The Shadow of a Black Hole

R.S. Wharton -- Pulsar Journal Club -- 24 Apr 2019

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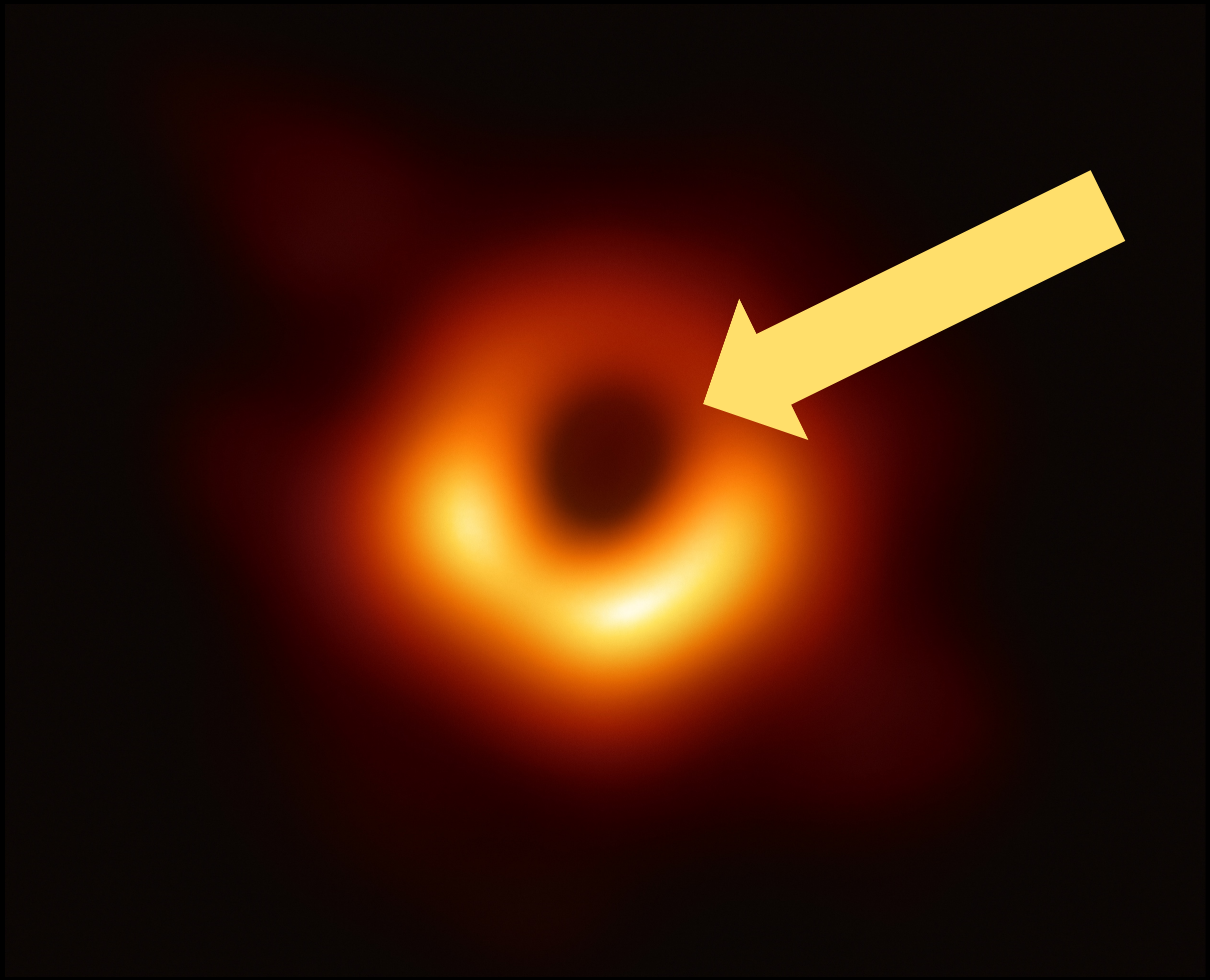

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Sizes

M87* Event Horizon:

$M_{\mathrm{M87}} = 6 \times 10^9 M_\odot$

$D_{\mathrm{M87}} = 16.8 \times 10^6 \mathrm{pc}$

$R_{\mathrm{s,M87}} = 1.8 \times 10^{10}\ \mathrm{km} \approx 120\ \mathrm{AU}$

$\theta_{\mathrm{s,M87}} \approx 8\ \mu\mathrm{as}$

Sgr A* Event Horizon:

$M_{\mathrm{Sgr\ A}} = 4 \times 10^6 M_\odot$

$D_{\mathrm{Sgr\ A}} = 8 \times 10^3 \mathrm{pc}$

$R_{\mathrm{s,Sgr\ A}} = 1.2 \times 10^7\ \mathrm{km} \approx 0.08\ \mathrm{AU}$

$\theta_{\mathrm{s,Sgr\ A}} \approx 10\ \mu\mathrm{as}$

A quick note on units

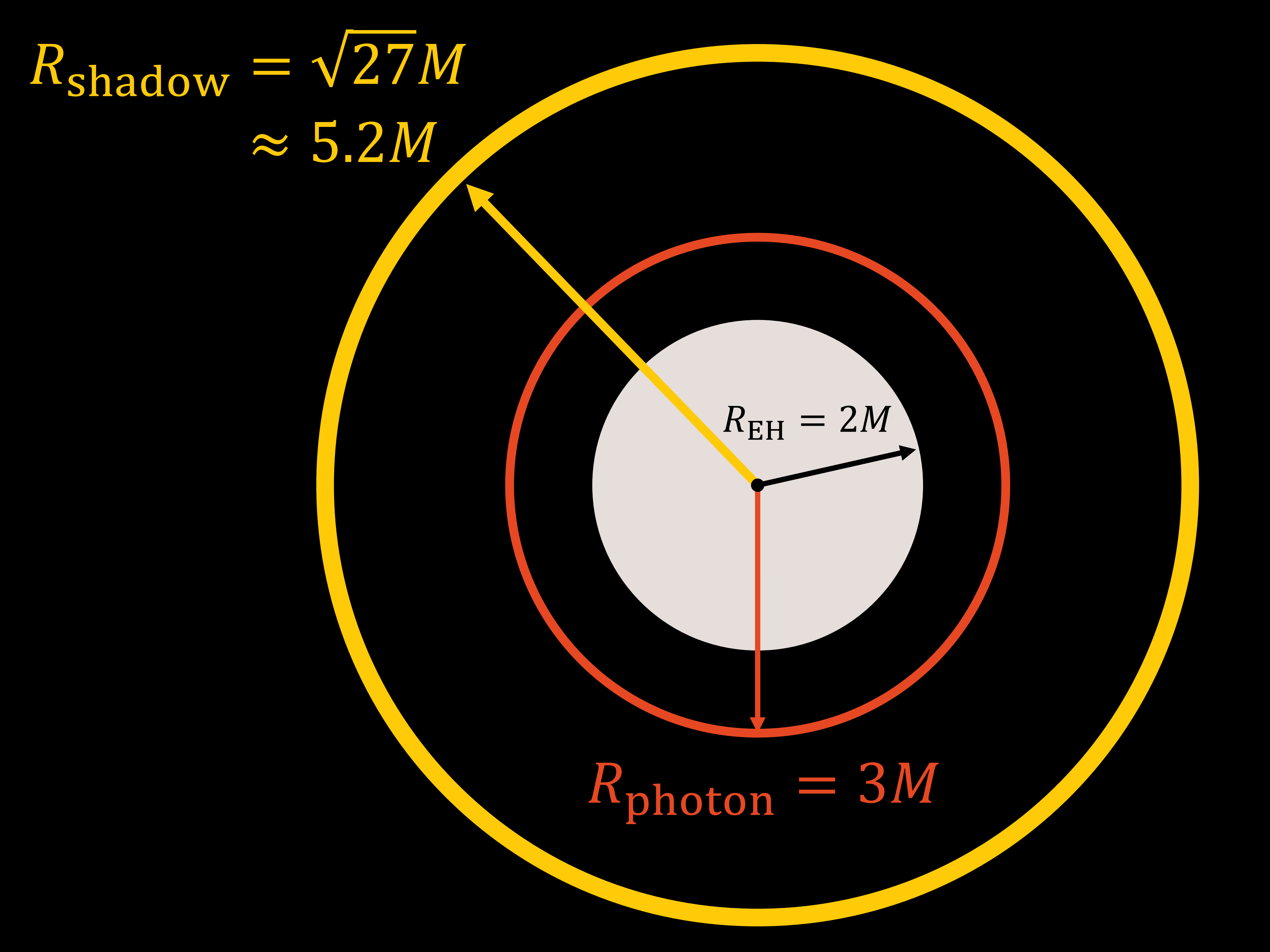
Use Fancy Units:

$$G = c = 1$$

Express things in terms of Mass:

$$R_S = \frac{2GM_\odot}{c^2} \Longrightarrow R_S = 2M$$

Note: $\frac{GM_\odot}{c^2} \approx 1.5\ \mathrm{km} \approx 10^{-8}\mathrm{AU}$



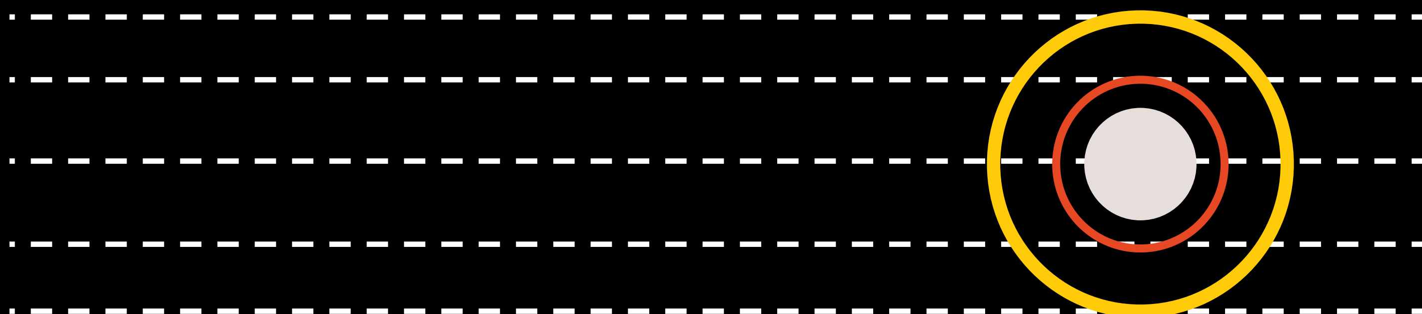
$R_{\text{shadow}} = \sqrt{27}M$
$\approx 5.2M$
$R_{\text{EH}} = 2M$
$R_{\text{photon}} = 3M$

Space Plato

Black Hole

Space Plato

Black Hole



Space Plato

Black Hole

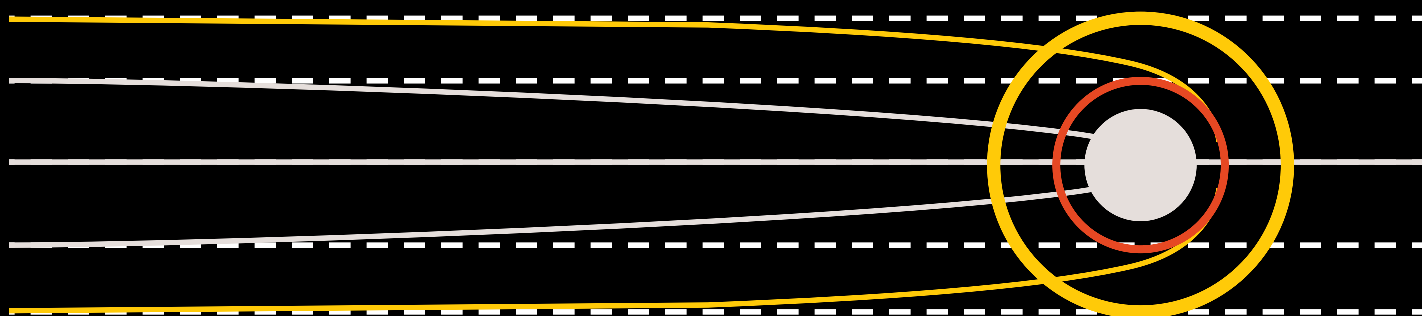
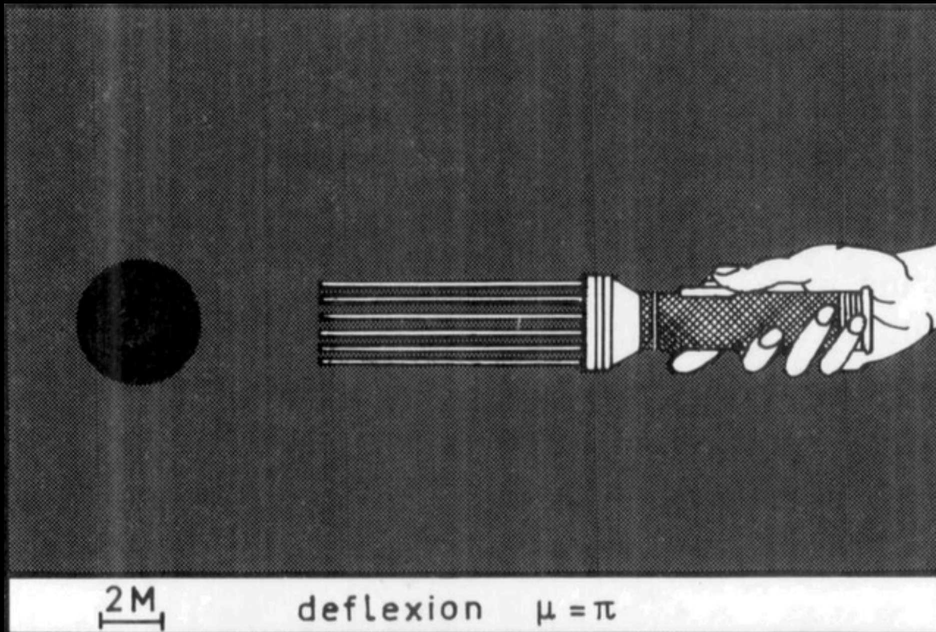


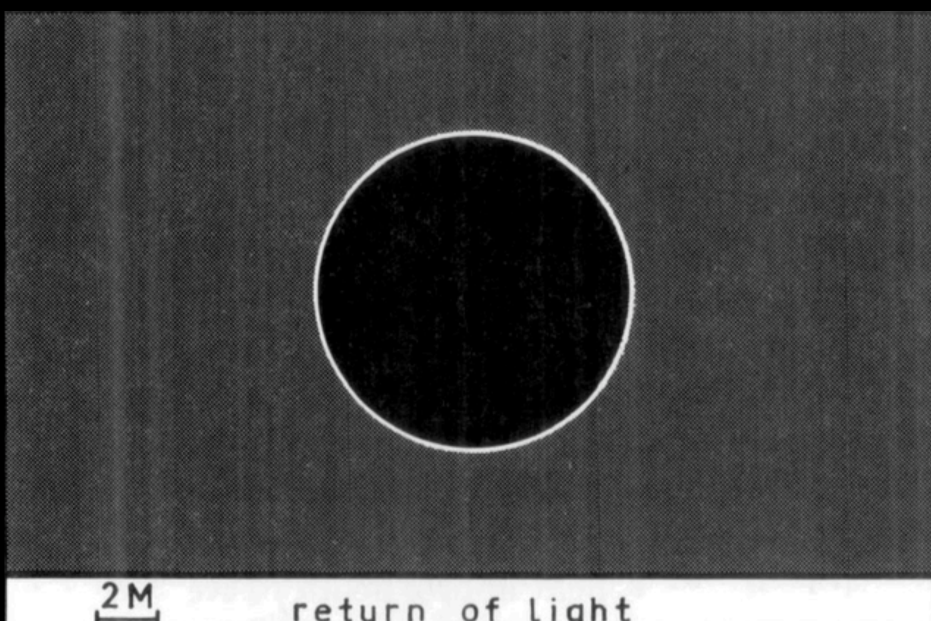
Image of a Spherical Black Hole with Thin Accretion Disk

