Relativistic Jets in the Next Decade of Chandra Science

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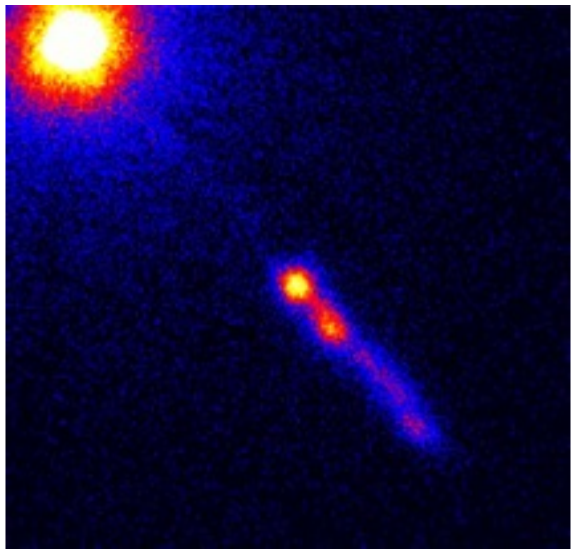
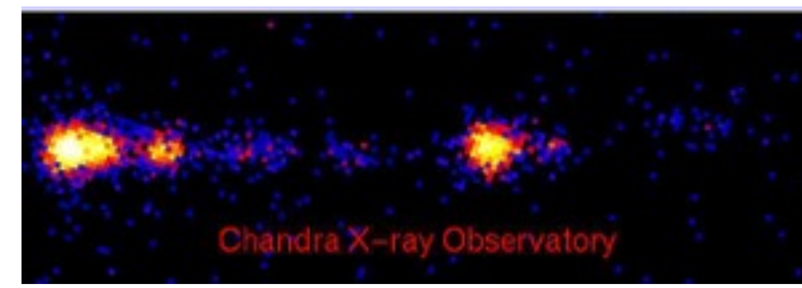
X-ray Jets Resolved by Chandra!

3C 273

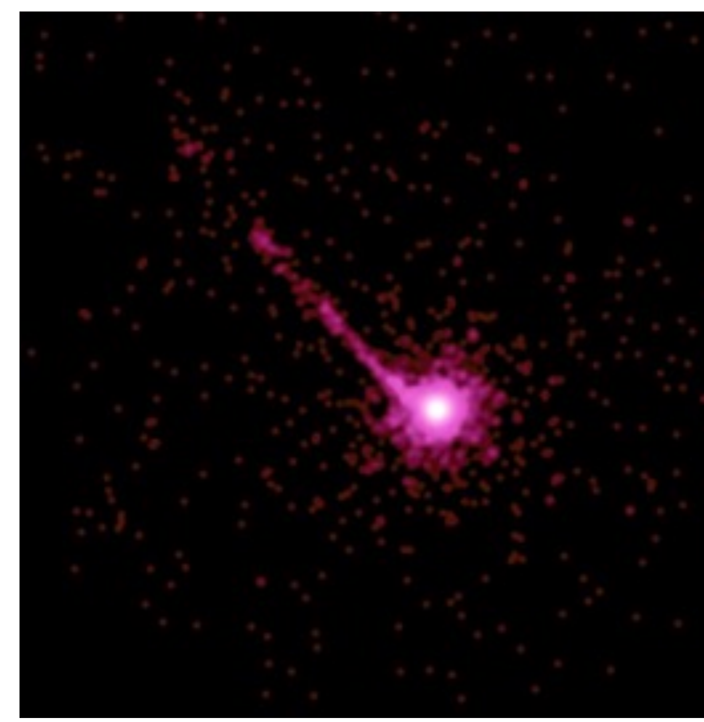


PSF - sub-arcsec resolution
Sharp - Dynamic range to detect faint emission close to the core

M87

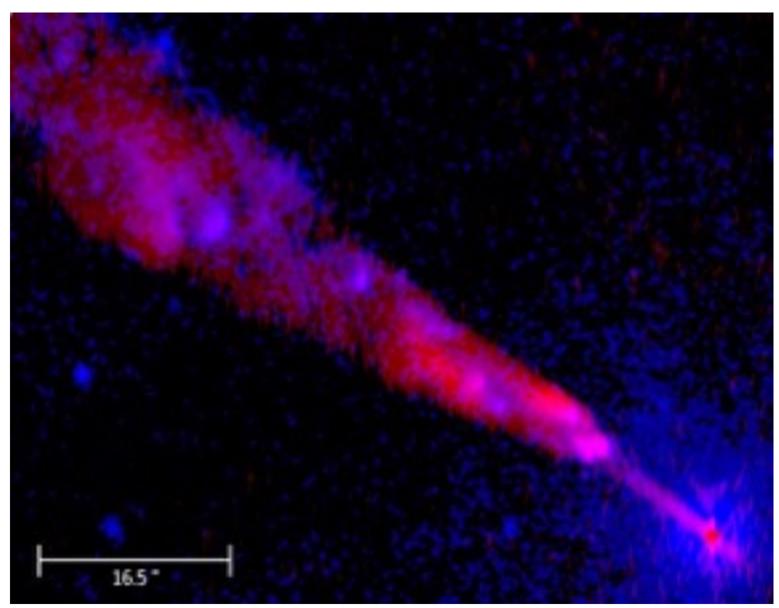


PKS 1127-145



4C+29.30

Cen A



Jets X-ray emission is ubiquitous!

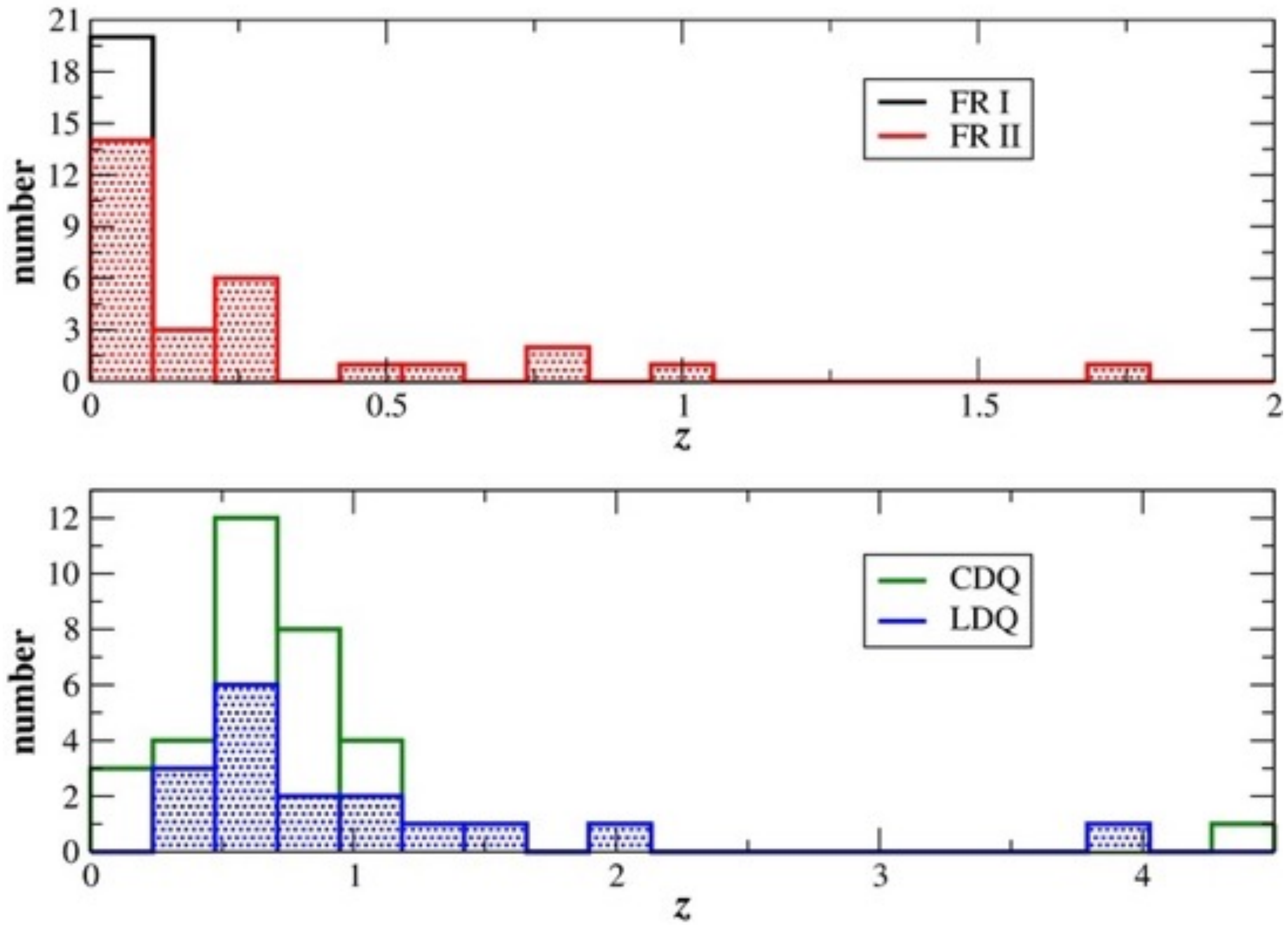
Why Jets?

