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

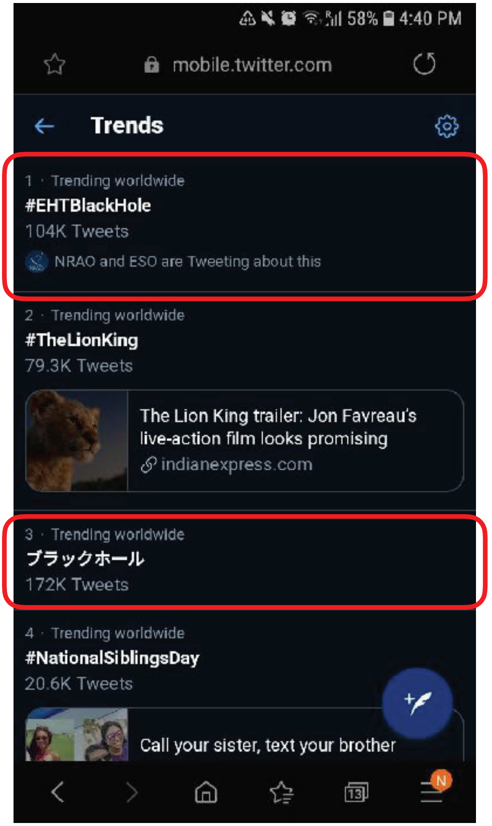
Yosuke Mizuno
Institute for Theoretical Physics
Goethe University Frankfurt

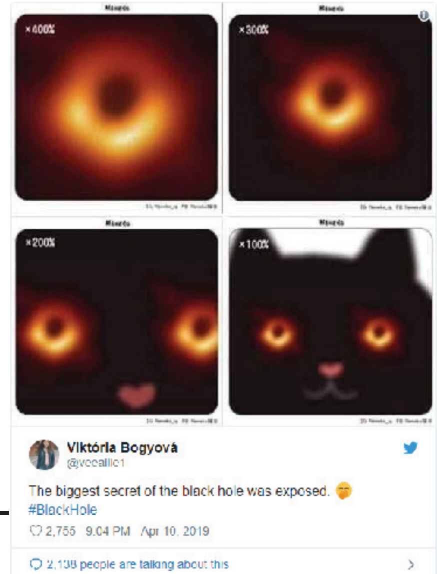
on behalf of Event Horizon Telescope collaboration

ECT* workshop: Simulating Gravitation and Cosmology in Condensed Matter and Optical System, Trento, Italy, 22-26, July, 2019

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

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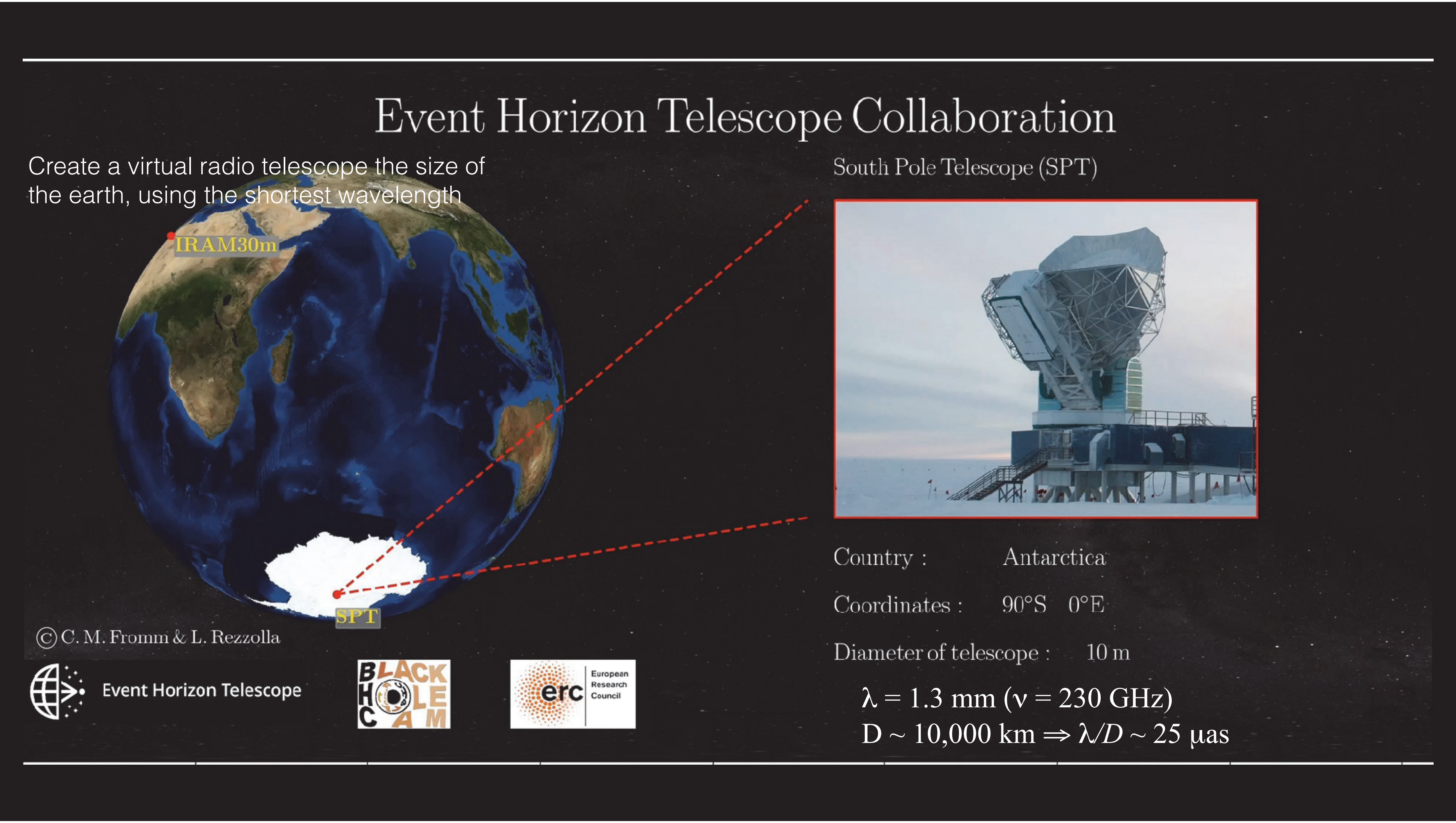
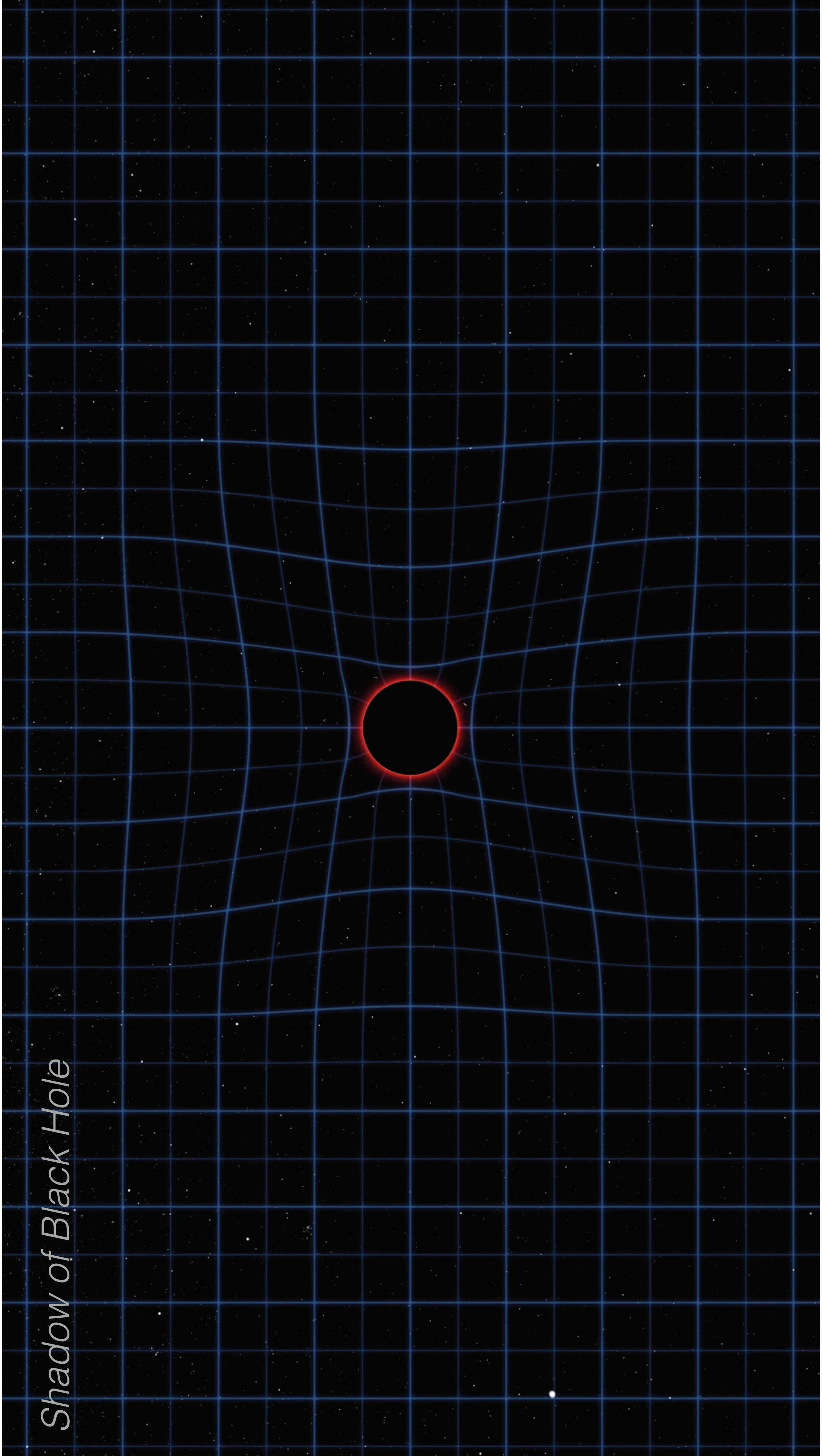
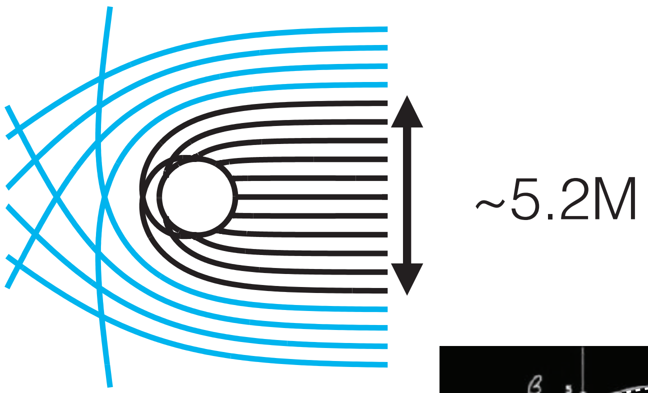

