Event Horizon Telescope

Introduction to Black Hole Accretion

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with EHT results on behalf of the EHT Collaboration

KISS Sept 2019

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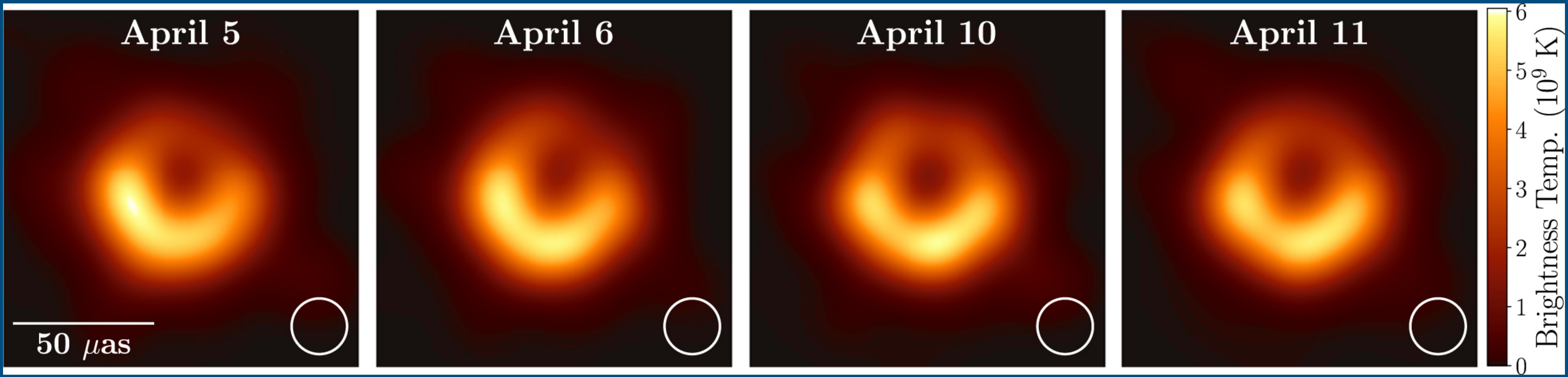
Event Horizon Telescope

Four Images of a Black Hole Accretion Flow



EHTC+ 2019

- accretion flows make black holes visible
- black hole characterized by *mass* M and *spin* a (in GR!).
- accretion flow characterized by *accretion rate* $\dot{M}$ and *magnetic flux* ϕ.

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Black Hole Mass $\equiv$ **M**

Black Hole Spin $\equiv$ **a**

Accretion Rate $\equiv$ $\dot{M}$

Magnetic Flux $\equiv$ ϕ

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Black Hole Mass ≡ M

Black Hole Spin ≡ a

$r_g \equiv GM/c^2$

$t_g \equiv GM/c^3$

$6\ M_\odot \lesssim M \lesssim 10^{10}\ M_\odot$

M87:

$M \simeq 6 \times 10^9\ M_\odot$ (EHTC+ 2019)

$GM/c^2 \simeq 59$ AU

$GM/c^3 \simeq 8.2$ hr

Accretion Rate ≡ $\dot{M}$

Magnetic Flux ≡ ϕ

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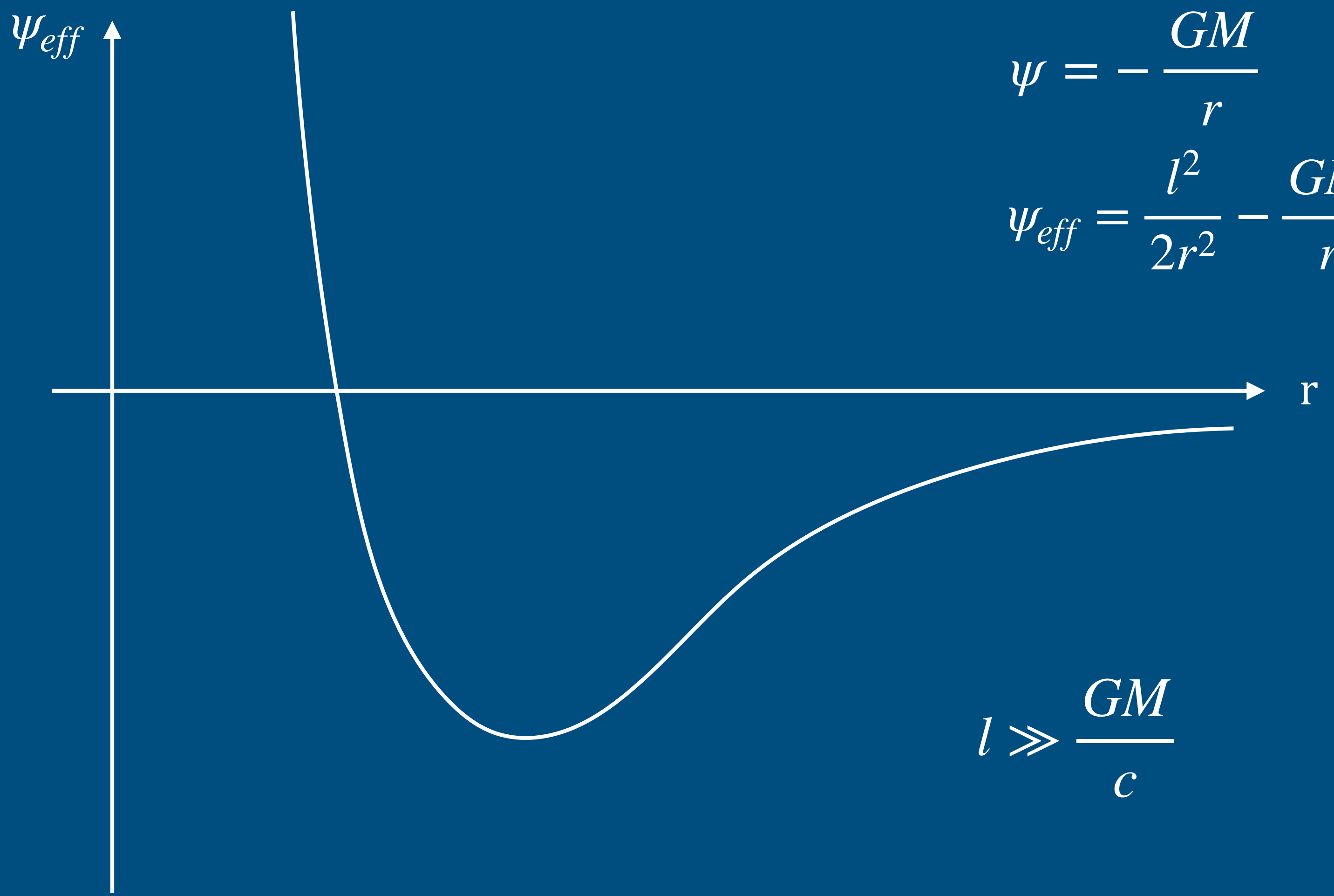
Particle Motion Near a Black Hole: Effective Potential



