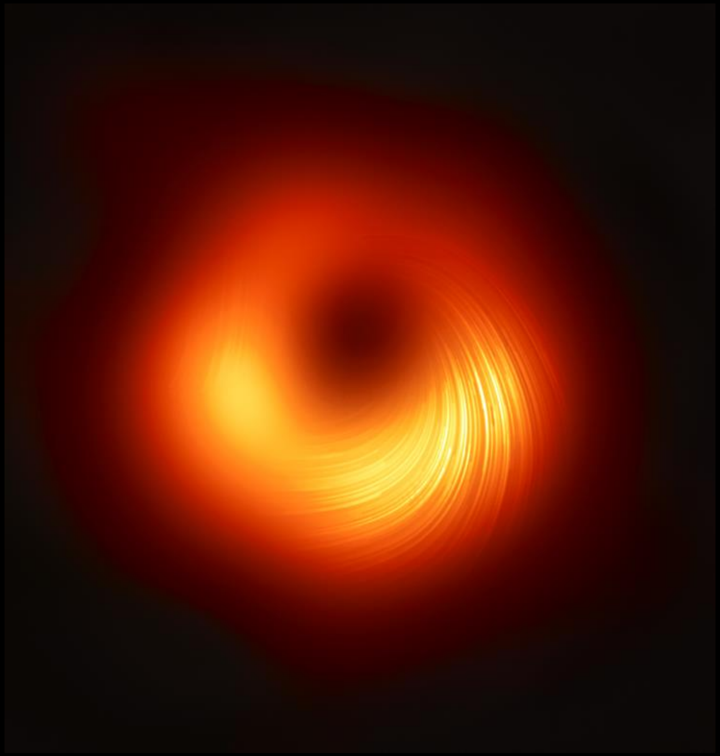
Imaging Supermassive Black Holes with the Event Horizon Telescope

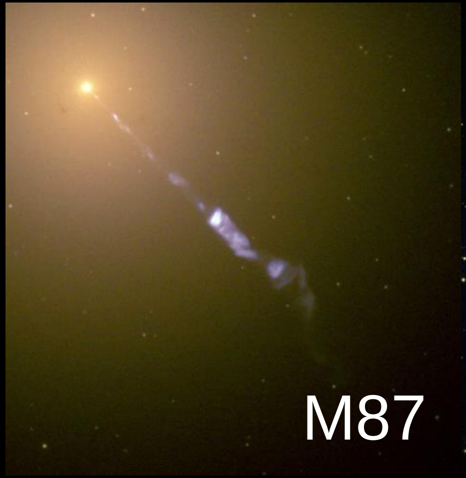
Andrew Chael

Princeton Gravity Initiative

11/4/2022

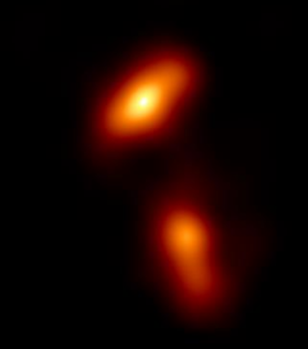


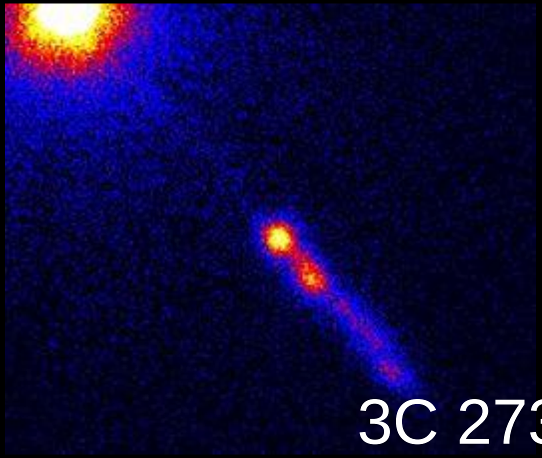
Supermassive black holes are everywhere


M87


Cyg A


Cen A


3C 279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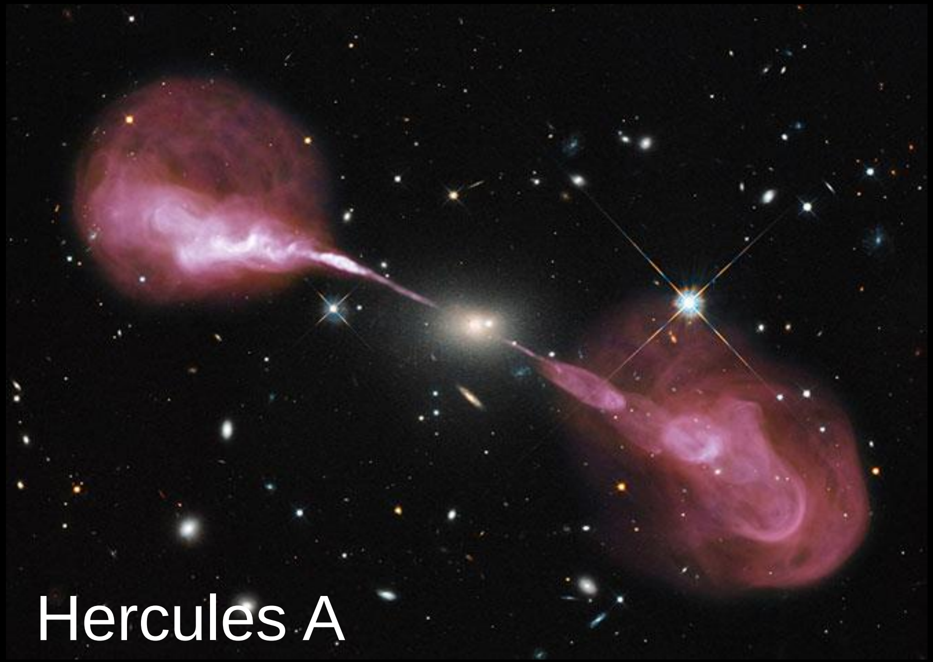
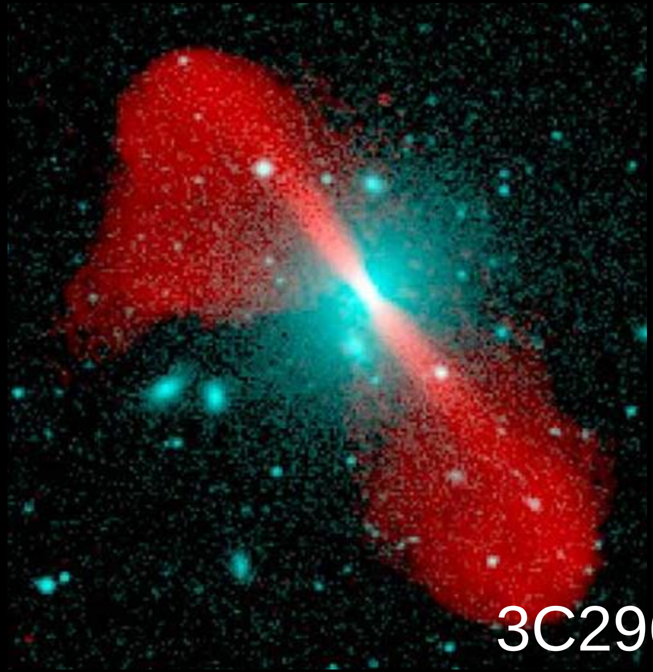

Hercules A


NGC 1265

3C31


3C296

Slide Credit: Sara Issaoun
Credits: (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C279, EHT),(3C293, Chandra),(Hercules A, HST/VLA),(NGC1265,M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; SDSS), (3C31, VLA), (3C296, AUI, NRAO)

M87 & M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$

$D = (16.8 \pm 0.8)\mathrm{Mpc}$

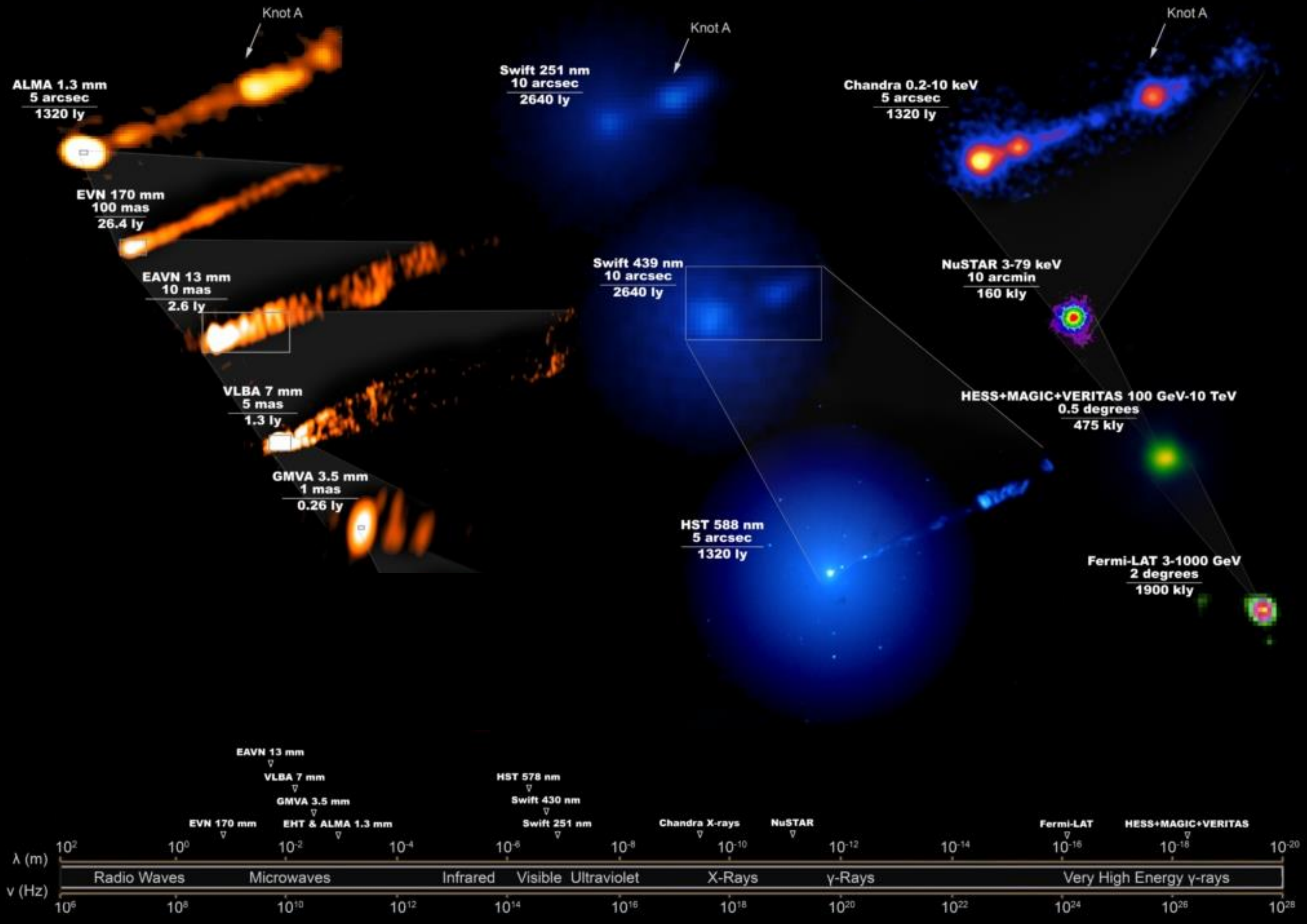


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Sgr A*

$$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$$
$$D = (8.12 \pm 0.03)\mathrm{kpc}$$

