Event Horizon Telescope Next Steps:
EHT 2020s, ngEHT, and Space Extension

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Event Horizon Telescope

NRAO

HAYSTACK OBSERVATORY

First M87 Results: Where are we now?

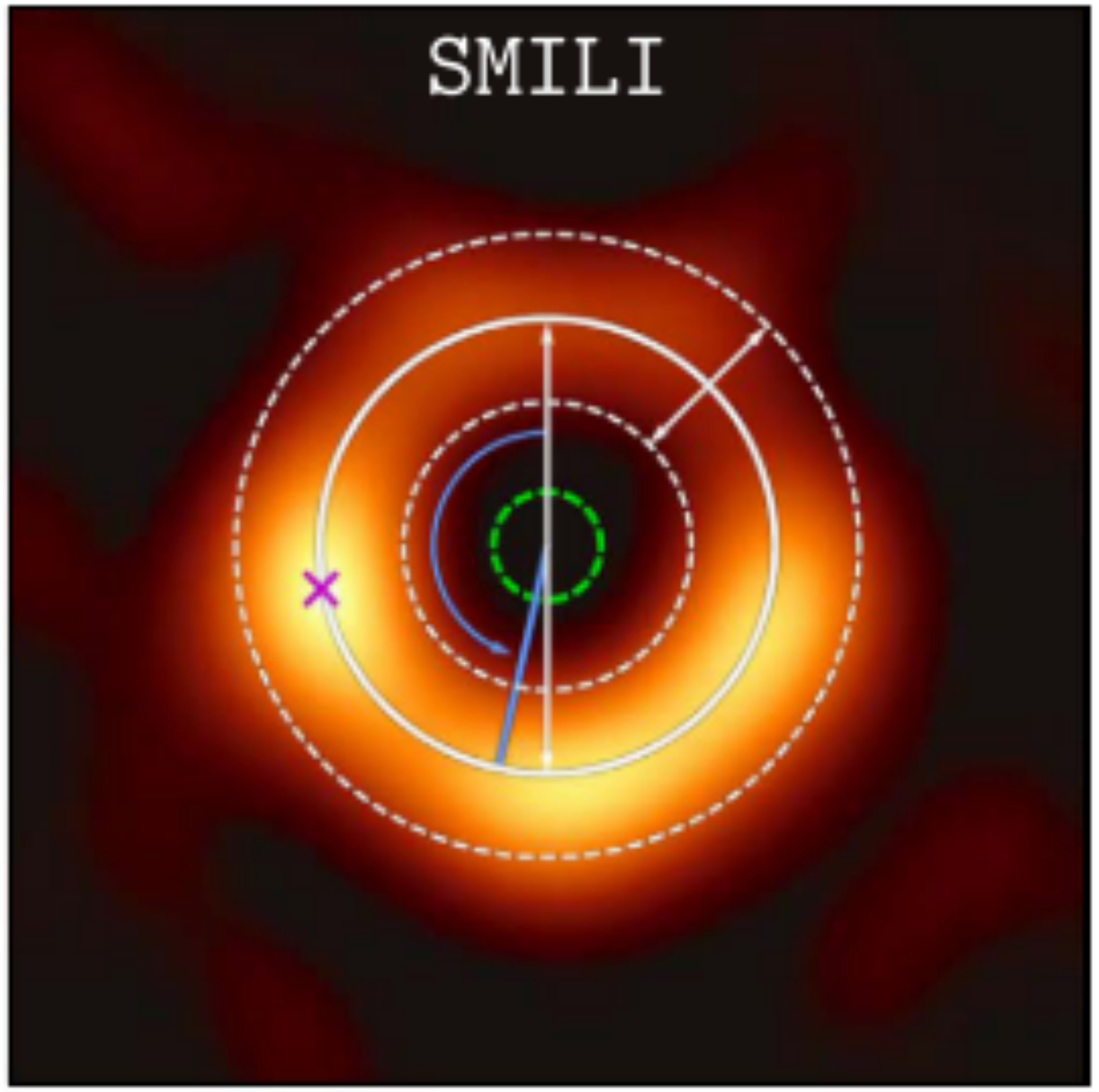
- Einstein's GR has passed a new test at an extremely strong gravitational field
- The strongest evidence for the presence of a supermassive black hole
- The M87 central black hole is most likely spinning
- An AGN and associated jet are powered by a supermassive black hole
- The stellar dynamical mass is correct (6.5 billion masses)
- Day-to-day variations on horizon scale

