# The most distant relativistic jet resolved with Chandra

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et many al.

25 Years of Science with Chandra

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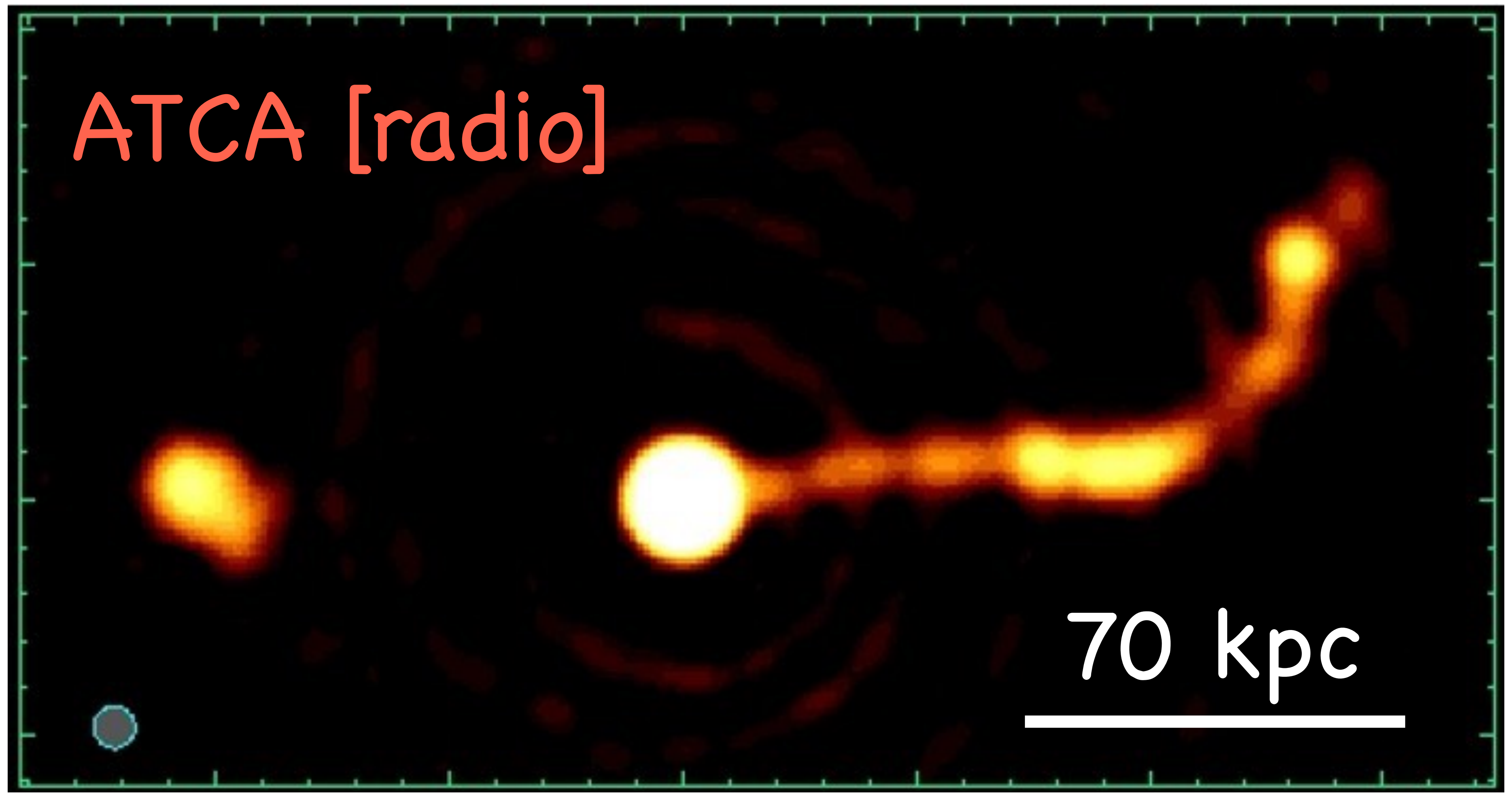
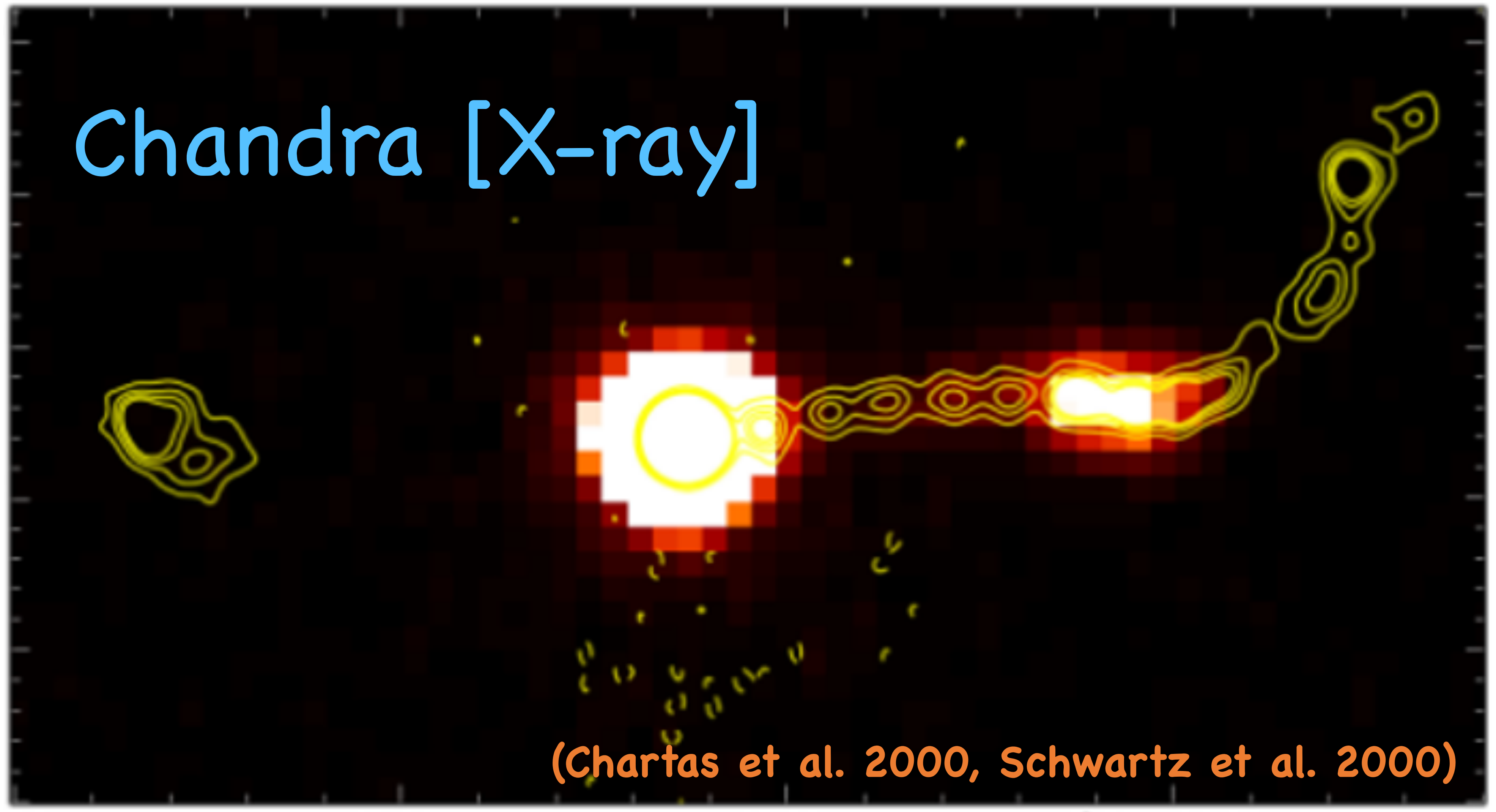
# Large-scale relativistic jets

XJET: https://hea-www.harvard.edu/XJET/
Massaro F., Cheung C., Harris D.

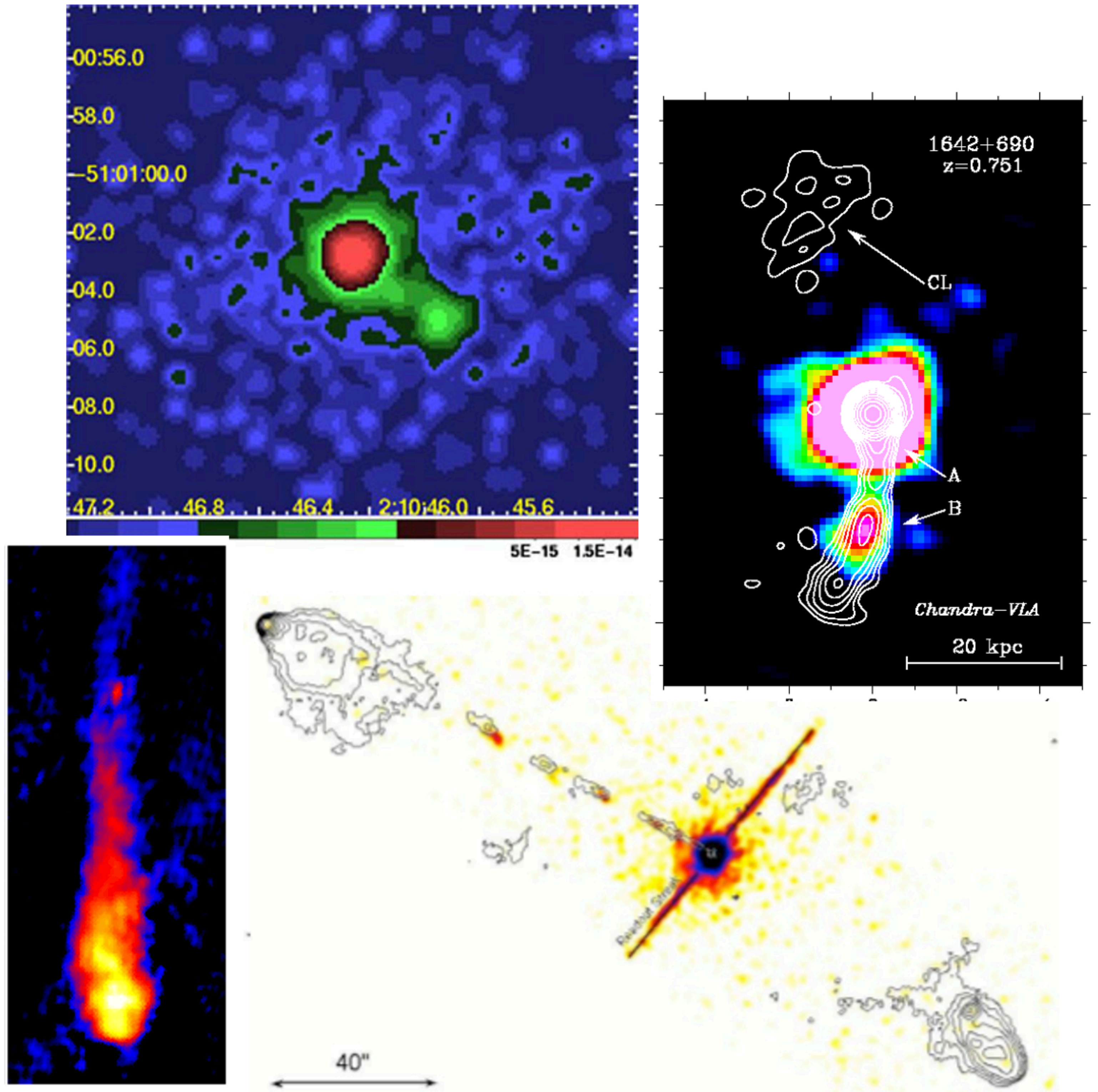
PKS J0637-752 @ z=0.65




CHANDRA
X-RAY OBSERVATORY

>120 X-ray jets




Powerful X-ray emission observed hundreds of kilo-parsecs away from the central engine

## ¿ Origin ?

no seed photons from other AGN components.
Synchrotron self-Compton unphysical

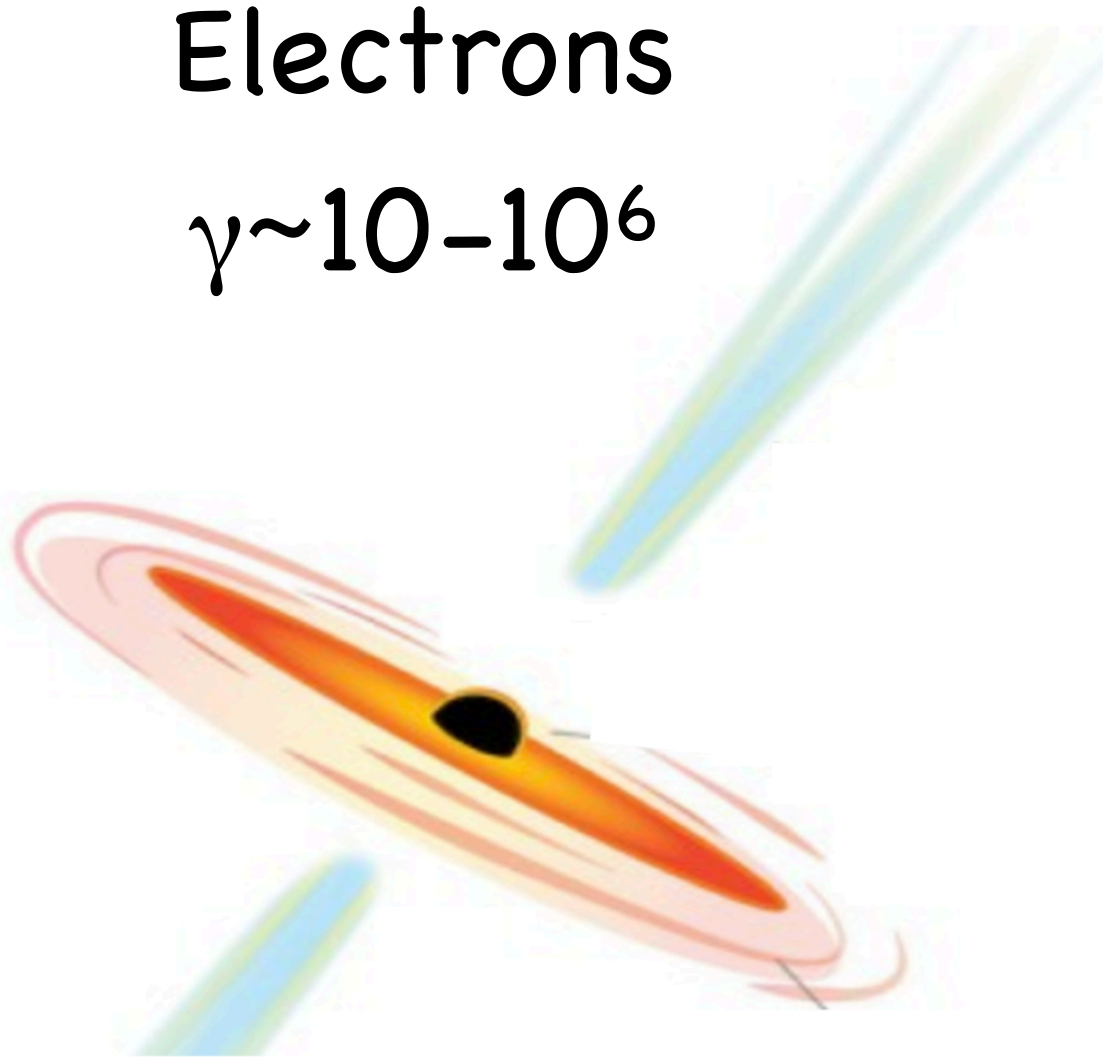
# IC / CMB interaction

## Tavecchio (2000) & Celotti et al. (2001)

Inverse Compton interaction electrons within the jet with the Cosmic Microwave Background (CMB) assuming $\Gamma$~10-20 at kpc-scales

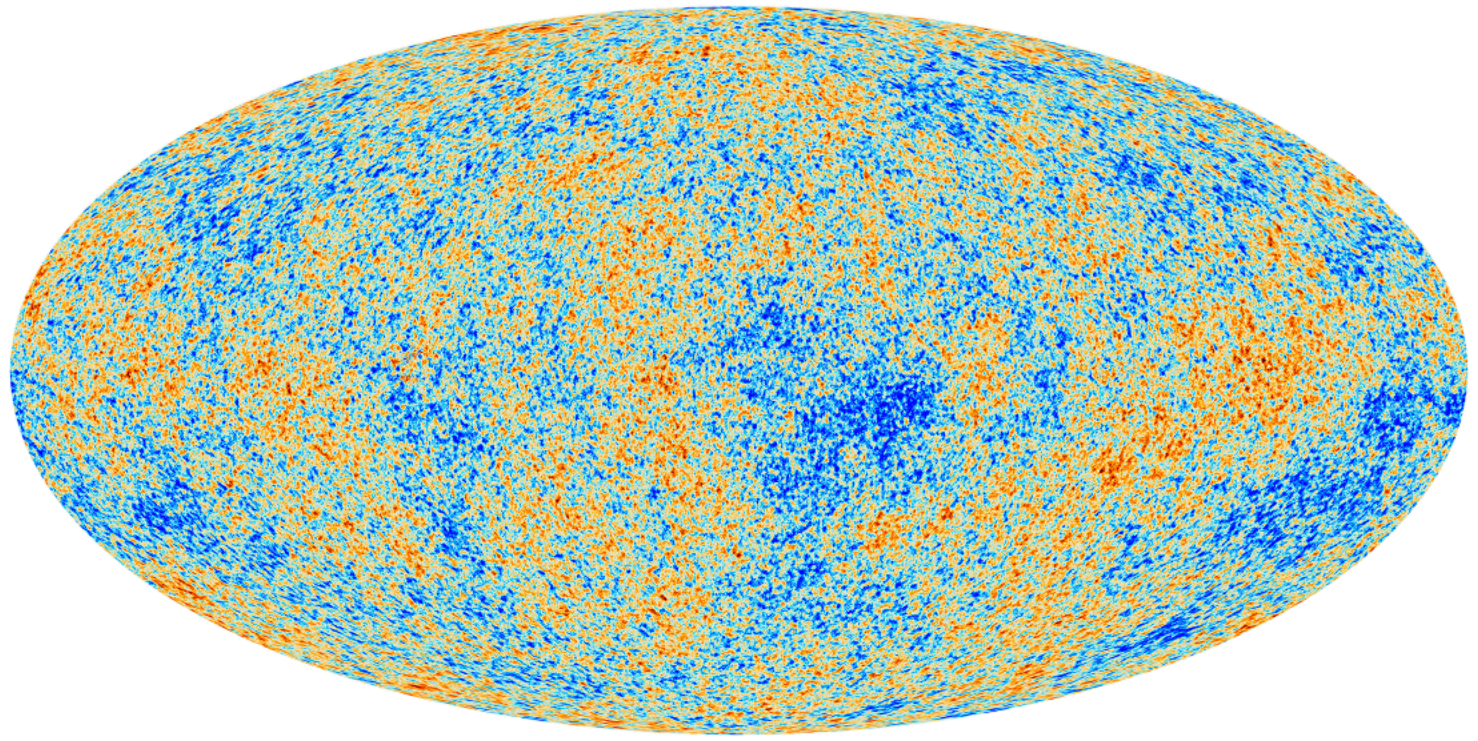
Electrons

$\gamma$~10-$10^6$



Seed photons

$\upsilon$ ~ 160 GHz x (1+z)



**IC/CMB**

Emitted radiation for $\Gamma$~10

$\upsilon$ ~ $10^{15}$-$10^{25}$×(1+z)

X-rays -- $\gamma$-rays

Radio and X-$\gamma$-rays produced by the same electrons —> model their emission to constrain important physical parameters:
**Power jets carry on kpc-scales and available for feedback**

