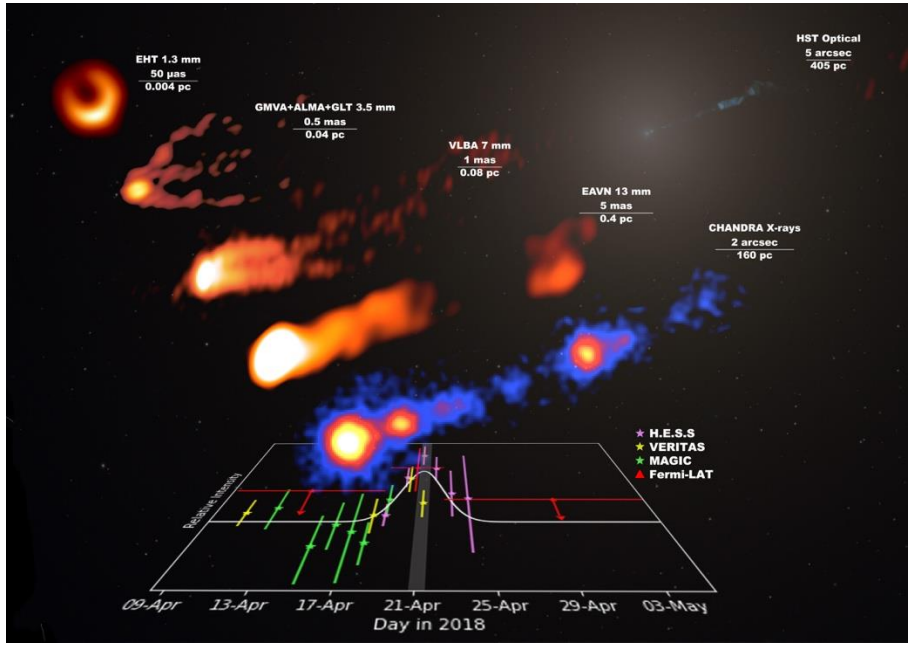
Synergy between high-resolution VLBI and VHE γ-ray observations in the study of AGN jets



The extreme Universe viewed in very-high-energy gamma-rays 2024

ICRR, Jan. 7-8 2025

Kazuhiro Hada (Nagoya City Univ. / NAOJ)

Outline

- Brief introduction
- EHT+MWL observations of M87 jet
- East Asia VLBI observations TeV AGN

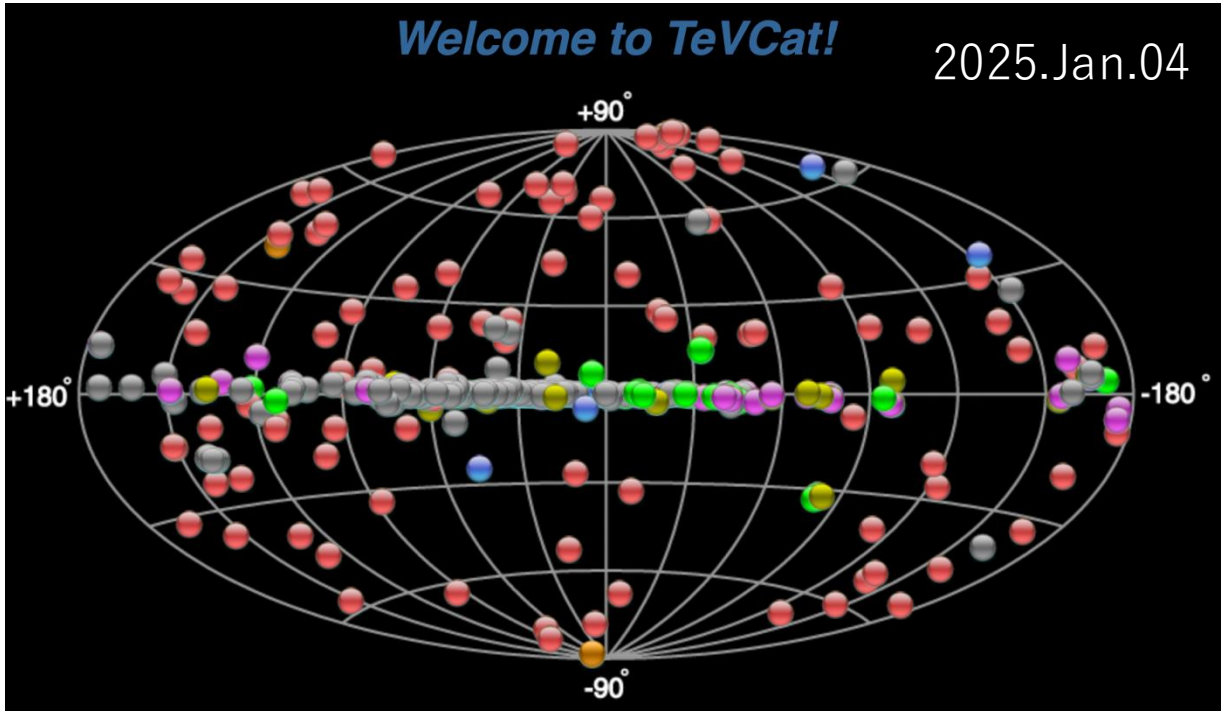
TeV gamma-ray sky

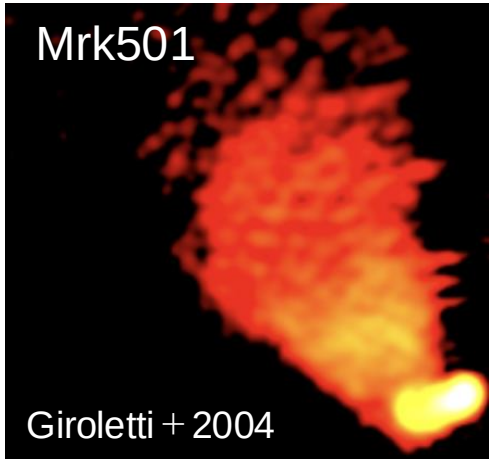
- More than 25% of known TeV sources are extragalactic AGN
- Rapid TeV variability - tiny sizes of emission region (light-days - light weeks), impossible to spatially resolve with current TeV instruments

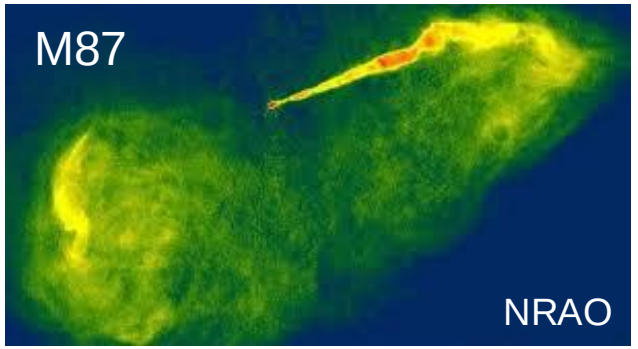
- Virtually all TeV-detected AGN are bright in radio bands (“radio-loud”)
  - Blazars (mainly HBL)
  - QSOs, Radio galaxies, LLAGN etc

↓

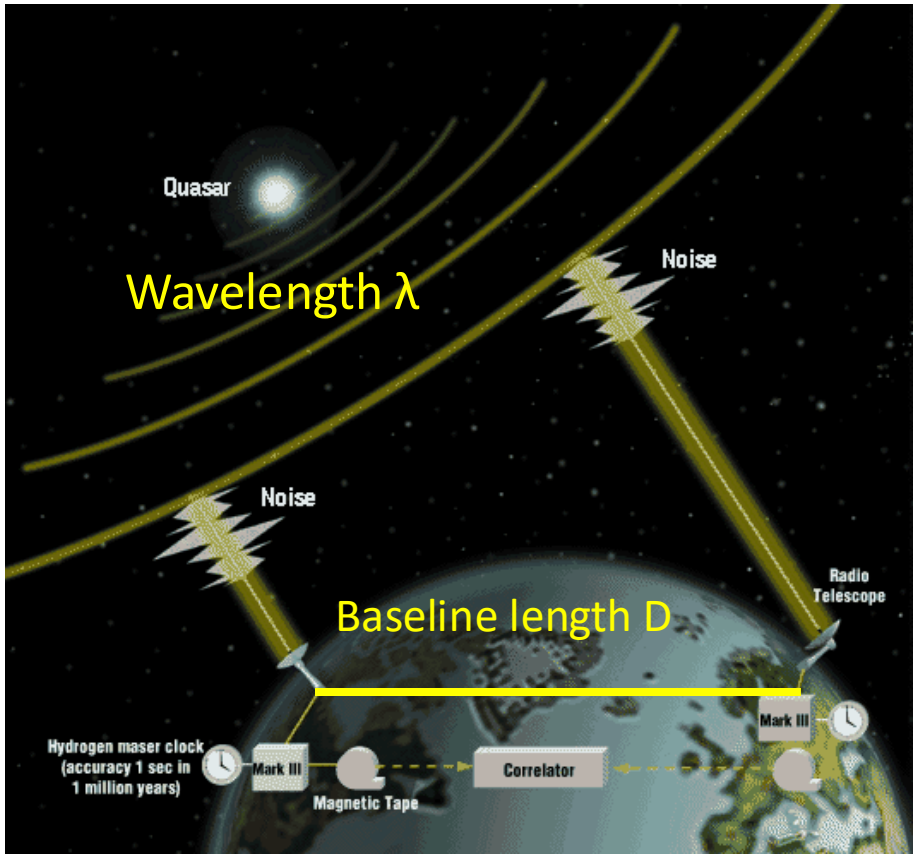
High-resolution observations at radio wavelengths



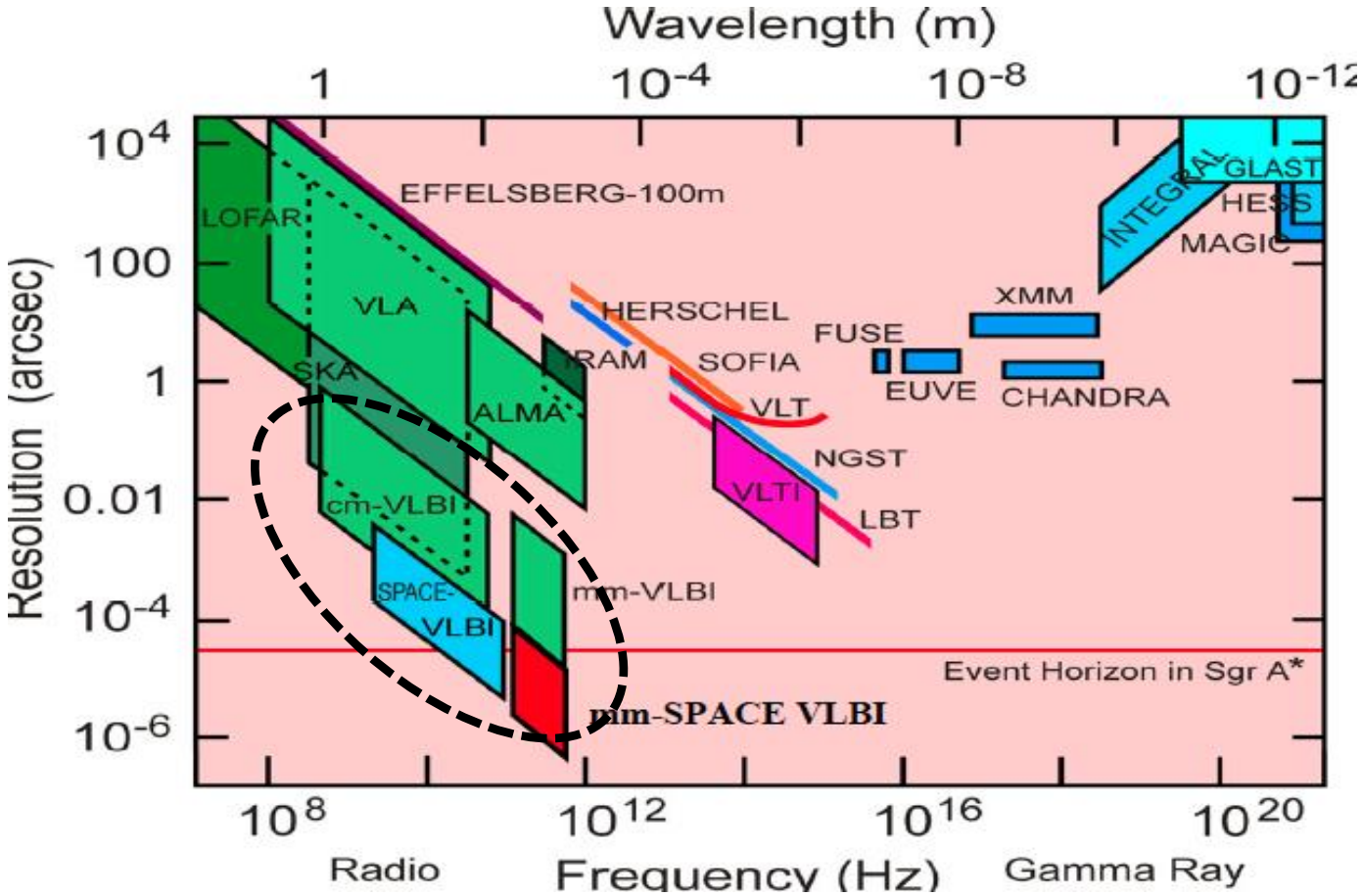




Very long baseline interferometry (VLBI)



