Probing CO-dark Gas and Blazar Jet Power with ALMA Calibrators: Toward the Origin of High-Energy Neutrinos

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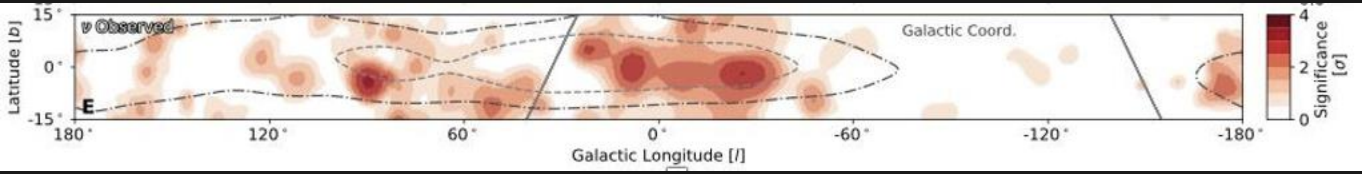
Where do high-energy neutrinos come from?

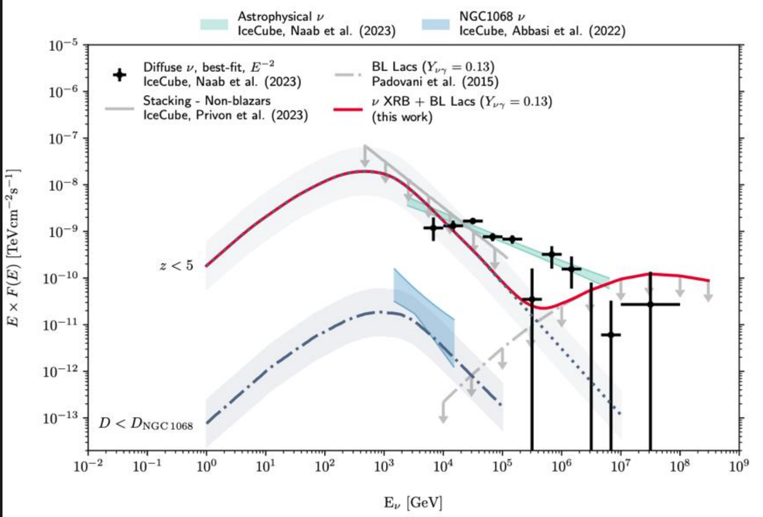
- IceCube detects astrophysical neutrinos at TeV–PeV energies
- Galactic
  - Diffuse neutrino emission from the Galactic plane



IceCube Collaboration (2023), Science, 380, 1338

- Extragalactic
  - Nearly isotropic diffuse neutrino flux
  - Neutrino associations with blazars, such as TXS 0506+056
  - Jetted AGNs may contribute? (E > PeV)

(e.g., Padovani 2024)



Padovani 2024

Two Ingredients for High-Energy Neutrino Production

- Hadronic neutrino production requires both efficient particle acceleration and a target for interaction.

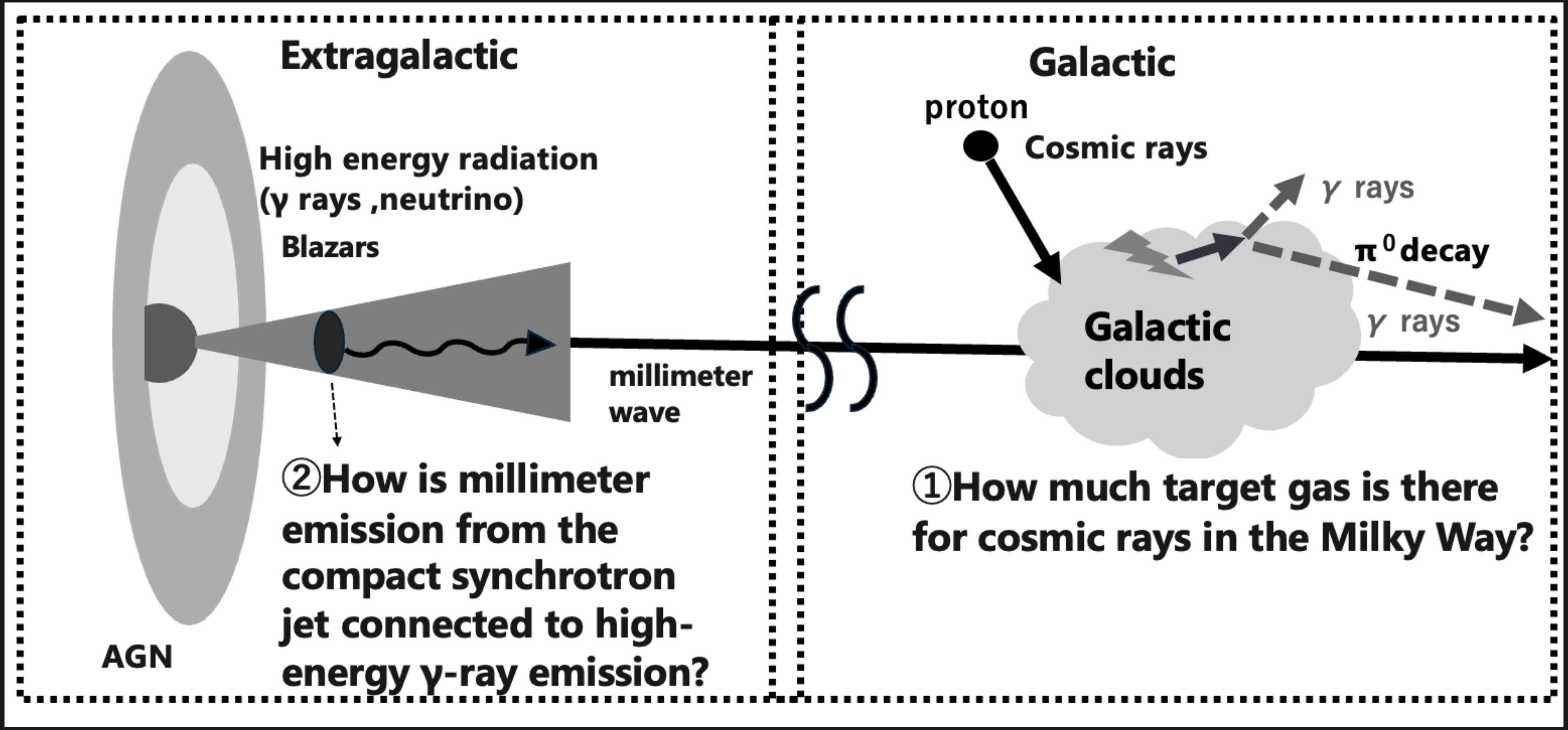
$$p + p \text{ or } p + \gamma \rightarrow \pi^{\pm} \rightarrow \nu$$