- **'Link'** between BH and large scale (Mpc) environment.
- **Nature** of radio emission? Why only a small fraction of all quasars have relativistic jets?
- Jet **formation process**? Particle **acceleration** at large distances from BH?
- **Impact on environment:** Young Radio Sources, Clusters, Role in the Feedback especially in the early Universe?
- **Evolution of radio properties** with redshift?

XJET Project

X-ray Emission from Extragalactic Radio Jets
http://hea-www.cfa.harvard.edu/XJET/

Redshift distribution



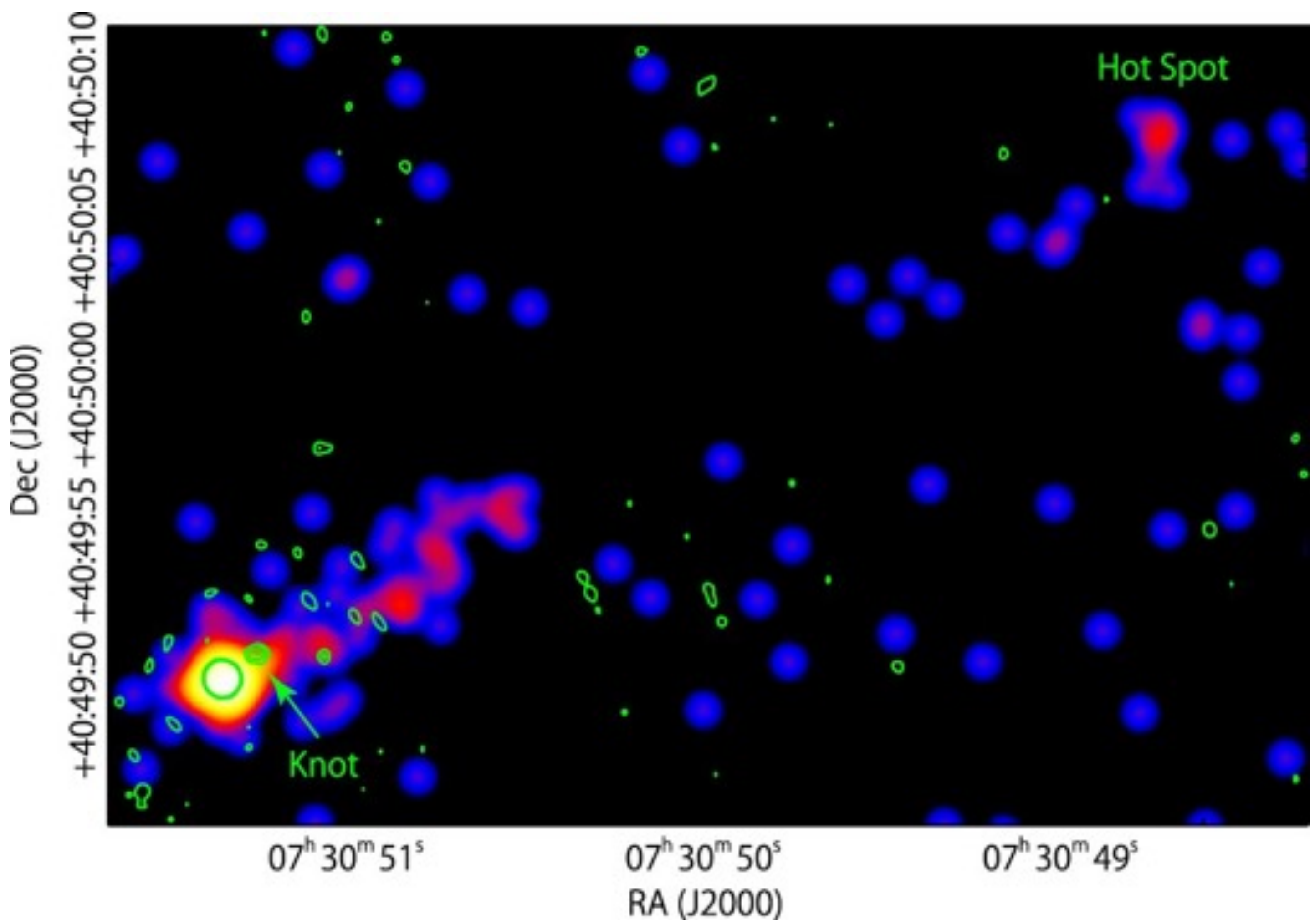
Massaro et al. (2011)

Dan Harris

>100 jets

B3 0727+409 z=2.5

Chandra ACIS-S Image
contours VLA 4.86 GHz



Simionescu et al. 2016

- ~100 kpc X-ray jet with no radio counterpart
- The strongest case for X-ray IC/CMB emission

