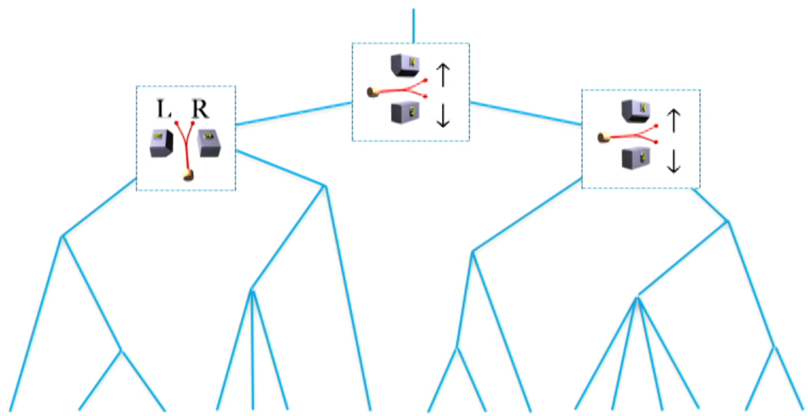
Title: PI Day - Mar. 14, 2018 - Part 2

Date: Mar 14, 2018 03:30 PM

URL: http://pirsa.org/18030115

Abstract:

Rigorously defining the branches of the wavefunction

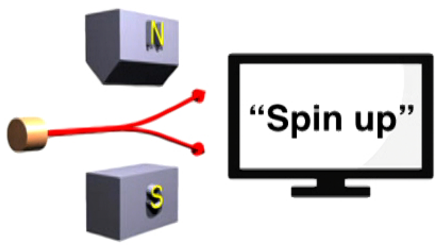


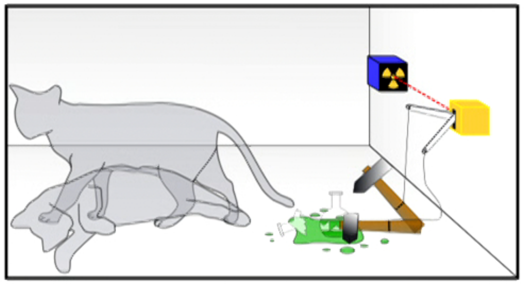
C. Jess Riedel

with Martin Ganahl (PI), Markus Hauru (PI), Curt von Keyserlingk (Birmingham), Noah MacAulay (UT), Ash Milstead (PI), Elliot Nelson (PI), Daniel Ranard (Stanford), Tian Wang (Caltech)

Macroscopic superpositions are everywhere

- Macroscopic superpositions are not just rare situations created by carefully designed equipment

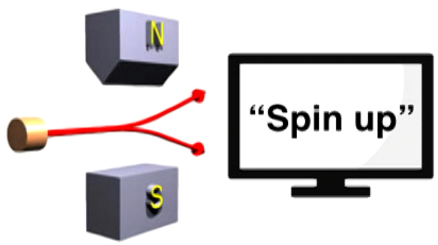


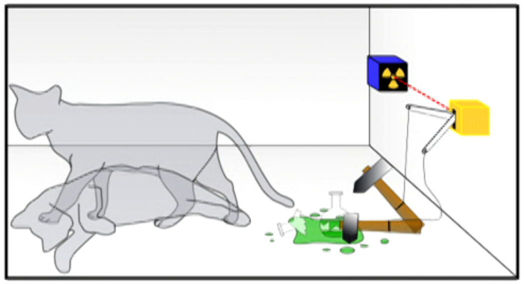


- Macroscopic superpositions are created generically by macroscopic chaotic systems
    - Which is pretty much everything

Macroscopic superpositions are everywhere

- Macroscopic superpositions are not just rare situations created by carefully designed equipment

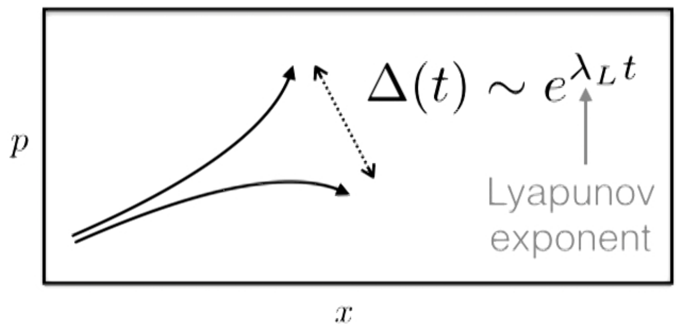


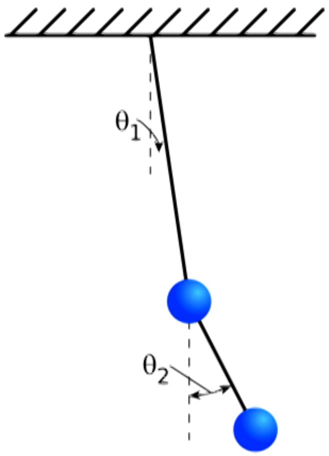


- Macroscopic superpositions are created generically by macroscopic chaotic systems
  - Which is pretty much everything

Macroscopic superpositions are everywhere

- Even minimal uncertainty wavepackets are stretched over the entire available phase space after several multiples of the Lyapunov time





- Not eliminated by classical limit

$$T^{\text{macro}}_{\text{superpos}} \sim \lambda_L^{-1} \ln \frac{S_0}{\hbar}$$

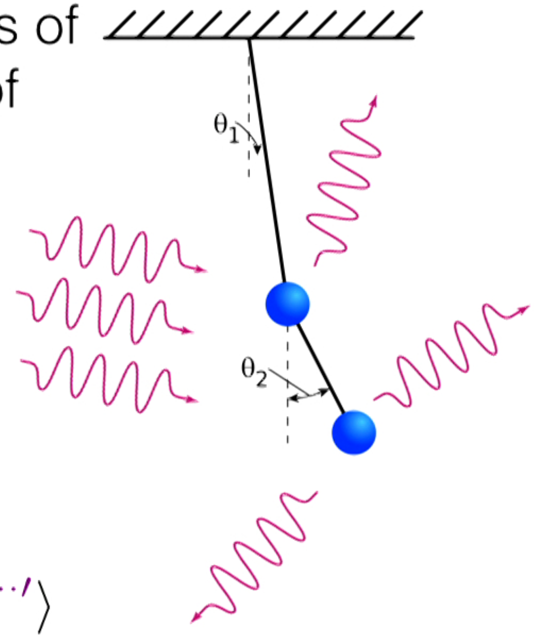
← Scale of system's action

Macroscopic superpositions decohere

- Macroscopic superpositions are continuously decohered by their environment as they are created
- A generic feature seen in models of decoherence is the generation of GHZ-like correlations

“Redundant records”

Different classical trajectories



$$|\Psi^0\rangle = \left[\sum_i |S_i\rangle\right] |\gamma_0\rangle|\gamma_0'\rangle \cdots |\gamma_0^{\prime\cdots\prime}\rangle$$

$$\rightarrow |\Psi\rangle = \sum_i |S_i\rangle|\gamma_i\rangle|\gamma_i'\rangle \cdots |\gamma_i^{\prime\cdots\prime}\rangle$$

Outline

- Ultimately, we seek to precisely define wavefunction branches “out there in the real world”
- Today we describe a precise but imperfect definition on a lattice
- Outline:
  - Gather some imprecise desiderata
  - Present a scale-dependent precise definition
  - Argue that this can be useful for simulating many-body systems out of equilibrium

Wavefunction branch desiderata

- Branches are time-dependent orthogonal decomposition of many-body wavefunction

$$|\Psi^{(t)}\rangle = \sum_i |\Psi_i^{(t)}\rangle \qquad \langle\Psi_i^{(t)}|\Psi_j^{(t)}\rangle = 0, \quad i \neq k$$

- Coherent superposition indistinguishable from corresponding incoherent mixture for correlators of local observables

$$\langle \mathcal{O}_1 \cdots \mathcal{O}_m \rangle_\Psi = \langle \mathcal{O}_1 \cdots \mathcal{O}_m \rangle_\rho \qquad \rho = \sum_i |\Psi_i\rangle\langle\Psi_i|$$

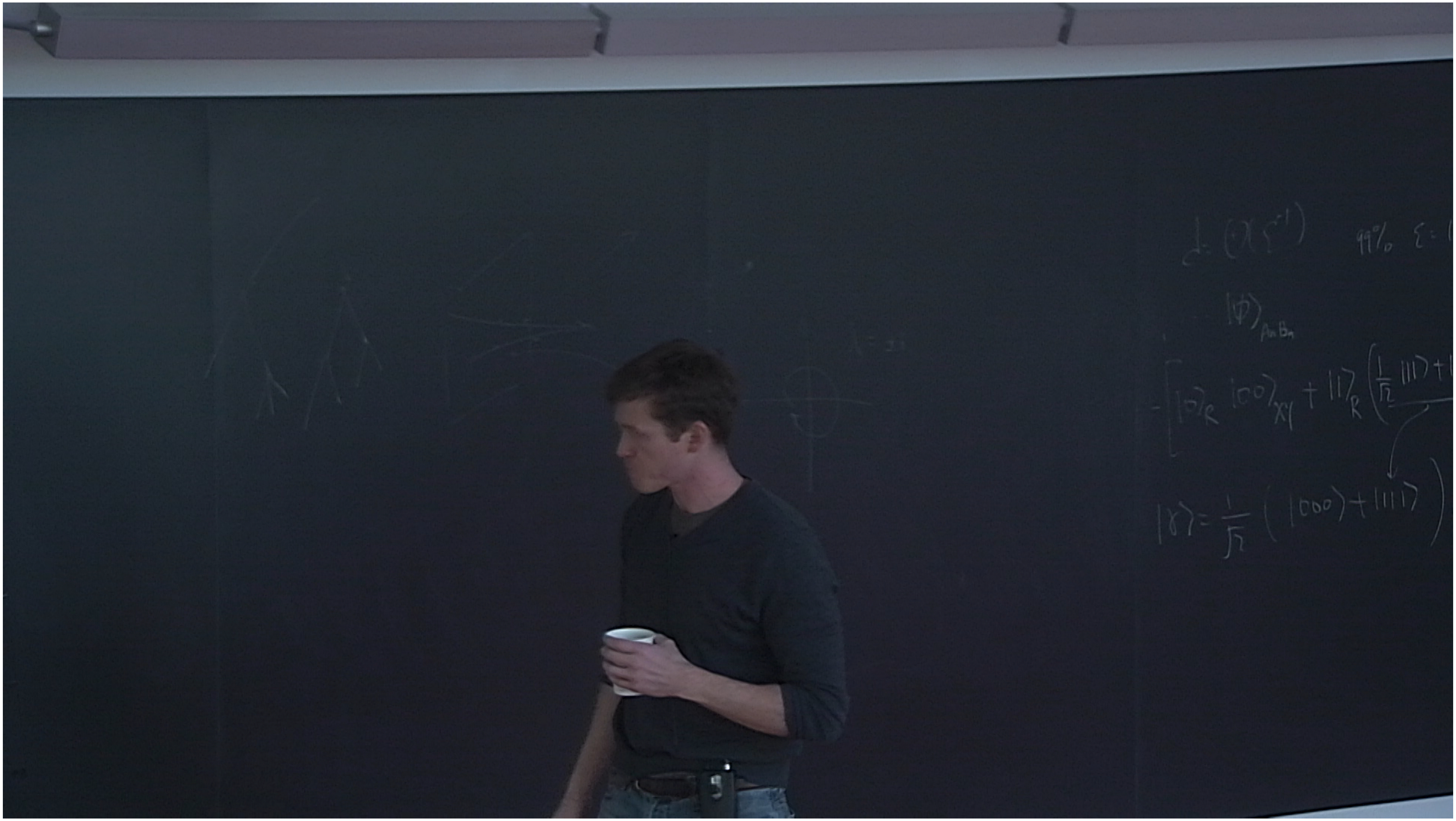
Wavefunction branch desiderata

- Branches fine-grain under time evolution

$$U_{t_1 \to t_2} |\Psi_{i_1}^{(t_1)}\rangle = \sum_{i_2} |\Psi_{(i_1,i_2)}^{(t_2)}\rangle$$

- $\Rightarrow$ Number of branches cannot decrease with time

- Branches are approximate eigenstates of macroscopic (e.g. hydrodynamic) observables:
  - Net magnetization of spins over large regions
  - Center-of-mass position and momentum of large objects
  - Outcomes of laboratory experiments


|γ⟩ = 1/√2 (|000⟩ + |111⟩)

Scale-dependent definition

- Define a **redundant** set of observable at scale L to be a set of several (m>2) observables local to disjoint regions with size $O(L)\ldots$

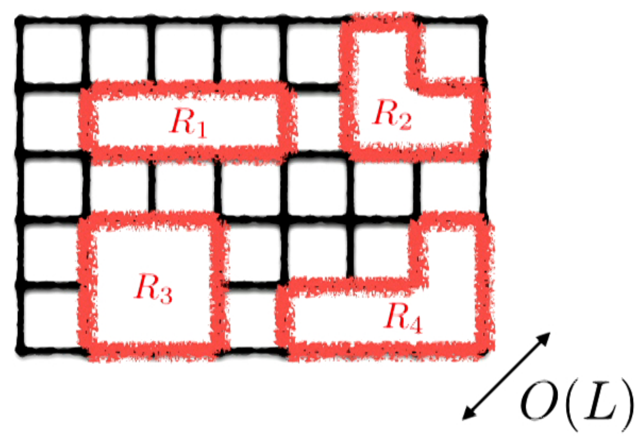
Eigenvalues

z-th observable

z-th region

$$\mathcal{O}^{(z)} = \sum_j \lambda_j P_j^{R_z}$$

Orthogonal projectors
onto eigenspaces



…that are classically correlated on the state

$$P_j^{R_1}|\Psi\rangle = P_j^{R_2}|\Psi\rangle = P_j^{R_3}|\Psi\rangle = \cdots$$

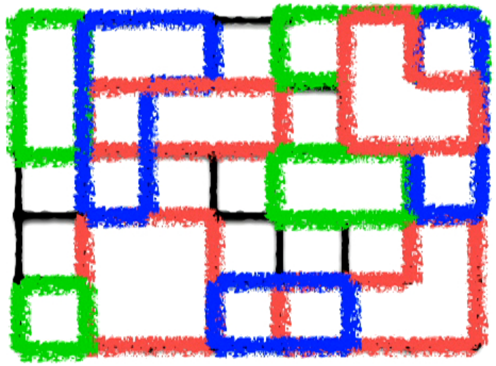
Scale-dependent definition

- Can be shown that *all* redundant sets of observables at same scale necessarily commute

z_a-th and z_b-th regions

$$\left[\mathcal{O}_a^{(z_a)}, \mathcal{O}_b^{(z_b)}\right] |\Psi\rangle = 0$$

a-th and b-th redundant sets

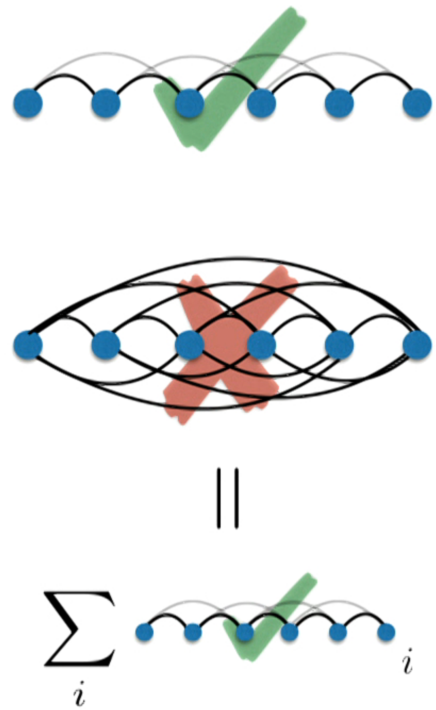


- Define **branches** at scale L to be the simultaneous eigenstates:

$$|\Psi\rangle = \sum_{i=(i_1, i_2, \cdots)} |\Psi_i\rangle \qquad \mathcal{O}_a^{(z_a)} |\Psi_i\rangle = \lambda_{i_a}^{(a)} |\Psi_i\rangle$$

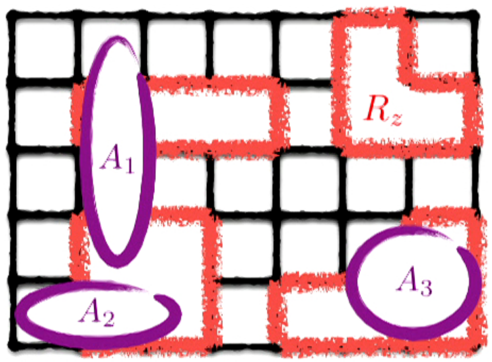
Simulate non-equilibrium with branches

- States with efficient tensor-network (TN) description have low long-range entanglement
- Out-of-equilibrium states of non-integrable Hamiltonians generically generate long-range entanglement
  - TN simulation becomes infeasibly slow
- Strategy: decompose state into branches, each of which have less long-range entanglement
- Estimate correlators by sampling branches



Estimate correlators by sampling branches

- When expanding correlator of local operators at same scale, off-diagonal terms connecting different branches vanish



$$\langle A_1 \cdots A_{m-1} \rangle_\psi = \sum_{i,j} \langle \Psi_i | A_1 \cdots A_{m-1} | \Psi_j \rangle$$

$$= \sum_{i,j} \langle \Psi_i | P_{i_a}^{(R_z)} A_1 \cdots A_{m-1} | \Psi_j \rangle$$

$$= \sum_{i,j} \langle \Psi_i | A_1 \cdots A_{m-1} P_{i_a}^{(R_z)} | \Psi_j \rangle$$

$$= \sum_{i} \langle \Psi_i | A_1 \cdots A_{m-1} | \Psi_i \rangle$$

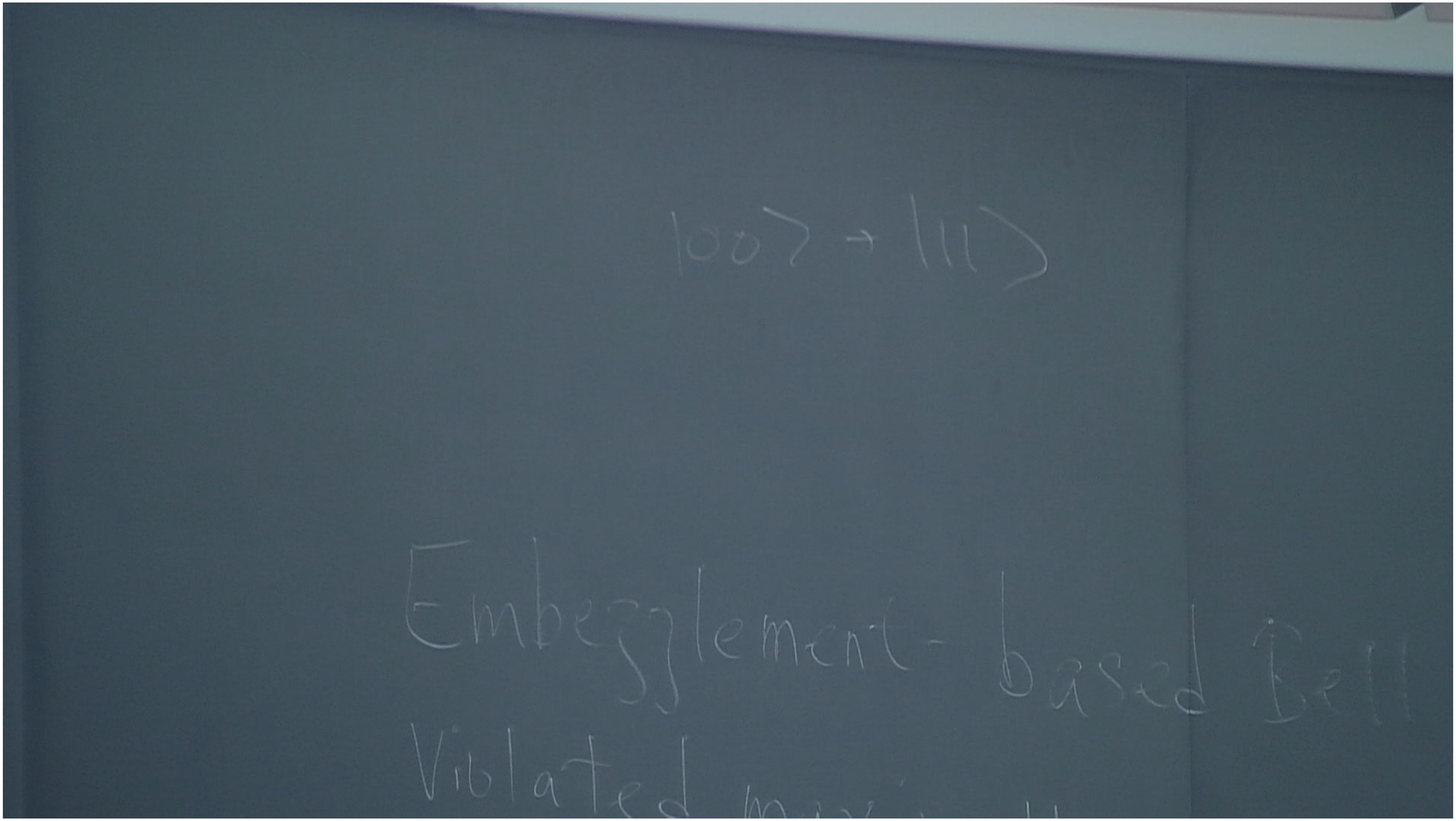
Branches are eigenstates

For *some* region in redundant set

Off-diag terms annihilate

- Can get accurate estimate of correlator with fixed-size sample, even with exponentially large number of branches

$$\langle A_1 \cdots A_{m-1} \rangle_\psi = \sum_{i \in S} \langle \Psi_i | \langle A_1 \cdots A_{m-1} | \Psi_i \rangle$$


|00⟩ → |11⟩
Embezzlement-based Bell
Violated

Branches equivalent to MPS blocks

(Only slide where you need to know what a tensor network is)

- Archetype state with branches is multipartite GHZ state

$$|\Psi_{\text{GHZ}}\rangle = |0\cdots 0\rangle + |1\cdots 1\rangle \qquad |\Psi_i\rangle = |i\cdots i\rangle, \quad i = 1,2$$

- Shows up as simultaneous diagonal structure in matrix-product state representation

$$|\Psi\rangle = \sum_{\sigma_N,\cdots,\sigma_N} \Gamma^{\sigma_1}\cdots\Gamma^{\sigma_N}|\sigma_1\cdots\sigma_N\rangle \qquad \Gamma = \begin{pmatrix} |0\rangle & 0 \\ 0 & |1\rangle \end{pmatrix}$$

- Generic branches show up as block-diagonal MPS structure:

$$\Gamma = \begin{pmatrix} |X\rangle & |Y\rangle & 0 & 0 & 0 \\ |Z\rangle & |W\rangle & 0 & 0 & 0 \\ 0 & 0 & |Q\rangle & 0 & 0 \\ 0 & 0 & 0 & |A\rangle & |B\rangle \\ 0 & 0 & 0 & |C\rangle & |D\rangle \end{pmatrix}$$

Proof of concept

- Searching for blocks correctly identifies intuitive branches formed by collisions of quasiparticles

Spin-polarized fermions

$$H = \sum_i \left(c_i^\dagger c_{i+1} + c_{i+1}^\dagger c_i \right) + V \sum_i \left(c_i^\dagger c_i - \frac{1}{2} \right) \left(c_{i+1}^\dagger c_{i+1} - \frac{1}{2} \right)$$

