Connection of gamma rays to radio, VLBI and EHT

Marcello Giroletti
INAF Istituto di Radioastronomia, Bologna

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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:

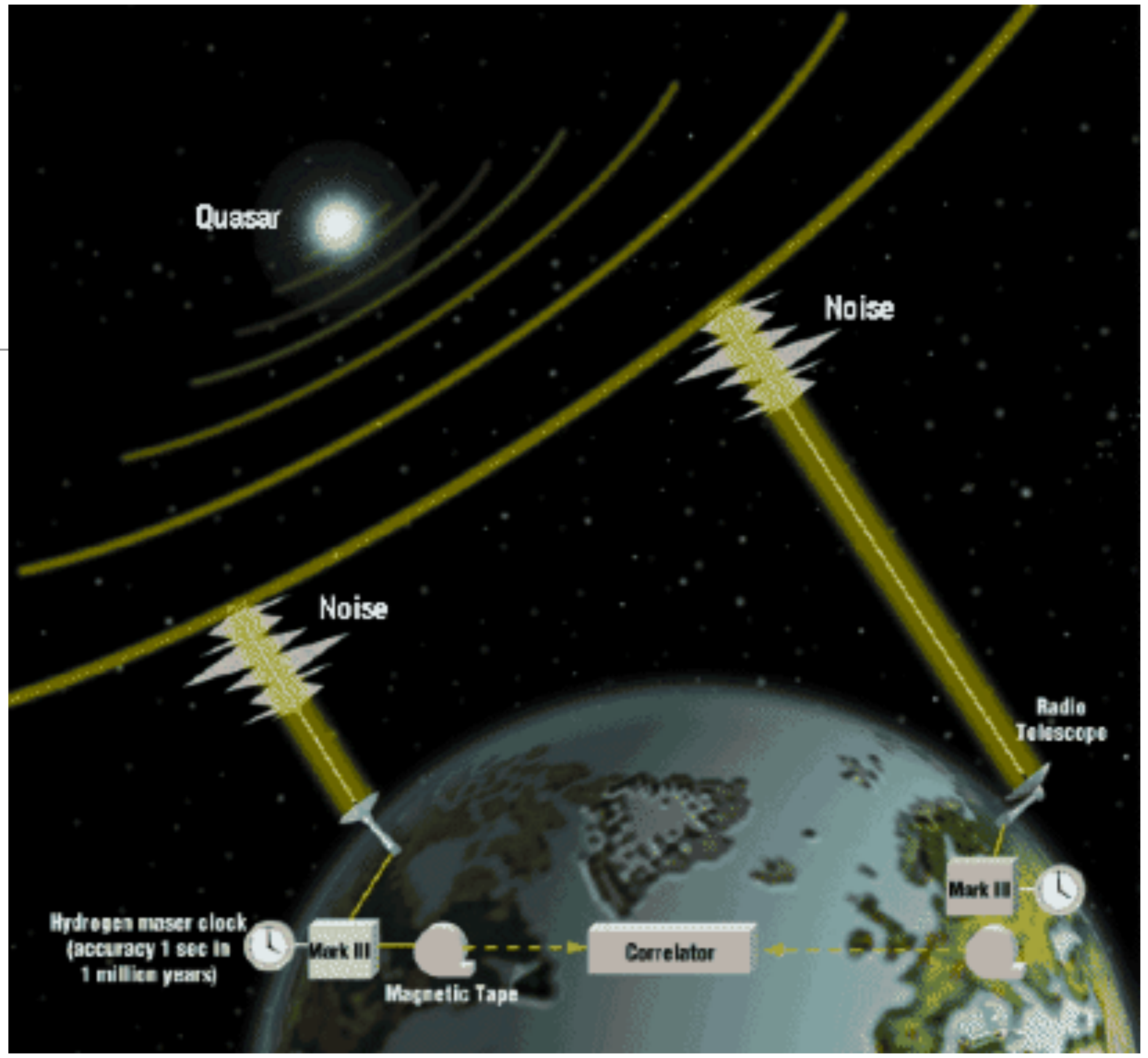
1. Every identified VHE source is also a radio emitter (esp. extragalactic/radio-loud)

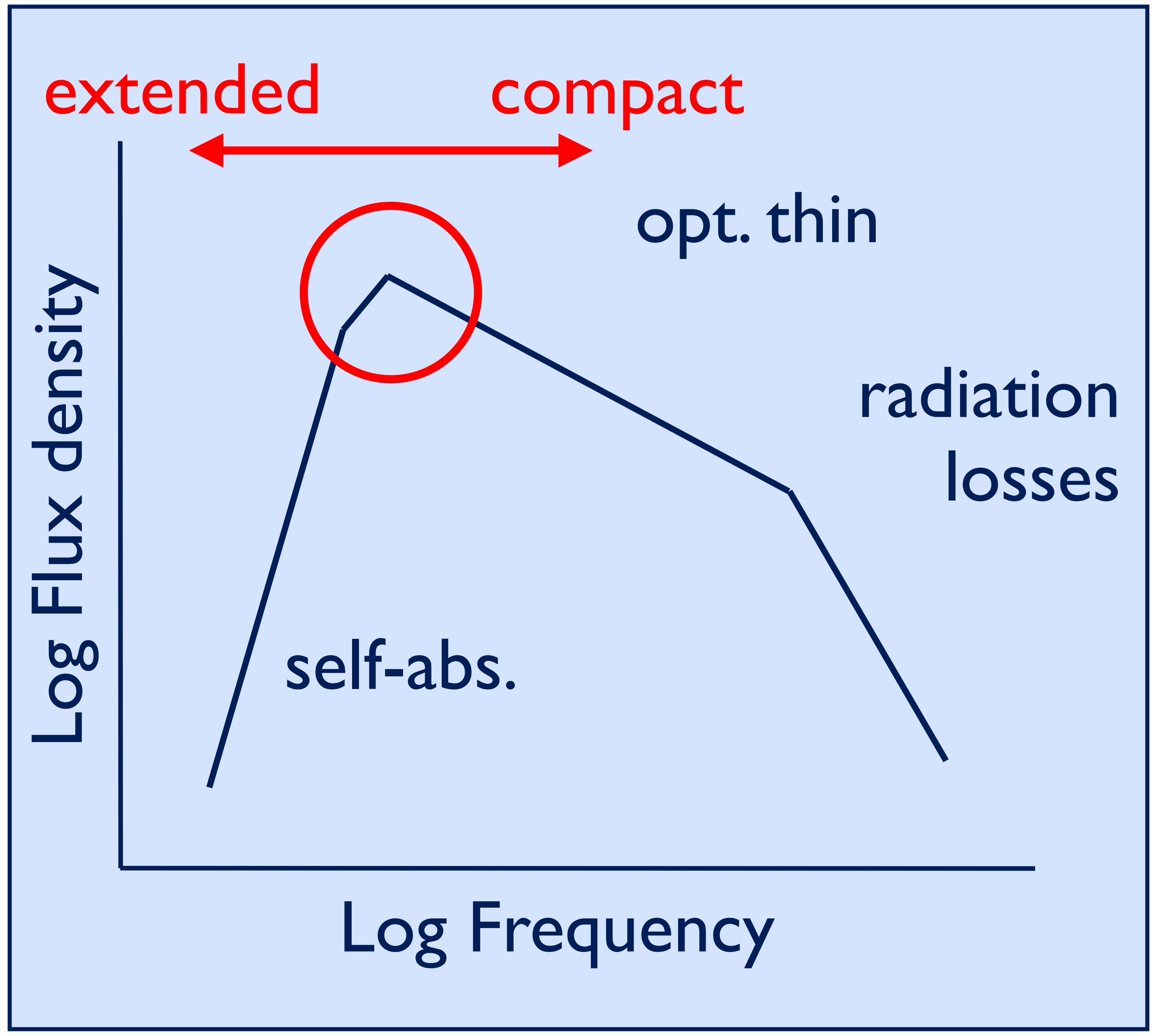
2. Radio waves (through VLBI technique) are the only tool to obtain images on angular scales close to the ones probed by VHE variability time scales (sub-pc)

(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

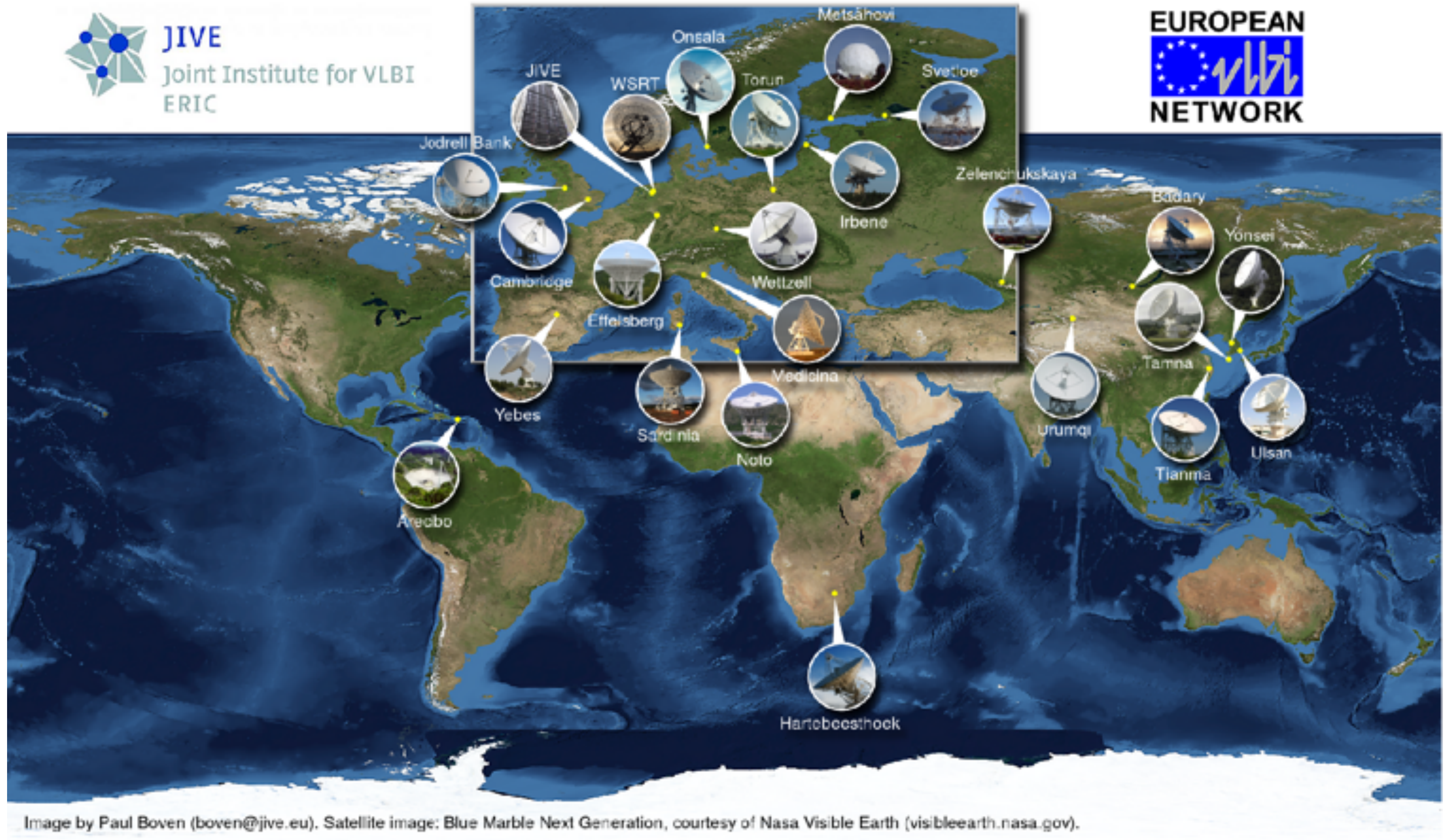
Connected interferometers

10⁷ Hz

LOFAR, GMRT, VLA, ATCA, ALMA
MeerKAT, ASKAP
~arcsec angular resolution
~1-10 μJy sensitivity (now!)