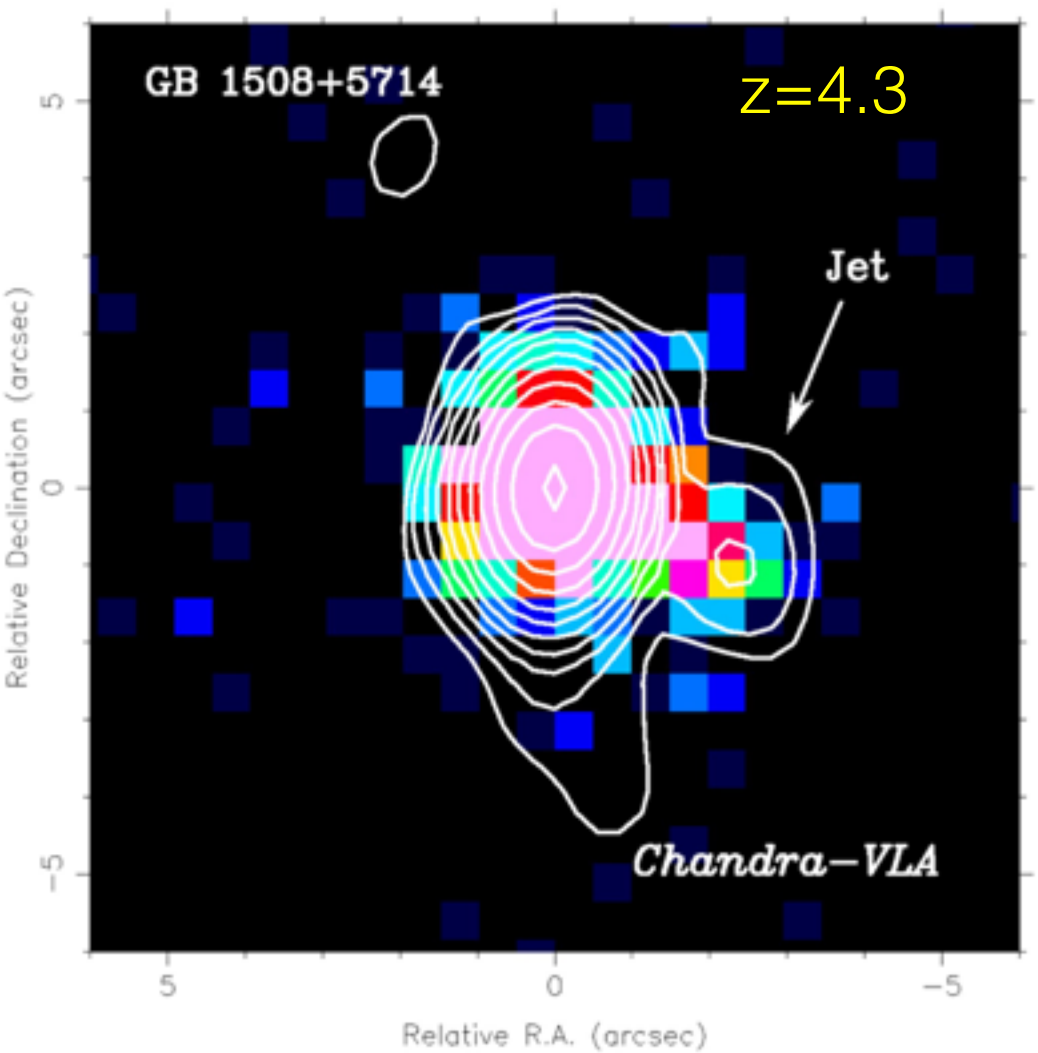
$U_{CMB} \sim (1+z)^4$

jet bulk Lorentz factor ~10

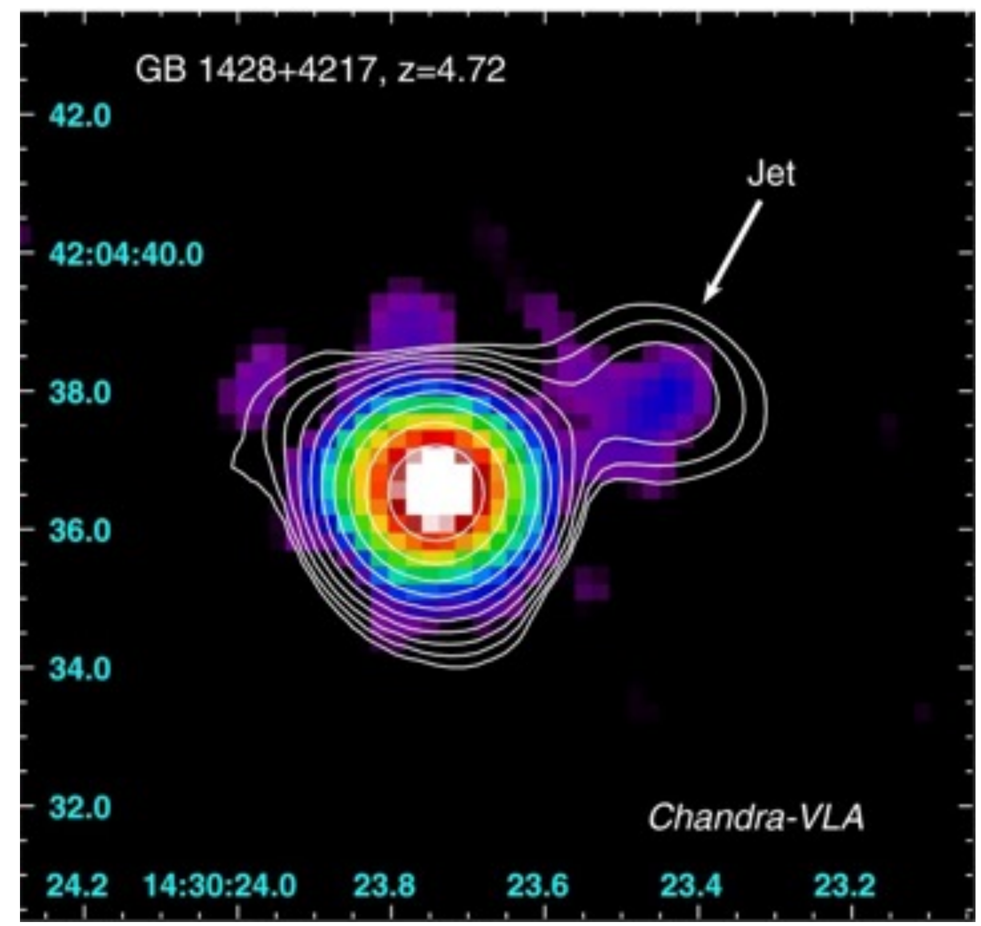
$L_{jet} \sim (0.3\text{-}3) \times 10^{47}$ erg/s

