



**INAF**

ISTITUTO NAZIONALE  
DI ASTROFISICA



# The curious case of the FR0s Jet morphology

ESO seminar 15/09/2026

PhD University of Cagliari, INAF-OAC

**LEONARDO PENNA**

# RLAGN, RGs

~10-20% AGN are Radio Loud (RL) (Urry & Padovani 1995)

- High radio-to-optical flux
- Collimated relativistic jets



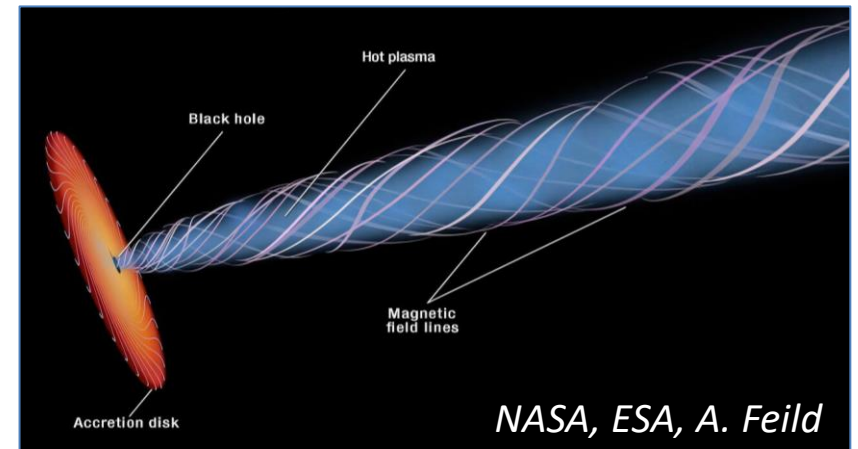
## Radio Galaxies, Morphology (Fanaroff & Riley, 1974)

### □ FR Is

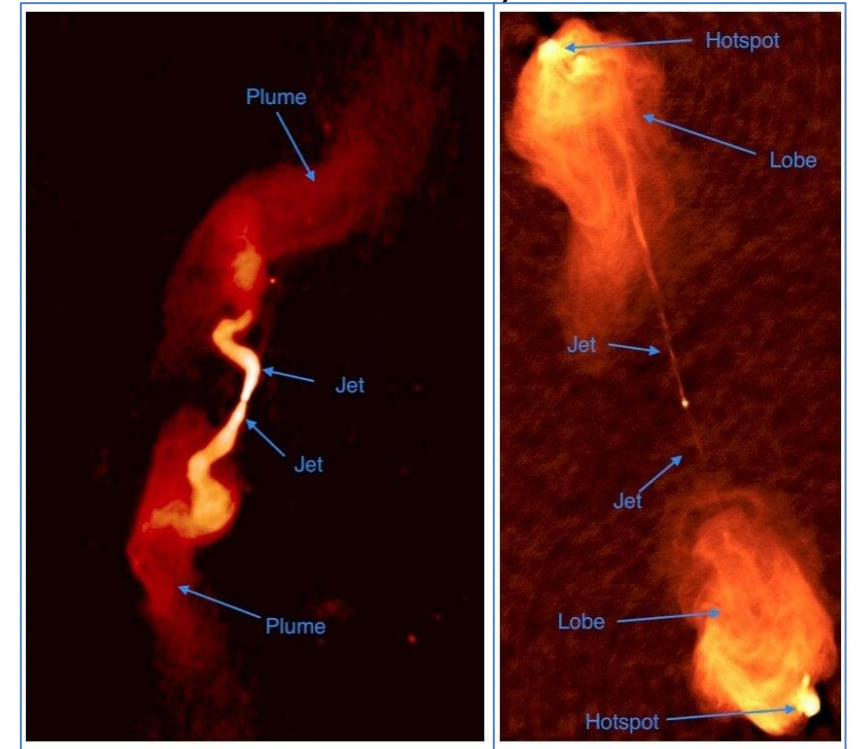
- Edge darkened

### □ FR IIIs

- Edge-brightened
- More collimated jets



NRAO/AUI



FRI 3C31

FRII CygnusA

# Adding the FR0

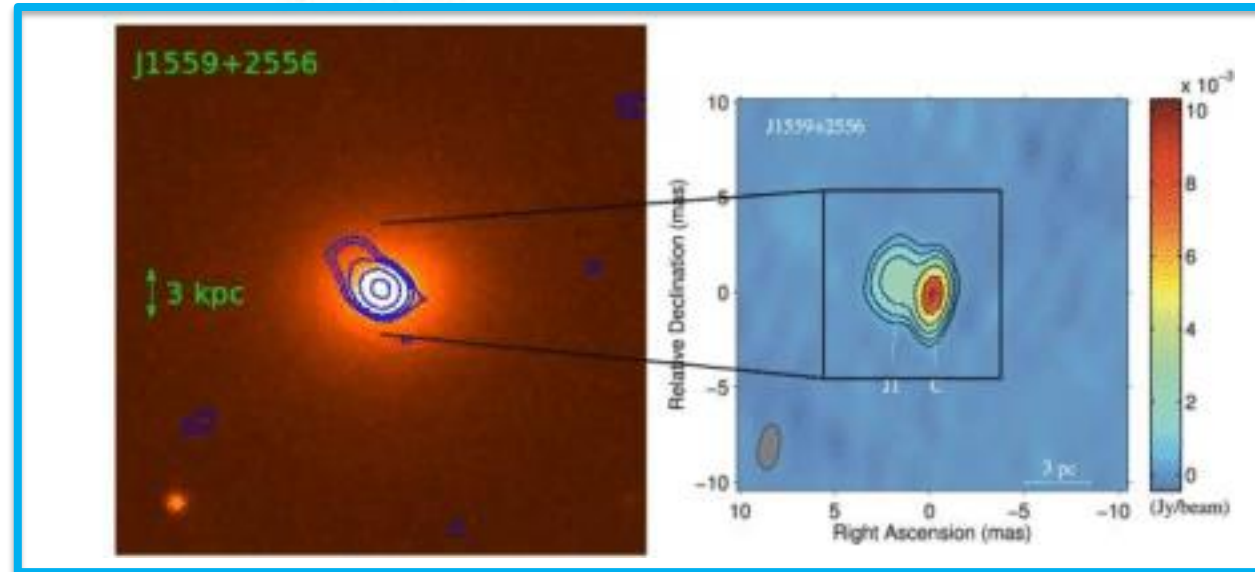
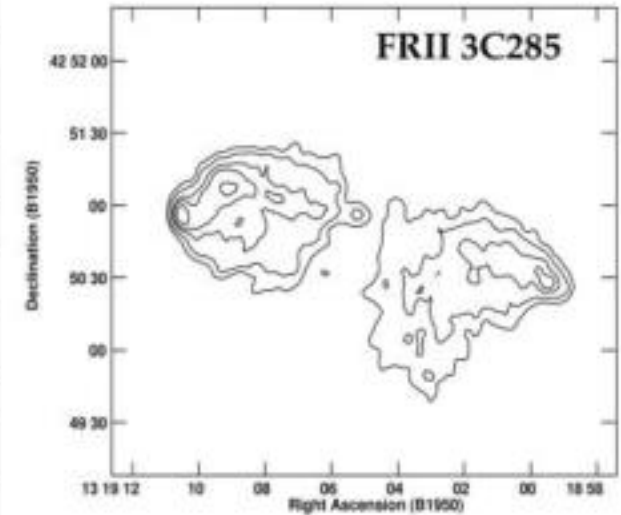
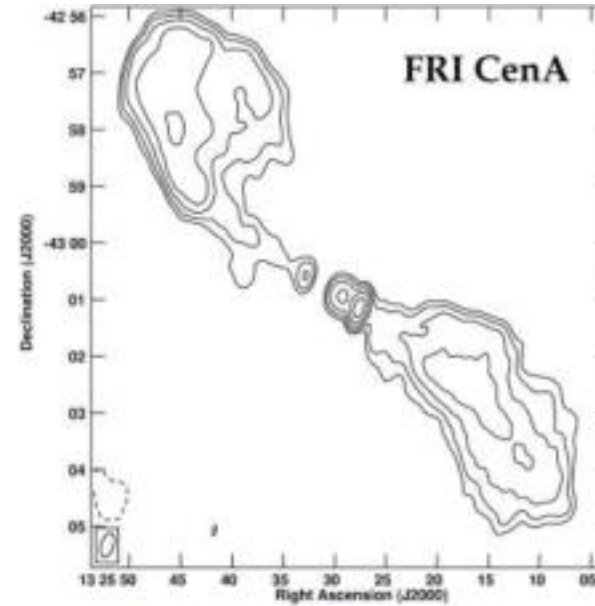
## FR 0s:

- Mostly Compact (< few kpc)
- low-luminosity RLAGN in ETGs
- Inefficient low-accretion

## Where are the Jets?

- mas-scale (VLBI):
  - $\gtrsim 80\%$  resolved  $\rightarrow$  pc-scale jets

*Baldi et al. (2023)*



# Adding the FR0

## WHY FR0s ARE IMPORTANT?

- Low-luminosity RL-AGN → Inefficient ACCRETION-EJECTION
- $\sim 5\times$  FRIs at  $z \lesssim 0.1$  → **Dominant RL-AGN in local Universe** (*Baldi et al., 2023*)
- Low-power jets → May have more efficient ISM-coupling (*Mukherjee2025*)

## WHY FR0s LACK EXTENDED EMISSION?

- **Dynamic scenario** → Young/Recurrent RGs
- **Static scenario** → Intrinsically compact

# The Dataset

➤ 27 FR0s with **LOFAR**, **VLA**

**FR0CAT**  
(Baldi et al. 2018)

104 FR0s  
 $z \lesssim 0.05$   
Compact in FIRST(5") – 1.4 GHz

**LOFAR**

0.15 GHz  
6.0"

**VLA**

1.5 GHz  
1.5"

**VLA**

4.5 GHz  
0.6"

**VLA**

7.5 GHz  
0.4"

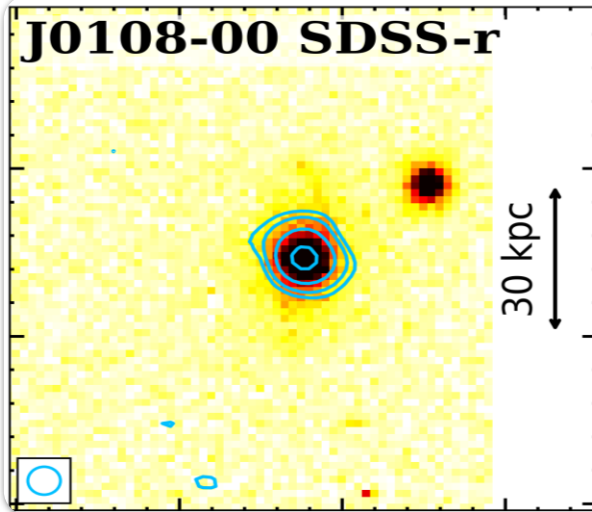
~6.0 kpc

~0.3 kpc

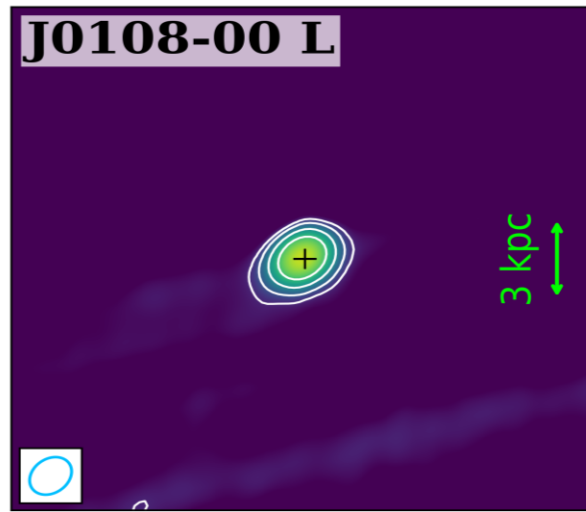
# The Dataset

➤ 27 FR0s with **LOFAR**, **VLA** → **AIMs** { Morphology  
Spectral properties  
Accretion – Ejection

