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Potential of Miniature Radio Galaxies at HE/VHE Domain

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Radio Galaxies

- ➢ In 1960s, the Third Cambridge (3C) Catalog provided the first view of ***Radio Galaxies*** (RGs).
- ➢ Powered by SMBH actively accreting matter and characterized with the presence of relativistic jets misaligned to the line of sight.
- ➢ Traditionally classified into FRI and FRII as per Fanaroff-Riley Classification.

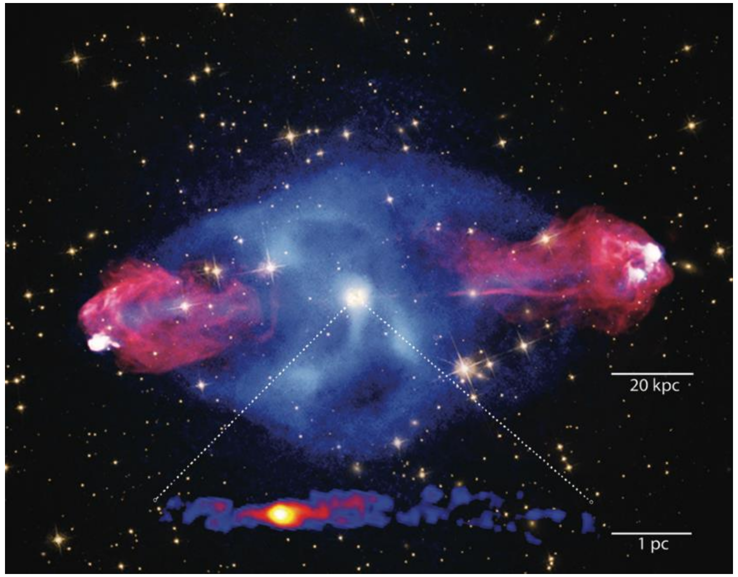


Fig 1. Comparison of radio (red), X-ray (blue),and optical images of the Cygnus A FR-II radio galaxy. Adopted from Bandford et al. (2019)

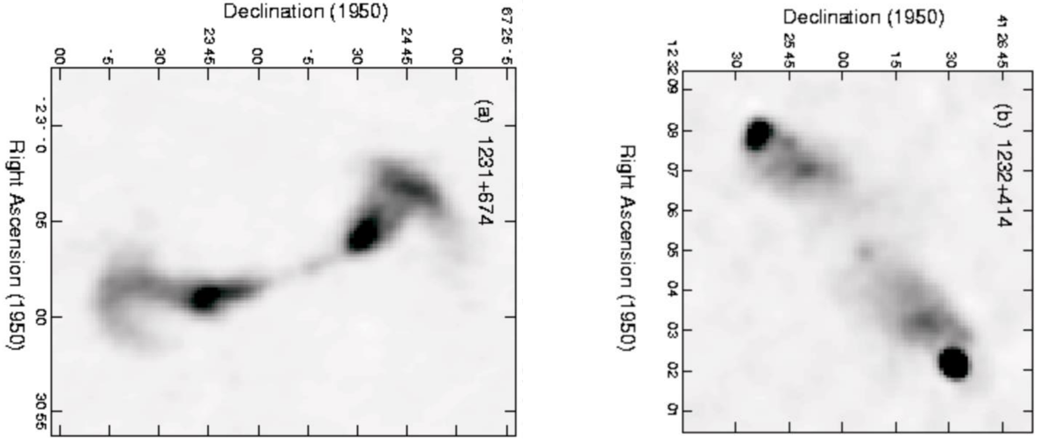


Fig 2. . Left: FRI radio galaxy. Right: FRII radio galaxy

Beyond the Unified Model of AGN

- Radio-optical surveys revealed new regions in the space parameter of RL-AGN phenomenology, which the Unified model (UM) cannot explain.
- Best explained by incorporating time-variability in the UM, where parameters can evolve across time.

