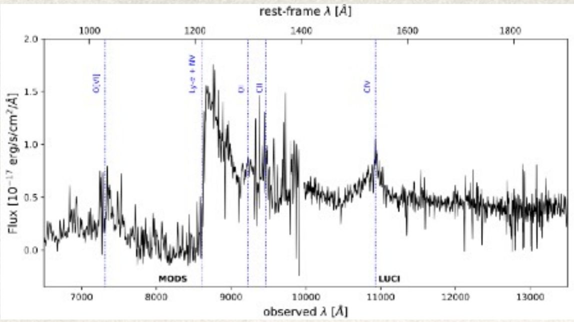
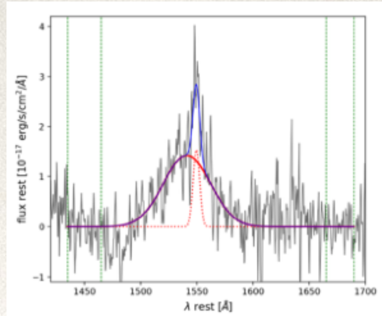
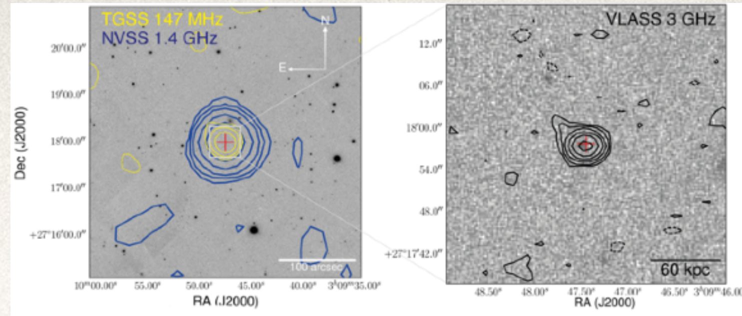
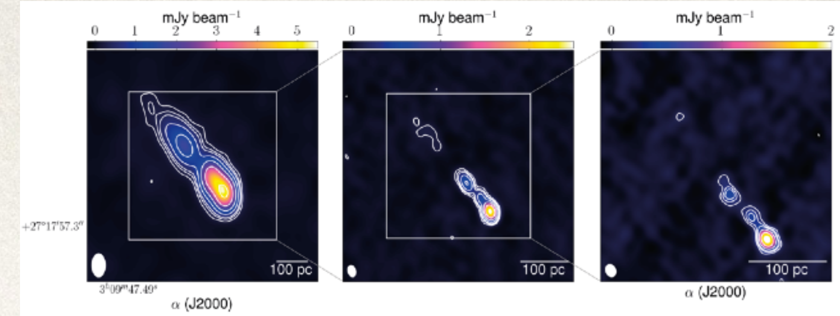
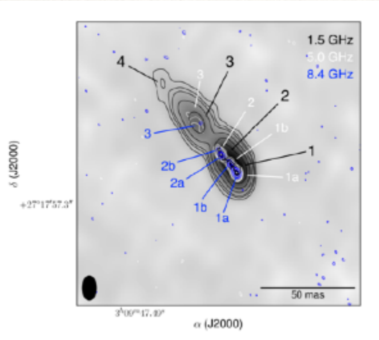


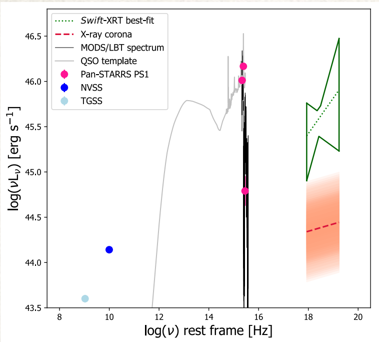


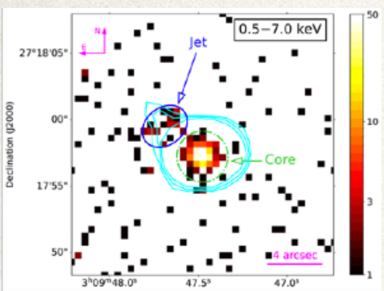


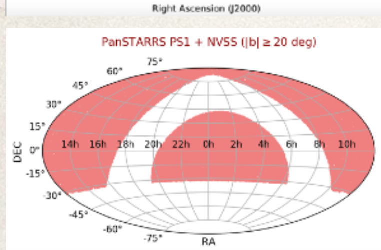


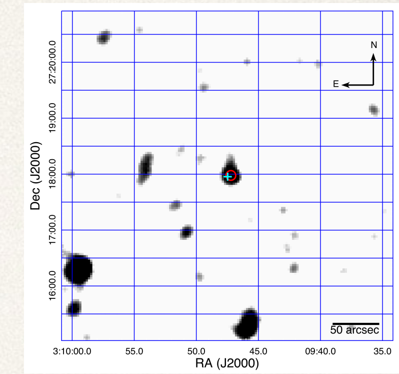
A detailed overview of PSOJ0309+27: a blazar at z>6

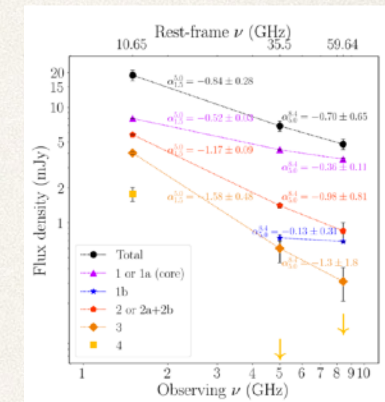


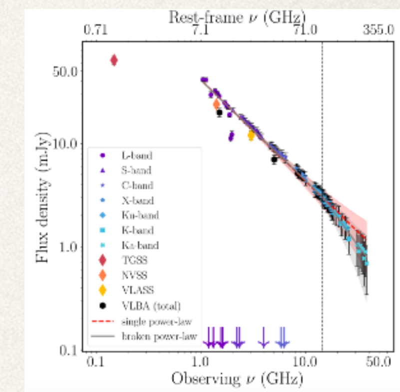












Silvia Belladitta
INAF-OA Brera
DiSAT-Università degli studi dell'Insubria

Main collaborators: ***A. Moretti*** *(OA Brera) ,* ***A. Caccianiga*** *(OA Brera), L. Ighina (Univ. Insubria), C. Spingola (IRA-INAF, Univ. Bologna) , P. Severgnini (OA Brera), R. Della Ceca (OA Brera), D. Dallacasa (IRA-INAF, Univ. Bologna), G. Ghisellini (OA Brera), T. Sbarrato (OA Brera), M. Giroletti (INAF-IRA), M. Orienti (INAF-IRA), A. Diana (Univ. Bicocca), L. P. Cassarà (INAF-IASF), M. Pedani (INAF-)*

Published papers: Belladitta et al. 2020; Spingola et al. 2020; Moretti et al. 2021; Ighina et al. 2022; Belladitta et al.2022

INAF-IASF Sala Virtuale 02/03/2022

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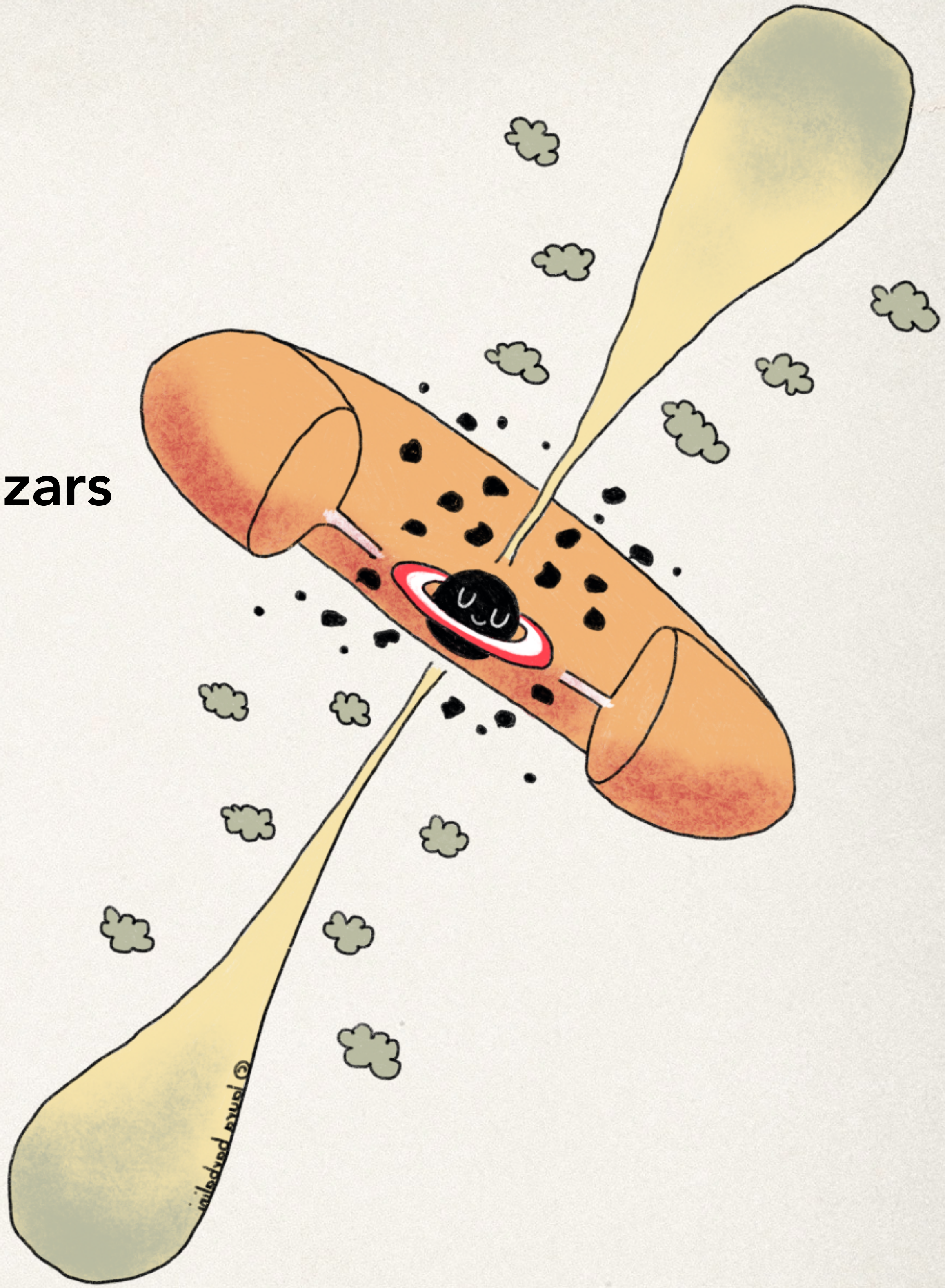
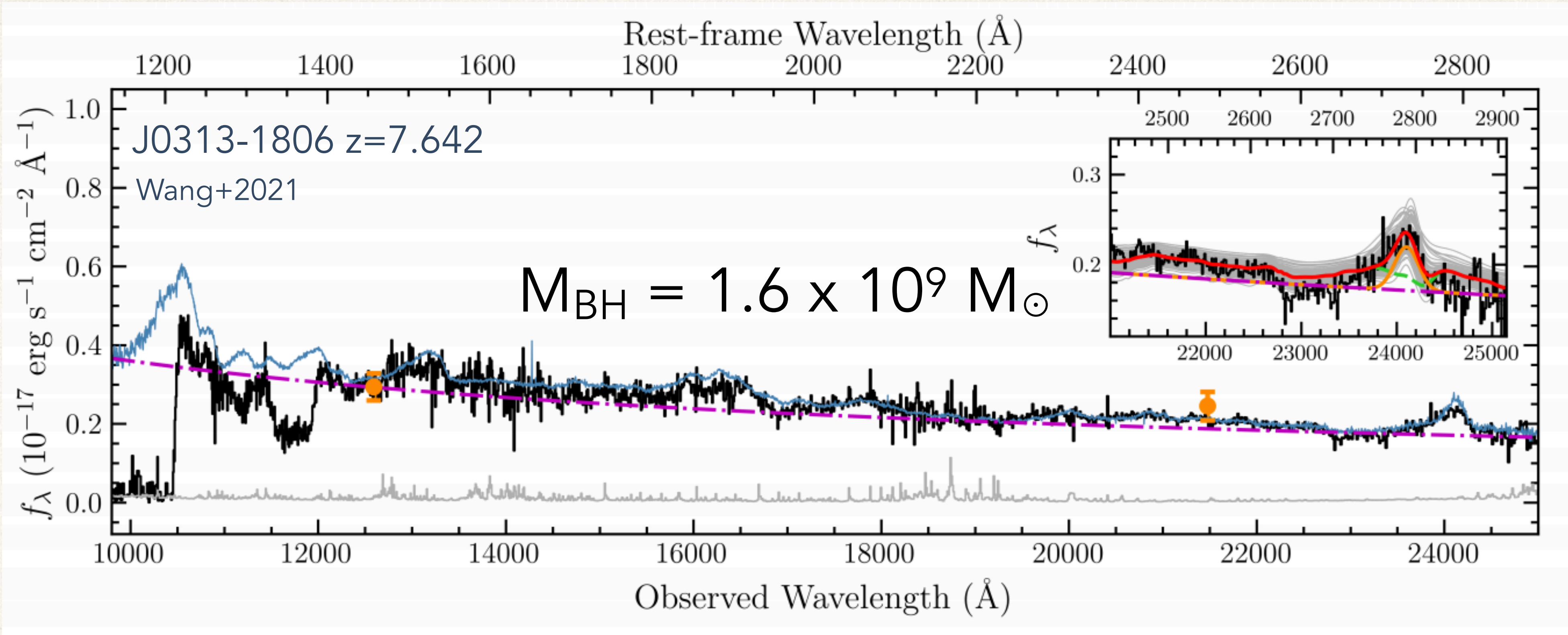


When and how the first SMBHs formed in the Universe?