Gravity Collaboration, 2018

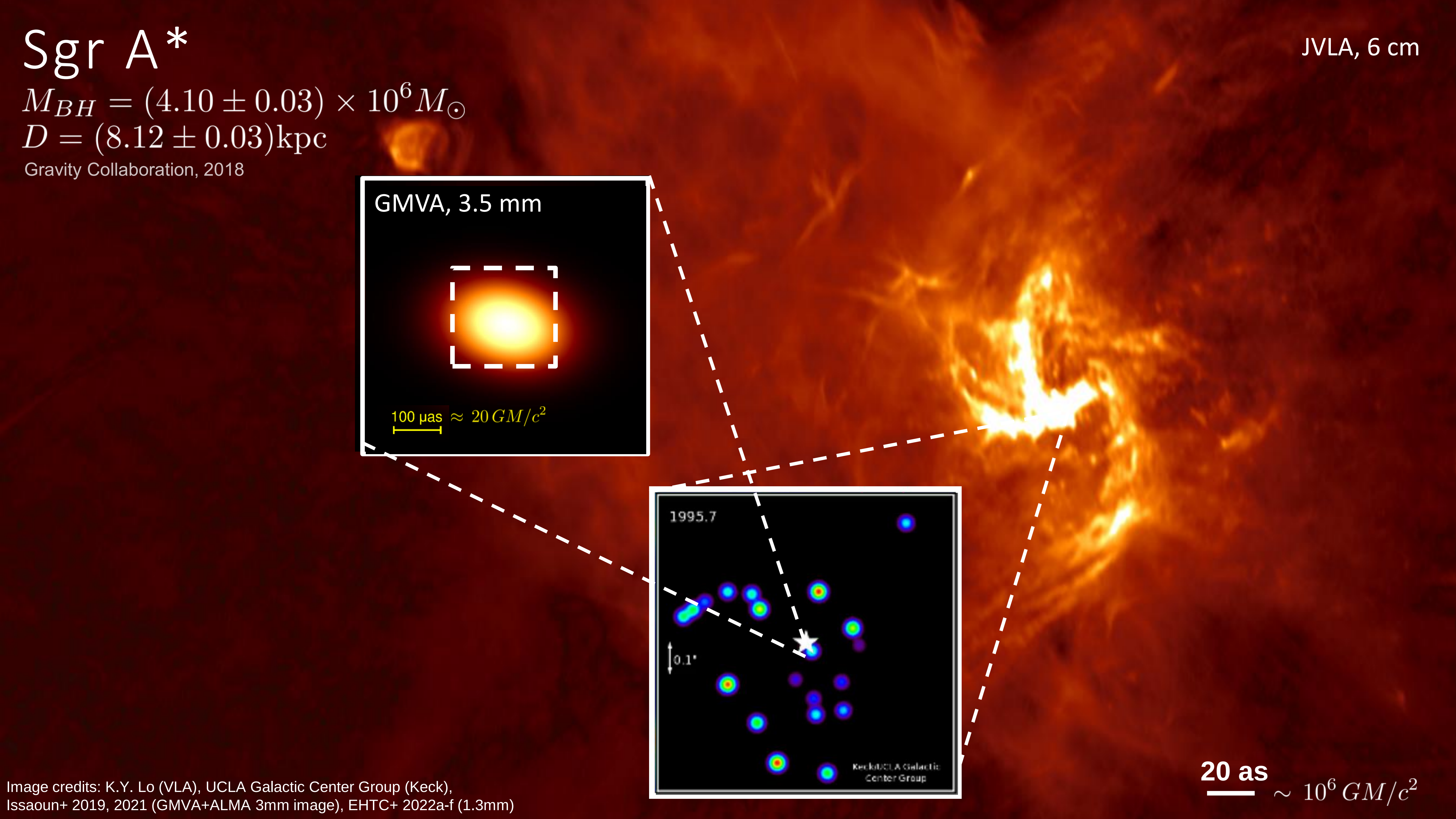
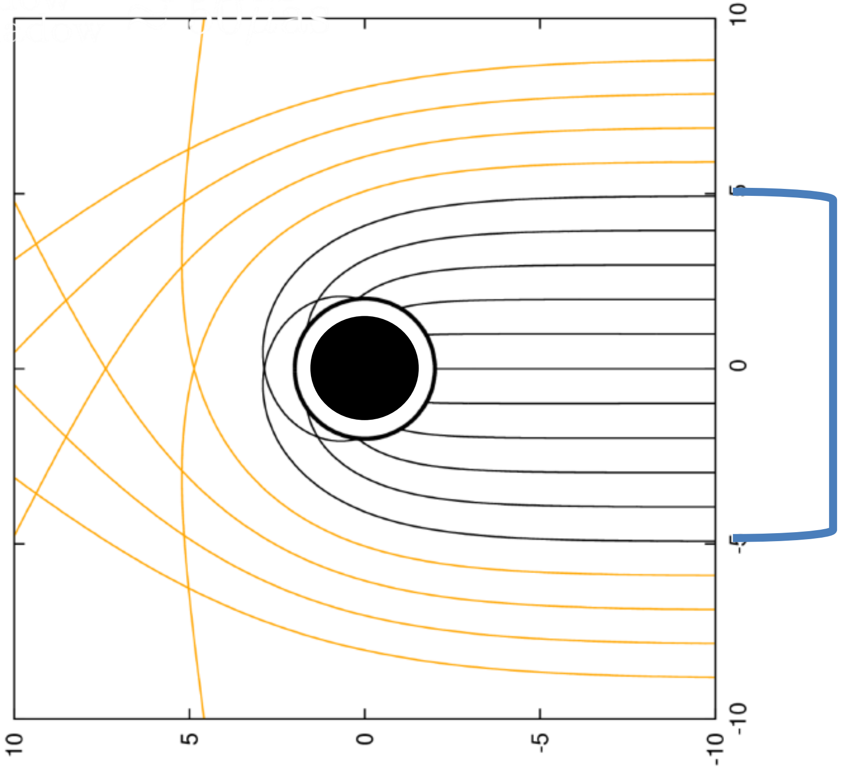
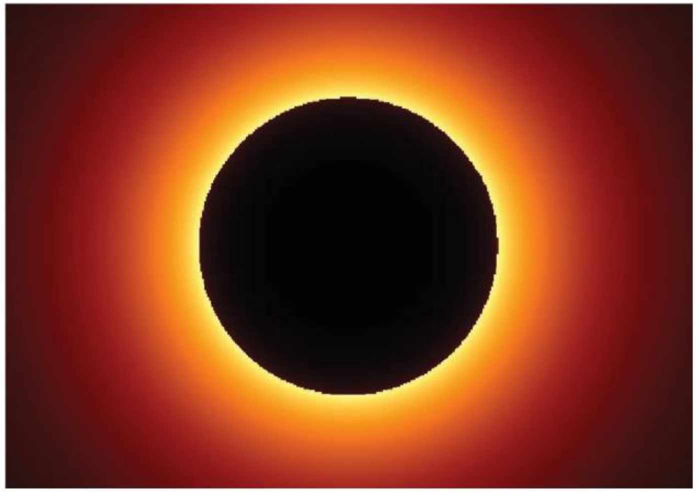


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHTC+ 2022a-f (1.3mm)