# IC / CMB interaction

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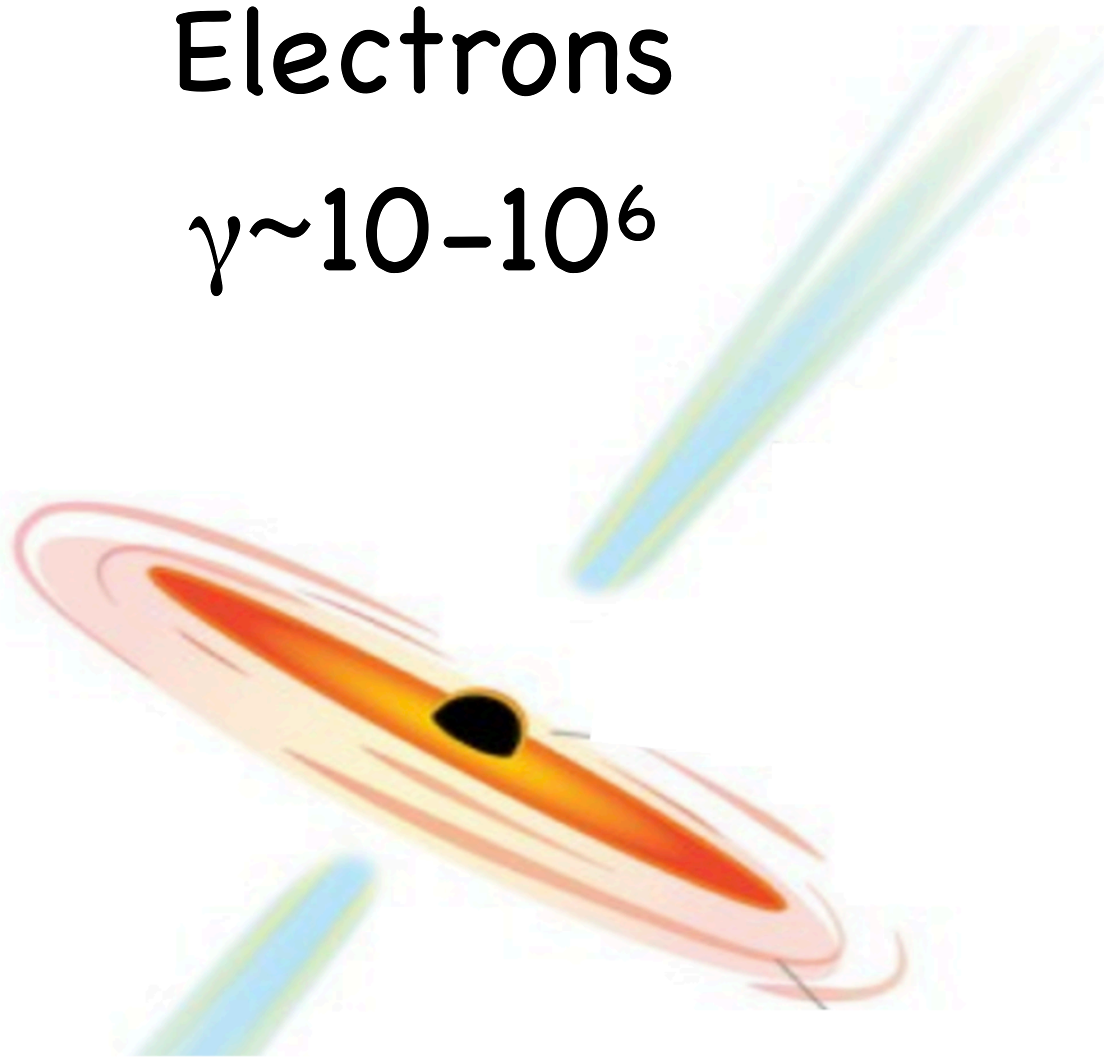

**IC/CMB**

Emitted radiation for $\Gamma$~10

$\upsilon \sim 10^{15}$-$10^{25} \times (1+z)$

X-rays -- $\gamma$-rays

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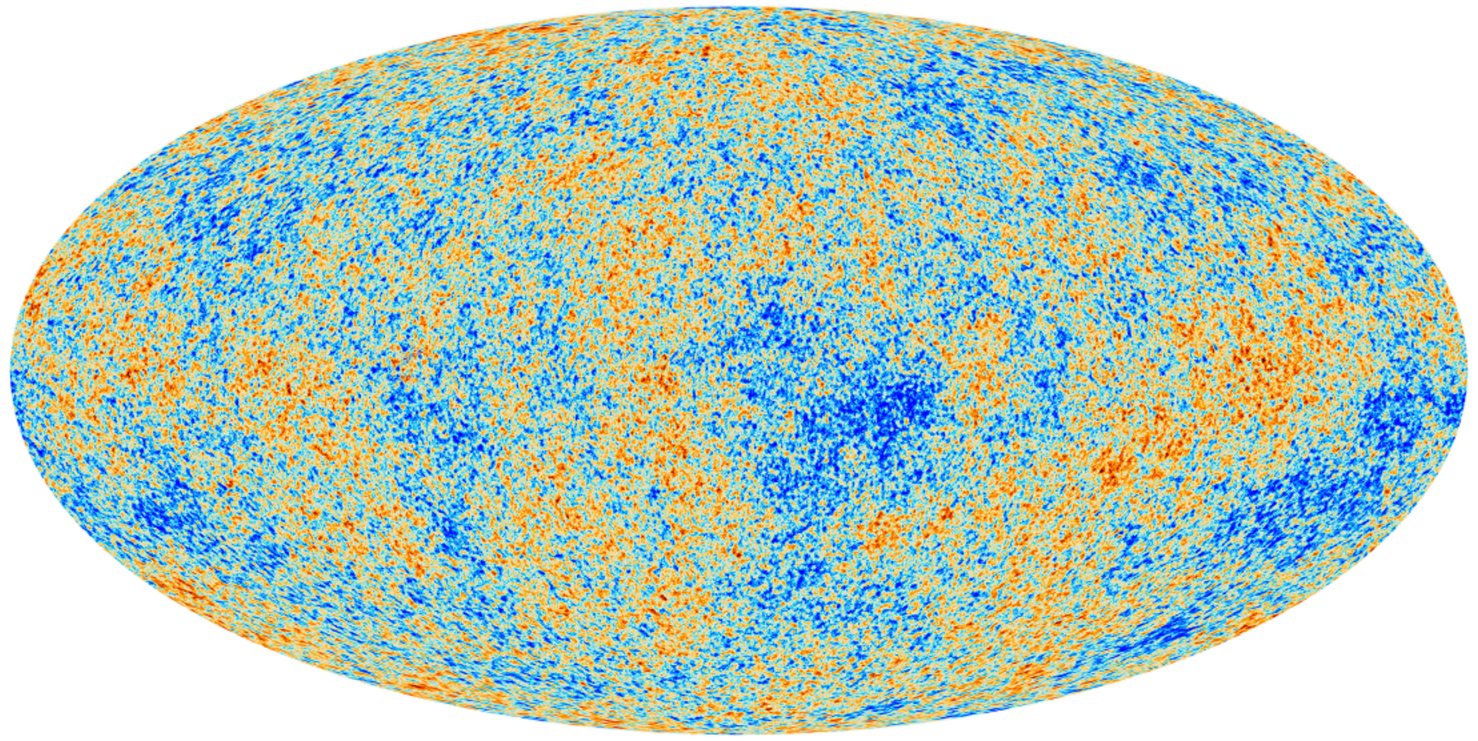


**Problems/Challenges**

**Physical assumptions:**

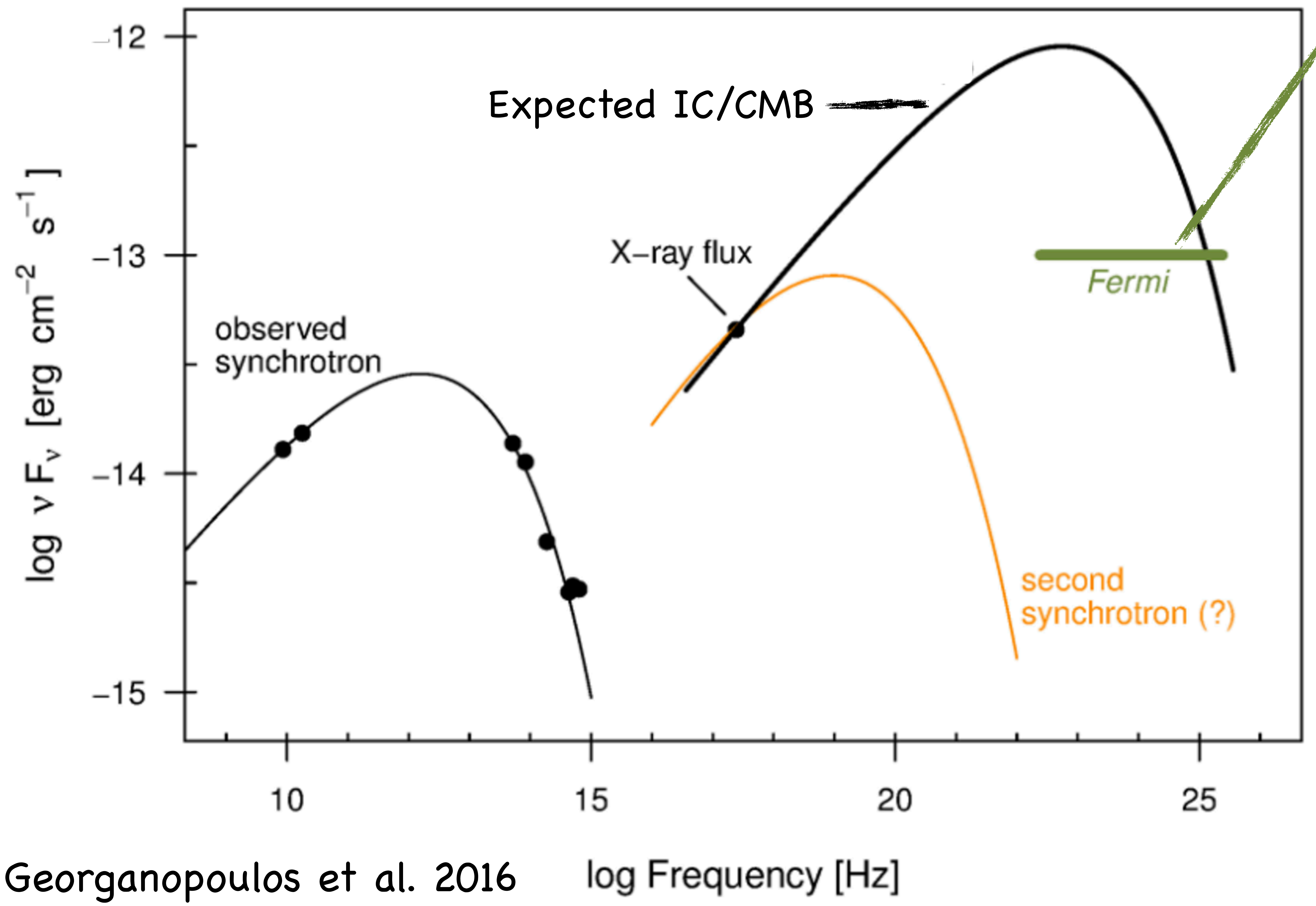
- Highly relativistic jets ($\Gamma$~10-20) at kpc-scales
- Many low energy electrons ($\gamma$~10) —> large power

**Observational constraints:**

- Morphology (e.g. Reddy et al. 2021)
- Polarisation (e.g. Cara et al. 2013)
- $\gamma$-rays upper limits from FERMI-LAT

# IC/CMB or Synchrotron ?

PKS J0637-752 @ z=0.65




Georganopoulos et al. 2016

IC/CMB ruled out in many systems at z<1 based on the non-detection of high $\gamma$-rays emission with Fermi-LAT (see Breiding et al. 2022)

Fermi Gamma-ray Space Telescope

## ¡ Another mechanism at place !

Second population of electrons, extremely energetic up to $\gamma$~$10^{8\text{-}9}$ (~100TeV), which emits in the **X-rays trough synchrotron**
(e.g. Harris & Krawczynski 2002)

How are they accelerated ?
See e.g. Stawarz et al. 2002, Tavecchio et al. 2021

See talk by E. Meyer

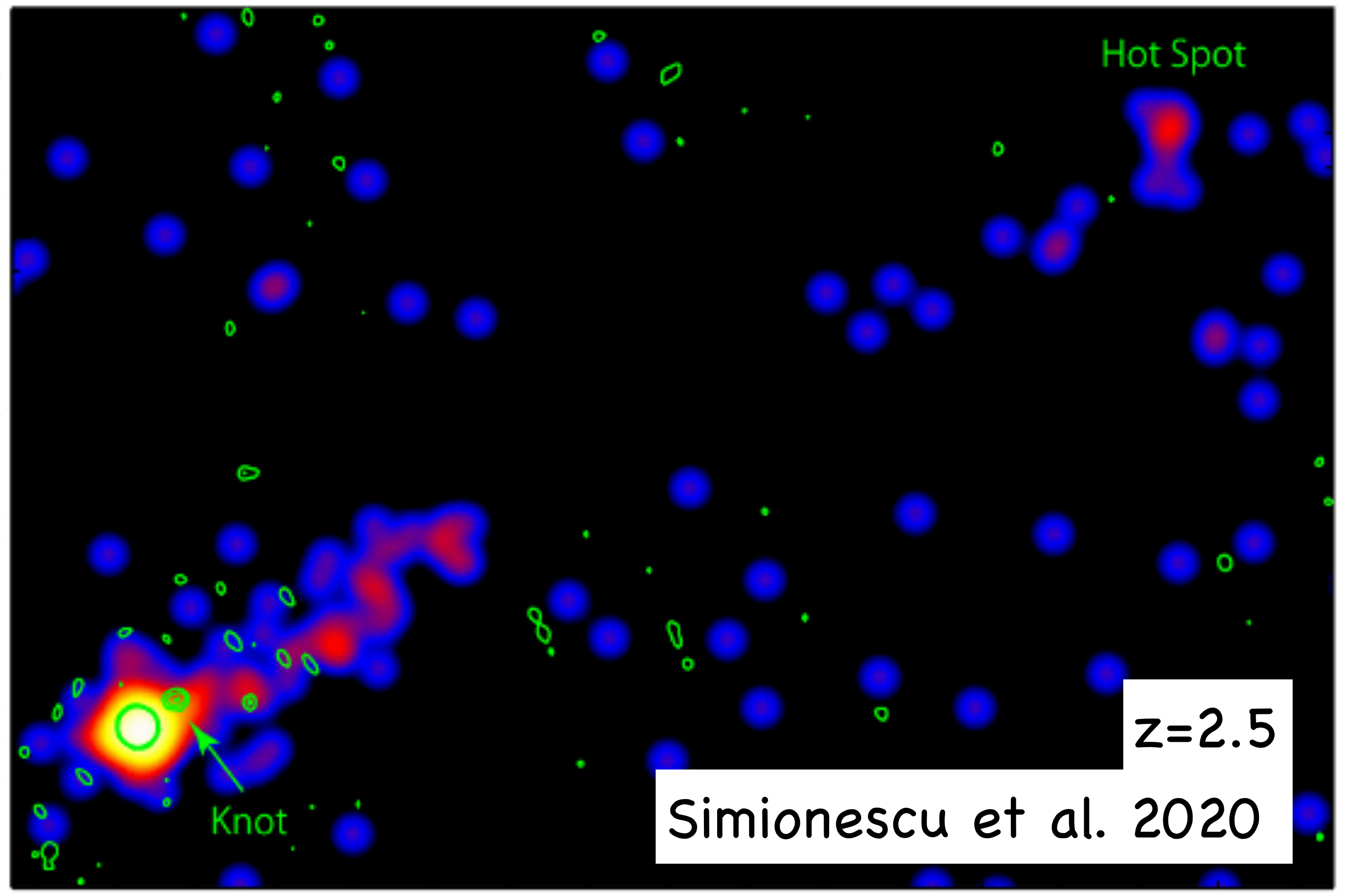
# IC/CMB where to look

**IC/CMB unavoidable**

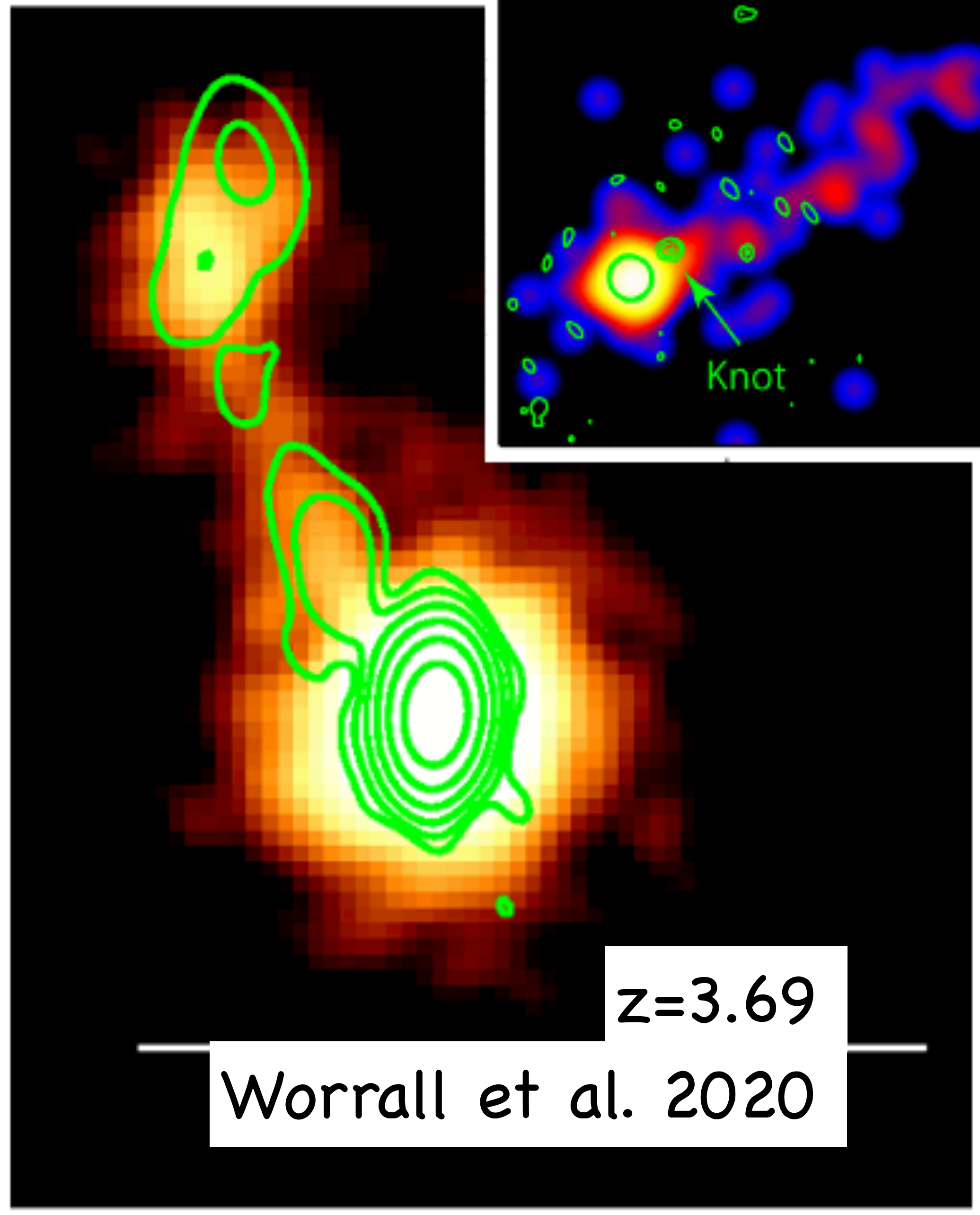
What is its contribution to the total X-ray emission ?