$$(r, \theta)$$

$$l \equiv r^2 \dot{\theta}$$

$$\psi = -\frac{GM}{r}$$

$$\psi_{eff} = \frac{l^2}{2r^2} - \frac{GM}{r}$$

$$l \gg \frac{GM}{c}$$

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Particle Motion Near a Black Hole: Effective Potential

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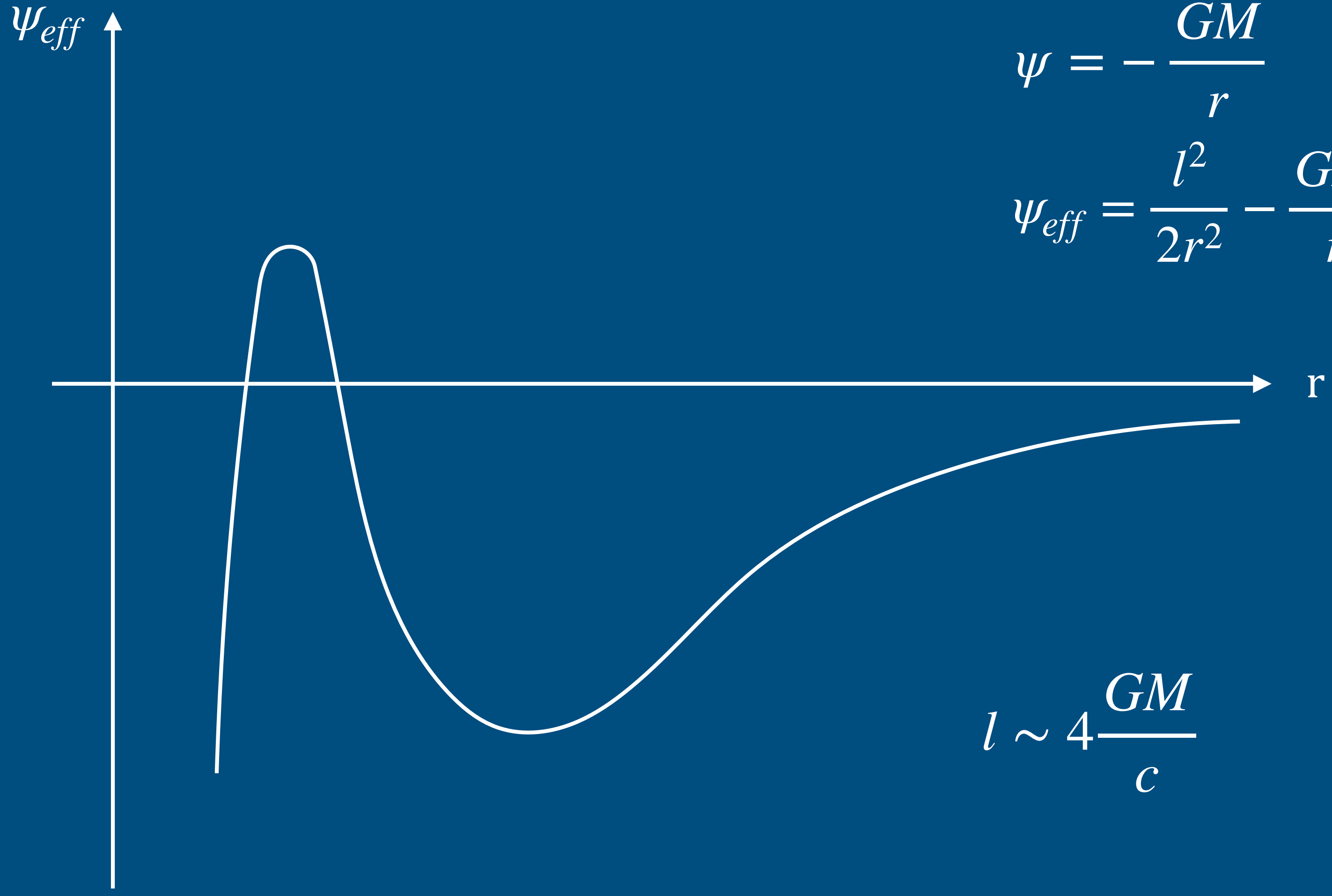