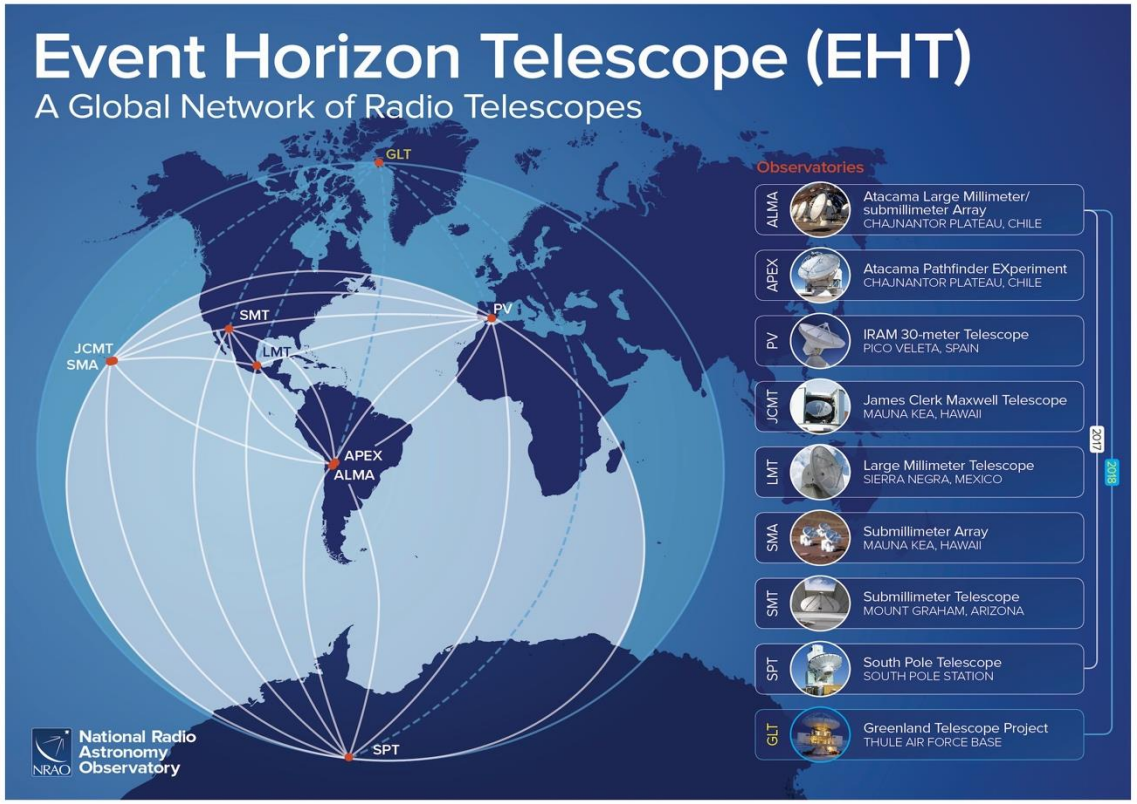
NASA



$$\theta = \lambda / D$$

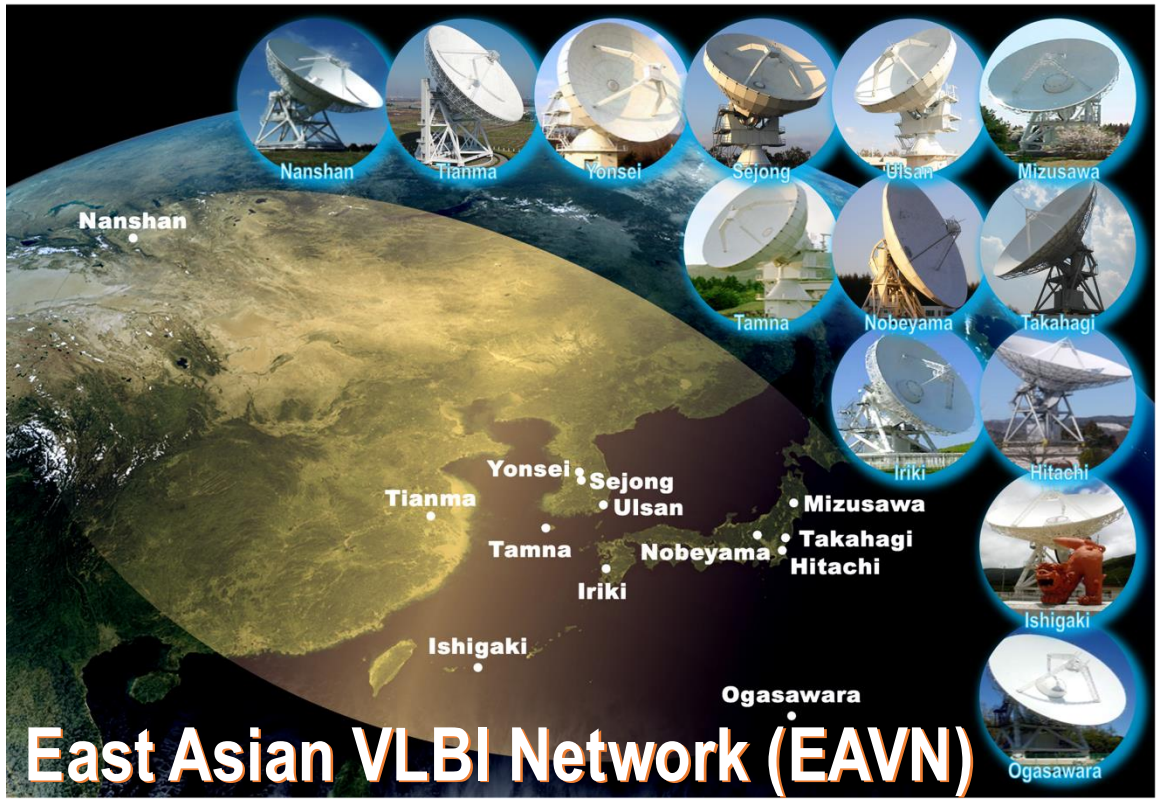
VLBI networks

VLBI @ mm



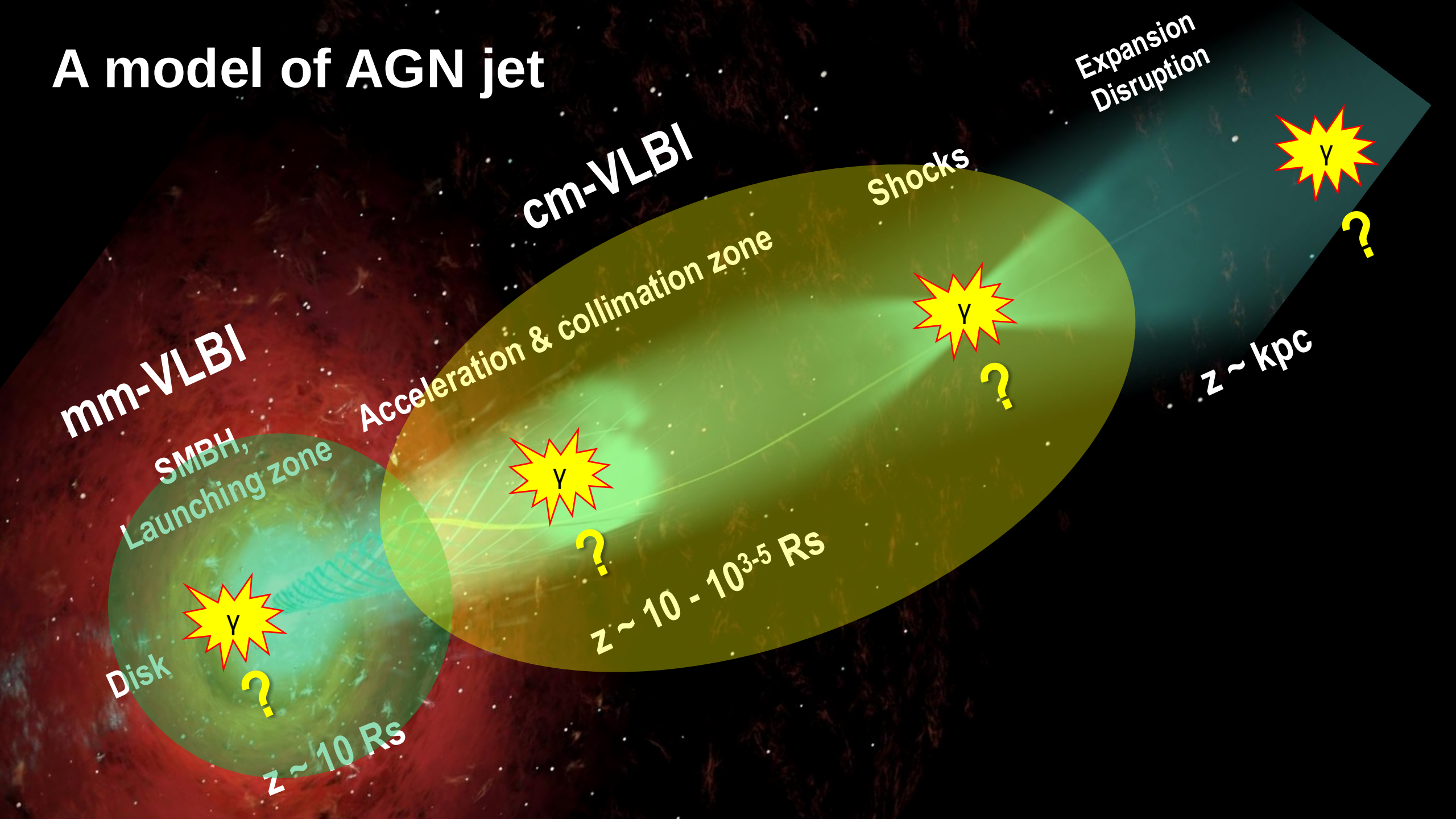
- λ ~ 0.87 - 1.3mm (230-345GHz)
- θ ~ 20 micro-arcseconds
- Higher resolution, higher transparency

VLBI @ cm



- λ ~ 3mm – 20cm (1-86GHz)
- θ ~ 1 - 0.1 milli-arcseconds
- Higher sensitivity, larger FoV

A model of AGN jet



EHT+MWL observations of M87

- EHT MWL Science WG et al. 2021
- EHT MWL Science WG et al. 2024

See also KH+2024 A&AR

Astron Astrophys Rev (2024)32:5
https://doi.org/10.1007/s00159-024-00155-y

REVIEW ARTICLE

M 87: a cosmic laboratory for deciphering black hole accretion and jet formation

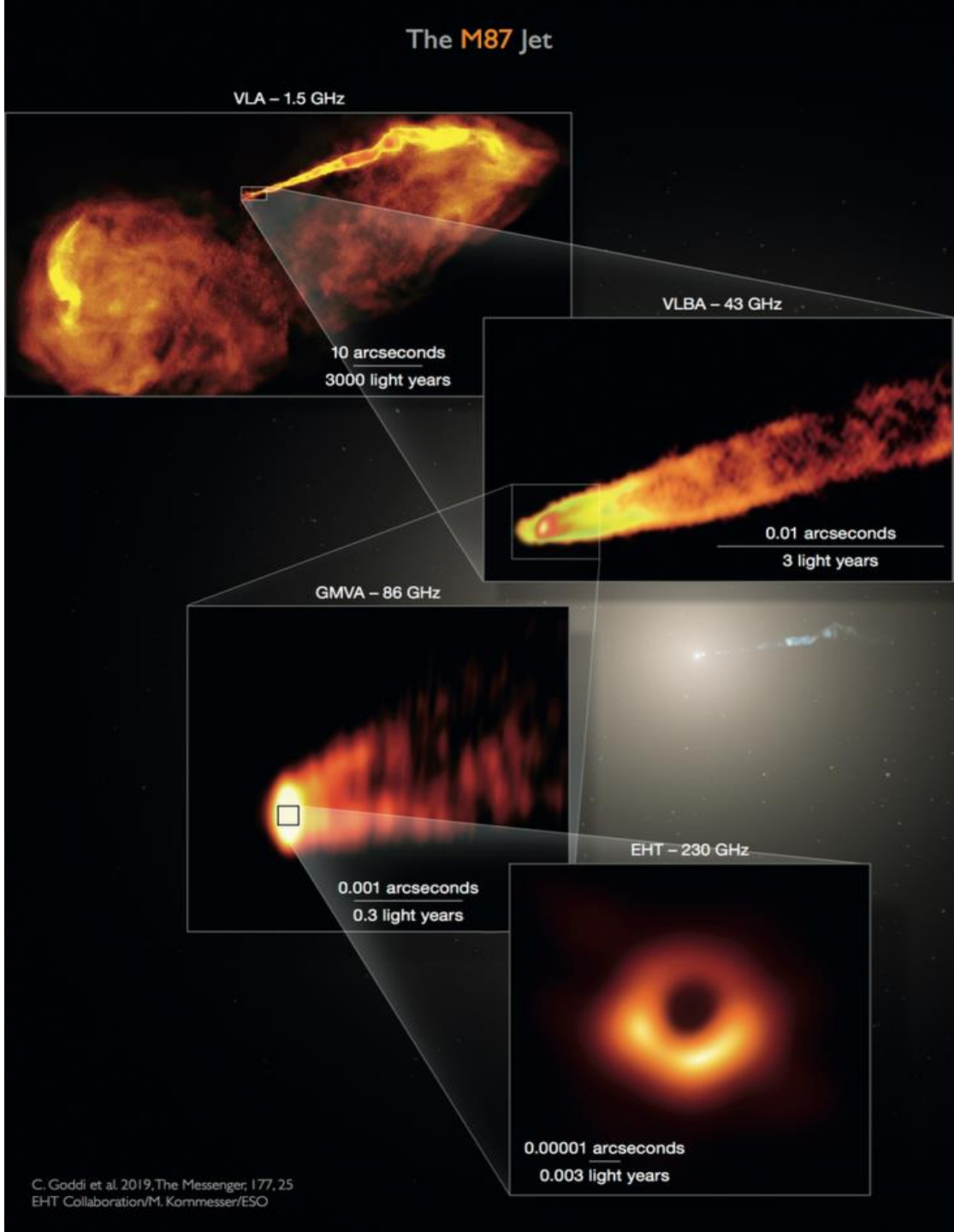
Kazuhiro Hada[1,2,3] · Keiichi Asada[4] · Masanori Nakamura[4,5] · Motoki Kino[6,7]

