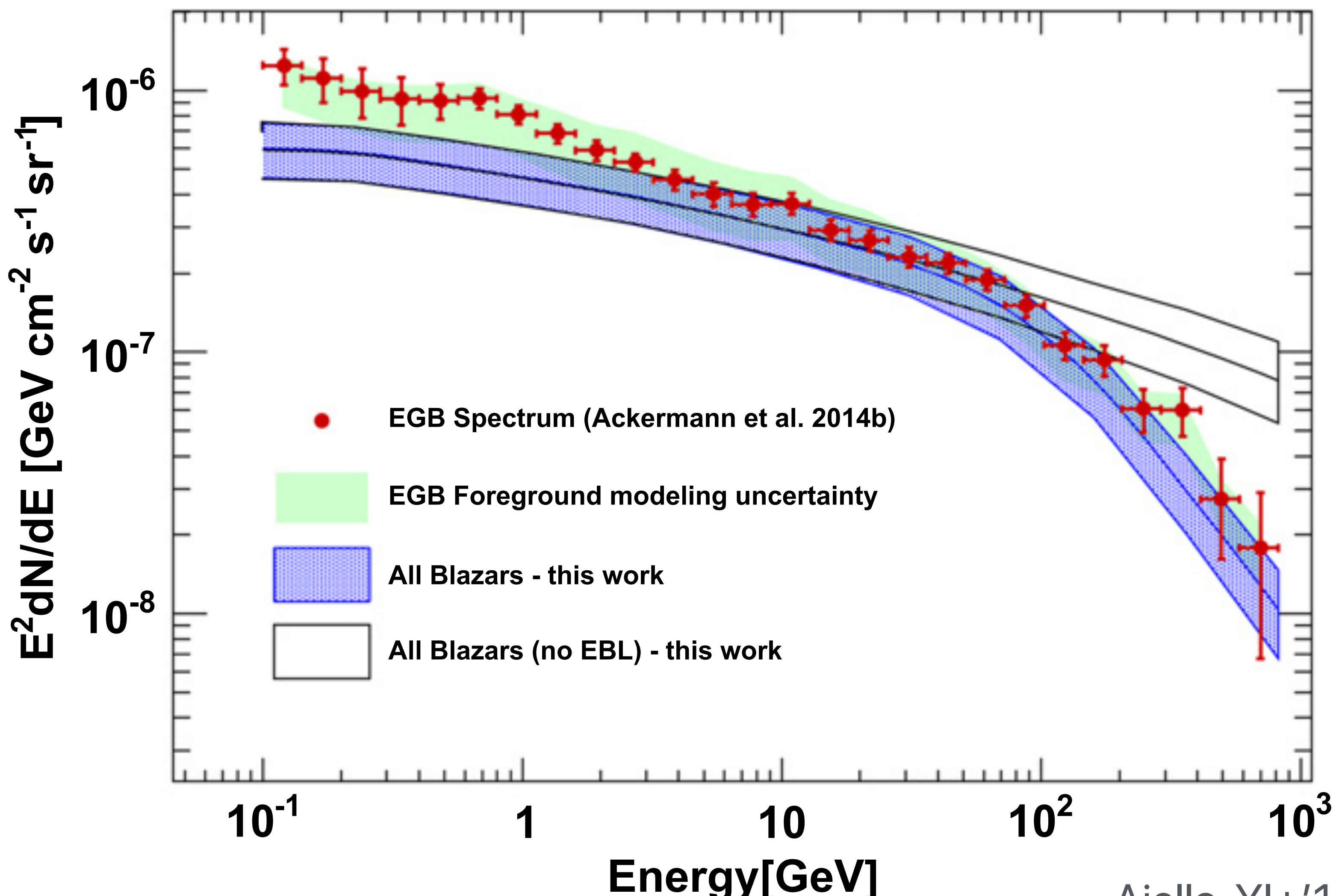
Components of Cosmic Gamma-ray Background



Ajello, YI +'15

- FSRQs (Ajello+'12), BL Lacs (Ajello+'14), Radio gals. (YI'11), & Star-forming gals. (Ackermann+'12) makes almost 100% of CGB from 0.1-1000 GeV.

