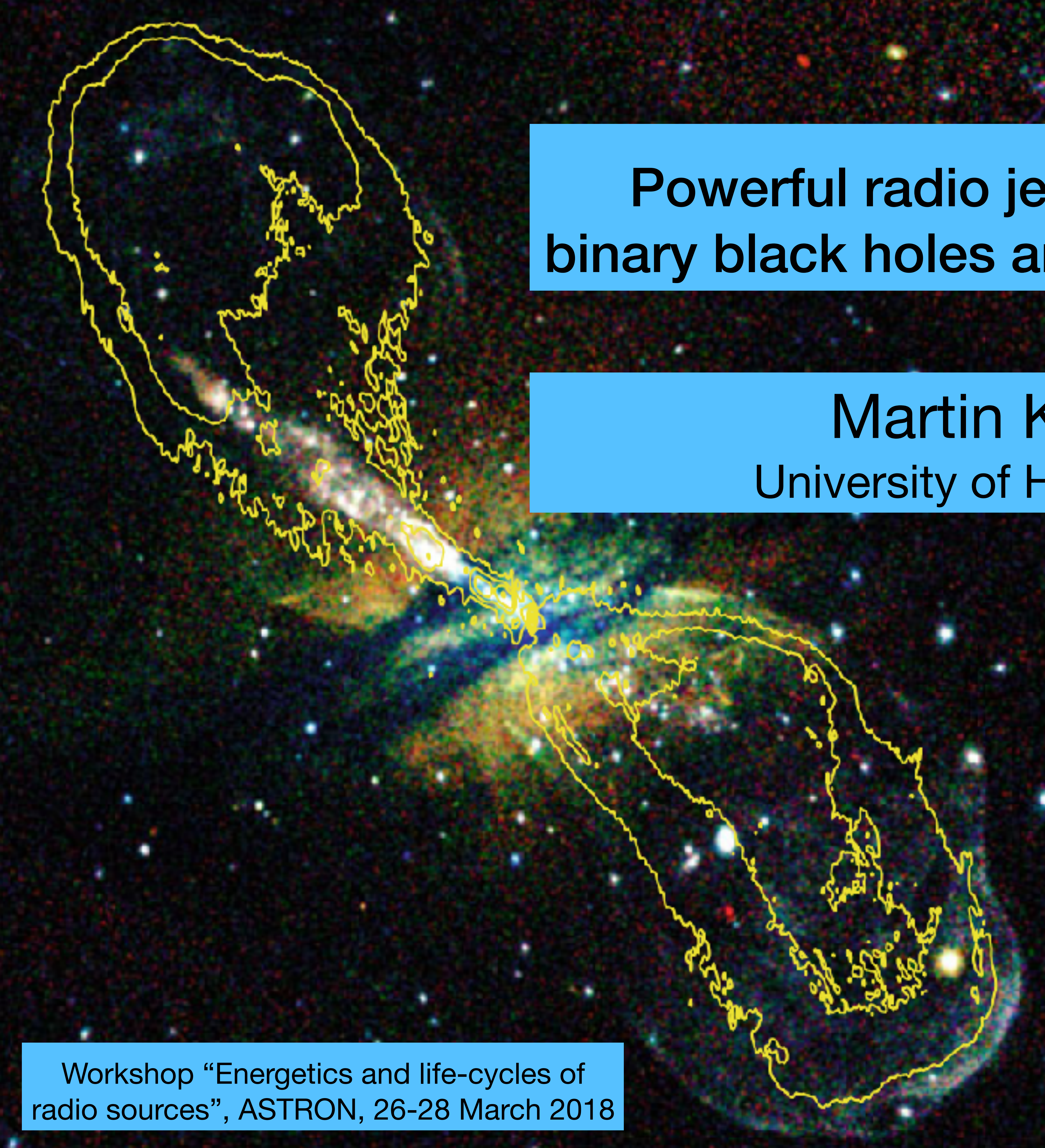


Powerful radio jets are linked to binary black holes and galaxy mergers

Martin Krause

University of Hertfordshire

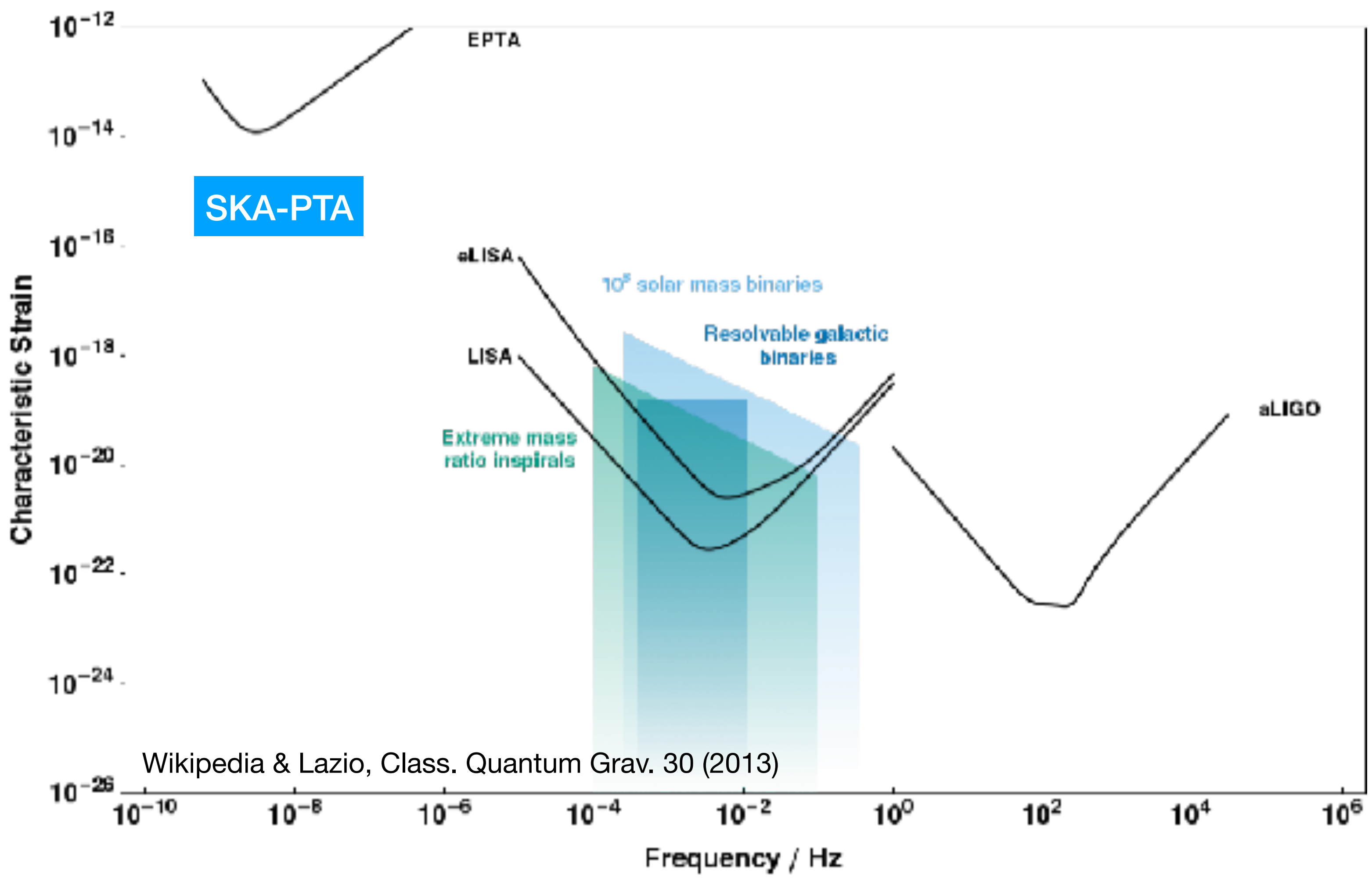
with

Geoffrey V. Bicknell, Hans Böhringer, Gayoung Chon, Roland Diehl, Martin Hardcastle, Mohammad A. Nawaz, Marc Sarzi, Stanislav S. Shabala, Alexander Y. Wagner

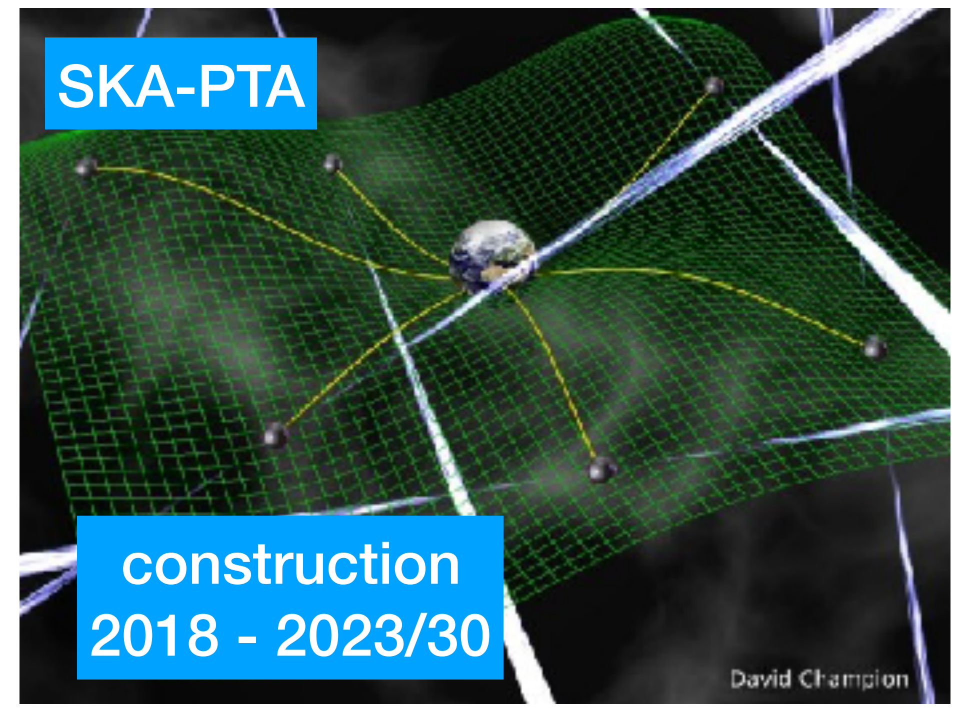
Workshop “Energetics and life-cycles of radio sources”, ASTRON, 26-28 March 2018

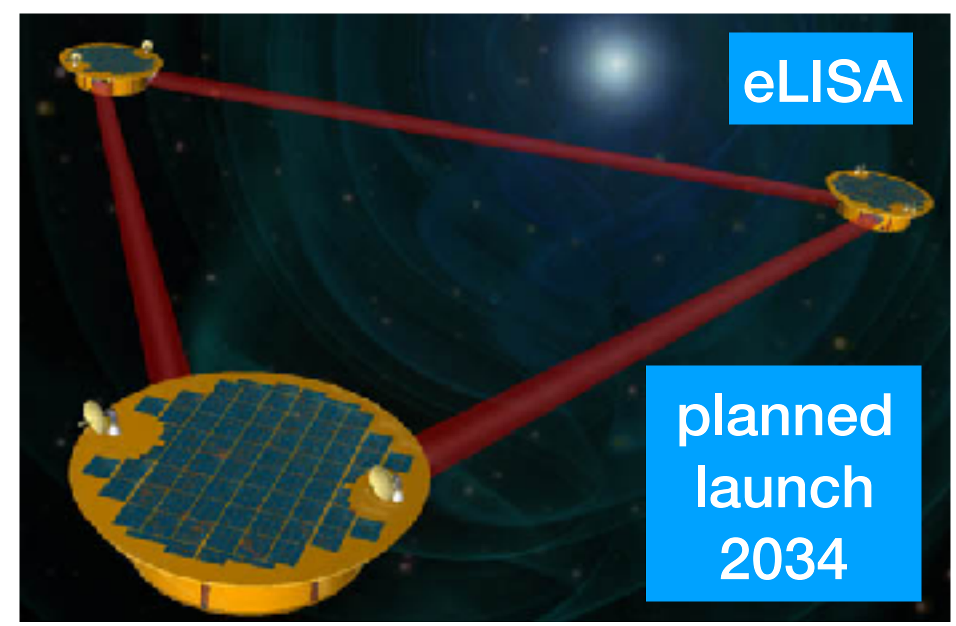
Supermassive Binary Black Holes (SMBBH)

- Pulsar Timing Arrays
  ⇒ upcoming Square Kilometre Array radio telescope (SKA), supermassive BH
- eLISA - space interferometry, up to 10^7 Msun

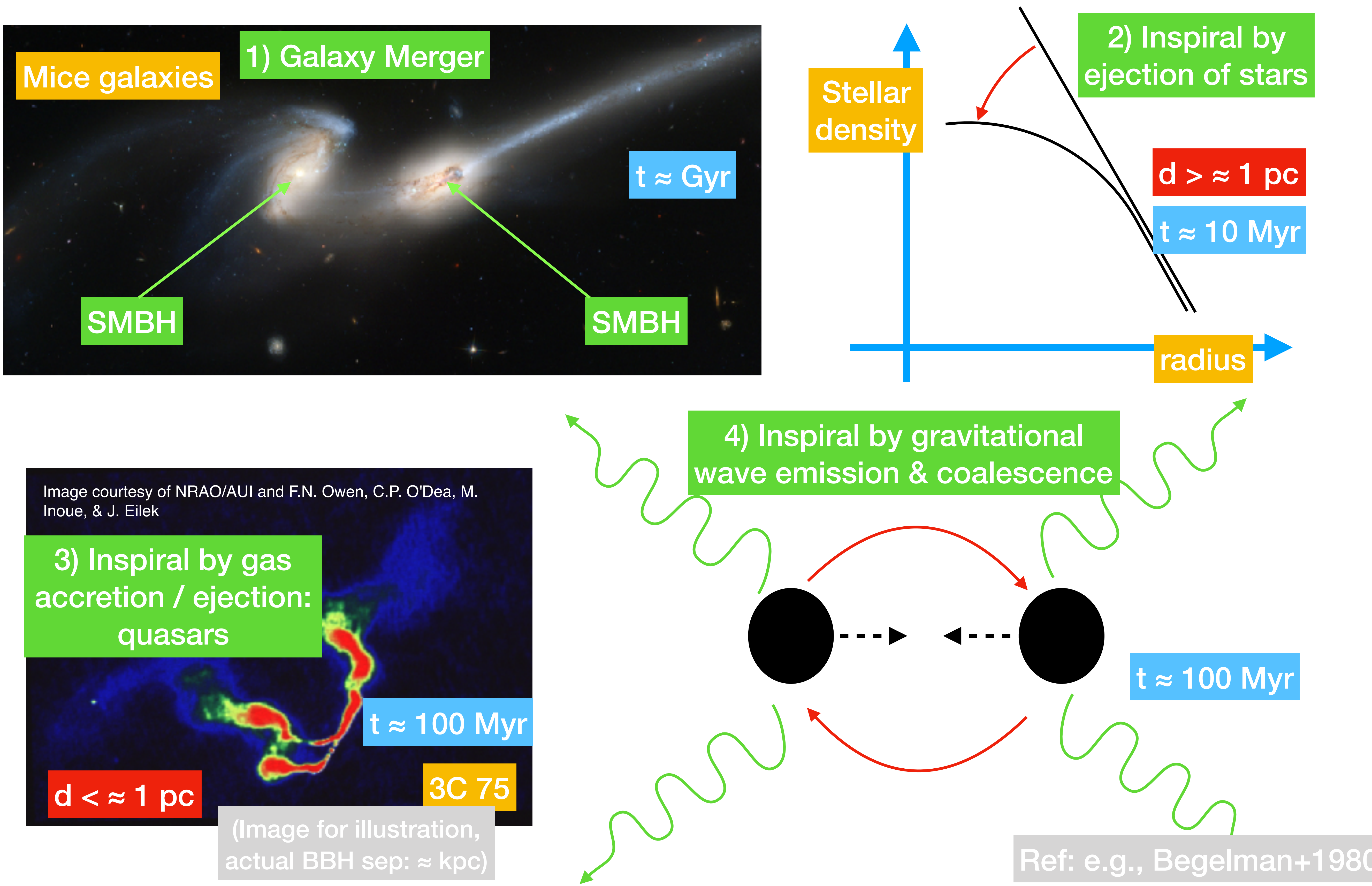


Wikipedia & Lazio, Class. Quantum Grav. 30 (2013)