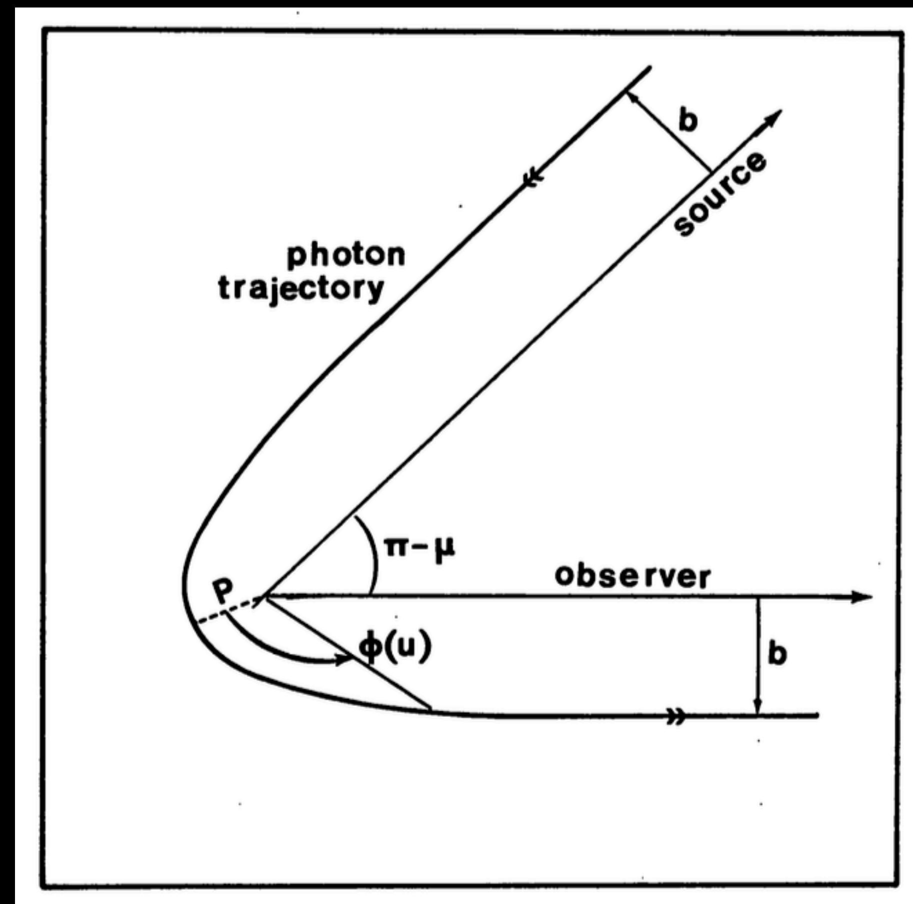
J.-P. Luminet

Groupe d'Astrophysique Relativiste, Observatoire de Paris, Section d'Astrophysique, F-92190-Meudon, France

Received July 13, 1978







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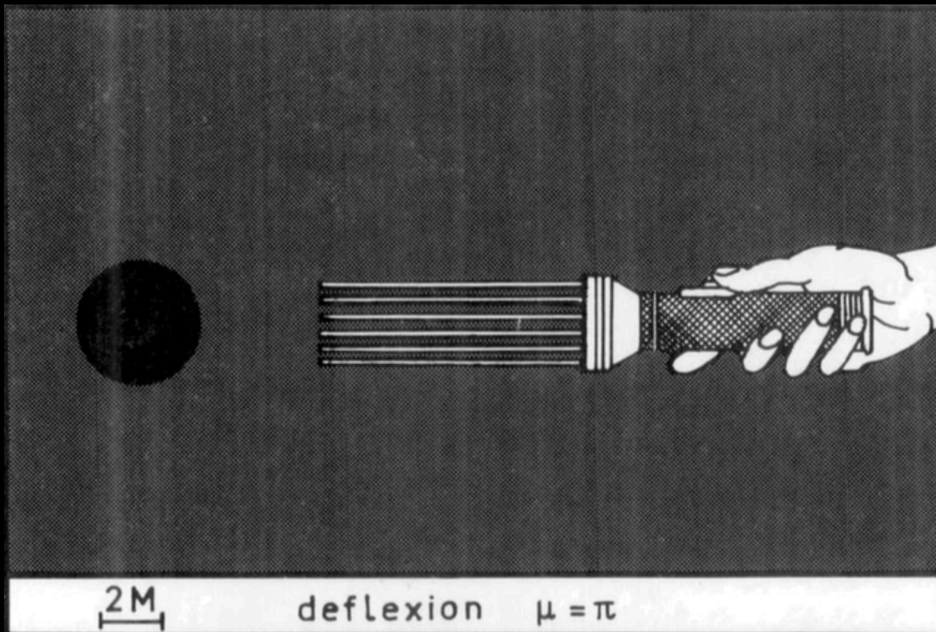
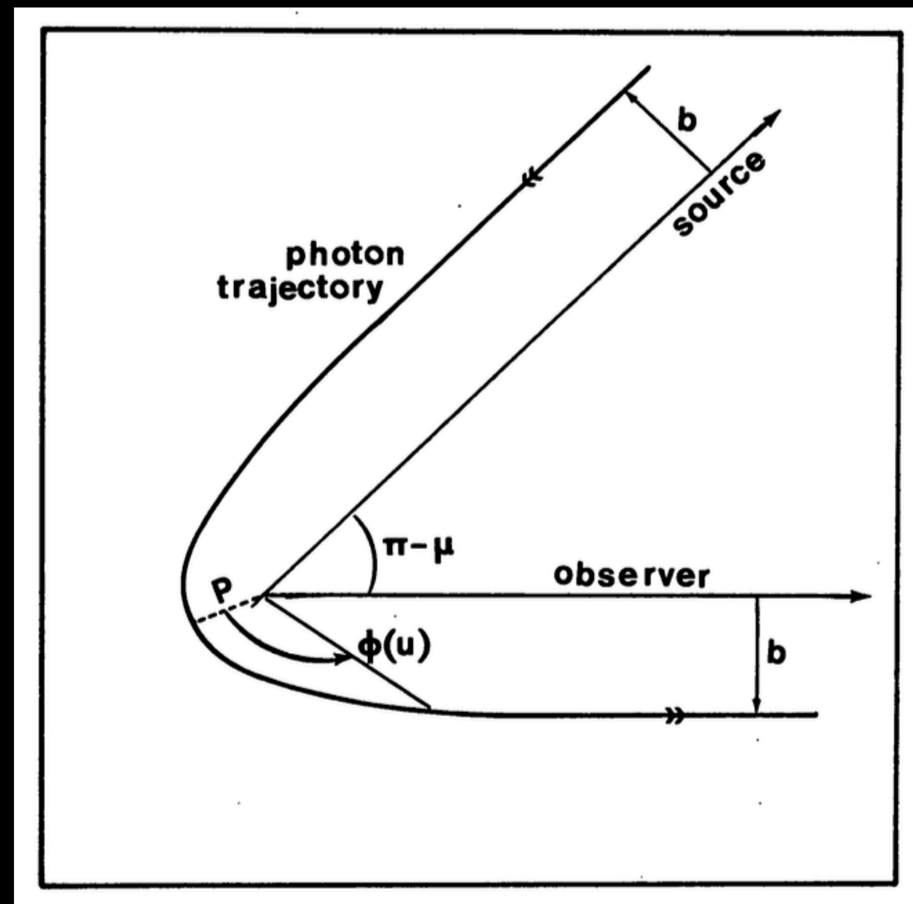




