X-ray properties of mJy Radio Galaxies

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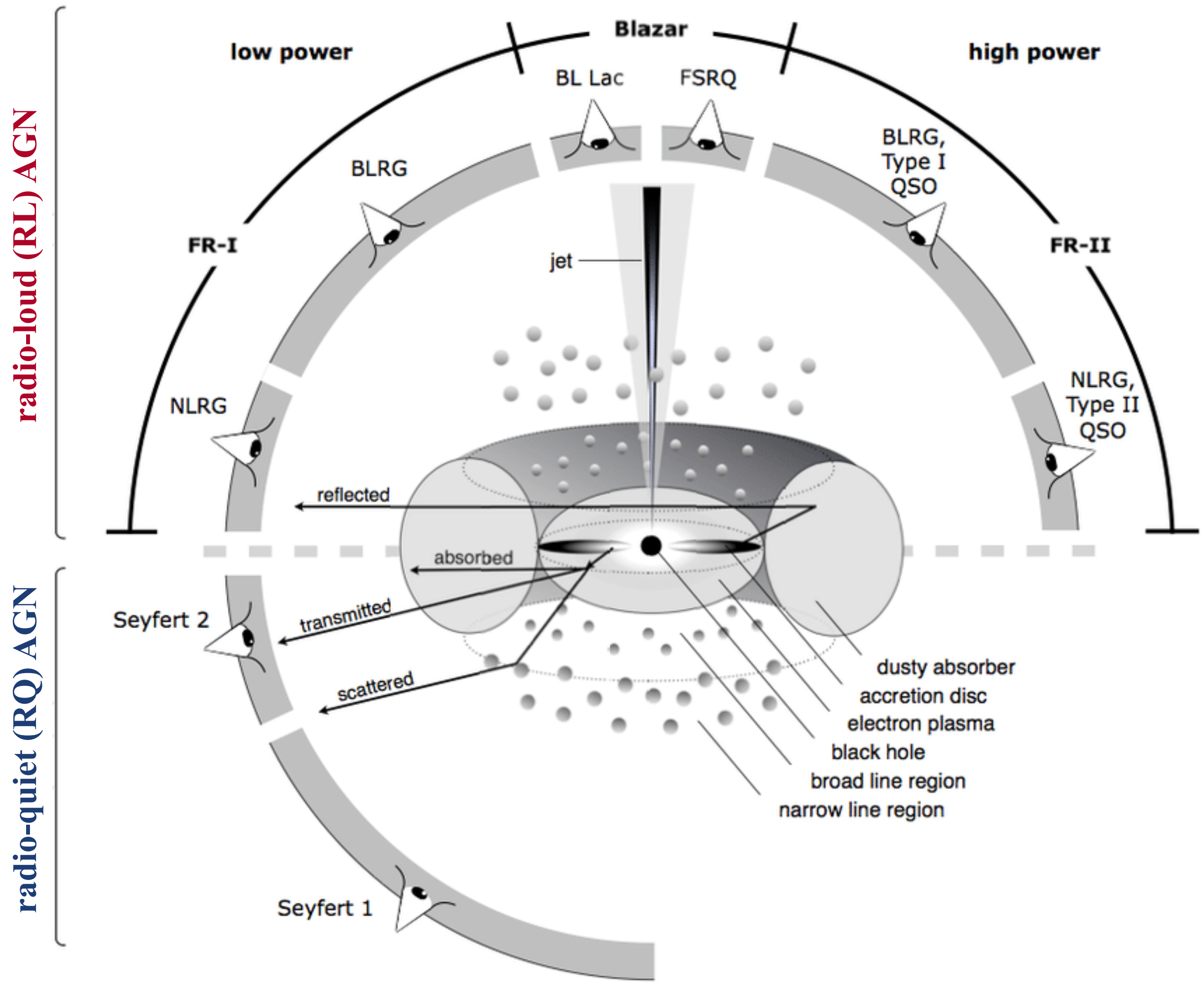
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INAF ISTITUTO NAZIONALE DI ASTROFISICA
OAS BOLOGNA

Astroparticle Physics seminar,
DESY Zeuthen, Germany
07 March 2025

Active galactic nuclei (AGN)

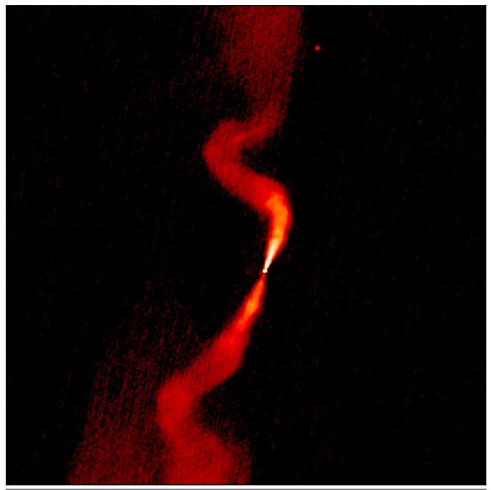
a compact region at the centre of the galaxy, which is powered
by the accretion of matter by a Supermassive Black Hole (**SMBH**).



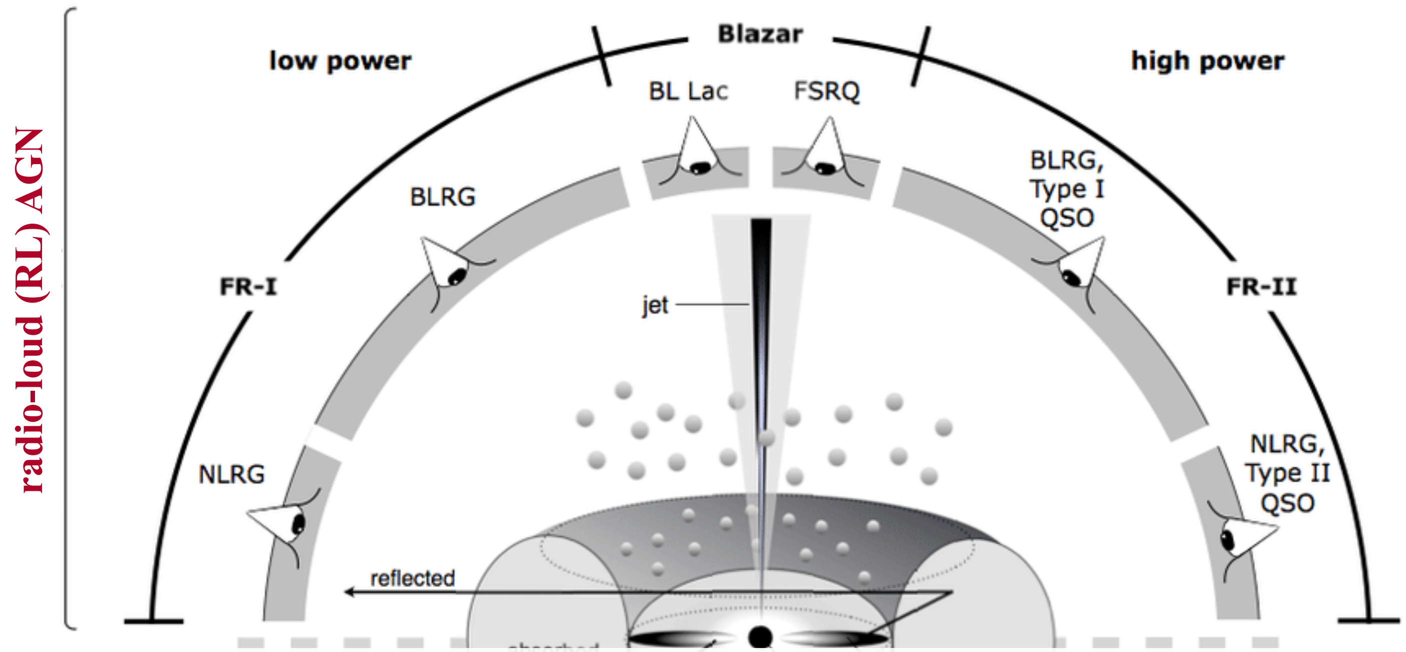
Radio-loud (RL) AGN / Radio Galaxies (RG)

a compact region at the centre of the galaxy, which is powered by the accretion of matter by a Supermassive Black Hole (**SMBH**).

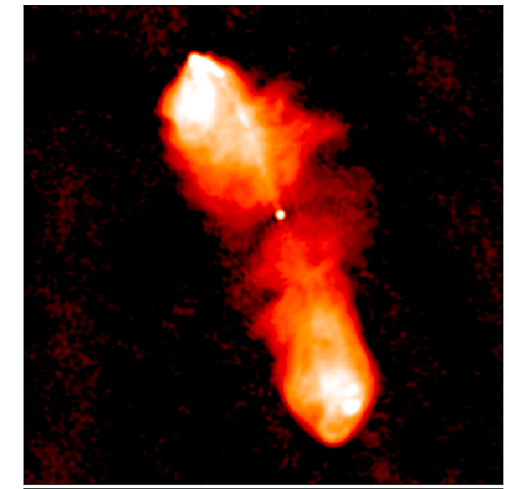
FRI



Hardcastle & Croston (2020), NewAR, 88



FRII



Hardcastle & Croston (2020), NewAR, 88

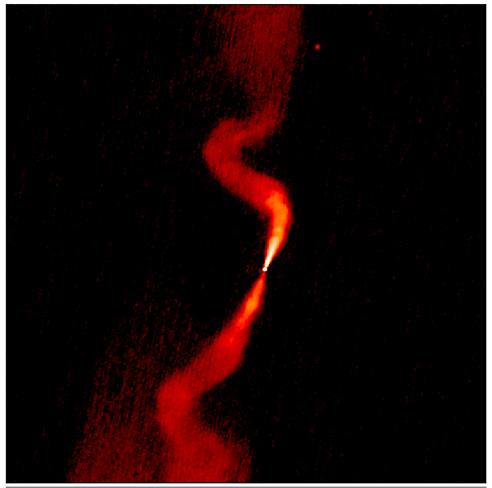
Radio morphology classification:

FRI "edge darkened" vs FRII "edge brightened"

Fanaroff and Riley 1974

Radio-loud (RL) AGN / Radio Galaxies (RG)

FRI



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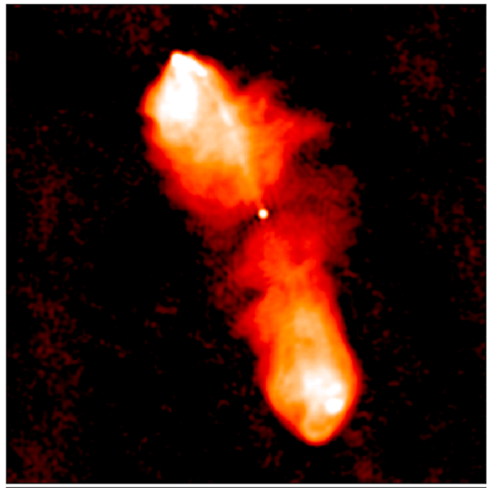


Hardcastle & Croston (2020), NewAR, 88

Reasons of radio morphology diversity?

Internal differences:

- black hole parameters (mass, spin)
- accretion disk properties (rate and mode of accretion, general structure of AGN, type of fuel, etc.)
- jet context

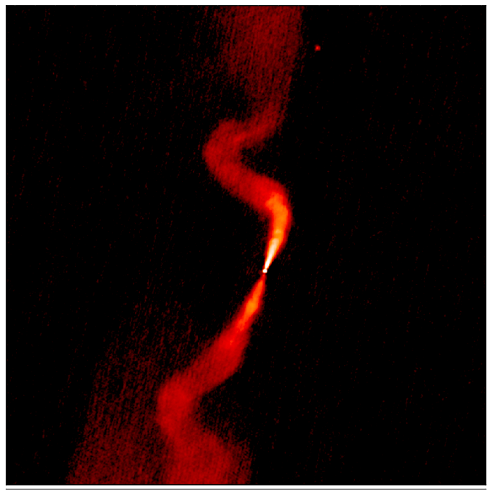
External differences:

- host galaxy properties (gas/dust context, etc.)
- large-scale environment (clusters, group etc.)

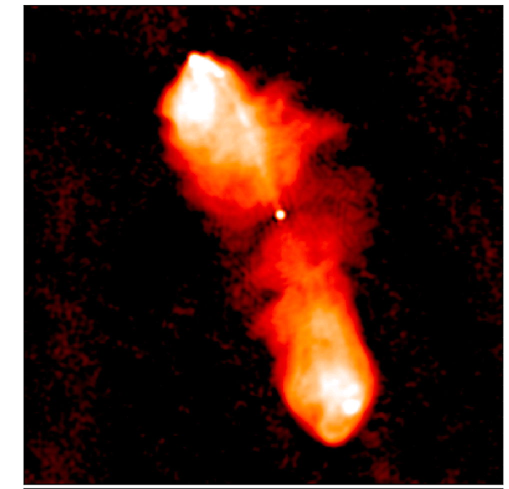
+ particular stage of AGN evolution?

Radio-loud (RL) AGN / Radio Galaxies (RG)

FRI



FRII



Radio morphology classification:

FRI "edge darkened" vs FRII "edge brightened"

Fanaroff and Riley 1974

Optical classification:

LERG vs HERG

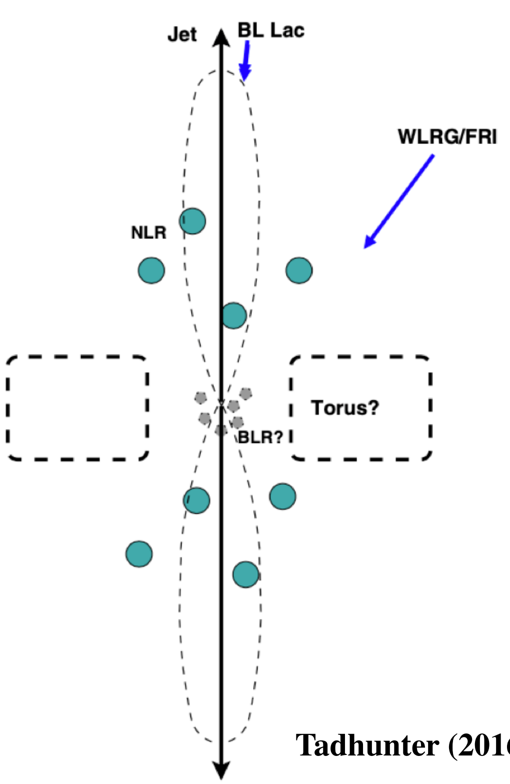
(low-excitation and high-excitation radio galaxies)

Laing et al. 1994

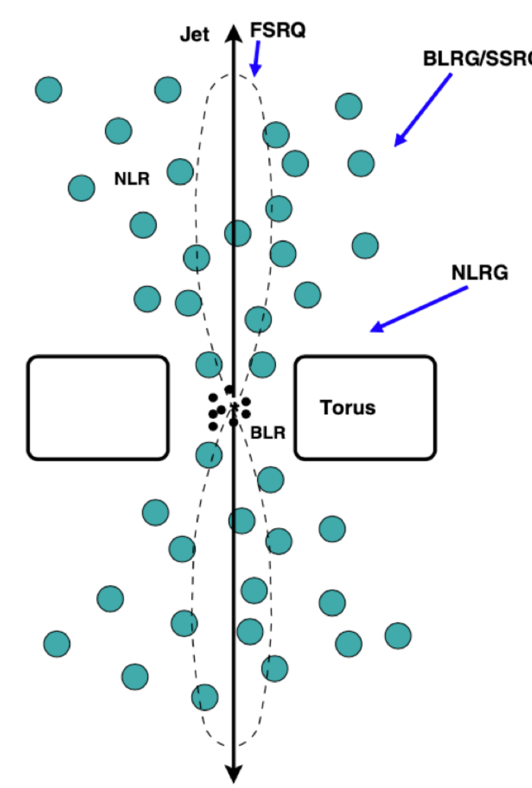
Radiatively inefficient accretion
<1% Eddington