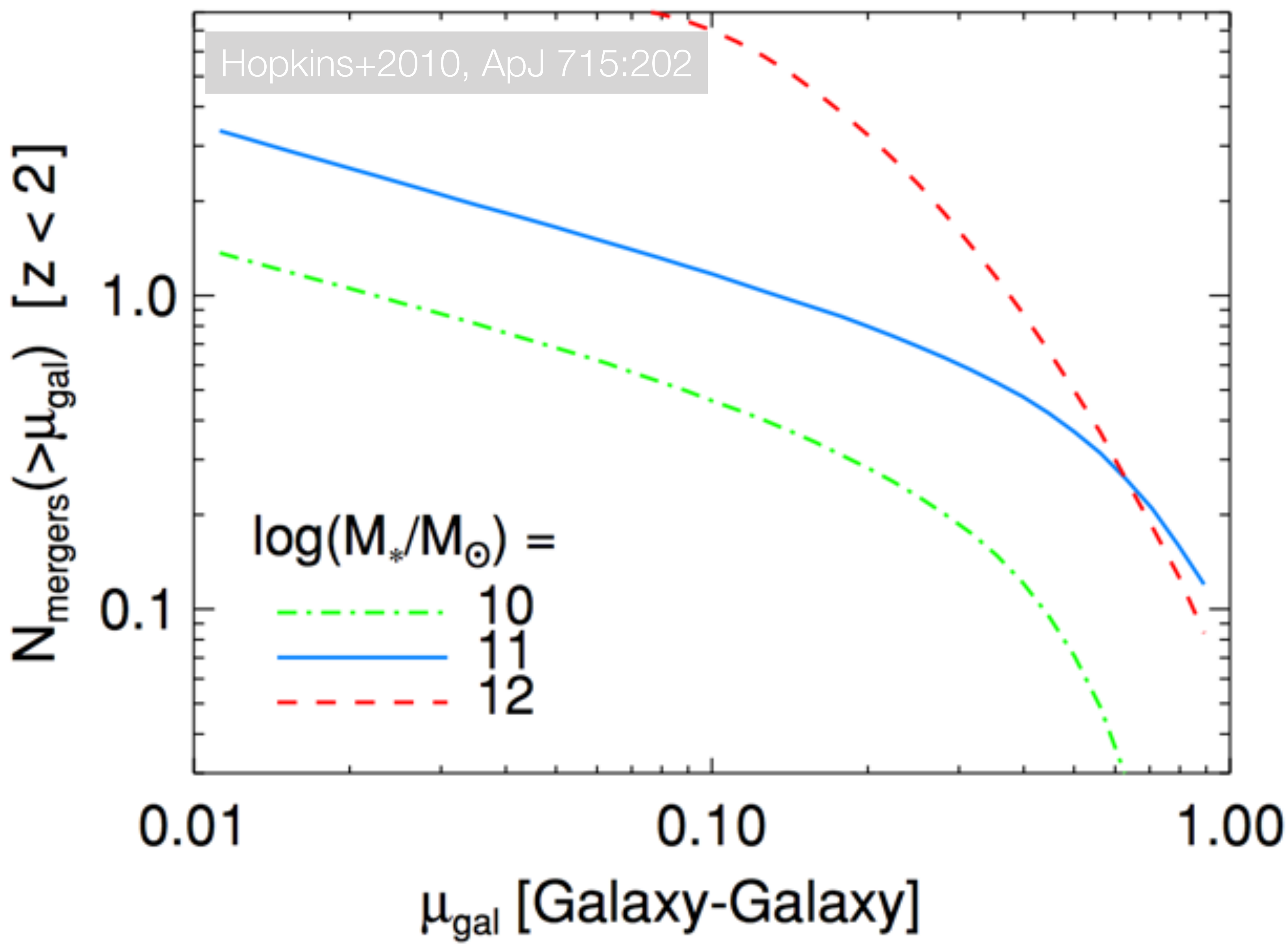




How do you get an SMBBH?



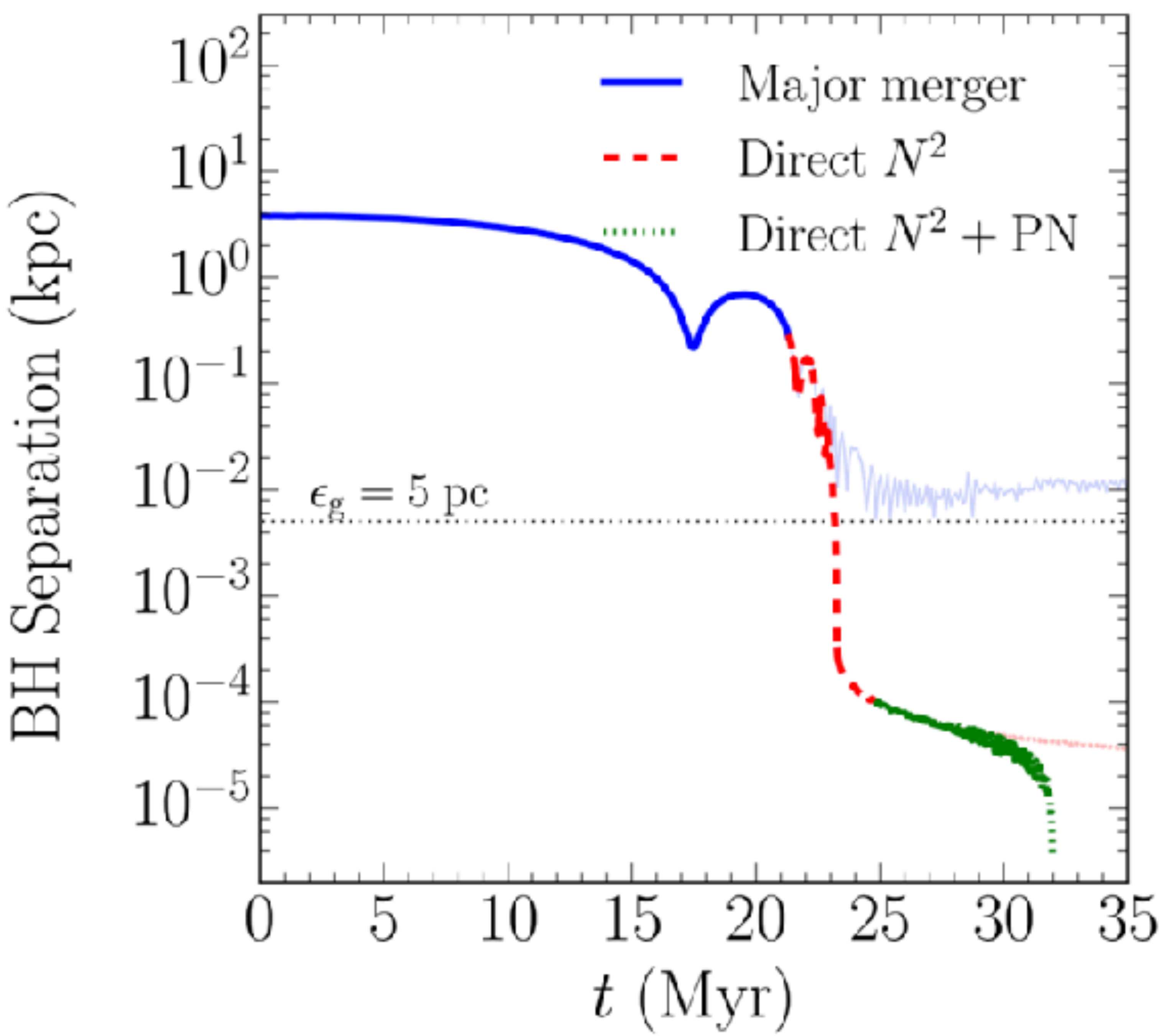
How many mergers?



⇒ Big galaxies (=big black holes) eat smaller galaxies at a rate of ≈ 1 / Gyr

⇒ expect frequent SMBBHs

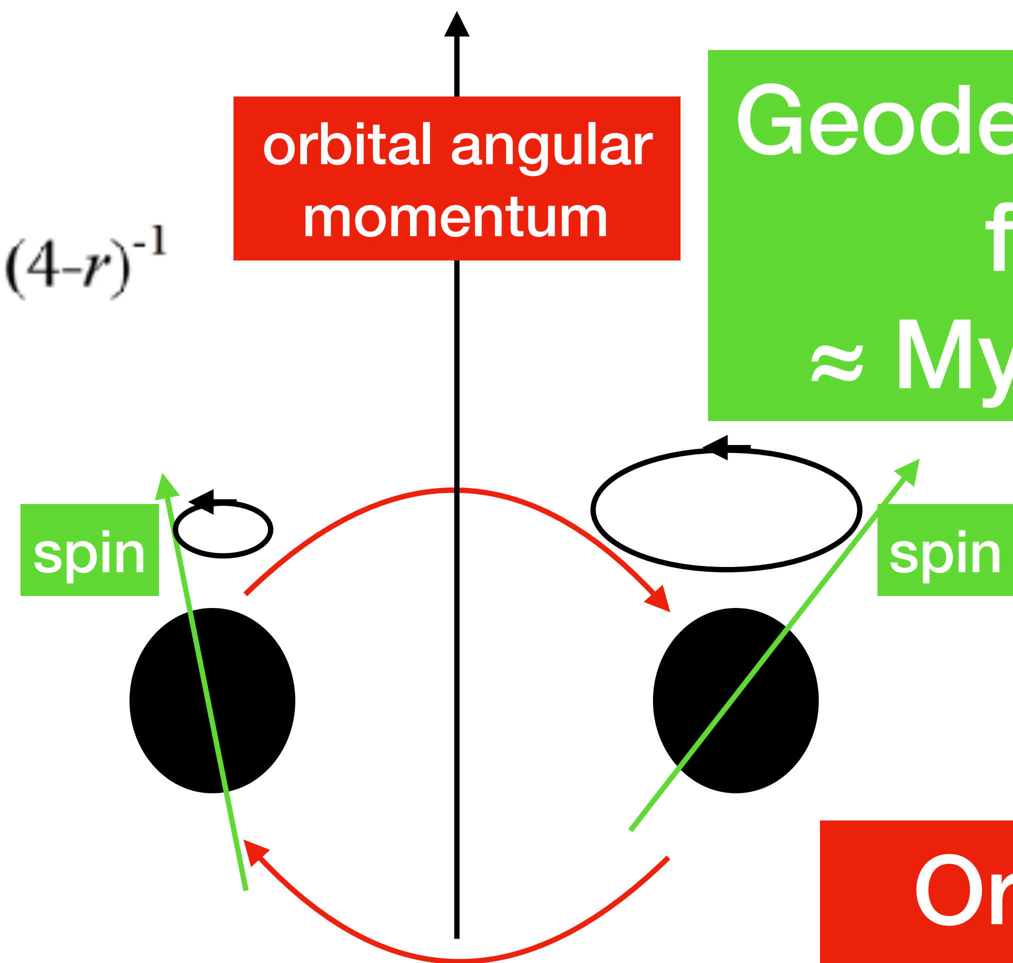
What binary separations?



Merger simulation
Mayer et al. 2017

Dynamics of black hole binaries

$$P_{gp} = 41 \text{ Myr } d_{pc}^{5/2} M_9^{-3/2} \; r^{-1} (4-r)^{-1}$$

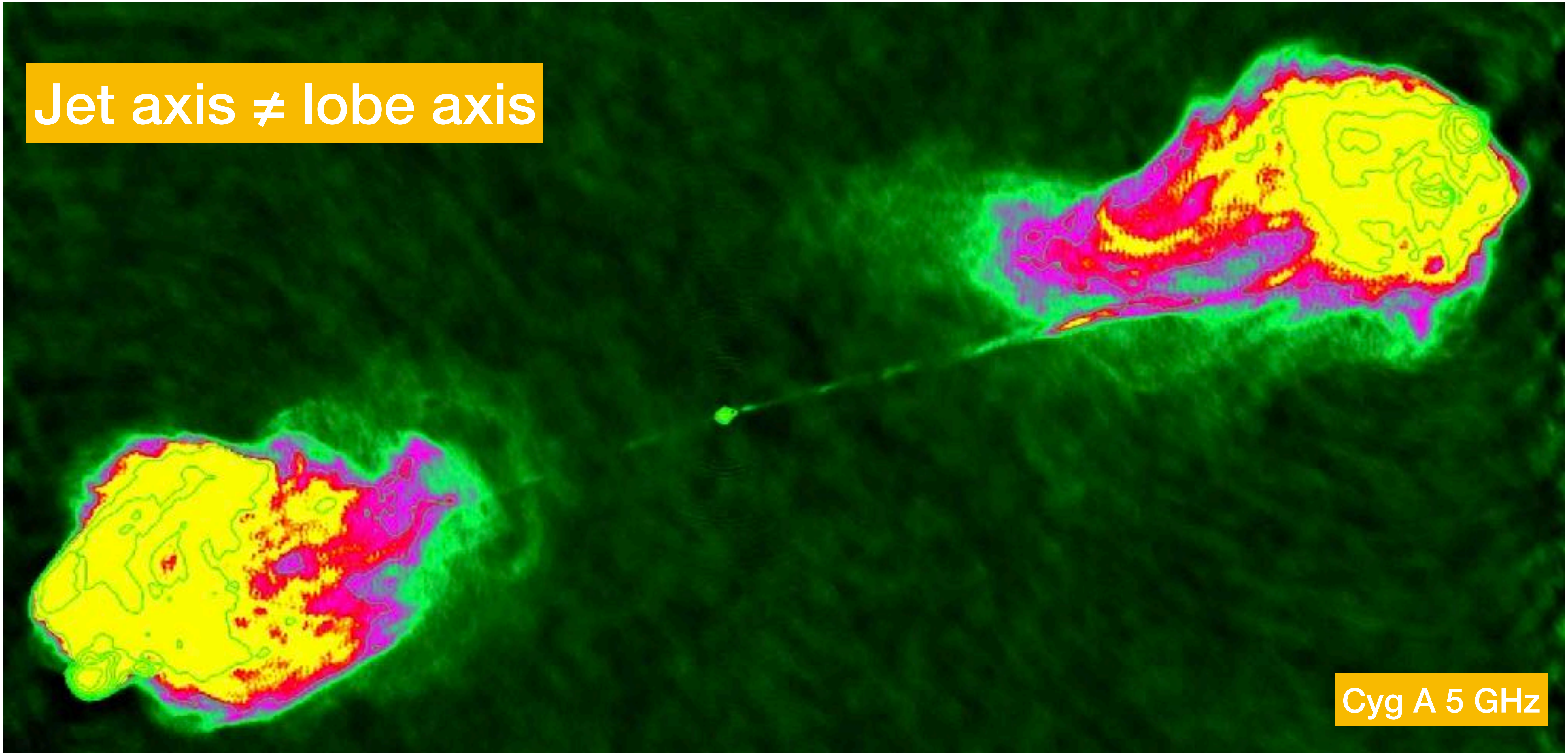


Geodetic precession for spins: ≈ Myr @ sep < pc

Orbital period @ sep < pc: 10s- 1000s of years

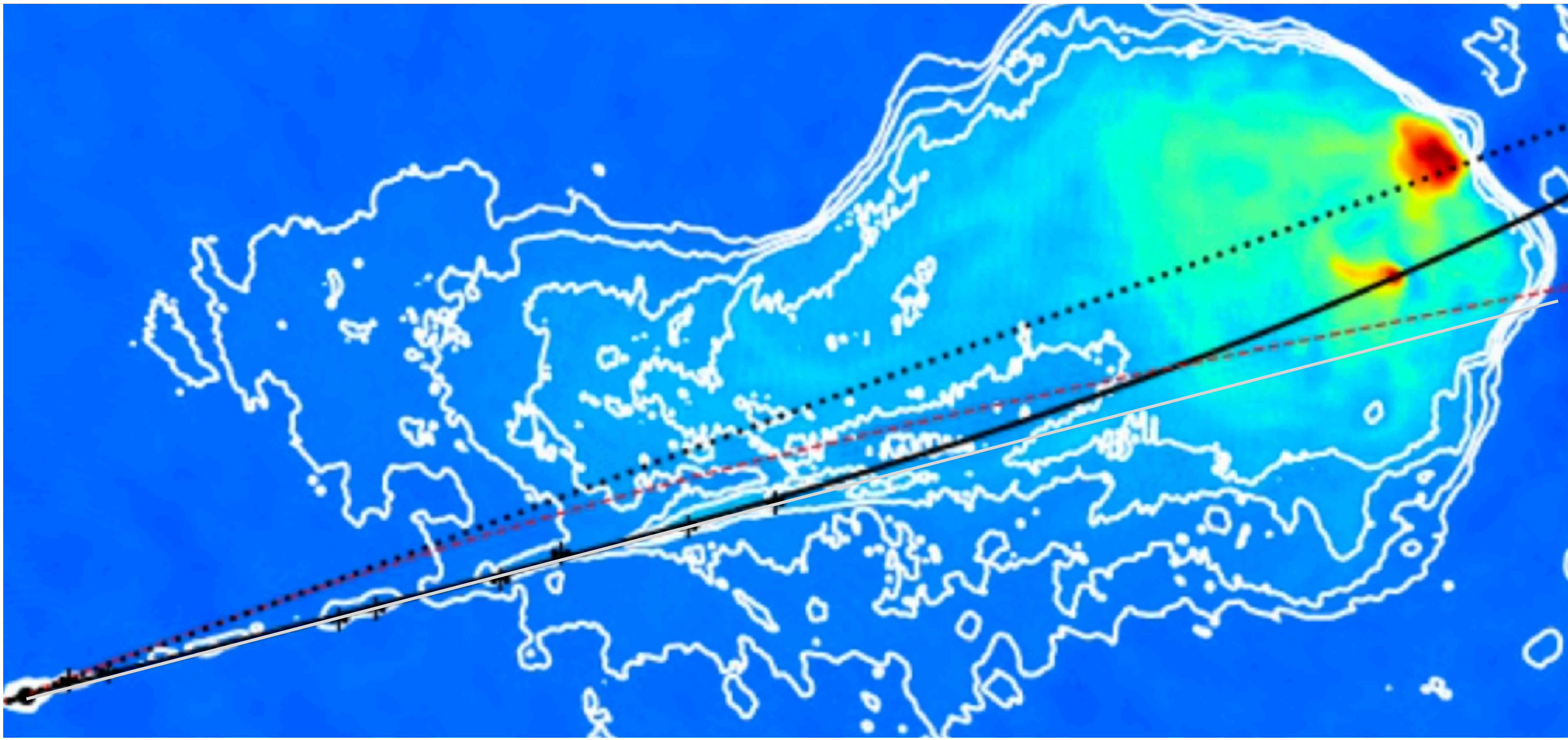
Jets ejected in direction of spin vector (and opposite).
Jets should trace both motions.

