Multi-band properties of FR0 radio galaxies

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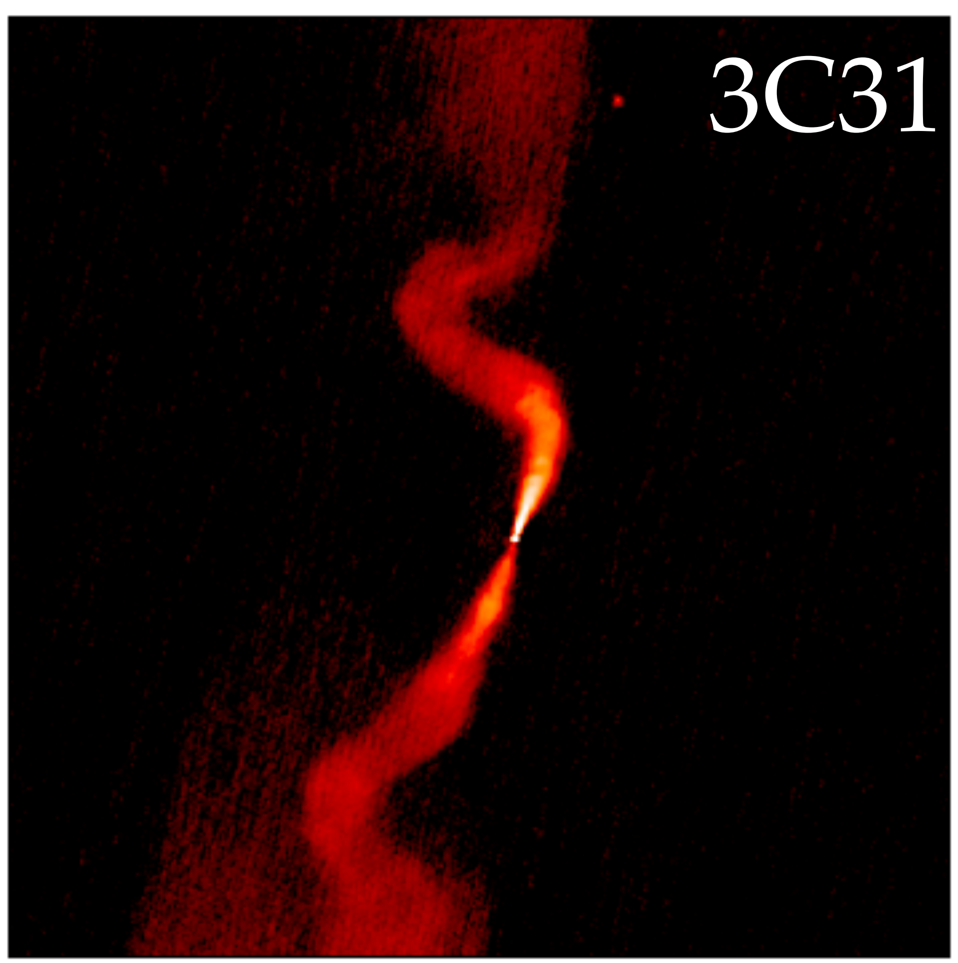
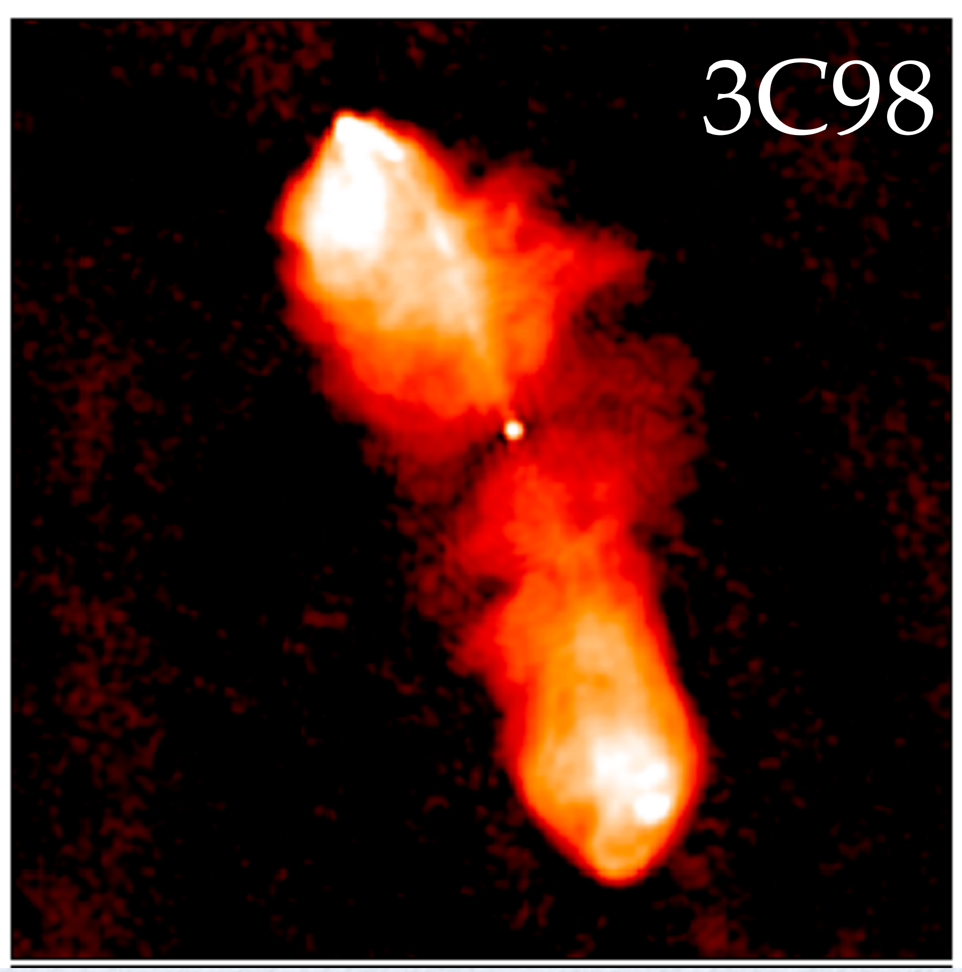
Classic FR-type classification

- **Radio Galaxies** are RL AGNs (***$L_{radio}/L_{optical}$ > 10***) with $L_r = 10^{36} - 10^{46}$ erg s^{-1}.
- Morphologies of extended radio galaxies from pc to Mpc
- **Collimated relativistic jets** connecting the optical galaxy with the extended lobes/plumes
- Typically associated with red massive elliptical galaxies and $M_{BH} > 10^8\ M_{\odot}$ (but exceptions)

FRI - core brightened



FRII - edge brightened



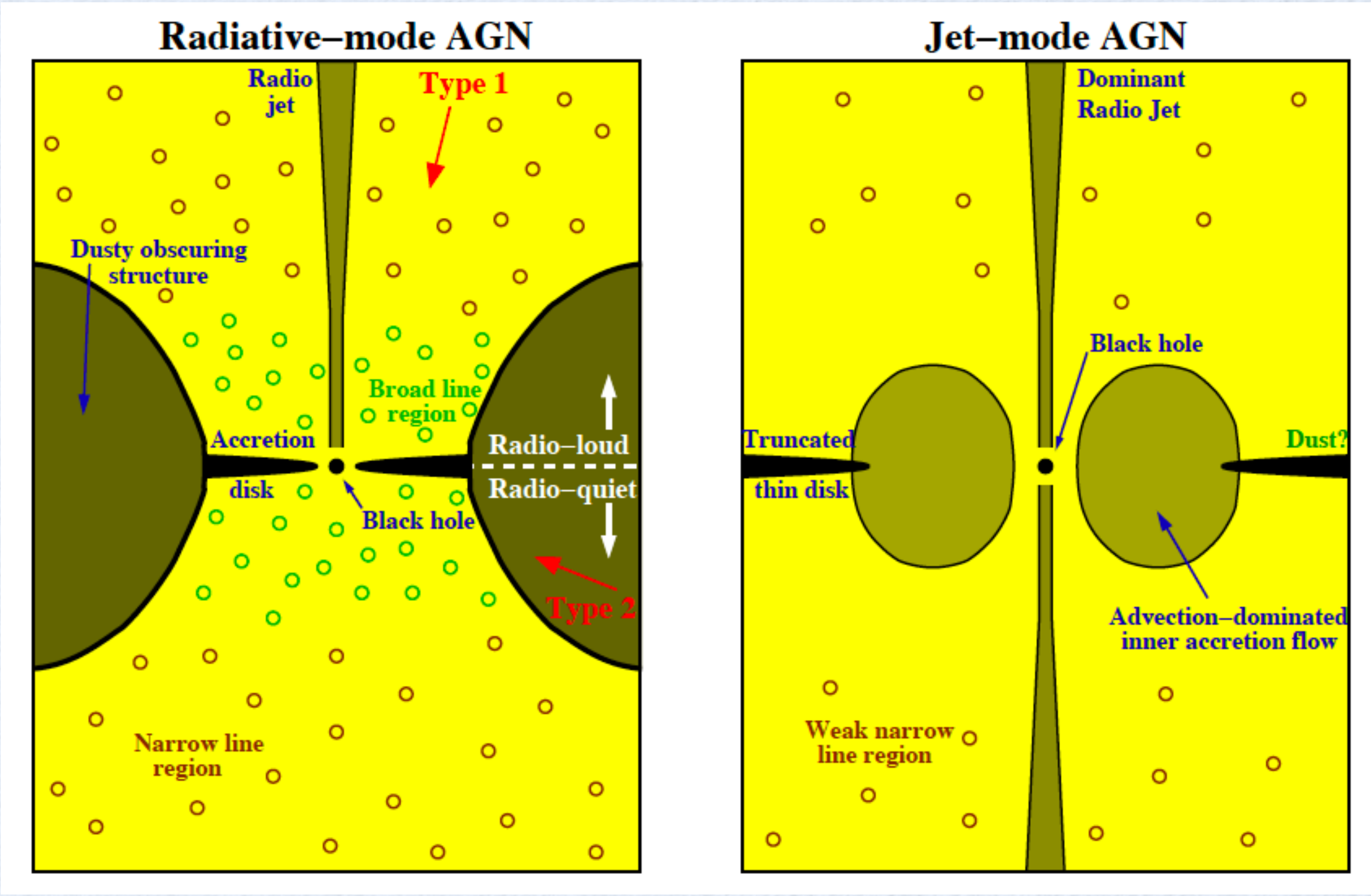
Fanaroff & Riley (1974): pure morphological classification

Two AGN modes

..from emission line ratios (BPT diagrams, e.g. Kewley et al 2006, Buttiglione et al 2010)

RADIATIVE MODE

- Radiatively efficient disc (S&S disc)
- Seyfert/HERG
- Red & blue massive galaxies
- High accretion rate ($\lambda_{Edd} > 10^{-2}$)
- Cold gas accretion
- Powerful jets (FRII)



Heckman & Best (2014)

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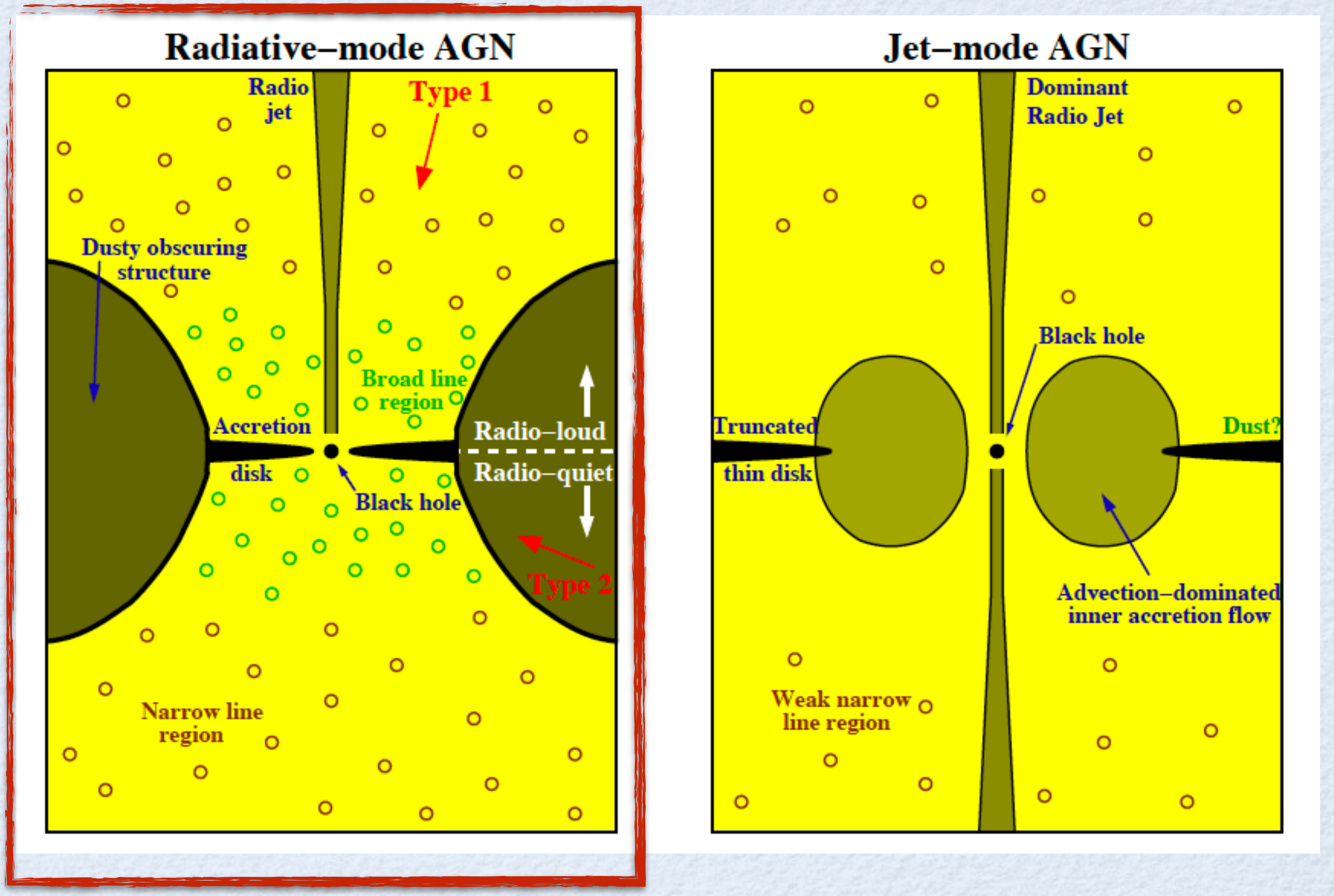


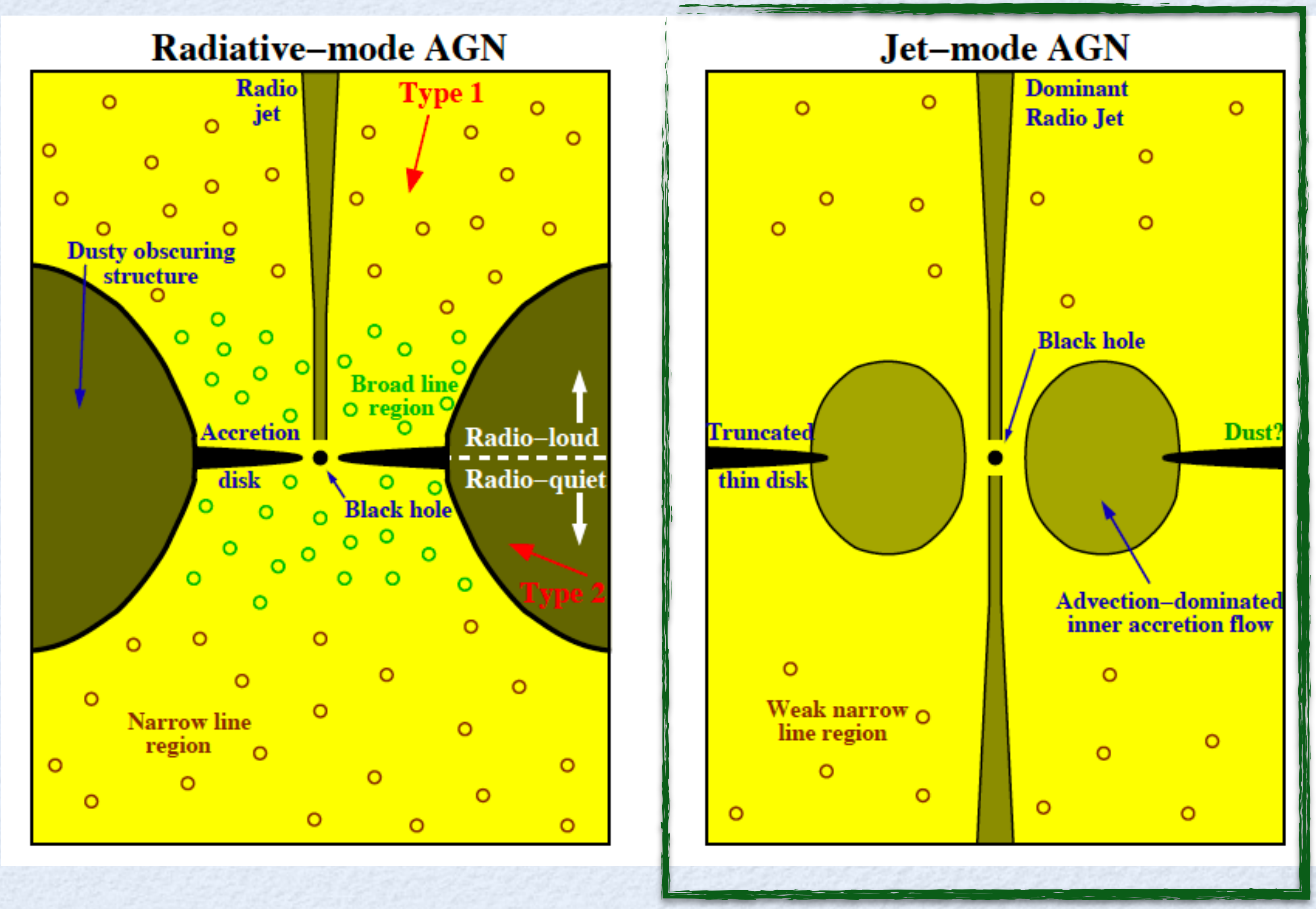
Heckman & Best (2014)

Two AGN modes

..from emission line ratios (BPT diagrams, e.g. Kewley et al 2006, Buttiglione et al 2010)

JET-MODE

- RIAF disc
- LINER/LERG
- Red massive galaxies
- Low accretion rate ($\lambda_{Edd} < 10^{-2}$)
- Hot gas accretion
- Weak and powerful jets (FRI-FRII)

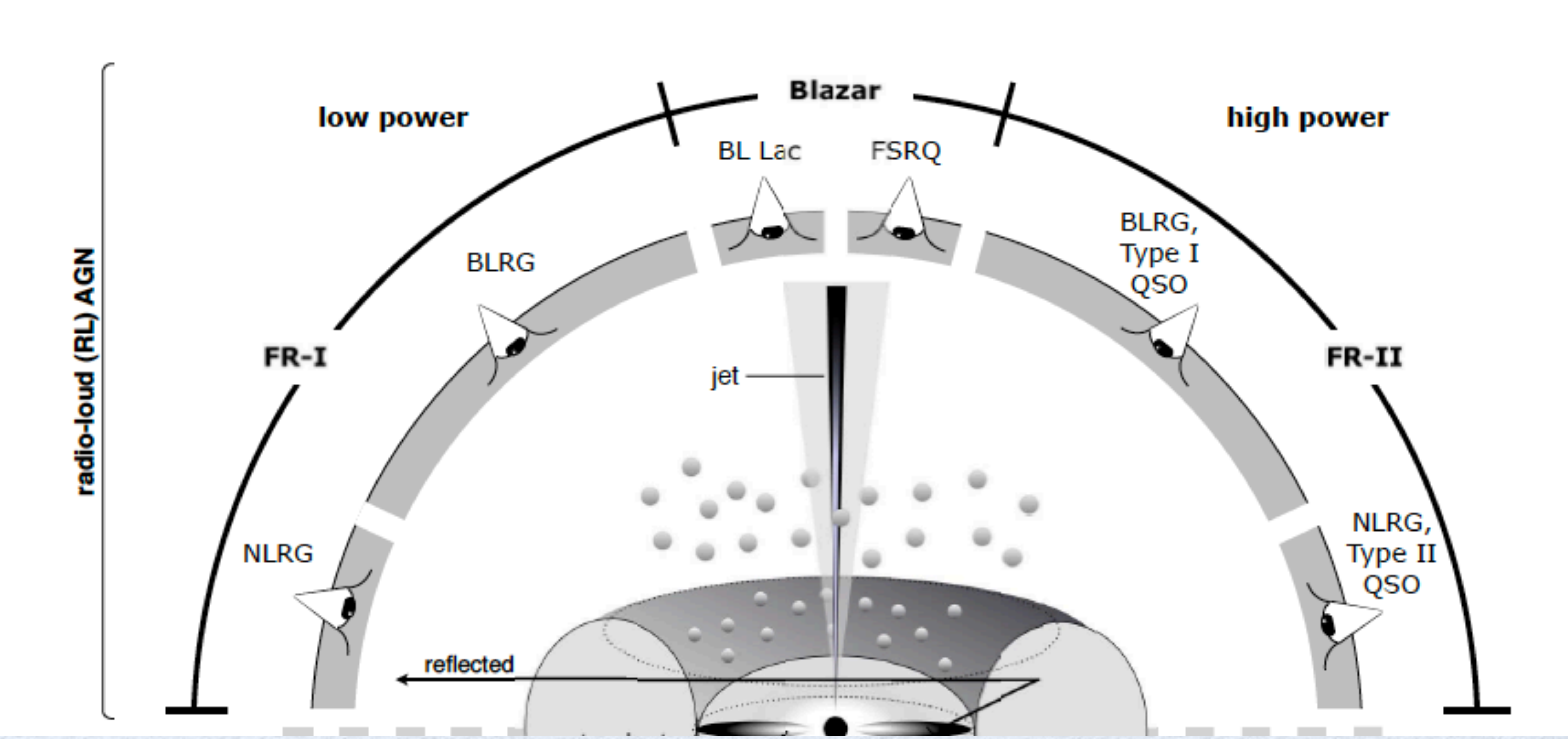


Heckman & Best (2014)

Unification scheme

Orientation-based unification scheme can explain the general radio morphological and multi-band properties of RL AGN, but is not fully successful in describing the details of each class

Urry & Padovani (1995)



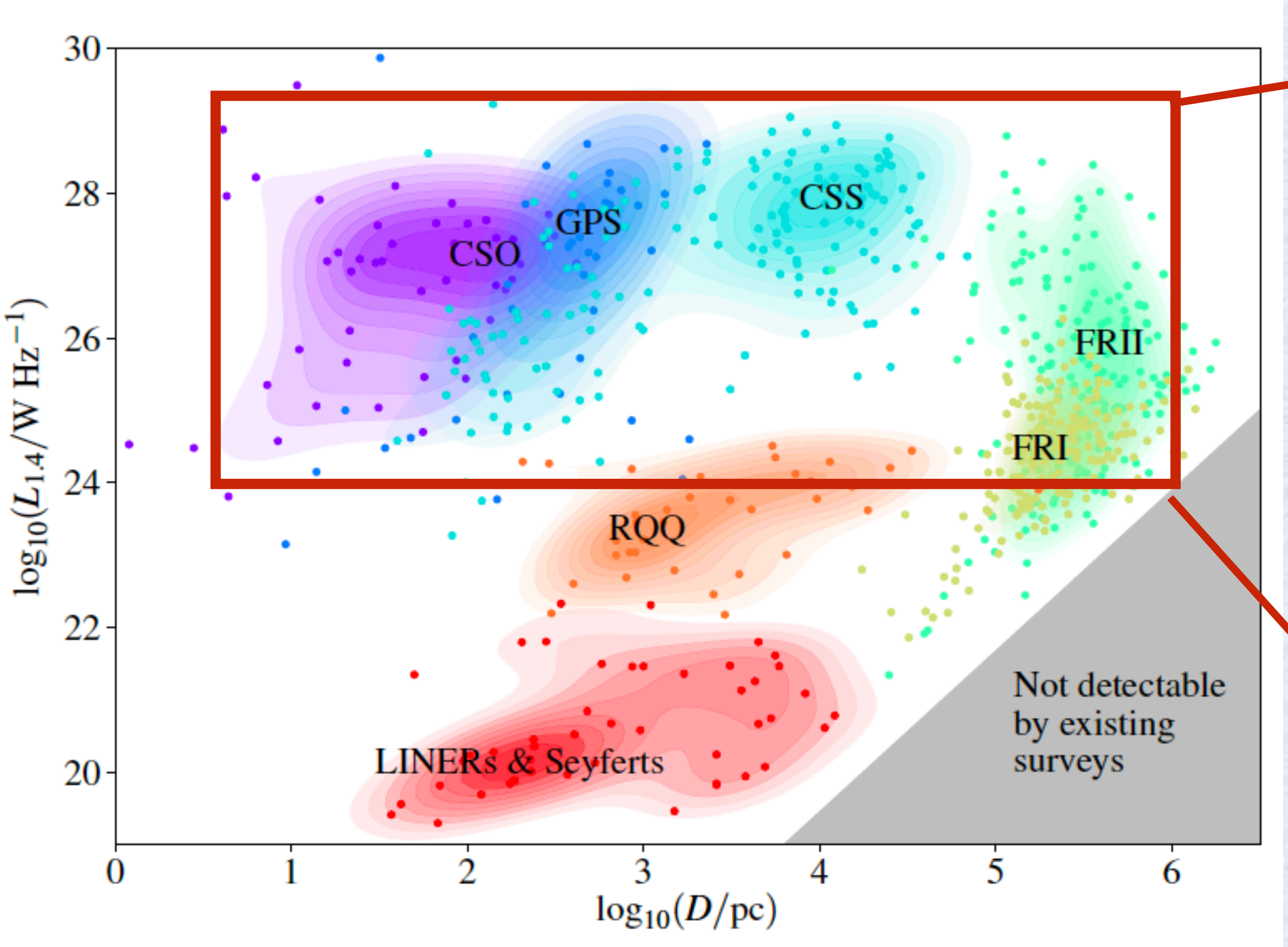
Credits to Beckmann & Shrader (2013)