Dawn of a New Era of Black Hole Astrophysics

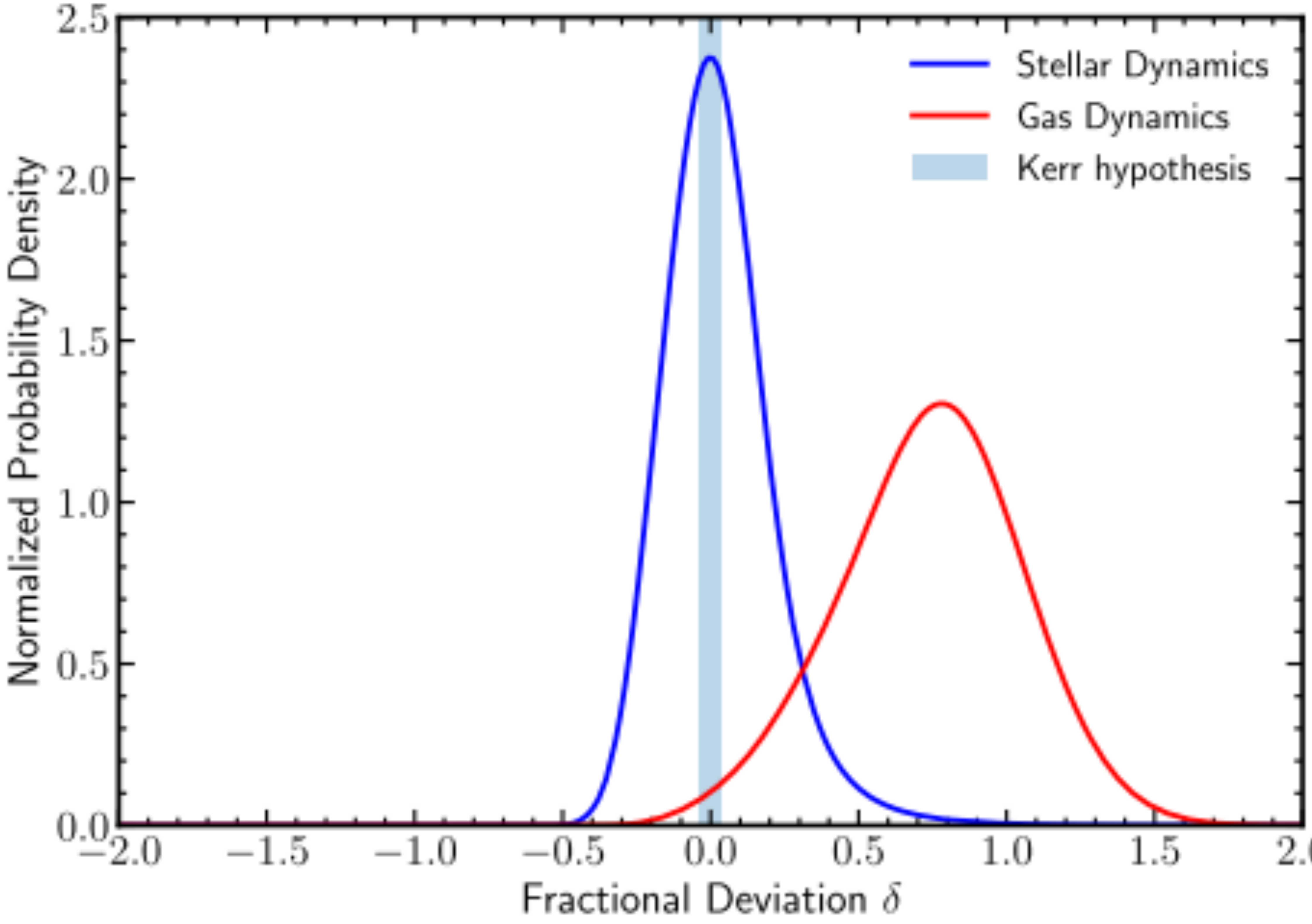
First M87 Results: Remained Issues

Testing General Relativity

M87 Mass: the mass uncertainty is large



~5 Rs



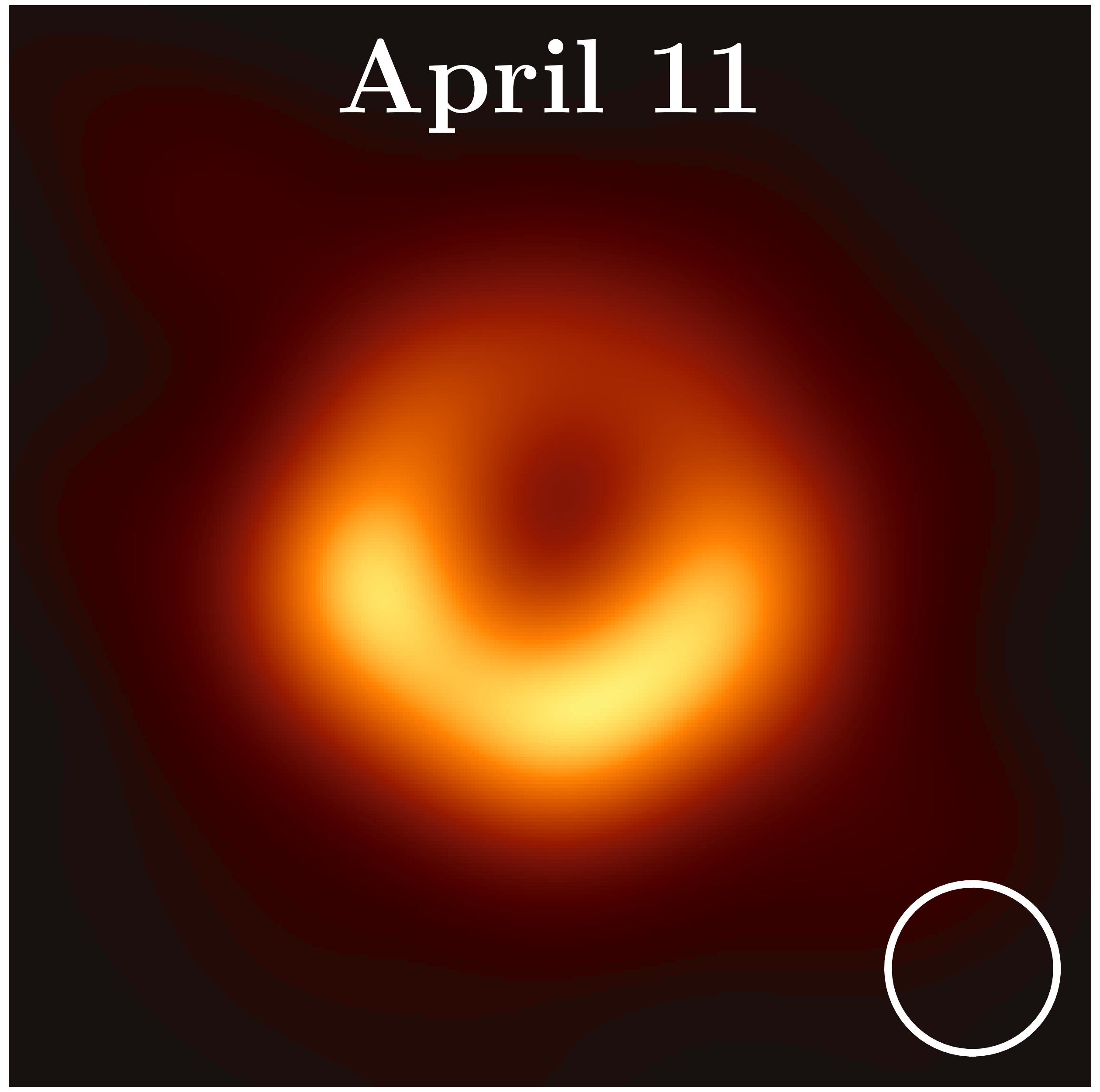
EHTC Paper+19 IV & VI

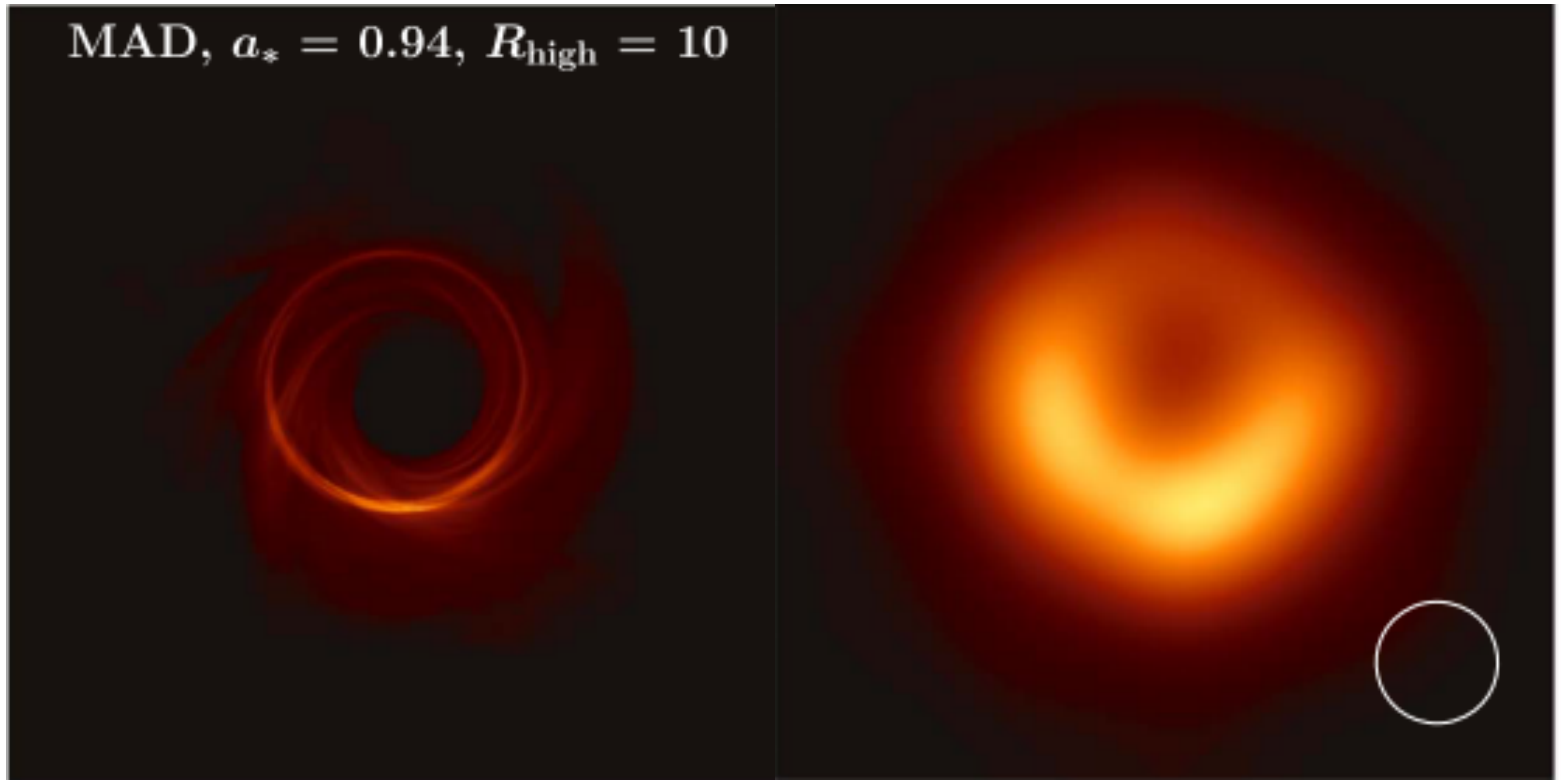
First M87 Results: Remained Issues

Testing General Relativity

M87 Mass: the mass uncertainty is large

Separate the photon ring emission from the surrounding accretion flow and jet





EHTC+19 Paper I

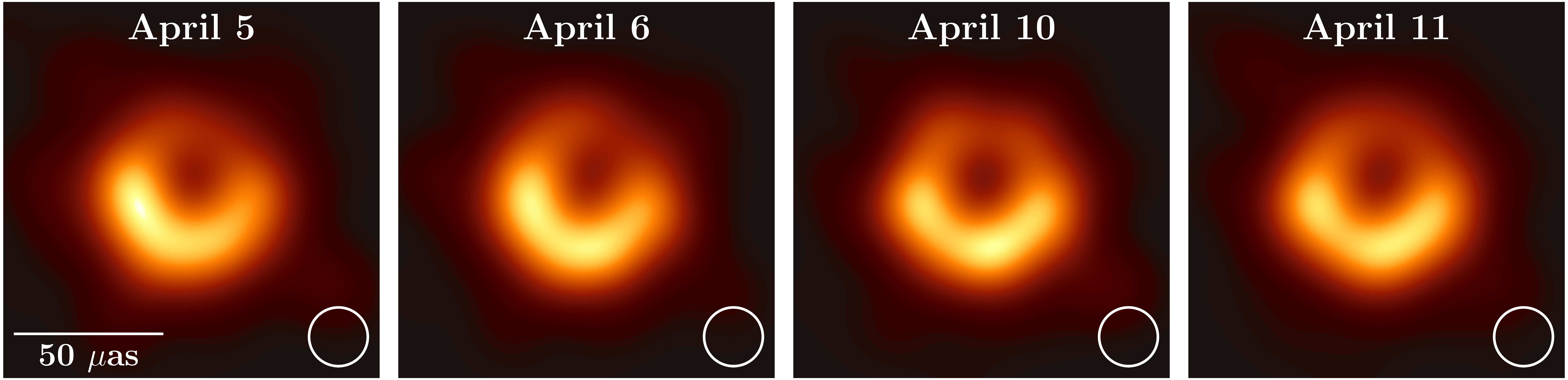
First M87 Results: Remained Issues

Testing General Relativity

M87 Mass: the mass uncertainty is large

Separate the photon ring emission from the surrounding accretion flow and jet

Short time window (< a week): may significantly be affected by transient feature



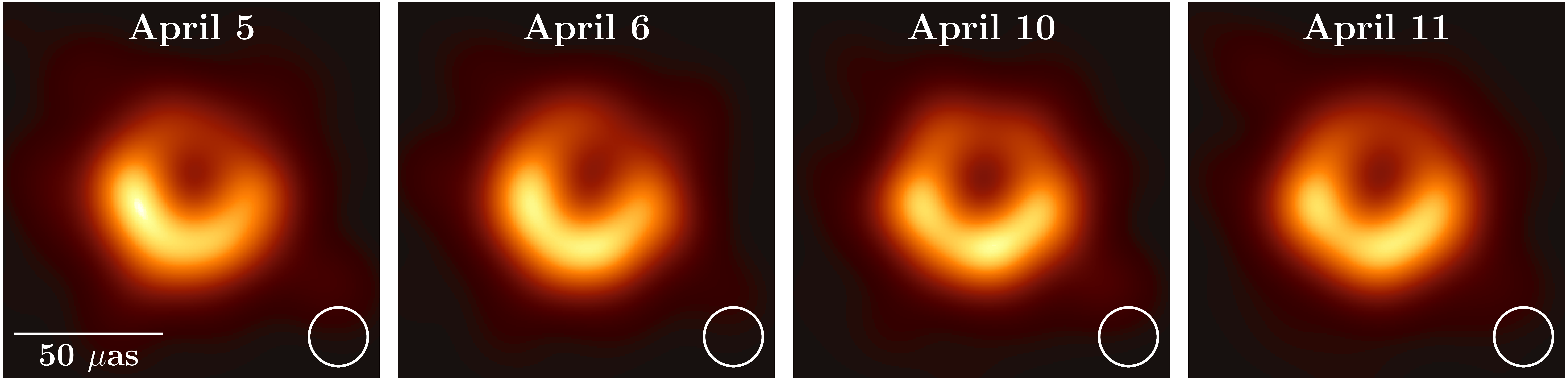
EHTC+19 Paper IV

Event Horizon Telescope

First M87 Results: Remained Issues

BH Magnetosphere, Accretion and Jet

Tracking evolving features in M87



EHTC+19 Paper I

First M87 Results: Remained Issues

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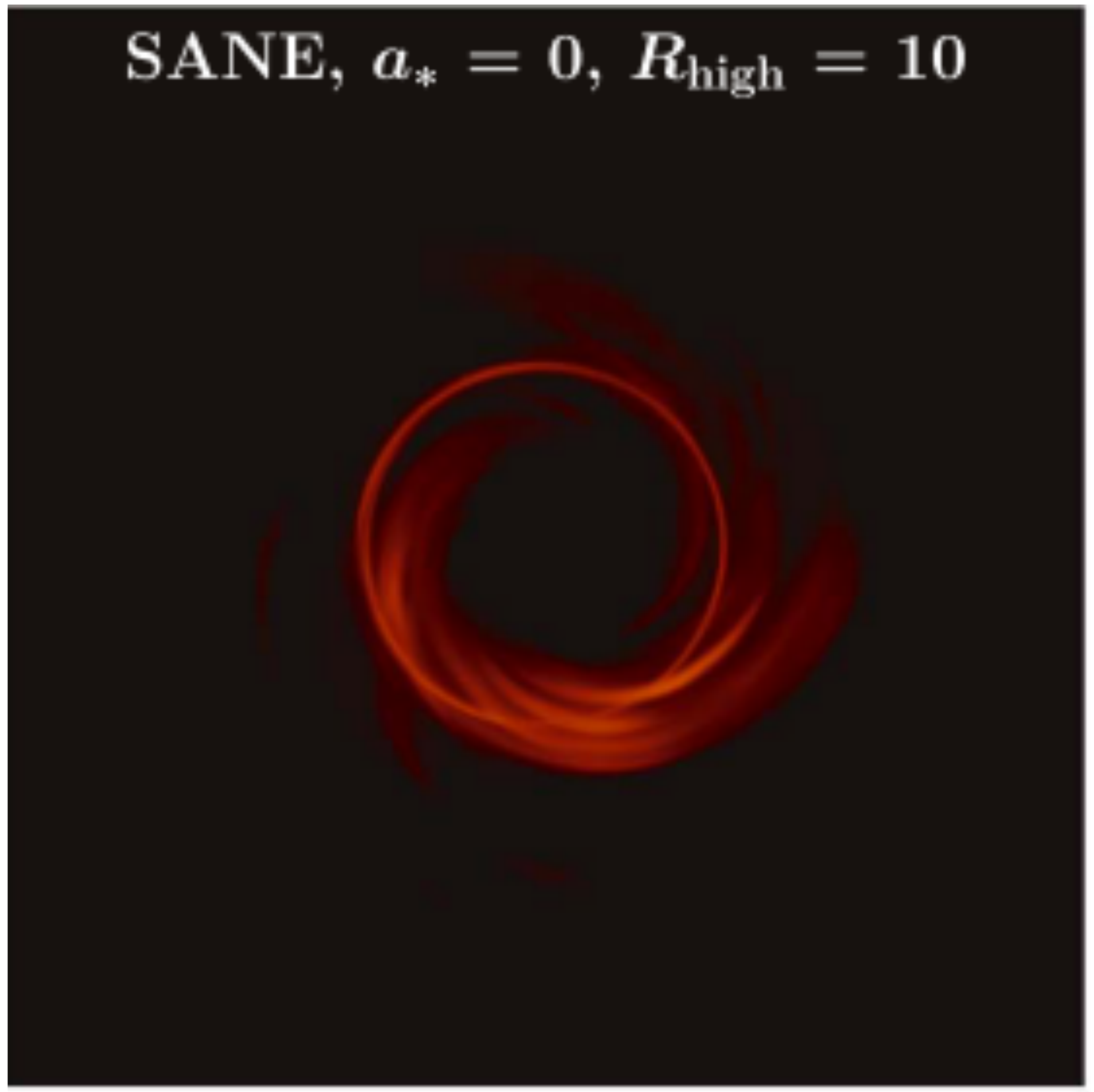
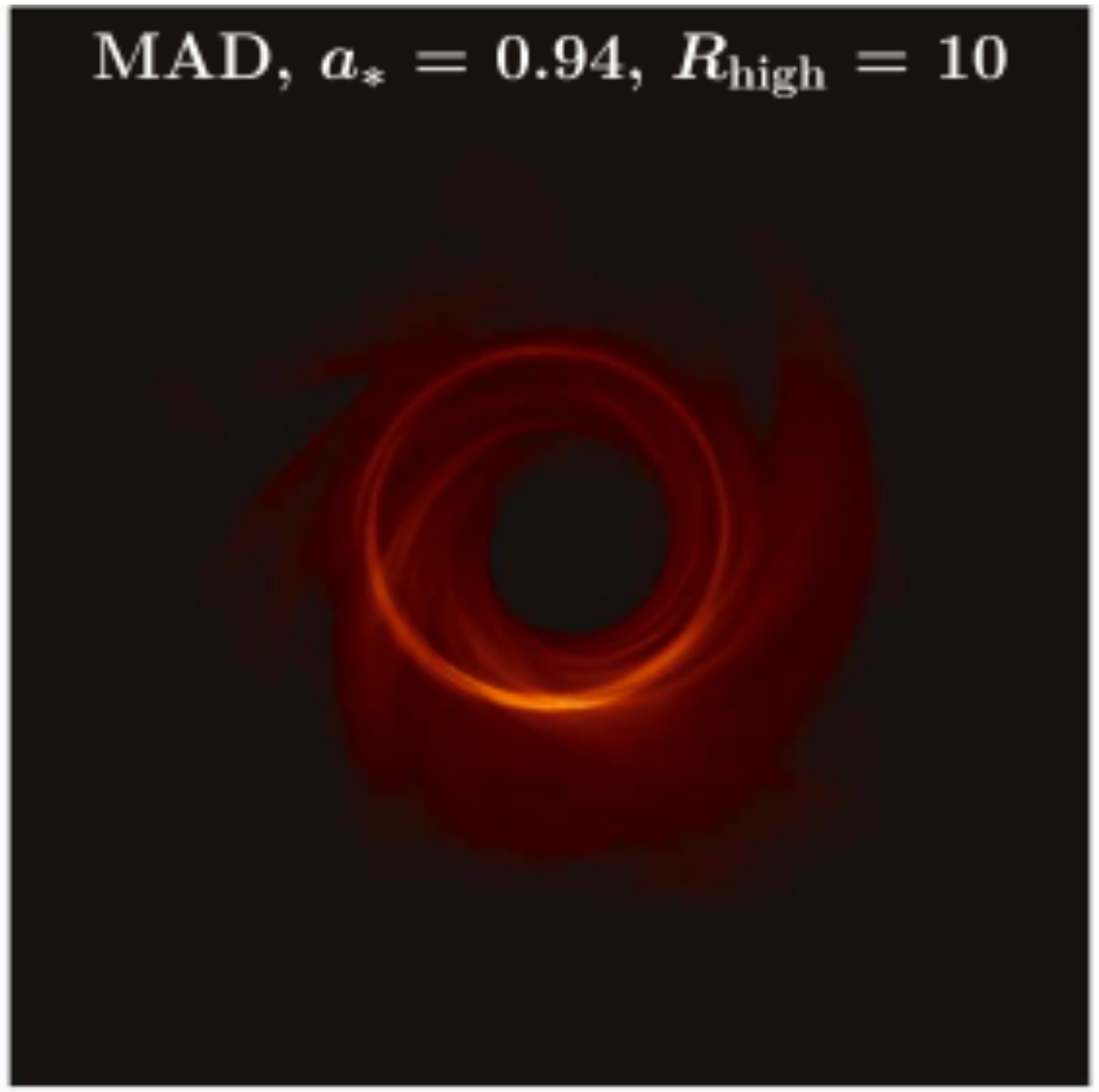
Black Hole Magnetosphere: Magnetic Flux (SANE / MAD)





