Radio Signatures of Supermassive Black Hole Binaries

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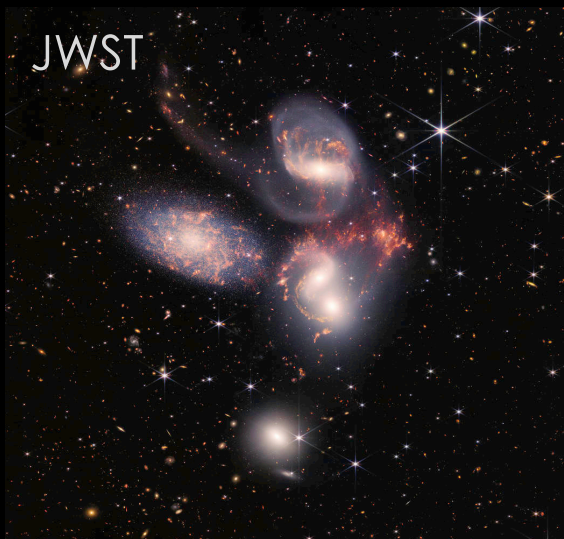
Very Long Baseline Interferometry

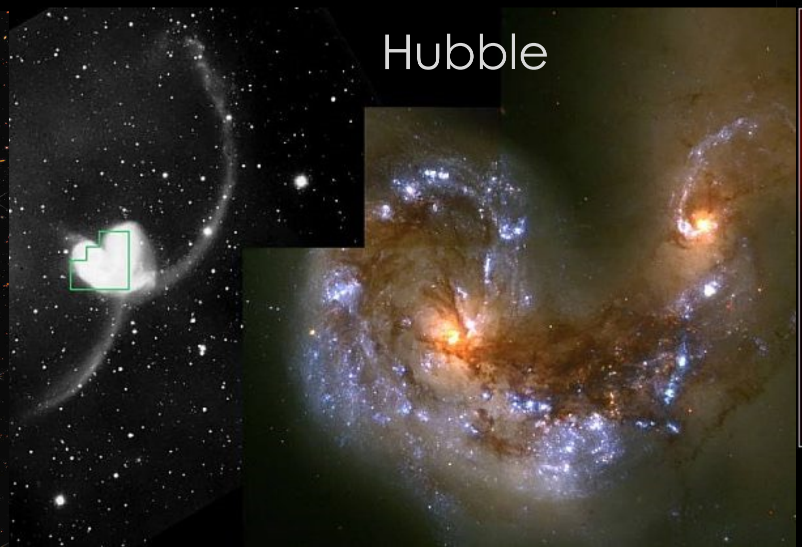
Max-Planck-Institut für Radioastronomie

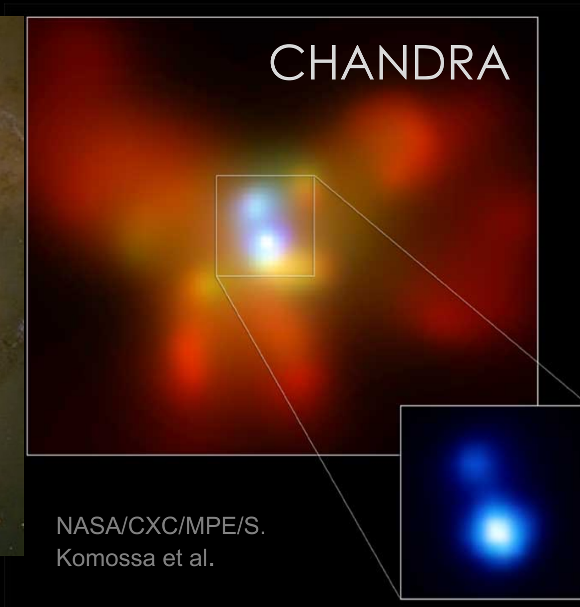
Binary Simulation: Nasa Goddard Space Flight Center

Royal Astronomical Society
14 of April 2023

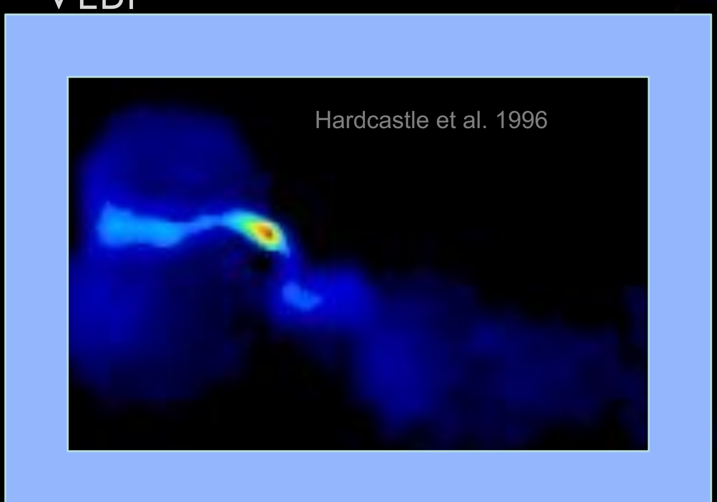
Supermassive *Binary* Black Holes from galaxy collisions



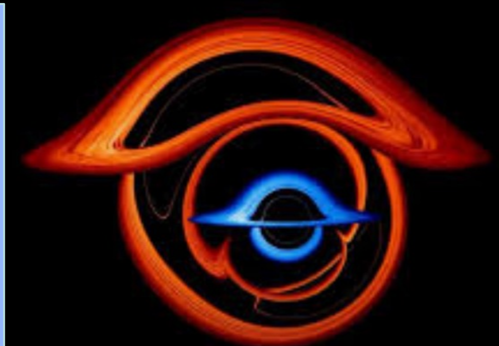




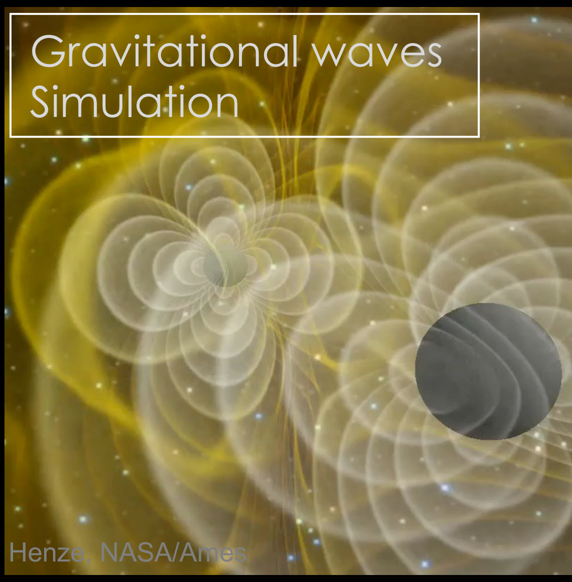
VLBI



Simulation



Schnittman / NASA



How many massive binaries can we expect to find?

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Unveiling the hosts of parsec-scale massive black hole binaries: morphology and electromagnetic signatures

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a classical bulge structure or in elliptical galaxies. Besides, the scaling relations followed by MBHBs are indistinguishable from the ones of single massive black holes. We find that the occupation fraction of parsec-scale MBHBs reaches up to $\sim$50 per cent in galaxies with $M_{stellar} > 10^{11}\,M_\odot$ and drops below 10 per cent for $M_{stellar} < 10^{11}\,M_\odot$. Our model anticipates that the majority of parsec-scale MBHBs are unequal mass systems and lie at $z \sim 0.5$, with $\sim$20 objects per deg^2 in the sky. However, most of these systems are inactive, and only 1–0.1 objects per deg^2 have an electromagnetic counterpart with a bolometric luminosity in excess of 10^{43} erg s^{-1}. Very luminous phases of parsec-scale MBHBs are more common at $z > 1$, but the number of binaries per deg^2 is $\lesssim 0.01$ at $L_{bol} > 10^{45}$ erg s^{-1}.

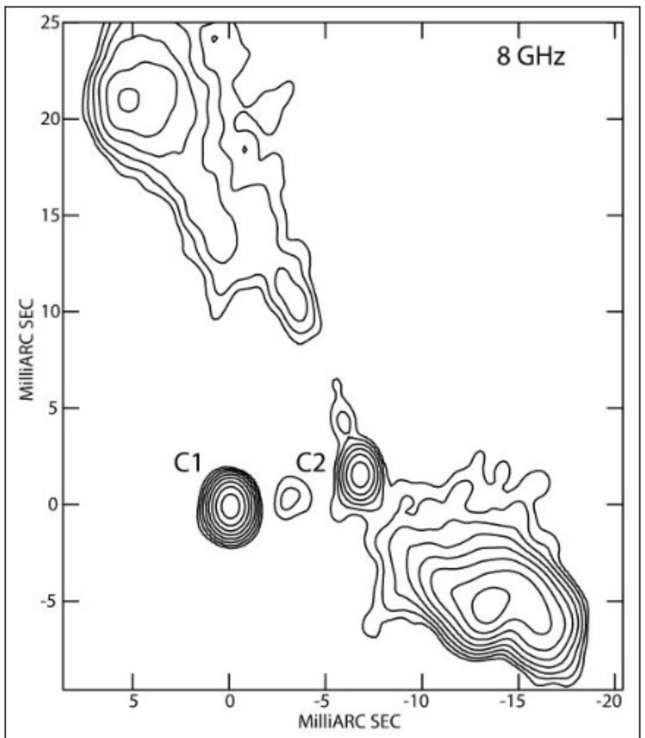
.... this implies an order 400 "very luminous" parsec scale SMBHB in the whole sky. How many of those have we found?

Have we found one?