Event Horizon Telescope Collaboration
Create a virtual radio telescope the size of the earth, using the shortest wavelength
IRAM30m
SPT
South Pole Telescope (SPT)
Country : Antarctica
Coordinates : 90°S 0°E
Diameter of telescope : 10 m
λ = 1.3 mm (ν = 230 GHz)
D ~ 10,000 km ⇒ λ/D ~ 25 μas
© C. M. Fromm & L. Rezzolla
Event Horizon Telescope
BLACK HOLE CAM
erc European Research Council


Shadow of Black Hole

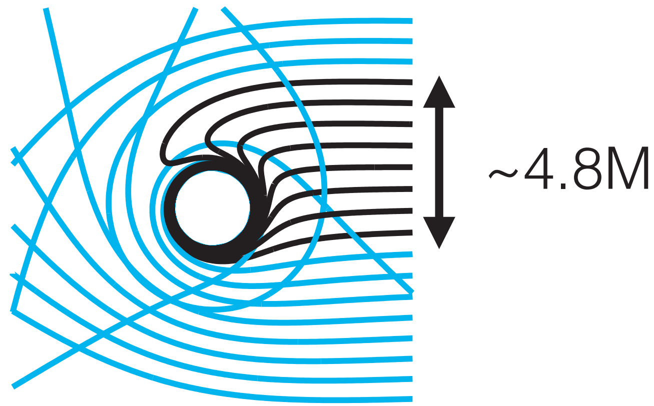
The Shadow of a Black Hole

top view

Non-spinning Black Hole

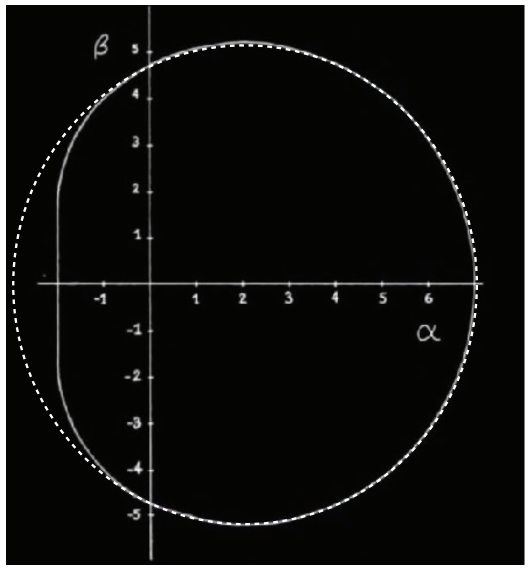


Maximumly Rotating Black Hole



(Figure credit: Hung-Yi Pu)

i=90 deg



Black Holes cast shadows

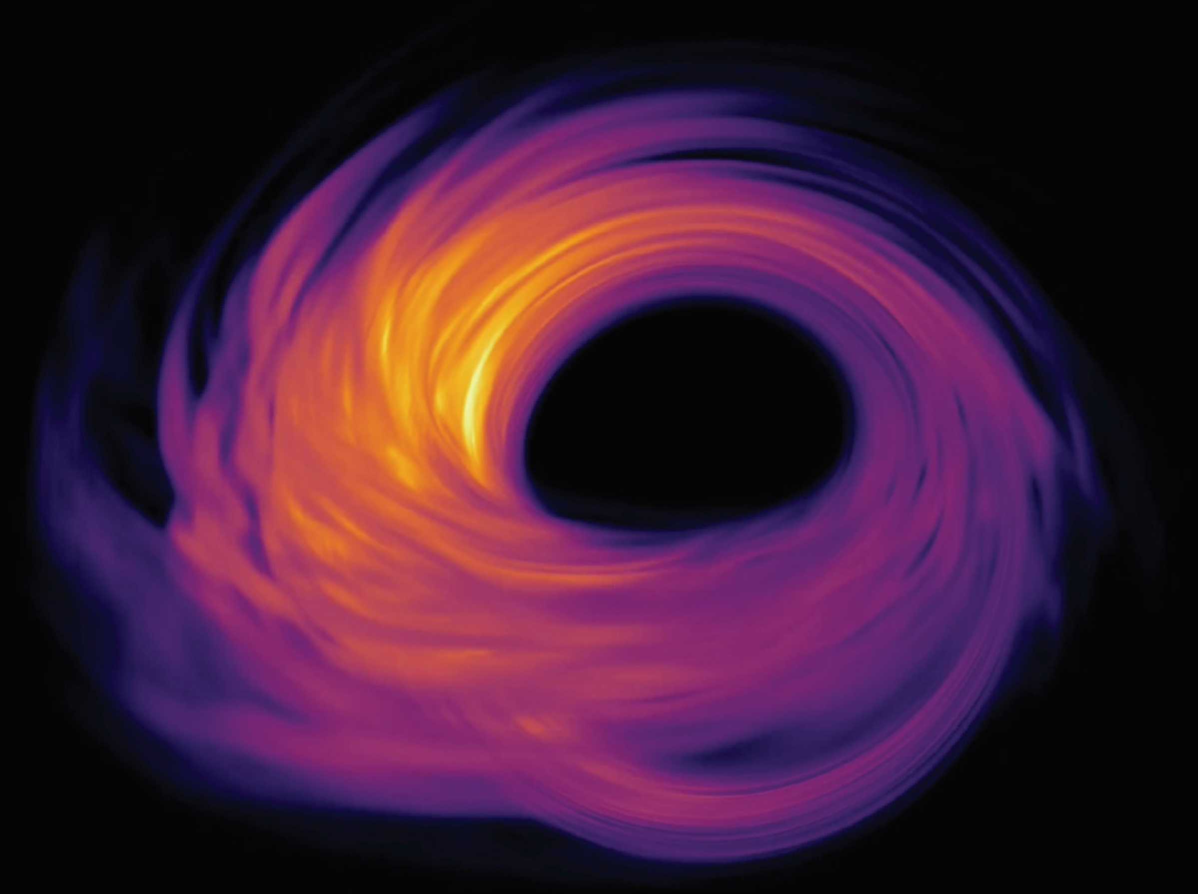
(Bardeen 1973; Falcke et al. 2000)

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)

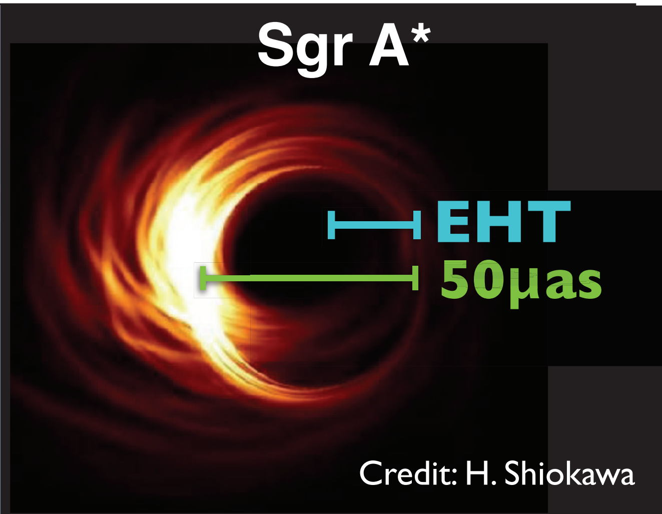
Movie: Z. Younsi

Black Holes with the Largest Angular Sizes

Source	BH Mass (M_{solar})	Distance (Mpc)	1 R_g (µas)
Sgr A*	4×10^6	0,008	10
M87	~~**3.3 - 6.2 x 10⁹**~~ **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

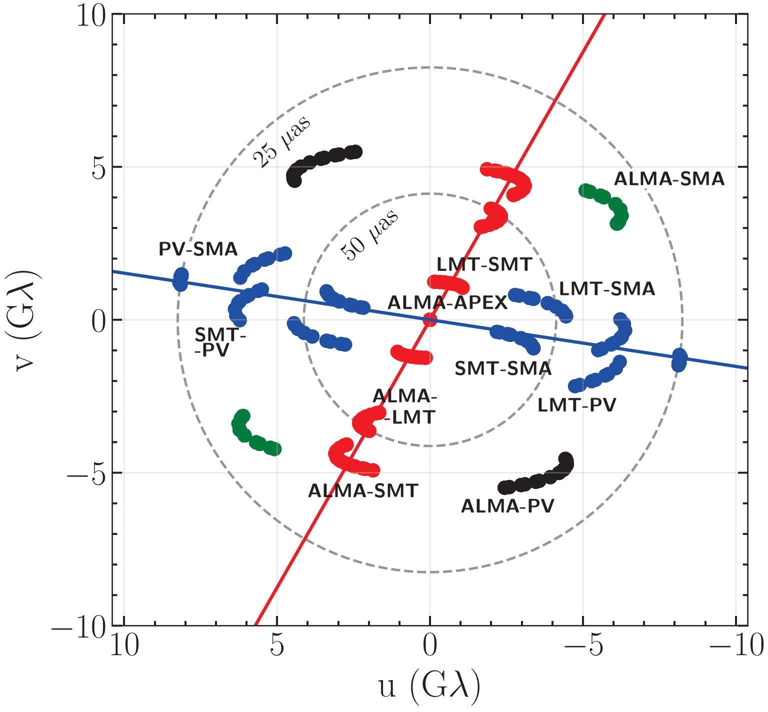
Event Horizon Telescope 2017

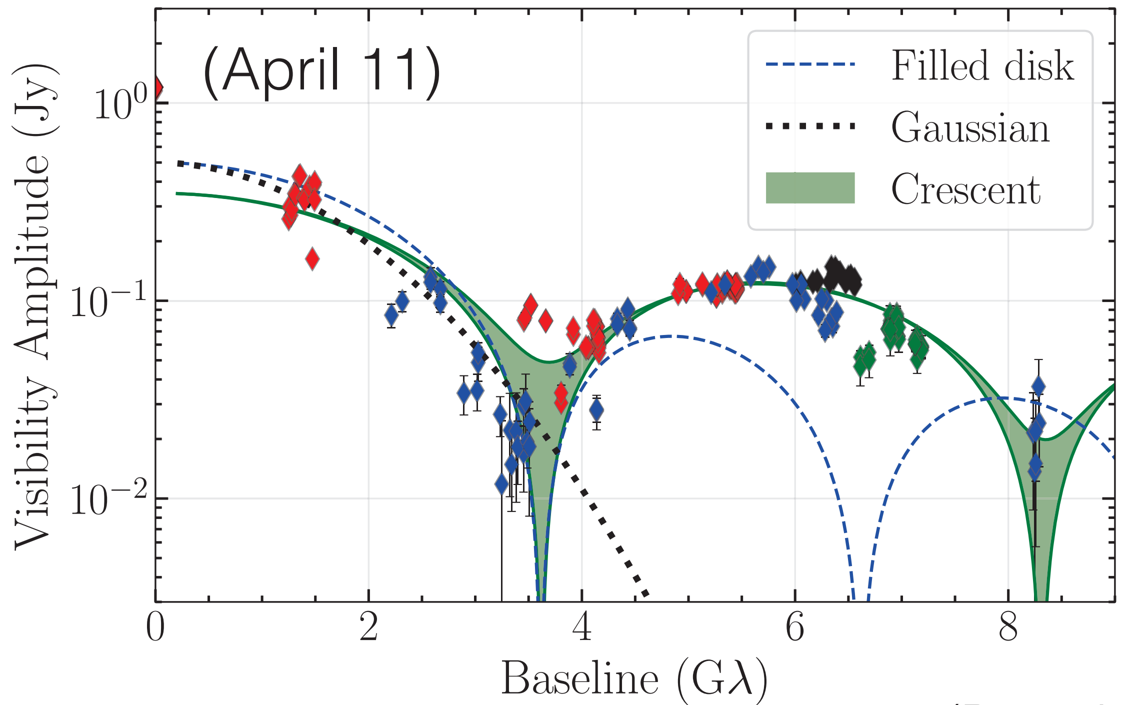


Calibrated data sets (before imaging)