The Highest Redshift X-ray Jets

z > 4

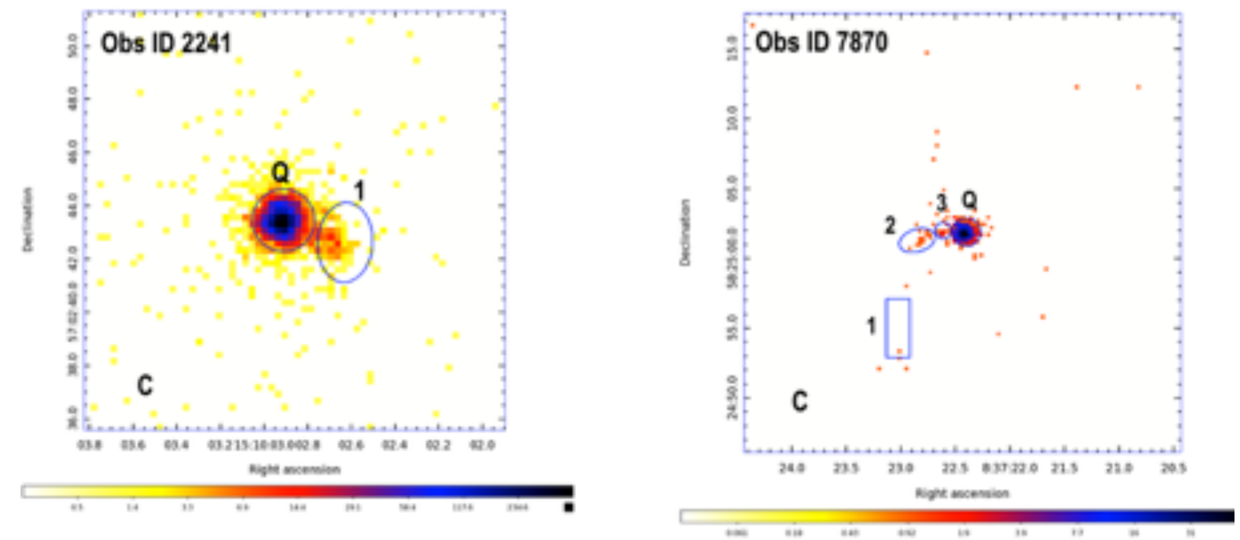


Siemiginowska et al. 2003
Cheung 2004

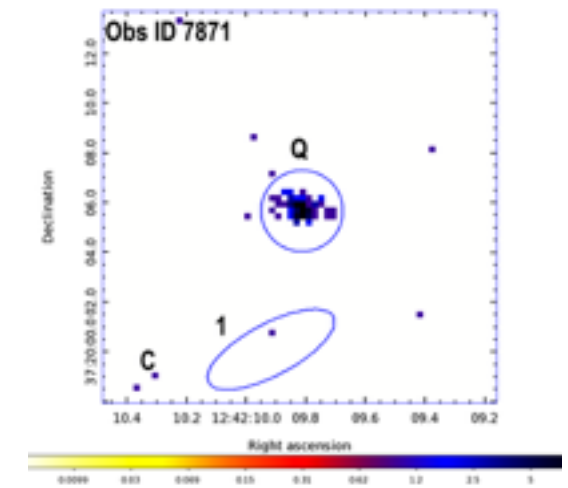


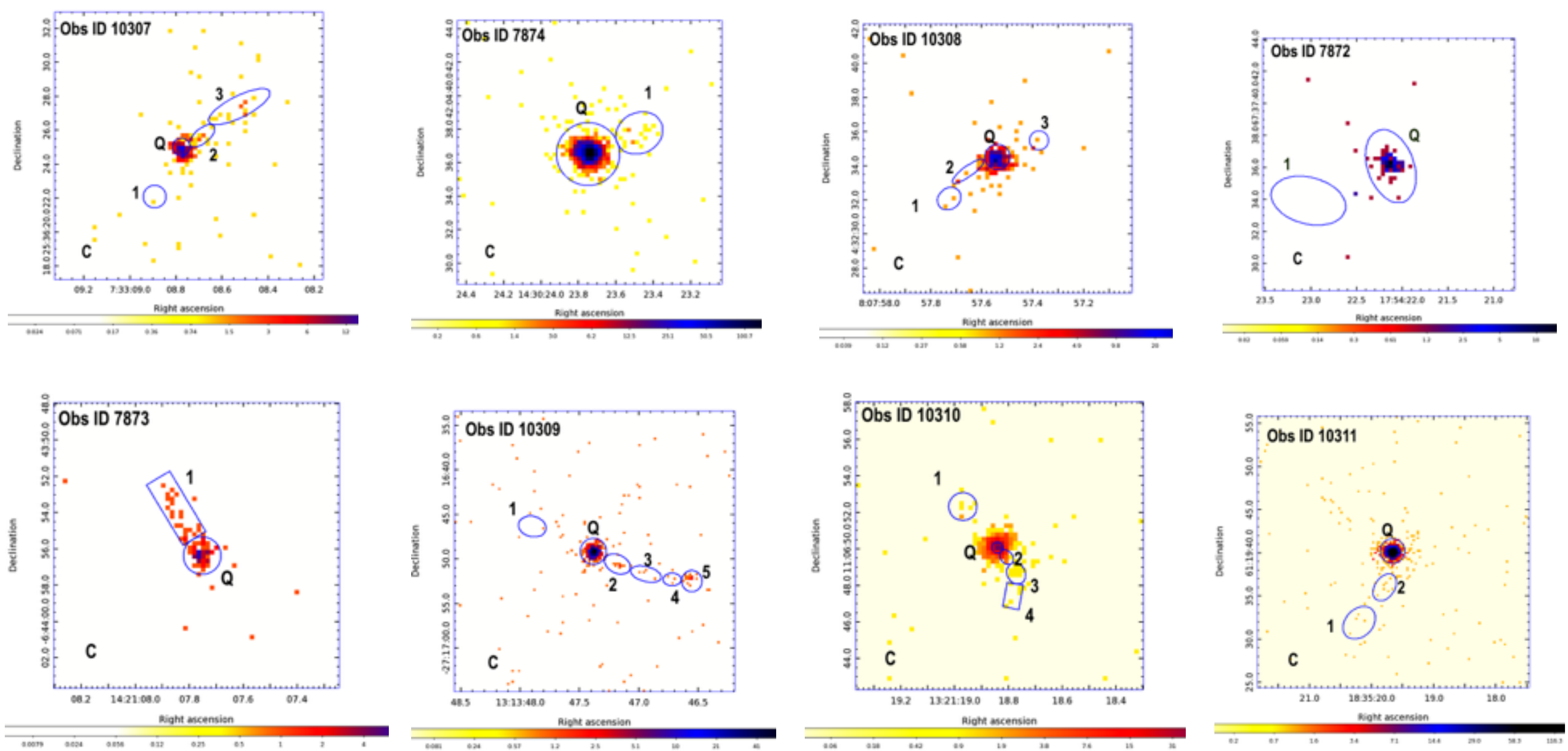
Cheung et al. 2012

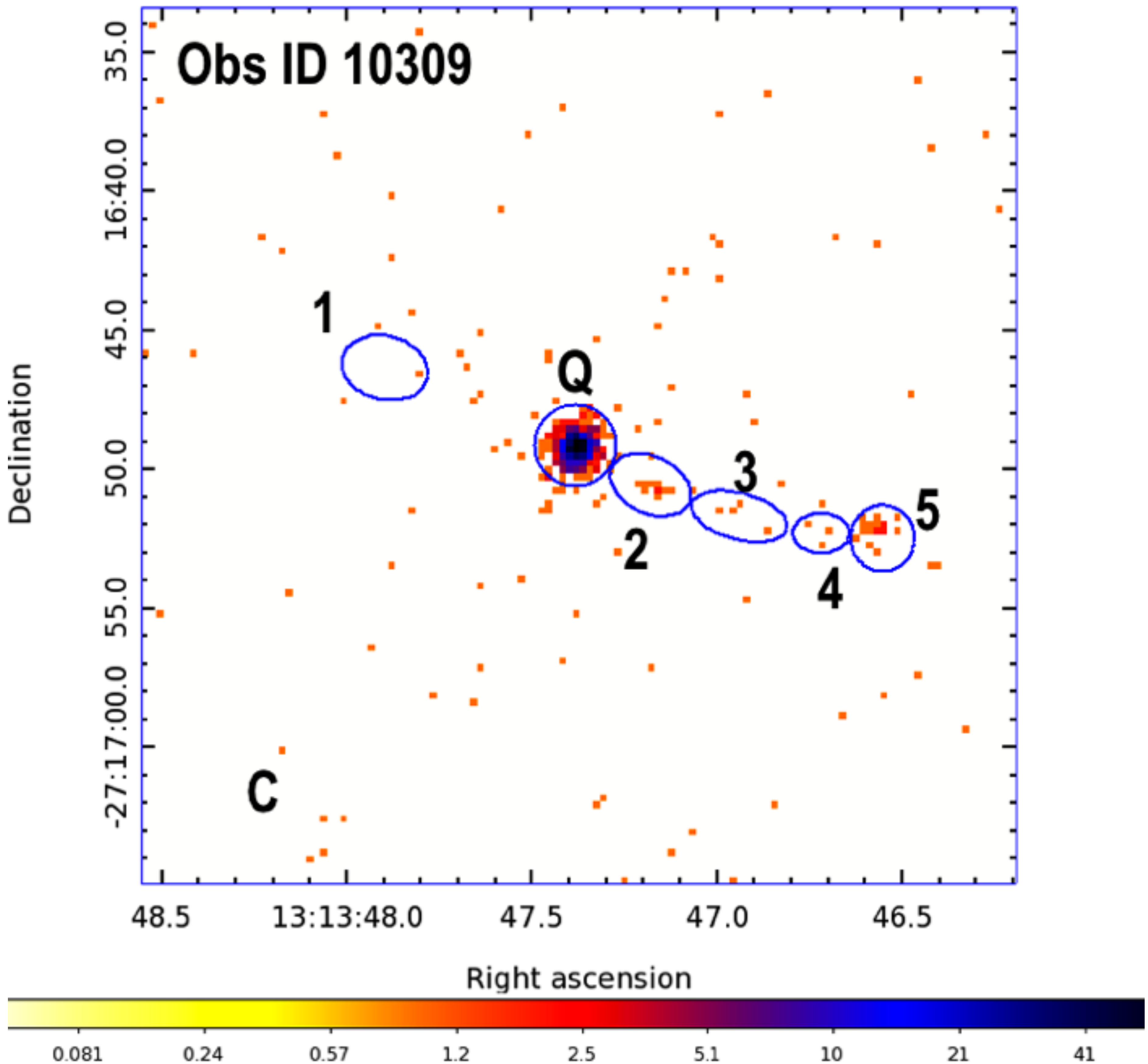
Projected size: ~15 kpc and 24 kpc
Deprojected size: ~150-200 kpc



Chandra Jets
High-z Sample
z > 2







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47.5
47.0
46.5
Right ascension
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0.57
1.2
2.5
5.1
10
21
41

LIRA
Low-counts Reconstruction and Analysis

Algorithms in Connors and Van Dyk (2007), Stein et al. (2015)

Next generation of EMC2 deconvolution
(Esch, Connors, Karovska and Van Dyk (2004))

Code and tutorials available:
https://github.com/astrostat/LIRA

CHASC Astrostatistics: David Van Dyk, Vinay Kashyap, Nathan Stein
PhD Students in statistics: Katy McKeough (HU), Vasileios Stampoulis (Imperial)

LIRA

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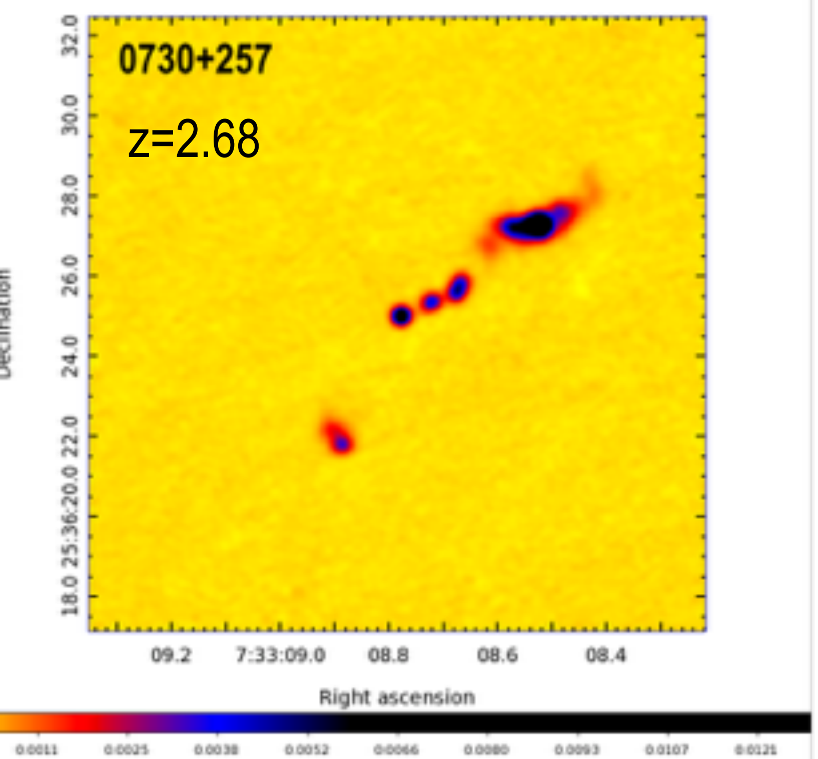
- ACIS image is modeled as Poisson counts from:

  (quasar+background) + additional unknown structure

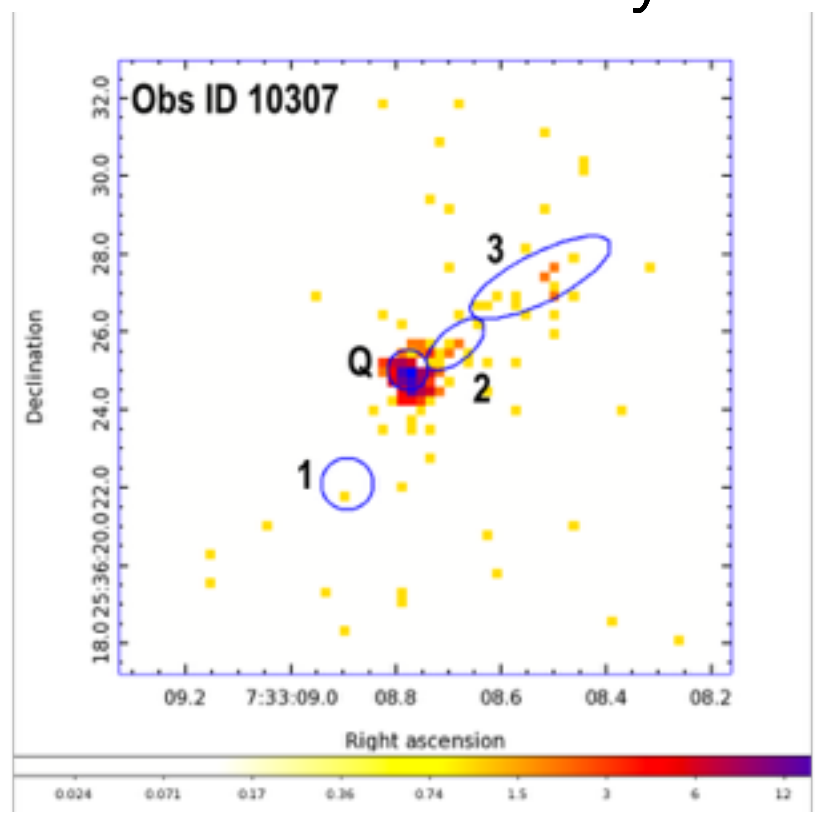
- Bayesian Inference to fit the image
- LIRA generates MCMC images at each iteration
- Calculate p-value in the pre-defined regions (Stein et al 2015)

Detecting Jets

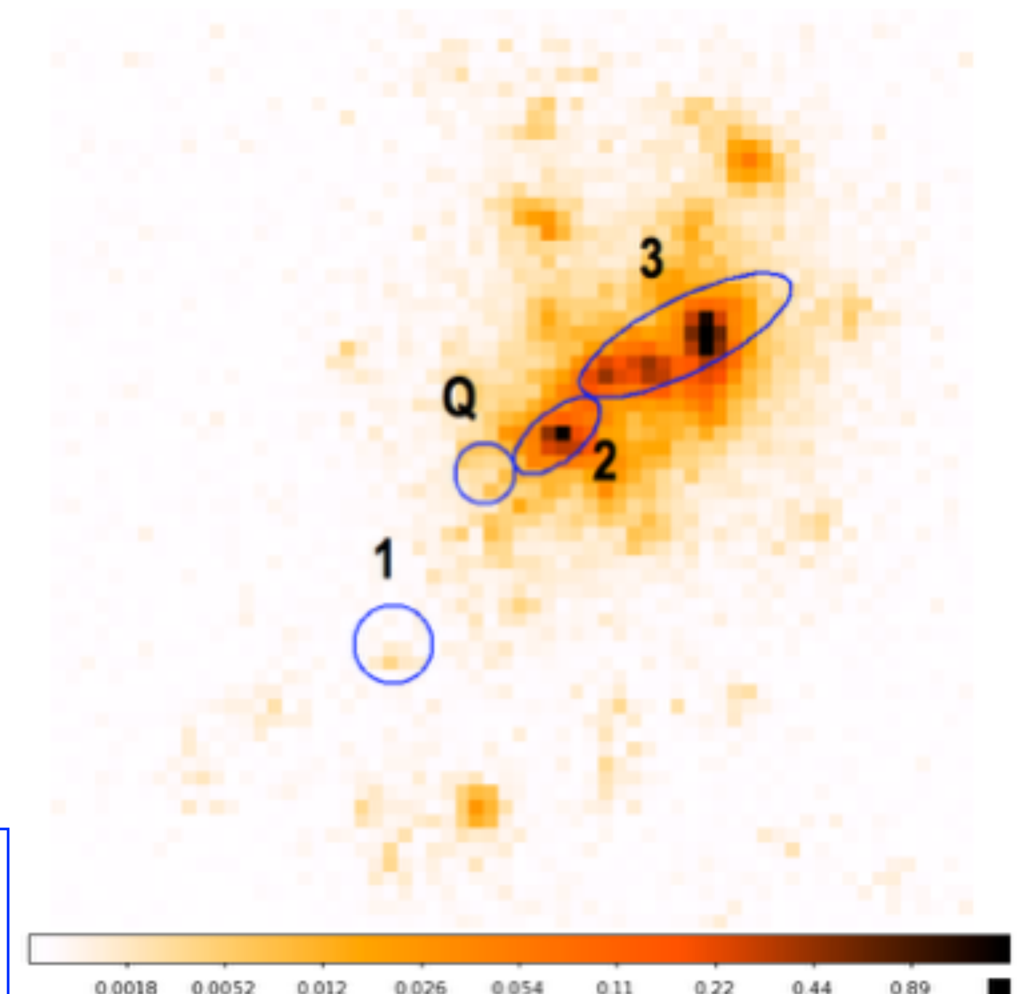
Radio



Chandra X-rays



LIRA MCMC mean image
X-rays with Quasar Removed



11 quasars at z > 2.5

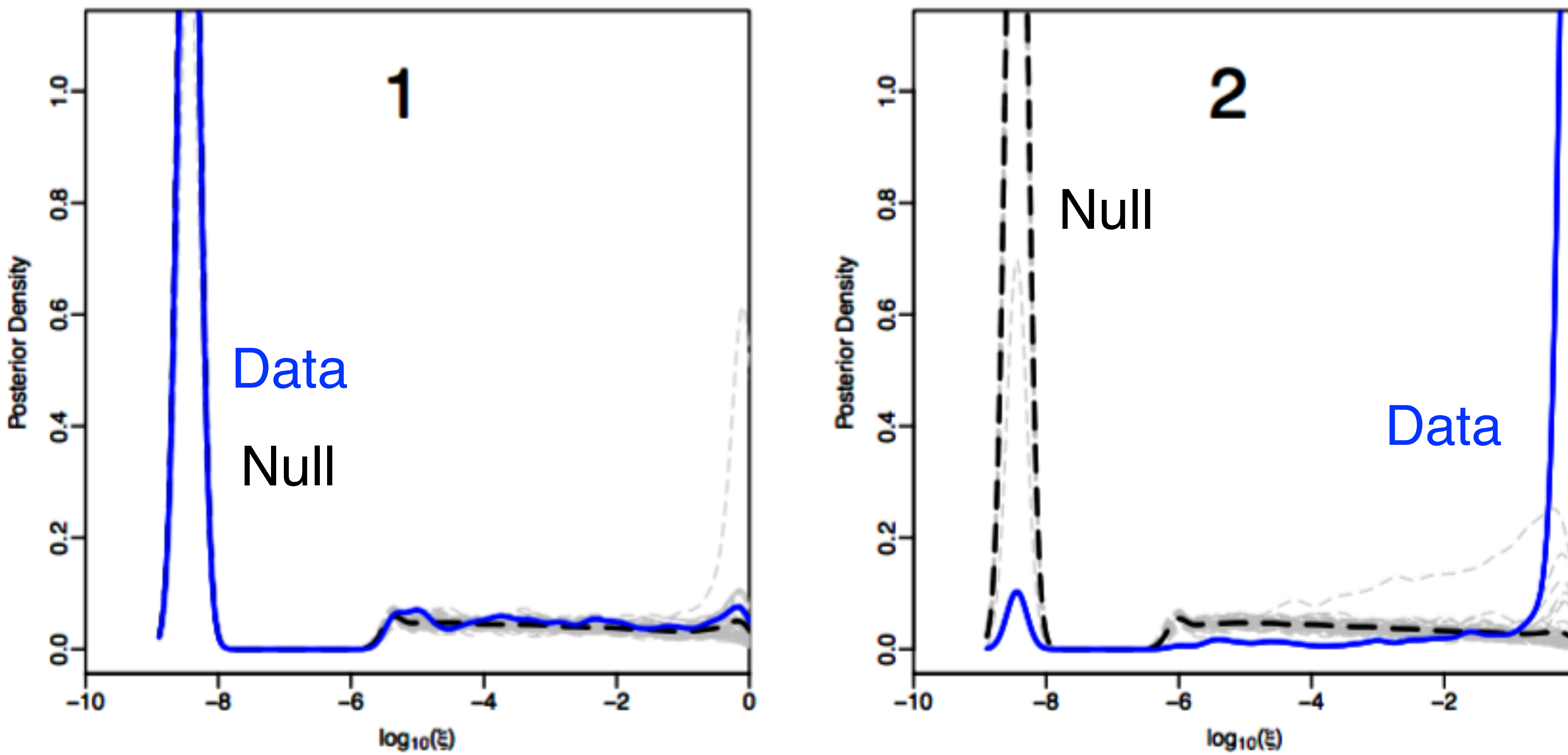
- Short observations with a small number of counts.
- LIRA algorithm to look for any excess emission outside the quasar core.
- Emission regions defined by the radio morphology.
- Calculate the significance of a jet feature based on the simulations using Stein et al. 2015.

