First M87 Event Horizon Telescope Results: The Shadow of the Supermassive Black Hole

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Institute for Theoretical Physics
Goethe University Frankfurt

on behalf of Event Horizon Telescope collaboration

Seminar, Kavli IPMU, 28, May, 2019

First Image of a Black Hole

EHT Collaboration

Social Media Reaction (News paper)

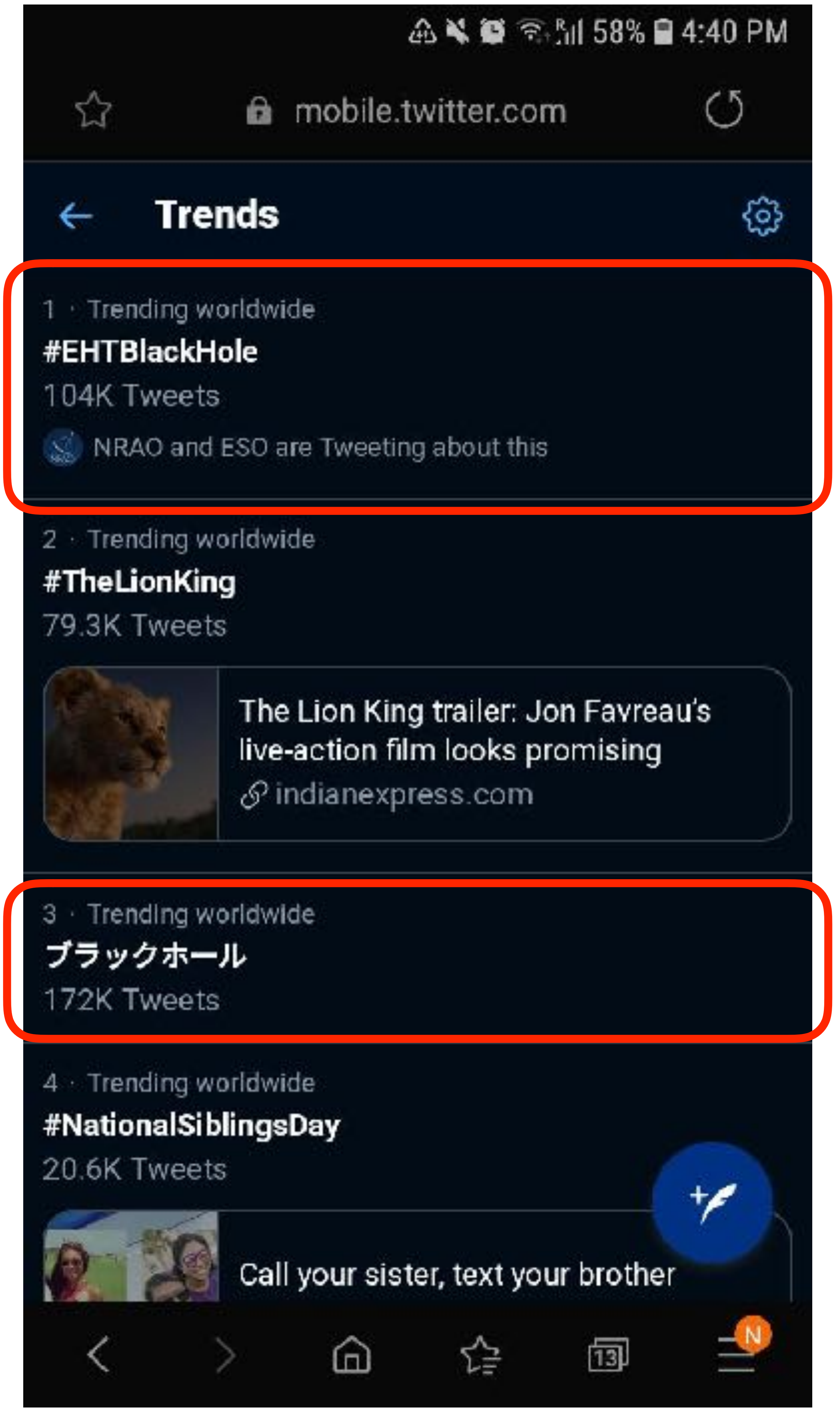
Cover page all over the world!

Event Horizon Telescope

The Black Hole Shadow in M 87
Cover Pages

Social Media Reaction (Twitter)

hashtag of EHT is 1st of trends



Event Horizon Telescope

The First M87 EHT Results: Six ApJ Letters

17P Paper I: The Shadow of the Supermassive Black Hole (Summary Paper)

Coordinators: G. Bower, H. Falcke & D. Psaltis

28P Paper II: Array and Instrumentation (Instrumentation Paper)

Coordinators: S. Doeleman, V. Fish & R. Tilanus

32P Paper III: Data Processing and Calibration (Calibration Paper)

Coordinators: L. Blackburn, S. Issaoun & M. Wielgus

52P Paper IV: Imaging of the Central Black Hole in M87 (Imaging Paper)

Coordinators: K. Akiyama, K. Bouman, A. Chael, J. Gomez & M. Johnson

31P Paper V: Physical Origin of the Asymmetric Ring (Theory Paper)

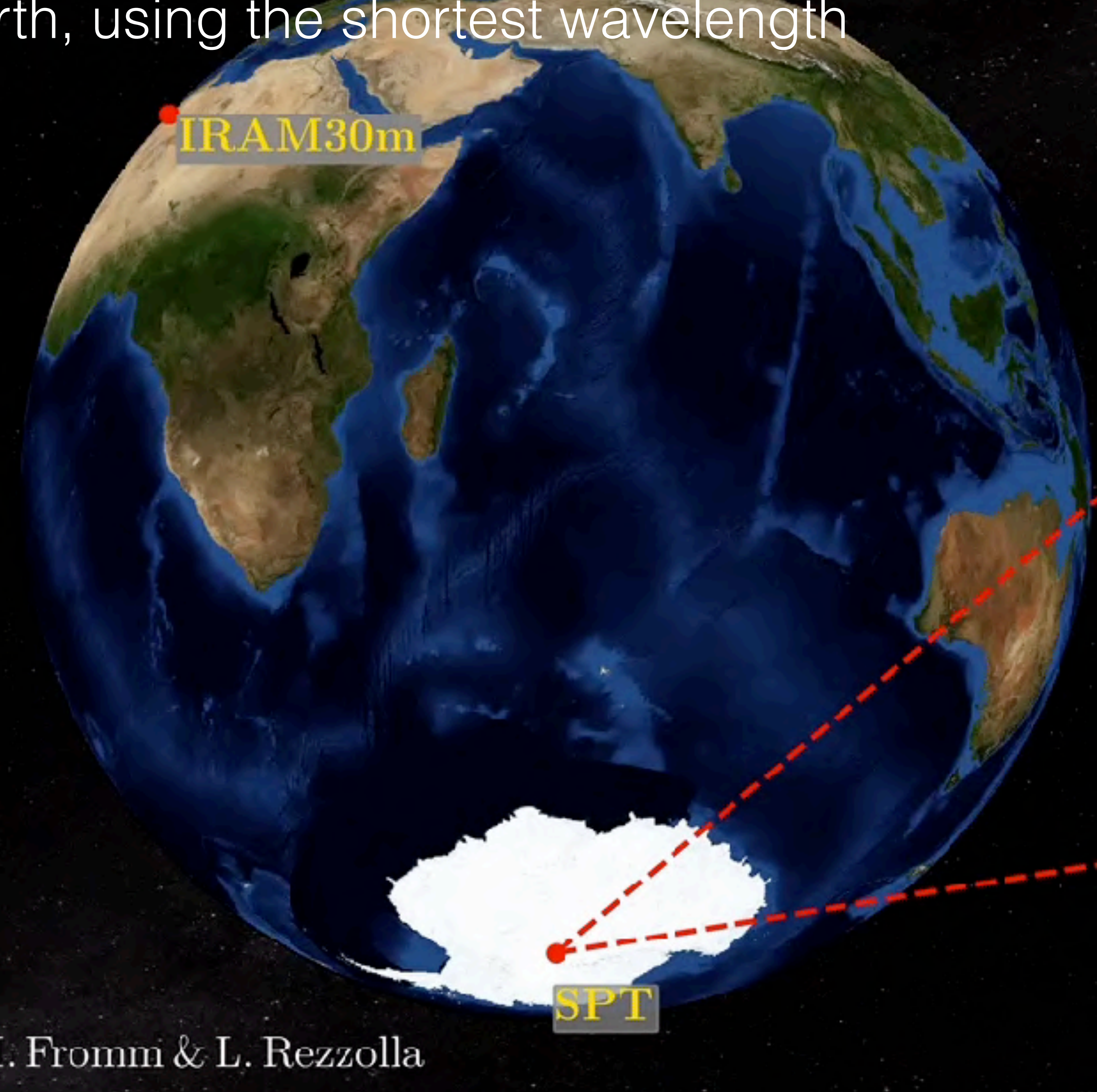
Coordinators: C. Gammie, Y. Mizuno, H.-Y. Pu

44P Paper VI: The Shadow and Mass of the Central Black Hole (Modeling Paper)

Coordinators: K. Asada, A. Broderick, J. Dexter, F. Ozel

Event Horizon Telescope Collaboration

Create a virtual radio telescope the size of the earth, using the shortest wavelength



South Pole Telescope (SPT)

Country : Antarctica

Coordinates : 90°S 0°E

Diameter of telescope : 10 m

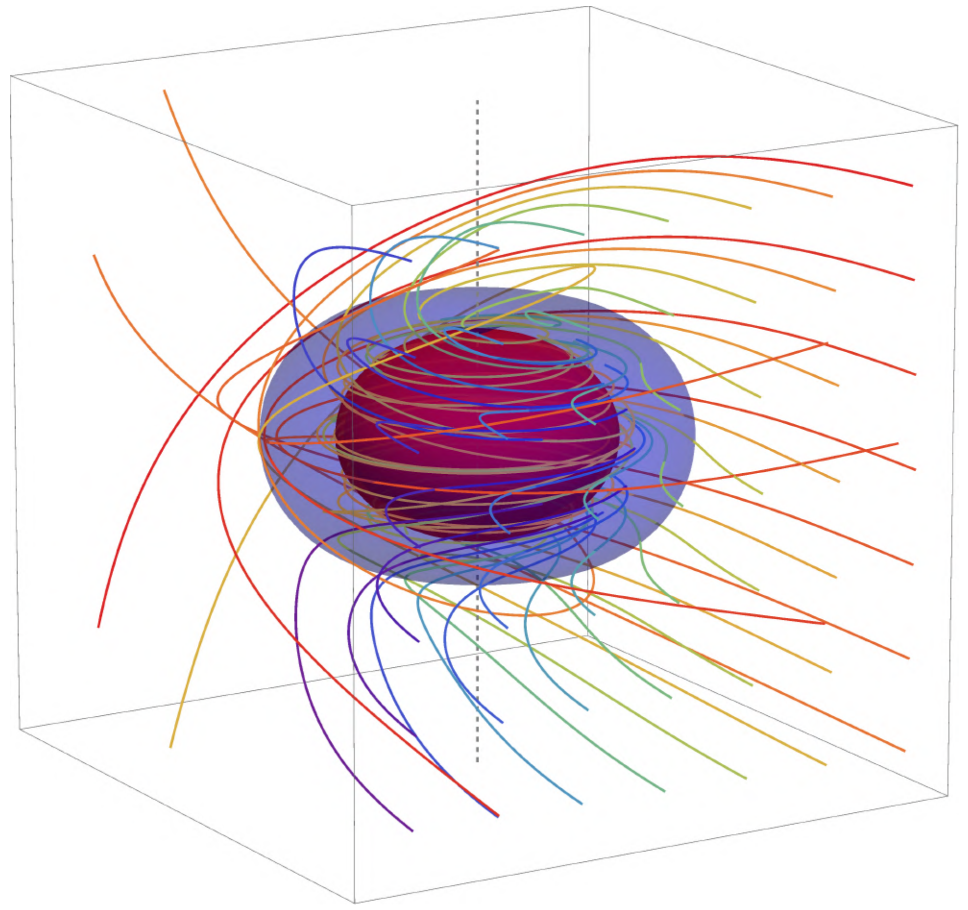
λ = 1.3 mm (ν = 230 GHz)

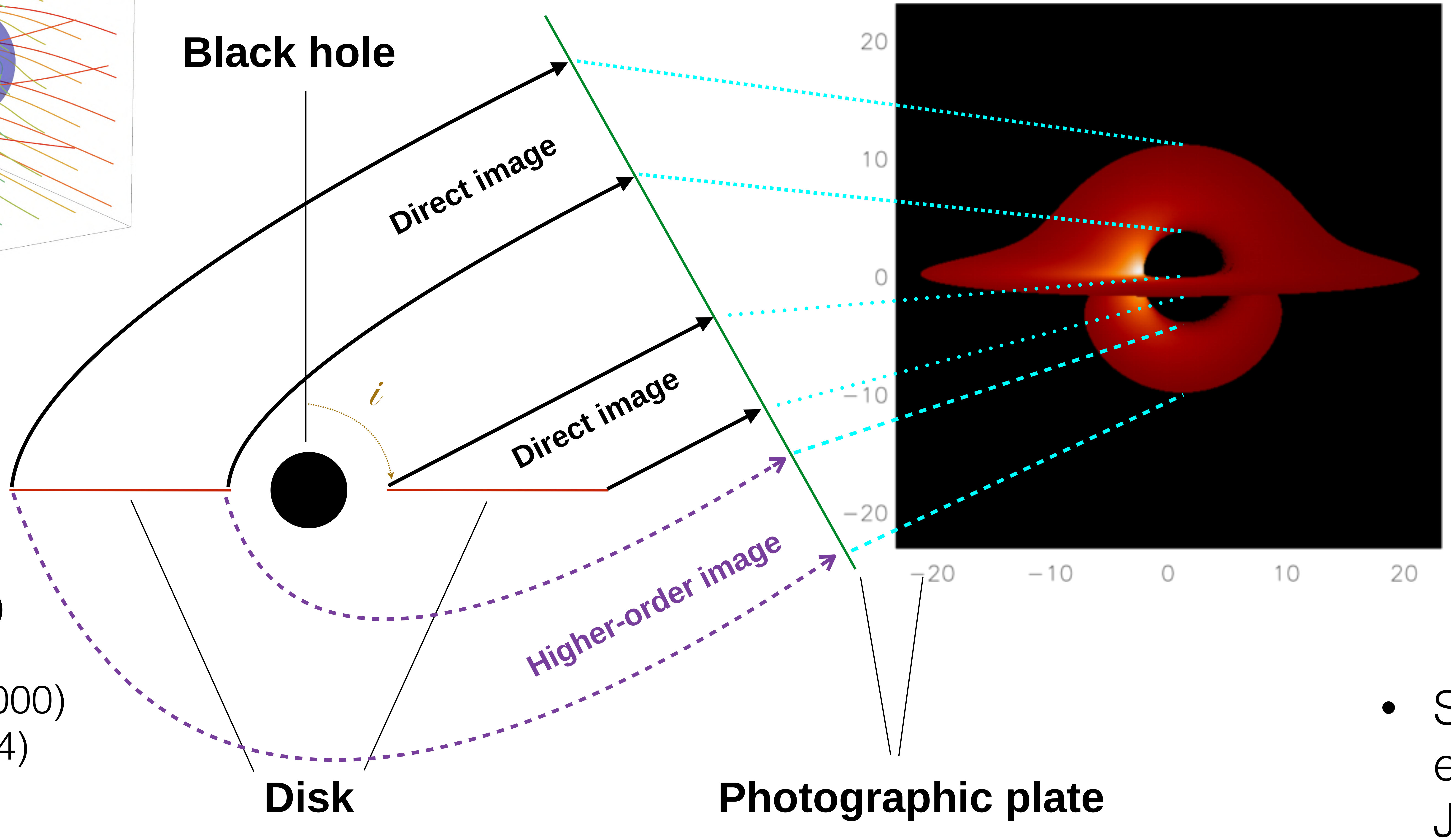
D ~ 10,000 km $\Rightarrow$ λ/D ~ 25 μas

Event Horizon Telescope

European Research Council

Strong GR: Black Hole Shadow





Shadow diameter:

Non-spinning (a=0)
$D_{sh} \sim 5.2 * R_g$

Spinning (a=1)
$D_{sh} \sim 4.8 * R_g$

- Shadow size and shape encodes GR (e.g., Johannsen & Psaltis 2010)

Bardeen (1973)
Luminet (1979)
Falcke et al. (2000)
Takahashi (2004)
etc.

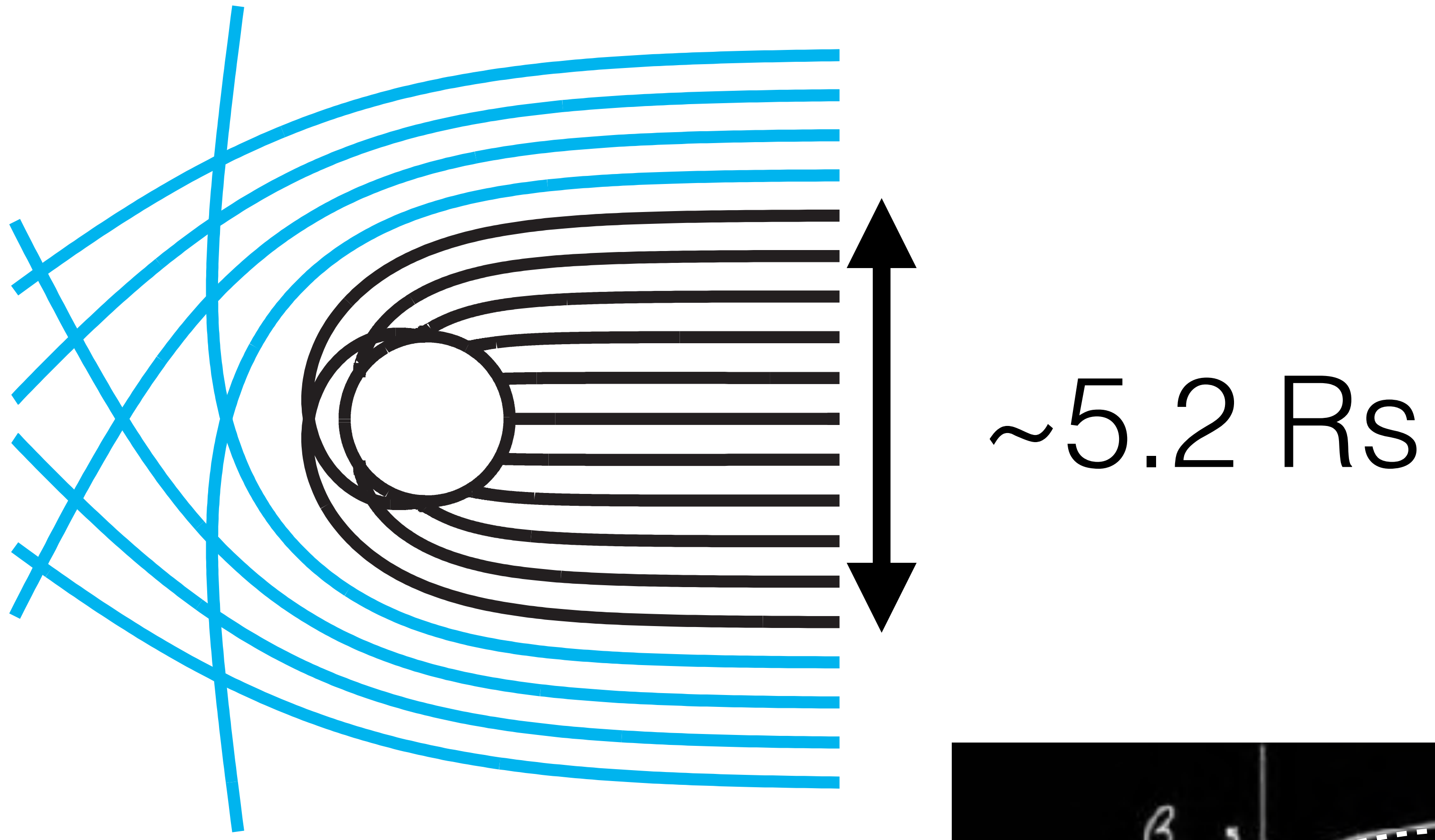
Event Horizon Telescope

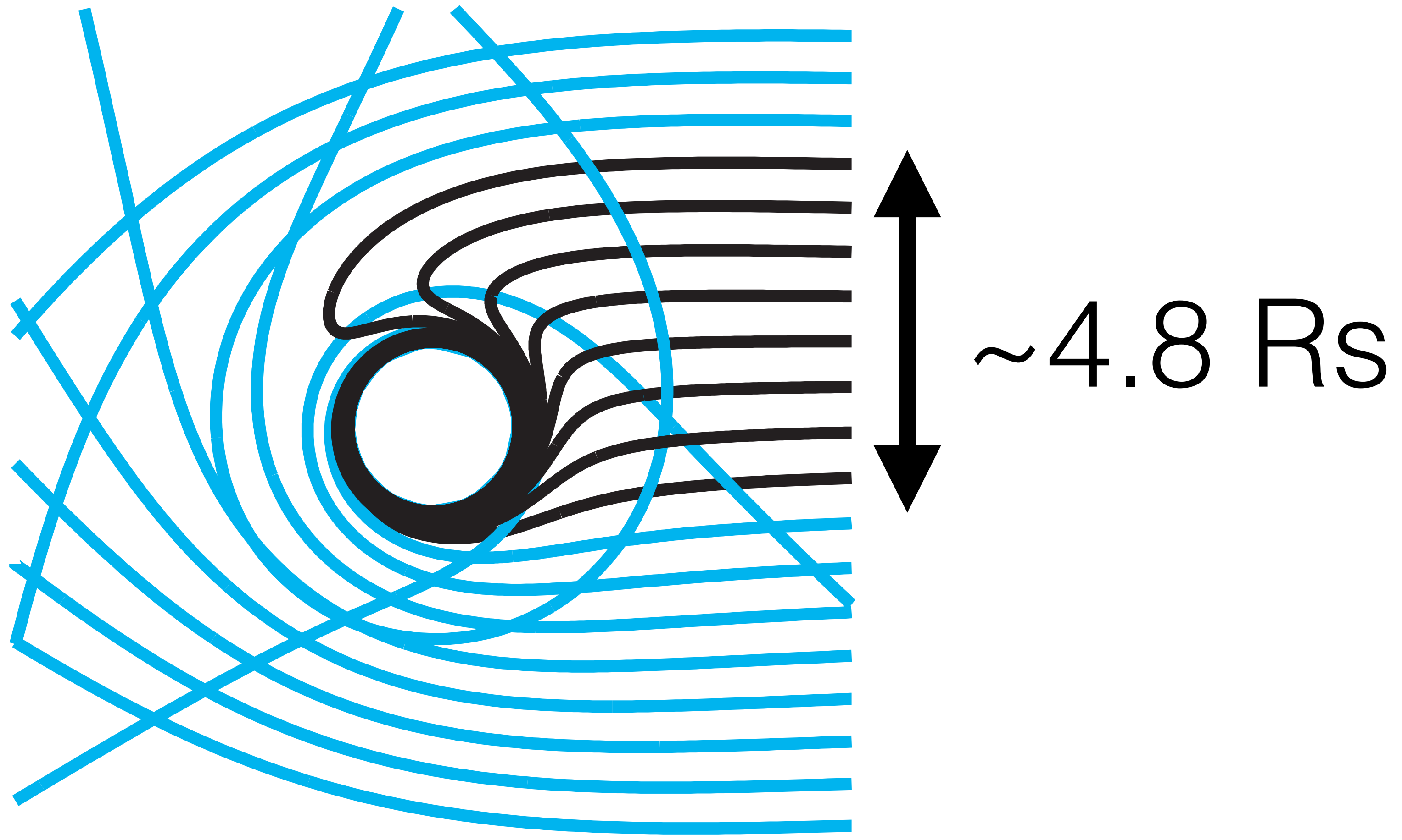
The Shadow of a Black Hole

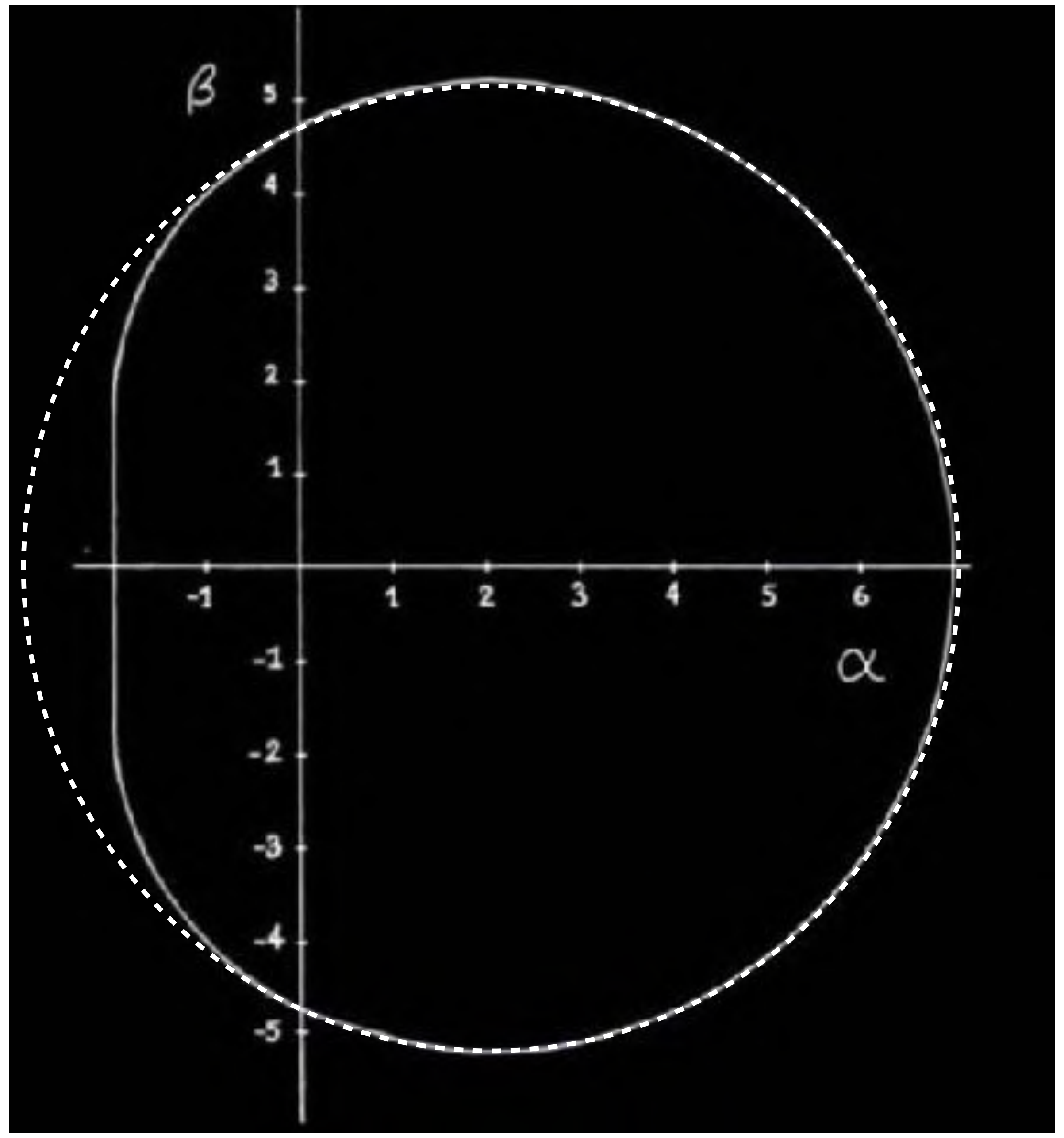
Non-spinning Black Hole

Maximumly Rotating Black Hole

top view







i=90 deg

(Figure credit: Hung-Yi Pu)

Black Holes cast shadows

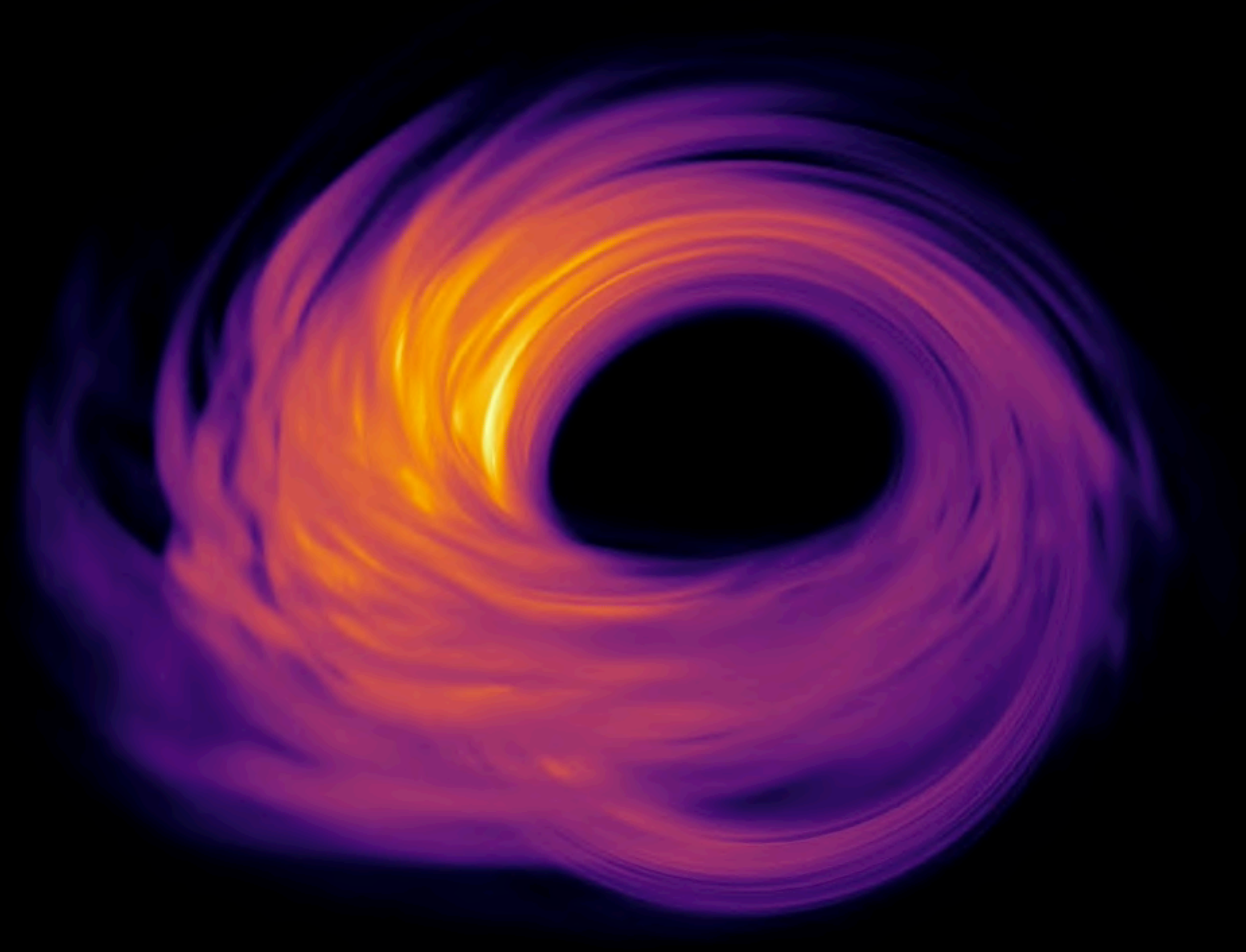
(Bardeen 1973; Falcke et al. 2000)

with a radius that changes

only by 4% with the spin

(Johannsen & Psaltis 2010)

Shadow of Black Hole



Snapshot image of GRMHD simulation
of Kerr BH with a=0.94

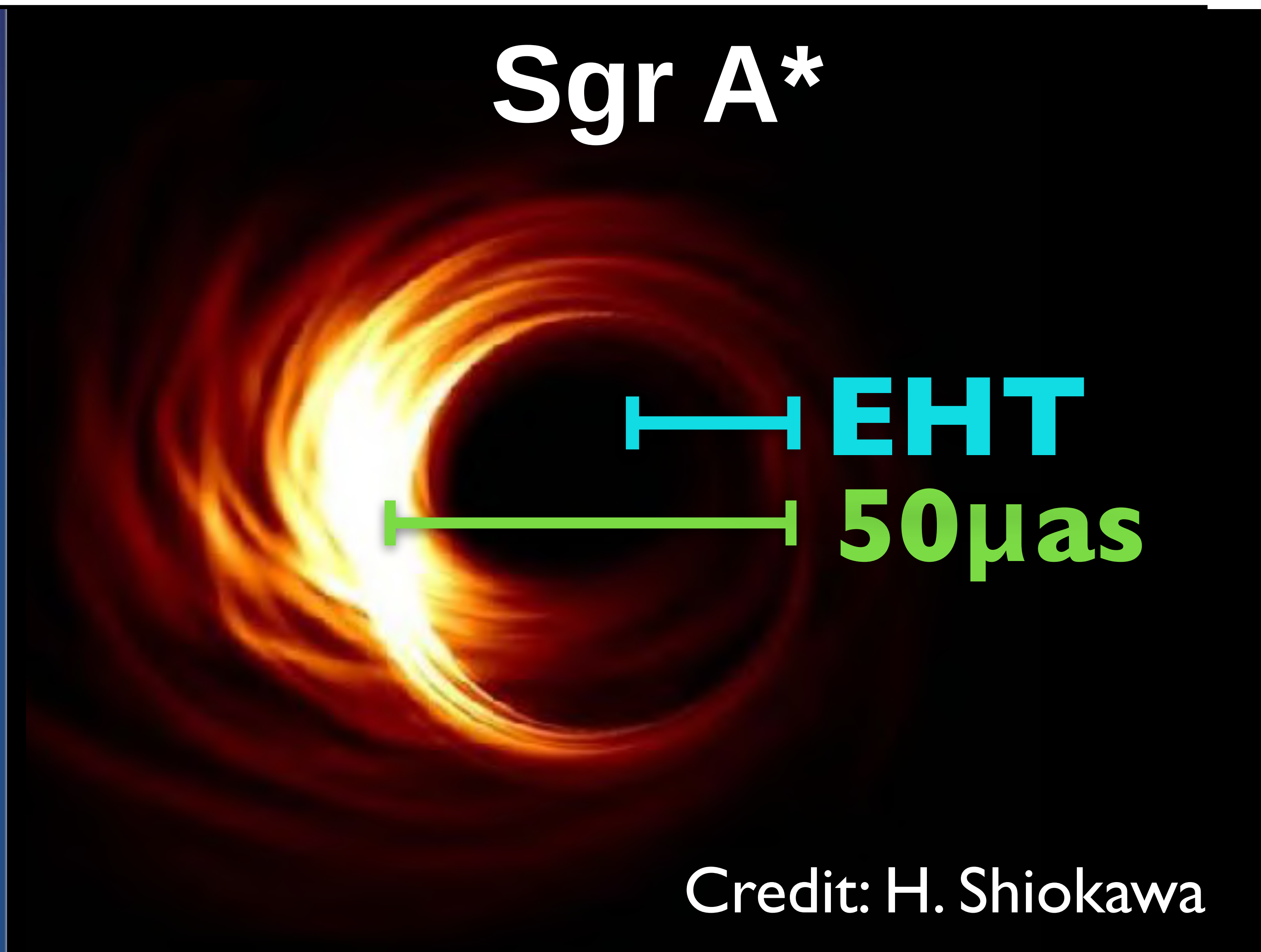
Changing viewing angle (theta & phi)

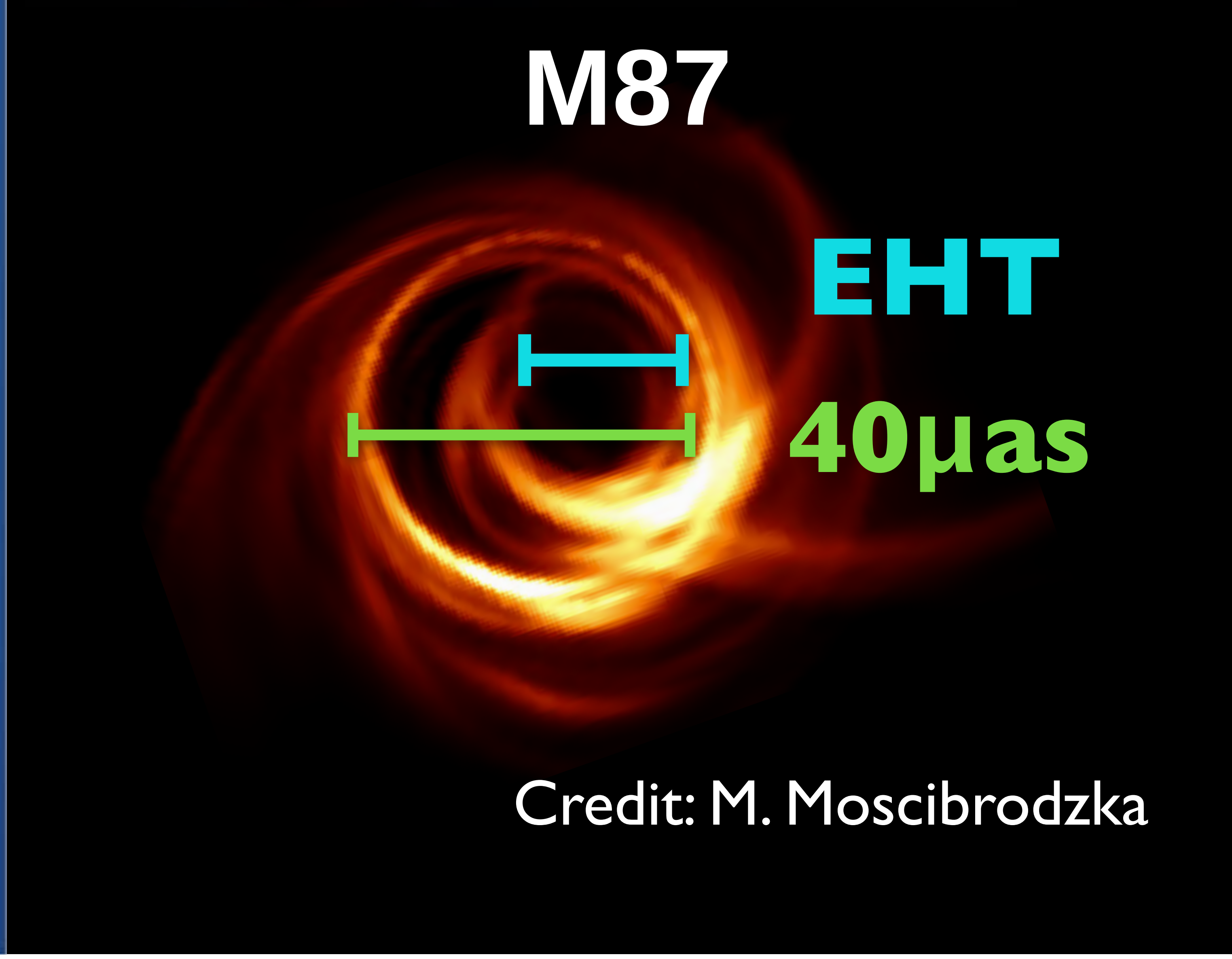
Movie: Z. Younsi

Black Holes with the Largest Angular Sizes

Source	BH Mass (M_{solar})	Distance (Mpc)	1 R_S (µas)
Sgr A*	4×10^6	0,008	10
M87	~~**$3.3 - 6.2 \times 10^9$**~~ **6.5×10^9**	**16,8**	~~**3.6 - 7.3**~~ **7.6**
M104	1×10^9	10	2
Cen A	5×10^7	4	0,25

Event Horizon Telescope 2017

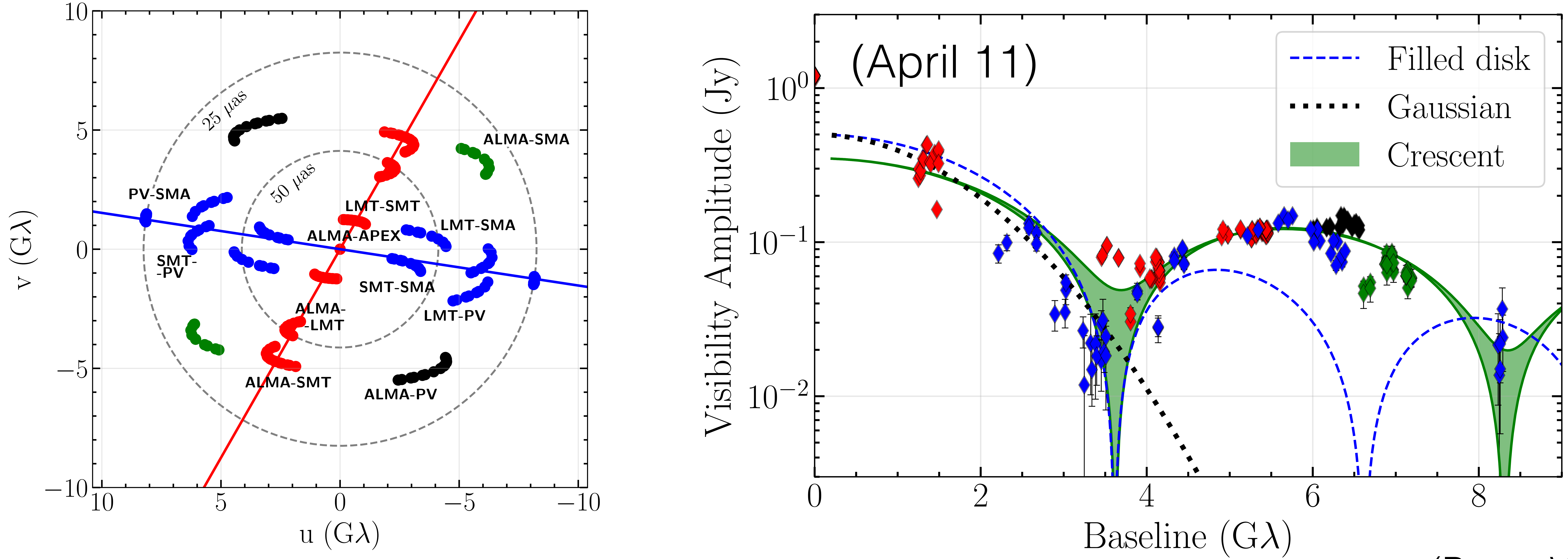




Calibrated data sets (before imaging)

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

Fourier domain



(Paper VI)

Event Horizon Telescope

Fantastic Four: Black Hole Image Hunters

Team 1

Americas

US & Chile

(SAO, U. Arizona, U. Conception)

Leader: K. Bouman & A. Chael

new method

(regularised max likelihood)

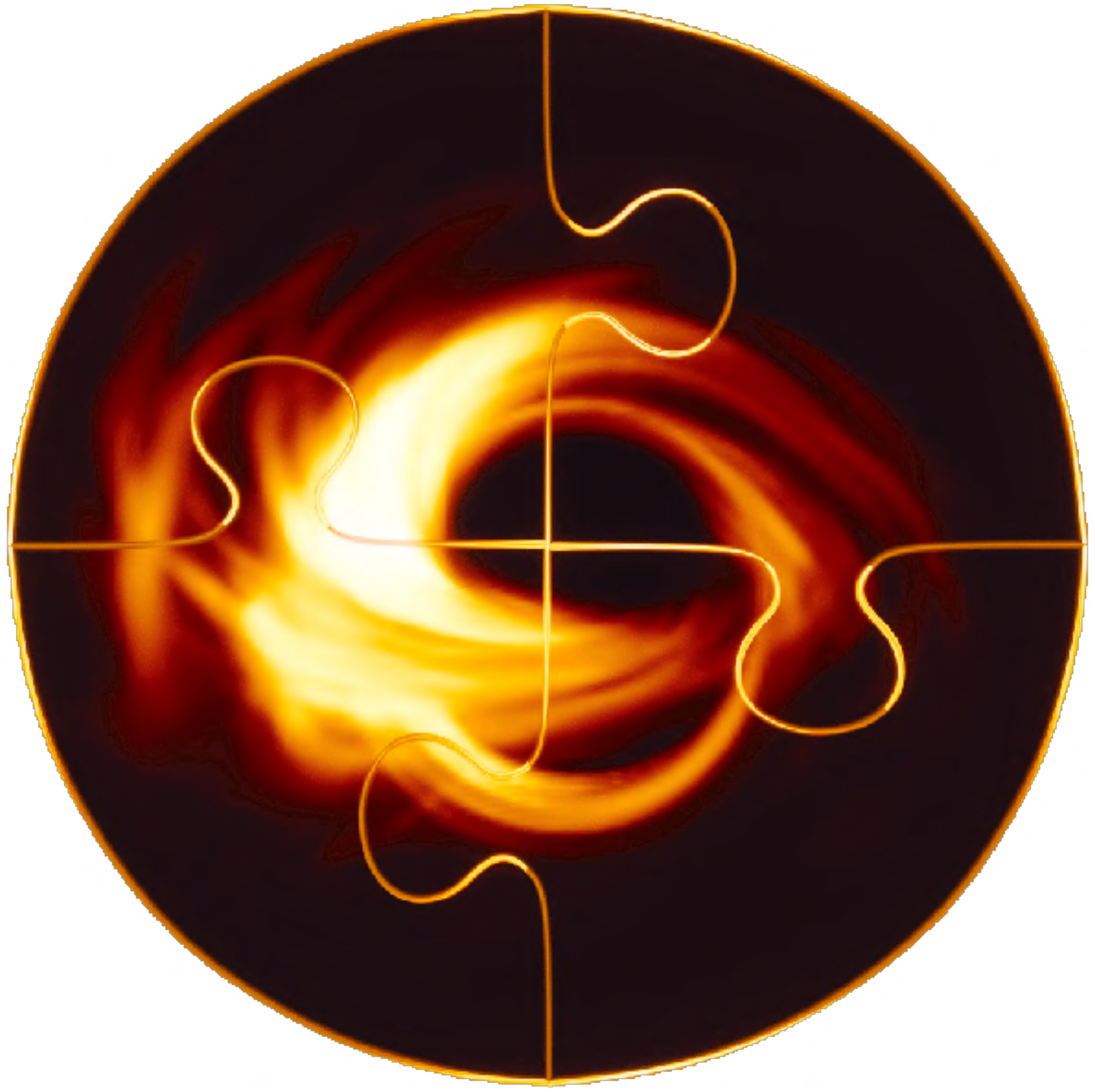
Team 2

Global

US, Japan, Netherland

(MIT, NAOJ, Hiroshima U., Radboud U.)