EHTC+19 Paper I

First M87 Results: Remained Issues

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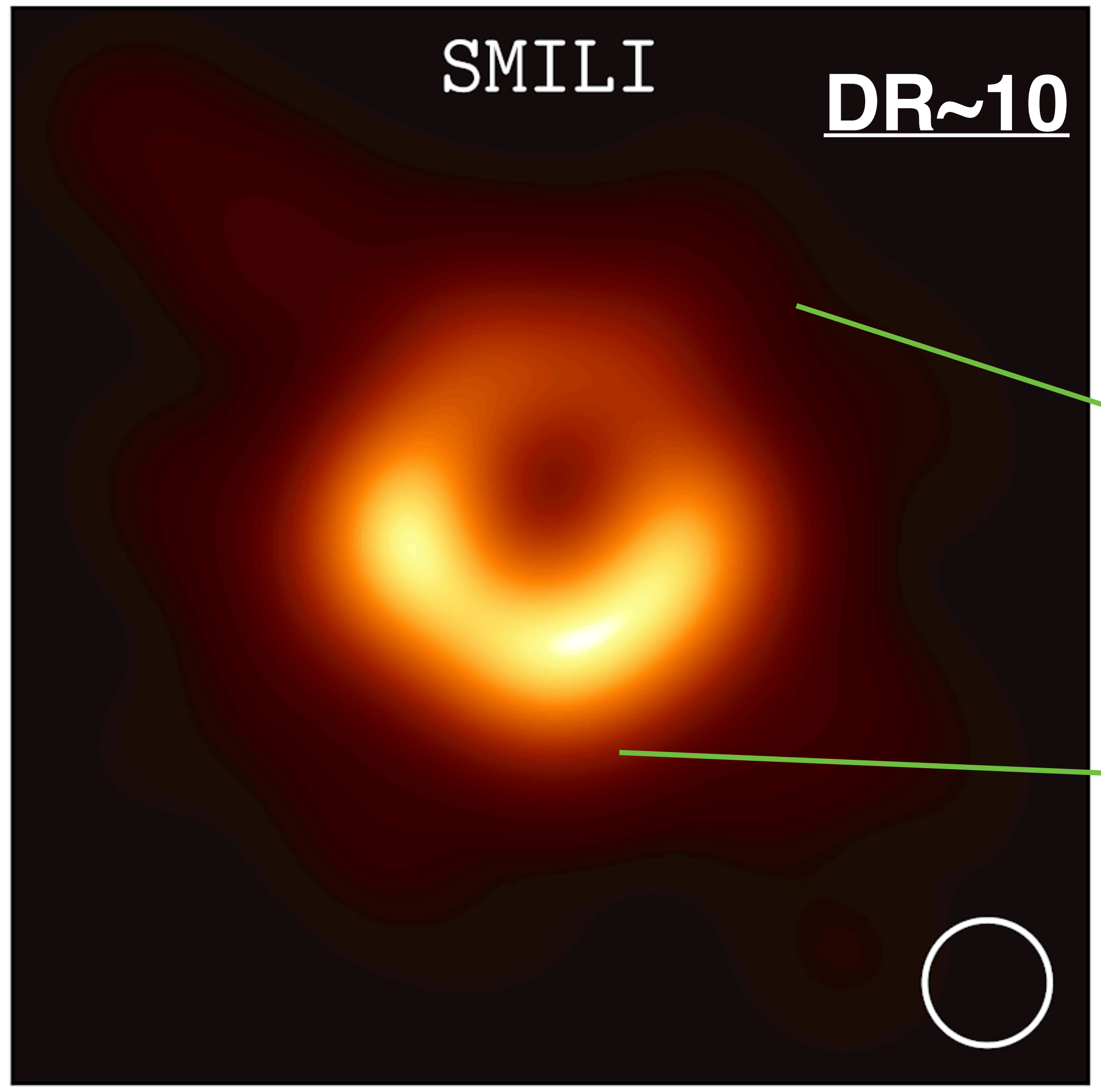
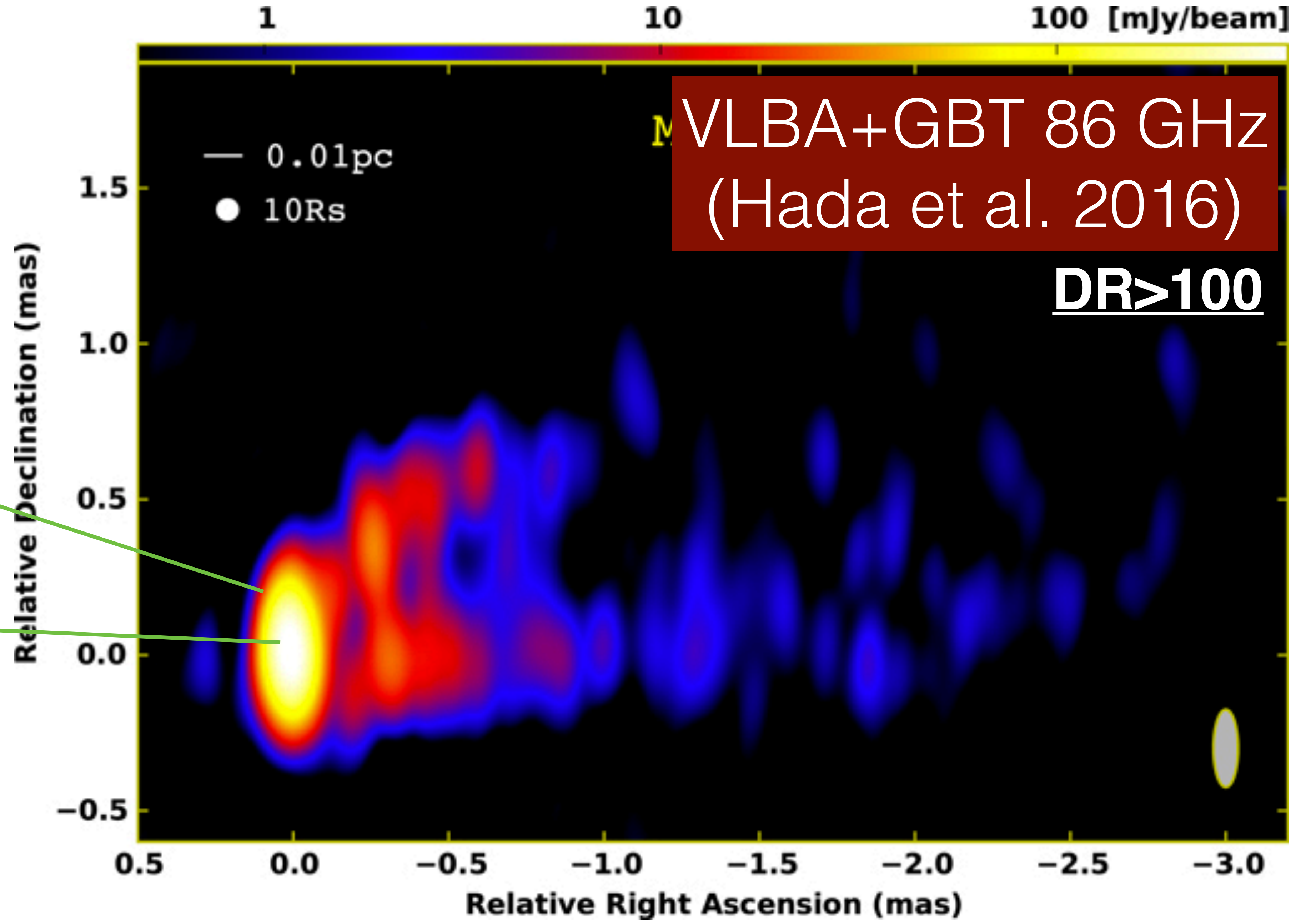
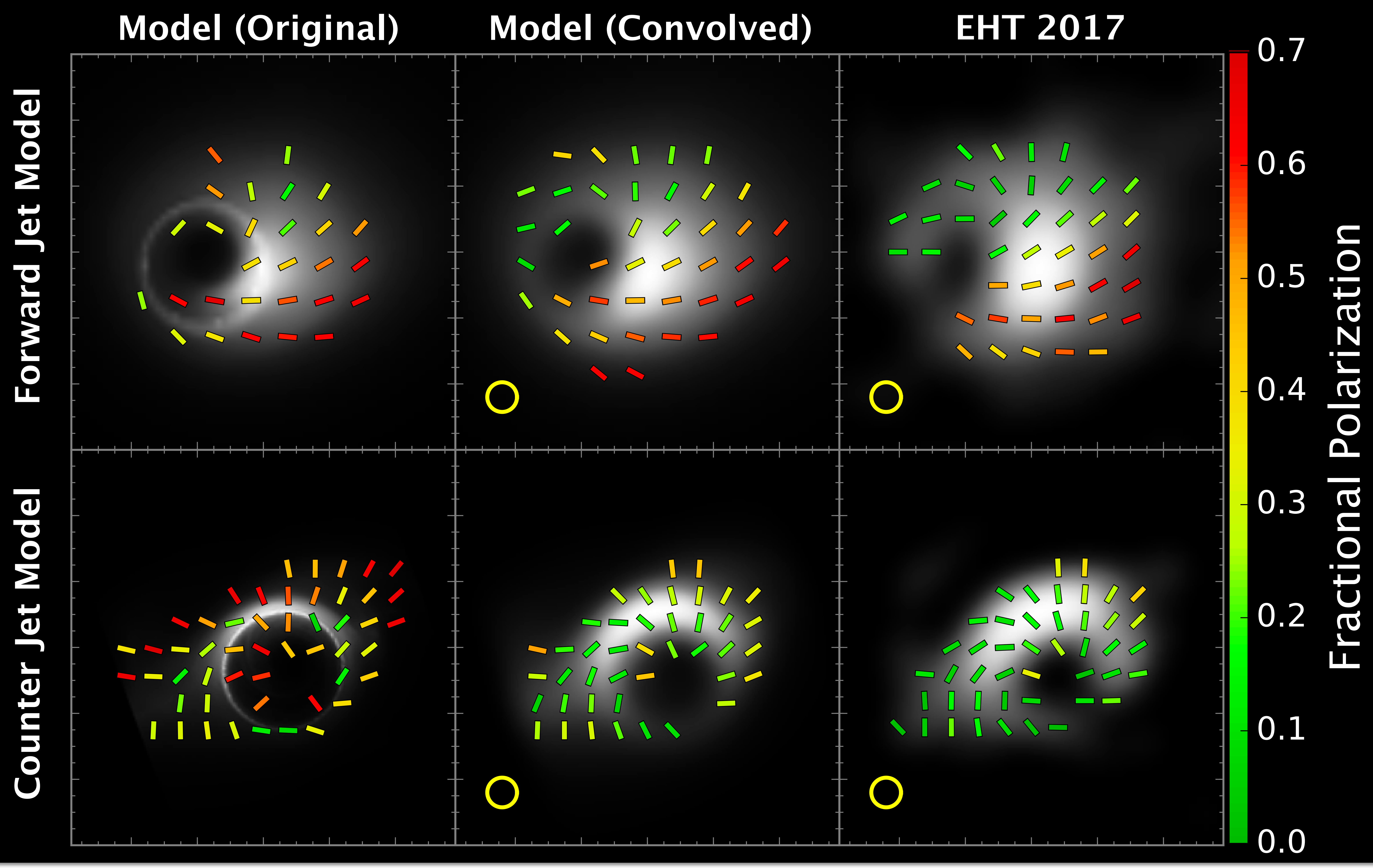
Black Hole Magnetosphere: Magnetic Flux (SANE / MAD)

Jet launching: how is the energy extracted from the black hole?





M87 Polarimetry: Coming Soon



Akiyama et al. 2017, Chael et al. 2016

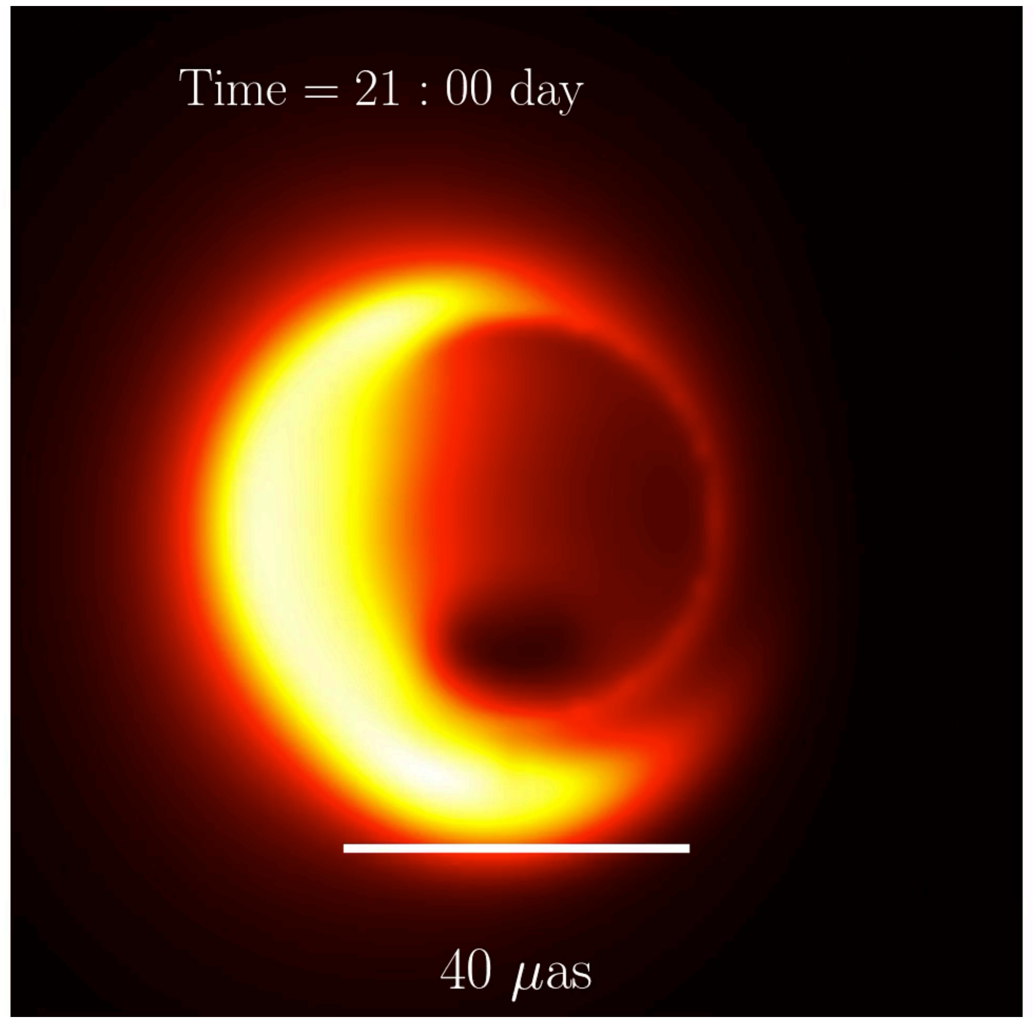
Sgr A*: Another Horizon-scale Target

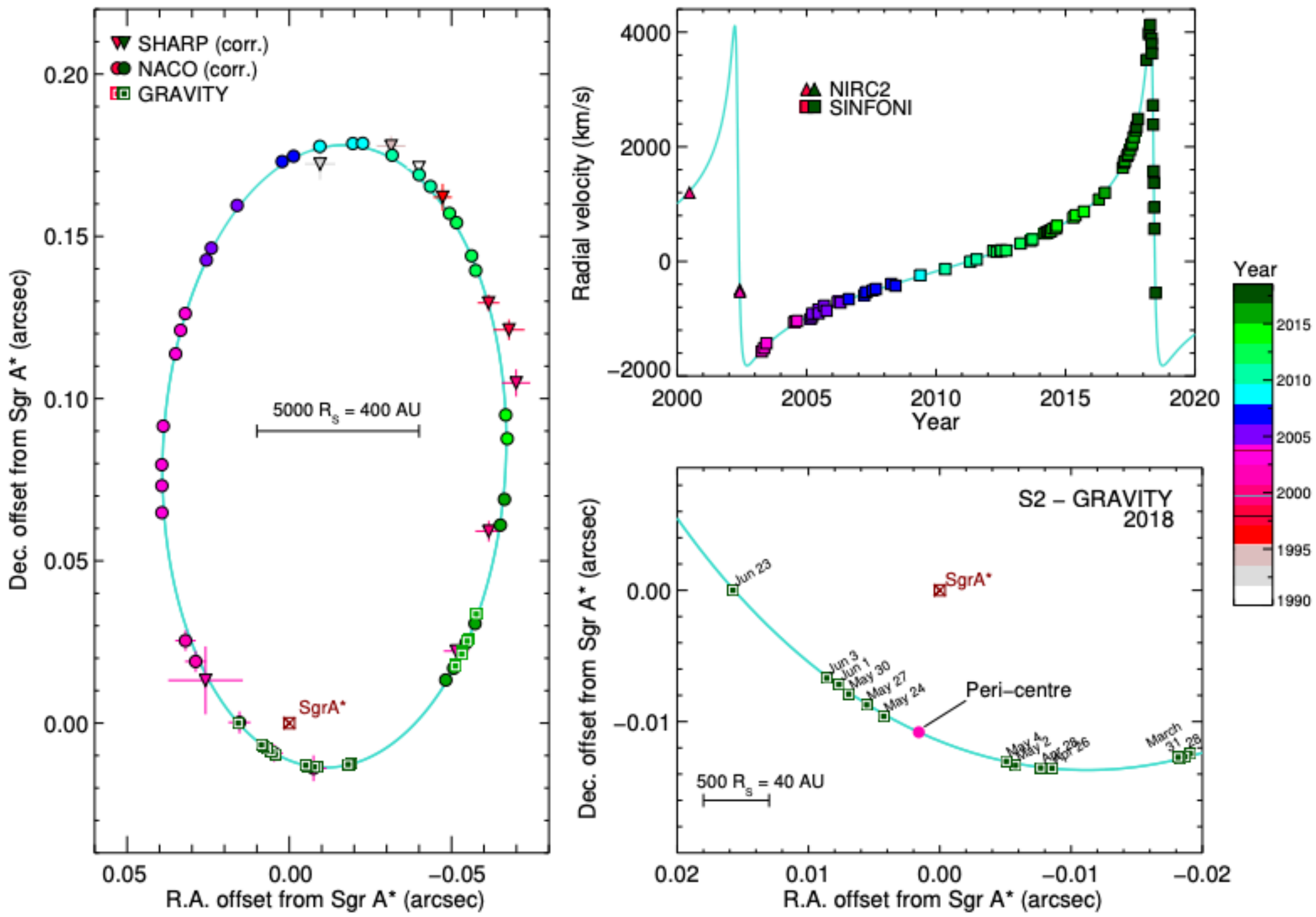
Best target for the GR test

- Mass & Distance are accurately measured (GRAVITY Collaboration+2018)

Current challenges

- Time variations: on minutes time scales
- Interstellar Scattering: much less dominant

