Title: What Can We Learn From Event Horizon Telescope Movies?

Speakers: Charles Gammie

Series: Strong Gravity

Date: July 11, 2023 - 11:00 AM

URL: https://pirsa.org/23070047

Abstract: Event Horizon Telescope (EHT) has produced images of the black hole in the galaxy M87 and in the center of our galaxy, and I will briefly review what we have learned from the images. In the near future we expect that repeated visits to M87, or high fidelity images of the galactic center, will produce movies of the turbulent plasma in these sources. The statistical properties of the movies can be predicted using state-of-the-art numerical simulations. I will explore what information can be extracted from the movies, especially information about source inclination and black hole spin.

Zoom link TBA

What Can We Learn from Event Horizon Telescope Movies?

Charles F. Gammie

wIth N. Conroy, V. Dhruv, A. Joshi, D. Lee, B. Prather, B. Georgiev, A. Broderick

Perimeter 11 July 2023

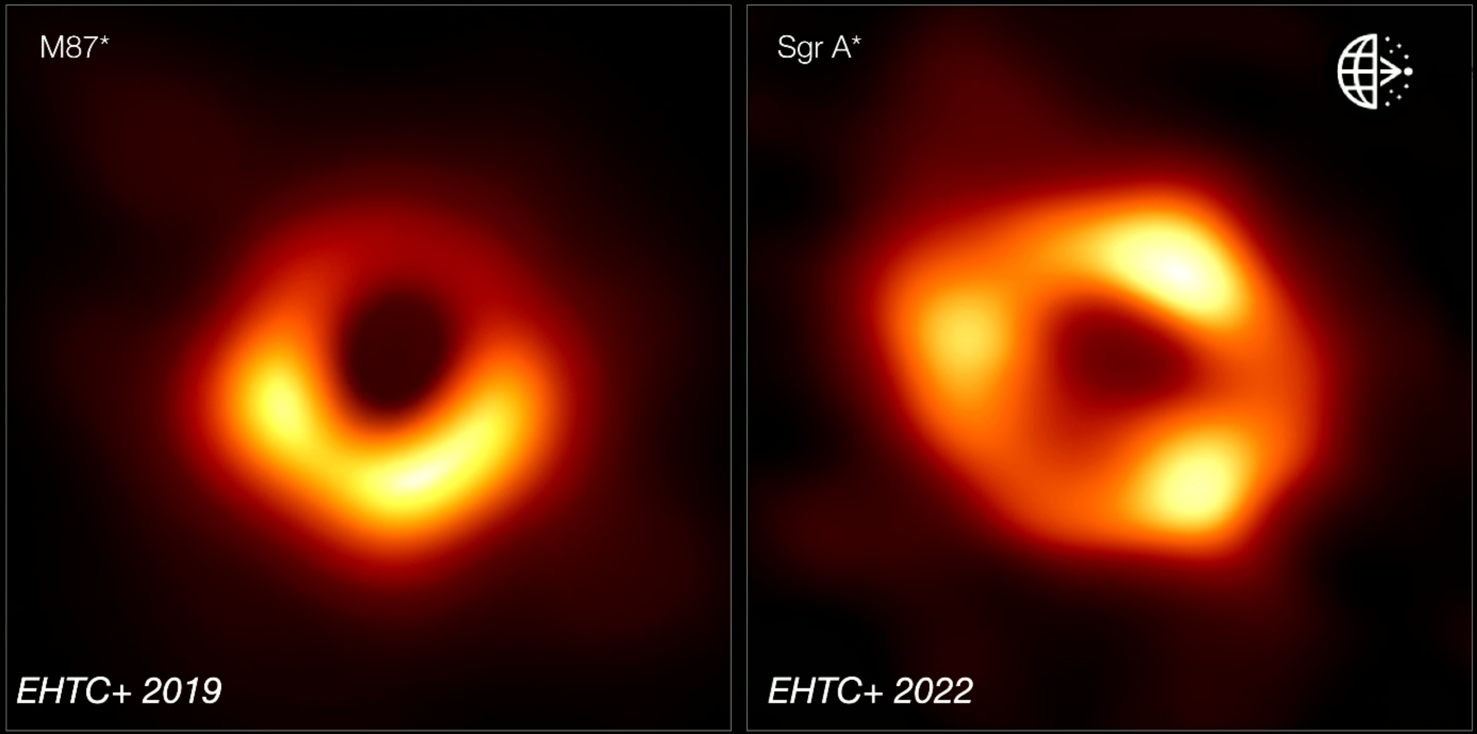
ILLINOIS

Review of EHT images

EHT movies: pattern speeds

EHT movies: pitch angles

ILLINOIS



$$M \simeq 6.6 \times 10^9\,\mathrm{M}_\odot$$

$$\theta_g \equiv \frac{GM}{c^2 D} \simeq 3.8\,\mu\mathrm{as}$$

$$t_g \equiv \frac{GM}{c^3} \simeq 9.0\,\mathrm{hr}$$

$$M \simeq 4.1 \times 10^6\,\mathrm{M}_\odot$$

$$\theta_g \equiv \frac{GM}{c^2 D} \simeq 5.0\,\mu\mathrm{as}$$

$$t_g \equiv \frac{GM}{c^3} \simeq 20.4\,\mathrm{sec}$$

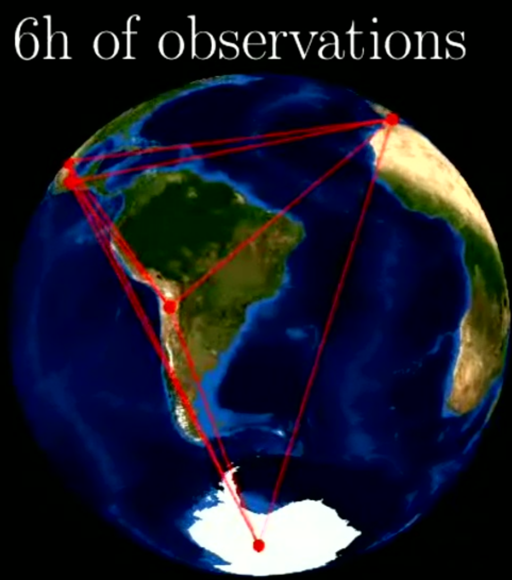
ILLINOIS

EHT: millimeter VLBI

- 1.3mm VLBI network, $\Delta\theta \sim \lambda/D \sim (1.3mm)/(2\ R_\oplus) \sim 25\mu as$
- 2017 campaign: April 5, 6, 7, 10, 11; 6 targets, incl M87* & Sgr A*
- 8 telescopes at 6 sites

ILLINOIS

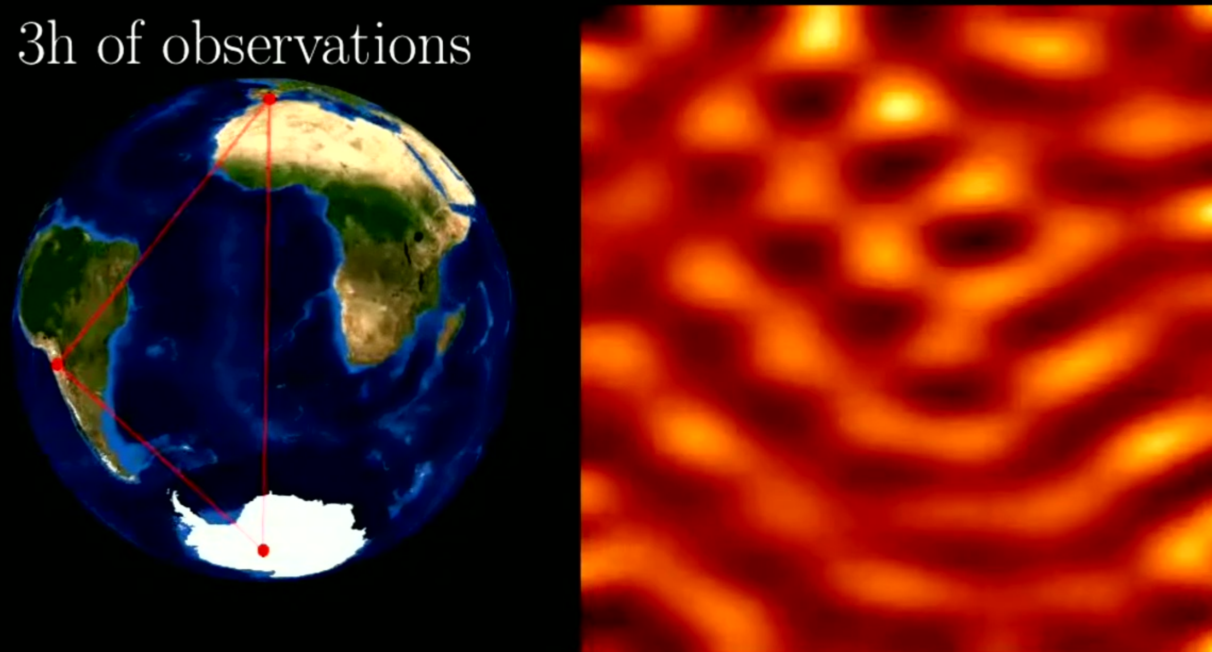
EHT: millimeter VLBI



- 1.3mm VLBI network, $\Delta\theta \sim \lambda/D \sim (1.3\text{mm})/(2\ R_\oplus) \sim 25\mu\text{as}$
- 2017 campaign: April 5, 6, 7, 10, 11; 6 targets, incl M87* & Sgr A*
- 8 telescopes at 6 sites

ILLINOIS

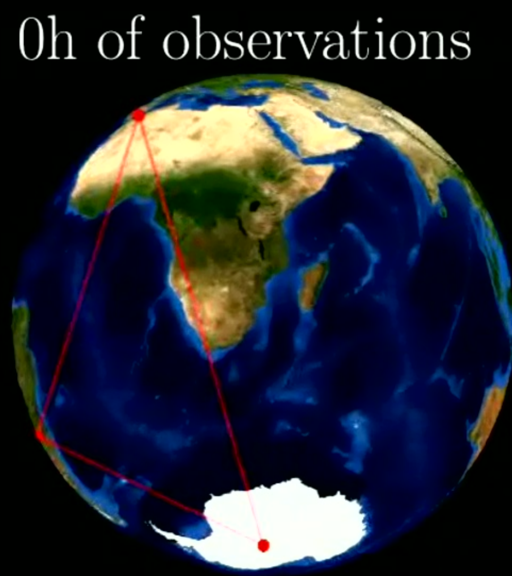
EHT: millimeter VLBI

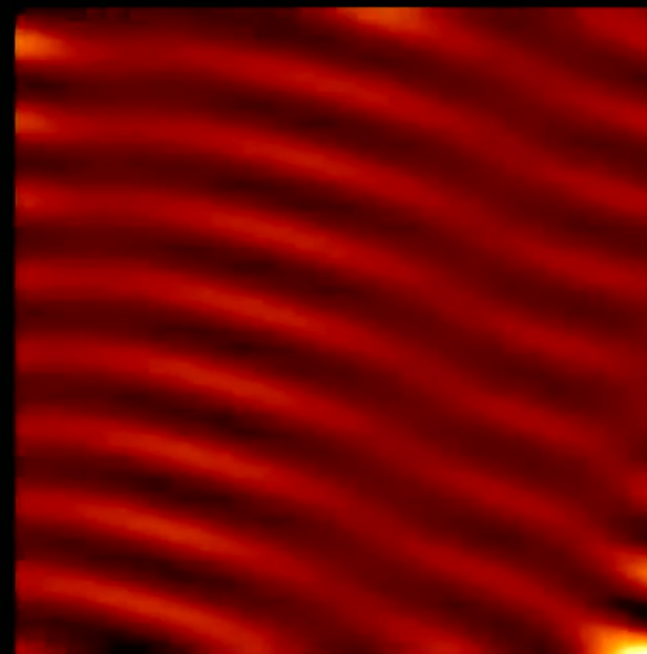


- 1.3mm VLBI network, $\Delta\theta \sim \lambda/D \sim (1.3\text{mm})/(2\,R_{\oplus}) \sim 25\mu\text{as}$
- 2017 campaign: April 5, 6, 7, 10, 11; 6 targets, incl M87* & Sgr A*
- 8 telescopes at 6 sites

