The Future of Black Hole Imaging

Charles F. Gammie
on behalf of the Event Horizon Telescope Collaboration

Texas Symposium / Shanghai

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窥视黑洞，何去何从

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Event Horizon Telescope Images

Modeling EHT sources

Future of Black Hole Imaging

Hot Spots and Model Predictions

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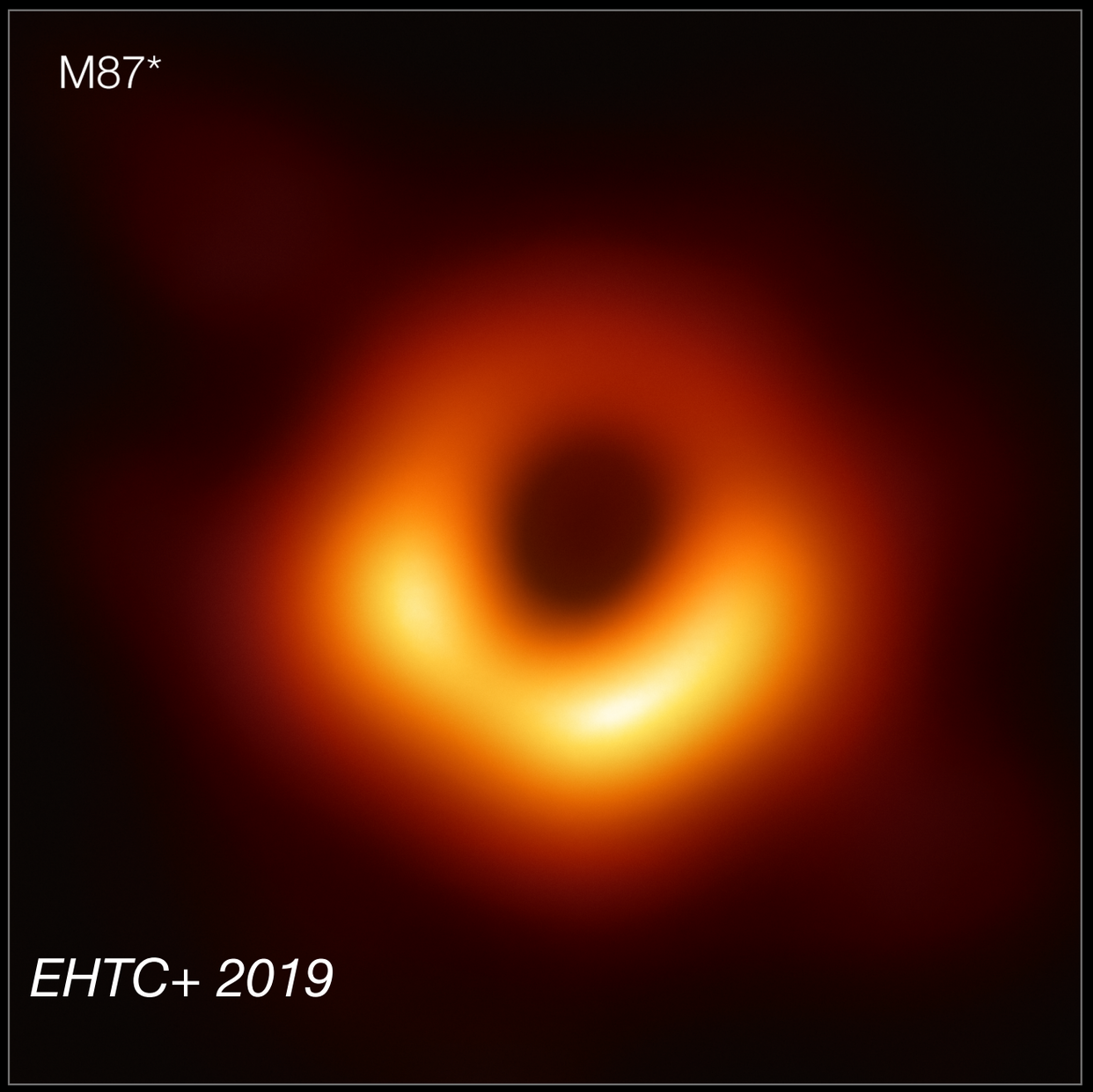

First image of a black hole

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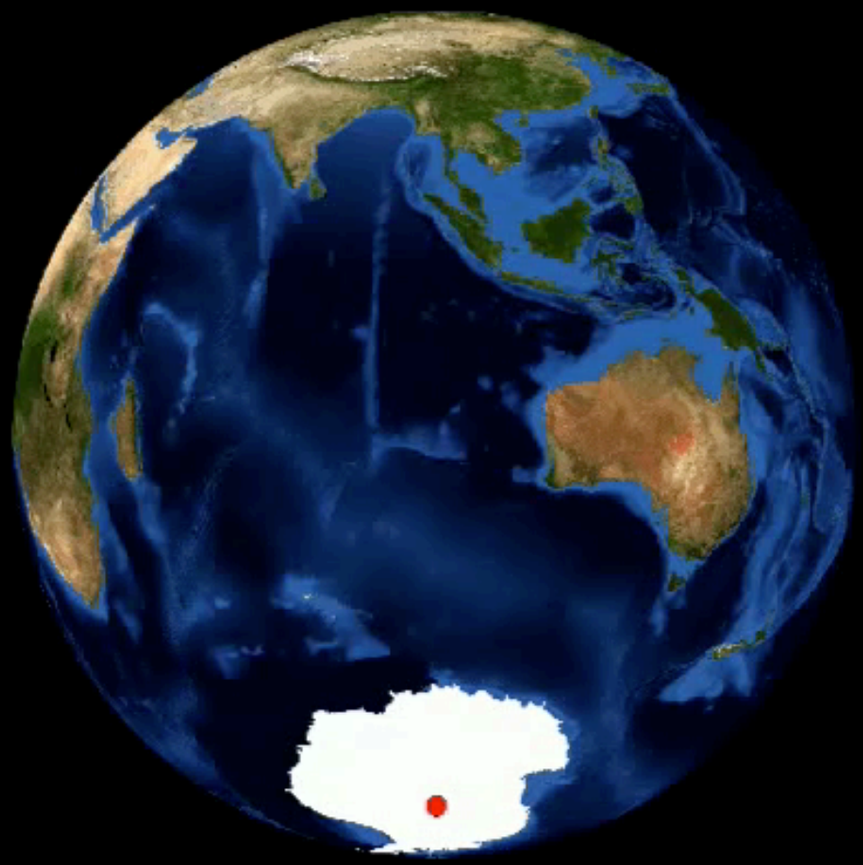
EHT: millimeter VLBI



- 1.3mm VLBI network, $\Delta\theta \sim \lambda/D \sim (1.3\text{mm})/(2\ R_\oplus) \sim 20\mu\text{as}$
- 2017 campaign: April 5, 6, 7, 10, 11; 6 targets, incl M87* & Sgr A*
- 8 telescopes at 6 sites

