SHADOW OF THE SUPPERMASSIVE BLACK HOLE IN M87

: EHT Observations and Theoretical Interpretation

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  - intensity map & new polarization map
- Theoretical interpretation of shadow of M87 from new polarization results
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- Summary

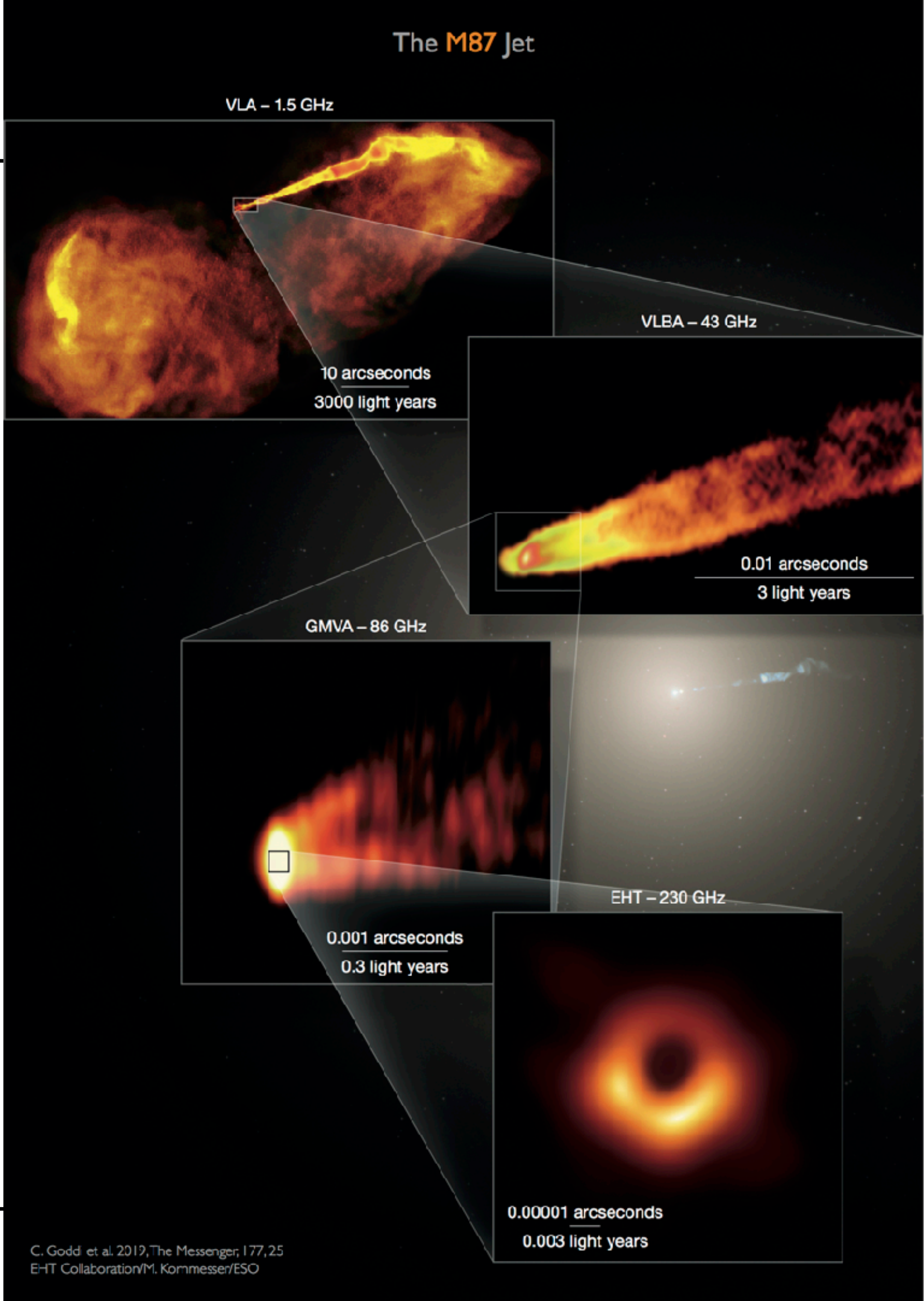
Black Holes with the Largest Angular Sizes

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

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)



Event Horizon Telescope

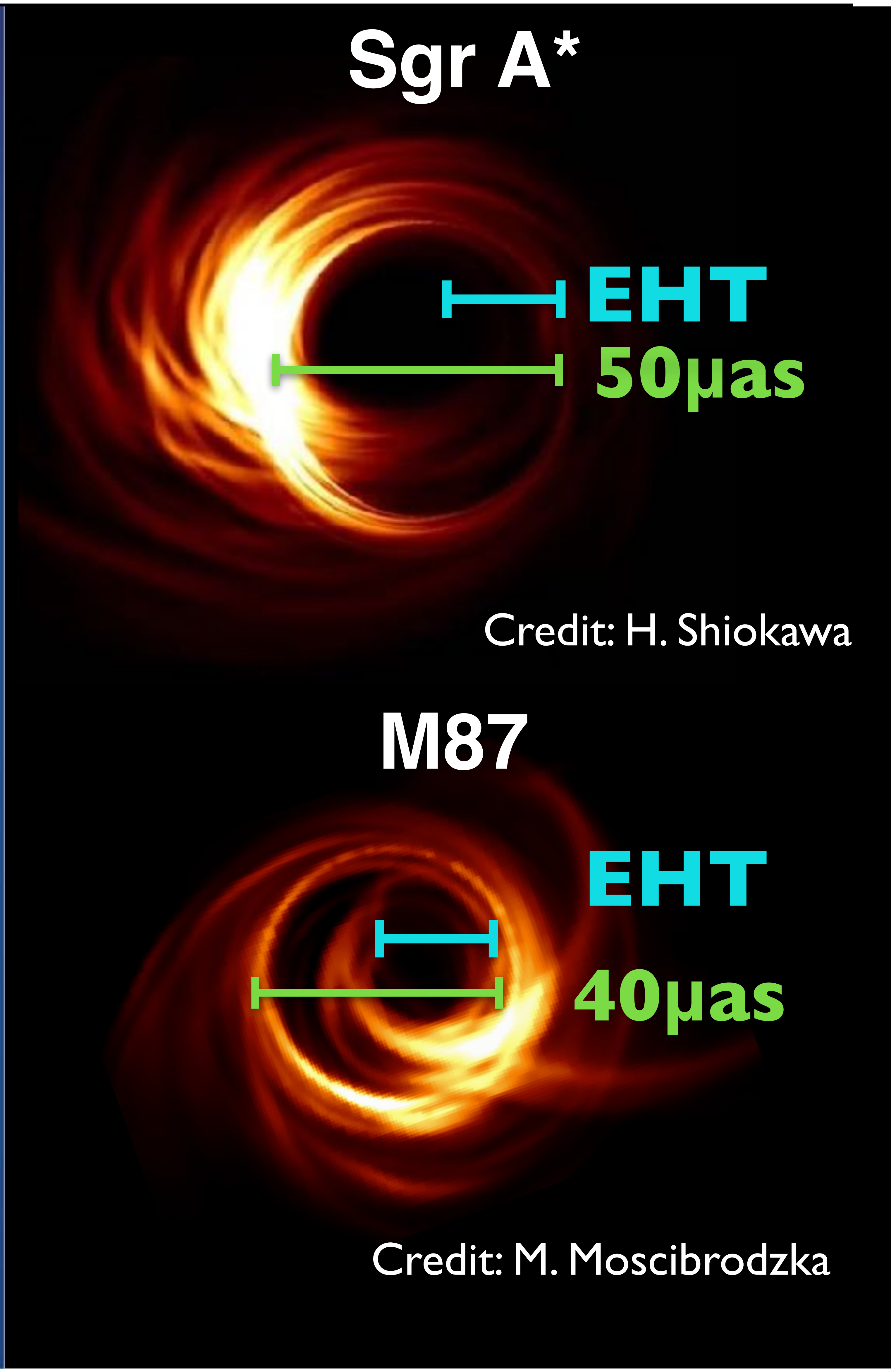
The Event Horizon Telescope Collaboration

- >300 members, >60 institutes, 18 countries in Europe, Asia, Africa, North and South America.
- EHTC aims to image for the first time the shadow of a black hole using sub-mm VLBI

Event Horizon Telescope

Event Horizon Telescope 2017

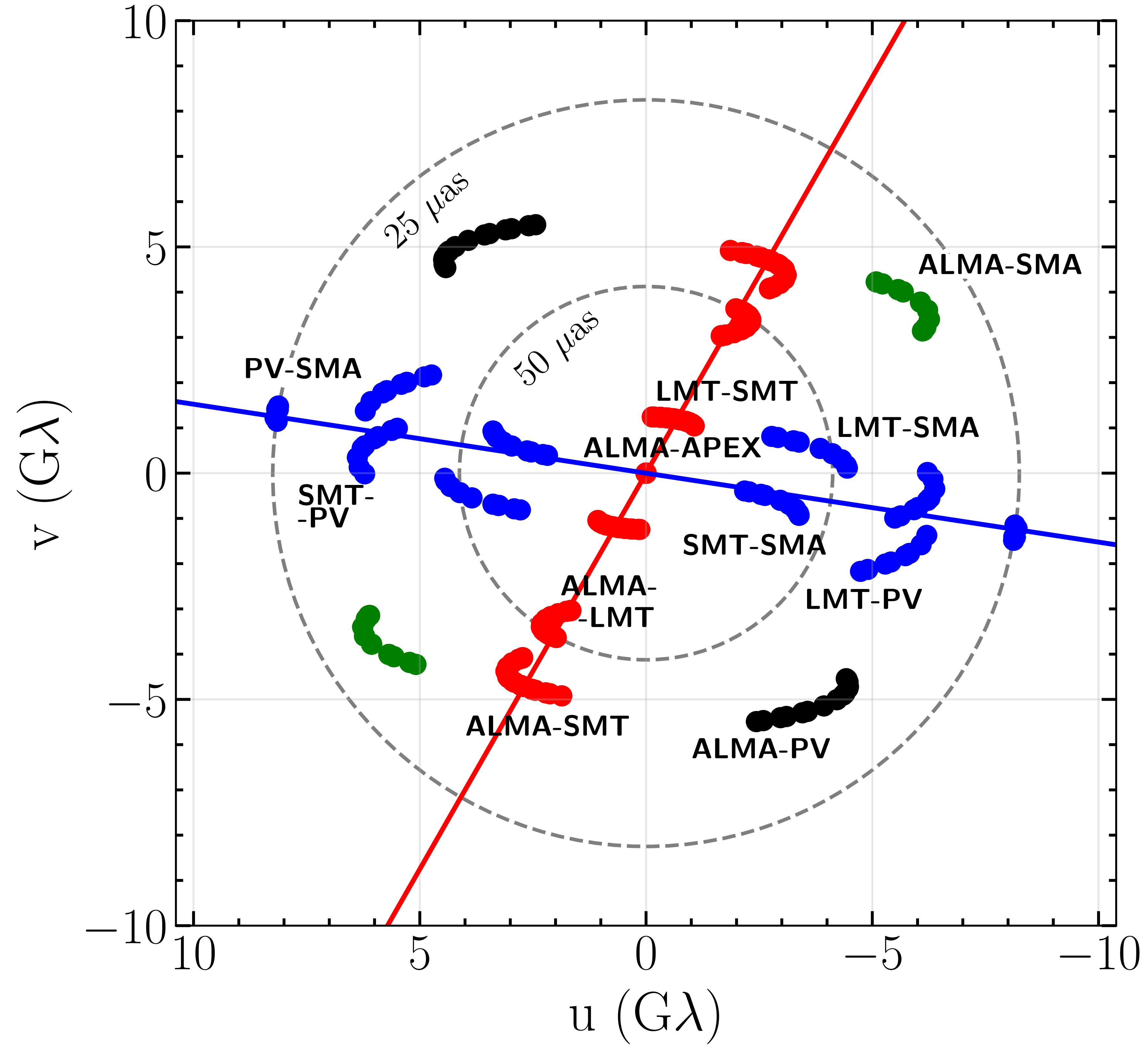
$D_{sh} \sim 5.2 * R_g$

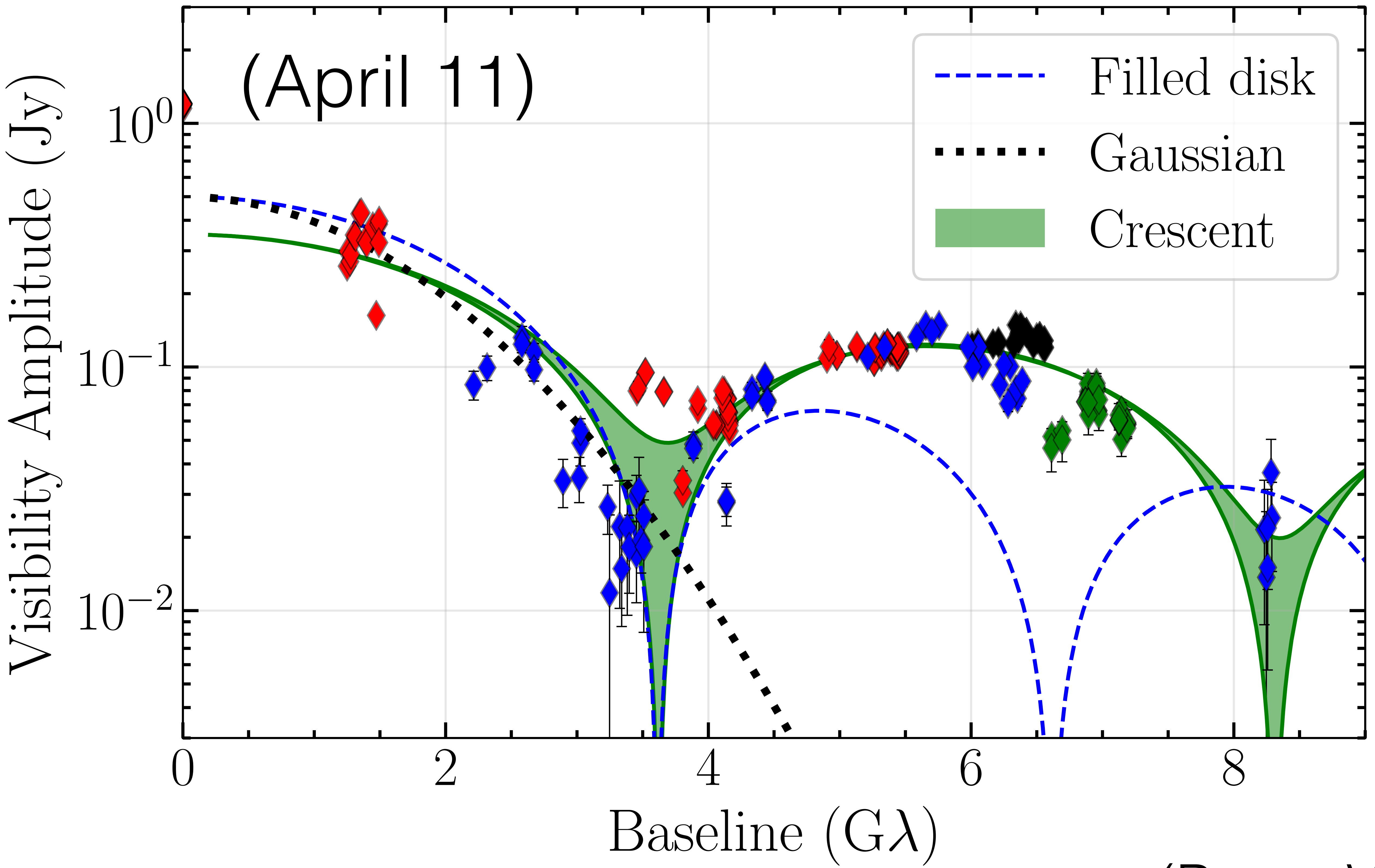


Calibrated data sets (before imaging)

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

Fourier domain





(Paper VI)

Event Horizon Telescope & Black Hole Shadow

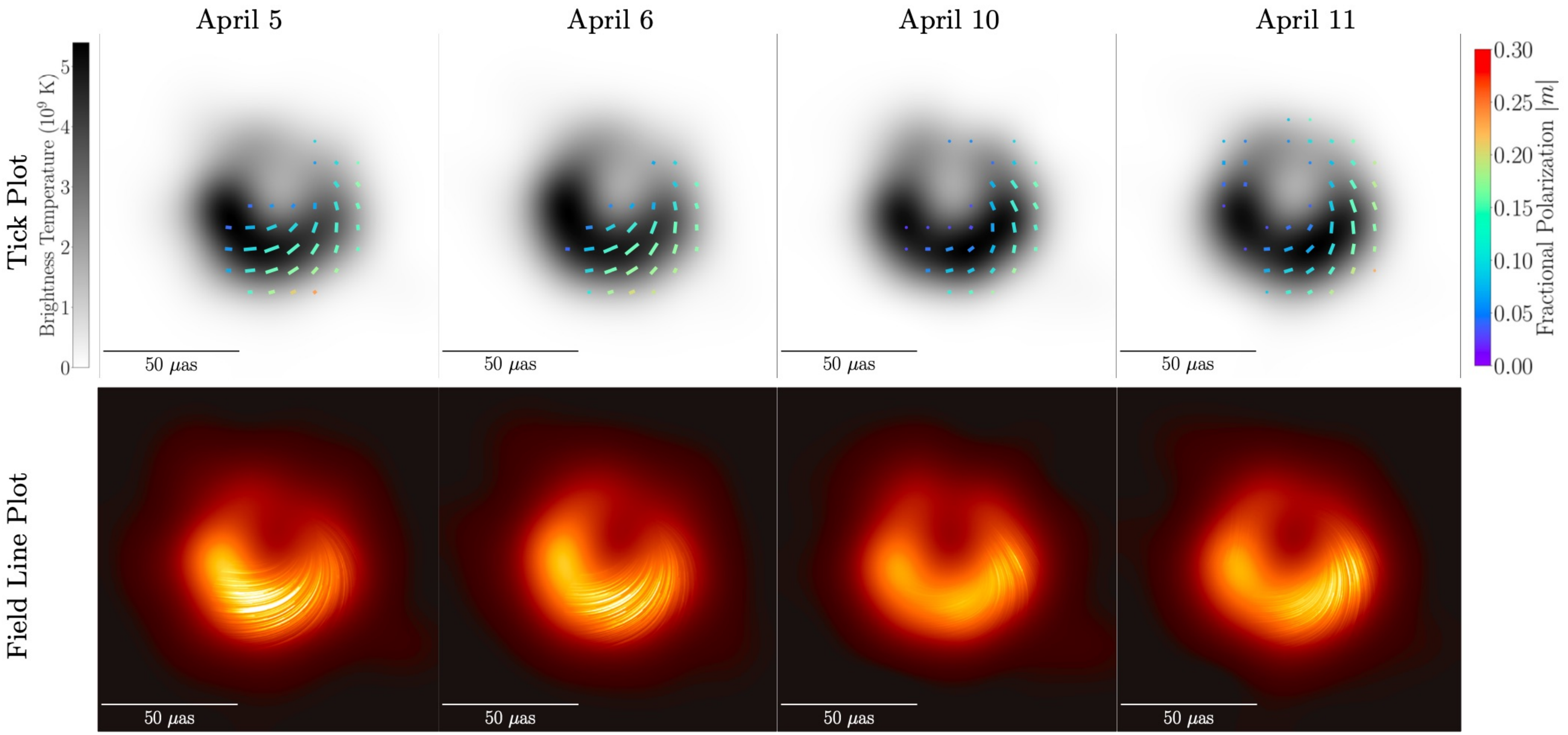
- In April 2017, EHT has observed asymmetric ring morphology of the central compact radio source in M87.
- Interpreted as lensed emission surrounding the spinning Kerr black hole shadow

