EHT & ALMA: a view of the local Universe

Violette Impellizzeri

Leiden Observatory

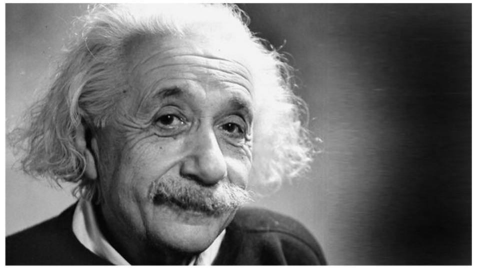
On behalf of the EHTC

Event Horizon Telescope

Credit: Bettymaya Foott

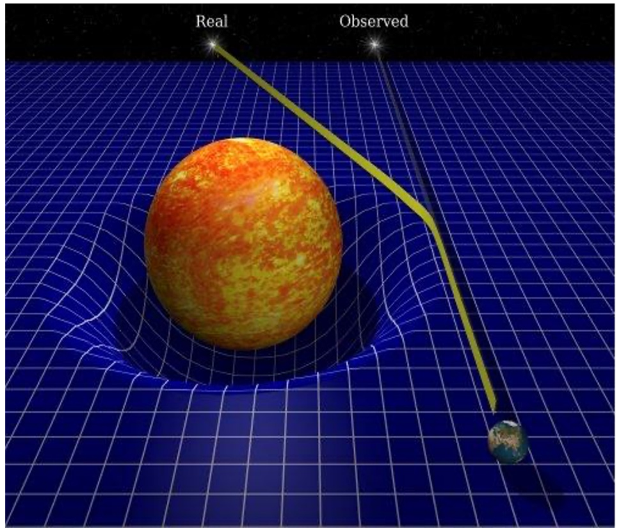
General Relativity and Black Holes

1916: Einstein publishes the
General Theory of Relativity (GR)
=> *describes successfully Gravity*



1916: Schwarzschild finds solution to
Einstein's equations
=> *infinite curvature of space-time and singularity*

1967: Wheeler first uses the expression *black hole*



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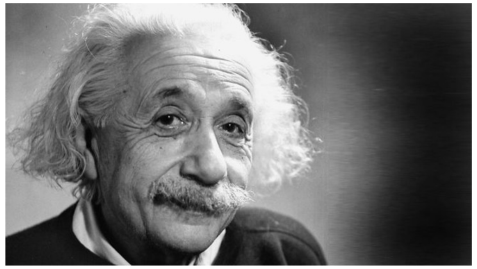

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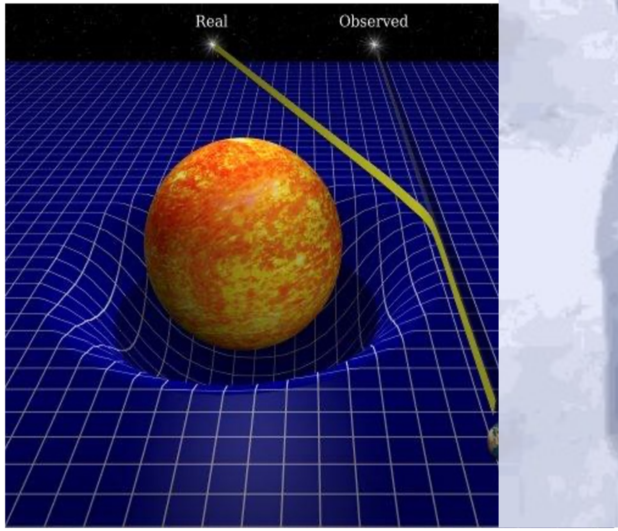



HAVE YOU EVER HEARD OF A "BLACK HOLE," CAPTAIN?
I'M AFRAID NOT, MR. SPOCK! PLEASE EXPLAIN!

1974

Astrophysical Targets?

$$R_{Sch} = (2\ G/c^2)\ M_{BH}$$

$$\theta_{Sch} = R_{Sch}/D$$

$$\approx 0.02 \text{ nano-arcsec } (M_{BH}/M_{\odot})/(\text{kpc}/D)$$

- Stellar mass BHs ($D \sim 1$ Kpc, $M_{BH} \sim 10\ M_{\odot}$)
- Super-massive BHs ($D \sim 1$ Mpc-1Gpc, $M_{BH} \sim 10^6$-$10^9\ M_{\odot}$)

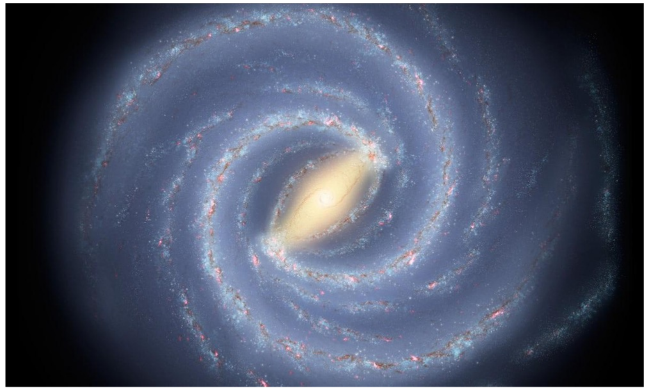
=> Both generally too small

Astrophysical Targets: Best candidates

Sgr A* :

25000 light years

~4 milions solar masses



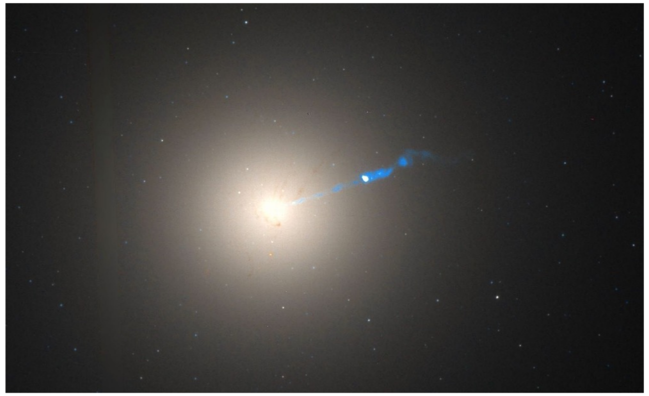
D~8 kpc, M_{BH} ~4.3x10^6 $M_\odot$

=> $\boldsymbol{\theta_{Sch}}$ **~** 10 micro-arcseconds

M87 :

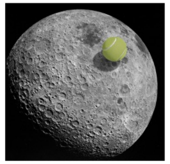
55 milions light years

~7 billions solar masses



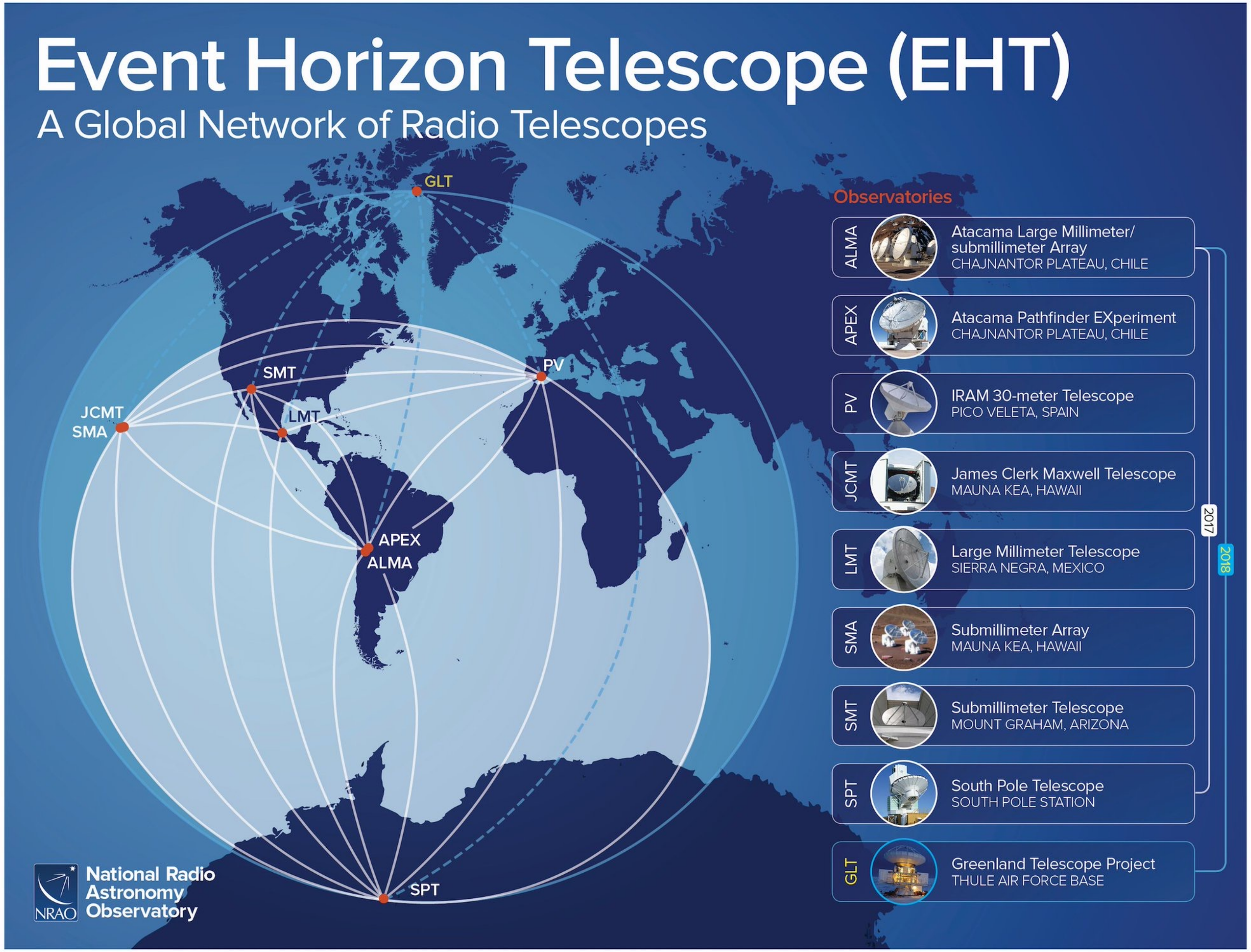
M87 : D~17 Mpc, M_{BH} ~6.5x10^9 $M_\odot$ => $\boldsymbol{\theta_{Sch}}$ **~** 8 micro-arcseconds

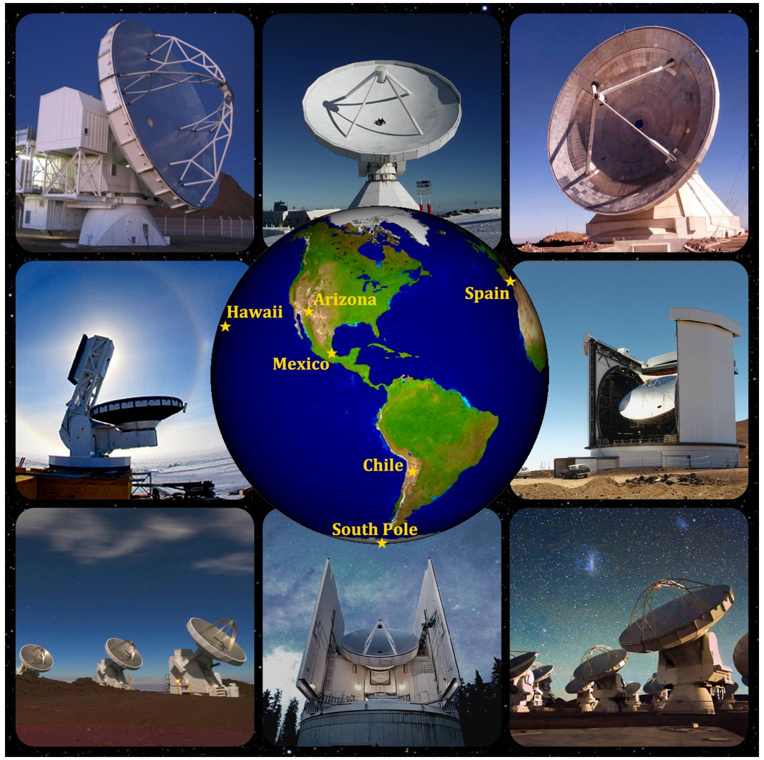
M87 is ~2000 times more distant but almost 2000 more massive!



=> Gravitationally-lensed size ~40-**50 micro-arcseconds**

The first mm- earth-sized telescope: Event Horizon Telescope





M. Johnson/SAO

EHT collaboration - stakeholders

2016: 13 international institutes join forces and create the EHT consortium

Academia Sinica Institute of Astronomy and Astrophysics

University of Arizona

University of Chicago

East Asian Observatory

Goethe-Universität Frankfurt

Institut de Radioastronomie Millimétrique

Large Millimeter Telescope

Max Planck Institute for Radioastronomy

MIT Haystack Observatory

National Astronomy Observatory of Japan

Perimeter Institute for Theoretical Physics

Radboud University

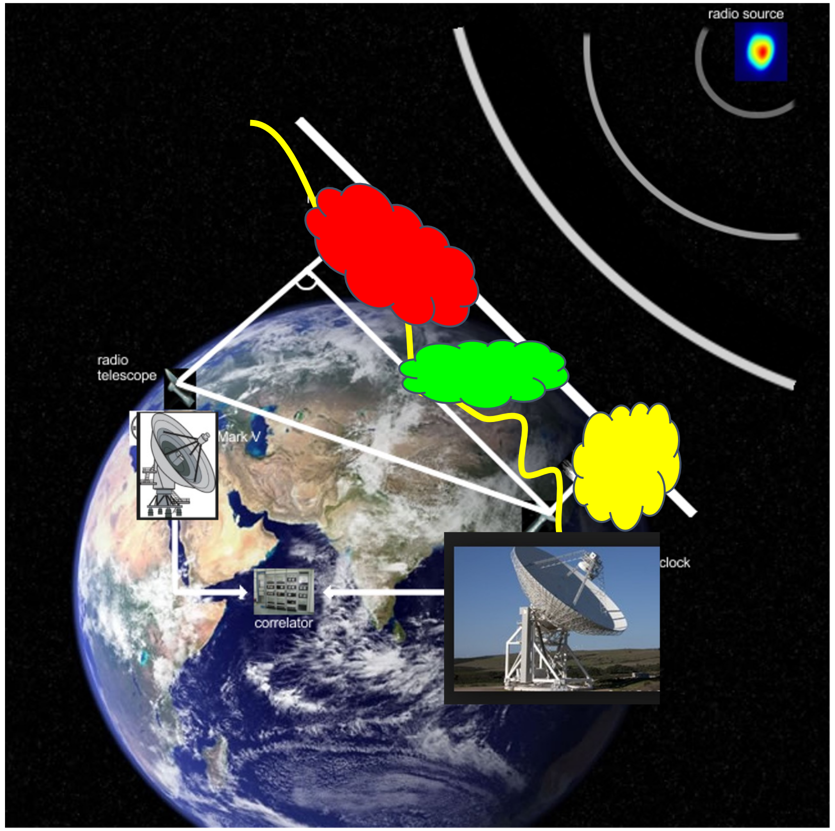
Smithsonian Astrophysical Observatory

EHT collaboration - affiliated

EHT Associated Logos

EHTC– collaboration meeting 2022

Why EHT VLBI is ground-breaking



It observes at ~**230 GHz** frequency

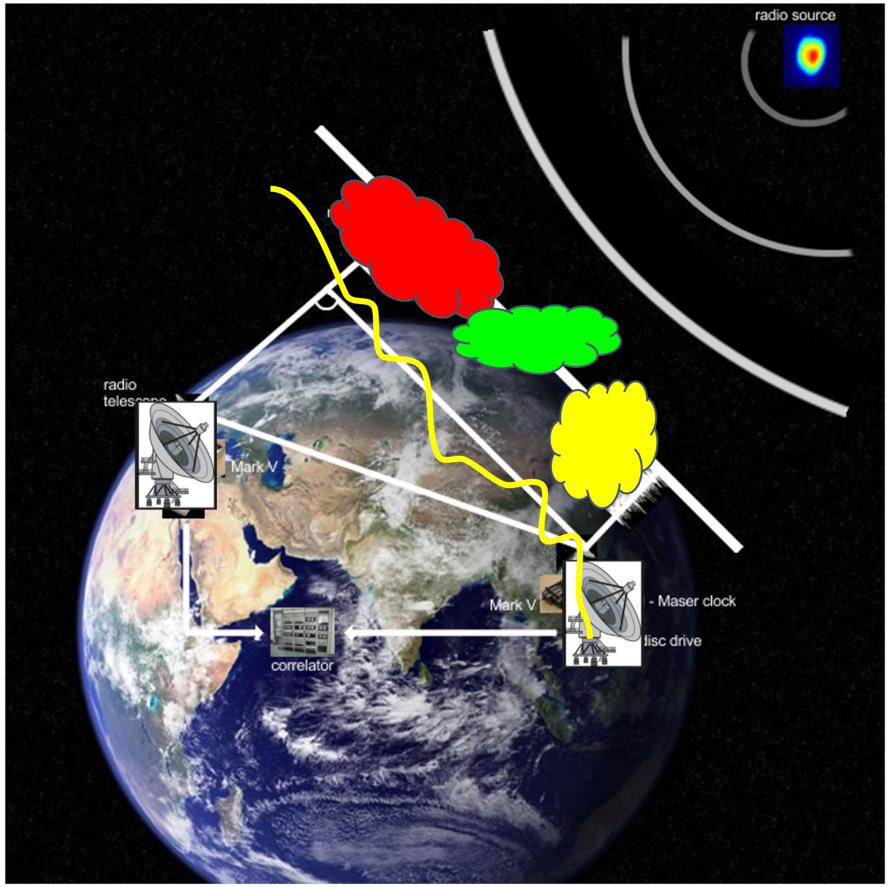
In the array, antennas are **not homogenous**!!