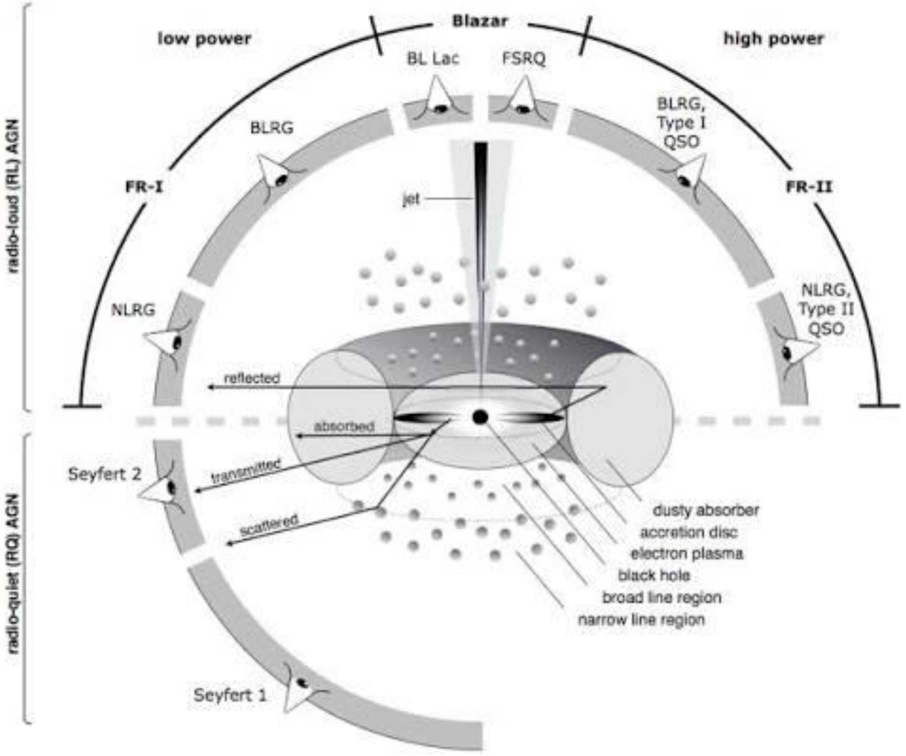


Fig 3. Unified Model of AGN

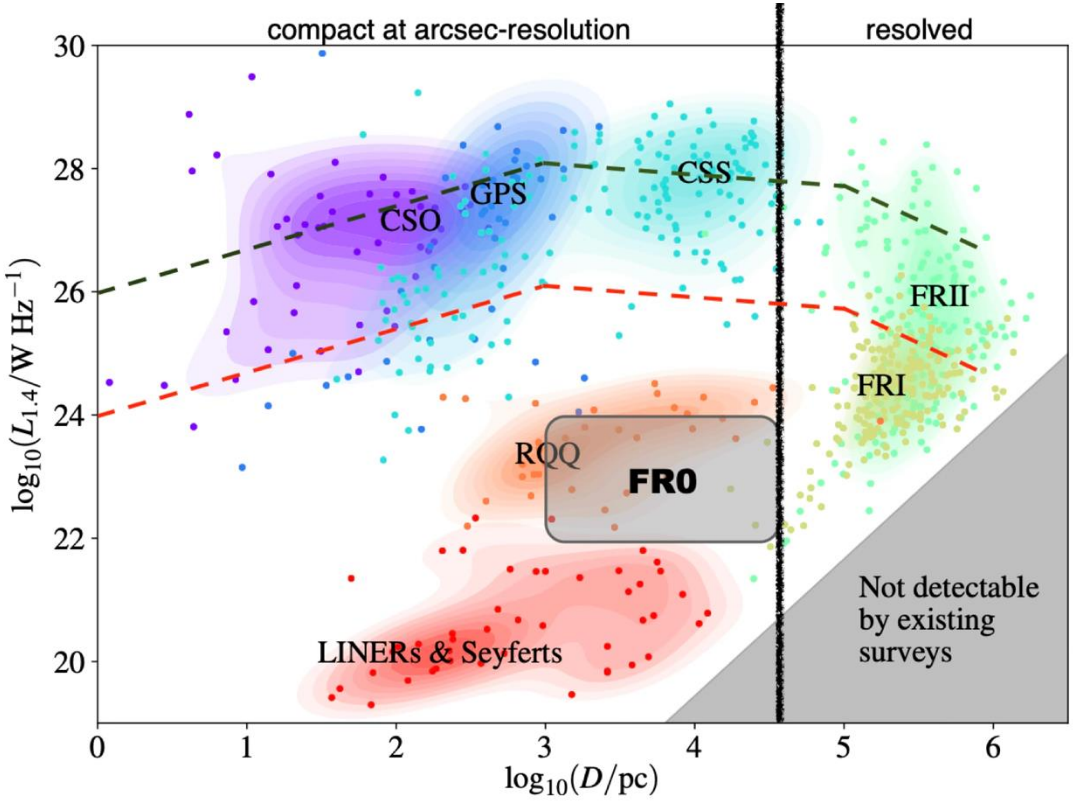


Fig 4. P-D Diagram. Figure adopted from Baldi, R. D. (2023)

Miniature Radio Galaxies (MiRG)

- Best et. al. (2005b) selected a large sample of local radio-loud AGNs (RLAGN), revealing that the local RLAGN population is dominated by low power radio galaxies.
- Characterized by a higher core dominance and weak/absent extended jet structures.

Miniature Radio Galaxies

CoreG

- Classification purely on the basis of radio properties
- Scaled-down versions of traditional FRI RGs.

FR0

- Classification on the basis of radio and optical properties.
- Unique population with poor jet-efficiency.

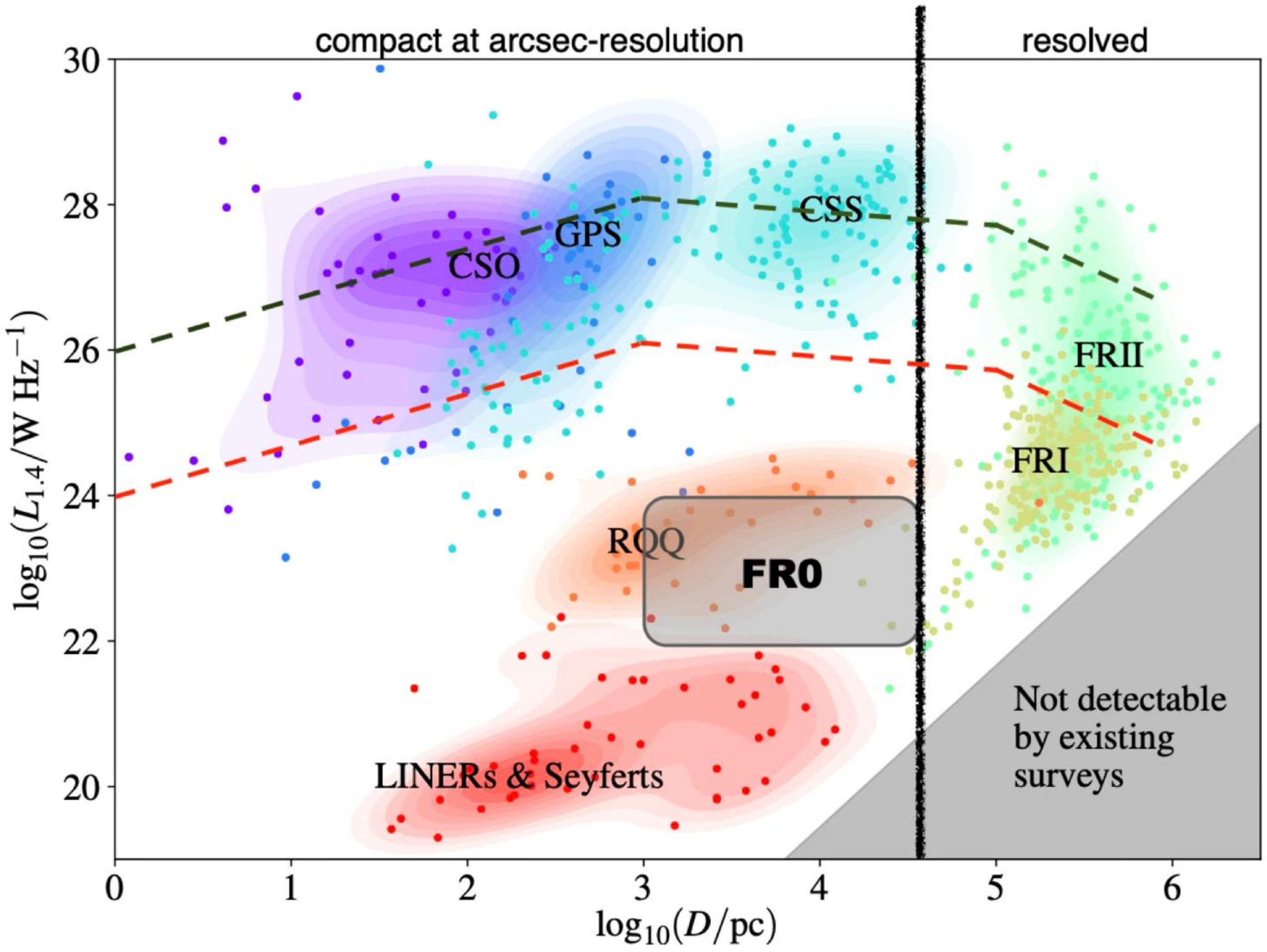


Fig 4. P-D Diagram. Figure adopted from Baldi, R. D. (2023)

"FR0" Radio Galaxies

- Ghisellini et. al. 2011 introduced the term FR0 in literature.
- Characterized by the presence of weak jets which extend from pc-sub kpc scale.
- Represent the bulk of the RLAGN population in the local Universe (z < 0.05).
- Space density ~4.5 times of FRIs and ~100 times of FRIIs.
- Higher core dominance, ~30 times compared to FRIs.

Properties	FR0	FRI	FRII
Jet Extension	pc – sub-kpc	kpc scale	Mpc scale
Jet Morphology	Unresolved	Core-brightened	Edge-brightened
Accretion Rate	Low	Low	High
Spectral Shape	Flat	Steep	Steep

Table 1 Comparison of FR0, FRI and FRII properties.