Event Horizon Telescope

(EHTC et al. 19d)

Averaged Polarimetric Images

- high polarization at bright region of ring
- EVPA pattern is following ring structure
- Similar results obtained in 4 different days (small change between first and last two days)
- Position shift: south ⇒ west, similar to Intensity



Event Horizon Telescope

(EHTC Paper VII)

Image-Averaged Quantities

net linear polarization fraction

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

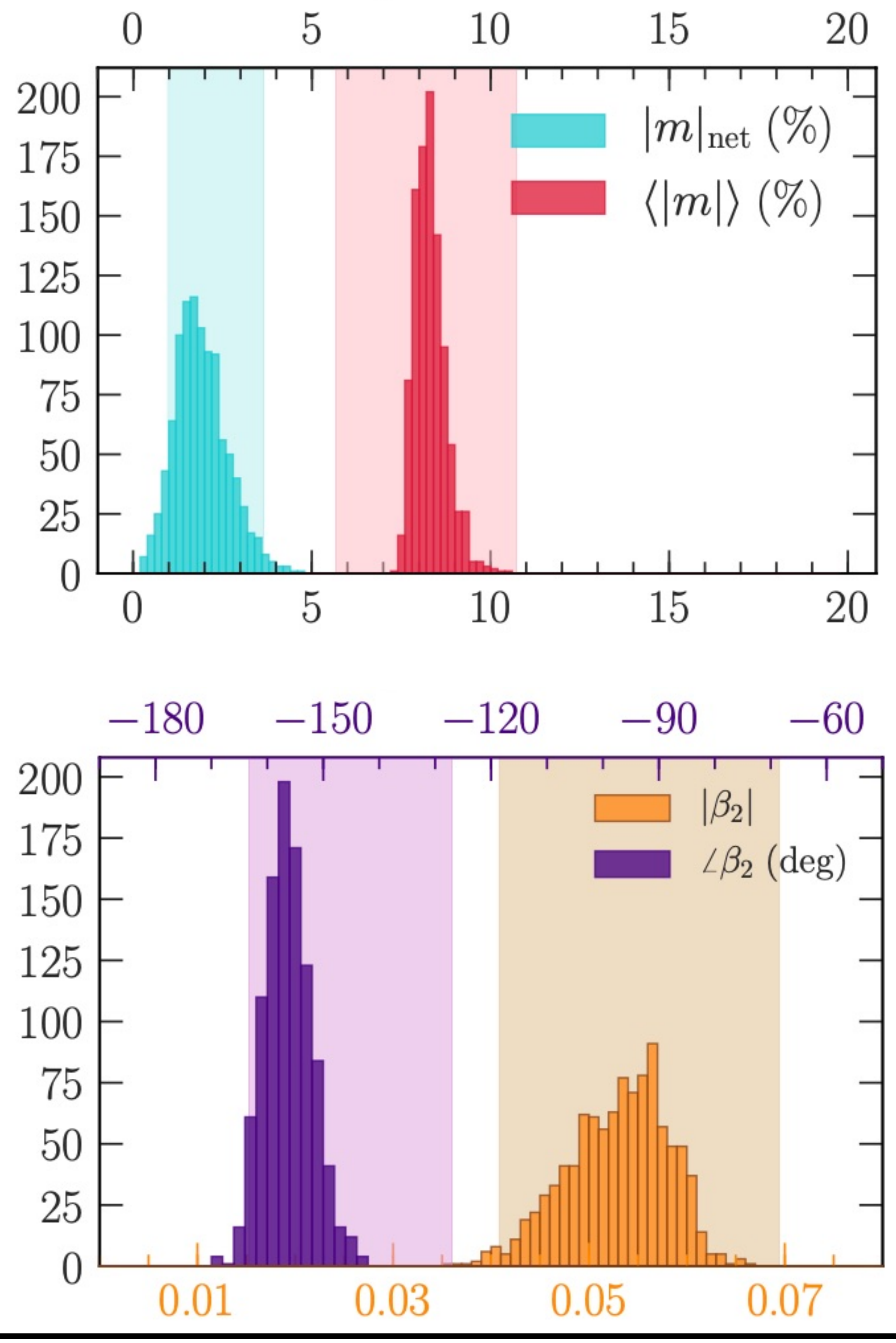
intensity-weighted average polarization fraction

$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

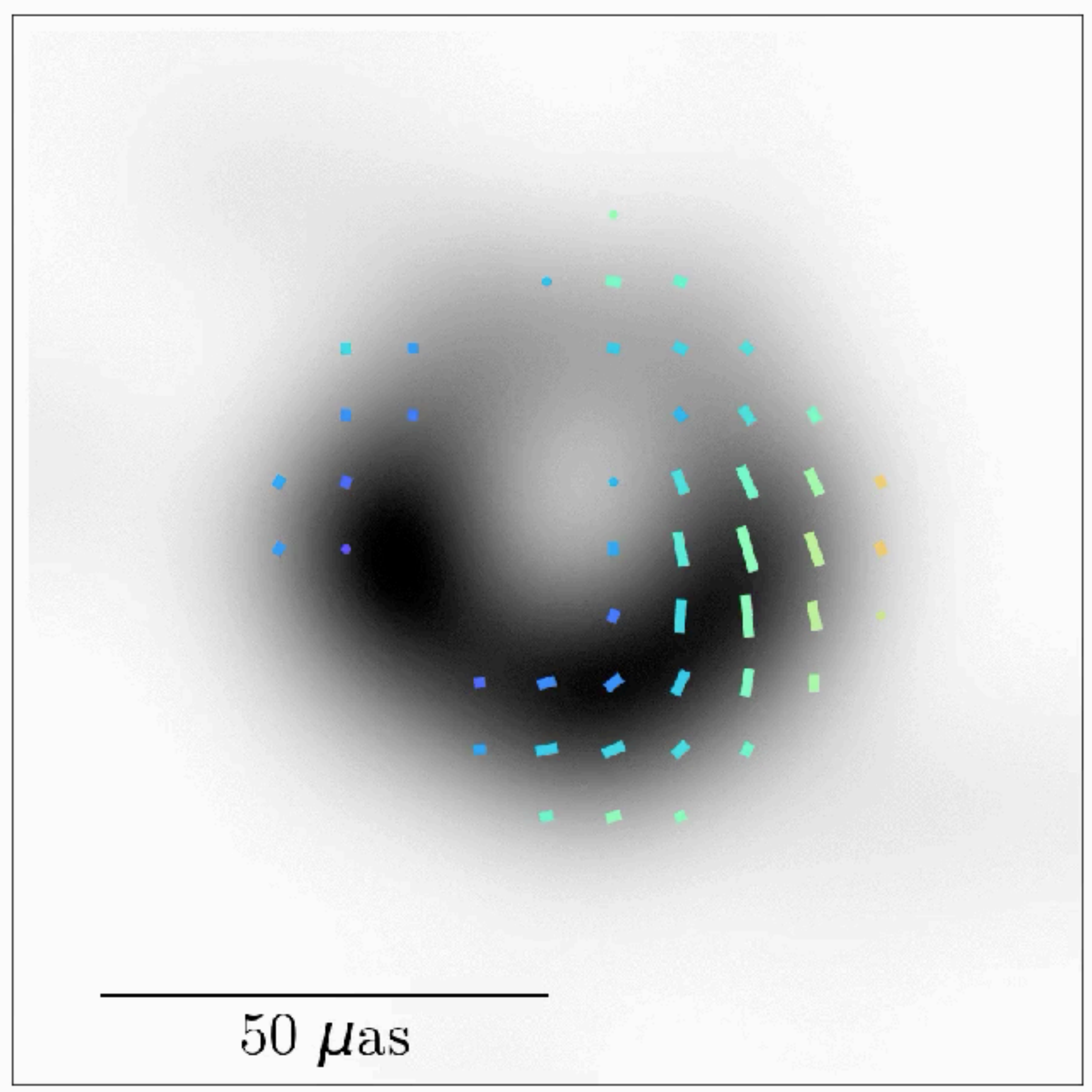
polarization structure with a decomposition into azimuthal mode (Palumbo et al. 20)

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

Distribution based on M87 images with different D-term calibration



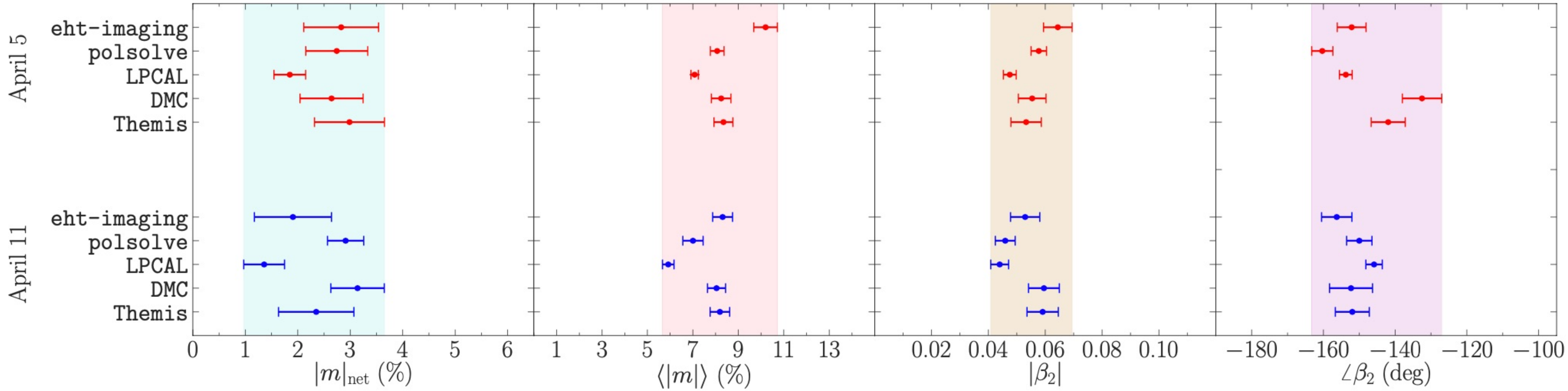
M87 April 11, single pipeline example (ehtim)



Event Horizon Telescope

(EHTC+ 21a)

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)

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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)

Theoretical Modeling Pipeline

What ingredients do we need for realistic theoretical model of BH Shadow?

1. Plasma dynamics (accretion flow & jet) around the black hole
2. Radiation process
3. BH Spacetime
4. VLBI array configuration and schedule (for EHT 2017 observation)

BHAC: Porth, YM. et al. (17), Olivares, YM + (19)
BHOSS: Younsi, YM + (21)
GENA: Fromm, YM + (19)

computational infrastructure

post-process

GRMHD simulations in arbitrary spacetimes (BHAC) ⇒ ray-traced, deconvolved images (BHOSS) ⇒ comparison with observations (GENA)

developed in Frankfurt team

Event Horizon Telescope

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

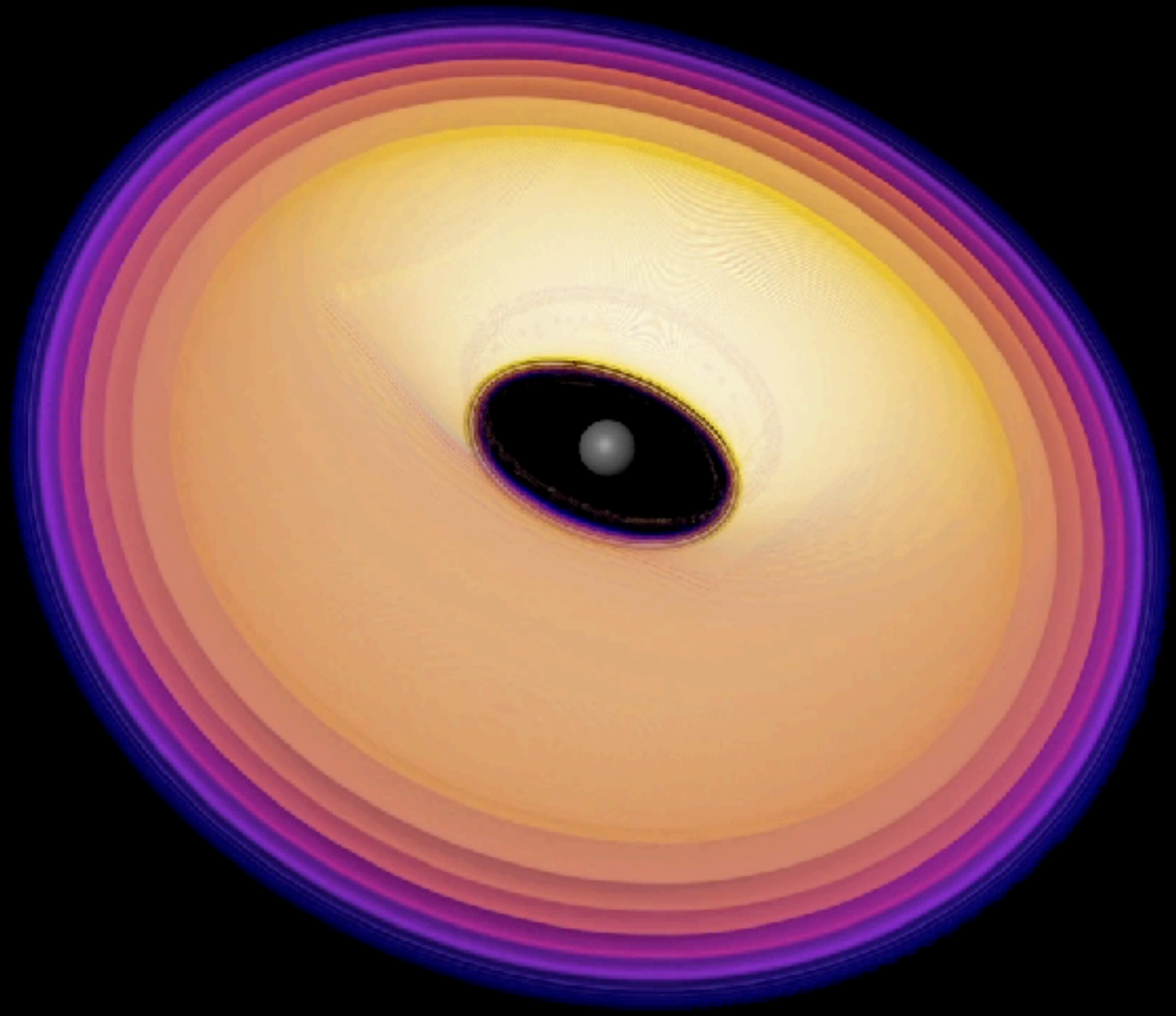
- BH mass: 6.2e9 or 3.5e9 Msun
- Inclination angle: 17 or 163 deg with jet position angle 288 deg

Event Horizon Telescope

GRMHD Simulations

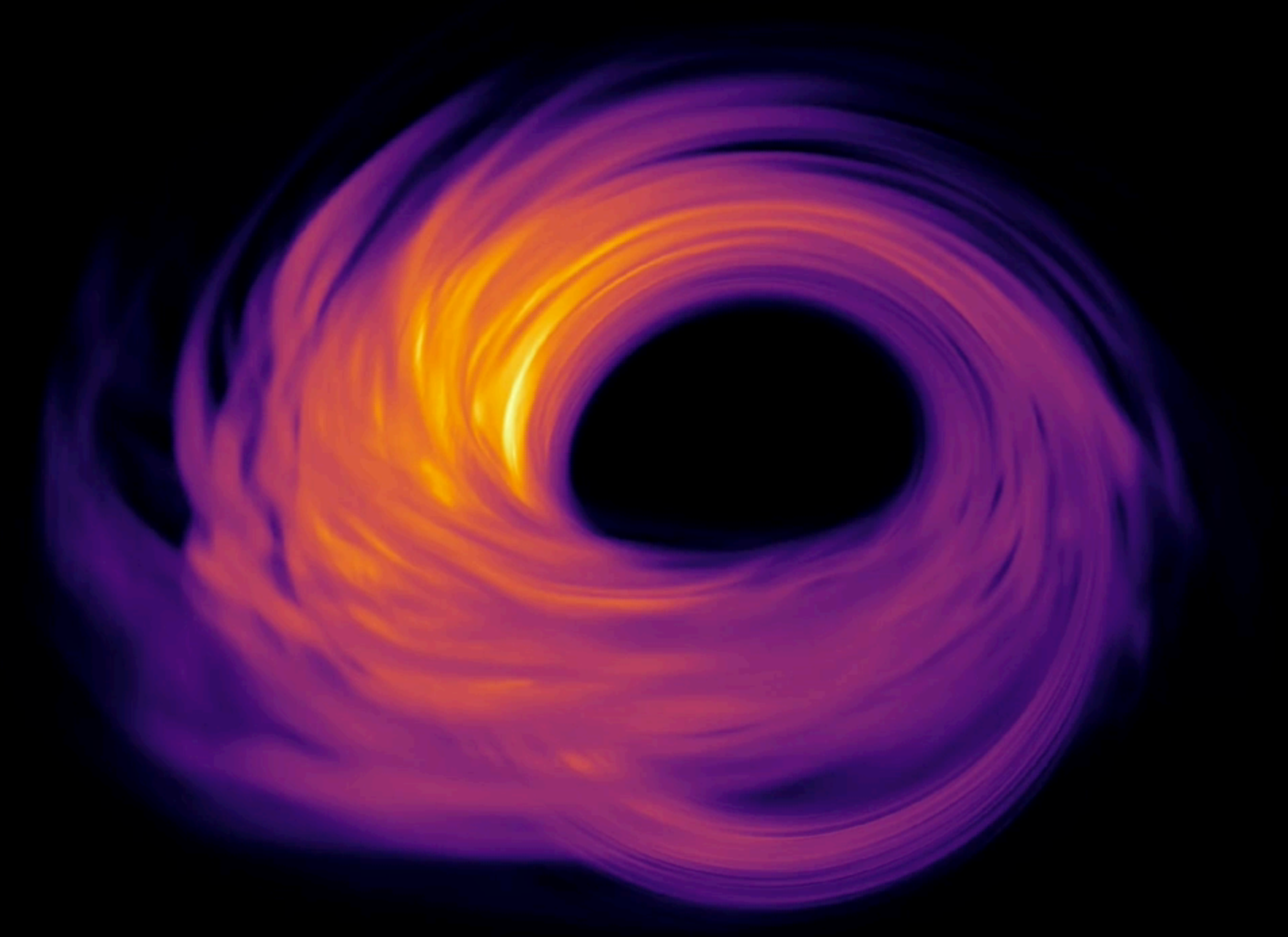
- Model the accretion flow (RIAF) onto a black hole
- Torus in hydrodynamical equilibrium with poloidal B-field
- Monitor accretion rate and evolve until quasi-steady state