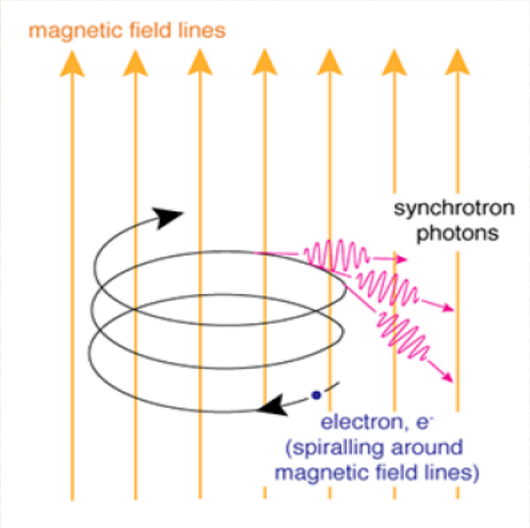
Efficient and faster accretion process

Radio-Loud Active Galactic Nuclei (RL AGNs)

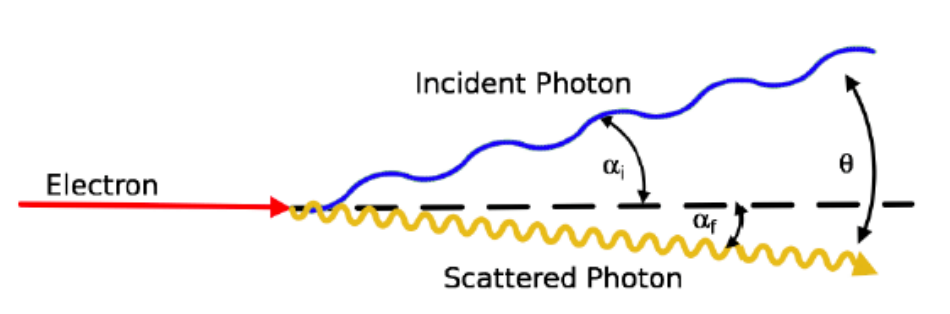
10% of the total population (e.g. Bañados+15, Liu+20)

Relativistic jets launched directly from the central BH

Jet emission: non thermal processes → synchrotron



inverse Compton



Jet formation: a combination of magnetic fields and rotation → *Kerr (spinning) BH*

Blandford+77

Blandford+97; Tchekhovskoy+11

High radiation efficiency = longer growth time

$L = \eta \dot{M} c^2$ with $\eta = 0.3$

Difficult to explain observed 10^8 - 10^9 $M_\odot$ SMBHs hosted in RL AGNs at high redshift

very massive seed black holes ($M_{BH} > 10^6$ $M_\odot$)

not already predicted from theoretical models *e.g. Volonteri+10, Valiante+17*

A census of high-z RL AGNs → Role of relativistic jets in BH and galaxy growth

Volonteri+15

Problem: the jet emission depends on the viewing angle (ϑ)

$$S_{obs} = S_{em} \times \delta^{n-\alpha}$$

$$\delta = \frac{1}{\Gamma[1-\beta cos(\theta)]}$$

Doppler factor

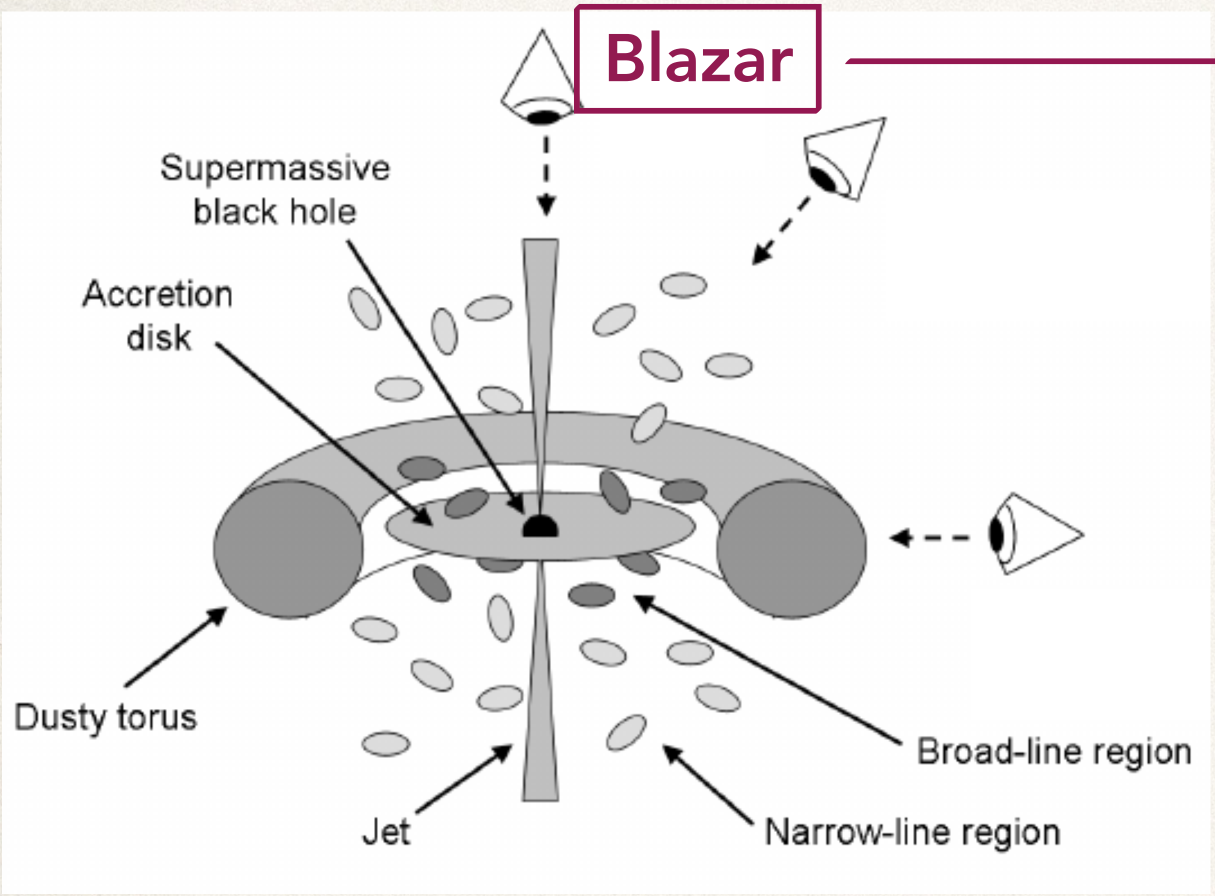
$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Bulk Lorentz factor, Γ~5-15

ϑ≤(1/**Γ**)

FSRQ, BL Lac

Blazar



Relativistic beaming —> amplified luminosity

. Statistical relevance

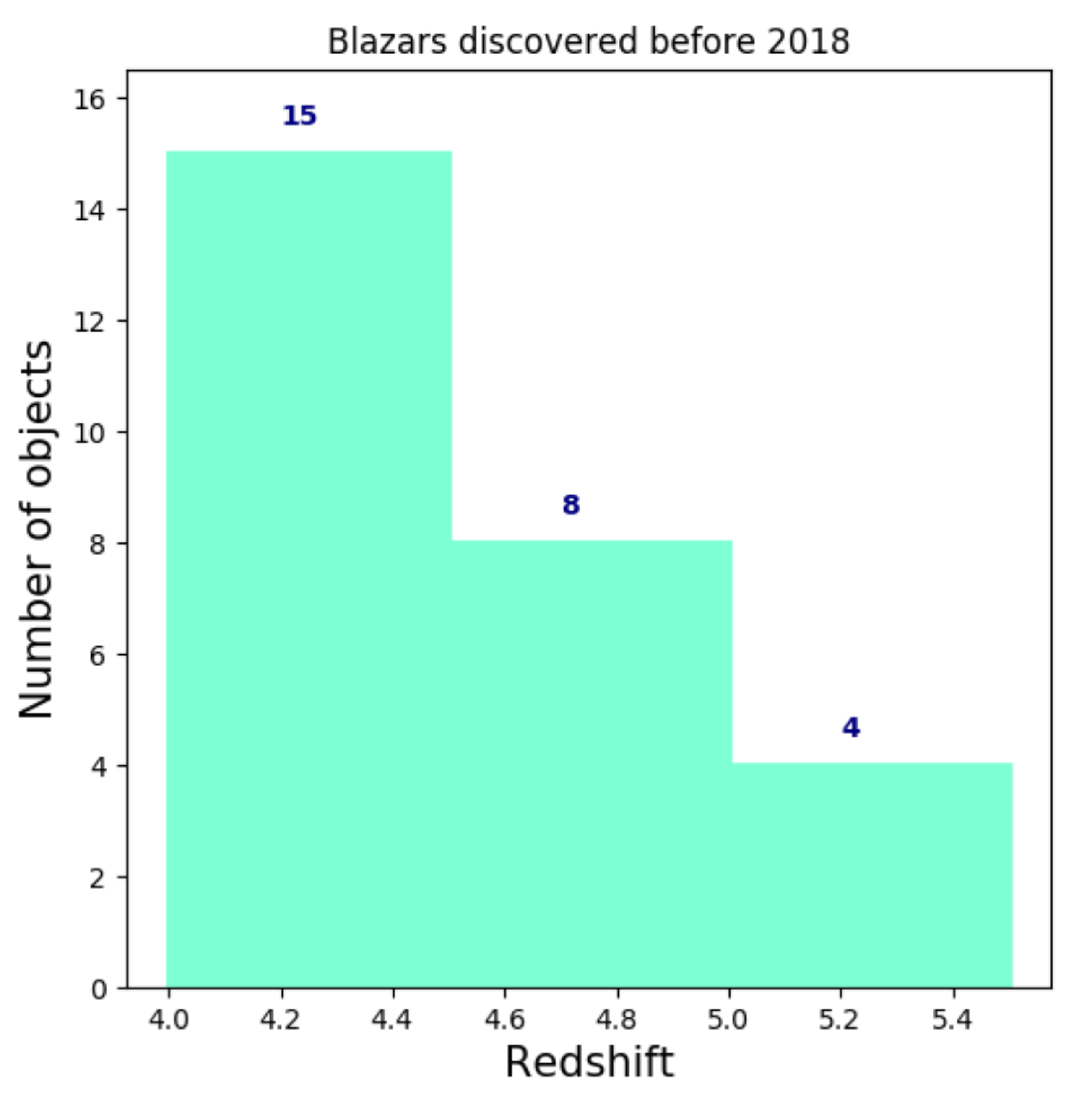
$$N_{tot} \approx N_{blazar} \times 2\Gamma^2$$

Ghisellini+10, Volonteri+11, Sbarrato+15

Census (free from orientation effects) of the RL AGN population (and SMBHs)

"Find one to count an hundred"

The state of art:



The most distant : z=5.47

Romani et al. (2004)

-Selection of the largest statistically complete sample of z>4 blazars —> Caccianiga, Moretti, SB et al. (2019)

-Discovery of new blazars at z > 5 —> e.g. Belladitta et al. (2019)

-Search for blazars at z between 5.5 and 6.5

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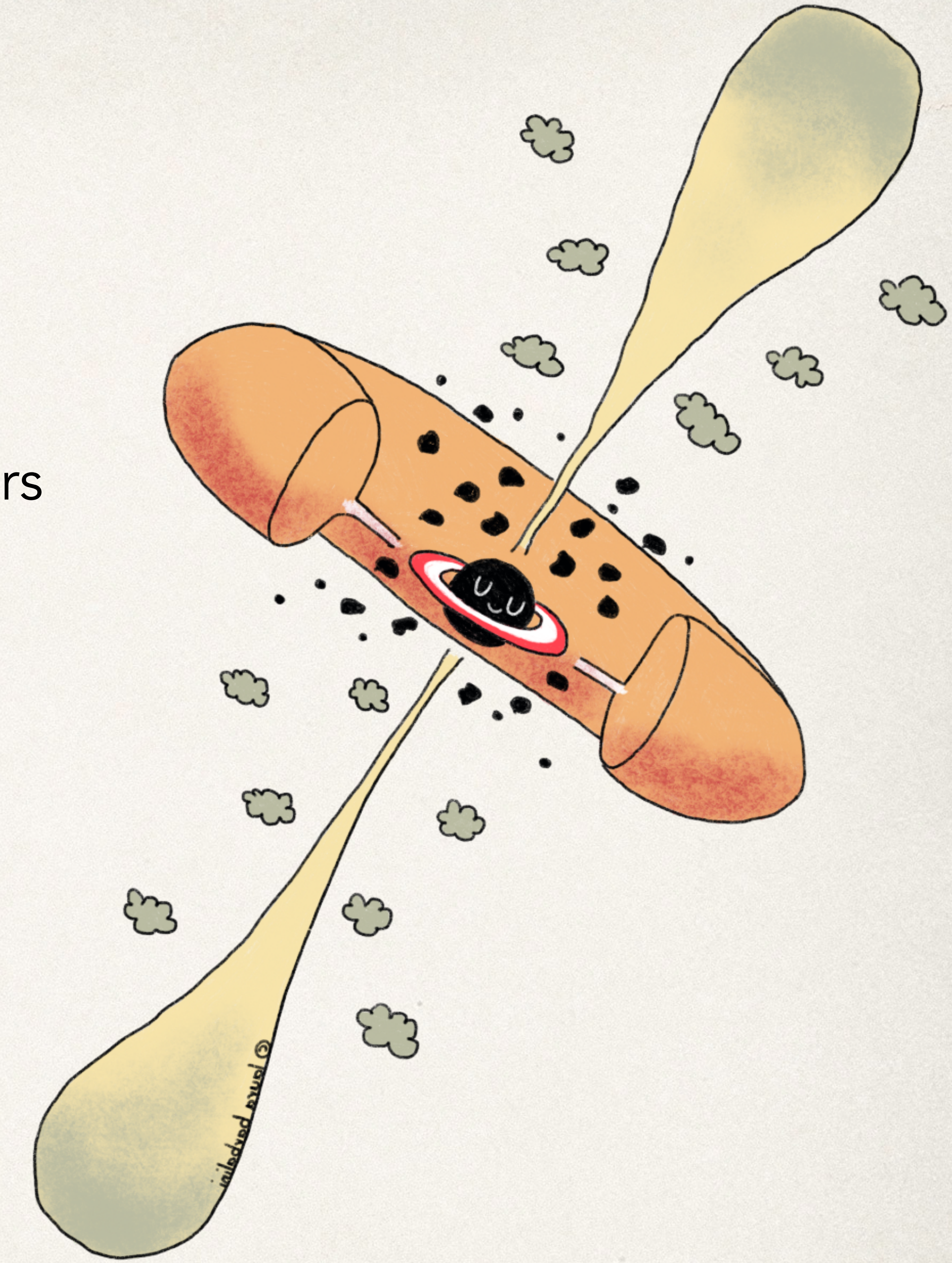
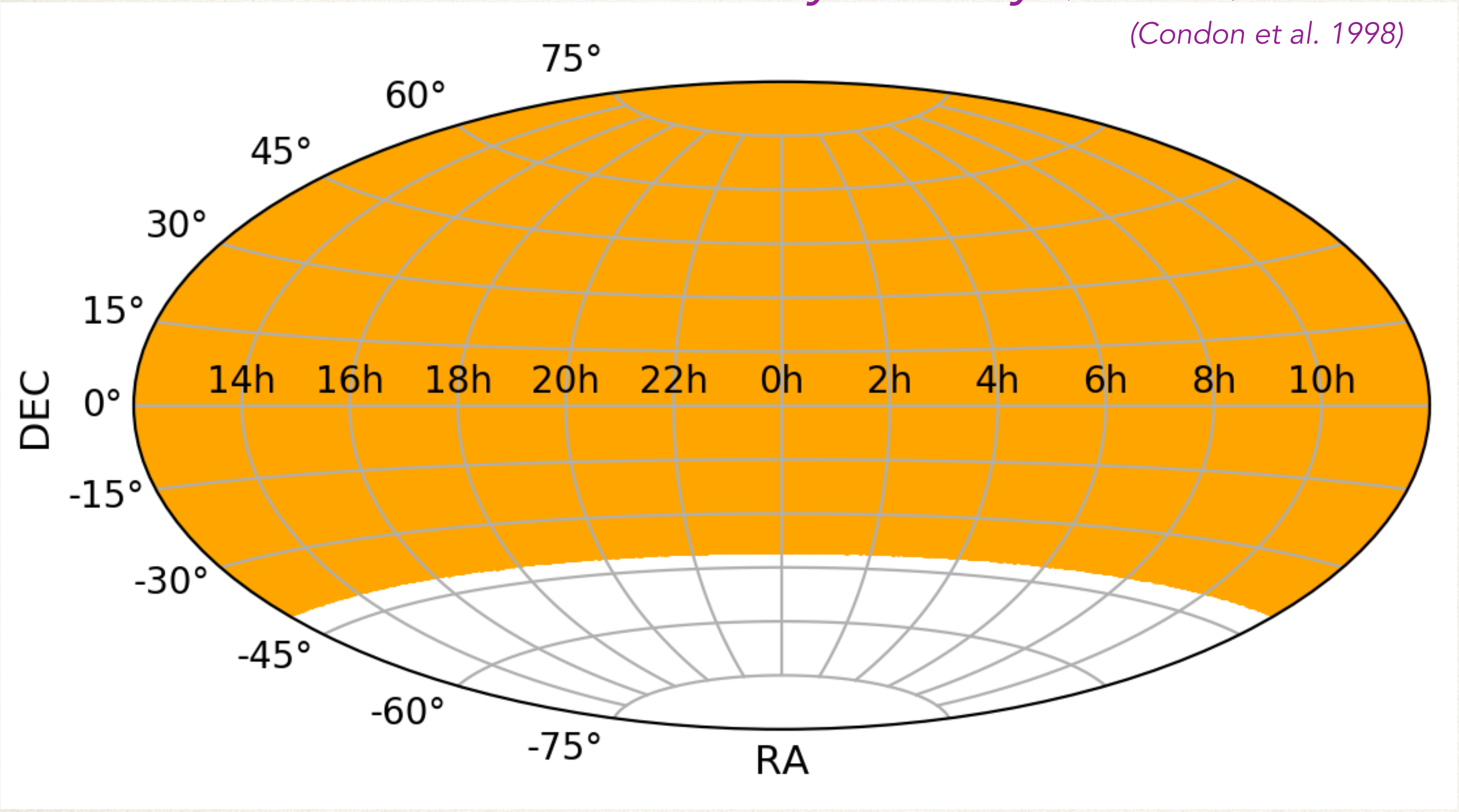