>10¹¹ Hz

Very Long Baseline Interferometry

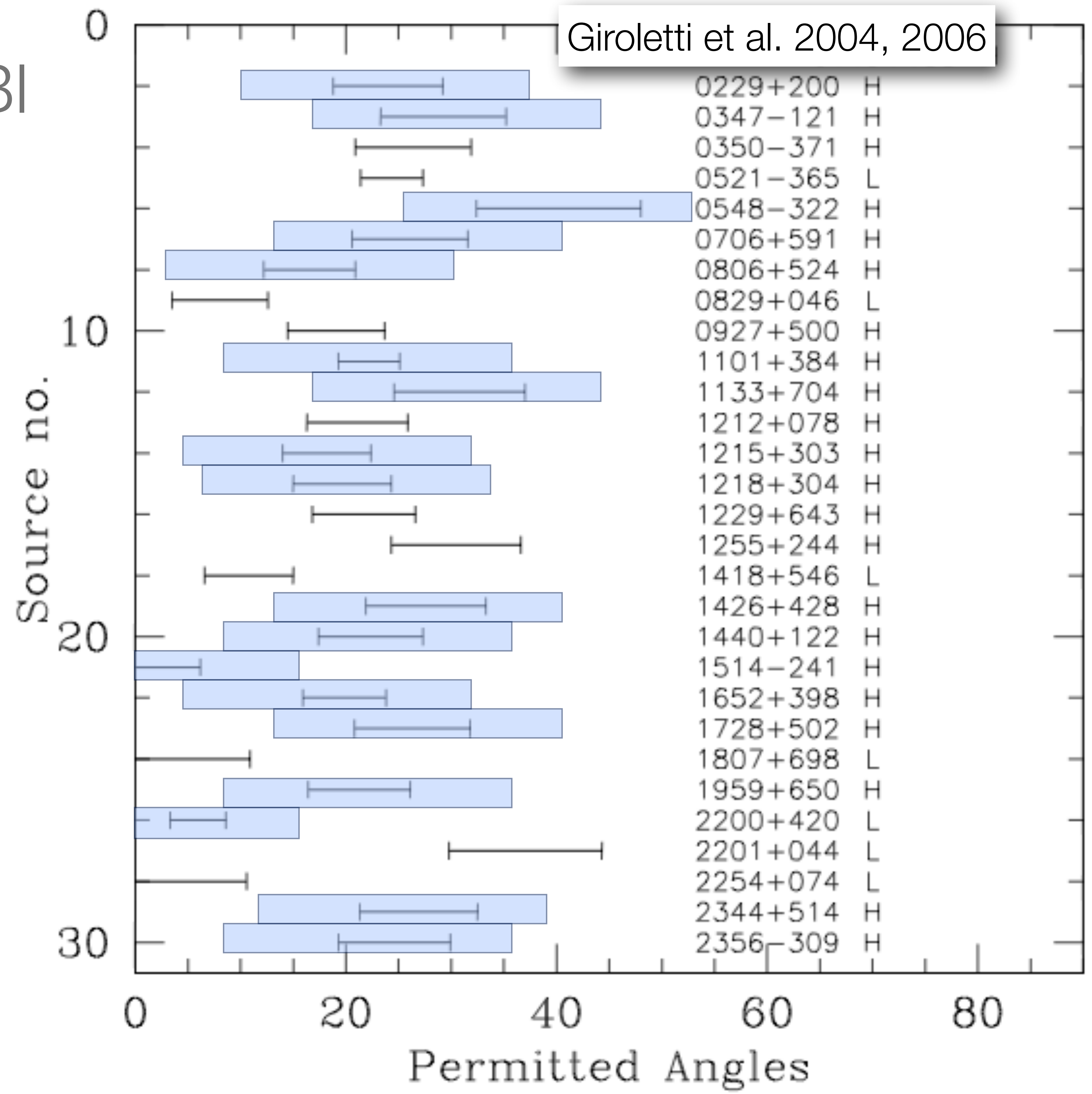


VLBA, EVN, LBA
~mas angular resolution
~100 μJy sensitivity
Event Horizon Telescope

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 ~20deg
- Core peak @5 GHz ~ 100 mJy
- $\mathrm{LogP_{1.4}}$~24.7 W $\mathrm{Hz^{-1}}$ (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

HBLs: 17/22; last one in 2011



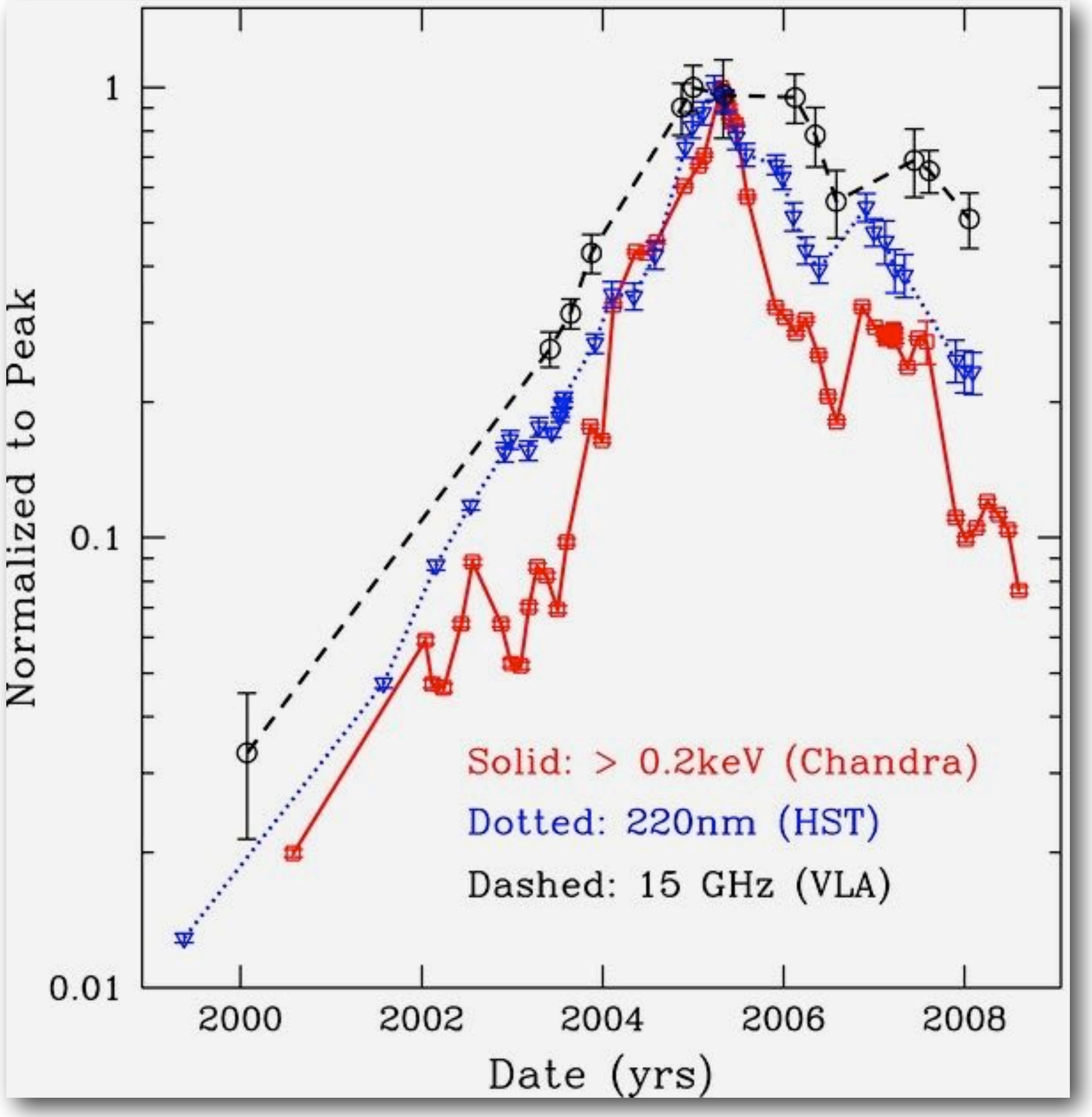
M87 radio-VHE connection: context

M87 radio-VHE connection: history #1

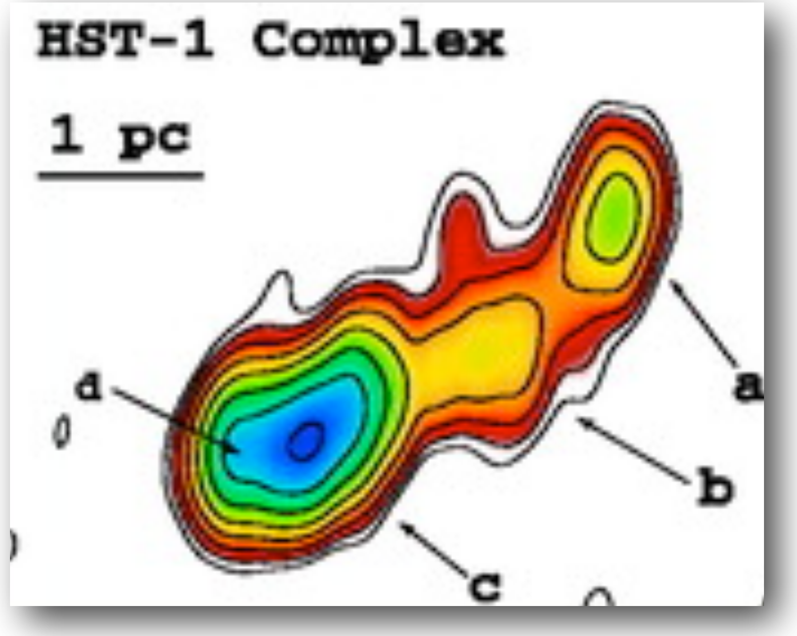
- VHE observations between 2003 and 2006 report fast variability (~days), suggesting very compact region (near supermassive black hole? Aharonian et al. 2006)

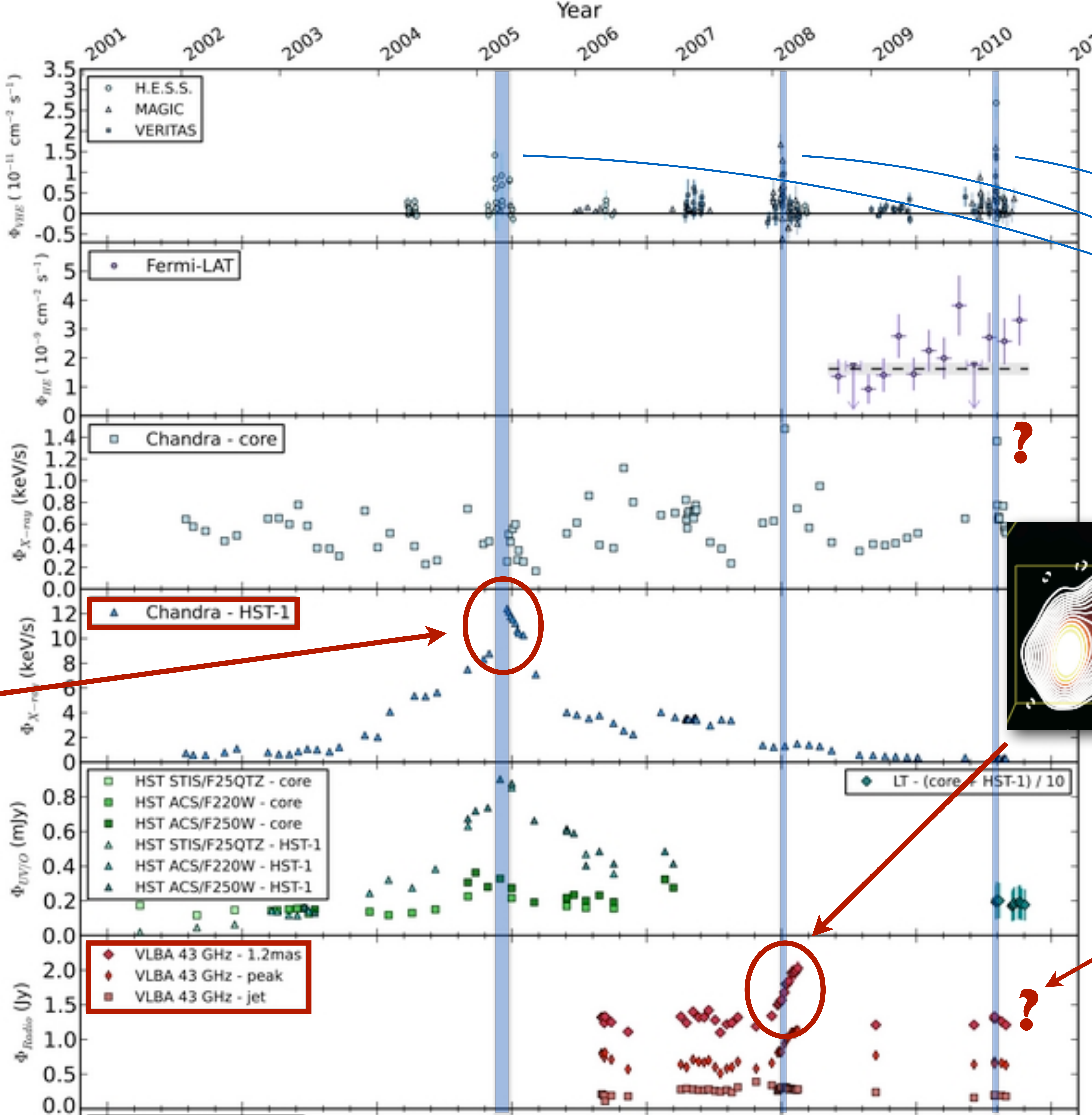
- TeV activity simultaneous with X-ray, optical, and radio flare in superluminal HST-1, ~70 pc downstream the core! (Acciari et al. 2008, Harris et al. 2006)