M87

- Nearby FR-I (D=16.7 Mpc)
- Large SMBH (M_{BH} = 6.5 x $10^9 M_{sun}$)

In radio bands

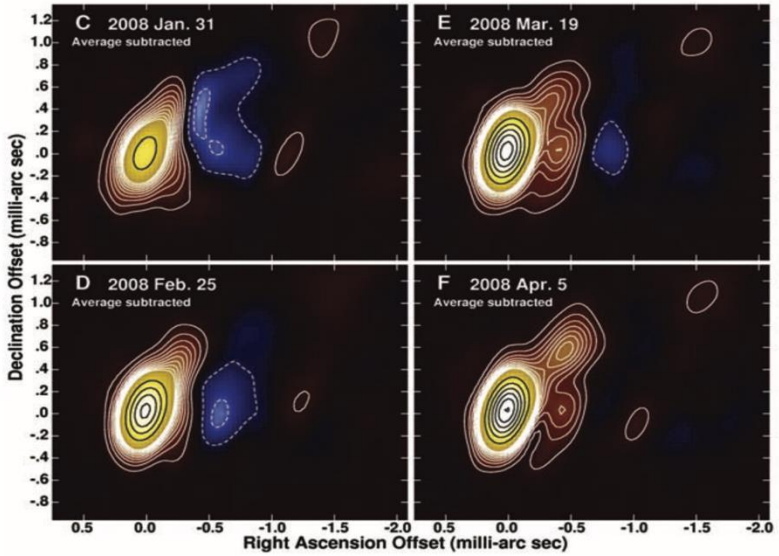
- Spatially-resolved SMBH shadow
- Spatially-resolved relativistic jets from horizon to kpc scales



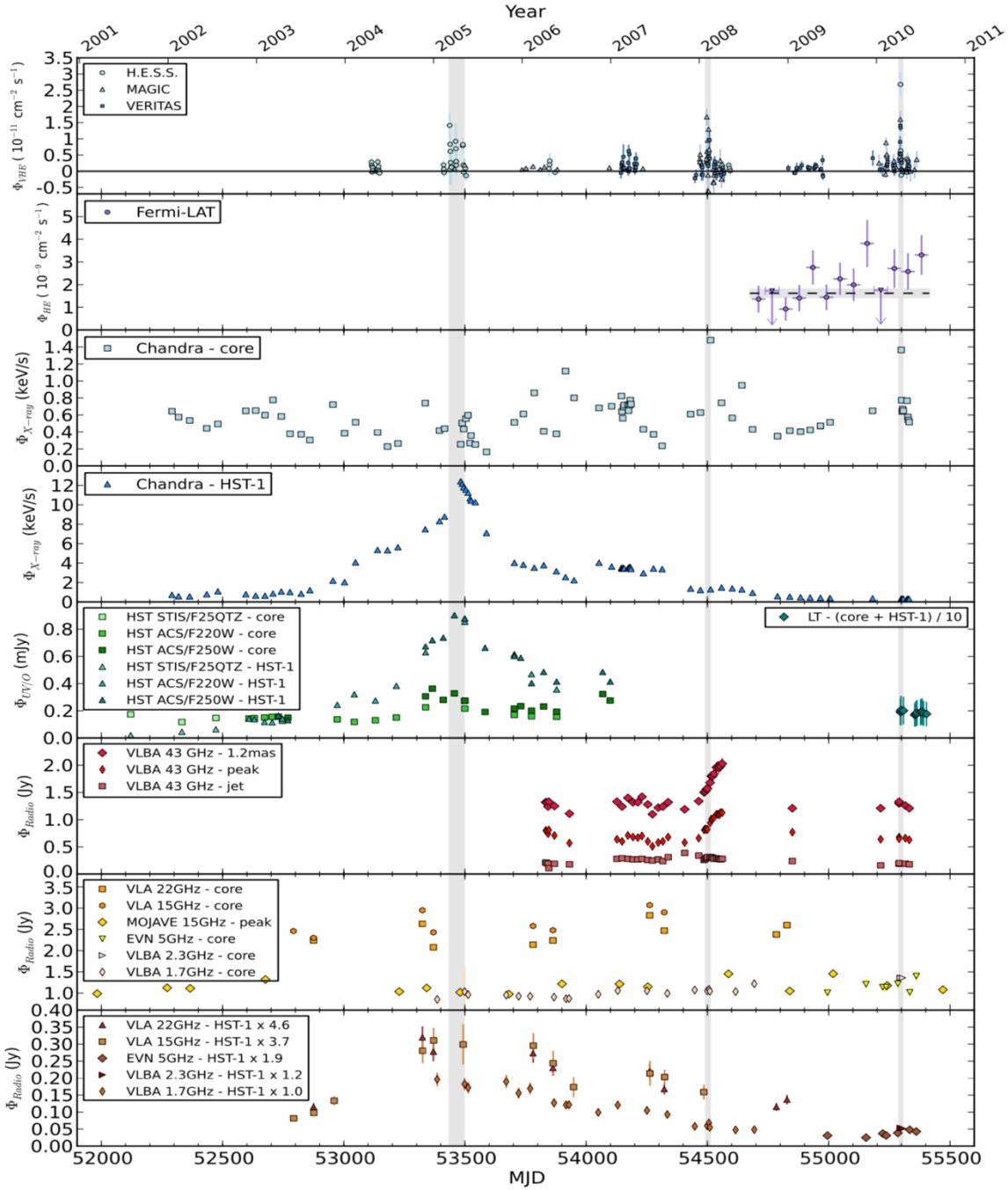
Goddi et al. 2019

M87 as a γ-ray emitter

- One of few VHE detected radio galaxies
- Past VHE observations suggest:
  - $R_{VHE} \sim a\ few\ \times\ Rs\ \delta\ \Delta t_{days}$
- In the 2008 VHE event, superluminal ejection from the VLBI core at jet base
- (At least part of) VHE emission must originate from the very vicinity of SMBH

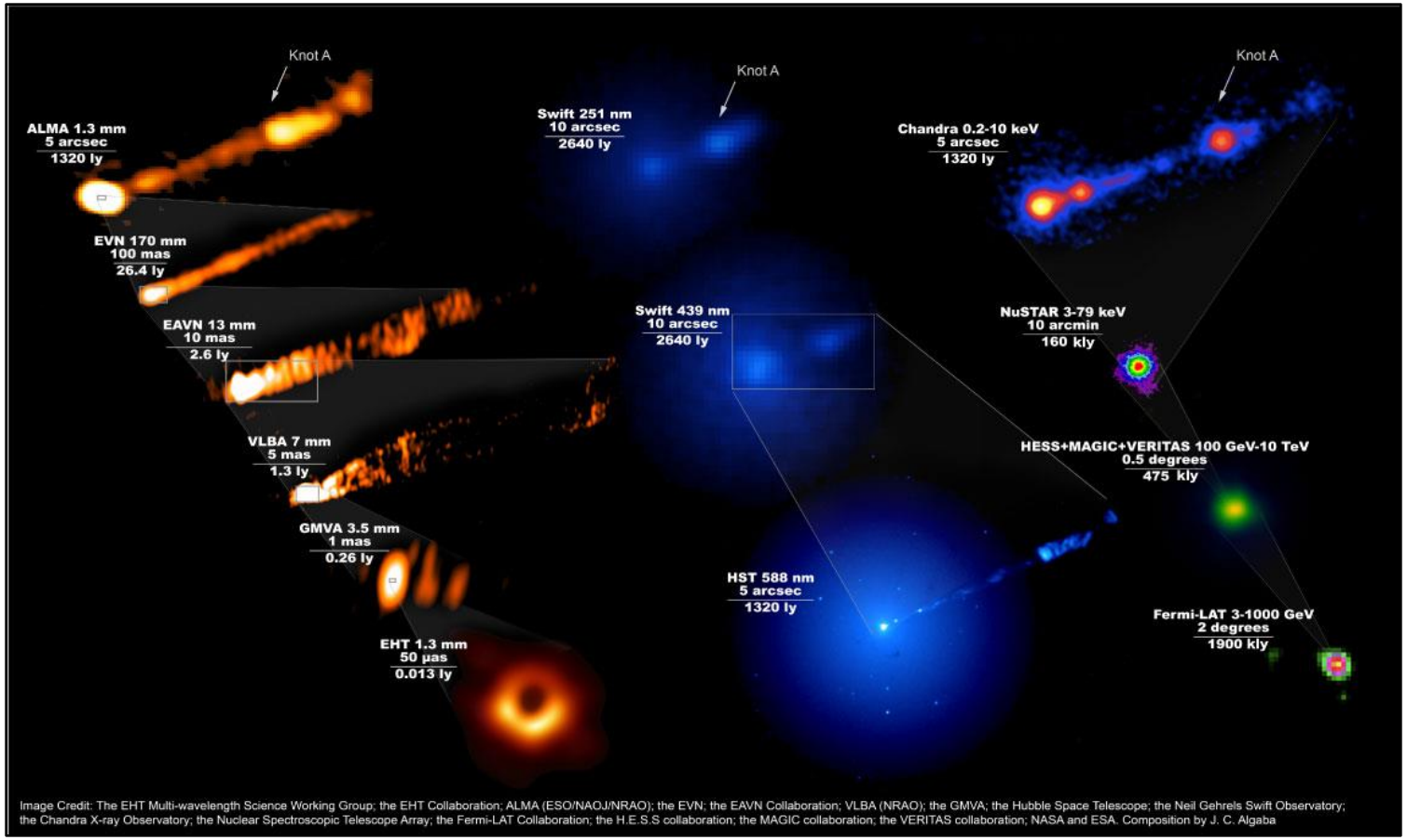


Acciari+2009



Abramowski+2012

A new era has begun in the MWL study of M87

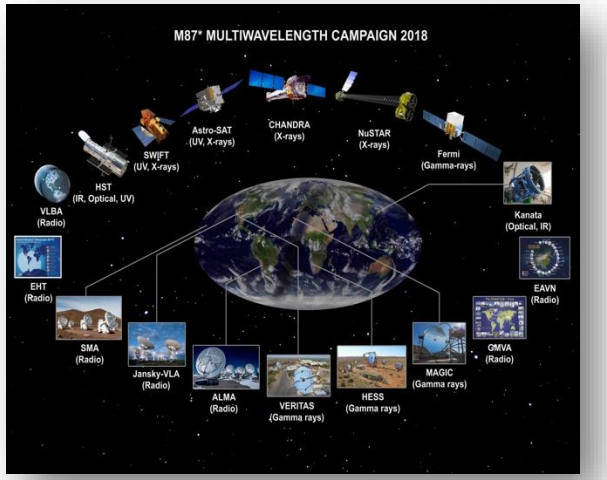


EHT MWL Science WG et al. 2021

- Since 2017, EHT has joined the annual MWL campaign of M87
- Quasi-simultaneous MWL data including EHT images

→ Scales of "R_{VHE}" can be spatially resolved & imaged !

Cumulative summary of EHT-MWL campaigns 2017-2024



Facility/Sources	M87					SgrA*						3C279						OJ287						3C273						NRAO530						J1924				Mrk501			PKS1510		CenA			3C84		NGC4261	1055+018	3C454.3	J1555+111	BLLac	CygA
Year of Observation	17	18	21	22	24	17	18	21	22	23	24	17	18	21	22	23	24	17	18	21	22	23	24	17	18	21	22	23	24	17	18	21	22	23	24	21	22	23	24	18	21	22	18	22	17	21	22	22	23	23	24	21	22	23	23	23
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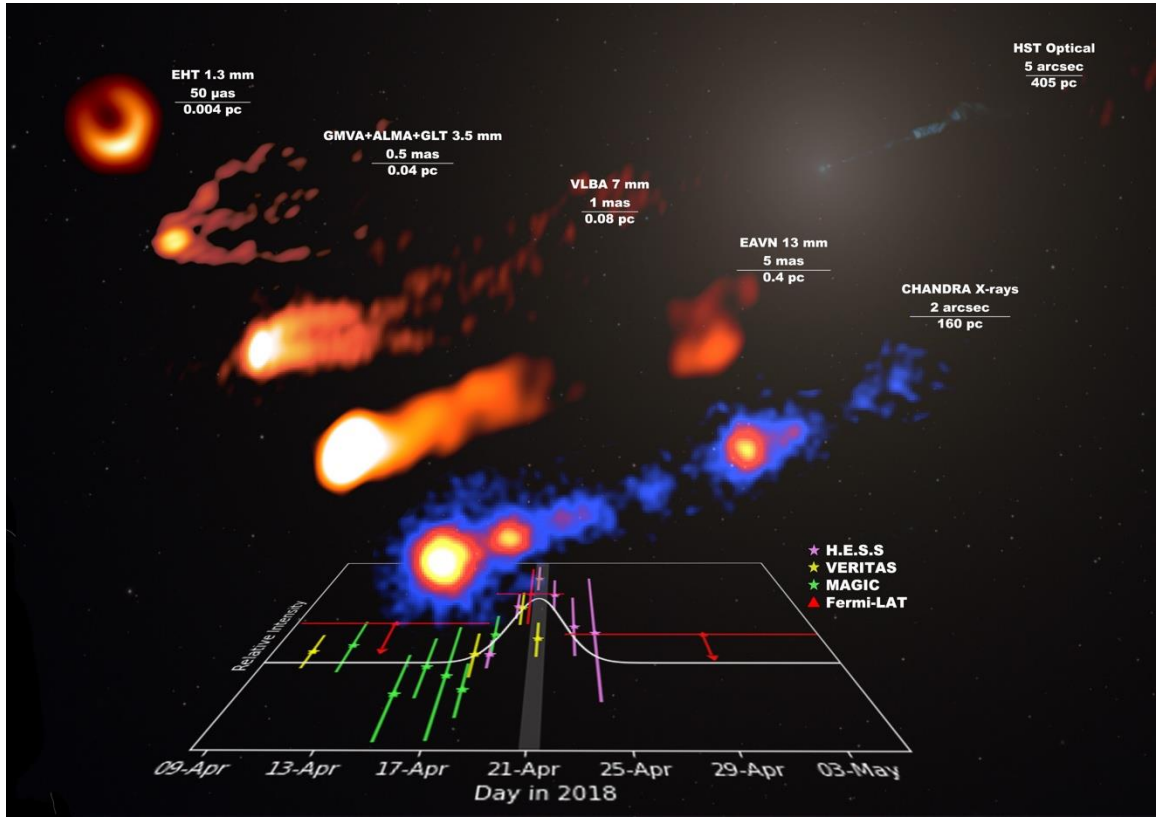
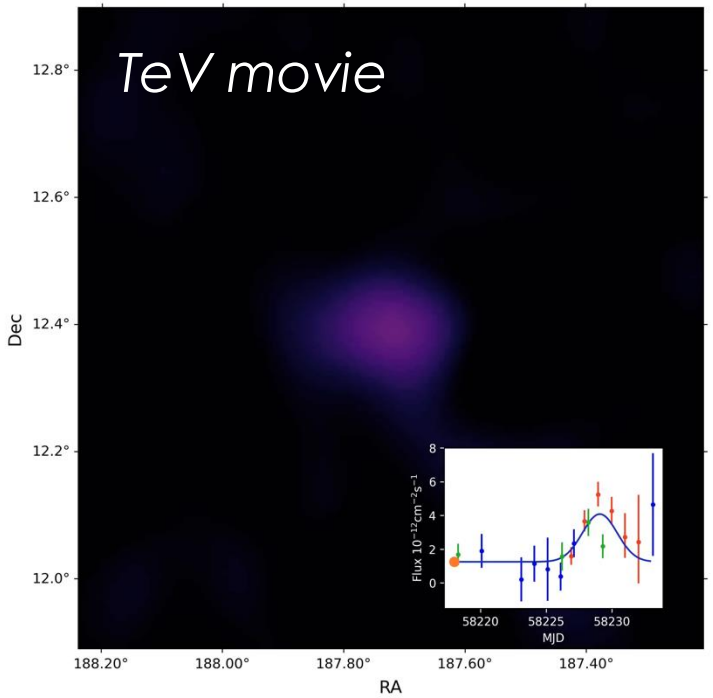
Detection of a VHE γ-ray flare during EHT-2018