VIEWING THE SHADOW OF THE BLACK HOLE AT THE GALACTIC CENTER

HEINO FALCKE,[1] FULVIO MELIA,[2,3] AND ERIC AGOL[4]

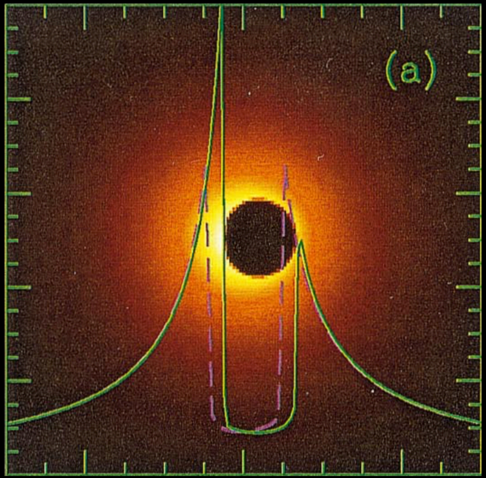
Received 1999 September 14; accepted 1999 October 26; published 1999 December 7

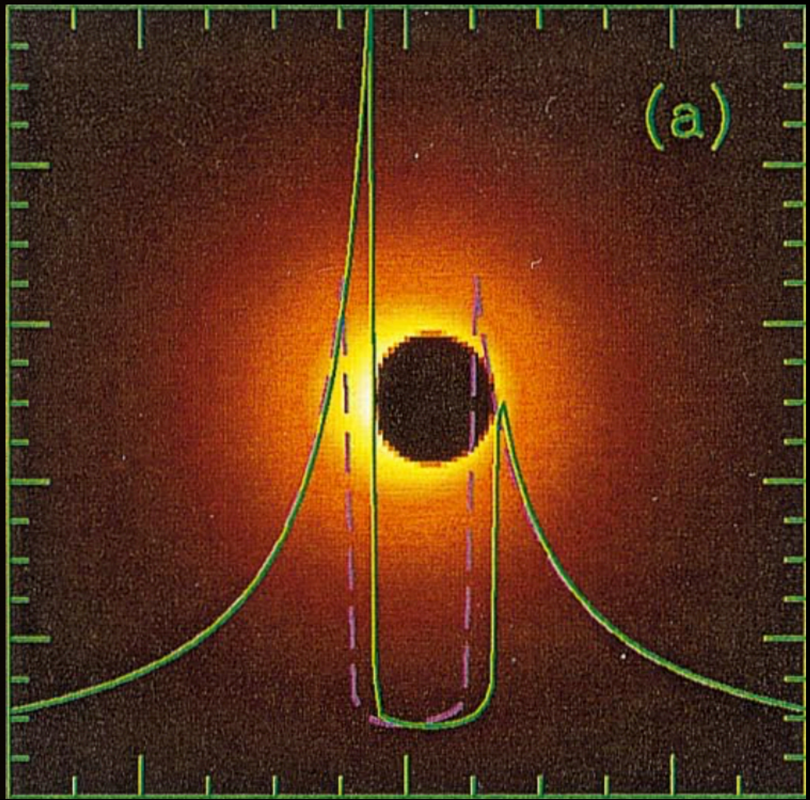
ABSTRACT

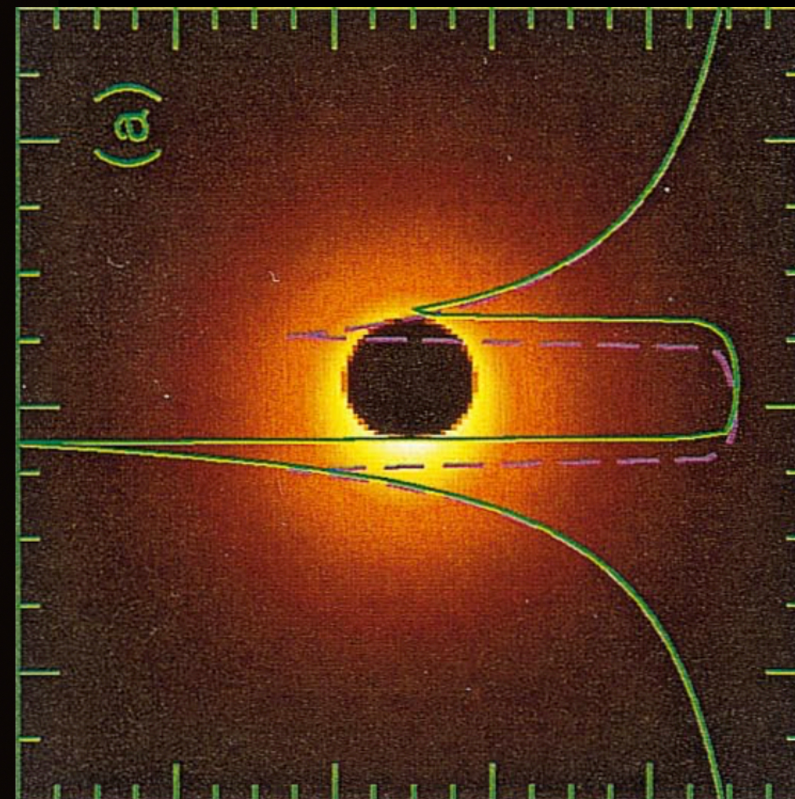
In recent years, evidence for the existence of an ultracompact concentration of dark mass associated with the radio source Sagittarius A* in the Galactic center has become very strong. However, unambiguous proof that this object is indeed a black hole is still lacking. A defining characteristic of a black hole is the event horizon. To a distant observer, the event horizon casts a relatively large "shadow" with an apparent diameter of ~10 gravitational radii that is due to the bending of light by the black hole, and this shadow is nearly independent of the black hole spin or orientation. The predicted size (~30 μas) of this shadow for Sgr A* approaches the resolution of current radio interferometers. If the black hole is maximally spinning and viewed edge-on, then the shadow will be offset by ~8 μas from the center of mass and will be slightly flattened on one side. Taking into account the scatter broadening of the image in the interstellar medium and the finite achievable telescope resolution, we show that the shadow of Sgr A* may be observable with very long baseline interferometry at submillimeter wavelengths, assuming that the accretion flow is optically thin in this region of the spectrum. Hence, there exists a realistic expectation of imaging the event horizon of a black hole within the next few years.

Subject headings: black hole physics — galaxies: active — Galaxy: center — relativity — submillimeter — techniques: interferometric

The technical methods to achieve such a resolution at wavelengths shortward of 1.3 mm are currently being developed, and a first detection of Sgr A* at 1.4 mm with VLBI has already been reported. The challenge will be to push this technology even further toward 0.8 or even 0.6 mm VLBI. Over the next decade, many more telescopes are expected to operate at these wavelengths. Depending on how short a wavelength is required, the projected timescale for developing the necessary VLBI techniques may be about 10 yr. A fundamental problem preventing such an experiment is not now apparent, but in light of our results, planning of the new submillimeter telescopes should include sufficient provisions for VLBI experiments.




(a)


(a)

What is Required?