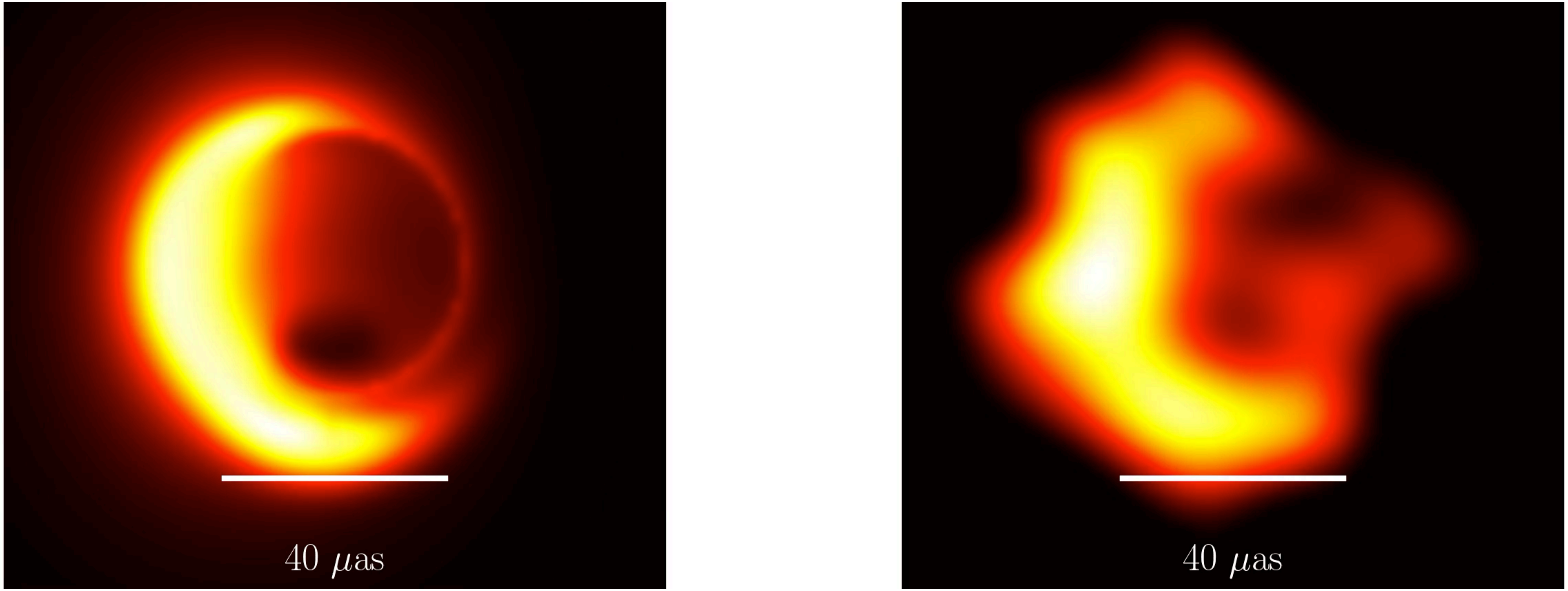




GRAVITY Collaboration+2018

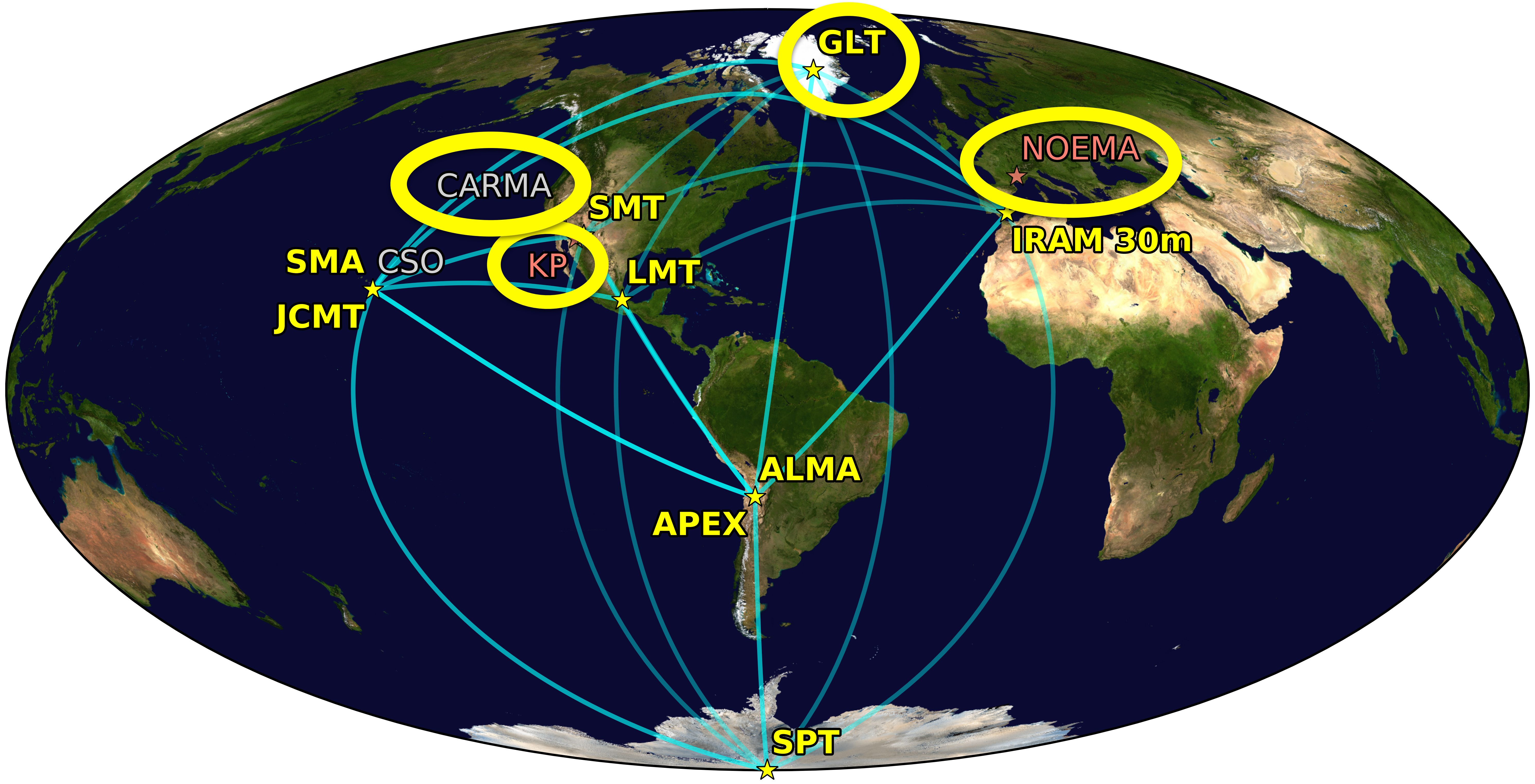
Weather forecast: Sgr A*

An illustrative full-closure imaging simulation with EHT 2017 array



Model: Broderick & Loeb 2006, Imaging: Kotaro Moriyama

EHT2020s: EHT within 3 years from now



2018:
- **Bandwidth:** 32 Gbps -> 64 Gbps
- **New Station:**
  GLT (under commissioning)

2020:
- **New Stations:**
  GLT (official)
  NOEMA & Kitt Peak (KP)

2023:
- **New Station:** Owens Valley (OVRO)
- **345 GHz Capability**

Doeleman et al. 2019, Astro2020 white paper

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2017: 230 GHz,         32 Gbps,  8 stations @  6 sites
2023: 230 & 345 GHz, 64 Gbps, 12 stations @ 10 sites
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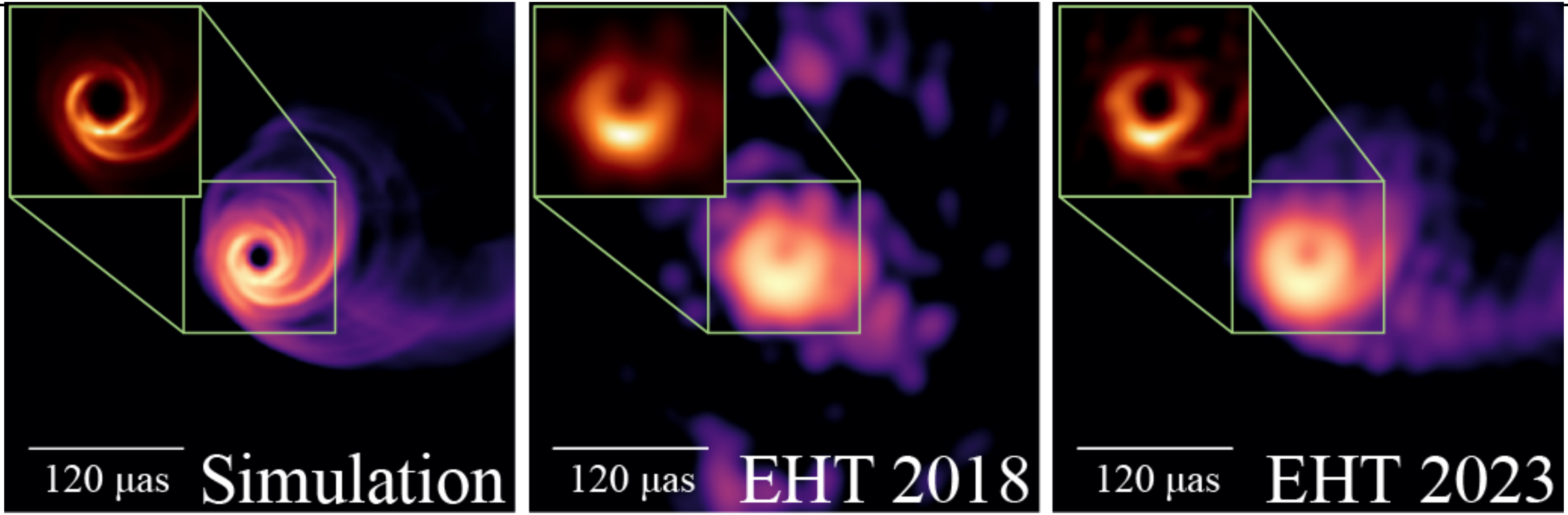
EHT 2020s: Deeper, Shaper & Multi-frequency Images



230 GHz
EHT2017+GLT

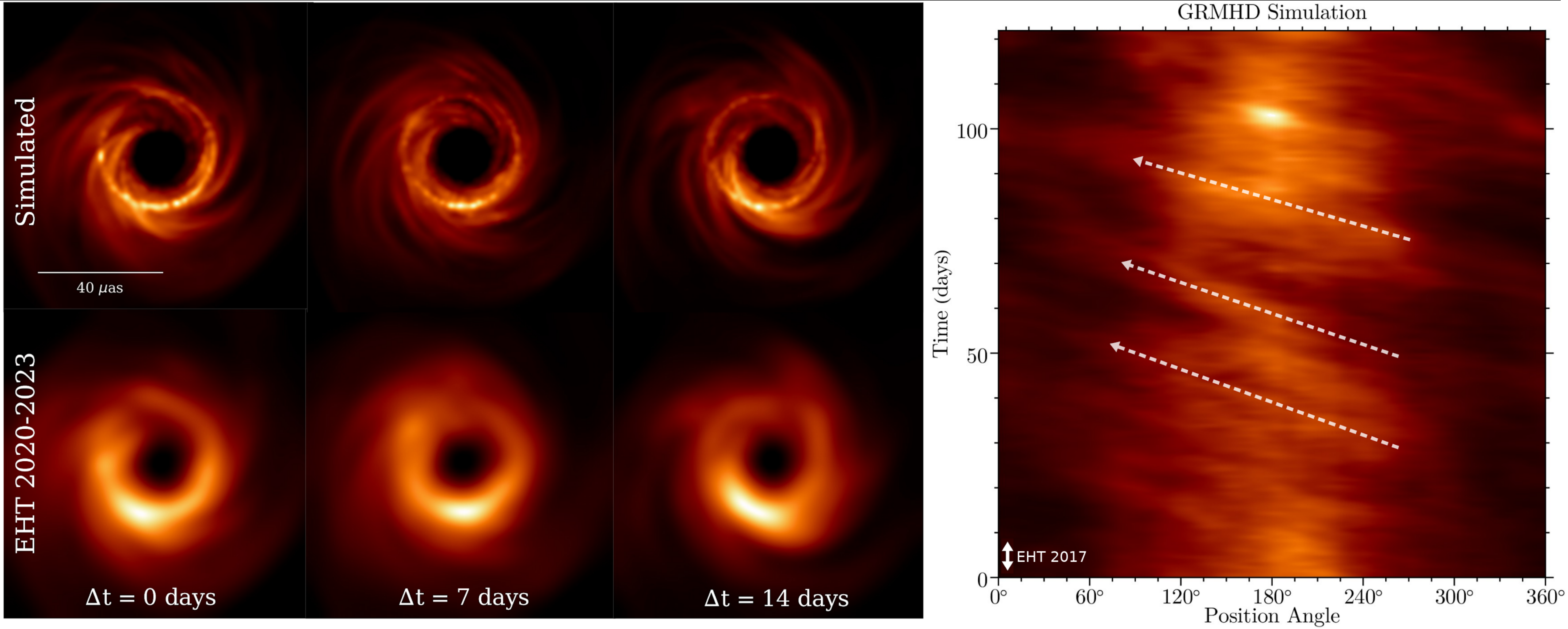
230+345 GHz
EHT2017+GLT+KP+NOEMA+OVRO

Further new capabilities: Faraday Rotation Imaging

Active developments of multi-frequency (Chael+) and multi-scale (Akiyama+) Imaging

Simulations: Andrew Chael, Imaging: Kazu Akiyama

EHT 2020s: Tracking Evolving Features

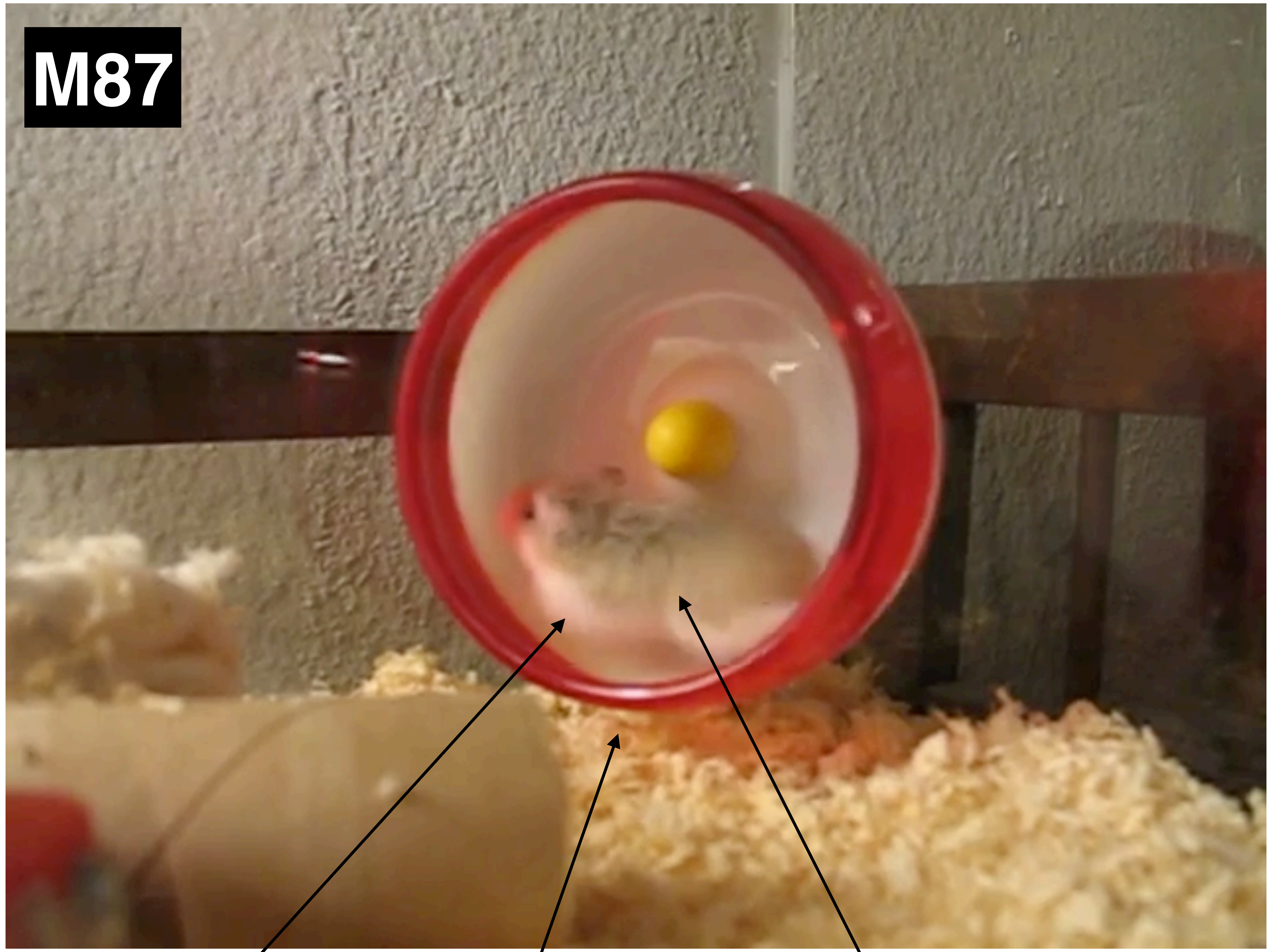


Regular monitoring observation capabilities on weekly scales

Simulations: Charles Gammie, George Wong et al., Imaging: Michael Johnson

Event Horizon Telescope

EHT 2020s: Precision Black Hole Astrophysics



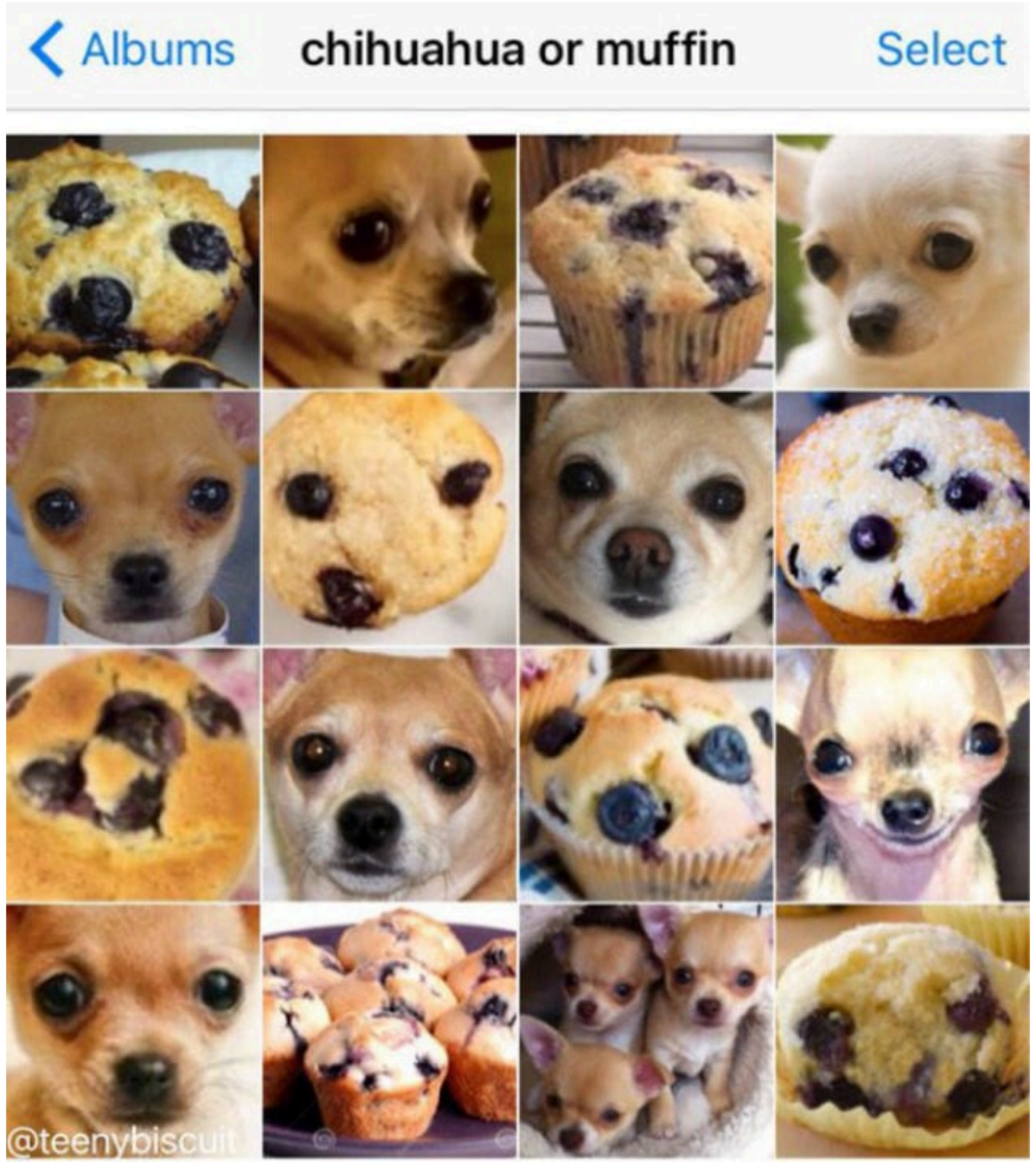
Mass ?   Spin ?   Accretion flow types?