The selection method: the drop-out technique

Blazars = radio emitters —> starting point = radio catalogs
= rare sources —> wide field surveys (covering large fraction of sky)

NRAO VLA Sky Survey (NVSS)

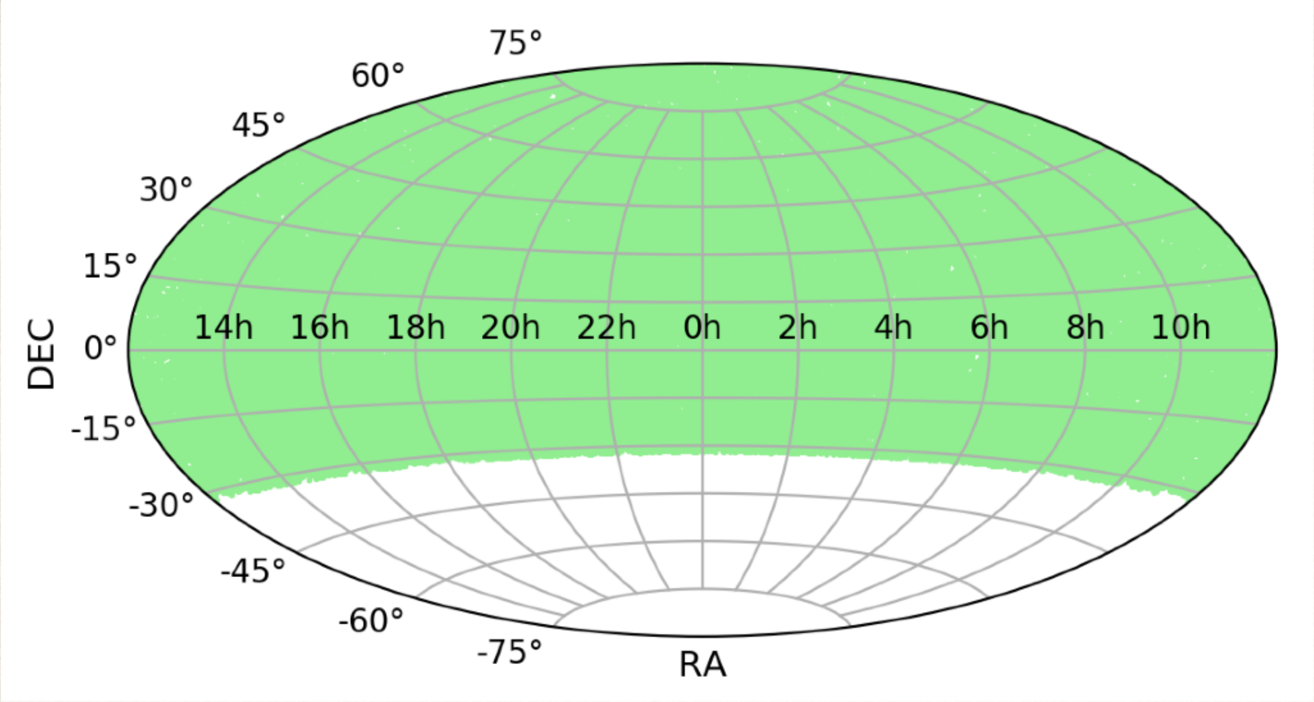


Frequency (GHz)	1.4
Area (deg^2)	33800
Flux limit (mJy)	2.3
Resolution (arcsec)	45

Cross-match with an optical/IR catalog

Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)

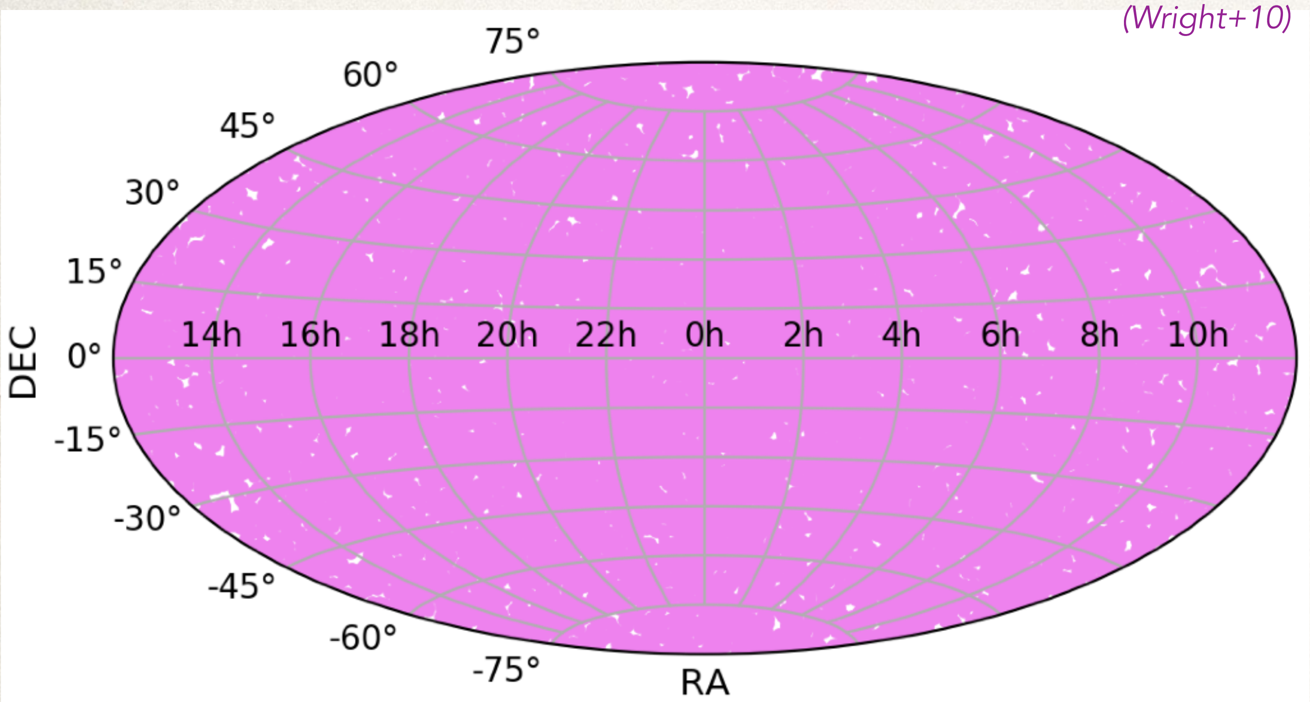
(Kaiser+02, +10, Chambers+16)



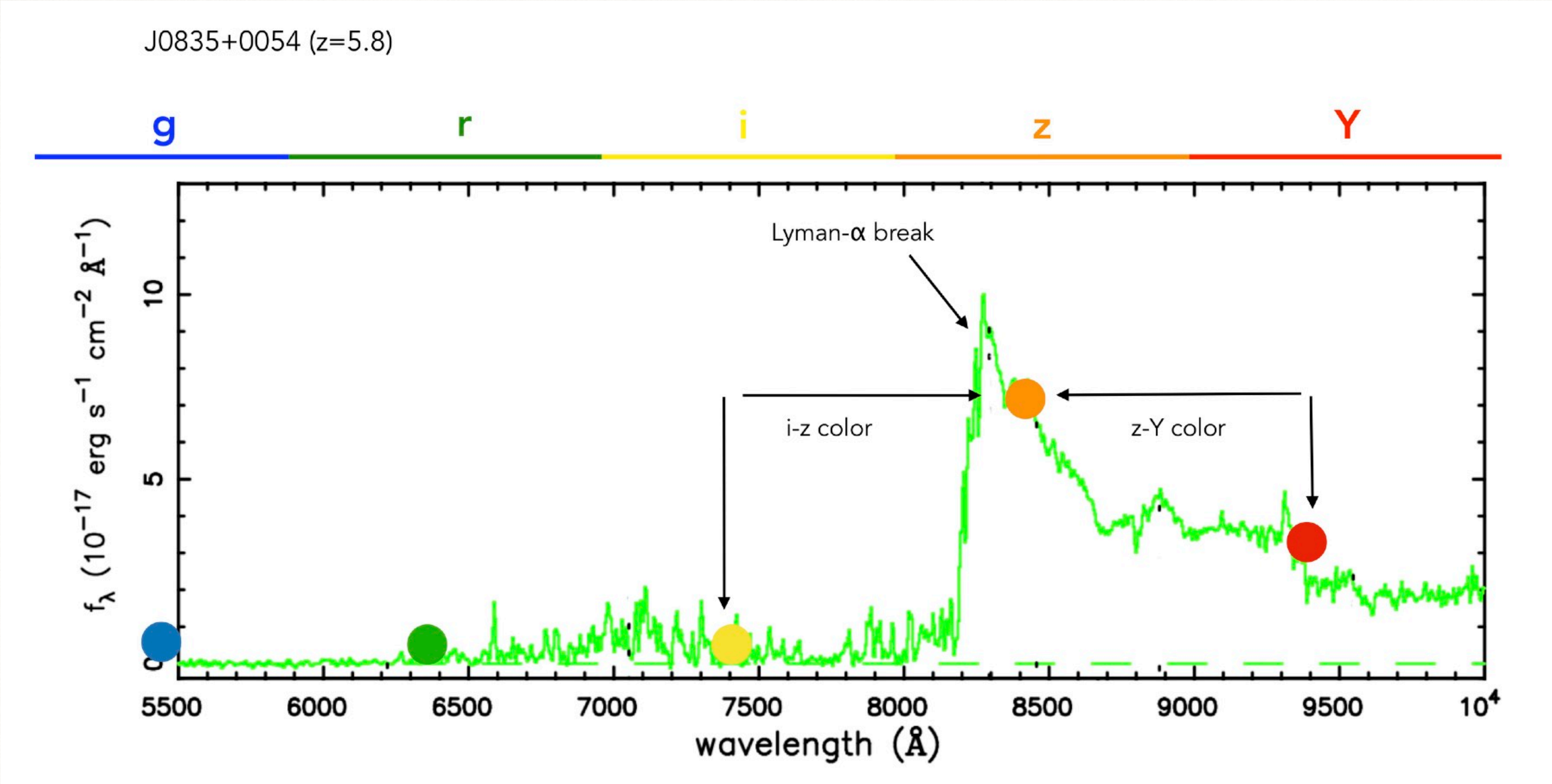
	Area (deg^2)	Filters	Mag limit
Pan-STARRS	28800	g,r,i, z,y	23.3 23.2 23.1 22.4 21.4
WISE	All sky	w1,w2, w3,w4	19.6 19.3 16.7 14.6

Wide-field Infrared Survey Explored (WISE)

(Wright+10)



Broad band photometry (mag) in different filters



Search for sources with **red color** between two filters (i-dropout)