Radiatively efficient accretion
1-100% Eddington

LERG



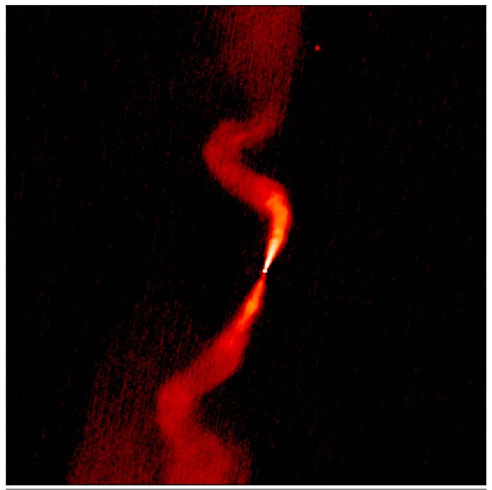
HERG



Tadhunter (2016) A&AR, 24, 1

Radio-loud (RL) AGN / Radio Galaxies (RG)

FRI



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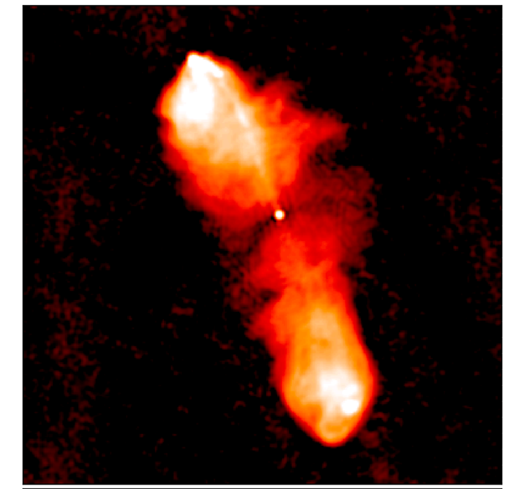

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Optical classification:

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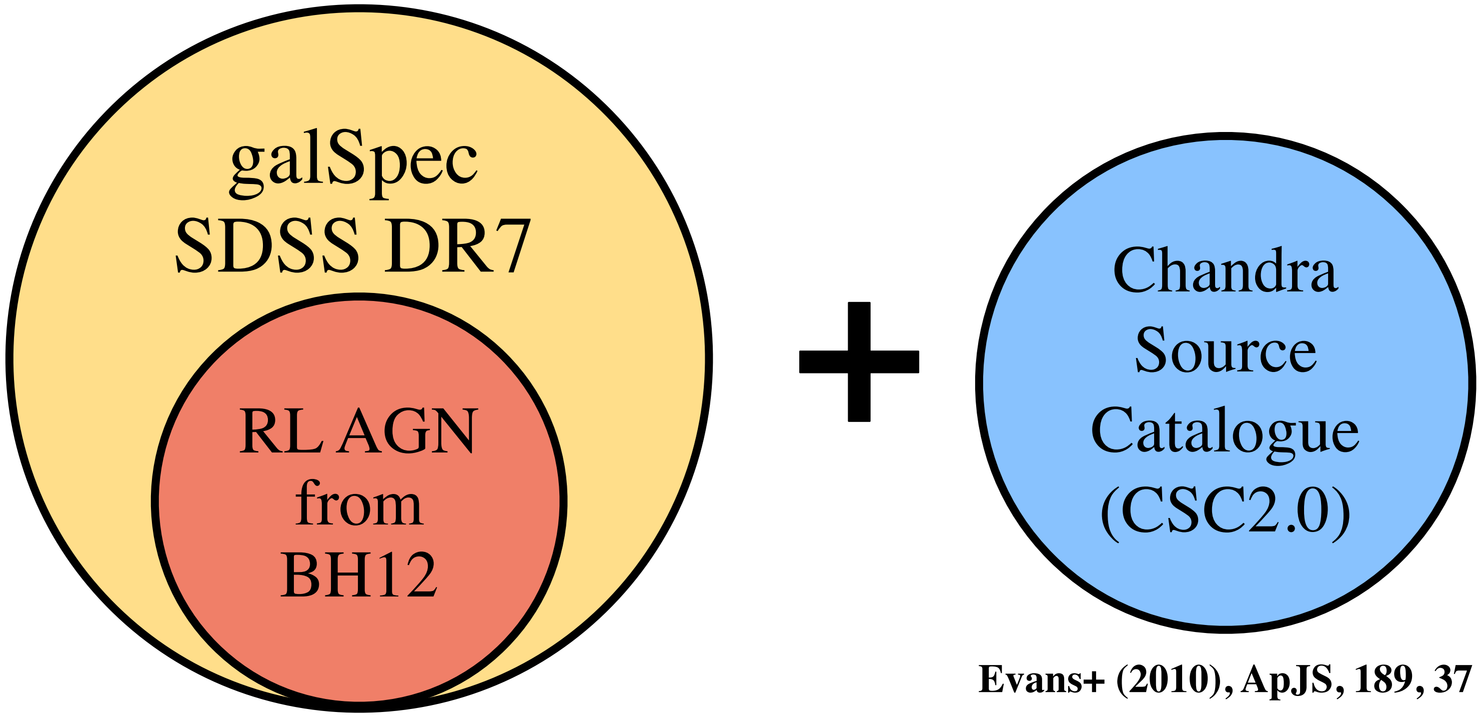
Laing et al. 1994

+ Compact radio sources:

- *orientation*: **Blazars** (BL Lac, FRSQ);
- *unresolved* (by VLA):
  - compact symmetric objects (**CSO**),
  - gigahertz-peaked spectrum (**GPS**) & compact steep spectrum (**CSS**) sources (O'Dea and Baum,1997)
  - low-luminosity **FR0** (Baldi+ 2015)

+ Hybrid FRI/FRII radio galaxies

The sample of mJy RG + X-ray data



Evans+ (2010), ApJS, 189, 37

Best & Heckman (2012), MNRAS, 421, 1569

Chandra Source Catalogue (CSC2.0)

449 X-ray detections for **263 sources**

Optical	X-ray	Radio
Emission lines parameter, D4000 break Velocity dispersion — M_{BH} Stellar mass (M_*) Star formation rate (SFR) LERG/HERG/SF classification	…	1.4GHz luminosity from FIRST & NVSS

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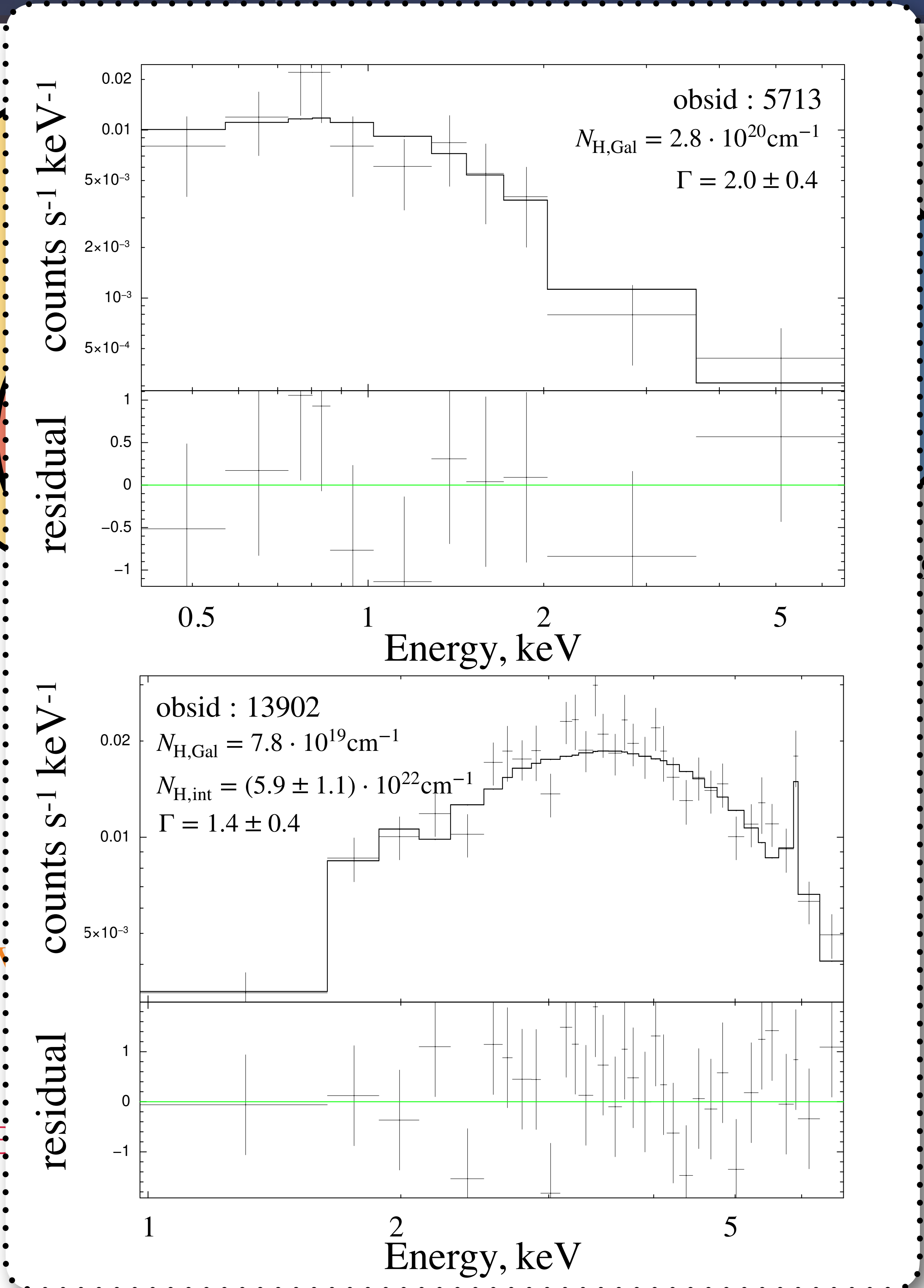

9, 37

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- ➡ no CSC data products (<3 counts);
- ➡ sources with high pile-up;

	Radio
LE	1.4GHz luminosity from FIRST & NVSS

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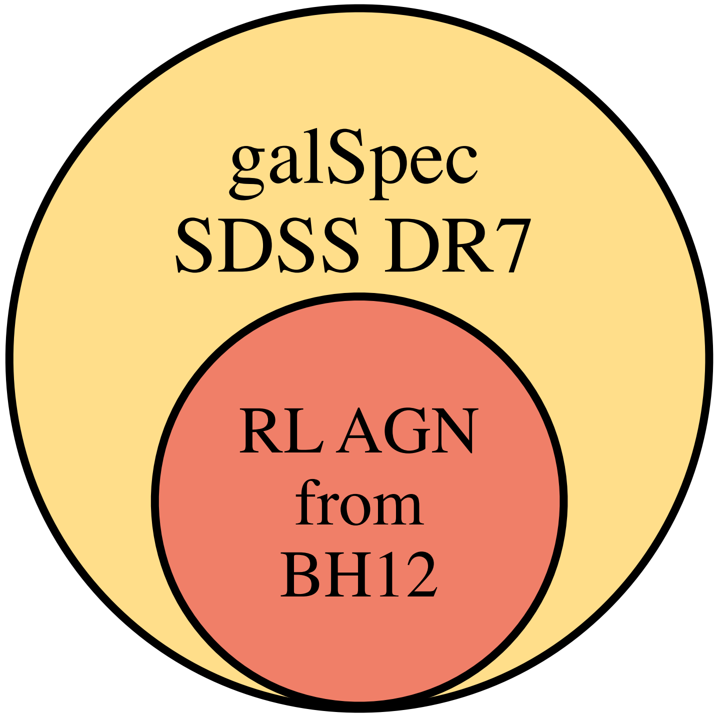

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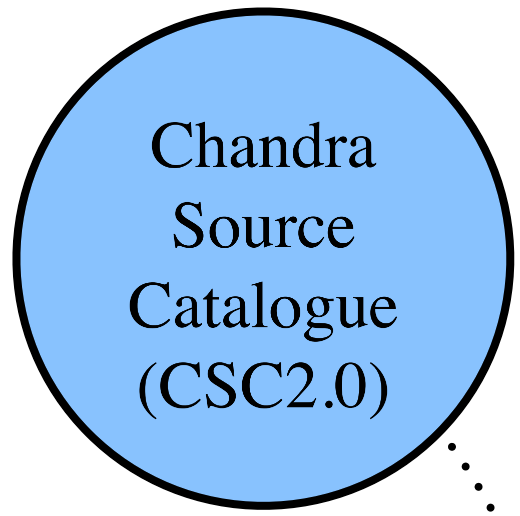
+



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Chandra Source Catalogue (CSC2.0)

449 X-ray detections for **263 sources**

- ➡ no CSC data products (<3 counts);
- ➡ sources with high pile-up;

X-ray parameters on **216* sources**

***42 sources are with upper limits**

Optical	**X-ray**	**Radio**
Emission lines parameter, Balmer break (D4000) Velocity dispersion — M_{BH} Stellar mass (M_*) Star formation rate (SFR) LERG/HERG/SF classification	Photon index Γ, $N_{H,gal}$ and N_H* kT* Emission lines parameters* 2-10 keV flux & luminosity *for some sources	1.4GHz luminosity from FIRST & NVSS

+clustering information

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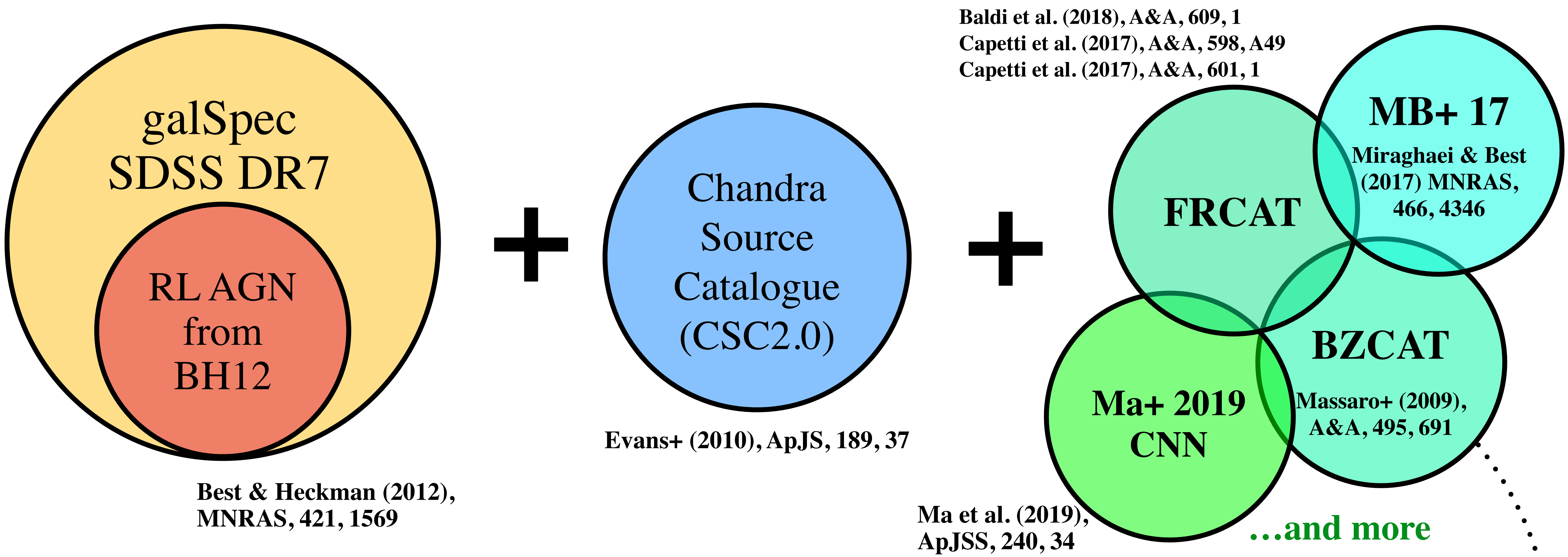
The sample of mJy RG + X-ray data + Radio morphology



Optical	X-ray	Radio
Emission lines parameter, Balmer break (D4000) Velocity dispersion — M_{BH} Stellar mass (M_*) Star formation rate (SFR) LERG/HERG/SF classification	Photon index Γ, $N_{H,gal}$ and N_H* kT* Emission lines parameters* 2-10 keV flux & luminosity *for some sources	1.4GHz luminosity from FIRST & NVSS Radio morphology class: from visual inspection, machine learning approach etc.

