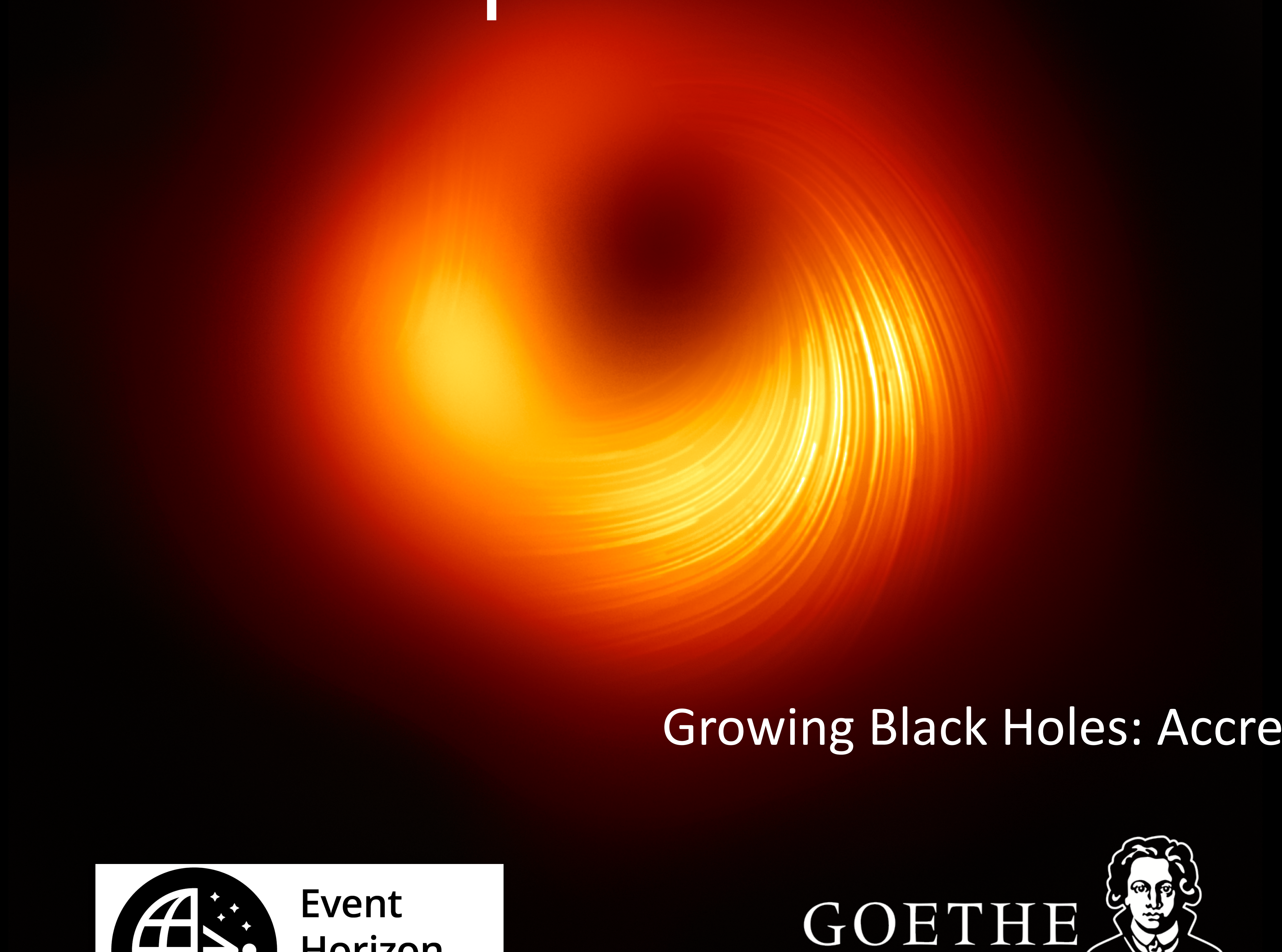
The shadow of the supermassive black hole in M87



Alejandro Cruz Osorio
Institute for Theoretical Physics,
Goethe University Frankfurt, Germany

Growing Black Holes: Accretion and Mergers, Kathmandu, Nepal, May 15-20, 2022

Event Horizon Telescope

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

ITP Institute for Theoretical Physics

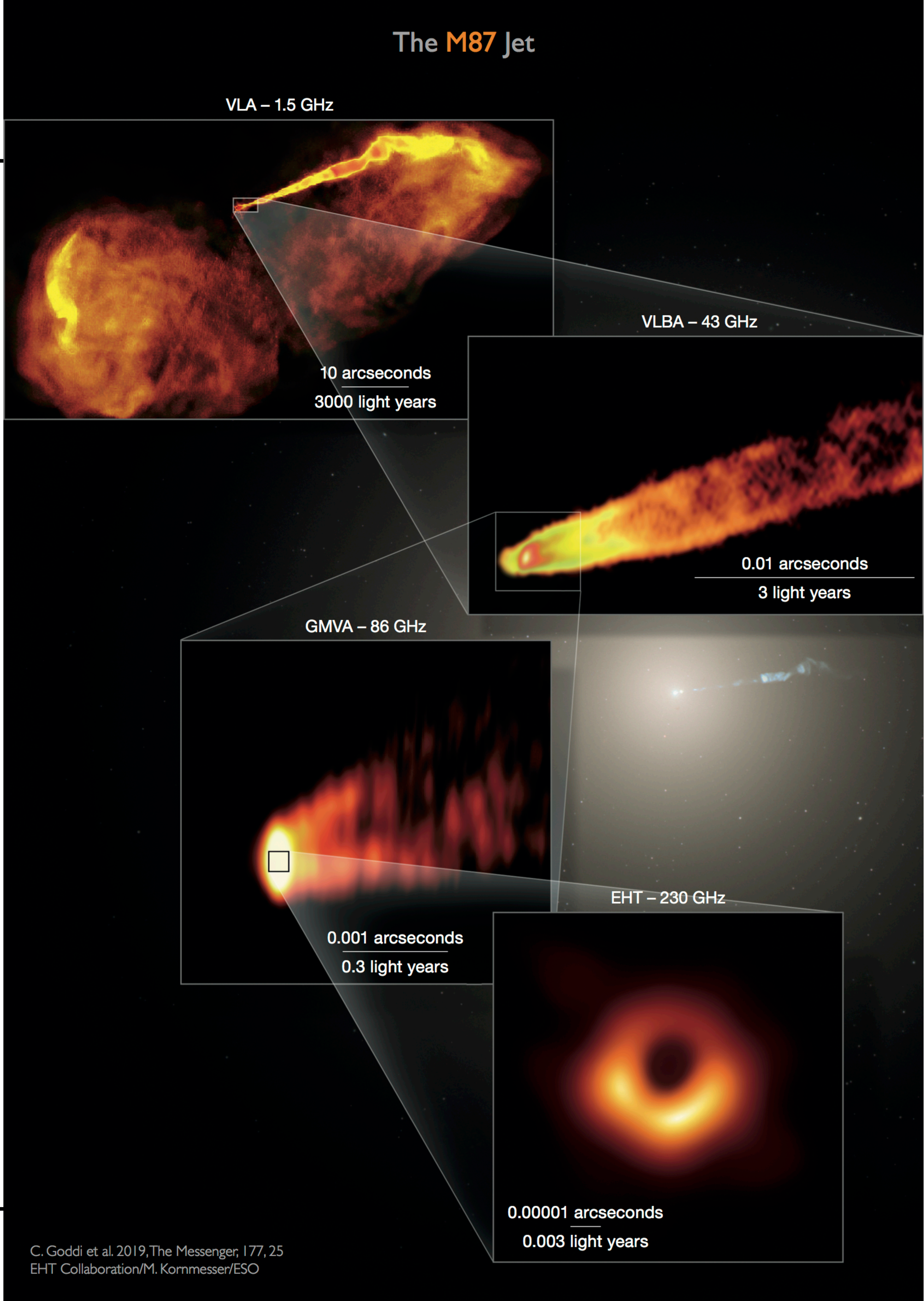
JETSET

Table of Contents

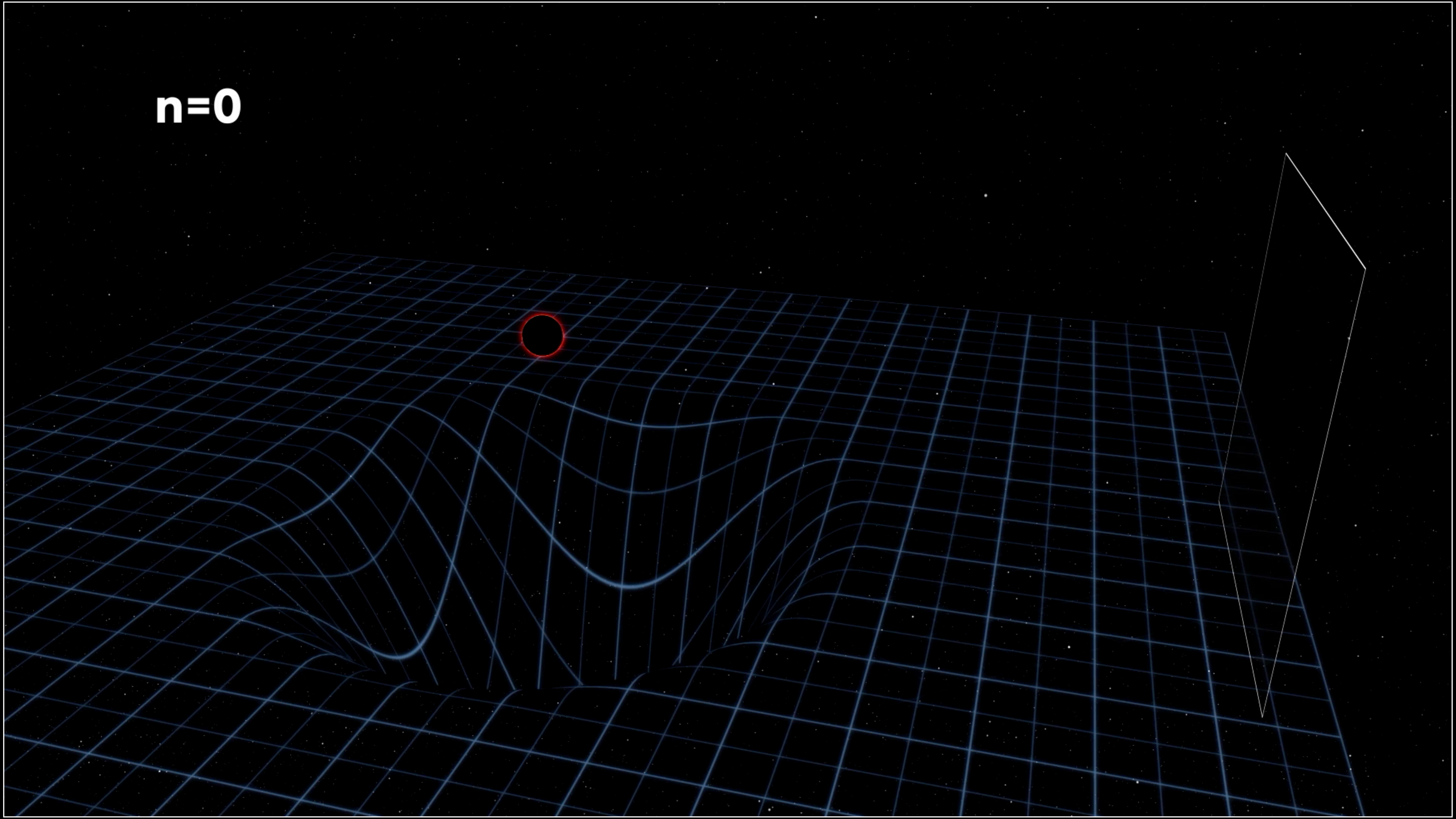
Relativistic Jets

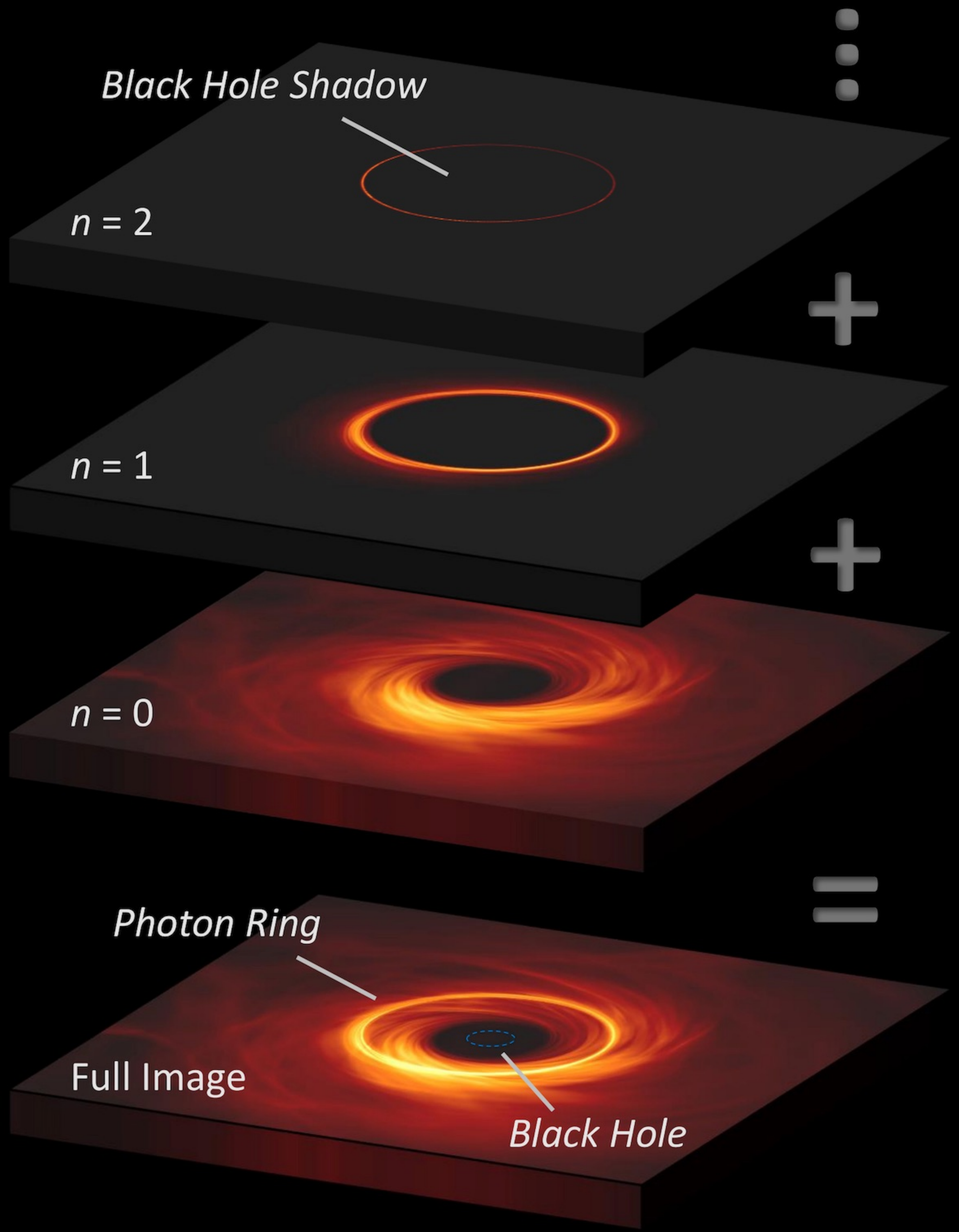
- Outflow of highly collimated plasma
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ～c
  - Generic systems: Compact object (Neutron Star, Black Hole)   + accretion flows
  - Jets are common in the universe

- Key Issues of Relativistic Jets
  - Acceleration & Collimation
  - Propagation & Stability
  - Origin of high energy particle (particle acceleration)



Black Hole Photon Ring





Johnson et al. (2019)

Black Holes with the Largest Angular Sizes

Source	BH Mass (M_{solar})	Distance (Mpc)	1 R_g (μas)
Sgr A*	4×10^6	0,008	10
M87	**$3.3 - 6.2 \times 10^9$**	**16,8**	**3.6 - 7.3**
M104	1×10^9	10	2
Cen A	5×10^7	4	0,25

Event Horizon Telescope

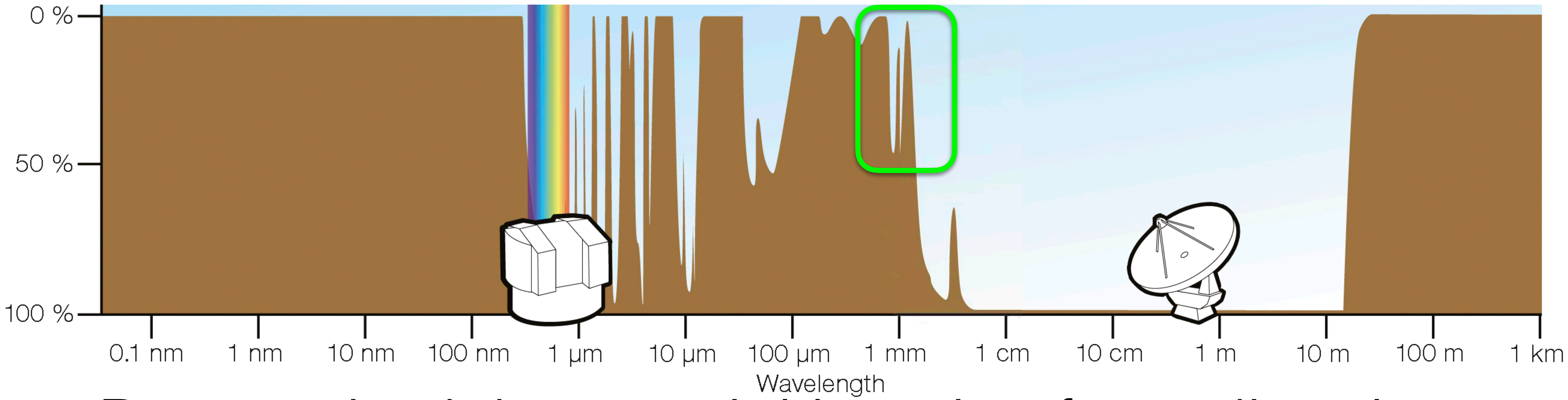
Design for Event Horizon Telescope

Required angular resolution: $\theta \approx 20\ \mu$as   Rayleigh criterion: $\theta = \lambda/D$