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

Fourier domain





(Paper VI)

Fantastic Four: Black Hole Image Hunters

Team 1

Americas

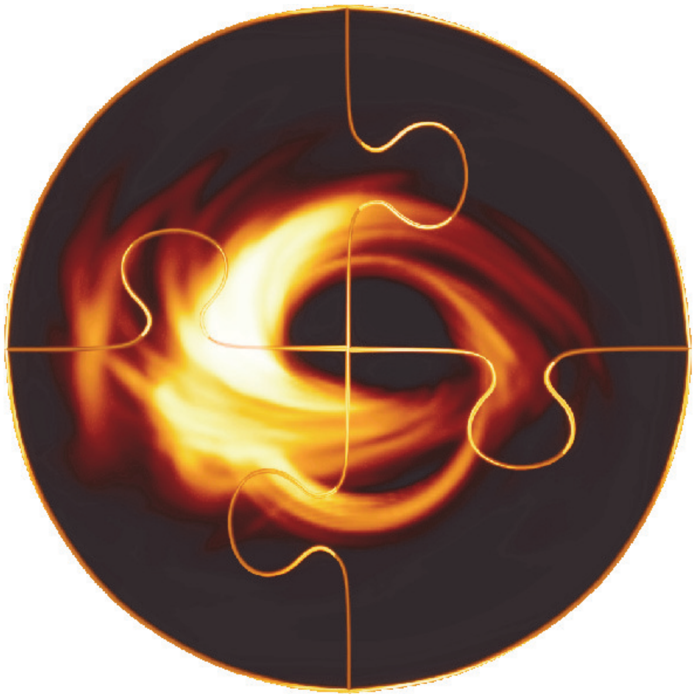
US & Chile
(SAO, U. Arizona, U. Conception)
Leader: K. Bouman & A. Chael

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

Event Horizon Telescope

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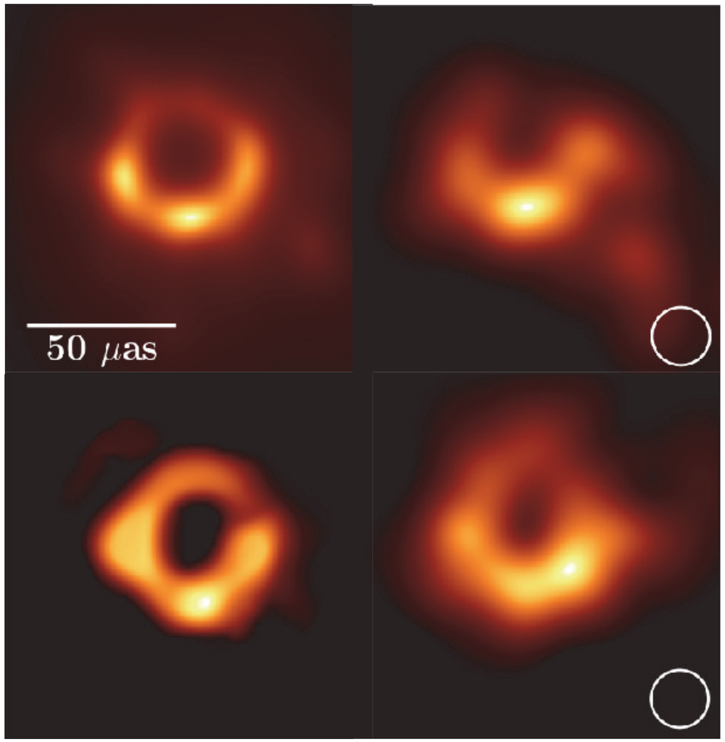
The First EHT Images of M87
July 24, 2018



Each team blindly reconstructed images
Goal: Assess human bias

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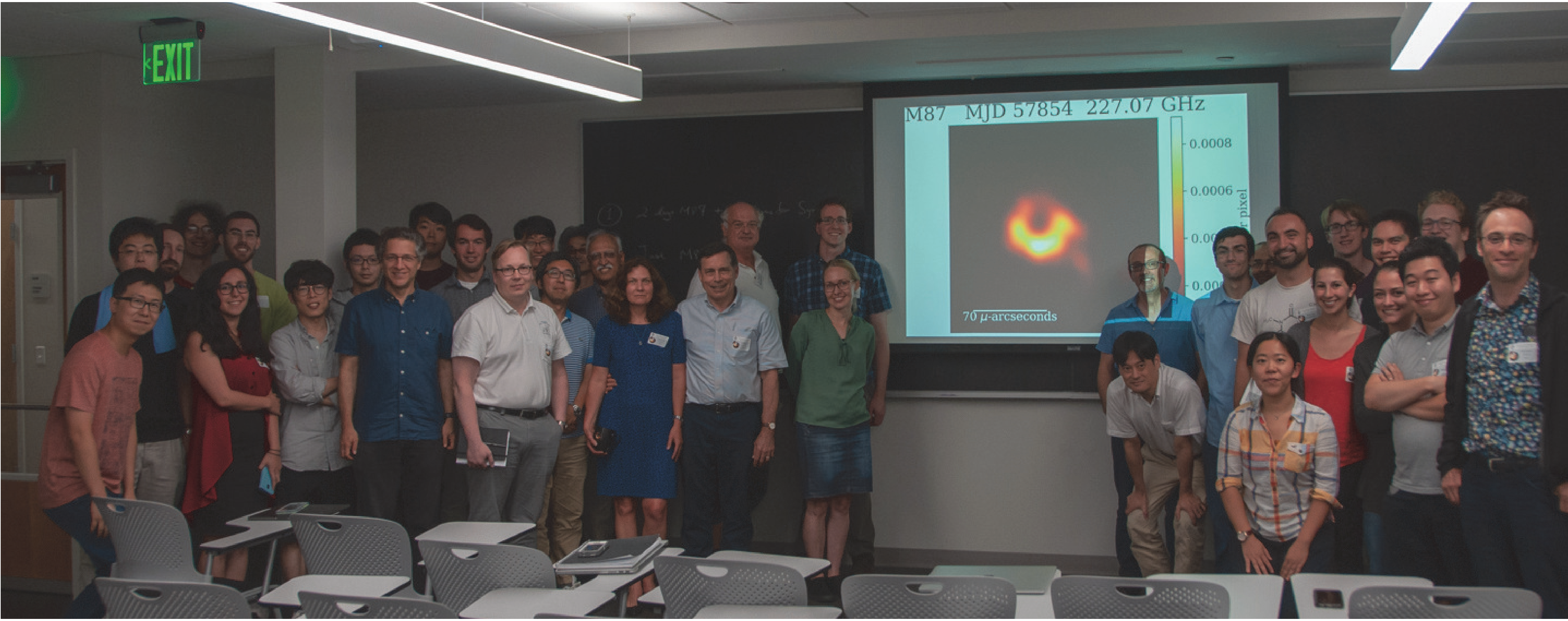
Event Horizon Telescope

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

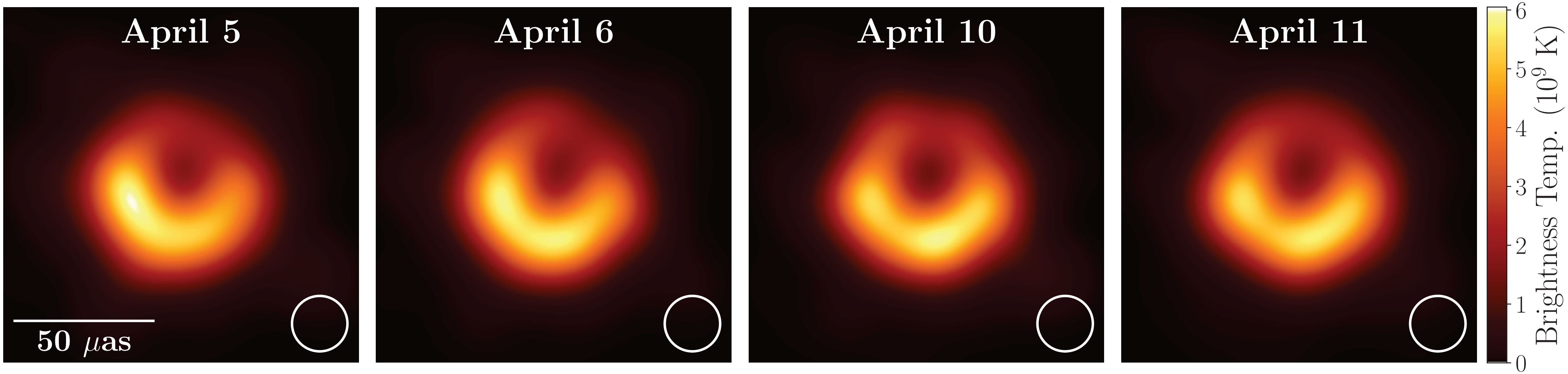


Event Horizon Telescope

2nd EHT Imaging Workshop

Averaged Images

EHT 2017 M87 reconstructed averaged images look like asymmetric rings
(diameter: 42±3 μas)



No significant changes are observed during the 6-day span of the 2017 EHT campaign
(but some time variability?)