Blazars in the Cosmic Gamma-ray Background

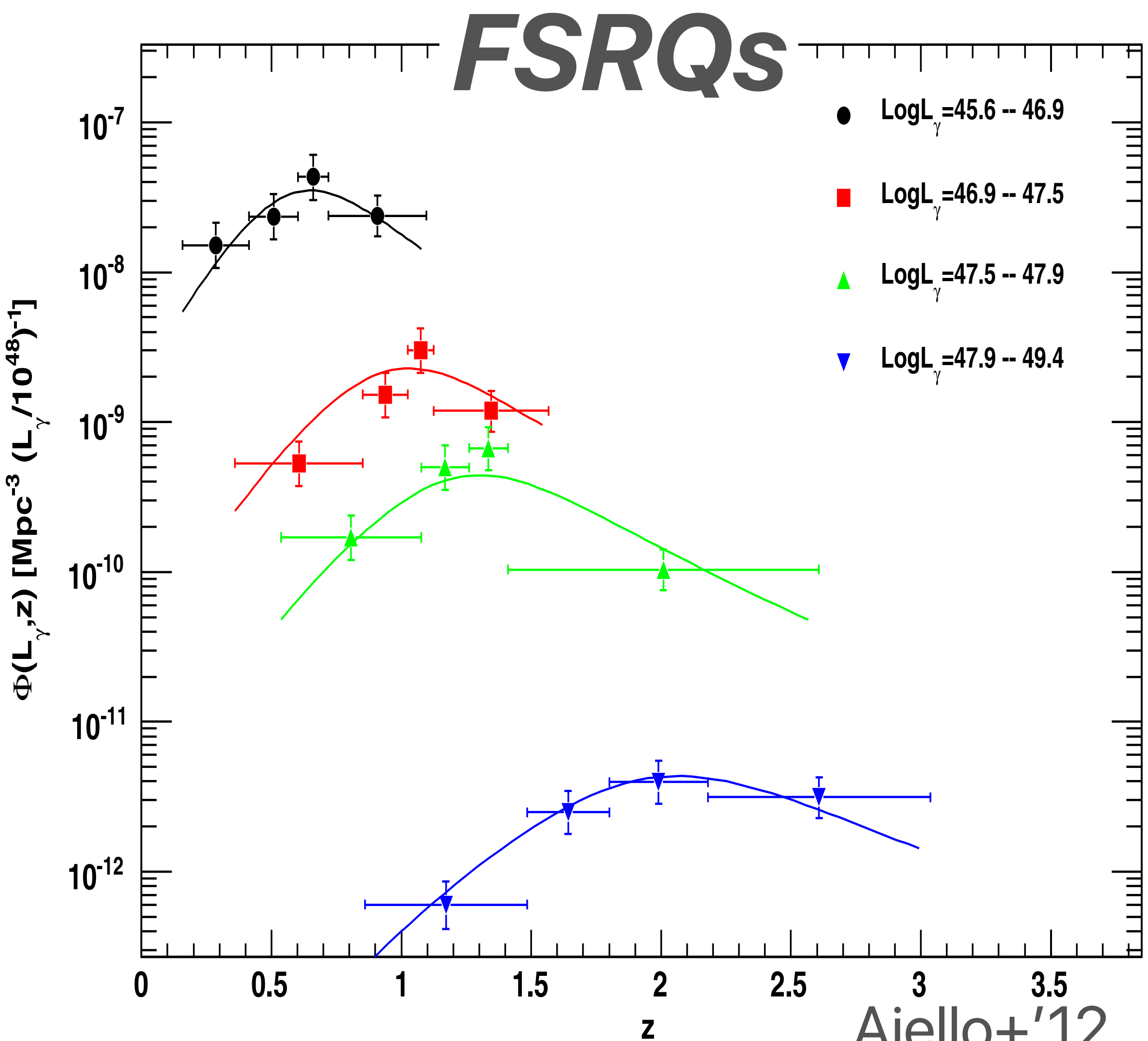


Ajello, YI+'15

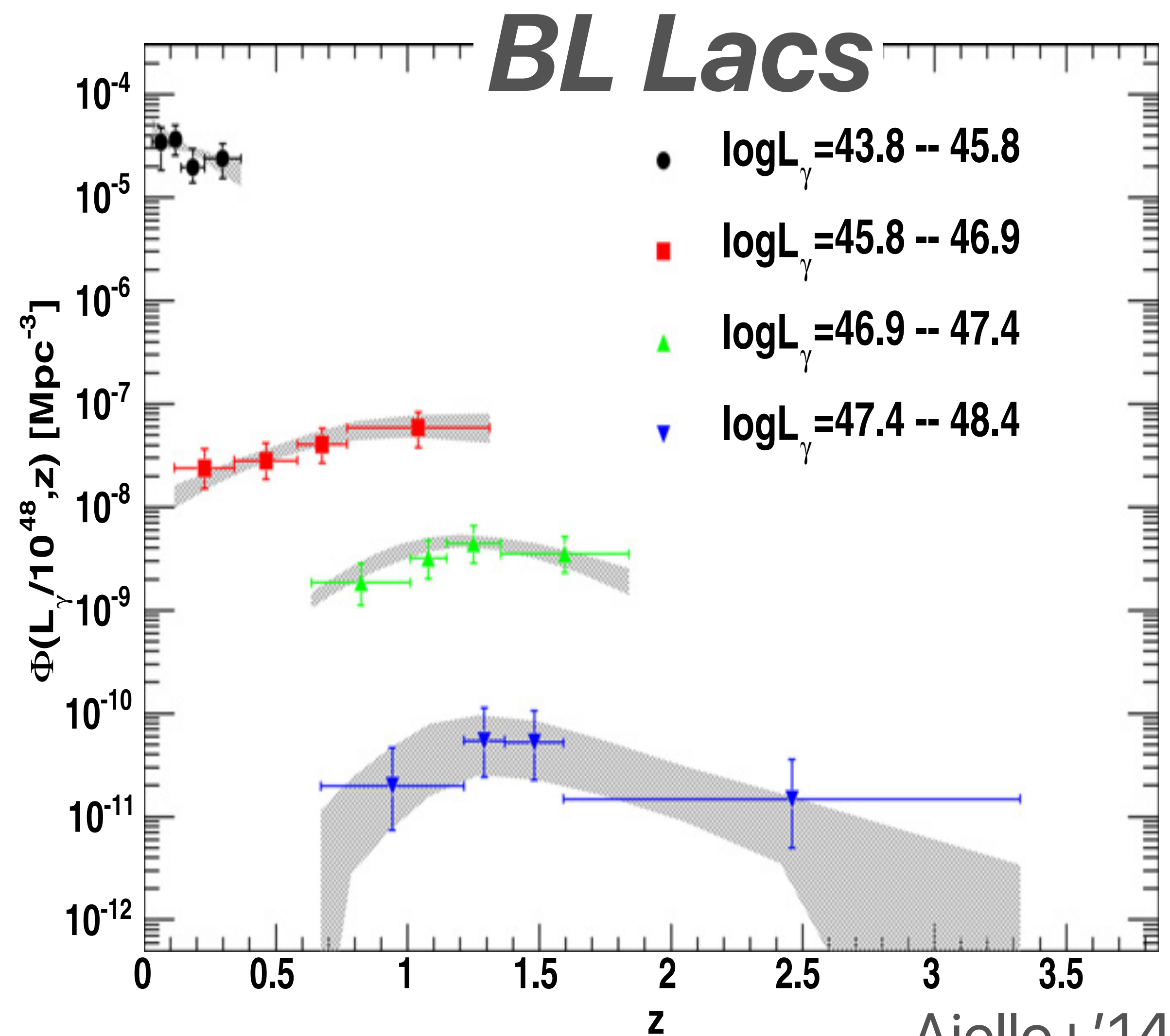
- Padovani+'93; Stecker+'93; Salamon & Stecker '94; Chiang + '95; Stecker & Salamon '96; Chiang & Mukherjee '98; Mukherjee & Chiang '99; Muecke & Pohl '00; Narumoto & Totani '06; Giommi +'06; Dermer '07; Pavlidou & Venters '08; Kneiske & Mannheim '08; Bhattacharya +'09; ***YI & Totani '09***; Abdo+'10; Stecker & Venters '10; Cavadini+'11, Abazajian+'11, Zeng+'12, Ajello+'12, Broderick+'12, Singal+'12, Harding & Abazajian '12, Di Mauro+'14, Ajello+'14,Singal+'14, Ajello, YI, +'15,

- Blazars explain ~50% of CGB at 0.1-100 GeV.
  - explain ~100% of CGB at >100 GeV.

Cosmological Evolution of Blazars



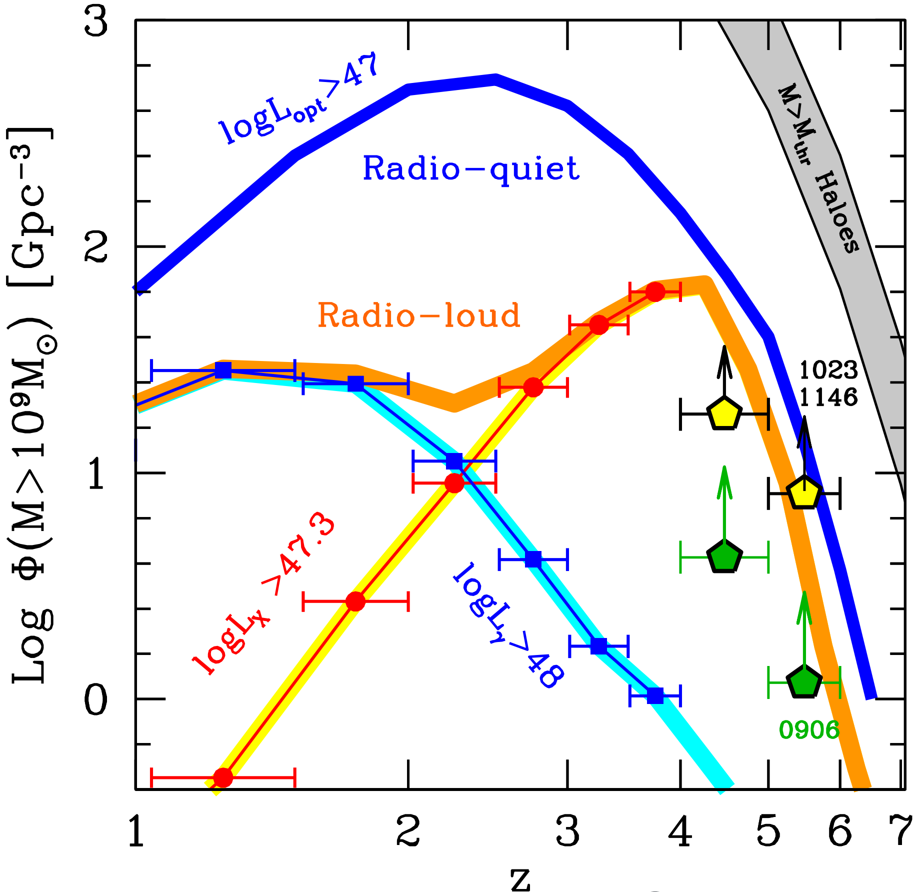
Ajello+'12



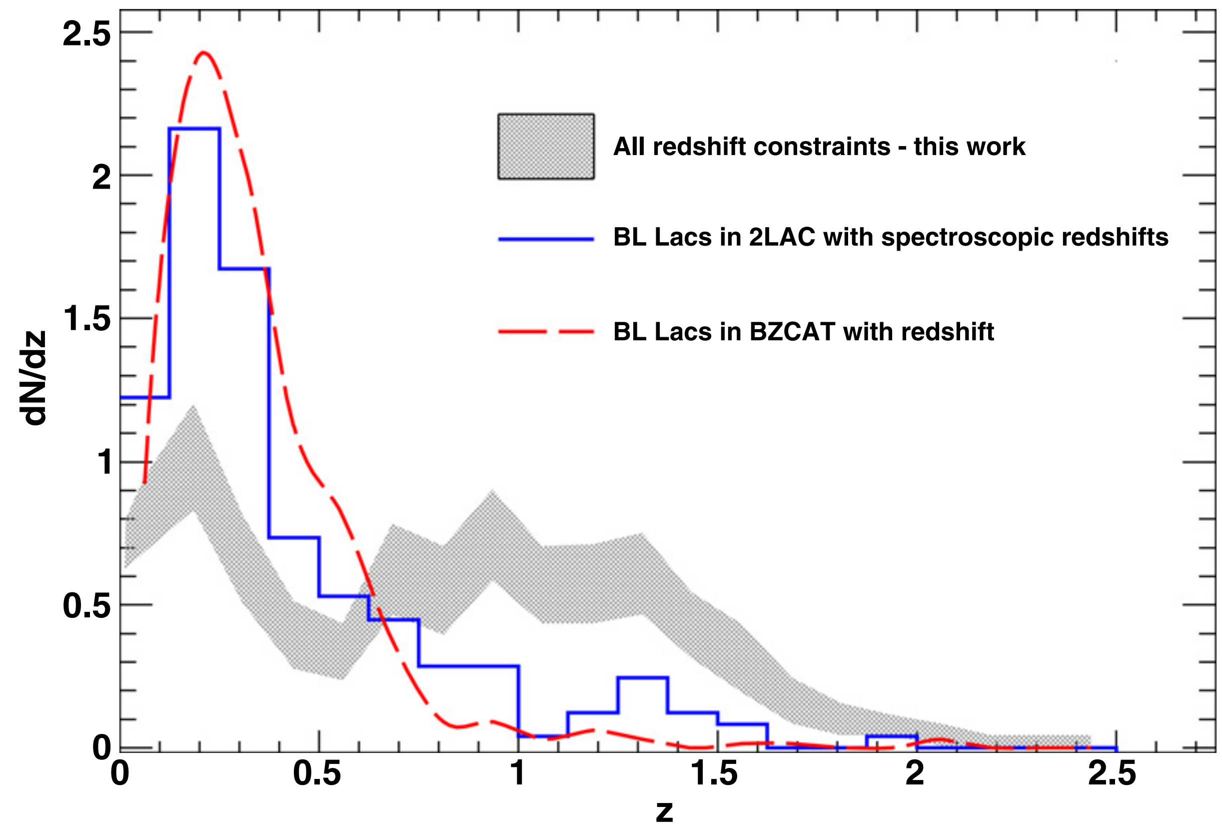
Ajello+'14

- FSRQs, luminous BL Lacs show positive evolution.
- low-luminosity BL Lacs show negative evolution unlike other AGNs.