The Black Hole Shadow



$$d_{\text{shadow}} = 2\sqrt{27}GM/c^2$$



Shadow sizes on Earth

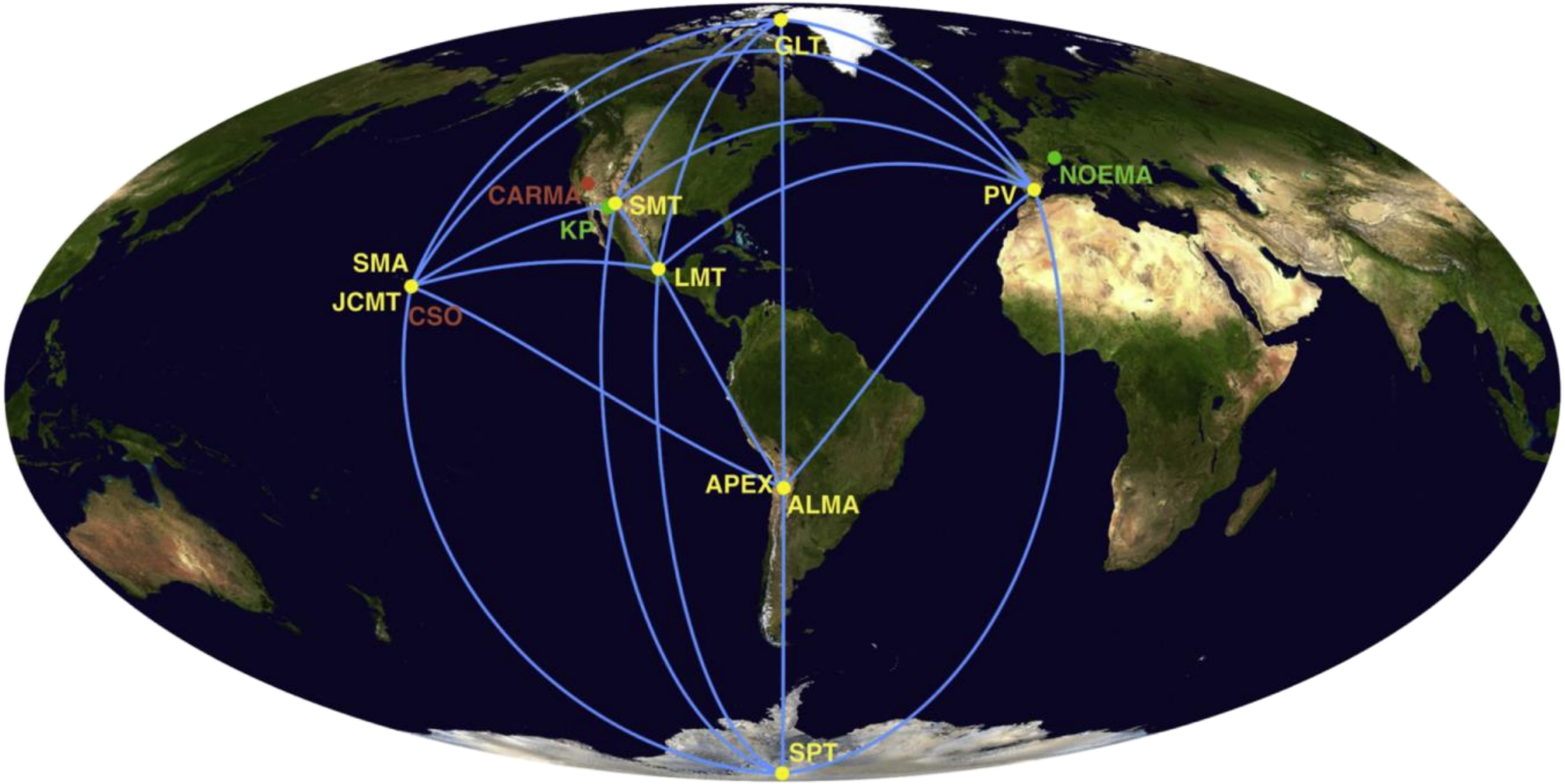
Sgr A*: 50 μas -> 1.4 x 10^{-8} degrees

M87*: 40 μas -> 1.1 x 10^{-8} degrees

*The precise shape and size of a black hole image depends on how and where the emission is produced

Image credit: Keiichi Asada

The Event Horizon Telescope



$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

EHTC+ 2019 (Paper II)

M87 & M87*

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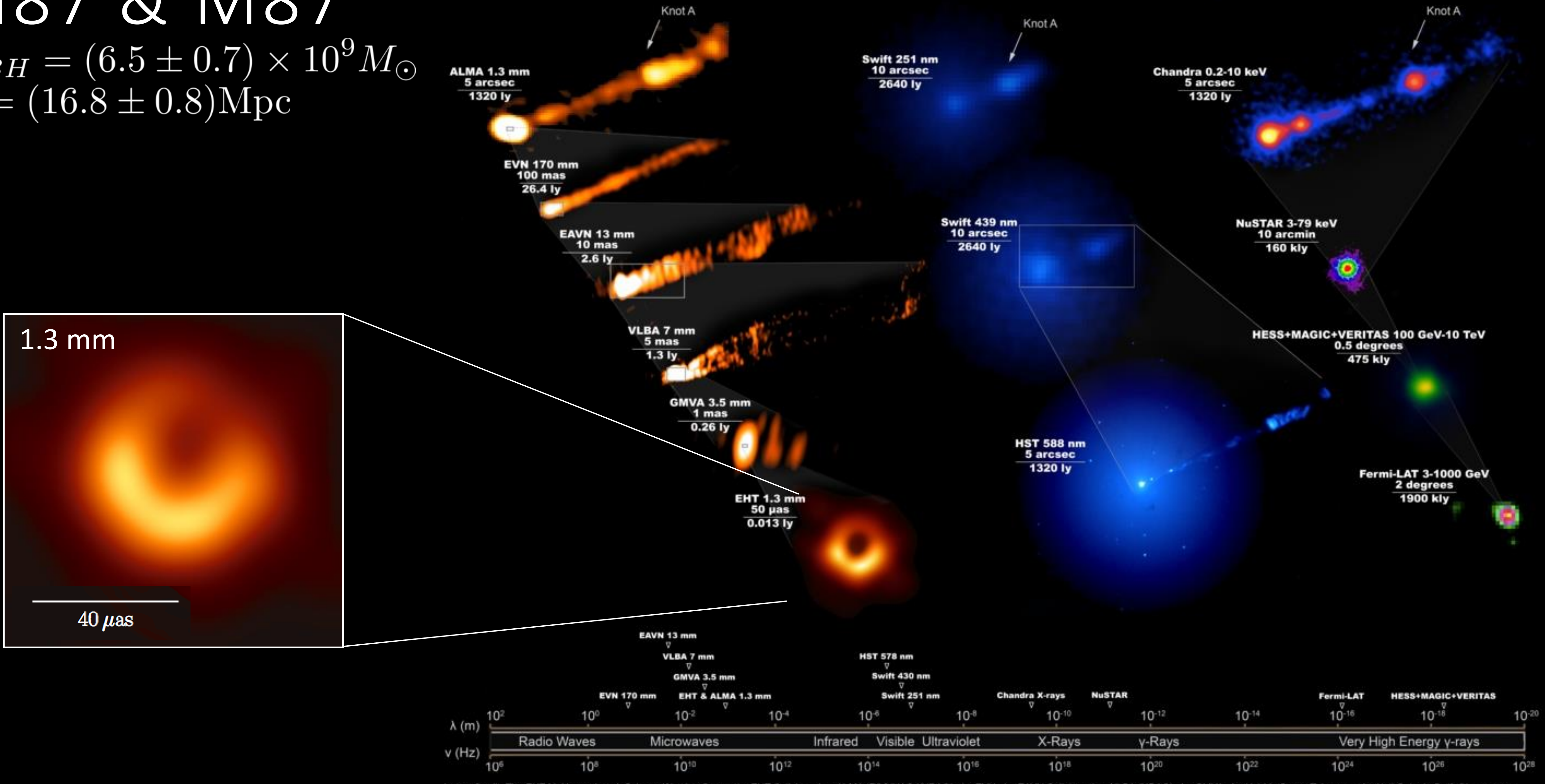


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Sgr A*

$$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$$
$$D = (8.12 \pm 0.03)\mathrm{kpc}$$

Gravity Collaboration, 2018

$$d_{\mathrm{shadow}} \approx 50\mu\mathrm{as}$$

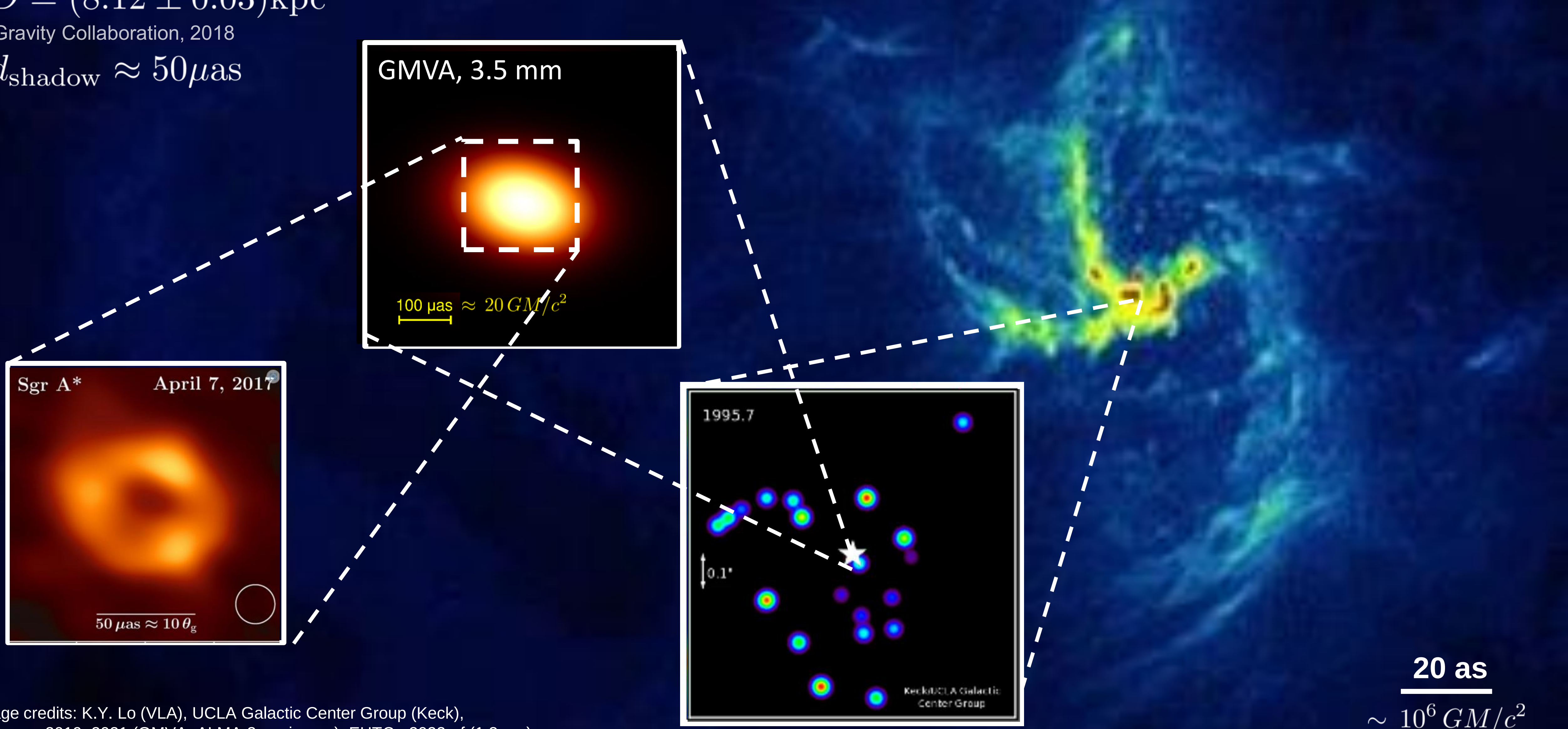


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHTC+ 2022a-f (1.3mm)

At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Synchrotron Emission from very hot ($T \gtrsim 10^{10}\,\mathrm{K}$) plasma close to the event horizon
- Launches a powerful relativistic jet ($P_{\mathrm{jet}} \geq 10^{42}$ erg s^{-1})

Questions:

- Where exactly does the emission come from?
- What is the temperature/distribution of the emitting particles?
- What is the strength and configuration of the magnetic field?
- What will we see with next-generation EHT observations?