Leader: K. Akiyama & S. Issaoun



Team 4

East Asians

Korea, Japan & Taiwan

(ASIAA, KASI, NAOJ)

Leader: S. Koyama

traditional method

(CLEAN + self-cal)

Team 3

Cross Atlantic

US, Spain, Germany, Finland

(Boston U, MPIfR, IAA, Aalto, GU)

Leader: A. Marscher

Fantastic Four: Black Hole Image Hunters

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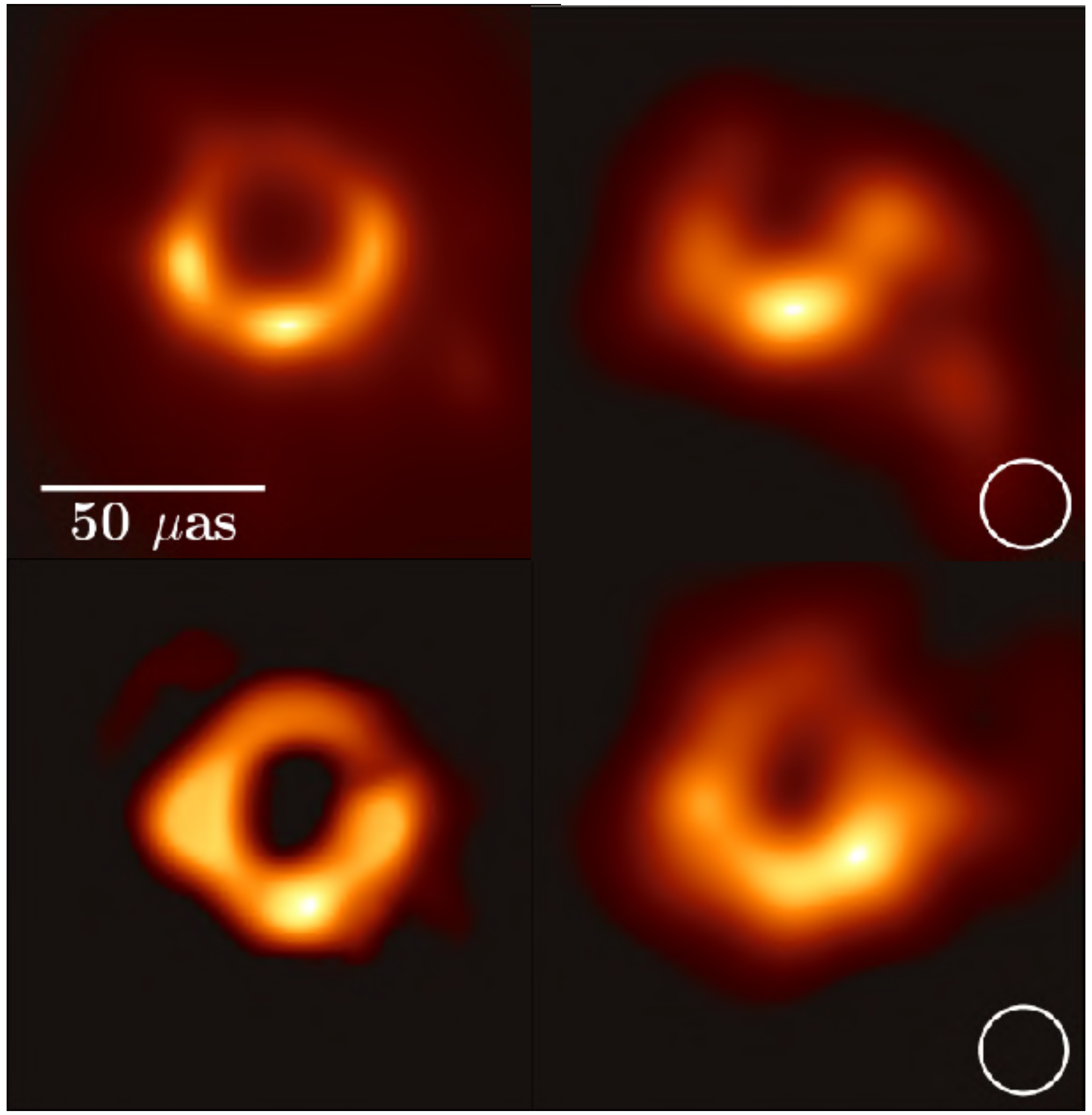
The First EHT Images of M87
July 24, 2018



Each team blindly reconstructed images
Goal: Assess human bias

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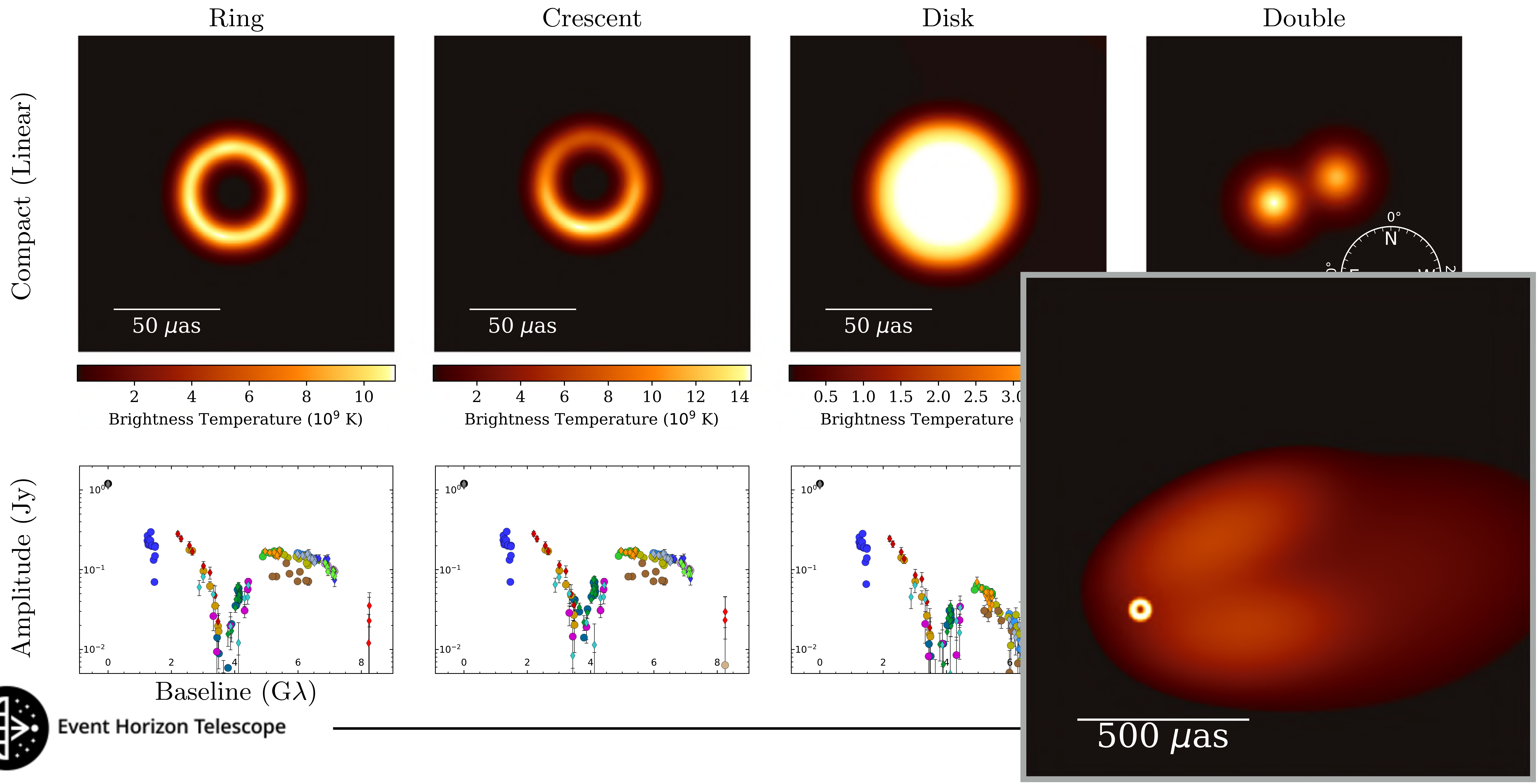
Event Horizon Telescope

The First EHT Images of M87 (July 24, 2018)

Models with Different Morphologies but Similar Visibility Amplitudes



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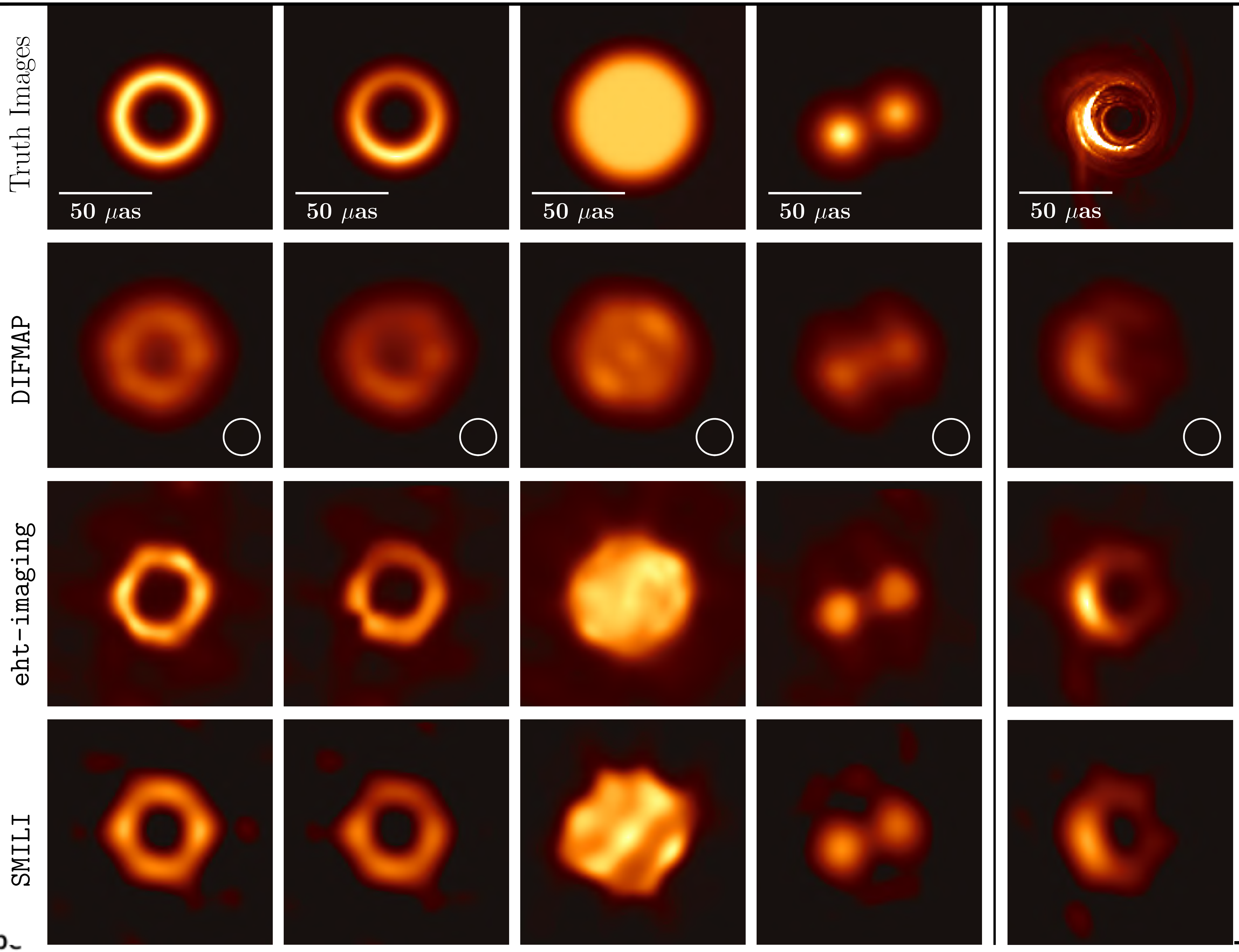
Fiducial Synthetic Data Images



Event Horizon Telescope

Averaged Images

EHT 2017 M87 reconstructed averaged images look like asymmetric rings

No significant changes are observed during the 6-day span of the 2017 EHT campaign

(Paper IV)

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)

computational infrastructure

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

developed in Frankfurt

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

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

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

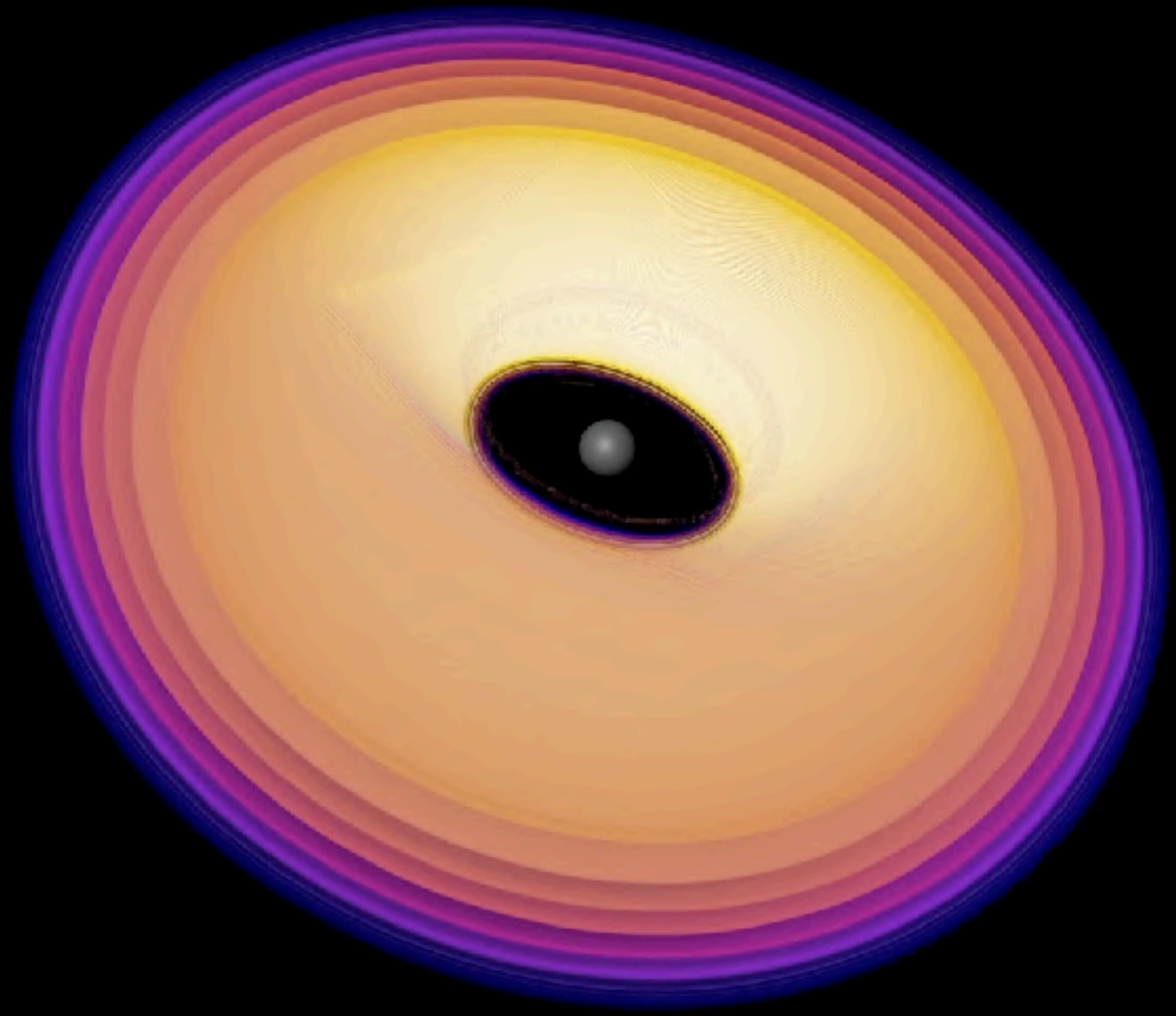
Prior knowledge from observations

- 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 (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

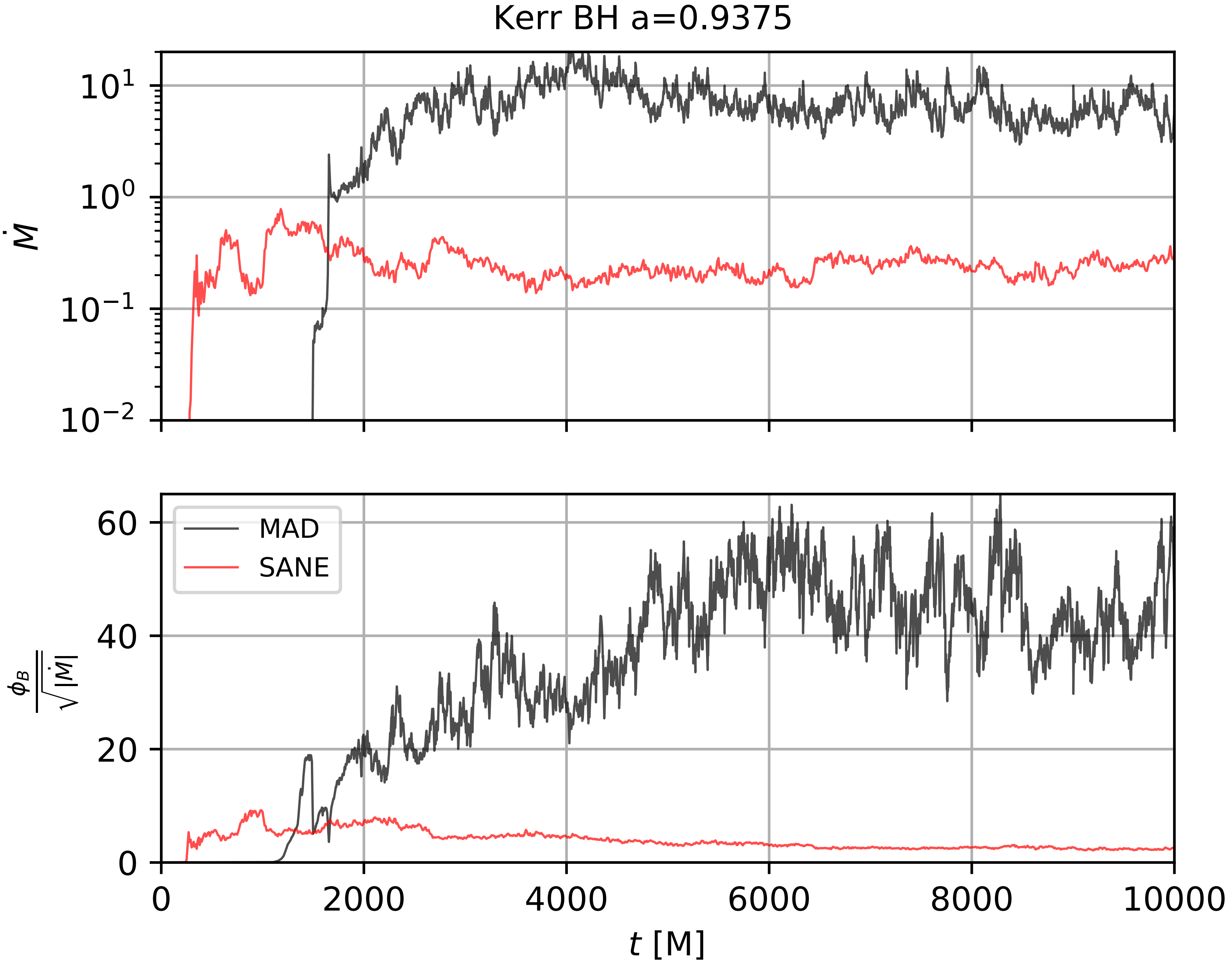


Credit: L.Weih, L. Rezzolla,
Frankfurt BHCam team

MAD vs SANE (GRMHD Simulations)

RIAF model, two extreme situation

3D GRMHD simulations
with a=0.94

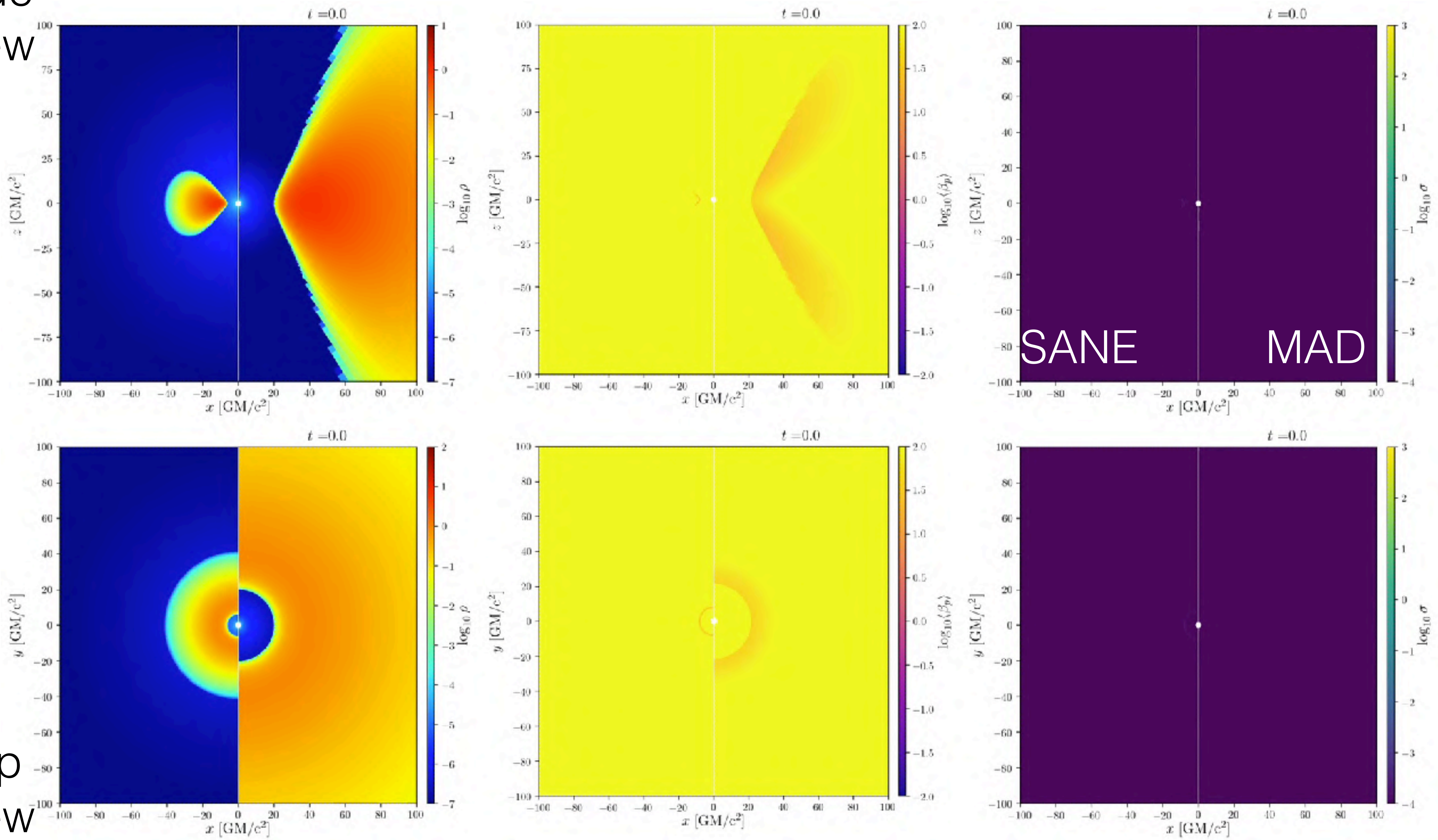


density

plasma beta

magnetisation

side view



top view

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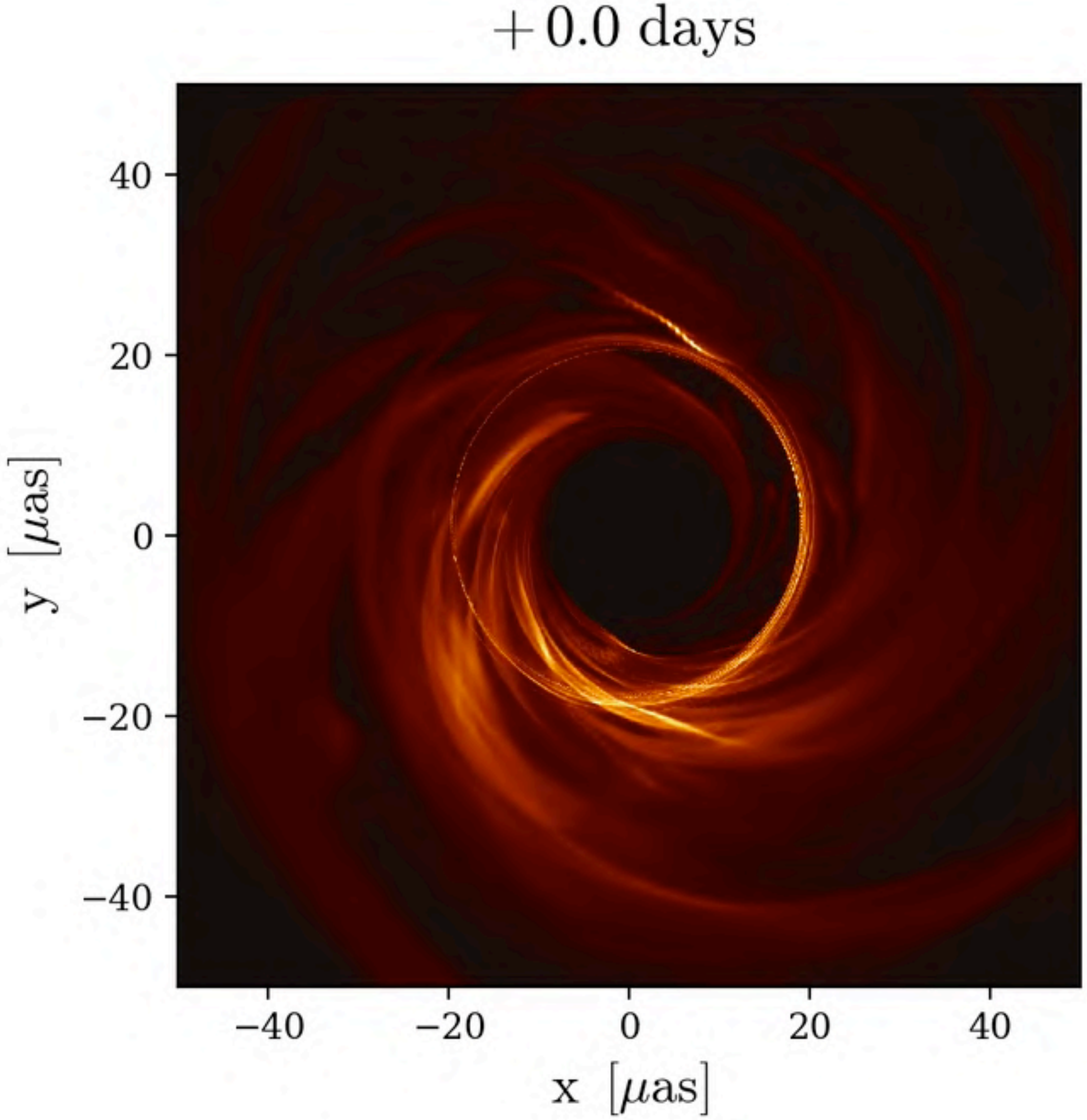
GRRT Image at 230 GHz

- MAD, a=+0.94, R_{high}=160
- i=163 deg
- each frame corresponds to 1M (~0.35 day)



(Paper V)

Event Horizon Telescope


image library
(Paper V)

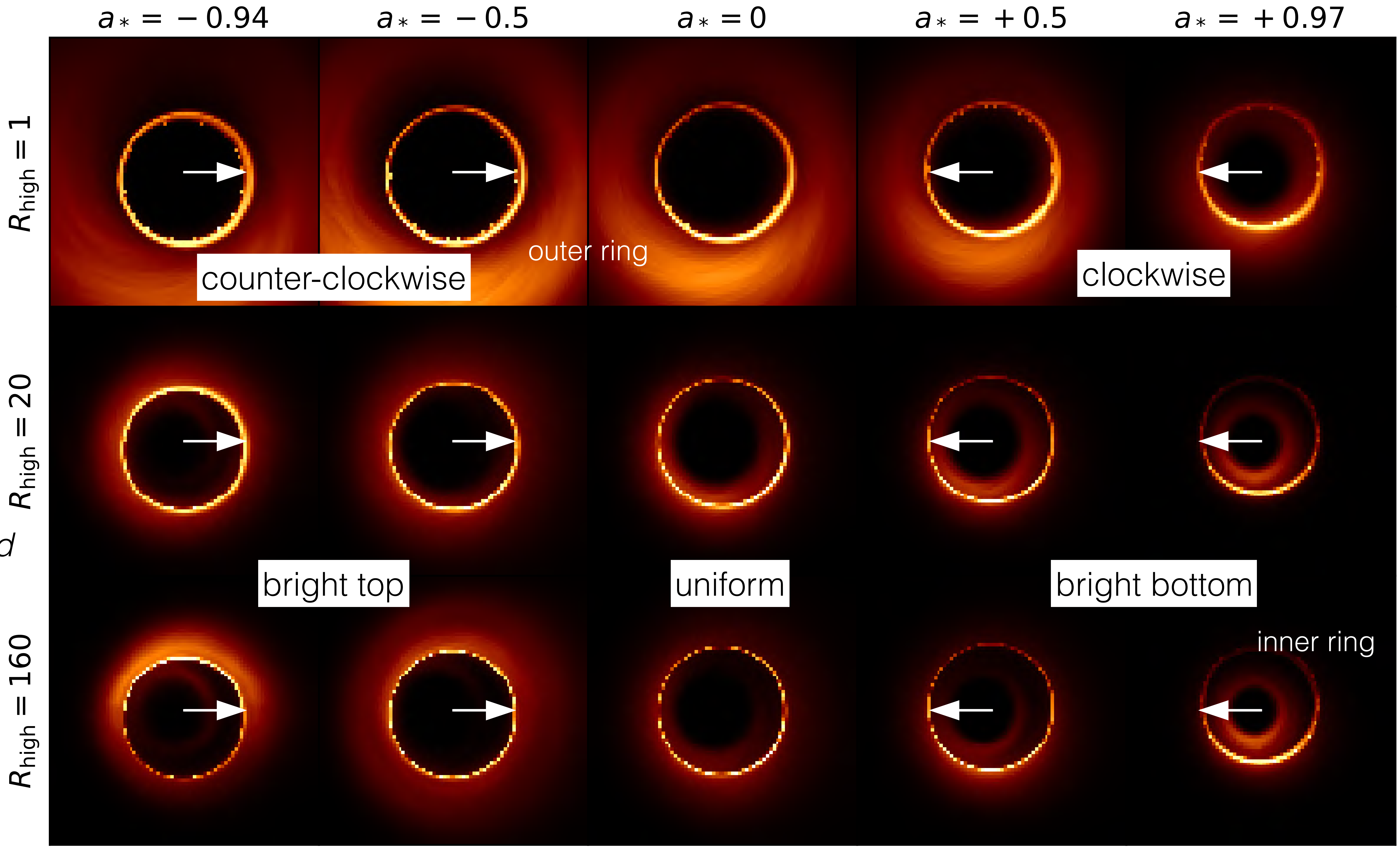
SANE averaged GRRT images

i=163 deg

black hole rotational axis

the forward jet is pointed to the right in all panels

(Paper V)



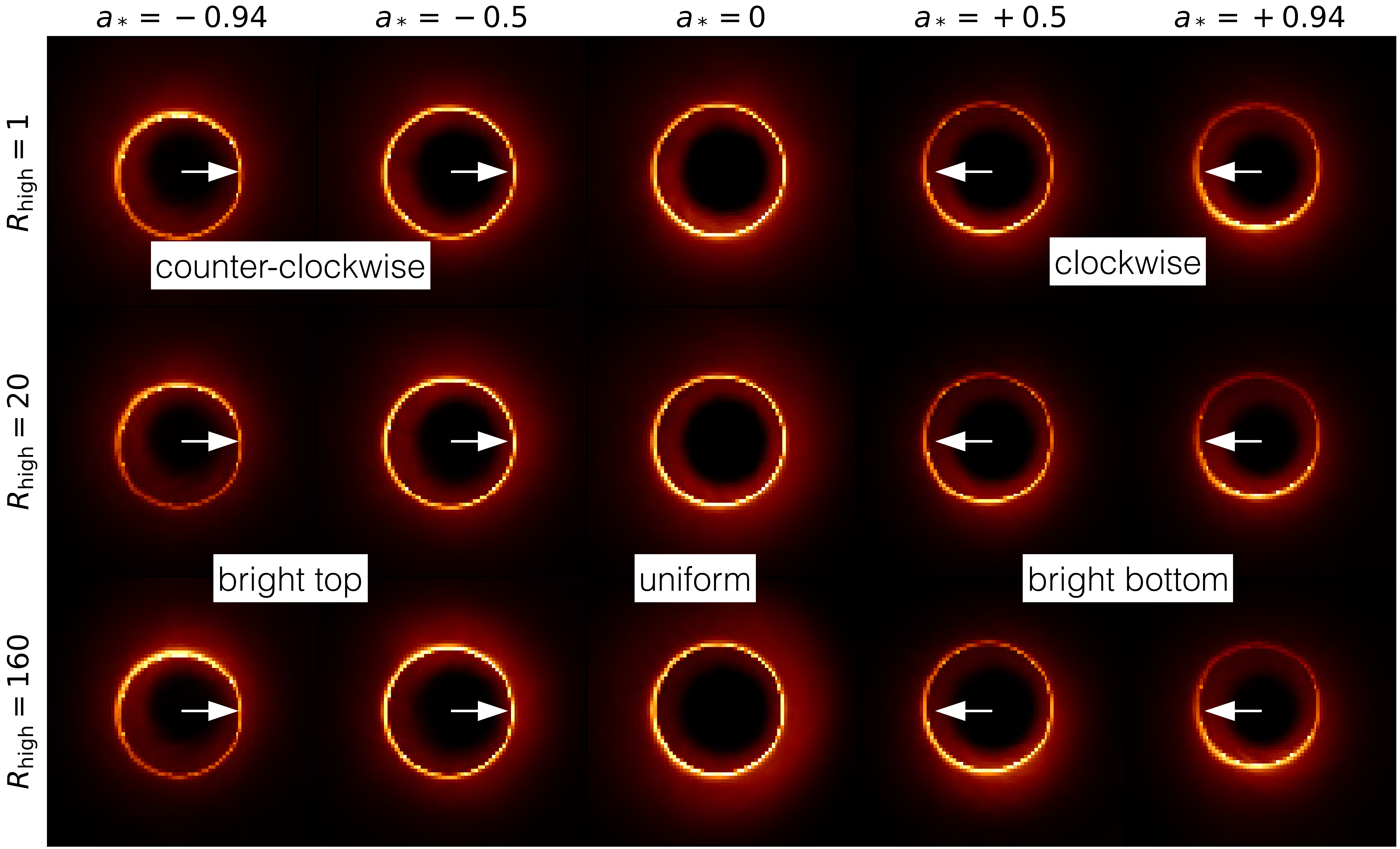
Event Horizon Telesco

MAD averaged GRRT images

i=163 deg

black hole rotational axis

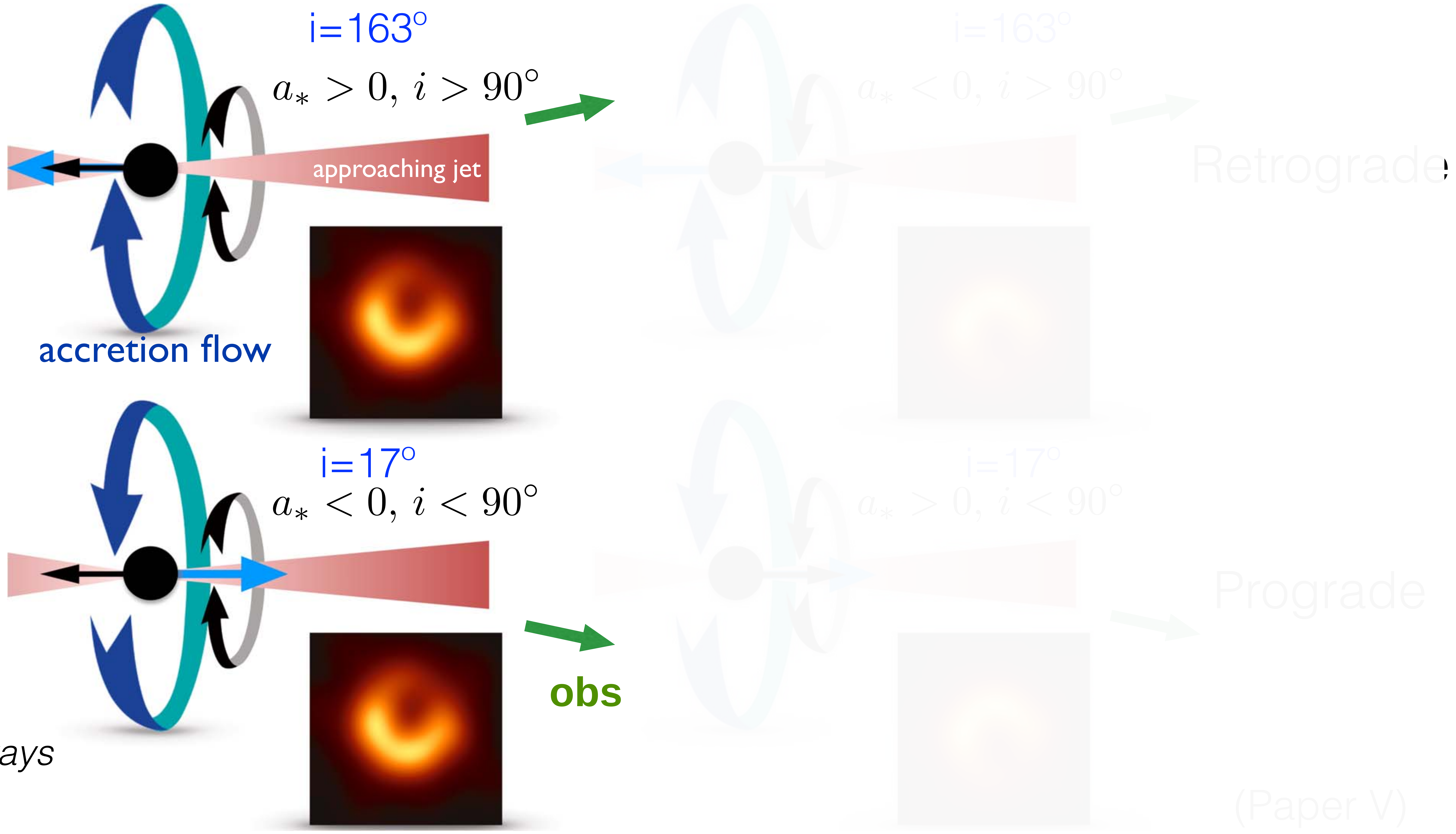
**the forward jet is pointed to the right in all panels*



Event Horizon Telescope

Why is it asymmetric?

Prograde

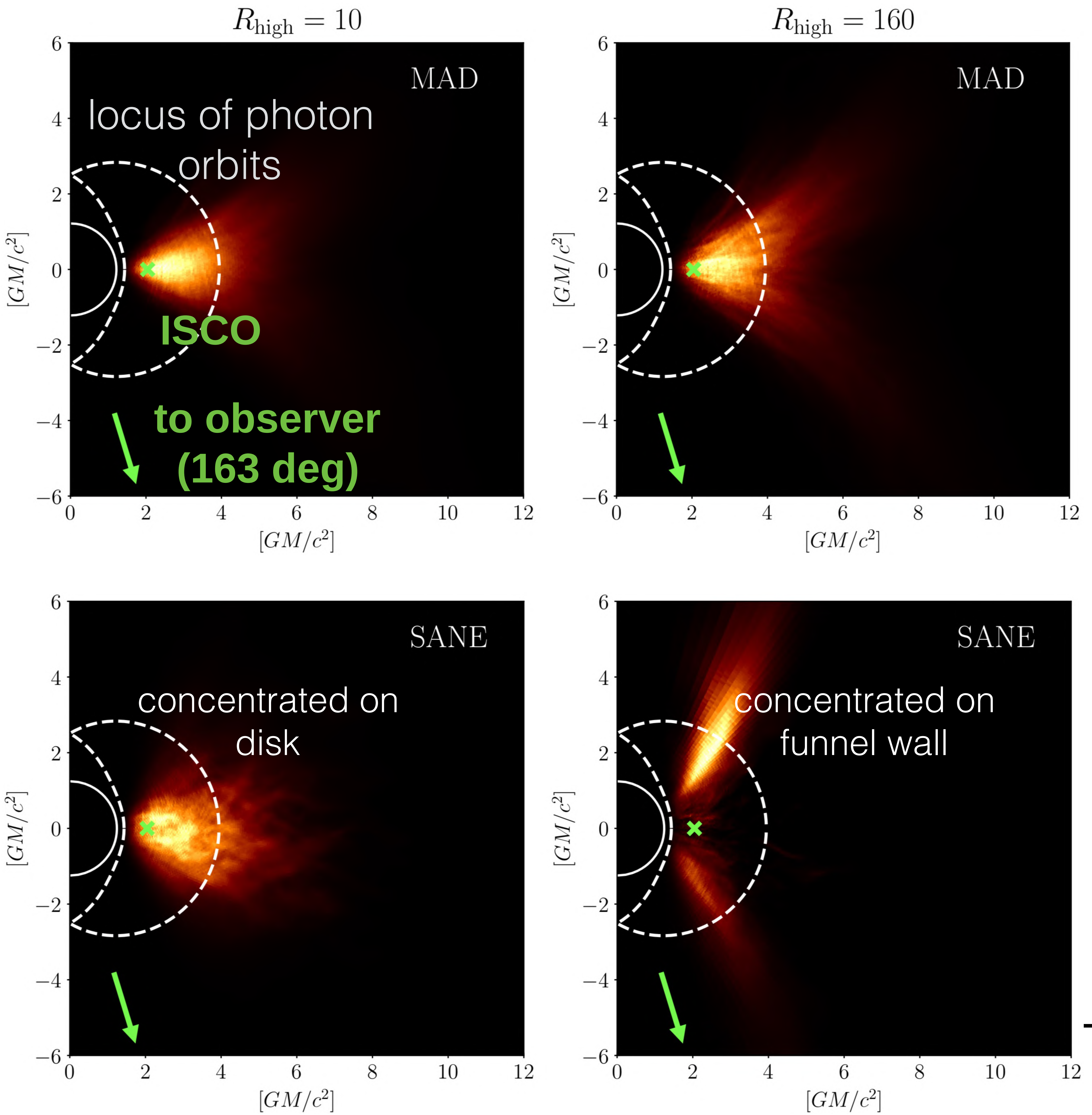


More likely

Retrograde

Emitting plasma is always co-rotated with BH

Where do mm photons originate?



