

# Towards a renewed view of compact radio sources in the galactic plane

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From 9 to 40: the SST Telescopes and  
Gamma-Ray Science with ASTRI and CTAO  
Haus Sexten, 20–24 Jul 2026





# Radio-VHE connection, why bother?

Radio waves and VHE gamma rays are the most distant bands of the observed electromagnetic spectrum, yet they are very relevant to each other:

1. Every identified VHE source is also a radio-loud object
2. Radio waves (through VLBI technique) are the only tool to obtain images on angular scales close to the ones probed by VHE variability time scales (sub-pc)

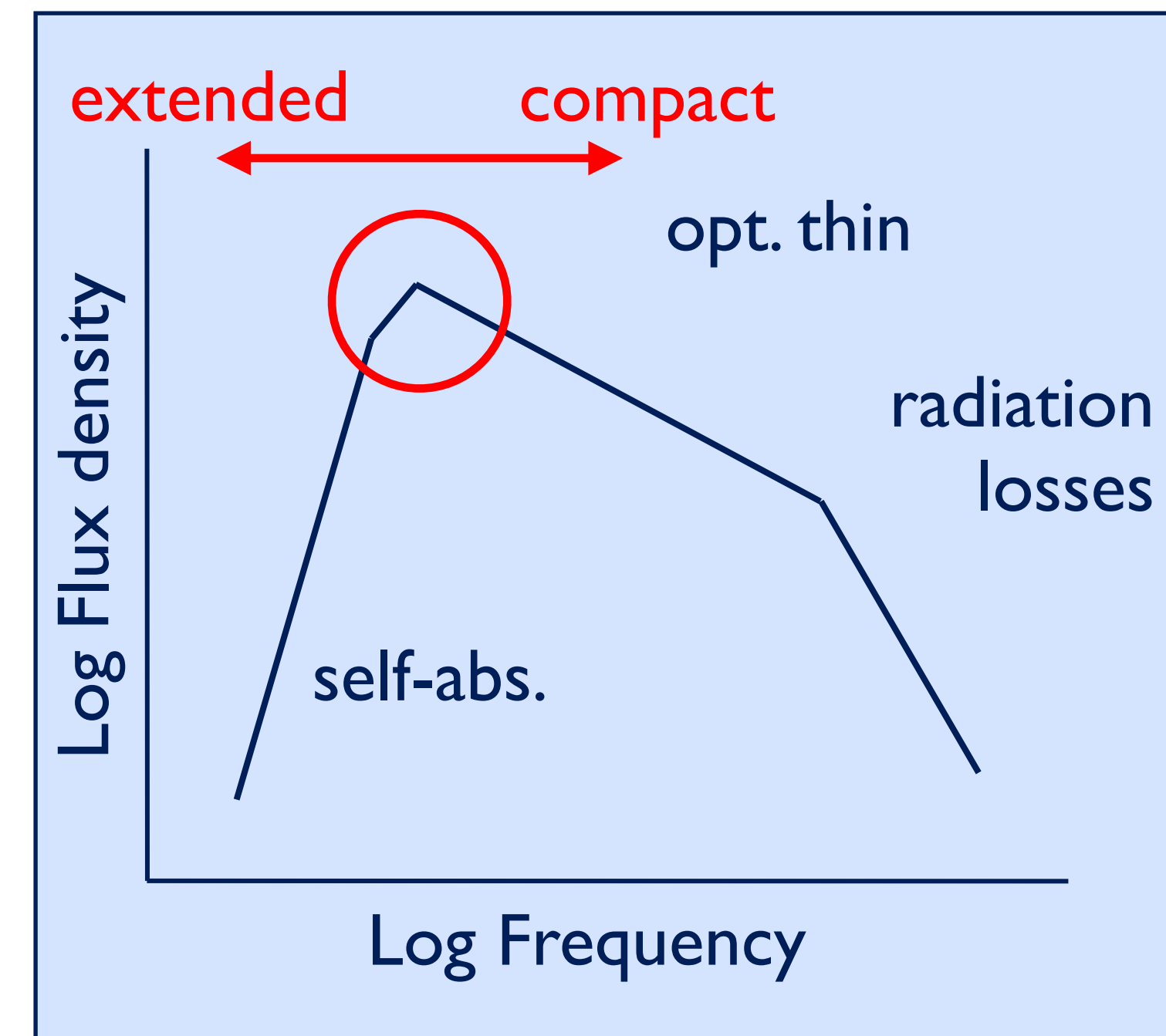
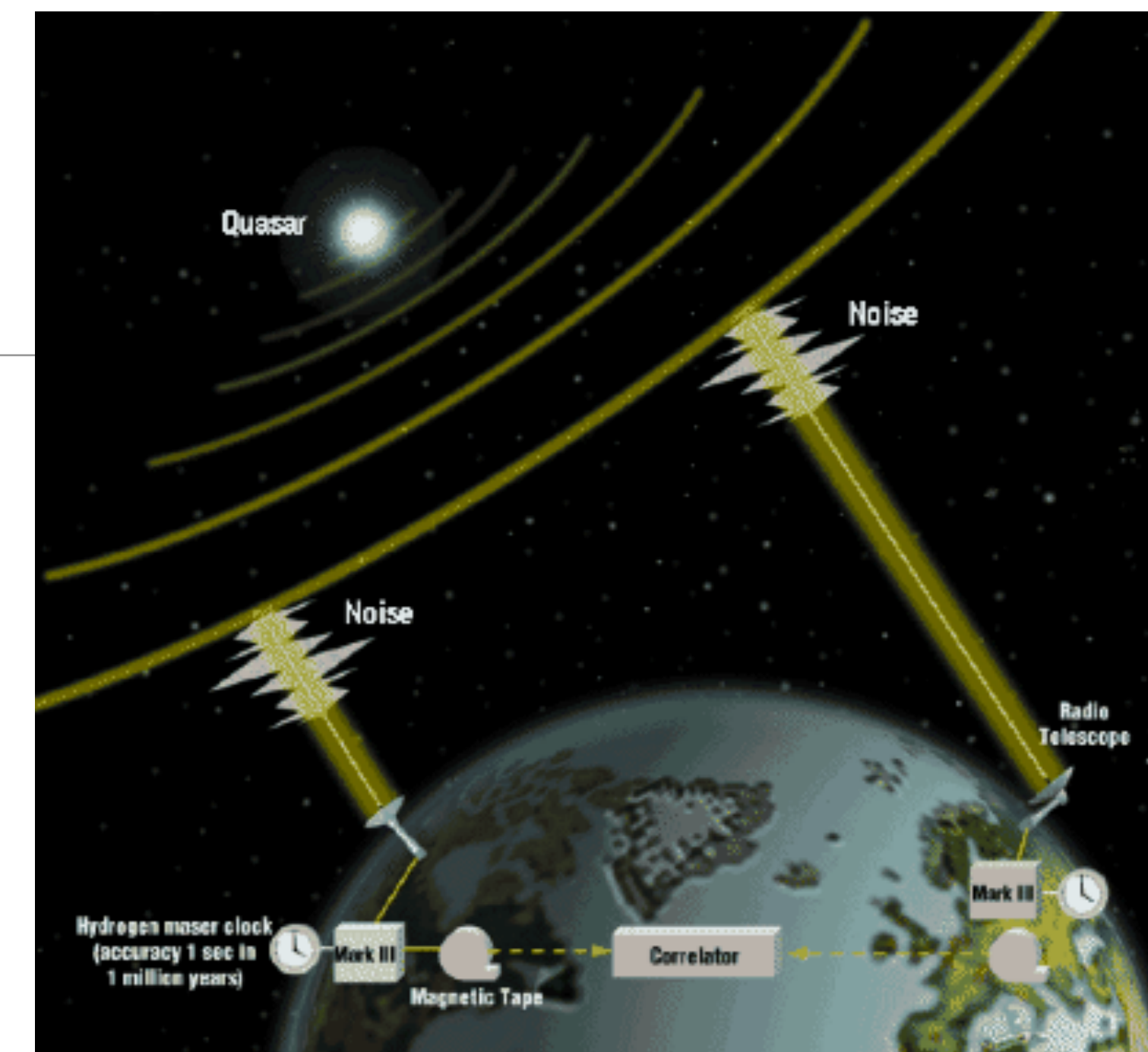




# (Very Long Baseline) Interferometry is the key

- Collecting photons is relatively cheap in radio (large areas, plenty of emission)
- Interferometry is necessary to improve angular resolution and separate different emission components
- Short wavelengths further improve sensitivity and allow access to self-absorbed regions (at the cost of more challenging observing conditions - atmosphere, mechanics, electronics, field of view)

$$\theta = \frac{\lambda}{B}$$





# Huge parameter space in frequency and angular resolution

## Connected interferometers



$10^7$  Hz

LOFAR, GMRT, VLA, ATCA, ALMA  
MeerKAT, ASKAP

~arcsec angular resolution  
~1-10  $\mu$ Jy sensitivity

$>10^{11}$  Hz

## Very Long Baseline Interferometry

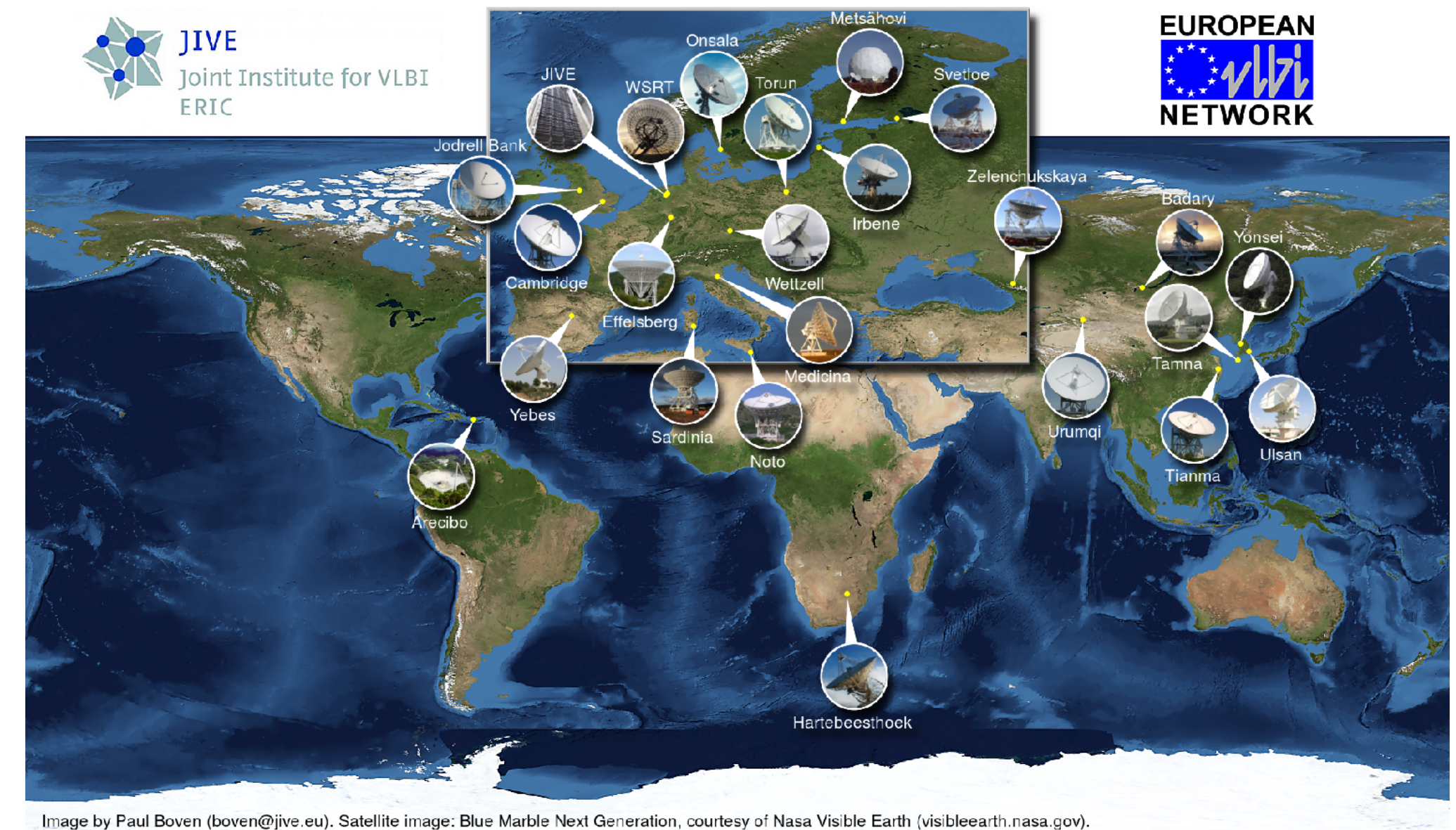


Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

VLBA, EVN, LBA

~mas angular resolution

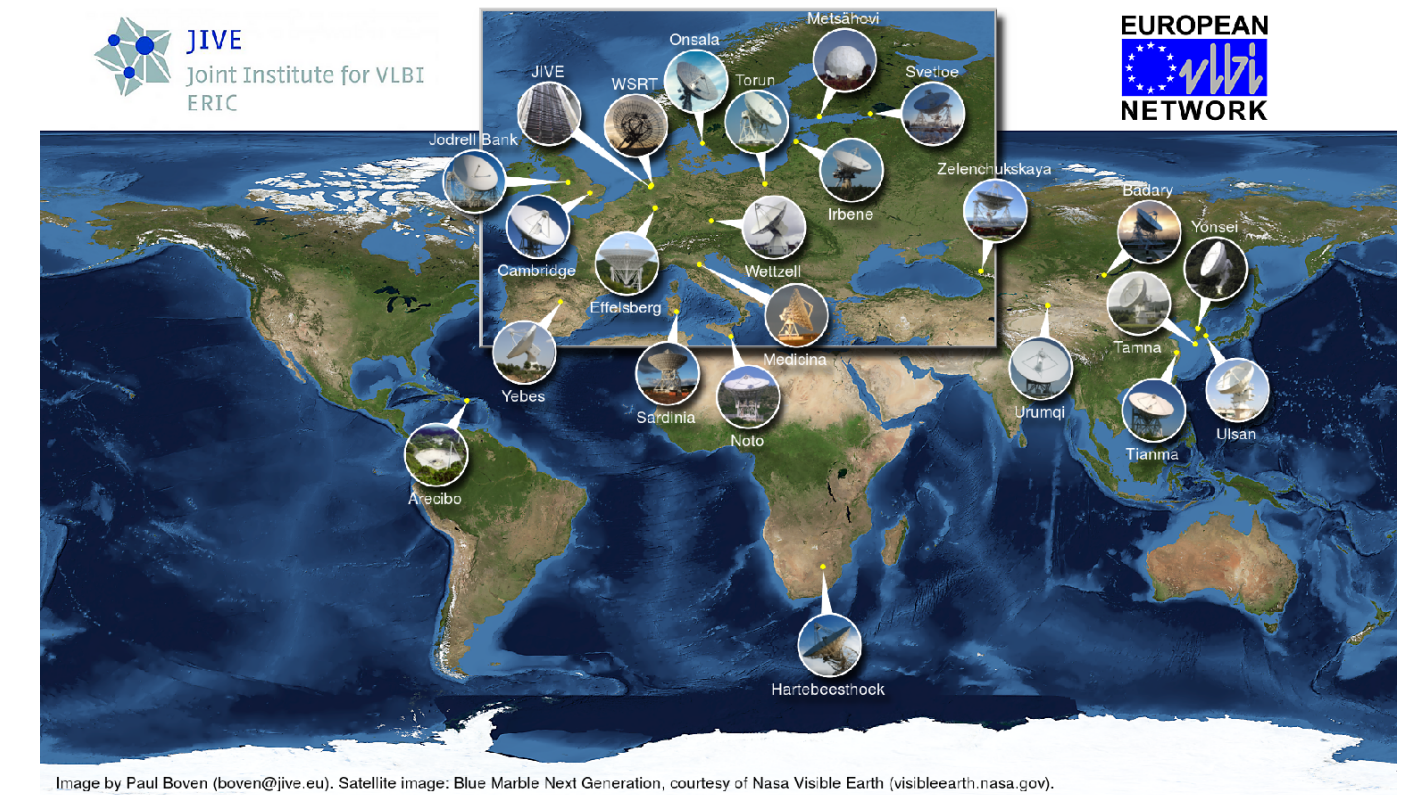
~100  $\mu$ Jy sensitivity

Event Horizon Telescope



# Very Long Baseline Interferometry - pros & cons

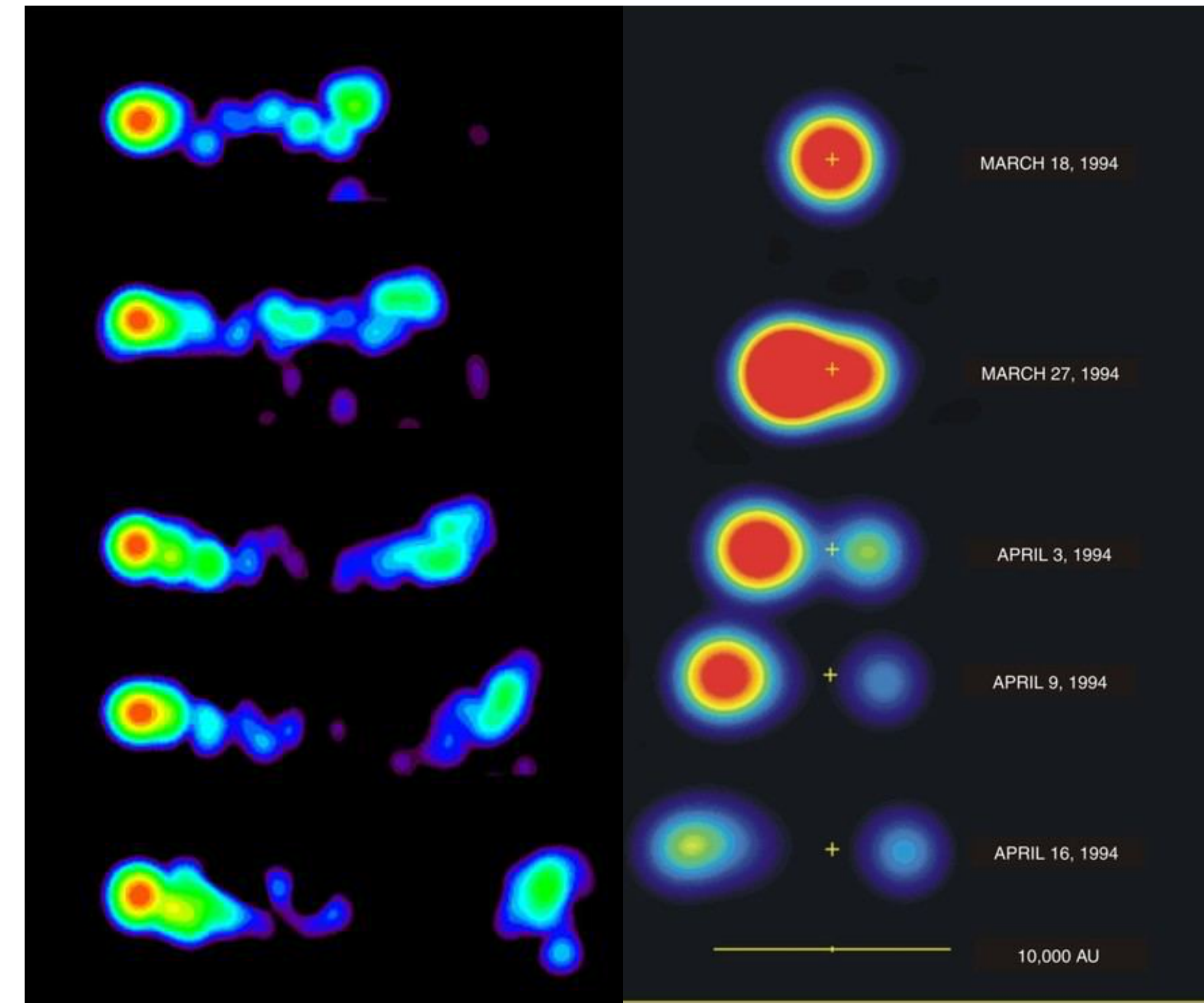
- Pros
  - More resilient to interference (site dependent)
  - Increases sensitivity
  - Filters out diffuse emission (same source or foregrounds)
  - Only way to study structural evolution
- Cons
  - Some added complexity in experiment setup and data analysis
  - Optically thick regions remain inaccessible (need *submm*-VLBI)





# VLBI - reference scales

- In the Galaxy (@1 kpc)
  - 1 mas = 1 AU
  - $\Delta t = 1 \text{ hr}$ ,  $c\Delta t = 7 \text{ AU}$
  - 1 mJy  $\sim 10^{28} \text{ erg s}^{-1}$
- Extragalactic (@ $z=0.05$ )
  - 1 mas  $\sim 1 \text{ pc}$ ;
  - $\Delta t = 1 \text{ yr}$ ,  $c\Delta t = 0.3 \text{ pc}$
  - 1 mJy  $\sim 10^{38} \text{ erg s}^{-1}$
- Sensitivity typical of high  $T_b$  emission (synchrotron/coherent)



QSO 3C 279

XRB 1915+105



# VLBI vocabulary - Relevant acronyms & false friends

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- **VLBI** (Very Long Baseline Interferometry): the technique
- **VLBA** (Very Long Baseline Array): the US full-time dedicated instrument to do VLBI
- **EVN** (European VLBI Network): the European\* consortium for VLBI
- **JIVE** (Joint Institute for VLBI in Europe): the ERIC running the EVN correlator, and more

\* including INAF telescopes



# European VLBI Network (EVN)



- A set of individually operated different telescopes across (and beyond) Europe; *heterogeneous in sensitivity, spacings, receiver set*
- Agreement between operating institutions grants 3x3weeks regular sessions per year, plus  $\sim 10 \times 2$ days real time sessions
- **Real time capable & very sensitive;** *limited flexibility, challenging calibration (both being worked on!)*





# European VLBI Network (EVN)



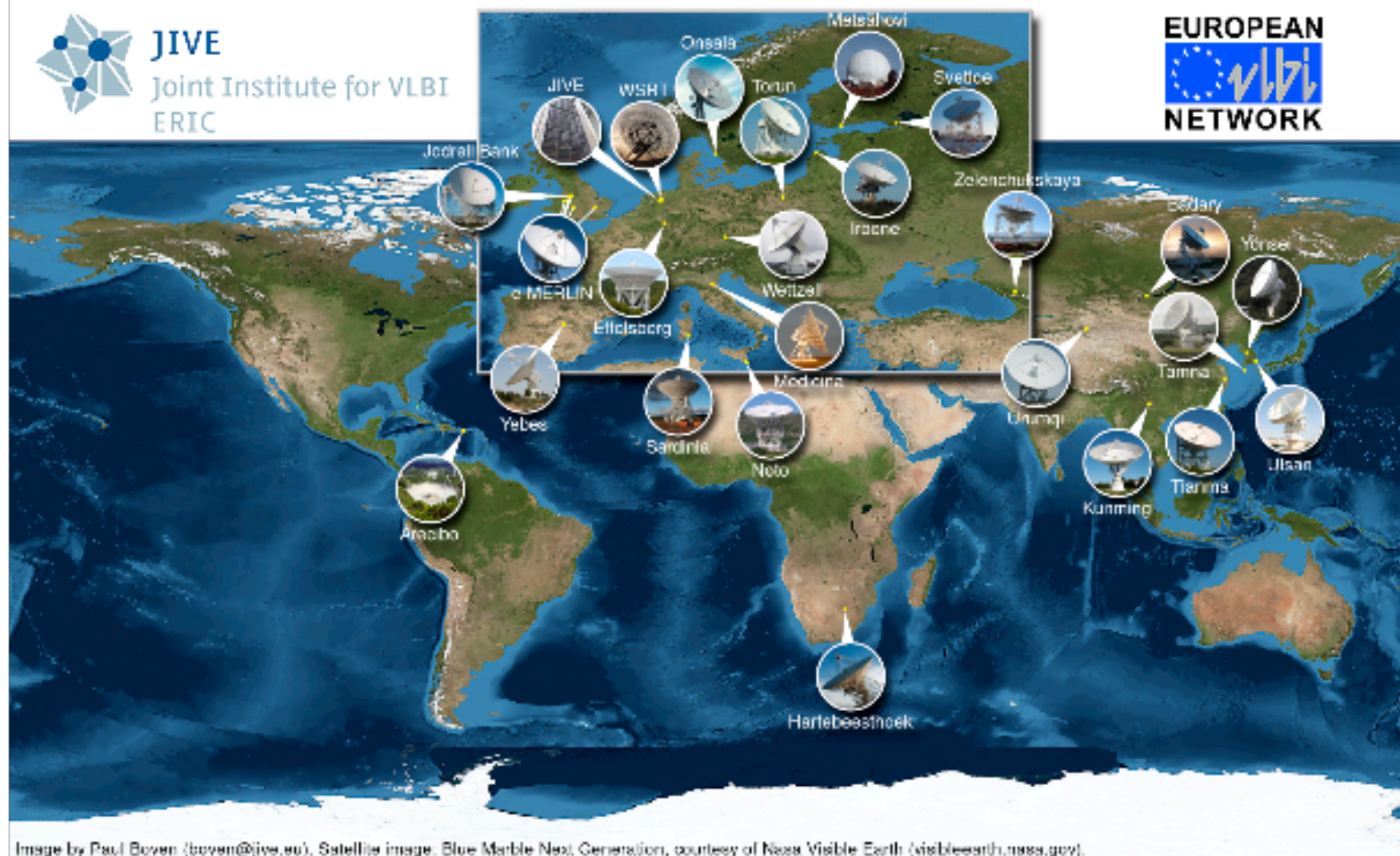
## VLBI20-30: a scientific roadmap for the next decade

The future of the European VLBI Network

Editors: Tiziana Venturi, Zsolt Paragi & Michael Lindqvist

Venturi et al. 2020

- Core stations in Europe, long baselines to East Asia, South Africa
- Primary frequencies: 1.6 & 5 GHz; 8, 22 GHz also available; extension to 22/43/86 GHz (simultaneously!) planned
- Recent additions: MeerKAT, uGMRT: extra sensitivity in L-band
- Longest baselines: ~9000km, and more with "Global VLBI"



*Cosmology; Galaxy formation and evolution; Innermost regions of AGN; Explosive phenomena, transients; Stars and stellar masers in the Milky Way; Earth and Space; A new vision for VLBI*



*Sardinia, 64m*



*What about Italy?*



*Medicina,  
32m*



*Noto, 32m*

**INAF collecting area: 4825 m<sup>2</sup>**

**VLBA collecting area: 4909 m<sup>2</sup>**

*Bologna,  
DiFX correlator*





# INAF radio telescope tables (pre-upgrades)



Table 1. INAF radio telescopes.

| Location | Code | Size | Year | Latitude       | Longitude      | Elevation | Operating receivers |
|----------|------|------|------|----------------|----------------|-----------|---------------------|
| Medicina | Mc   | 32 m | 1983 | 44° 31' 15'' N | 11° 38' 49'' E | 25 m      | L, S, C, C+, X, K   |
| Noto     | Nt   | 32 m | 1988 | 36° 52' 34'' N | 14° 59' 21'' E | 78 m      | P, L, C+, K         |
| Sardinia | Sr   | 64 m | 2011 | 39° 29' 34'' N | 9° 14' 42'' E  | 600 m     | L, S, C, C+, X, K   |

Table 2. INAF VLBI baseline length and sensitivity.

| Baseline | Length (km) | Sensitivity (mJy min <sup>-1</sup> Gbps <sup>-1</sup> ) |         |        |
|----------|-------------|---------------------------------------------------------|---------|--------|
|          |             | L-band                                                  | C+-band | K-band |
| Mc-Nt    | 893         | 5.9                                                     | 7.8     | 6.1    |
| Mc-Sr    | 592         | 1.8                                                     | 1.7     | 2.5    |
| Nt-Sr    | 580         | 1.8                                                     | 1.9     | 2.7    |