(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)

SANE: Standard and Normal Evolution
MAD: Magnetically Arrested Disk

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

Simulation Library
>15 GRMHD runs

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)

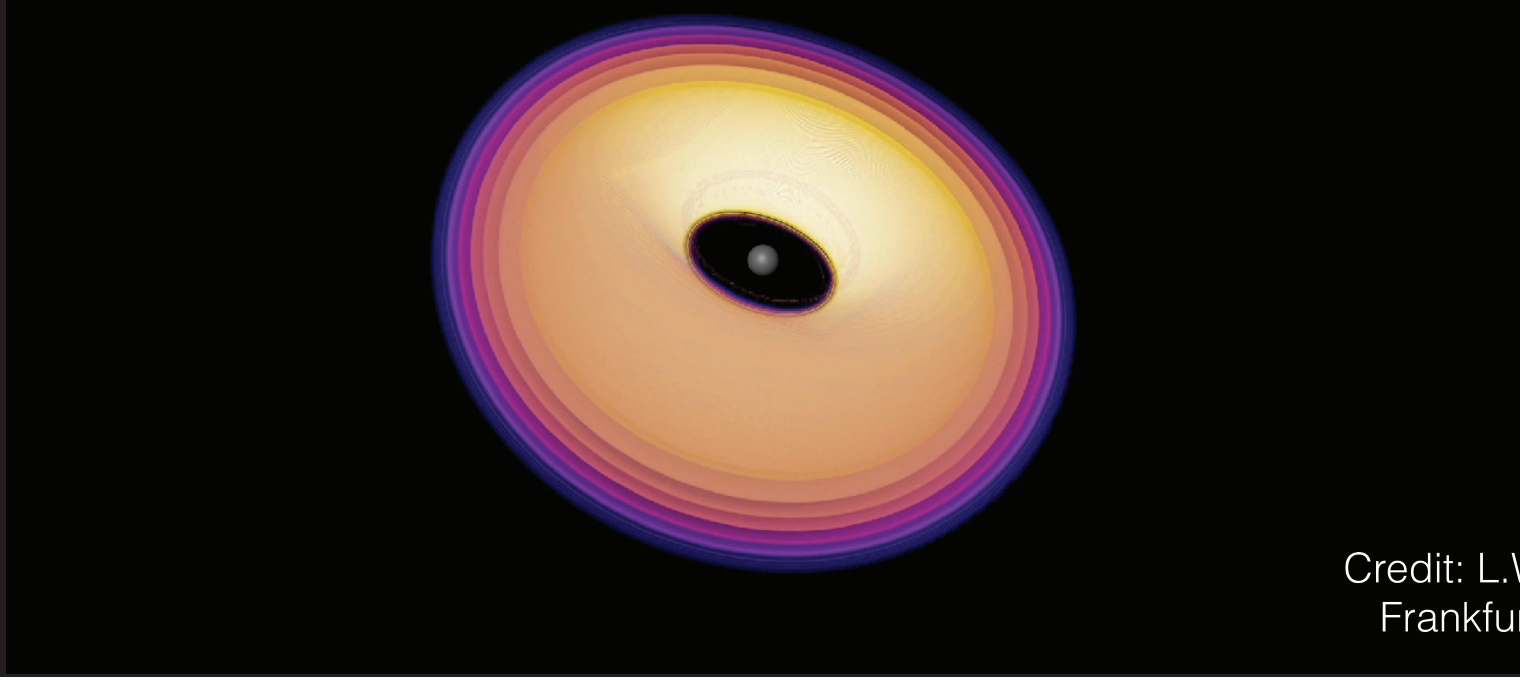
Prior knowledge from observations

- 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

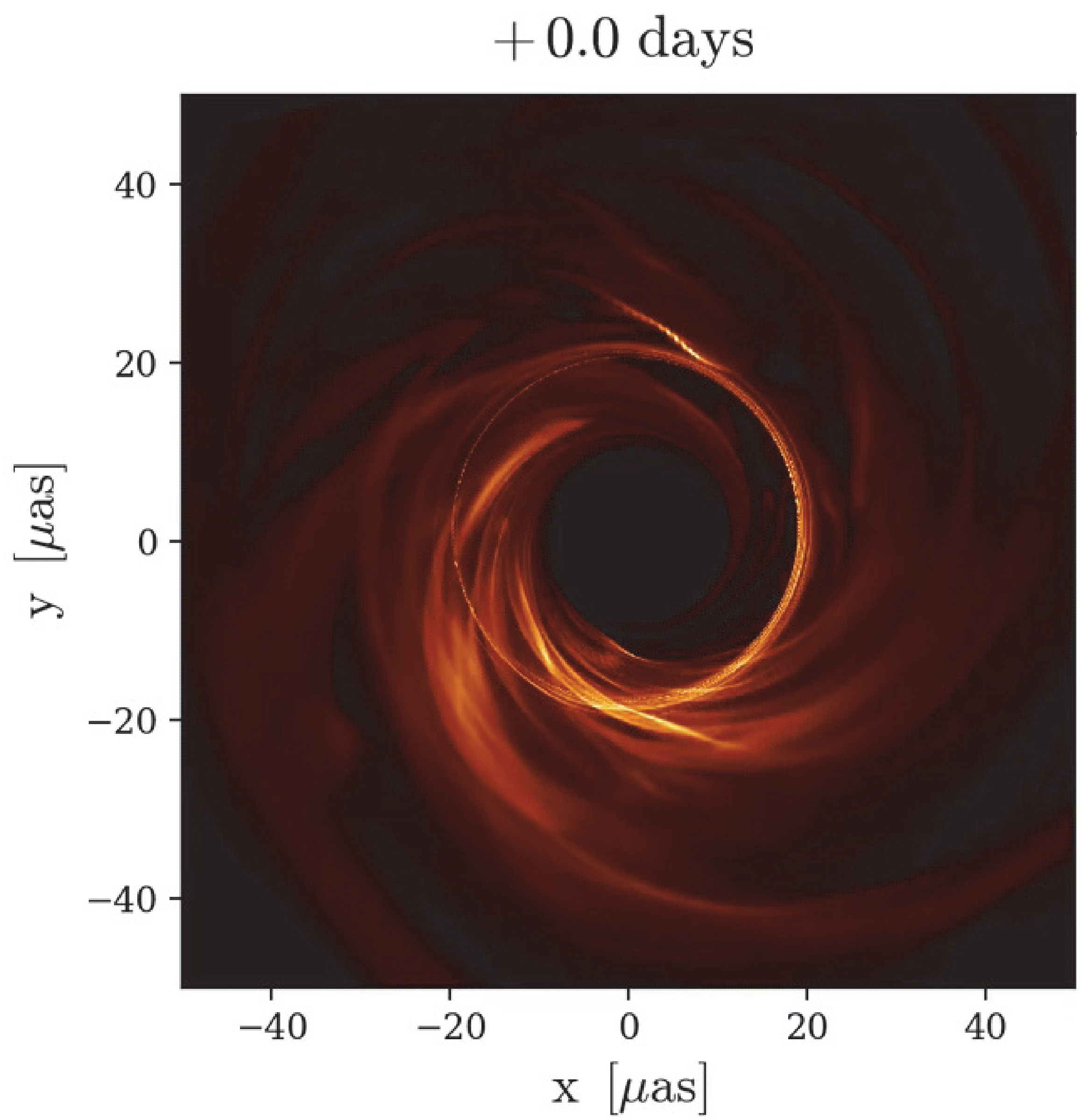
Kerr black hole with a=0.94,
SANE model



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

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)

