Photographing Black Holes with the Event Horizon Telescope
- Past, Present and Future -

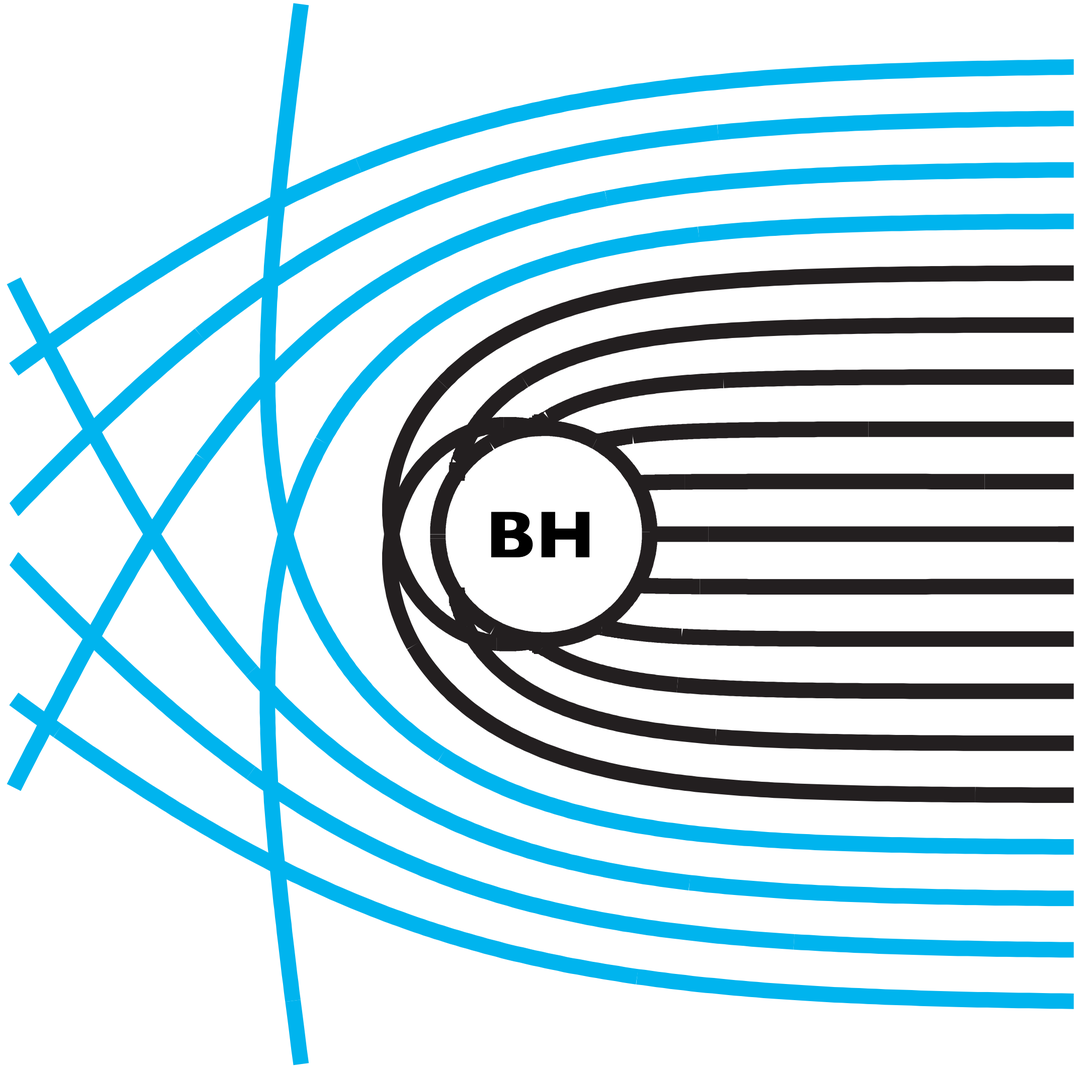
Kazu Akiyama

MIT Haystack Observatory

Event Horizon Telescope

HAYSTACK OBSERVATORY

The Shadow of a Black Hole



~5.2 Rs

$Rs = 2GM_{BH}/c^2$

(Hilbert 1916)

Credit: Hung-Yi Pu

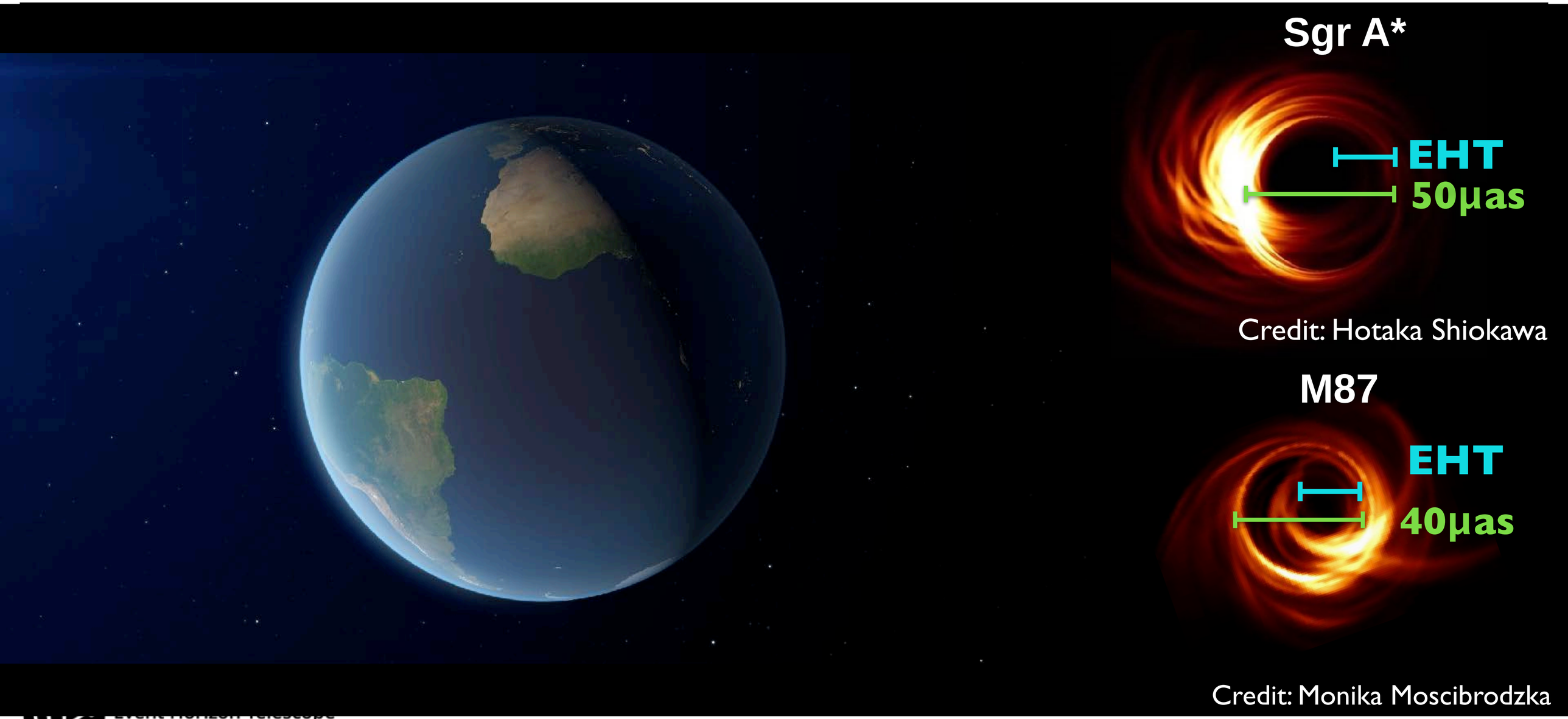
Event Horizon Telescope

Event Horizon Telescope

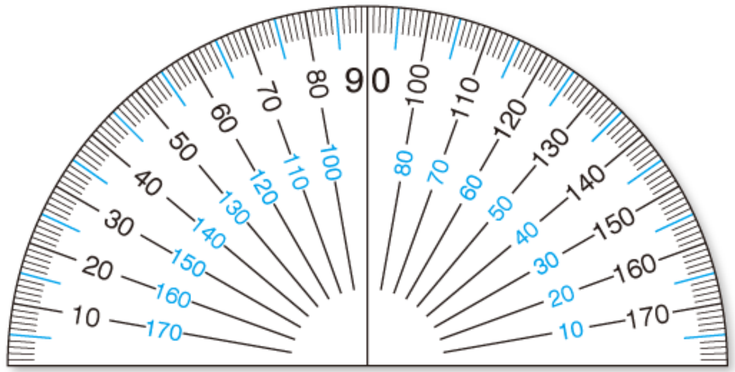
2017 OBSERVATIONS

ALMA	Atacama Large Millimeter/ submillimeter Array CHAJNANTOR PLATEAU, CHILE
APEX	Atacama Pathfinder EXperiment CHAJNANTOR PLATEAU, CHILE
30-M	IRAM 30-M Telescope PICO VELETA, SPAIN
JCMT	James Clerk Maxwell Telescope MAUNAKEA, HAWAII
LMT	Large Millimeter Telescope SIERRA NEGRA, MEXICO
SMA	Submillimeter Array MAUNAKEA, HAWAII
SMT	Submillimeter Telescope MOUNT GRAHAM, ARIZONA
SPT	South Pole Telescope SOUTH POLE STATION

Event Horizon Telescope



Units of the Angular Size



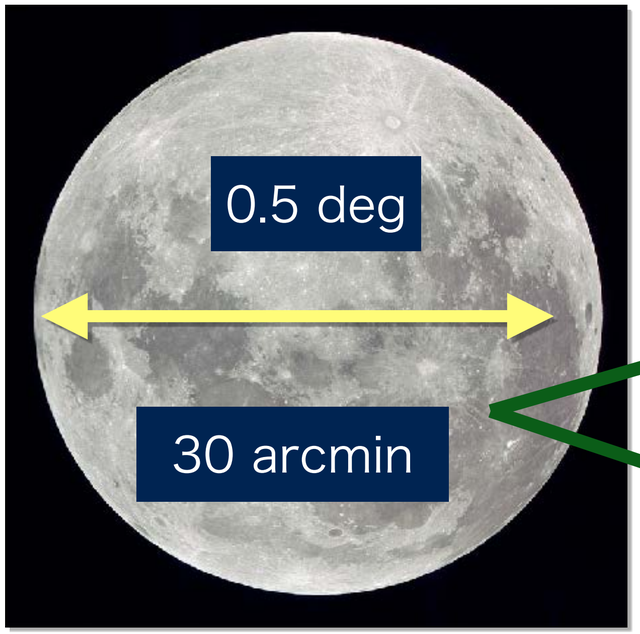
Protractor：1 ticks = 1 degree

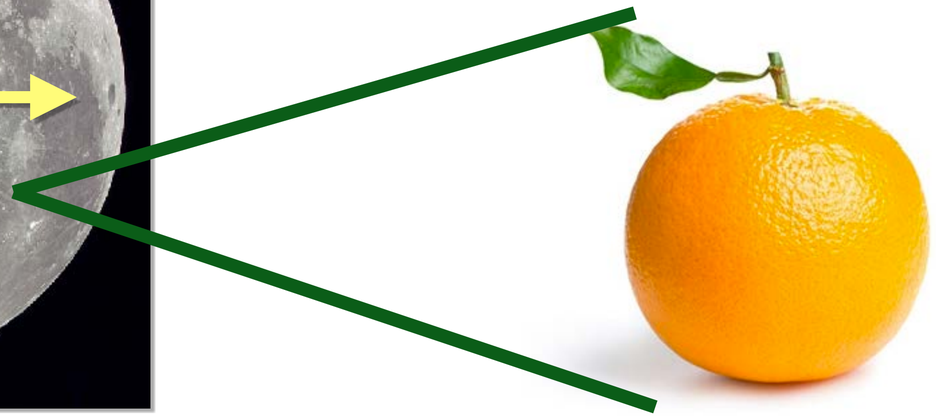
x 1/60 = 1 arcmin

x 1/60 = 1 arcsec

x 1/1000 = 1 mas

x 1/1000 = 1 μas





40 - 50 μas

Event Horizon Telescope Collaboration

>300 members, >59 institutes, >18 countries in North & South America, Europe, Asia, and Africa.

Event Horizon Telescope

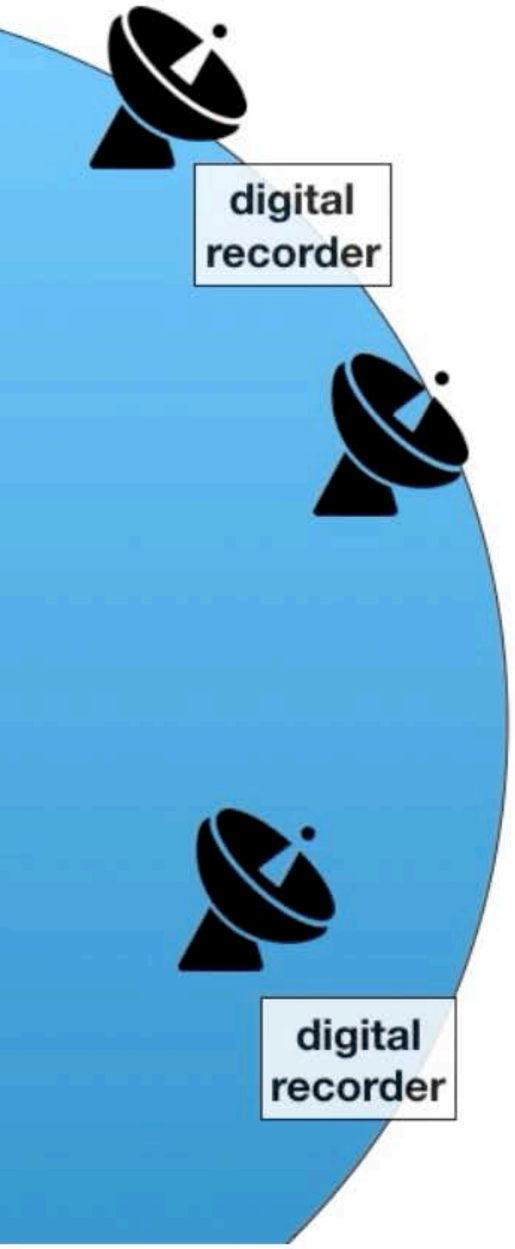
Meet the Telescope

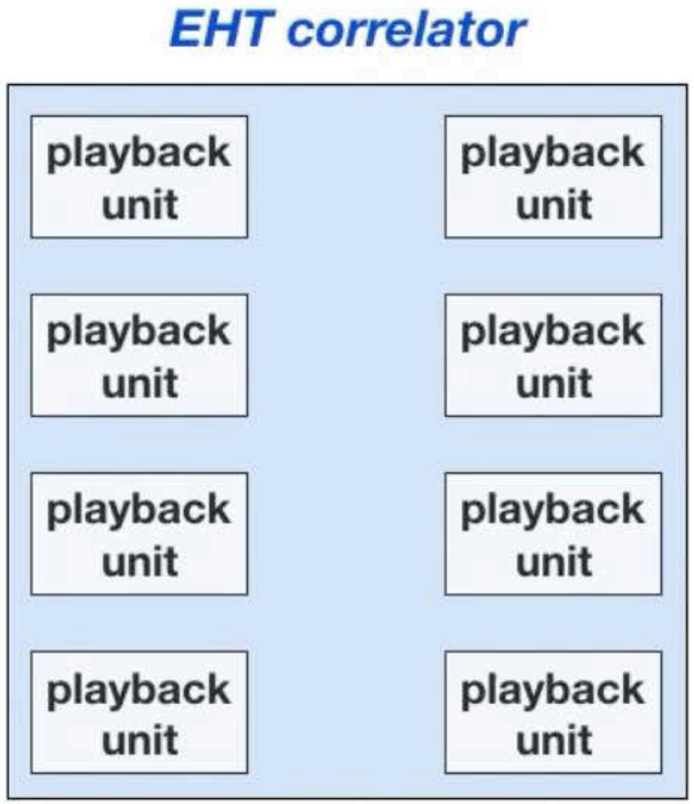
Photos: ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann, David Sanchez, Daniel Michalik, Jonathan Weintroub, William Montgomerie