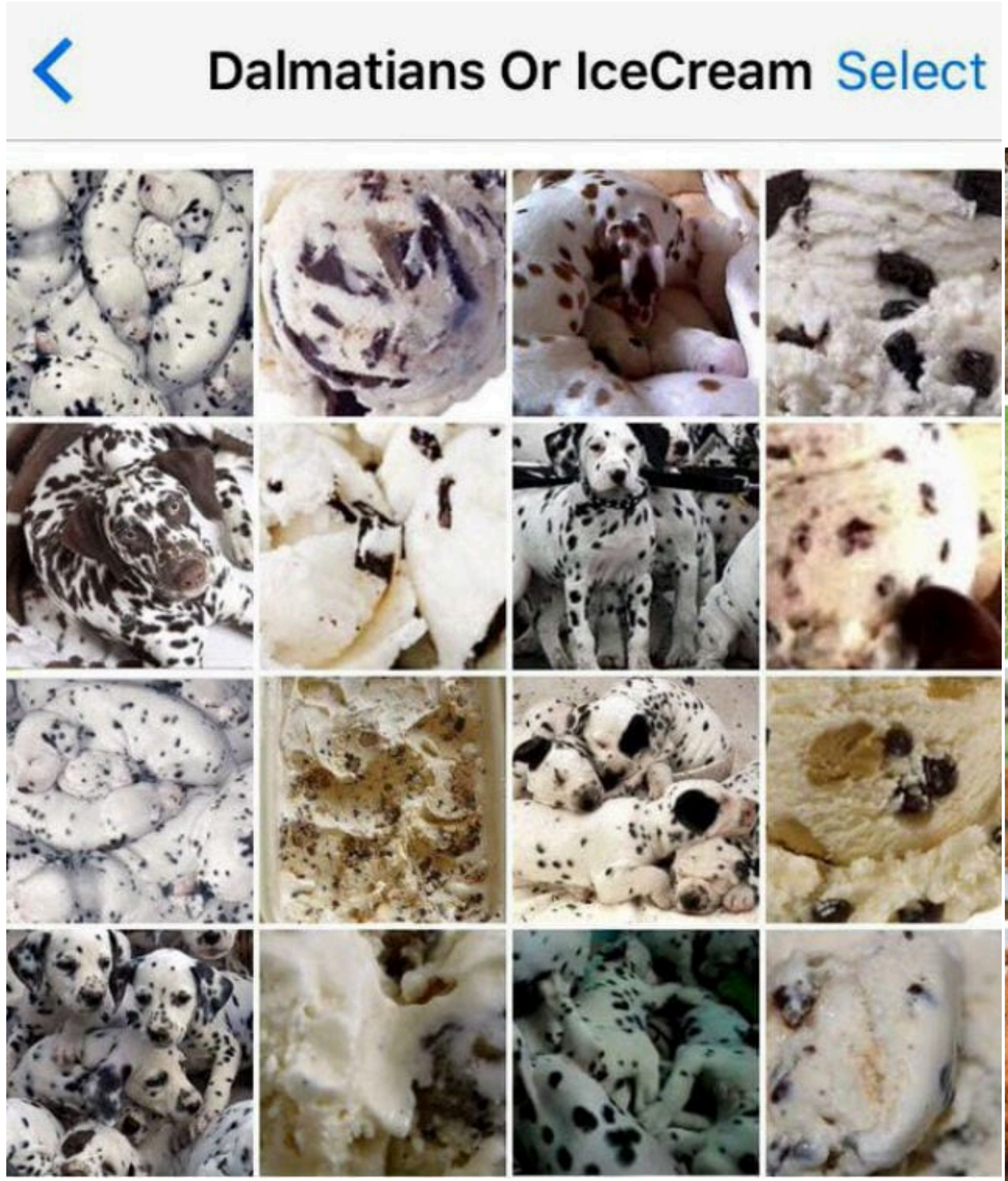
Viewing Geometry?

https://www.youtube.com/watch?v=0ymmnHlnDVY

EHT 2020s: Precision Black Hole Astrophysics

Are black hole images confusing for scientists and/or AI?



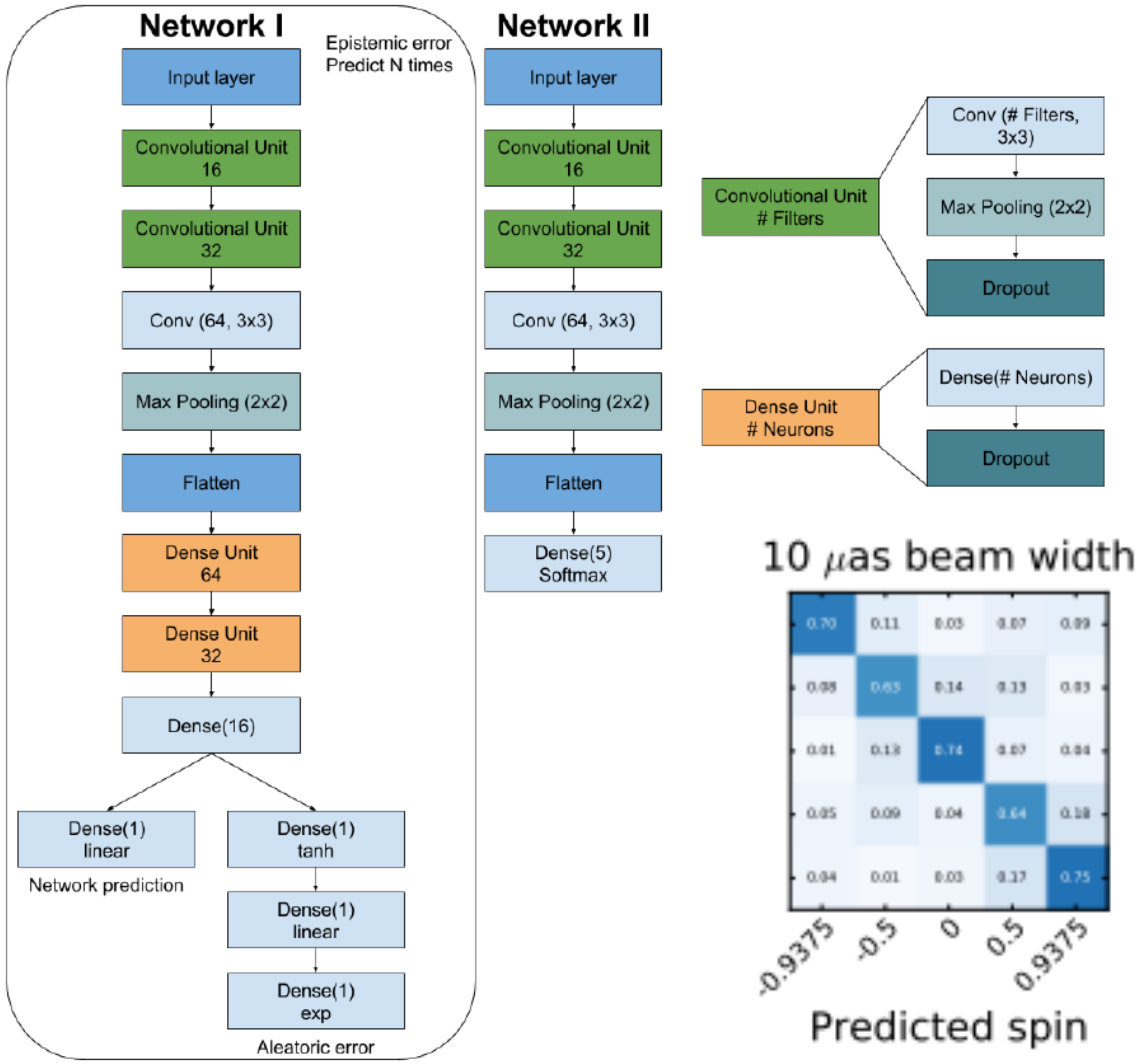


Doodle or Fried Chicken

https://barkpost.com/humor/doodle-or-fried-chicken-twitter/

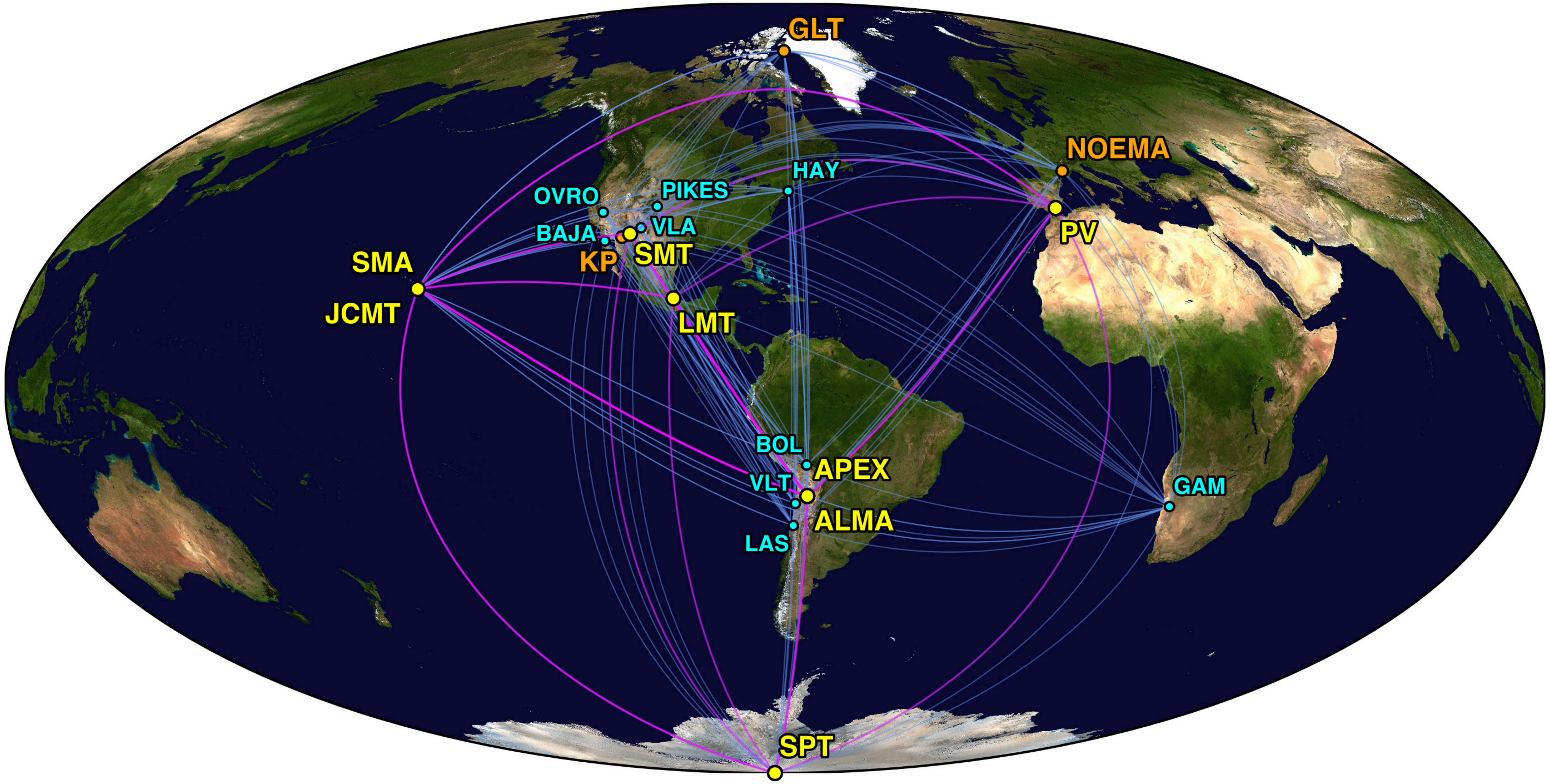
EHT 2020s: Precision Black Hole Astrophysics

Current forecast: Horizon-scale images are much less confusing!