↑ Kinetic term

↑ Interaction term

Proof of concept

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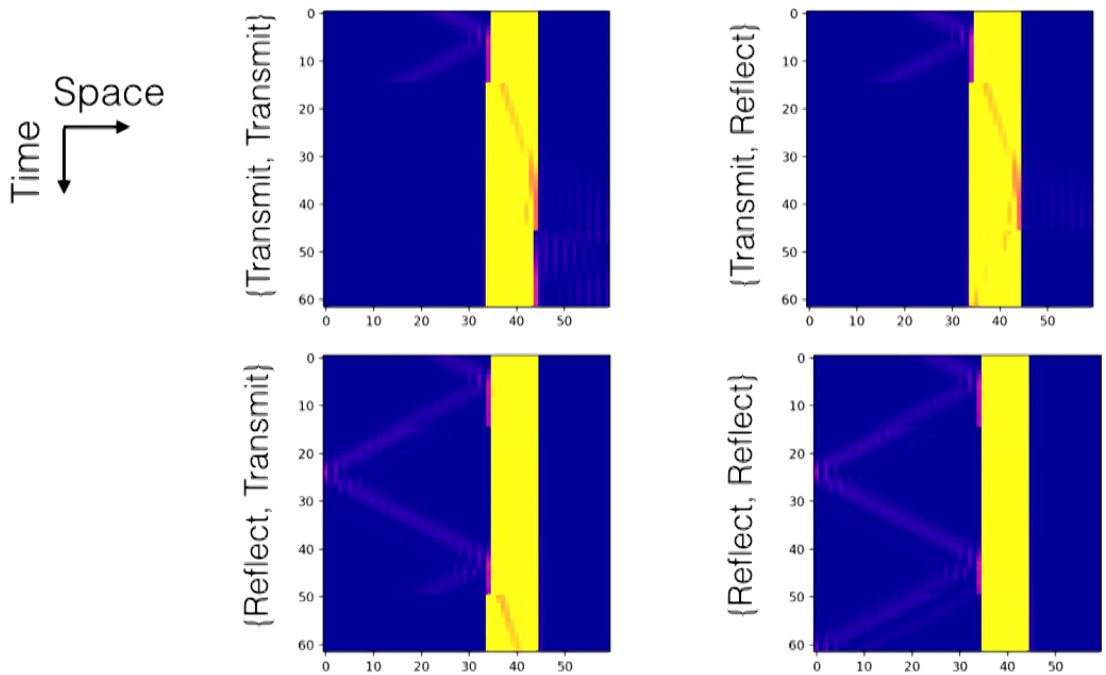
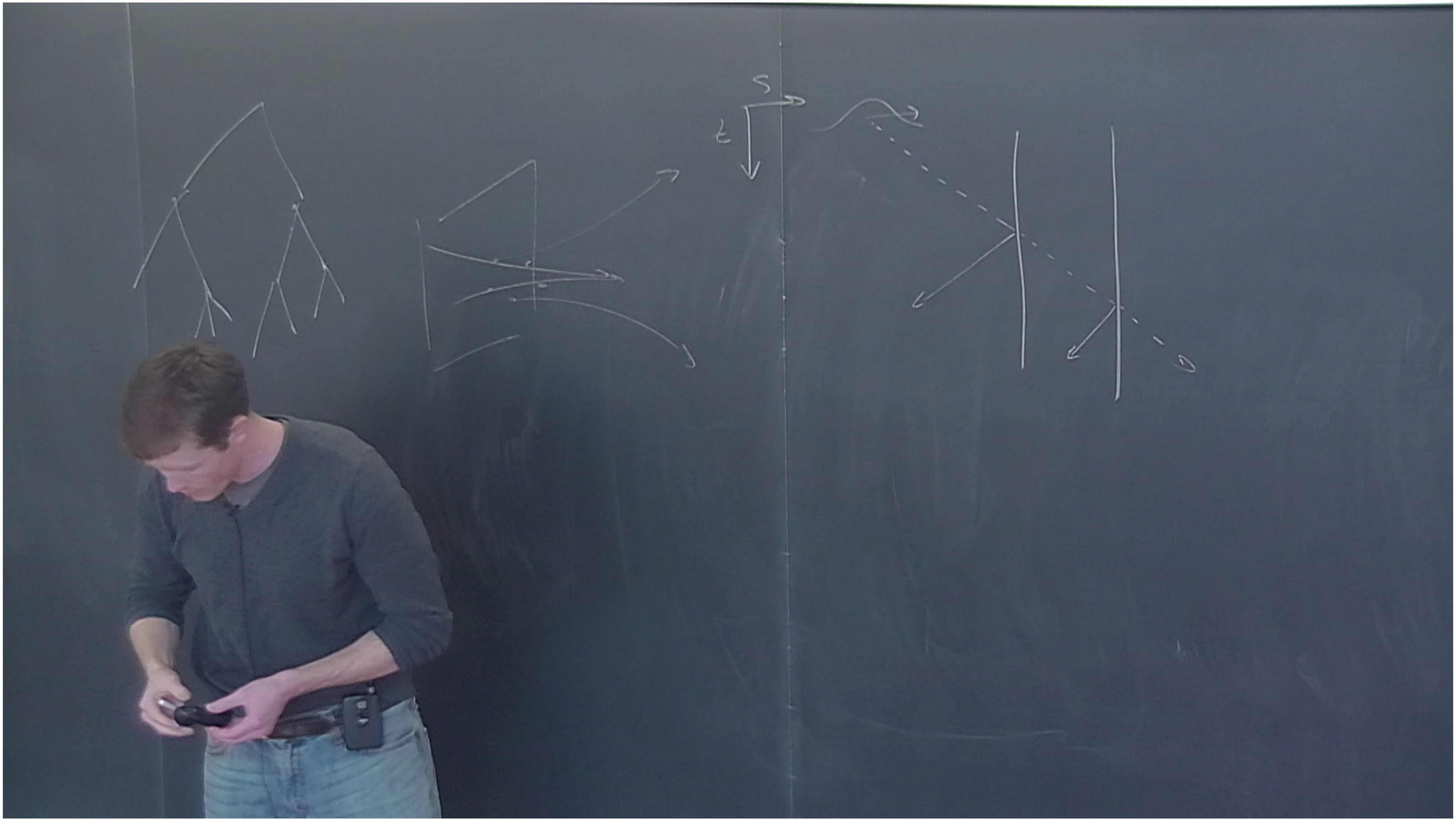


Simulation:
Noah MacAulay


s
t

Some next steps

- Near-term goal: Identify collective variable obeying classical equations of motion
  - Branches are eigenstates of collective variable (e.g., net magnetization)
- Medium-term goal: Simulate hydrodynamic system
  - Branches are simultaneous eigenstates of collective local variables (e.g., local magnetizations)

Some next steps

- ∞-term goals…
  - Are branches defined by approximately conserved variables associated with "prethermalization"?
  - What happens when there is no more room for branches? Thermalization?
  - Universal definition for wavefunction branches — at least as precise as thermodynamic irreversibility
    - "Lab measurements" become just a subset of natural, mathematically described phenomena

Learn more

- Quantum-info and cosmology work that motivated this:
  - arXiv:1608.05377 [PRL 118, 120402 (2017)]
  - arXiv:1704.00728 [IJMPD 26, 1743006 (2017)]
  - arXiv:1711.05719
- Nothing written up yet about tensor-network applications
  - Come talk to my collaborators and me!

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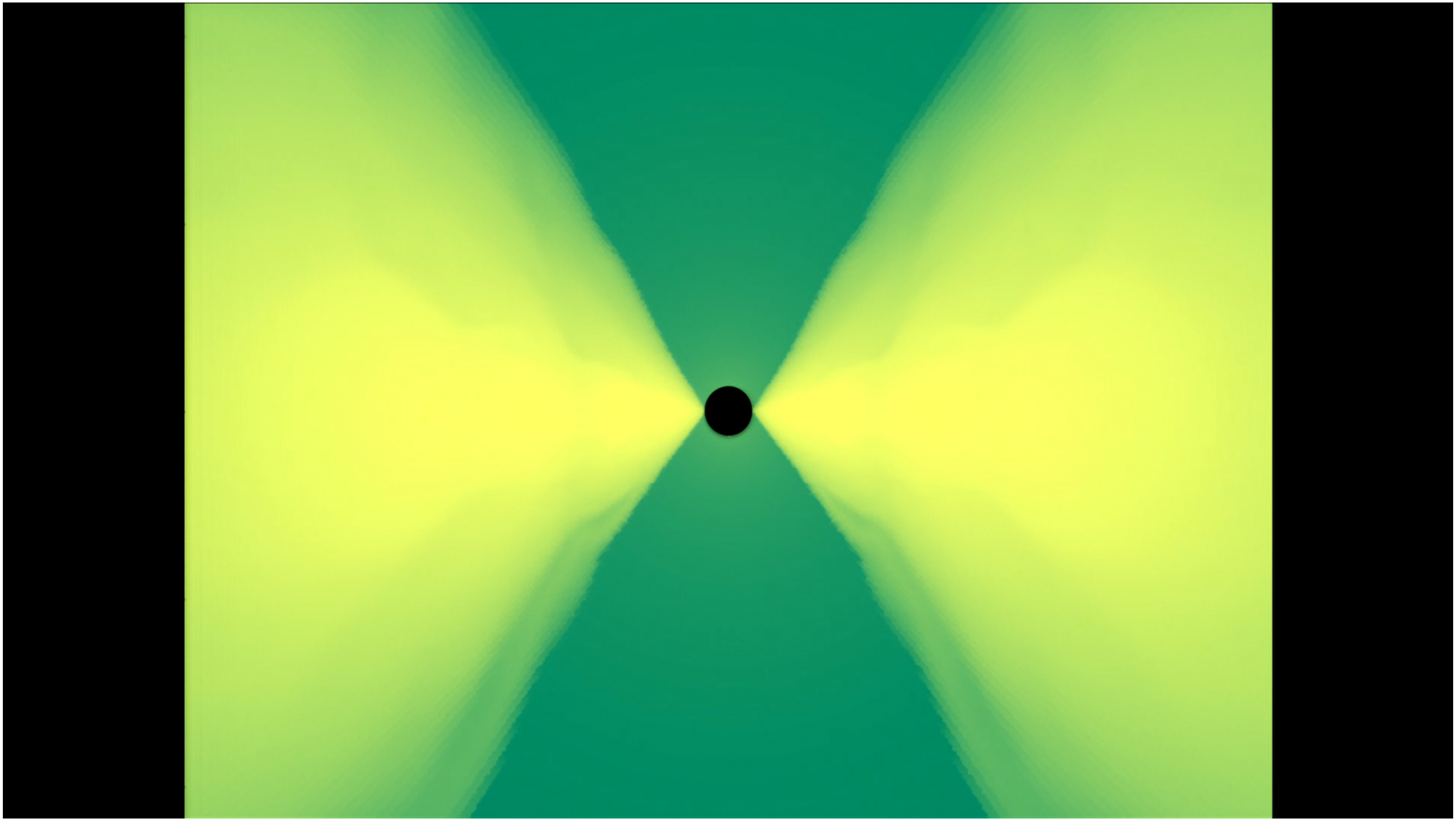
Probing the Innermost Black Hole Accretion Flow Structure

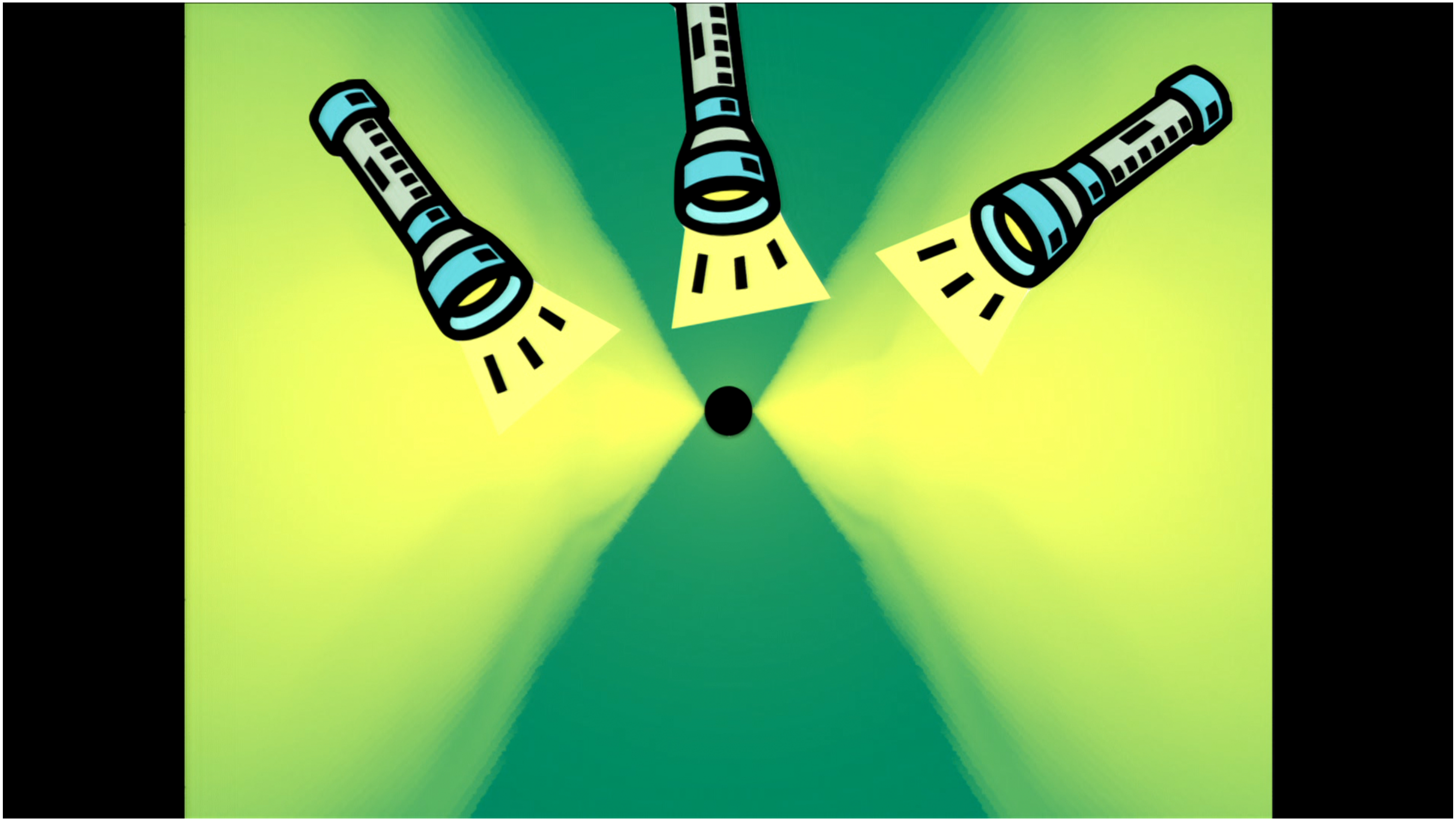
and General Relativistic Effects

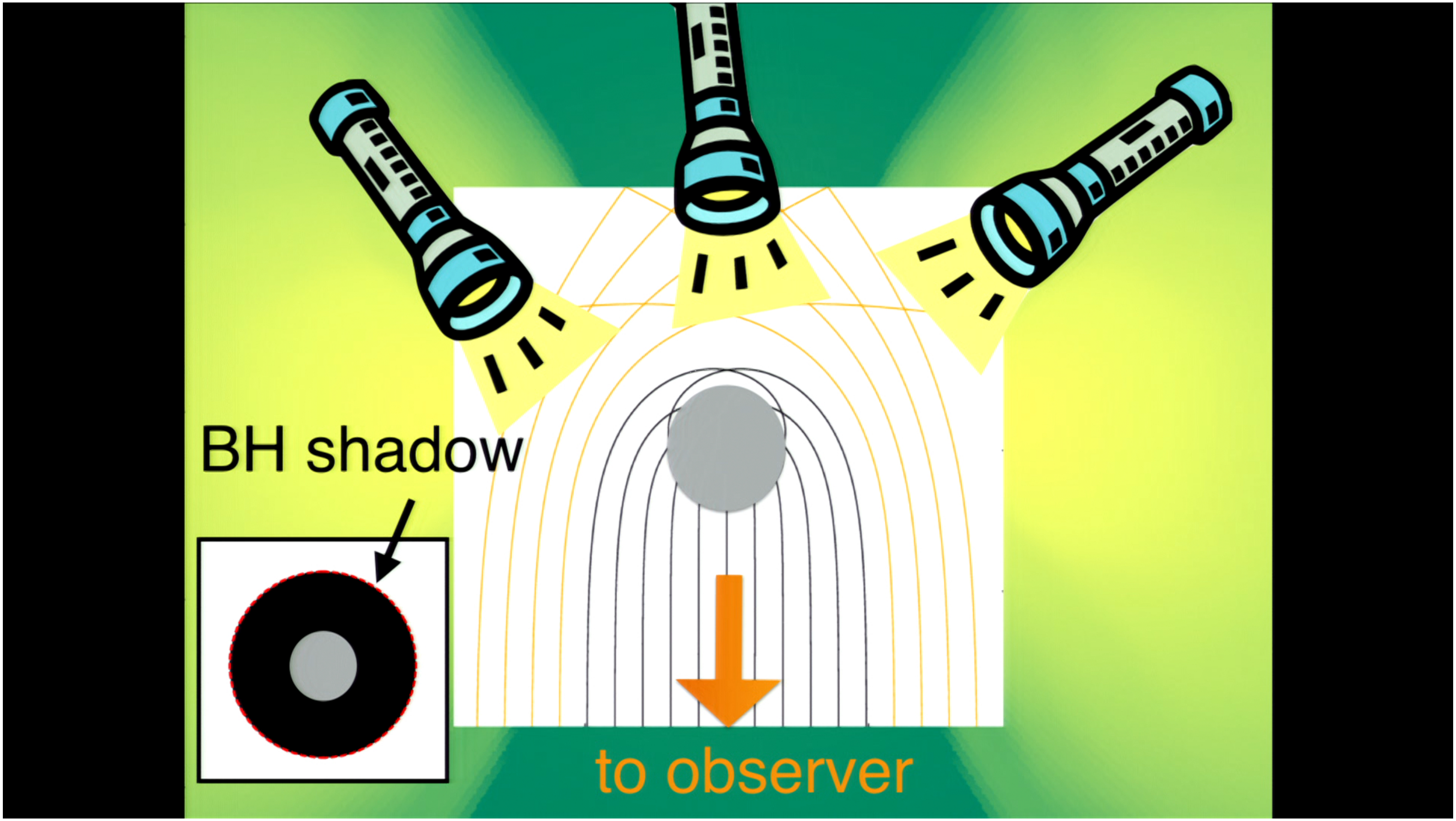
with Event Horizon Telescope

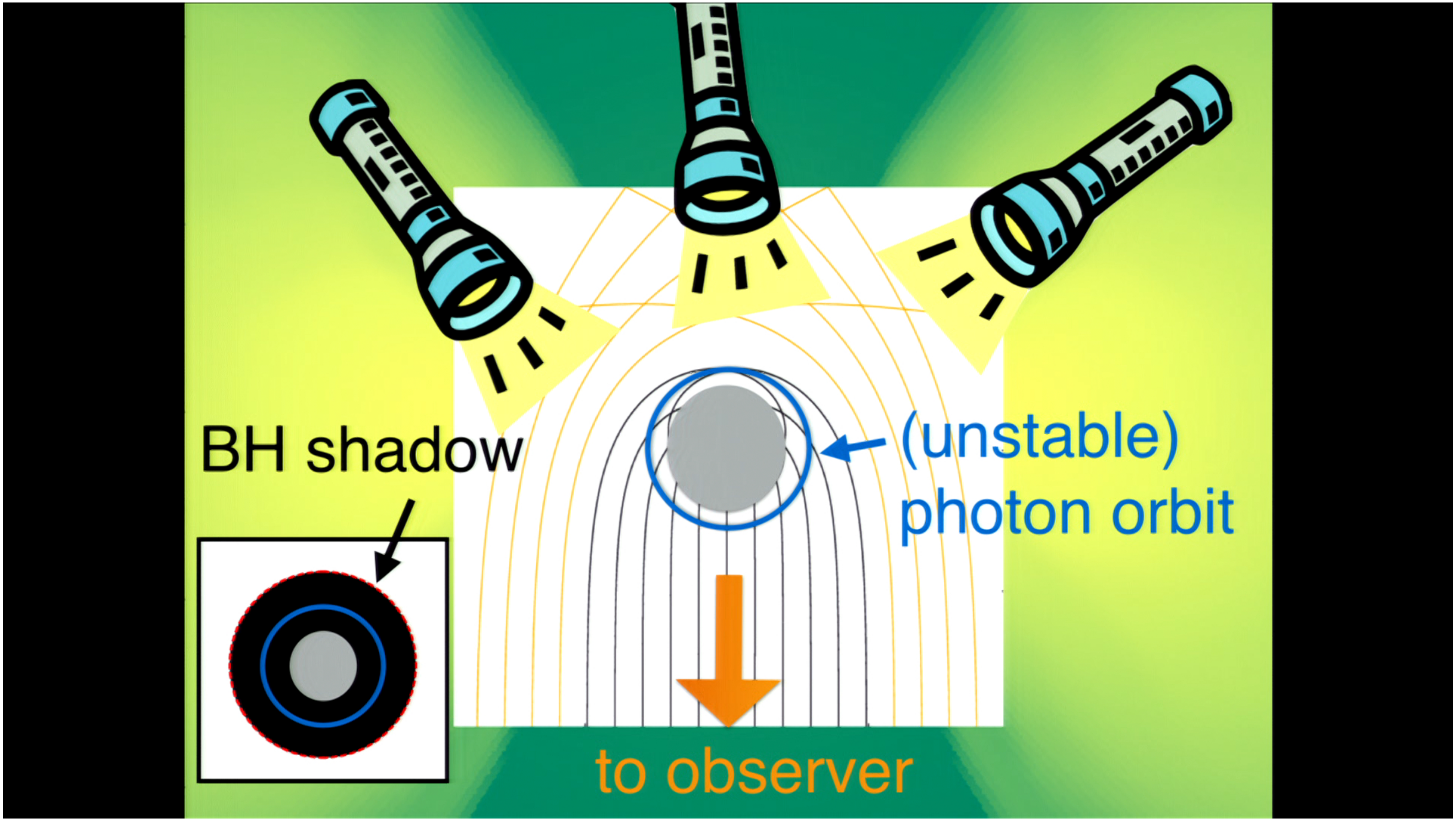
PERIMETER INSTITUTE

Hung-Yi Pu 2018 PI day





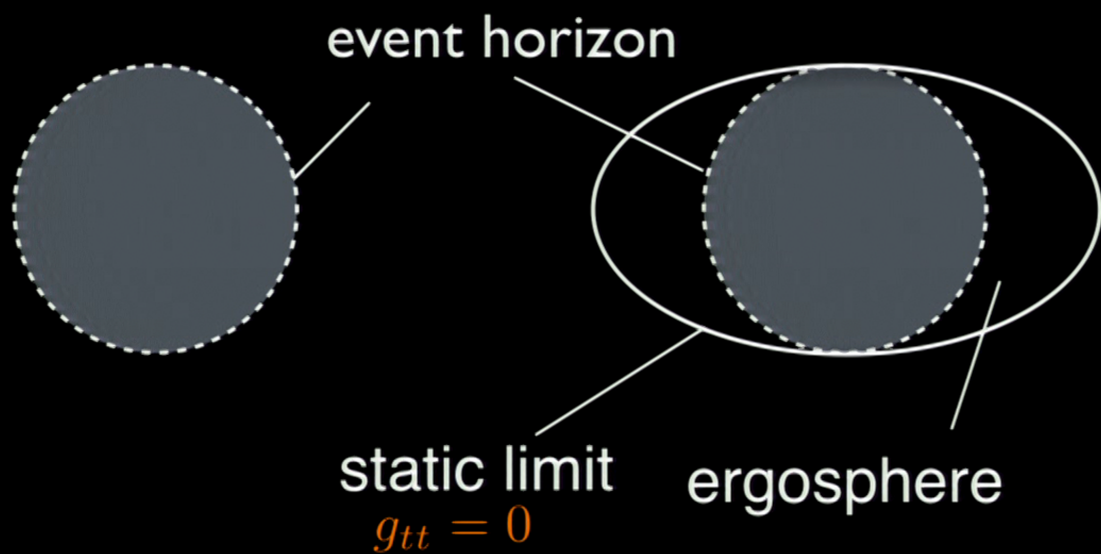

BH shadow
to observer

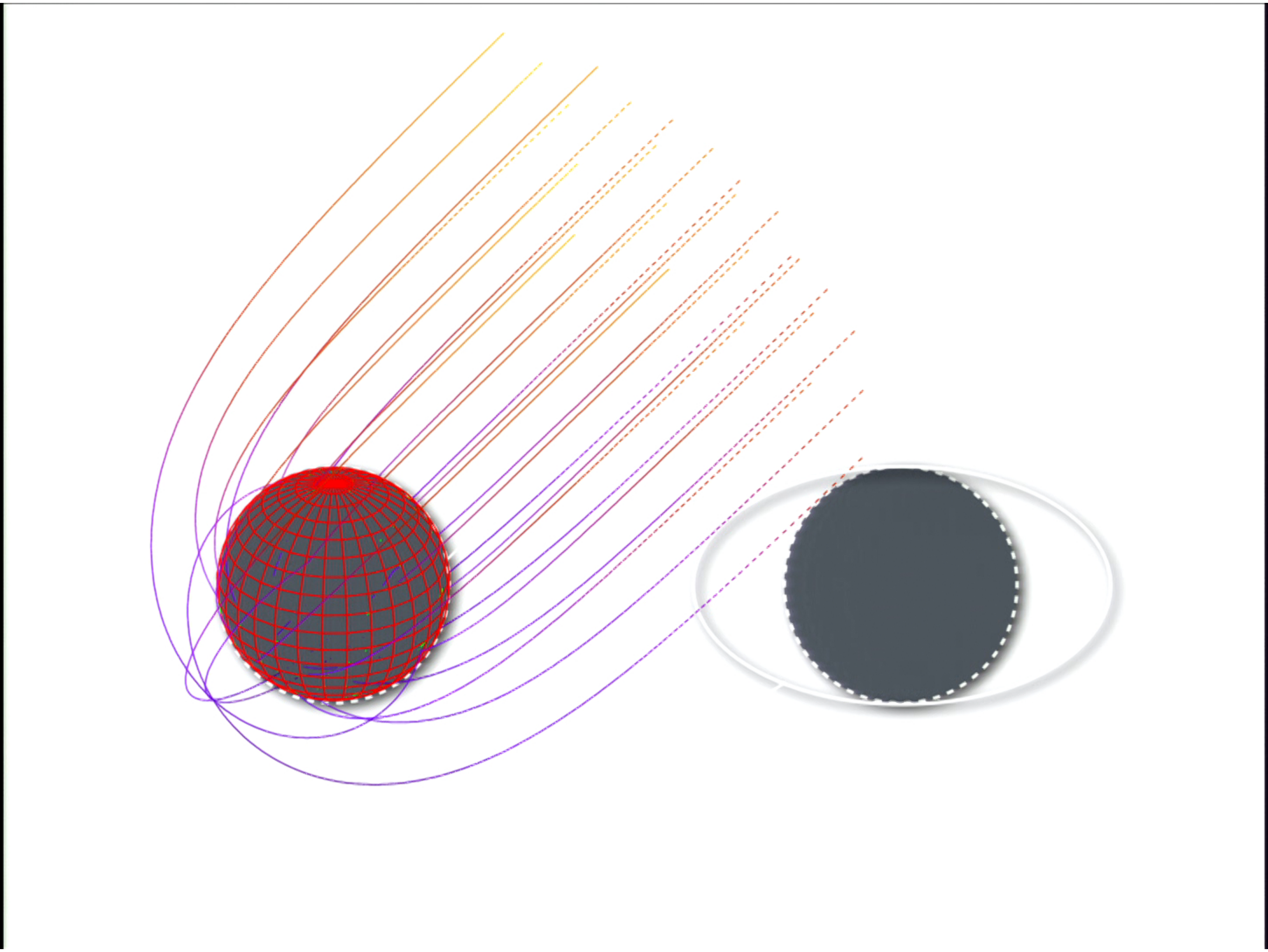

BH shadow
(unstable)
photon orbit
to observer

non-rotating and rotating BHs

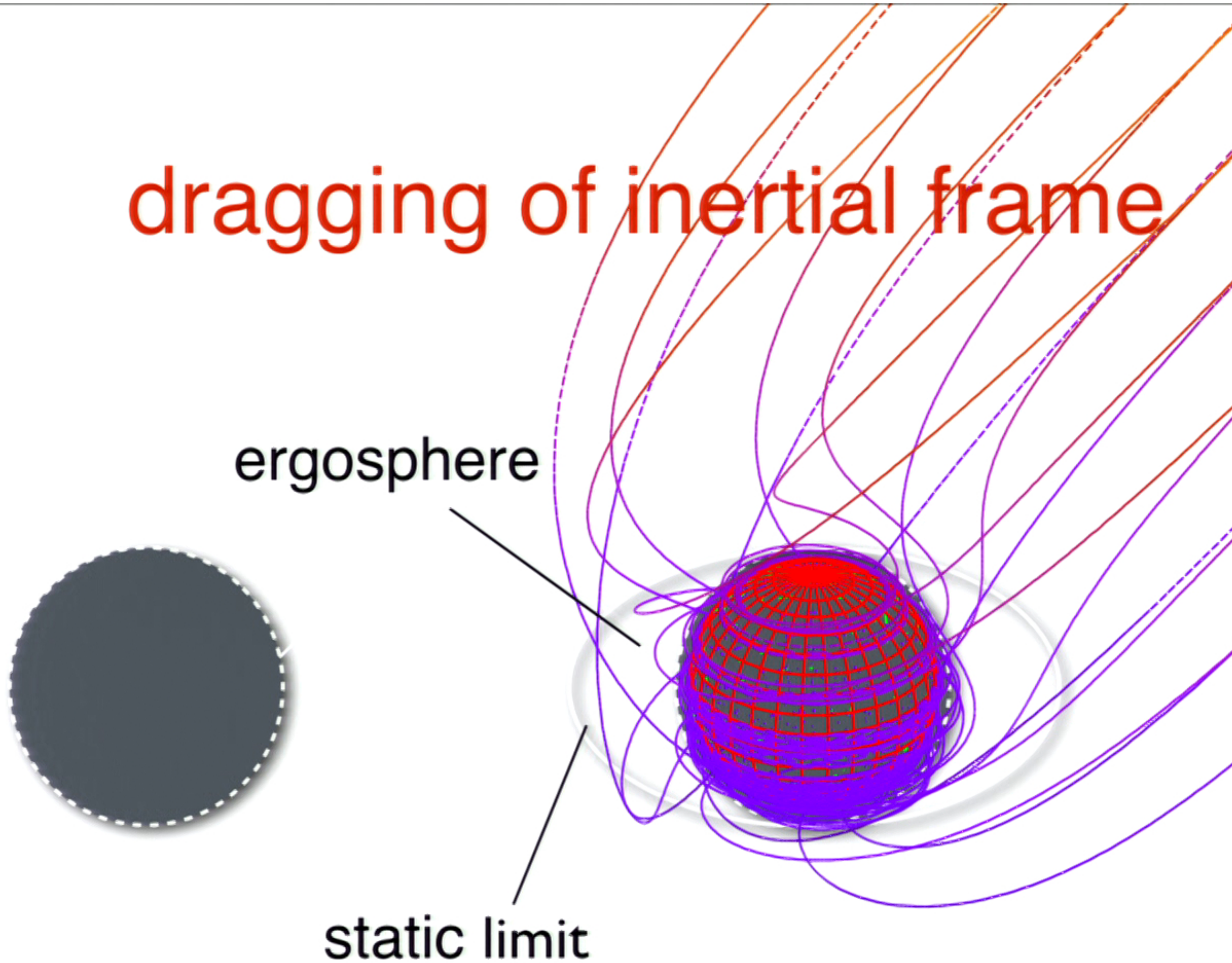
Non-rotating BH:
described by Schwarzschild metric