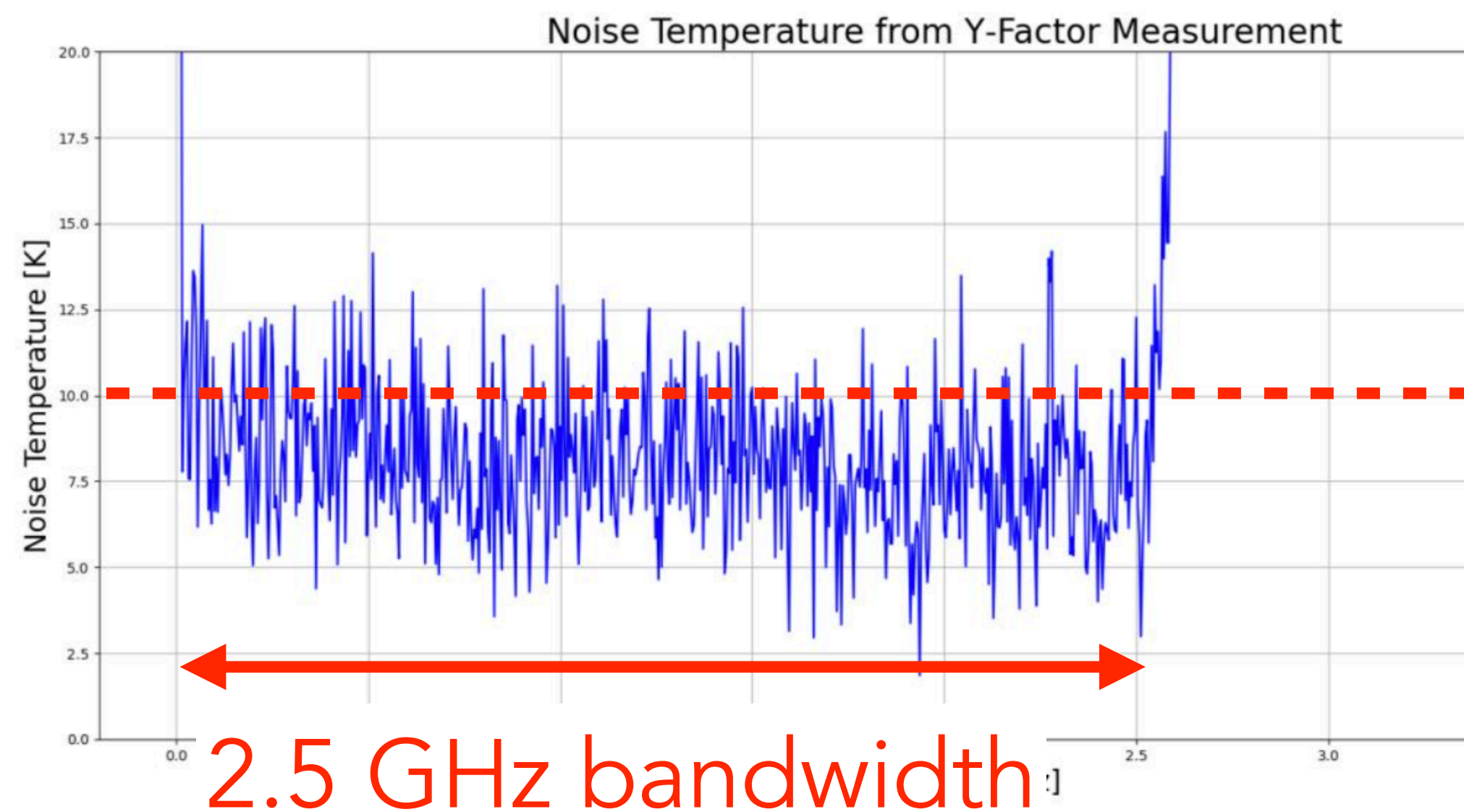
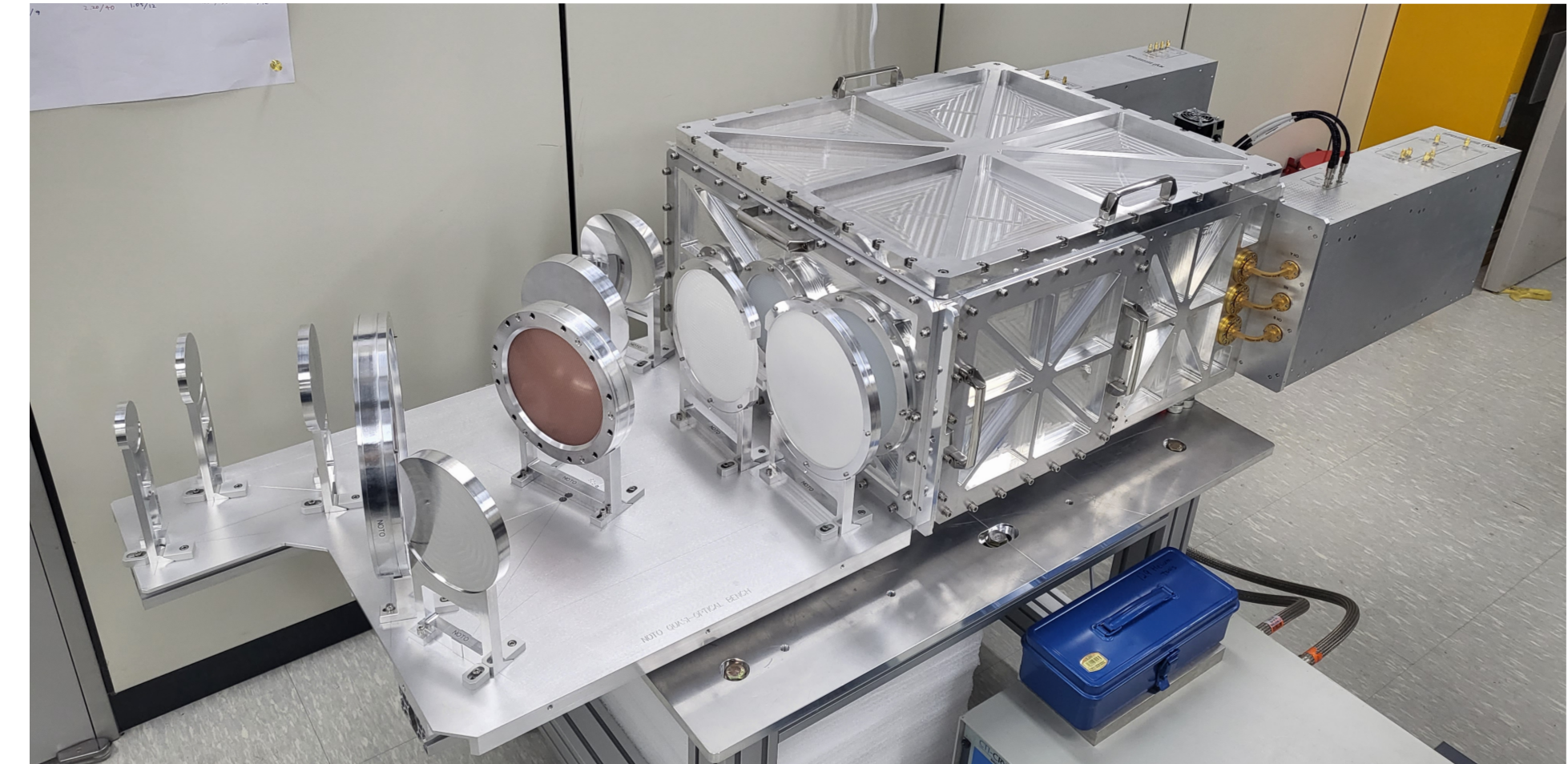
From Eating VLBI review (Giovannini et al. 2023)



# INAF radio telescope upgrades

One of the three compact triple band receivers  
for simultaneous 22/43/86 GHz observations

- PON: compact triple-band receivers to enable VLBI observations up to 100 GHz
- PNRR CTA+: broadband 4-9 GHz receivers to enable sensitive in cm- $\lambda$  band (most dependable for transient studies)



One of the new broadband receivers  
for 4.2-9.0 GHz observations



# Status tables, 2017-> 2026

|                       | Medicina (Mc)  | Noto (Nt)             | Sardinia (Sr)        |
|-----------------------|----------------|-----------------------|----------------------|
| <b>diameter</b>       | 32m            | 32m                   | 64m                  |
| <b>active surface</b> | N              | Y                     | Y                    |
| <b>L</b>              | Y              | Y/N (not operational) | Y                    |
| <b>S/X</b>            | Y              | Y                     | N                    |
| <b>C</b>              | Y              | Y                     | N/Y (designed)       |
| <b>C - high</b>       | Y (not cooled) | Y (not cooled)        | Y                    |
| <b>K</b>              | Y (2-beam)     | Y                     | Y (7-beam)           |
| <b>Q</b>              | N              | Y/N (not operational) | N/Y (designed)       |
| <b>W</b>              | N              | N (being considered)  | N (being considered) |
| <b>e-VLBI</b>         | Y              | Y                     | almost!              |

|                       | Medicina (Mc)  | Noto (Nt)      | Sardinia (Sr) |
|-----------------------|----------------|----------------|---------------|
| <b>diameter</b>       | 32m            | 32m            | 64m           |
| <b>active surface</b> | Y              | Y              | Y             |
| <b>L</b>              | Y              | Y              | Y             |
| <b>S/X</b>            | Y              | Y              | N             |
| <b>C</b>              | Y              | Y              | Y             |
| <b>C - high</b>       | Y (not cooled) | Y (not cooled) | Y             |
| <b>K</b>              | Y (2-beam)     | Y              | Y (7-beam)    |
| <b>Q</b>              | Y              | Y              | Y             |
| <b>W</b>              | Y              | Y              | Y             |
| <b>e-VLBI</b>         | Y              | Y              | Y             |



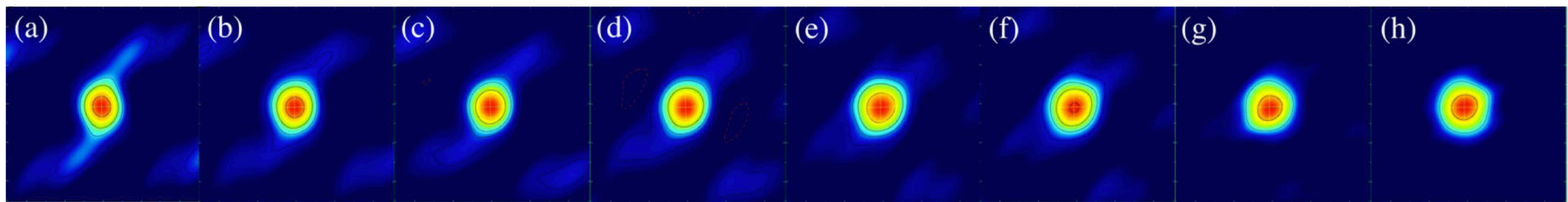
# What can a three-station network do?

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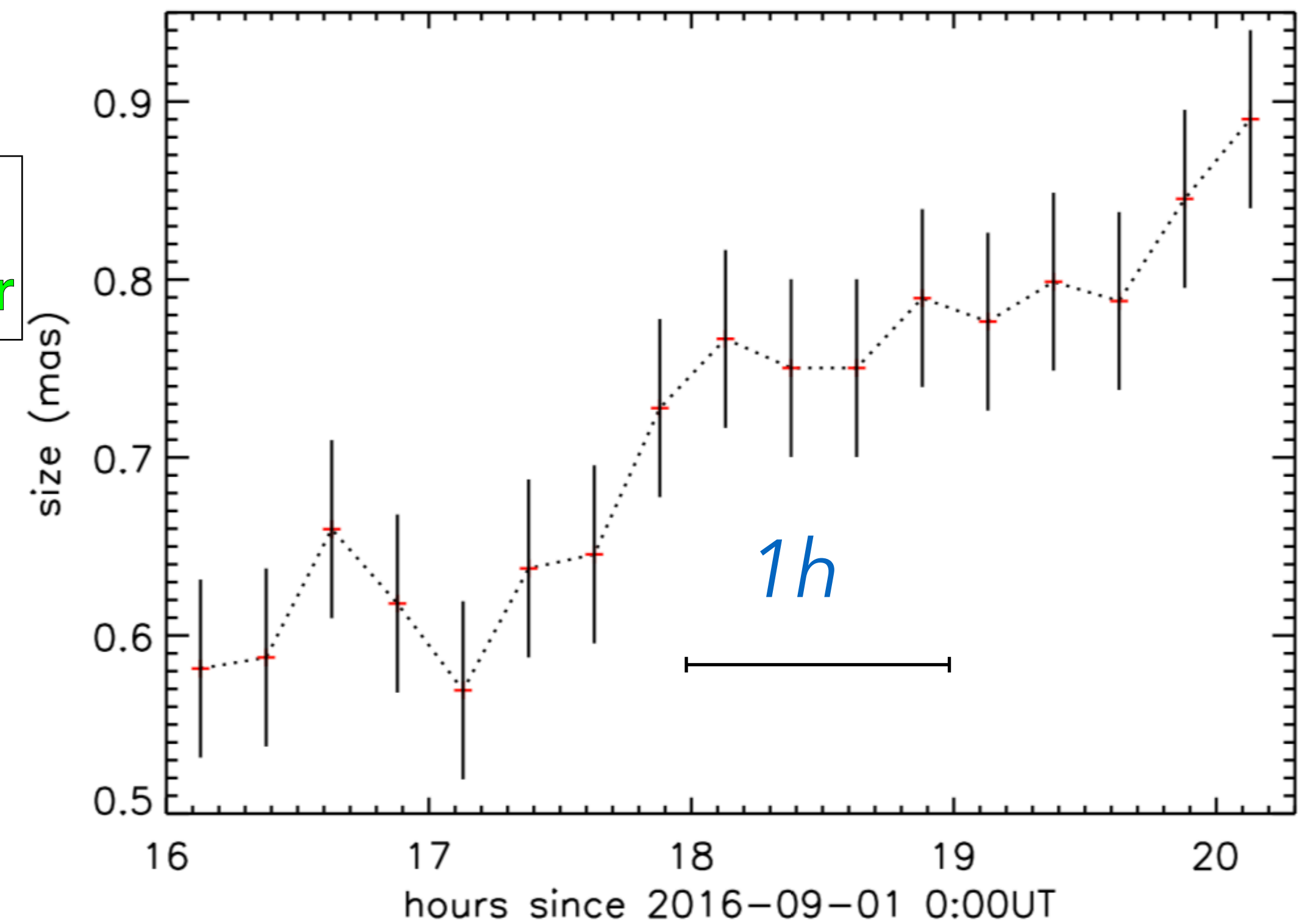
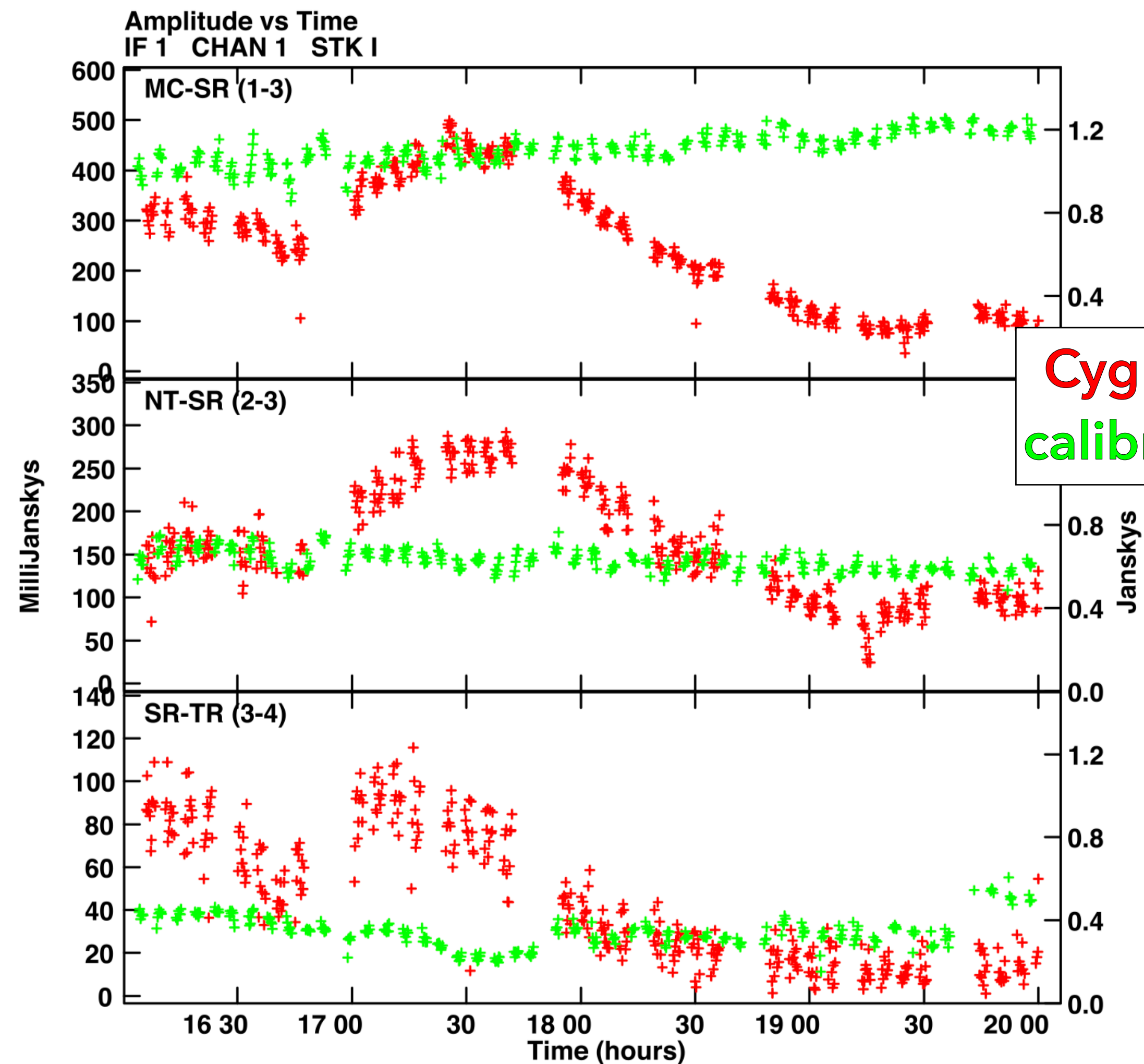
- Same country: homogenous source elevation constraints
- Same institute: flexible, have a fast access
- One high sensitivity telescope (Sardinia 64-m)
- Monitoring, surveys, filtering of candidates
- Limited imaging capabilities: high fidelity follow ups devoted to more extended arrays
- One test case: a survey of the Cygnus region



# Cyg X-3



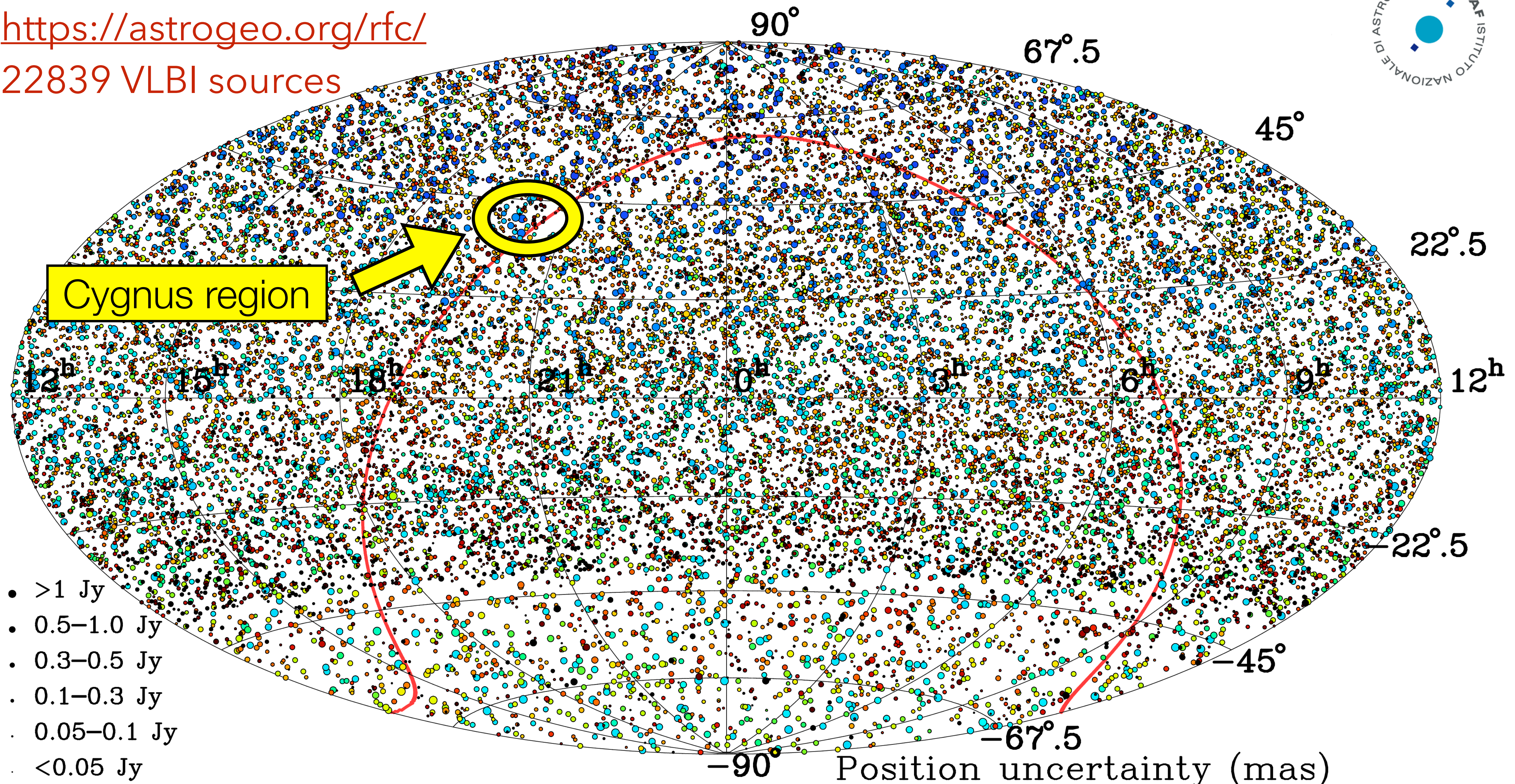
*Egron et al. 2017, first Italian VLBI paper (+Ys/On/Tr)*





# Radio fundamental catalogue

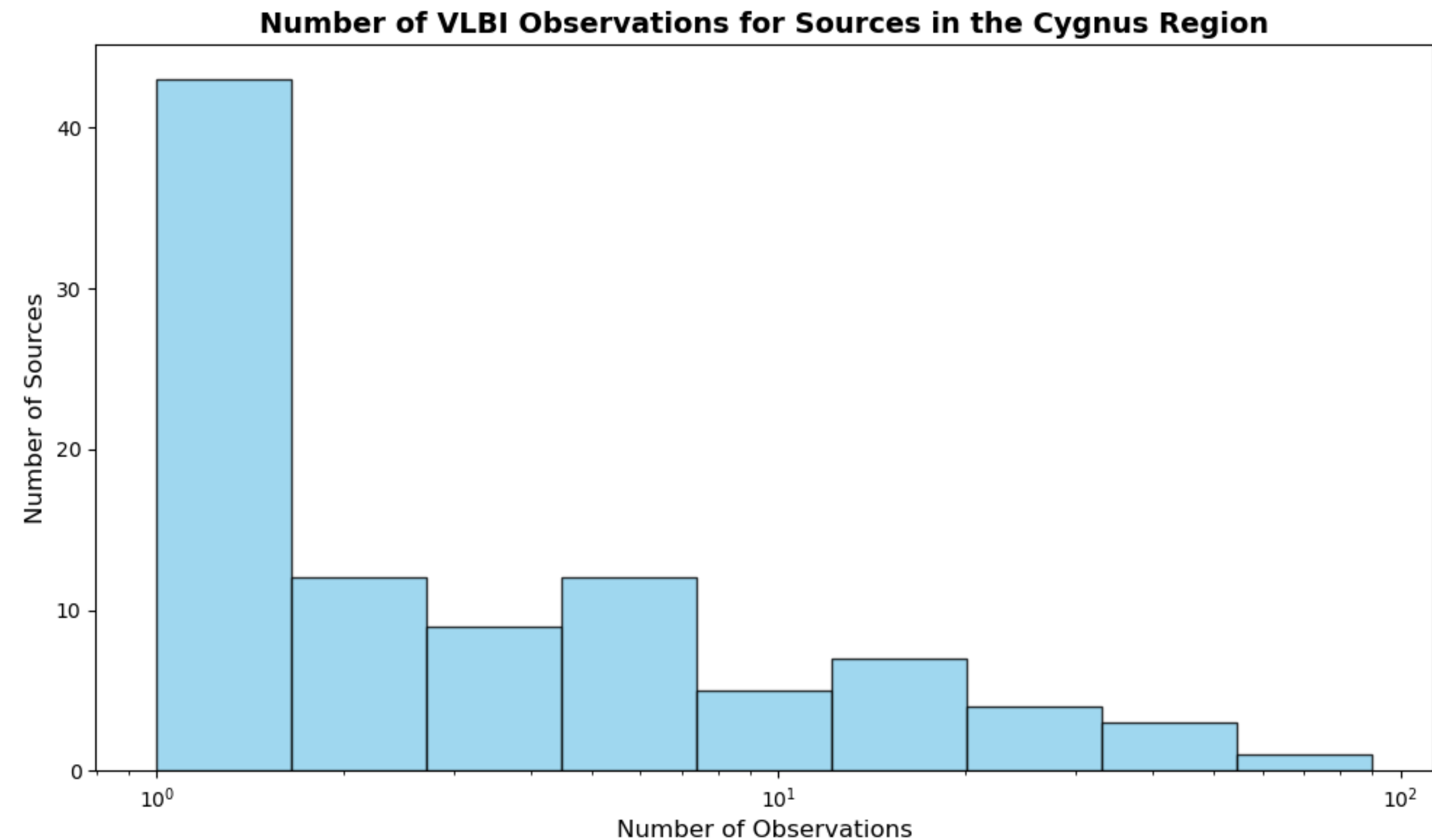
<https://astrogeo.org/rfc/>  
22839 VLBI sources