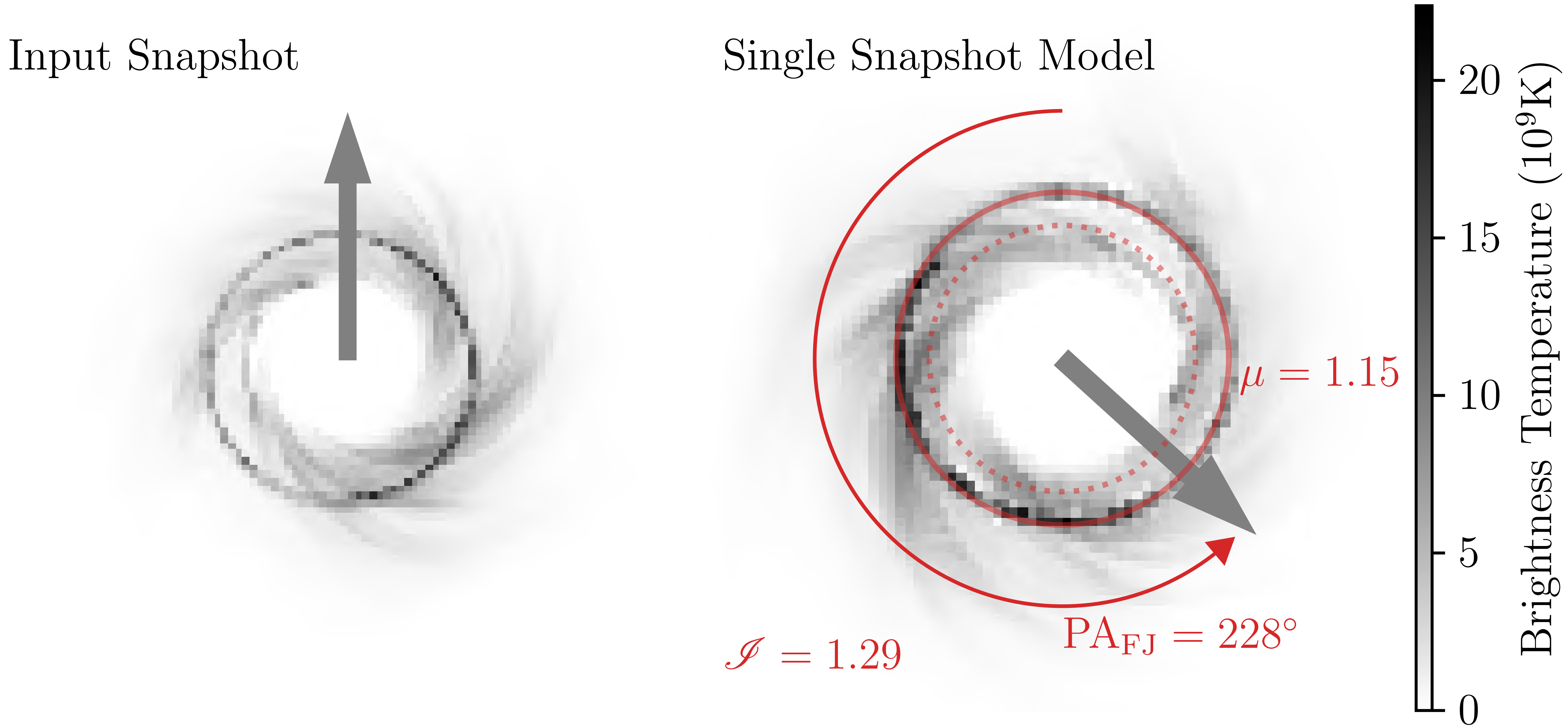
MAD, a=0.94

SANE, a=0.94

Event Horizon Telescope

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)

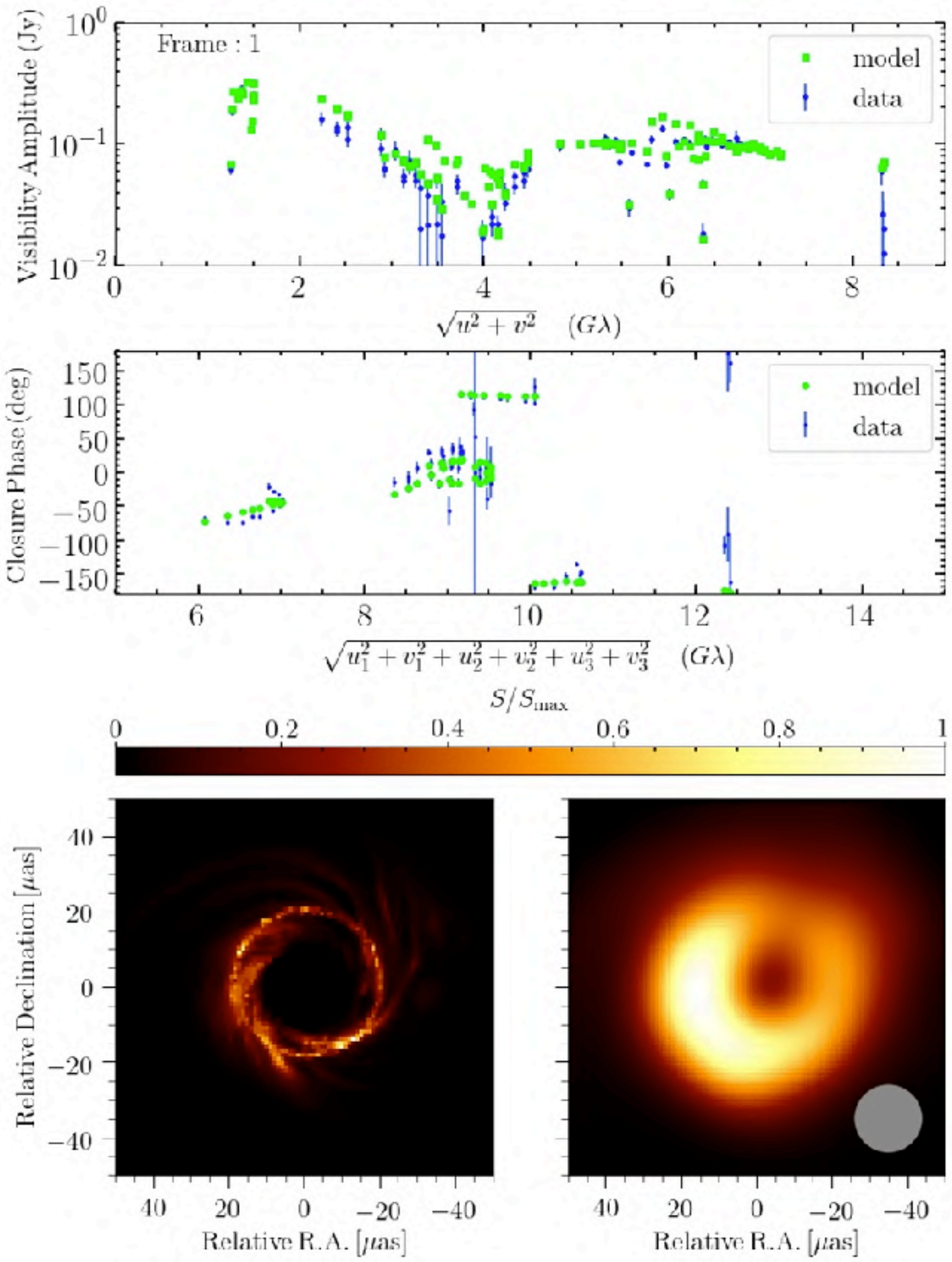
Two independent codes: MCMC (Themis) & evolutionary algorithm (GENA)

Fitting GRRT images to EHT data

visibility amplitude (VA)

Closure phase (CP)

GRMHD image (left) & convolved image (right)



GENA fitting procedure

(a single GRMHD simulation)

(Paper V)

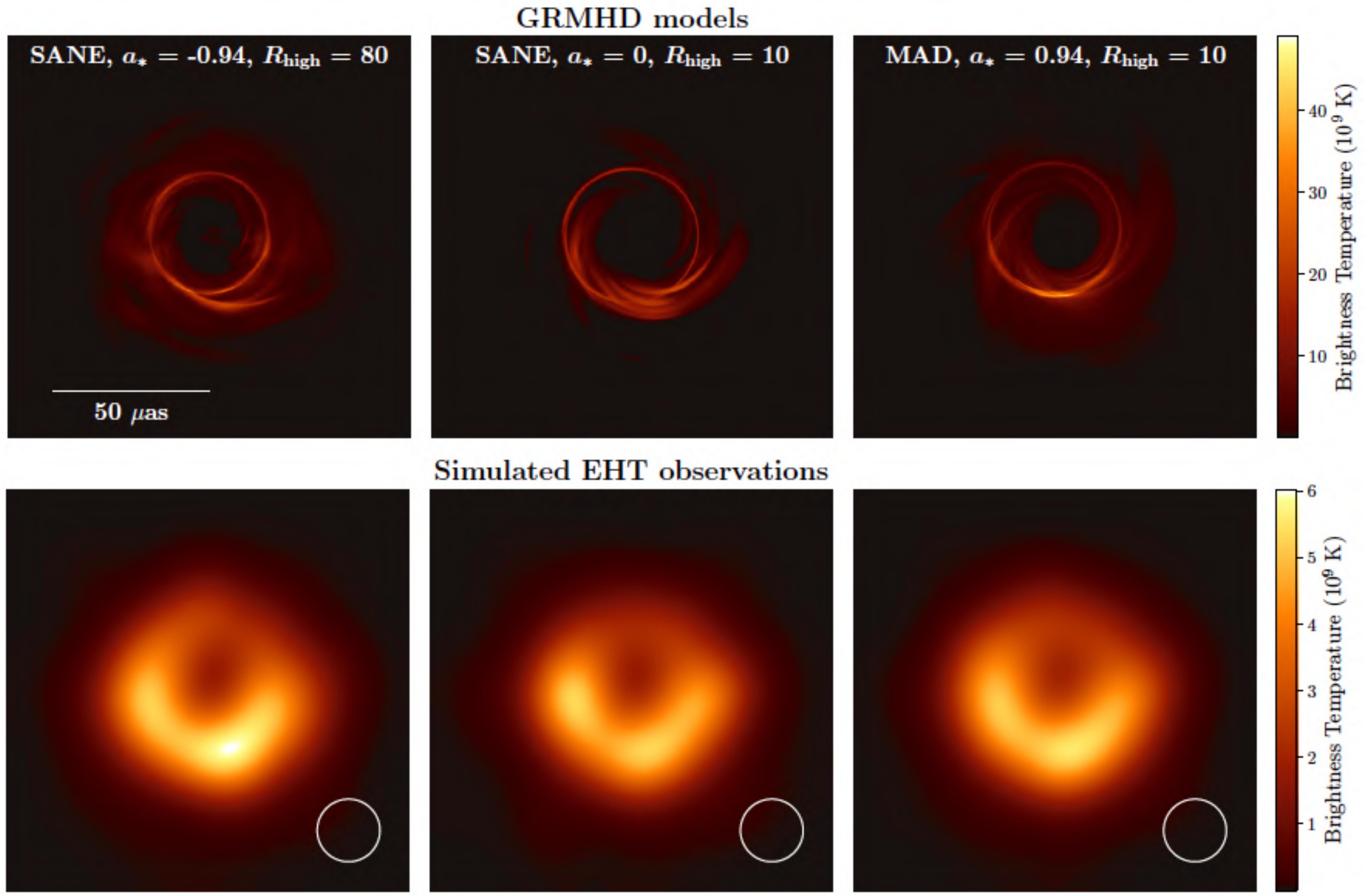
OBSERVATIONS

THEORETICAL MODEL

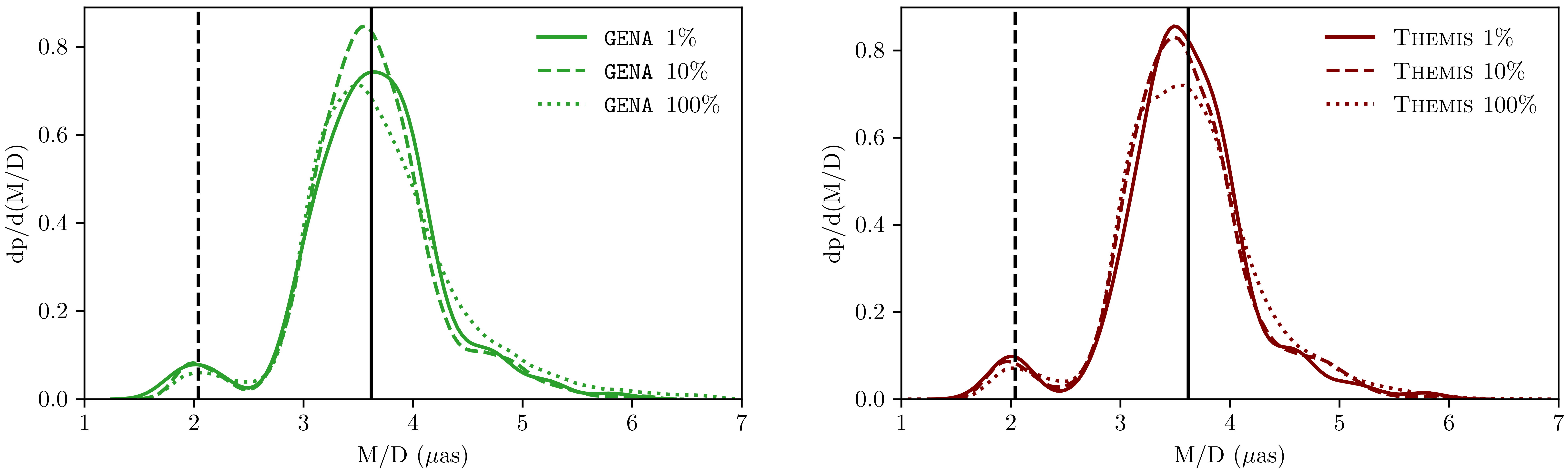
Best Fitting Images

- 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.



Distribution of Best-Fit Black Hole Angular Size

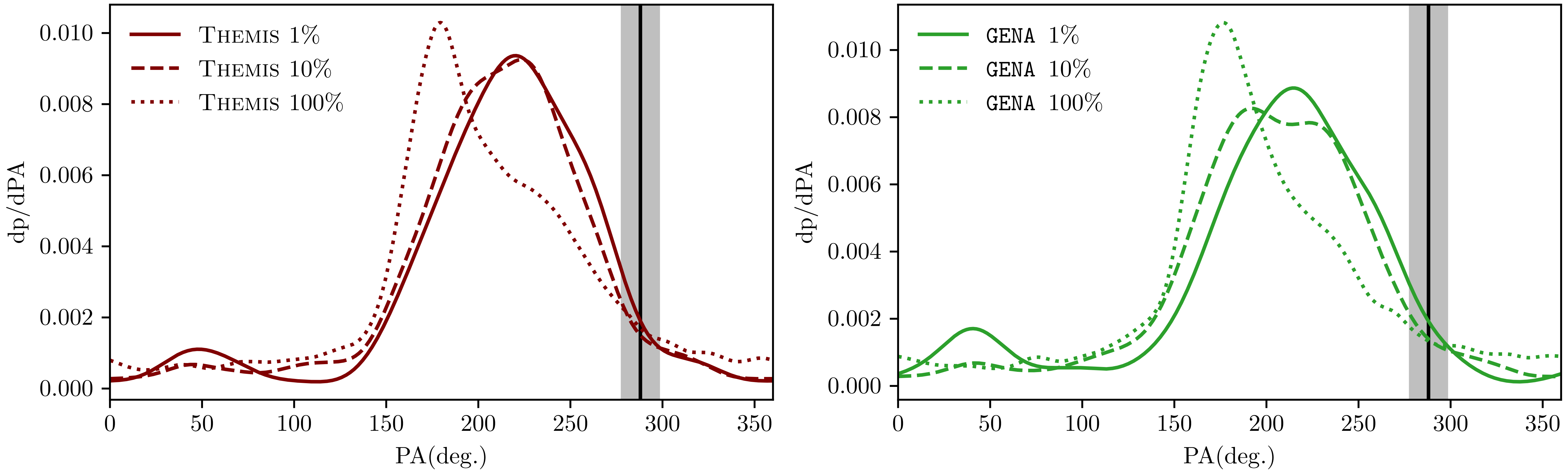


- Distribution of M/D from fitting Image Library snapshots to 2017 April 6th EHT data
- Results by Themis & GENA pipelines are qualitatively similar
- The distribution peaks close to M/D ~ 3.6 μas with a width of ~0.5 μas
- The models are broadly consistent with stellar mass estimate
- $M = 6.5 \times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

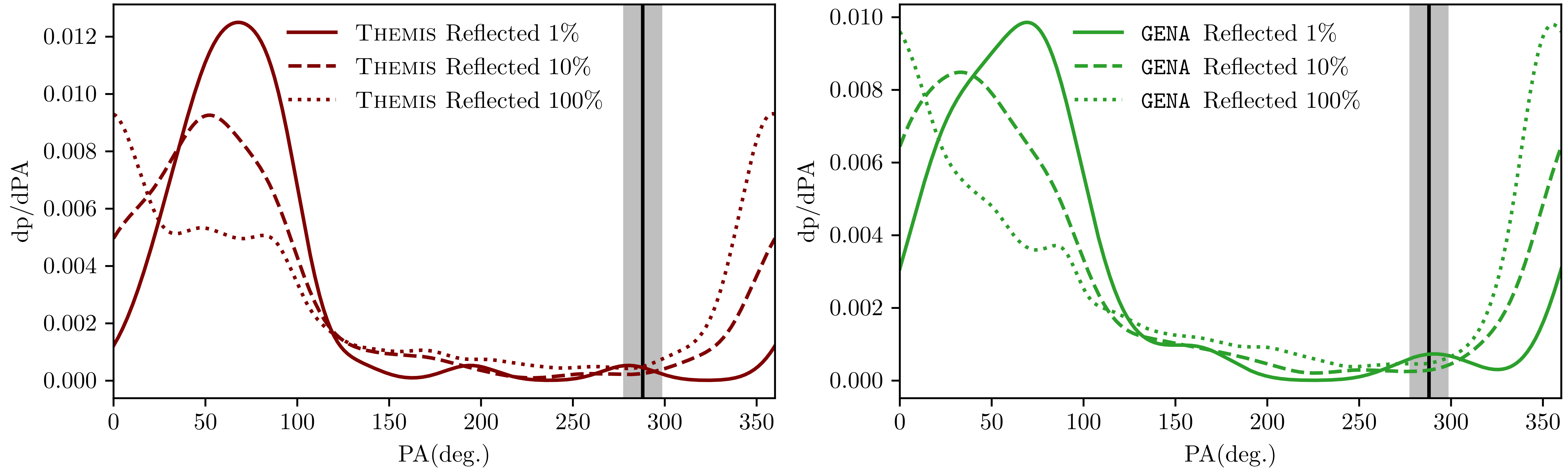
Event Horizon Telescope

Distribution of Model Best-Fit Position Angle

BH spin vector pointing away from Earth



BH spin vector pointing toward Earth



- Large scale jet orientation lies on the shoulder of the spin-away models (⟨PA⟩ ~ 200 deg, σ_{PA} ~ 55 deg)
- Large scale jet orientation lies off the shoulder of the spin-toward models
- BH spin-away models are strongly favored
- Width of distributions arises from brightness fluctuations in the ring

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	+-+-	+-+-	+++-	+++-	++++	++++

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	+—+	+-++	++++	++++	++++	++++

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 realsistic theoretical modeling of shadow image

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.

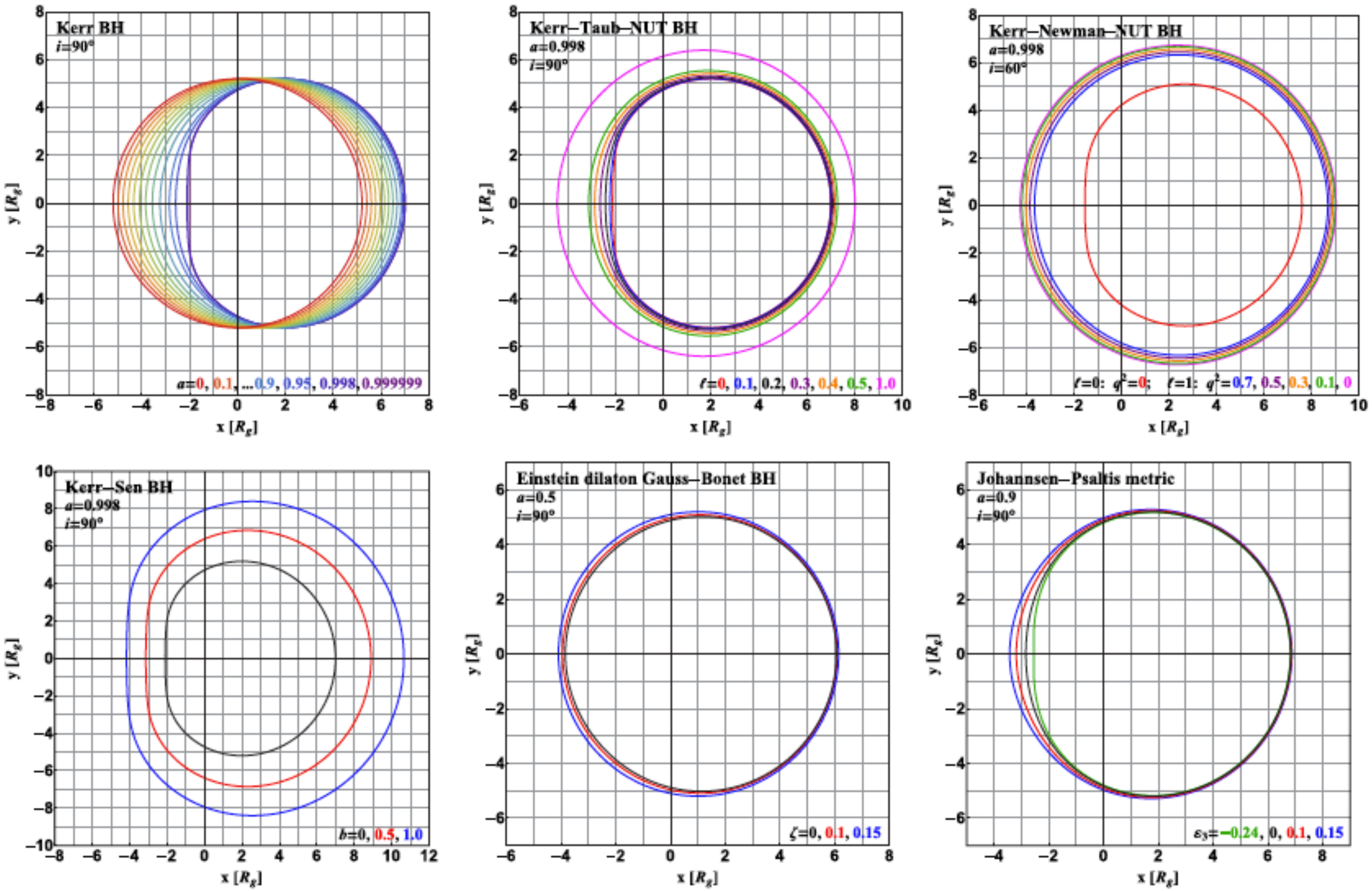
3. black hole “mimickers,” i.e., exotic compact objects (with or without surface), both within GR or in alternative theories
   - w.o. event horizon: e.g., naked singularity, supersupinars, wormhole
   - w.o. event horizon & w.o. surface: e.g., boson star
   - w.o. event horizon & w. surface: Gravastar

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)

Event Horizon Telescope


Stellar Mass: 6.2 x 10⁹ Msun
(Gebhardt et al. 2011)
Gas Mass: 3.5 x 10⁹ Msun
(Walsh et al. 2013)
Black Hole: 4.84-5.2 Rs
Black Hole: 4.84-5.2 Rs
Worm Hole: ~2.7 Rs
(e.g., Bambi 2013)
Naked Singularity: 1 Rs
(superspinar)
(e.g., Bambi & Freese 2009)
6 Billion Solar Mass Black Hole

What we have learned from data and images?

- Einstein's GR has passed another test at a strong gravitational field

- The strongest evidence for the presence of black holes

- AGN and jets are powered by super massive black hole

- The M87 Black hole is likely spinning (from GRMHD fits + constraints)

- The stellar dynamical mass is correct (6.5 billion masses)

- Testing BH alternatives are important topic for next EHT

Testing BH Alternatives

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

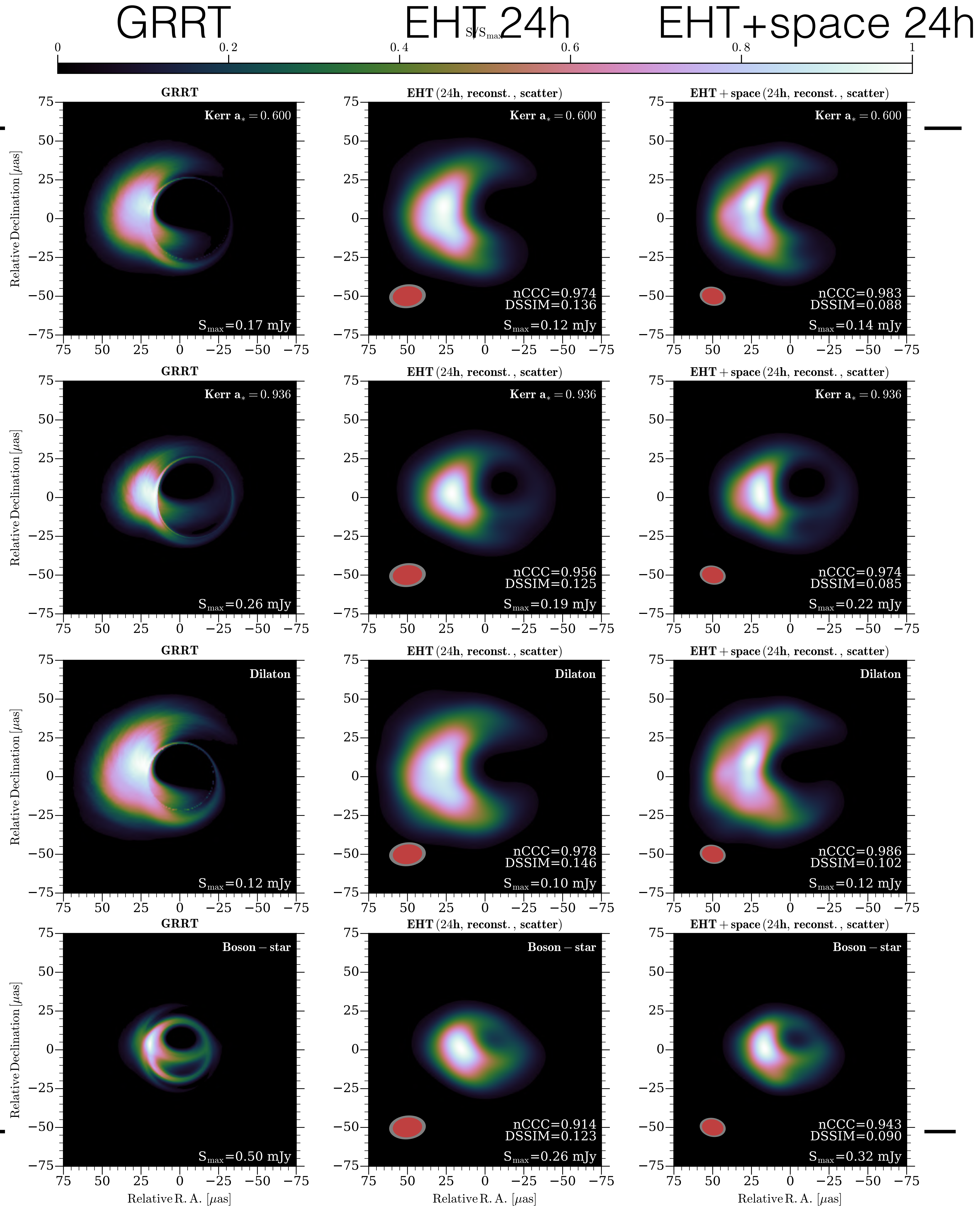
- Dilaton BH (alternative theories of gravity), Mizuno et al. (2018)
- Boson Star (w.o. event horizon & surface), Olivares et al. (2019)
- Gravastar (w.o. event horizon, w. surface), Olivares et al. (2019 in prep)

Kerr BH (a=0.6)

Kerr BH (a=0.9375)

Dilation BH (b=0.5)

Boson star



Considered Future EHT array (including 345GHz & space-VLBI)

(Fromm et al. 2019 in prep.)

Event Horizon Telescope

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

Testing BH Alternatives

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

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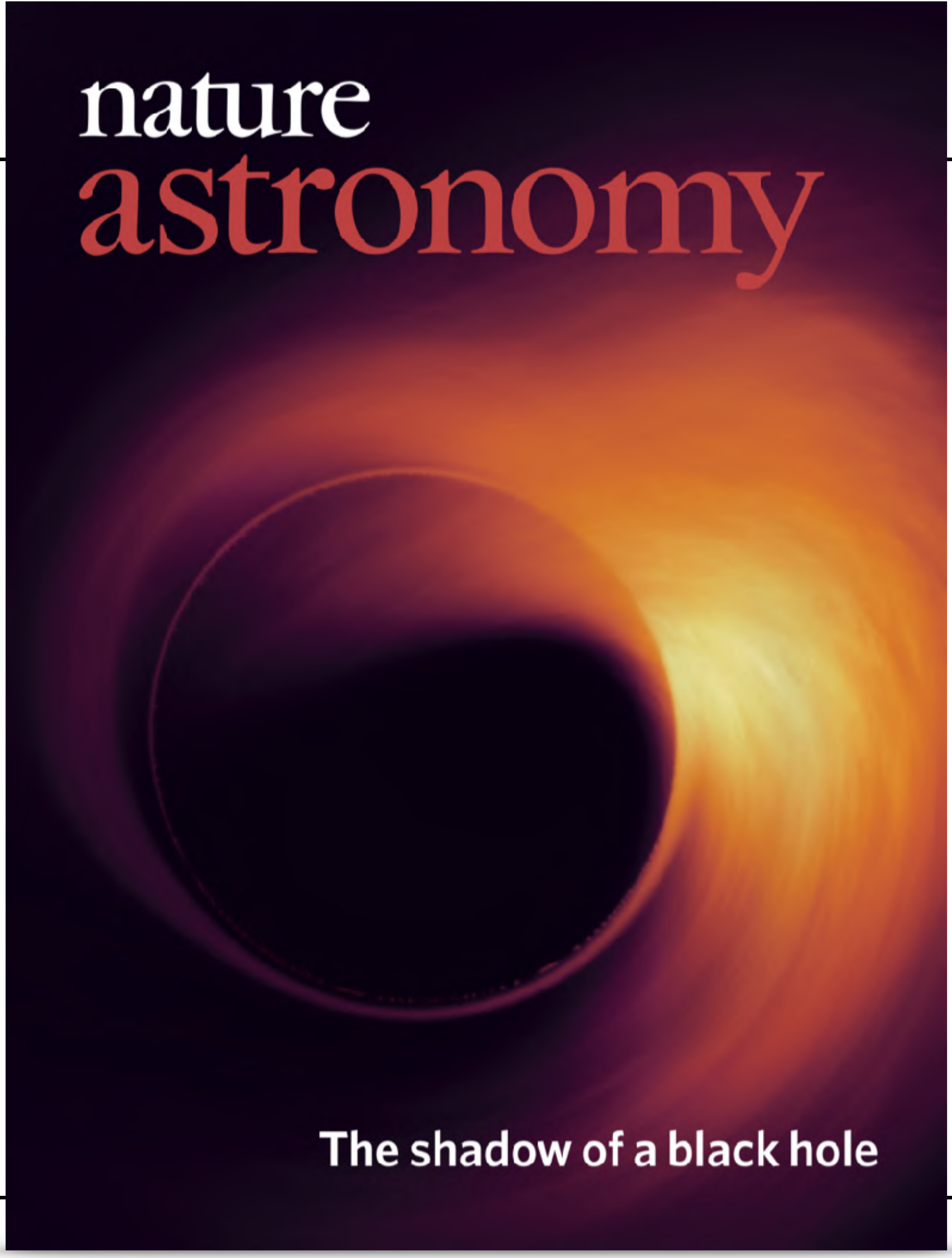

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Weather forecast

(Chael et al. 2019)

(RML Reconstruction with SMILI)

EHT Collaboration, ALMA Cycle 7 M87 Proposal

Concluding Remarks

Dr. Elisabeth Mills
@astronomills

Following

I still love you, Sgr A* #EHTBlackHole

Event Ho

NO, NO, Sgr A*, WE STILL LOVE YOU, TOO

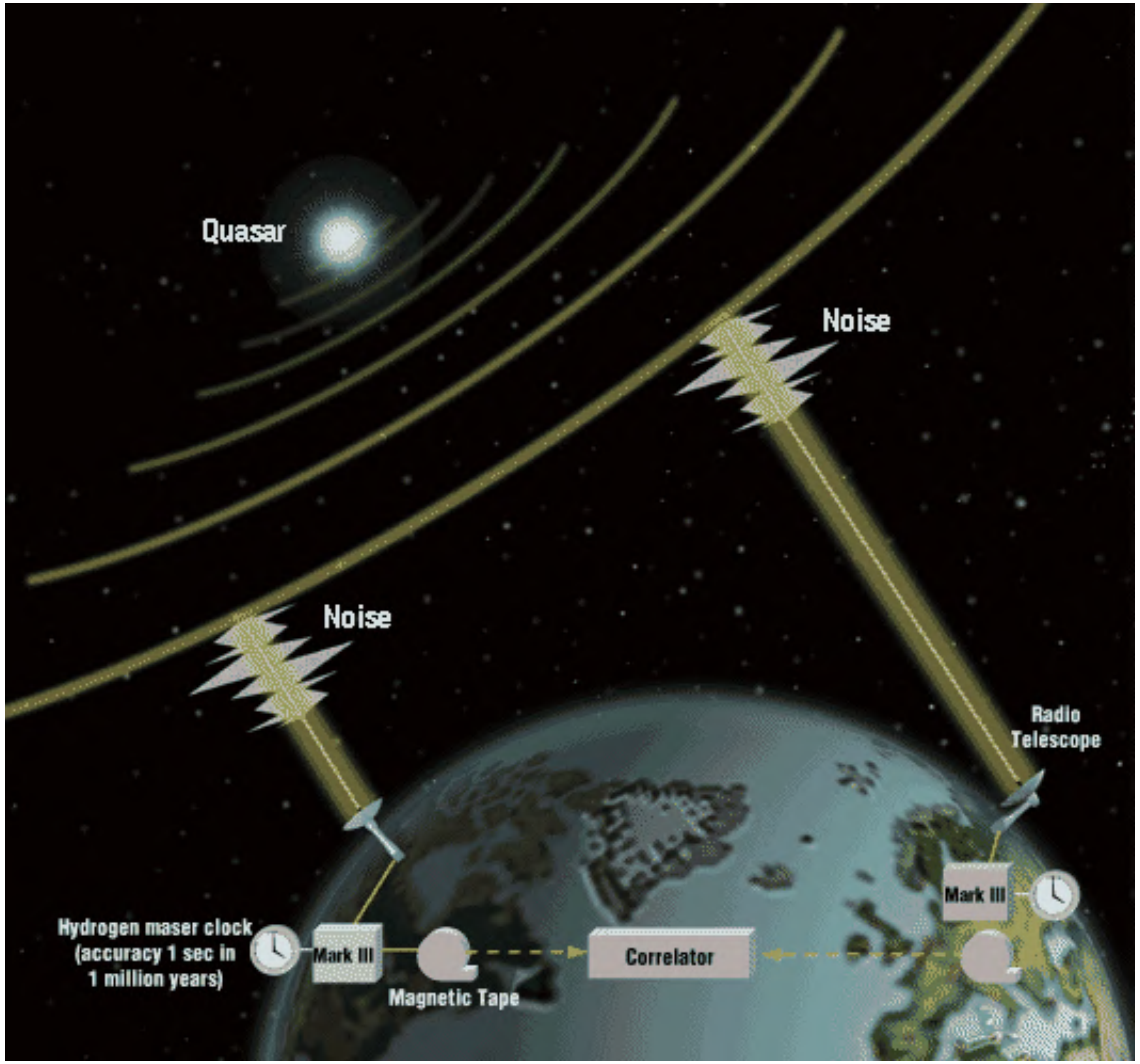
Thank you for listening

2018 EHT collaboration meeting

Back Up Slide

EHT related slide

Short wavelength VLBI



Angular Resolution:

λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

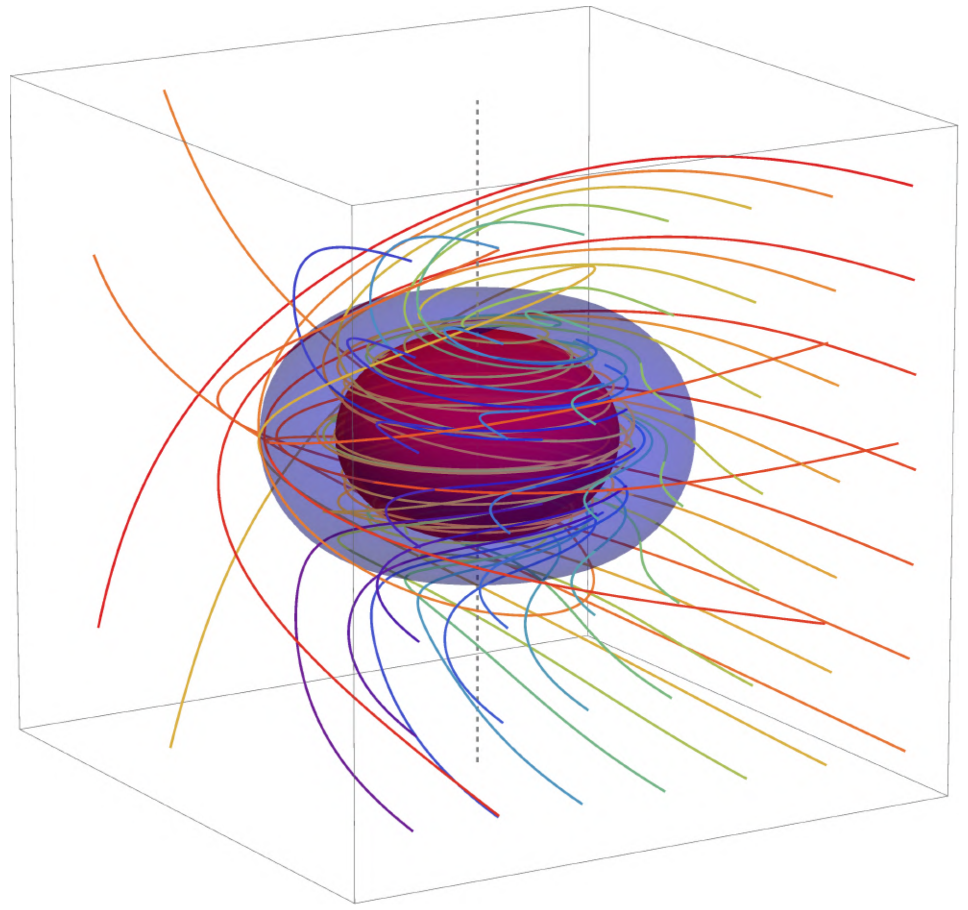
ISM scatter (Sgr A*):

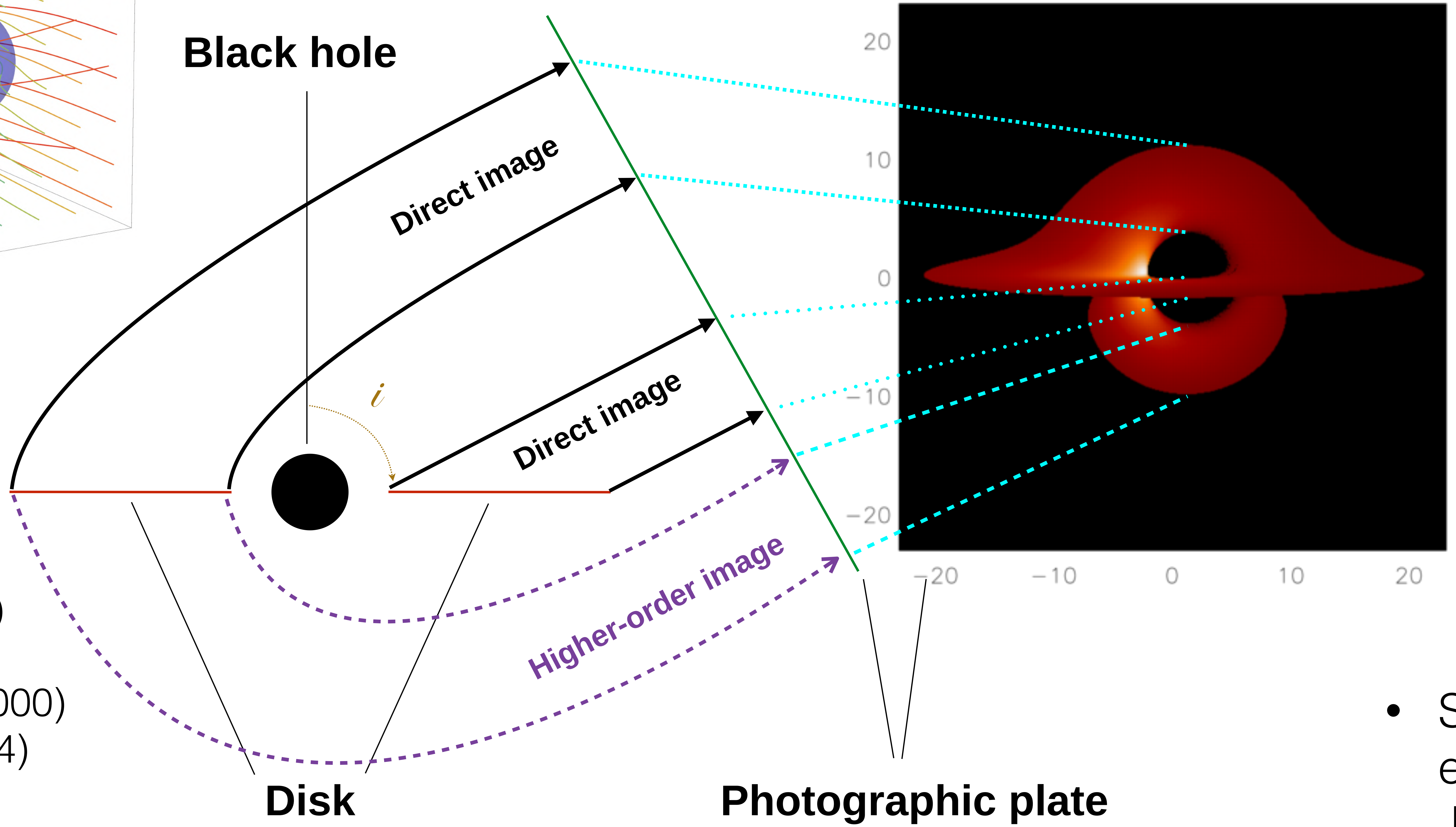
$\Theta_{scat} \sim \lambda^2$

BH Shadow size:

Sgr A*: 50 μas
M87: 40 μas

Strong GR: Black Hole Shadow





Shadow diameter:

Non-spinning (a=0)
$D_{sh} \sim 5.2 * R_{sch}$

Spinning (a=1)
$D_{sh} \sim 4.8 * R_{sch}$

- Shadow size and shape encodes GR (e.g., Johannsen & Psaltis 2010)

Bardeen (1973)
Luminet (1979)
Falcke et al. (2000)
Takahashi (2004)
etc.