Blazar evolution?



Sbarrato+'15

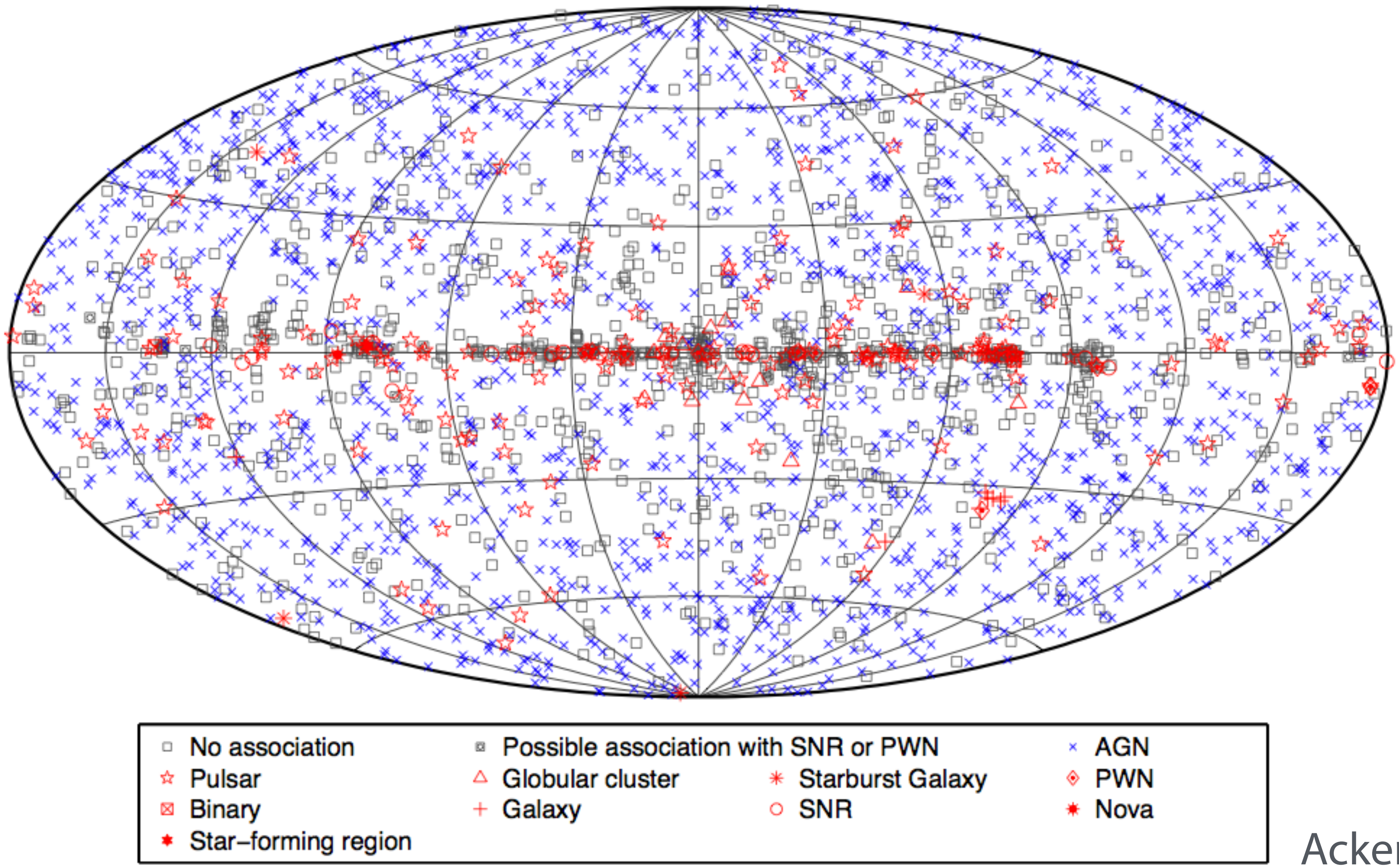


Ajello+'14

- Stronger evolution in X-ray selected blazars?
- Redshifts of 50% of Fermi BL Lacs are unknown.
  - ~10 hr exposure w/ 10-m telescope for TXS 0506+056