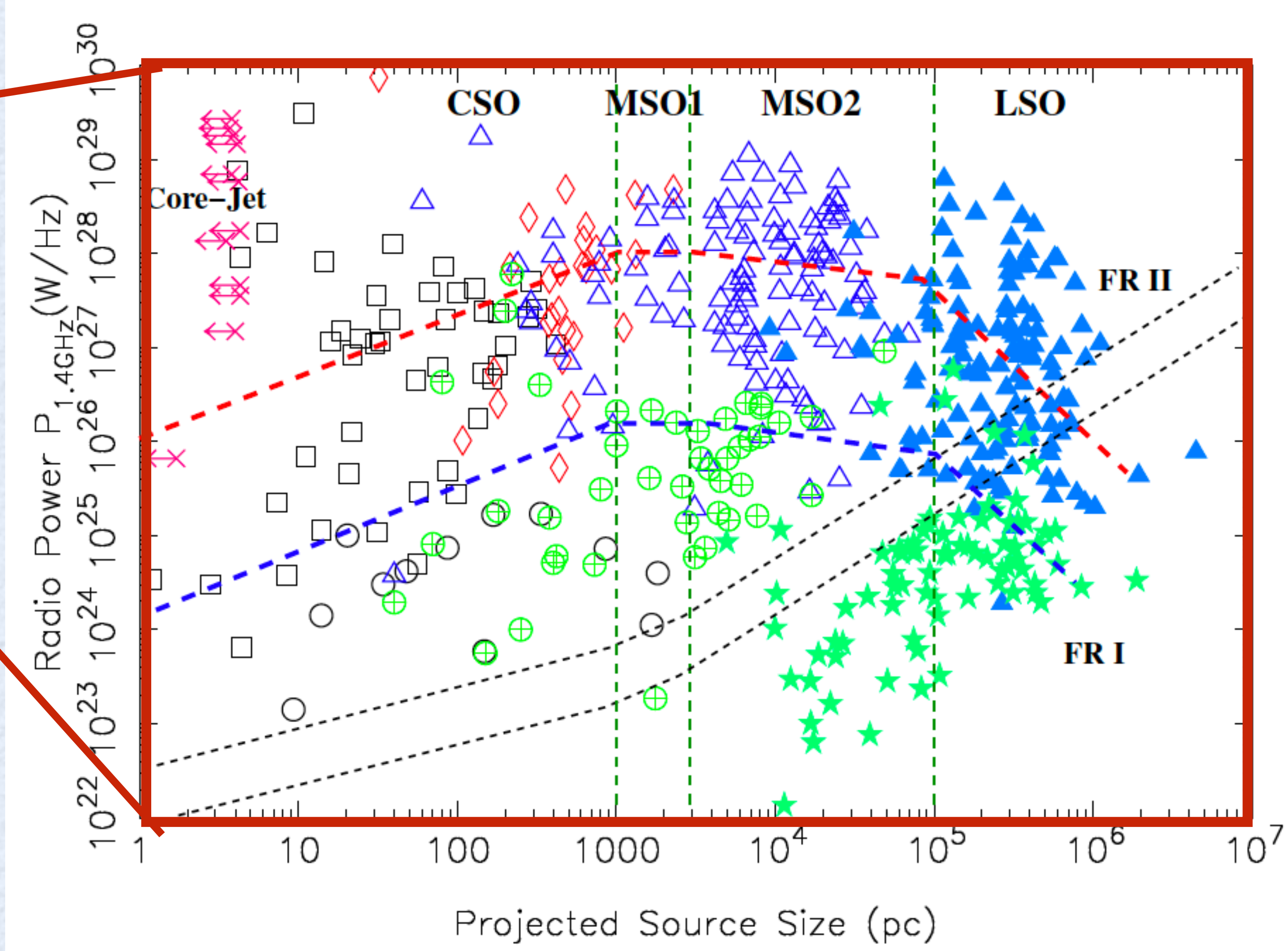
LUMINOSITY - SIZE

Radio size and luminosity can be used as proving of an evolving jetted structure

Hardcastle & Croston (2020)

An & Baan (2012)



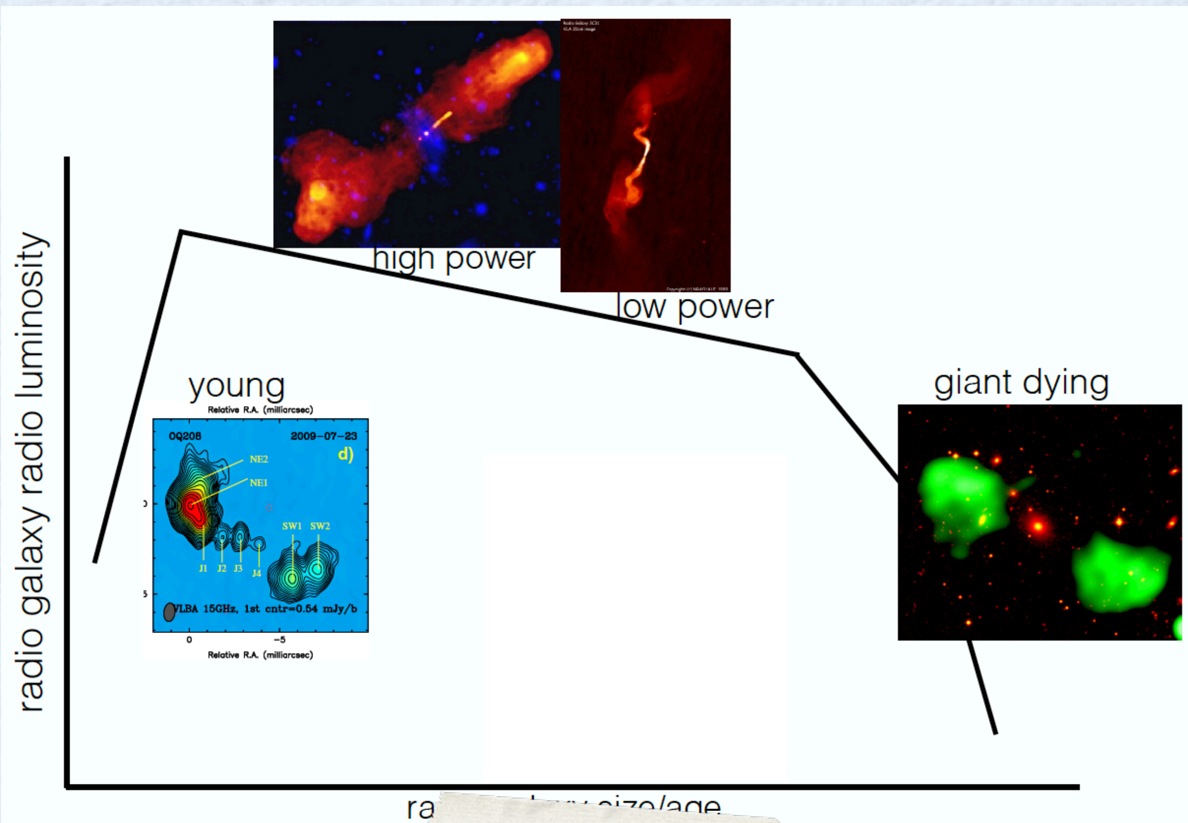


The high luminosity young RGs (CSO, CSS/GPS) could be evolving largely into FRII sources, while the low-luminosity young RGs into FRIs (e.g Kunert-Bajraszewska et al 2010, An & Baan 2012, Kunert-Kunert-Bajraszewska 2016).

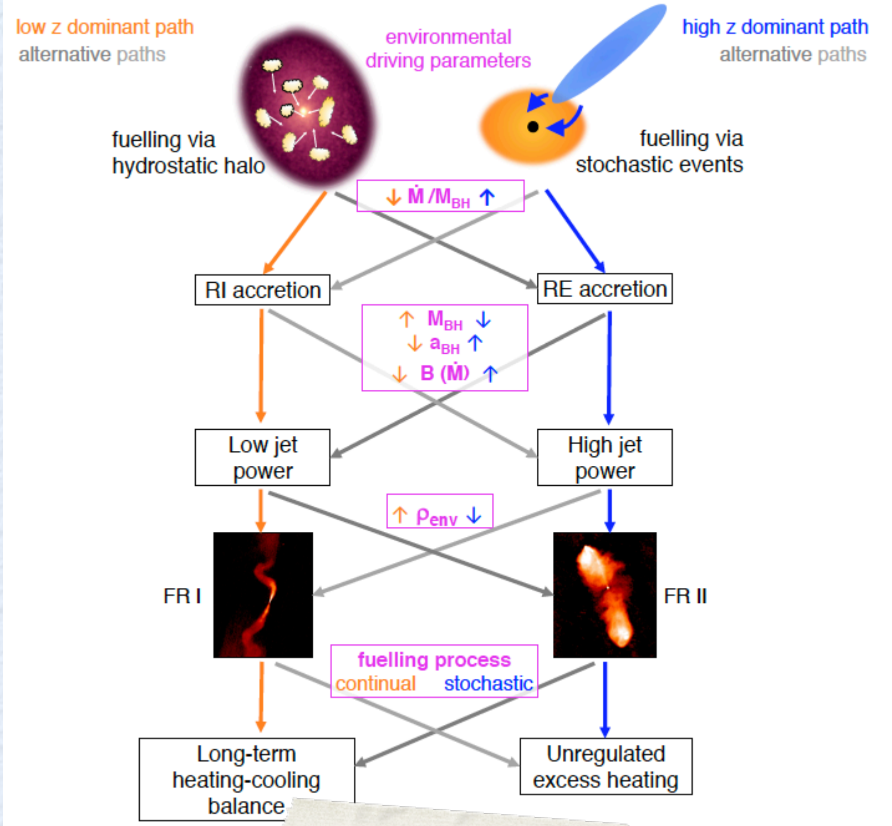
Evolution scheme

Linear lifetime

Credits to G. Migliori



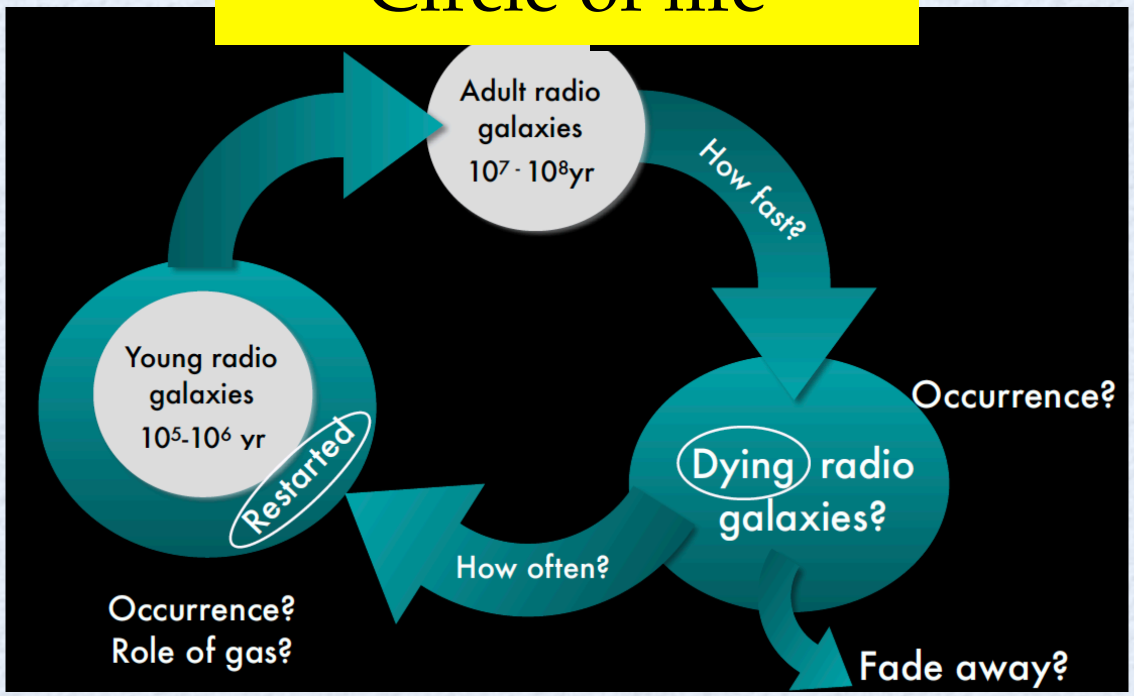
Fuelling / environment



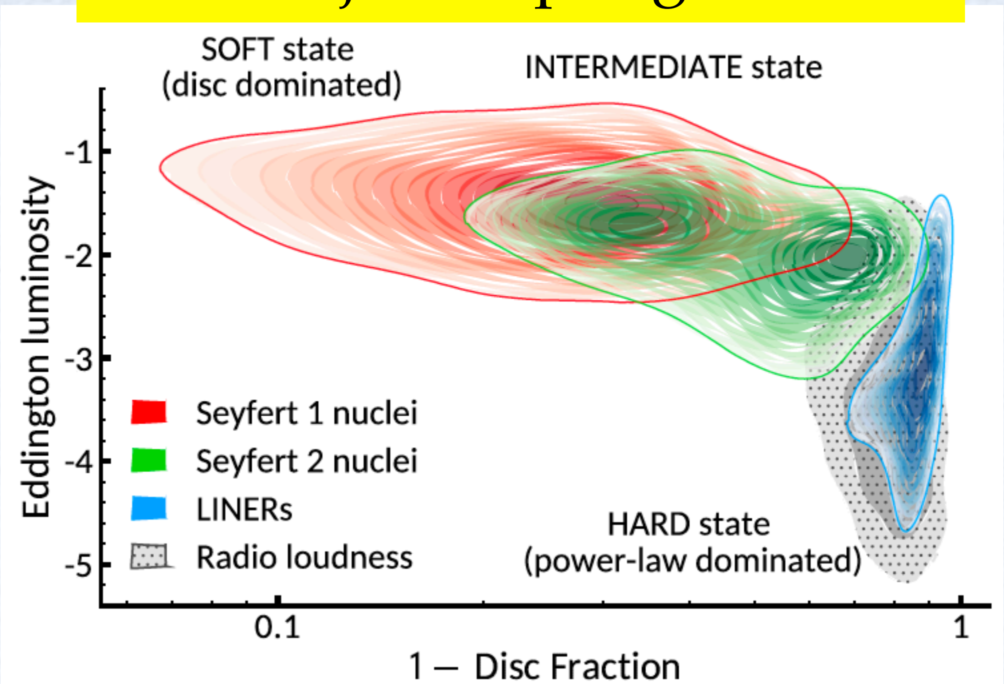
Hardcastle & Croston (2020)

Circle of life

Credits to R. Morganti

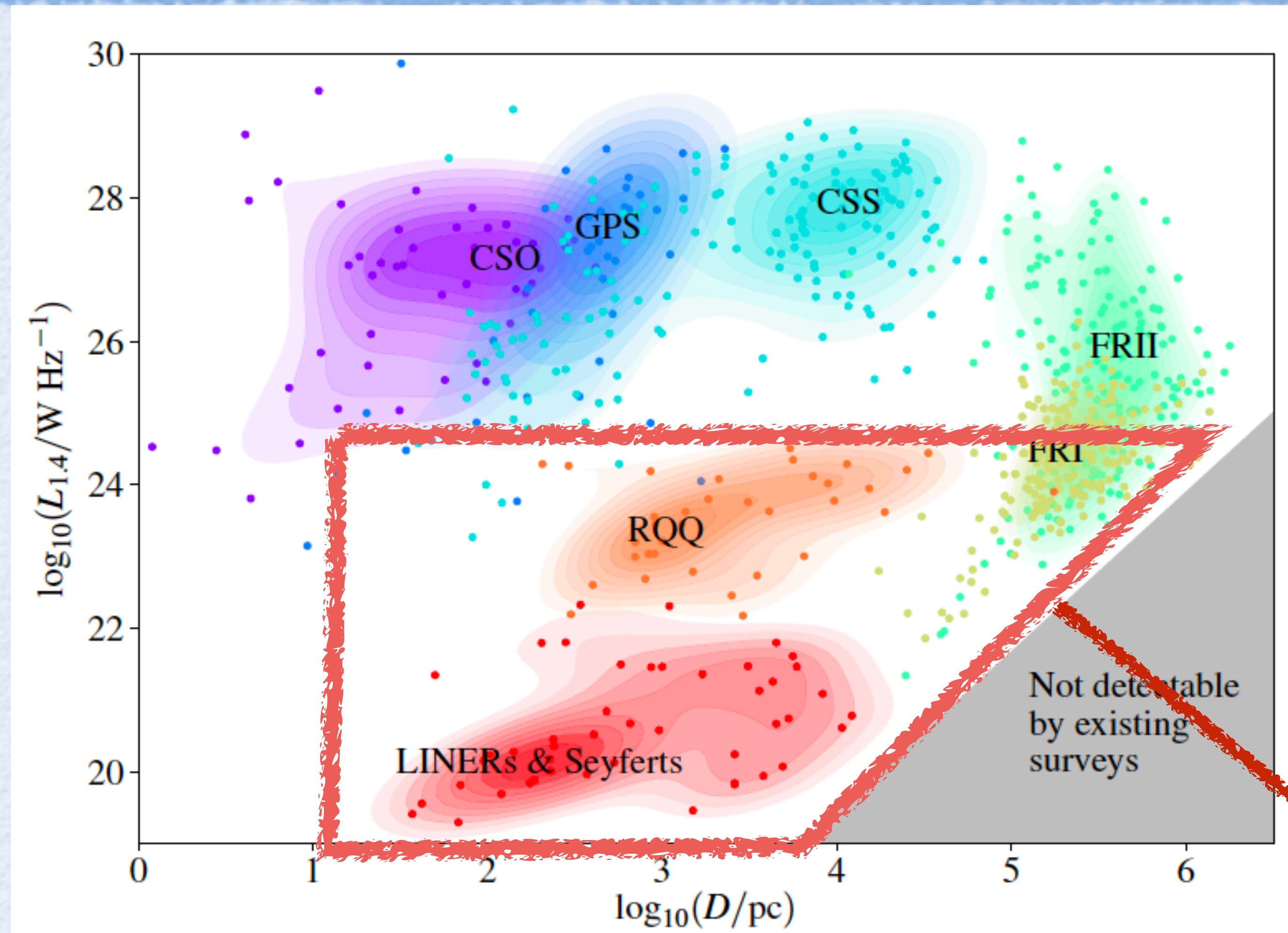


Disc-jet coupling: XRB

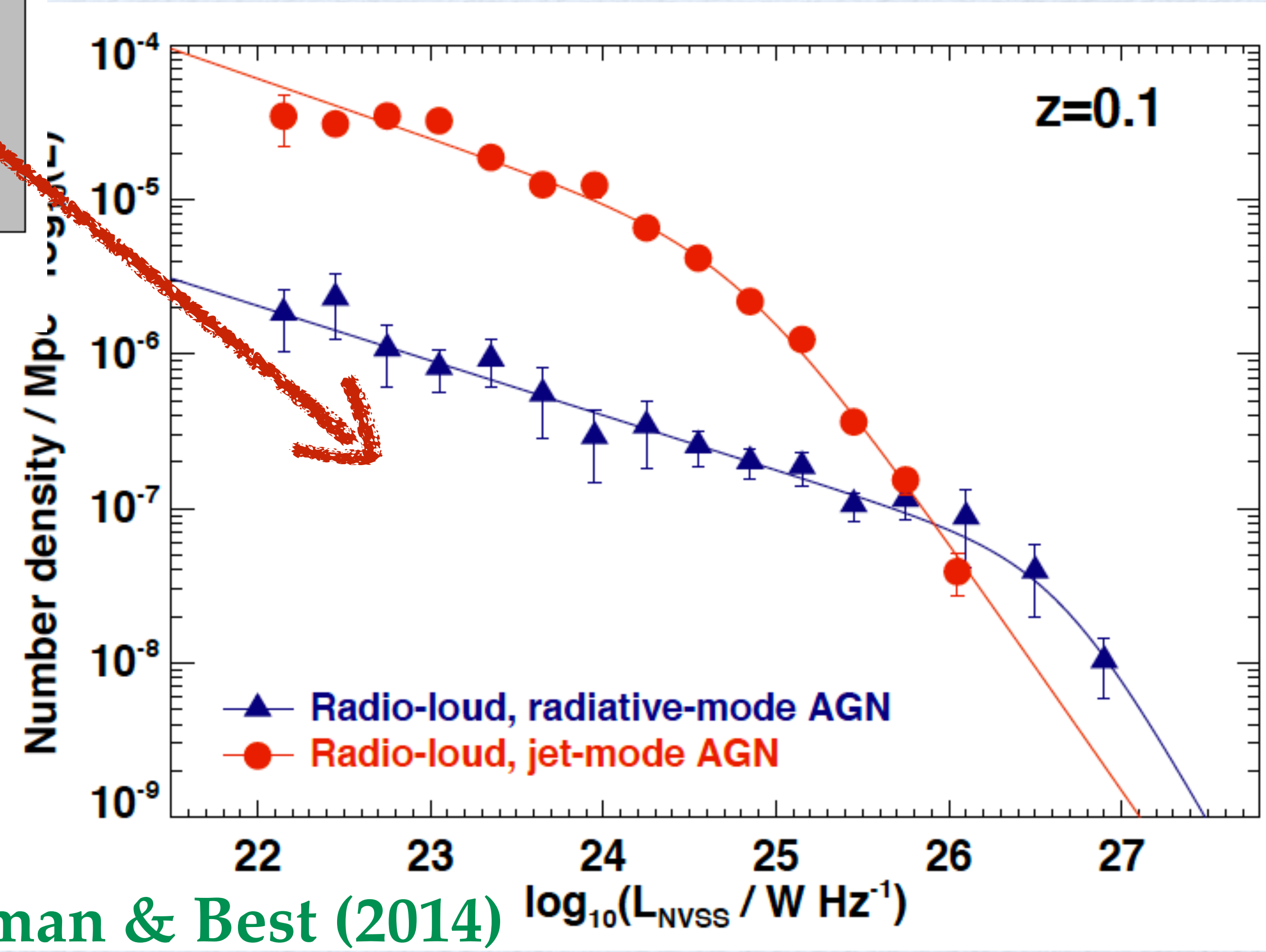


Fernandez-Ontiveros & Munoz-Darias (2021)

RADIO LUMINOSITY FUNCTION



The bulk of the low-luminosity RG population is still unexplored



At lower radio luminosities and sizes the RL AGN models start to be uncertain and no clear picture on their evolution

Heckman & Best (2014)

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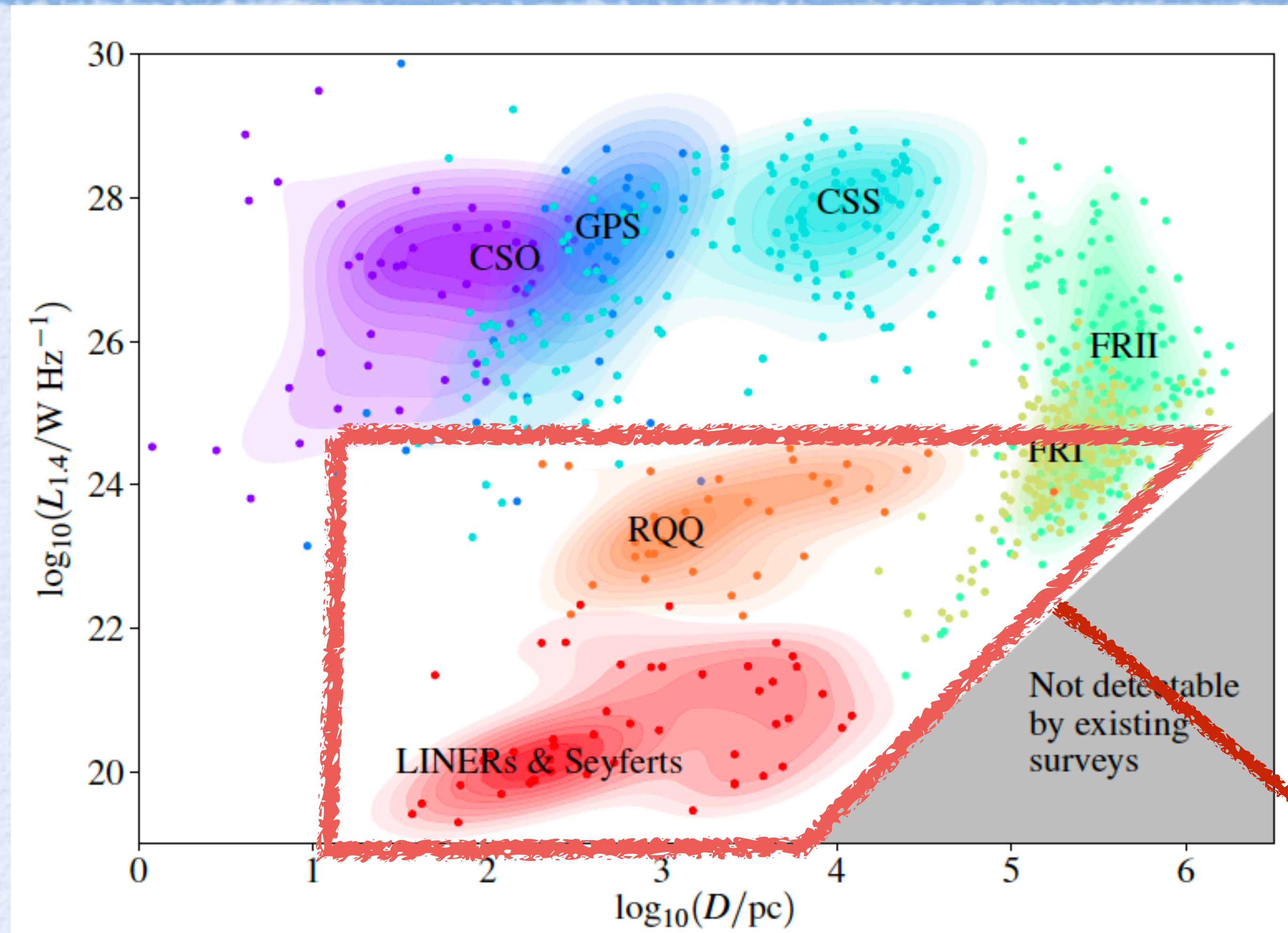

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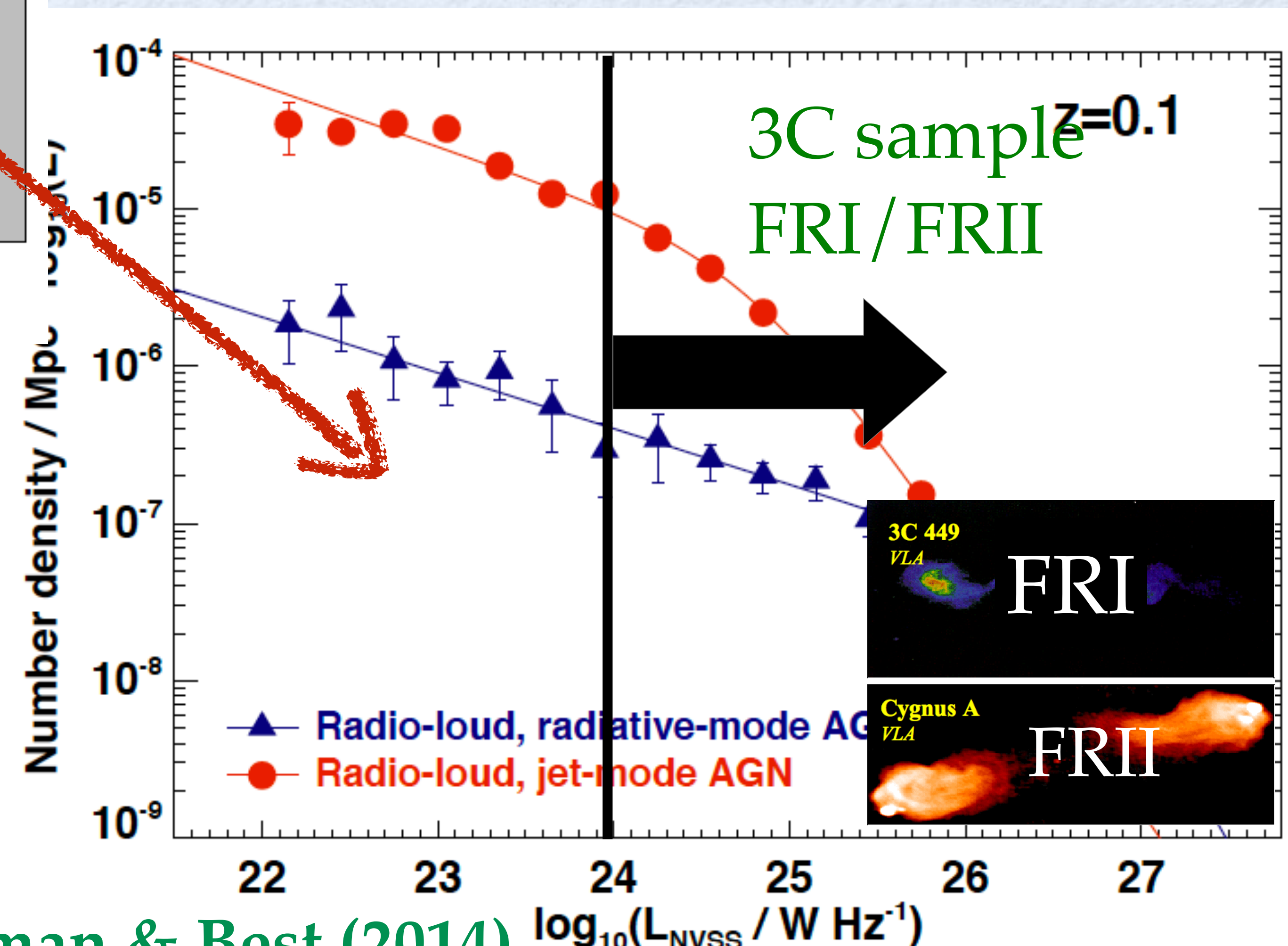

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Heckman & Best (2014)

Why Low-Luminosity radio galaxies are important?