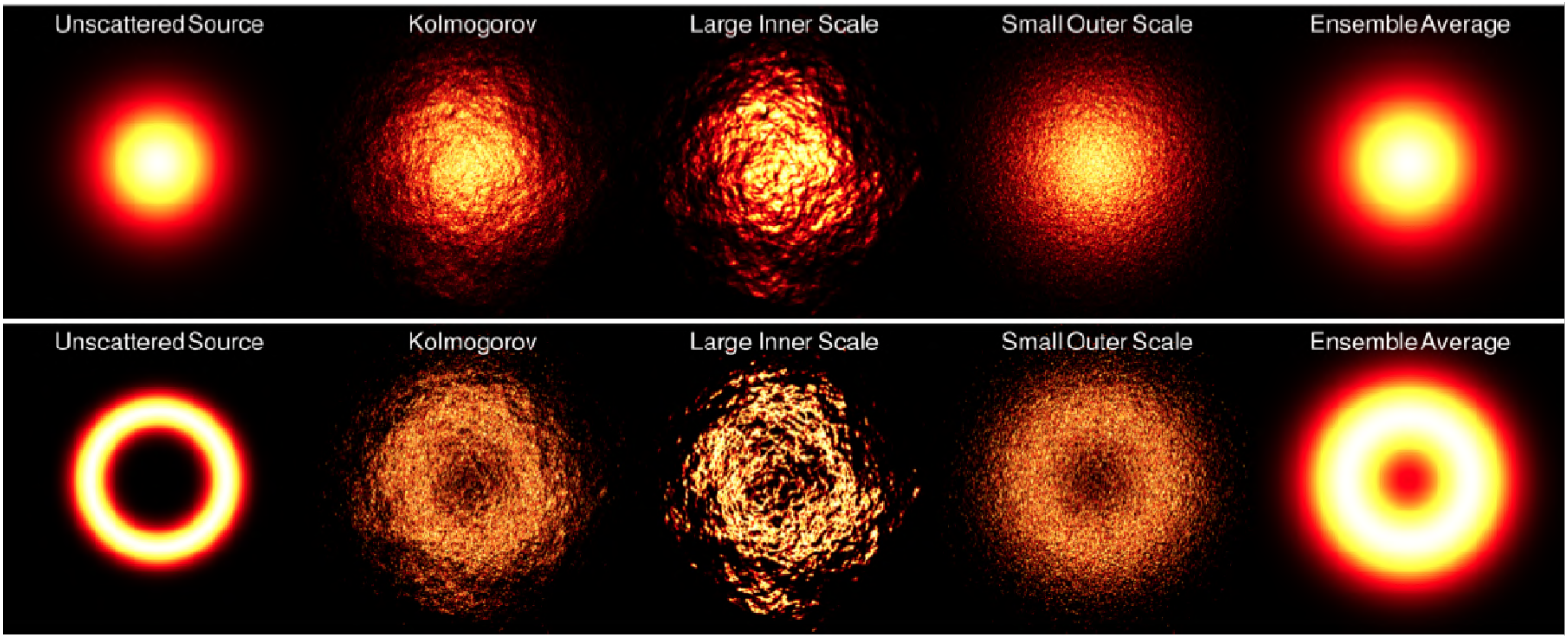
Event Horizon Telescope

Shadow of Black Hole

Sgr A* vs M87

	M87	Sgr A*
Mass (M_{sun})	3-6 x 10^9 (?)	4 x 10^6
Distance	16 Mpc	8.5 kpc
Luminosity	10^{44} erg/s	10^{36} erg/s
Mdot (M_{edd})	10^{-4}	10^{-8}
BH Spin Axis	Gal disk?	10-25 deg los
@ the BH?	Maybe	Yes
B field @ BH	60-130 G	10-100 G
Scattered?	No	yes
Shadow Size	640 AU	0.5 AU
Shadow Angle	20-40 μas	52 μas
GM/c3	8 hrs	20 sec
ISCO Period	4-54 days	4-54 min
Jet Power	10^{42}-10^{43} erg/s	?

Better Modeling of ISM Scatter



Johnson & Gwinn (2015)

From Sky Brightness to Visibility

1. An Interferometer measures the interference pattern produced by two apertures.
2. The interference pattern is directly related to the source brightness. In particular, for small fields of view the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

(van Cittert-Zernike theorem)

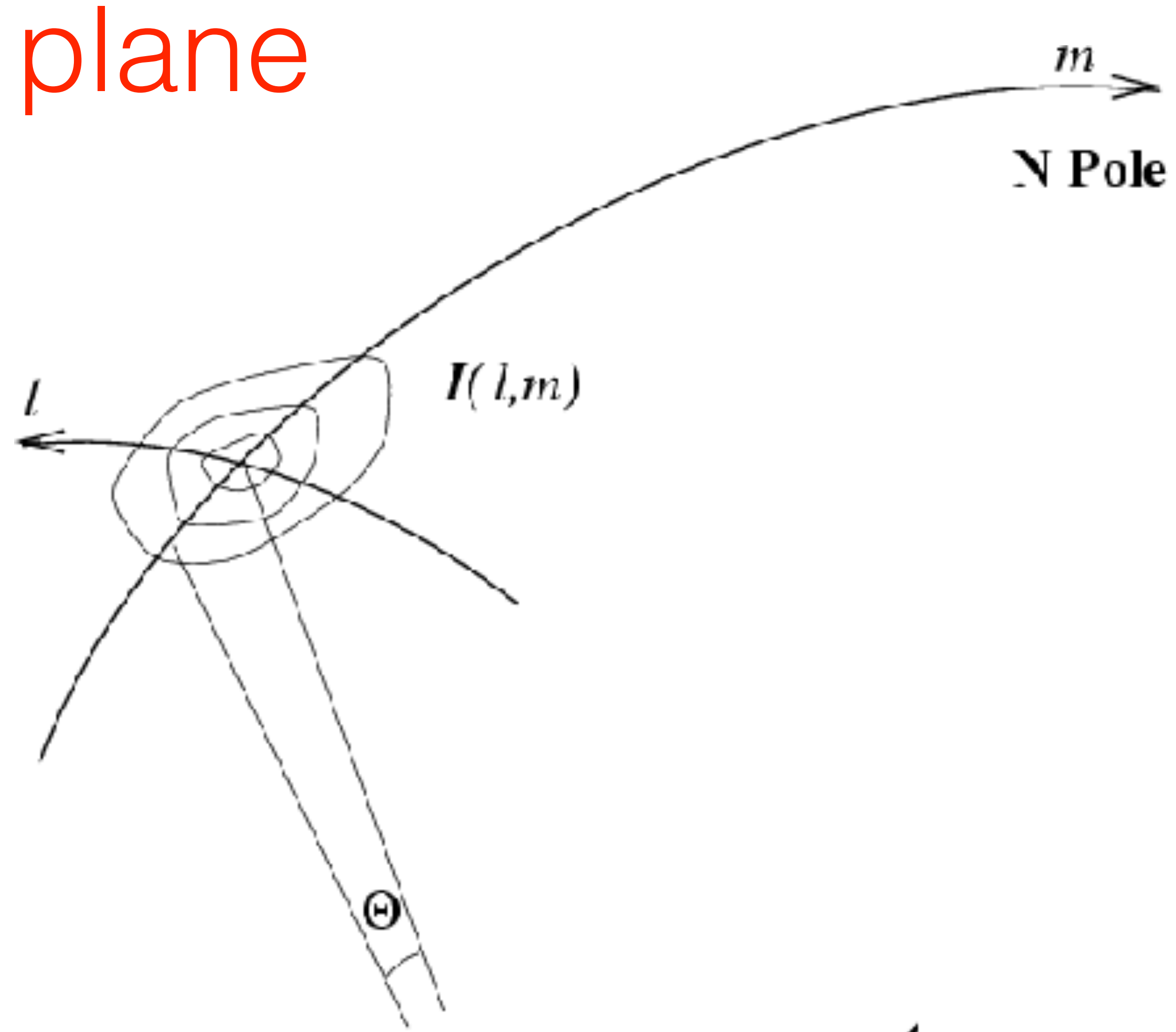
Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dx dy$$

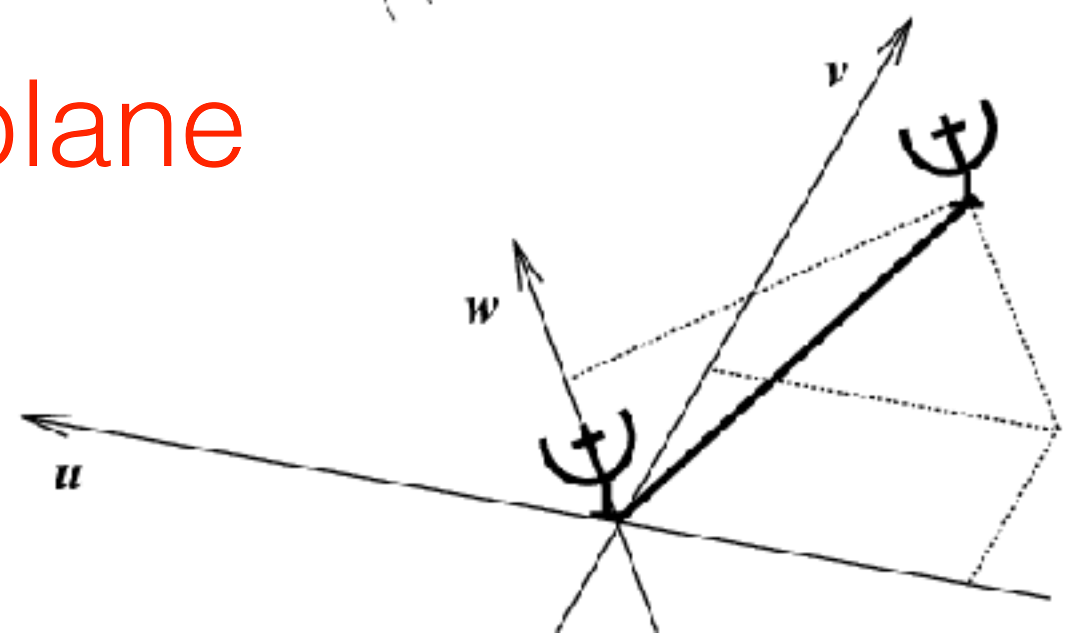
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

Image space/domain

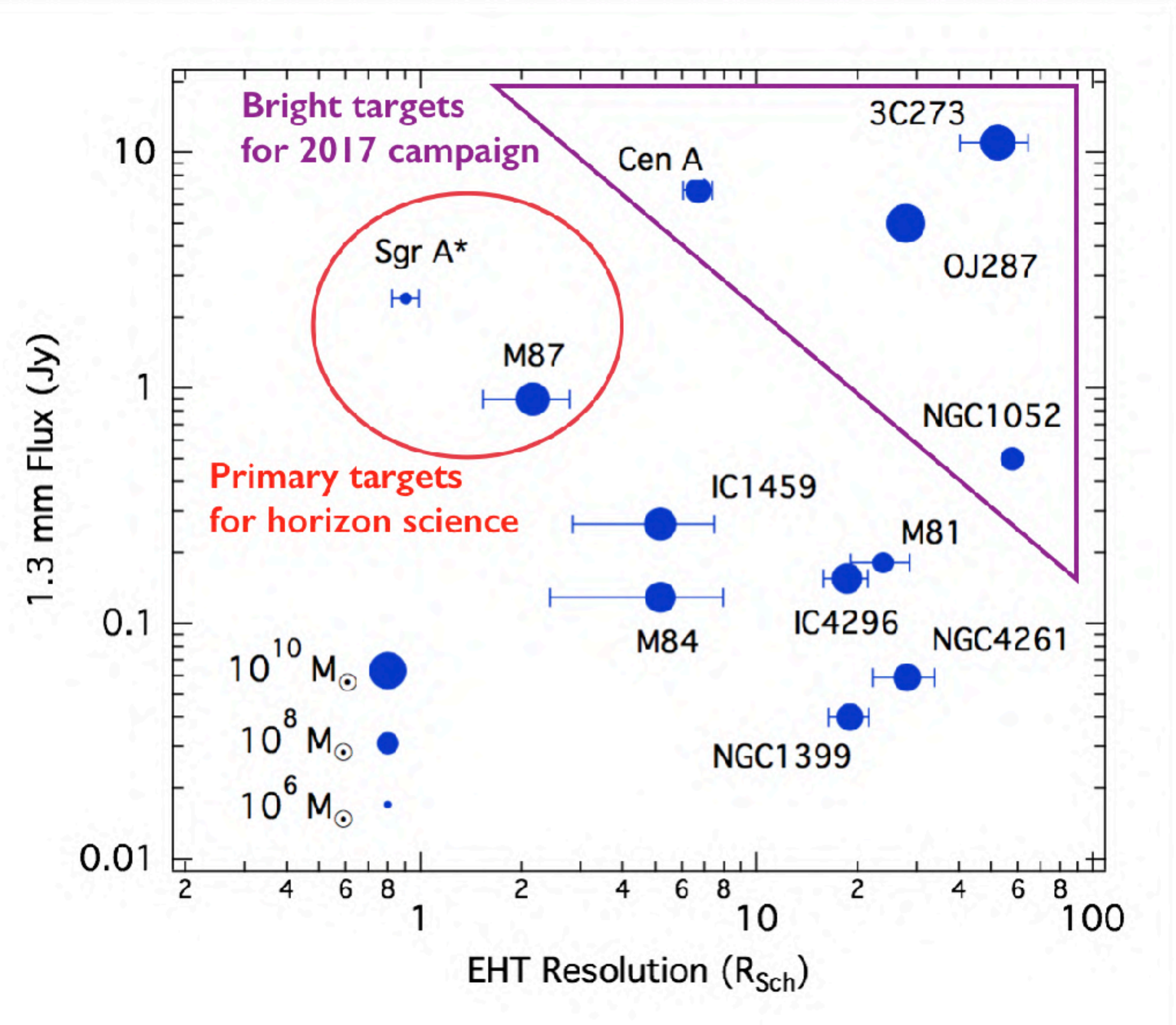
Image plane



UV plane



Primary Target for EHT

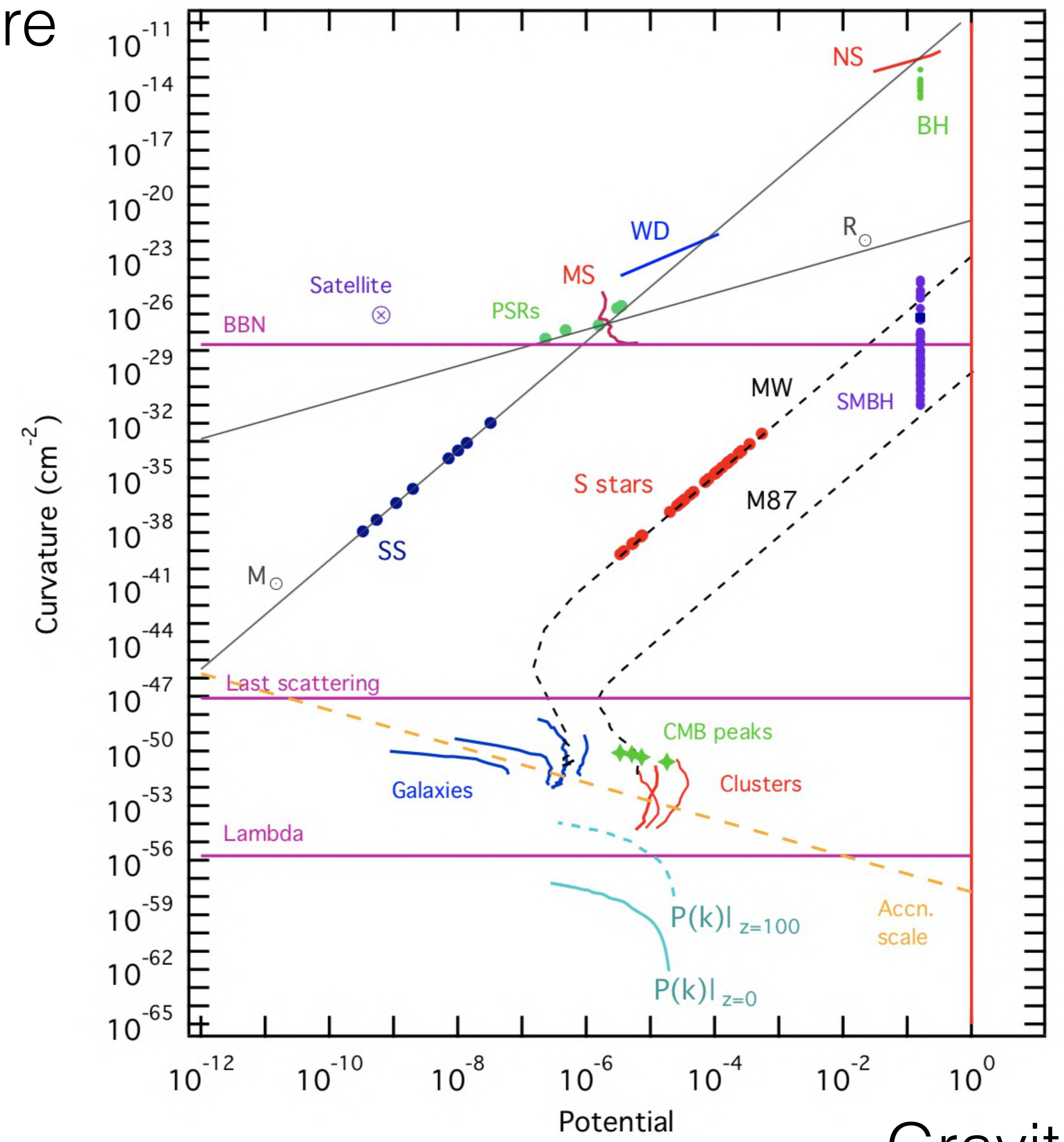


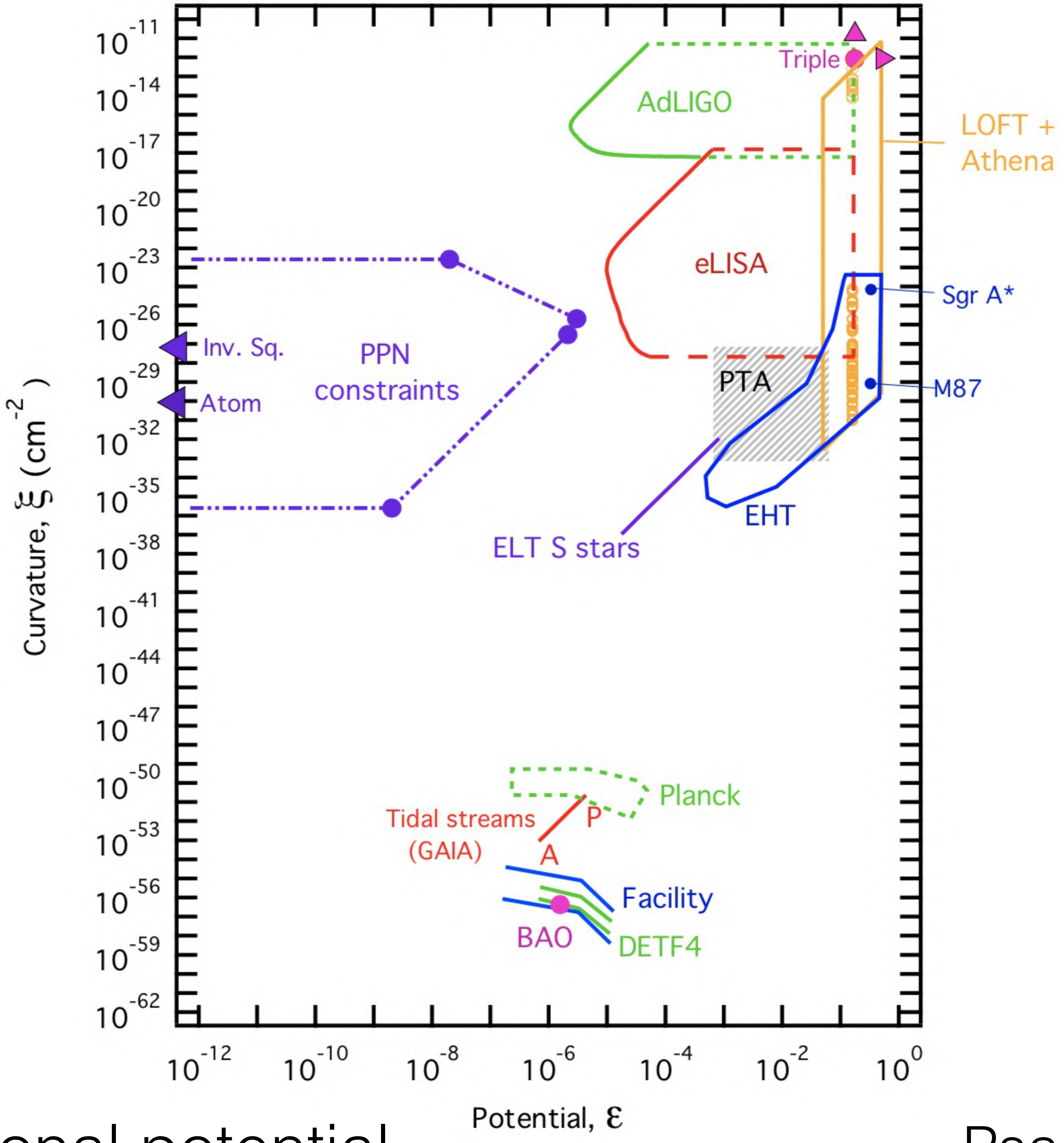
Psaltis (2018)

Event Horizon Telescope

Testing Theory of Gravity (experiments)

Curvature





Gravitational potential

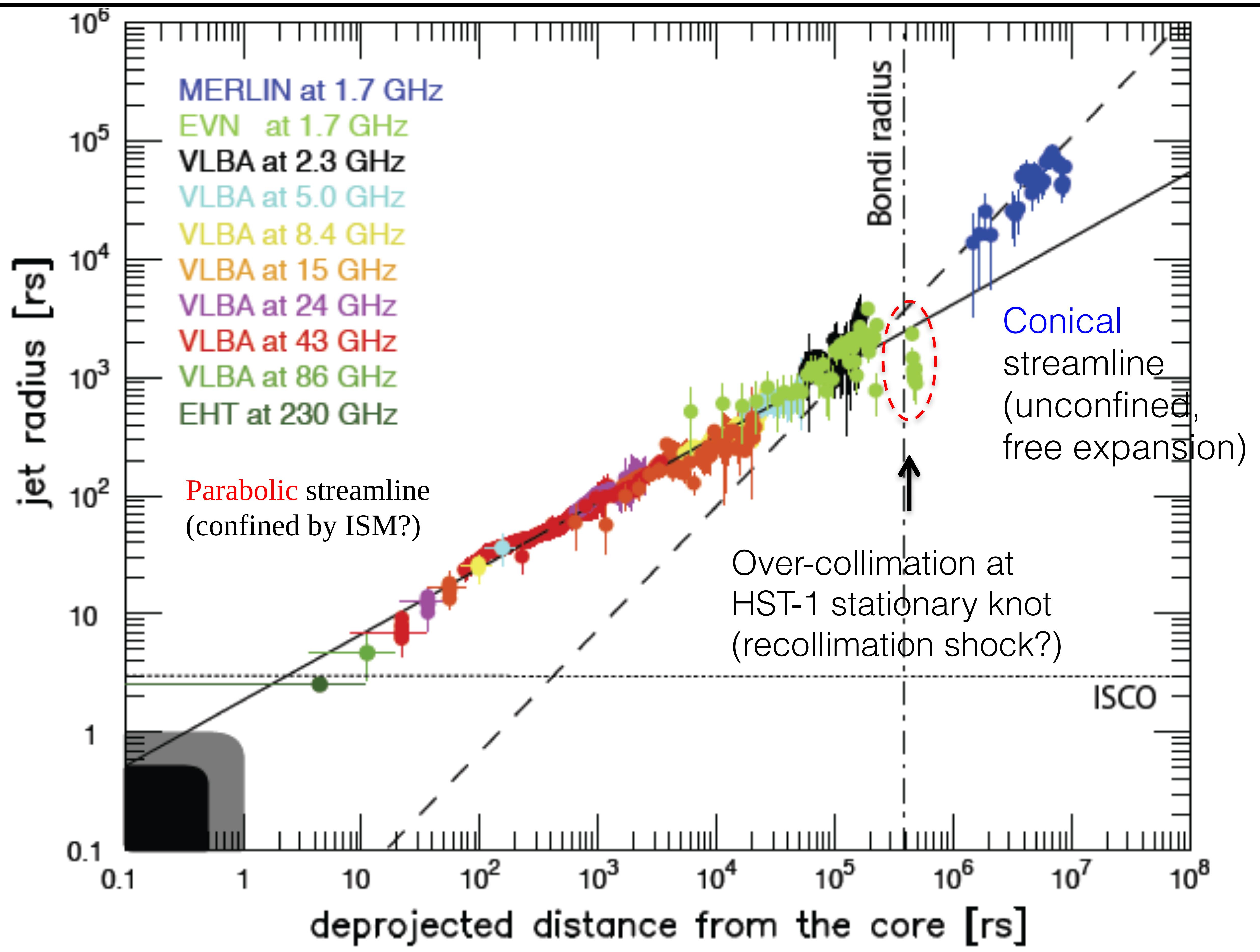
Psaltis (2018)

Event Horizon Telescope

M87

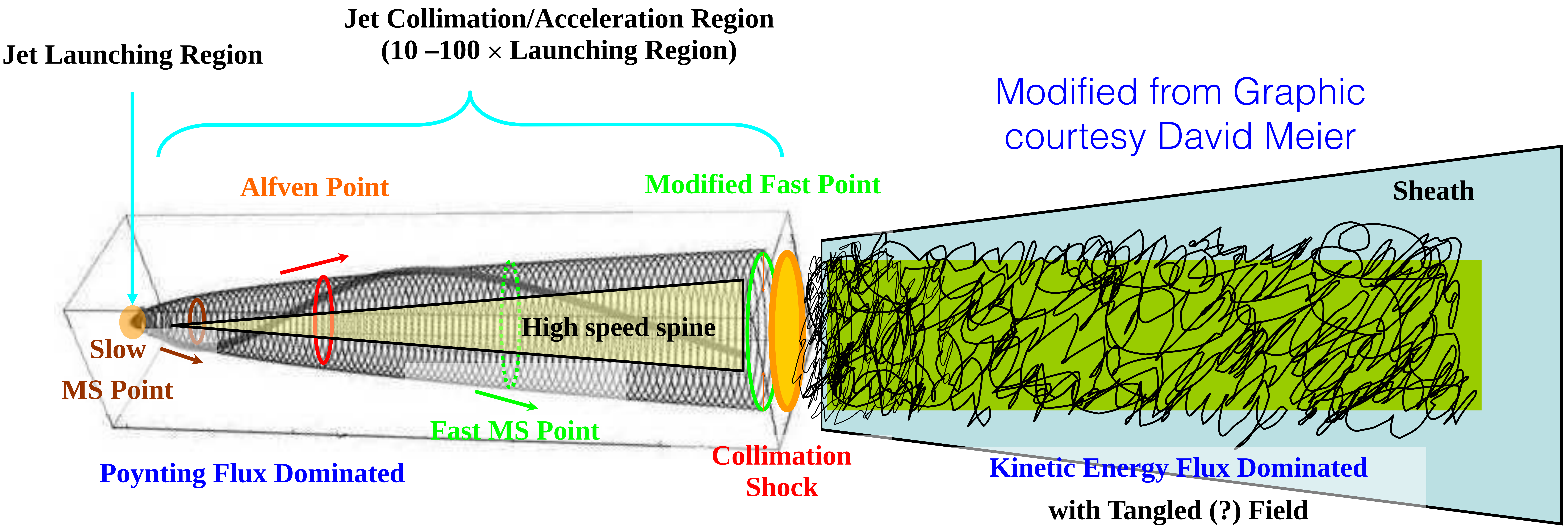
Global Structure of M87

- The parabolic structure ($z \propto r^{1.7}$) maintains over 10^5 r_s, external confinement is worked.
- The transition of streamlines presumably occurs beyond the gravitational influence of the SMBH (= Bondi radius)
- In far region, jet stream line is conical ($z \propto r$)
- Stationary feature HST-1 is a consequence of the jet recollimation due to the pressure imbalance at the transition



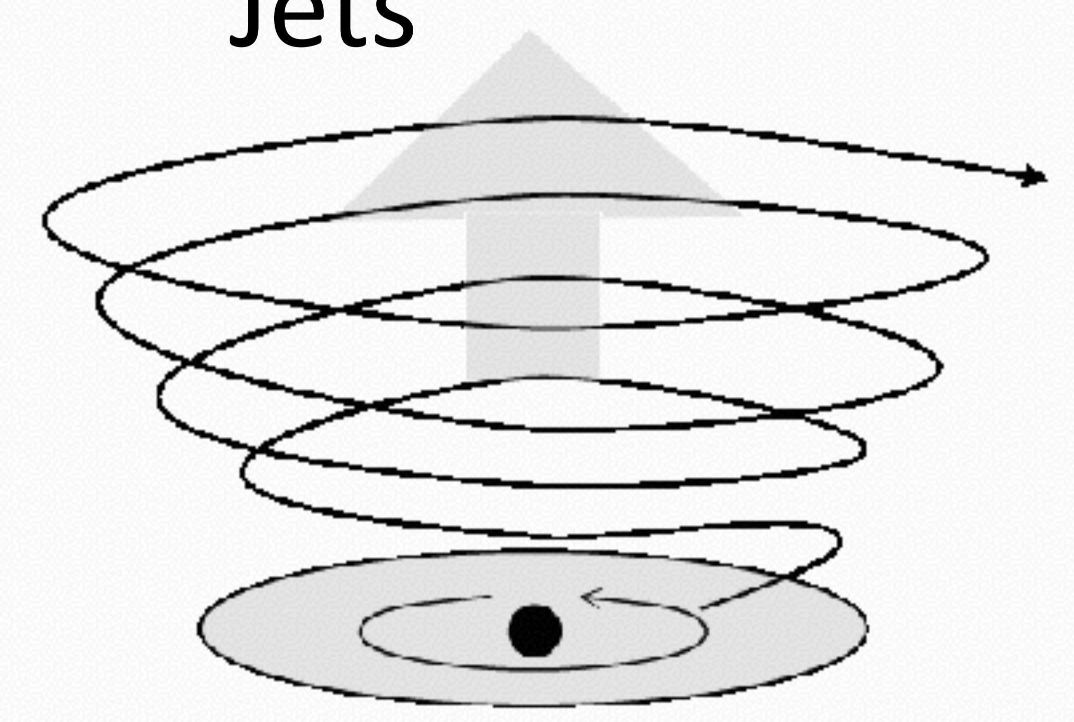
Asada & Nakamura (2012), Hada et al. (2013)

Regions of AGN Jet Propagation



- Jet launching by MHD process ⇒ Poynting flux dominated jet with twisted magnetic field
- Need rapid magnetic energy dissipation to make a kinetic energy dominated jet

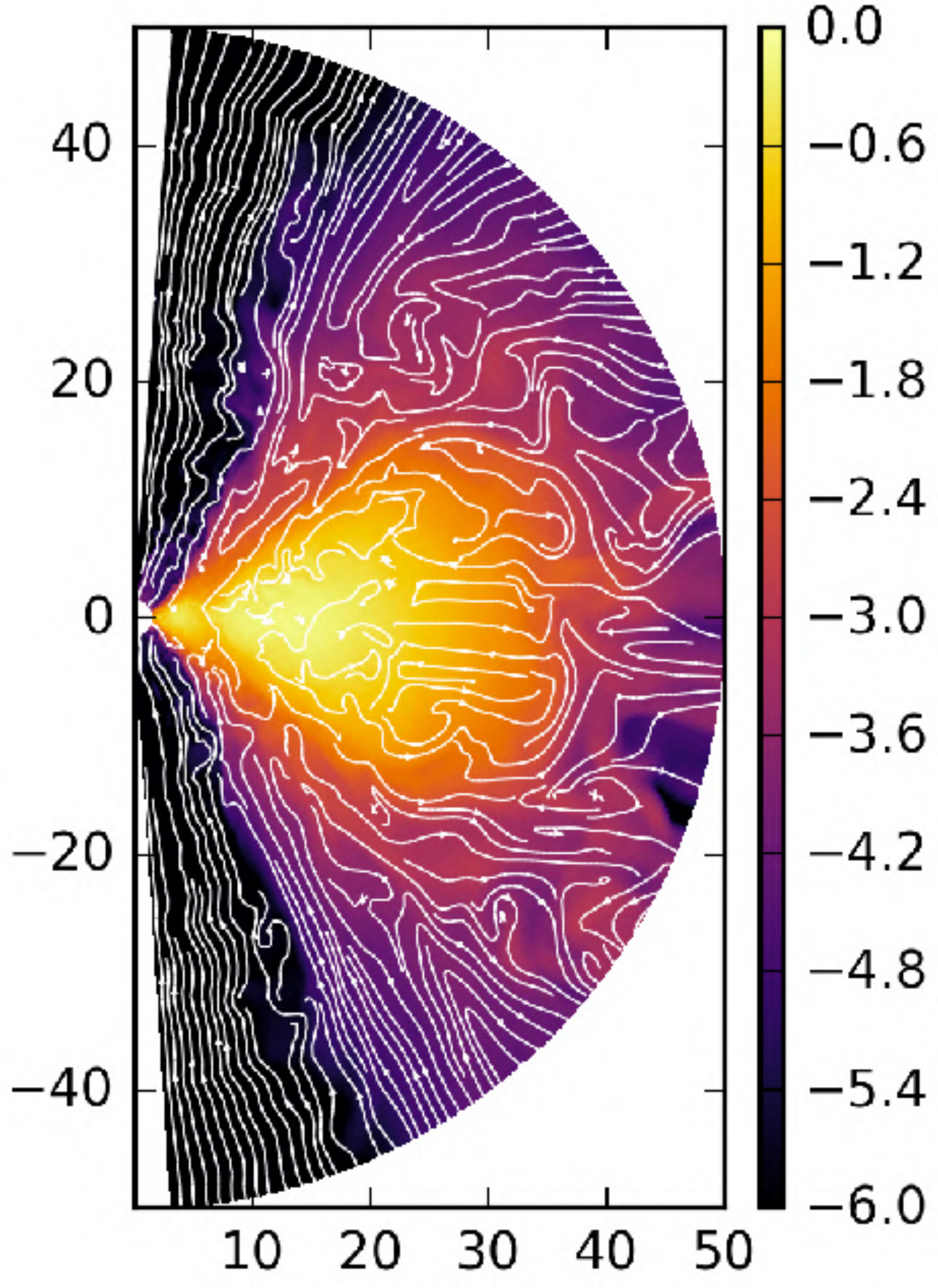
Theory of Jet Formation & Acceleration



MHD process
(schematic picture)

- Relativistic jet is formed and accelerated by macroscopic plasma (MHD) process with helically twisted magnetic field
- Collimated jet is formed near the central BH and accelerates $\gamma >> 1$
- But, it has problems
  - Most of energy remains in Poynting energy (magnetic energy)
  - Acceleration need take longer time (slow acceleration efficiency)

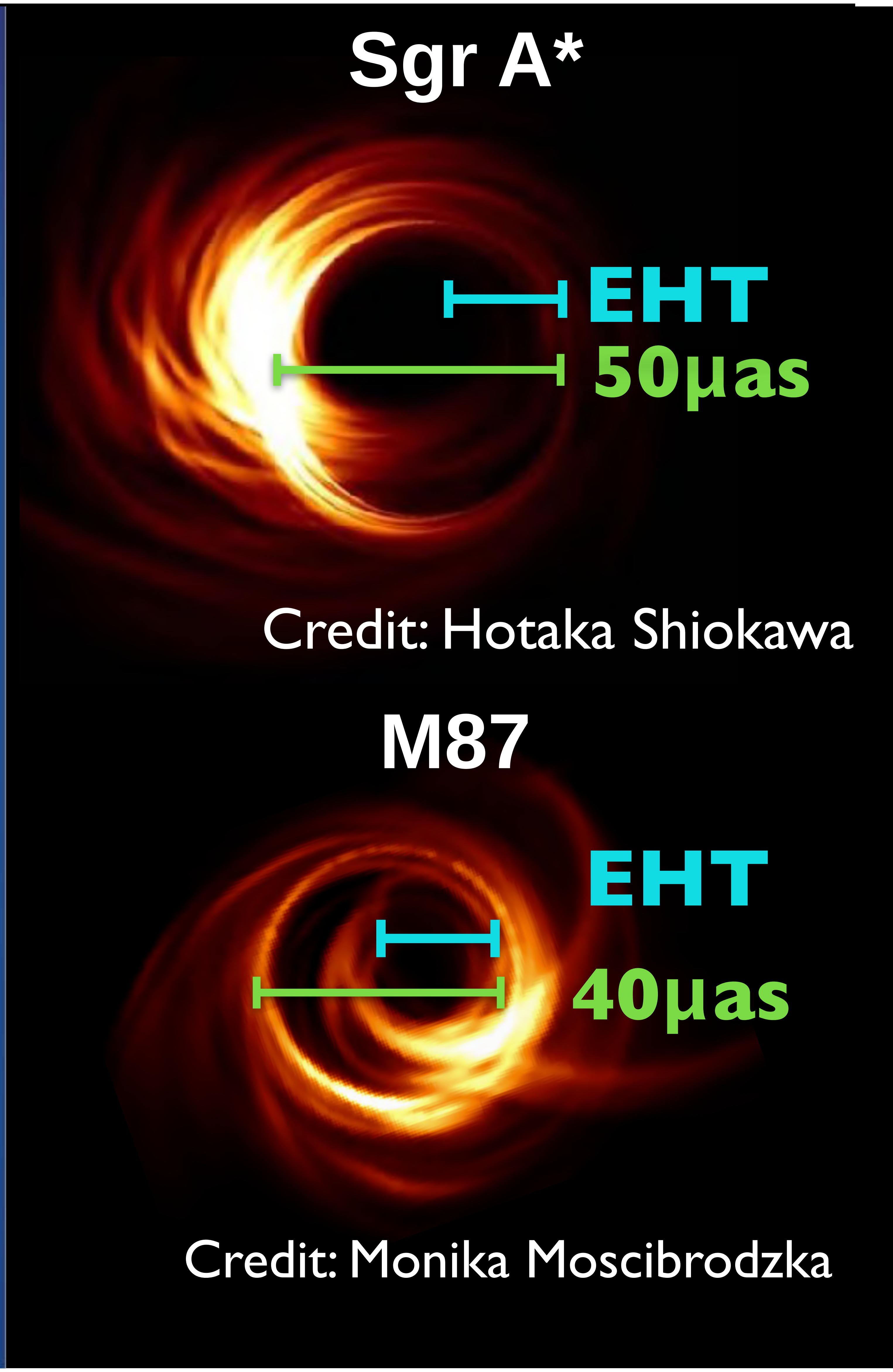
$\Rightarrow$ Rapid energy conversion (dissipation) should be considered



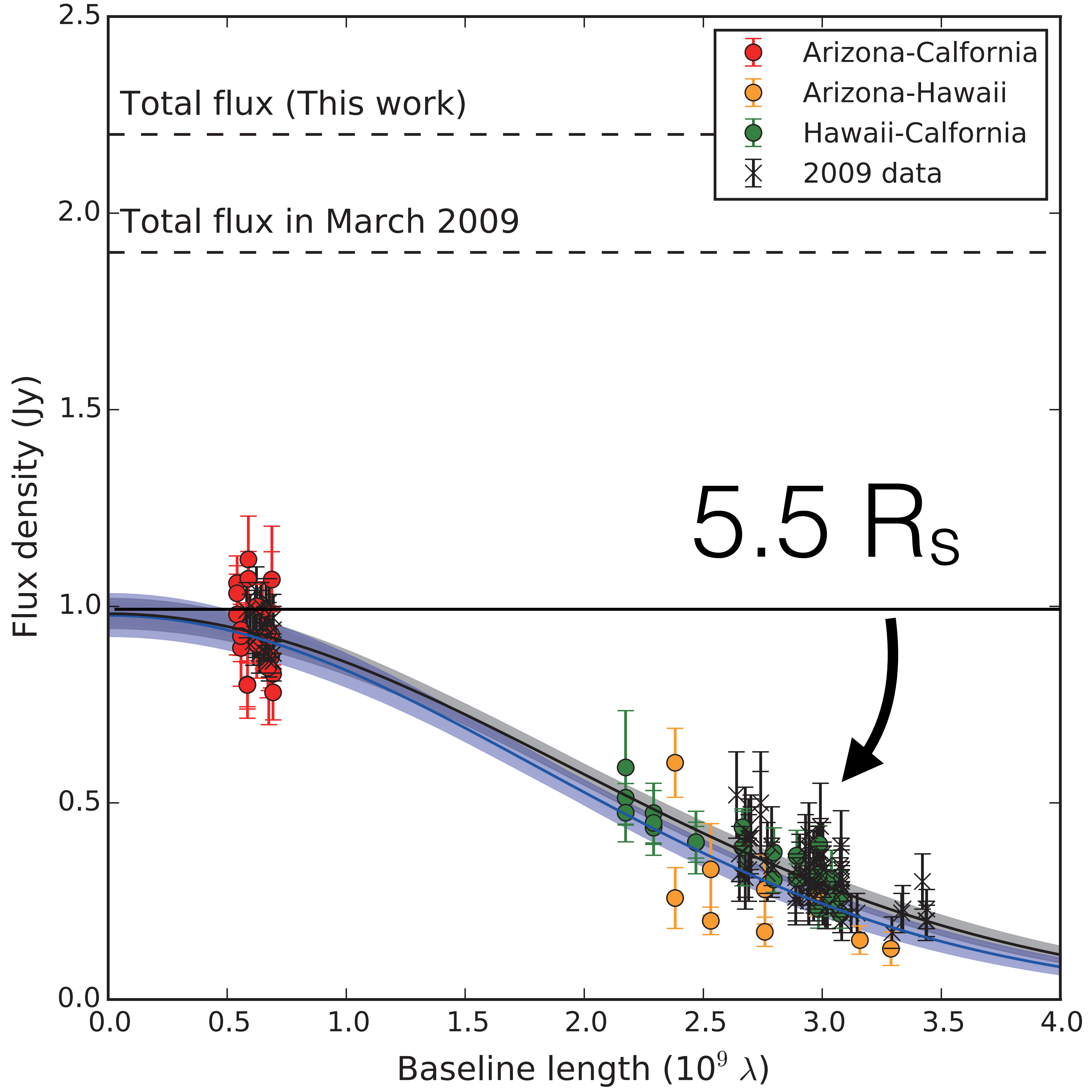
GRMHD simulations
By BHAC code (Porth et al. 17)