Ask for **telescope time** to spectroscopically observed the selected candidates

Contaminants → **Brown Dwarf**

→ **Low-z (z=1-2) AGNs** *Elliptical radio galaxies / Reddened AGNs*

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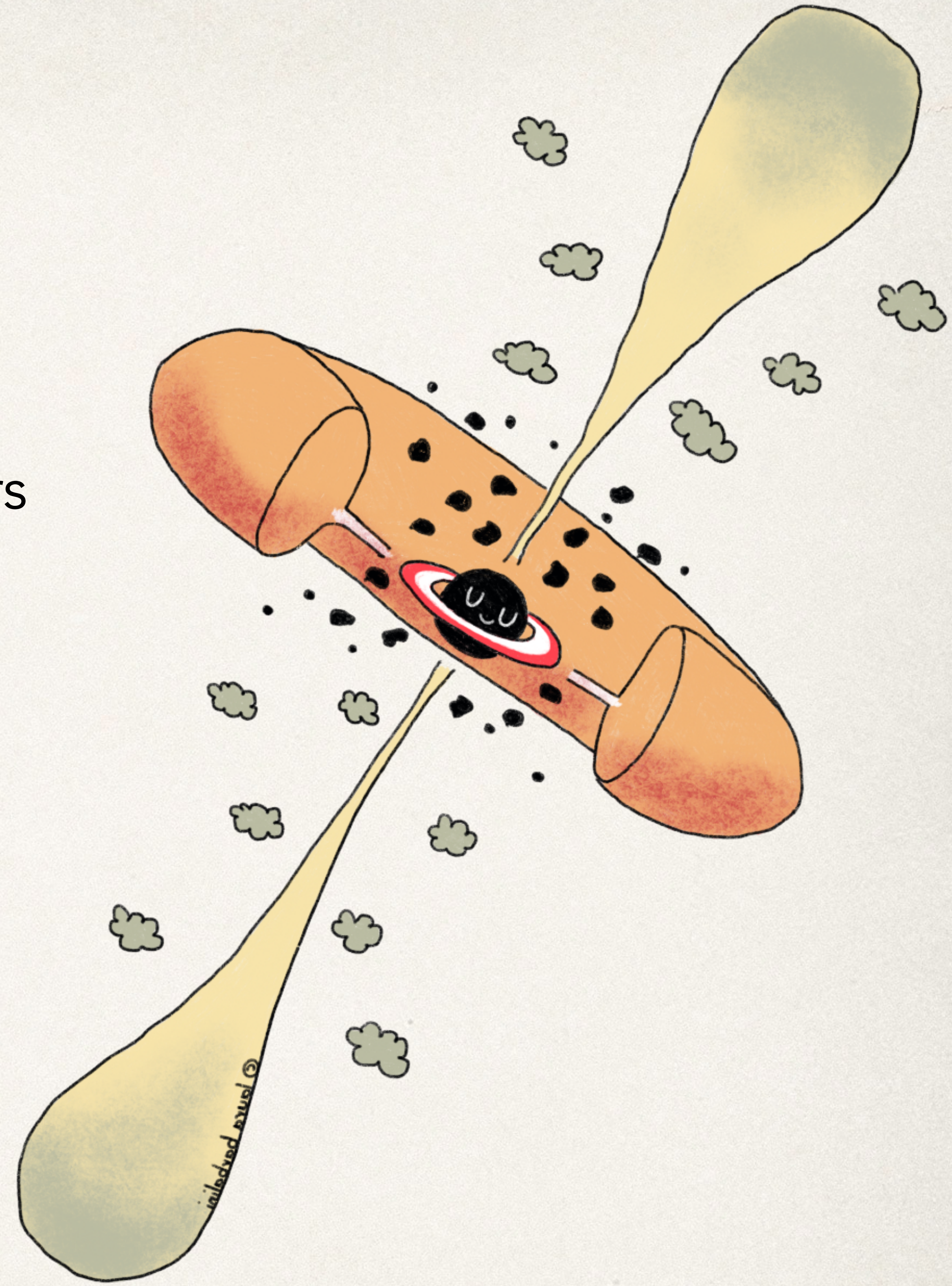
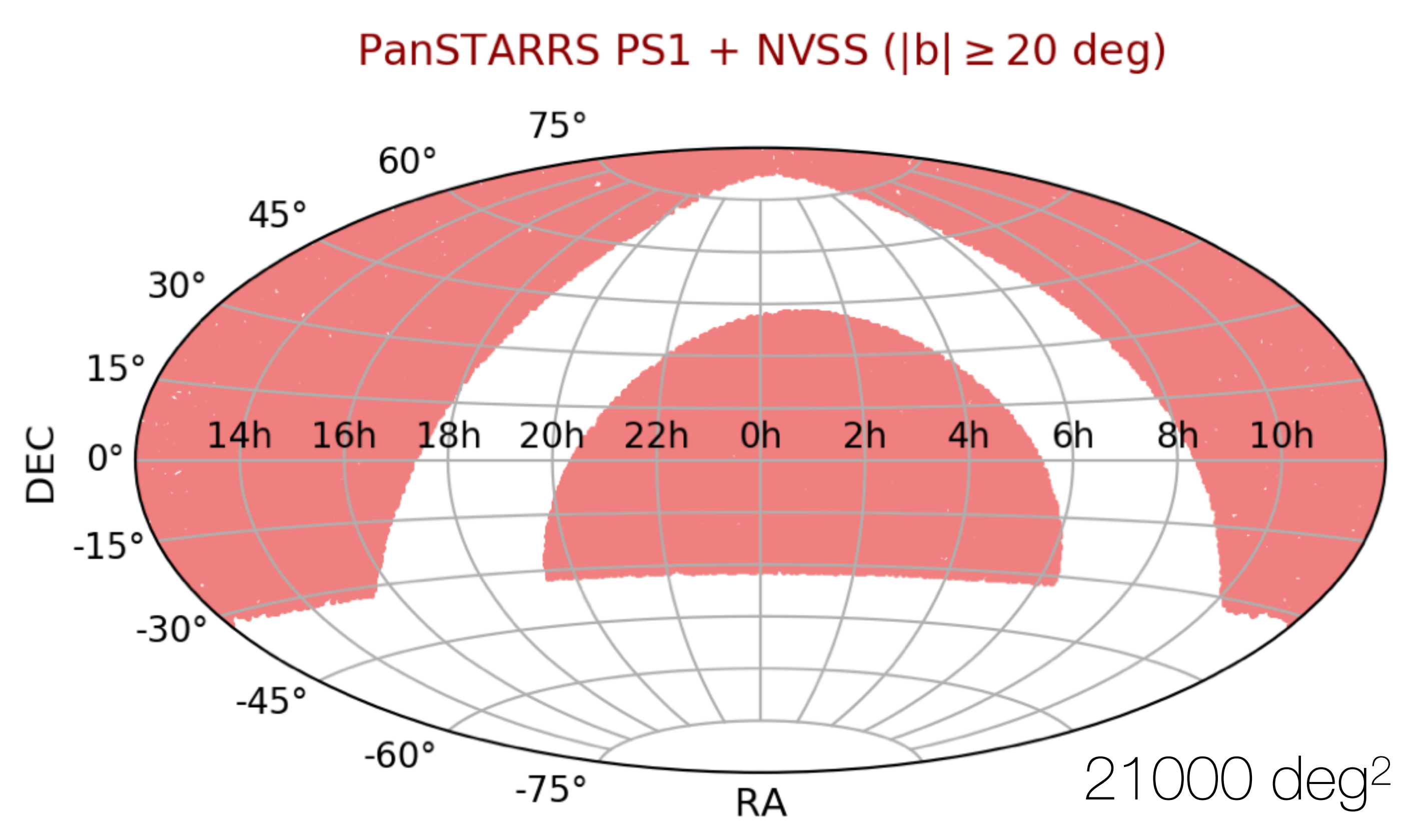


Searching for 5.5<z<6.5 blazars in the NVSS+PS1 surveys

i-dropout
(high i-z)

Selection criteria:

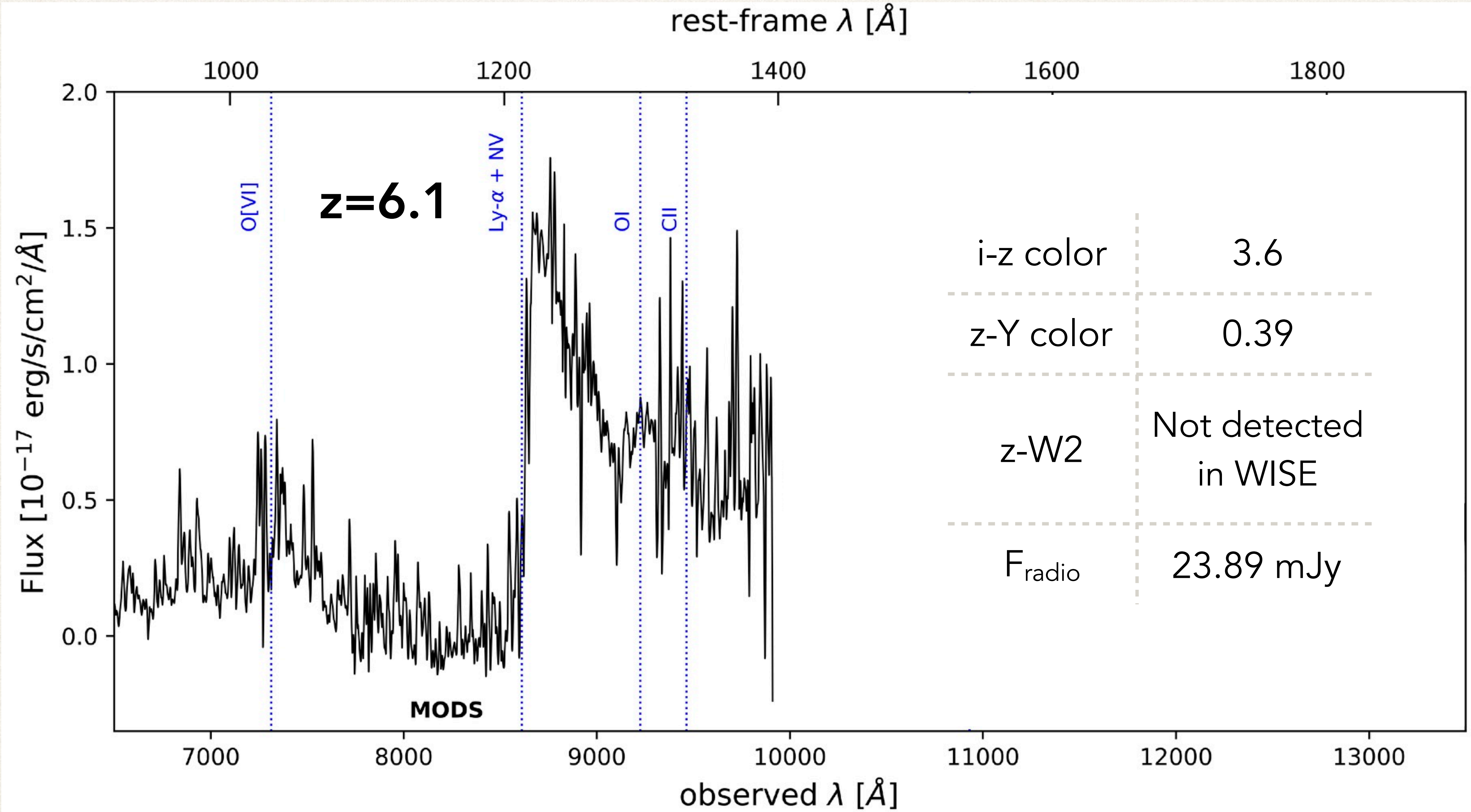
. F radio > 9 mJy
. Point like (both radio and optical)
. z mag < 21.5
. i-z > 1.1
. z-Y < 0.5
. z-W2 < 5
. No detection in g and r bands
. lbl>20°



7 candidates
(1 RL AGN already discovered by Bañados+18)
6 proposed for LBT observations

4 observed between 2019 and 2021

. 2 Stars
. Low-z galaxy
. **PSOJ030947.49+271757.31**



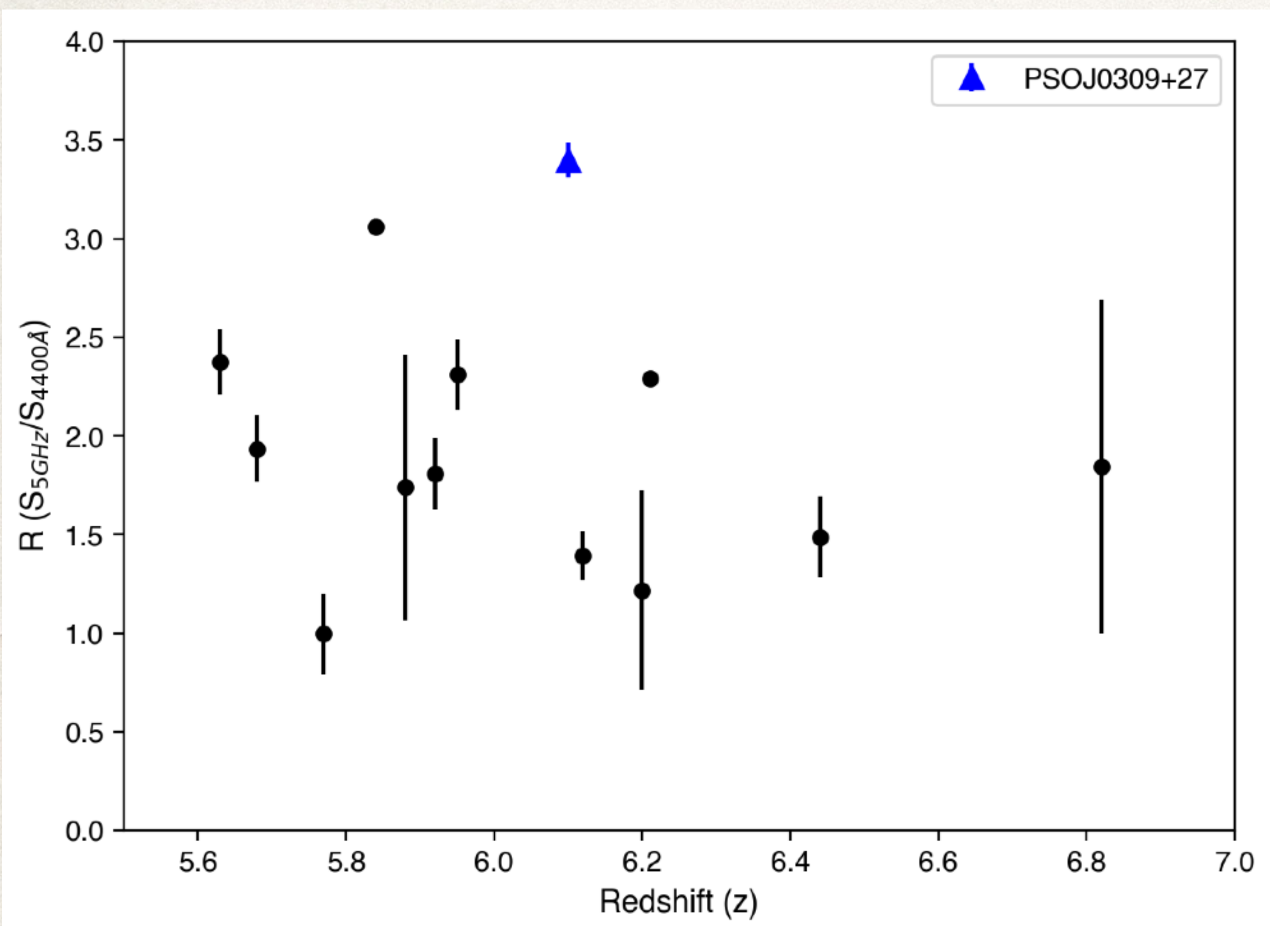
i-z color	3.6
z-Y color	0.39
z-W2	Not detected in WISE
F_{radio}	23.89 mJy

"Blazar-ness"

-flat radio spectrum : α = 0.4 (between 0.15 (TGSS) and 1.4 (NVSS) GHz)

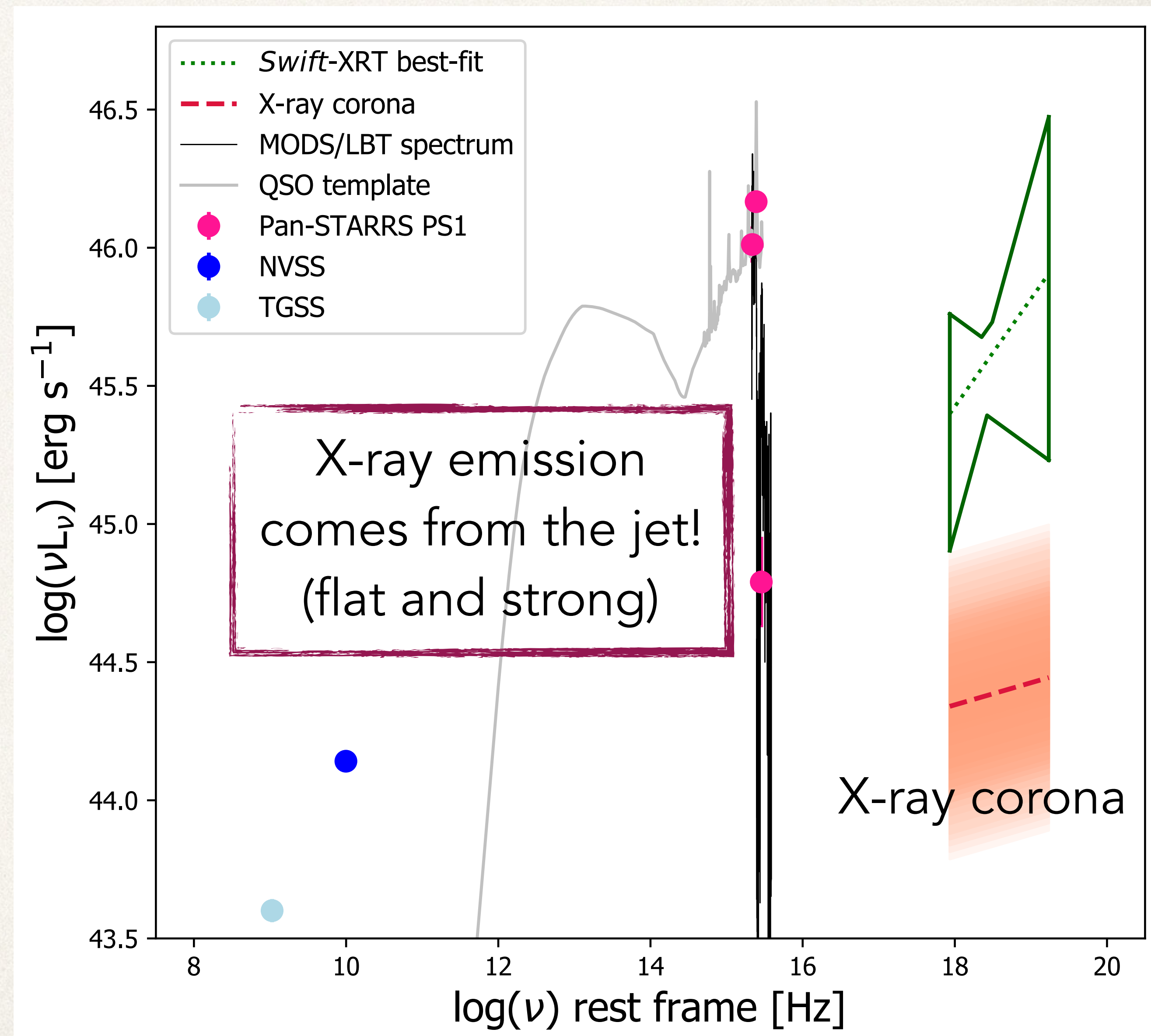
-very powerful in radio band : R = 2500

-very powerful in X-ray band : Γ_x = 1.6 ; Flux [0.5-10]keV = 3.4×10^{-14} erg/s/cm^2