- Galactic - A complete census of target gas is needed (Part 1)
  - CO emission can miss diffuse / CO-poor gas
  - What is the hidden molecular gas?

- Extragalactic - A population approach is needed (Part 2)
  - Blazar jets are promising sites of high-energy particle acceleration
  - Individual neutrino–blazar associations remain challenging due to limited statistics and angular localization
  - A population-level view of blazar jets is therefore needed, with millimeter emission probing the compact jet close to the jet base

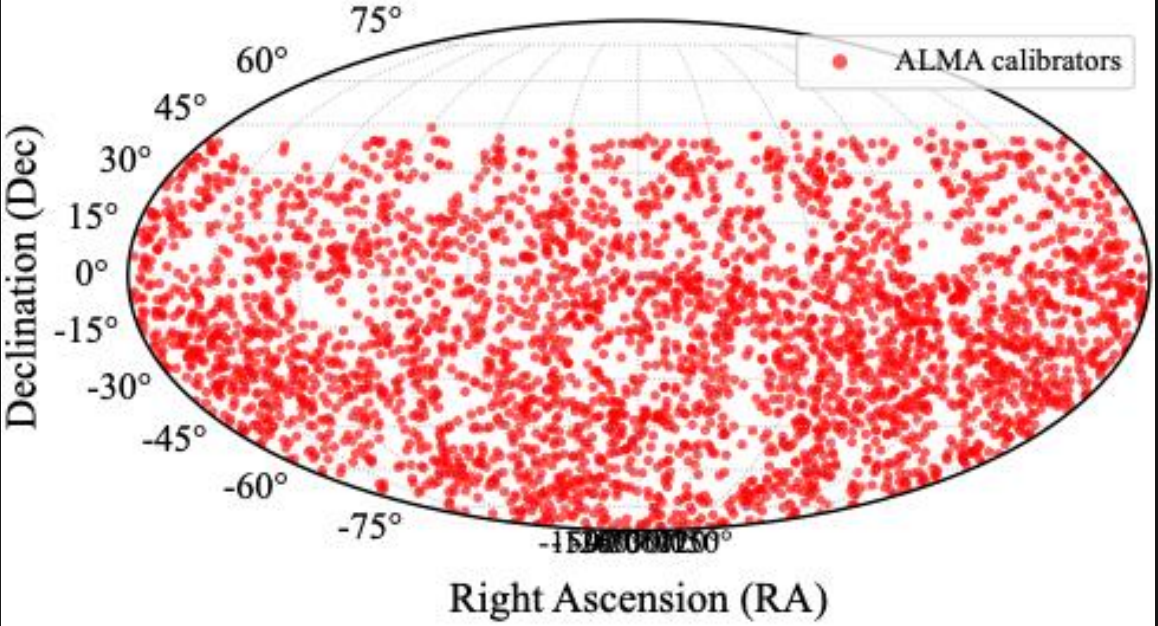
Milli-Meter blazars as a ideal laboratory

- The same mm blazars probe both jet environment and foreground target material.



A New Approach: ALMA Calibrator Data

- **Atacama Large Millimeter/submillimeter Array (ALMA)**
- **Exploiting more than a decade of ALMA archive data**
  - A large, homogeneous, and systematically observed sample of >3,000 compact sources
  - ALMA calibrators are predominantly bright blazars, including γ-ray-detected sources, with typical continuum flux densities of several hundred mJy to a few Jy.