Pre EHT results

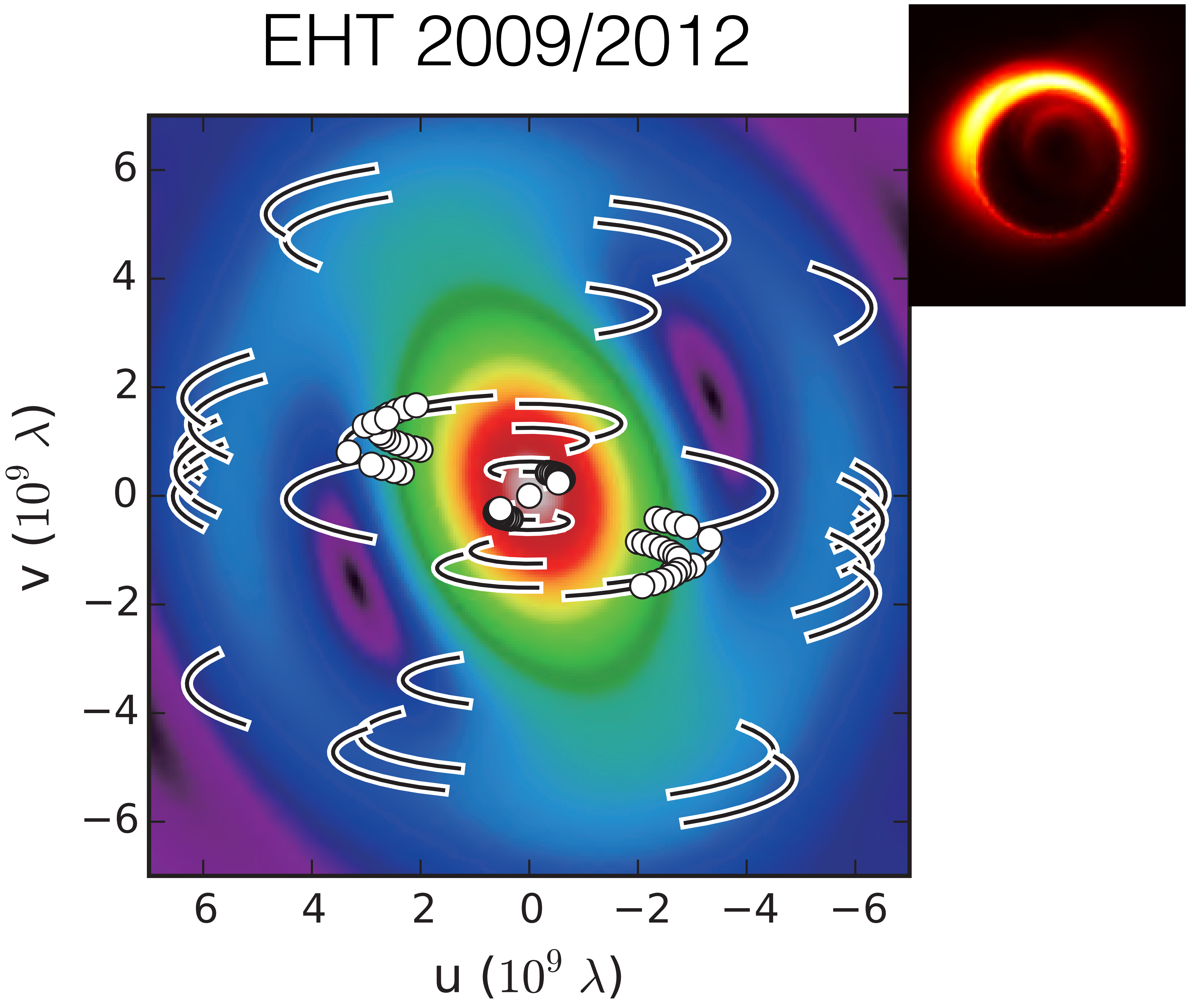
Event Horizon Telescope



Early EHT M87 Results: 2009 and 2012 observations



(Doeleman et al. 2012; Akiyama et al. 2015)

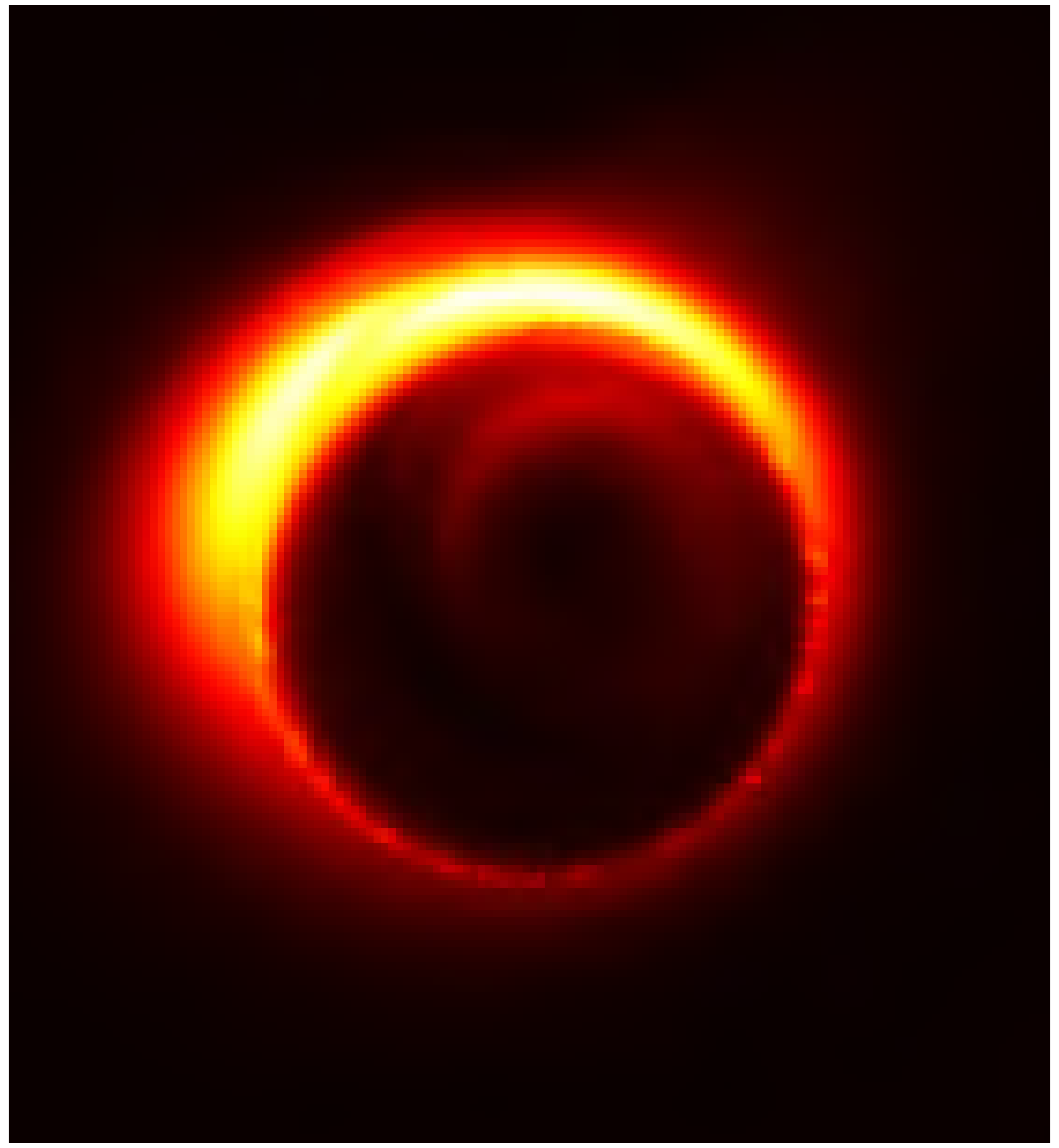


(Akiyama et al. 2015)

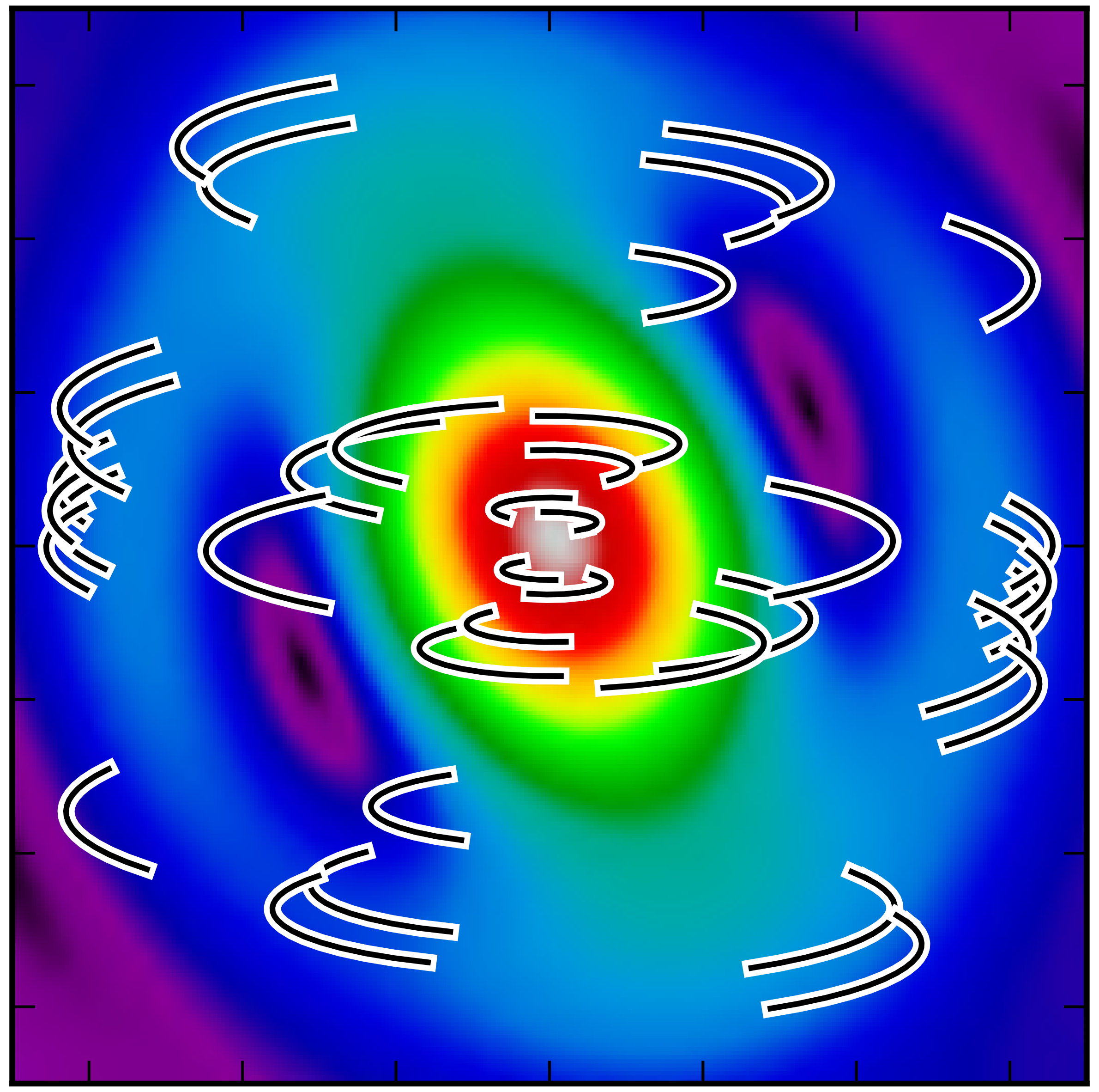
EHT Imaging

How the EHT works?

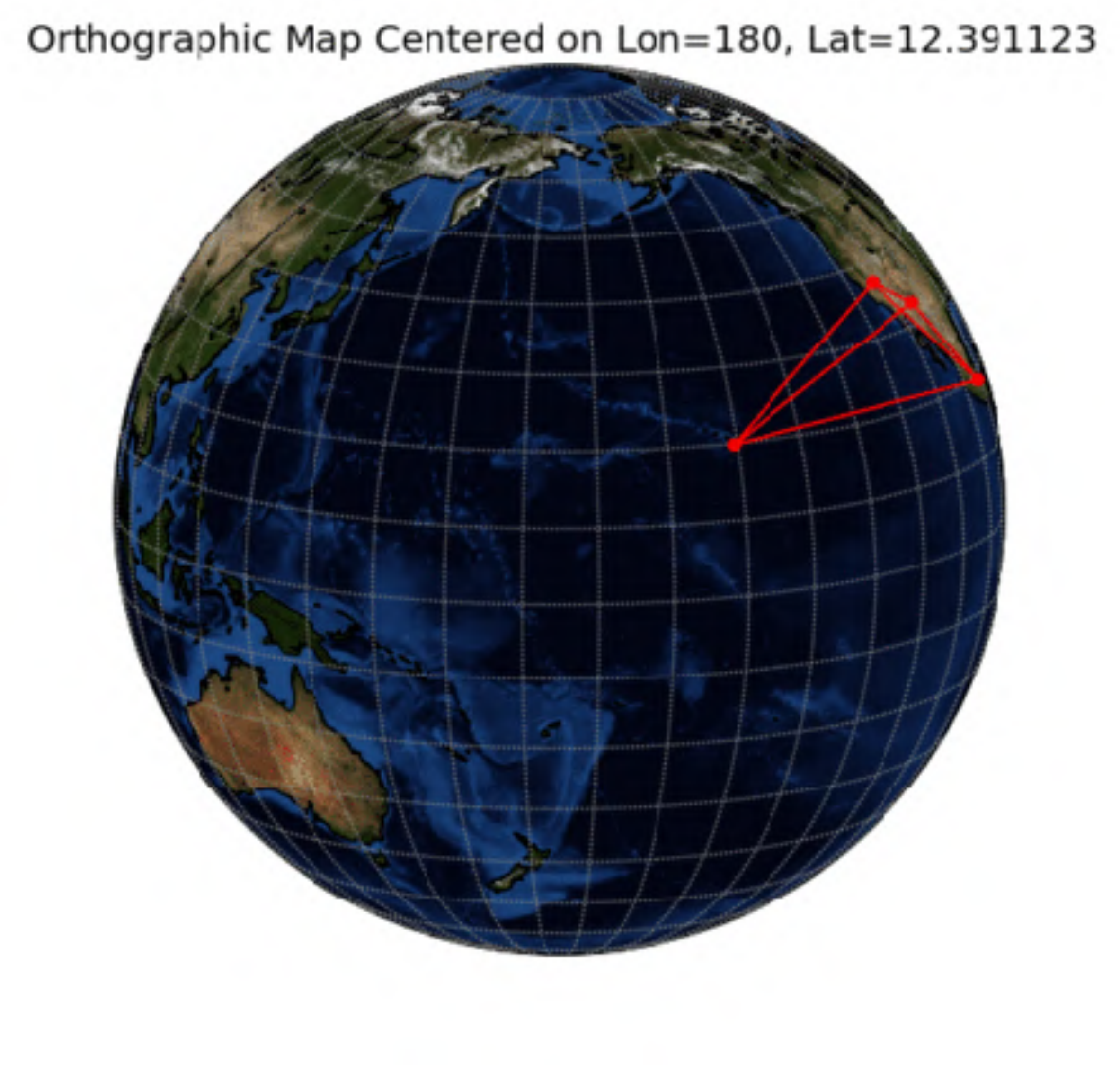
Image



Fourier Domain
(*Visibility*)



Sampling Process
(Projected Baseline = Spatial Frequency)



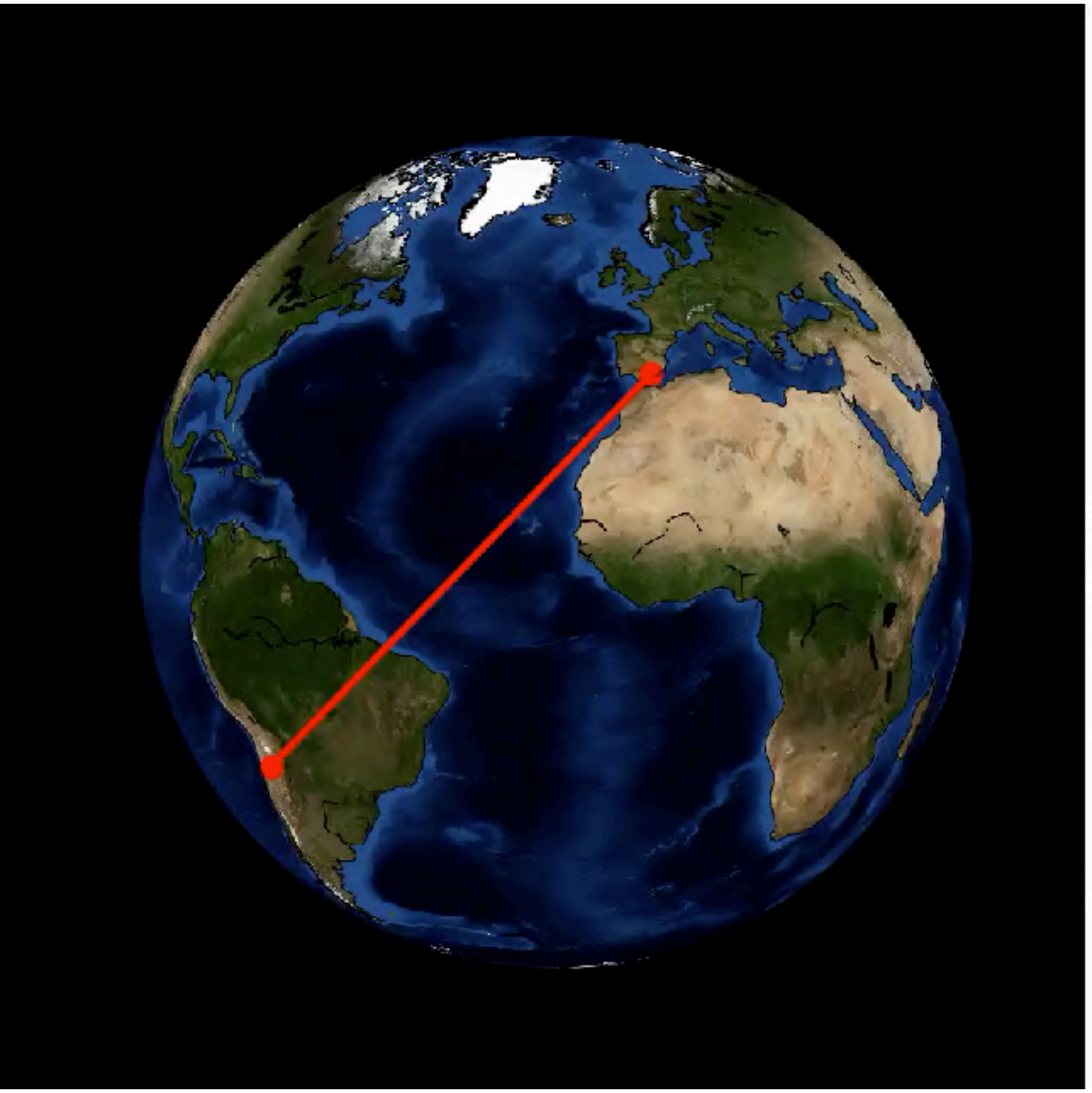
(Images: Akiyama et al. 2015; Movie: L. Vertatschitsch)

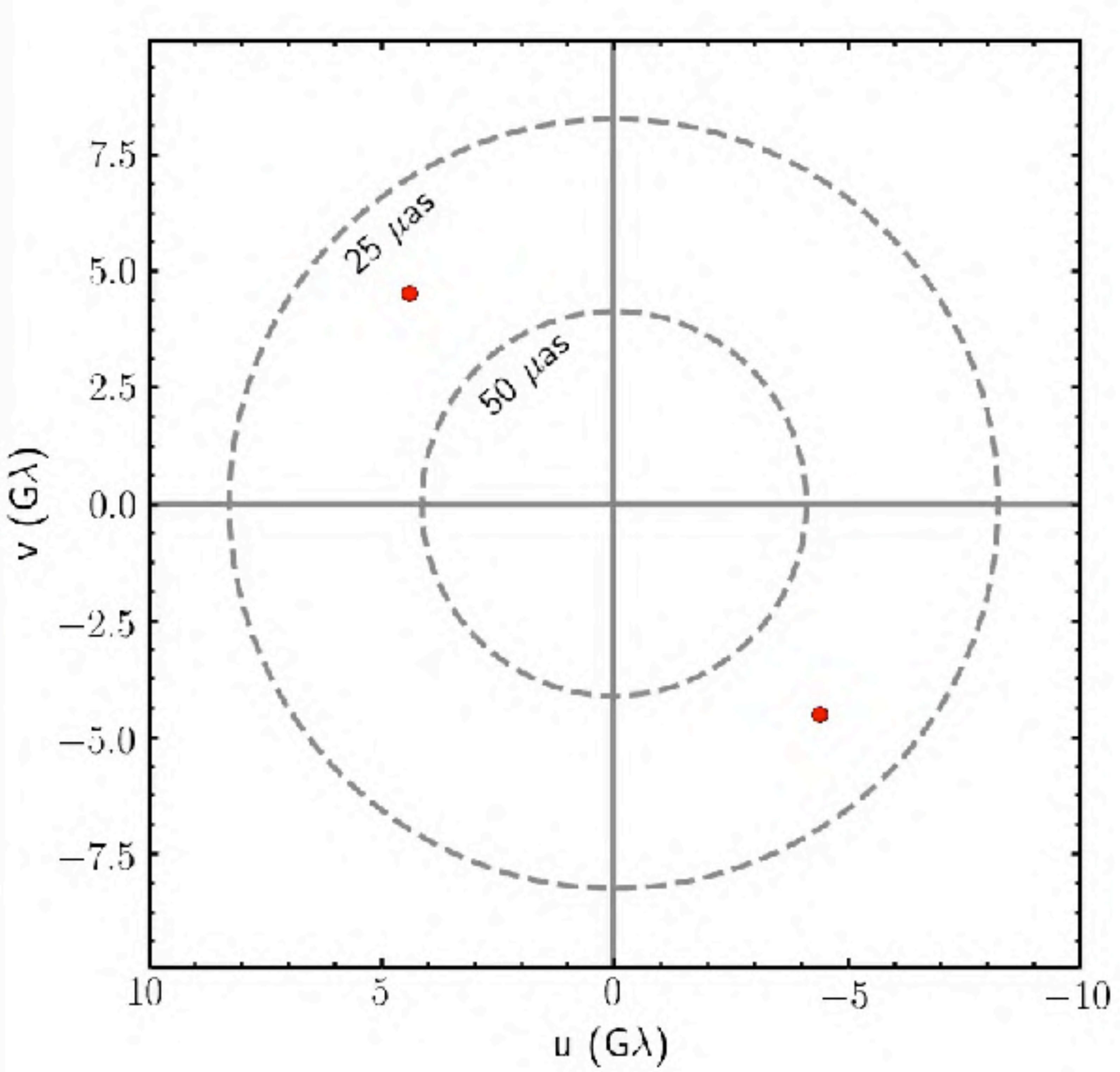
Spatial Frequency = Baseline Length

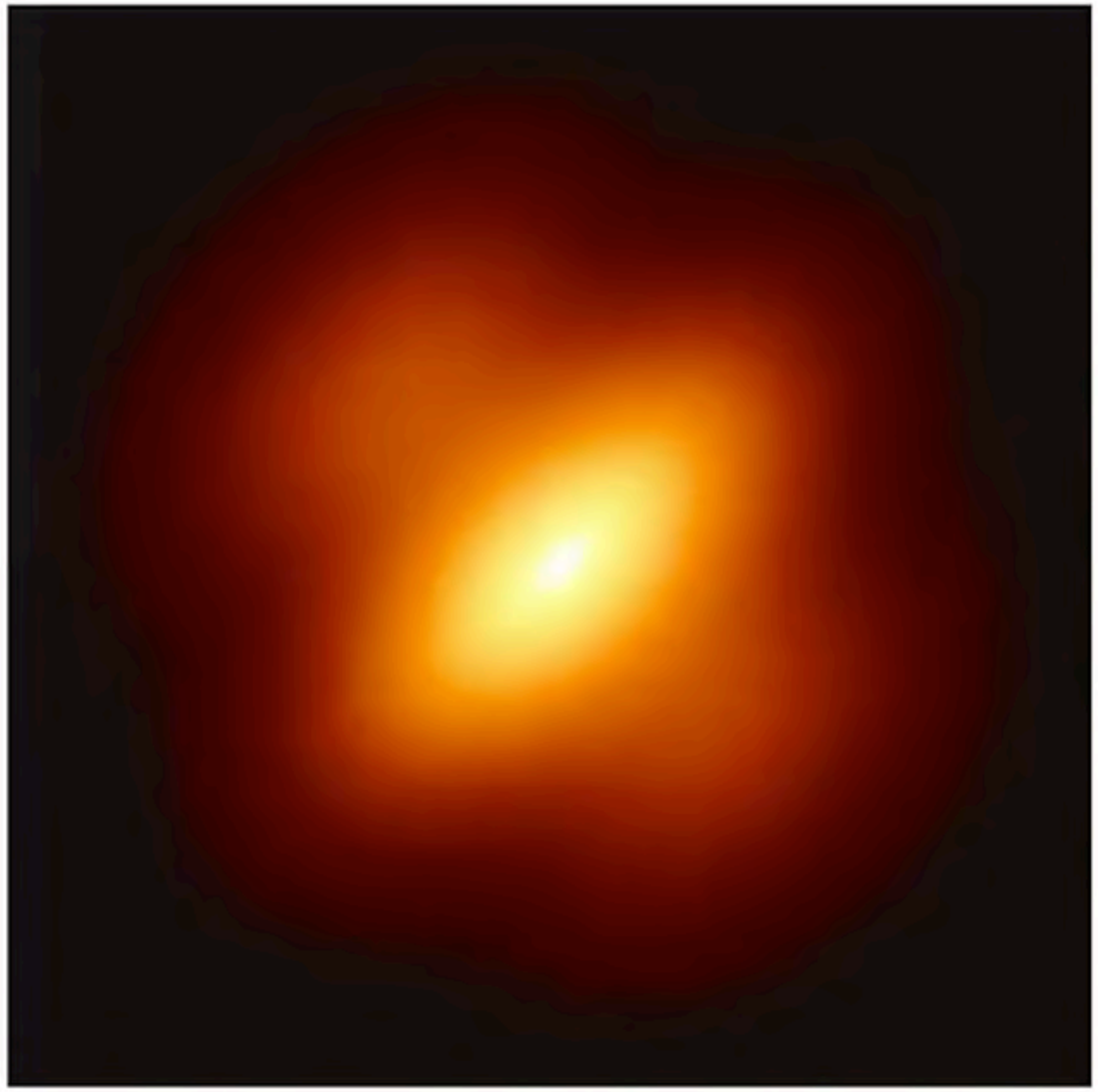
Longer Baselines trace more compact structure

Earth Rotation Synthesis

EHT 2017 observation of M87

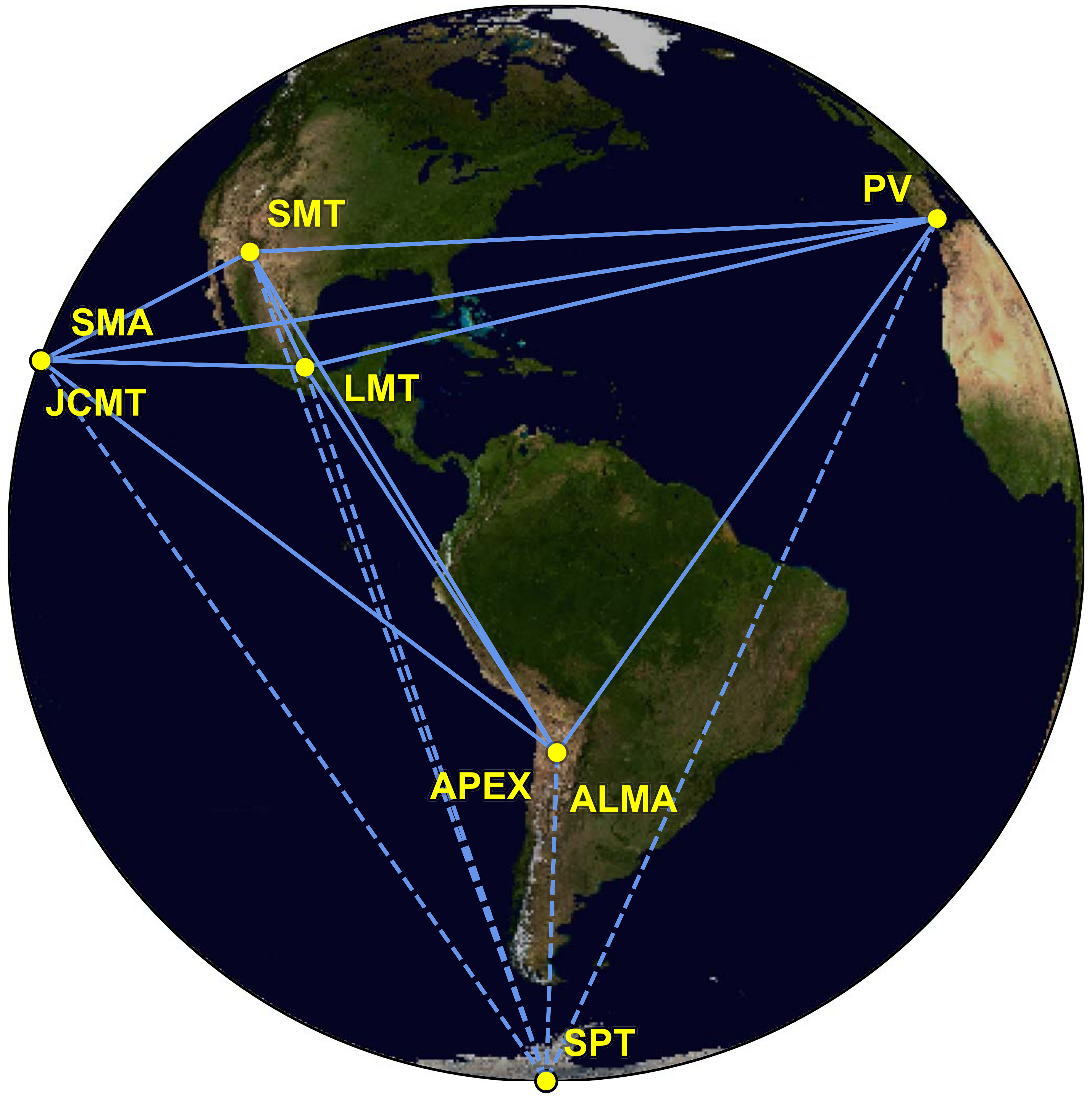






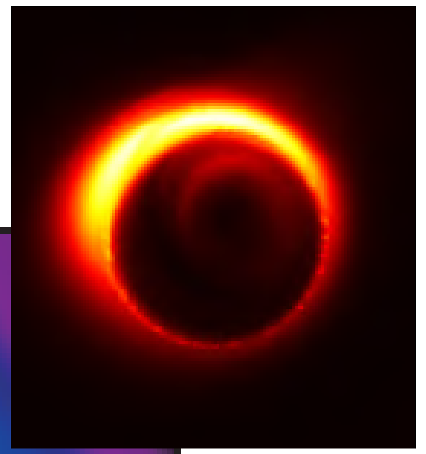
Credit: Daniel Palumbo

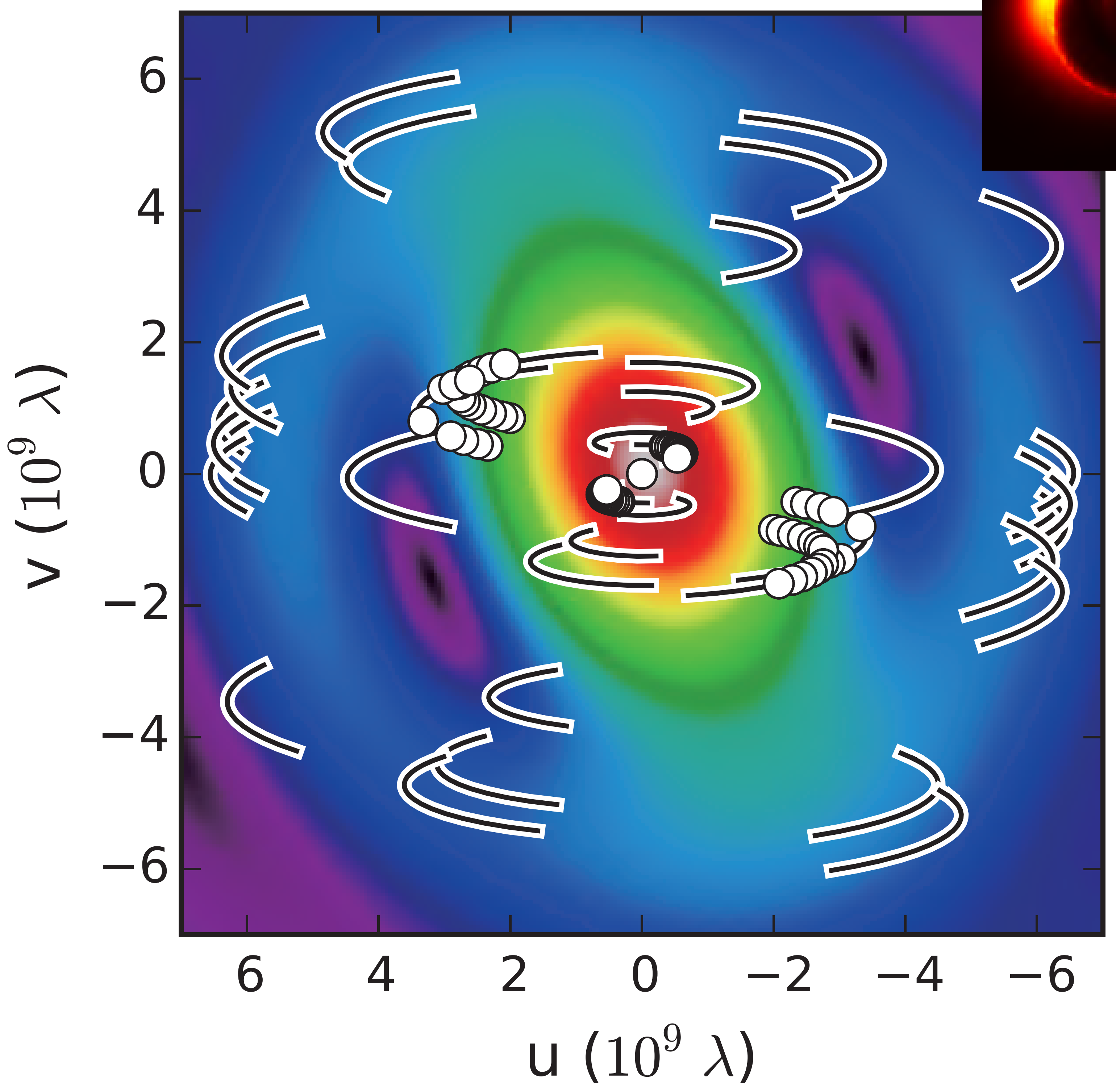
Event Horizon Telescope 2017 Observations



(Paper III)

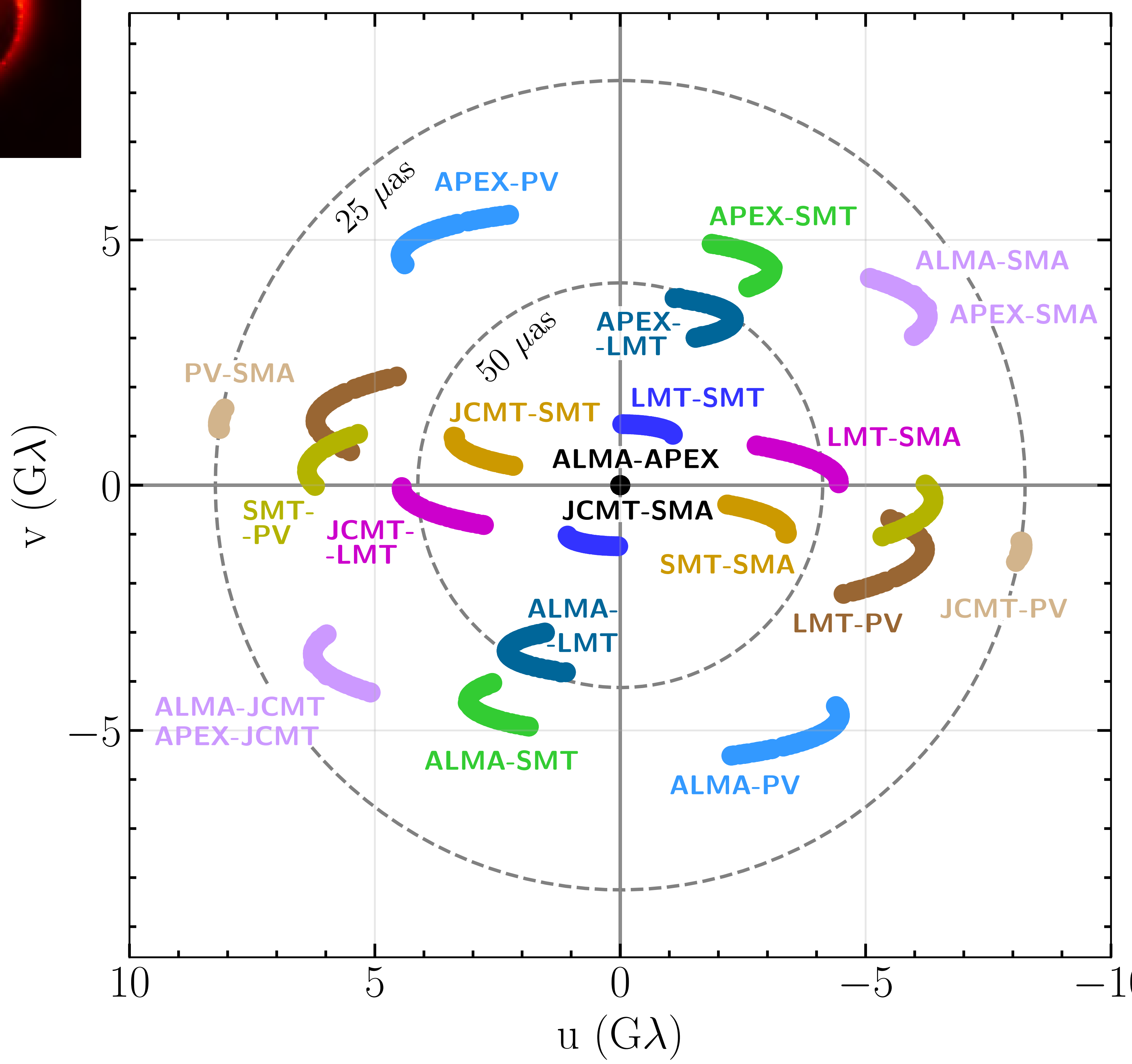
EHT 2009/2012





(Akiyama et al. 2015)

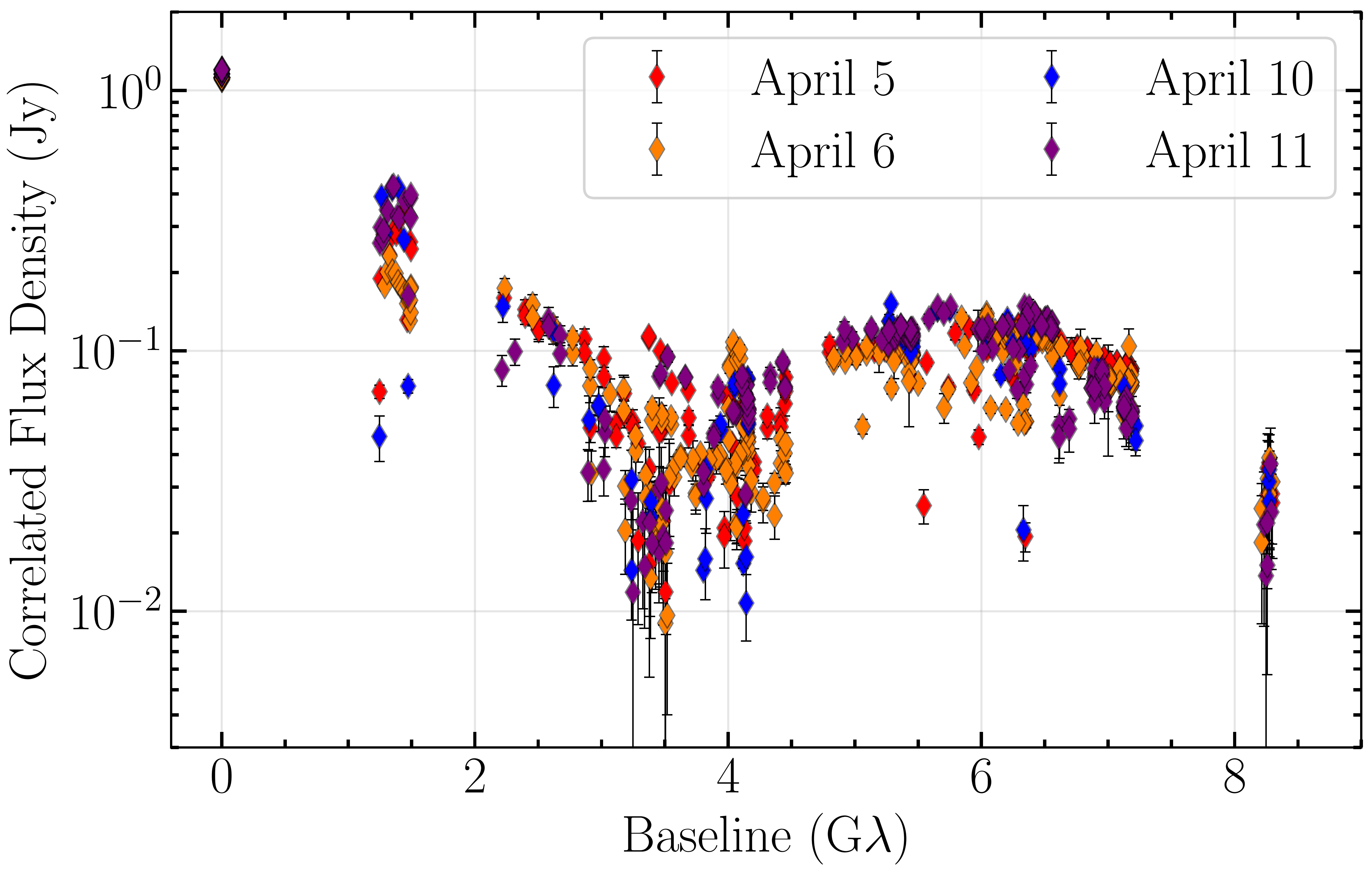
EHT 2017



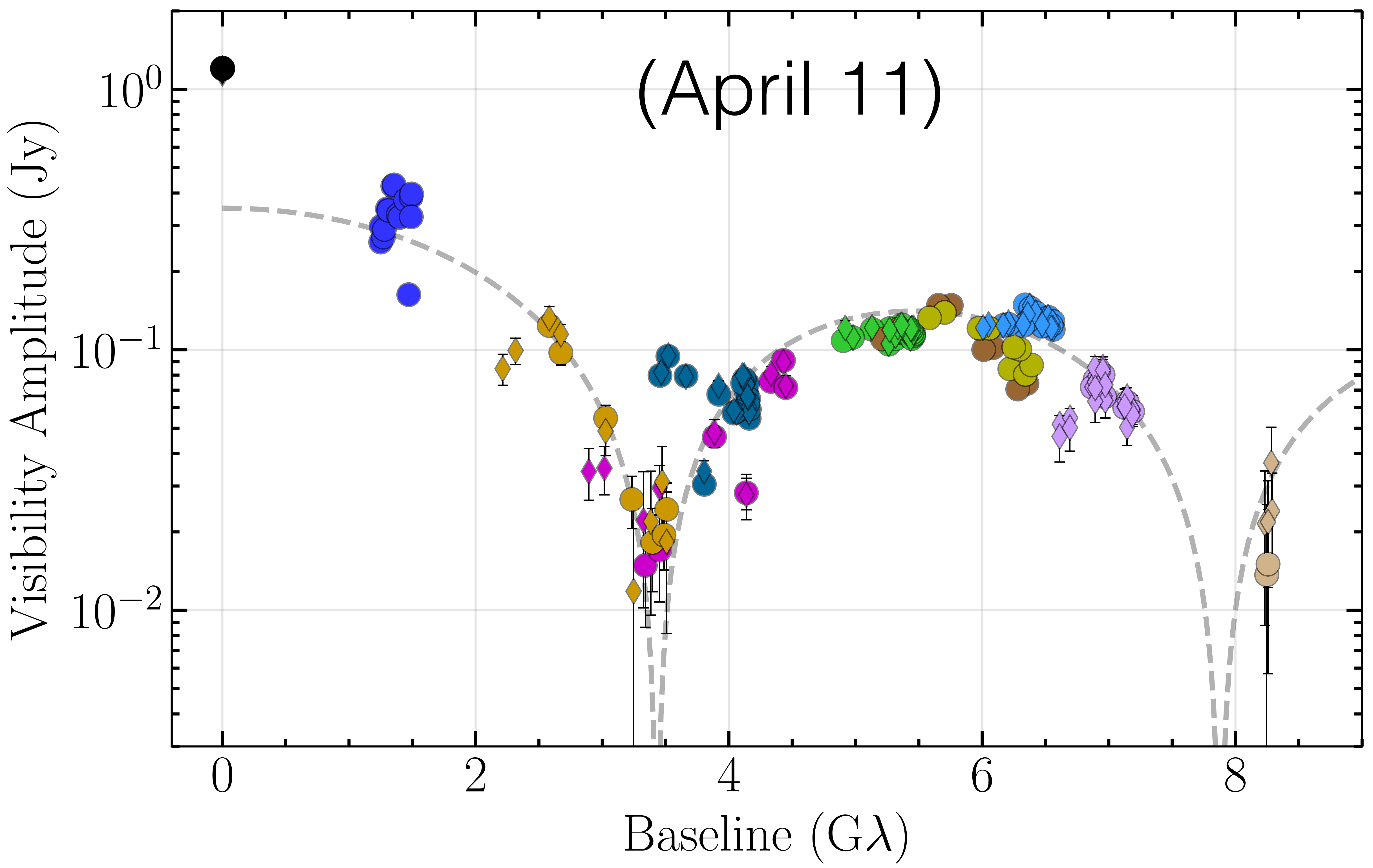
(Paper III)