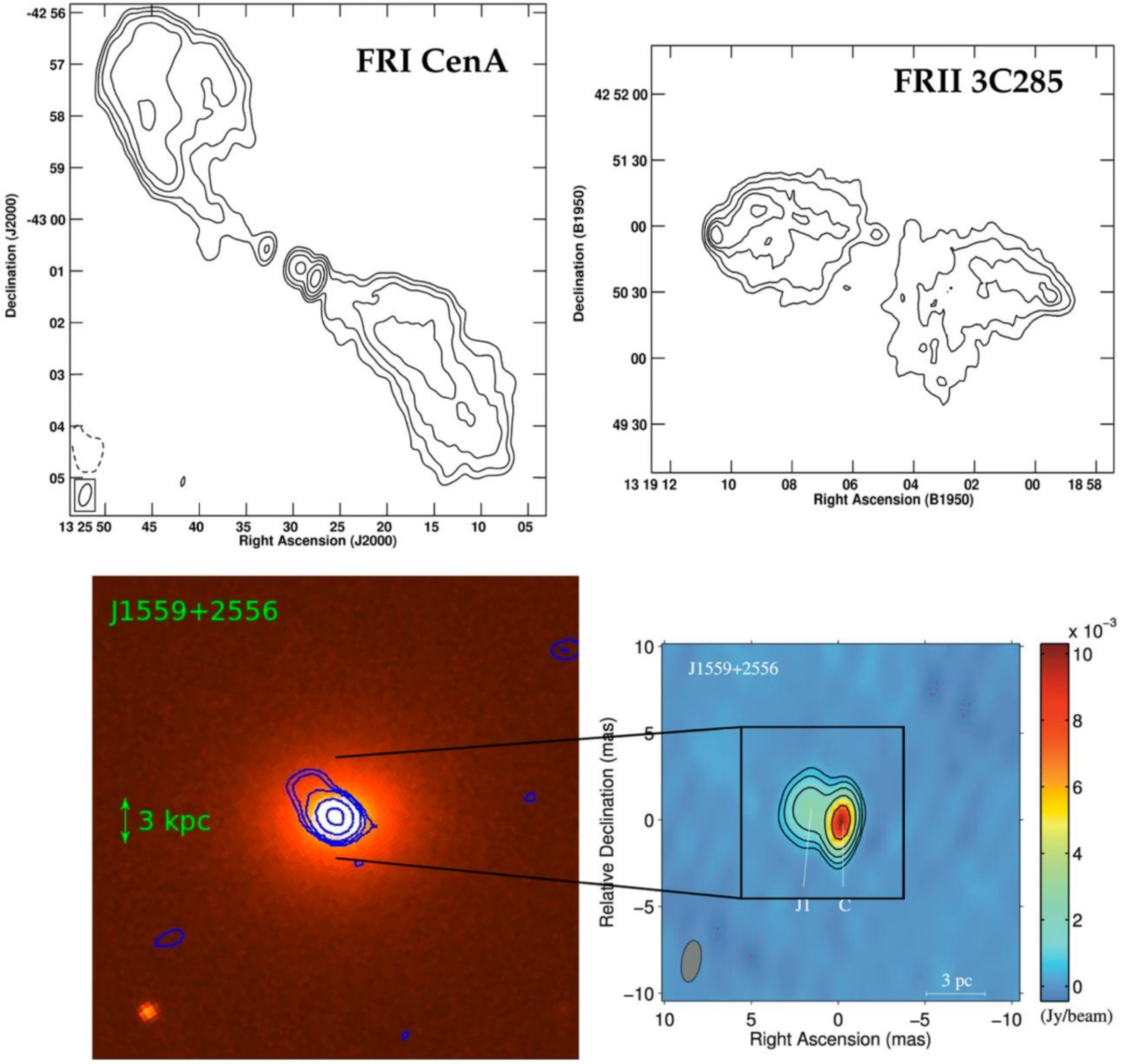


Fig. 5 Top: Examples of FR I (Cen A) and FR II (3C 285) morphologies. Bottom: FR 0 host galaxy (SDSS r-band with VLA 4.5 GHz contours and zoomed radio core (VLBI). Figure reproduced from Baldi (2023)

"FR0" Radio Galaxies

Properties	FR0CAT	FRICAT
M_{BH}	$10^{7.5}$ – 10^{9} $M_{\odot}$	10^{8} – $10^{9.5}$ $M_{\odot}$
Accretion Rates (L_{bol}/L_{edd})	10^{-5} ~ 10^{-2}	10^{-5} ~ 10^{-2}
$L_{1.4GHz}$	10^{38} – 10^{40} erg/s	10^{39} – $10^{41.3}$ erg/s
Jet Extension	< 2.5 kpc	> 30 Kpc

Table 2 Comparison of FR0CAT, FRICAT and FRIICAT.

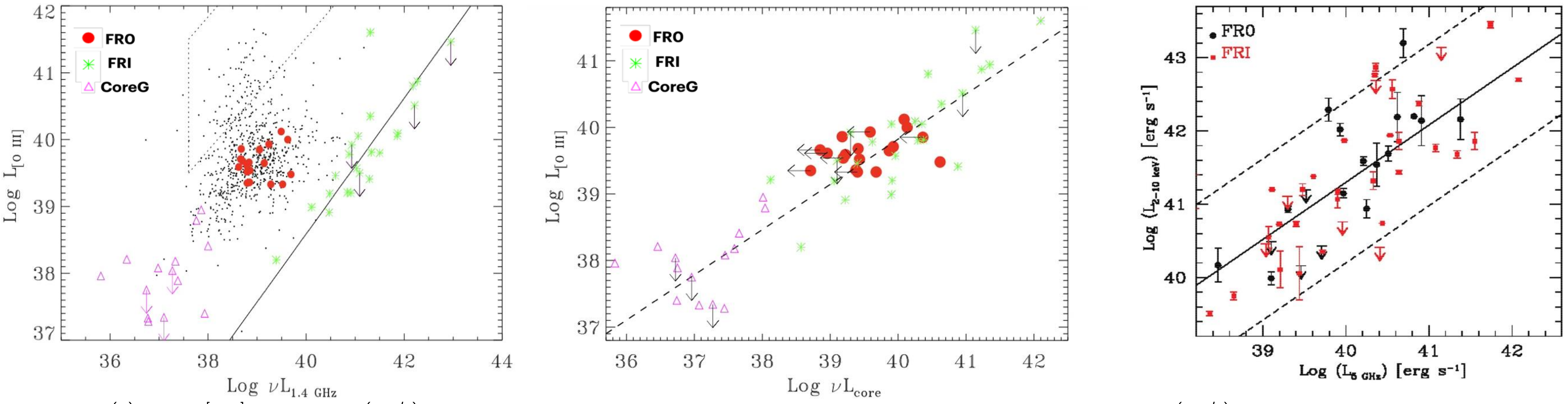


Fig. 6(a) Left Plot: [O III] line luminosity (erg/s) vs VLA radio core (5 GHz), . Figure adopted from Baldi (2023) (b) Middle plot: |O III| line luminosity (erg/s) vs NVSS. Figure adopted from Baldi (2023) (c) Right Plot:: VLA radio core (5 GHz) vs X-ray luminosity (2-10 keV)., Figure adopted from Toressi et. al. (2018)

Why study them?