EHT MWL Science WG et al. 2024





- A VHE flare during EHT observations in April 2018 (↔ low state in 2017)
- Enhanced fluxes also from GeV/Fermi and the X-ray/Chandra core

How was at radio?

TeV

GeV

X-ray

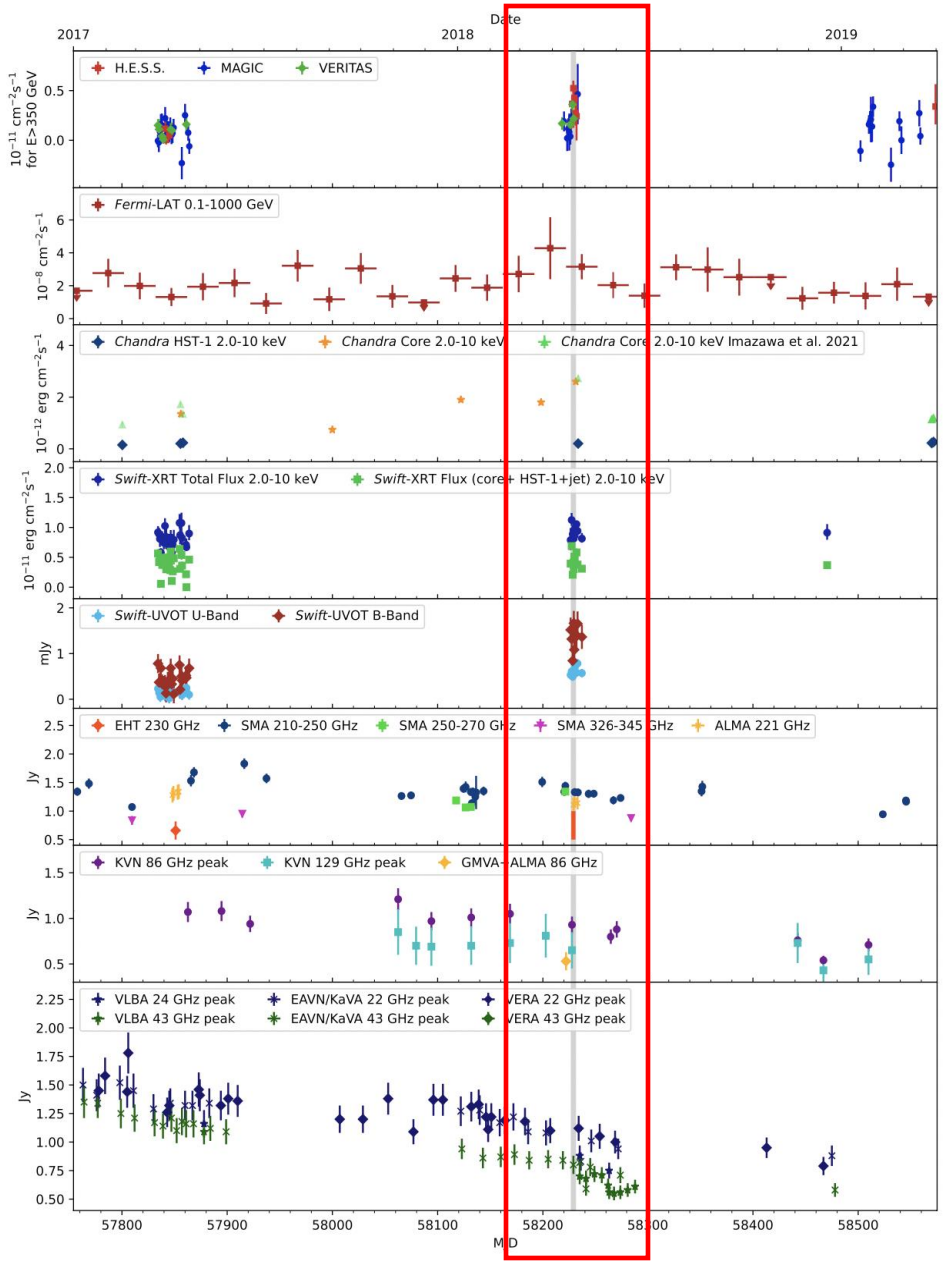
X-ray

UV

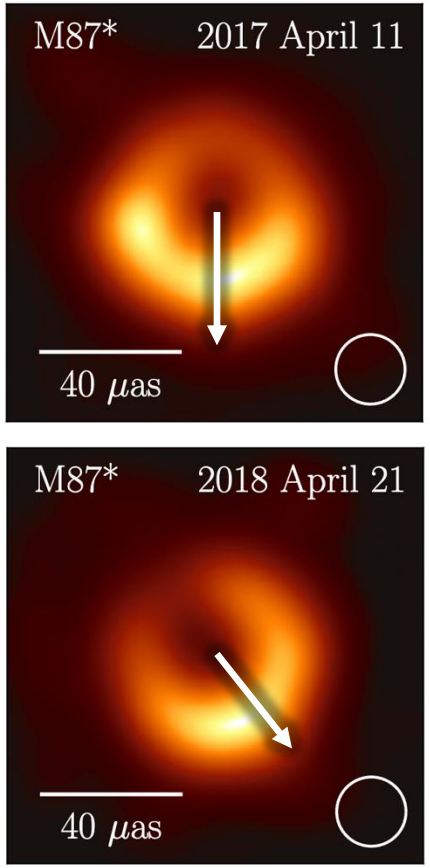
230/350 GHz

86/130 GHz

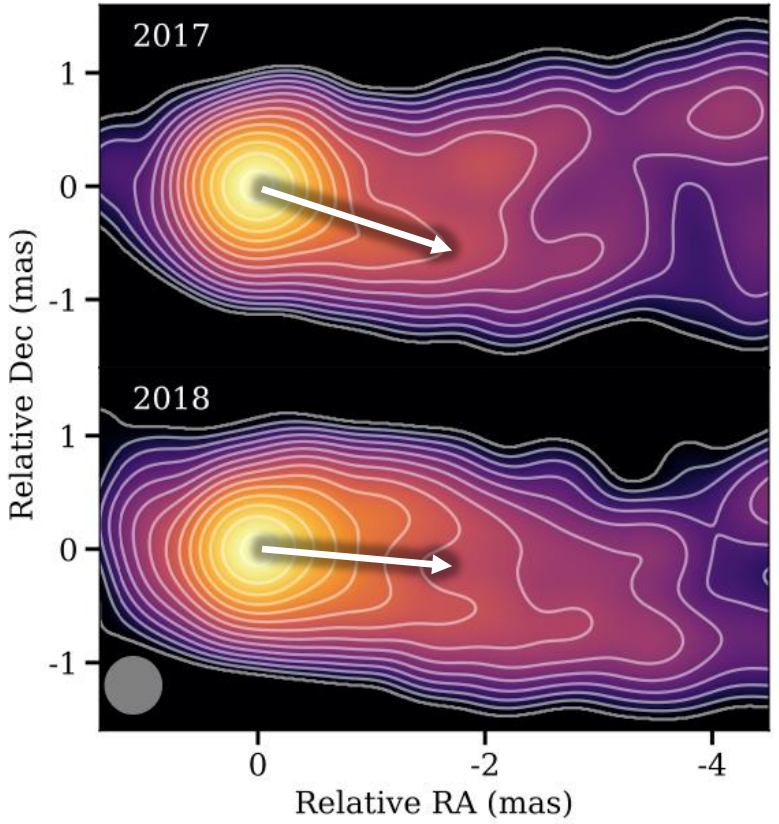
22/43 GHz



EHT (230GHz)



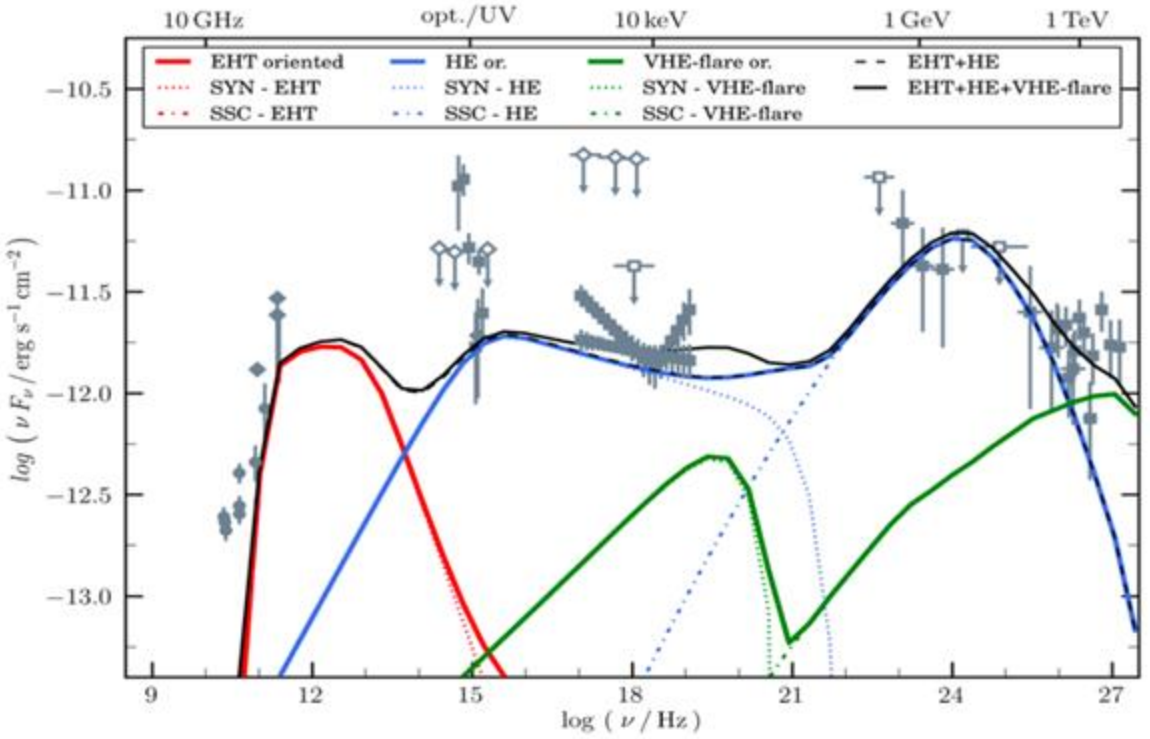
EAVN (43GHz)



- No significant flux enhancement or jet ejection at radio
  - Not able to pinpoint the exact location of TeV event
- Significant change in PA of both the EHT ring and jet between 2017 and 2018