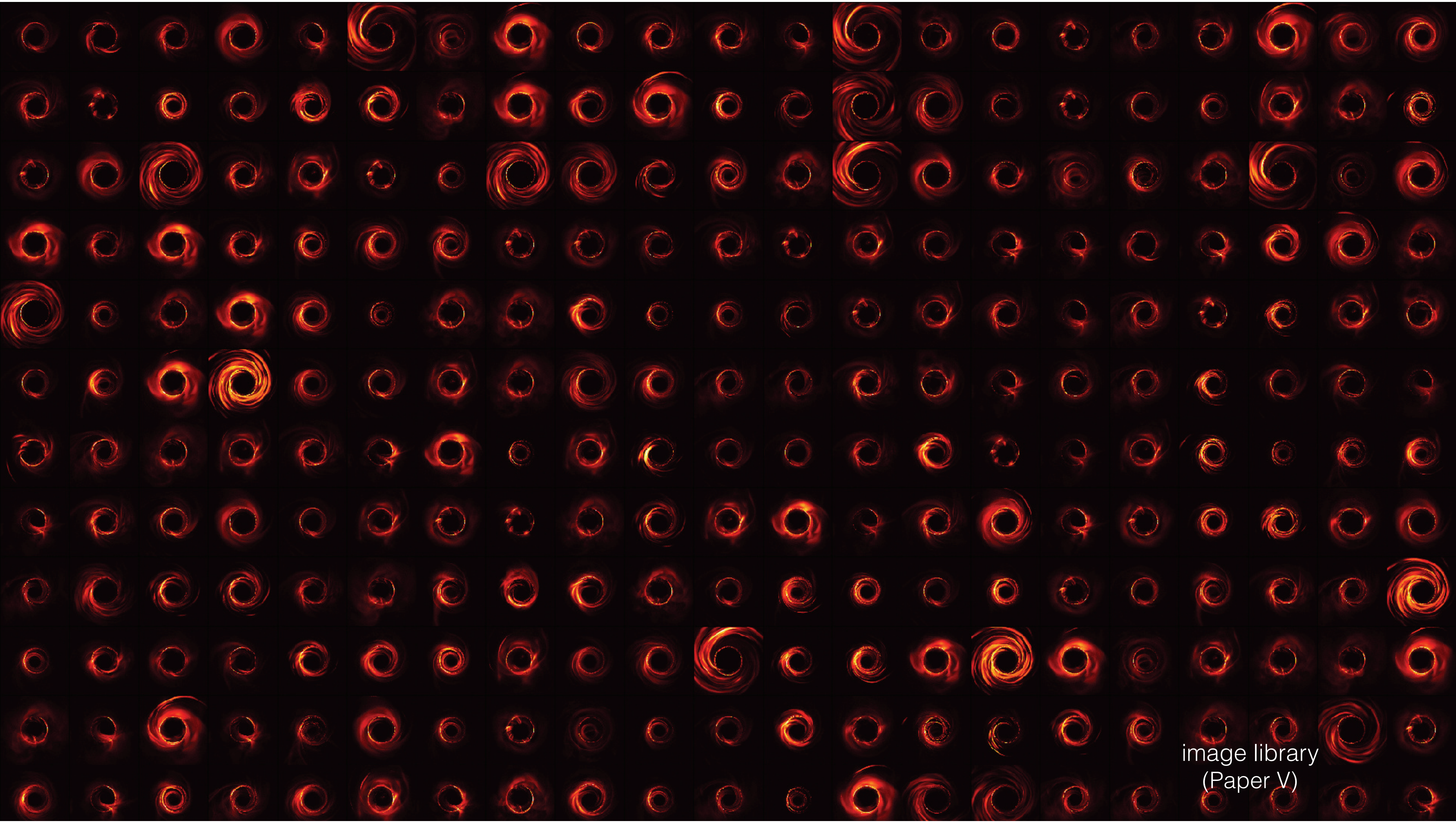


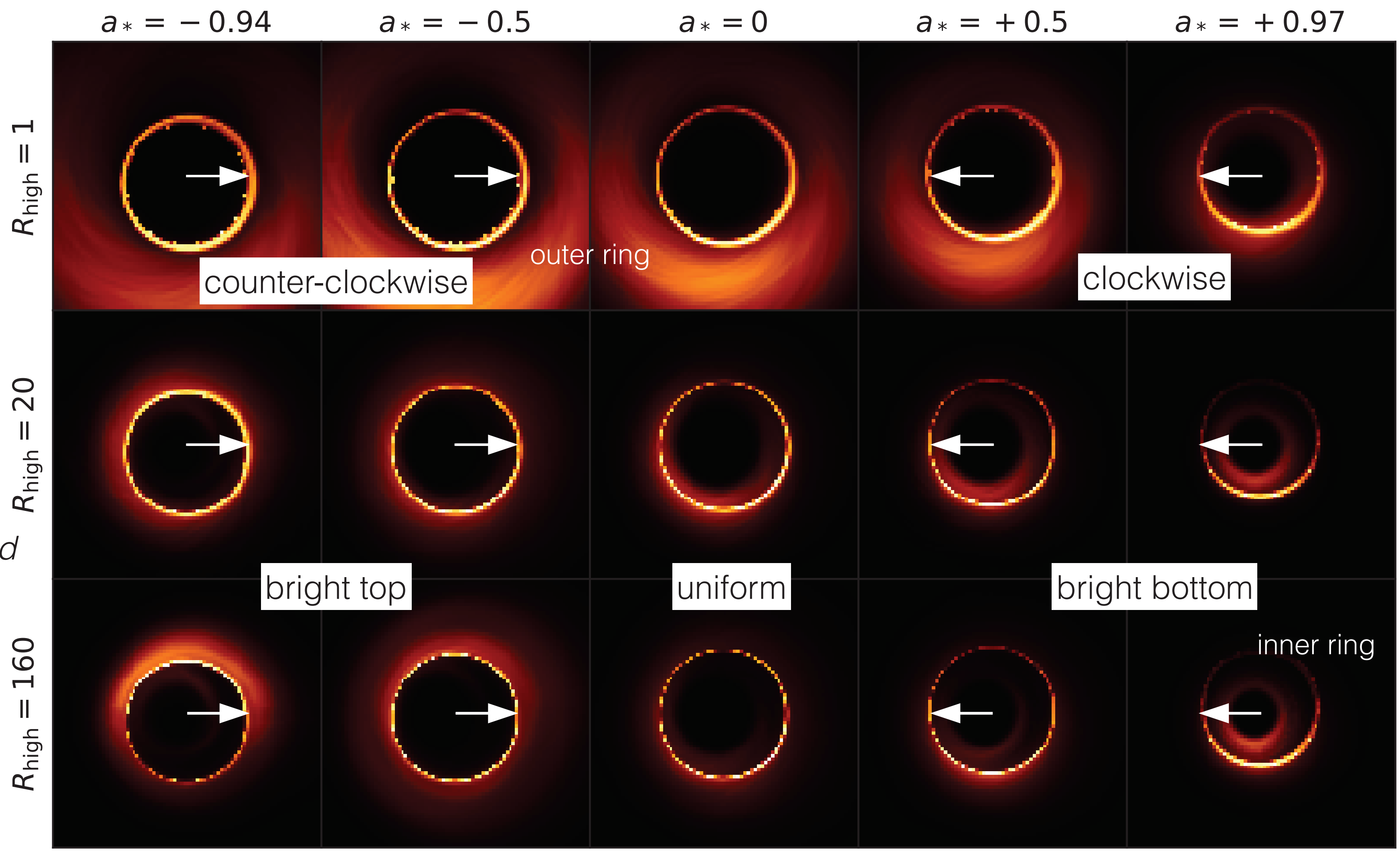
image library
(Paper V)

SANE averaged GRRT images

i=163 deg

black hole rotational axis

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

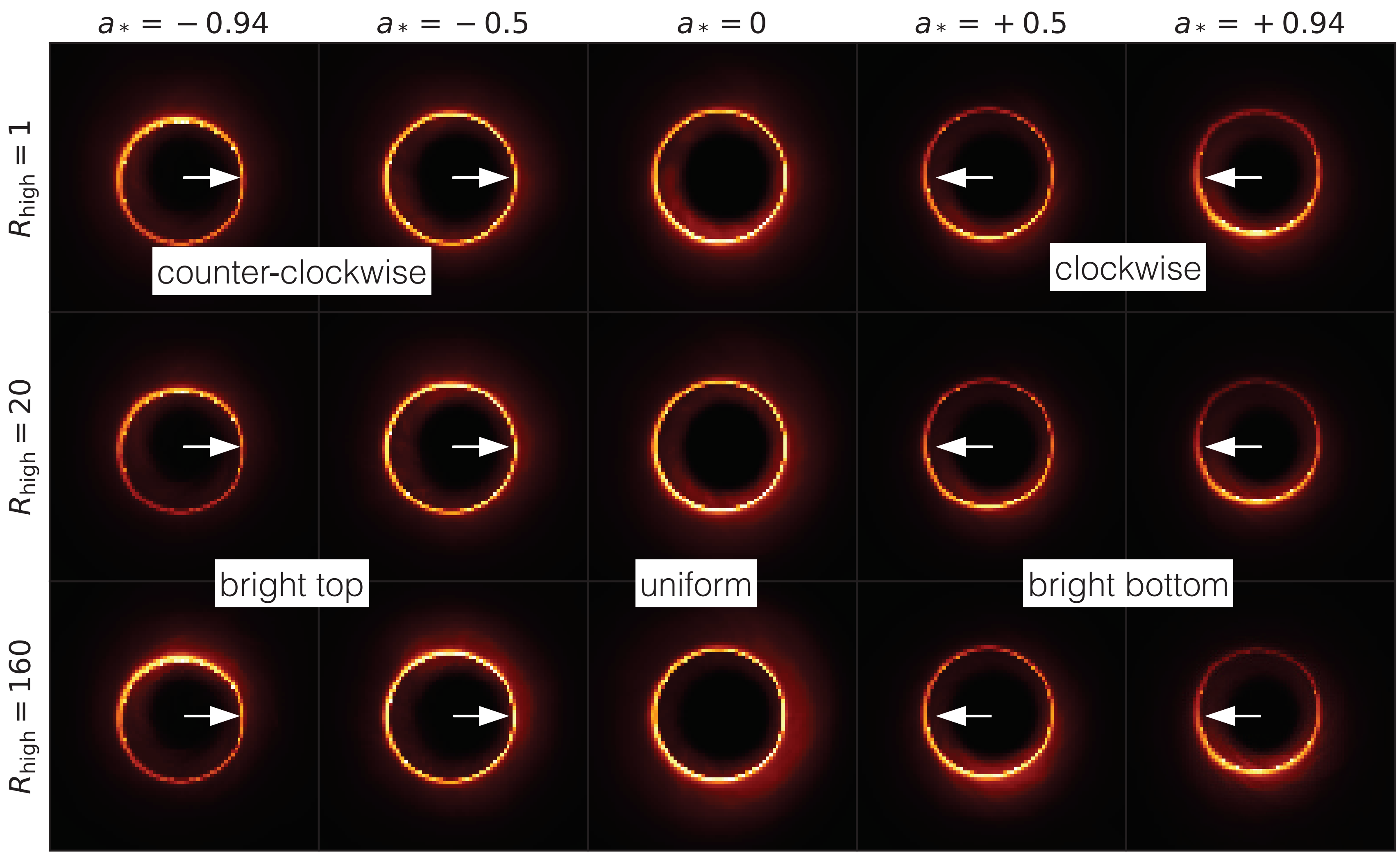


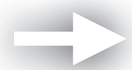
(Paper V)

Event Horizon Telesco

MAD averaged GRRT images

i=163 deg





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

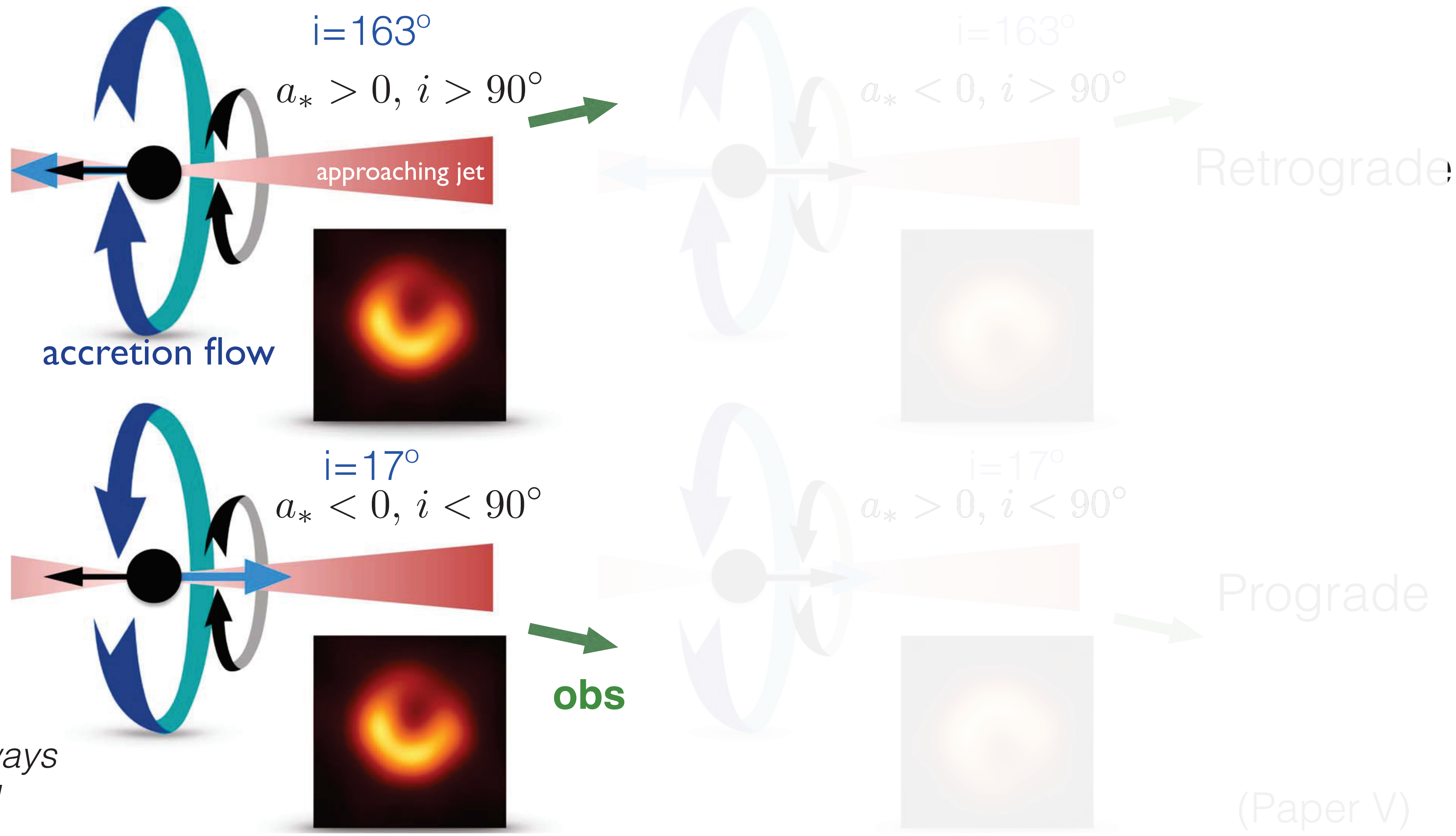
Event Horizon Telescope

Why is it asymmetric?