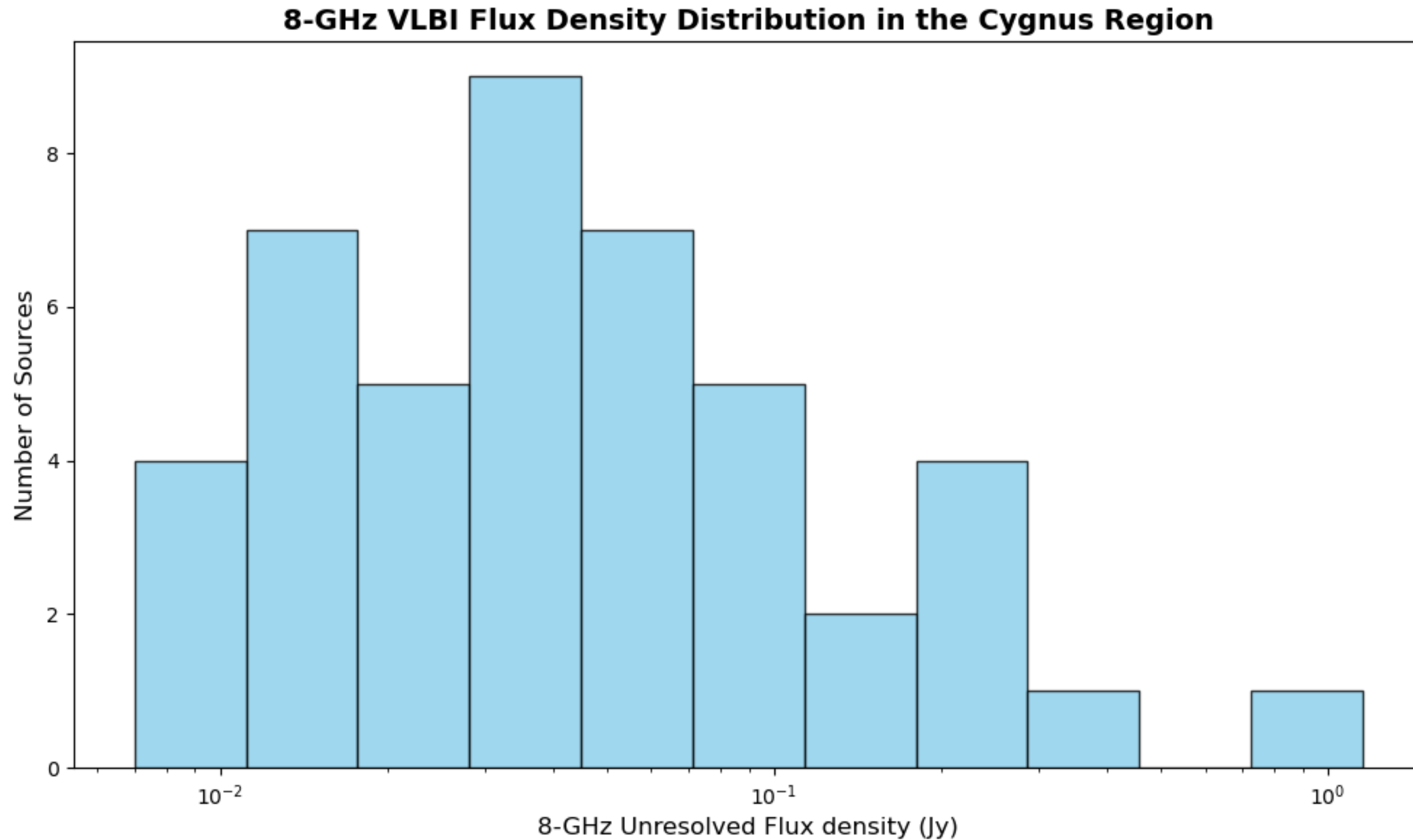
# Cygnus region

- Assuming boundaries of  $19.5\text{h} < \text{r.a.} < 21.0\text{h}$ ,  $35.0\text{d} < \text{dec} < 46.0\text{d}$
- 96 candidate VLBI calibrators (out of 22839 in whole sky)
  - ~50% only observed once
- 46 confirmed with 8-GHz VLBI detection (24 at 5-GHz),
  - brightest one is J2015+3710 (1.154 Jy at 8-GHz)
- Other “famous” objects: Cygnus A, Cygnus X-3





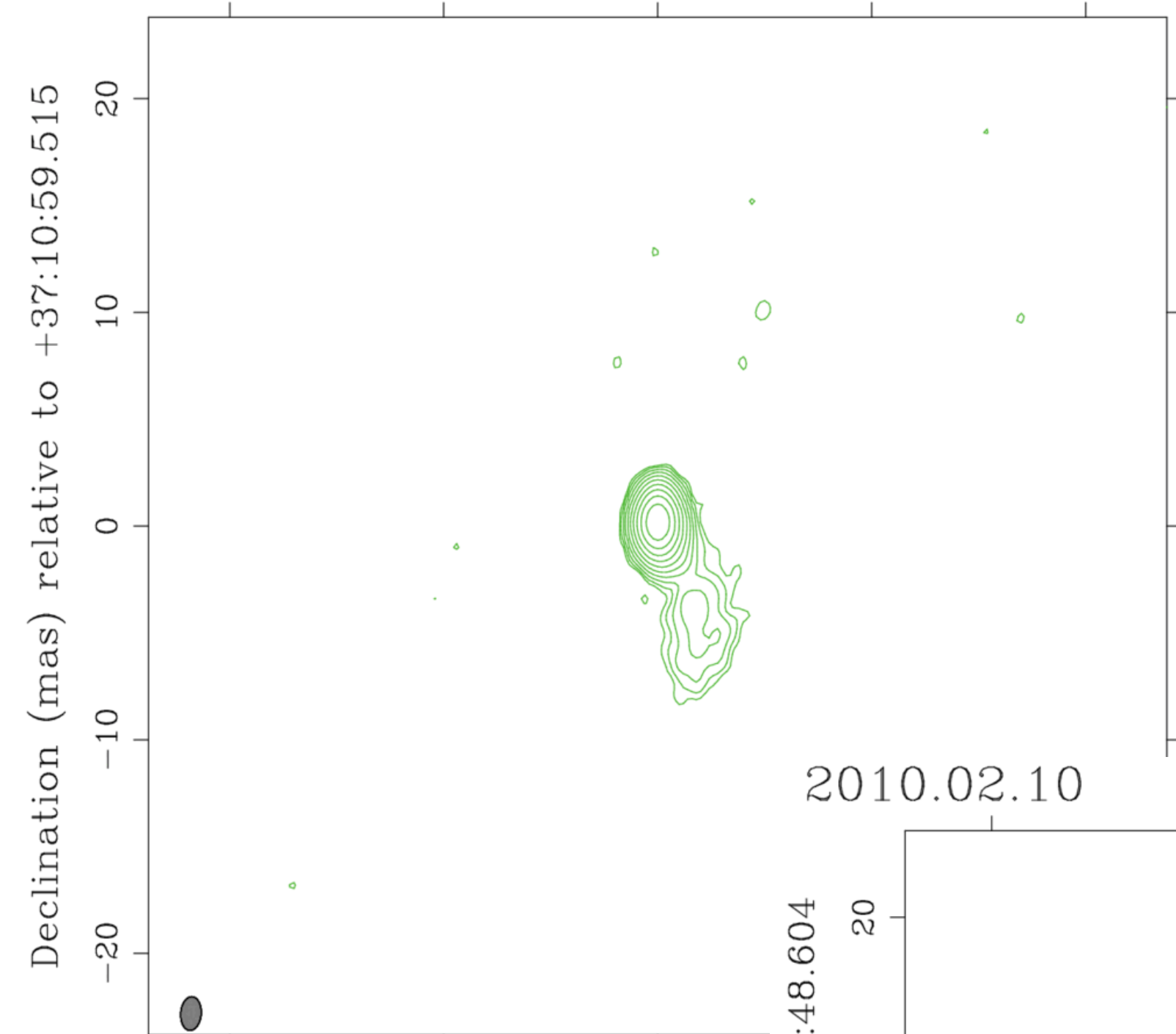
# Cygnus region existing VLBI data



Brightest sources  
are typically  
extragalactic

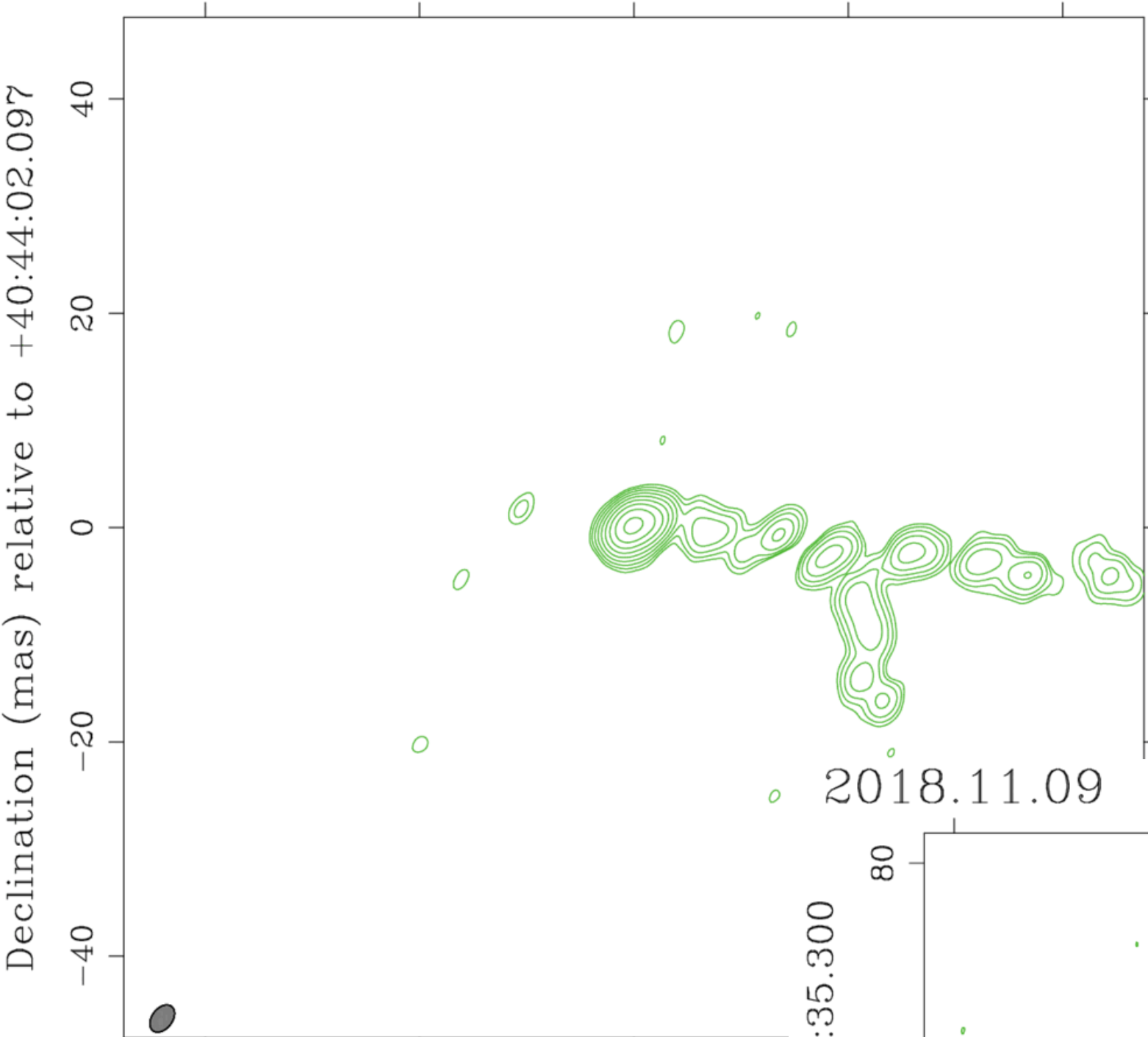


2017.06.10 **J2015+3710** Freq: 8.7 GHz



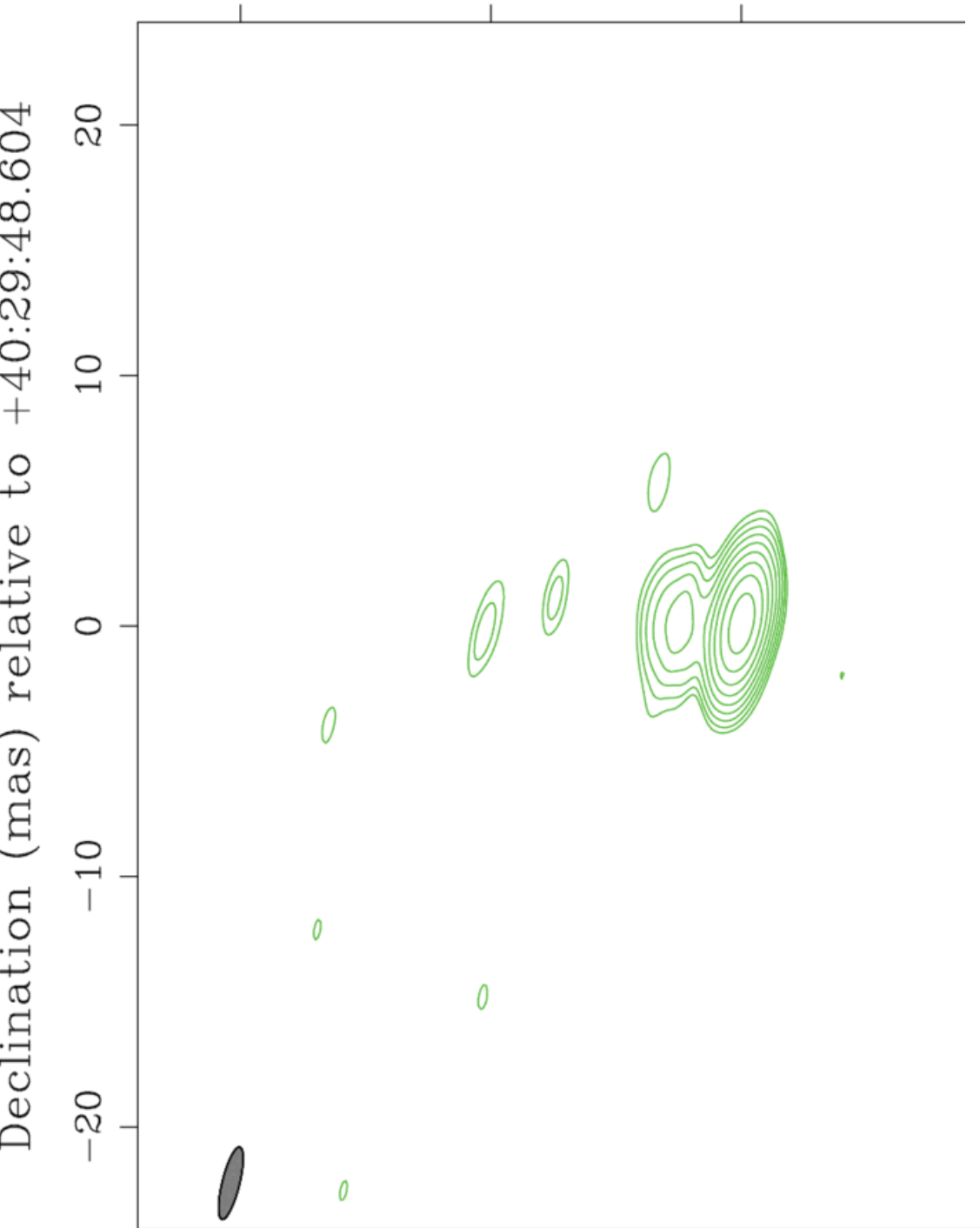
Right ascension (mas) relative to +37:10:59.515  
Peak\_level= 1.903 Jy/beam  
Rms\_noise= 0.3 mJy/beam  
Levels: 2, 4, 8, 16, 31, 63, 125, 250, 501, 1002

2013.07.17 **J1959+4044** Freq: 7.6 GHz



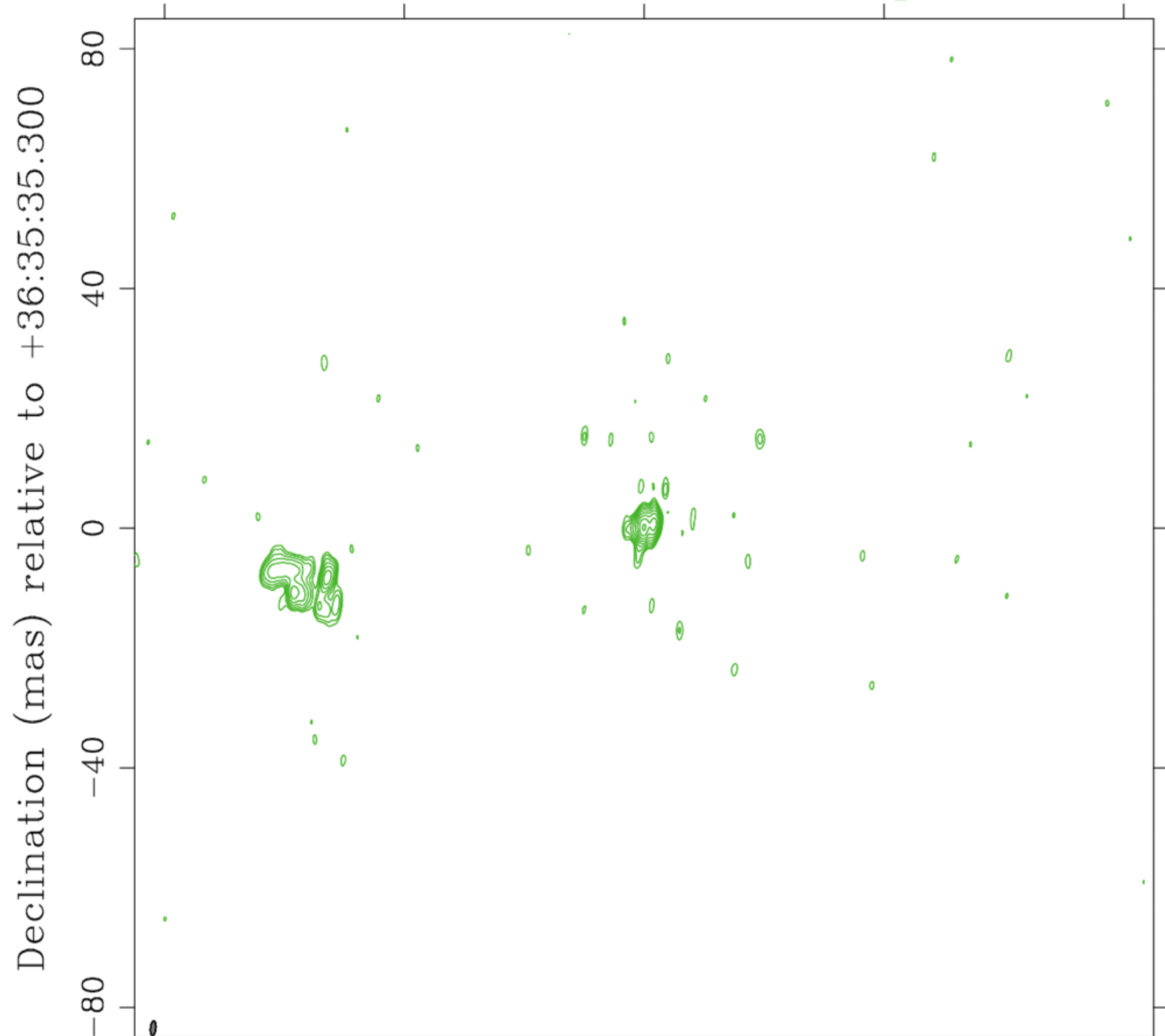
Right ascension (mas) relative to +40:44:02.097  
Peak\_level= 0.624 Jy/beam  
Rms\_noise= 0.3 mJy/beam  
Levels: 2, 4, 8, 16, 31, 62, 124, 249, 497 mJy/beam

2010.02.10 **J2007+4029** Freq: 7.6 GHz



Right ascension (mas) relative to 20:07:44.9448  
Peak\_level= 1.166 Jy/beam  
Rms\_noise= 0.7 mJy/beam  
Levels: 3, 6, 12, 23, 47, 94, 187, 374, 749 mJy/beam

2018.11.09 **J2052+3635** Freq: 7.6 GHz



Right ascension (mas) relative to 20:52:52.0550  
Peak\_level= 0.364 Jy/beam  
Rms\_noise= 0.3 mJy/beam  
Levels: 1, 3, 5, 10, 20, 41, 81, 163, 326 mJy/beam





# Science goals

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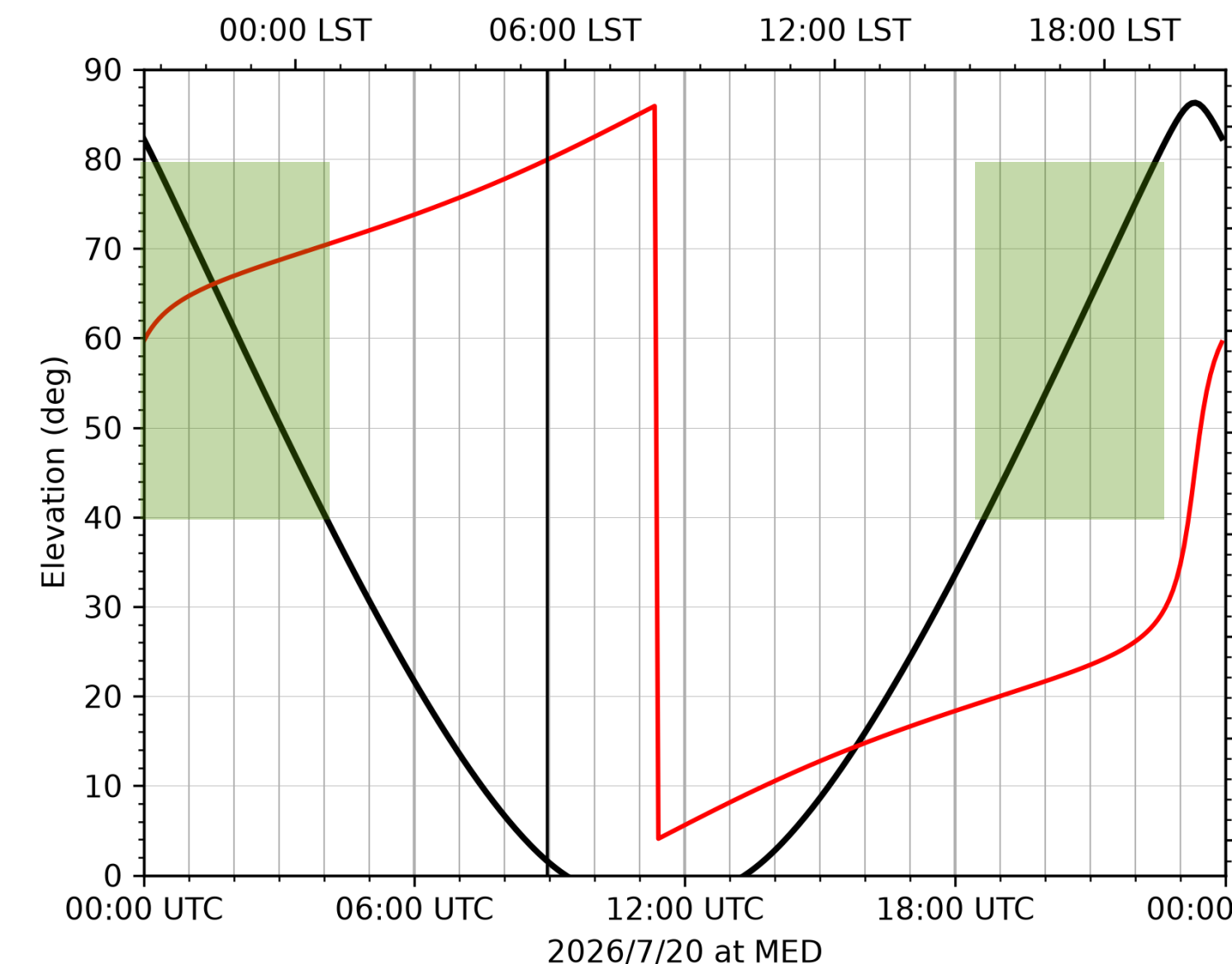


- Already detected sources:
  - Blazars: determine physical parameters
  - Binaries: monitor flux density evolution in comparison with X-ray, VHE, other telescopes
  - Uncertain sources: contribute to classification, e.g. through astrometry (proper motion)
- Sources not yet detected/observed, especially
  - Perform new observations in multiple possible states
    - Especially at low galactic latitude
  - Interstellar plasma studies



# Feasibility

- ~100 sources in radio fundamental catalogue
- ~100 more sources to be added at low latitude
- ~10 observations per source
- ~10 min per observation (detection threshold ~5 mJy)
- ~ $2 \times 10^4$  min total ~ 14 days of observation
  - 8 hr/day with  $40\text{deg} < \text{elev} < 80\text{deg}$
  - 10 epochs x (4x8hr) runs
- Beyond Cygnus region:
  - impractical to survey the whole (northern) galactic plane (esp. with multi-epoch obs.), but worthwhile to extend to VHE detected sources





# Outlook and take home

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- Updated census for 100-200 targets
  - Accurate positions, mas flux density, compact-to-extended flux density ratio, variability (intrinsic, extrinsic), spectral index
  - Galactic and extragalactic
- Simultaneity with ASTRI? CTAO?
  - Coordinated variability, any systematic difference between  $\gamma$ -ray detected/undetected sources?
- Pathfinder for CTAO, EVN, ...