Evidence for precession



- Jet axis: current spin axis
- Lobe axis: orbital angular momentum of binary

Relativistic aberration model

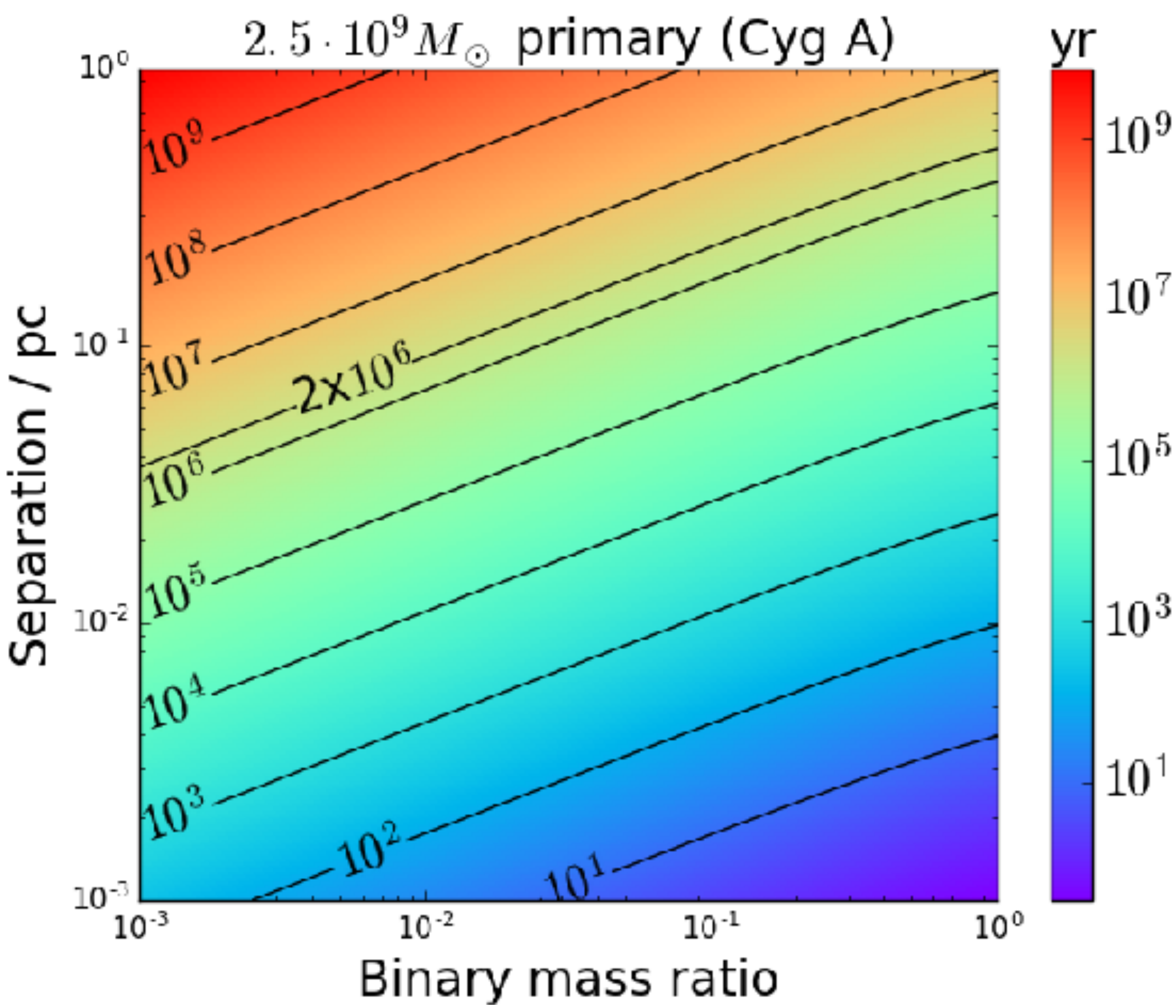


- Fit: precession period = 1.3 Myr

{ < source age ≈ 20-30 Myr / morphology

  > plasma travel time through jet, 0.2-0.3 Myr

Geodetic precession: constraints on binary

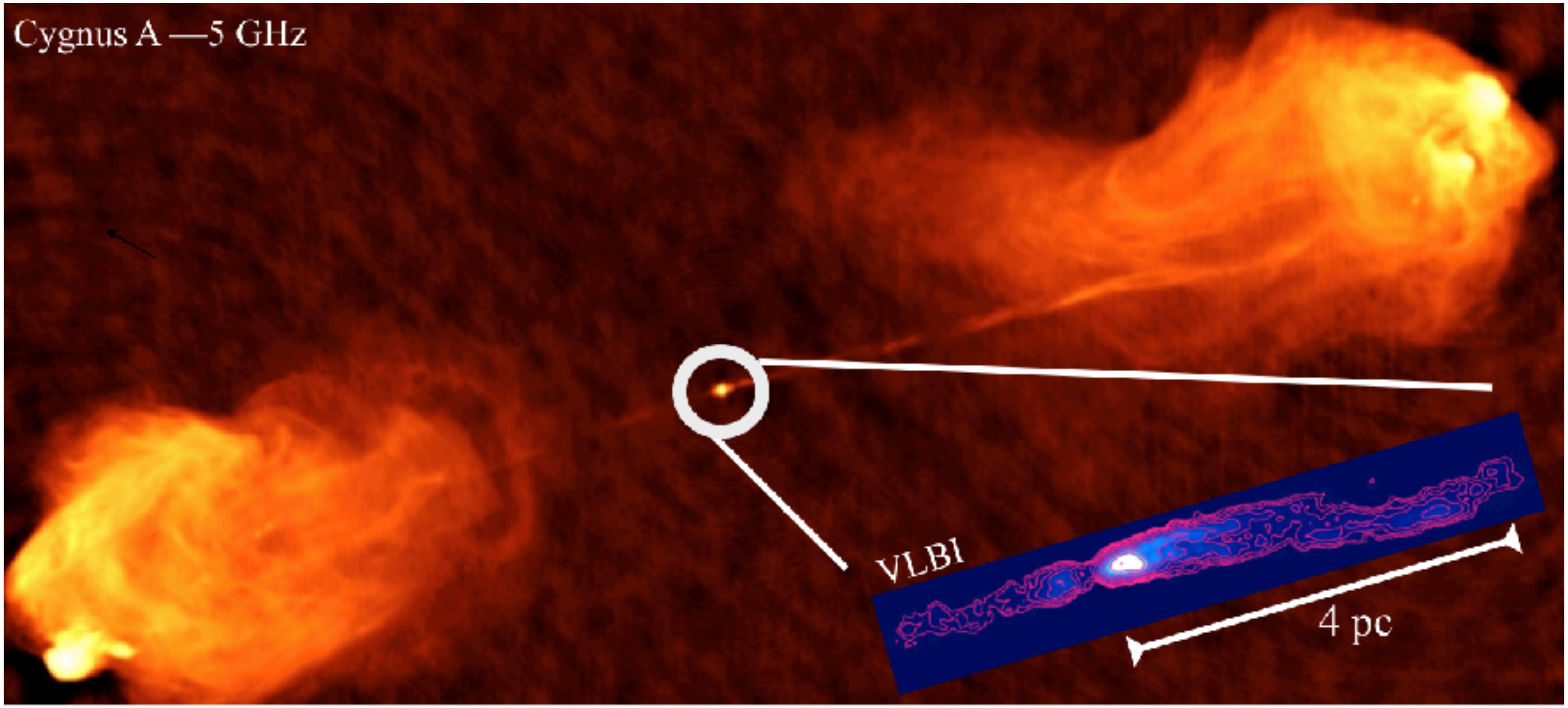


$P_{gp} = 41\ \mathrm{Myr}\ d_{pc}^{5/2}\ M_9^{-3/2}\ r^{-1}\ (4\text{-}r)^{-1}$

Black hole mass:
$2.5 \times 10^9\ M_{sun}$

Binary separation
< 0.5 pc

VLBI

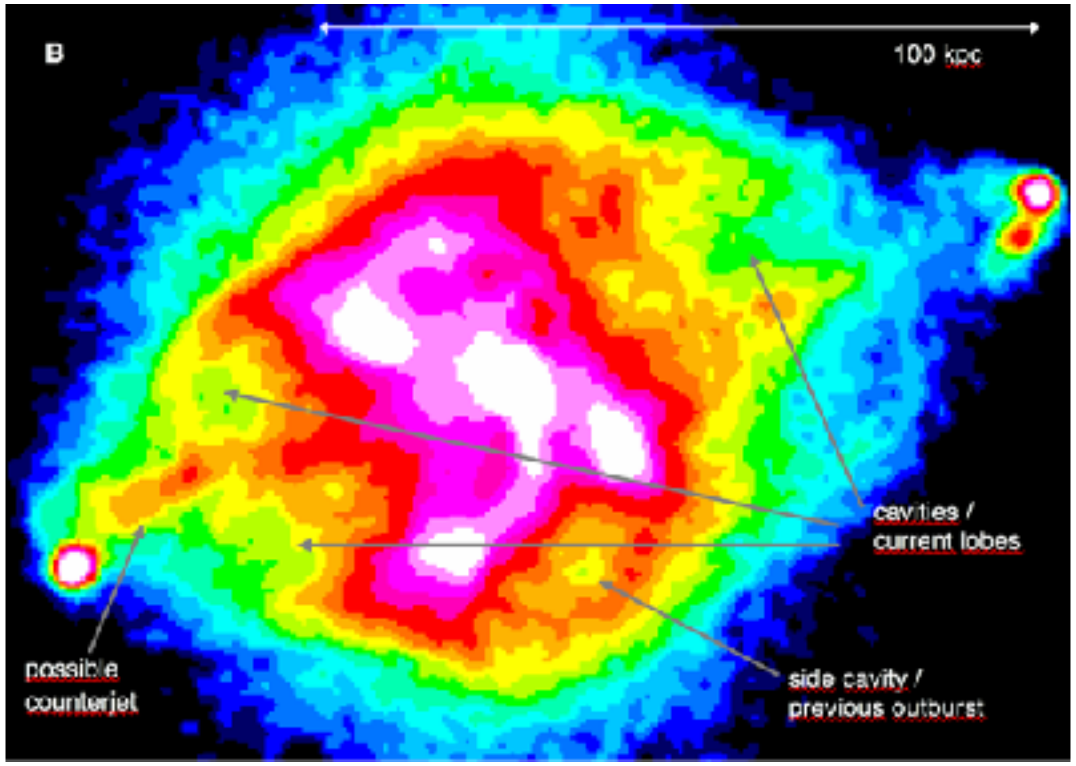


- Helix for parsec scale jet reveals orbital period:
  T_{orbit} = 4 pc / (jet velocity) = 18 years ⇒ **binary sep = 0.05 pc**

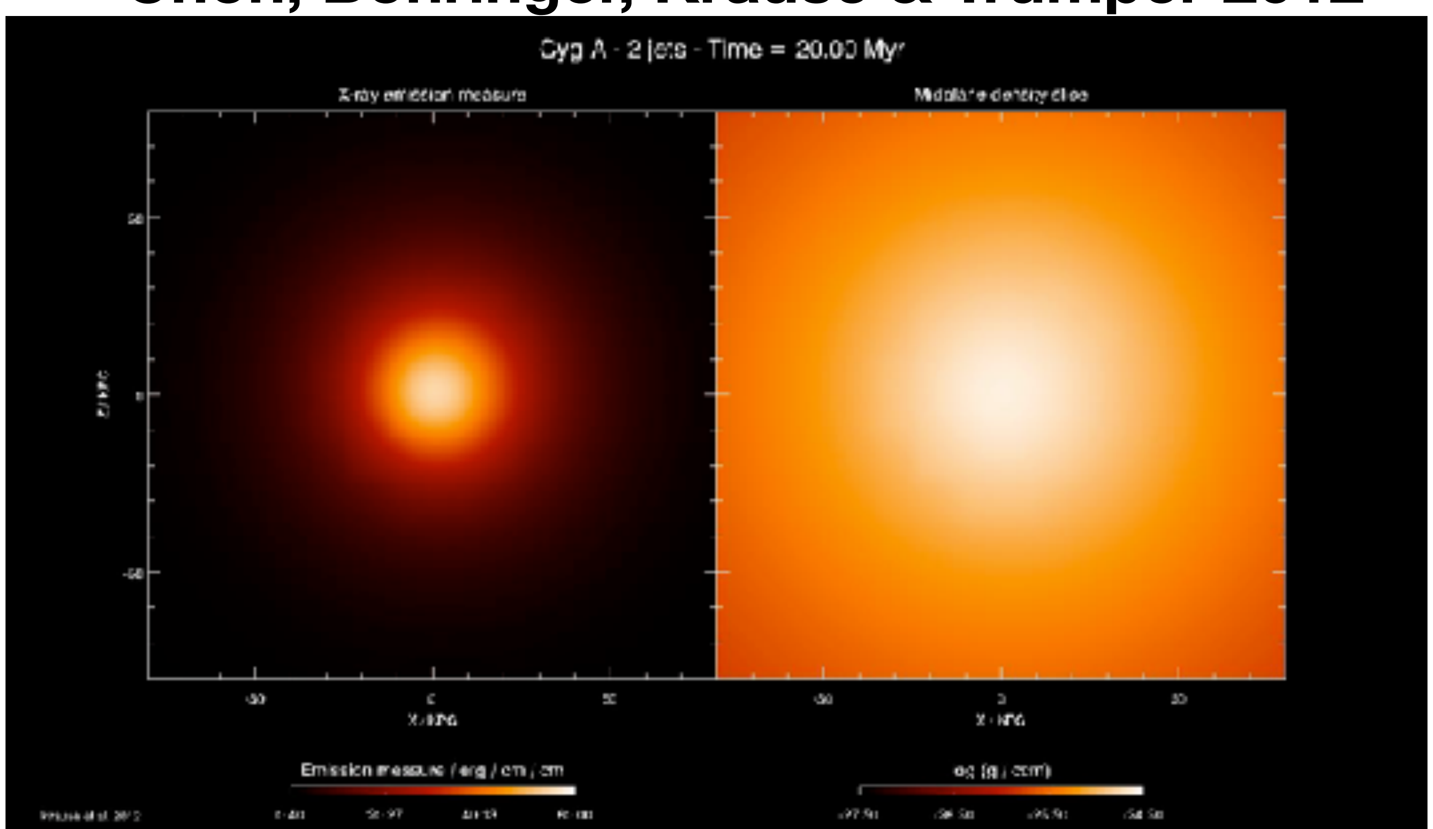
- Gravitational wave losses moderately strong.