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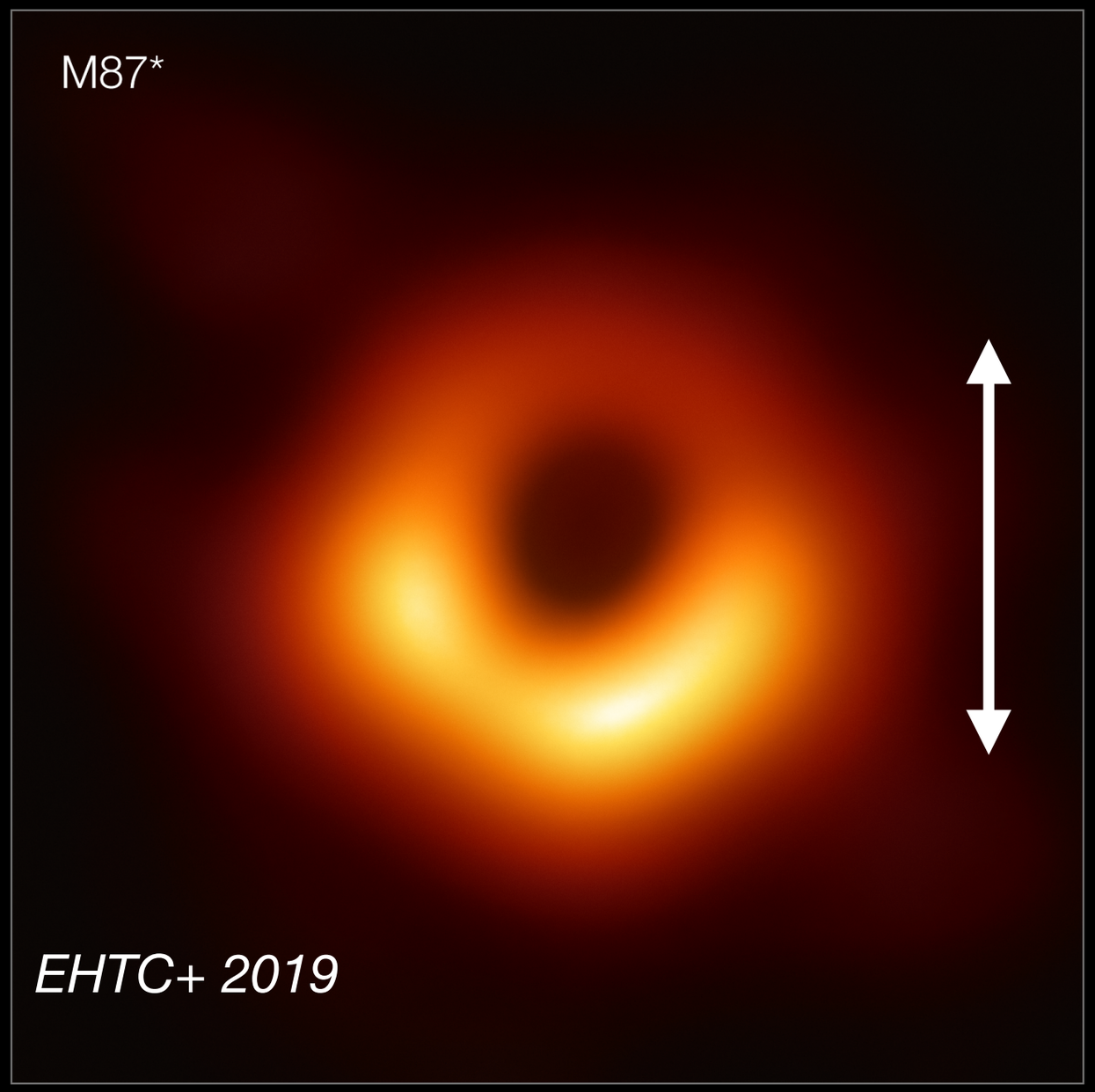

First image of a black hole

angular diameter

$$\textbf{42μas} = \sqrt{27}\,\frac{2GM}{c^2 D}$$

$$\Rightarrow M \simeq 6.5 \pm 0.7 \times 10^9\,\mathrm{M}_\odot$$

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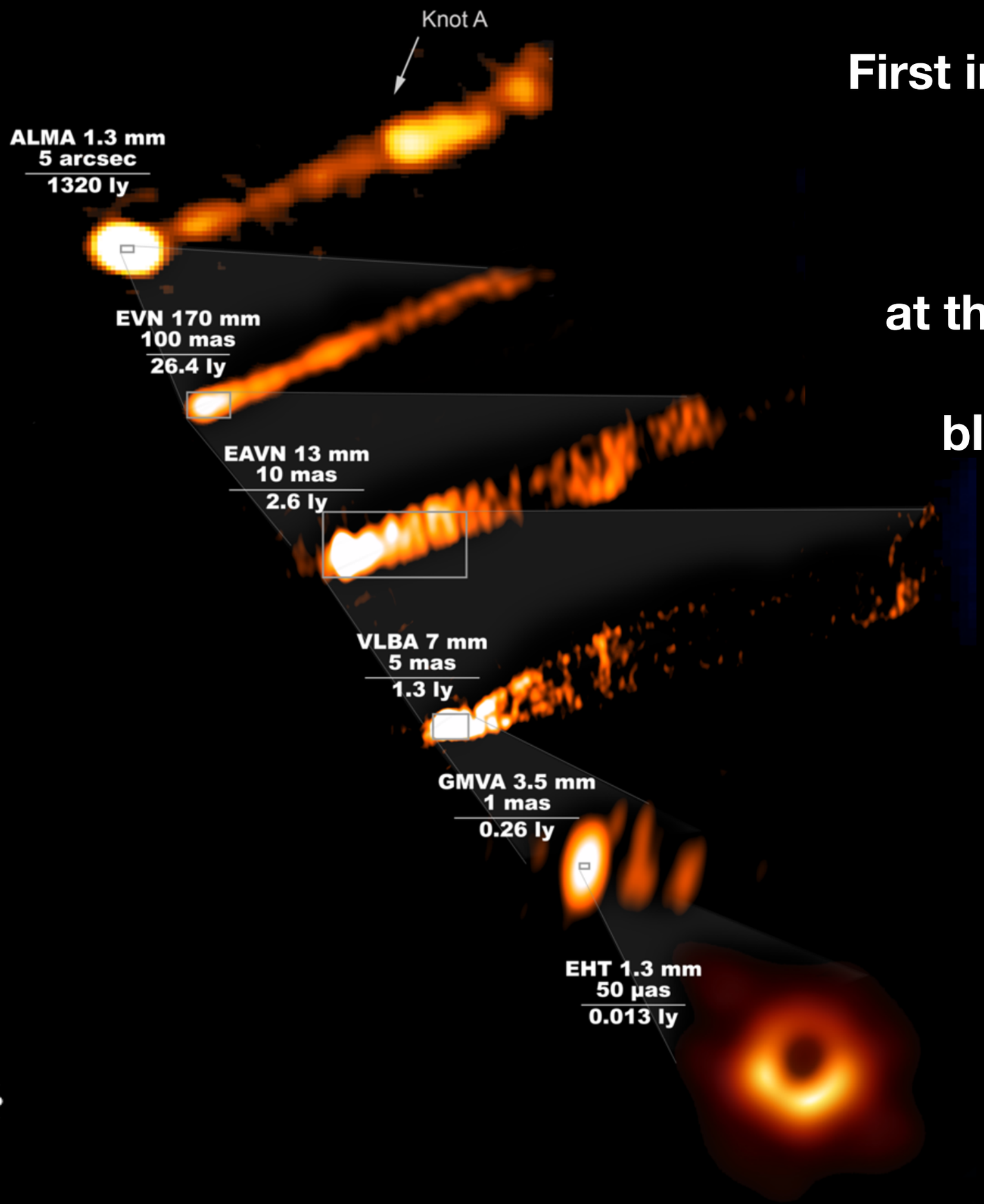

First image of a black hole

black hole is at the base of M87's jet

black hole powers the jet

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M87*
First *polarized* image of a black hole

EHTC+ 2021

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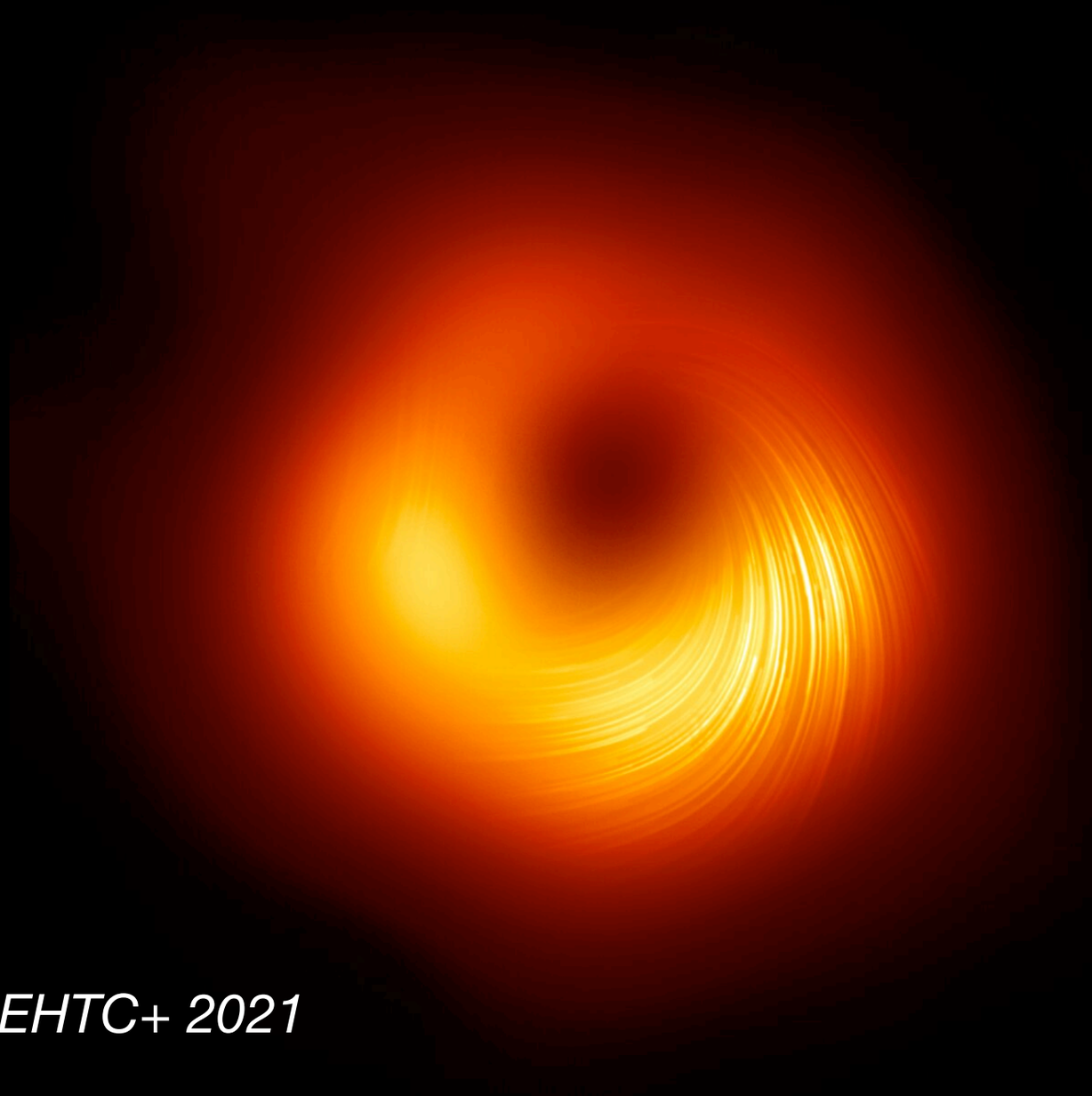