Different contributions = different physical conditions

1) $U_{CMB} \propto (1+z)^4$

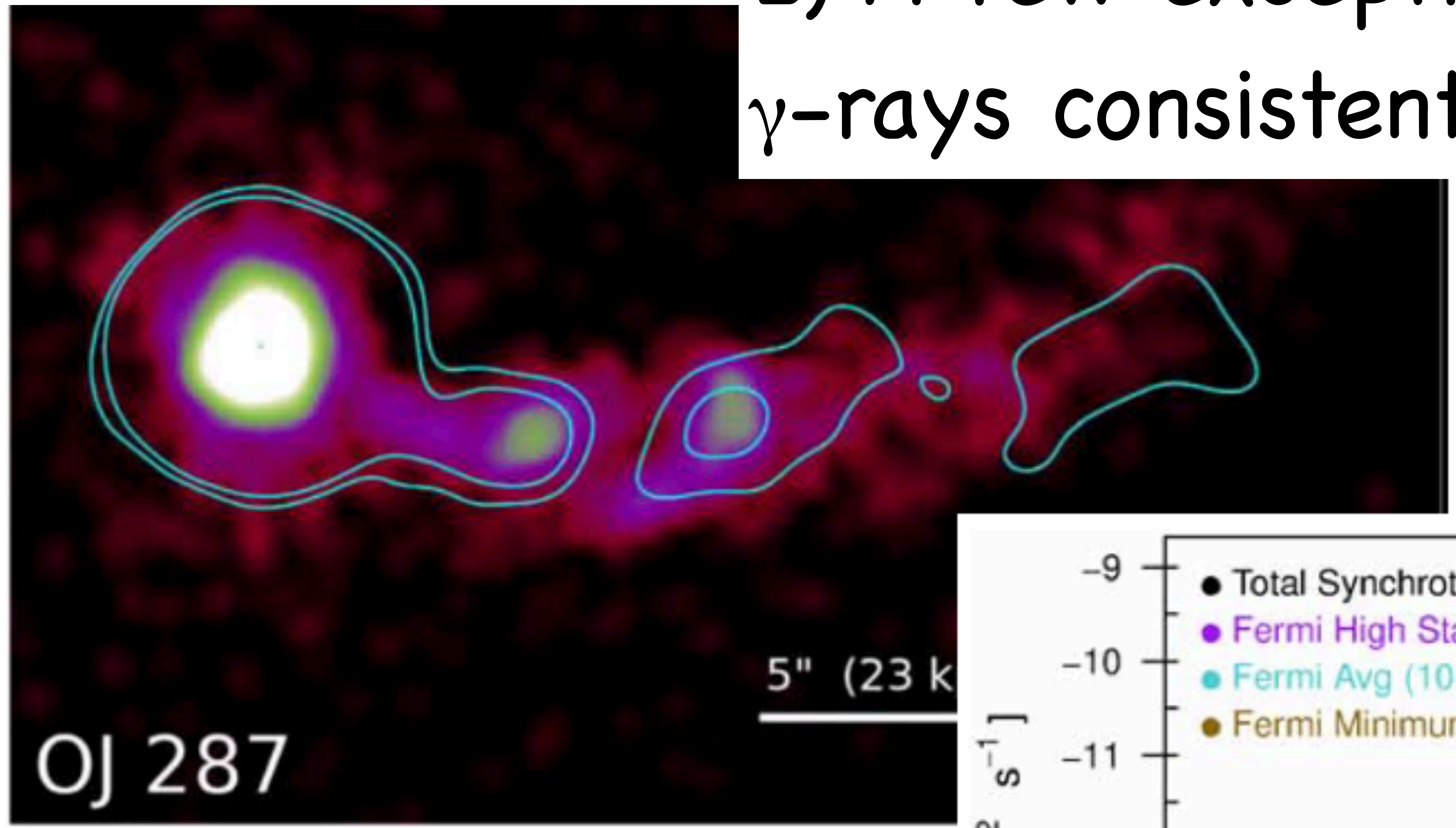


z=2.5
Simionescu et al. 2020

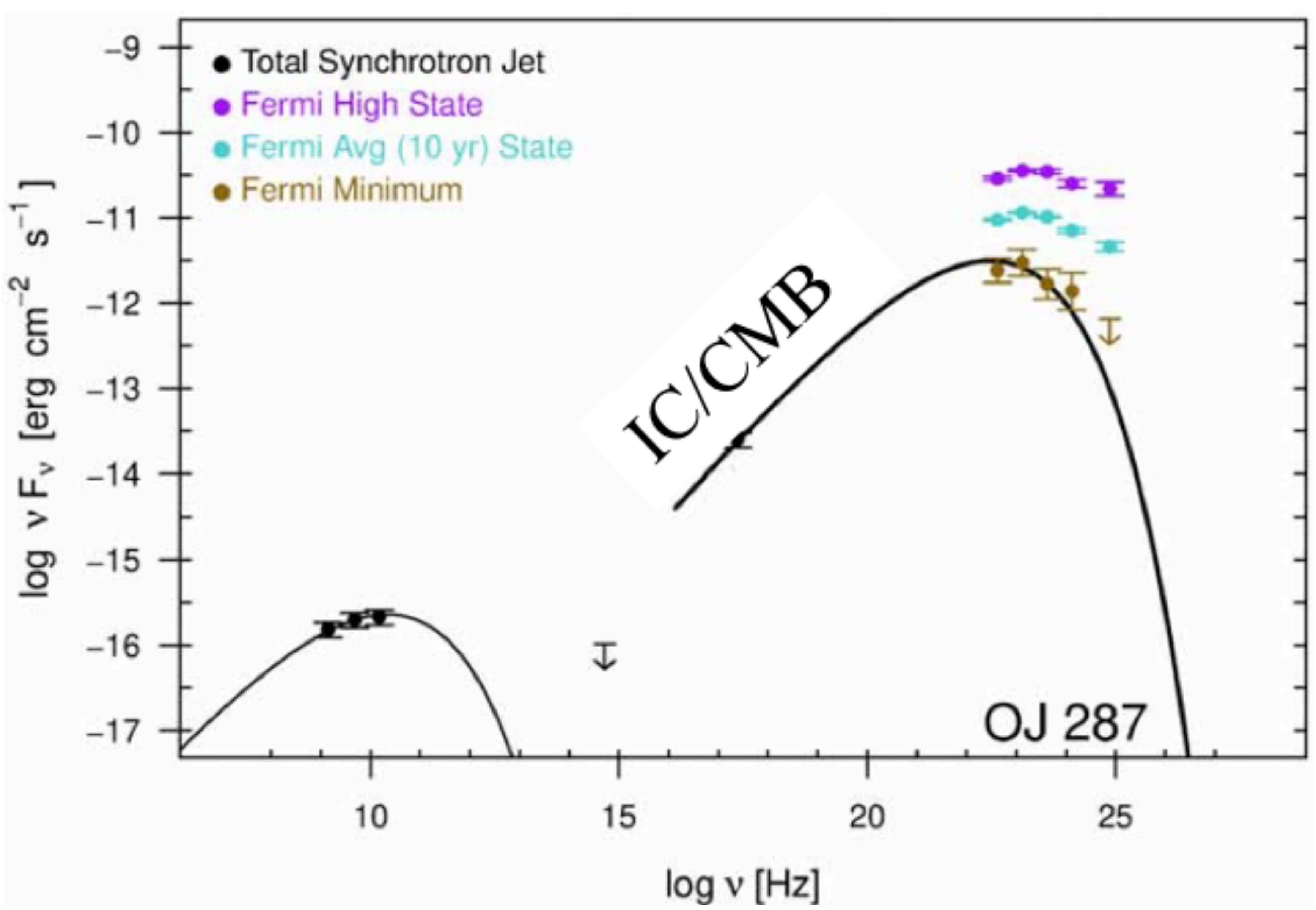

z=3.69
Worrall et al. 2020

2) A few exceptions at z~0.3 where $\gamma$-rays consistent with the IC/CMB

**Blazars**

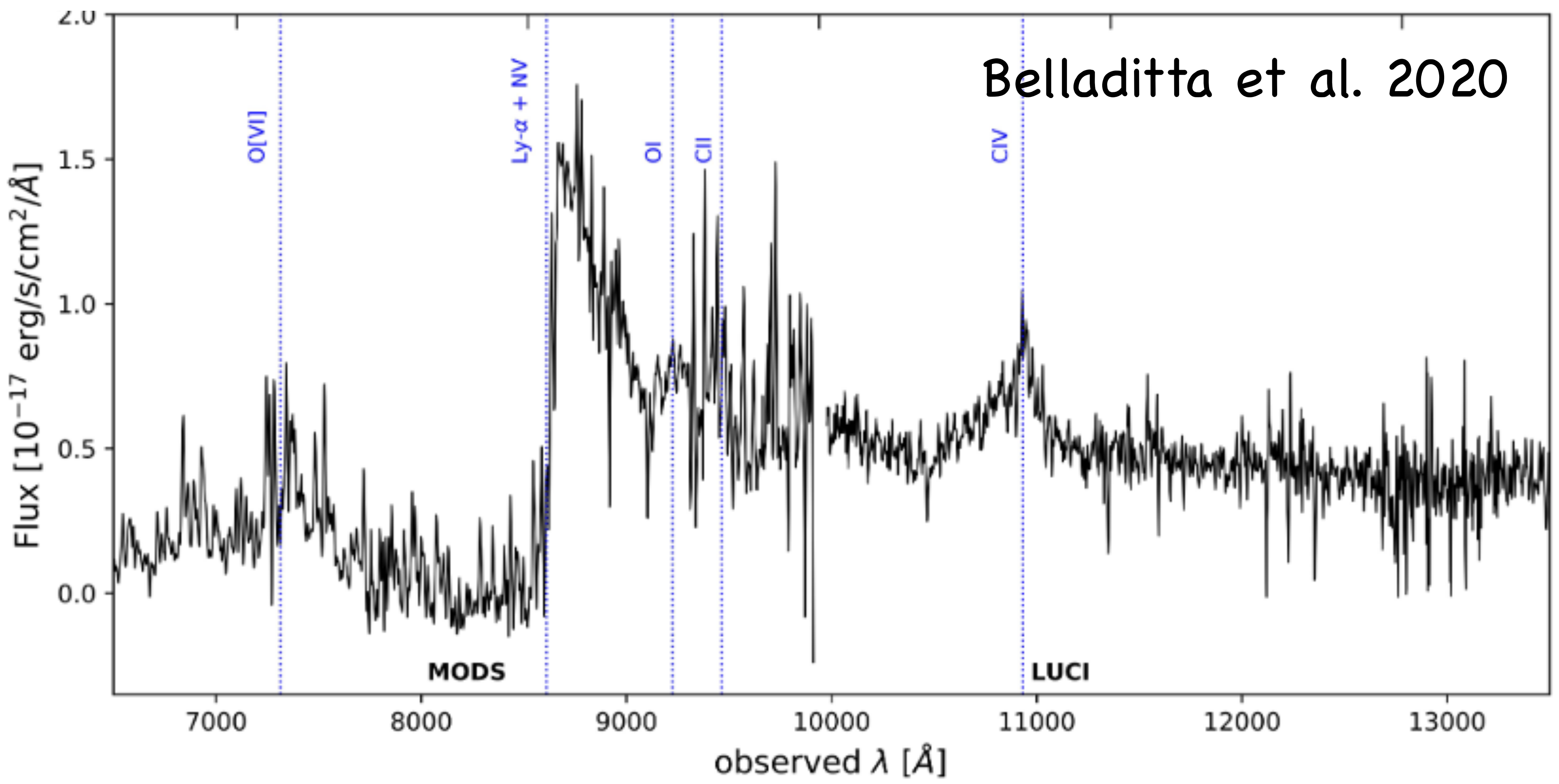



Meyer et al. 2019; z=0.306




**¡ Focus on high-z blazars !**

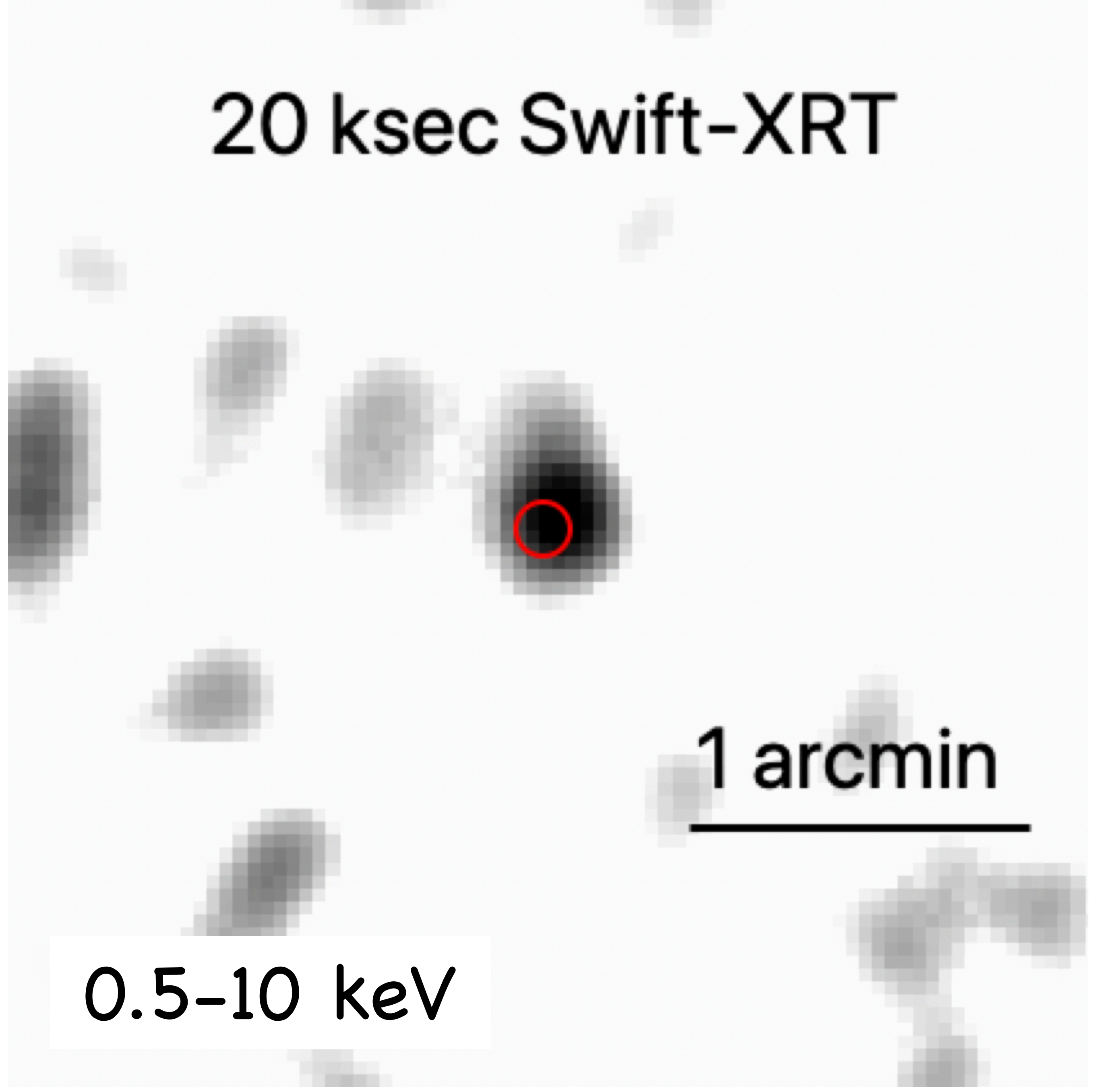
# PSO J0309+27 @ z=6.1



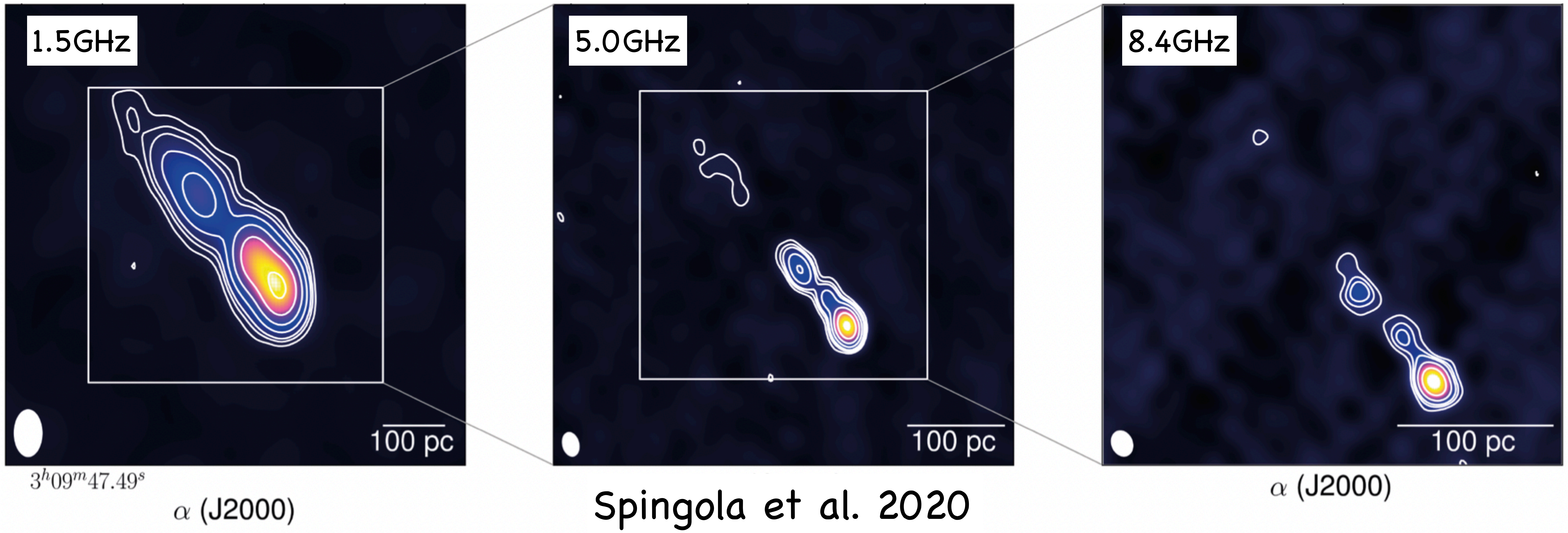

One of the only two z>6 blazars

One of the brightest quasars in the radio and X-ray band at z>6

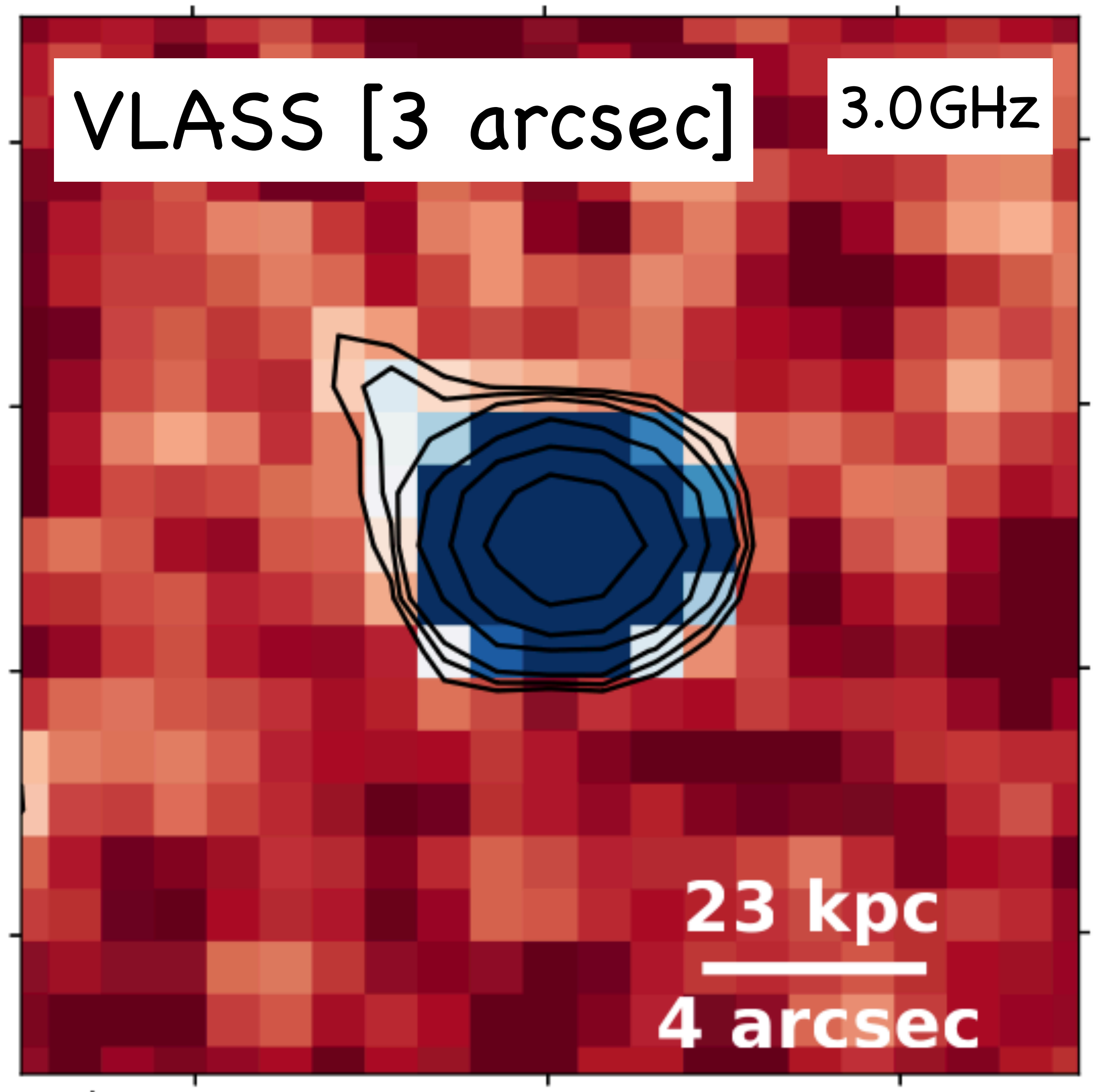
Powerful radio jet on VLBI scales (~500pc)