Boccardi et al. 2016a,b

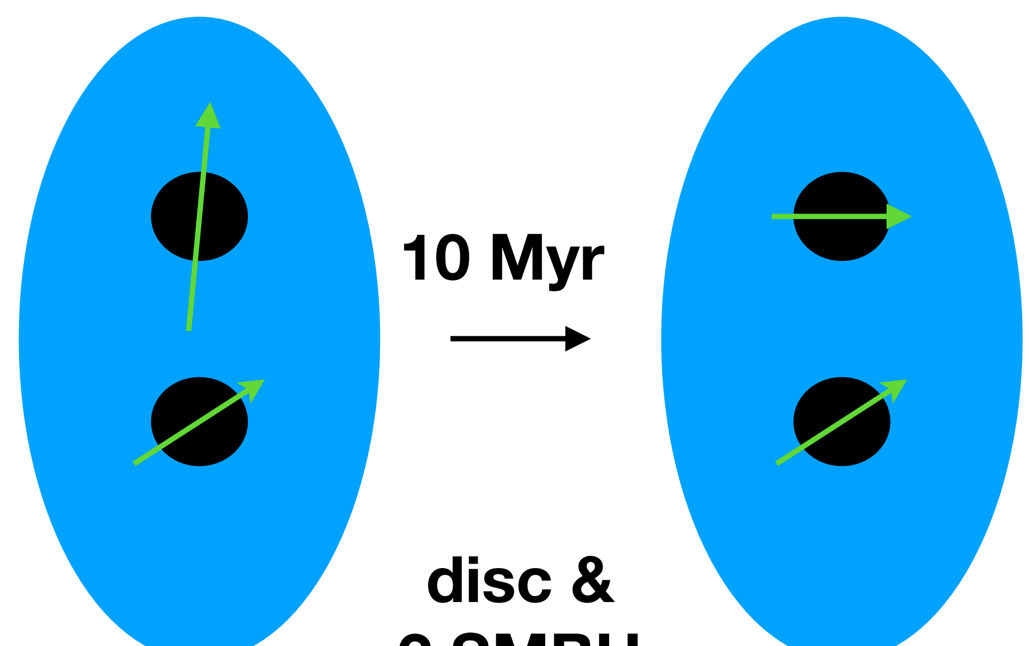
Cygnus A - suggested history



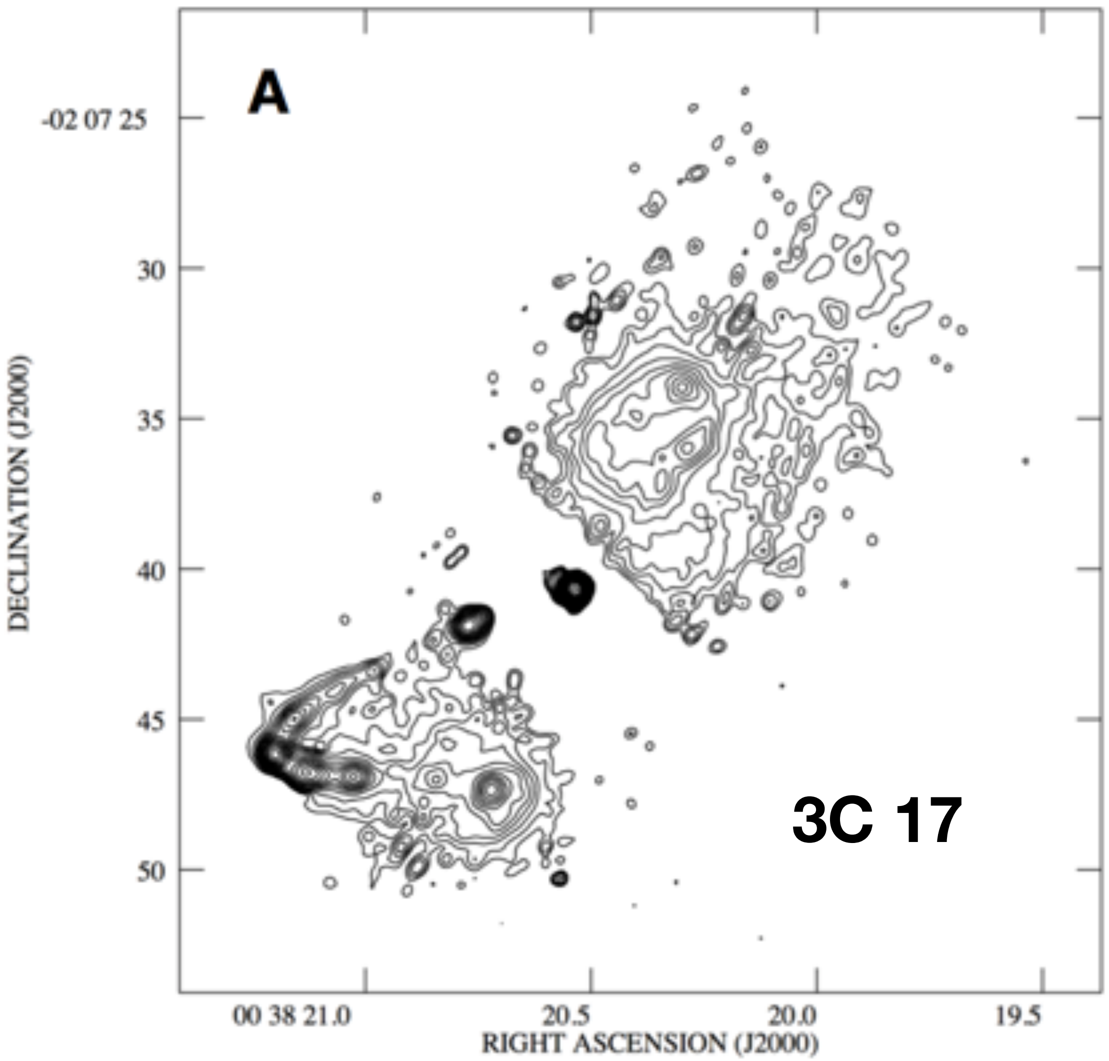
Chon, Böhringer, Krause & Trümper 2012

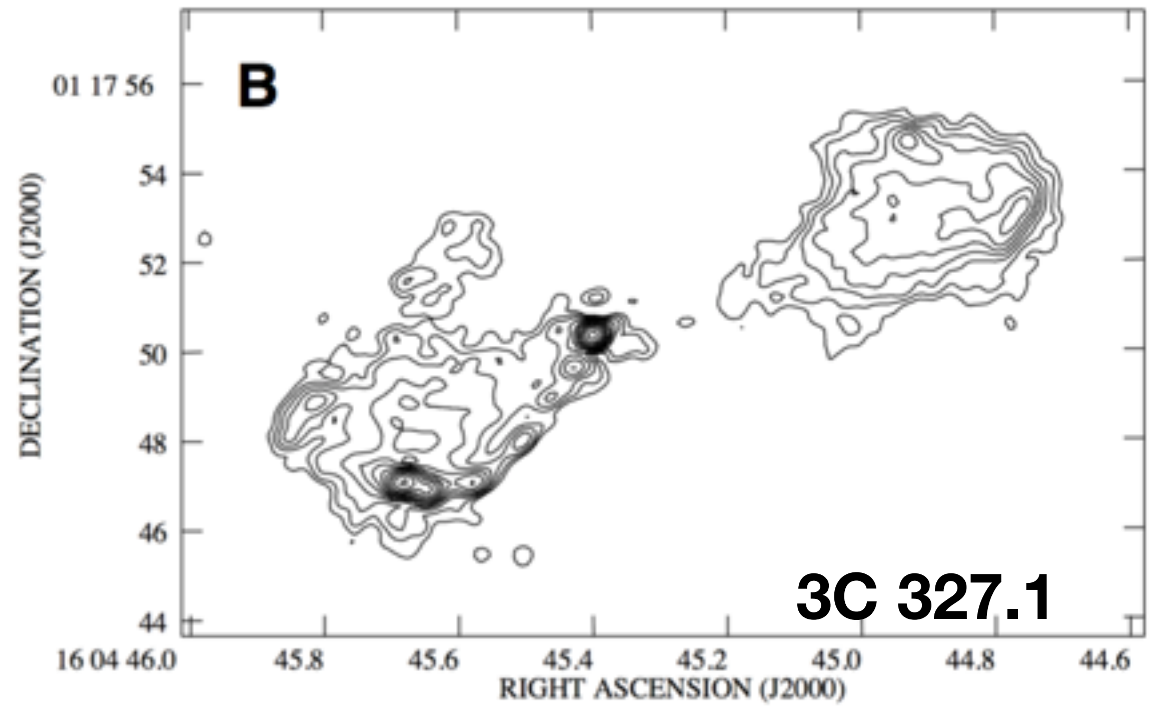


- Side cavities witness preceding outburst ≈ 10 Myr before current episode @ large angle
- disc aligns small SMBH spin vector
- now jets in almost same direction



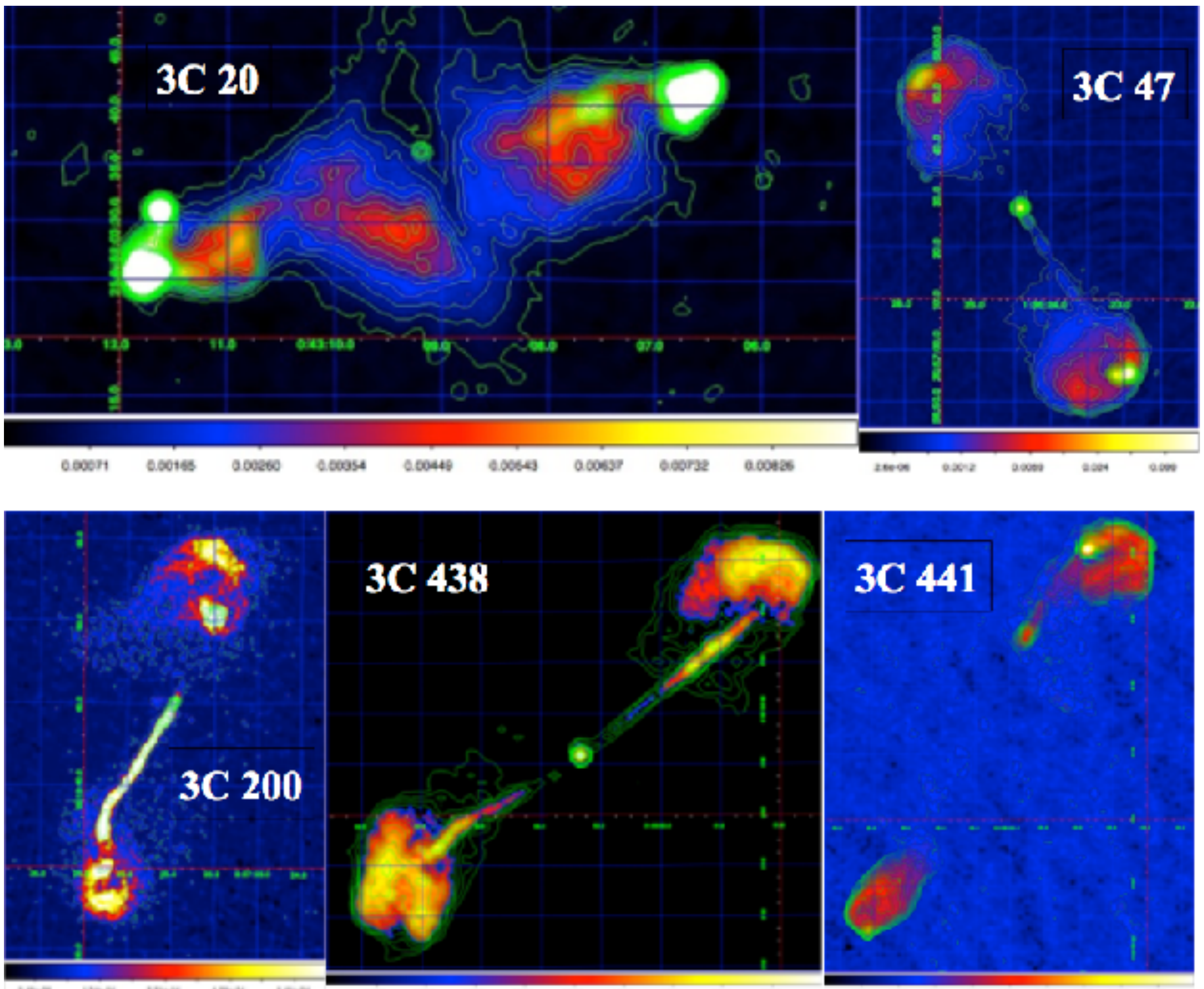
Other objects: broad line radio galaxies



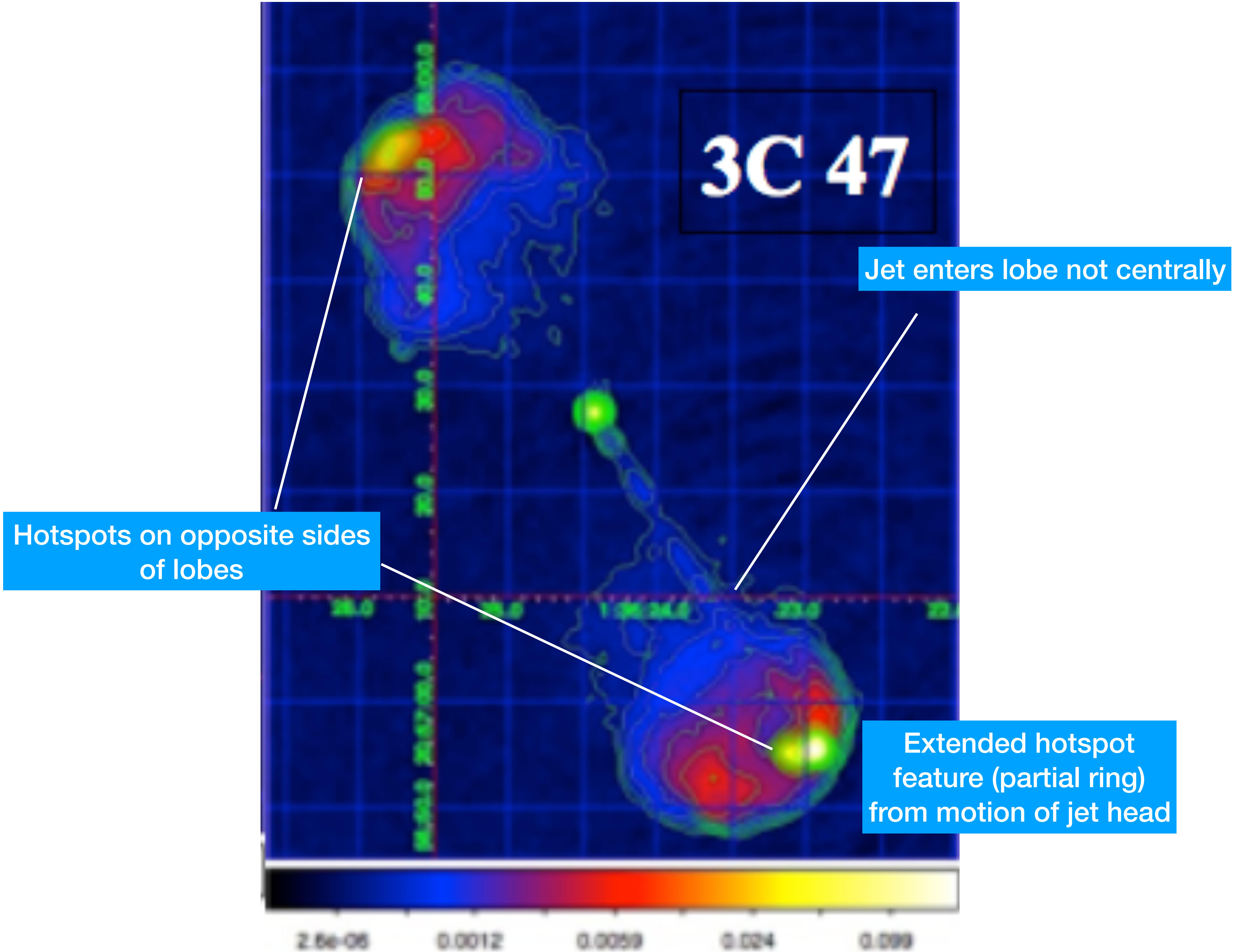


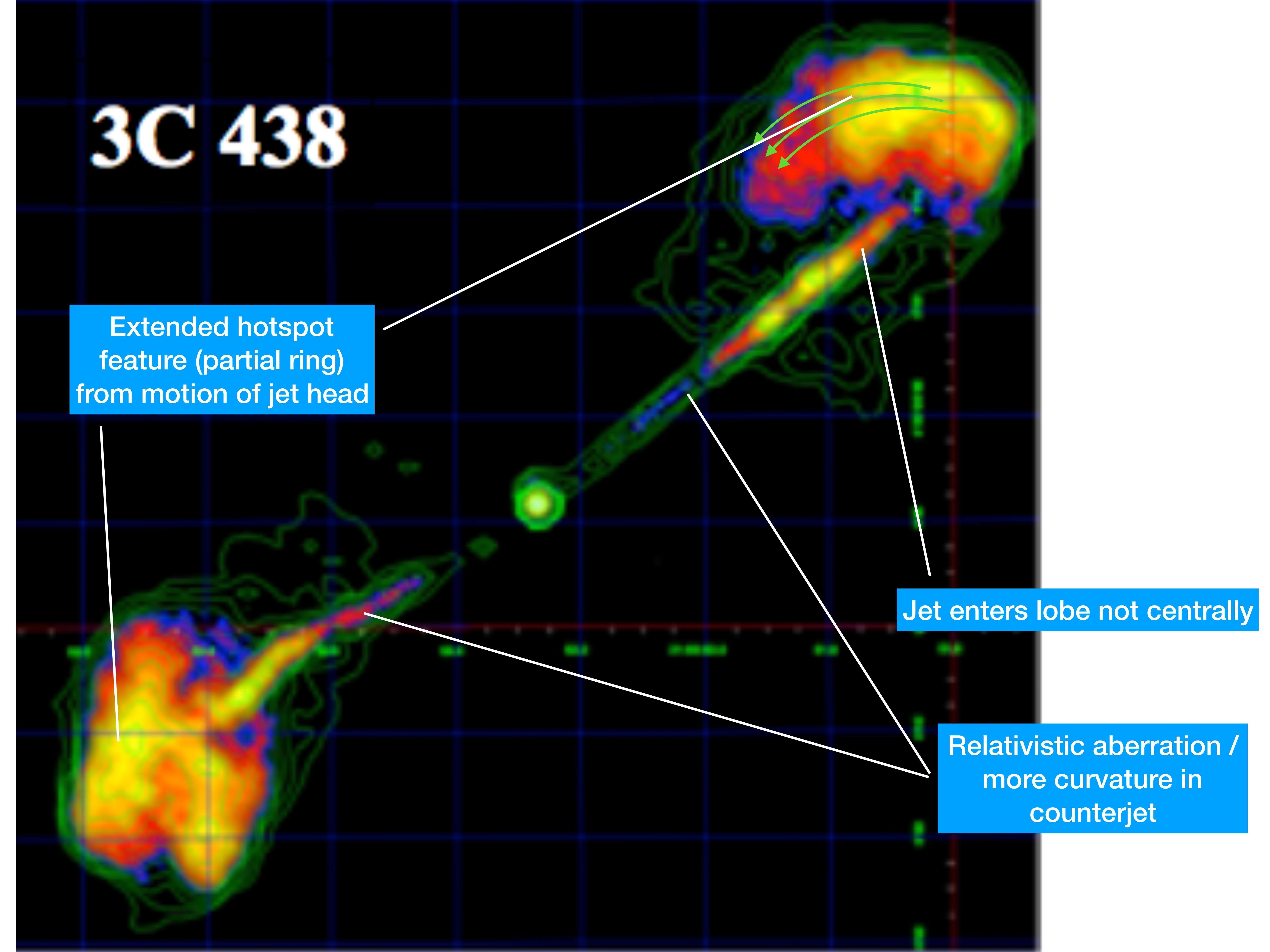
- Jet close to line of sight.
- Only suitable objects in 2Jy sample
- Clear cases of precession @ ≈ Myr
- Very similar to Cygnus A