ILLINOIS

EHT: millimeter VLBI





- 1.3mm VLBI network, $\Delta\theta \sim \lambda/D \sim (1.3\text{mm})/(2\,R_\oplus) \sim 25\mu\text{as}$
- 2017 campaign: April 5, 6, 7, 10, 11; 6 targets, incl M87* & Sgr A*
- 8 telescopes at 6 sites

ILLINOIS

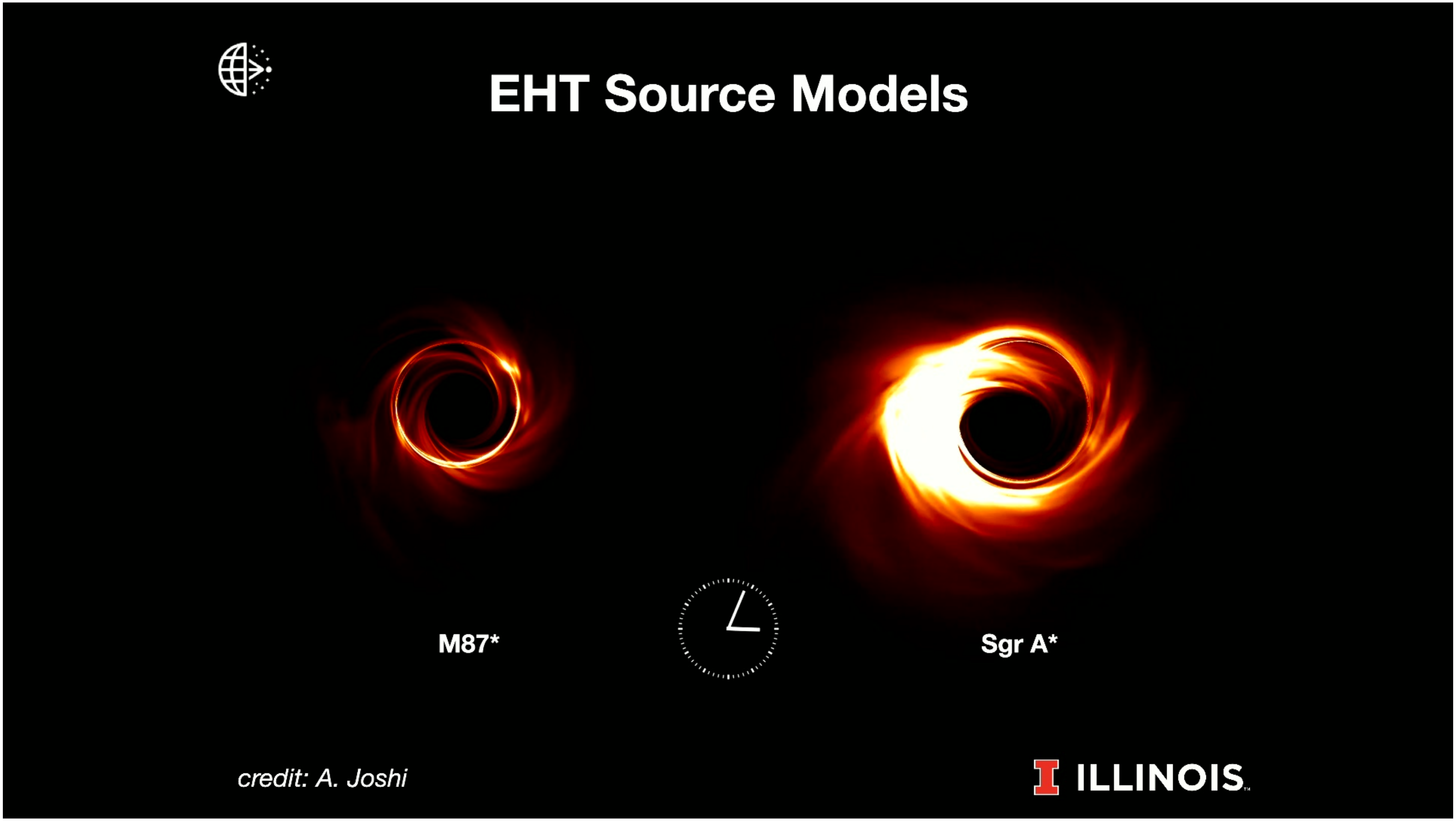
EHT Source Models

M87*

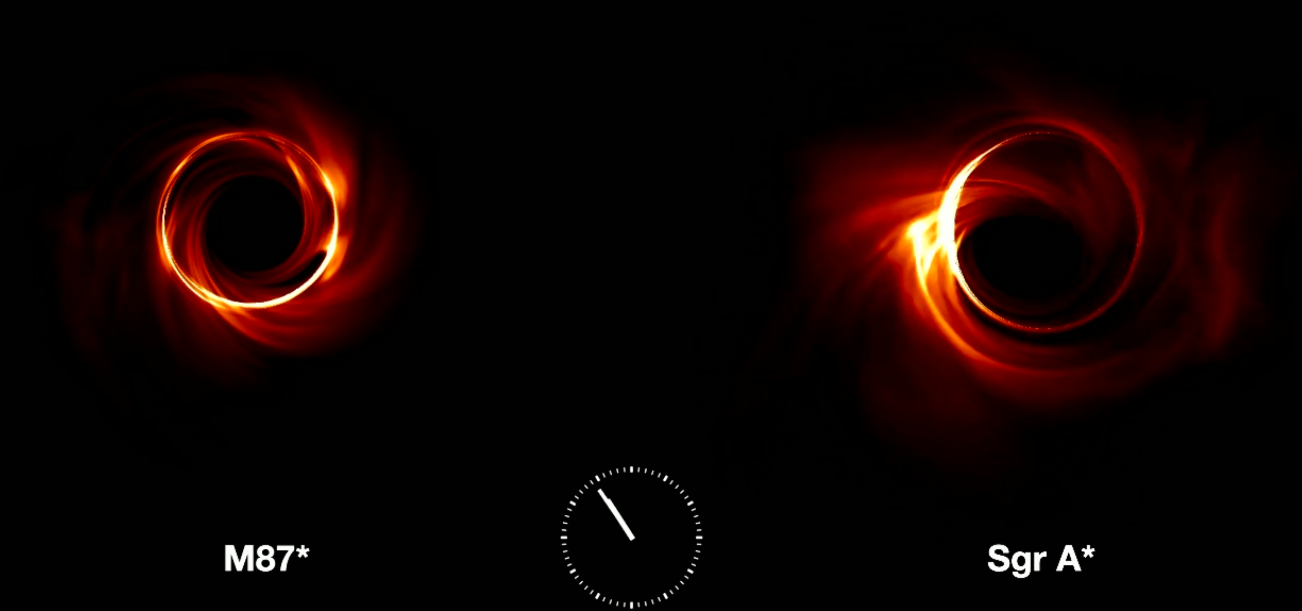
Sgr A*

credit: A. Joshi

ILLINOIS


EHT Source Models
M87*
Sgr A*
credit: A. Joshi
ILLINOIS

EHT Source Models

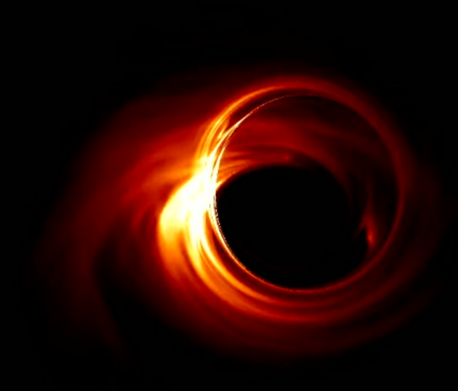


credit: A. Joshi

ILLINOIS

EHT Source Models

M87*



Sgr A*

credit: A. Joshi

ILLINOIS

EHT Source Context

M87*

NASA and the Hubble Heritage Team (STScI/AURA)

$M \simeq 6.6 \times 10^9\, \mathrm{M}_\odot$

Sgr A*

L. Landolfi

$M \simeq 4.1 \times 10^6\, \mathrm{M}_\odot$

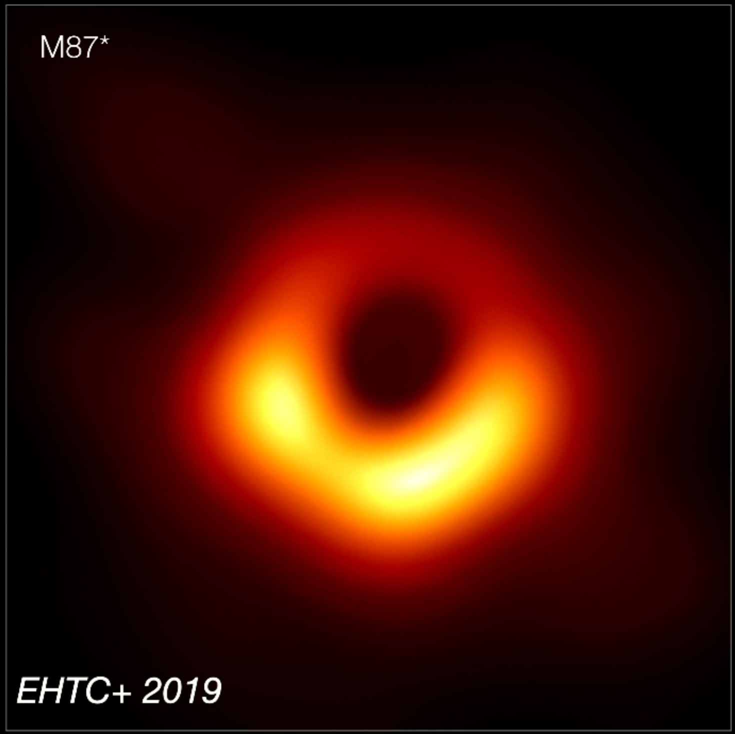
ILLINOIS

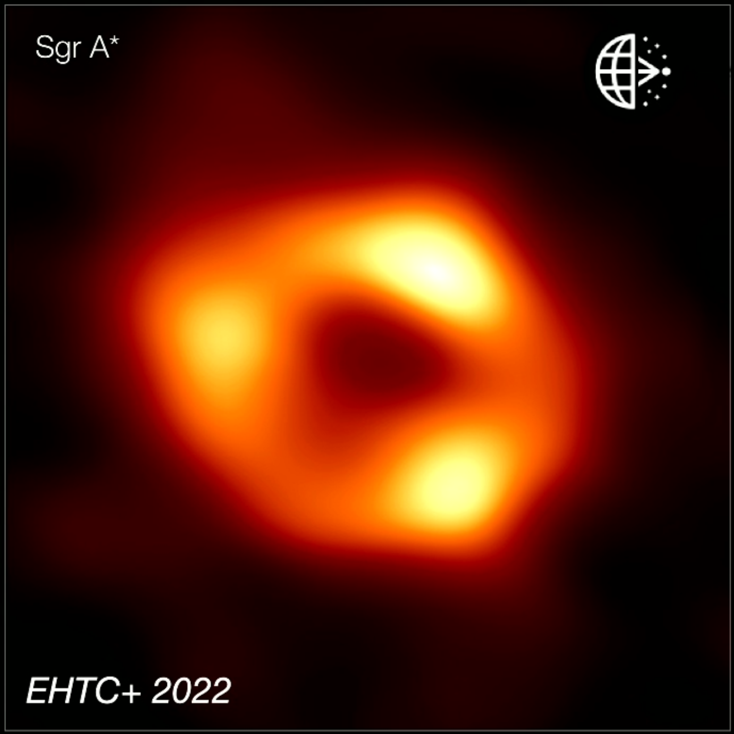
What Did We Learn from EHT Images?