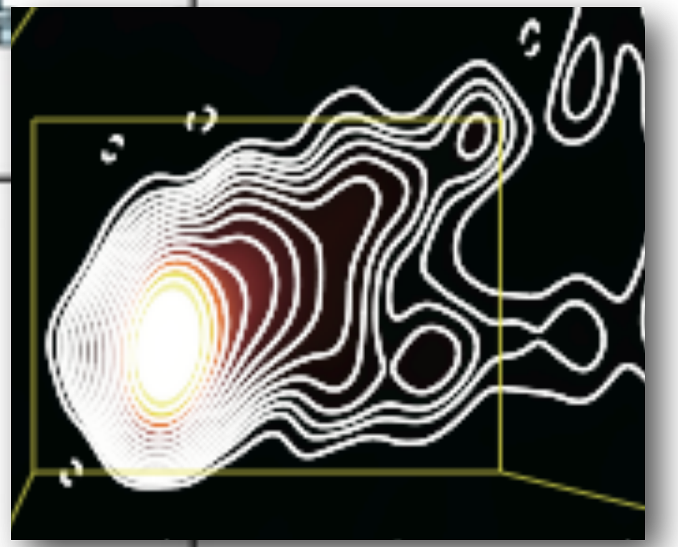
HST-1 radio, optical, X-ray light curves (Harris et al. 2009)



M87 radio-VHE connection: history #2



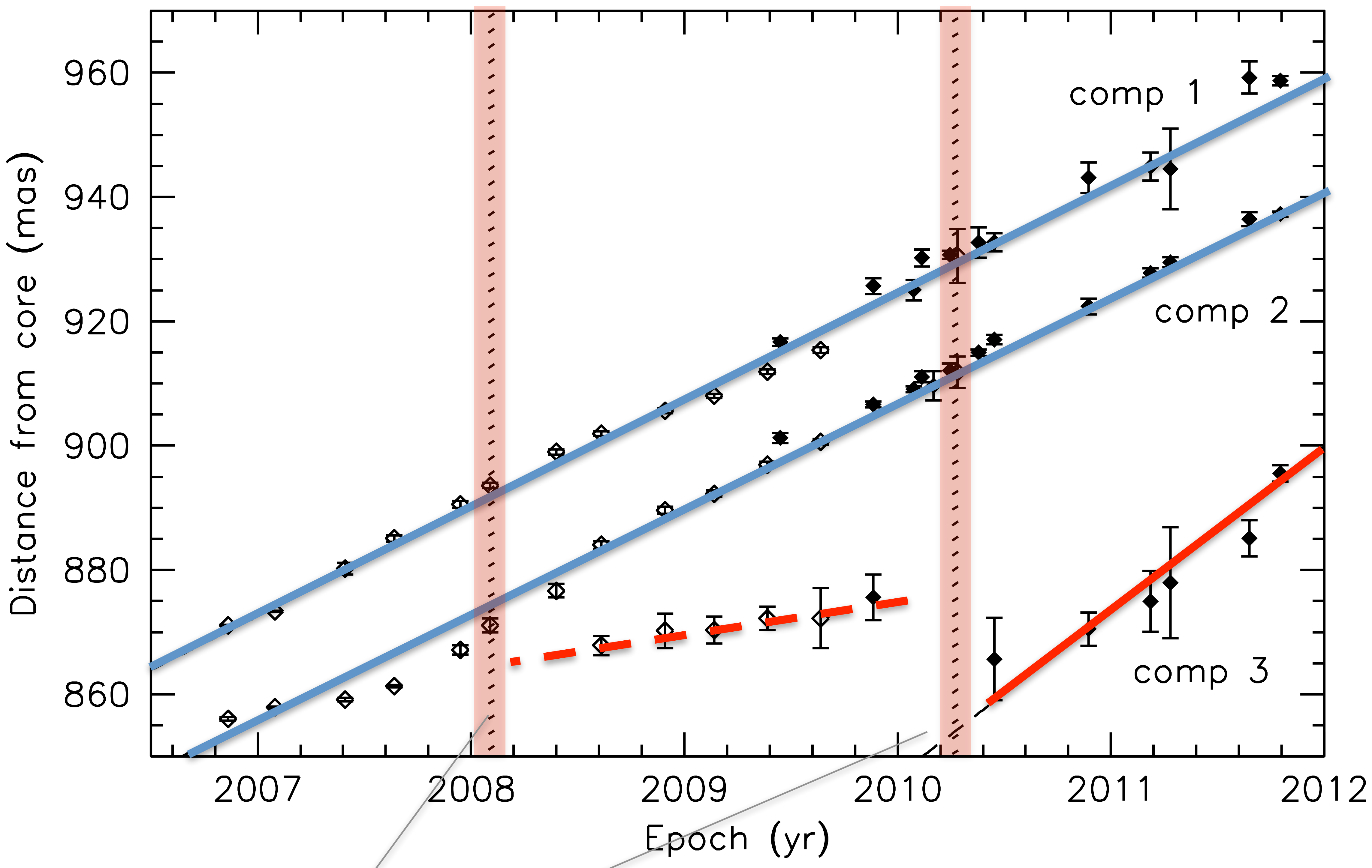




Abramowski et al. 2012

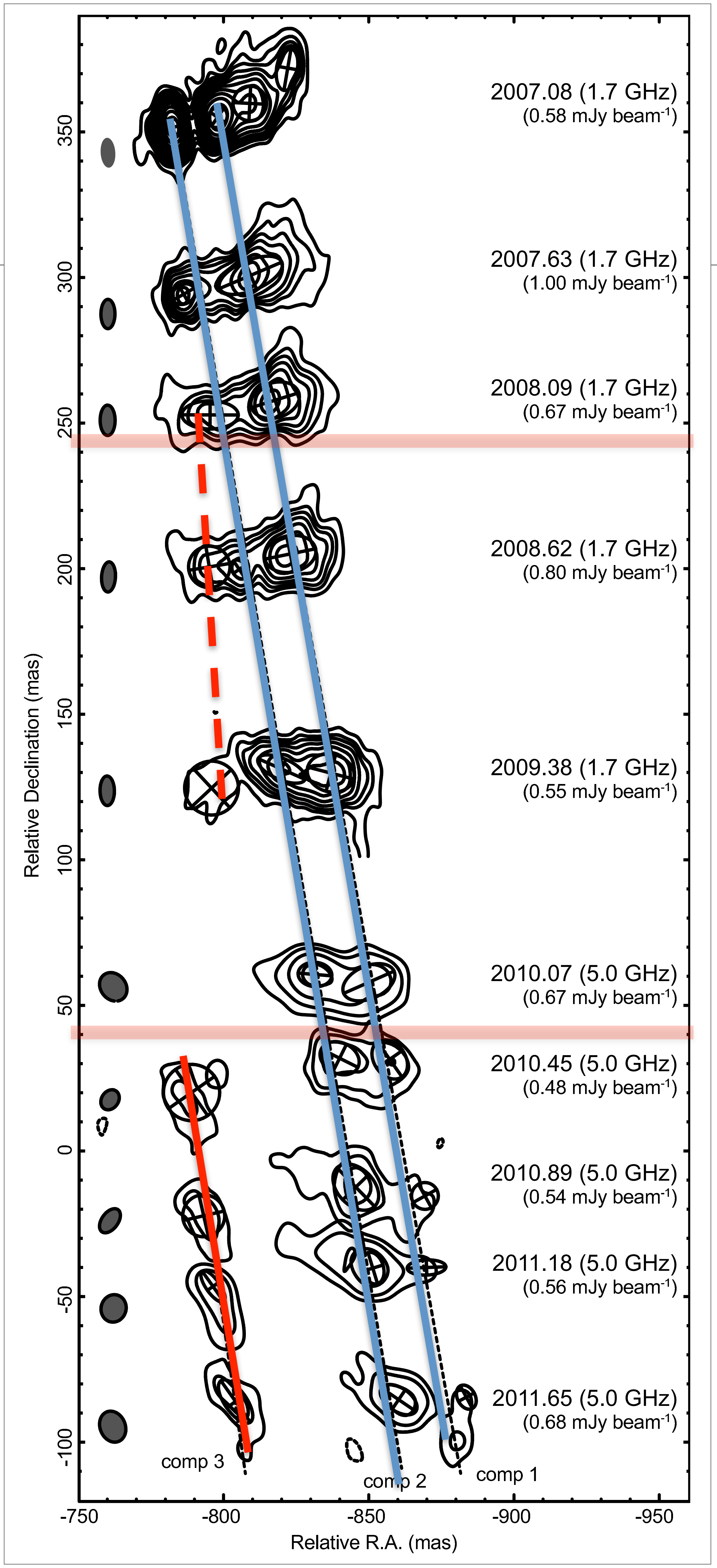
see Hada et al. (ApJL, 2012)