- Diameter dishes
- Site issues
- Basic telescope Properties

- Huge **data volume** (0.5 Pb per site)

→ Need special calibration and imaging techniques

VLBI in the mm - challenges



At <3mm VLBI is still **challenging**:

- ***weaker*** astronomical signal
- distortion effect by the ***troposphere*** → *dependence on weather, short time coherence*
- Worse receiver performances
- typically *small dishes* (10-15 m)
- *small number* of telescopes

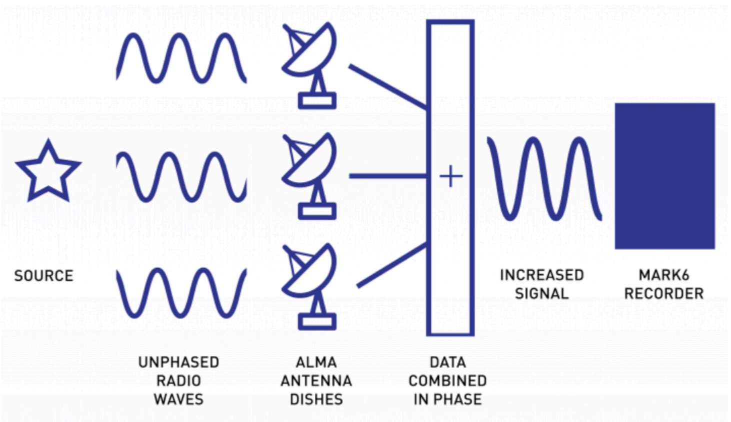
  → **lower sensitivity**

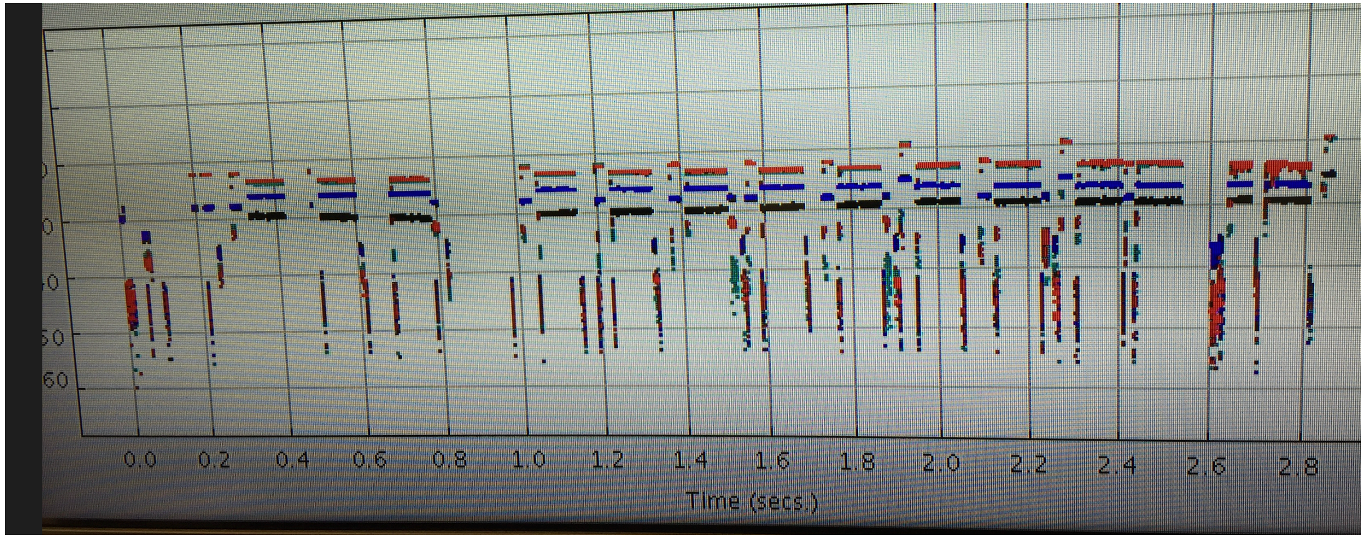
For an interferometer :

$$\sigma_S \approx \frac{2\,k\,T_{\rm sys}}{A_{\rm eff}\,\sqrt{n(n-1)}\times\Delta\nu\times\eta_{\rm pol}\times t_{\rm int}}\;[{\rm Jy}]$$

ALMA as part of the the EHT array

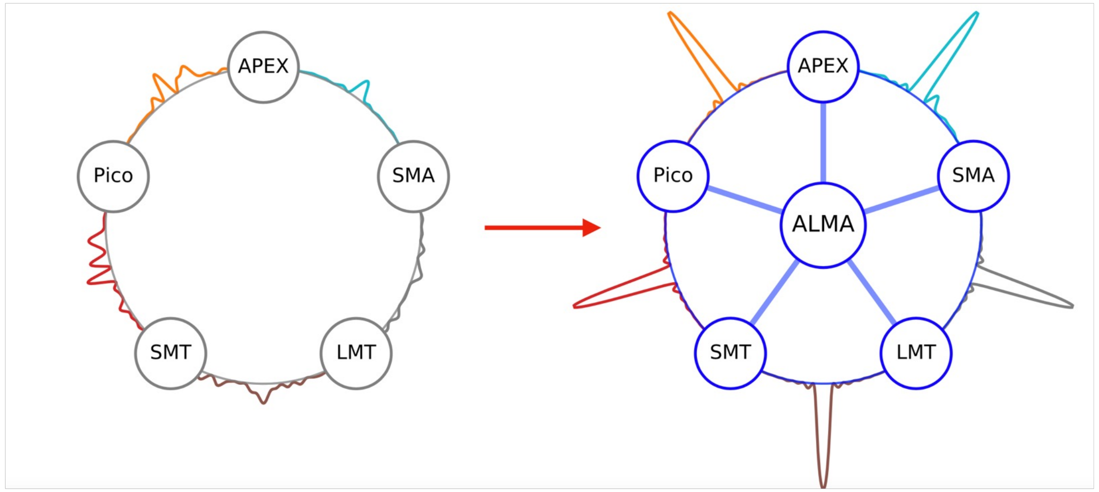
- In 2017, ALMA participated for the first time in EHT observations
  - The ALMA Phasing Project (APP) —> sum signal of all ALMA antennas (2013-2017 - ongoing: spectral line capability is being worked on!)★
  - With ~ 50 x12m antennas, ALMA corresponds to a single dish of up to 84 m diameter!
  - Second biggest antenna is LMT (50 m in Mexico)





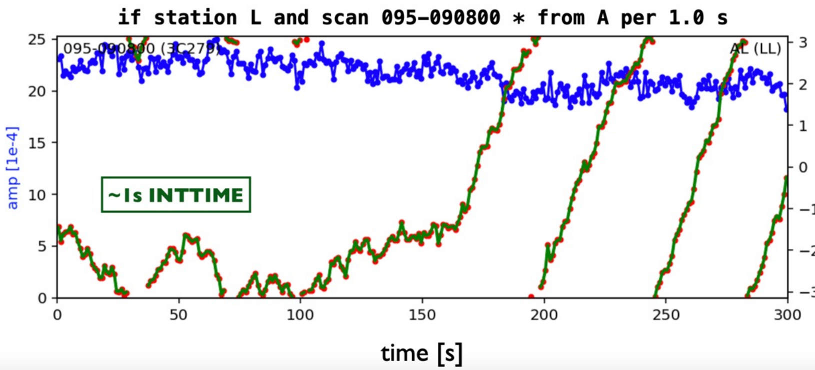
★Lead: MIT Haystack

ALMA as part of the the EHT array



when ALMA is in the array, high SNR usually enables phase stabilization at short timescal

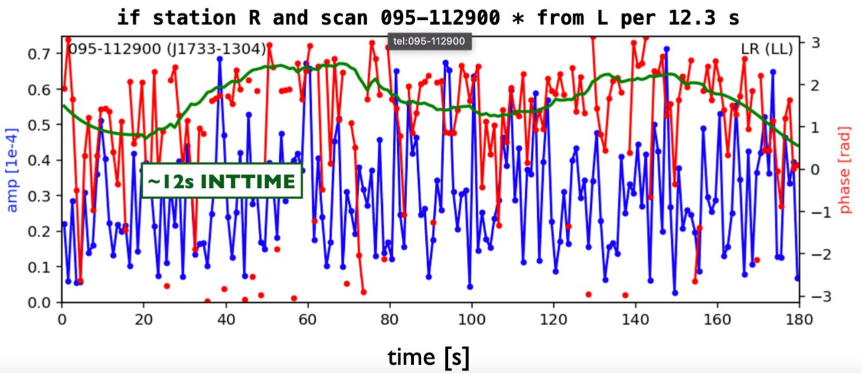
ALMA-LMT
SNR=1848



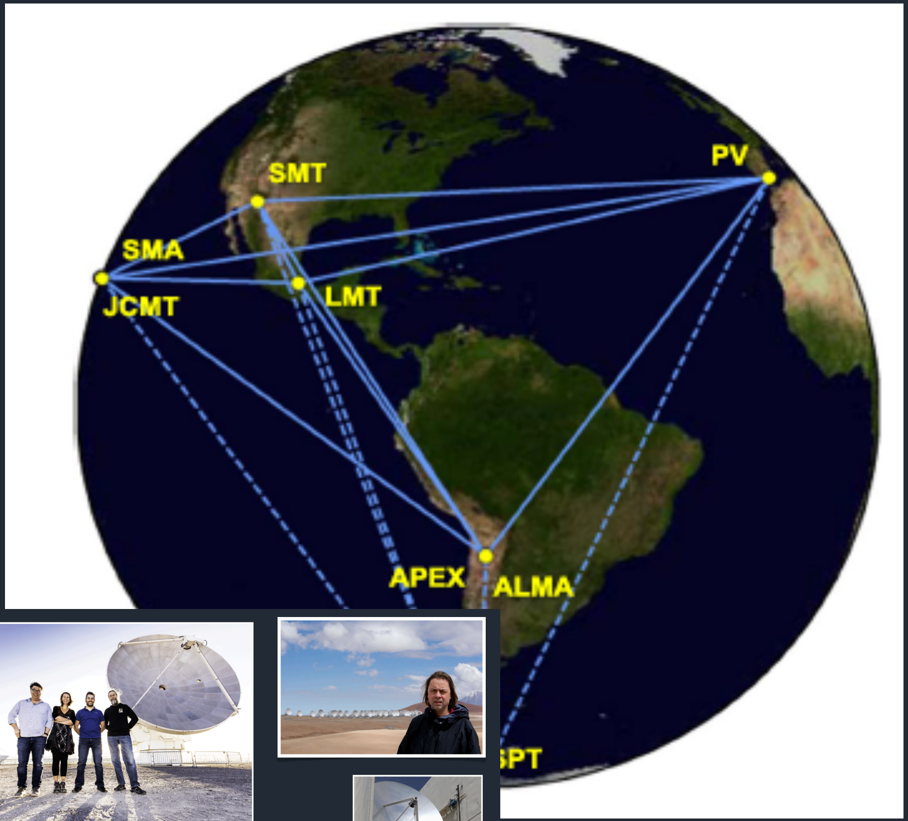
when ALMA is missing, a different reference station is chosen and timescales automatically adjust

LMT-SMAR
SNR=11

(no ALMA)



2017 EHT campaign



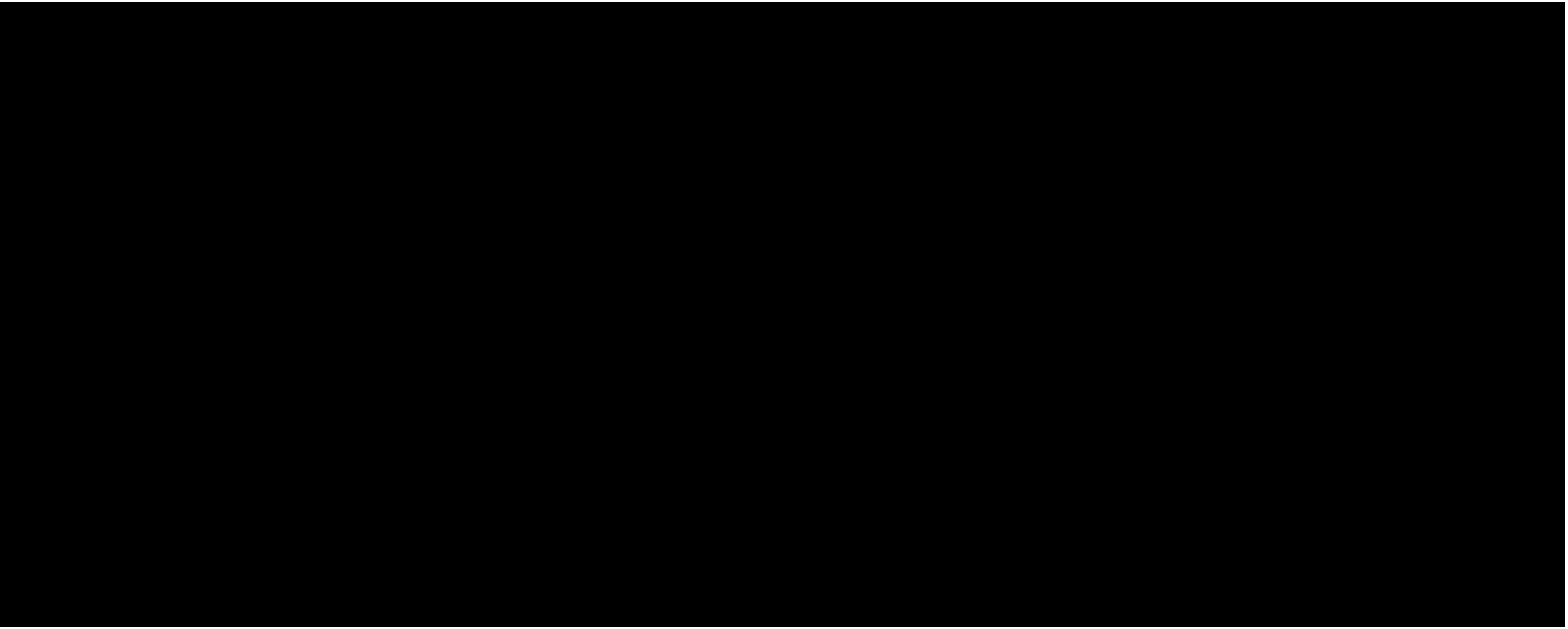
- April 5-6-10-11 2017
- 8 telescopes in 6 sites

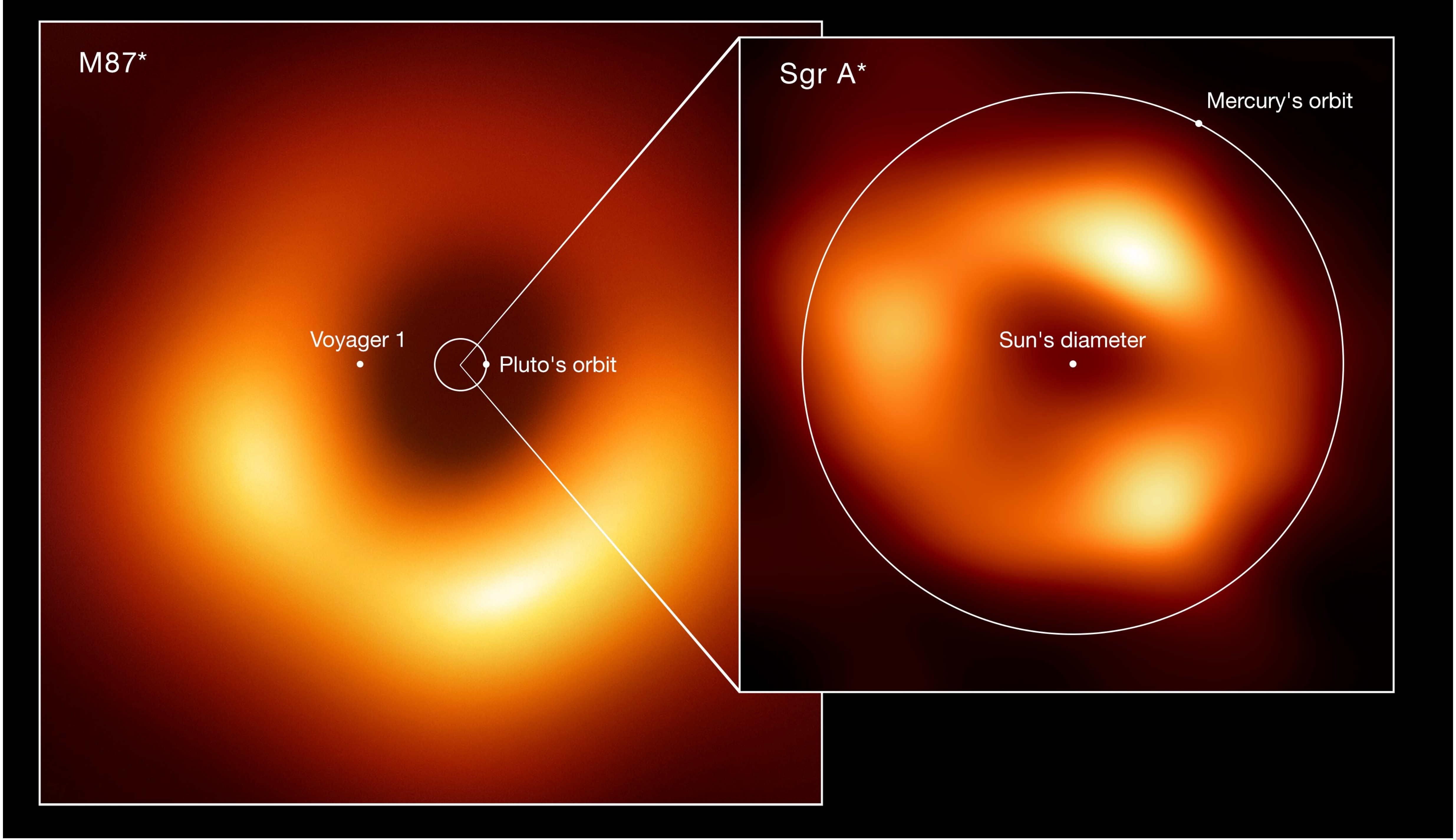
Largest 1mm VLBI experiment ever

- total of ~60h
- ~4 PB raw data
- only minor technical issues
  (fraction of lost data small)
- overall excellent weather!