# Summary of VLBI/VHE synergy results

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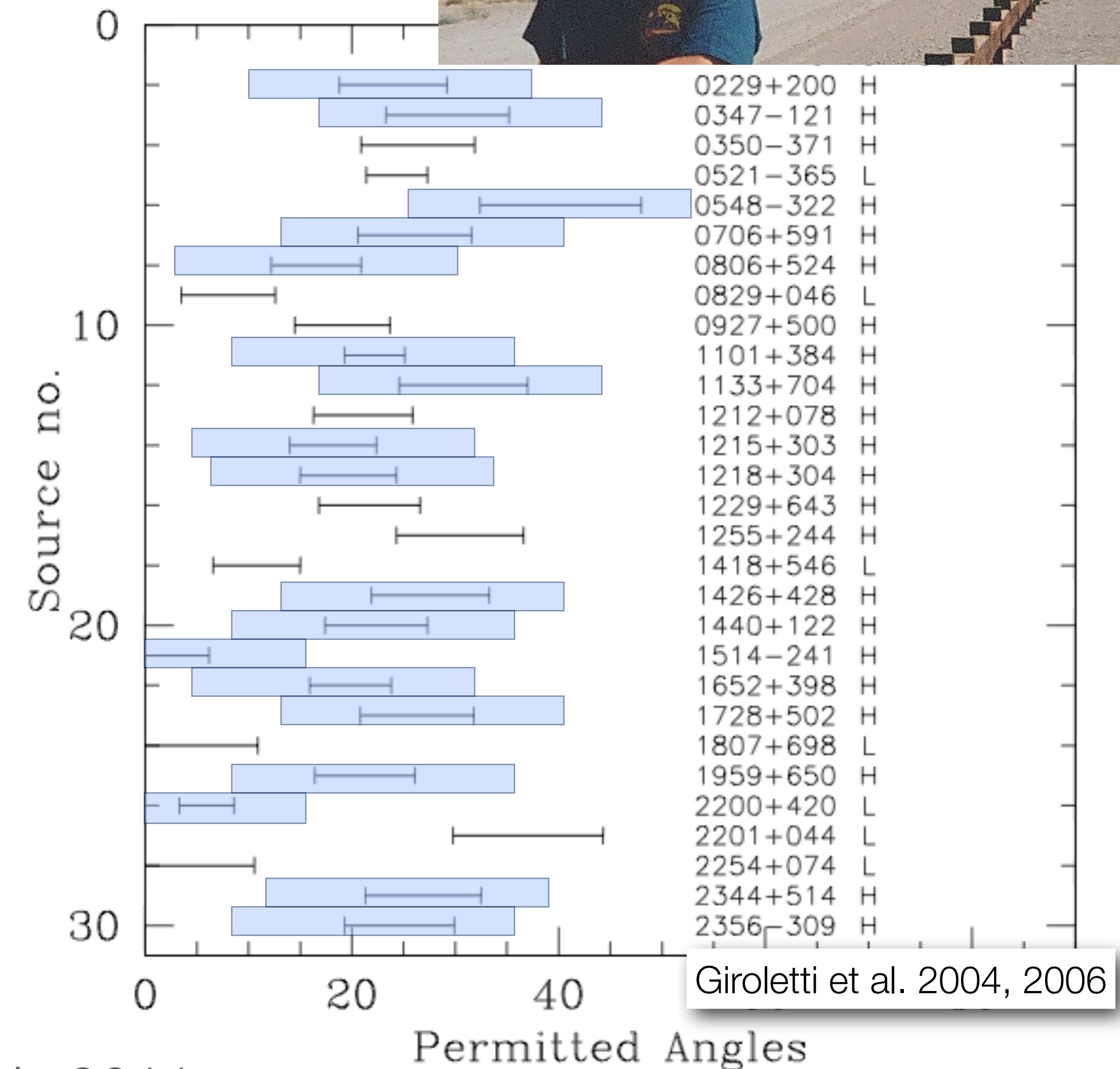




# 20 years ago... a PhD student struggling with radio interferometry



- Sample of 29  $z < 0.2$  BL Lacs observed with VLBI
- Typical tools to estimate jet parameters (jet sidedness, core dominance, proper motions)
- Viewing angle  $\sim 20^\circ$
- Core peak @5 GHz  $\sim 100$  mJy
- $\text{Log} P_{1.4} \sim 24.7$  W Hz $^{-1}$  (41 in erg/s)
- clearly not the most outstanding guys in the radio universe...
- ...yet, one by one, 18/29 sources have been detected at VHE

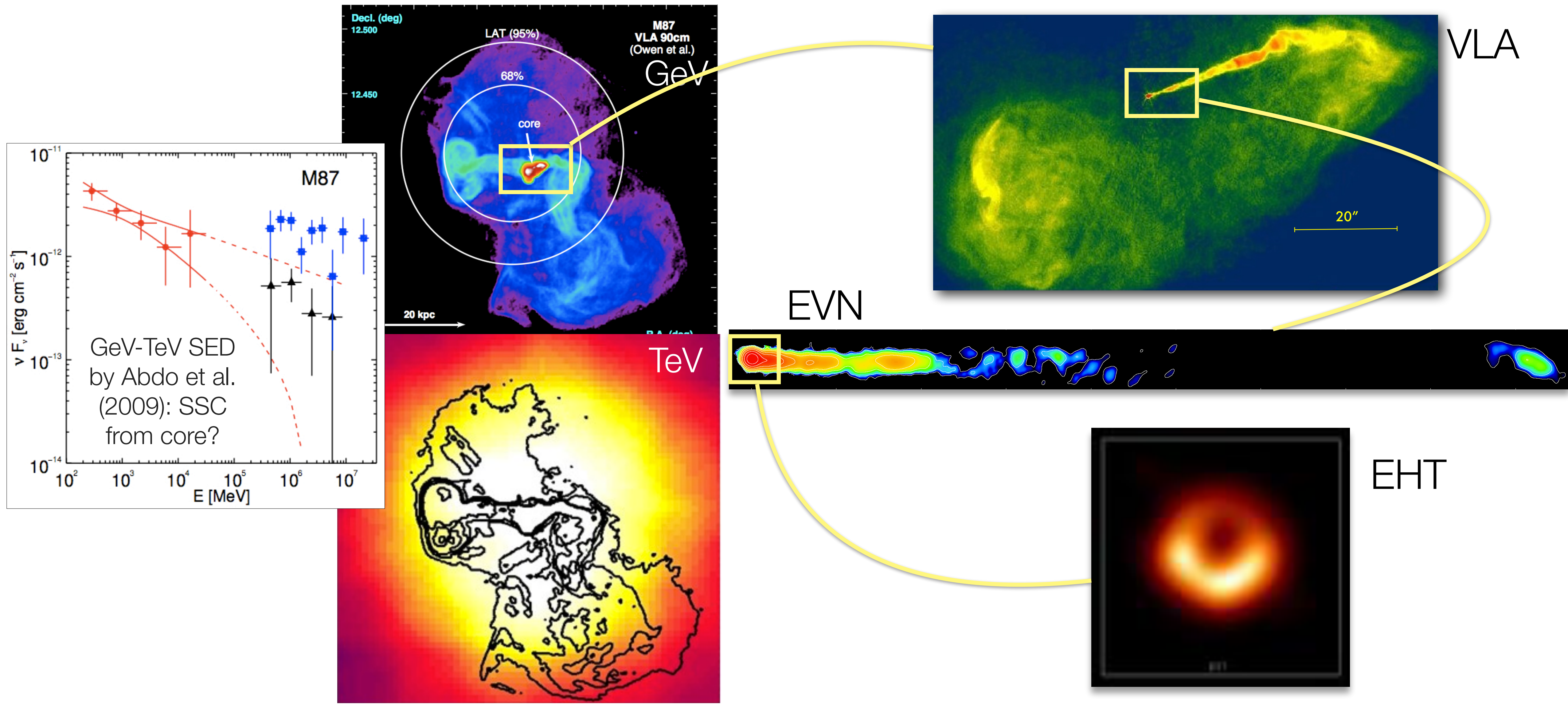


Giroletti et al. 2004, 2006

*HBLs: 17/22; last one in 2011*



# M87 radio-VHE connection: context

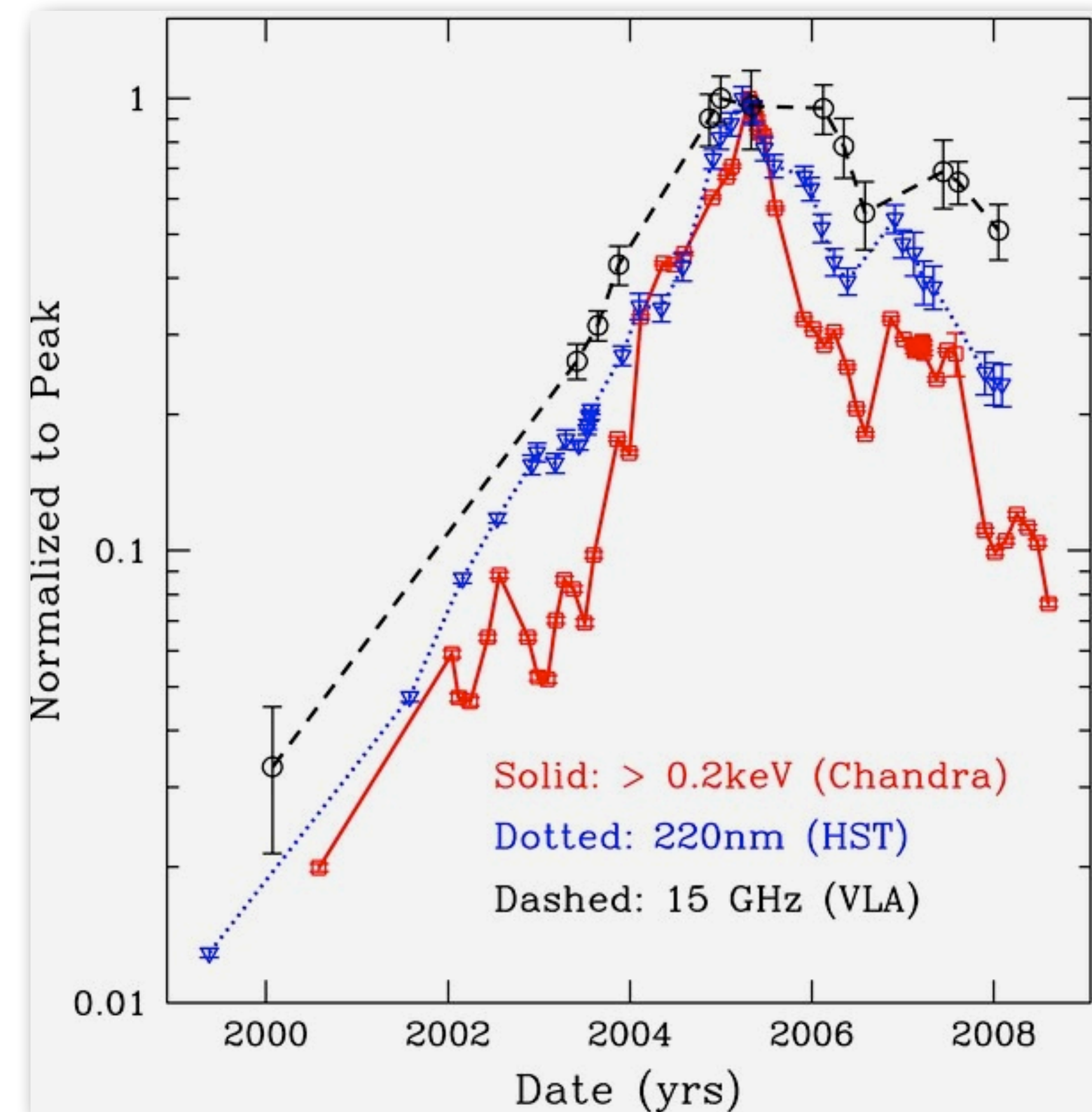




# M87 radio-VHE connection: history #1

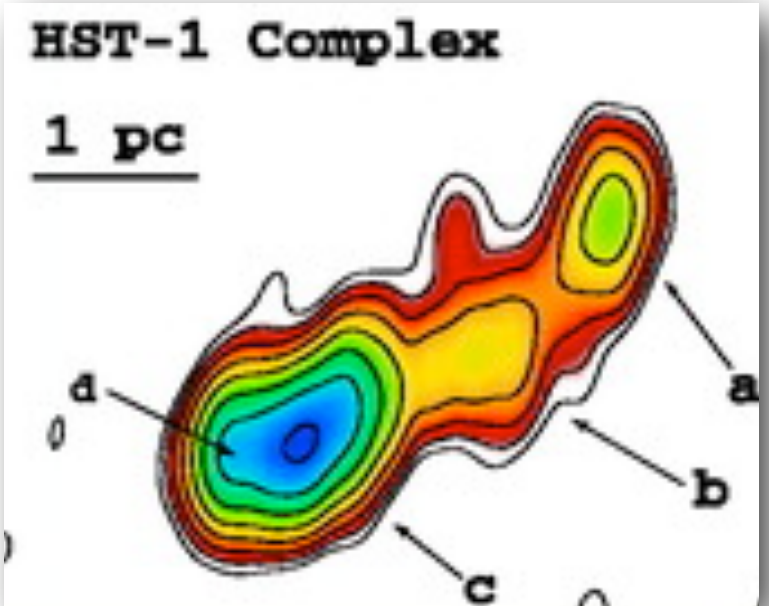
- VHE observations between 2003 and 2006 report fast variability ( $\sim$ days), suggesting very compact region (near supermassive black hole? Aharonian et al. 2006)
- TeV activity simultaneous with X-ray, optical, and radio flare in superluminal HST-1,  $\sim 70$  pc downstream the core! (Acciari et al. 2008, Harris et al. 2006)

HST-1 radio, optical, X-ray light curves (Harris et al. 2009)

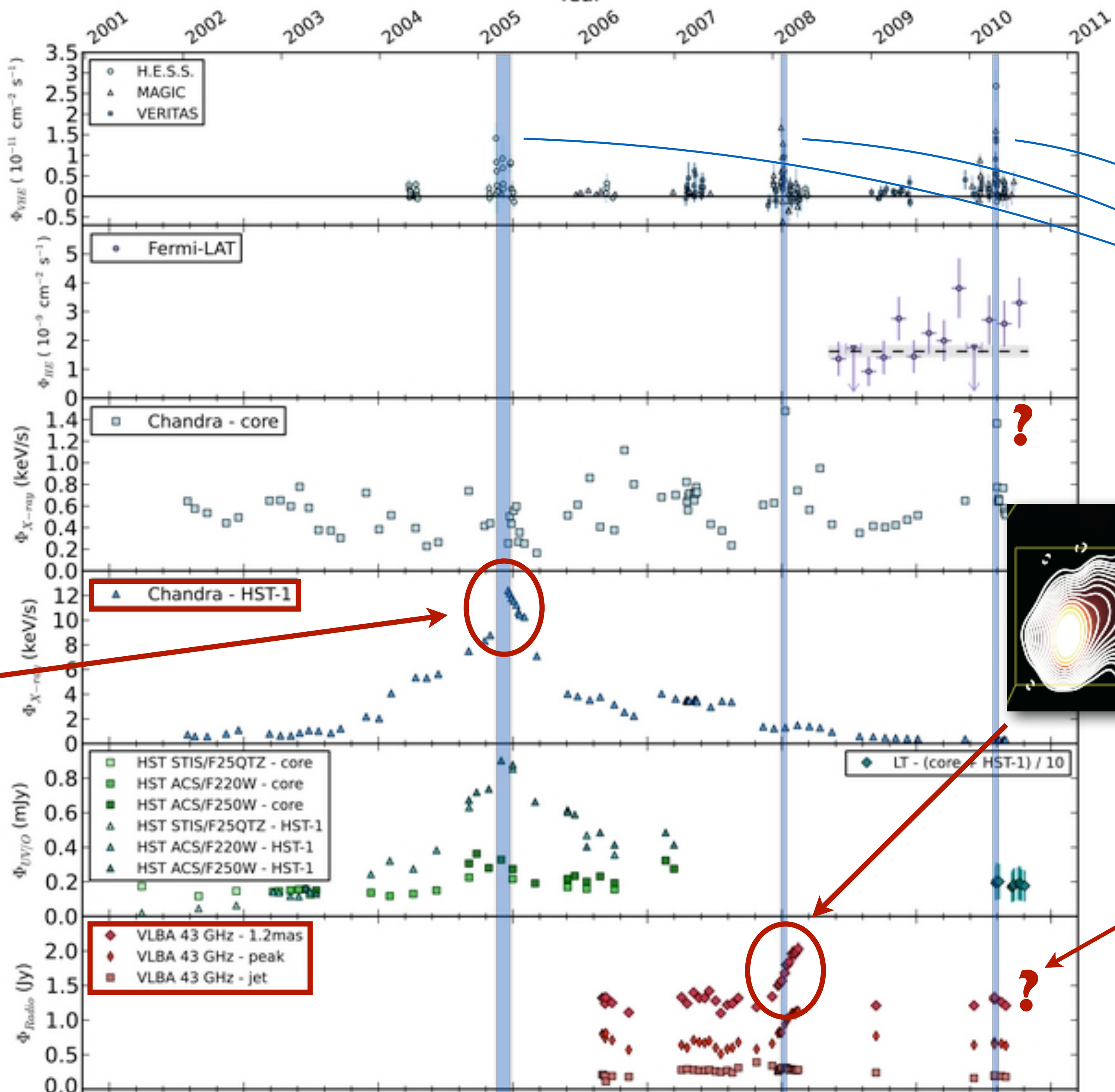




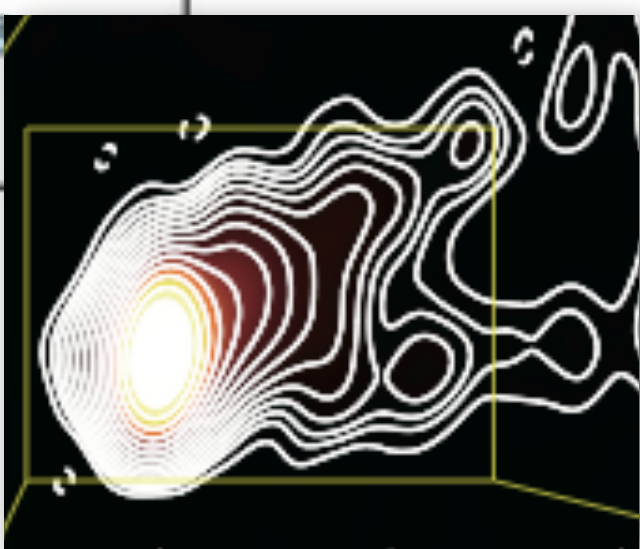
M87 radio-VHE connection:  
history #2



Abramowski et al. 2012



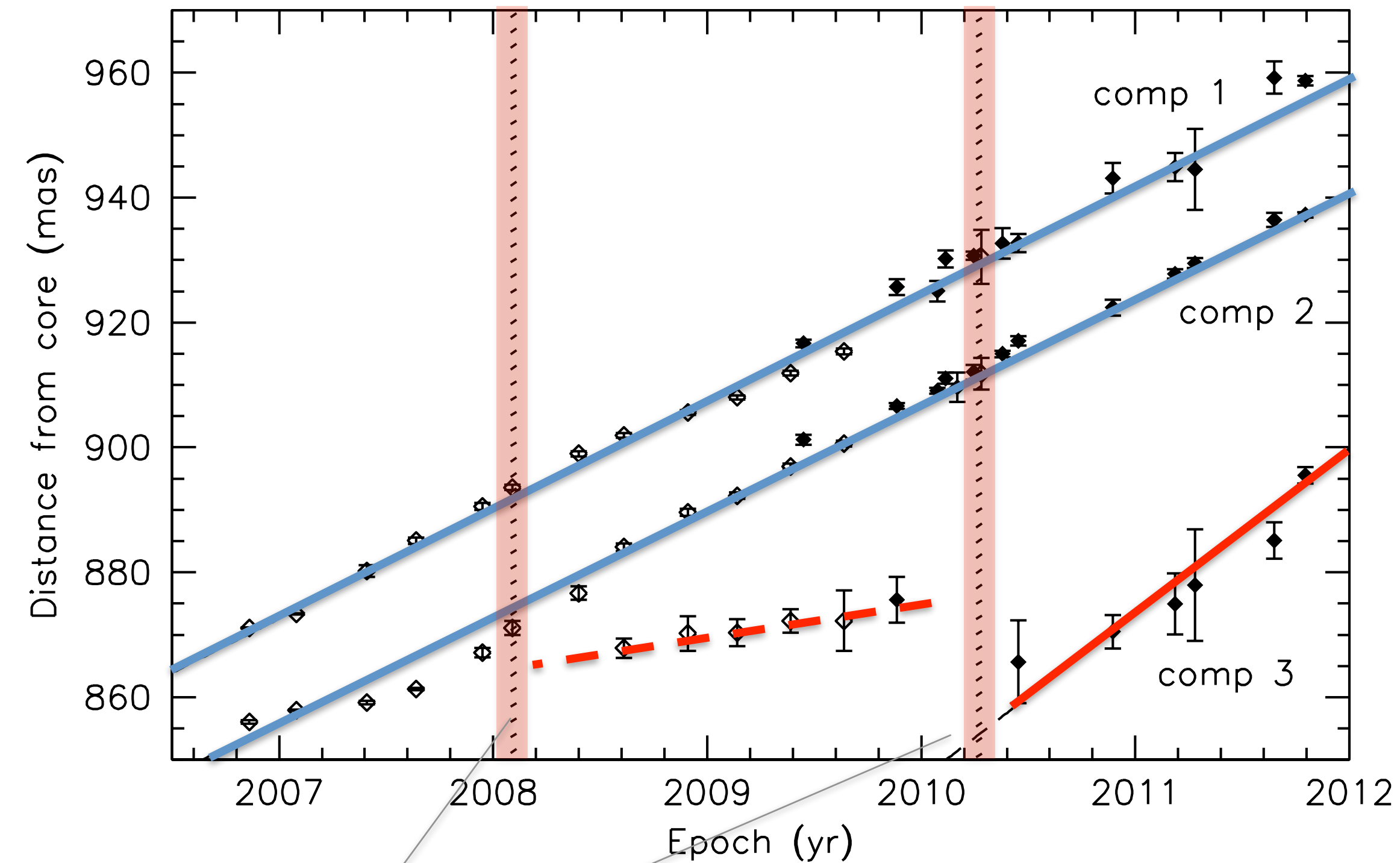
VHE flares



see Hada et al.  
(ApJL, 2012)

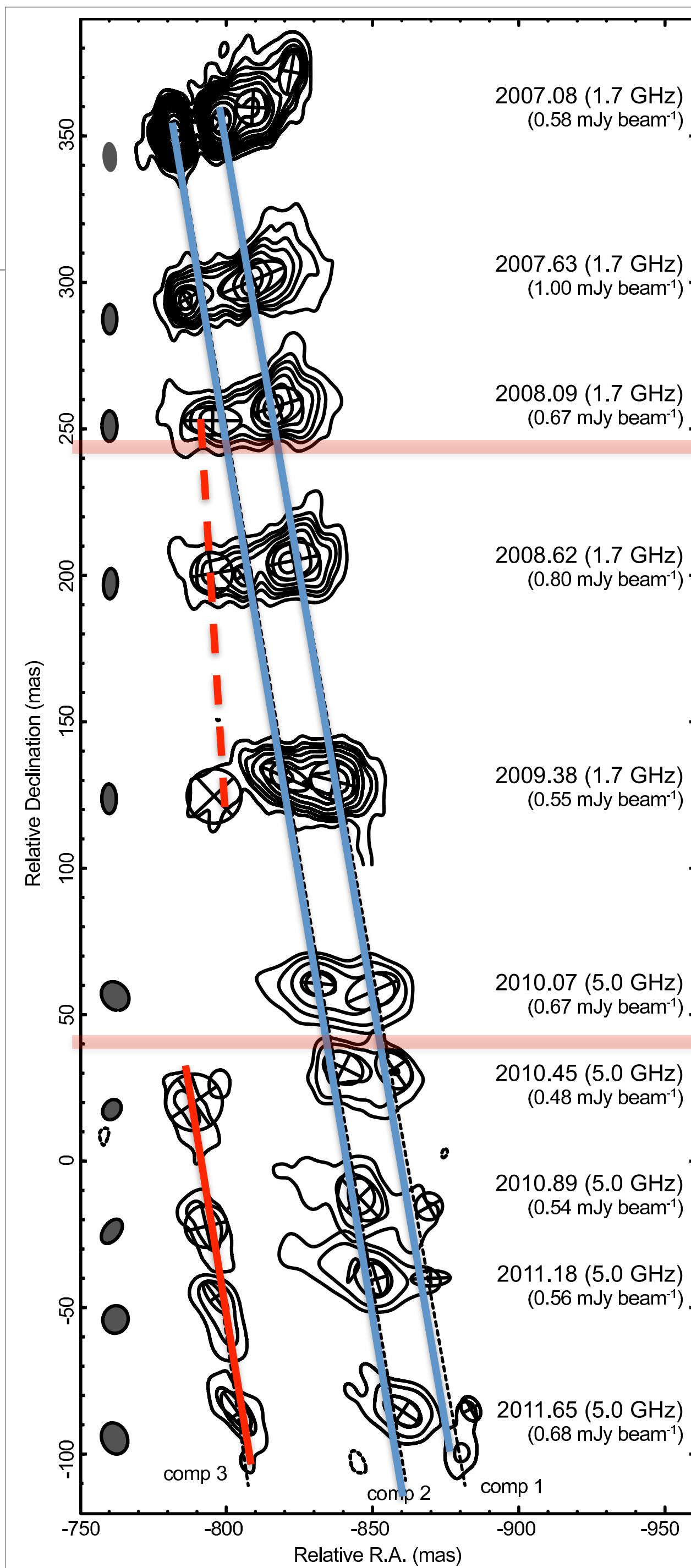


# M87: the EVN core & HST-1 monitoring



VHE  
flares

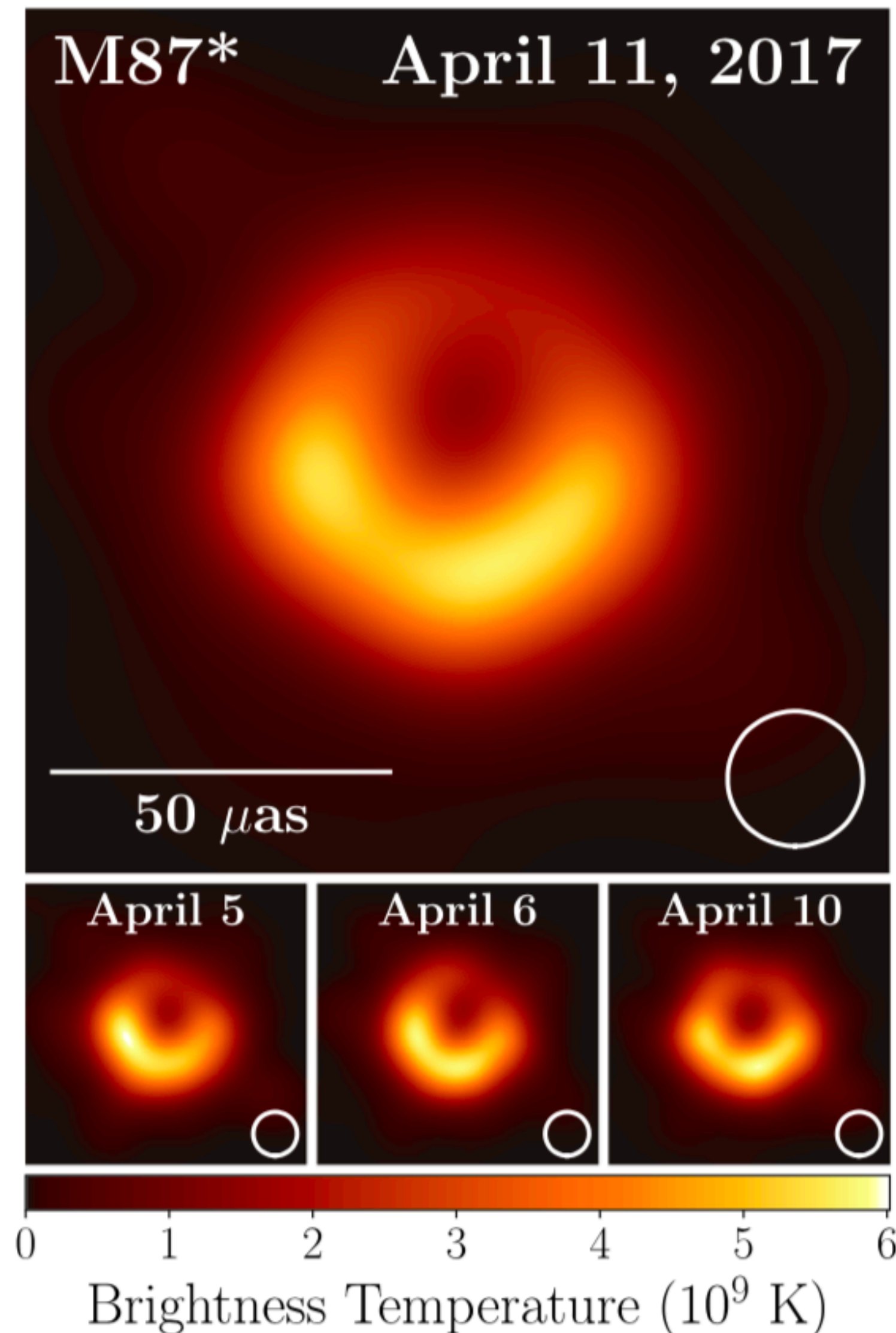
Giroletti et al. 2012



- Significant proper motions ( $>80$  mas) over 5 years
- Main features (in the downstream) are clearly moving with  $\sim 4c$ :  $\Gamma=4-6$ ,  $\delta=1.5-4$
- Upstream components emerging near VHE flares



# M87: the Event Horizon Telescope image



- Observations in 2017
  - $\nu=230$  GHz ( $\lambda=1.3$  mm); 6 sites, including ALMA
- Image consistent with magnetised accretion flow orbiting a Kerr black hole within a few  $R_g$
- Asymmetric ring produced by strong gravitational lensing+relativistic beaming
- Central flux depression is the BH shadow signature
- Excludes  $a^*=-0.94$  MAD models, other accretion modes allowed



# M87: the EHT-MWL campaign

THE ASTROPHYSICAL JOURNAL LETTERS, 911:L11 (43pp), 2021 April 10  
© 2021. The Author(s). Published by the American Astronomical Society.