The one and only „visual binary“ - so far - on pc-scales

Based on VLBI observations alone, it seems only possible to prove unambiguously the AGN nature of a candidate dual source if *both companions are radio AGN.*

The typical mas-scale angular resolution achievable with VLBI networks at cm wavelengths allows us to directly resolve pairs with projected linear separation as small as about *a pc in the local Universe and ~ 10 pc at any redshift.*



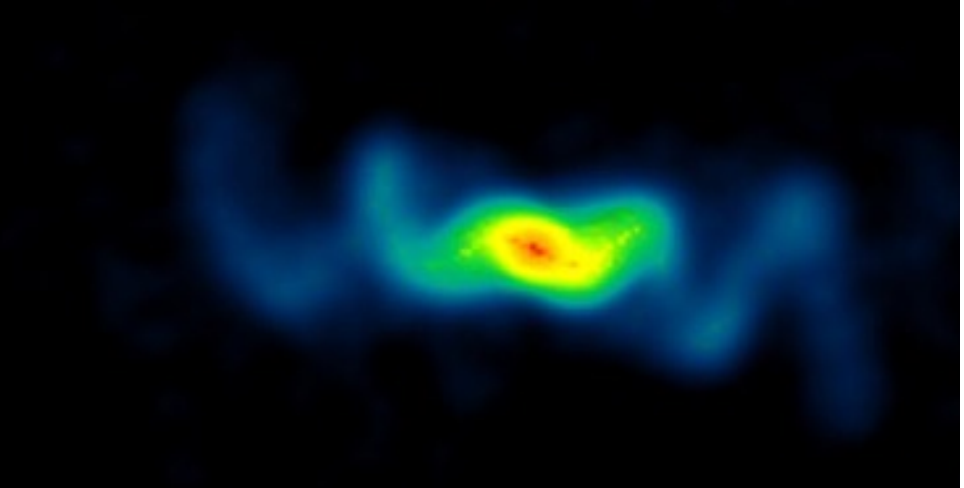
Radio VLBA image contours of the system **0402+379** at 8 GHz. Components C1 and C2 correspond to the two radio nuclei at projected separation of **7.3 pc** (Rodriguez et al. 2006).

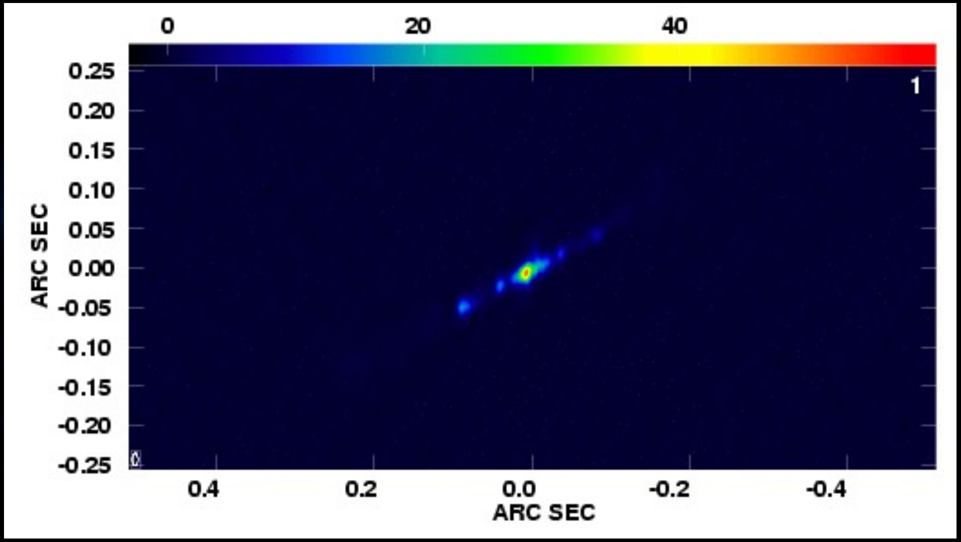
Based on the analysis of VLBA data spanning 12 yr, Bansal et al. (2017) claimed the detection of *relative motion of the companion* AGN.
If this is due to orbital motion, and assuming a circular orbit, the authors could derive an orbital period of about 3 × 10^4 yr.

Curved jet structures (Precession) can reveal the supermassive binary black hole at the center

Collage, not to scale

The show-case example for *precession*

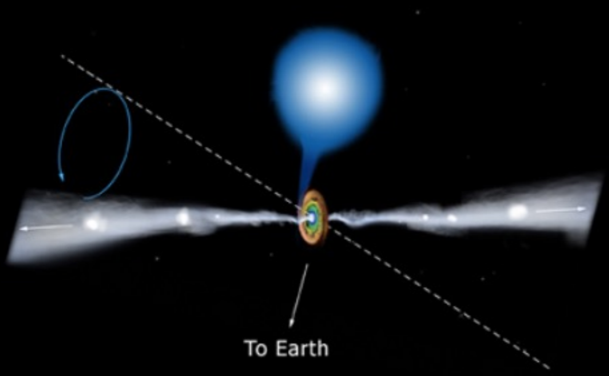




SS 433 Corkscrew

Blundell & Bowler, NRAO/AUI/NS (VLA) (left) and A. Mioduszewski et al. for VLBA images (right)

SS 433 is a neutron star or black hole orbited by a "normal" companion star.
The disk in SS 433 wobbles like a child's top, causing its jets to trace a corkscrew in the sky every 162 days.



NASA/CXC/U.Amsterdam/S.Migliari et al.

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OJ287: deciphering the '*Rosetta* stone of blazars*'

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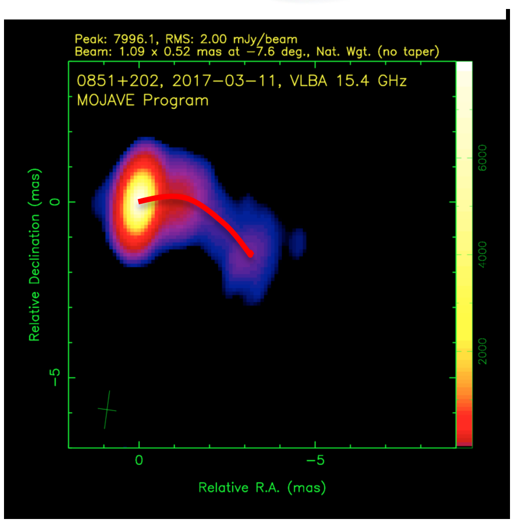
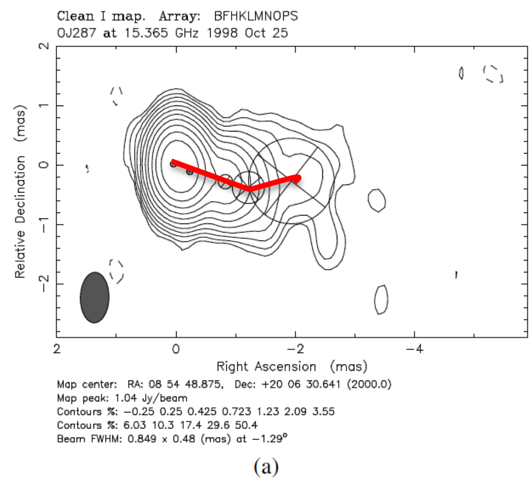
A precessing jet in OJ 287

- we re-analyzed **120 VLBA** data sets (Apr. 1995 – Apr. 2017) obtained at 15 GHz within the **MOJAVE** (**M**onitoring **O**f **J**ets in **A**ctive galactic nuclei with **V**LBA **E**xperiments) survey
- http://www.physics.purdue.edu/astro/MOJAVE/index.html