1. Angular Resolution
2. Fourier Coverage

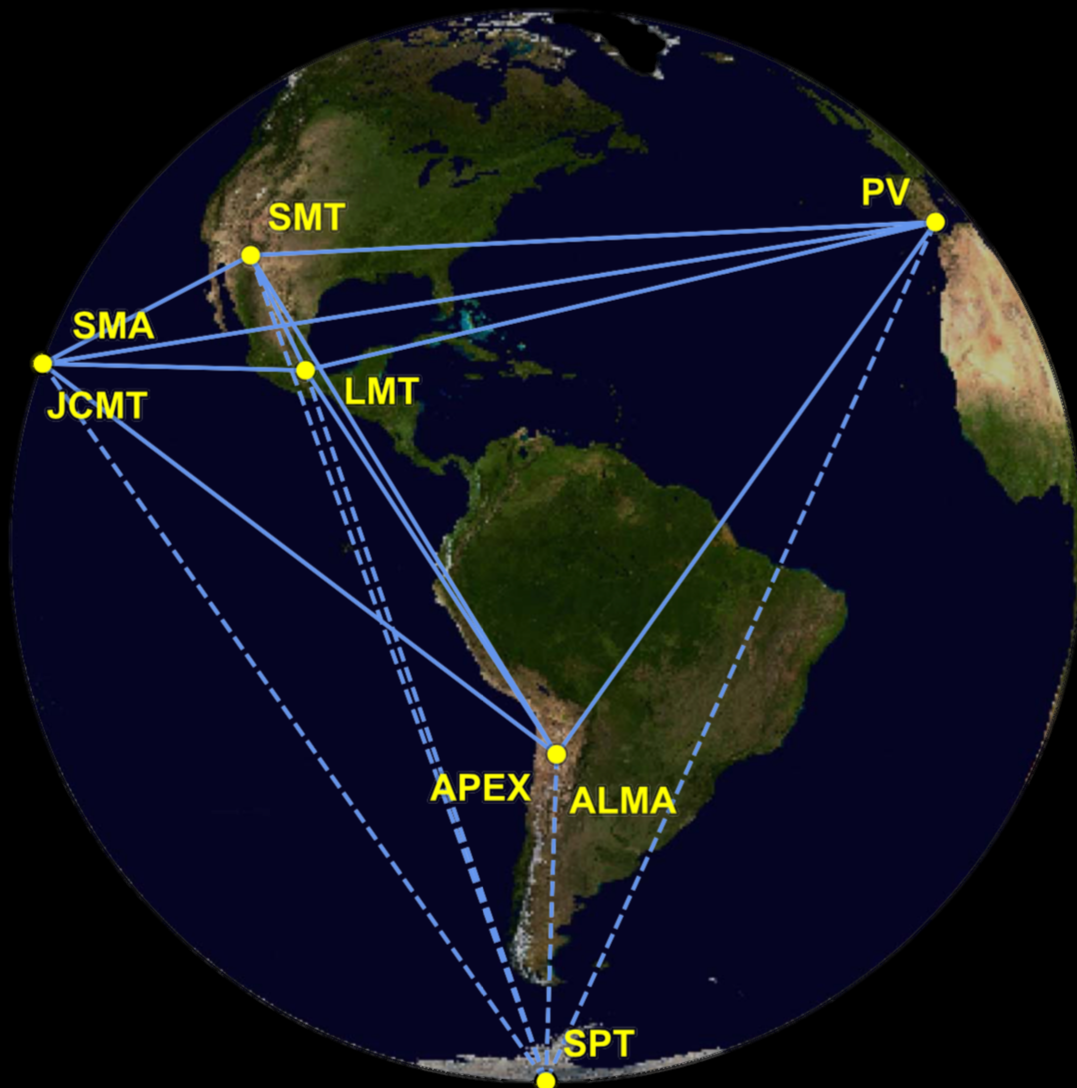
} Global VLBI

3. Atm Transparency
4. Optically Thin Accretion

} $\lambda \sim \mathrm{mm}$

$$\theta \sim \frac{\lambda}{d} \sim 20\mu as \left(\frac{\lambda}{1.3\ \mathrm{mm}}\right)\left(\frac{d}{12{,}800\ \mathrm{km}}\right)$$

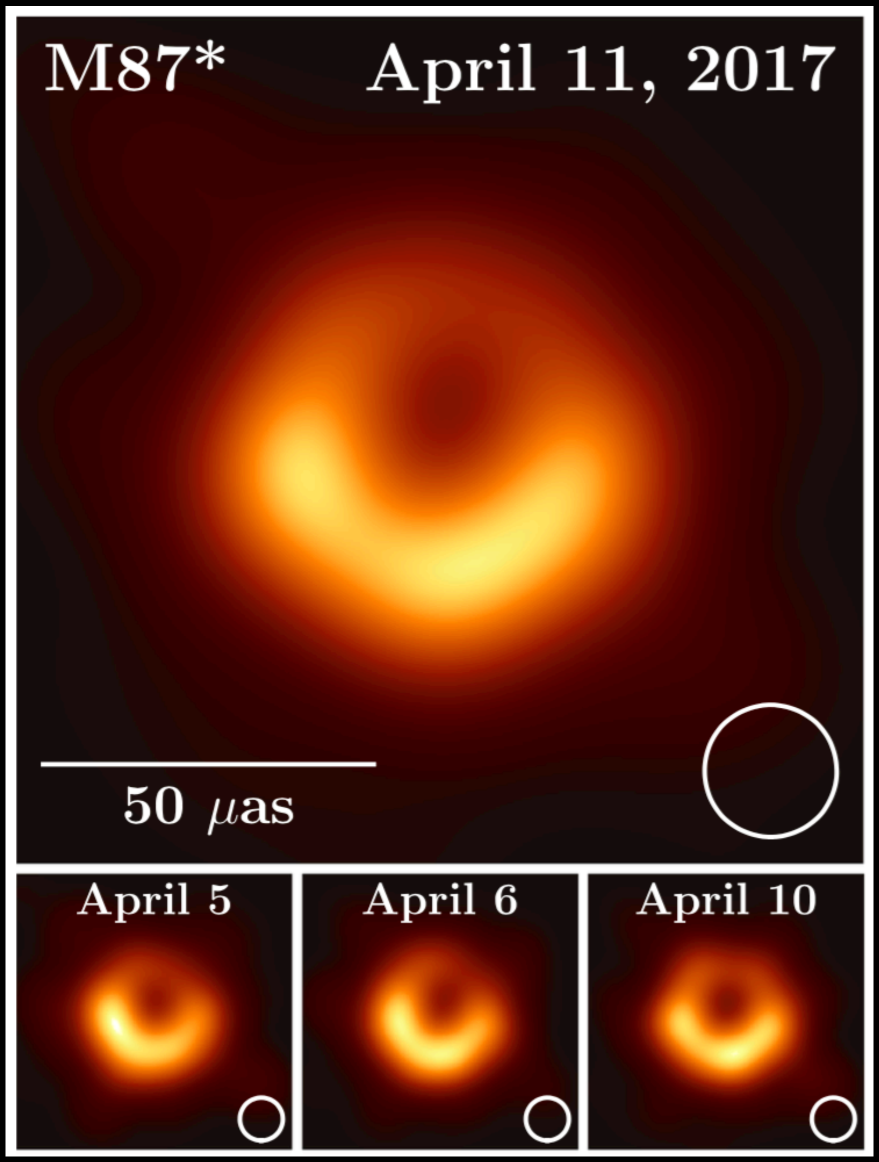
The Event Horizon Telescope



First EHT Results: Six Papers

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole	Summary Paper (9 Pages)
First M87 Event Horizon Telescope Results. II. Array and Instrumentation	The EHT (22 Pages)
First M87 Event Horizon Telescope Results. III. Data Processing and Calibration	Calibration (28 Pages)
First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole	Deconv/Imaging (47 Pages)
First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring	Accretion + Jet (25 Pages)
First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole	Parameter Est. (39 Pages)

Paper I: Summary of Results



Measure shadow of M87* at 1.3 mm (230 GHz)

$$\theta_{\mathrm{ring}} = 42 \pm 3\ \mu as$$

Determine mass of BH:

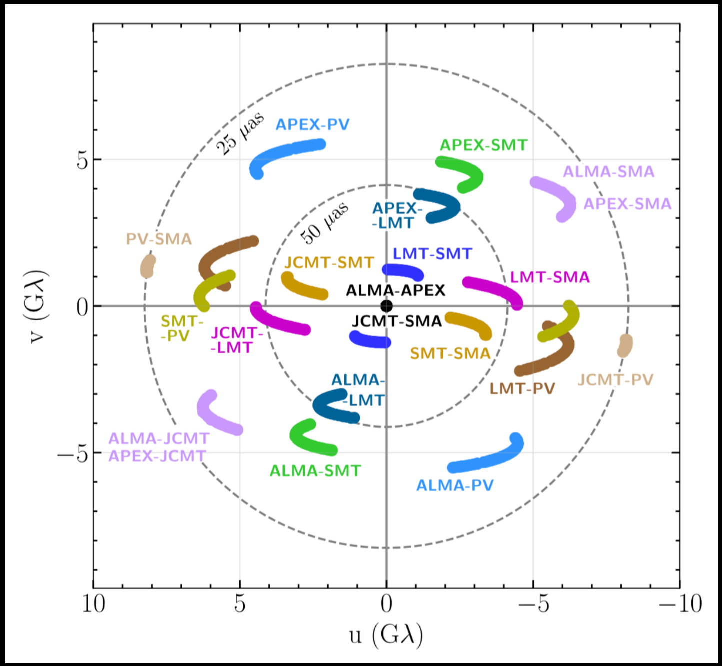
$$M_{BH} = (6.5 \pm 0.7)\times 10^{9} M_{\odot}$$

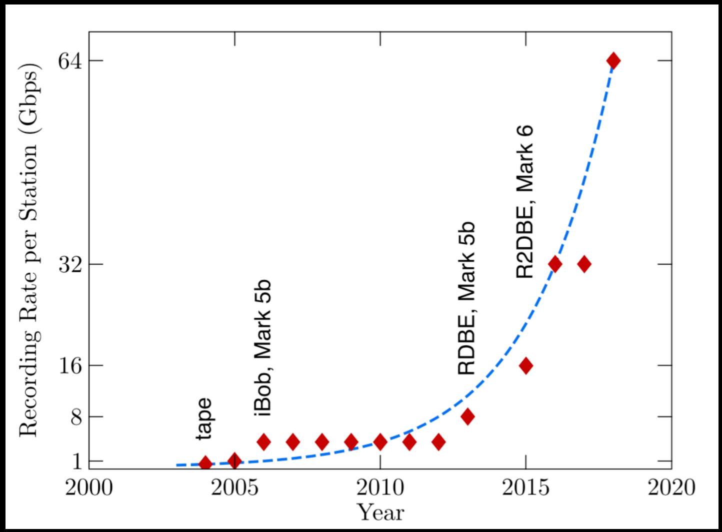
Pretty circular:

$$\frac{\theta_{\mathrm{major}}}{\theta_{\mathrm{minor}}} \leq \frac{4}{3}$$

Completely consistent with Kerr BH predicted by GR

Paper II: Array + Instrumentation





8 Telescopes in 6 Places

$$\lambda = 1.3 \text{ mm} \qquad \nu = 230 \text{ GHz}$$

Huge Data Rates:

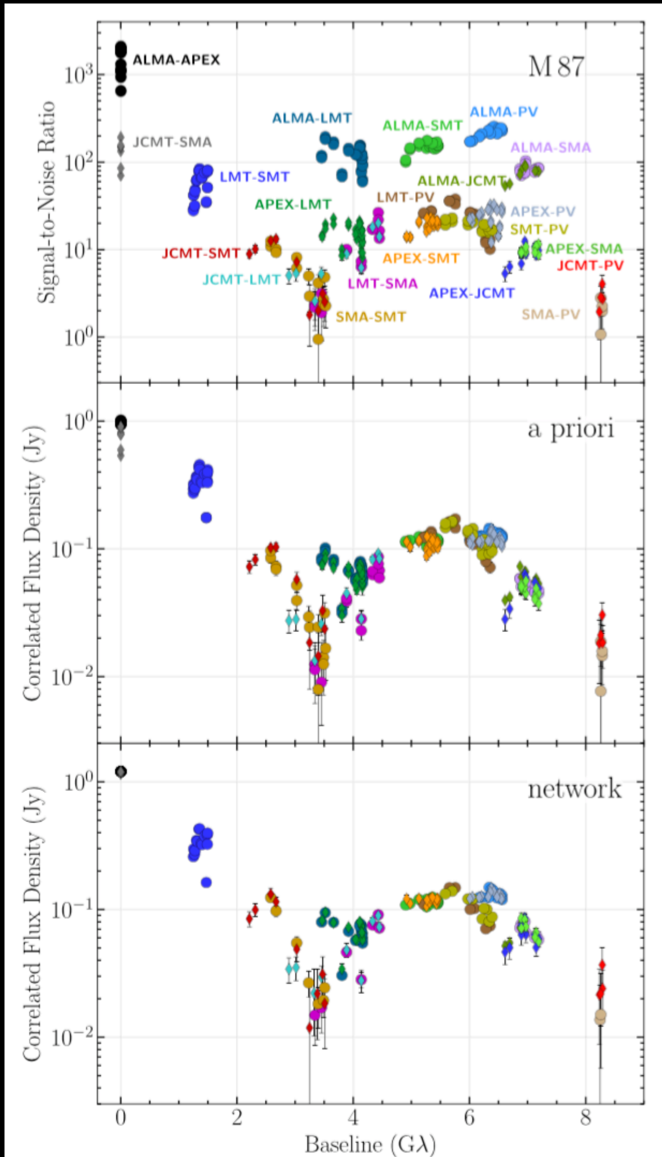
$$64 \text{ Gbps} \times 8 \text{ stations} = 240 \text{ TB hr}^{-1}$$

Spatial Scales Sampled:

$$\theta = 25 - 160 \; \mu as$$

Extremely Impressive Technical Achievement

Paper III: Data Proc + Calibration



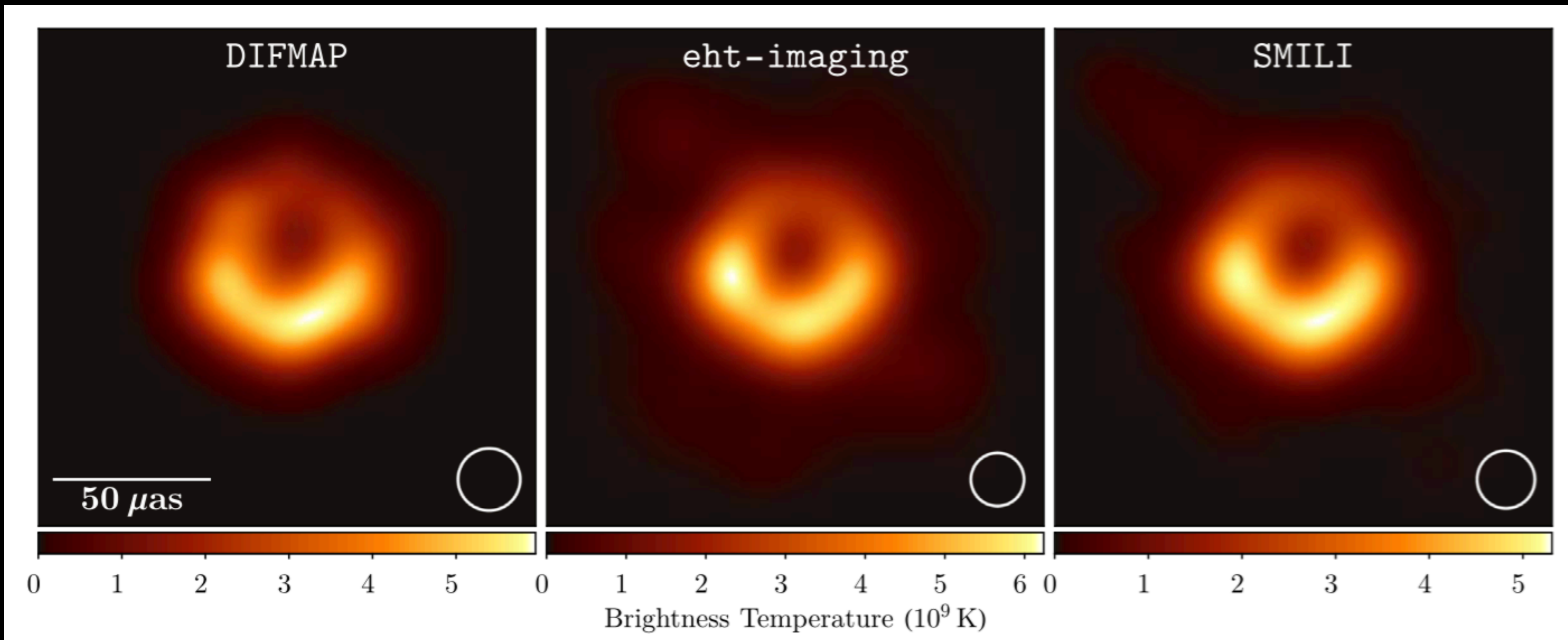
Heterogeneous Data Set

Three Pipelines:

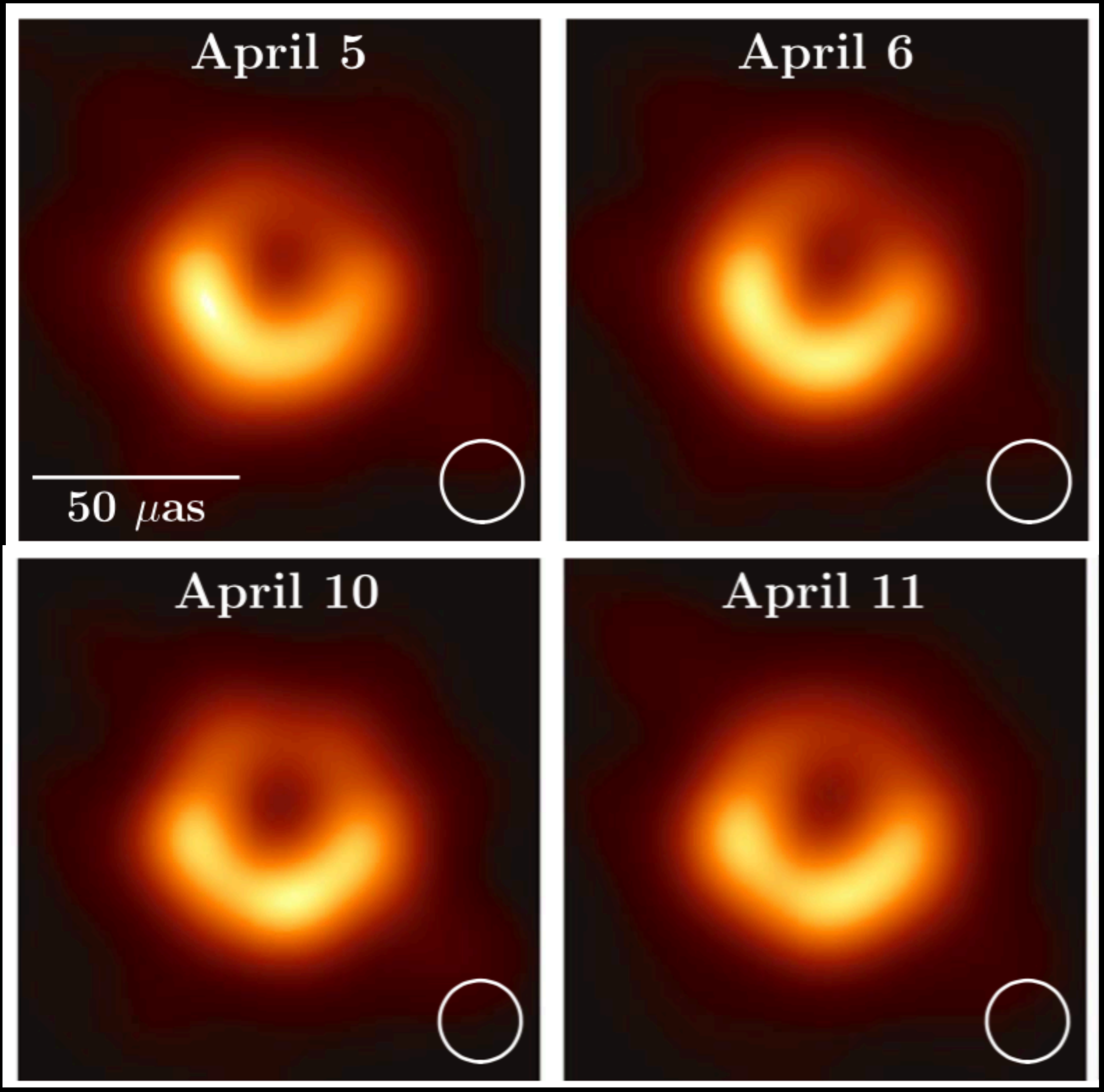
1) AIPS
2) CASA
3) HOPS

Robust Calibration!