Kerr black hole with a=0.94,
SANE model



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

Shadow of Black Hole



Snapshot image of GRMHD simulation (SANE)
of Kerr BH with a=0.94

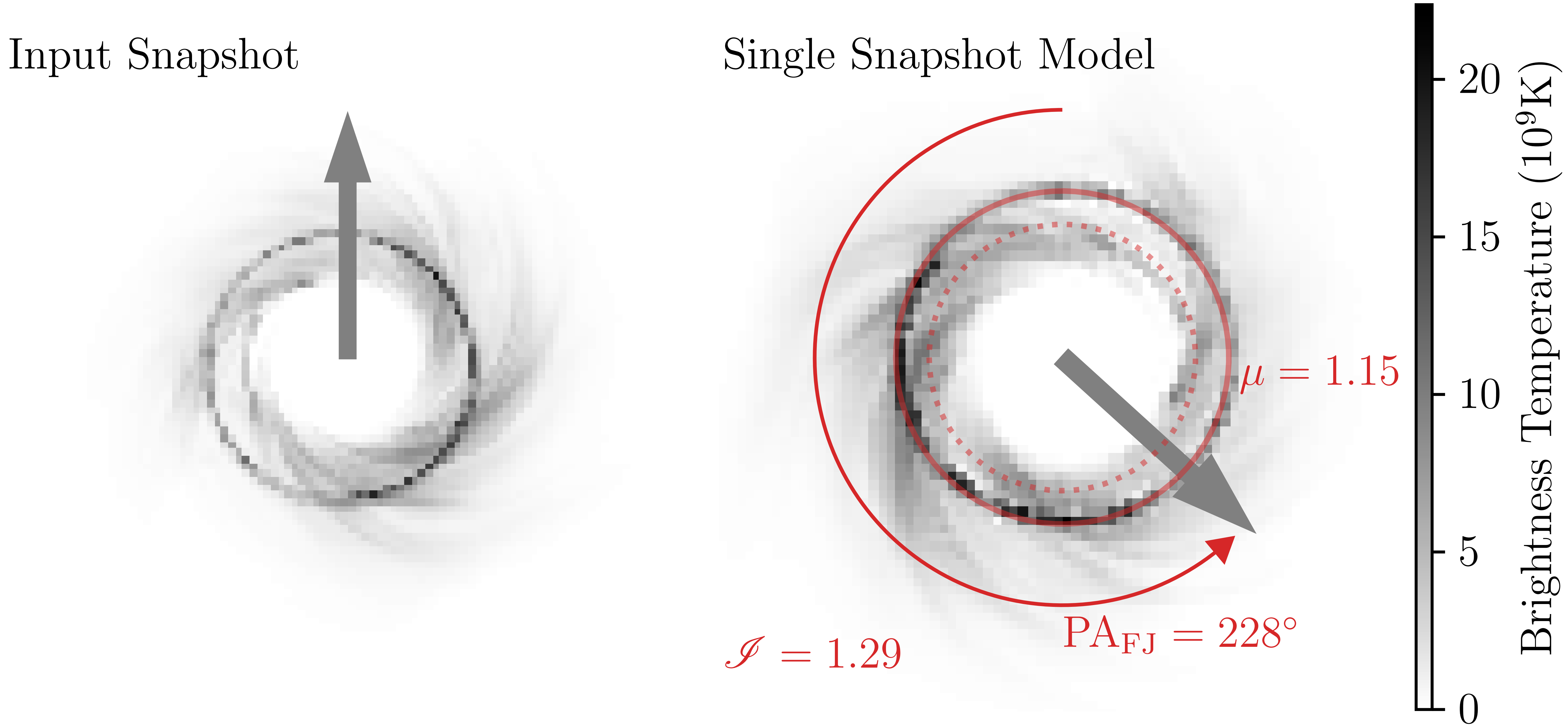
Changing viewing angle (theta & phi)
(logarithmic scale)

Movie: Z. Younsi
by BHOSS code


Library of black hole shadow images for M87 (62k images)
(EHT Paper V)

Fitting GRRT images to EHT data

- Fourier transformed synthetic images (visibility data) and fit to observed data
- Re-scale flux, stretch (M/D), and rotate image (P.A.) (allowed when optically thin)



(Paper VI)

Two independent codes: MCMC (Themis) & evolutionary algorithm (GENA)

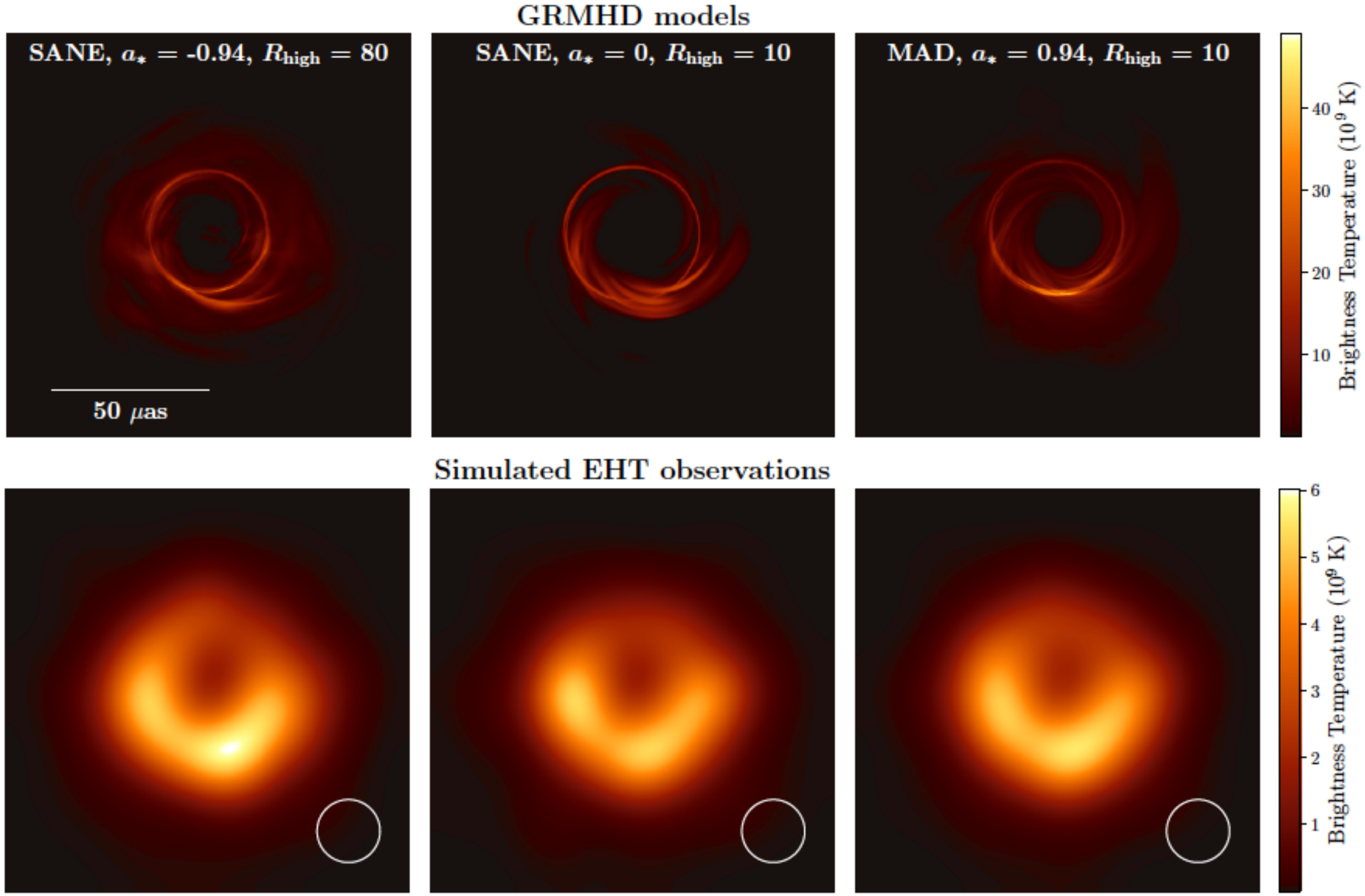
Event Horizon Telescope

Fromm, YM+ (19)

Best Fitting Images

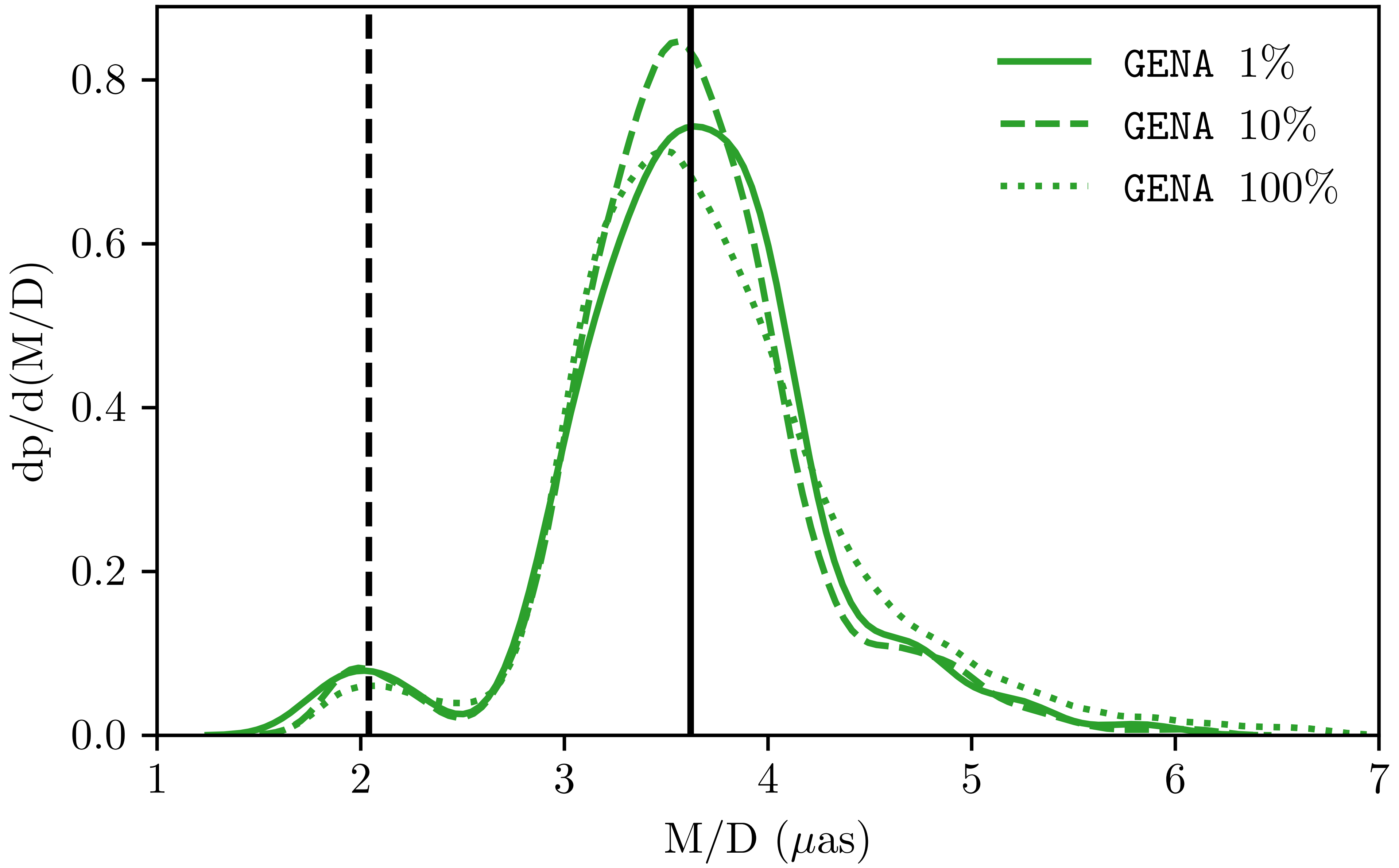
- Degeneracies are present in the physical conditions and scenarios.

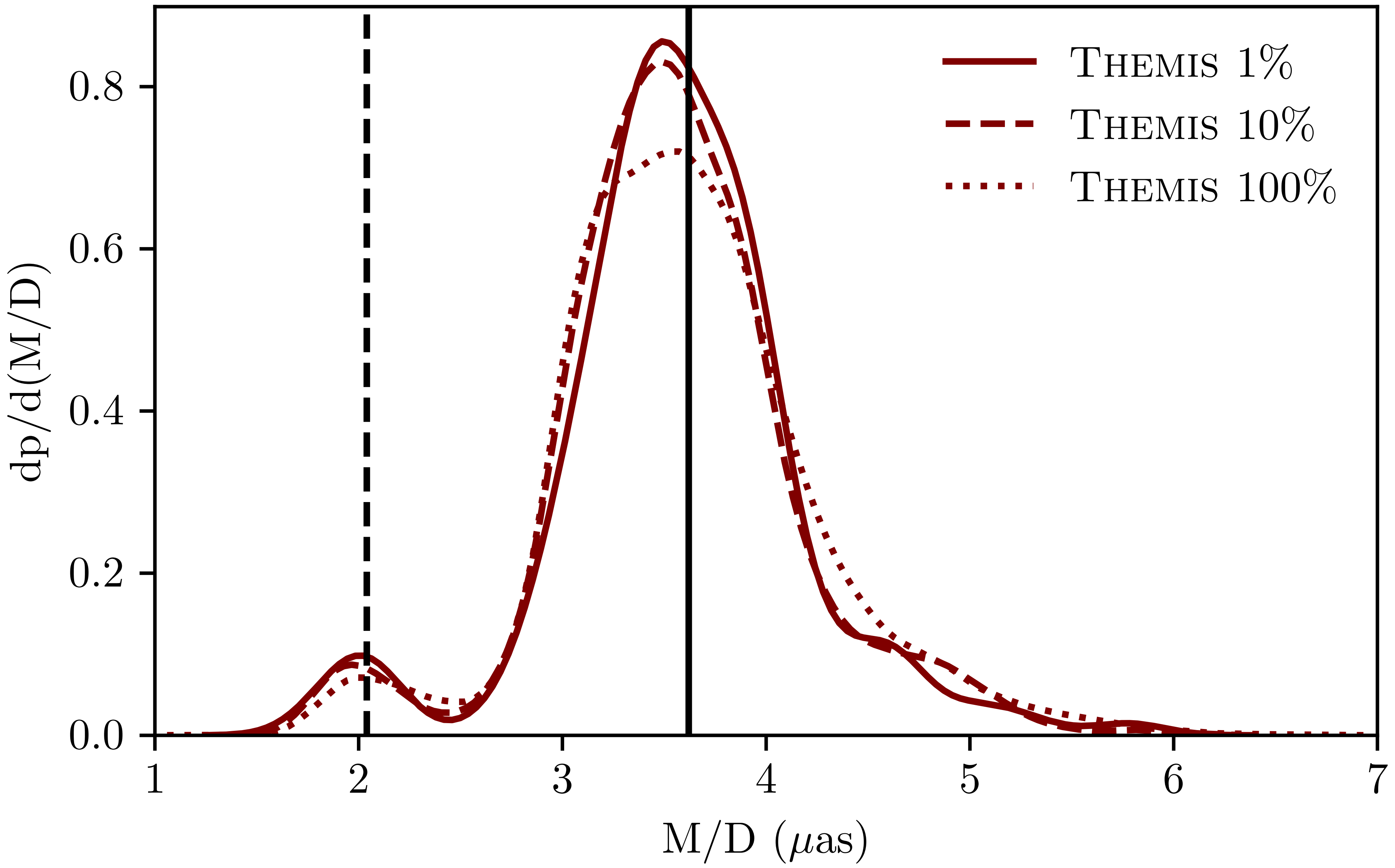
- Good and bad: robustness conclusions (*EHT observed image is BH shadow*) and more accurate observations to determine black-hole spin.



(EHT+ 19e)

Distribution of Best-Fit Black Hole Angular Size





- Distribution of M/D from fitting Image Library snapshots to 2017 April 6th EHT data
- Results by Themis & GENA pipelines are qualitatively similar
- The distribution peaks close to M/D ~ 3.6 μas with a width of ~0.5 μas
- The models are broadly consistent with stellar mass estimate
- $M = 6.5 \times 10^9 M_{sun}$ (using D = 16.8 Mpc)

Other Constraint

Apply three additional constraints:

1. Close to radiative equilibrium
   - Radiative efficiency < classical thin disk model radiative efficiency

2. Must not overproduce X-rays (in SED)
   - 2-10 keV luminosity: $L_X = 4.4 \pm 0.1 \times 10^{40}$ erg/s (NuSTAR & Chandra obs.)