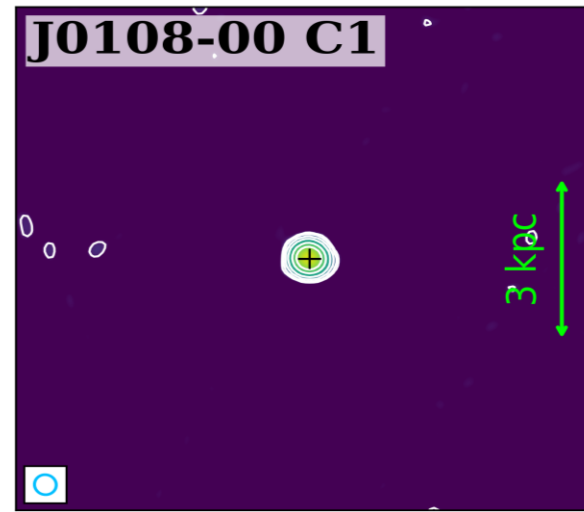
**LOFAR** – 0.15 GHz



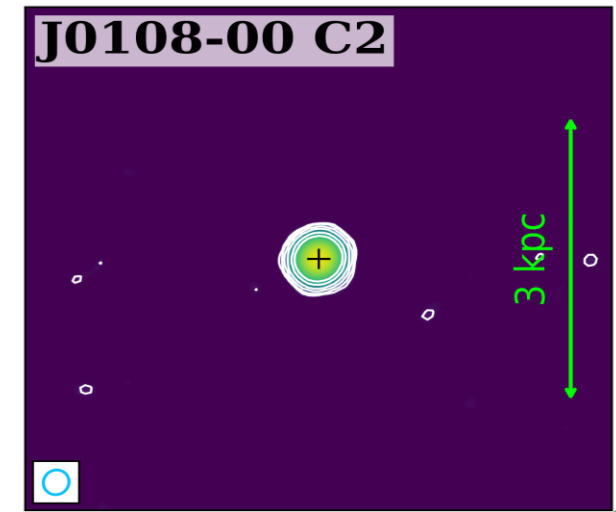
**VLA** – 1.5 GHz



**VLA** – 4.5 GHz



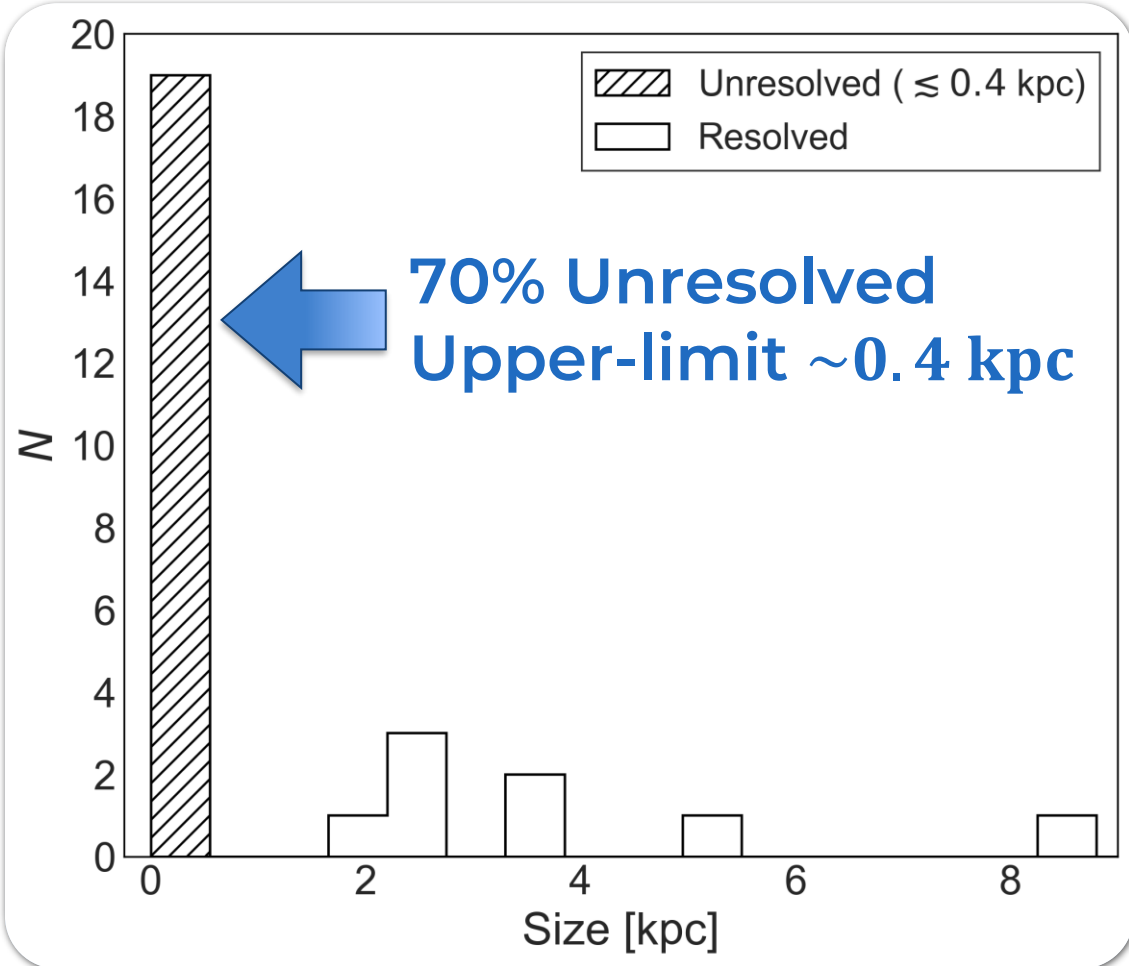
**VLA** – 7.5 GHz



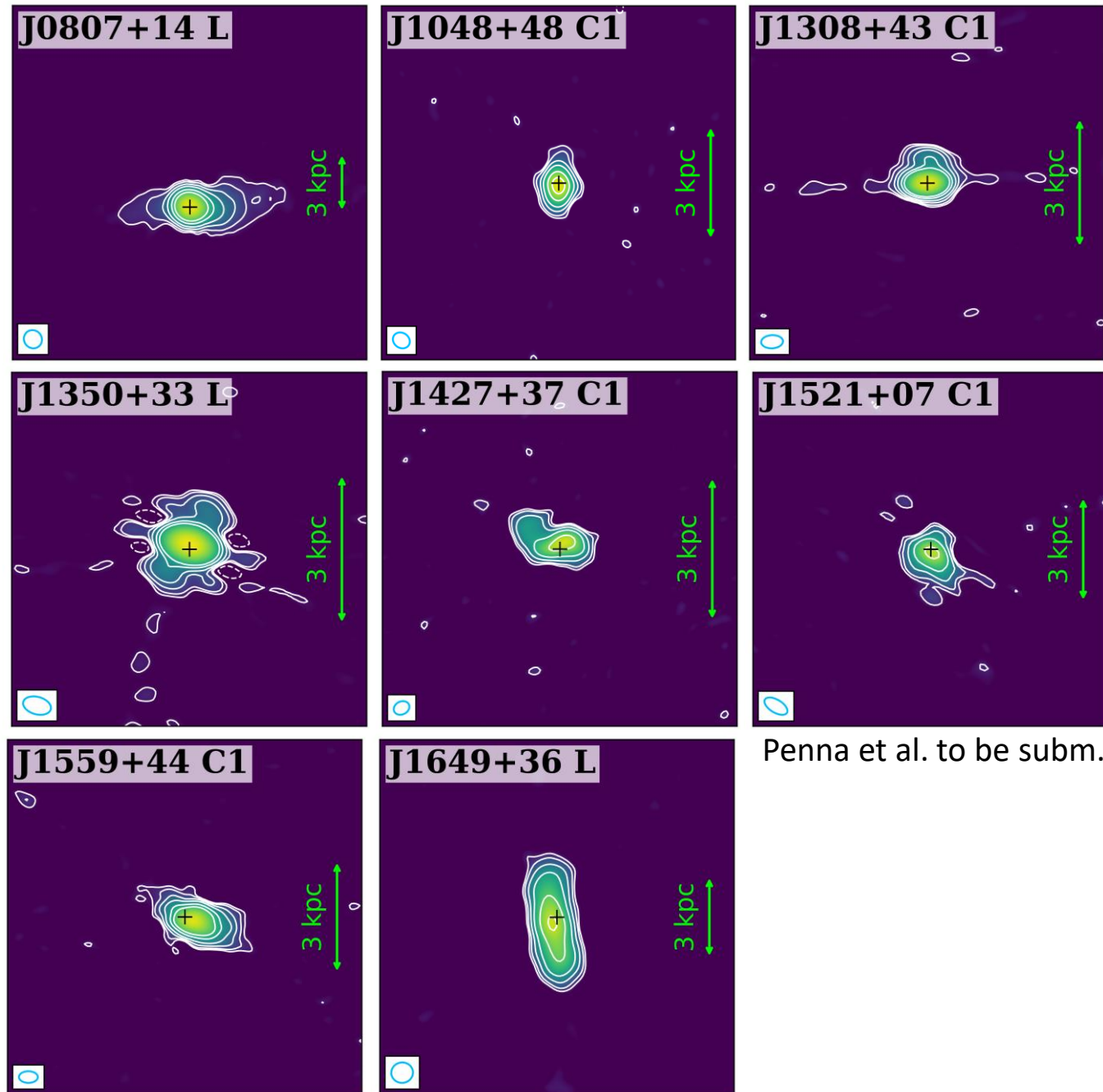
Penna et al. to be subm.

~6.0 kpc → ~0.3 kpc

# Morphology



Penna et al. to be subm.

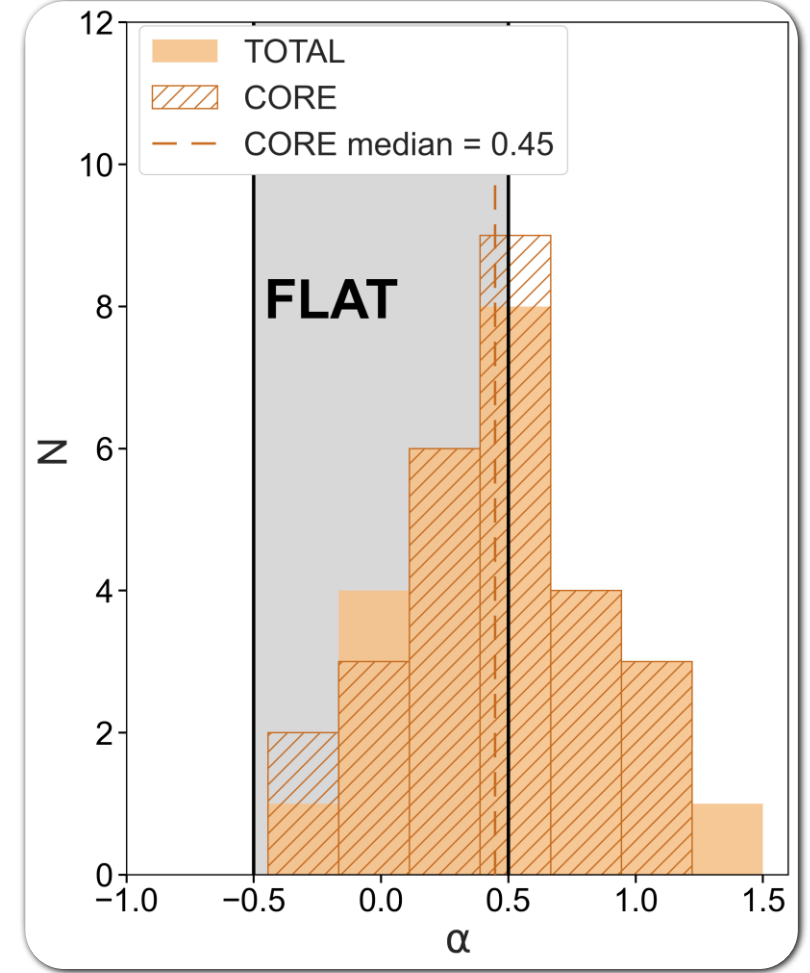
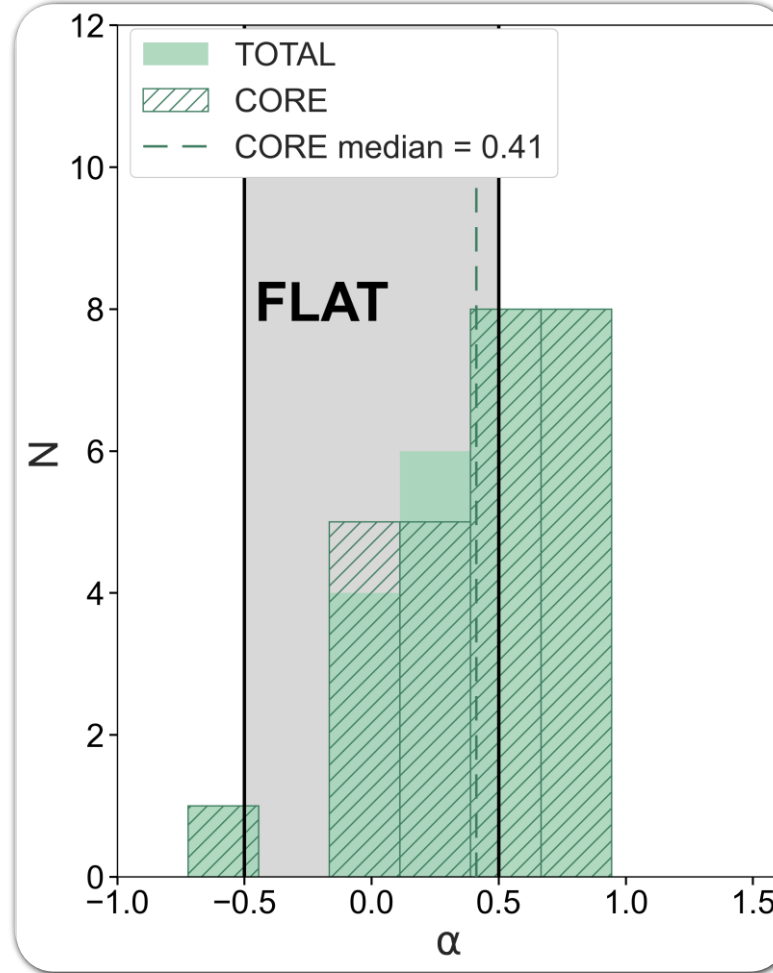
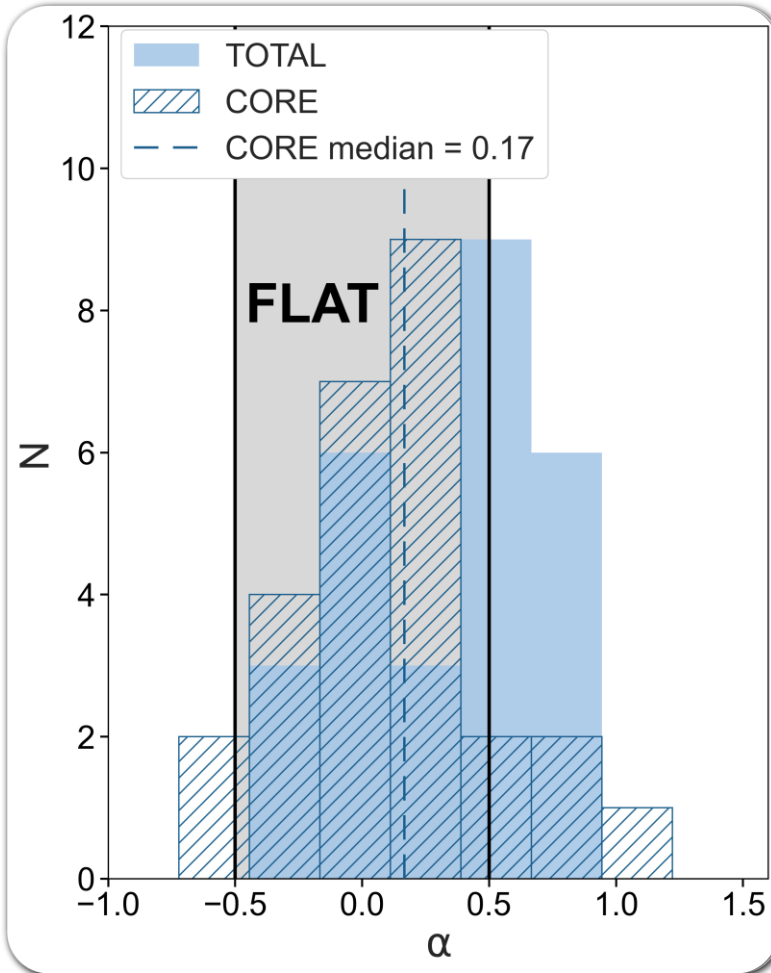