M87: the EVN core & HST-1 monitoring



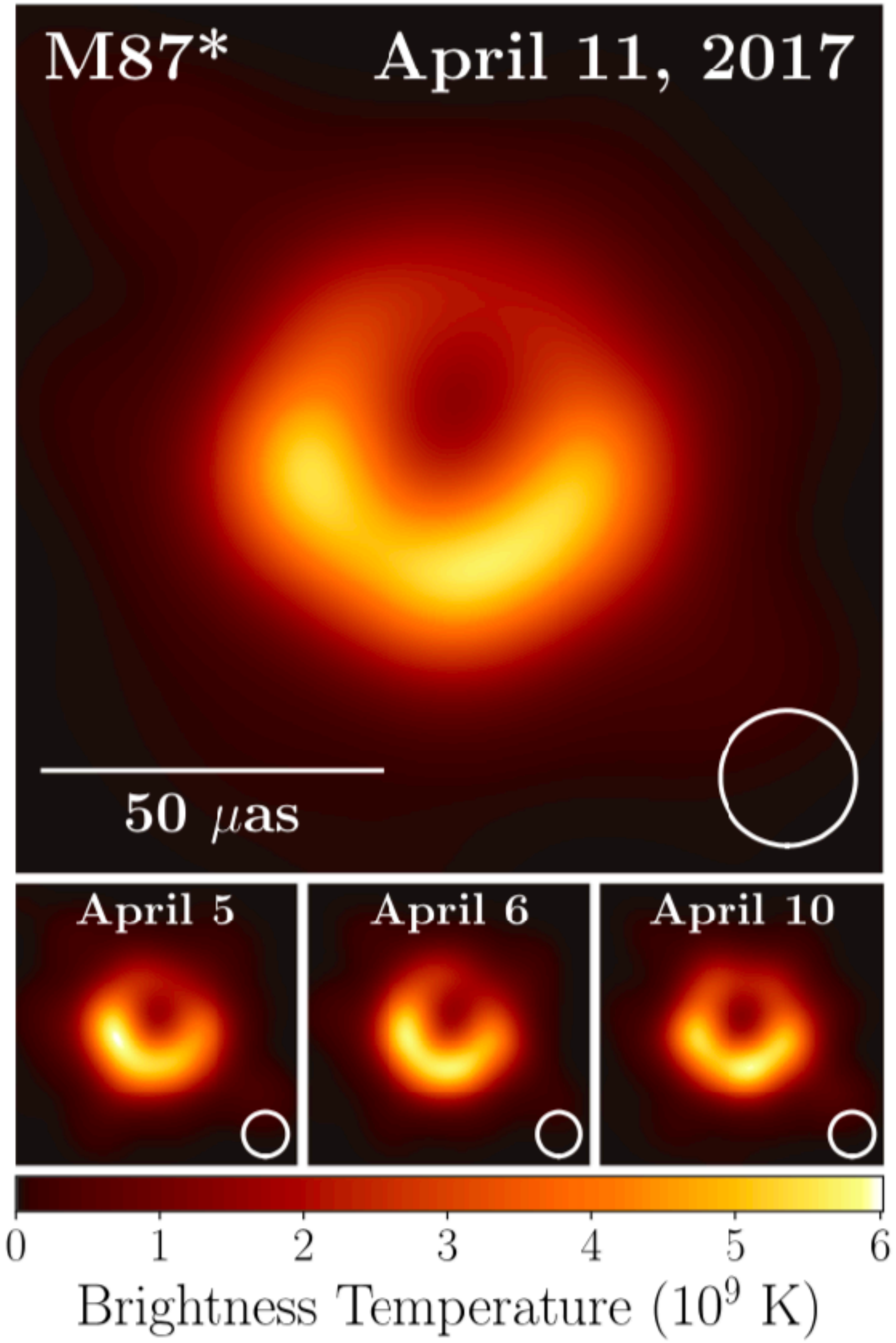
VHE flares

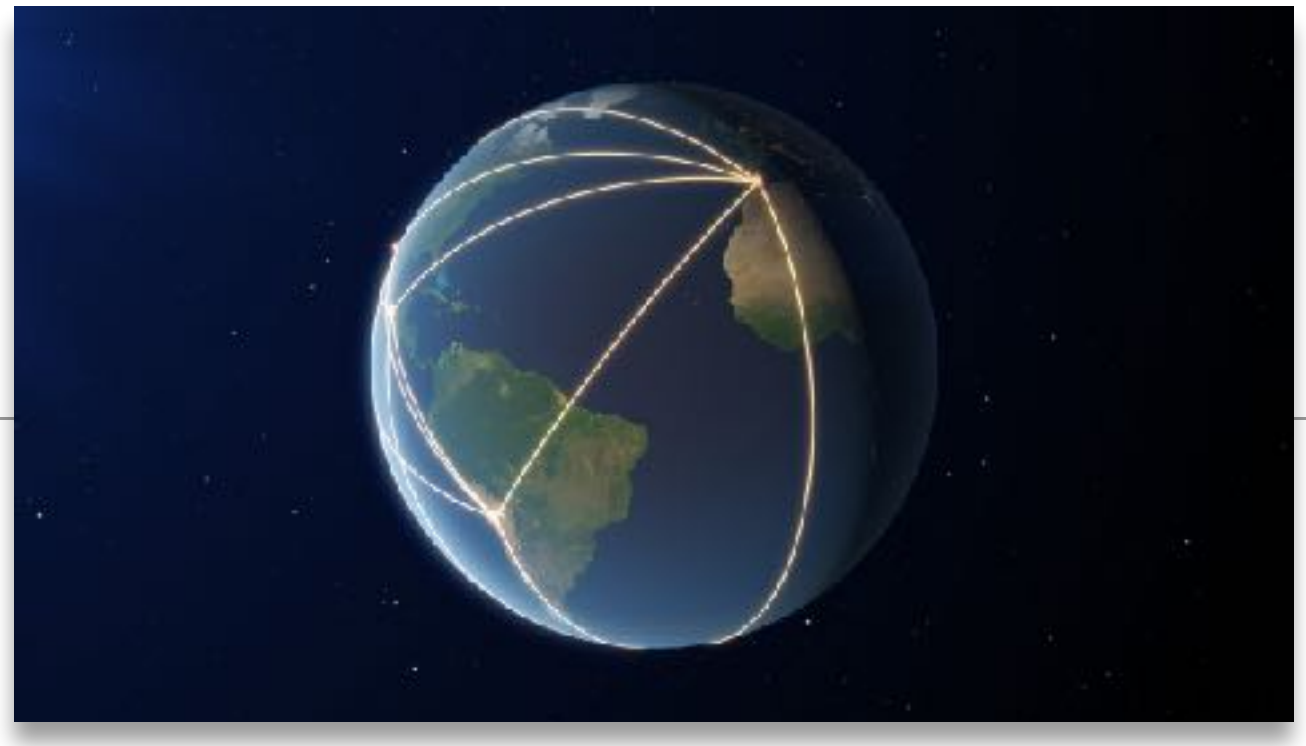
Giroletti et al. 2012



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

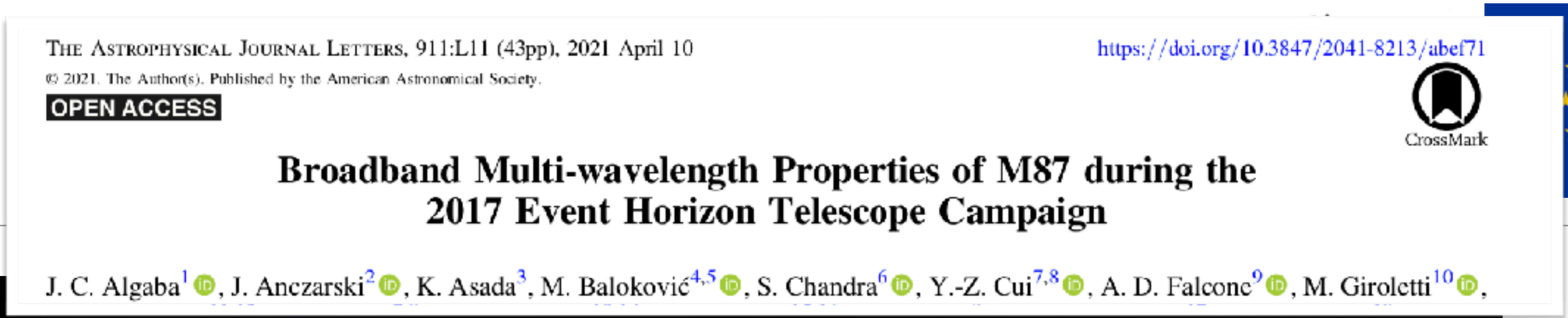
M87: the Event Horizon Telescope image





- Observations in 2017
  - ν=230 GHz (λ=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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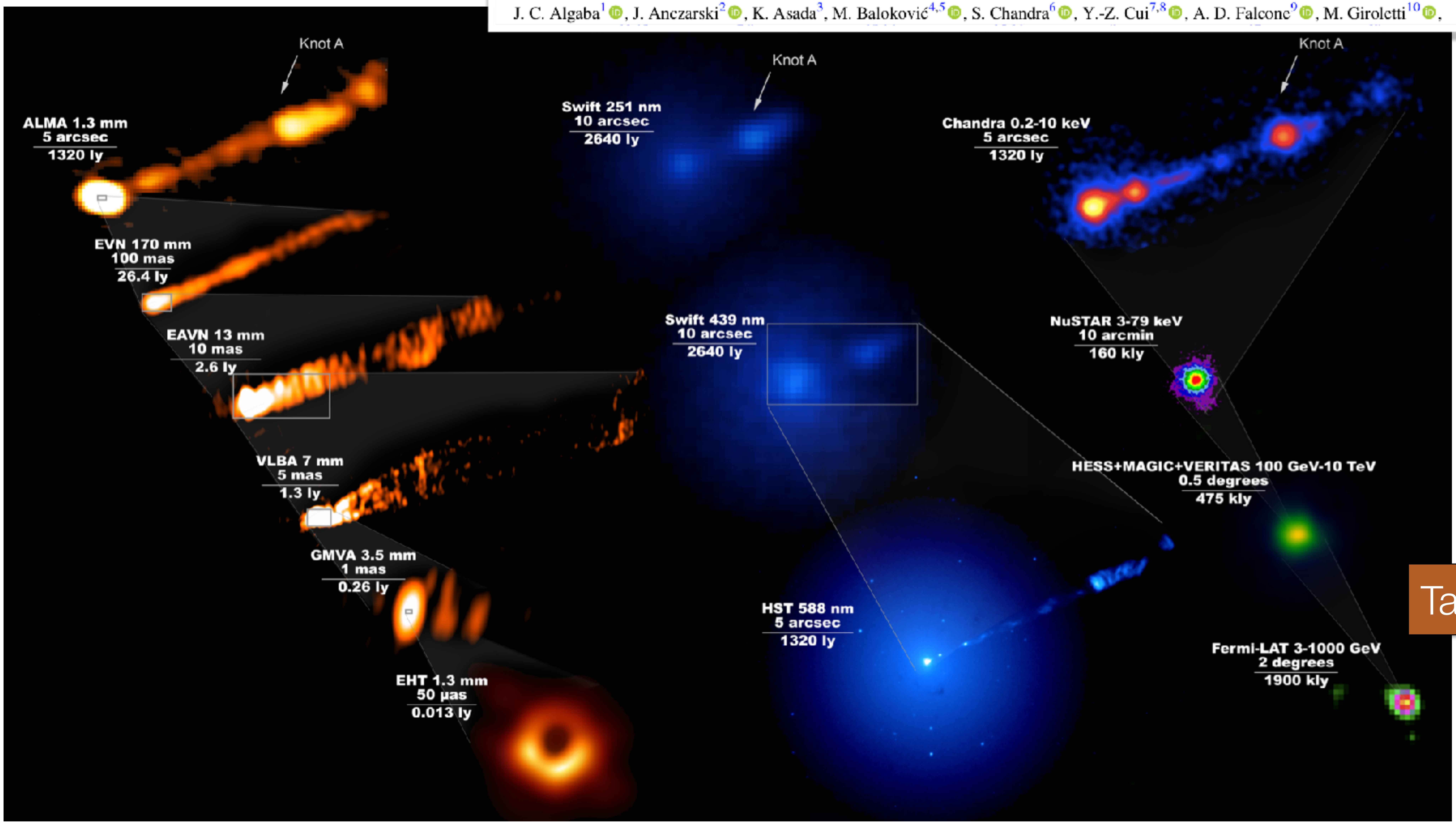
Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign

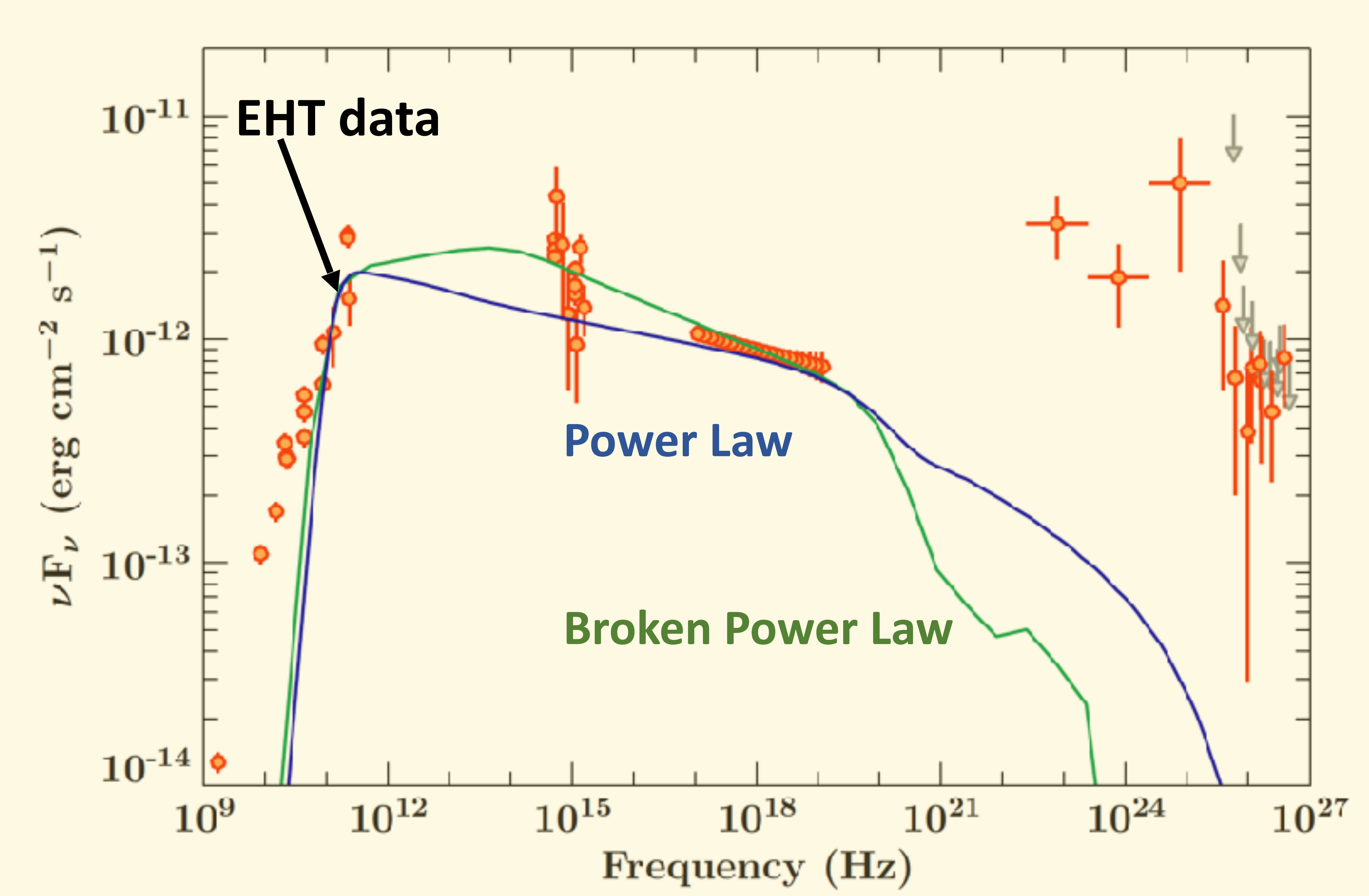
J. C. Algaba[1], J. Anczarski[2], K. Asada[3], M. Baloković[4,5], S. Chandra[6], Y.-Z. Cui[7,8], A. D. Falcone[9], M. Giroletti[10],