- Detection of MiRGs in HE/VHE domain.
  - 2 FR0 RGs detected at HE by Fermi-LAT. [Paliya et. al. 2021]
  - CoreG, NGC 4278 detected at VHE by LHAASO. [Cao et. al. 2024]

- At Very-High Energies: 89 AGNs detected
  - 83 Blazars
  - 4 Radio Galaxies (all FRI-type, low-power RGs)
  - 2 BL Lac + Radio Galaxy

- Upcoming commissioning of multiple LSTs will improve sensitivity, enabling many more of these sources to be detected in HE and VHE gamma rays.

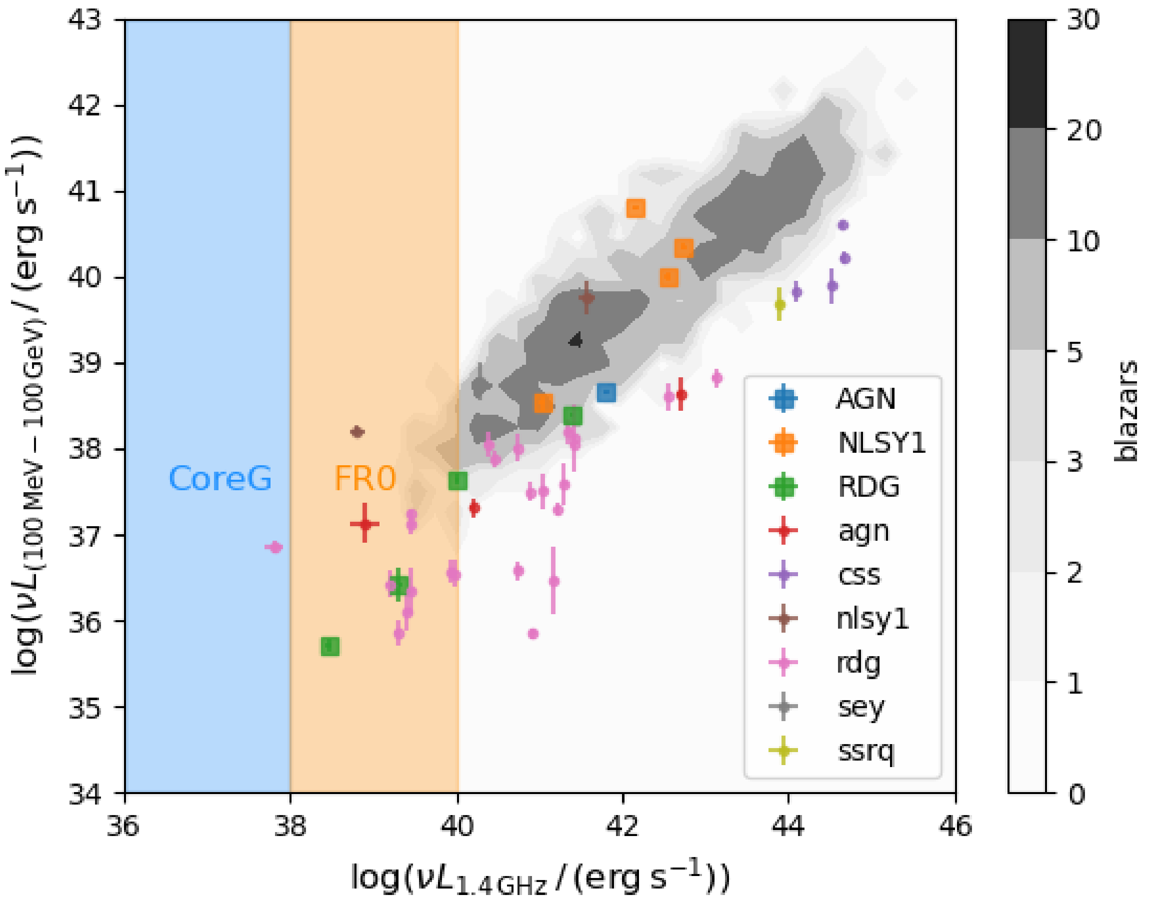


Fig 7. Radio and gamma-ray luminosities of radio-emitting AGN detected by the Fermi-LAT telescope. Squared markers denoting firm identification.The ranges of radio powers of CoreG and FR0 are highlighted.