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The radio morphology classification

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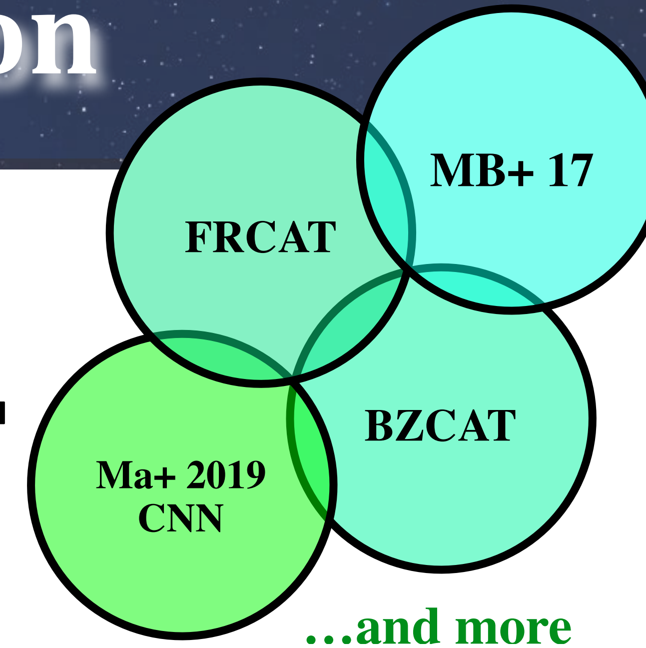
Class:	Total (lit/our)
FRI	34 (32/2)
FRII	19 (16/3)
FR0	7 (7/—)
Blazars (BL Lac, FSRS)	15 (15/—)
Compact (incl. CSS/CSO/GPS)	111 (36/75)
'Mixed': FRI-II transition; X-/Z-/S-shaped RG; FRI/FRII poor resolution; different classifications available	20 (15/5)
Extended	10 (1/9)

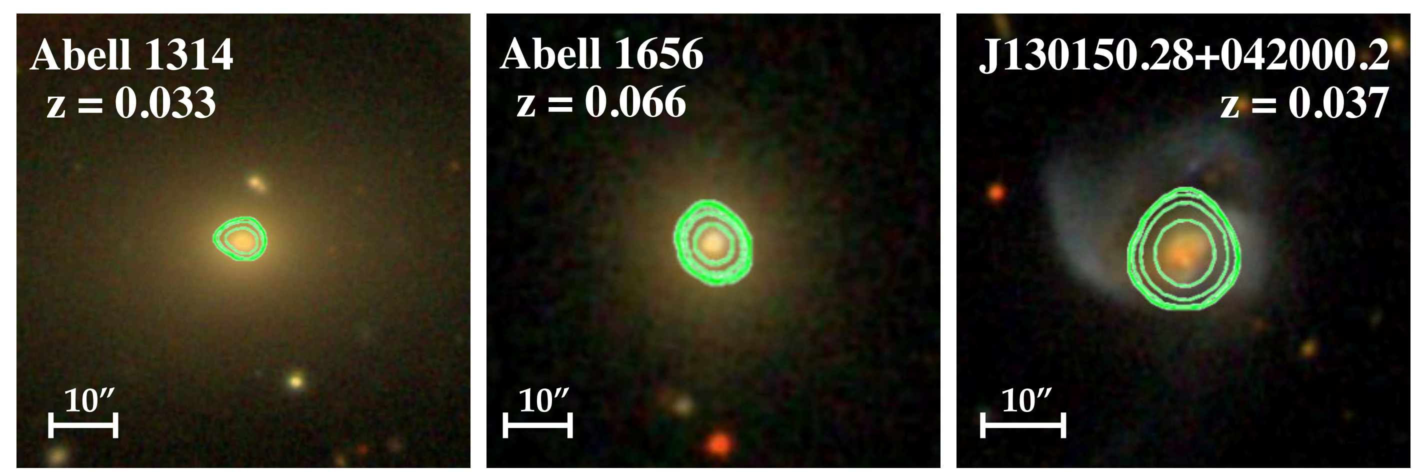
Our visual inspection based on VLASS images

+



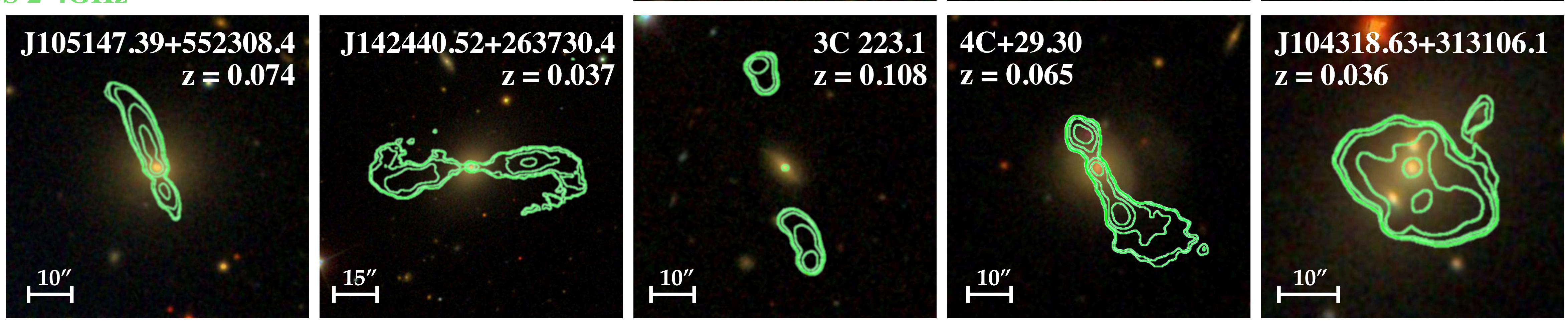
…and more

FR0 | BL Lac | Compact



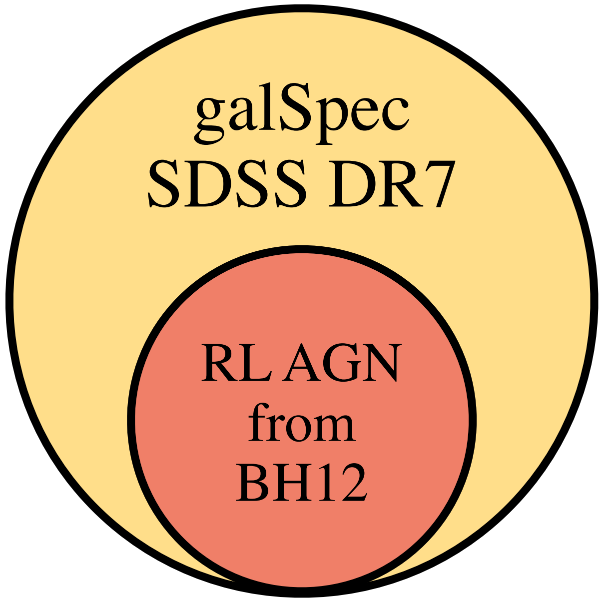
VLASS 2-4GHz

SDSS



FRI | BT-FRI | FRII | FRI-II transition | Extended

The revised optical classification



- BPT-diagnostics (Baldwin+ 1981, Veilleux & Osterbrock 1987)
- Excitation index (Buttiglione+ 2009)

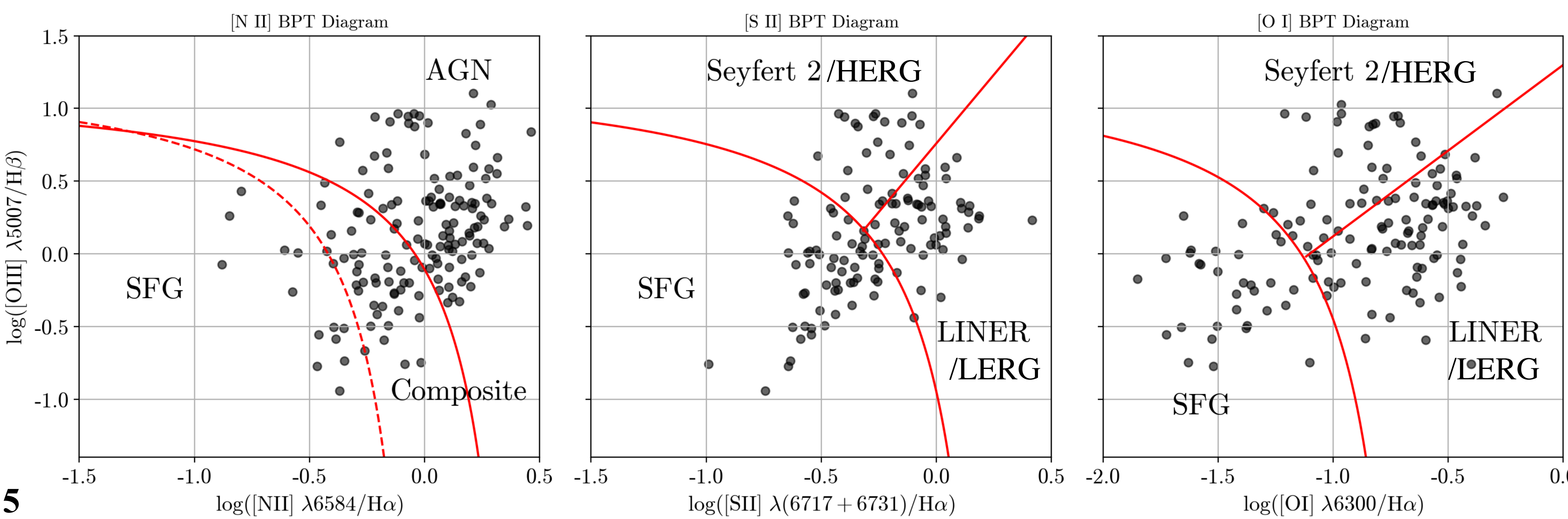
$$\mathrm{EI} = \log\left(\frac{[\mathrm{OIII}]}{\mathrm{H}\beta}\right) - \frac{1}{3}\left(\log\left(\frac{[\mathrm{NII}]}{\mathrm{H}\alpha}\right) + \log\left(\frac{[\mathrm{SII}]}{\mathrm{H}\alpha}\right) + \log\left(\frac{[\mathrm{OI}]}{\mathrm{H}\alpha}\right)\right)$$

$\mathrm{EI} < 0.95$ for LERGs and $\mathrm{EI} > 0.95$ for HERGs

- EW criteria for [OIII] λ5007Å:

$$\mathrm{EW}_{[\mathrm{OIII}]} > 5\text{Å} \quad \text{for HERGs}$$

Class:	**N**
HERGs	25
LERGs	142
SF	42



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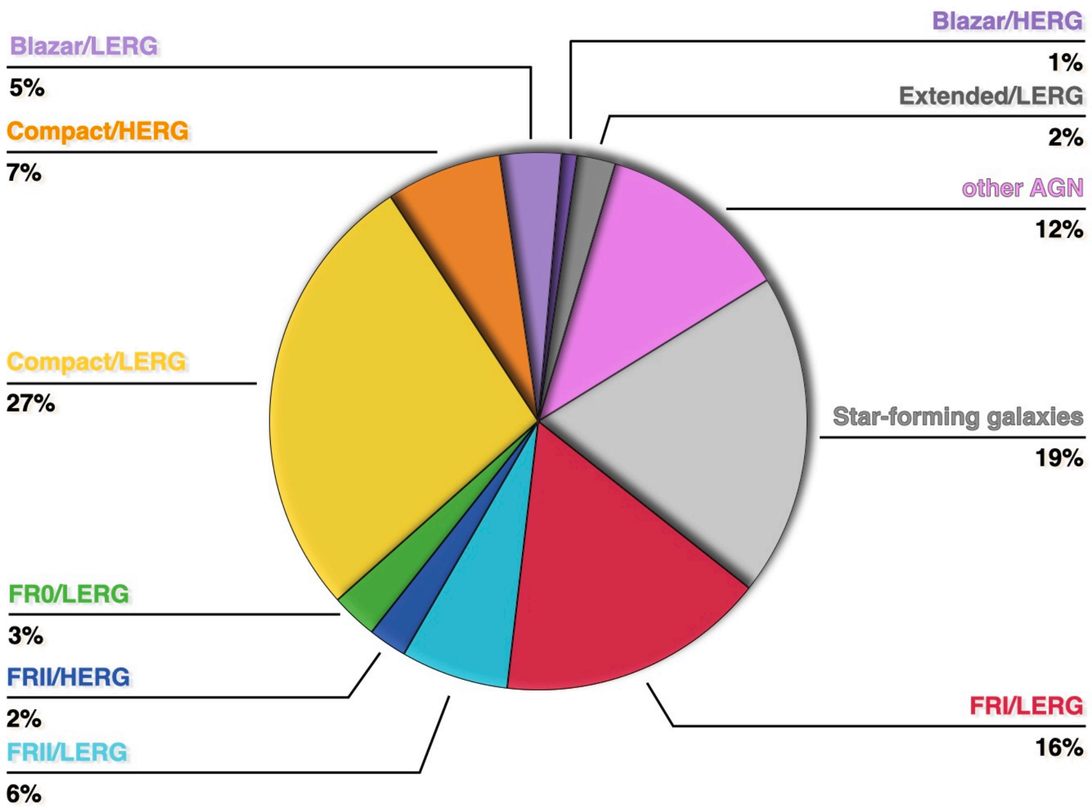
The "final" sample of mJy RG

Radio class: \ Optical class:	HERG	LERG	SF
FRI	x	35	x
FRII	5	14	x
FR0	x	7	x
Compact	15	59	37
Blazars	2	8	x
'Mixed'	3	14	1
Extended	x	5	5

+6 with power-law continuum in their optical spectra (blazars)



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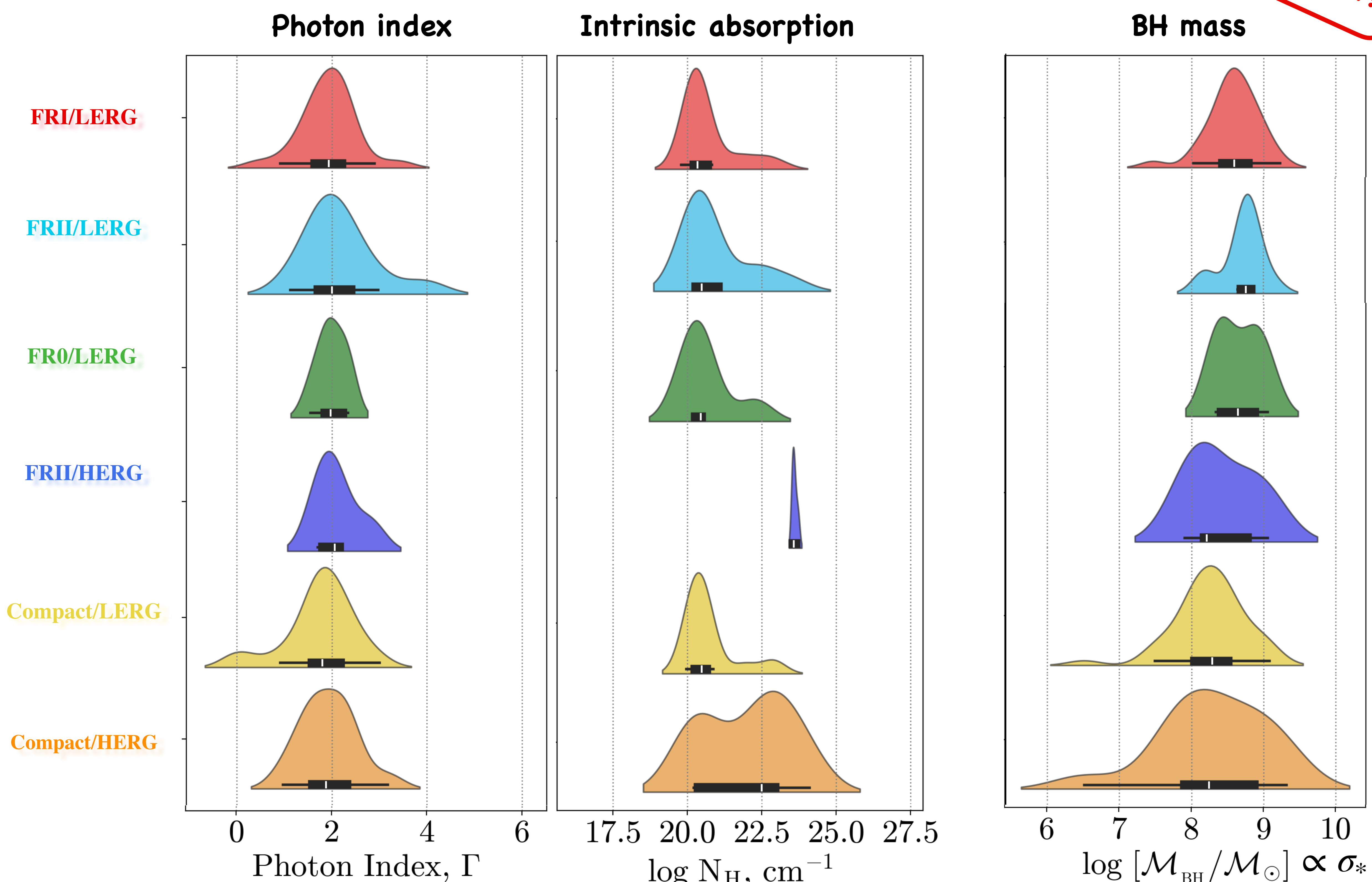
The X-ray properties

PRELIMINARY!