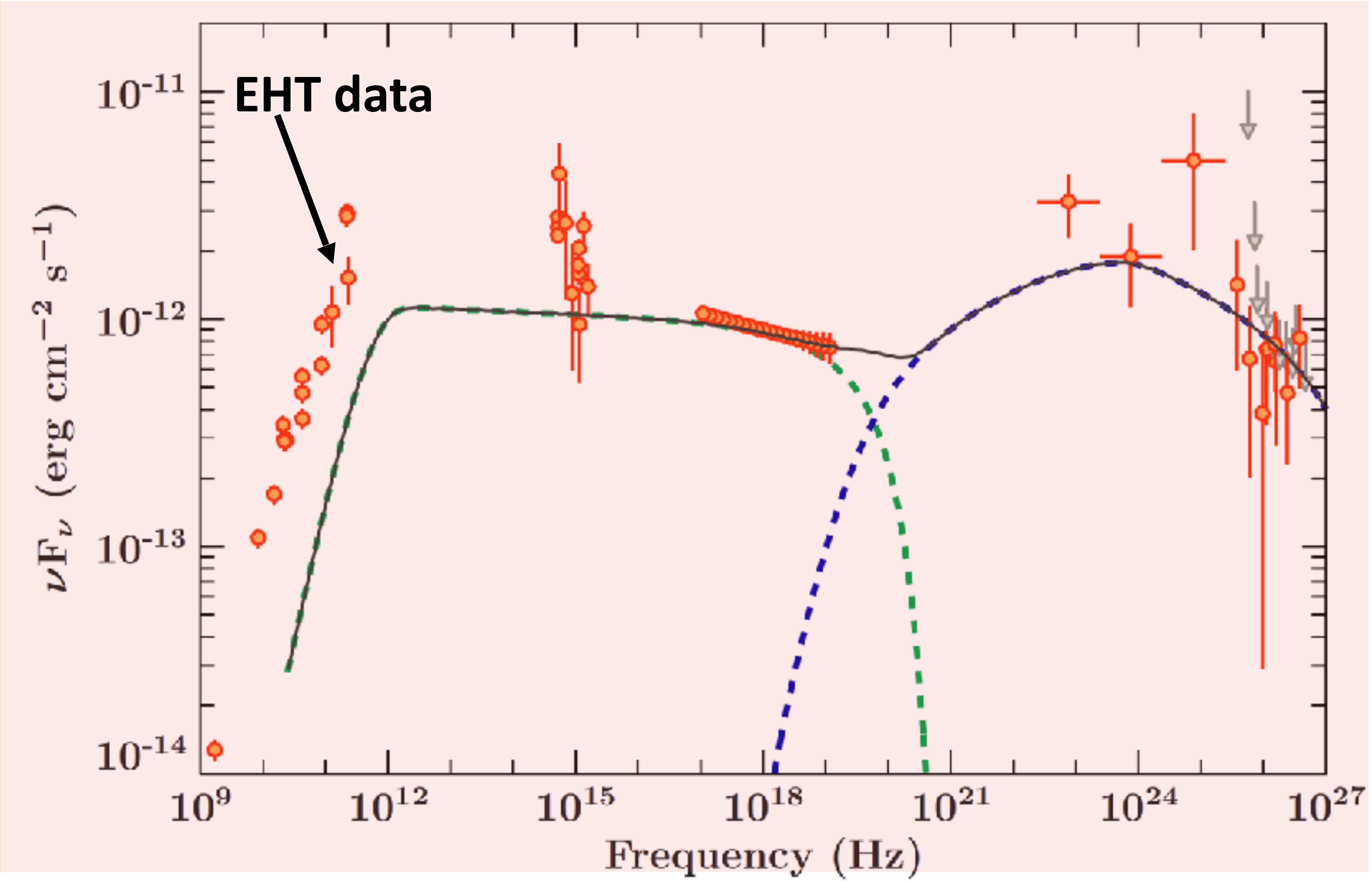


Talk Horan

M87 EHT-MWL: Leptonic SED models

1a/b





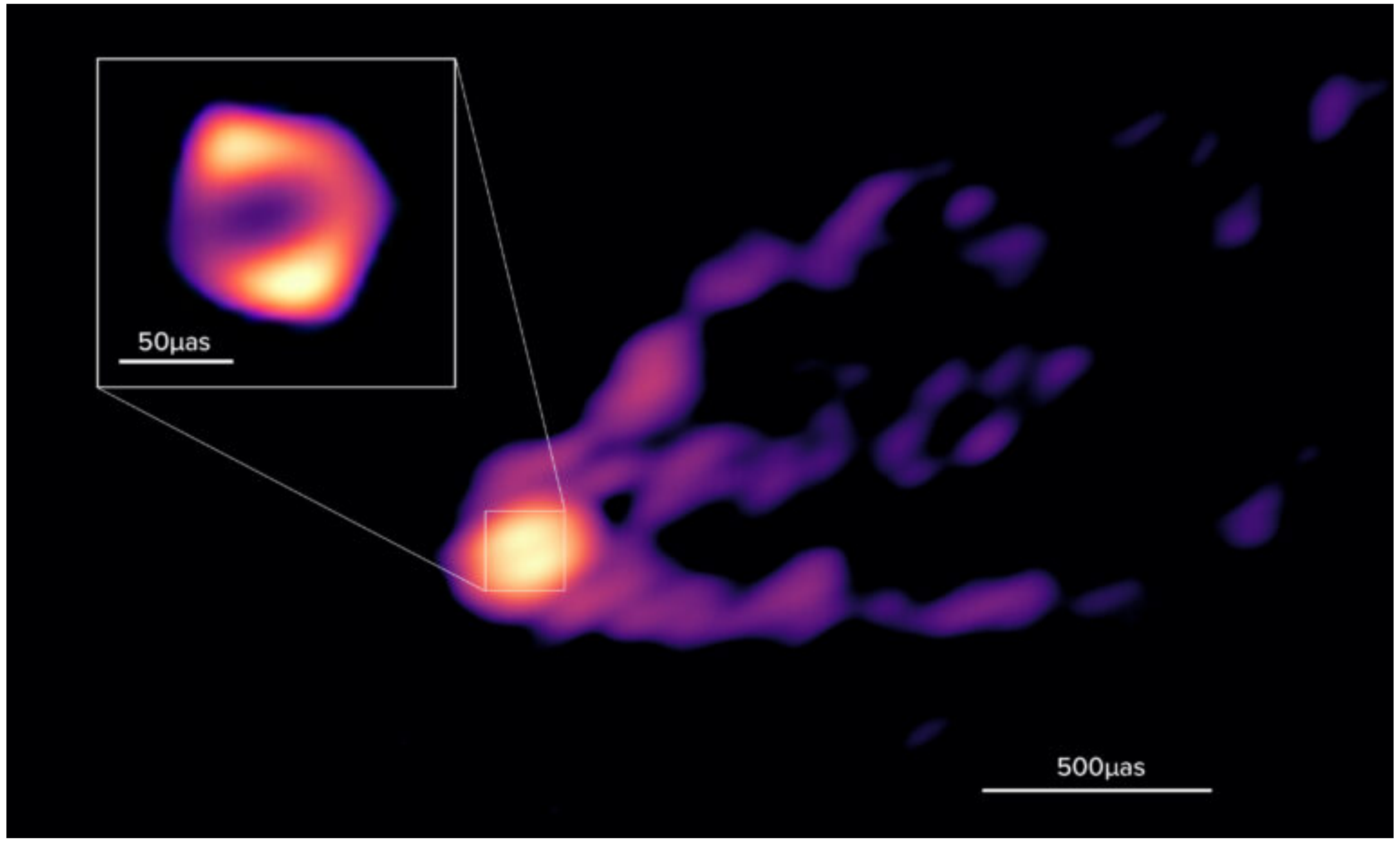
2

Model	L_j [L_{Edd}][a]	δ	R [r_g][b]	n_e [cm^{-3}] [c]	B [G]	γ_{min}	γ_{br}	γ_{max}	p_1	p_2	U_e/U_B
model 1a	6×10^{-3}	1	5.6	3.6×10^5	4.7	1	–	3.5×10^6	2.2	–	2.3
model 1b	1×10^{-3}	1	5.2	1.8×10^5	10	2	1.5×10^3	2×10^6	2.9	3.25	0.16
model 2	$2.8^{+2.0}_{-1.4} \times 10^{-5}$	3.3	626^{+256}_{-301}	9.5×10^{-3}	1.5×10^{-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 γ rays

Moderate magnetic domination at jet base, outer particle dominated region responsible for γ rays

M87: the latest results



Lu et al. (Nature 2023)

3.5mm VLBI+ALMA observations

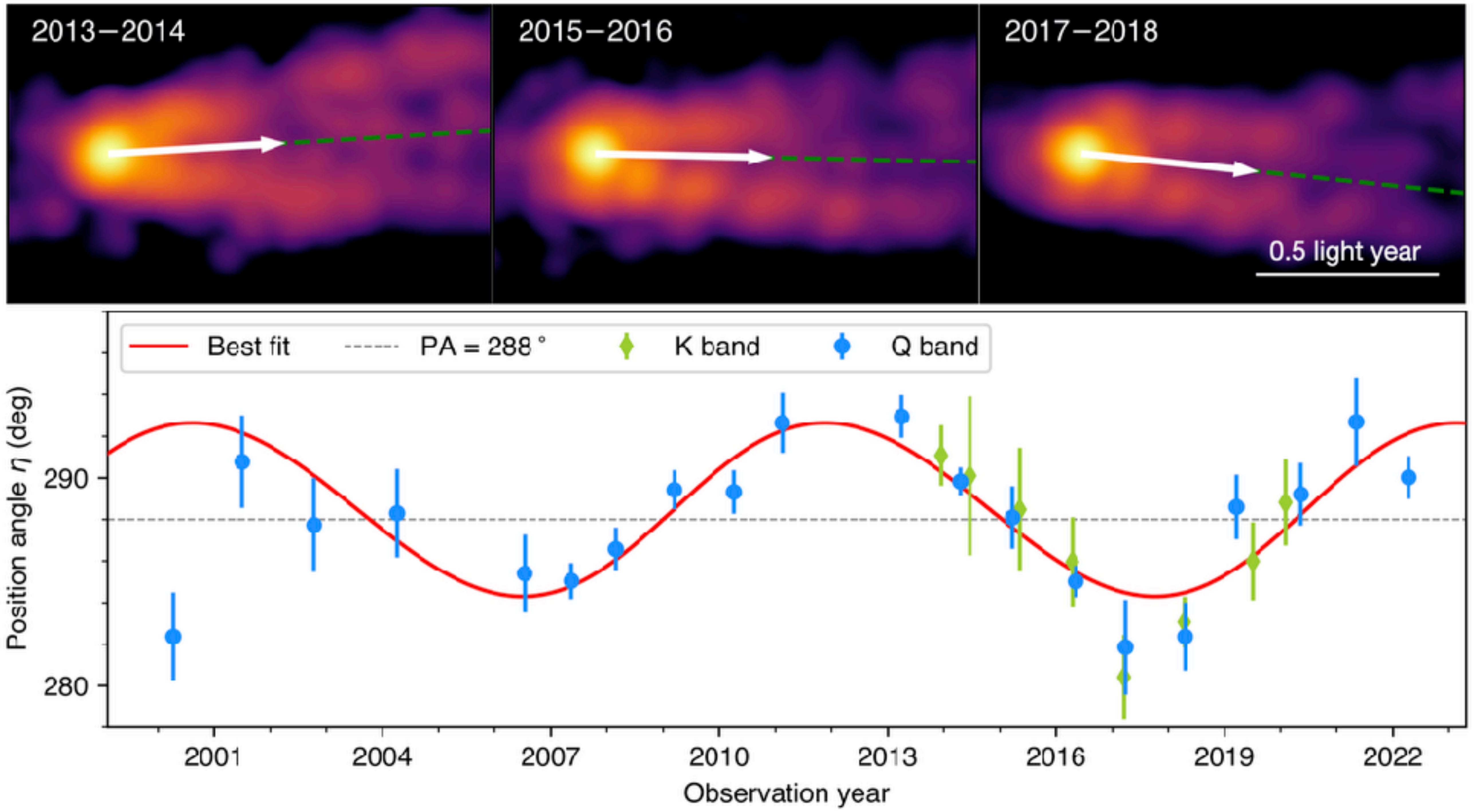
BH shadow and jet launching region imaged simultaneously!