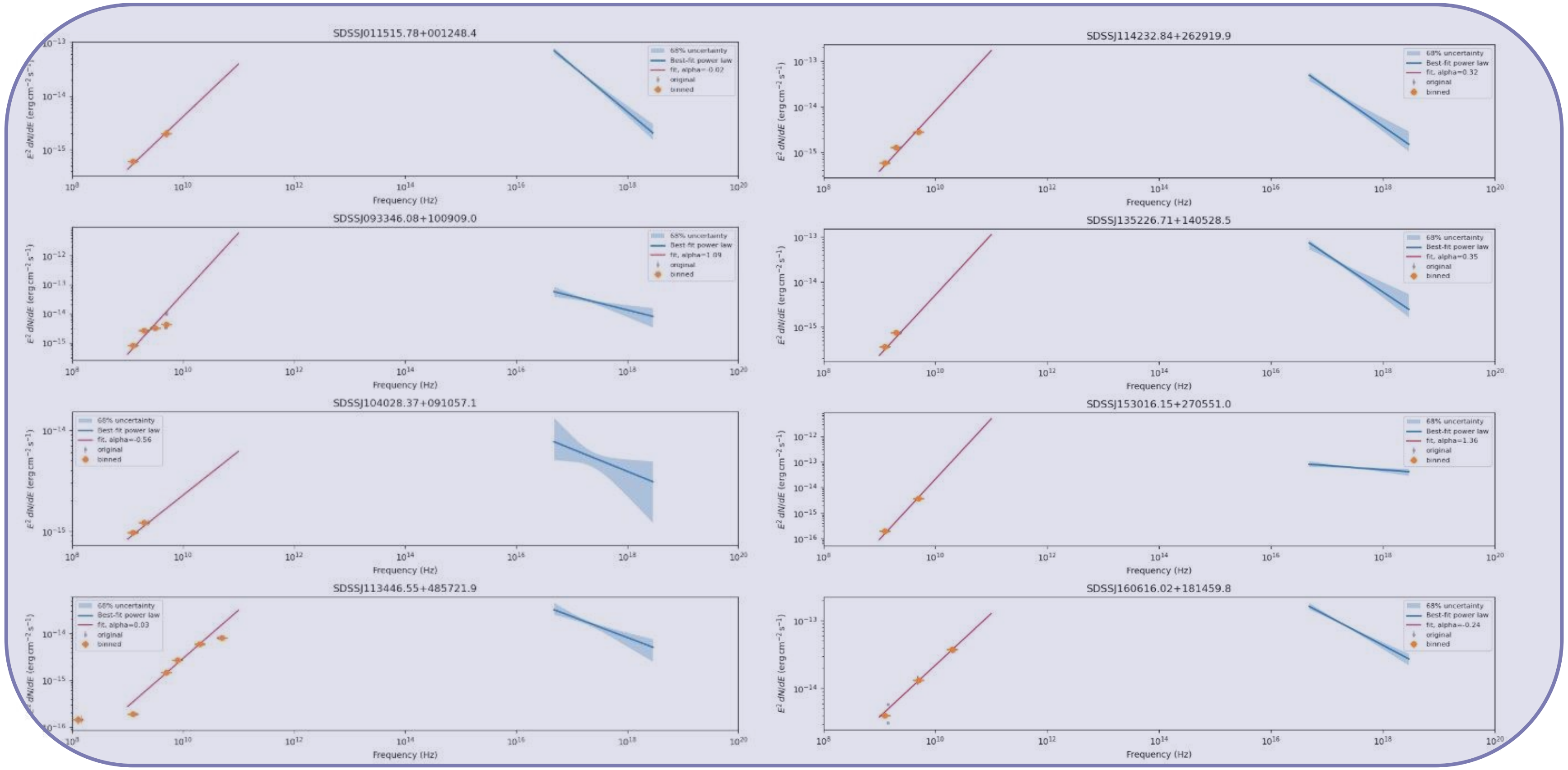
Radio – X-ray Connection

Case I

Rising radio spectrum + falling X-ray spectrum

↓

Single Synchrotron component?



Case II

Rising radio spectrum + rising X-ray spectrum

↓

RIAF related Compton emission?

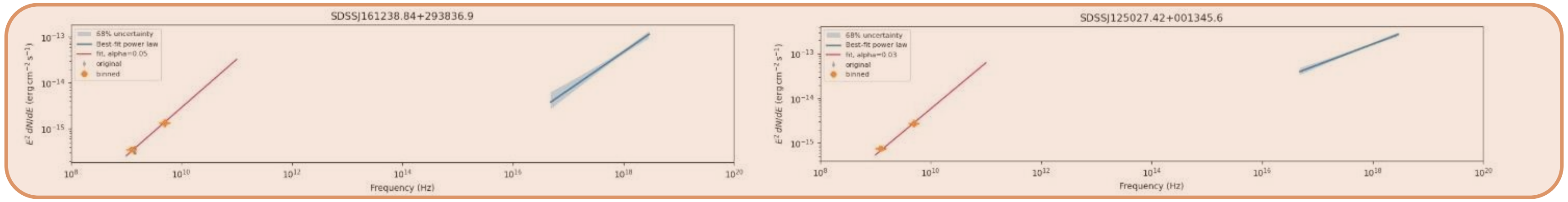


Fig. 8. Radio - X-ray connection of 5XMM-DR15 identified FR0 sources. Best-fit power law obtained from 5XMM-DR15.

Fermi Identification

- LEDA 55267
  - 4FGL counterpart: 4FGL J1530.3+2709
  - The Fermi-LAT spectrum is relatively hard with an $\Gamma \sim 1.91$.
  - Variability Index: 29
  - Fermi-LAT spectrum remains unconstrained above 100 GeV.
- LEDA 58287
  - 4FGL counterpart: 4FGL 1628.8+2529
  - The Fermi-LAT spectrum is relatively hard with an $\Gamma \sim 1.92$.
  - Variability Index: 10

Source	Normalization	Photon Index	Eflux
4FGL 1530.3+2709	0.483	1.91	1.11e-06
4FGL 1628.8+2529	0.506	1.92	8.35e-07

Table 3 Best-fit Fermi-LAT SED parameters.

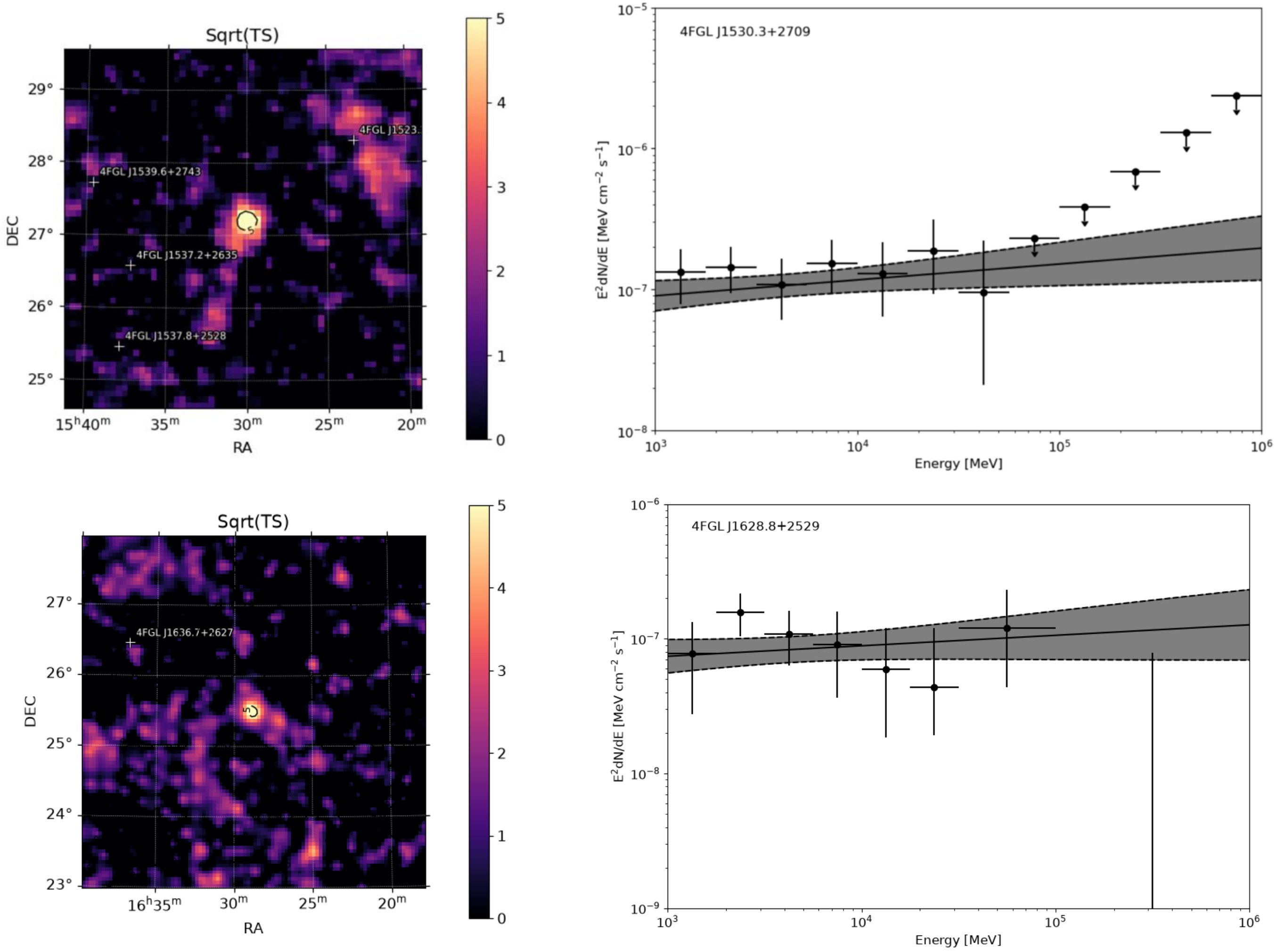


Fig 9. Top: Significance map and Fermi-LAT SED for LEDA 55267 .Bottom: Significance map and Fermi-LAT SED for LEDA 58287.