Belladitta S. et al. (2020)

LBT, Media INAF, Insubria press release



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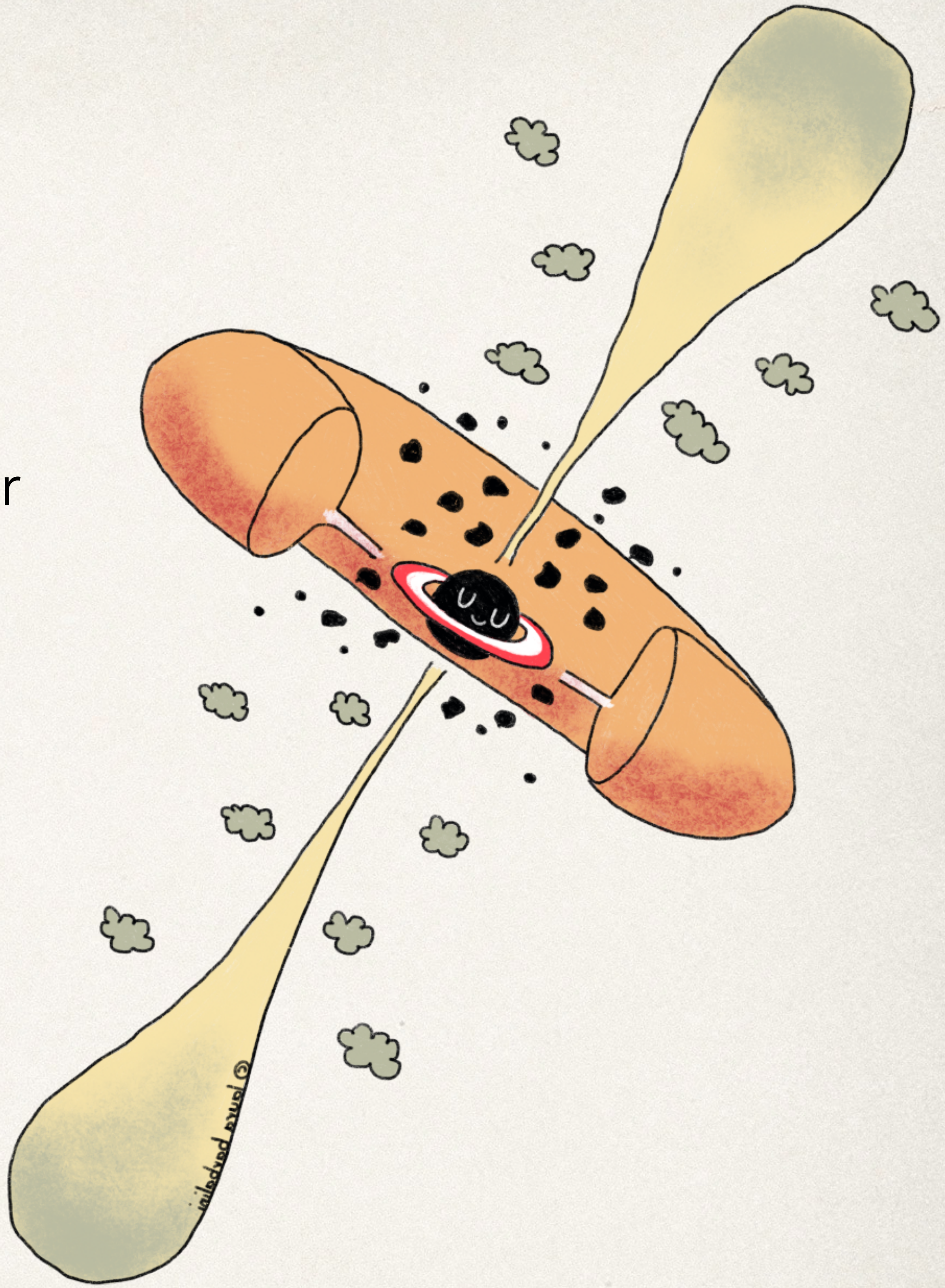
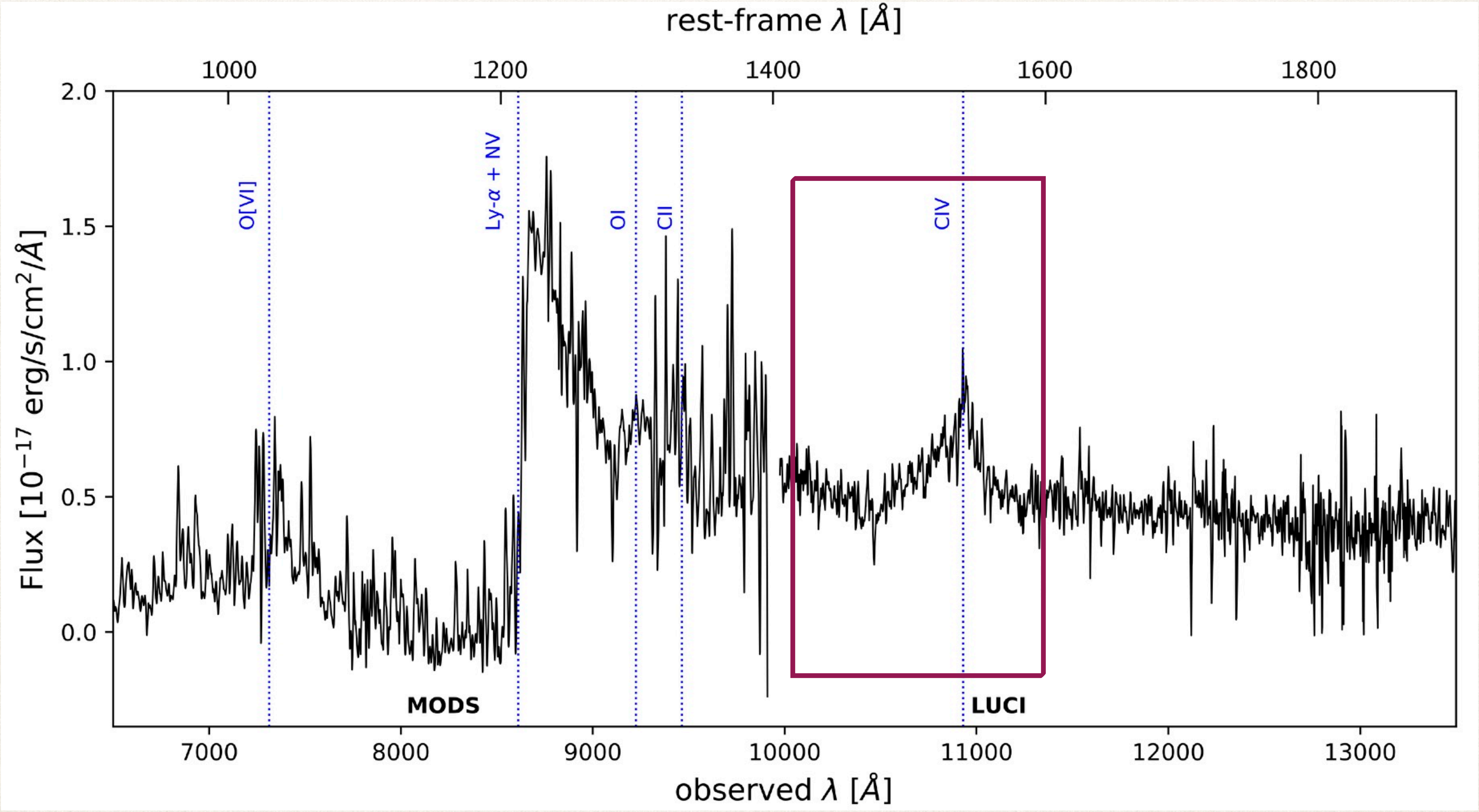


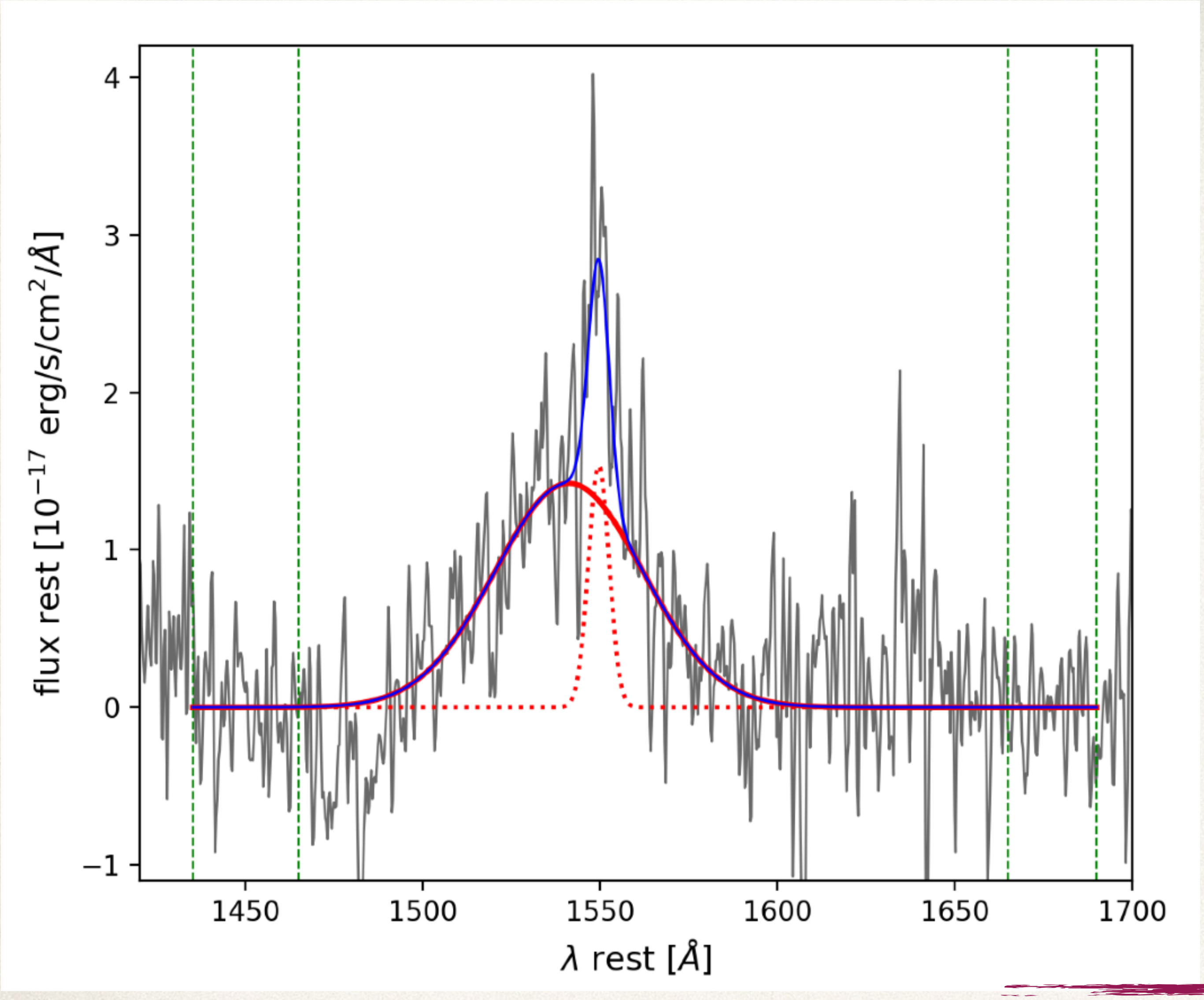
The central engine of PSO : compute its SMBH mass

Spectroscopic follow-up with LUCI/LBT

goal: detect the CIV1549Å emission line



Belladitta S. et al. (2022)



Virial /single-epoch method

e.g., Peterson+04, Vesterggard+06. Shen+11, Shen+19, Dalla Bontà+20

$$M_{\rm BH} \sim \frac{L^{\alpha} \times (line\_width)^2}{G}$$

$$M_{\rm BH} = 10^{6.73} \times (\frac{\sigma(km/s)}{10^3 km/s})^2 \times (\frac{\lambda L_{\lambda_{1350\text{Å}}}}{10^{44} erg/s})^{0.53}$$

Vestergaard & Peterson 2006

$\sigma_{\rm line}$ ~ 3800 km/s

$L_{1350\text{Å}}$ = 2.5x10^{46} erg/s

M_{BH} = 1.45 (0.6-3.3) **x10^9 $M_\odot$**

Disk modeling

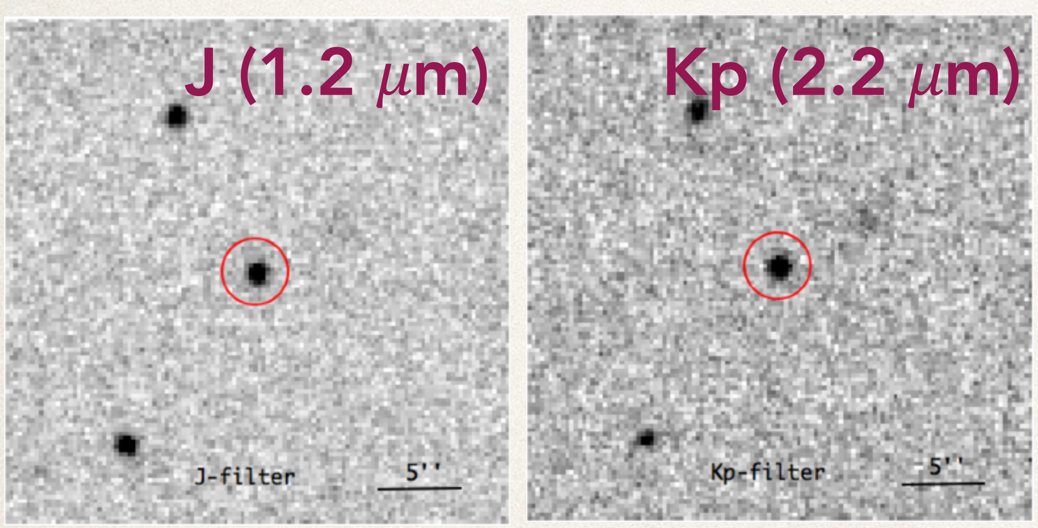
e.g., Sbarrato+2012,+2021;Calderone+2013; Ghisellini+2015,;Palyia+2019

Optical/UV continuum emission of the AGN is produced by an optically thick, geometrically thin accretion disk that emits according to the Shakura & Sunyaev (1973, SS73) model.