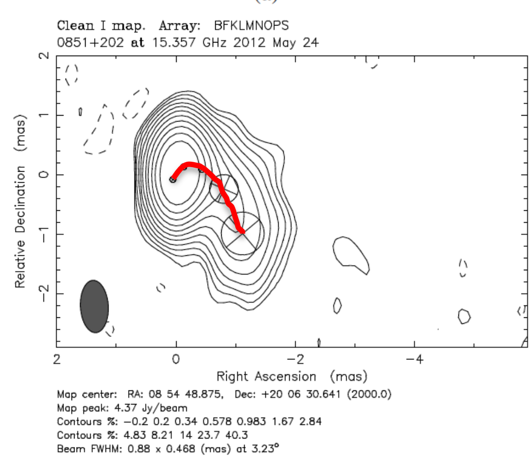


2017



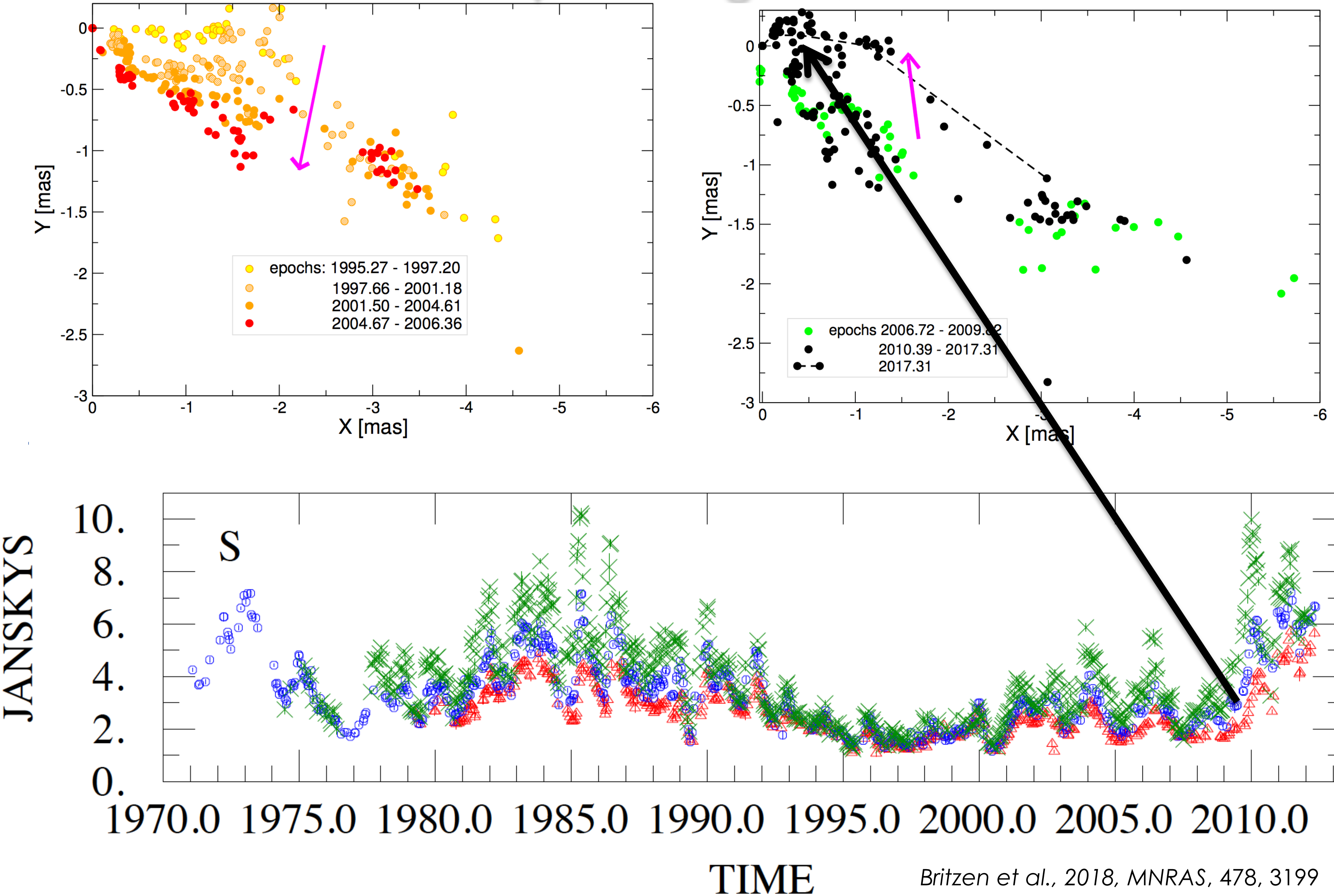
1998

Something is going on …

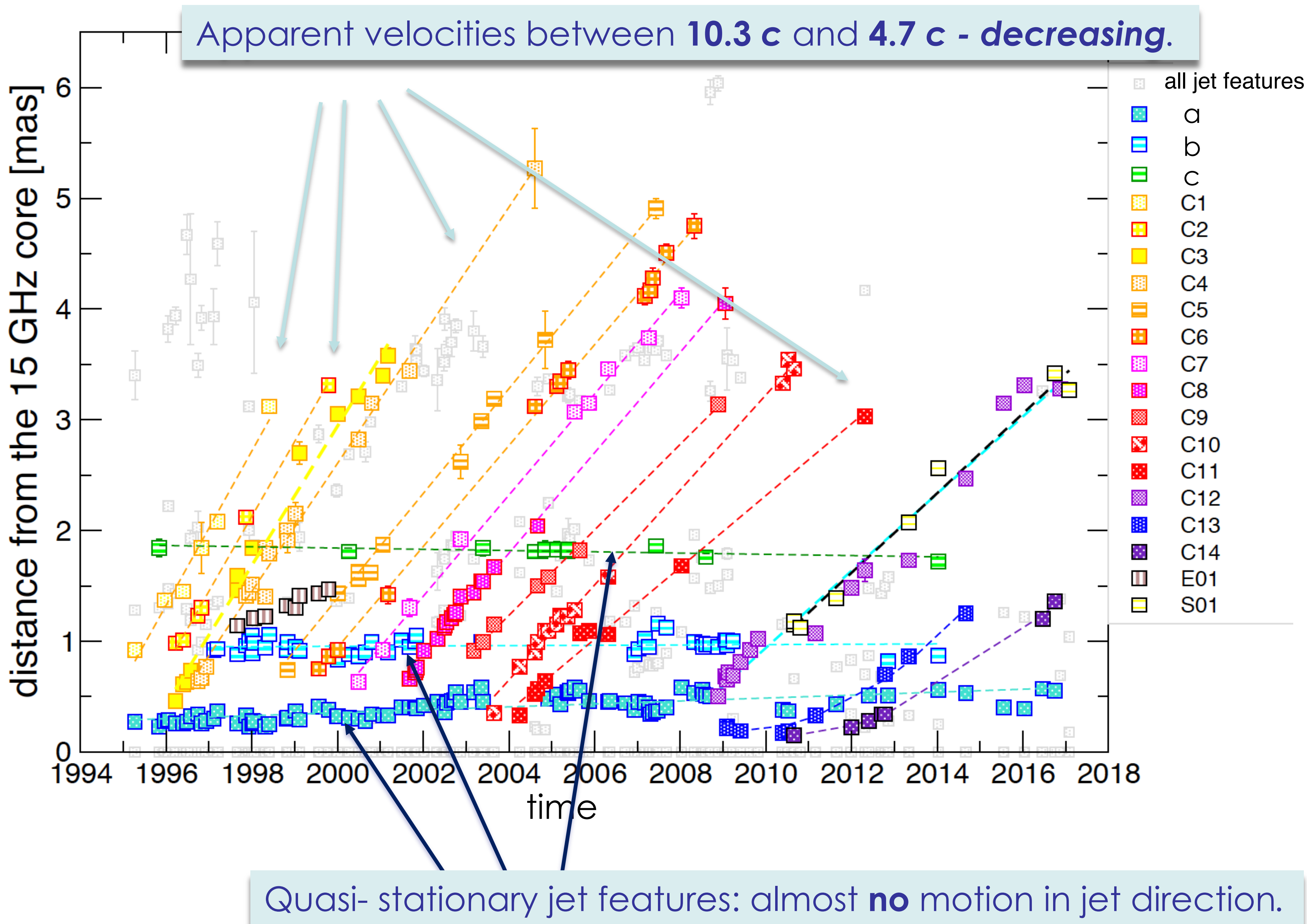


2012

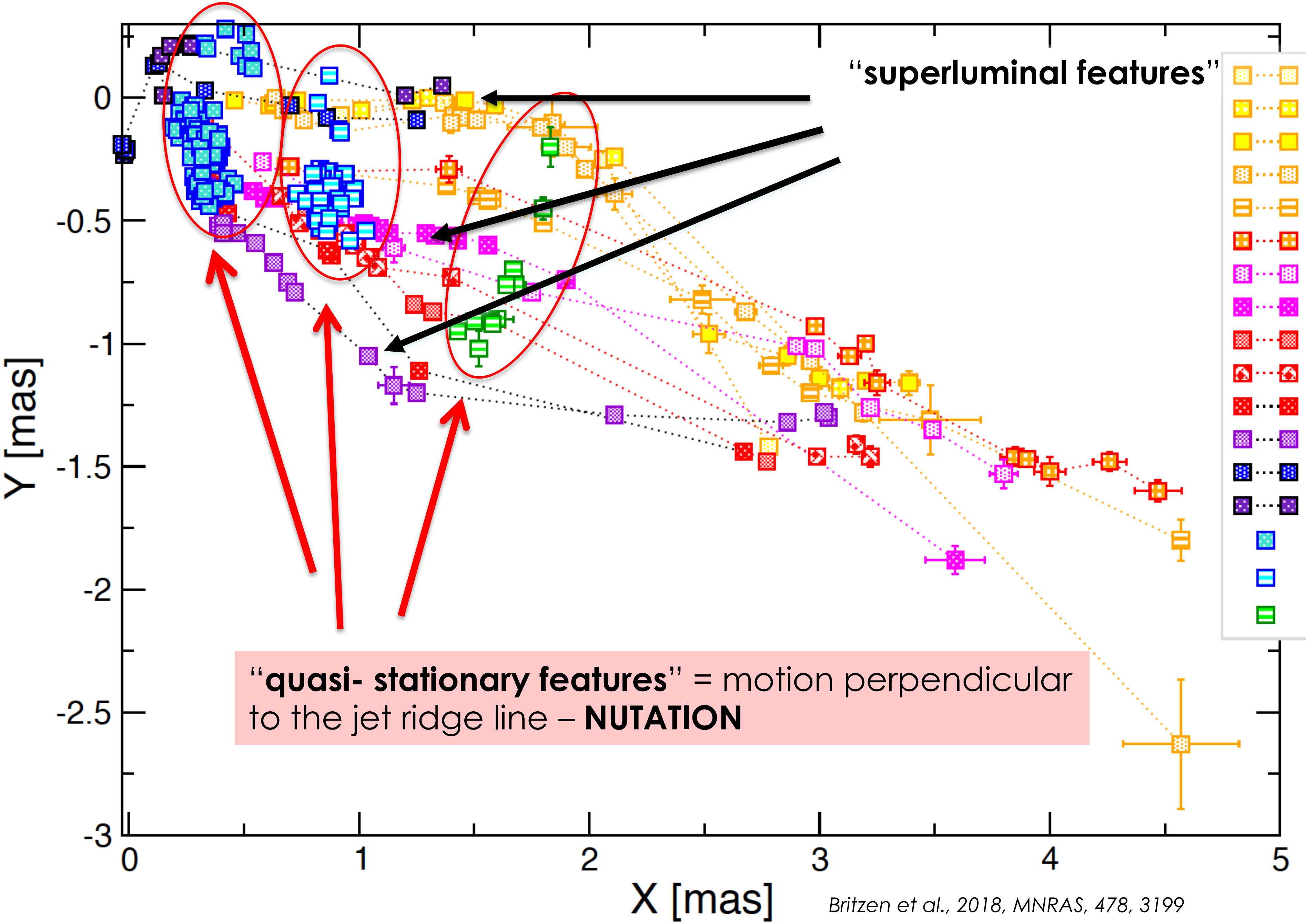
The jet is wandering in the sky – Precession explains brightness variations