LEDA 55267

- Variability:
  - Classified as a variable source in 4FGL-DR4, <1% change of being a steady source.
  - Flux increased by a factor of ~3 between 2021 and 2022.
  - Variability index increased from 12 to 29 from Fermi's 4FGL-DR3 to 4FGL-DR4.

Properties	4FGL-DR3	4FGL-DR4
Variability Index	12.23	29.71
Varitability Threshold	24.72	27.7
Peak Photon Flux	--	4.11e-9 +/- 1.05e-9

Table 4 Variability Index for LEDA 55267.

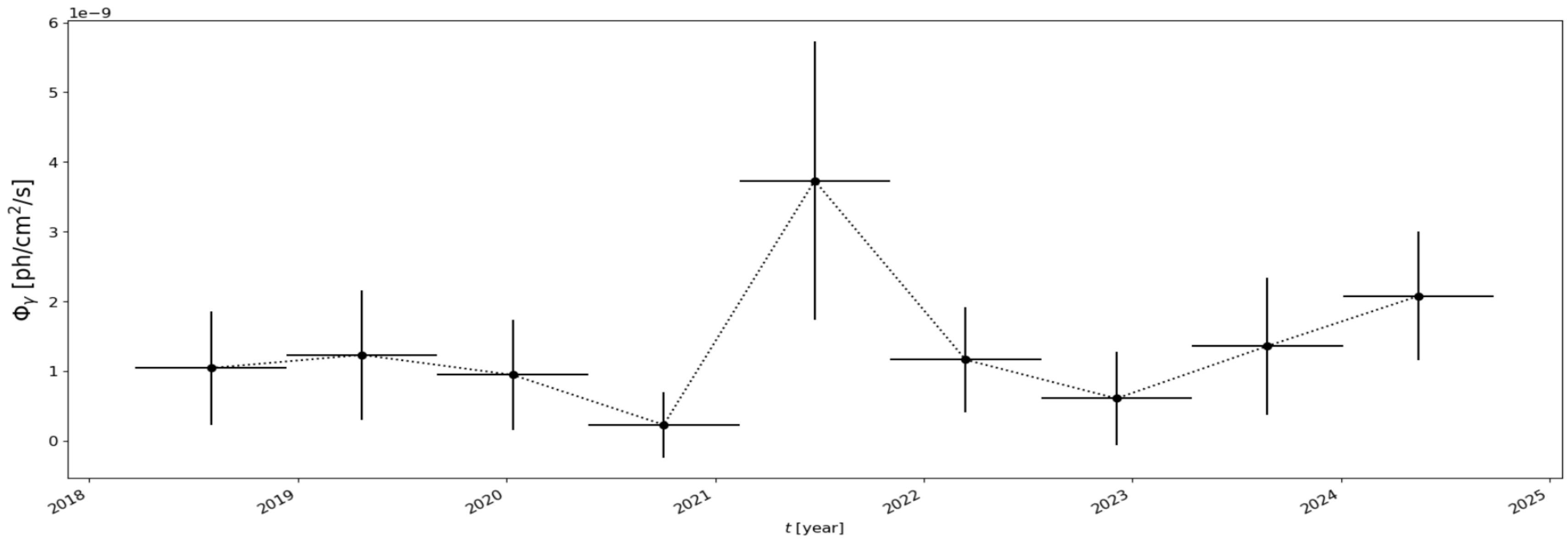


Fig 10. Light Curve of LEDA 55267

Potential at VHE?

State	Normalization	Photon Index	Eflux
High	0.483	1.91	1.11e-06
Average	1.154	1.87	2.81e-06

Table 5 Best-fit Power Law during the high state for LEDA 55267.

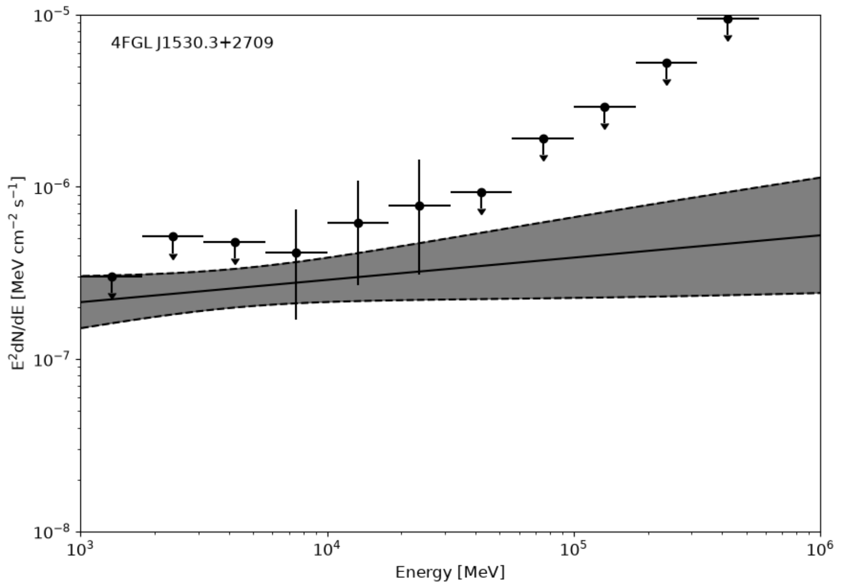
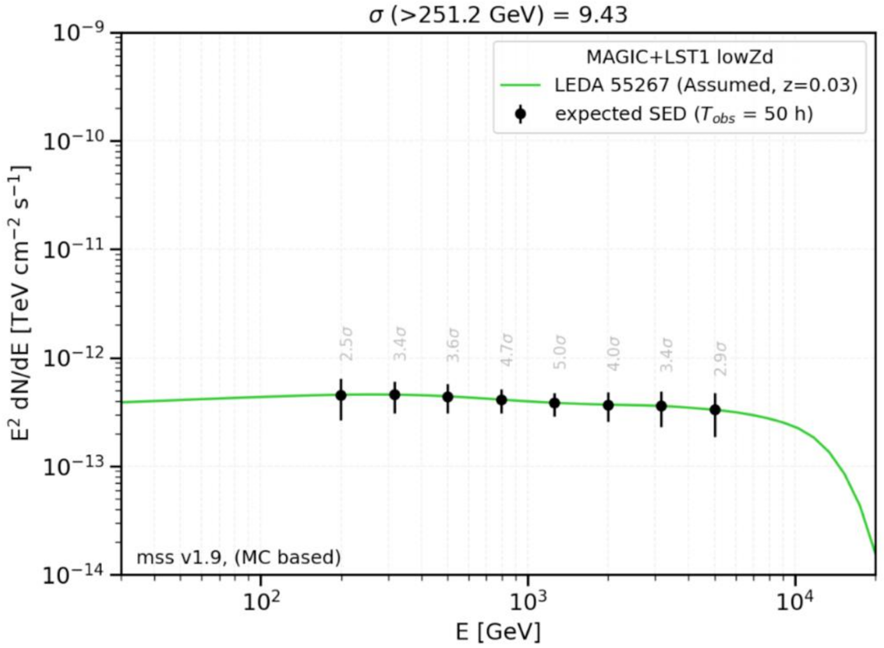