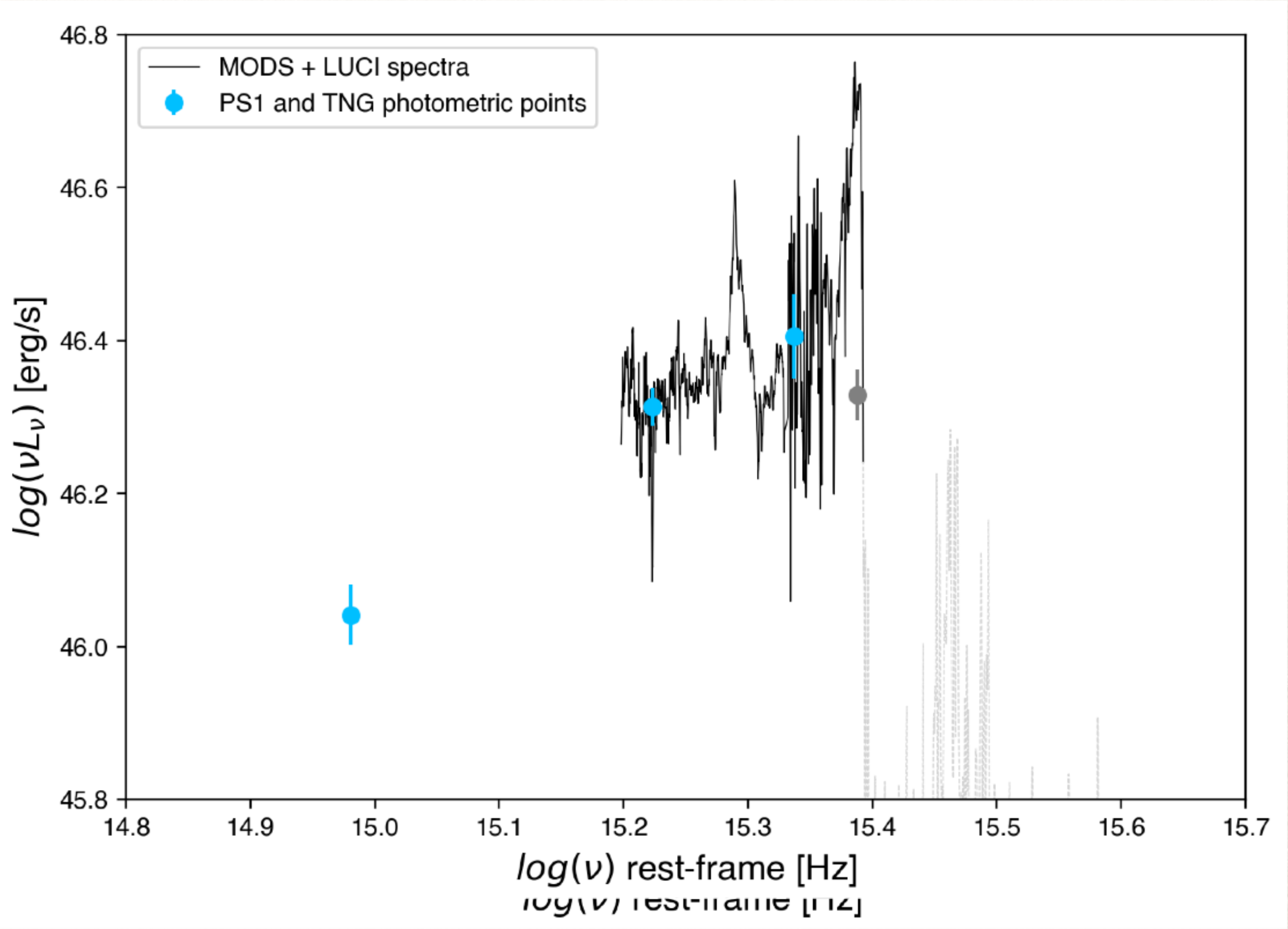
$$L(\nu, M_{BH}, \dot{M})d\nu = 4\pi^2 \int_{R_{in}}^{R_{out}} RB_\nu[T(R, M_{BH}, \dot{M})]d\nu dR,$$

M_{BH} = 6.9 (5.2-8.8) x10^8 $M_\odot$

TNG follow-up in Feb. 2021



http://www.tng.iac.es/news/2022/02/24/rs_blazar/



Implication for BH growth model

$$t_{growth} = \tau \times ln(\frac{M_{BH}}{M_{BH,seed}})$$

Shapiro 2005; Volonteri & Rees 2005

Assumption: the BH seed grows at a constant λ_{Edd} during the process

$$\tau = 0.45(\frac{\eta}{1-\eta})(\frac{1}{\lambda_{Edd}})(\frac{1}{f_{act}(M,t)})Gyr$$ e-folding time scale

<u>Model parameters:</u>

. efficiency (**η**) → 0.1 (non spinning BH) ; 0.3 (Kerr BH)

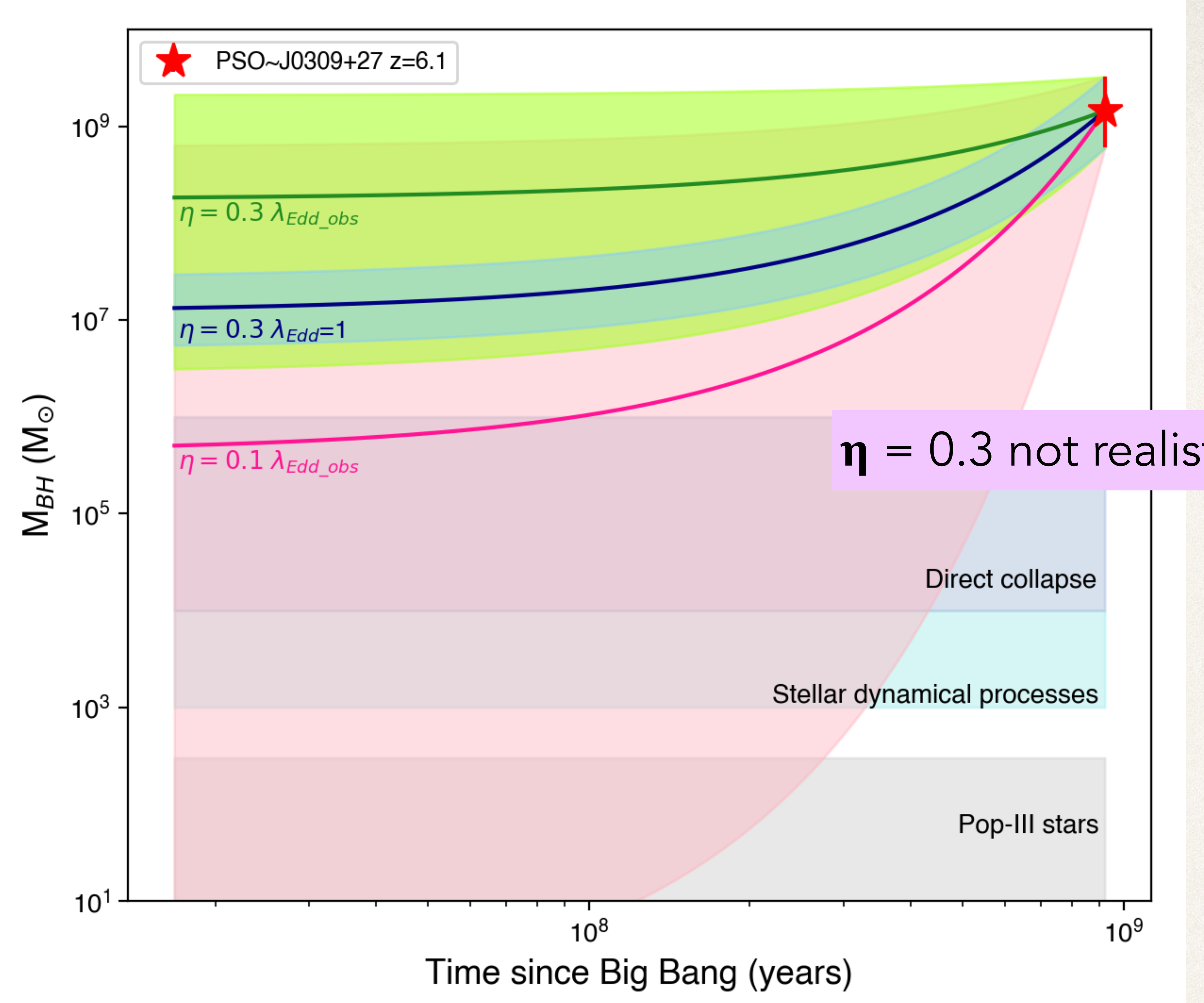
. Eddington ratio (λ_{Edd}) → Observed and equal to 1

. *f(act)* → Equal to 1

. t_{start} = when the BH started to growth → z=30 *Bromm+04,+11*

$\lambda_{Edd}=L_{bol}/L_{Edd}\sim0.4$

$L_{bol} = L_{1350Å} \times K_{bol}$



η = 0.3 not realistic!

Possible solutions:

. SuperEddington accretion episodes

. η_{disk} and (1-η_{disk}) *(Jolley+08, Ghisellini+15)*

RL AGNs live in the most dense environment at any redshift

e.g., Hill & Lilly 1991; Kurk+2000; Pentericci+2000; Venemans+2002, 2004; Zheng+2006; Galametz+2013; Wylezalek+2013; Hatch+2014; Rigby+2014; Croston+2019;Gilli+2019

Rich of star forming galaxies

(Lyman-break galaxies, LBGs,

and Lyman-alpha Emitters, LAEs) → Trigger the radio-jet?

The environment of PSOJ0309+27

Search for galaxies over density with LBC / LBT

↓

Tracing one of the most distant protocluster

Search of **Lyman-break galaxies**

Morselli+2014,
Balmaverde+2017
Mignoli+2020
Field of J1030 (RQ at z=6.3)