EHTC+ 2021

M87*
First polarized image of a black hole

consistent with left-handed spiral in magnetic field

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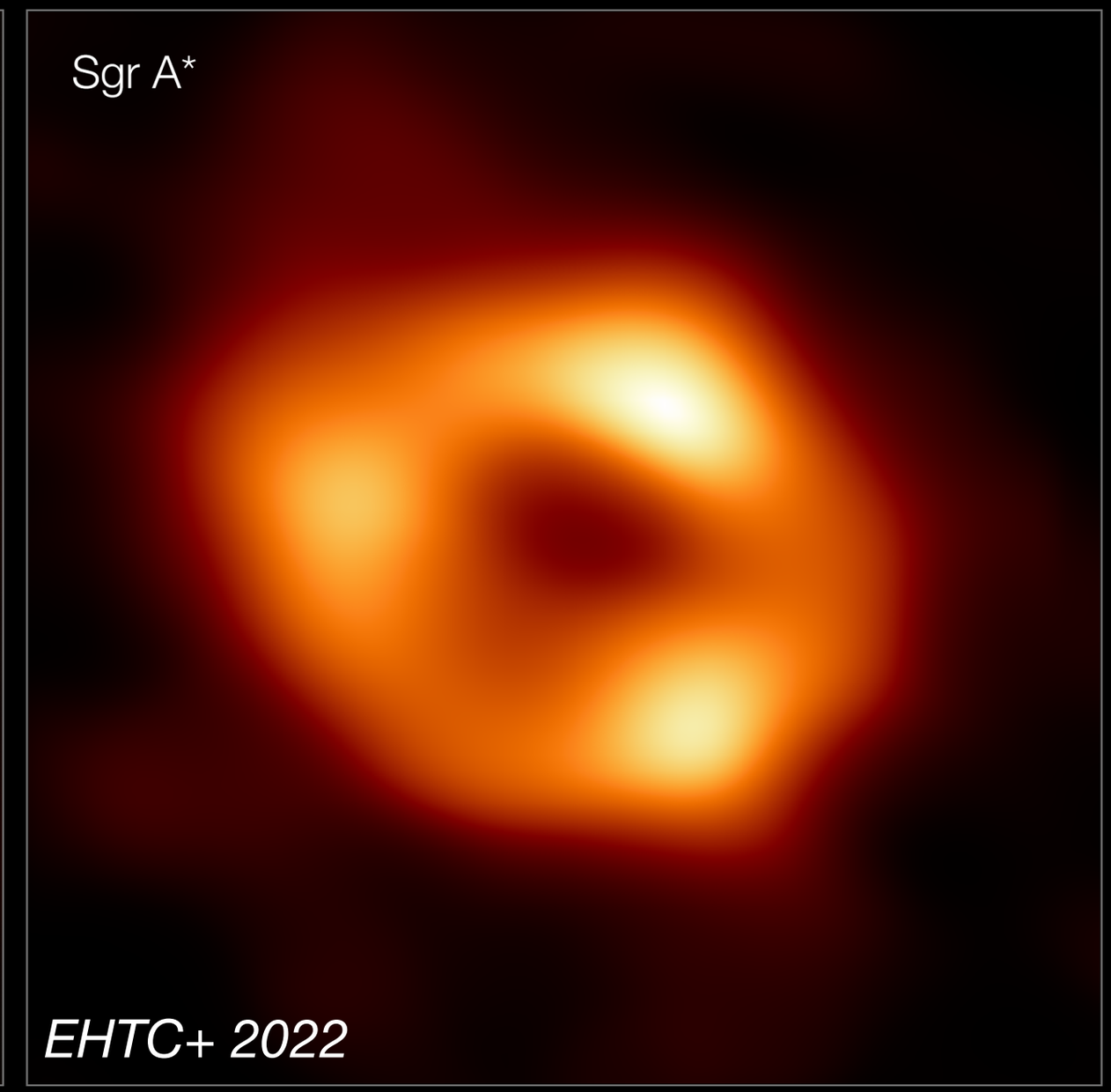

First image of the galactic center black hole

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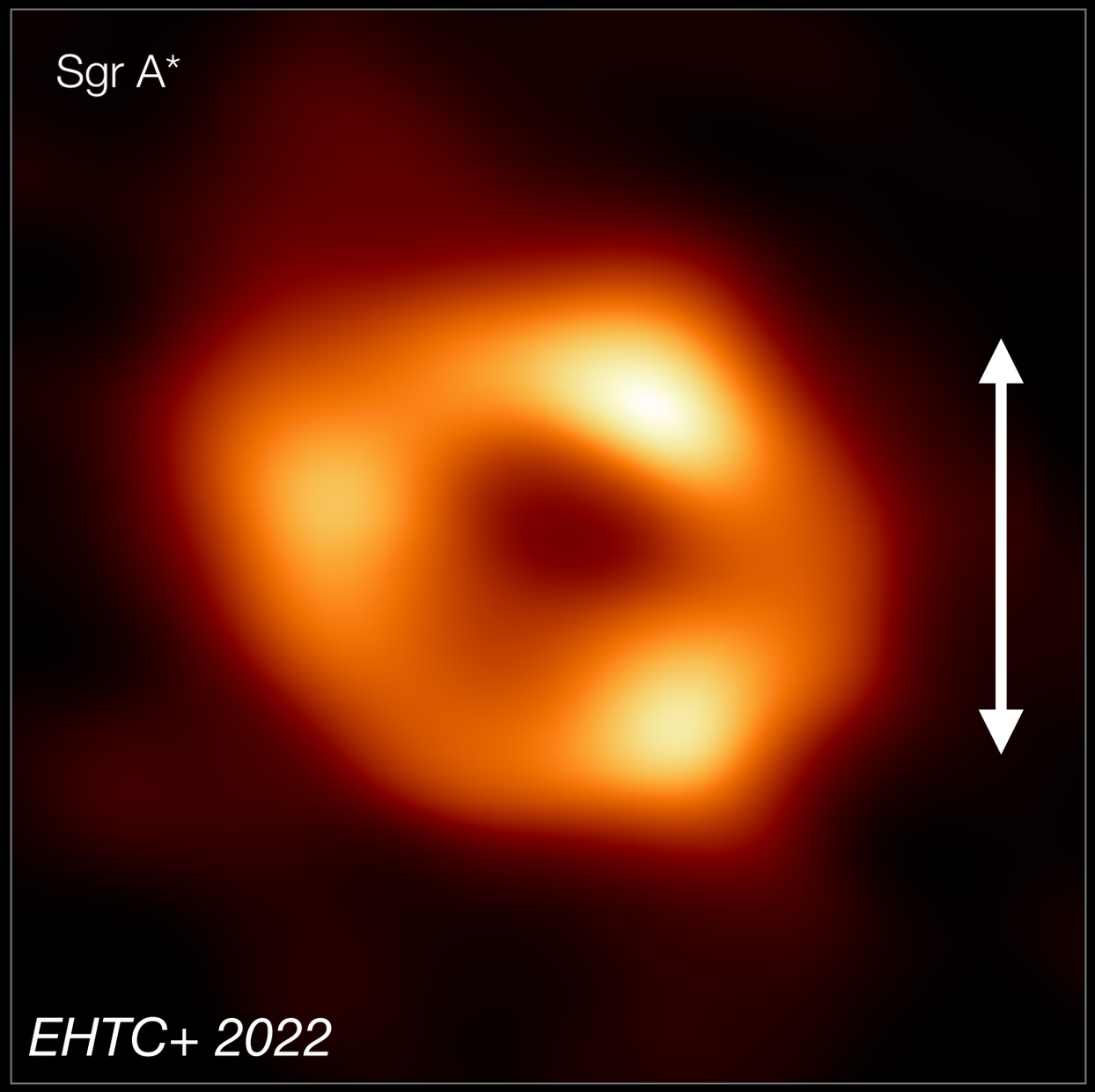

First image of the galactic center black hole

angular diameter

52μas = $\sqrt{27}\,\frac{2GM}{c^2D}$

$$\Rightarrow M \simeq 4.0^{+1.1}_{-0.6} \times 10^6\,\mathrm{M}_\odot$$

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What shapes the EHT images?