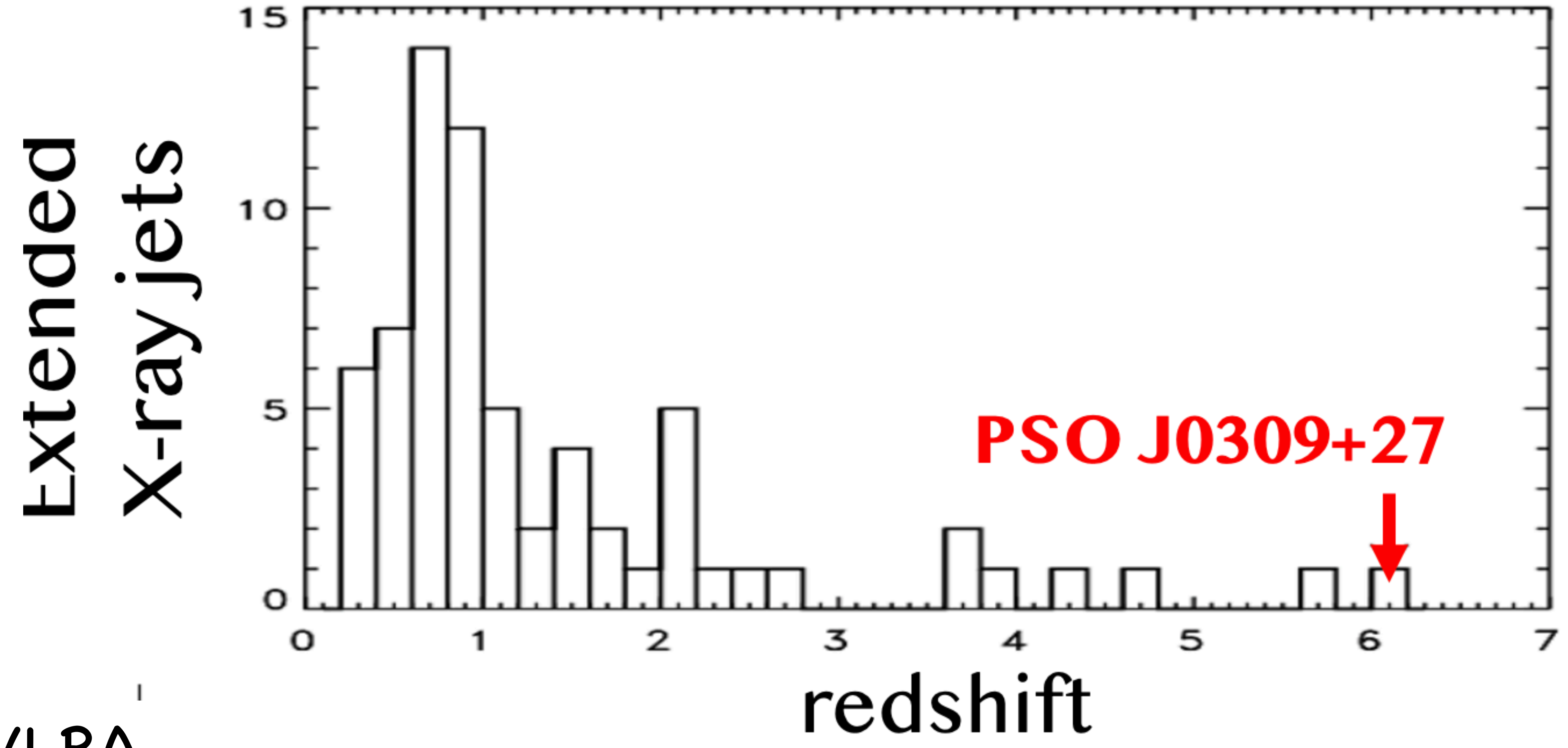

VLBA [4-13 mas]



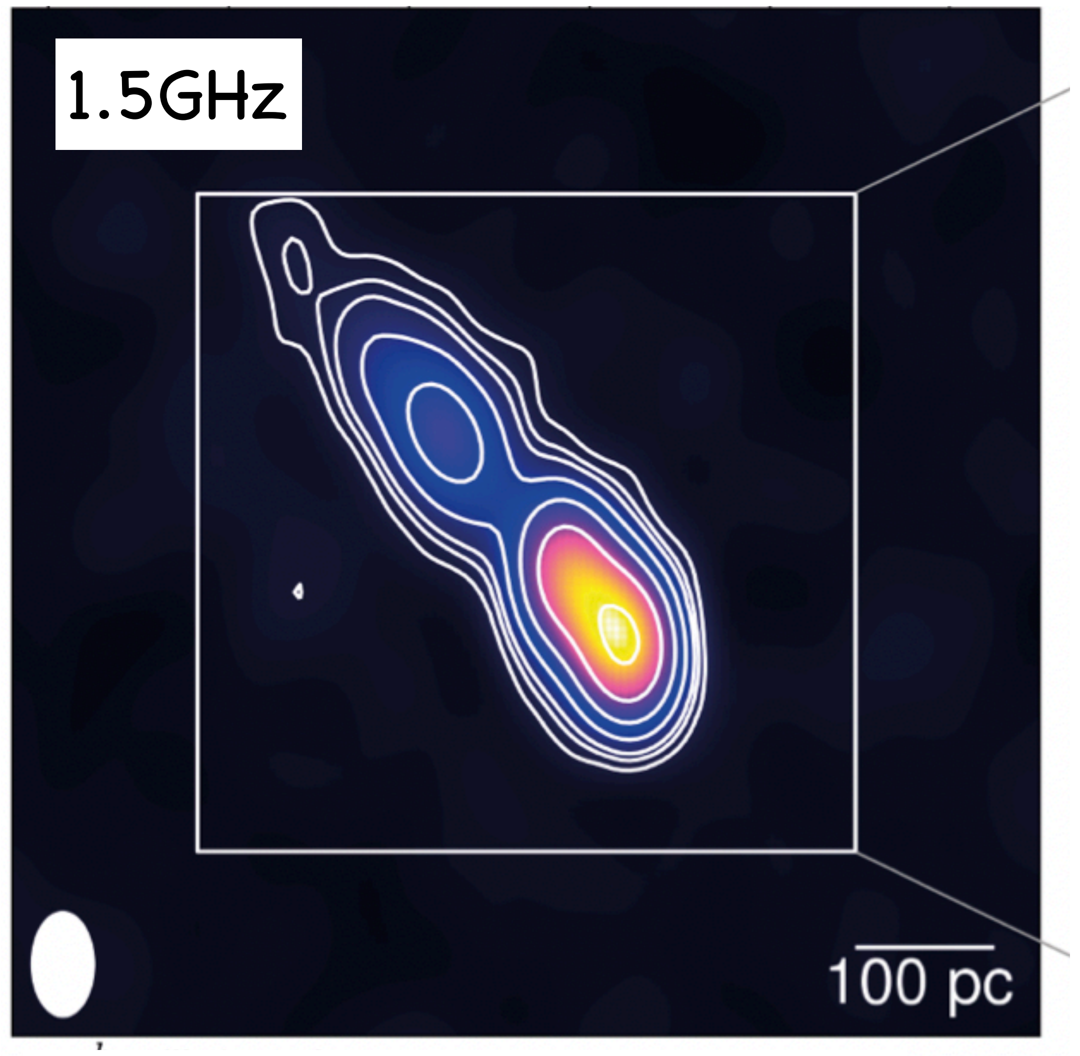

Spingola et al. 2020



# PSO J0309+27 @ z=6.1 in the X-rays



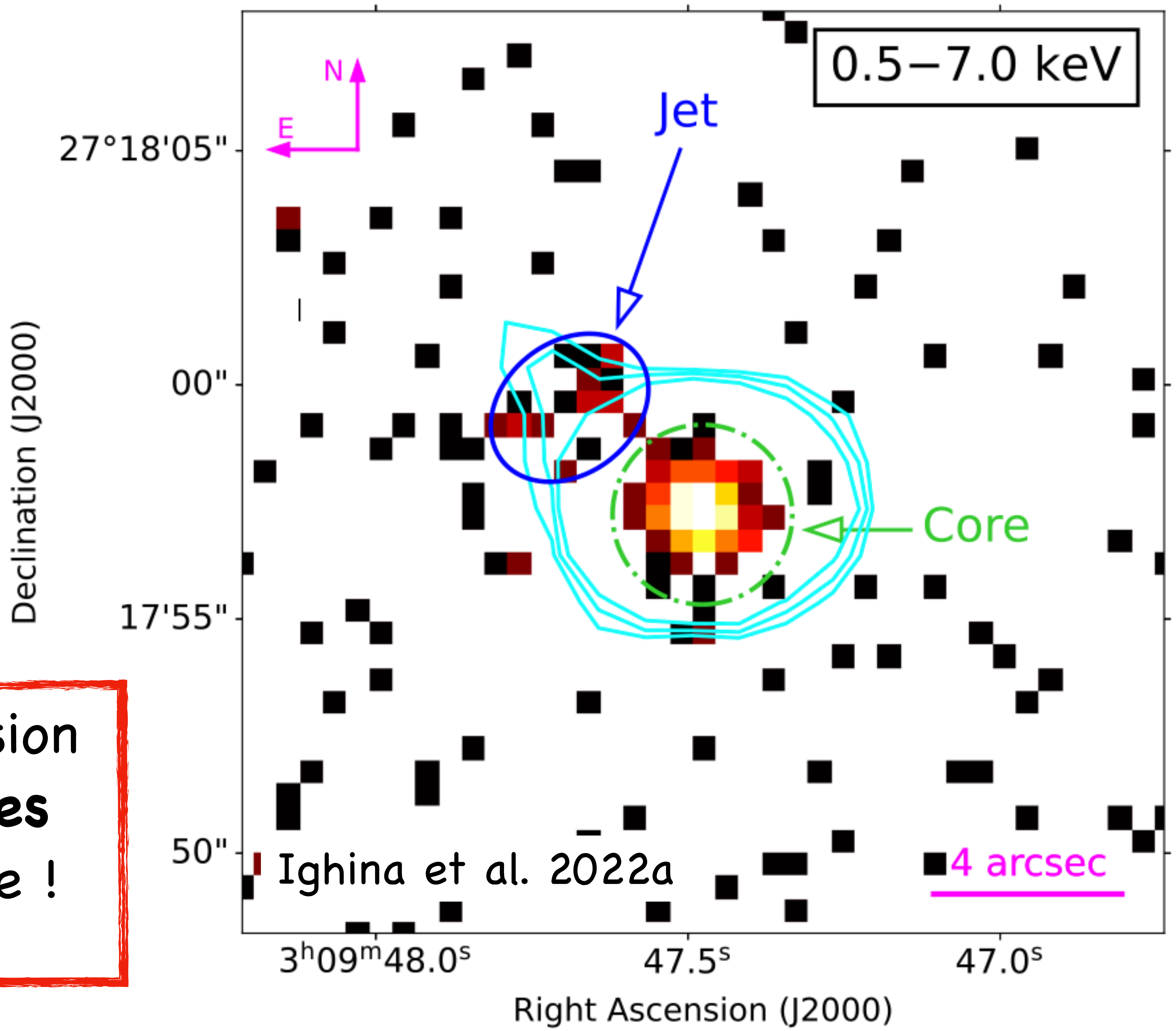

VLBA




Spingola et al. 2020

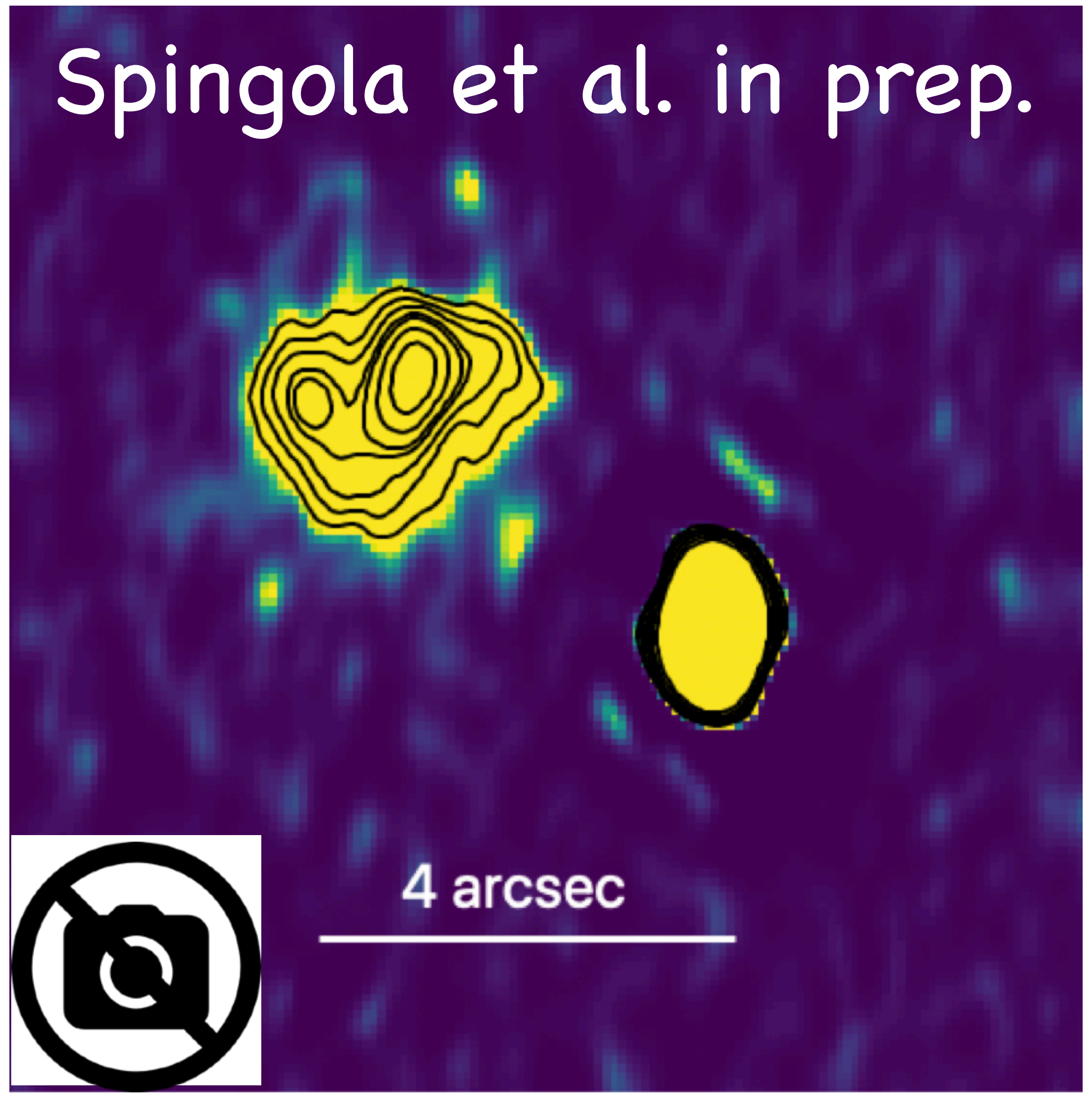
Radio and X-ray emission from the **jet at scales >20kpc** from the core !
Ighina et al. 2022a

Chandra 125 ksec (PI Moretti)