McKeough et al. 2016
ApJ submitted

Detecting Jets

Significance of the emission in the region:

LIRA to calculate the expected emission in the simulated images based on the assumed null model (only quasar) and in the Chandra image



No detection

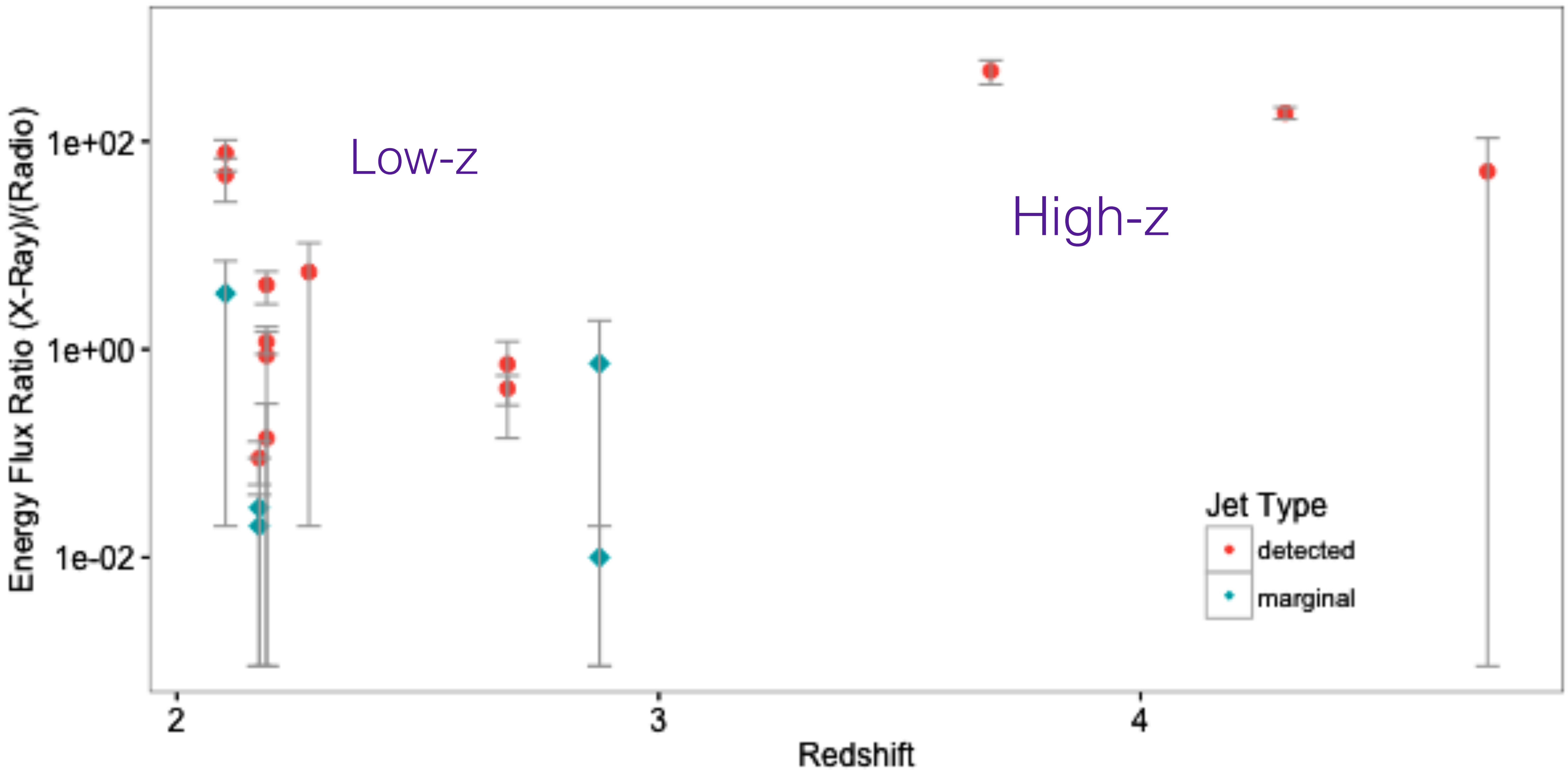
Detection

p-value = 0.006

Jets at High Redshift

$$\rho_{xr} \propto u_{\mathrm{CMB}}/u_{\mathrm{B}} \propto (1+z)^4(\delta/B)^2$$

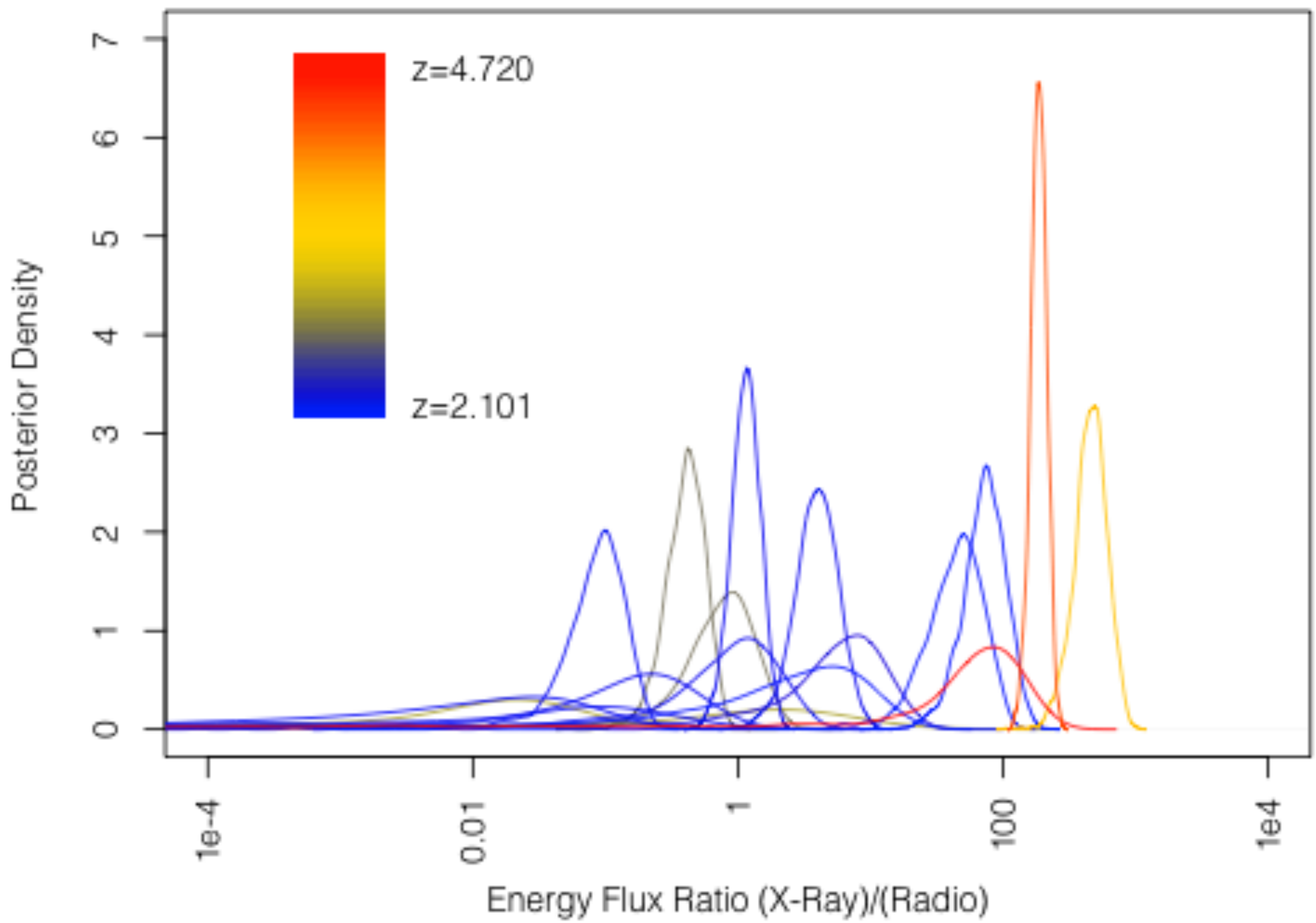
Ratio of the X-ray to radio flux for the **18** jet features



Is there a difference between low-z and high-z jets?