Other (recent) topics about blazars

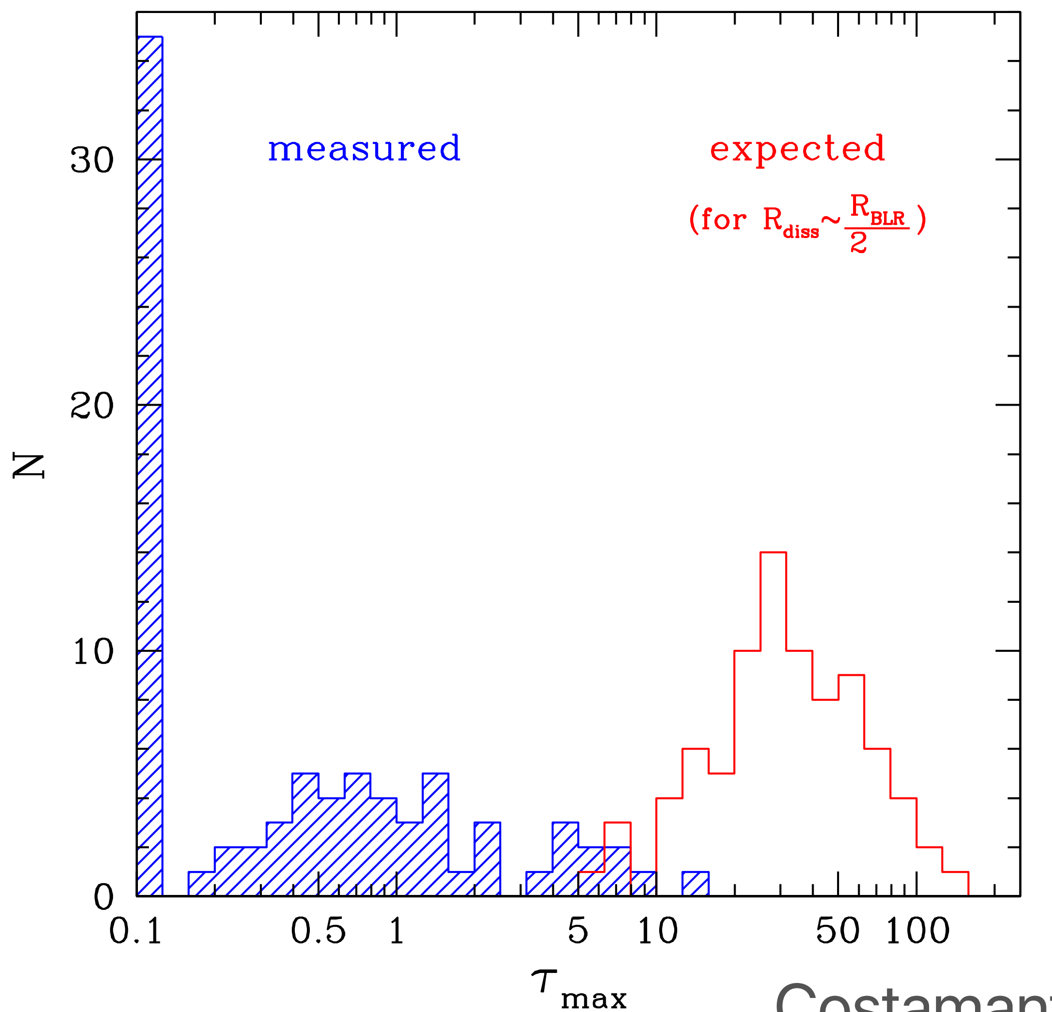
Golden Era for Blazar Studies



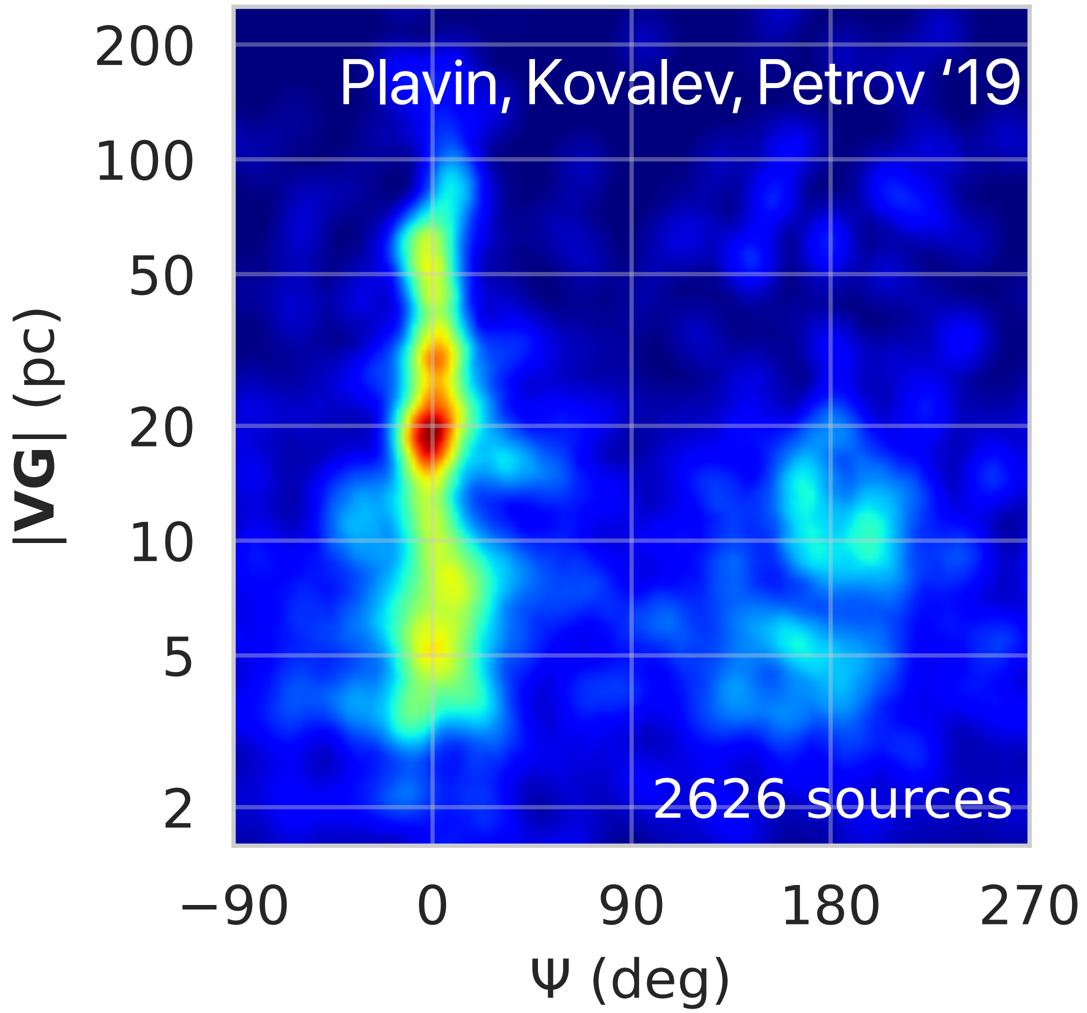
Ackerman+'15

- Fermi has detected 3033 sources in its 4-year survey.
  - 1591 AGN samples (467 FSRQs and 632 BL Lacs)

Location of Blazar Emission



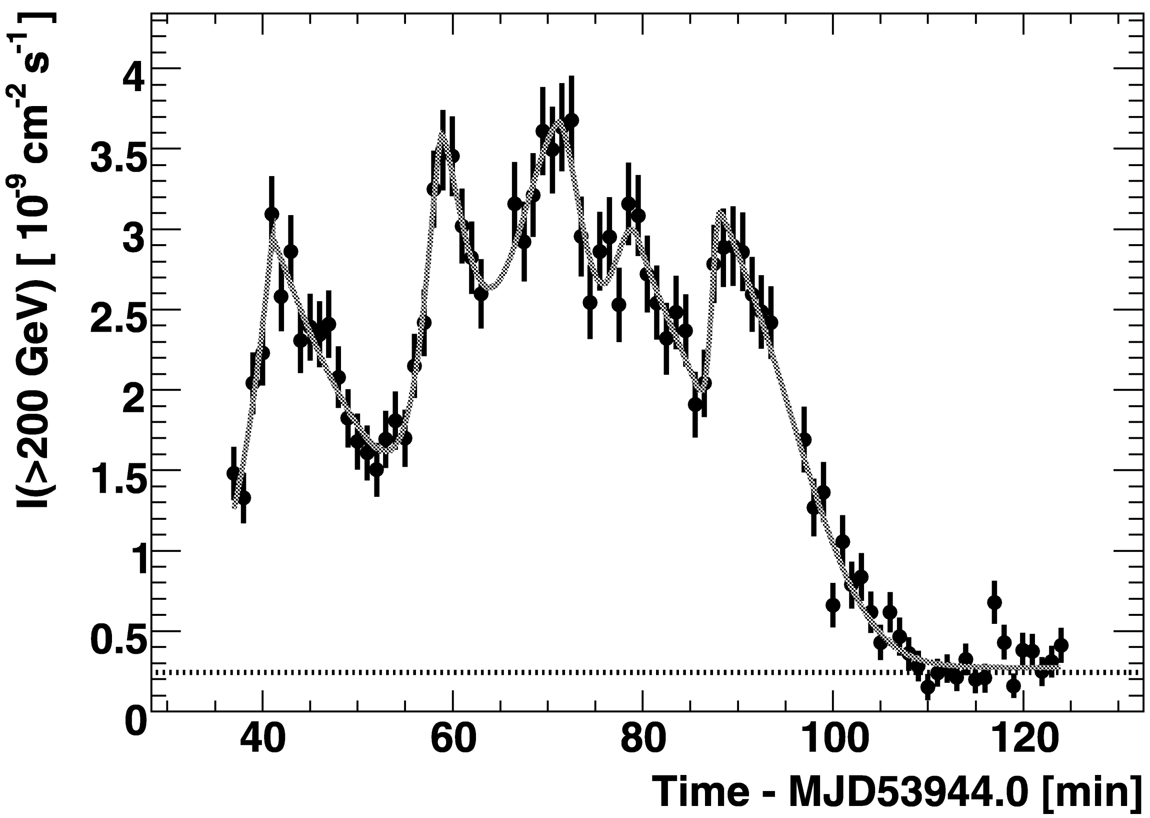
Costamante+'18



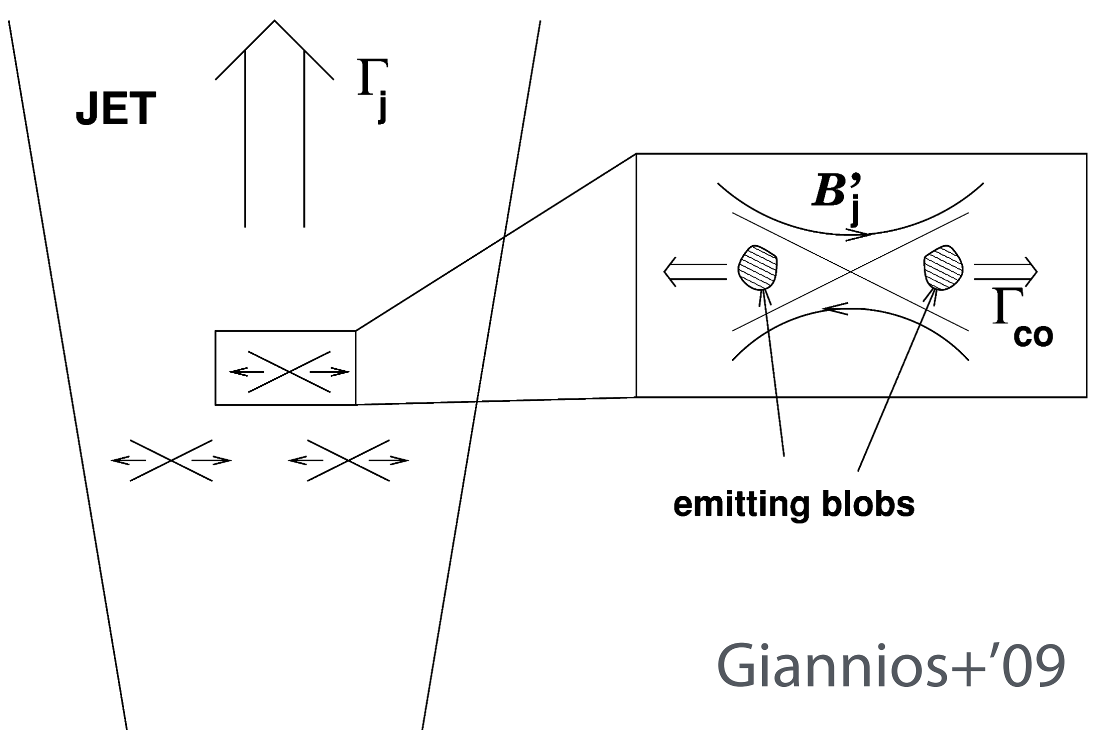
Offset relative to jet

- Lack of BLR photon attenuation signature in Fermi (gamma-ray) data (Costamante+'18)
- Gaia (optical) emission locates ~20-50 pc away from the VLBI (radio) core (Plavin, Kovalev, Petrov '19)