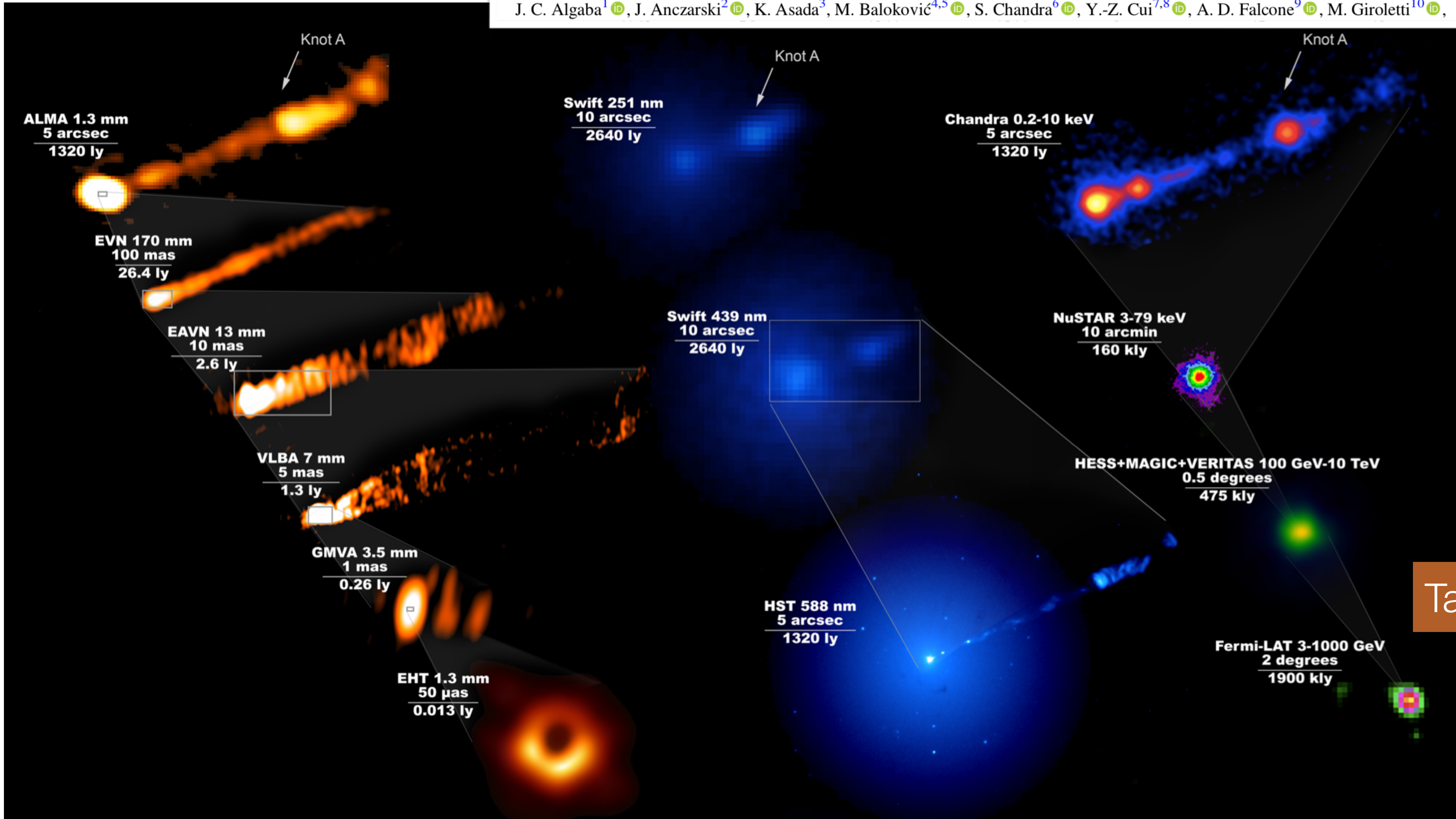
OPEN ACCESS

<https://doi.org/10.3847/2041-8213/abef71>



## Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign

J. C. Algaba<sup>1</sup> , J. Anczarski<sup>2</sup> , K. Asada<sup>3</sup>, M. Baloković<sup>4,5</sup> , S. Chandra<sup>6</sup> , Y.-Z. Cui<sup>7,8</sup> , A. D. Falcone<sup>9</sup> , M. Giroletti<sup>10</sup> ,

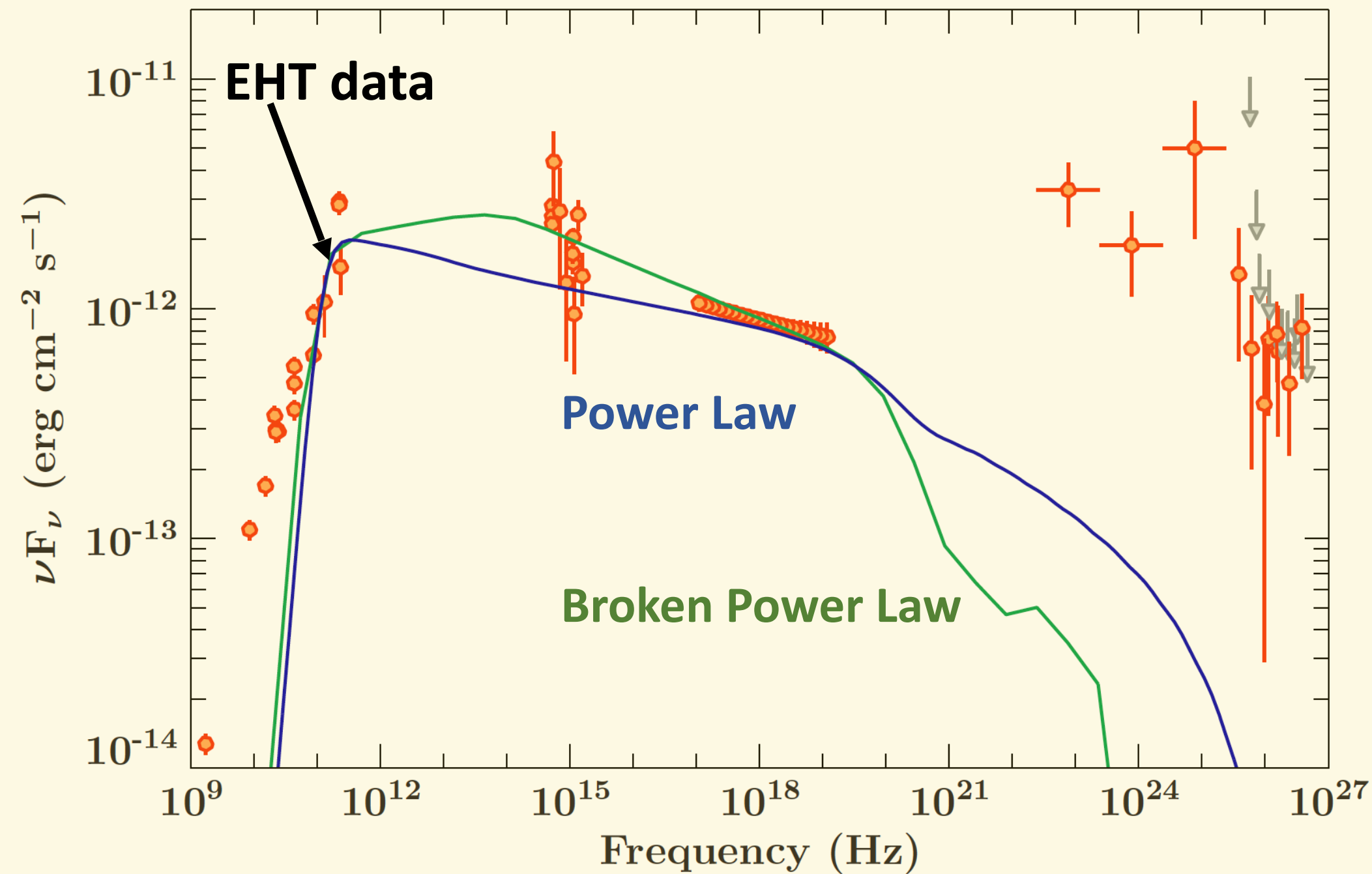


Talk Horan

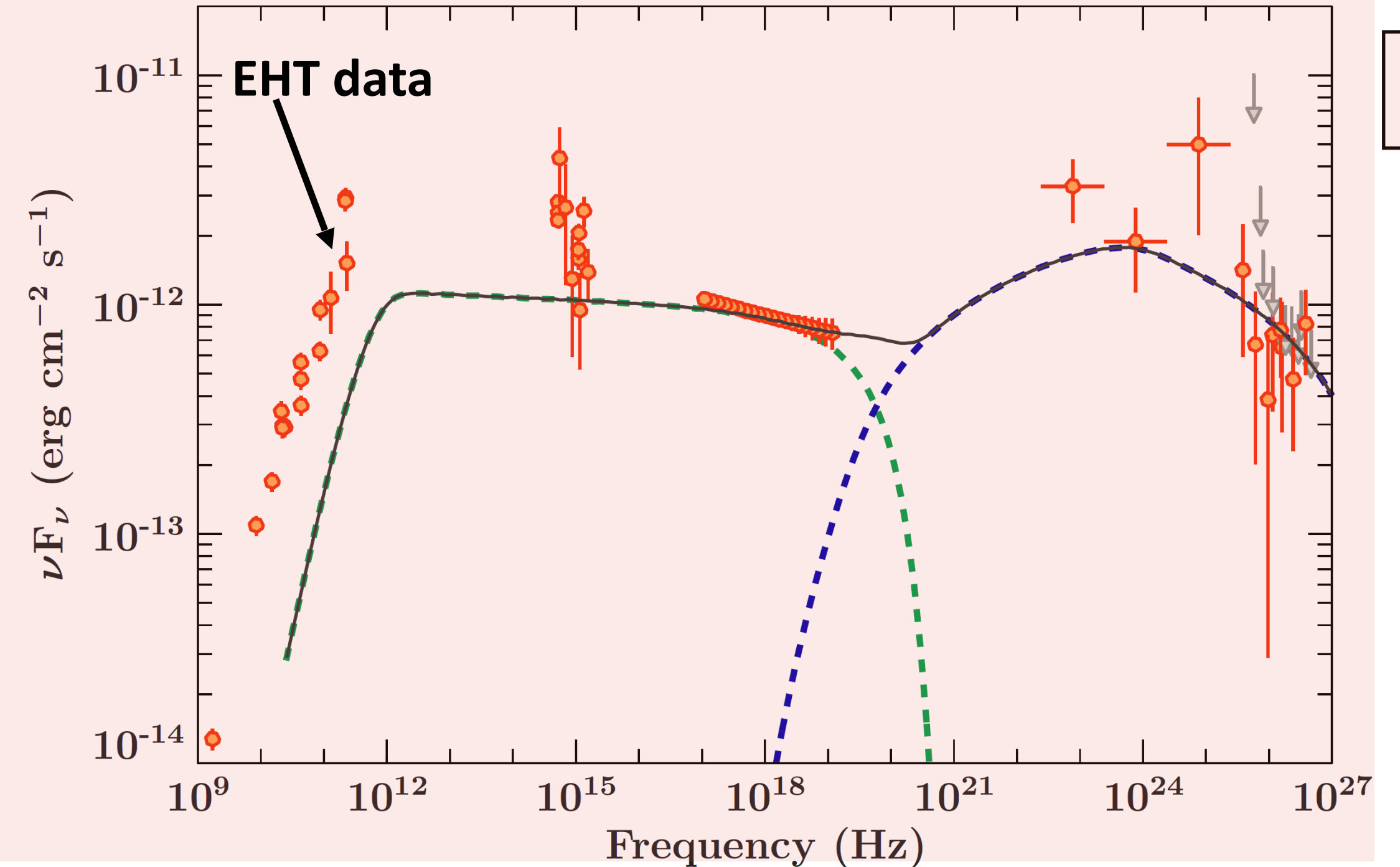


# M87 EHT-MWL: Leptonic SED models

1a/b



2



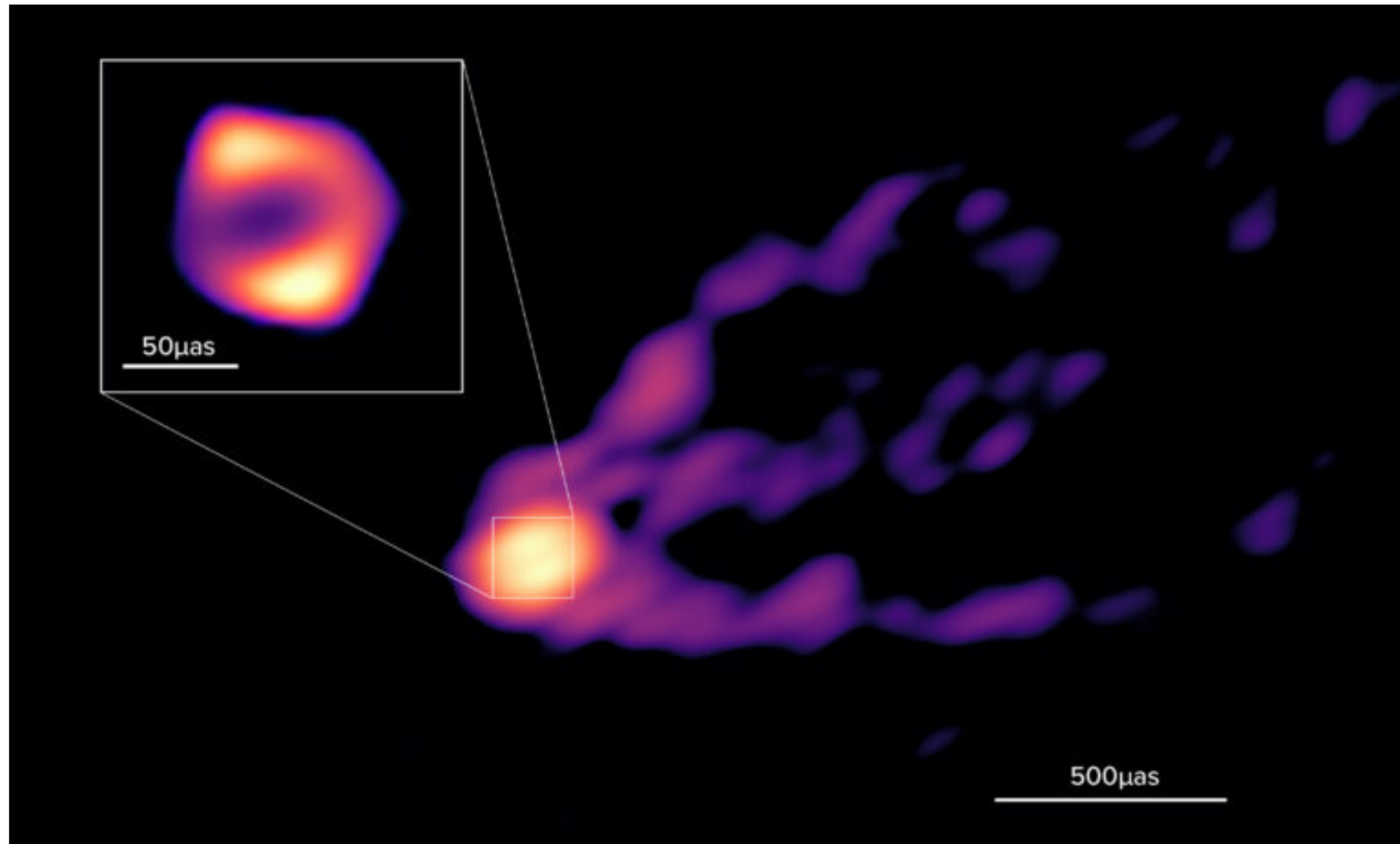
| Model    | $L_j [L_{\text{Edd}}]^a$           | $\delta$ | $R [r_g]^b$         | $n_e [\text{cm}^{-3}]^c$ | $B [\text{G}]$       | $\gamma_{\text{min}}$           | $\gamma_{\text{br}}$ | $\gamma_{\text{max}}$           | $p_1$ | $p_2$                  | $U_e/U_B$           |
|----------|------------------------------------|----------|---------------------|--------------------------|----------------------|---------------------------------|----------------------|---------------------------------|-------|------------------------|---------------------|
| model 1a | $6 \times 10^{-3}$                 | 1        | 5.6                 | $3.6 \times 10^5$        | 4.7                  | 1                               | —                    | $3.5 \times 10^6$               | 2.2   | —                      | 2.3                 |
| model 1b | $1 \times 10^{-3}$                 | 1        | 5.2                 | $1.8 \times 10^5$        | 10                   | 2                               | $1.5 \times 10^3$    | $2 \times 10^6$                 | 2.9   | 3.25                   | 0.16                |
| model 2  | $2.8^{+2.0}_{-1.4} \times 10^{-5}$ | 3.3      | $626^{+256}_{-301}$ | $9.5 \times 10^{-3}$     | $1.5 \times 10^{-3}$ | $4.1^{+2.1}_{-1.5} \times 10^3$ | —                    | $6.4^{+2.6}_{-3.6} \times 10^7$ | —     | $3.03^{+0.03}_{-0.05}$ | $635^{+465}_{-288}$ |

Need for structured jet - additional component other than the EHT-core to explain  $\gamma$  rays

Moderate magnetic domination at jet base, outer particle dominated region responsible for  $\gamma$  rays



# M87: the latest results



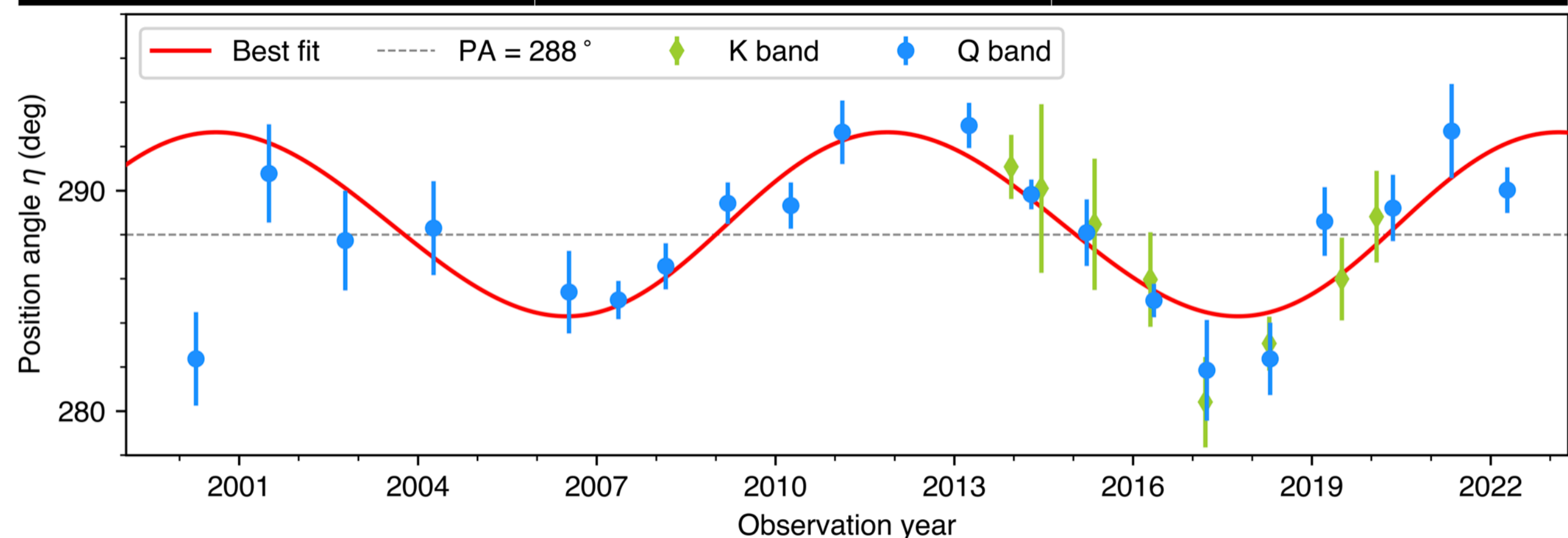
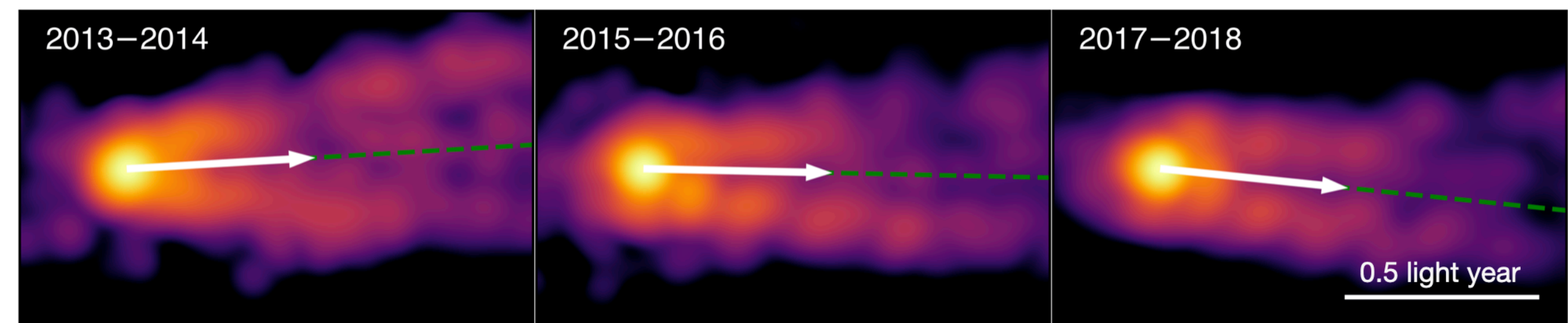
Lu et al. (Nature 2023)  
3.5mm VLBI+ALMA observations  
BH shadow and jet launching region  
imaged simultaneously!

Cui et al. (Nature 2023)

164 VLBI epochs over 22 years

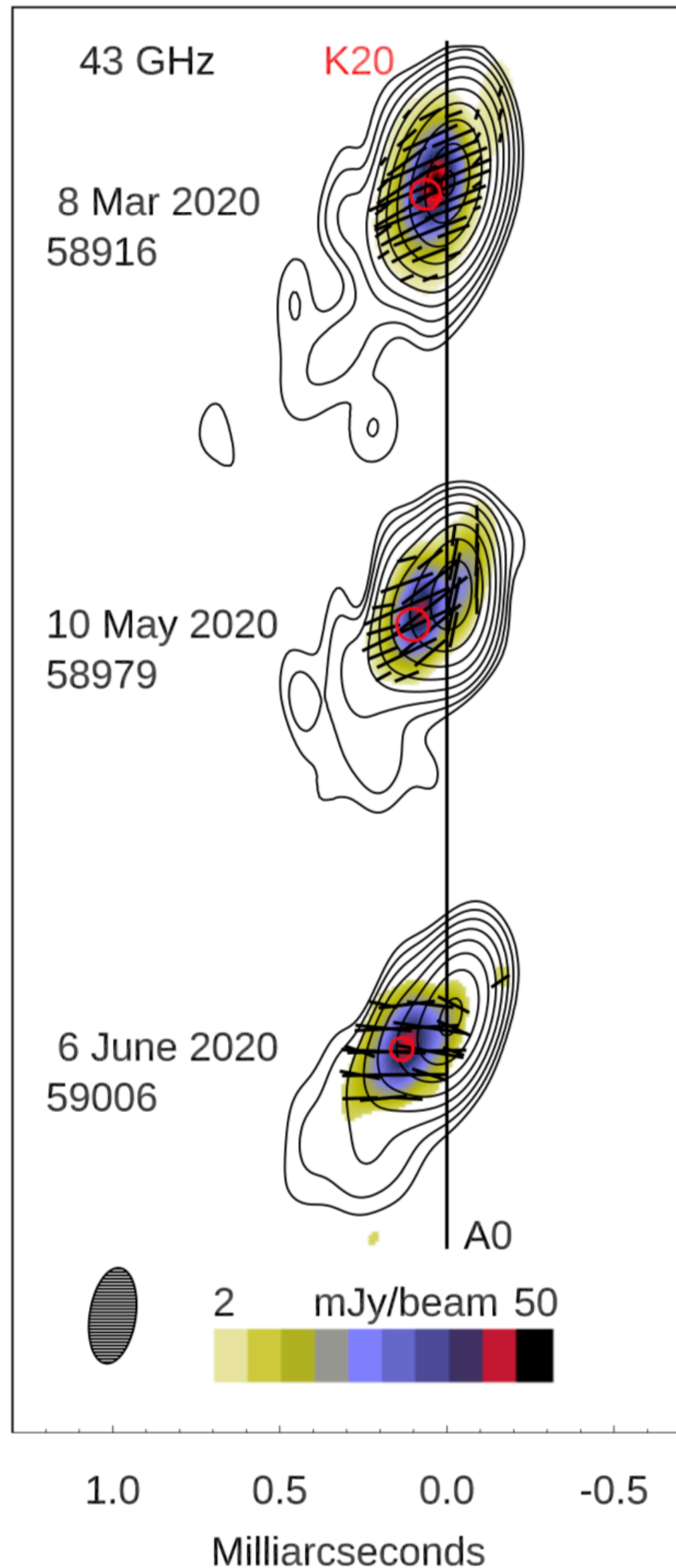
11 year periodicity in jet p.a. orientation

Precession due to misalignment between  
accretion disk and rotating BH





# Radio-VHE connection: other examples



## FSRQ B1420+326

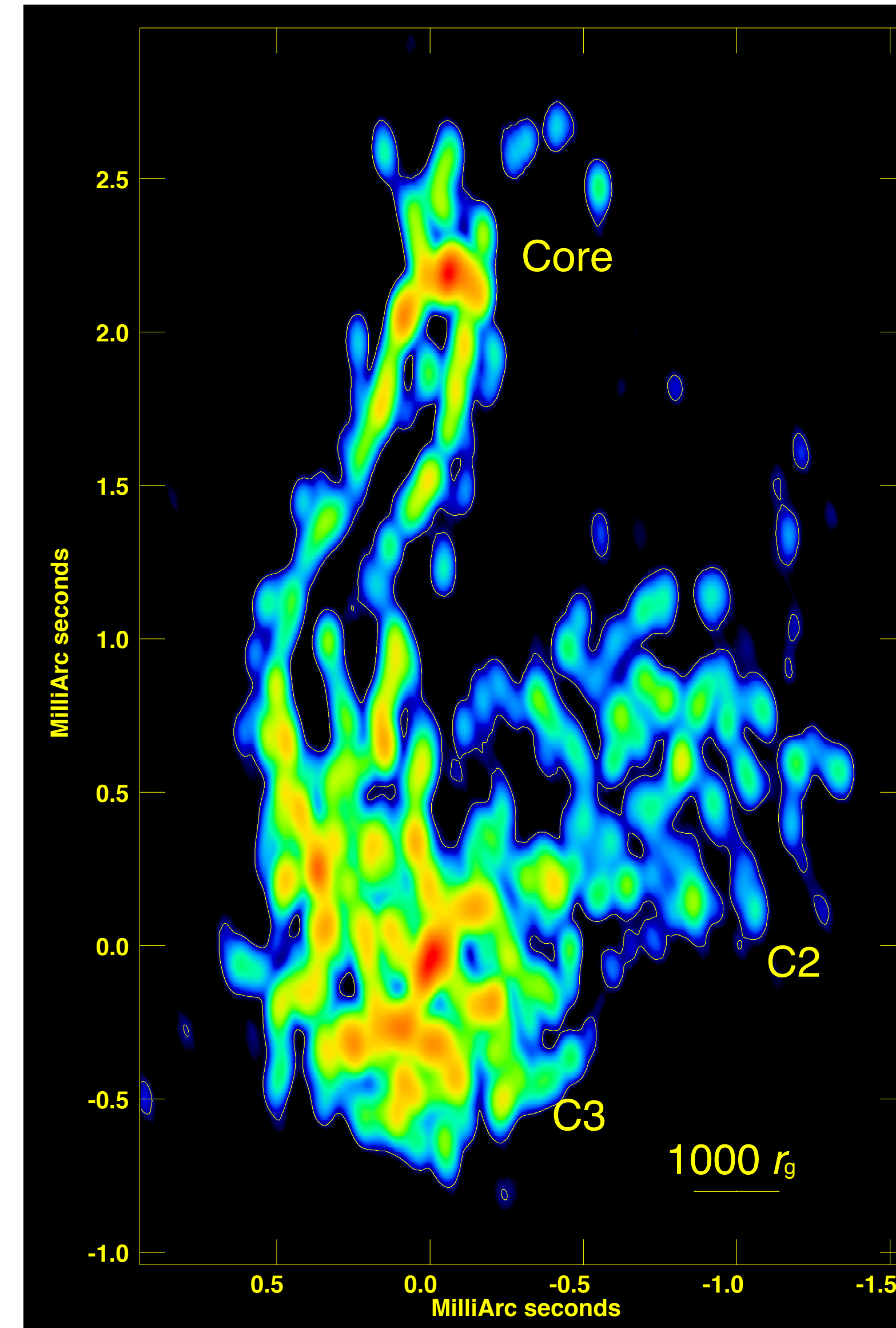
Ejection of new VLBI component associated with VHE emission and EVPA rotation (Acciari et al. 2021)

Talks Sahakyan, Arbet-Engels, Prandini, Lindfors

determination of physical & geometrical parameters  
systematic differences between FSRQs and HSPs  
discovery and interpretation of transverse structures  
intensive single dish/MWL monitoring campaigns