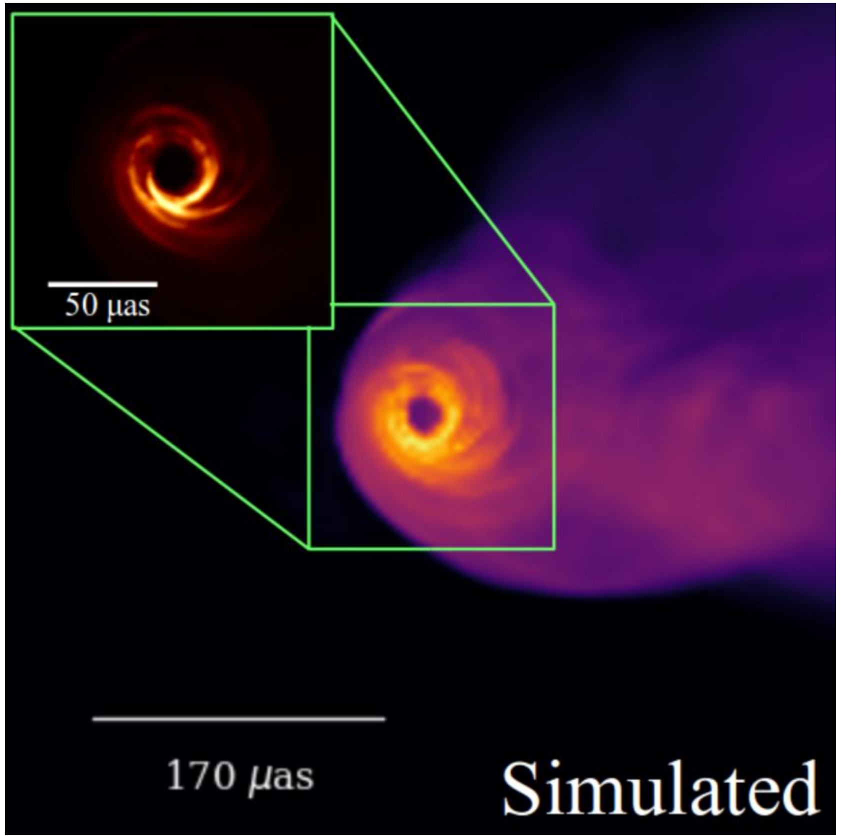


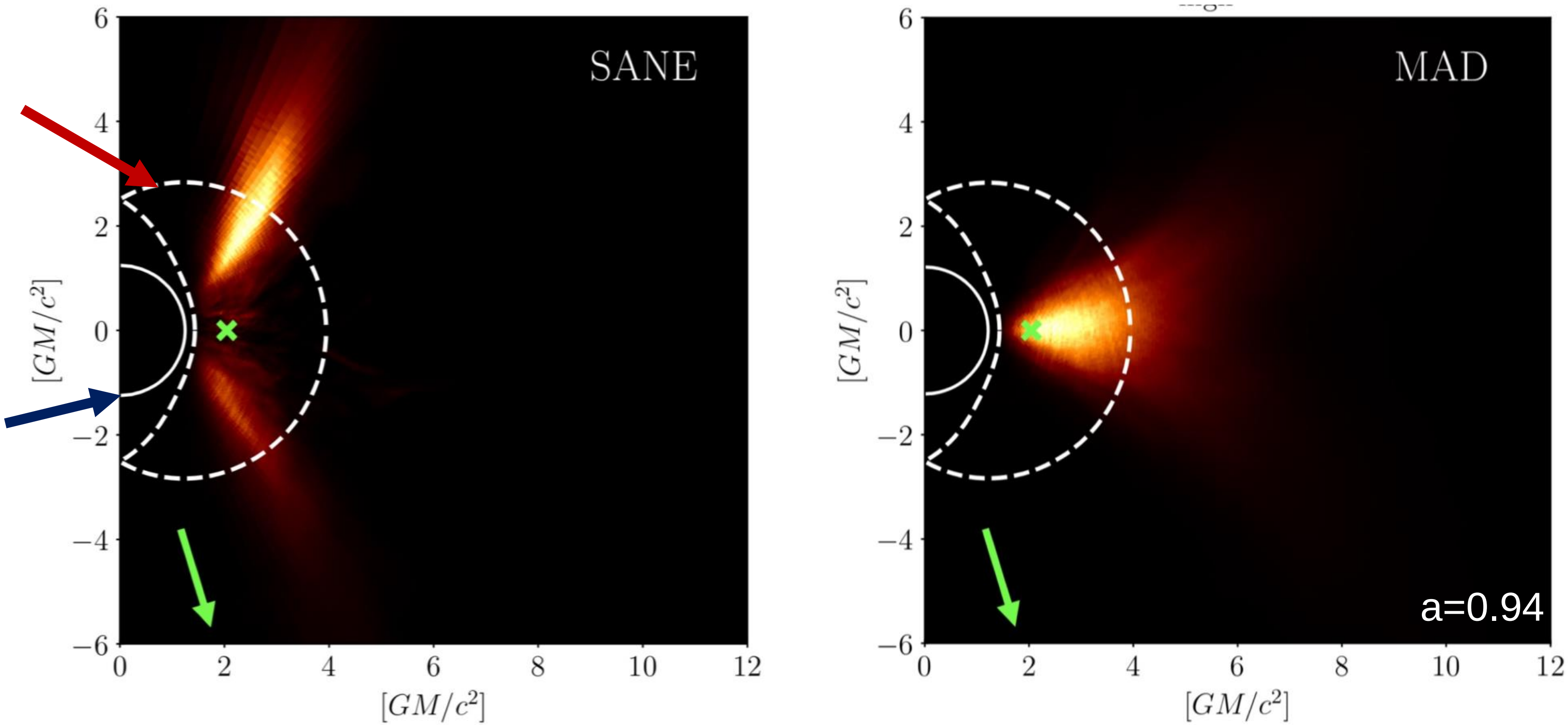
Image credit: Andrew Chael, Lindy Blackburn

Where does the emission come from?

All simulations show emission region is within a few Schwarzschild radii of the black hole, but in different spatial regions

Locus of photon orbits

Event Horizon



Can we determine if emission mostly originates in inflow or outflow?
How exactly is the emission lensed by the black hole?

EHTC+ 2019, Paper V

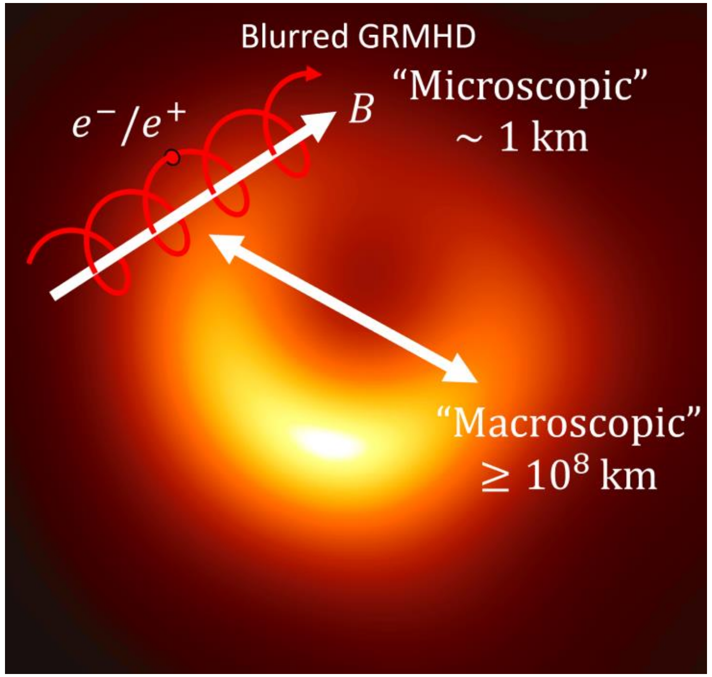
What is the distribution of emitting electrons?

- Coulomb coupling between ions and electrons is **inefficient**:

$$T_\mathrm{e} \neq T_\mathrm{i}$$

- The electron temperature is sensitive to radiative **cooling** and microscale **heating** processes
  - several options for the heating mechanism
    e.g. magnetic reconnection, Landau damping

- A big source of uncertainty in simulations, which don't resolve heating directly.