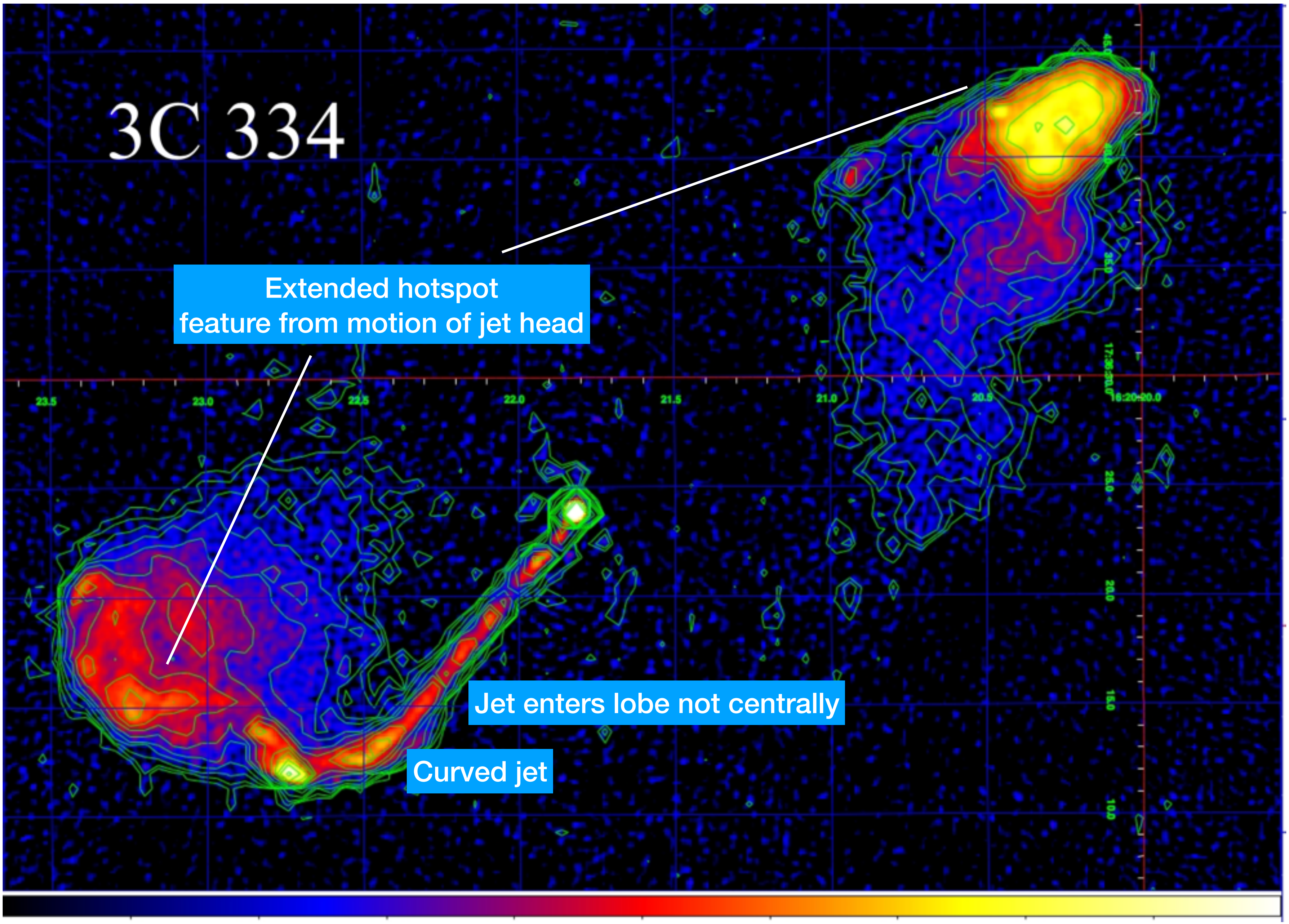
Complete Sample



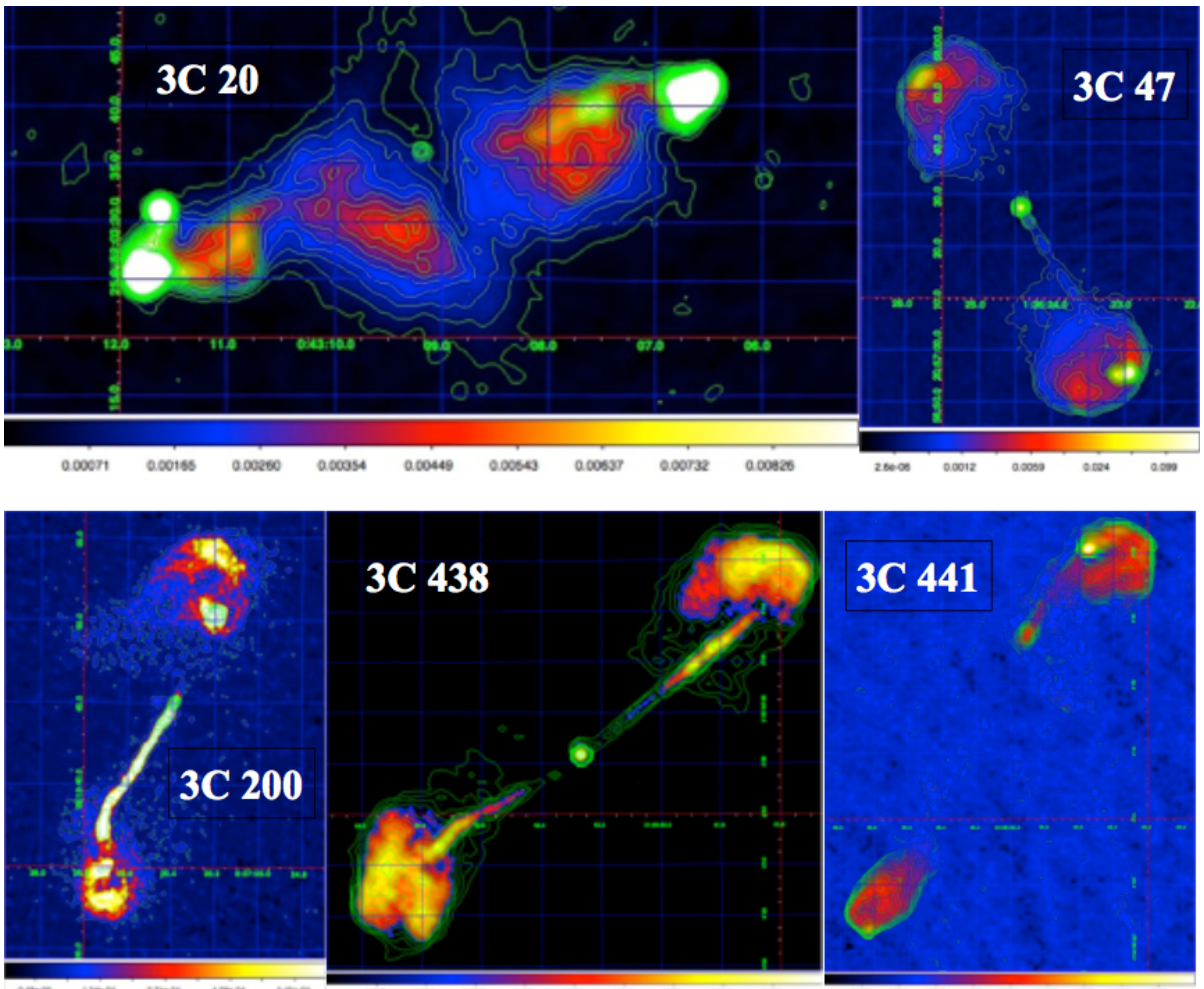
- FR II
- redshift <1
- flux @ 178 MHz > 10.9 Jy
- declination > 10°
- Galactic latitude |b| > 10°
- jet visible
- 33 sources


3C 47
Jet enters lobe not centrally
Hotspots on opposite sides of lobes
Extended hotspot feature (partial ring) from motion of jet head
2.6e-06
0.0012
0.0059
0.024
0.099


3C 438
Extended hotspot feature (partial ring) from motion of jet head
Jet enters lobe not centrally
Relativistic aberration / more curvature in counterjet


3C 334
Extended hotspot feature from motion of jet head
Jet enters lobe not centrally
Curved jet

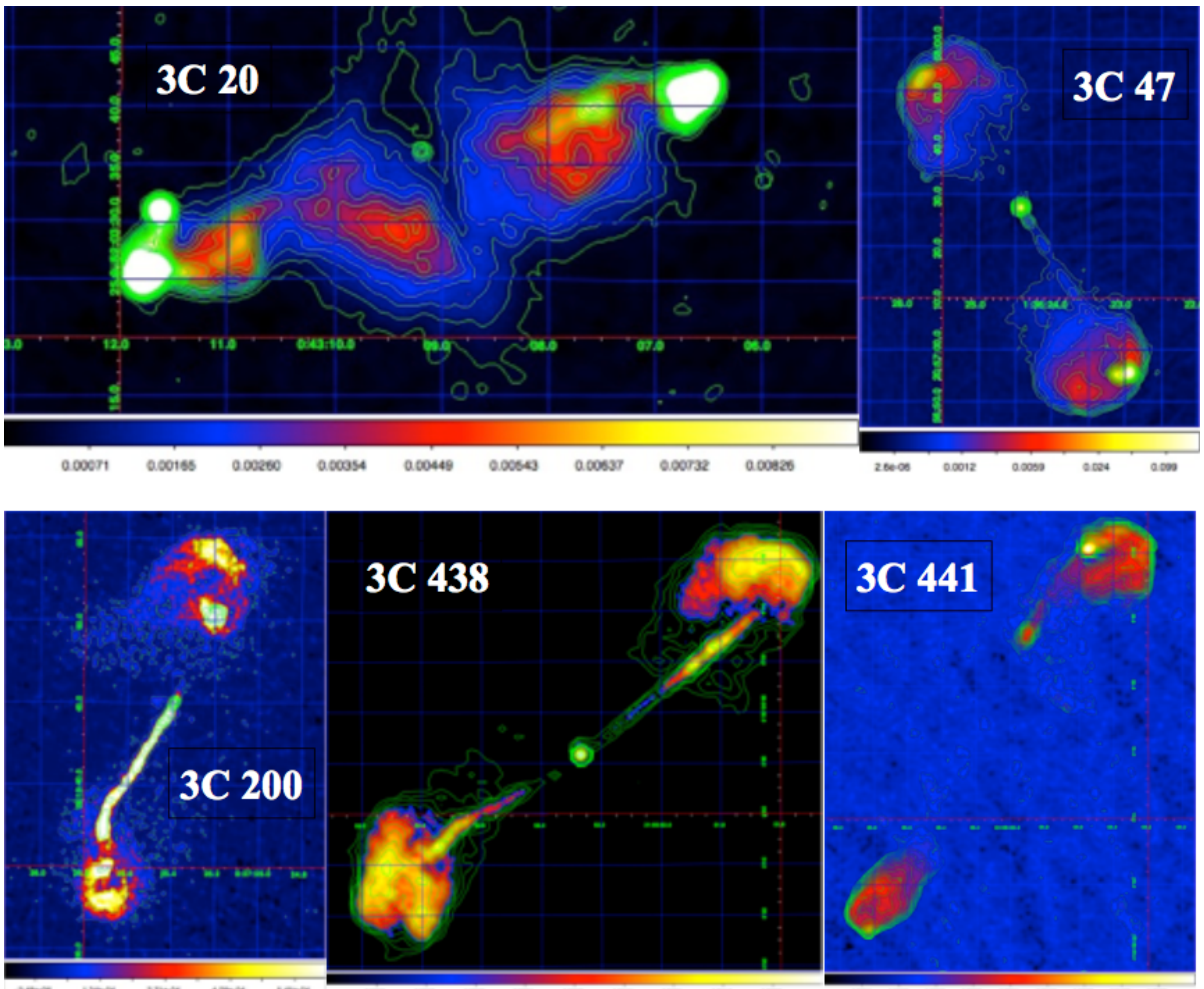
Complete Sample



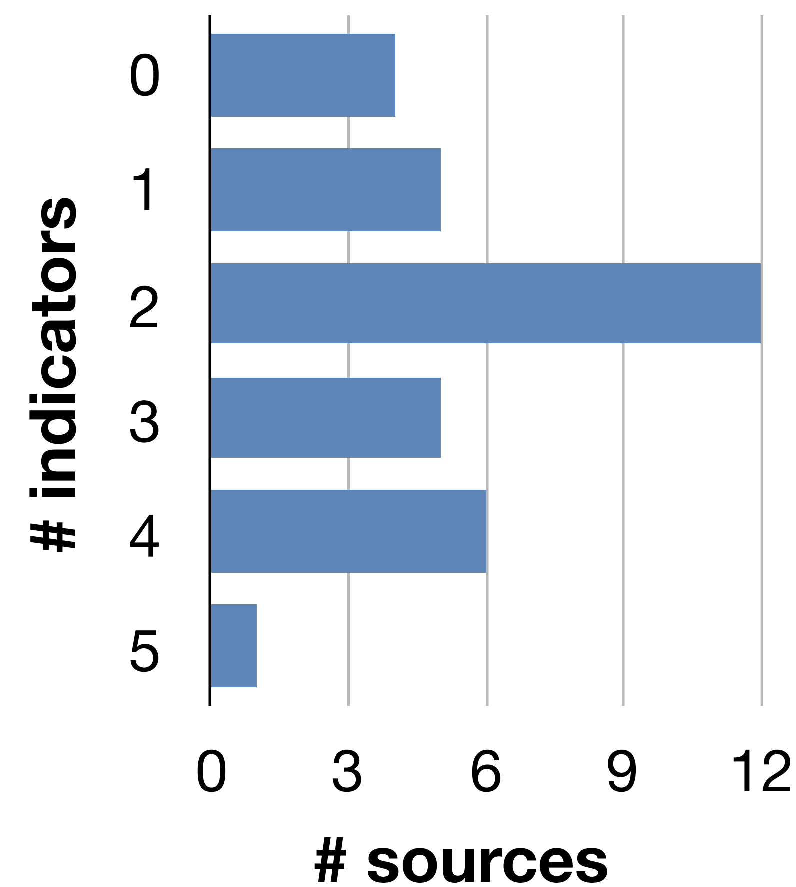
Precession criteria:

- Jet / lobe misalignment
- S - symmetry
- Jet curvature
- Ring structure
- Lobe extensions

Complete Sample



Result:



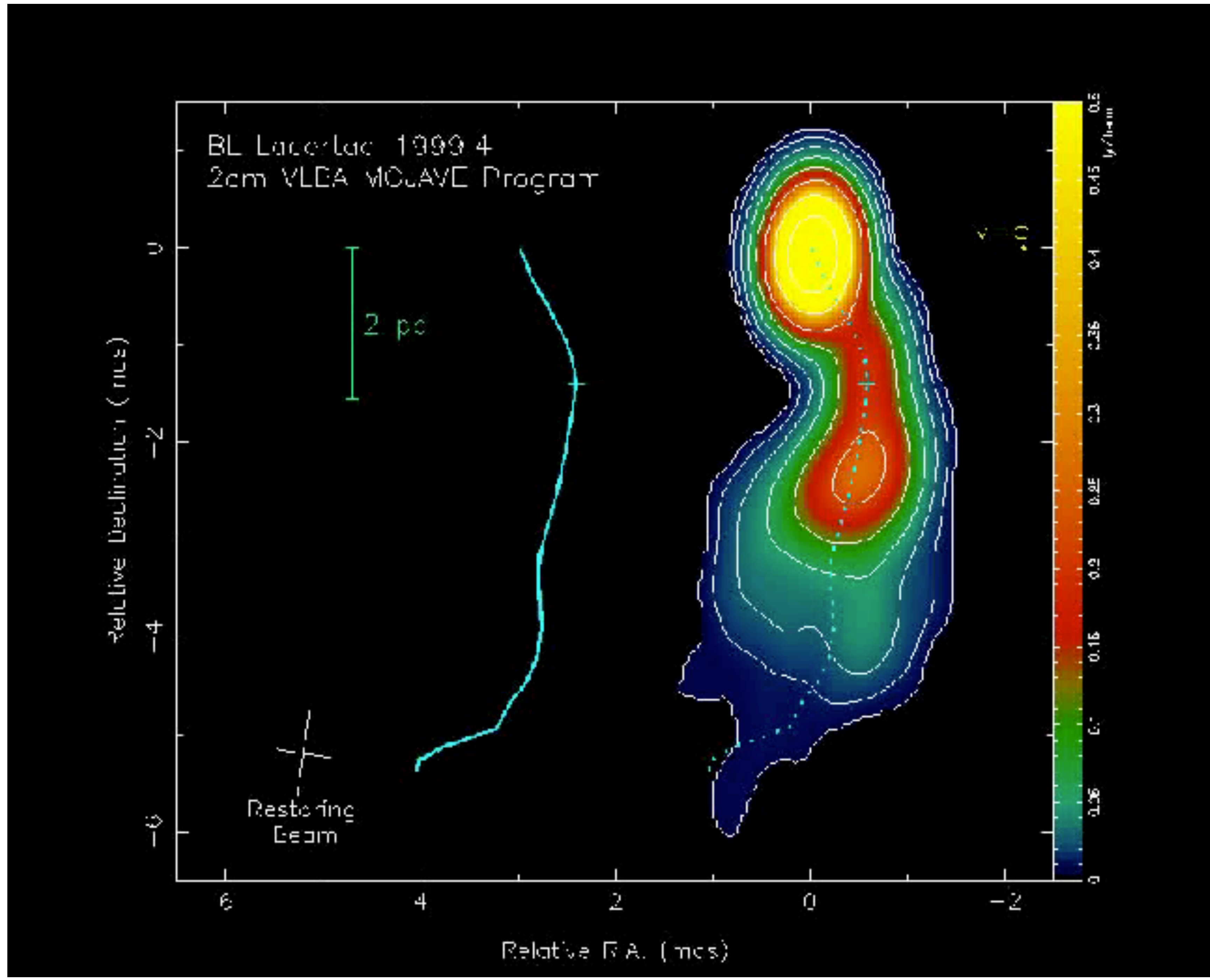
Robust precession cases (>2 indicators):
24 =: 73%