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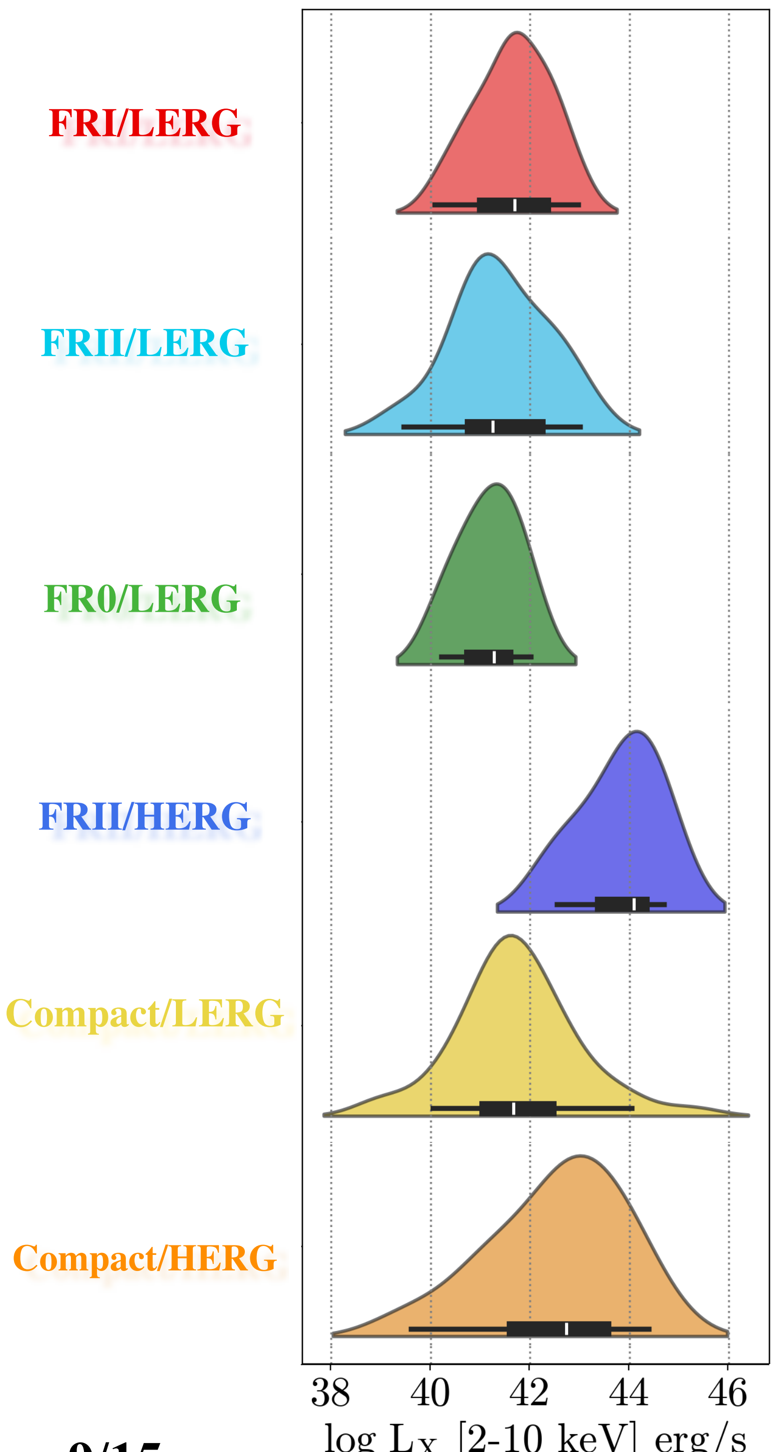
The X-ray properties

X-ray luminosity



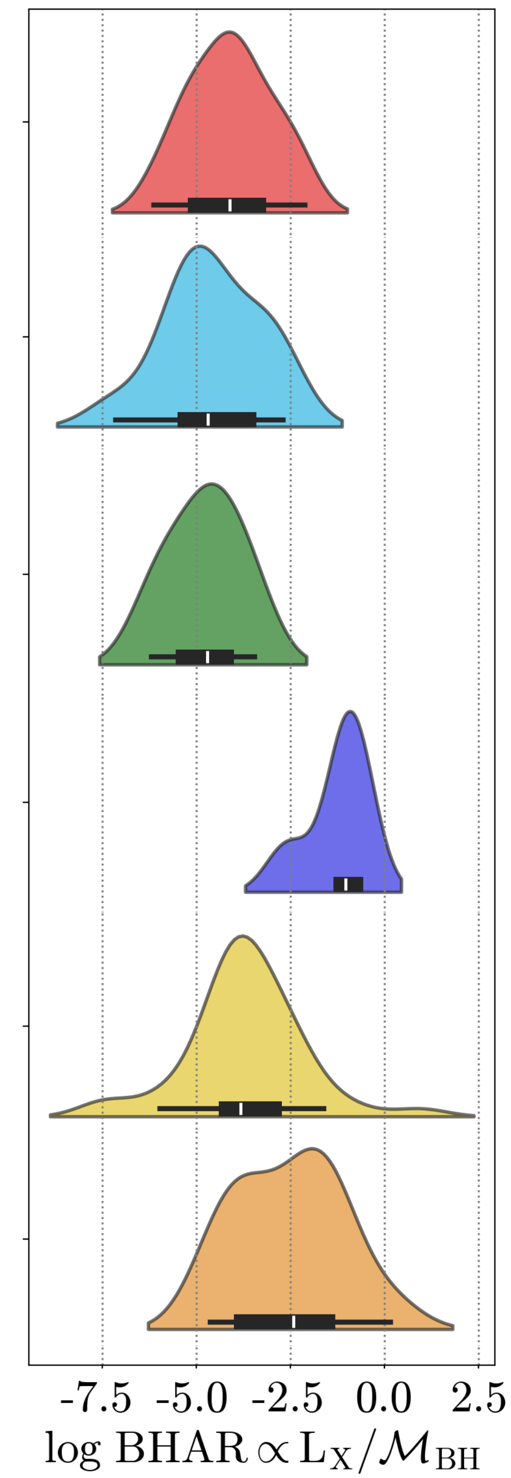
The confidence level P-value < 0.05

MWU test (p-value)

$BHAR_X$ (upper triangle) / L_X (lower triangle)

	FRI/LERG	FRII/LERG	FRII/HERG	FR0/LERG	Compact/LERG	Compact/HERG
FRI/LERG		0.284	$4.3\cdot10^{-5}$	0.172	0.127	0.001
FRII/LERG	0.351		$3.2\cdot10^{-4}$	0.682	0.047	0.002
FRII/HERG	$4.3\cdot10^{-5}$	0.001		0.004	$4.2\cdot10^{-4}$	0.034
FR0/LERG	0.123	0.750	0.004		0.050	0.002
Compact/LERG	0.986	0.355	$5.3\cdot10^{-4}$	0.180		0.022
Compact/HERG	0.016	0.022	0.056	0.026	0.039	

BHAR



LERGs with different morphologies (FR0, FRI, and FRII) having similar X-ray luminosity (and BHAR), which is smaller than for FRII/HERGs

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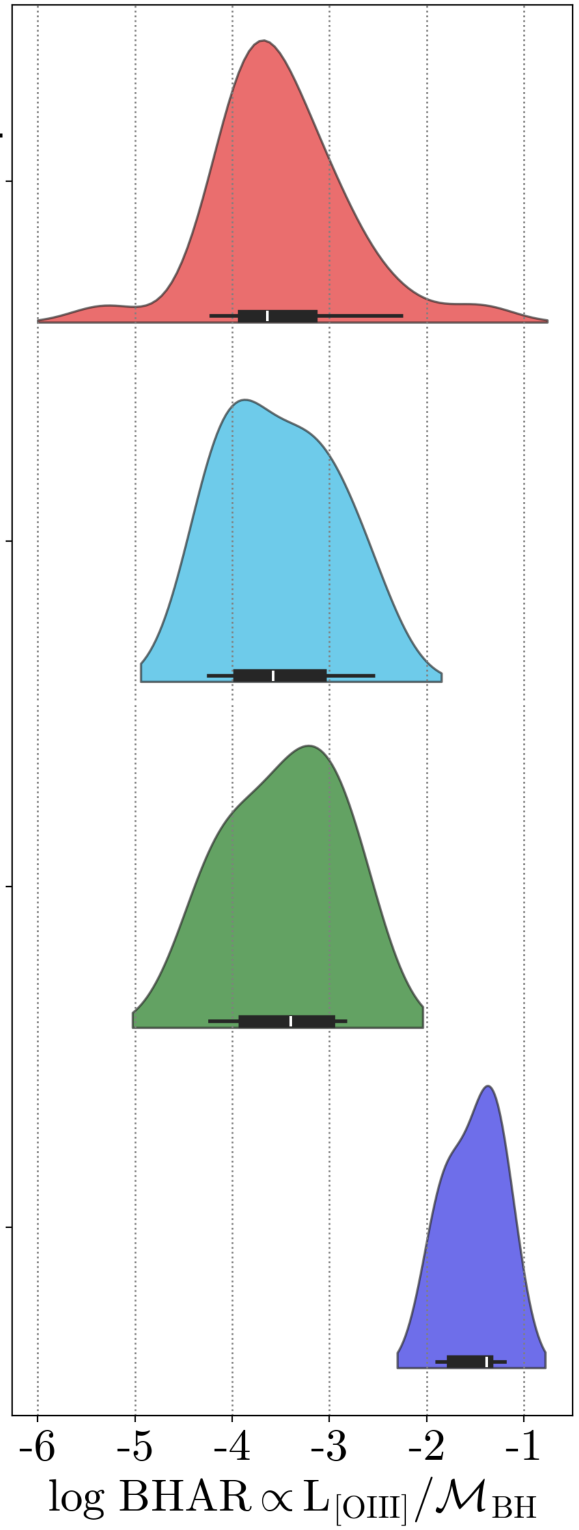
BHAR: X-ray vs [OIII] 5007Å

Optical band: [OIII] 5007Å

$$\mathrm{BHAR}_{[\mathrm{OIII}]} = \frac{3500\,\mathrm{L}_{[\mathrm{OIII}]}}{1.3\cdot 10^{38}\times[M_{\mathrm{BH}}/M_{\odot}]}$$



FRI/LERG

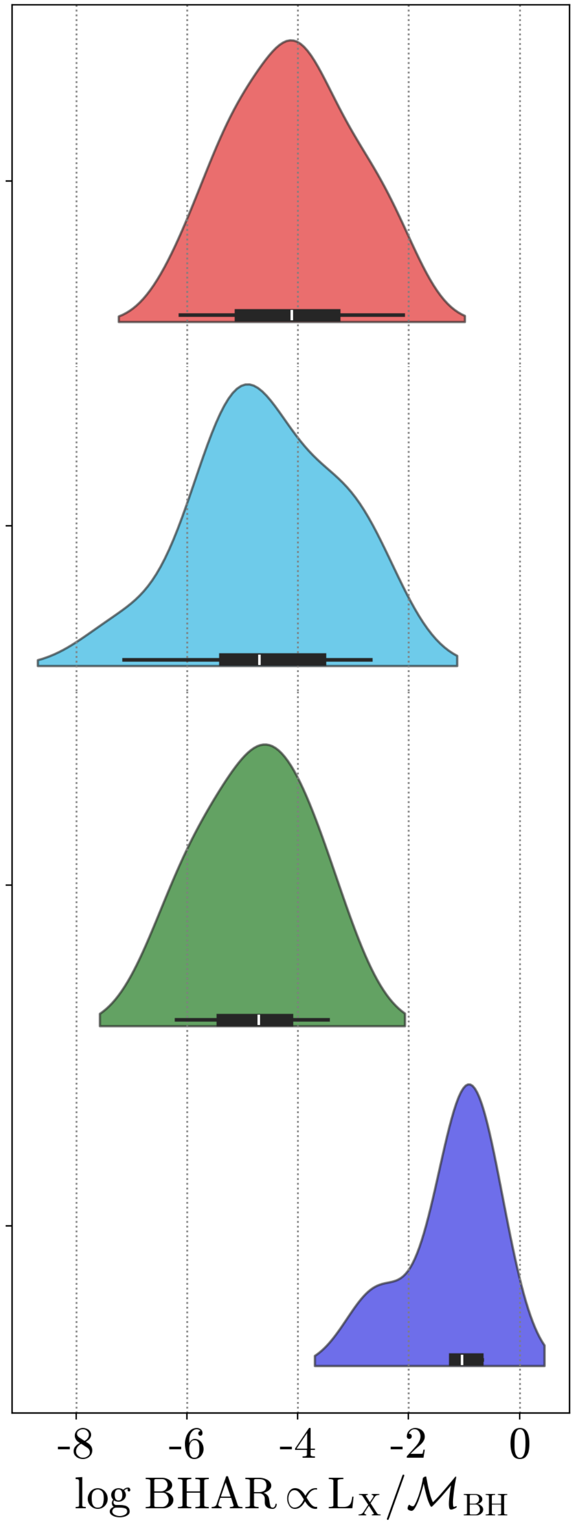
FRII/LERG

FR0/LERG

FRII/HERG

X-ray band: 2-10 keV

$$\mathrm{BHAR}_{\mathrm{X}} = \frac{k_{\mathrm{bol}}\mathrm{L}_{\mathrm{X}}}{1.3\cdot 10^{38}\times[M_{\mathrm{BH}}/M_{\odot}]}$$