$$l \sim 4\frac{GM}{c}$$

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Particle Motion Near a Black Hole: Effective Potential

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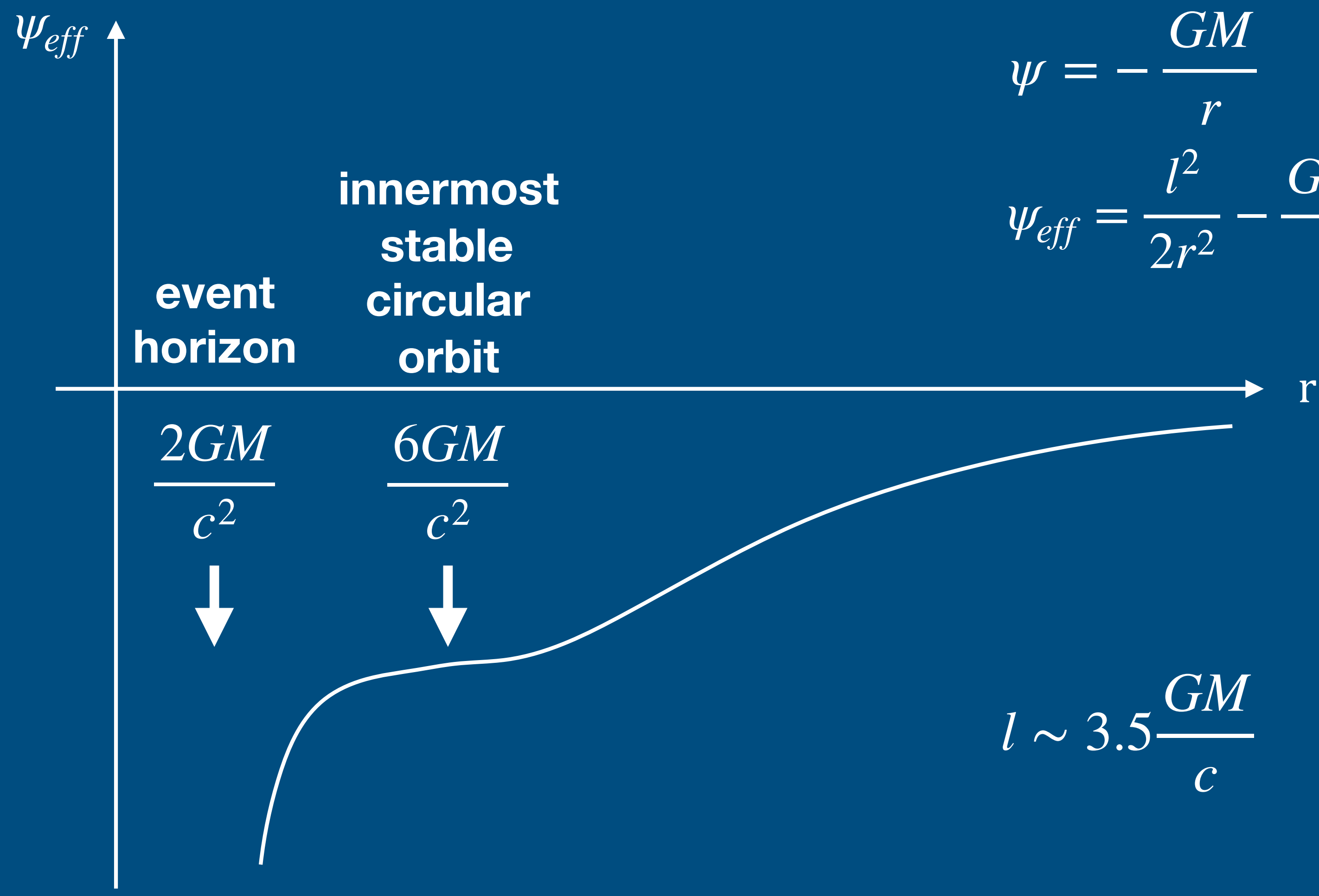