3. Must produce jet power > minimal jet power = 10^{42} erg/sec

Results: SANE model

Constraint: (data fitting, radiative efficiency, X-ray, jet power)

a/R_{high}	1	10	20	40	80	160
-0.94	-+++	++++	++++	++++	++++	-+++
-0.5	++- -	++- -	+++-	+++-	-++-	++-+
0	+++-	+++-	++- -	+++-	++- -	++- -
0.5	+++-	+++-	+++-	+++-	+++-	+++-
0.94	+-+-	+-+-	+++-	+++-	++++	++++

+: passed, - : failed

Results: MAD model

Constraint: (data fitting, radiative efficiency, X-ray, jet power)

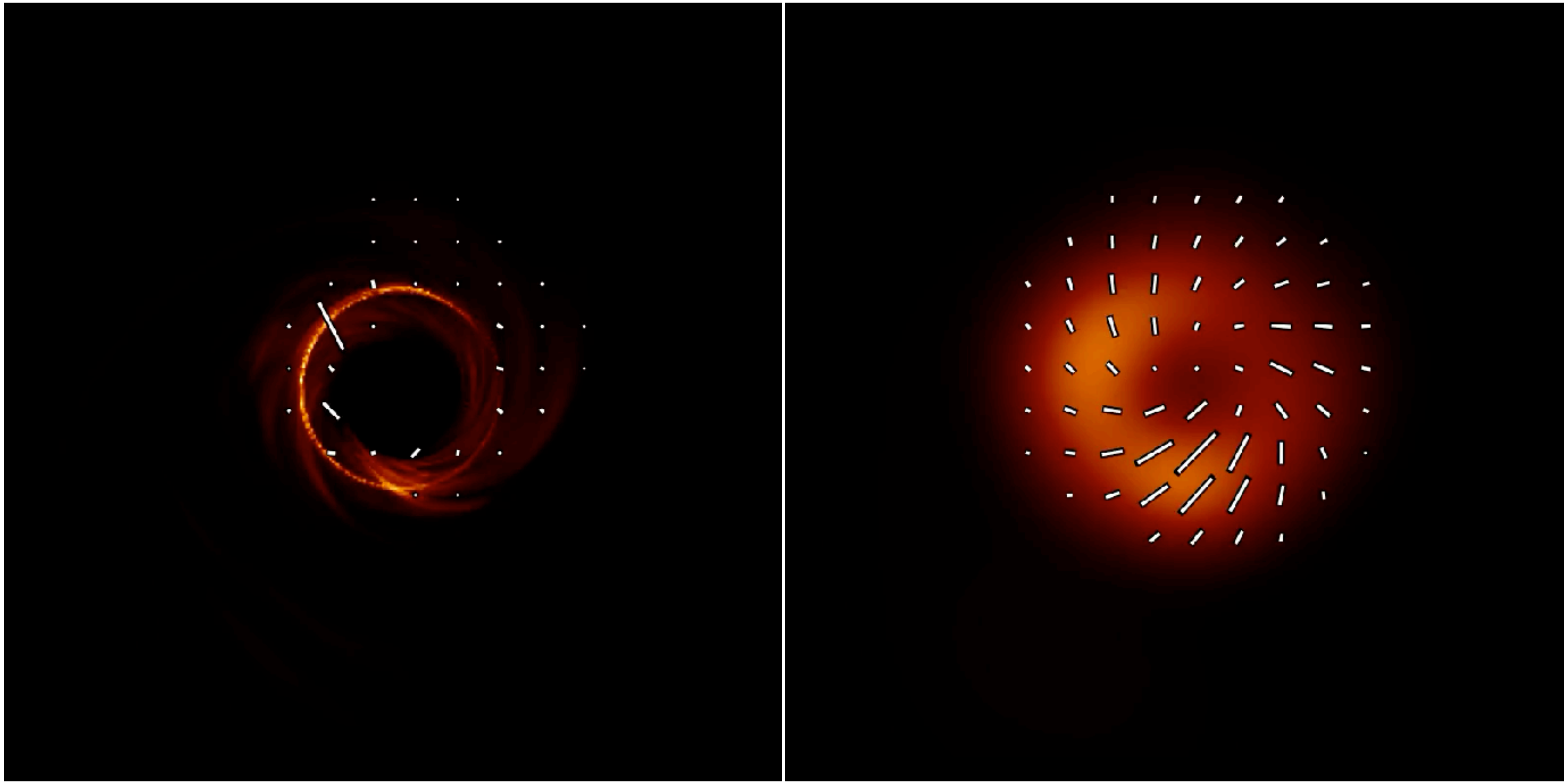
a/R_{high}	1	10	20	40	80	160
-0.94	- -++	-+++	-+++	-+++	-+++	-+++
-0.5	+-+-	+++-	++++	++++	++++	++++
0	+-+-	+++-	+++-	+++-	+++-	+++-
0.5	+-+-	++++	++++	++++	++++	++++
0.94	+- -+	+-++	++++	++++	++++	++++

+: passed, - : failed

GRRT Image at 230 GHz for M87

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

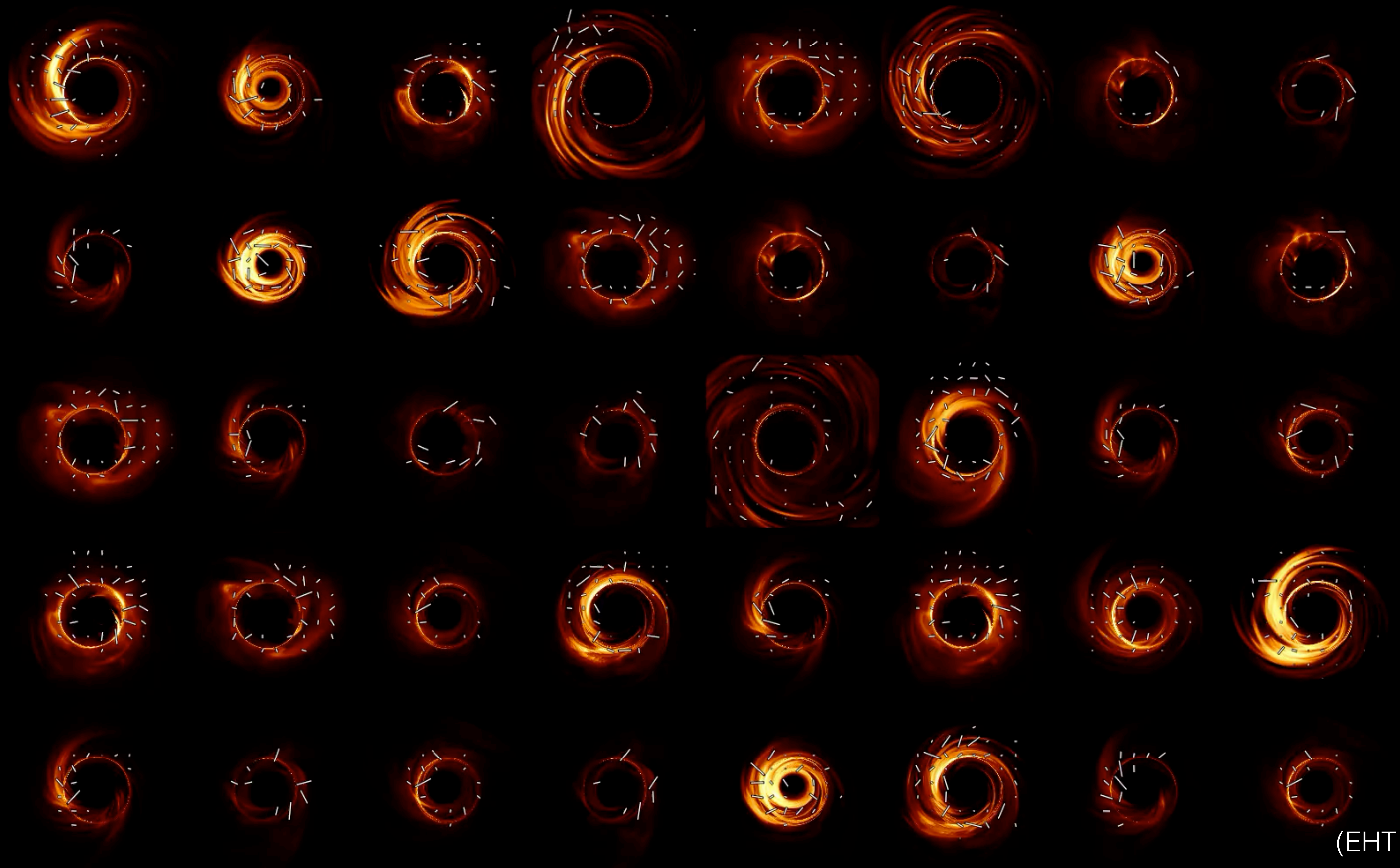
GRRT GRRT+blurred



Event Horizon Telescope

(EHT Paper VIII)

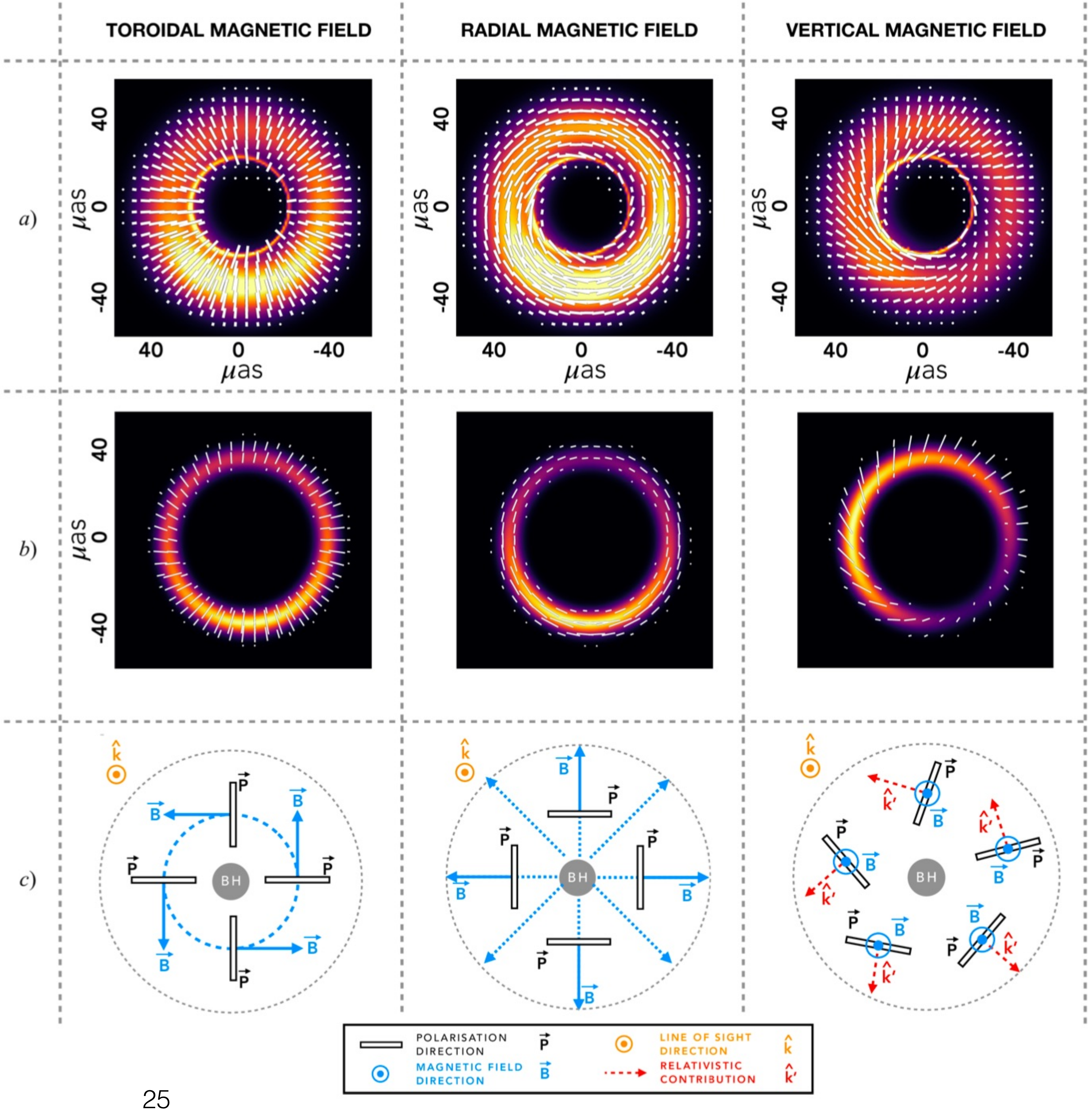
Library of polarized black hole shadow images for M87 (72k images)



(EHT Paper VIII)

Magnetic Field Configuration

- Consider simple equatorial plane emission
- Different magnetic field configuration (toroidal, radial, and vertical)
- Vertical magnetic field can produce similar azimuthal EVPA pattern observed by EHT



Event Horizon Telescope

Model Constraint from Polarimetry

1. image-integrated net linear polarisation: $1\% < |m|_{net} < 3.7\%$ (EHT pol. image)

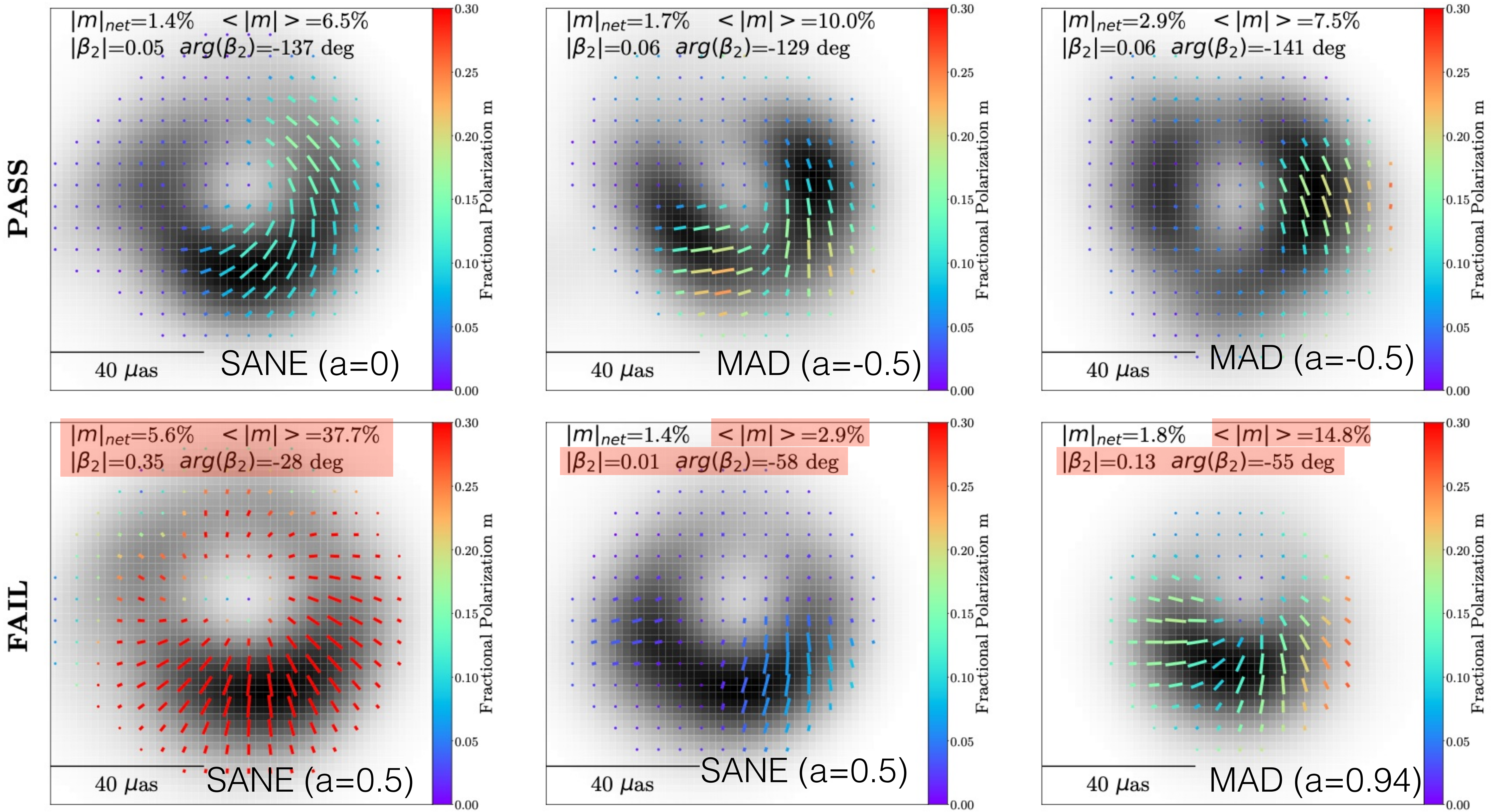
2. image-integrated net circular polarization: $|v|_{net} < 0.8\%$ (ALMA-only data)

3. image averaged linear polarization: $5.7\% < \langle|m|\rangle < 10.7\%$ (EHT 20μas resolution)

4. amplitude & phase of complex β_2 coefficient

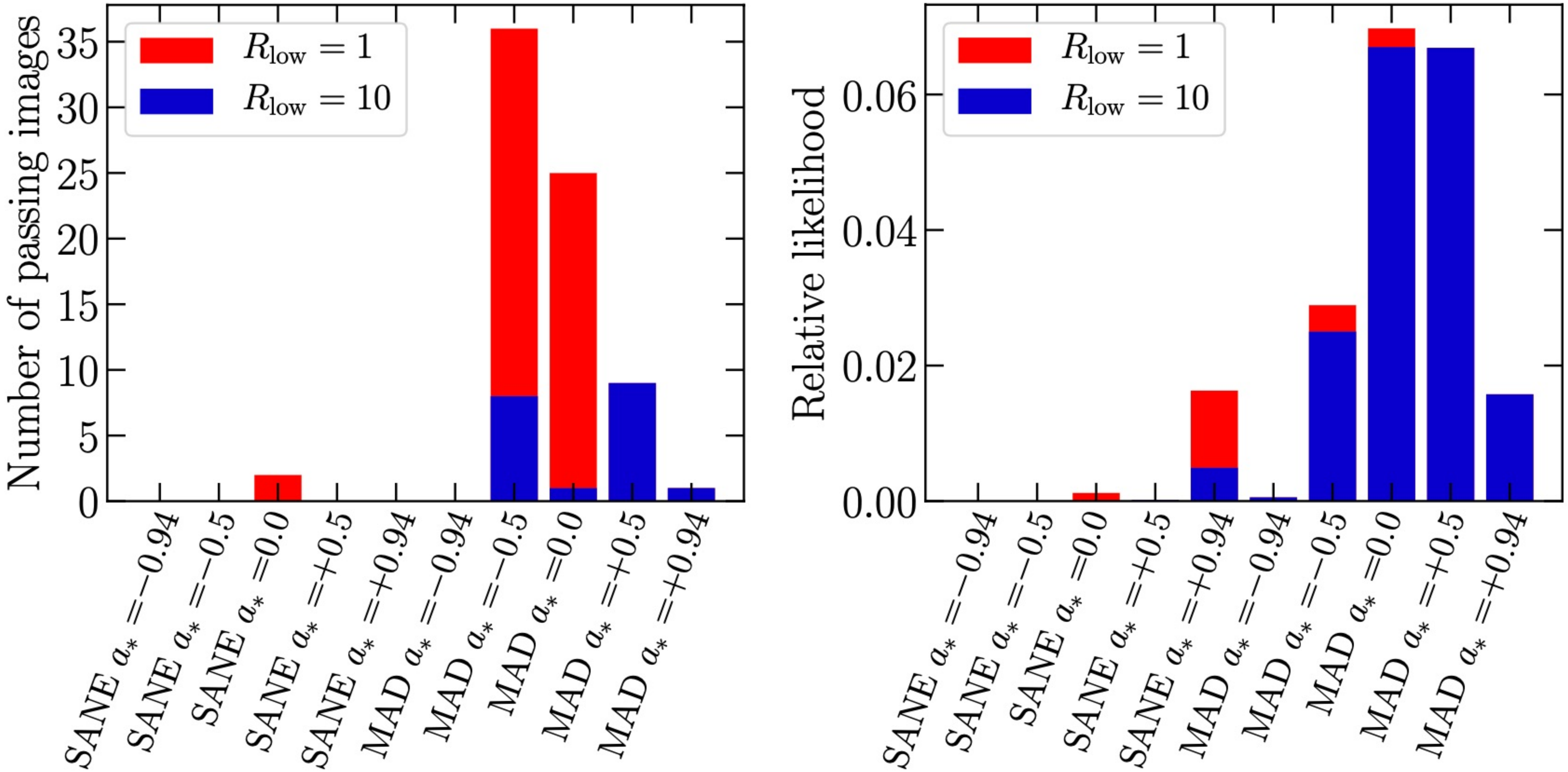
   $0.04 < |\beta_2| < 0.07$, -163 deg $< \mathrm{ang}[\beta_2] < -129$ deg