Prograde

More likely

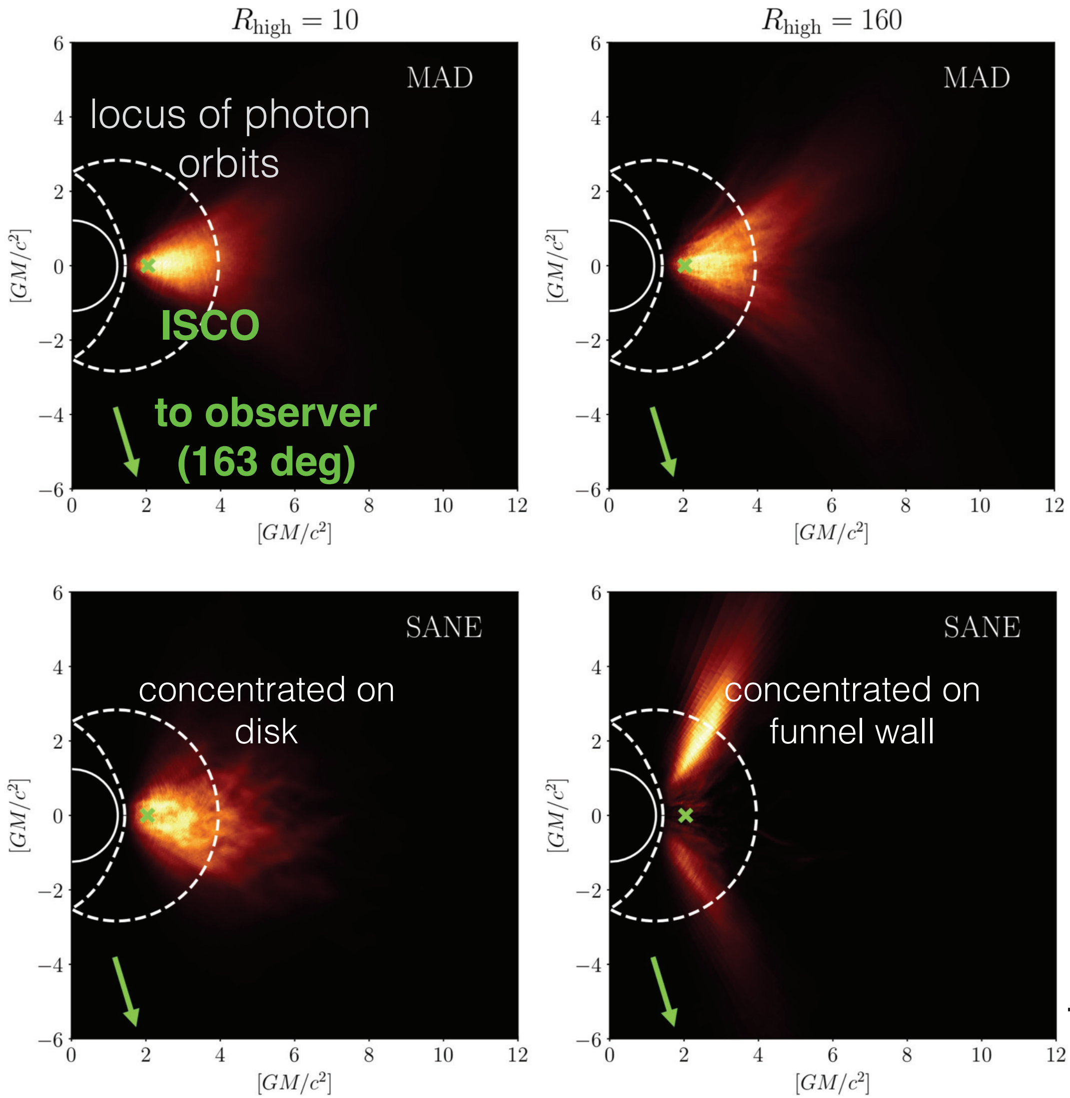
Retrograde



Emitting plasma is always co-rotated with BH

Event Horizon Telescope

Where do mm photons originate?



MAD, a=0.94

SANE, a=0.94

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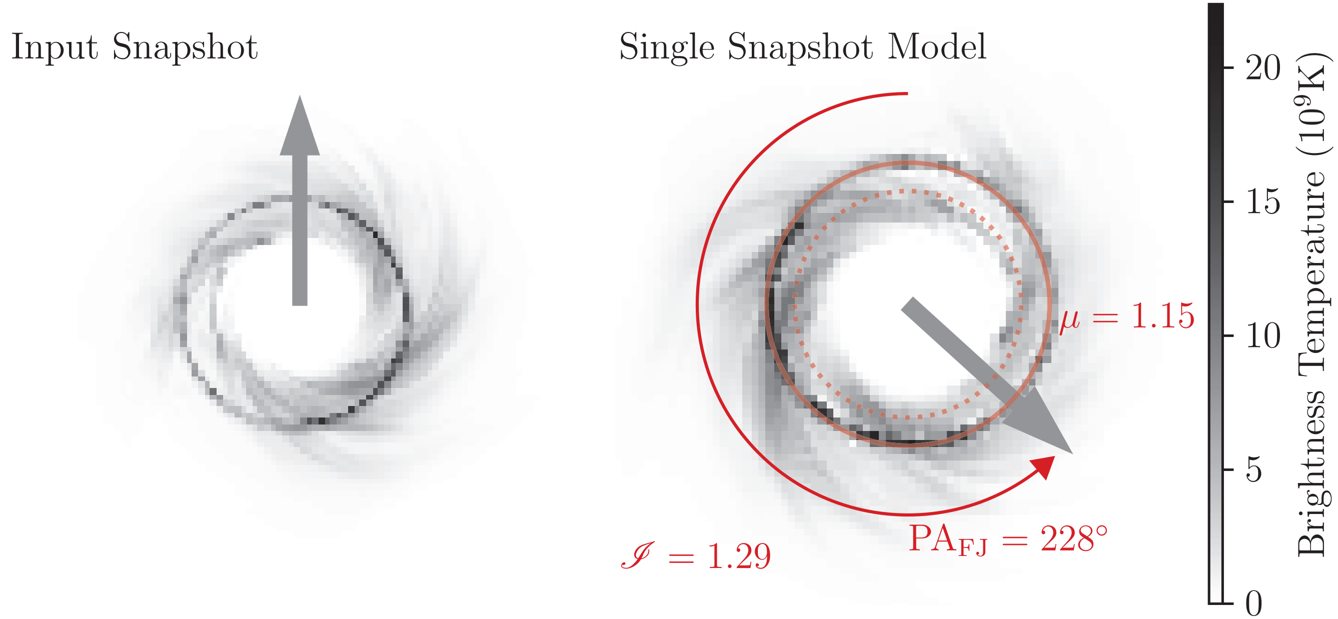
Fitting GRRT images to EHT data

- 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)

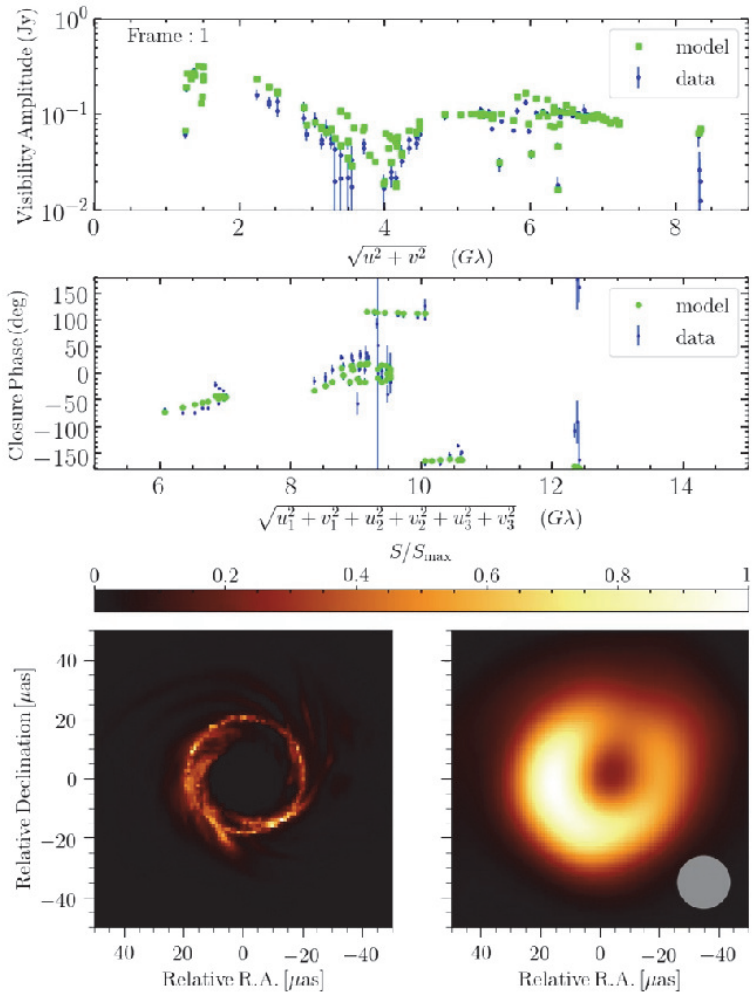
Two independent codes: MCMC (Themis) & evolutionary algorithm (GENA)

Fitting GRRT images to EHT data

visibility amplitude (VA)

Closure phase (CP)