$$l \sim 3.5\frac{GM}{c}$$

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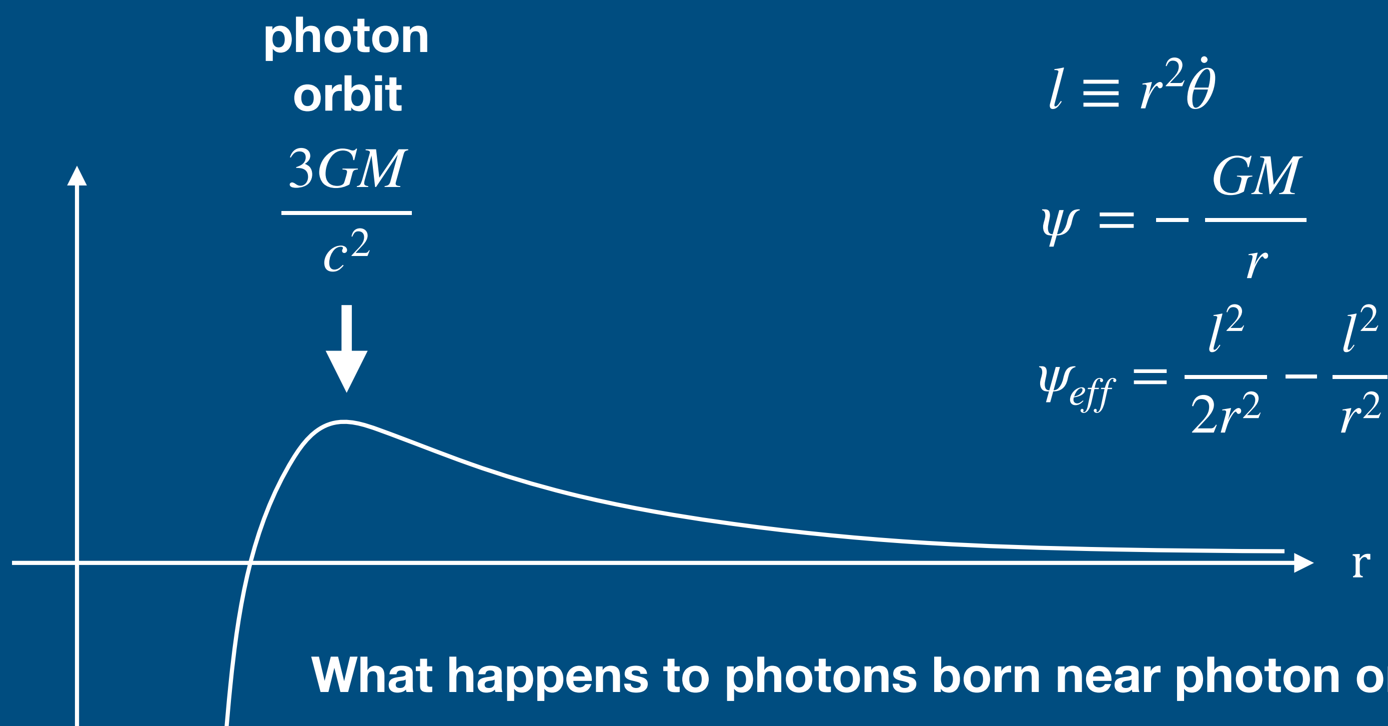
Photon Orbits Near a Black Hole: Effective Potential

$$(r, \theta)$$

$$l \equiv r^2 \dot{\theta}$$

$$\psi = -\frac{GM}{r}$$

$$\psi_{eff} = \frac{l^2}{2r^2} - \frac{l^2}{r^2}\frac{GM}{c^2 r}$$



What happens to photons born near photon orbit?

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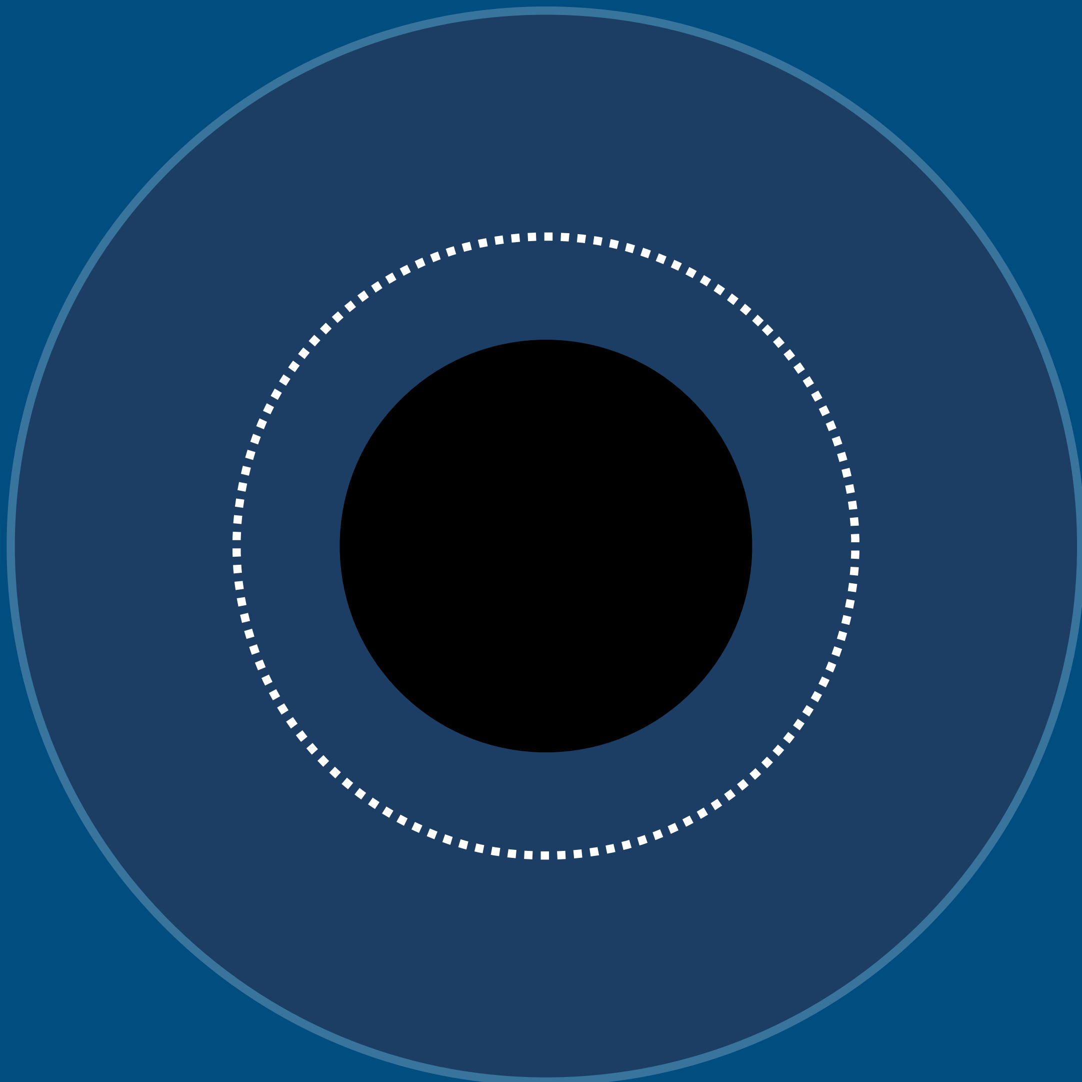
Photon Motion Near a Black Hole: Effective Potential