Implications from SED

EHT MWL SWG et al. 2024



EHT oriented zone

HE oriented zone

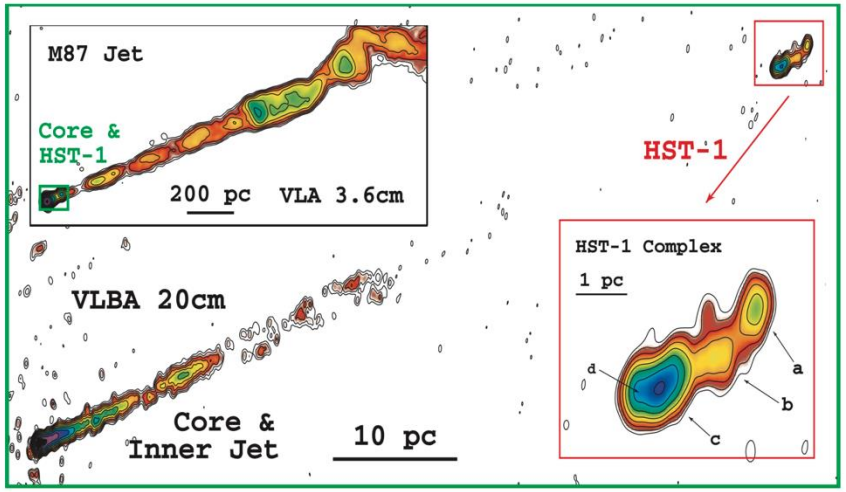
VHE oriented zone

Model	B (EHT)	B (HE)	B (VHE-flare)
δ	1	1.82	2.55
$R\ [r_g]$ (1),(2)	5.0	10.0	20.0
$n'_e\ [\mathrm{cm}^{-3}]$ (3)	4.0×10^5	1.6×10^3	1.5×10^1
B' [G]	10	2.5×10^{-2}	4.0×10^{-3}
γ_{min}	1	30	10^3
γ_{br}	4×10^2	3×10^5	–
$\gamma_{\mathrm{max}}/10^6$	10	100	60
p_1	2.8	2.1	2.5
p_2	4.5	3.15	–
U_e/U_B (4)	0.18	7.6×10^3	5.8×10^4
$L_e\ [\mathrm{erg\ s}^{-1}]$	1.6×10^{42}	2.5×10^{42}	3.7×10^{42}
$L_{\mathrm{poy}}\ [\mathrm{erg\ s}^{-1}]$	9.0×10^{42}	3.4×10^{38}	6.4×10^{37}

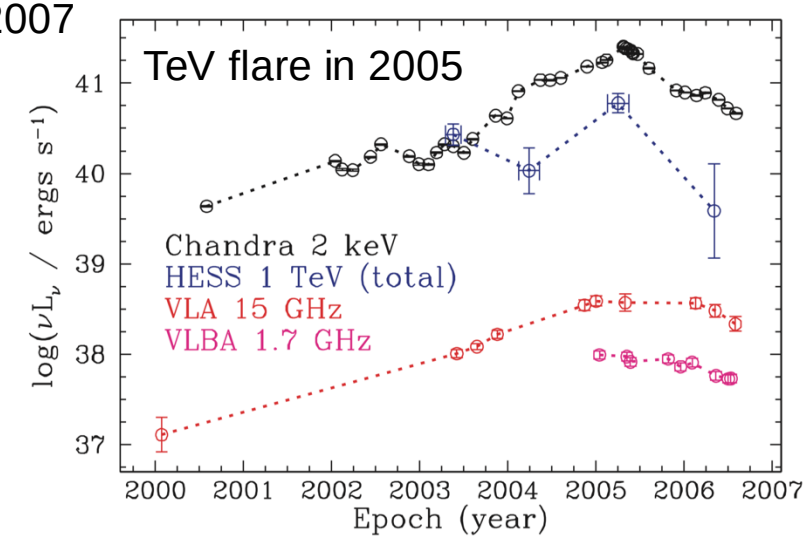
- EHT tightly constrains the size/location/flux/B-field of compact radio emitting region
- The observed radio-to-TeV SED cannot be modeled by one-zone models. Multiple components with different physical parameters required

2017&2018 SED data publicly available!

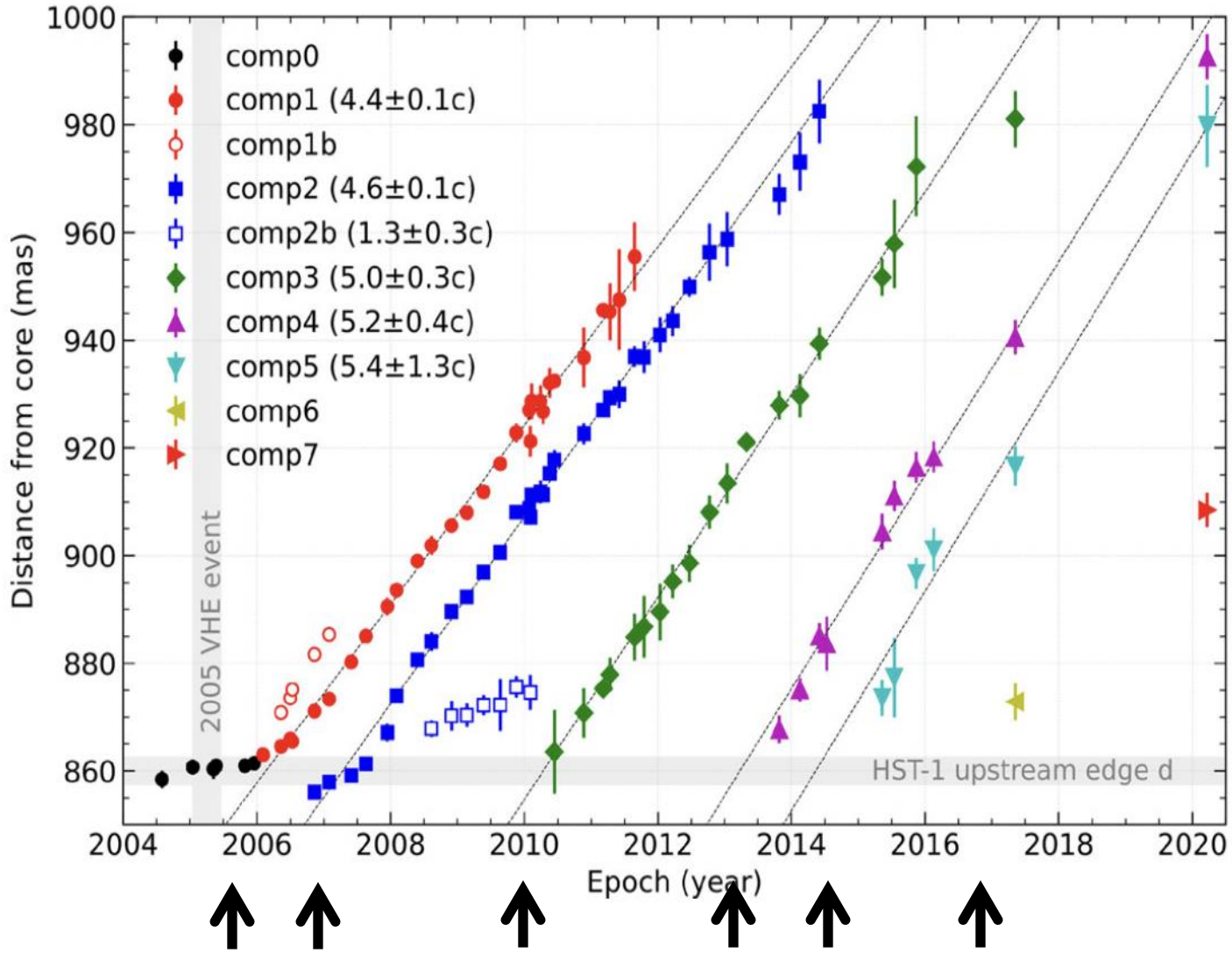
Notes on HST-1



Cheung+2007



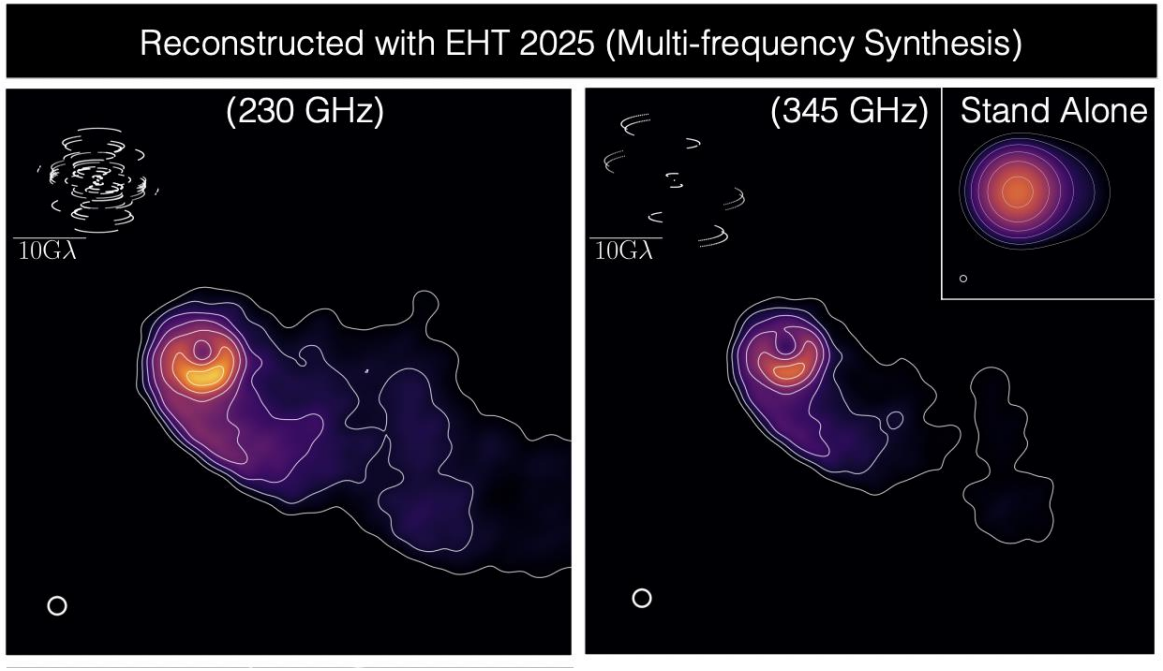
VLBI HST-1 monitoring 2004-2020 (Hada+2024)



- Another interesting candidate of TeV activities (e.g., 2005 event)
- Very weak in recent years, but continues repeated ejections of superluminal knots from the upstream edge

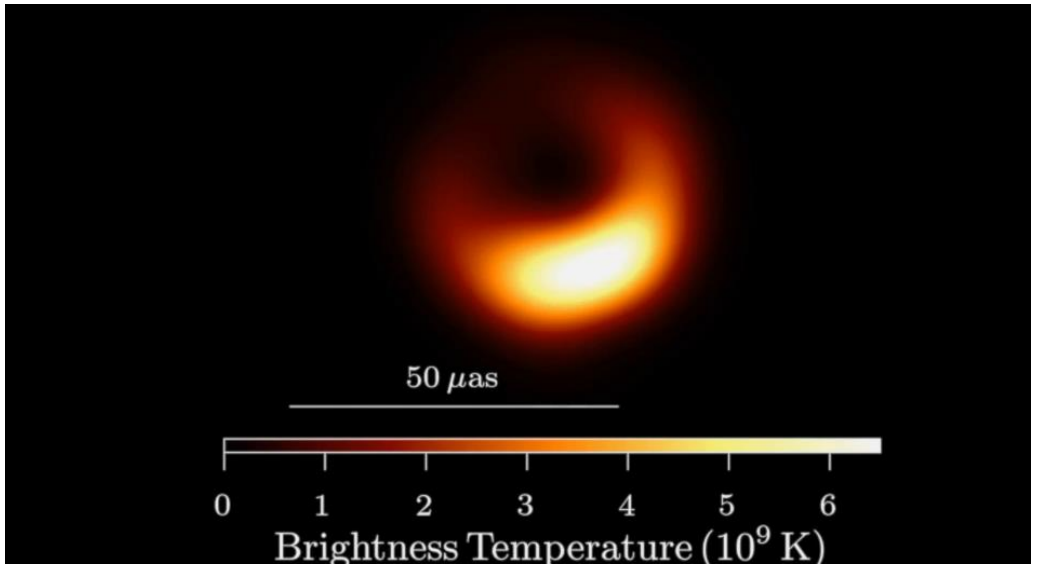
Evolving EHT network

Sensitivity upgrade & more frequencies



EHT Collaboration 2024, arXiv

”Movie” campaign



Mizuno et al

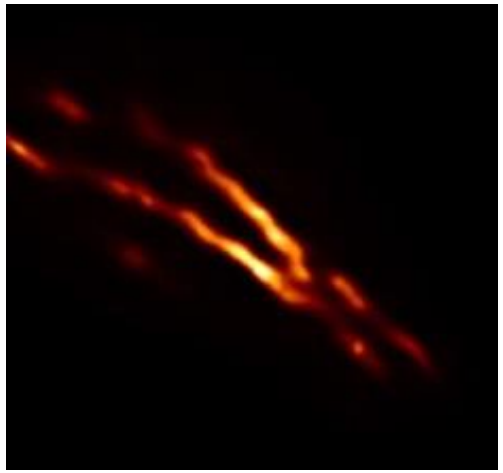
Enhancement of EHT array in coming years will greatly increase the chance to pinpoint the VHE site in M87!