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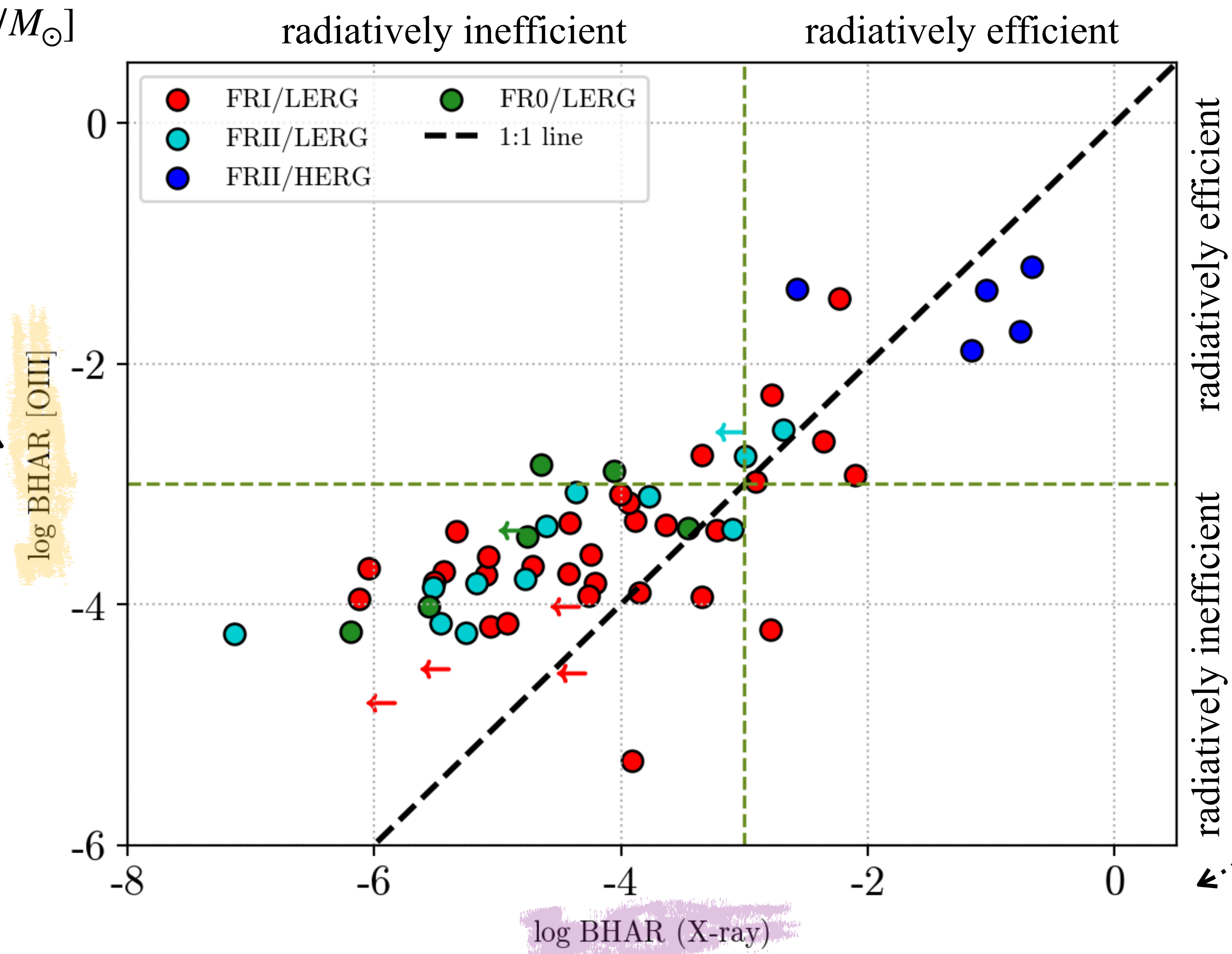

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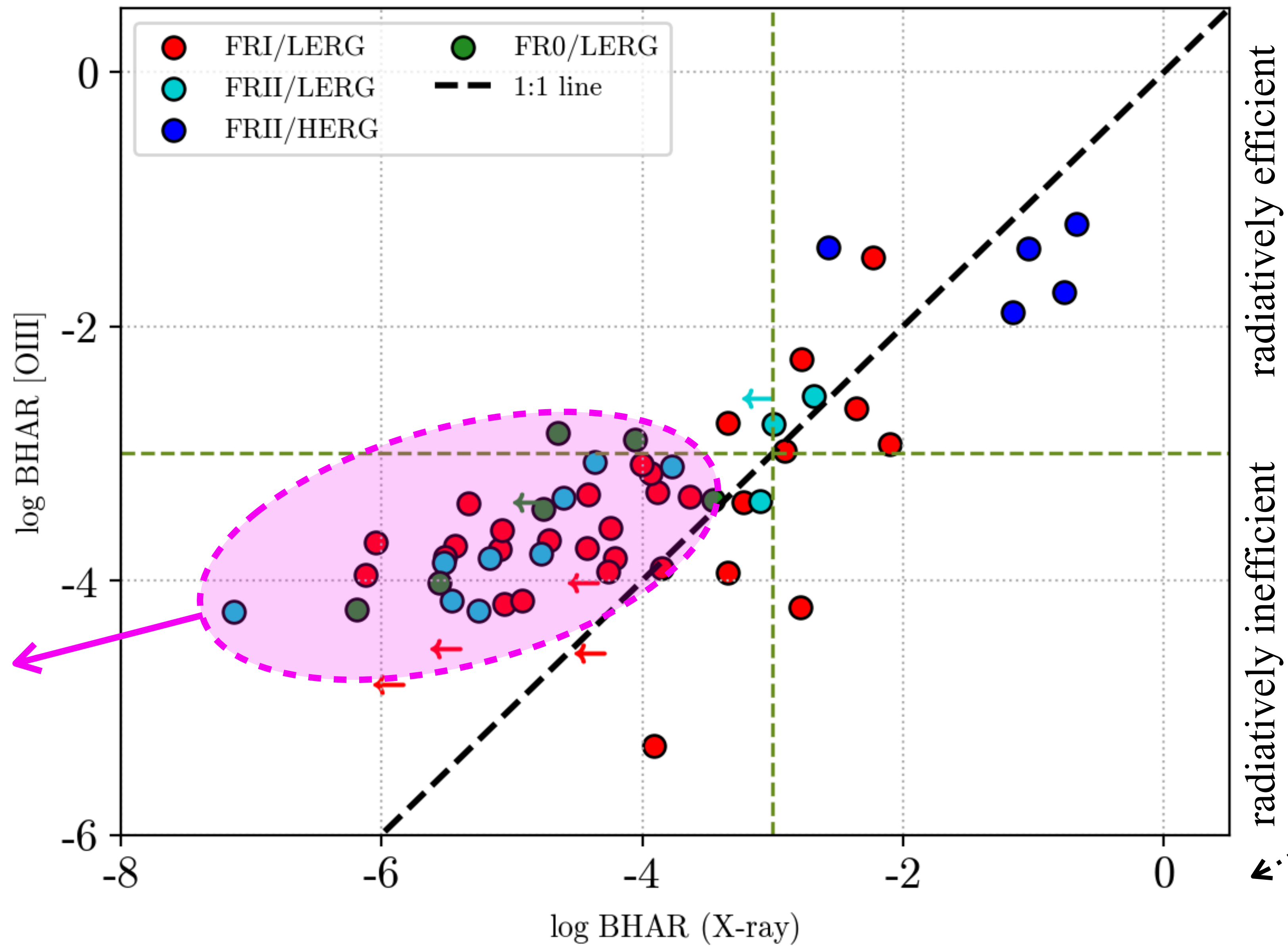

enhanced [OIII] emission due to jet-induced shocks in ISM?

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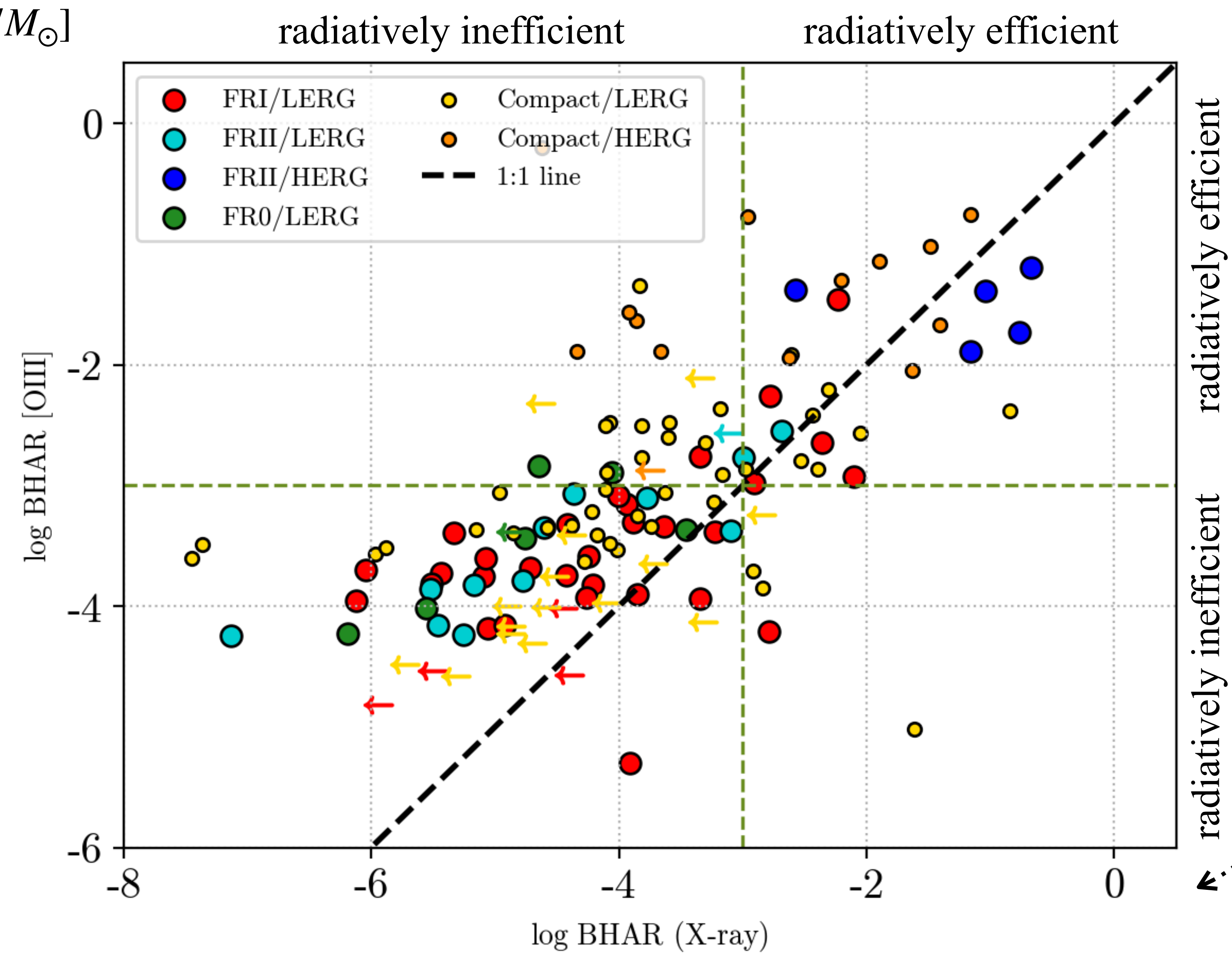

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X-ray vs 1.4GHz radio luminosity

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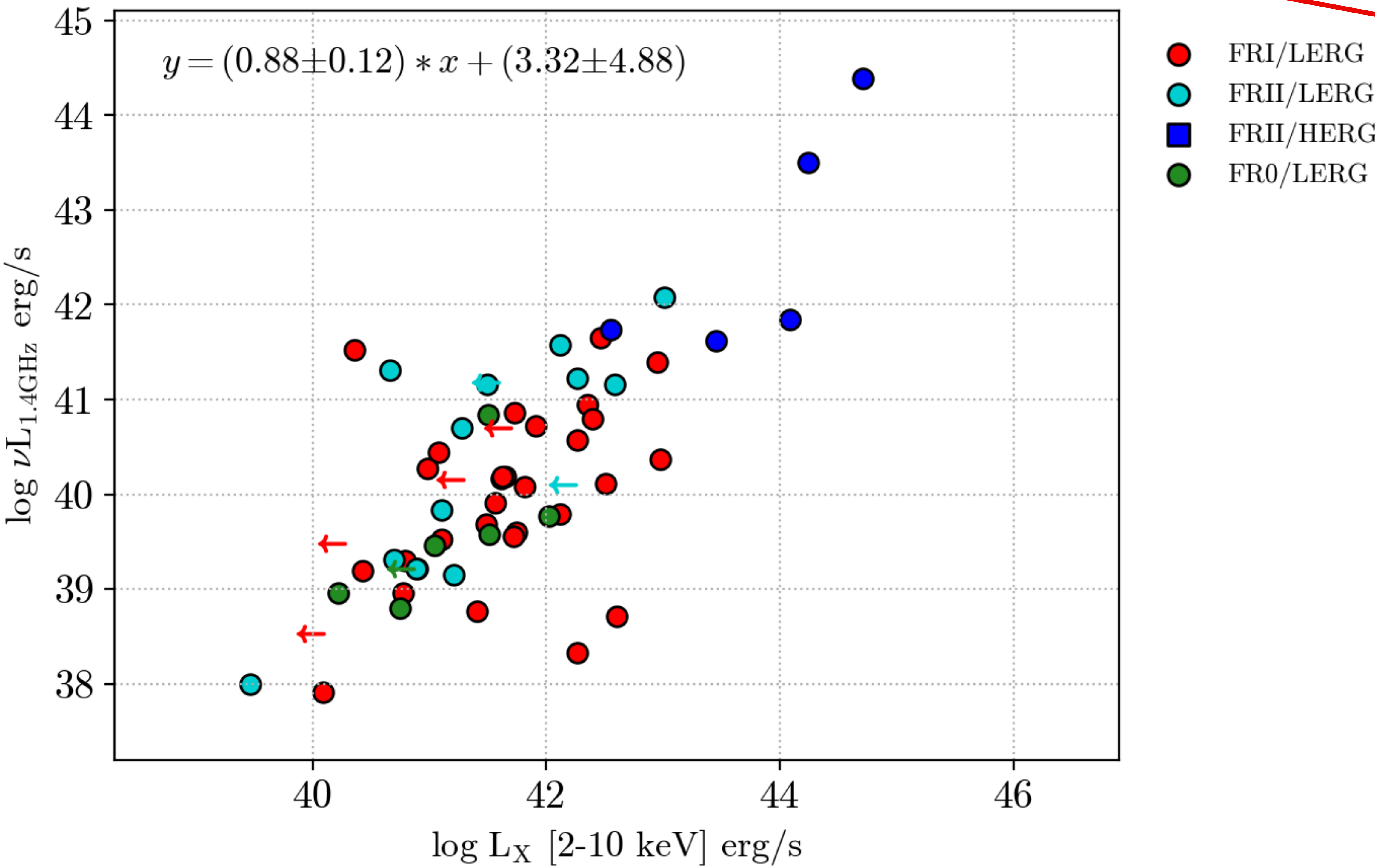