Britzen et al., 2018, MNRAS, 478, 3199



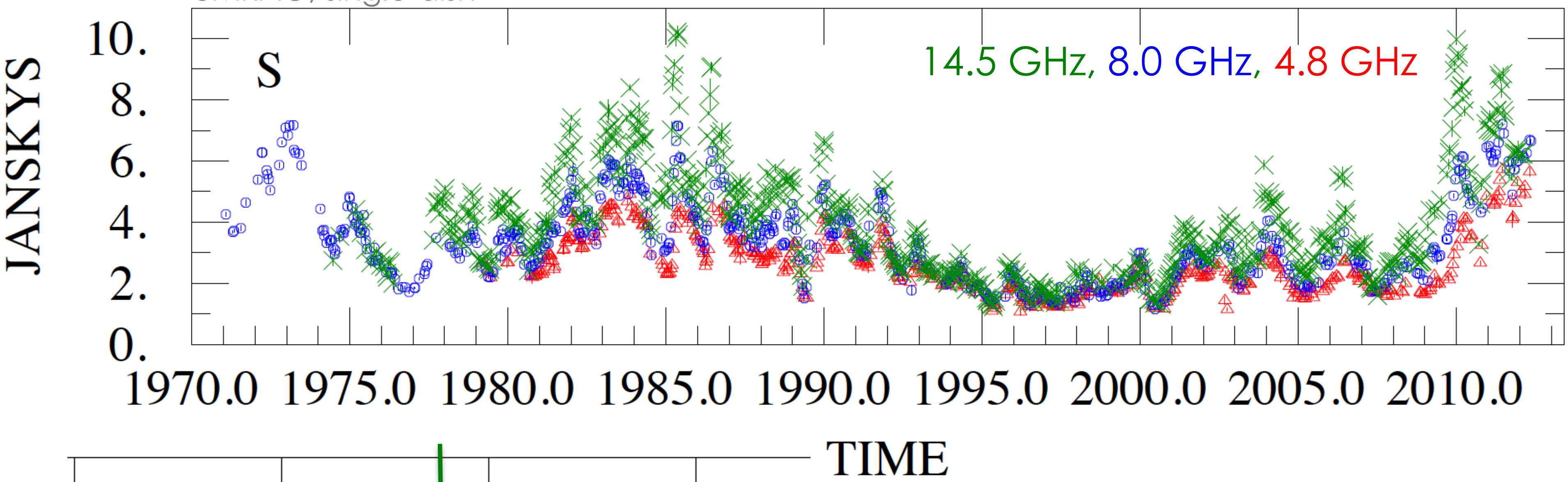
Britzen et al., 2018, MNRAS, 478, 3199

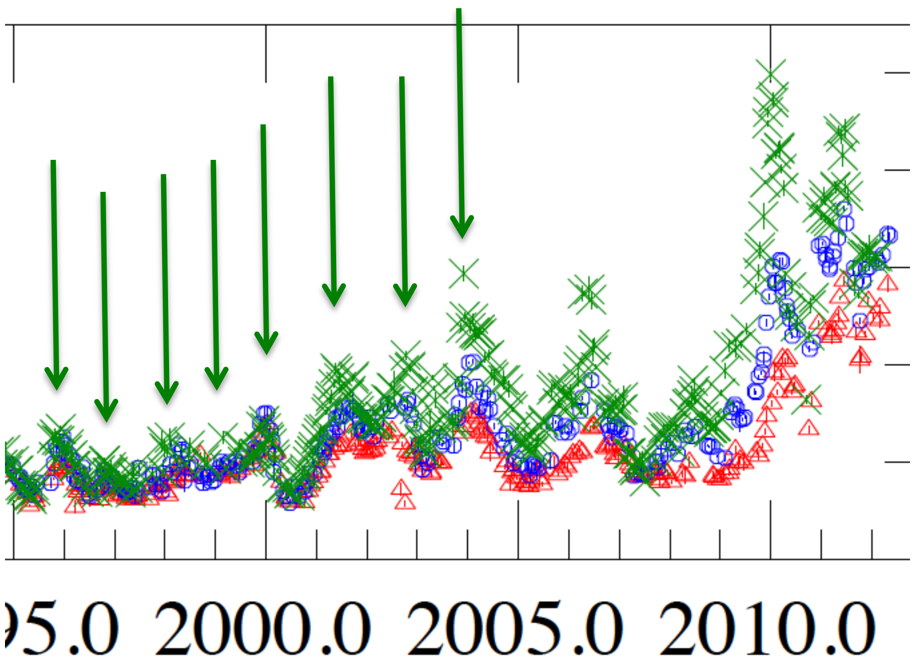


Britzen et al., 2018, MNRAS, 478, 3199

Radio Light-curve **long-term variability** = **Jet precession**

UMRAO, single-dish



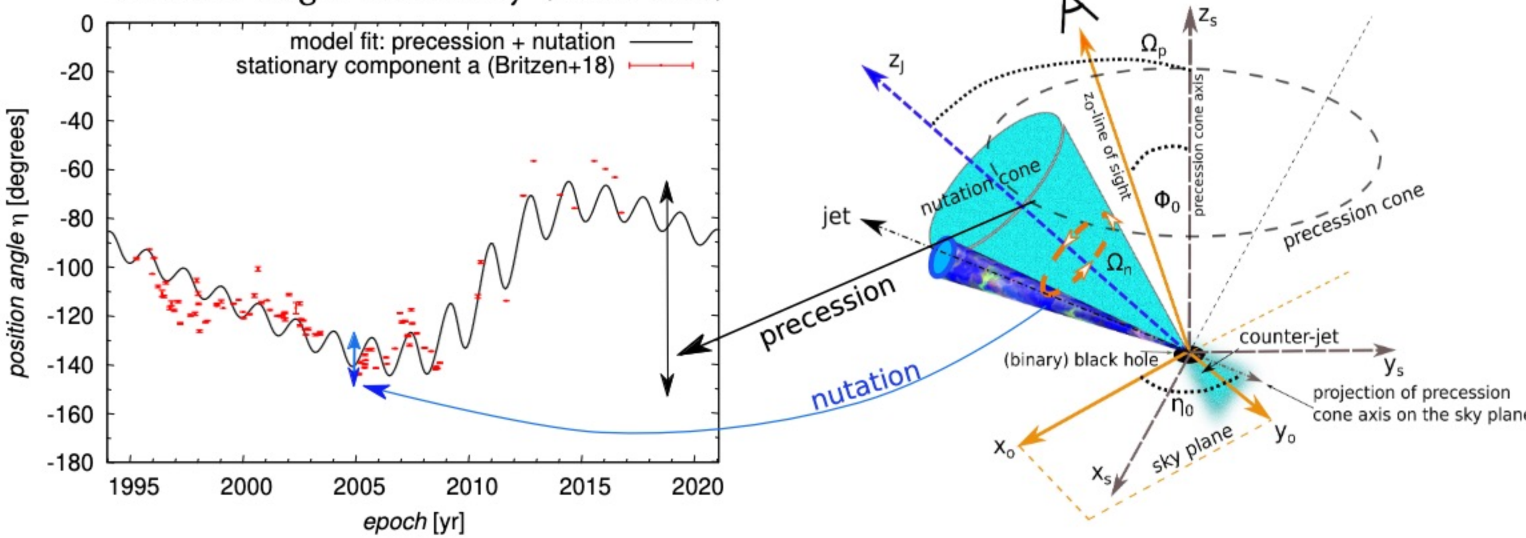


short-term variability
in the 15 GHz light-curve
originates in the
jet nutation

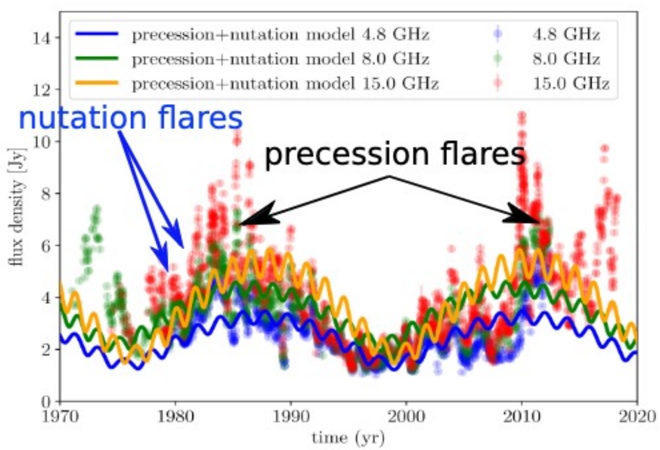
It's all geometry.

Britzen et al., 2018, MNRAS, 478, 3199

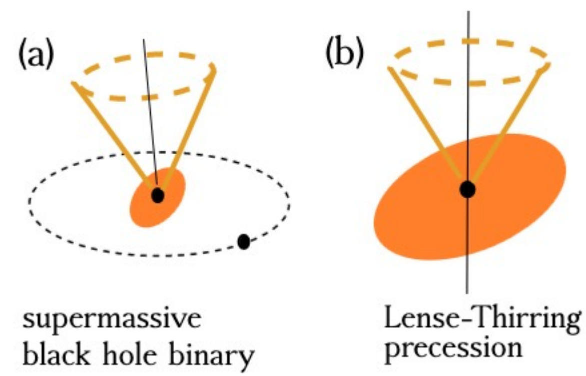
Position-angle variability (VLBI data)



Flux-density variability (single-dish data)



Jet precession mechanisms



Britzen et al., 2023, ApJ

NEW!!
Spectral Energy Distribution (SED) can be directly related to the jet's precession phase