λ: observational wavelength D: diameter of telescope

λ	1mm	1cm	10cm	1m	10m
D [km]	1×10^4	1×10^5	1×10^6	1×10^7	1×10^8

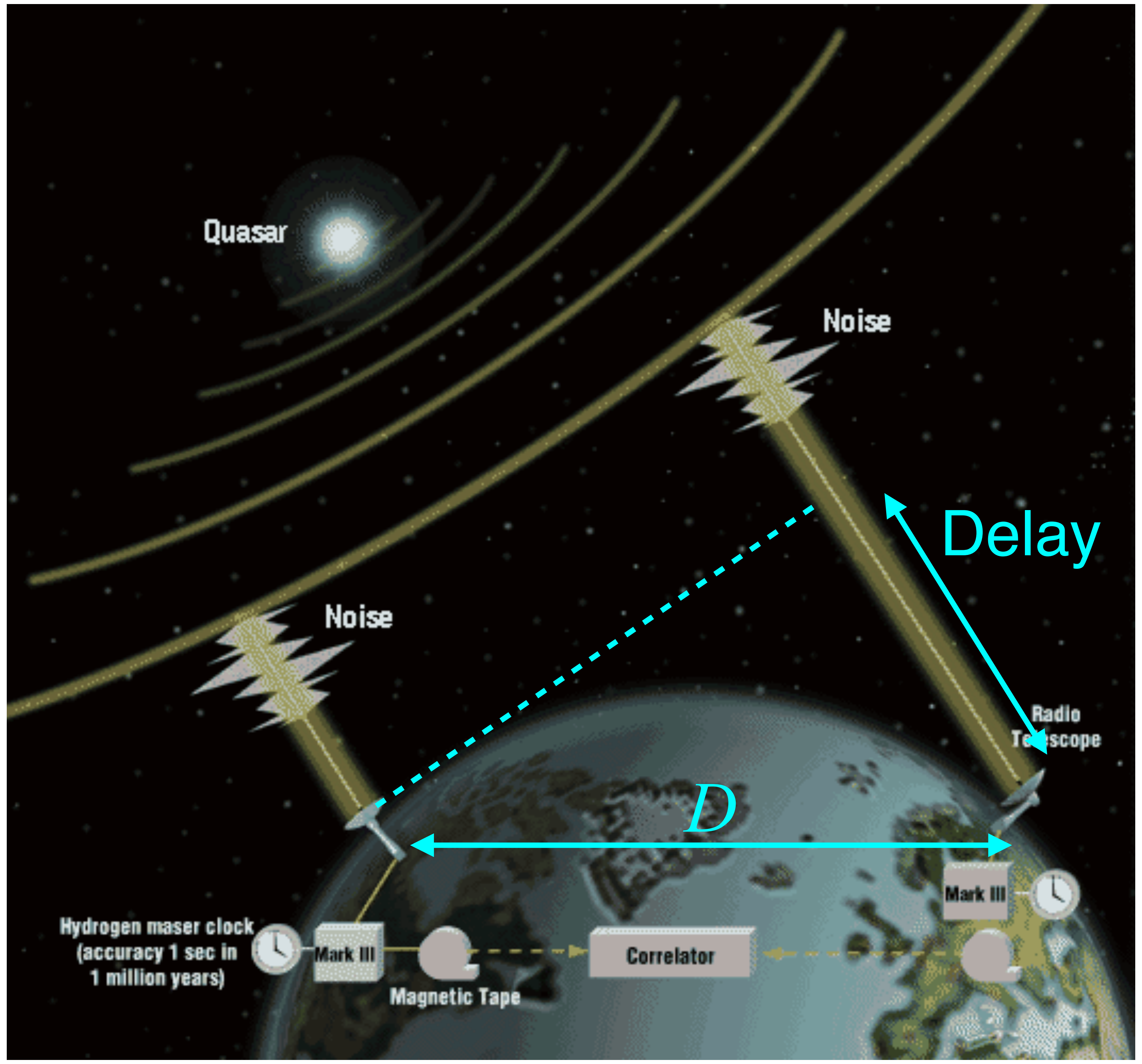
Earth diameter ~ 1.2×10^4 km



But required the special location for radio telescopes (high height above sea level & dry)

Event Horizon Telescope

Design for Event Horizon Telescope



How do you build a telescope with diameter of 10,000 km?
⇒ one telescope is impossible.

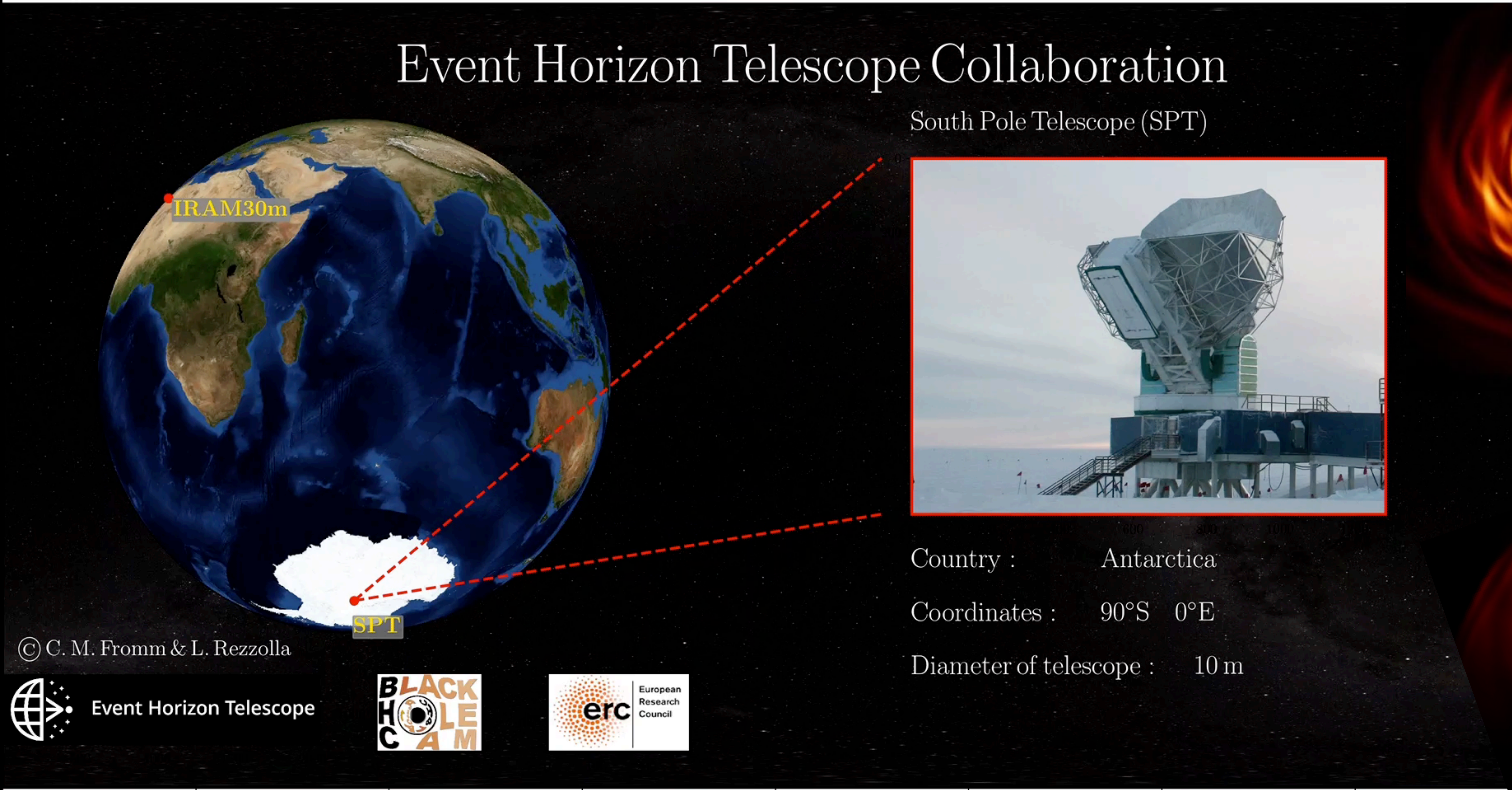
We combine multiple telescopes by using Very Long Baseline Interferometry (VLBI)

VLBI is a technique to connect with multiple radio telescopes to create one big radio telescope (diameter of telescope = longest baseline of telescopes)

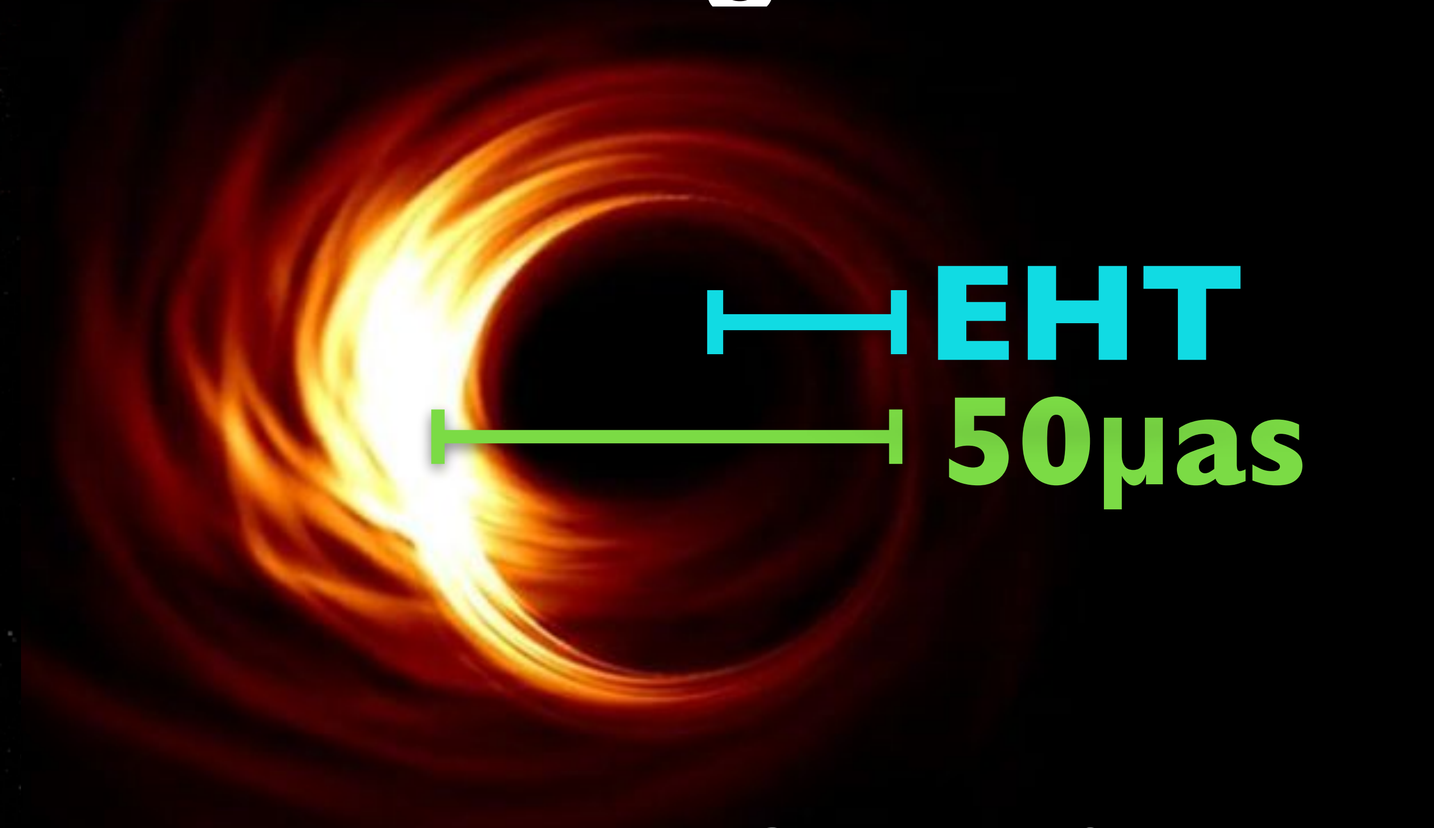
Interferometry measures the brightness distribution of a source in Fourier space

Complex visibility: $V_{ij}(u,v) = \int\int dxdy I(x,y) e^{-2\pi\imath(ux+vy)/\lambda}$

Create a Earth size virtual radio telescope
by using VLBI

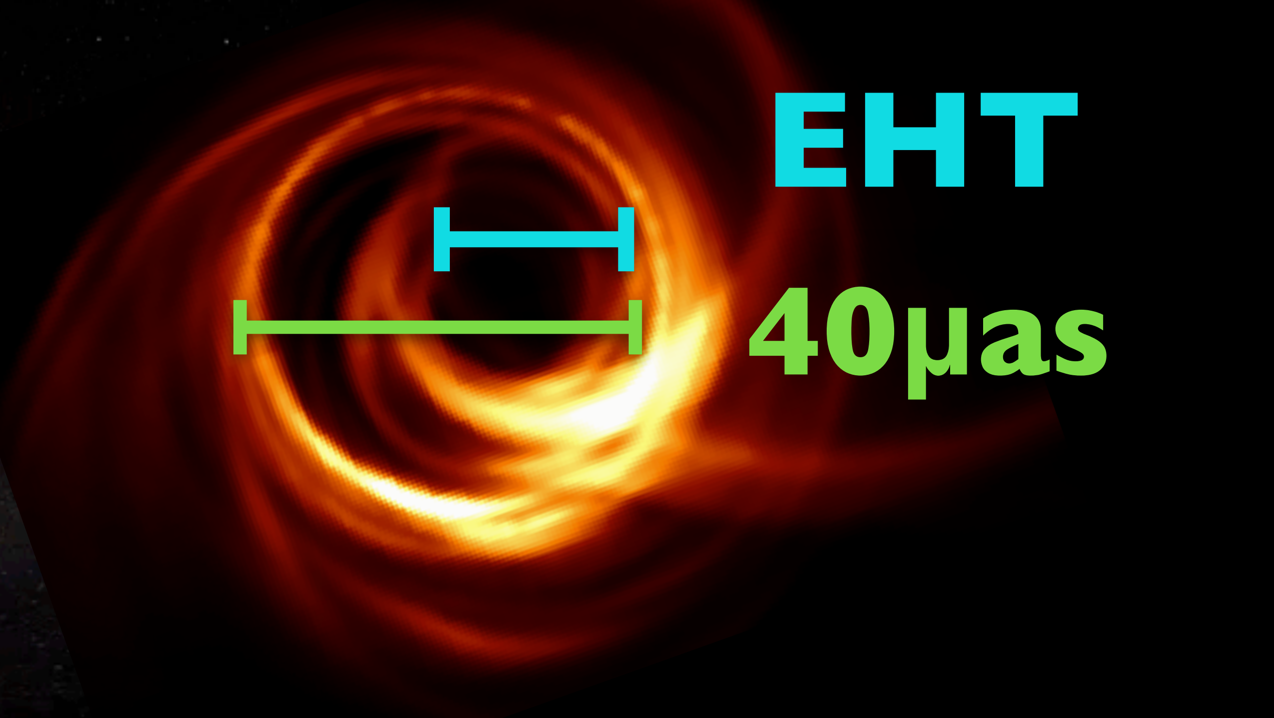


Sgr A*



Credit: H. Shiokawa

M87



Credit: M. Moscibrodzka

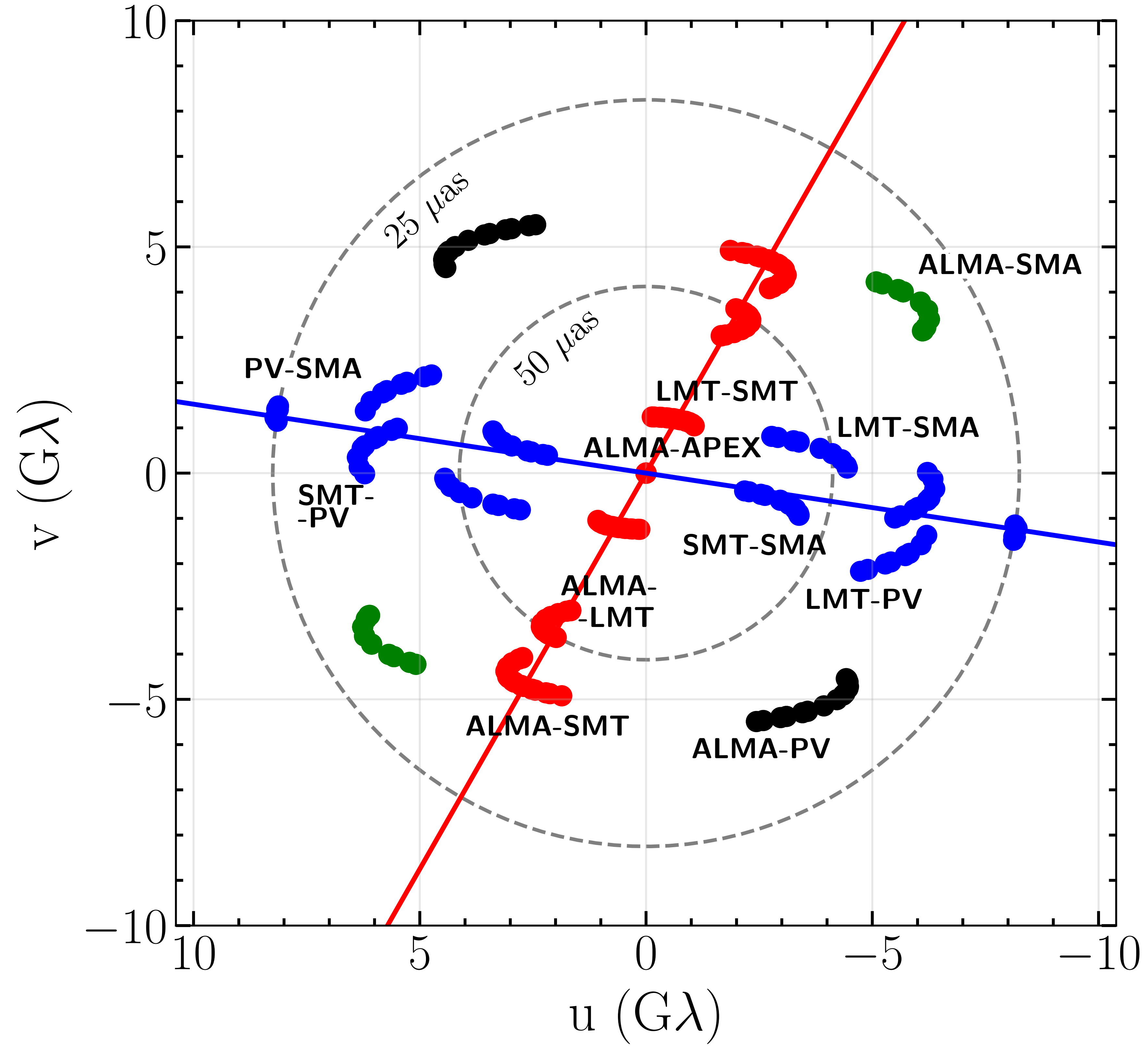
$\lambda = 1.3$ mm ($\nu = 230$ GHz)