Other EHT targets

3C279

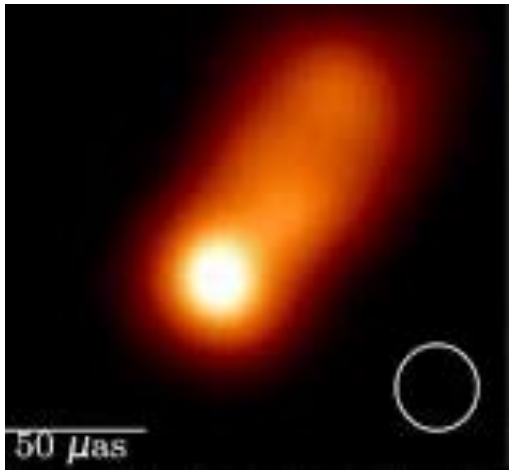
Kim et al. 2020

Cen A



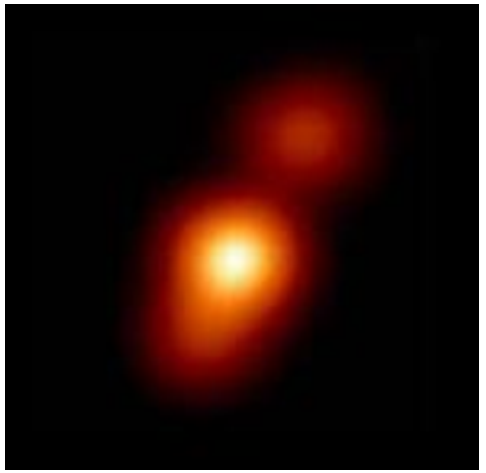
Janssen et al. 2021

NRAO530



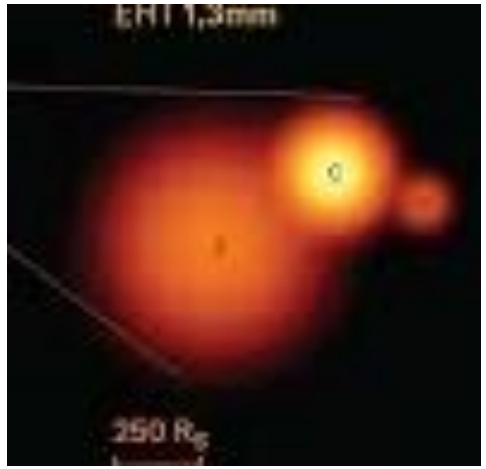
Jorstad et al. 2023

J1924-2914



Issaoun et al. 2022

3C84



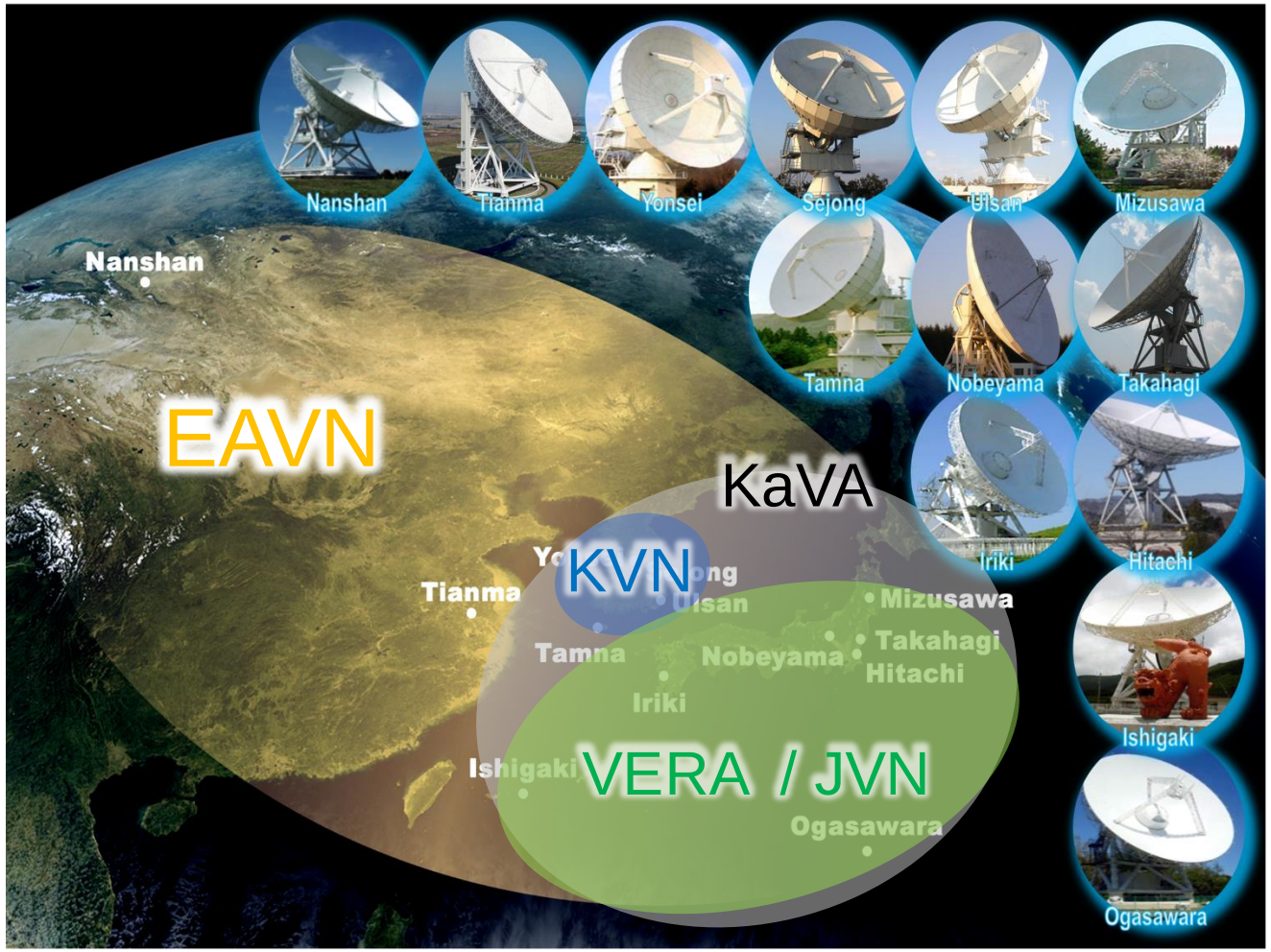
Paraschos et al. 2024

…and more to come (OJ287, Mrk501 etc)

- EHT observes not only M87/SgrA* but also a number of bright radio sources (either as calibrators or PI-based targets). Many of them are known as active γ-ray sources
- EHT-MWL papers in preparation (3C279, OJ287 etc)

East Asia VLBI studies of TeV AGNs

VLBI arrays in East Asia

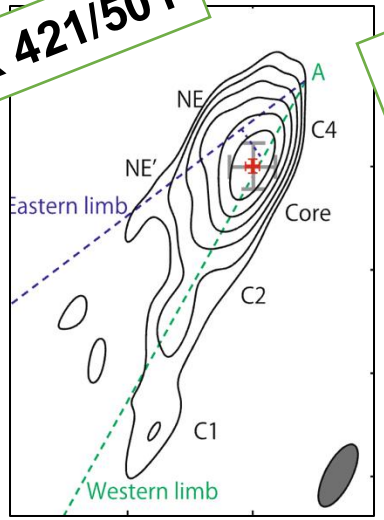


- EAVN is a combined VLBI network of VERA, JVN, KVN, CVN (& more)
- Mainly 22/43GHz but also 86GHz
  - Complementary to EHT
- Many advantages for AGN studies
  - Sub-mas angular resolution
  - High quality & sensitivity imaging
  - Regular monitoring throughout the year
  - Polarization
  - ToO supported
- Easy access for EA community

Various types of AGN being actively monitored

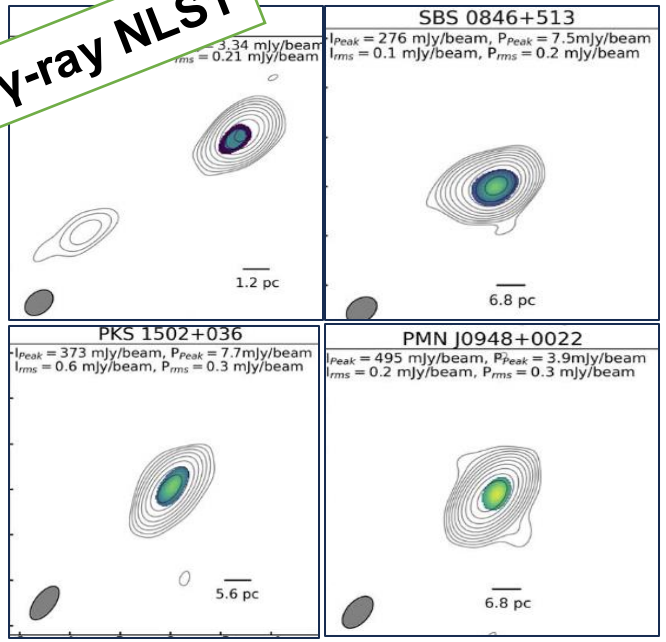
Many of them are also well-known GeV/TeV targets