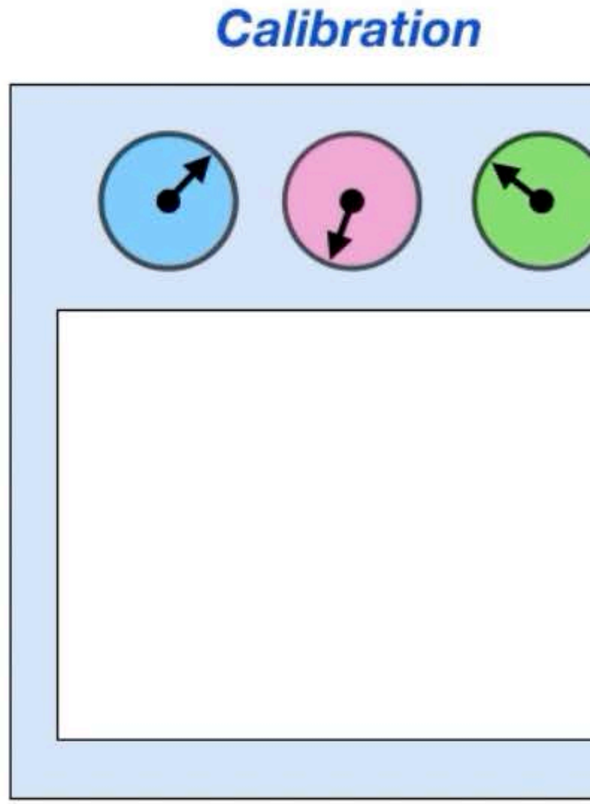
Meet the Telescope

Photos: ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann, David Sanchez, Daniel Michalik, Jonathan Weintroub, William Montgomerie

From Observations to Images



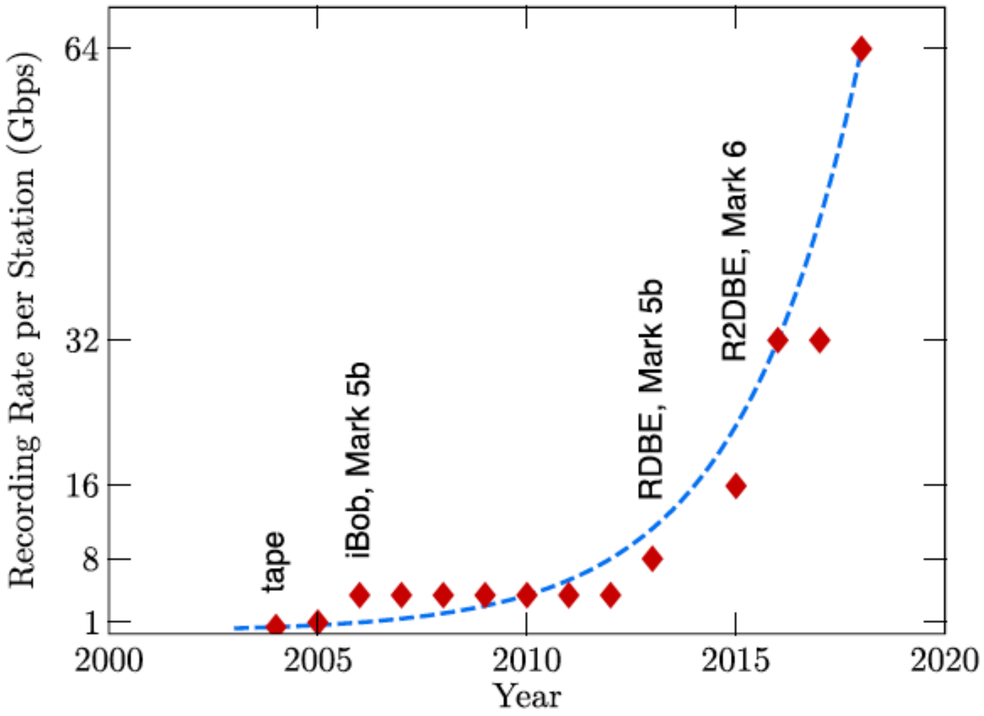




Credit: Lindy Blackburn

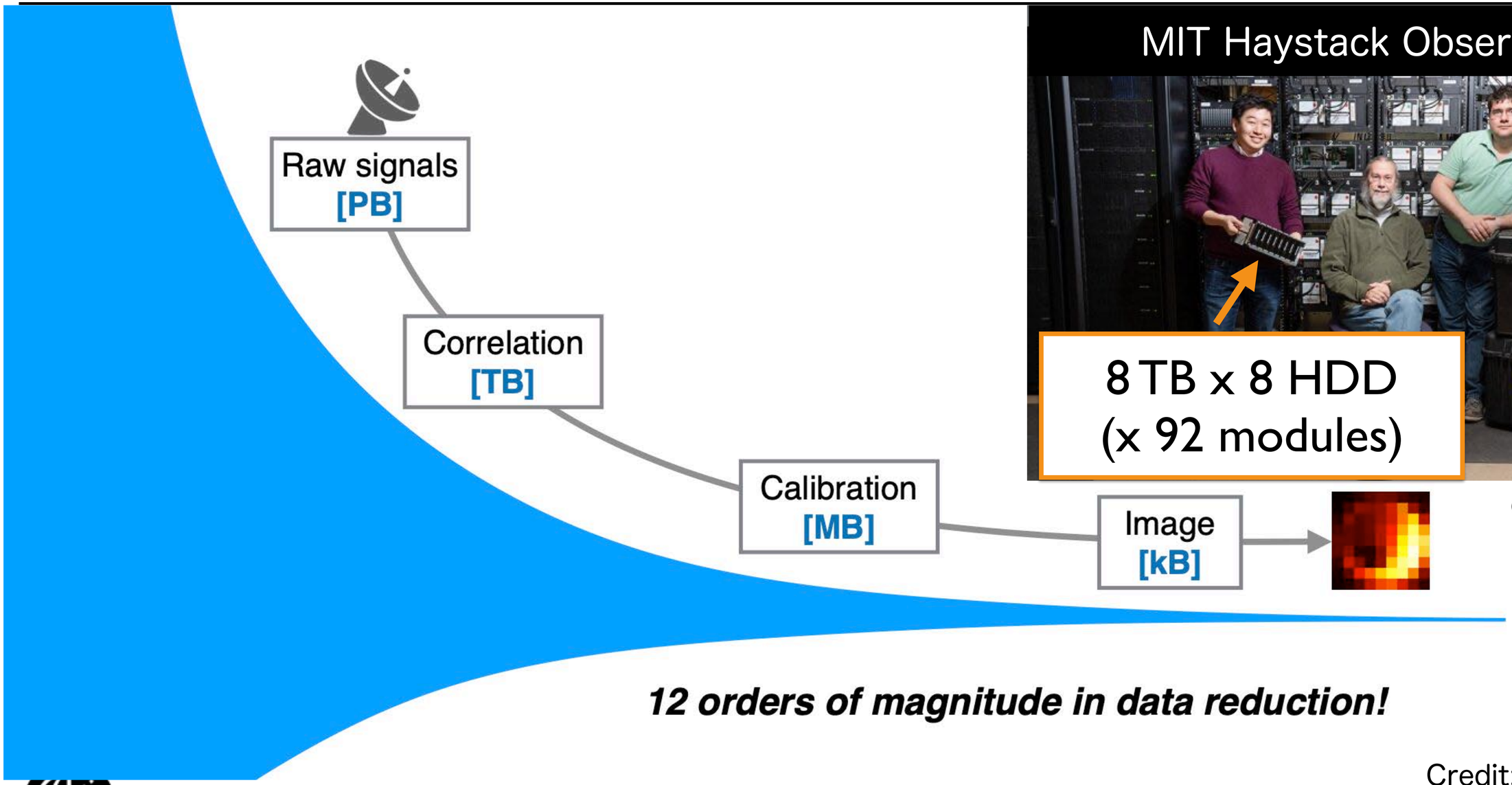
EHT Hardware

EHT Backend
(R2DBE, Mark 6)



Recording Rate:
- VLBA, GMVA: 2-4 Gbps
- EHT: 32 Gbps (2017), 64 Gbps (2018-)

From Observations to Images

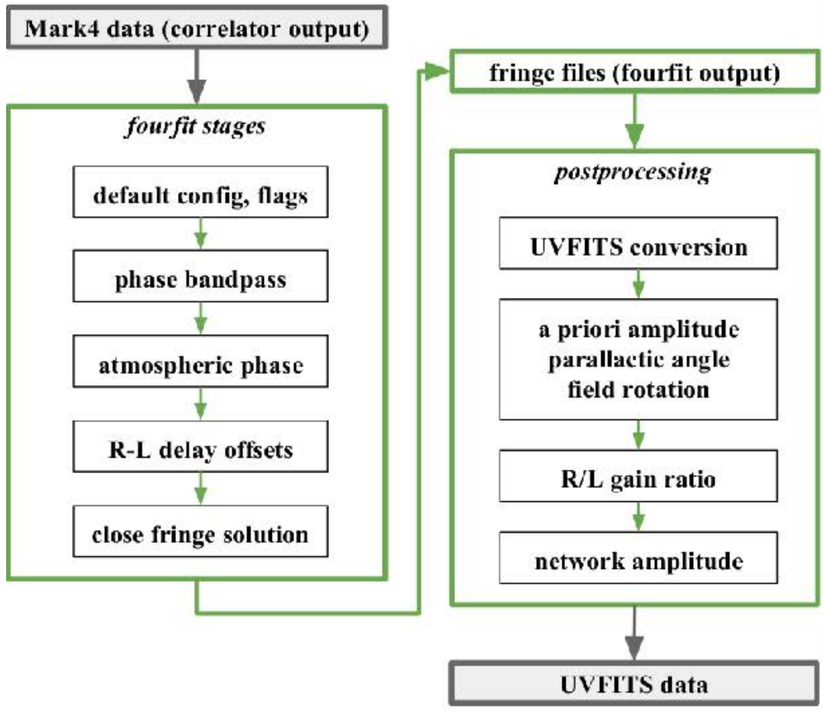


Credit: Bryce Vickmark

Credit: Lindy Blackburn

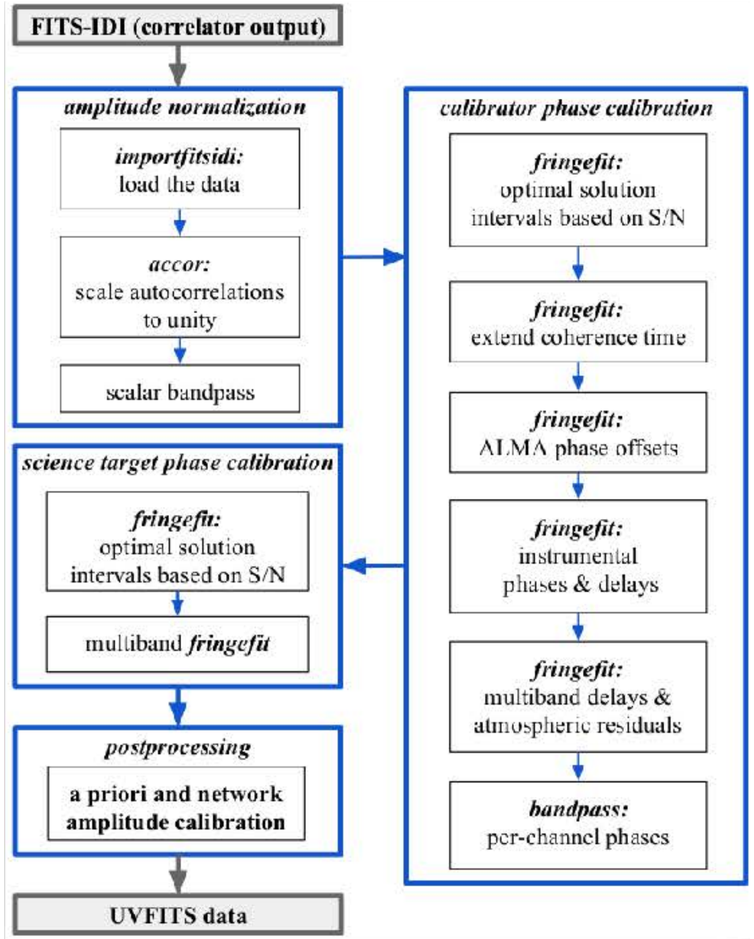
Data Calibration

HOPS Pipeline (EHT-HOPS)



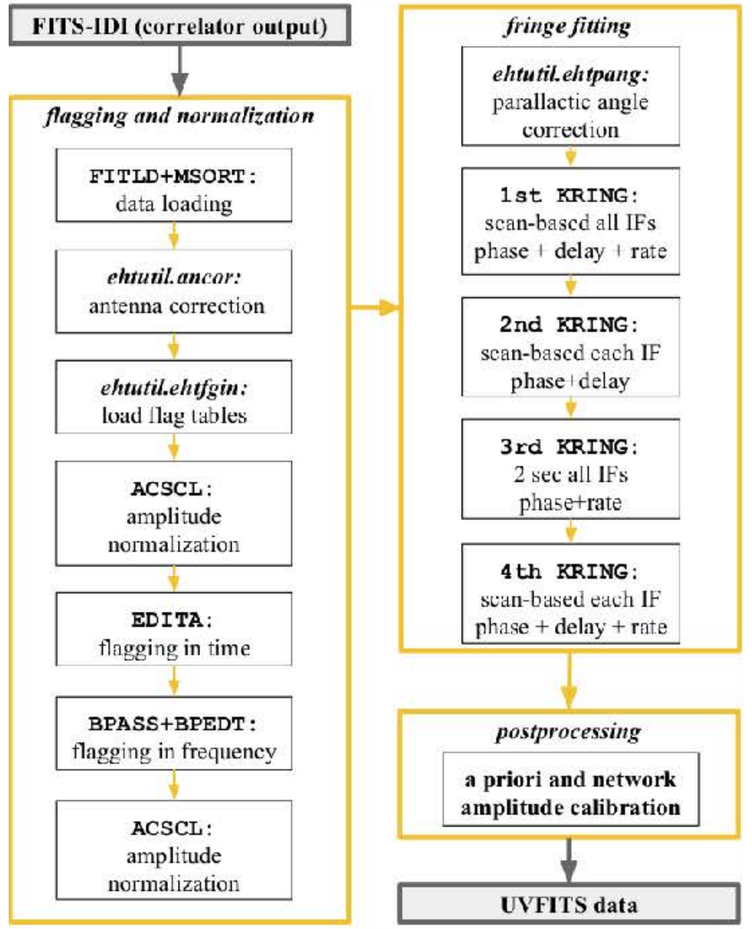
Blackburn et al. 2019

CASA Pipeline (rPICARD)



Janssen et al. 2019

EHT AIPS Pipeline

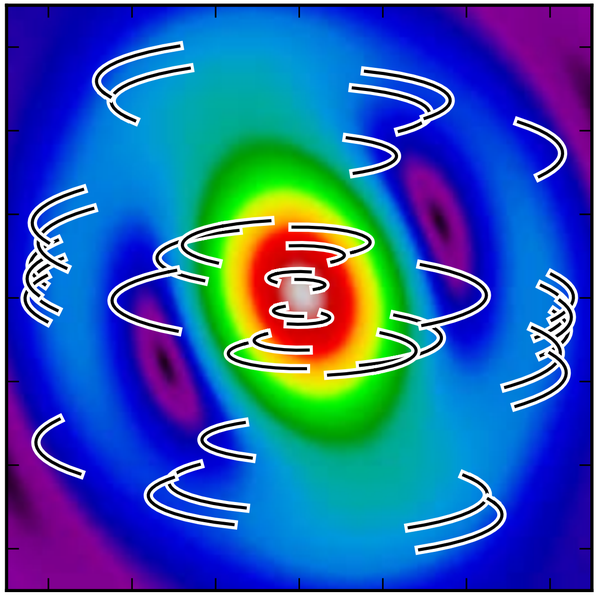


EHT Collaboration 2019, ApJL, 875, L3

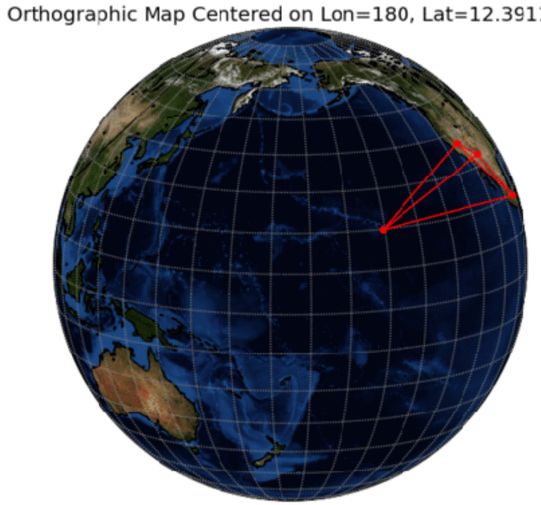
Interferometric Imaging

Image

Fourier Domain
(*Visibility*)