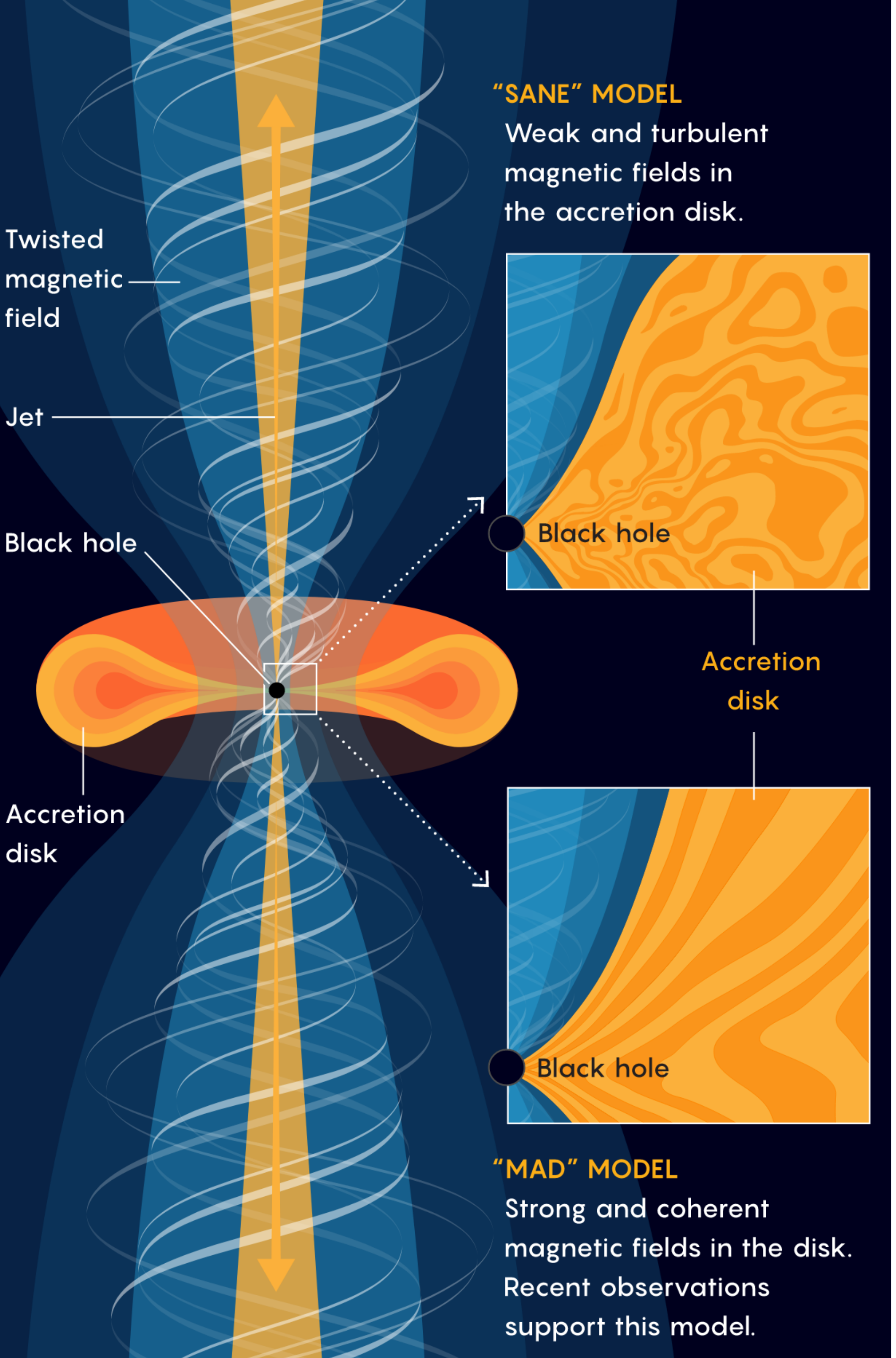


Huge scale separation in hot accretion flows

e.g. Mahadevan 1998
reconnection heating: e.g. Rowan+ 2017, Werner+ 2018. Turbulent damping: e.g. Howes 2010

Image credit: Bart Ripperda

What is the magnetic field structure?



Two accretion states that depend on the accumulated magnetic flux on horizon

Magnetic fields are weak and turbulent

"Standard and Normal" Evolution

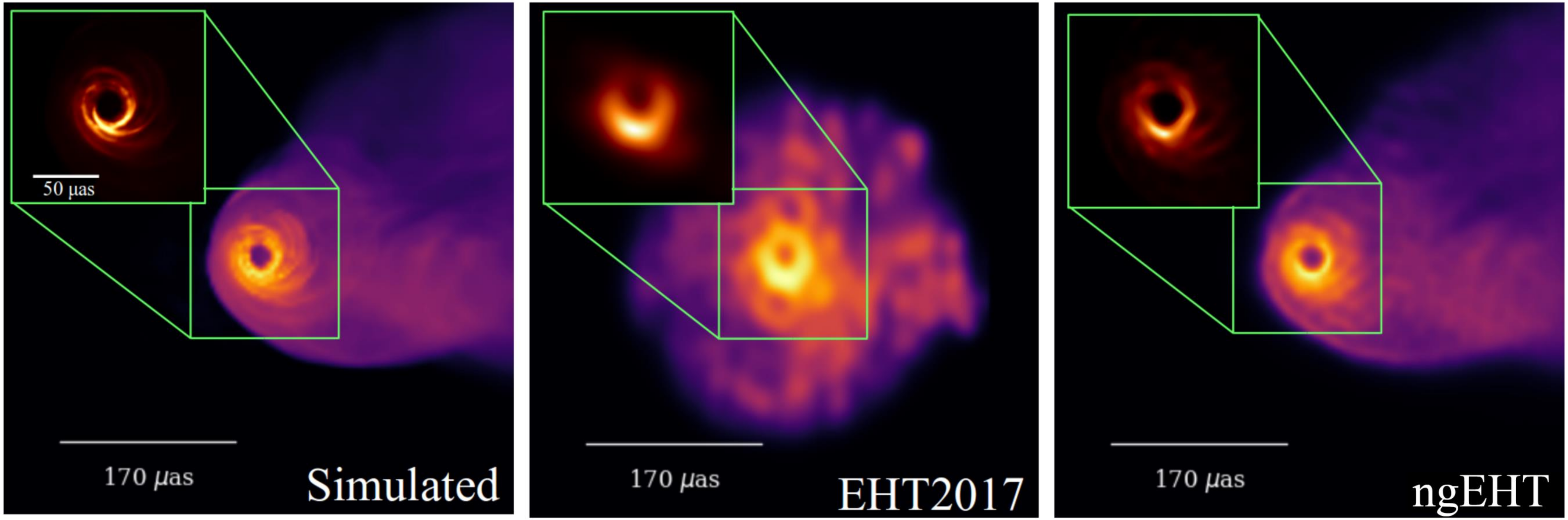
Strong, coherent magnetic fields build up on the horizon

Magnetically Arrested Evolution

Note: 'strong' fields = 10-100 G at the horizon for M87*

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: O'Riordan+ 2017, Quanta Magazine

What will we see with next-generation EHT observations?



- Increased (u,v) filling from new telescope sites in next-generation EHT can enhance image **dynamic range** from ~10 (EHT2017) to > 1000.
- High dynamic range images will illuminate the **BH-jet connection**

See EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)
Simulation credit: Chael+ 2019

This talk:

Focused on M87*, not Sgr A* (but ask me questions!)

Two takeaways:

1. **Polarization** is the key for EHT science
2. **We are just getting started** with what we can learn about black holes from resolved images

Outline

1. Black hole magnetic fields from EHT polarization images

Connection: where does emission originate around the M87* black hole?

2. Next-generation black hole images at high dynamic range

Part I:
What do polarized images of M87* tell us about magnetic fields near a supermassive black hole?

EHTC+ 2021 Papers VII, VIII

The EHT Collaboration

300+ members
60 institutes
20 countries
from Europe, Asia, Africa,
North and South America.

Slide credit: E. Traianou, MPIfR

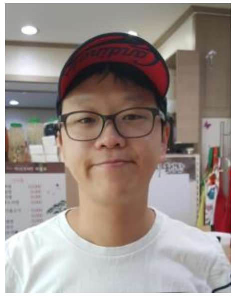
EHTC Paper VII + VIII writing team

Monika Mościbrodzka

Iván Martí-Vidal

Sara Issaoun

Jongho Park



Maciek Wielgus

Angelo Ricarte

Jason Dexter

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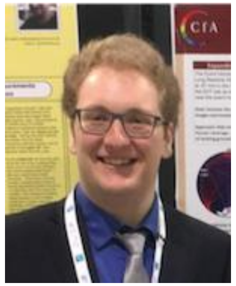
Daniel Palumbo



Dom Pesce

John Wardle

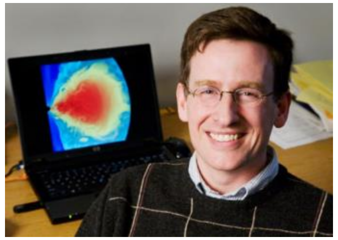
EHTC+ VII, VIII 2021
Arxiv: 2105.01169, 2105.01173

