Observing the unobservable: a black hole primer

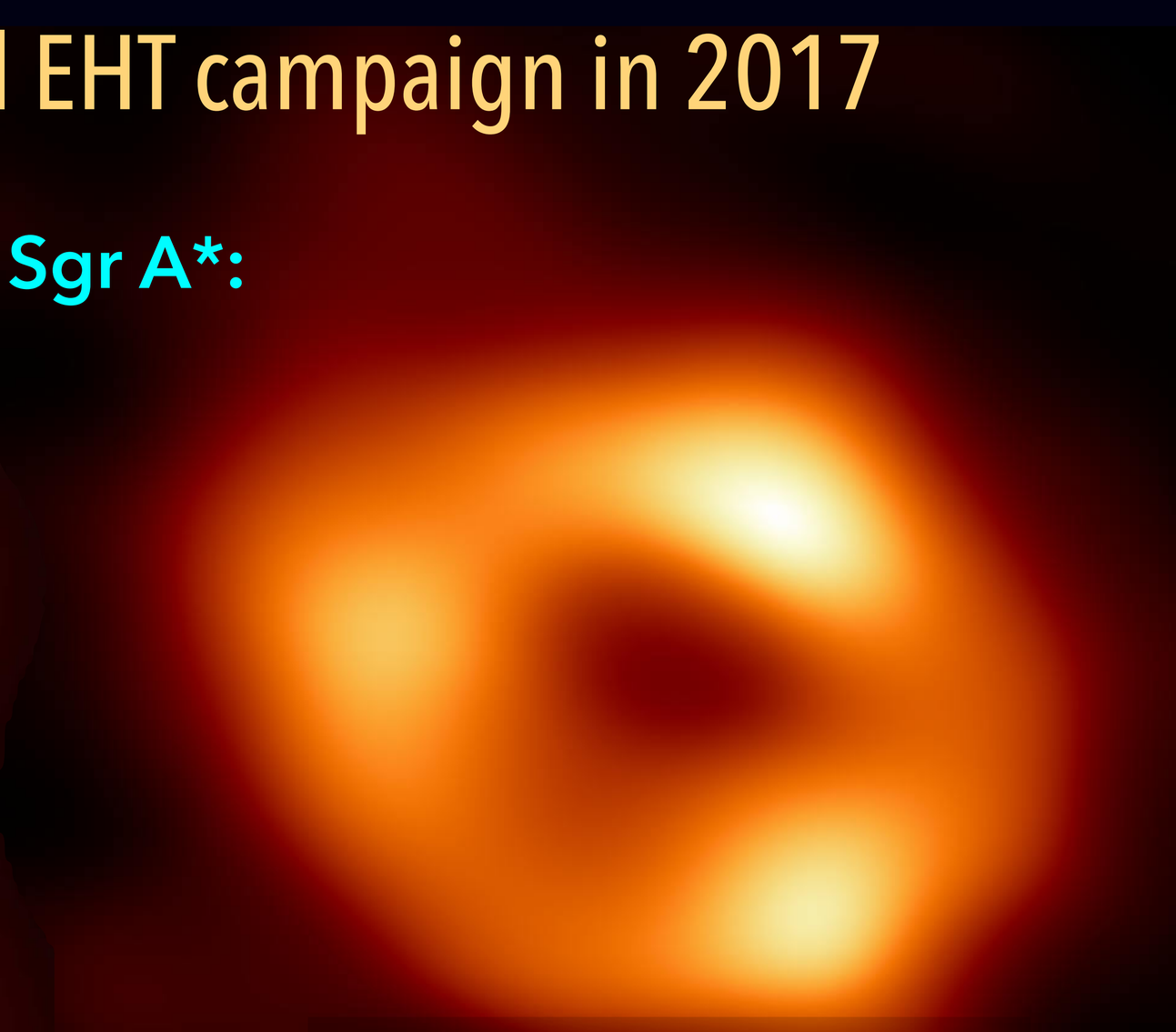
Prof. Sera Markoff, API/GRAPPA, University of Amsterdam
EHT/ngEHT Collaborations + EHT Science Board & Multiwavelength WG Co-coordinator
+ Cherenkov Telescope Array Consortium

Images from the first full EHT campaign in 2017

M87*:

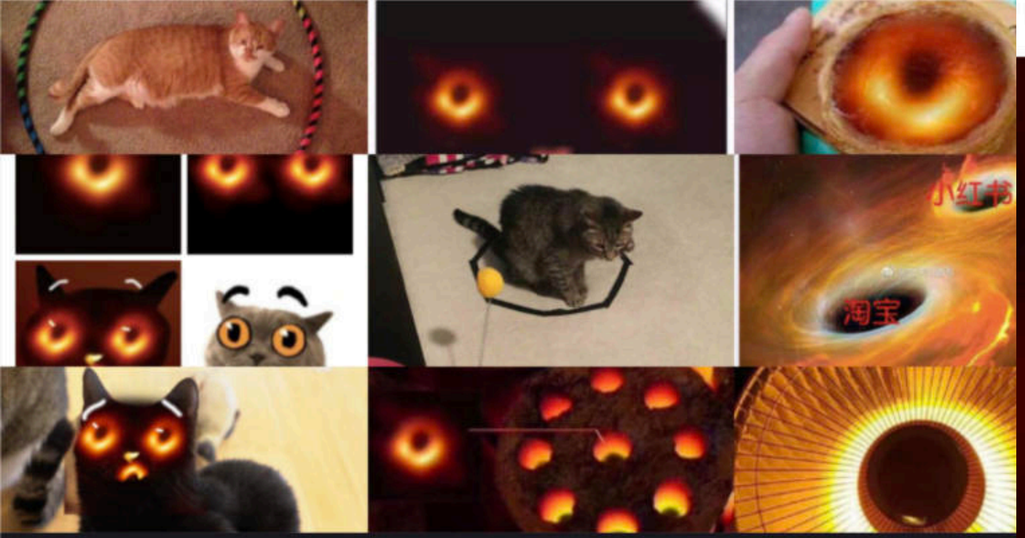
M ≈ 6.5 billion solar masses
D ≈ 55 million light years
In M87 galaxy in Virgo Cluster

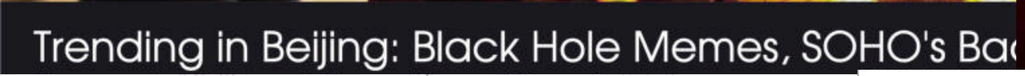
Sgr A*:

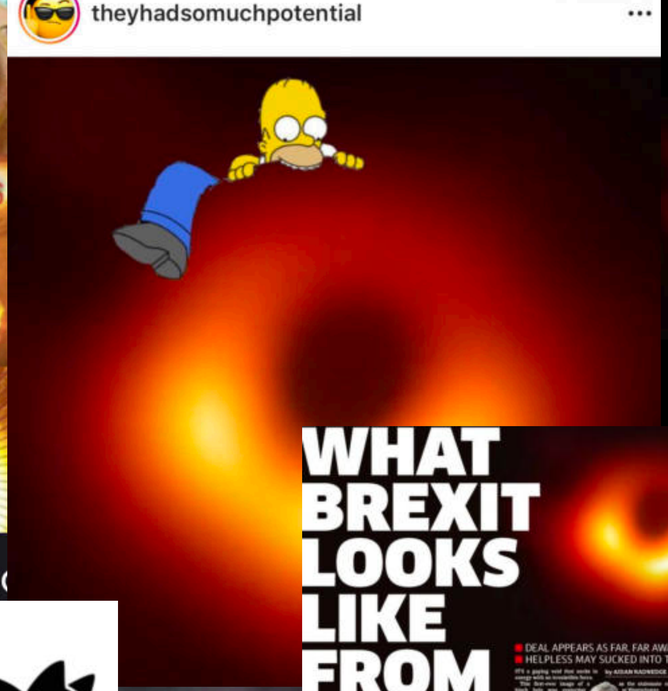


M ≈ 4 million solar masses
D ≈ 27000 light years
In our own Milky Way's centre!

EHTC M87* paper I (2019); Sgr A* paper I (2022)




Trending in Beijing: Black Hole Memes, SOHO's Ba


theyhadsomuchpotential

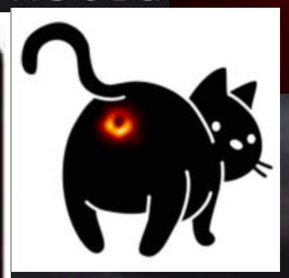

2019
NOW

WHAT BREXIT LOOKS LIKE FROM SPACE
DEAL APPEARS AS FAR, FAR AWAY AS THIS BLACK
HELPLESS MAY SUCKED INTO THE BRUSSELS VO


×400%
×300%


boredpanda.com

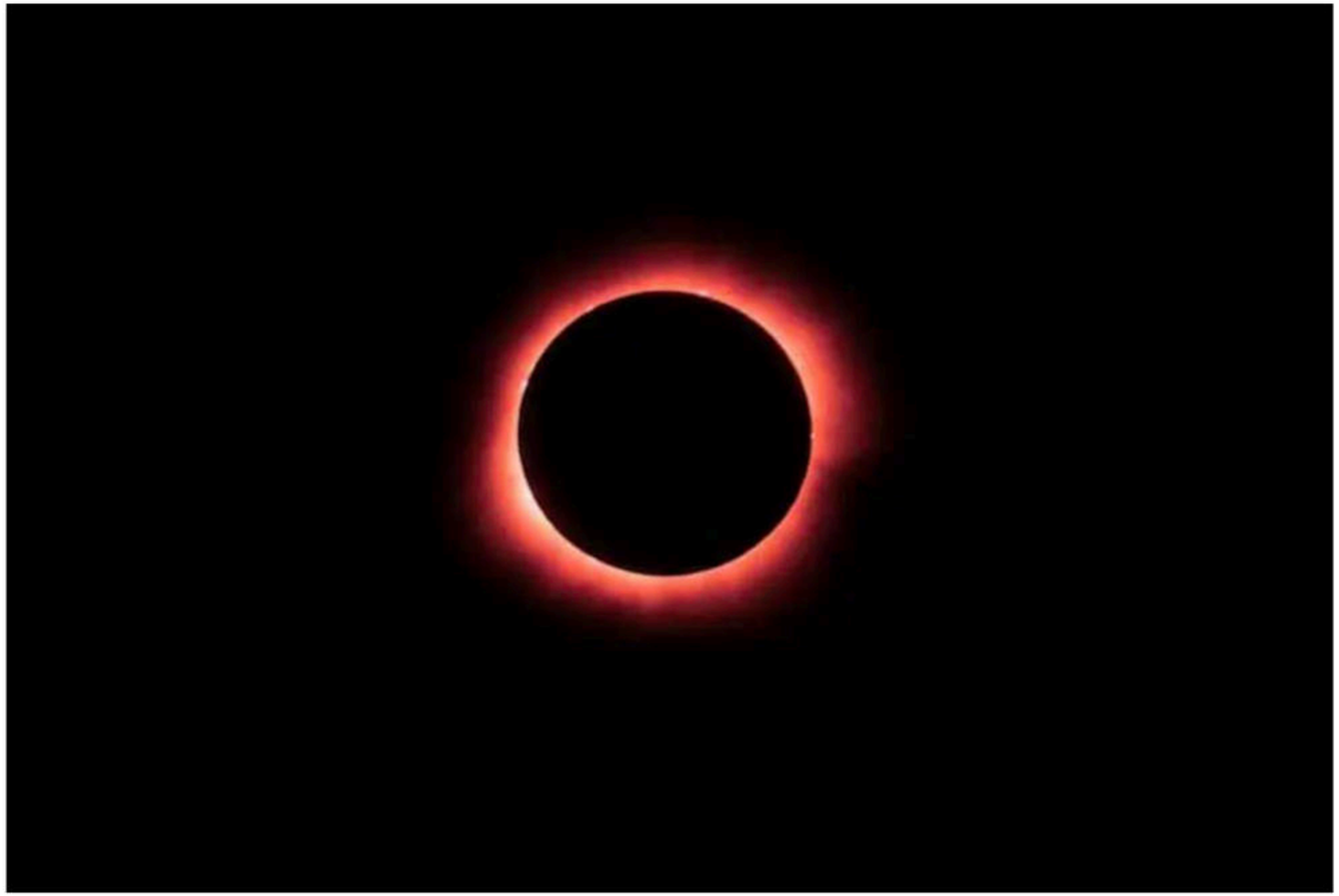
×200%



What is the scariest thing you can see in the sky?

First look: Total solar eclipse mesmerizes Mexico

MND Staff April 8, 2024 4



The 2024 total solar eclipse in Mazatlán, Mexico. (Presidencia/Cuartoscuro)

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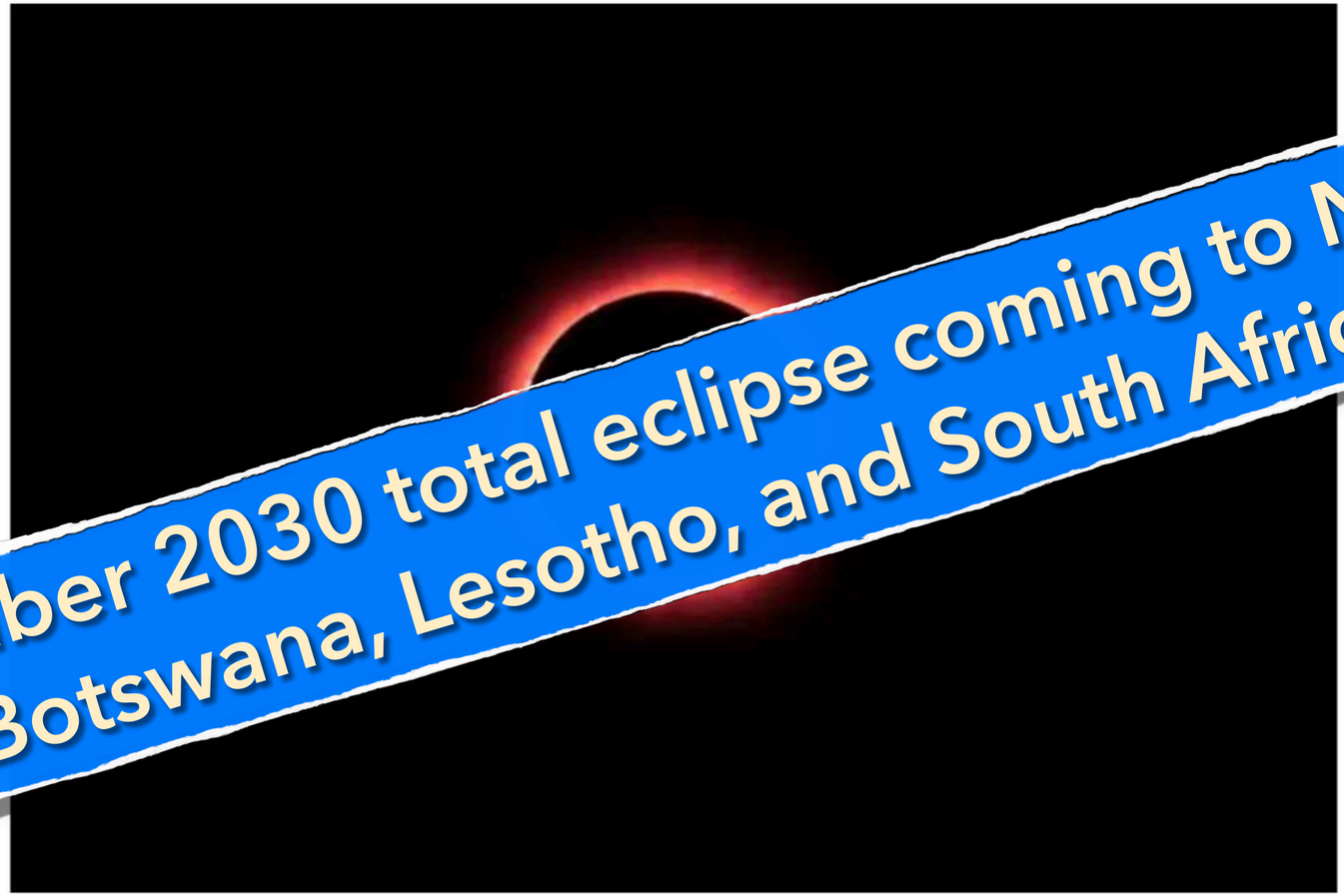


The 2024 total solar eclipse in Mazatlán, Mexico. (Presidencia/Cuartoscuro)

November 2030 total eclipse coming to Namibia, Botswana, Lesotho, and South Africa!!

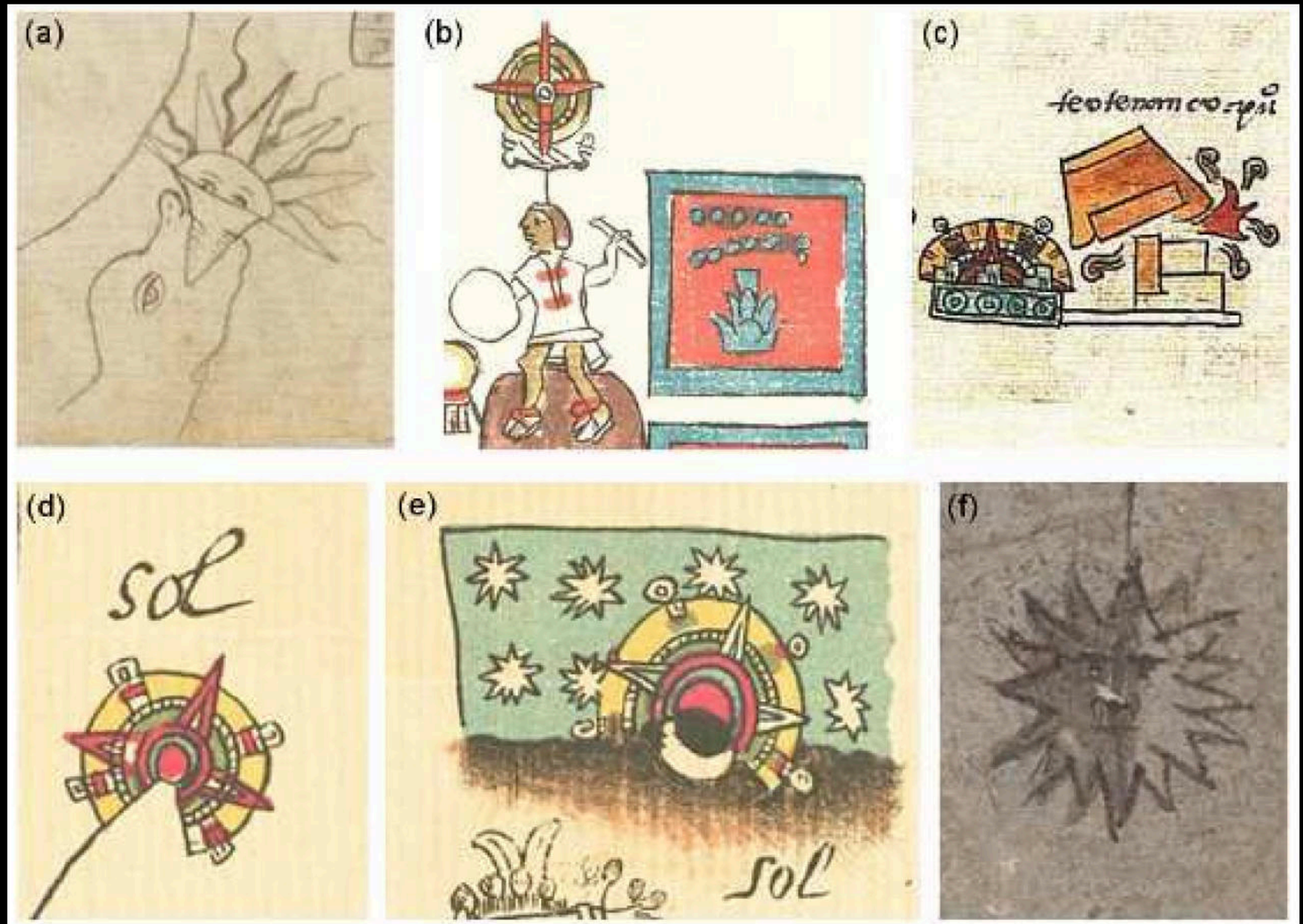
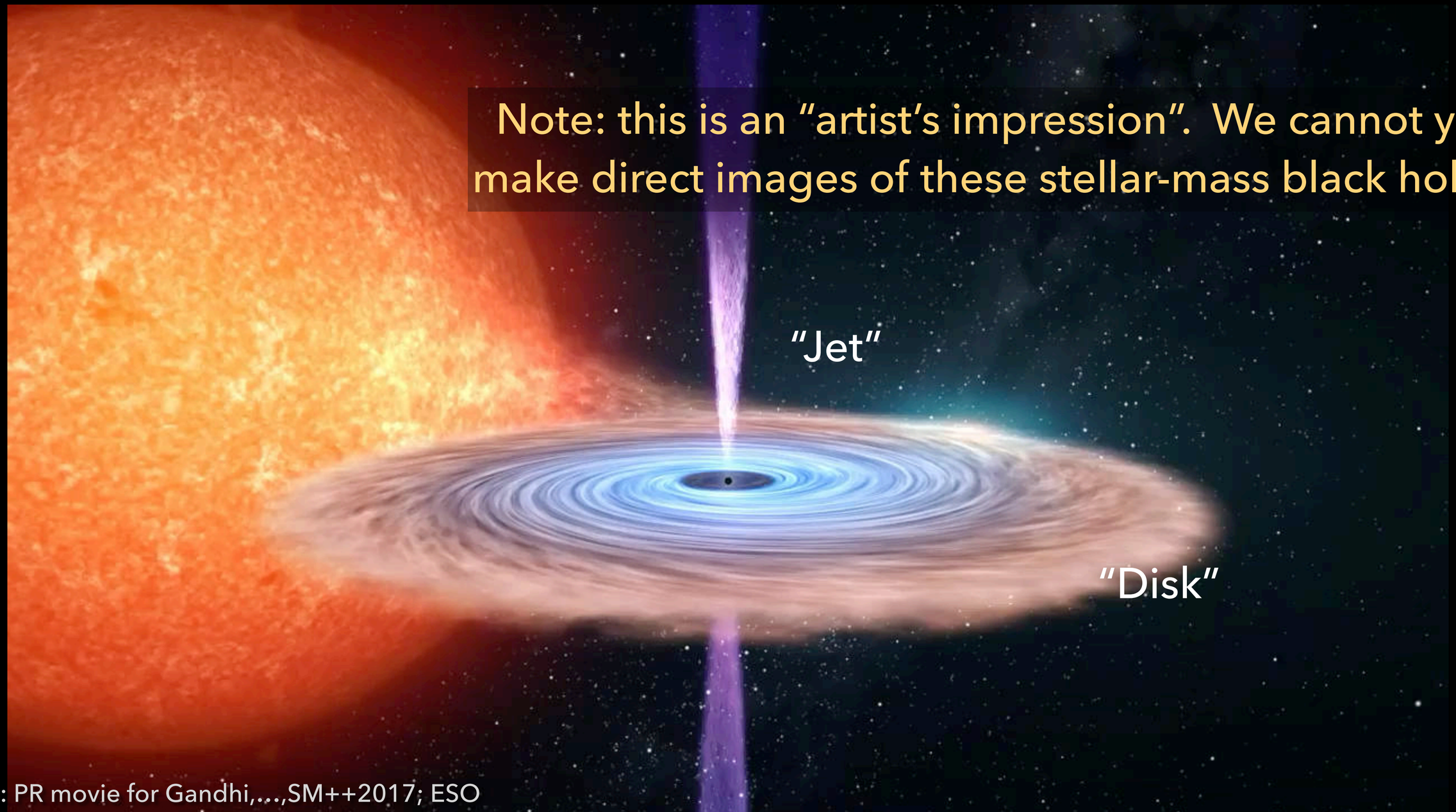


Figure 1: Various glyphs for eclipses from the codices. (a) Azcatitlan, 7v: eclipse of 1301, 1303, or 1311. (b) Vaticanus A, 76r: eclipse of 1437. (c) Mendoza, 10r: eclipse of 1477. (d) Telleriano, 37r: eclipse of 1477. (e) Telleriano, 40v: eclipse of 1496. (f) Mexicanus, p56: eclipse of 1524(?).