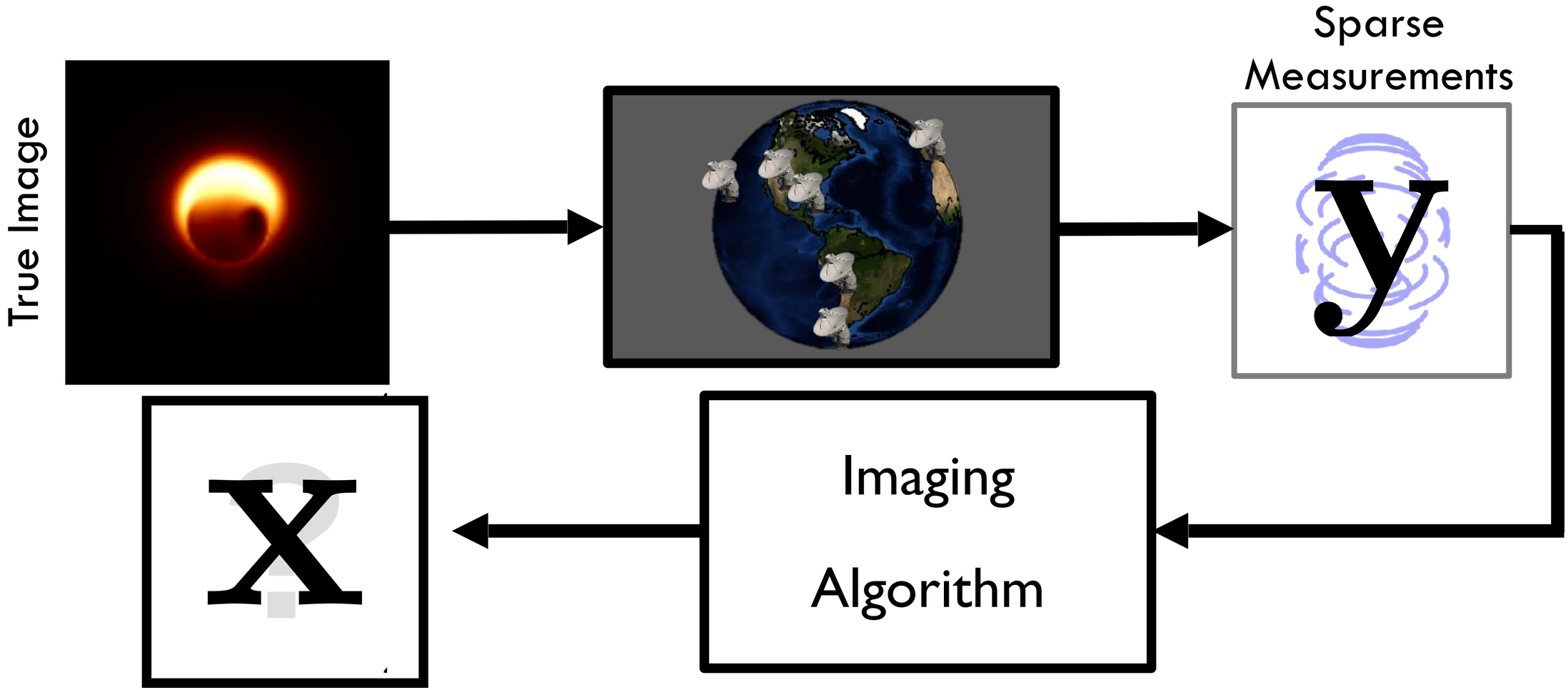


Sampling Process
(Projected Baseline = Spatial Frequency)



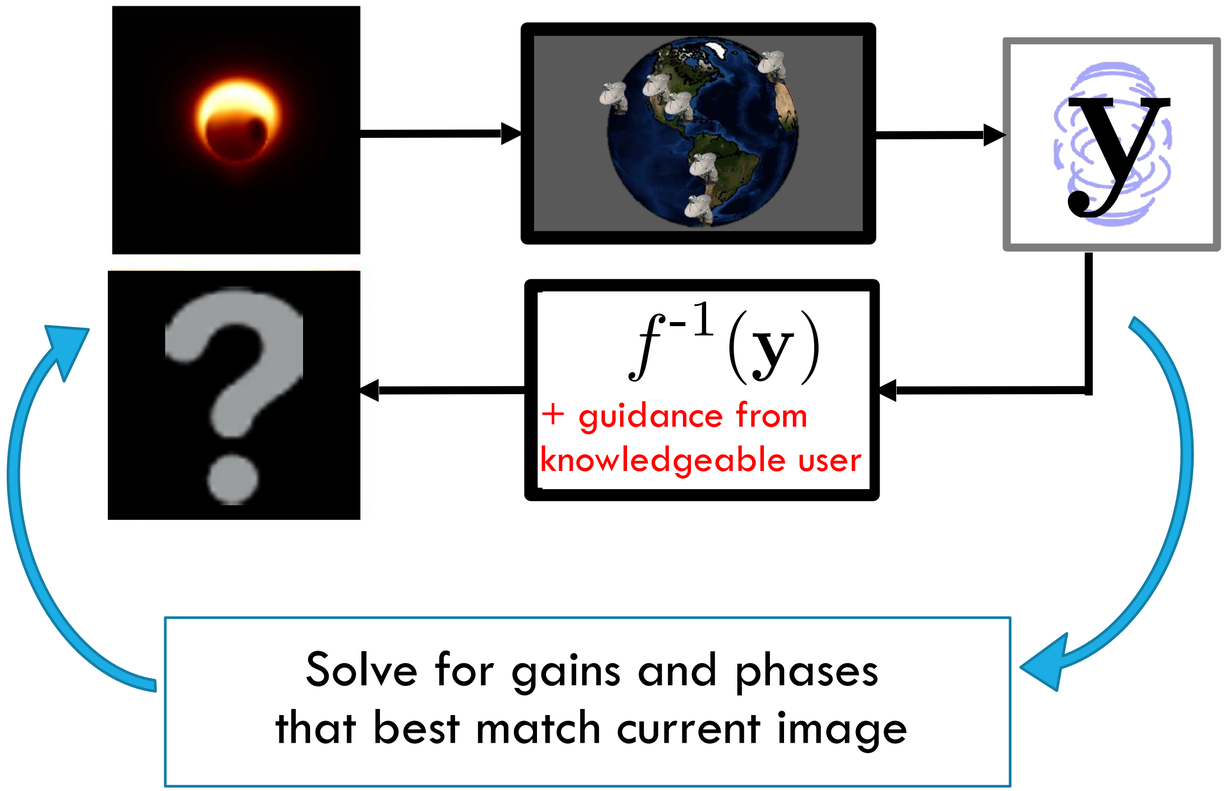
(Images: adapted from Akiyama et al. 2015, ApJ ; Movie: Laura Vertatschitsch)

Interferometric Imaging



Two Classes of Imaging Algorithms

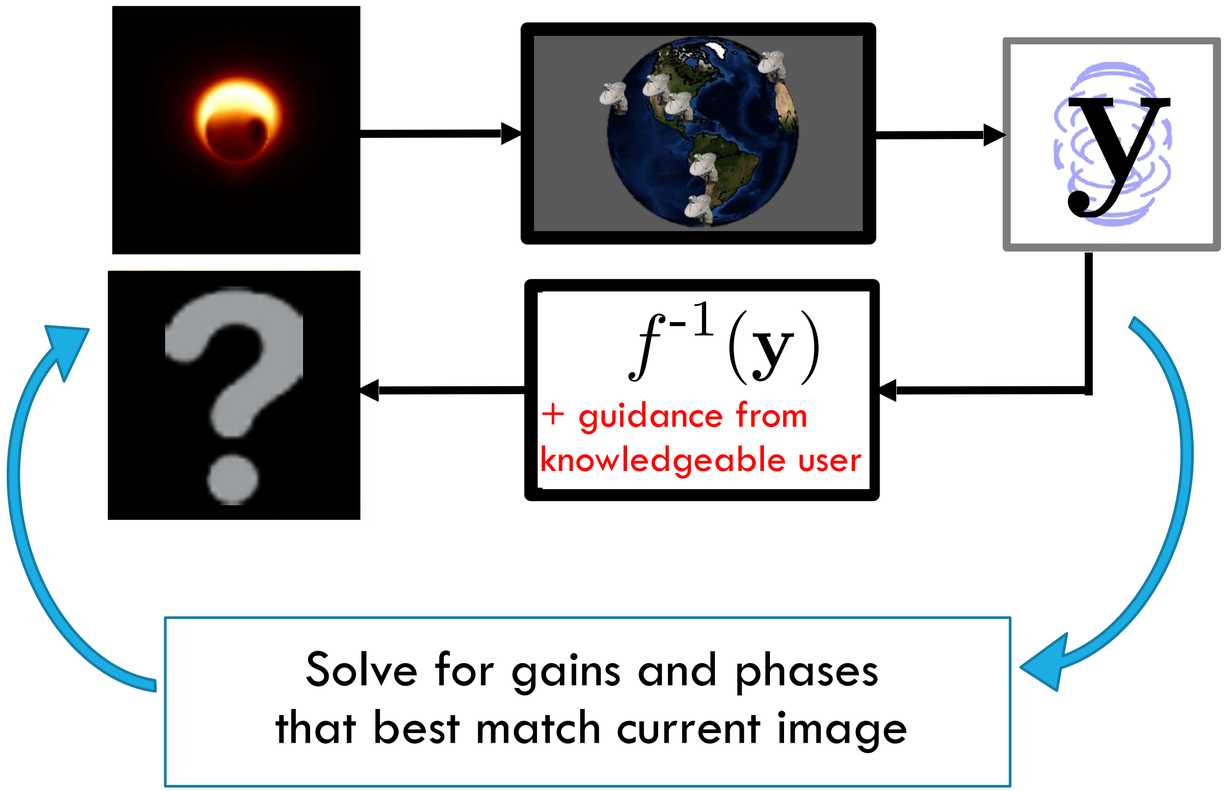
Credit: Katie Bouman



Traditional Inverse Modeling (CLEAN + Self-Calibration)

Two Classes of Imaging Algorithms

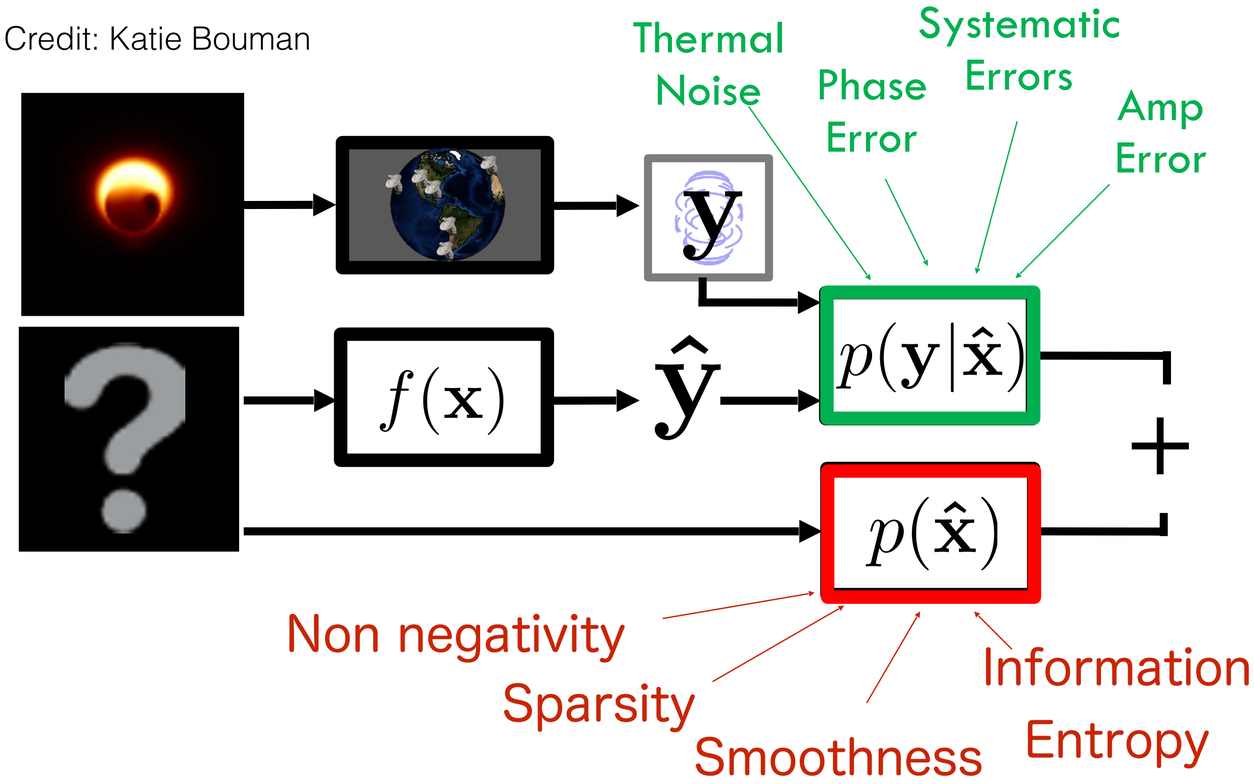
Credit: Katie Bouman



Traditional

Inverse Modeling (CLEAN + Self-Calibration)

Credit: Katie Bouman



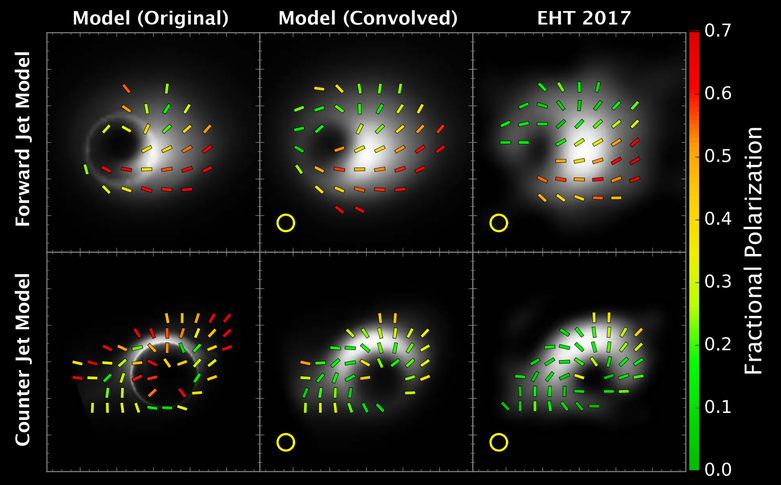
$$\hat{\mathbf{x}}_{\mathrm{MAP}} = \mathrm{argmax}_{\mathbf{x}} \left[\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})\right]$$

Forward Modeling (Bayesian Inspired Optimization)

New Imaging Methods

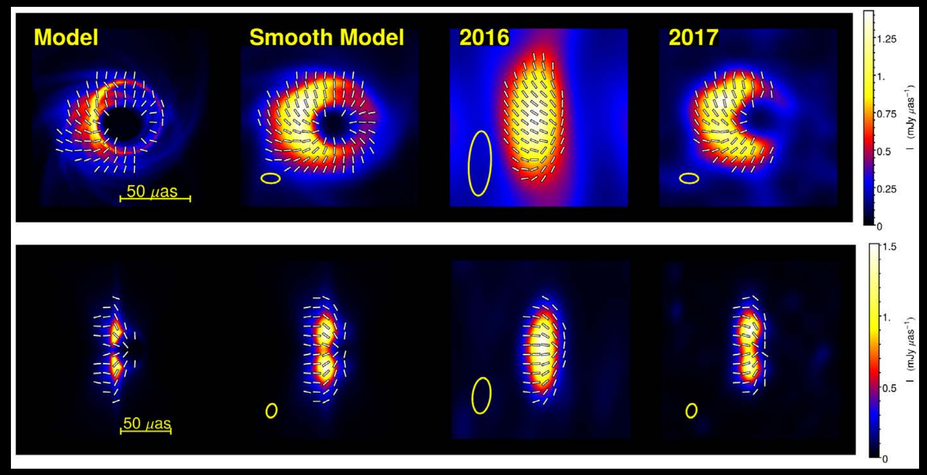
Sparse Modeling

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



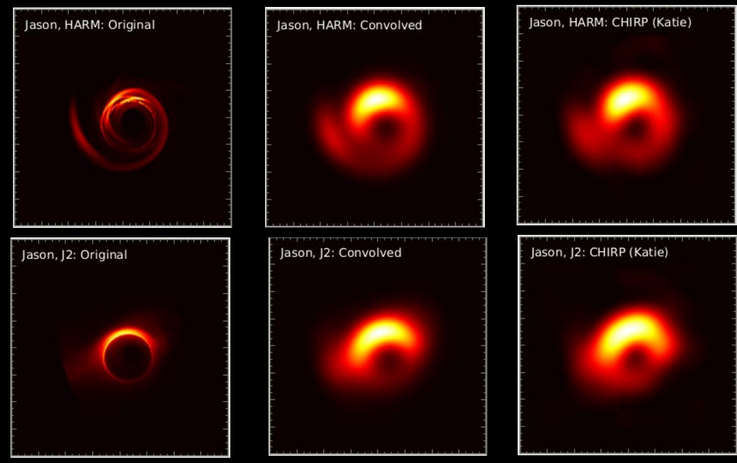
Maximum Entropy Method (MEM)