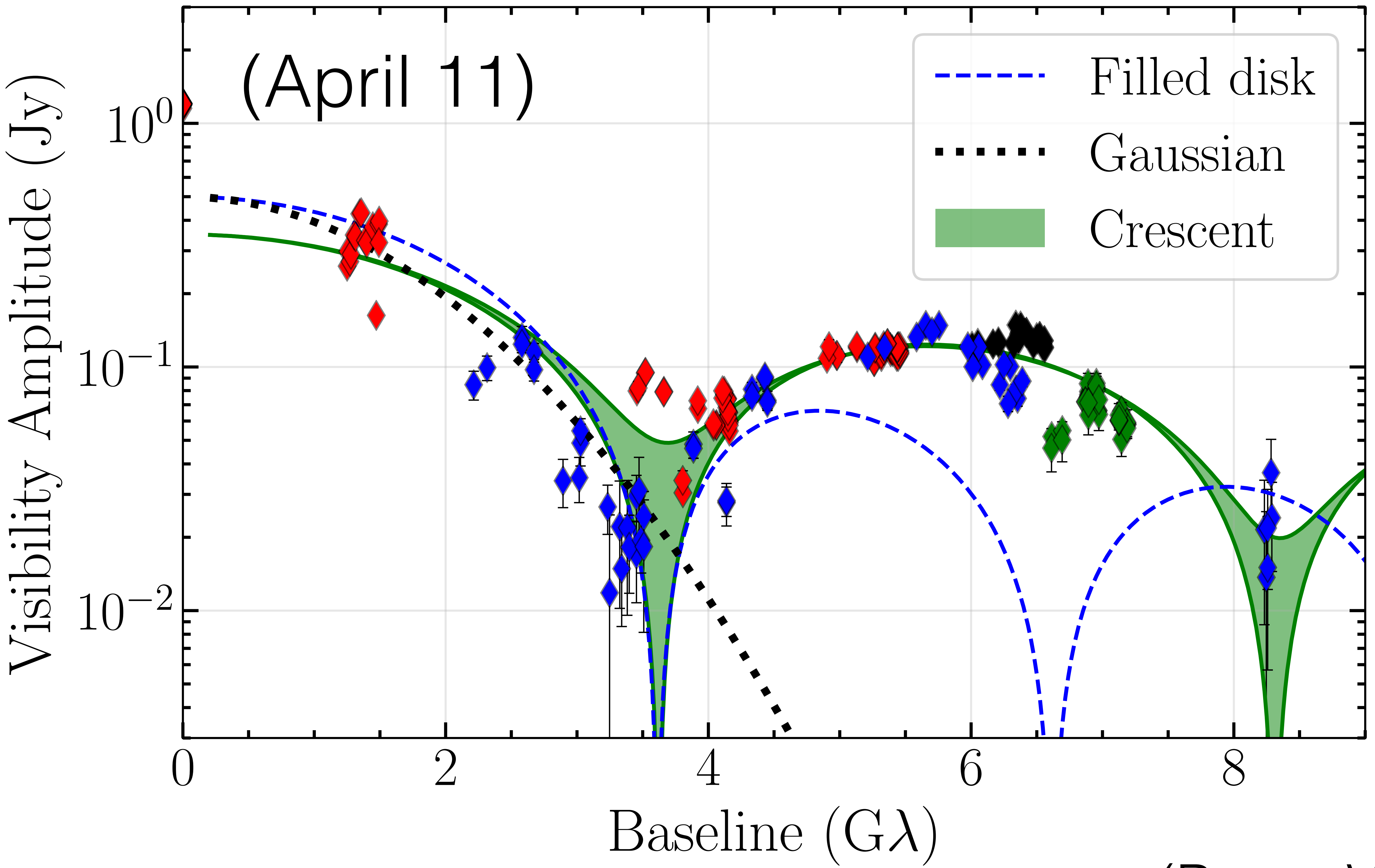
D ~ 10,000 km $\Rightarrow \lambda/D \sim 25$ μas

Calibrated data sets (before imaging)

EHT 2017 M87 data look consistent with an asymmetric ring (“crescent”)

Fourier domain





(Paper VI)

Event Horizon Telescope

Event Horizon Telescope & Black Hole Shadow

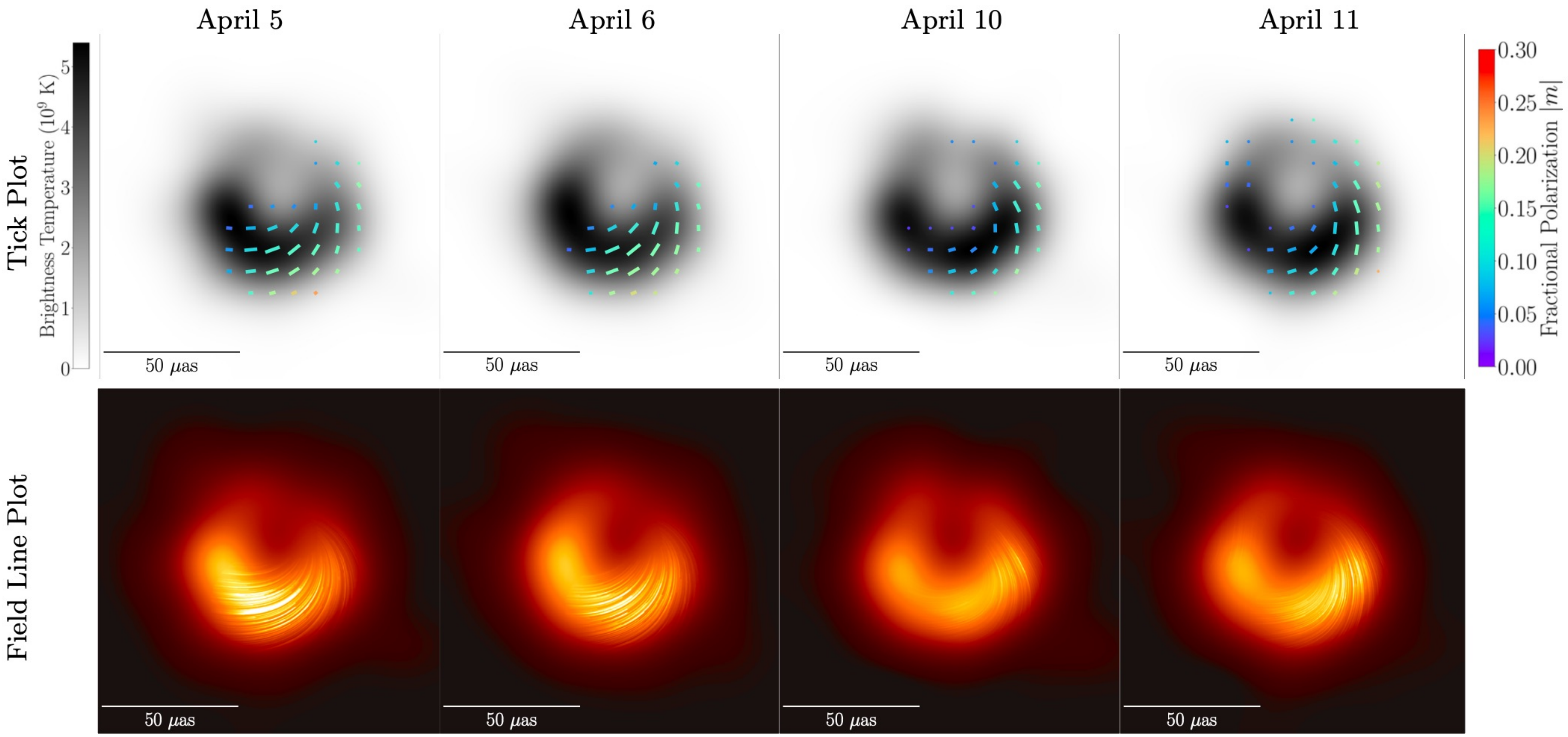
- In April 2017, EHT has observed asymmetric ring morphology of the central compact radio source in M87.
- Consistent with 4 days.
- Interpreted as lensed emission surrounding the spinning Kerr black hole shadow

Event Horizon Telescope

(EHTC et al. 19d)

Averaged Polarimetric Images

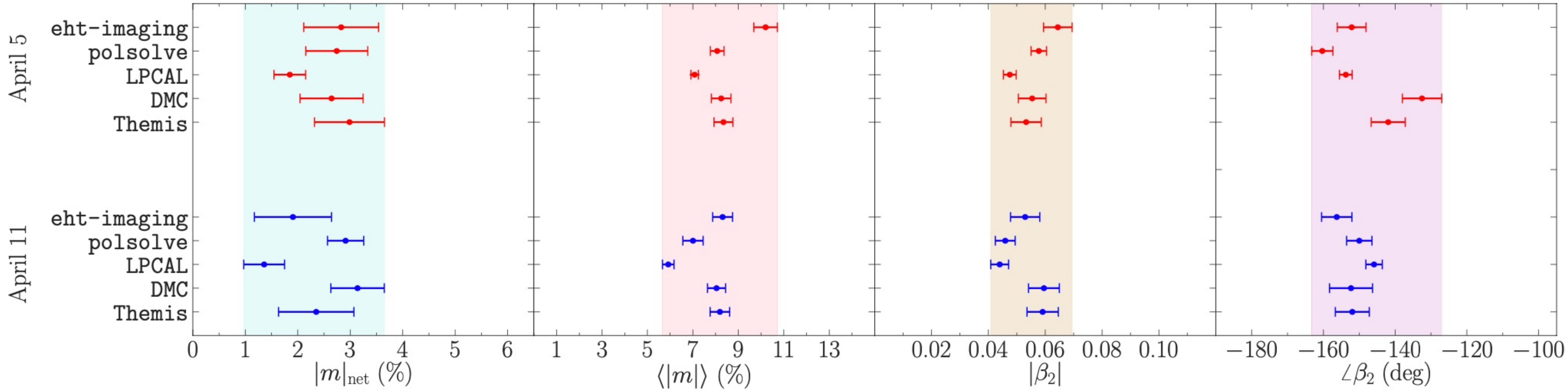
- Emission ring is polarized in south-west.
- Overall weakly polarized: fractional pol. ~15%
- electric vector position angles (EVPA) pattern is following ring structure
- Slight difference in polarization structure in first two-days and last-two days



Event Horizon Telescope

(EHTC Paper VII)

Image-Averaged Quantities



net linear polarization fraction $|m|_{\rm net} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$

intensity-weighted average polarization fraction $\langle|m|\rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$

polarization structure with a decomposition into azimuthal mode (Palumbo et al. 20)

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho,\varphi)\, e^{-2i\varphi}\, \rho\, d\varphi\, d\rho$$

amplitude & phase

Parameter	Min	Max
$\lvert m\rvert_{\rm net}$	1.0%	3.7 %
$\langle\lvert m\rvert\rangle$	5.7 %	10.7 %
$\lvert\beta_2\rvert$	0.04	0.07
$\angle\beta_2$	-163 deg	-127 deg

Use these values for model constraint

Event Horizon Telescope

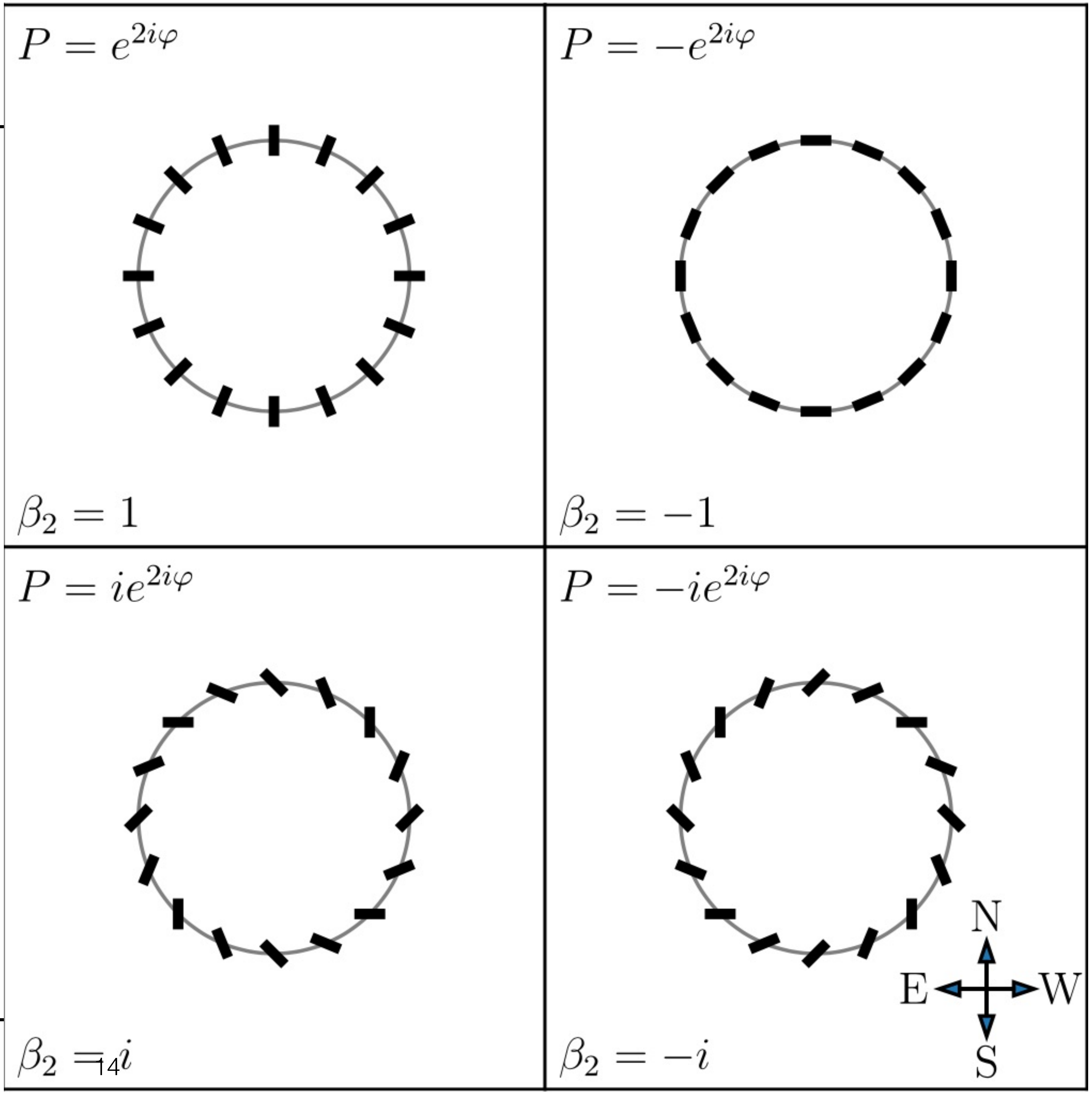
(EHTC+ 21a)

Azimuthal mode of Polarized Structure

Expand a linearly polarized image from multipole series in polar coordinates (ρ,φ).

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_{0}^{2\pi} P(\rho,\varphi)\, e^{-2i\varphi}\, \rho\, d\varphi\, d\rho$$

β_2 value (m=2 mode) reflects electric vector position angles (EVPA) pattern.



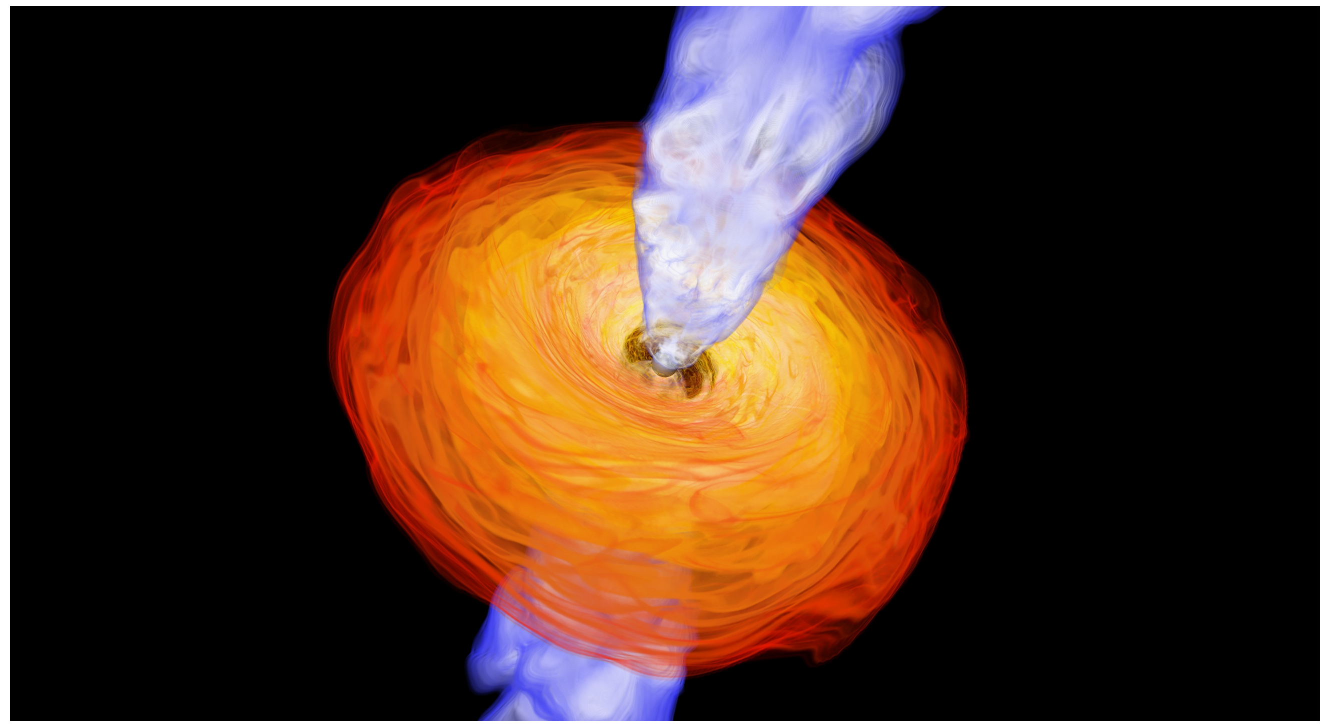
(Palumbo et al. 20)

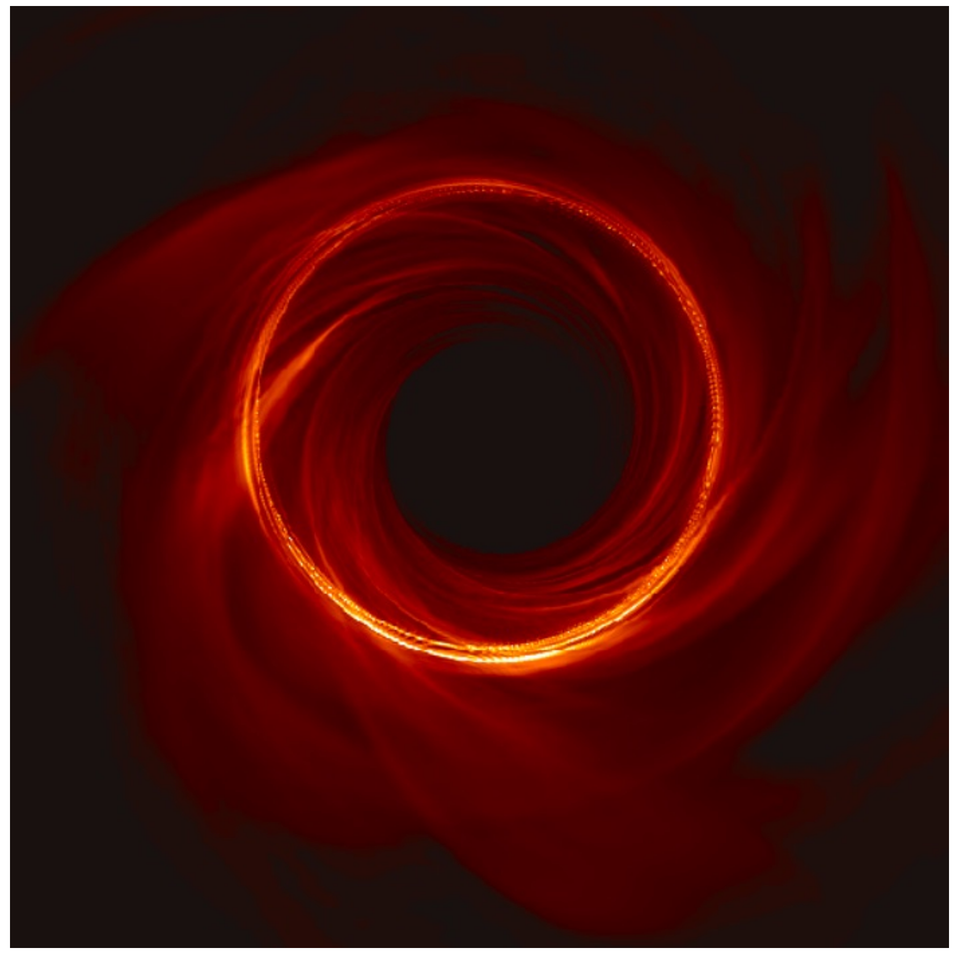
Event Horizon Telescope

Synthetic modeling in simulations

GRMHD:

- spacetime
- Disk evolution
- Magnetic field
- Jet launching & propagation



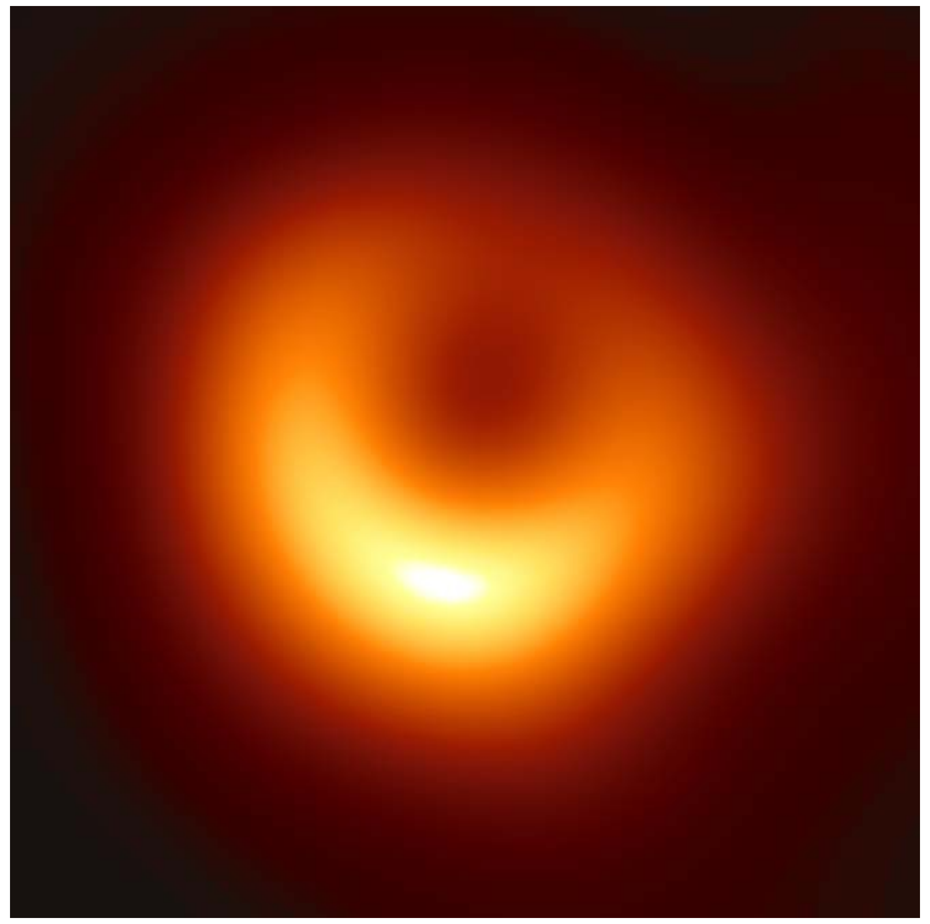


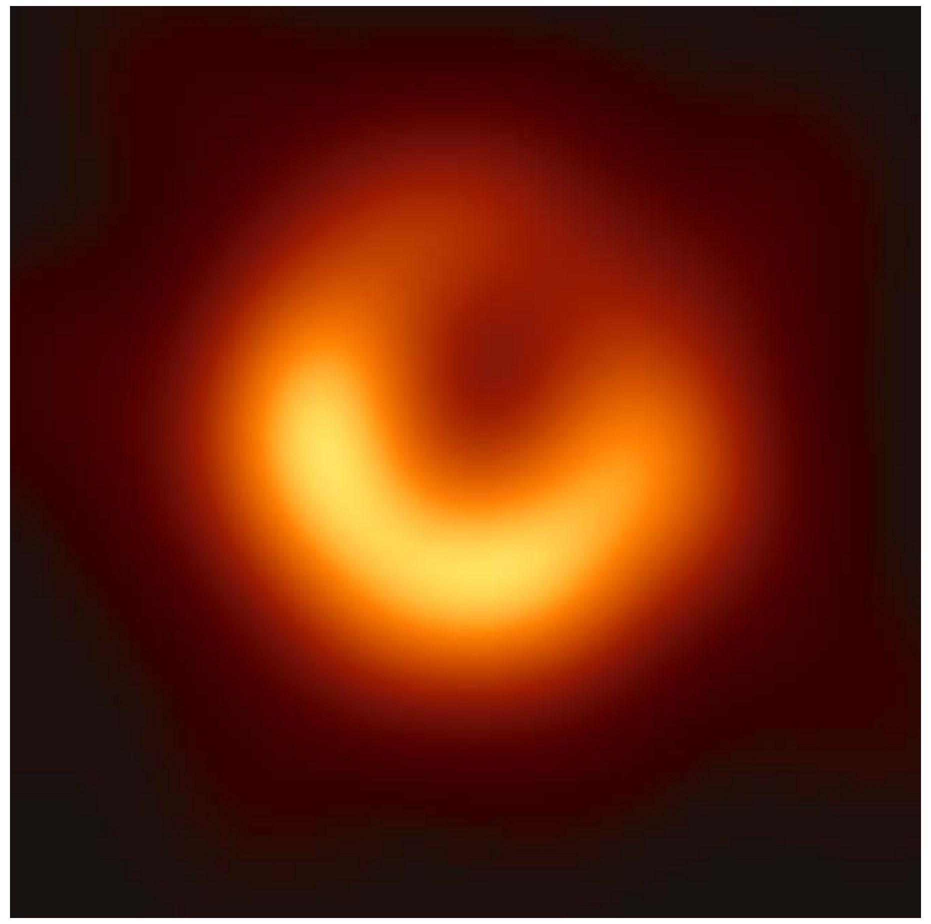
GRRT:

- Mass & distance
- microphysics
- Emission model

Theoretical prediction:

- Synthetic data (VLBI observation)
- Image generation





Observations:

- Data comparison
- Model prediction

What about the parameter space?

GRMHD

- Black Hole spin -1 < a* < 1
- Accretion type (SANE or MAD depends on magnetic flux)

Simulation Library
>15 GRMHD runs

SANE: Standard and Normal Evolution
MAD: Magnetically Arrested Disk

4 GRMHD codes (BHAC, iharm, KORAL, H-AMR)

GRRT

- Black Hole mass
- Accretion rate
- Radiation microphysics (thermal synchrotron, eDF: R-beta model)
- Orientation towards the observer (inclination and jet position angle)

3 GRRT codes (BHOSS, ipole, Raptor)

Image Library
>60,000 images

$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$

Electrons colder at high plasma beta (disk), warmer at low plasma beta (jet)

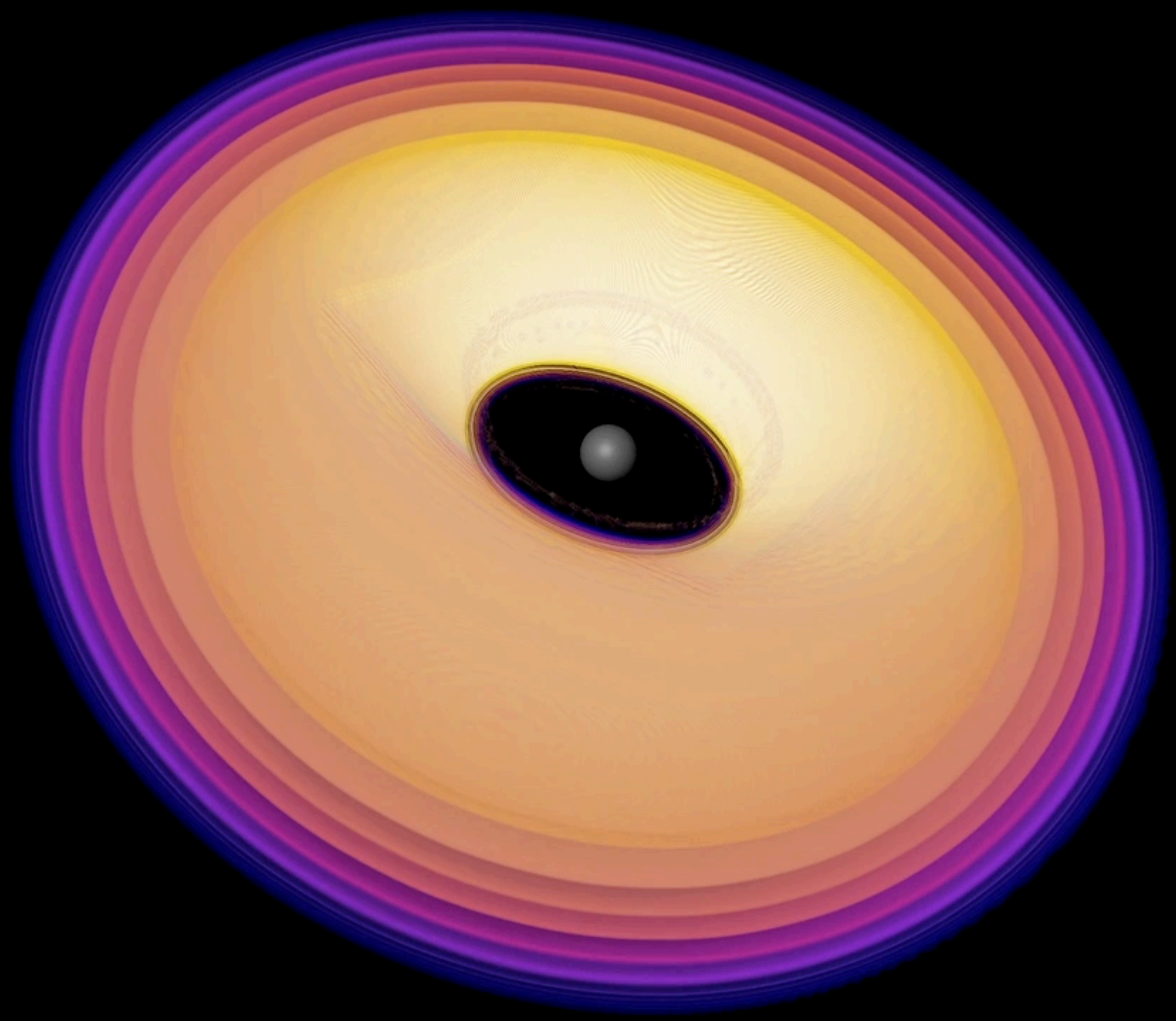
Prior knowledge from observations

- BH mass: 6.2e9 or 3.5e9 Msun
- Inclination angle: 17 or 163 deg with jet position angle 288 deg

GRMHD Simulations

- Model the accretion flow radiatively inefficient accretion flow (RIAF) onto a black hole
- Torus in hydrodynamical equilibrium with poloidal B-field
- Monitor accretion rate and evolve until quasi-steady state

Kerr black hole with a=0.94,
SANE model

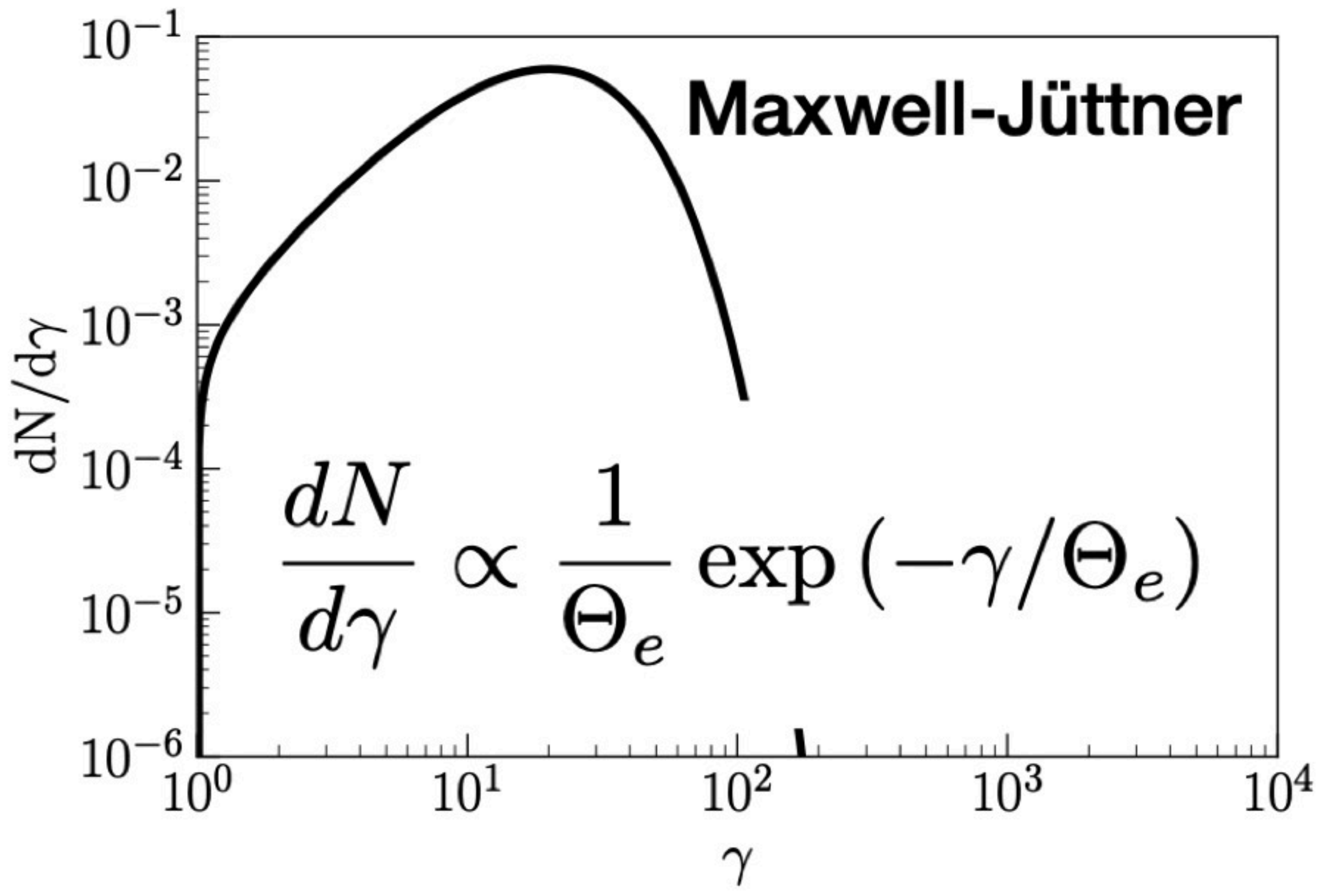


Credit: L.Weih, L. Rezzolla,
Frankfurt BHCam team

GRRT calculation

- Compute the emission structure: BHOSS (Younsi et al. 2021)
- Scale to source: black hole mass, distance, accretion rate, electron distribution function (eDF) & emission process

