AGN and Quasars
Accretion Processes
Relativistic Jets

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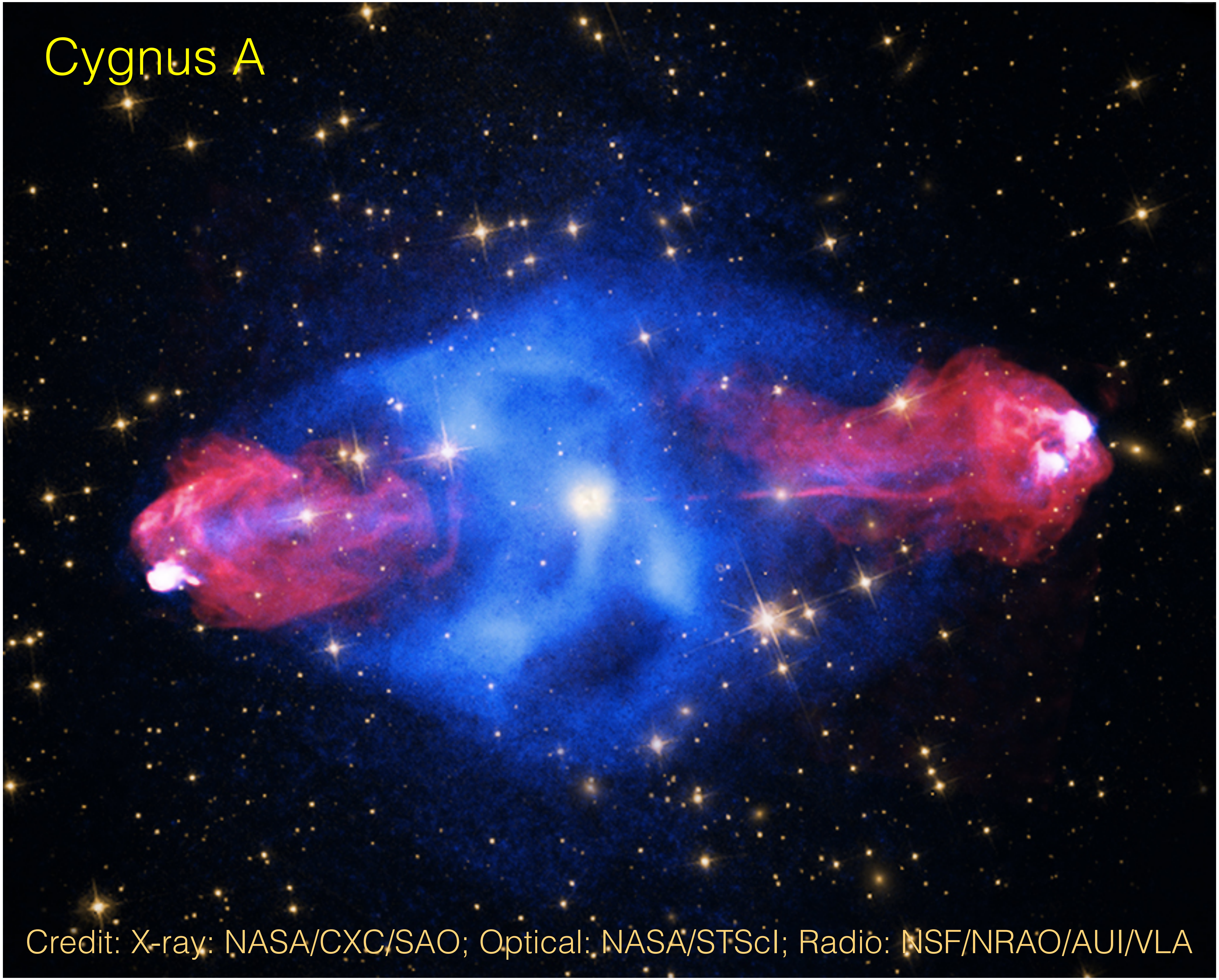
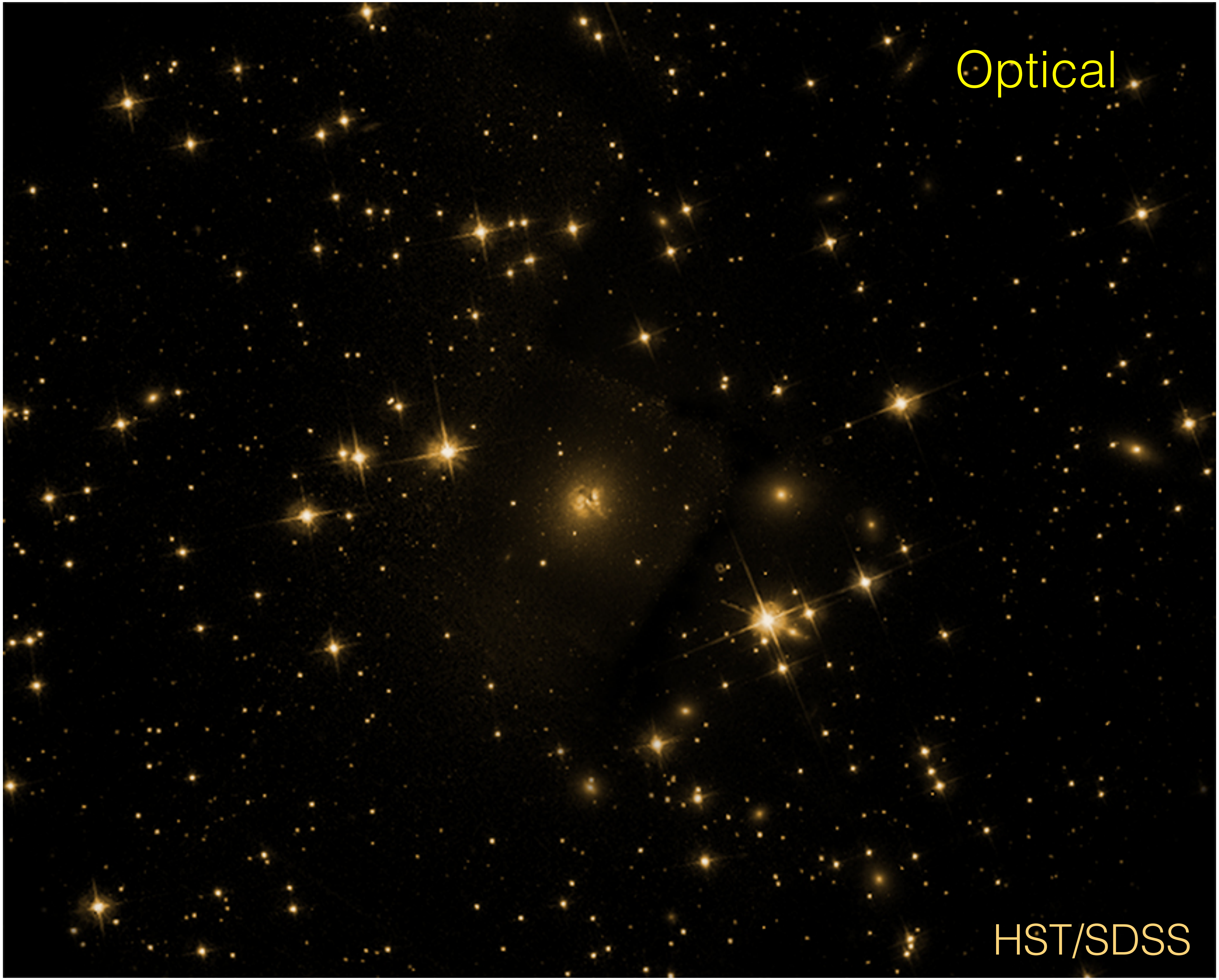
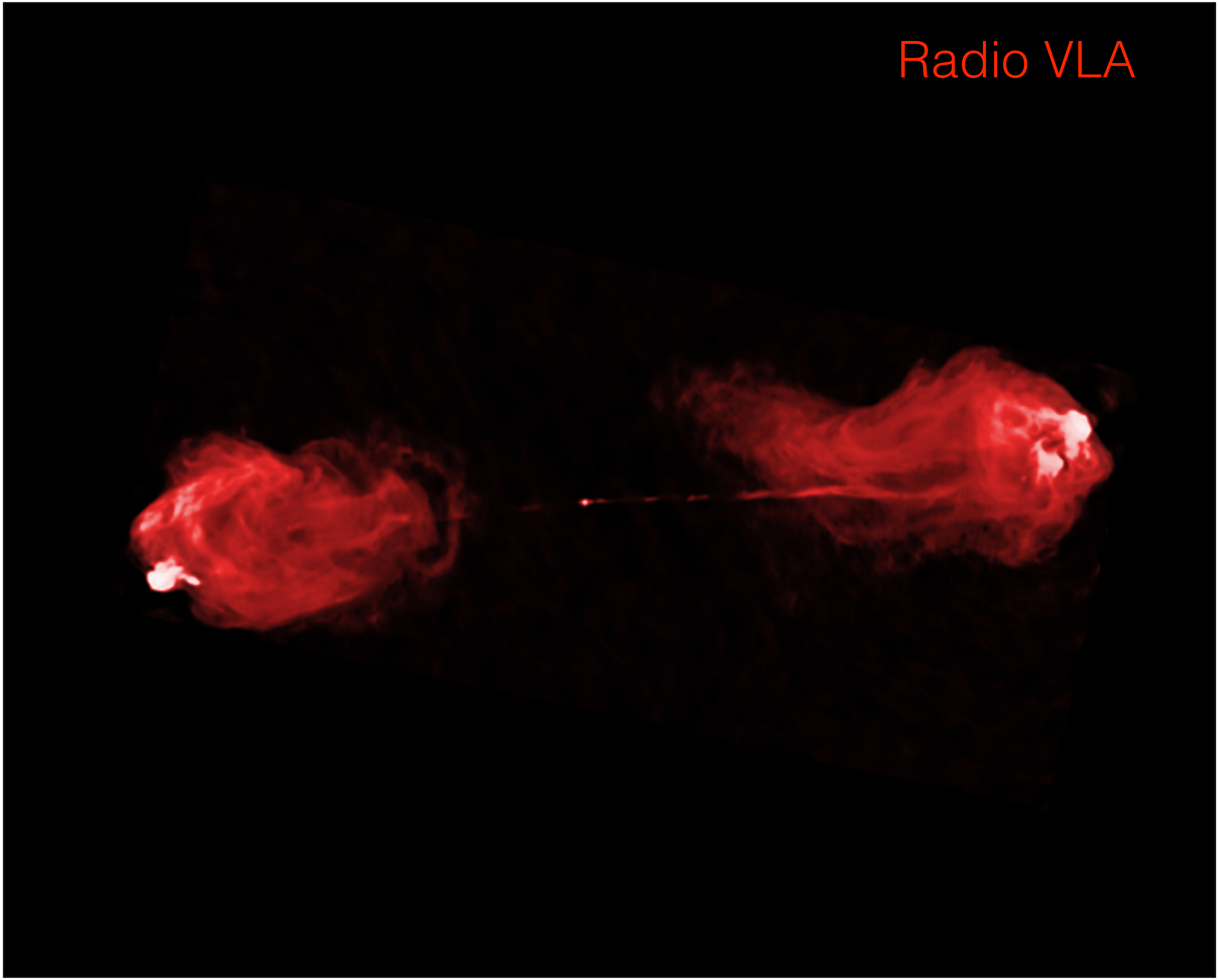
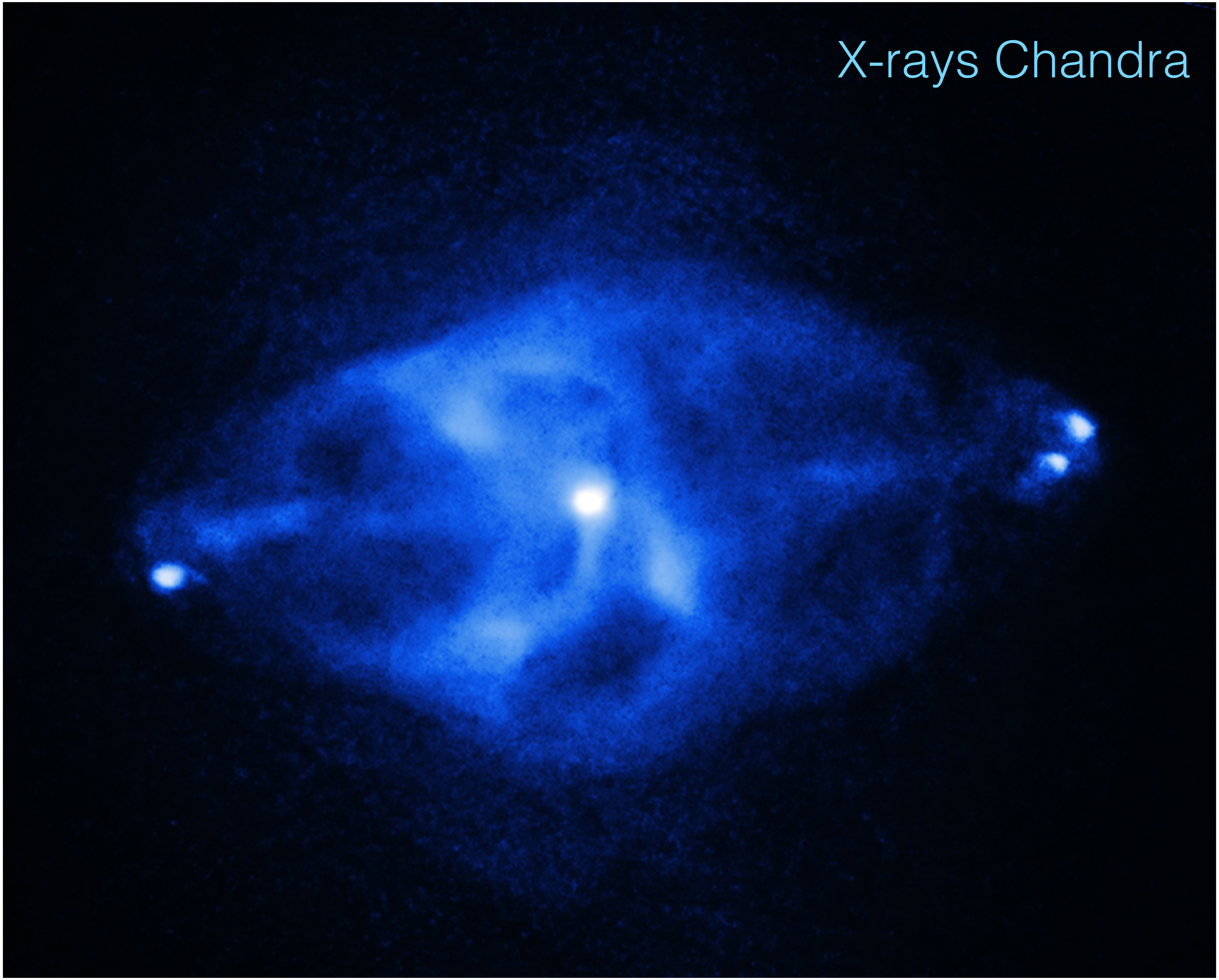
A few Questions