Chael et al. 2016, Fish et al. 2014,
Lu et al. 2014, 2016



CHIRP (Machine-learning)

Bouman et al. 2016

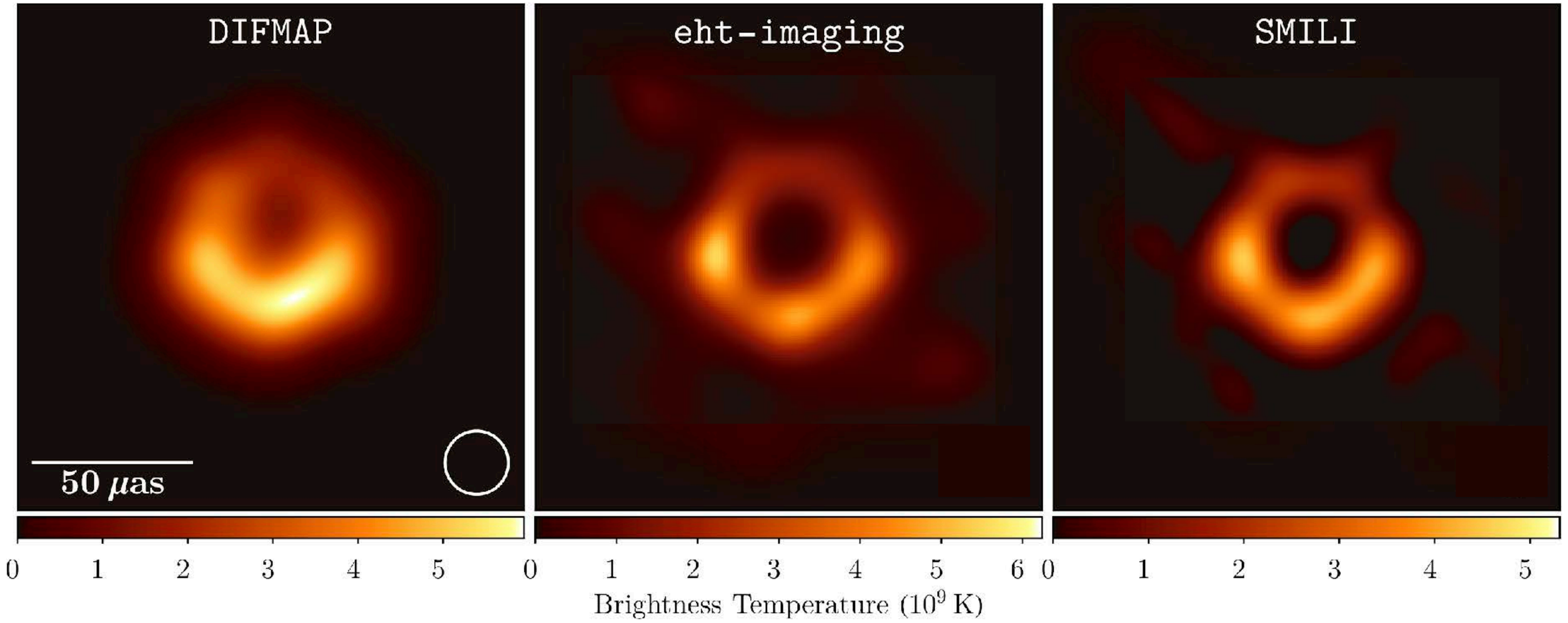


Two Imaging Libraries

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

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

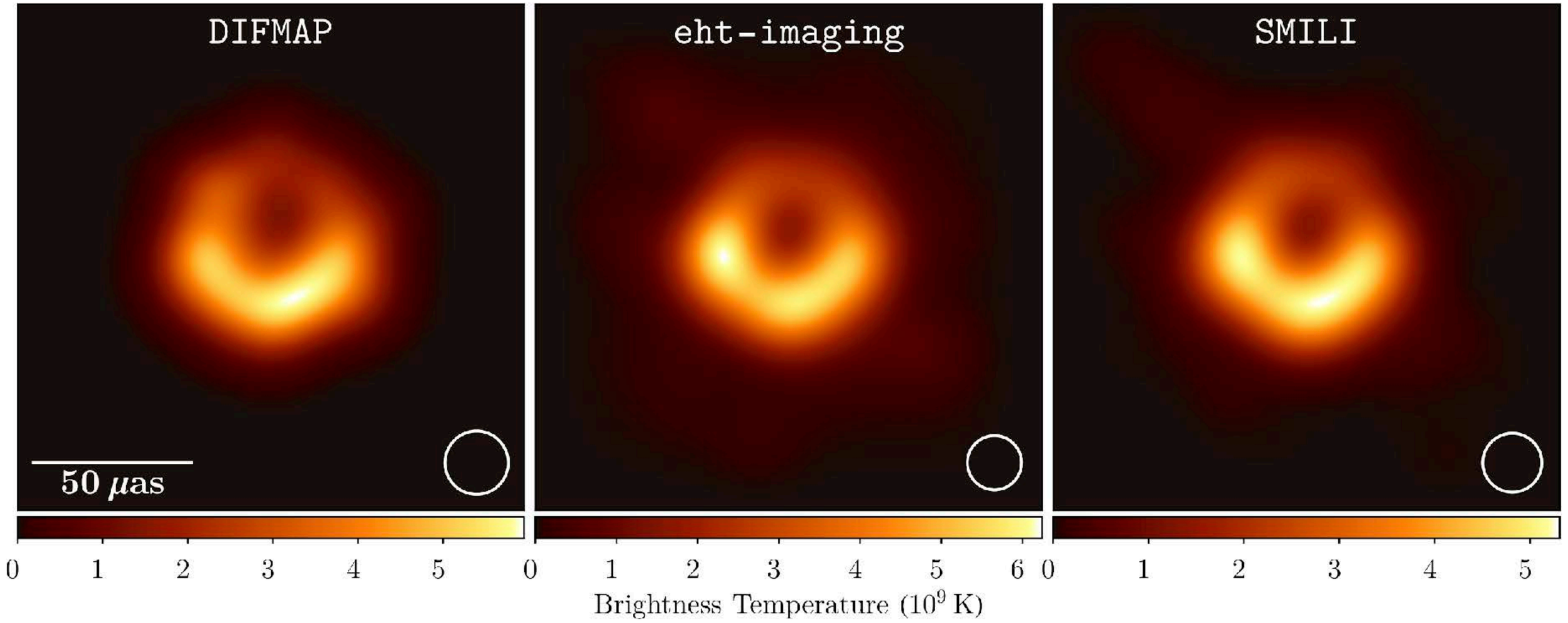
Fiducial Images on Apr 11



Event Horizon Telescope

EHT Collaboration 2019d, ApJL, 875, L4

Fiducial Images on Apr 11



Event Horizon Telescope

EHT Collaboration 2019d, ApJL, 875, L4

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

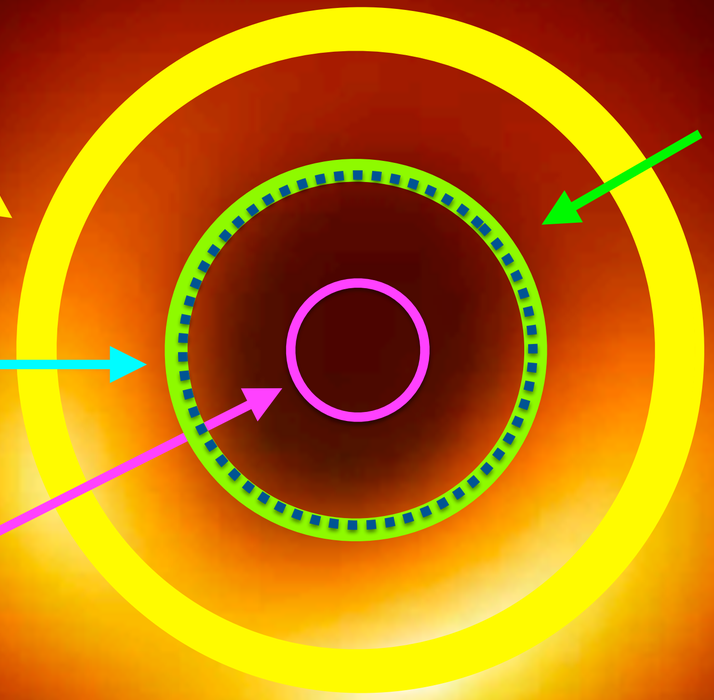
Gas Mass: 3.5 x 10^9 M_{sun}
(Walsh et al. 2013)

Black Hole: 4.84-5.2 R_s

Black Hole: 4.84-5.2 R_s

A worm Hole: ~2.7 R_s

Naked Singularity: 1 Rs
(extremely spinning)



6.5 Billion Solar Mass Black Hole

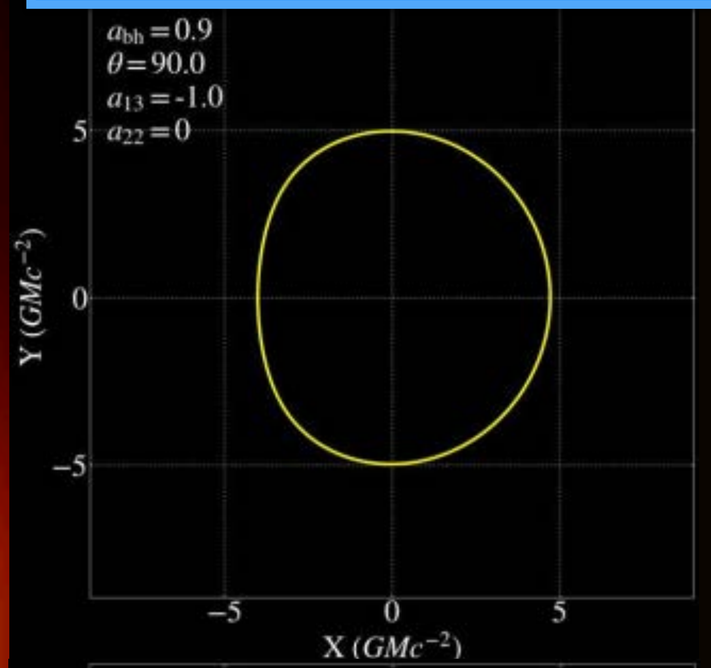
Event Horizon Telescope

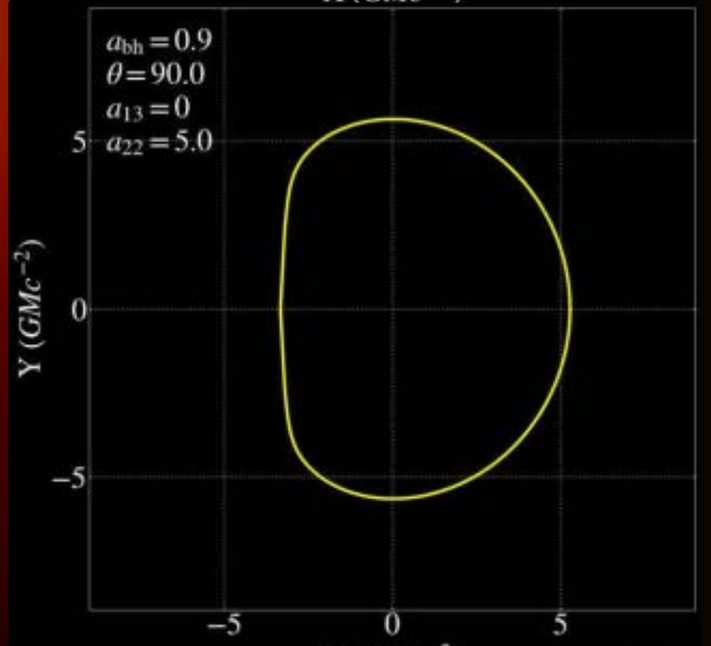
EHT Collaboration 2019a, ApJL, 875, L1 (Paper I)

Deviation from the circle < within 10%
No significant deviations from GR

Black Hole: 4.84-5.2 R_s

Non GR Shadow

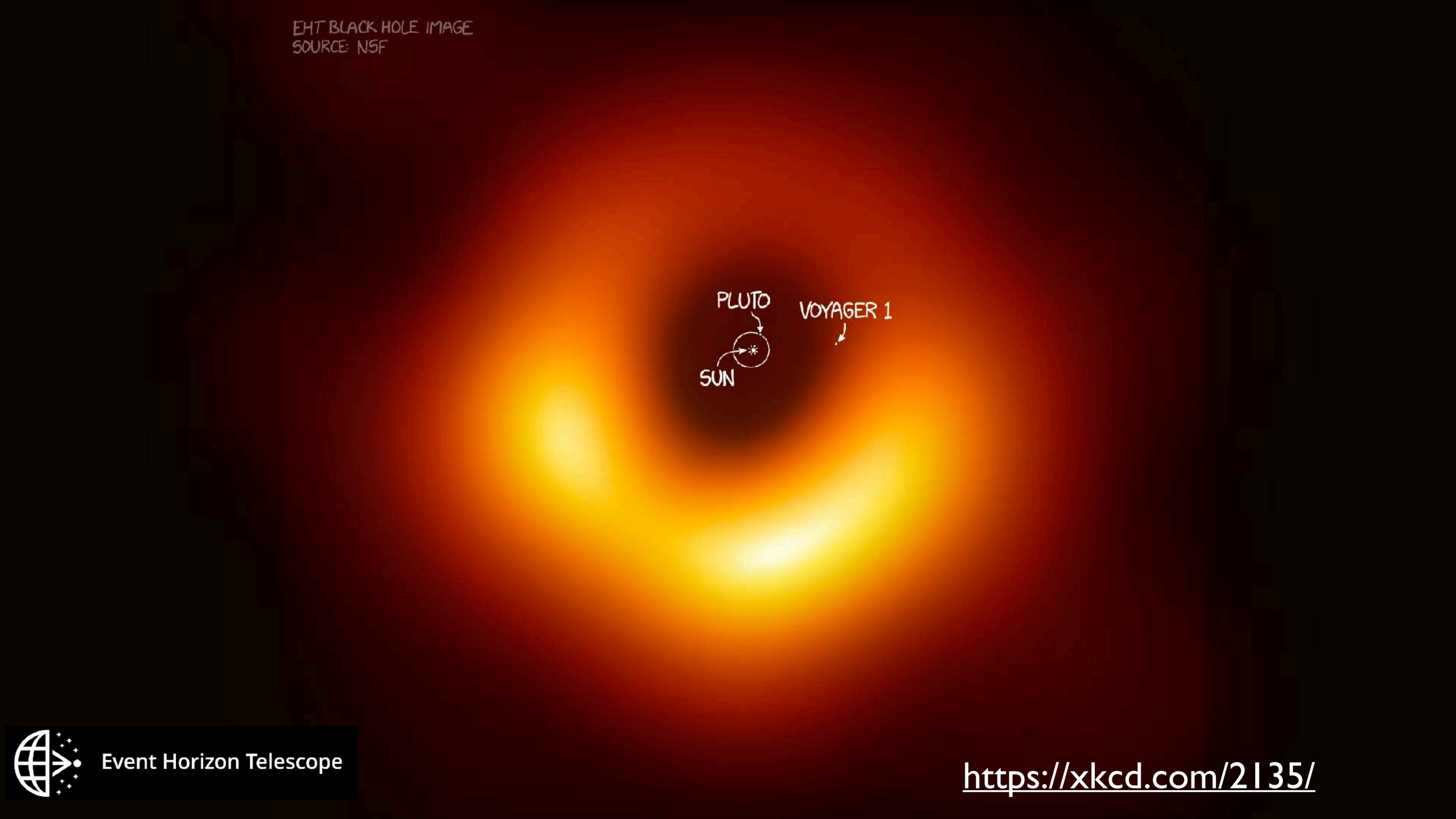




Event Horizon Telescope

EHT Collaboration 2019f, ApJL, 875, L6 (Paper VI)