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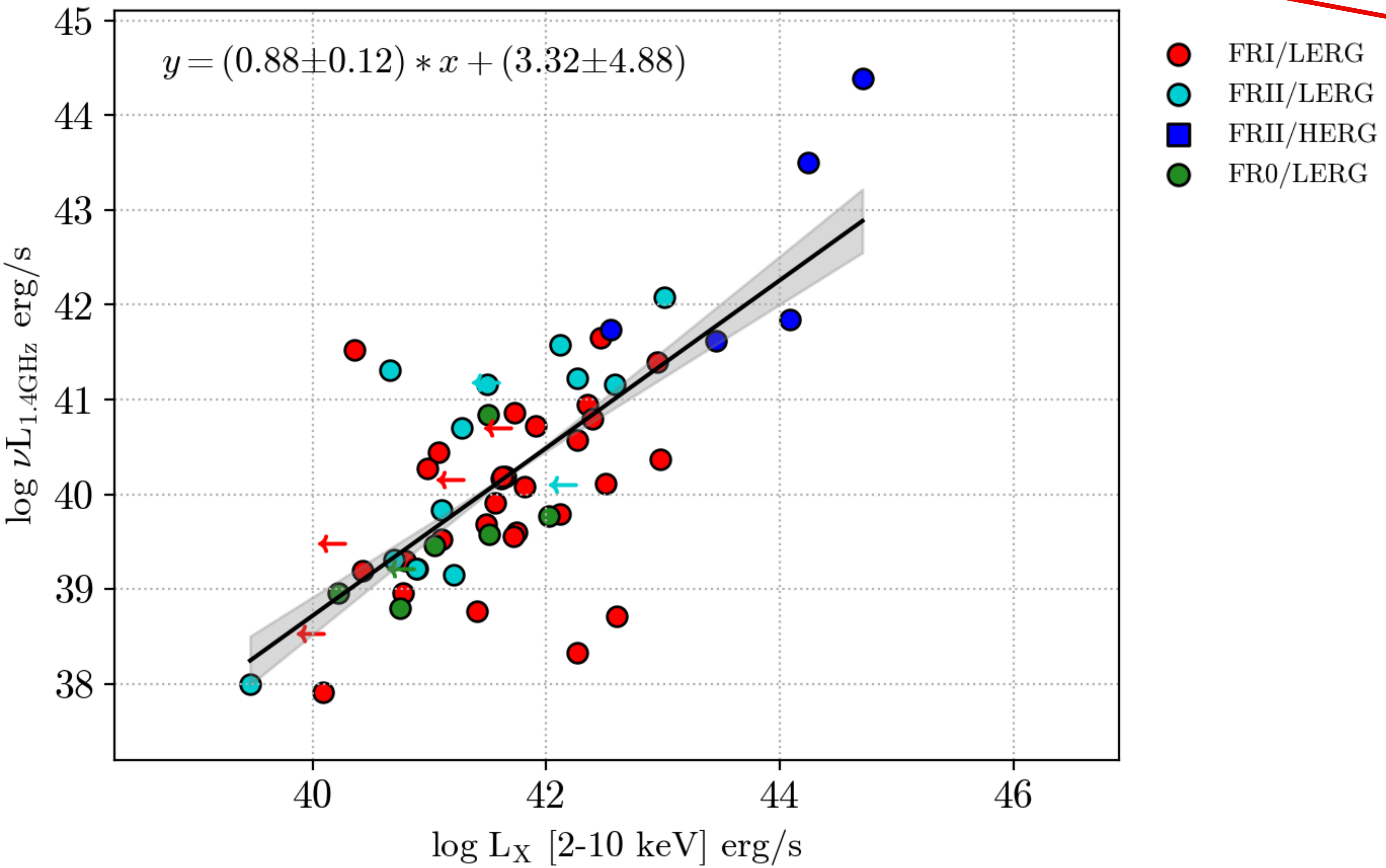

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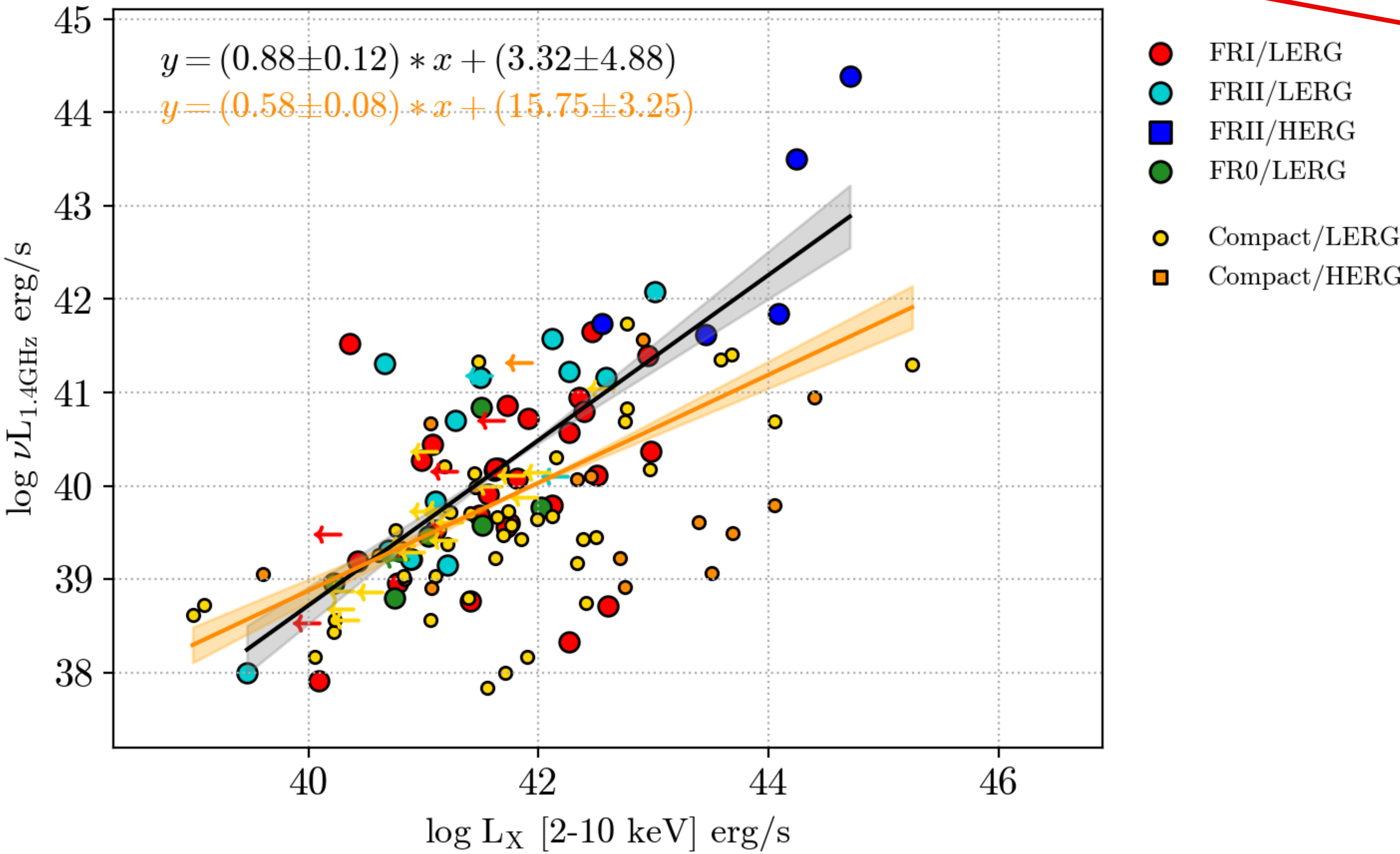

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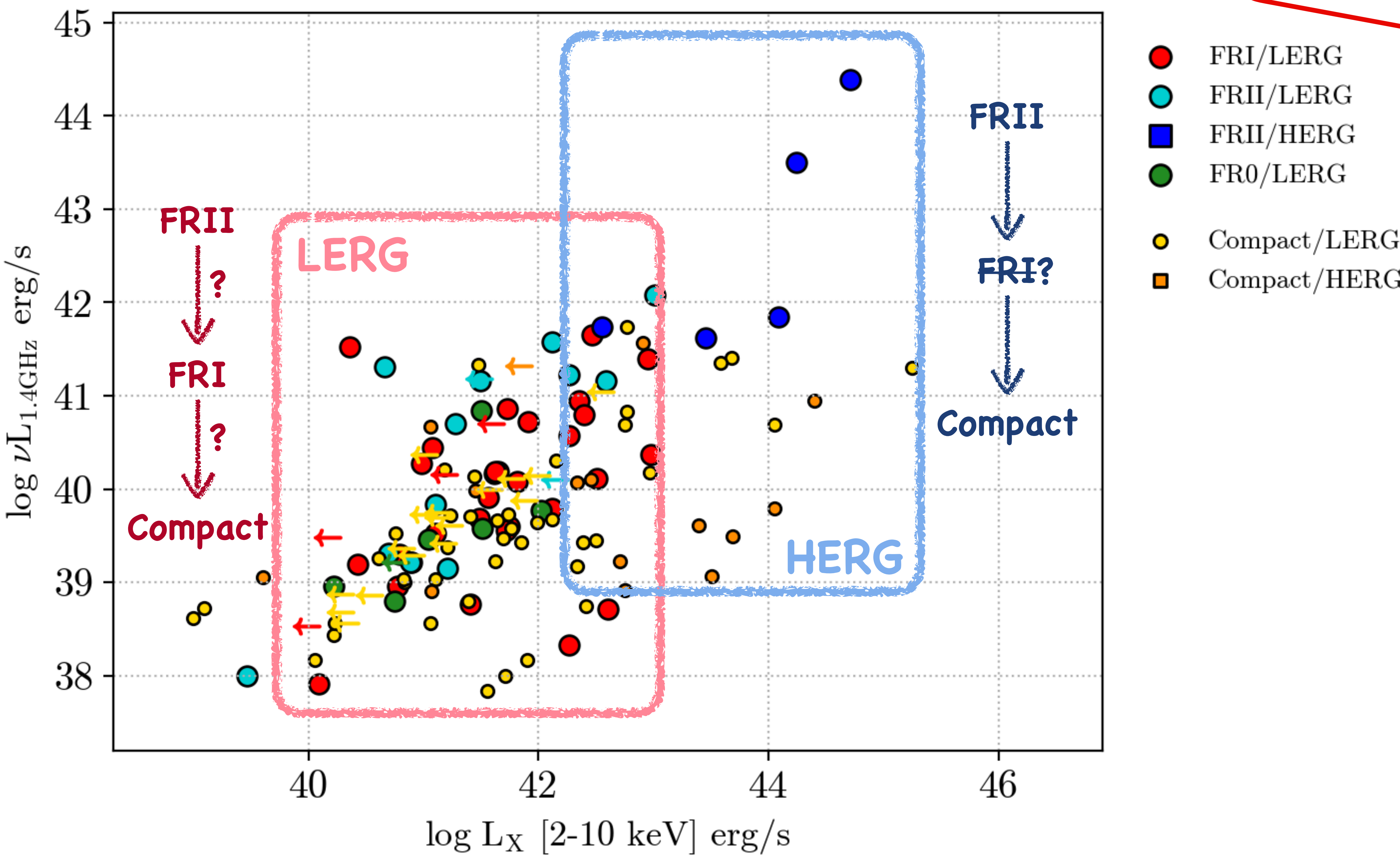

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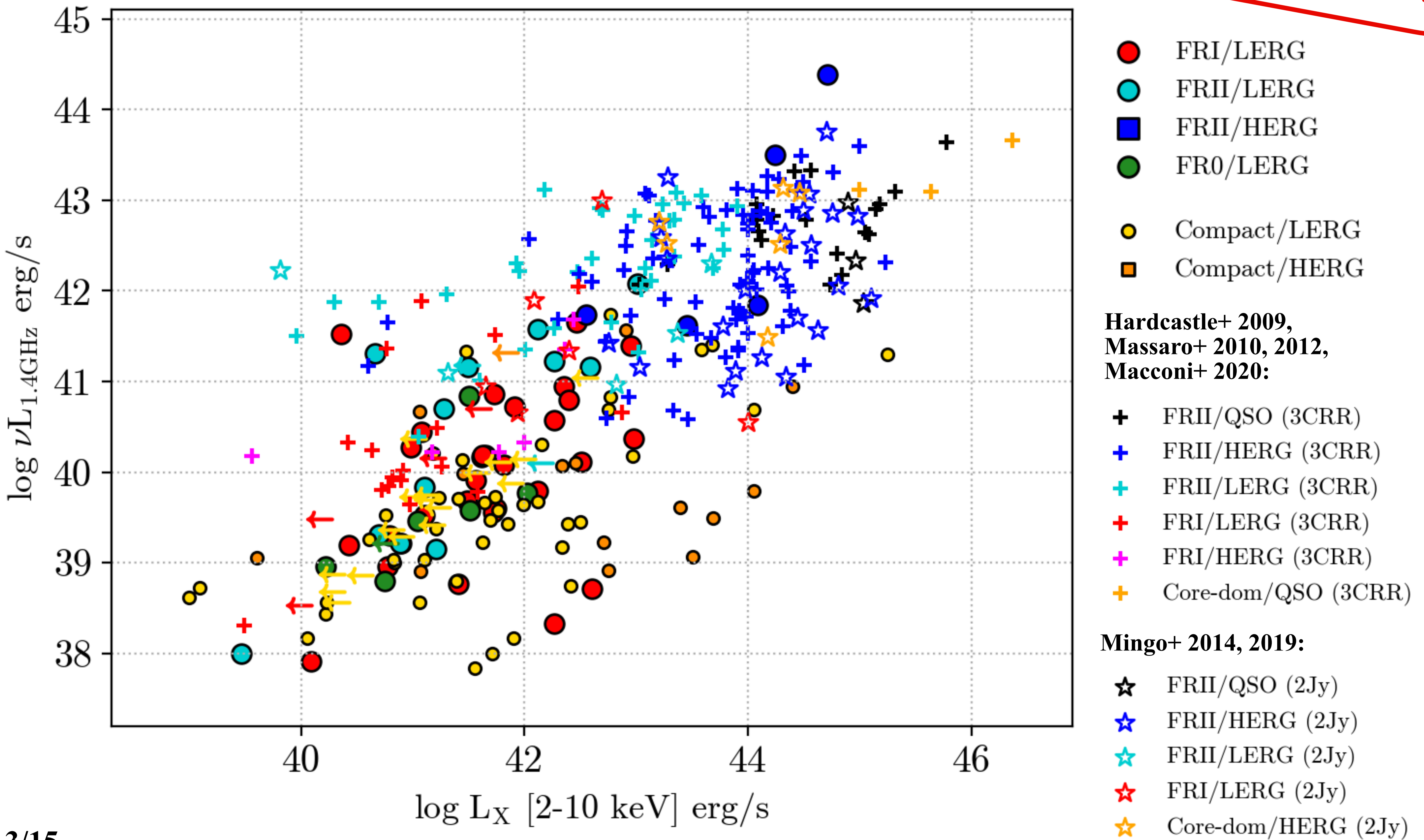

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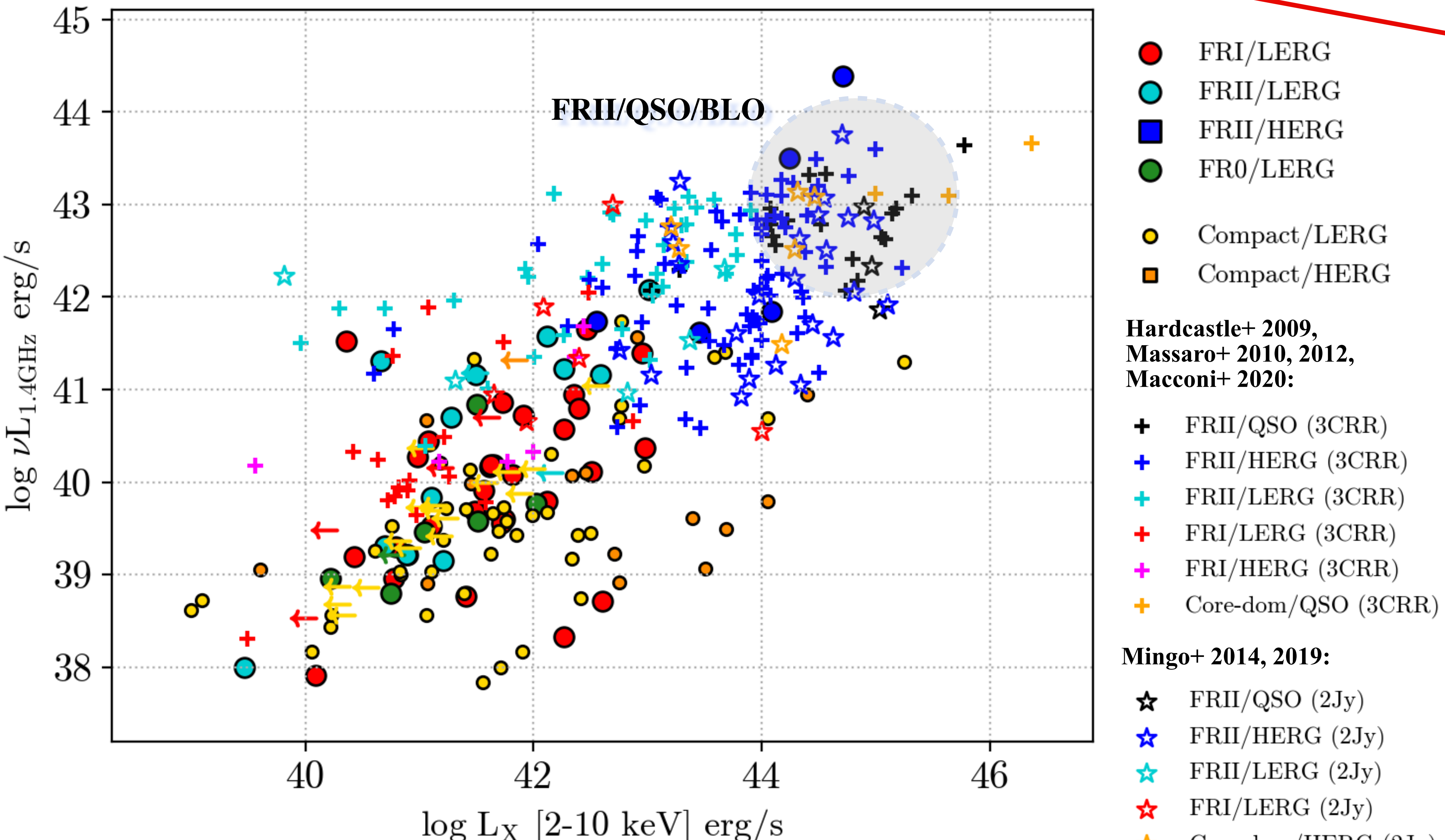