1) get eDF + emission

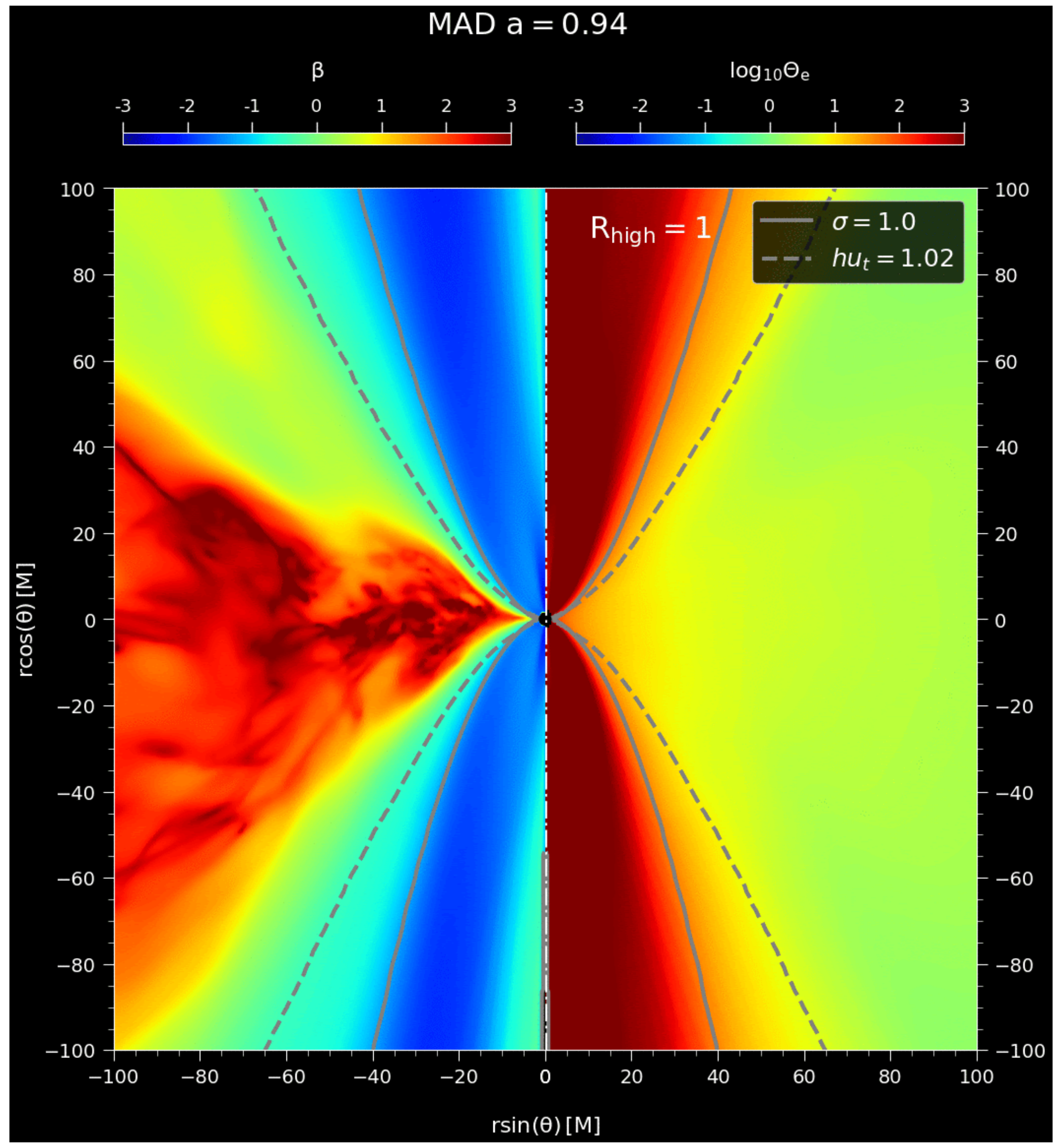


⇒ thermal synchrotron

⇒ electron temp., Θ_e unknown

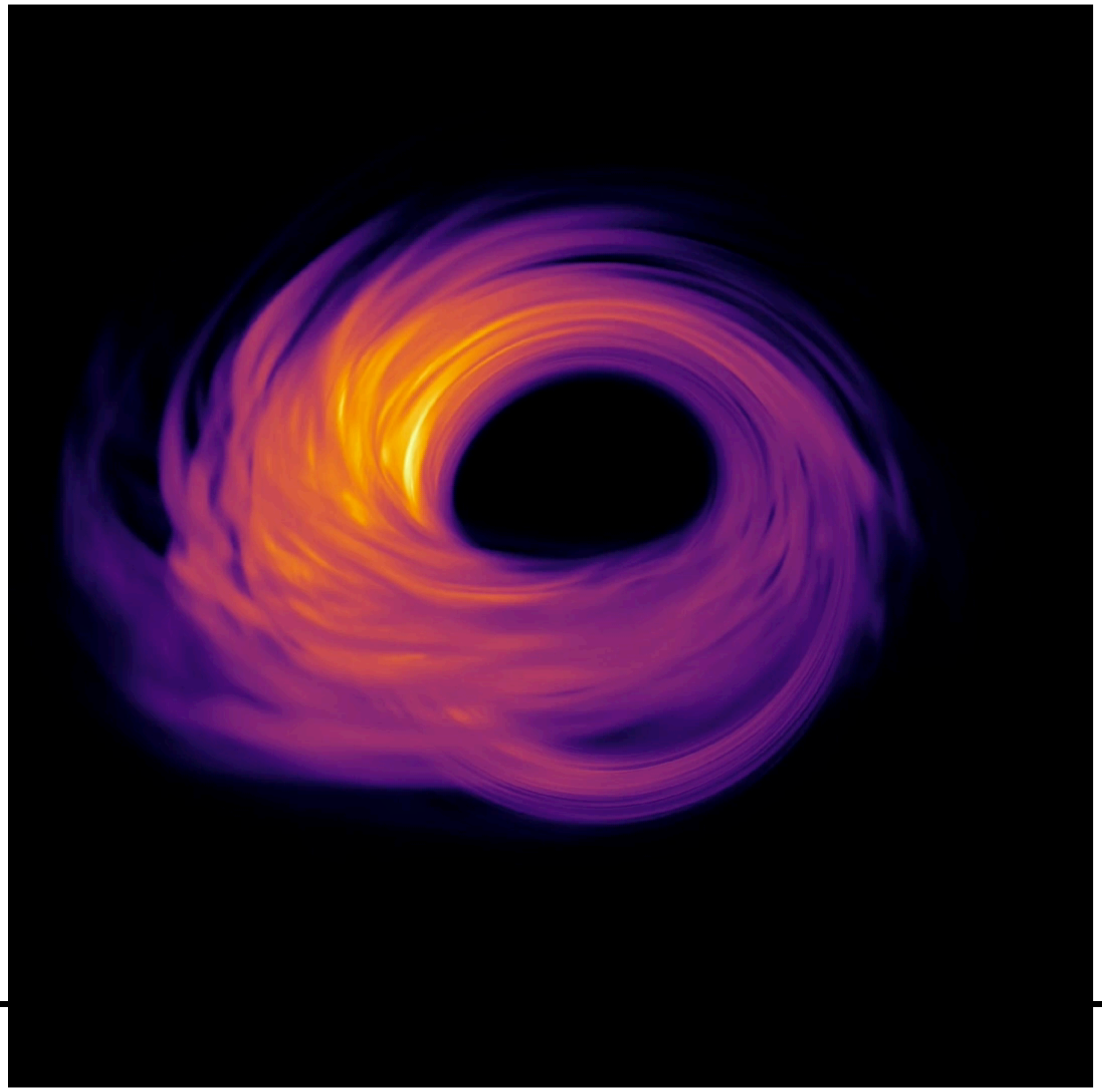
2) connect to GRMHD

$$\frac{T_i}{T_e} = R_{\mathrm{high}} \frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$



⇒ emission+absorp. coeffs.

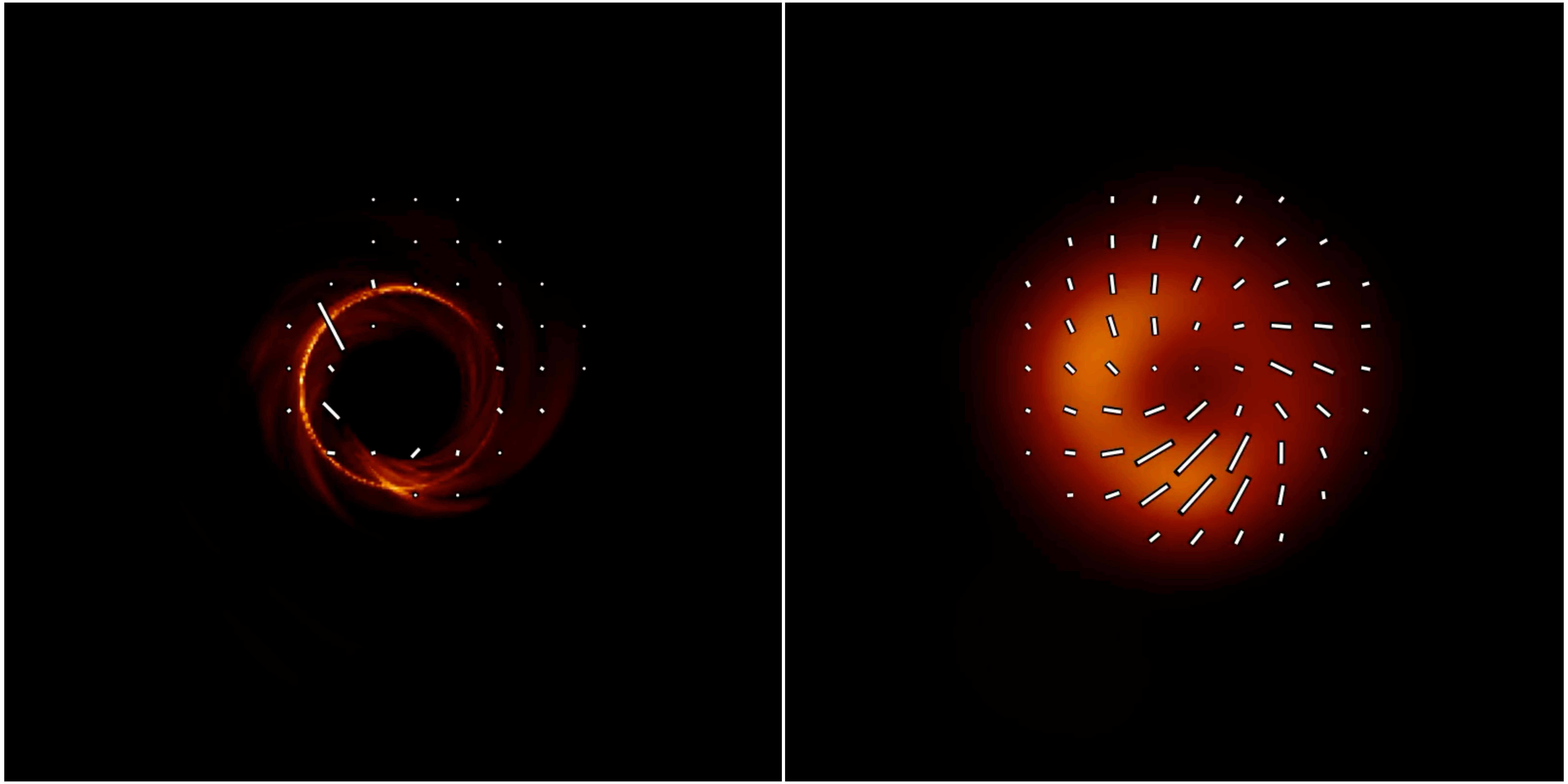
3) get geodesics + radiation transfer



GRRT Image at 230 GHz for M87

- MAD, a=+0.5
- i=163 deg
- each frame corresponds to 1M (~0.35 day)

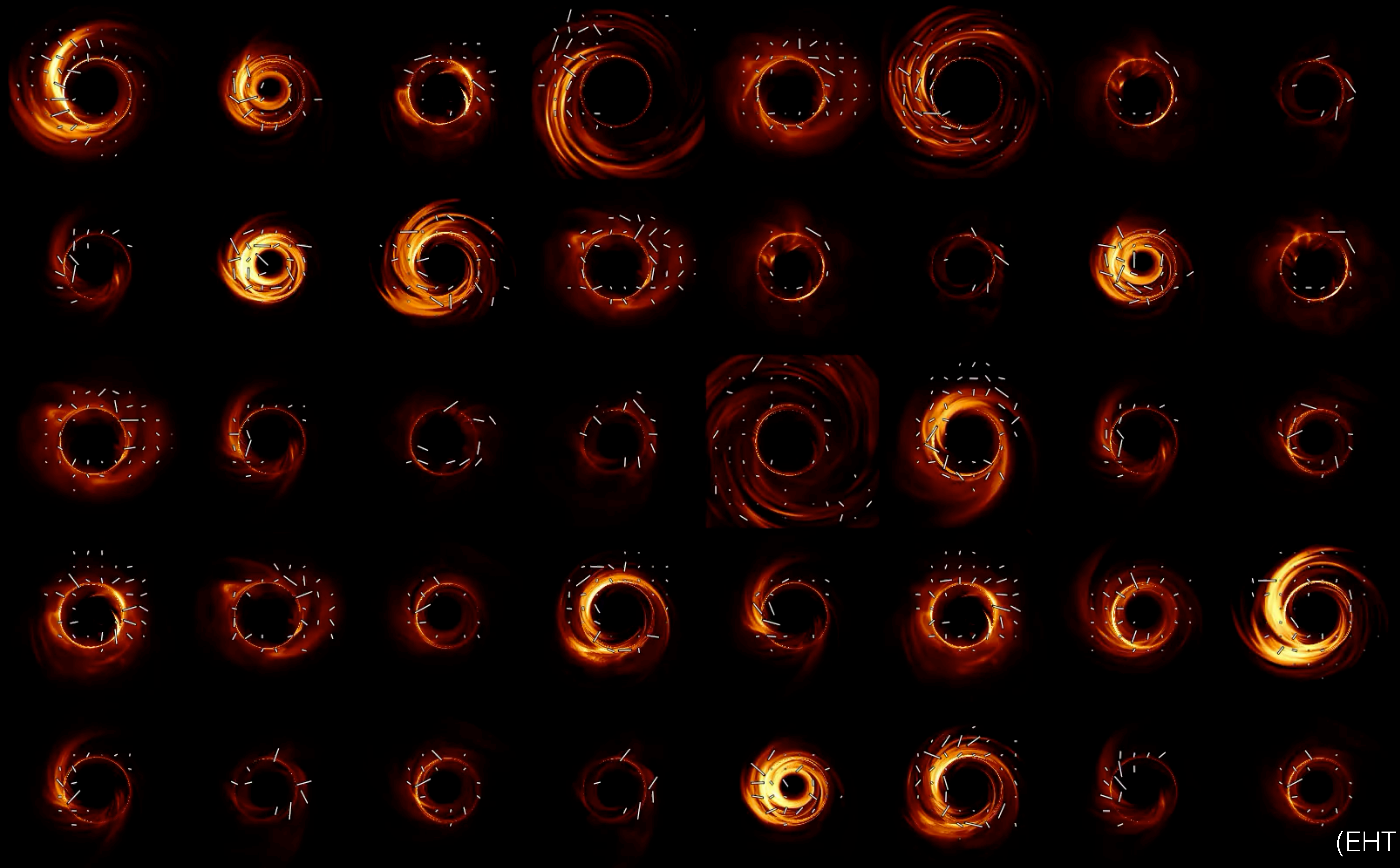
GRRT GRRT+blurred



Event Horizon Telescope

(EHT Paper VIII)

Library of polarized black hole shadow images for M87 (72k images)



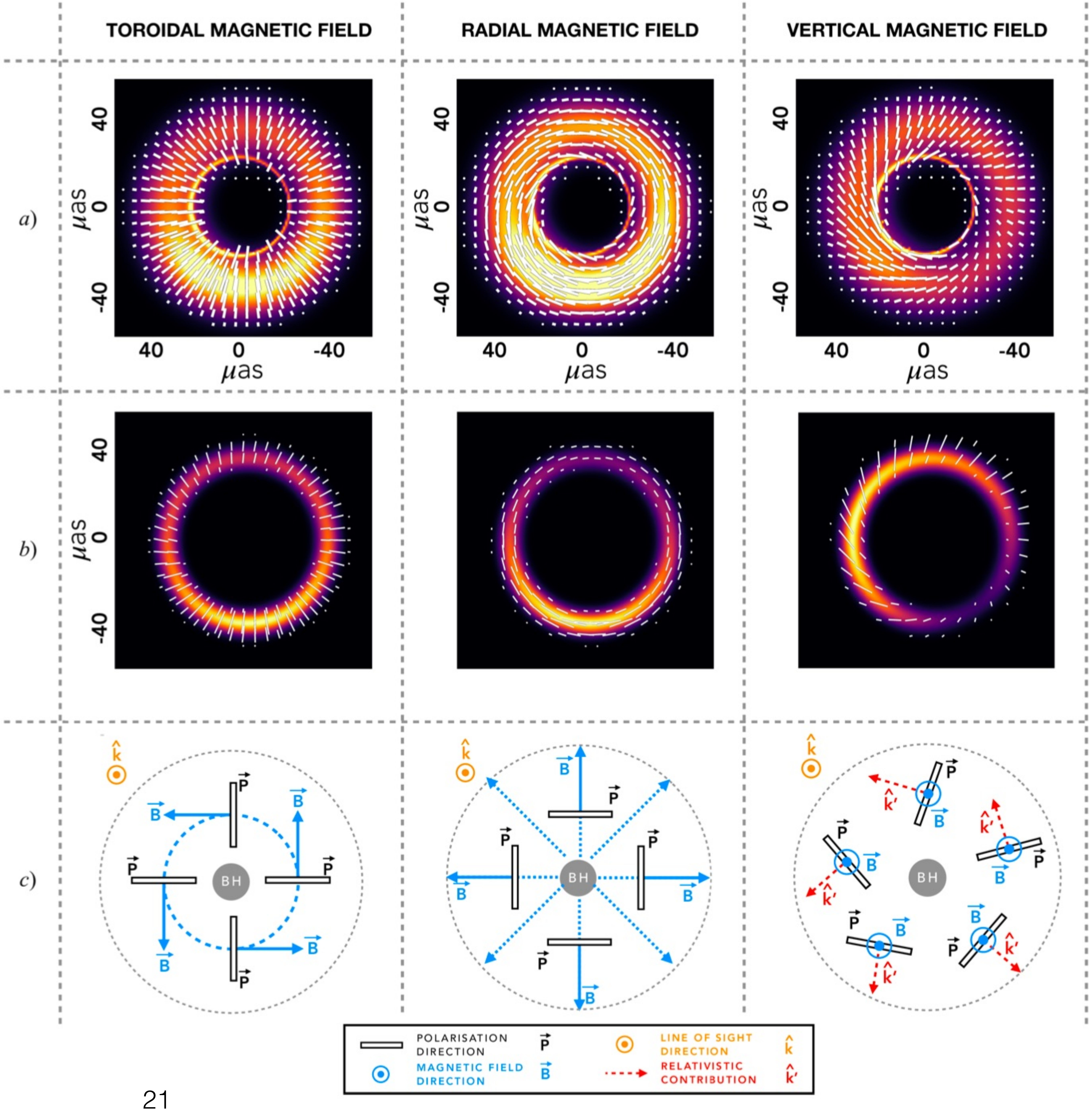
(EHT Paper VIII)

Magnetic Field Configuration

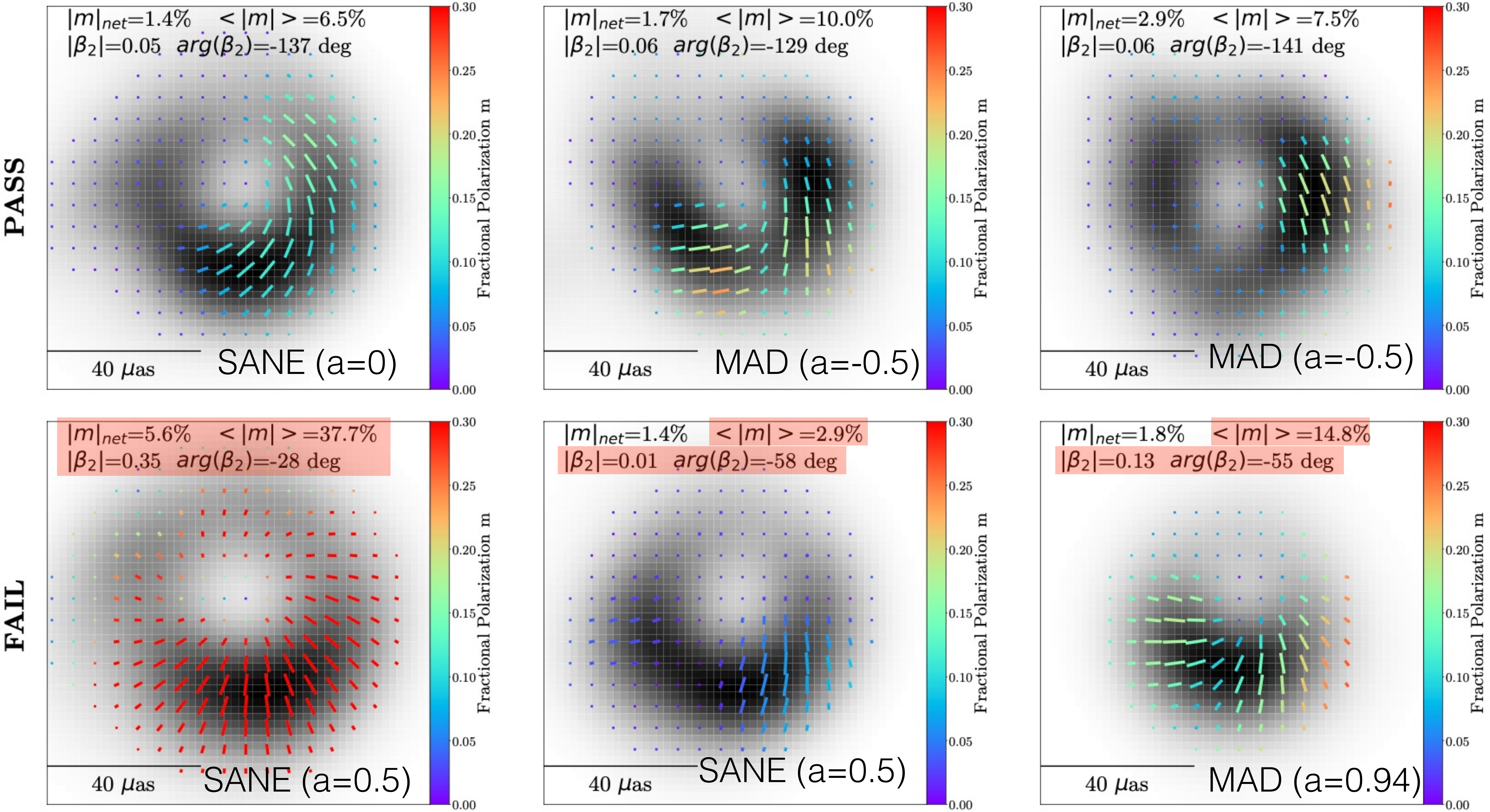
- Consider simple equatorial plane emission