Cui et al. (Nature 2023)

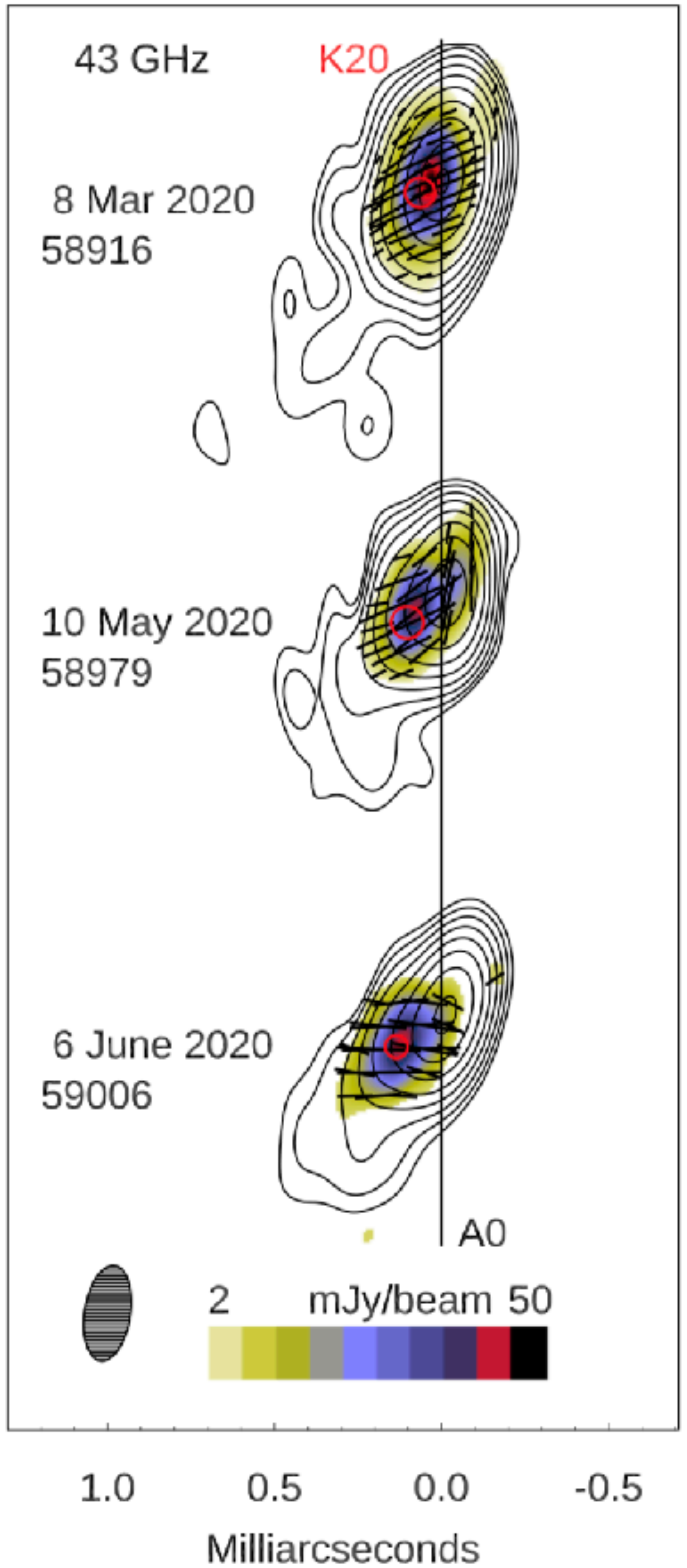
164 VLBI epochs over 22 years

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

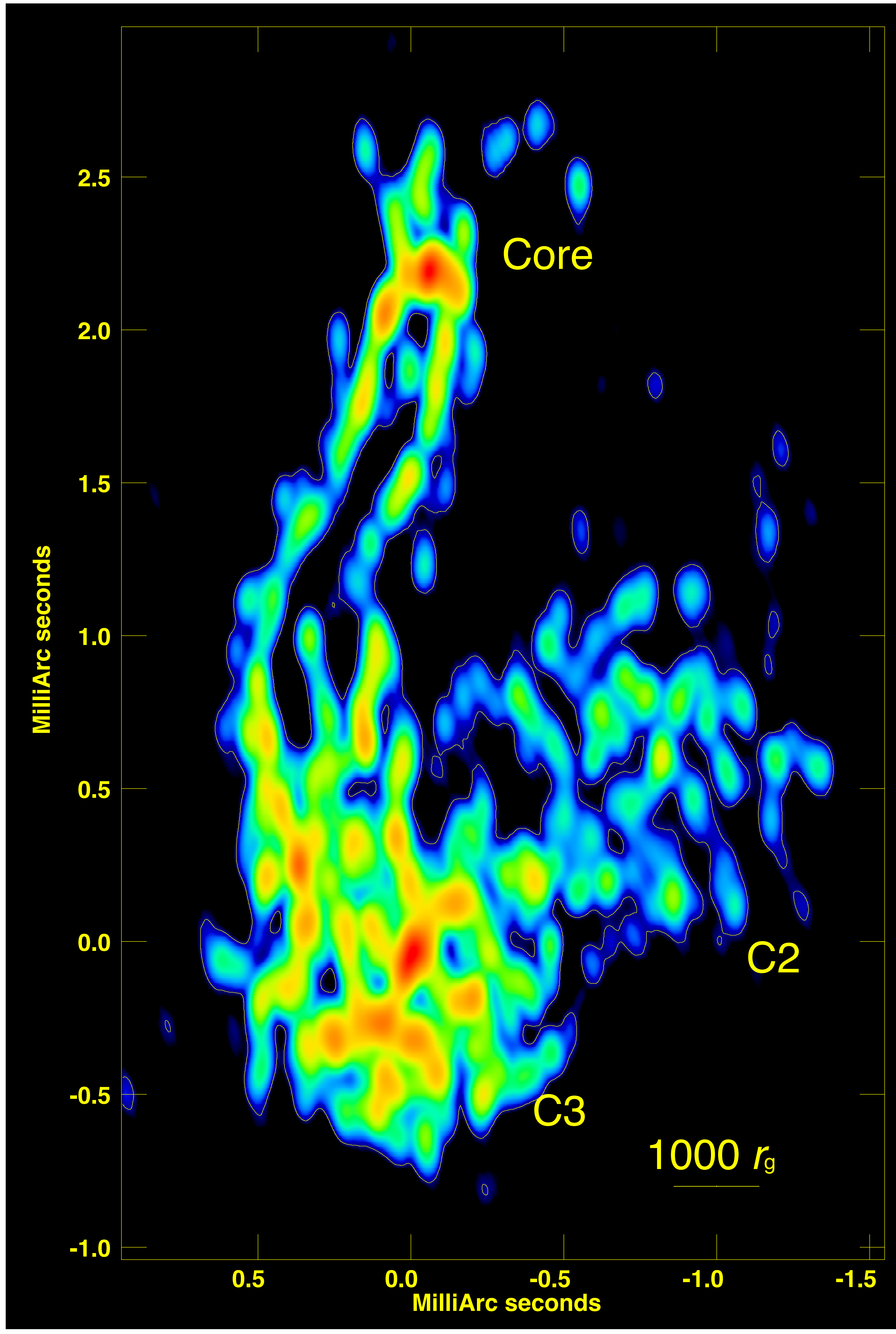
Ejection of new VLBI component associated with VHE emission and EVPA rotation (Acciari et al. 2021)

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 enhancment) with very wide opening angle at jet base (Giovannini et al. 2018, NatAst)

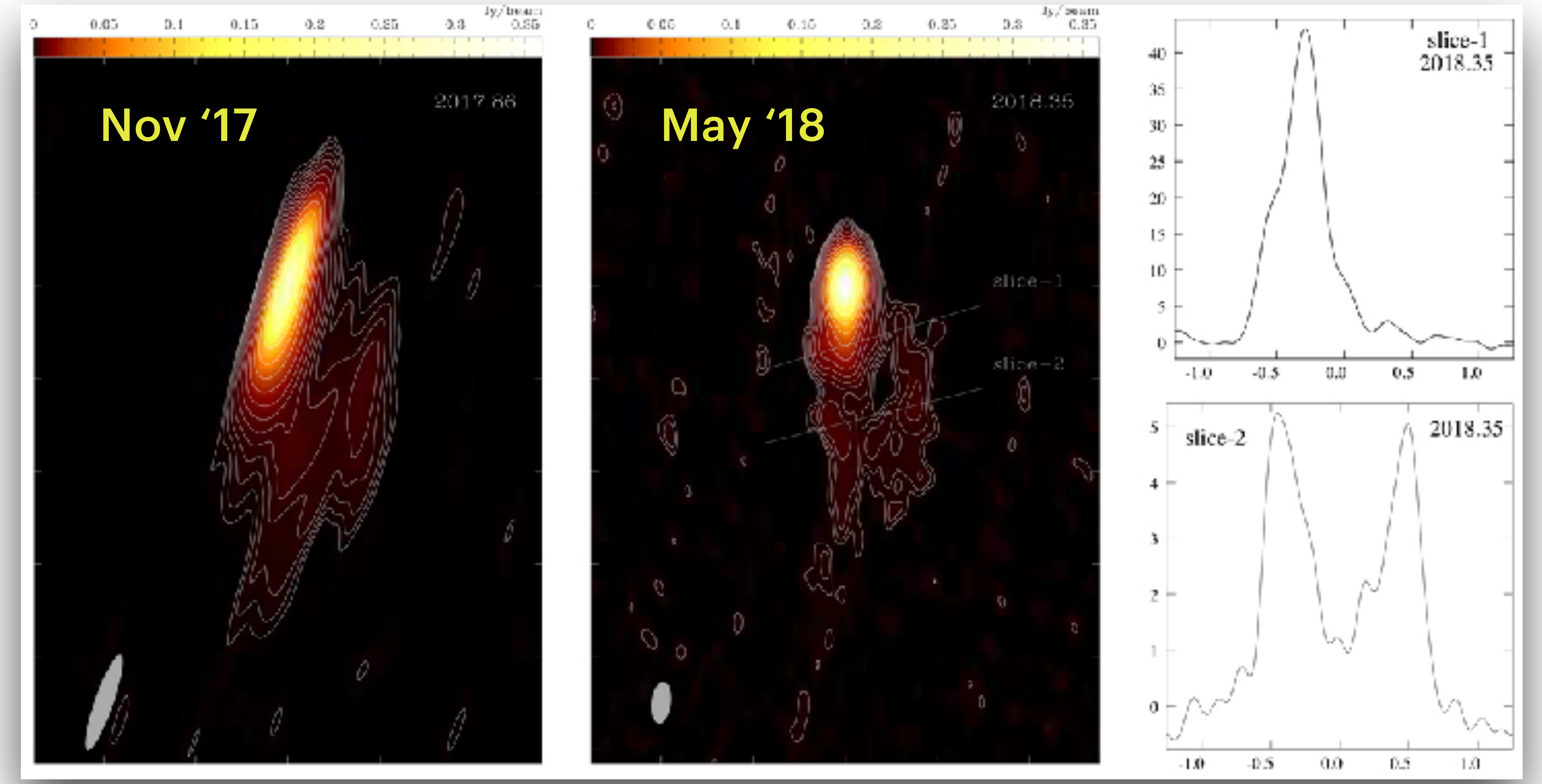


TXS 0506+056, 43 GHz

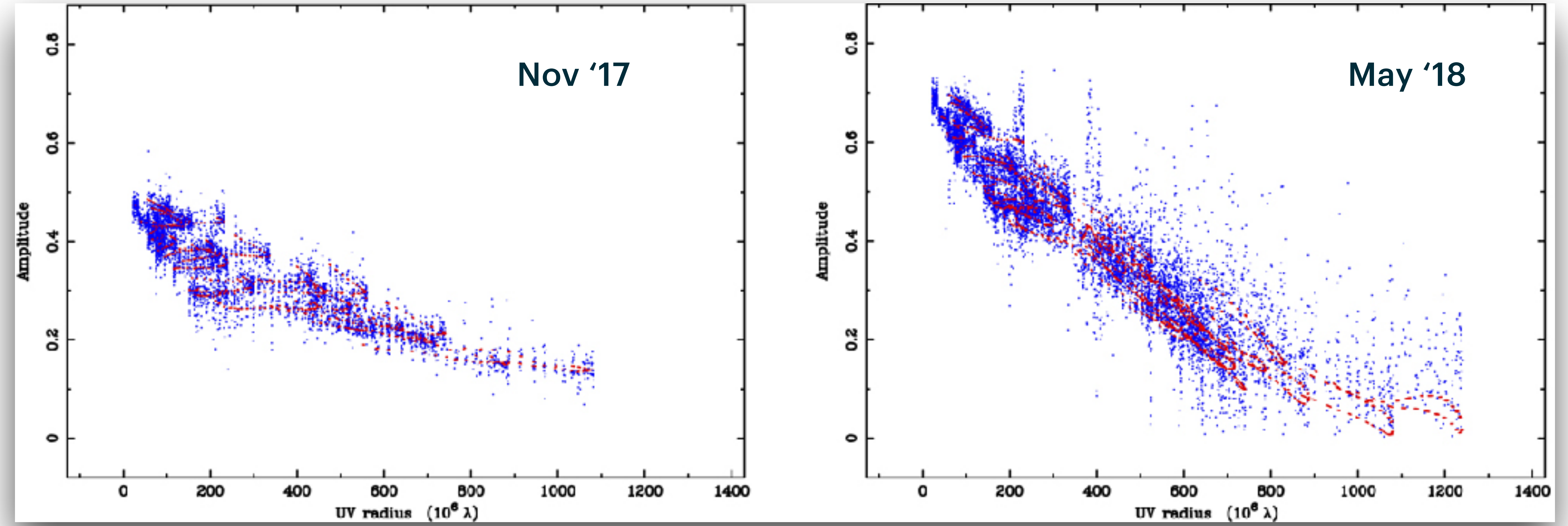
Talks Halzen, Santander, Asano

- 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 ν production (e.g. Tavecchio et al., 2014)