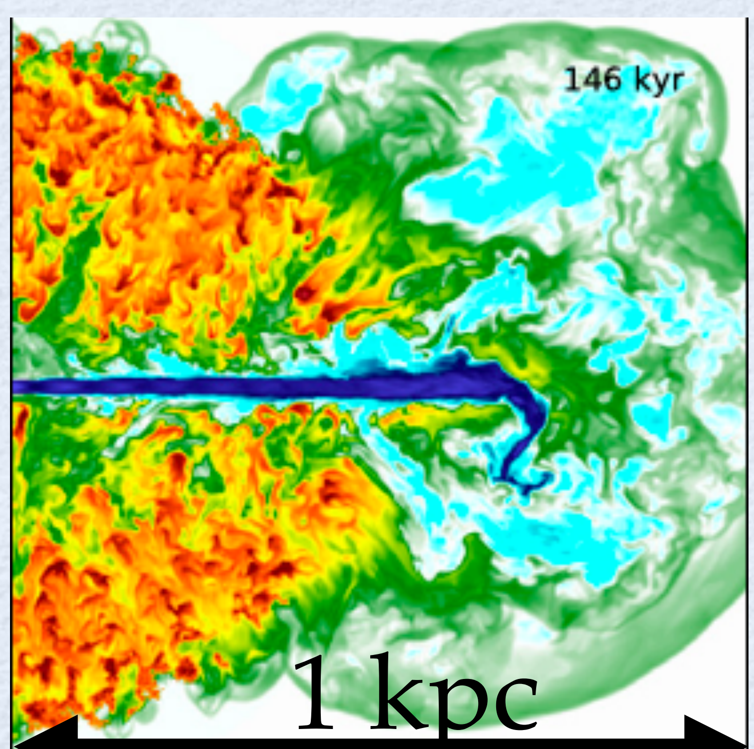
★ The bulk of RL AGN population

snapshot of the ordinary relation between the SMBH and its host

★ low-power galactic-scale jets can have a tremendous impact on their hosts by continuously injecting and depositing energy into the host as supported by the state-of-the-art jet simulations.

Morganti et al 2017, Jarvis et al 2019, 2021 Hardcastle et al 2020, Smith et al 2020, Venturi et al 2020, Webster et al 2021

Wagner & Bicknell (2011), Massaglia et al (2016), Mukherjee et al (2018, 2020), Rossi et al (2020)

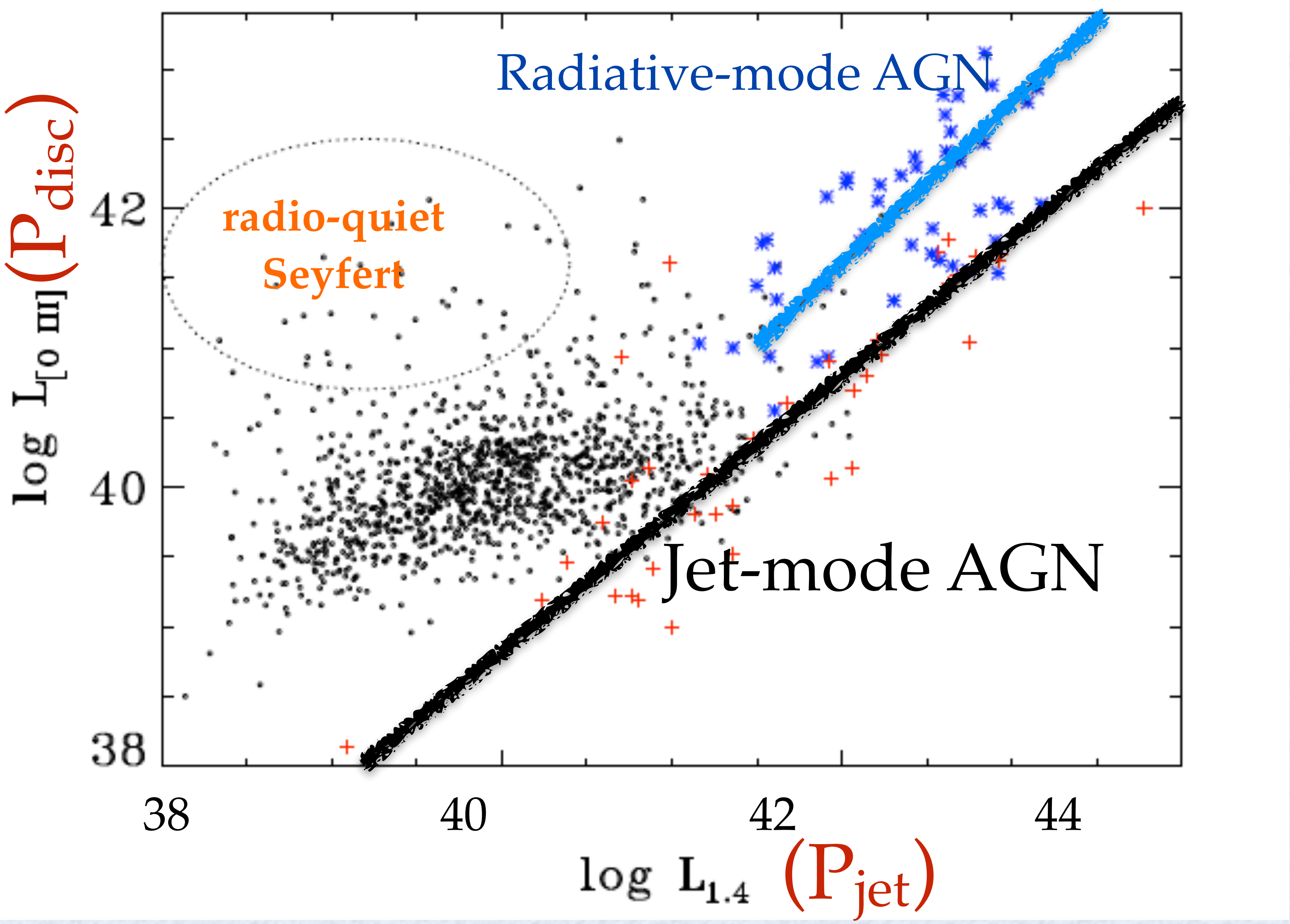


See talk of F. Ubertosi & C. Tadhunter

Studying low luminosity (compact) RGs is crucial to explore the validity of US and ES of RL AGN

Local Radio-Loud AGN population

Best et al. (2005/2012) select 2215/7302 low-luminosity radio-loud AGN cross-matching SDSS (DR2/DR7) and NVSS and FIRST with Flux > 5 mJy in the local Universe (z < 0.3)



Most of the Best et al. sample shows a clear deficit in total radio emission with respect to the classical RG (FRI and FRII).

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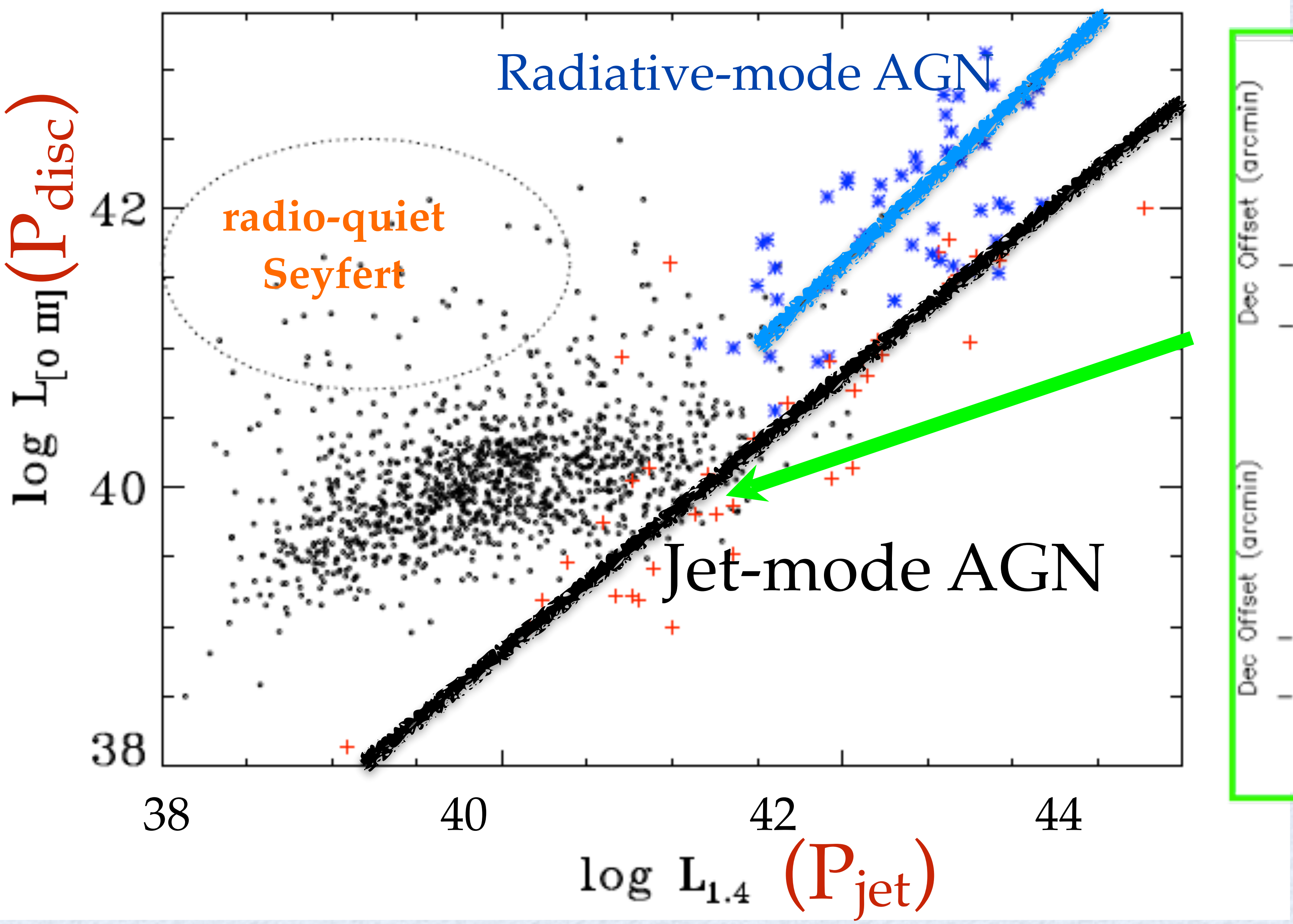

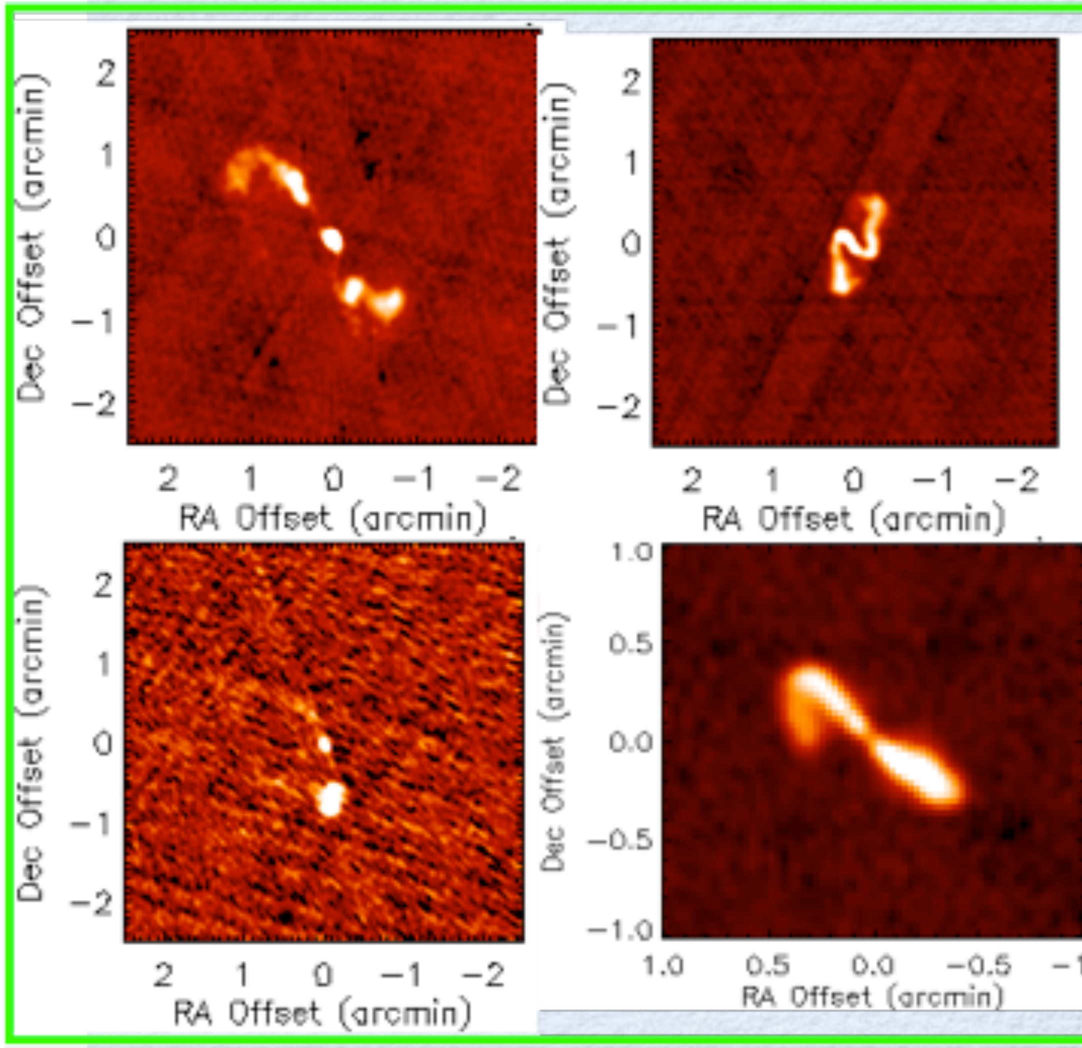

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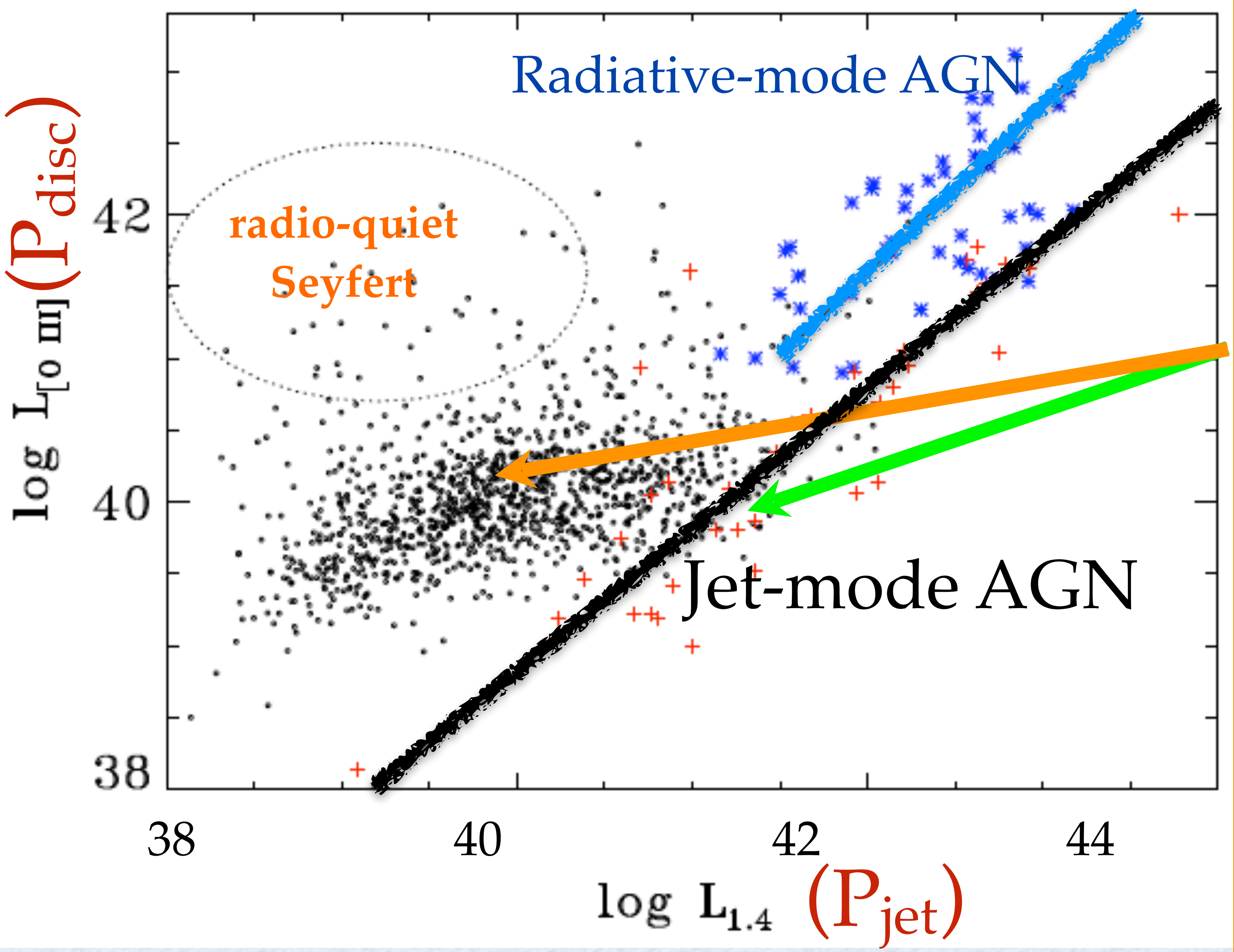