- M87 black hole mass to ~ 20%
  previously uncertain to ~ 2
- Sgr A* black hole mass
  consistent w. Ghez/Genzel to ~20%
- Confirmed black hole at base of M87 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, 2022

ILLINOIS





$$M \simeq 6.6 \times 10^9\,\mathrm{M}_\odot$$

$$\theta_g \equiv \frac{GM}{c^2 D} \simeq 3.8\,\mu\mathrm{as}$$

$$t_g \equiv \frac{GM}{c^3} \simeq 9.0\,\mathrm{hr}$$

$$M \simeq 4.1 \times 10^6\,\mathrm{M}_\odot$$

$$\theta_g \equiv \frac{GM}{c^2 D} \simeq 5.0\,\mu\mathrm{as}$$

$$t_g \equiv \frac{GM}{c^3} \simeq 20.4\,\mathrm{sec}$$

ILLINOIS

What Did We Learn from EHT Images?

- M87 black hole mass to ~ 20%
  previously uncertain to ~ 2
- Sgr A* black hole mass
  consistent w. Ghez/Genzel to ~20%
- Confirmed black hole at base of M87 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, 2022

ILLINOIS

What Did We Learn from EHT Images?

- M87 black hole mass to ~ 20%
  previously uncertain to ~ 2
- Sgr A* black hole mass
  consistent w. Ghez/Genzel to ~20%
- Confirmed black hole at base of M87 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, 2022

ILLINOIS

next: EHT movies

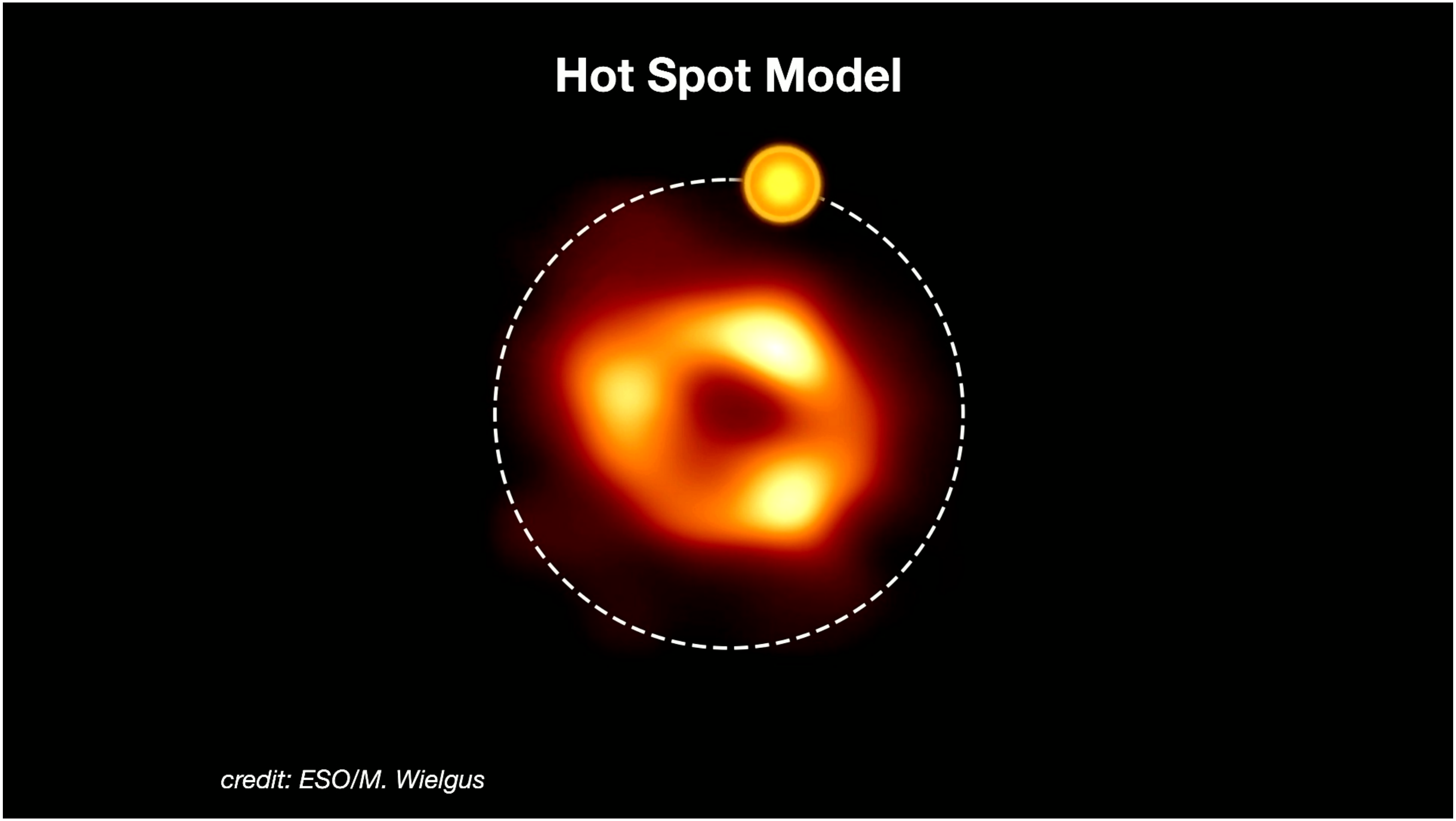
EHT Movies

repeated images of Sgr A*, M87*
practical in a few years
movie-making differs for Sgr A*, M87*

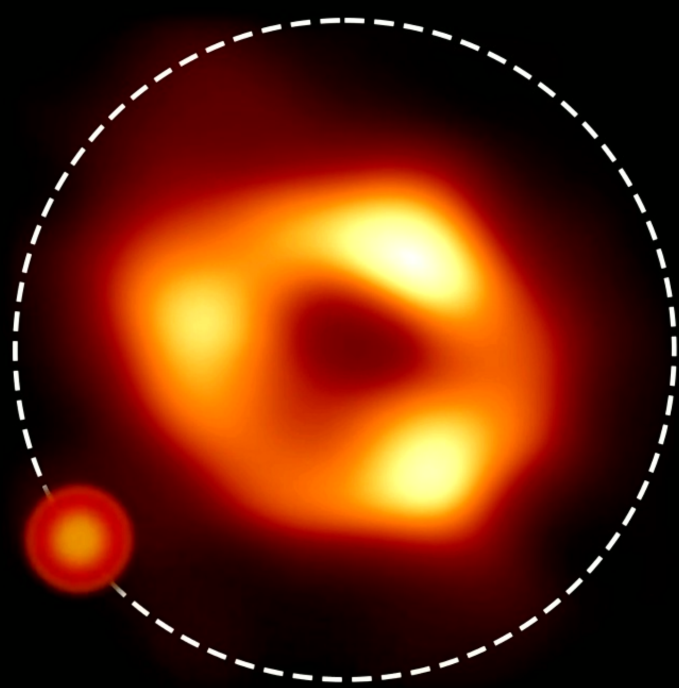
Observables:

1. Rotation frequency Ω_p
2. Spiral wave pitch angle ψ

What do models predict?