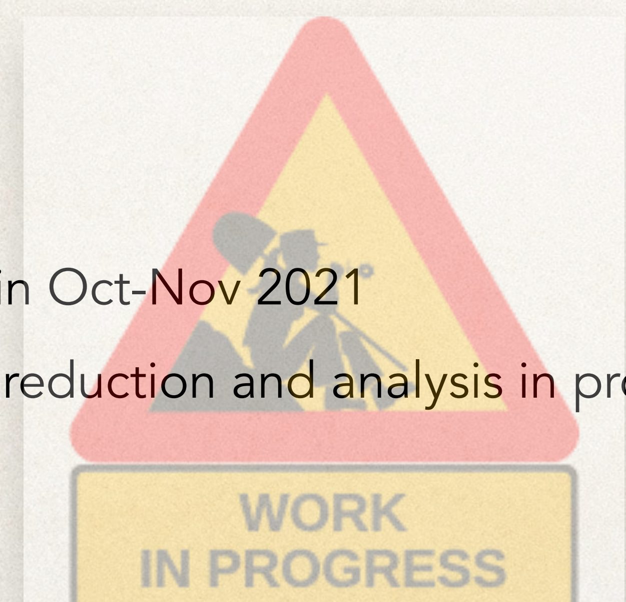
Images in r,i and z-bands

i-z>1.1-1.3

r-z>2

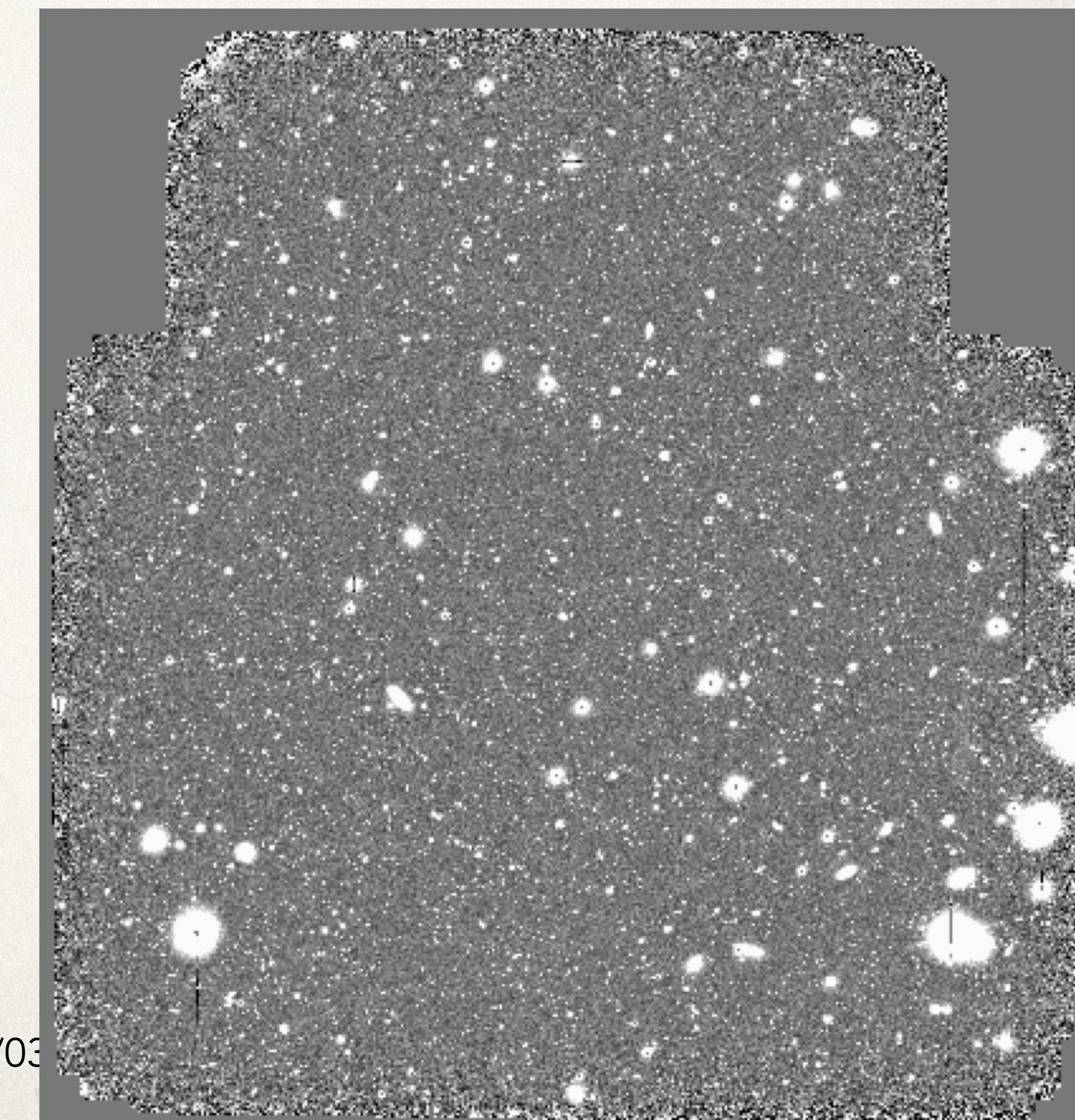
r-band ~27

z-band ~25-25.5



Obs in Oct-Nov 2021

Data reduction and analysis in progress



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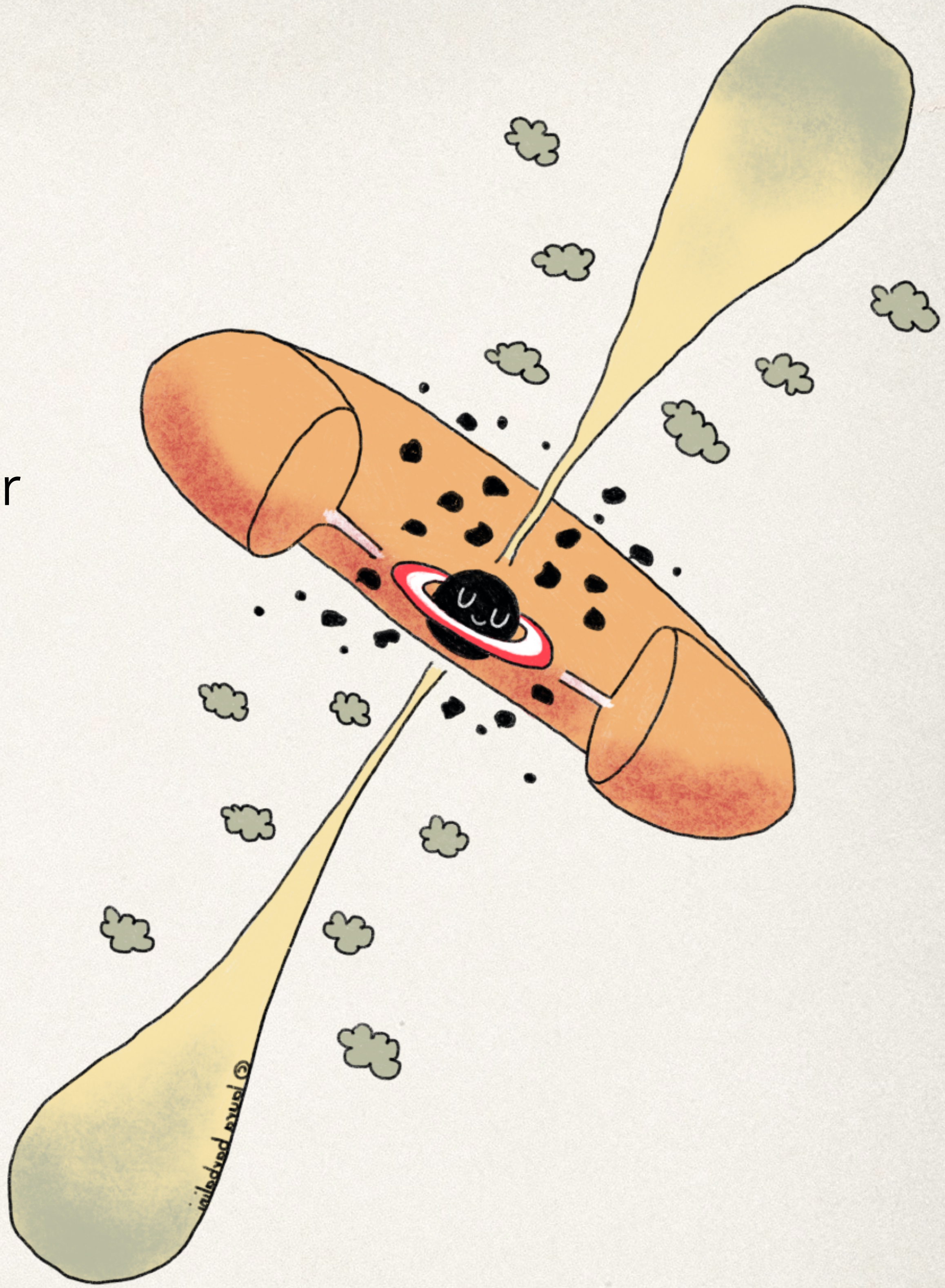
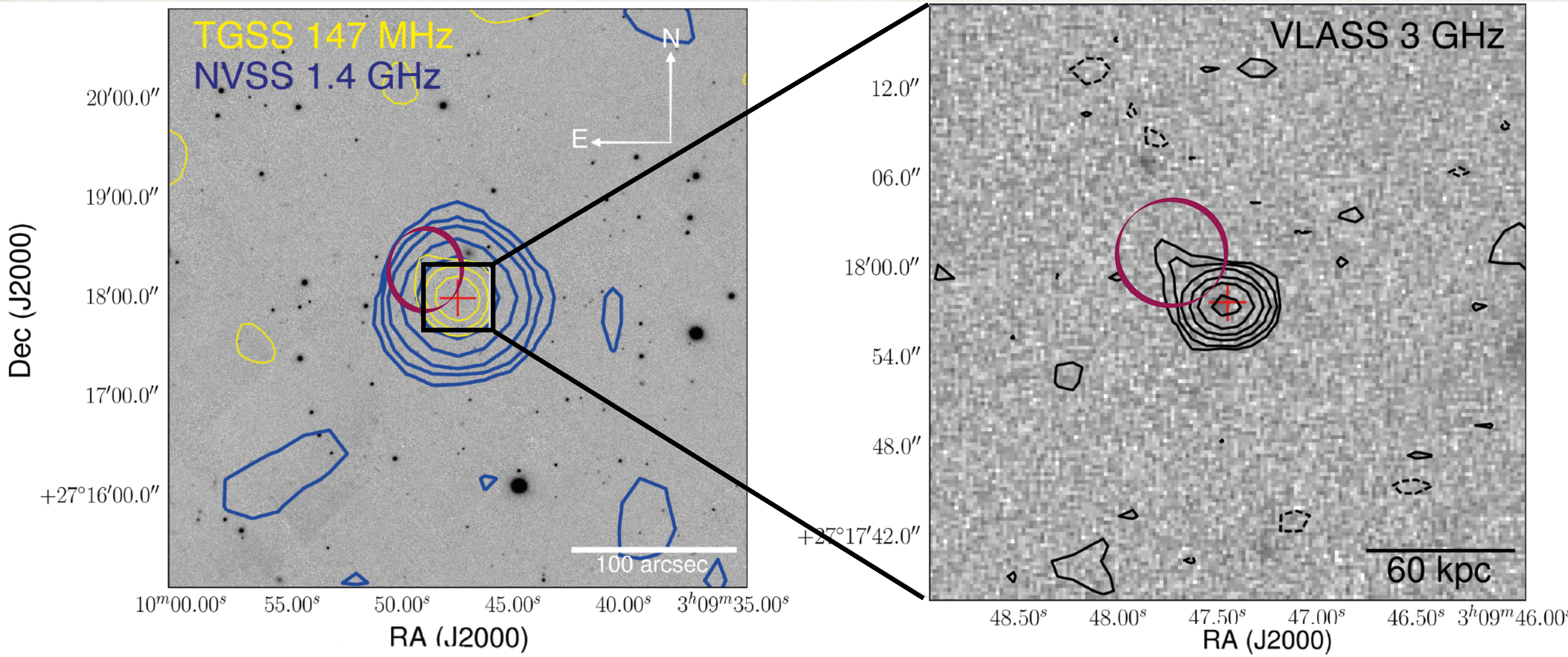


Radio properties:



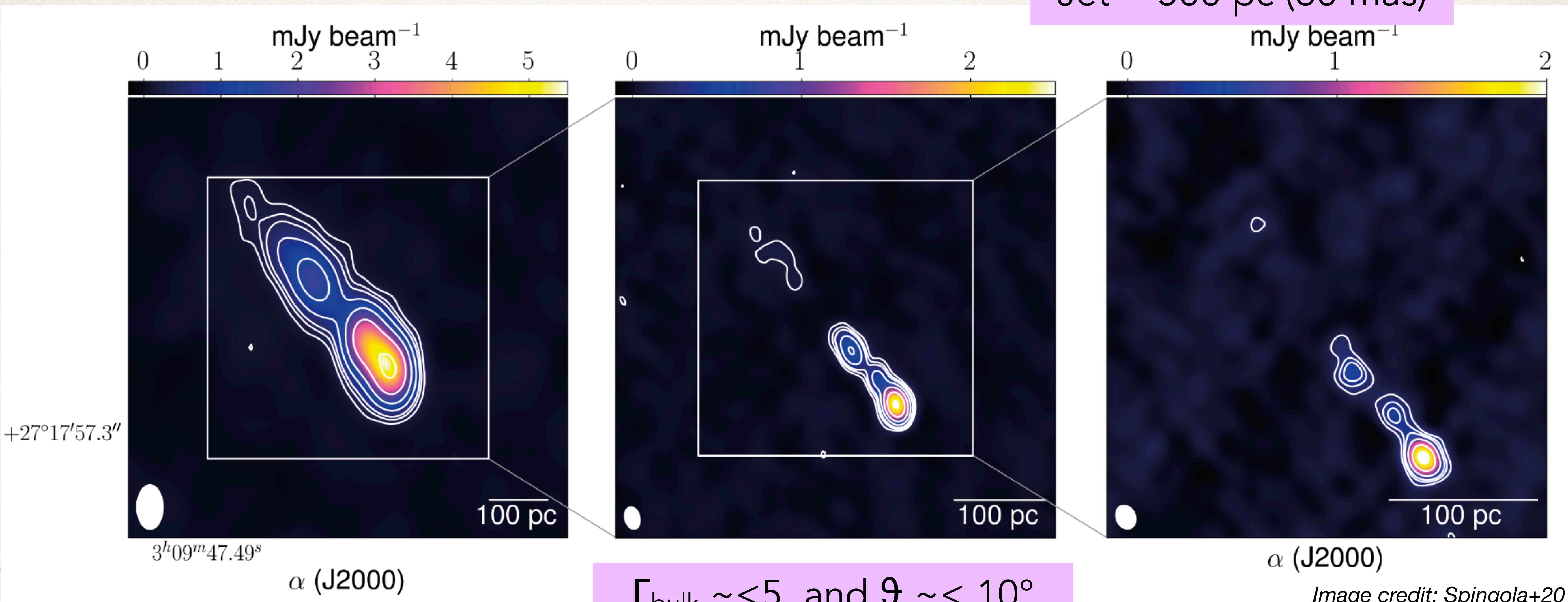
Obs. frequency (GHz)	S_ν (mJy)	survey
0.150	64.2 ± 6.2	TGSS
1.4	23.89 ± 0.87	NVSS
3	12.0 ± 1.2	VLASS

VLBA follow up at 1.4, 5 and 8.4 GHz

(April 2020, PI: Spingola, Co I: SB)

Sub-arcsecond resolution

Jet ~ 500 pc (80 mas)



Γ_{bulk} ~<5 and ϑ ~< 10°

Image credit: Spingola+20

Freq. (GHz)	Total flux density (mJy)	Peak surface brightness (mJy beam^{-1})
1.5	20 ± 2	7.2 ± 0.7
5.0	7.0 ± 0.7	4.1 ± 0.4
8.4	5.1 ± 0.5	3.2 ± 0.3

Spingola, Dallacasa, SB, et al. (2020)

(VLBA+VLA)

Media INAF, NRAO, NSF, Insubria press releases

Obtained follow-up

EVN + eMERLIN follow-up (VLBI) at 1.4 and 22 GHz

P.I. Spingola C, Co.I. SB et al.

1.4 GHz: de-blending jet and core + variability

22 GHz: better resolve the core emission

LOFAR follow-up at 54 and 150 MHz

P.I. Spingola C, Co.I. SB et al.

Trace the jet at low frequency

(resolve the TGSS jet)

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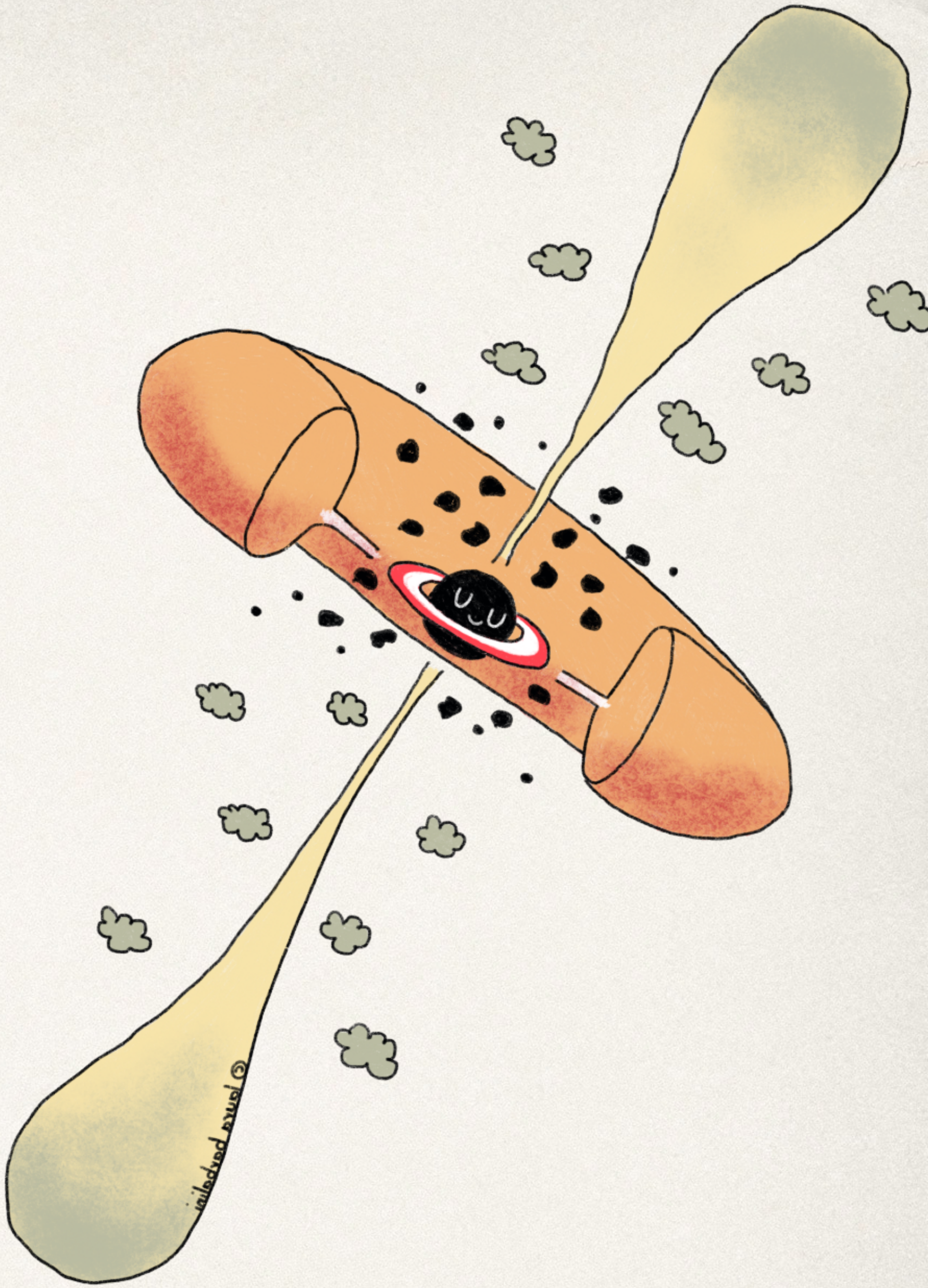
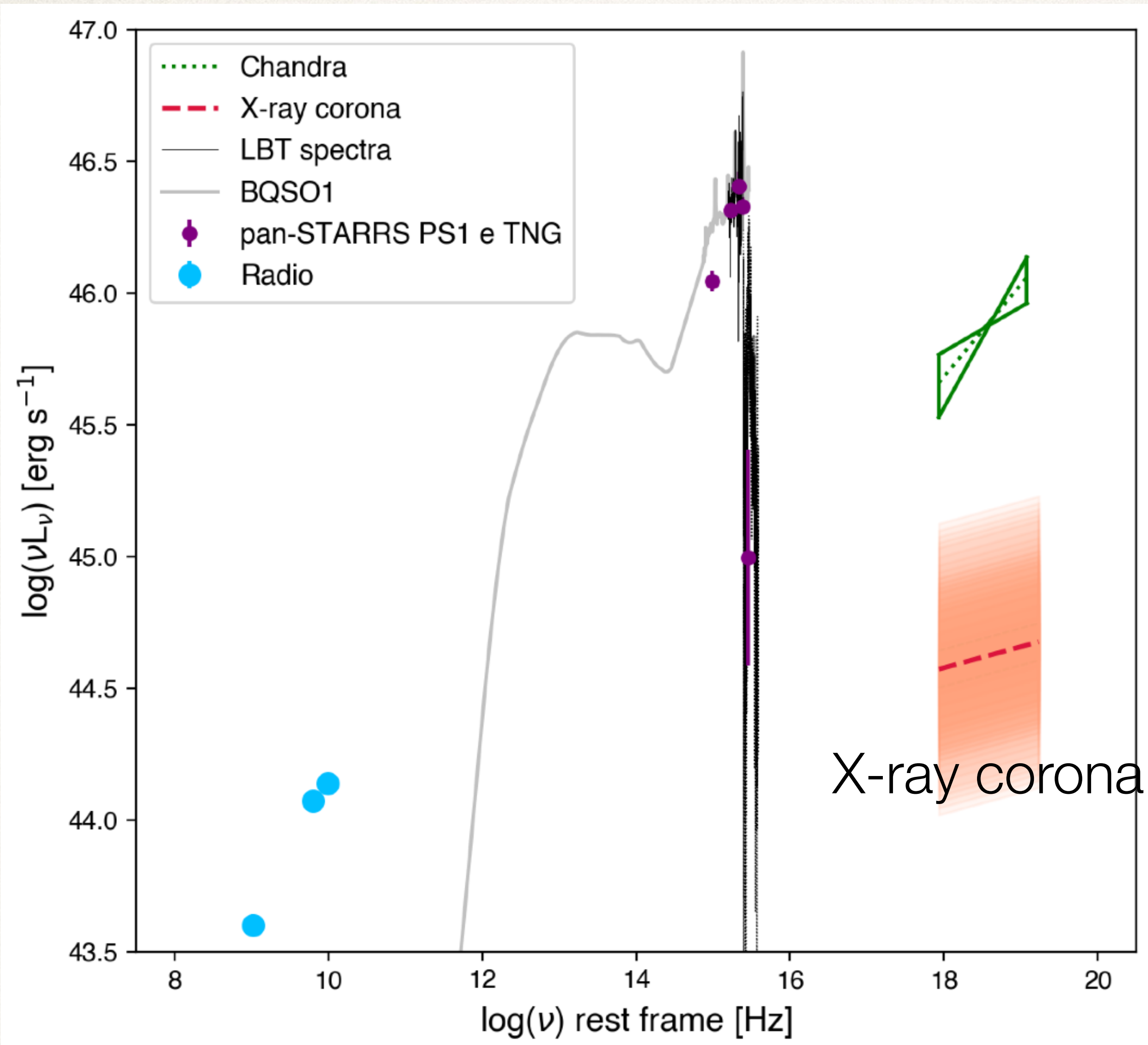