- **ALMA is the most sensitive telescope**: 1mJy on ALMA baselines, 10 mJy w/o ALMA

Phase Referencing

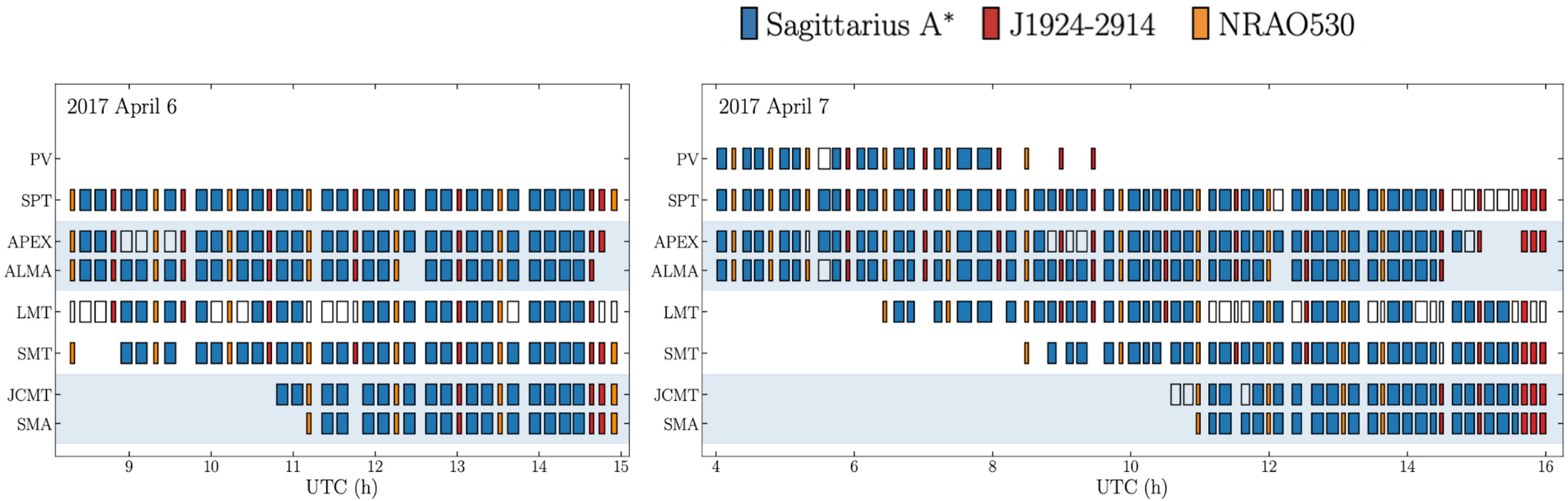



M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter

The End

…but what about other black holes???

EHT Sgr A* Campaign - calibration



- EHT observed Sgr A* in 2017 on Apr 5, 6, 7, 10 and 11
- Focus on 2017 Apr 6 & 7 (highest quality data for imaging)

AGN observations with the EHT in 2017

with good uv-coverage:

OJ287 (PI: Gomez)
1055+018 (calibrator)
3C273 (calibrator)
3C279 (PI: Krichbaum)
Cen A (PI: Mueller)
NRAO530 (calibrator)
1749+096 (calibrator)
1924-2914 (calibrator)

with snap-shot uv-coverage:

J0006-0623, J0132-1654, NGC1052 (PI: Kadler, Ros), 3C84, CTA102, 3C454.3, BLLac

complementary observations with GMVA:

OJ287 (Gomez, w.ALMA MG002; Marscher MM007B)
1055+018 (Marscher MM007B)
3C273 (Akiyama, w. ALMA MA008; Marscher MM007B)
3C279 (Marscher MM007; Asada/Kim MA009)
not obs.
NRAO530 (Brinkerink, Issaoun, w. ALMA MB007)
not obs.
1921-293 (Brinkerink, Issaoun, w. ALMA MB007)

NGC1052 (Baczko, MB005)
3C84 (Nagai, MN001)
3C454.3 (Marscher/Krichbaum MM007B)
CTA102 (Marscher/Krichbaum MM007B)
BLLac (Marscher/Krichbaum MM007B)

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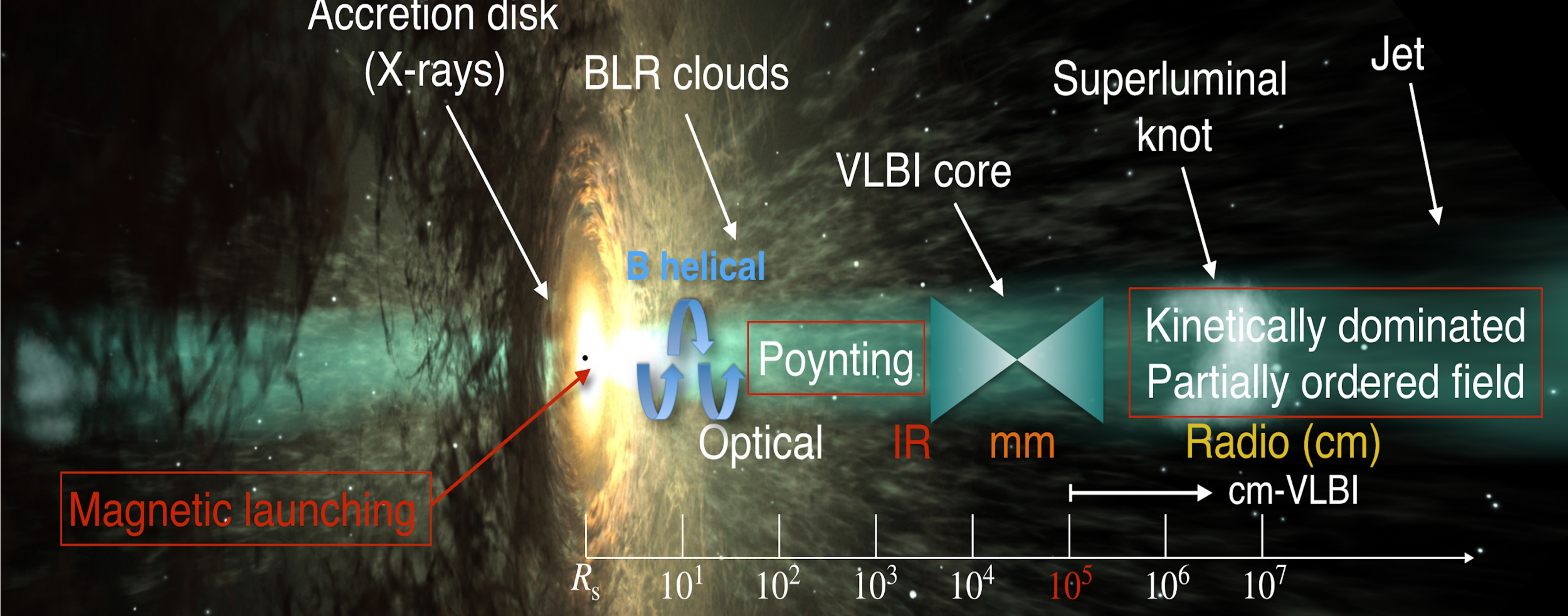


Key questions to address

- Magnetic launching: Blandford & Znajek (black hole) or Blandford & Payne (disk)
- Magnetic field, velocity stratification, and collimation profile in the acceleration and collimation zone
- Transition between the Poynting (ordered B, accelerating) to kinetically-flux (partially disordered B, conical) regimes.

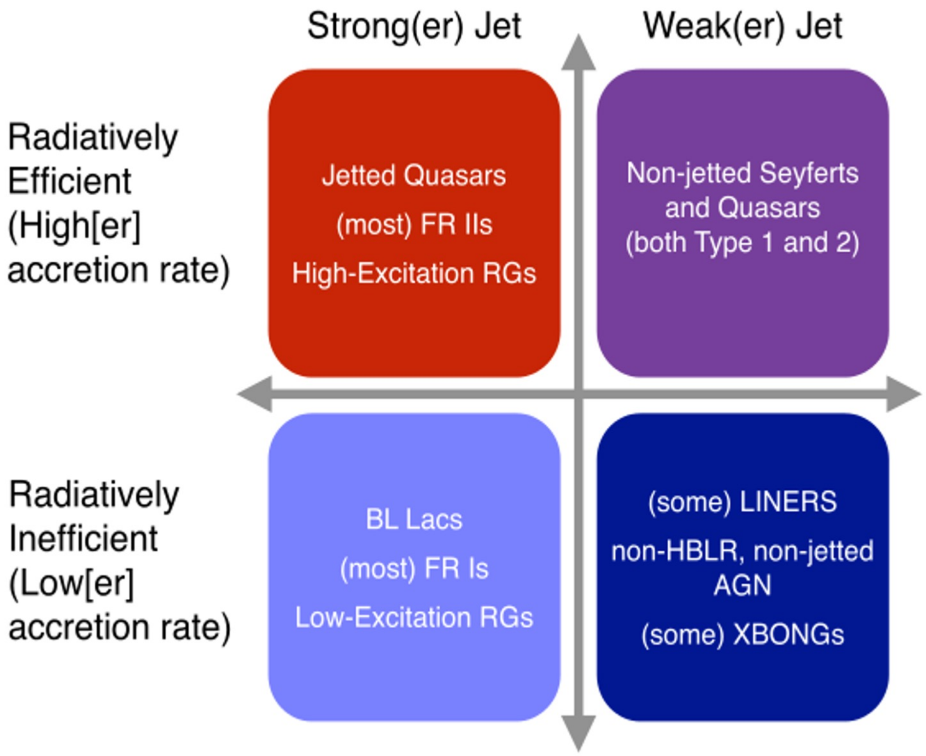
Polarimetric VLBI imaging at resolution ≲50 μas (≲10^4 R_s) is required

HIGH RESOLUTION IMAGING OF AGN WITH THE EHT

Science Motivation:

1. study jet formation over a wide range of source classes (FRI/FRII, FSRQ/BLLac), luminosities, BH masses
2. check if BP or BZ mechanism depends on source class, luminosity, BH mass. Check if BP & BZ occur in mixed mode (stratification)
3. SgrA/M87 have low accretion rates (hot accretion, RIAF), FSRQs have higher accretion rates (cold accretion, standard thin disk)
4. SgrA/M87 are relative weak high-energy emitters, but AGN are strong. AGN better suited to study physical origin of high energy emission
5. SgrA/M87 are only weakly polarized, AGN are usually more polarized -> AGN may be better suited for polarimetry, RM measurement, studies of B-fields, accretion flow, fine structure of (standing) shocks
6. Difference in B-field topology between FSRQs and BLLacs? (EVPA || jet in BLLacs, but oblique in FSRQs)

A simple AGN Unification model



Padovani+2017 (AARev)

Overview of targets

J1924-2914 (Issaoun et al. 2022)

$z = 0.353$

$M_{BH} \sim 8 \times 10^8\ M_\odot$

$\sim 20\ \mu as = 0.1\ pc$ or $10^3\ R_S$

OJ287 (Zhao et al. 2023)

$z = 0.306$

Primary black hole $M_{BH} = \sim 1.8\times10^{10}\ M_\odot$

Secondary : $\sim 1.4 \times 10^8\ M_\odot$

$\sim 26\ \mu as = 0.112\ pc$

NGC 530 (Jorstad et al. 2023)

$z = 0.902$

$100\ \mu as = 0.803\ pc$

M_BH= $3\times10^8\ M_\odot$ - $2\times10^9\ M_\odot$

3C279 (Kim et al. 2020)

$z = 0.536$

$20\ \mu as$, or $\sim 0.13\ pc$ $\sim 1700\ R_s$

MBH $\sim 8 \times 10^8\ M_\odot$

Centaurus A (Jansen et al. 2020)

$z = 0.00183$

$(5.5 \pm 3) \times 10^7\ M_\odot$

$R \sim 200\ R_s \approx 0.6$ light days

Takeaway message

- Large scale jets show different morphologies/angles from compact jets
- Helical magnetic fields seem to dominate –> also precession
- Variability is associated with intristic structural changes
- Total intensity and polarization peaks offset
- Some inner jets edge-brightened
- → Polarization information at highest scales still needed

3C279

z = 0.536
MBH $\sim 8 \times 10^8 M_\odot$

One of the first sources to provide evidence for rapid structural variability (Knight et al. 1971) + superluminal motion (Unwin et al. 1989)

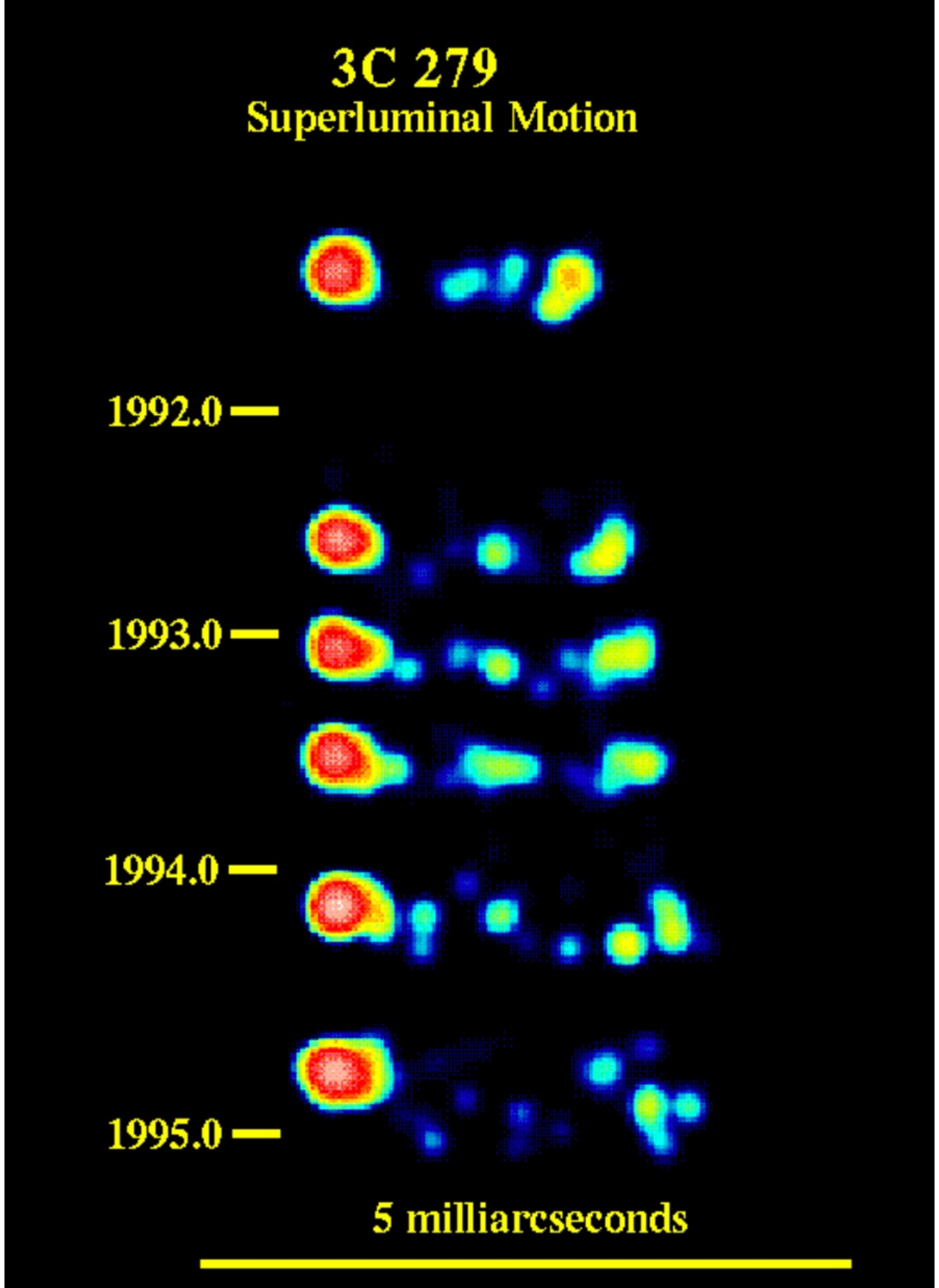
Jet extends to kpc scales

high fractional linear polarization (10%), and strong circular polarization on the order of ~1% is also detected in the core region at ≤ 15GHz

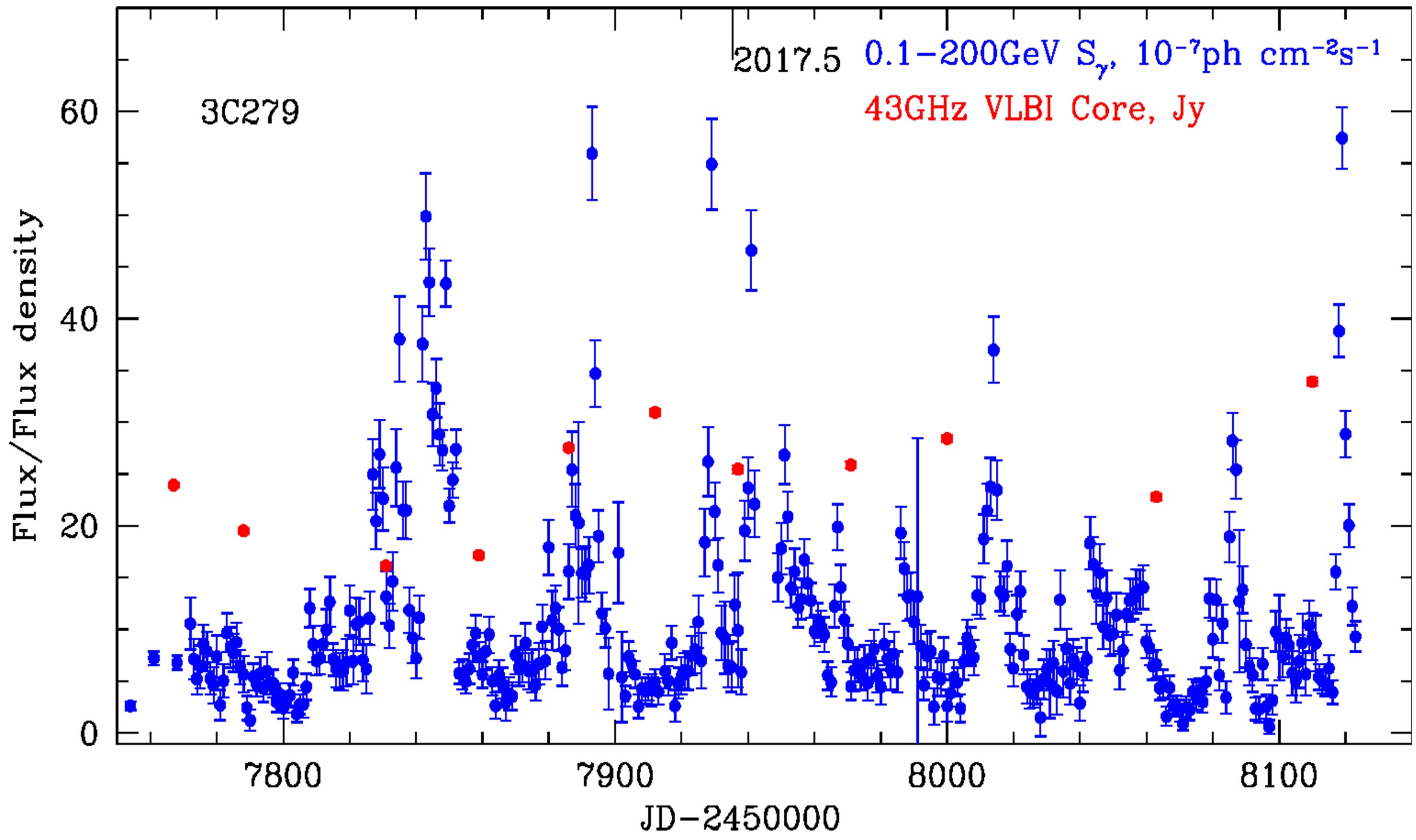
Inner jet morphology displays various position angles