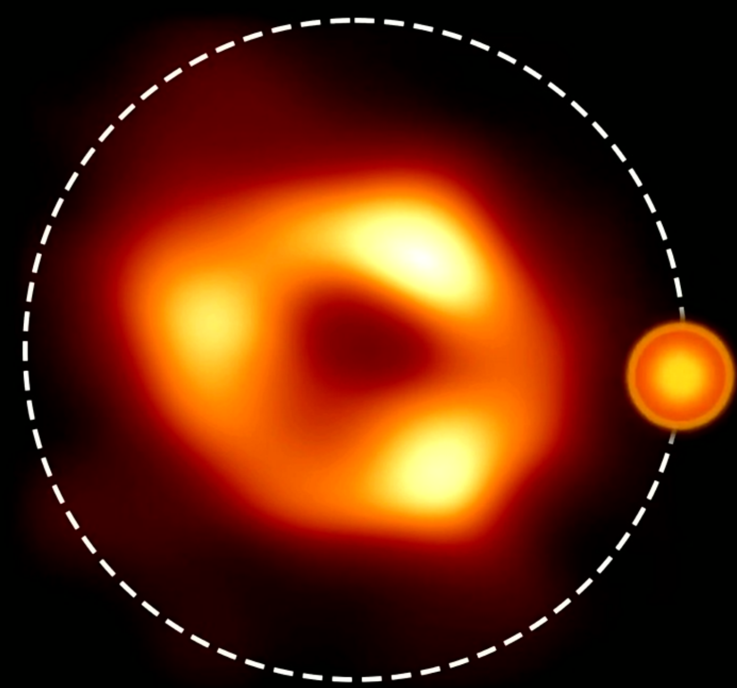

Hot Spot Model
credit: ESO/M. Wielgus

Hot Spot Model

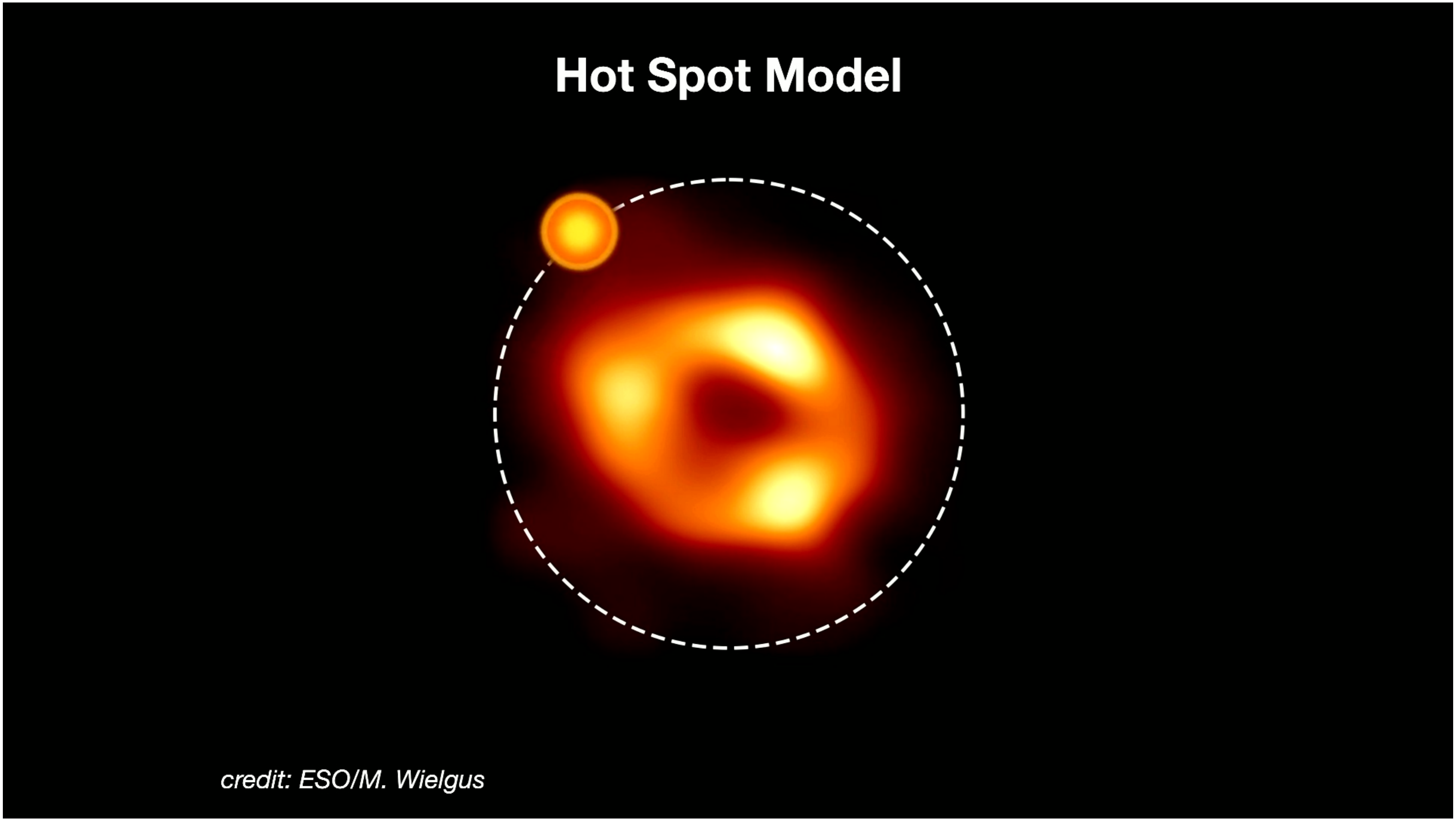


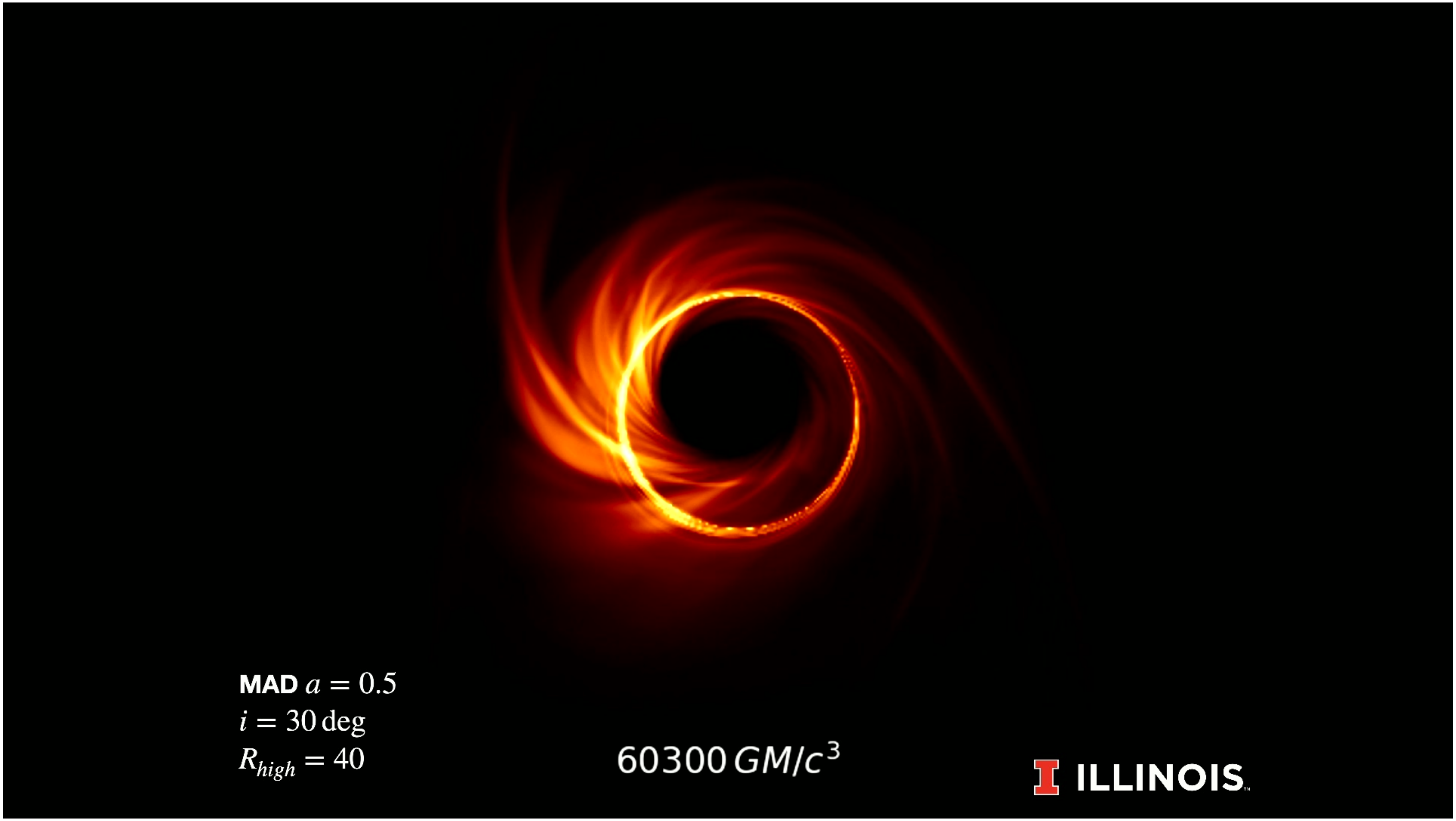
credit: ESO/M. Wielgus

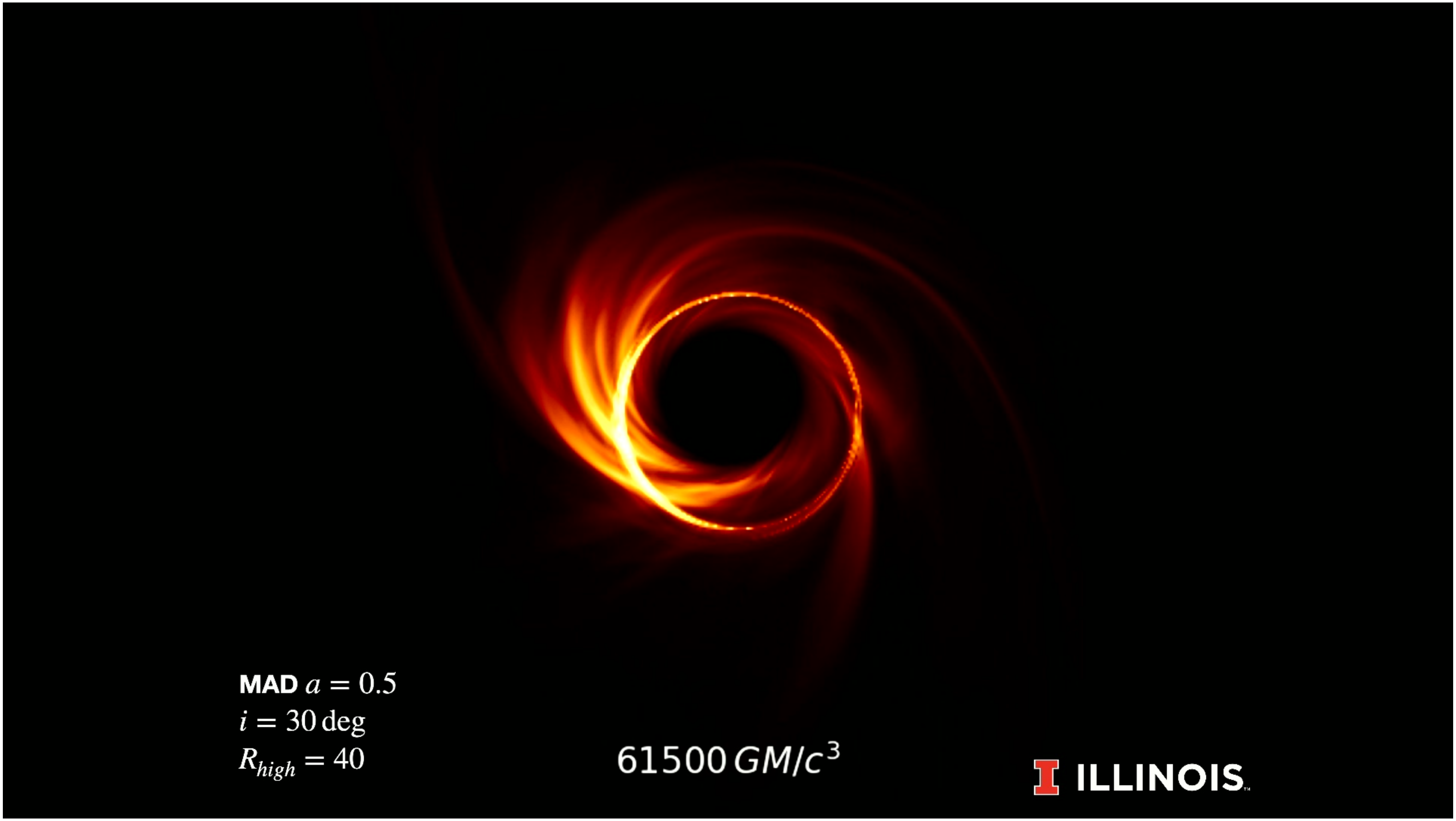
Hot Spot Model

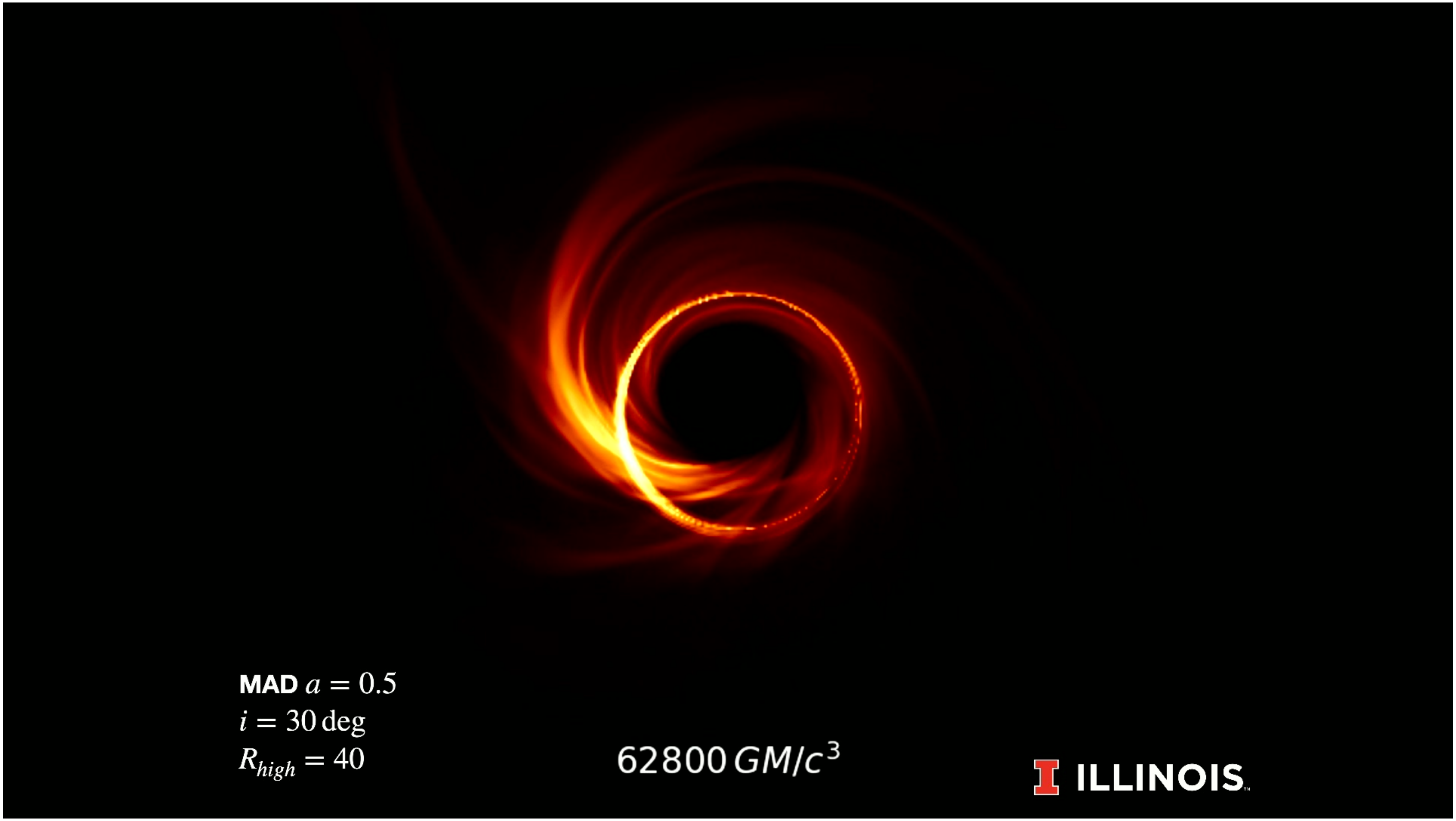


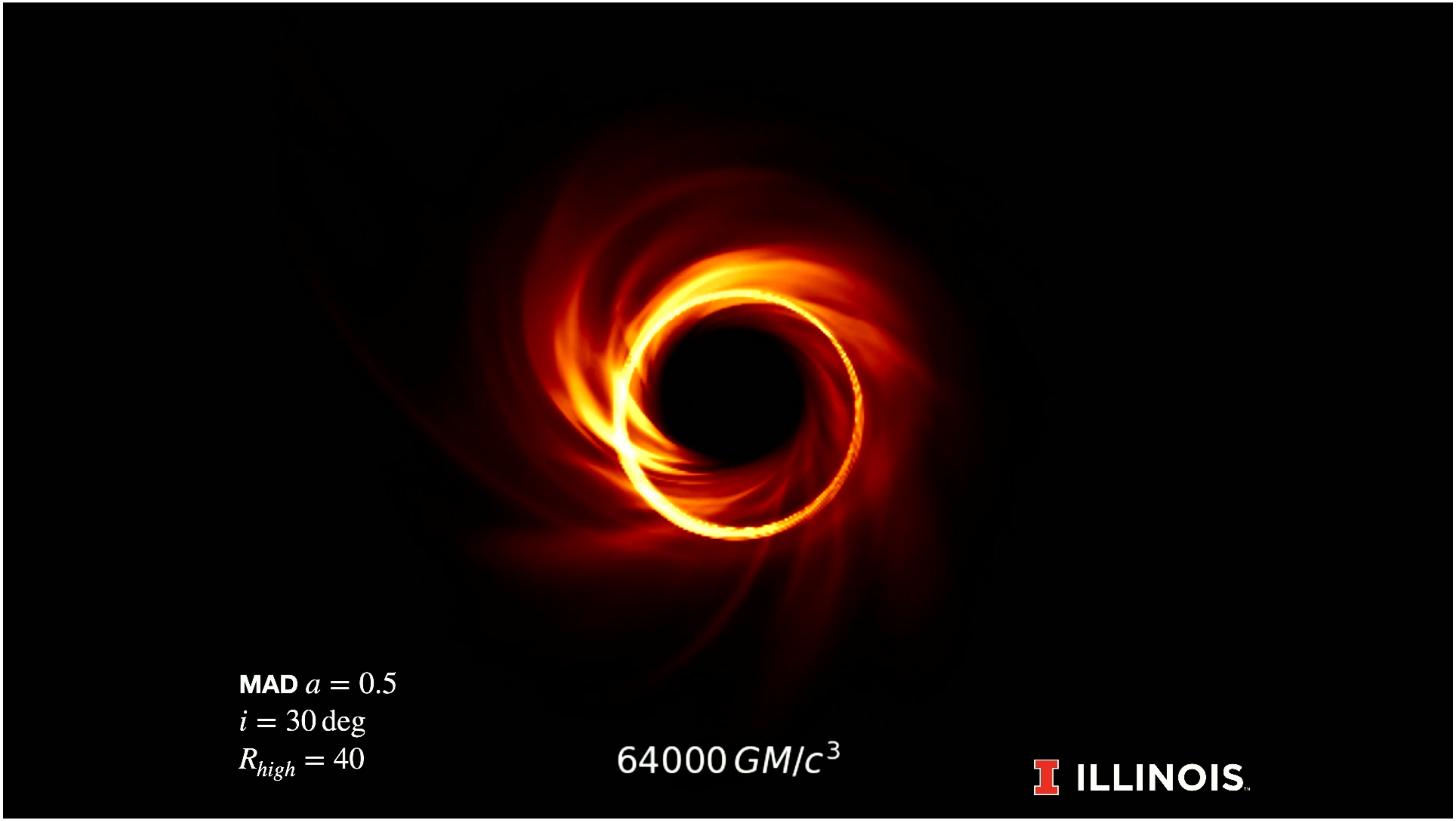
credit: ESO/M. Wielgus

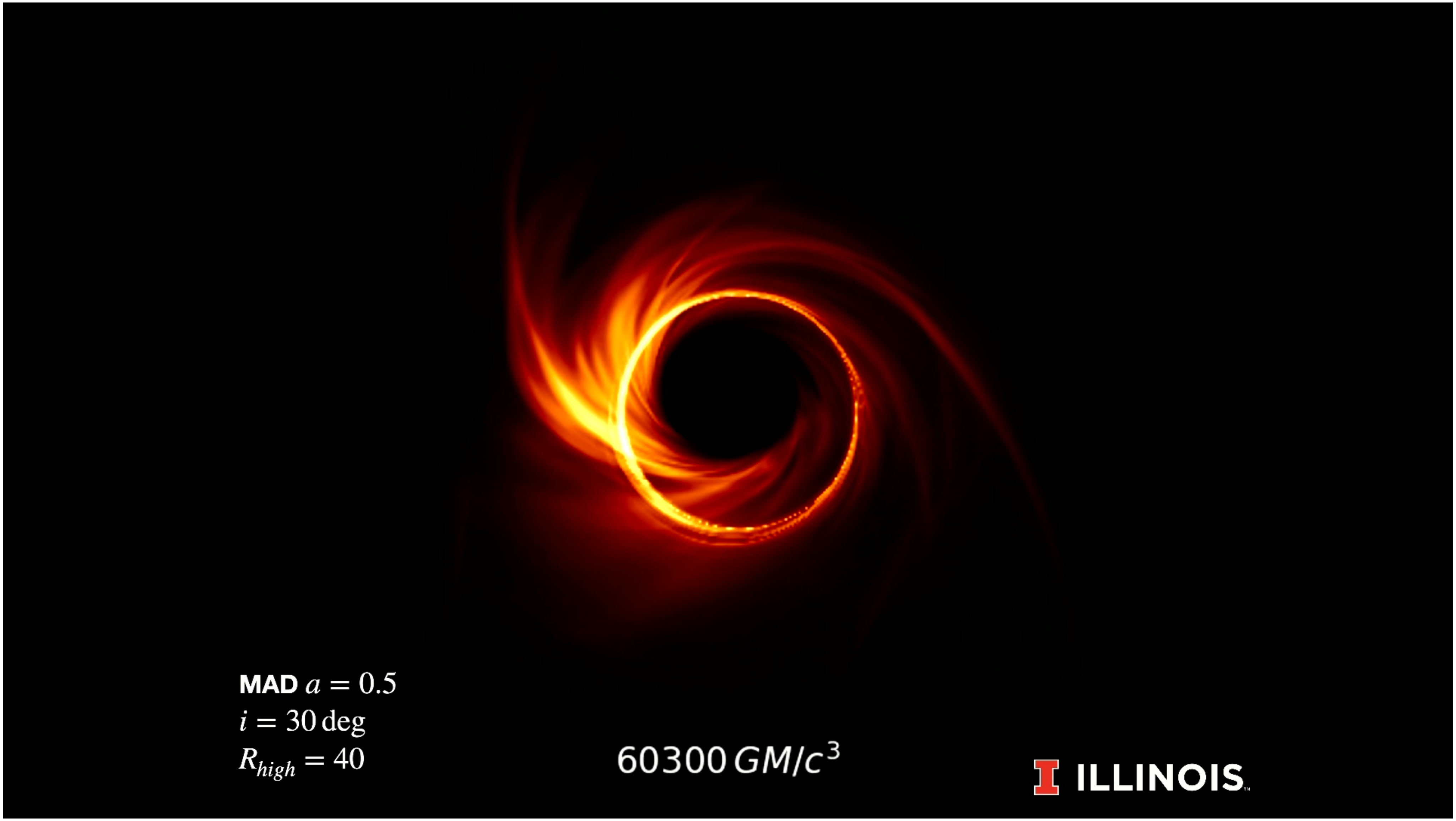

Hot Spot Model
credit: ESO/M. Wielgus

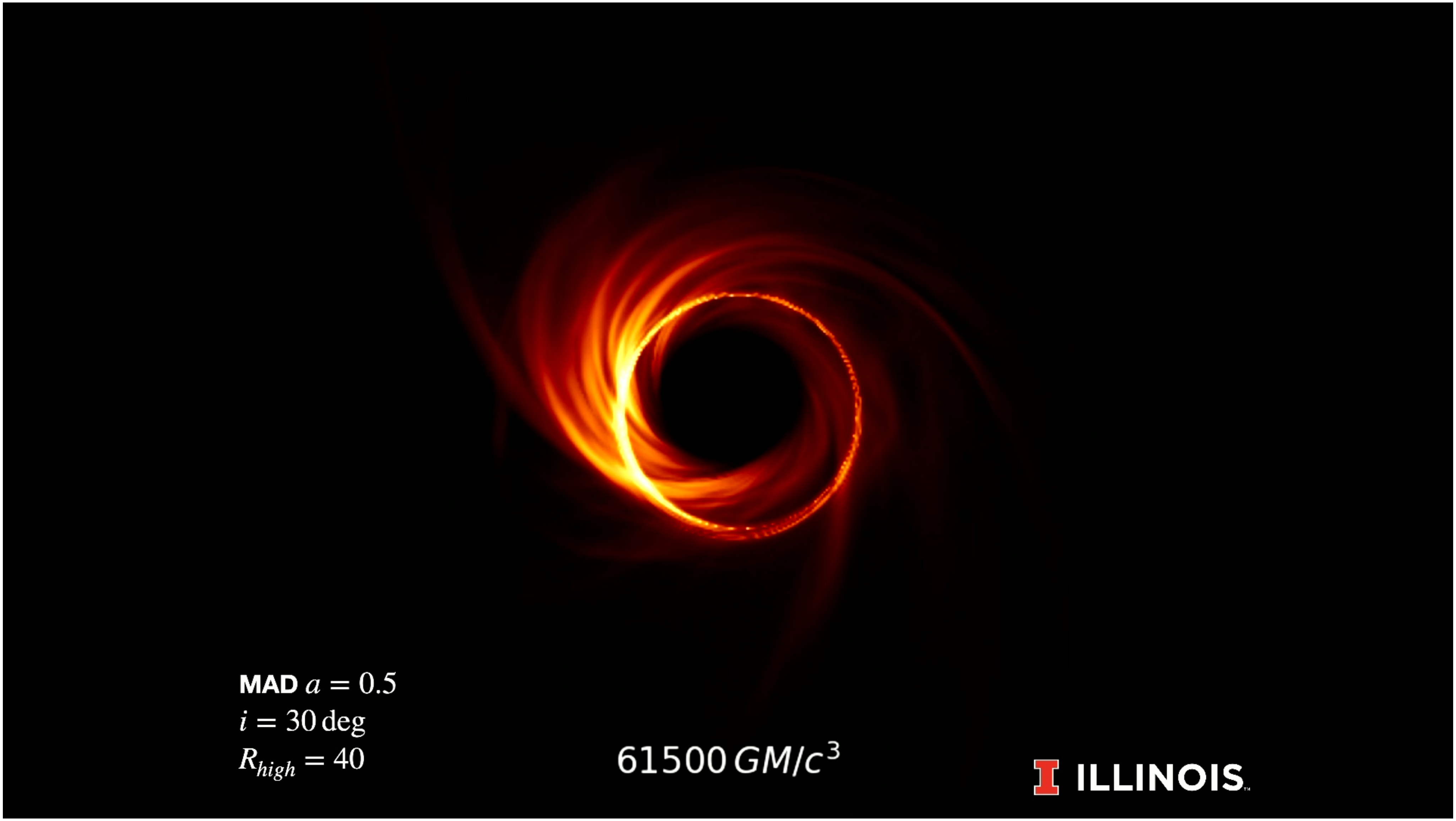

MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$60300\,GM/c^3$
ILLINOIS


MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$61500\,GM/c^3$
ILLINOIS

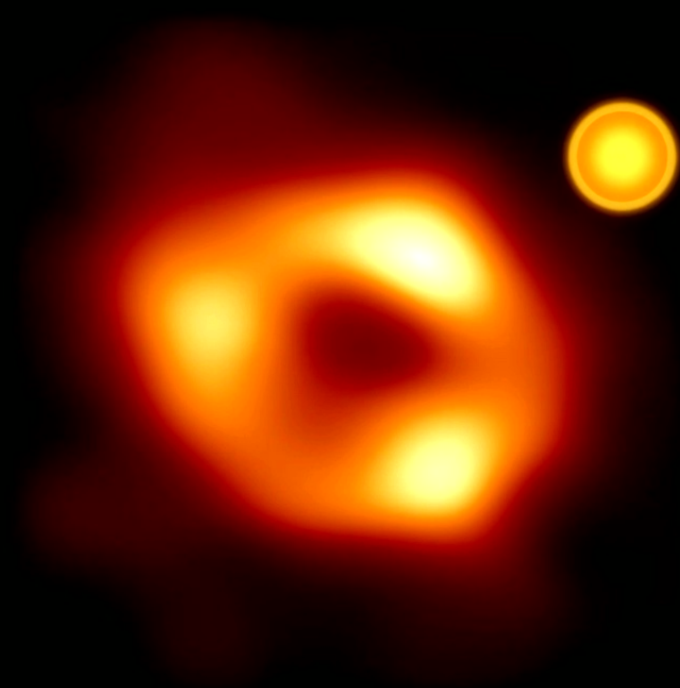

MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$62800\,GM/c^3$
ILLINOIS


MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$64000\,GM/c^3$
ILLINOIS


MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$60300\,GM/c^3$
ILLINOIS

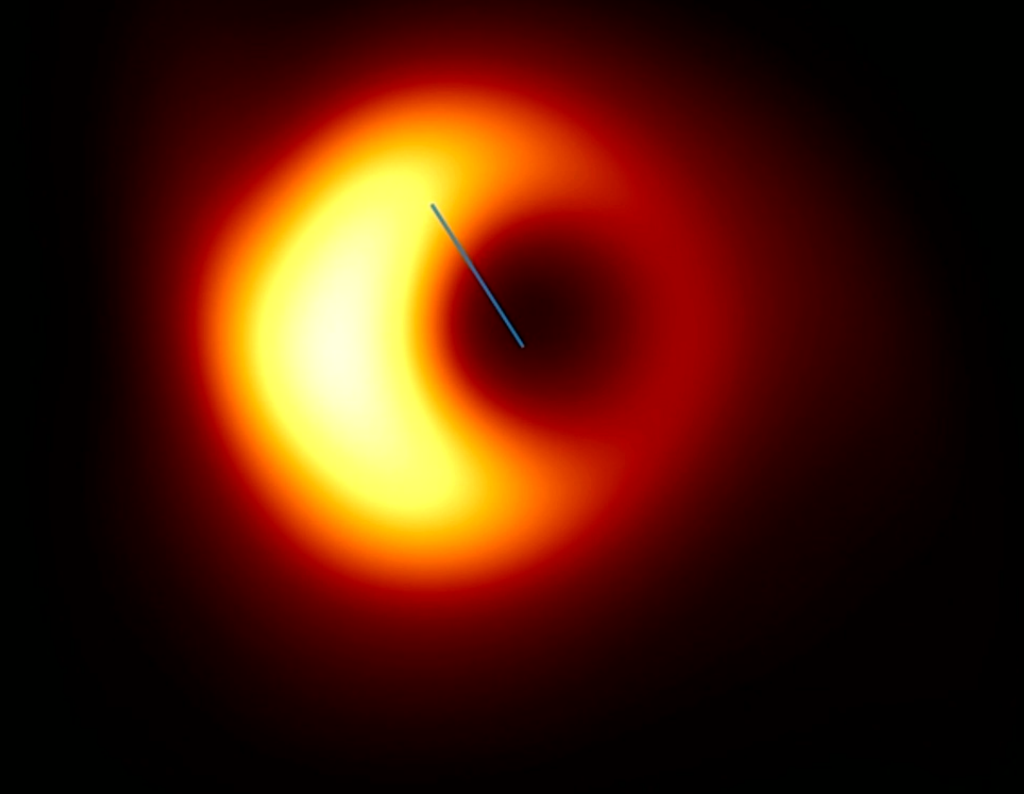