Complementary evidence

Pc-scale jets:

- ***all*** change jet angle more or less periodically on timescales yr - kyr (Lister et al. 2013) ⇒ *sub-pc SMBBH*

- most are curved

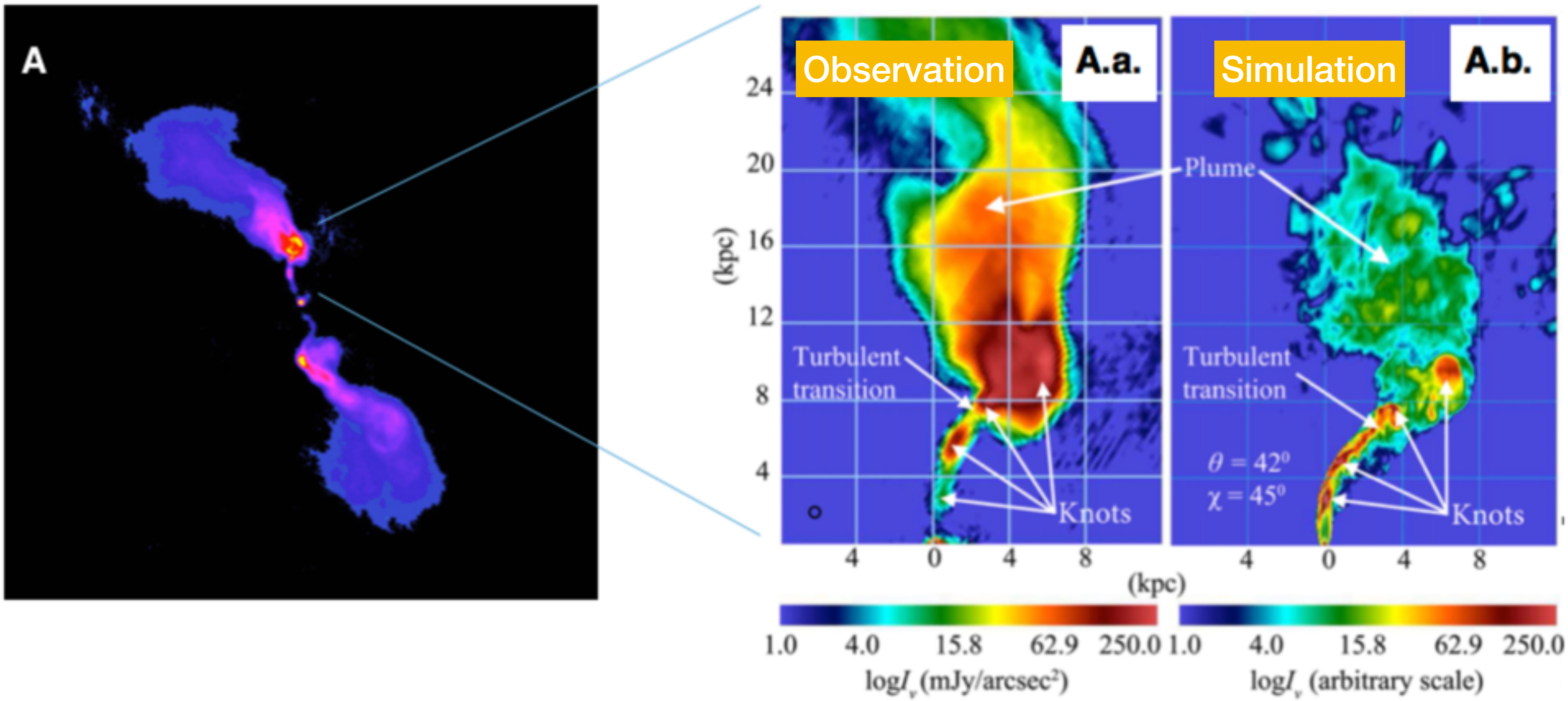


http://www.physics.purdue.edu/astro/MOJAVE/index.html

Complementary Evidence

- Stellar density distributions: cores in jet sources, as expected for SMBBHs; Richings & Körding, MNRAS 415, 2158–2172 (2011), Sarzi private com., …)
- Jet bubbles in galaxy clusters: isotropic, as expected for precessing SMBBHs; Babul et al. ApJ 768:11 (2013)
- pc vs. kpc jet misalignment distribution: peaks at 0 and 90 deg, as expected for SMBBH if sometimes pc-jet from secondary is brighter; Kharb+ApJ 710:764-782 (2010)
- Gamma-ray light curves of Blazars: ≈ 10 yr periods as expected for sub-pc SMBBH; Rieger, Astrophys Space Sci 309: 271-275 (2007)
- Jets are very frequent in merging galaxies, Sabater et al. MNRAS 430, 638–651 (2013), Ramos Almeida et al. MNRAS 436, 997–1016 (2013)

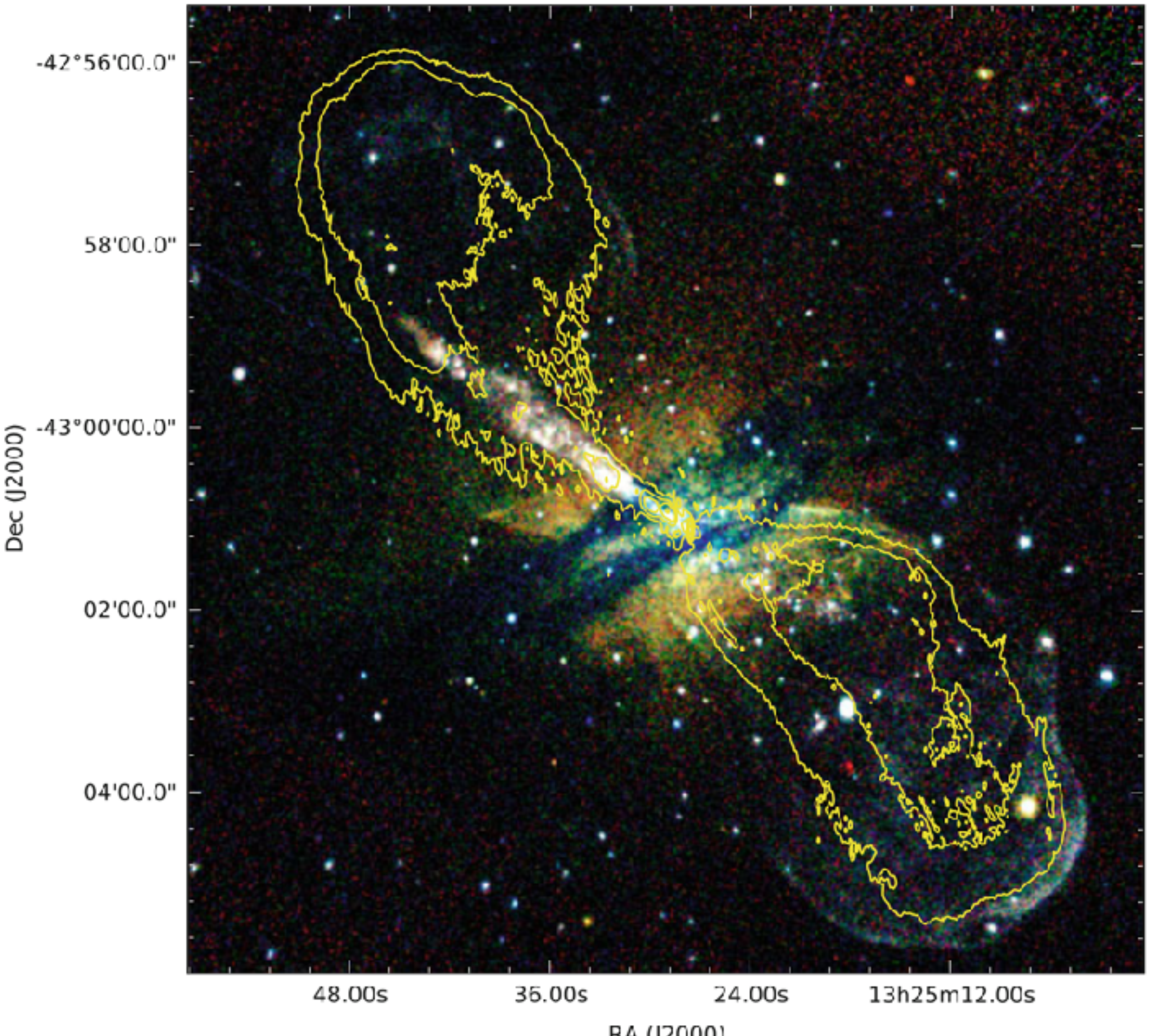
Closest AGN jet sources



Hydra A: precession @ 1 Myr

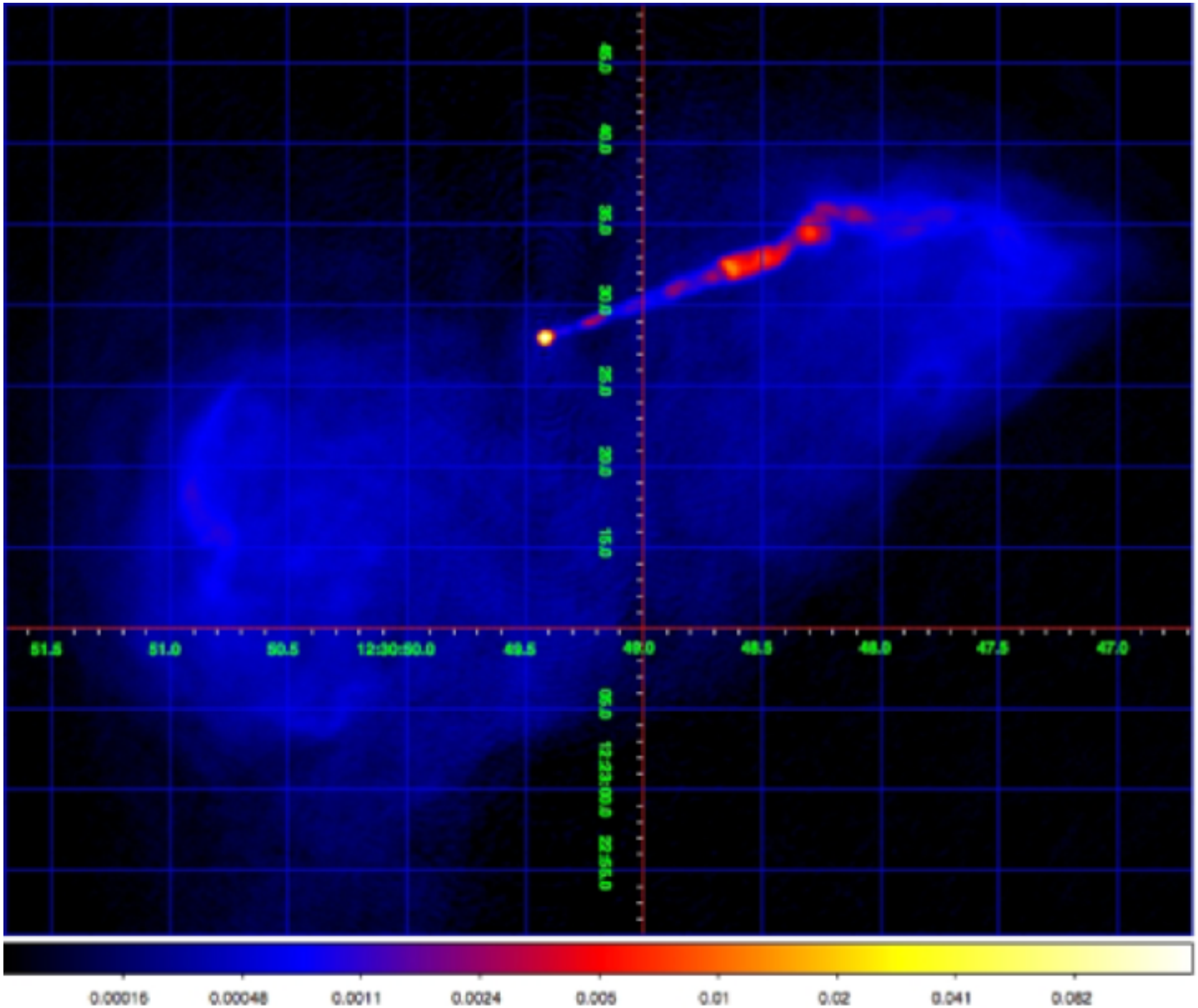
Nawaz, Bicknell, Wagner, Sutherland, McNamara 2016

Closest AGN jet sources



Cen A:
precession
@ 2 Myr

Closest AGN jet sources



Virgo A / M87: precession @ 6 Myr

Predictions for gravitational wave detections

Source	d_L / Mpc	M_9	$P_{gp,Myr}$	$h_0 / 10^{-17}$
Centaurus A	11	0.055 ± 0.01	2.0 ± 1.5	0.5 ± 0.4
Cygnus A	237	2.5 ± 0.3	1.5 ± 0.5	0.4 ± 0.3 (7.8)
Fornax A	22.7	0.15 ± 0.08	0.015 ± 0.01	6.1 ± 5.8
Hydra A	240	0.5 ± 0.4	1.0 ± 0.5	0.5 ± 0.5
Virgo A / M87	22.2	6.6 ± 0.4	6 ± 2	113 ± 113

- SKA - pulsar timing array, limiting strain $h_0 = 6 \times 10^{-16}$.
- Detection of M87 is possible.

Conclusions

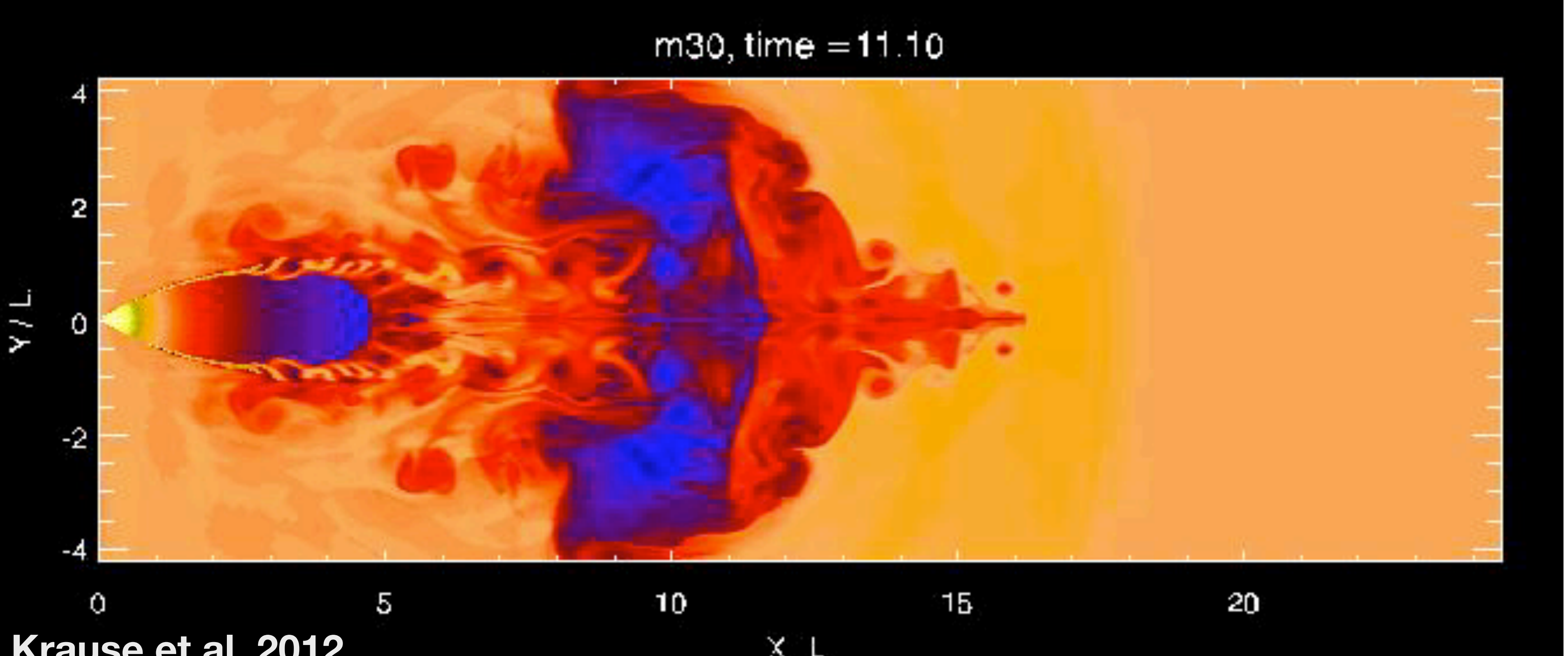
- We expect close binary black holes from galaxy mergers
- We expect to see them frequently as AGN
- Precession and helical motion for jet systems shows evidence for close SMBBHs very frequently
- All complementary evidence agrees with the idea that jets signify close binary black holes, and hence may be linked to galaxy mergers
- Open questions:
  - Do SMBBHs simply merge rarely so jets always highlight the binary “leftover” from last galaxy merger?
  - Is there something in the physics of close binaries that makes jets more powerful?