From "*Eclipses in the Aztec Codices*", Emil Khalisi, 2020

The ultimate eclipse: black holes eating suns!



Credit: PR movie for Gandhi,…,SM++2017; ESO

Talk outline

★ From imagination to discovery

★ The astrophysical role of black holes

★ Event Horizon Telescope and its results

★ New horizons including the AMT in NA

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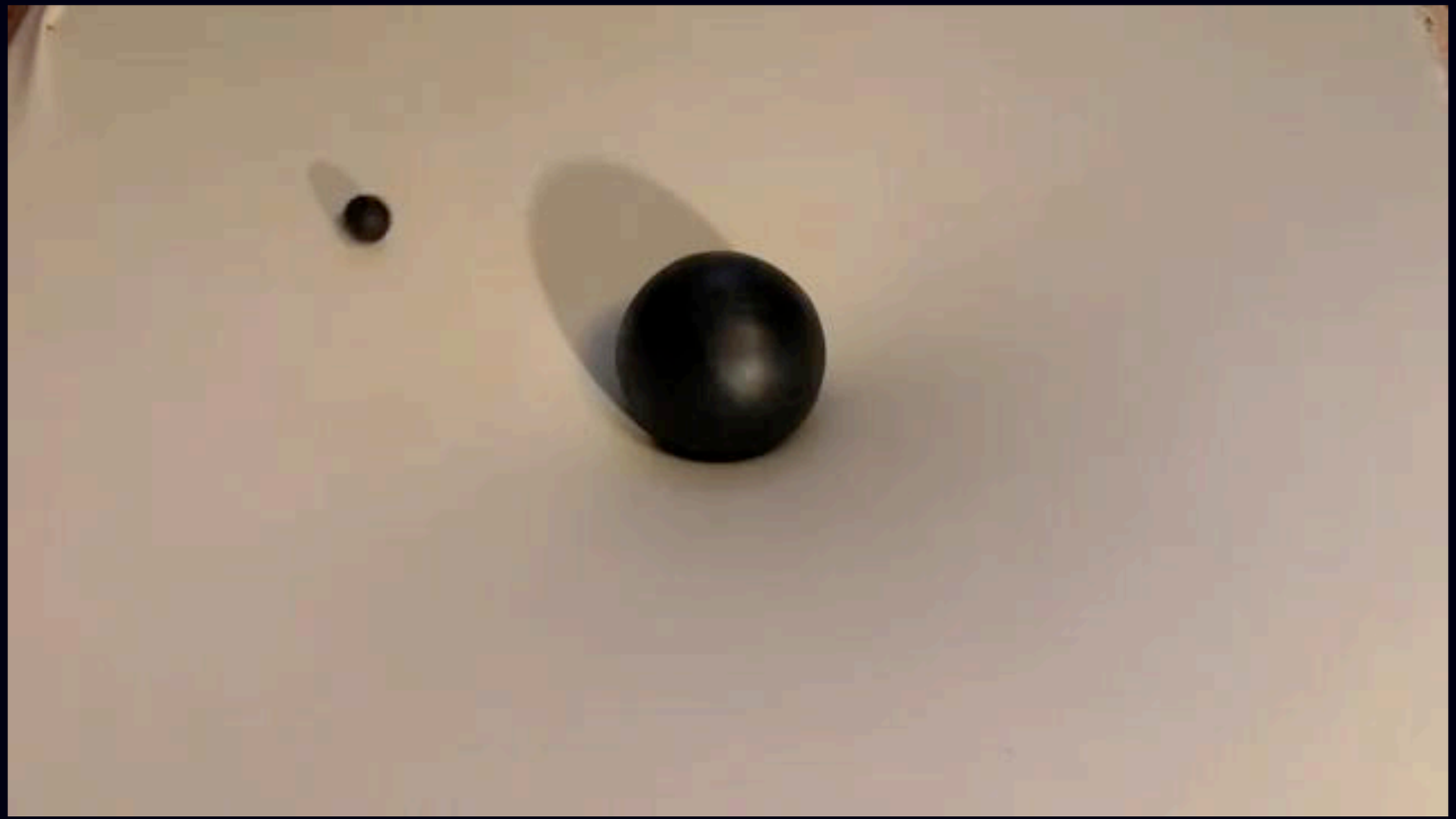
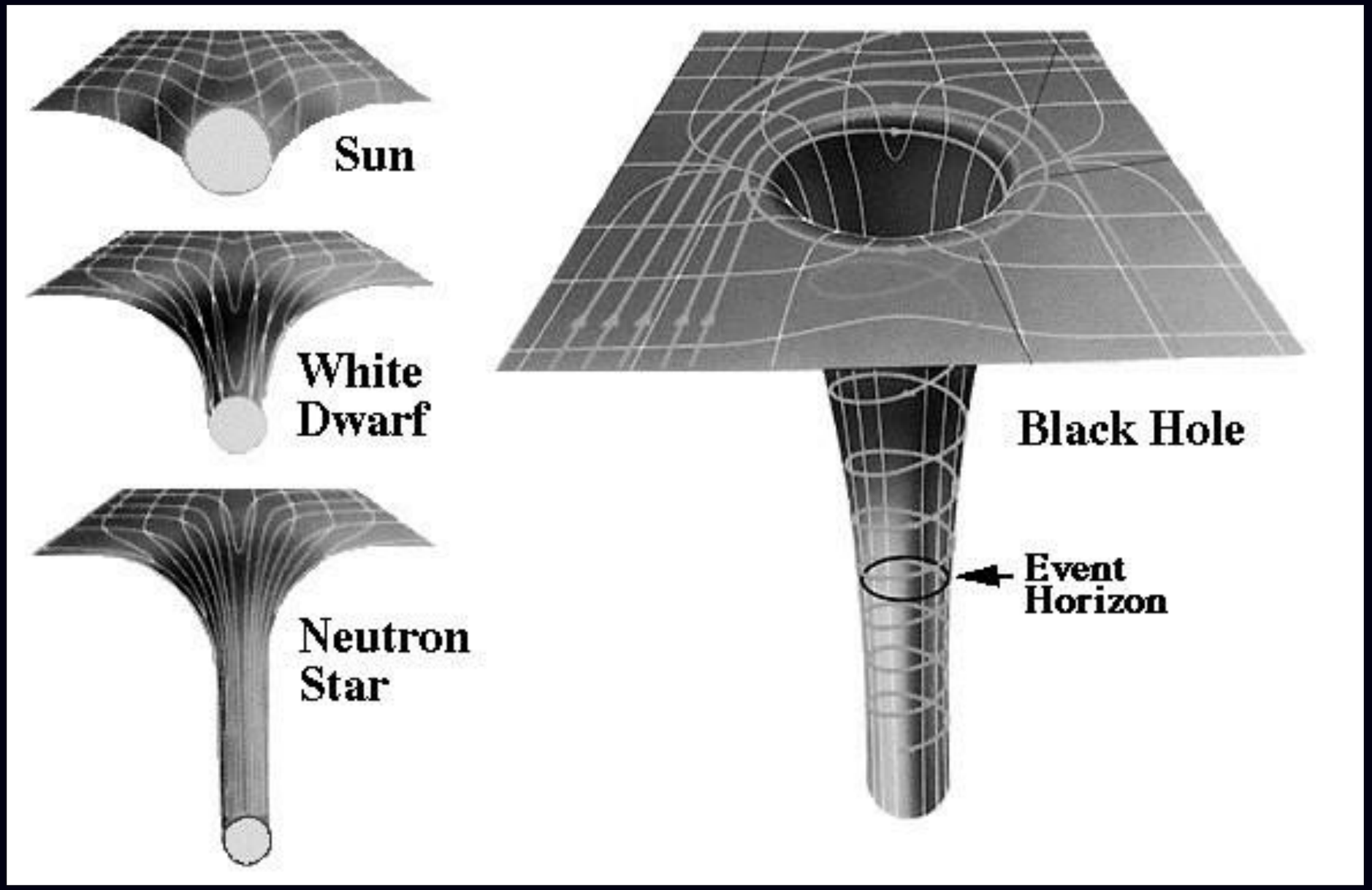
Einstein's (1908-1915) Theory of General Relativity (GR): Gravity is not a force like the others!

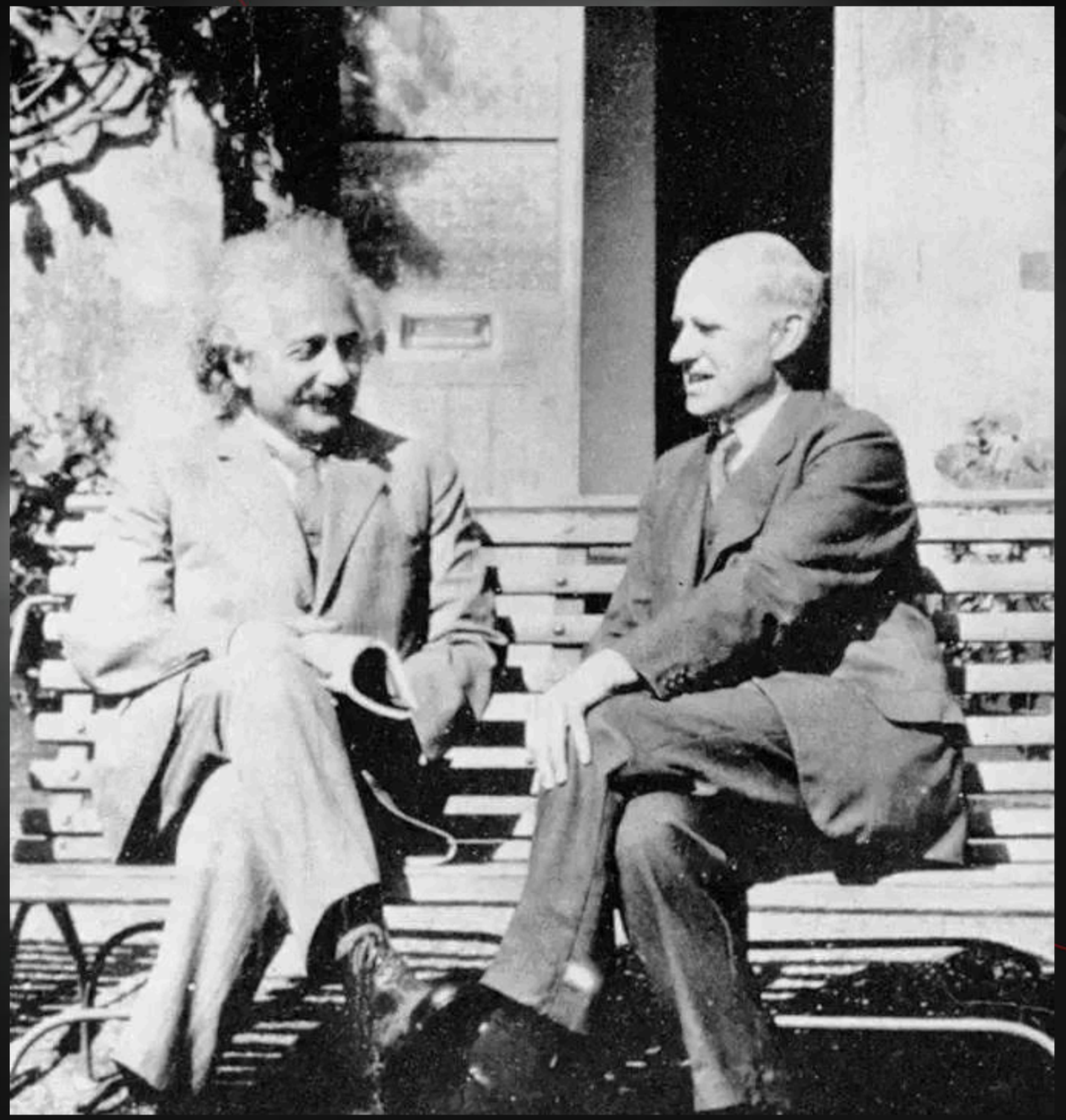
Gravity is a "*byproduct*" of spacetime curvature



Prediction: all massive objects bend spacetime (even you)



1919: African solar eclipse expedition by Eddington proves GR is correct



HR1375

Taurus

72 Tauri

69 Tauri

ESO/Landessternwarte Heidelberg-Königstuhl/F. W. Dyson, A. S. Eddington, & C. Davidson - https://www.eso.org/public/images/potw1926a/

1939: Oppenheimer & Snyder: star can collapse smoothly through its own event horizon

"Gravitationally completely collapsed stars"
➠ Black Holes!

ON CONTINUED GRAVITATIONAL CONTRACTION*

J. R. OPPENHEIMER and H. SNYDER

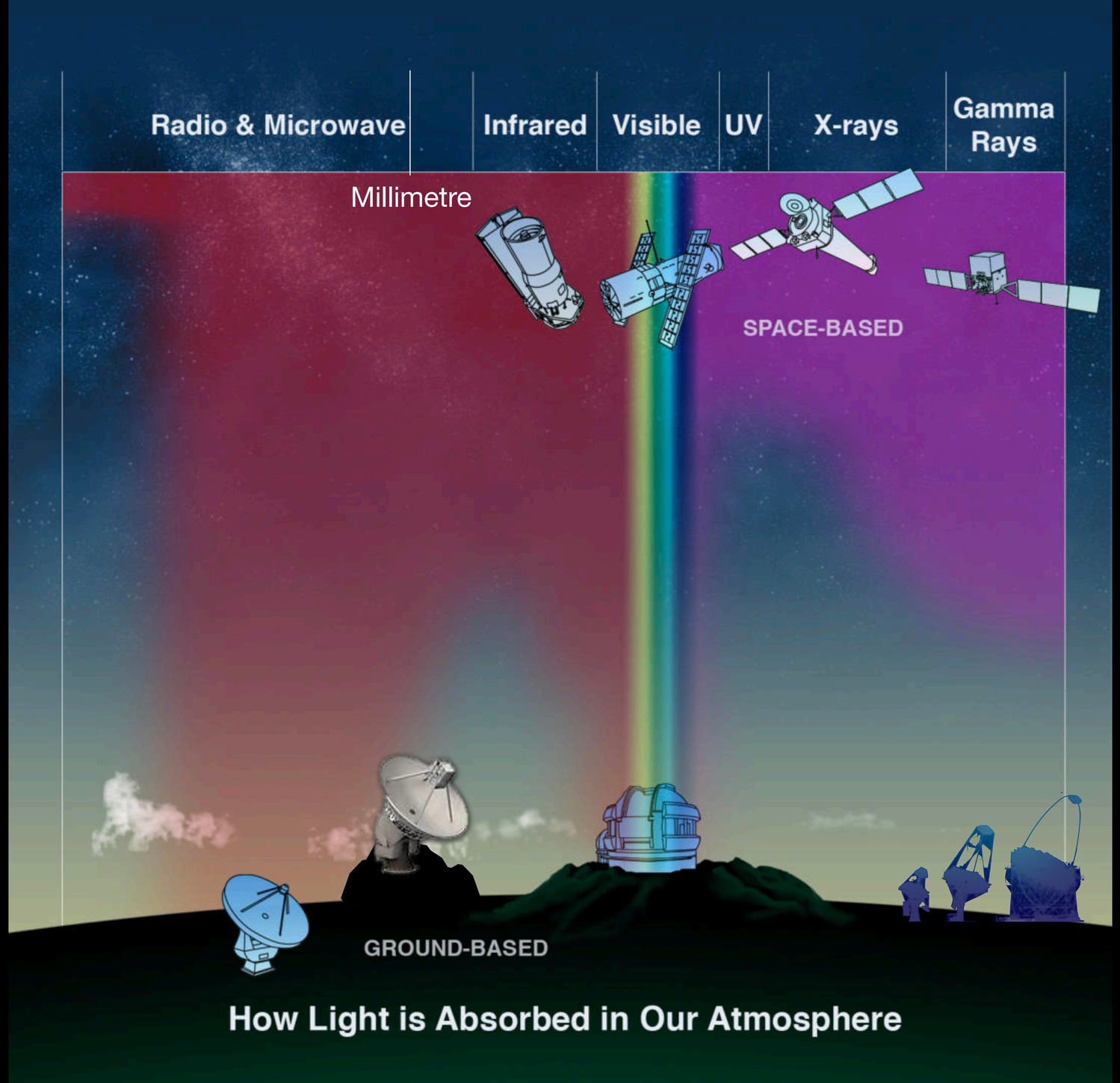
Abstract. When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse. Unless fission due to rotation, the radiation of mass, or the blowing off of mass by radiation, reduce the star's mass to the order of that of the sun, this contraction will continue indefinitely. In the present paper we study the solutions of the gravitational field equations which describe this process. In **1**, general and qualitative arguments are given on the behavior of the metrical tensor as the contraction progresses: the radius of the star approaches asymptotically its gravitational radius; light from the surface of the star is progressively reddened, and can escape over a progressively narrower range of angles. In **2**, an analytic solution of the field equations confirming these general arguments is obtained for the case that the pressure within the star can be neglected. The total time of collapse for an observer comoving with the stellar matter is finite, and for this idealized case and typical stellar masses, of the order of a day; an external observer sees the star asymptotically shrinking to its gravitational radius.

1

Recently it has been shown (Oppenheimer 1939) that the general relativistic field equations do not possess any st ns for a spherical distribution of cold neutrons if the total mass of the ter than $\sim 0.7\odot$. It seems of interest to investigate the behavior of no field equations.

In this work we will be concerned sses, $>0.7\odot$, and which have used up their nuclear s se circumstances would collapse under the influen se energy. This energy could be divided into fo of the particles in the star, (2) radiation, (3) layers of the star which could be blown aw which could divide the e sufficiently

Photographed by Arnold Newman

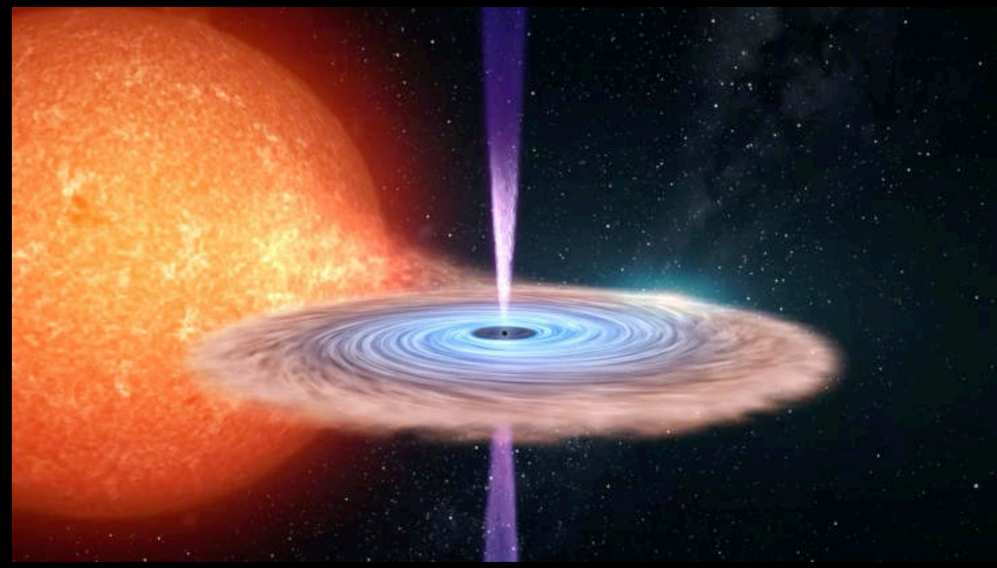


How Light is Absorbed in Our Atmosphere

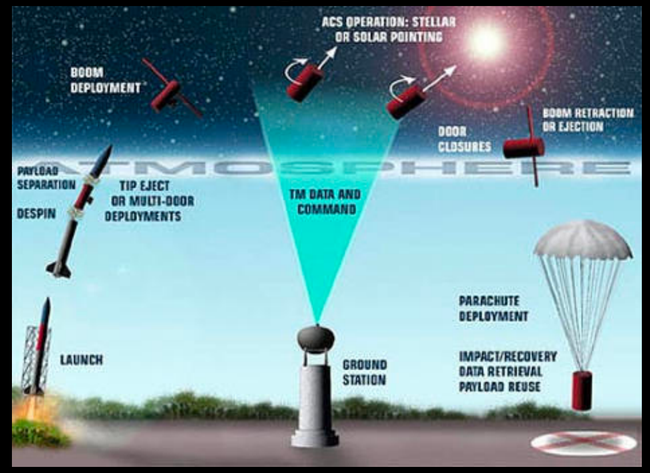
The path to establishing ‘real’ black holes (space:1950’s-1960’s)

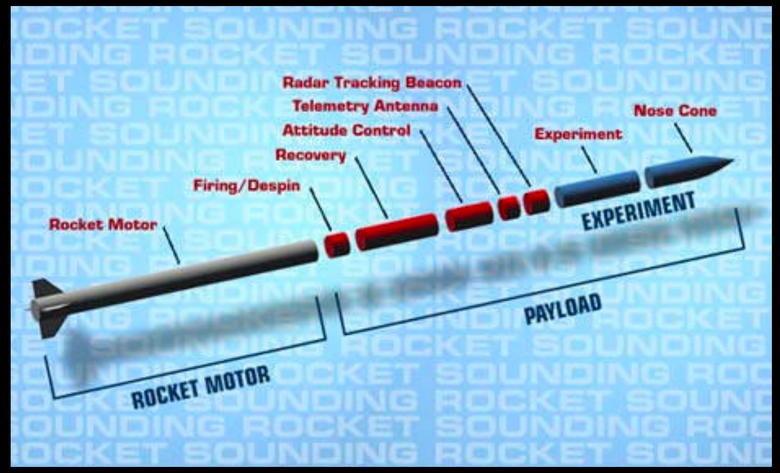
1957: Sputniks I & II launched, US responds with Space Act creating NASA!

1962-1964: Found Cygnus X-1 instead, the first black hole candidate!
(21x the mass of our sun!)