Short time Variability



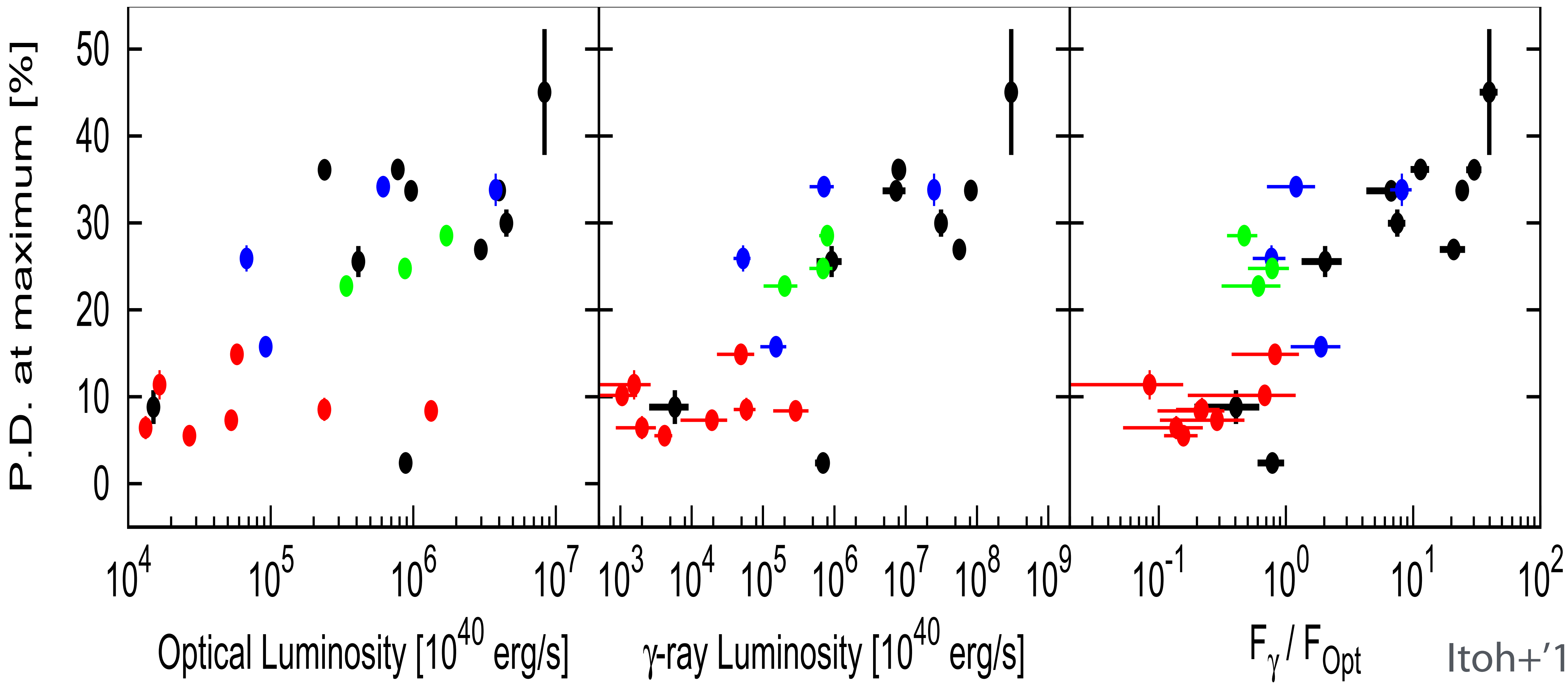
Aharonian+'07



Giannios+'09

- Fast variabilities ~200 s (Aharonian+'07, Albert+'08)
- requires very compact emitting region with Γ~100
- Jet-in-Jet (Giannios+'09) ?
- Star-Jet Interaction (Barkov+'12)?
- BH Magnetosphere (Aleksic+'14)?

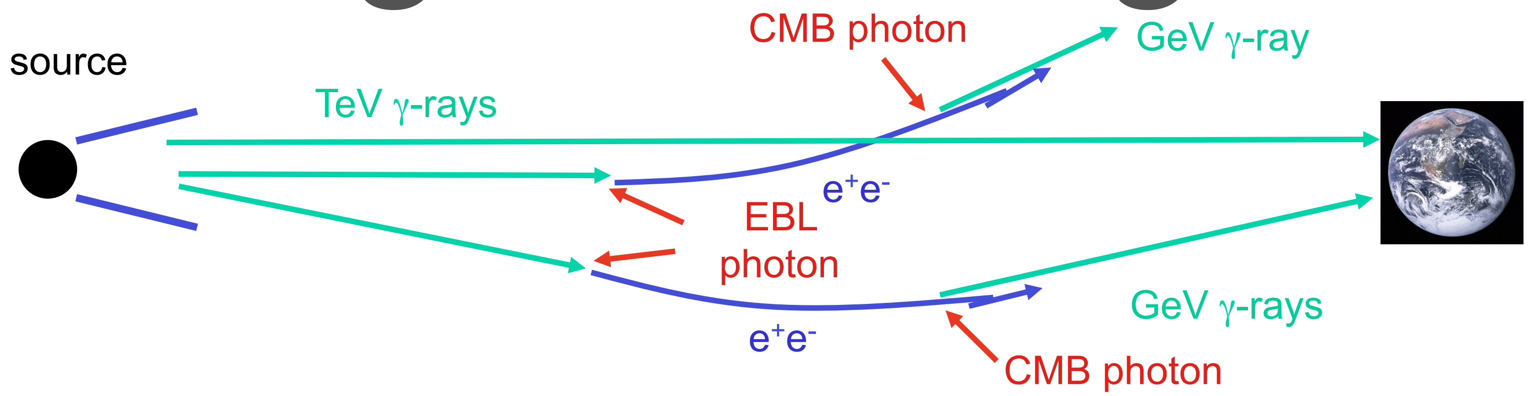
Polarization



Itoh+’16

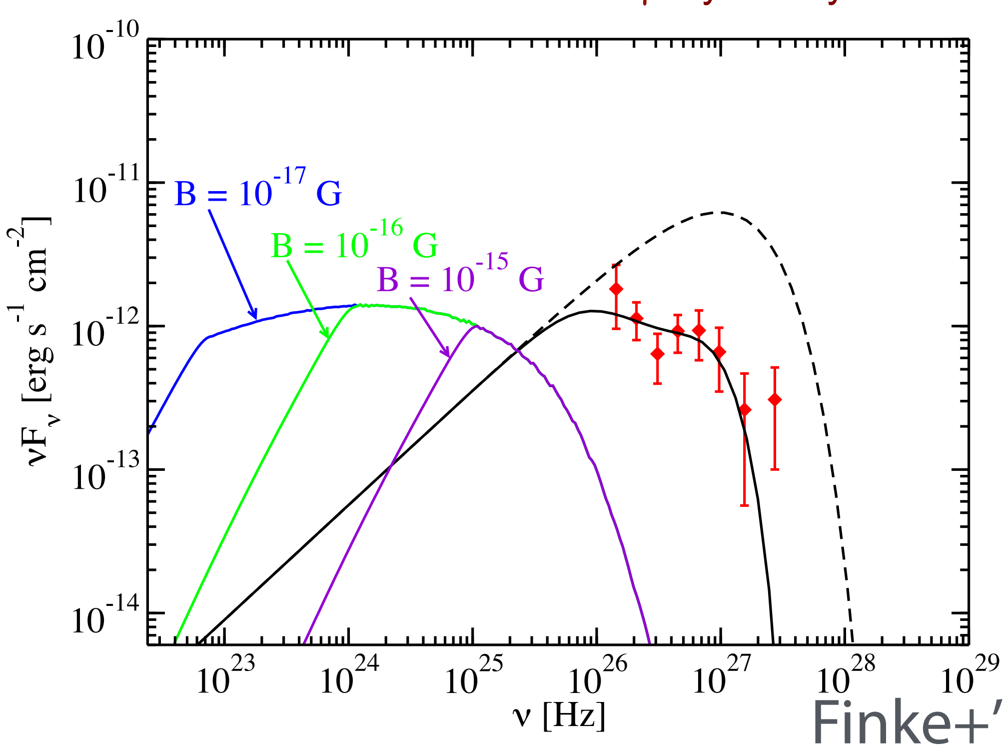
- Luminous blazars tend to show higher maximum polarization degrees.
  - Superposition of multiple emission regions in spine-sheath jet (Itoh+’16)?