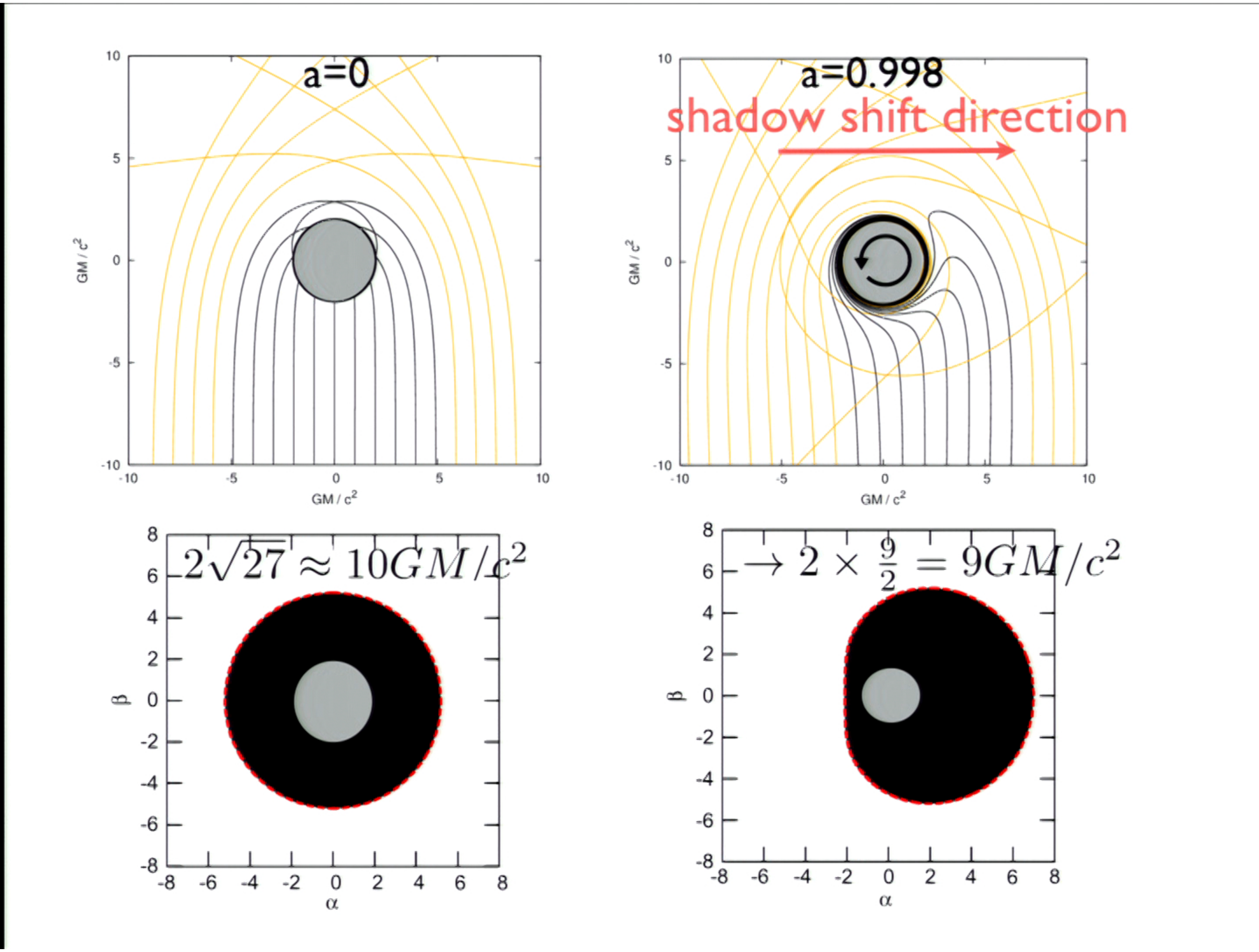
Rotating BH:
described by Kerr metric





dragging of inertial frame

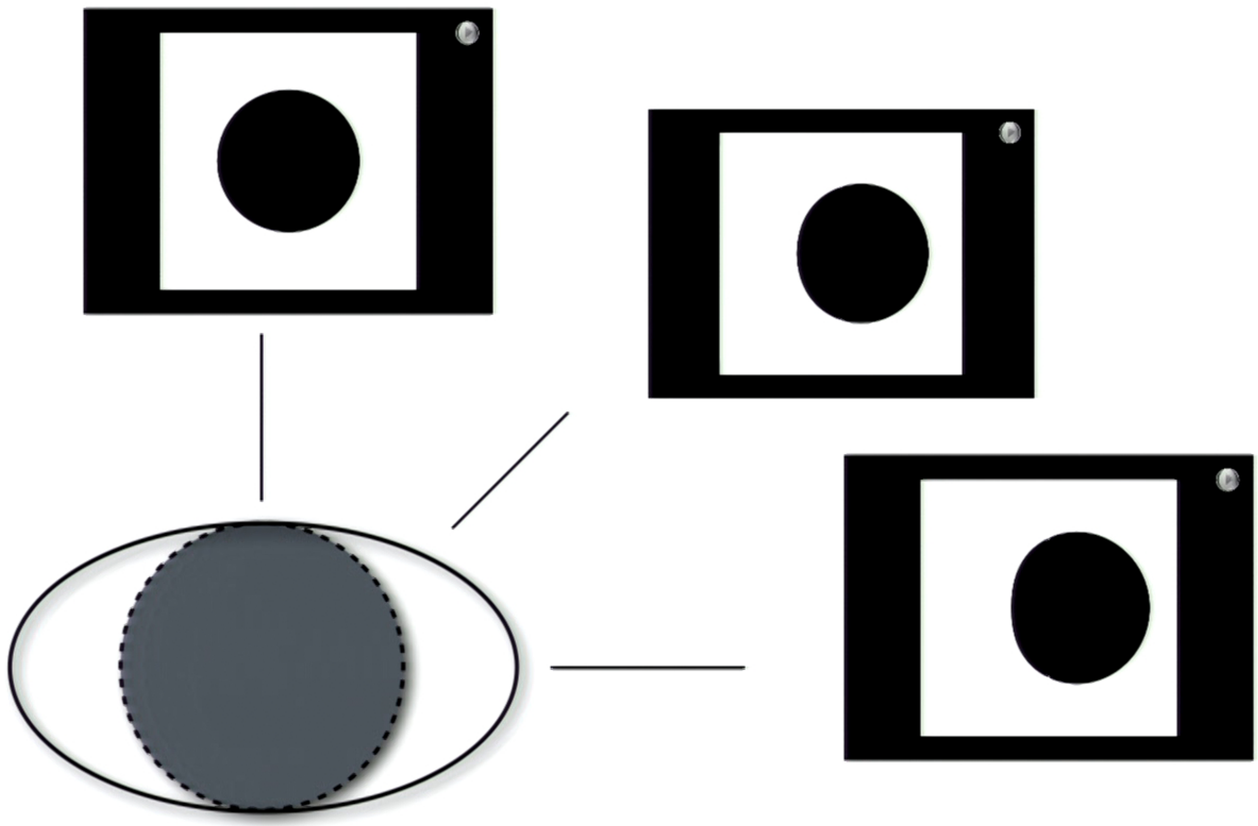


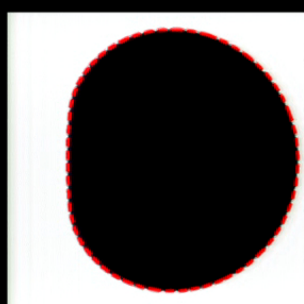


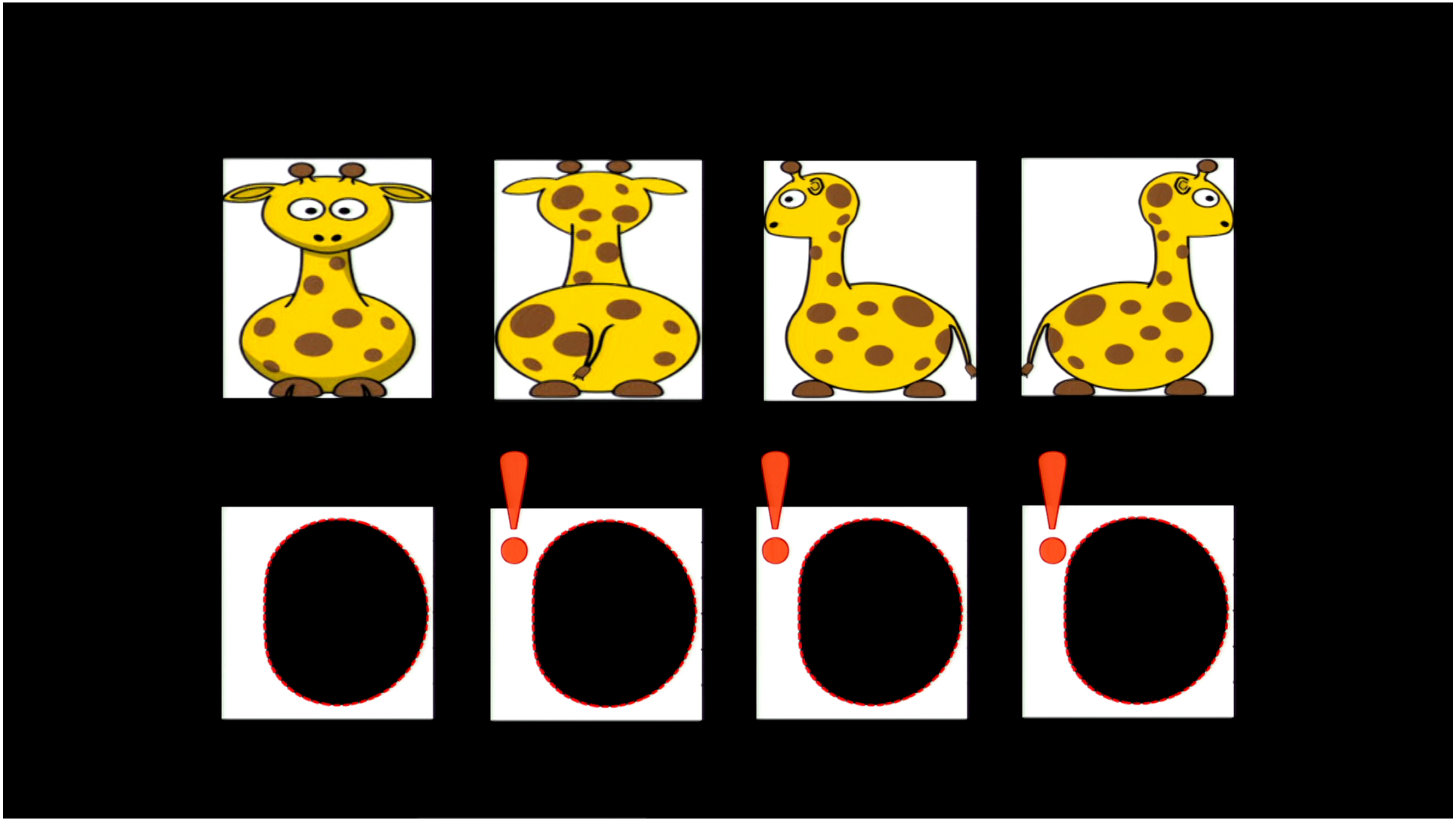
a=0
a=0.998
shadow shift direction
GM / c²
$2\sqrt{27} \approx 10GM/c^2$
$\rightarrow 2 \times \frac{9}{2} = 9GM/c^2$
α
β

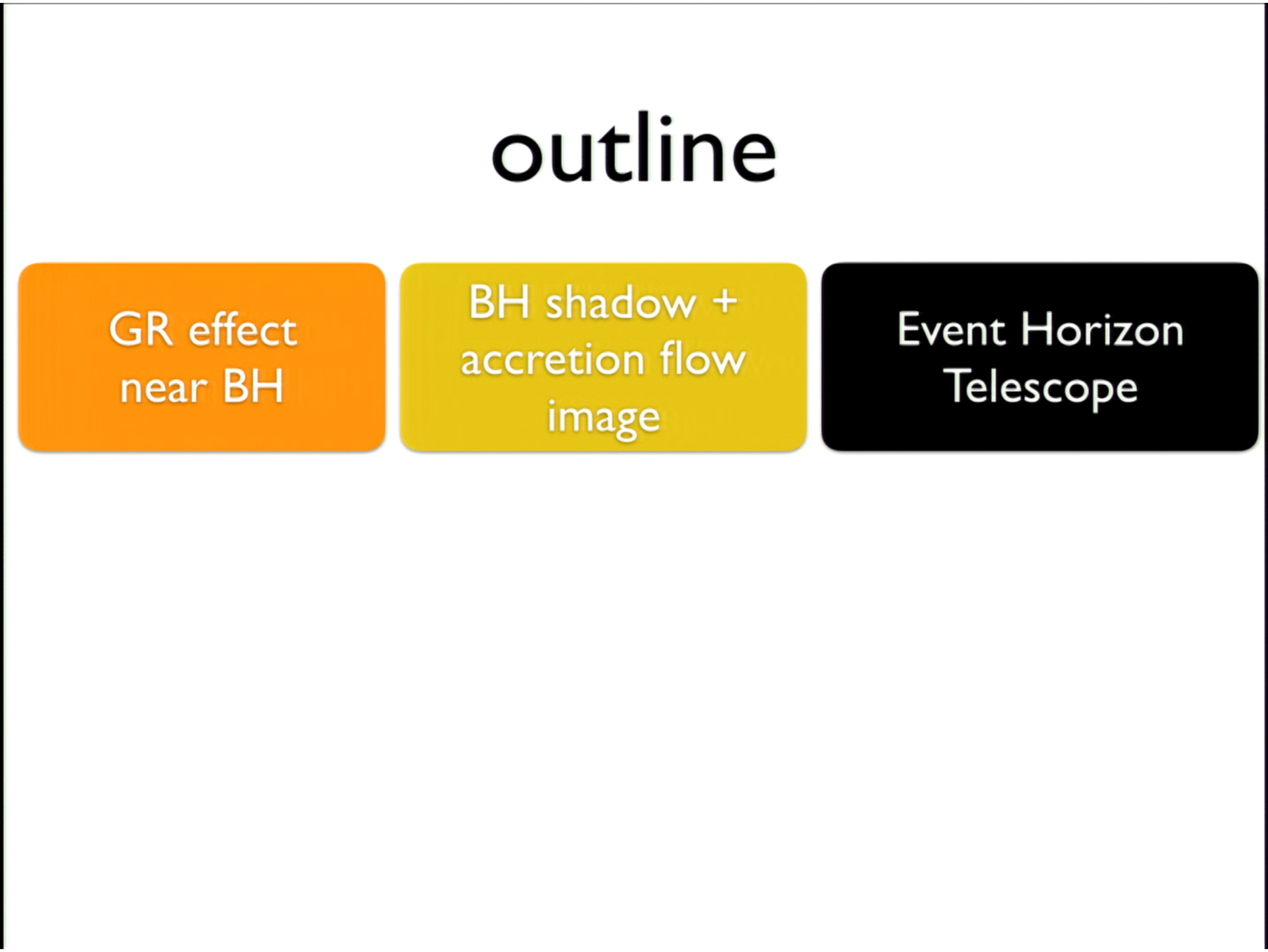
Black Hole Shadow

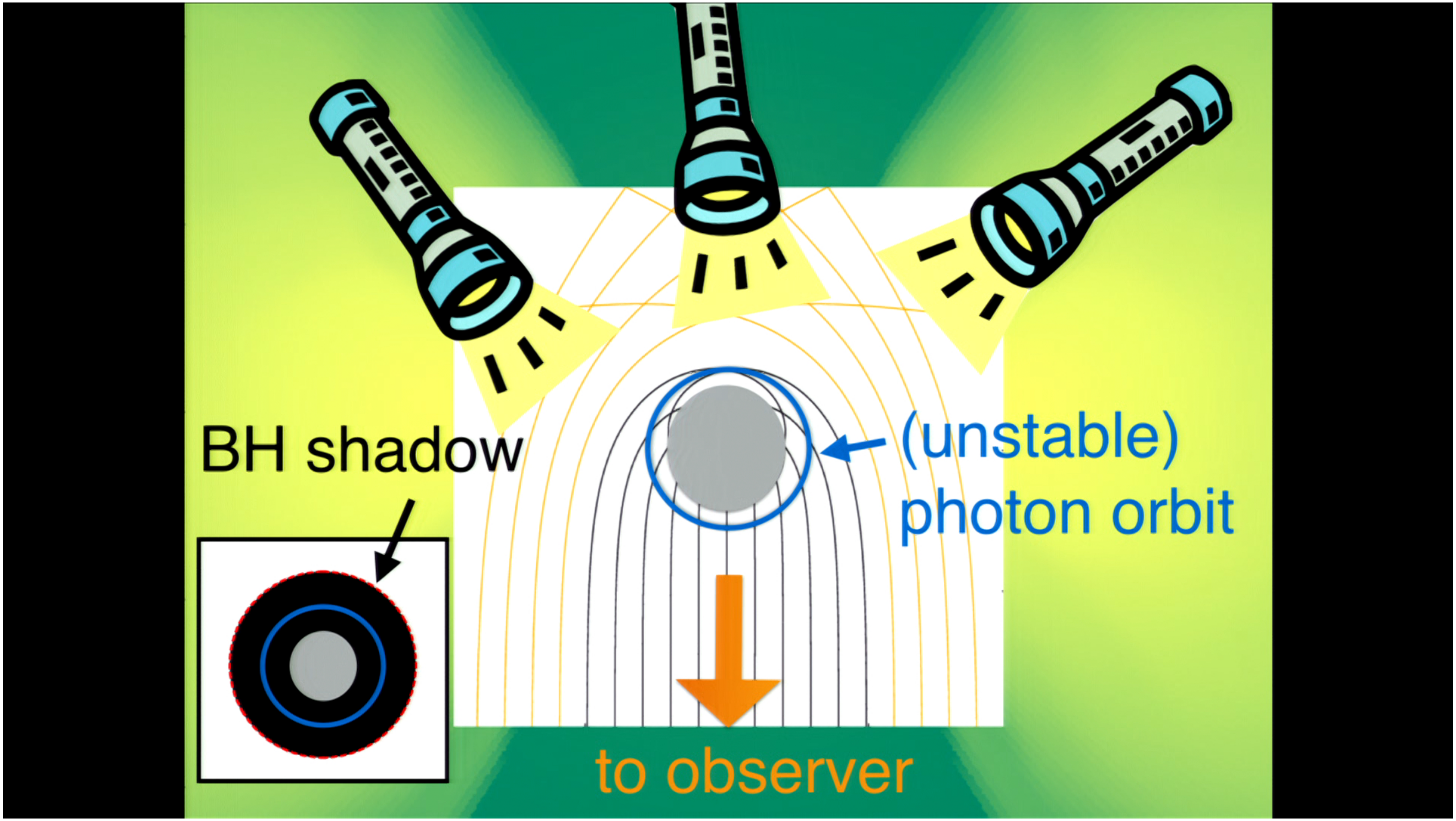
determined by the background spacetime








outline
GR effect near BH
BH shadow + accretion flow image
Event Horizon Telescope