1962: American Science & Engineering launches sounding rockets looking for solar X-rays (lunar)





Credit: NASA

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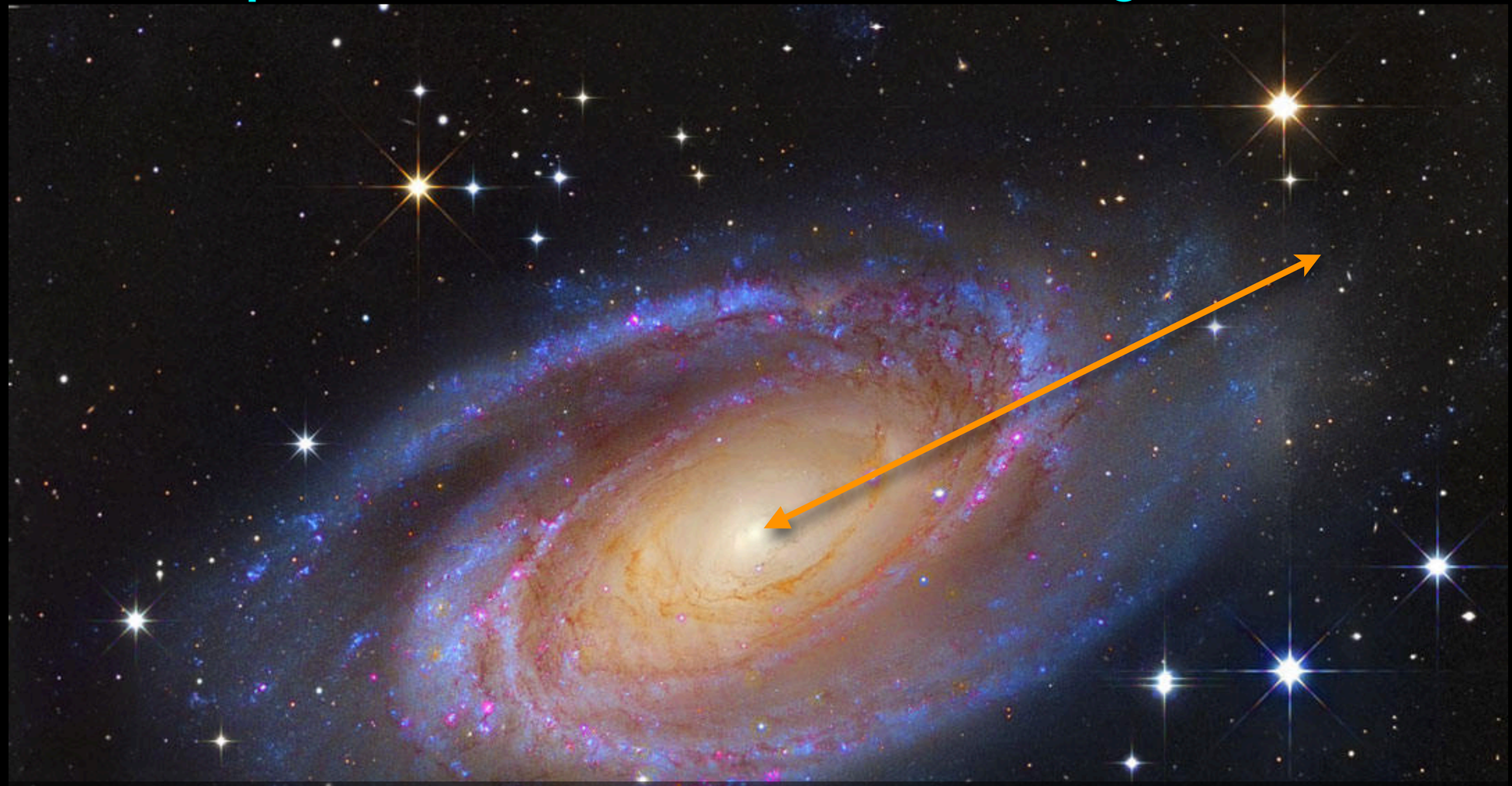
Black holes spend most of their time being rather harmless

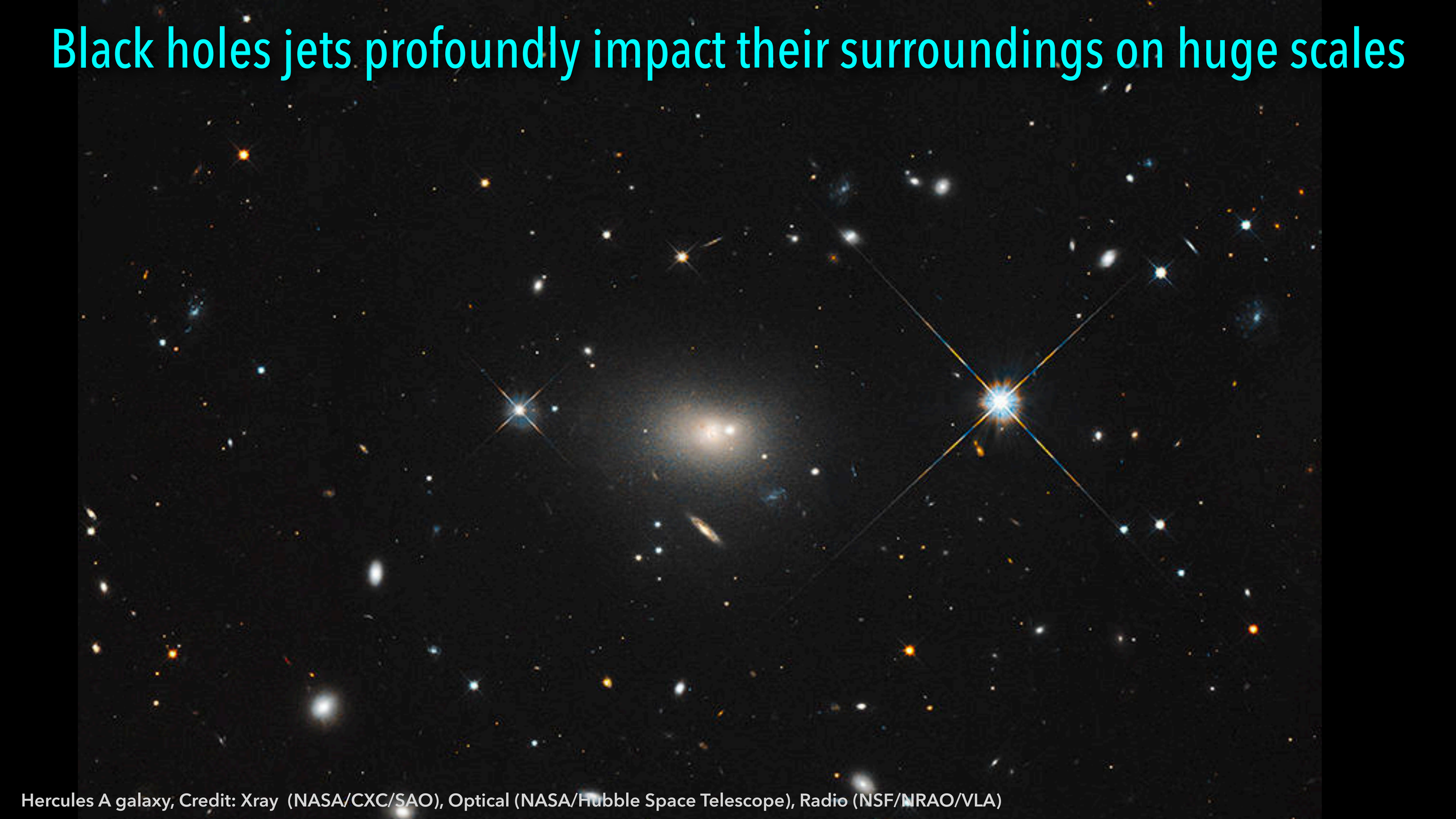


Black hole's "reach" is ~100,000 times larger than its event horizon

e.g., Milky Way is ~500,000 times larger than Sgr A*'s reach!

M81 Galaxy ("proxy" for Milky Way; NASA HST and Subaru Telescope, NAOJ)

Black holes jets profoundly impact their surroundings on huge scales



Hercules A galaxy, Credit: Xray (NASA/CXC/SAO), Optical (NASA/Hubble Space Telescope), Radio (NSF/NRAO/VLA)

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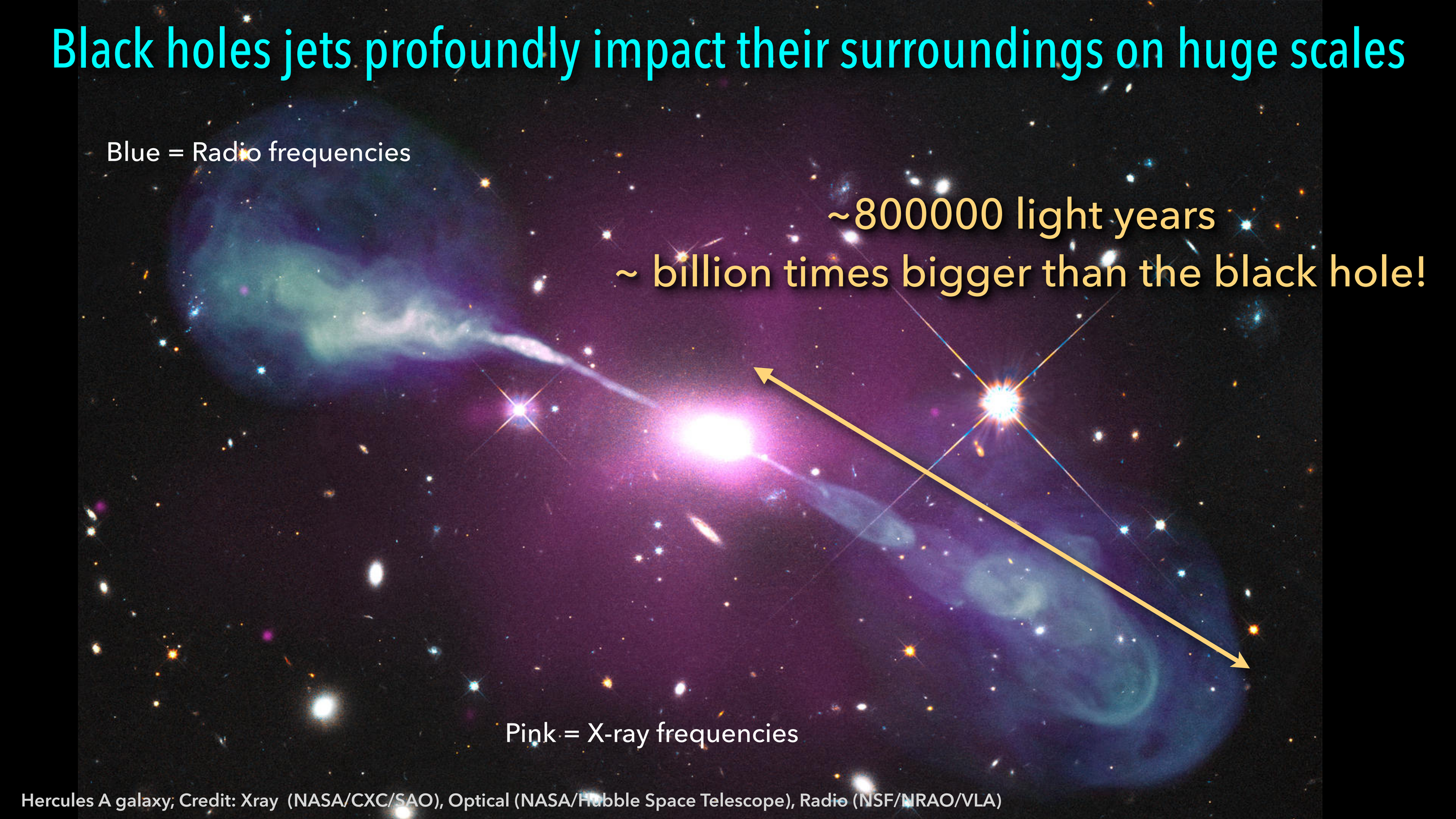
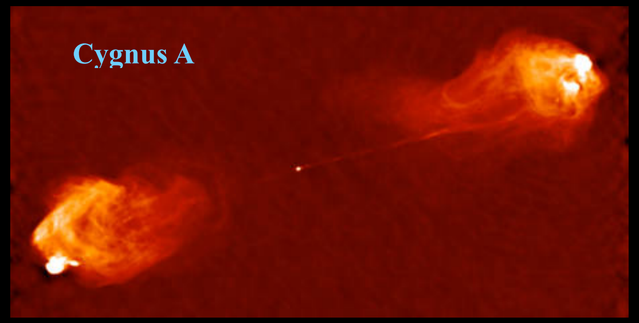
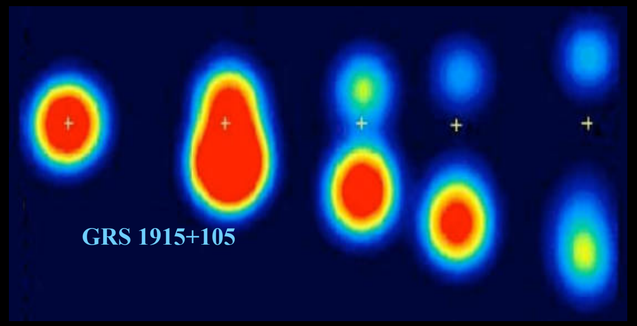
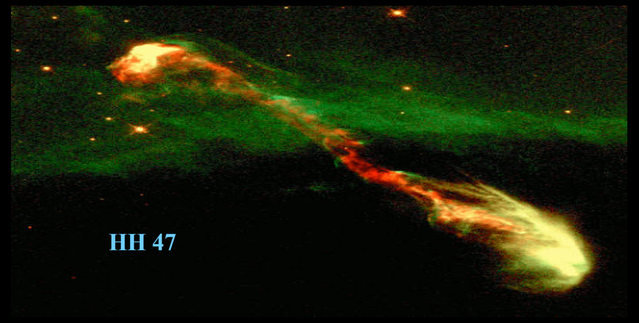


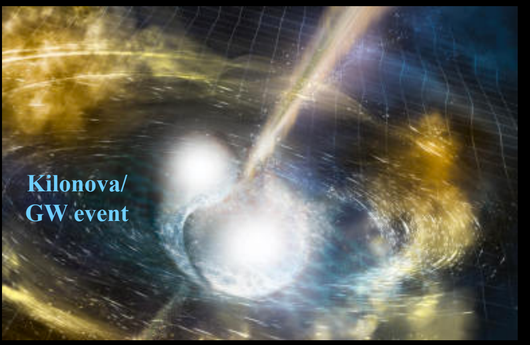
Hercules A galaxy; Credit: Xray (NASA/CXC/SAO), Optical (NASA/Hubble Space Telescope), Radio (NSF/NRAO/VLA)

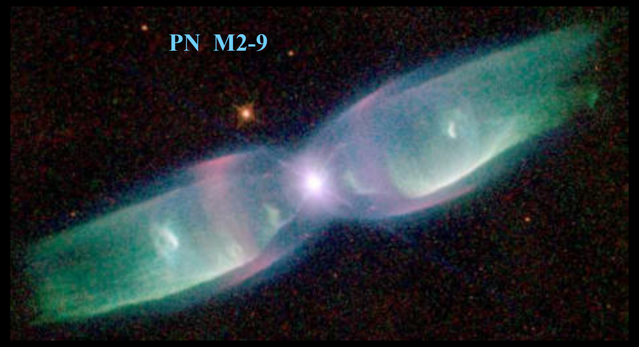
Physics of gravity-driven objects seems to be universal

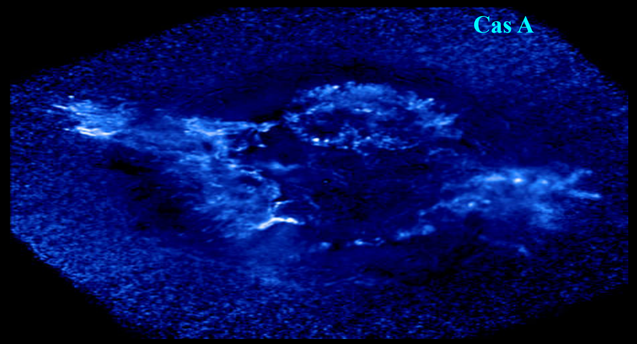


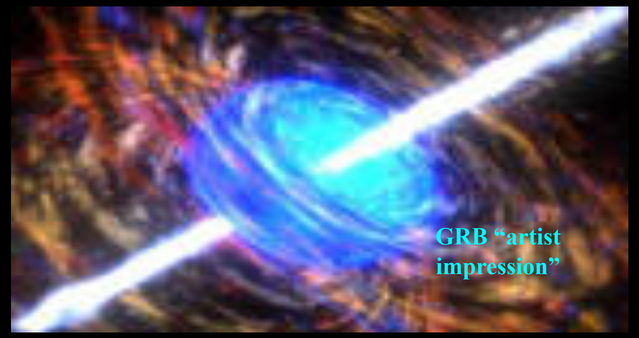


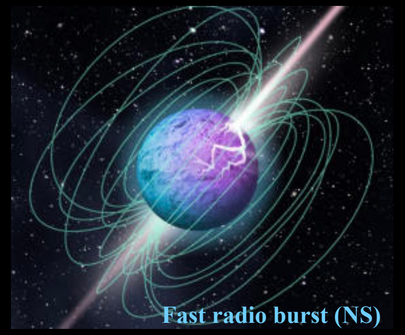


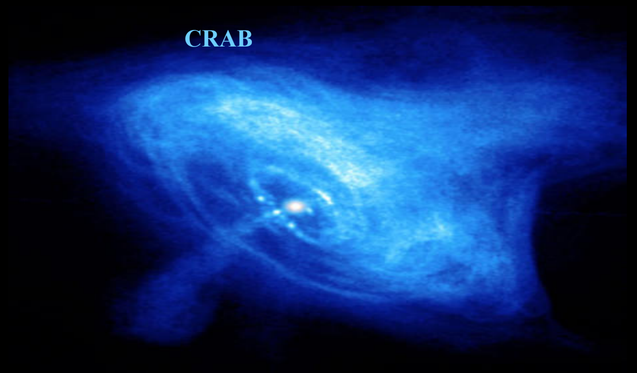












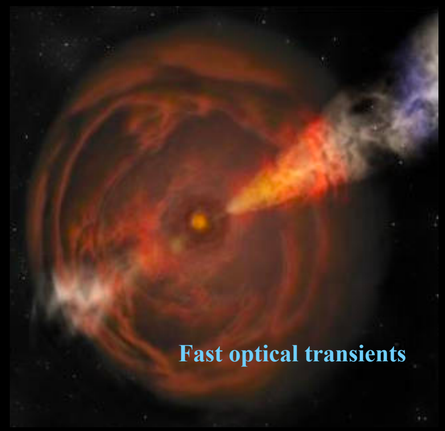


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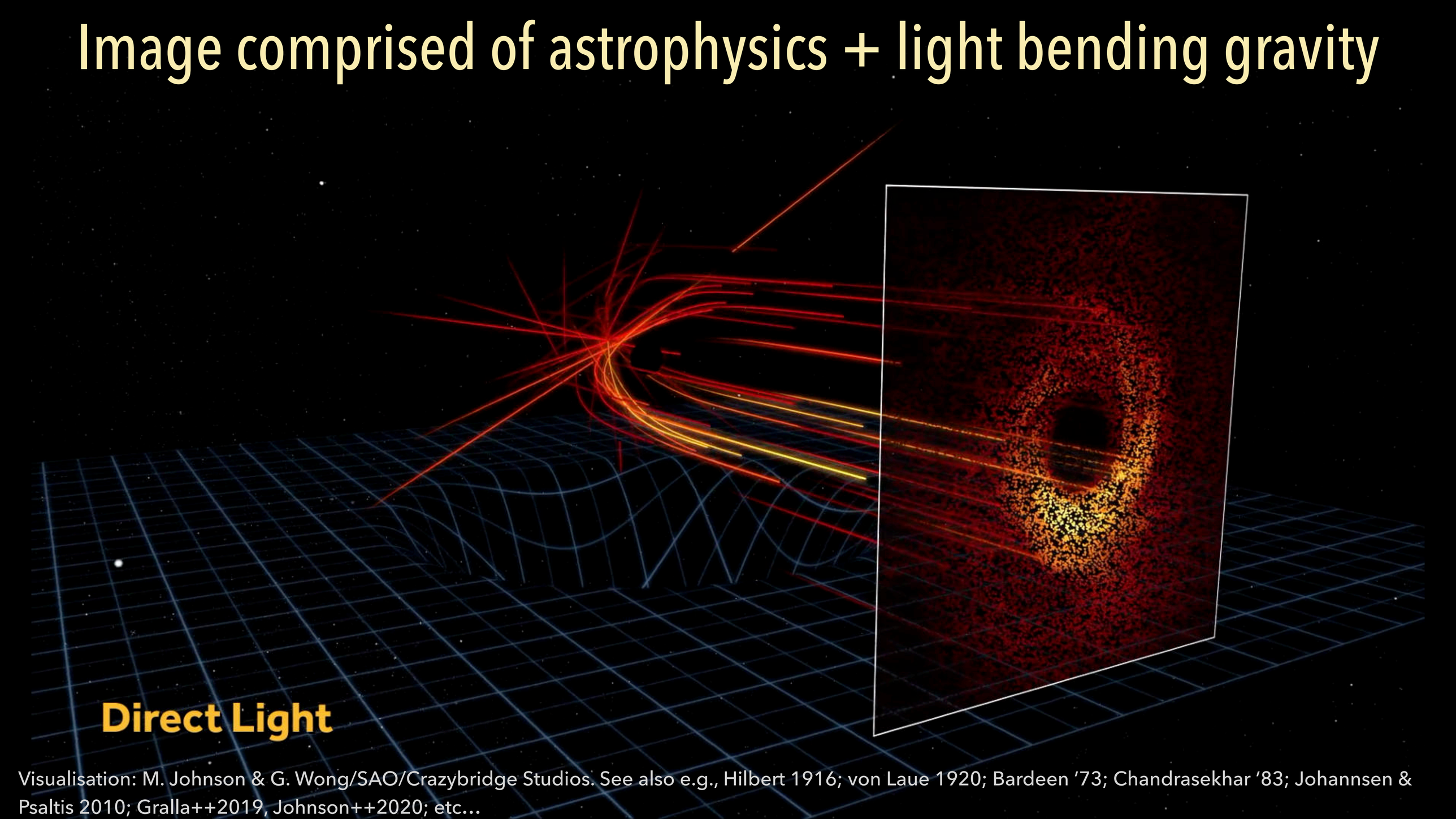
Image comprised of astrophysics + light bending gravity



Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen ‘73; Chandrasekhar ‘83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc…