Plasma Flow, Lensing, Electron Physics

credit: Raley et al., Uni Primary School; NSF 20-07936

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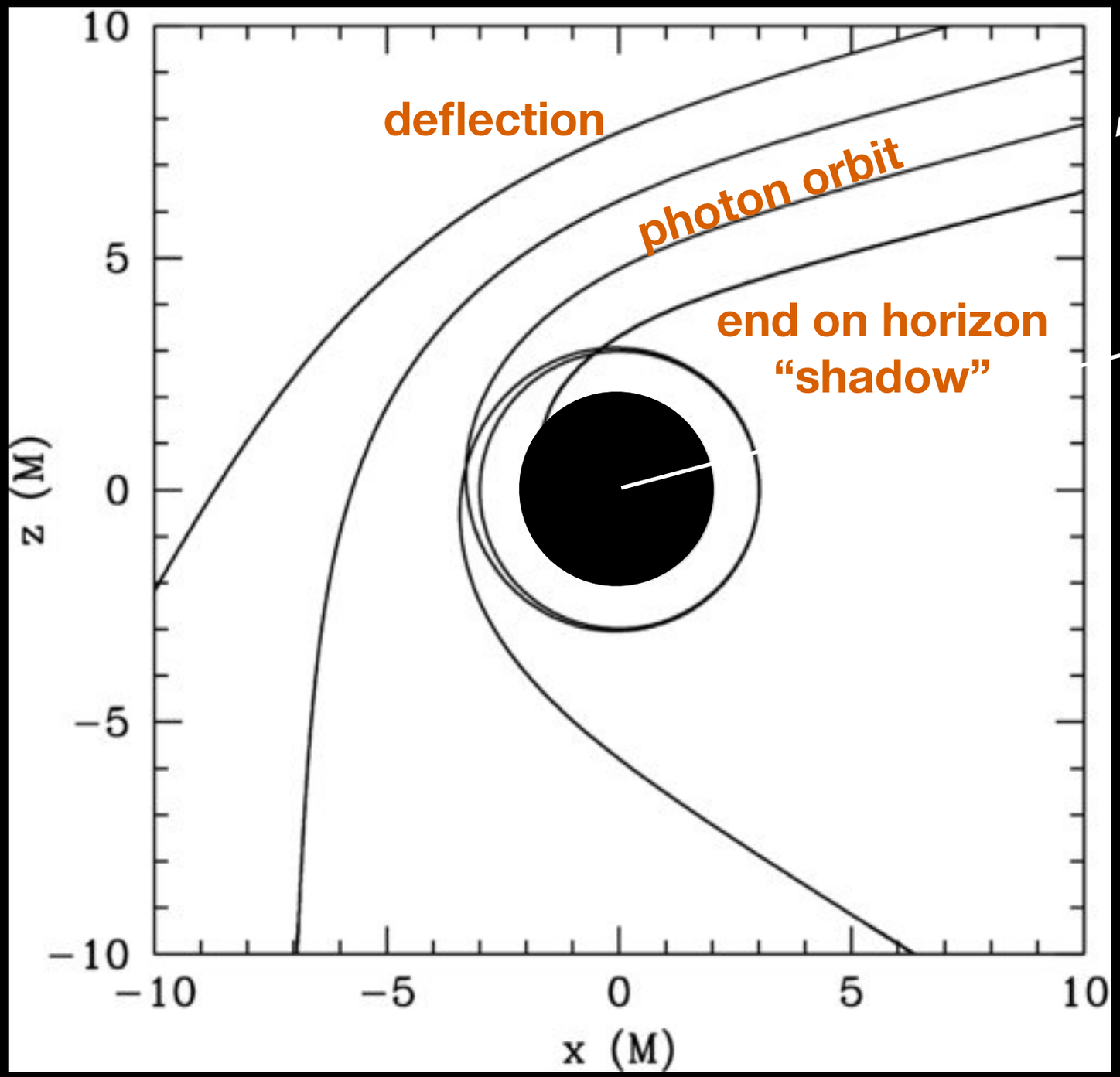
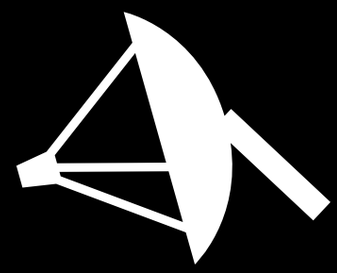
Gravitational Macrolensing



impact parameter $\sqrt{27}GM/c^2$



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1. (magneto)hydrodynamic simulation

2. assign electron distribution function

3. radiative transfer calculation

$\Rightarrow$ Stokes $IQUV(\nu, x, y, t)$

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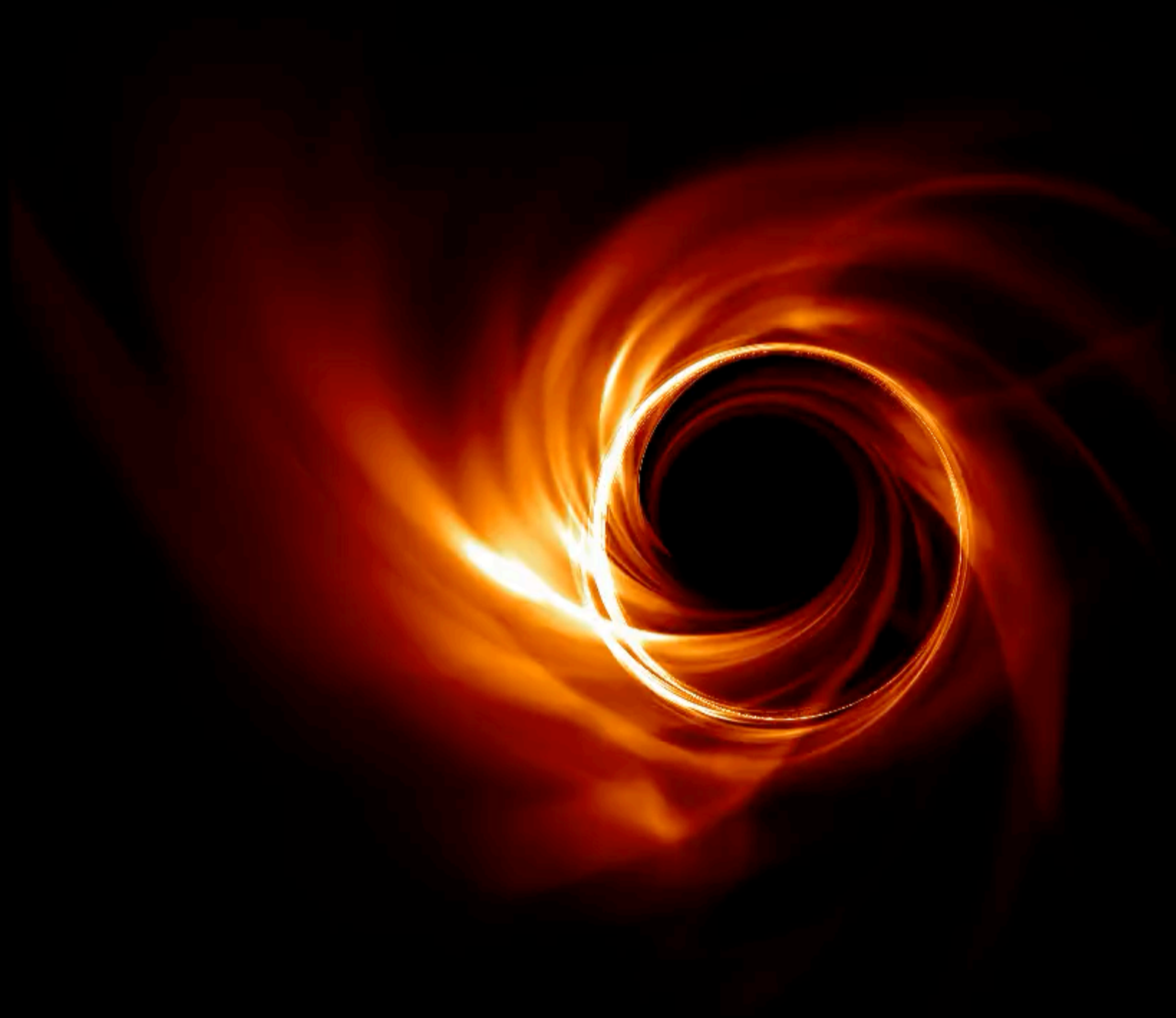
credit: A. Joshi