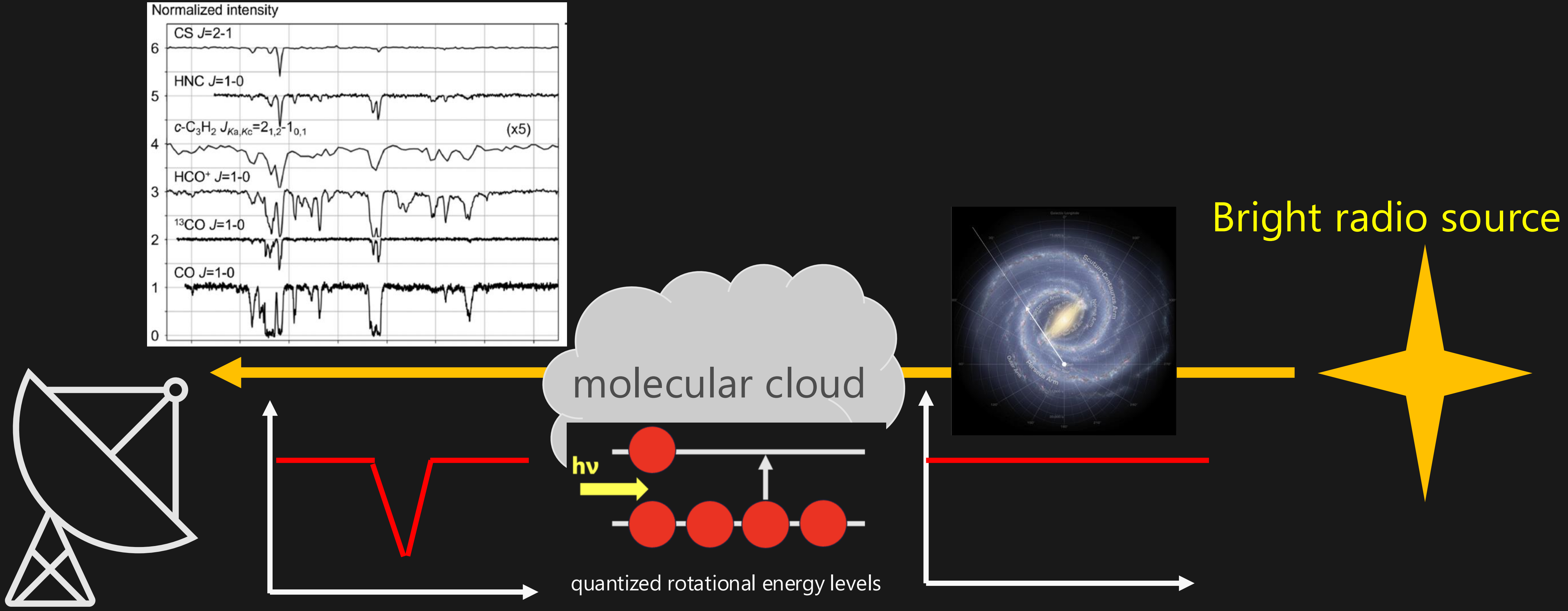


Part I : Target Material

Kanako Narita et al 2024 ApJ 969 102

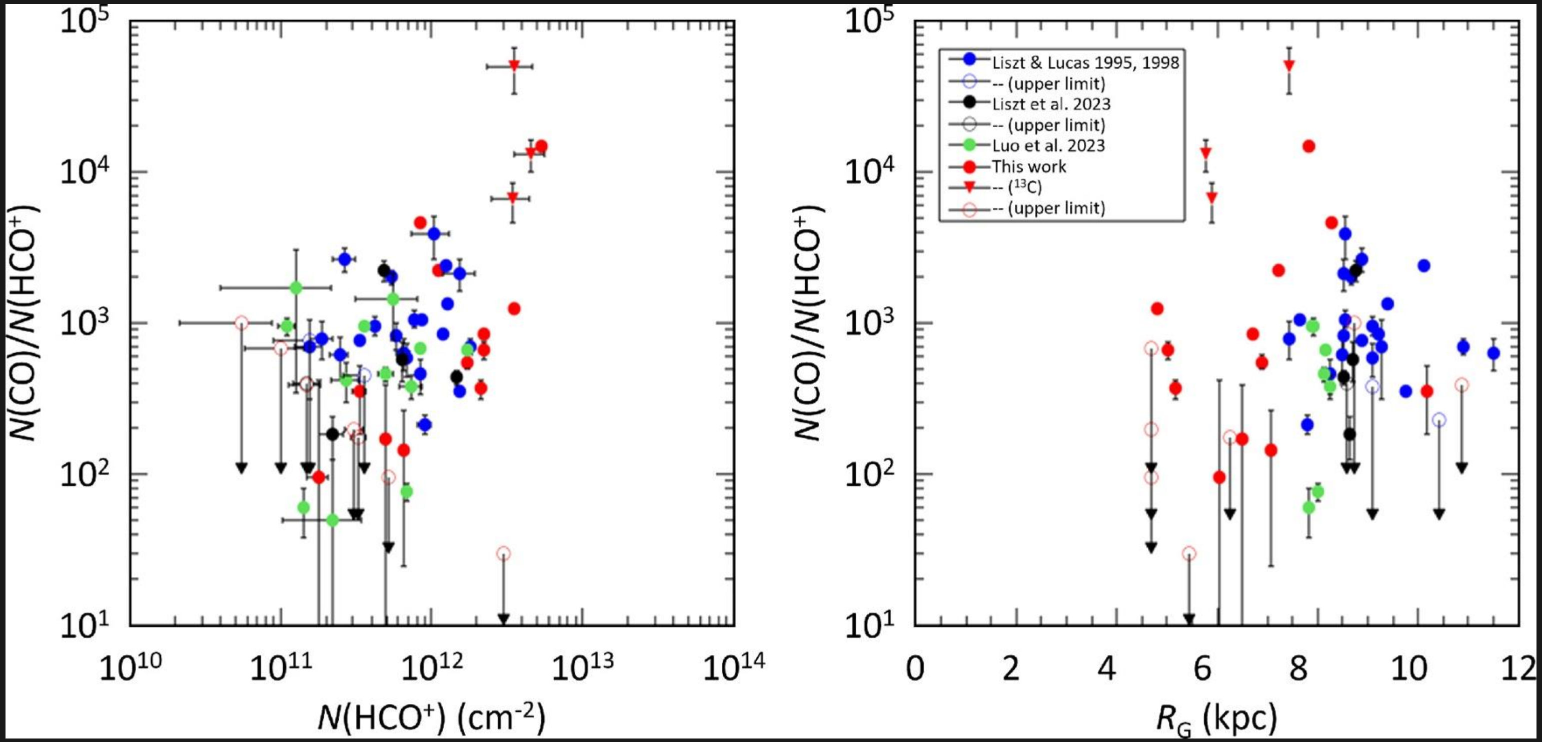
Observing Diffuse Interstellar Molecular Gas