Jets at High Redshift

Probability distribution of the ratio for each detected jet feature



Is there a difference between low-z and high-z jets?

Jets at High Redshift

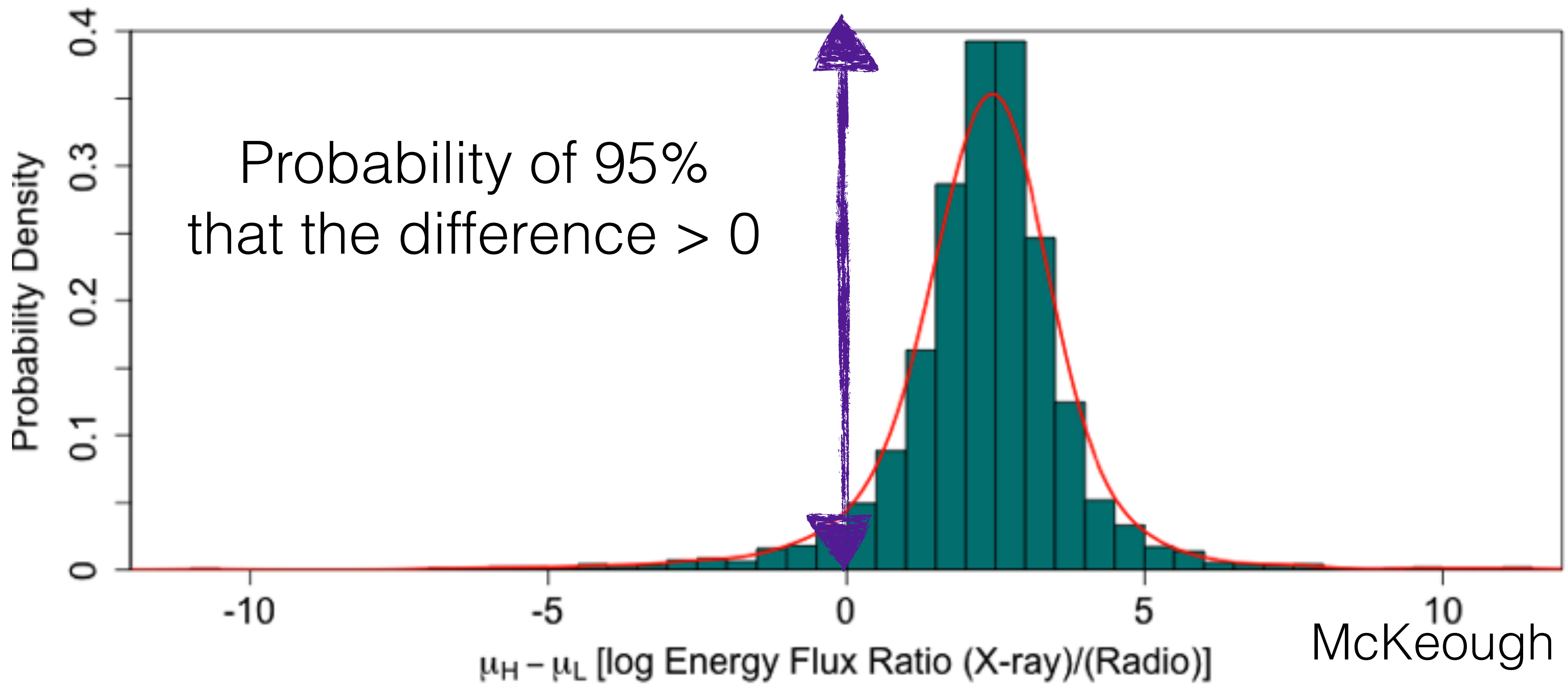
Statistical test: difference of the flux ratio between z < 3 (15) and z > 3 (3) jets

Gaussian distributions:

$$R_i \overset{\text{indep}}{\sim} N(\mu_L, \sigma_L) \text{ for low } z\text{, i.e., for } i = 1, \ldots, 15$$

$$R_i \overset{\text{indep}}{\sim} N(\mu_H, \sigma_H) \text{ for high } z\text{, i.e., for } i = 16, \ldots, 18$$

Monte Carlo to estimate of the difference in the mean



McKeough et al 2016

Summary

- We found evidence for the difference between the jets in two redshift groups.
- This can indicate that the radio-loud quasars at $z > 3$ are different. Note Volonteri et al (2011) suggested that the jets at $z > 3$ might be systematically slower.
- Need more observations to study and understand the nature and broader impact of this difference.

Chandra Next Decade

- **Only** Chandra can resolve the X-ray jet emission.
- **Only 2 high-z jets** have been observed during the past 17 years of Chandra.
- Relatively long observations (> 20 ksec) are required for detecting the jets.
- The **Chandra Survey of High-z Jets** should be one of the key legacy projects in the Next Decade.

X-ray Emission Process?

- Synchrotron radiation in low power radio galaxies - M87, Cen A
- Quasar jets:
    - Synchrotron emission in low-z quasars 3C273
    - Complex morphology structure - 3C 273, PKS1127-145
    - Inverse Compton scattering of Cosmic Microwave Background photons on relativistic electrons in the jet (IC/CMB)
    - High-z jets in higher density CMB field ~ $(1+z)^4$
- Majority of quasar jets in Chandra archive are at low redshift z<1 and most are at z~0.5
- Only two quasar X-ray jets detected at z>4

- First jets were observed in optical images. A note by Herbert Curtis in 1918 about M87 image: *"A curious straight ray lies in a gap in the nebulosity in p.a. 20 deg apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11 arcsec from the nucleus."*

- First association of radio emission with relativistic jets in the 50-ties

- First jets resolved in X-rays in the *Einstein* HRI images in the 70-ties. Only 3 jets were resolved: Cen A, M87 and 3C 273.

- First ideas about the X-ray emission processes

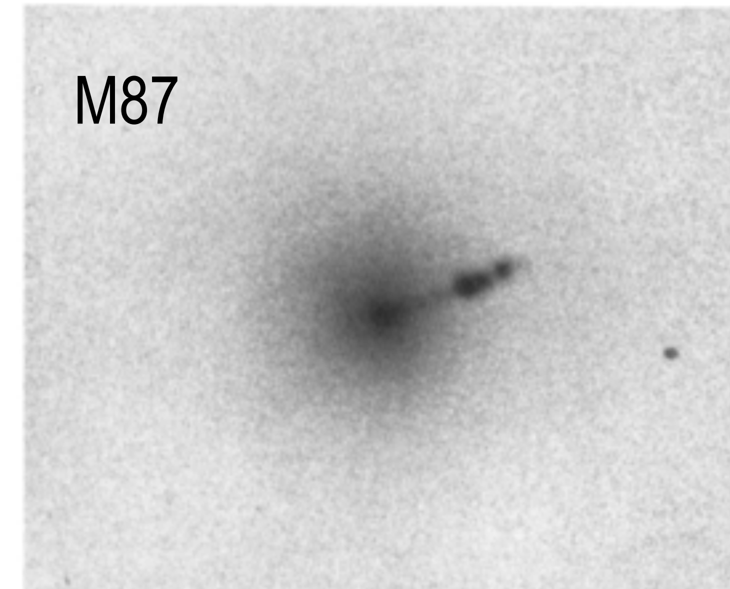
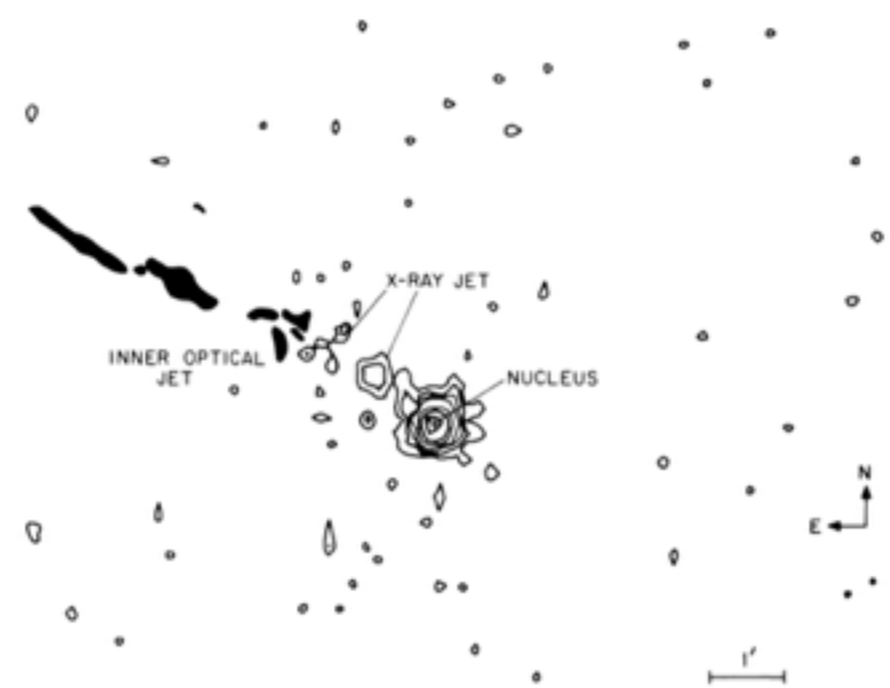