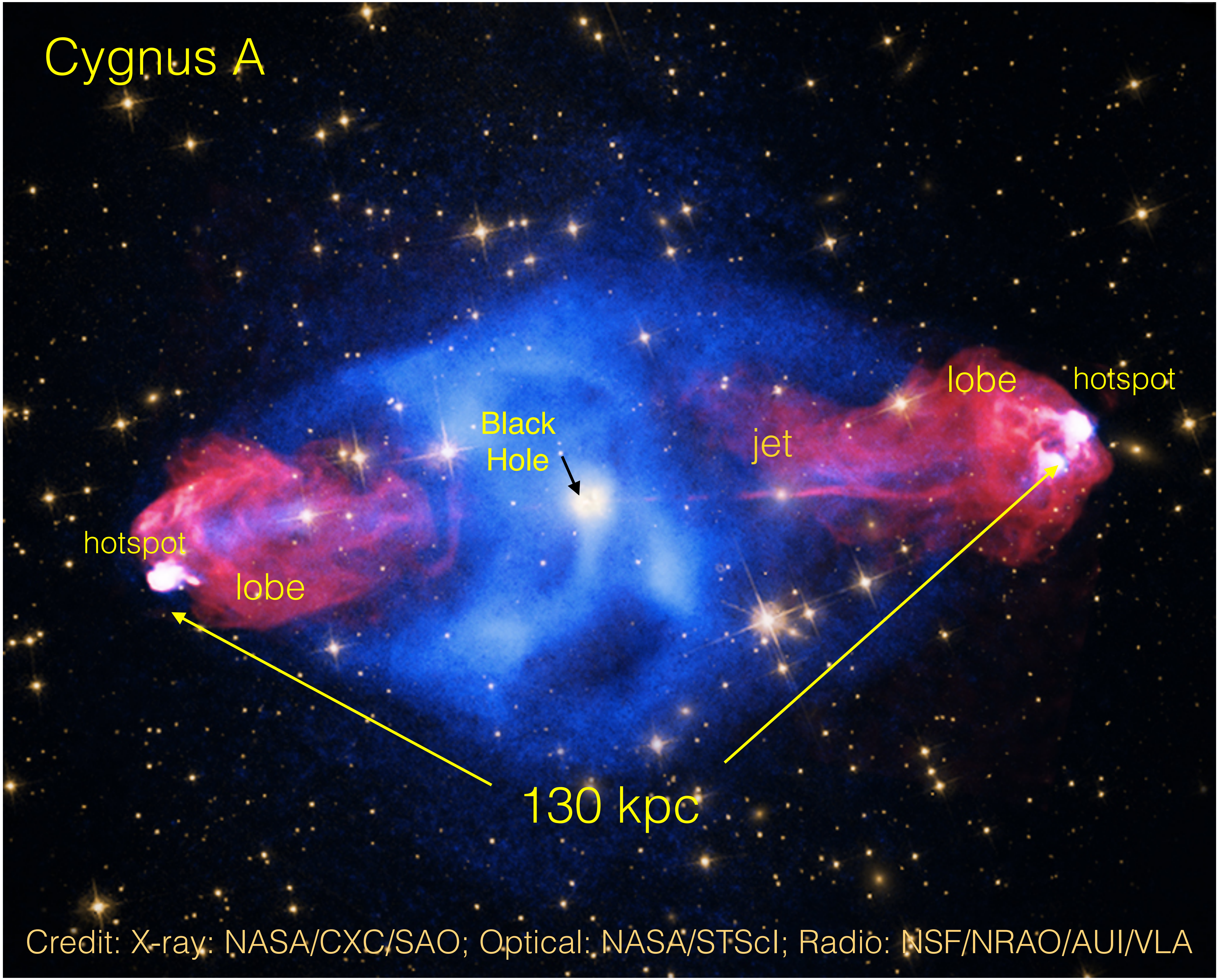
- Why do we have jets?
- How do jets form and accelerate?
- Why do jets survive?


Cygnus A
Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA

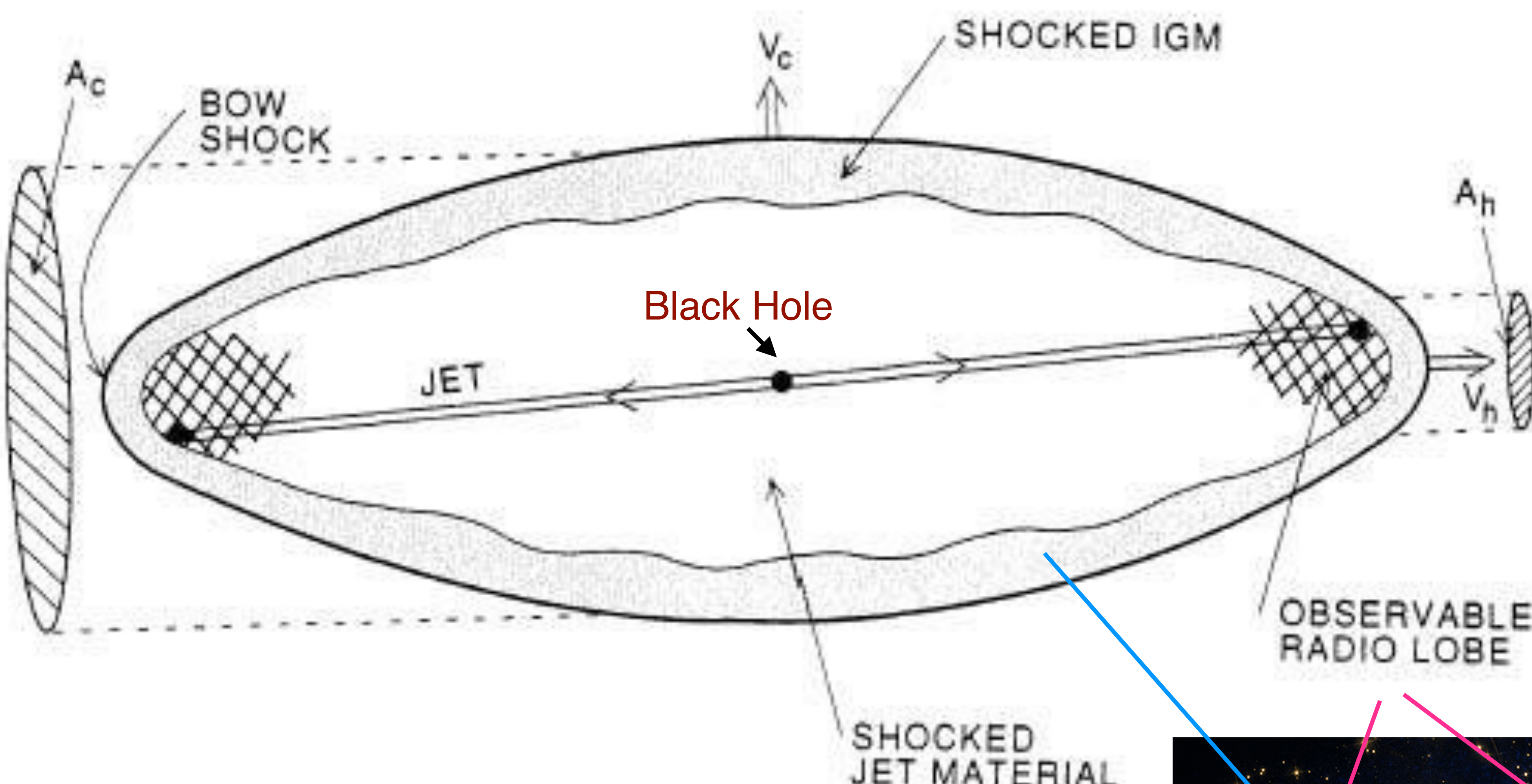

Optical
HST/SDSS


Radio VLA

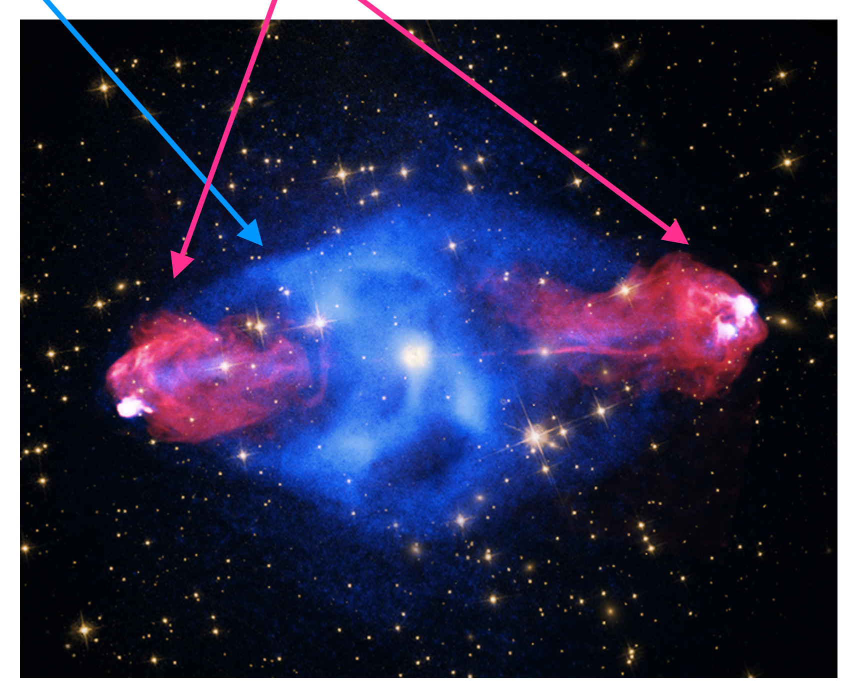

X-rays Chandra


Cygnus A
hotspot
lobe
Black
Hole
jet
lobe
hotspot
130 kpc
Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA

Cygnus A - Model



Scheuer 1974
Begelman & Cioffi (1989)



Cygnus A: Observational Constraints

$z=0.056$

$M_{bh} \sim 2.5_{(+/-0.7)} \times 10^9\ M_{sun}$ HST/Keck Tadhunter et al 2003,

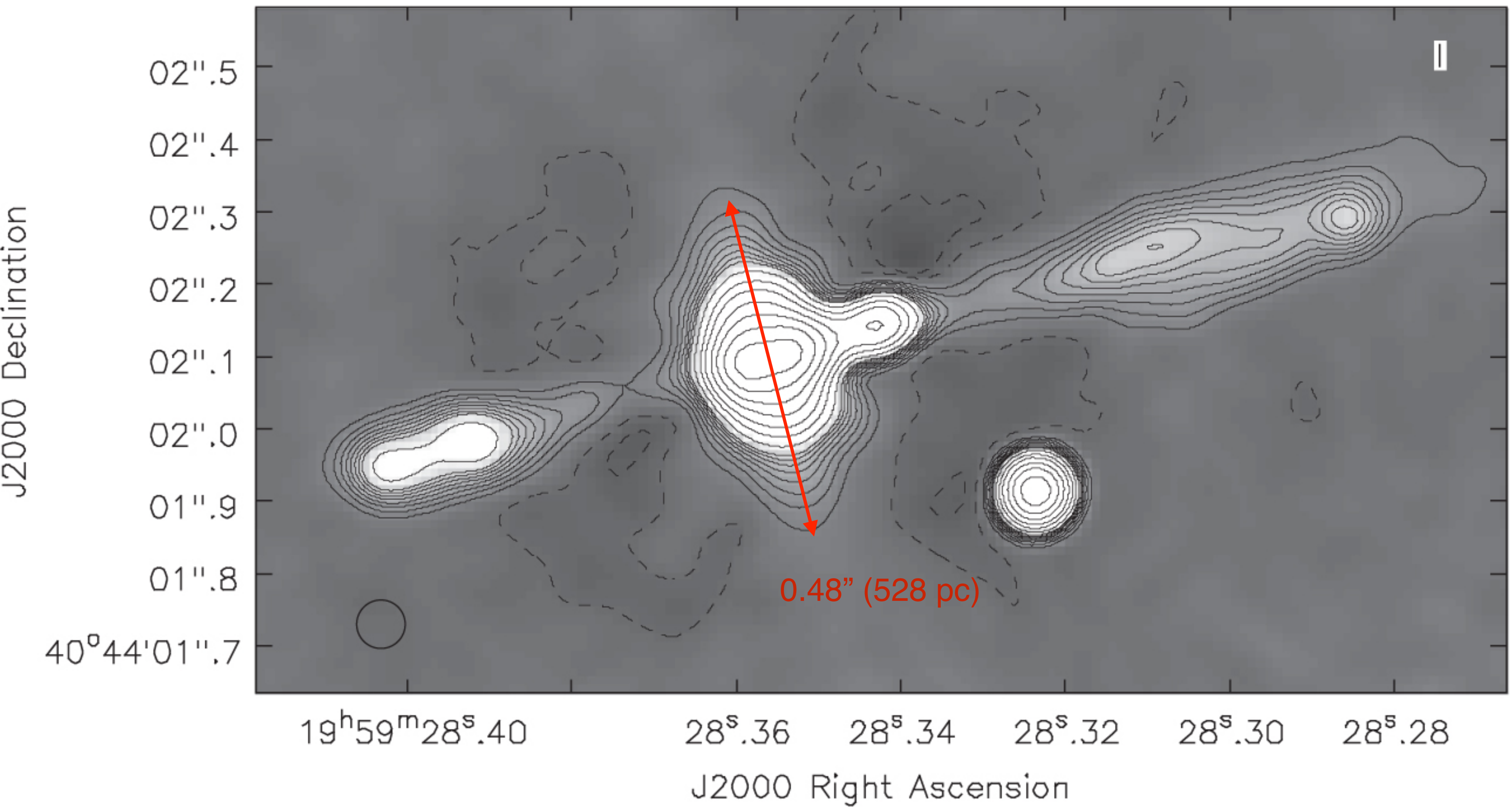
$L_{bol} \sim 10^{46}$ erg/s ~ 0.01 L/L_{Edd}

X-rays: $N_H \sim 3 \times 10^{23}\ cm^{-2}$ => hidden AGN

Young et al,. 2002,
Reynolds et al 2015

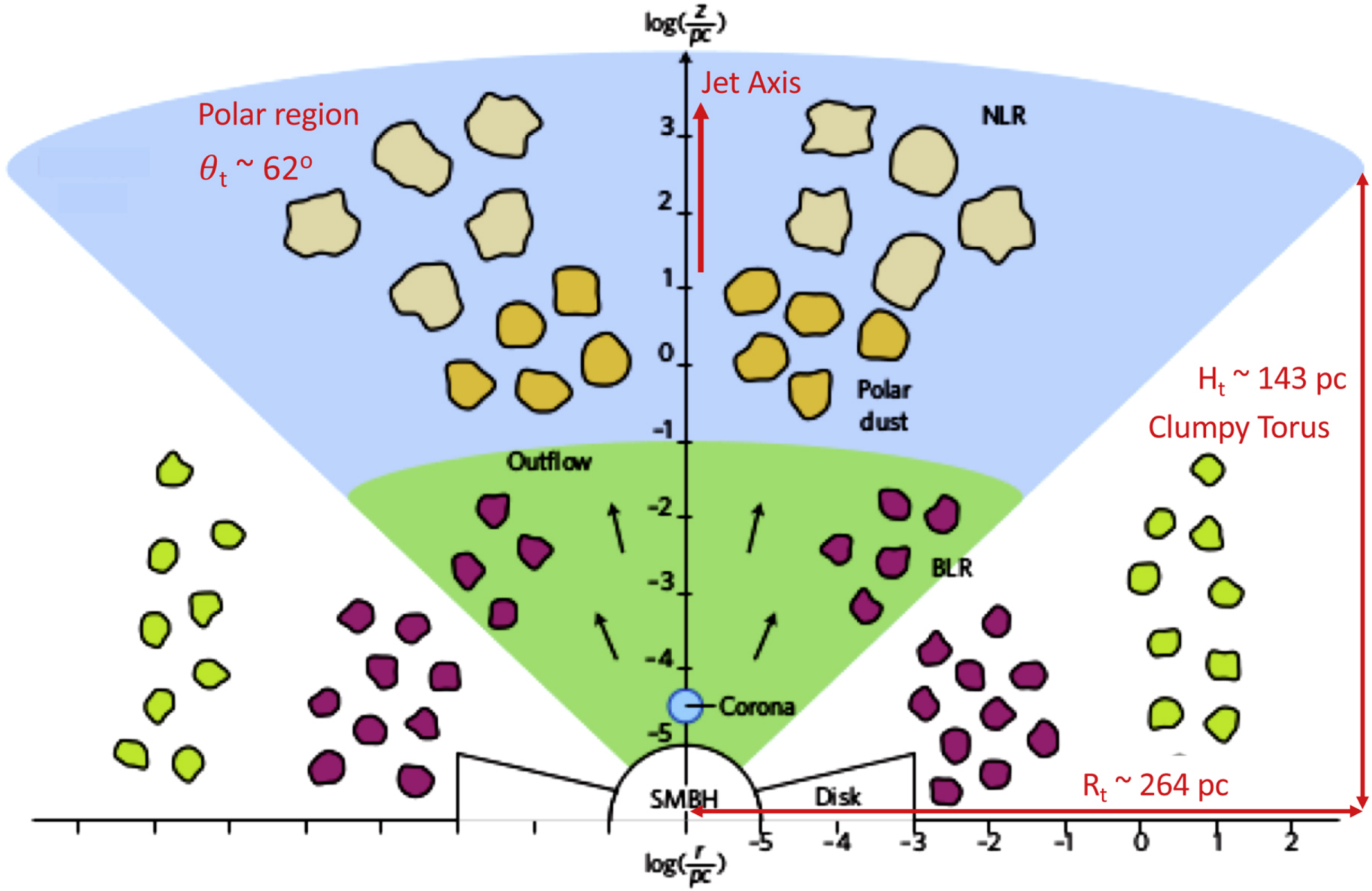
several absorption components ,
H1, clumpy torus, ionized wind