Misaligned jet components modeled as spatially bent (and perhaps helical) jet structures

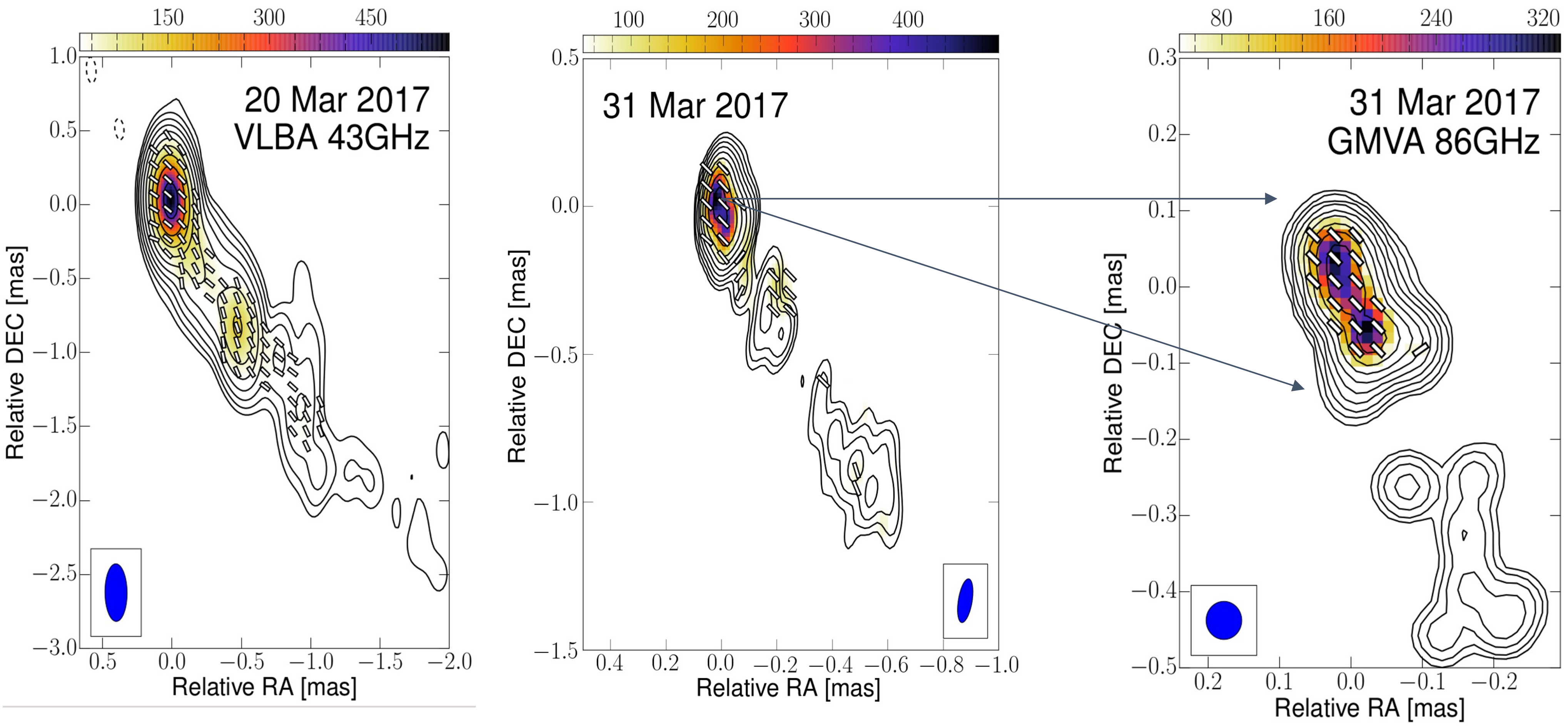
Second brightest γ-ray blazar (Kniffen et al. 1993)



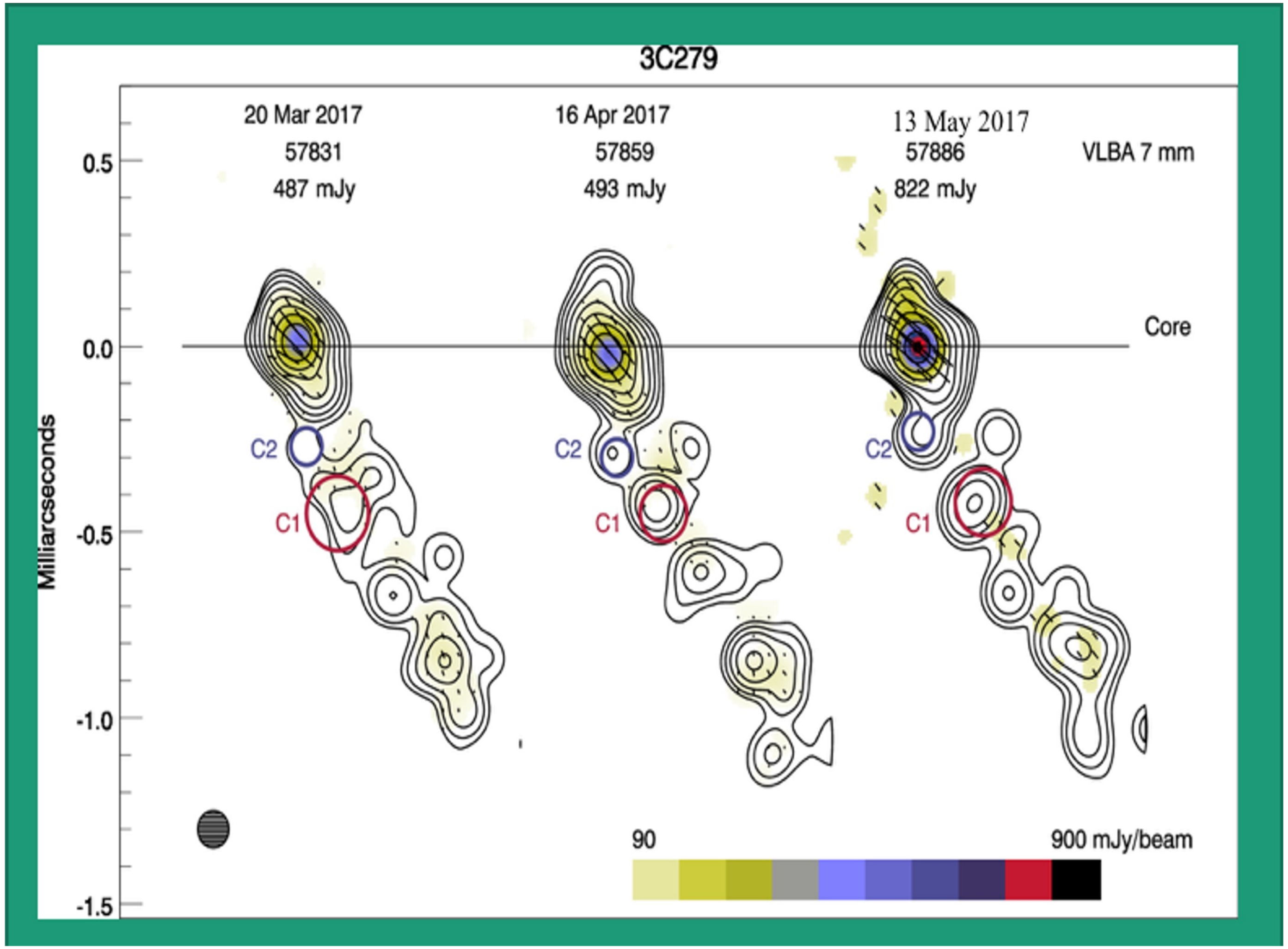
3C279 - Gamma-ray Variability

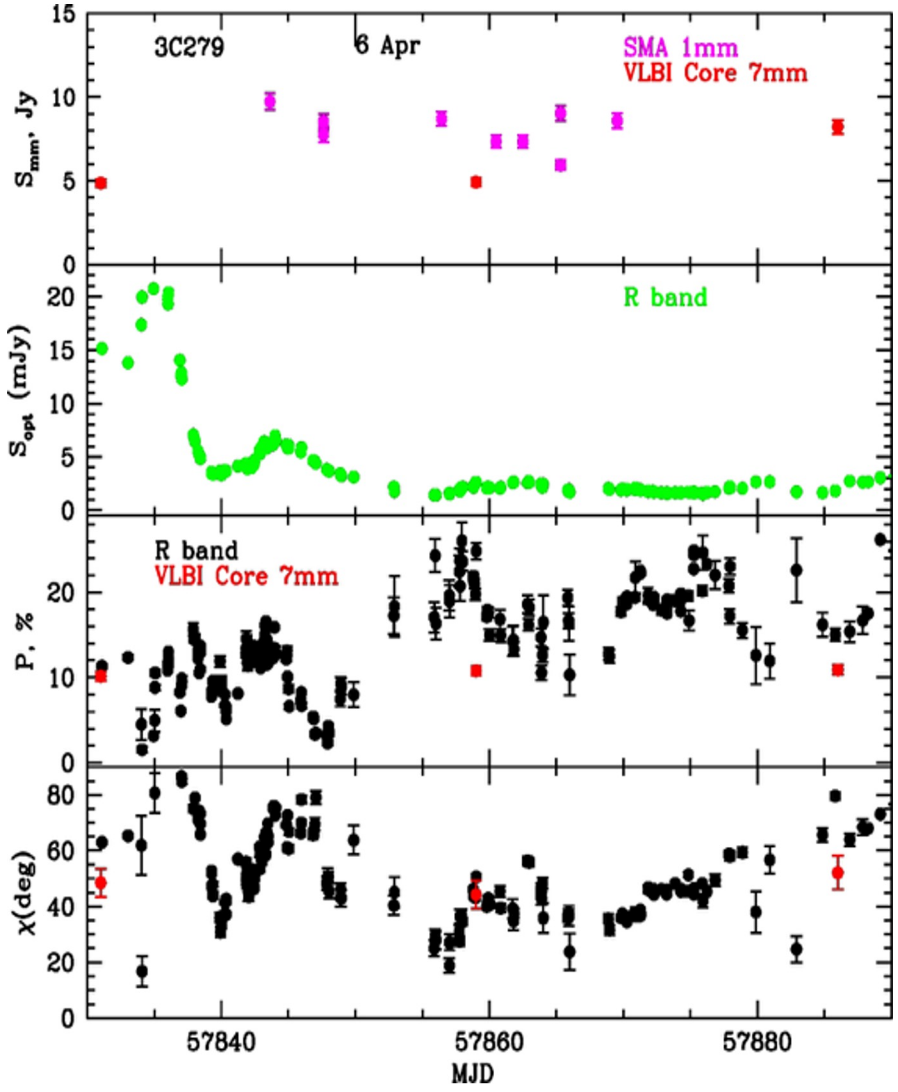


3C279 - VLBI maps at longer Wavelengths



7 mm VLBA Images and Optical Behavior of 3C279 during the 2017 EHT Campaign

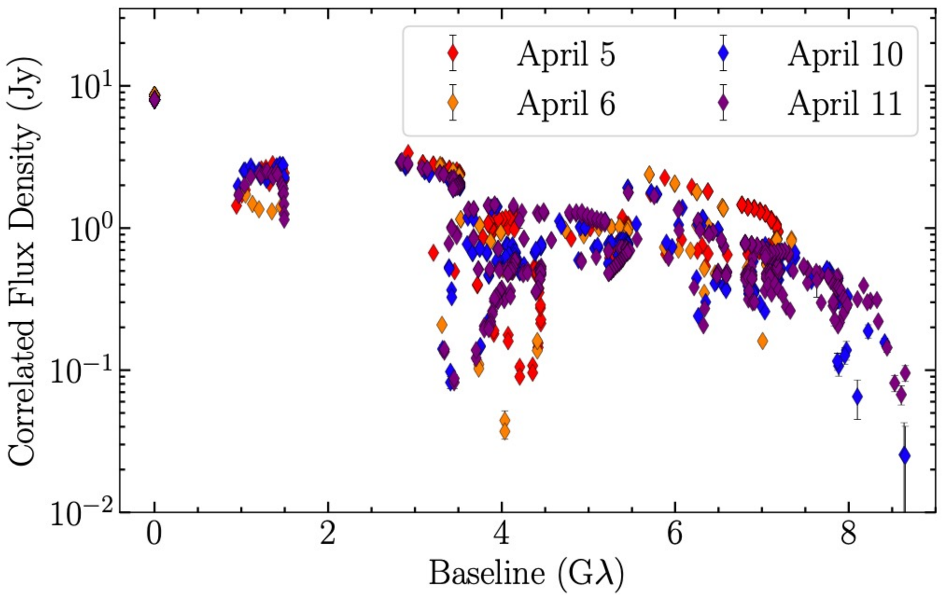


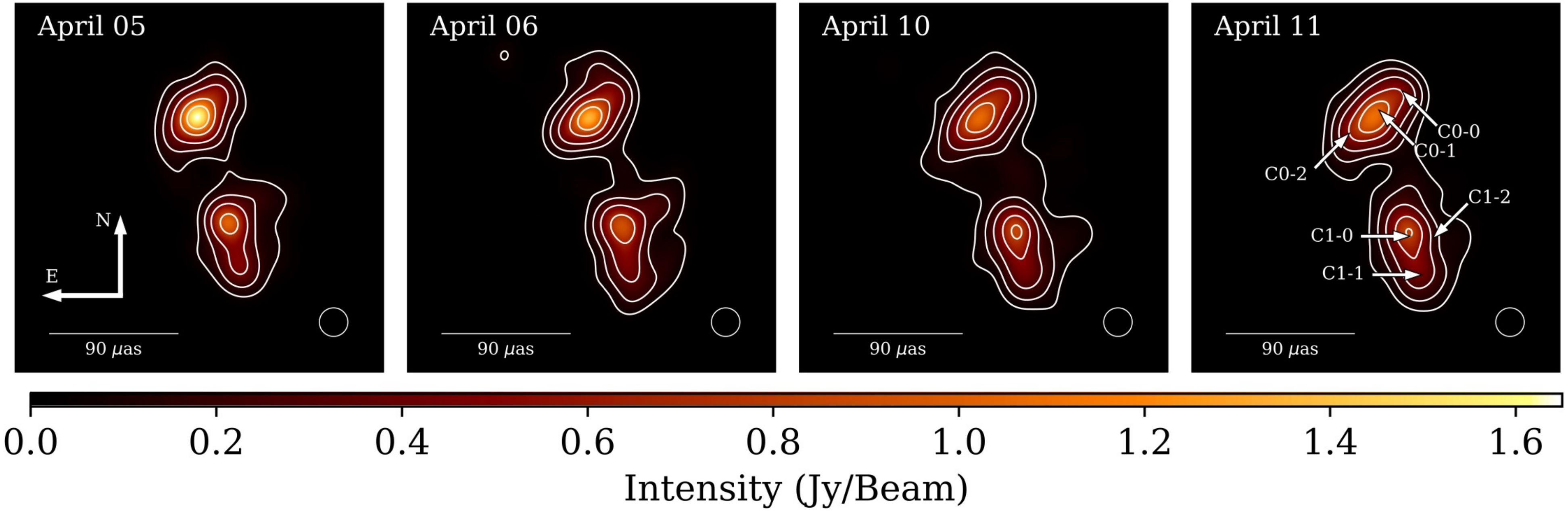


Variability

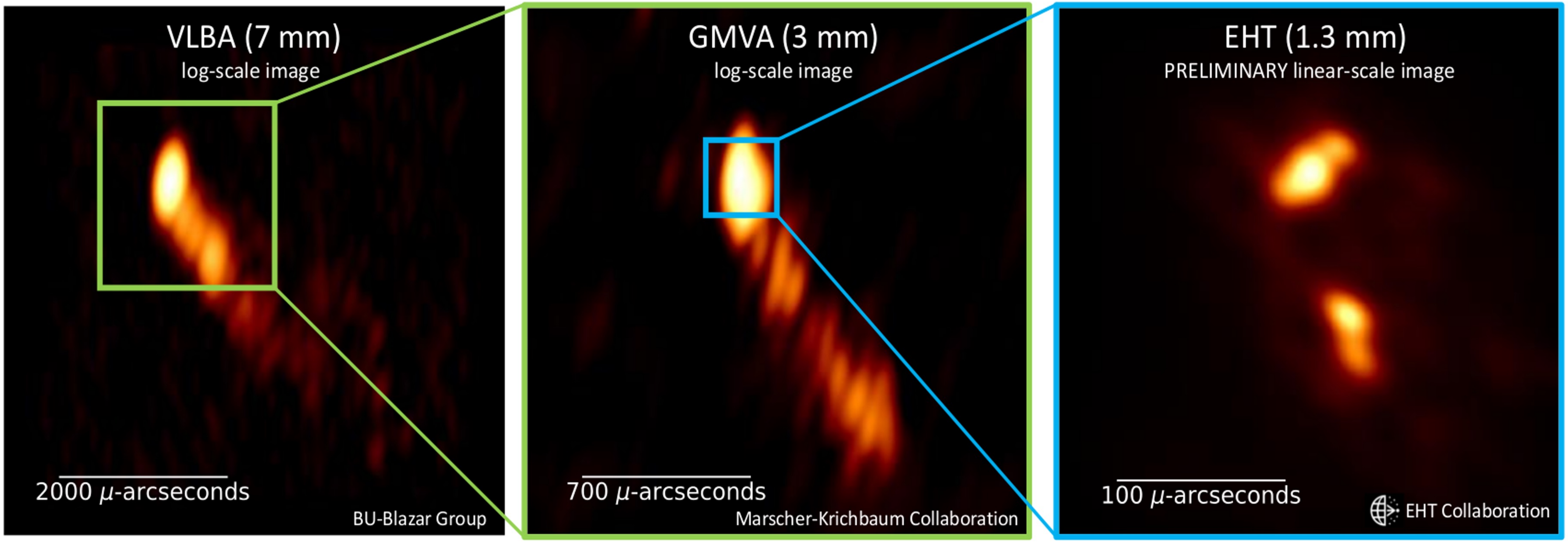
A prominent and rapid change of the brightness in the center of the C0 region over ~6 days

Inter-day closure phase variations are also detected!