Penna et al. to be subm.

# Spectral Index

$$S_\nu \propto \nu^{-\alpha}$$

Penna et al. to be subm.



0.15 – 1.5 GHz

1.5 – 4.5 GHz

4.5 – 7.5 GHz

CORE:

5 steep

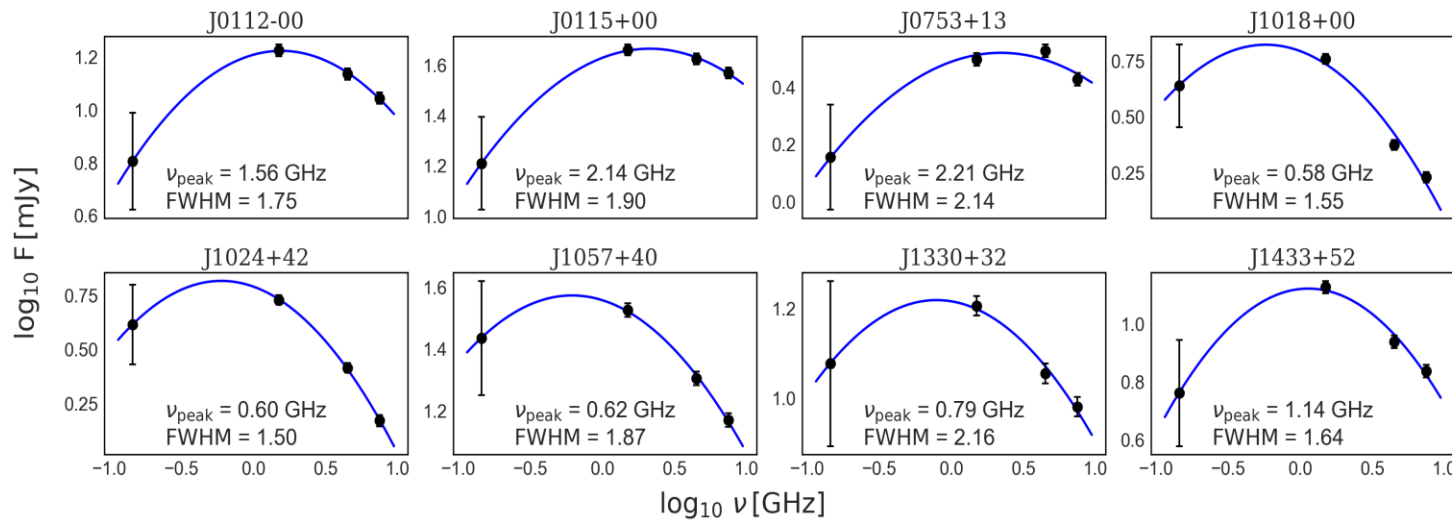
10 steep

11 steep

# Are they Young RGs?

Testing the dynamic scenario

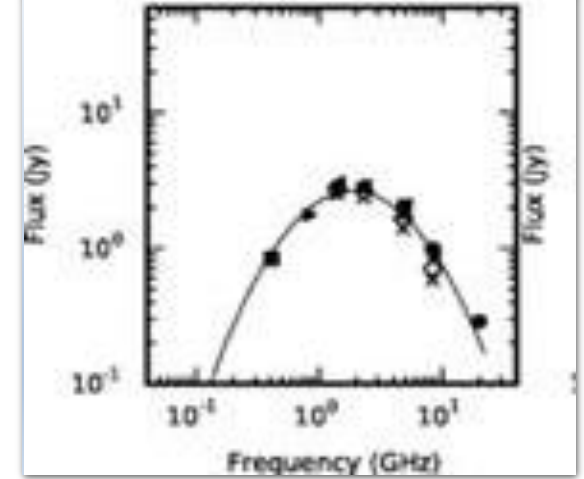
$$\log S(\nu) = \log S_m - b(\log \nu - \log \nu_m)^2$$



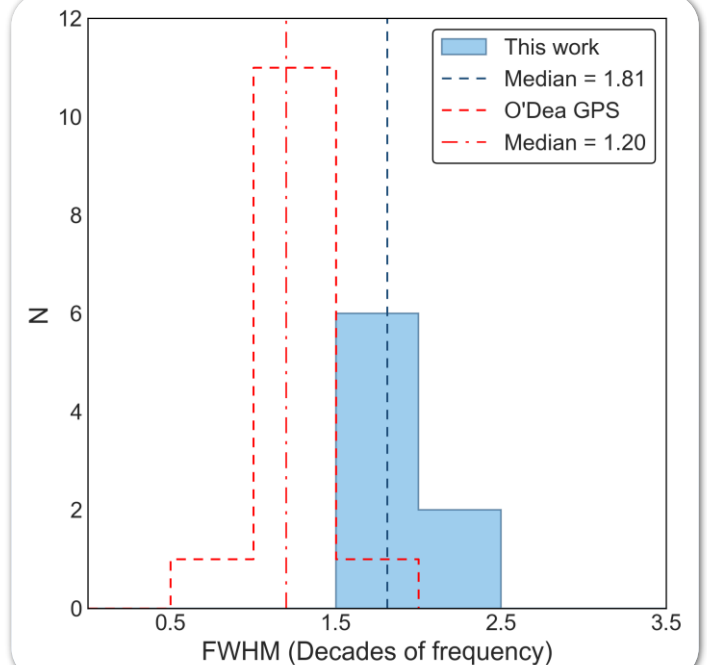
Penna et al. to be subm.