BH shadow
(unstable)
photon orbit
to observer

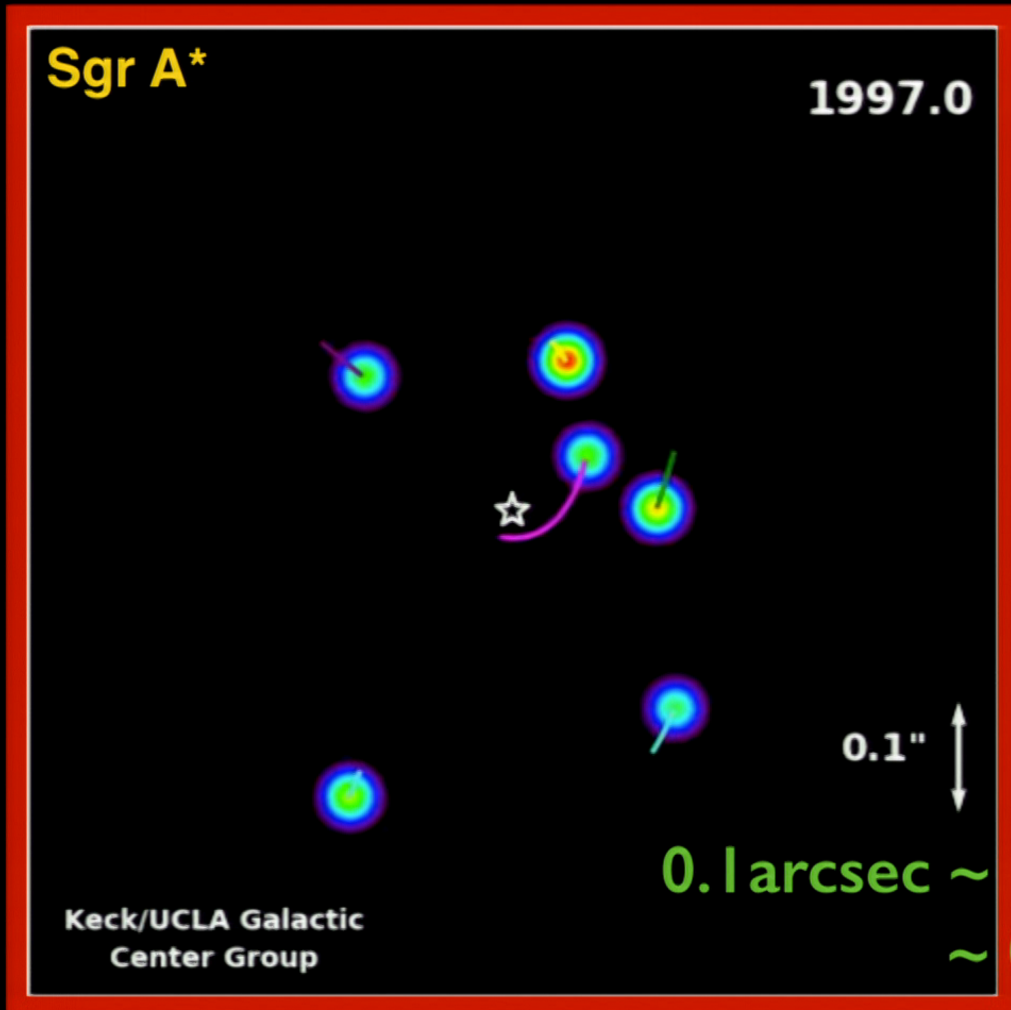
GR effect near BH

BH + accretion: flow image properties

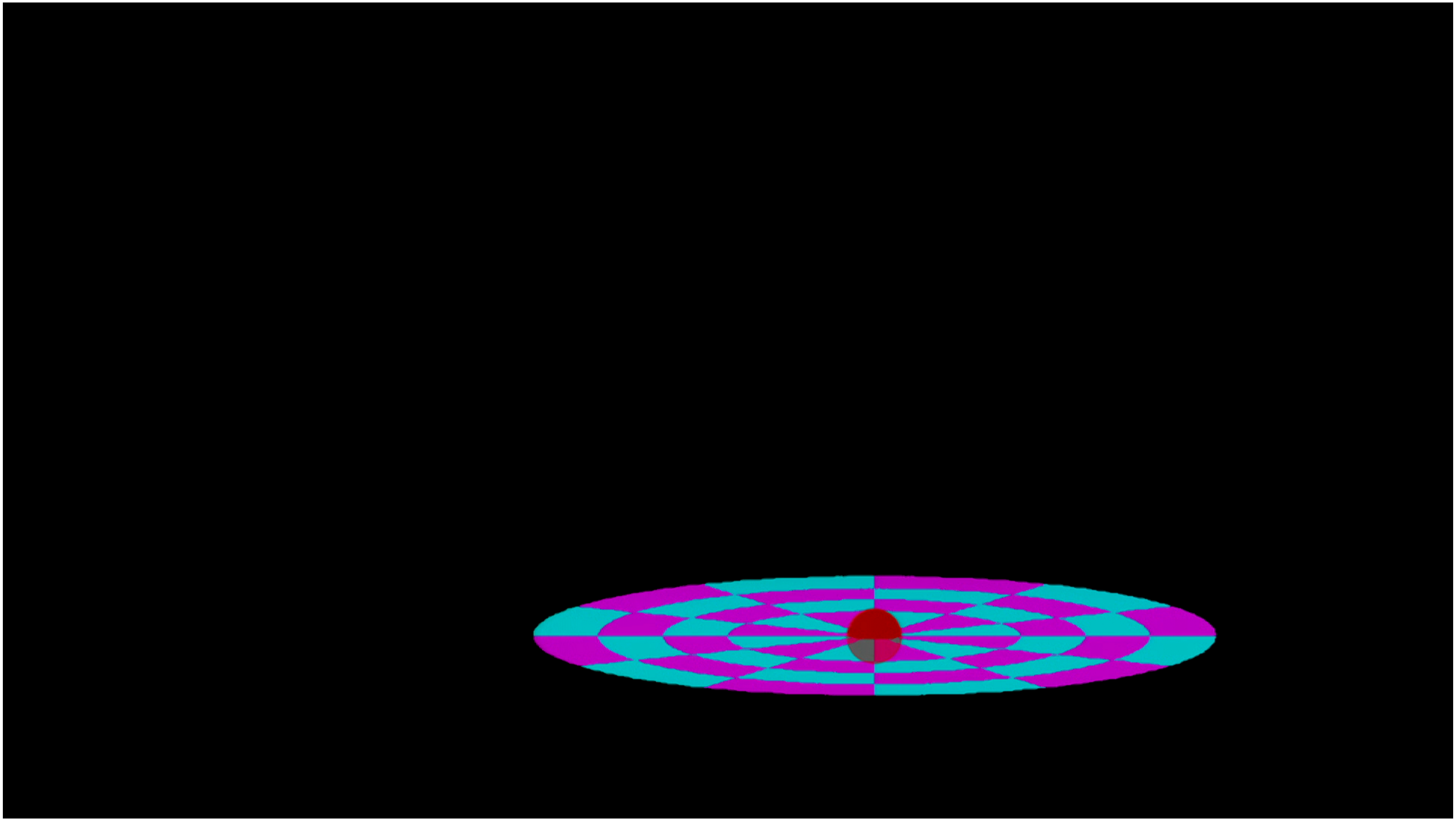
Event Horizon Telescope

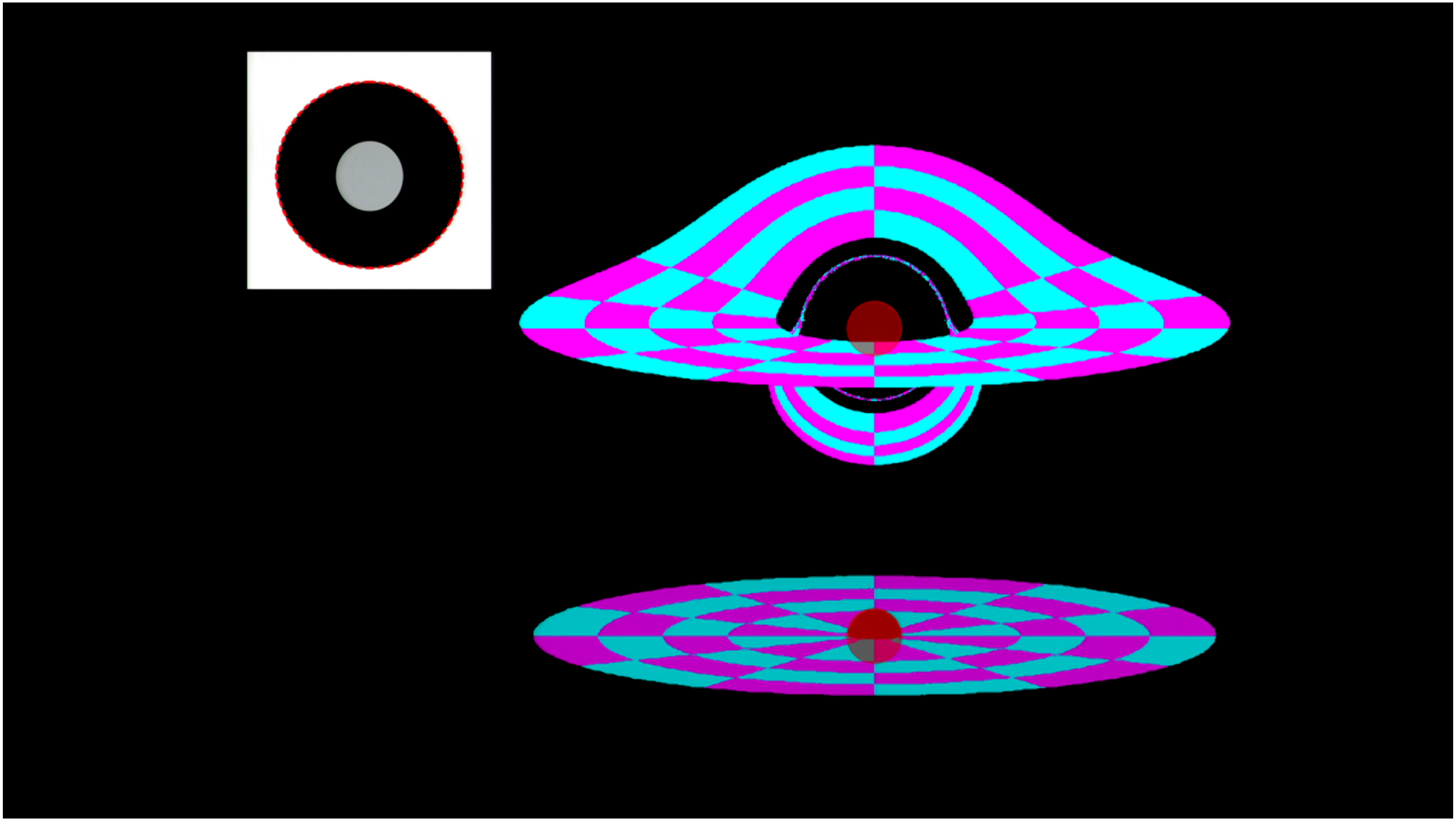
Source	Sgr A* (Southern sky, without jet, interstellar scattering)	M 87 (Northern sky, with jet)
BH Mass	$0.045 \times 10^{8}\, M_{\odot}$	$66 \times 10^{8}\, M_{\odot}$
Distance	0.008 Mpc	16.7 Mpc
"radius of a BH" ($2GM/c^2$)	11 µas	8 µas
"**BH shadow**" ($\sim 10GM/c^2$)	55 µas	40 µas

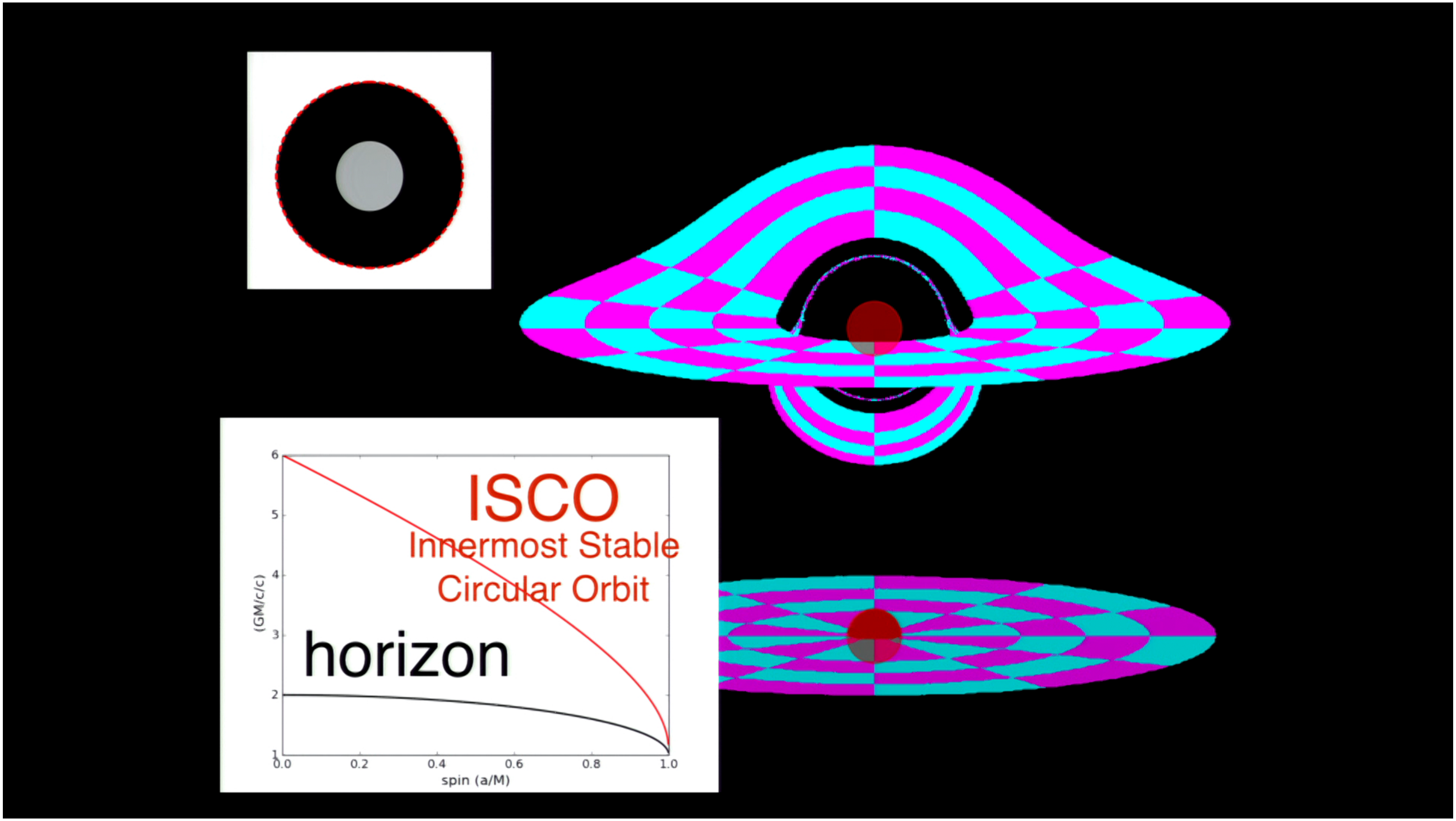
required angular resolution: µas

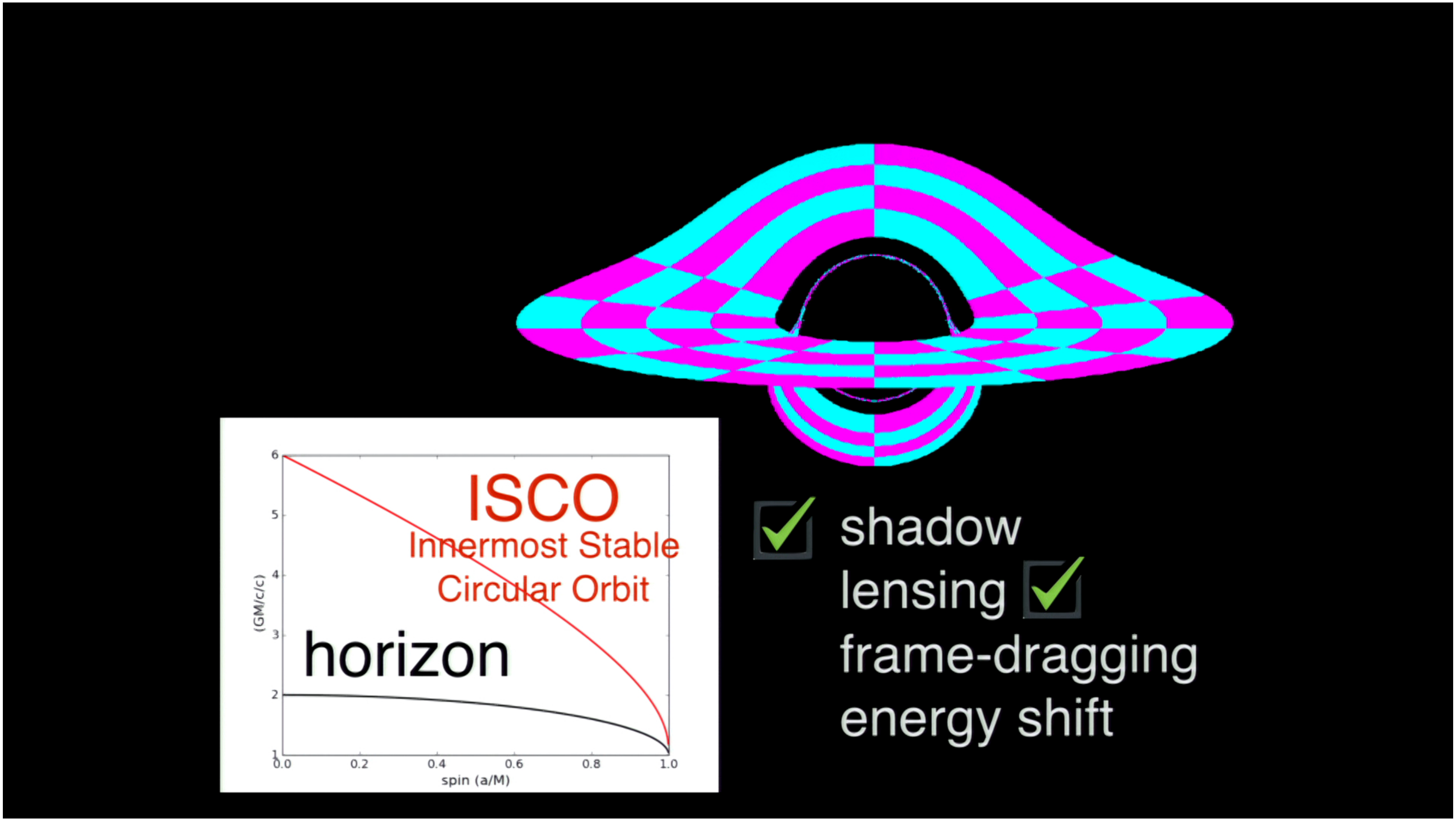


0.1arcsec ~ $10^{4\text{-}5}$ GM/c^2
~ 0.004 pc

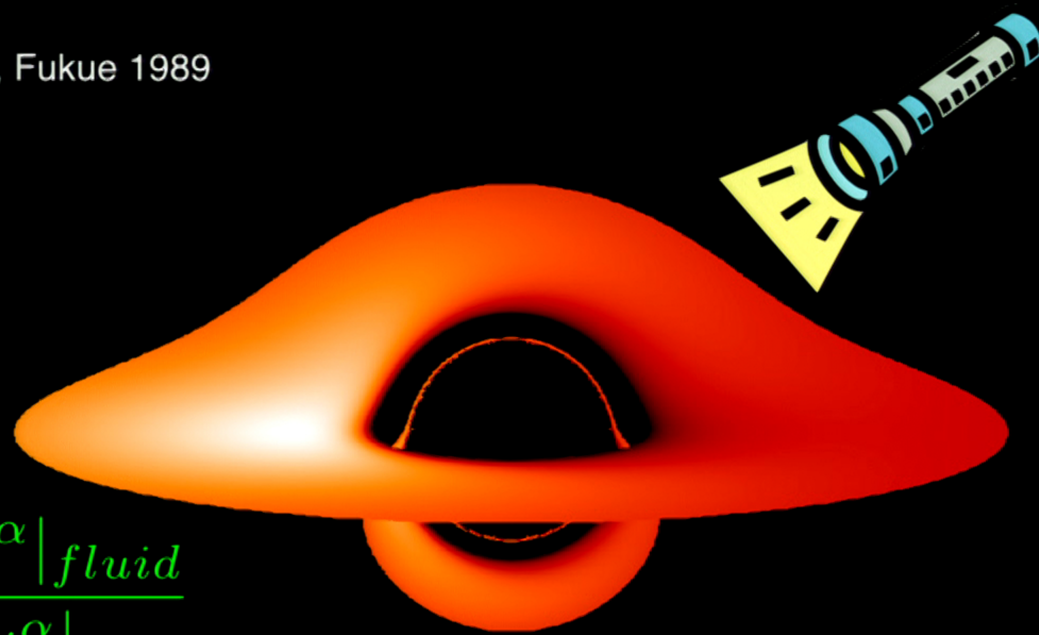





ISCO
Innermost Stable
Circular Orbit
horizon
(GM/c/c)
6
5
4
3
2
1
0.0
0.2
0.4
0.6
0.8
1.0
spin (a/M)


6
5
4
3
2
1
0.0
0.2
0.4
0.6
0.8
1.0
(GM/c/c)
spin (a/M)
ISCO
Innermost Stable
Circular Orbit
horizon
shadow
lensing
frame-dragging
energy shift

e.g, Fukue 1989



$$\frac{E_{fluid}}{E_{obs}} = \frac{p_\alpha u^\alpha|_{fluid}}{p_\alpha u^\alpha|_{obs}}$$

- ☑ shadow
- lensing ☑
- ☑ frame-dragging
- energy shift ☑

GR Radiative Transfer

*Photon p_α

*GR + HD/ MHD u^α

$\mathcal{I} = I_\nu/\nu^3 = \text{invariant}$

*energy shift $\frac{E_{\text{comoving}}}{E_{\text{obs}}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$

*radiative transfer $\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\tau_\nu} = -\mathcal{I} + \frac{\eta}{\chi}$

$\chi = \nu\alpha_\nu$ (invariant) $\eta = j_\nu/\nu^2$ (invariant)

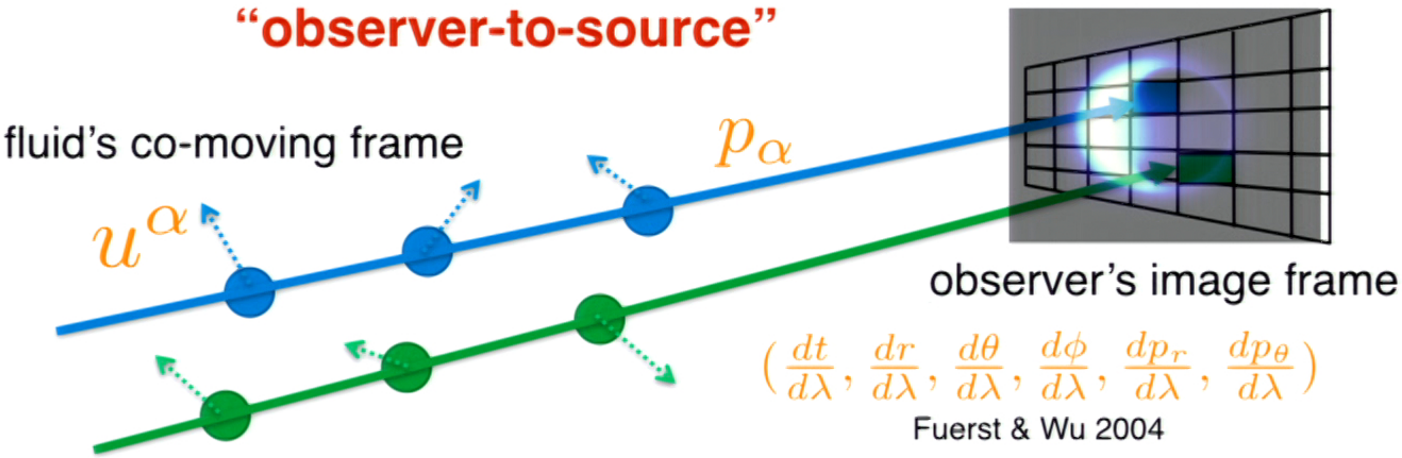
$$\gamma^{-1} \equiv \frac{E_{\rm comoving}}{E_{\rm obs}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$$

$$\mathcal{I} = I_\nu/\nu^3 = \text{invariant}$$

$$p_t = -E$$

$$p_\phi = L_z$$

“observer-to-source”



$$\left(\frac{dt}{d\lambda}, \frac{dr}{d\lambda}, \frac{d\theta}{d\lambda}, \frac{d\phi}{d\lambda}, \frac{dp_r}{d\lambda}, \frac{dp_\theta}{d\lambda}\right)$$

Fuerst & Wu 2004

$$\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\tau_\nu} = -\mathcal{I} + \frac{\eta}{\chi}$$

Younsi et al. 2012

$$\frac{\mathrm{d}\tau}{\mathrm{d}\lambda} = \gamma^{-1}\alpha_{0,\nu}$$

$$\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\lambda} = \gamma^{-1}\left(\frac{j_{0,\nu}}{\nu^3}\right)$$

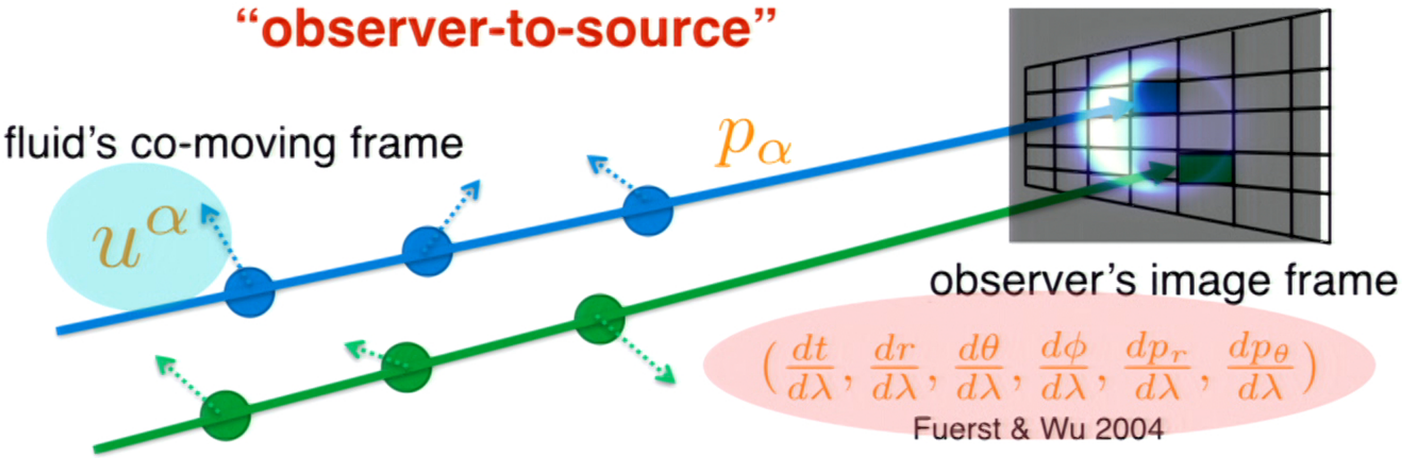
$$\gamma^{-1} \equiv \frac{E_{\rm comoving}}{E_{\rm obs}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$$

$$\mathcal{I} = I_\nu/\nu^3 = \text{invariant}$$

$$p_t = -E$$

$$p_\phi = L_z$$

"observer-to-source"