Fig 11. Fermi-LAT SED during the high state



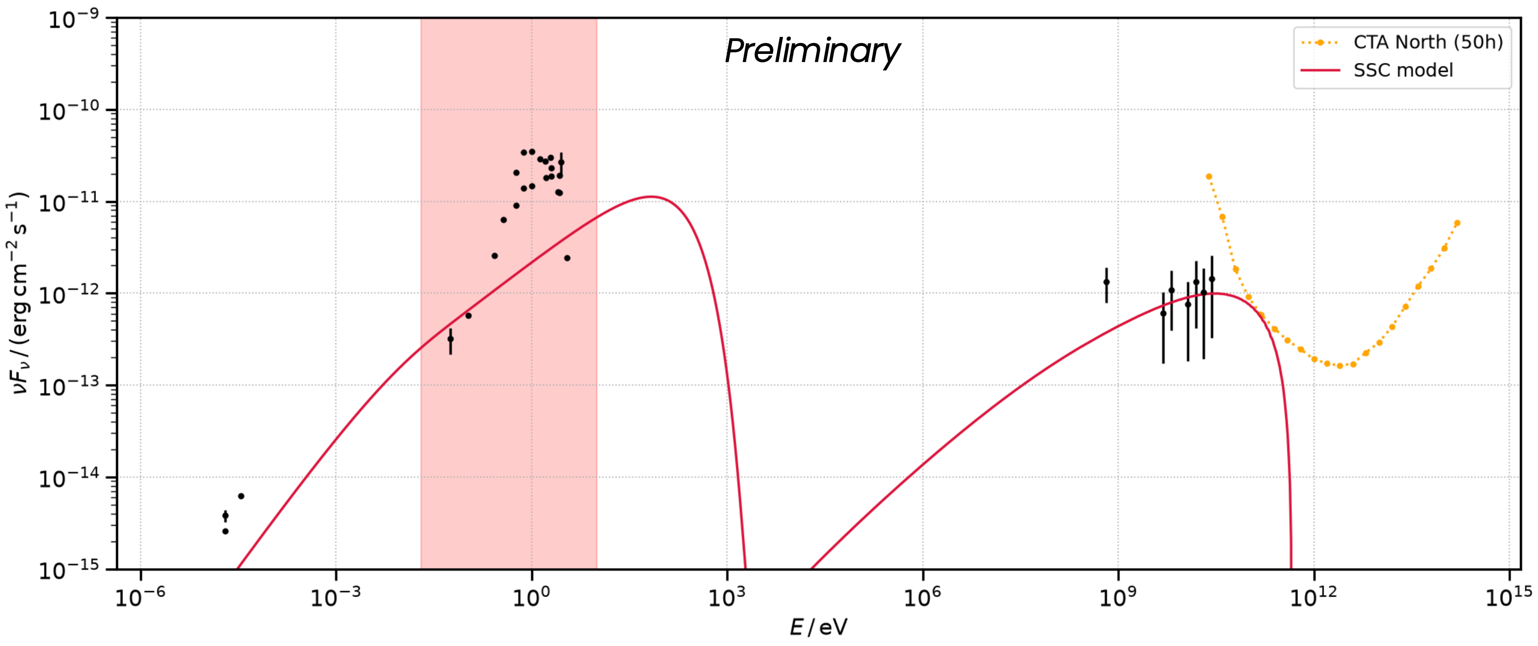


Fig 12. Left: Extrapolation of Fermi-LAT spectrum to VHE. Right: Fermi-LAT SED during the high state. Right: MWLSED fit during the active state for LEDA 55267.

Multiwavelength SED

- Performed MWL-SED fitting using a single-zone blob using with *agnpy for.*
  - *Averaged LEDA 58287 state*
  - *Averaged LEDA 55267 state*
- SSC model does not fit the X-ray data, as we expect it to arise due to the radiatively inefficient accretion flows.