Sgr A* Model

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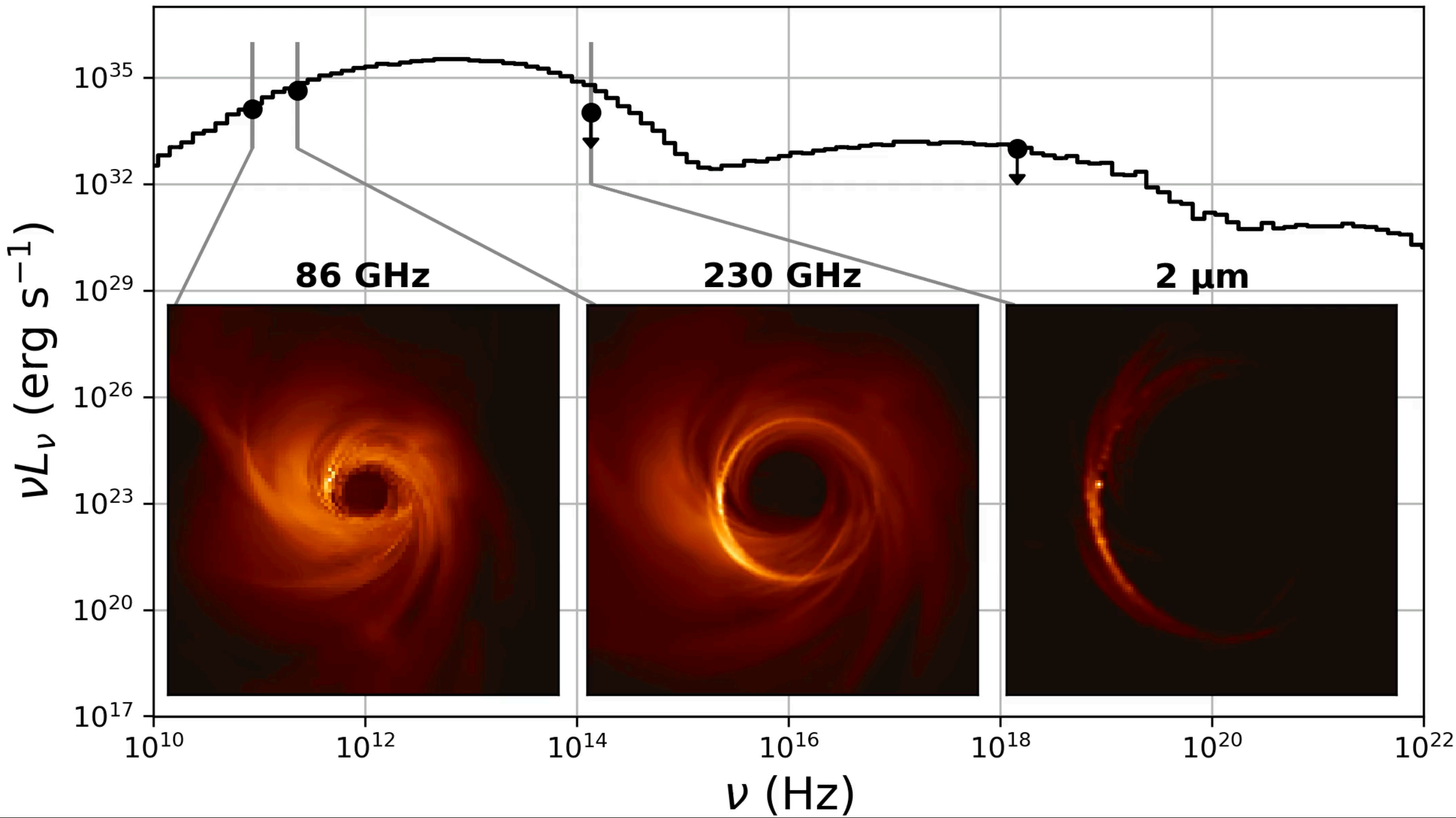

credit: B. Prather

Sgr A* Model

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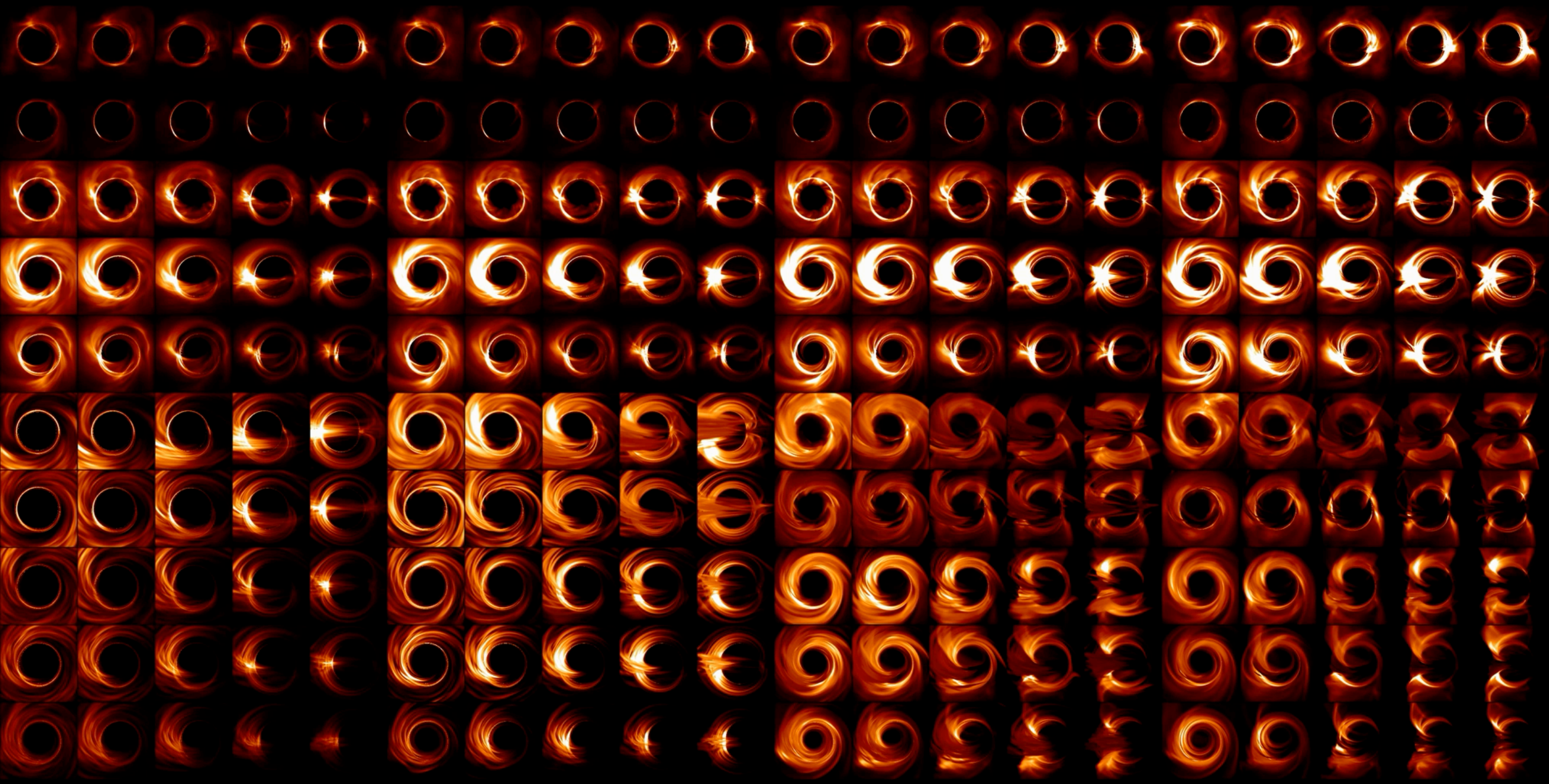

EHTC et al. 2022, Paper V

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Model Comparison Results

- M87 black hole mass to ~ 20% (models required)
  previously uncertain to ~ 2
- Sgr A* black hole mass (models required)
  consistent w. Ghez/Genzel to ~20%
- Confirmed black hole at base of M87 jet
  only spin > 0 models produce substantial jet
  consistent with Blandford-Znajek (1977) hypothesis
- Model comparison (spin, magnetization, inclination, e- dist):
  - magnetically dominated (MAD) models favored
  - M87* spin vector pointed away from Earth
  - Sgr A* has accretion flow inclination < 70deg
  - Sgr A* is **quieter than expected from models**

EHTC+ 2019, 2021, 2022

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If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it.