- High extinction toward QSO J1851+0035: $A_V = 78.59\text{mag}$
- **Exploration of the inner galaxy! Sampling about 20 clouds!**



A large CO/HCO^+ ratio implies CO dark (CO poor) gas

- **HCO+ is a one of good tracer of H_2**
- **A scatter in the CO/HCO^+ ratio spanning three orders of magnitude**
- **No dependence on distance from the Galactic center**



Narita +24

^{13}CO Emission Can Underestimate H_2 in CO-poor Gas

- **Assume**
  - LTE
  - optically thin (^{13}CO)
  - beam-filling (f = 1)
  - canonical abundance

- **Convert**

$$T_{mb} \cancel{\rightarrow} T_{ex} \cancel{\rightarrow} N(^{13}CO) \cancel{\rightarrow} N(H_2)$$

a potential underestimation of the H_2 column density by several orders of magnitude

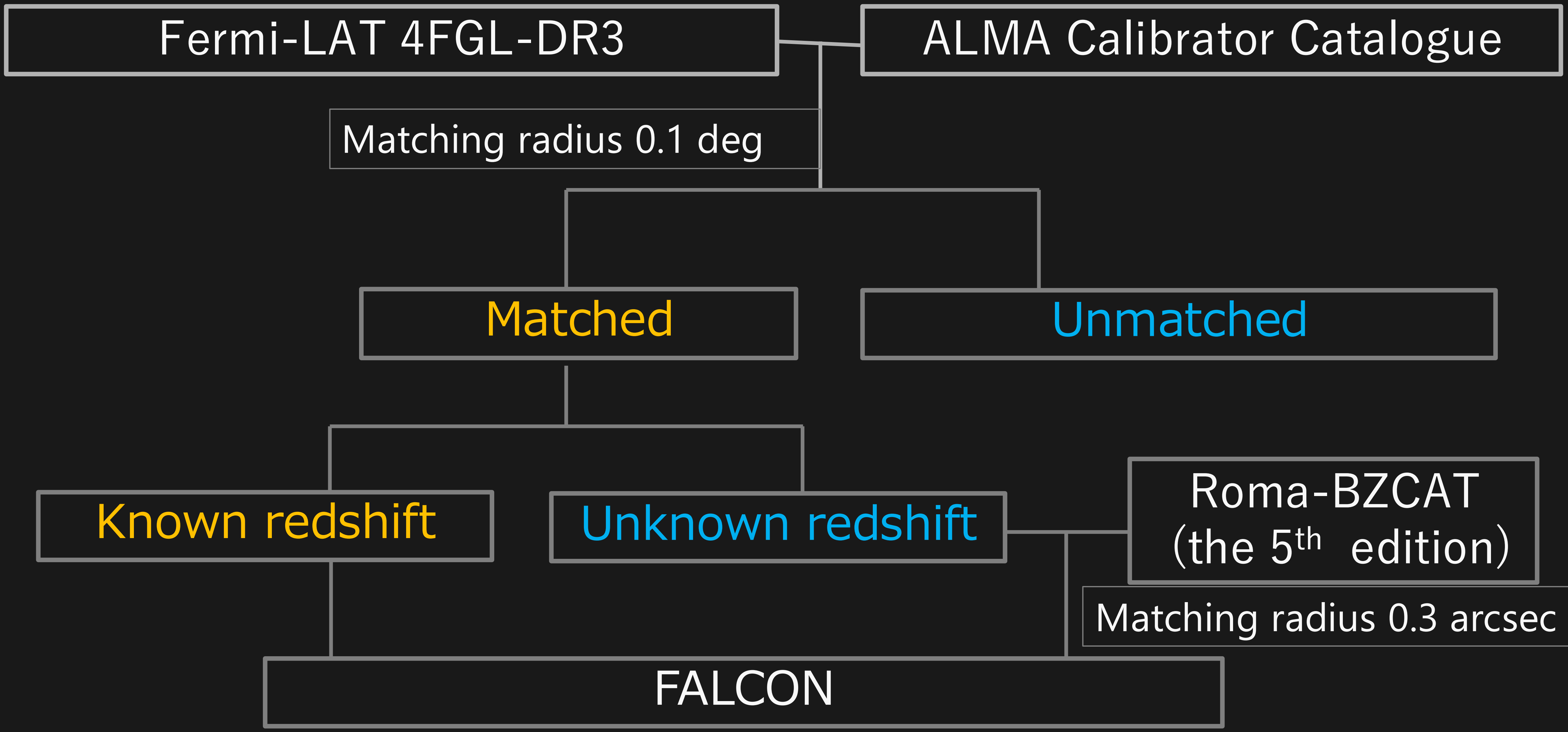
Part II : Blazar Population

Kanako Narita et al submitted to ApJ

Why a Population Study of Blazar Jets?