Mostly NOT young RGs, possible 10–15%

GPS source Spectrum



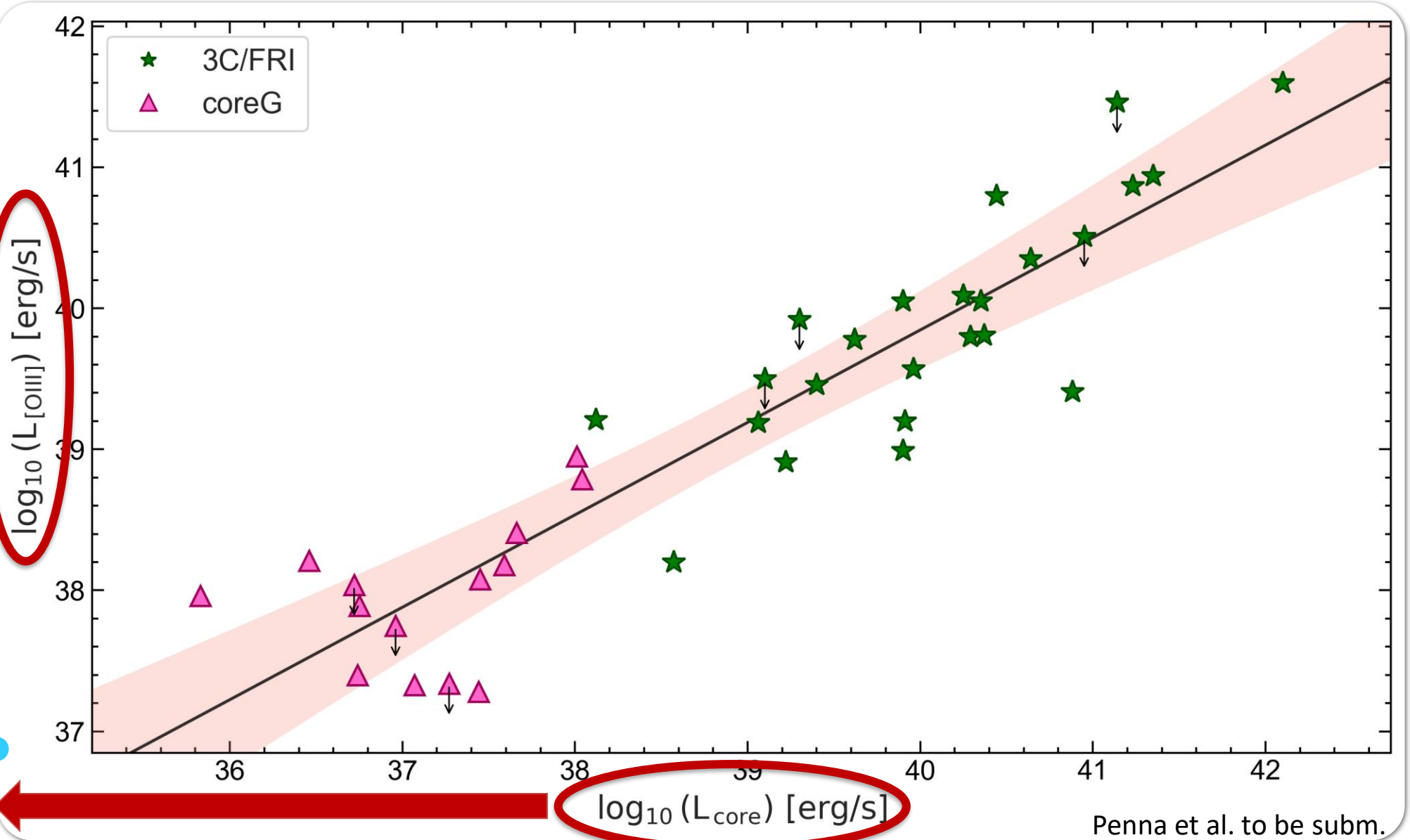
K. E. Randall et al 2011



Penna et al. to be subm.

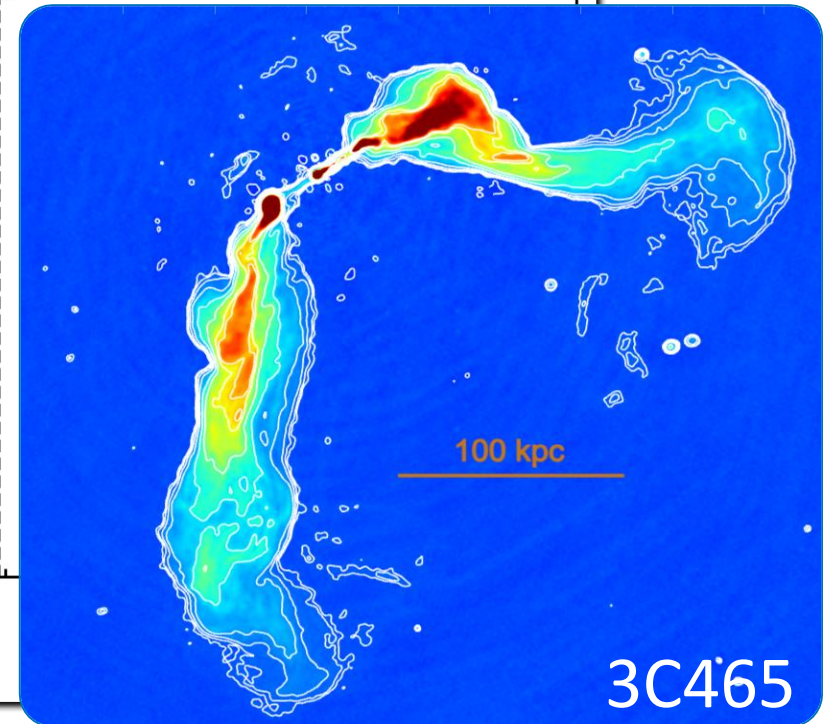
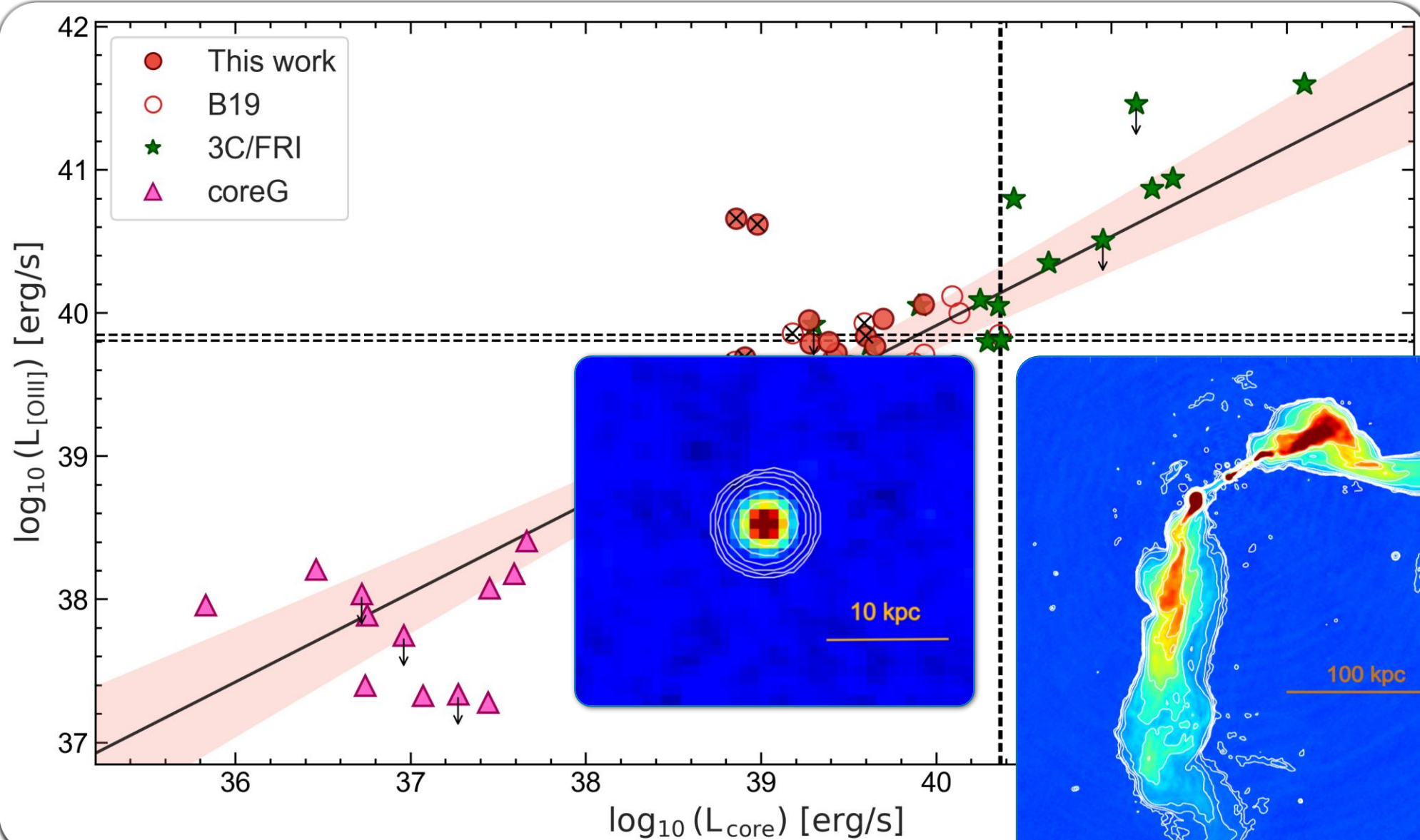
# Accretion – Ejection