## 3C84

Space-VLBI observations: limb brightened structure (appearing after radio/g enhancement) with very wide opening angle at jet base (Giovannini et al. 2018, NatAst)





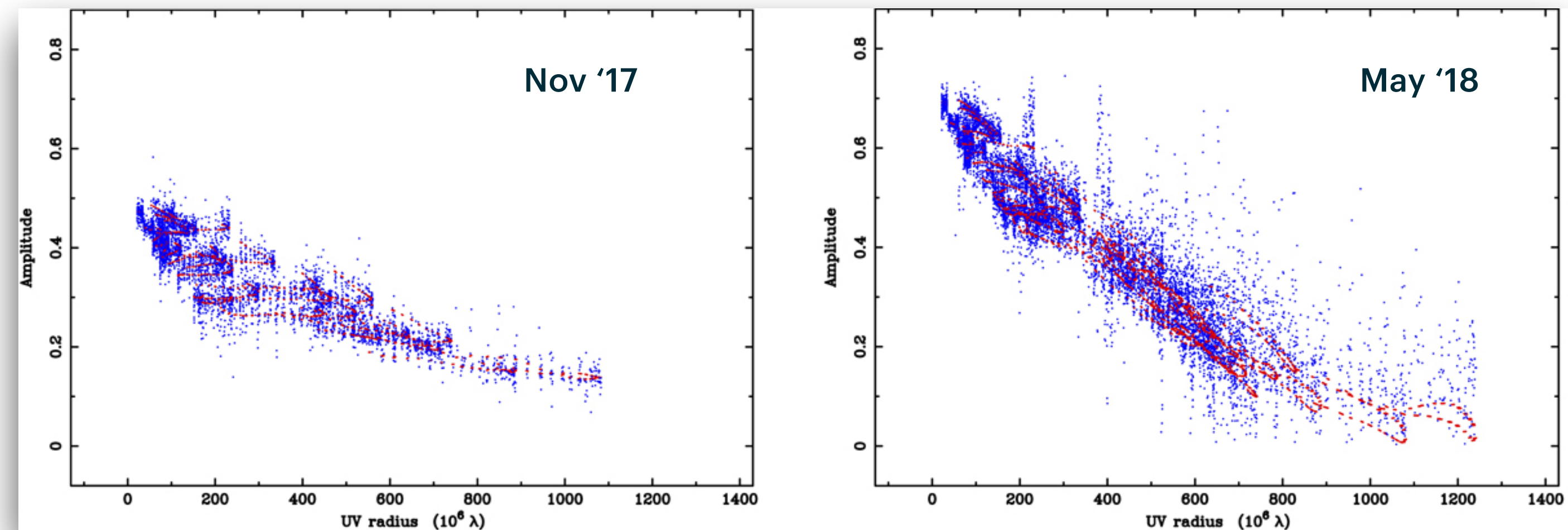
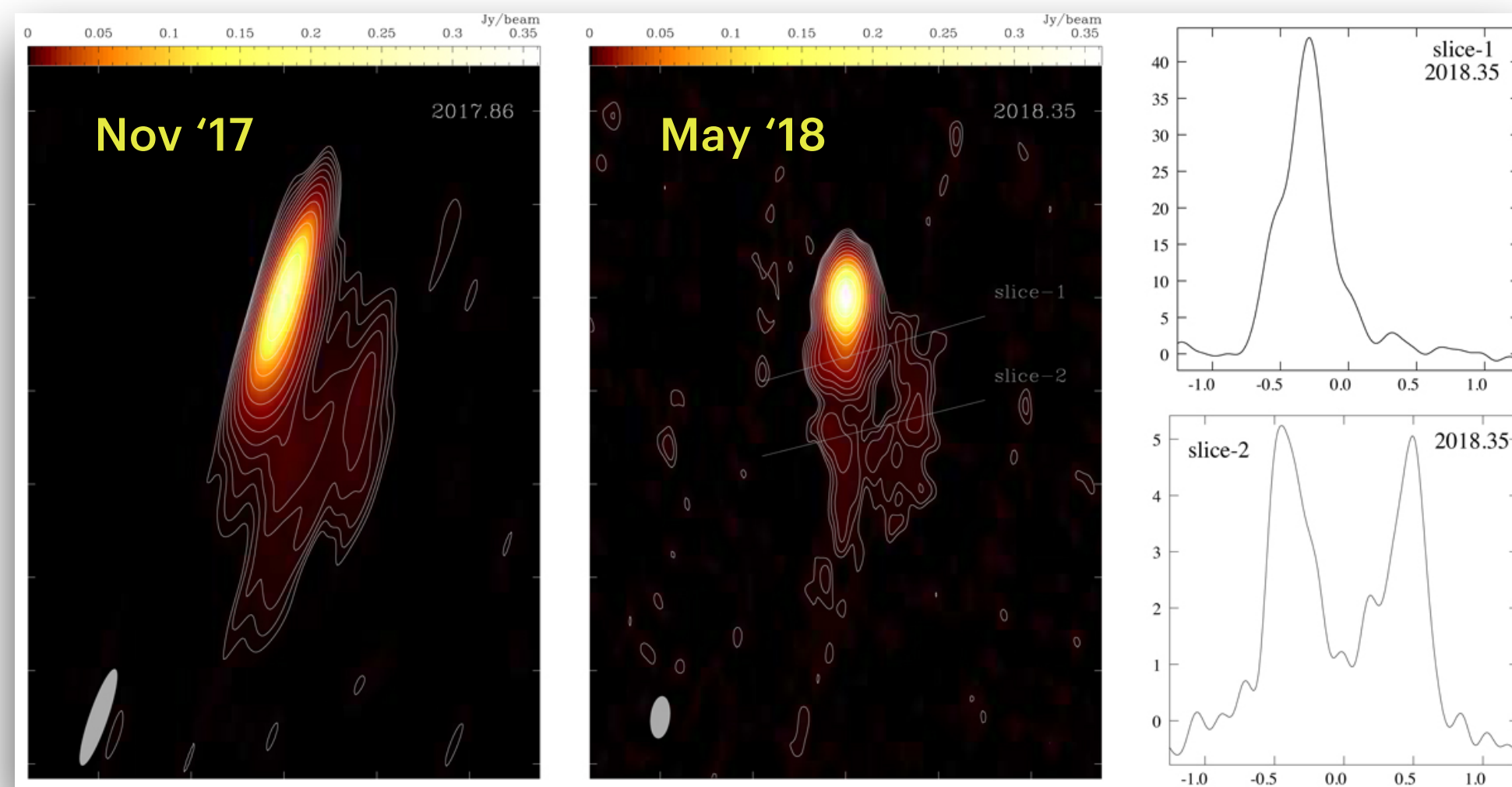
# TXS 0506+056, 43 GHz

Talks Halzen, Santander, Asano



- Radio emission from TXS 0506+056 was also flaring; investigation of the pc scale structure with two-epoch 43 GHz VLBA observations (Ros et al. 2020)

[ $z=0.3365$ , 1 mas=4.8 pc]



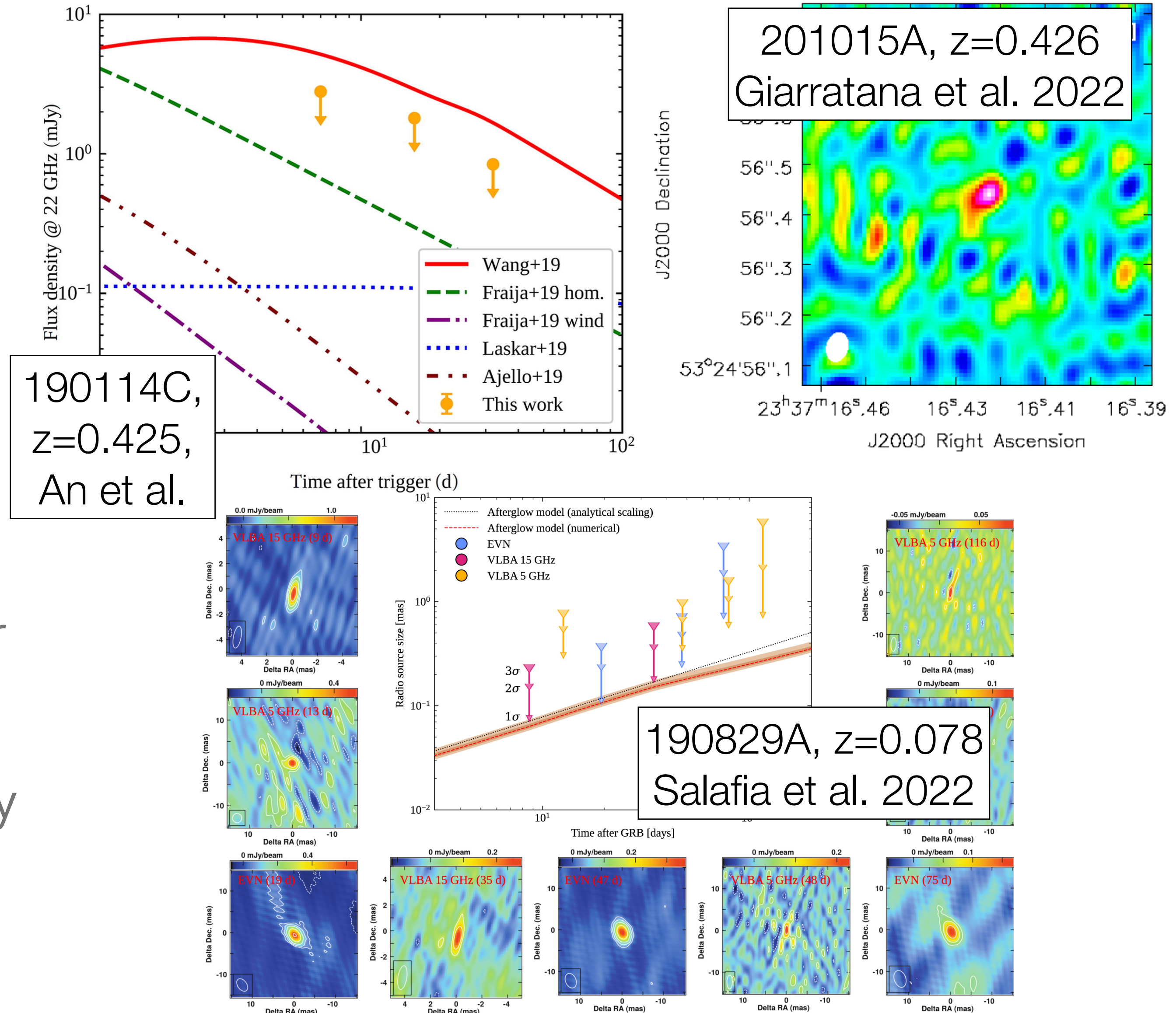
limb brightened jet - possible signature of velocity structure, suggested to be one region of efficient  $\nu$  production (e.g. Tavecchio et al., 2014)

45  $\mu$ as increase in core size during 6 months; corresponding to  $\sim 2c$  expansion speed



# VHE-VLBI: Gamma Ray Bursts

- Radio emission from afterglows can stay bright for months
- VLBI is the only way to have direct evidence of relativistic ejection implied by modelling:
  - on axis ("classical") events: blob expansion
  - misaligned ("atypical") events: proper motion
- A handful of VHE-detected GRBs (mostly by MAGIC), typically at low- $z$ : ideal for VLBI follow-up





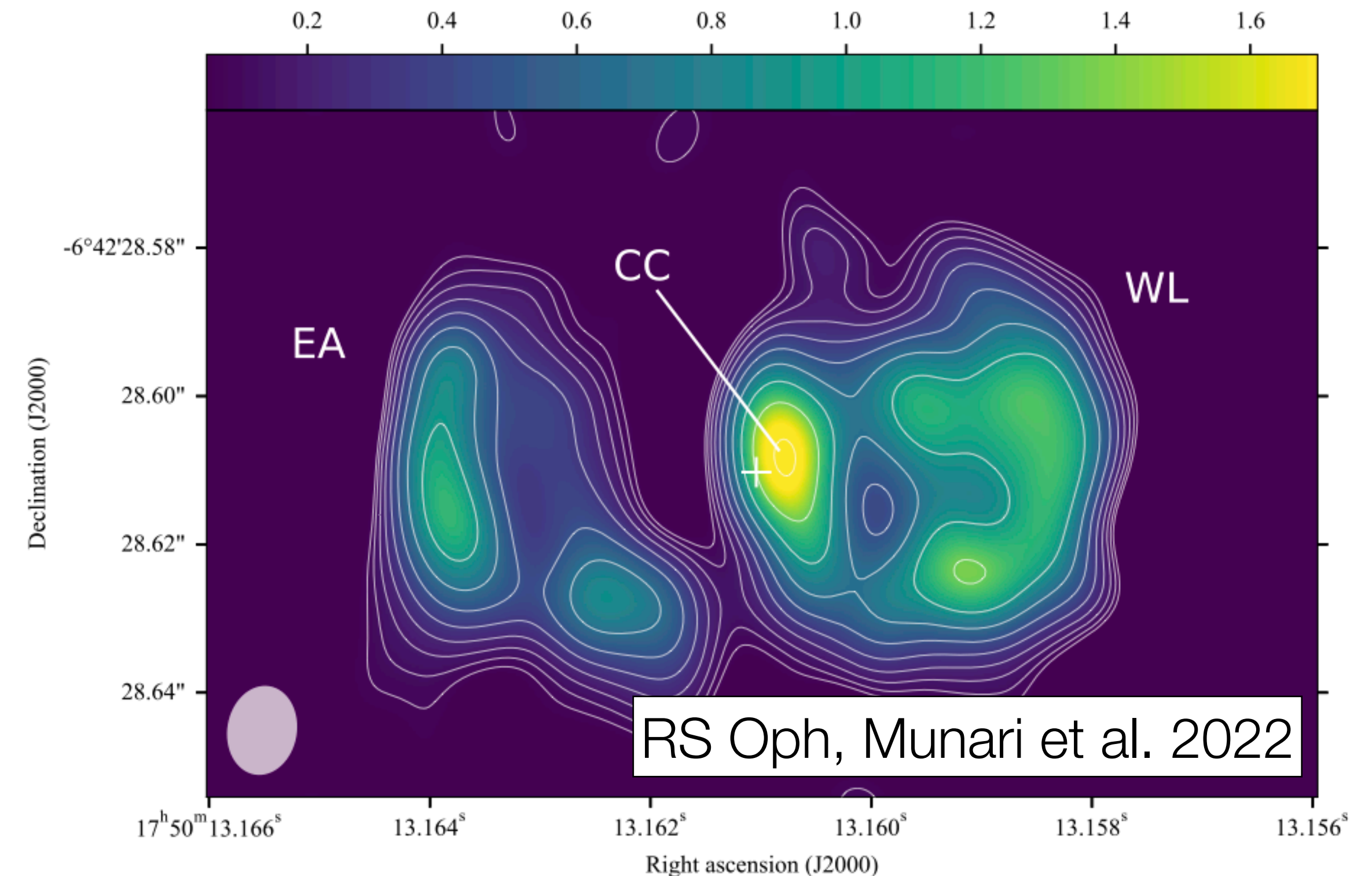
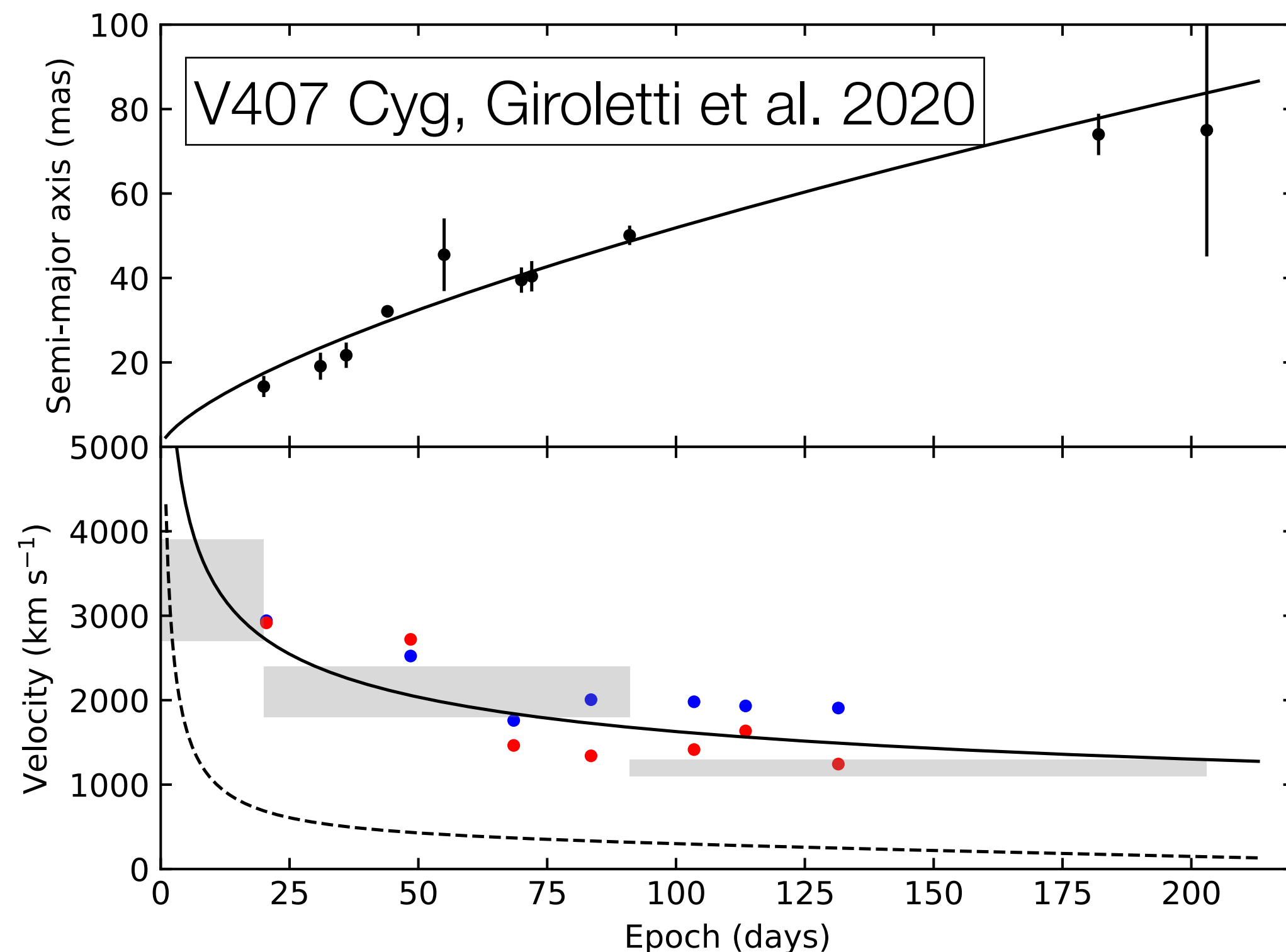
# VHE-VLBI: Galactic - (symbiotic) novae

Talk López Oramas



High angular resolution, multi-frequency, multi-epoch radio interferometric observations:

- separate thermal and non-thermal emission regions
- pinpoint location of shock-acceleration
- distinguish free expansion from deceleration induced by the sweep-up of the RG wind





# VHE-VLBI: transients towards CTA

Sardinia, 64m, Medicina, 32m, Noto, 32m  
Bologna, software correlator (DiFX)

collecting area

INAF: 4825 m<sup>2</sup>; VLBA: 4909 m<sup>2</sup>

*CTA+ project funded by Italian MUR*

- 2023-25
- build additional CTA telescopes
- strengthen INAF multi-wavelength facilities
  - **flexible VLBI network to facilitate transient follow-up**



Finanziato  
dall'Unione europea  
NextGenerationEU



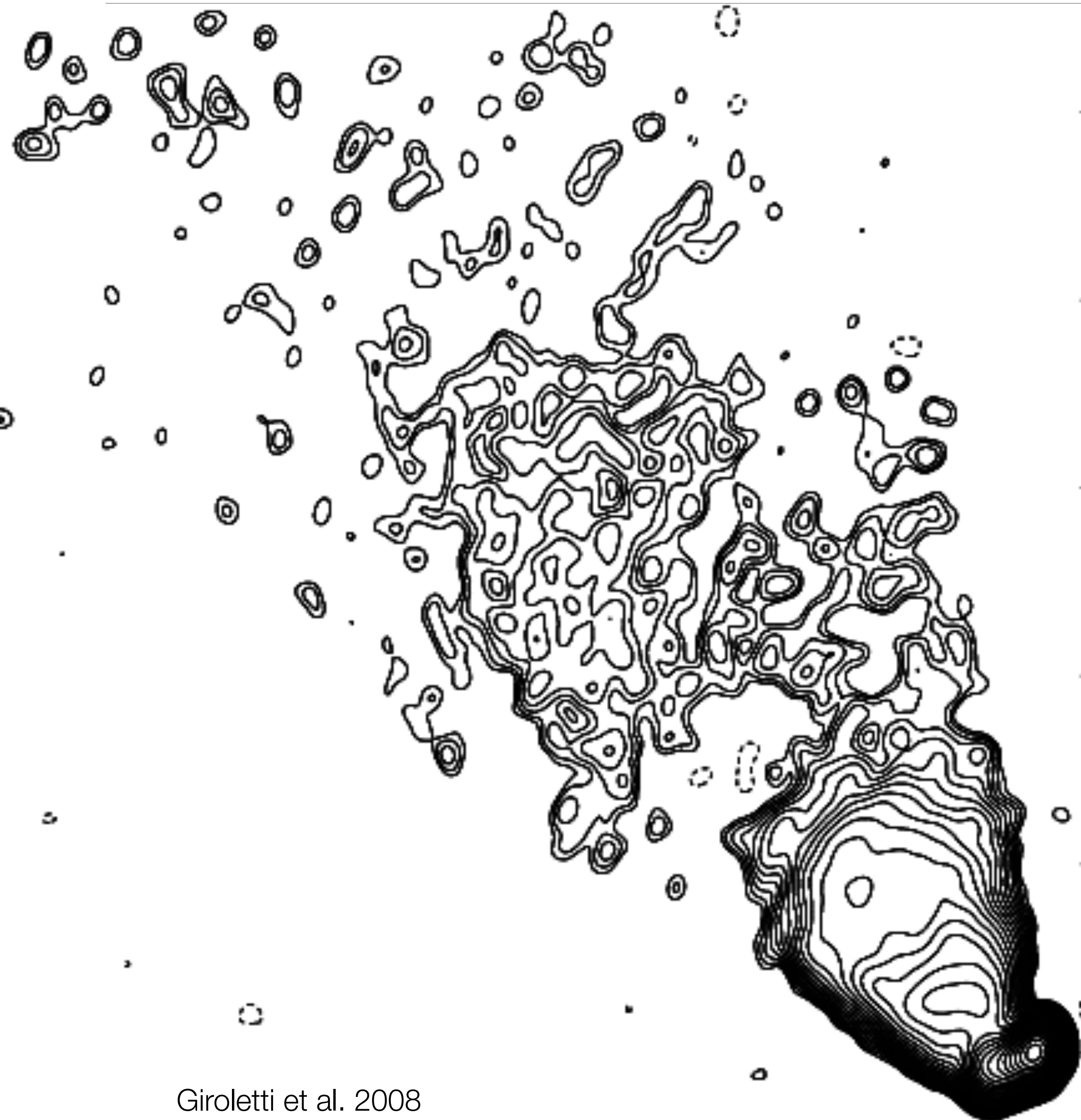
Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



# Take home messages



- Significant synergy/complementarity between VLBI and VHE (small physical scales, extreme non-thermal emission)
- In depth studies of single objects (eg M87) and systematic characterisation of samples/populations
- Now extending from AGNs to transient sources, galactic and extragalactic
- ...and I couldn't finish without an image of Mrk501!



# Outline

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- historic background
- technical background
- M87... (VHE flares and the core vs HST-1 debate; EHT black hole image; EHT MWL campaign; the latest results)
  - ...but there's more!
    - radio galaxies and blazars
    - GRBs
    - galactic sources (novae, binaries)



# Context

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- it's easy to study large samples - radio surveys are there and are growing (from NVSS to VLASS, GLEAM, RACS, ...)
- multi-wavelength, polarization, high cadence monitoring are well feasible for reasonably high number of sources (MOJAVE, BU)



# VHE-VLBI: Galactic - X-ray binaries

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# Radio interferometry

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$$\theta = \frac{\lambda}{D}$$

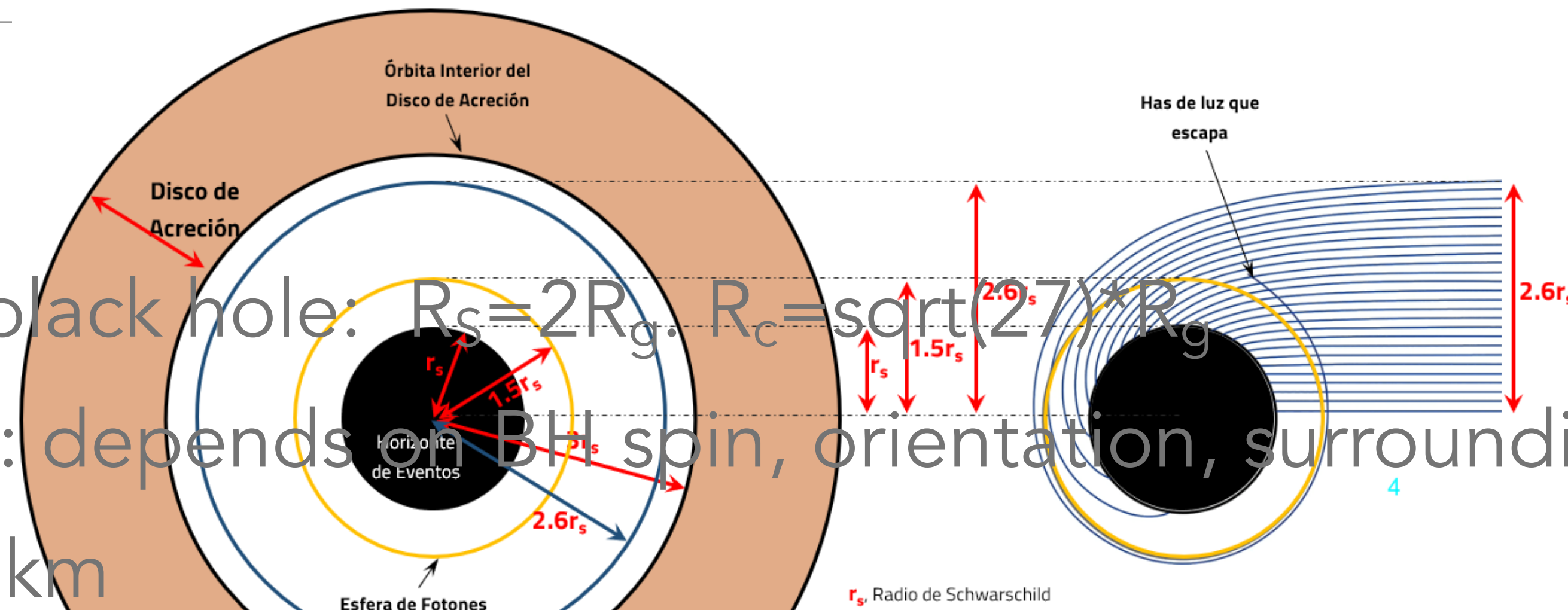
$$\sigma_S = \frac{2kT_{\text{sys}}}{A_{\text{eff}}[N(N-1)\Delta\nu_{\text{RF}}\tau]^{1/2}}$$

$$\sigma_S = \frac{2kT_{\text{sys}}}{A_{\text{eff}}(\Delta\nu_{\text{RF}}\tau)^{1/2}}$$