Event Horizon Telescope

Avery Broderick

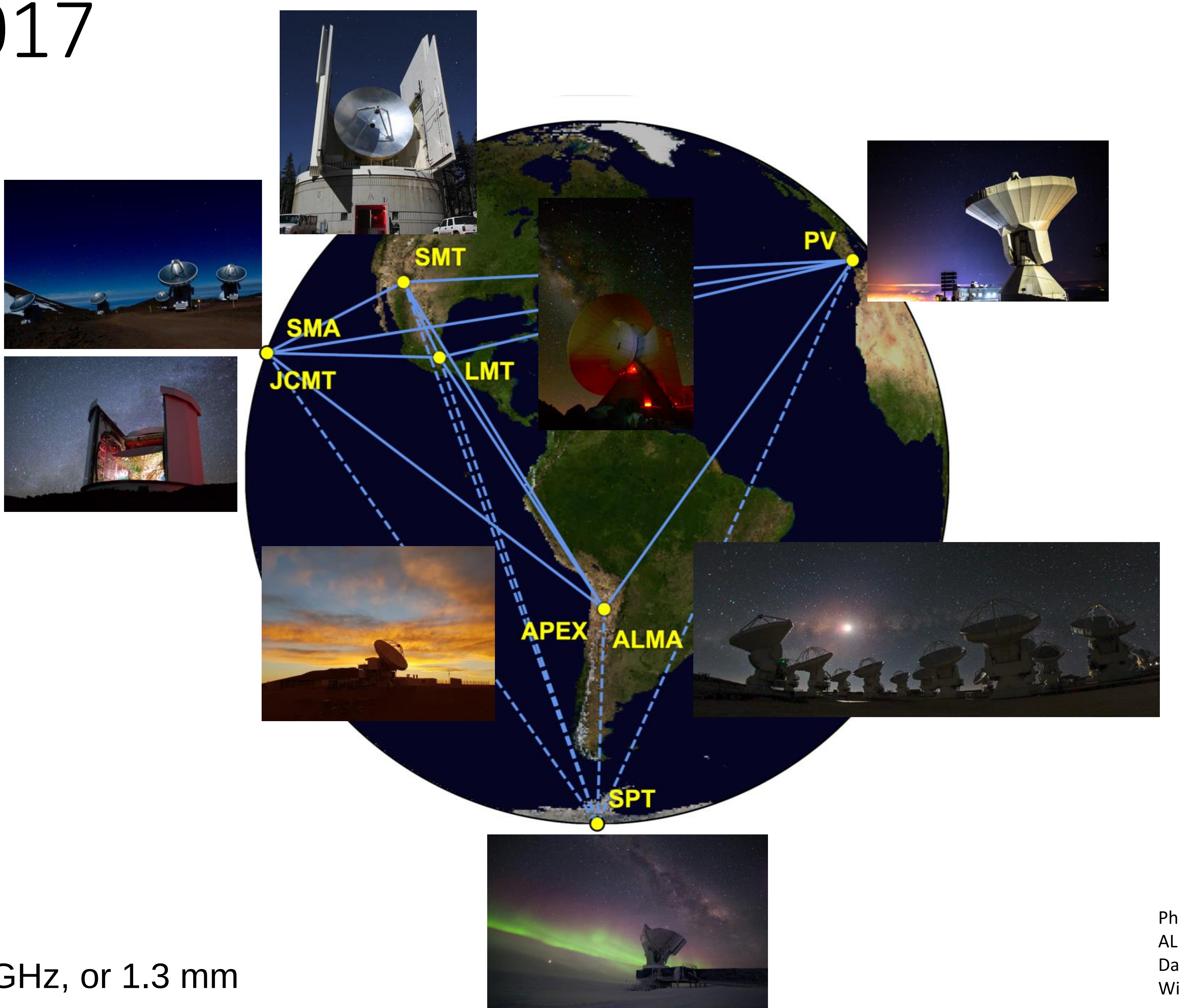
Ben Prather

Charles Gammie



George Wong

EHT 2017



Imaging at 230 GHz, or 1.3 mm

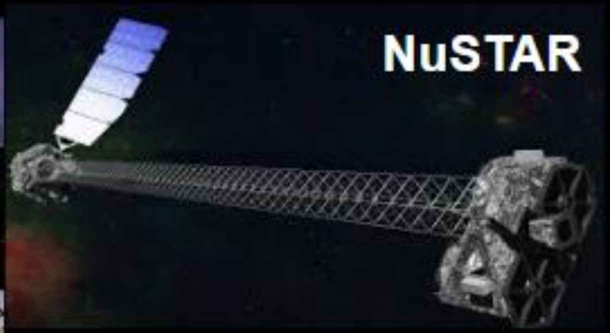
Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

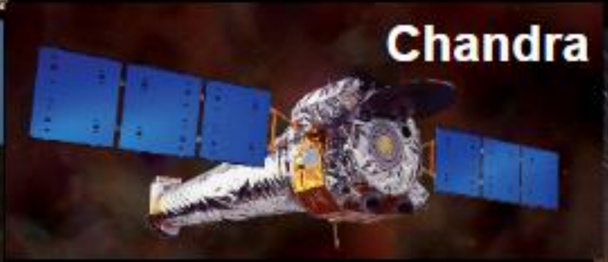
EHT 2017 Observations

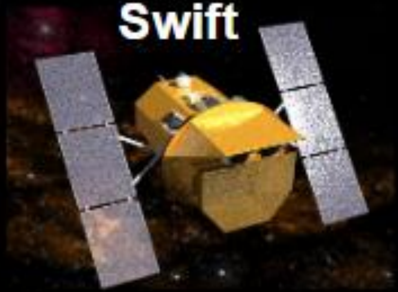
Observation run day three

Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

Our Multi-Wavelength Partners







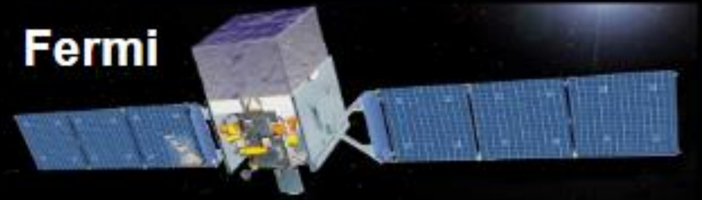
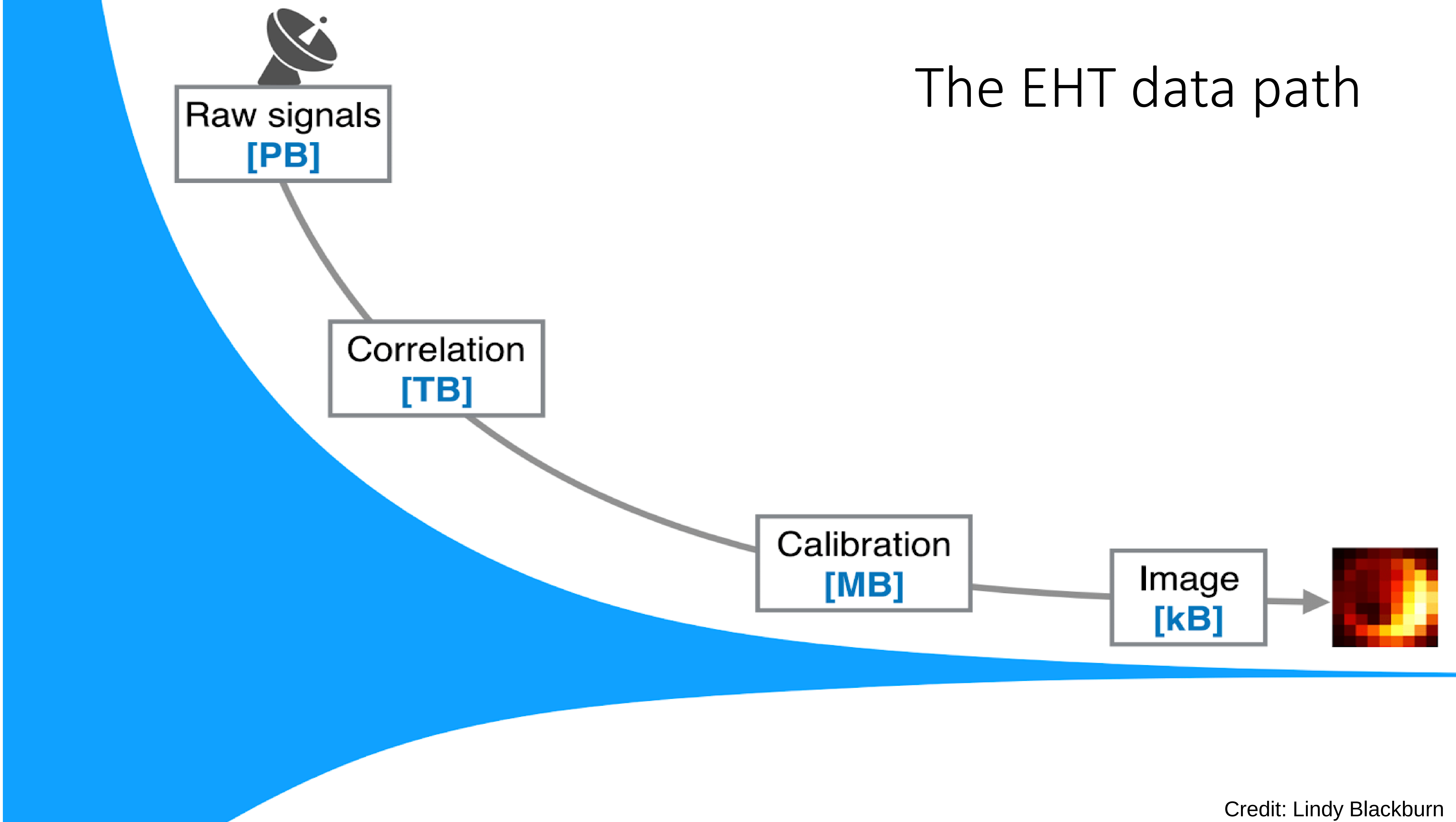


Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

Slide credit: S. Issaoun

The EHT data path



Raw signals
[PB]

Correlation
[TB]

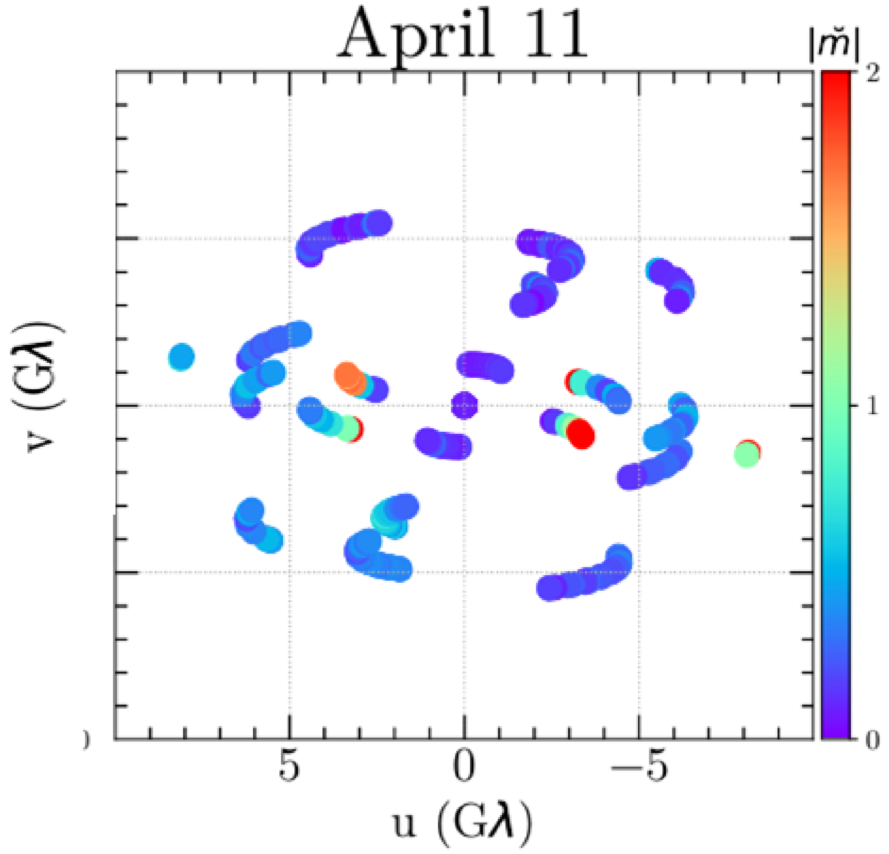
Calibration
[MB]

Image
[kB]