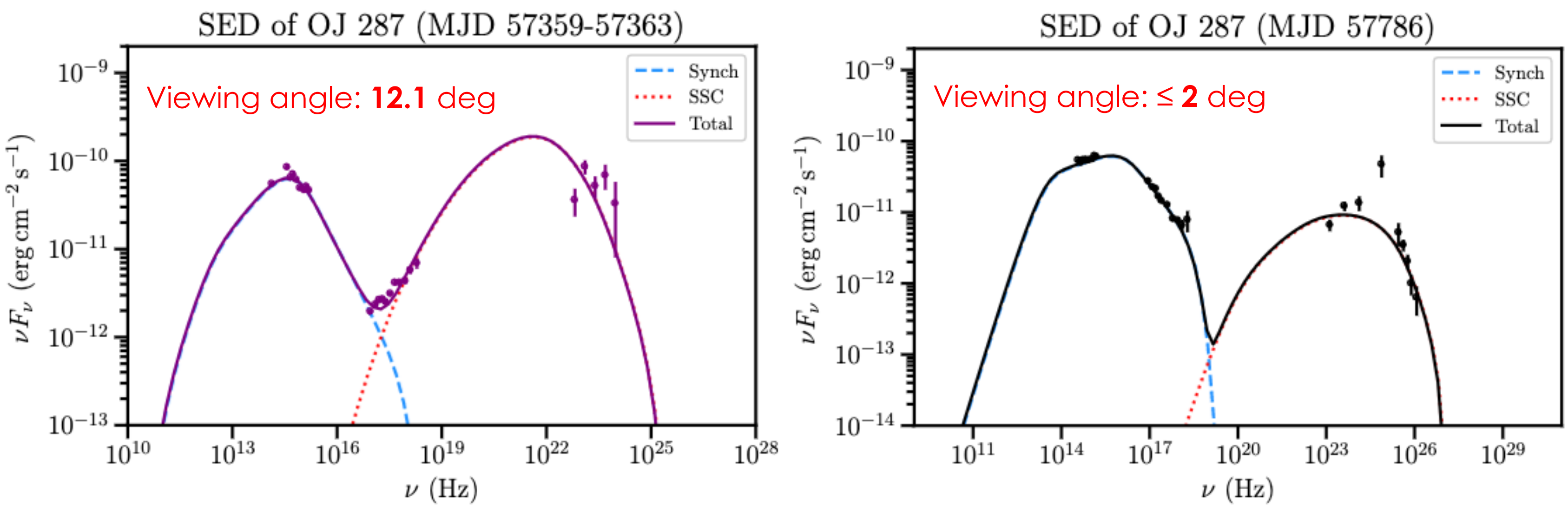
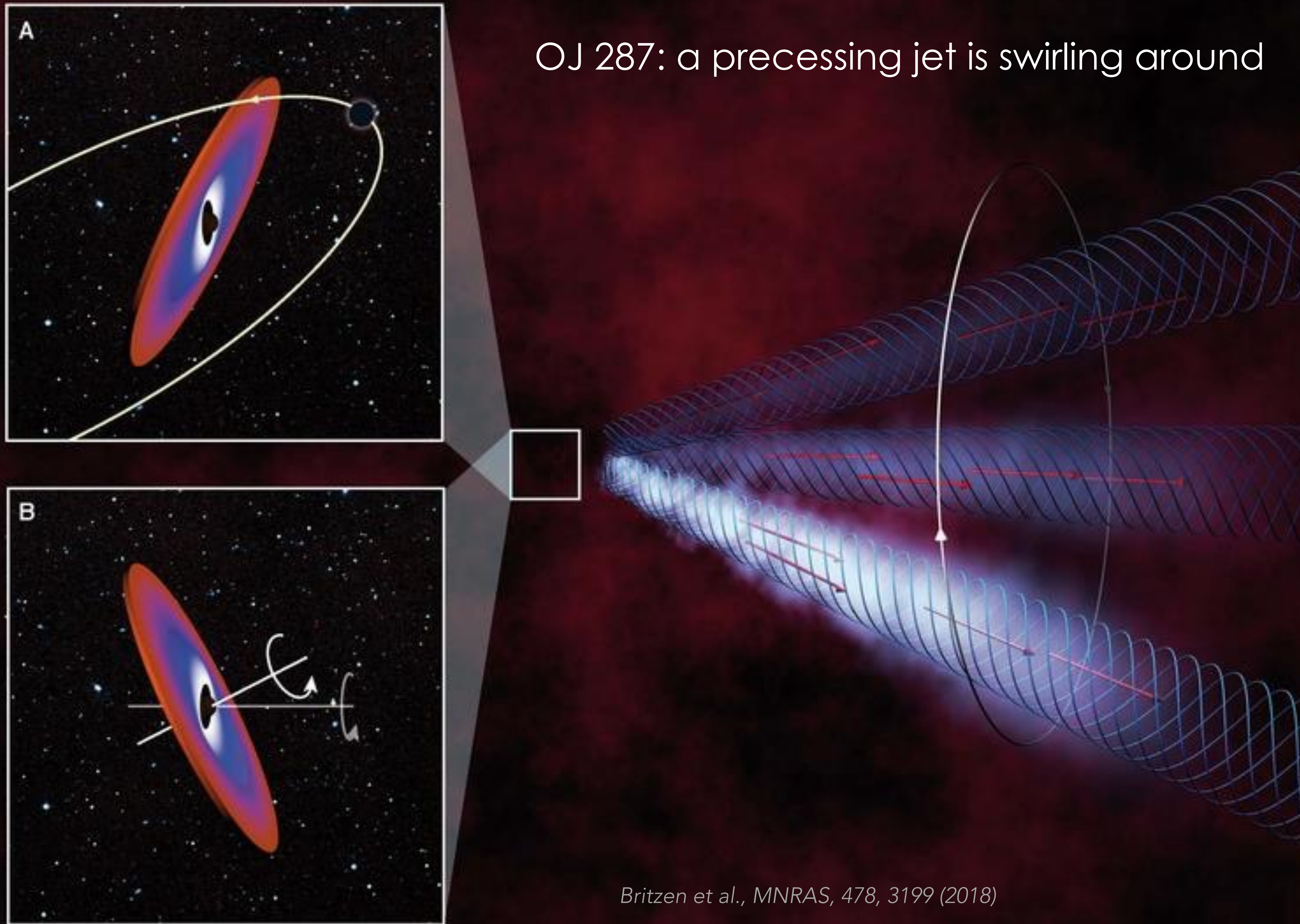


Figure 7. Pure leptonic SEDs for OJ 287 in different spectral states, where the SED points are adopted from Kushwaha (2020). *Left*: The dashed blue curve shows the (self-absorbed) synchrotron, the dotted red curve shows the SSC contribution to the total leptonic SED between MJD 57359-57363, that is shown by purple continuous line. *Right*. The dashed blue curve shows the (self-absorbed) synchrotron, the dotted red curve shows the SSC contribution to the total leptonic SED at MJD 57786, that is shown by black continuous line. The main difference between the models applied in the figures is the viewing angle of the jet (left plot $\Phi \approx 12.1^\circ$, right plot $\Phi \leq 2^\circ$) and the corresponding Doppler factor (left plot $\delta \approx 3.7$, right plot $\delta \approx 45.1$).

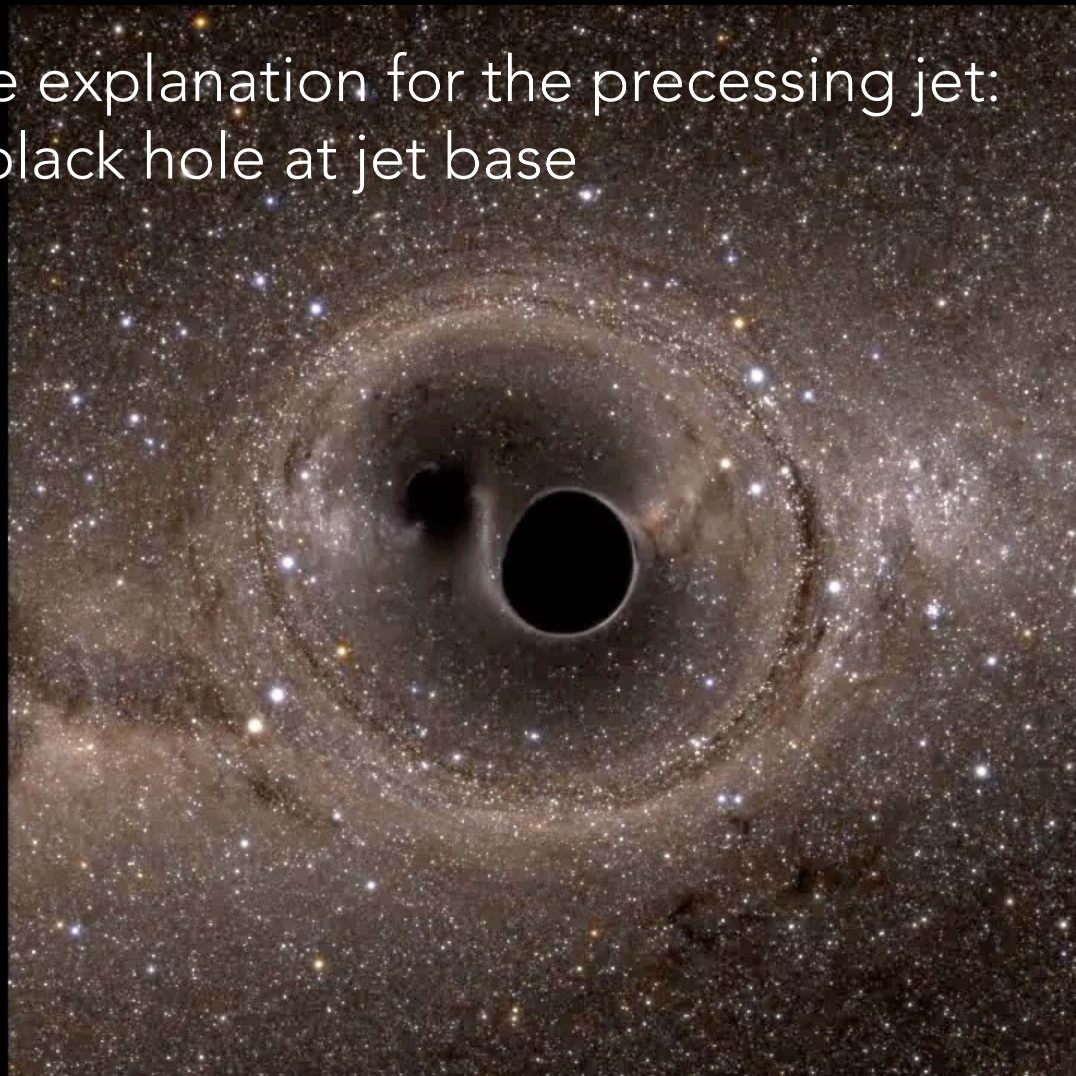
Britzen et al., 2023, ApJ

OJ 287: a precessing jet is swirling around



Britzen et al., MNRAS, 478, 3199 (2018)