Mrk 421/501

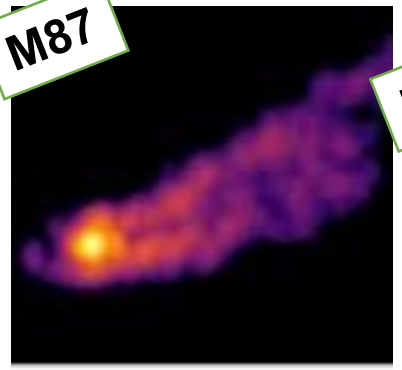


NGC 1275

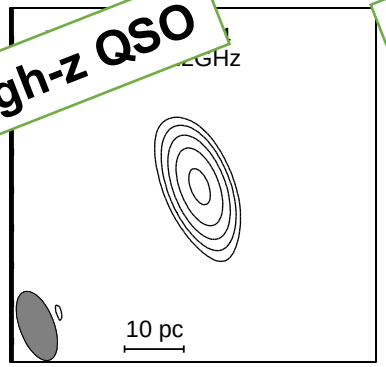
γ-ray NLS1



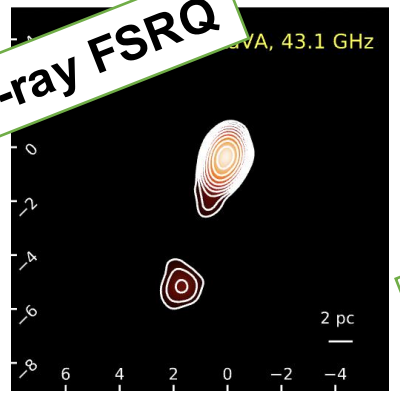
M87



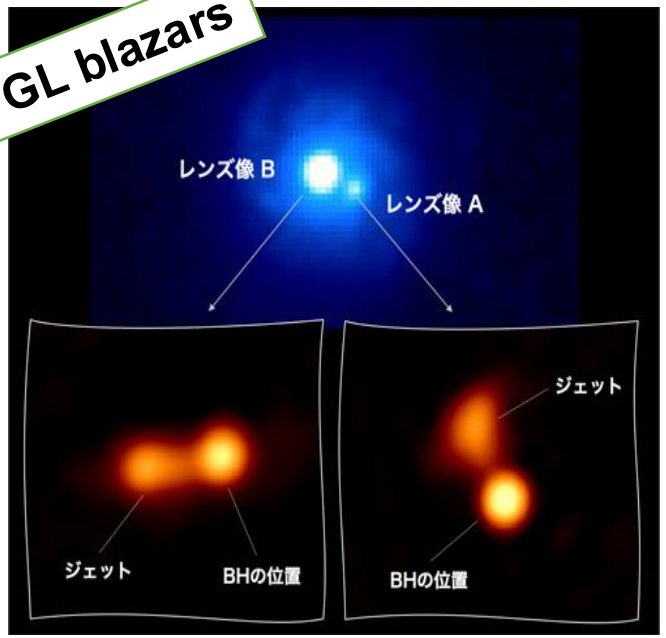
High-z QSO



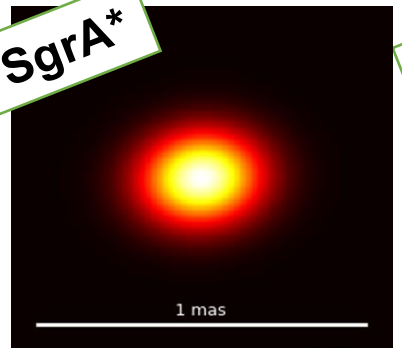
γ-ray FSRQ



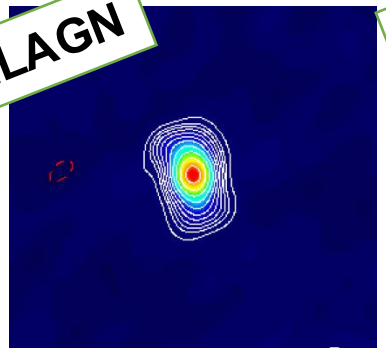
GL blazars



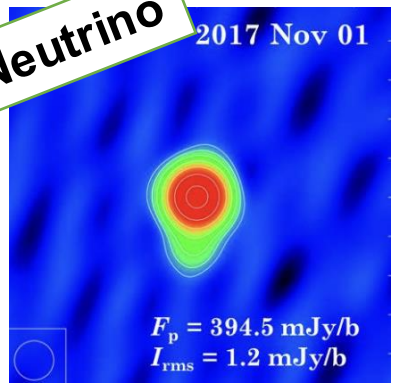
SgrA*



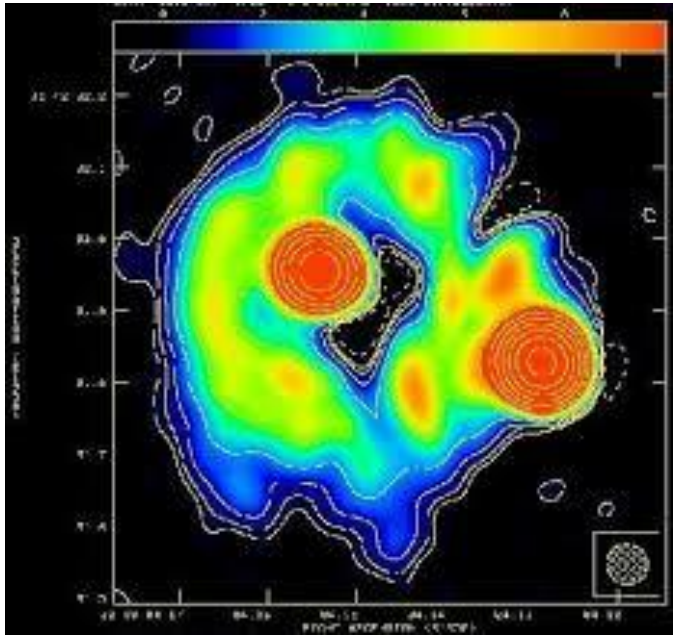
LLAGN



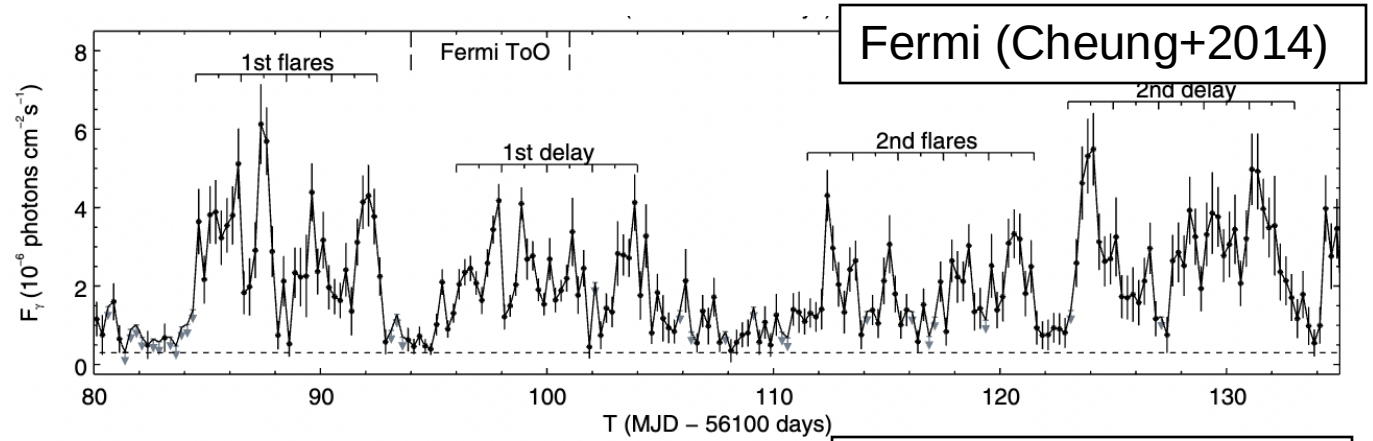
Neutrino

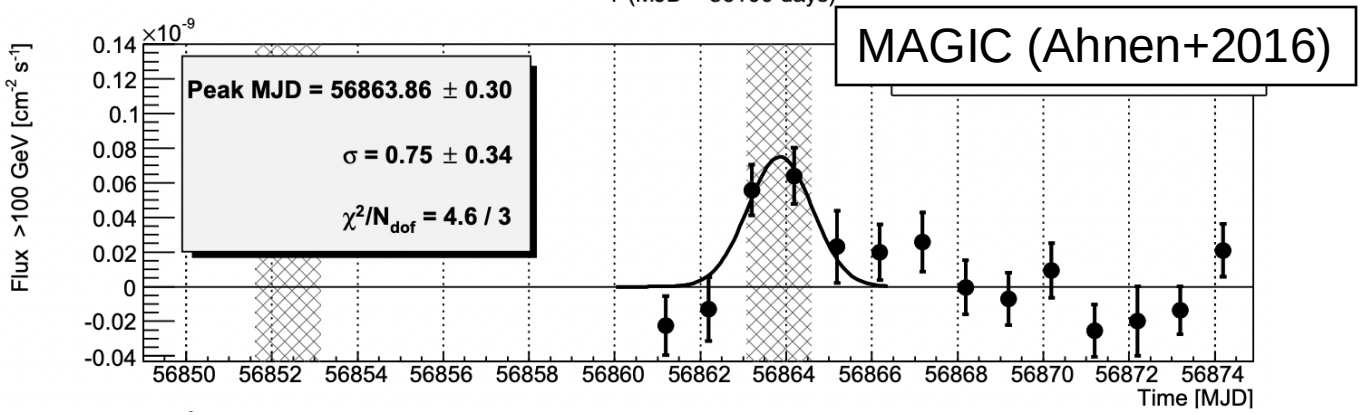


B0218+357

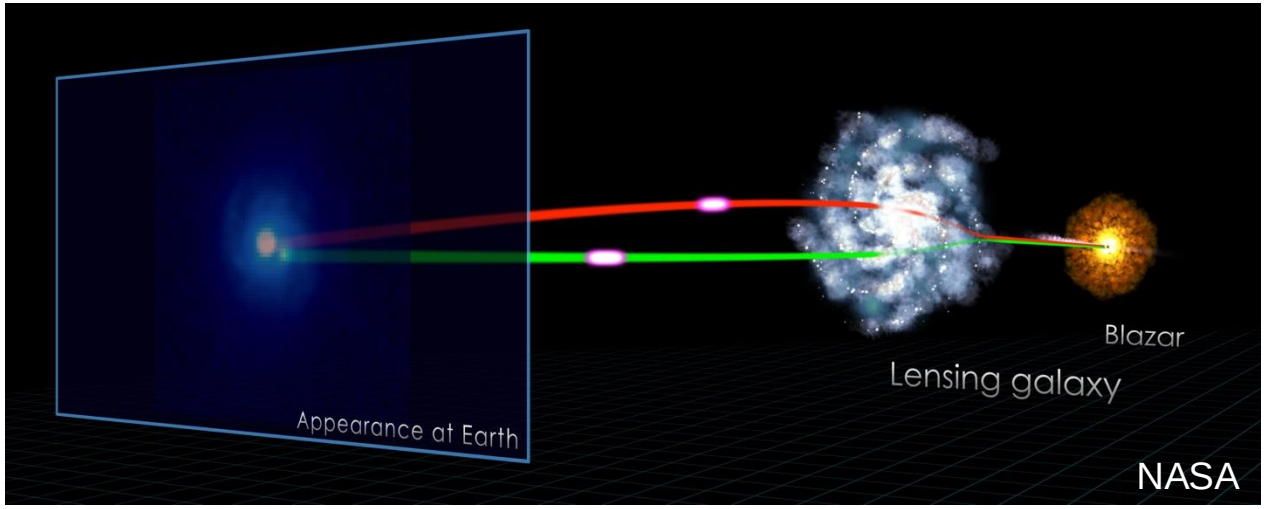


VLA image (Biggs+1999)

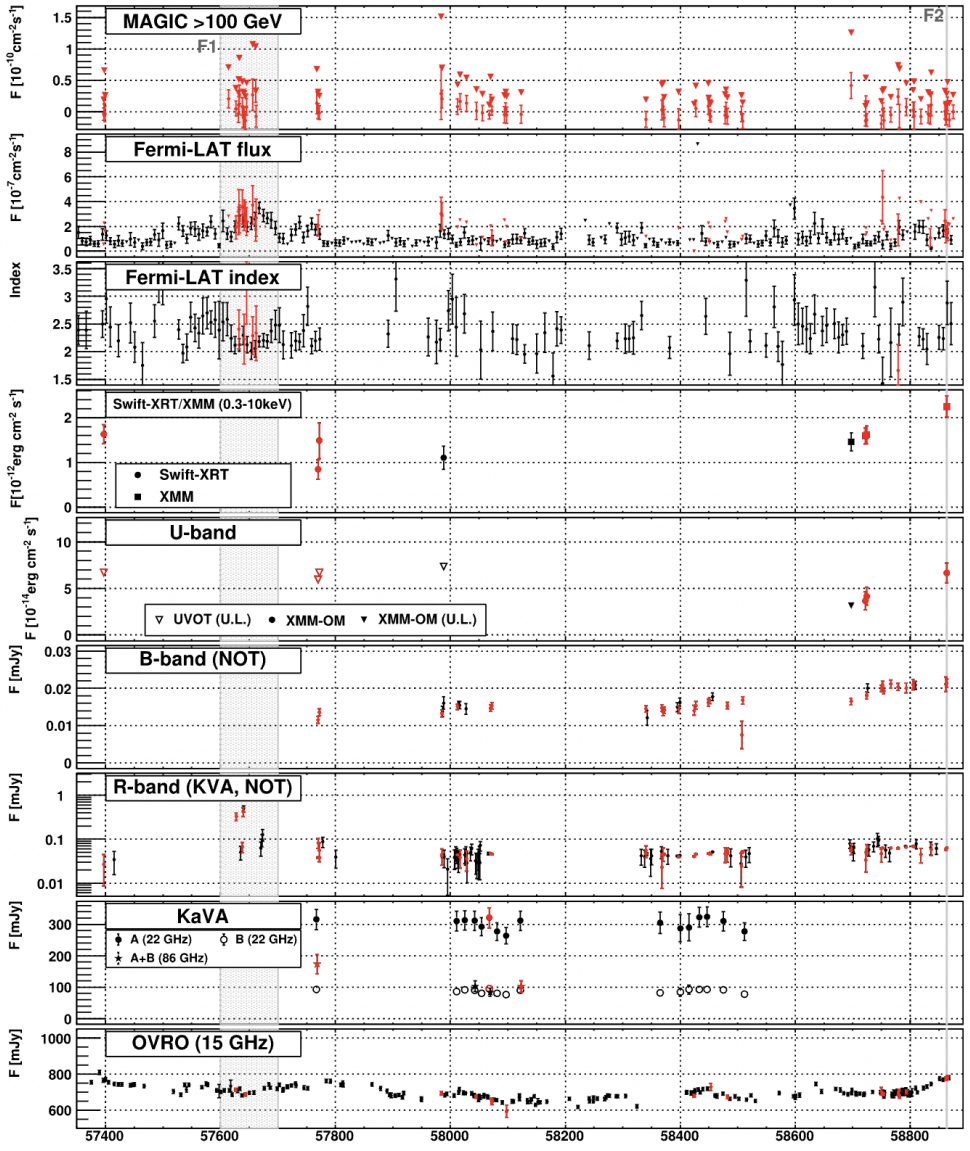




- A well-known GL blazar (z=0.944)
- One of the most distant TeV detected FSRQ

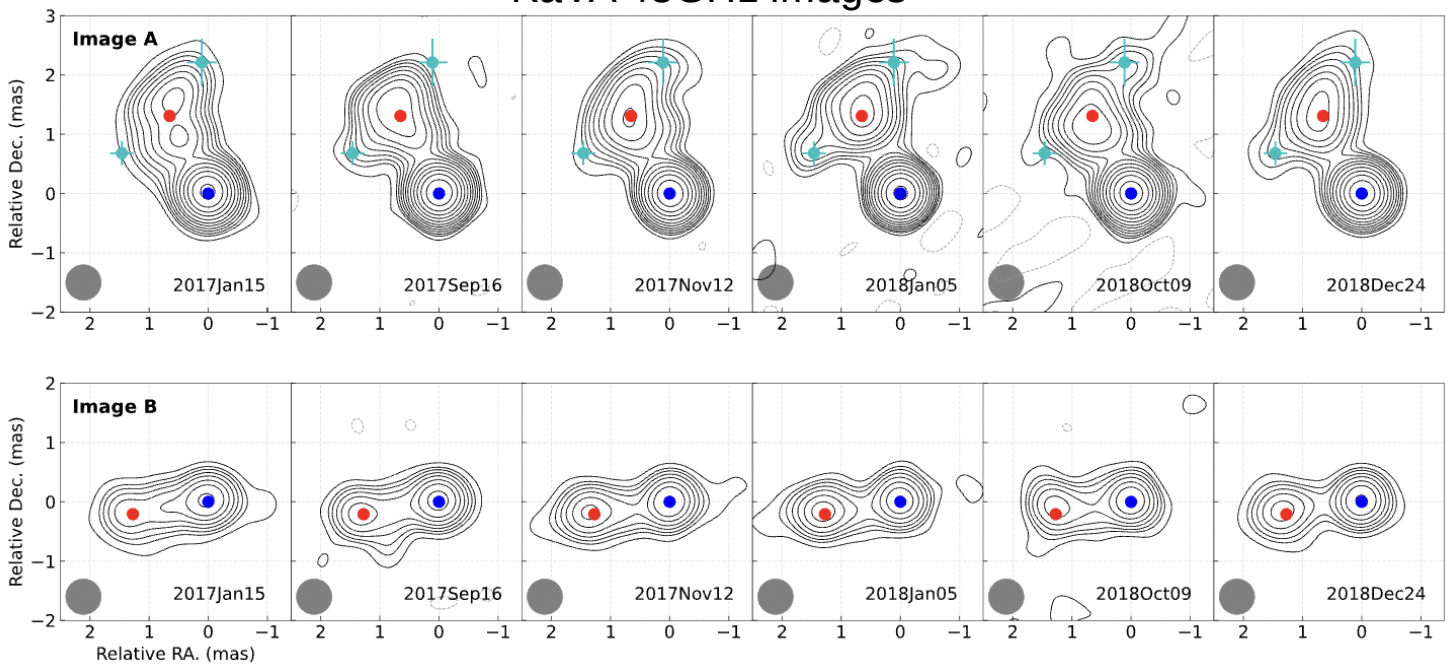


MWL campaign 2016-2020 (Acciari+2022, Hada+2020)



Acciari et al. 2022

KaVA 43GHz images

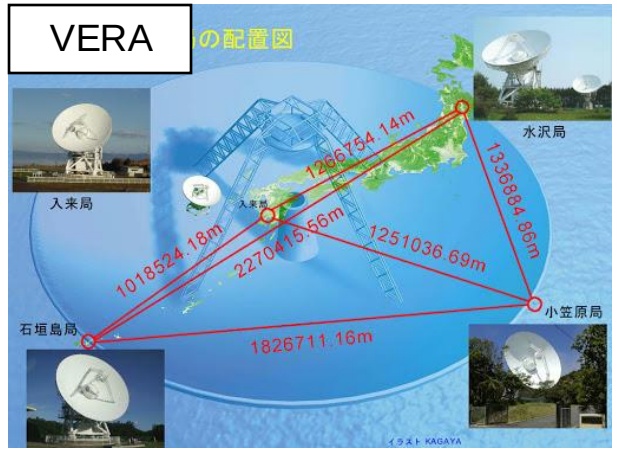


- GeV/X-ray/optical flares during the campaign
- KaVA revealed core-jet morphology of the lensed images
- At radio: no flux enhancement, no jet motion