projection on sky, nonspinning black hole

Distance $\equiv D$

M87: $GM/(c^2D) \simeq 3.8\,\mu\mathrm{as}$

Event Horizon: $2GM/(c^2D)$

Photon Orbit: $3GM/(c^2D)$

Photon Ring: $\sqrt{27}GM/(c^2D)$

Strong gravitational lensing

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Black Hole Mass ≡ M

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Accretion Rate ≡ $\dot{M}$

$$L = \epsilon \dot{M} c^2$$

$$L_{Edd} \equiv 4\pi G M m_p c/\sigma_T$$

M87:

$\dot{M}_{Edd} \simeq 137\ M_\odot\ \mathrm{yr}^{-1}$

$\dot{M}/\dot{M}_{Edd} \sim 10^{-5}$

(EHTC+ 2019)

Black Hole Spin ≡ a

$a \equiv J\ c/(GM^2)$

$-1 < a < 1$

hard to measure!

M87: $a \gtrsim 0.5$ models are consistent w data (EHTC+ 2019)

Magnetic Flux ≡ Φ

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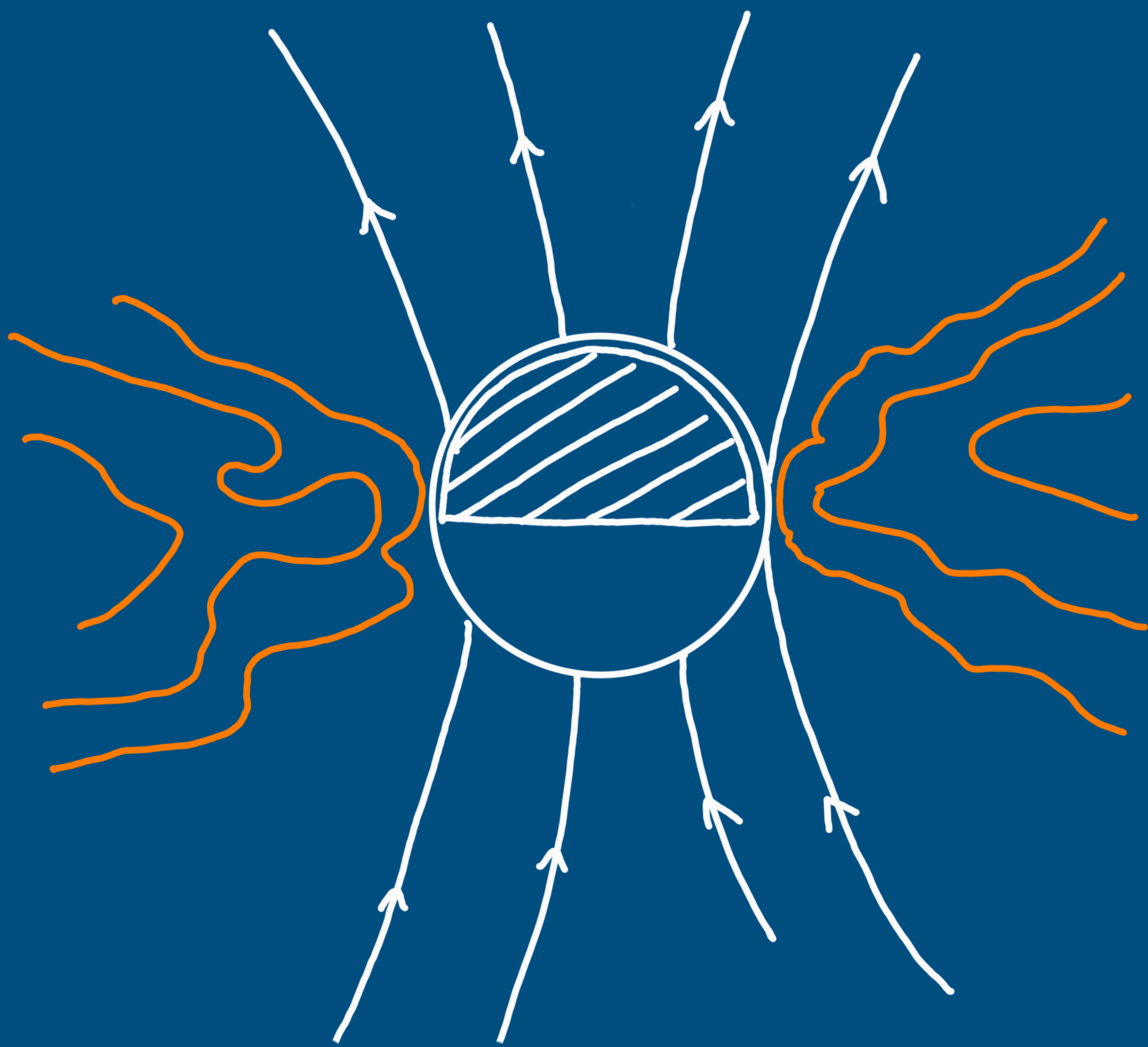