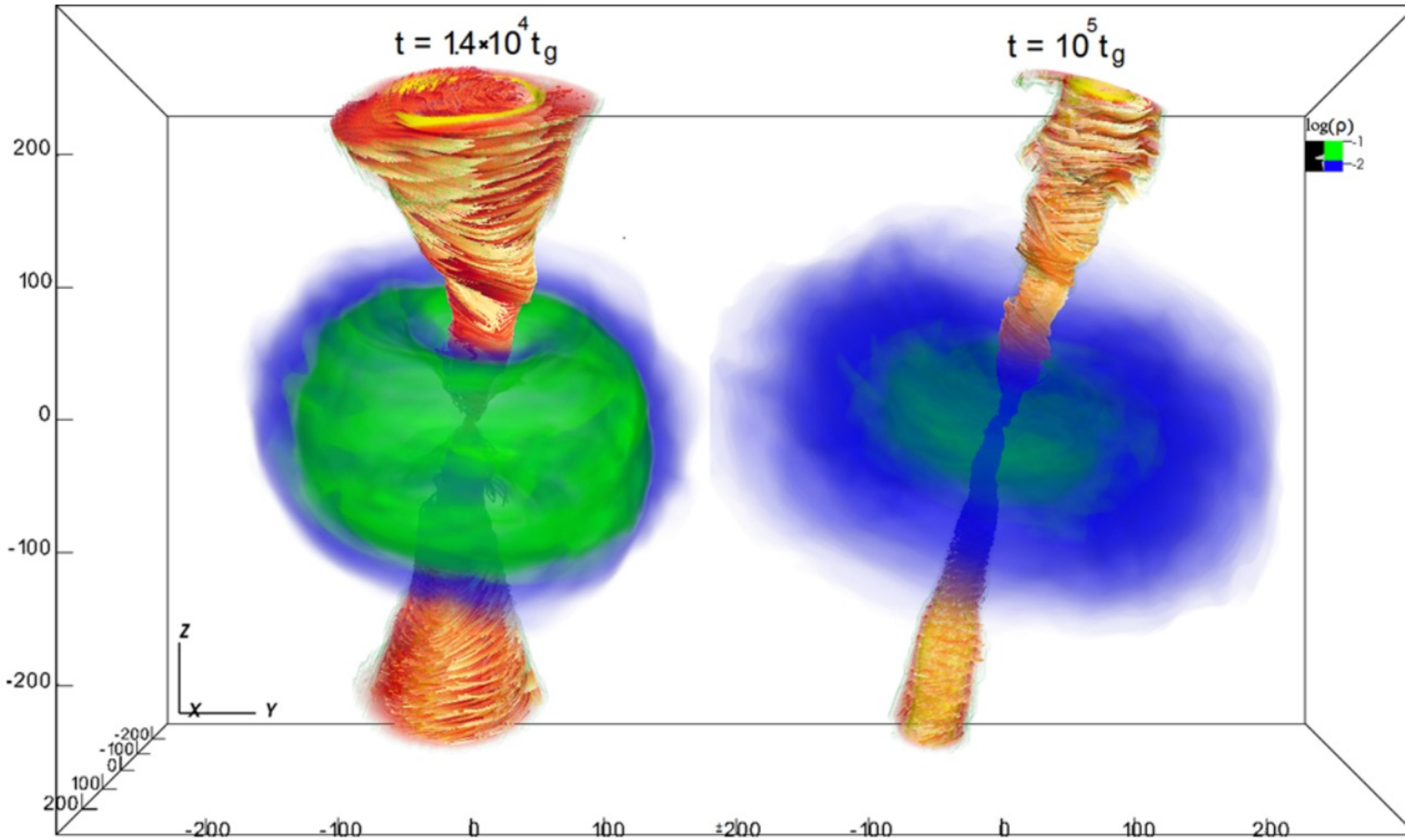
1. Possible explanation for the precessing jet: binary black hole at jet base



SXS Lensing

SXS collaboration uses the Spectral Einstein Code (SpEC) to simulate compact object mergers, be it with black holes or neutron stars (Taylor et al. 2013)

2. Possible explanation for precessing jet - wobbling accretion disk

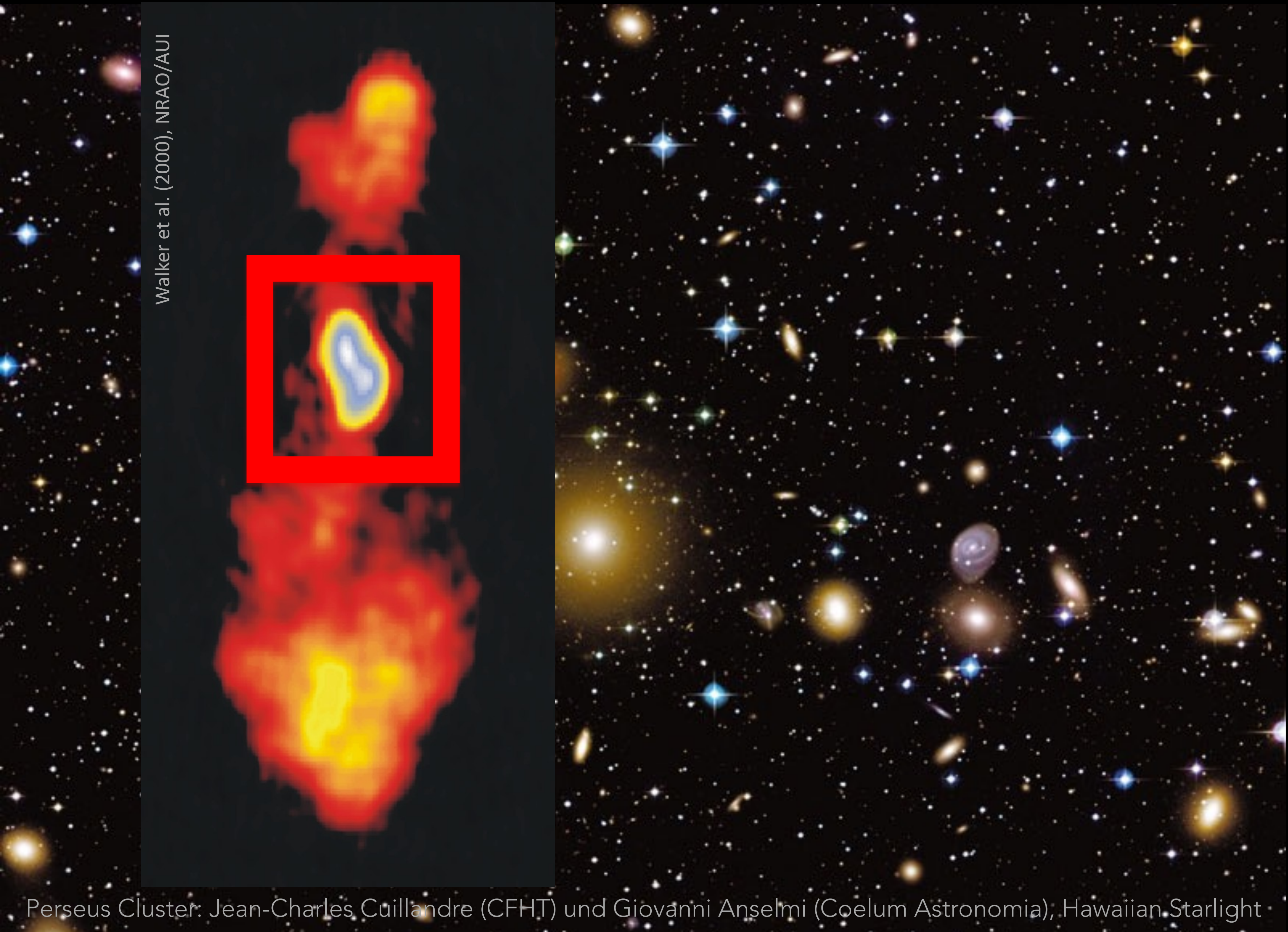


Disk (blue and green), magnetic field lines in the jets are shown with yellow–red lines. The disc–jet system precesses as a whole around the BH spin vector, which is vertical in the figure.

Liska et al. 2018

One more precessing AGN

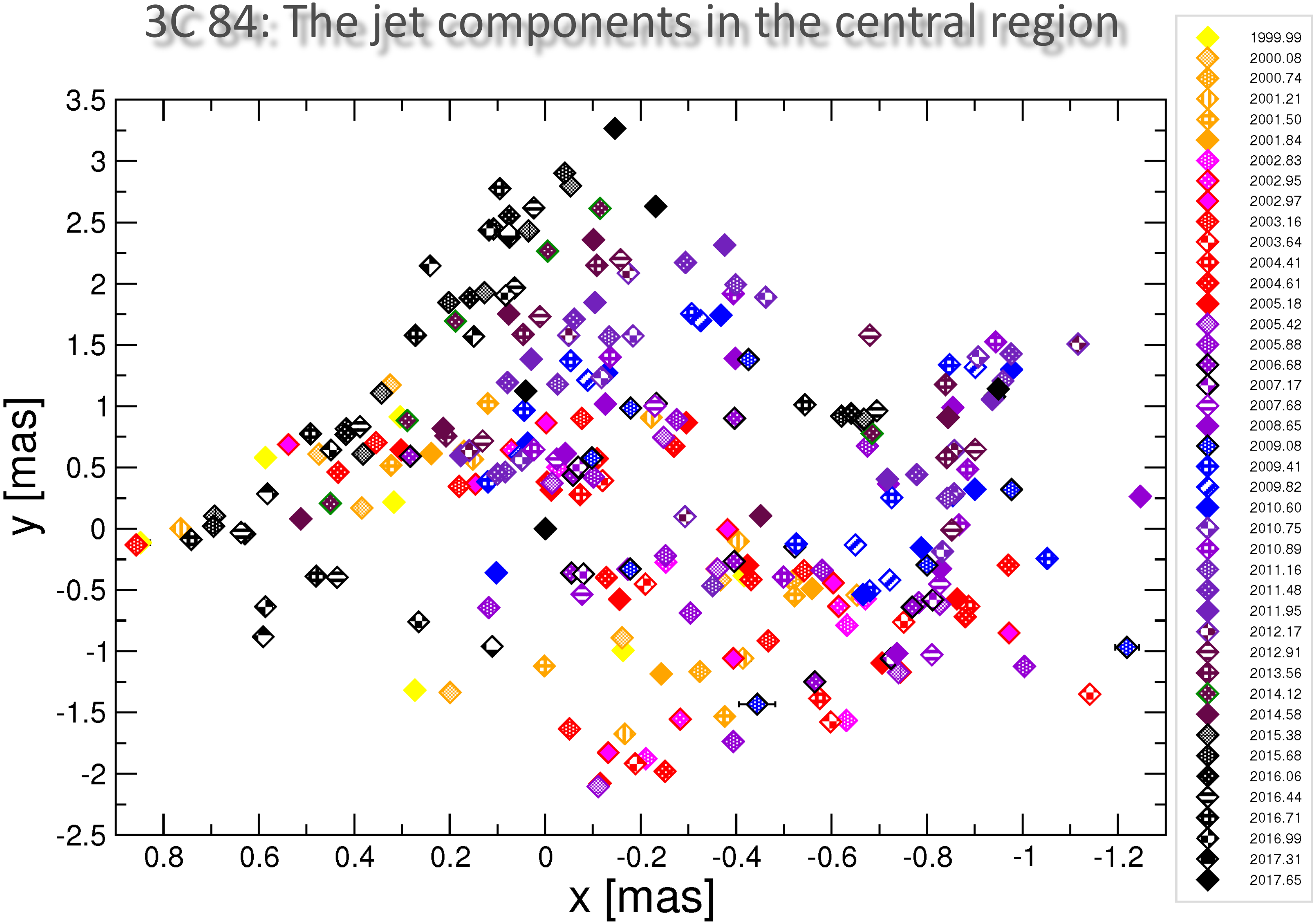
3C 84 (NGC 1275, Perseus A)



Walker et al. (2000), NRAO/AUI

Perseus Cluster: Jean-Charles Cuillandre (CFHT) und Giovanni Anselmi (Coelum Astronomia), Hawaiian Starlight