Credit: CK Chan



Event Horizon Telescope

https://xkcd.com/2135/

EHT as a GR Metric Tester

Spherically symmetric space time around a non-spinning 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)

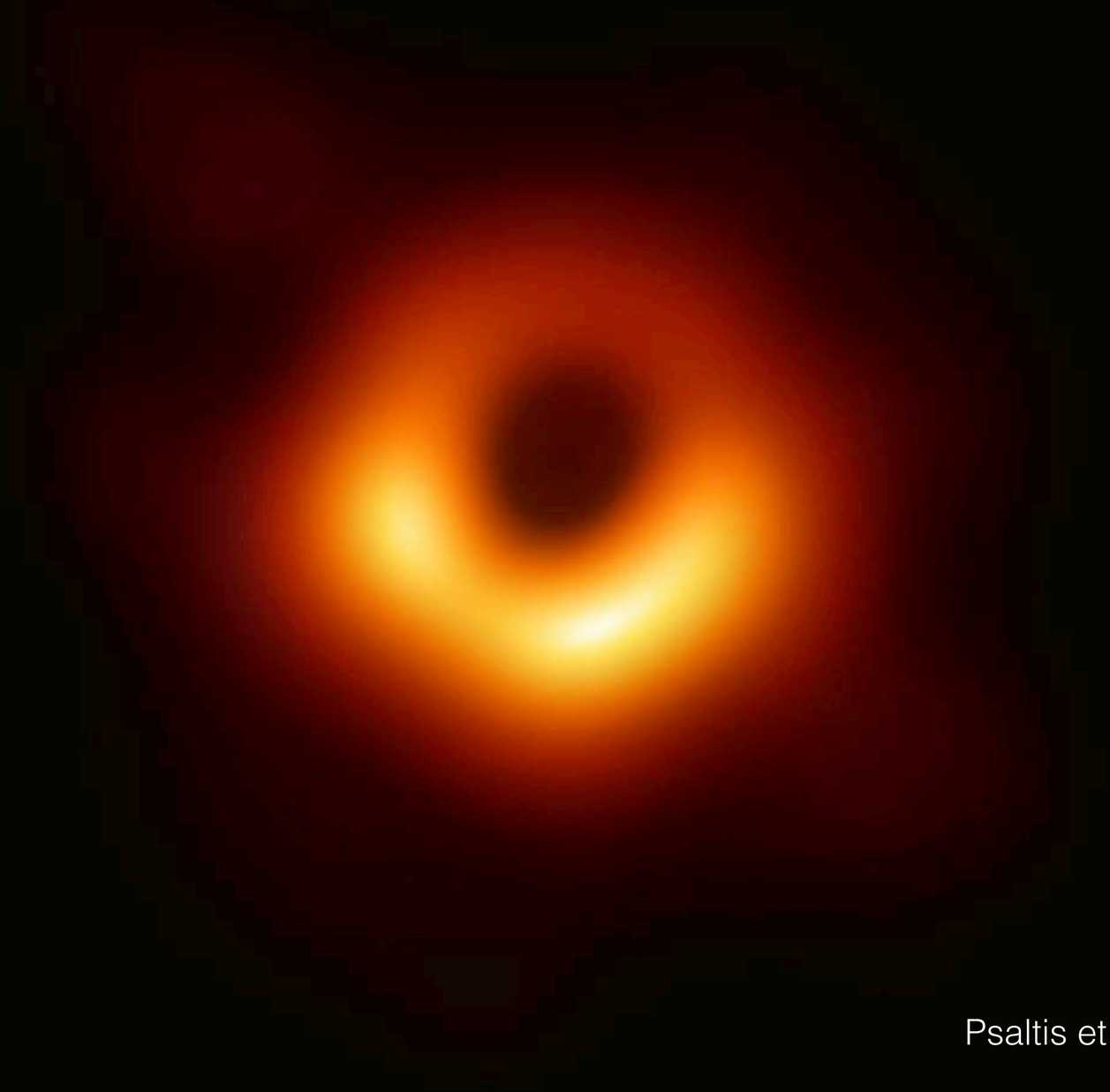
Weak-field test: < ~10^{-5}

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

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

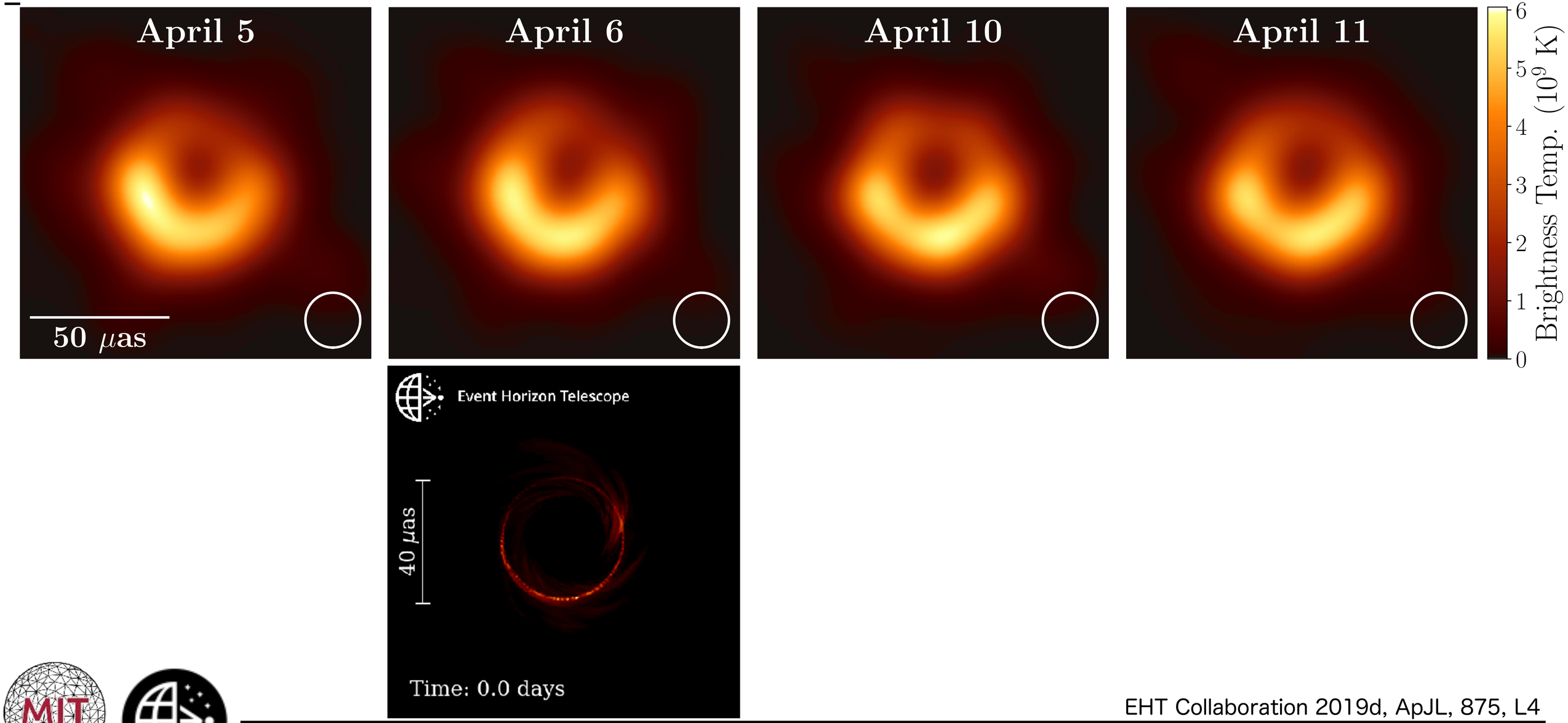
Psaltis et al. 2020, Physical Review Letters

“EHT measurements of the size of a black hole leads to metric tests that are inaccessible to weak-field tests”



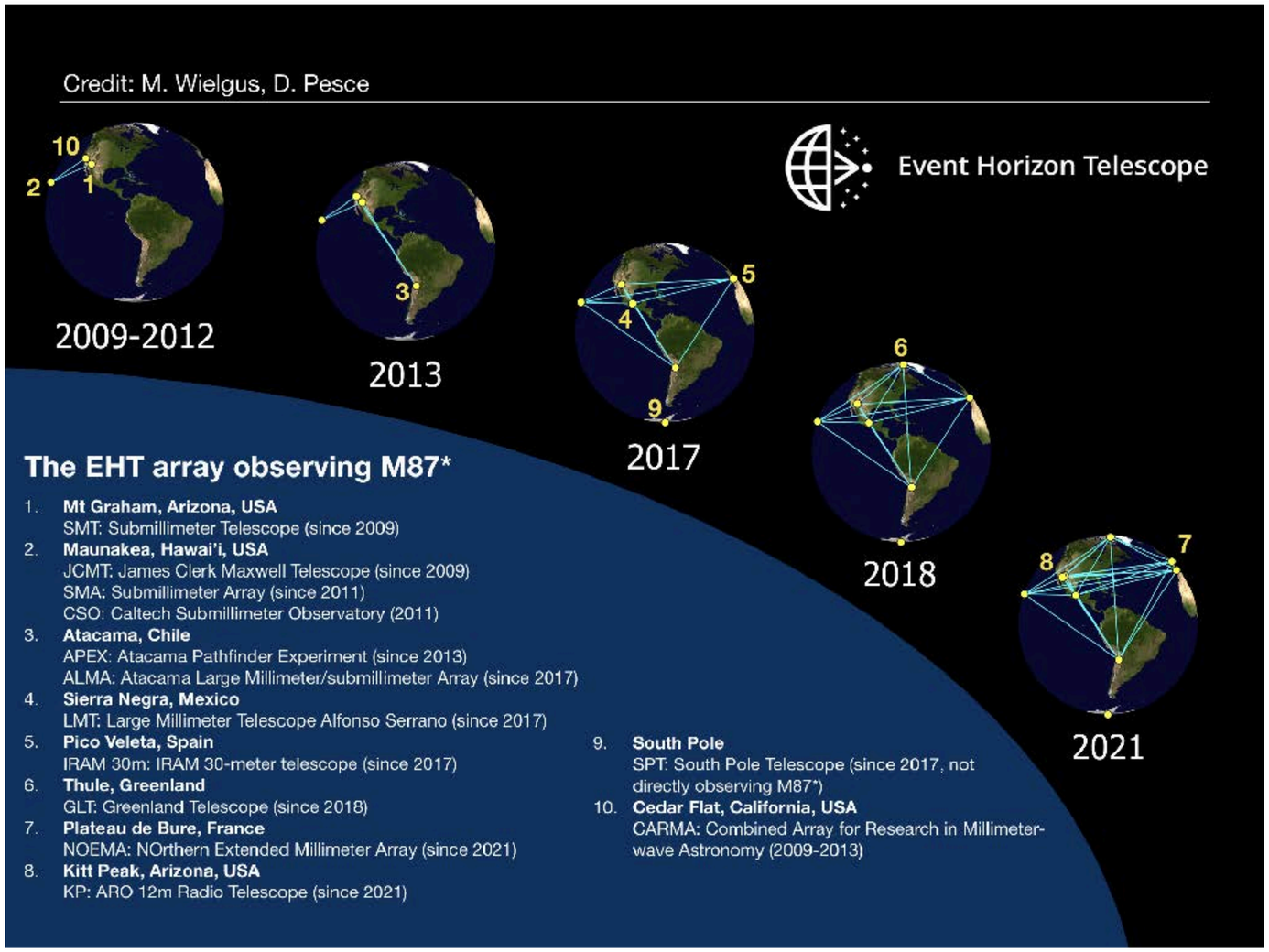
Psaltis et al. 2020, Physical Review Letters