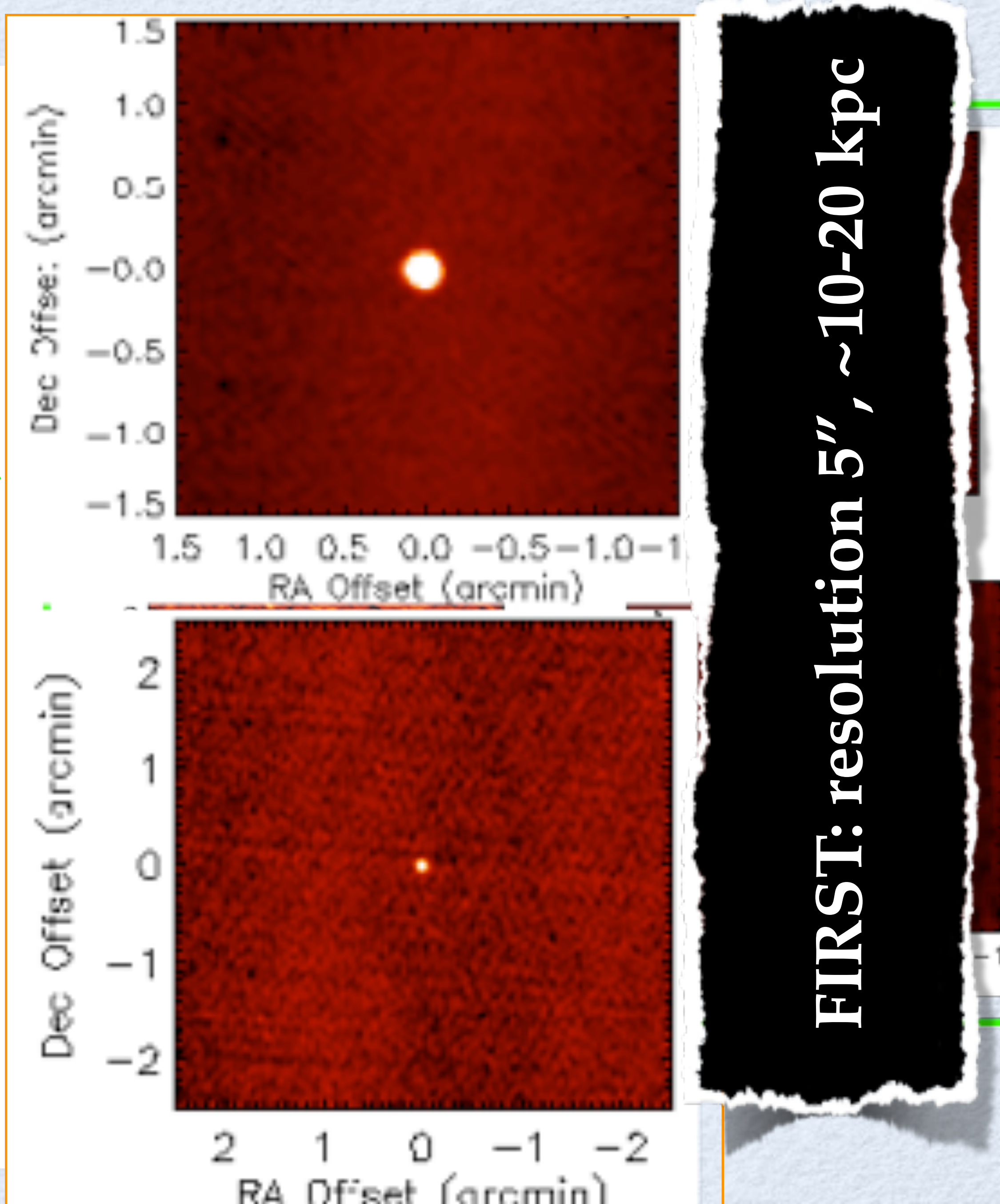

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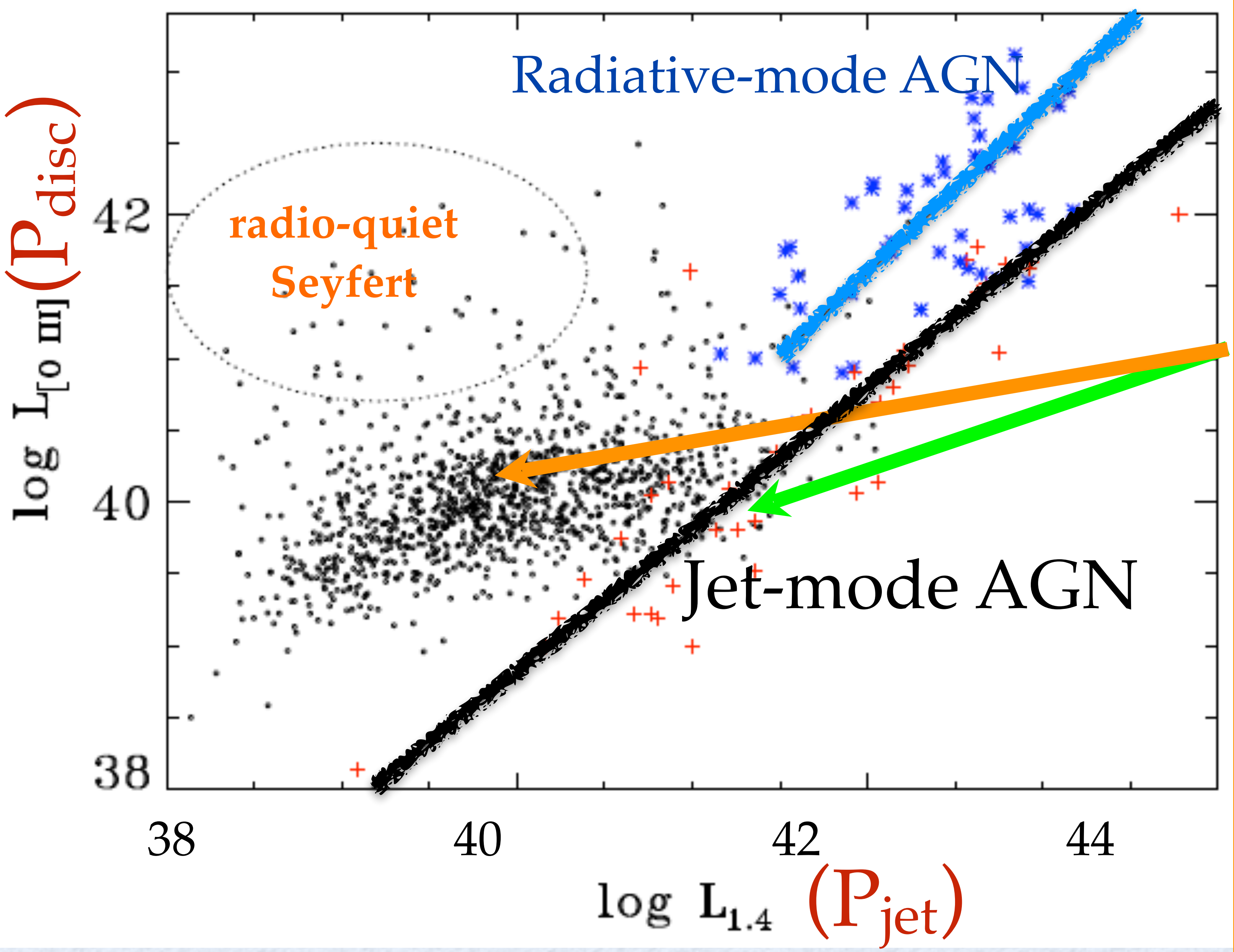
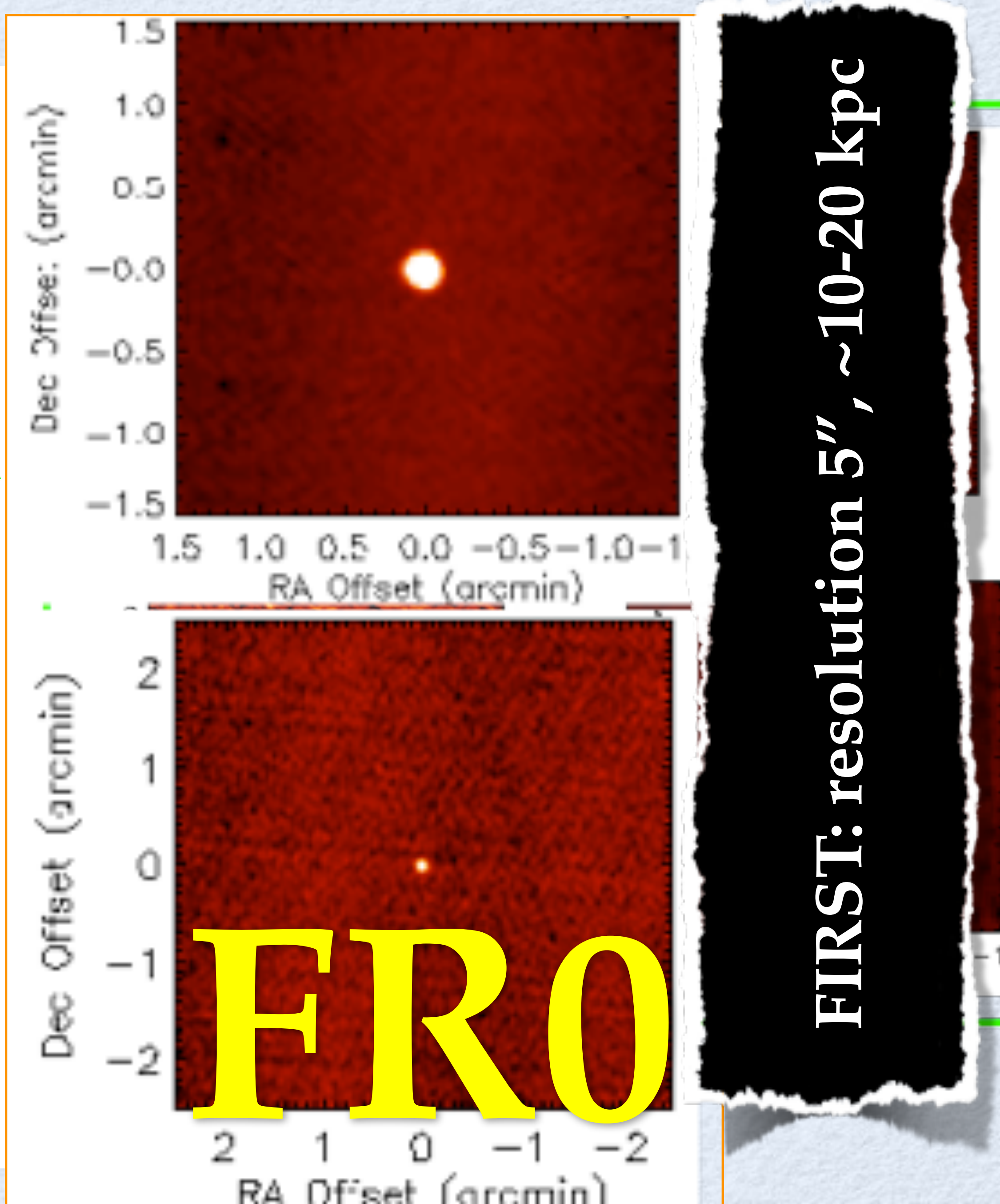




High Frequency | Low Frequency

- At 20 GHz, Sadler (2016) found most of FR0s in AT20G-6dfGS sample: mix of LERG and HERG and ETG and LTG
- Whittam et al. (2016) selected ~65 FR0s (>0.5 Jy) from 10C survey at 16 GHz

See talk of I. Whittam

- At 150 MH with LOFAR, Shimwell et al. (2017) found that most of LOTSS radio sources are unresolved at ~6″
- Deep observations of ELAIS-N1 field at 610 MHz reveal a large population of FR0s (Sirothia et al 2009, Iswara-Chandra et al 2020)

FR0s represent 70-80 % of RL AGN population
FR0s consists of a composite population:
LERG, HERG, elliptical, spirals and YRG

FR 0 radio galaxies

Ghisellini (2014) and Sadler (2016) «a convenient way of linking the compact radio sources … into the canonical FR classification scheme»

Are they a new class? NO.

Compact radio-sources at the center of early type galaxies (ETG) has been already recognized in the ’70s (Ekers & Ekers 1973) and later (Wrobel & Heeschen 1991, Sadler 1984, Slee et al. 1994)

Are they a well defined class? NO.

The «compact source» definition depends on the survey depth, resolution, frequency, and on the source distance.

Are they an interesting class? YES (I think so…).

Why most radio galaxies extend to, at most, a few kpc? How are they connected to the large objects? Are they small because they are young? Or are they different?

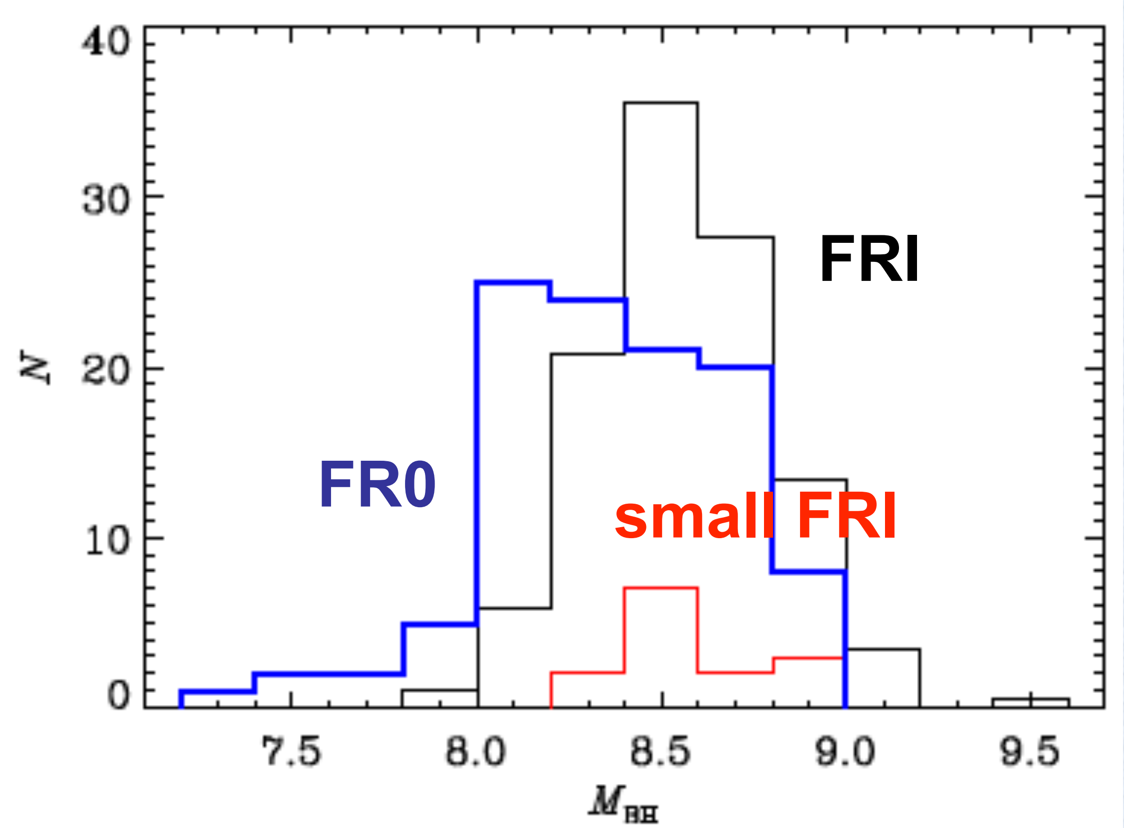
FR0CAT

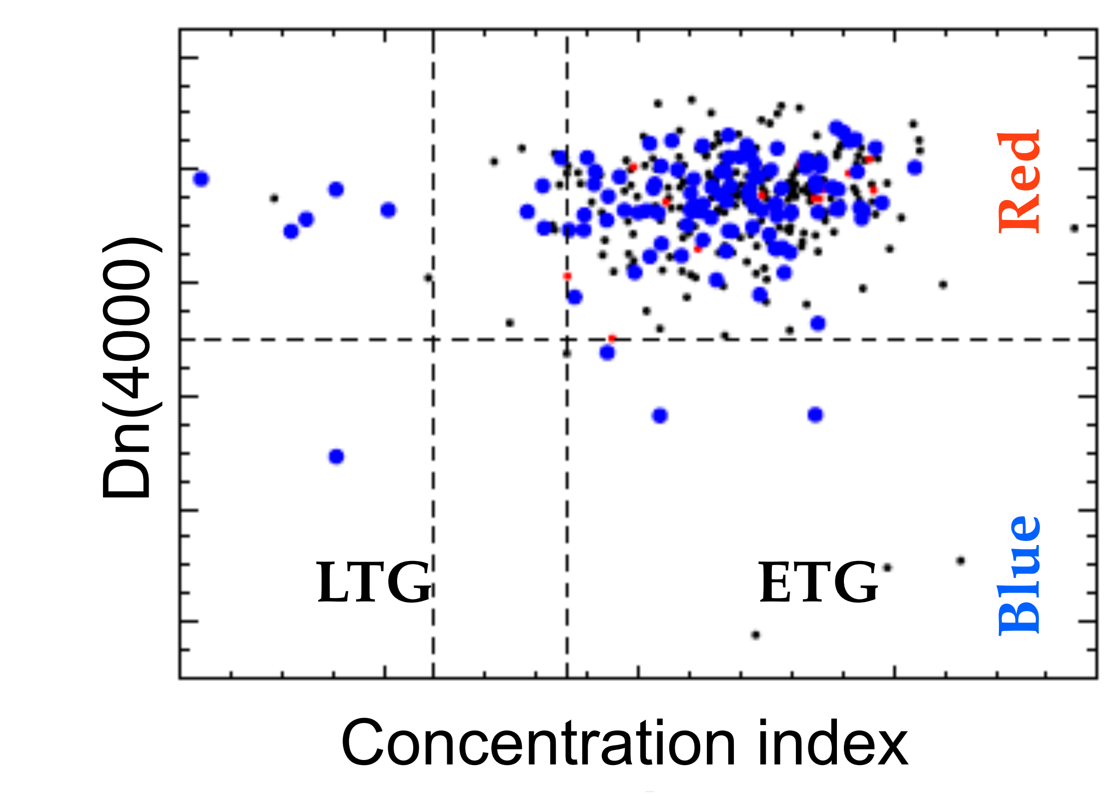
Baldi et al (2018) compiled a catalogue of 104 (bona-fide radio-loud) FR0s with z<0.05 with sizes <10 kpc:

- Unresolved in FIRST (5 “)
- Red massive ETGs (-21> M_r> -23)
- Massive BHs ($10^{7.5}$ - 10^9 $M_\odot$)
- LERG

FR0s consist of (compact) radio-loud AGN with nuclear and host properties, typical of FRIs and LERGs in general:

Jet-mode AGN!





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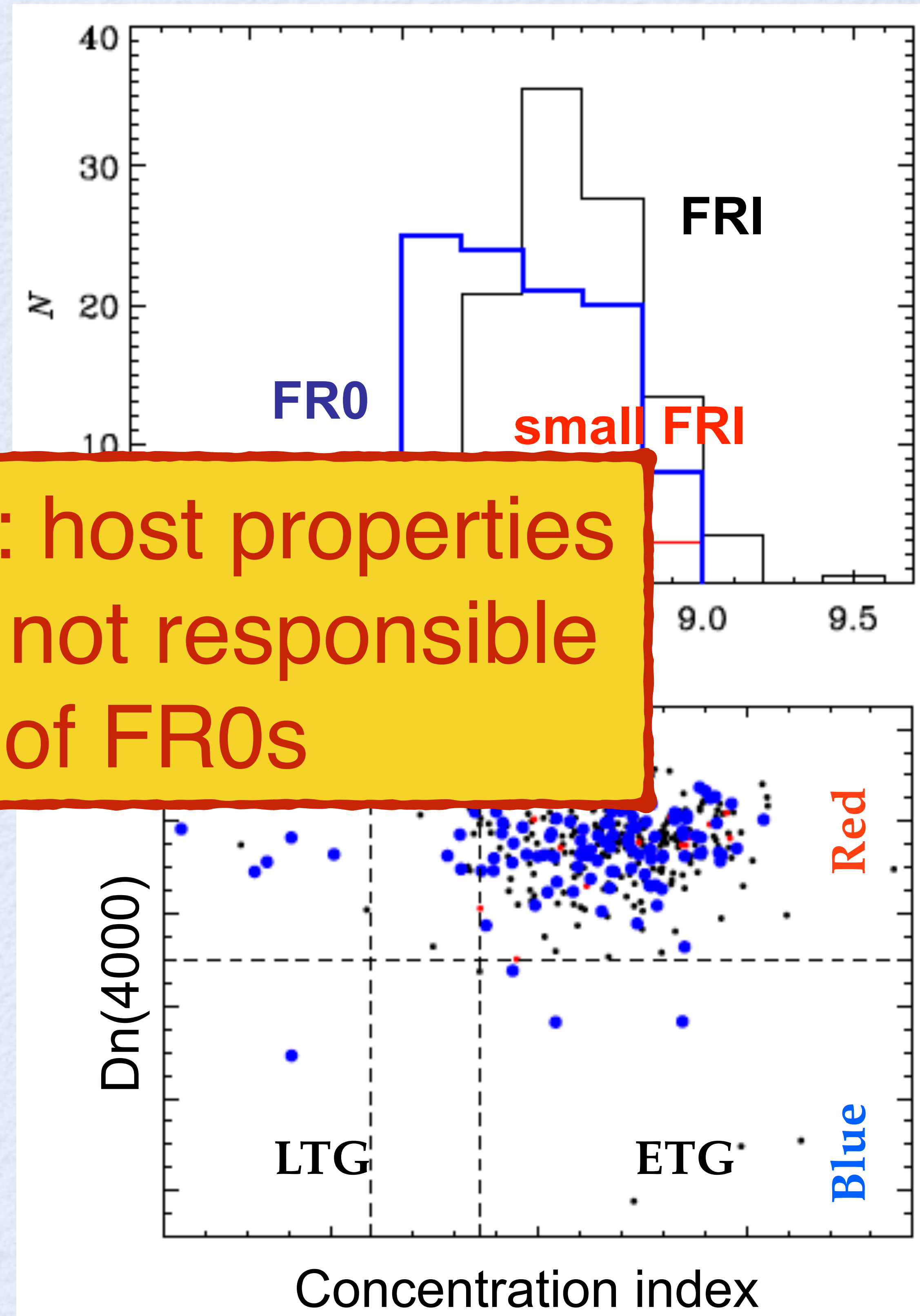
- Unresolved in FIRST (5 “)
- F
- N
- L

Similarity with FRI/LERGs: host properties (e.g. lack of cold gas) are not responsible to confine the jets of FR0s



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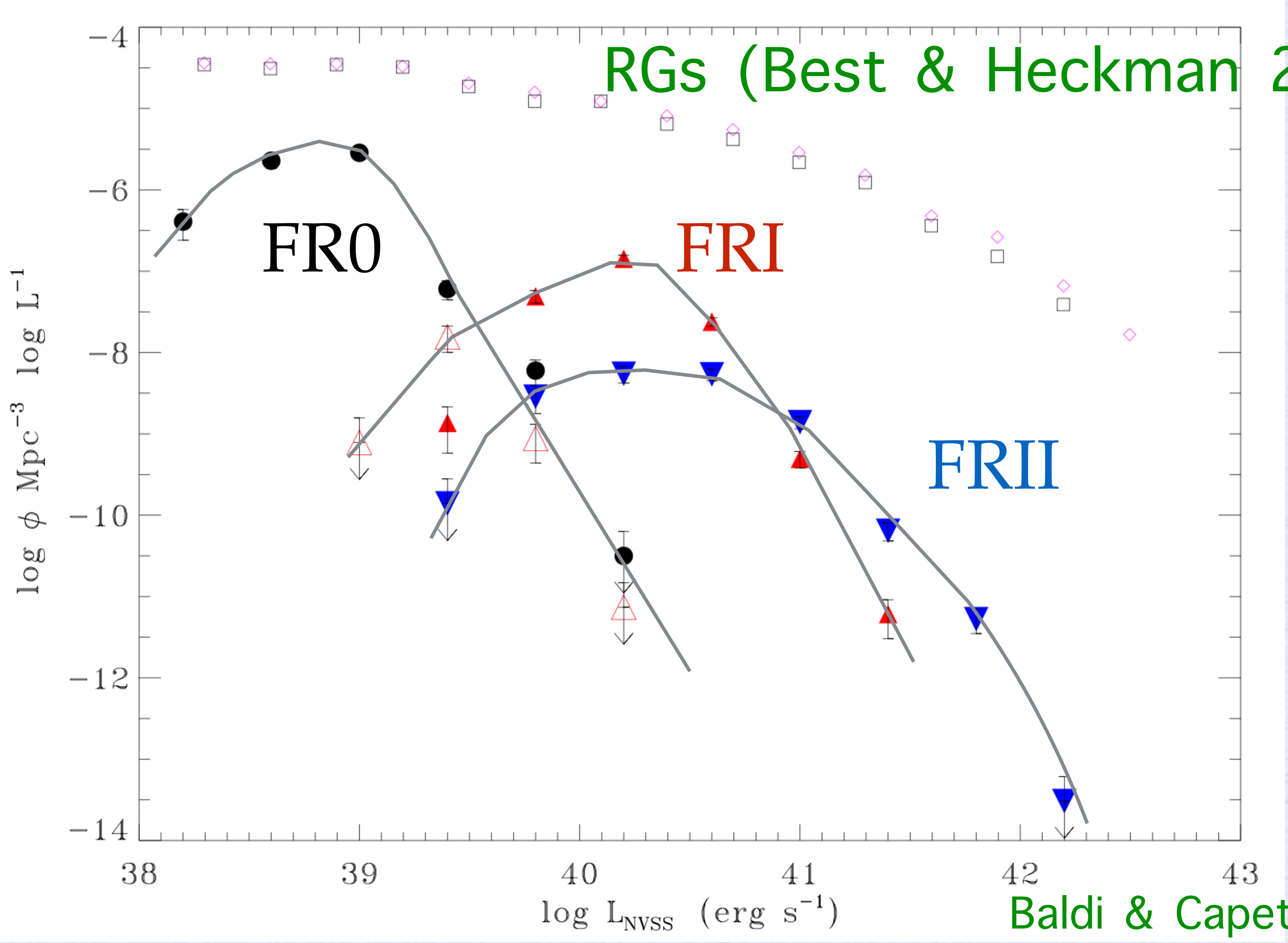
Jet-mode AGN!

LUMINOSITY FUNCTION

FR-0/I/II radio galaxies in FIRST/SDSS catalogue



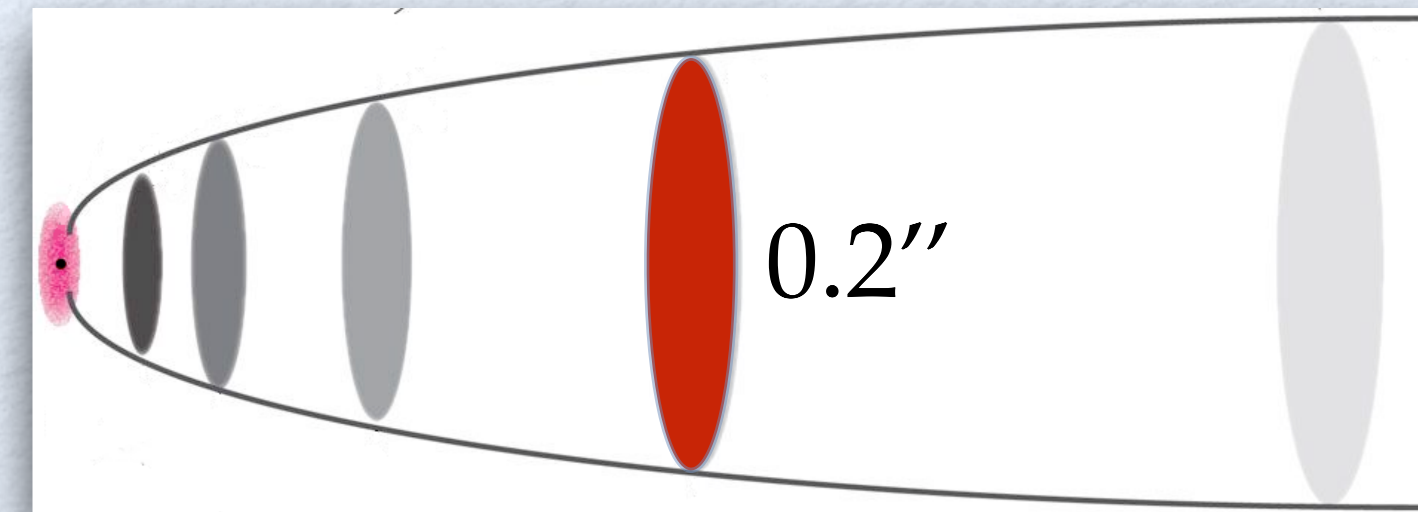
FR0s are 5 times more abundant than FRIs

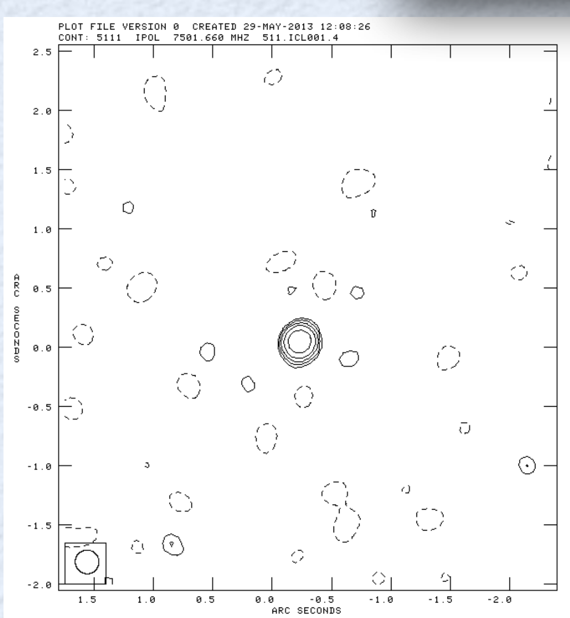
Baldi & Capetti A&A review in prep.