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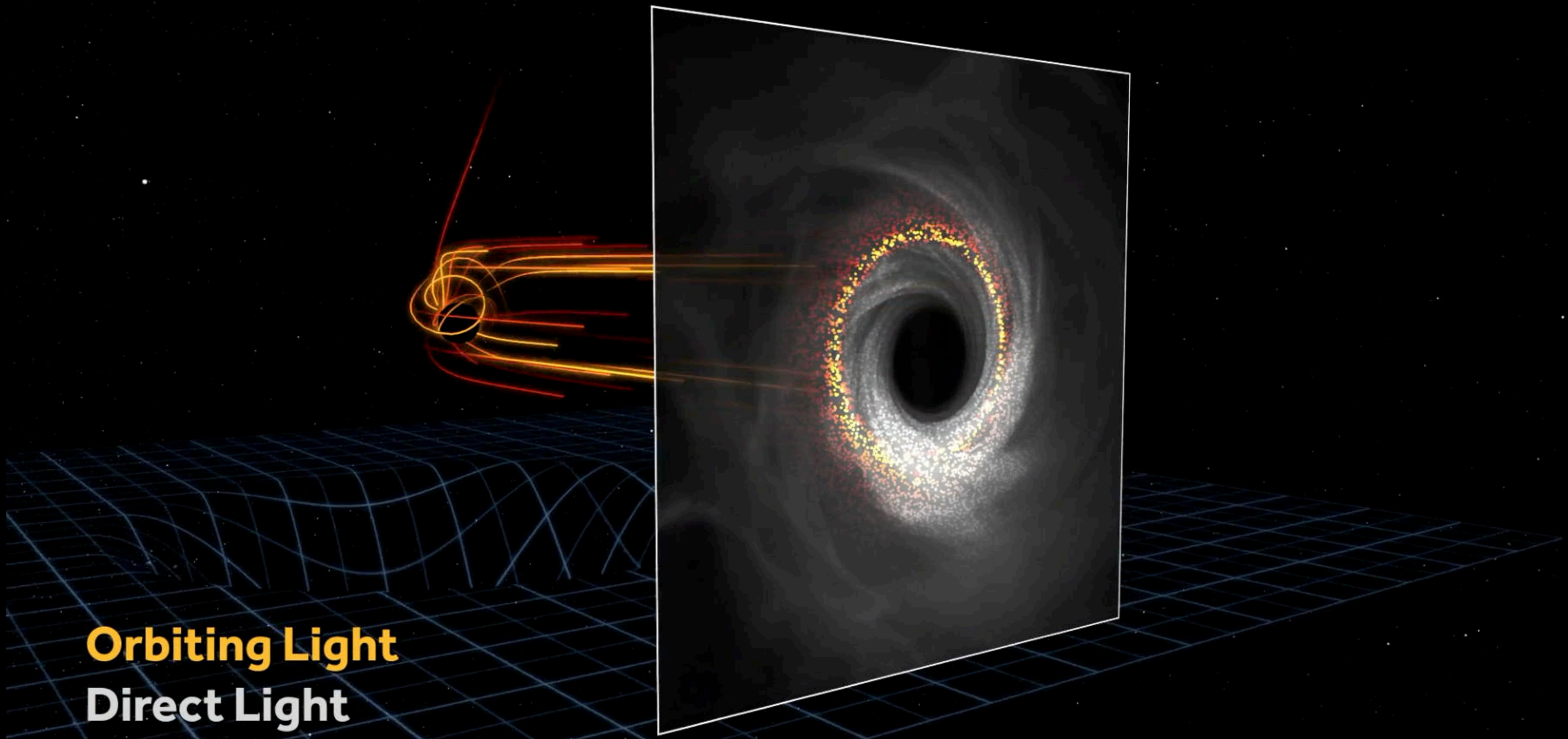

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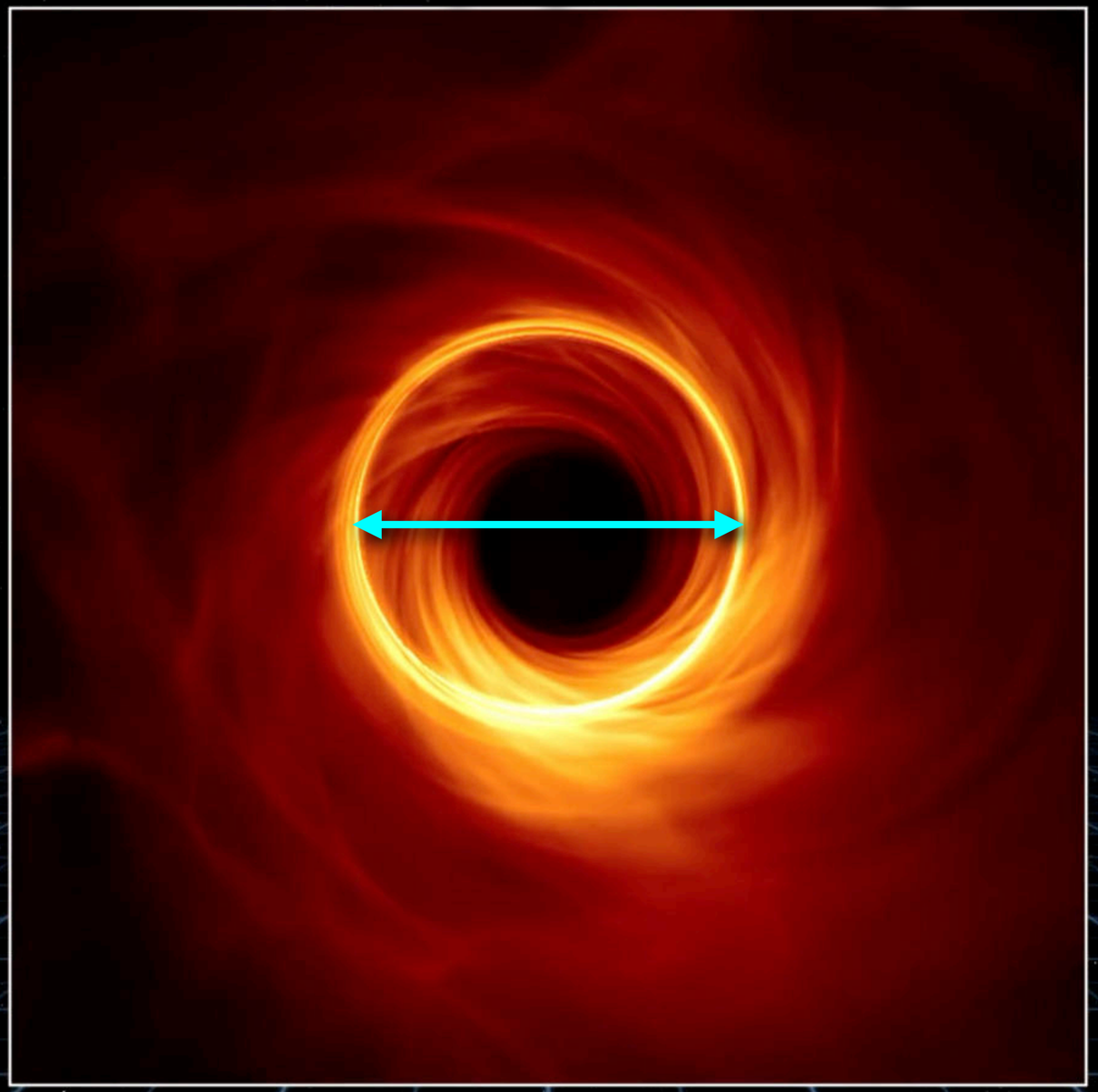
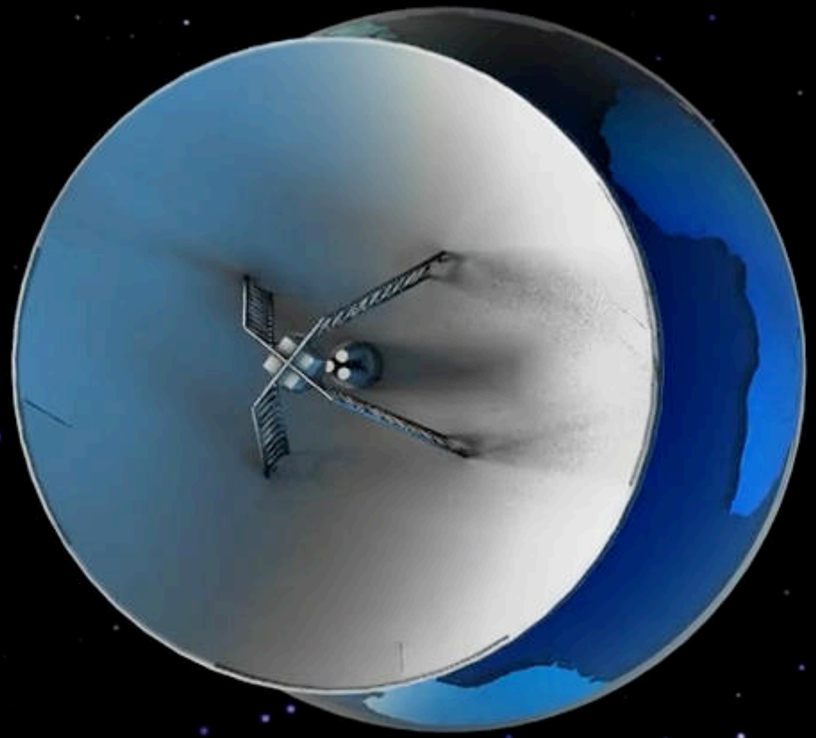


GR predicts:
"Photon ring" 5x bigger than the event horizon

Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen '73; Chandrasekhar '83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc...

Event Horizon Telescope (EHT): An Earth-sized telescope

"Very Long Baseline Interferometry" + trick: use earth's rotation!



Credit: Akiyama/Bouman/Hurt/Pyle (Caltech/Haystack)

Event Horizon Telescope (EHT): An Earth-sized telescope

"Very Long Baseline Interferometry" + trick: use earth's rotation!

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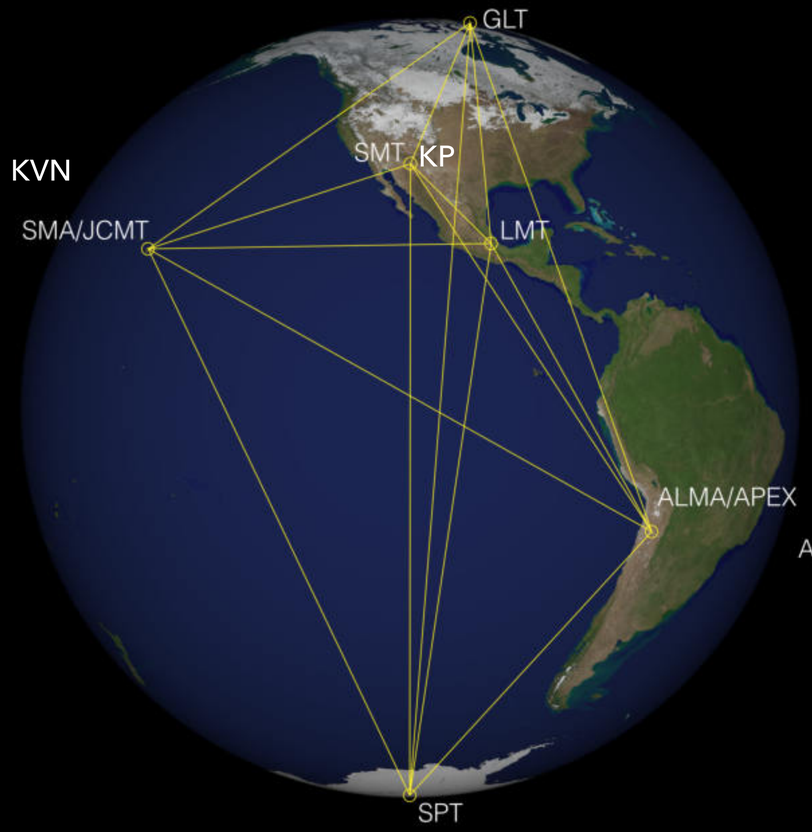
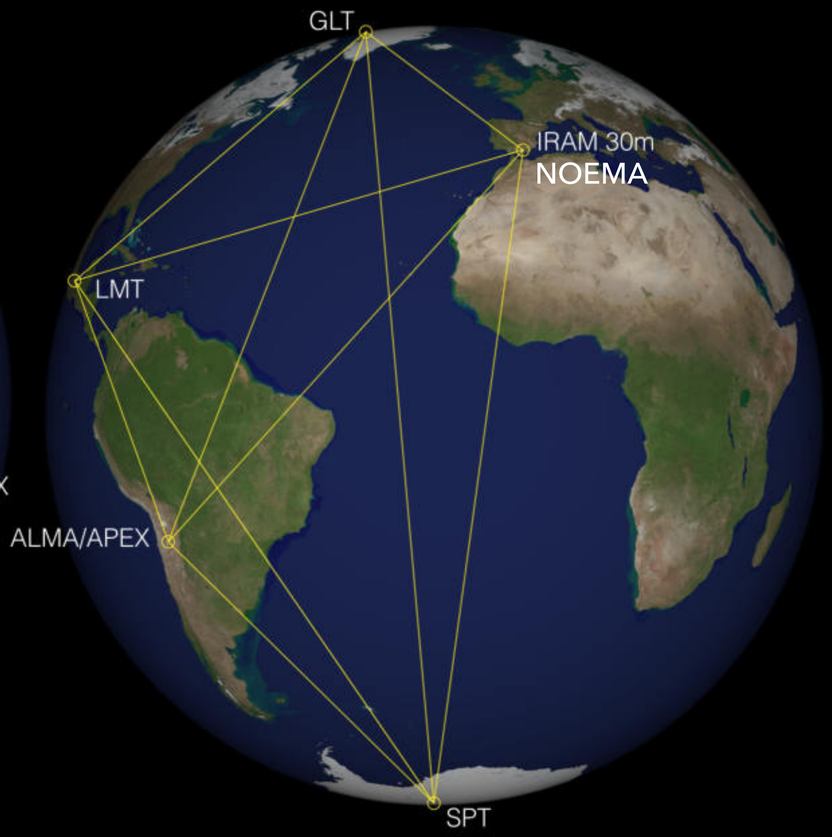
The Event Horizon Telescope (EHT) Collaboration is comprised of >400 members from >80 institutes....

...across 19 time zones!

“Living on borrowed time”: EHT’s annual campaigns

Event Horizon Telescope





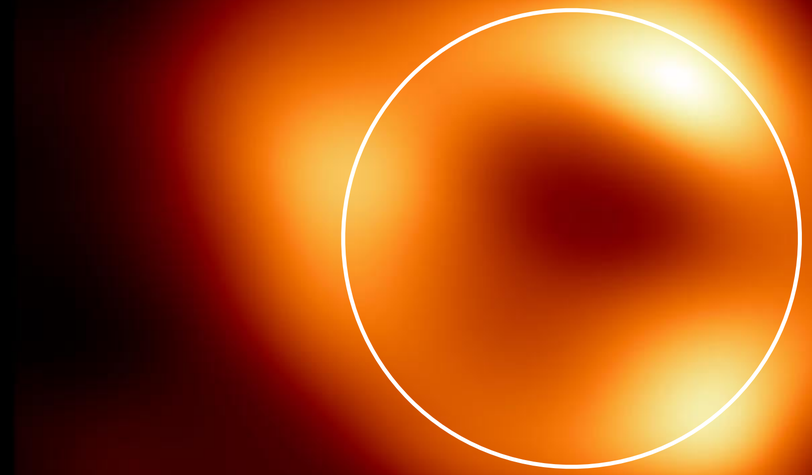
- We write competitive proposals to use the EHT for ~6/14 days annually
- 8 facilities in 2017, 9 in 2018 (+GLT)
- 2021-2023: added Kitt Peak dish + NOEMA array
- 2024: KVN & 0.8mm added/tested*
- Multiwavelength (MWL) coordination a challenge!

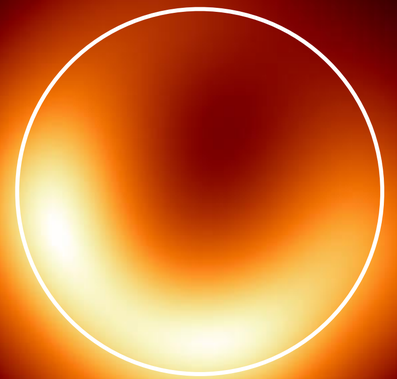
*Doeleman++2024, in press

Two directly imaged black hole “shadows” with EHT
Consistent with prediction of GR to within 10-17%

Sgr A*:
M ≈ 4 million solar masses
D ≈ 27000 light years
d ≈ 52 μas

M87*:
M ≈ 6.5 billion solar masses
D ≈ 55 million light years
d ≈ 42 μas

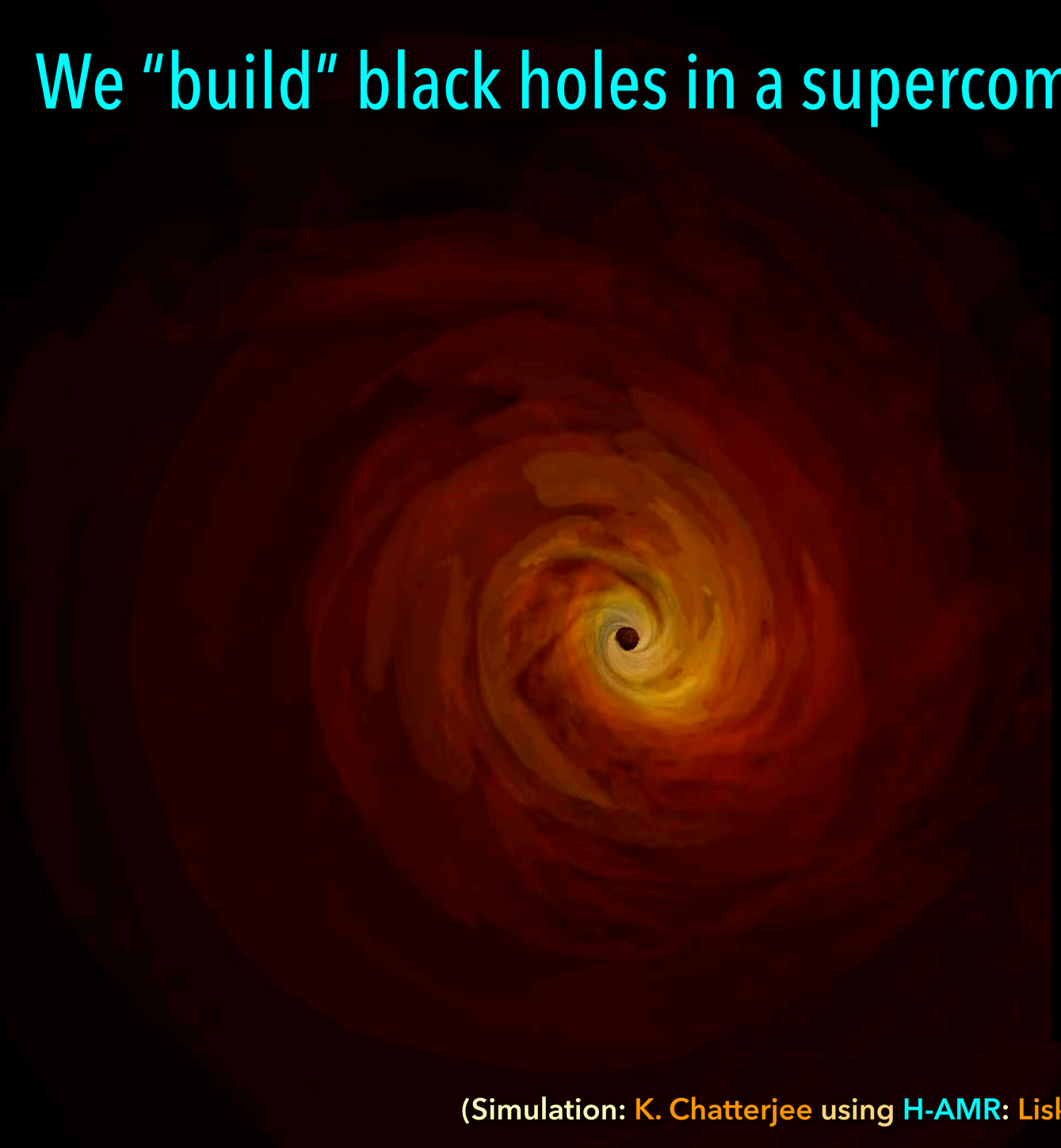


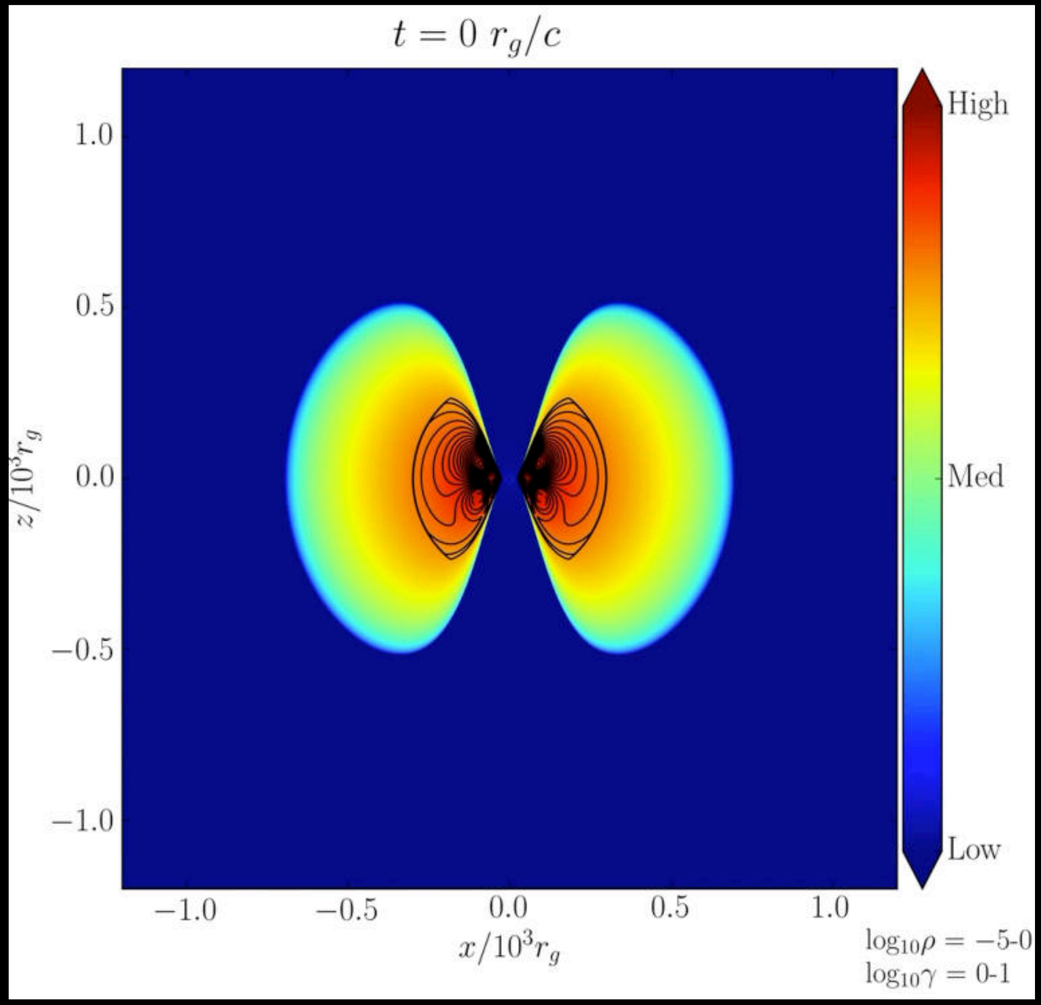


Event Horizon Telescope

EHTC M87* paper I, IV (2019); Sgr A* paper I (2022)