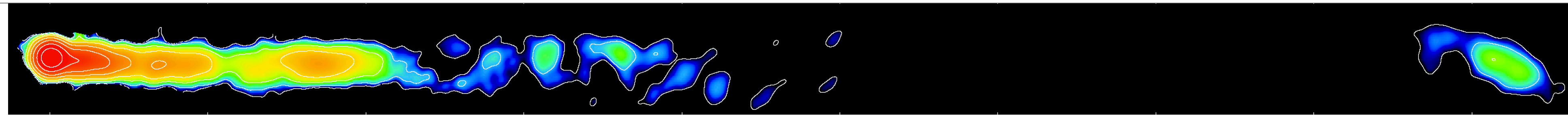
# The relevant scales

- $R_g = GM/c^2$
- Schwarzschild black hole:  $R_s = 2R_g$ .  $R_c = \sqrt{27} R_g$
- Kerr black hole: depends on BH spin, orientation, surrounding region
- $M = 1 M_{\text{sun}}$ ,  $R_s = 3 \text{ km}$
- $M = 4 \times 10^6 M_{\text{sun}}$ ,  $R_s = 1.2 \times 10^7 \text{ pc} = 4 \times 10^{-7} \text{ pc} = 12 \mu\text{as}$  (assuming  $d = 7 \text{ kpc}$ )
- $M = 6 \times 10^9 M_{\text{sun}}$ ,  $R_s = 6 \times 10^{-4} \text{ pc} = 7.3 \mu\text{as}$  (assuming  $d = 16.8 \text{ Mpc}$ )

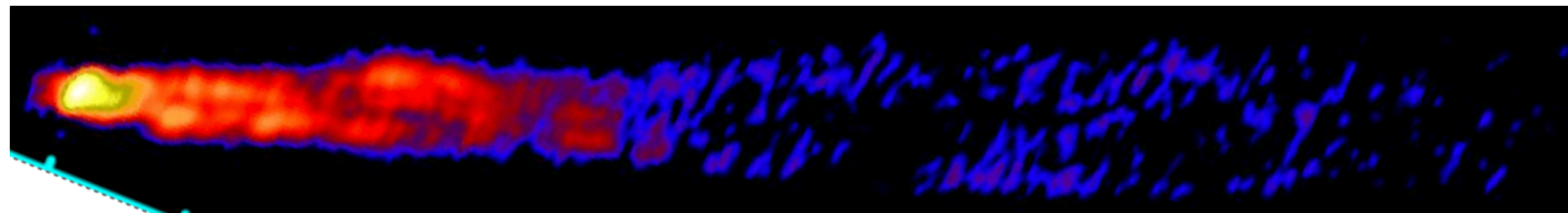




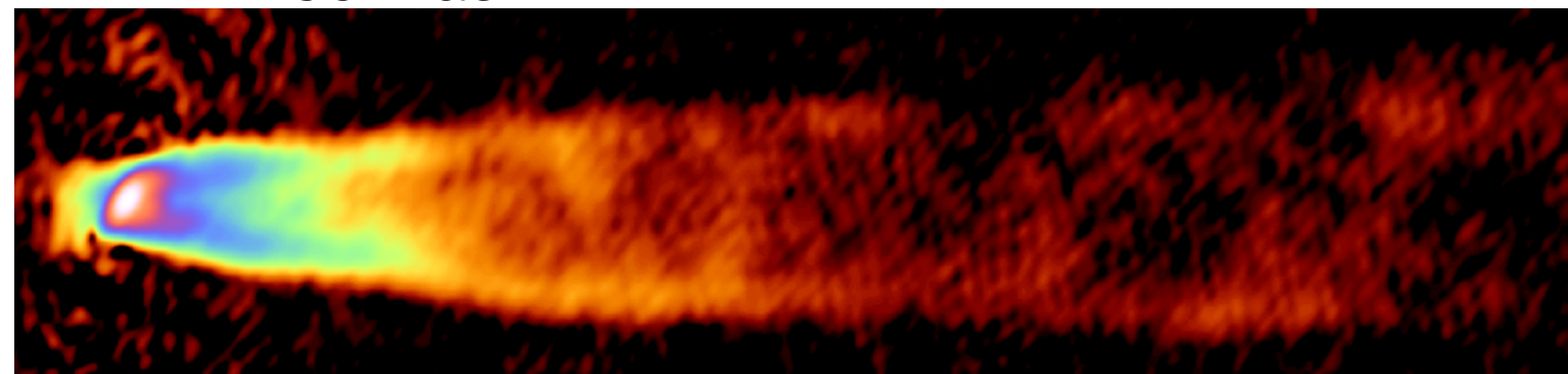
# M87 - jet base



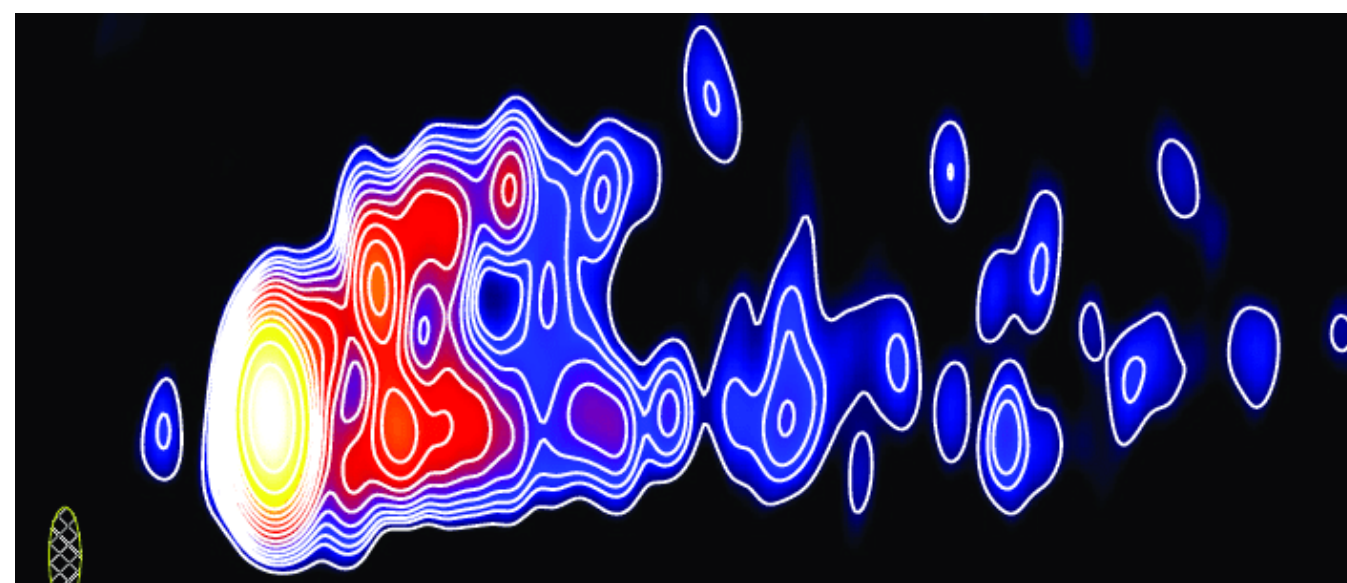
EVN 1.6 GHz,  
Giroletti



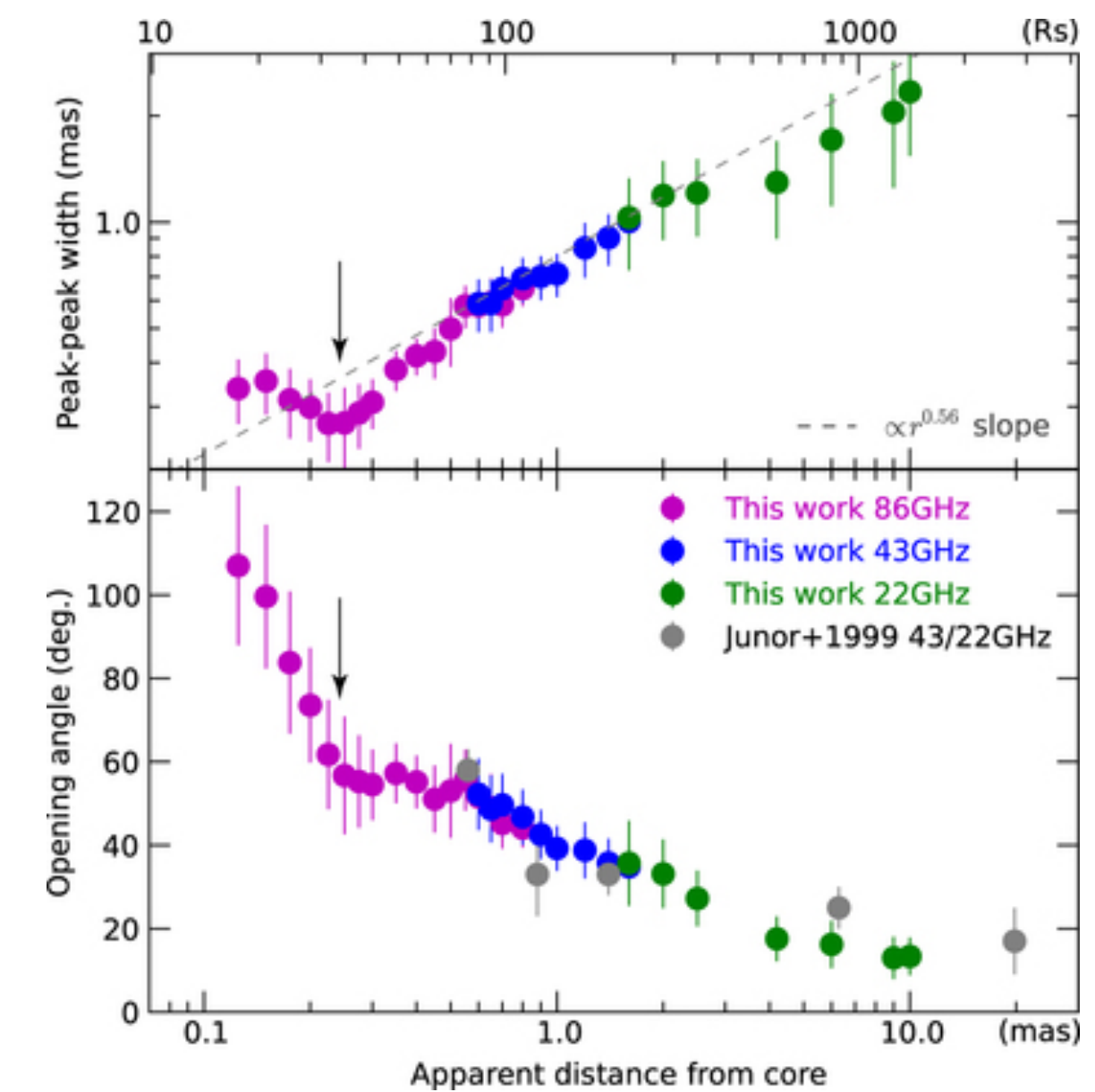
VLBA 15 GHz,  
Kovalev



VLBA 43 GHz,  
Walker



VLBA+HSA 86 GHz,  
Hada





# Interpretation - part 2

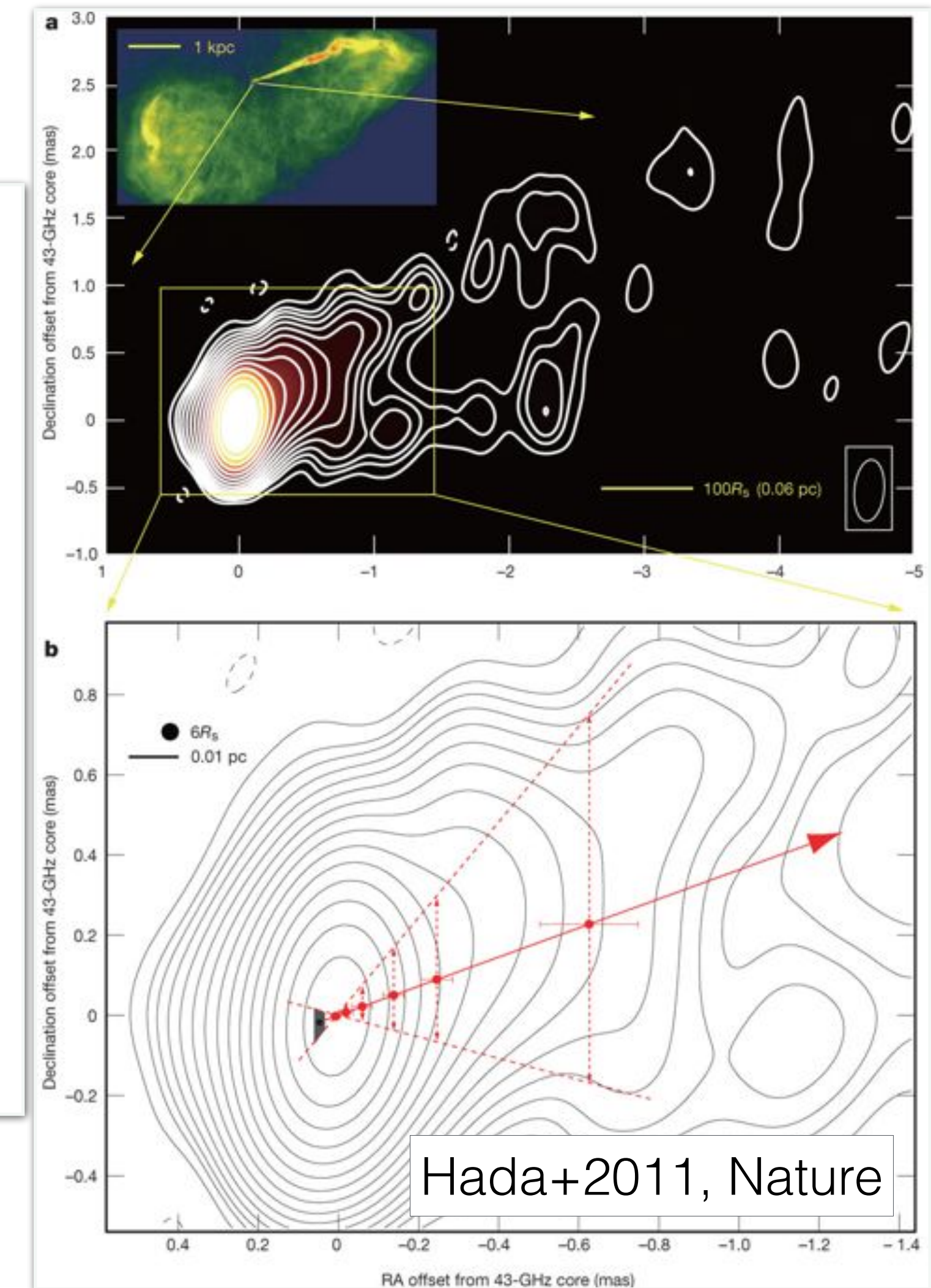
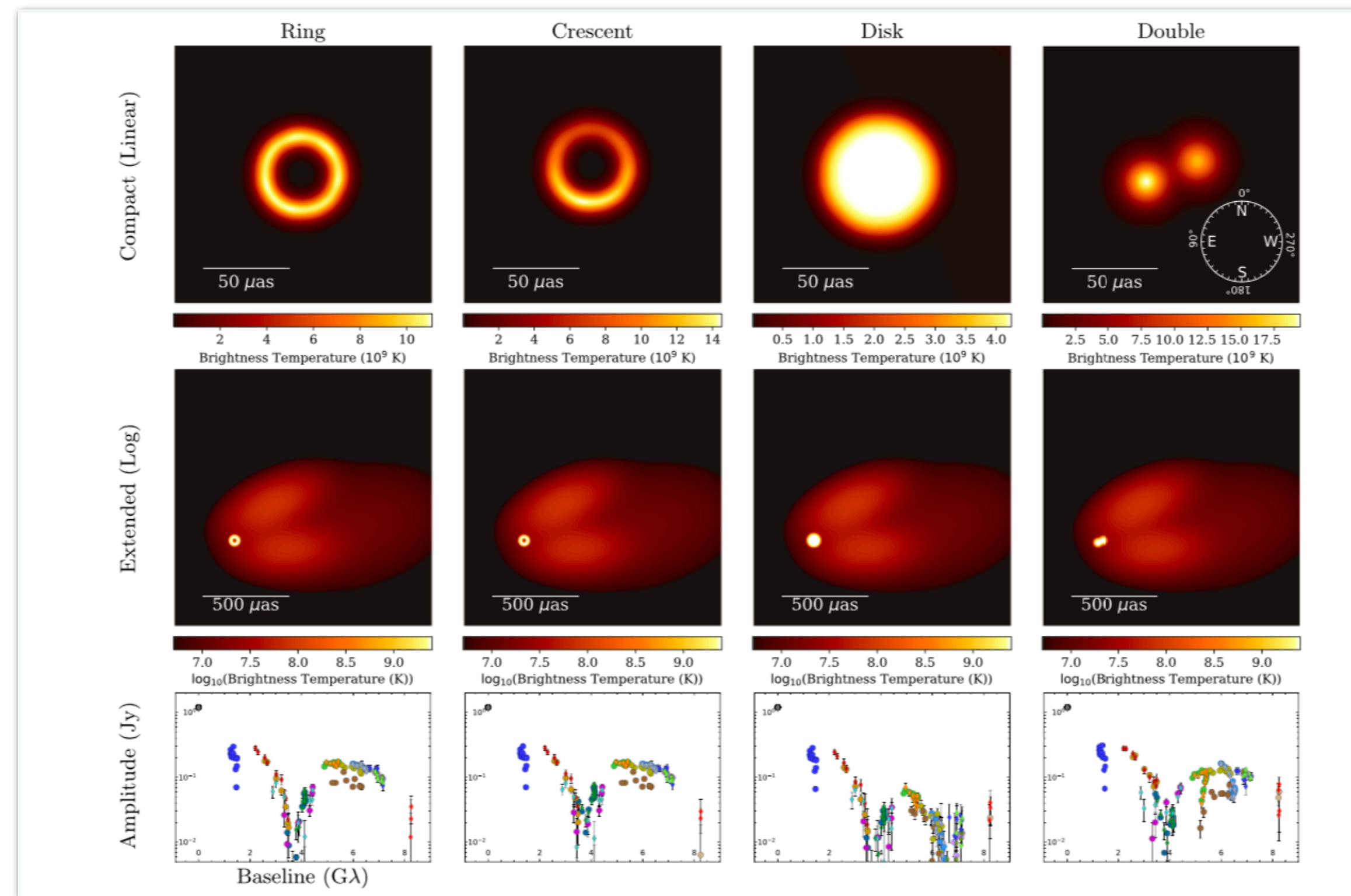
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5. N-S asymmetry is determined by BH spin. In corotating disk models, the funnel wall/jet sheath rotates with disk and BH; in counterrotating disk models, the luminous funnel wall rotates against the disk.
6. The observed asymmetry is consistent with models in which the BH spin is pointing away from Earth
7. Assuming jet viewing angle of  $17^\circ$  and a corotating disk model, matter in the bottom part of the image is moving toward the observer (clockwise rotation as seen from Earth)



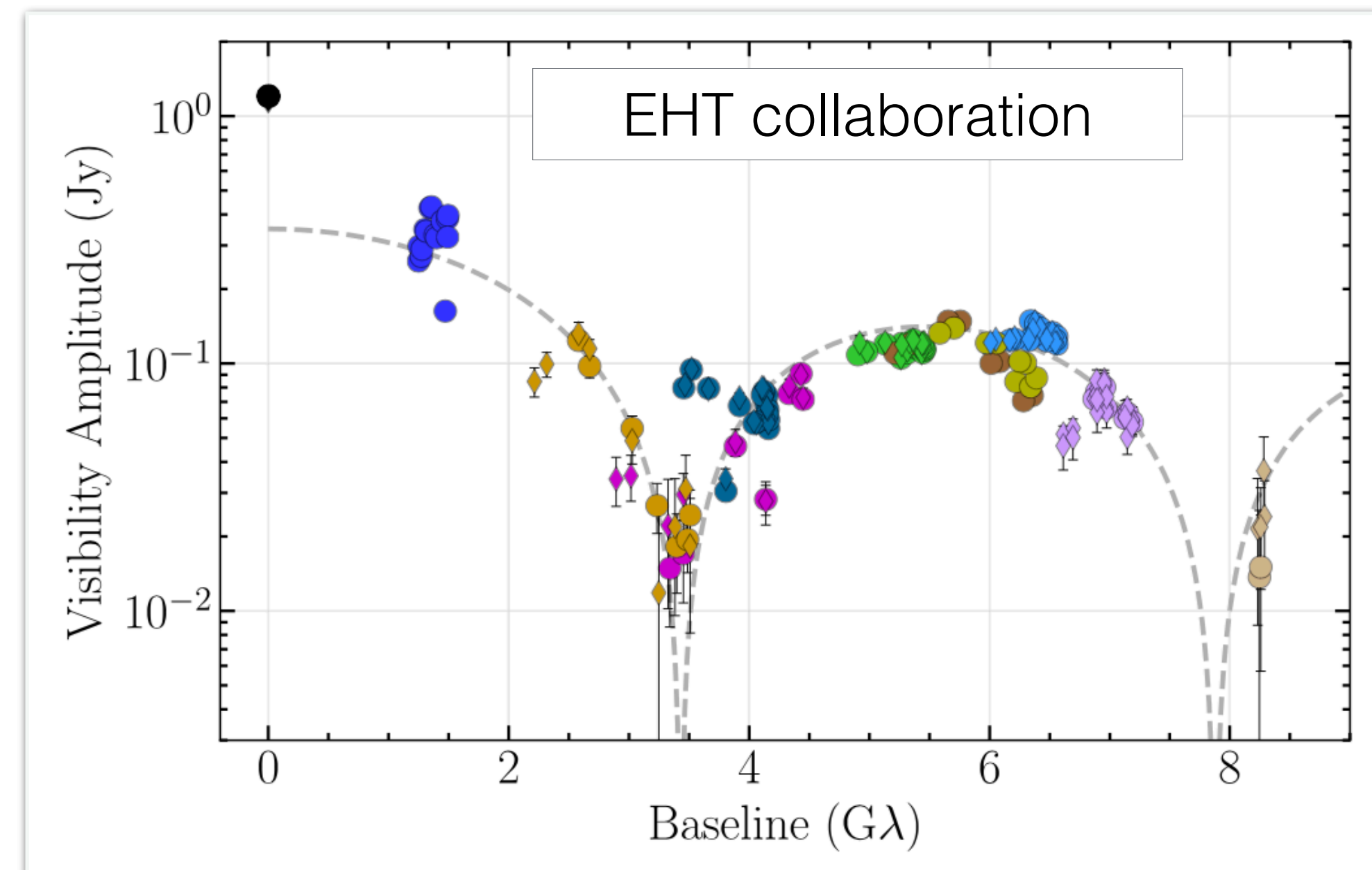
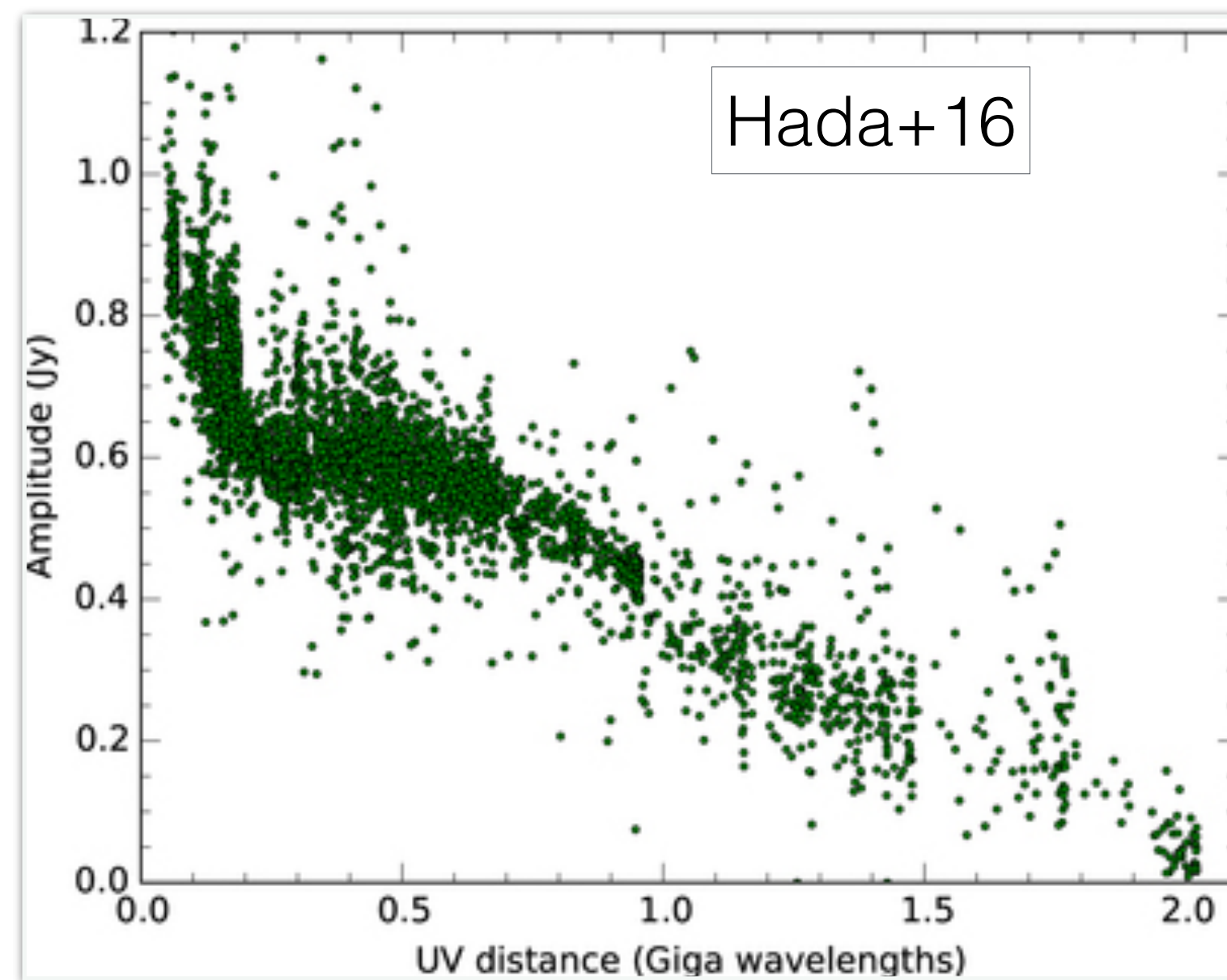
# Where is the black hole?