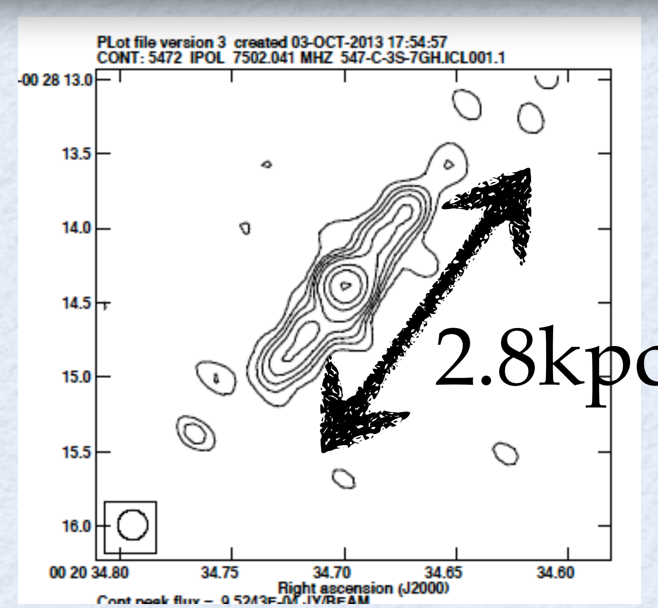
JVLA observations

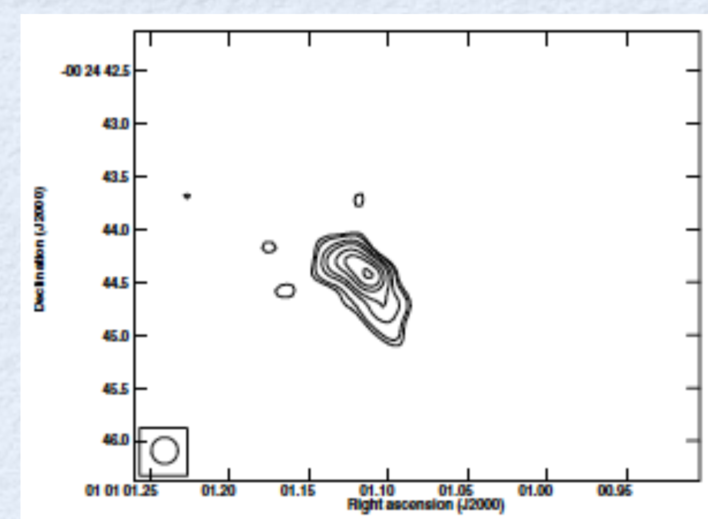
in 2015 we got JVLA data for a Pilot sample of 7 FR0s.
Only 2 sources show extended jets on kpc scale

Radio maps: < 0.2", < 3kpc









Baldi, Capetti, Giovannini 2015

Observations at 1.4, 4.5, and 7.5 GHz with resolution 1.2"-0.2" : core, core-jet, twin jet

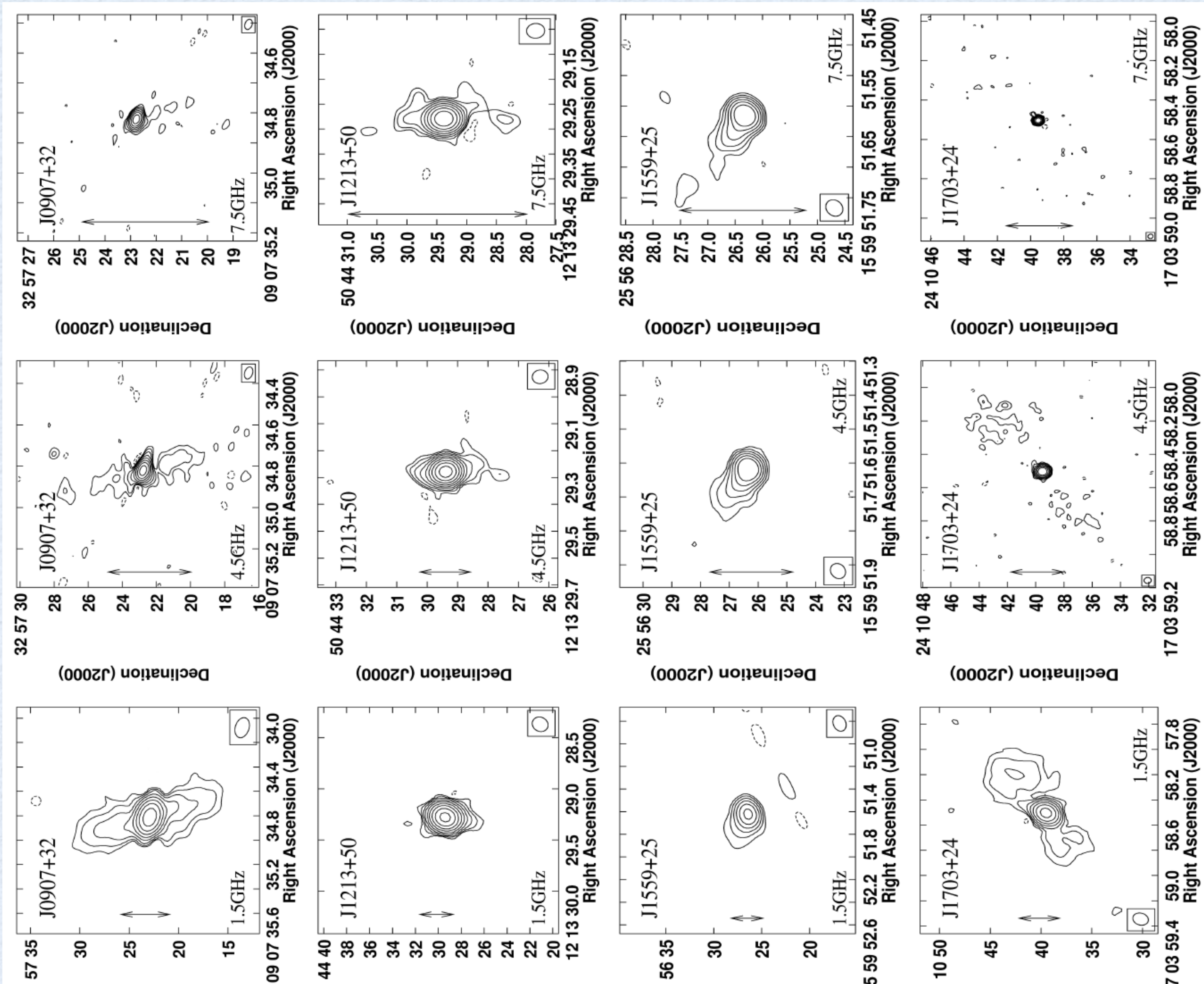
new JVLA observations for 18 sources

4/18 show jets

1.4 GHz, 1"

4.5 GHz, 0.3"

7.5 GHz, 0.2"



Baldi, Capetti, Giovannini 2019

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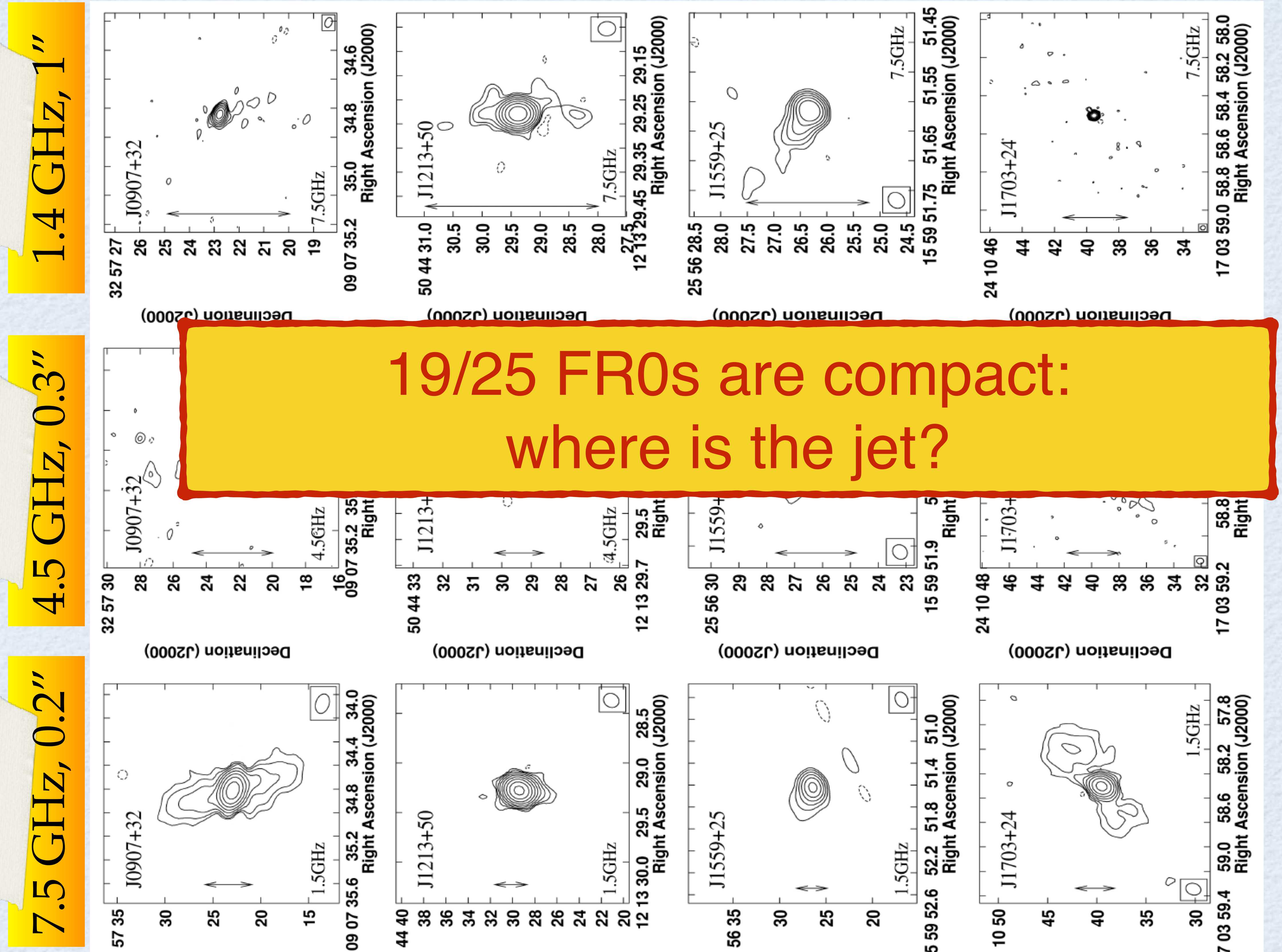
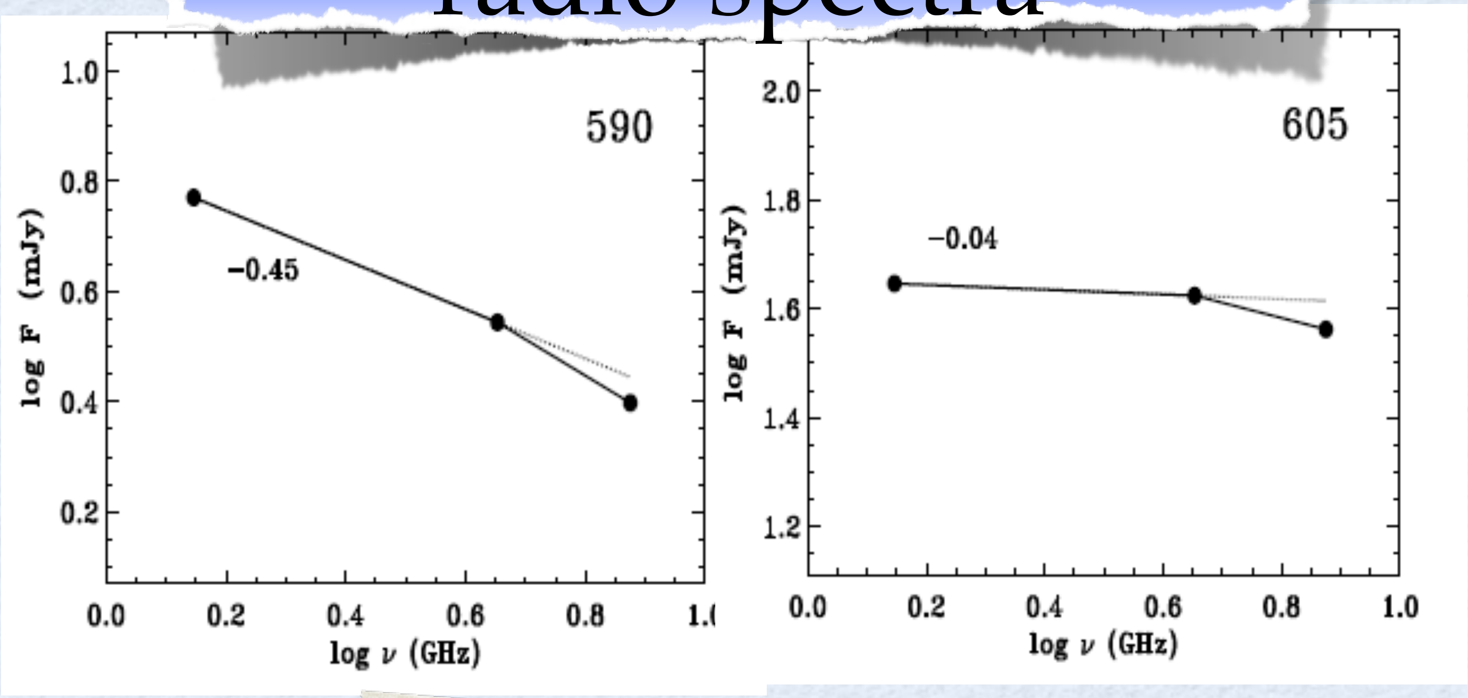


19/25 FR0s are compact:
where is the jet?

Baldi, Capetti, Giovannini 2019

GHz-regime properties

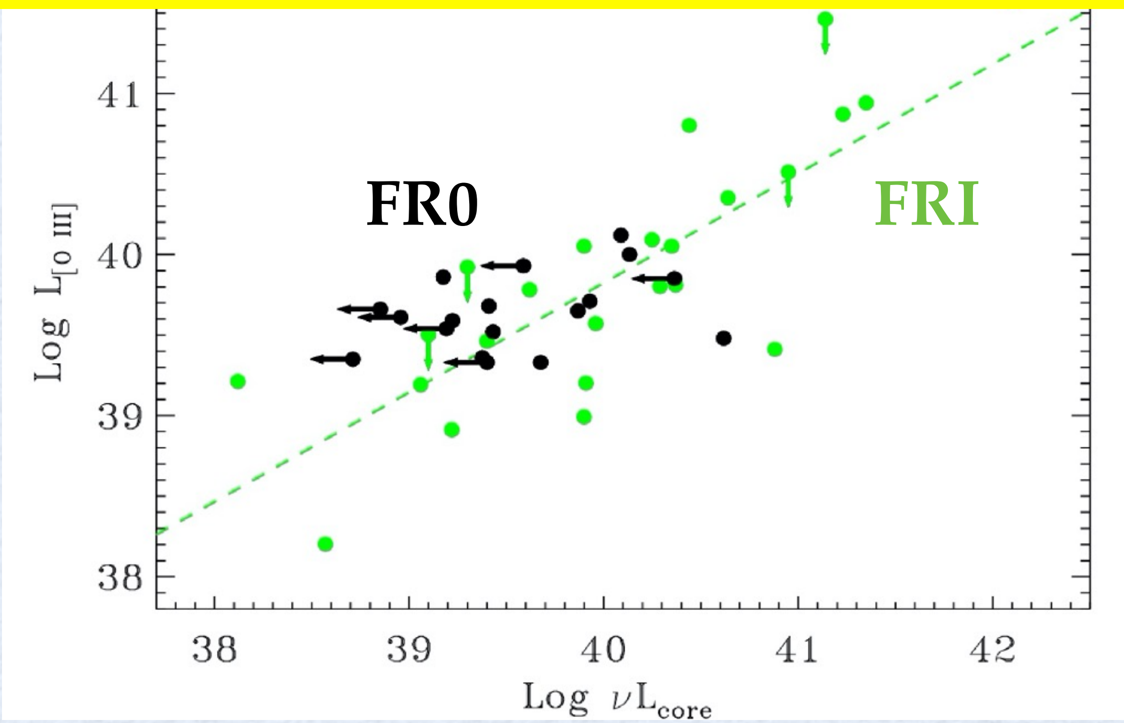
radio spectra



flat-spectrum
core-dominated sources
(A factor ~10 more
core-dominated than 3C/FRIs)

Baldi, Capetti & Giovannini (2015, 2019)
Baldi, Capetti, Massaro (2018)

No boosting / similar engine



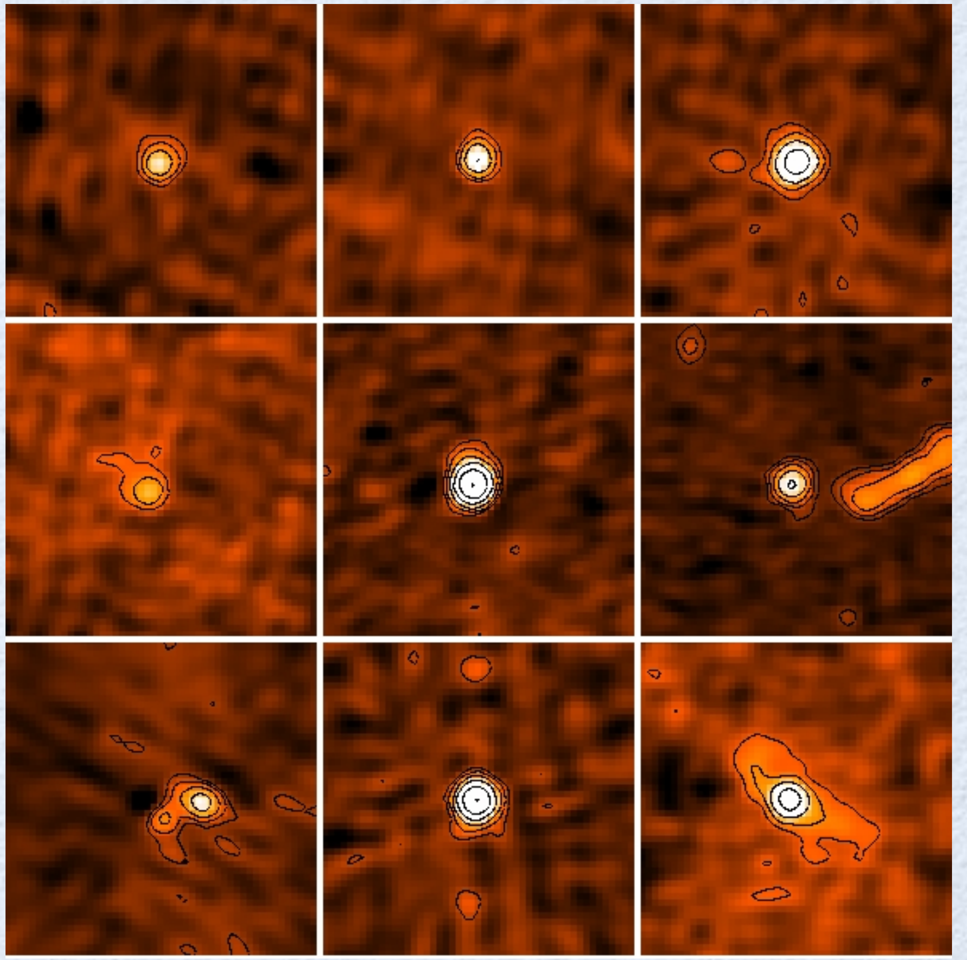
RGs with similar AGN powers, radio core powers, BH masses and host properties can produce different jet structures

MHz-regime: LOFAR

Low-frequency radio observations are ideal to detect extended radio emission (possibly from past radio activity)

- We cross-correlate the FR0 catalogue and the LOFAR survey (LoTTS, DR2, Shimwell et al 2019, at 150 MHz and 6")

Data available for 45 FR0CAT sources. (FOV 2', 80 kpc).



Only 12 extended sources

No diffuse emission: S < 10^{22} W/Hz within 100x100 kpc, compared to 10^{26} of the 3C FRI

Capetti, Brienza, Baldi et al (2020)

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FR0s were not FRI/IIs in the past (activity)

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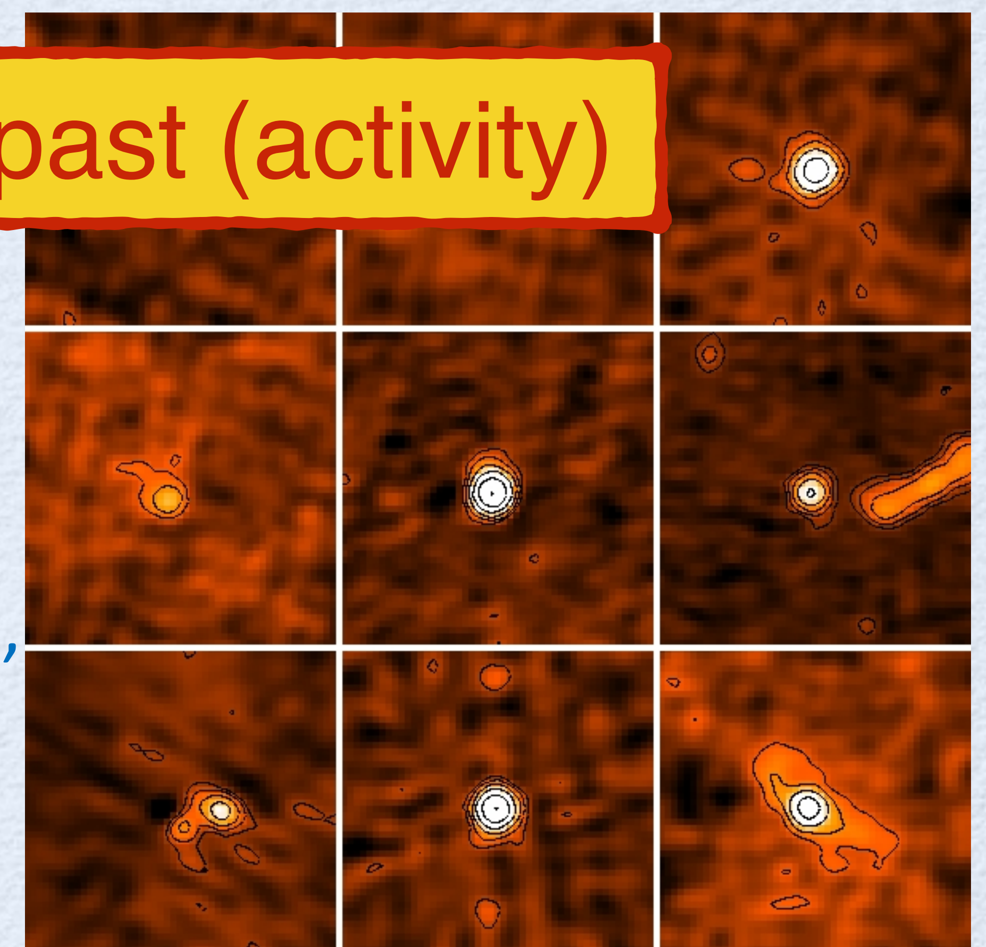

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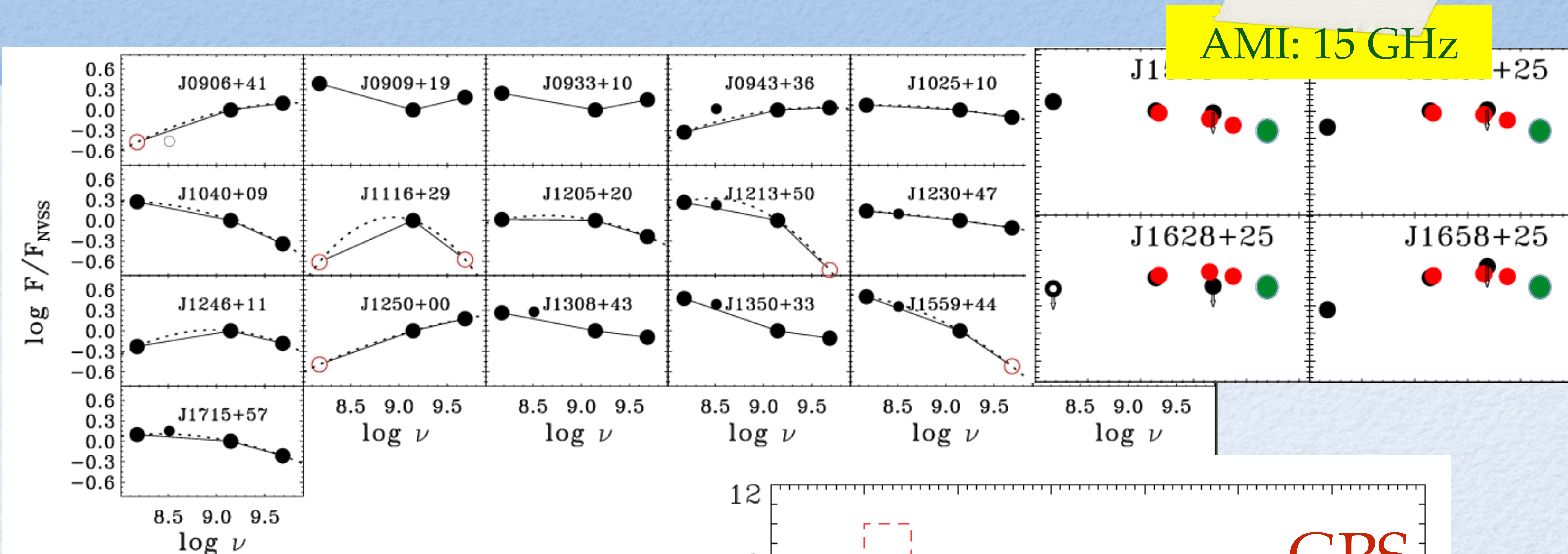
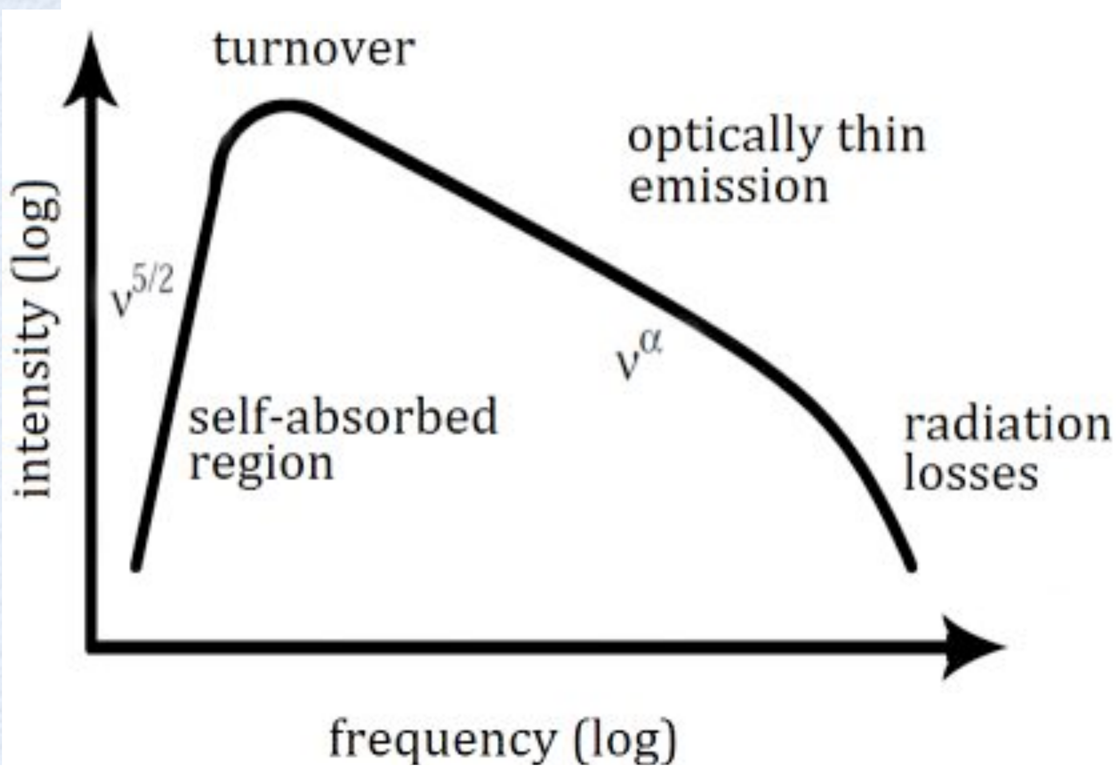
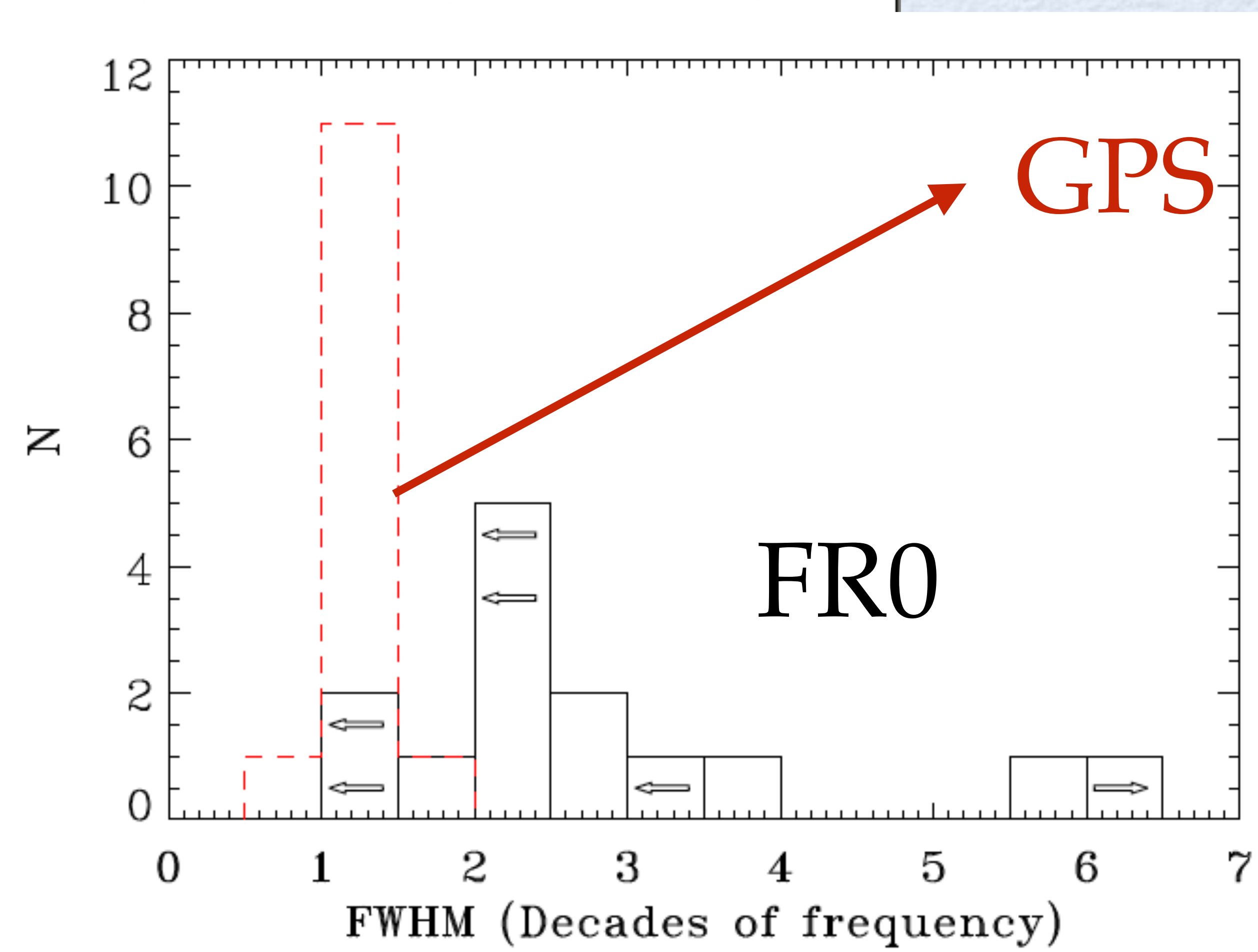
THE RADIO SPECTRAL PROPERTIES OF FR0s