-Feynman

Some Limitations

1. Ideal fluid model for collisionless plasma
2. Thermal model for electron distribution function
3. Local thermodynamic state controls electron distribution function (instantaneous adjustment)
4. Boundary condition dependence
5. Initial condition dependence
6. “Fast light” approximation

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EHT Imaging Campaigns

2017	SPT, ALMA, APEX, SMA, JCMT, LMT, SMT, PV	M87*: I, QU, V pub Sgr A*: I pub, QU in process
2018	+GLT	M87*: I in process
2021	+KP, NOEMA, -LMT	M87*: I in process
2022	+LMT	
2023	-PV; +345GHz	

+GMVA campaigns and other simultaneous multiwavelength campaigns

partial key: SPT = south pole telescope, SMA = submillimeter array (Mauna Kea, Hawaii),
LMT = large millimeter telescope (Sierra Negra, Mexico),
SMT = submillimeter telescope (Mt. Graham, Arizona)
PV = IRAM 30m (Pico Veleta, Spain), GLT = Greenland Telescope (Thule, Greenland)
KP = 12m telescope (Kitt Peak, Arizona)

EHT Imaging Campaigns

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EHT New Capabilities

1. **345 GHz:** $\Delta\theta \sim \lambda/D$
   nominal resolution 20 μas → 13 μas

2. **Agile Observing: repeated imaging of M87***
   MOVIES!

3. **new sites: African Millimetre Telescope**
   ngEHT ~4 new sites, higher UV covering fraction

4. **Space!** $\Delta\theta \sim \lambda/D$
   geosynch nominal resolution 20 μas → 5 μas

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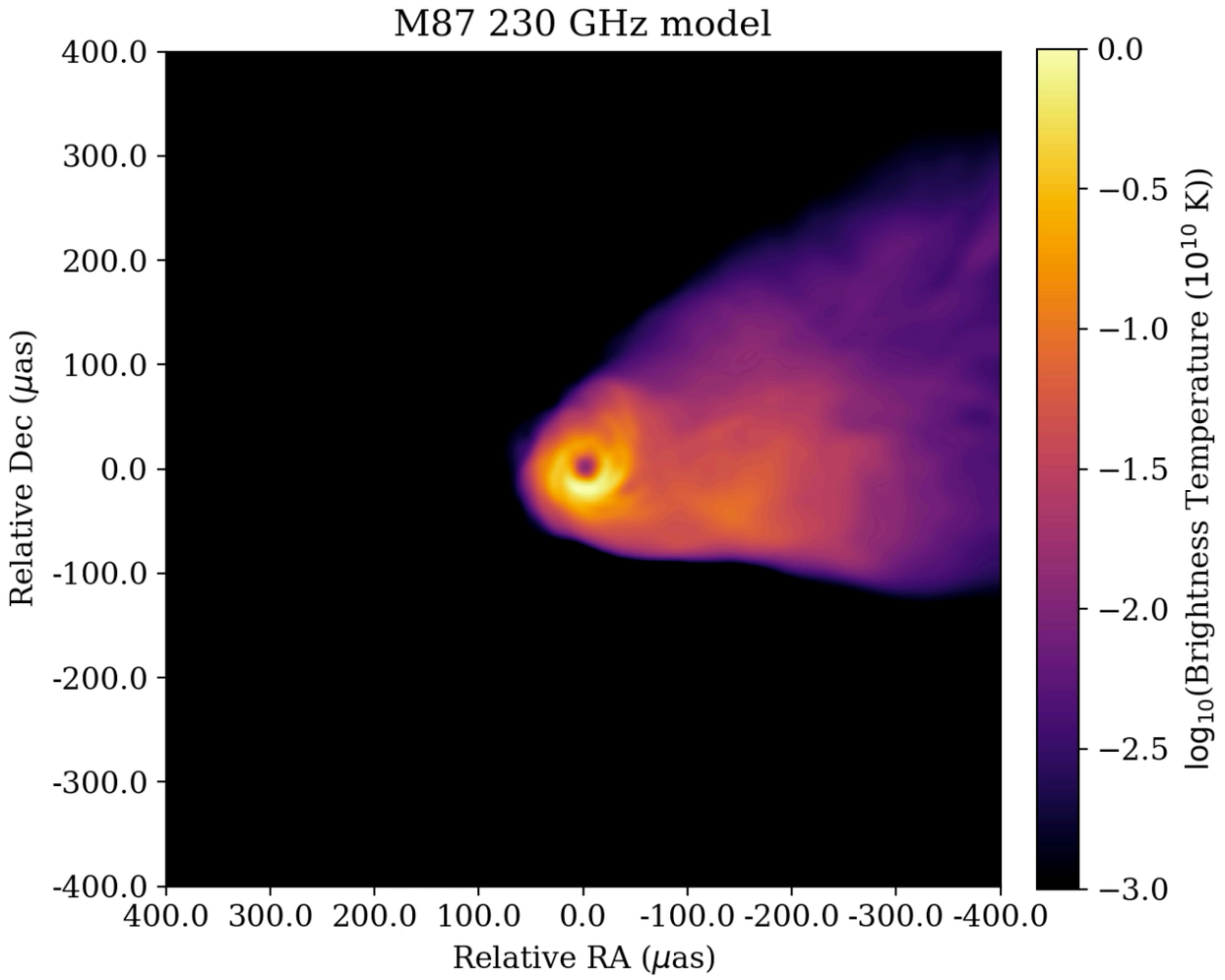
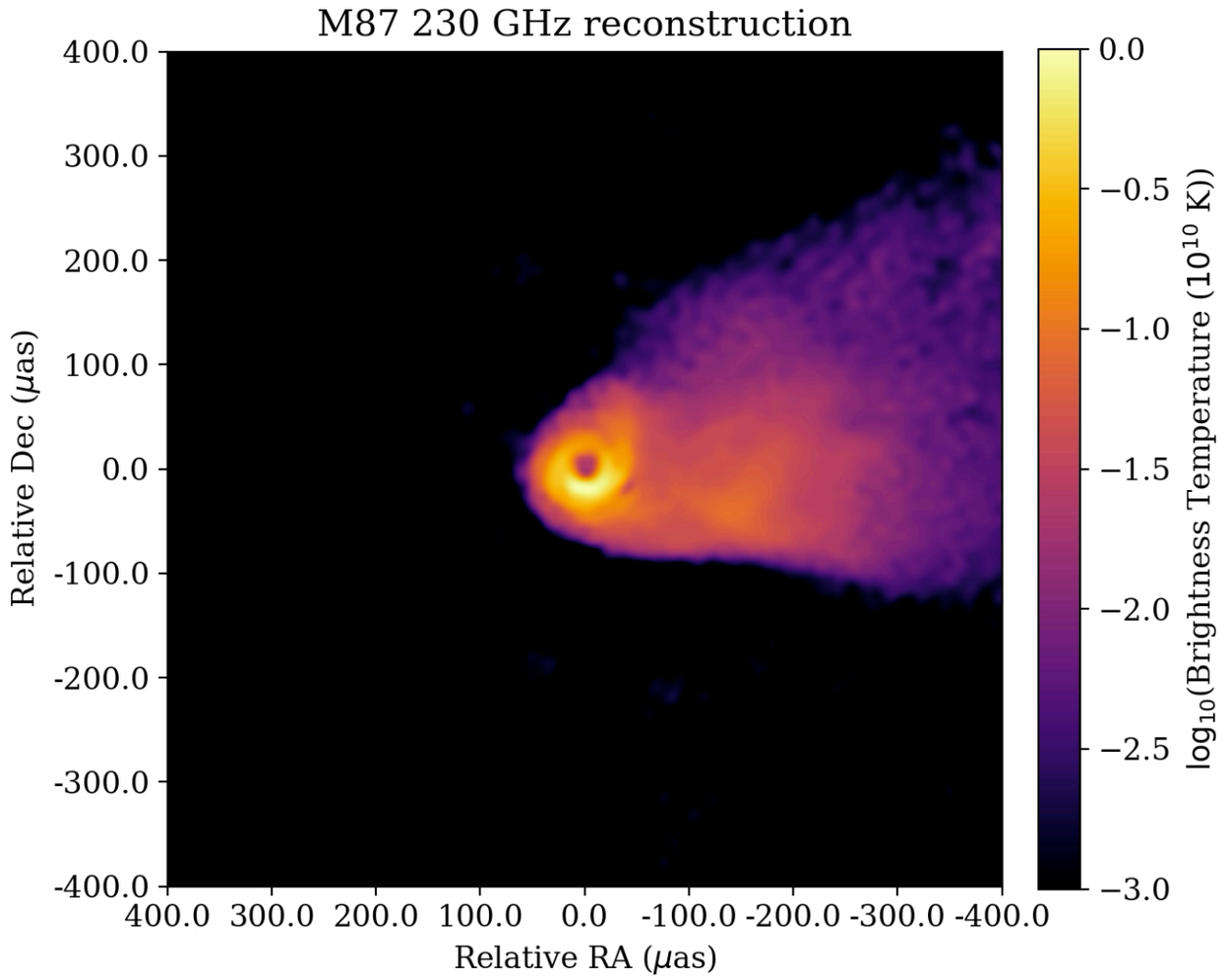
ngEHT Capabilities