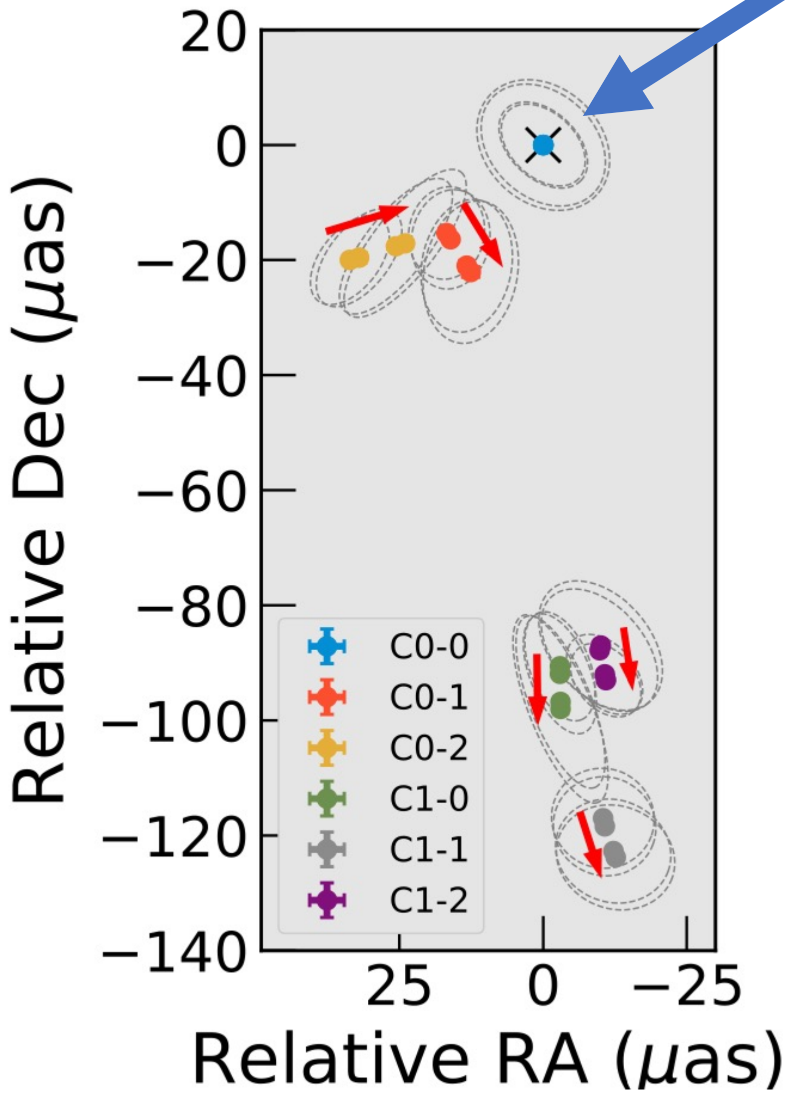
Zooming into the core of 3C279



core region elongated perpendicular to outer jet by 30-40 μas

Jorstad et al. 2017 ; Kim et al. 2023

Model fitting and component motion

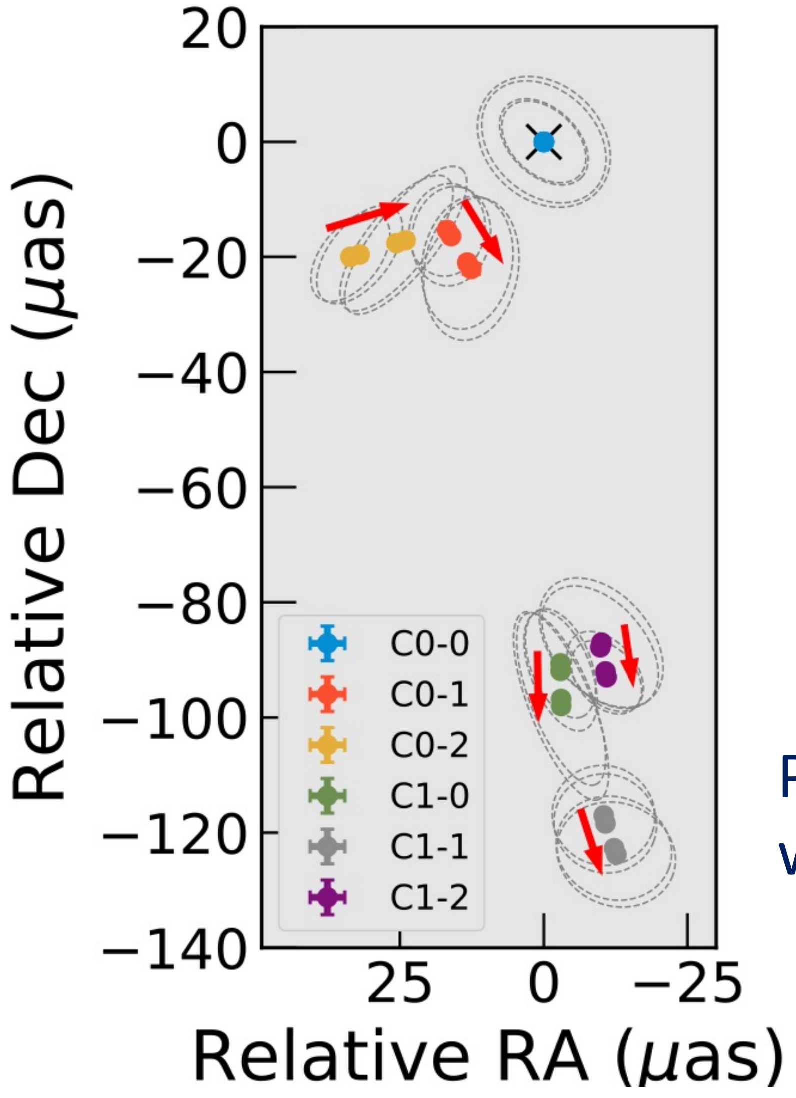


Model fitting is consistent with outward ~1.1–1.2 μas day^{-1} proper motions of all C1 components when the C0-0 feature is used as a reference.

(i) peculiar substructures, can be interpreted as a bent jet, or linear, knotty structure from large-scale magnetic reconnection (Blandford et al. 2017) or plasma instabilities (Lobanov & Zensus 2001)

This morphology has not been seen by VLBA at 15 and 43 GHz

Model fitting and component motion



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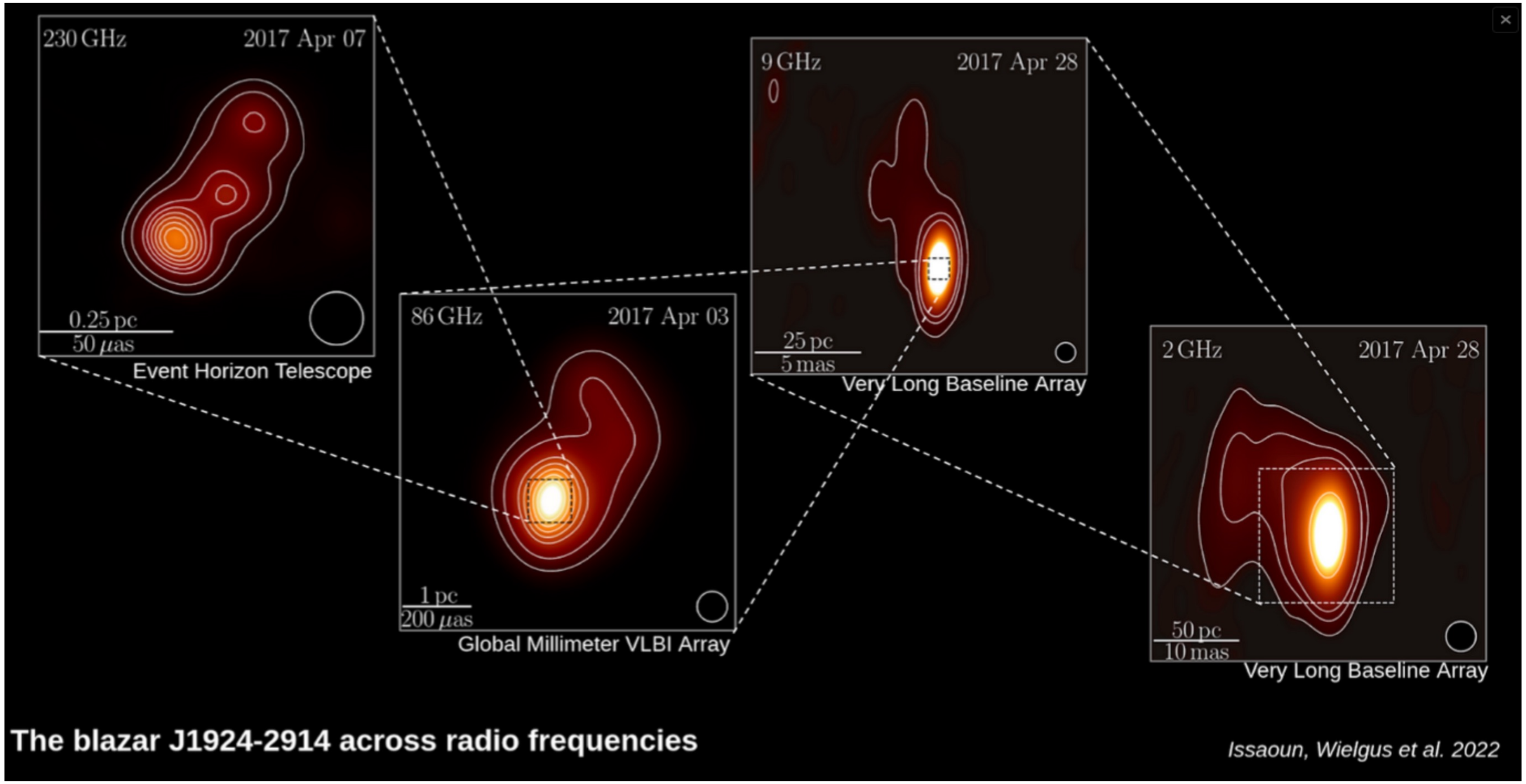
PREDICTIONS → future EHT pol observations of the EVPA would be perpendicular to the elongated emission structure

J1924-2914

$z = 0.353$
$M_{BH} \sim 8 \times 10^8\, M_\odot$ (no robust mass estimate)
$20\ \mu as = 0.1\ pc$ or $10^3\, R_S$

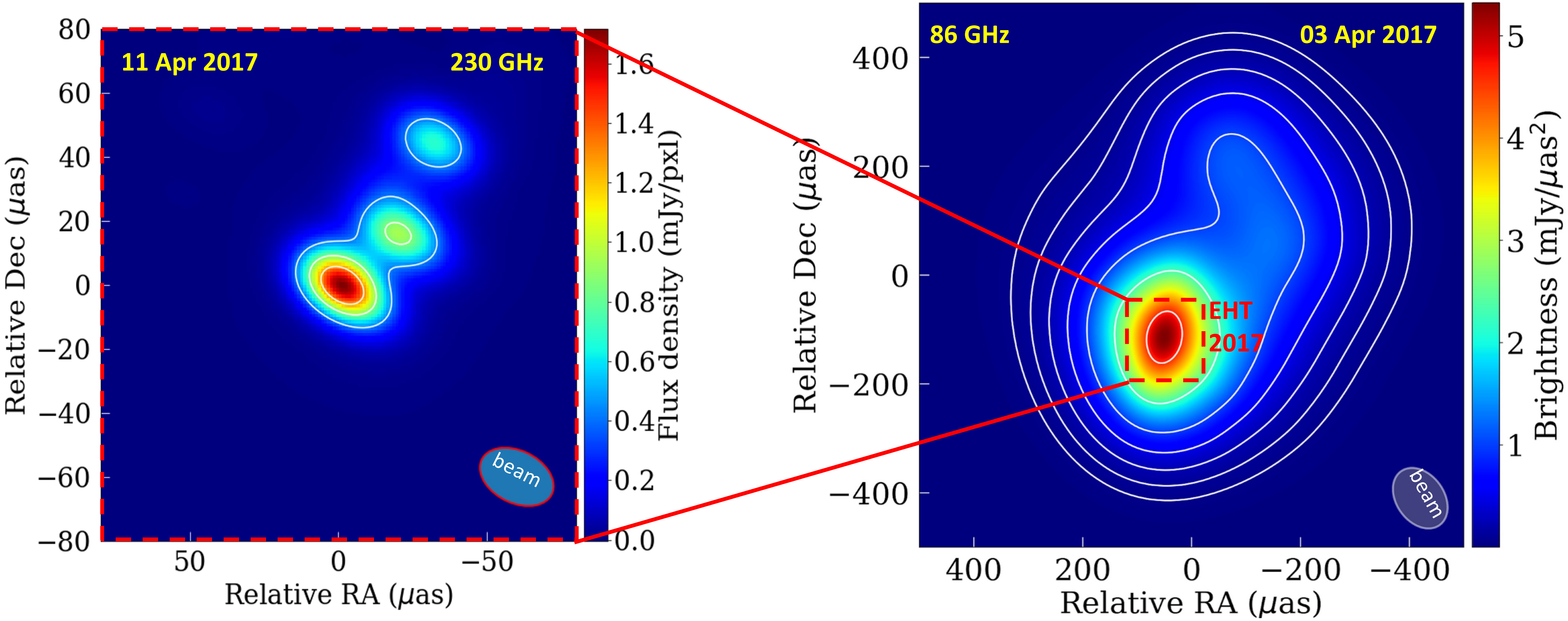


Highly polarized & compact at long radio wavelengths

Little variability on a timescale of several days—(best available EHT calibrator close to Sgr A* on the sky!)

Source of γ-ray radiation identified in the Fermi-LAT catalog (Abdollahi et al. 2020)

EHT/GMVA+ALMA 2017 observations of J1924-2914

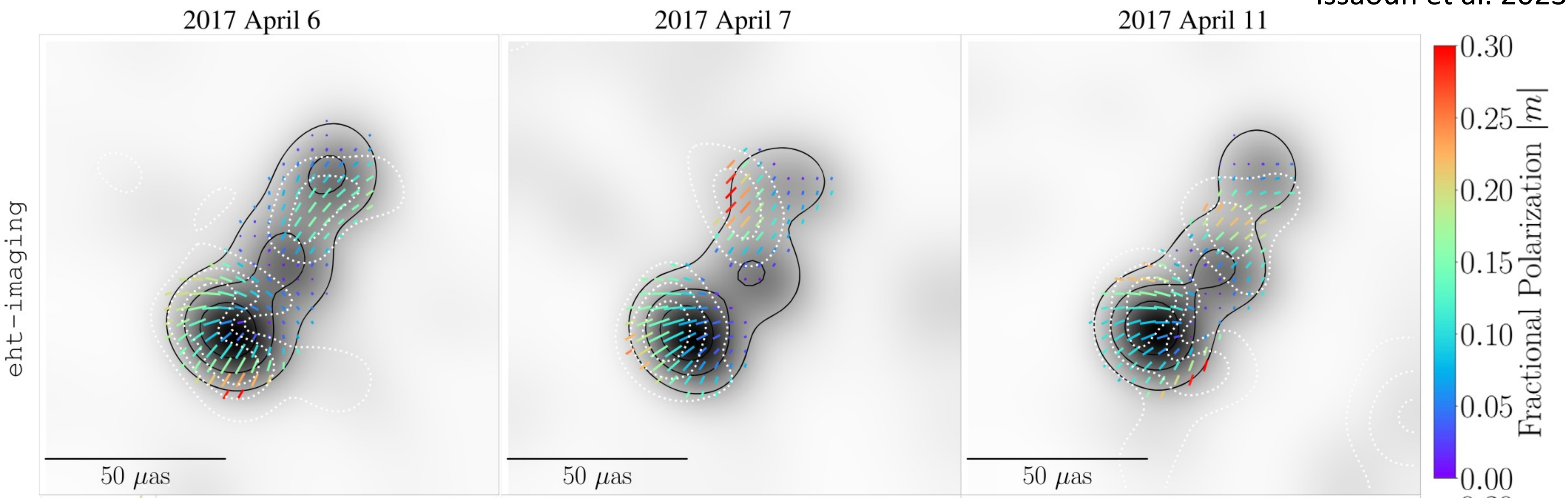


Average image from the four team submissions during the 2nd imaging workshop (25, 50, 75% contours) - Imaging WG

Closure imaging using the `eht-imaging library` (Chael et al. 2018), the contour levels start from 1.2% of the peak and increase in factors of two (Issaoun+ submitted)

J1924–2914 – core *polarization*

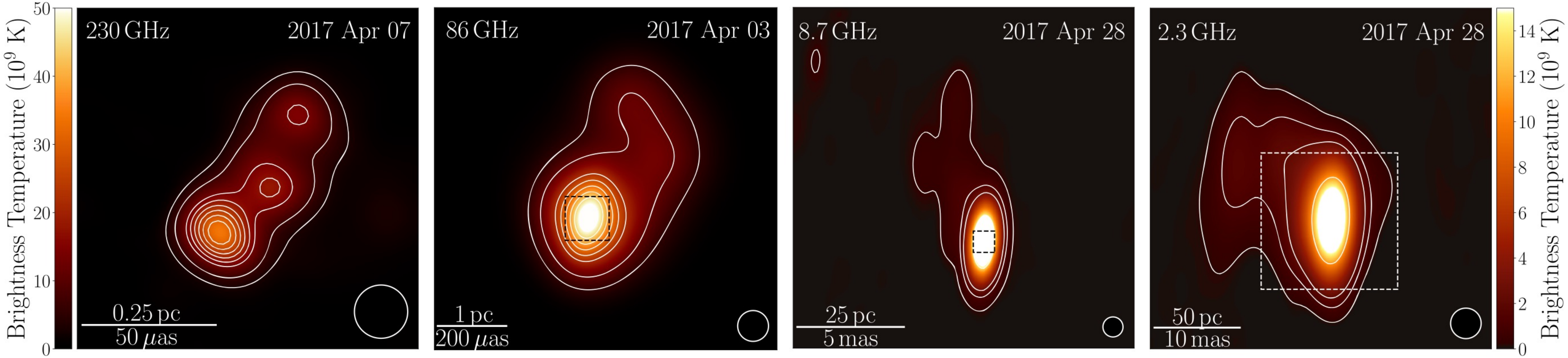
Issaoun et al. 2023



Large fractional polarization of about 15%

Core - rotation of the EVPA, suggestive of the presence of toroidal magnetic fields (Molina et al. 2014)

J1924–2914 – *Jet direction*

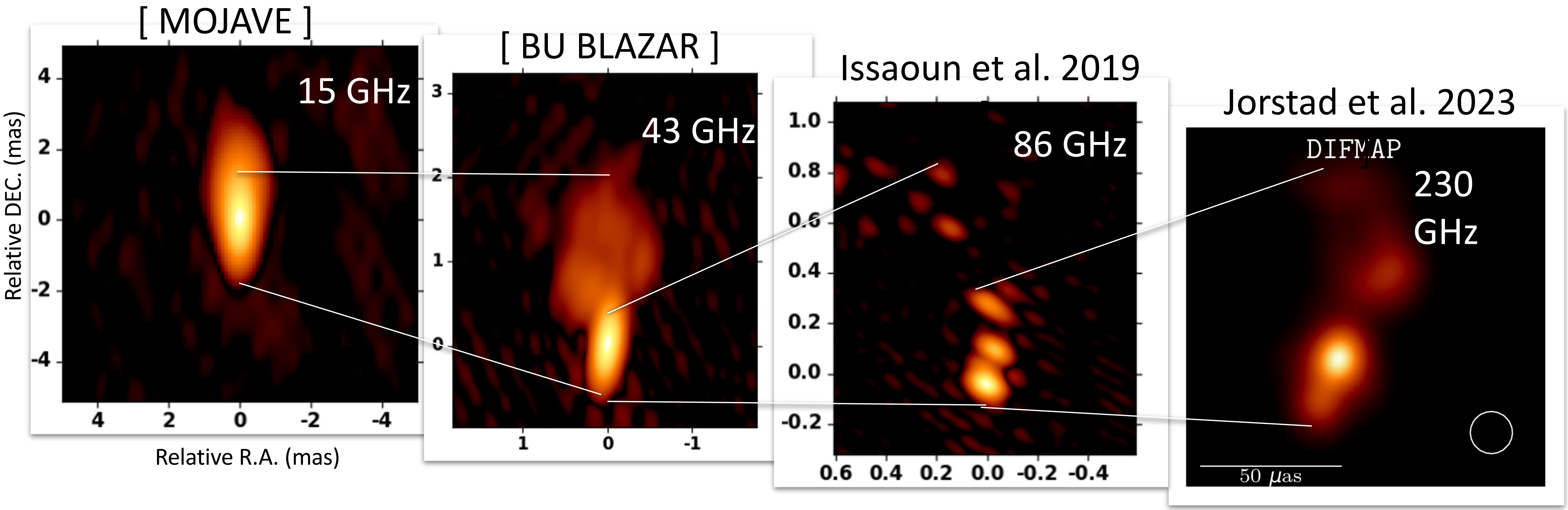


Jet - clockwise rotation of the jet direction in J1924–2914 as we go from long to short observing wavelength --> helical jet???