Additional slides

Jet-environment interaction
Type 1: large opening angle

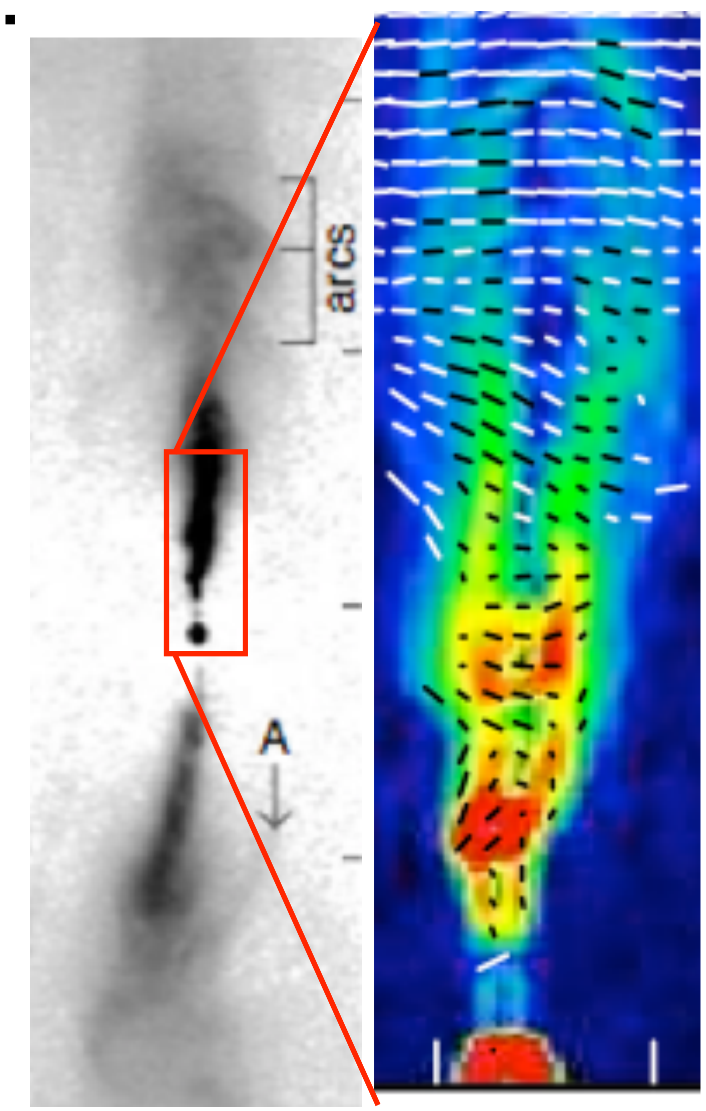
- Wide opening angle jets (>24 deg) don't collimate
- Terminal shock stalls at (30 deg opening angle):

$$L_{1c} = 2\,\mathrm{kpc}\left(\frac{Q_0}{10^{43}\,\mathrm{erg\,s^{-1}}}\right)^{1/2}\left(\frac{p_\mathrm{x}}{10^{-11}\,\mathrm{dyn\,cm^{-3}}}\right)^{-1/2}$$



Krause et al. 2012

Fanaroff-Riley class I

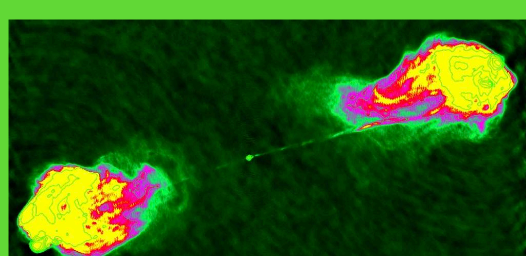


RAiSE models

Radio Luminosity

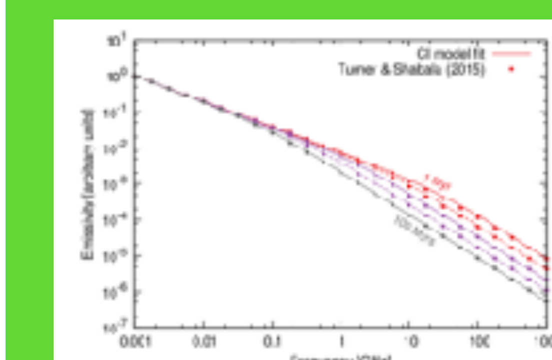
Size ~ (jet power / ambient density)^a time^b

Radio size measurement



Host opt. mag
⇒
(Gal Evol model)
DM halo
⇒
gas density profile

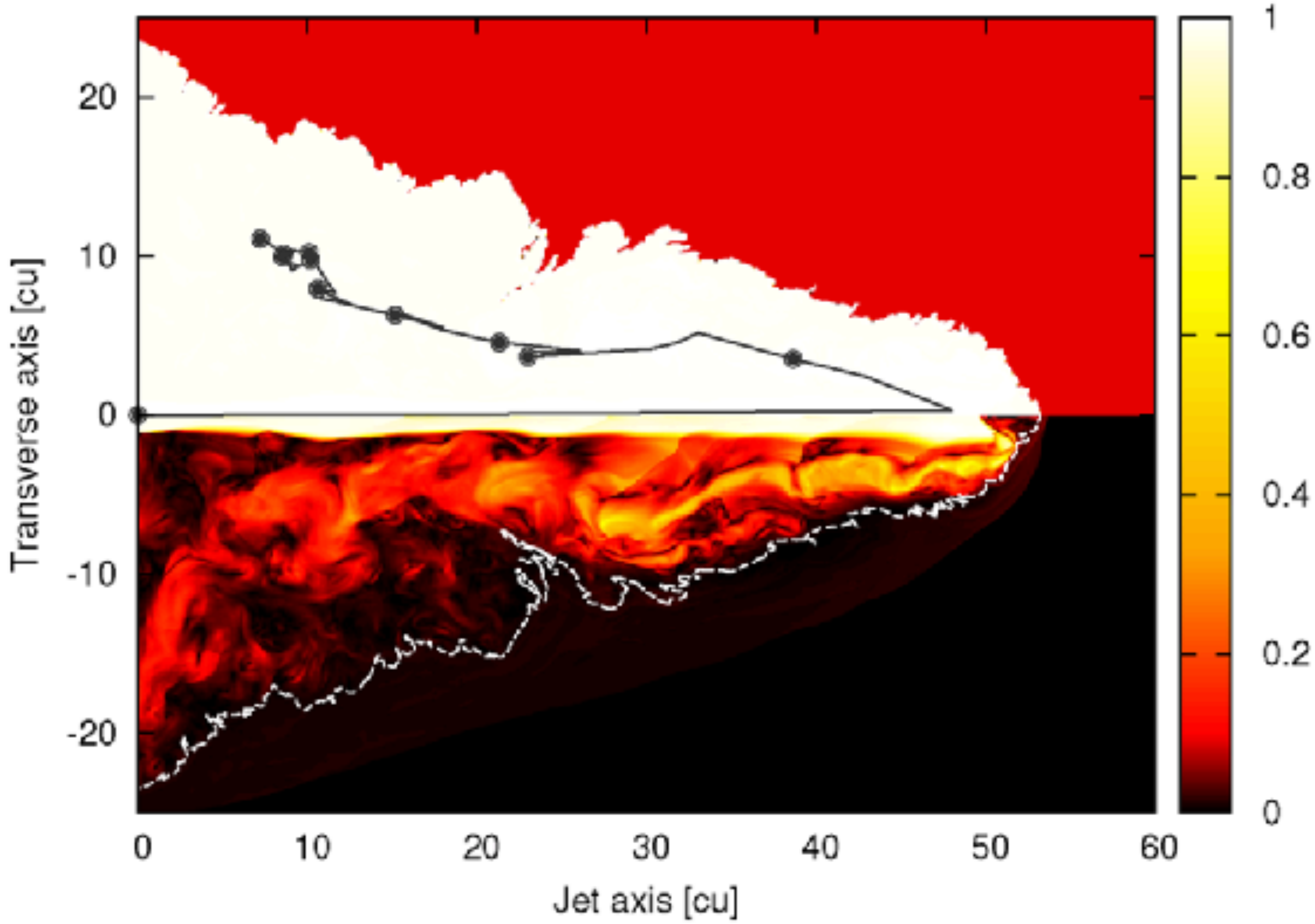
Spectral Brake



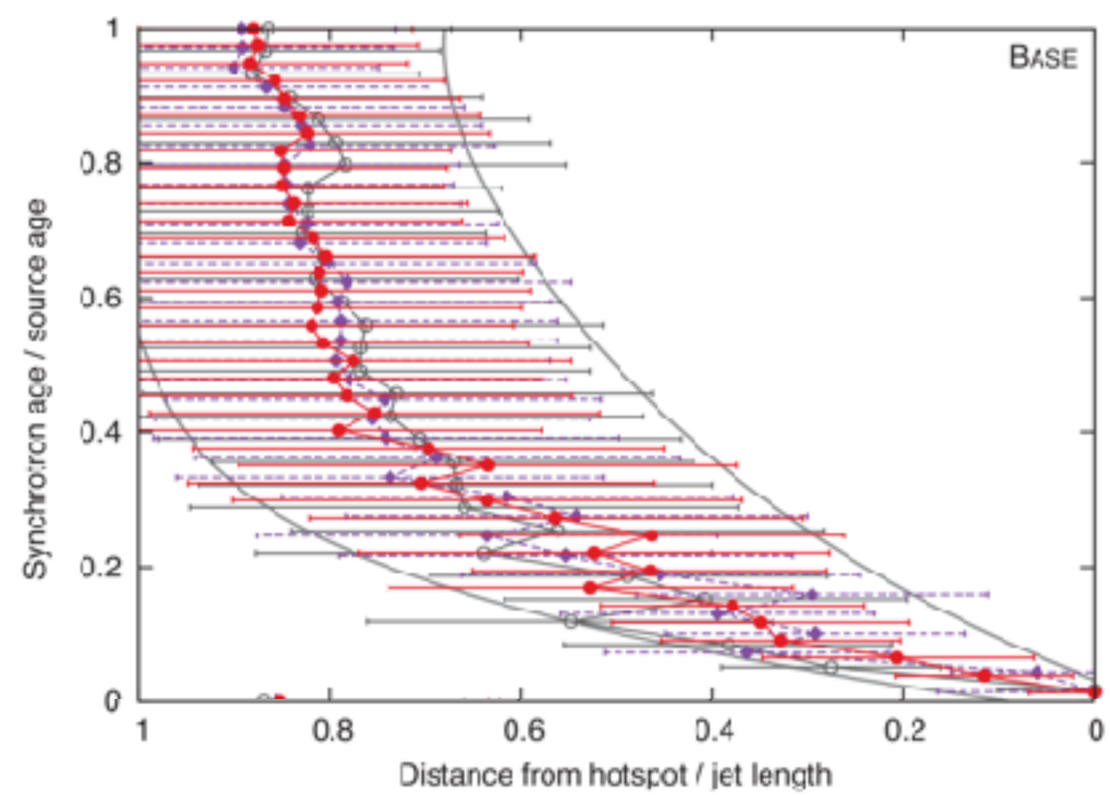
Turner, Shabala & Krause 2018

How to distribute the electrons?

2D axisymmetric jet simulation with 50 electron colour tracers



1-sigma spread of of positions Of electron packets in the lobe



Turner, Rodgers, Shabala & Krause 2018

Turner, Rodgers, Shabala & Krause 2018

Resolved spectral modelling

Get jet power, Source age, etc. From analytic source model

→

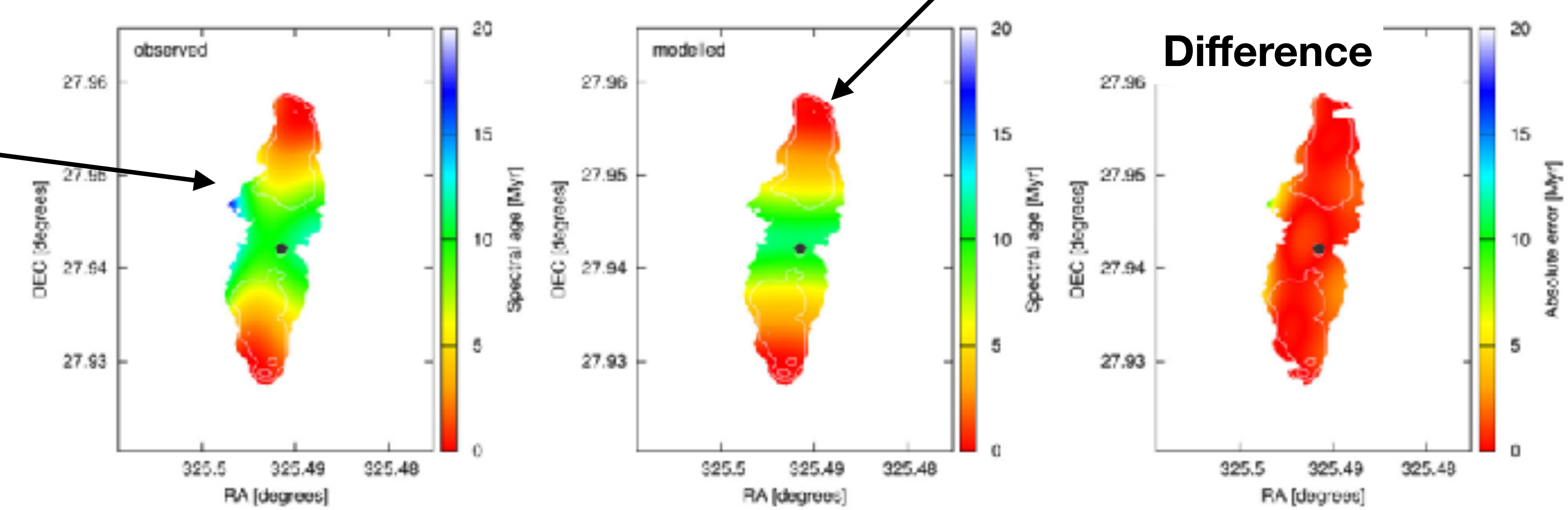
Model luminosity history of electron packets in modelled lobe (simulation)

→

Fit synchrotron age as function of position in synthetic radio map

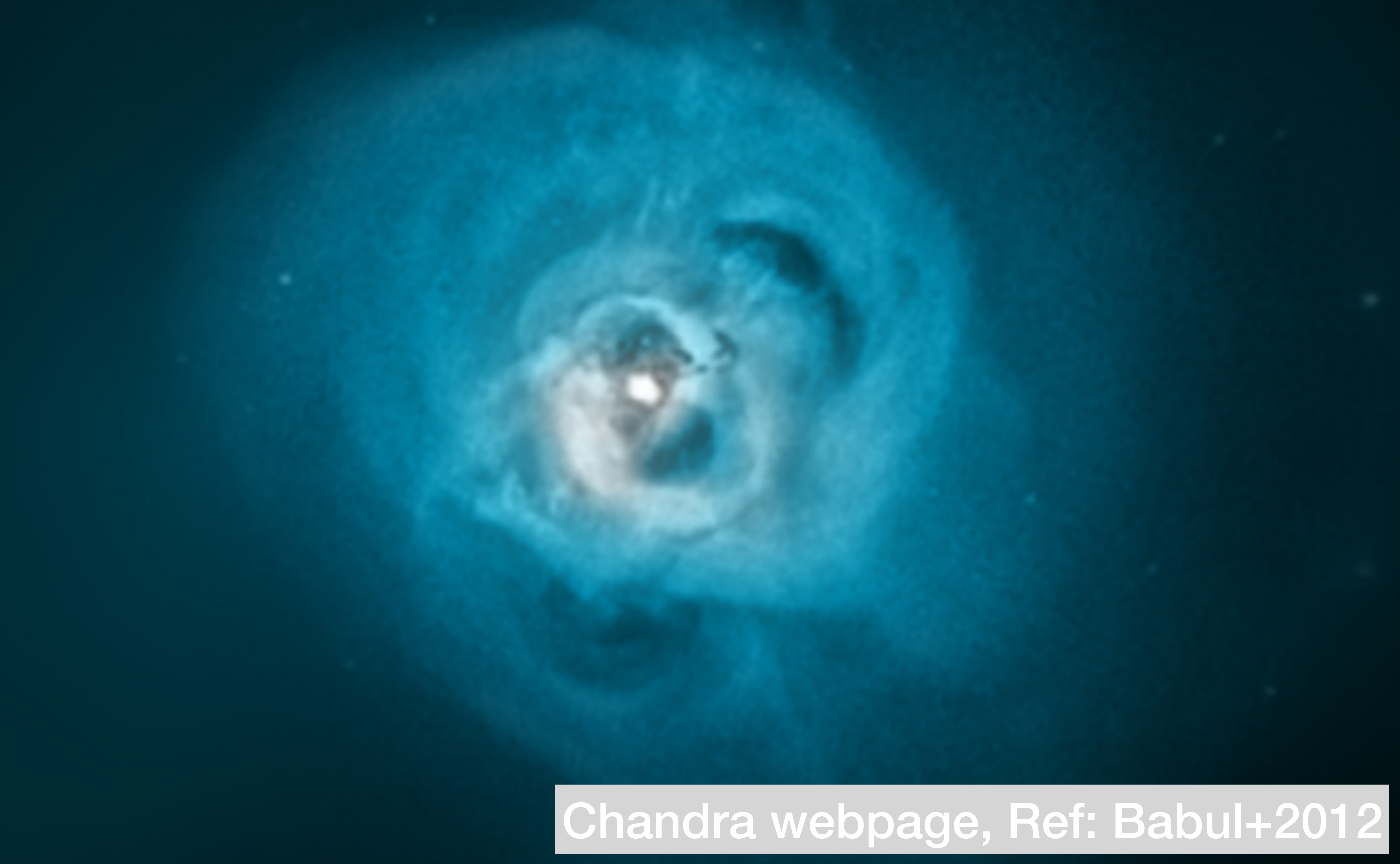
Fit synchrotron age to observed, spatially resolved SEDs