L. Blackburn

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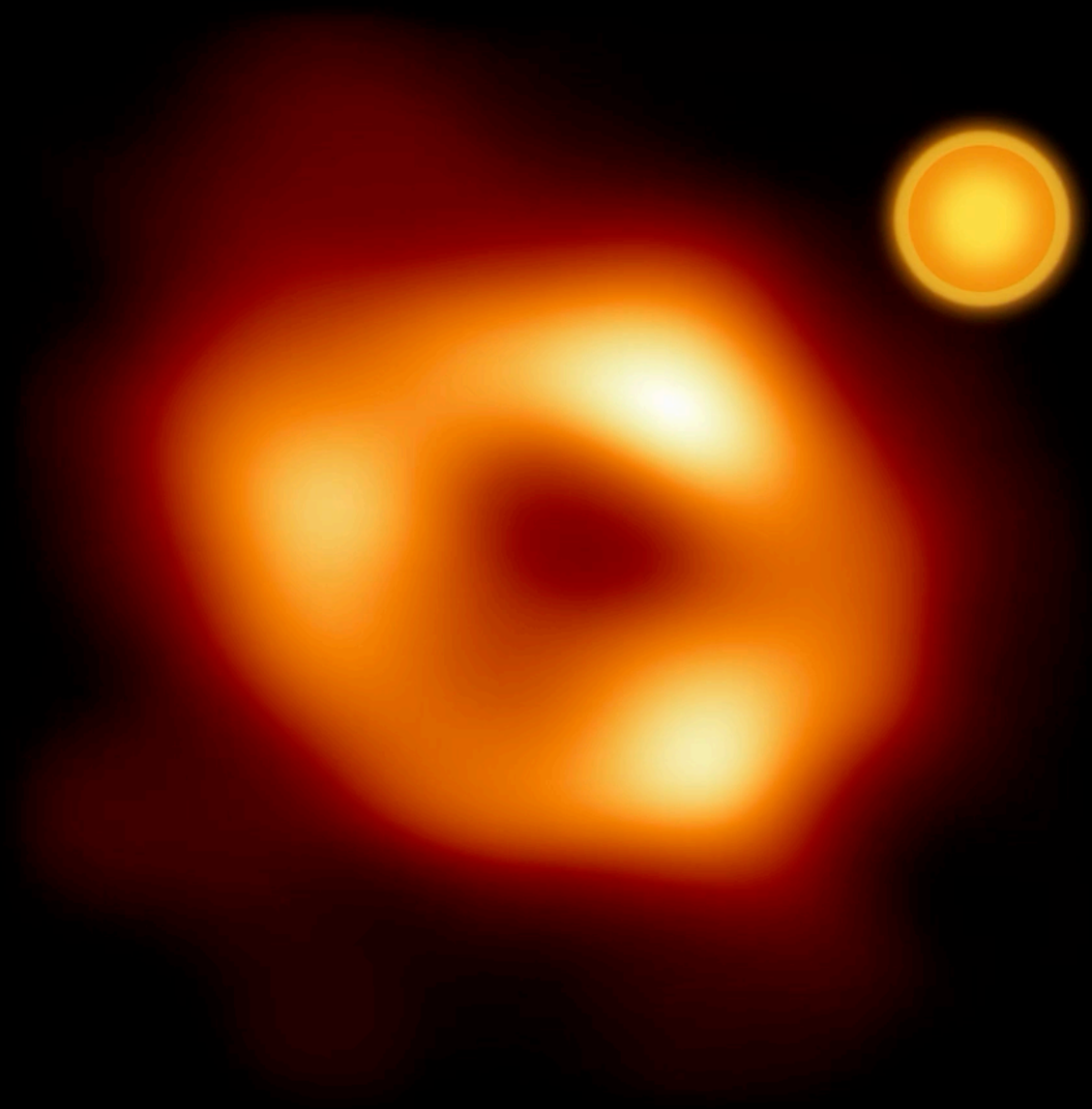
Hot Spot Model



credit: ESO/M. Wielgus

Sgr A*

MAD $a = 0.5$

$i = 30\,\mathrm{deg}$

$R_{high} = 40$

$60000\,GM/c^3$

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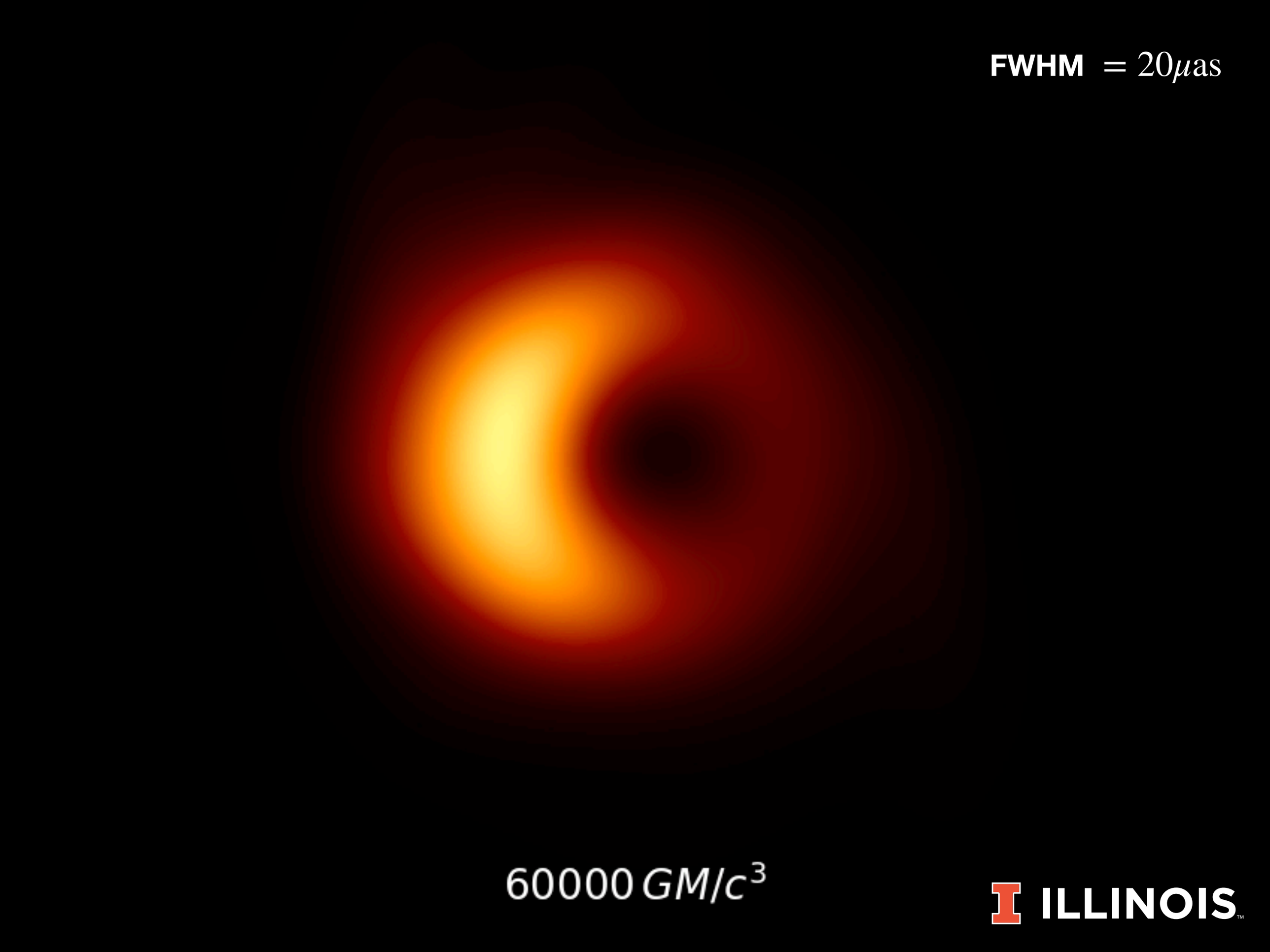