[OIII] luminosity  
proxy accretion



Core luminosity  
proxy ejection

# Accretion – Ejection



# Cosmological Neighbours

| Cosmological Neighbours |          |                        |         |
|-------------------------|----------|------------------------|---------|
| Sample                  | <i>N</i> | $N_{\text{cn}}^{2000}$ |         |
|                         |          | Median                 | Average |
| FR0CAT                  | 104      | 13                     | 21.95   |
| FRICAT                  | 23       | 44                     | 47.87   |
| This work               | 27       | 11                     | 23.96   |
| This work + B19         | 45       | 11                     | 19.20   |

FR0  
FRI

Penna et al. to be subm.

Capetti et al, 2020

# Conclusions

**FR0s**: compact RLAGN, few exceptions

➤ **Core SEDs**  
mostly **NOT YOUNG**

➤ **ACCRETION-EJECTION:**

➤ **MORPHOLOGY**  
mostly **COMPACT**

➤ **CORE EMISSION**  
mostly **FLAT**



**Dynamic scenario**

Compact because young or recurrent phase of RLAGN

1) Not due to *line of sight*,

2) **similar engine to FRIs, but:**



**Static scenario**

Compact because Intrinsic properties  
e.g. low BH spin, weak B, jet composition

# **The radio properties of FR0 radio galaxies: a multi-frequency study with VLA and LOFAR**

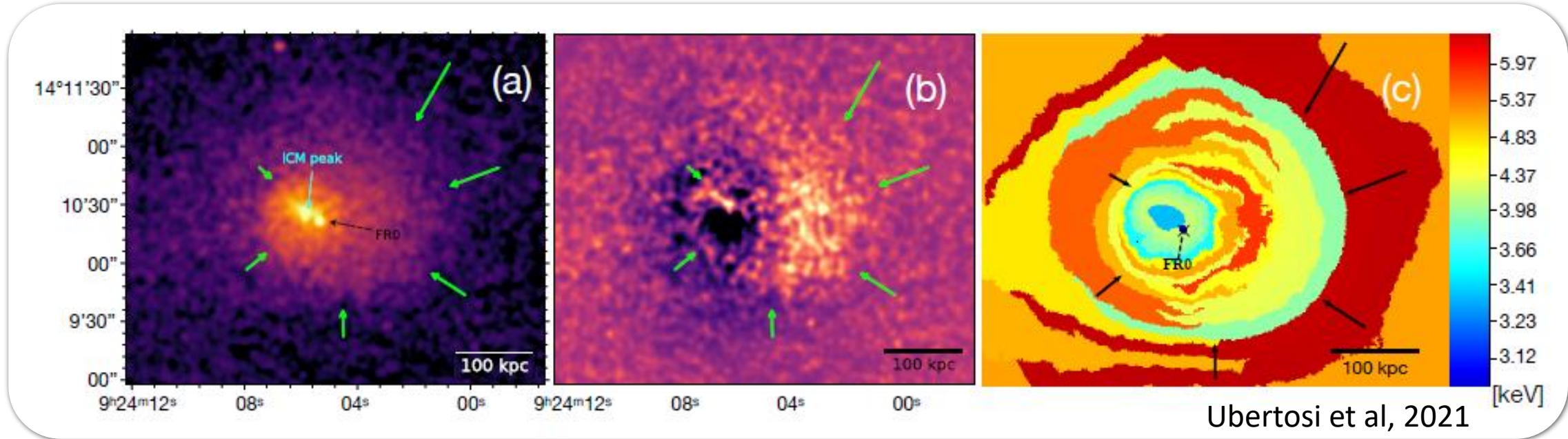
L. Penna<sup>1,2</sup>, R. D. Baldi<sup>3</sup>, M. Brienza<sup>3</sup>, M. Gitti<sup>1,3</sup>, A. Capetti<sup>4</sup>, F. Loi<sup>2</sup>, G. Giovannini<sup>1,3</sup>, and V. Vacca<sup>2</sup>

# Thanks!



*Extra Slides*

# Environment 1: X-RAY & feedback



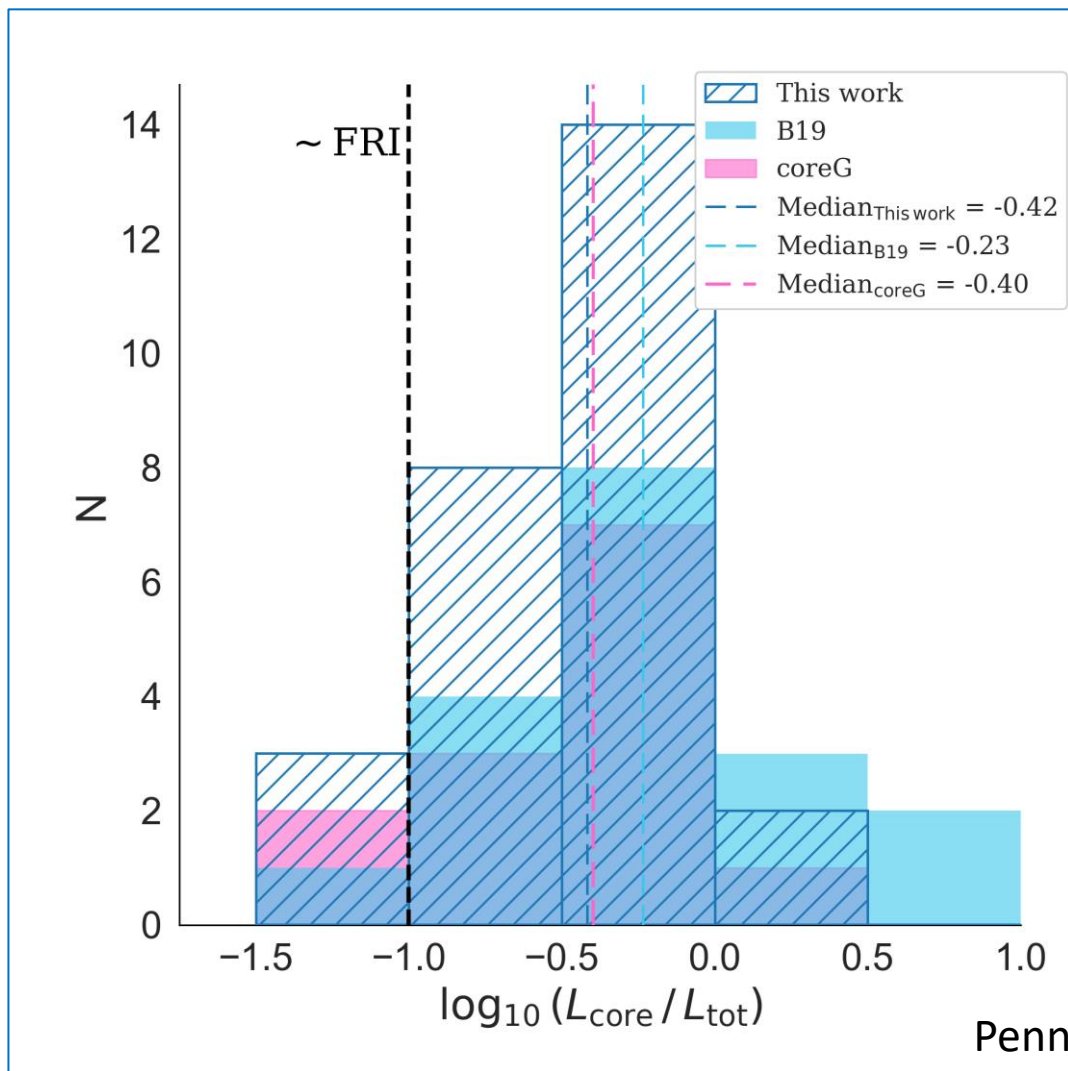
The position of a pair of X-ray cavities is consistent with a sloshing-influenced uprise of the bubbles, Need for deeper observations.