Imaging AGN Torus



JVLA 18-48 GHz imaging

Carilli et al 2019



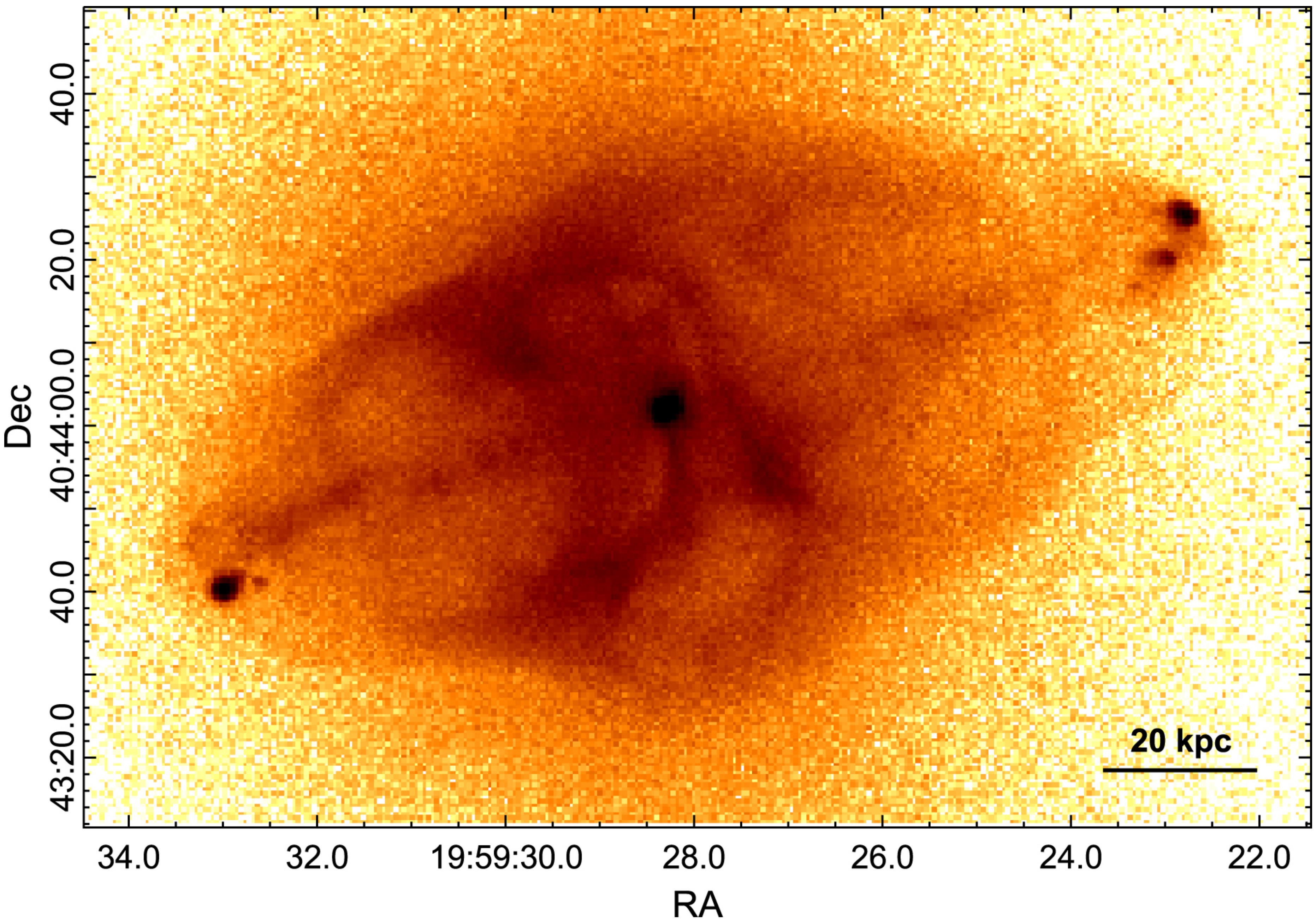
log(z/pc)
Jet Axis
Polar region
θ_t ~ 62°
NLR
3
2
1
0
-1
-2
-3
-4
-5
Polar dust
Outflow
BLR
Corona
SMBH
Disk
H_t ~ 143 pc
Clumpy Torus
R_t ~ 264 pc
-5 -4 -3 -2 -1 0 1 2
log(r/pc)

n>4000 cm^{-3}

Cygnus A: Observational Constraints

M_{bh}~2.5 x10^9 M_{sun}

L_{bol} ~10^{46} erg/s ~ 0.01 L/L_{Edd}



filaments

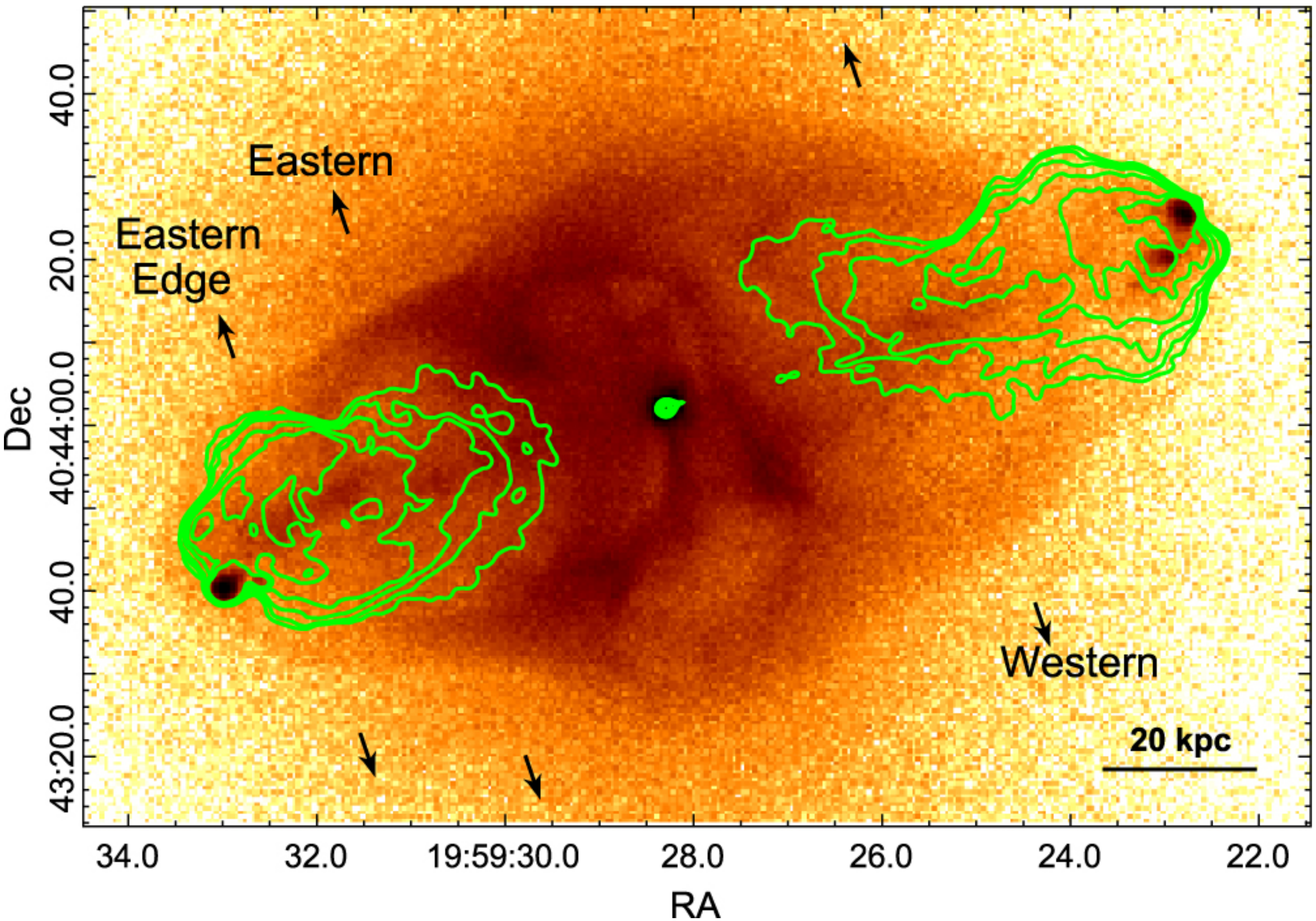
hotspots

Snios et al 2018
Duffy et al 2018

Cygnus A: Observational Constraints

$M_{bh} \sim 2.5 \times 10^9 M_{sun}$

$L_{bol} \sim 10^{46}$ erg/s ~ 0.01 L/L_{Edd}



Mach ~1.2-1.6

$t_{outburst} \sim 1.8 \times 10^7$ yrs

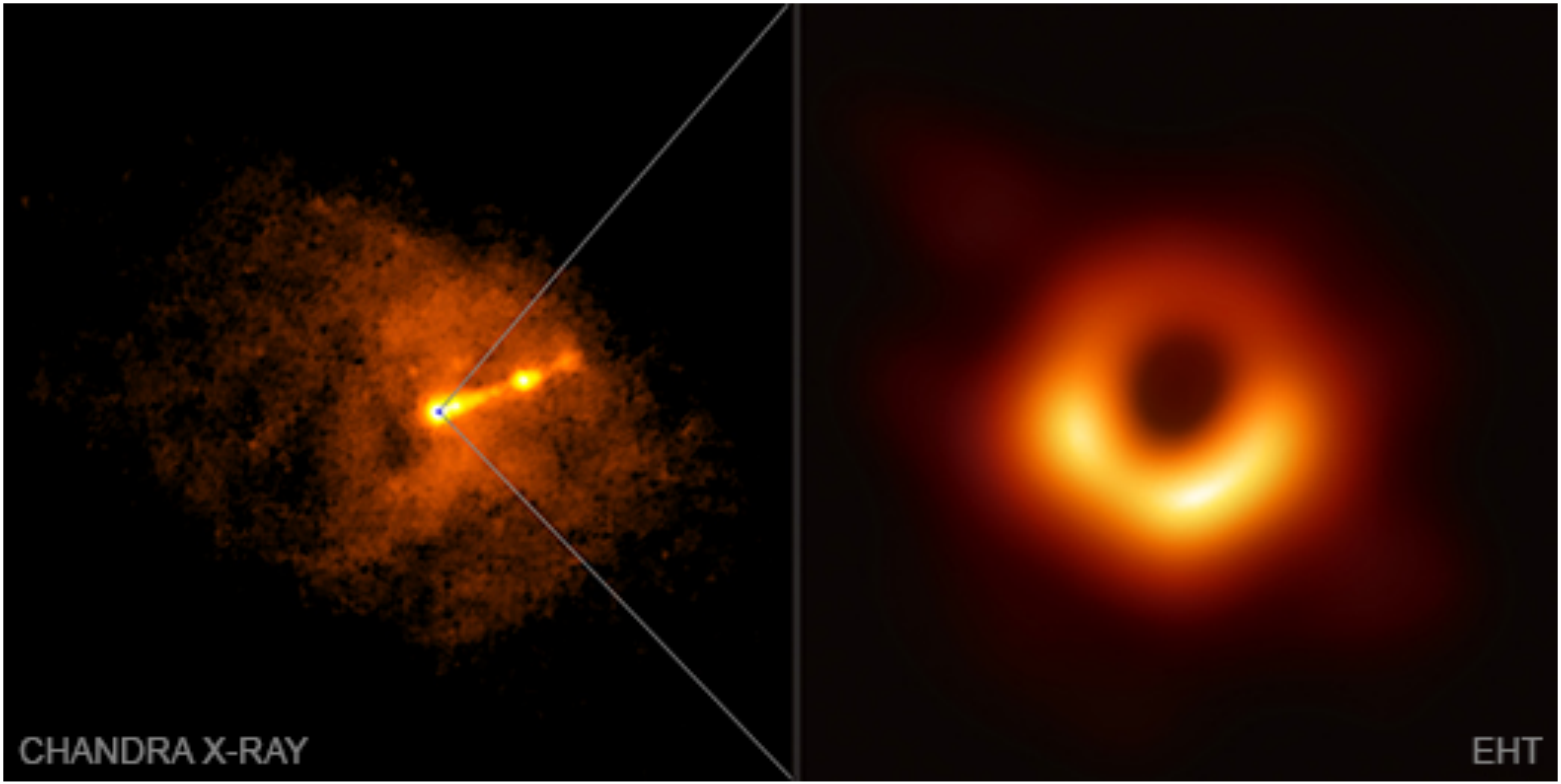
$E_{ave} \sim 5 \times 10^{60}$ erg

Snios et al 2018
Duffy et al 2018

- Cygnus A:
  - Hidden AGN surrounded by a clumpy torus
  - Cocoon shock - total power of the outburst
  - Continuous jet delivers energy to the hotspots
  - Filaments - disintegration of the cool core
  - $M_{dot} \sim 0.01\ L/L_{Edd}$