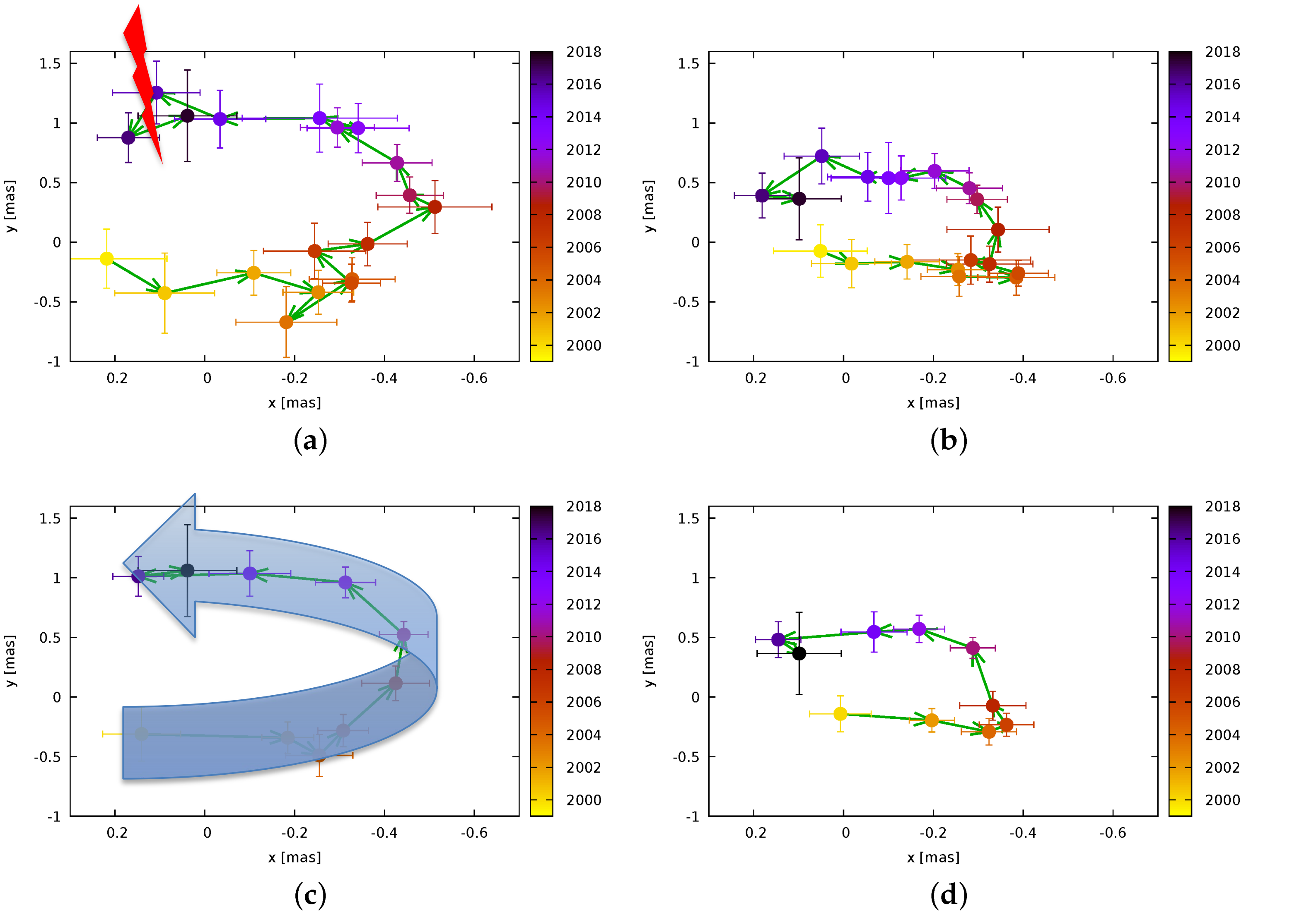
3C 84: The jet components in the central region



Britzen et al., *Galaxies* **2019**, *7*(3), 72

3C 84: Precession

TeV-flare detected by MAGIC



Britzen et al., *Galaxies* **2019**, 7(3), 72

(a) Average values for the data in yearly intervals. The green arrows indicate the direction of the precessing motion. (b) The same relation as in (a) but averaged over two years in time.

(b) (c) Flux-density weighted average values in yearly intervals and averaged in two years in (d).

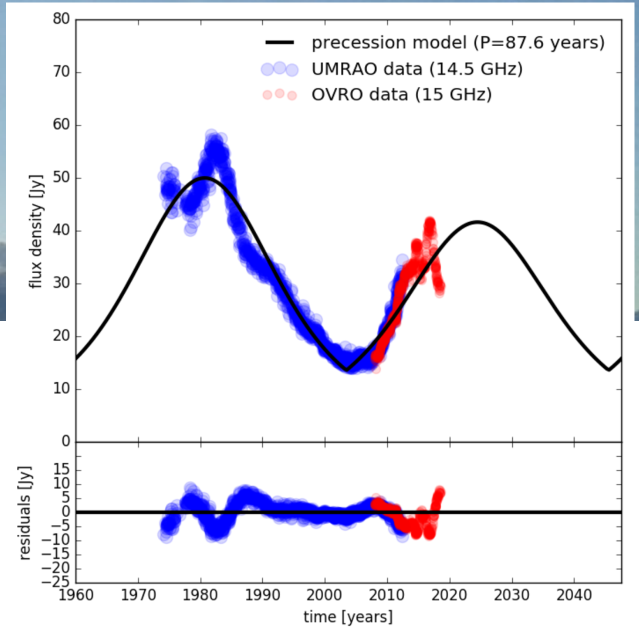
Precession explains Brightness variations

VLBA data provide evidence for precession of the central radio structure of 3C 84.

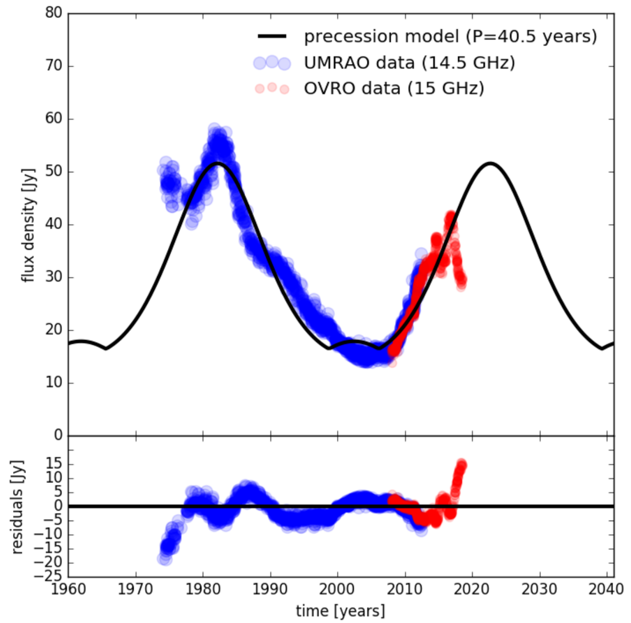
Fitting a precession model to the single-dish radio data (OVRO + UMRAO, 15 GHz) provides evidence for precession as well.

Going back to the archival data: maps from 40yrs ago show similar morphology – further evidence for precession

3C 84 is **precessing** with a **time-scale of about 40 yrs**



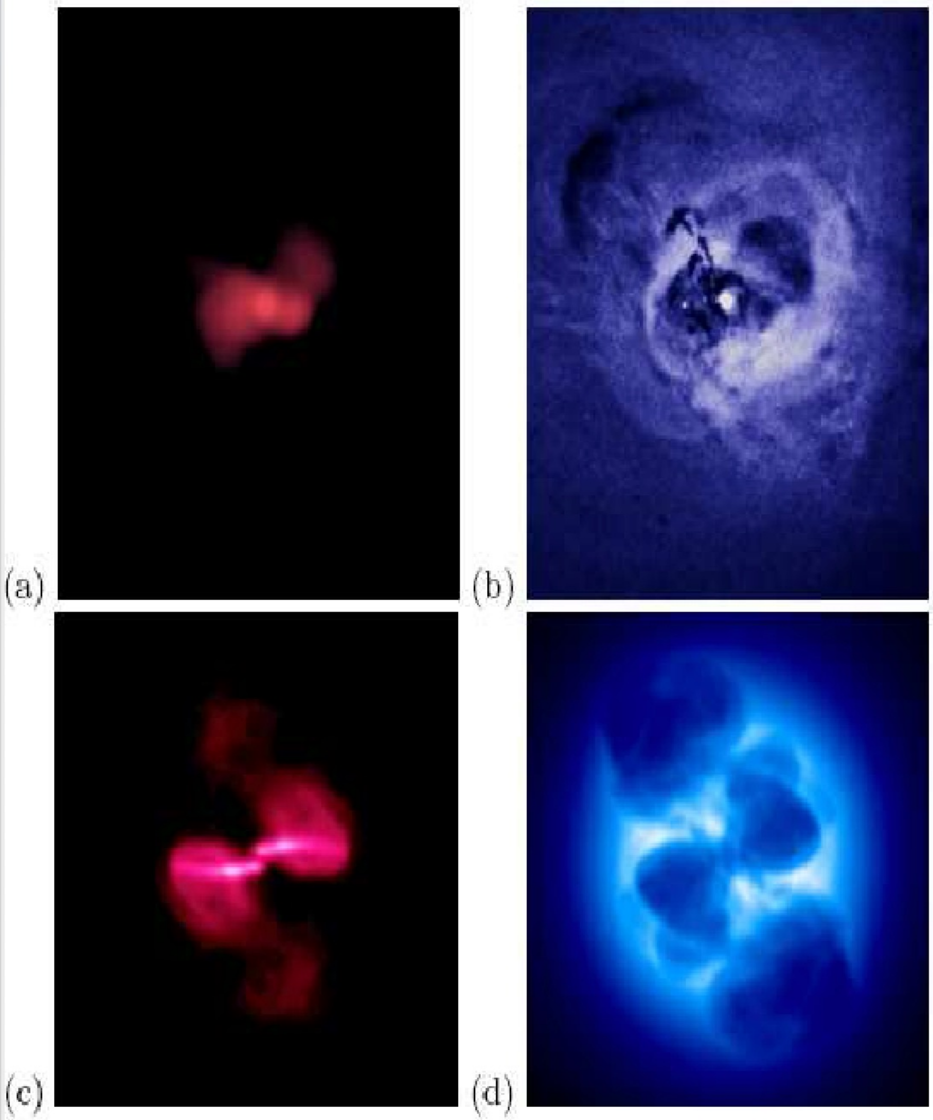
(a)