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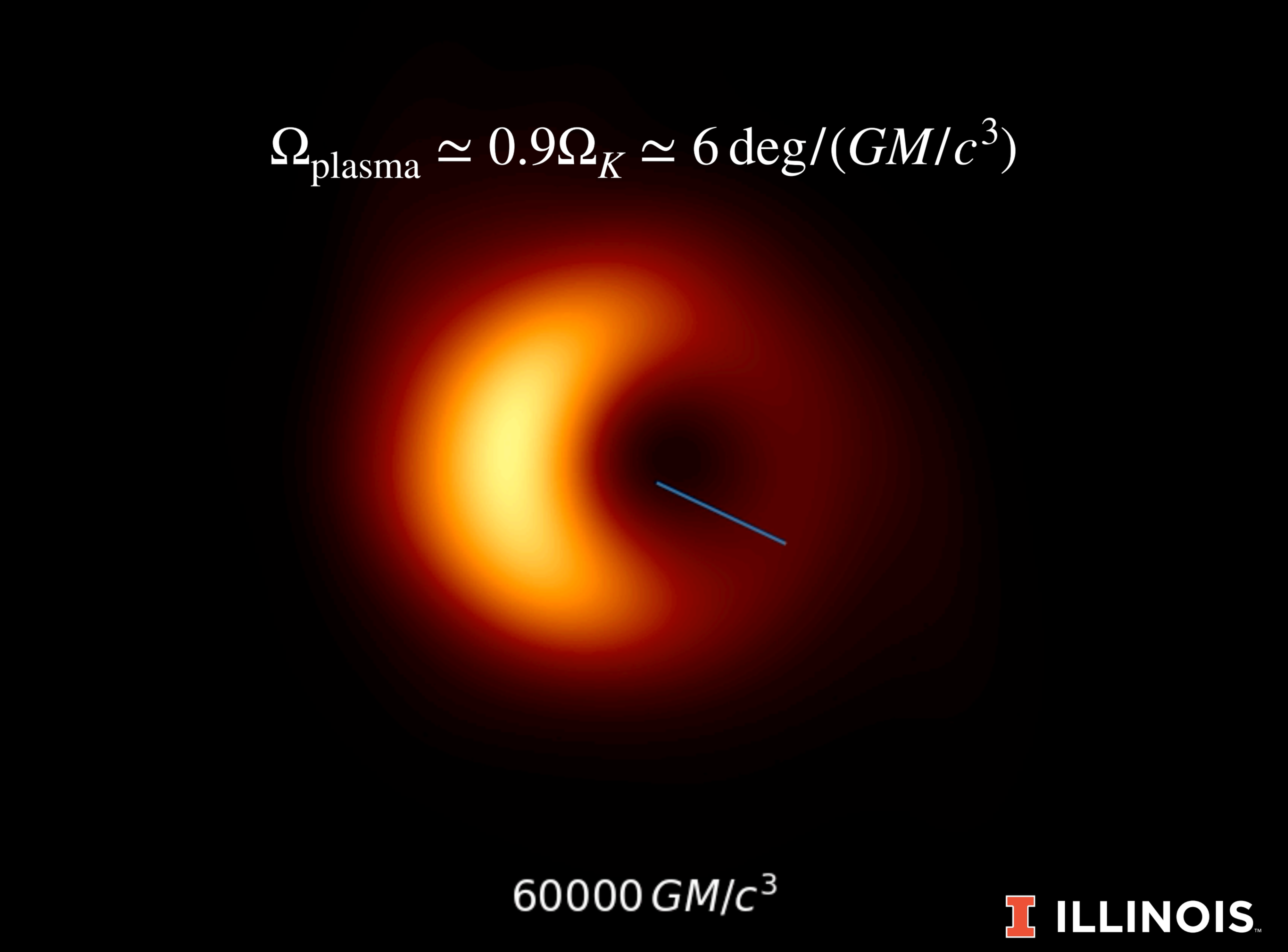
$$\Omega_{\rm plasma} \simeq 0.9\Omega_K \simeq 6\,{\rm deg}/(GM/c^3)$$



$60000\,GM/c^3$

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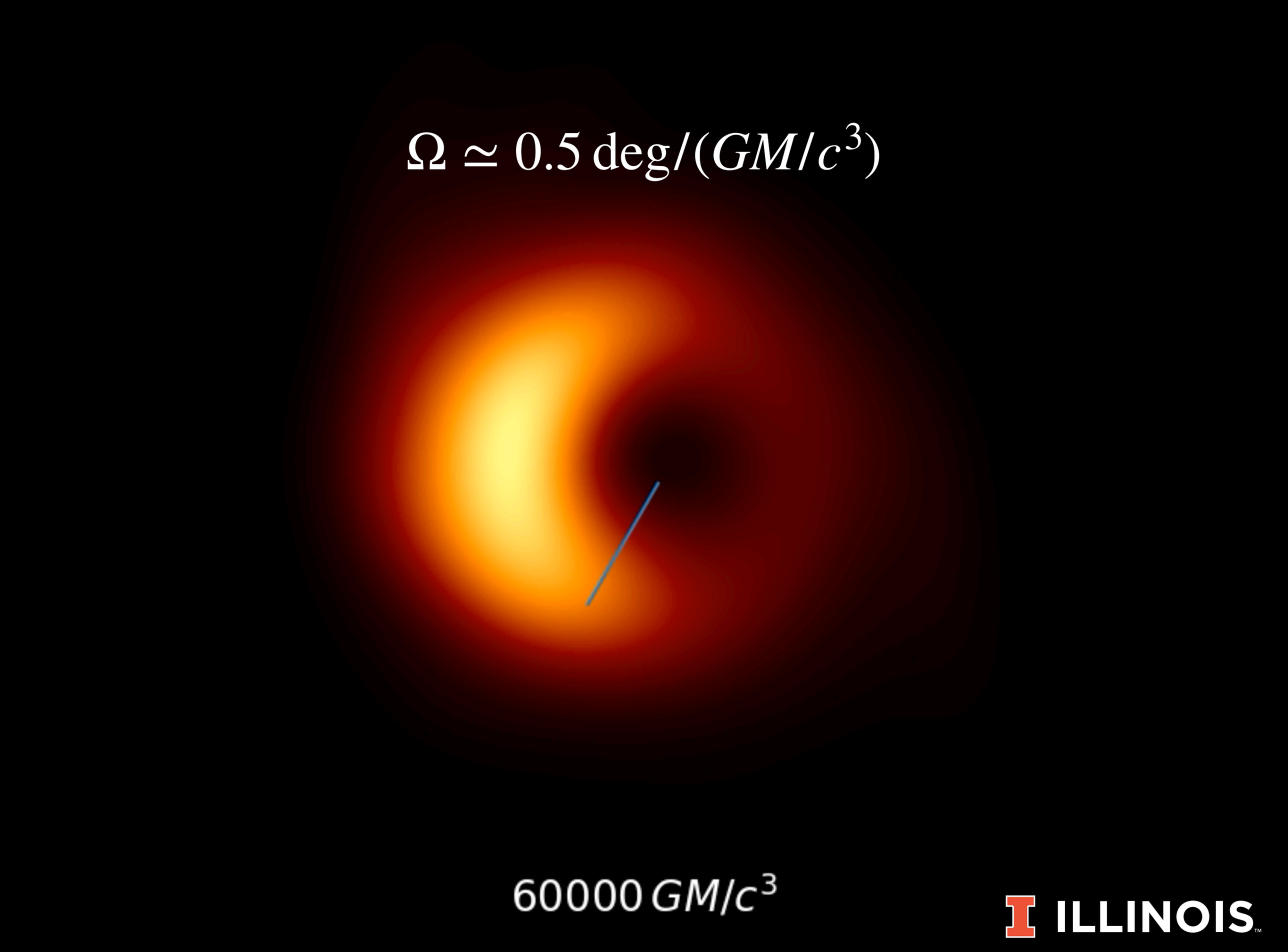
$$\Omega \simeq 0.5\,\mathrm{deg}/(GM/c^3)$$



$60000\,GM/c^3$

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(ng)EHT Movies

GRMHD models predict:

- Rotation at $\sim \Omega_K/10$
- Brightness variations dominated by pressure, not entropy, fluctuations
- Rotation depends on black hole spin

Conroy et al. 2023

Summary

Event Horizon Telescope Images

M87, Sgr A*, multiple epochs, full polarization*

Modeling EHT sources

GRMHD models + radiative transfer

Future of Black Hole Imaging

Higher fidelity, resolution images, movies!

Hot Spots and Model Predictions

Models predict slow, non-ballistic rotation

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