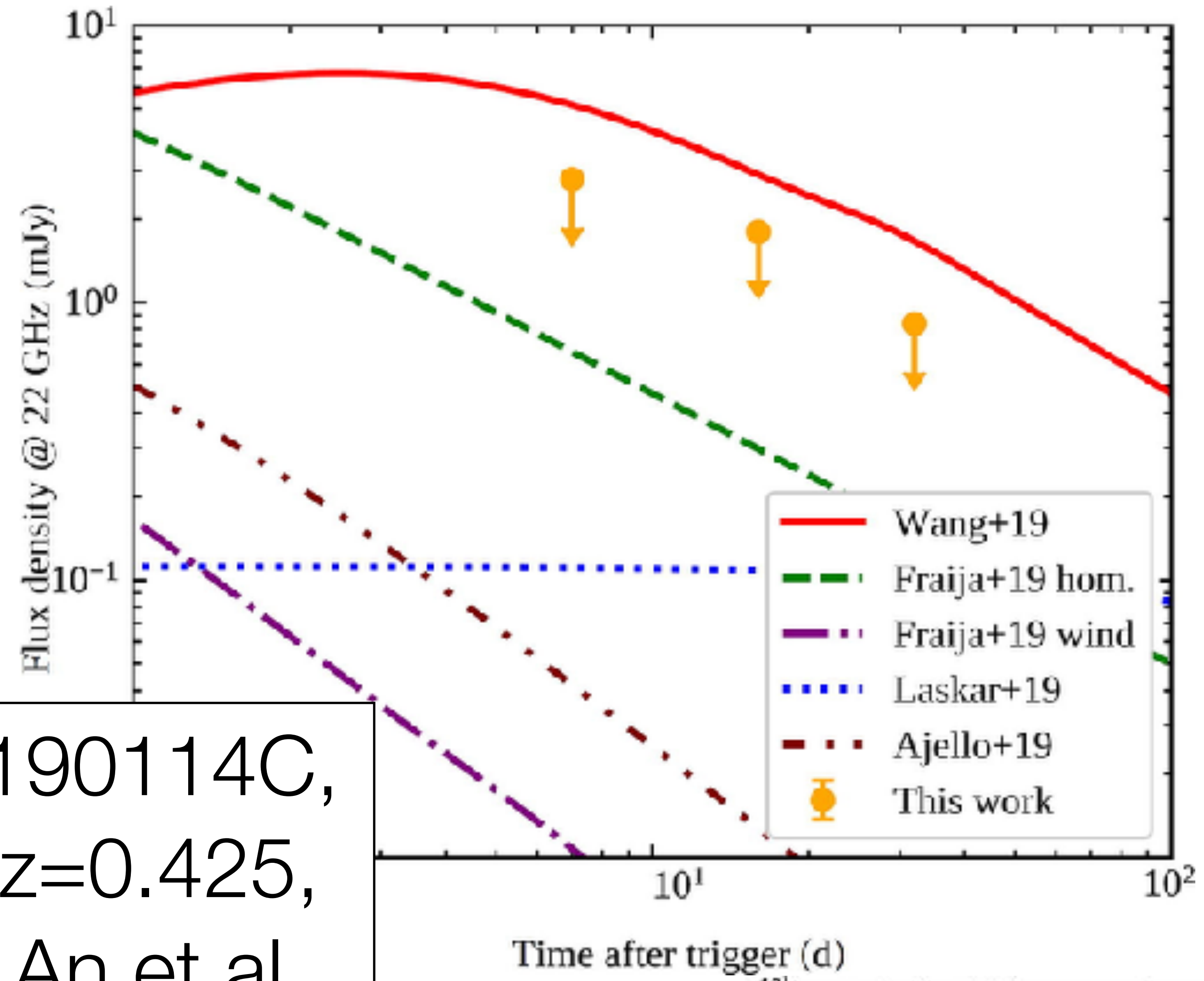
45 µas increase in core size during 6 months; corresponding to ~2c expansion speed

VHE-VLBI: Gamma Ray Bursts

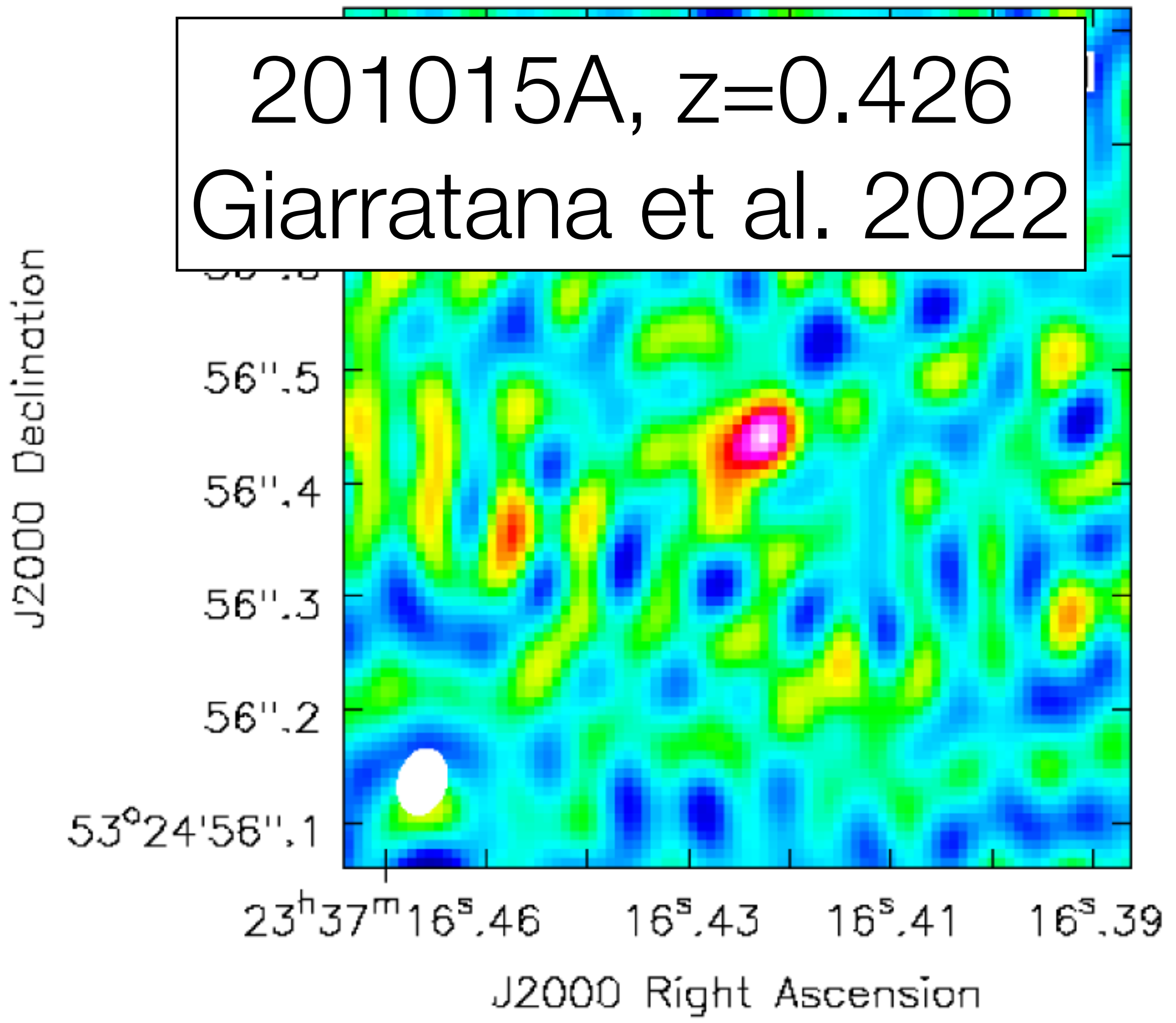
Talks Ghirlanda, Berti

other extragalactic transients: Marcote, Salafia

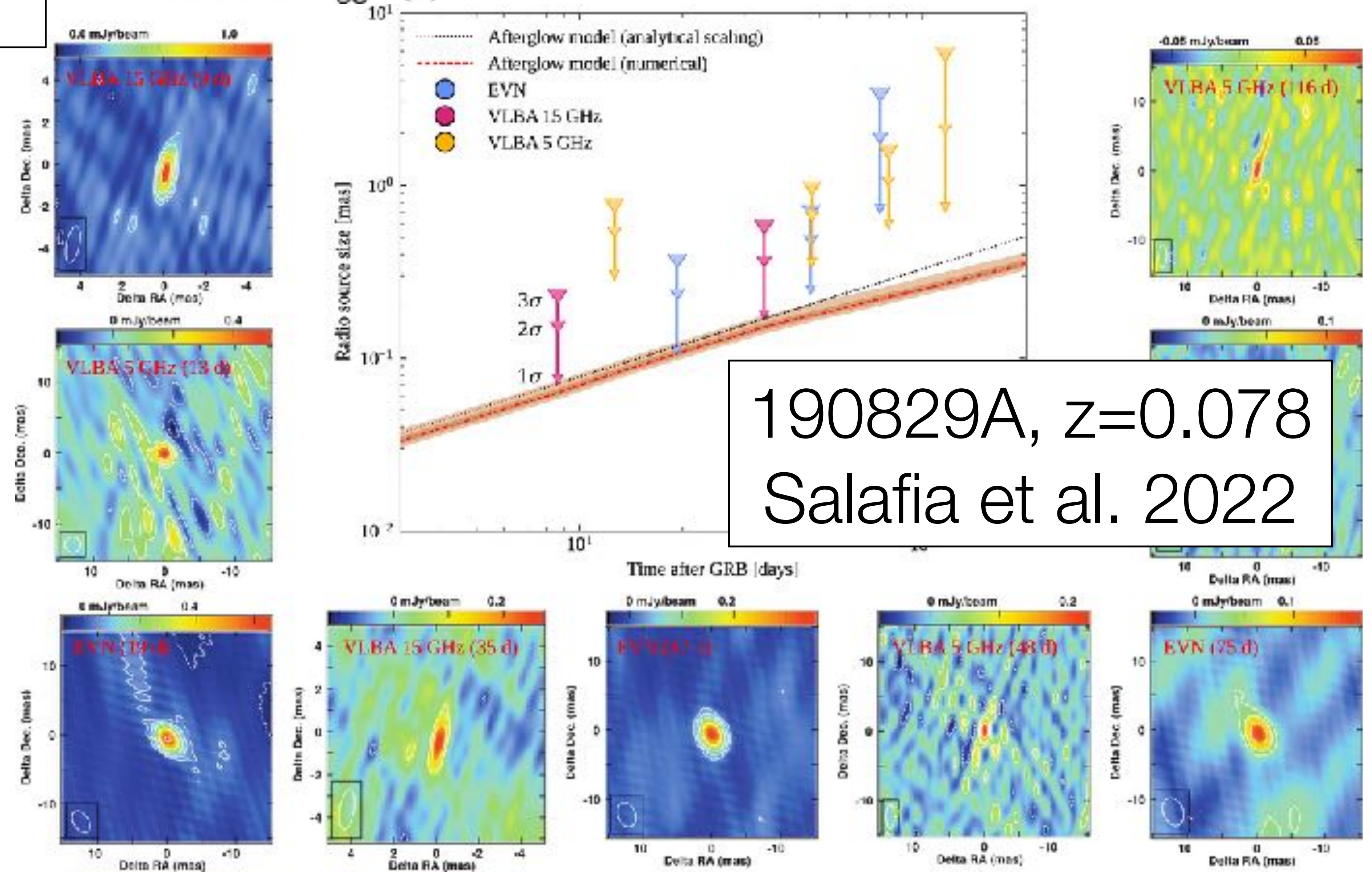
- Radio emission from afterglows can stay bright for months
- VLBI is the only way to have direct evidence of relativistic ejection implied by modelling:
  - on axis ("classical") events: blob expansion
  - misaligned ("atypical") events: proper motion
- A handful of VHE-detected GRBs (mostly by MAGIC),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



190114C, z=0.425, An et al.