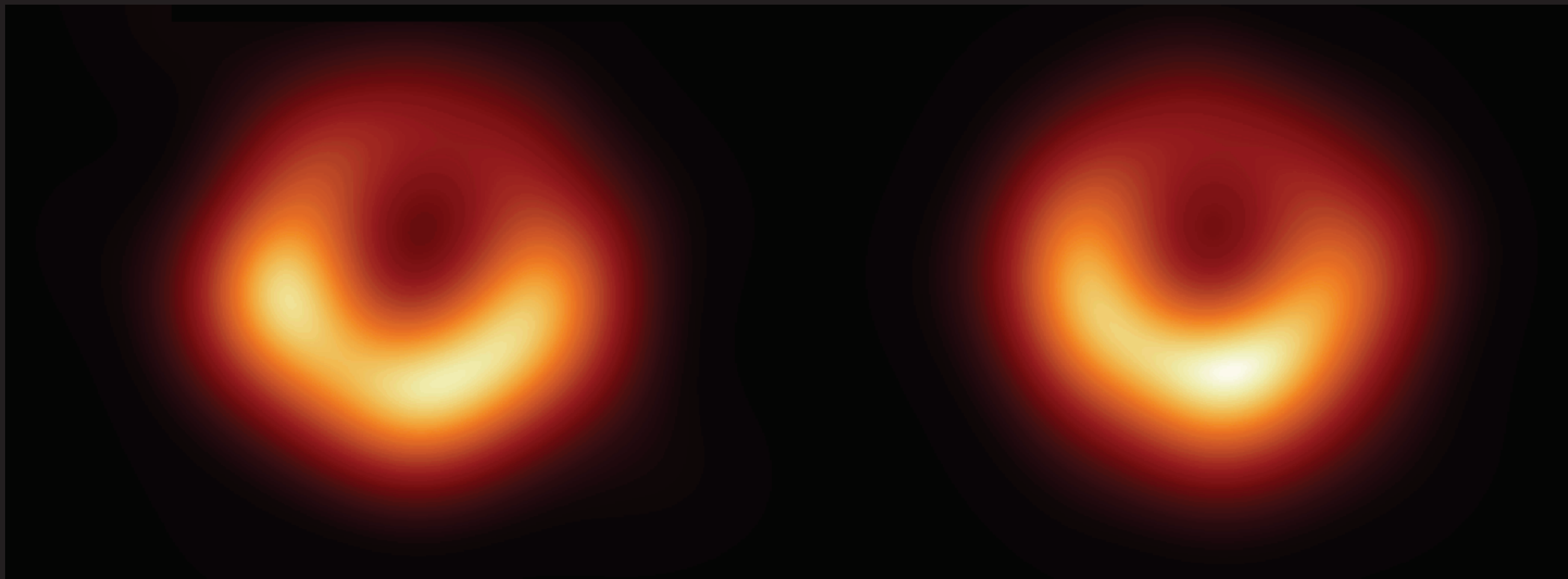
GRMHD image (left) & convolved image (right)



GENA fitting procedure
(a single GRMHD simulation)

(Paper V)

Event Horizon Telescope



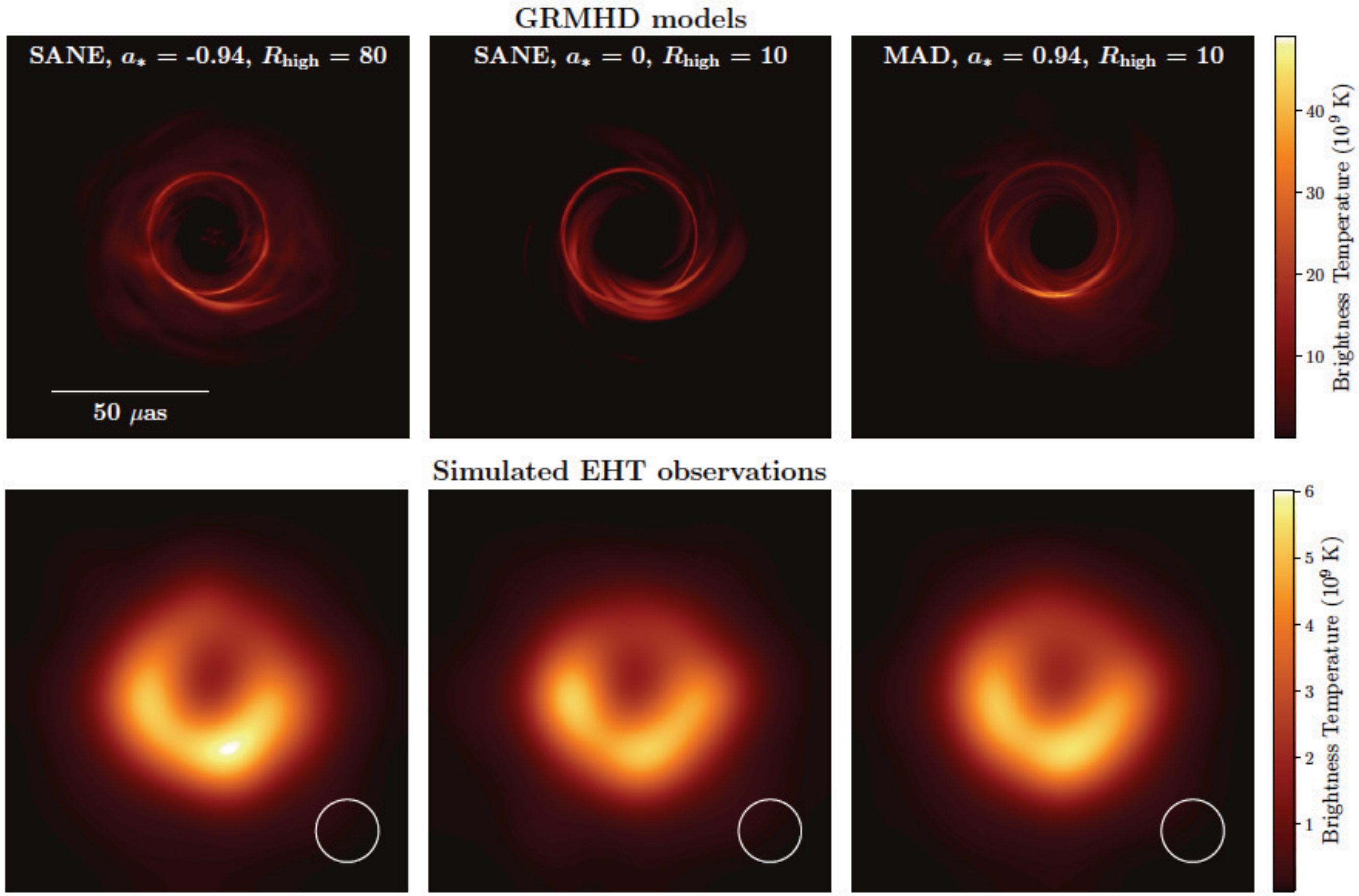
OBSERVATIONS

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.



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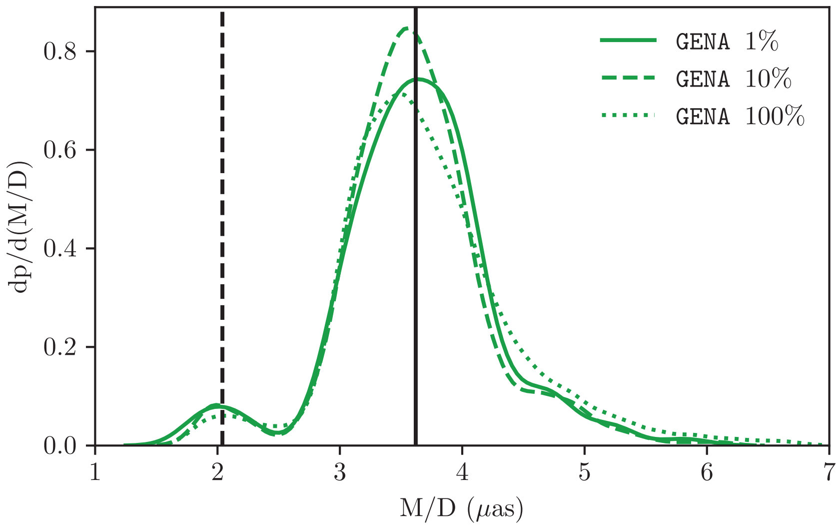
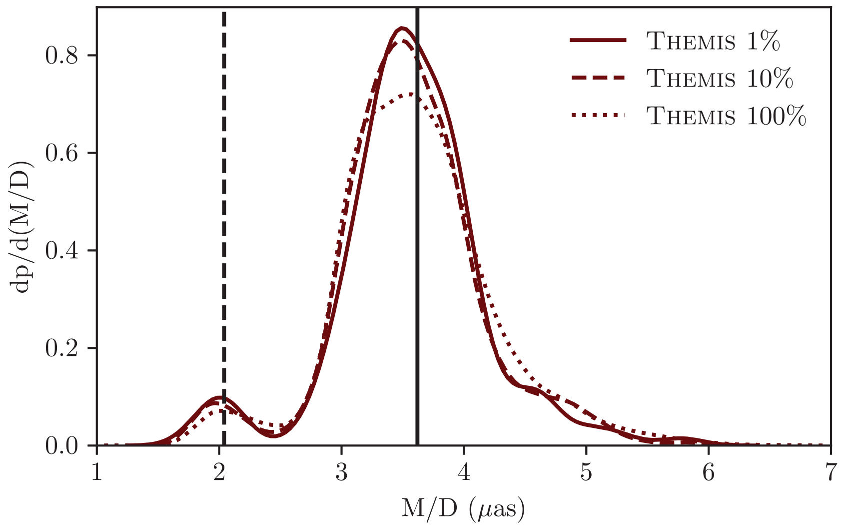
Distribution of Best-Fit Black Hole Angular Size

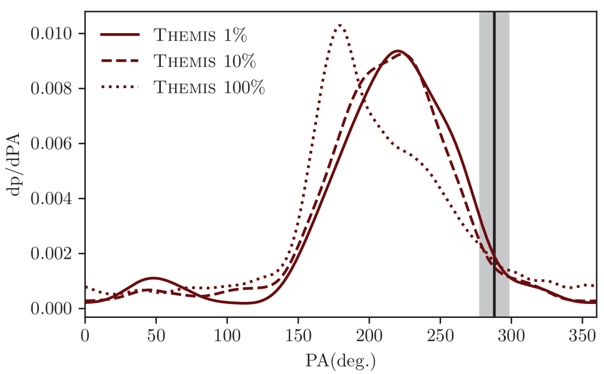


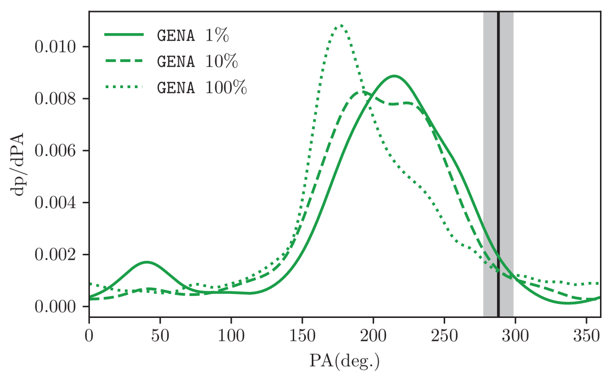


- Distribution of M/D from fitting Image Library snapshots to 2017 April 6th EHT data
- Results by Themis & GENA pipelines are qualitatively similar
- The distribution peaks close to M/D ~ 3.6 μas with a width of ~0.5 μas
- The models are broadly consistent with stellar mass estimate
- M = 6.5 x 10^9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

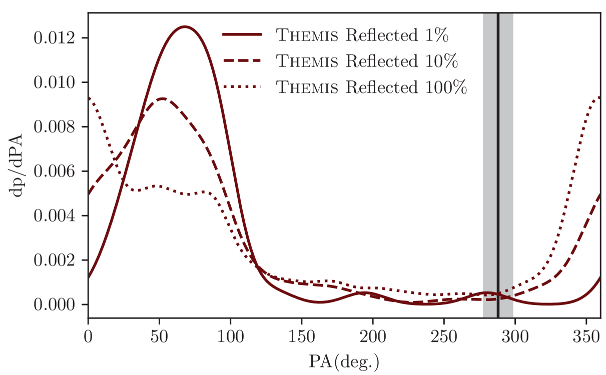
Distribution of Model Best-Fit Position Angle

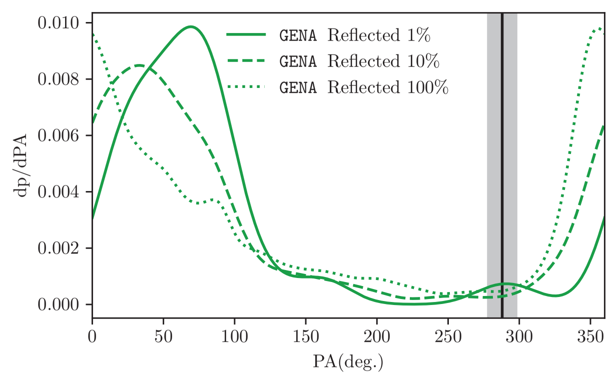
BH spin vector pointing away from Earth





BH spin vector pointing toward Earth





- Large scale jet orientation lies on the shoulder of the spin-away models ($\langle PA \rangle \sim 200$ deg, $\sigma_{PA} \sim 55$ 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	+-+-	+-+-	+++-	+++-	++++	++++

Event Horizon Telescope

+: 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	+- -+	+-++	++++	++++	++++	++++

Event Horizon Telescope

+: passed, - : failed

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.