# Multi-scale and multi-frequency radio jet

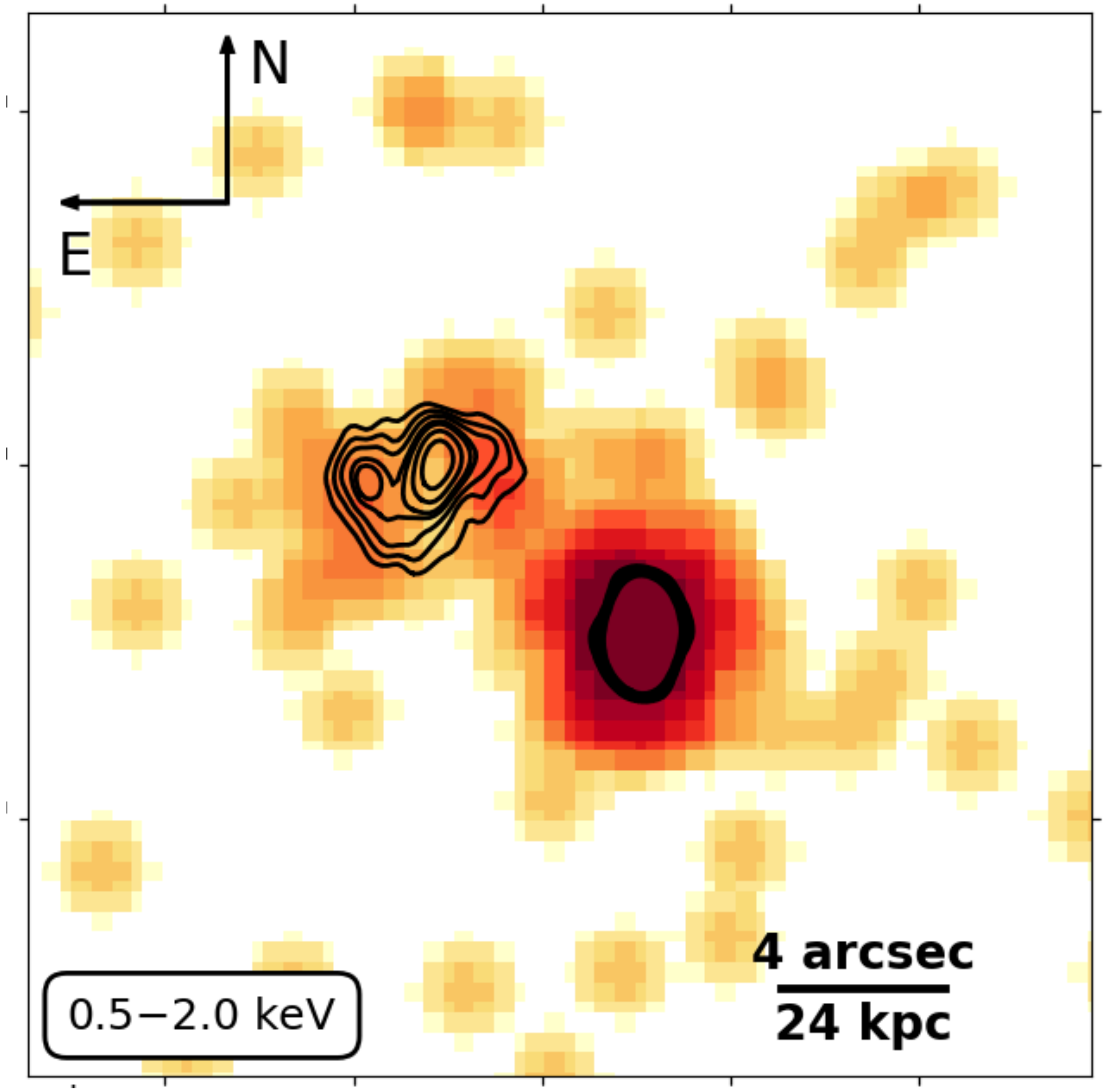
LOFAR-VLBI 0.3 arcsec 144 MHz



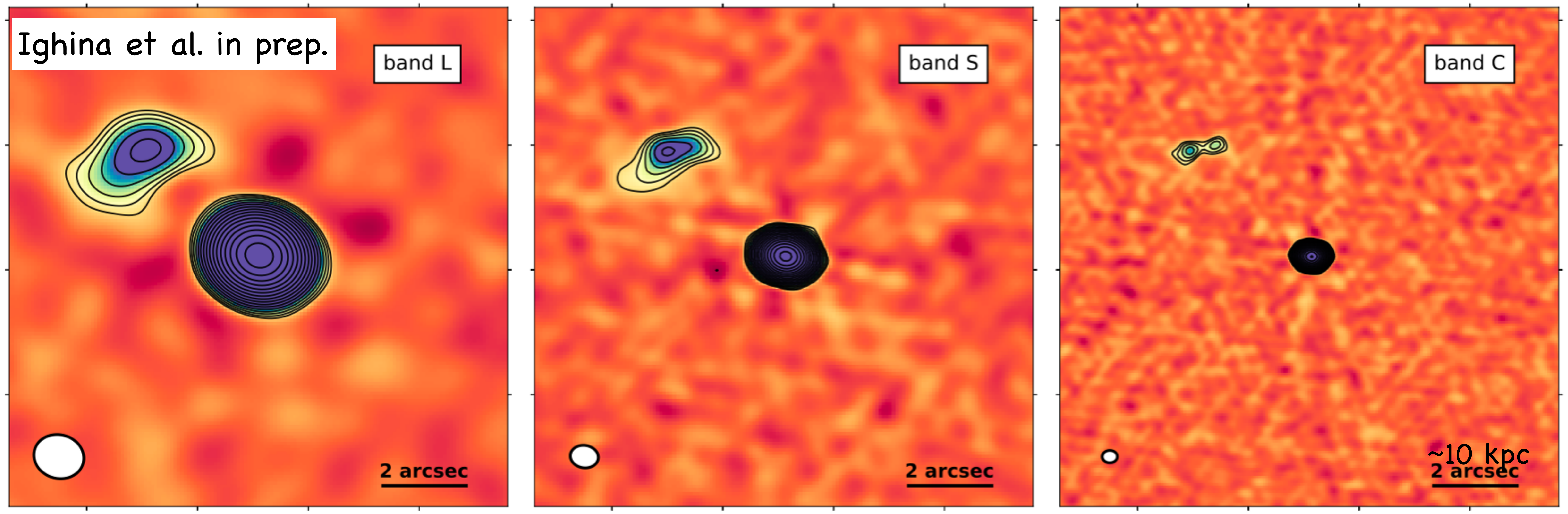


+ e-MERLIN data at 1.5 and 6GHz obtained —> 0.05-0.2 arcsec

Chandra (~300ksec) P.I. Ighina




VLA conf. A: 0.3-1.5 arcsec



# Extended Jet SED modelling

1) X-ray emission **fully consistent** with the **IC/CMB** without requiring extreme conditions ($\Gamma$~2)

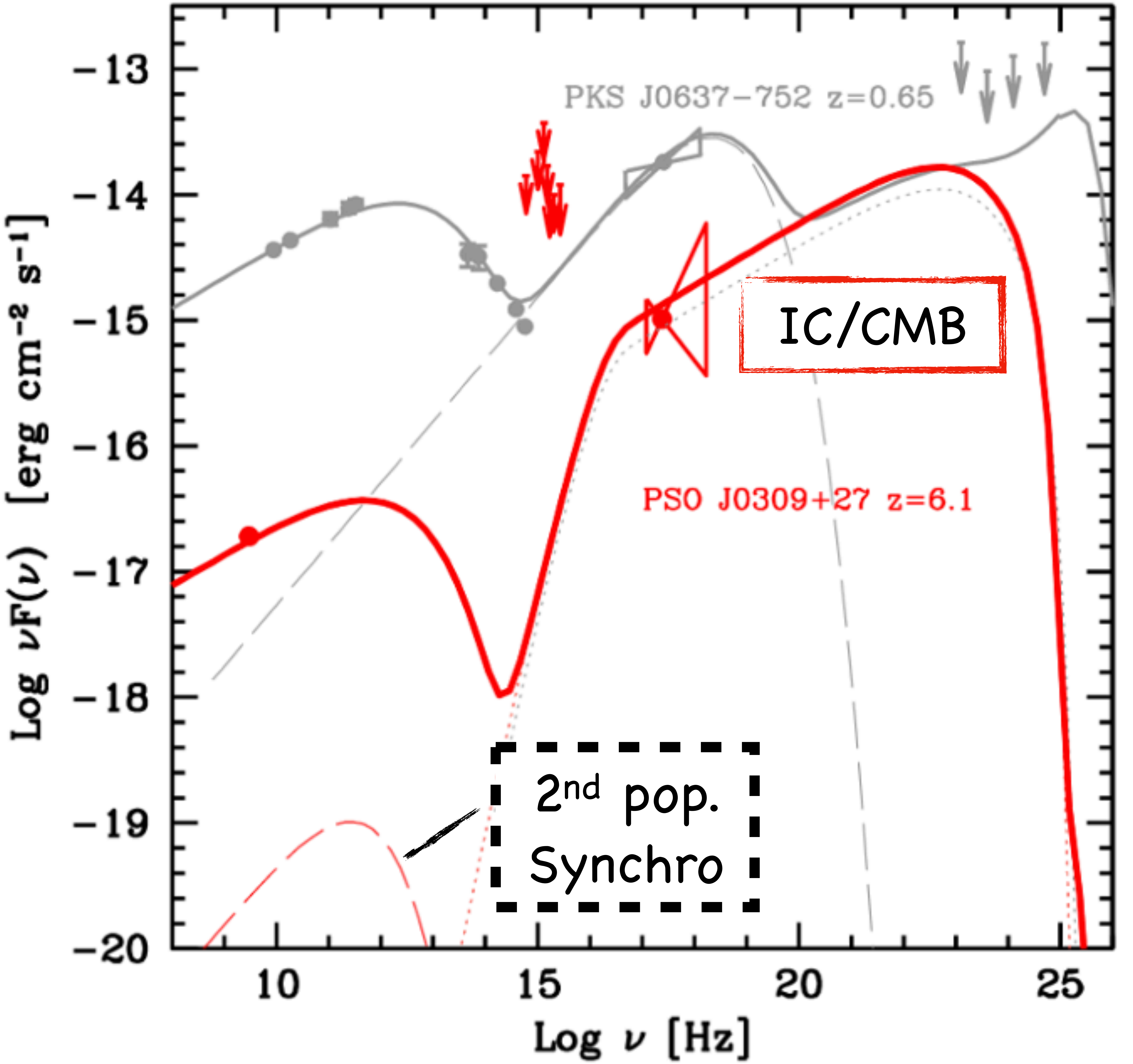
$$U_{CMB}(z = 6.1) \approx 350 \times U_{CMB}(z = 0.65)$$

2) 2nd population of **electrons cannot be accelerated up to very-high energies** (see Tavecchio 2021)

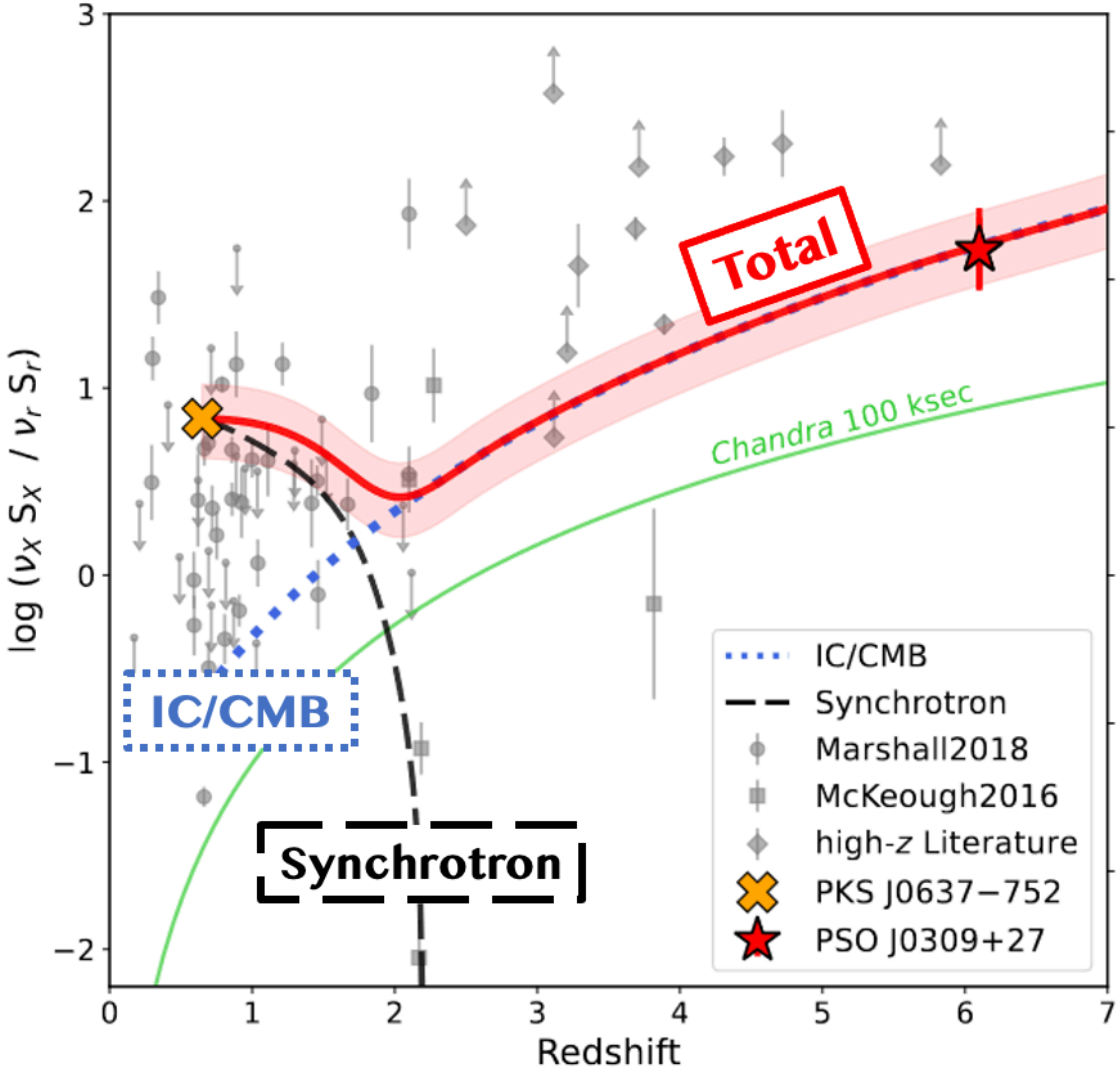
IC/CMB cooling timescale:

$$\tau \approx 2.3 \times 10^{12} \Gamma^{-2} \gamma^{-1} (1+z)^{-4} \quad \text{yr}$$

**~100 yr** ($\Gamma$=2, $\gamma$=$10^6$, z=6.1)



# X-ray emission vs redshift




What is the mechanism responsible for the high-energy emission of large-scale jets ?

Both IC/CMB and Synchrotron

Synchrotron dominant at low-z

$U_{CMB} \propto (1+z)^4$

Boosts IC/CMB & quenches Synchro.

IC/CMB dominant at high-z

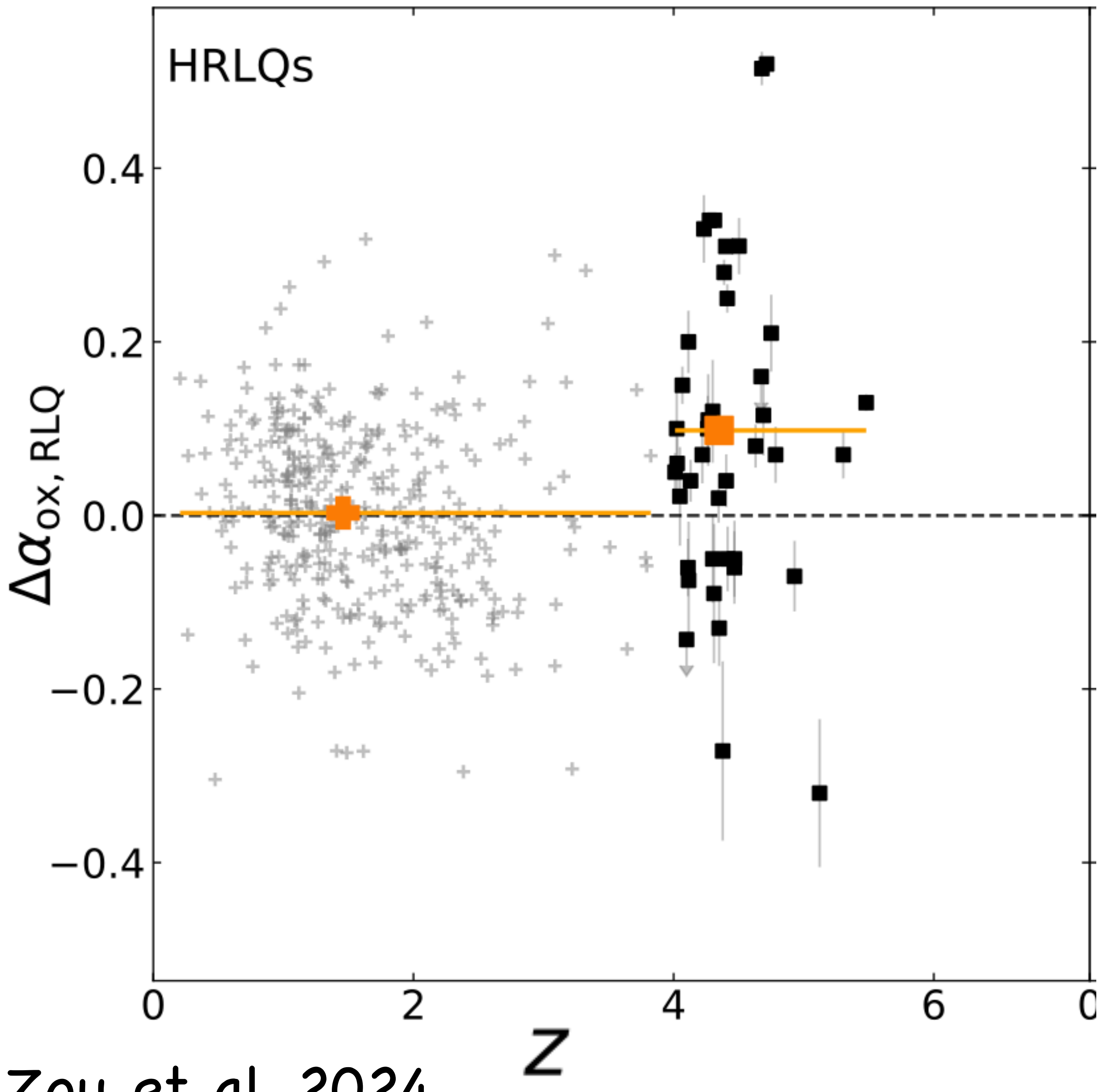
Extremely low statistics at z>2 !

120ksec with Chandra to observe 2<z<3.5 kpc-scale radio jets (PI Ighina)

# Impact on the observed X-ray space density

Overall X-ray emission (resolved and not) of jetted quasars increases as a function of redshift

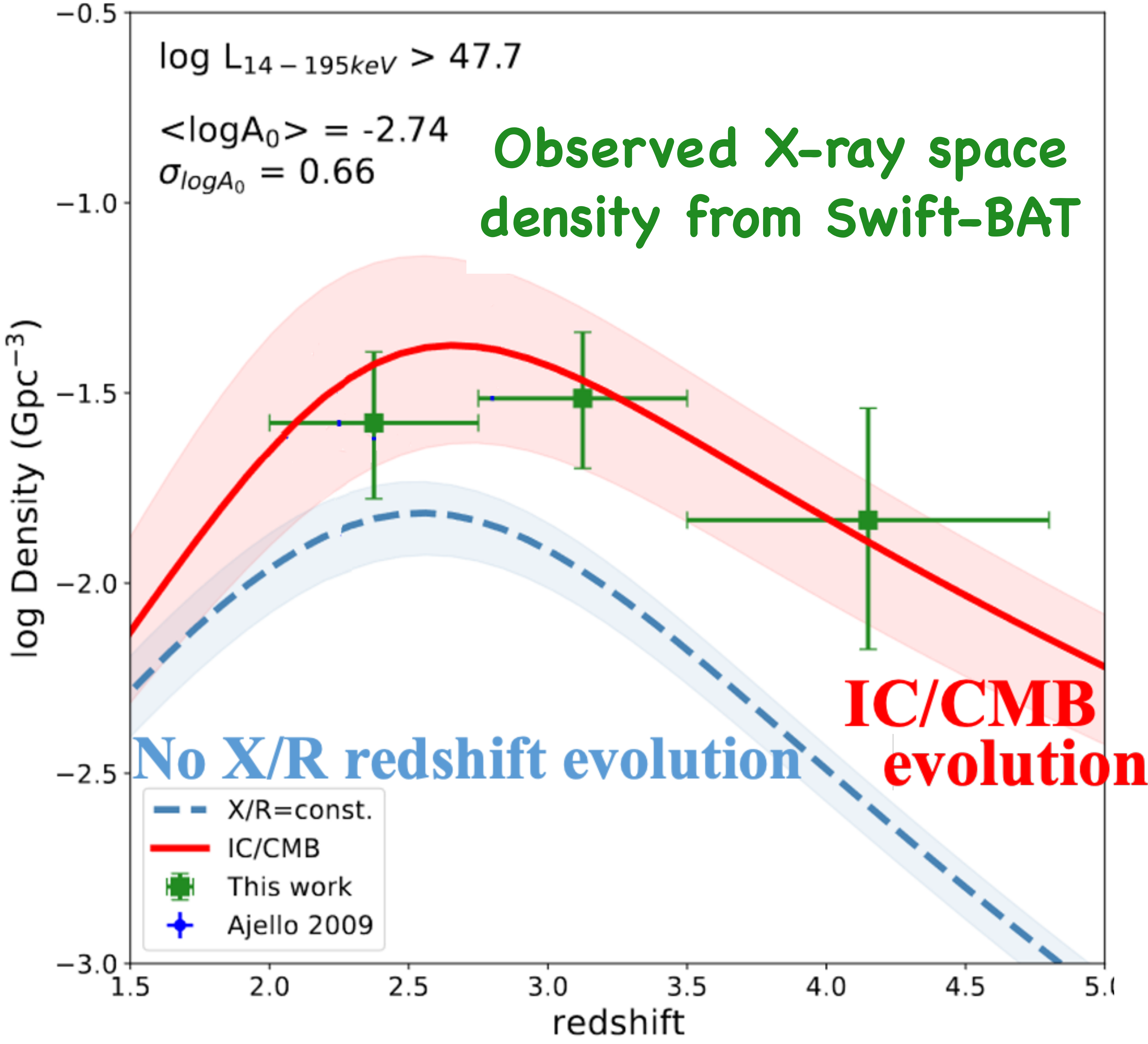
Ighina et al. 2019, 2021b,
Zhu et al. 2021




Zou et al. 2024

Affects the observed evolution of jetted quasars and their SMBHs

Ighina et al. 2021b



# ¡ Thank you for the attention !

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- Chandra —> only X-ray telescope to resolve and study relativistic jets at kpc-scale;
- Detection of an X-ray jet at z=6.1 —> The high-energy emission from relativistic jets is evolving as a function of redshift
- This evolution can impact the observed space density evolution of jetted systems with z
- Deeper radio+X-ray observations of PSO J0309+27 will allow us to constrain important physical parameters of jets (e.g. power) up to z~6!