Three Data Processing Pipelines: HOPS (Blackburn+19), CASA (Janssen+19), AIPS

Calibrated data sets (before imaging)



(Paper III)



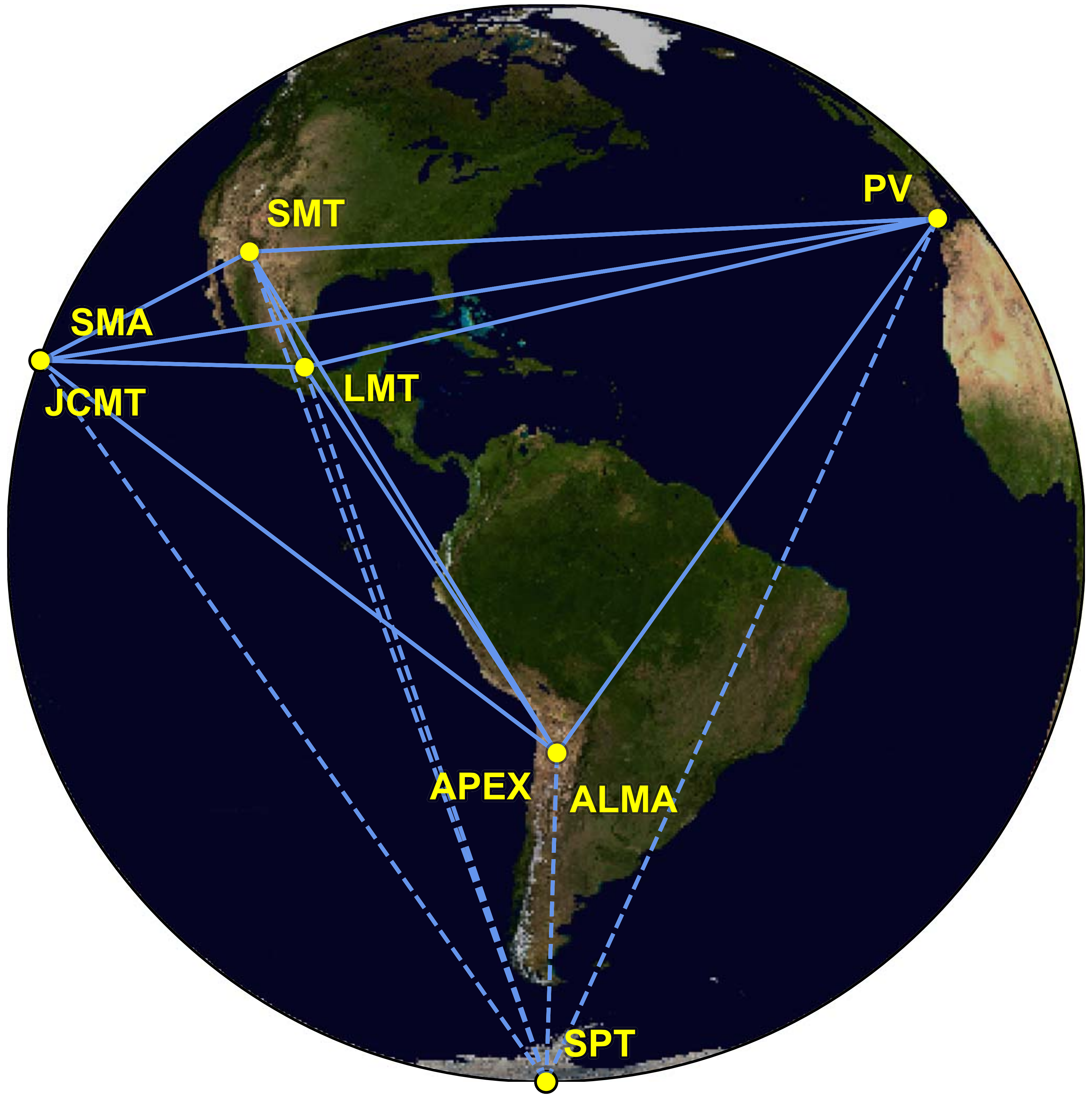
(Paper I)

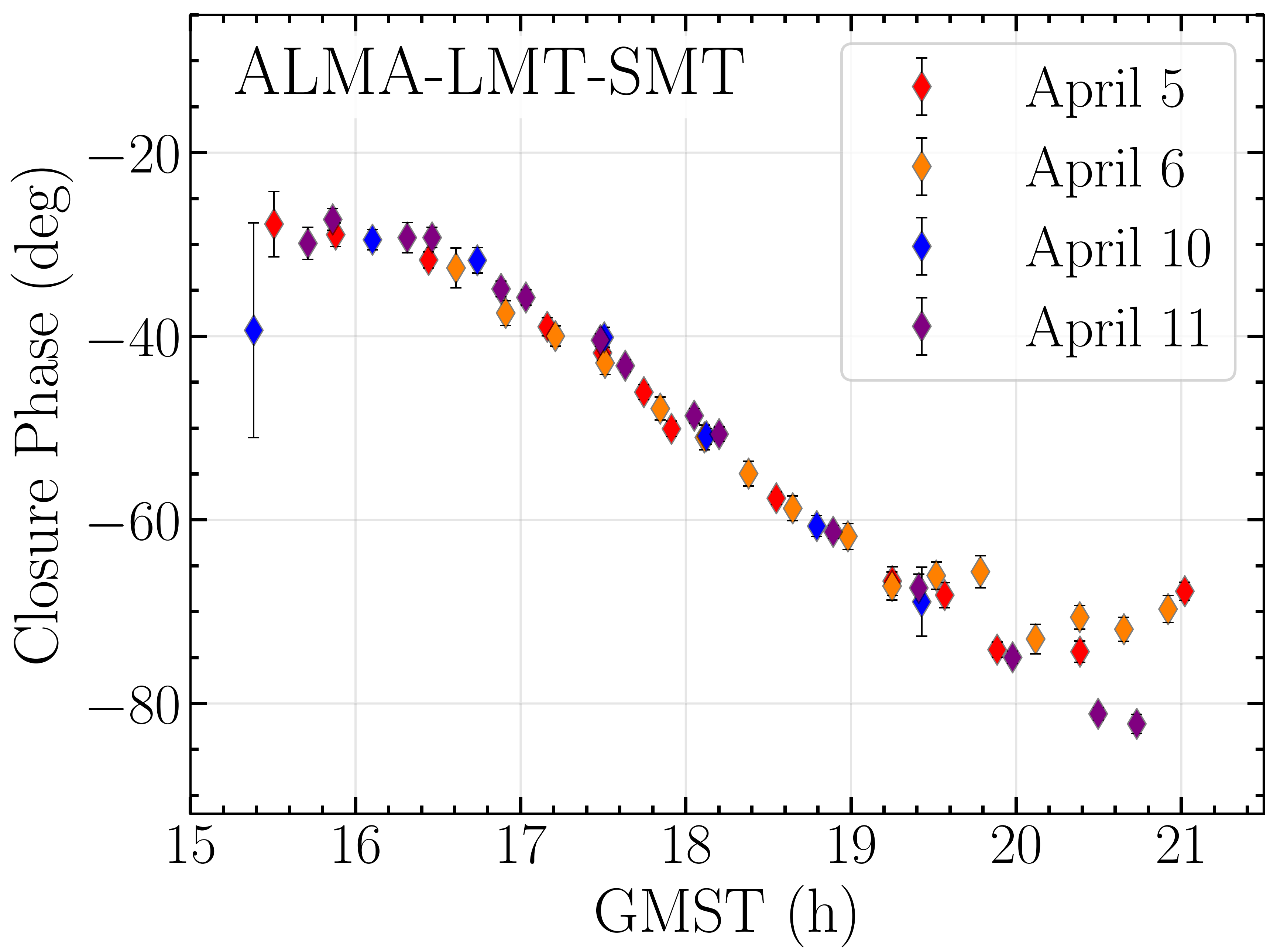
Slowly Building Up Data

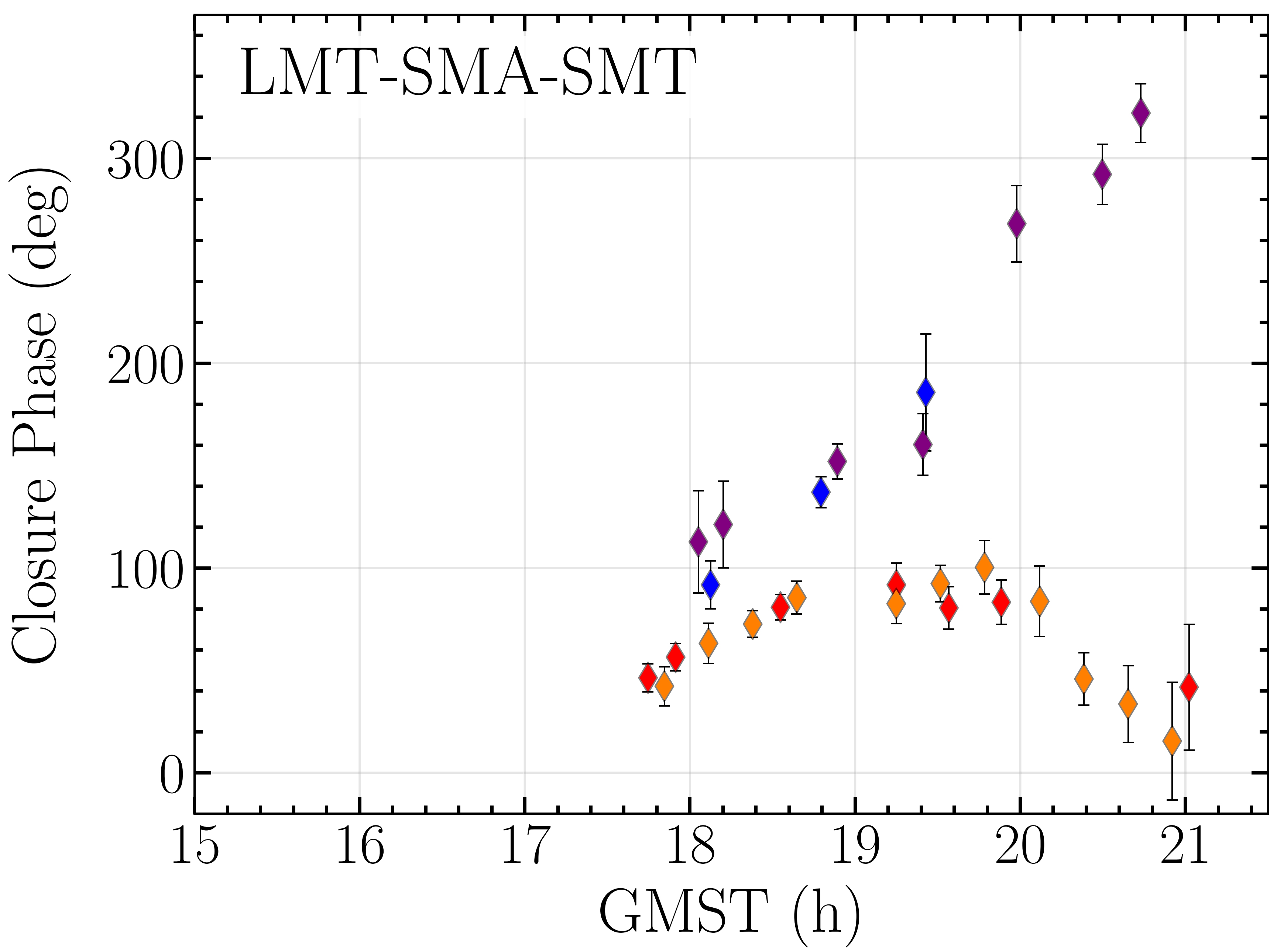
Lo-band eht-imaging on April 11

Credit: Palumbo & Wielgus

Closure Phases: Mildly asymmetric & time-variable structure







(Paper IV)

Challenges and Philosophy of EHT Imaging

Difficulties

- Extremely sparse baseline coverage
- Large amplitude uncertainties
- No information from previous 1.3 mm images

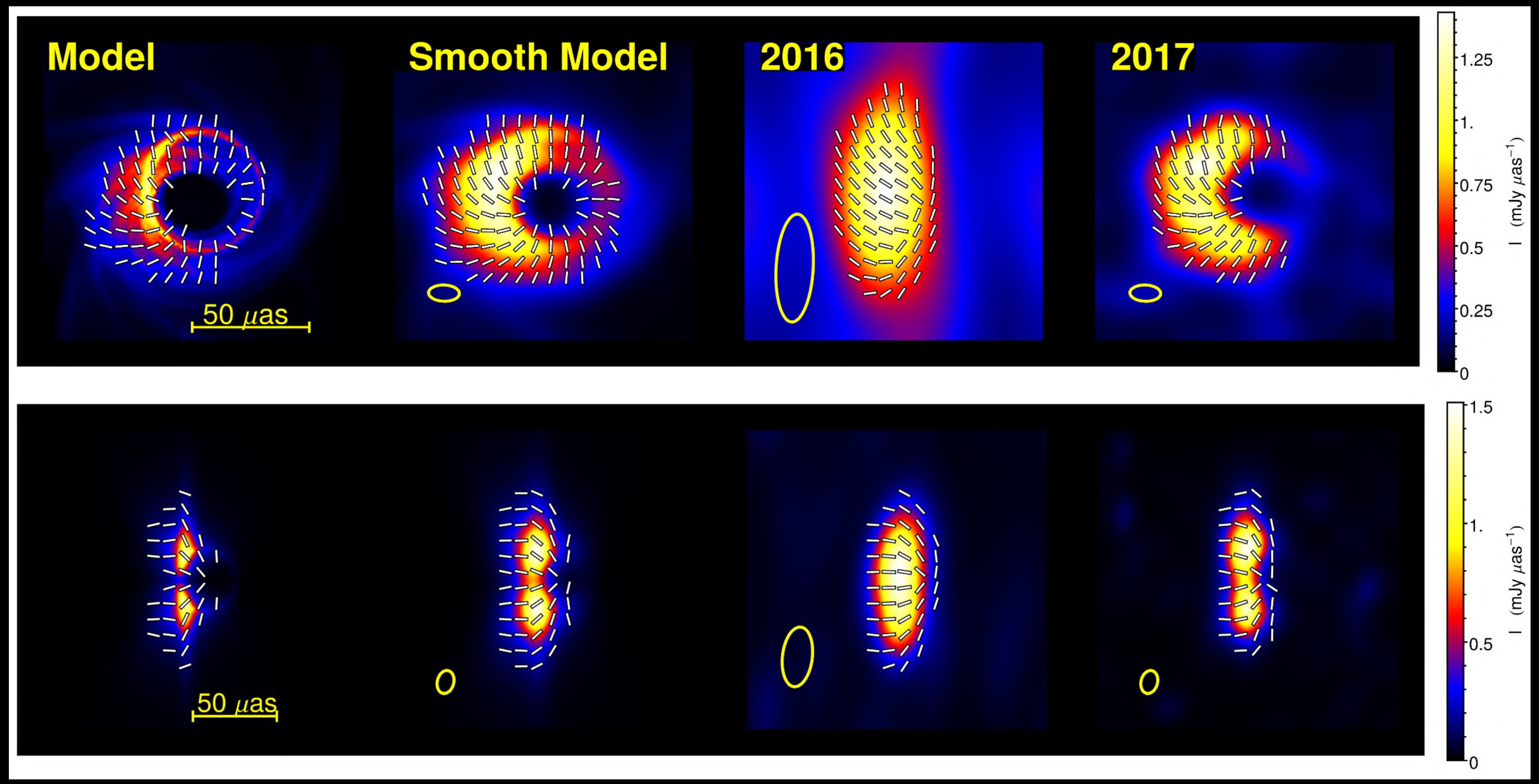
Major Risk:

Developing false confidence in features the may not have unambiguous support

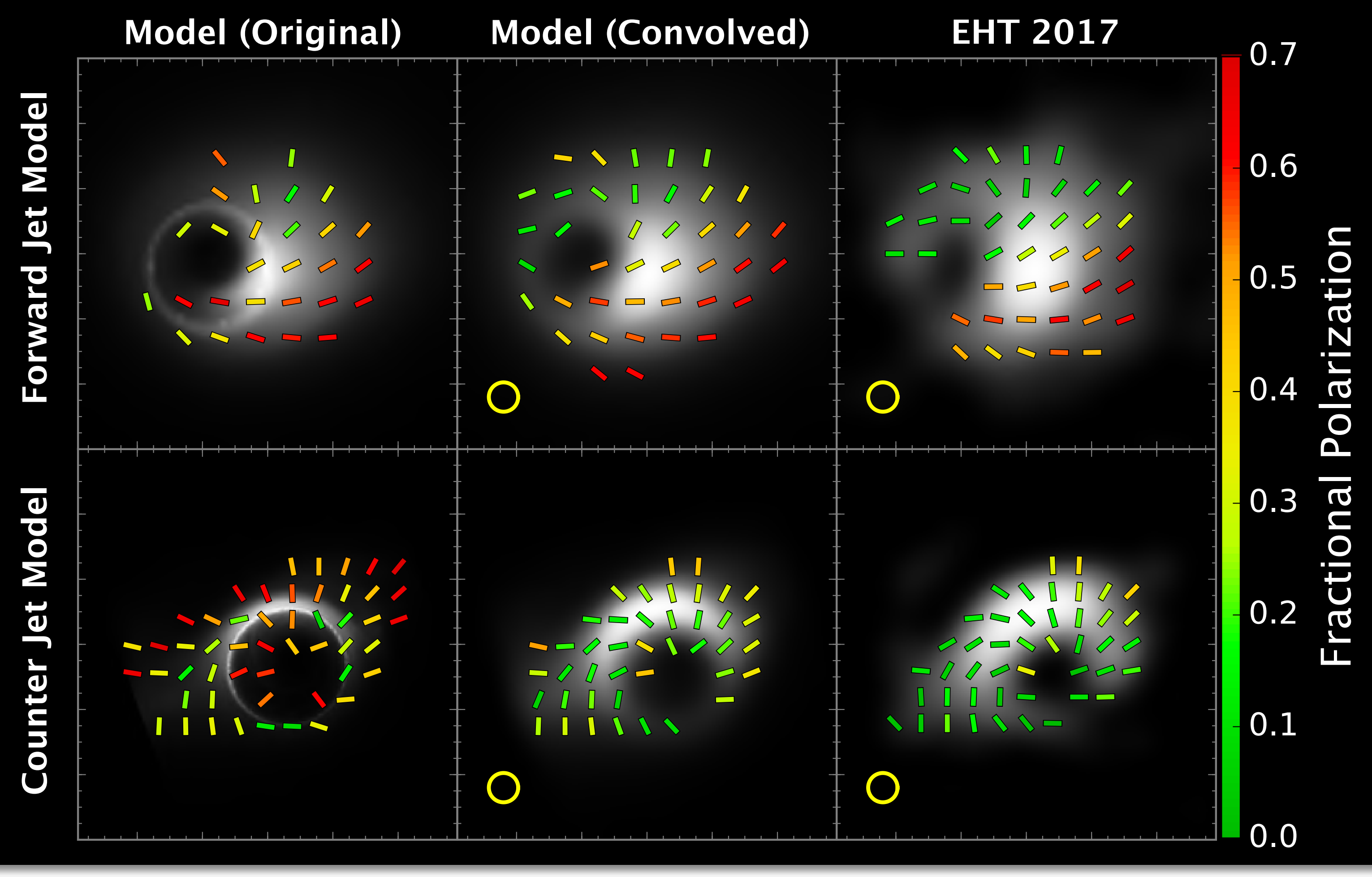
Agnostic:	Images should be among our most agnostic EHT outputs with the ability to reveal unexpected features and source properties
Exploratory:	We have focused on exploring a broad space of possible algorithms and imaging algorithms to be optimal on a narrow class of images
Emphasis:	Simple algorithms over complex black boxes Reproducible and scriptable results

New Imaging Methods

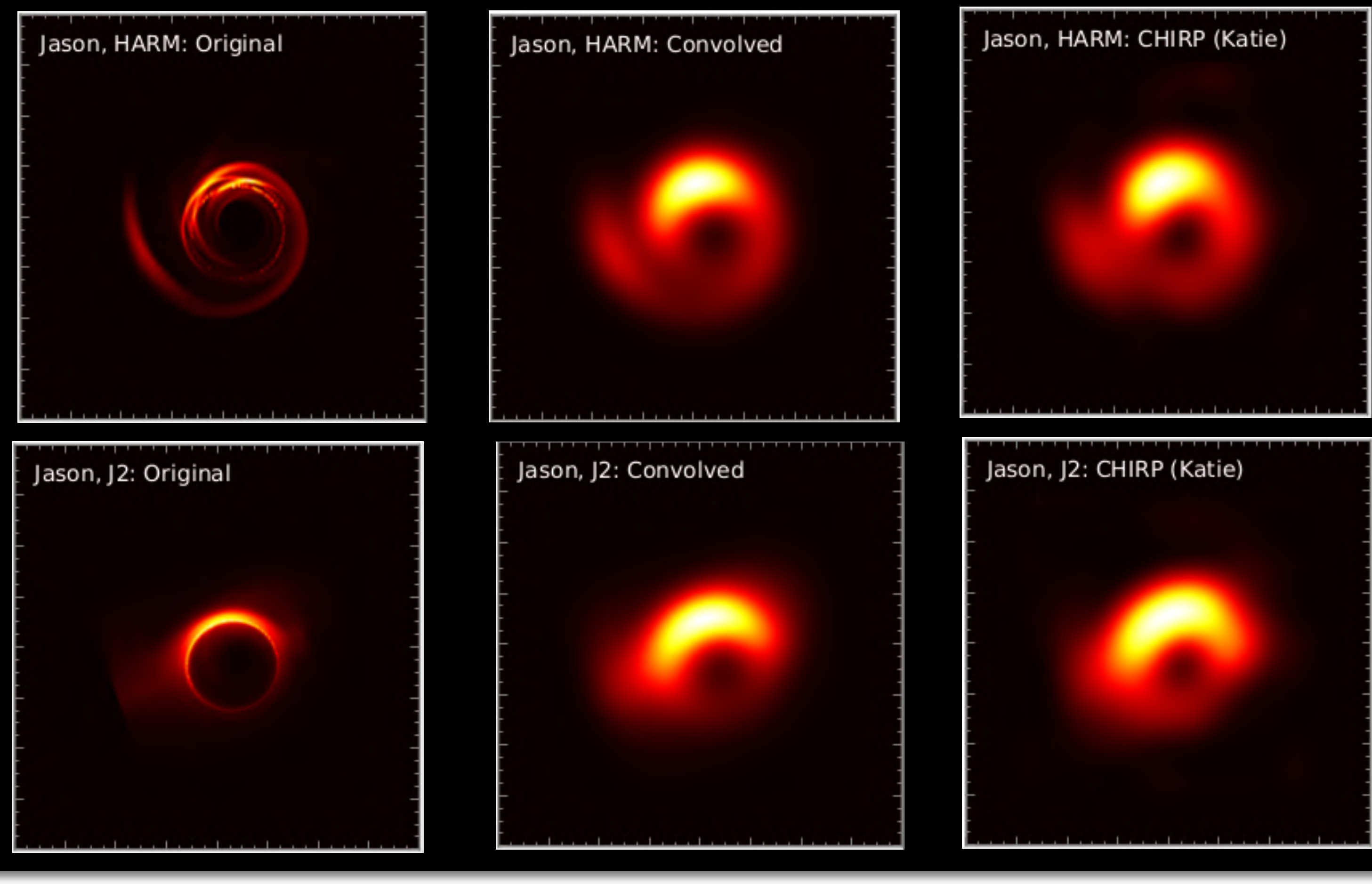
Maximum Entropy Method (MEM)
Chael et al. 2016, Fish et al. 2014,
Lu et al. 2014, 2016



Sparse Modeling
Akiyama et al. 2017a, 2017b
Ikeda et al. 2016, Honma et al. 2014



CHIRP (Machine-learning)
Bouman et al. 2016



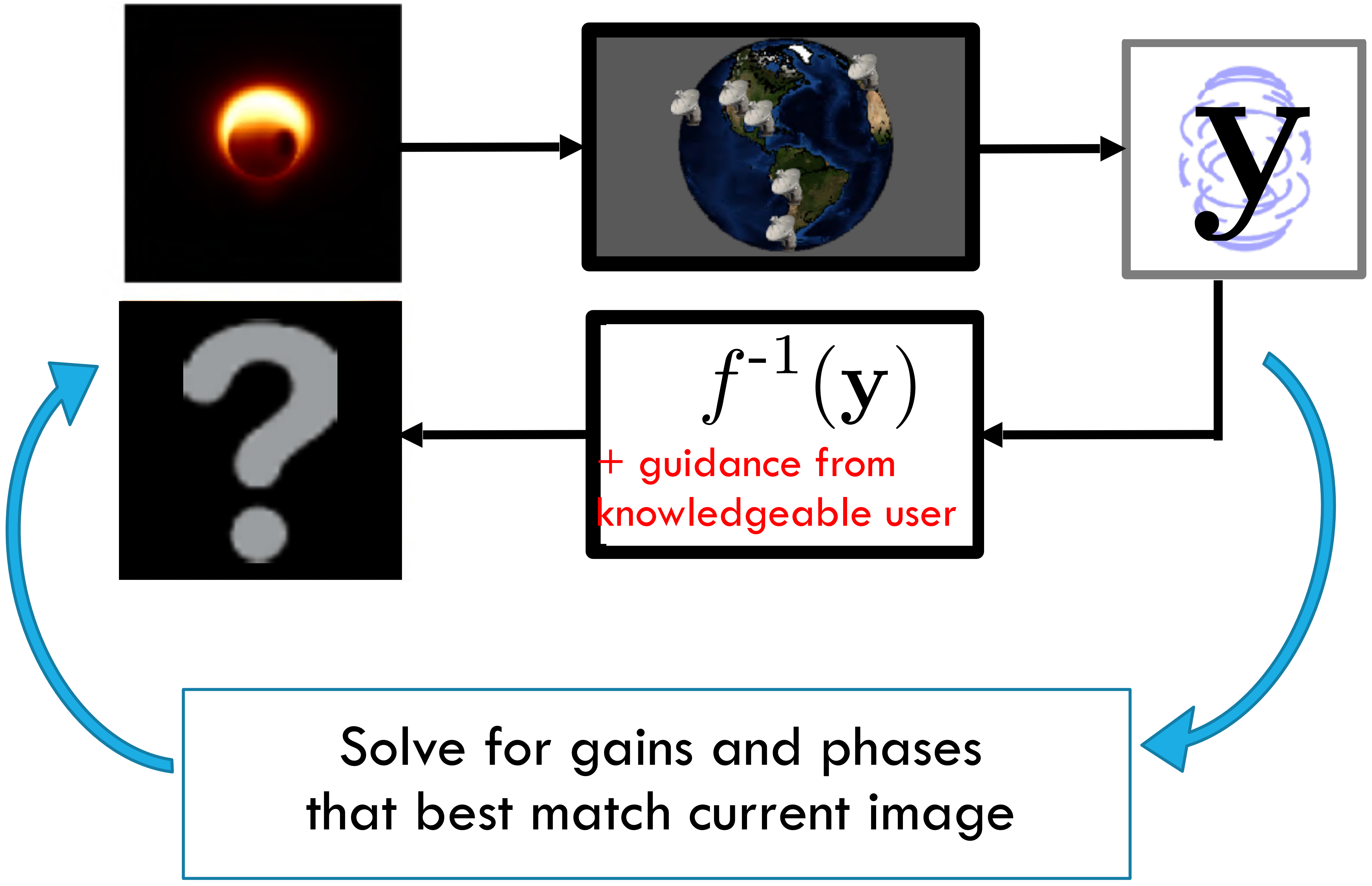
Two Imaging Libraries

eht-imaging (Chael+2016,2018) : https://github.com/achael/eht-imaging

SMILI (Akiyama+2017a,b) : https://github.com/astrosmili/smili

Two Classes of Imaging Algorithms

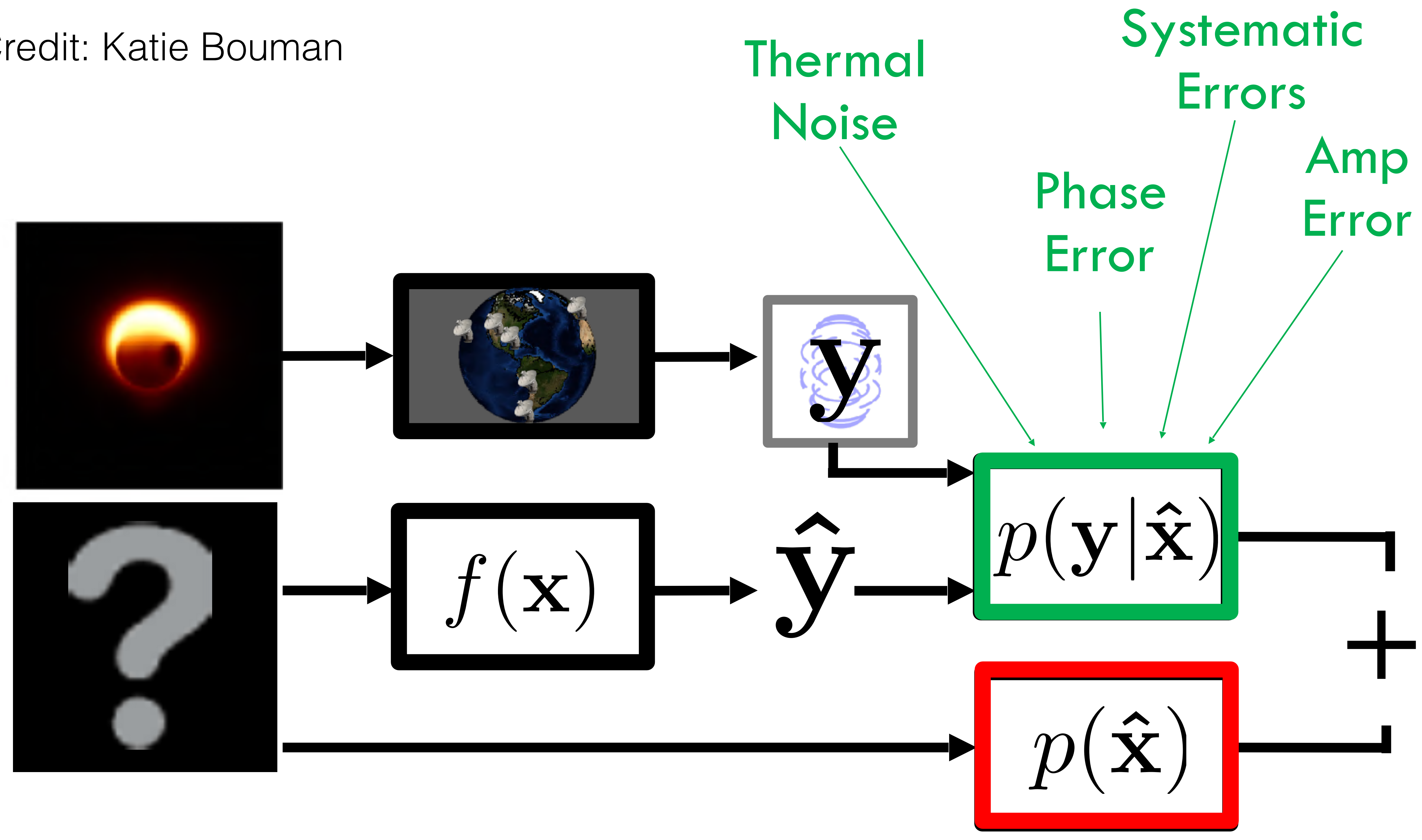
Credit: Katie Bouman



Traditional

Inverse Modeling (CLEAN + Self-Calibration)

Credit: Katie Bouman

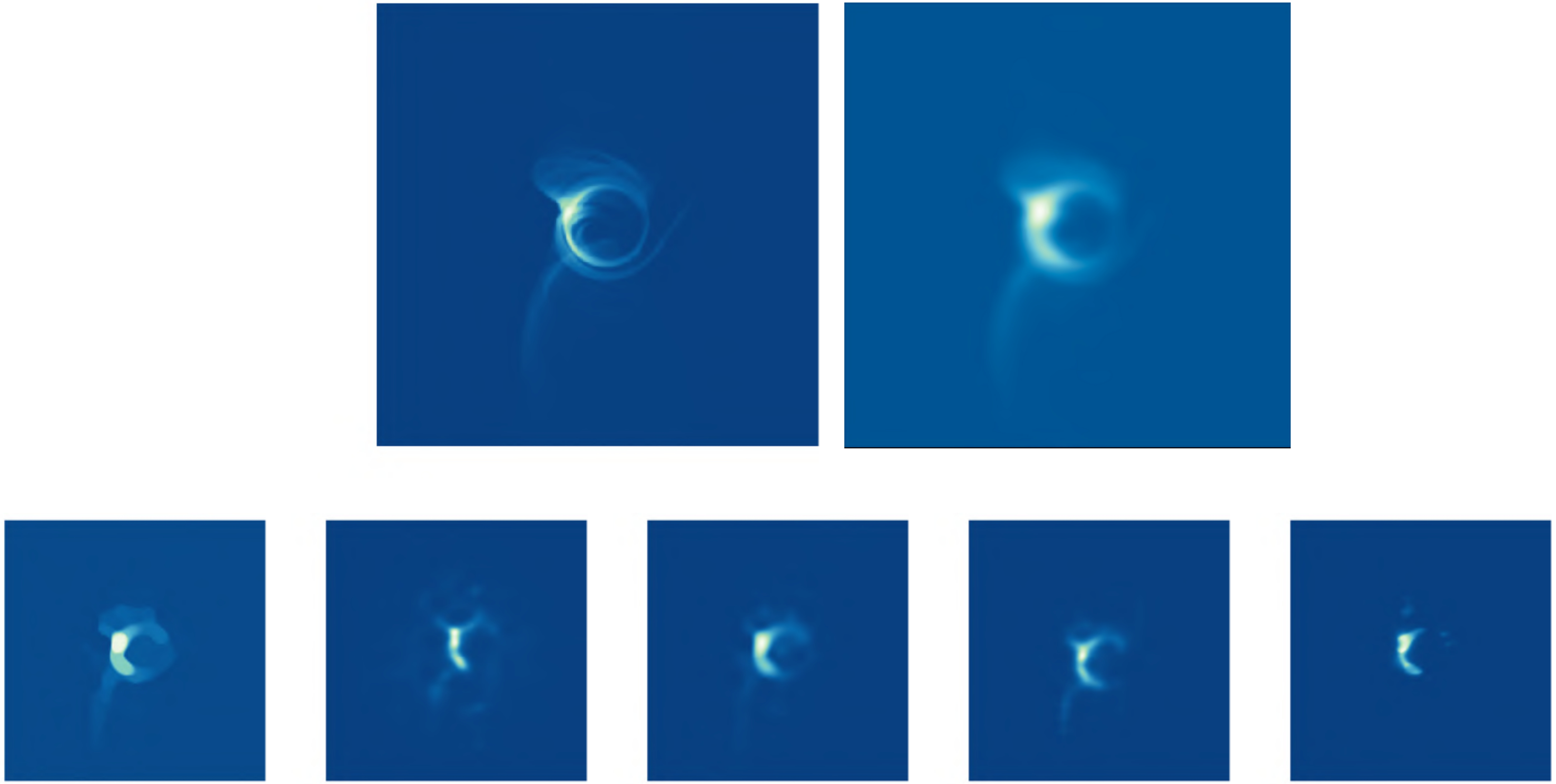


$$\hat{\mathbf{x}}_{\mathrm{MAP}} = \mathrm{argmax}_{\mathbf{x}} \left[\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})\right]$$

Forward Modeling (Bayesian Inspired Optimization)

Event Horizon Telescope

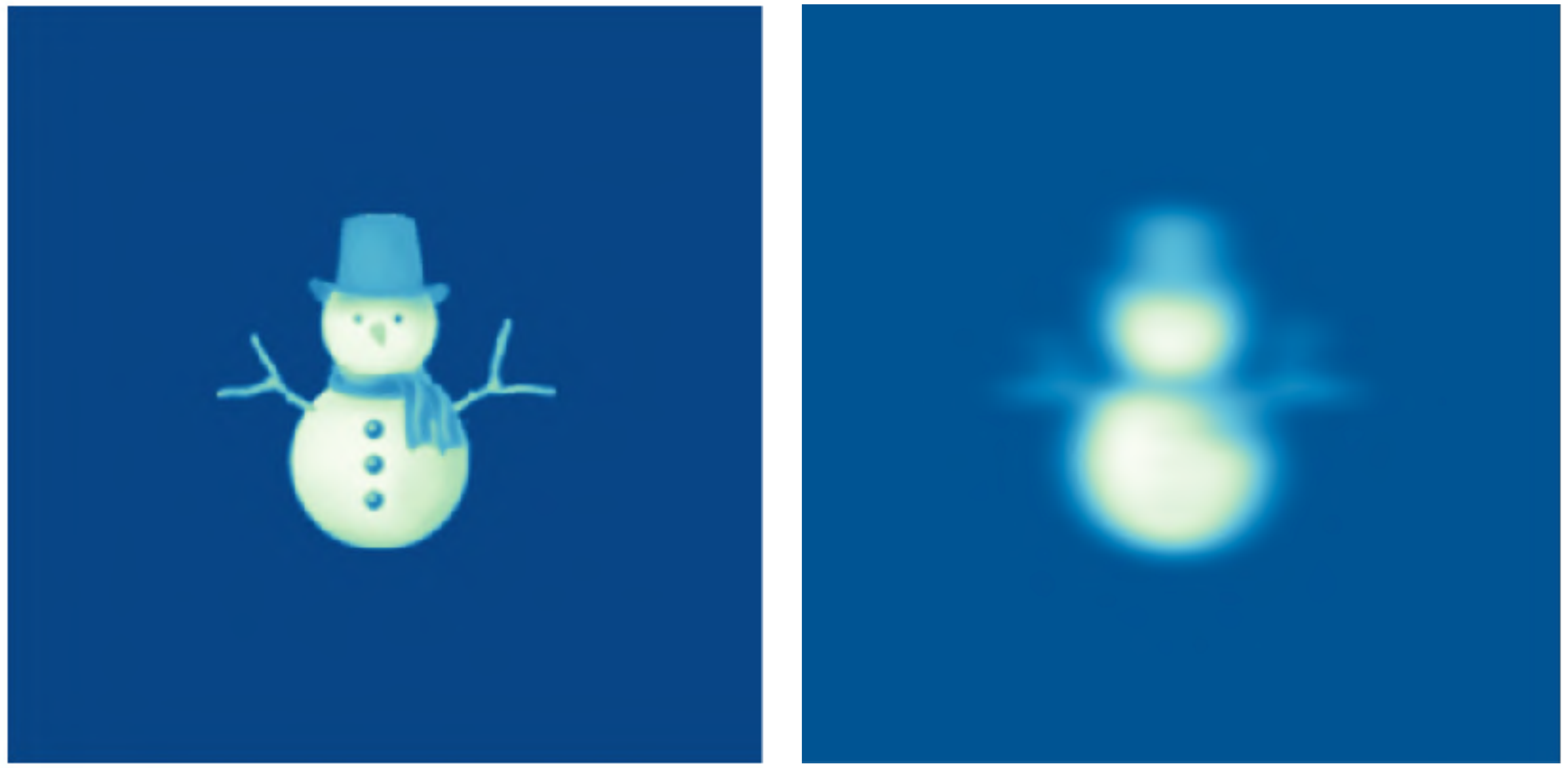
EHT Blind Imaging Challenges (2016 -)



Method 1　　Method 2　　Method 3　　Method 4　　Method 5

(Katie Bouman 2016, PhD thesis; the EHT Imaging WG)

EHT Blind Imaging Challenges (2016 -)



Method 1 | Method 2 | Method 3 | Method 4 | Method 5

(Katie Bouman 2016, PhD thesis; the EHT Imaging WG)

Imaging Pipelines: Human Choices

DIFMAP (CLEAN + Self Calibration)	eht-imaging (Regularized Max Likelihood)	SMILI (Regularized Max Likelihood)
Compact Flux Stop Condition Weighting on ALMA Mask Size Data Weights	Compact Flux Initial Gaussian Size Systematic Error Regularizes MEM TV TSV L1	Compact Flux L1 Soft Mask Size Systematic Error Regularizes TV TSV L1
(Sheperd et al. 1997,1998)	(Chael et al. 2016, 2018)	(Akiyama et al. 2017a,b)