We “build” black holes in a supercomputer to model/interpret our data





(Simulation: K. Chatterjee using H-AMR: Liska, Chatterjee, Tchekhovskoy++ 2022)

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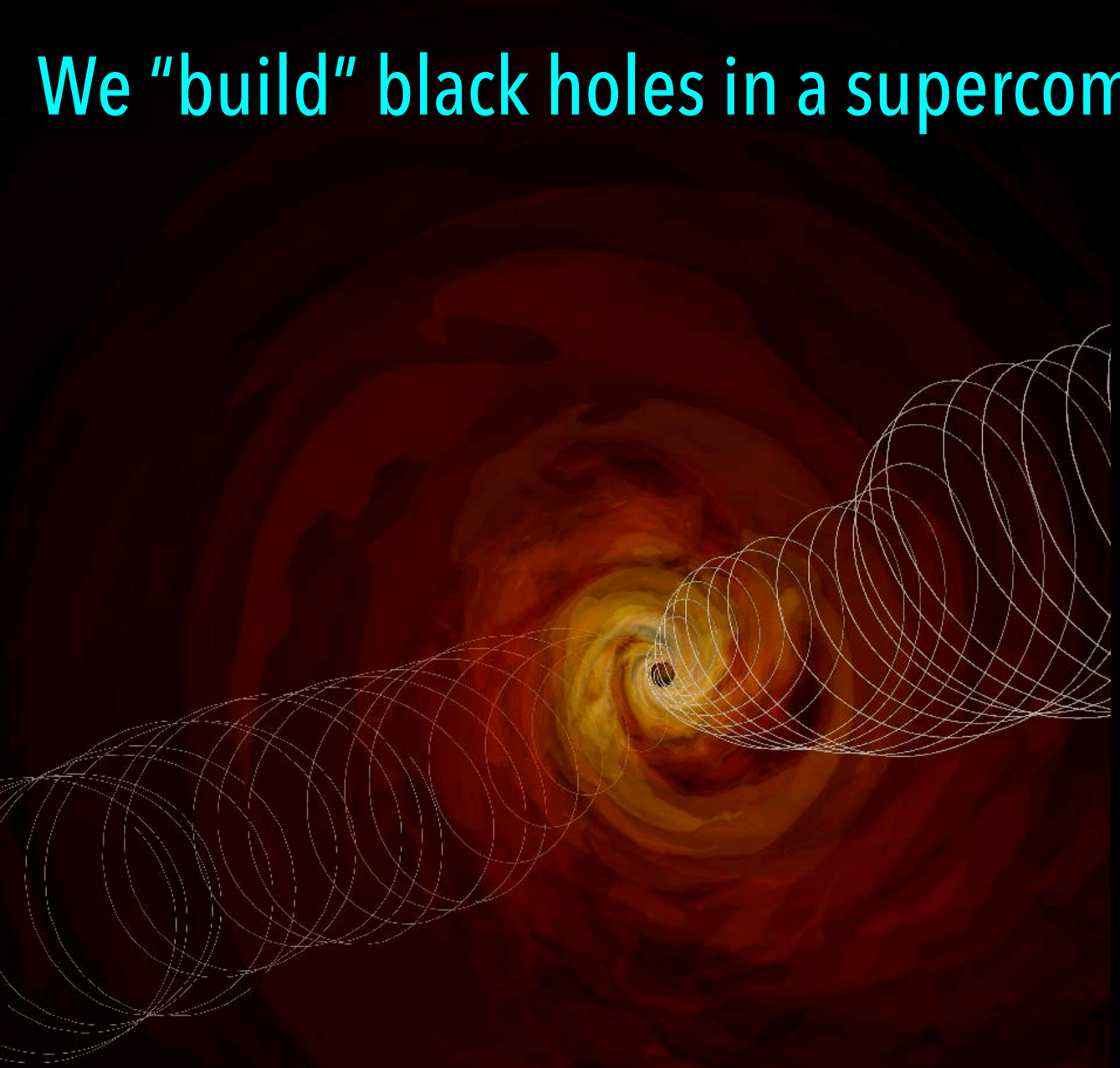

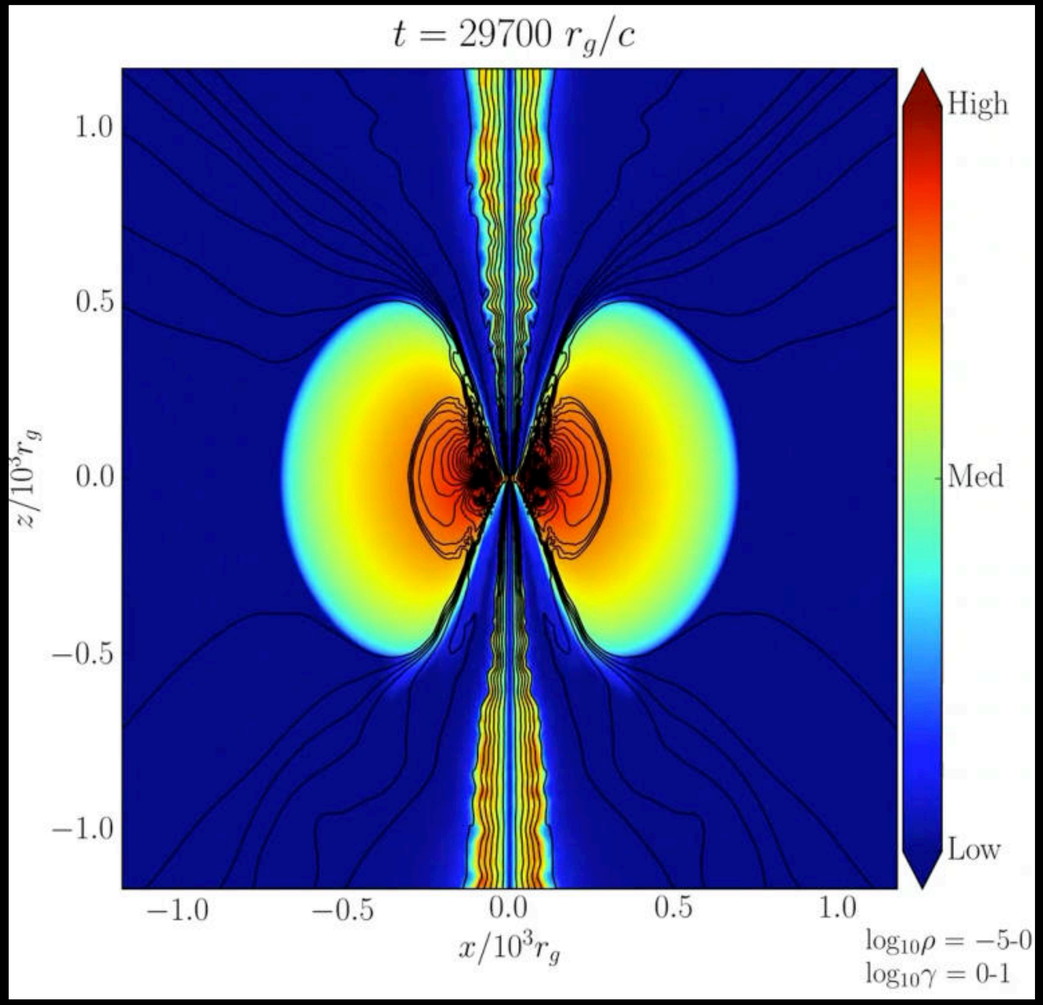

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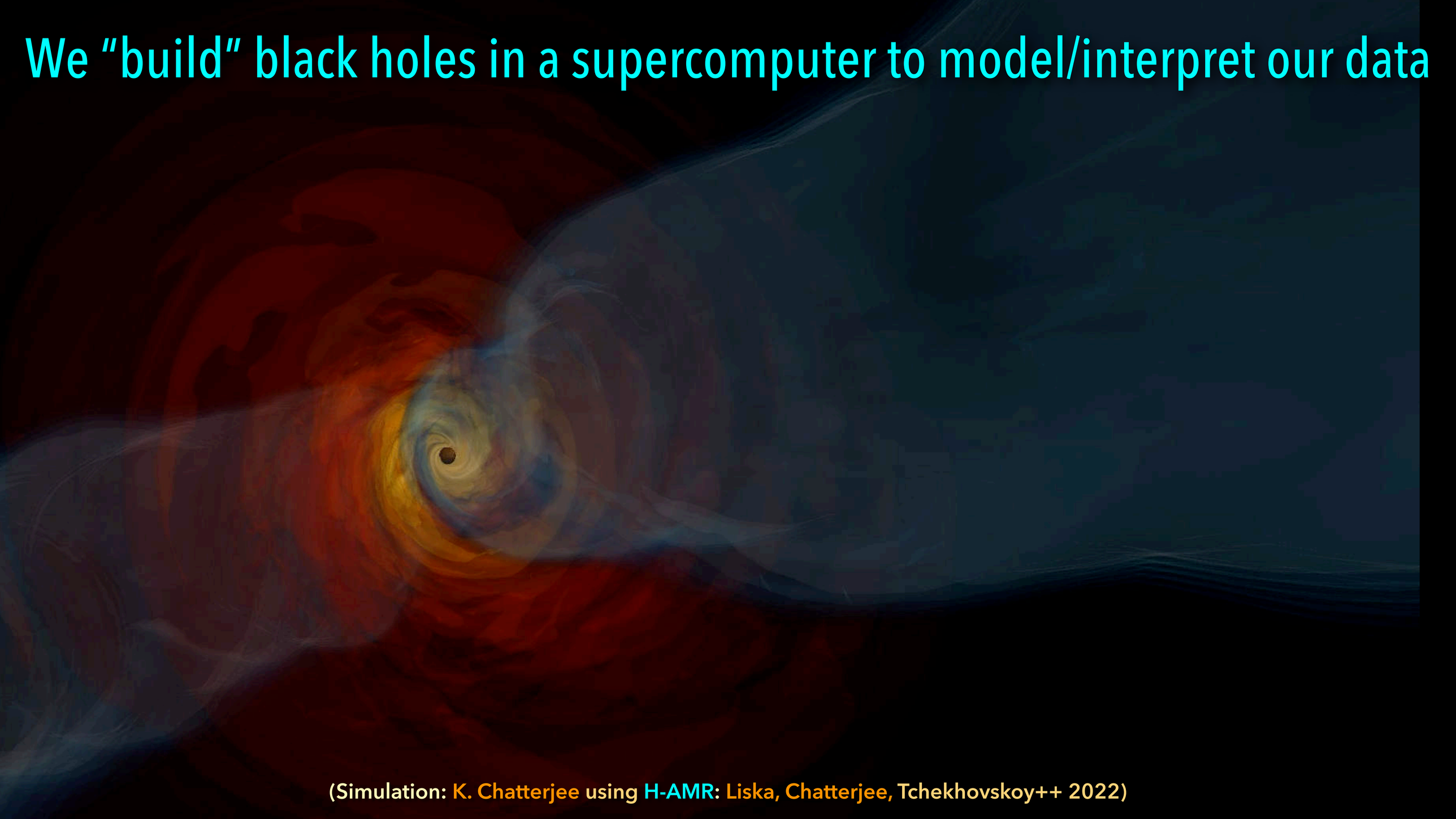

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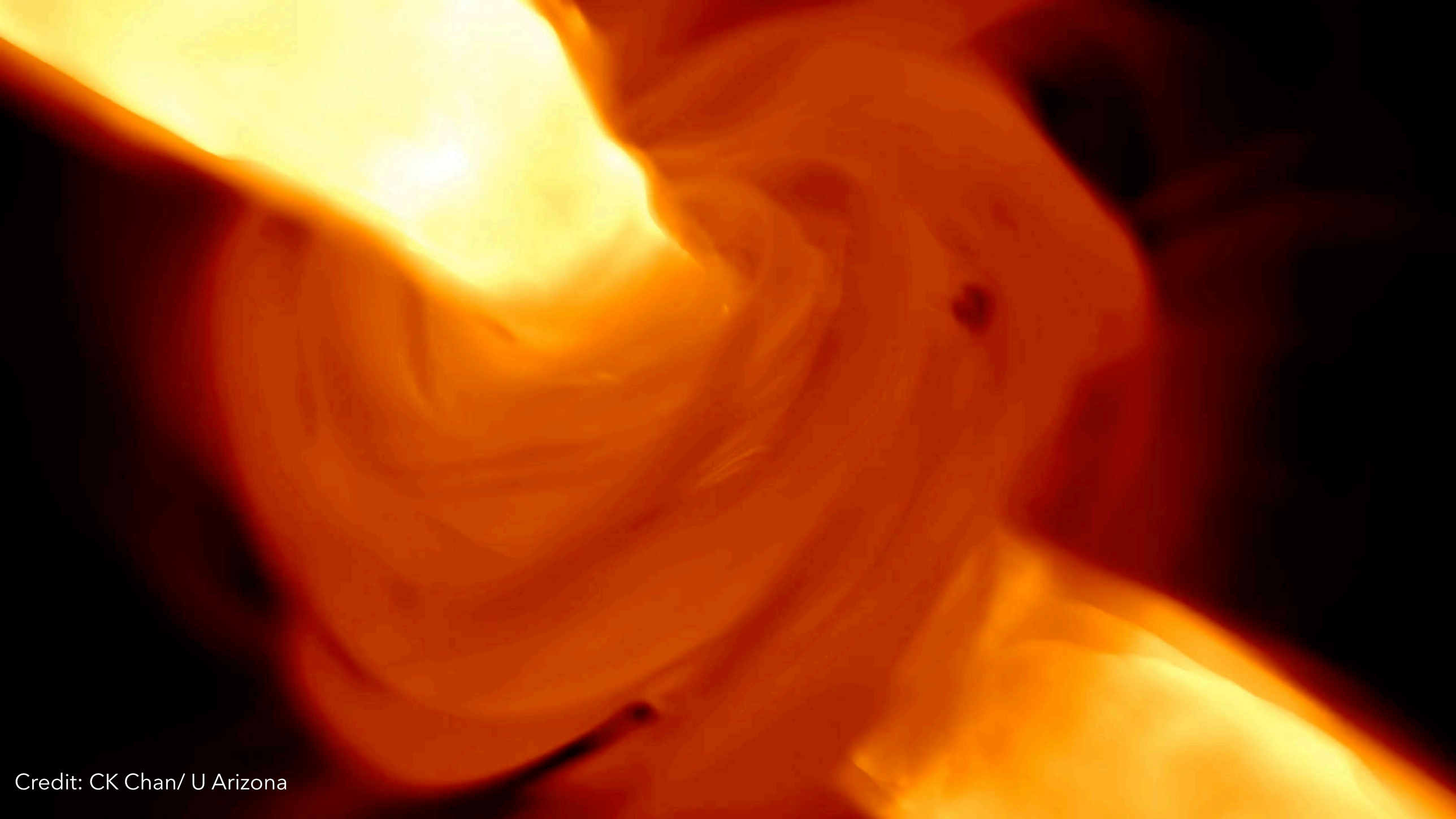

Credit: CK Chan/ U Arizona

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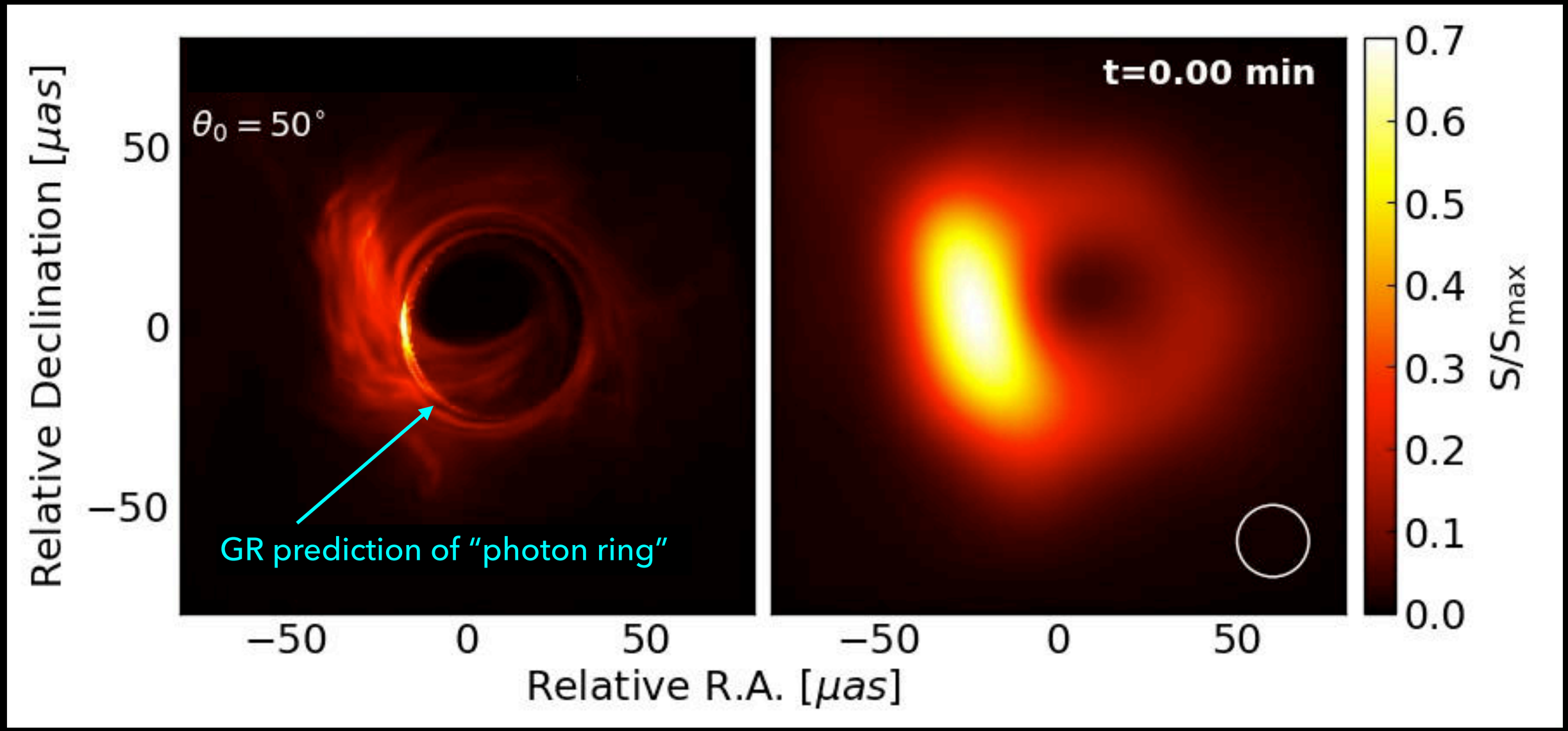
Blurry ring is a mix of astrophysics and spacetime warping



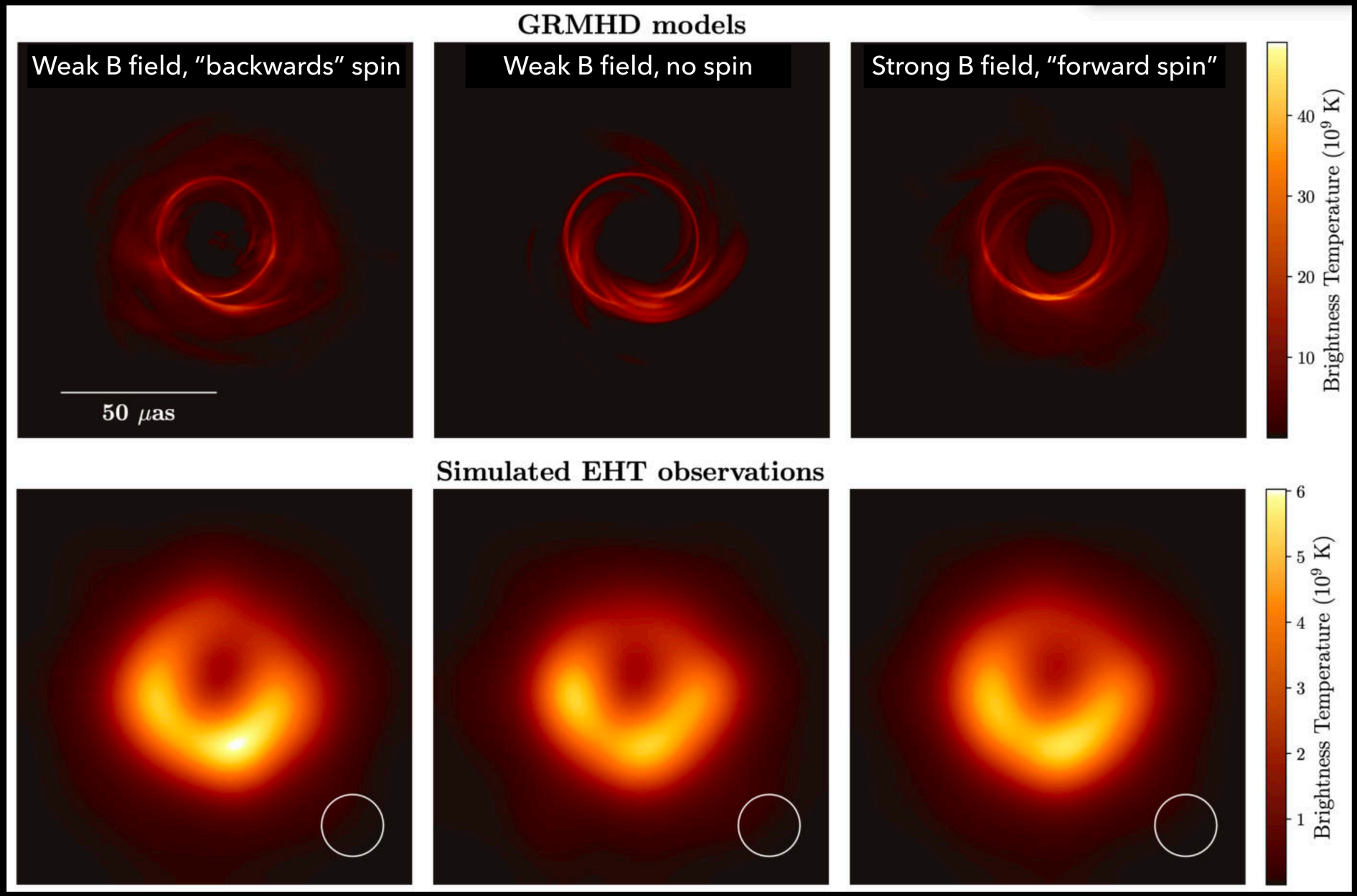
(GRMHD simulation D. Yoon; see Yoon, Chatterjee, SM++2020. Using H-AMR code; Liska, Chatterjee++2019;2022)

EHT's M87* Simulation Library: 50 models, 23 TB, 60k snapshot images

(Paper V; EHT Collaboration 2019. Slide credit: A. Broderick)

Event Horizon Telescope

We still don't know which model is correct (from many):