Scenarios: such as a putative supermassive black hole binary in the core, or a tilted large- scale accretion flow compared to the black hole spin axis, or shock regions as the jet interacts with the external medium.

NRAO 530

z = 0.902
100 μas = 0.803 pc
M_BH= $3\times10^8 M_\odot$ - $2\times10^9 M_\odot$



- Calibrator for SgrA*
- Most distant object imaged by the EHT
- Source variability not detected during EHT run

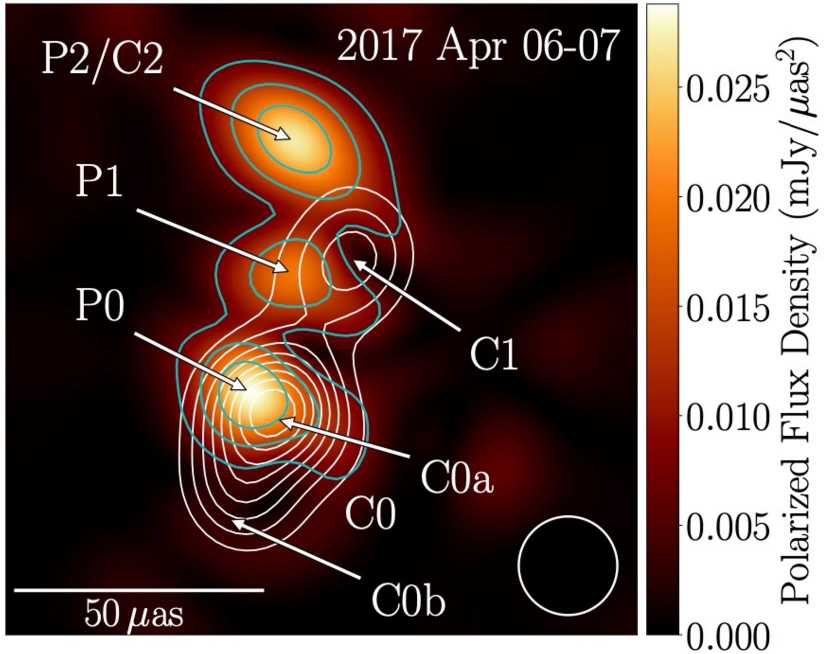
NRAO 530 - *polarization*

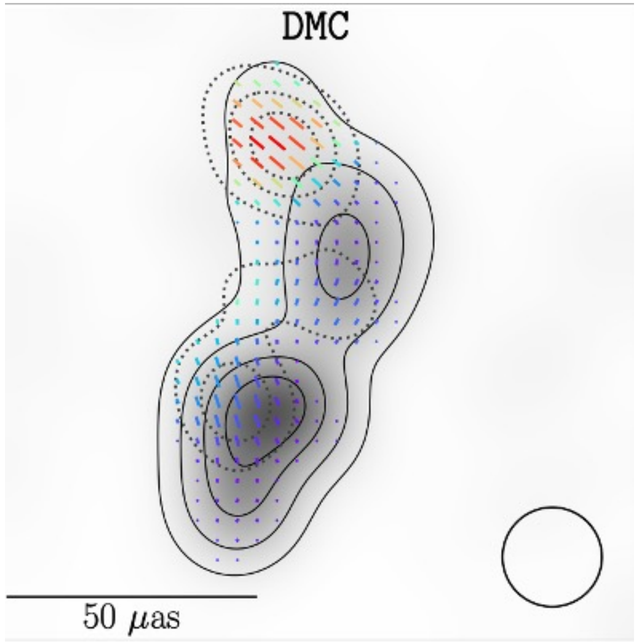
- Polarized components P0, P1, and P2 & total intensity components C0, C1, and C2
- The polarized knots P0 and P1 are shifted from the total intensity knots C0 and C1

→ Could be due to an ordered magnetic field on the eastern side of the jet, connected with a helical structure of the magnetic field, or a stronger interaction between the jet and the external medium on this side

- Feature C2 has the highest degree of polarization in the jet, ~ 20%. peak polarization of ~ 60% (core 5%)

→ Could be due to uniform magnetic field





Jorstad et al. 2023

NRAO 530 - *polarization*

- Polarizec
  compone
- The pola
  intensity

→ Could be
side of th
magnetic
and the e

- Feature C
  jet, ~ 20

Laing 1980

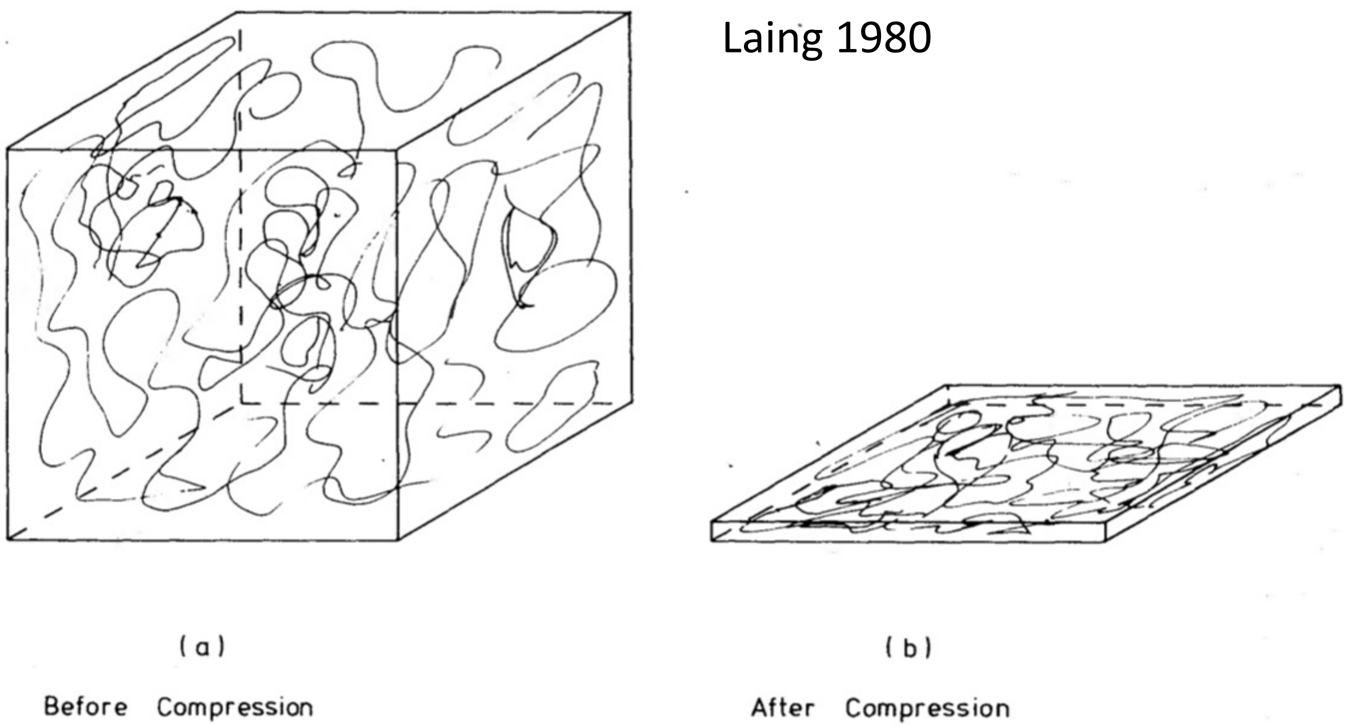
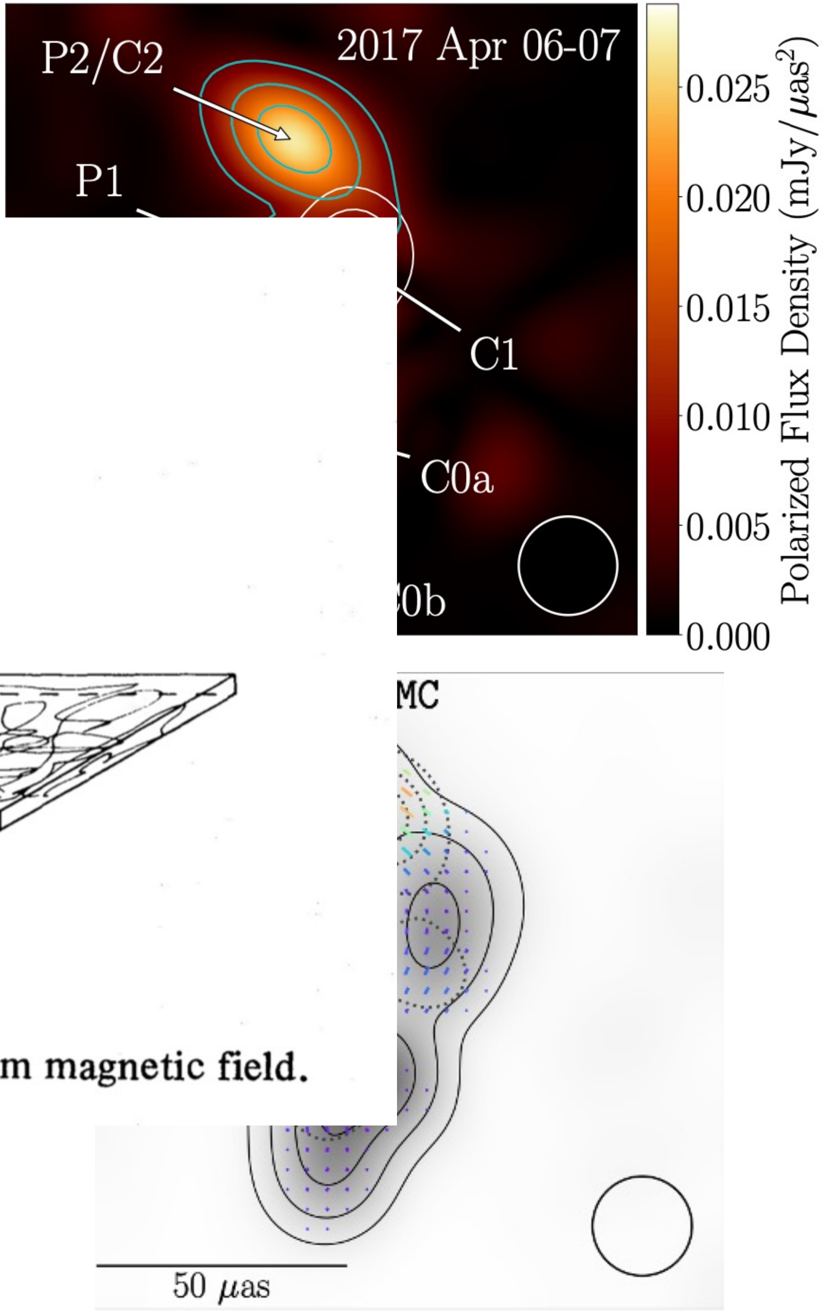


Figure 1. The compression of a cube containing an initially random magnetic field.



→ Could be due to uniform magnetic field

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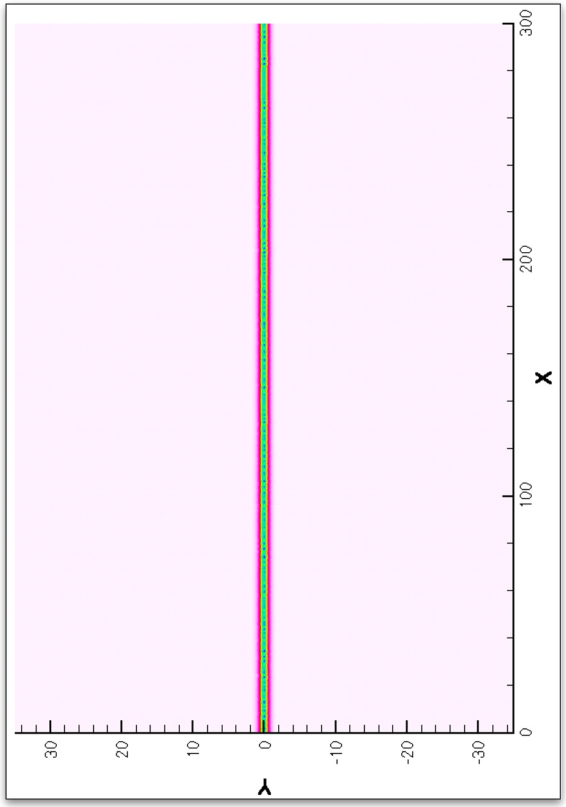
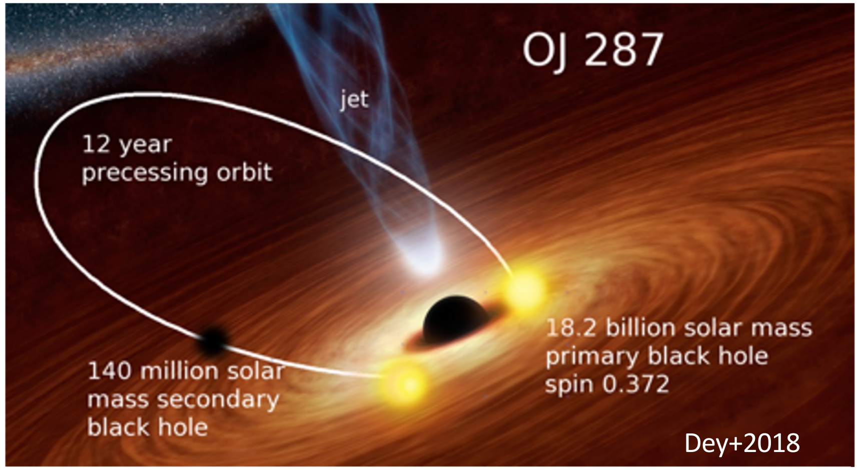
The curvature could be caused by an imbalance between the pressure inside and outside the jet resulting in the development of instabilities in the flow, or jet precession.



multi-wavelength VLBI images of NRAO530 contemporaneous with the 230 GHz EHT image will be presented in Lisakov et al. (in prep.).

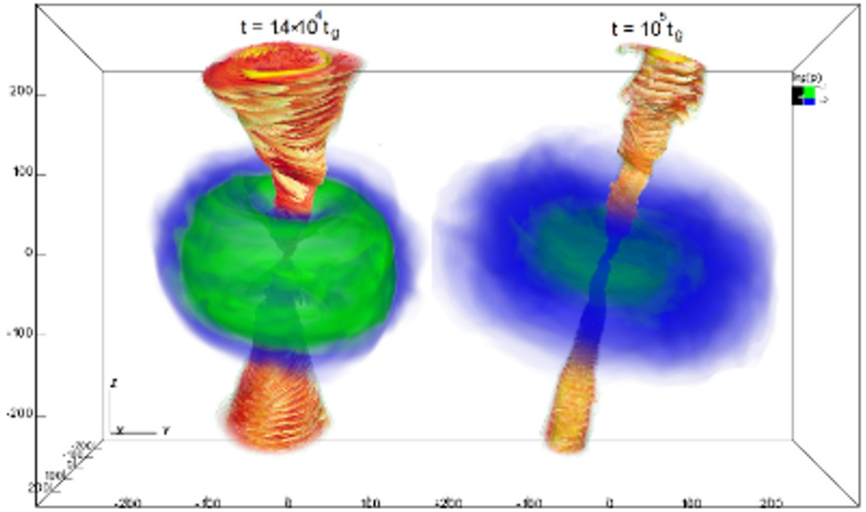
OJ287

z = 0.306
Primary black hole $M_{BH} = \sim 1.8\times10^{10}\ M_{\odot}$
Secondary : $\sim 1.4 \times 10^{8}\ M_{\odot}$
$\sim 26\ \mu as = 0.112\ pc$



OJ287 is one of the best candidates for hosting a supermassive binary black hole system.

Orbital modeling (i.e., Valtonen+2016) requires a binary system in an eccentric (ε=0.7) orbit with a major axis of 0.1 pc (~26 μas), which could be spatially resolved by mm-VLBI.

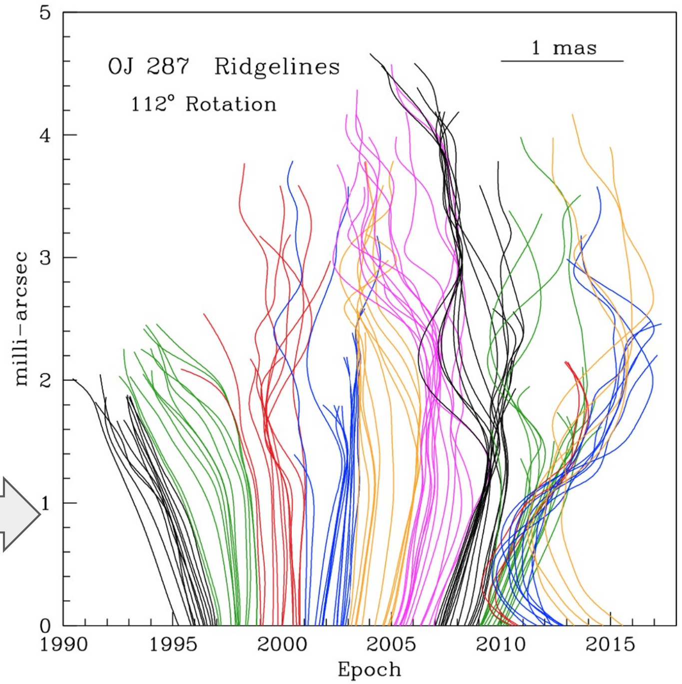


(Liska+2018)

Alternatively, the innermost jet structure may result from the precession of a tilted accretion disk.