Probing Intergalactic Magnetic Fields?

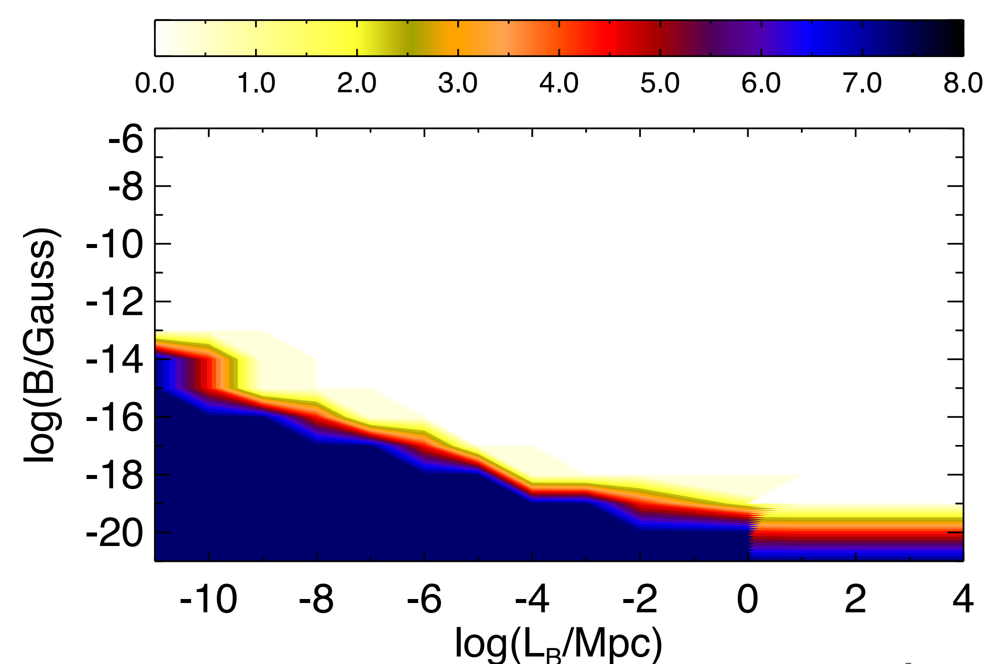


GeV γ-rays delayed due to slower e+e- speed and greater distance traveled

© J. Finke



Finke+'15



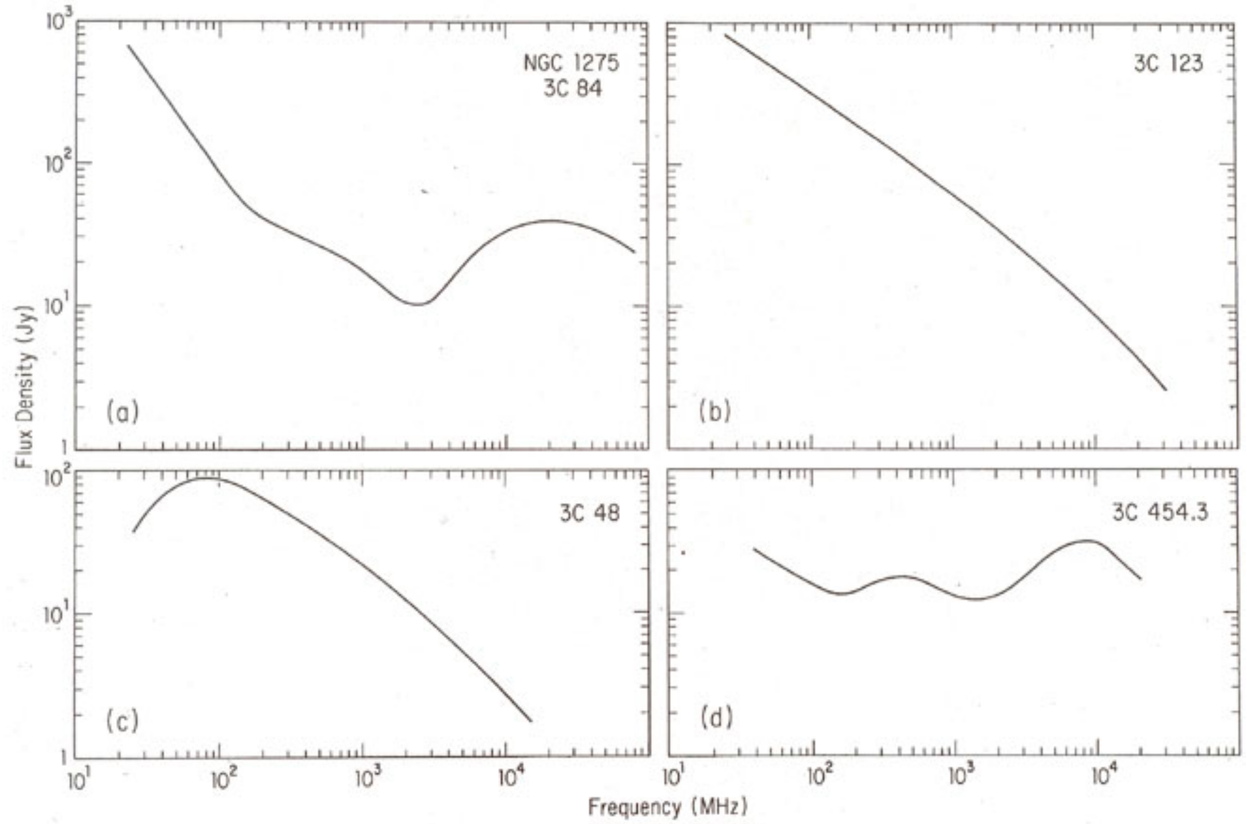
Finke+'15

- Delayed cascade emission and pair halos are probes of intergalactic magnetic fields (Plaga'95, Neronov & Semikoz '07, Ichiki+'08,....)
- Current constraint rules out low B values, $B<10^{-19}$ G for $L_B > 1$ Mpc (Finke+'15).

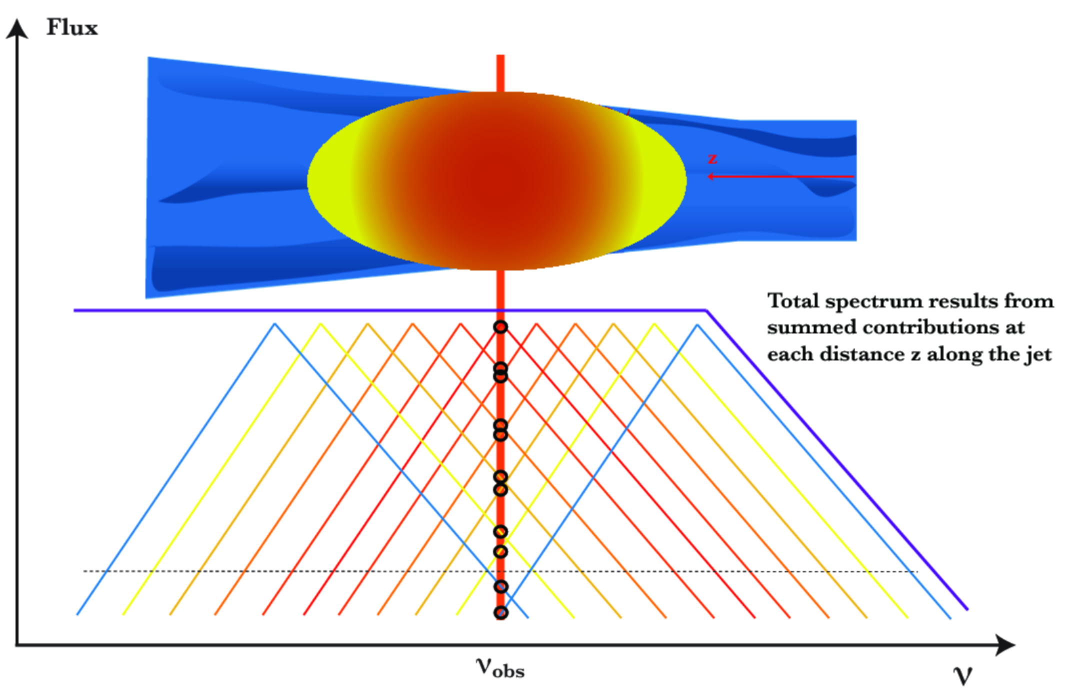
Blazars?