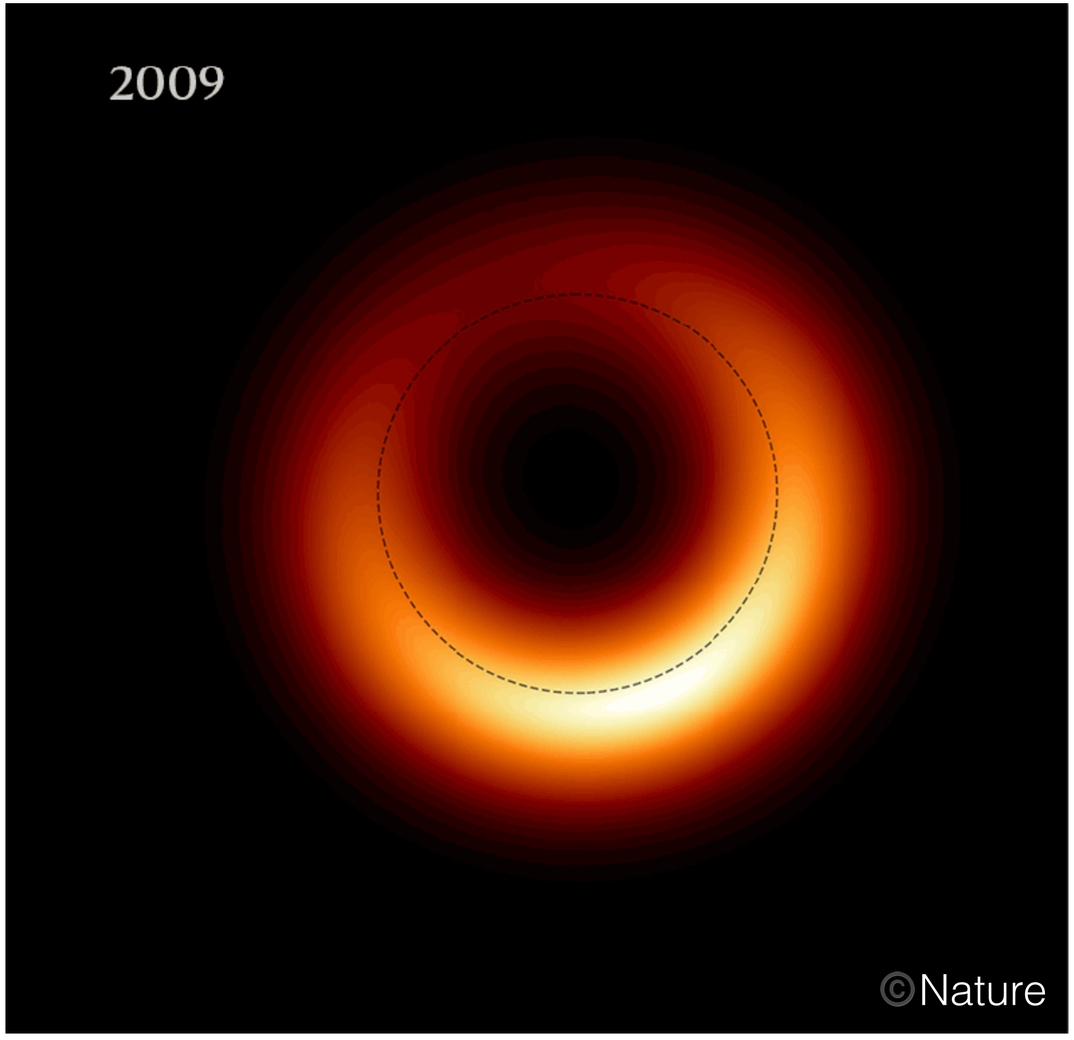
EHT 2017 Images of M87*



EHT Collaboration 2019d, ApJL, 875, L4

Multi-year EHT Observations





Wielgus et al. 2020, ApJ

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

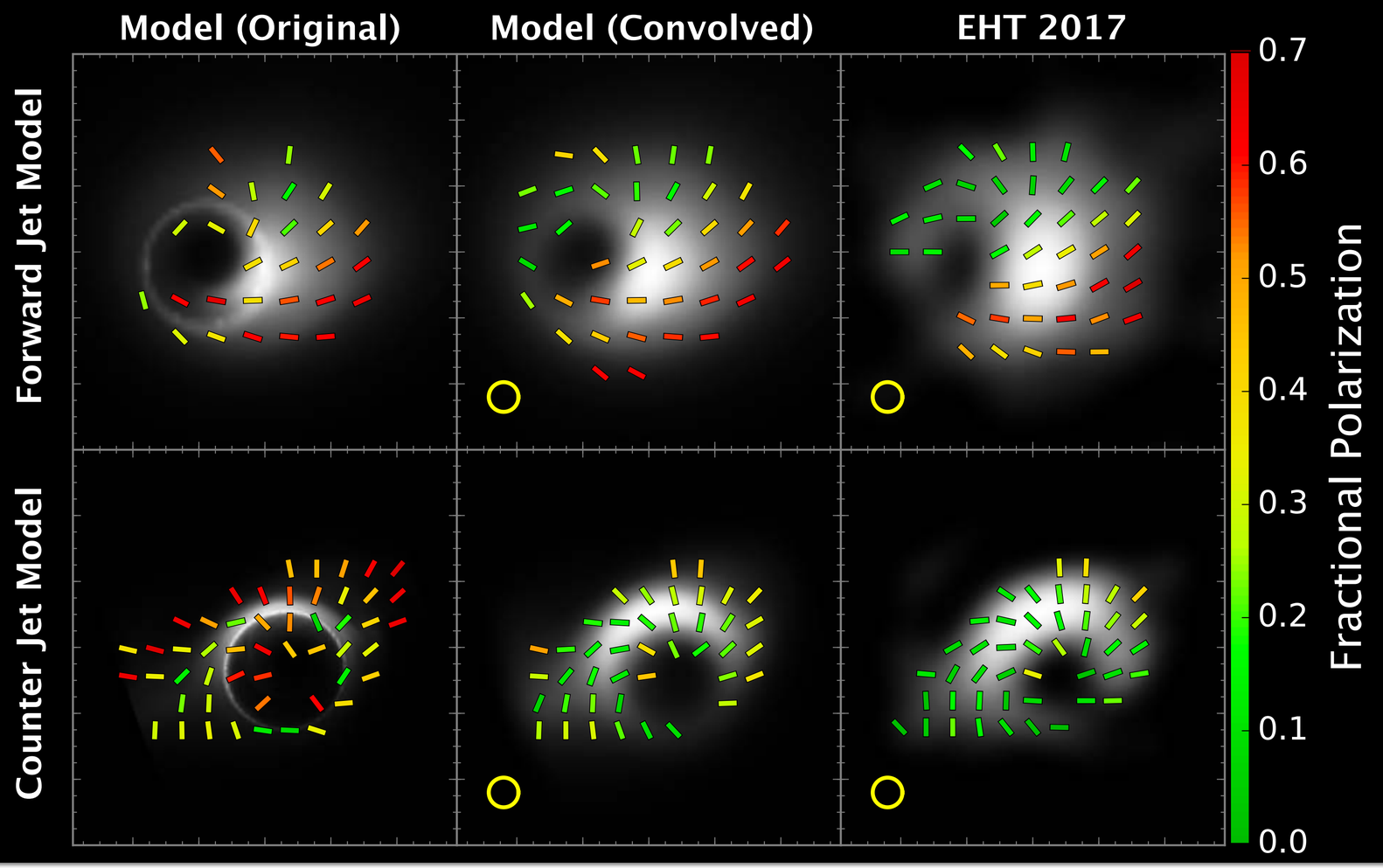
- An AGN and associated jet are powered by a supermassive black hole

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

- Day-to-day & Multi-year variations on horizon scale

Dawn of a New Era of Black Hole Astrophysics

M87 Polarimetry: Coming Soon

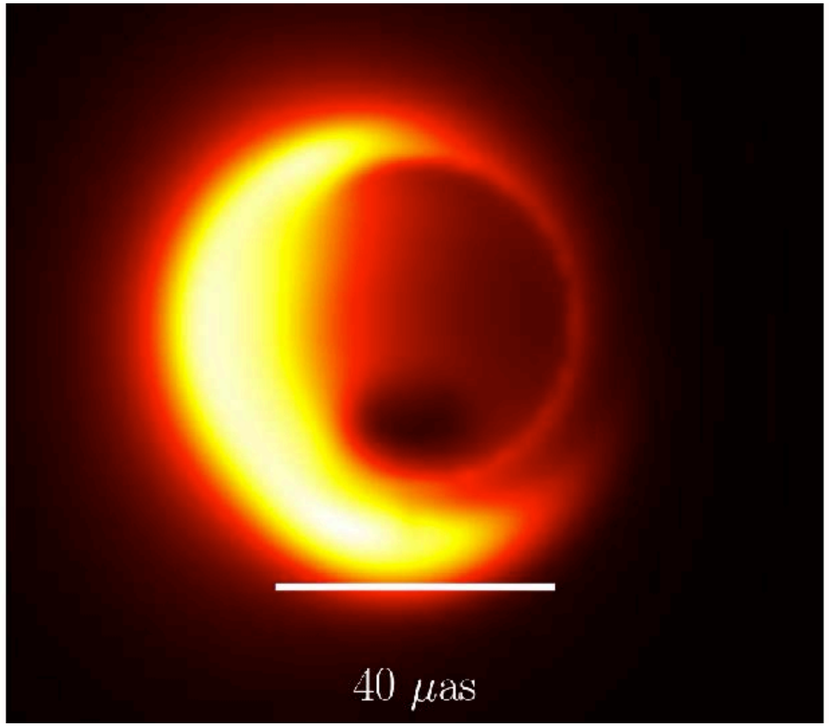


Akiyama et al. 2017, Chael et al. 2016

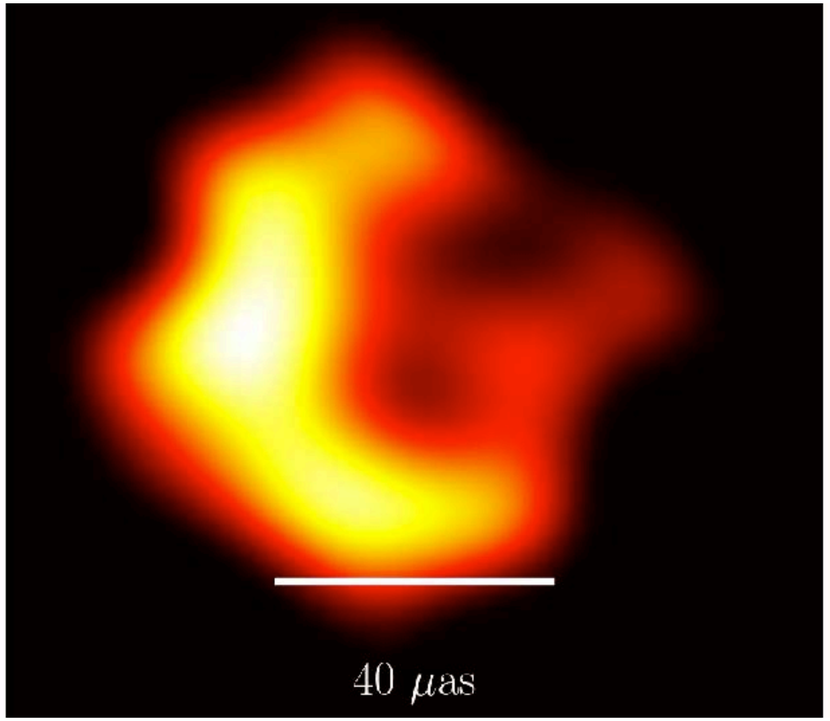
First Horizon-scale Imaging of Sgr A*: Coming soon

RML Video Reconstruction (3D Imaging)

Model

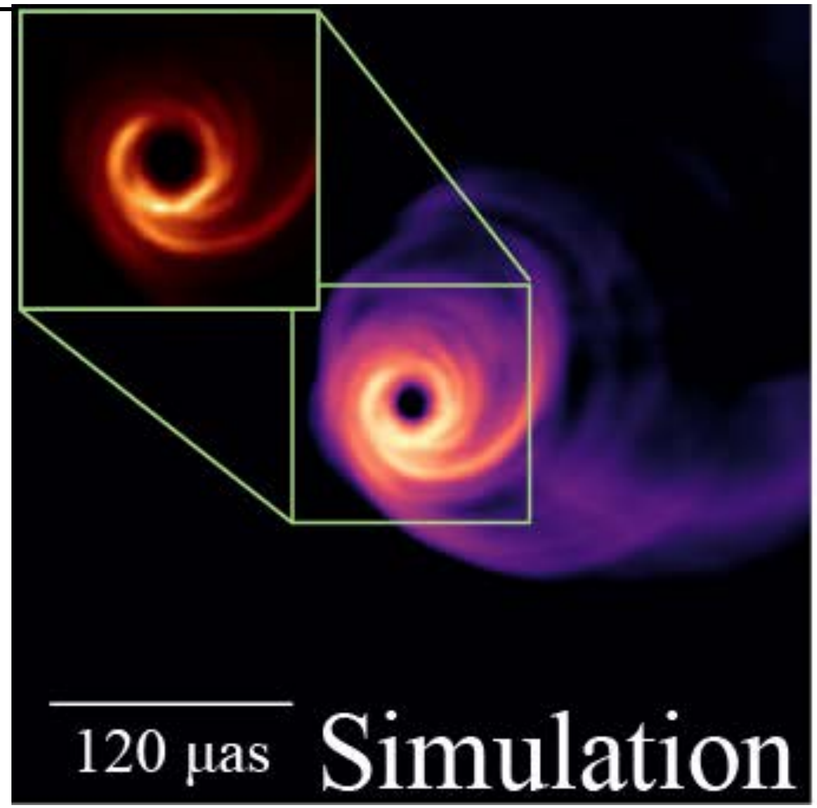


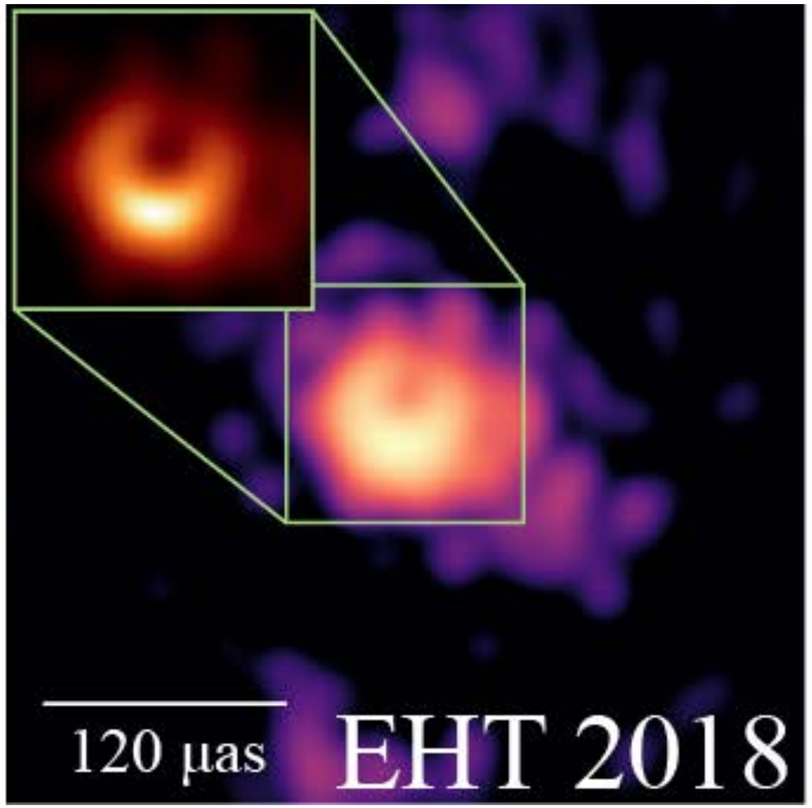
EHT 2017 Simulation



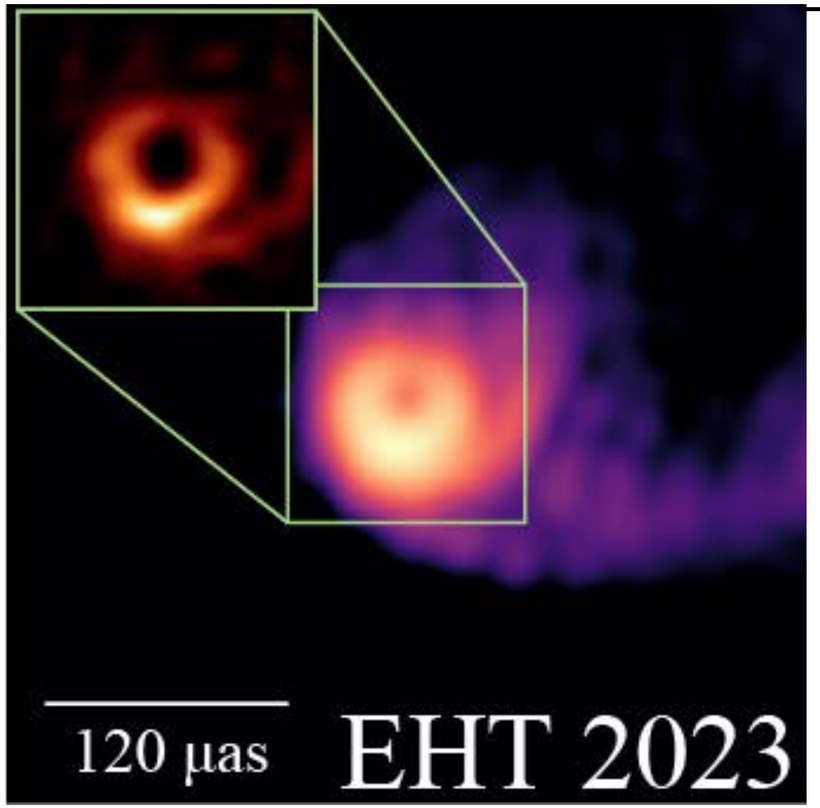
Model: Broderick & Loeb 2006, Imaging simulation: Kotaro Moriyama

EHT 2020s: Deeper, Shaper & Multi-frequency Images





230 GHz
EHT2017+GLT



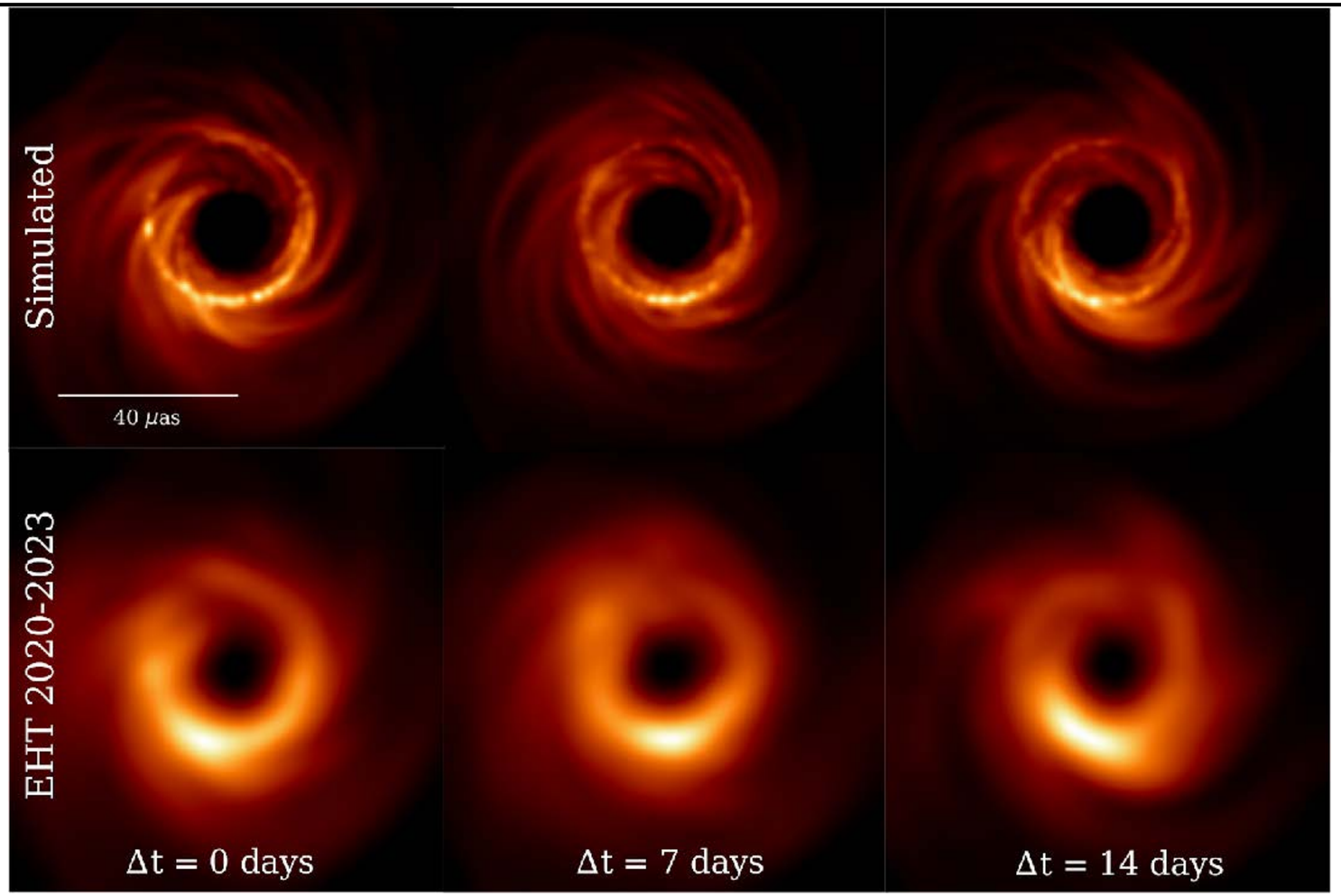
230+345 GHz
EHT2017+GLT+KP+NOEMA+OVRO

Further new capabilities: Faraday Rotation Imaging (5 Dimensional Imaging)