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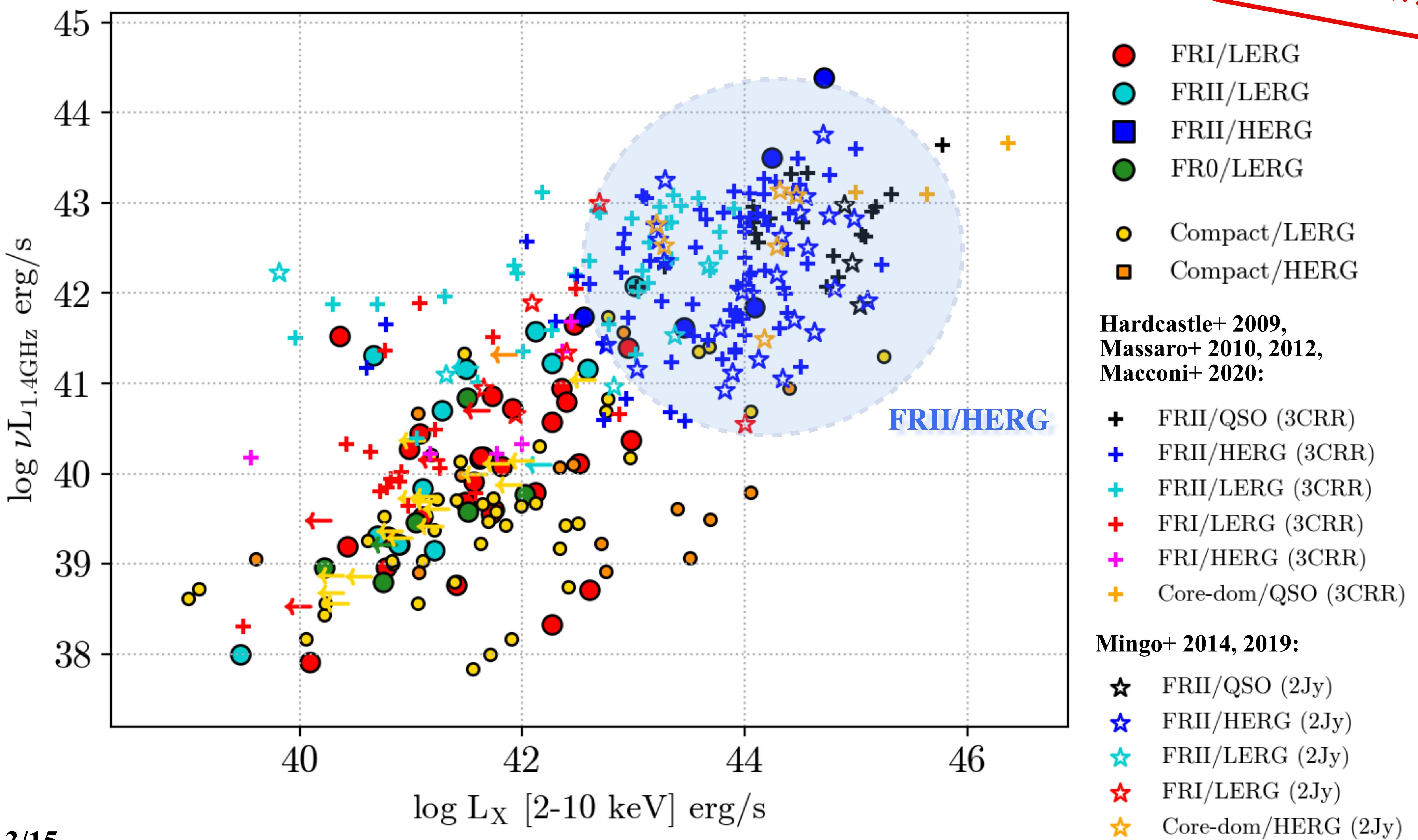

X-ray vs 1.4GHz radio luminosity

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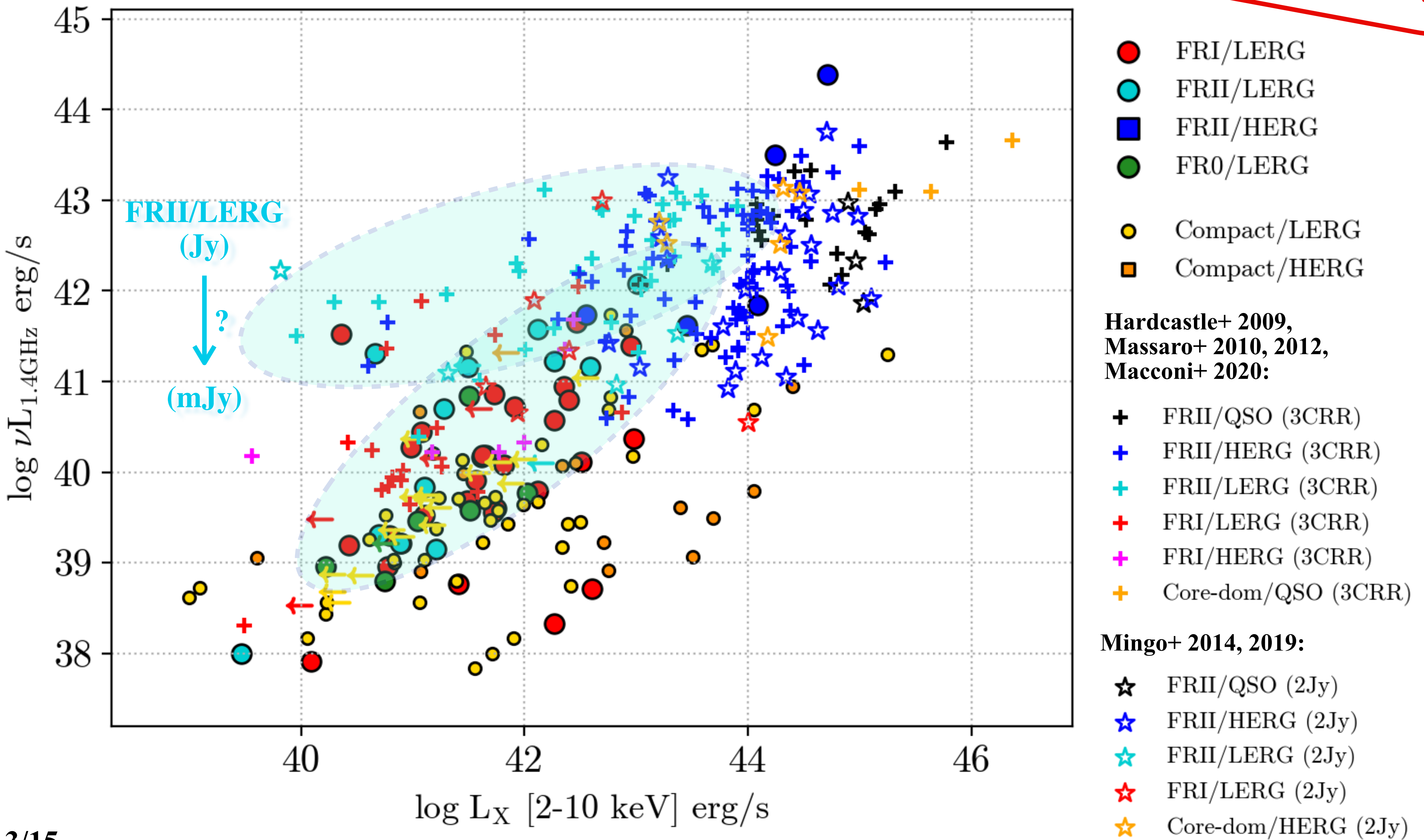

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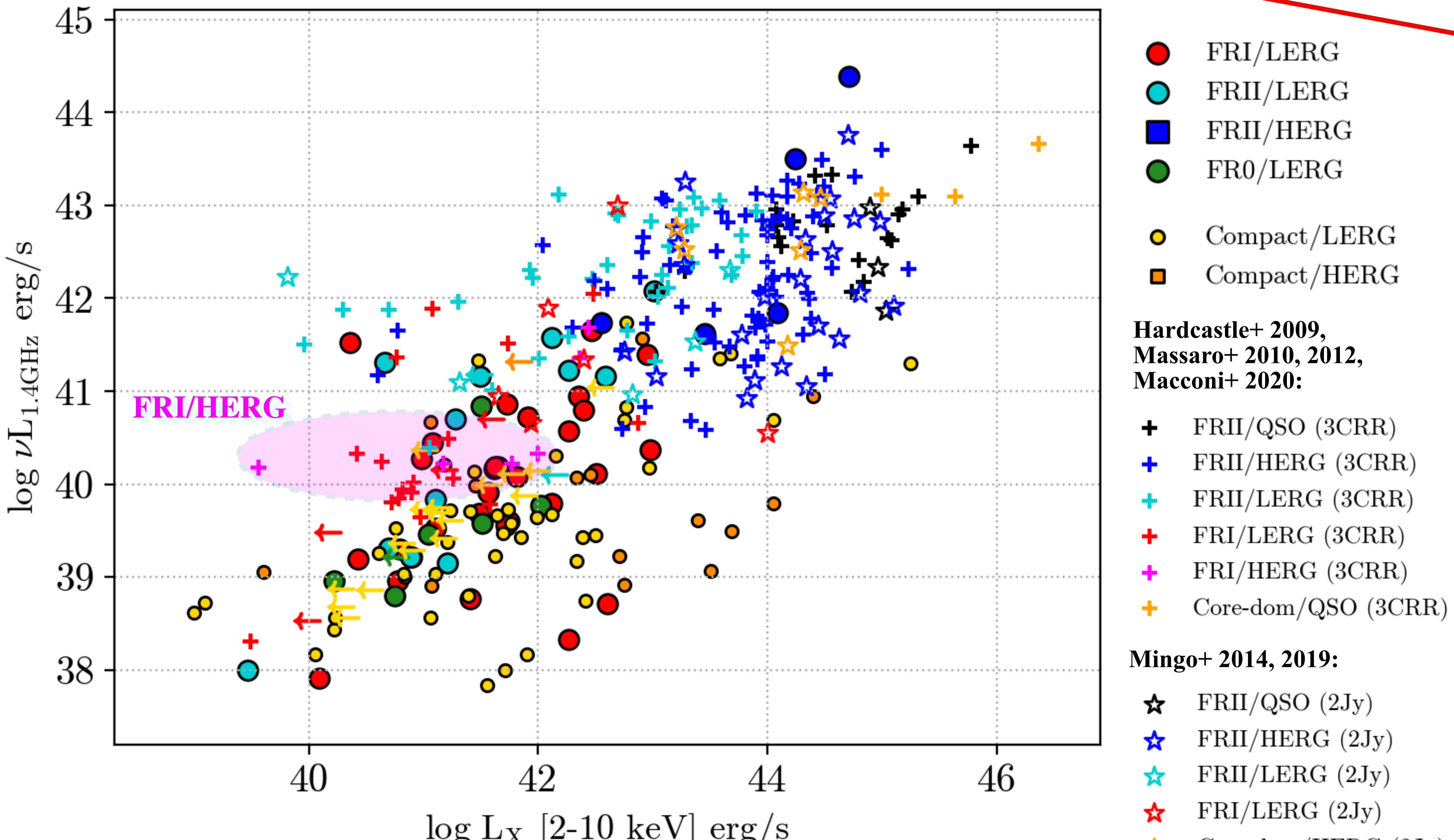

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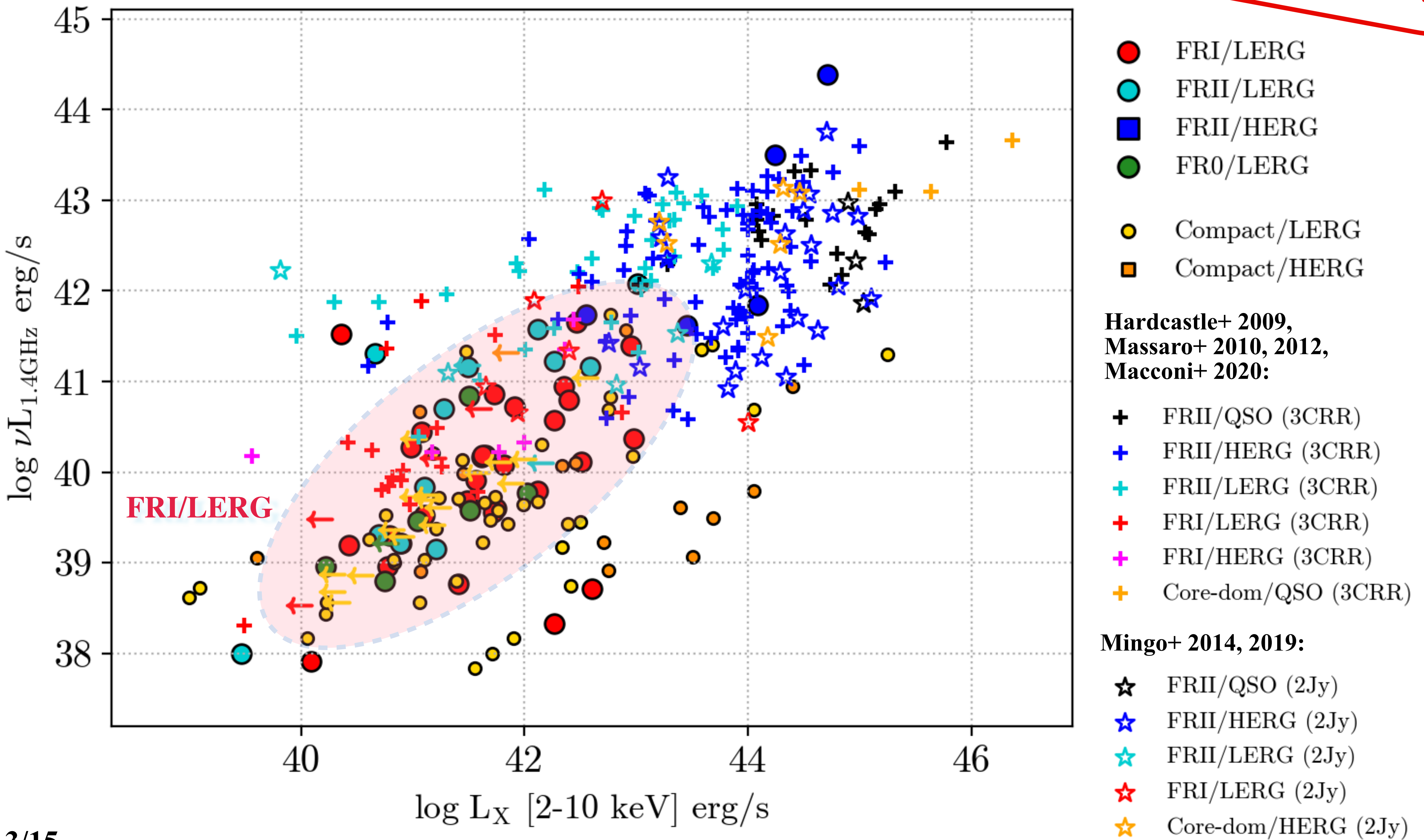