BH in M87

$M_{BH} \sim 6.5\times10^{9}$ Msun

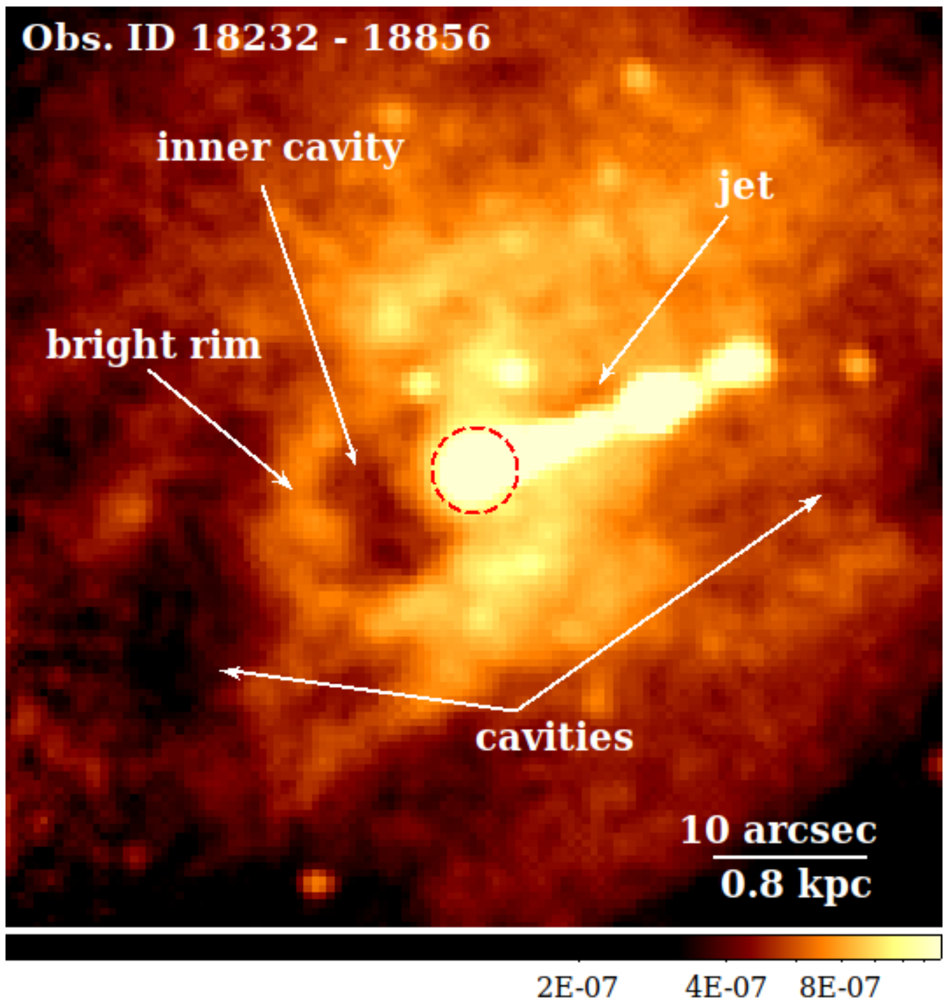


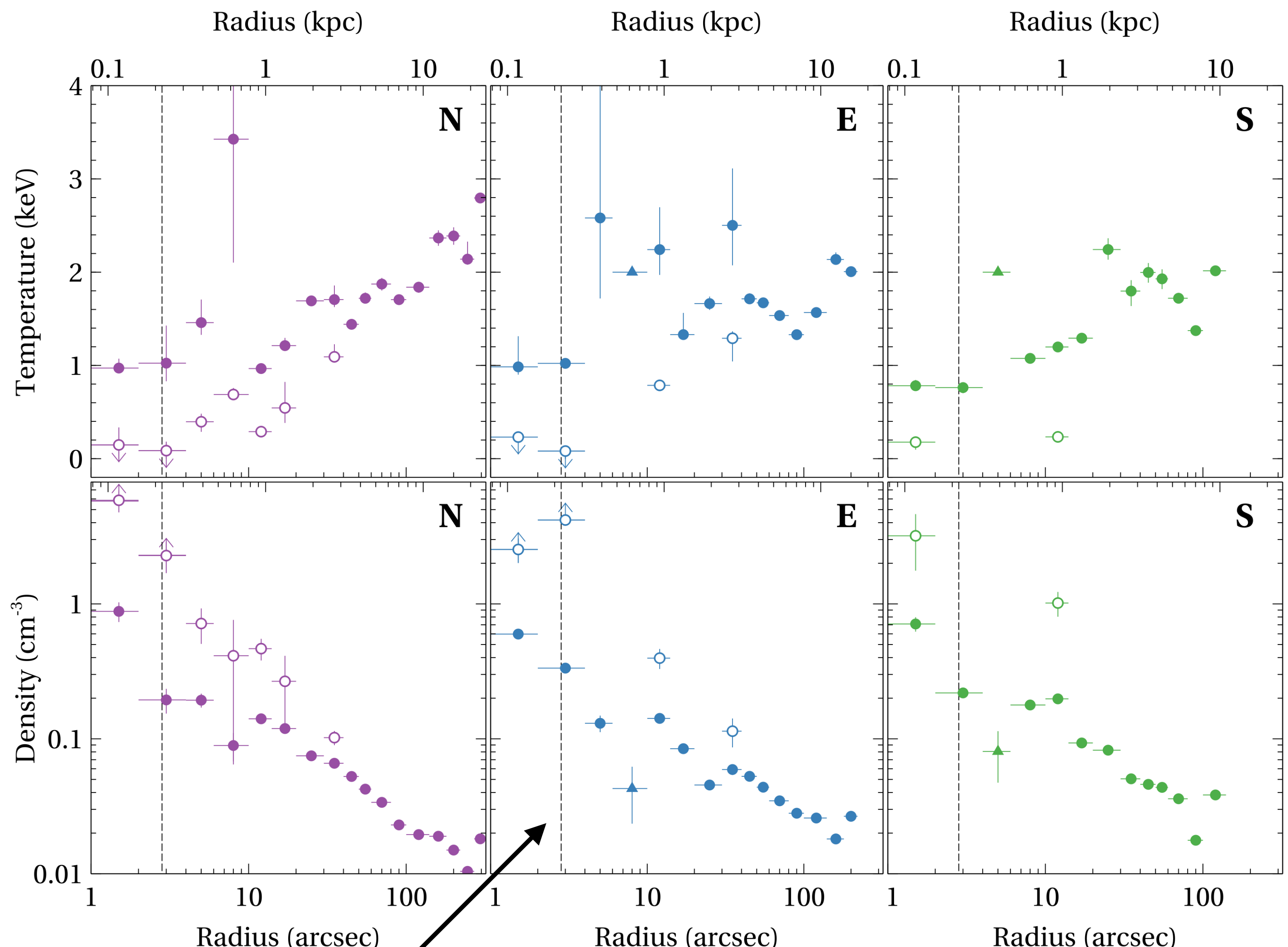
1.3 mm emission radius $5r_g$

$M_{dot} \sim 10^{-5}\ L/L_{Edd}$

Constraints on BH Accretion in M87

M_{BH} ~6.5x10^9 Msun





Bondi radius
0.22 kpc

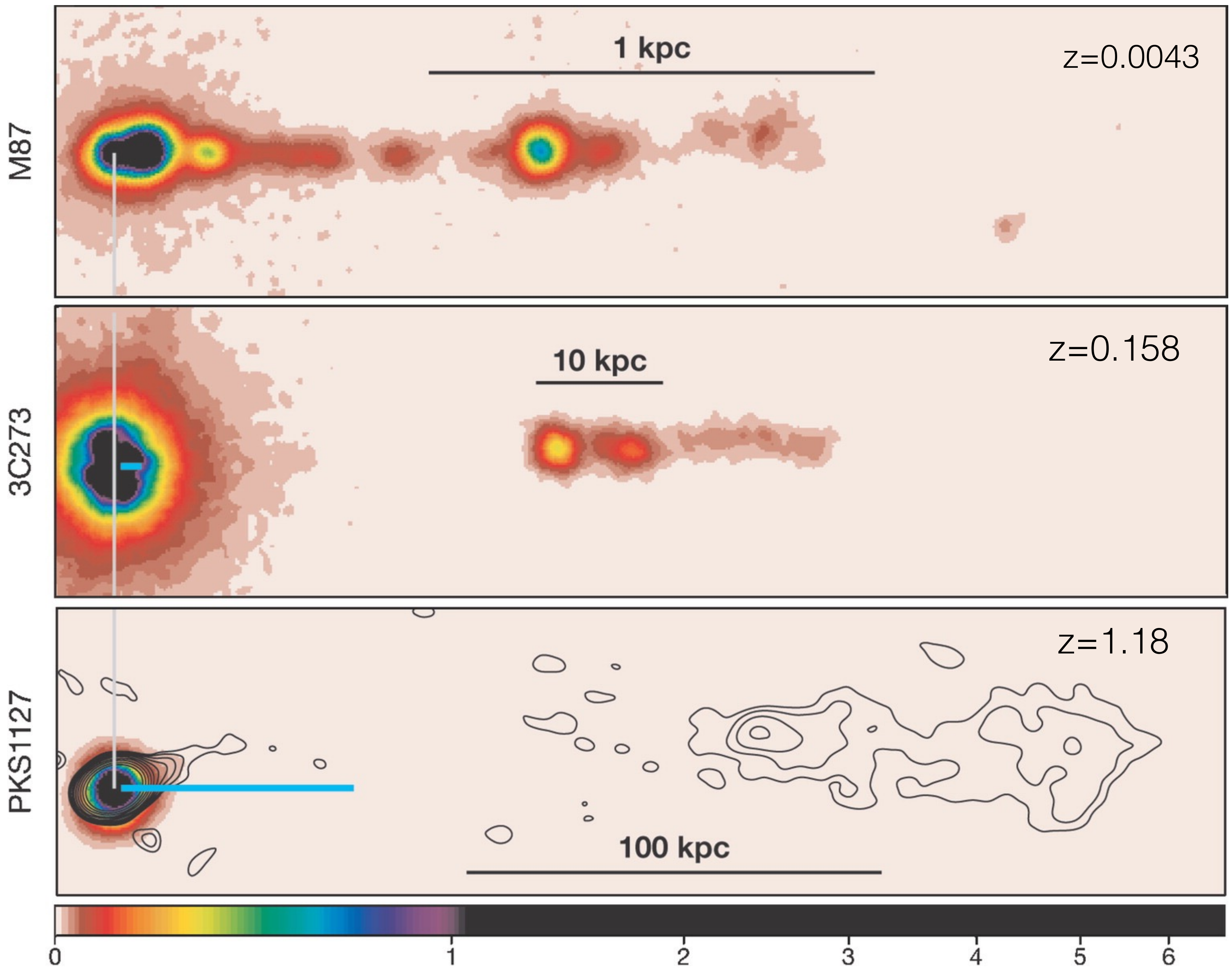
cooling time ~10^5 yrs

$M_{dot\ (Bondi)} < 0.001\ L/L_{Edd}$

$M_{dot}\ (5r_g) \sim 10^{-5}\ L/L_{Edd}$

Russell et al. 2018

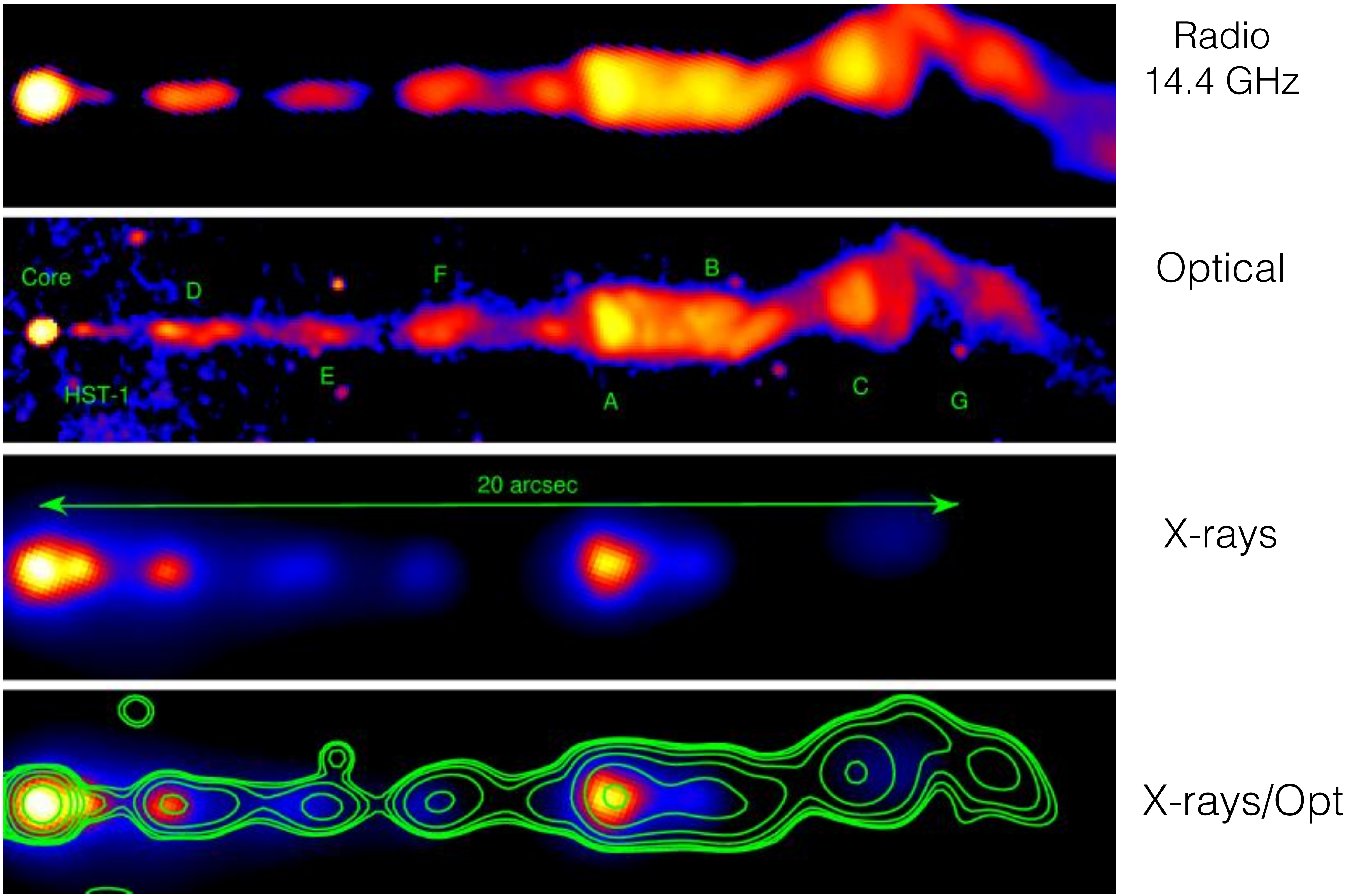
Jets Span Different Scales



Resolved X-ray Jets