Blazars in radio band

Radio spectra of radio galaxies and blazars (Longair 2011)

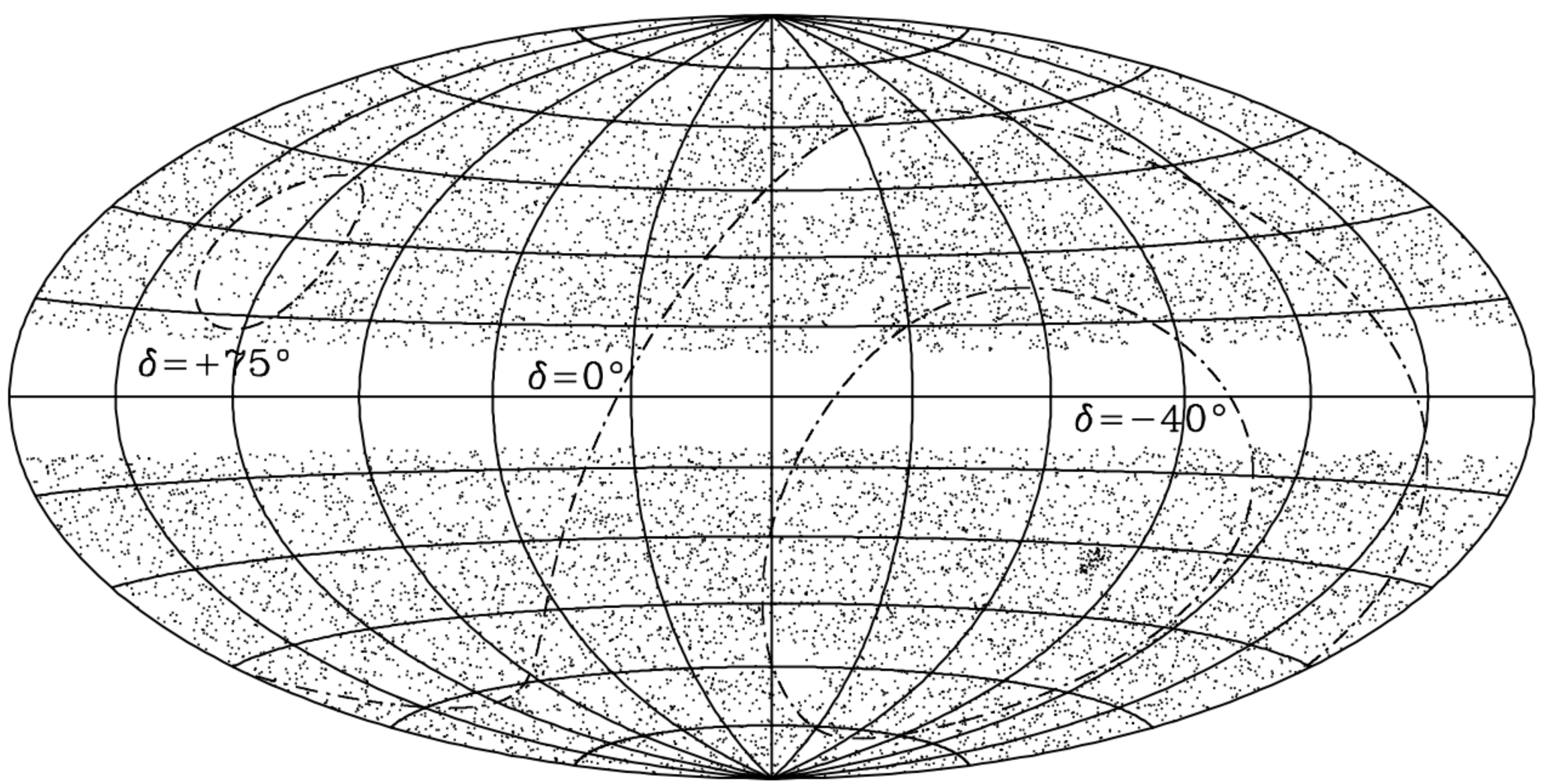


- Compact and flat spectrum of α> -0.5 ($F_\nu \propto \nu_\alpha$)
- Flat radio spectrum is caused by superposition of self-absorbed synchrotron emission regions (e.g., Markoff+10)
- **Flat radio spectrum is the key to select blazars**

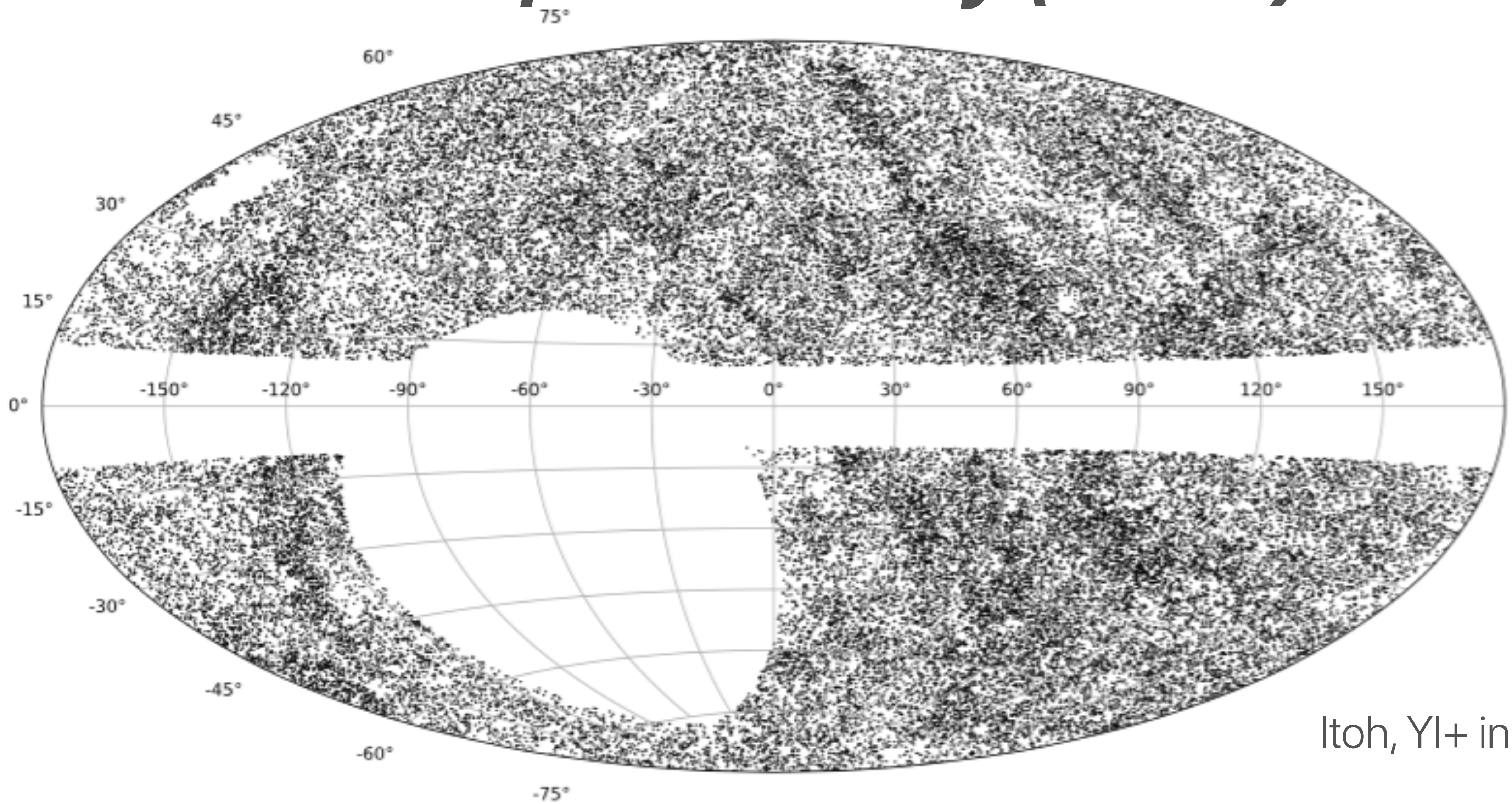


CRATES blazar candidate catalog (Healey et al. 2007)