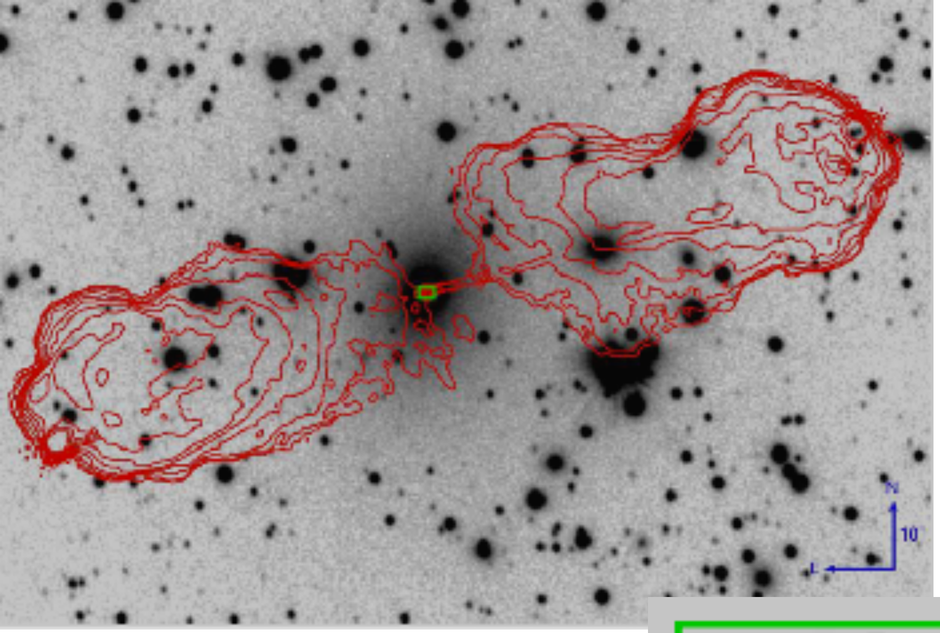
3C 436



Excellent agreement, true (model) source age: 37 Myr, sync age: 11 Myr (mixing)

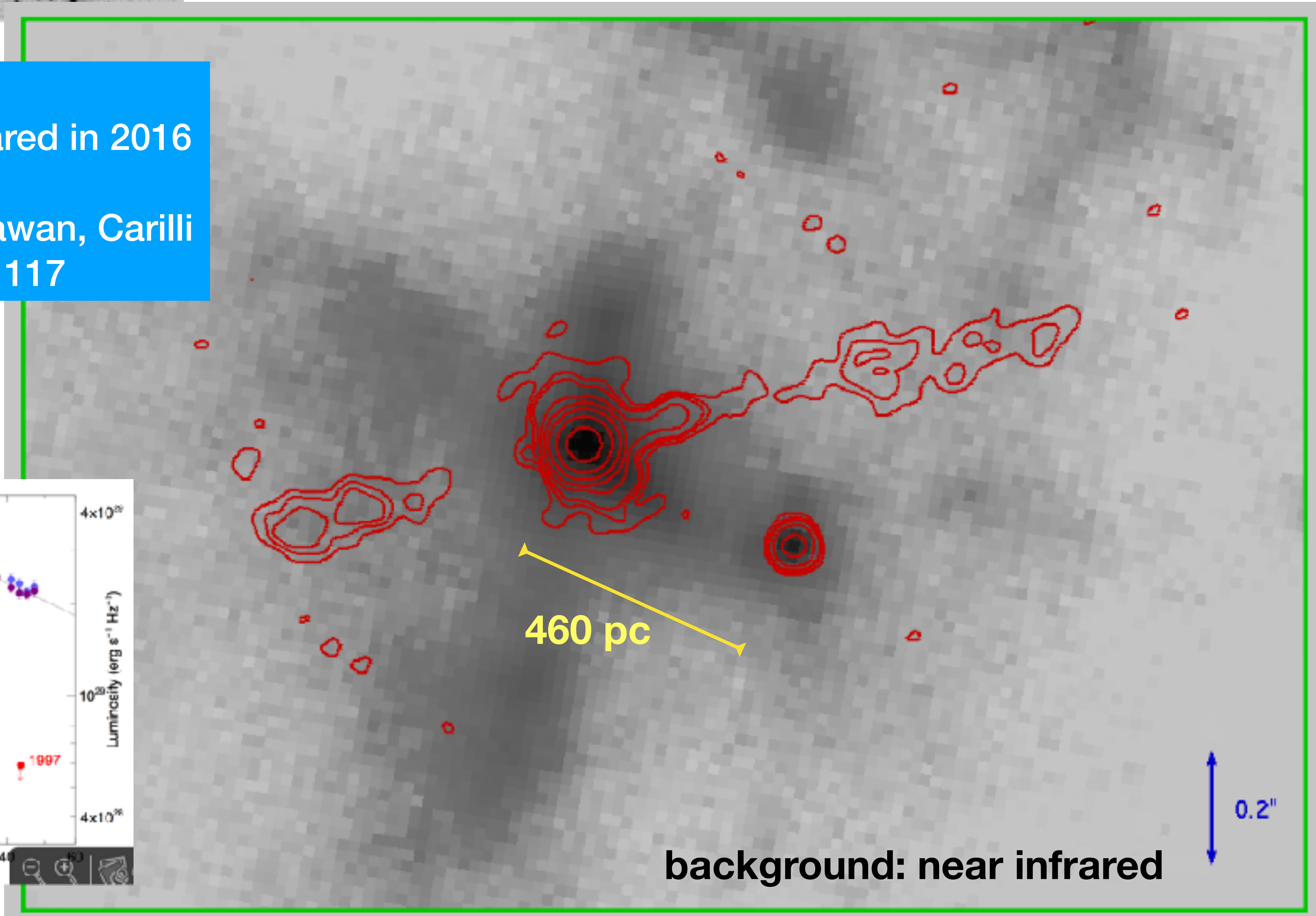
Perseus A galaxy cluster:
X-ray cavities likely related to jet outbursts /
no consistent directions

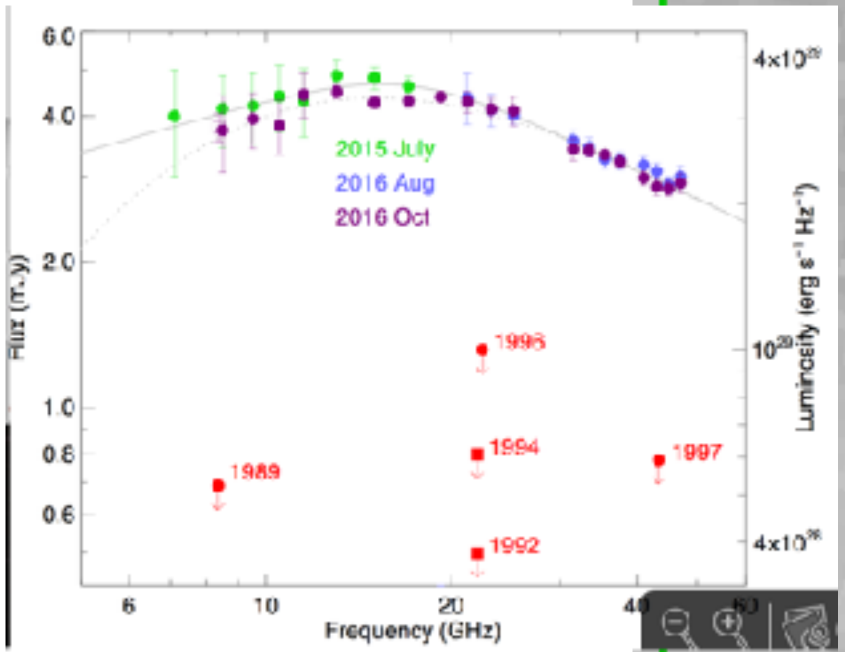




Triple SMBH systems

Cygnus A:
- new source appeared in 2016
- possibly a SMBH
- Perley, Perley, Dhawan, Carilli 2017, ApJ 841, id. 117

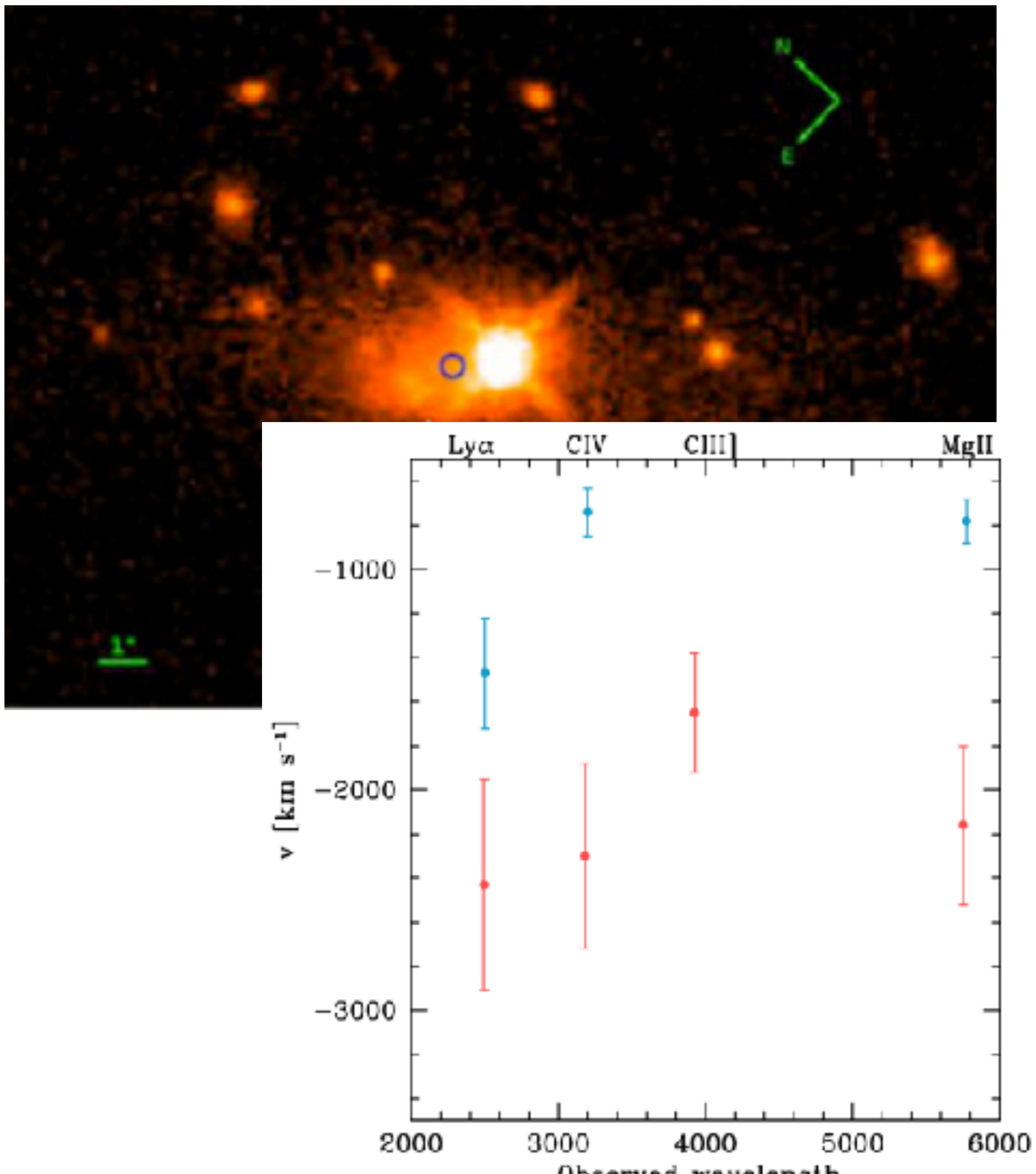


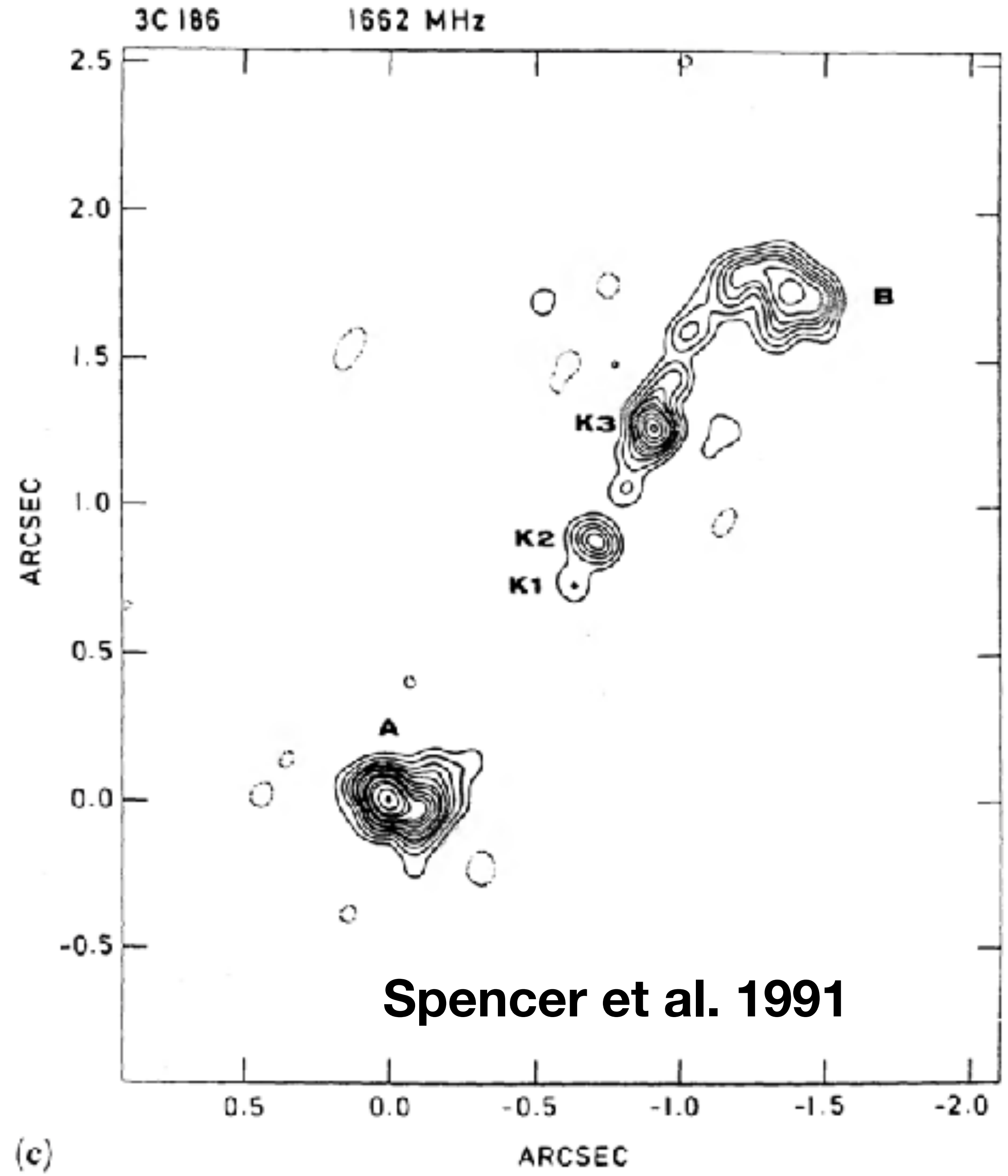


Radio QSO 3C 186:

- central cluster galaxy, redshift=1
- quasar escaping from galaxy centre, possibly 3-body interaction (Chiaberge et al. 2017, A&A 600, A57)
- radio source is precessing, so likely QSO is still binary

Triple SMBH systems





Spencer et al. 1991