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

M87 Jet

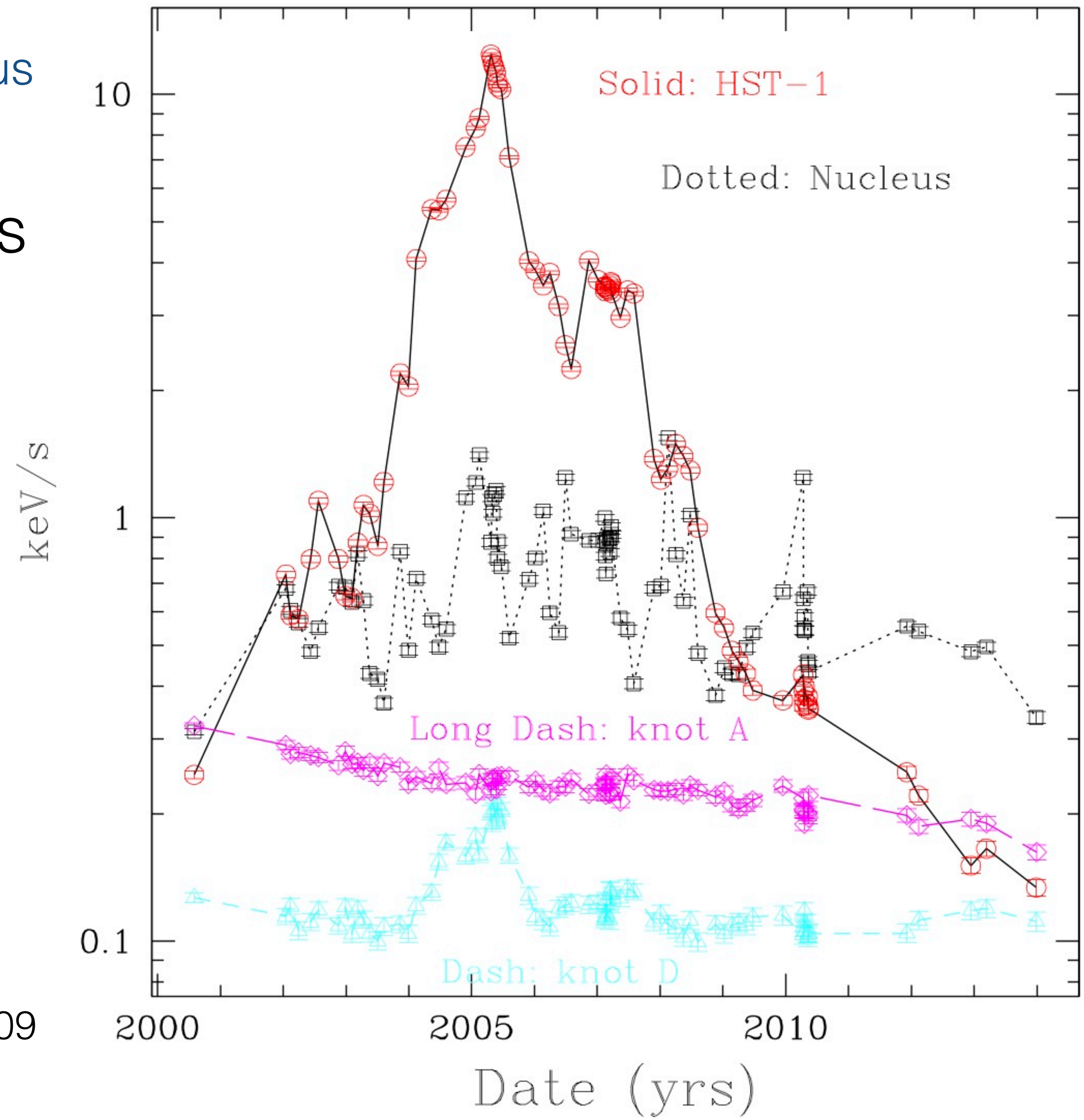


Marshall et al 2002

X-ray Flare from Jet Knot HST-1

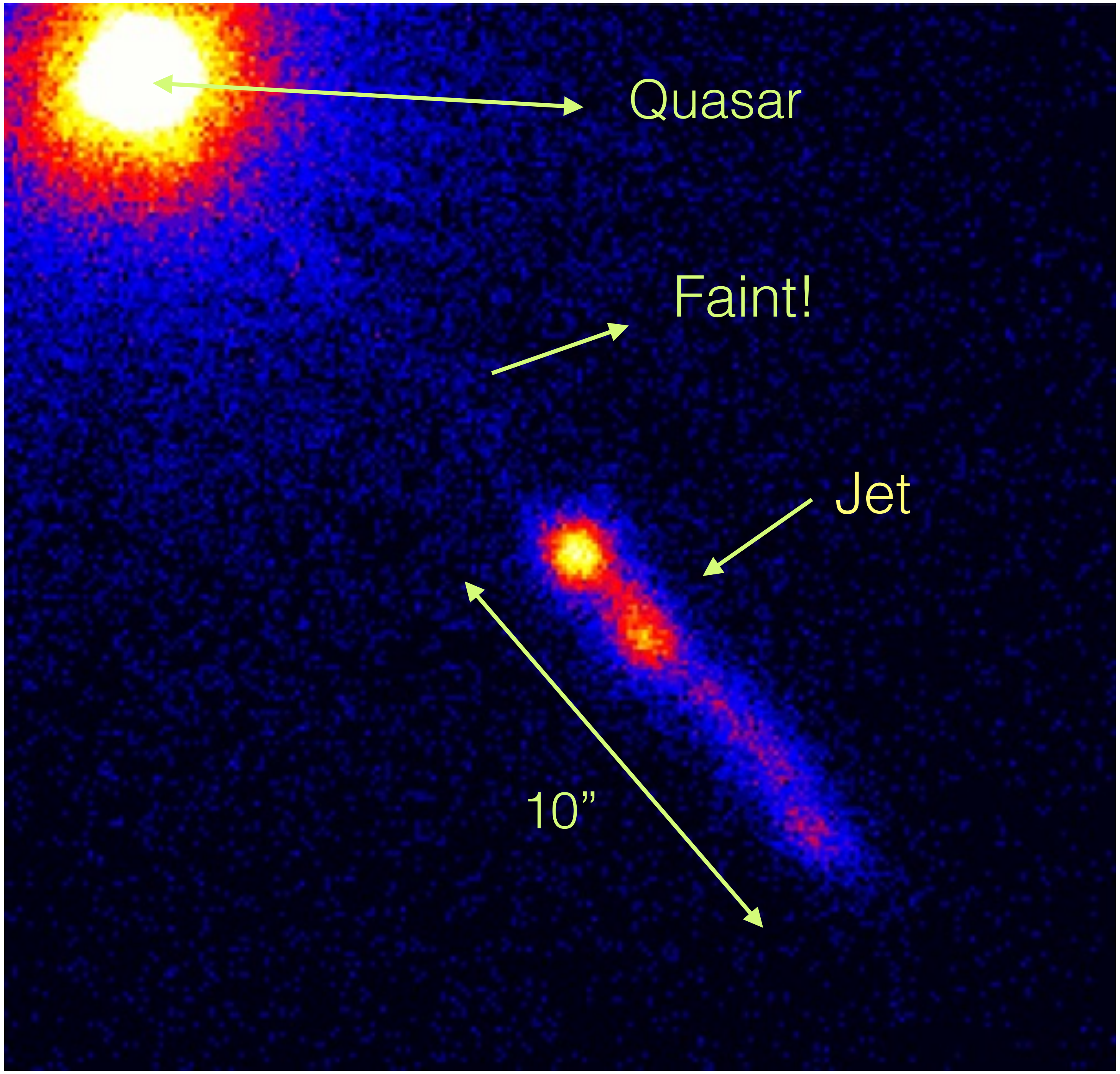
~66 pc distance from the nucleus

Flare duration ~ 5 years



Harris et al 2009

X-ray Jet of 3C 273 Quasar

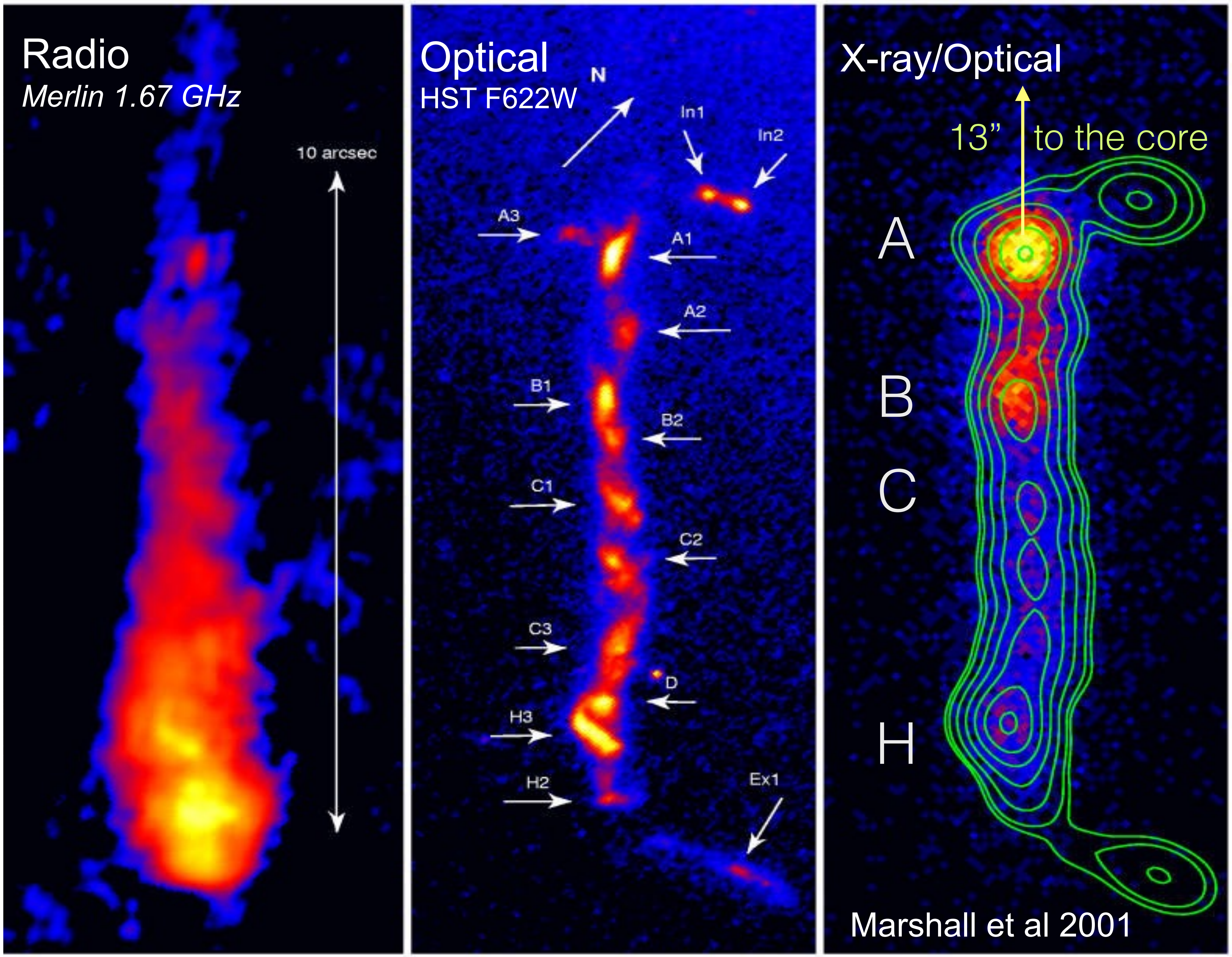


Chandra ACIS-S
PSF FWHM = 0.5 arcsec
90% EEF < 5 arcsec

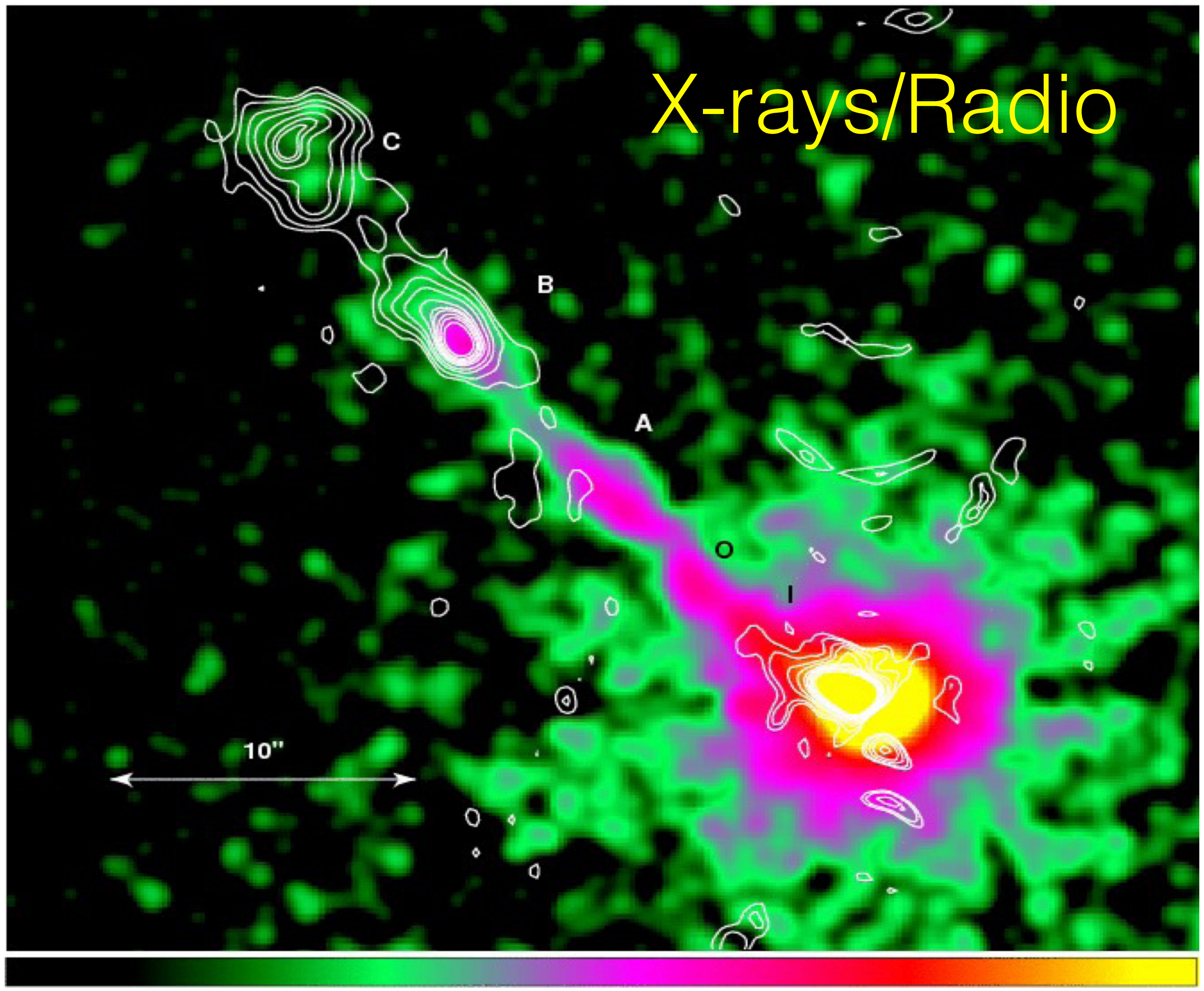
3C 273 quasar
at z = 0.158
10 arcsec = 27.5 kpc

X-ray Jet propagates
outside the host galaxy.