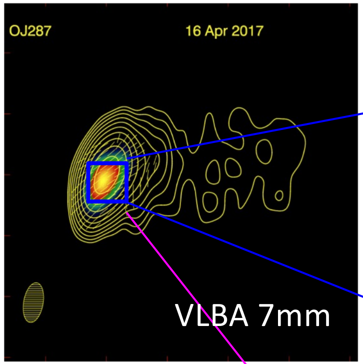
Decades of MOJAVE, BU, & GMVA monitoring have revealed the presence of a rotating jet (e.g. Cohen 2016)

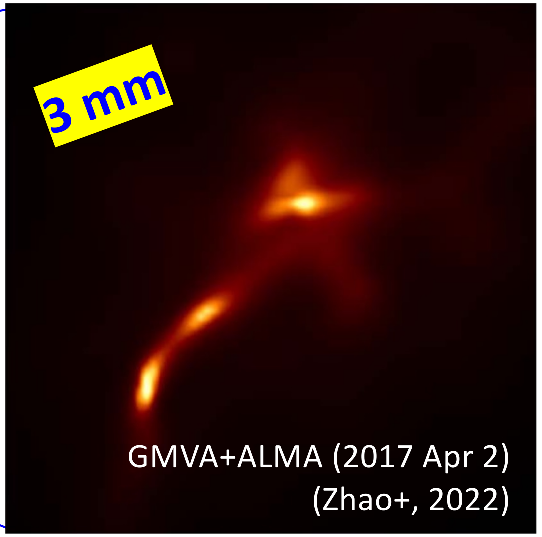
Ridgeline rotation with time

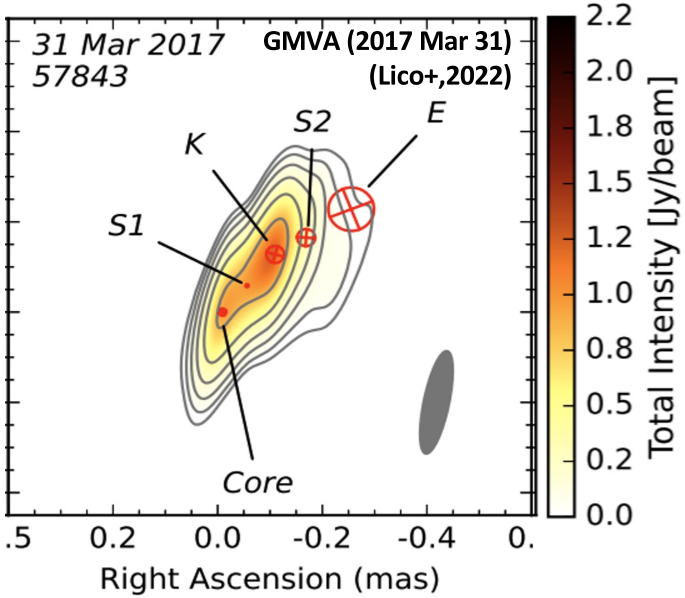


Cohen (2016)

Imaging and modeling

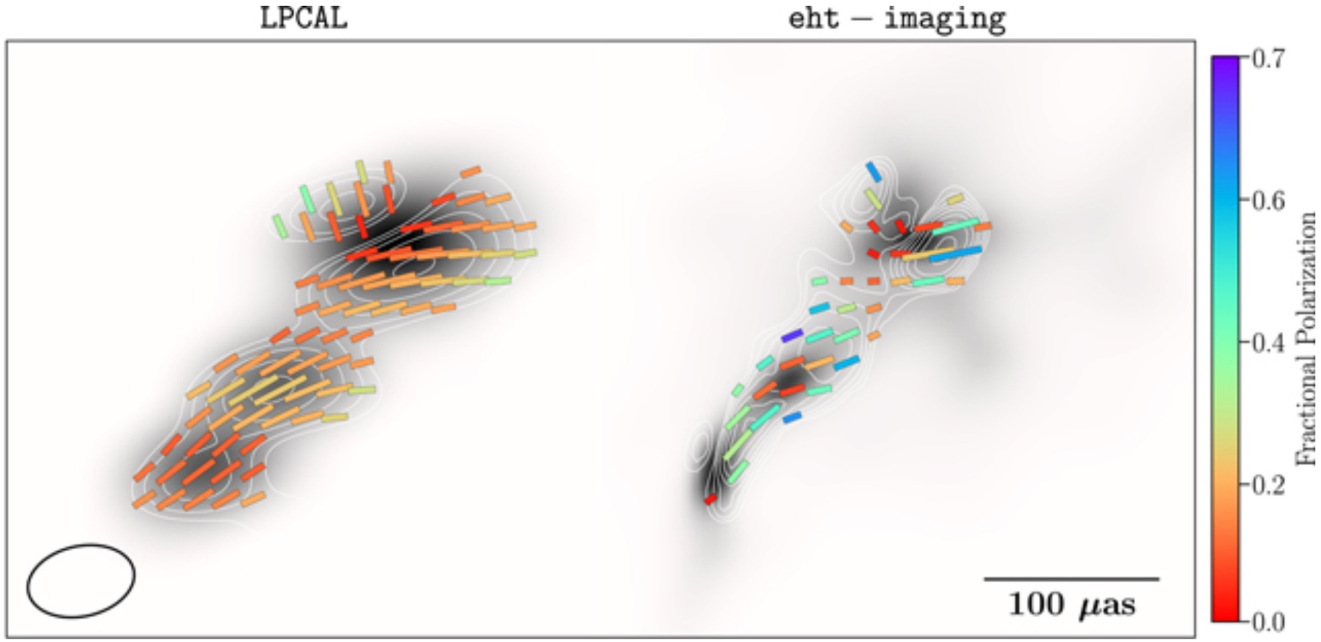






1 mm ?

In prep!



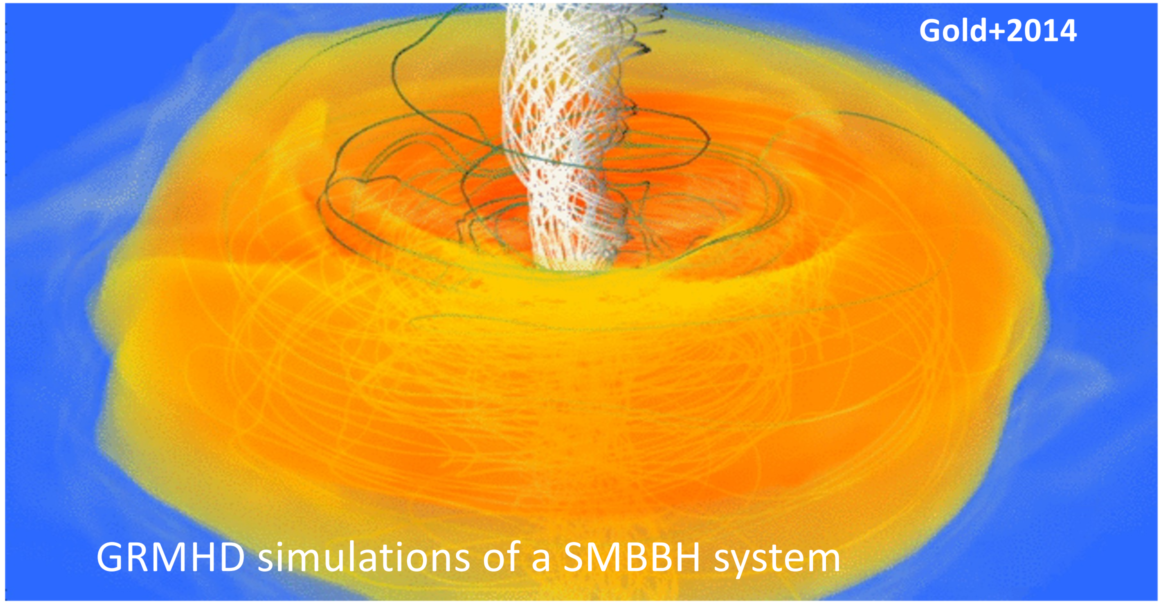
Jet Precession

Rotating helical jet on timescales of days?

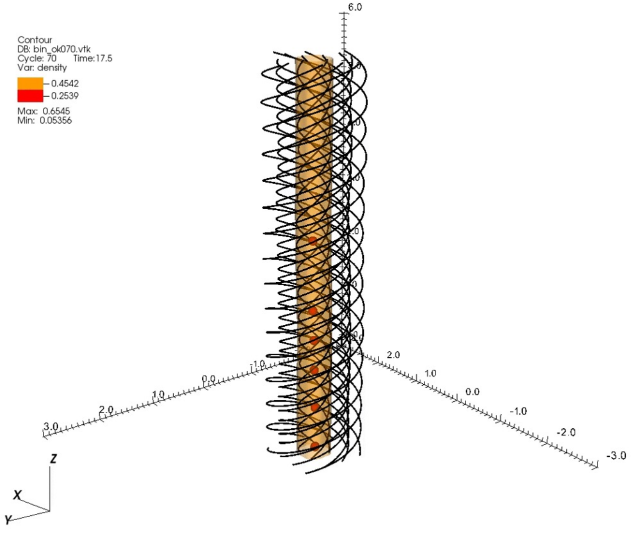
- Powered by **supermassive binary black hole**?
  - currently the most studied scenario that reproduces most of the observations.

Other scenarios?

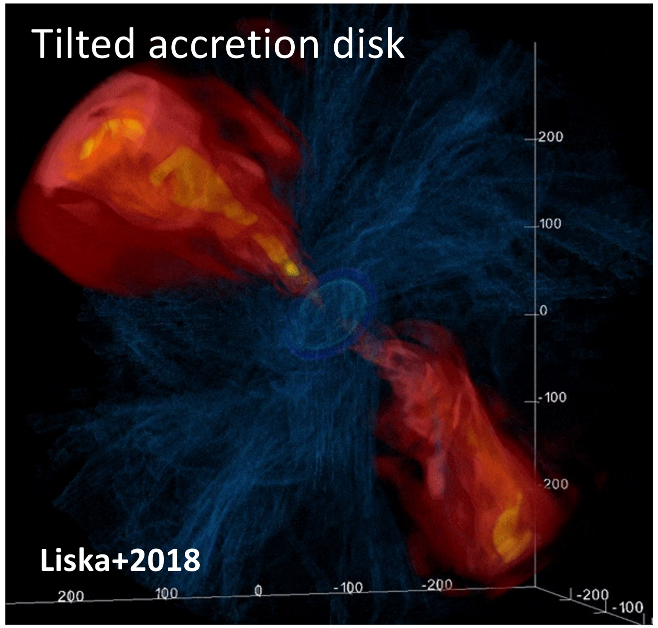
- Jet precession plus nutation due to BBH or Lense-Thirring precession (e.g. Britzen+2018)
- Tilted accretion disks (Liska+2018)
- Current driven kink instabilities (Mizuno+)
- ...



Current-driven kink instabilities



Mizuno+ (09, 11b, 12, 14b), Singh, YM+ (15), Kadowaki, YM+ (20)



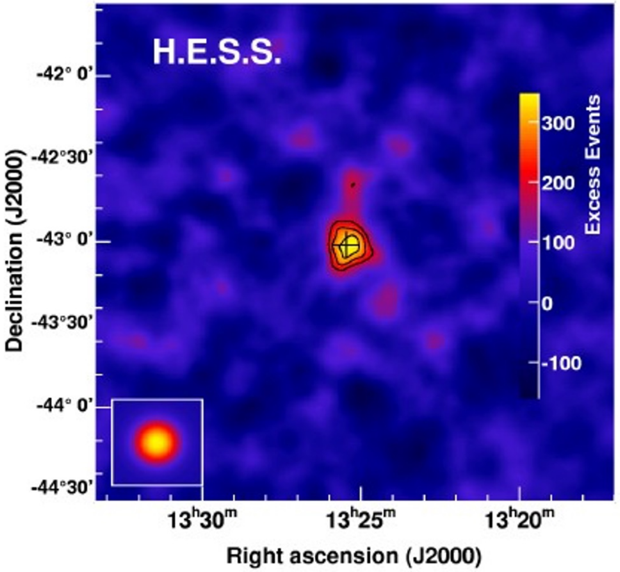
Centaurus A

z= 0.00183 (3.8 Mpc)
$(5.5 \pm 3) \times 10^7 M_\odot$
$R \sim 200\, R_s \approx 0.6$ light days

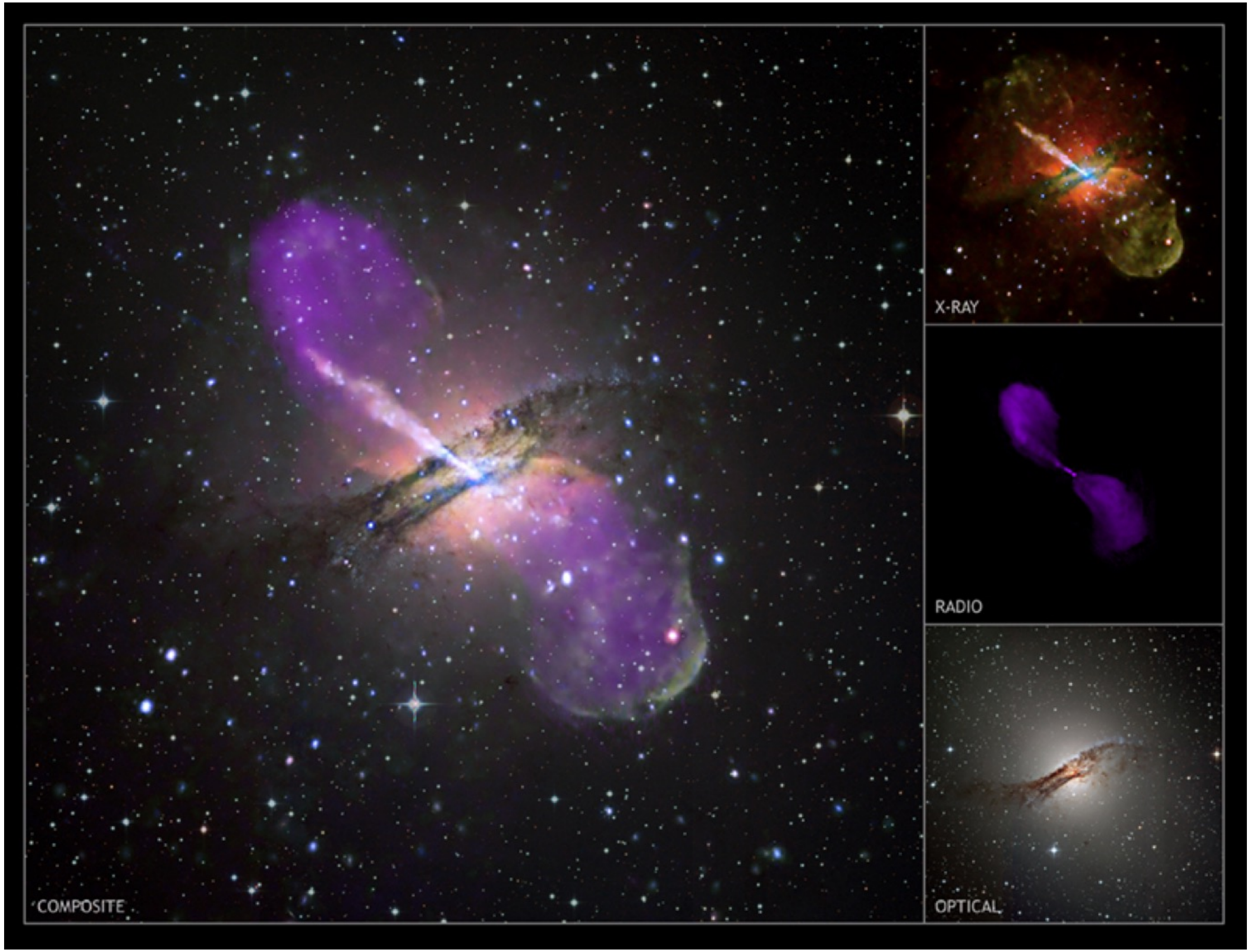
X-ray: NASA/CXC/CfA/R.Kraft et al.
Radio: NSF/VLA/Univ.Hertfordshire/M.Hardcastle
Optical: ESO/WFI/M.Rejkuba et al.

Centaurus A is the closest radio-loud source to Earth

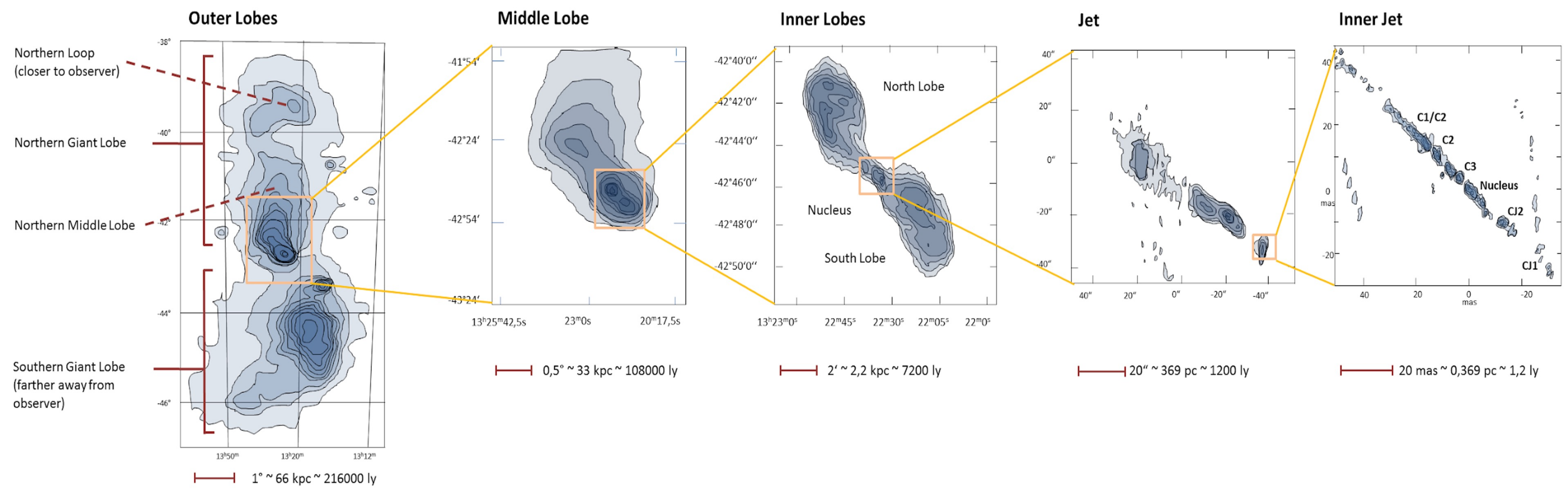
It bridges the gap in accretion and mass between M87 and SgrA*



"Discovery of very high energy gamma-ray emission from Centaurus A with H.E.S.S", H.E.S.S. collaboration, F. Aharonian et al., Astrophysical Journal Letters, 695 (2009) L40-L44.