FIG. 8.—Center of NGC 4486. $\lambda < 4000$; 100-inch; 1 mm = 0″.8

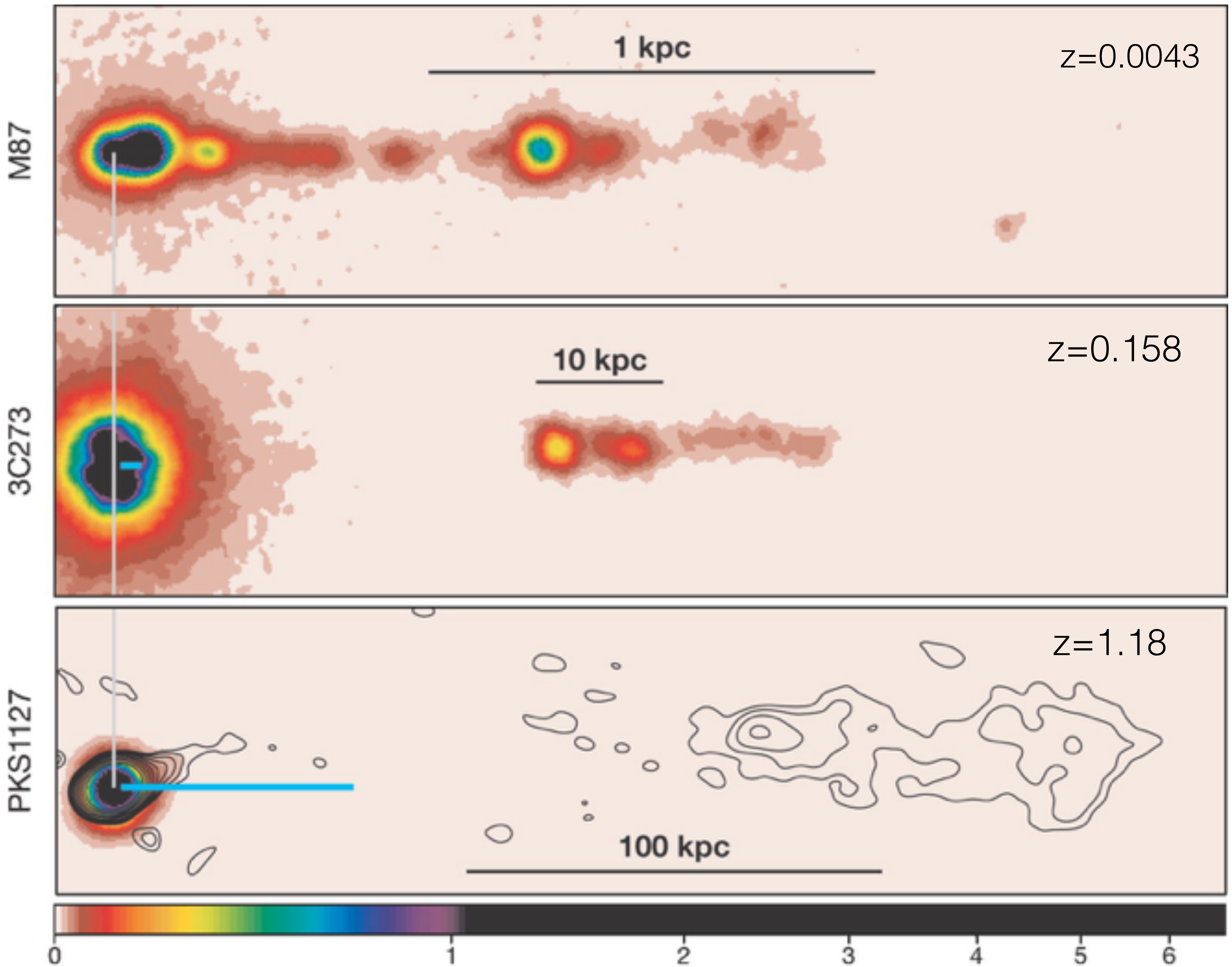
Baade & Minkowski 1954

Cen A

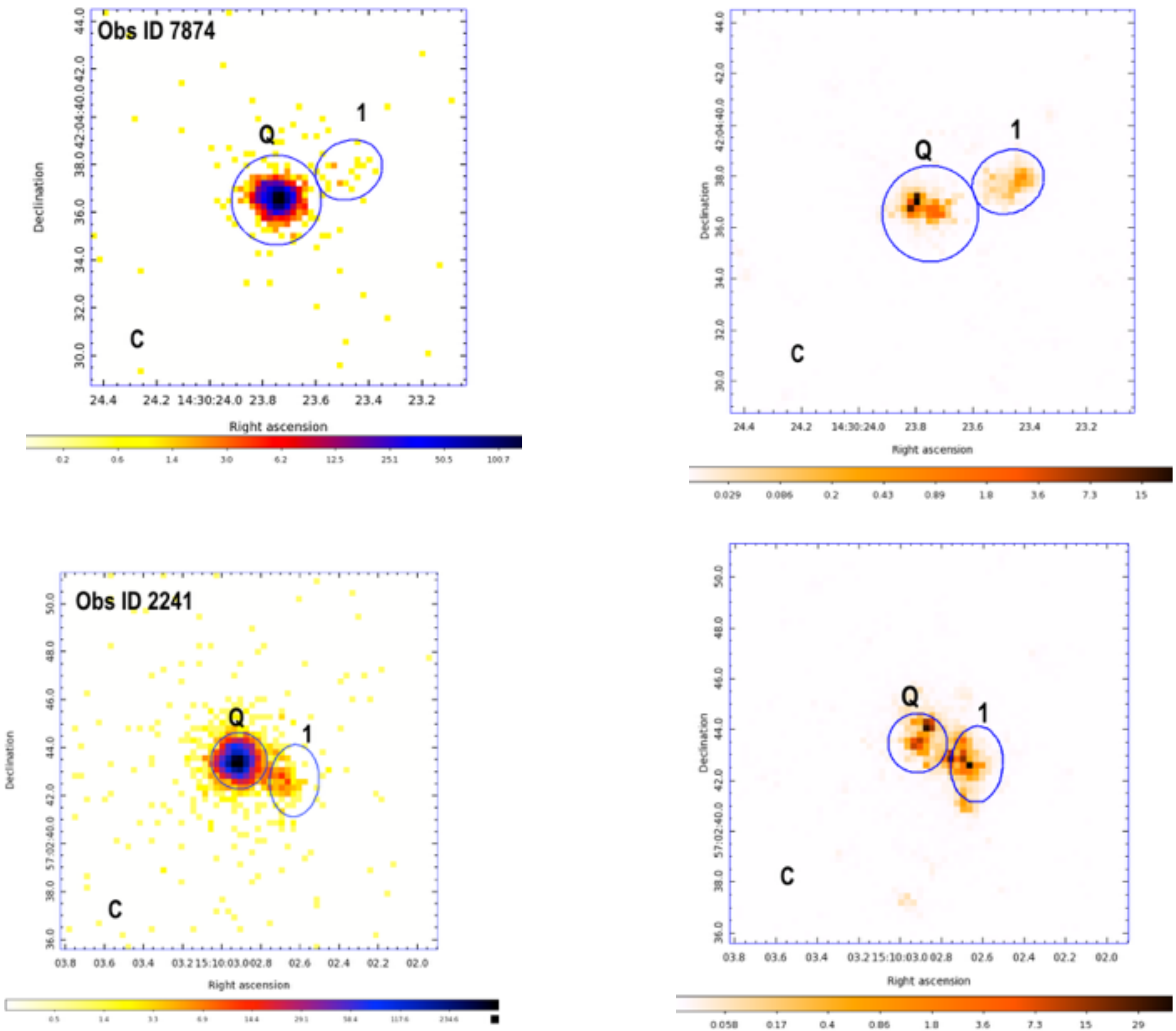
SCHREIER *ET AL.*



Jet Span Different Scales!



Harris DE, Krawczynski H. 2006.
Annu. Rev. Astron. Astrophys. 44:463–506



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