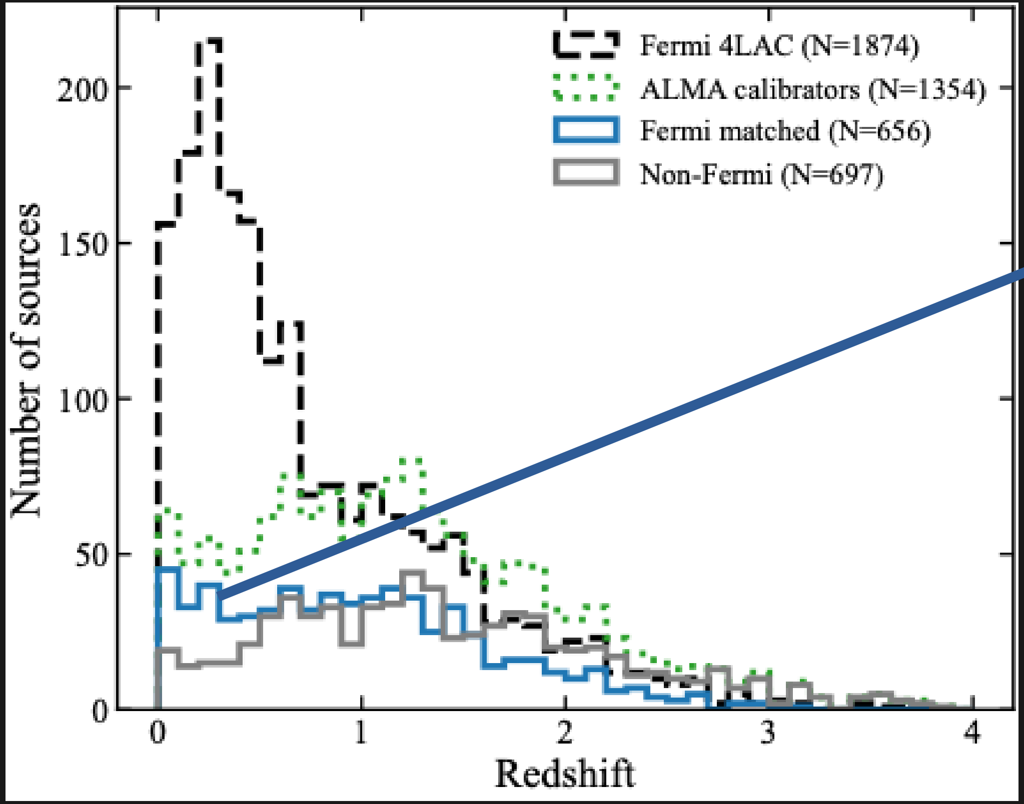
- **Individual neutrino–blazar associations exist**
  e.g., TXS 0506+056
- **No significant correlation in blazar stacking analyses**
- **Are neutrino-emitting blazars a special subset?**
- **Characterize blazar populations through the mm–γ connection**
  - **mm:** compact synchrotron-emitting jet
  - **GeV γ-rays:** high-energy activity
- **Cross-match ALMA calibrators with Fermi-LAT sources**
  → FALCON

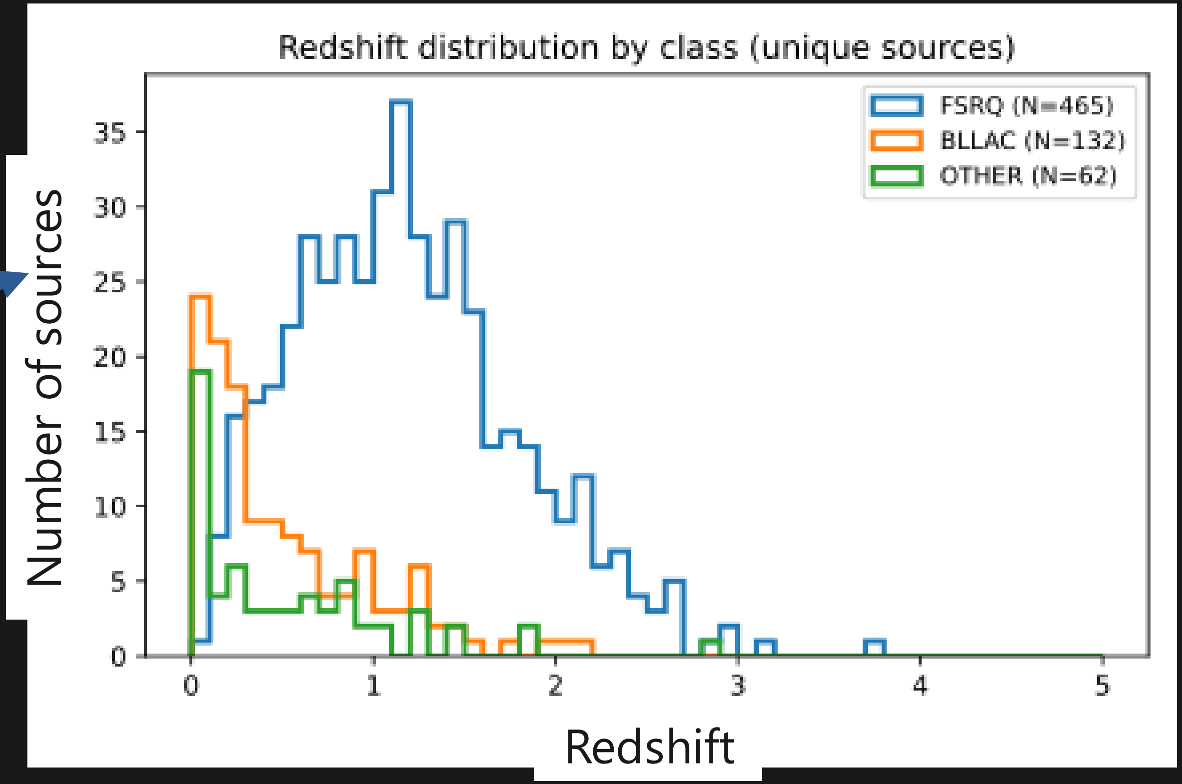
FALCON Catalog (FERMI–ALMA Calibrator ObservatioN)