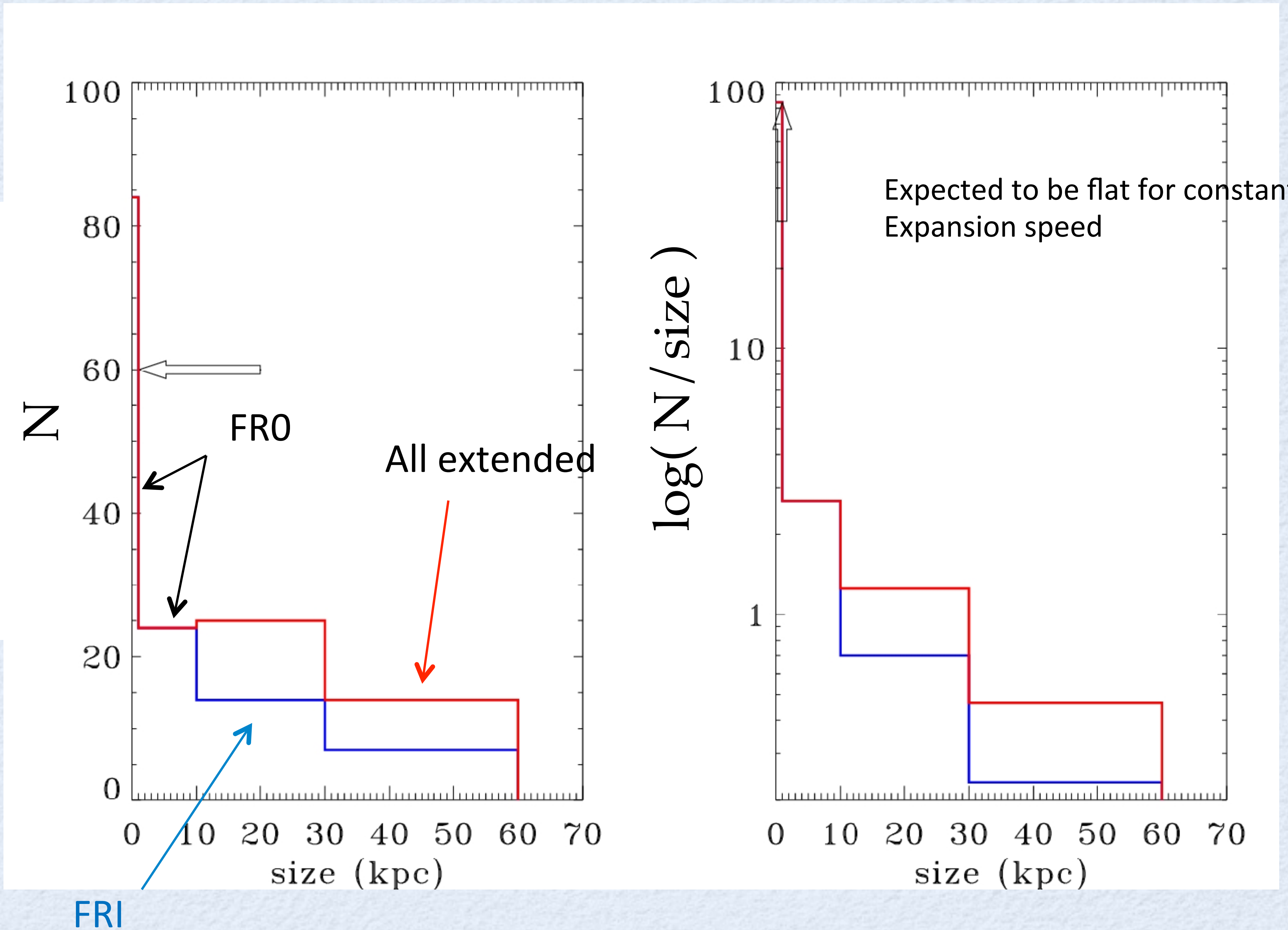




Many FR0s show convex spectra but with low curvature (not like YRG)

Are FR0 young FRI?

Clues from number densities



FR0 can not ALL evolve into FRI because their relative number density is too high.

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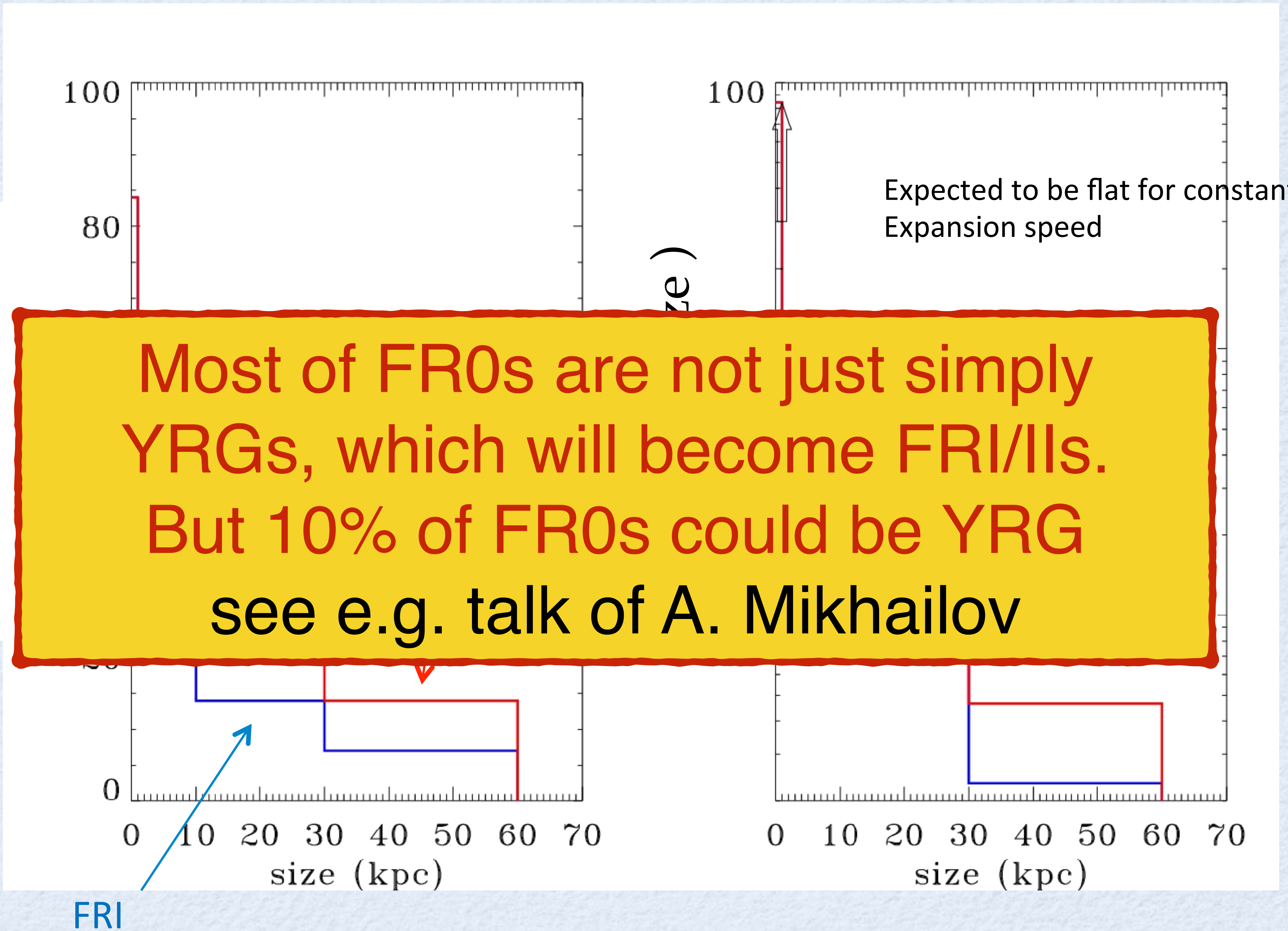
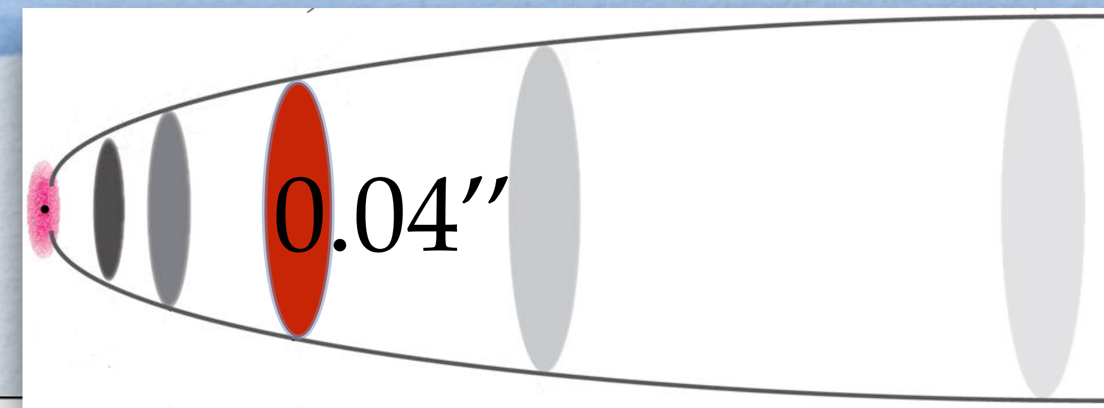


Most of FR0s are not just simply YRGs, which will become FRI/IIs. But 10% of FR0s could be YRG see e.g. talk of A. Mikhailov

FR0 can not ALL evolve into FRI because their relative number density is too high.

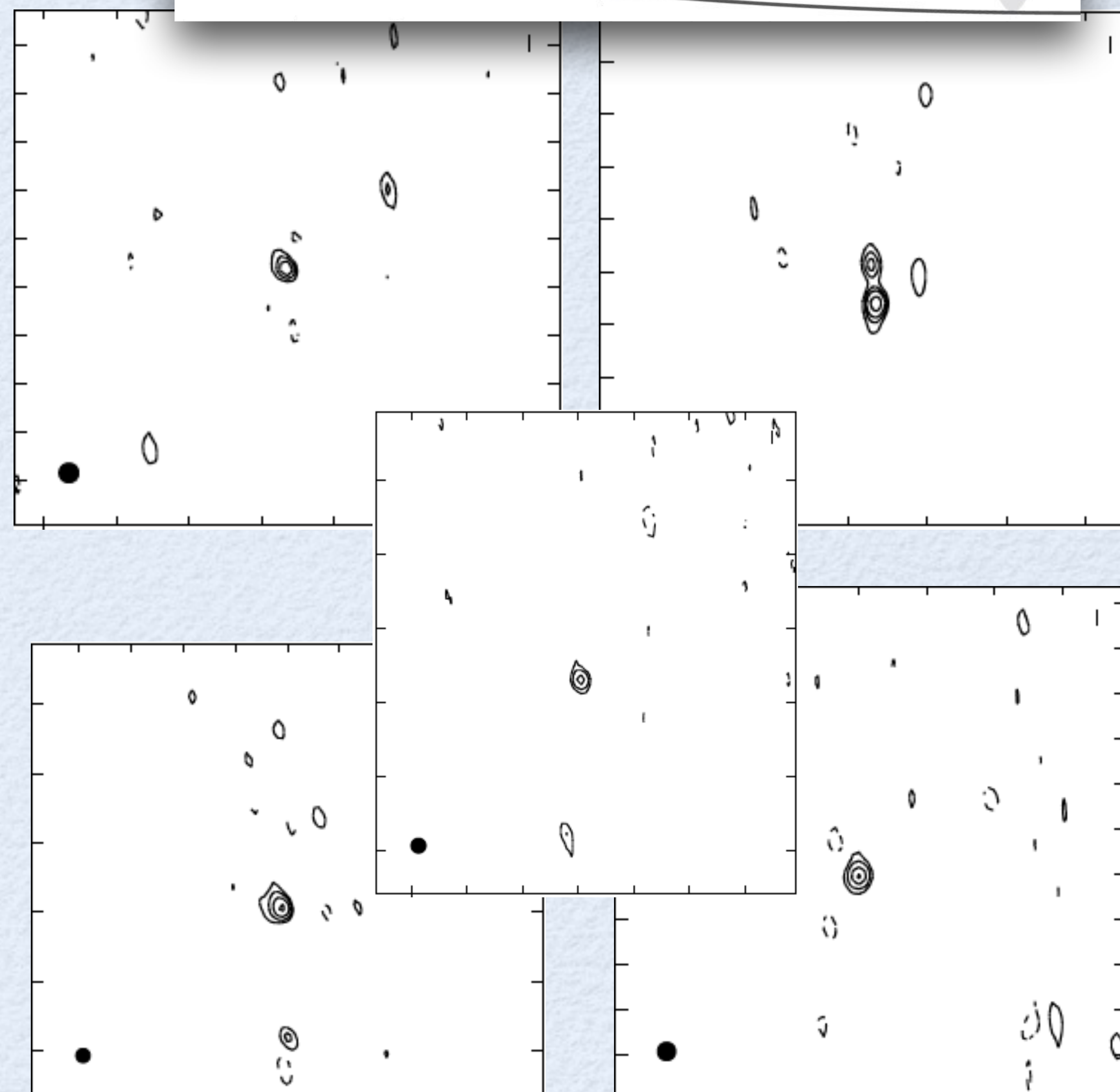
eMERLIN observations



eMERLIN observations of 5 FR0s at 5 GHz:

- resolution: 40 mas, 10 higher than JVLA resolution
- flux a few mJy; ~5 times weaker than JVLA cores

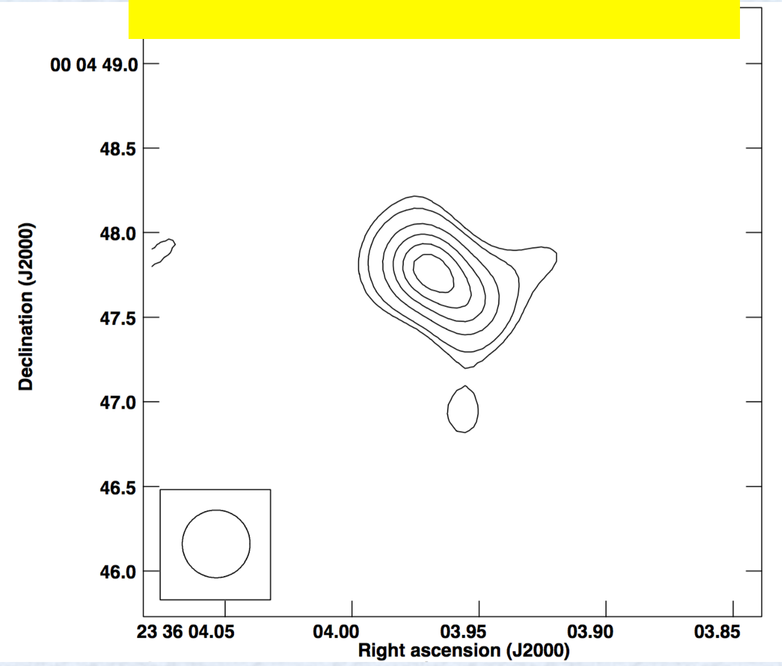
No clear jets appear!!



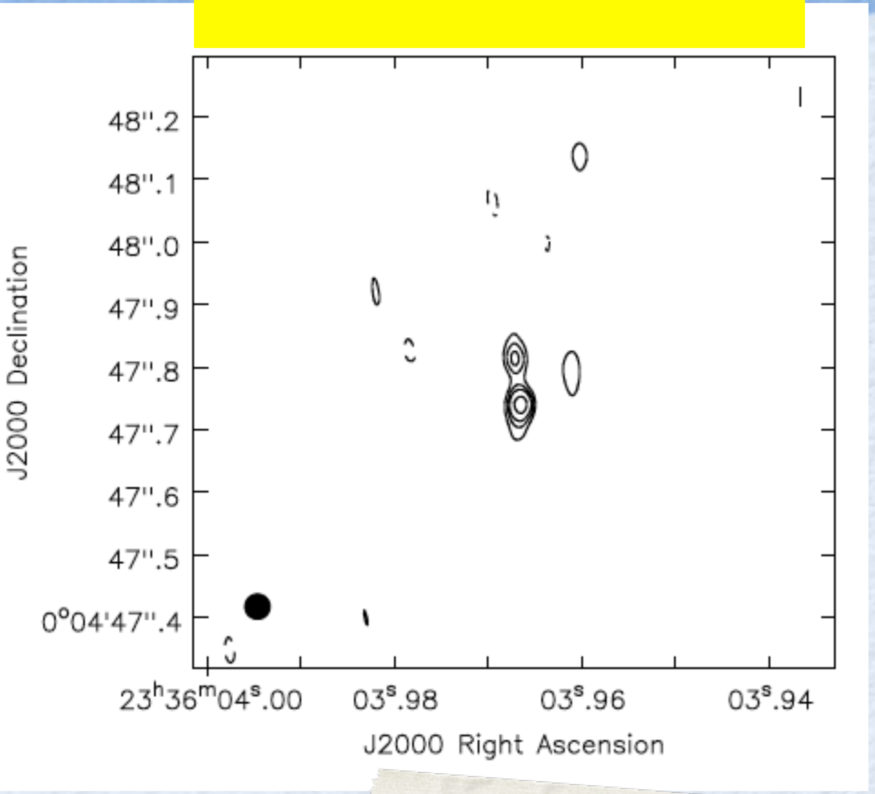
Baldi et al in prep.