EHT Collaboration 2019 Papers I-VI

Talk outline

★ From imagination to discovery

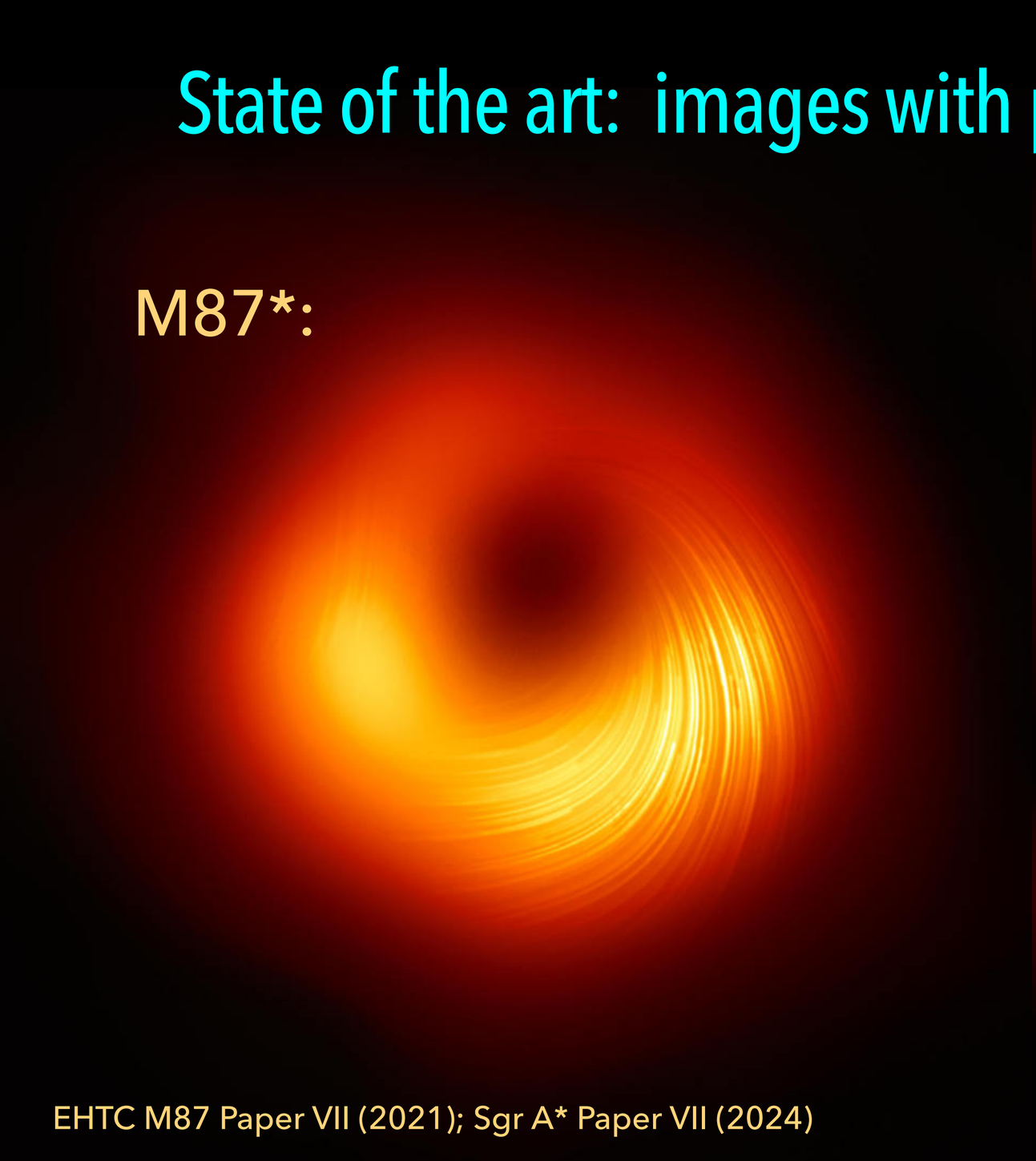
★ The astrophysical role of black holes

★ Event Horizon Telescope and its results

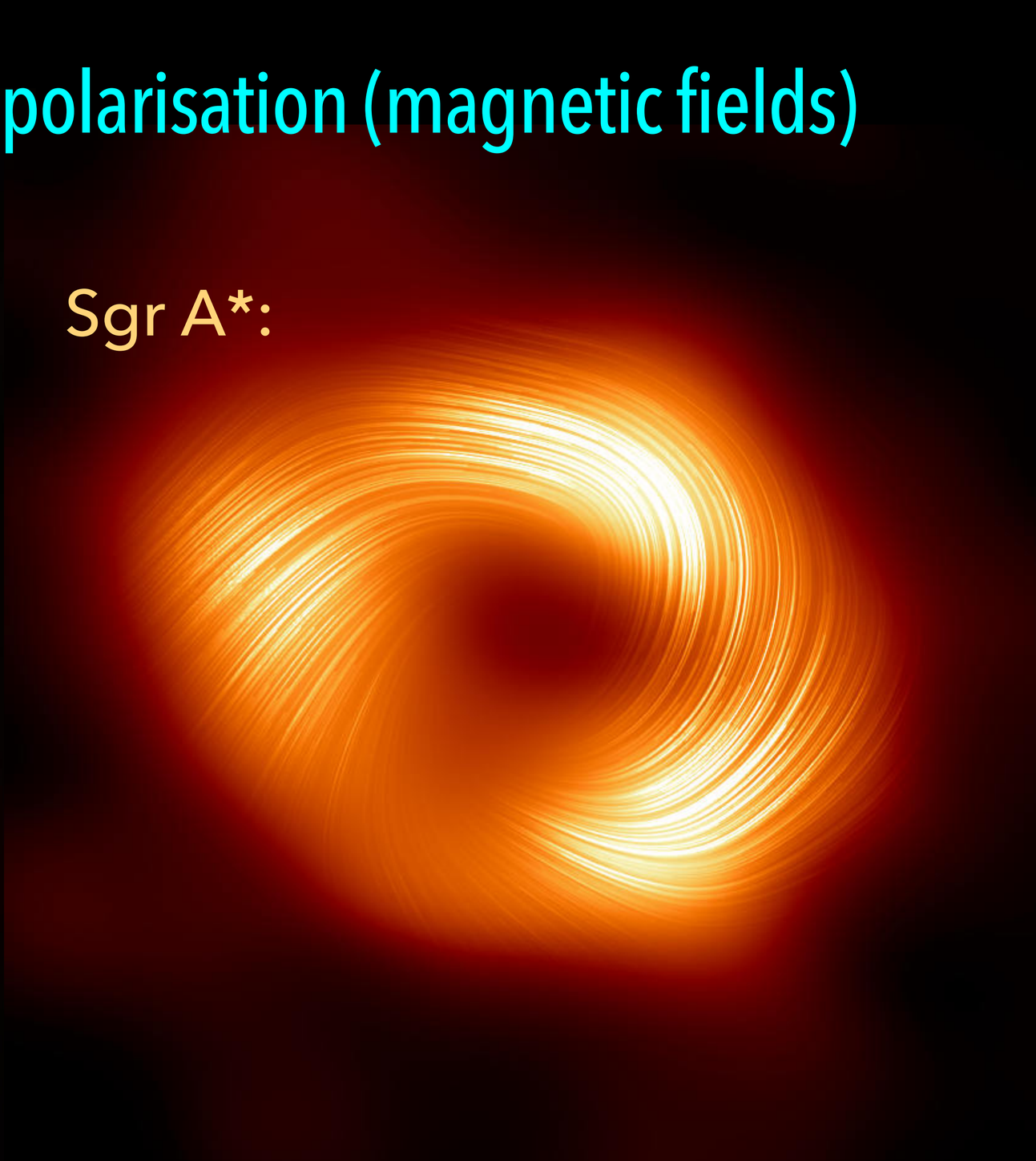
★ New horizons including the AMT in NA

State of the art: images with polarisation (magnetic fields)

M87*:



Sgr A*:

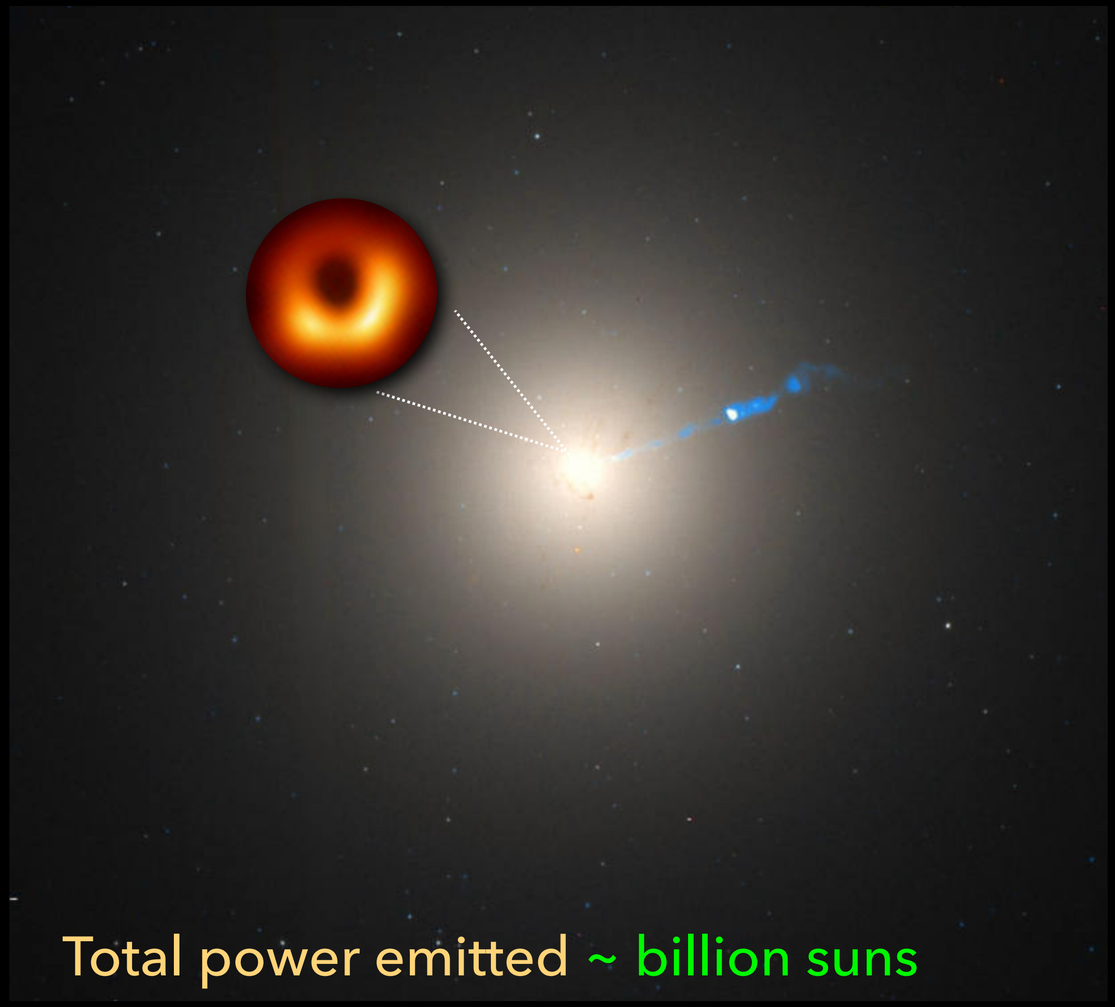


EHTC M87 Paper VII (2021); Sgr A* Paper VII (2024)

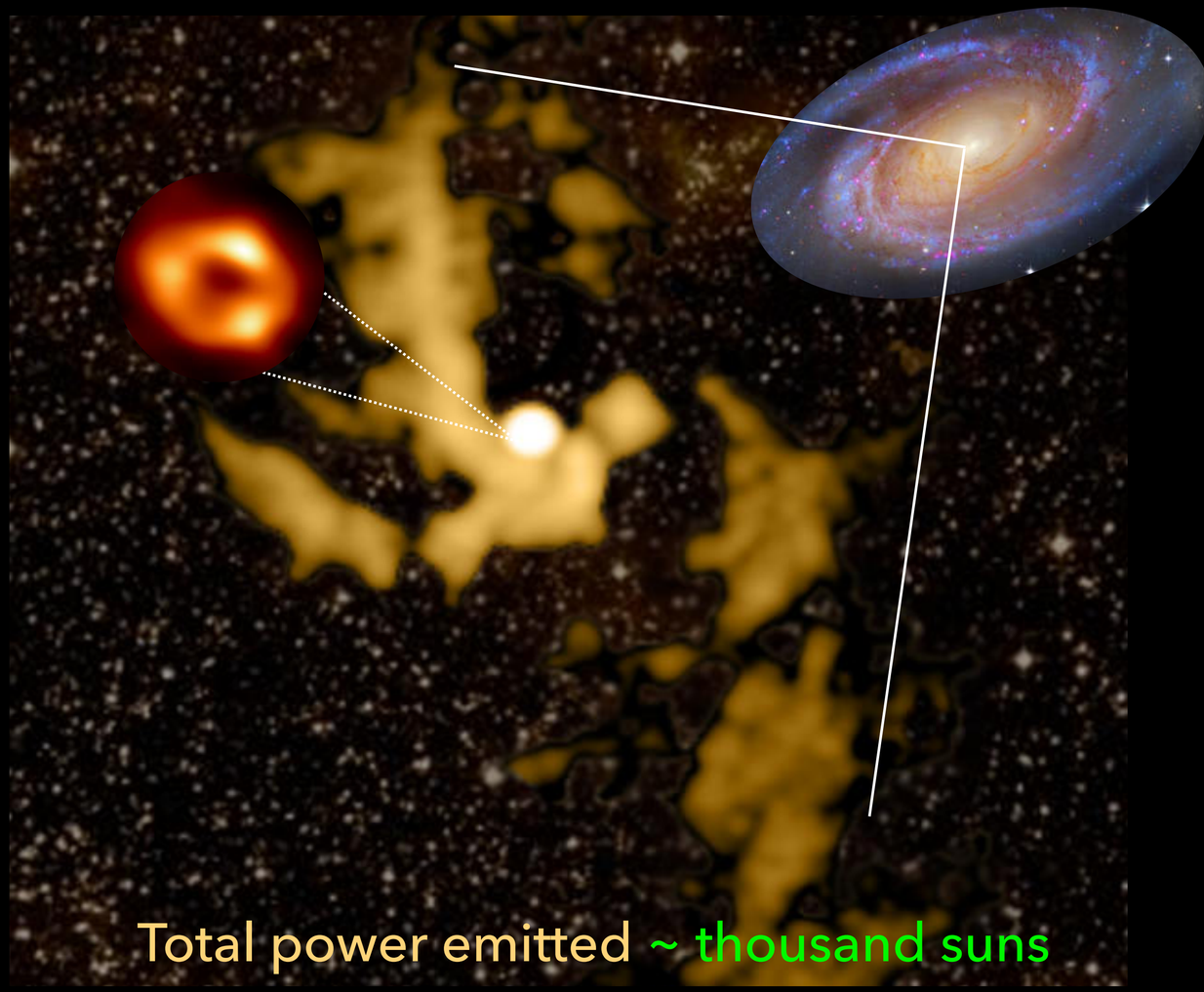
M87*/Sgr A* are in very different systems *yet our preferred models suggest they are remarkably similar down near the black holes!*

M87: Elliptical Galaxy, black hole mass ~6.5 billion times the sun's mass, launches a huge jet

Sgr A*: Spiral galaxy, black hole mass is ~4 million times the sun's mass, and has no (obvious) jet

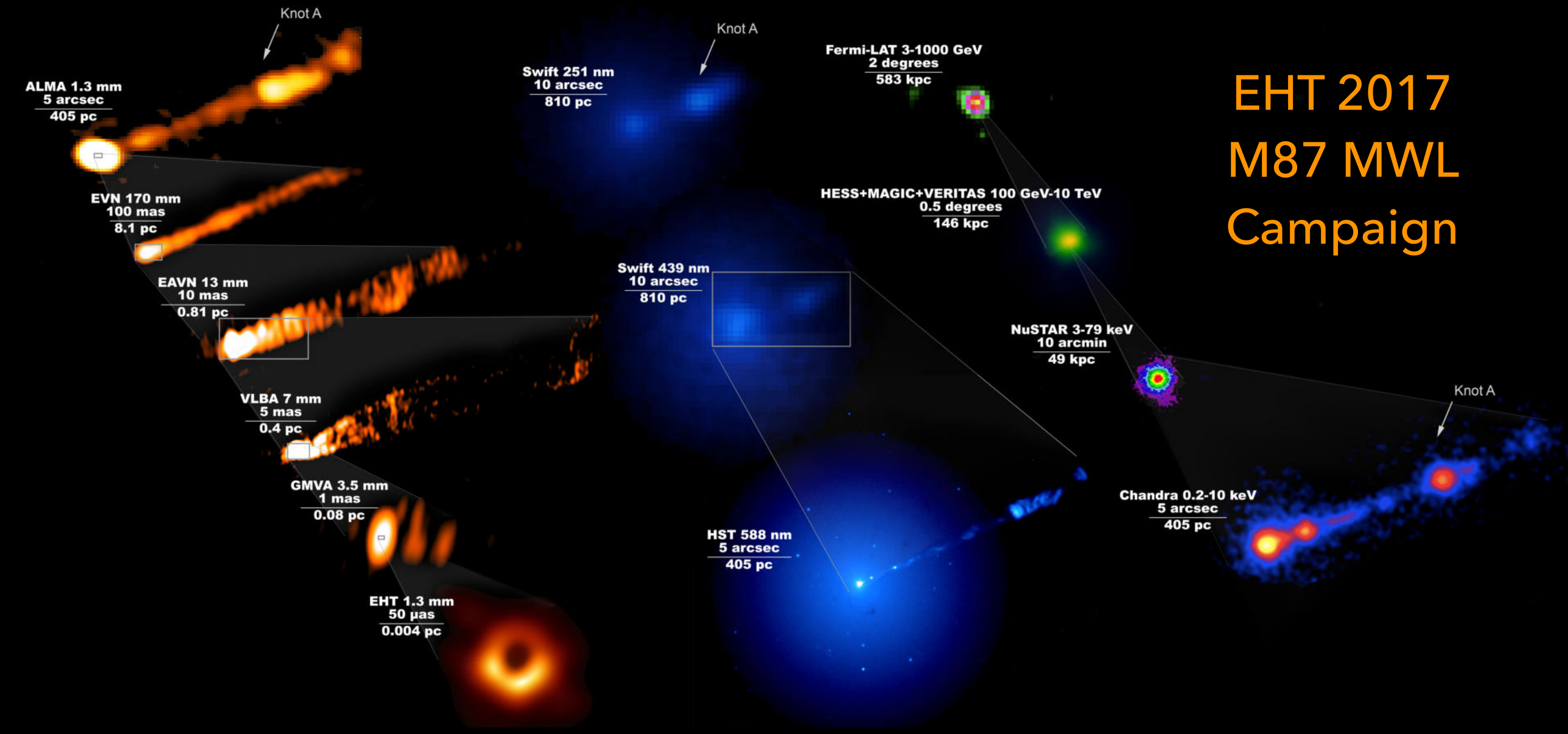


M87 Galaxy (NASA Hubble Space Telescope)



Centre of Milky Way; ALMA image of 'Minispiral" (NOAO/Rushton & Falcke)

New horizon I: need to account for the entire system including jets

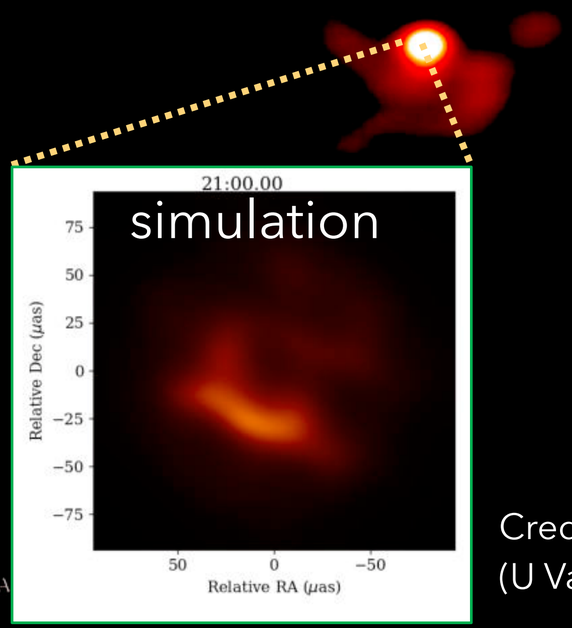


EHT 2017
M87 MWL
Campaign

(EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN, EAVN 2021, ApJL)

Sgr A* continually flickers from radio to X-ray bands

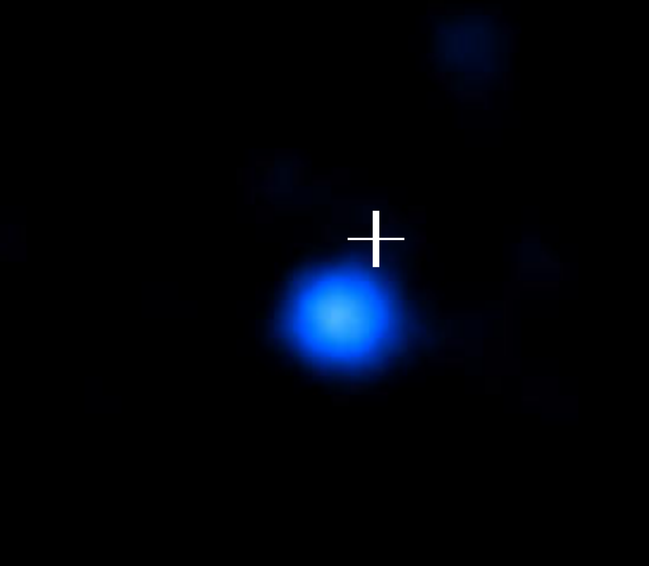
mm-radio (EHT/AMT)



Credit: I. Marti-Vidal (U Valencia)

near-infrared

X-rays

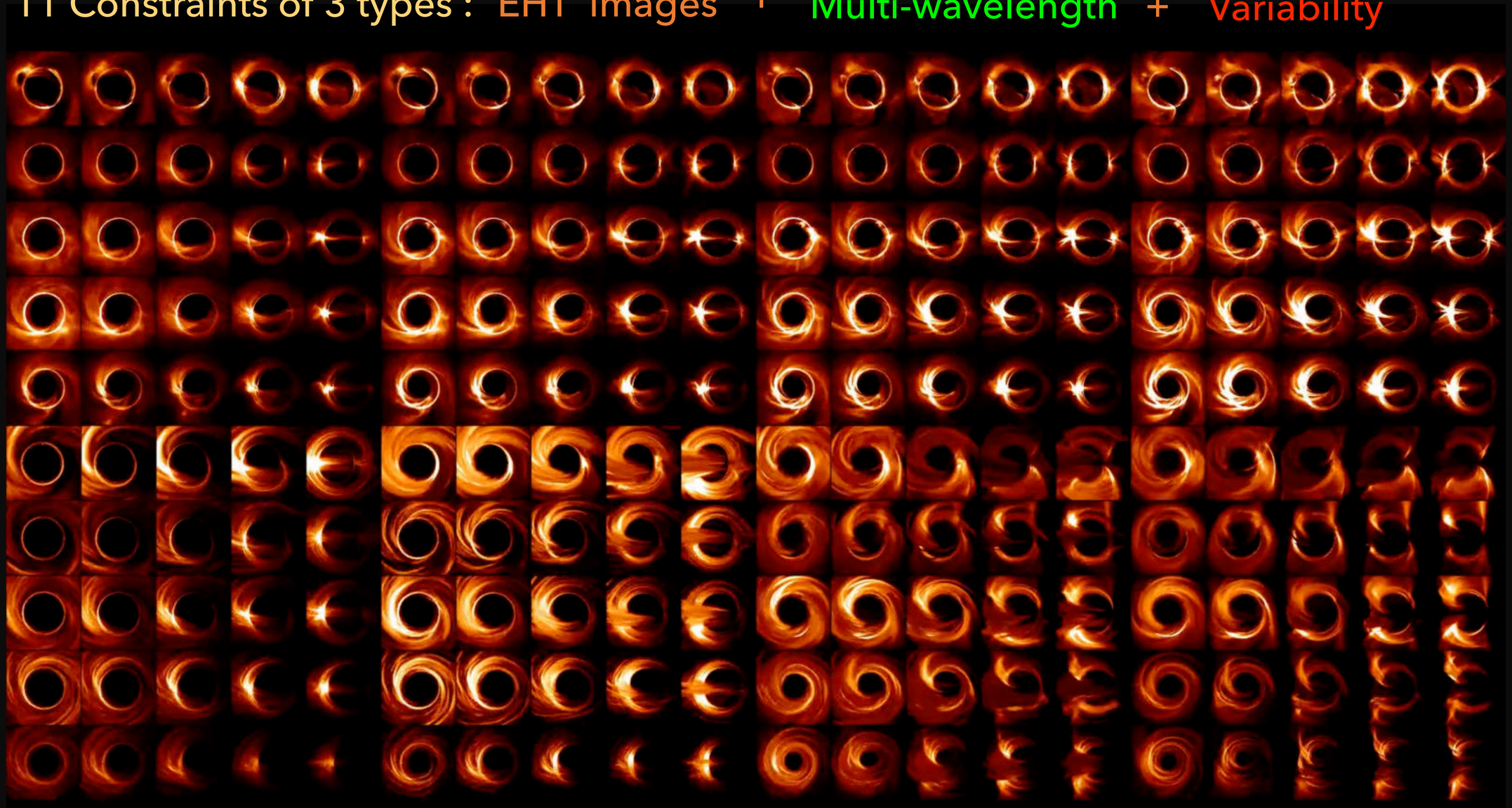


Credit: NASA/CXC/D.Haggard et al.