...

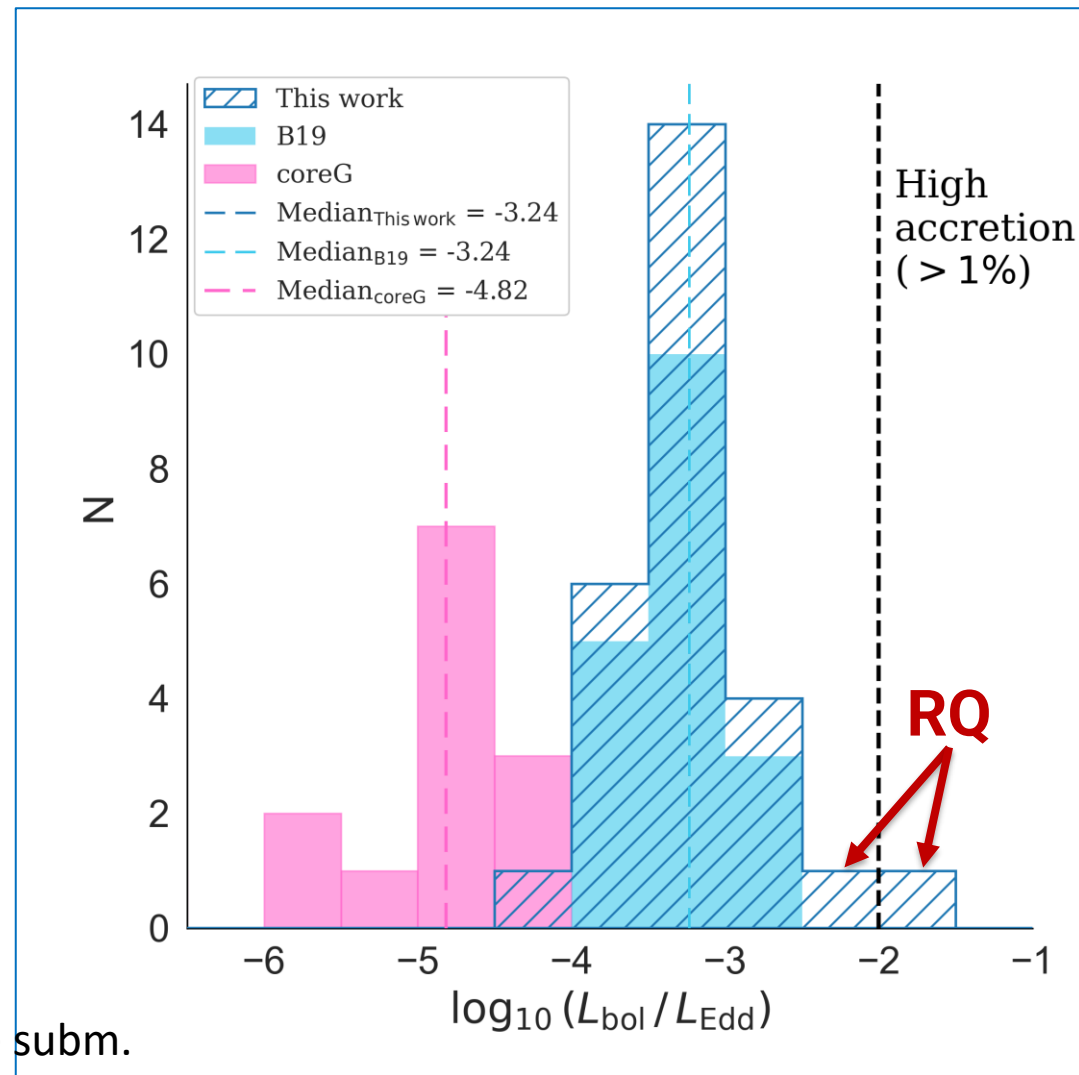
|    |                      |          |       | closest Galaxy Cluster (< 10' on NED) |                               |       | closest Galaxy Group (< 10' on NED) |                      |       |                     |
|----|----------------------|----------|-------|---------------------------------------|-------------------------------|-------|-------------------------------------|----------------------|-------|---------------------|
|    | SDSS name            | ID       | z     | 2 Mpc neighbours                      | Name                          | z     | separation (arcmin)                 | Name                 | z     | separation (arcmin) |
| 1  | J010852.48-003919.40 | J0108-00 | 0.045 | 7                                     | WHL J010917.2-003649          | 0.309 | 6.68                                | Mr19:[BFW2006] 10999 | 0.045 | 7.09                |
| 2  | J011204.61-001442.40 | J0112-00 | 0.044 | 1                                     | GMBCG J017.95351-00.13010     | 0.375 | 7.95                                | Mr19:[BFW2006] 11587 | 0.018 | 7.23                |
| 3  | J011515.78+001248.40 | J0115+00 | 0.045 | 39                                    | CODEX WL 55320                | 0.064 | 0.001                               | Mr19:[BFW2006] 11690 | 0.048 | 4.38                |
| 4  | J075354.98+130916.50 | J0753+13 | 0.048 | 11                                    | GMBCG J118.51222+13.29983     | 0.354 | 8.93                                | [TTK2017] 24032      | 0.049 | 1.50                |
| 5  | J080716.58+145703.29 | J0807+14 | 0.30  | 9                                     | MSPM 00337                    | 0.029 | 2.30                                | [TTK2017] 43125      | 0.030 | 1.10                |
| 6  | J084701.88+100106.60 | J0847+10 | 0.048 | 5                                     | -                             | -     | -                                   | PGC1 1373744 GROUP   | -     | 4.20                |
| 7  | J101806.67+000559.70 | J1018+00 | 0.048 | 5                                     | SDSS CE J154.452652-00.028628 | 0.095 | 8.94                                | PM2GC GR1152         | 0.064 | 5.00                |
| 8  | J102403.28+420629.80 | J1024+42 | 0.044 | 19                                    | WHL J102403.3+420240          | 0.451 | 3.83                                | SDSSCGB 59915        | -     | 3.33                |
| 9  | J104811.90+045954.80 | J1048+04 | 0.034 | 5                                     | MSPM 00986                    | 0.026 | 2.43                                | [TTK2017] 09838      | 0.027 | 2.59                |
| 10 | J104852.92+480314.80 | J1048+48 | 0.041 | 9                                     | WHL J104834.7+475950          | 0.432 | 4.58                                | -                    | -     | -                   |
| 11 | J105731.16+405646.10 | J1057+40 | 0.025 | 8                                     | GMBCG J164.43209+41.00995     | 0.132 | 4.50                                | [TTK2017] 17104      | 0.026 | 5.65                |
| 12 | J112029.23+040742.10 | J1120+04 | 0.050 | 19                                    | -                             | -     | -                                   | Mr19:[BFW2006] 07373 | 0.049 | 8.27                |
| 13 | J130837.91+434415.10 | J1308+43 | 0.036 | 53                                    | WHL J130907.0+433756          | 0.352 | 8.21                                | [TTK2017] 09371      | 0.037 | 0.68                |
| 14 | J133042.51+323249.00 | J1330+32 | 0.034 | 43                                    | -                             | -     | -                                   | [TTK2017] 28676      | 0.036 | 5.24                |
| 15 | J134159.72+294653.50 | J1341+29 | 0.045 | 52                                    | NSCS J134159+295116           | 0.050 | 4.38                                | V1CG 207             | 0.044 | 6.14                |
| 16 | J135036.01+334217.30 | J1350+33 | 0.014 | 7                                     | -                             | -     | -                                   | WP 27                | -     | 1.01                |
| 17 | J142724.23+372817.00 | J1427+37 | 0.032 | 22                                    | MSPM 00149                    | 0.032 | 2.80                                | [TTK2017] 30044      | 0.033 | 1.63                |
| 18 | J143312.96+525747.30 | J1433+52 | 0.047 | 46                                    | WHL J143313.0+525748          | 0.046 | 0.004                               | Mr18:[BFW2006] 09950 | 0.044 | 2.33                |
| 19 | J152151.85+074231.69 | J1521+07 | 0.045 | 81                                    | WBL 564                       | 0.045 | 0.001                               | [DRS2017] 000065     | 0.045 | 3.07                |
| 20 | J154147.28+453321.70 | J1541+45 | 0.037 | 24                                    | -                             | -     | -                                   | Mr19:[BFW2006] 17031 | 0.037 | 2.91                |
| 21 | J154426.93+470024.20 | J1544+47 | 0.038 | 15                                    | MSPM 00366                    | 0.037 | 2.20                                | [TTK2017] 14156      | 0.038 | 1.36                |
| 22 | J154451.23+433050.60 | J1544+43 | 0.037 | 11                                    | -                             | -     | -                                   | -                    | -     | -                   |
| 23 | J155953.99+444232.40 | J1559+44 | 0.042 | 10                                    | WHL J160009.1+444158          | 0.439 | 2.74                                | Mr18:[BFW2006] 08475 | 0.041 | 6.82                |
| 24 | J160641.83+084436.80 | J1606+08 | 0.047 | 9                                     | MSPM 01147                    | 0.047 | 0.003                               | SDSSCGB 35387        | 0.328 | 7.13                |
| 25 | J161256.85+095201.49 | J1612+09 | 0.017 | 2                                     | -                             | -     | -                                   | -                    | -     | -                   |
| 26 | J162944.98+404841.60 | J1629+40 | 0.029 | 127                                   | SDSS-C4 3021                  | 0.030 | 0.019                               | SDSSCGB 05030        | -     | 1.32                |
| 27 | J164925.86+360321.30 | J1649+36 | 0.031 | 8                                     | MSPM 01154                    | 0.031 | 0.003                               | SDSSCGB 24334        | -     | 0.55                |