Credit: Katie Bouman

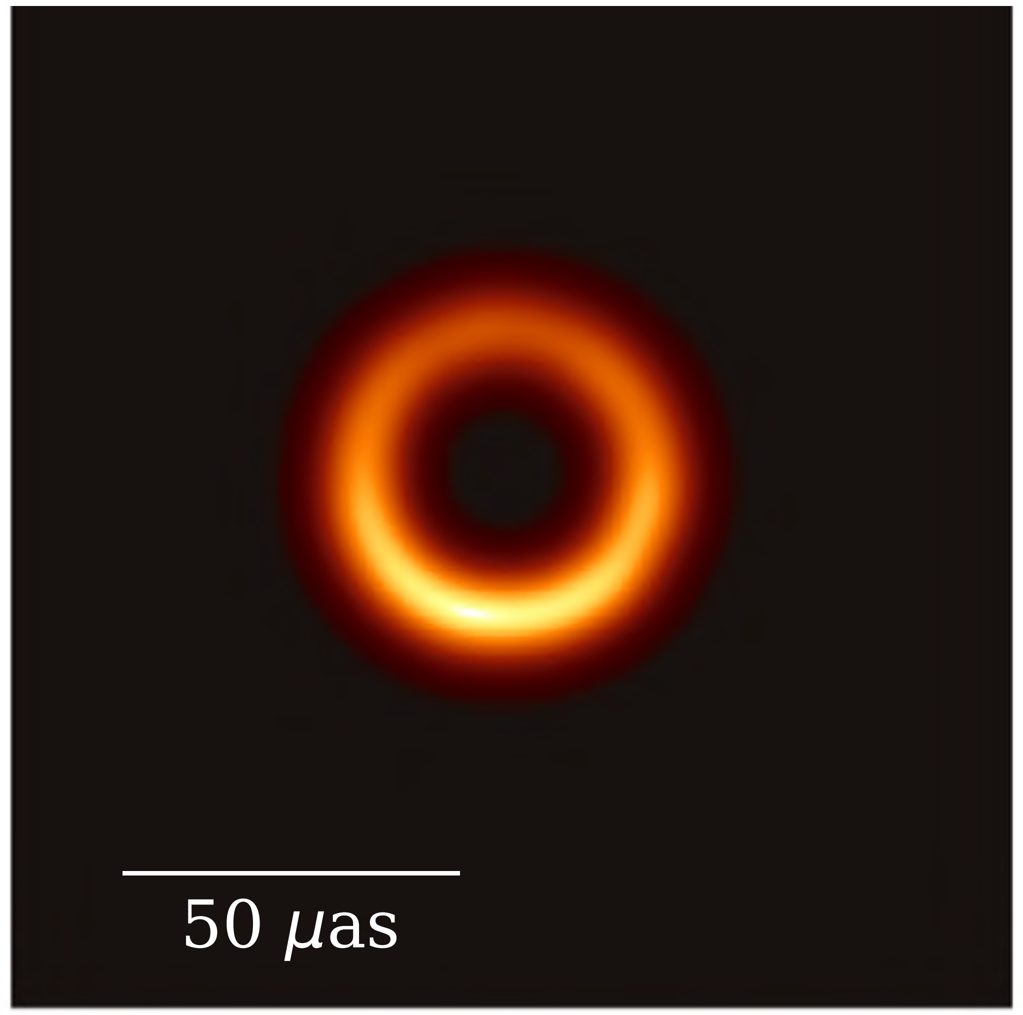
Training Imaging Process

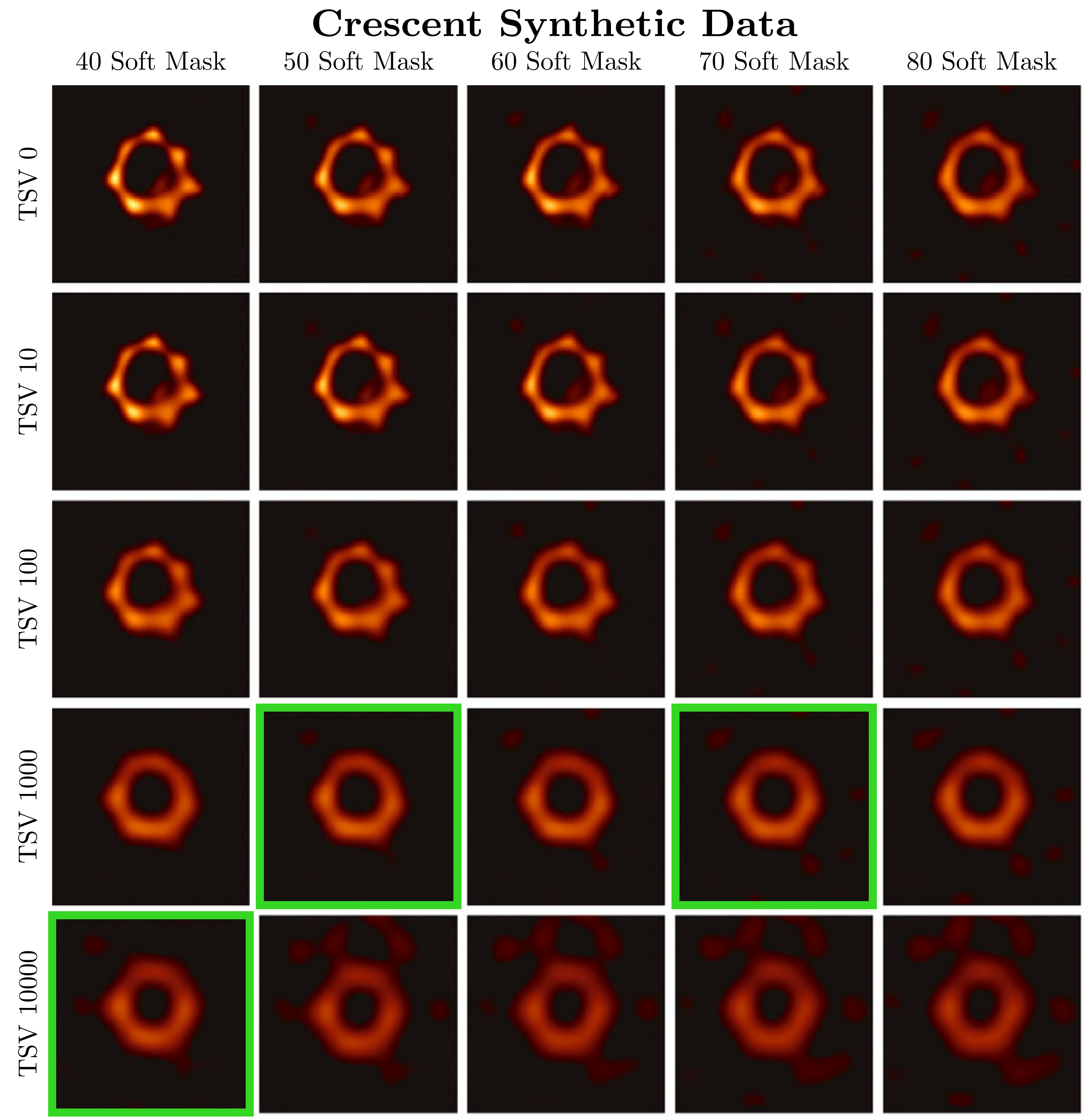
Fiducial Reconstructions

Massive Parameter Surveys

Total 50k parameters

Google Cloud



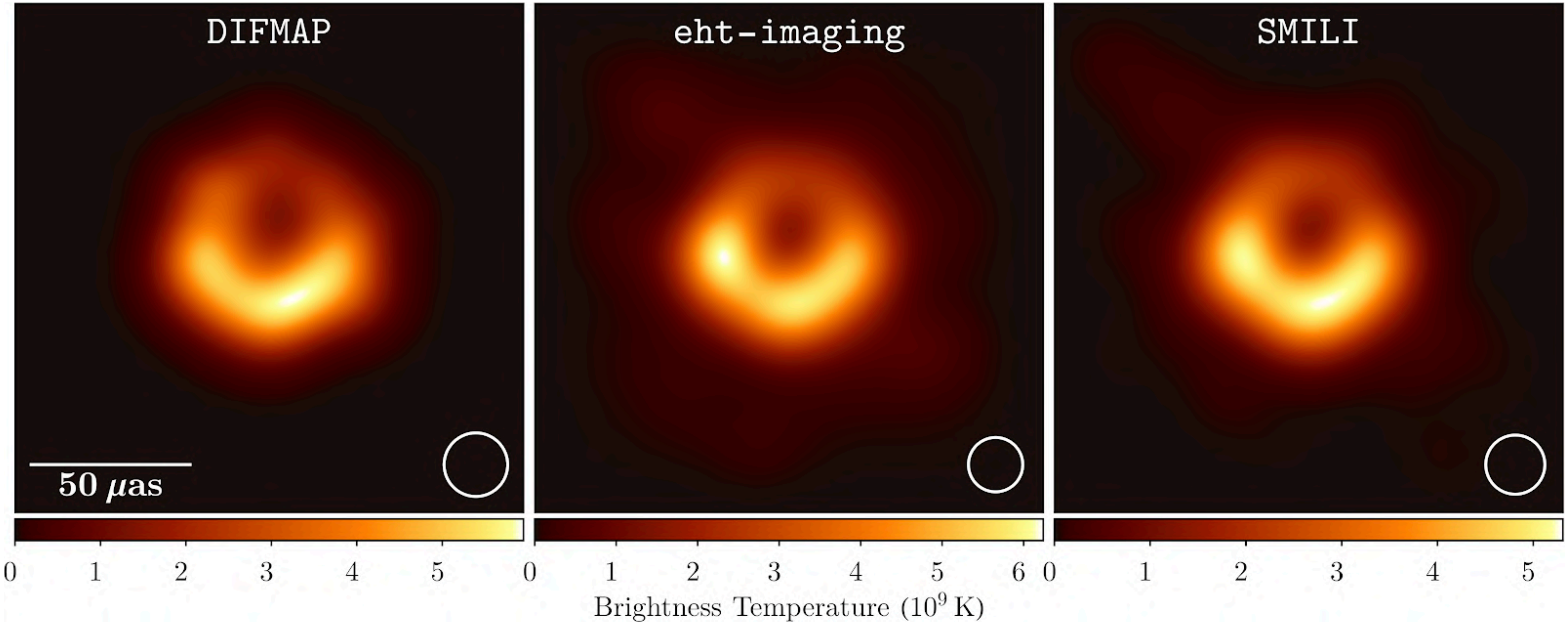


Select Optimal Parameter Sets

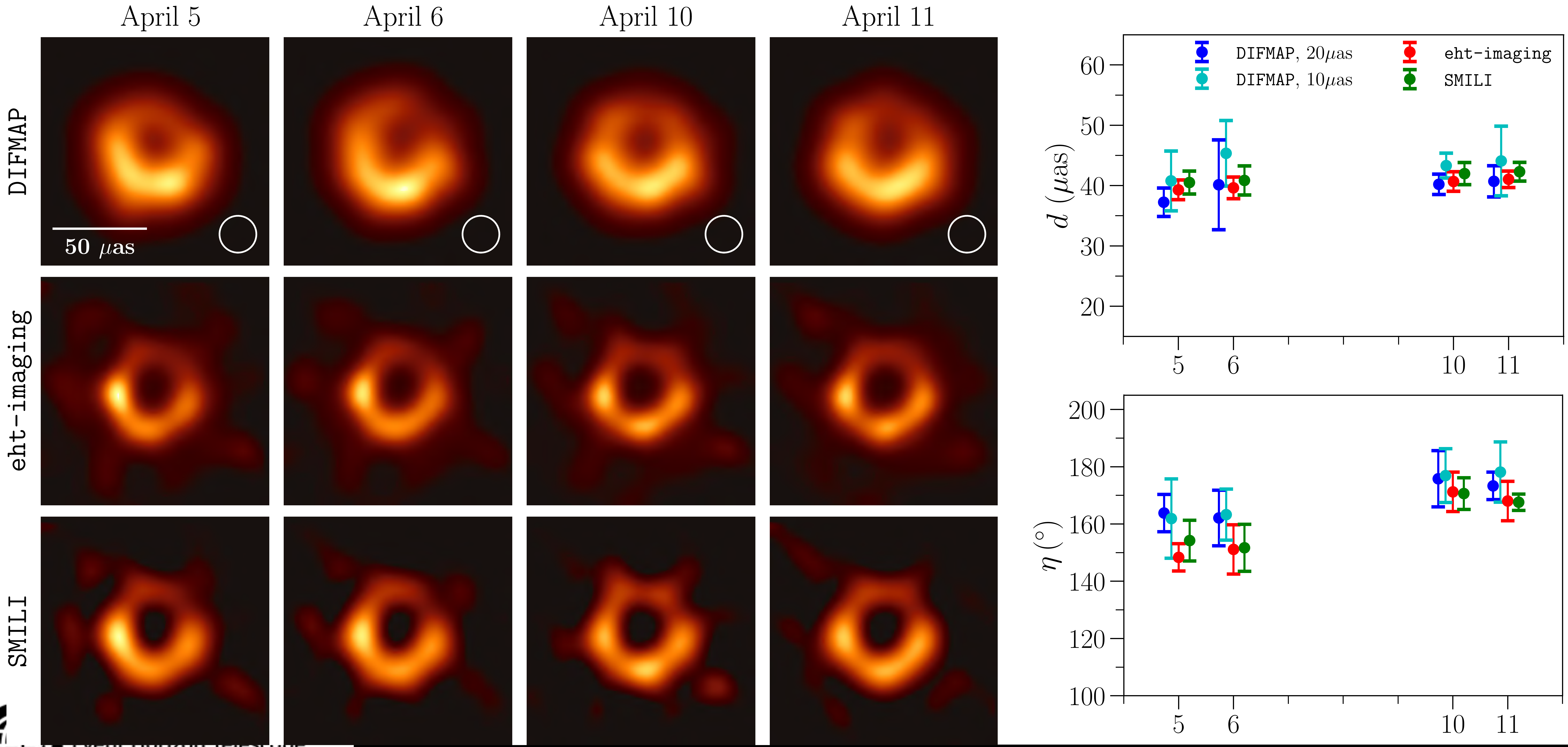
1) Good fits to M87 data
2) Good fidelity to all of synthetic images

Fiducial Images

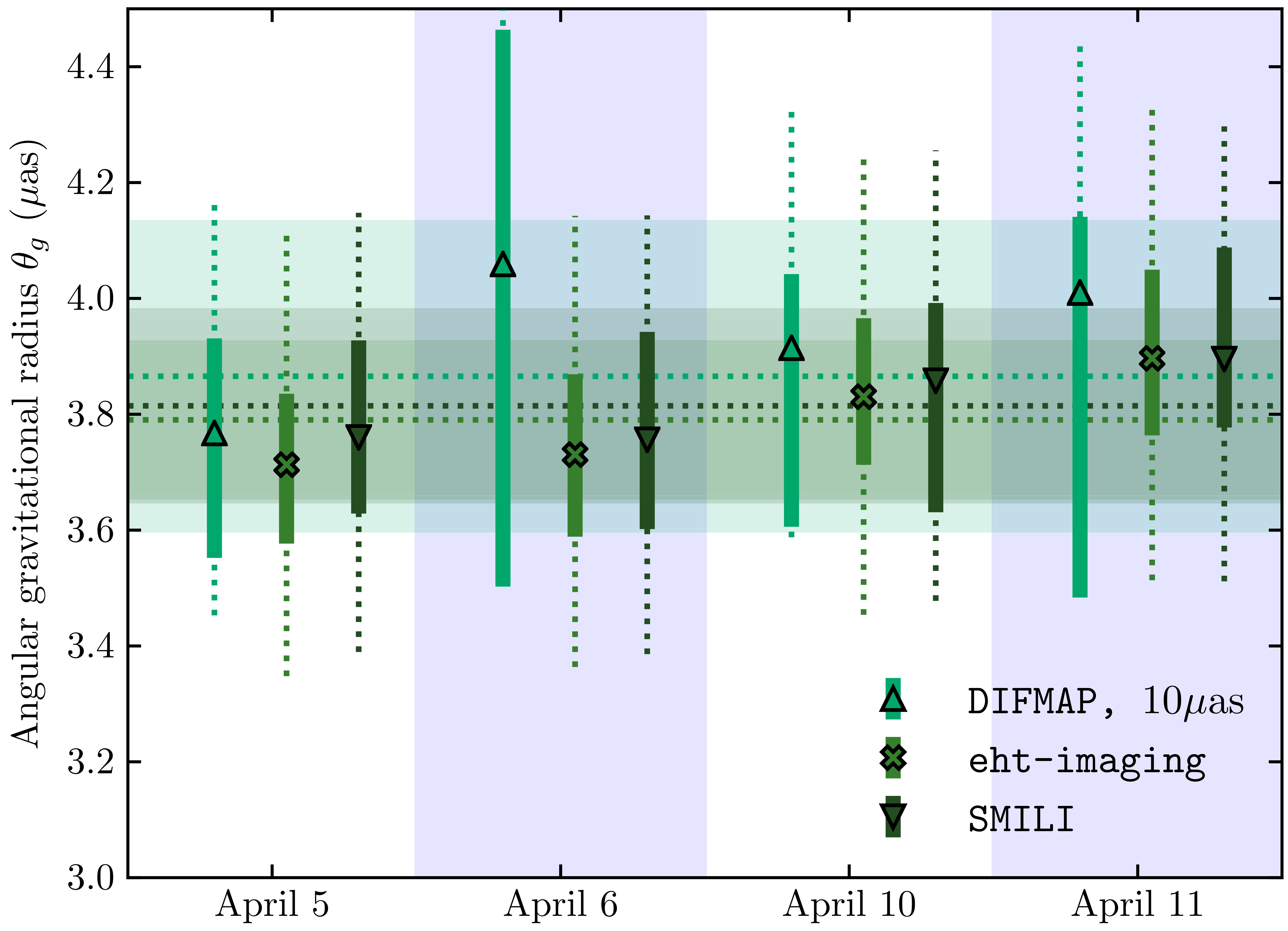
Fiducial images of M87 for April 11 restored to an equivalent resolution show remarkably similar structure



Fiducial M87 Images



Bias-corrected Ring diamaters



(Paper VI)

Event Horizon Telescope

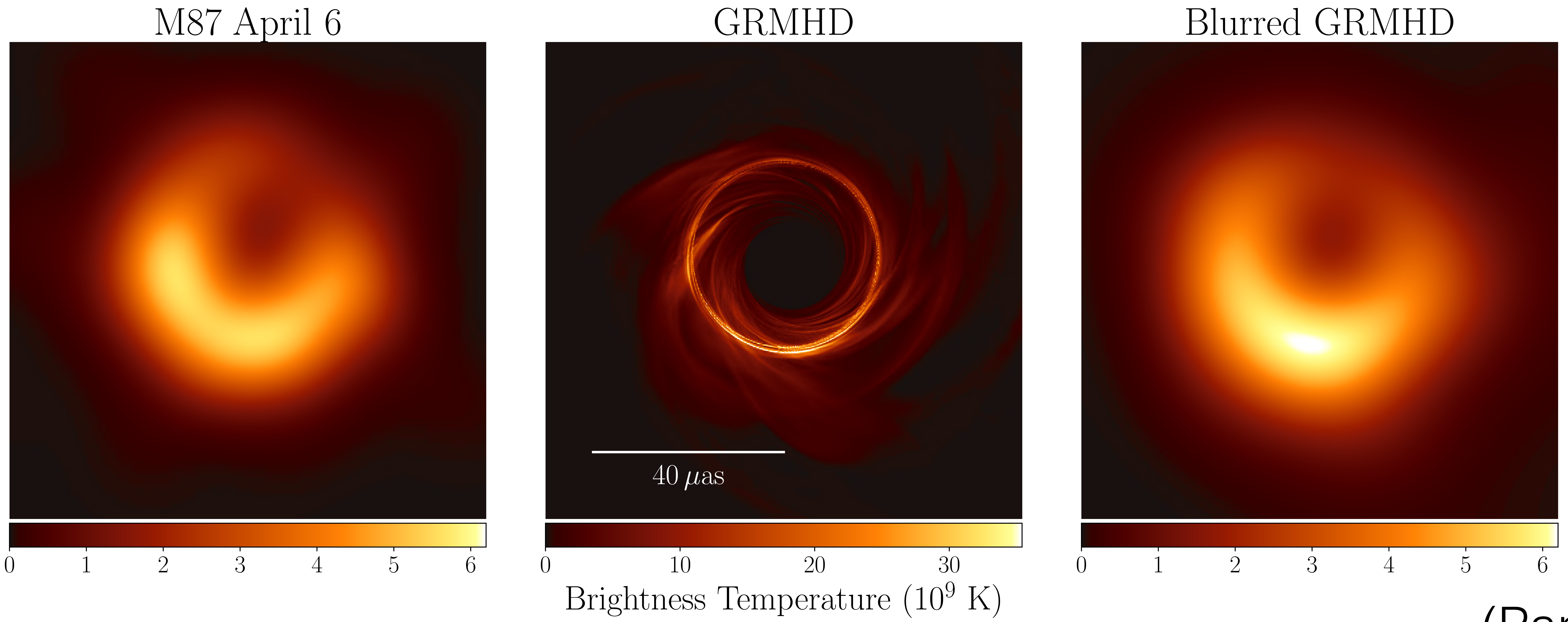
EHT Theory & Simulations

Representative GRMHD Model Image of M87

EHT2017 image

Simulated image from GRMHD model

Simulated image convolved with 20 μas beam



(Paper V)

Simulation Library

- 3D GRMHD simulations from: BHAC, iharm3d, KORAL, H-AMR

- Two accretion states according to accumulated magnetic flux on horizon:
  - SANE (Standard and Normal Evolution)
  - MAD (Magnetically Arrested Disk)

- BH spin parameter:
  - SANE: -0.94, -0.5, 0, 0.5, 0.75, 0.88, 0.94, 0.97, 0.98
  - MAD: -0.94, -0.5, 0, 0.5, 0.75, 0.94

43 GRMHD numerical simulations

Image Library

- 1.3mm modeled images from: ipole, RAPTOR, BHOSS
- Observer inclination angles: i=12, 17, 22, 158, 163, 168 deg
- Thermal electrons:

  Ion/electron temperature ratio depends on R_{high}=(1, 10, 20, 40, 80,160),
  plasma beta $\beta_p \equiv P_g/P_{mag}$.

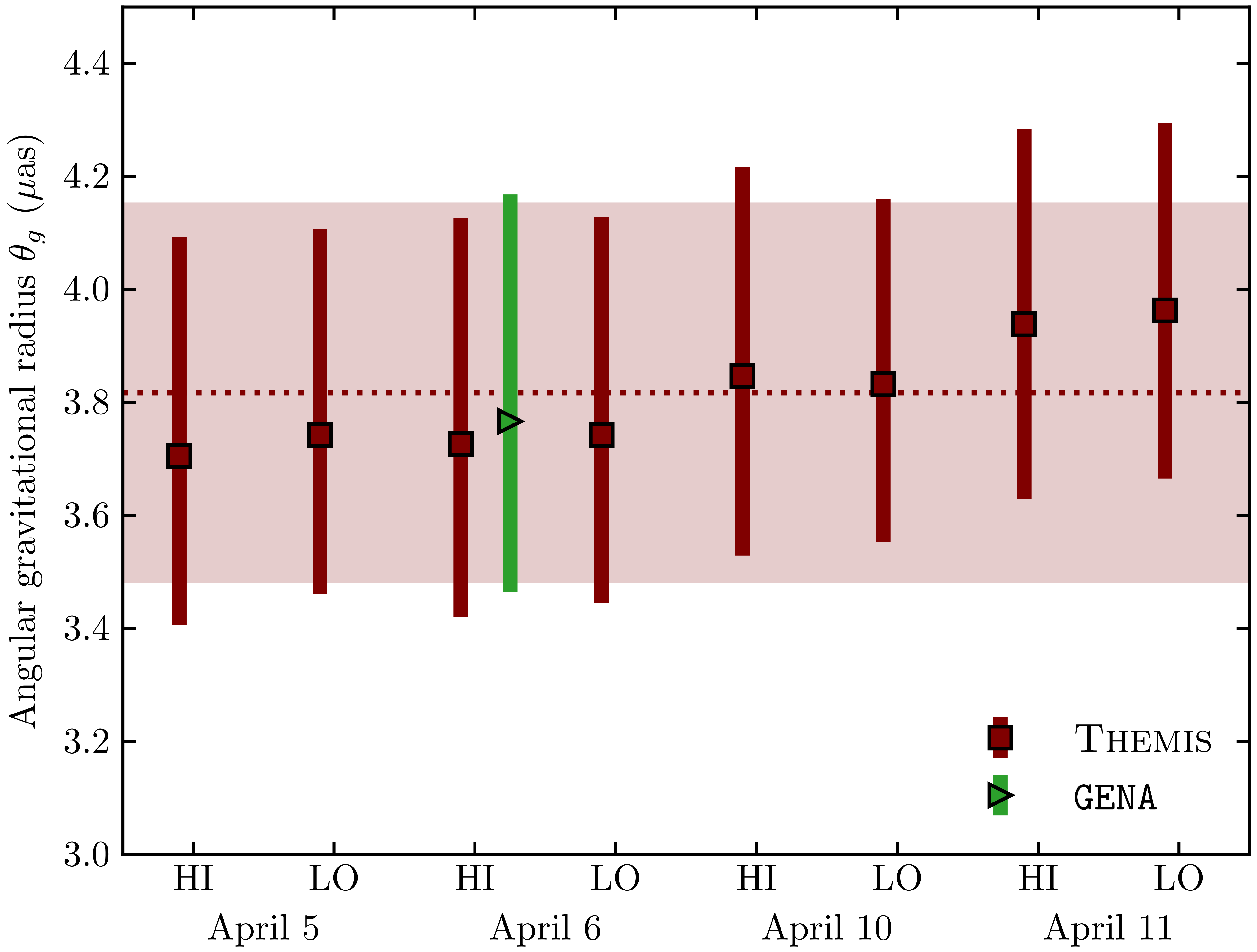
  Electrons colder at high plasma beta (disk), warmer at low plasma beta (jet)

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

> 60,000 images

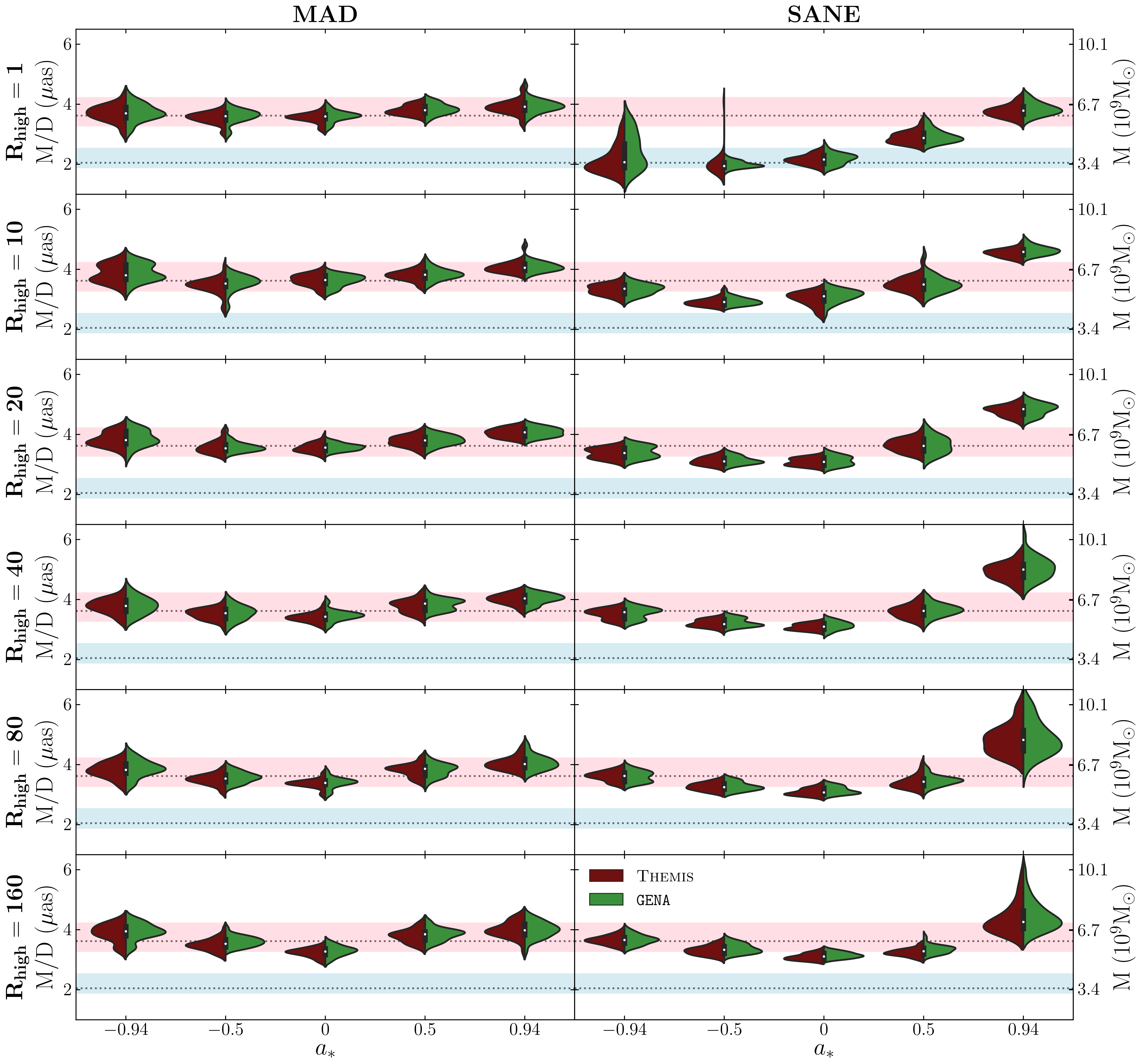
GRMHD model fitting: angular gravitational radius

- Estimate of angular gravitational radius (M/D) using the best 10% of snapshot images from all allowed models



Distribution of M/D

- Distribution of M/D of different BH spin and R_{high} for SANE & MAD models
- BH mass is calculated with D=16.9 Mpc
- Most individual models favour M/D close to 3.6 μas
- a < 0, SANE, R_{high}=1 model favors M/D ~ 2 μas due to outer ring at scale of counterrotating disk ISCO
- a =0.94, SANE favors M/D > 3.6 μas due to secondary inner ring



Event Horizon Telescope

Average Image Scoring Summary

Flux[b]	a_*[c]	$\langle p \rangle$[d]	$N_{\rm model}$[e]	MIN(p)[f]	MAX(p)[g]
SANE	−0.94	0.33	24	0.01	0.88
SANE	−0.5	0.19	24	0.01	0.73
SANE	0	0.23	24	0.01	0.92
SANE	0.5	0.51	30	0.02	0.97
SANE	0.75	0.74	6	0.48	0.98
SANE	0.88	0.65	6	0.26	0.94
SANE	0.94	0.49	24	0.01	0.92
SANE	0.97	0.12	6	0.06	0.40
MAD	−0.94	0.01	18	0.01	0.04
MAD	−0.5	0.75	18	0.34	0.98
MAD	0	0.22	18	0.01	0.62
MAD	0.5	0.17	18	0.02	0.54
MAD	0.75	0.28	18	0.01	0.72
MAD	0.94	0.21	18	0.02	0.50

- Compare:
  data - ⟨model⟩
  model - ⟨model⟩
  using Themis-AIS
- Rejects a = -0.94 MAD models
- This model exhibit highest morphological variability

Radiative Equilibrium

- Calculate radiative efficiency, $\epsilon \equiv L_{\rm bol}/(\dot{M}c^2)$
- Reject model if $\varepsilon > \varepsilon$(classical thin disk model); inconsistent; would cool quickly
- $L_{\rm bol}$: calculated by Monte Carlo code: grmonty
- Rejects MAD models with $a \geq 0$ and $R_{\rm high} = 1$ (hot midplane electrons)

X-ray constraint

- X-ray data: simultaneously Chandra, NuSTAR observations during EHT2017 Campaign
  - 2-10 keV luminosity: $L_X = 4.4 \pm 0.1 \times 10^{40}$ erg/s

- Compare data to SEDs generated from simulations
  - X-ray flux is produced by inverse Compton scattering of synchrotron photons

- Reject models that consistently *overproduce* X-ray

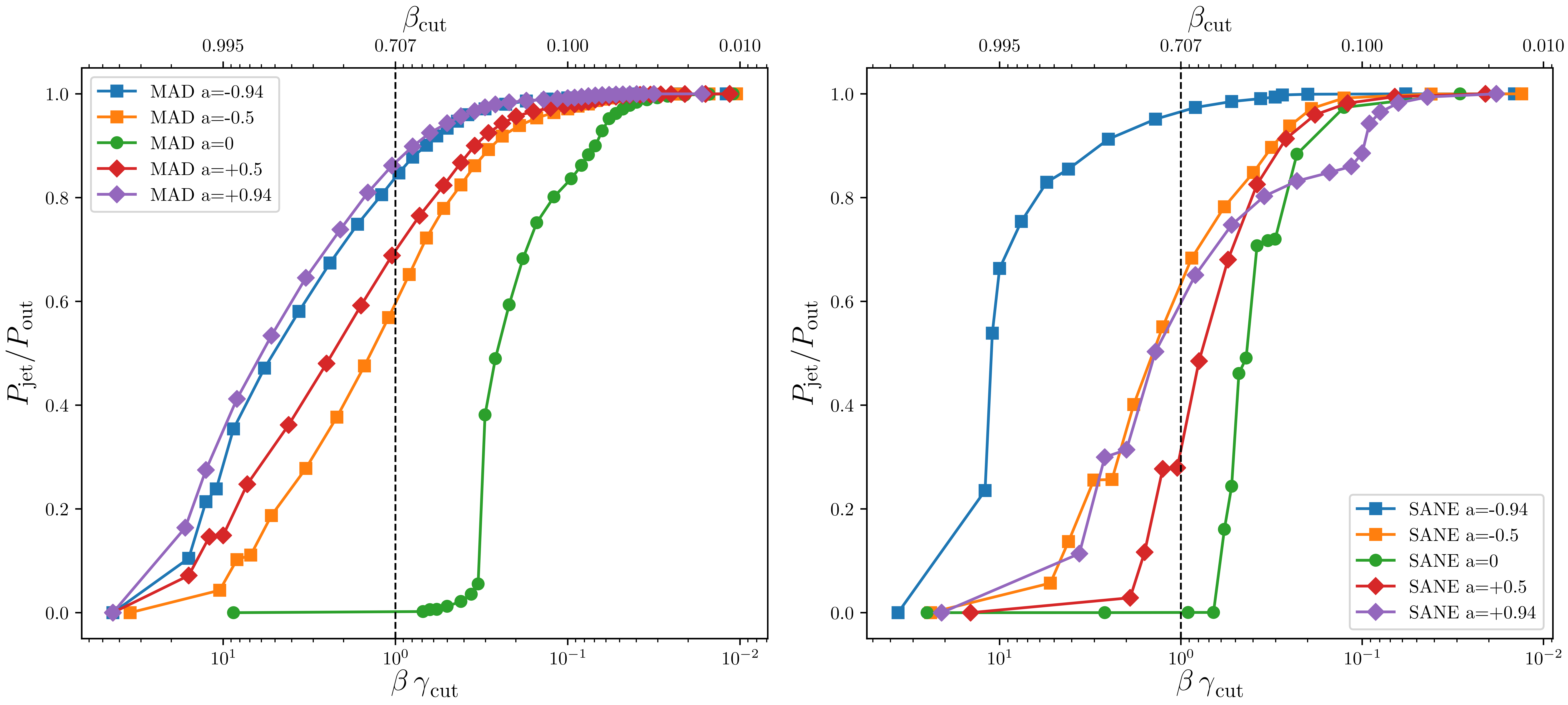
- Overluminous model: mostly SANE with $R_{high} \leq 20$.

- L_X is sensitive to R_{high}, very low values of R_{high} are disfavored.

Jet Power

- M87's jet power (P_{jet}) estimates range from 10^{42} to 10^{45} erg/s
- Adopt conservative lower limit on jet power, $P_{jet,min} = 10^{42}$ erg/s
- P_{jet} defined as total energy flux in polar regions where $\beta\gamma > 1$
- P_{out} defined as energy flux in all polar outflow regions (includes wide-angle, low velocity wind)
- P_{out} is *maximal* definition of jet power
- Constraint $P_{jet} > P_{jet,min} = 10^{42}$ erg/s rejects all a=0 models ($P_{jet} = 0$). These models also have $P_{out} < 10^{42}$ erg/s
- SANE models with $|a| < 0.5$ rejected
- Most $|a| > 0$ MAD models acceptable
- P_{jet} dominated by Poynting flux; driven by extraction of black hole spin energy through Blandford-Znajek process

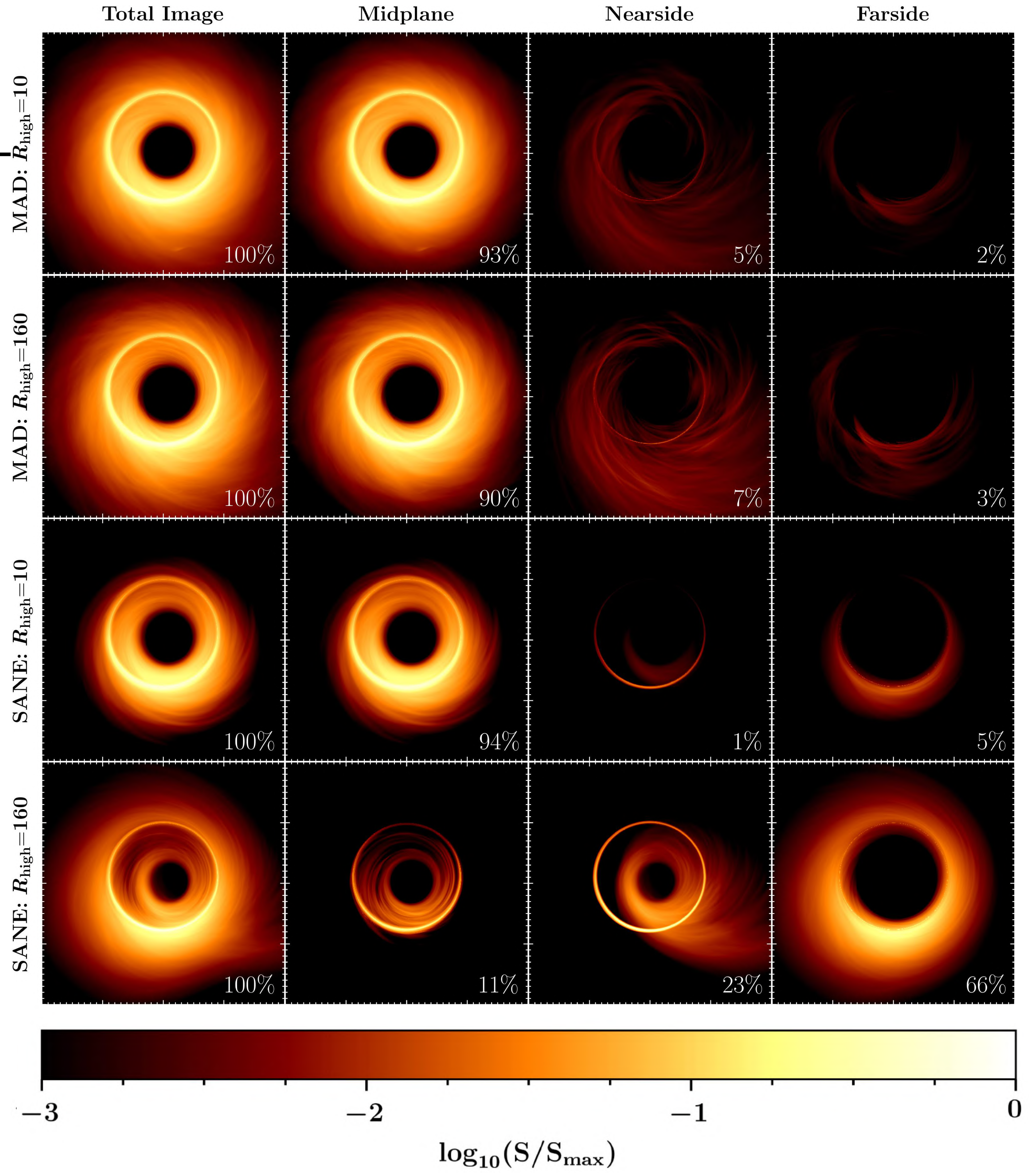
P_{jet}/P_{out} vs $\beta\gamma_{cut}$



- P_{jet} depends on $\beta\gamma$ cutoff used in definition
- P_{jet} small for a = 0 because energy flux in relativistic outflow is small

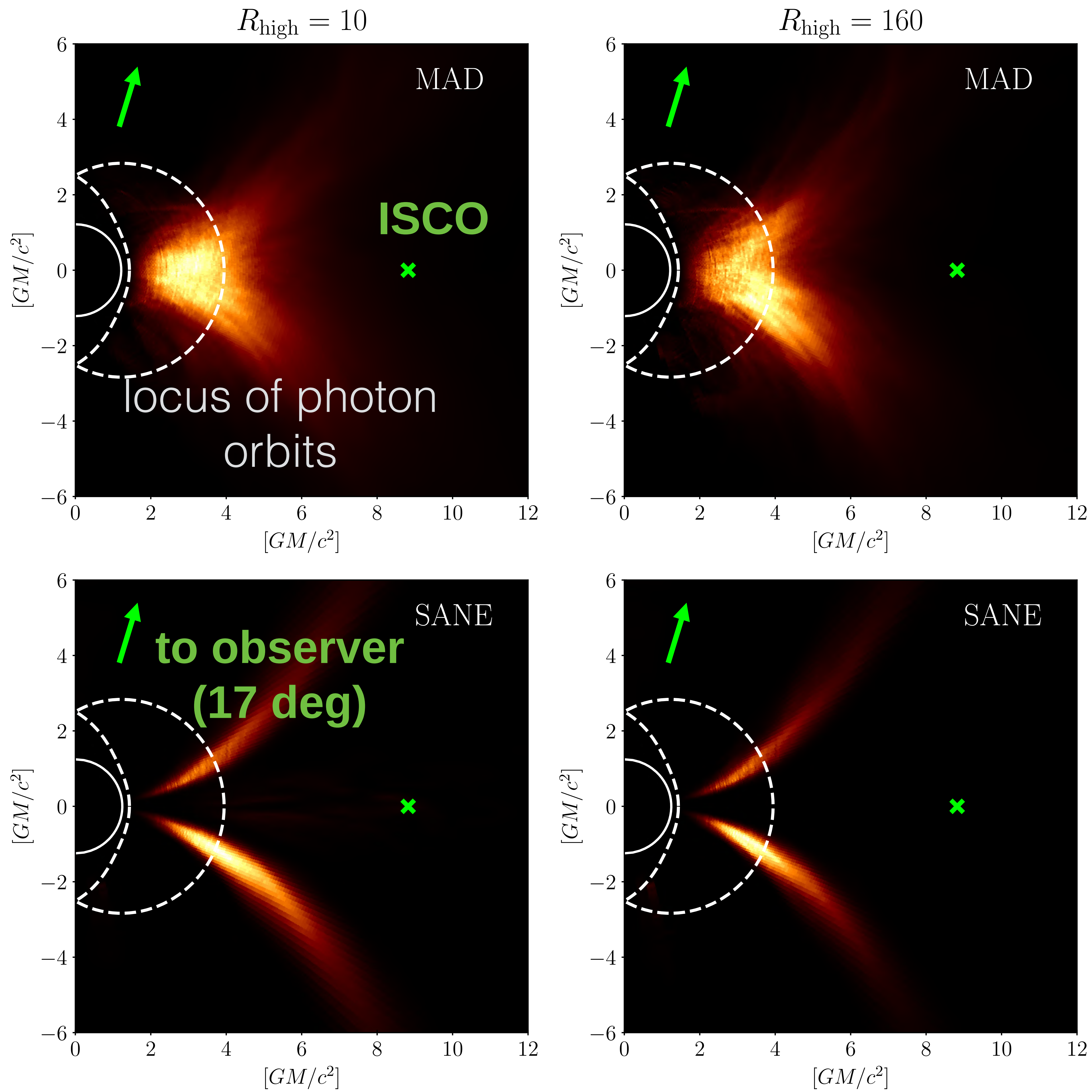
Image decomposition

- Decompose into components: midplane, nearside (within 1 rad of polar axis nearest to the observer), and farside (within 1 rad of polar axis furthest form the observer)
- MAD, SANE at low R_{high} (hot midplane): midplane emission dominates
- SANE with high R_{high} (cold midplane): farside emission dominates



Event Horizon Telescope

Where do mm photons originate?