- Different magnetic field configuration (toroidal, radial, and vertical)

- Vertical (poloidal) magnetic field can produce similar azimuthal EVPA pattern observed by EHT

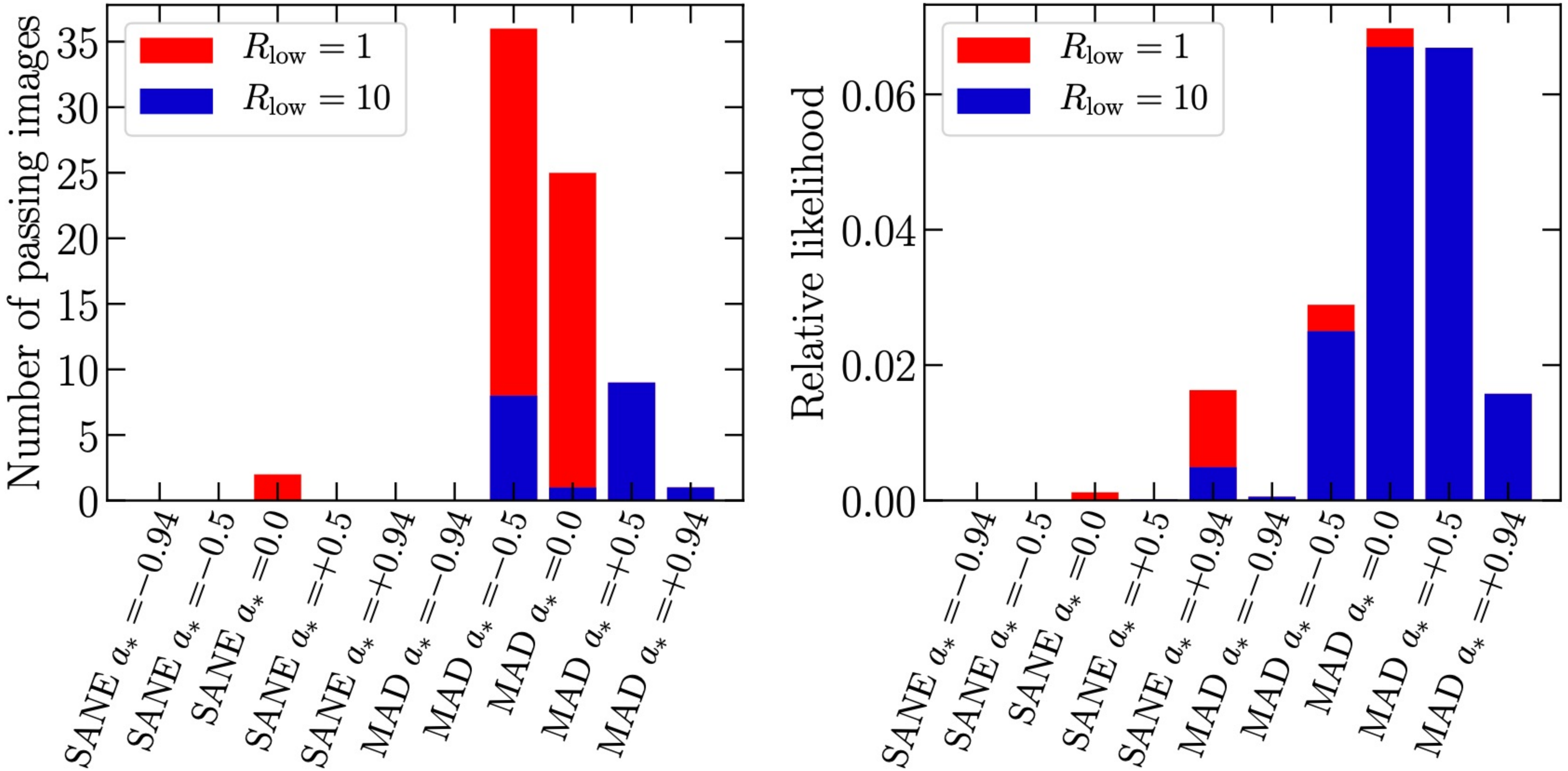


Scoring Results



- Passed only 73/72000 snapshot images across 15/120 models
- Azimuthal EVPA pattern is made by vertical magnetic field

Scoring Results



- Scoring results prefer MAD than SANE.
- SANE & MAD a=0 model would be ruled out from jet power constraint (same as Paper V)

✓ Stellar Mass: 6.2 x 10^9 M_{sun} (Gebhardt et al. 2011)

✓ Black Hole: 4.84-5.2 R_g

✓ Diameter of image ~ 39-45 Rg

✓ Crecent in the ring

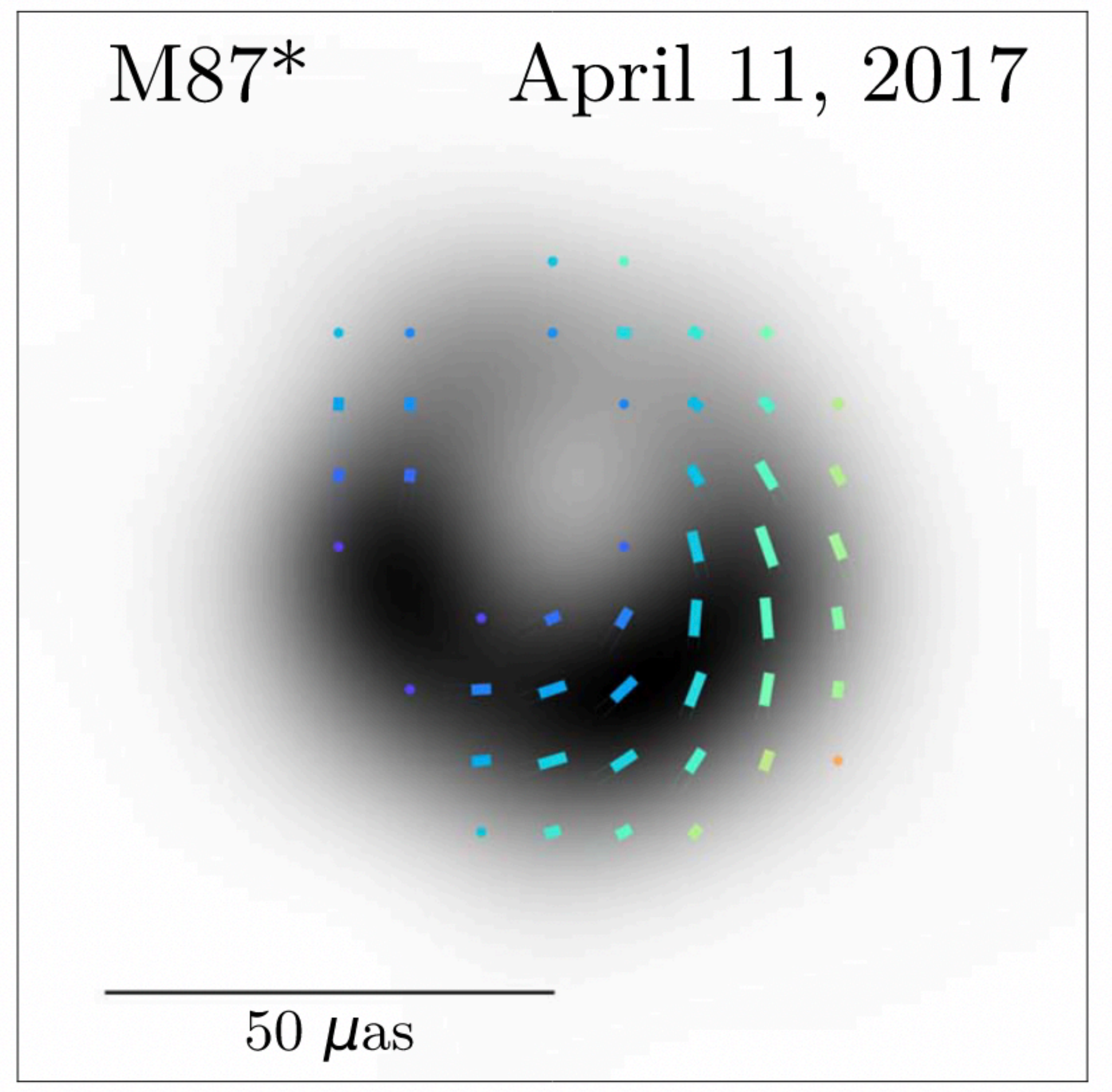
Linear polarisation

✓Spin of BH ~ 0.5

✓B fields ~ 1-20 G

✓Electron temperature Te ~ (1-10)X 10^9 Kelvins

✓EVPA pattern is made by vertical magnetic field



6.5 Billion Solar Mass Black Hole at distance of 16.8 Mpc

Simultaneous MWL observation of M87

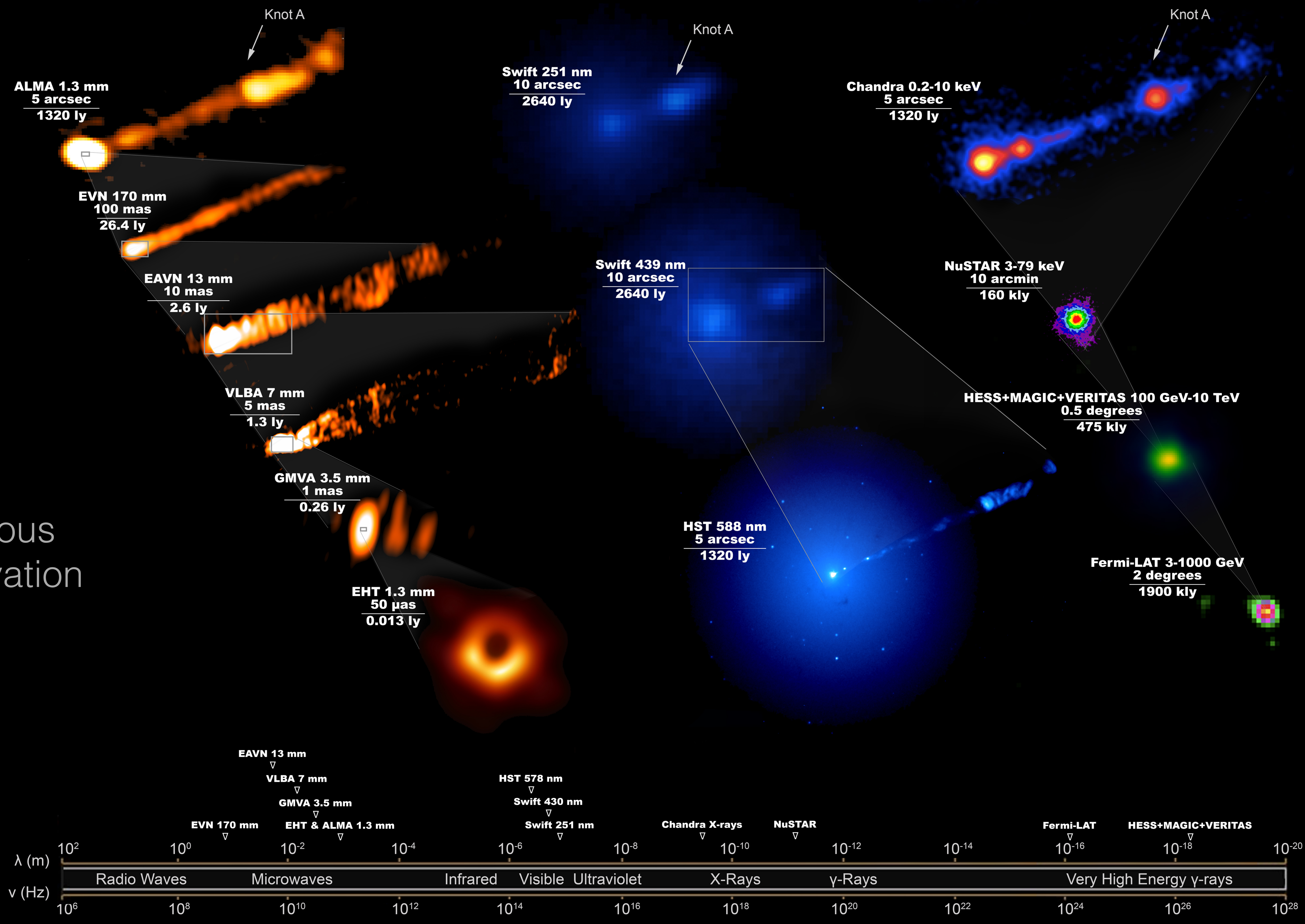
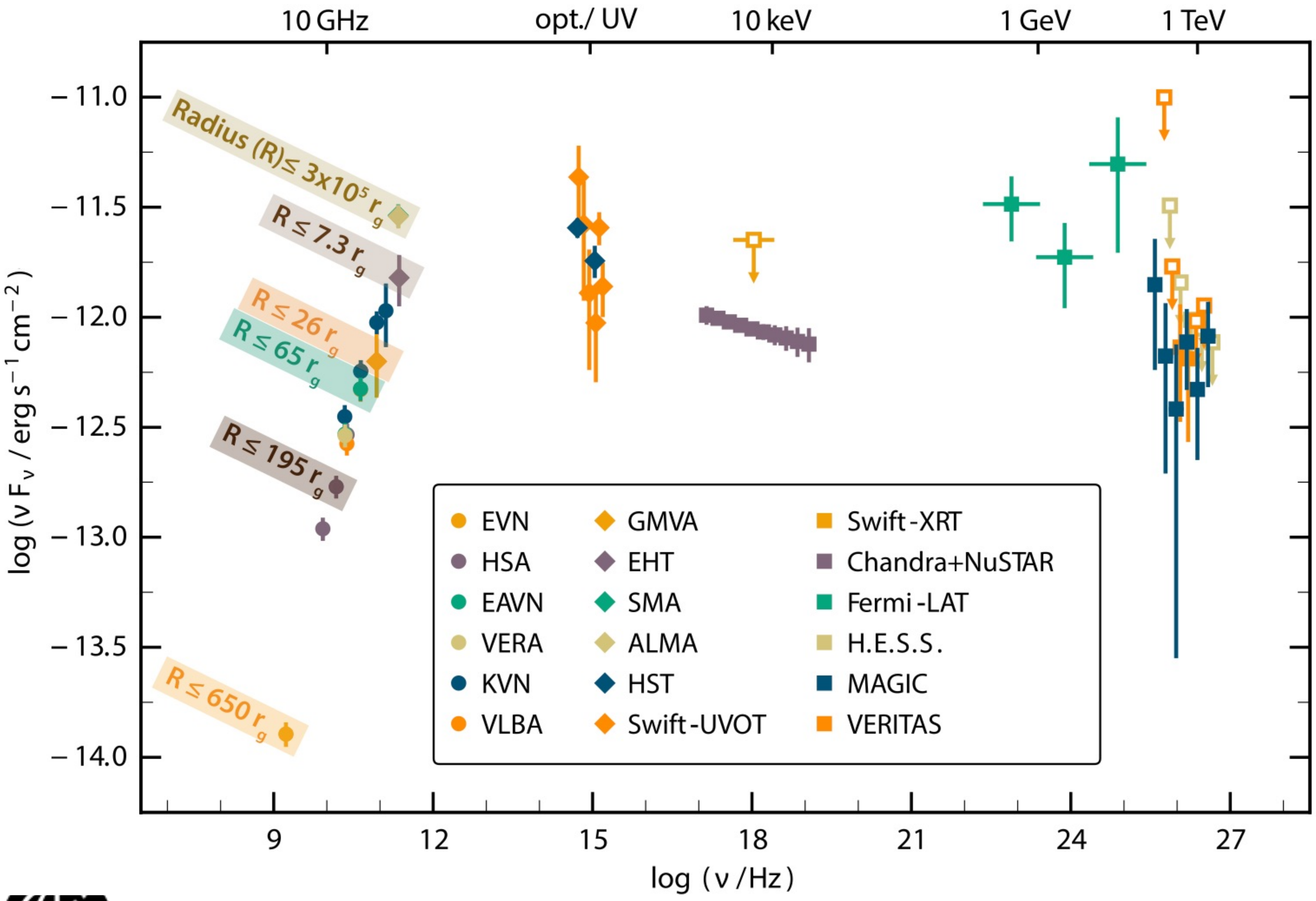


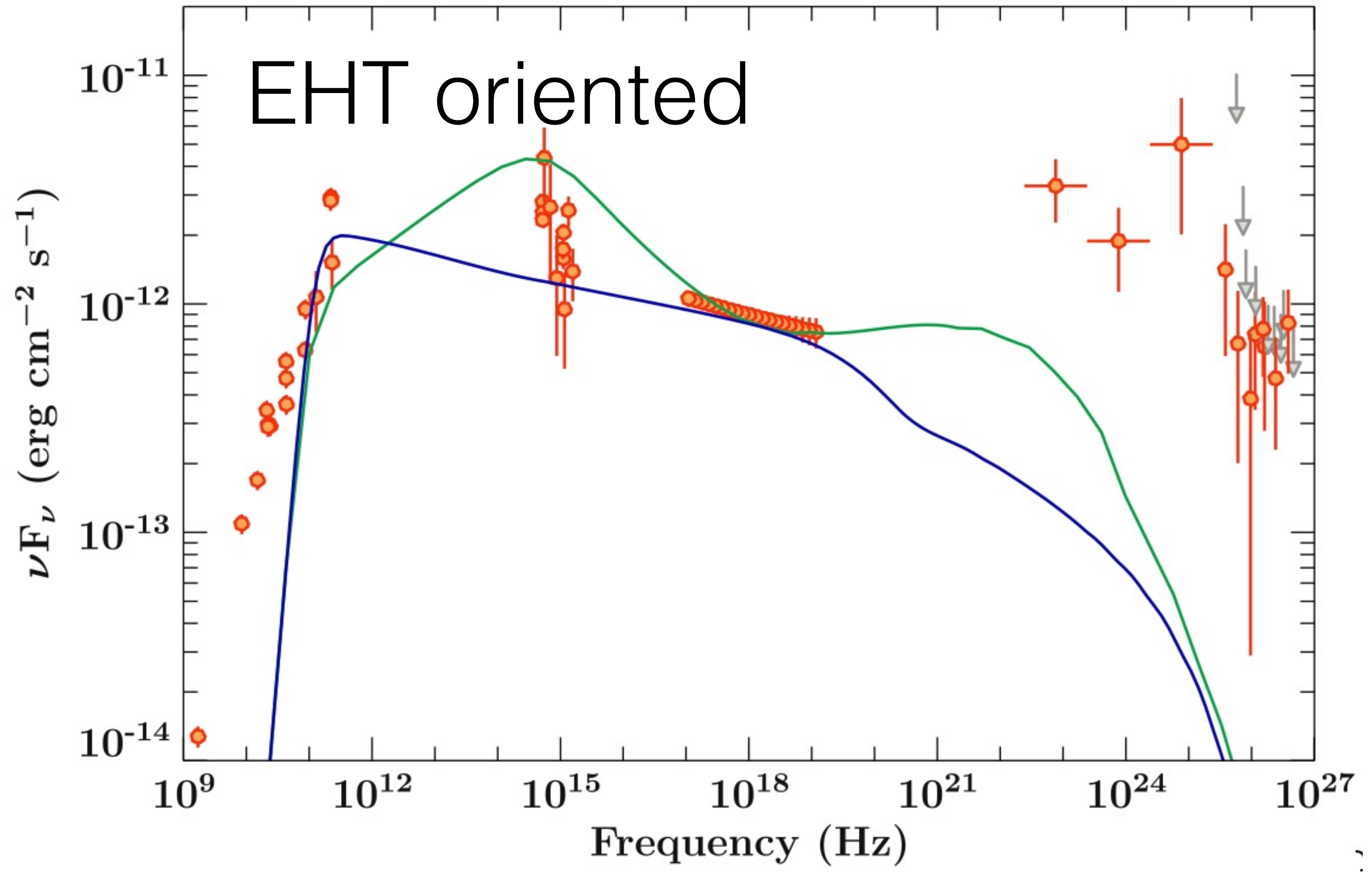
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