Multi-band view of 3C 273 Jet



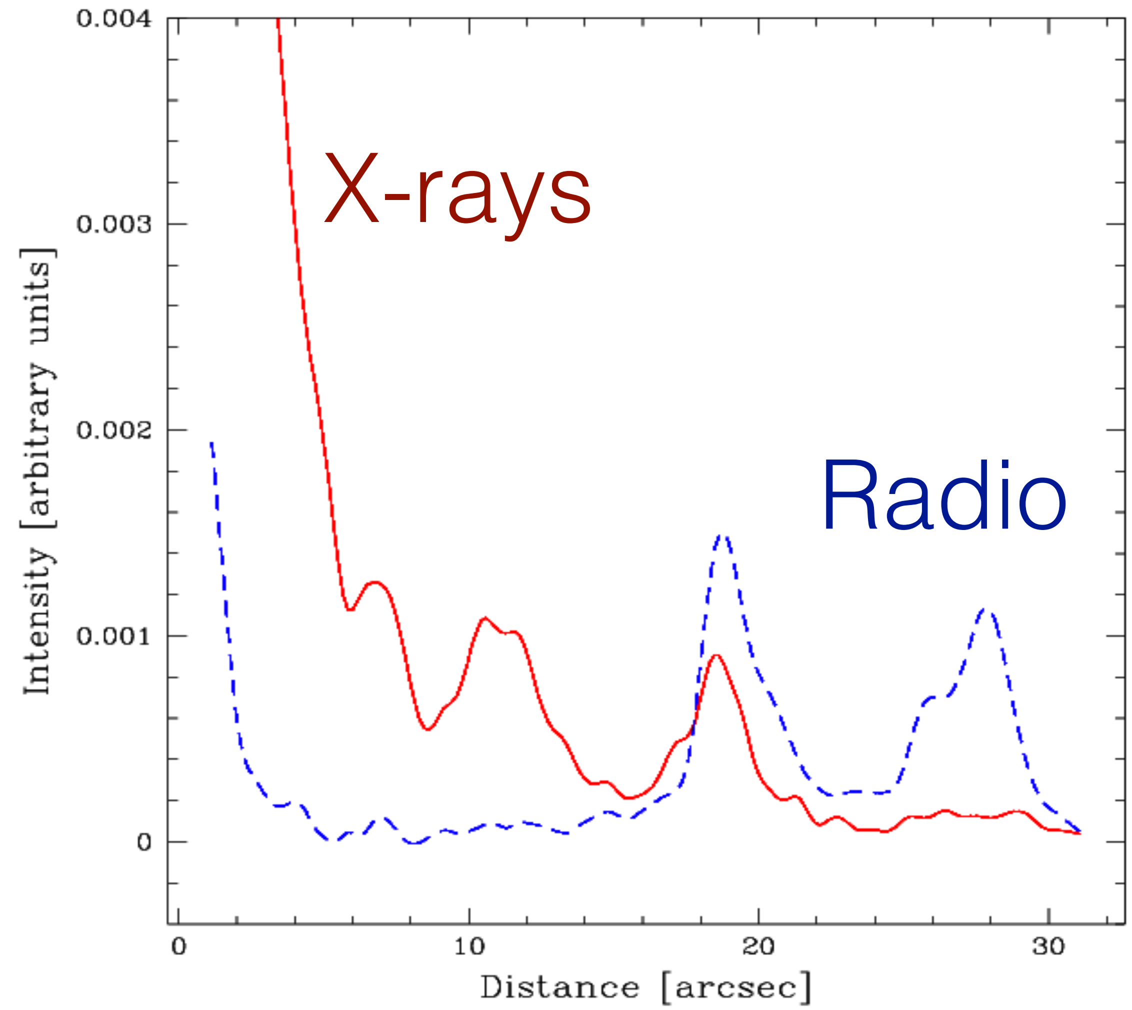
300 kpc Quasar Jet of PKS1127-145



100 ksec Chandra image

Siemiginowska et al 2002, 2007

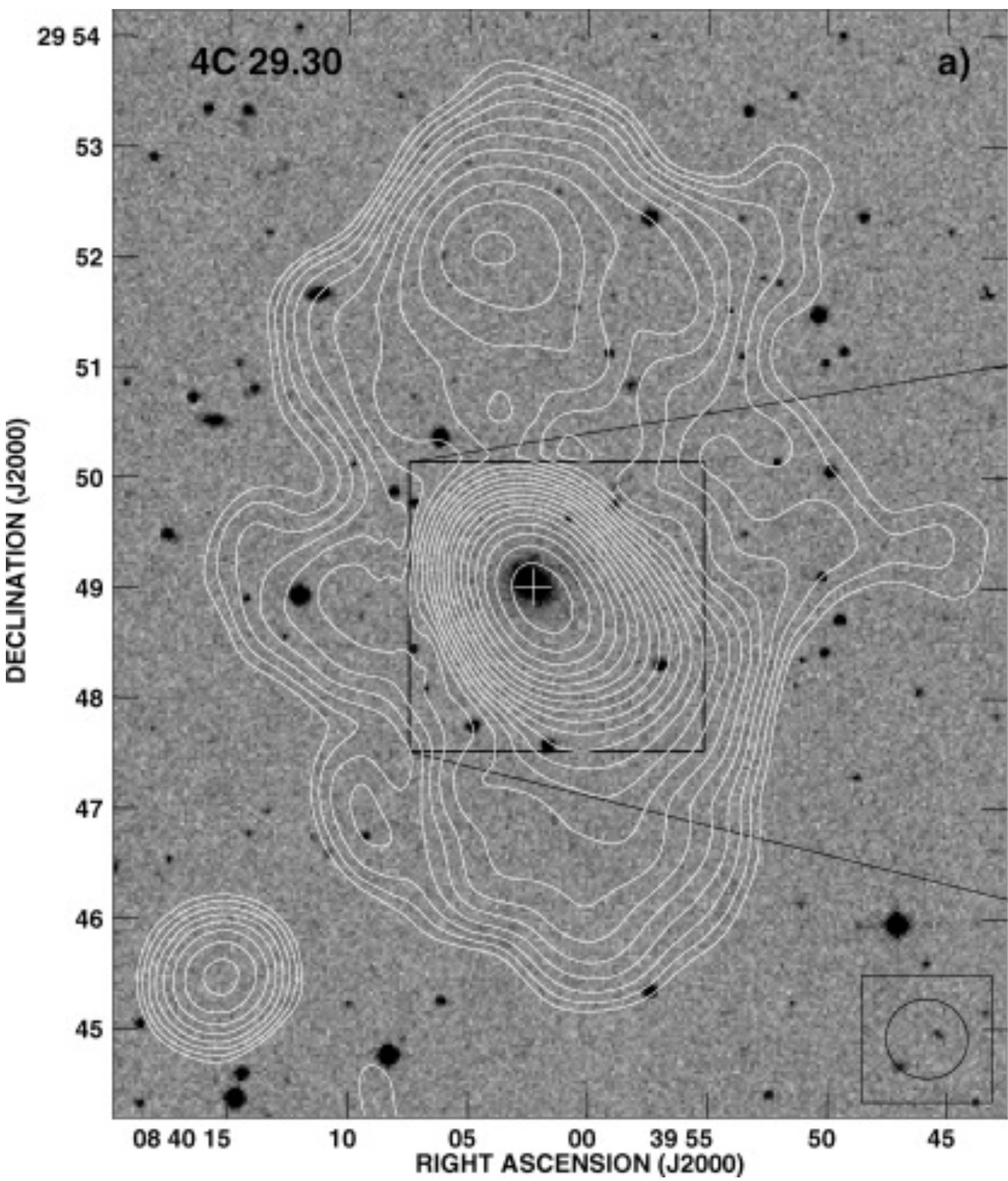
Surface Brightness Profile

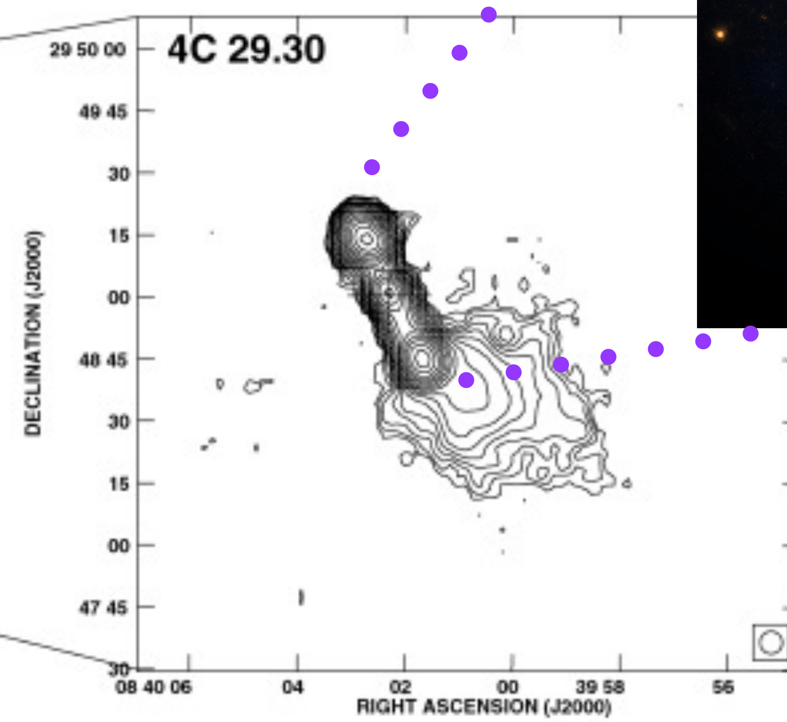


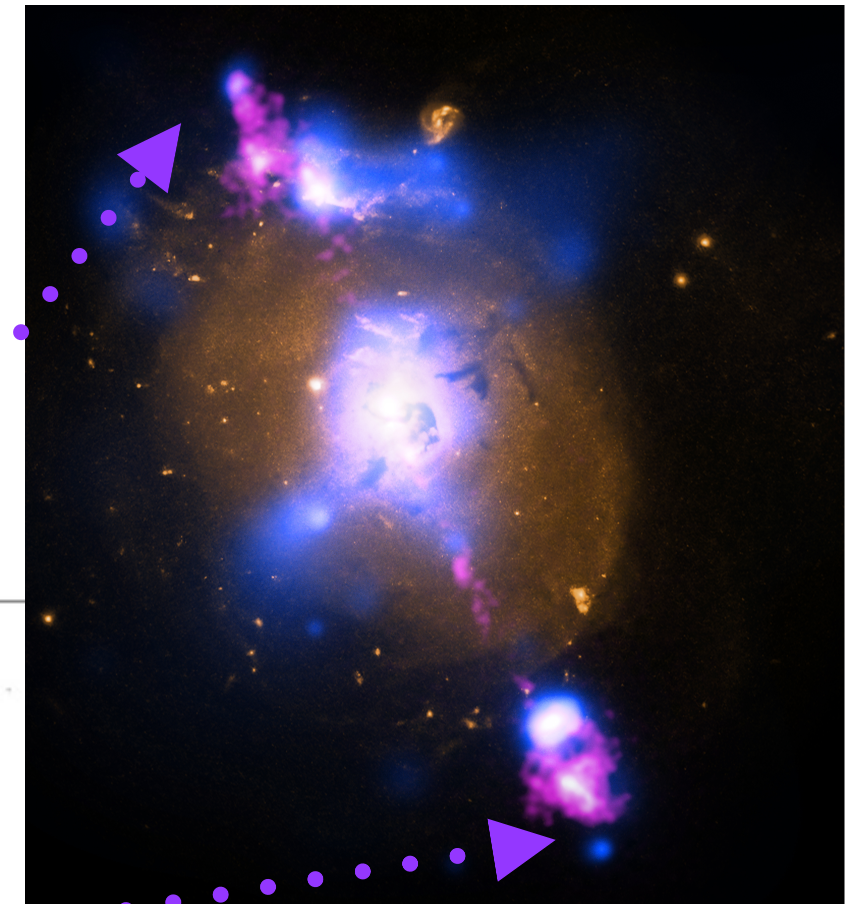
Jet Structure: Spine and Sheath

Intermittent activity?

Intermittent jet in 4C 29.30







Siemiginowska et al 2012

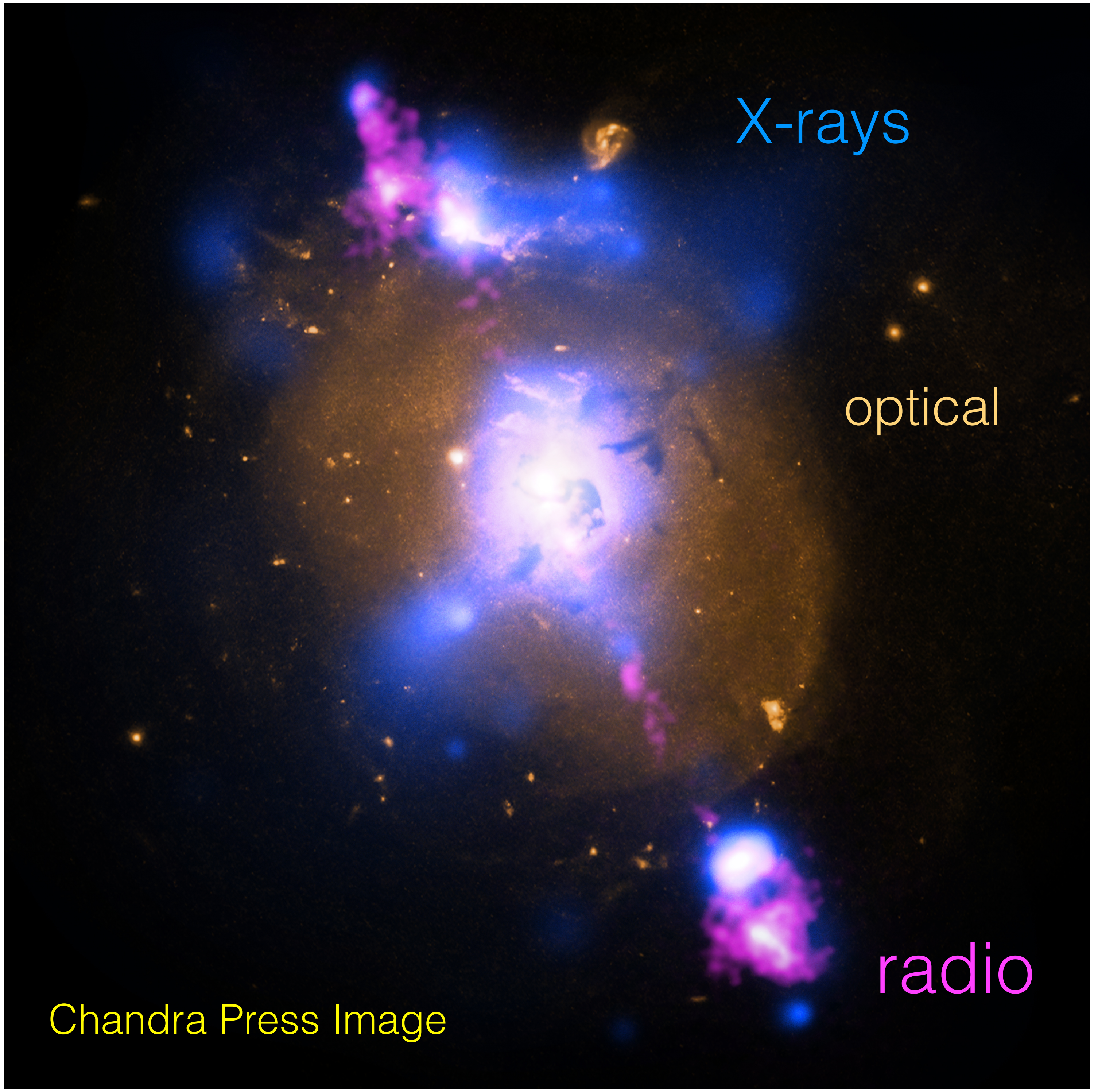
New radio jet:

age < 30 Myr

radio relic: age > 220 Myr

Jamrozy et al. 2007

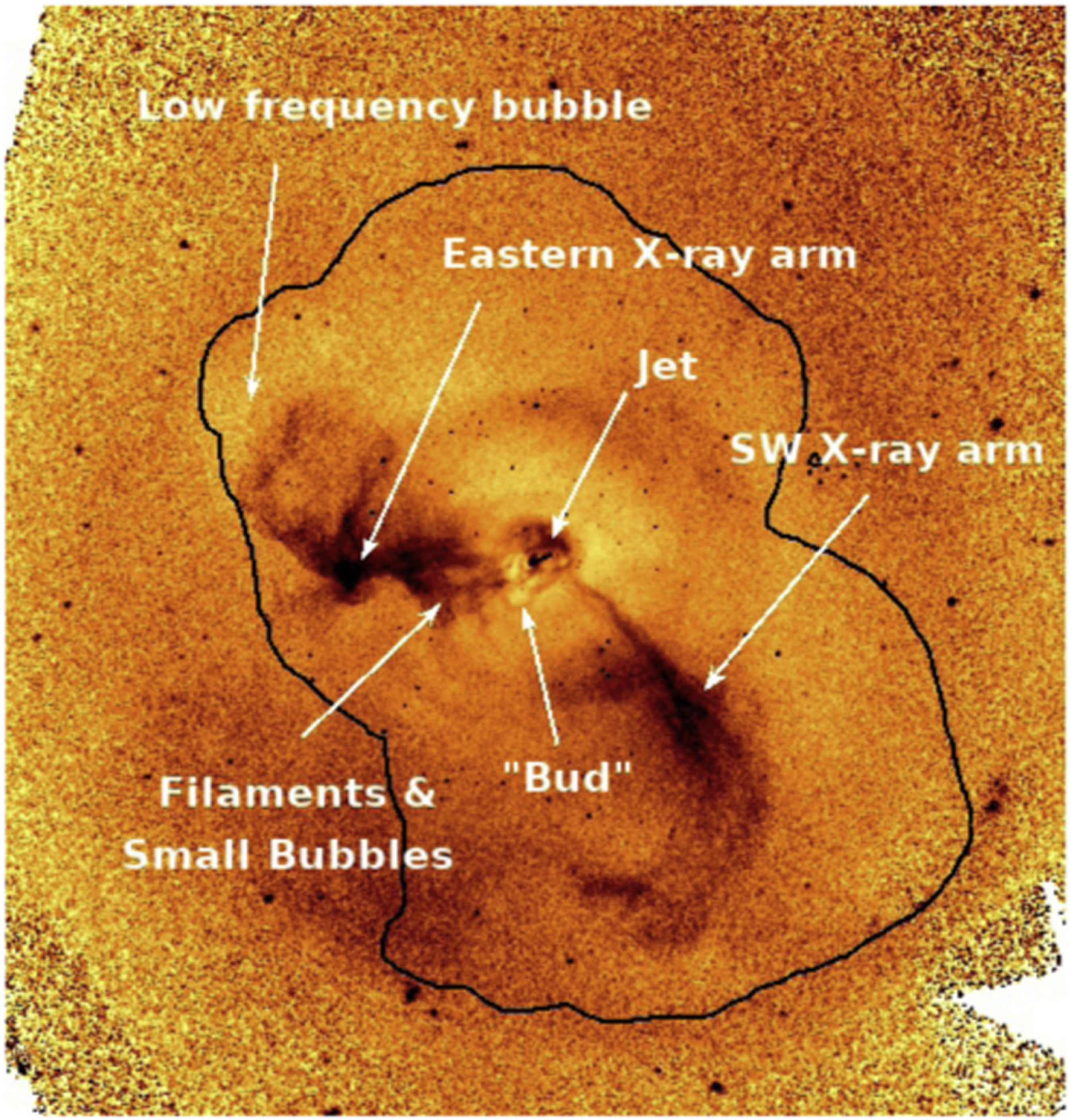
Intermittent jet in 4C 29.30



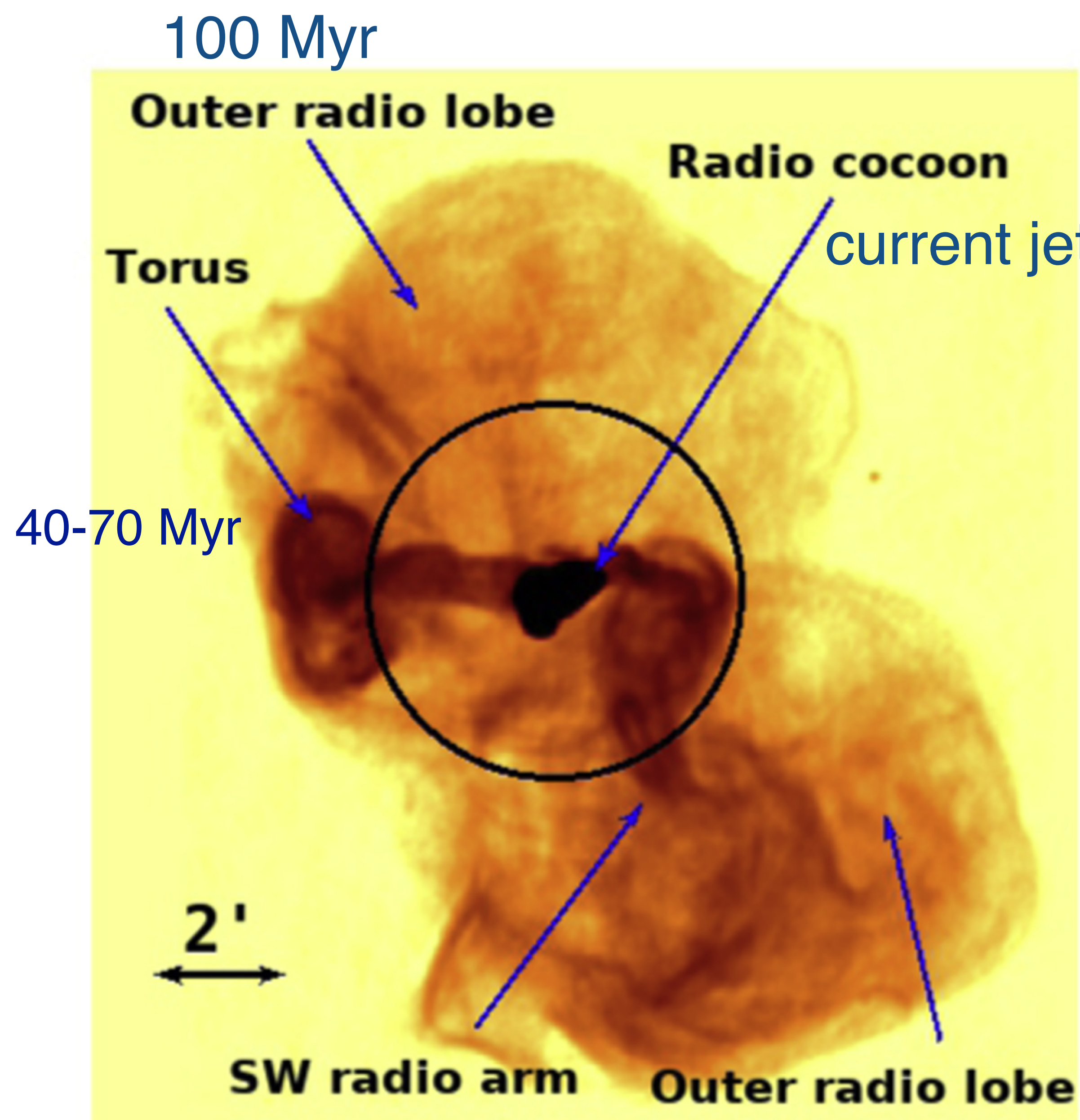
Siemiginowska et al 2012
Sobolewska et al 2012

Low-z galaxy
60 kpc Radio Jet
~ 30 Myr old

Past Activity of M87 BH



Chandra X-rays



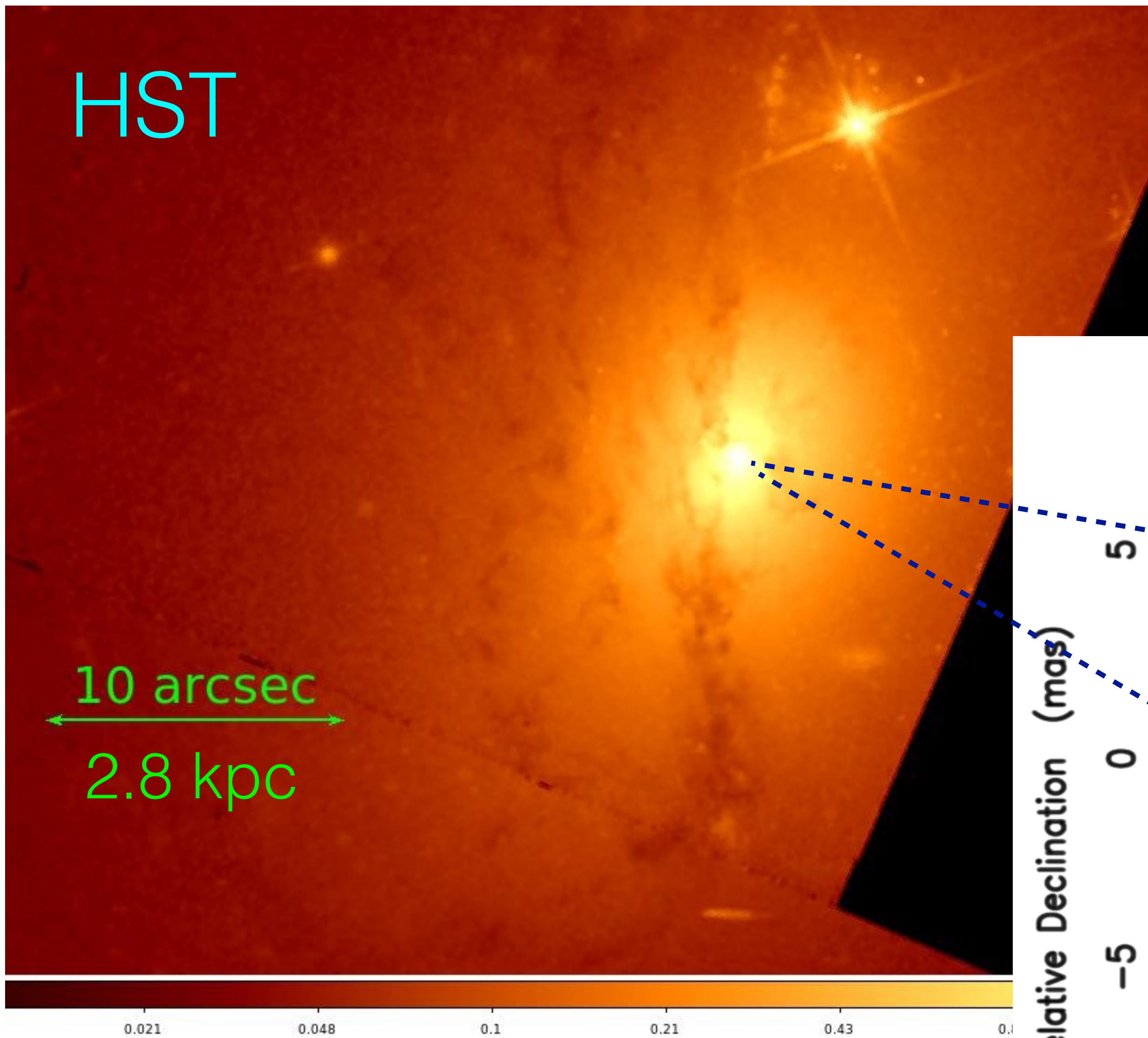
VLA/Radio

Forman et al 2015

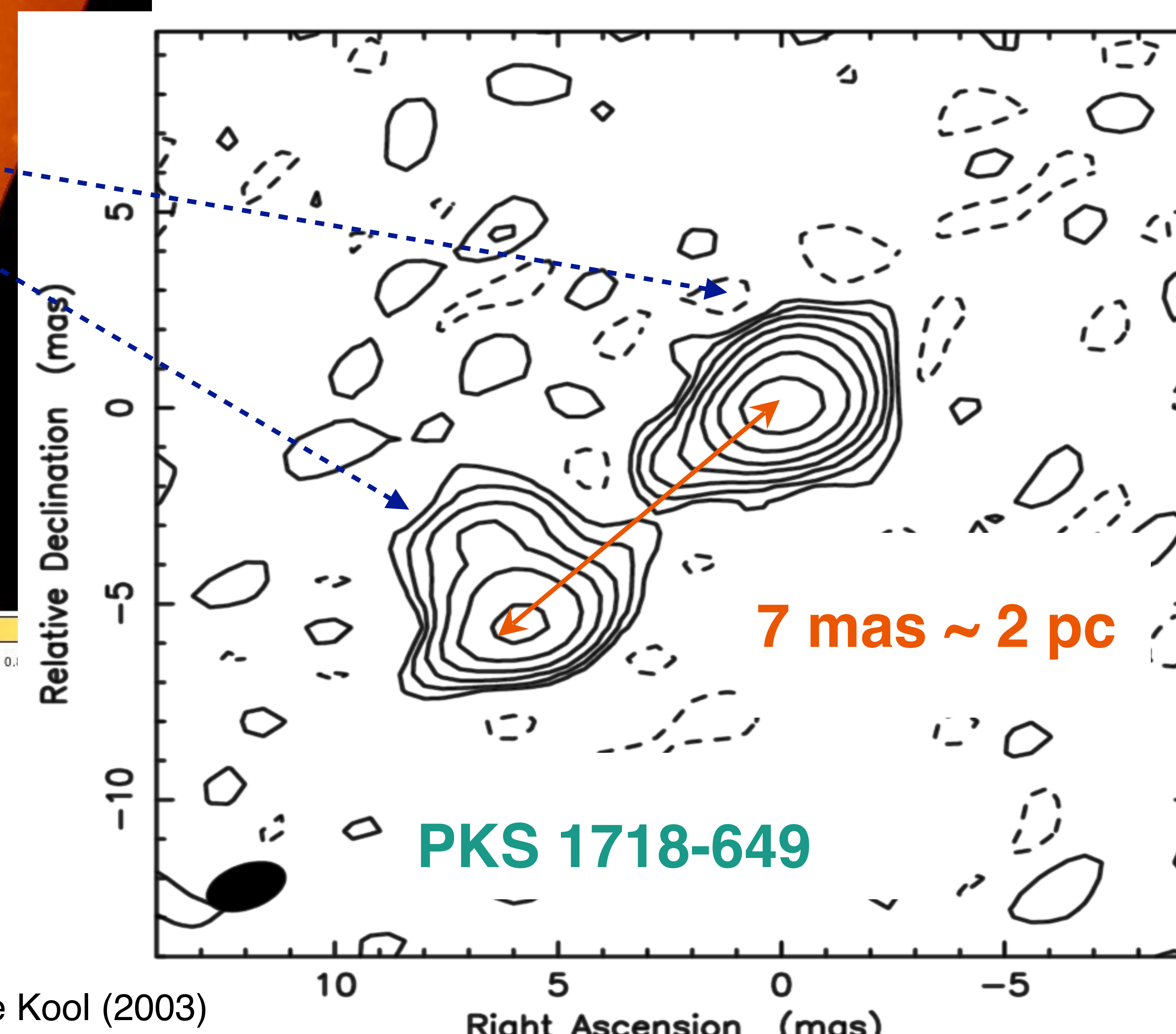
- Continuous current jet in Cygnus A and M87
- Intermittent outbursts