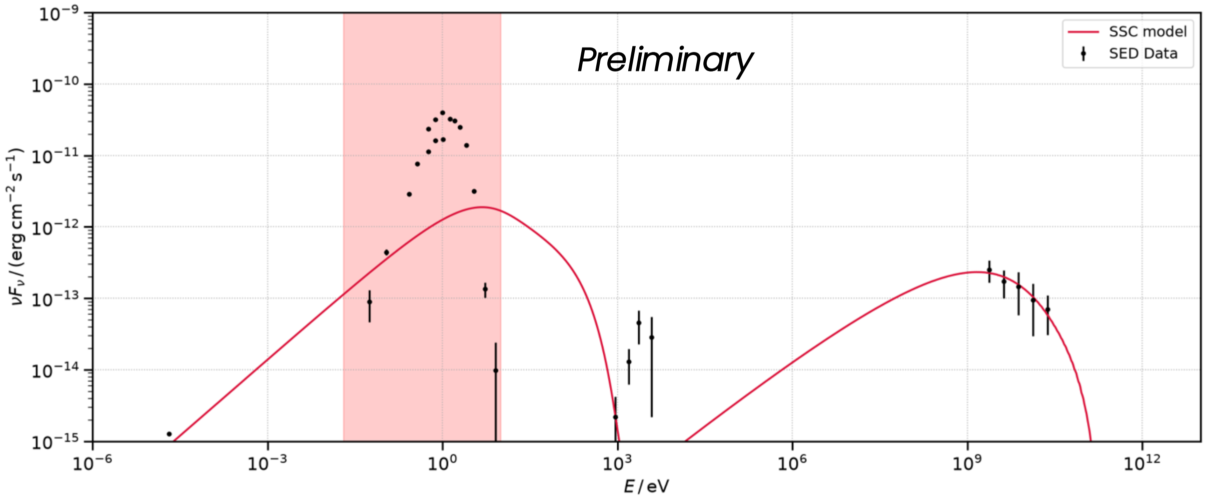


Fig 13. MWLSED Fit. For LEDA 58287

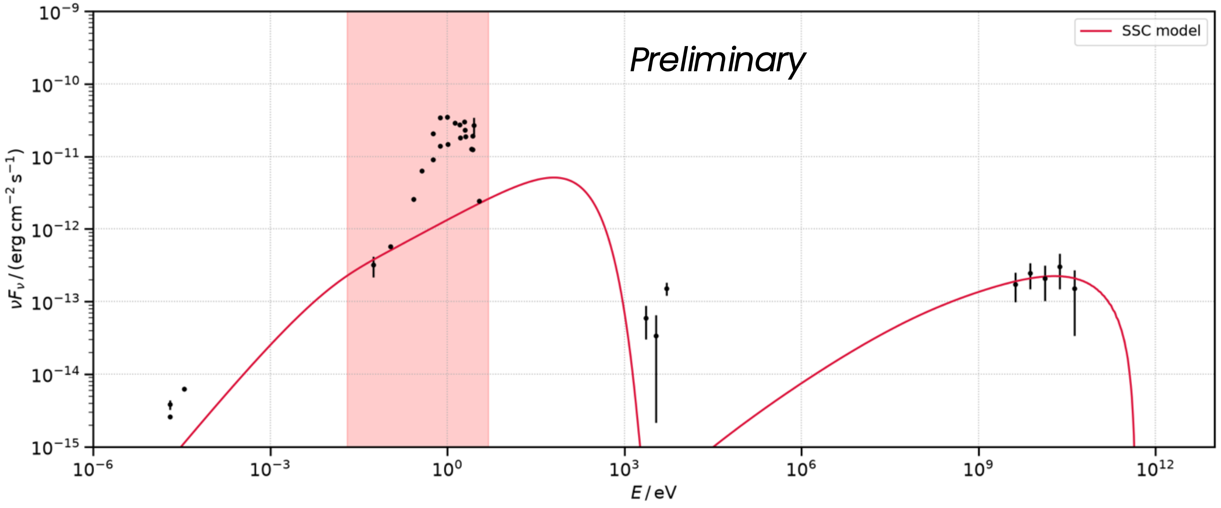


Fig 14. MWLSED Fit. For LEDA 55267.

Case of NGC 4278

- Nearby Core Galaxy hosting a LINER-like nuclei
  - $D_L \sim 16.4$ Mpc, z = 0.0021
- LHAASO detection *[Cao, Z et. al. 2024]*
  - Enhanced gamma-ray activity between August 23, 2021 and January 10, 2022
  - Long term variability ~ 140 days active state
  - TeV Flux increased by a factor of ~7
- History of high variability:
  - Archival Chandra data: Factor of ~17 between 2004 and 2010
  - Listed in Fermi Transient Catalog (1FLT)
- Not detected by IACT as of now.
- First evidence of low-luminosity compact radio source accelerating particles to multi TeV-energies.

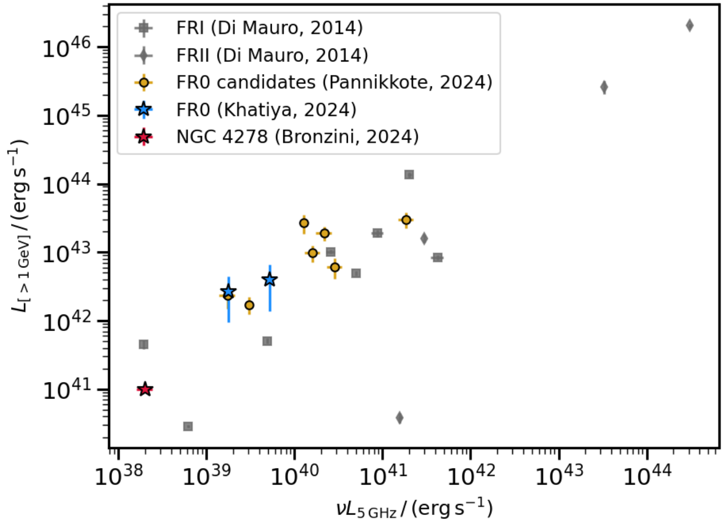


Fig 15. Gamma ray Luminosity vs Radio core luminosity for MiRGs, MiRG candidates, FRI, FRII and the CoreG NGC 4278

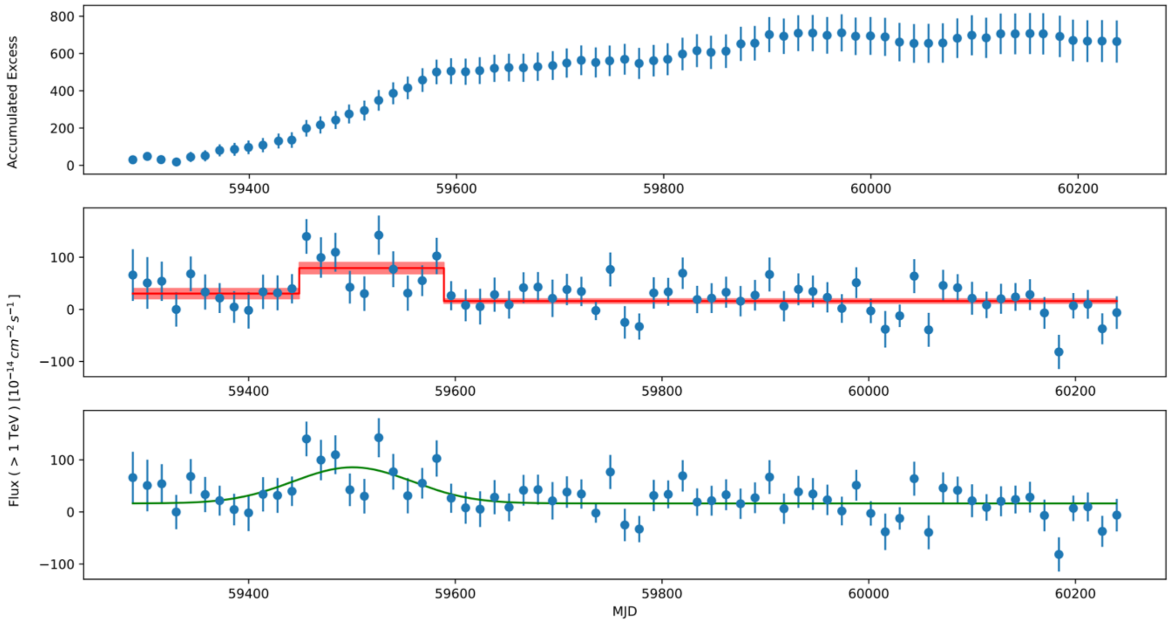


Fig 16. Light curves of NGC 4278. Figures adopted from Cao, Z. et al. (2024)

Summary

- The recent identification of NGC 4278 by LHAASO represents a remarkable discovery, indicating that weak, compact jets have the potential to accelerate particles to TeV energies.
- FR0s appear to outnumber traditional radio galaxies in the local Universe. So they may represent an important, previously unexplored component of the radio-galaxy population and can help us understand fundamental questions about
    - Typical accretion-ejection mechanism
    - Jet formations, propogation and evolution.
- The standard AGN Unified Model says that many observed differences between AGN can be explained by orientation, accretion and jets but FR0s introduce another dimension: intrinsic jet properties and evolution.
- Miniature Radio Galaxies are already well within the detection capability and the next generation gamma ray telescopes will significantly improve sensitivity, enabling many more of these sources to be detected in both HE and VHE gamma rays.

THANK YOU

Udai Sharma

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