Scoring Results



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

Scoring Results

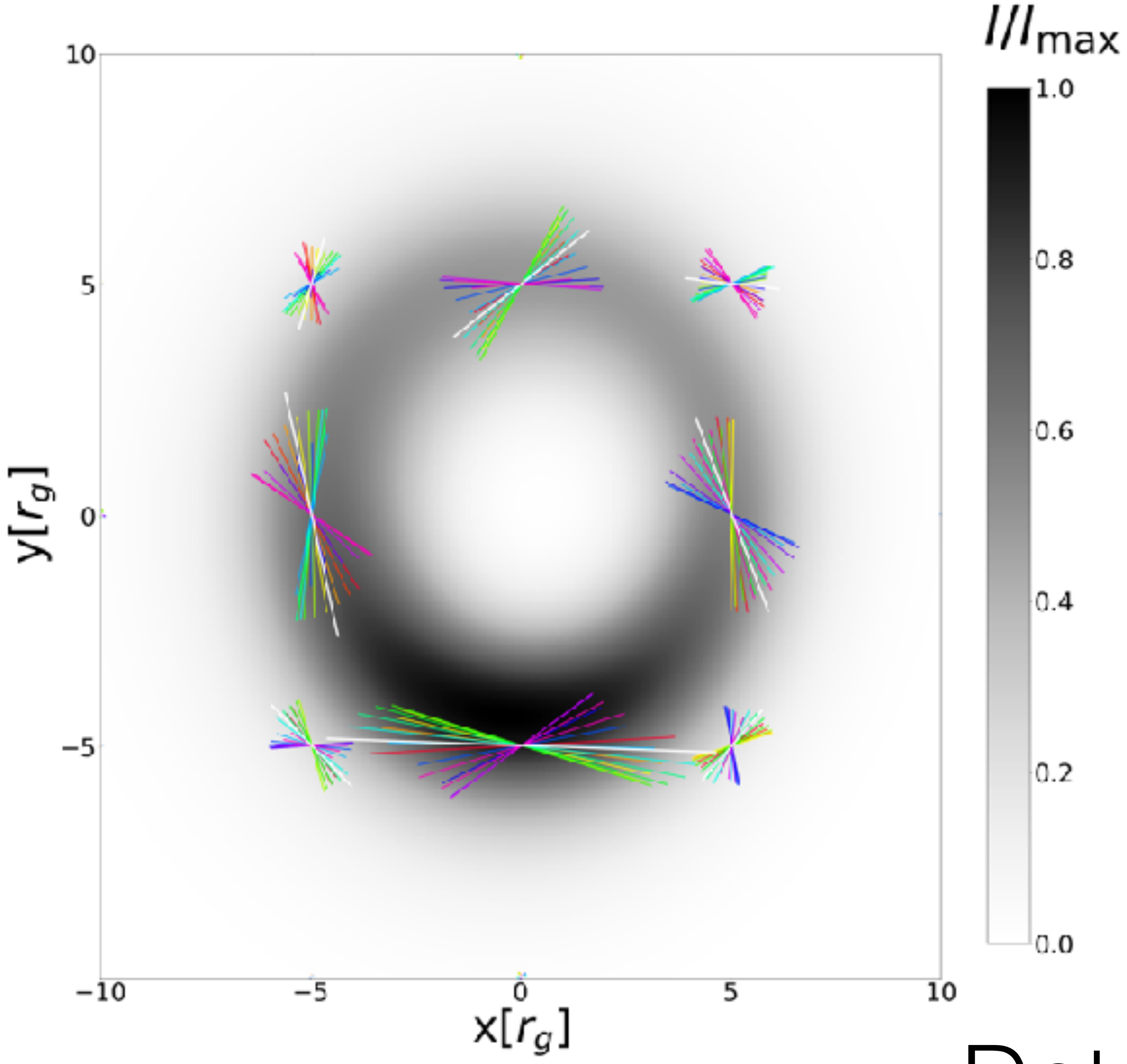


- Scoring results prefer MAD than SANE.
- SANE & MAD a=0 model would be ruled out from jet power constraint (same as Paper V)

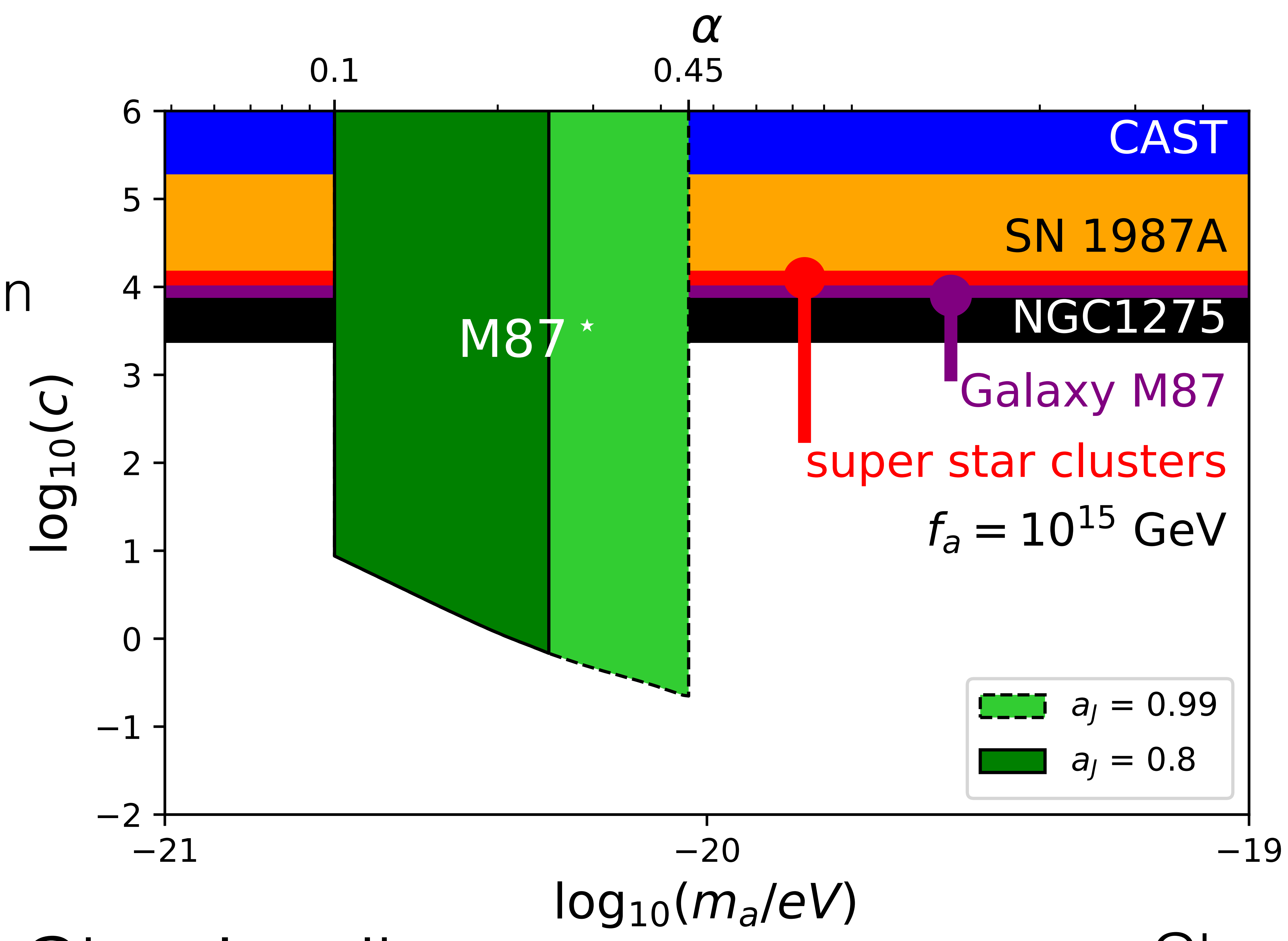
Event Horizon Telescope

Constraint of Axion-Photon coupling

- Near SMBH, axion cloud is produced by superradiance (gravitational bound state).
- Axion cloud makes birefringence of polarised emissions ⇒ oscillation of EVPA
- Polarised ring emission of BH shadow in M87 would be affected it ⇒ constraint of axion-photon coupling.



axion-photon coupling



Chen et al. (2021)

Detail for Yifan Chen's talk

Event Horizon Telescope

Which Gravitational Theory?

- VLBI observation of EHT has provided the first images of the BH shadow in M87* and will be soon provide it in our galactic centre, Sgr A*.

- If the observations are sufficiently accurate, it will provide

1. the evidence for the existence of an event horizon
2. Testing the no-hair theorem in GR
3. Testing of GR itself against a number of alternative theories of gravity.

We investigate alternatives of Kerr black hole through realistic theoretical modeling of shadow image

Deviation from GR from EHT Shadow Image

Spherically symmetric spacetime around a black hole

$$ds^2 = g_{tt}dt^2 + g_{rr}dr^2 + r^2 d\Omega \; .$$

Parametrized Post-Newtonian (PPN) formalism

$$-g_{tt} = 1 - \frac{2}{r} + 2\left(\frac{\bar{\beta} - \bar{\gamma}}{r^2}\right) - 2\left(\frac{\zeta}{r^3}\right) + \mathcal{O}\left(r^{-4}\right)$$

General Relativity (Schwarzwild metric)

1st order Deviation (1PN)

2nd order Deviation (2PN)

Weak-field test: < ~10^{-5}

The Diameter of the black hole shadow: sensitive to the 2nd order deviation

$$r_{\rm sh} = 3\sqrt{3}\left(1 + \frac{1}{9}\zeta\right)$$

Event Horizon Telescope

Psaltis et al. (2020)

Deviation from GR from EHT Shadow Image

Using two parameterized metric (JP, MGBK)

$$r_{\mathrm{sh,JP}} = 3\sqrt{3}\left[1 + \underline{\frac{1}{27}\alpha_{13} - \frac{1}{486}\alpha_{13}^2 + \mathcal{O}(\alpha_{13}^3)}\right]$$

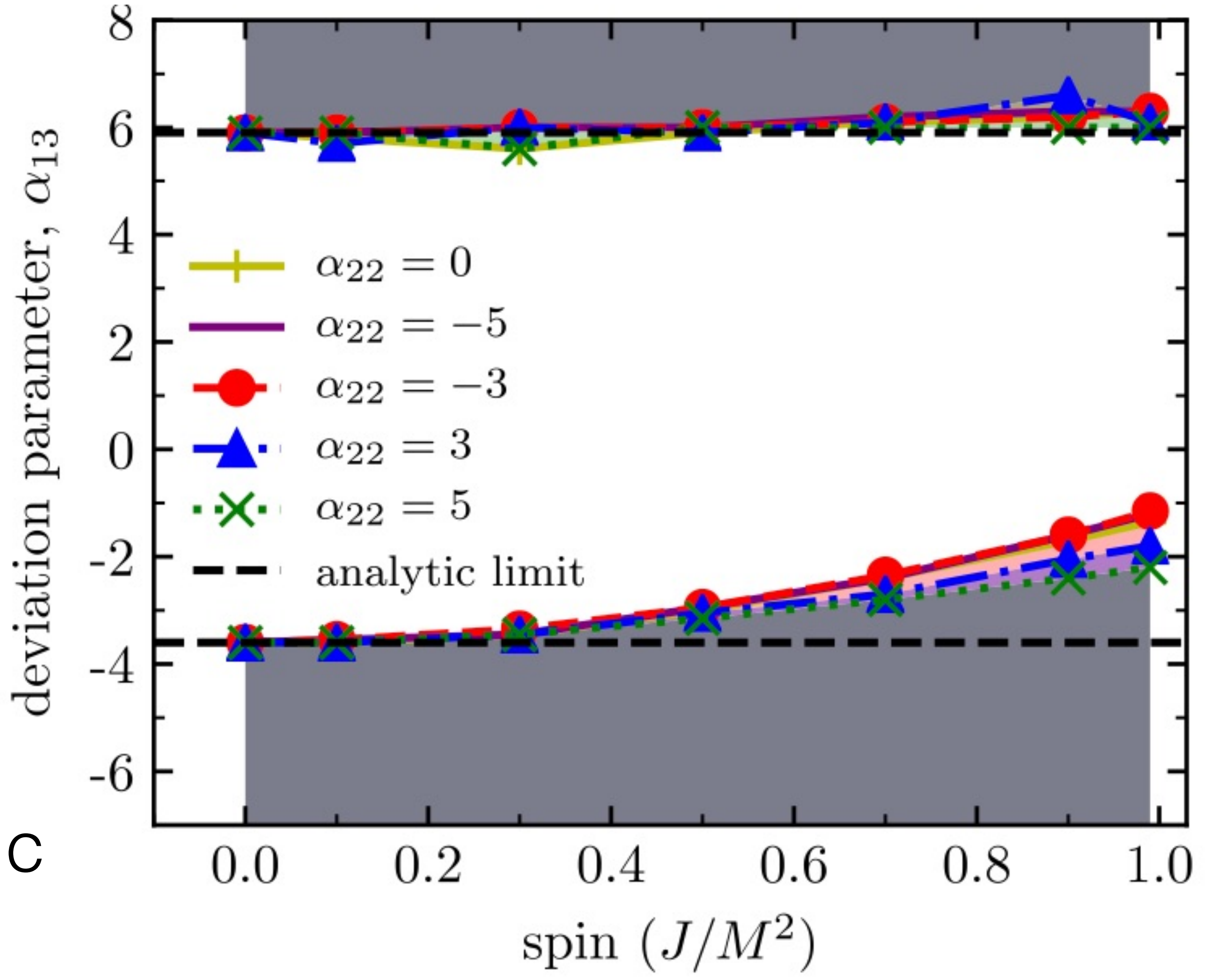
$$r_{\mathrm{sh,MGBK}} = 3\sqrt{3}\left[1 + \underline{\frac{1}{27}\gamma_{1,2} + \mathcal{O}(\gamma_{1,2}^3)}\right]$$

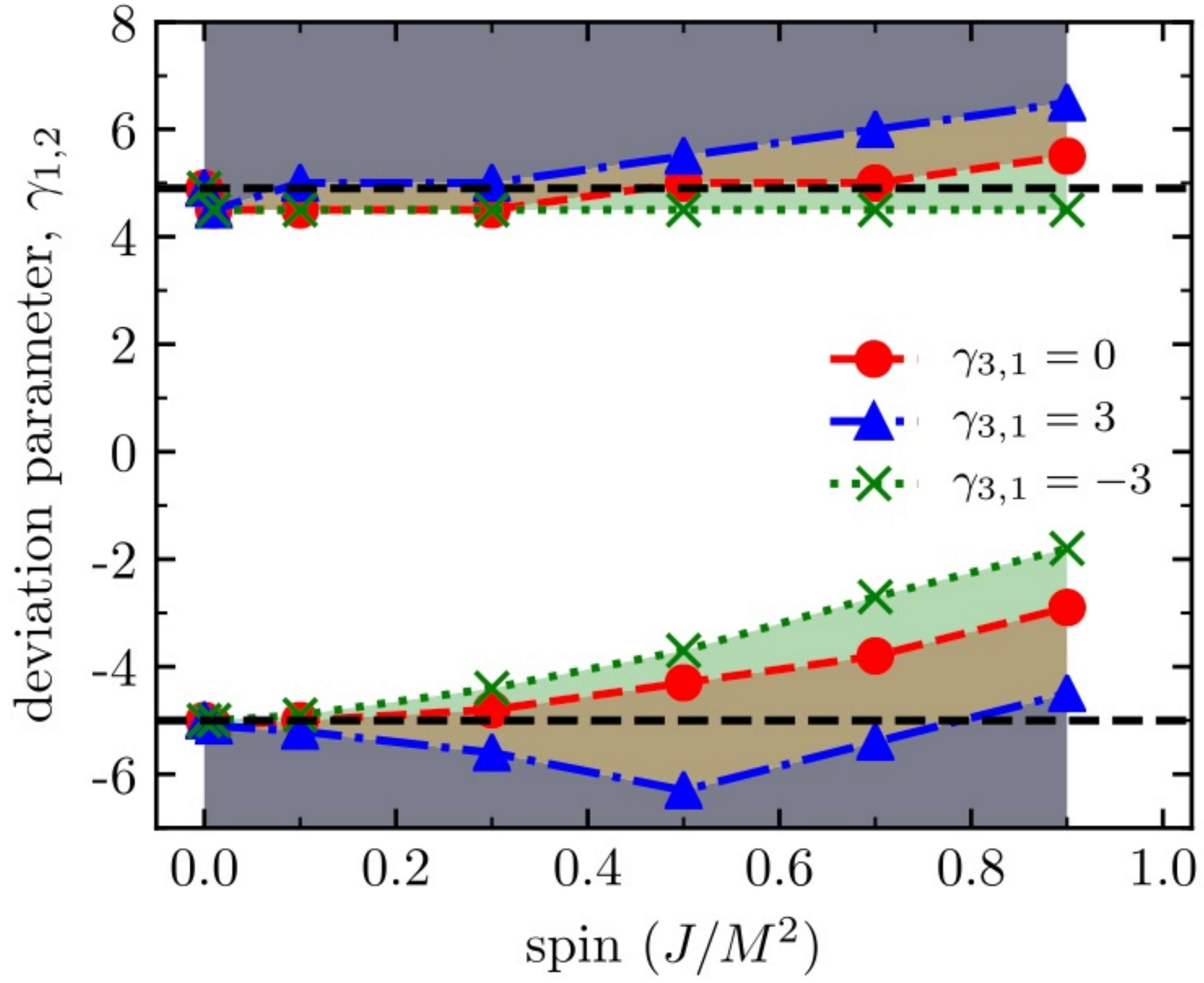
Metric	$\bar{\beta} - \bar{\gamma}$ (1 PN)	ζ (2 PN)
Kerr	0	0
JP	0	α_{13}
MGBK	$-\gamma_{1,2}/2 - \gamma_{4,2} \to 0$	$-\gamma_{1,2} - 4\gamma_{4,2} \to \gamma_{1,2}$

Shadow size is within 17% of 2017 EHT observation

-3.6 < α_{13} < 5.9

-5.0 < $\gamma_{1,2}$ < 4.9





JP: Johannsen-Psaltis metric

MGBK: Modified Gravity Bumpy Kerr metric

Event Horizon Telescope

Psaltis et al. (2020)

BH Alternatives

1. black holes within GR that include additional fields
   - e.g., electromagnetic charge, NUT charge, cosmological constant, dark matter halo, hair etc.