MAD $a = 0.5$
$i = 30\,\mathrm{deg}$
$R_{high} = 40$
$61500\,GM/c^3$
ILLINOIS

Hot Spot Model



credit: ESO/M. Wielgus

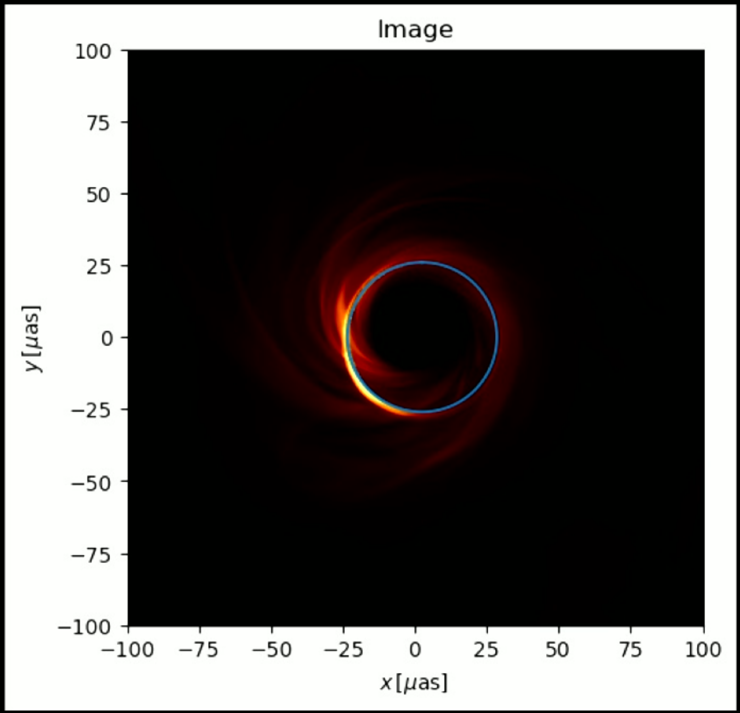
$$\Omega_{\rm plasma} \simeq 0.9\Omega_K \simeq 6\,{\rm deg}/(GM/c^3)$$



$60300\, GM/c^3$

ILLINOIS

Measuring Ω_p



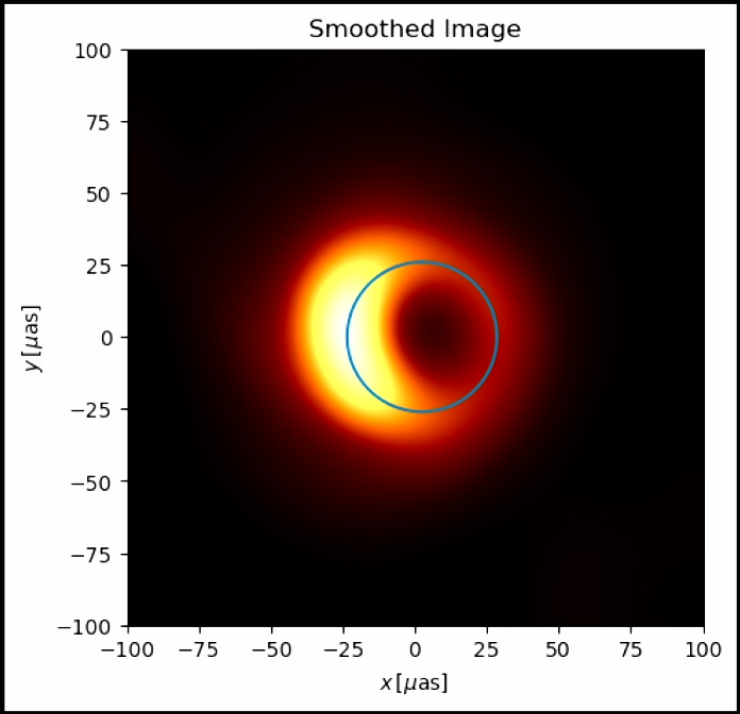
1. In each image, identify ring

$$x \simeq 2a \sin i + \sqrt{27}(1 - a^2/18)\sin \mathrm{PA} \quad y \simeq \sqrt{27}(1 - a^2 \cos^2 i/18)\cos \mathrm{PA}$$