Sgr A* Paper II 2022; Wielgus, EHT++2022; La Bella ++2023

Sgr A*: Only 2/200 models consistent w/combined EHT+MWL data

11 Constraints of 3 types : EHT images + Multi-wavelength + Variability



Visualization credit: Ben Prather, University of Illinois at Urbana-Champaign.
Image library credit: EHT Theory Working Group, CK Chan. EHTC Sgr A* Paper I, Paper V (2022), Paper VIII (2024)

New horizon II: going from snapshots to movies

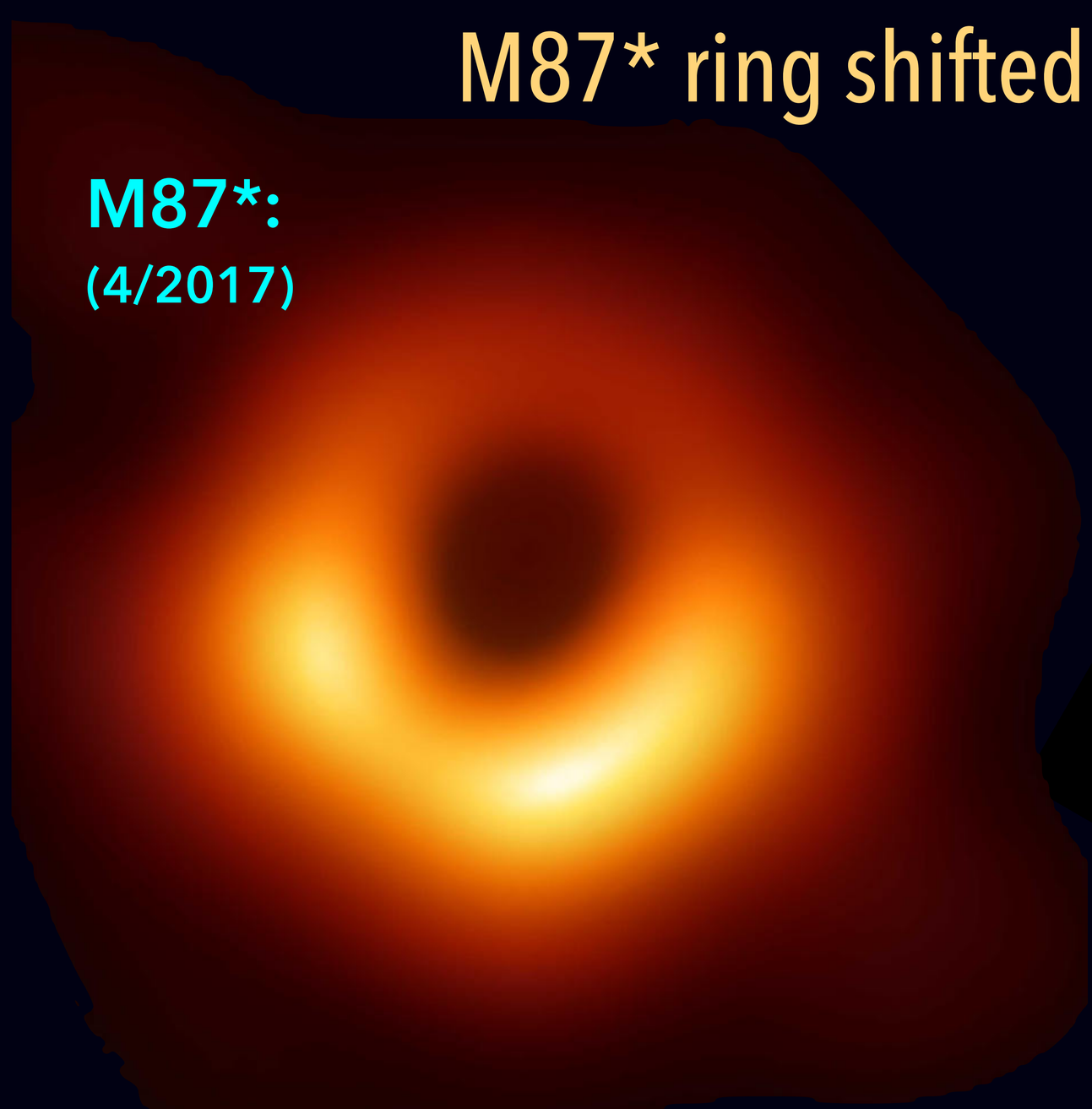
M87*:

Sgr A*:

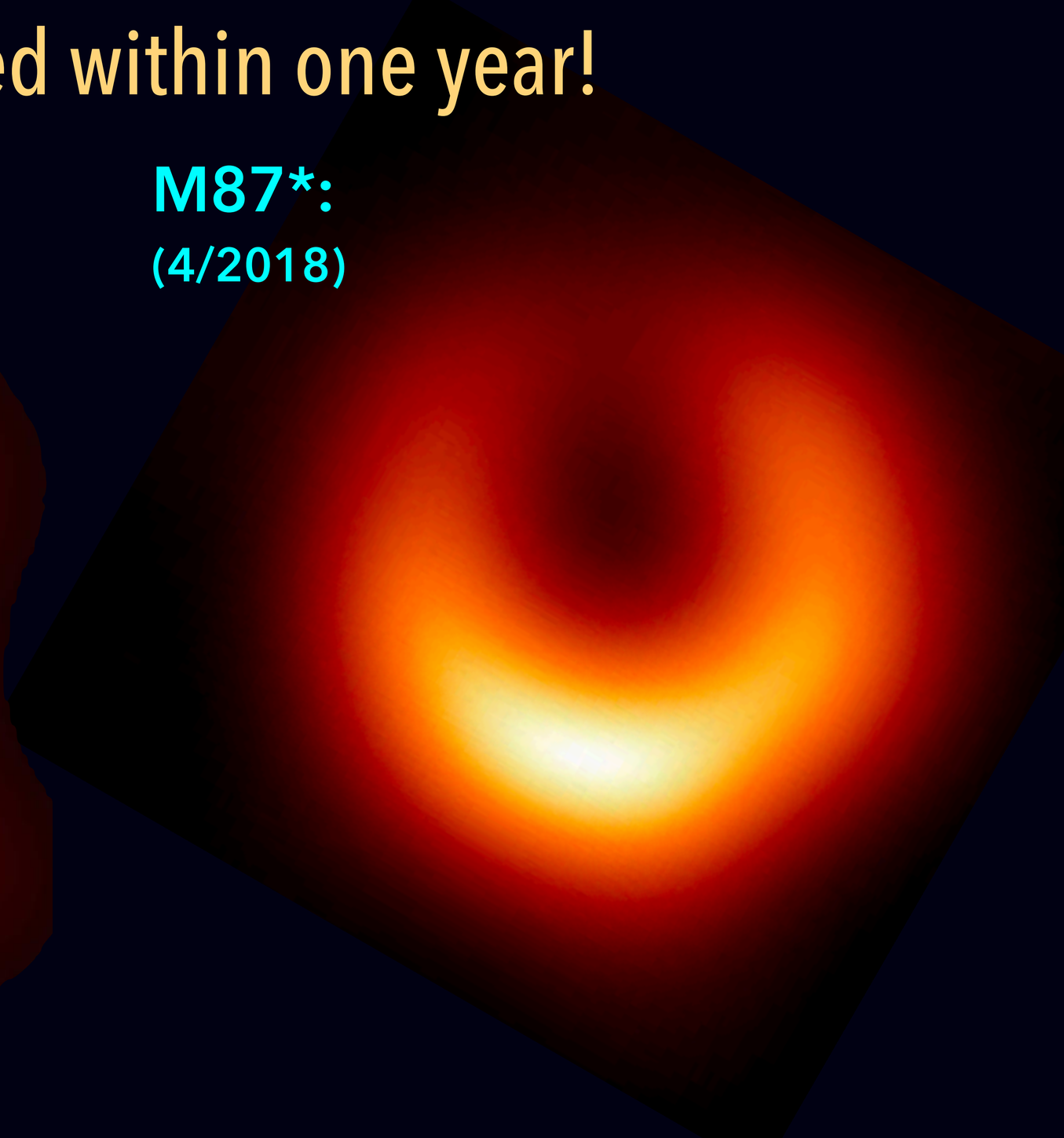
Simulation/movie credit: Abhishek Joshi / UIUC, EHTC

M87* ring shifted within one year!

M87*:
(4/2017)



M87*:
(4/2018)



EHTC M87* 2017 paper I (2019); M87* 2018 paper I (2024)

M87* ring shifted within one year!

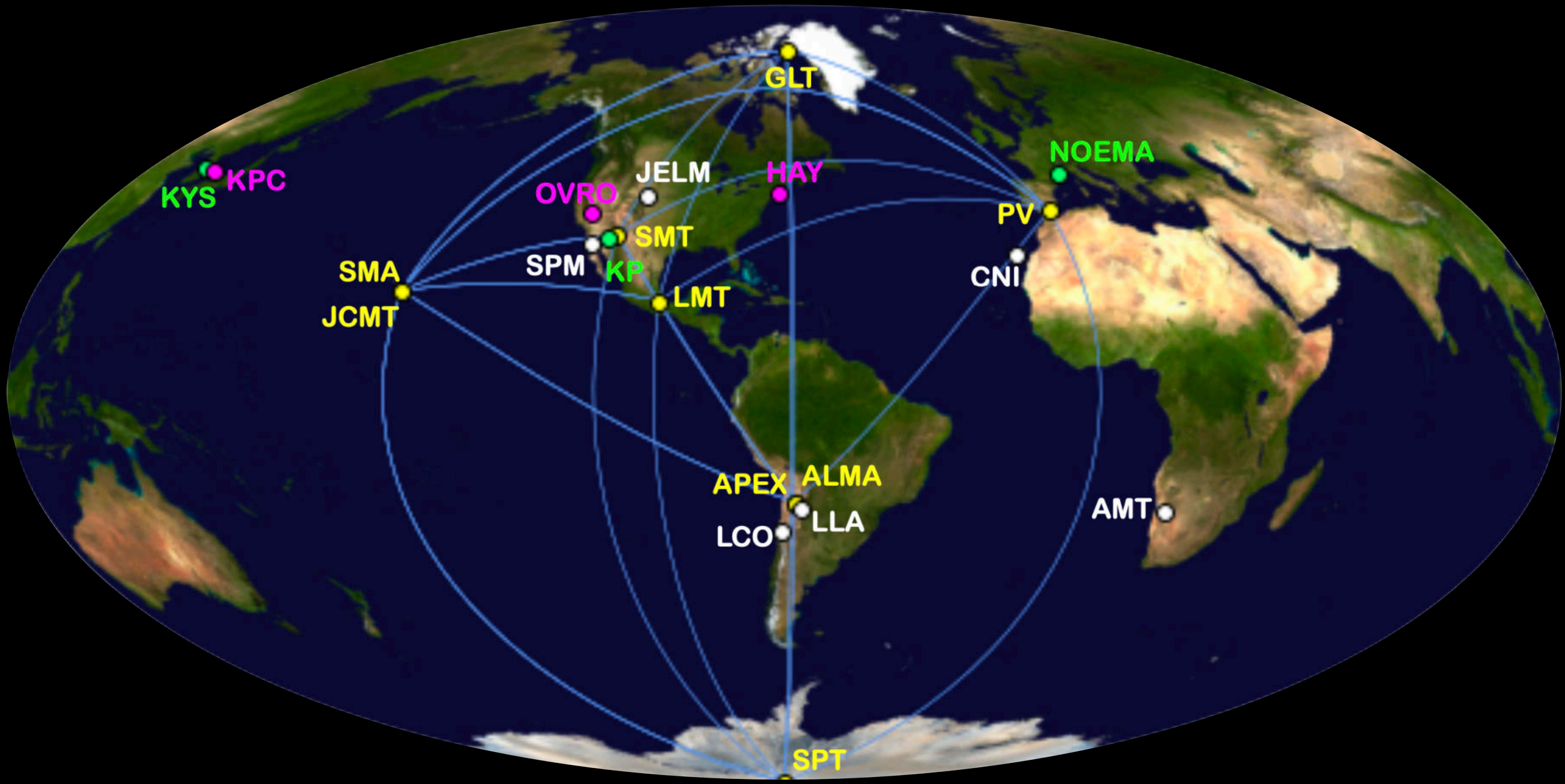
M87*:
(4/2017)

M87*:
(4/2018)

Plans afoot for an EHT M87 movie campaign in 2026!!

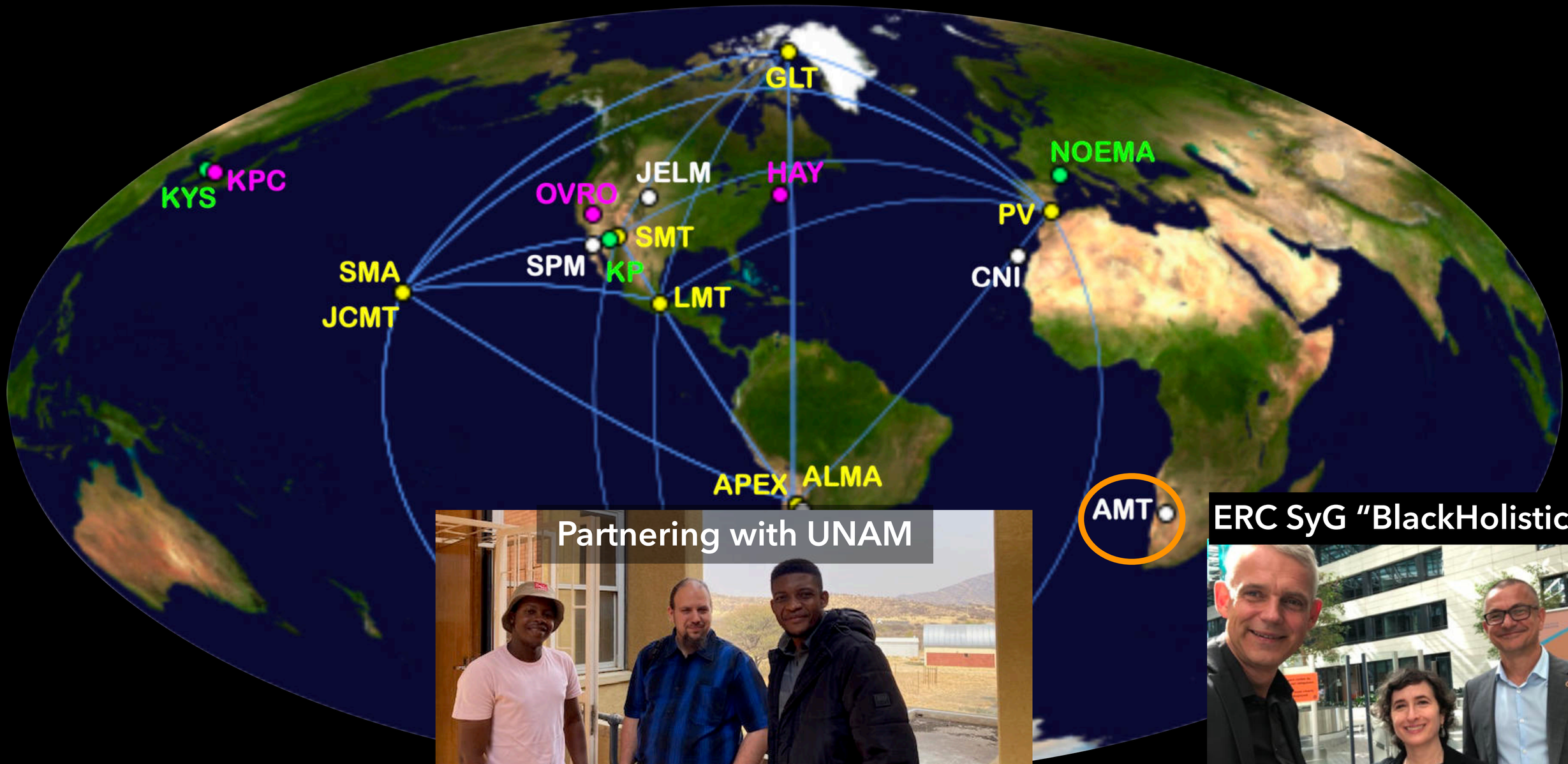
EHTC M87* 2017 paper I (2019); M87* 2018 paper I (2024)

(next-gen) EHT expansions on the ground in the coming ~decade



Johnson++2023: "Key Science Goals for the ng-EHT", *Galaxies special edition*

(next-gen) EHT expansions on the ground in the coming ~decade

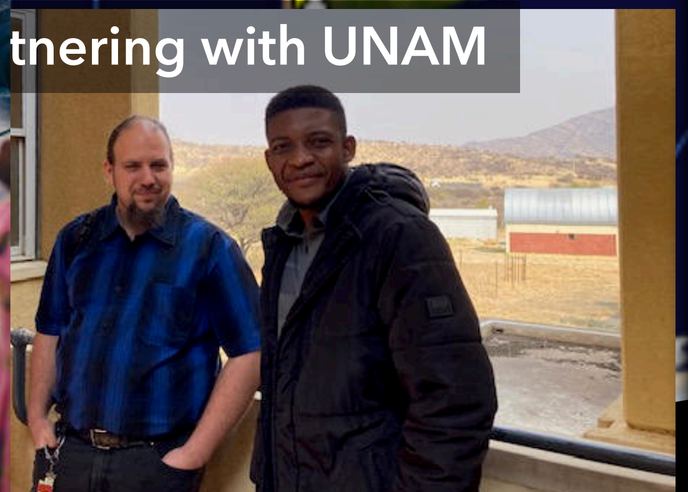


Partnering with UNAM

ERC SyG “BlackHolistic”