$$\Phi \equiv \int d\mathbf{A} \cdot \mathbf{B}$$

$$\Phi_{cr} \equiv (\dot{M} r_g^2 c)^{1/2}$$

cross section: black hole, magnetic field, accretion flow

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(EHTC+ 2019)

Magnetic Flux ≡ Φ

$$\Phi_{cr} \equiv (\dot{M} r_g^2 c)^{1/2}$$

SANE: $\Phi/\Phi_{cr} \lesssim 15$

MAD: $\Phi/\Phi_{cr} \simeq 15$

(Igumenshchev+ 2003)

M87: ?

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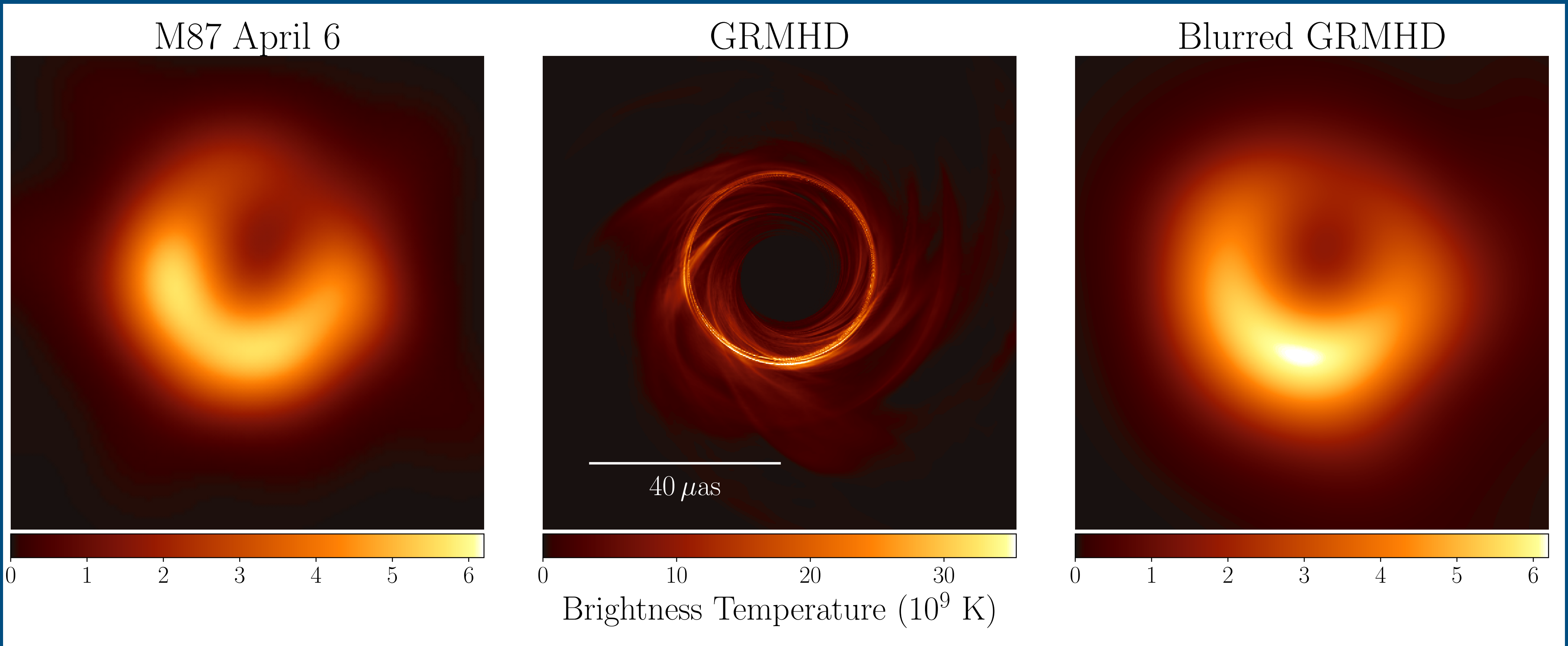
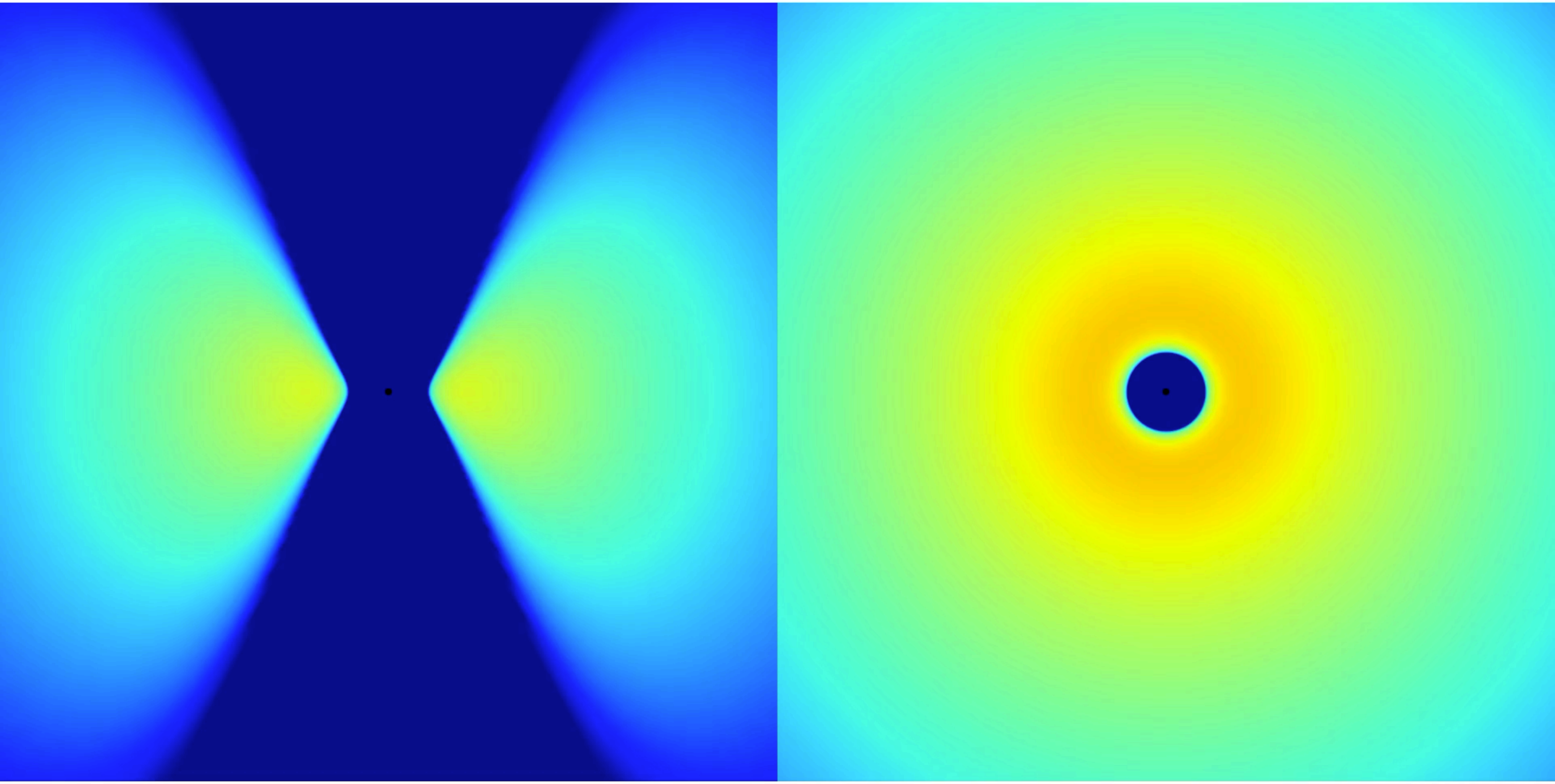
Accretion Flow Models



EHTC+ 2019

Accretion Flow Dynamical Model



color shows rest-mass density

Wong, Prather, CG

a = 0.94; $\dot{M}/\dot{M}_{Edd} \ll 1$ (nonradiative); MAD

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General Relativistic Magnetohydrodynamics Models

Covariant, magnetized fluid model for accreting plasma

3D, time dependent

Kerr-Schild coordinates: inner boundary inside horizon

Captures turbulent fluctuations

Codes (`harm`, `koral`, `bhac`, …) consistent (Porth+ 2019)

Inside the sausage factory:

ILES = no explicit dissipation (viscosity, resisitivity, heat conduction)

Plasma is *collisionless*

Initial conditions are artificial

Radiation not included

Pair production physics not included

Blandford-Znajek Effect

Black hole free energy associated with |a| > 0 (Penrose 1969)

Extractable via magnetic fields (Blandford & Znajek 1977)