**Direct observation of an extended X-ray jet at $z = 6.1$**

L. Ighina[1,2], A. Moretti[1], F. Tavecchio[3], A. Caccianiga[1], S. Belladitta[1,2], D. Dallacasa[4,5], R. Della Ceca[1], T. Sbarrato[3], and C. Spingola[5]

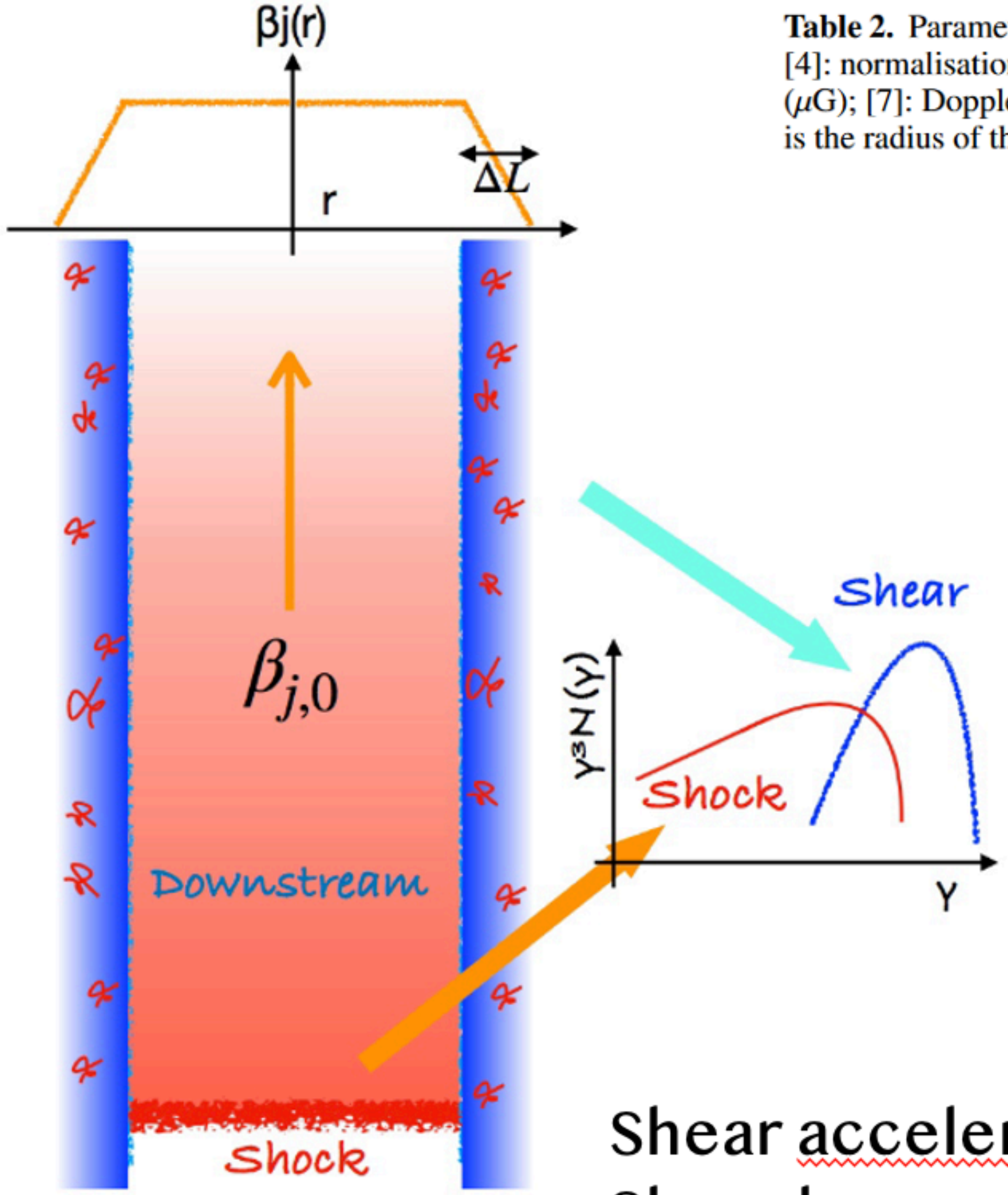
**The impact of the CMB on the evolution of high-$z$ blazars**

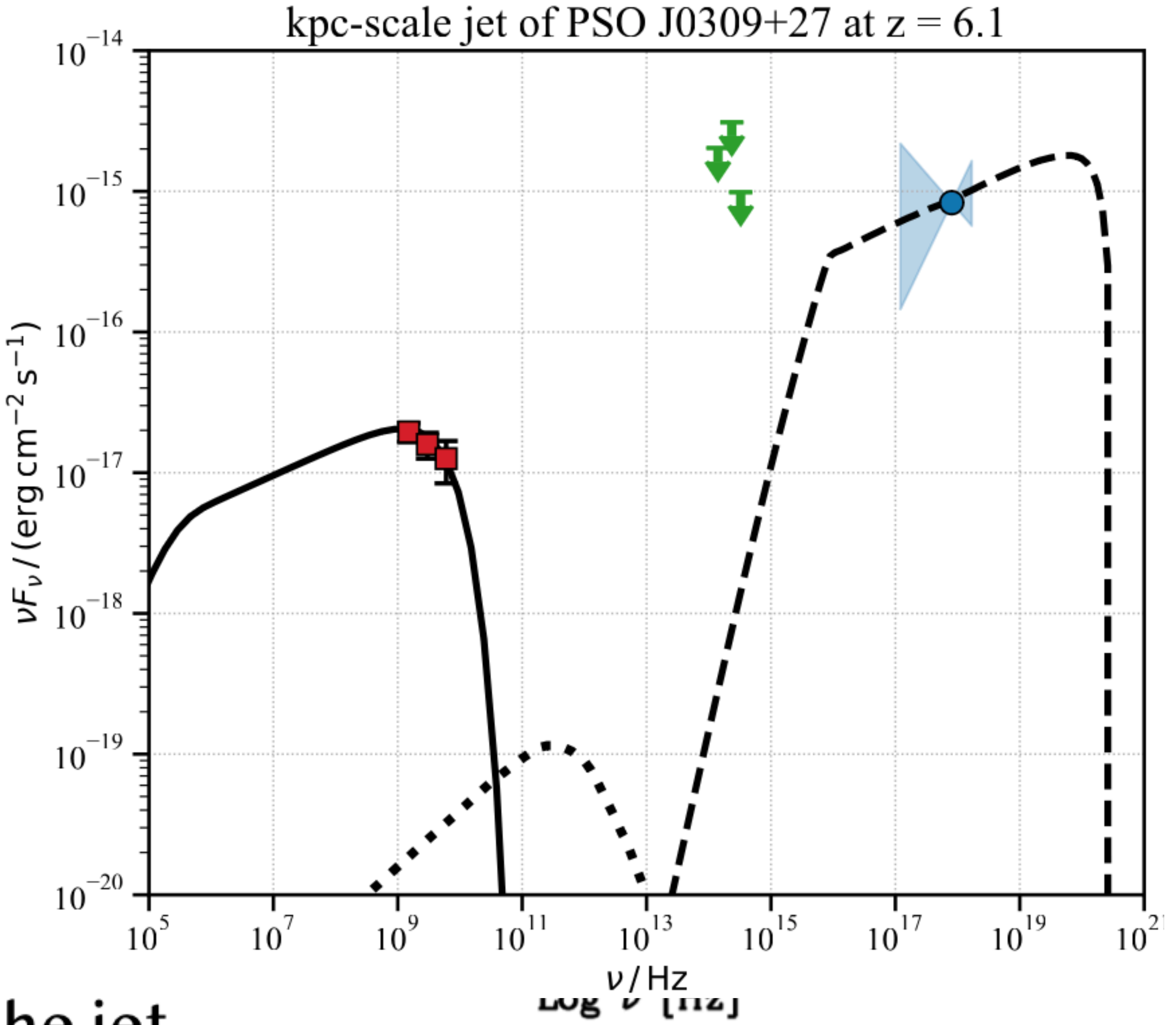
L. Ighina,[1,2★] A. Caccianiga,[1] A. Moretti,[1] S. Belladitta,[1,2] R. Della Ceca[1] and A. Diana[3]

# Tavecchio et al. 2021

| $\Gamma_b$ | $\theta$ | $\gamma_{\rm cut}$ ($\times 10^5$) | $K$ | $n_{\rm sh}$ | $B$ | $\delta$ | $R$ | $\tau_{\rm inj}$ | $t$ | $P_{\rm jet}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10] | [11] |
| 1.7 | 20 | 4 | 0.45 | 2.5 | 13 | 2.5 | $2\times10^{21}$ | $5\times10^{2}$ | 10 | 2.2 |

**Table 2.** Parameters of the model. [1]: Jet bulk Lorentz factor; [2]: viewing angle (deg); [3]: cutoff electron Lorentz factor of the shock component; [4]: normalisation of the shock electron energy distribution (particle cm$^{-3}$); [5]: slope of the shock electron energy distribution; [6]: magnetic field ($\mu$G); [7]: Doppler factor; [8]: jet radius (cm); [9]: injection timescales for the shear acceleration in units of the light-crossing time, $r_j/c$ (where $r_j$ is the radius of the jet); [10]: time in units of the light-crossing time, $r_j/c$. [11]: jet power ($10^{46}$ erg s$^{-1}$).




Shear acceleration:
Shear layer around the spline of the jet,
with strong radial gradient of velocities

PKS 0605-08→ offset
Reddy et al. 2021

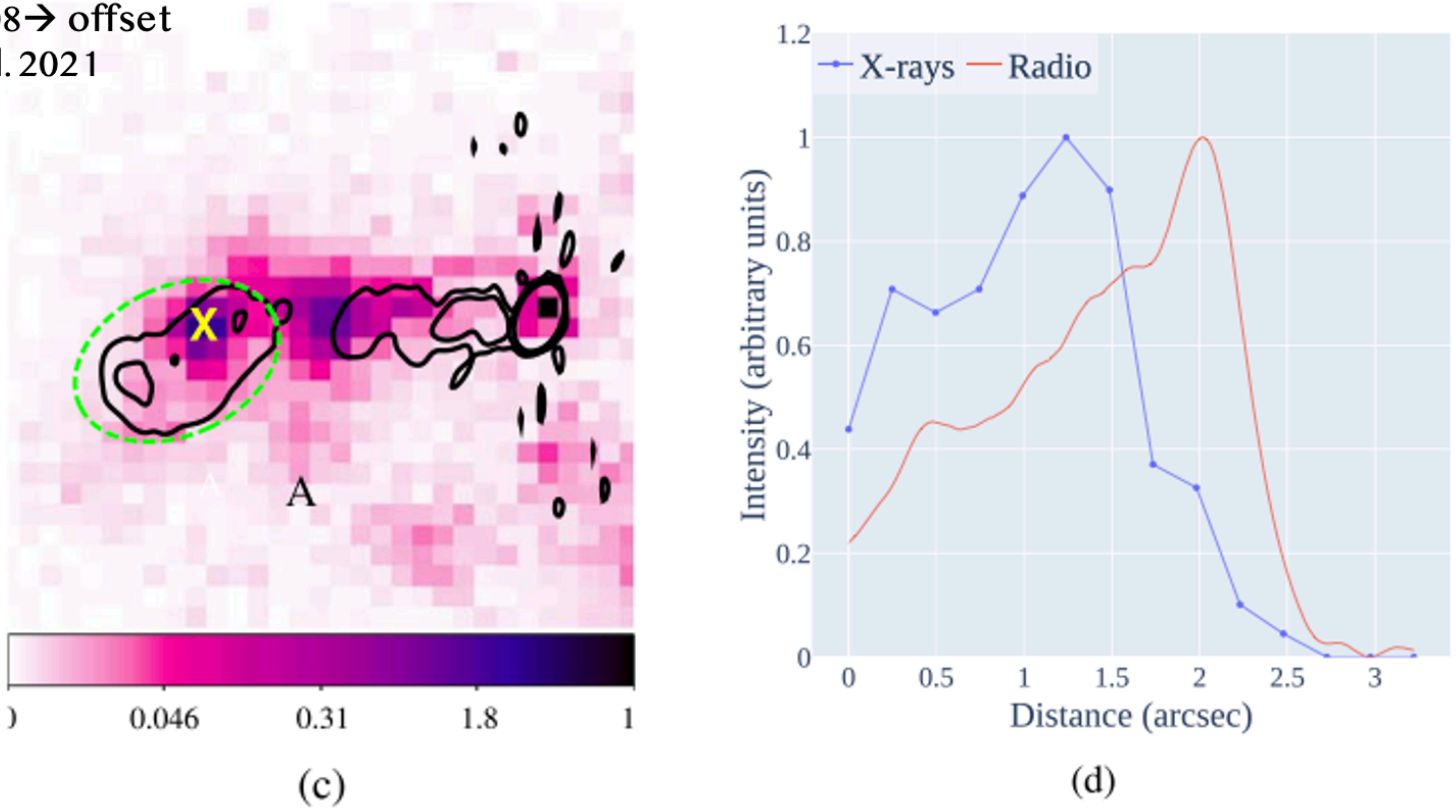
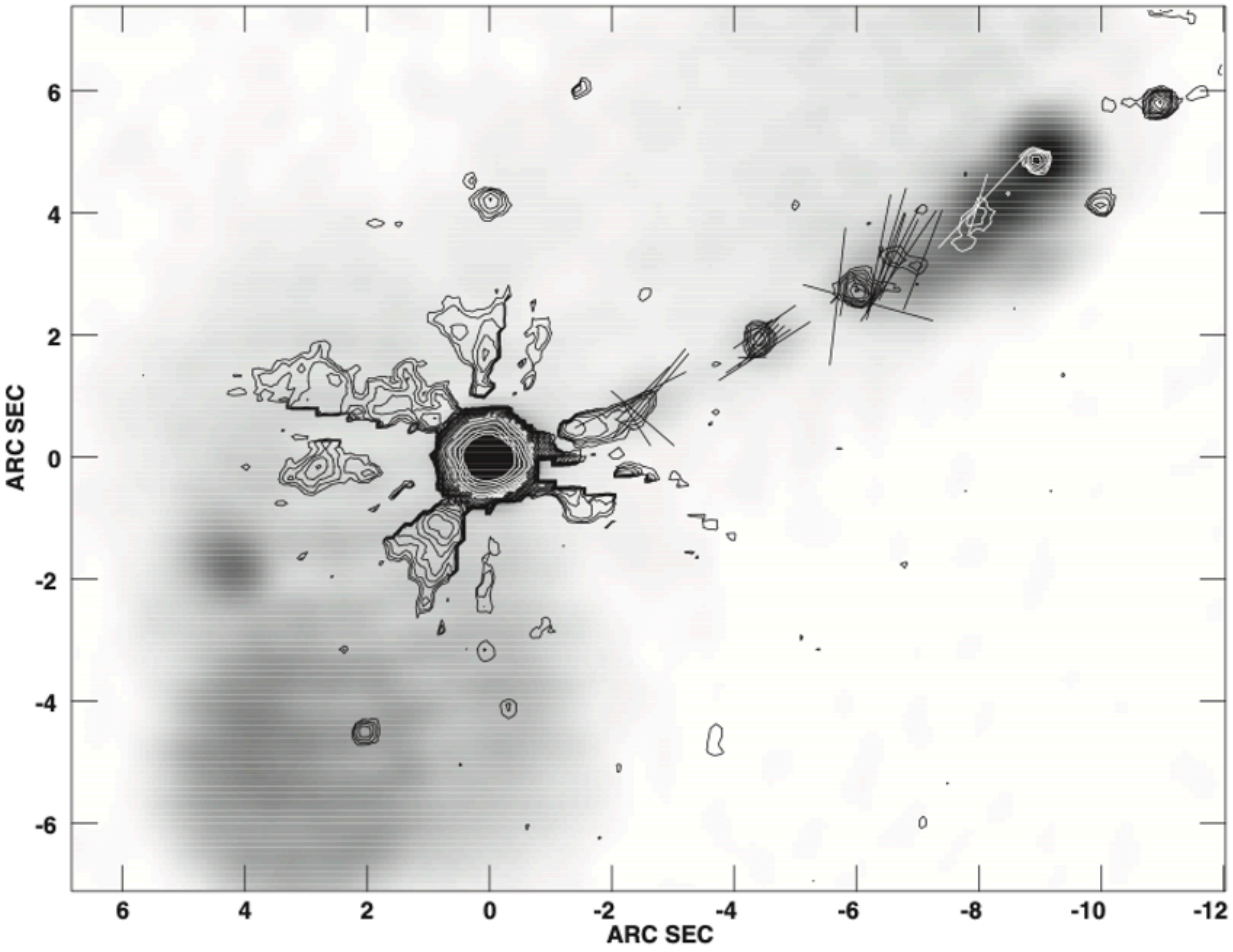



**Figure 1.** Using LIRA to infer an offset in a low-count Chandra image of PKS 0605–08. With the VLA 5 GHz radio contours overlaid, (a) a merged 62.8 ks observation binned by a factor of 1/20 and (b) a 2 ks observation binned by a factor of 1/2. The solid circle indicates the region used to extract the spectrum of the core and the green dot indicates the centroid of the dashed-green ellipse. (c) The average added component of the 2 ks observation. The yellow X marks the centroid of the dashed-green ellipse, which differs from the radio peak by $\sim 0\farcs9$. (d) The longitudinal intensity profile of knot B computed using the deep observation (dashed-green rectangle in (a)). The X-rays peak upstream of the radio (Sambruna et al. 2004), thereby confirming the offset as inferred using LIRA. (e) The posterior