# Core dominance + Accretion

## Core Dominance



## Eddington Ratio



# Future Works

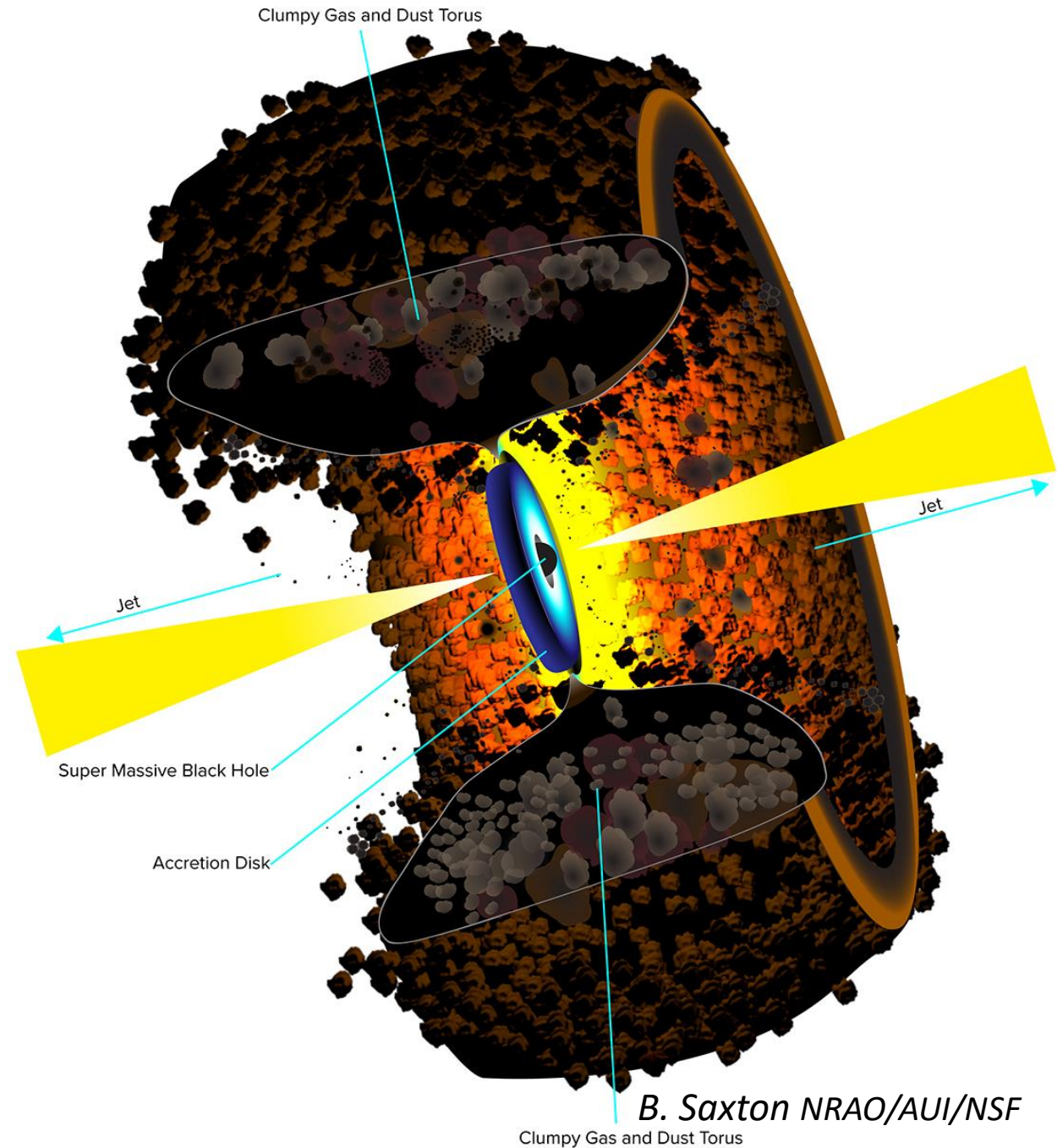
- ❑ Complete FR0CAT sample with high-resolution VLA (1.5 - 4.5 - 7.5 GHz)
- ❑ Multi-frequency observations (e.g. X-ray, gamma-ray)
- ❑ VLBI (eMERLIN, EVN, VLBA) → morphology, jet velocity, jet-sidedness  
→ variability and duty cycle (through multi-epoch campaigns)
- ❑ Pc to kpc-scale follow up → fraction that retains more powerful jets → feedback
- ❑ Expand MHz–GHz observations → presence of optically thin component  
→ help misclassification of young RGs as FR0s

# AGN, RLAGN, RG

- ❑ Central SMBH ( $10^6 - 10^{10} M_{\odot}$ )
- ❑  $\sim 10\%$  active (= accretion)  $\rightarrow$  **AGN**
- ❑ Panchromatic SED
- ❑ Feedback (= ejection)



SMBH-host coevolution



# Data Reduction

❑ *A priori* calibration with VLA pipeline

❑ Manual self-calibration



**86 images**

**$F \sim 1 - 120 \text{ mJy}$**

**$L \sim 10^{38} - 10^{40} \text{ erg/s}$**

❑ Additional surveys:

➤ **LoTSS** → 0.15 GHz, 6''

➤ **RACS** → 0.89 GHz, 25''

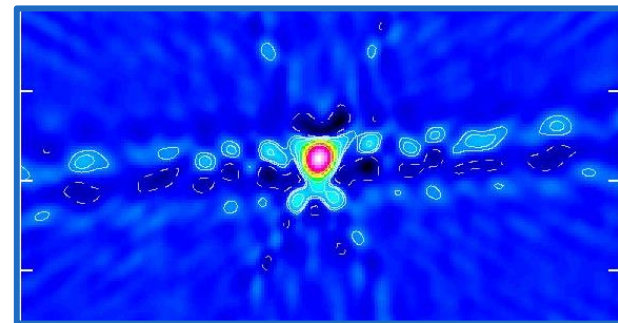
➤ **FIRST** → 1.4 GHz, 5''

➤ **NVSS** → 1.4 GHz, 45''

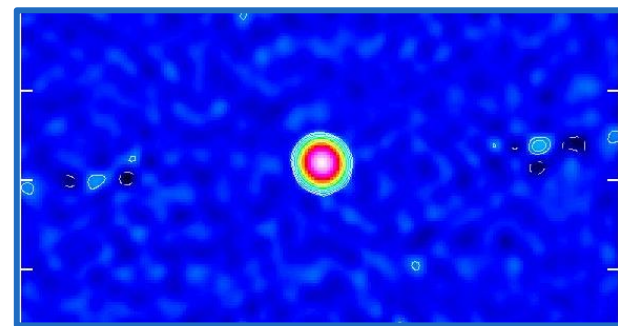
**SEDs**

**0.15 – 7.5 GHz**

**0.3 – 45 arcsec**



**SELF CAL**



# Jet-Sidedness

Jet-ratio= $\frac{F_{Jet,1}}{F_{Jet,2}}$  

| Sample                          | Average jet-ratio |       |
|---------------------------------|-------------------|-------|
|                                 | VLA               | LOFAR |
| Project 2                       | 1.45              | 1.37  |
| B19 ( <i>baldi et al 2019</i> ) | 1.43              | -     |
| Project 1                       | 1.23              | 1.16  |

Penna et al. to be subm.