Conroy+ 2023

ILLINOIS

Measuring Ω_p

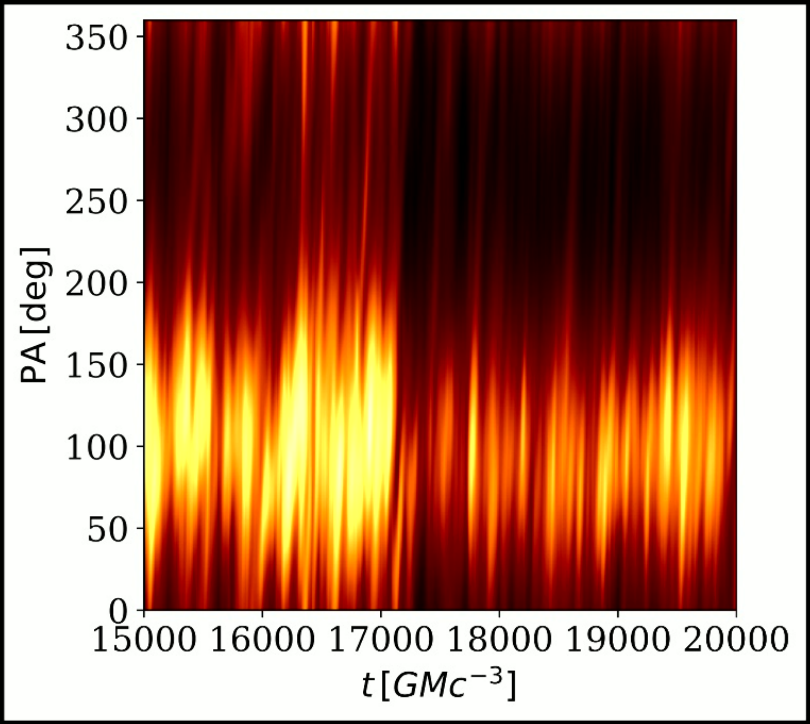


2. Smooth to nominal 20μas FWHM resolution

Conroy+ 2023

ILLINOIS

Measuring Ω_p

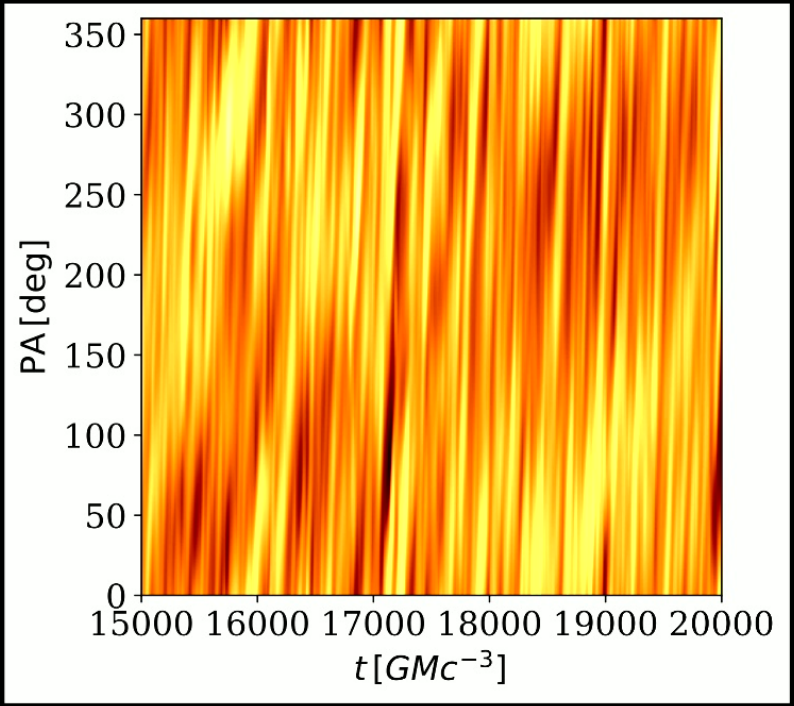


3. Extract $T_b(\mathrm{PA}, t)$

Conroy+ 2023

ILLINOIS

Measuring Ω_p

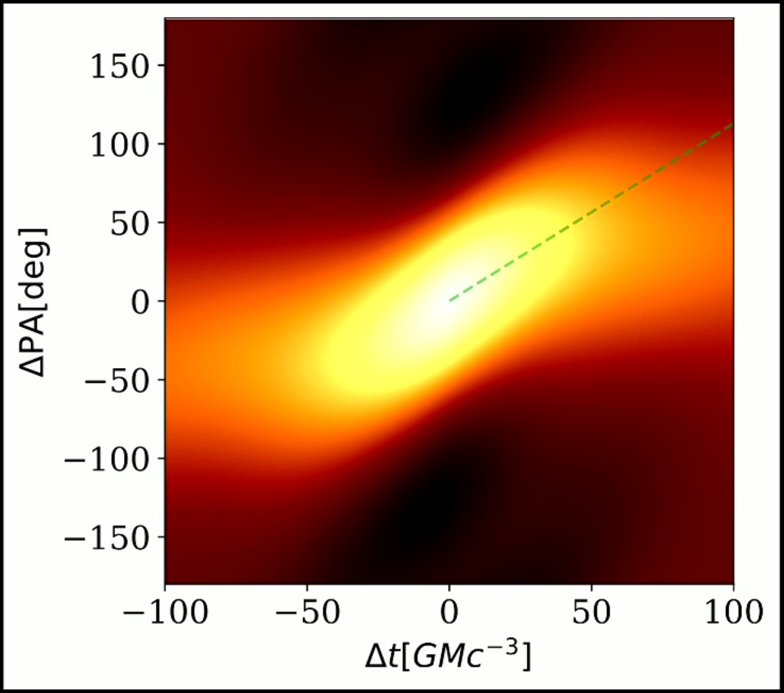


4. Log, mean subtract at each t, PA

Conroy+ 2023

ILLINOIS

Measuring Ω_p



6. Find autocorrelation function $\xi(\Delta \mathrm{PA}, \Delta t)$

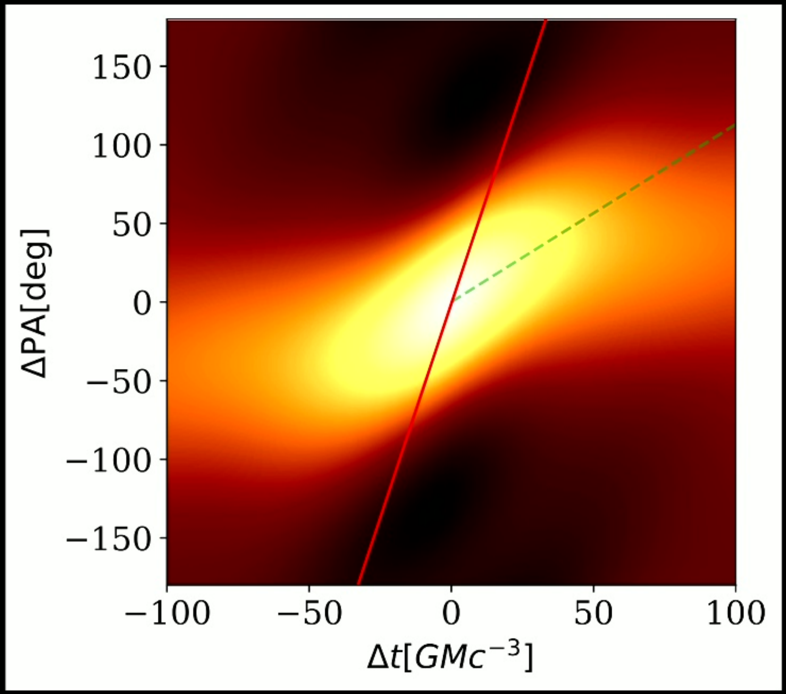
7. Measure slope of $\xi(\Delta \mathrm{PA}, \Delta t)$

8. Test procedure against Gaussian random field $\xi_{\mathrm{GRF}}(\Delta \mathrm{PA}, \Delta t)$

Conroy+ 2023

ILLINOIS

Measuring Ω_p



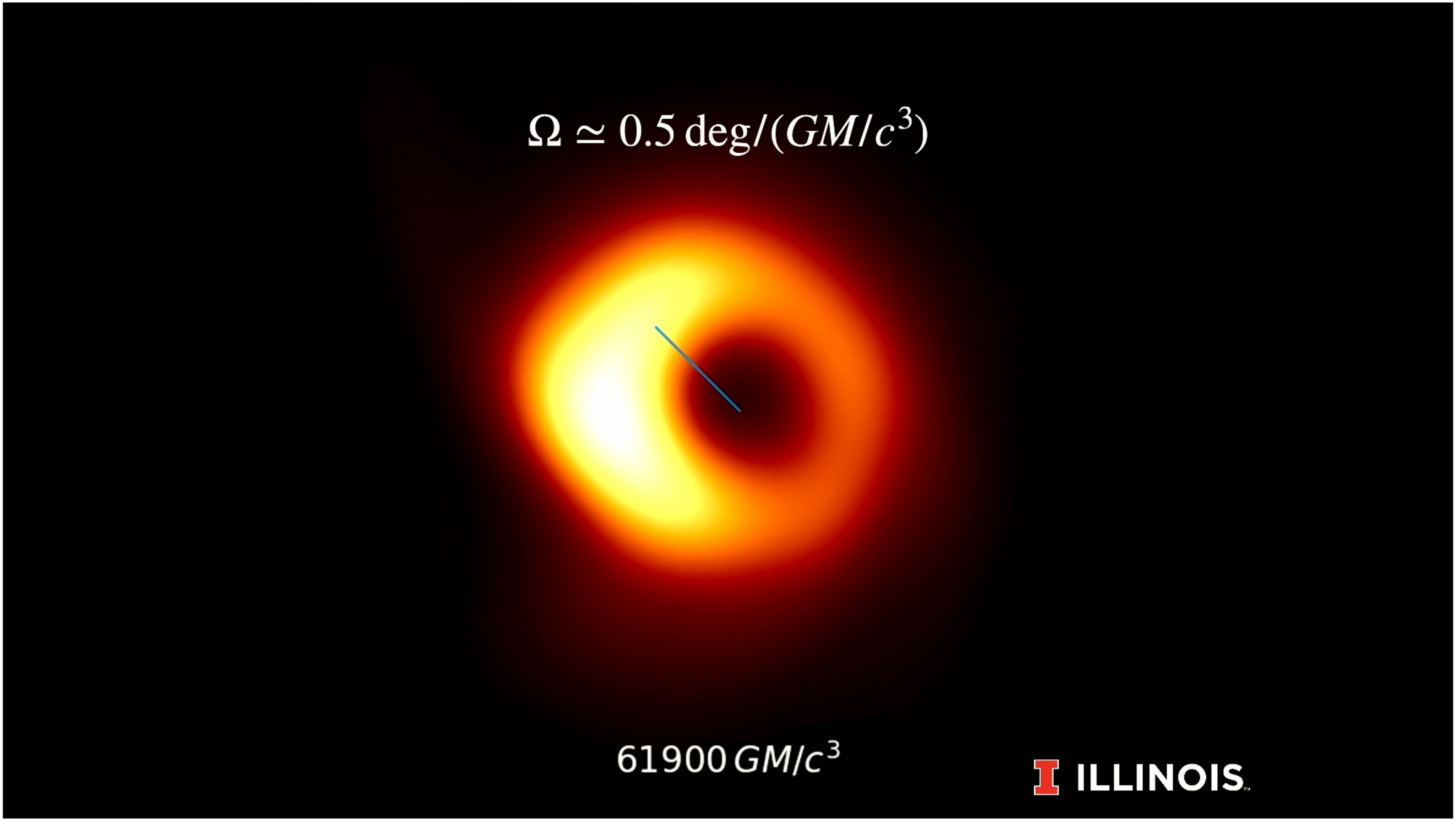
6. **Find autocorrelation function** $\xi(\Delta \mathrm{PA}, \Delta t)$