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Younsi et al. 2012

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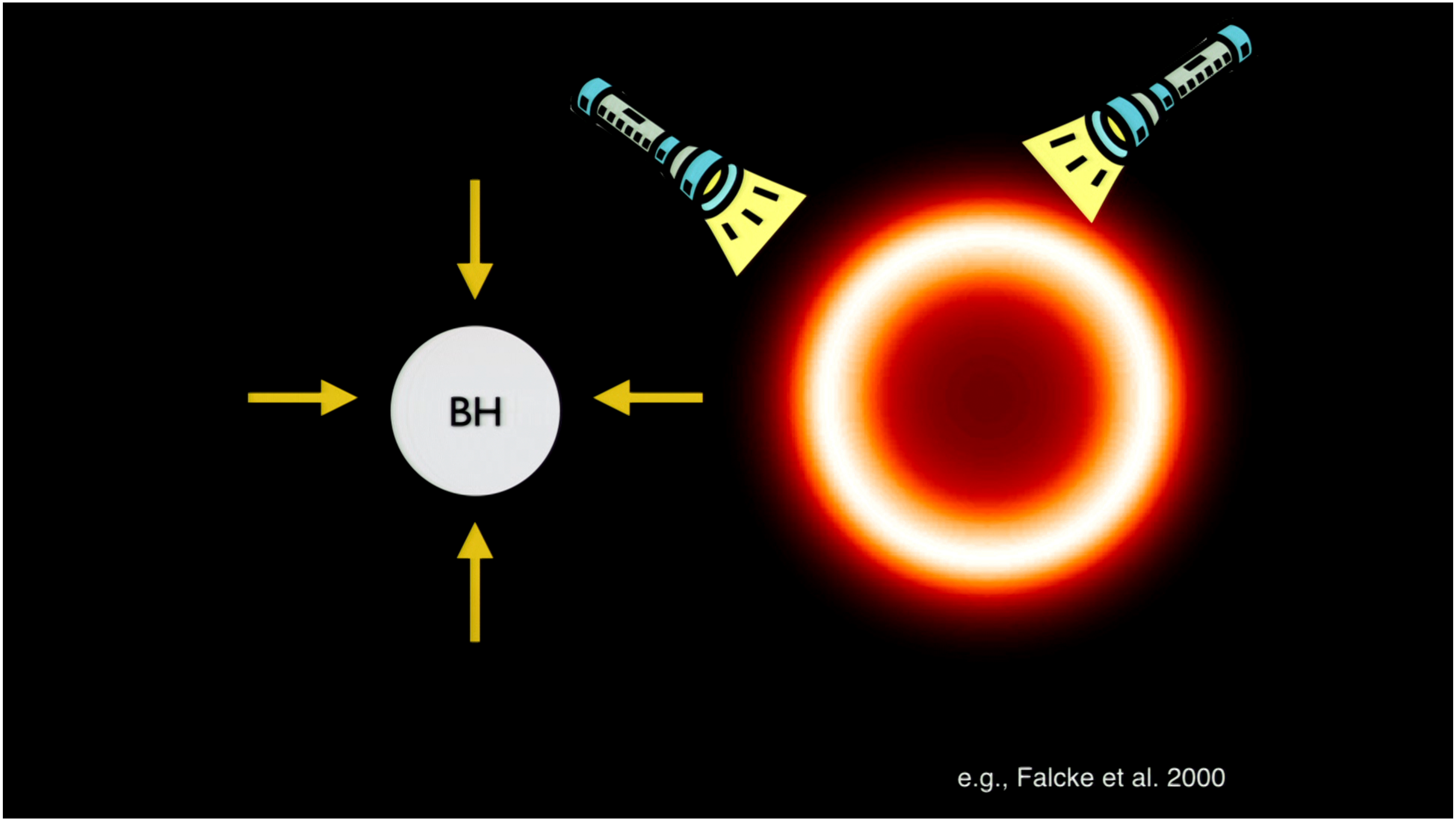
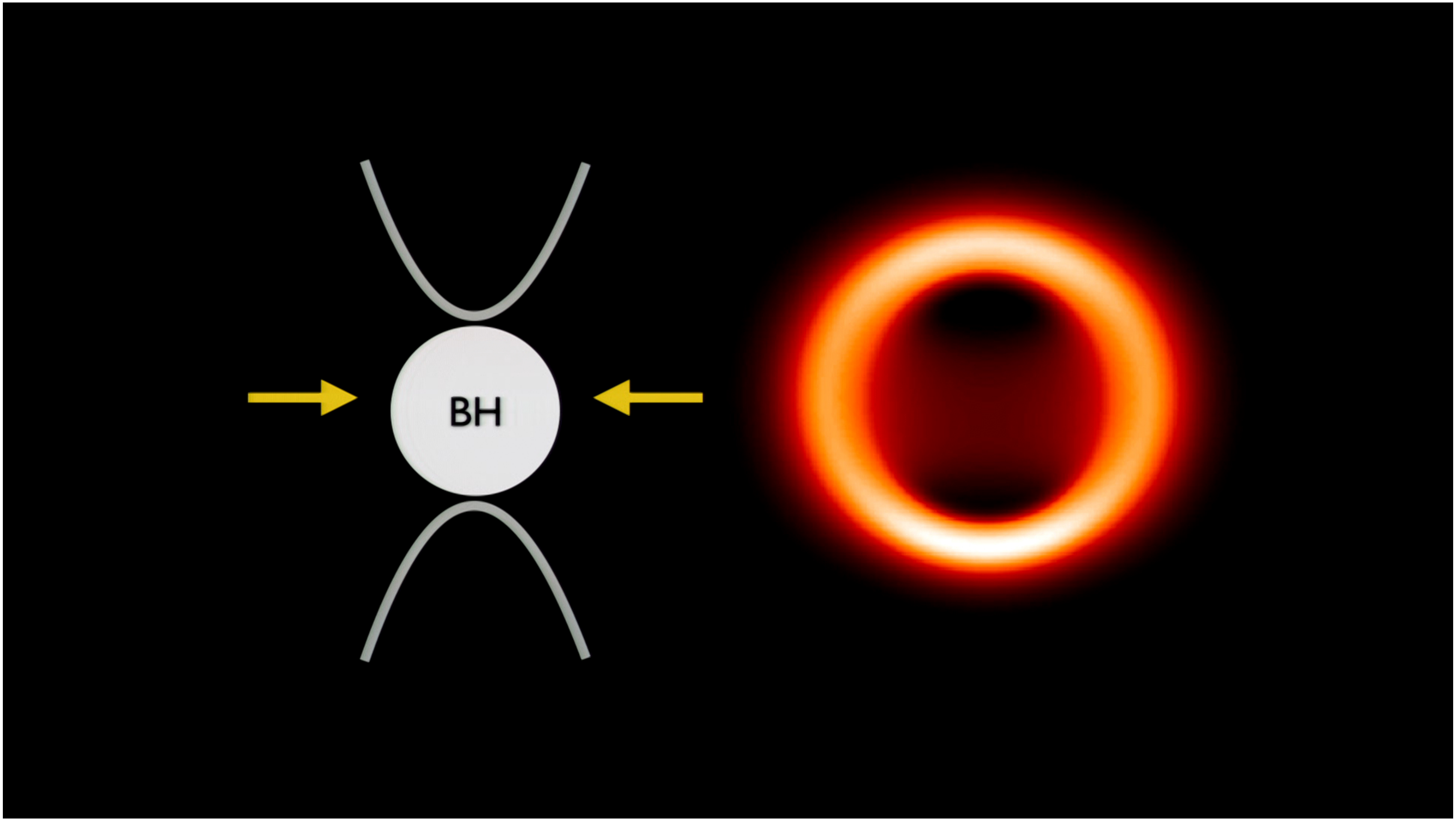
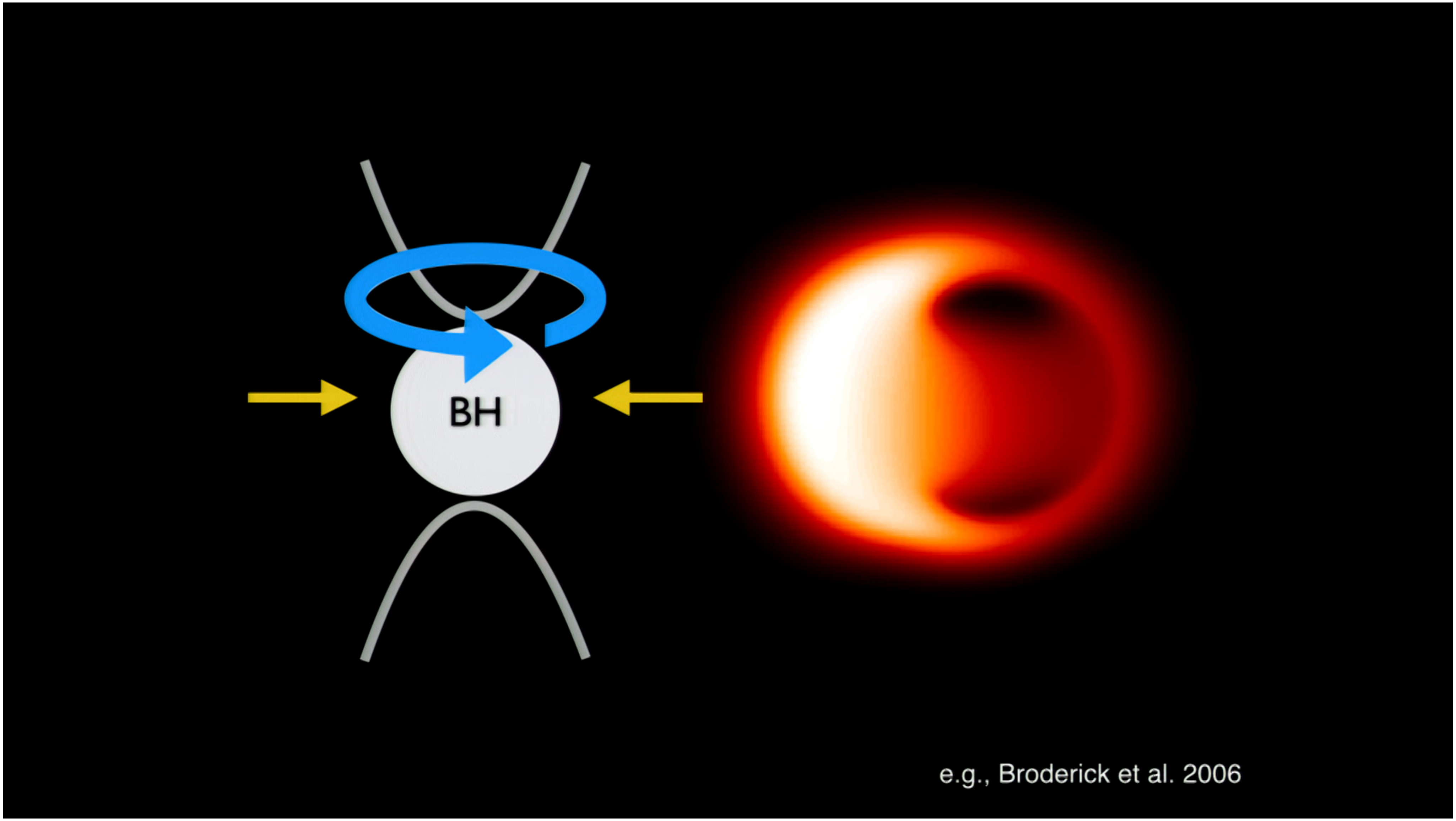
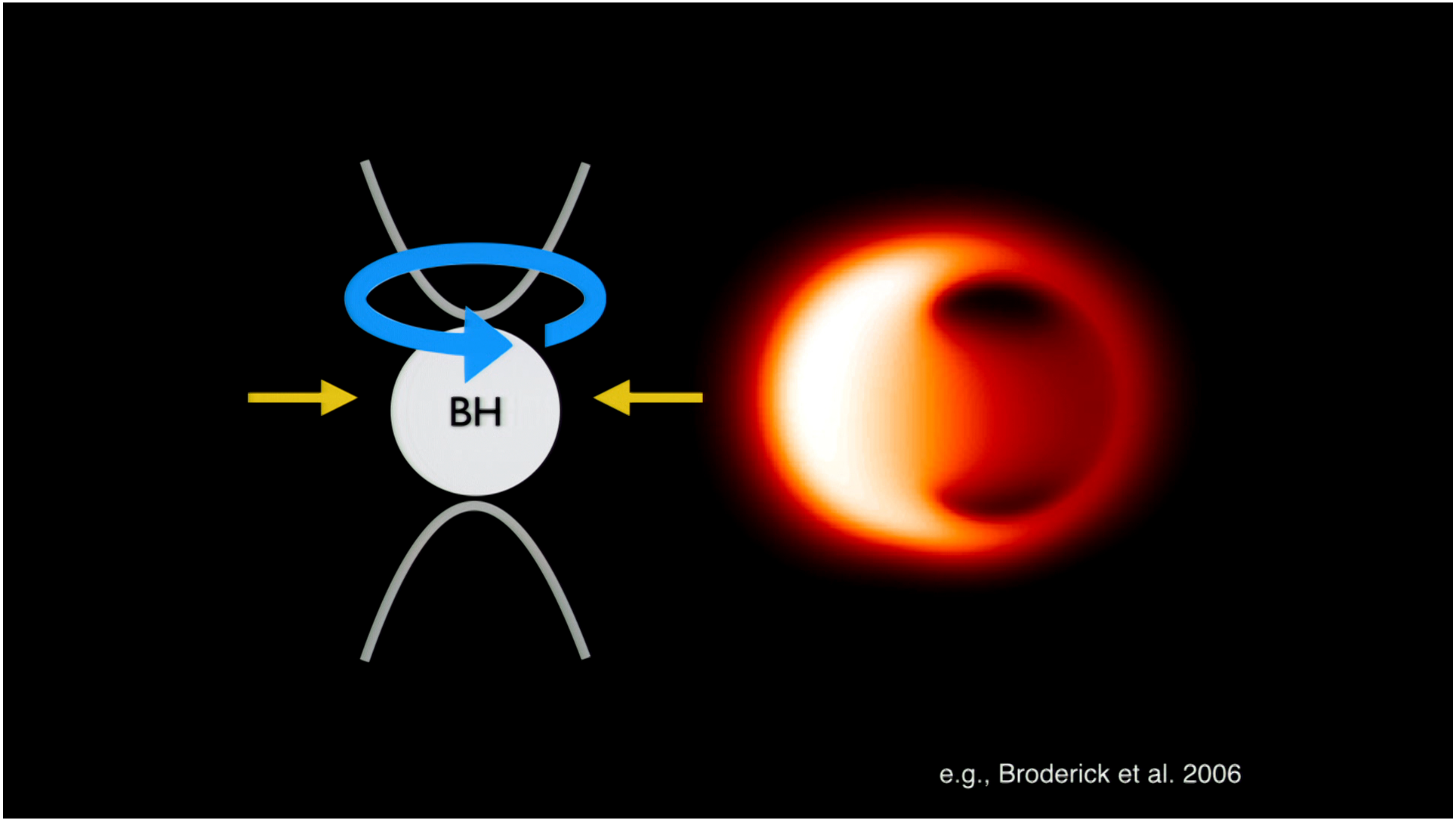
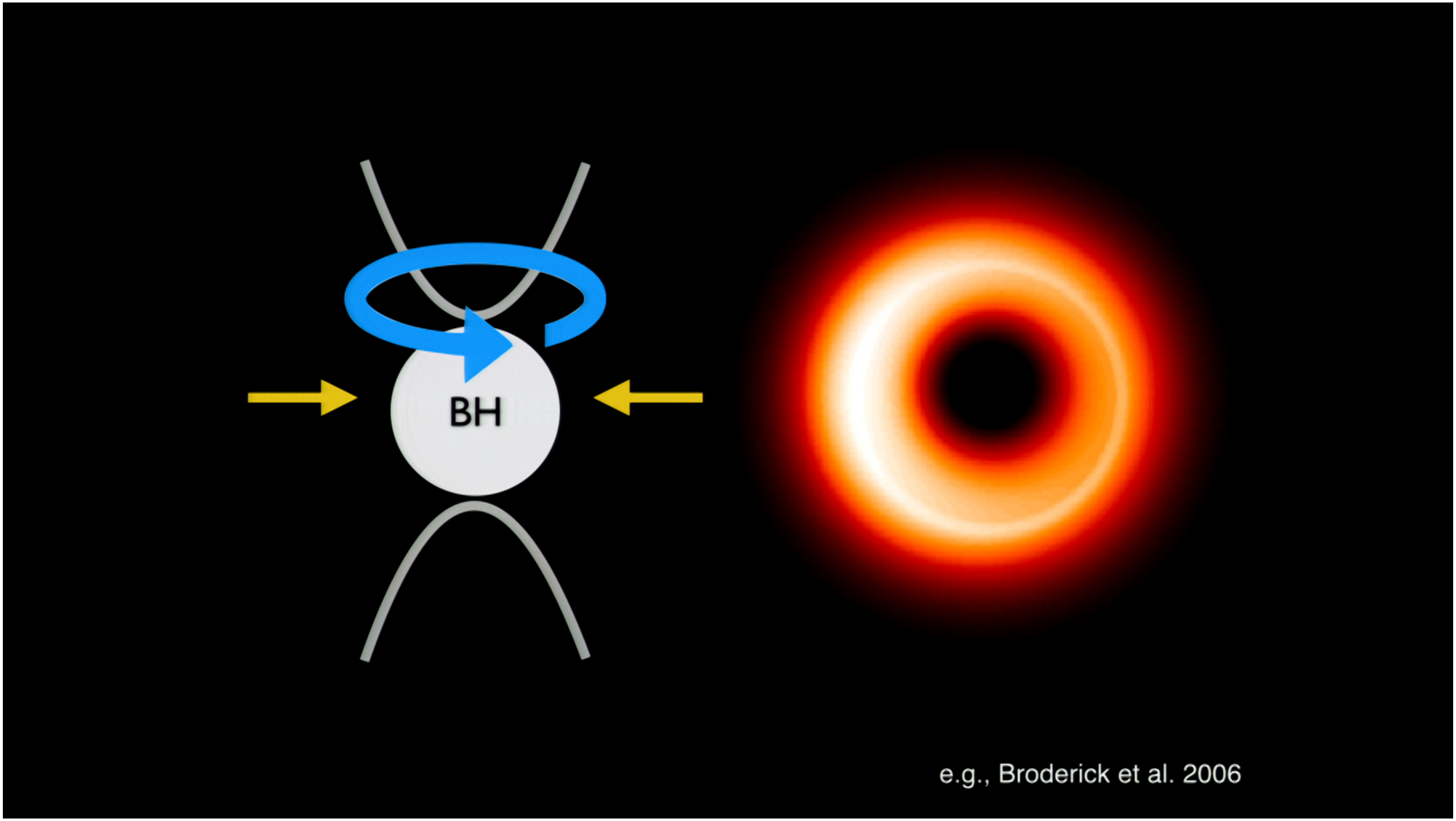