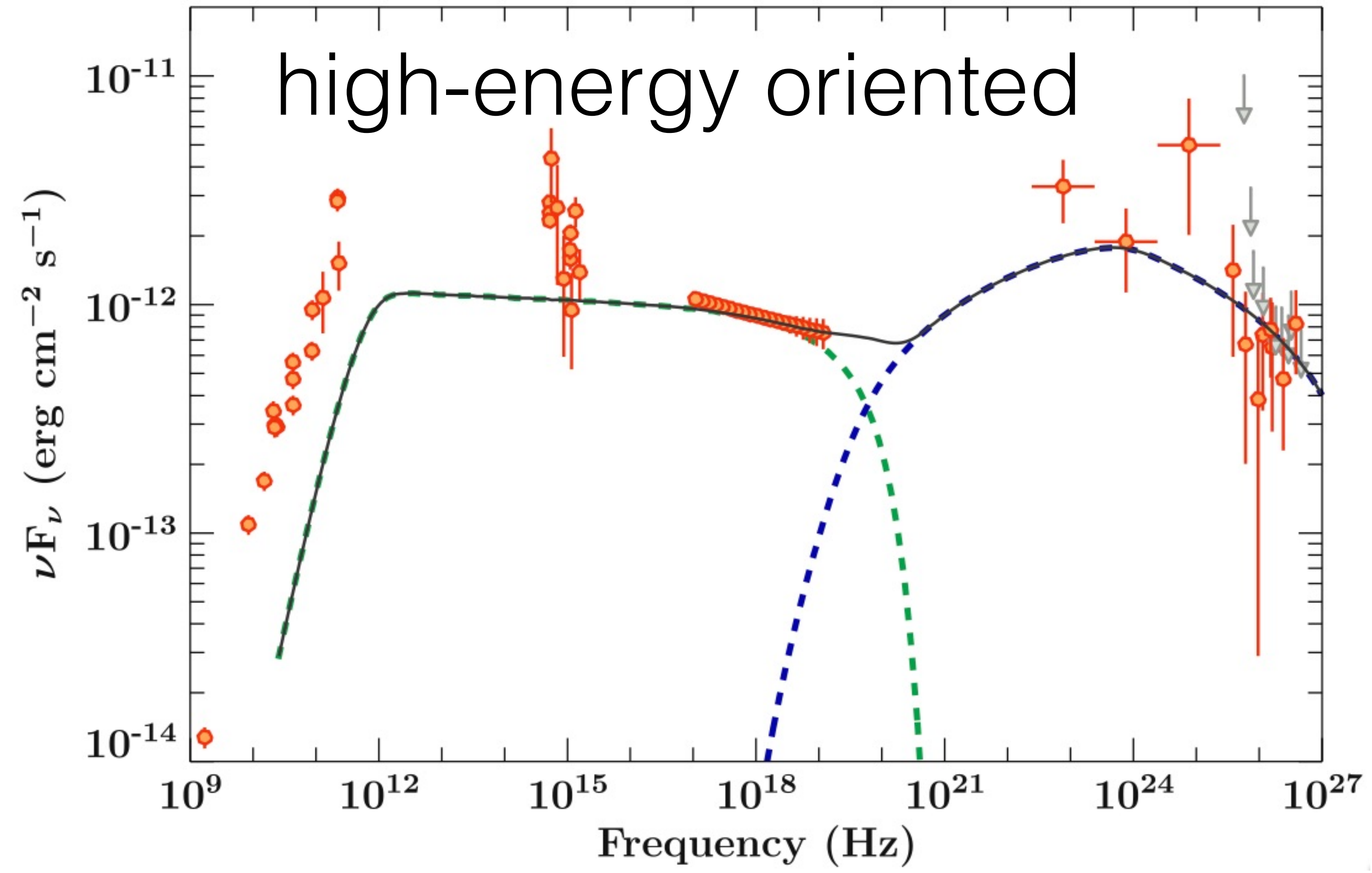
(EHT MWL +21)

SED of M87 in EHT MWL Observations



one-zone SED model



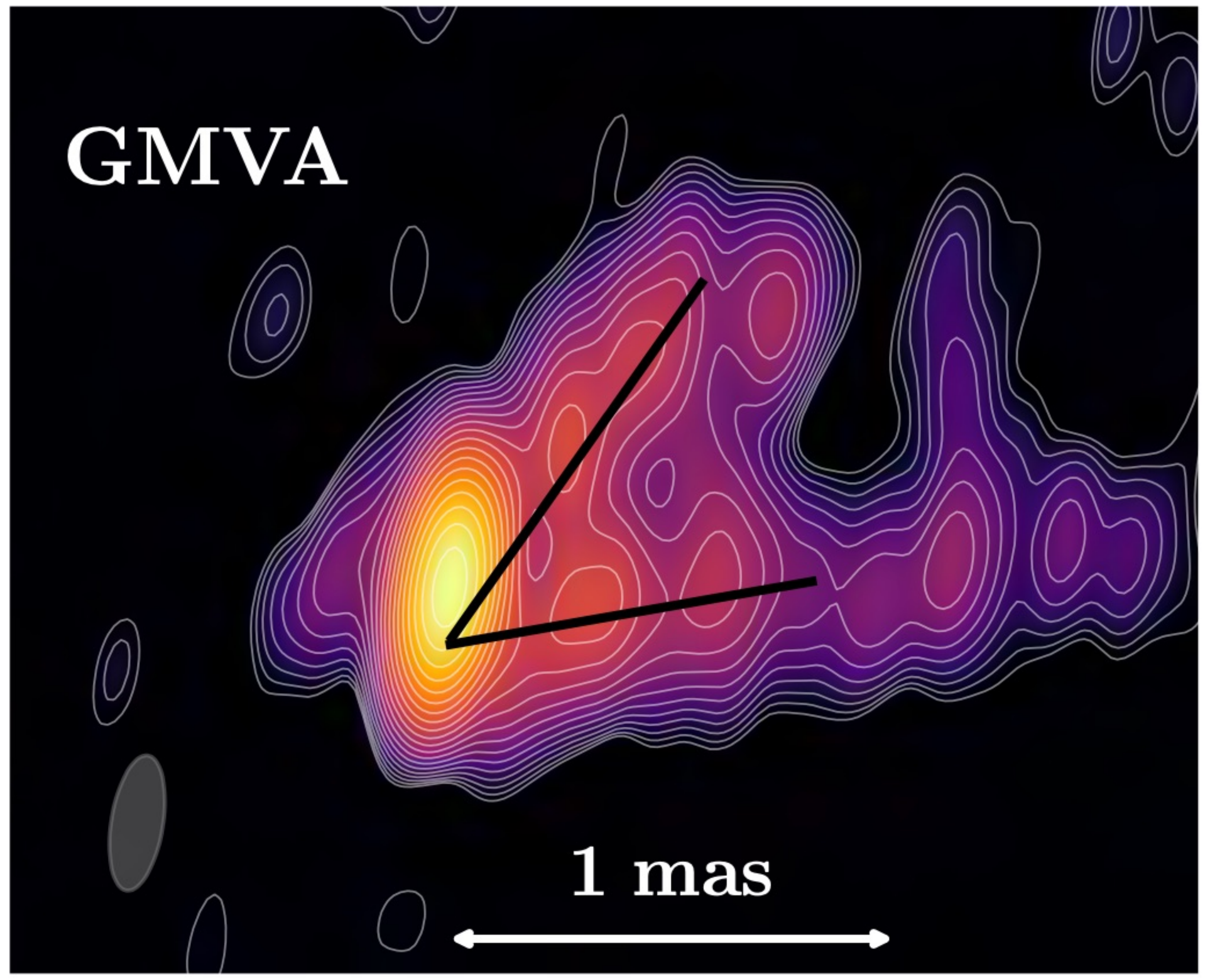


EHT MWL Algaba+ (21)

M87 multi-frequency observations

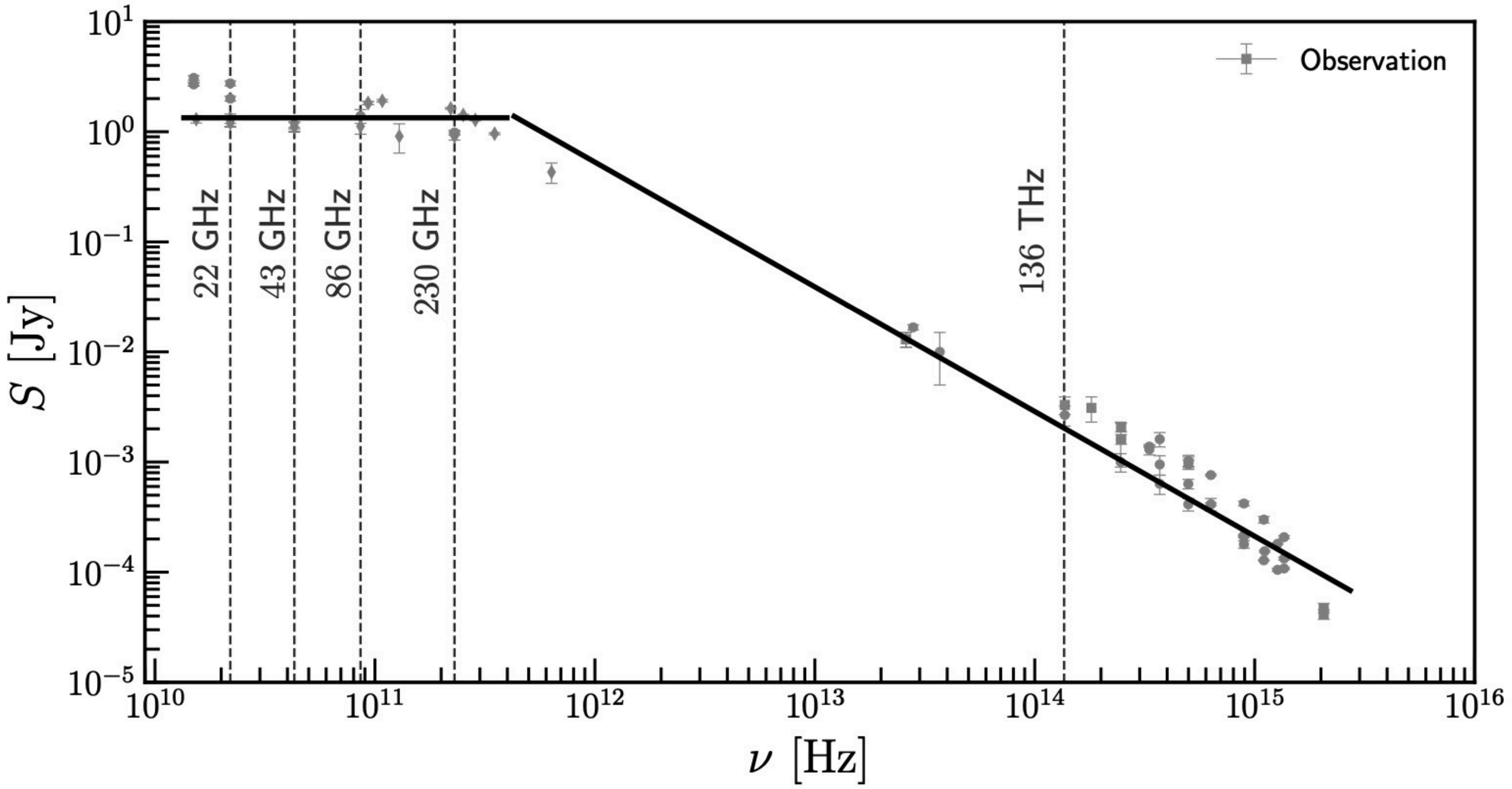
Compare with 86GHz Global Millimetre VLBI observations and board band SED

VLBI @ 86GHz (jet structure)



- wide opening angle
- edge brightening

broad band spectrum



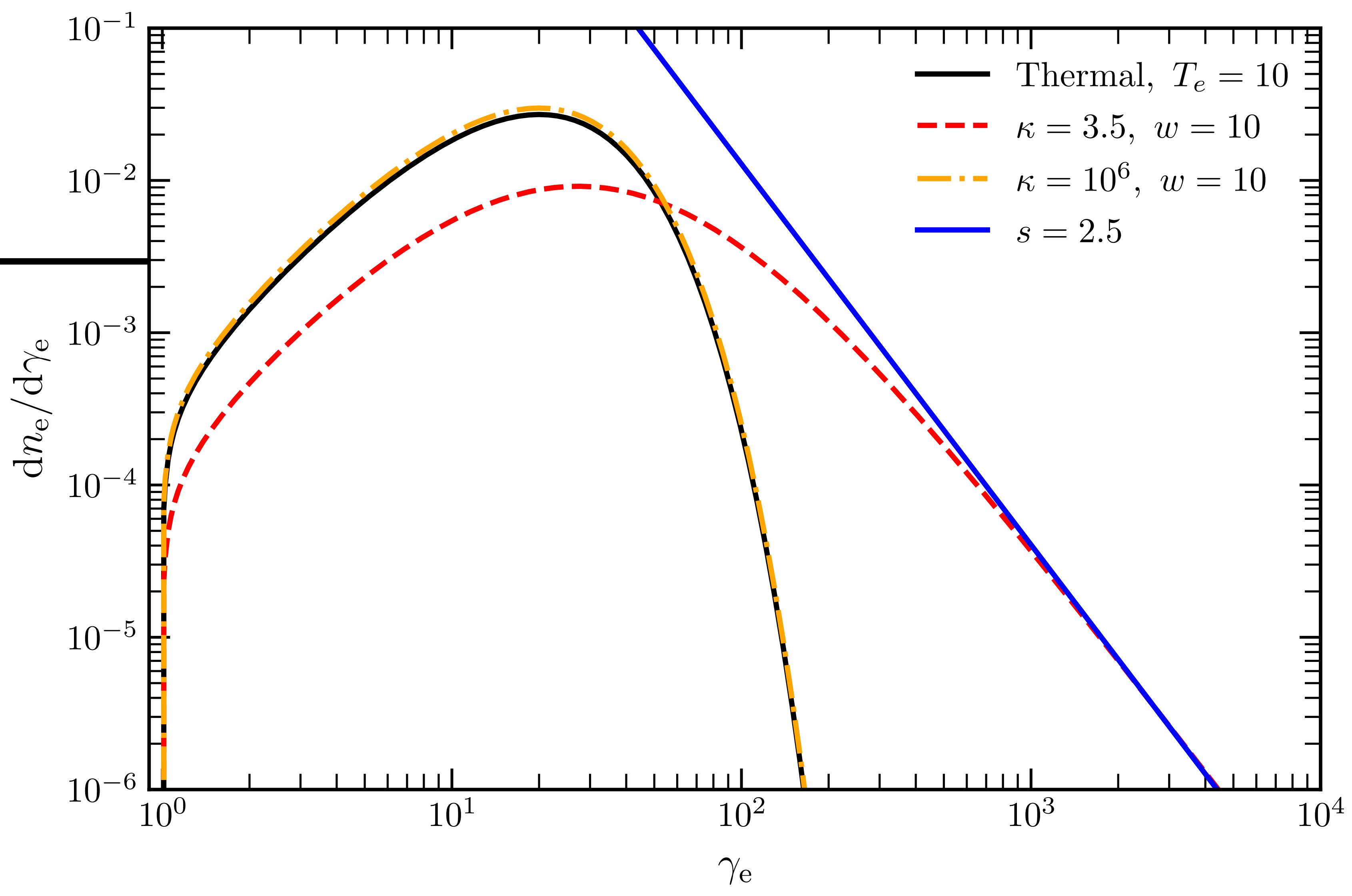
- flat spectrum ($\nu < 10^{12}$ Hz)
- power-law decay spectrum ($\nu > 10^{12}$ Hz)

GMVA: Kim et al. 2018
Spectrum: Kim et al. 2018, Prietro et al. 2016, Doeleman et al. 2012, Akiyama et al. 2015

kappa distribution function

$$\frac{dn_\mathrm{e}}{d\gamma} = N\gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa w}\right)^{-(\kappa+1)}$$

kappa eDF = thermal core + non-thermal tail



- thermal core at low values of the Lorentz factor, asymptotically turns into a power-law
- power-law index, $p=\kappa-1$
- In the limit of $\kappa \to \infty$, the κ-distribution becomes the Maxwell–Jüttner DF
- $\kappa\ (\beta,\sigma) \leftarrow$ subgrid model from PIC simulation