2. black hole solutions from alternative theories of gravity or incorporating quantum effects
   - classical modification to GR as well as the effect of quantum gravity.

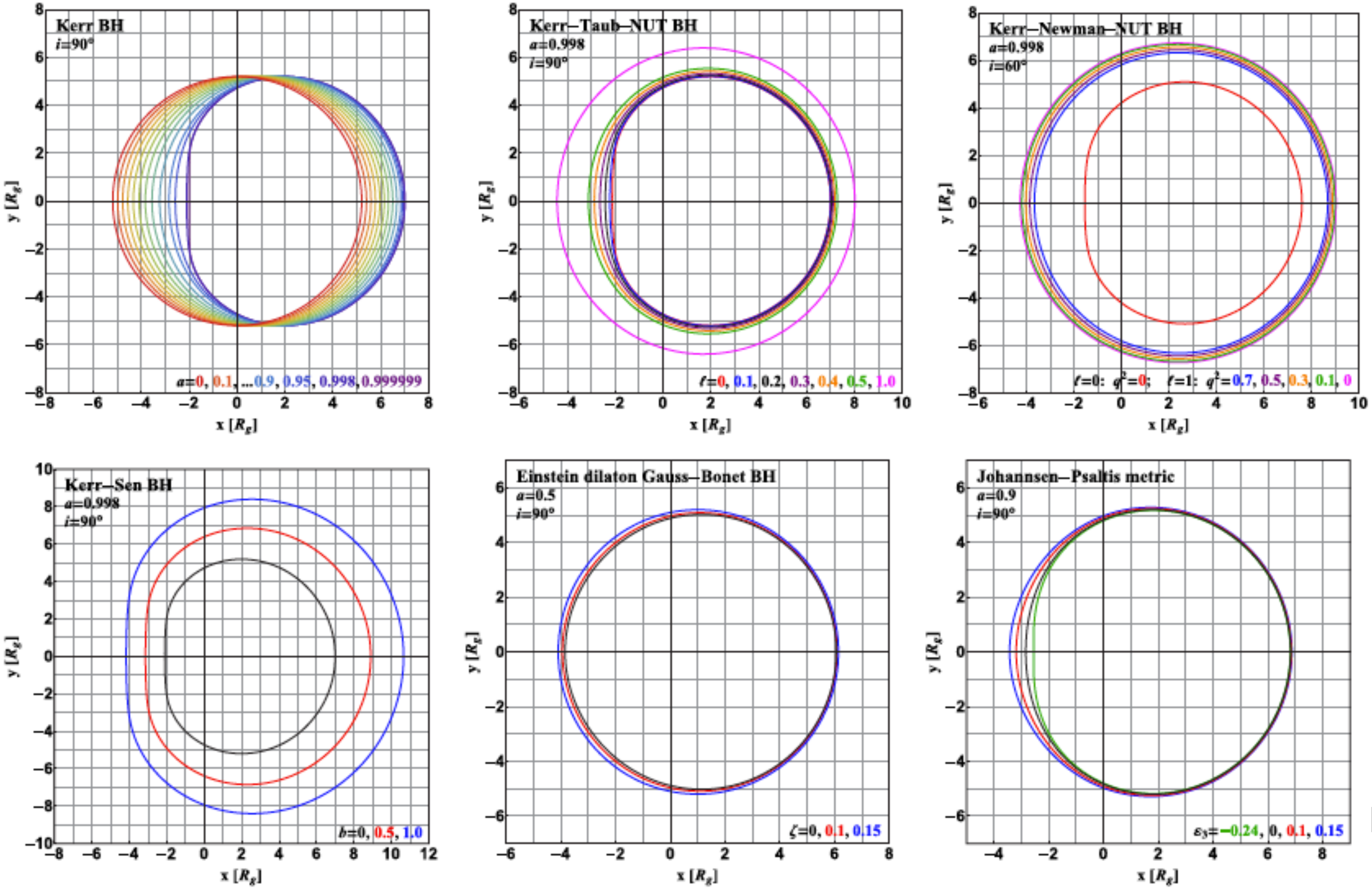
3. black hole “mimickers,” i.e., exotic compact objects (with or without surface), both within GR or in alternative theories
   - w.o. event horizon: e.g., naked singularity, supersupinars, wormhole
   - w.o. event horizon & w.o. surface: e.g., boson star
   - w.o. event horizon & w. surface: Gravastar

Most of alternatives represent a shadow similar to a Kerr black hole

Shadow Industry: Different Spacetime

Variety of BH shadow boundary curve in different theory of gravity

Younsi et al. (2016)



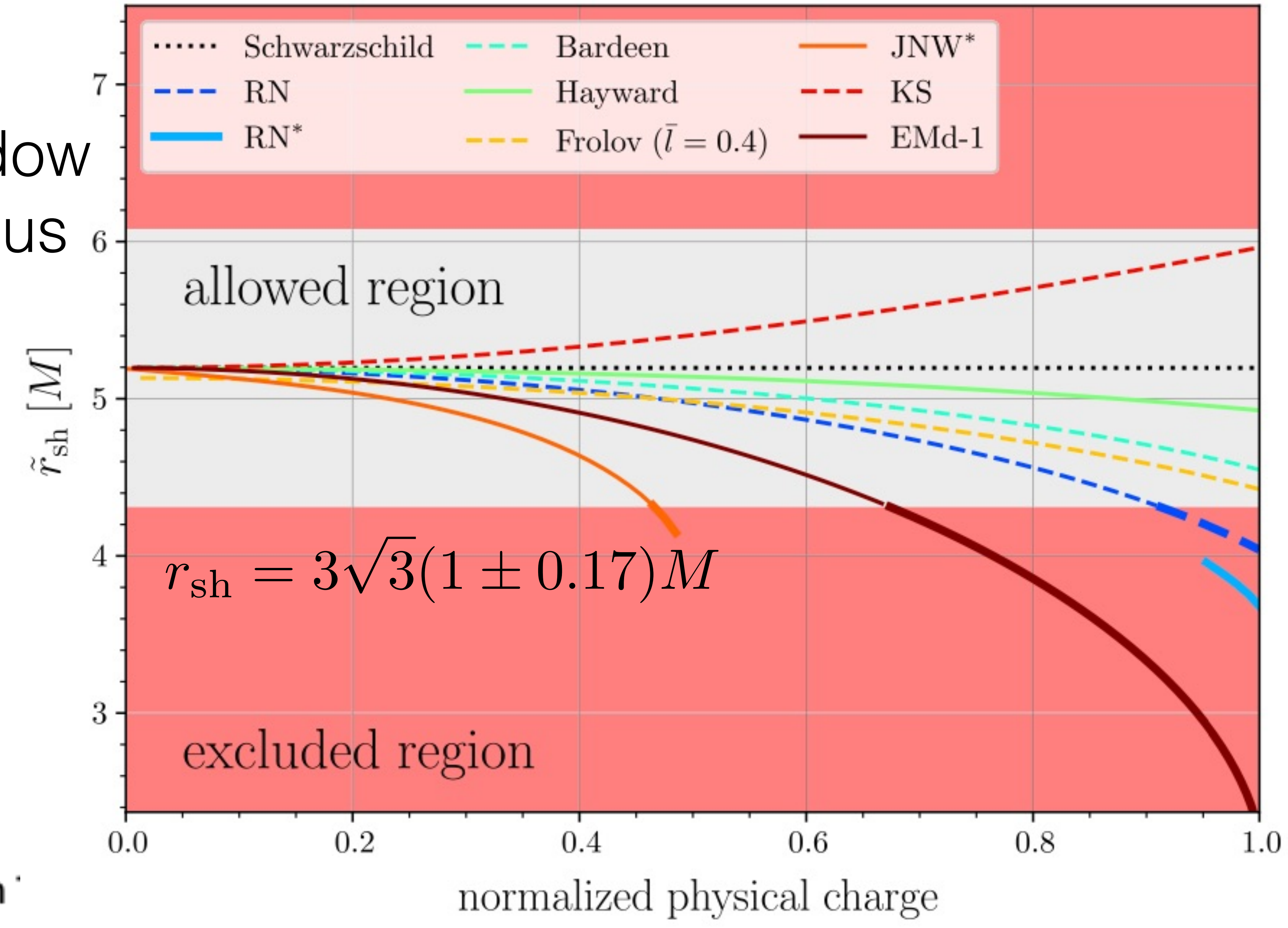
From BHCam review by Goddi et al. (2017)

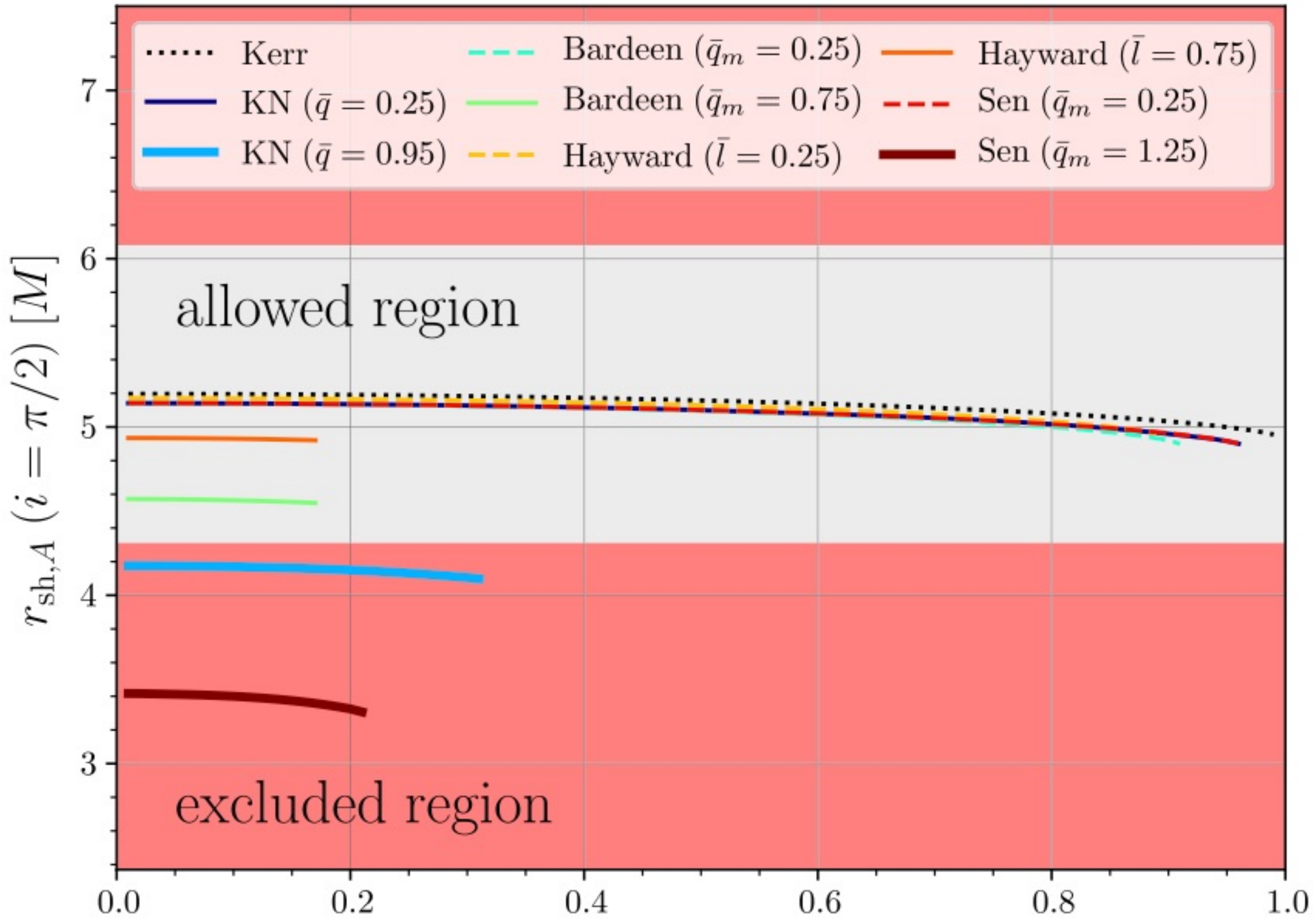
Constraint of Black Hole Charge

- Black Hole shadow size depends on BH physical charge (electric charge, scalar charge etc)
- Using EHT 2017 M87 image, give the constraint on physical charges of large variety of BH

Spacetime	Rotation	Singularity	Spacetime content
KN [73]	Yes	Yes	EM fields
Kerr [72]	Yes	Yes	vacuum
RN [62]	No	Yes	EM fields
RN* [62]	No	Yes	EM fields
Schwarzschild [62]	No	Yes	vacuum
Rot. Bardeen [75]	Yes	No	matter
Bardeen [63]	No	No	matter
Rot. Hayward [75]	Yes	No	matter
Frolov [65]	No	No	EM fields, matter
Hayward [64]	No	No	matter
JNW* [71]	No	Yes	scalar field
KS [66]	No	Yes	vacuum
Sen† [74]	Yes	Yes	EM, dilaton, axion fields
EMd-1† [67,68]	No	Yes	EM, dilaton fields
EMd-2† [70]	No	Yes	EM, EM, dilaton fields

shadow radius





BH spin

Event Horizon

Kocherlakota et al. (2021)

Testing BH Alternatives

Realistic shadow imaging (GRMHD simulation of accretion flows onto central object+GRRT imaging) for BH alternatives

- Dilaton BH (alternative theories of gravity), Mizuno+ (2018)
- Boson Star (w.o. event horizon & surface), Olivares, YM+ (2020)
- Gravastar (w.o. event horizon, w. surface), Olivares, YM+ (2021 in prep)

Considered Future EHT array (including 345GHz & space-VLBI)
(Fromm, YM+ 2021)

Event Horizon Telescope

Kerr BH (a=0.9375)

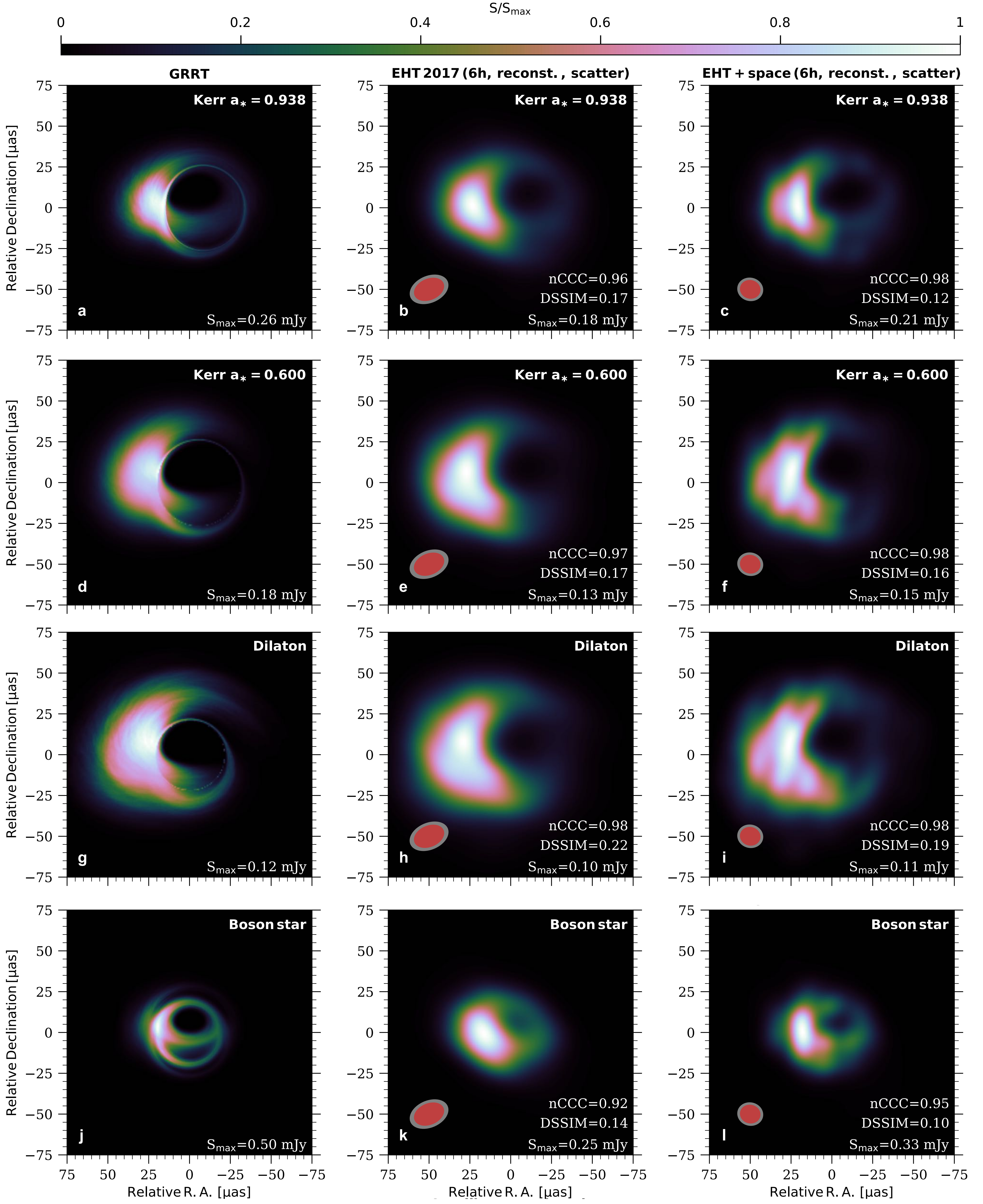
Kerr BH (a=0.6)

Dilation BH (b=0.5)