BH
e.g., Falcke et al. 2000


BH

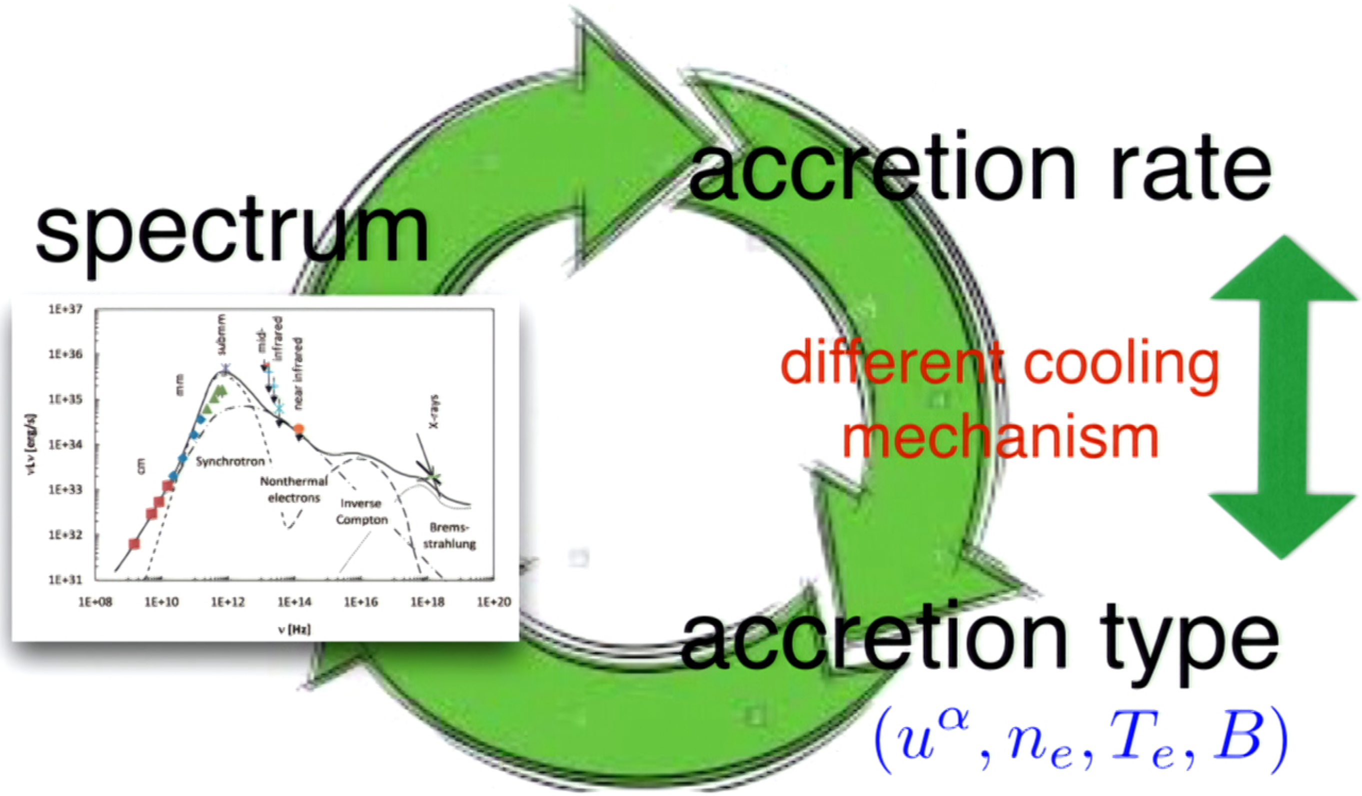

BH
e.g., Broderick et al. 2006


BH
e.g., Broderick et al. 2006

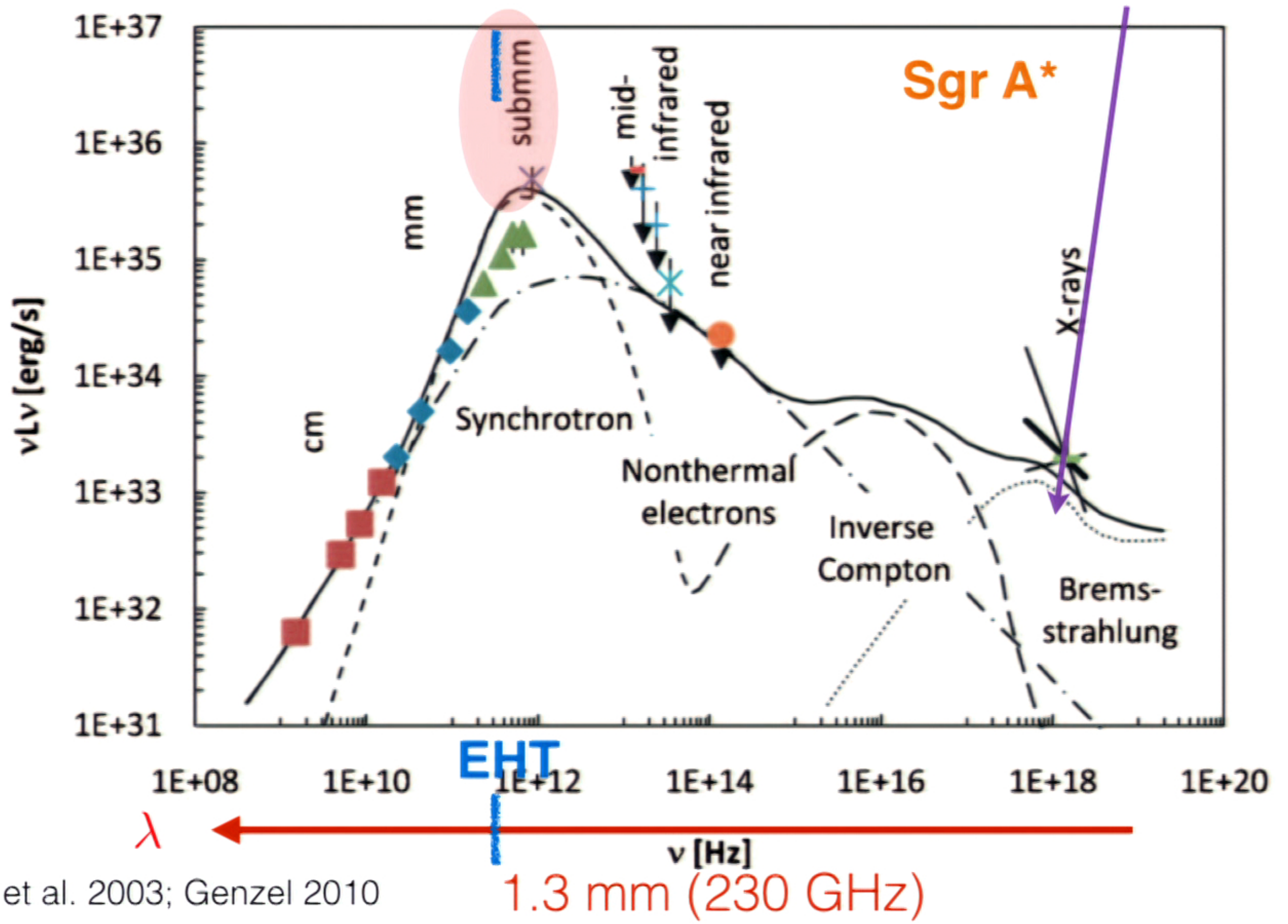

BH
e.g., Broderick et al. 2006

Observation

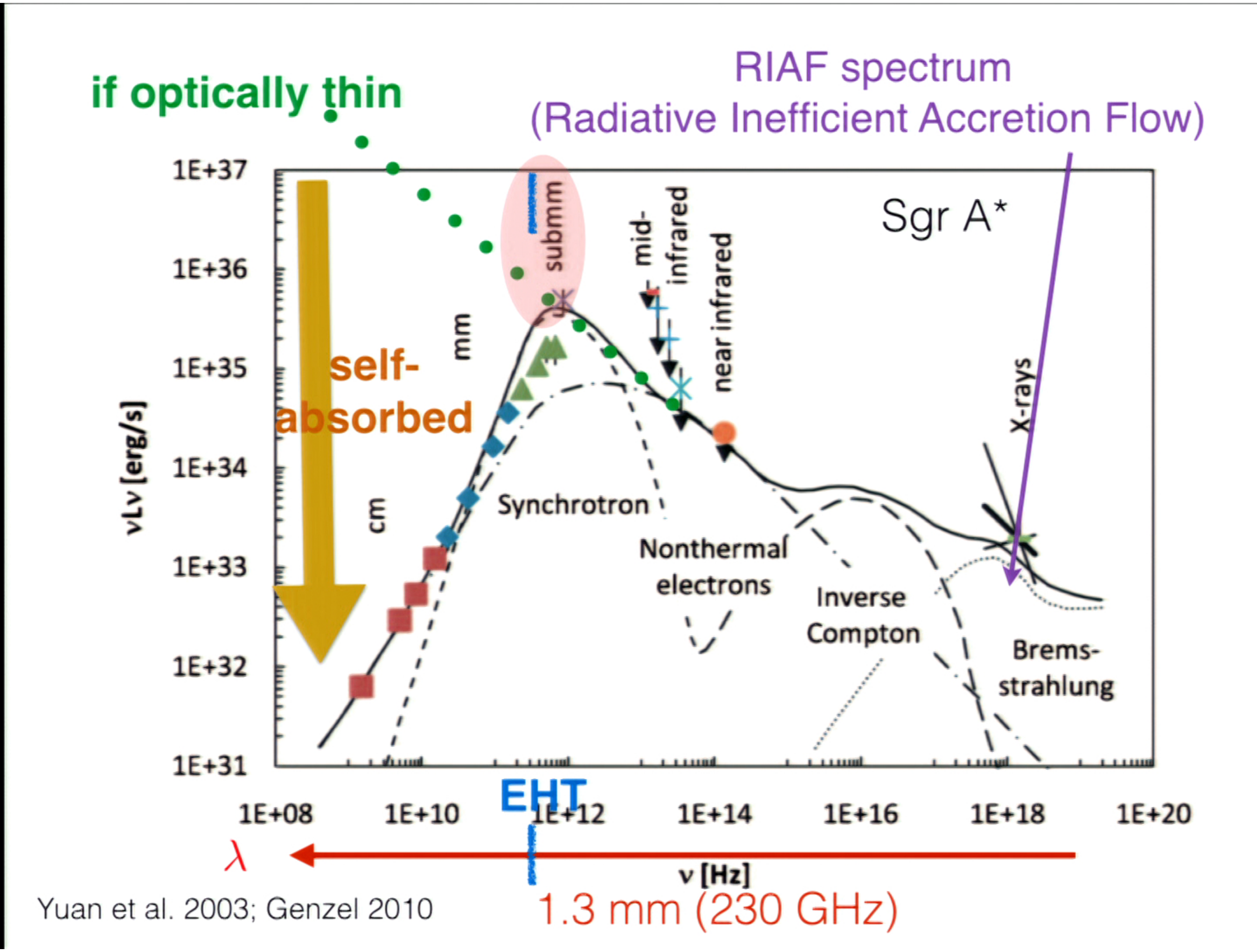
Theory



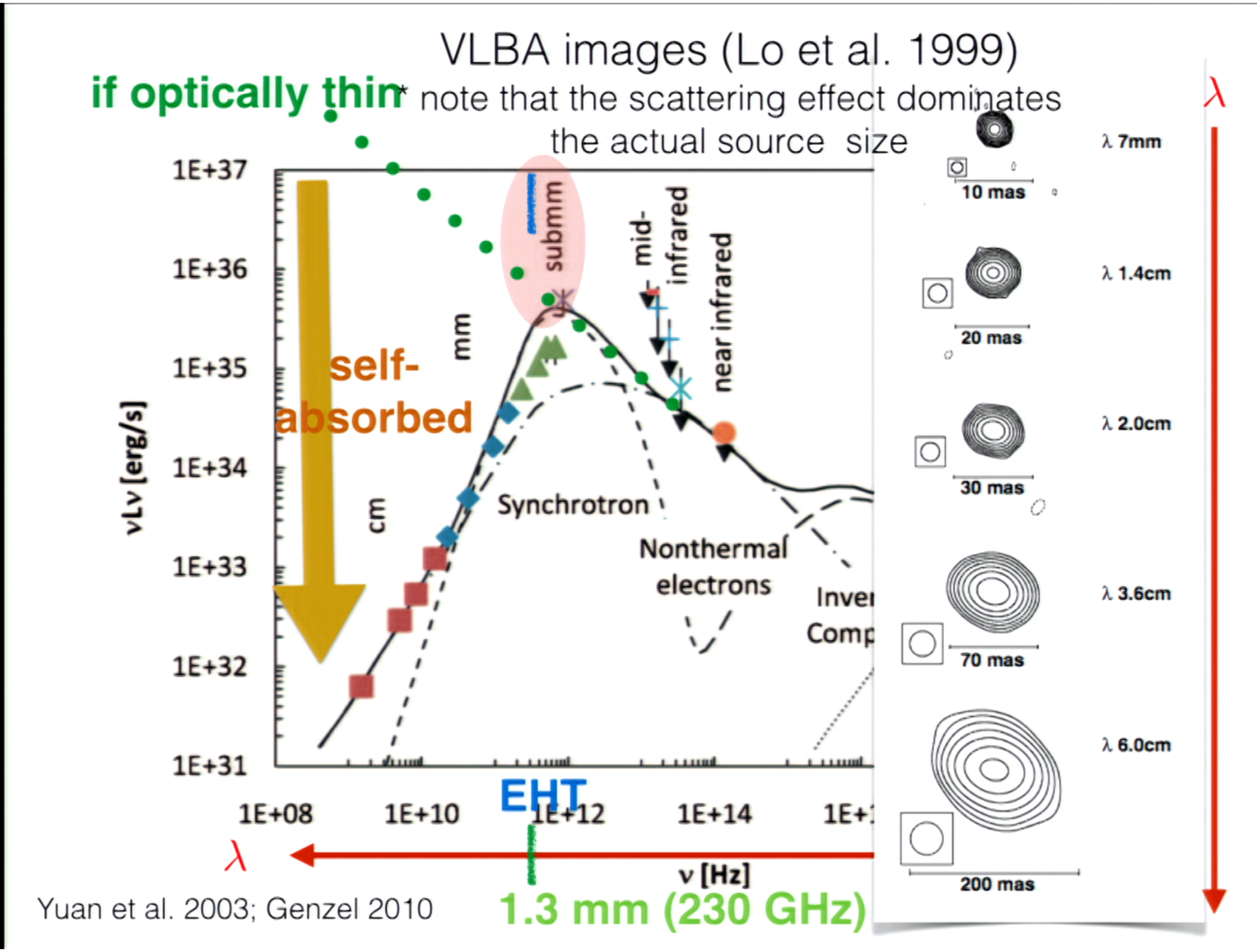
RIAF spectrum
(Radiative Inefficient Accretion Flow)

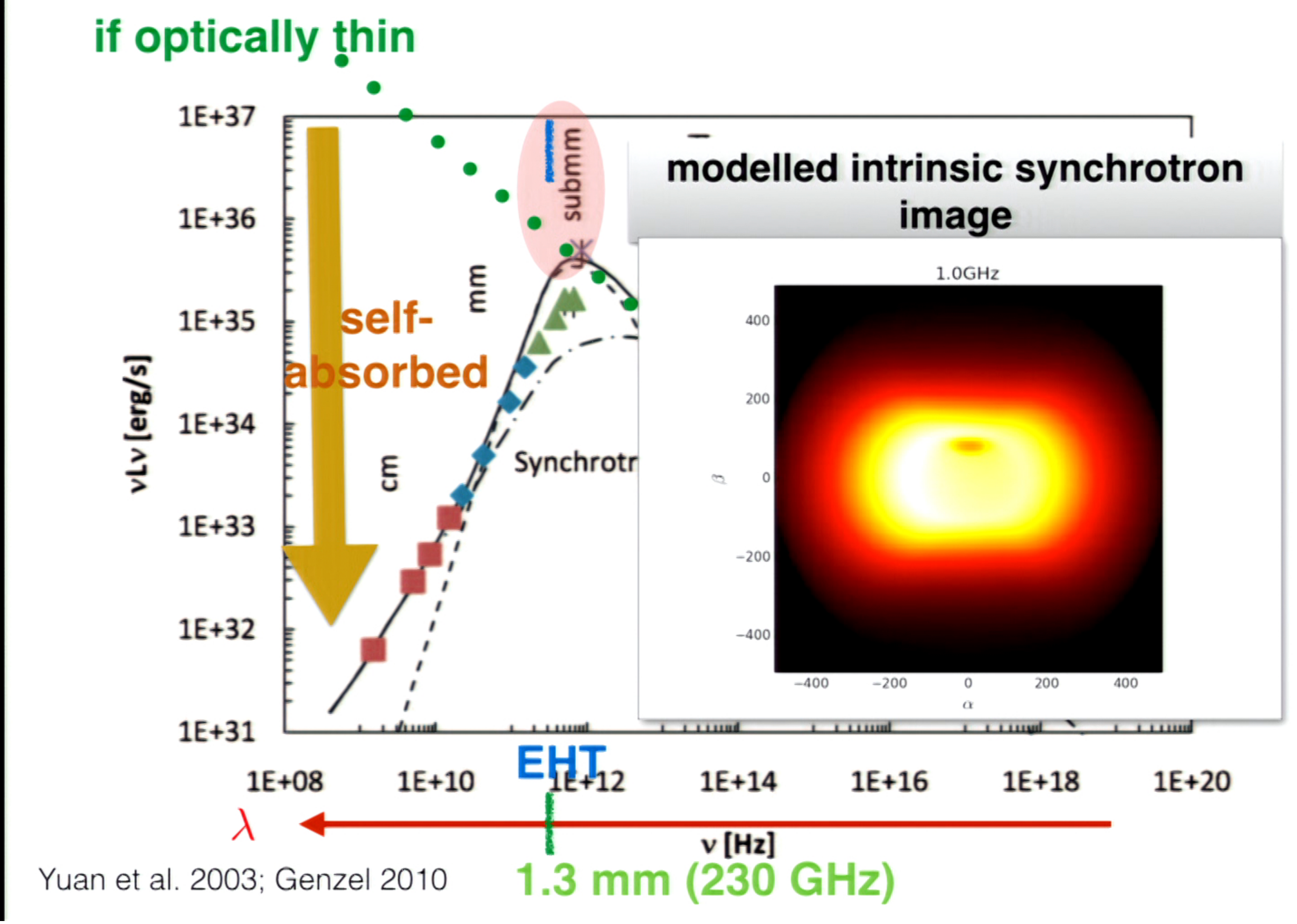


Yuan et al. 2003; Genzel 2010

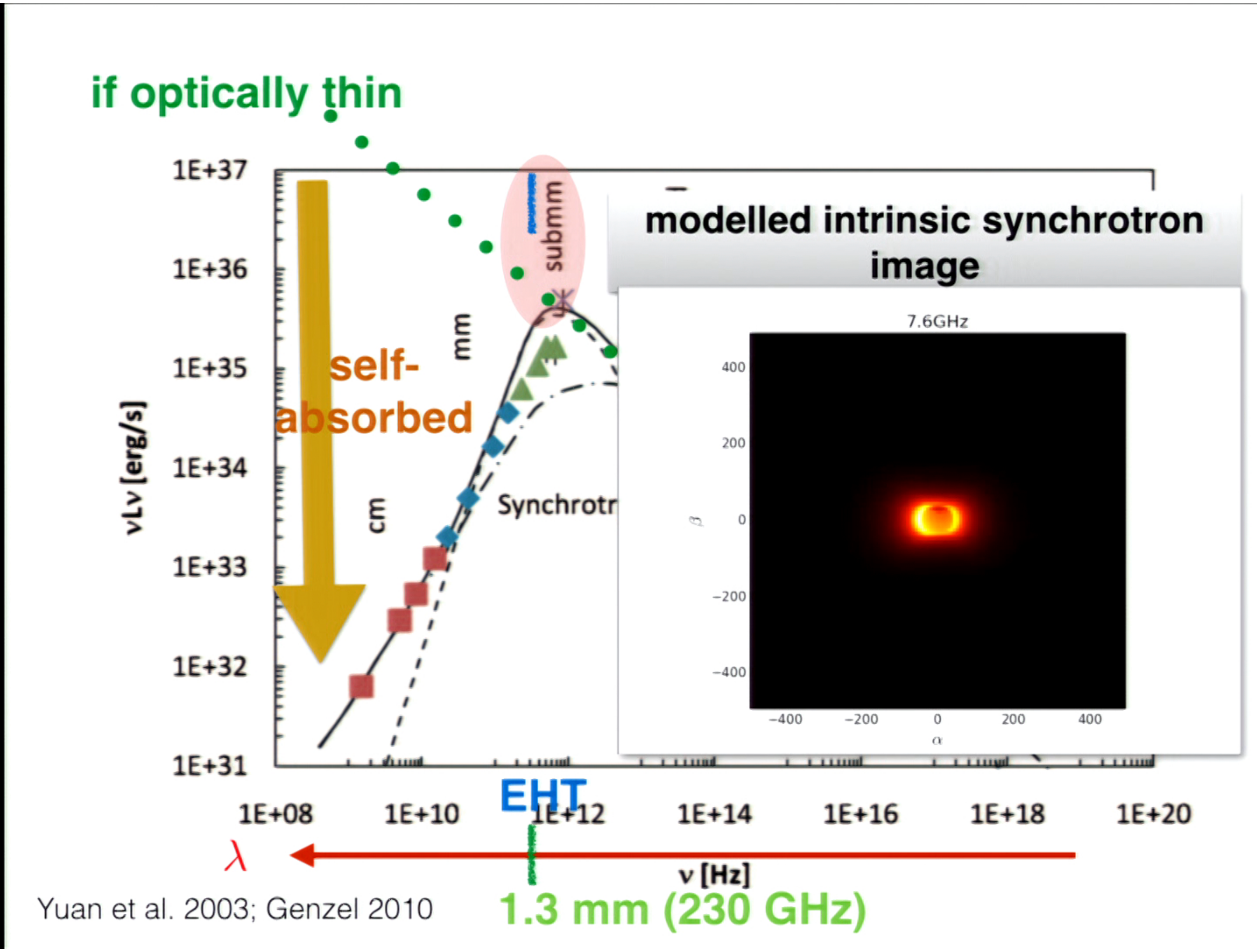


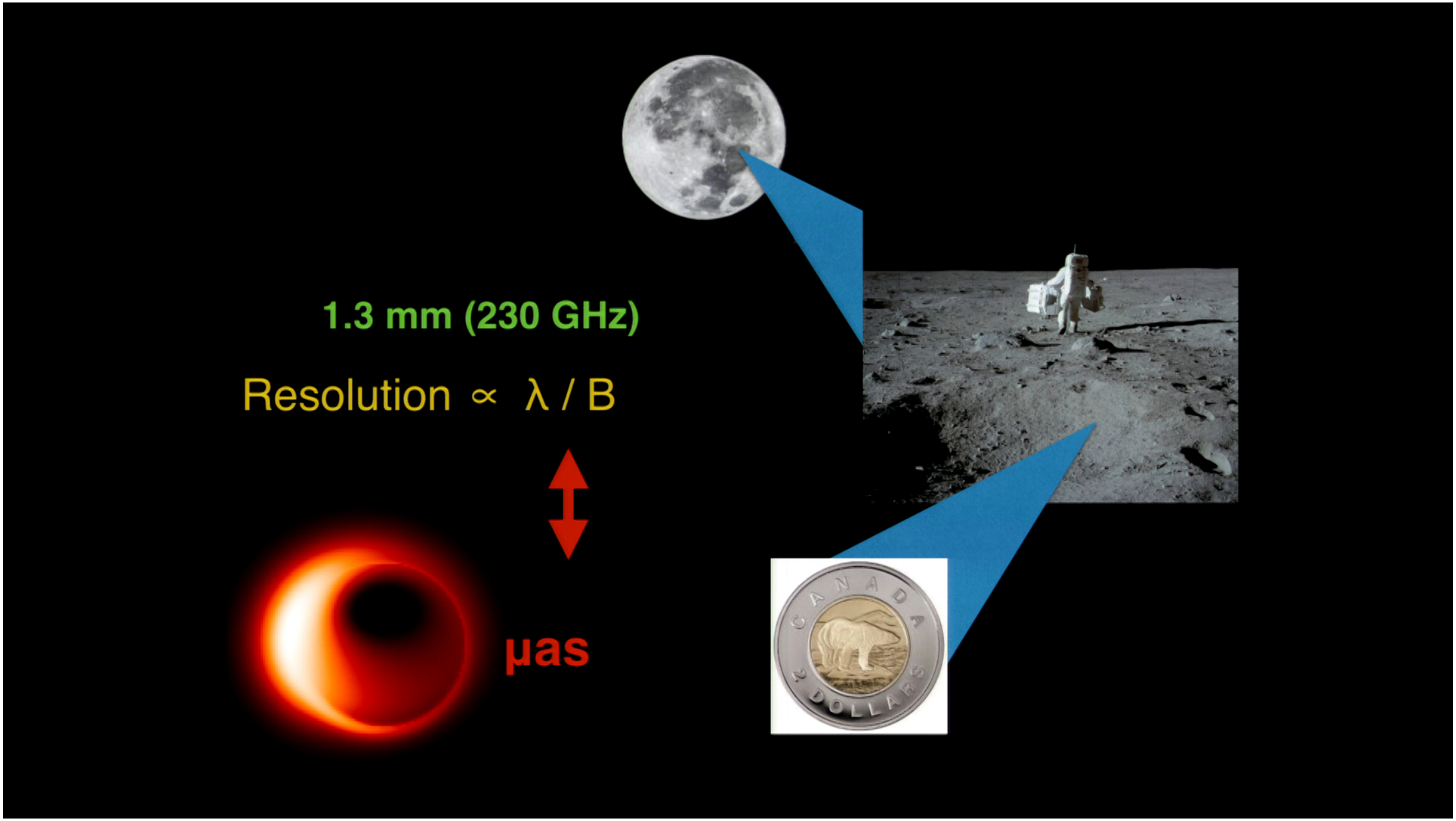
if optically thin
RIAF spectrum
(Radiative Inefficient Accretion Flow)
Sgr A*
submm
mm
cm
mid-infrared
near infrared
X-rays
self-absorbed
Synchrotron
Nonthermal electrons
Inverse Compton
Brems-strahlung
νLν [erg/s]
1E+37
1E+36
1E+35
1E+34
1E+33
1E+32
1E+31
1E+08
1E+10
1E+12
1E+14
1E+16
1E+18
1E+20
EHT
λ
ν [Hz]
1.3 mm (230 GHz)
Yuan et al. 2003; Genzel 2010


VLBA images (Lo et al. 1999)
if optically thin
* note that the scattering effect dominates the actual source size
1E+37
1E+36
1E+35
1E+34
1E+33
1E+32
1E+31
νLν [erg/s]
self-absorbed
cm
mm
submm
mid-infrared
near infrared
Synchrotron
Nonthermal electrons
Inver
Comp
1E+08
1E+10
1E+12
1E+14
EHT
ν [Hz]
λ
1.3 mm (230 GHz)
Yuan et al. 2003; Genzel 2010
λ 7mm
10 mas
λ 1.4cm
20 mas
λ 2.0cm
30 mas
λ 3.6cm
70 mas
λ 6.0cm
200 mas



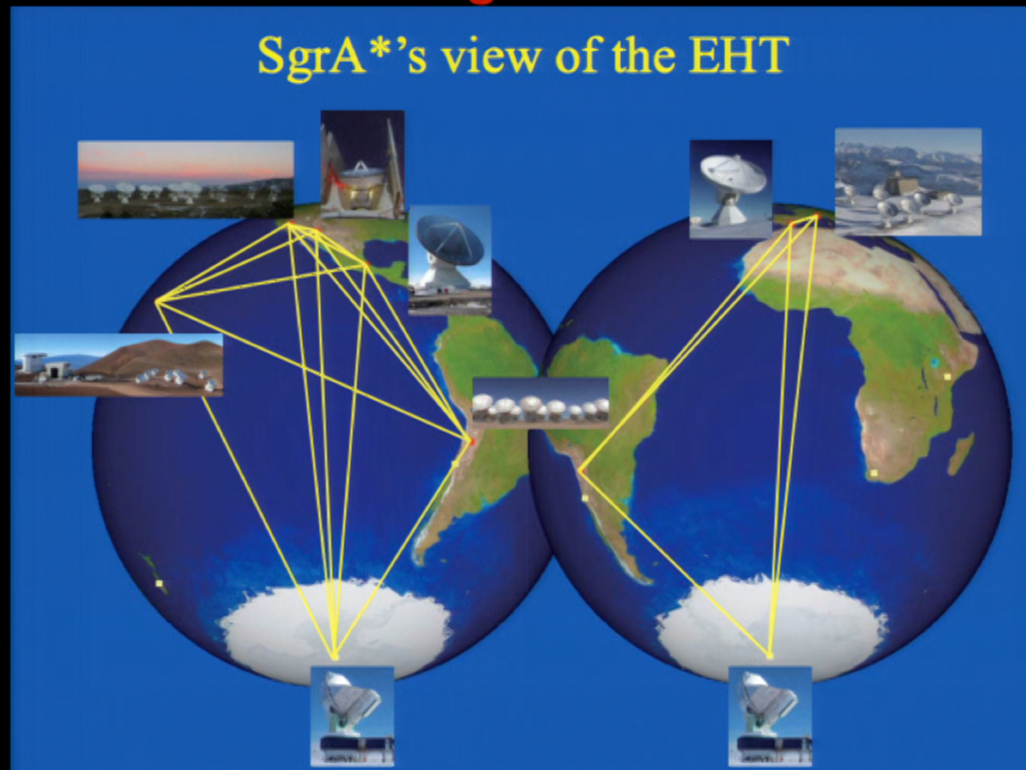
Yuan et al. 2003; Genzel 2010


if optically thin
1E+37
1E+36
1E+35
1E+34
1E+33
1E+32
1E+31
νLν [erg/s]
self-
absorbed
cm
mm
submm
Synchrotr
modelled intrinsic synchrotron image
7.6GHz
400
200
0
−200
−400
β
α
EHT
1E+08
1E+10
1E+12
1E+14
1E+16
1E+18
1E+20
λ
ν [Hz]
Yuan et al. 2003; Genzel 2010
1.3 mm (230 GHz)


1.3 mm (230 GHz)
Resolution ∝ λ / B
μas
CANADA
2 DOLLARS

Event Horizon Telescope

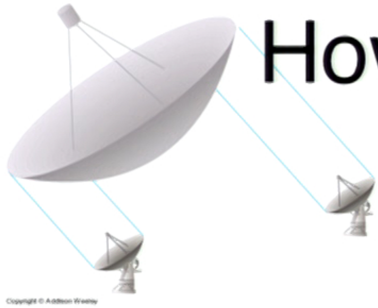
a global VLBI network



PI: Shep Doeleman (CfA)

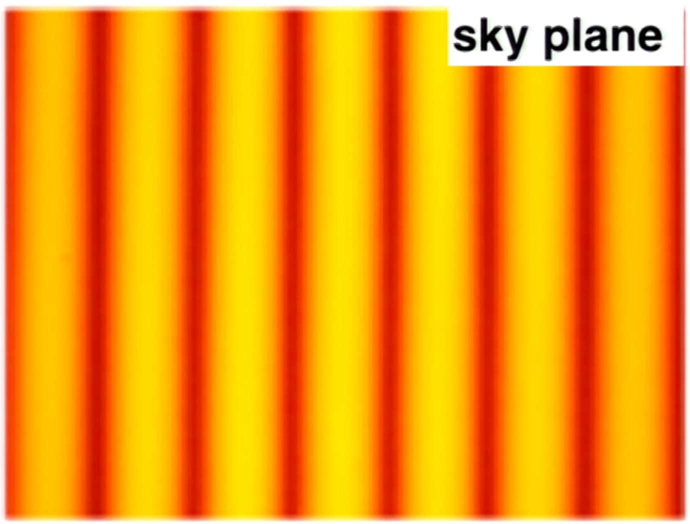
EHT Collaboration
MPIfR - Bonn
ASIAA
SAO/CfA
MIT Haystack
CARMA
NAOJ
U. Arizona
Radboud U.
NRAO
UC Berkeley
IRAM
APEX
JCMT
U. Concepcion
UNAM
Perimeter Inst.
U. Illinois UC
UMD
Onsala Space Obs.
U. Mass Amherst
LMT
INAOE
Frankfurt U.
PERIMETER INSTITUTE
MÉXICO
GOBIERNO DE LA REPÚBLICA
CONACYT
Smithsonian
SERIOUSLY AMAZING
NSF
NRAO
erc
European Research Council
XILINX
ALL PROGRAMMABLE
GORDON AND BETTY MOORE FOUNDATION
科研費
KAKENHI
NAOJ

“a virtual telescope”



How Interferometry works?