Active developments of Multi-scale, multi-dimensional imaging techniques

Simulations: Andrew Chael, Imaging: Kazu Akiyama

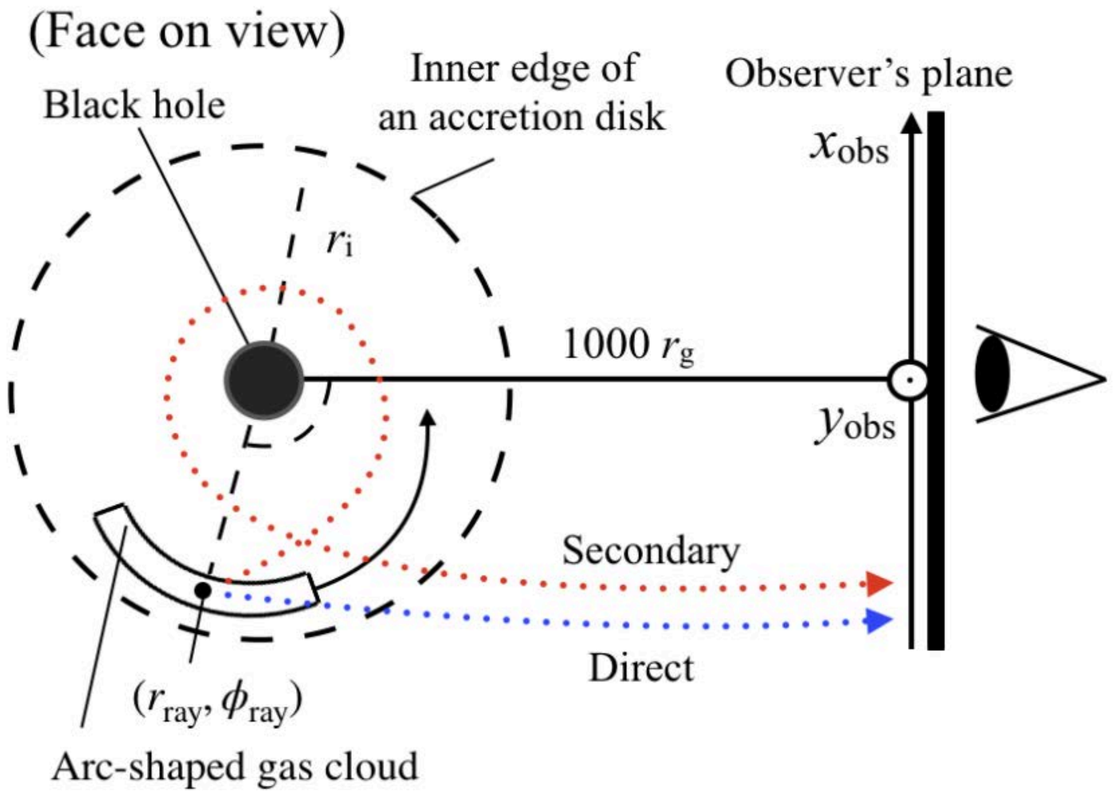
EHT 2020s: Tracking Evolving Features



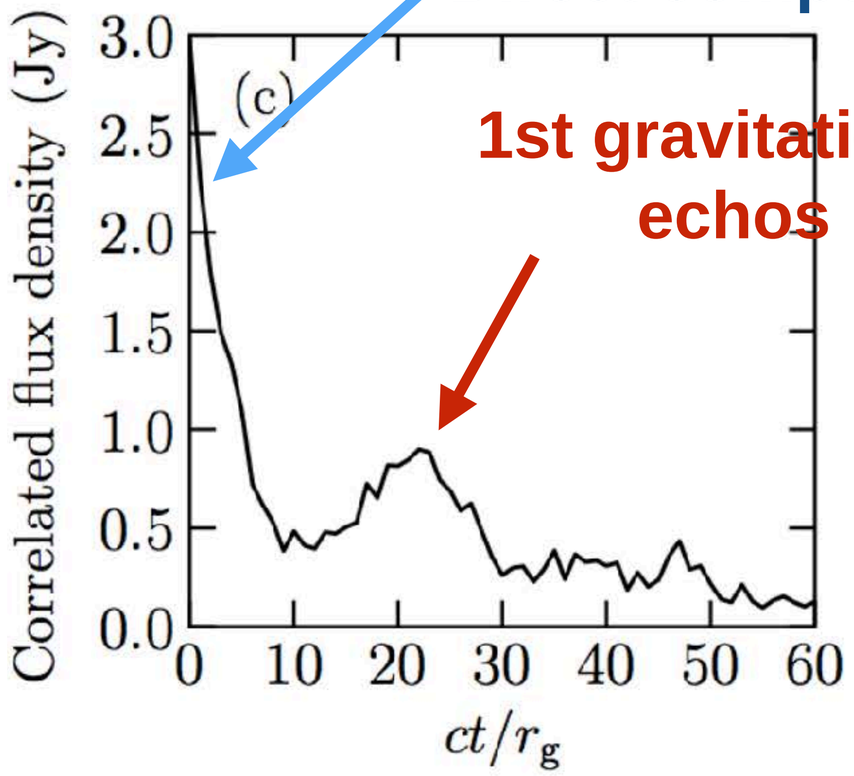
Regular monitoring observation capabilities on weekly scales

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

EHT2020: Spatially Resolved Time-domain Signature of Echos

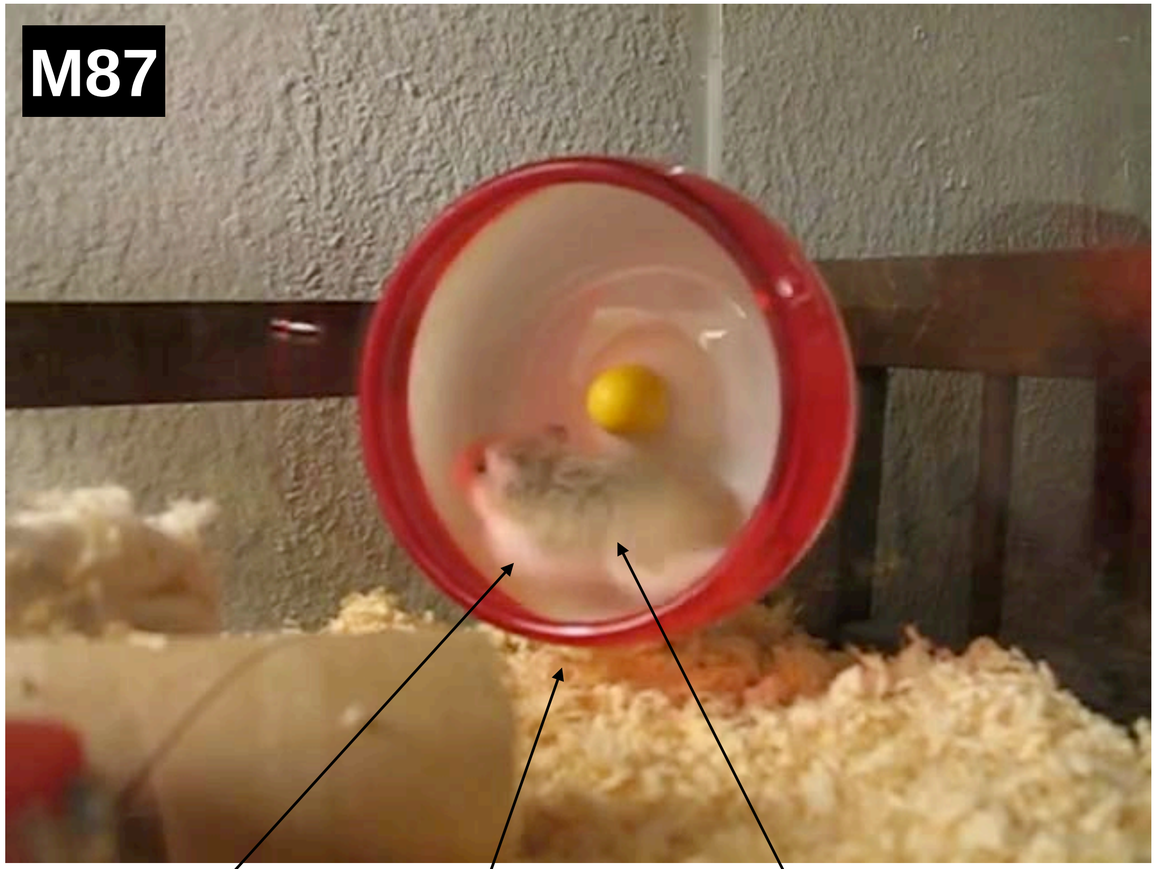


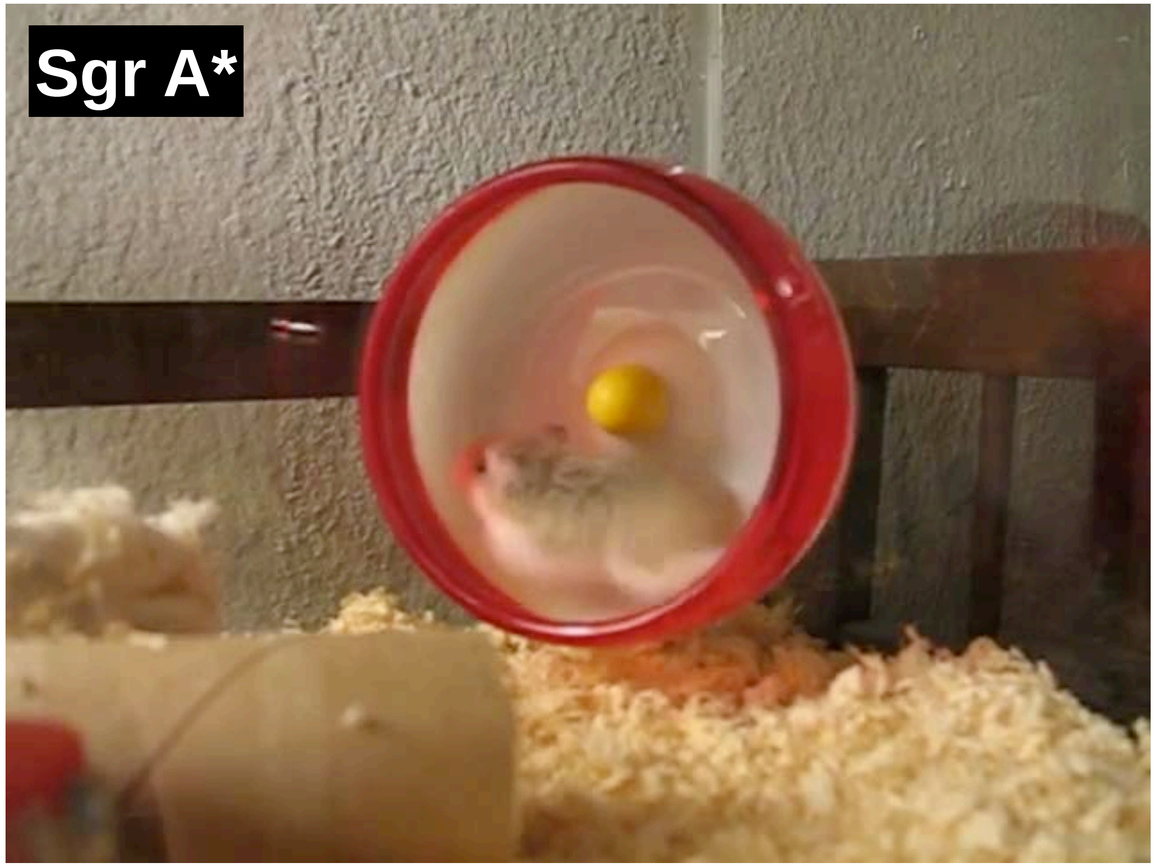
Stacked profile of correlated flux



See Kotaro Moriyama (MIT)'s Poster

EHT 2020s: Precision Black Hole Astrophysics





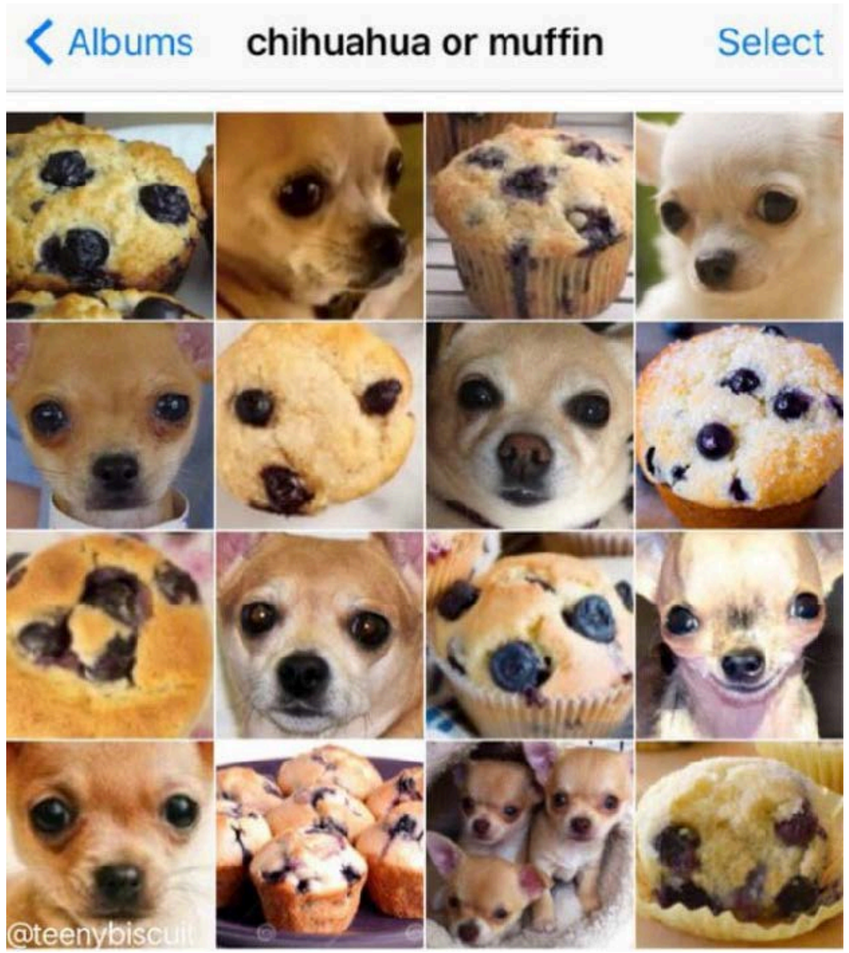
Mass ? Spin ? Accretion flow types?

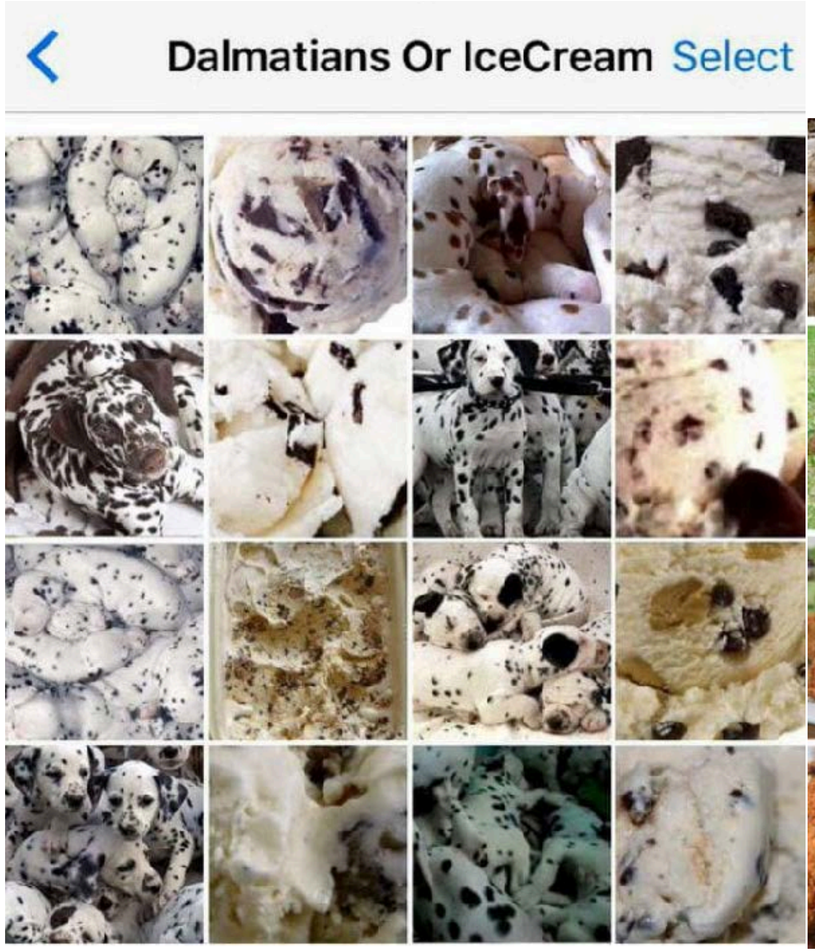
Viewing Geometry?