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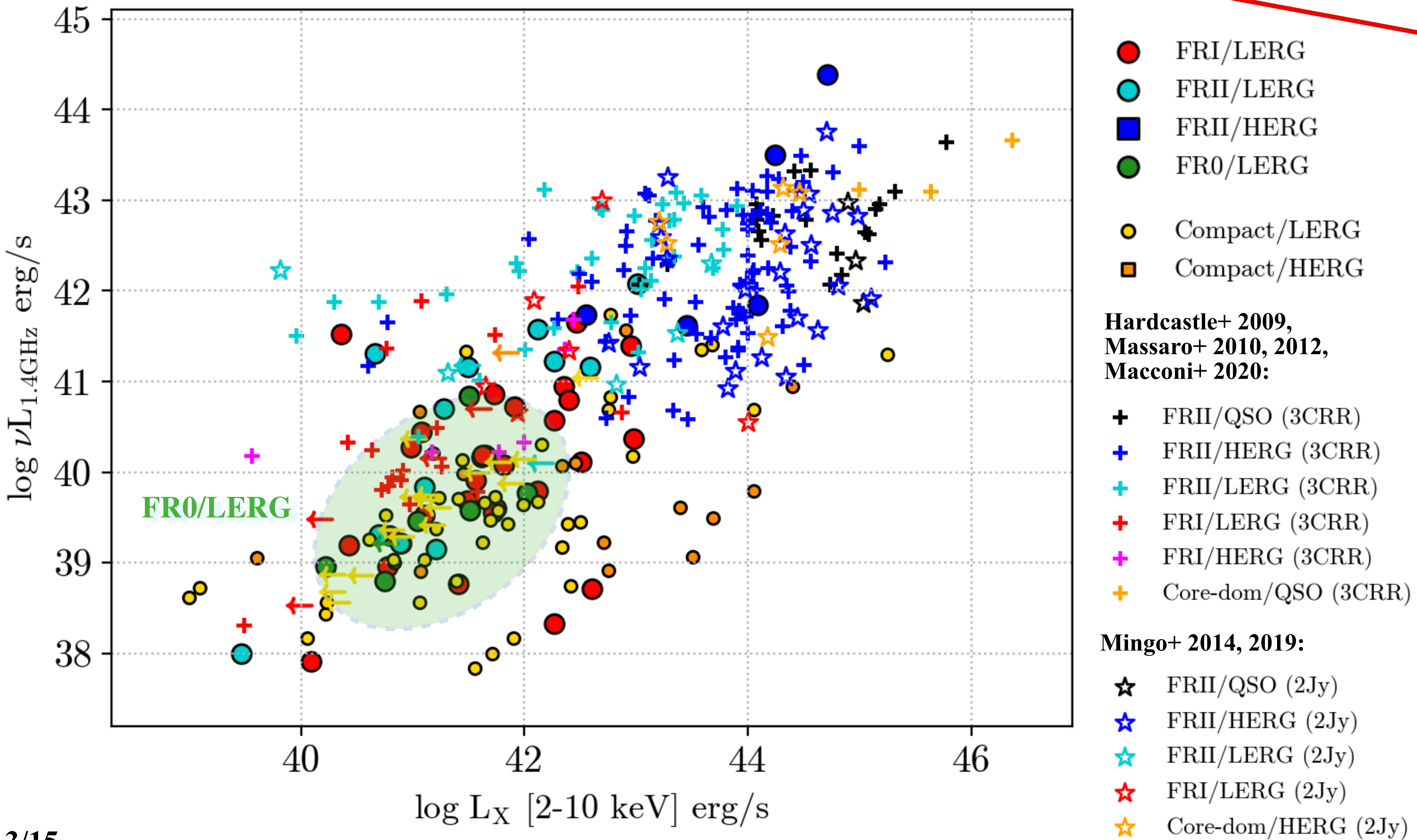

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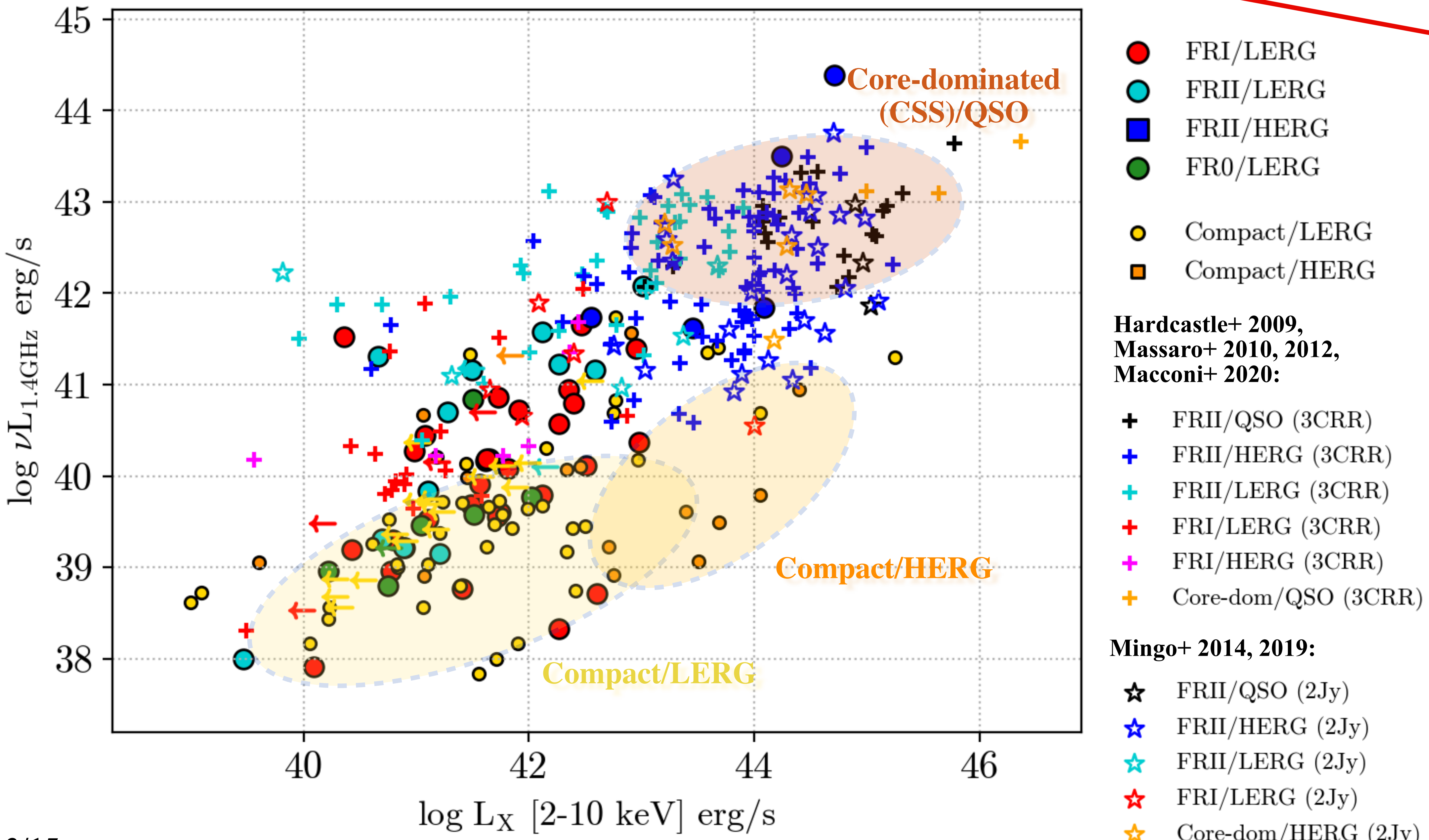
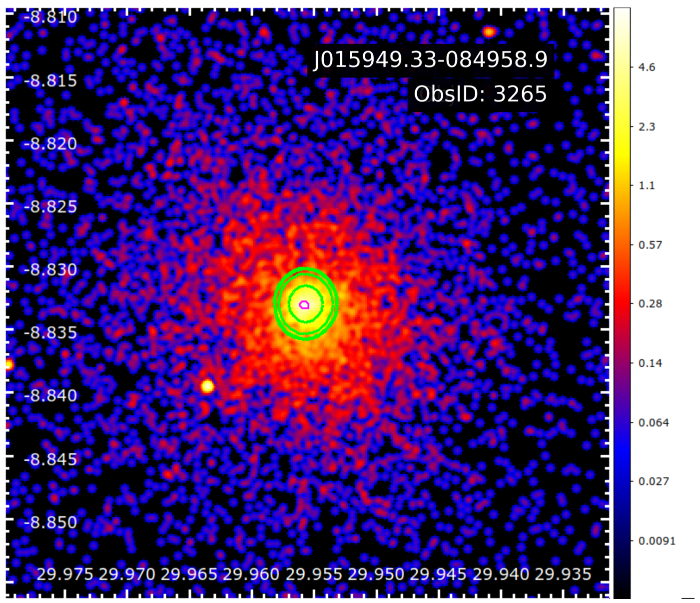


Environment of mJy RG

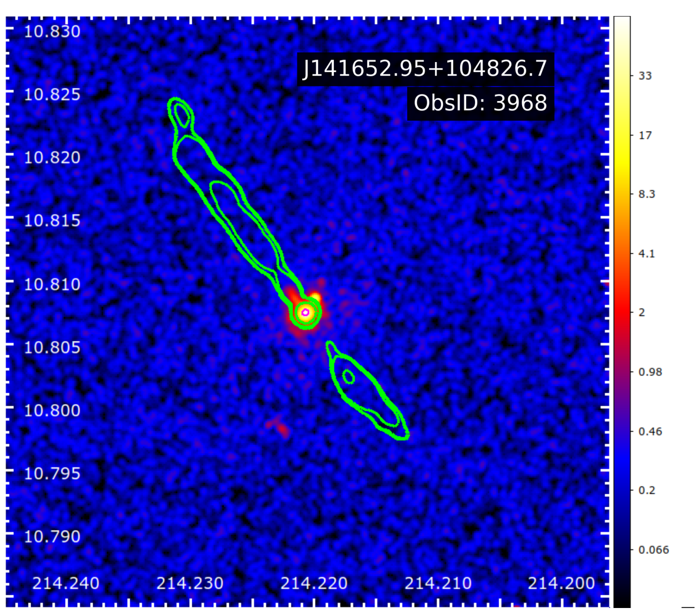
PRELIMINARY!

…based on X-ray images

Higher density environments (groups, clusters…)



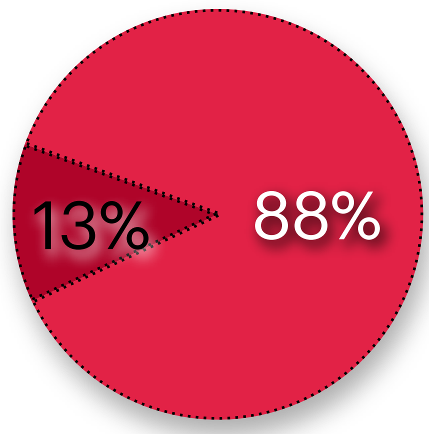
Less denser environments ('isolated')



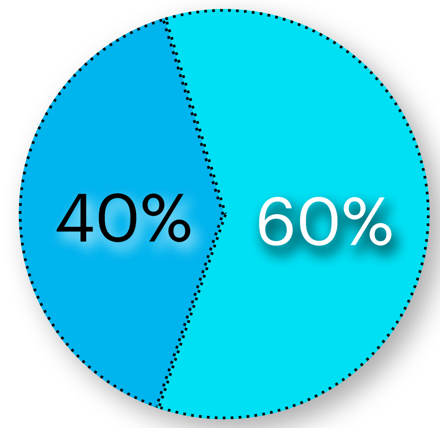
The environmental properties have been restored **only for 90 objects (out of 216)**

20 objects with the presence of the **cluster** vs **70 'isolated'**

Low statistics!

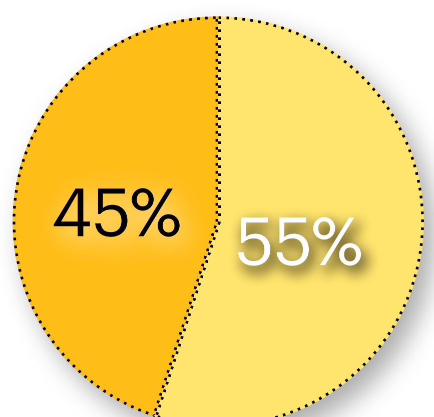


FRI/LERG

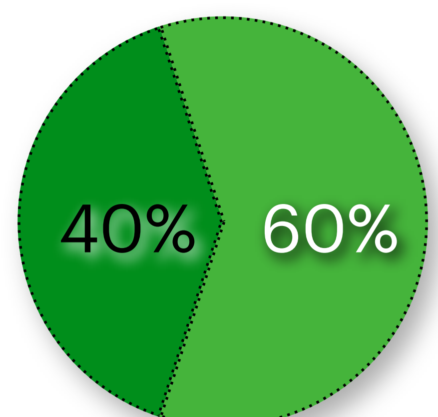


FRII/LERG

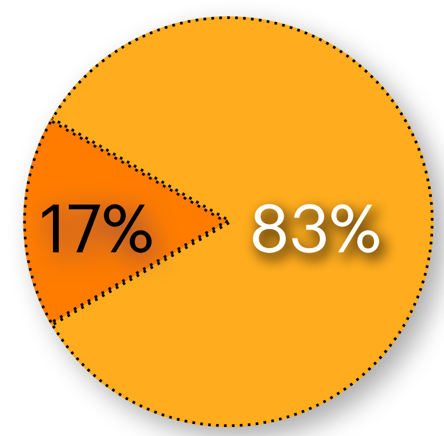
FRII/HERG



Compact/LERG



FR0/LERG



Compact/HERG

Good statistics!

Torbaniuk et al. 2025, *in preparation*

Conclussions

- We analysed the X-ray spectra from Chandra for **216 mJy radio galaxies** from the sample of Best & Heckman (2012) compiled from SDSS DR7 and NRAO NVSS + FIRST;
- When available, we collected *radio classifications* for objects in our sample from existing literature. For **97** objects (45%) lacking such classification, we conducted our own visual classification using VLASS radio images. Using spectroscopic criteria (e.g., BPT diagrams, excitation index), we *verified and updated optical classifications* (LERG/HERG/SF) for **35** galaxies;
- Our final sample includes **53** galaxies with extended **FRI** or **FRII** morphologies (mainly LERG, 10% HERG) and **133** compact galaxies (including **FR0** and **blazars**; 62% LERG, 11% HERG, 27% SF), and **30** objects showing *hybrid or uncertain* morphologies.

Preliminary and require additional analysis!

- LERGs with different morphologies (FR0, FRI, and FRII) are **less luminous** than HERGs in the X-ray band, implying a deficit of nuclear photons, as expected in a radiatively inefficient system. The X-ray results confirm that both X-ray and [OIII] emissions are good tracer of accretion;
- Sources with higher X-ray luminosities (i.e., more efficient accretion) are stronger radio emitters;
- The analysis of the X-ray images shows that HERGs seem to **avoid dense environments**, while LERGs are **not necessarily in rich environments** (they are often isolated or in small groups);

Thank you for your attention!

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