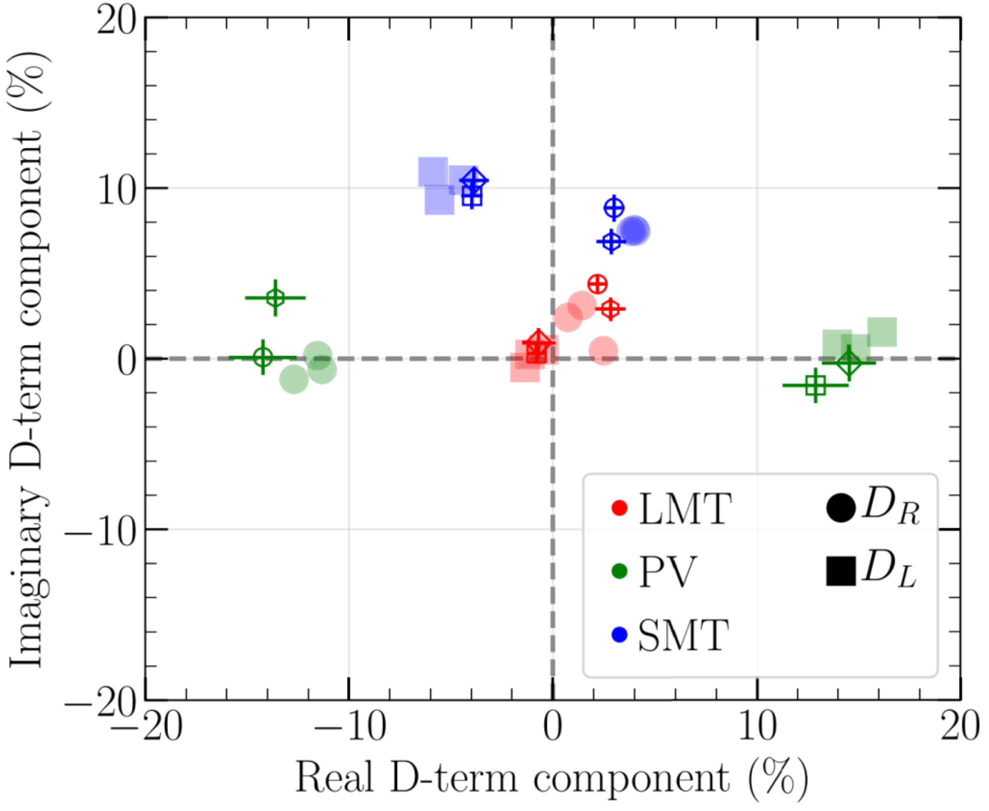
Credit: Lindy Blackburn

Challenges of EHT polarimetric imaging

EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

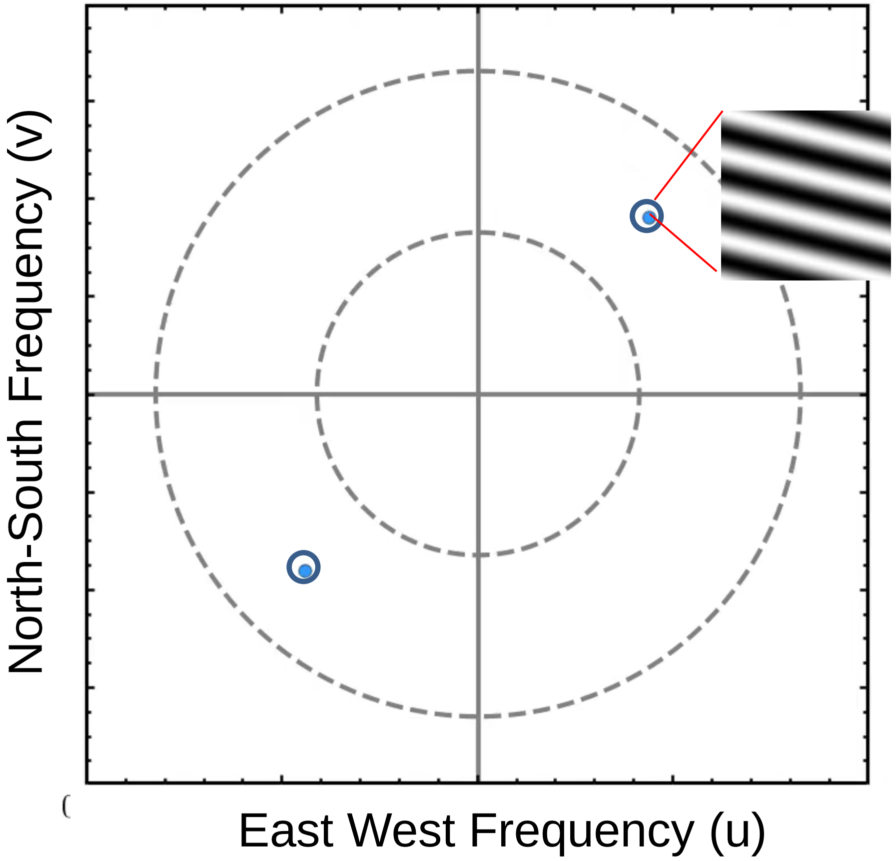


Data at each station are corrupted by unknown polarimetric **leakage** and complex gain factors



Credit: EHTC+ 2021, Paper VII

Very Long Baseline Interferometry (VLBI)



EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

movie credit: Katie Bouman, Daniel Palumbo

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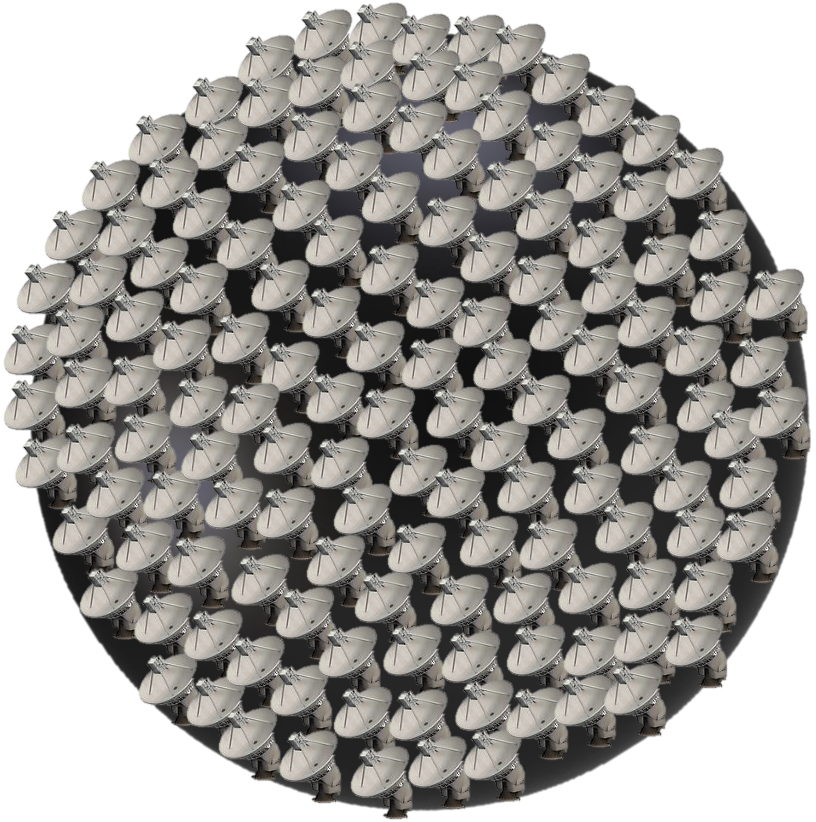