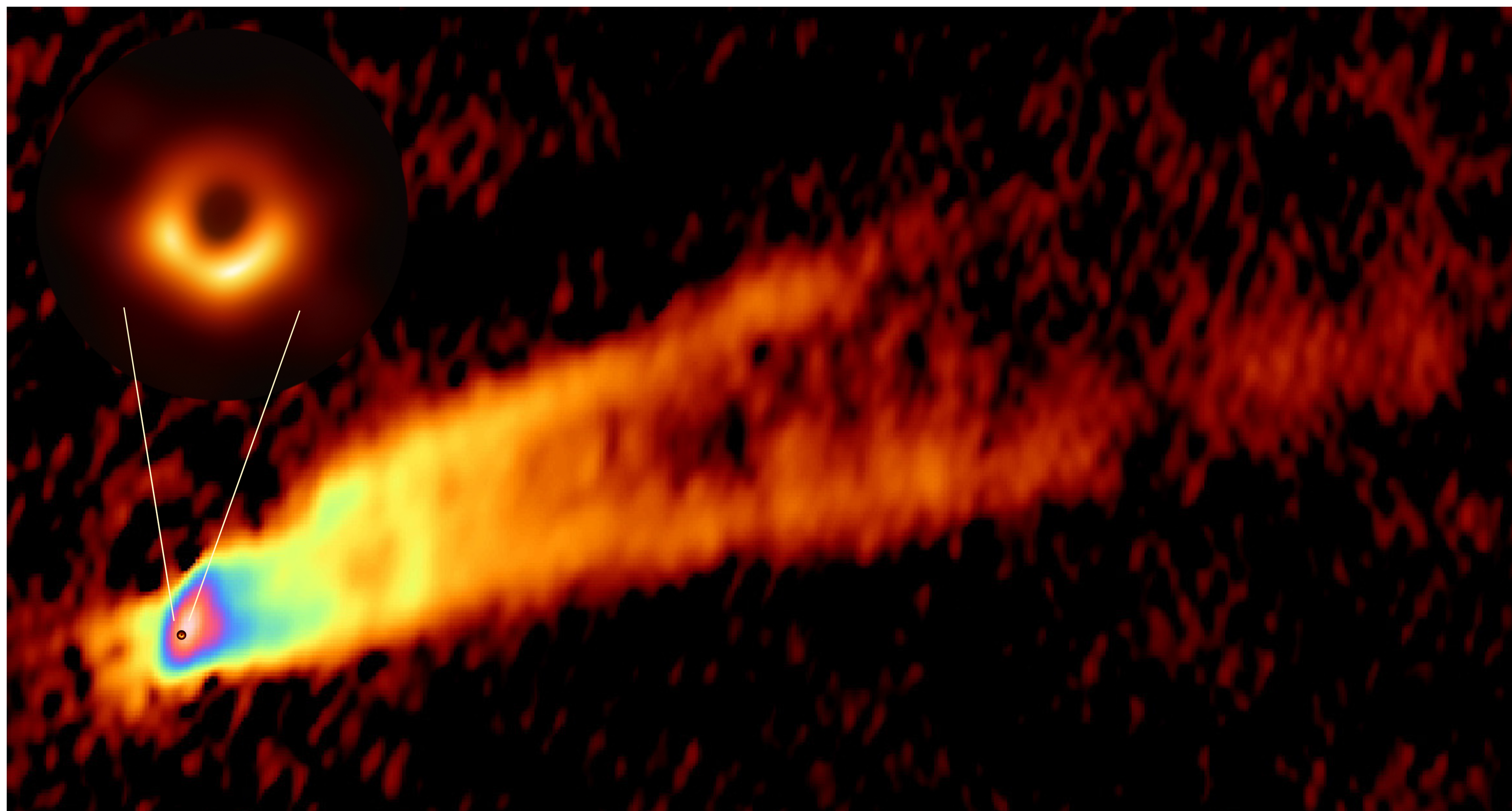
Hada+2011, Nature



# amplitude vs uv distance



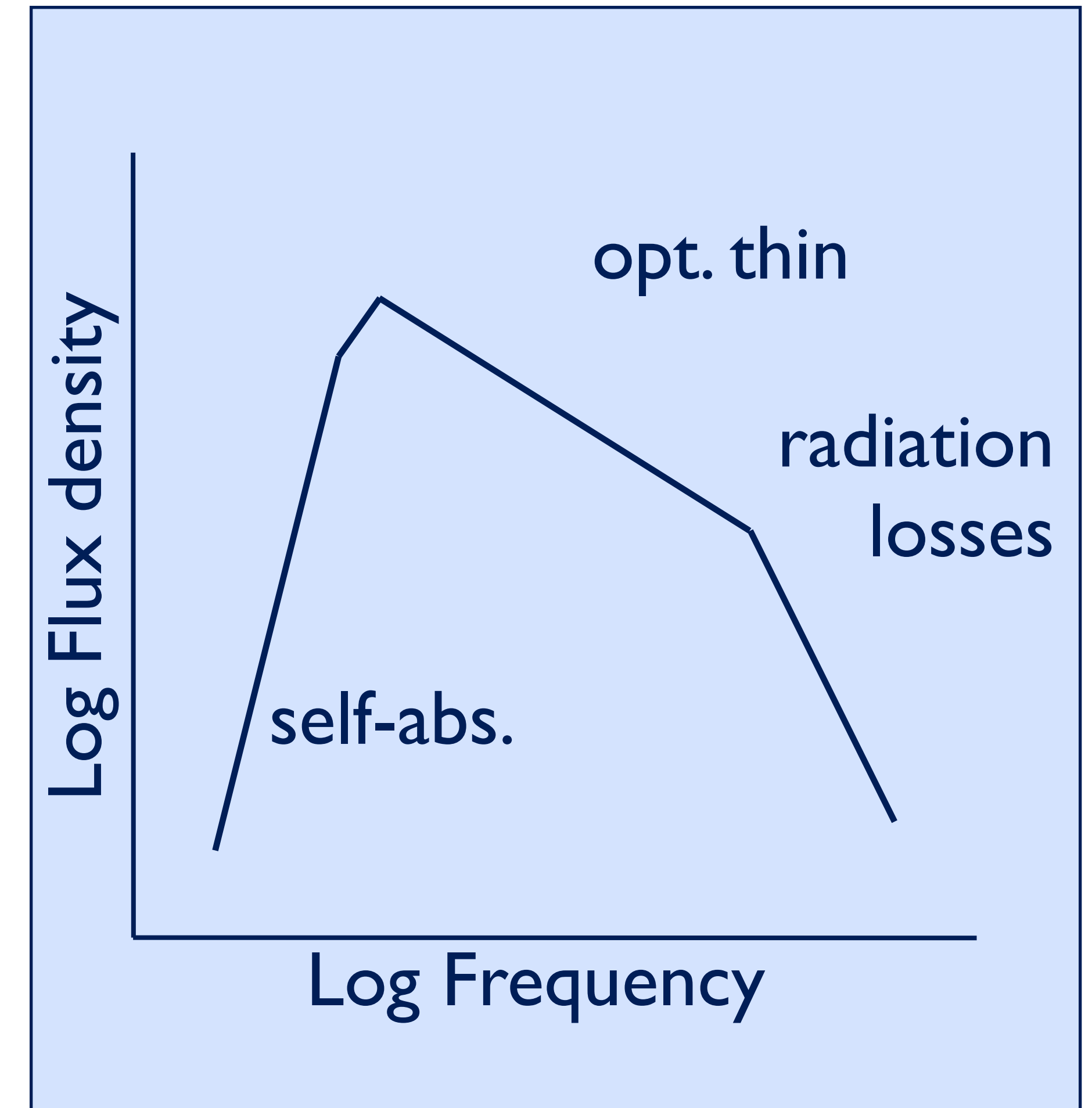






# Origin of the radio emission

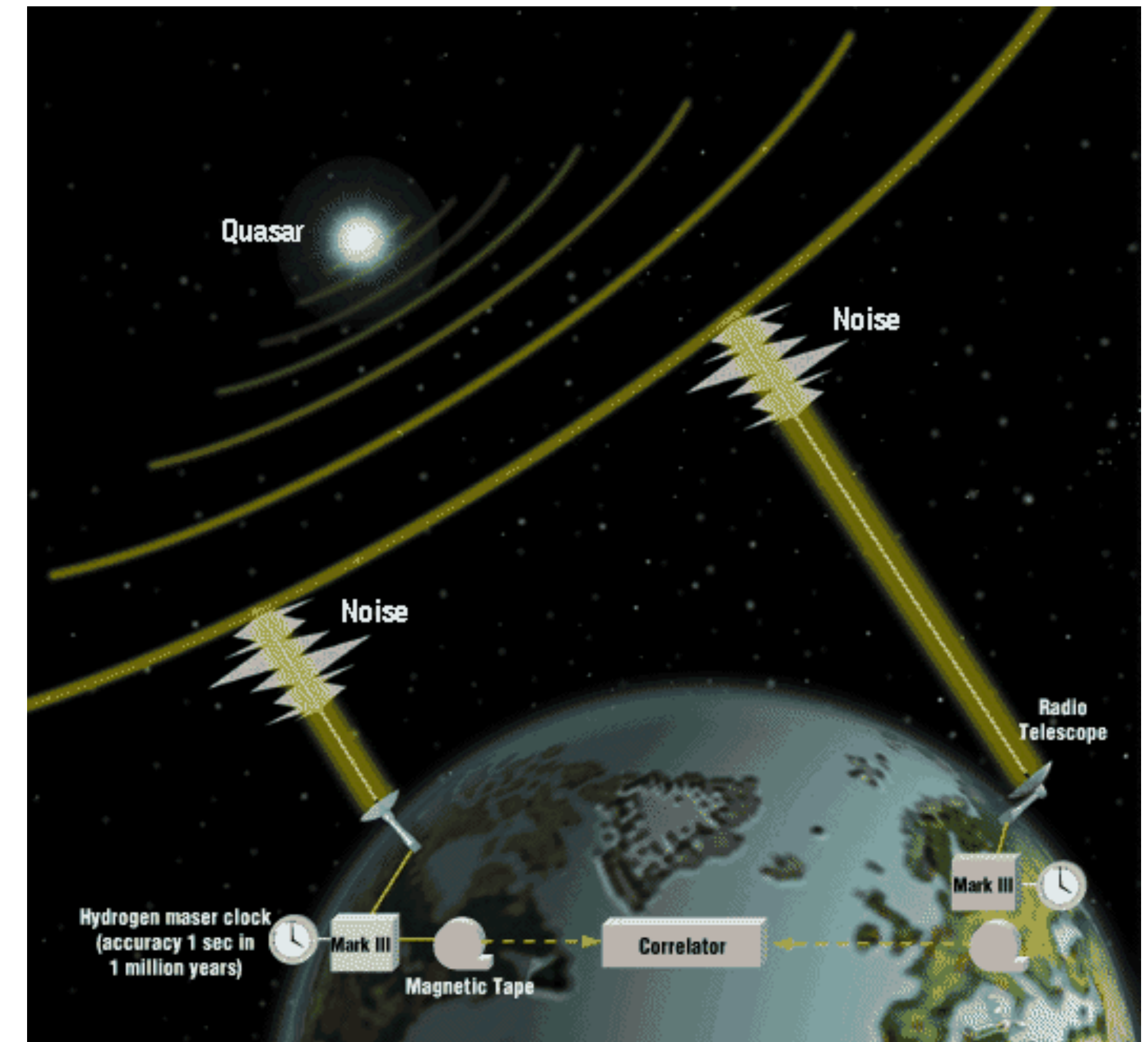
- $N(E)=N_0E^{-\delta}$
- Electrons emit at a frequency  $\nu=4.2 \cdot 10^{-6} \gamma^2 H$
- Electrons with  $\gamma=1000 \rightarrow$  emission at radio wavelengths
- $dE/dt = -bH^2E^2$ ,  $Q(t)=NE^{-\delta}$
- $S(\nu)=\nu^{-\alpha}$  if  $\nu < \nu^*$   
 $\nu^{-(\alpha+0.5)}$  if  $\nu > \nu^*$
- $\nu^*=10^9 \times t^{-2} \times H^{-3}$  (GHz, yr, mG)
  - multifrequency observations constrain  $\nu^*$ , and allow us to derive  $t_{spec}$





# VLBI: what is it?

- Very Long Baseline Interferometry
- As a reference: “very long” means  $> \sim 100$  km
- As long as the telescopes can point to the same sky position simultaneously, no limit in principle to upper end
- practical and astrophysical conditions apply





# VLBI pros and cons

## Pros

- Obvious: angular resolution!

$$\theta = \frac{\lambda}{D}$$

if  $\lambda \sim 10^{-2}$  m and  $D \sim 10^6$  m,  $\theta \sim 10^{-8}$ ,  
i.e.  $\sim 2$  milliarcseconds

- Sometimes the radio telescopes are there already!

## Cons

- There's only so much land you can build your telescopes on!
- **Mutual visibility** can be an issue
- The distance to the correlator is also "VL": **data transfer, clock reference**
- Coordination among elements
- Not all sources have a large enough **brightness temperature**



# VLBI: what do you need?

- A set of radio telescopes and for each telescope a set of **compatible receivers**, **time reference devices**, **recorder units** and **media**
- A target that is bright enough!

$$T_B = I_\nu \frac{\lambda^2}{2k_B} \quad I_\nu = \frac{S_\nu}{\text{beam area}} \sim \frac{S_\nu}{\pi\theta^2}$$

- The same flux density  $S_\nu$  distributed over a 1-mas beam compared to 1'' corresponds to a brightness temperature that is  $10^6$  times as large
- A reference case:  $\lambda=10^{-1}$  m,  $S_\nu=100$  mJy/beam at 1 mas angular resolution yields  $T_b=1.5 \times 10^9$  K: **non thermal radiation!**



# VLBI: what do you need?

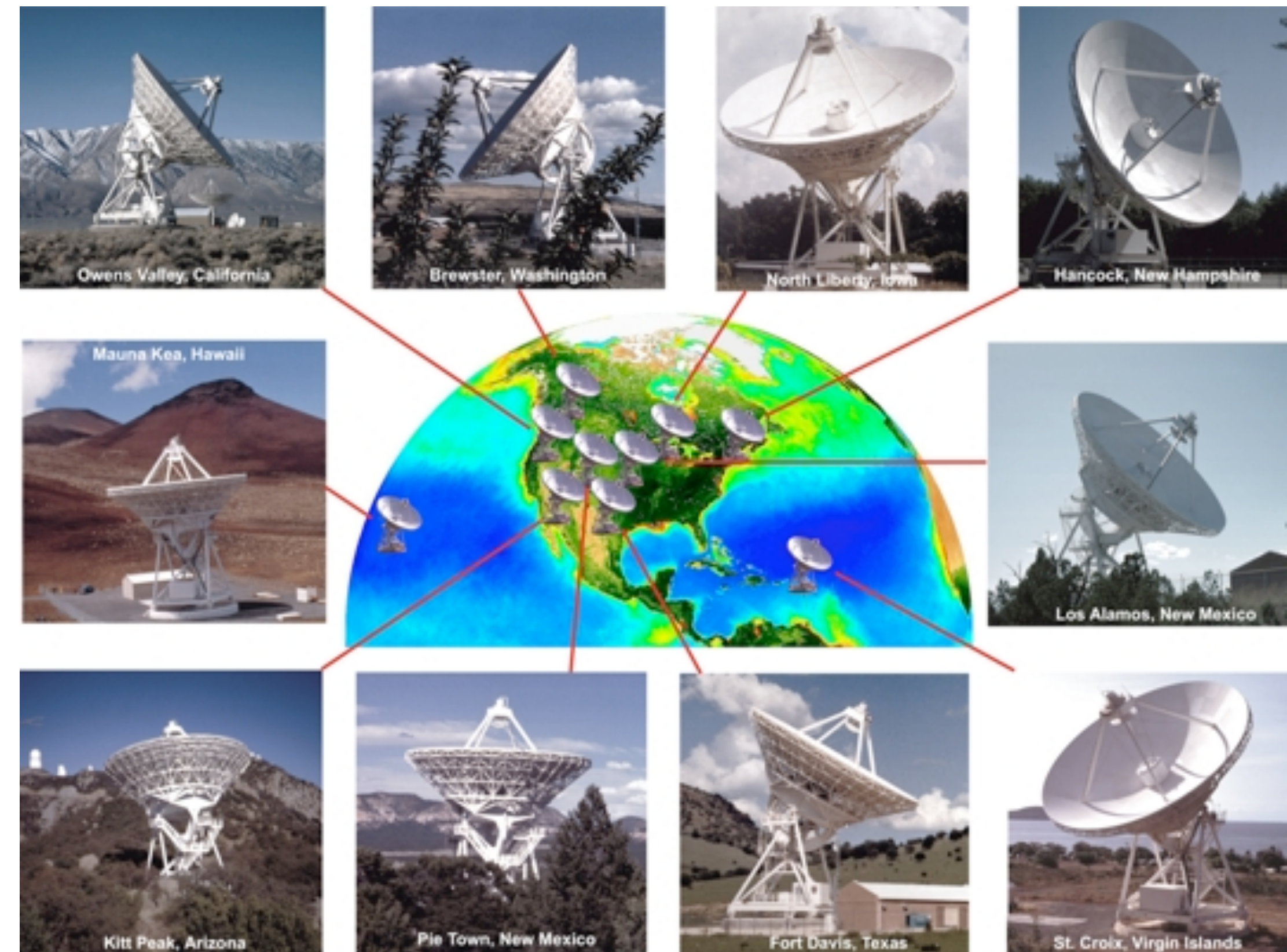


- **Compatible receivers - typically:**  $\Delta\nu/\nu < 1/10$ , with  $1 < \nu/\text{GHz} < 43$ 
  - **Note**  $\sigma \sim (t \Delta\nu)^{-0.5}$  so wide bandwidth is your friend when you can not have too many telescopes nor integrate indefinitely
- **Time reference devices** -  $c\Delta t = 0.3\text{m}$  if  $\Delta t = 1\text{nsec}$
- **Recorder units** - every stations needs to record in the same format
- **Media** - wide bandwidth is not your friend when you record at 4 Gbps for 24 hours ( $\sim 42\text{ TB day}^{-1}\text{ station}^{-1}$ )
- Of course, a **correlator** (hardware or software): JIVE-ERIC (NL), MPIfR (Germany), NRAO (Socorro), Pawsey (Aus), Shanghai, Bologna, ...



# Very Long Baseline Array (VLBA)

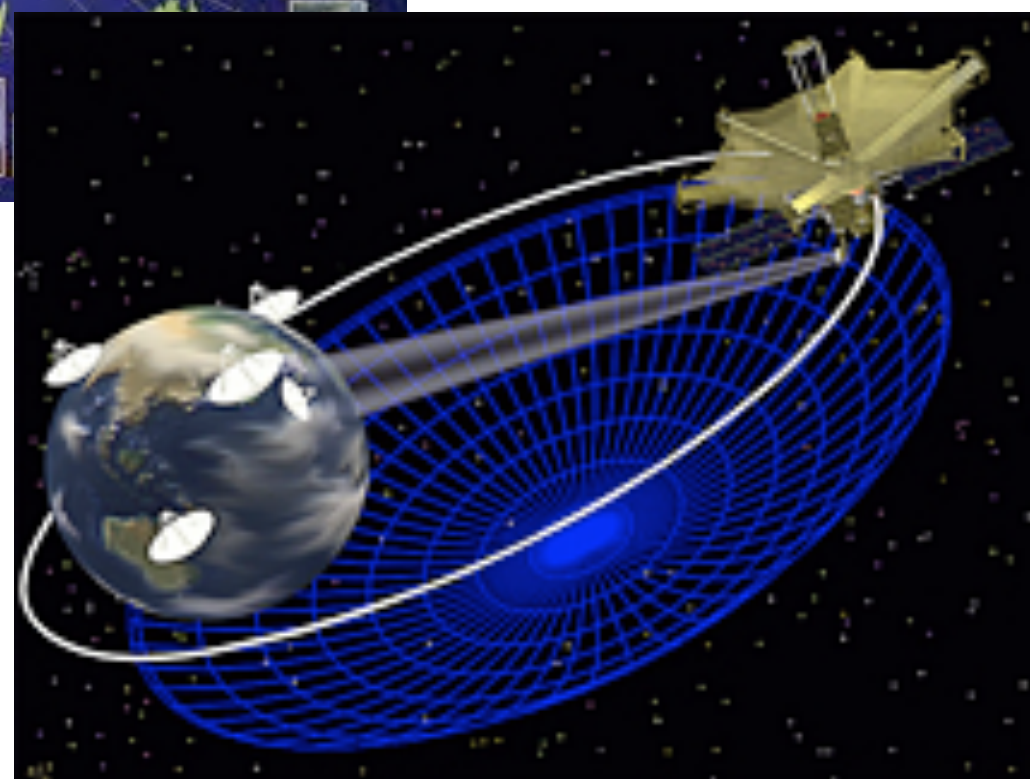
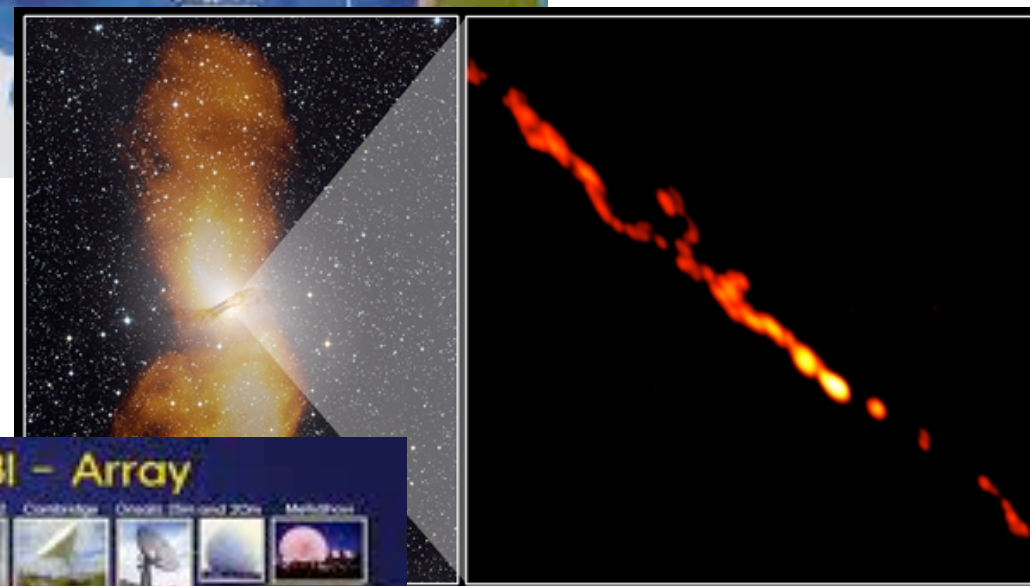
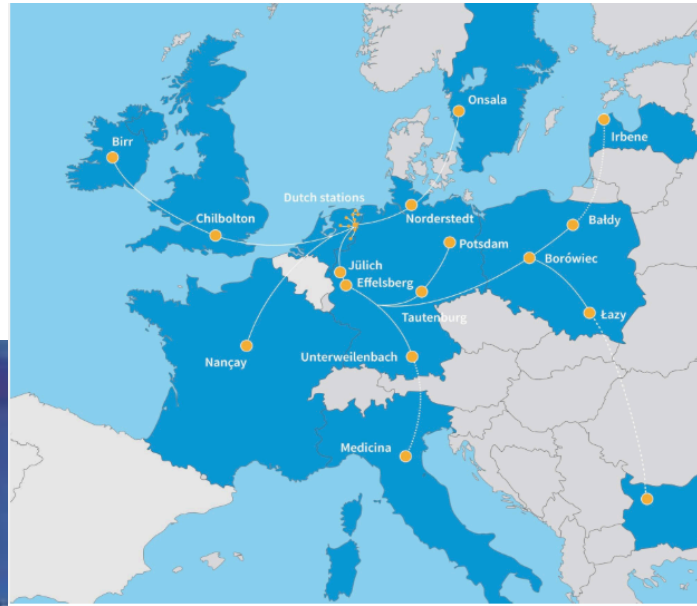
- first and **largest dedicated VLBI array**
- **10x** identical **25m** telescopes across US
- longest baseline **~9000 km**
- **optimised coverage** of the (u,v)-plane
- works **24/7**
- frequency agility, from **327 MHz** to **86 GHz** (*not continuous!*)
- no big telescopes, lack of short, sensitive baselines
- limited real time capability





# Other “niche” VLBI arrays

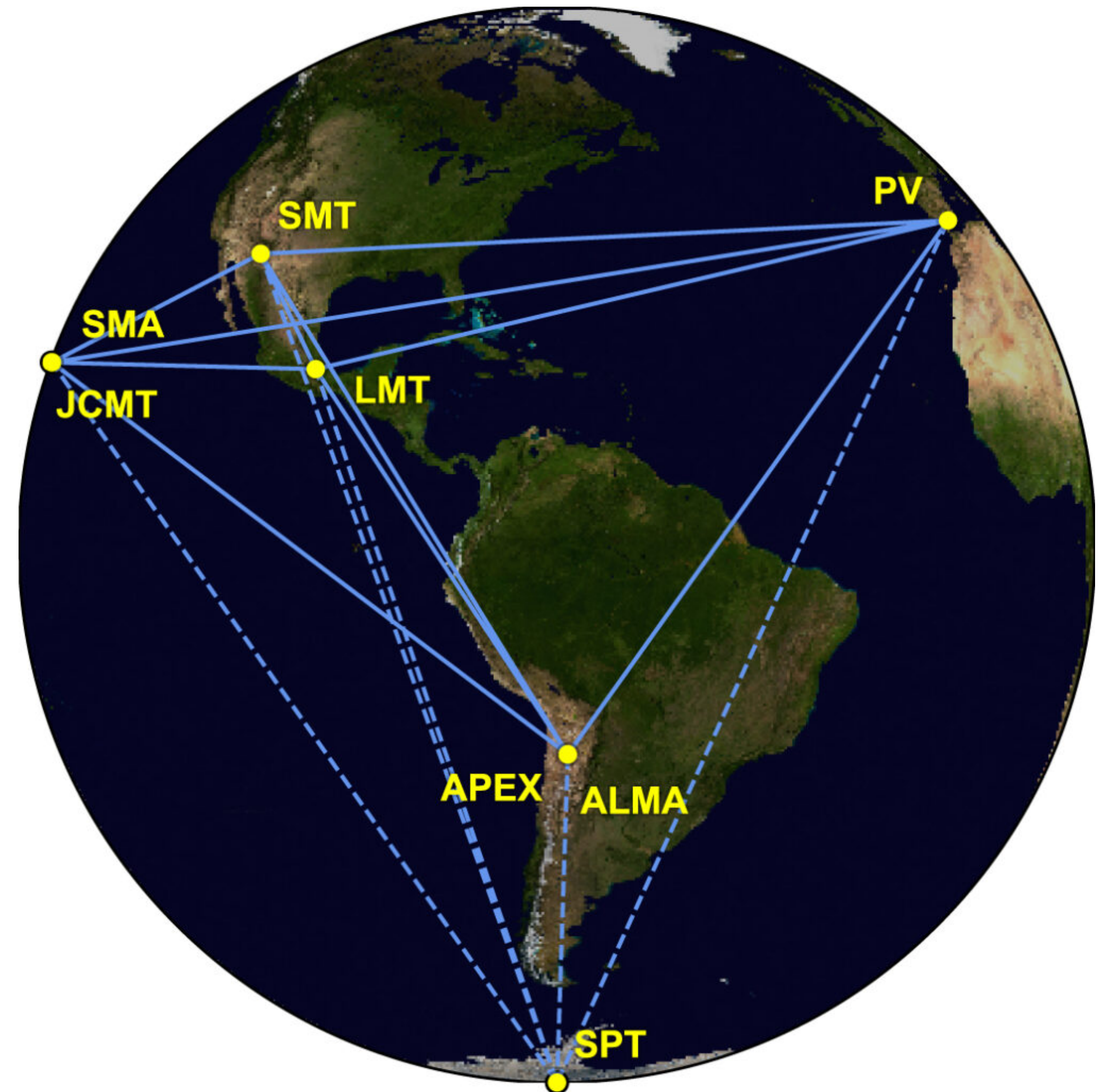
- International **LOFAR** Telescope:  $\nu < 240$  MHz
- Long Baseline Array: Australia, **southern hemisphere** sources
- VERA, KVN, **EAVN**: regional networks in Japan, Korea, East Asia; **high/multi-frequency, astrometry**  
*-> Eating VLBI (East Asia To Italy: Nearly Global VLBI)*
- Global Millimeter VLBI Array: **3mm** wavelength, improved angular resolution and access to optically thick regions
- Space VLBI: ground array + **space antenna** (HALCA, Radioastron)





# Event Horizon Telescope

- Difficulty in building large dishes with accurate surface
- Exceptional atmospheric conditions required: remote locations
- Extremely short coherence time
- Few suitable targets, especially before ALMA
- Working frequency: 230 GHz ( $\lambda=1.3\text{mm}$ ), angular resolution  $\theta=20\mu\text{as}$





# Event Horizon Telescope

- Primary targets: supermassive black hole vicinity
- Schwarzschild radius:  $r_s = \frac{2GM}{c^2}$
- SgrA\*,  $M_{\text{BH}}=4\text{e}6 M_{\text{sun}}$ ,  $d=8.2 \text{ kpc}$ ,  $R_s=10\mu\text{as}$
- M87,  $M_{\text{BH}}=6\text{e}9 M_{\text{sun}}$ ,  $d=16.8 \text{ Mpc}$ ,  $R_s=8\mu\text{as}$
- Emission from accretion flow, gravitationally bent by BH mass