Retrograde case

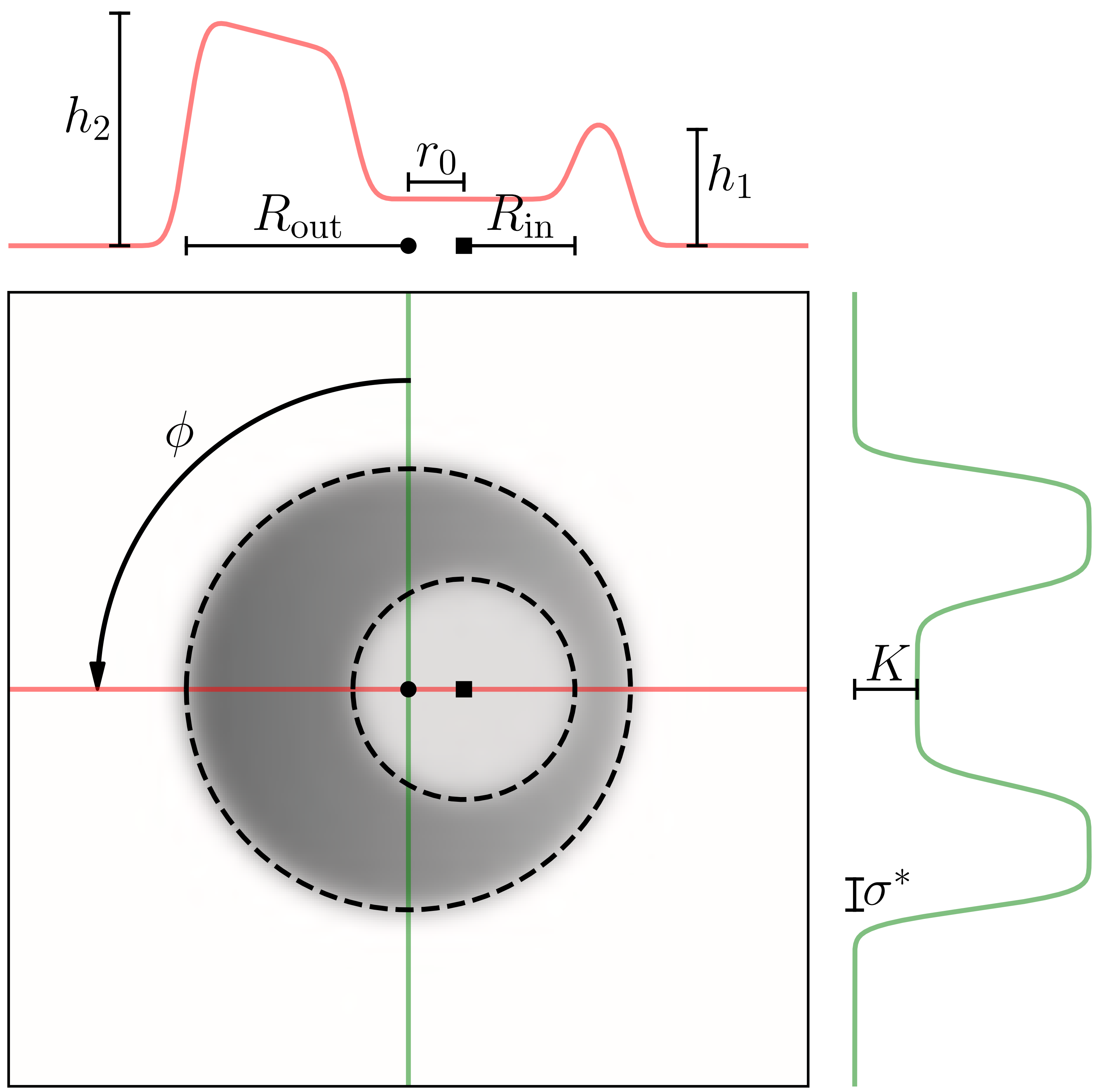
MAD, a=-0.94

SANE, a=-0.94

EHT Model Fitting

Quantify M87 Source Properties

Fit geometrical crescent models



Fit GRMHD models

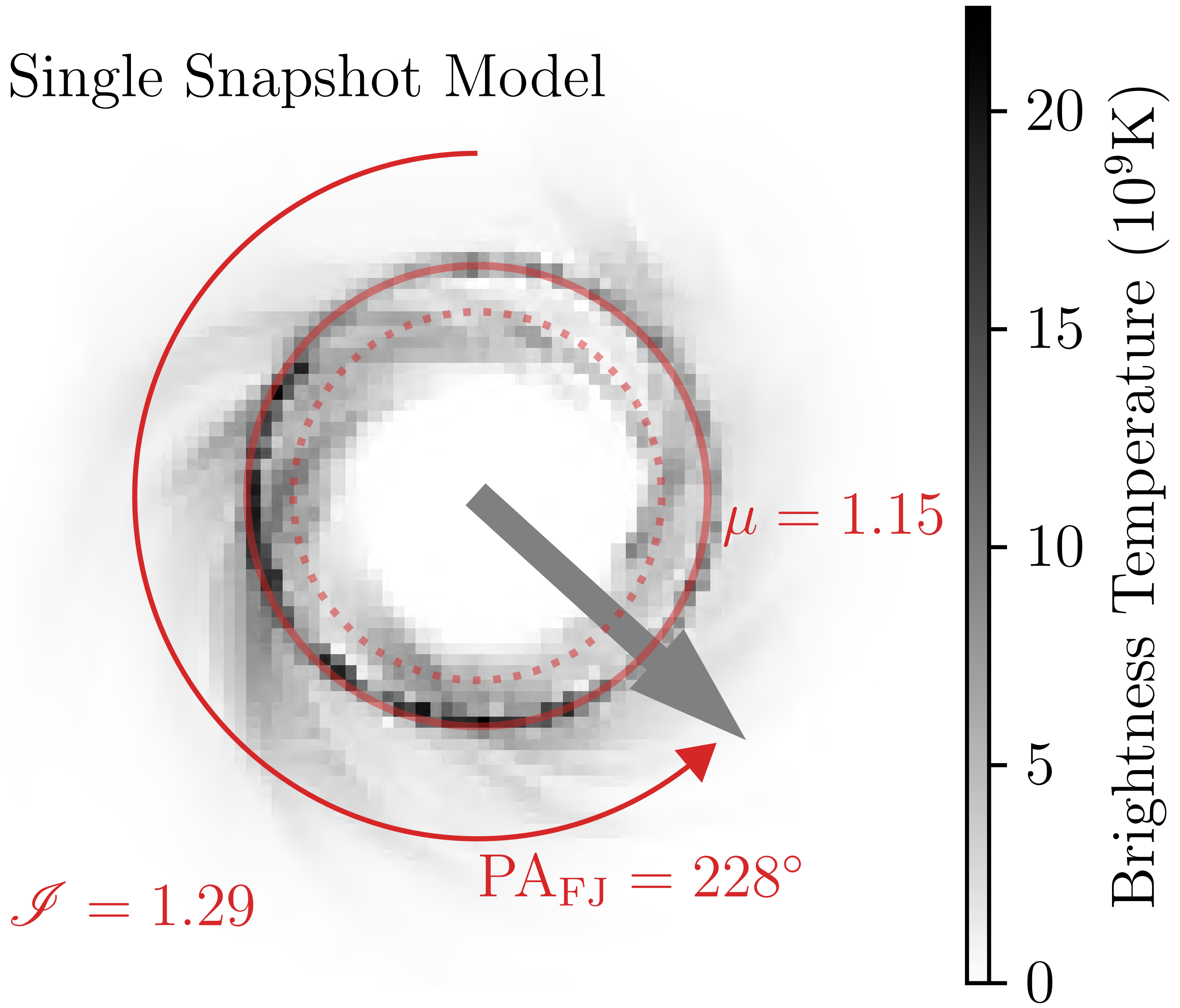
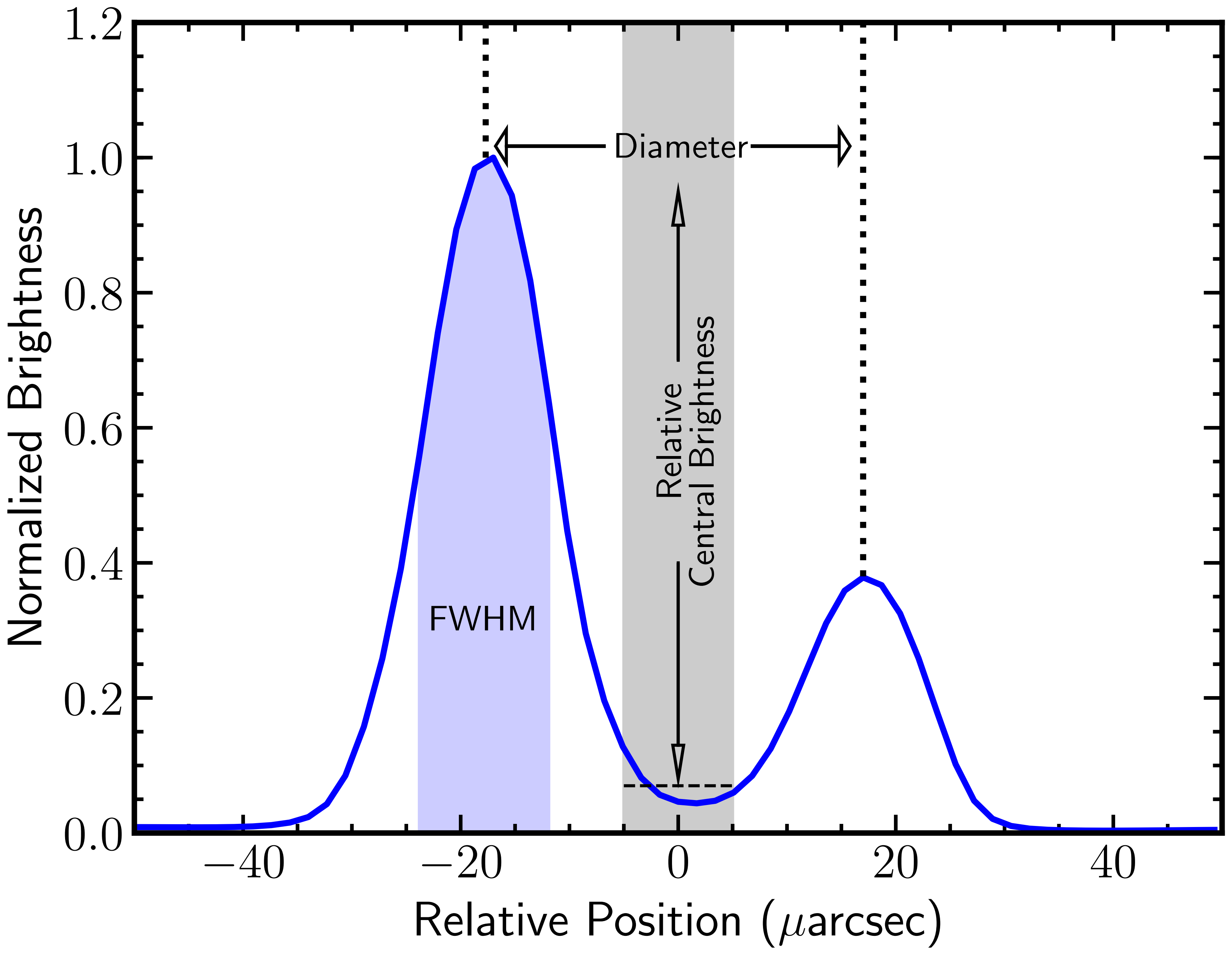


Image domain feature extraction

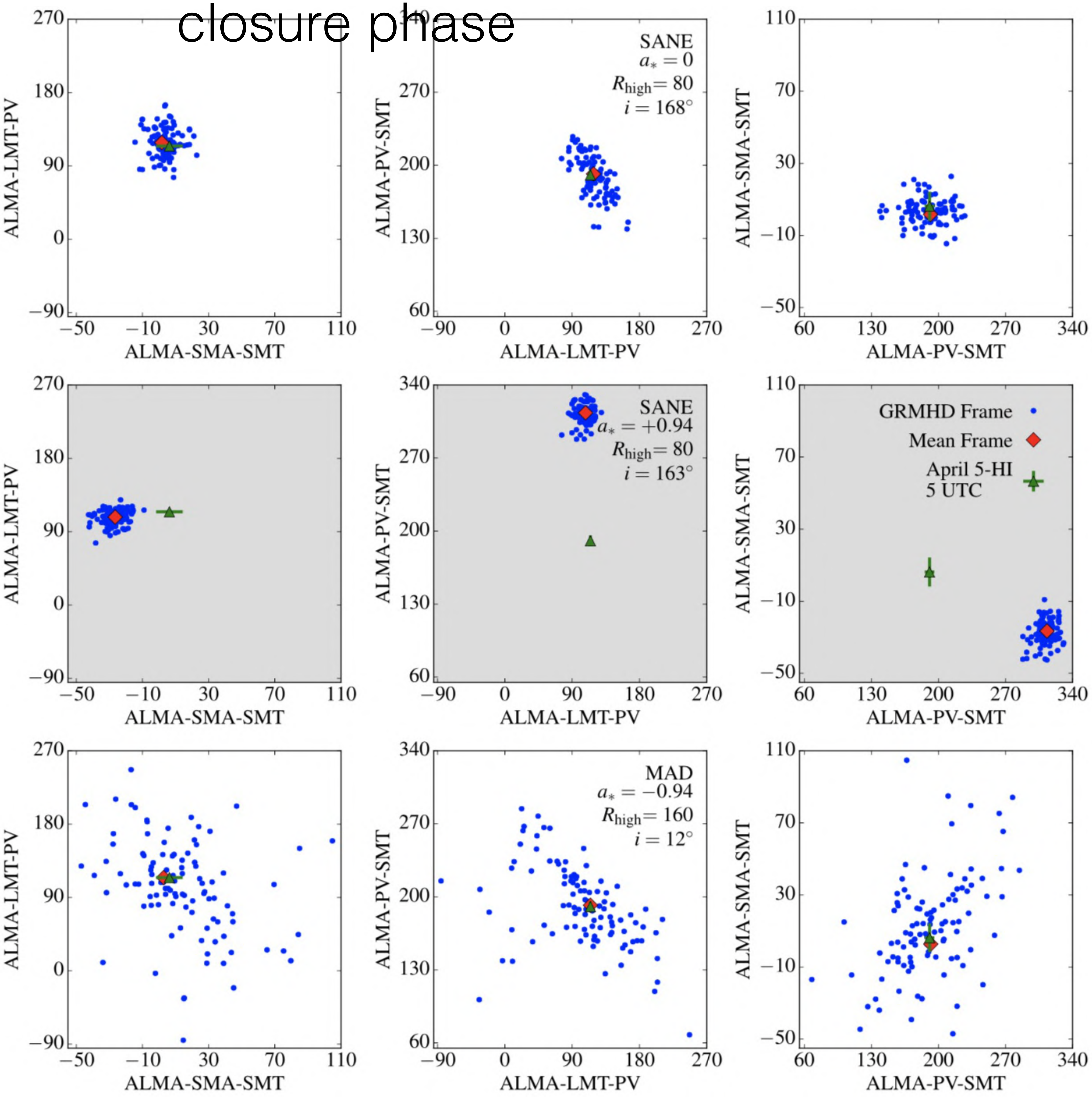


(Paper VI)

Average Image Scoring

Themis-AIS procedure for scoring theoretical model

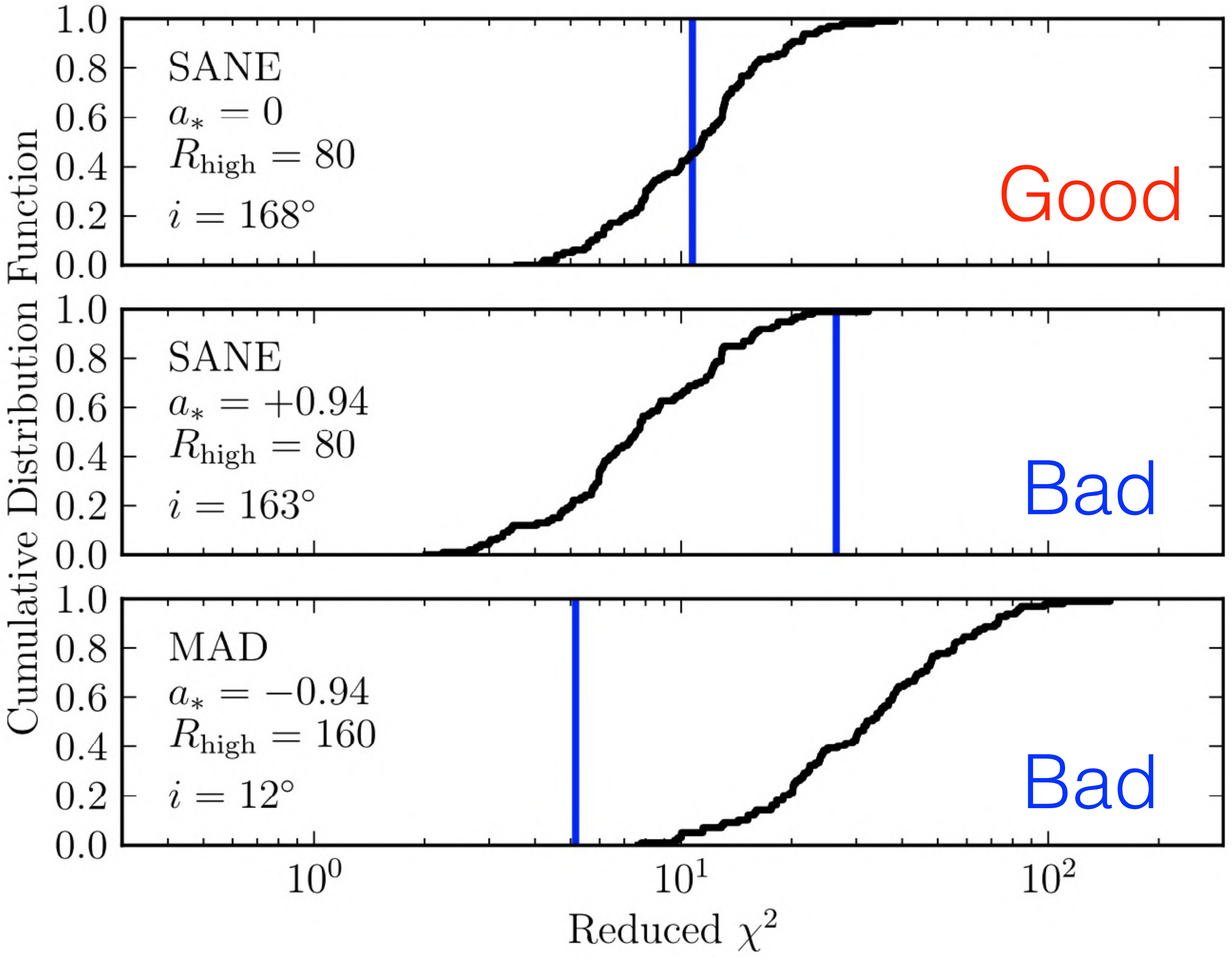
closure phase



Good model

Bad model

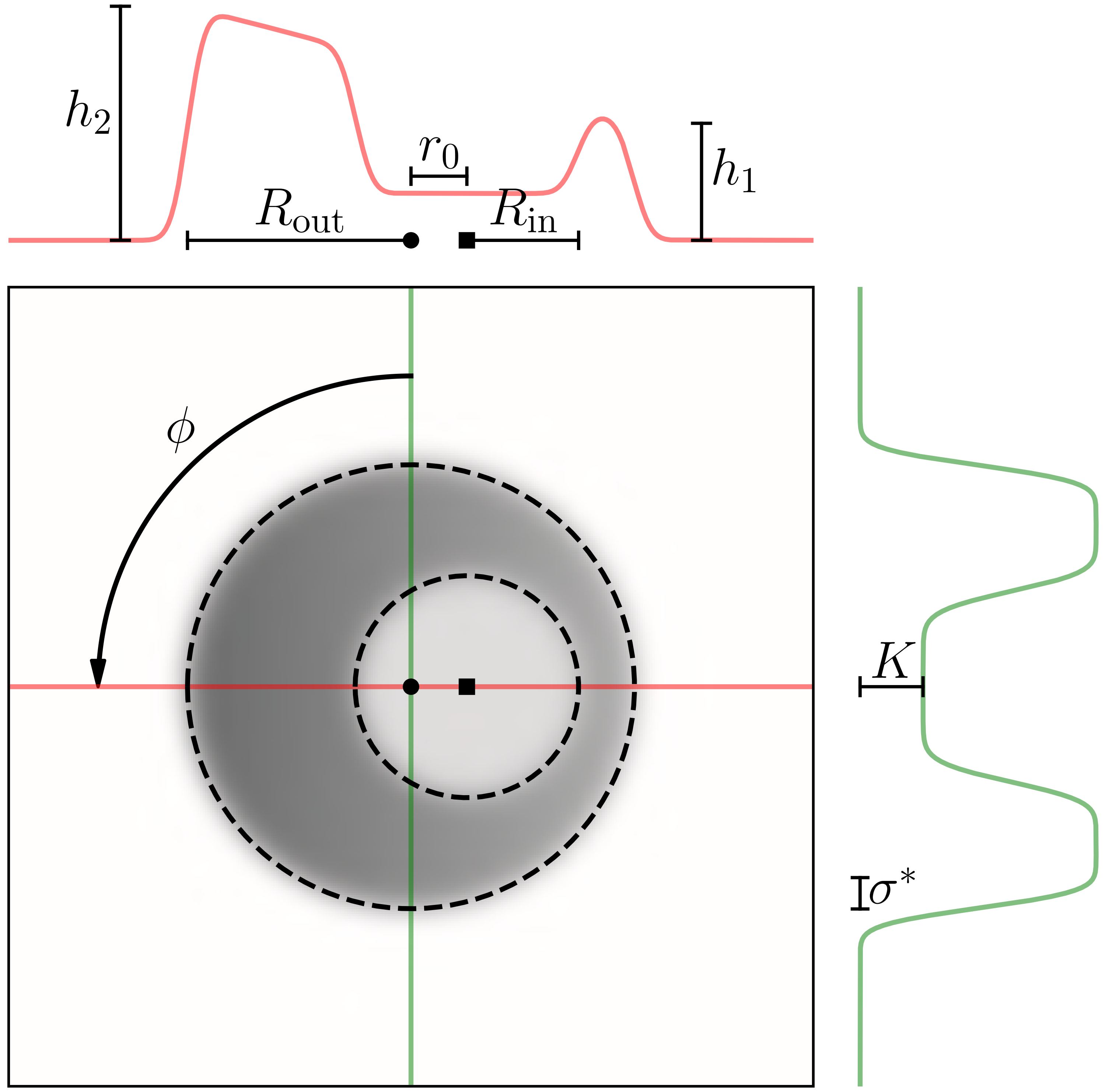
Bad model



Event Horizon Telescope

Quantify M87 Source Properties

Fit geometrical crescent models



Fit GRMHD models

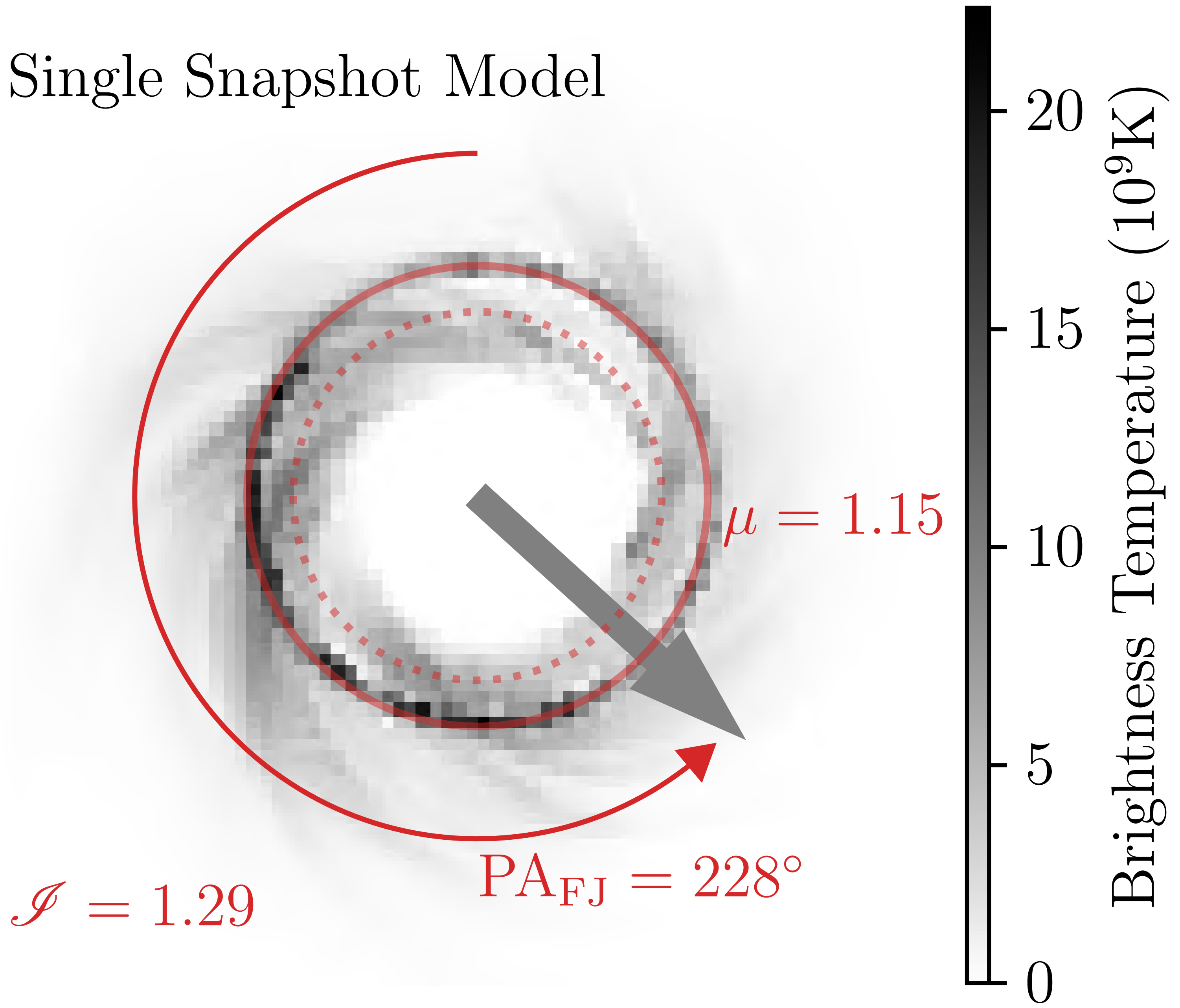
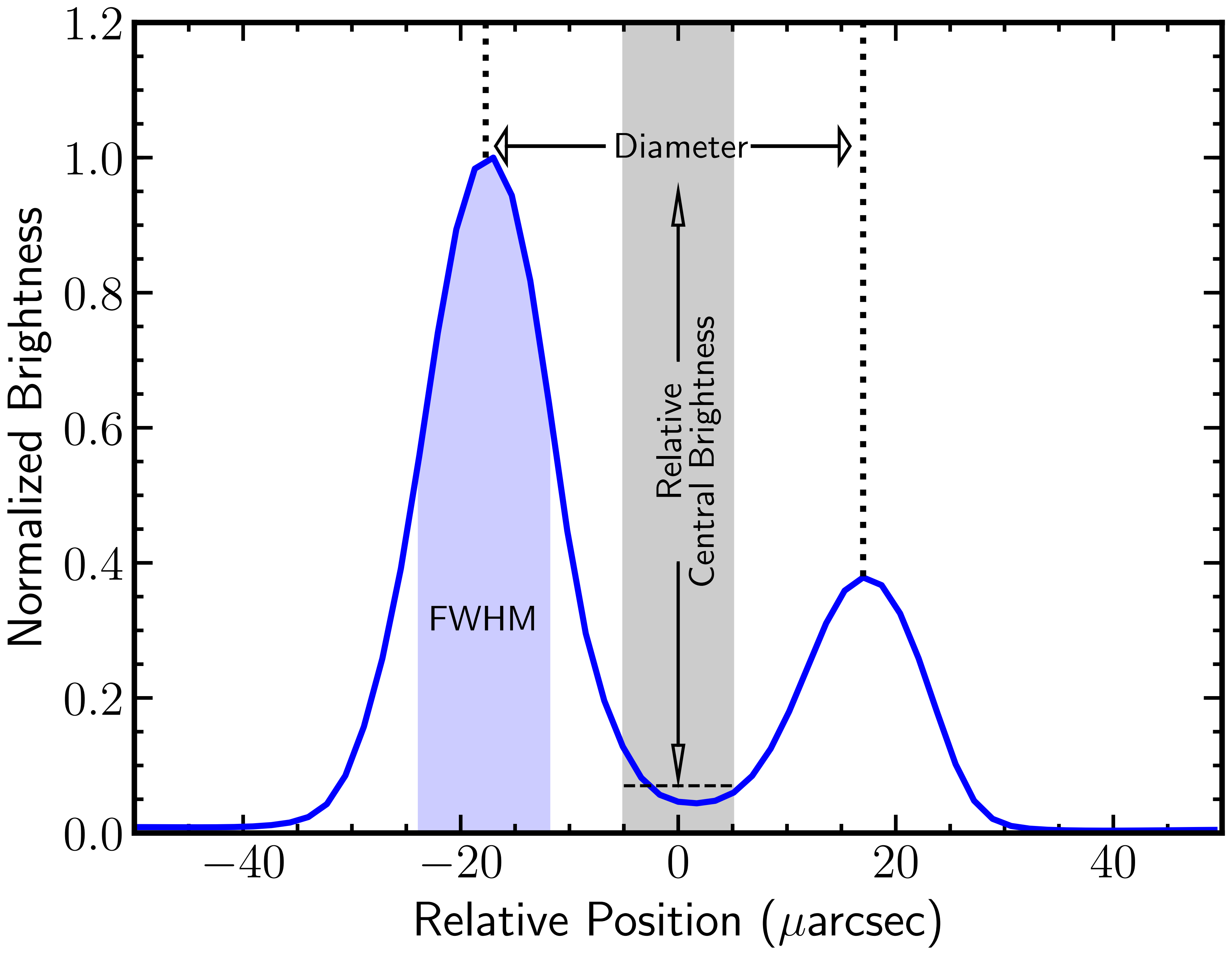


Image domain feature extraction

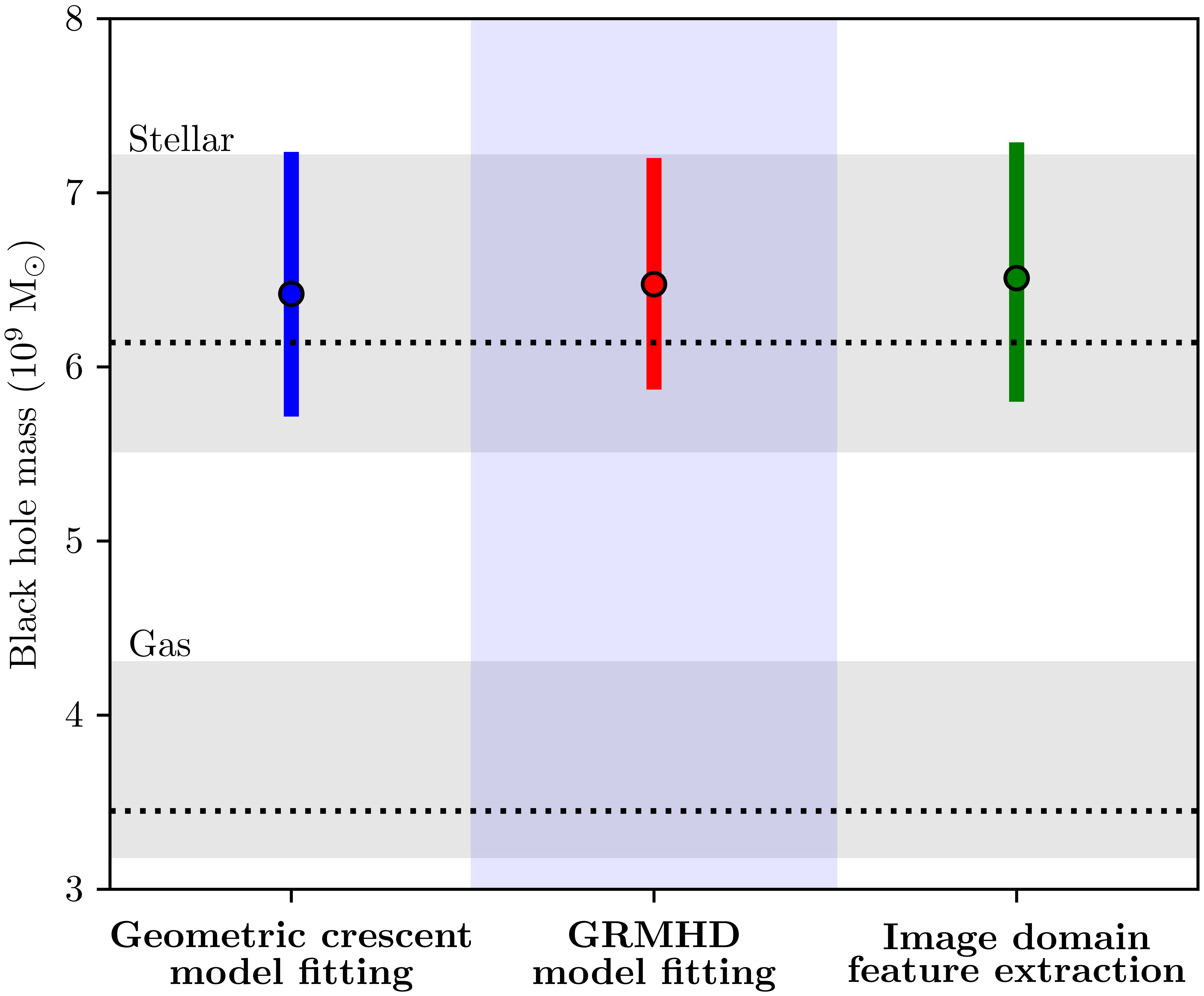


(Paper VI)

Event Horizon Telescope

Black Hole Mass Measurements

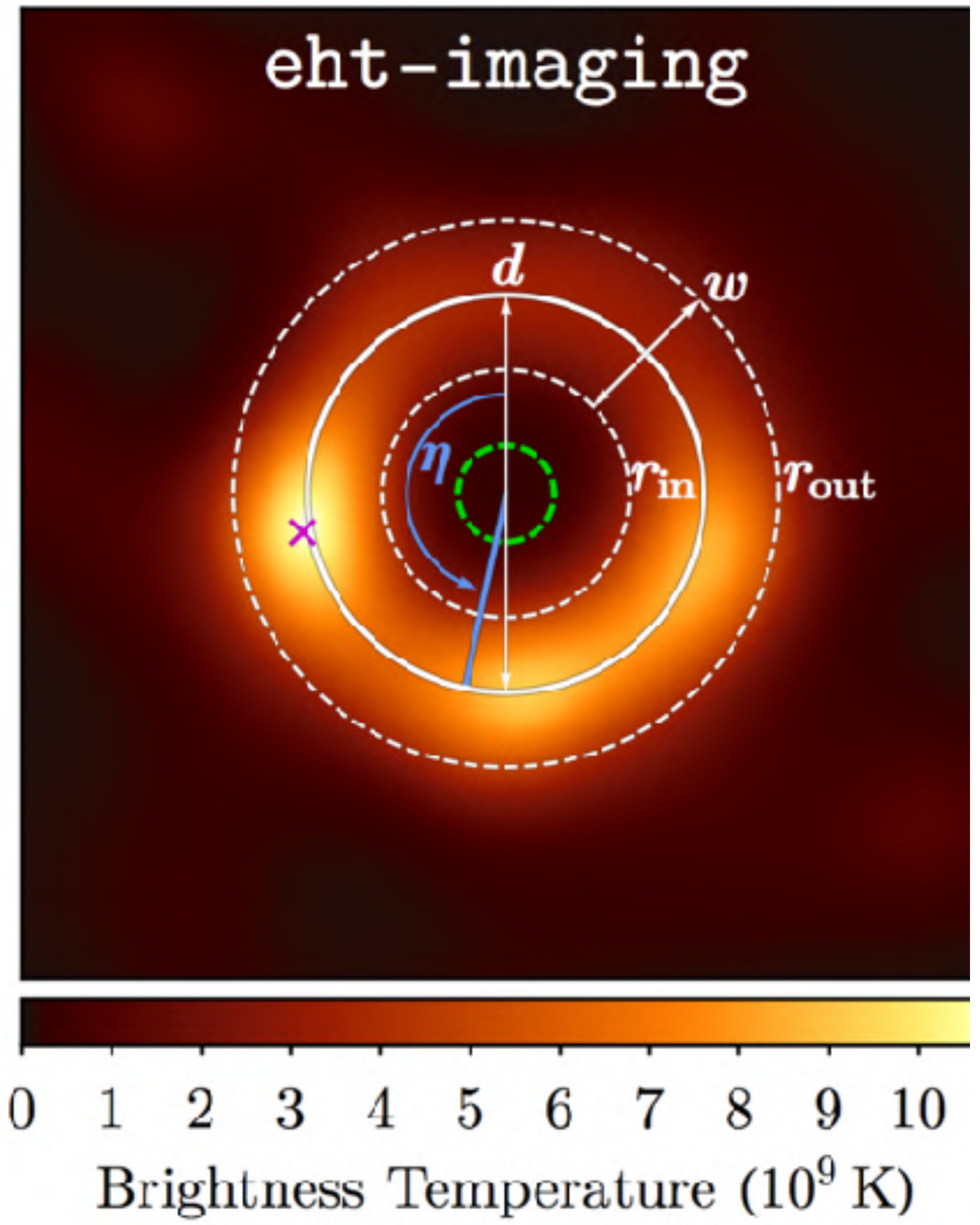
- $M = 6.5 \pm 0.7 \times 10^9\ M_{sun}$ (using $D = 16.8 \pm 0.7$ Mpc)
- Three methods in excellent agreement
- Excellent agreement with stellar dynamics mass estimate (Gebhardt+2011)

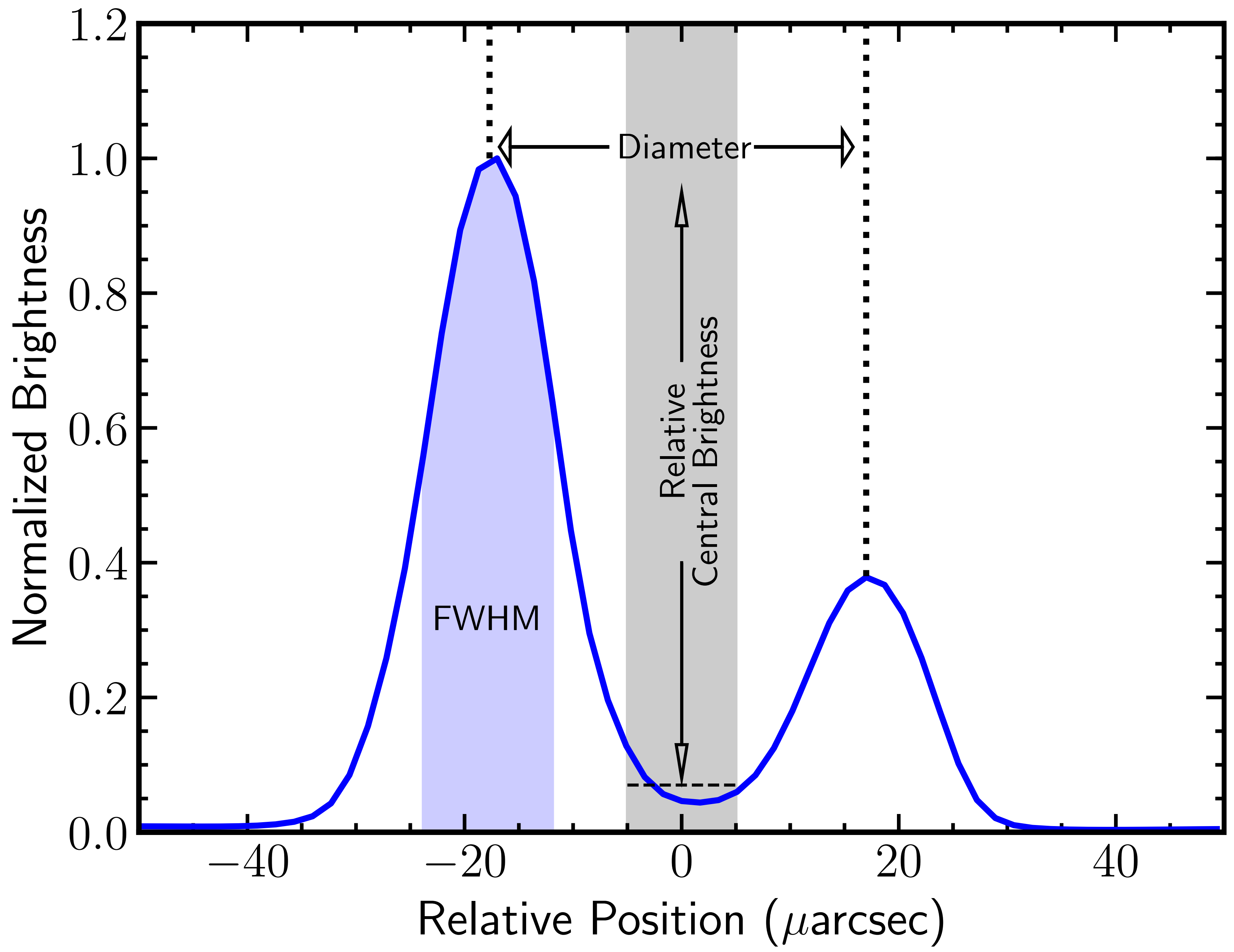


(Paper VI)

Image Domain Feature Extraction

- Independent measurements of shadow diameter and width





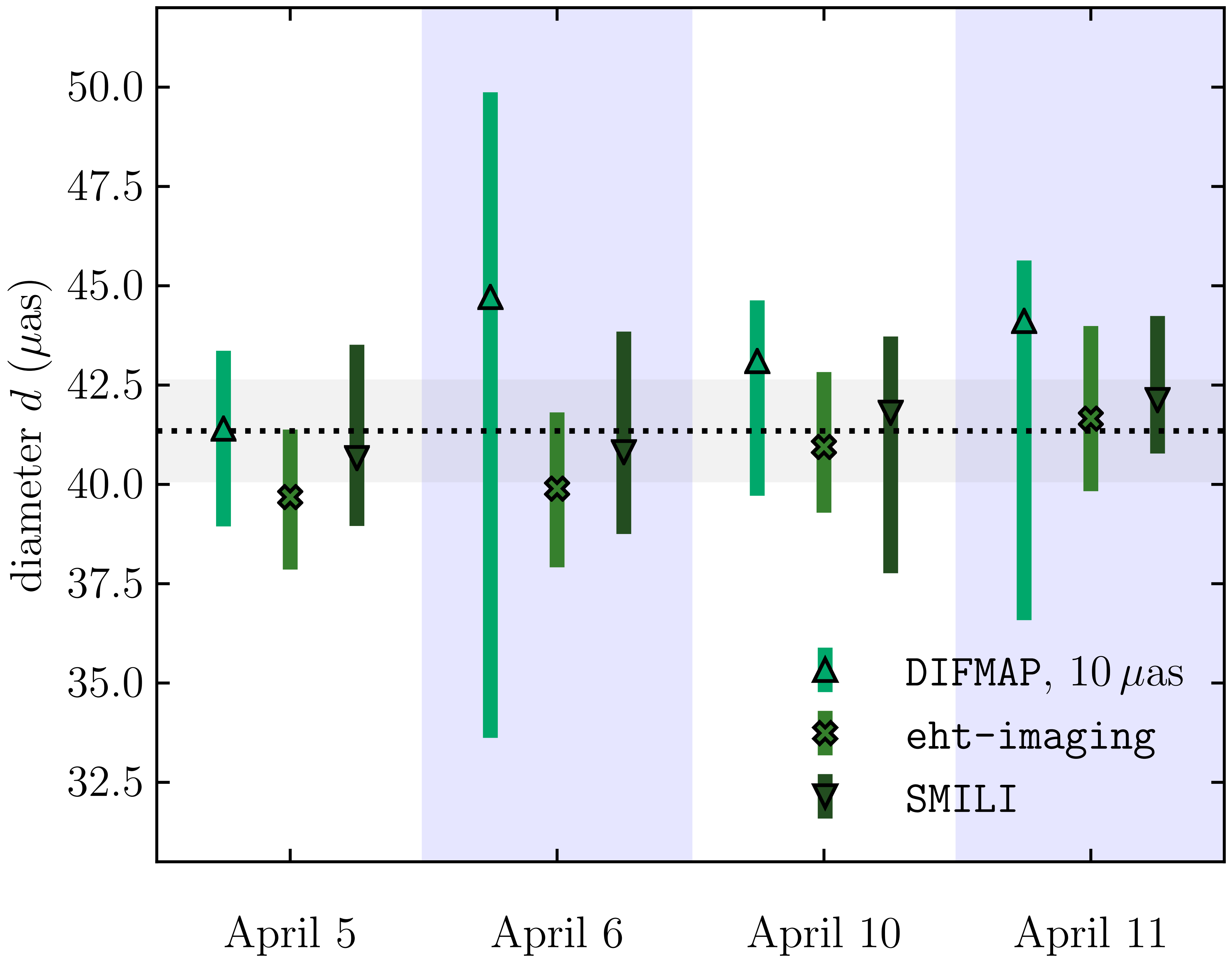


Image Circularity

- At low inclination of M87, shadow shape should be extremely circular for all values of black hole spin (e.g. Chan+2013)
- From reconstructed images, we measure an emission region that is circular to within ~4:3 in axis ratio
- Result is consistent with expectations from GRMHD models of M87
- Future: get to circularity of shadow and photon ring