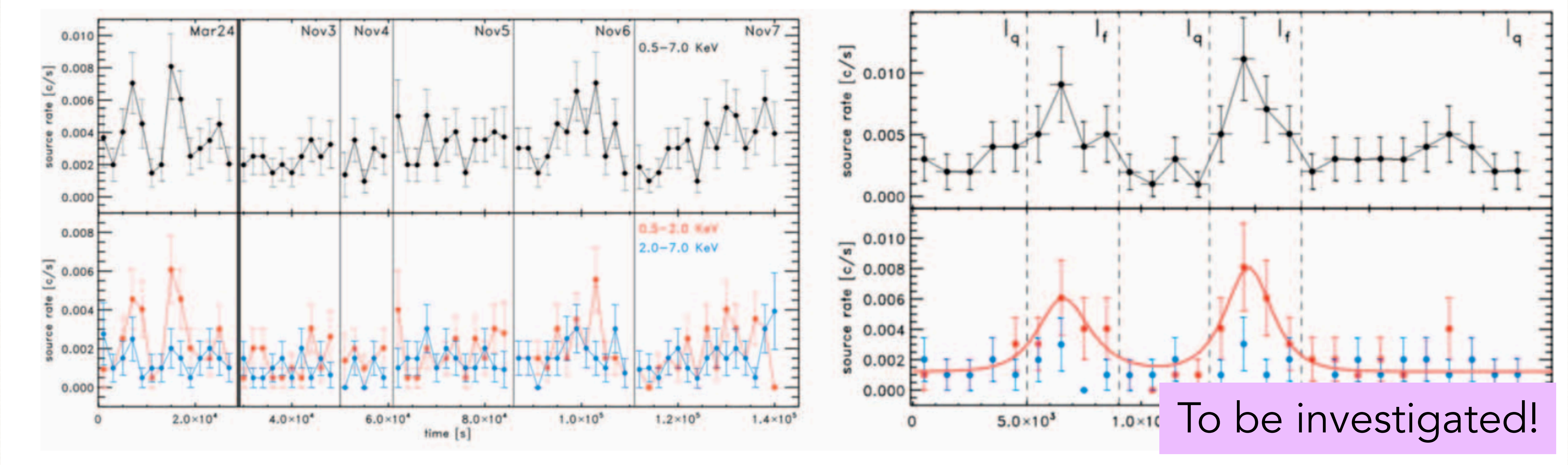
Chandra follow-up

(25 and 100 ks, March and Nov 2020, PI: Moretti, Co I: SB)



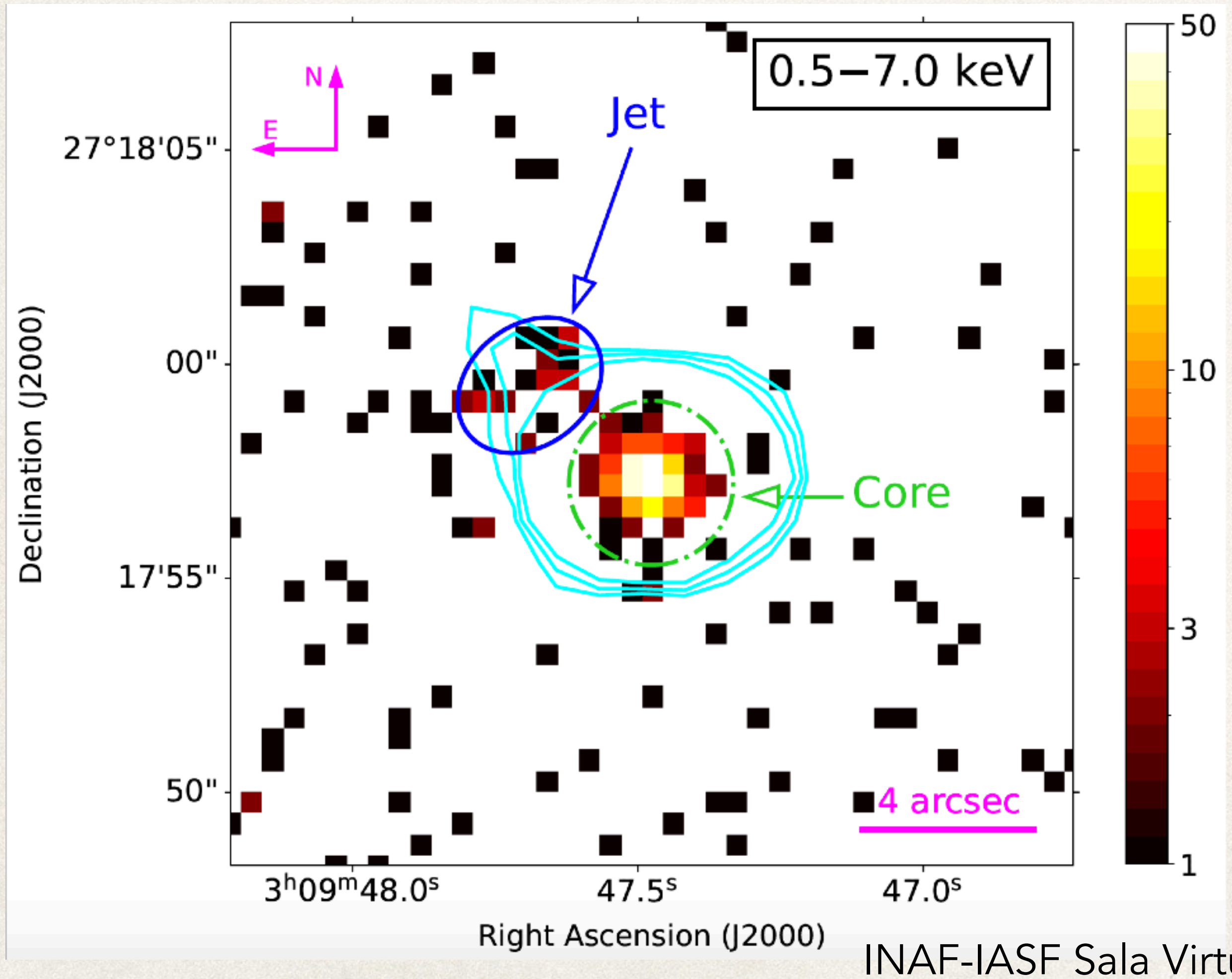
$\Gamma_X = 1.65 \pm 0.18$

Flux [0.5-7]keV = 4.8×10^{-14} erg/s/cm^2



Variability in the soft X-ray on minute time-scale —> Bulk Comptonization?

Moretti, […], SB et al. 2021



Ighina, […] SB et al. 2022

Extended X-ray jet in NE direction
(4″, ~70 kpc, ϑ~20°)

Interaction with CMB photons

Jet = 10%Core

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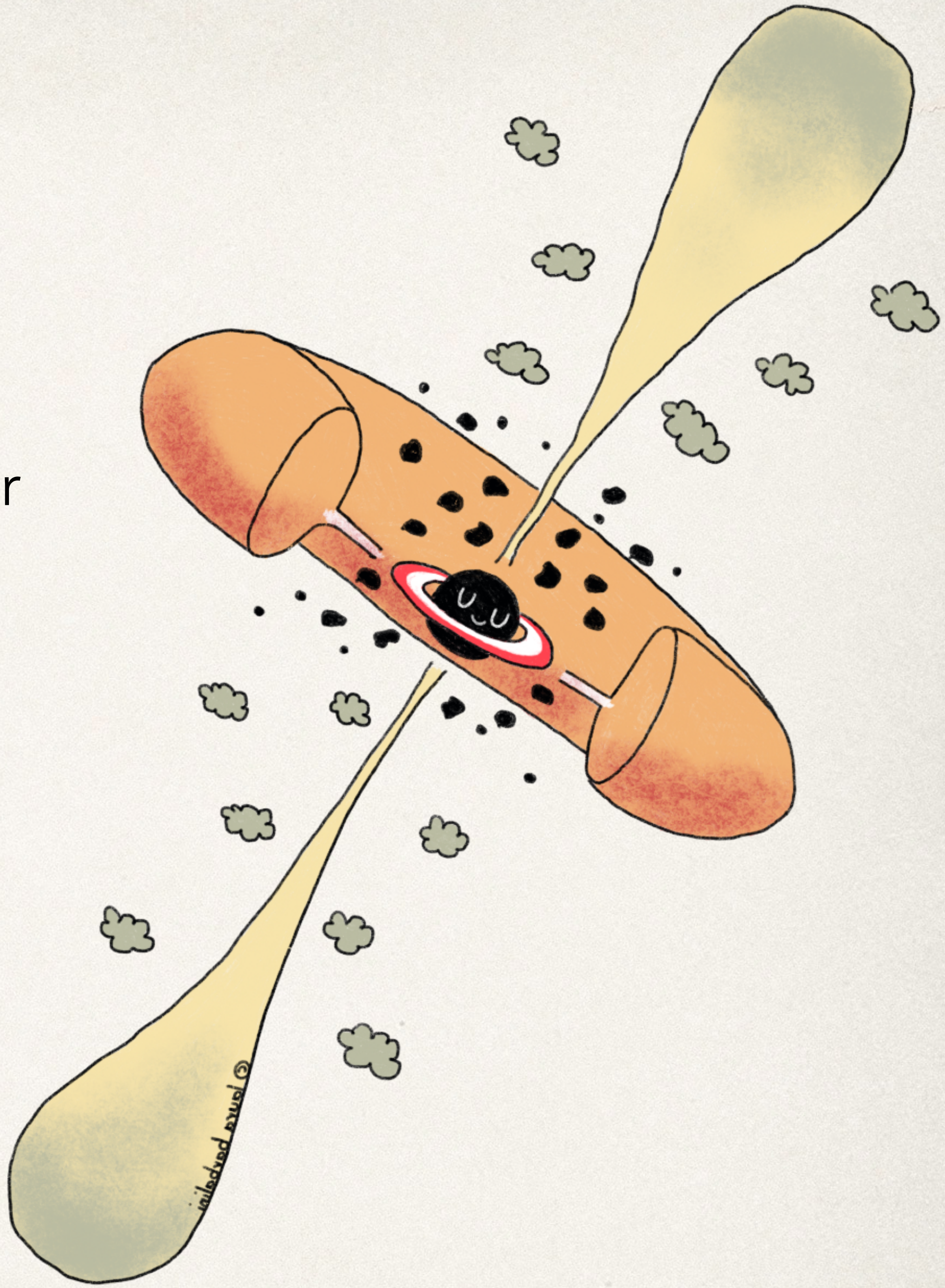
- X-ray Chandra follow-up: variability and jet
- **Future developments**



Future developments:

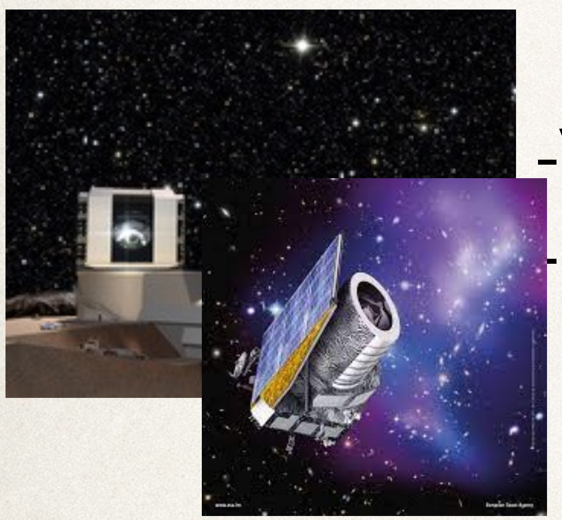
New generations of radio surveys:

-the Rapid Askap Continuum Survey (**RACS**) at 888 MHz (DR1 Dec 2020)

-the Evolutionary Map of the Universe (**EMU**) (ongoing pilot)

Deeper (μJy) and more accurate position (4″ for RACS)

>100 blazars at z>4



New generations of optical/infrared surveys:

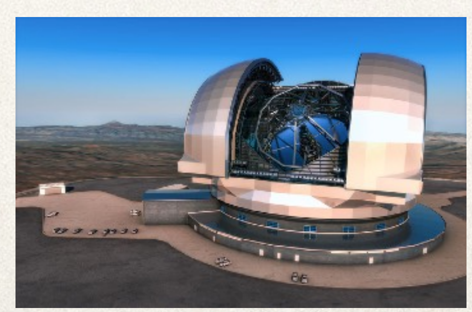
-Vera Rubin Observatory / **LSST** *Deeper (mag 26)*

-**Euclid**

New generation of telescopes:

-Extremely Large Telescope (**ELT**)

-Thirty Meter Telescope (**TMT**)



THANK YOU!