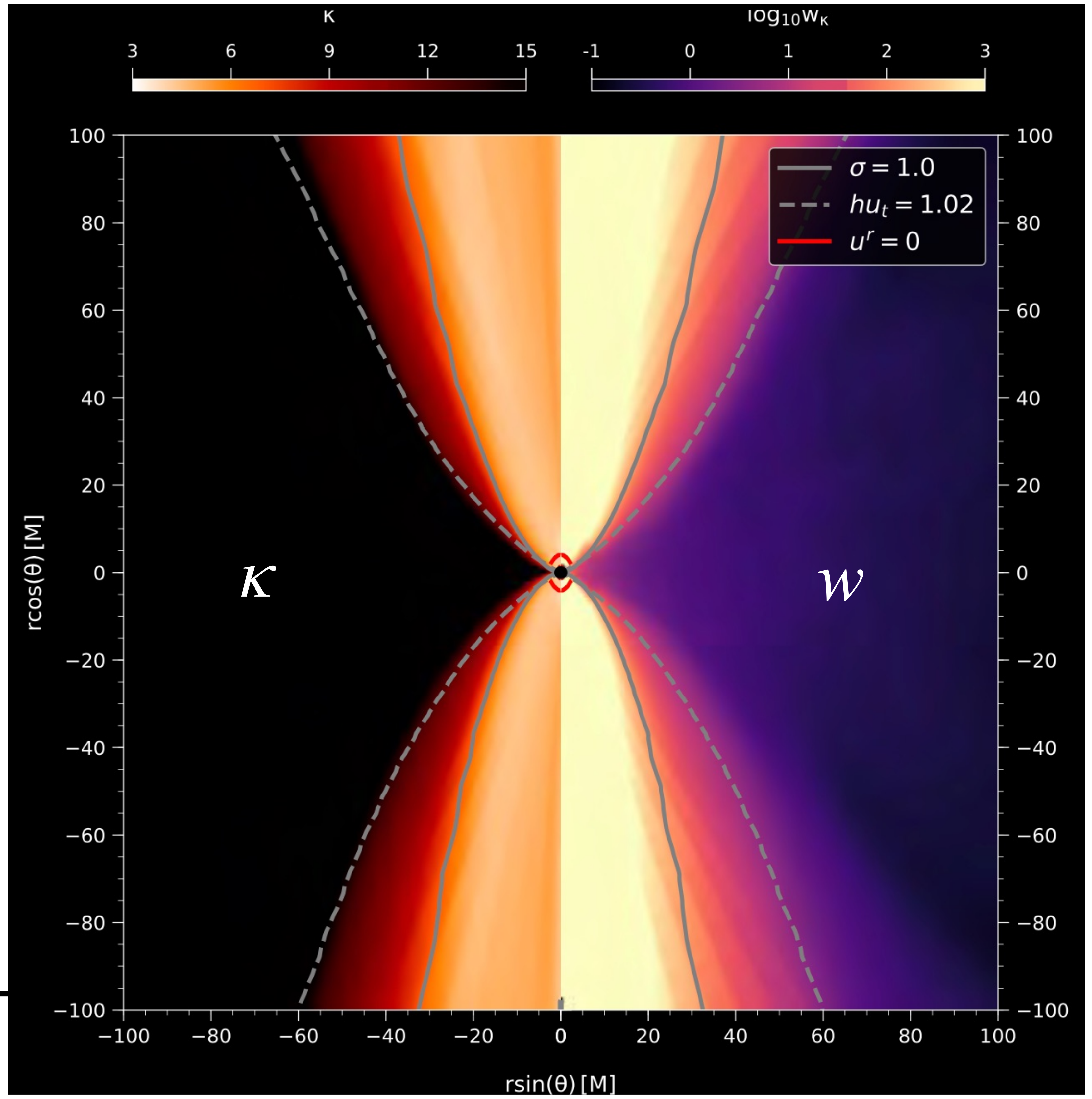
Energy content

$$w = \frac{\kappa - 3}{\kappa}\Theta_\mathrm{e} + \tilde{\epsilon}\frac{\kappa - 3}{6\kappa}\frac{m_\mathrm{p}}{m_\mathrm{e}}\sigma.$$

electron temp., Θ_e : R-beta parameterised prescription

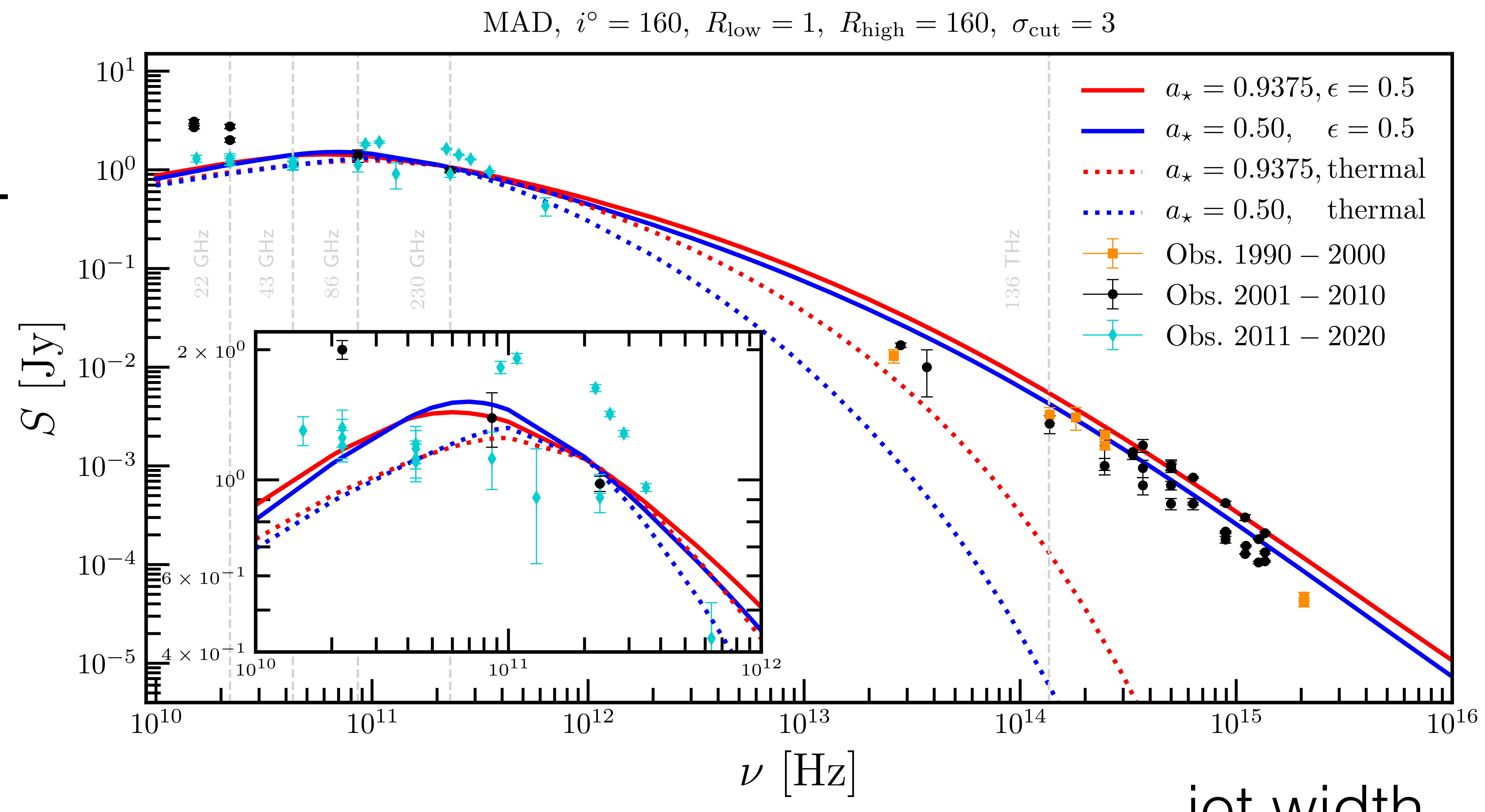
$$\frac{T_i}{T_e} = R_\mathrm{high}\frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$

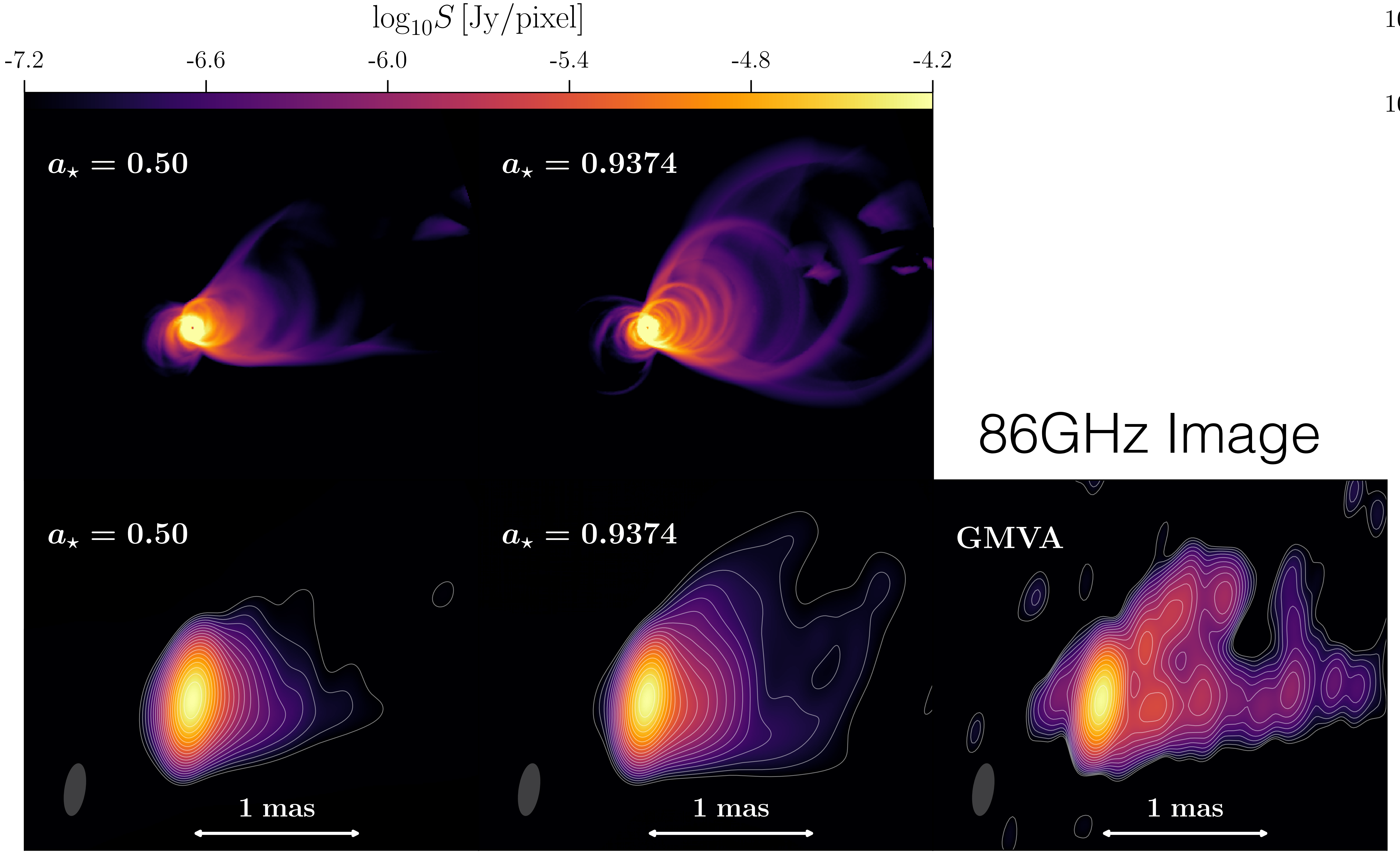
→ connect to GRMHD



M87 Jet Modeling at 86GHz

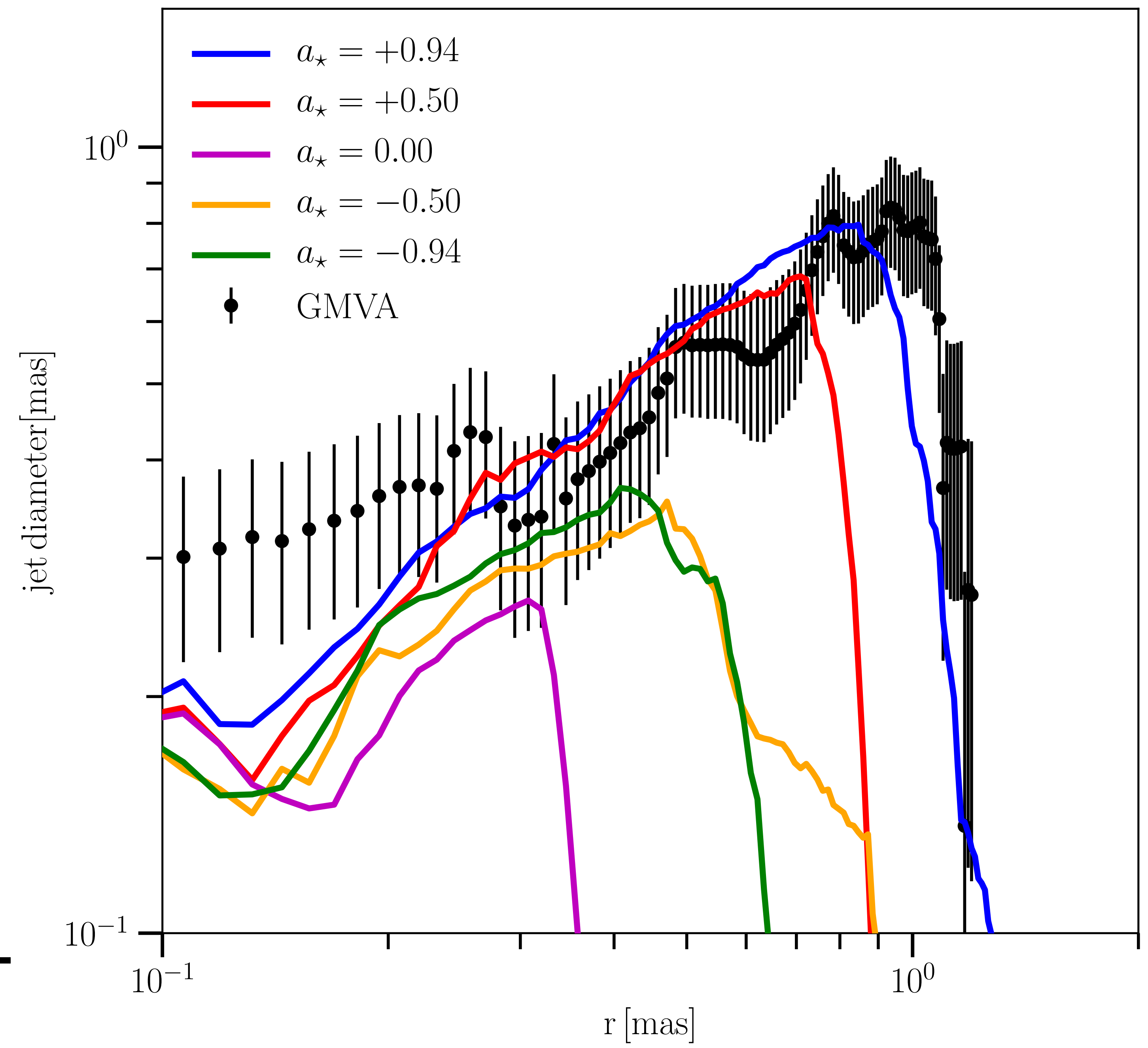
- 3D GRMHD simulations of MAD accretion flows + GRRT calculations (thermal + non-thermal eDF)
- MAD (a=0.94) fits SED & jet morphology at 86GHz





86GHz Image

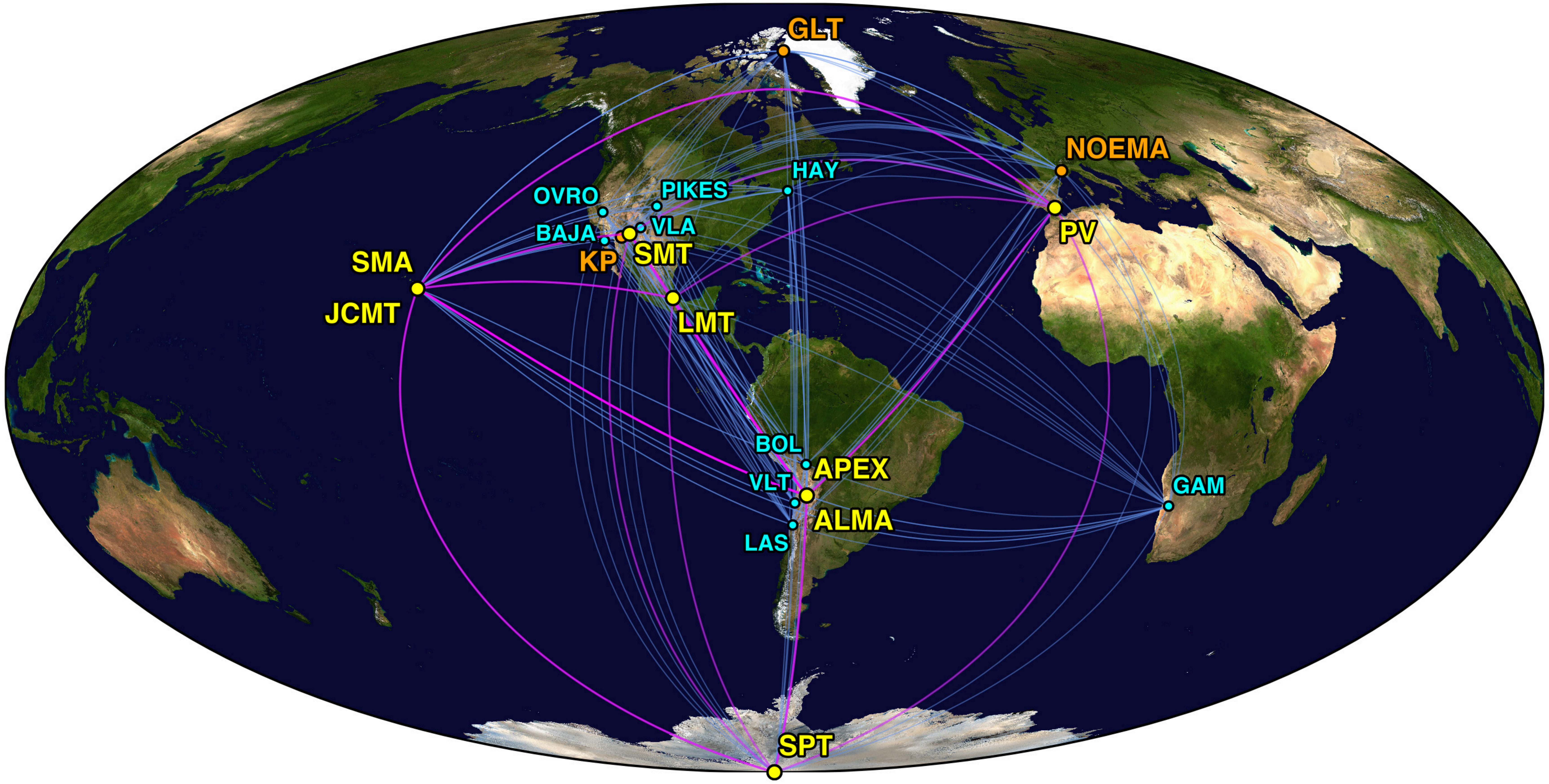
jet width



Event Horizon Telescope

Cruz-Osorio, Fromm, YM et al. (21)

next for Event Horizon Telescope



Phase I: 2019-2023 (Array Design Phase)

Phase II: 2023- (Constructions of several new sites)

Summary

- EHT has see a black hole shadow in M87 which is signature of light bending in Kerr BH metric and absorption by the event horizon
- In new polarized image, high polarised region follows bright ring structure with helical EVPA pattern
- From model comparison, MAD accretion model is favoured than SANE
- Near the BH horizon, poloidal magnetic field is dominated
- New EHT observations will provide the jet formation site and connection to large-scale jets in M87
- ~~Upcoming: Galactic center (Sgr A*) images~~

Event Horizon Telescope

Thank you for listening …