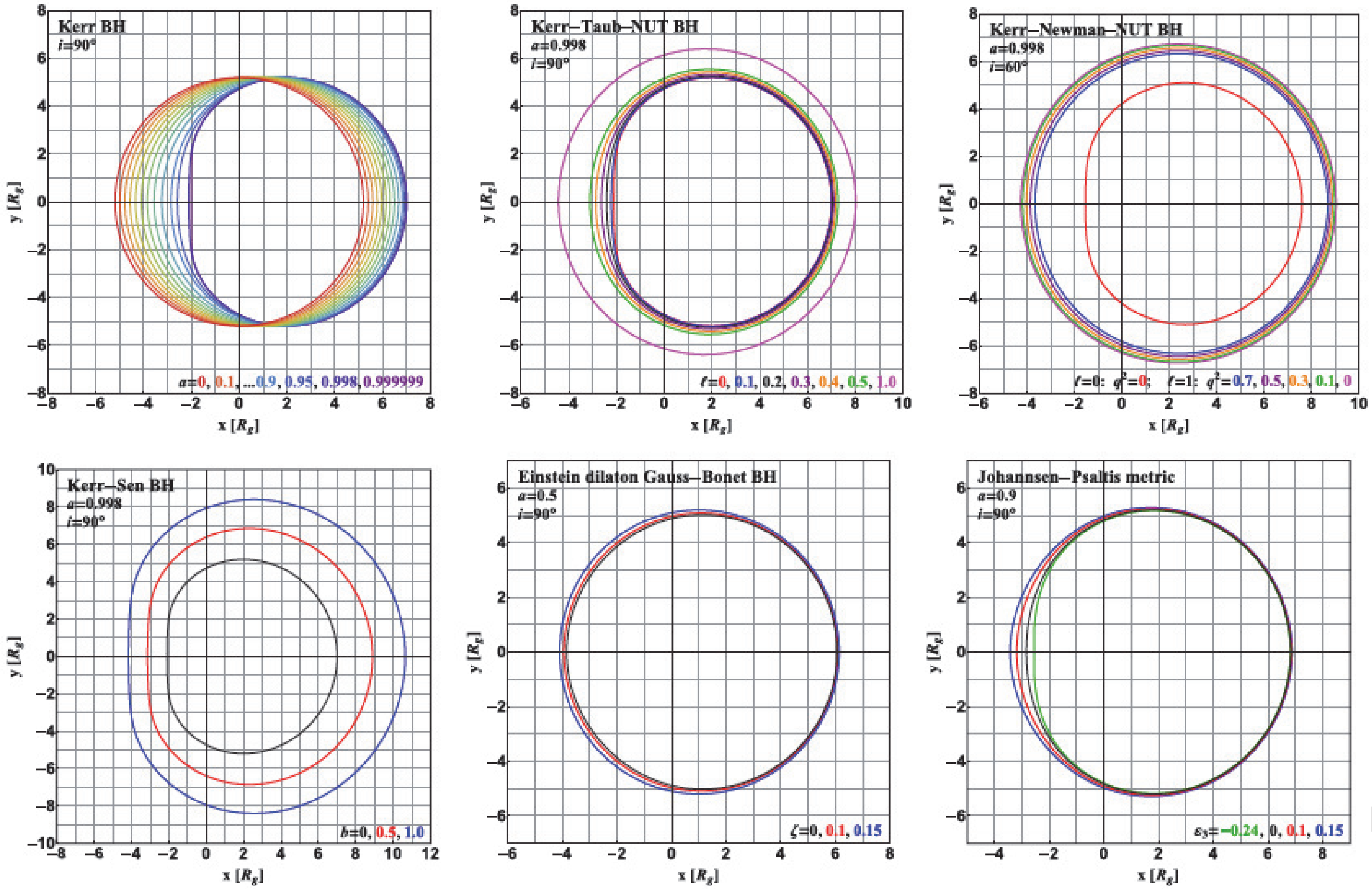
2. black hole solutions from alternative theories of gravity or incorporating quantum effects
   - classical modification to GR as well as the effect of quantum gravity.

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

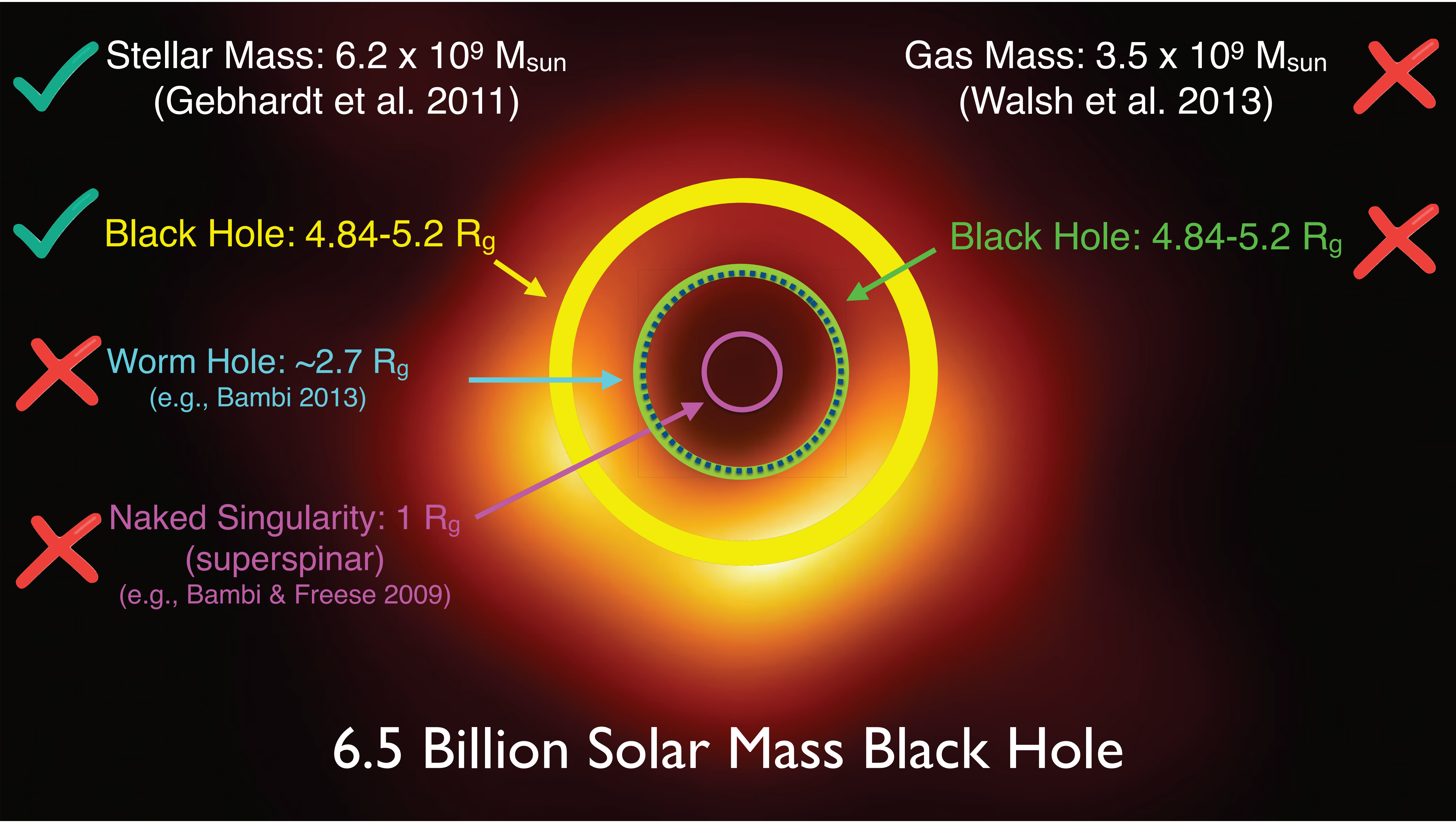
Shadow Industry: Different Spacetime

Variety of BH shadow boundary curve in different theory of gravity



Younsi et al. (2016)

From BHCam review by Goddi et al. (2017)



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 Rg
Black Hole: 4.84-5.2 Rg
Worm Hole: ~2.7 Rg
(e.g., Bambi 2013)
Naked Singularity: 1 Rg
(superspinar)
(e.g., Bambi & Freese 2009)
6.5 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

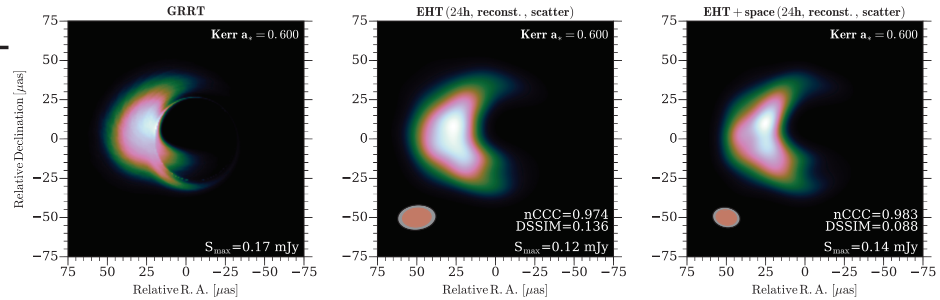
- AGN and jets are powered by super massive black hole

- 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)

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)

Event Horizon Telescope

Concluding Remarks

Dr. Elisabeth Mills
@astronomills
Following

I still love you, Sgr A* #EHTBlackHole

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


Thank you for listening
Event Horizon Telescope Collaboration Meeting
Welcome to Nijmegen!
Radboud University
2018 EHT collaboration meeting