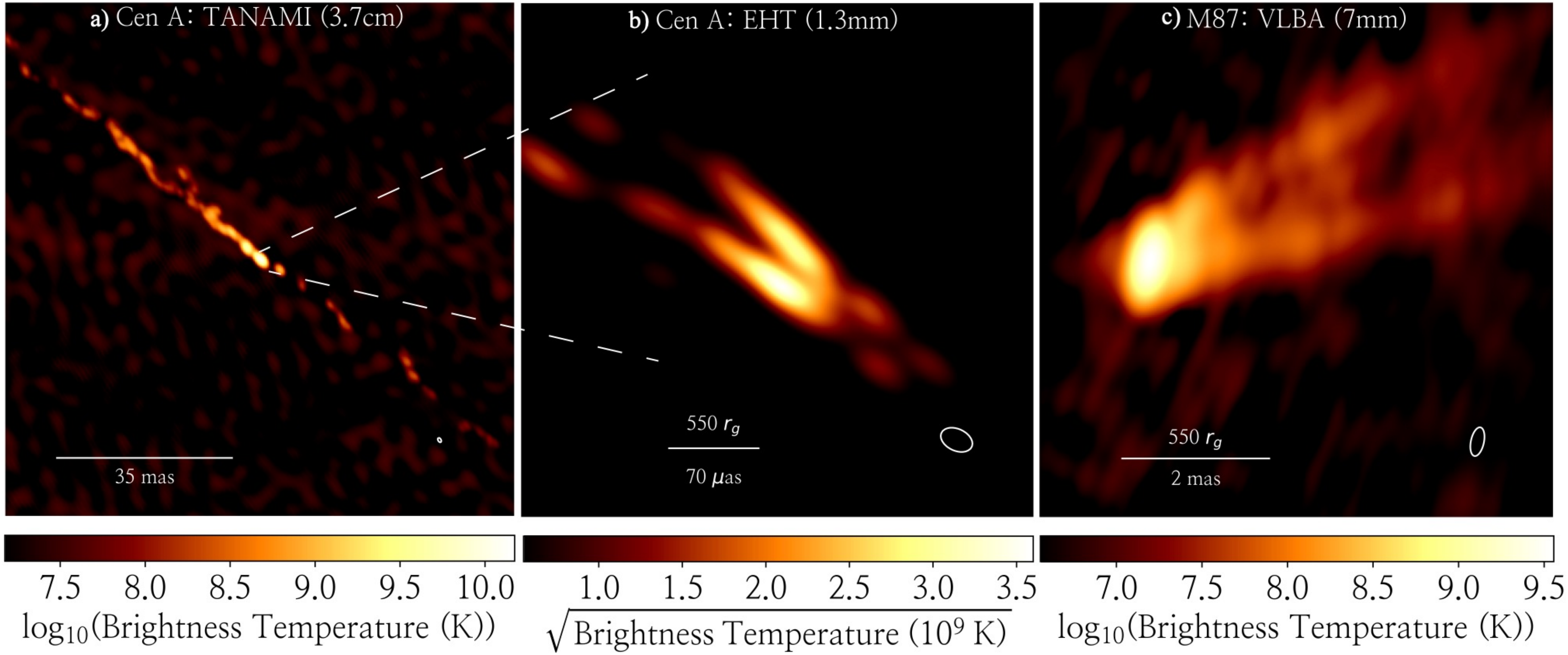


Cen A- VLA/VLBI maps at longer wavelengths



Source: https://ned.ipac.caltech.edu/level5/March01/Israel/Israel2.html / Published in Astronomy and Astrophysics Review 1998, Vol. 8, pp. 237-278 Outer/Middle lobes: Parkes 5.0GHz. Inner Lobes: VLA 4.9 GHz. Jet: VLA 1.5 GHz. Inner Jet: TANAMI VLBI @ 8GHz

Janssen et al. 2021



No emission in the jet spine

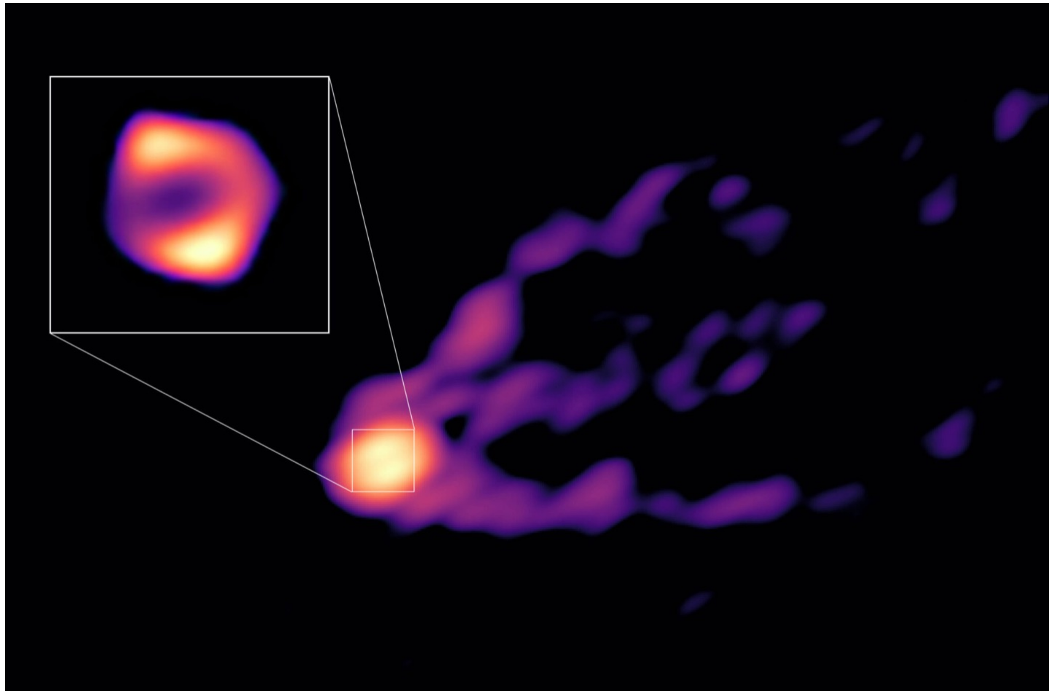
Narrow, collimated profile with pronounced edge-brightening, and a NW-SE brightness asymmetry

Three types of brightness asymmetries: between the jet and counterjet, the sheath and spine, and the NW vs. SE ridgelines

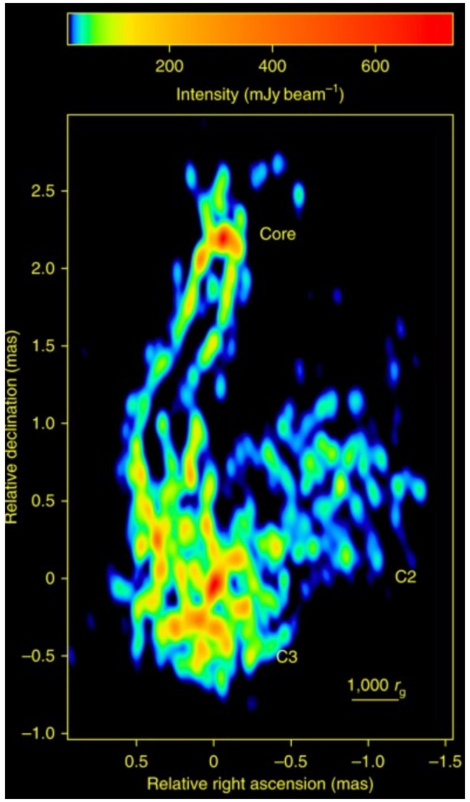
If we assume the two jet ridgelines to meet at the apex, we find θ > 40 degrees

Some conclusions on Cen A

- The expansion profile lies in between the parabolic profile of M 87 (k = 0.5) and the almost cylindrical profile of 3C 84 (k = 0.2)
- For Cen A jet: this suggests strong magnetic collimation or the presence of external pressure and density gradients --> may indicate the presence of winds
- The noticeable similarity and prominence of edge-brightened jet emission in M 87, 3C 84, and Cen A suggests the dominance of jet sheath emission to be an emerging feature in LLAGN

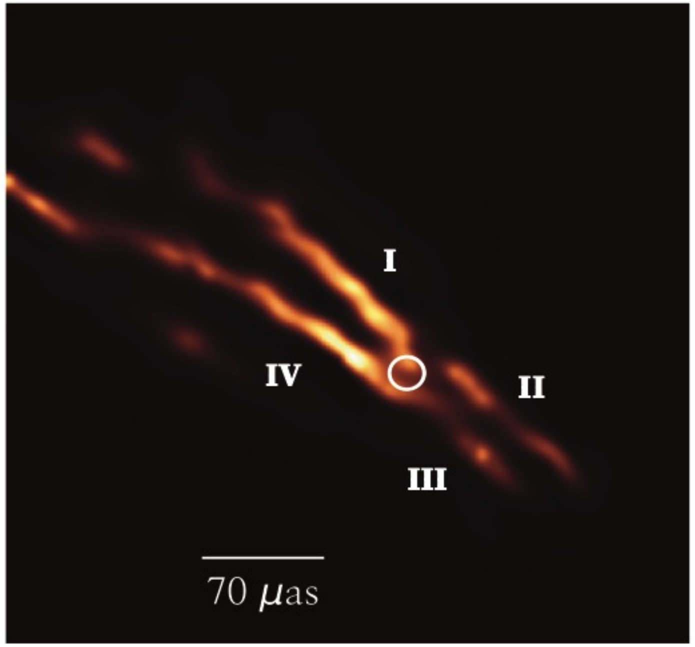


Credit: R.-S. Lu (SHAO), E. Ros (MPIfR), S. Dagnello (NRAO / AUI / NSF)



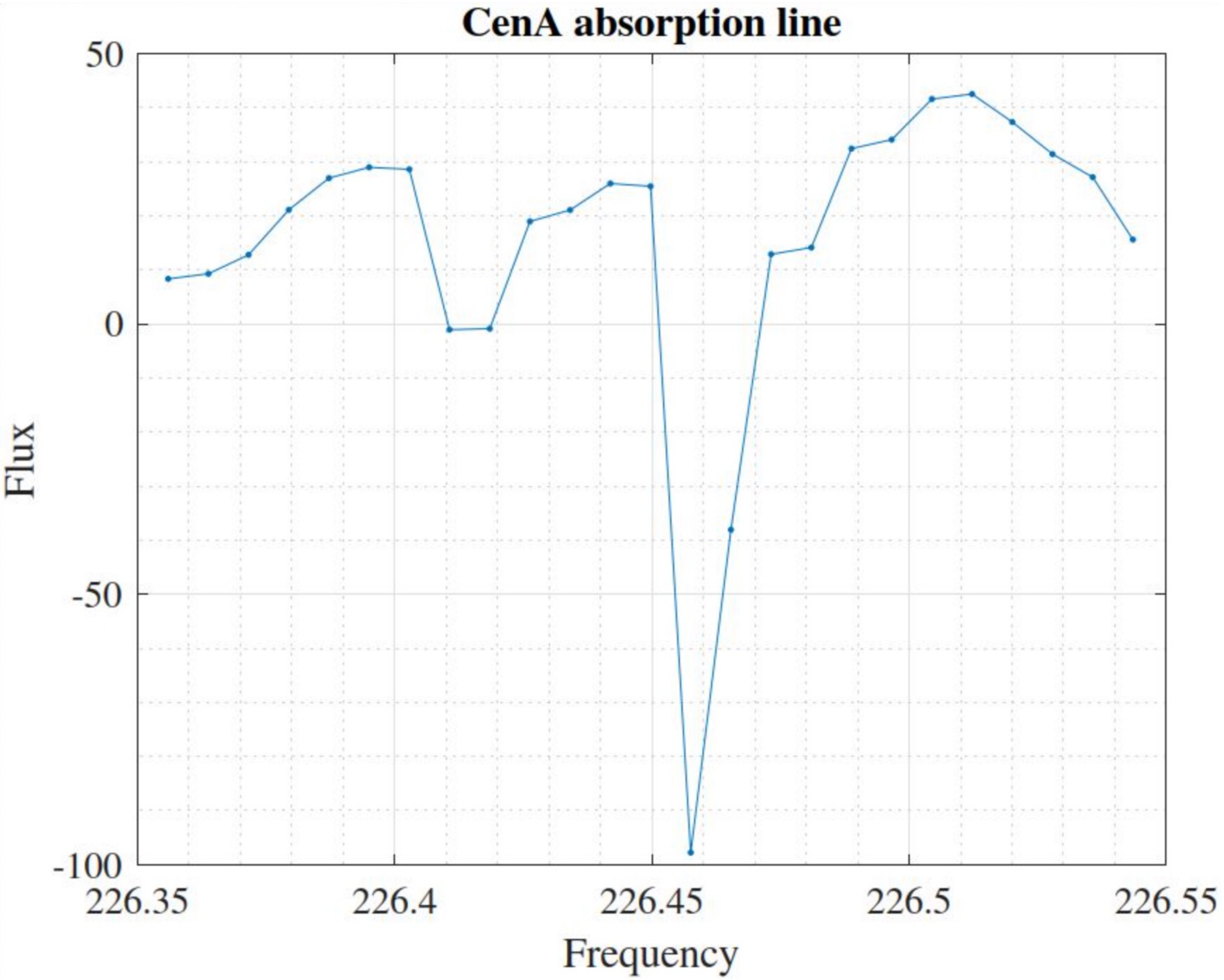
Giovannini et al. 2018

Janssen et al. 2021

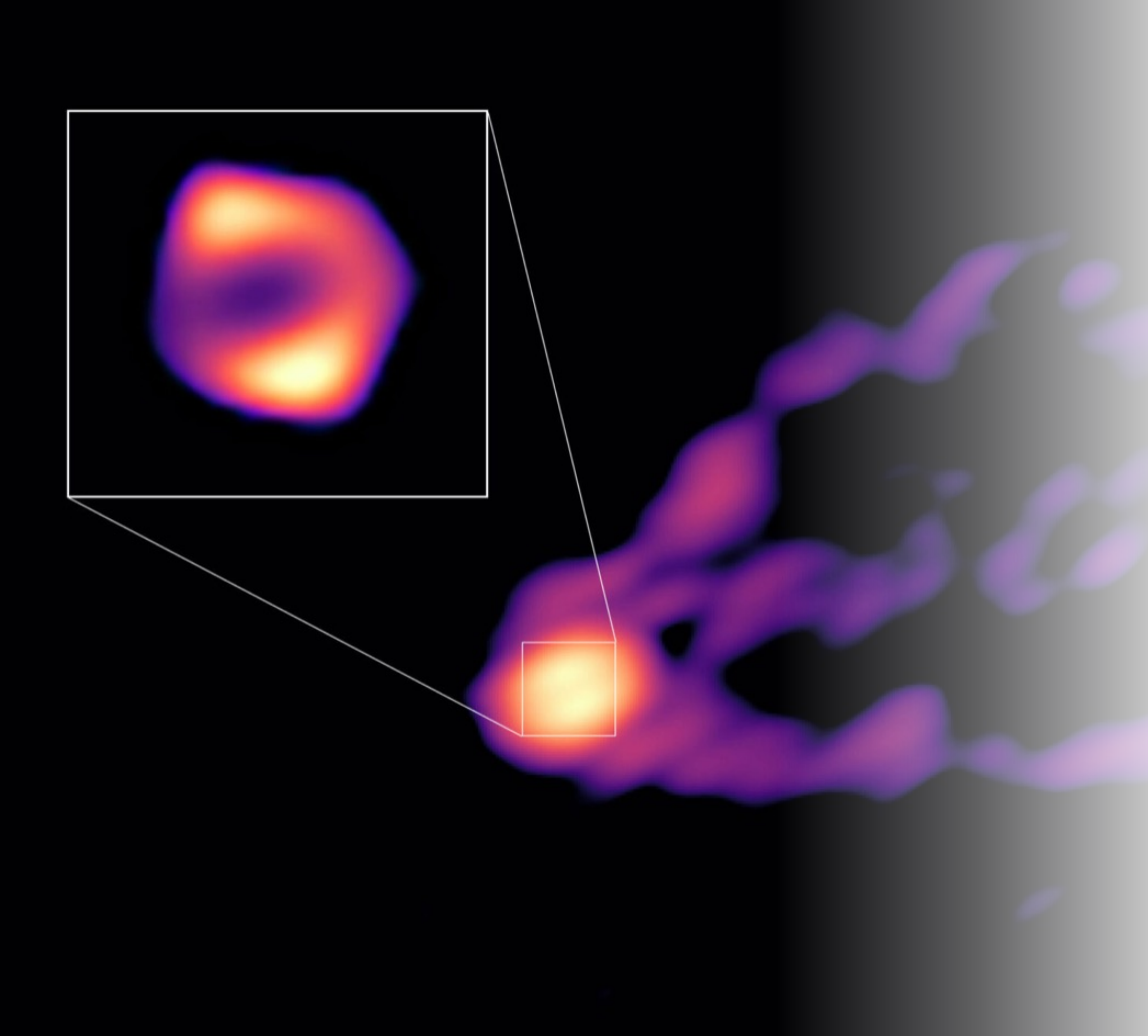


Absorption lines

- Serentidutous detection of an mm absorption line against the nucleus of Cen A
- Future observations will locate the gas relative to the jet/core
- Spectral line mmVLBI is now available to the community (from Cycle 10)



Impellizzeri, Ramakrishnan in progress…



Summary

- mmVLBI observations are powerful tools to study supermassive black hole properties at very high angular scales
- Much more than just a donut factory!
- Very soon: upcoming results at 1mm on OJ287, NGC 1052, 3C 84