Boson star

@230GHz, i=60 deg, for Sgr A*

GRRT | EHT 24h | EHT+space 24h



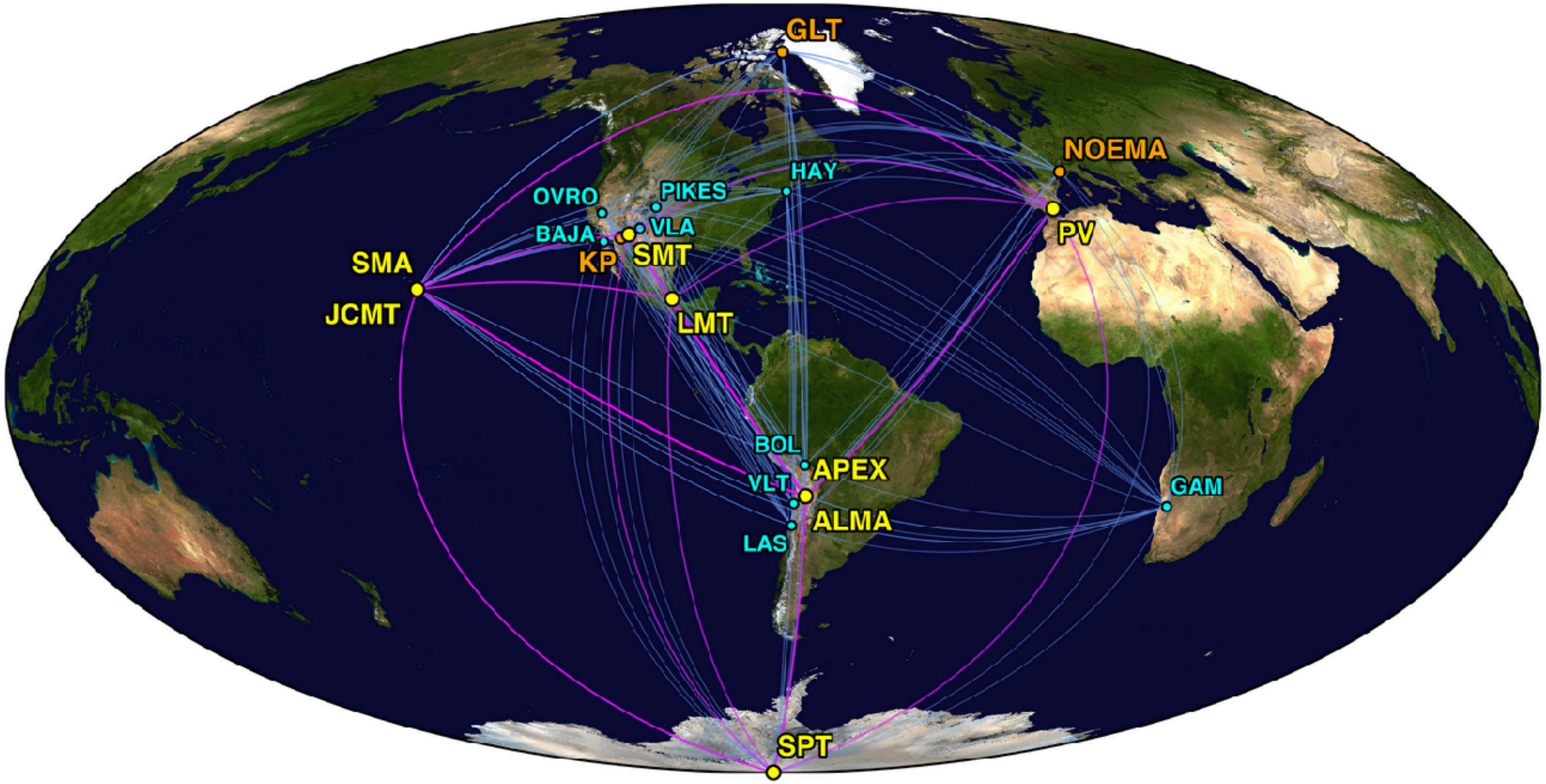
Array Evolution of EHT (2021~)

(RML Reconstruction with SMILI) **EHT 2021**

(Chael+ 19) GLT joined KP & NOEMA will join

EHT Collaboration, ALMA Cycle 7 M87 Proposal

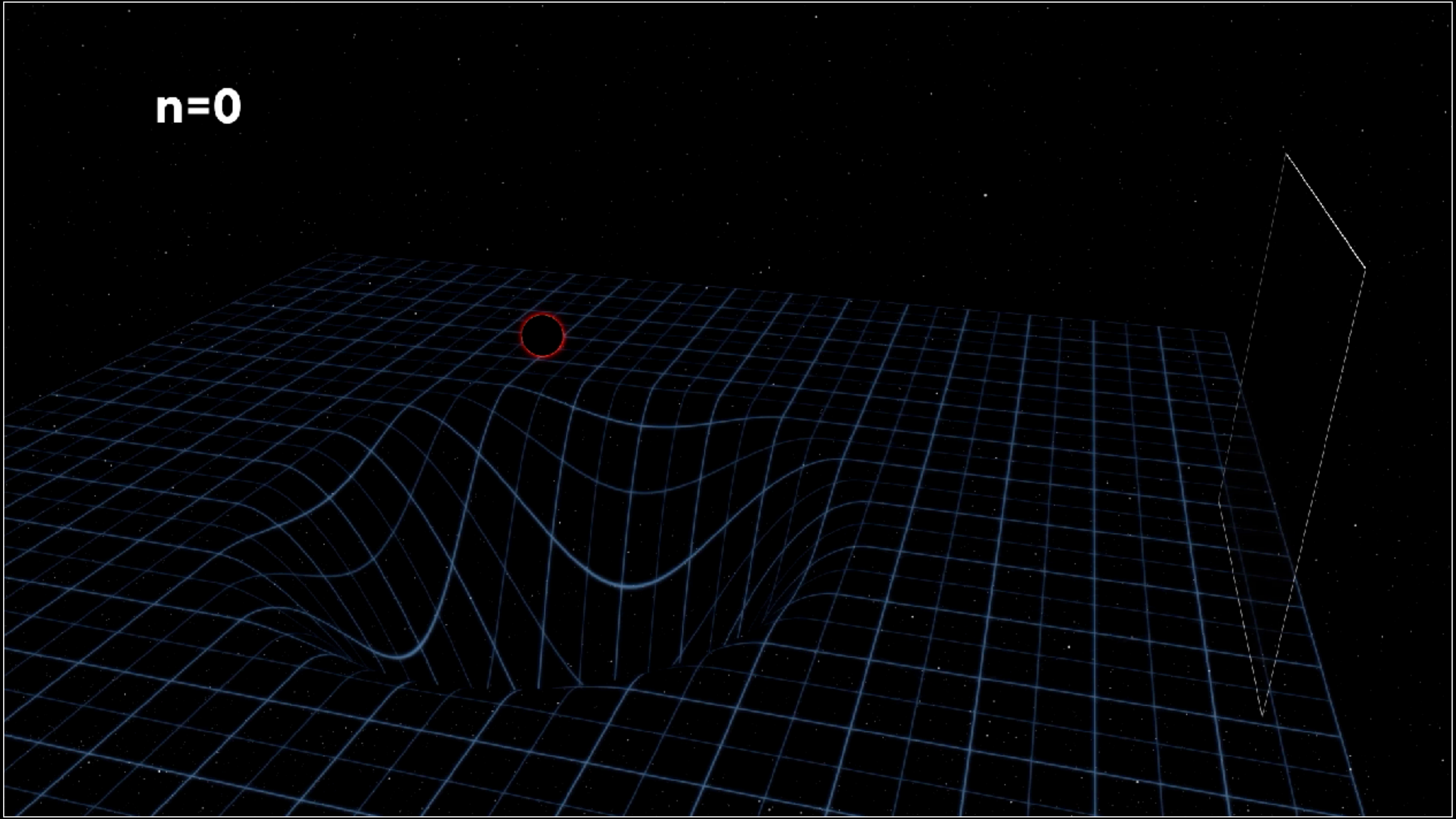
next general Event Horizon Telescope

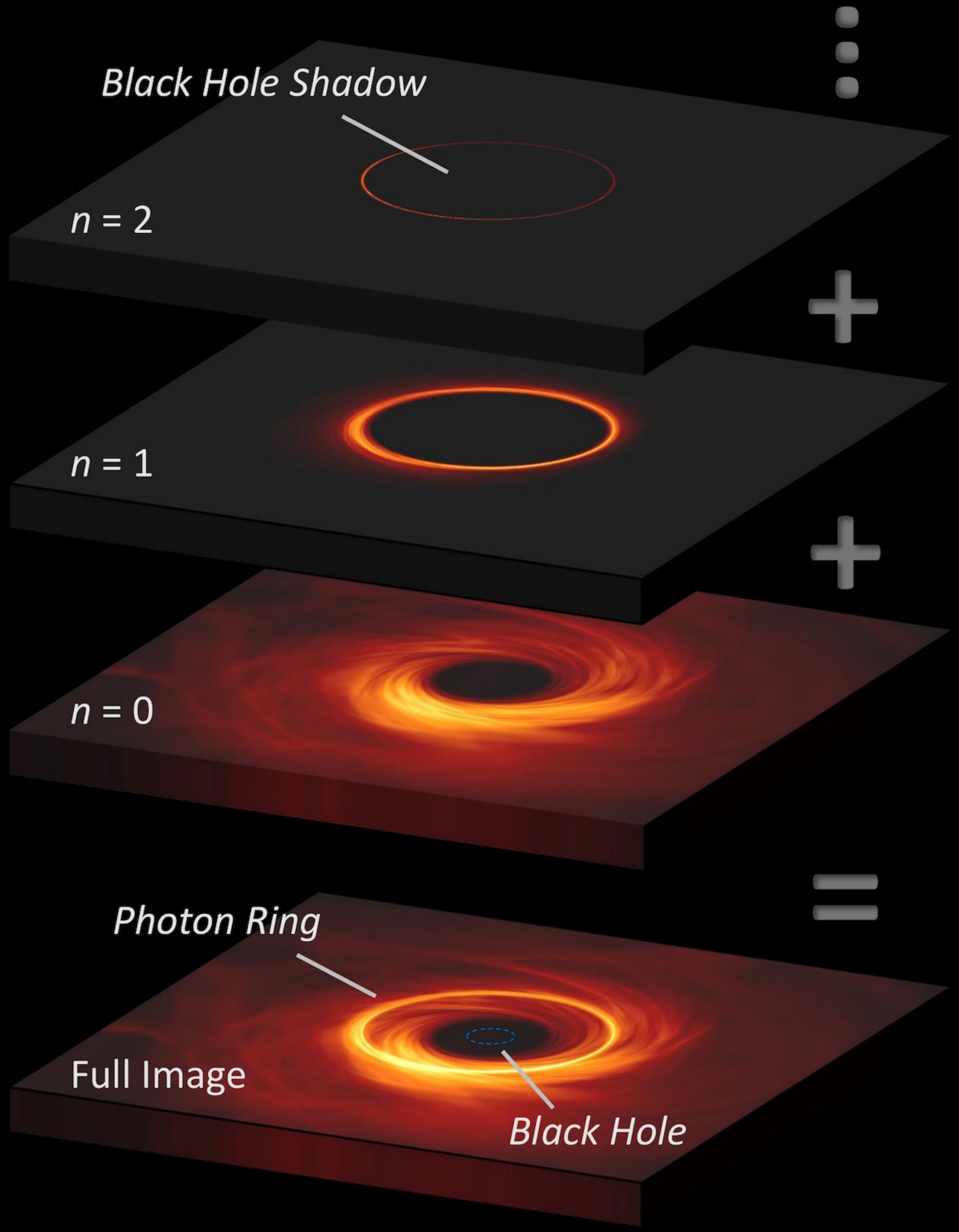


Phase I: 2019-2023 (Array Design Phase)

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

Black Hole Photon Ring

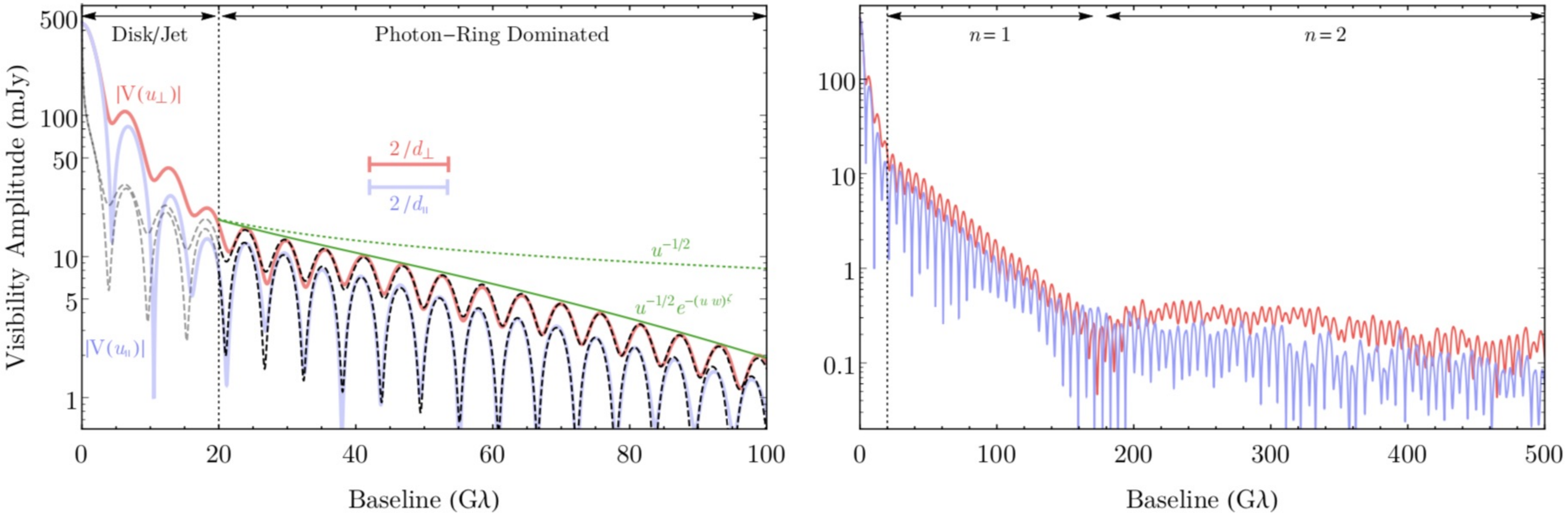


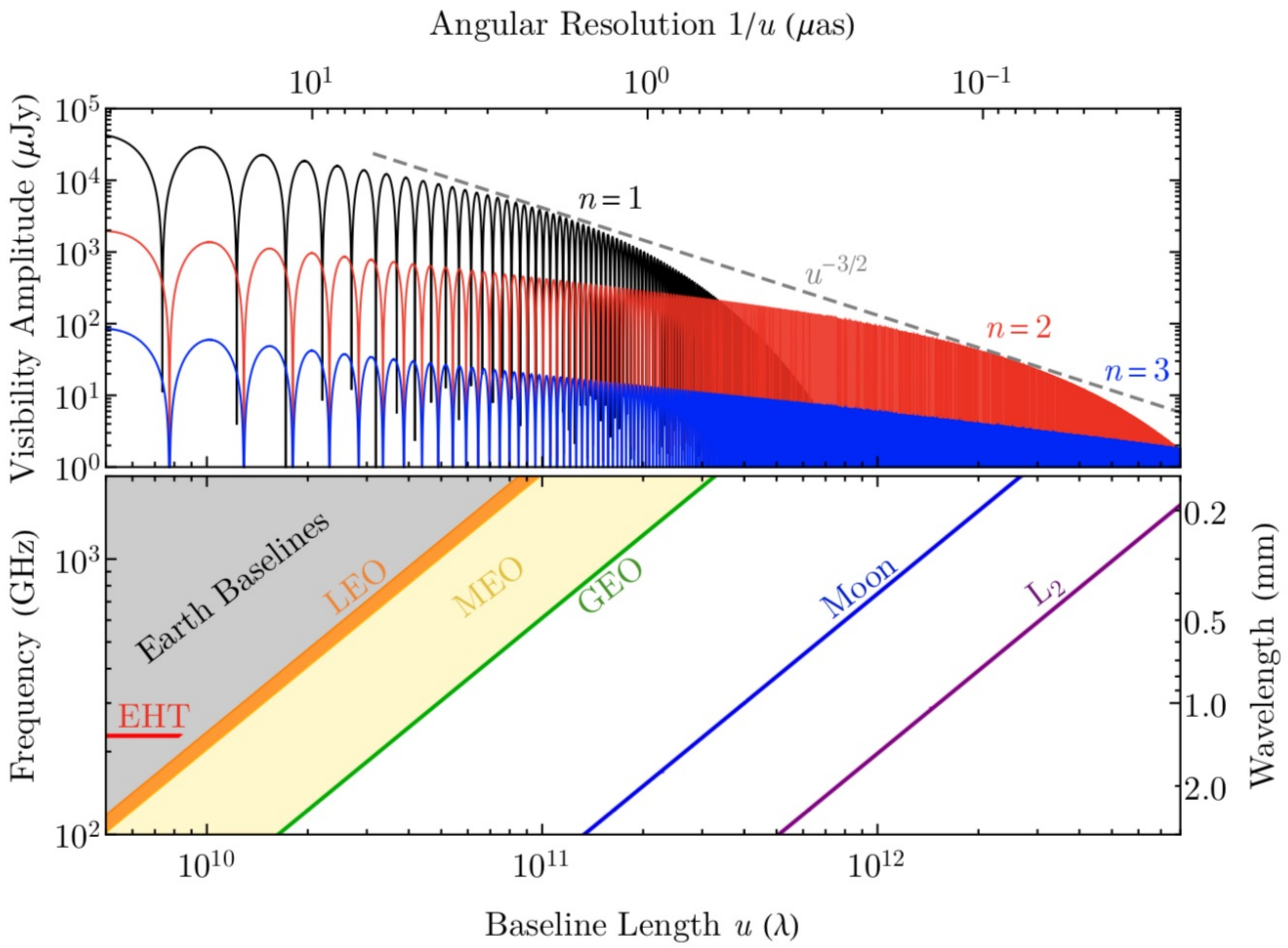


Johnson et al. (2019)

Black Hole Photon Ring

Johnson et al. (2019)





visibility amplitude of time-averaged GRMHD simulation for M87 (i=163 deg)