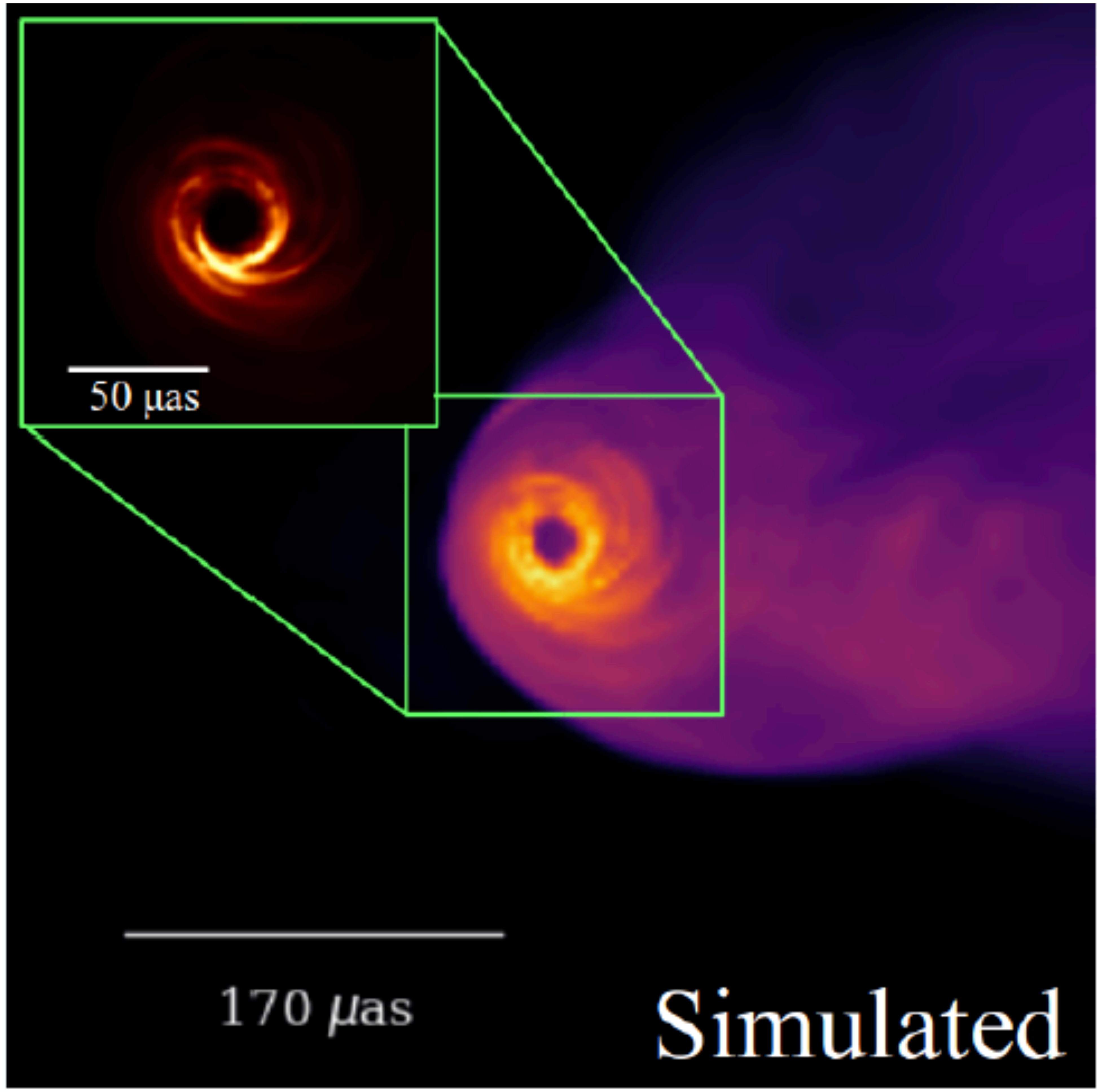
Van der Gucht et al. 2019

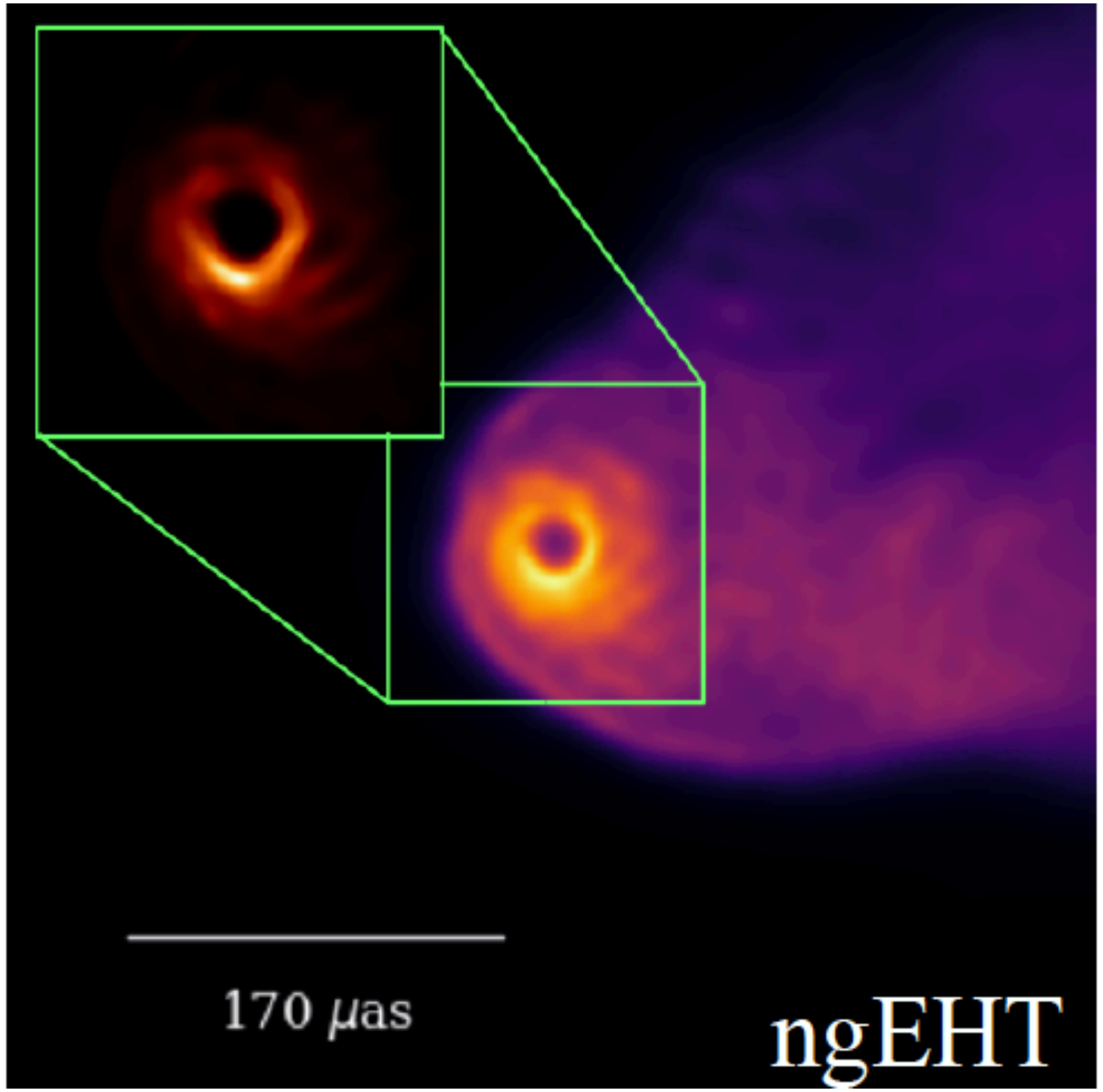
next generation Event Horizon Telescope (2023 -)



Phase I: 2019-2023 (Array Design Phase + MIT Haystack as a new site)
Phase II: 2023- (Constructions of several new telescopes)

M87 ngEHT images: ~10 years from now





Blackburn et al. 2019; Doeleman et al. 2019 (Astro2020 Decadal Survey White Papers)

ngEHT: far more details

Astro2020 APC White Paper

Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Lindy Blackburn[1,2,*] Sheperd Doeleman[1,2,*], Jason Dexter[12], José L. Gómez[16], Michael D. Johnson[1,2], Daniel C. Palumbo[1,2], Jonathan Weintroub[1,2], Joseph R. Farah[1,2,21], Vincent Fish[4], Laurent Loinard[18,19], Colin Lonsdale[4], Gopal Narayanan[28], Nimesh A. Patel[2], Dominic W. Pesce[1,2], Alexander Raymond[1,2], Remo Tilanus[17,22,23], Maciek Wielgus[1,2], Kazunori Akiyama[1,3,4,5], Geoffrey Bower[6], Avery Broderick[7,8,9], Roger Deane[10,11], Christian Michael Fromm[13], Charles Gammie[14,15], Roman Gold[13], Michael Janssen[17], Tomohisa Kawashima[4], Thomas Krichbaum[29], Daniel P. Marrone[20], Lynn D. Matthews[4], Yosuke Mizuno[13], Luciano Rezzolla[13], Freek Roelofs[17], Eduardo Ros[29], Tuomas K. Savolainen[29,30,31], Feng Yuan[24,25,26], Guangyao Zhao[27]

[1] *Black Hole Initiative at Harvard University, 20 Garden Street, Cambridge, MA 02138, USA* *and Particle Physics (IMAPP), Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*

Astro2020 APC WP

Blackburn+

Event Horizon Telescope

EHT beyond the Earth: Why do we need?

Ground limitations:

Telescope Coverages

- Not so many sites capable of sub-mm VLBI observations
- Snapshot coverages will be highly limited by Earth rotation

Limiting snapshot imaging of Sgr A* and multi-epoch observations

Angular resolution

- The maximum diameter = the Earth diameter
- Frequency / wavelength: limited by atmosphere (up to ~350 GHz)

Sub-Rs scale imaging of M87/Sgr A*, more horizon-scale targets

EHT beyond the Earth: Designing towards late 2020

1st KISS Workshop, Sep 2019

EHT beyond the Earth: Designing towards late 2020

- Astro 2020 Science and APC white papers
  (Doeleman+, Haworth+, Pesce+)

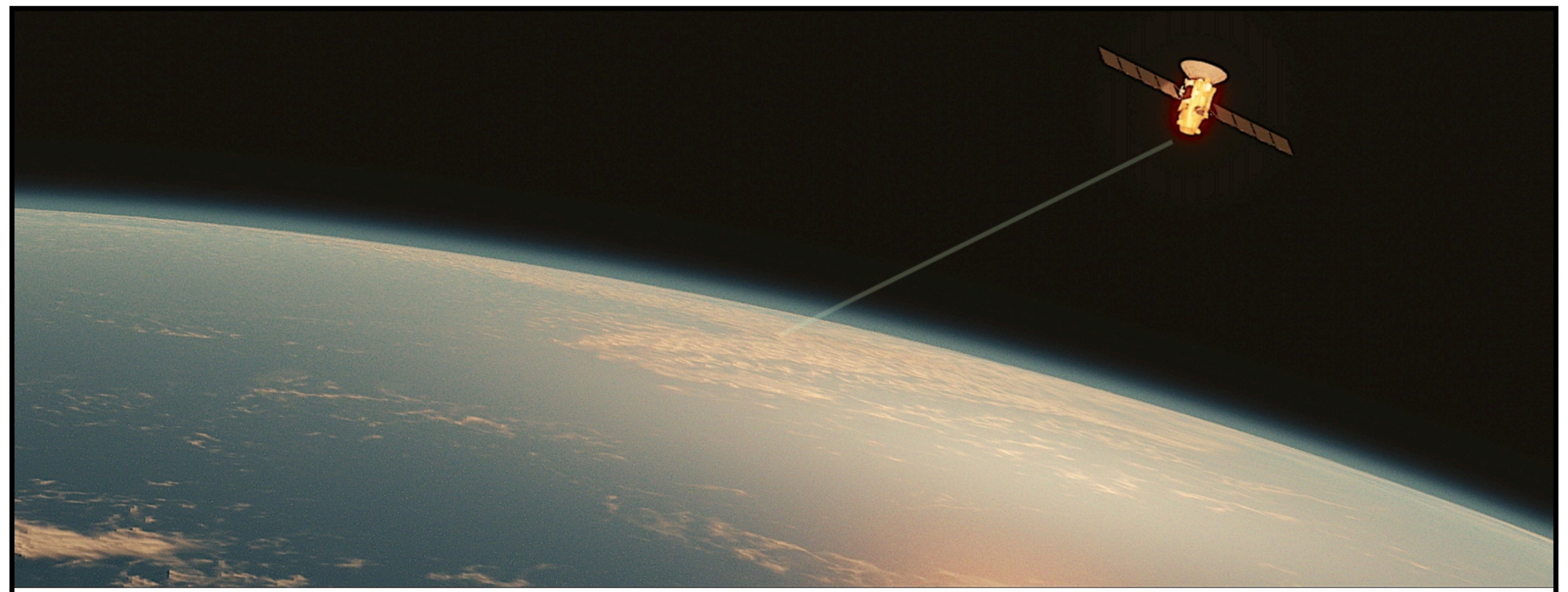
- Active International Discussions

Sep 2018: 1st International Space VLBI conference @ Netherland

Sep 2019: 1st KISS Workshop @ USA (invitation only)

Jan 2020: 2nd International Space VLBI conference @ USA (Next week!)

June 2020: 2nd KISS Workshop @ USA (invitation only)



Astro2020 APC White Paper

Studying black holes on horizon scales with space-VLBI

Kari Haworth[1,*], Michael D. Johnson[1,2,*], Dominic W. Pesce[1,2], Daniel C. M. Palumbo[1,2], Lindy Blackburn[1,2], Kazunori Akiyama[2,3,4,5], Don Boroson[6], Kather-

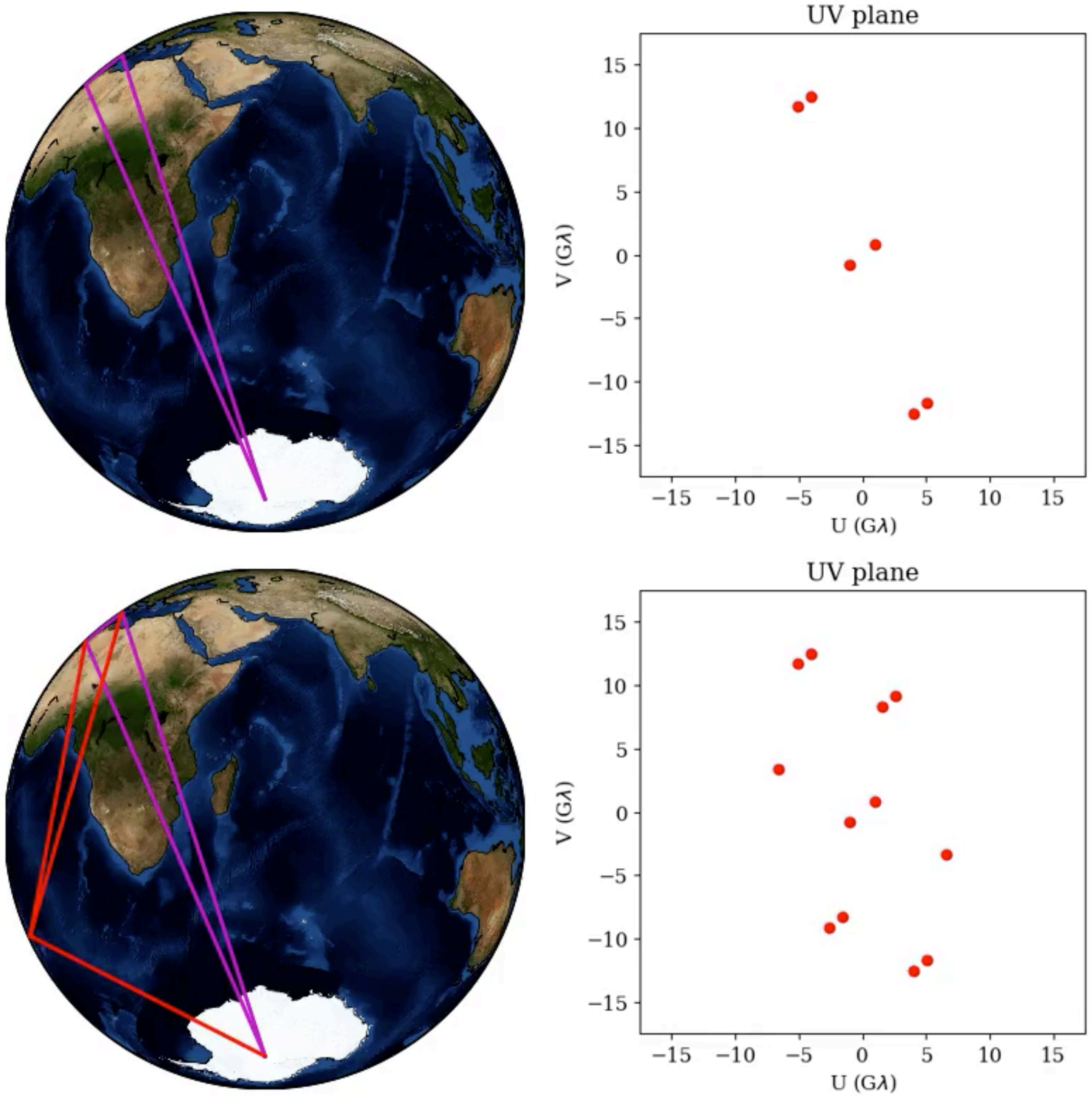
Astro2020 APC White Paper

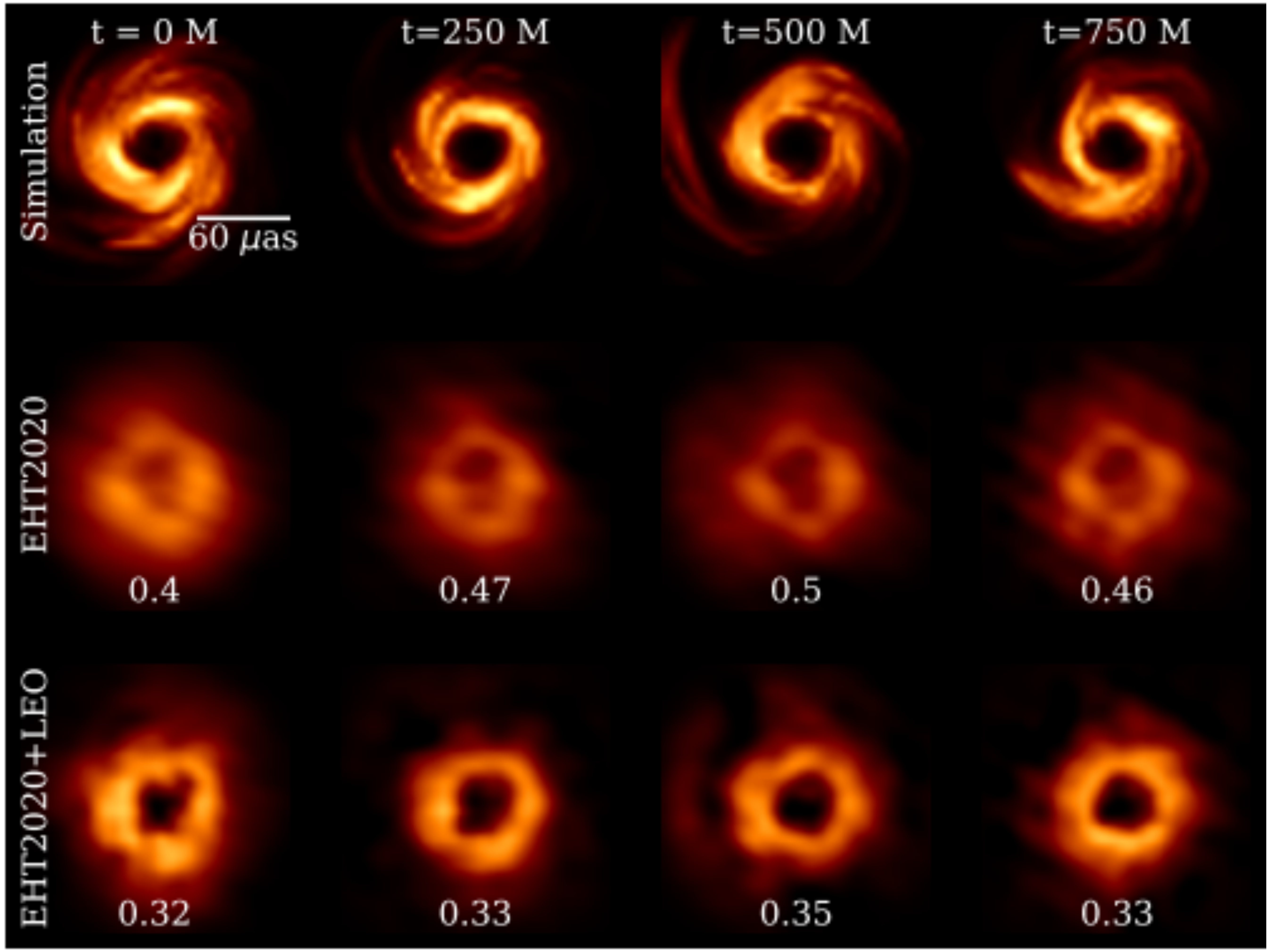
Extremely Long-Baseline Interferometry with the Origins Space Telescope