eMERLIN-VLA

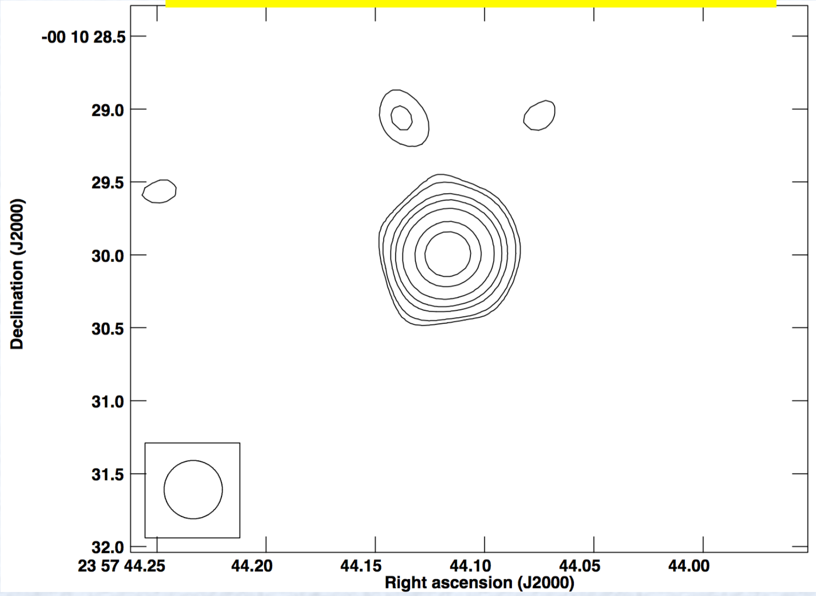
VLA



eMERLIN



VLA



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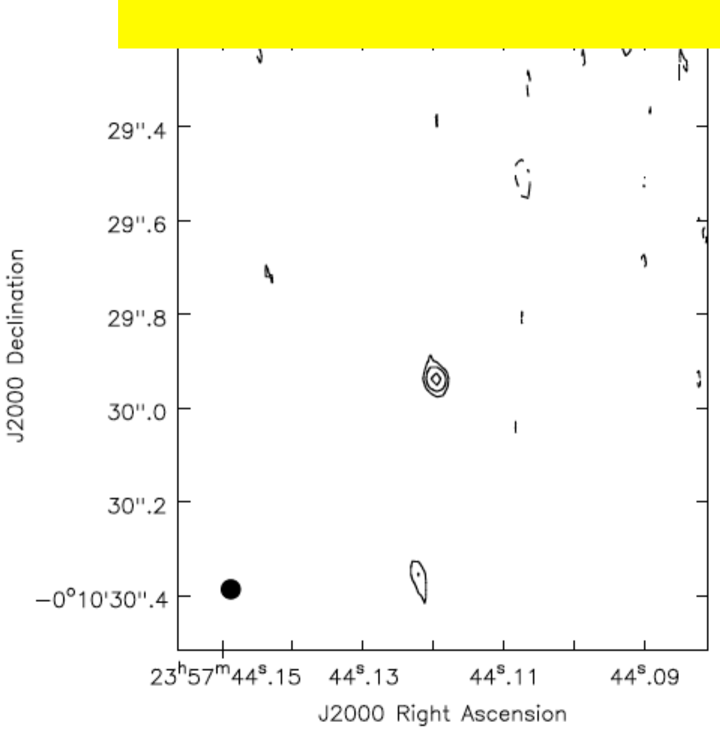
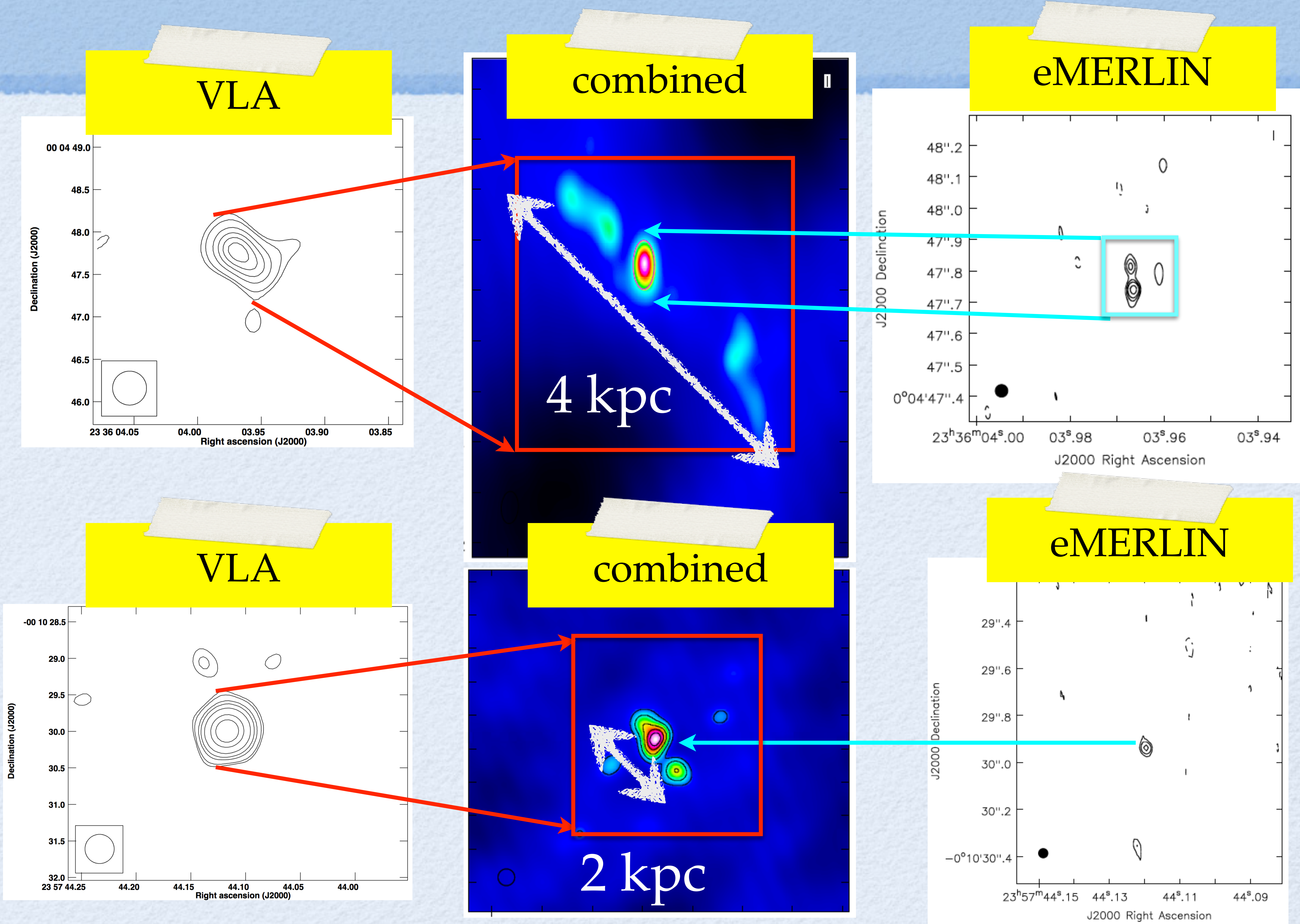
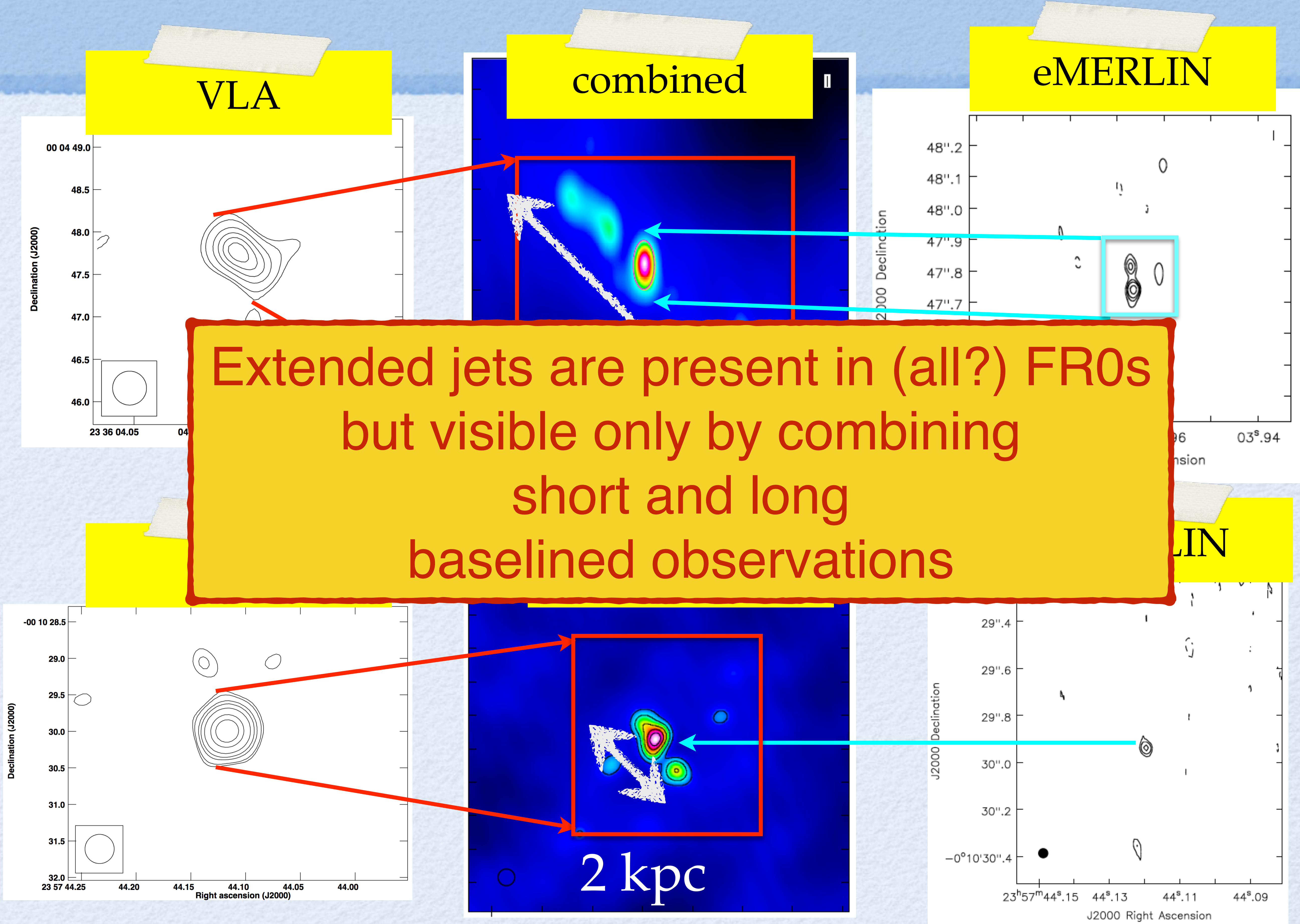


eMERLIN-VLA



VLA
combined
eMERLIN
4 kpc
Declination (J2000)
Right ascension (J2000)
J2000 Declination
J2000 Right Ascension
VLA
combined
eMERLIN
2 kpc
Declination (J2000)
Right ascension (J2000)
J2000 Declination
J2000 Right Ascension

eMERLIN-VLA

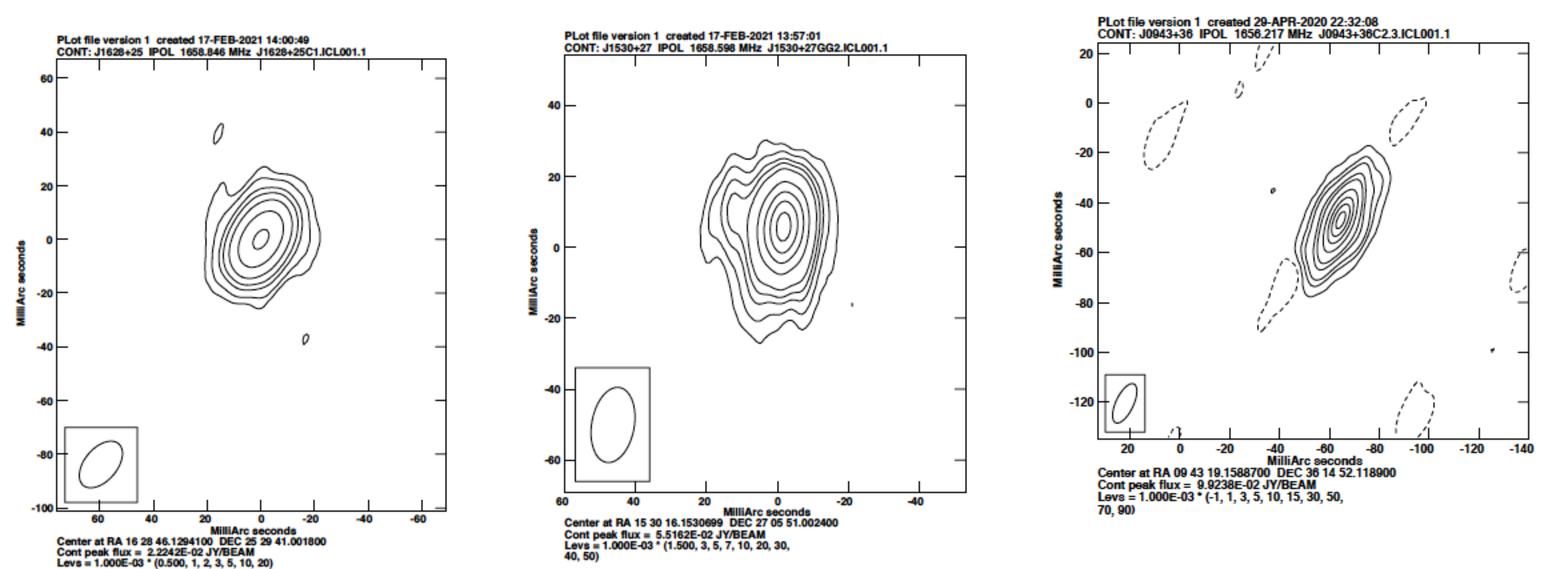


Extended jets are present in (all?) FR0s
but visible only by combining
short and long
baselined observations

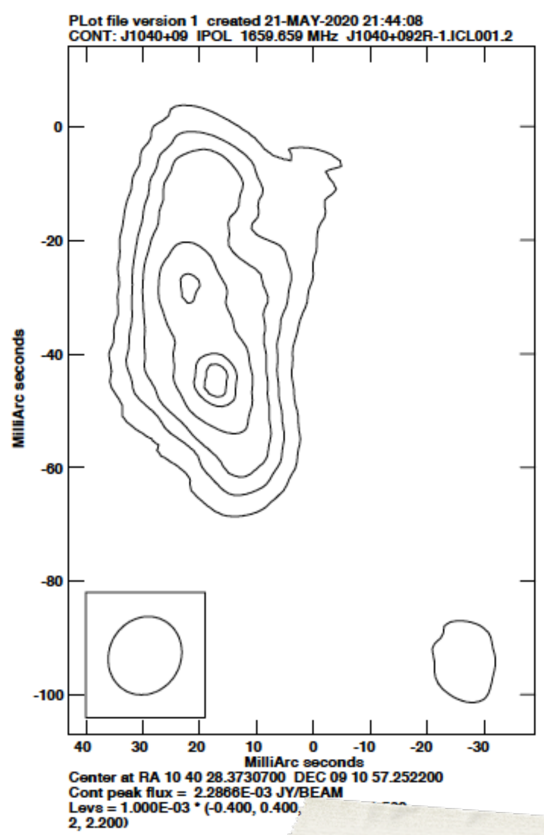
EVN

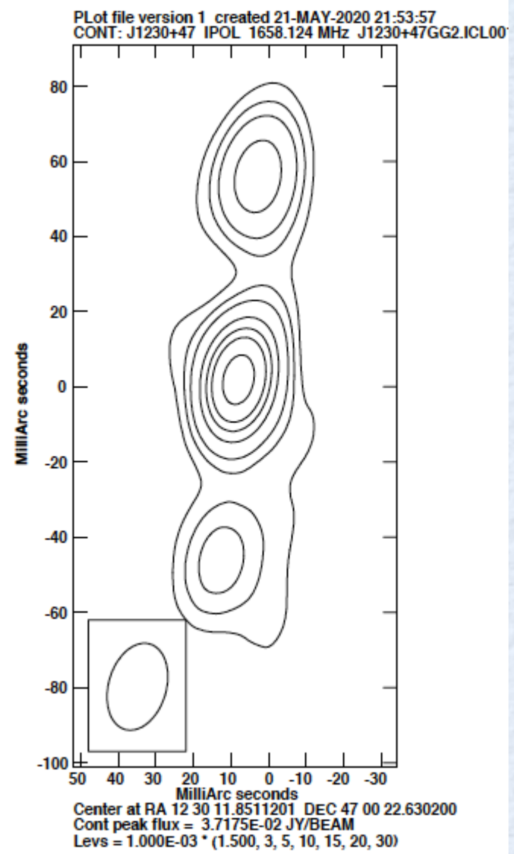
EVN observations (no eMERLIN included) of 10 FR0s from FR0CAT at 1.5 GHz with an angular resolution of ~20 mas

- flux some mJy; 2-3 times weaker than JVLA cores, high T_B
- 6 objects: core / core-jet, size < 20 pc



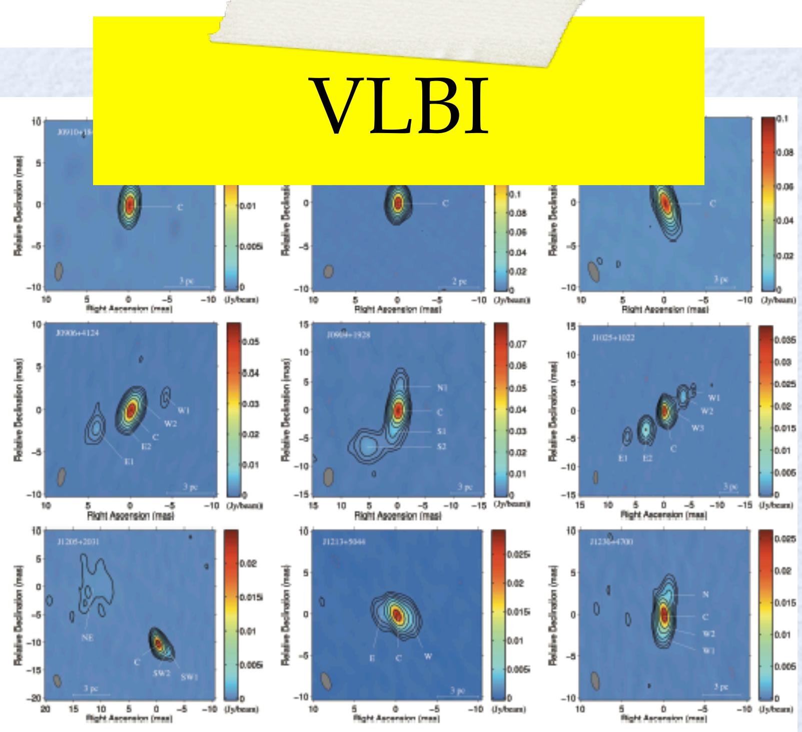
EVN OBSERVATIONS



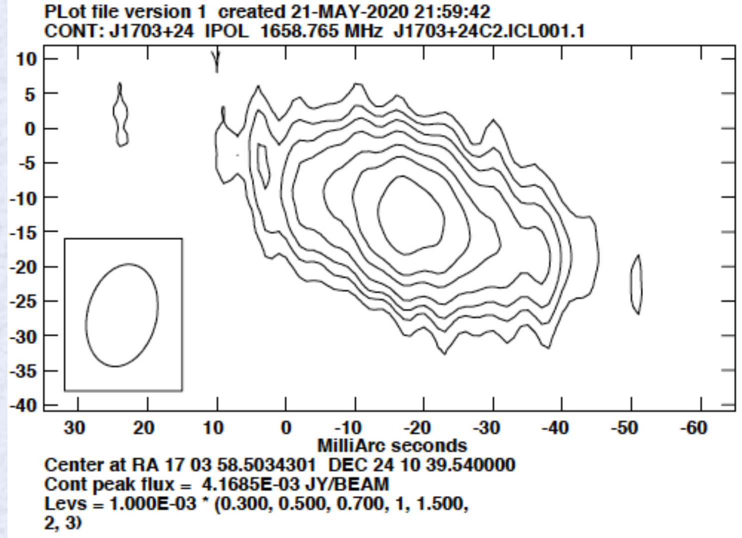


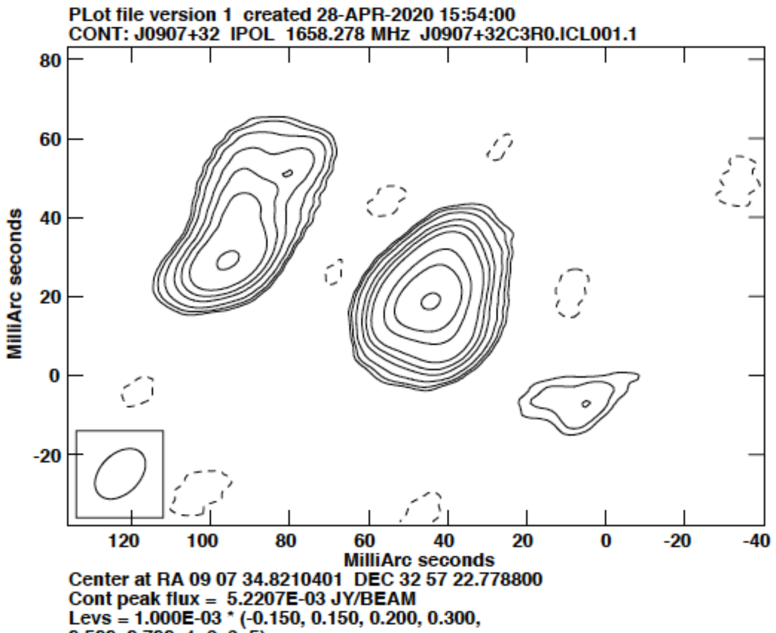
4 objects with
extended morphologies:

- double / triple sources
- twin jets
- size ~30-115 pc



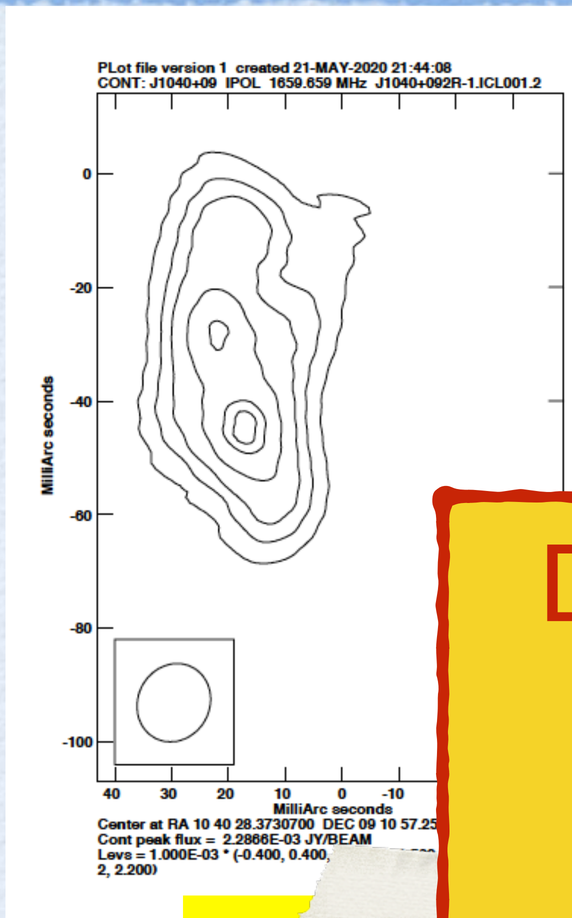
Cheng & An (2018)

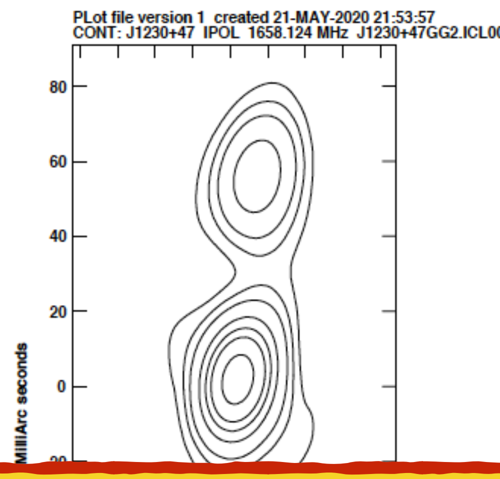




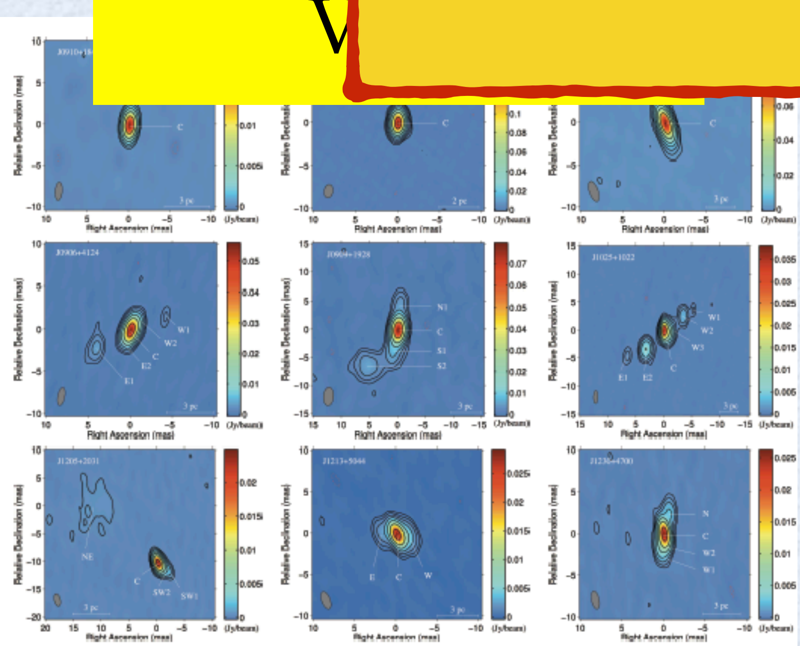
EVN observations

4 objects with
extended morphologies:
- double/triple sources

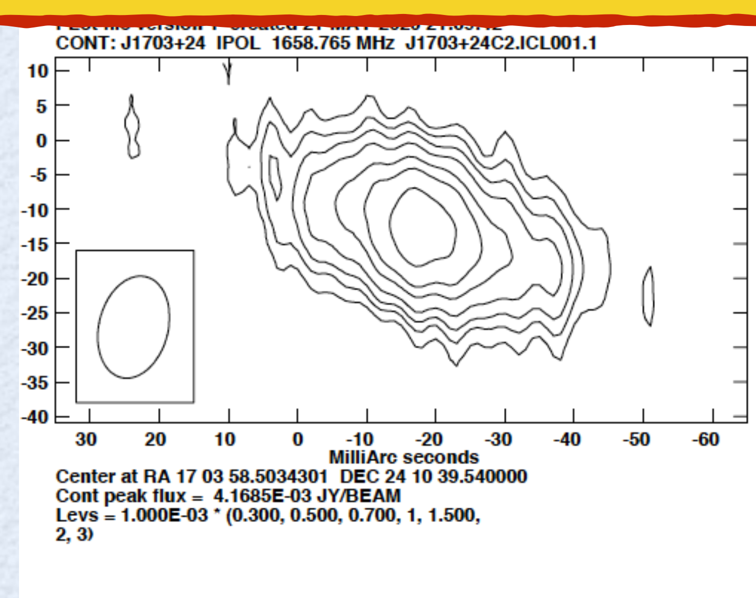


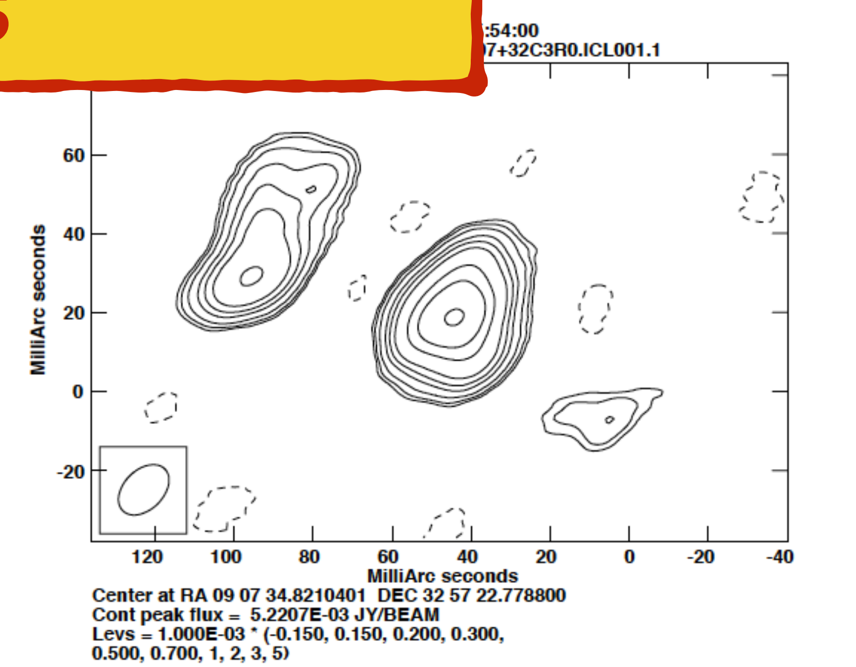


Different radio arrays probe different structures: broad and continuous distribution of FR0 radio properties

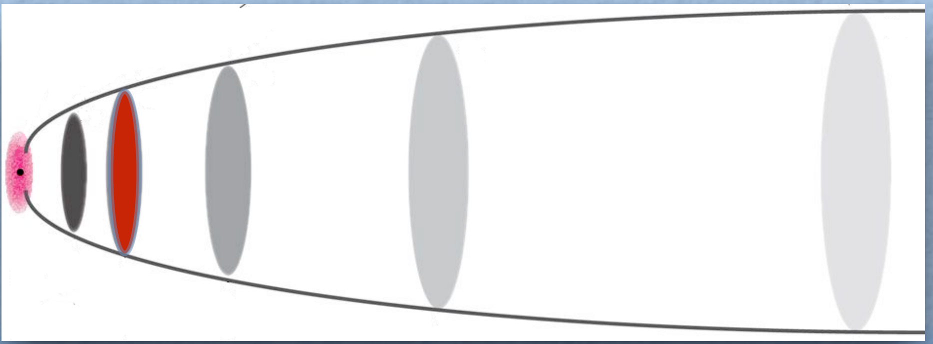


Cheng & An (2018)