(b)

Britzen et al., *Galaxies* **2019**, *7*(3), 72

Further support for Precession in 3C 84 based on modeling X-ray data



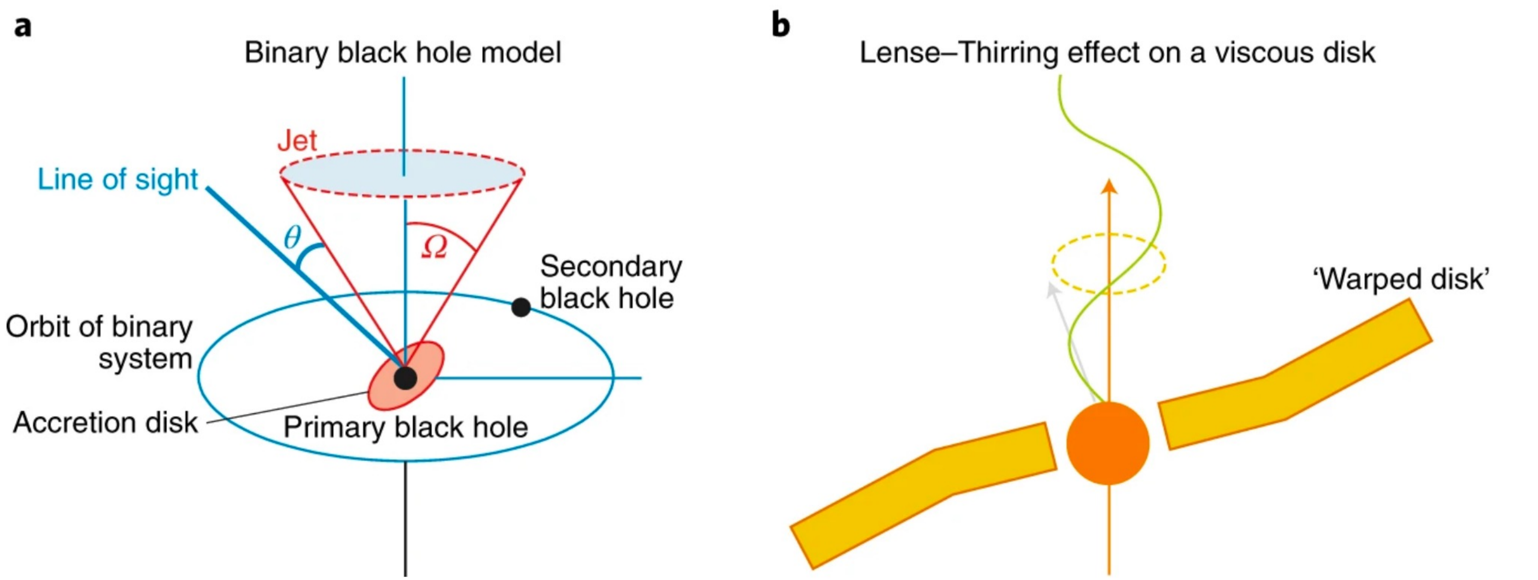
Precession in 3C 84 has been claimed before by several authors based on simulations (e.g., Dunn et al., 2006; Falceta-Goncalves et al., 2010) to explain the Chandra observations of the X-ray cavities (e.g., Fabian et al., 2011).

Falceta-Gonçalves et al., 2010

Fig. 4.— a) 328 MHz VLA radio map credit NRAO/VLA/G.Taylor, b) credit: NASA/CXC/IoA/A.Fabian, c) temperature integrated along the line of sight normalized by its maximum and d) emission measure normalized by its maximum value. Panels c and d correspond to the projection of the mentioned quantities along a line of sight inclined 40◦ with respect to the total angular momentum of the system. The synthetic maps shown were zoomed to better fit the observations. In both cases the total length of the image is 70kpc in each direction.

Precessing jets are game changers

- Jet precession has been found and modeled:
  - e.g., 3C 279 (Abraham & Carrara 1998), 3C 273 (Abraham & Romero 1999), PKS 0735+178 (Britzen+ 2010), 2200+420 (BL Lac, Caproni et al. 2013), PG 1553+113 (Caproni+ 2017), 3C 345 (Caproni & Abraham 2004), 3C 120 (Caproni & Abraham 2004), 1308+326 (Britzen+ 2017), 3C 84 (Dunn+2006, Britzen+ 2019), **TXS 0506+056** (Britzen+ 2019), **PKS 1502+106** (Britzen+2021), and **OJ 287** (e.g., Sillanpää+1988; Valtonen+2016, Britzen+2018, Britzen+2023), and many more.



a, The orbital motion of a supermassive black hole binary leads to the precession of the jet on the surface of a cone with opening angle Ω, at an angle θ from the observer's line of sight. **b**, A misalignment of the supermassive black hole spin (orange arrow) with the accretion disk angular momentum (grey arrow) leads to the Lense–Thirring effect and the precession of the relativistic jet (green line).

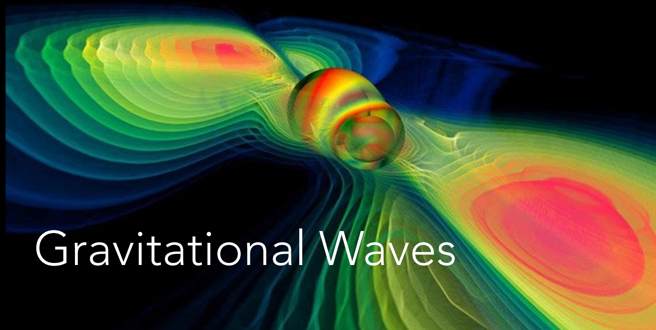
Abraham, Nature Astronomy, 2018

In the future?
Watching supermassive binary black holes dance

In this visualization, disks of bright, hot, churning gas encircle both black holes, shown in red and blue to better track the light source.
Image credit: NASA's Goddard Space Flight Center/Jeremy Schnittman and Brian P. Powell.

The animation shows two black holes: The bigger of the pair, which is about 200 million times the mass of our sun, is surrounded by red rings of hot gas called an accretion disk. Orbiting that giant is a second black hole weighing in at about half of that mass, and its gas and dust rings are illustrated in bright blue.

"Zooming into each black hole reveals multiple, increasingly distorted images of its partner," Jeremy Schnittman

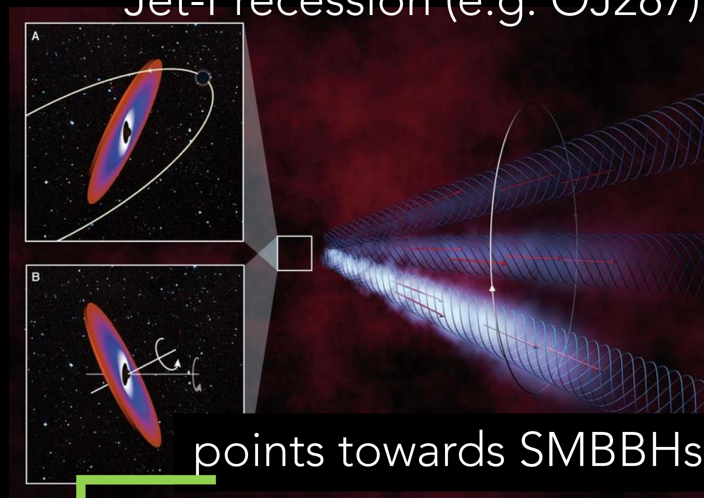


Gravitational Waves

LISA
PTA

ngEHT

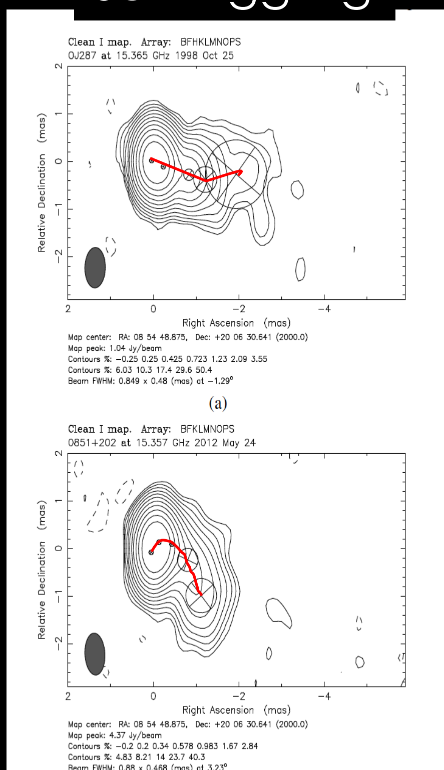
Jet-Precession (e.g. OJ287)



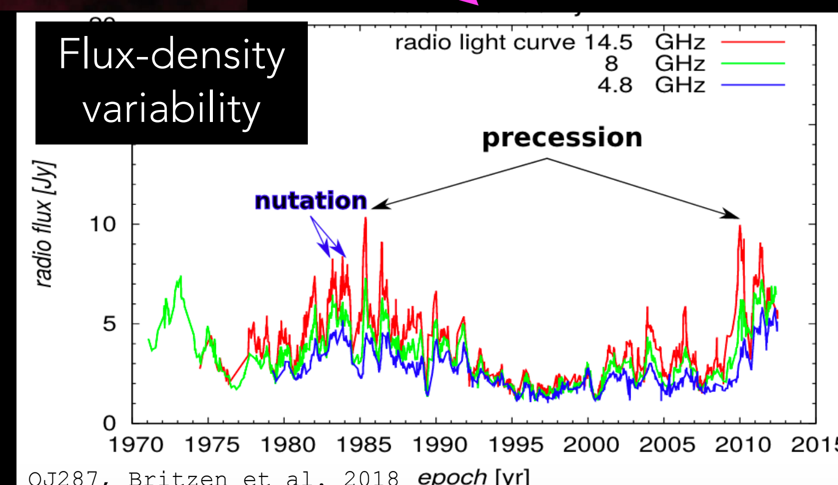
points towards SMBBHs

- Detecting binaries
- Binary evolution
- merging horizons
- potential to test
  - alternative gravity
  - etc.

Jet wiggling



Flux-density variability



Nasa Goddard Space Flight Center