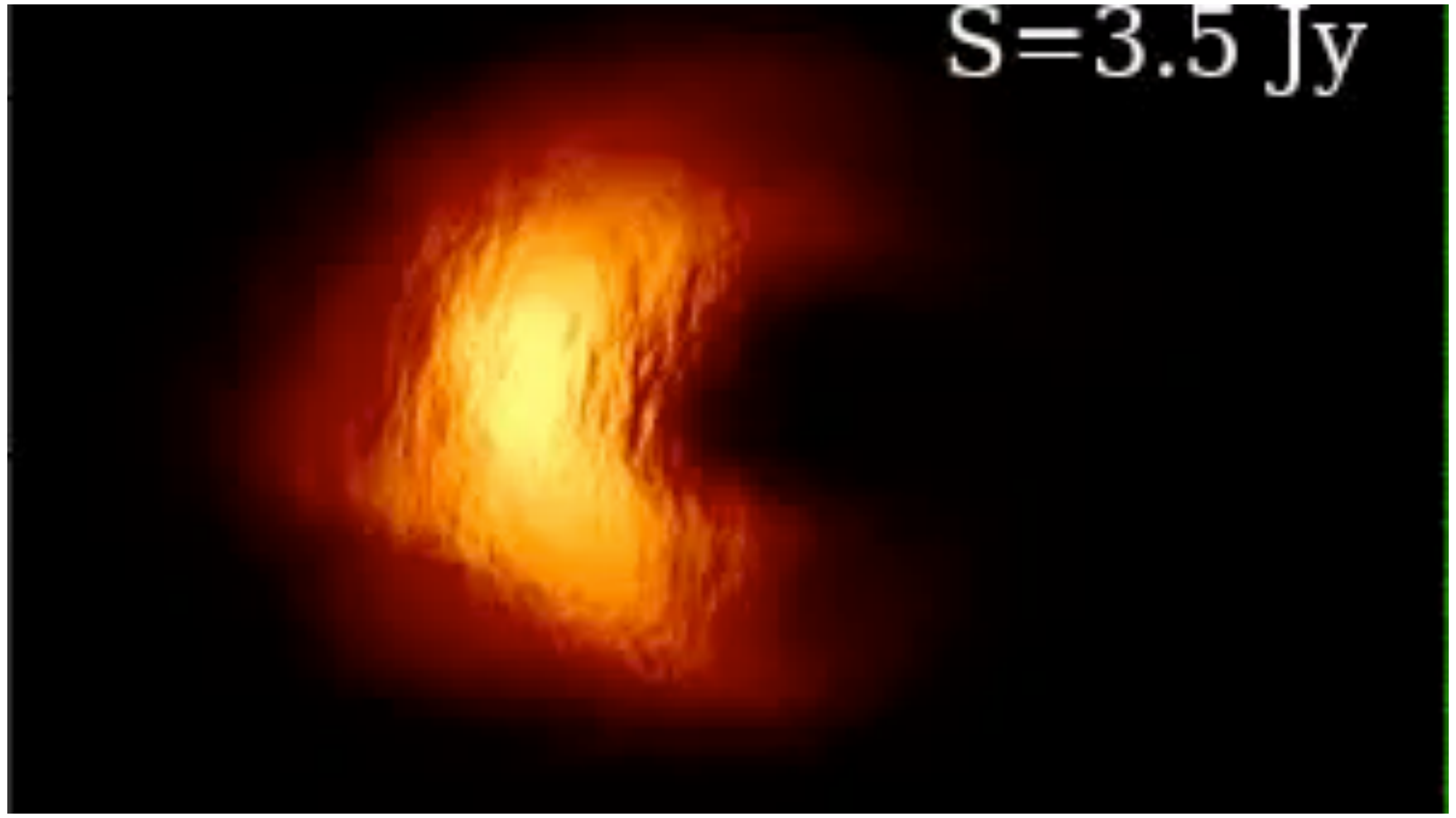
Blue: perpendicular intersection to BH spin axis
Red: parallel intersection to BH spin axis

short baseline: complex structure reflected disk/jet emission
long baseline (>20Gλ): dominated by photon ring (n=1,2,…)

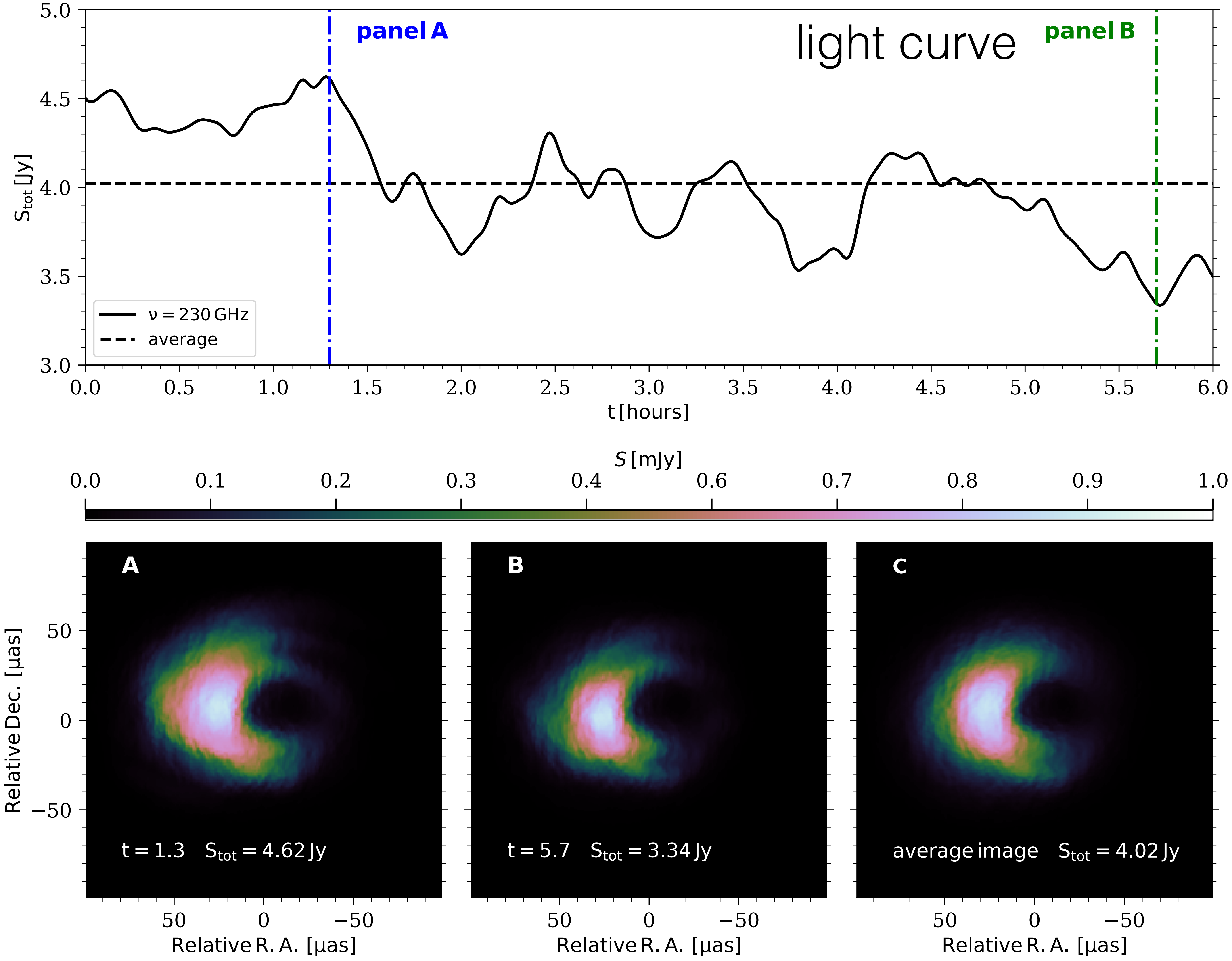
LEO: low Earth Orbit: < 2000 km
MEO: Medium Earth Orbit: 2000-36,000 km
GEO: Geostationary orbit: 36,000 km

Movie of Sgr A*

- Sgr A* is more complicated due to time variability & scattering during EHT observation period (~6h)
- Image snapshot => Movie



GRMHD + GRRT + scattering (SANE, a=0.6, i=60 deg)

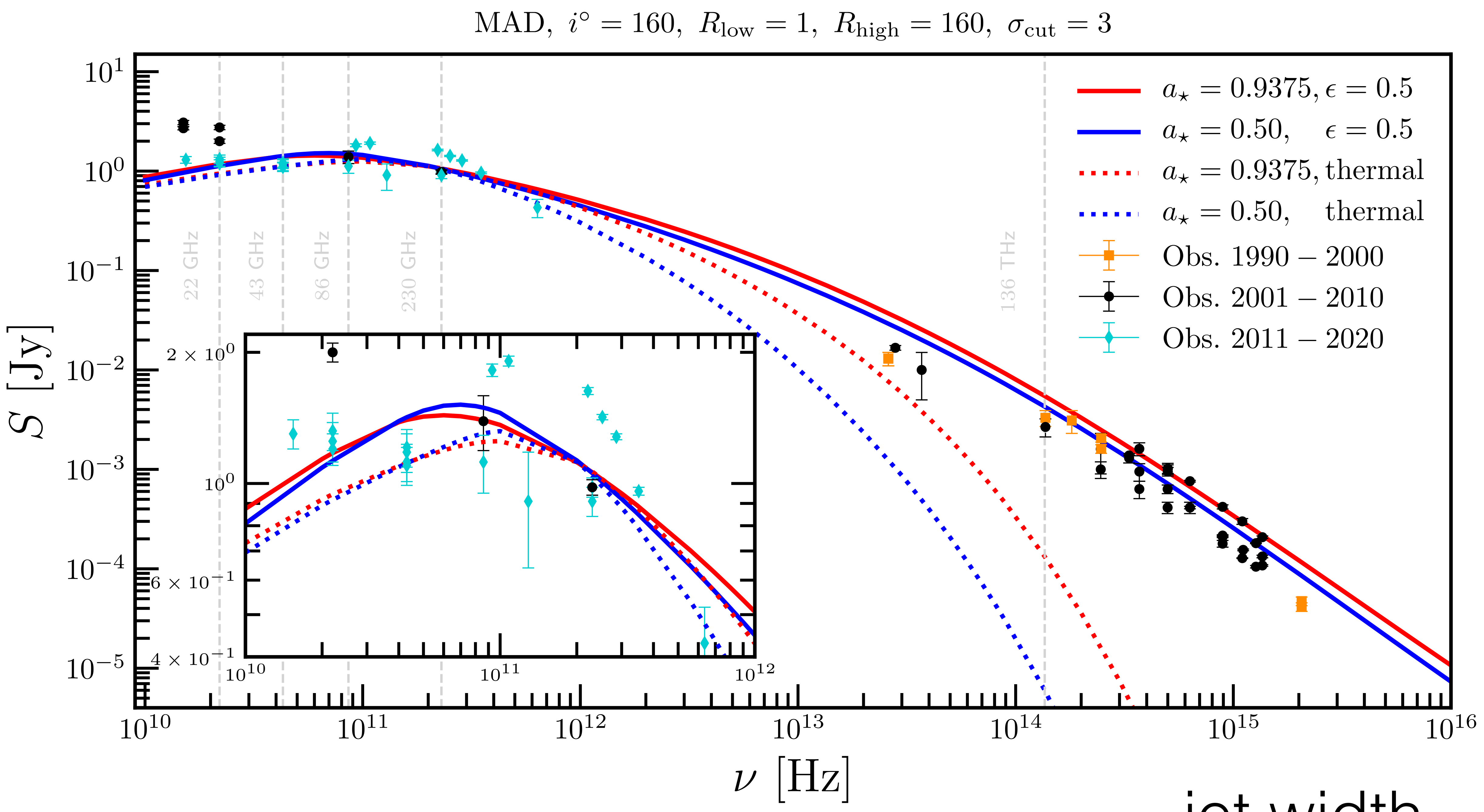


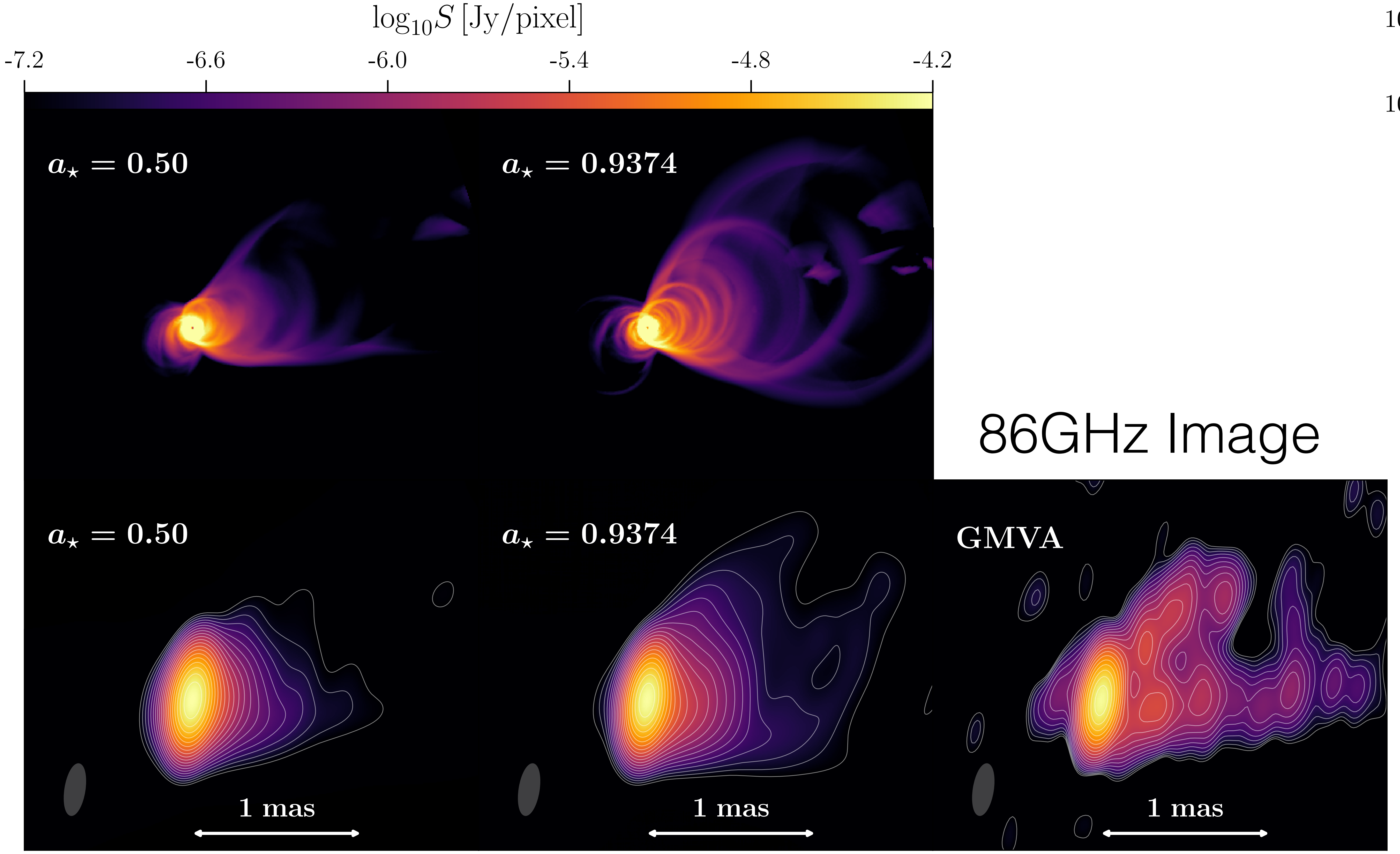
Event Horizon Telescope

Fromm, YM et al. (21)

M87 Jet Modeling at 86GHz

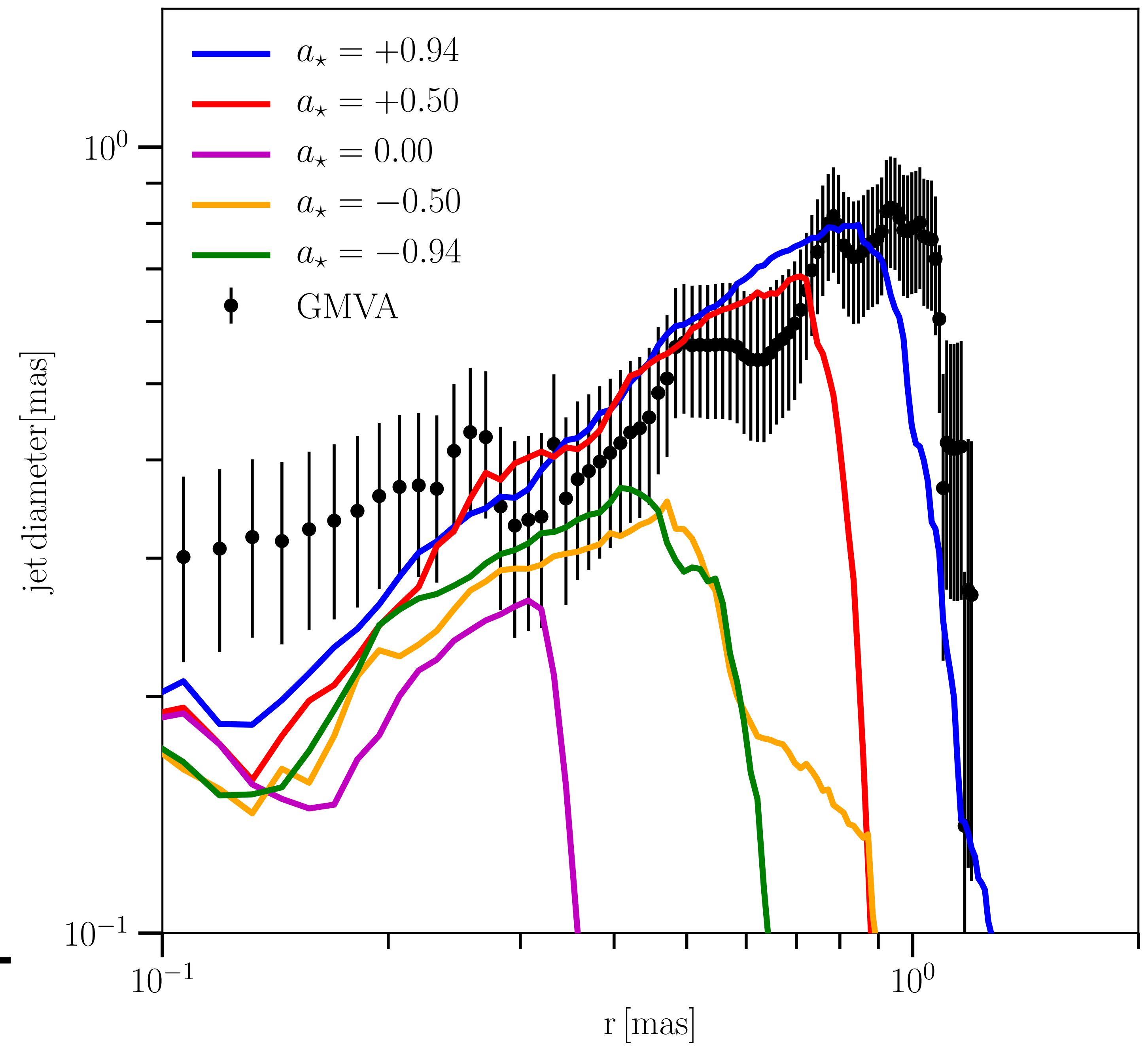
- 3D GRMHD simulations of MAD accretion flows + GRRT calculations (thermal + non-thermal eDF)
- MAD (a=0.94) fits SED & jet morphology at 86GHz





86GHz Image

jet width



Event Horizon Telescope

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

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
- From theoretical modeling, size, shape, & structure fit prediction of GR
- New polarized light is along bright ring structure of M87
- From model comparison, MAD accretion model is favoured than SANE
- Upcoming: Galactic center (Sgr A*) images
- In future, more and shaper images: +epoches (movies), +higher frequency, +new antennas
- New results will provide the possibility of testing theory of gravity via BH shadow images in more accurately.

Thank you for listening