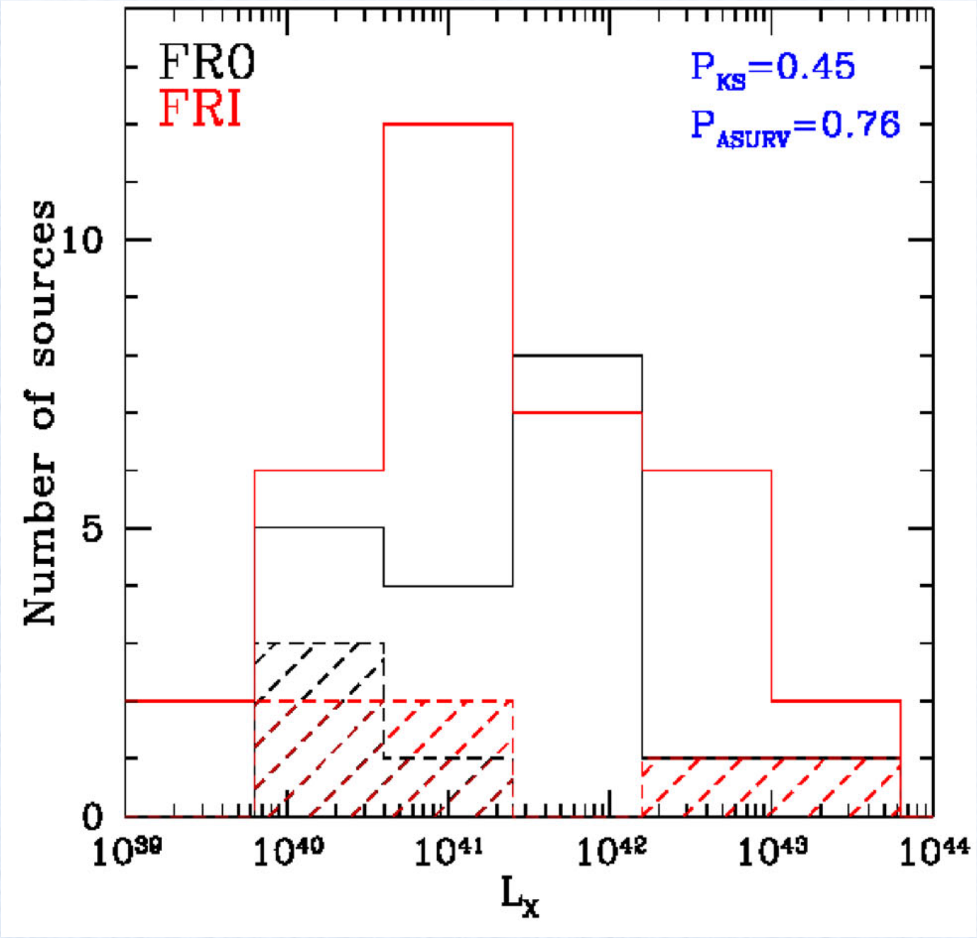


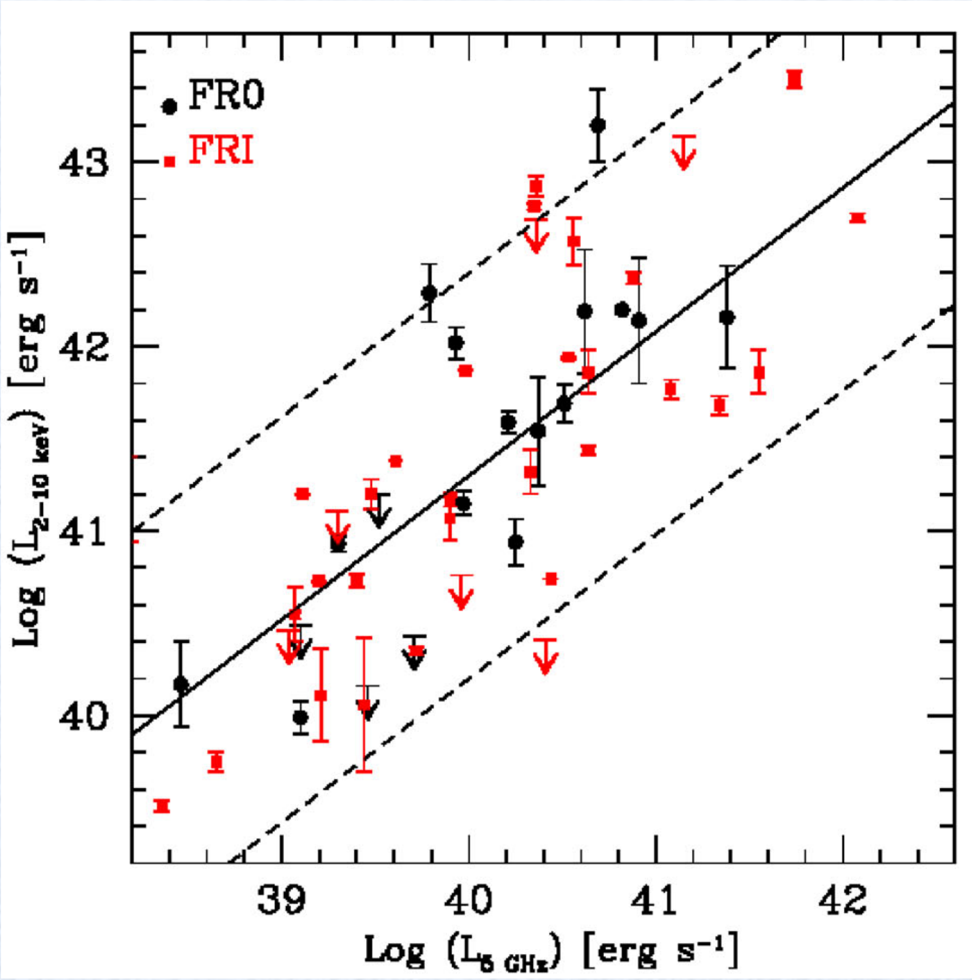
X-RAY



19 FR0s selected in radio (>30 mJy) and in X-ray (archival data available from Chandra, XMM, Swift)

Torresi et al 2018

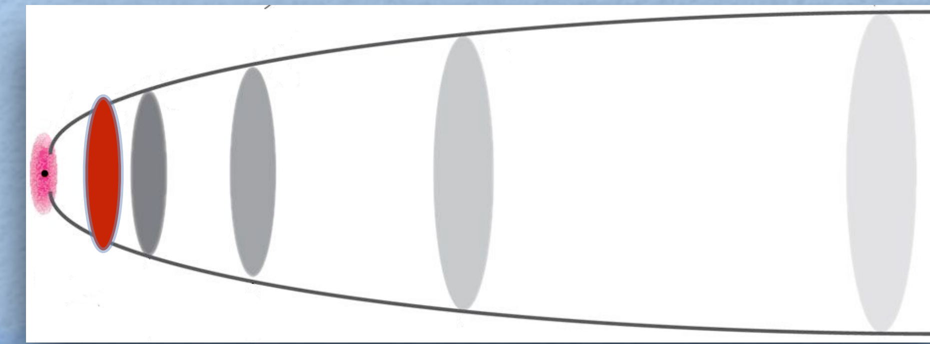




- **The X-ray photons are likely produced by the jet**
- **low Eddington ratios: RIAF disc (Allen et al 2006, Balmaverde et al 2008)**
- **X-ray properties of FRI and FR0 are indistinguishable:**

No nuclear intermittence expected

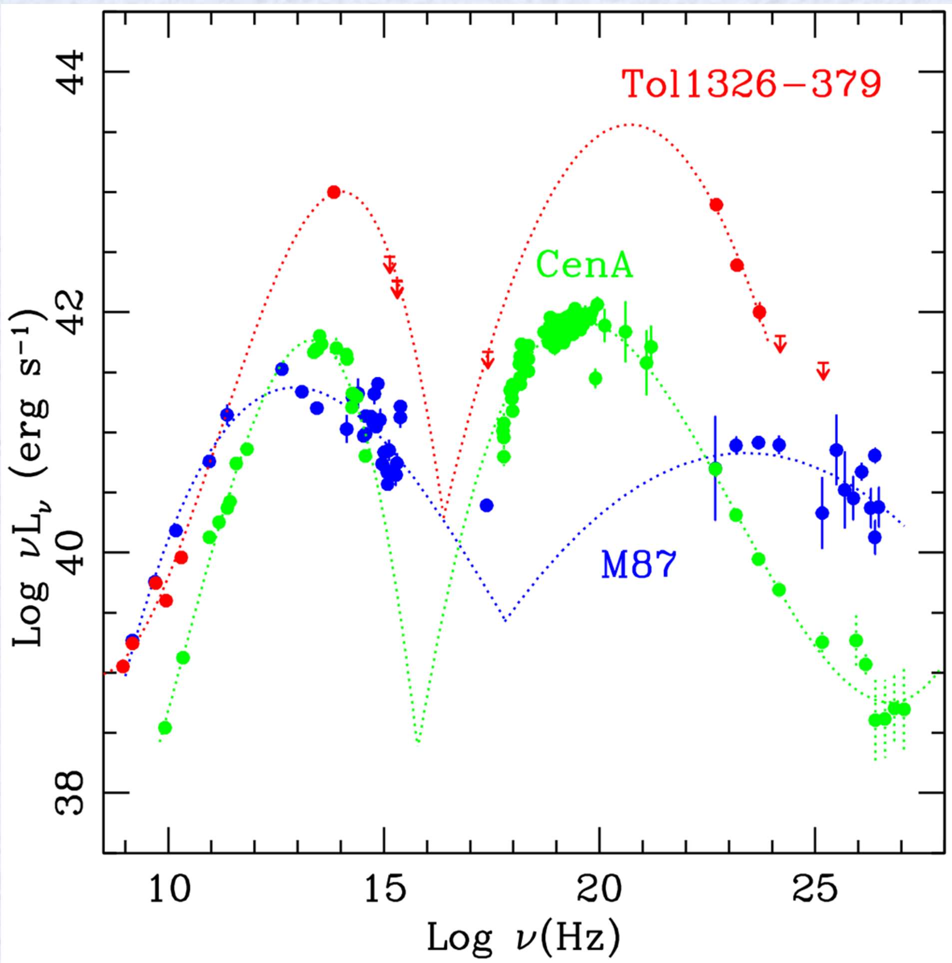
Gamma-ray

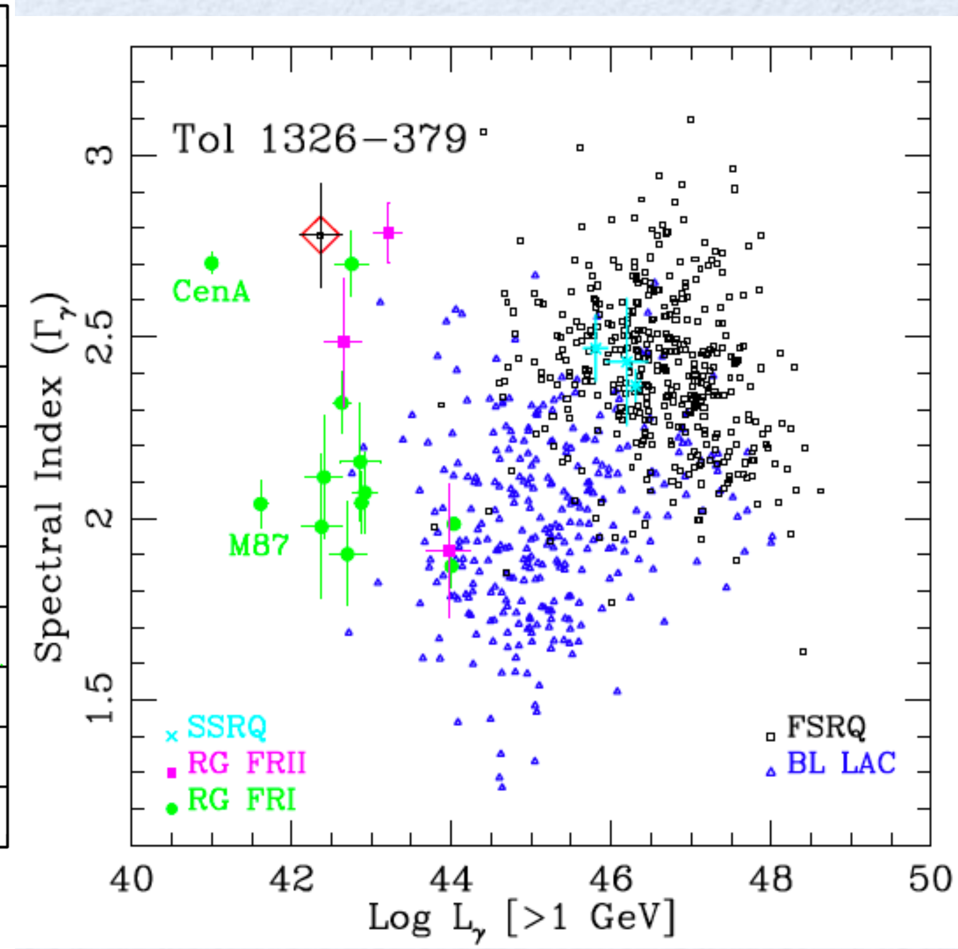


Tol 1326–379 is a FR0 detected by FERMI

$L_{>1GeV} \sim 2\times10^{42}$ erg s^{-1}, typical of FR Is, but with a steeper γ-ray spectrum ($\mathbf{\Gamma} = 2.8$)

Grandi et al 2016





(mildly)-relativist jets: different jet properties? viewing angle?

VLBI

Doppler factor 1.7-6 and jet proper motion 0.2-0.5 *c* (Cheng & An 2018)

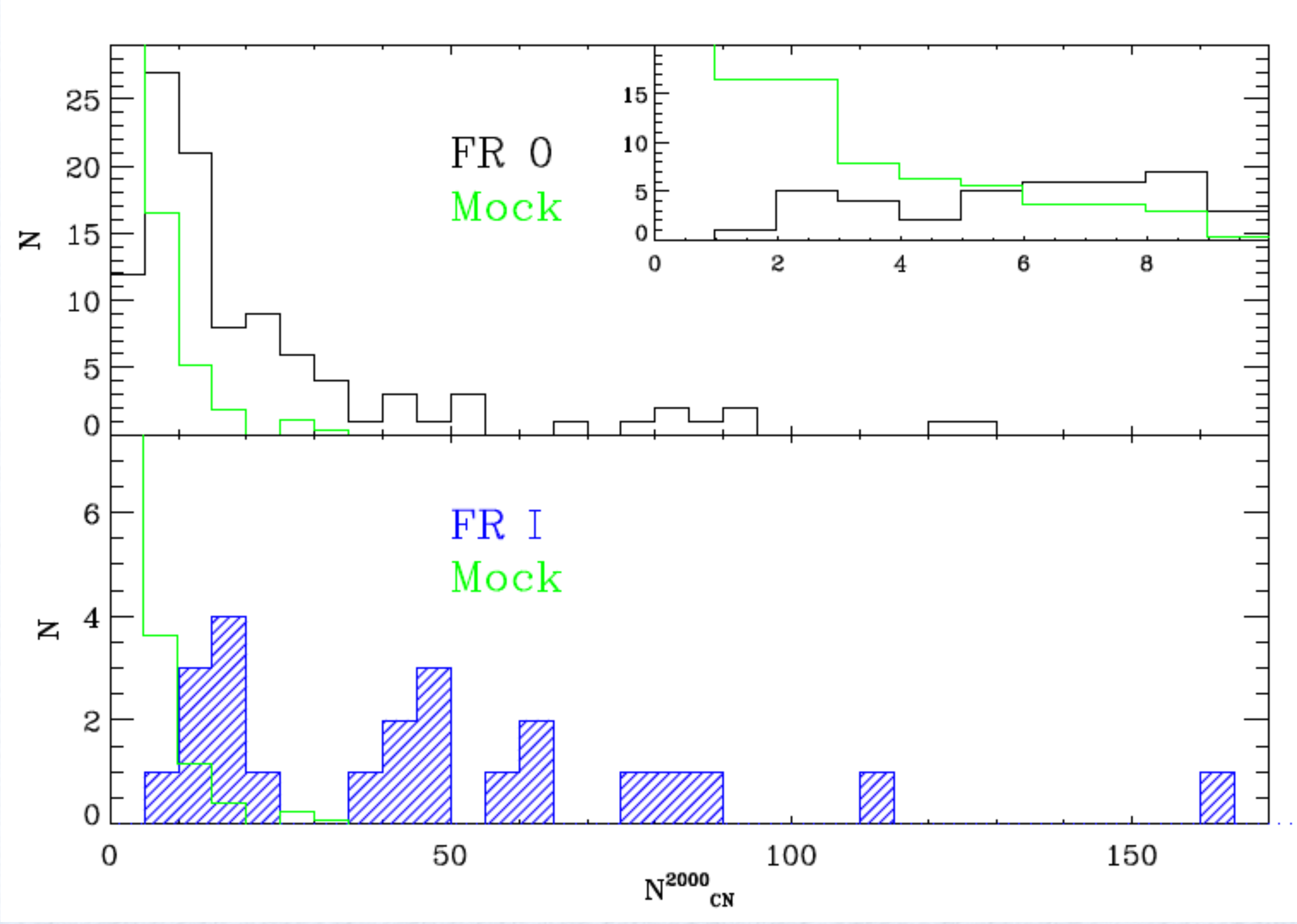
FR0s might contribute to 4-18% of the γ-ray sky background observed by Fermi (Stecker et al 2019).

FR0s are candidate sources for high-energy neutrinos (Tavecchio et al 2018) and ultra-high-energy cosmic rays (Lukas et al 2021).

large-scale environment

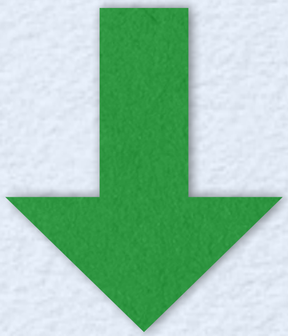
We explore the properties of the large-scale environment (< 2 Mpc) of FR0s using optical SDSS data.

Capetti, Massaro & Baldi (2020)



Cosmological neighbours: galaxies within 2 Mpc and $\Delta z = 0.005$

Most of FR 0s live in rich environment but a factor two lower density (< 15 members), on average, than FRIs.



Different cosmological evolution!?

What sets a FR0?

To account for the radio properties, the large abundance and for the environment of FR0s in the local Universe, the most plausible scenario is:

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~~No recurrence~~

~~No jet frustration~~

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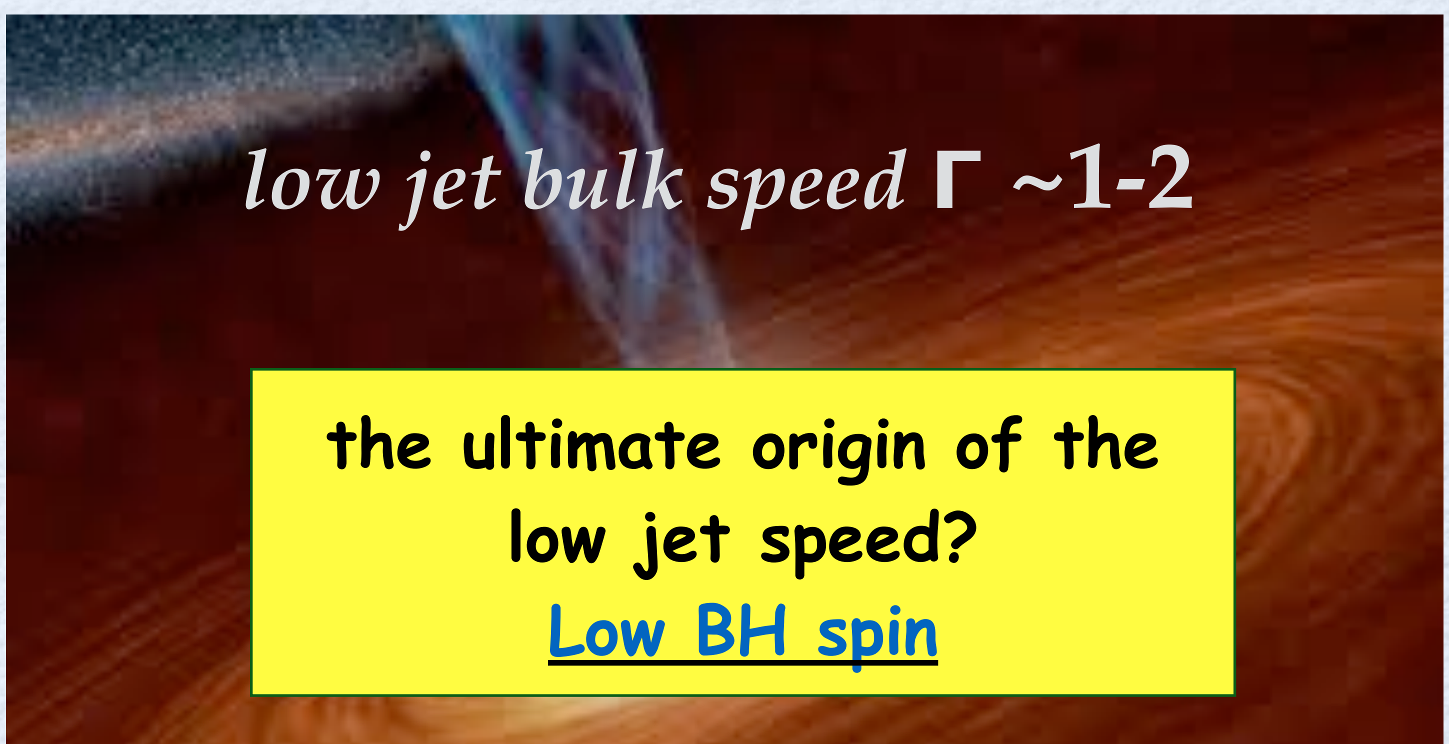
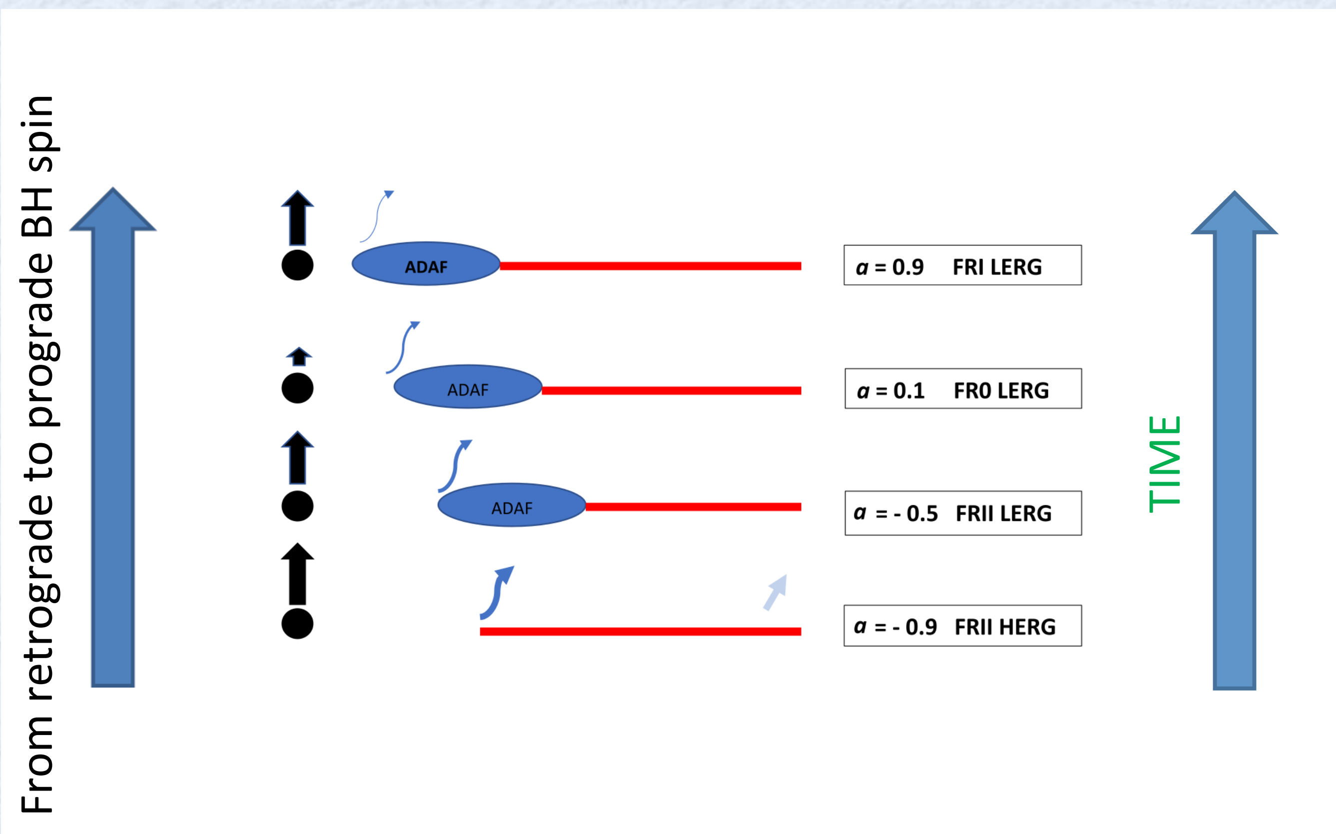


Spin evolution driven by accretion or mergers

Baldi & Capetti (A&A review, in prep)

ACCRETION DRIVEN SPIN

An evolutionary scheme for radio galaxies, including the FR0s (Garofalo & Singh 2019)



FR0 are transition objects between FRII HERGs and FRI.
An FR0 becomes an FRI after an accretion of 1/3 of its BH mass:
the FR0 phase might last longer in a poorer environment

MERGERs DRIVEN SPIN

The BH spin is mainly the result of BH-BH coalescence events.

In a poor environment major mergers of equal mass galaxies are rare. Difficult to obtain highly rotating SMBH.

The large scale environment generates differences in the BH spin distribution

environment →	BH spin →	jet speed →	morphology
Poor	low	low	FR0
Rich	high	high	FRI

Summary & Future

- FR0 population is the dominant class of RG in the local Universe
- VLA reveal kpc-scale extended jets only for 6 out of 25 FR0s
- 150-MHz (LOFAR): no clear jets and gentle convex spectra
- eMERLIN show cores but combined VLA-eMERLIN visibilities reveal the presence of low-brightness extended jets
- EVN/VLBI show cores and extended jetted FR0 on pc scale
- Most of FR0s are not just simply young RGs or consistent with FRI/II in the past
- X-ray properties are similar to those of FRI: a jet origin.
- FR0 can emit γ-ray emission: (mildly)-relativistic jet?
- Large-scale environment: FR0s live in less rich environments than FRIs
- Slow jets (low Γ) due to low BH spins may account for FR0 multi-band properties
- what next? radio (high resolution), deep X-ray, ad-hoc numerical simulations


THANK YOU