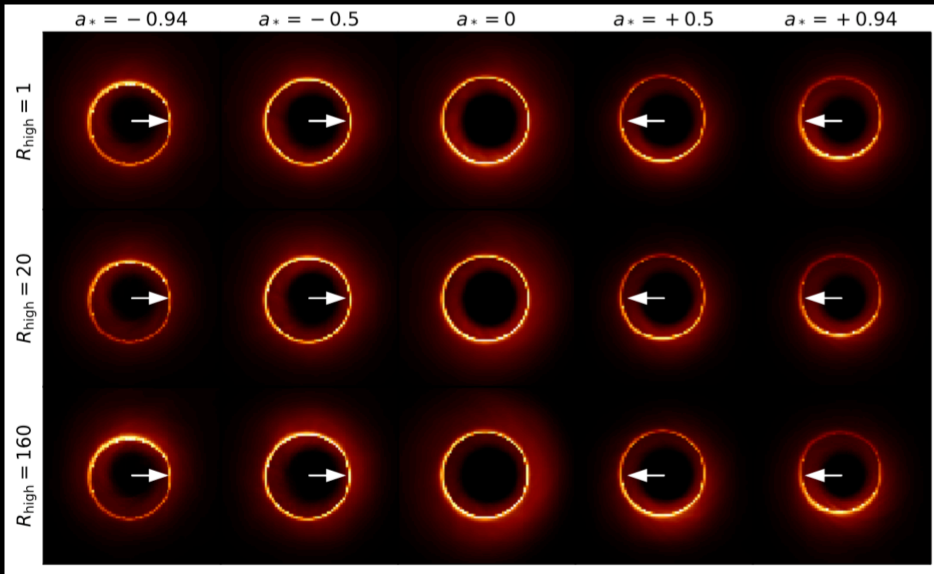
Paper IV: Imaging

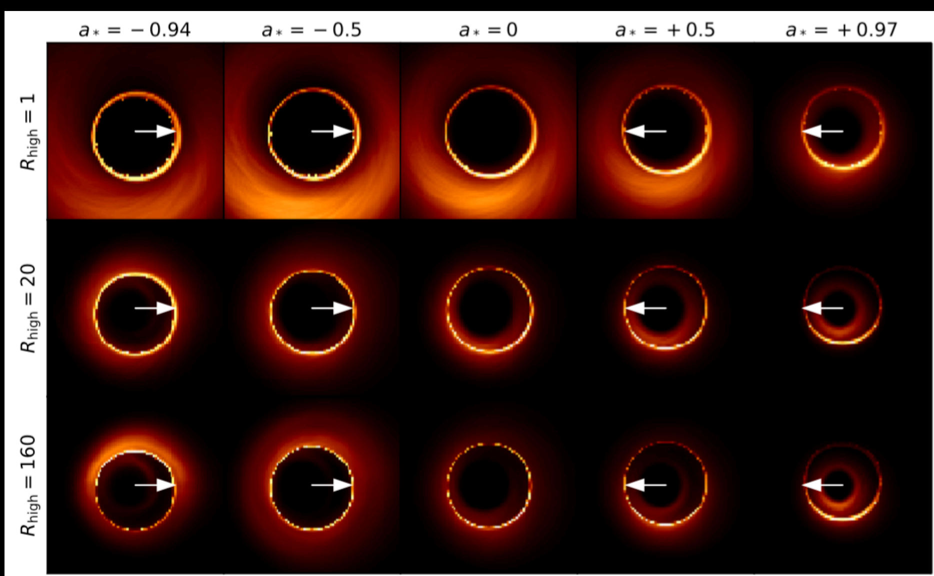


Probably the most robust
interferometric image ever created


April 5
April 6
April 10
April 11
50 μas

Paper V: Astrophysics





GRMHD Simulations + Ray Tracing

Simulate “observed” images and compare to actually observed image

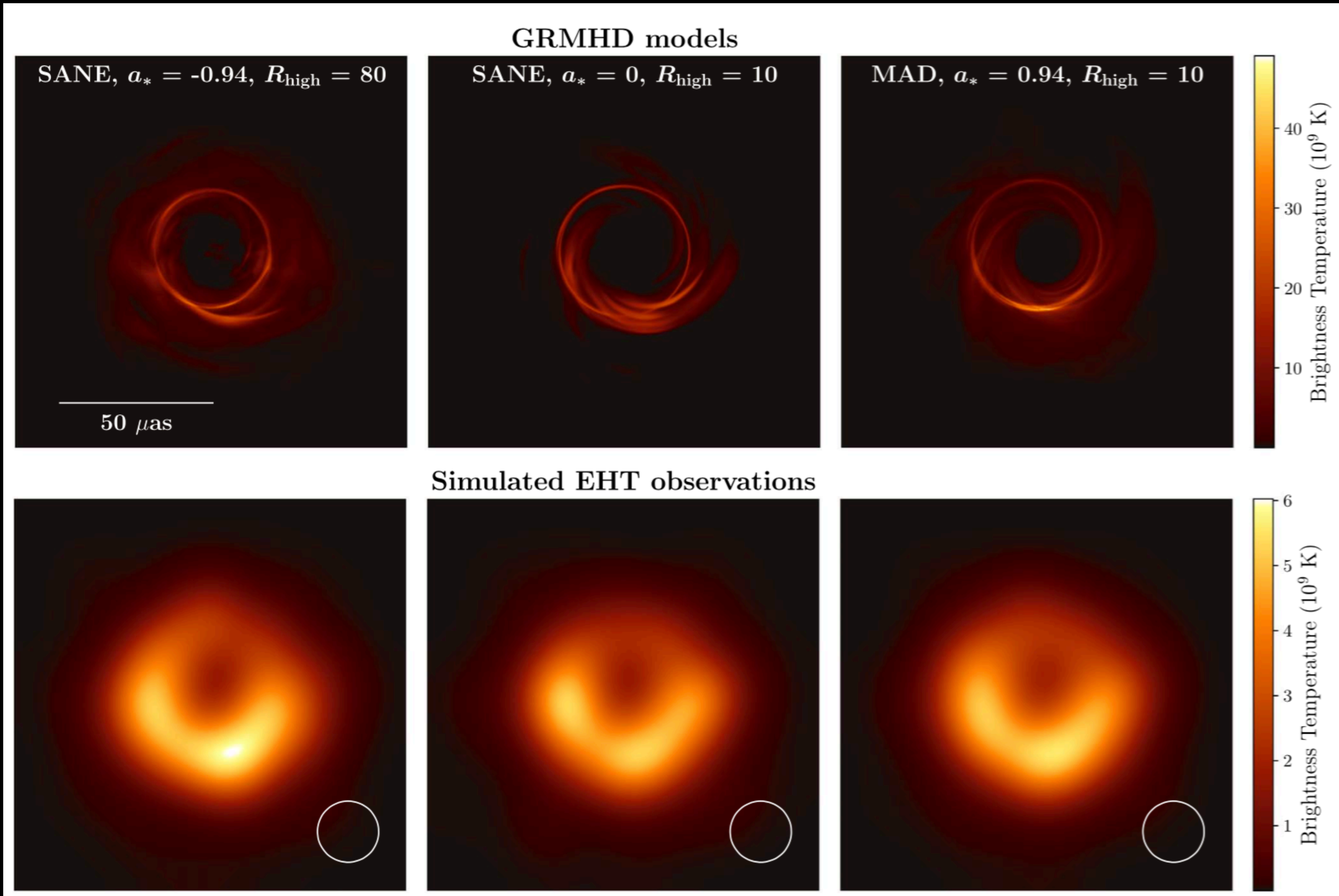
Two General Classes:

MAD –

Magnetically Arrested Disk

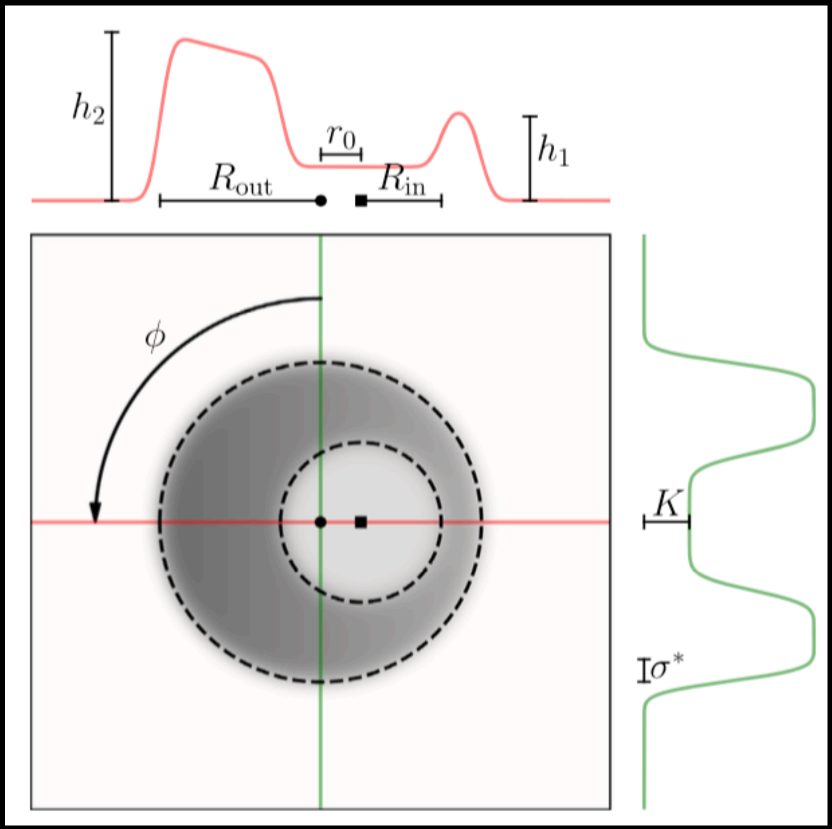
SANE –

Standard And Normal Evolution



GRMHD models
SANE, $a_* = -0.94$, $R_{\rm high} = 80$
SANE, $a_* = 0$, $R_{\rm high} = 10$
MAD, $a_* = 0.94$, $R_{\rm high} = 10$
50 μas
Brightness Temperature (10^9 K)
10
20
30
40
Simulated EHT observations
Brightness Temperature (10^9 K)
1
2
3
4
5
6

Paper VI: Parameter Extraction



How to get info out of the image?

Measure shadow size

Use this to set mass of BH assuming Kerr

THE END