Matching results

- **Final sample size: N=659 sources (965 ALMA–Fermi matched sources)**
- **Class distribution of the FALCON catalog**
  - FSRQ：465, zmedian = 1.11, zmax = 3.72
  - BL Lac：132, zmedian = 0.39, zmax = 2.12
  - Other AGNs：62





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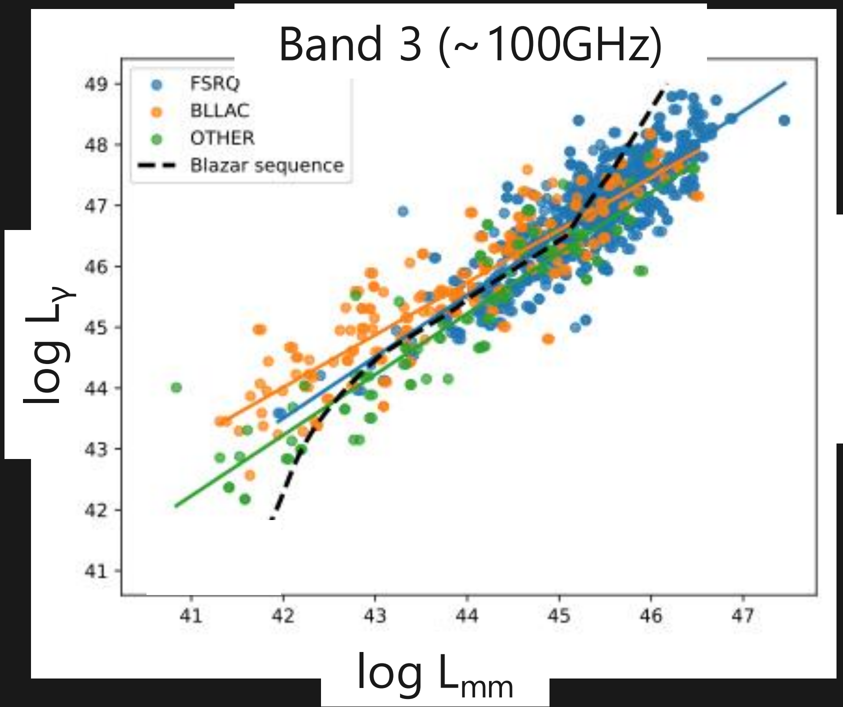
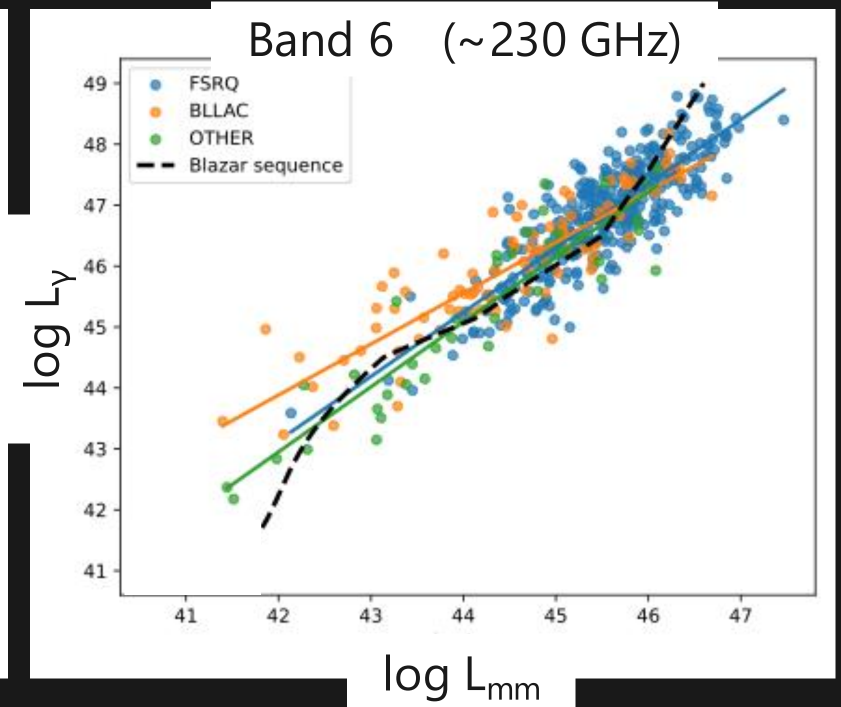
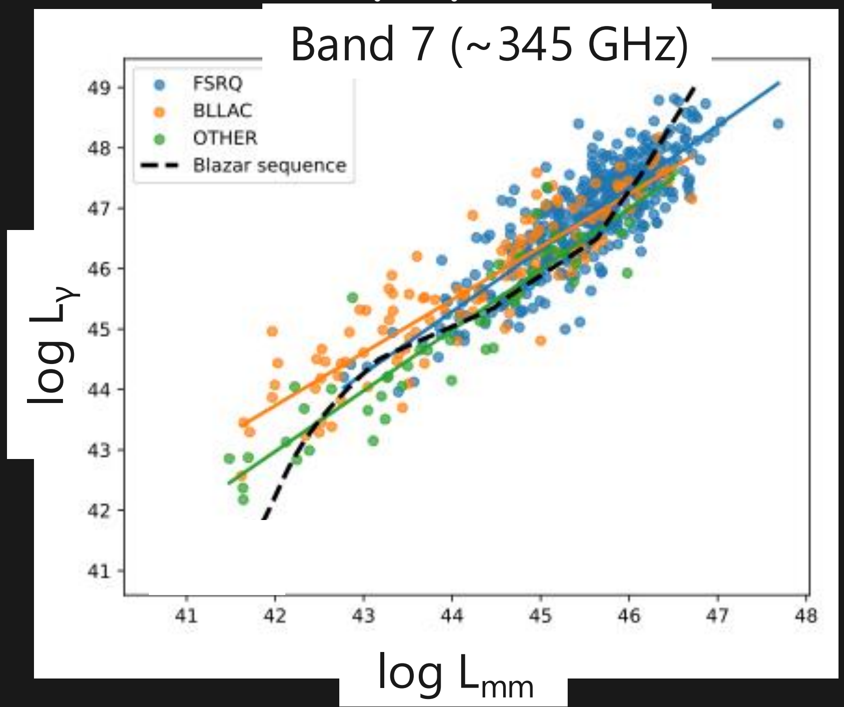
Correlation