Analogous stellar spin-down by magnetized wind

Collimated, pulsar-like wind:

$$L_{BZ} \sim a^2 \; 4\pi r_g^2 \; B^2 \; c$$

Use magnetic flux to link to $\dot{M}$ (e.g. Tchekhovskoy+ 2011),

$$L_{BZ} \simeq 0.01 \; a^2 \; \left(\frac{\Phi}{\Phi_{cr}}\right)^2 \dot{M}c^2$$

GRMHD models show BZ-like jet for |a| > 0

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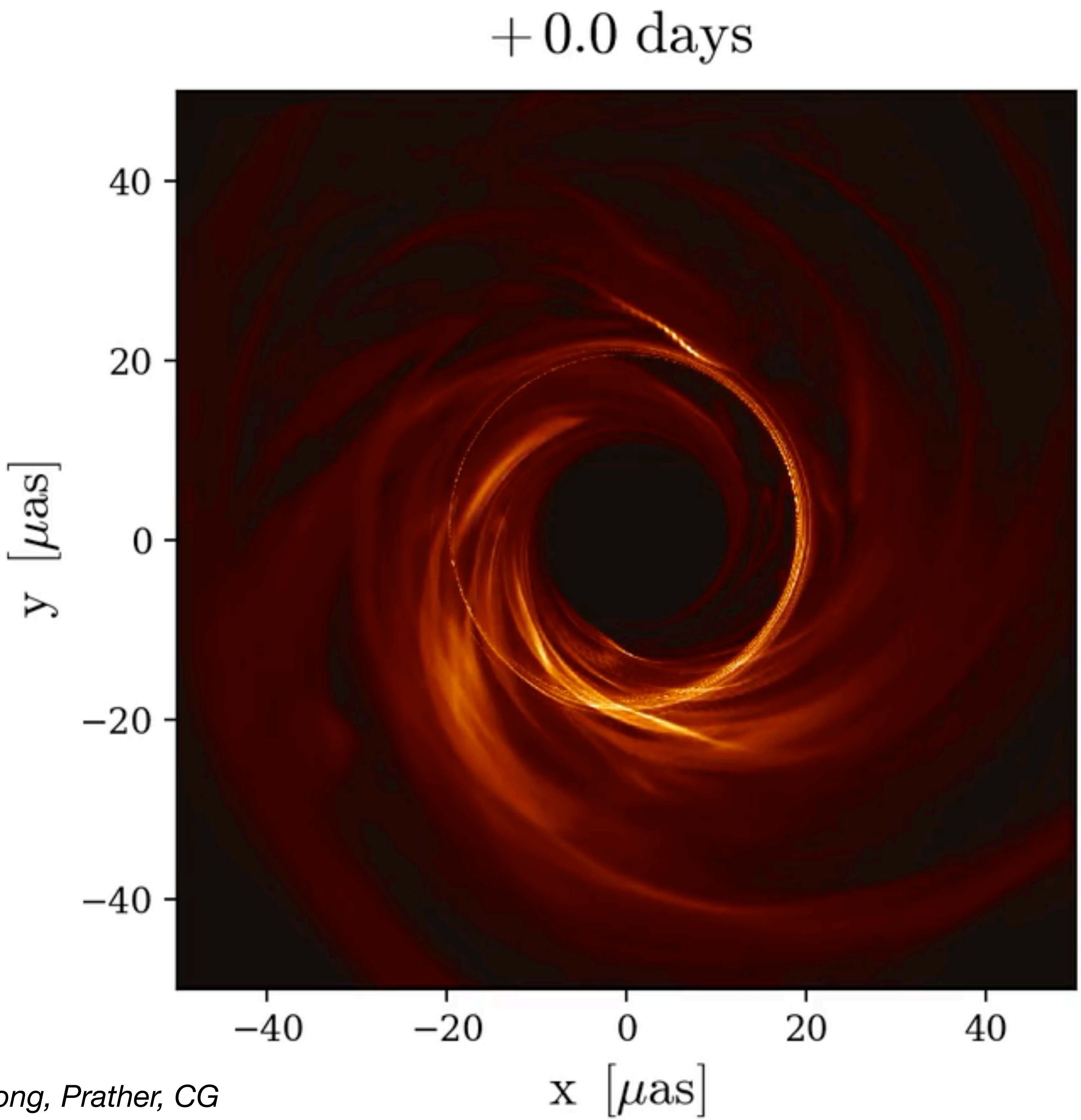

M87 model

M = 6.5 x 10^9 $M_\odot$
a = 0.94
$\dot{M}$ ~ 10^{-5} $\dot{M}_{Edd}$
MAD

synchrotron emission

Wong, Prather, CG

Radiative Transfer Models

Covariant, polarized radiative transfer model

Codes (`ipole, bhoss, grtrans,` ...) convergent (Gold+ 2019)

Electron distribution function ⇒ transfer coefficients

Inside the sausage factory:

Post-processing step (radiation not included in evolution)

electron distribution function *assumed*

Fast light approximation

Main Points

- **Accretion flows make black holes visible**
- **Four key parameters:** M, a, $\dot{M}$, φ/φ_{cr}
- **Strong gravitational lensing related to photon orbit produces photon ring**
- **General relativistic magnetohydrodynamics (GRMHD) models produce jets powered by Blandford-Znajek process**
- **GRMHD models + radiative transfer reproduce Event Horizon Telescope observations of M87**