Dominic W. Pesce[1,2], Kari Haworth[1], Gary J. Melnick[1], Lindy Blackburn[1,2], Maciek Wielgus[1,2], Alexander Raymond[1,2], Jonathan Weintroub[1], Daniel C. M. Palumbo[1,2], Michael D. Johnson[1,2], Sheperd S. Doeleman[1,2], David J. James[1,2]

1st KISS Workshop, Sep 2019

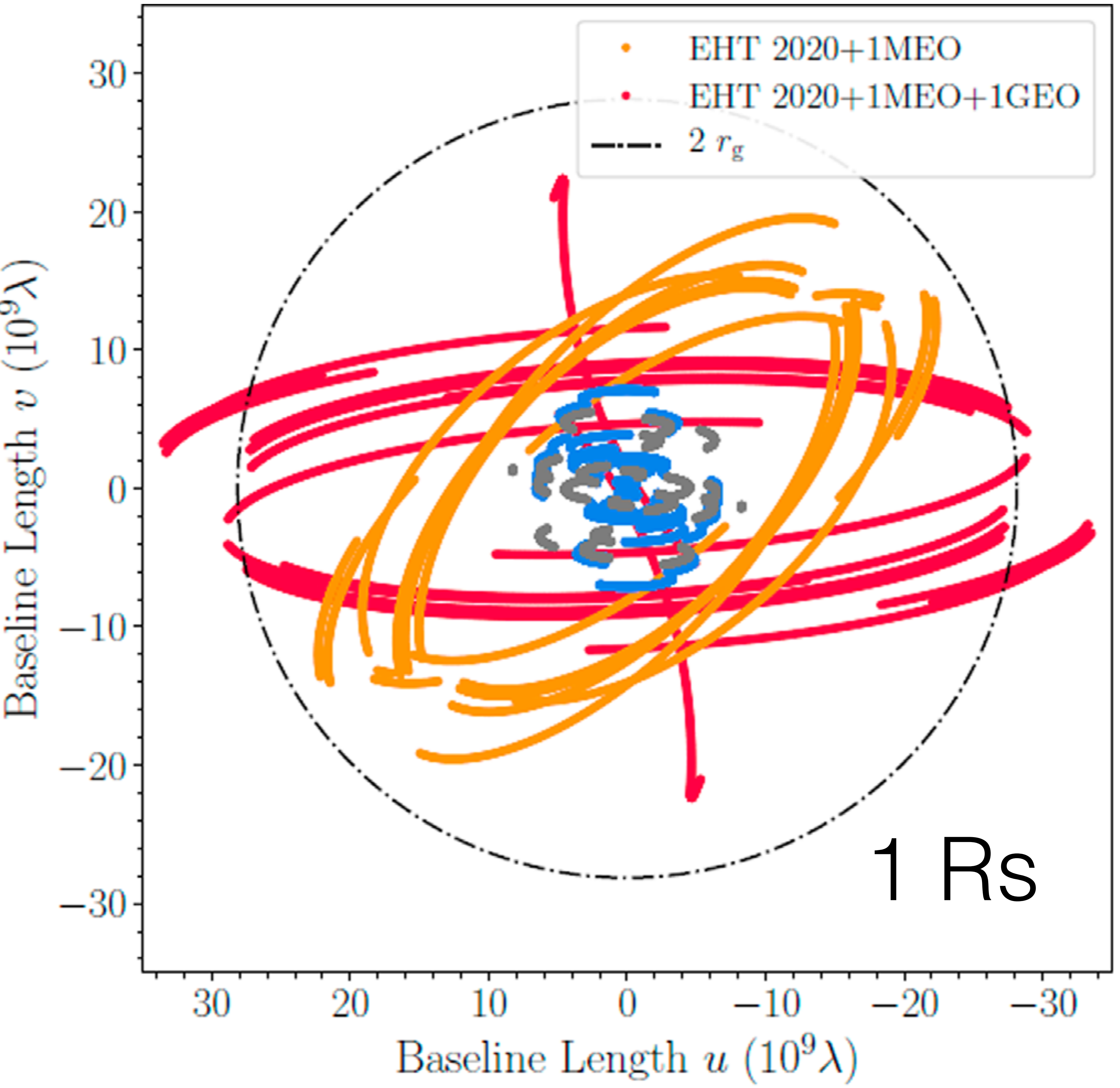
EHT+LEO: Better Snapshot Imaging



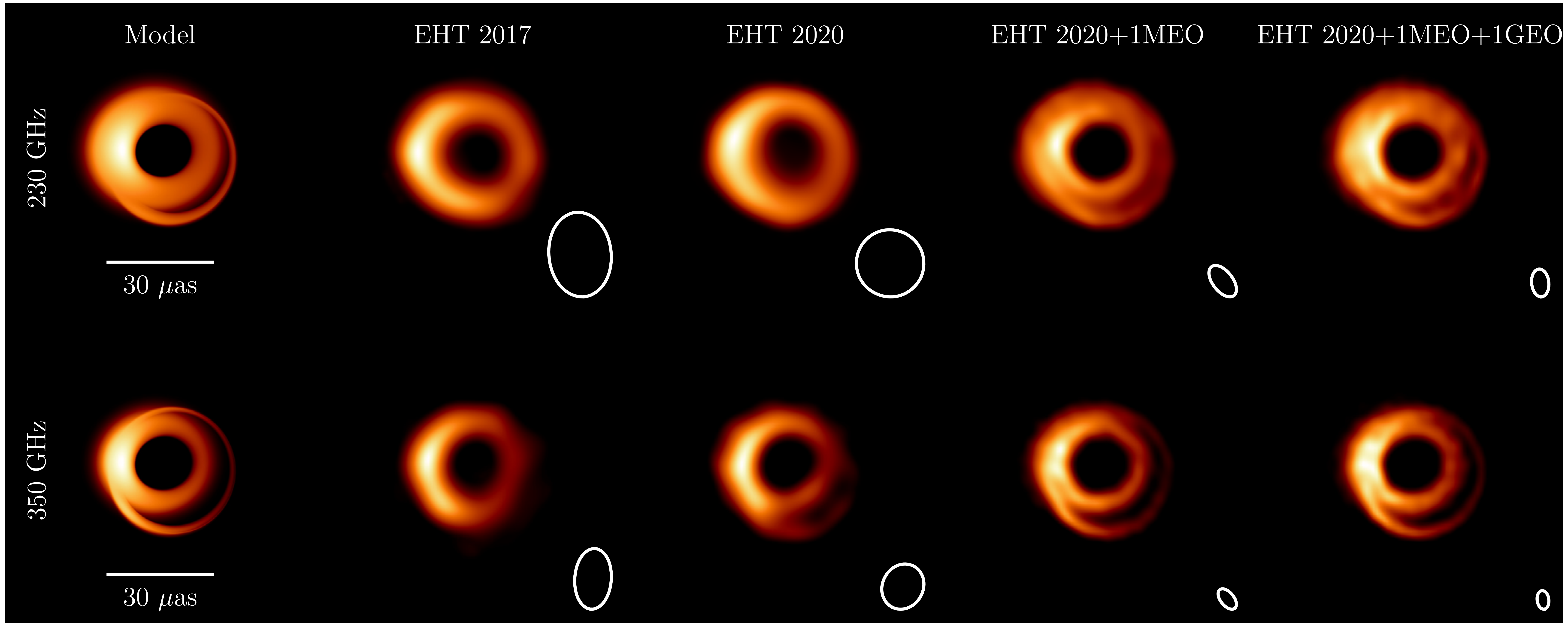


Palumbo et al. 2019, ApJ

EHT+MEO/GEO: (sub-)R_S-scale Imaging of M87 / Sgr A*

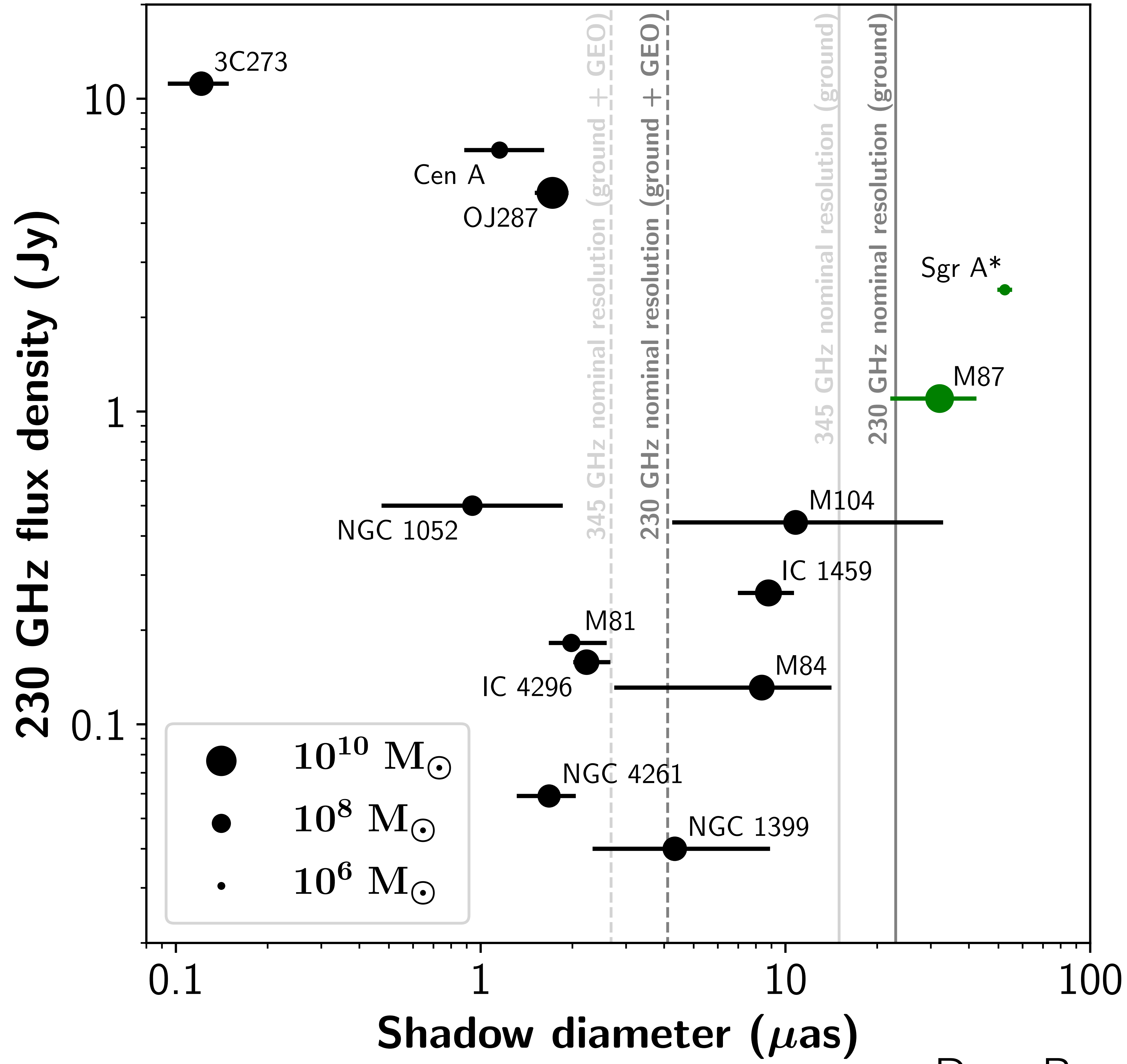


GRMHD simulations at a flaring state



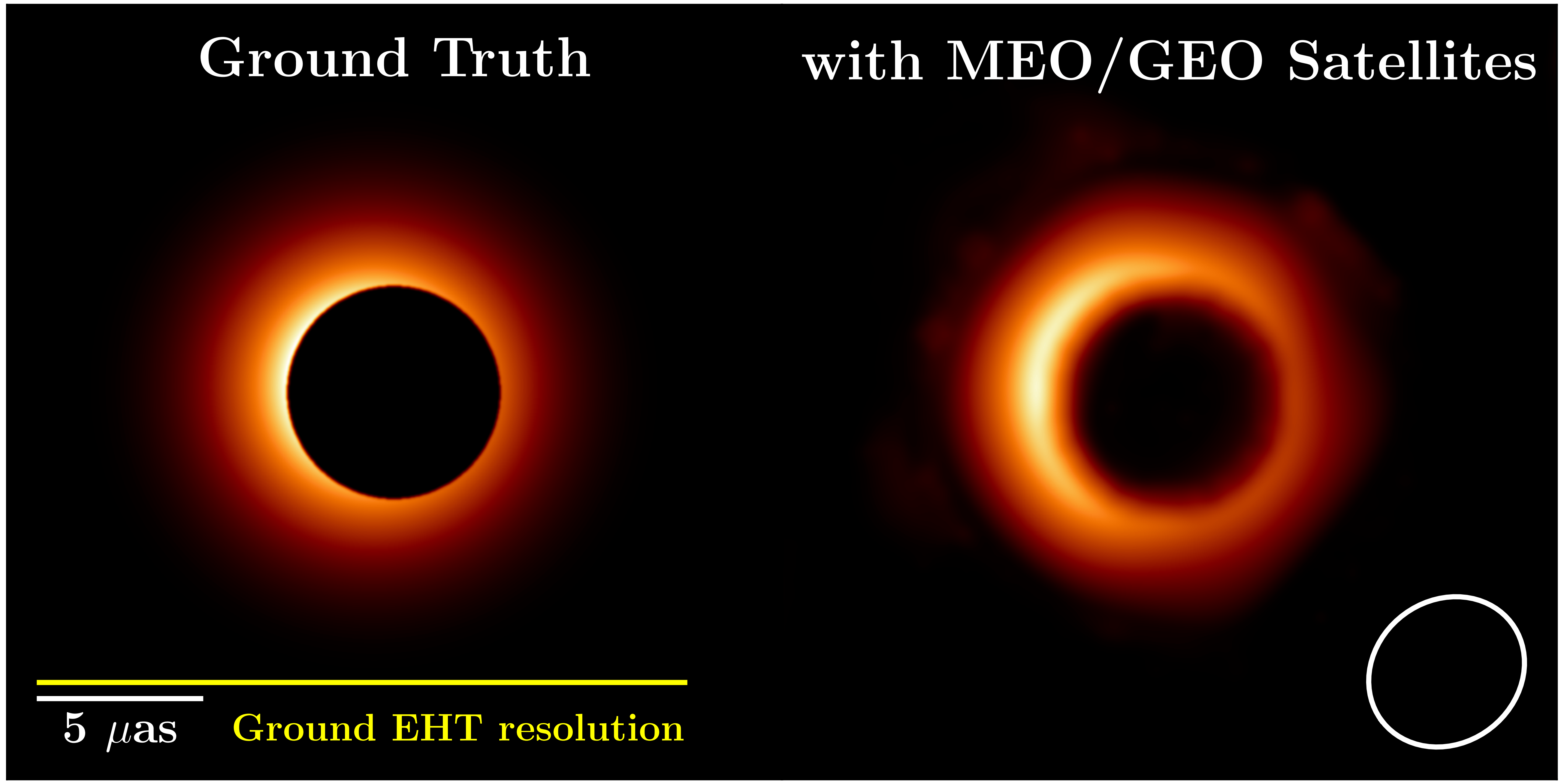
(Kawashima, Kino & Akiyama 2019, ApJ)