PKS 1136-135 → polarisation

Cara et al. 2013

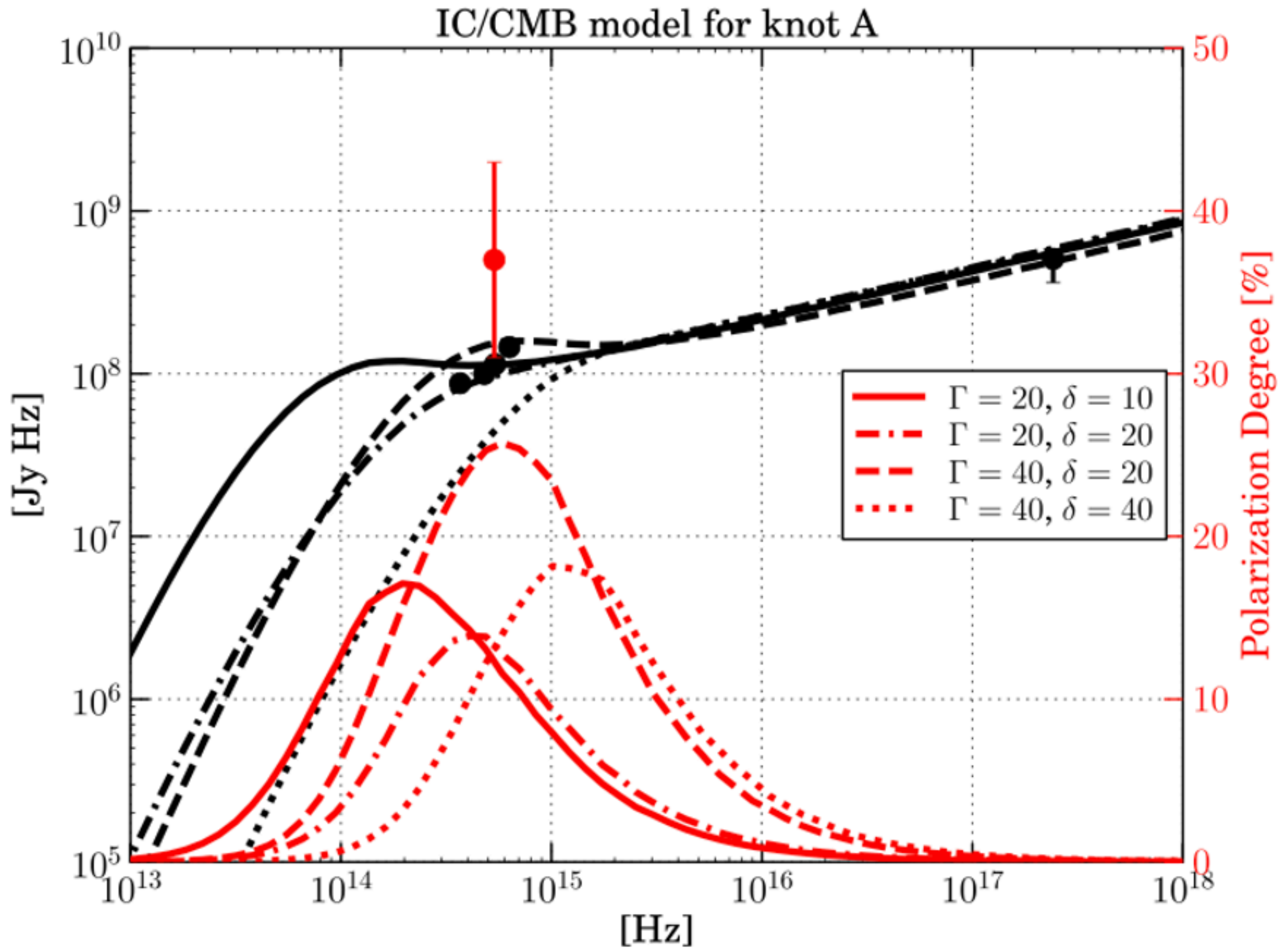
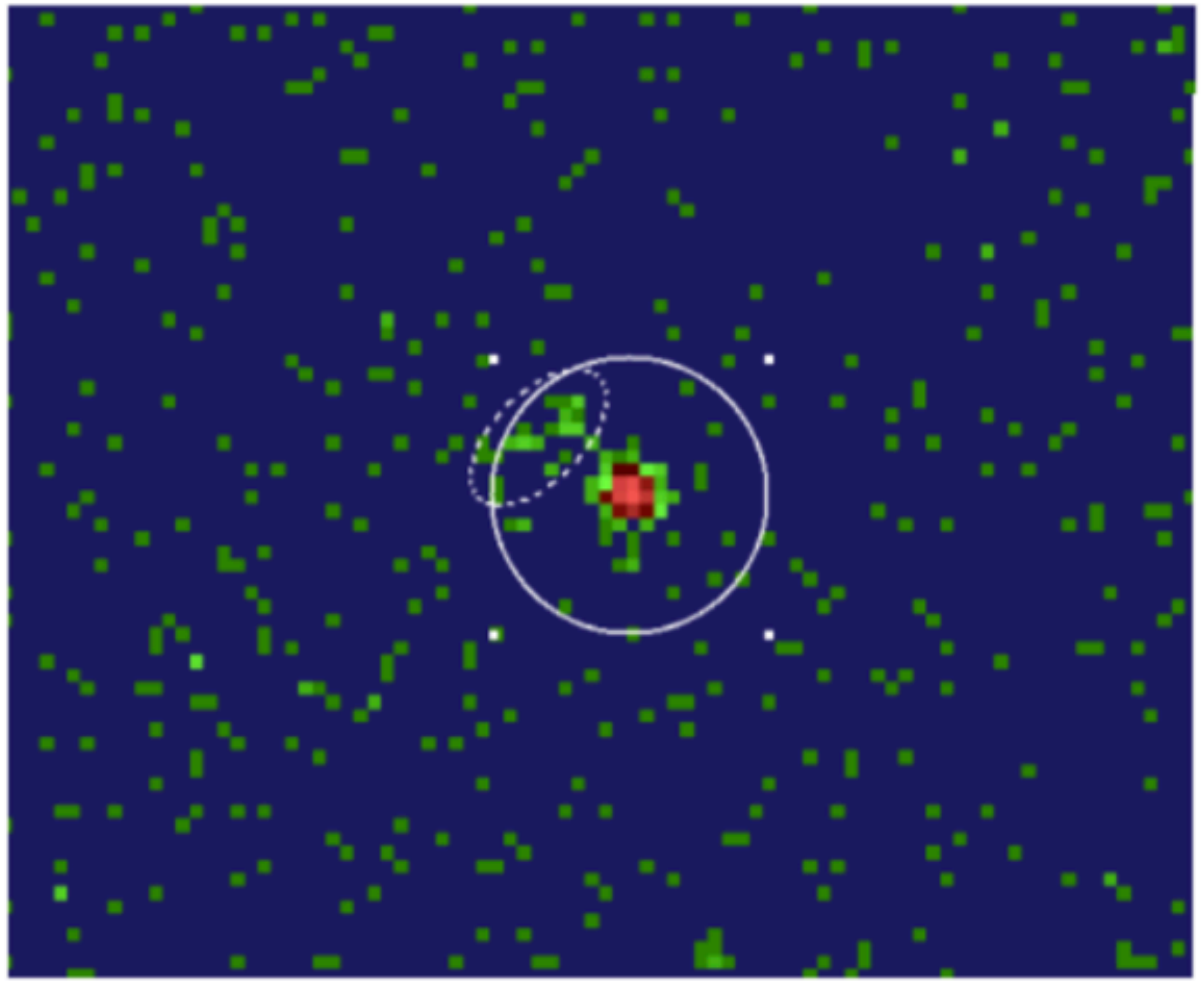
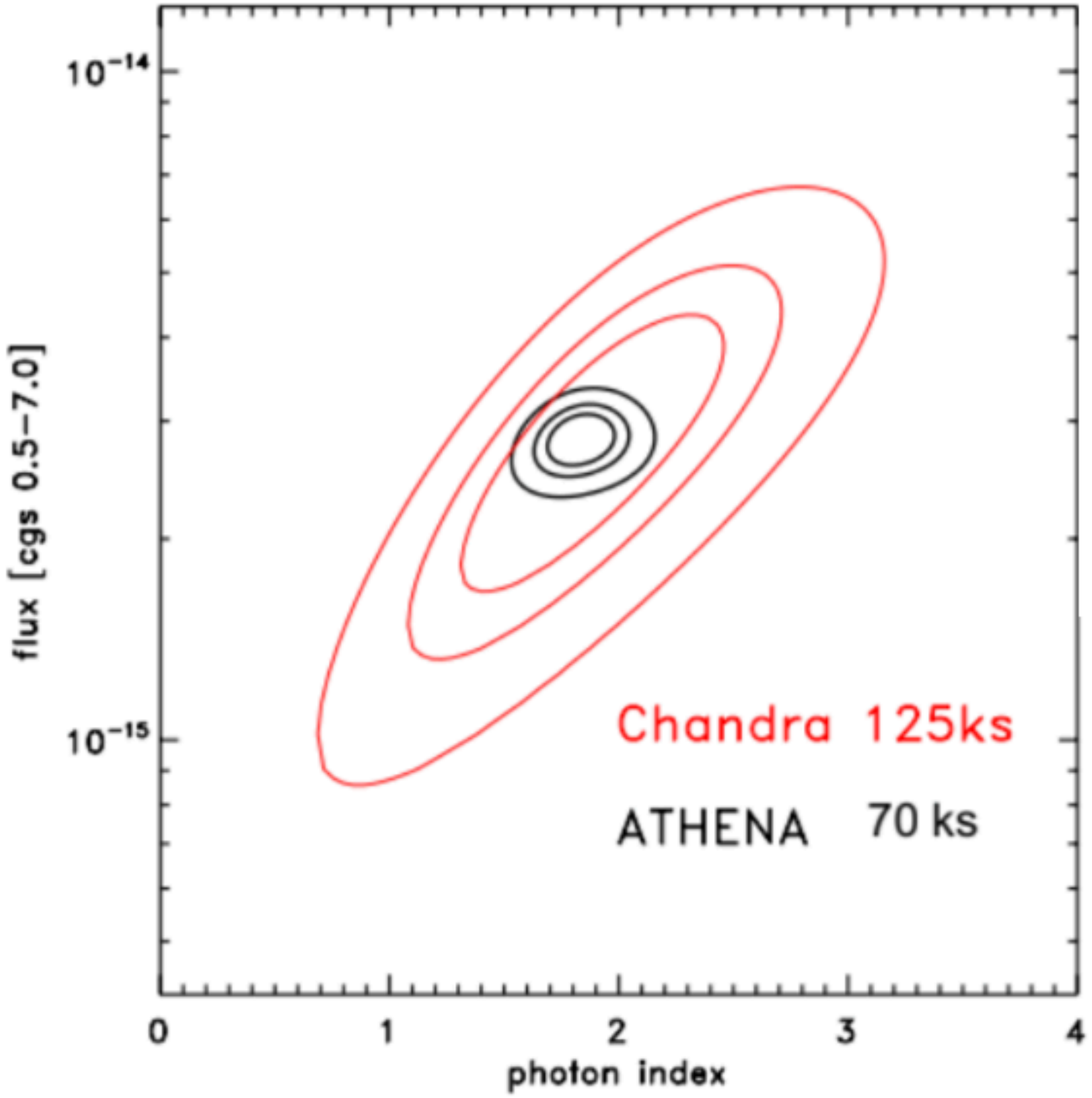


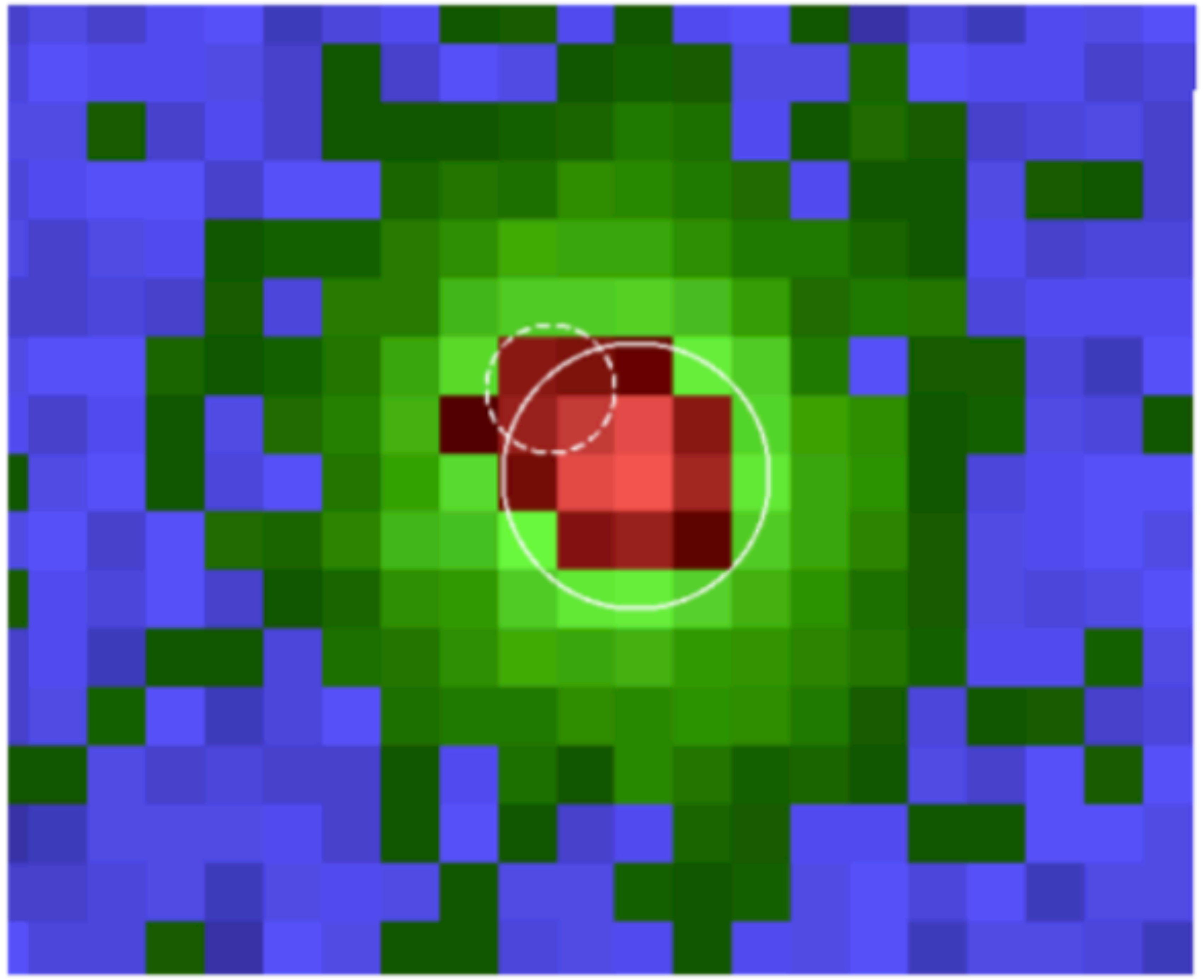

**Figure 5.** Intensity (black curves) and polarization degree (red curves) of the IC/CMB emission from a relativistic jet as a function of observing frequency. Data points present the *HST* results for knot A obtained in this paper. We show plots for jet bulk Lorentz factor $\Gamma = 20$ and 40, with beaming factor $\delta = \Gamma$ and $\delta = \Gamma/2$. See Section 4.1 for discussion.



Chandra 125 ksec

CHANDRA
X-RAY OBSERVATORY



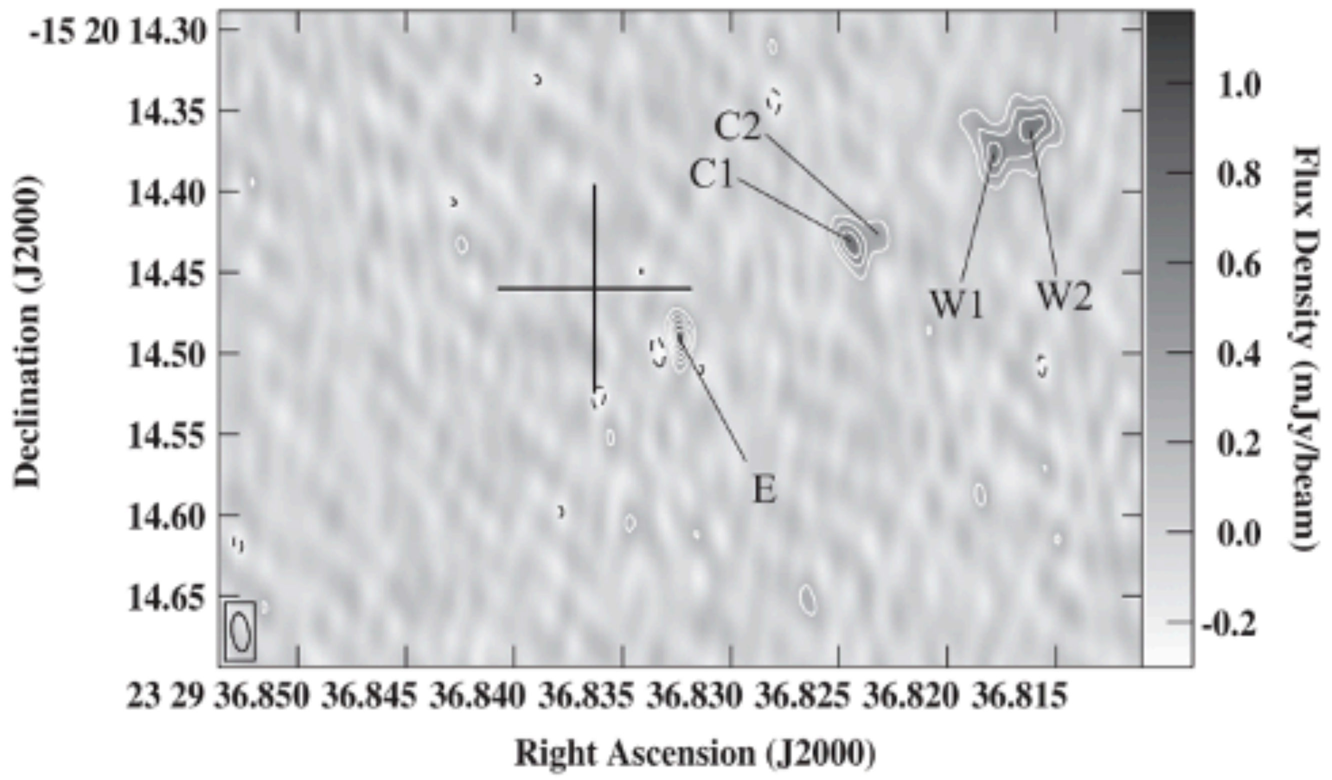



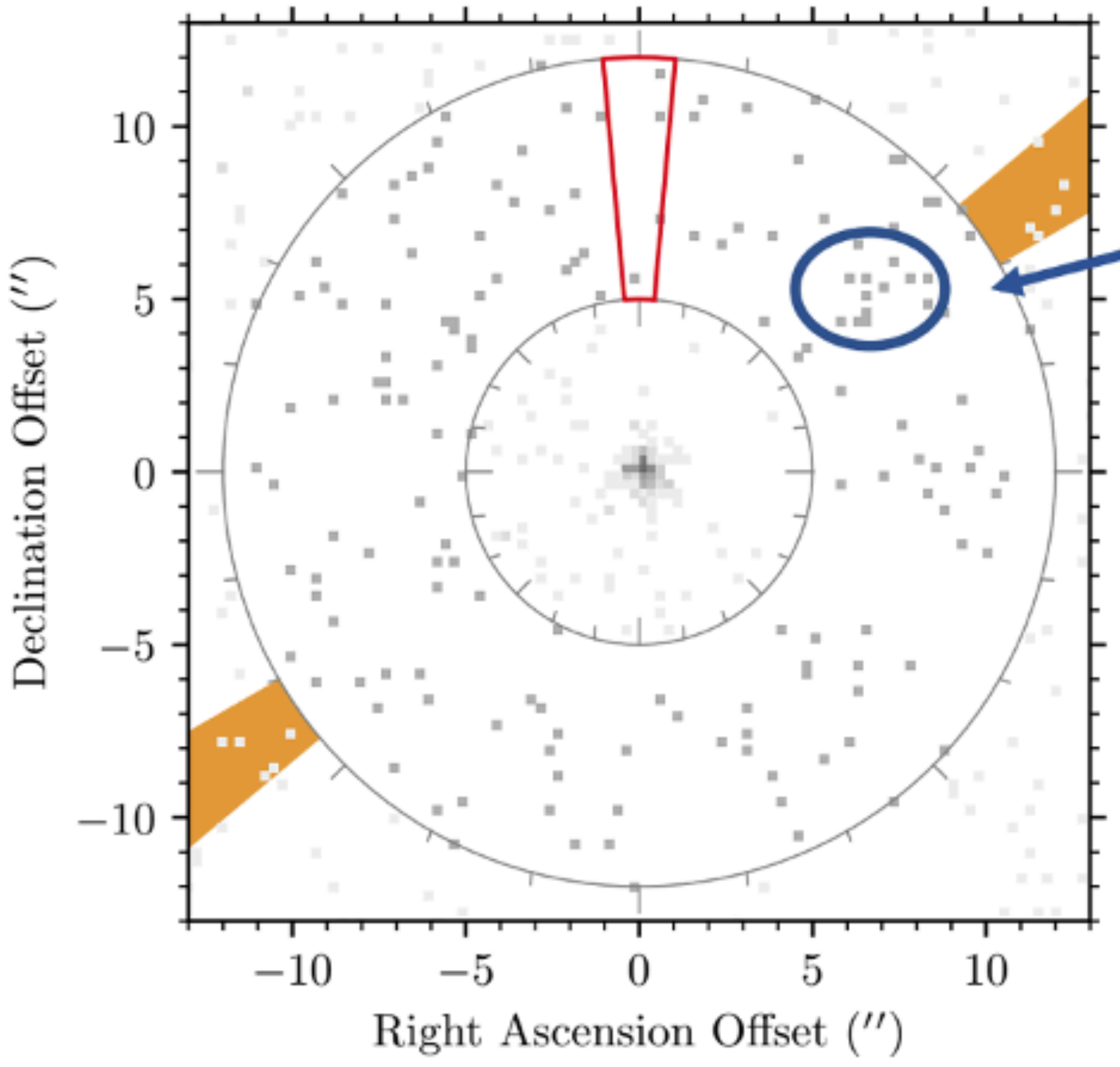
Athena-WFI 70 ksec

ATHENA

# PSO J352.4034–15.3373 at z=5.8

inner jet (VLBA)