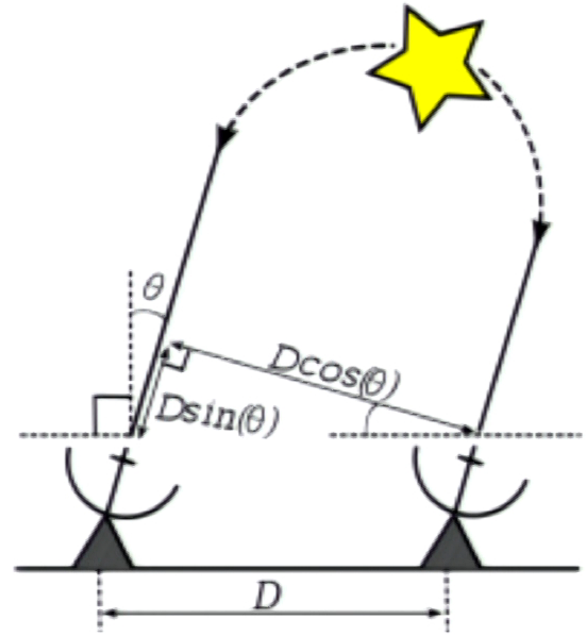
VLBI (Very Long Baseline Interferometry)



constructive interference

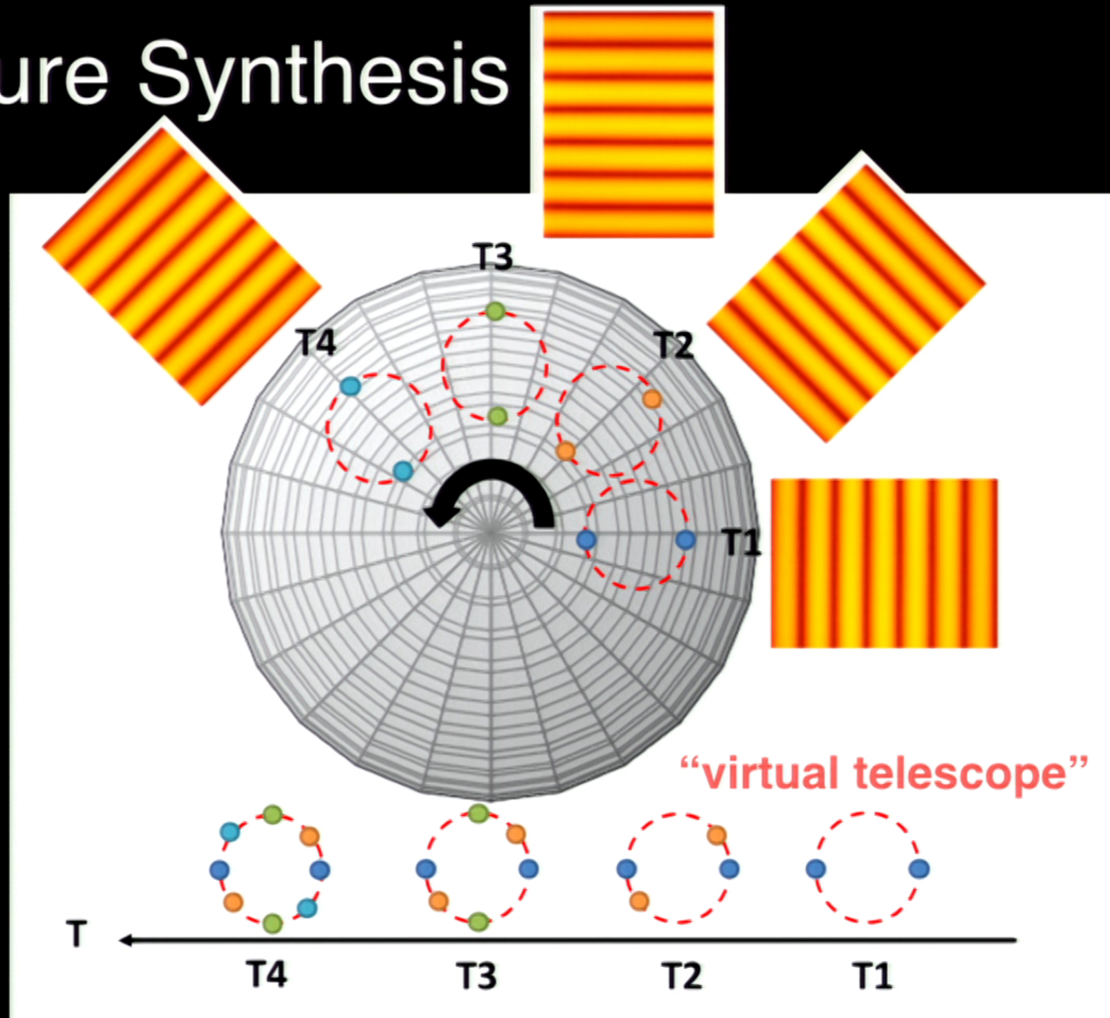
destructive interference

direction to source

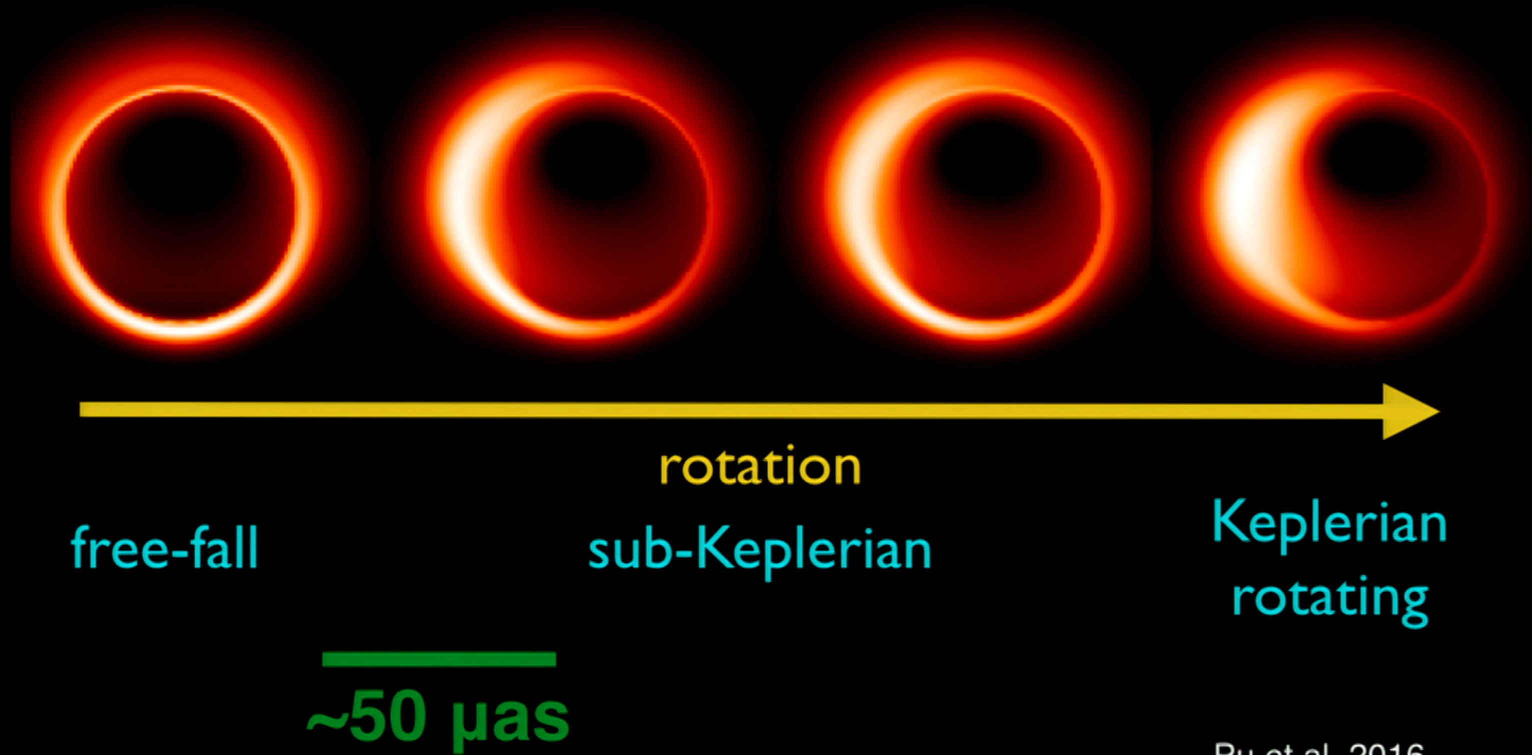


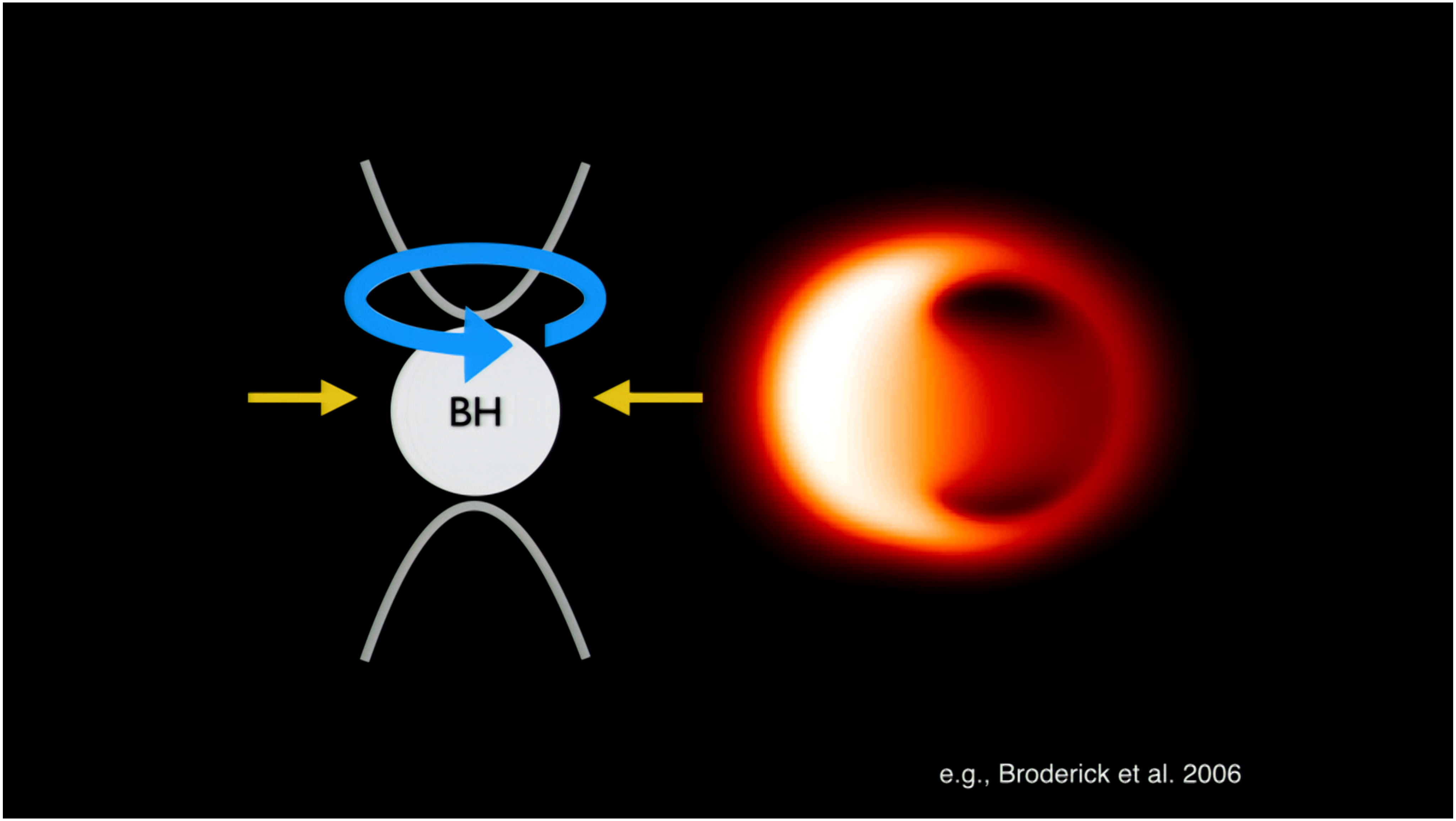
baseline

Aperture Synthesis

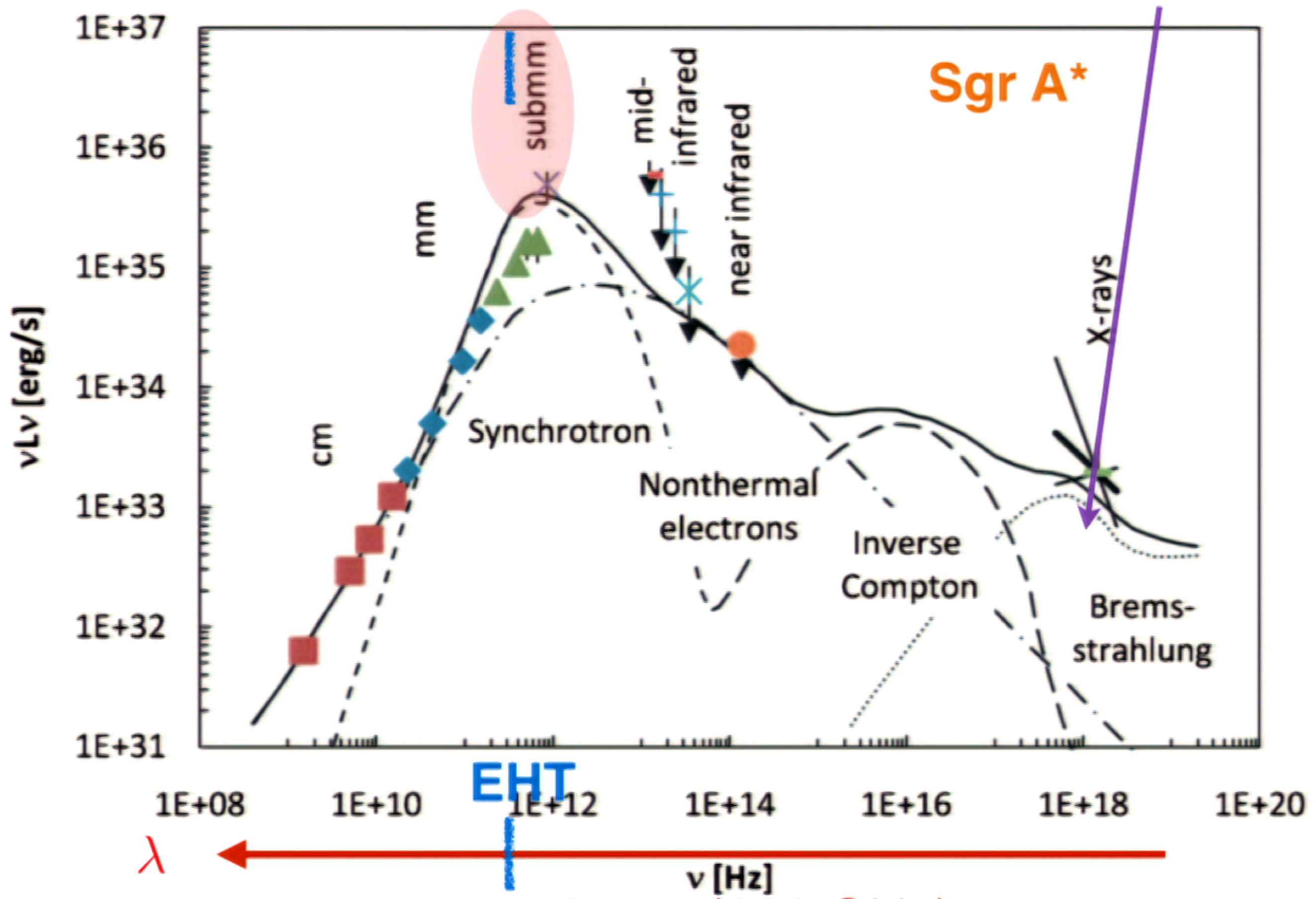


exploring flow dynamics



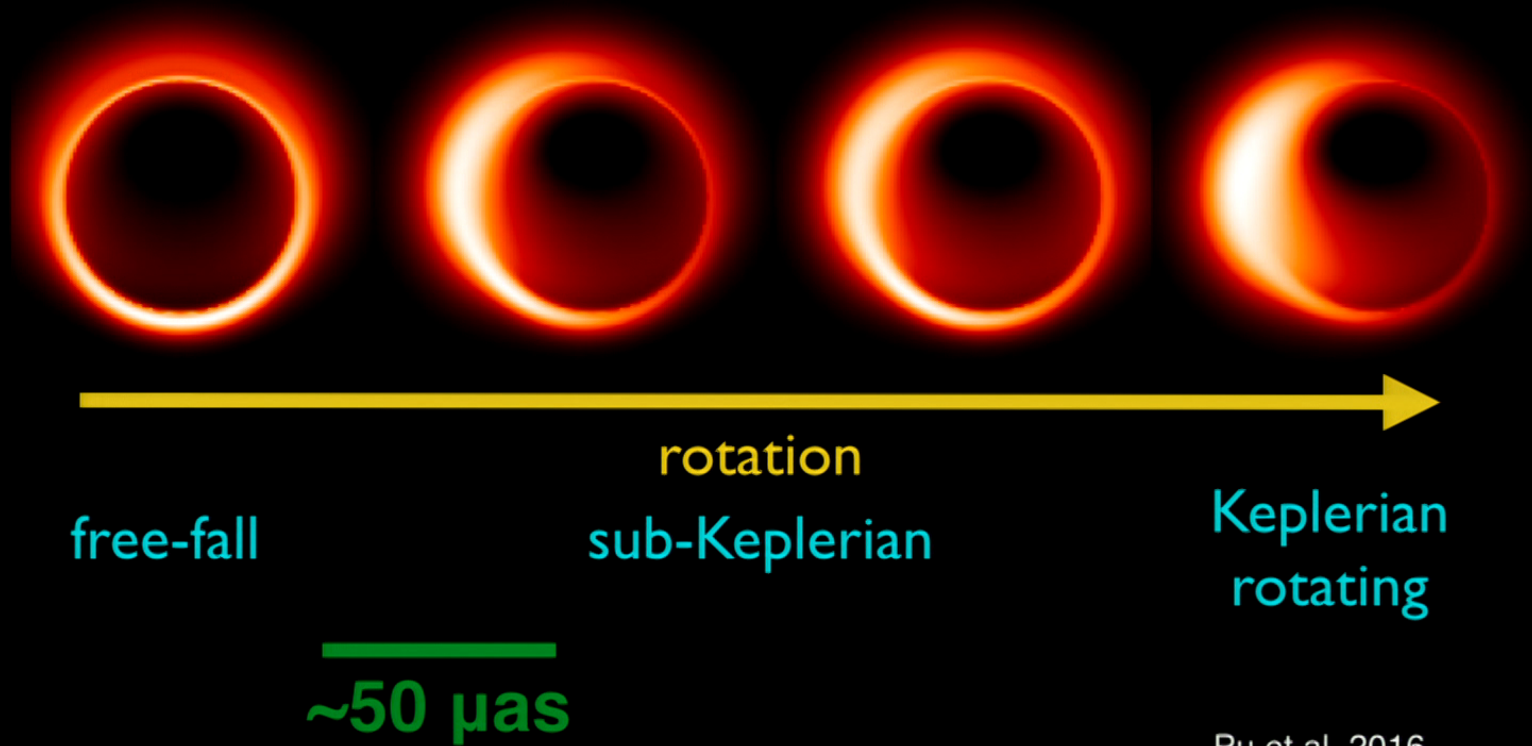

BH
e.g., Broderick et al. 2006

RIAF spectrum
(Radiative Inefficient Accretion Flow)



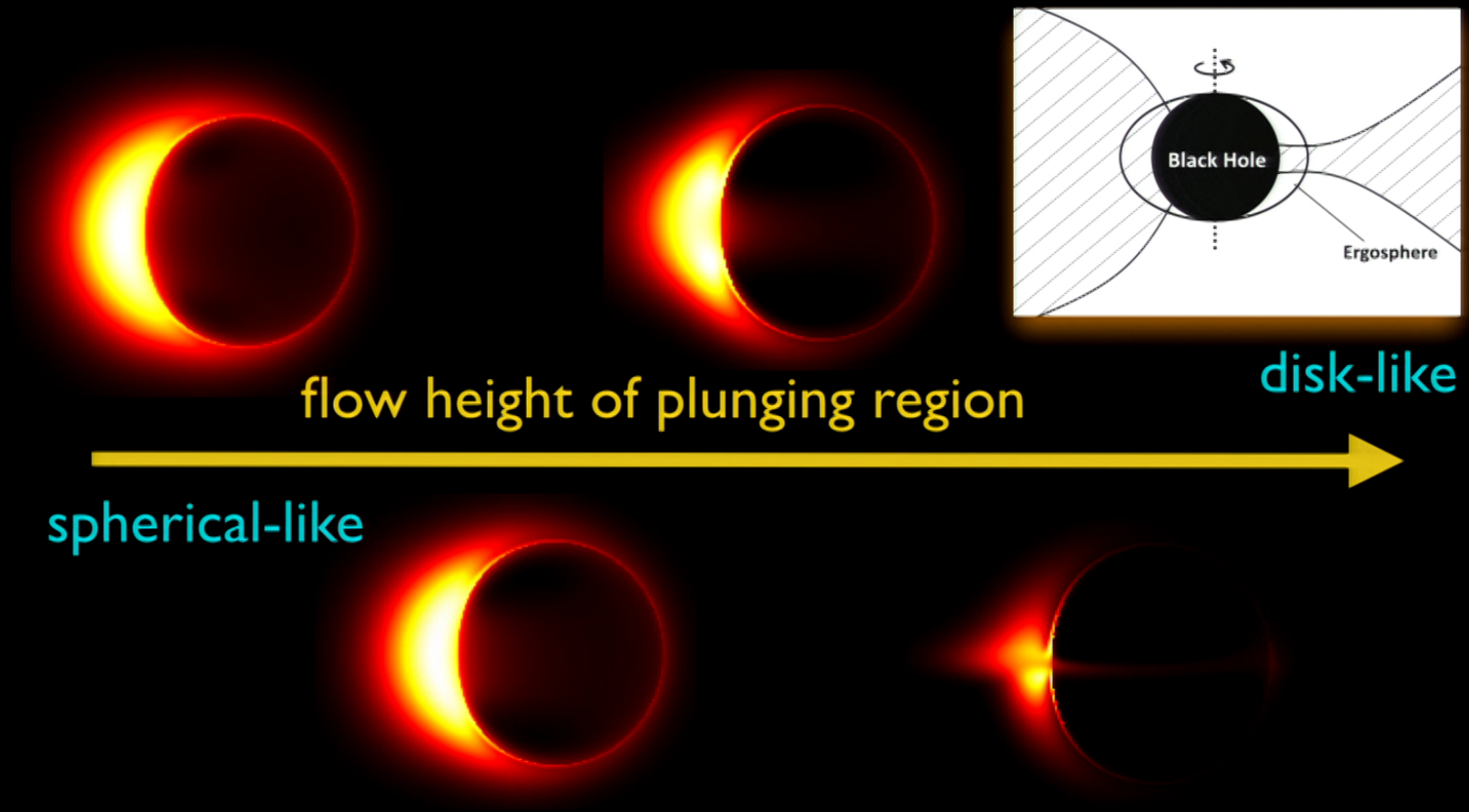
Yuan et al. 2003; Genzel 2010

exploring flow dynamics

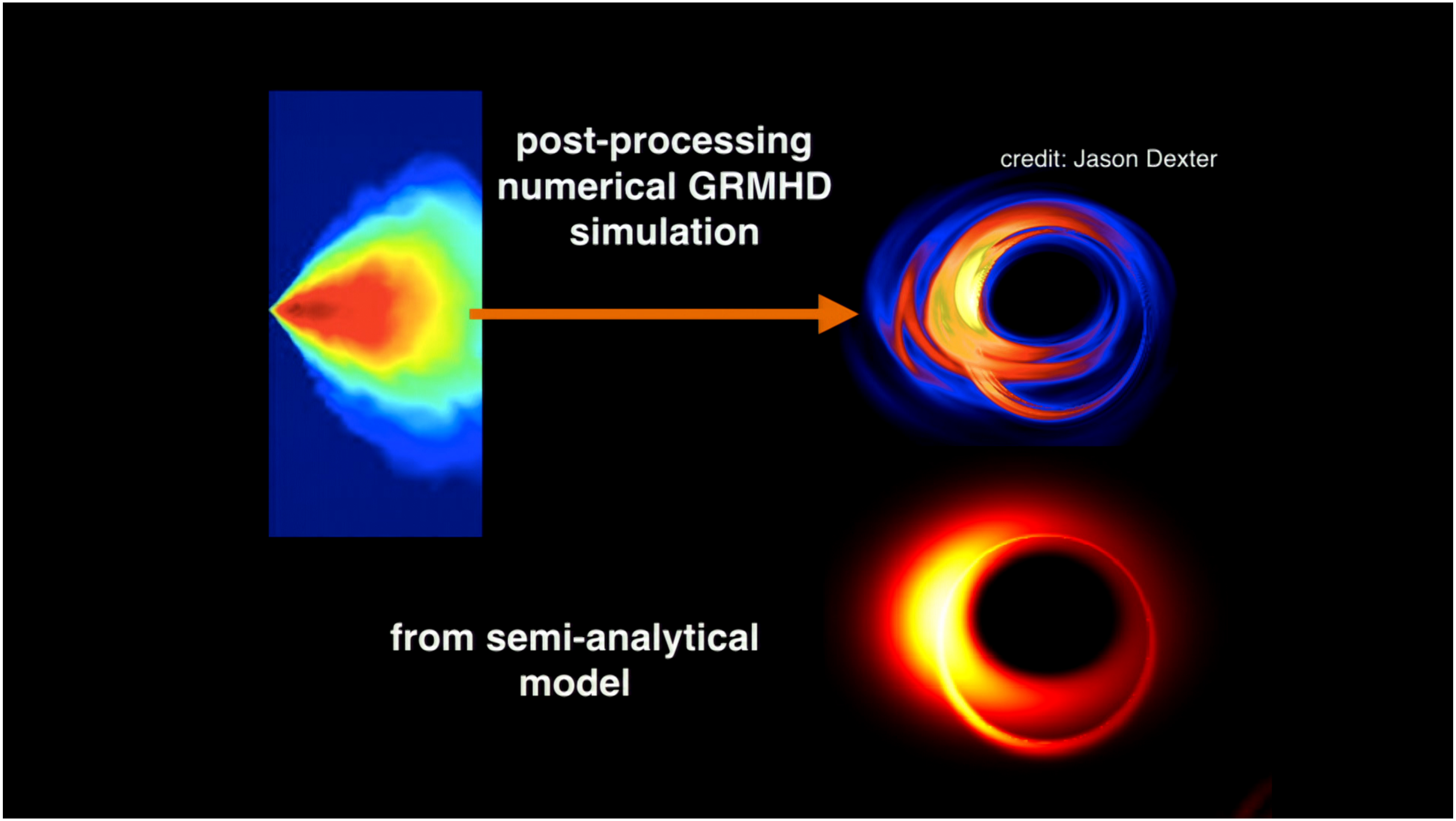


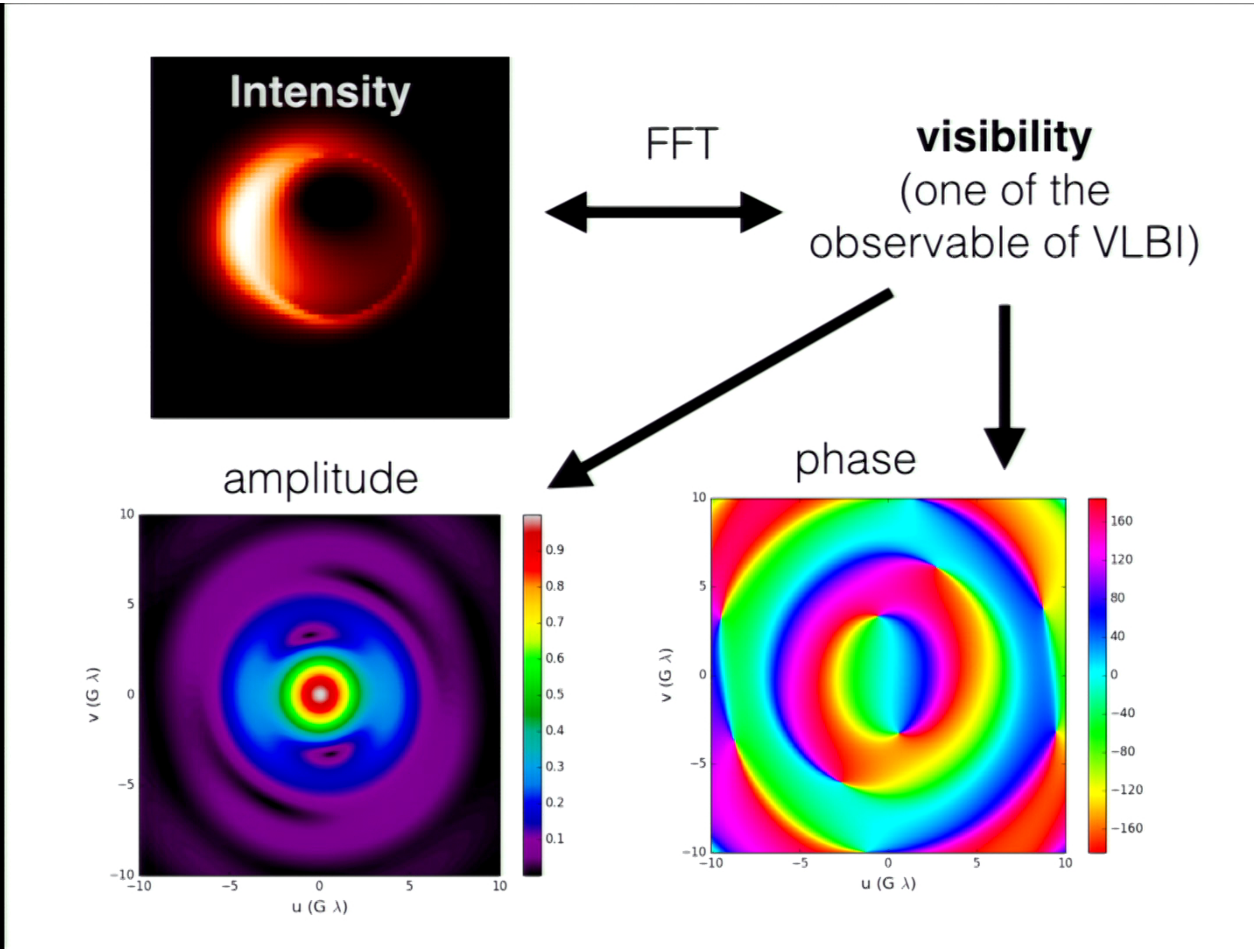
Pu et al. 2016

exploring plunging region



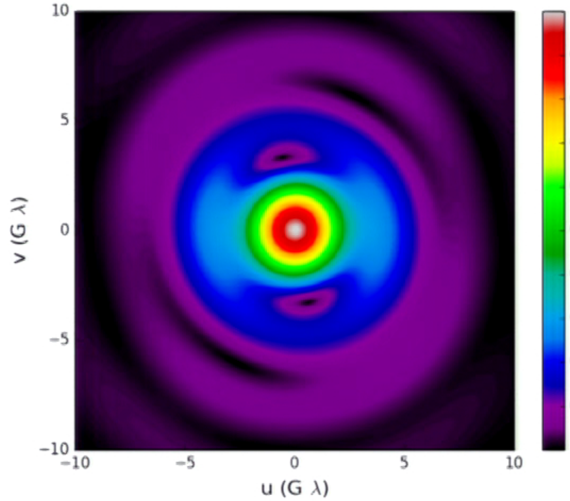
Pu et al. 2018 submitted


post-processing
numerical GRMHD
simulation
credit: Jason Dexter
from semi-analytical
model