- **Key results: millimeter–gamma-ray connection**
  - Strong correlation between mm and γ-ray luminosities
  - Persists after redshift correction (ρ~0.5–0.6)
  - Robust against non-simultaneous data
- **Implication**
  - mm emission traces the same average jet power as γ-rays

Narita in prep

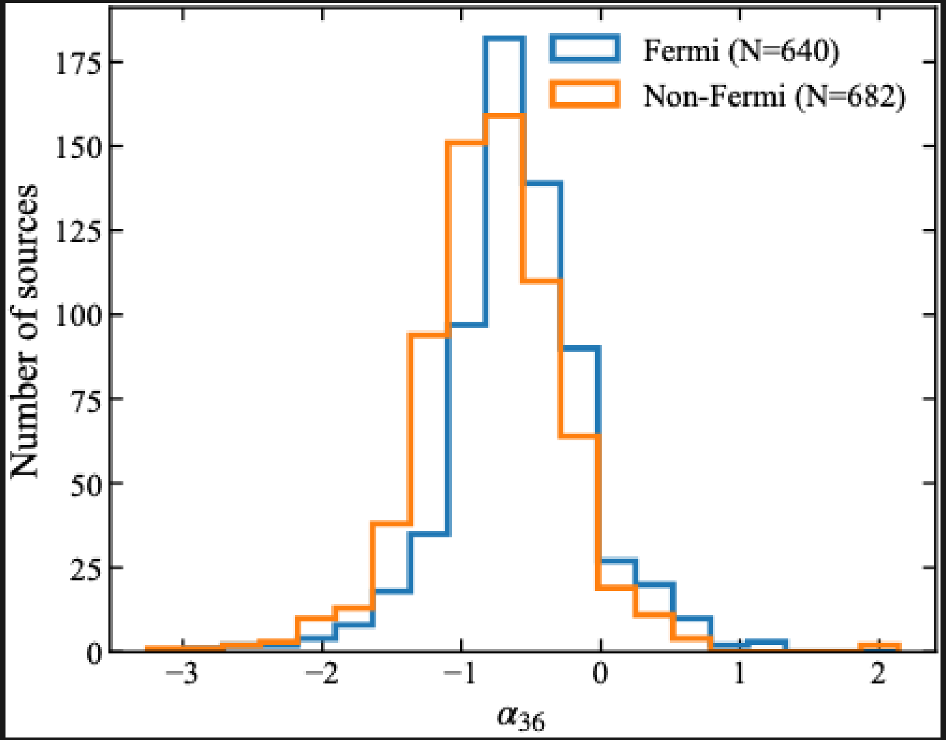


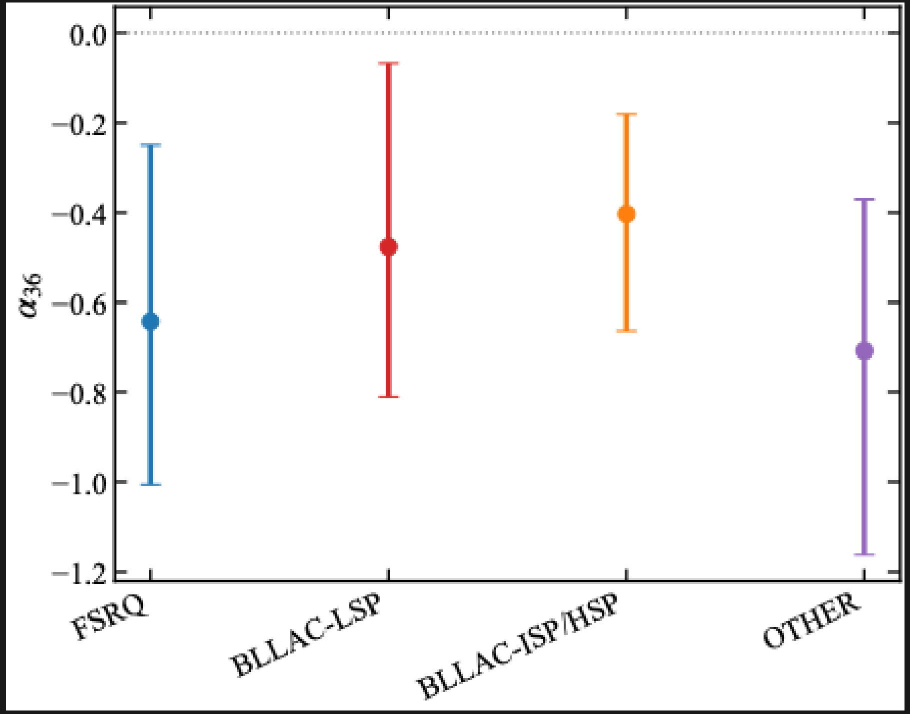




Millimeter Spectral Properties

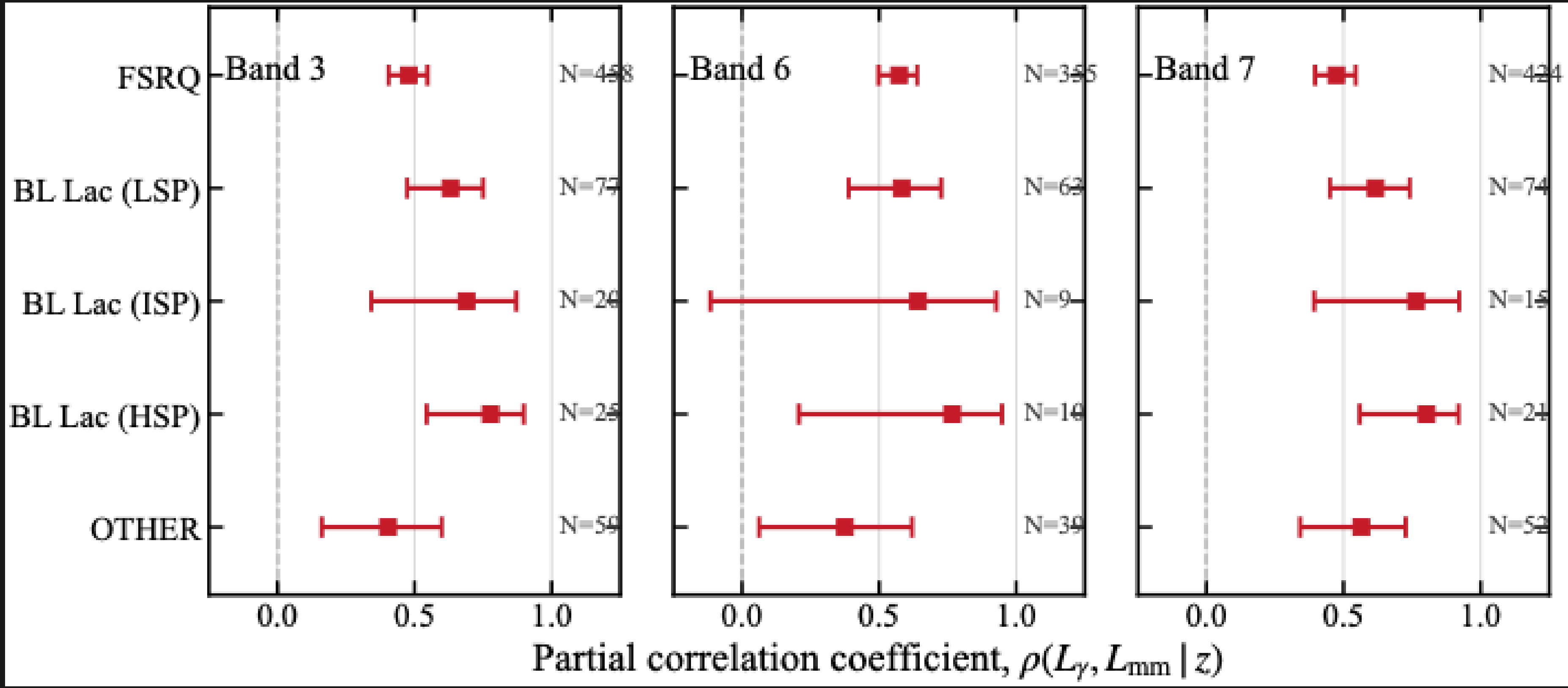
- **Gamma-ray-detected blazars show systematically flatter millimeter spectra**
  - Median α_{36}: −0.60 (Fermi) vs. −0.80 (non-Fermi)
  - K–S test: $p \approx 10^{-12}$
- **The millimeter spectrum tends to flatten from FSRQs toward ISP/HSP BL Lacs**





Millimeter–Gamma-Ray Connection

- The millimeter–gamma-ray correlation tends to weaken from HSP BL Lacs toward FSRQs.



Millimeter Properties along the Blazar Sequence

- **HSP BL Lacs: Higher synchrotron peak frequency**
  - Observed: flatter millimeter spectra
  - SSC → stronger mm–gamma connection
- **FSRQs: Lower synchrotron peak frequency**
  - Observed: steeper millimeter spectra
  - EC → weaker mm–gamma connection
- **Spectral trend may reflect different sampling of the synchrotron / SSA turnover.**

Summary

- **Target Material — Galactic Molecular Gas**
  - ALMA absorption spectroscopy reveals CO-poor molecular gas missed by conventional CO emission.
  - 13CO emission can severely underestimate NH2 in diffuse environments.
  - Hidden molecular gas provides an important constraint on target material for cosmic-ray interactions.

- **Accelerator — Blazar Jets**
  - FALCON reveals a strong mm–γ luminosity correlation across blazar populations.
  - The mm–γ connection and mm spectral properties systematically vary along the blazar sequence.
  - Millimeter observations provide a probe of jet states associated with high-energy activity.

- **ALMA calibrators provide complementary probes of both target material and high-energy particle accelerators.**