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

EHT 2020s: Precision Black Hole Astrophysics

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



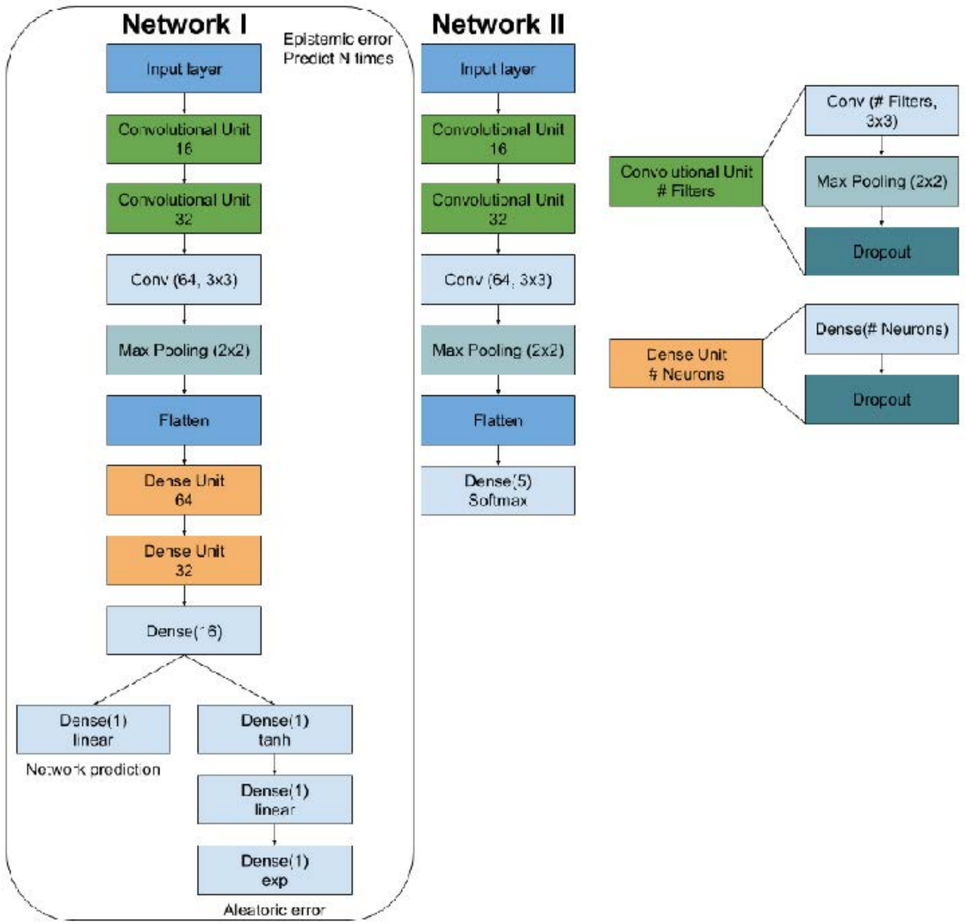


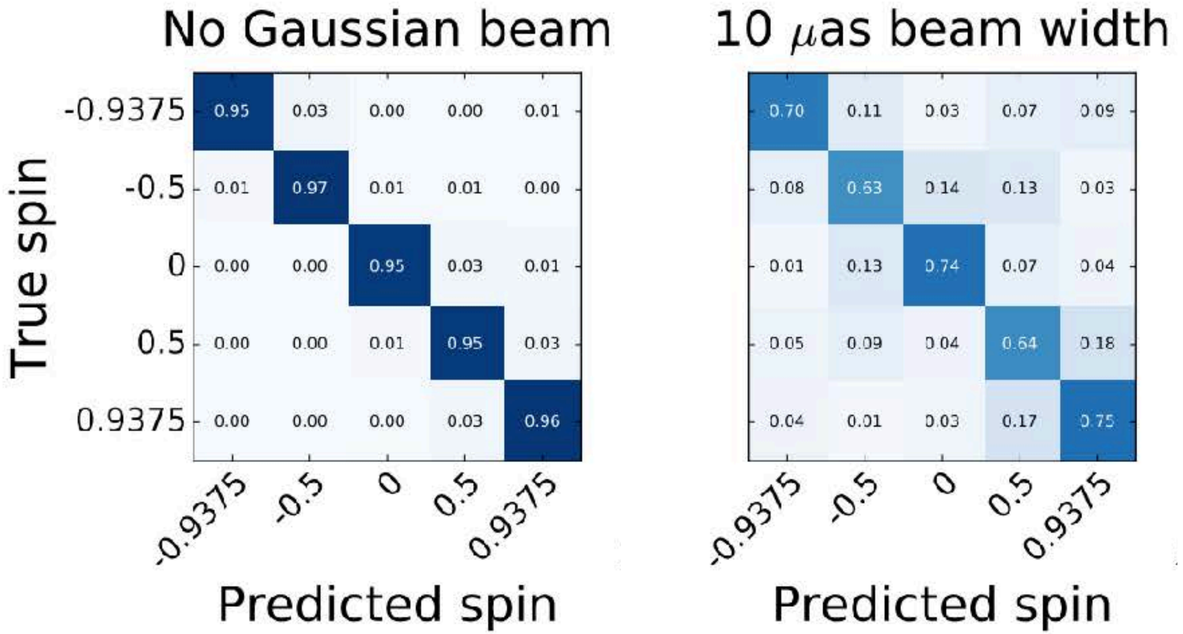
https://barkpost.com/humor/doodle-or-fried-chicken-twitter/

Event Horizon Telescope

EHT 2020s: Precision Black Hole Astrophysics

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

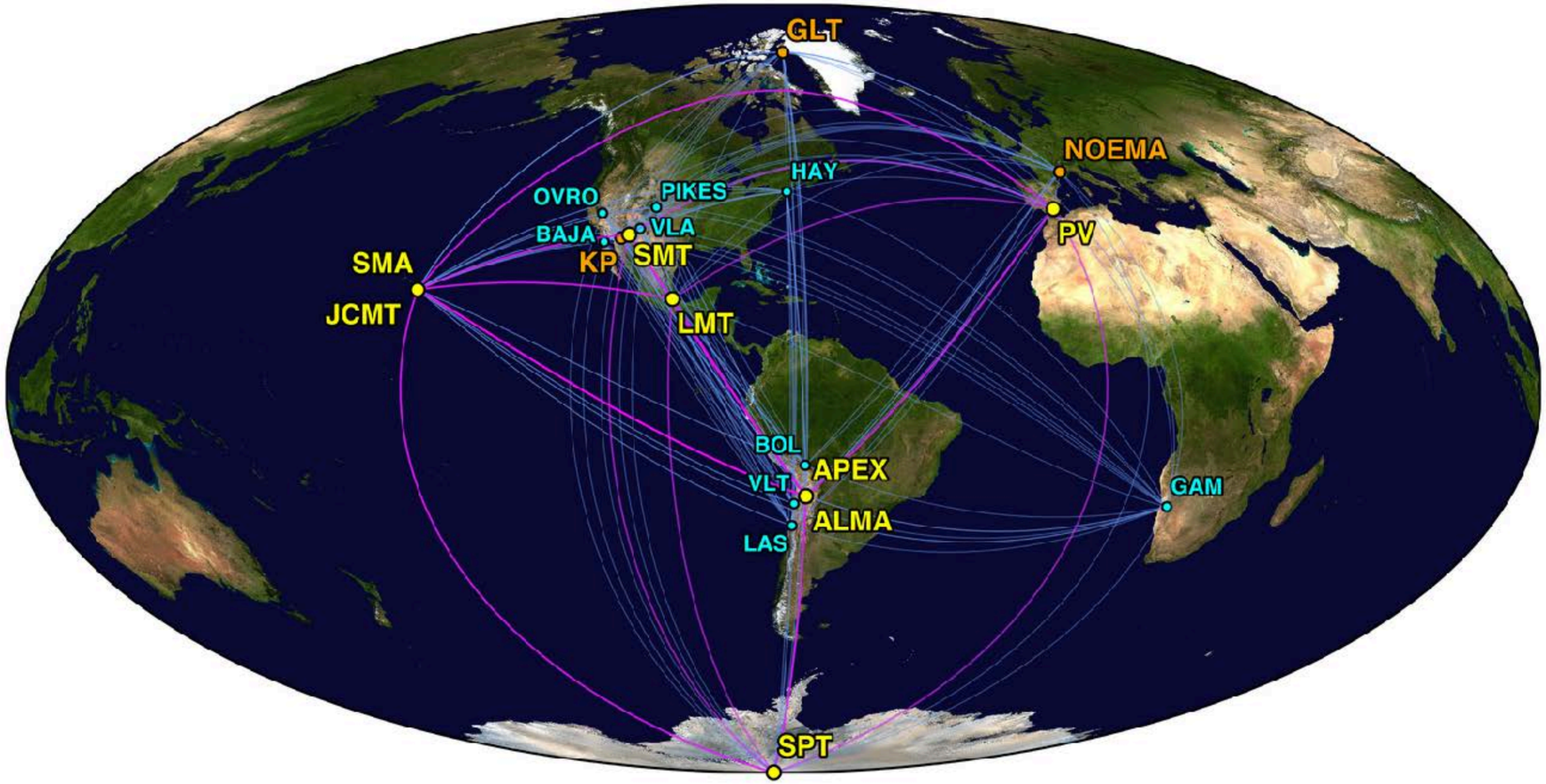




Van der Gucht et al. 2019

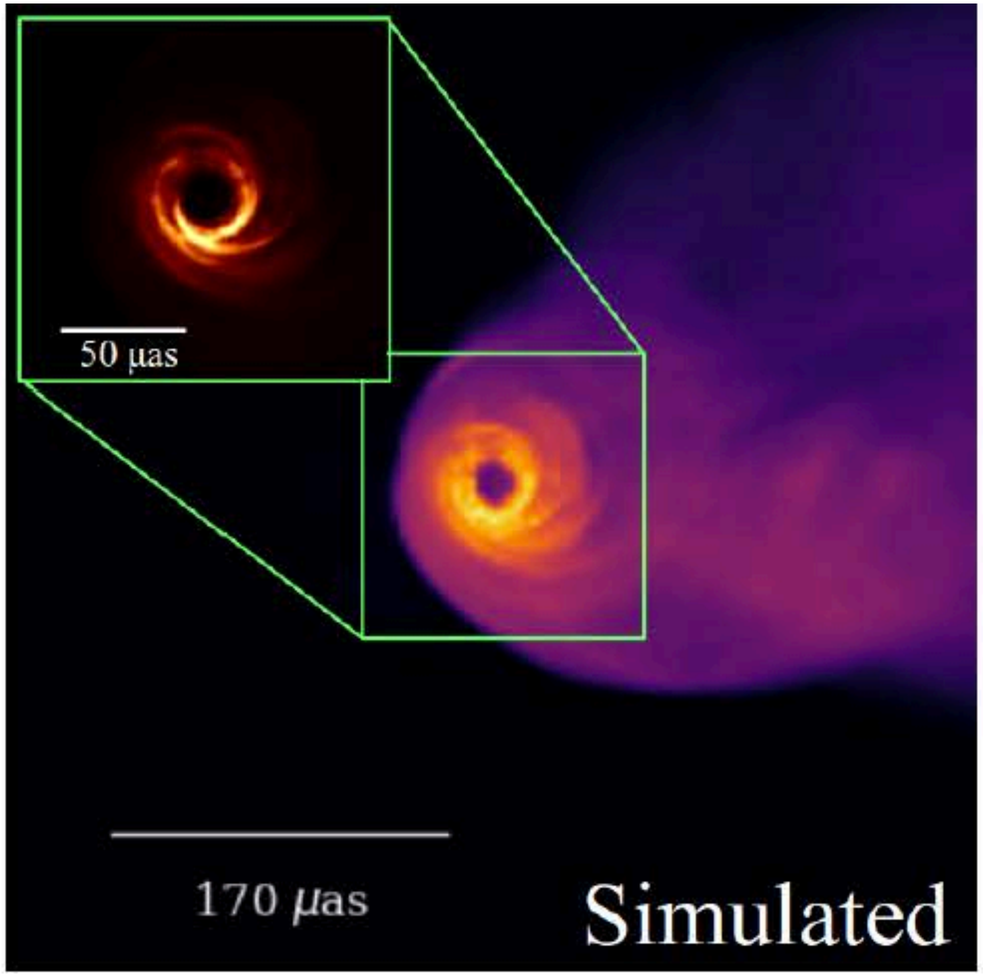
Ven der Gucht+, Yao-Yu Lin+, Sun & Bouman+

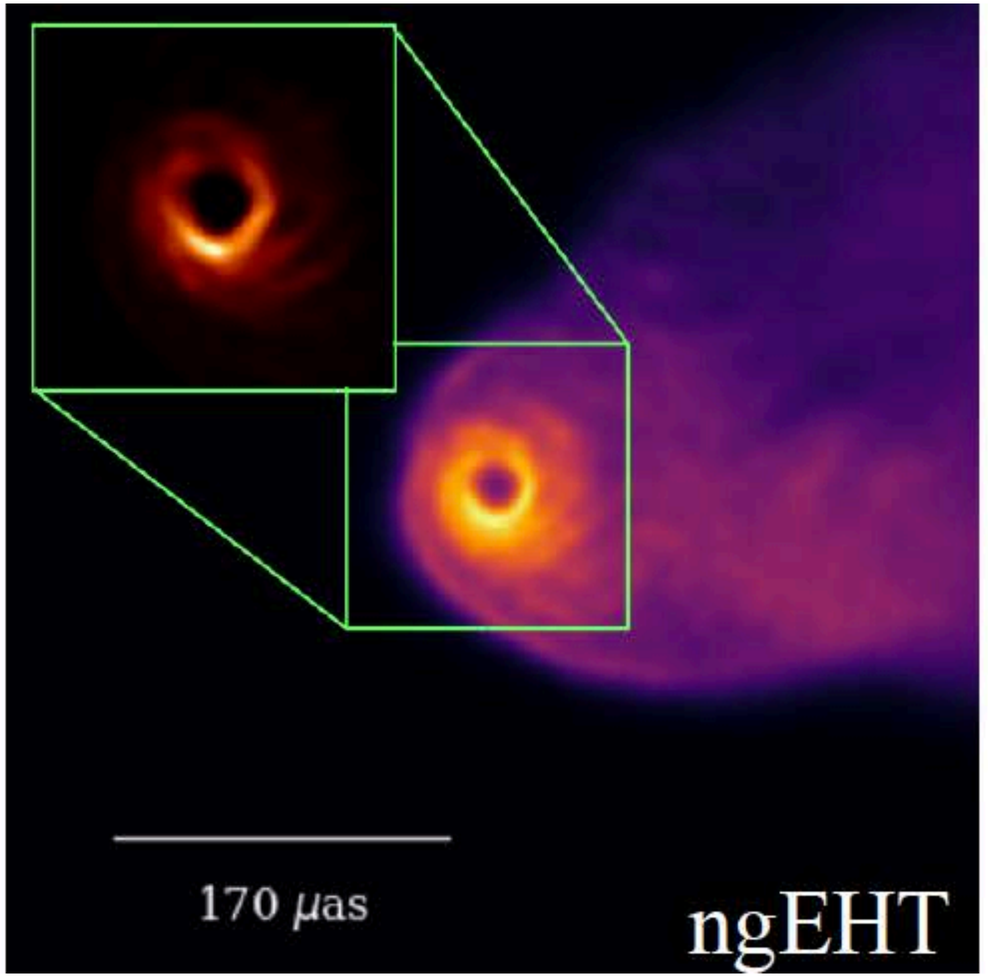
next generation Event Horizon Telescope



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

M87 ngEHT images: ~10 years from now





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

Thanks for listening!