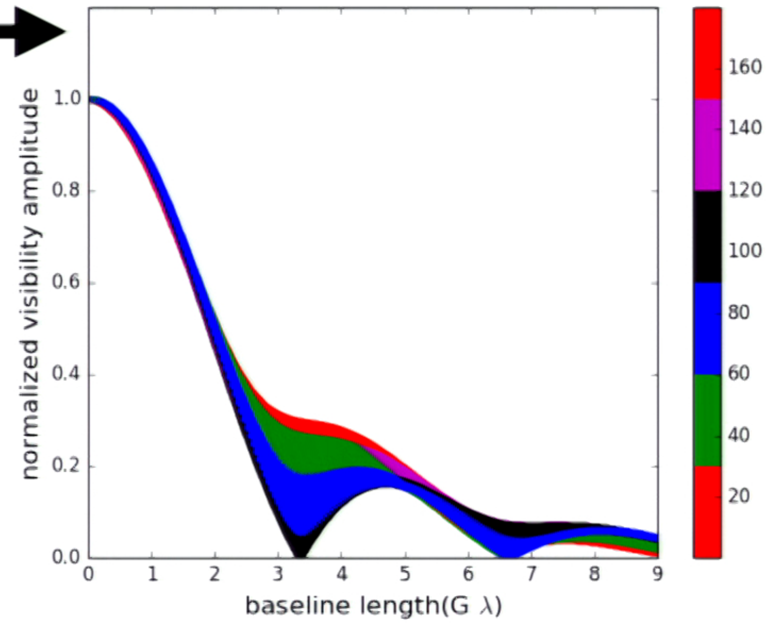


Intensity
FFT
visibility
(one of the observable of VLBI)
amplitude
phase
v (G λ)
u (G λ)

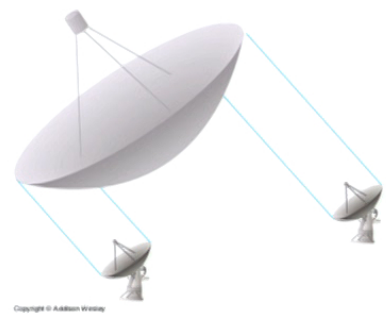
amplitude

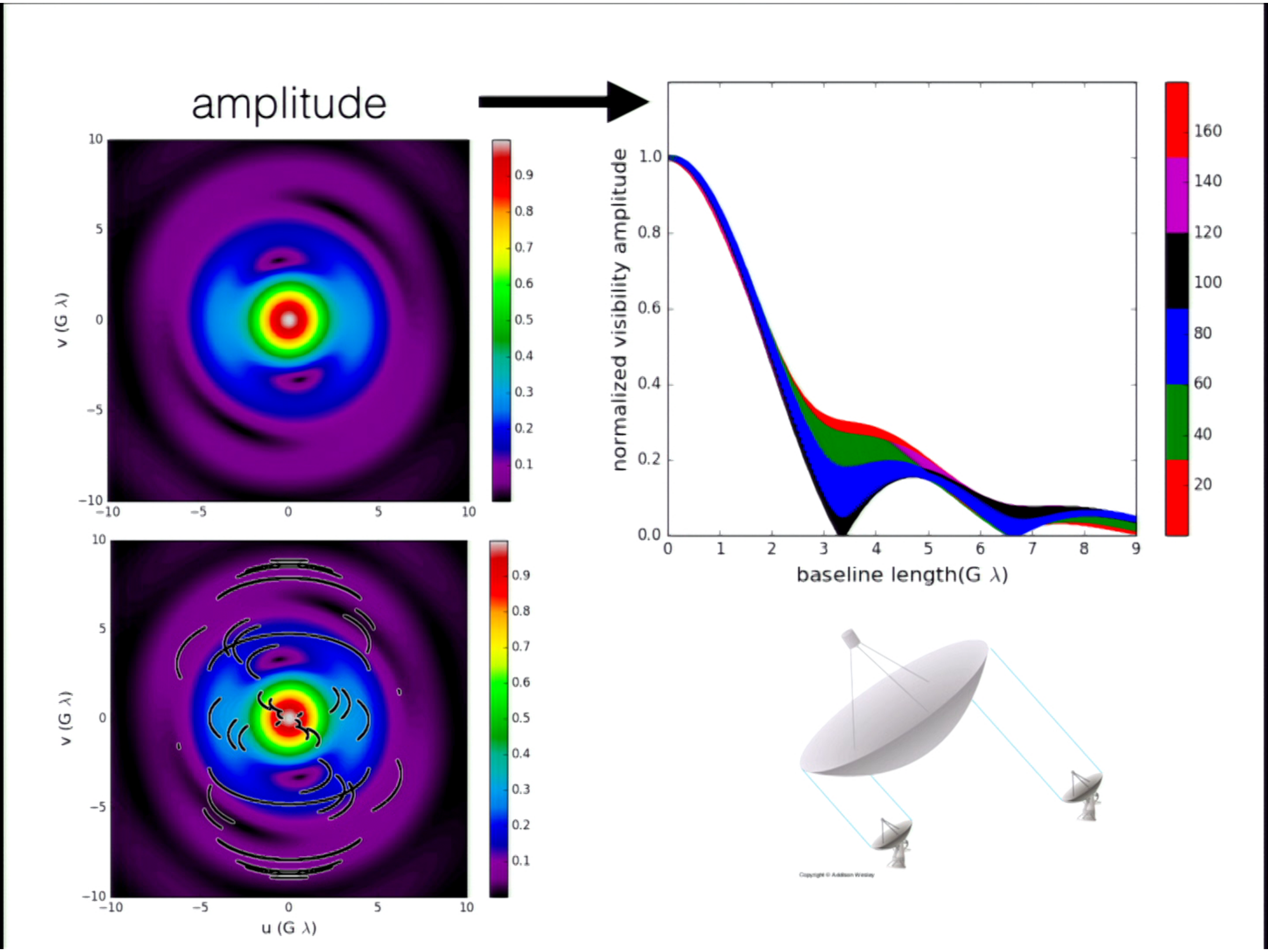


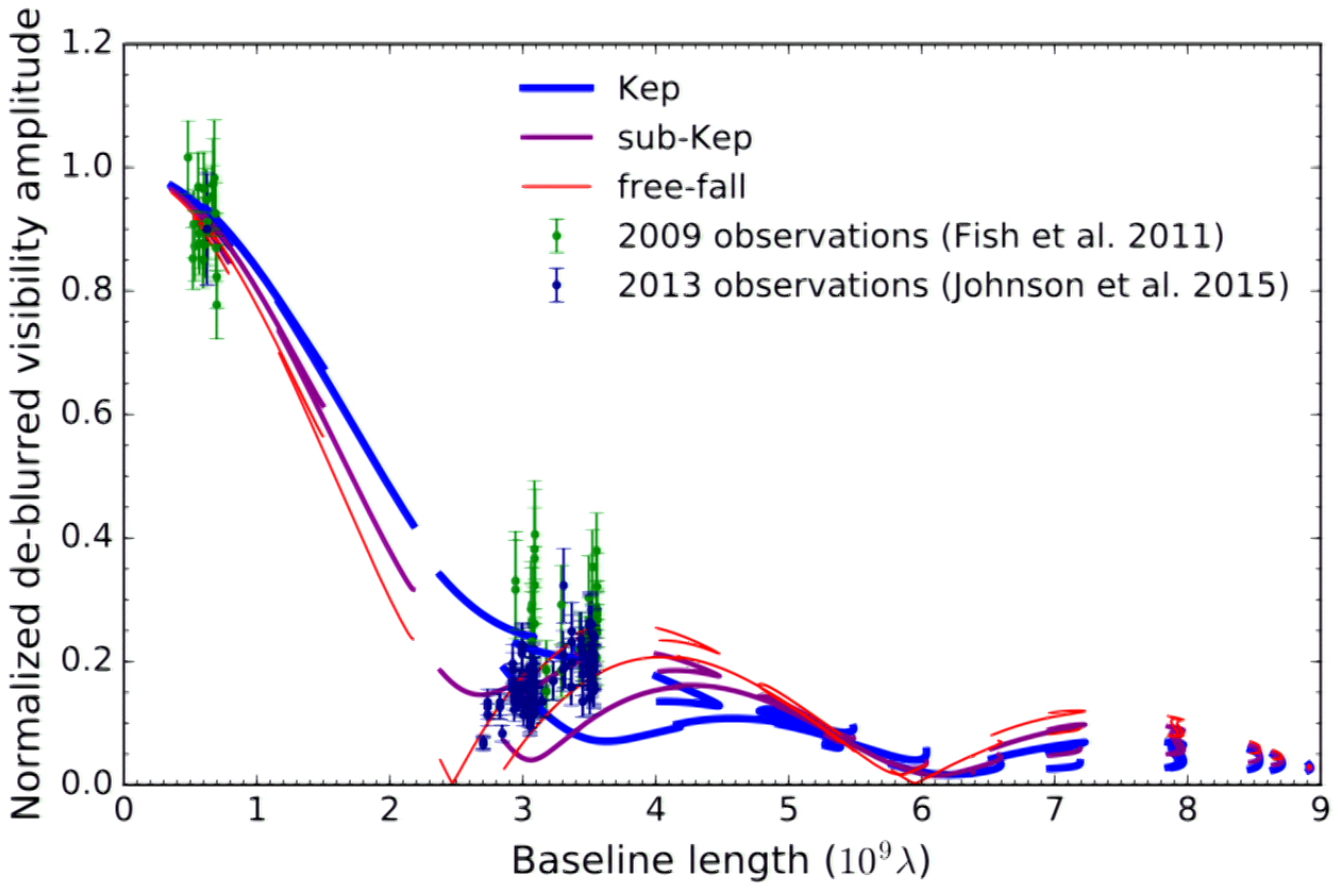
v (G λ)
u (G λ)
10
5
0
−5
−10
−10
−5
0
5
10
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1



normalized visibility amplitude
baseline length(G λ)
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
9
160
140
120
100
80
60
40
20

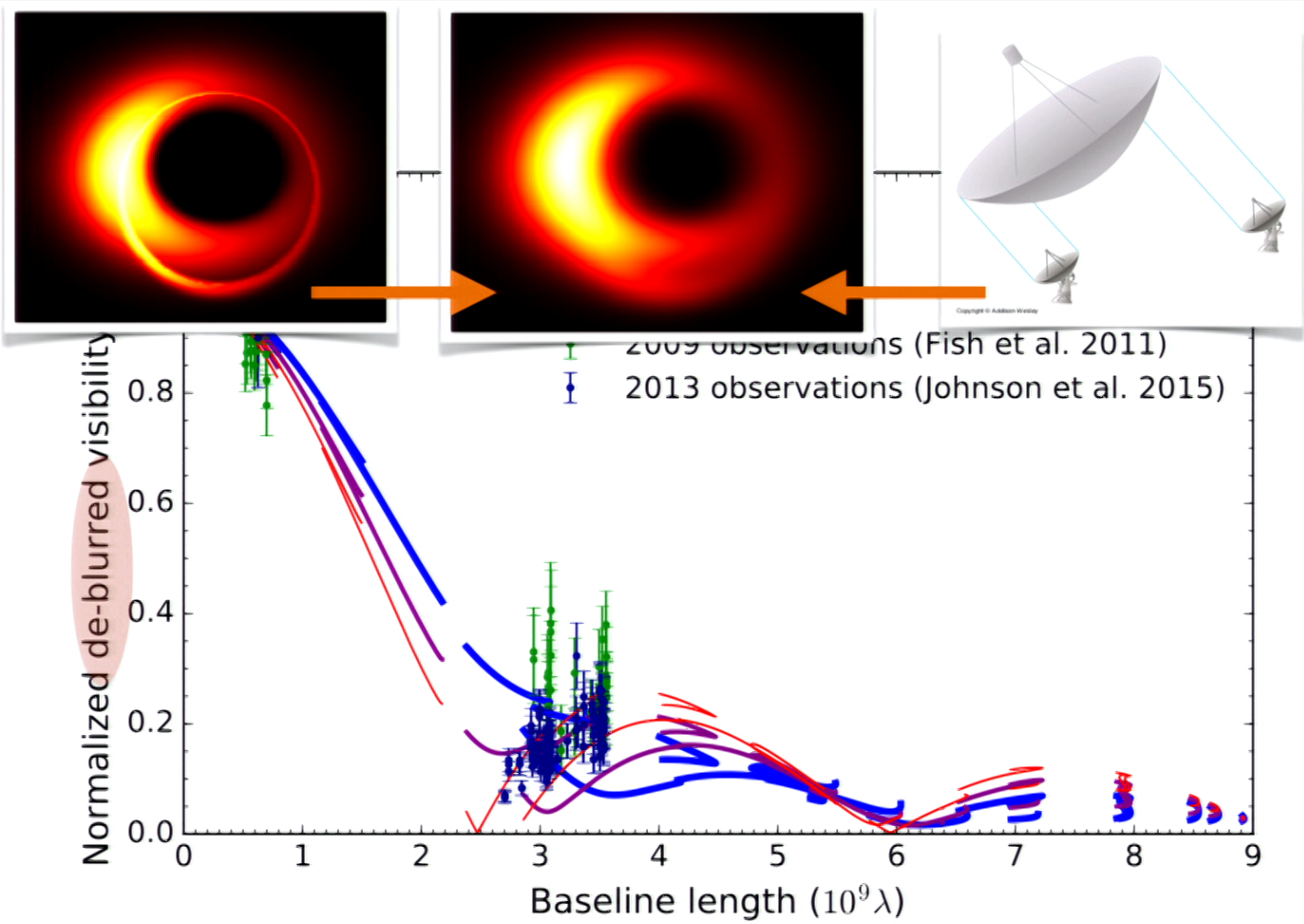



amplitude
v (G λ)
u (G λ)
normalized visibility amplitude
baseline length(G λ)
Copyright © Addison Wesley

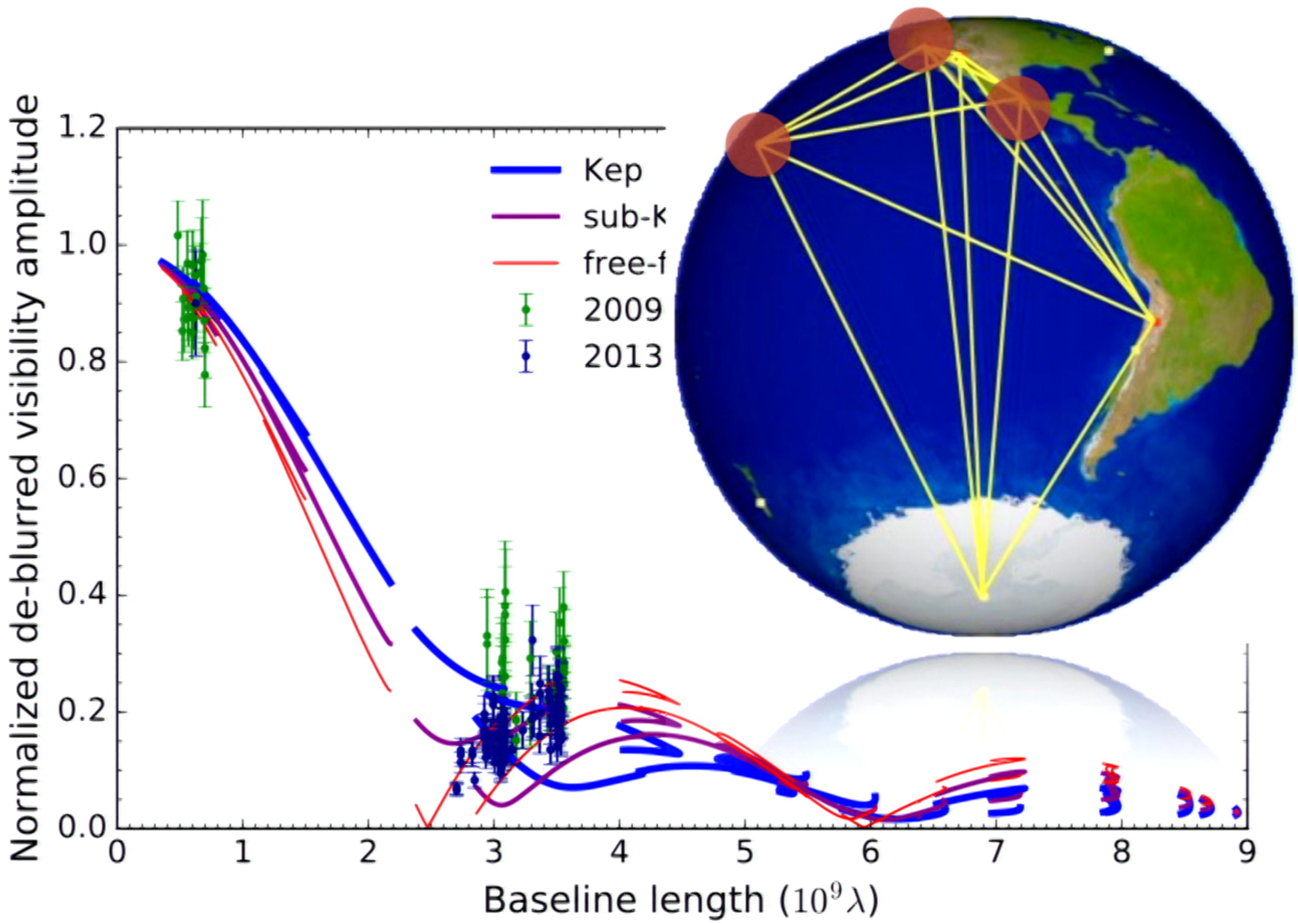


Normalized de-blurred visibility amplitude
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
9
Baseline length ($10^9 \lambda$)
Kep
sub-Kep
free-fall
2009 observations (Fish et al. 2011)
2013 observations (Johnson et al. 2015)

Pu et al. 2016

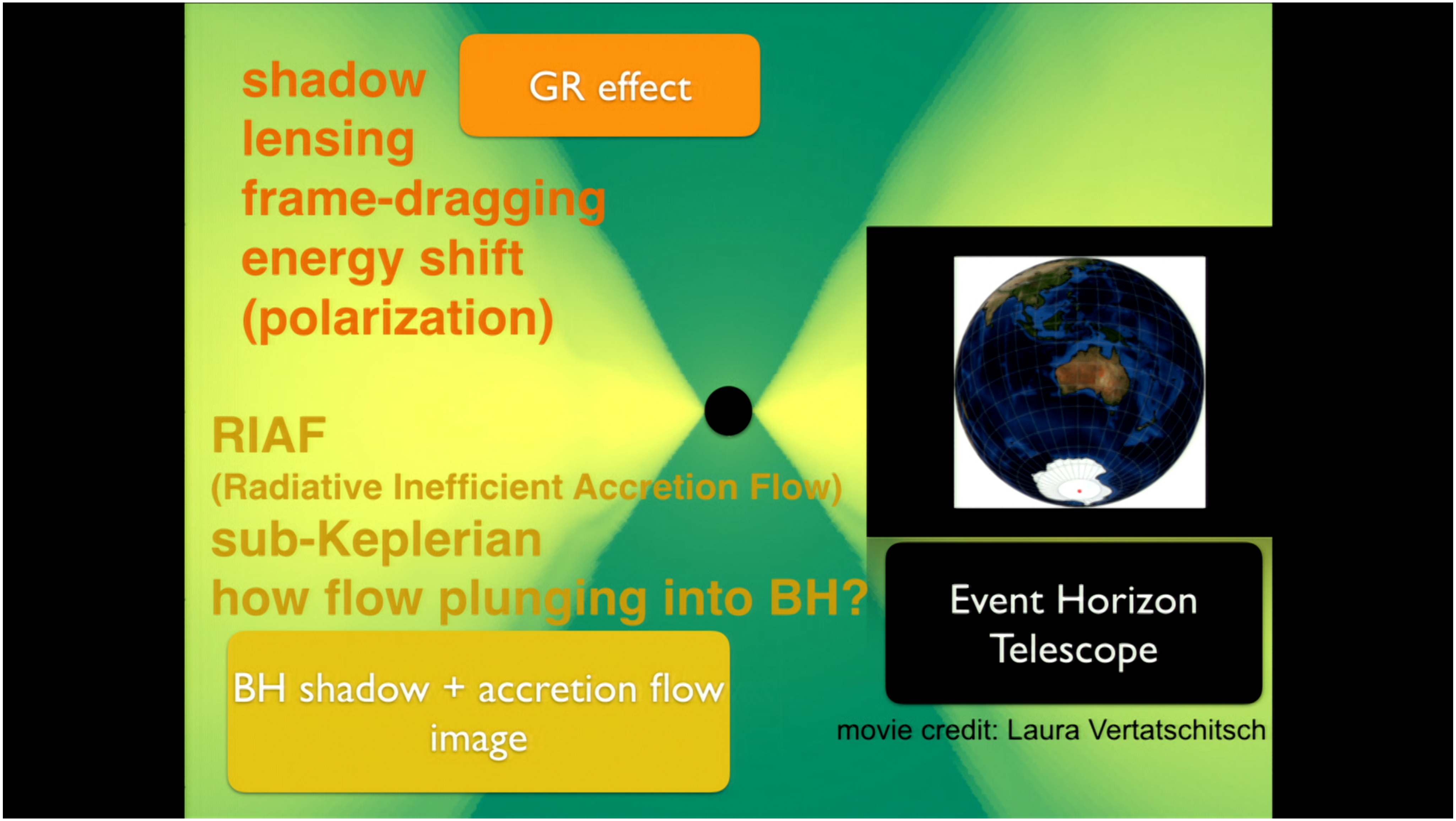

2009 observations (Fish et al. 2011)
2013 observations (Johnson et al. 2015)
Normalized de-blurred visibility
0.0
0.2
0.4
0.6
0.8
0
1
2
3
4
5
6
7
8
9
Baseline length ($10^9\lambda$)

Pu et al. 2016



Normalized de-blurred visibility amplitude
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
9
Baseline length $(10^9\lambda)$
Kep
sub-K
free-f
2009
2013

Pu et al. 2016


shadow
lensing
frame-dragging
energy shift
(polarization)
GR effect
RIAF
(Radiative Inefficient Accretion Flow)
sub-Keplerian
how flow plunging into BH?
BH shadow + accretion flow image
Event Horizon Telescope
movie credit: Laura Vertatschitsch