EHT+MEO/GEO: Horizon-scale Imaging of other SMBHs



Dom Pesce

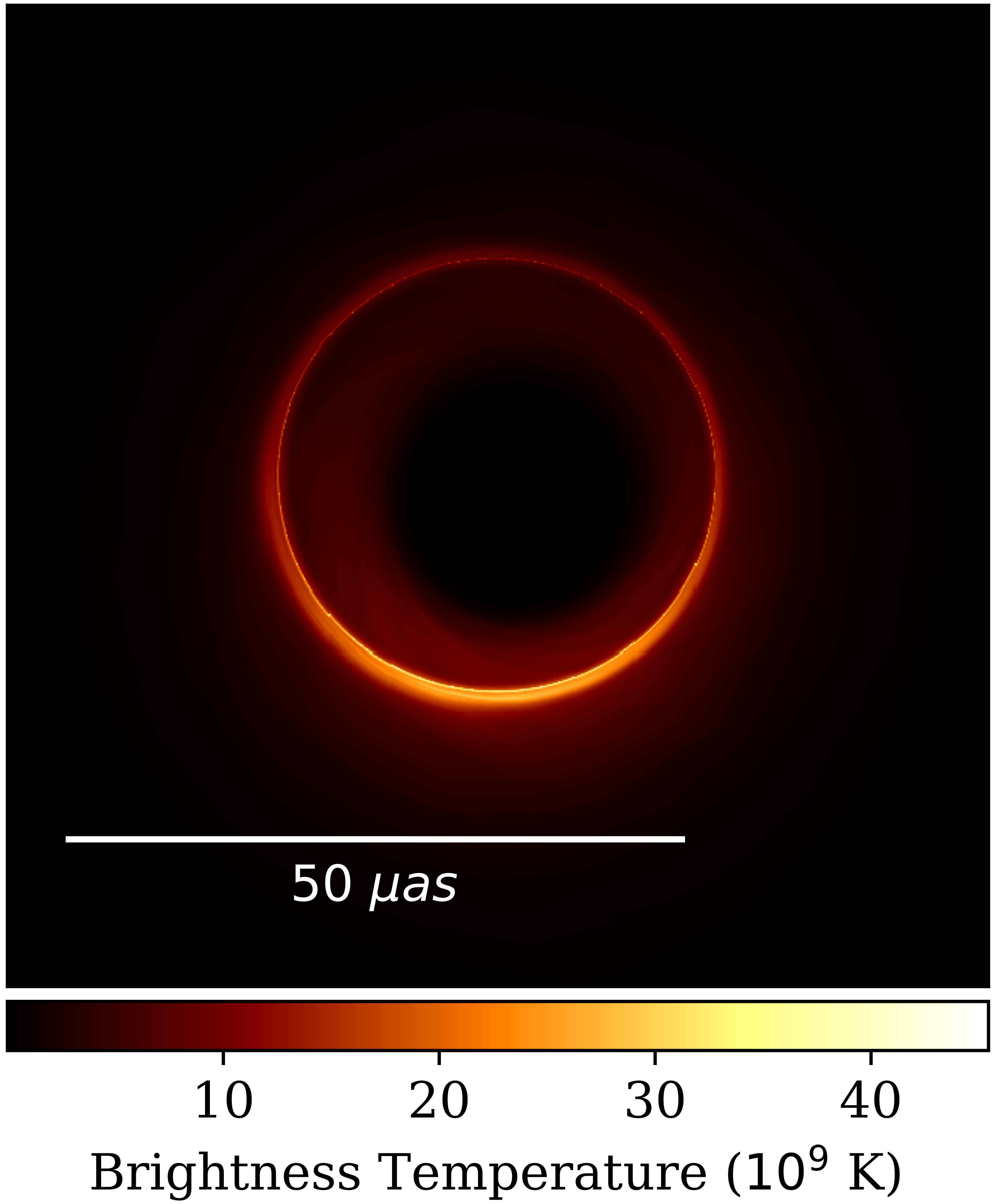
M104 (Sombrero Galaxy)

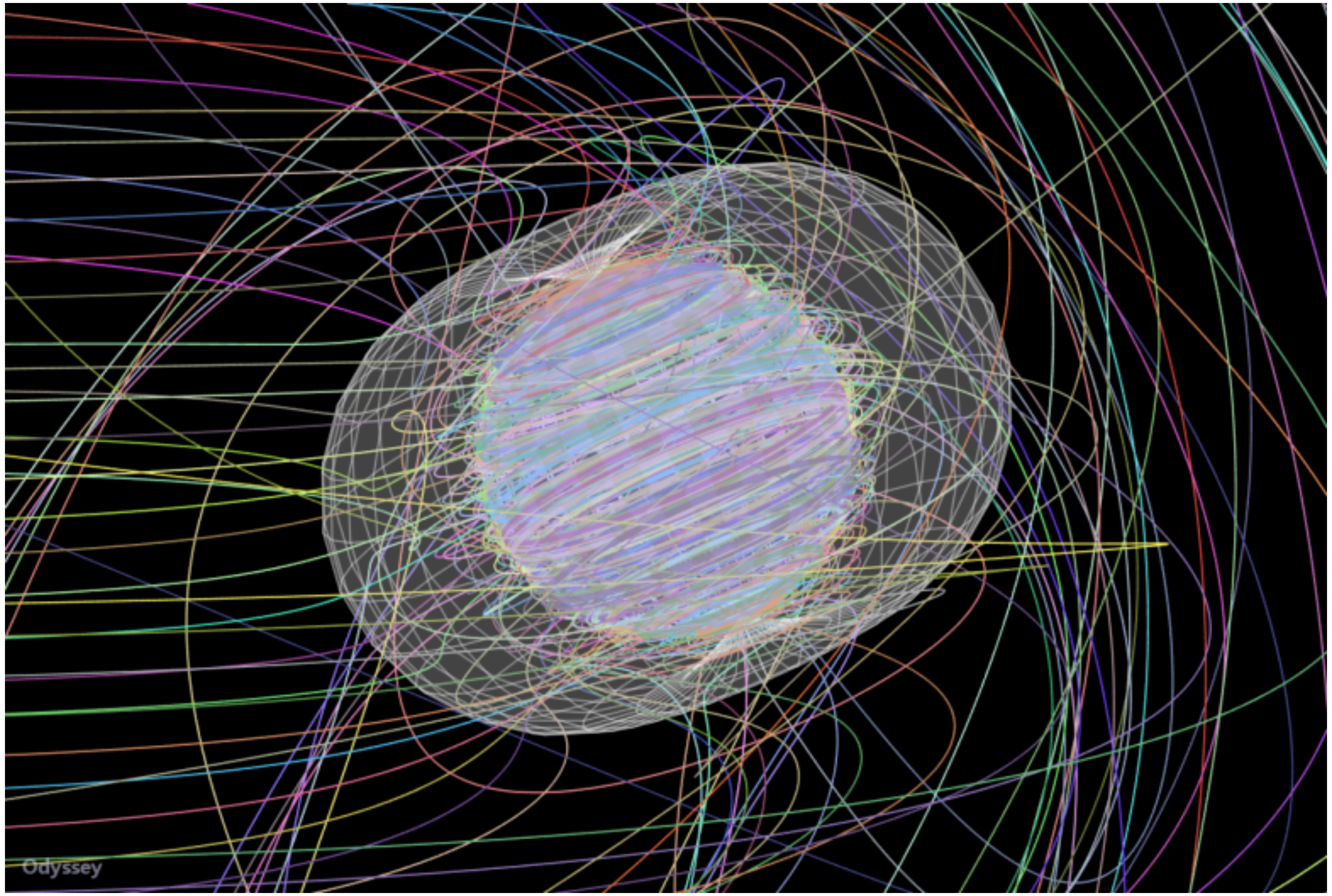


Fish, Shea & Akiyama 2019

Doeleman et al. 2019, Astro2020 white paper

Far more accurate shadow measurements?

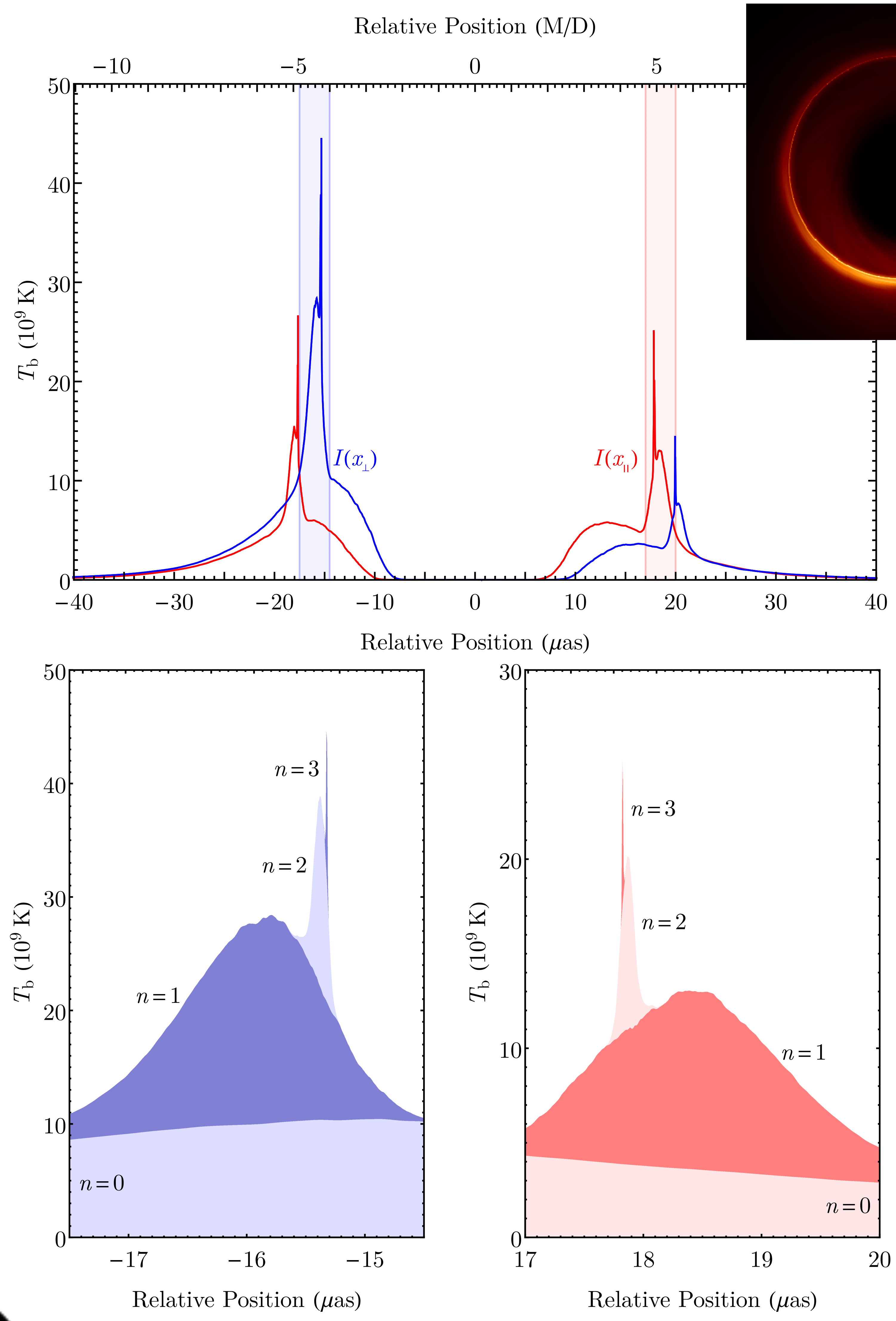


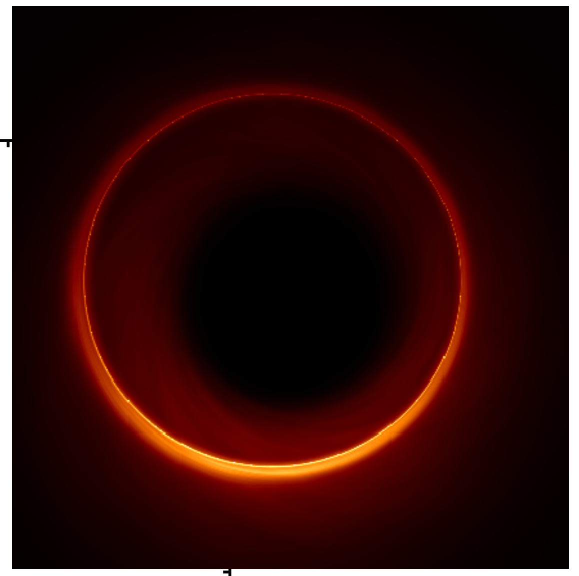


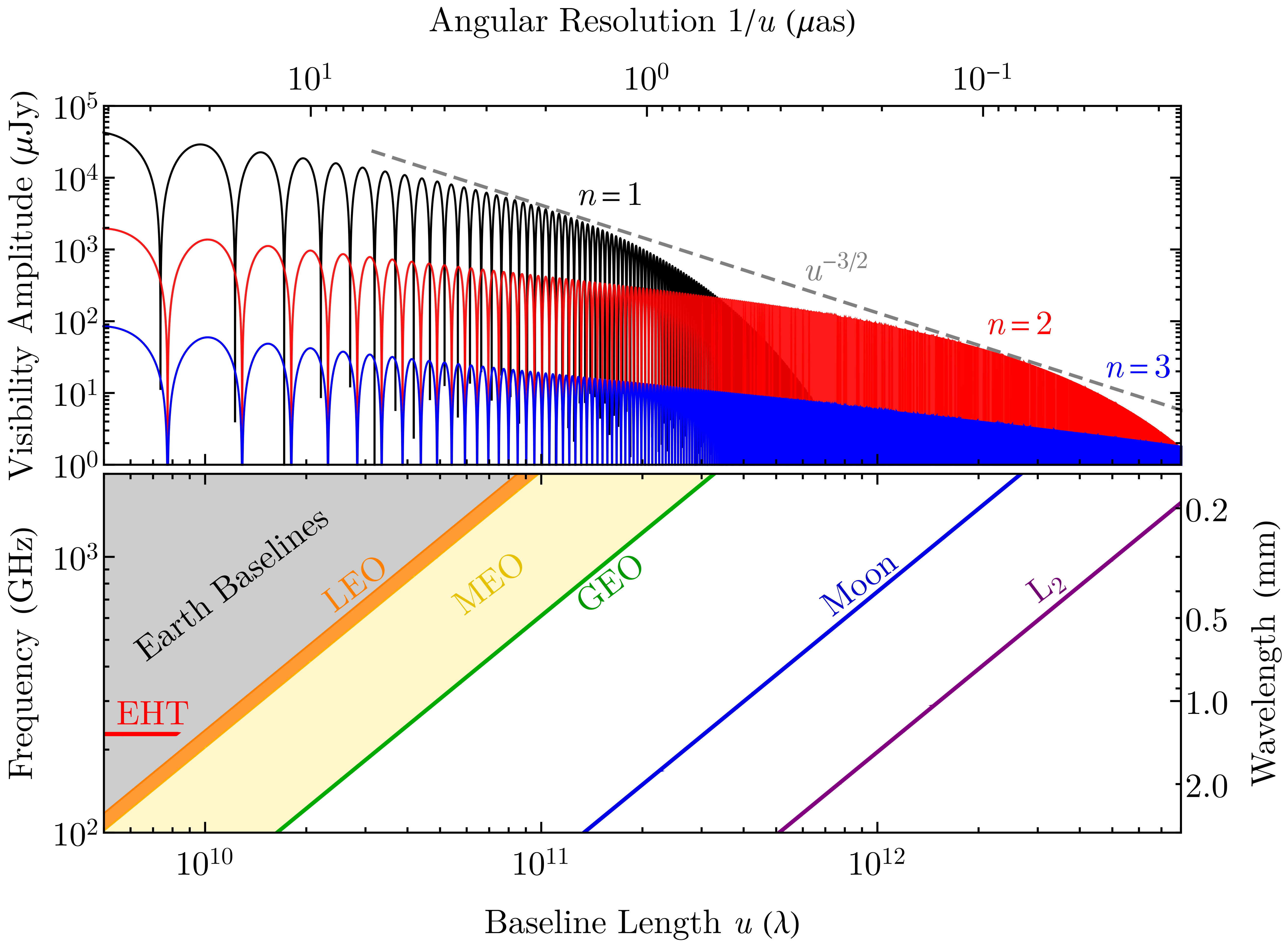
Hung-Yi Pu

Johnson et al. 2019

Far more accurate shadow measurements?







Space VLBI with Heterodyne receivers of the Origin Space Telescope at L2

Johnson et al. 2019, ApJ

Event Horizon Telescope

Weather Forecast of the EHT era: Awesome!

EHT in the next three years:

- Sgr A* & M87 Polarimetry
- Doubled bandwidth (2018-): Higher sensitivity & Rotation Measure Imaging
- Four new stations until 2023: Higher dynamic range (few/several 100s)
- Higher angular resolution: 345 GHz (0.87 mm)
- Time domain: Monitoring Capability

mid-late 2020s: Expanding the Array to the ngEHT

Higher Dynamic Range (~1000s), Better sensitivity

late 2020s-2030s: Expanding the ngEHT to space:

Better snapshot, sub-Rs-scale imaging, more horizon-scale targets