201015A, z=0.426
Giarratana et al. 2022



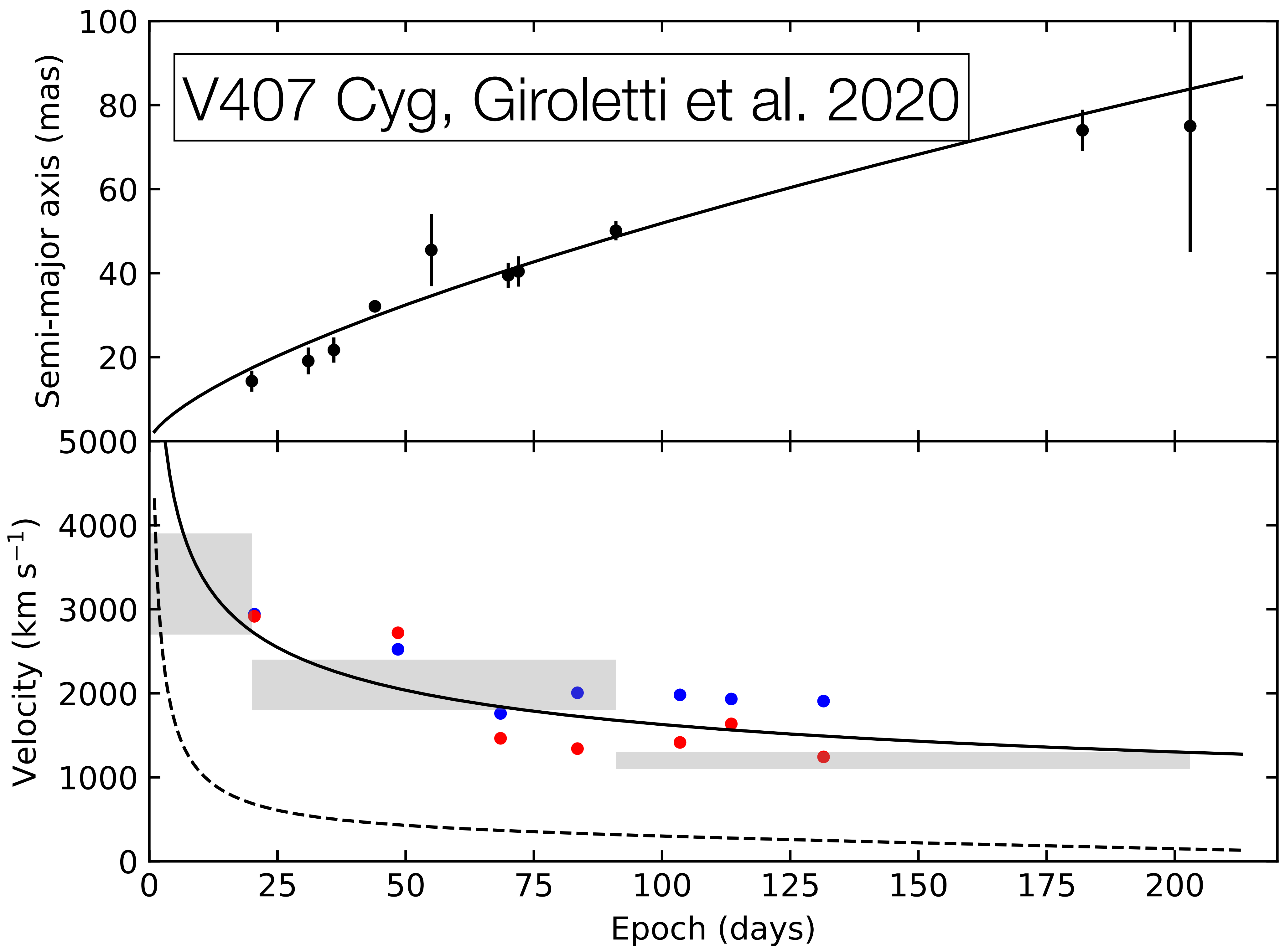
190829A, z=0.078
Salafia et al. 2022

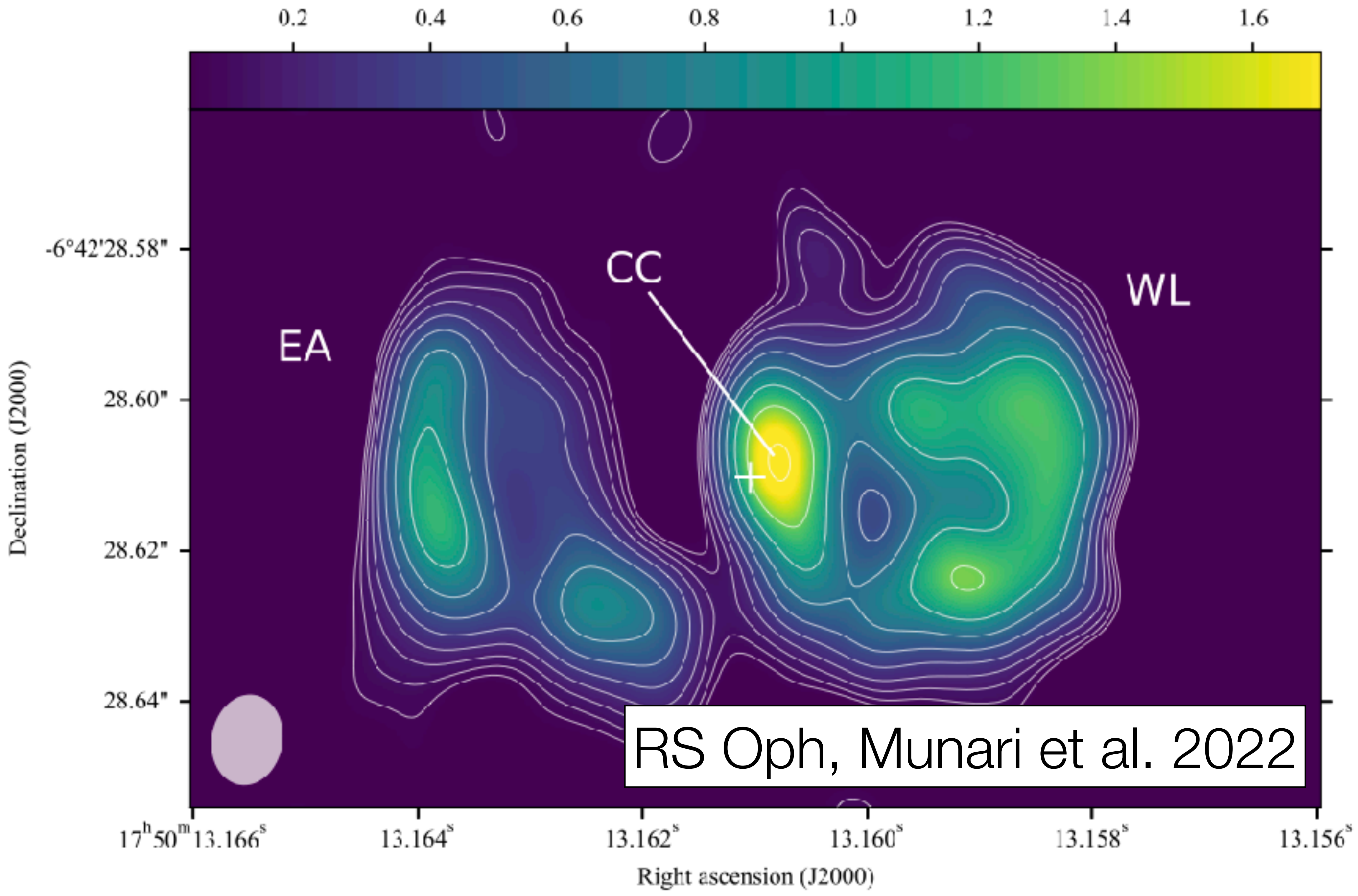
VHE-VLBI: Galactic - (symbiotic) novae

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

Talk Miceli

Sardinia, 64m, Medicina, 32m, Noto, 32m

Bologna, software correlator (DiFX)

collecting area

INAF: 4825 m^2; VLBA: 4909 m^2

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**

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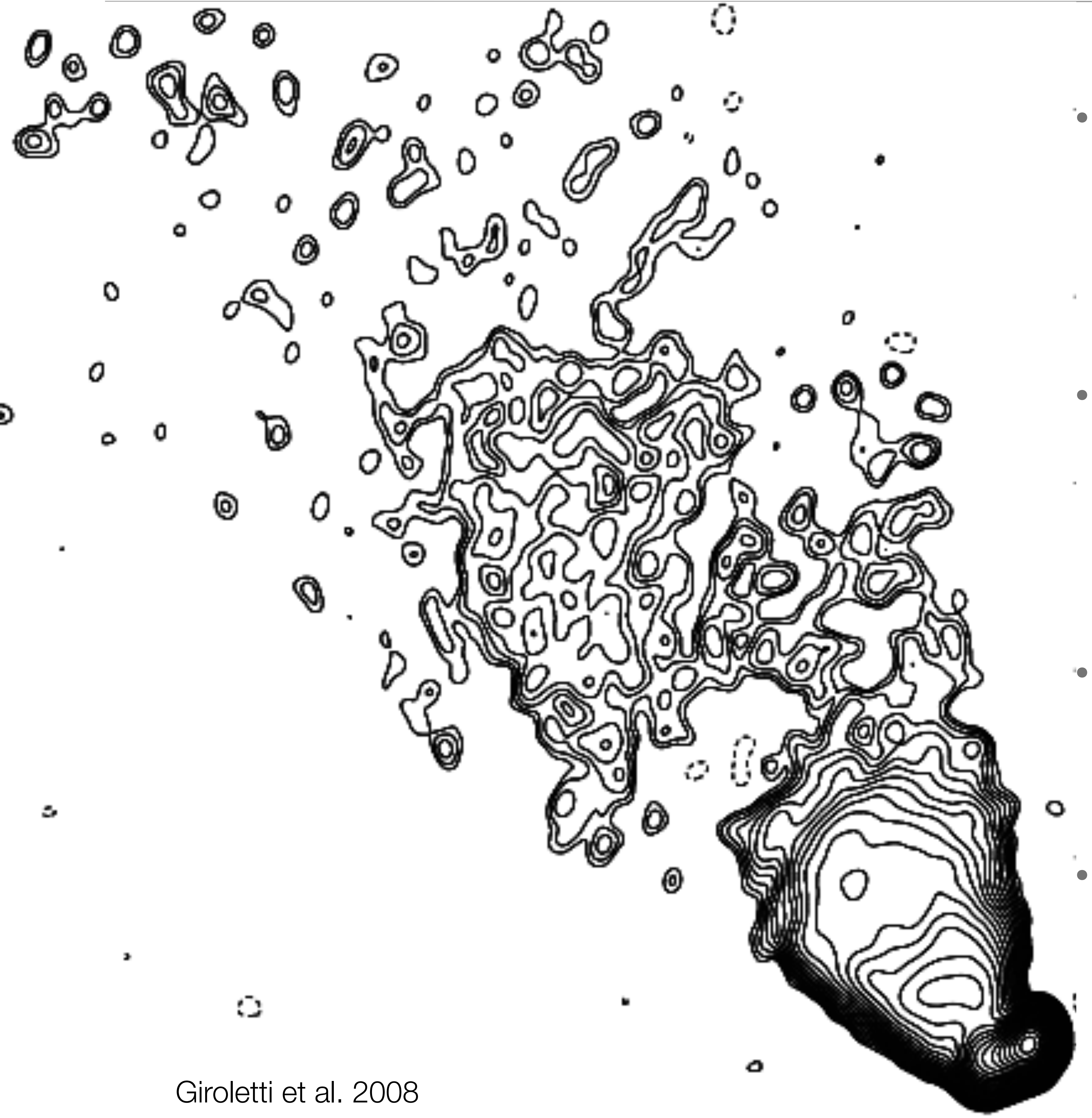
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Take home messages



Giroletti et al. 2008

- 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!