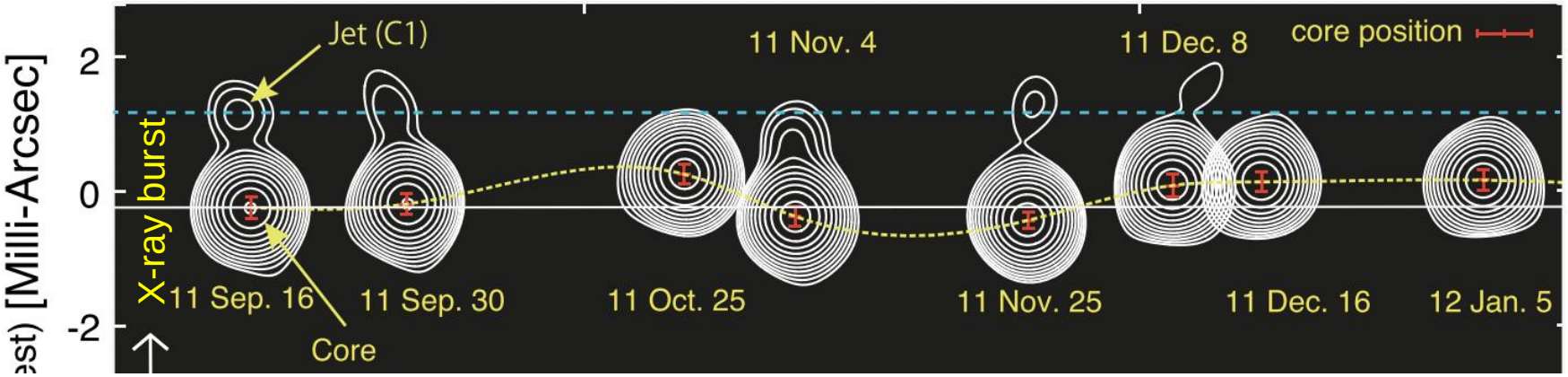
  → Multi-zone nature of the broadband emission
- KaVA images also helped improve the lens modeling

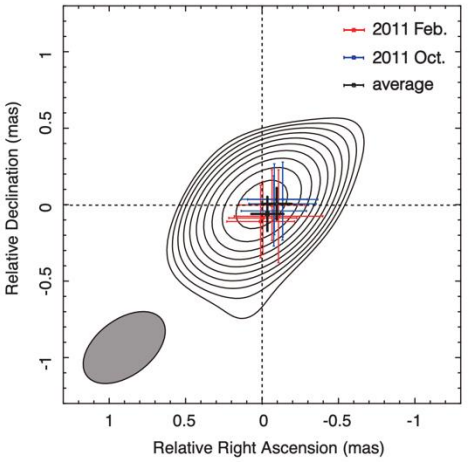
Mrk421 & 501: probing the location of flaring sites with astrometry

(Niinuma+2015, Koyama+2016, 2019)

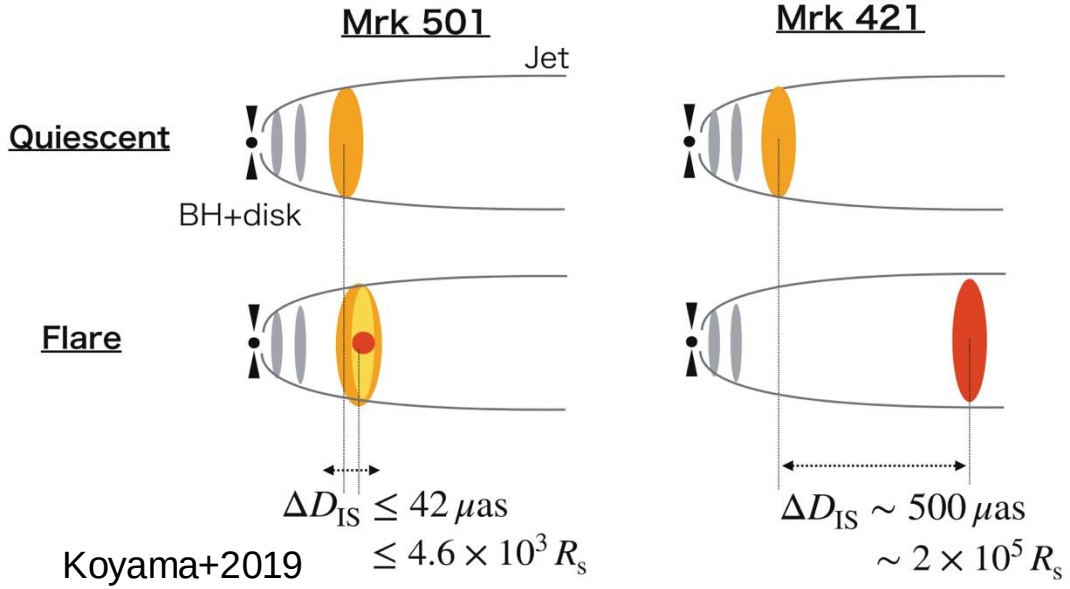


Mrk421 (Niinuma+2015)





Mrk501 (Koyama+2016)



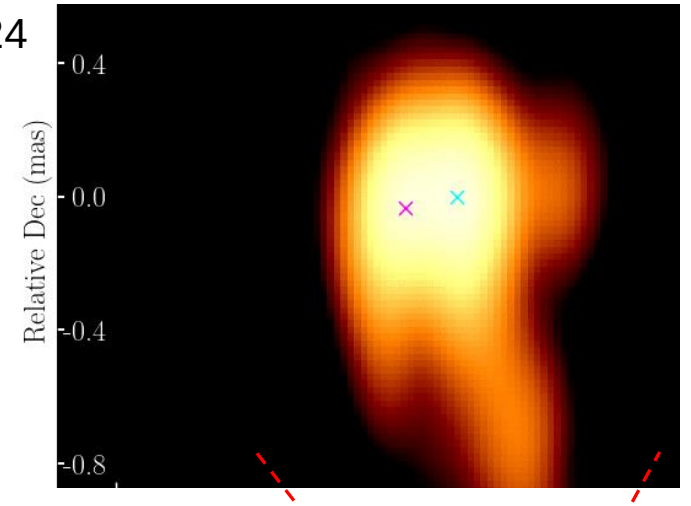
Koyama+2019

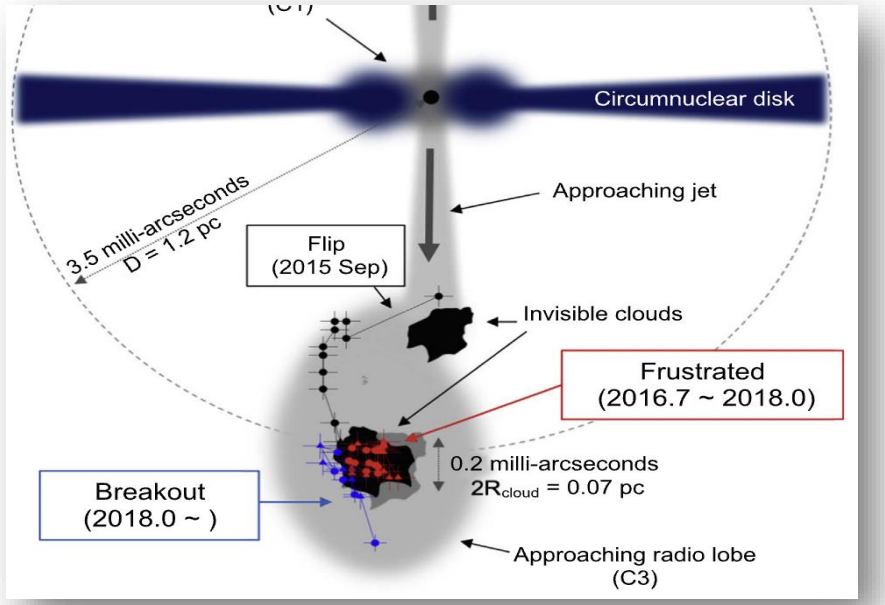
- VLBI can do micro-arcsec-precision astrometry of compact radio sources
- By doing VLBI astrometry near in time to high-energy flares, we can constrain the location of the flaring site in blazars

NGC1275 (3C84)

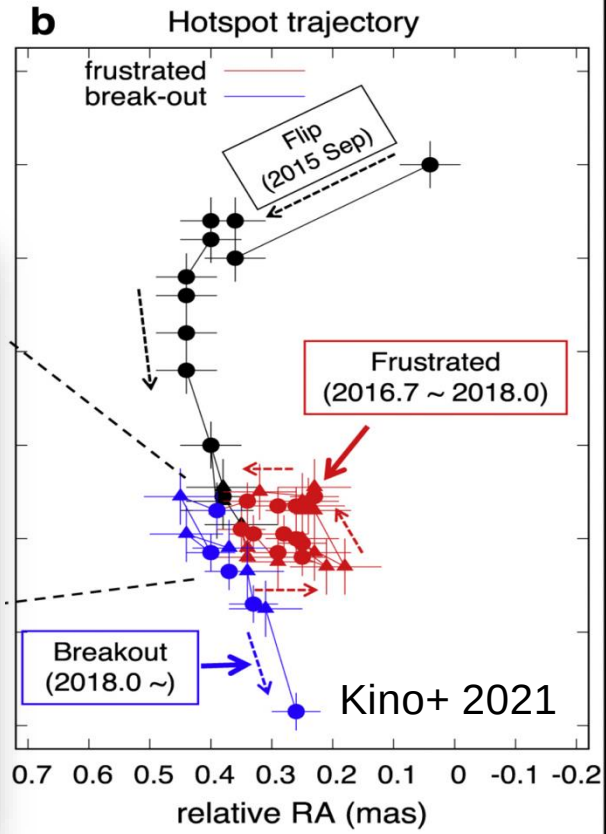
- One of a few TeV-detected RG
- Accumulated VLBI data reveal extremely complex nature of the nuclear region
  - Intermittent ejection of strong blobs
  - Strong interaction with surrounding medium
  - Double-core structure with curved jet launch
- Beaming factor may significantly evolve both in time and spatially

Park+ 2024

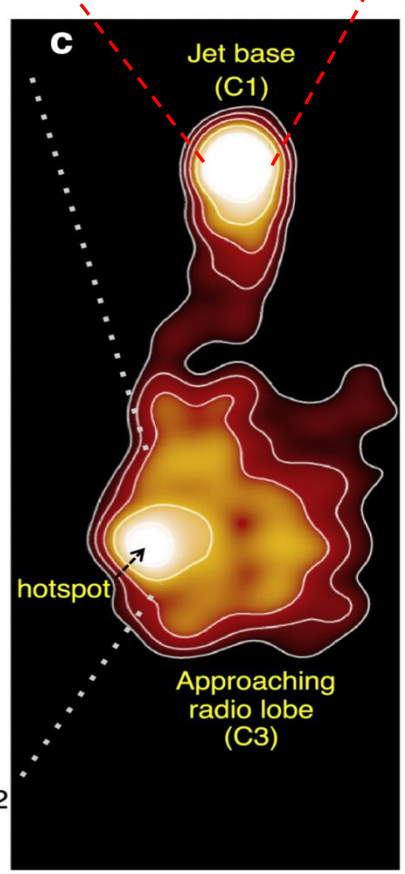




Kino+ 2021



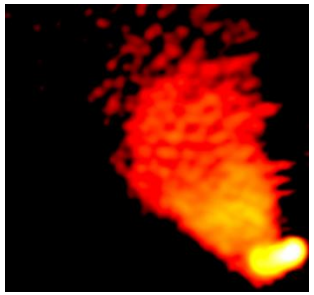
Kino+ 2021



Prospects for VLBI-VHE synergy in CTA era

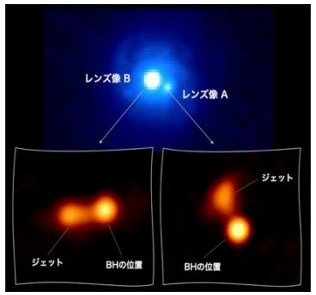
Known VHE sources

Blazars



Nearby RG

Distant QSO



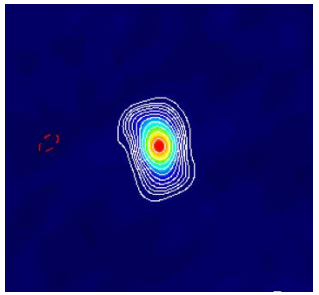
Richer VLBI images (higher-res, movie, wider frequency coverage)
+
Better statistics of VHE light curves (both in low & high states)

↓

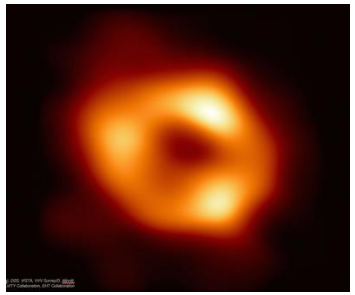
Robust localization of VHE sites
Jet formation mechanism

Less explored / unexplored

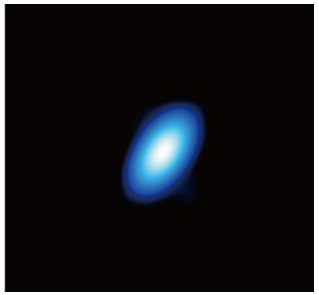
LLAGN



SgrA*



Sy / NLSy1



Increasing VLBI samples
+
VHE search at higher sensitivity?

↓

New discovery space !?

Summary

- High-resolution VLBI is a powerful partner for studying γ-ray AGN
- VLBI capability is rapidly evolving, uncovering the structure of SMBH & jet base in much greater detail than before
- Eager to collaborate with CTA - Looking forward to new discovery!