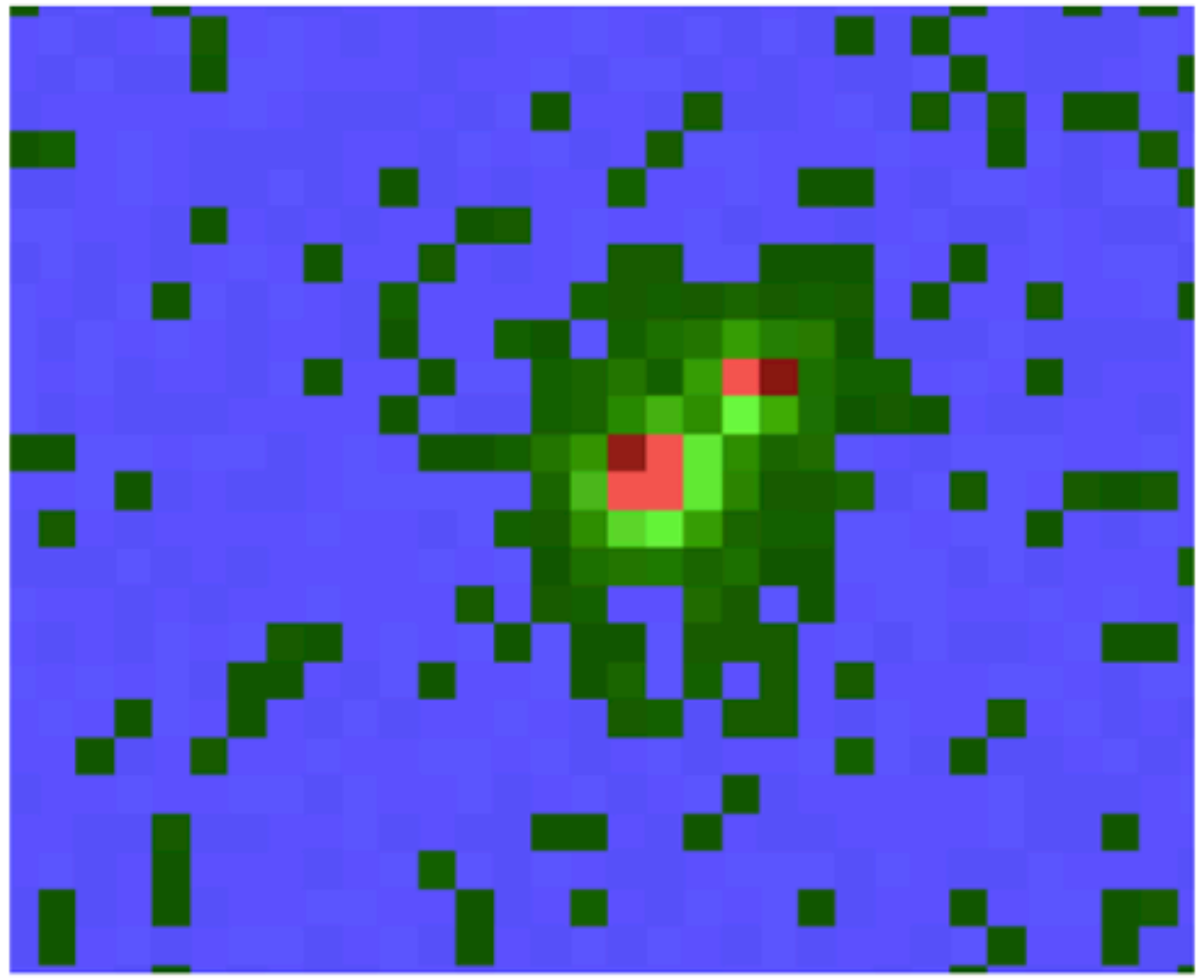



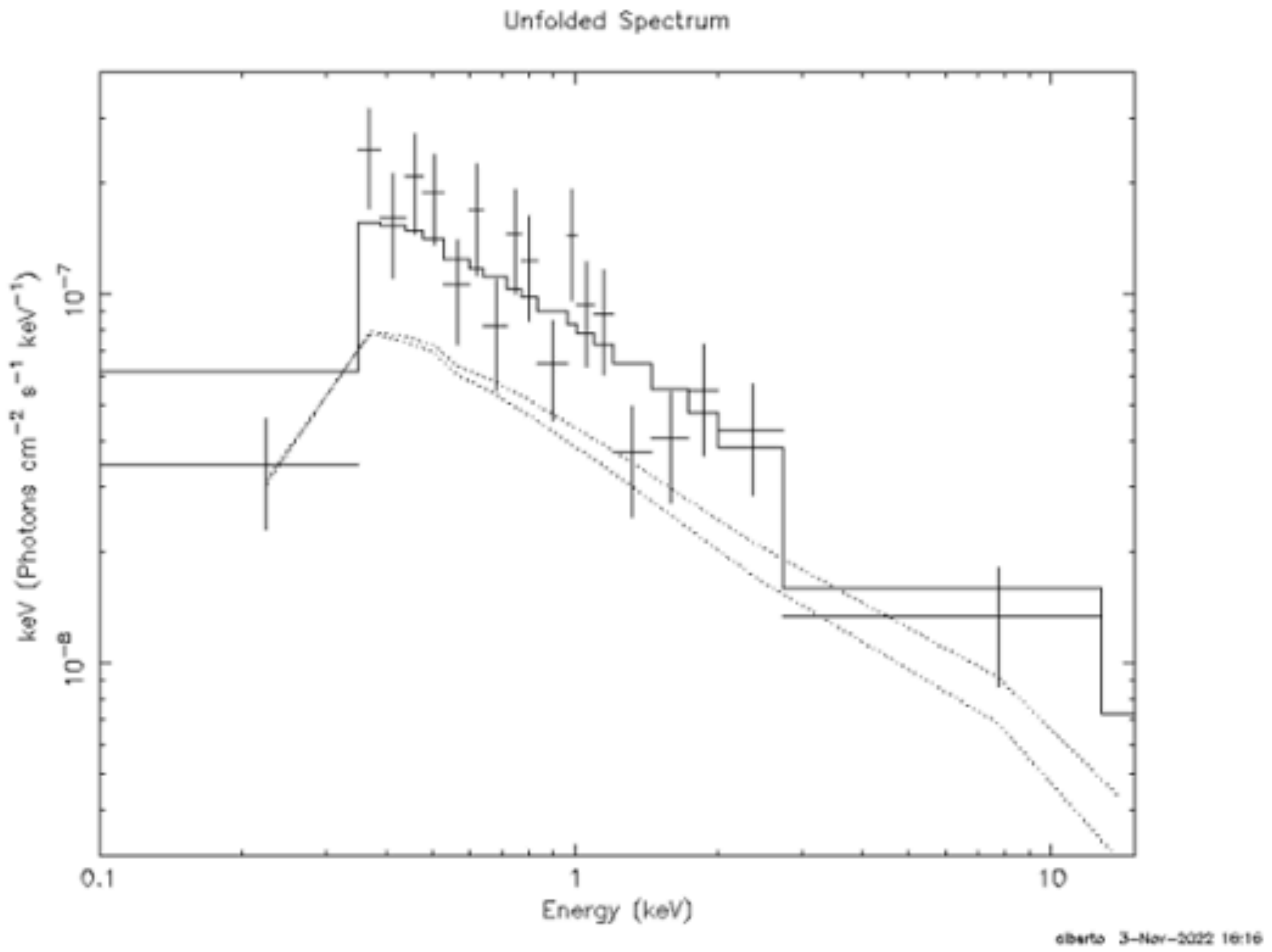

jet ~ 5% of the core flux
distance HS / core 8”
~ 8photons collected in 265 ks
chandra c.rate ~ 3e-5 (1 ph/10 hours … )

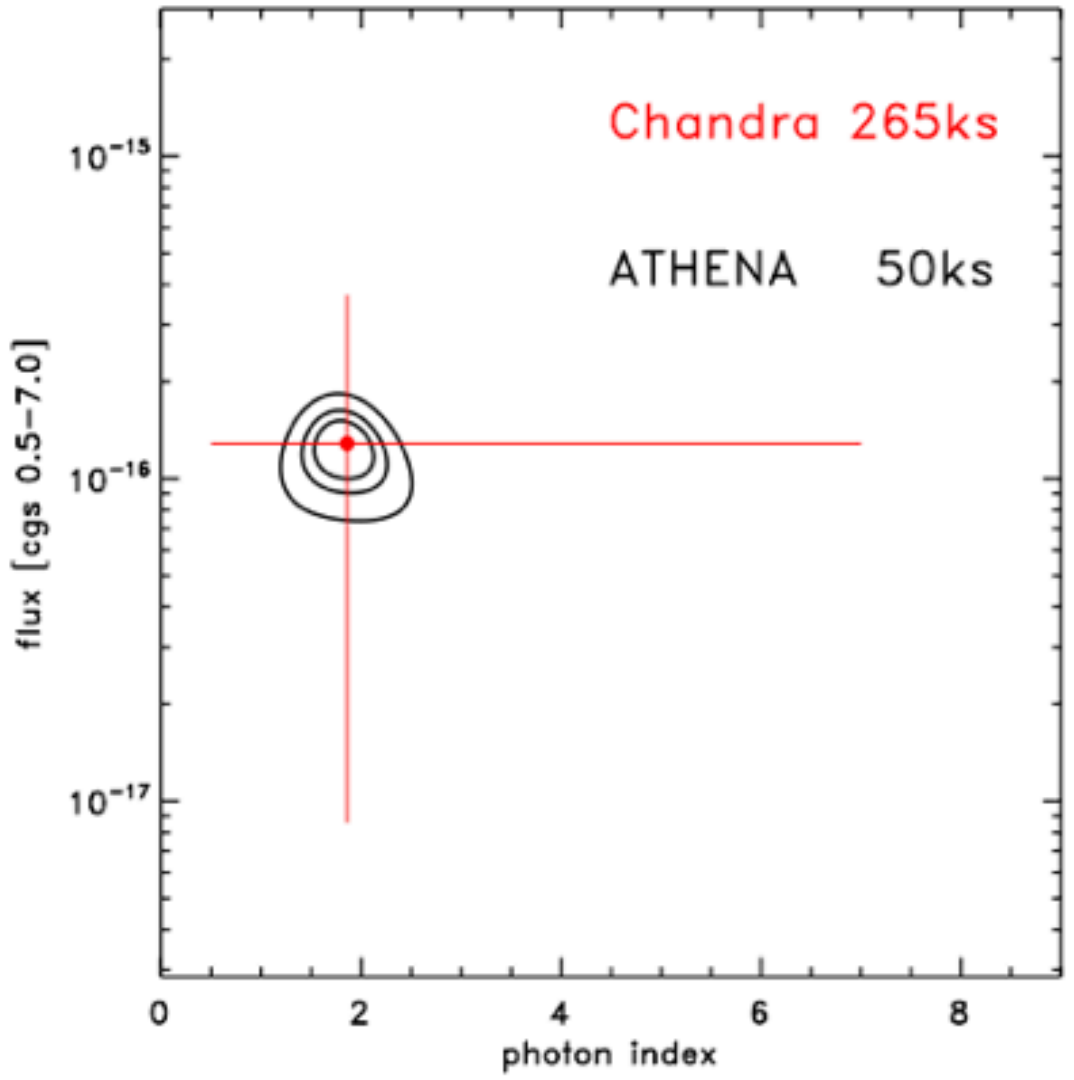
Chandra observation does not help …

ATHENA WFI c.rate ~ 3e-3

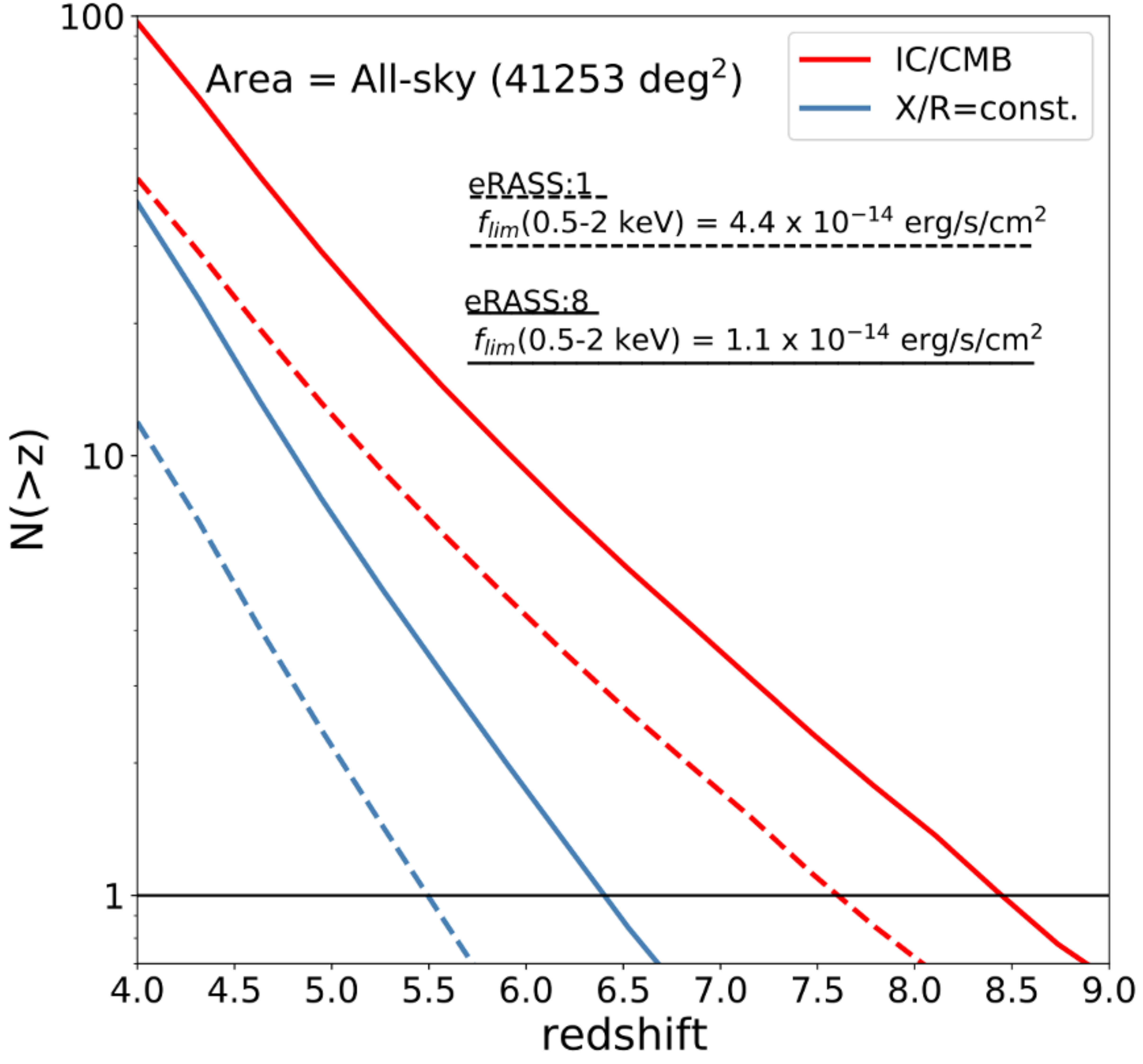
PSF core contamination :
~ 3% of the total PSF, 50% of the jet emission



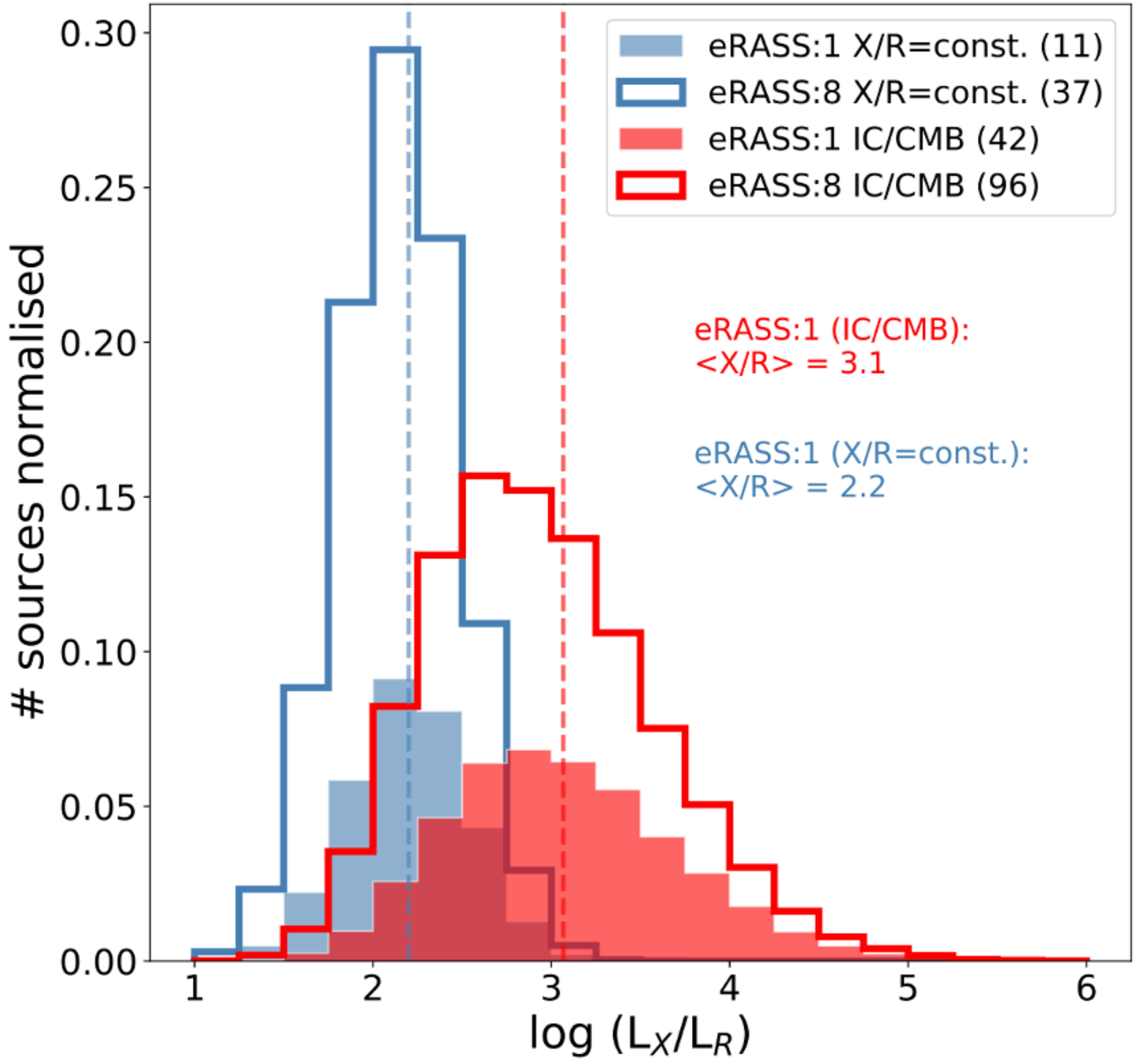



Courtesy of Alberto Moretti




From Ighina et al. 2022, MNRAS



# IC/CMB model

A fraction ($A_0$) of the X-ray emission is produced trough the interaction via Inverse Compton (IC) between the Cosmic Microwave Background (CMB) photons and the electrons within the most extended parts (kilo-parsec scales) of the jet

Since $U_{CMB} \propto (1+z)^4$ $\longrightarrow$ X-ray emission associated increases with redshift too

$$\boxed{\frac{L_X}{L_R}(z) = \frac{L_X}{L_R}(z=0)\left[(1-A_0) + A_0(1+z)^4\right]}$$

e.g. Wu et al. 2013

$A_0$ = relative importance of the IC/CMB at z=0