- Flat radio sources at 1.4 GHz, 4.8 GHz and 8.4 GHz using NVSS, GB6, and VLA archives
- 11131 sources with $F_{4.8GHz}$ > 65 mJy and located at |b|>10 deg
- It has been used to identify Fermi MeV/GeV blazars and unIDs at high Galactic latitude



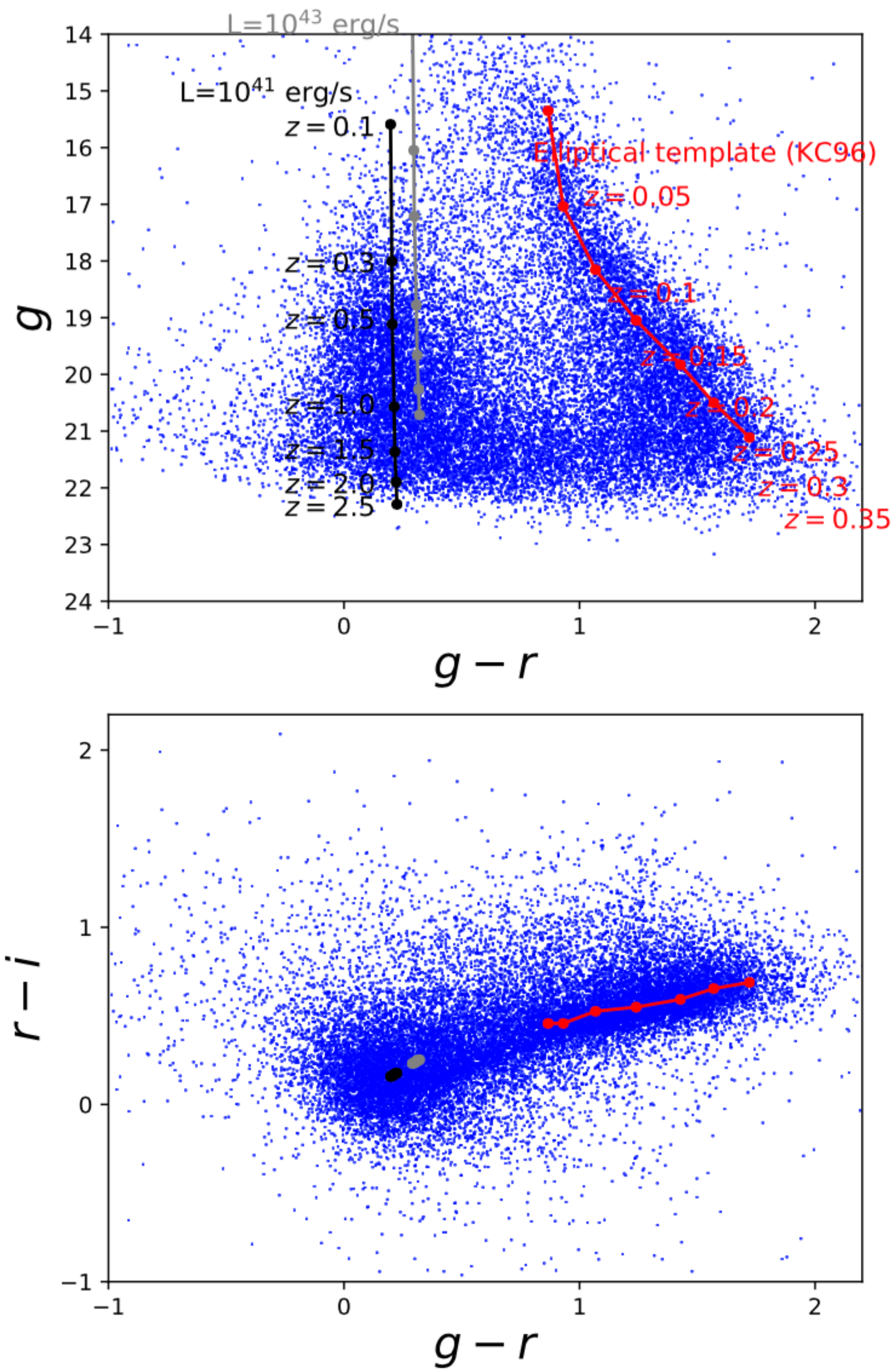
Blazar Radio and Optical Survey (BROS) Catalog



Itoh, YI+ in prep

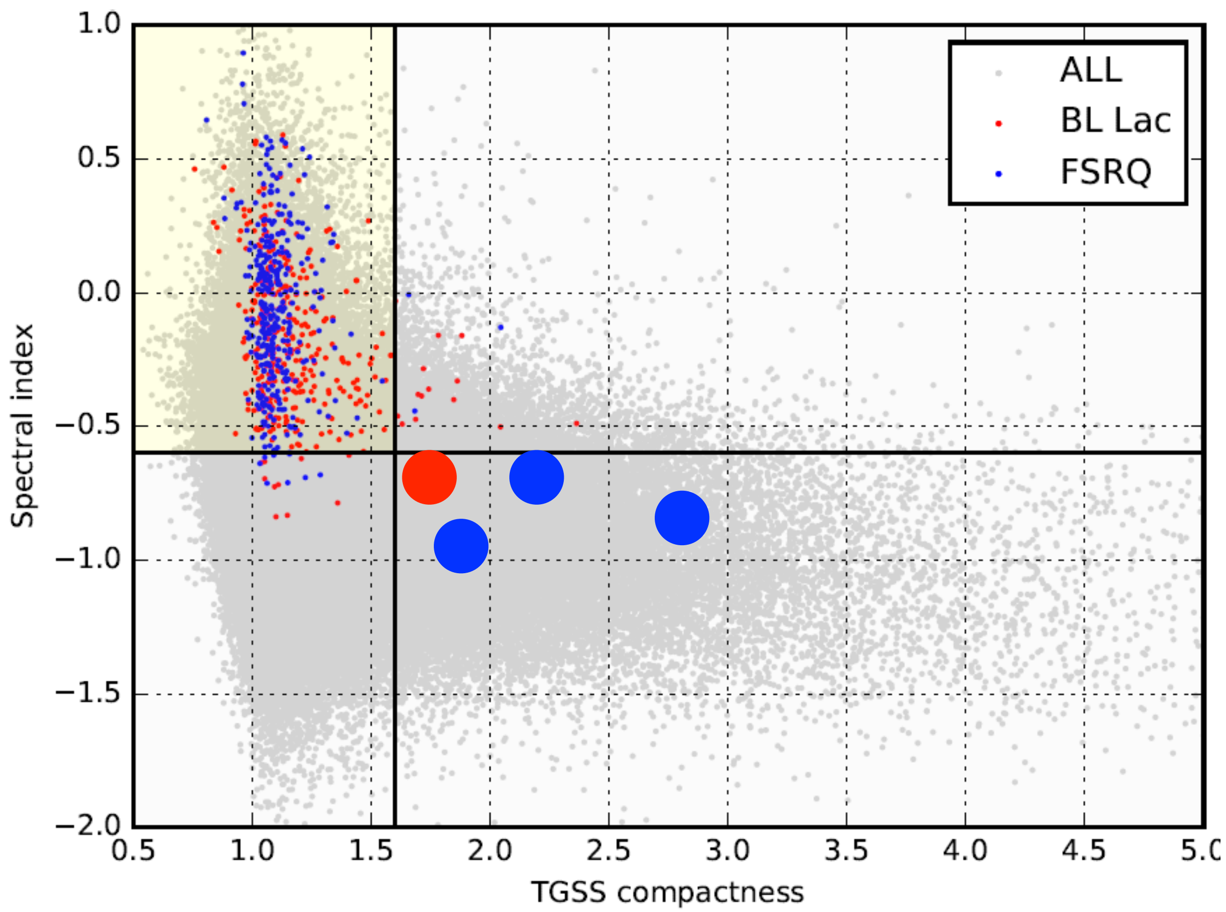
- A new blazar candidate catalog. (Itoh, YI+ in prep.)
  - NVSS-TGSS-PS1
  - >50,000 blazar candidates
    - ~35,000 with optical photometry data

Optical Color



- 2 populations are present:
  - ✓ Quasar-like (including blazar population)
  - ✓ Elliptical galaxy-like
- Elliptical galaxy templates of M=-21.5 at z<~0.3 well represents the "elliptical sequence"

What are blazars?



Itoh, YI, + in prep.

- Blazars are compact and flat spectrum in radio.
- Cross-matching with Fermi detected blazars
    - Some Fermi blazars are soft and extended in radio.

Summary

- Blazars may be neutrino emitters.
  - But, we should be careful about their energetics.
- ~50% of Fermi blazars do not have redshift information.
- Blazar emission region may be far away (>20 pc).
- Some blazars show extended structures and soft spectra.
  - What are blazars?