Johnson++2023: “Key Science Goals fo

(next-gen) EHT expansions on the ground in the coming ~decade



tnering with UNAM

RAS Awards 2024

Royal Astronomical Society

ANNIE MAUNDER MEDAL FOR OUTREACH

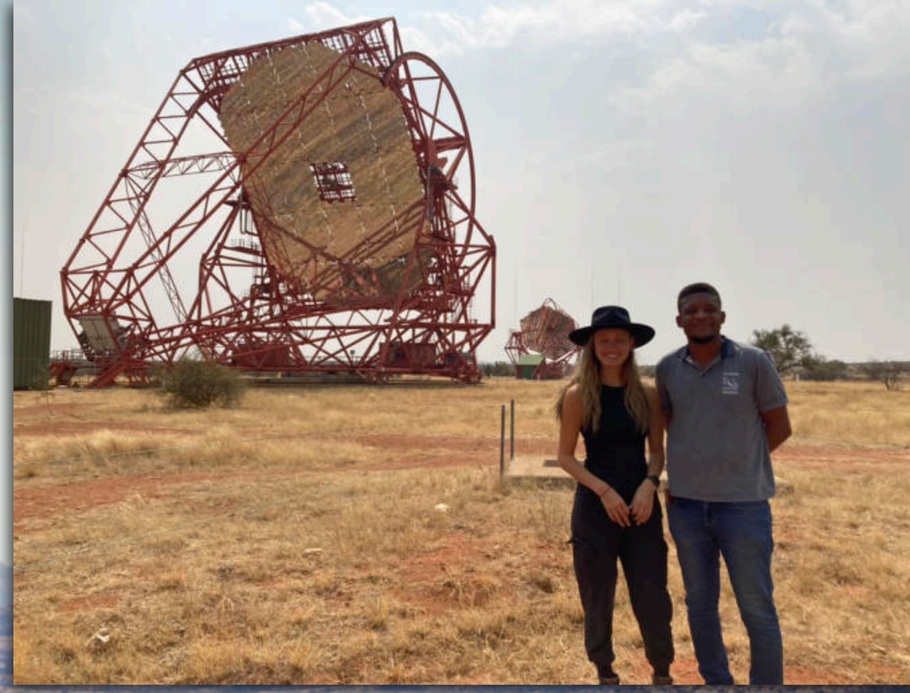
Annie Maunder Medal

AMT Mobile Planetarium Team, University of Namibia

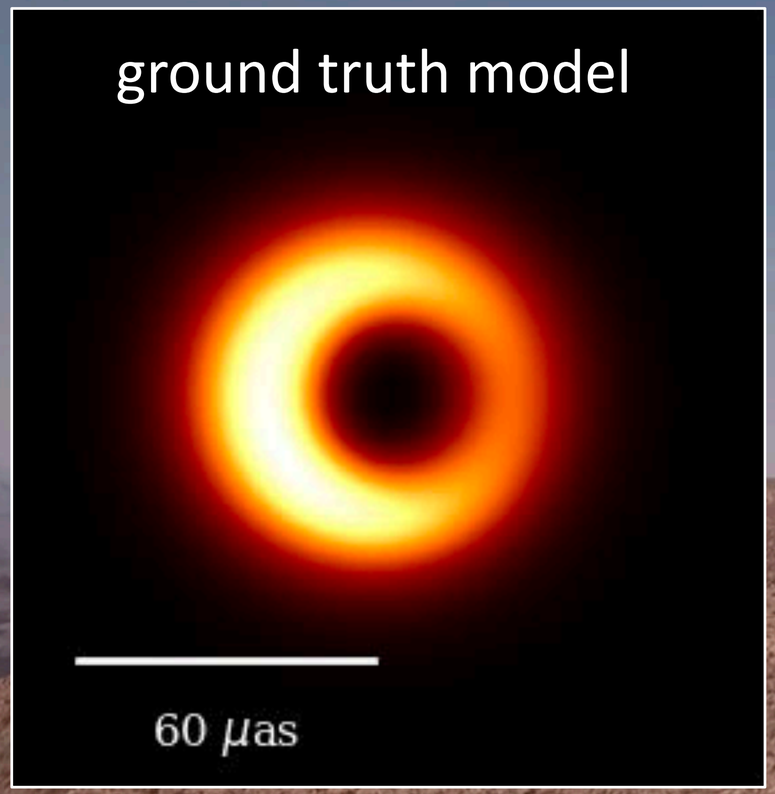
Gamsberg mountain: 2350 m

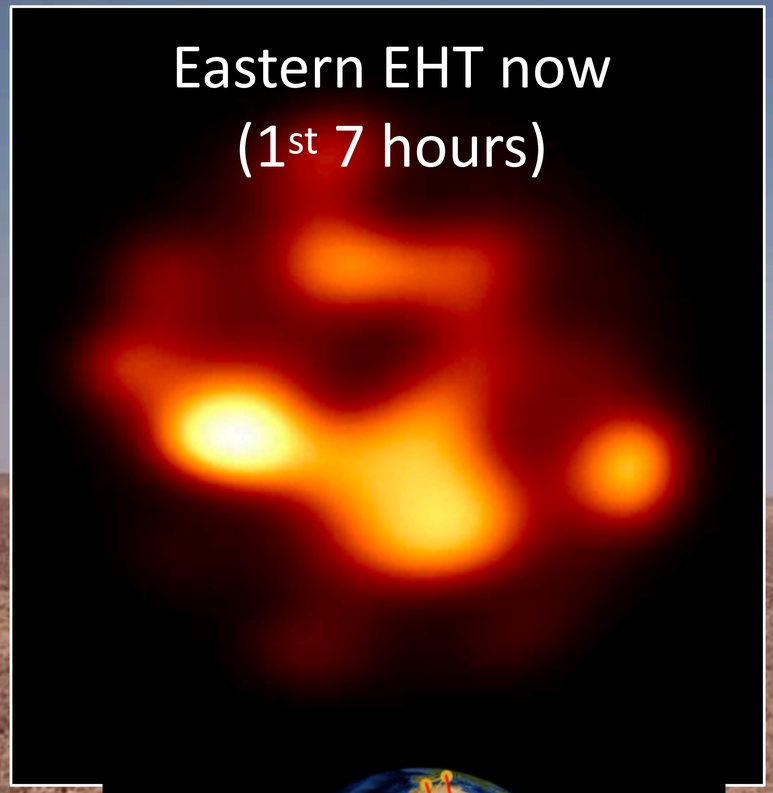
UNAM is in discussions with the Max-Planck-Gesselschaft
regarding purchasing the mountain back for development,
for AMT and hopefully other instruments!

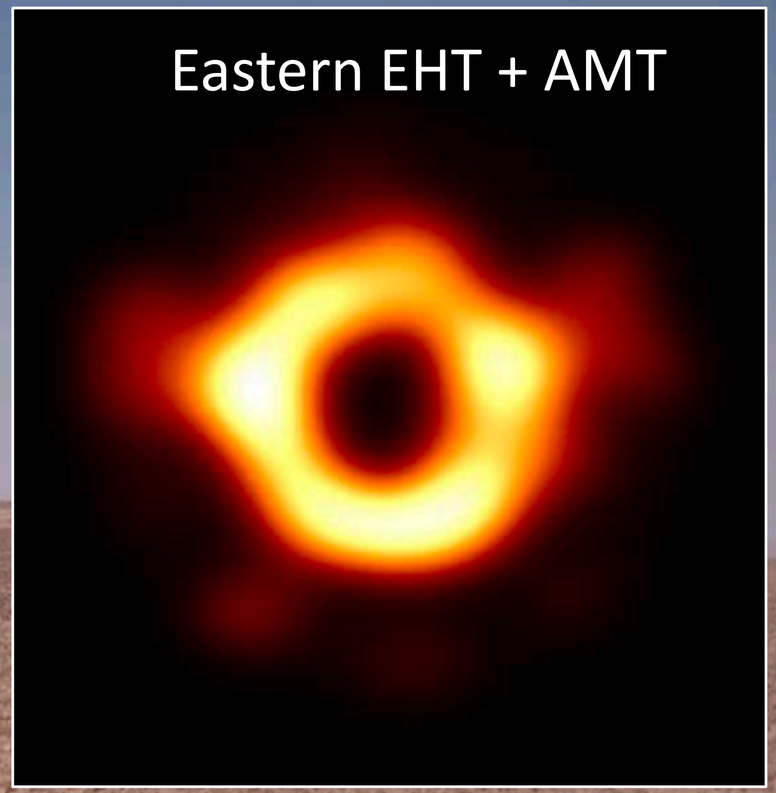
Near H.E.S.S. : 1900 m



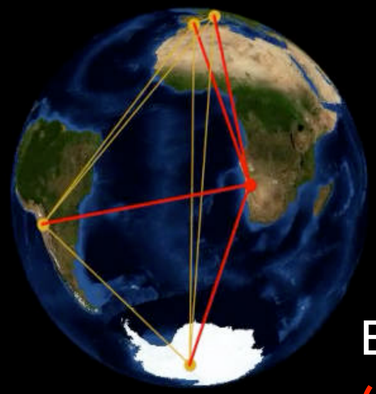
Africa mm-wave Telescope: enable first movies of Sgr A*







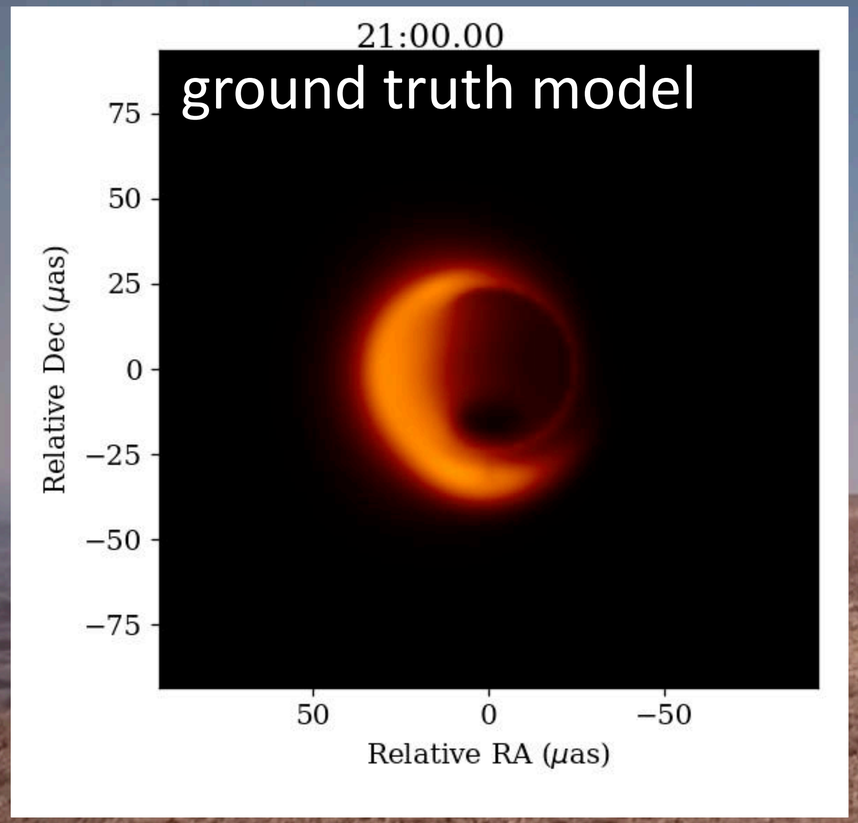
La Bella et al. (2023)



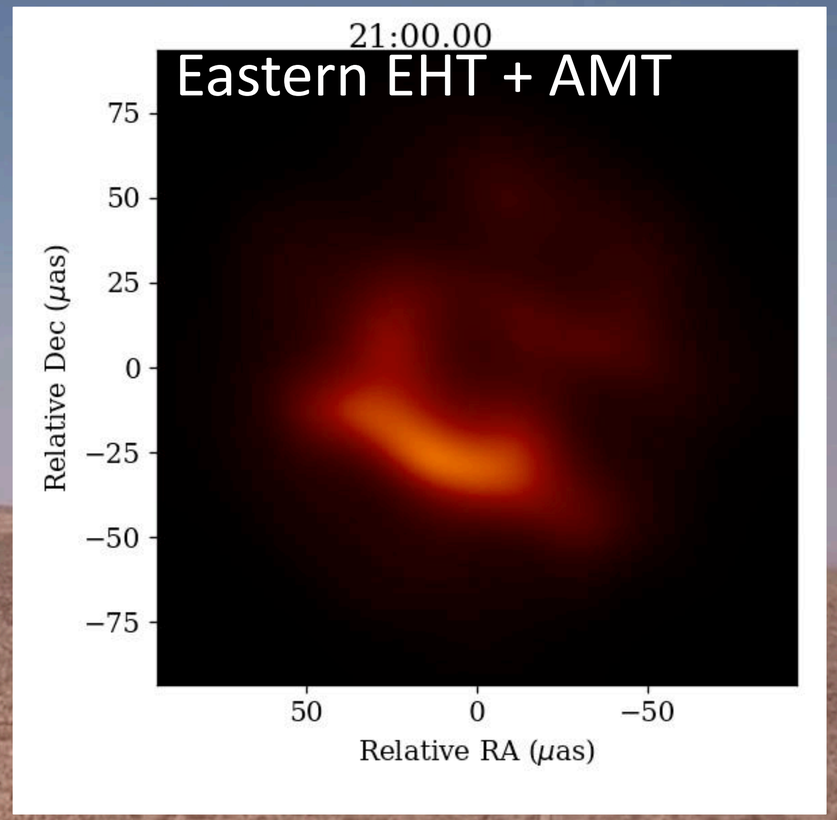
Event Horizon Telescope
(red=AMT baselines)

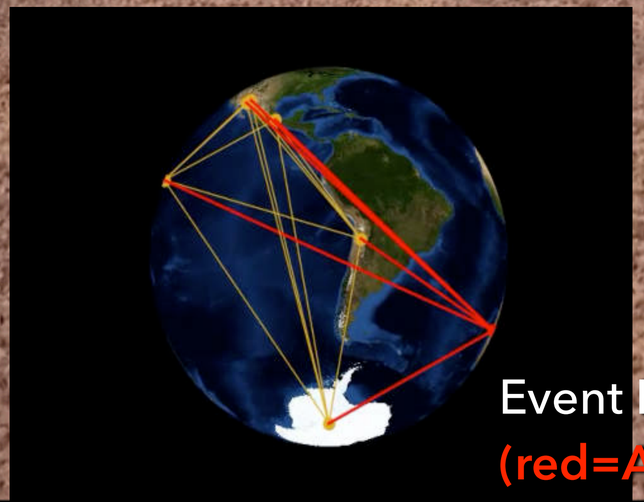
Gamsberg (Namibia)

Africa mm-wave Telescope: enable first movies of Sgr A*



La Bella et al. (2023)





Event Horizon Telescope
(red=AMT baselines)

Gamsberg (Namibia)

2018 “preview” of the ultimate NA combo: AMT/EHT + H.E.S.S.!

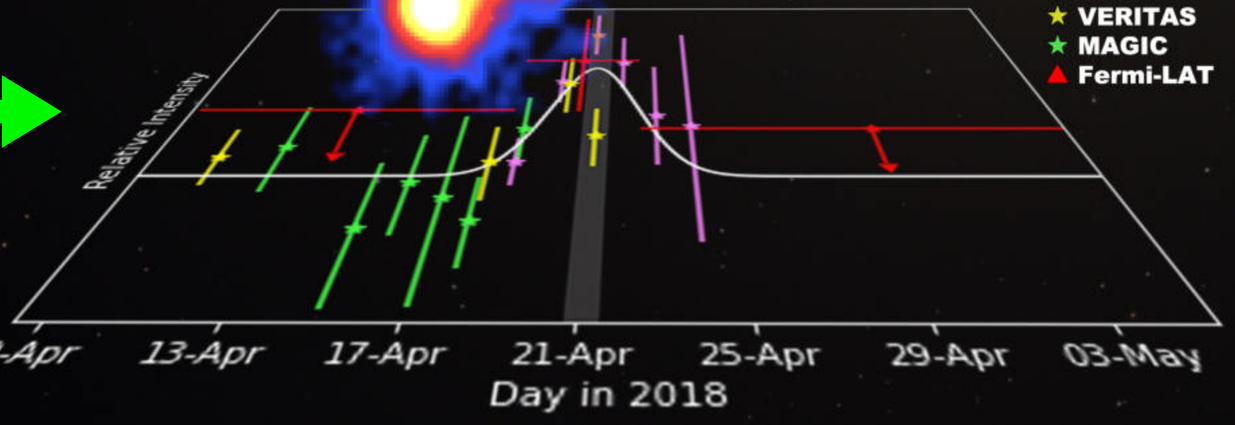
EHT 1.3 mm
50 μas
0.004 pc

GMVA+ALMA+GLT 3.5 mm
0.5 mas
0.04 pc

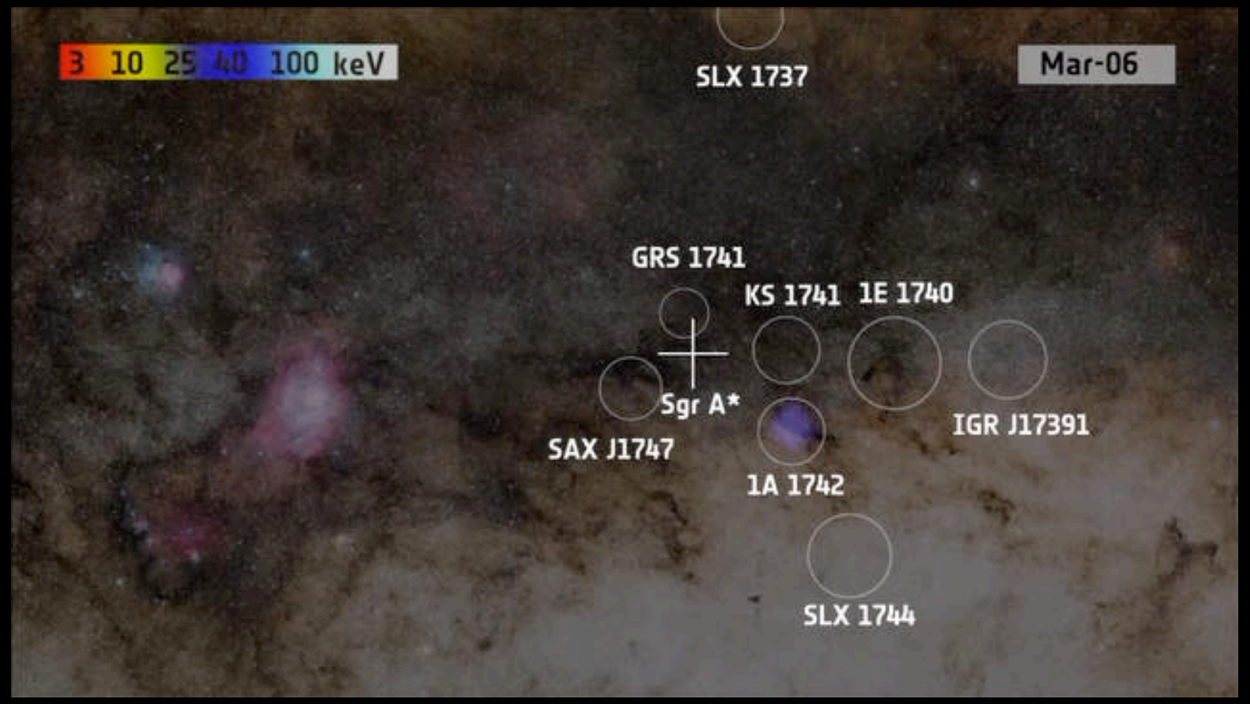
VLBA 7 mm
1 mas
0.08 pc

CHANDRA X-rays
2 arcsec
160 pc

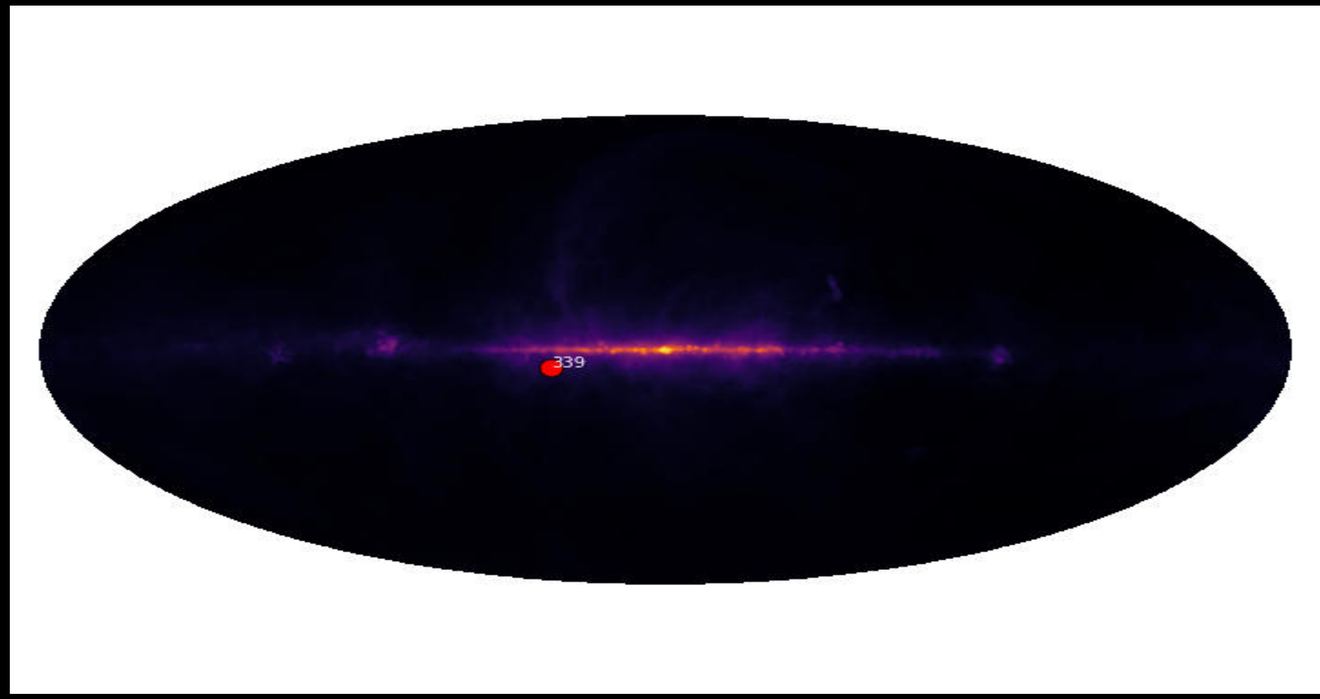
HST Optical
5 arcsec
405 pc



The sky is flickering with mysterious objects; AMT will discover & monitor them



The X-ray/gamma-ray transient sky from *INTEGRAL*



New radio transient monitoring with MeerKAT, co-led by ERC SyG Co-PI Fender (Oxford U)

AMT will enable the *first real-time census of black hole activity and explosive events* in the millimetre band, and AMT+EHT will actually be able to make direct images of their jets!

Summary

★It has been a whirlwind ~century: from imagining black holes could exist to making the first images of them

★EHT sets a new benchmark for testing general relativity & astrophysics (+OMG we can actually see black holes!!!)

★Black holes are important players in shaping the Universe we live in today, as well as our local environment

★There are lots of cool things we know about black holes that I didn't have time to talk about!

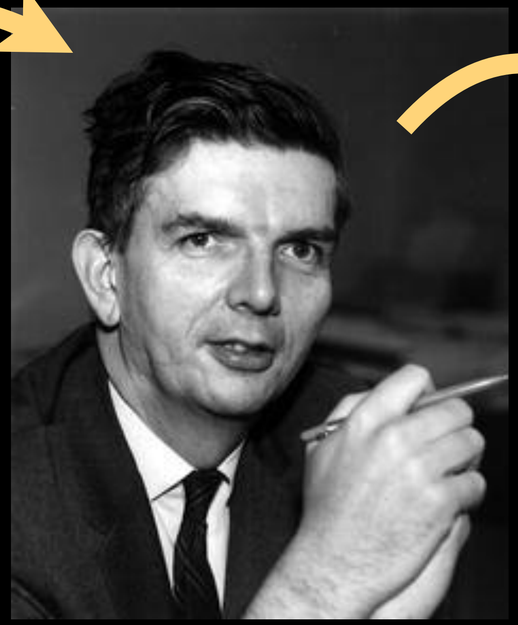
★The AMT will be the first expansion of EHT's network on Earth, allowing the first movies of Sgr A* and a wide range of new science

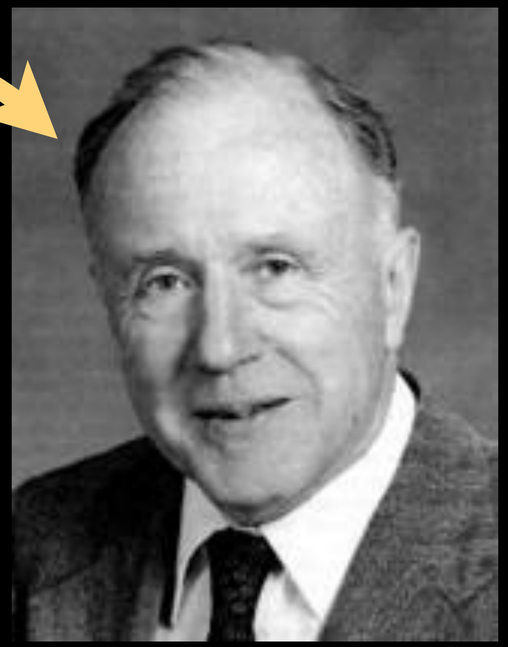
Extra Slides

"Gravitationally completely collapsed stars" ➠ "Black Hole"

The "Black Hole of Calcutta", 1756

early 1960s: Robert Dicke makes the dungeon connection, John Wheeler "markets"





See Herdeiro & Lemos (2019), M. Bartusiak, *Black Hole* (Yale University Press, Yale 2015)