Young Jets - Compact Radio Sources

Kinematic age ~100 years



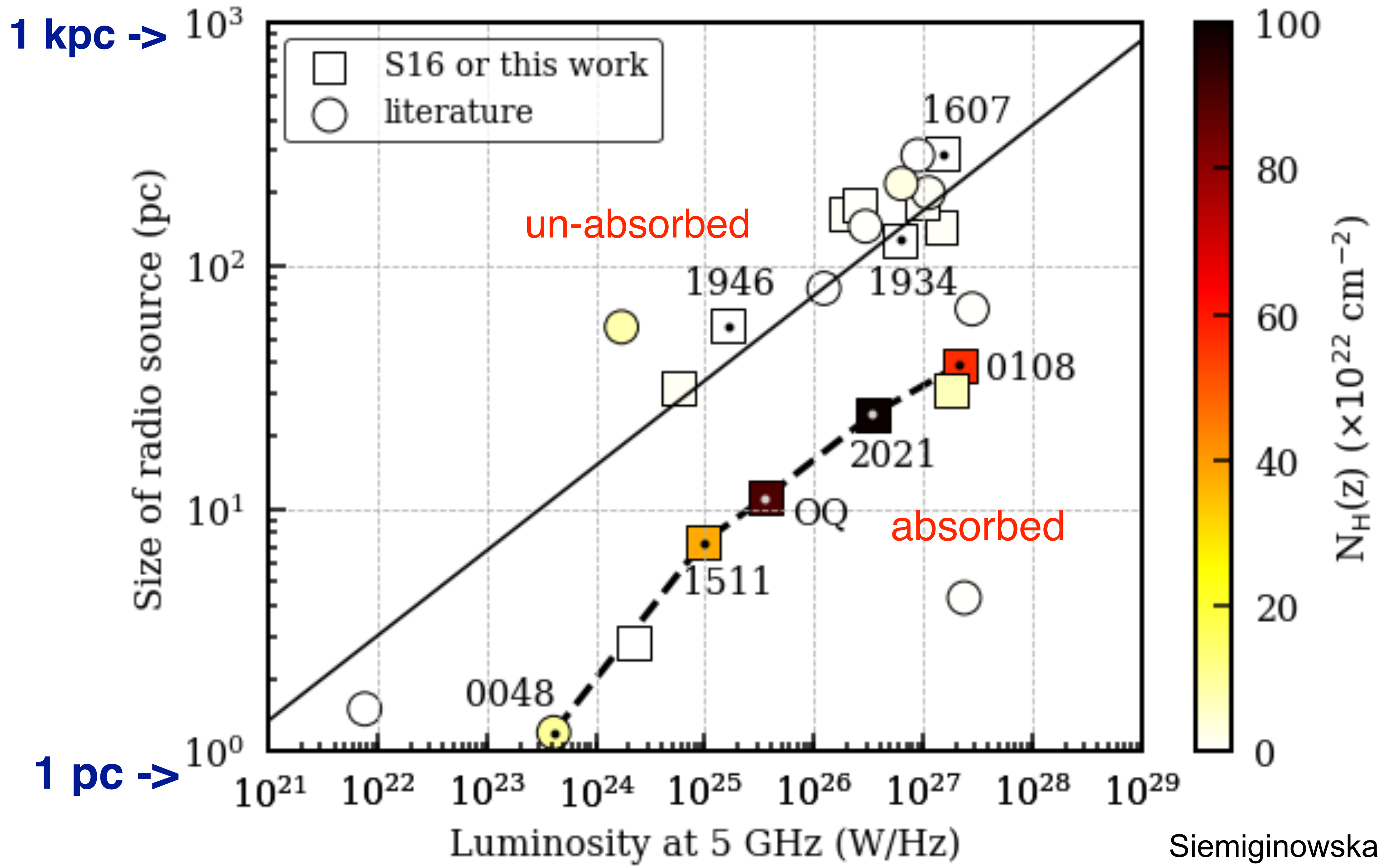
z = 0.014



Tingay, de Kool (2003)
22 GHz VLBI radio imaging

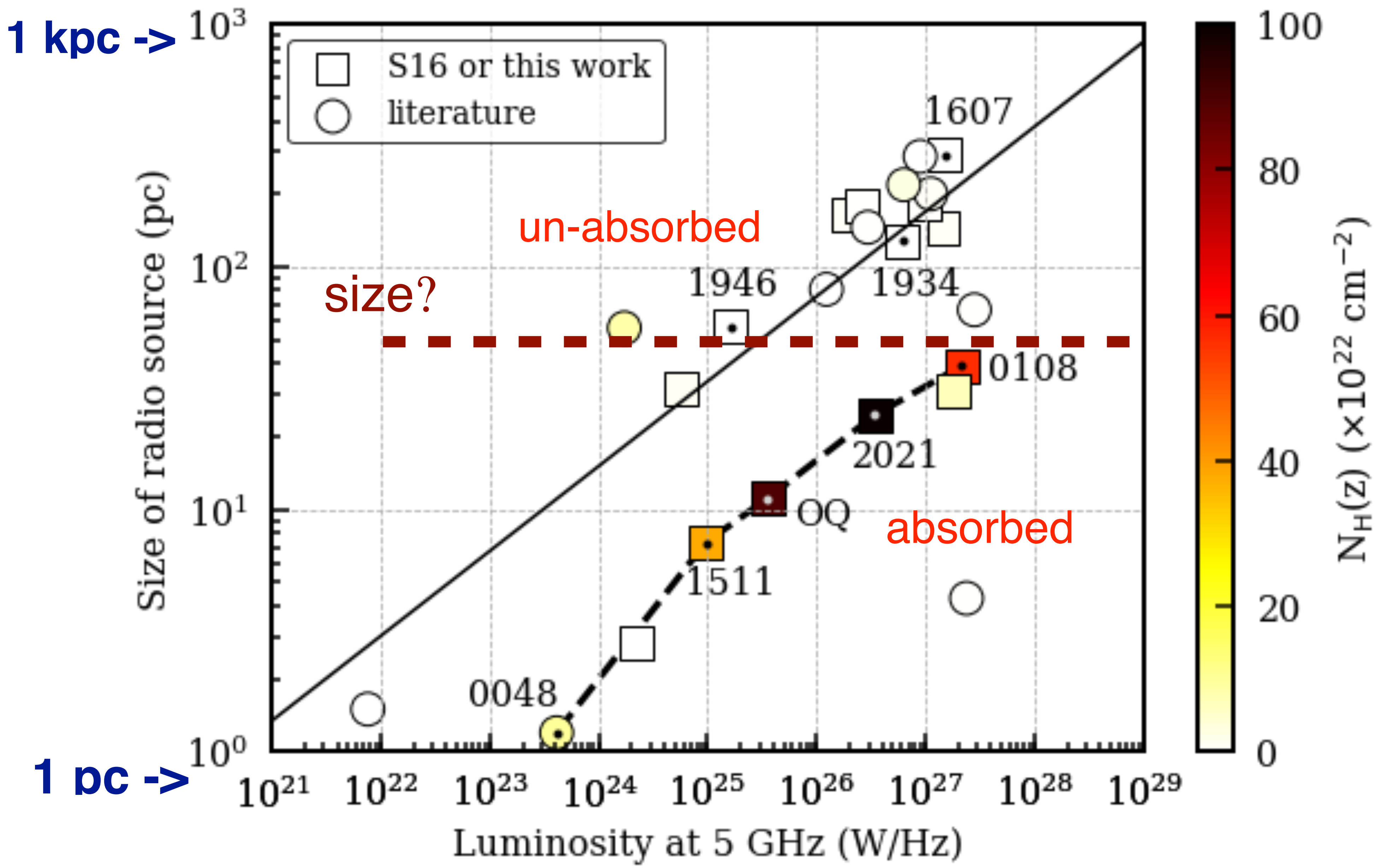
X-ray Absorption in CSOs

- X-ray **absorbed** CSOs appear to have **smaller radio size** than unabsorbed CSOs with the same radio luminosity at 5 GHz: **confinement?**



Siemiginowska et al. 2016
Sobolewska et al. 2019

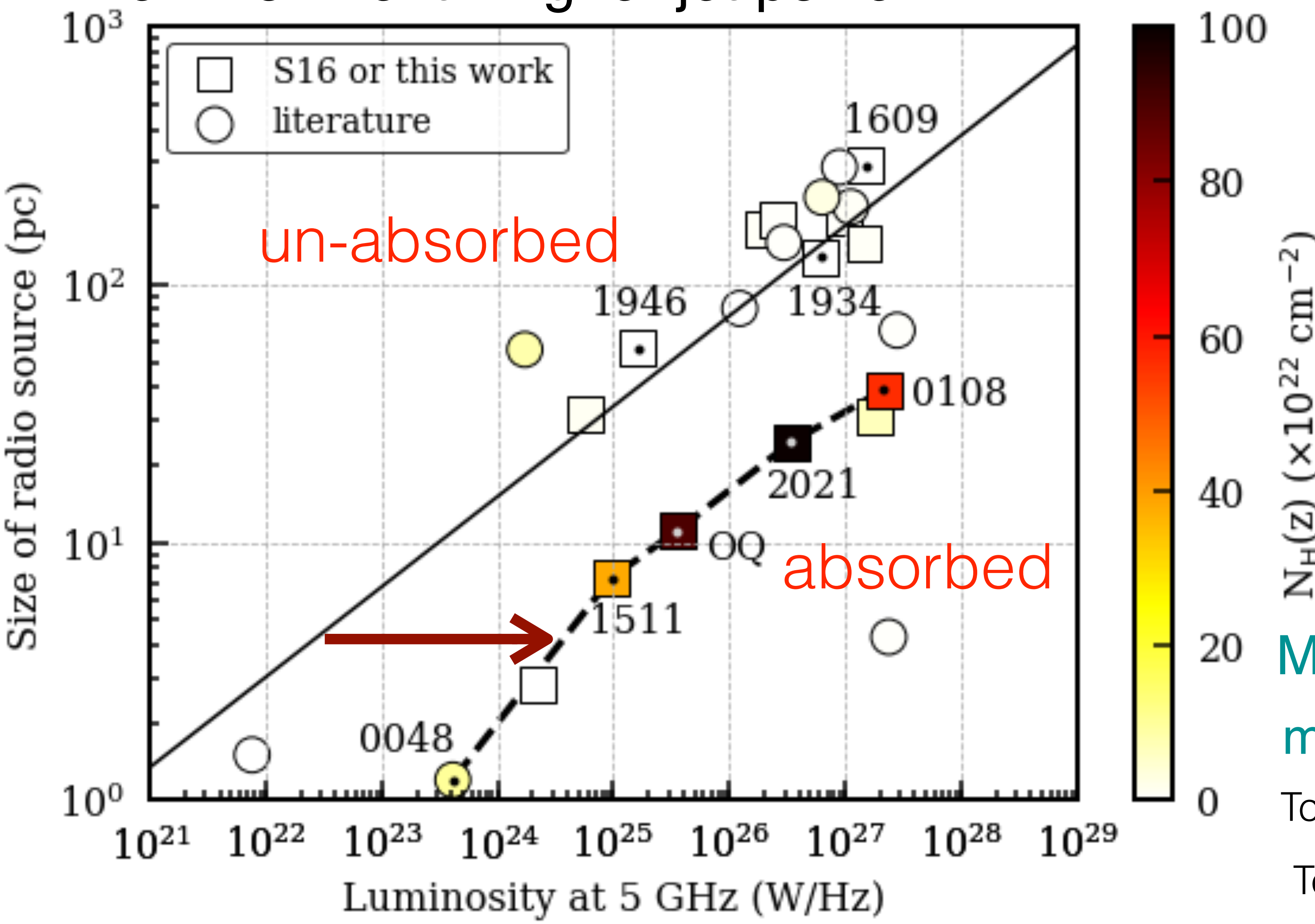
Compact Size of the Absorbers



- **No detection** of X-ray obscuration in CSOs with radio **sizes > few tens of** parsec: fundamental implications for:
  - the origin of X-ray emission
  - location of X-ray obscurer
  - interactions of expanding jet with the ISM

Jet Power? - High density Environment

- **X-ray absorbed CSOs appear to be more radio luminous** than X-ray unabsorbed CSOs with the same radio size: **born in high density environment? higher jet power?**



Blandford-Znajek

rotating BH

$$P_{jet} \propto \Omega_{BH}^2 \Phi_{BH}^2$$

angular frequency

poloidal magnetic flux

MAD - magnetically arrested disks

maximum efficiency of jet production

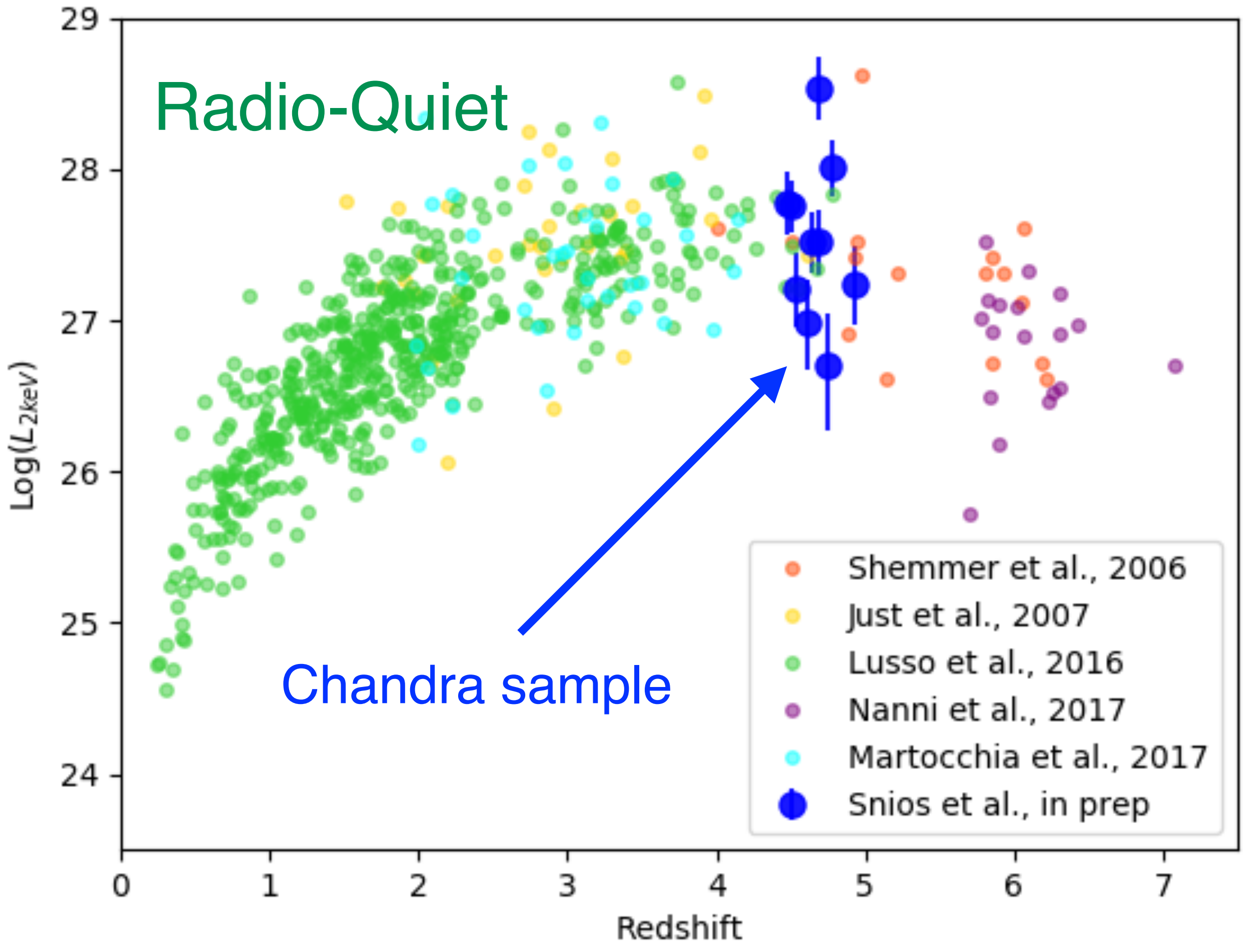
Tchekhovskoy, Narayan, McKinney 2011

Tchekhovskoy 2014

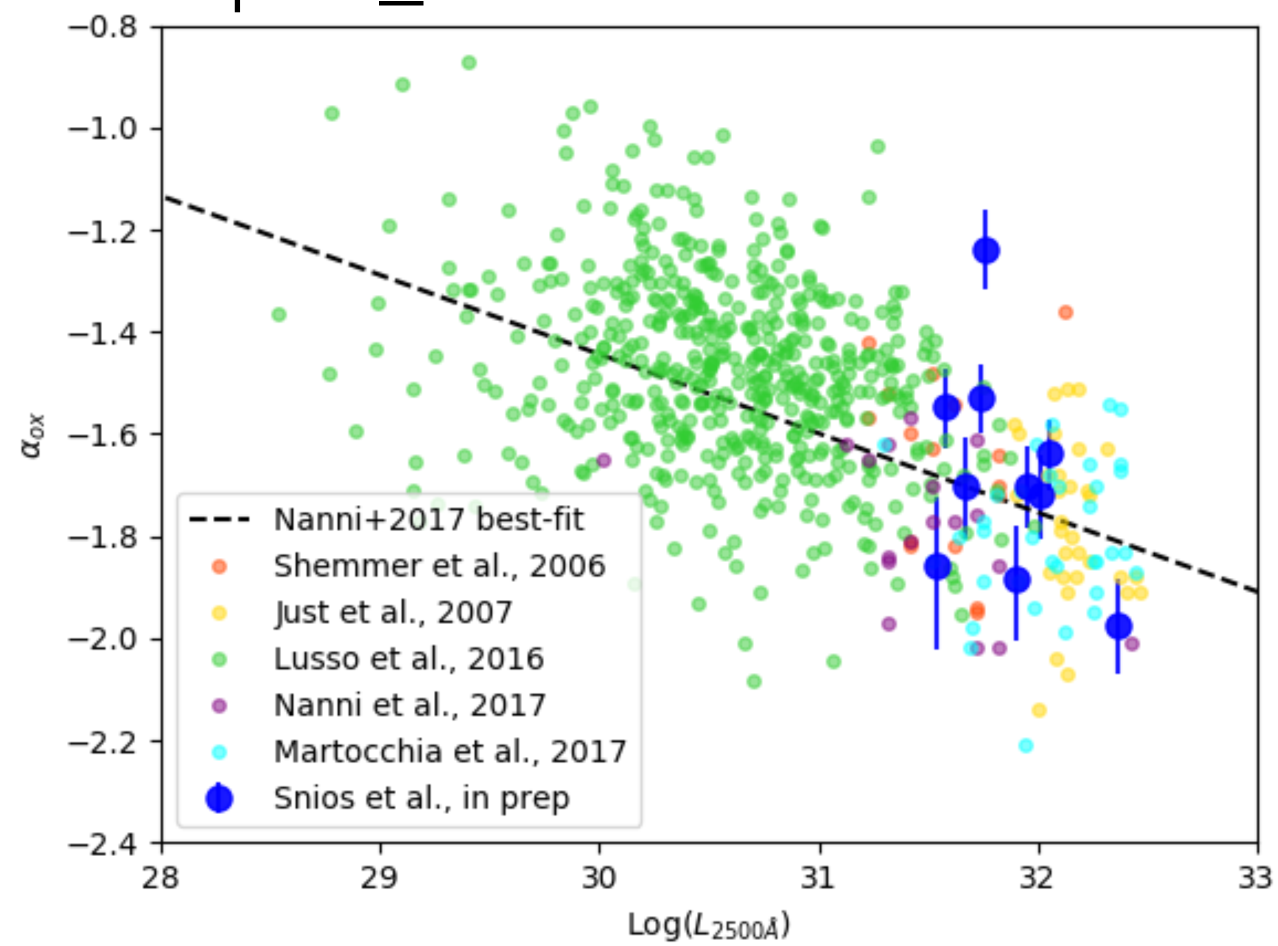
$$\Phi_{MAD} \approx 50(\dot{M} r_g^2 c)^{1/2}$$

Young Radio Sources at High Redshift

Luminosity at 2 keV



alpha_ox



Chandra sample of spectral peaked/steep radio sources at high-z

Jets at High Redshift

- Jets signal active black hole accretion.
- Require central nuclei of high-z galaxies to be well developed to sustain accretion
- Jet production process is efficient and persists long enough to produce the structures on scales of tens to hundreds of kiloparsecs.
- Jets can shock heat ambient gas and trigger early star formation in the early Universe.
- Jets can be amplified by increased energy density of the Cosmic Microwave Background

Timescales

- BH Mass ~10^9 M_{sun}
    - BH formation, constraints at high-z
- Fuel supply
    - amount? steady or intermittent?
- Galaxy scale
    - ISM interactions, energy dissipation, continuous activity
- Galaxy clusters
    - active jets in X-rays, hotspots, lobes - livetimes, and energetics, history?

A few Questions

- Why do we have jets?
    - accretion modes
- How do jets form and accelerate?
    - BZ/BP - need B field, spin, collimation
- Why do jets survive?
    - instabilities (e.g. KH, RT, CF) in 3D simulations

Summary

- History of AGN Black Hole activity is imprinted in the large scale structures
- Timescales: old and young structures
- What determines the onset of BH activity?
- Potential differences in the environment in very close vicinity of a BH - direct impact on BH feeding and feedback