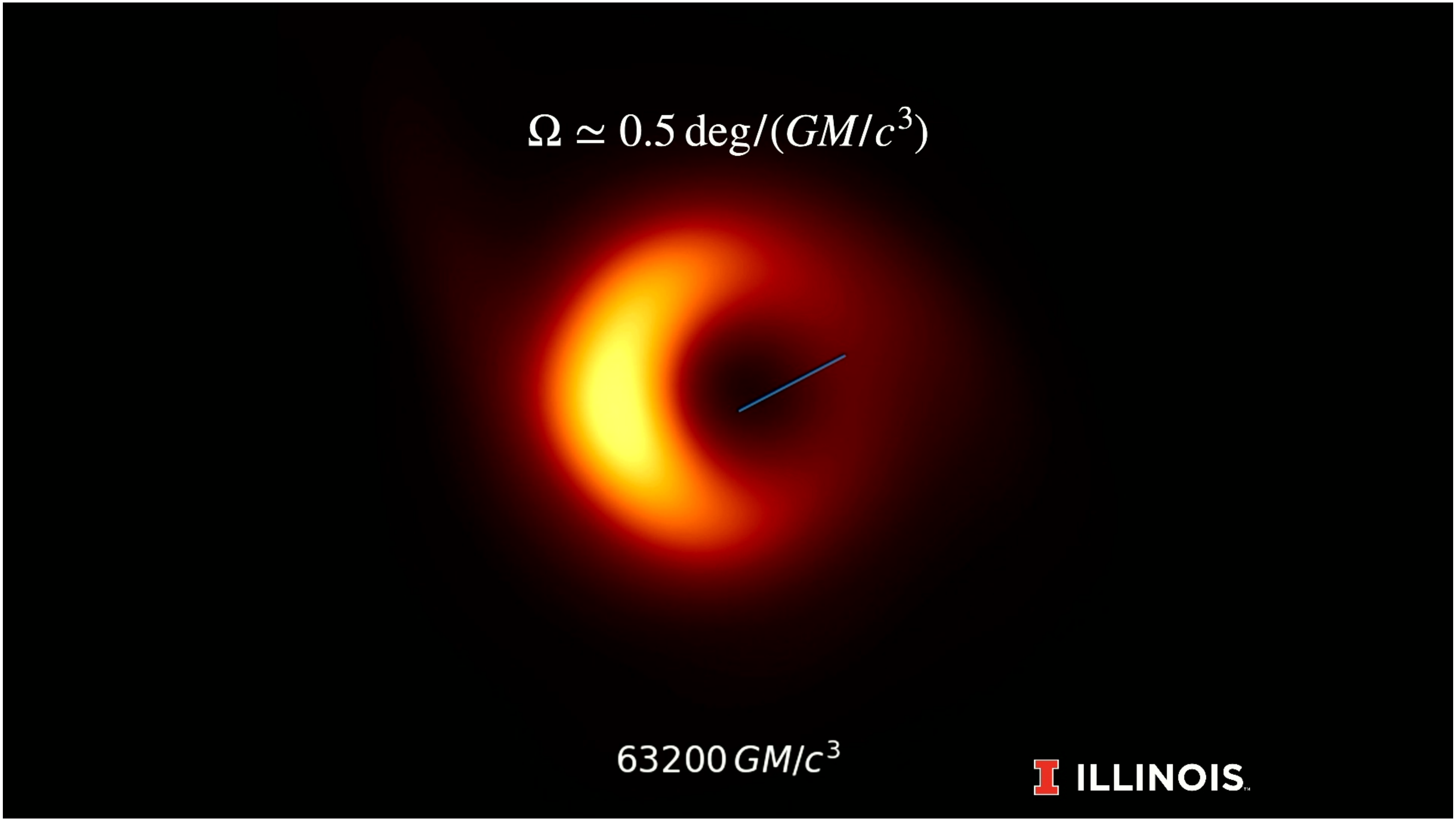
7. **Measure slope of** $\xi(\Delta \mathrm{PA}, \Delta t)$

8. **Test procedure against Gaussian random field** $\xi_{\mathrm{GRF}}(\Delta \mathrm{PA}, \Delta t)$

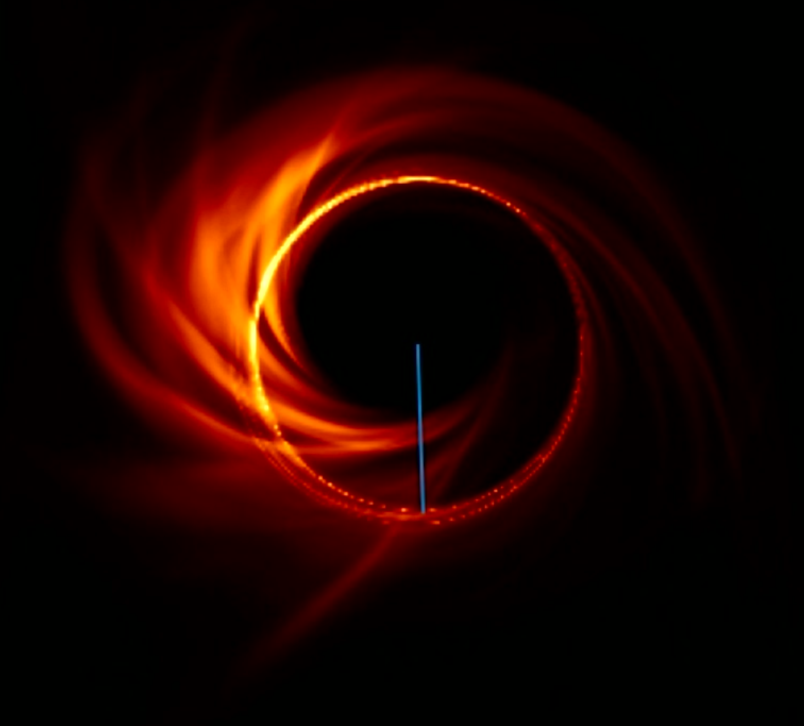
Conroy+ 2023

ILLINOIS


$\Omega \simeq 0.5\,\mathrm{deg}/(GM/c^3)$
$61900\,GM/c^3$
ILLINOIS


$\Omega \simeq 0.5\,\mathrm{deg}/(GM/c^3)$
$63200\,GM/c^3$
ILLINOIS

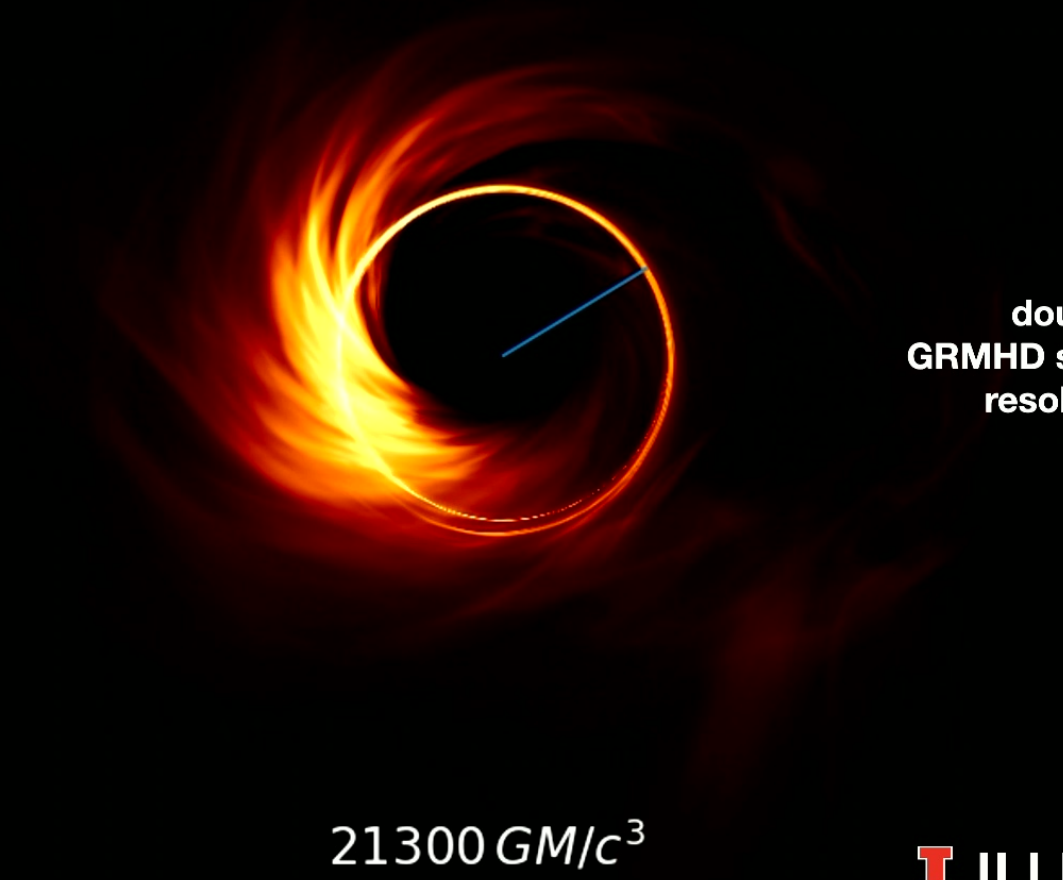
$$\Omega \simeq 0.5\,\mathrm{deg}/(GM/c^3)$$



$60000\,GM/c^3$

ILLINOIS

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



double
GRMHD simulation
resolution

ILLINOIS

Physical Origin of Low Pattern Speeds

Ingoing, rotationally modified sound waves/weak shocks

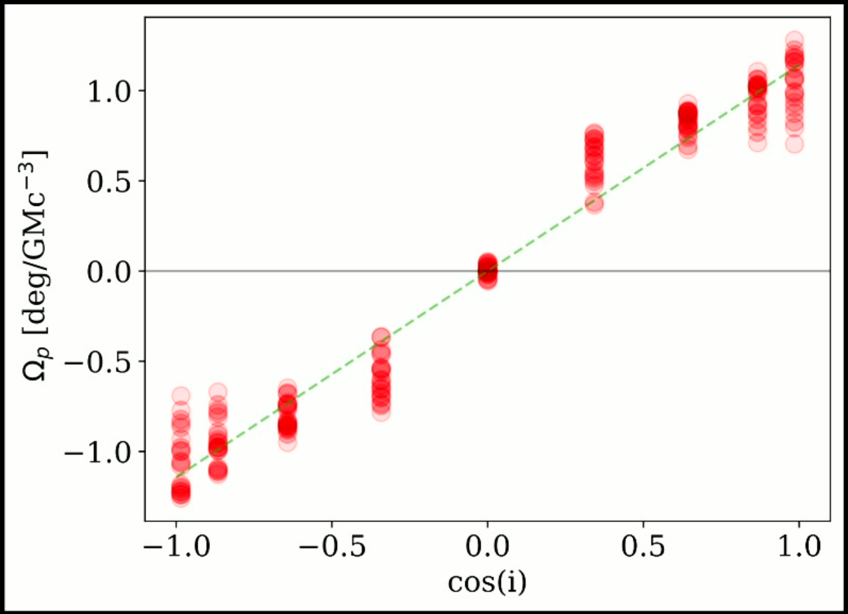
Familiar from galactic dynamics, but no self-gravity

$\Omega_p \simeq \Omega$ [radius of excitation] $\Rightarrow$ excited at r ~ 15M

dispersion relation:
(fluid frame frequency)$^2 = (\omega - \mathbf{k} \cdot \mathbf{v})^2 = \kappa^2 + c_s^2 k^2$

depends on geometry through $\mathbf{v}$, κ^2

What Do We Learn from Pattern Speeds?



$$\Omega_p \simeq (1.2 + 0.2a_*)\ \cos i \quad \deg M^{-1}$$ [MAD models]

What Can We Learn from EHT Movies?

- From Pattern Speed Ω_p
  - Test models: slow (sub-Keplerian) rotation
  - Sense of rotation: is M87* prograde or retrograde?
  - Sense of rotation: does Sgr A* rotate with GRAVITY flares?
  - Constraints on inclination, mass, spin
- From Pitch Angle ψ
  - Test models: trailing spirals away from photon ring
  - Modest constrain on spin

ILLINOIS