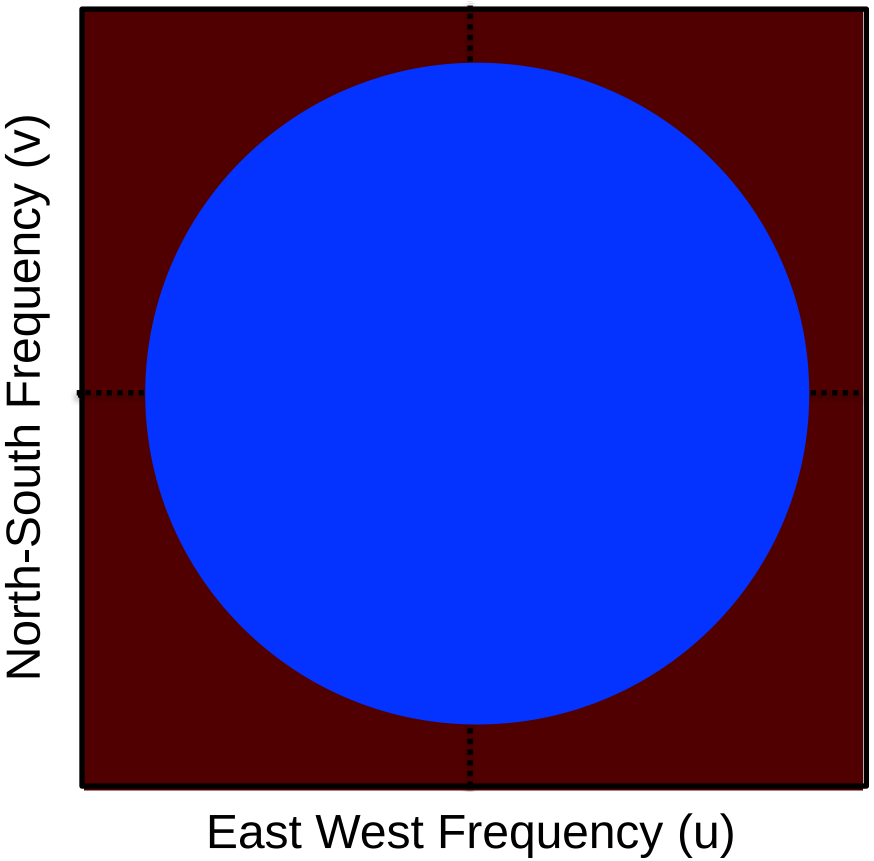

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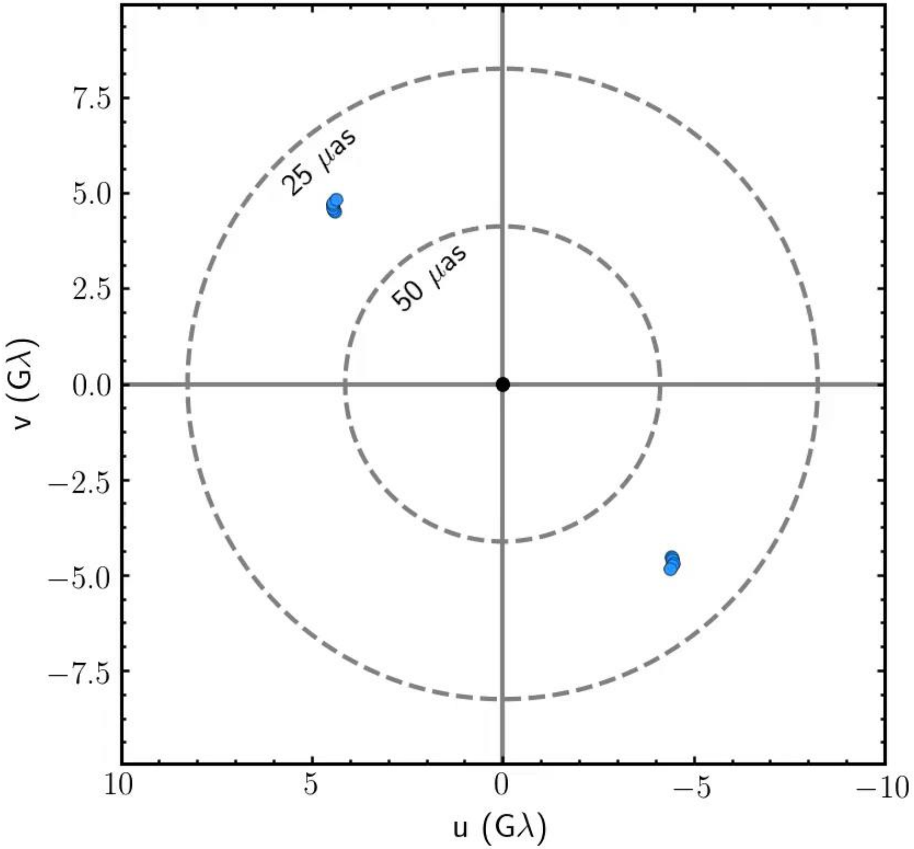
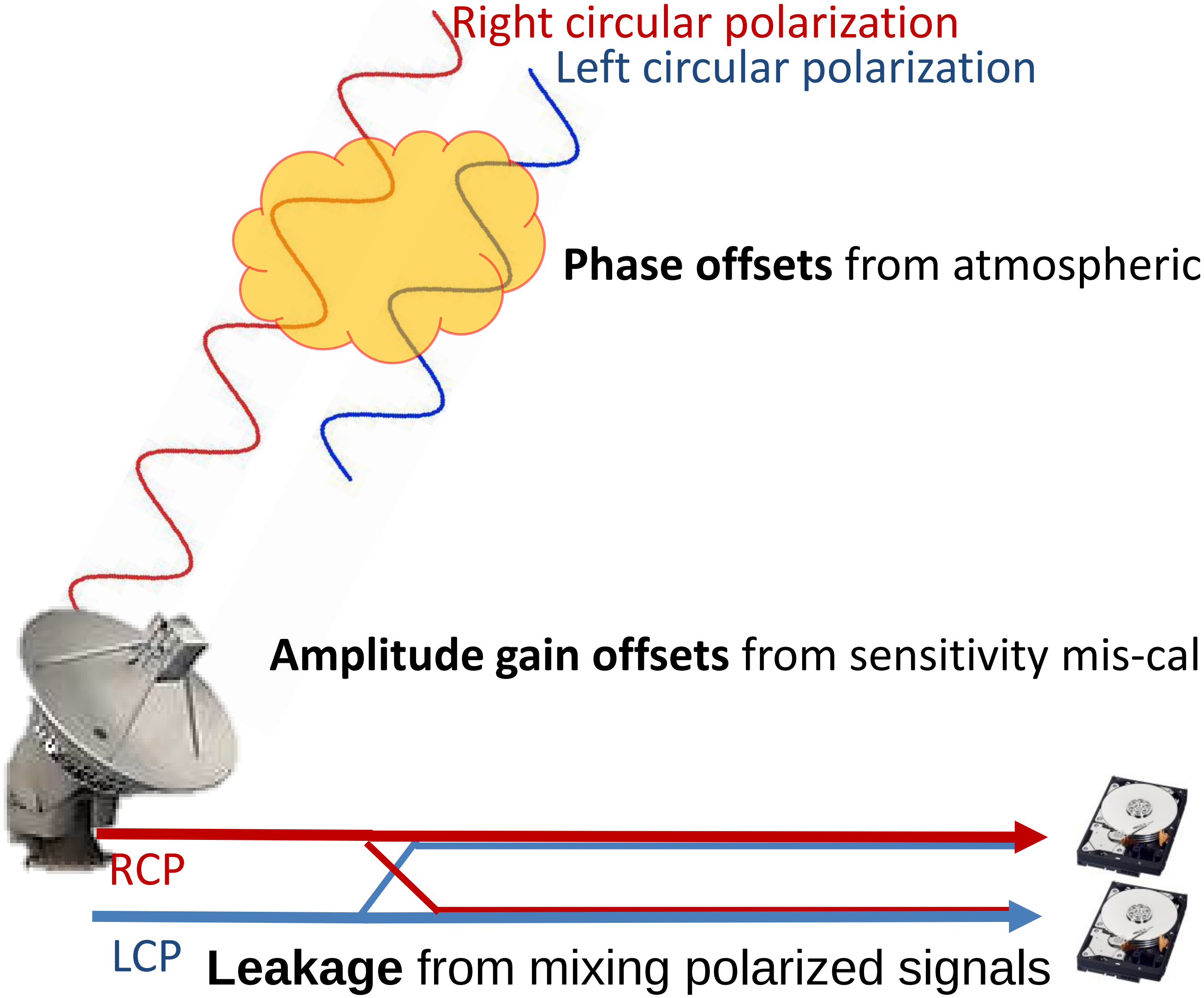


EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

movie credit: Katie Bouman, Daniel Palumbo

Why polarization is hard:
Corrupting effects at EHT stations



Right circular polarization

Left circular polarization

Phase offsets from atmospheric turbulence

Amplitude gain offsets from sensitivity mis-calibration

RCP

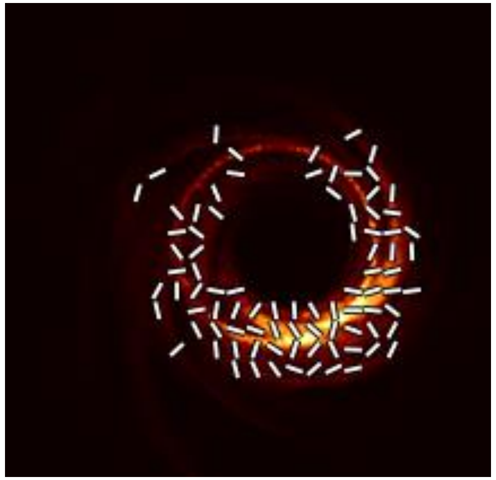
LCP

Leakage from mixing polarized signals

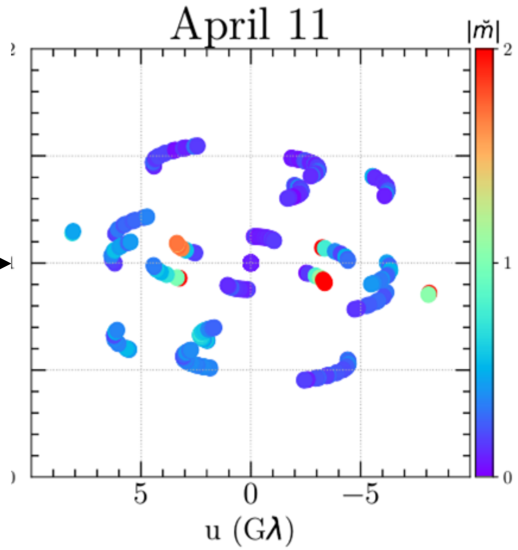
Data at each station are corrupted by unknown polarimetric **leakage** and complex gain factors

Solving for the Image

True Image

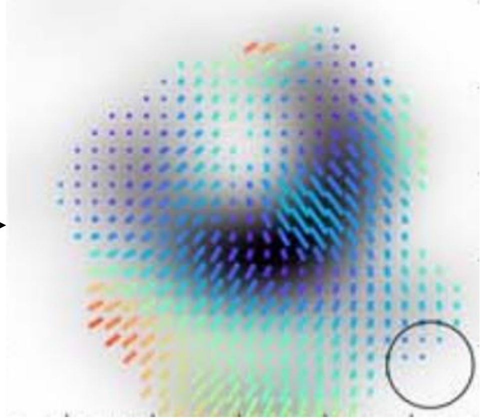


Sparse & Corrupted Measurements



Reconstruction Algorithm

Reconstruction



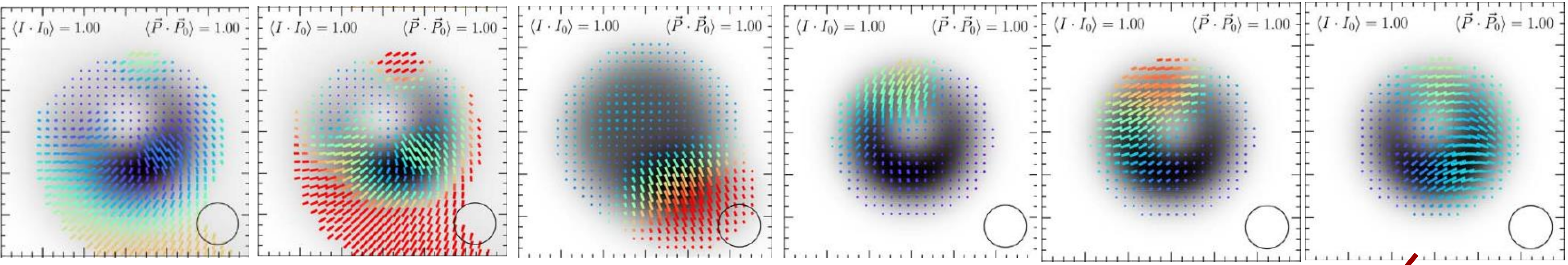
Several different types of reconstruction algorithms now used:

- **CLEAN-based**: standard and efficient, but can have difficulties on very sparse data
  - LPCAL/GPCAL (Park+ 2021) and polsolve (Marti-Vidal+ 21)
- **Regularized Maximum Likelihood / Gradient Descent**: fast and flexible, but lots of hyperparameters
  - eht-imaging (Chael+ 2016, 2018)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
  - Themis (Broderick+ 21), DMC (Pesce+ 21)

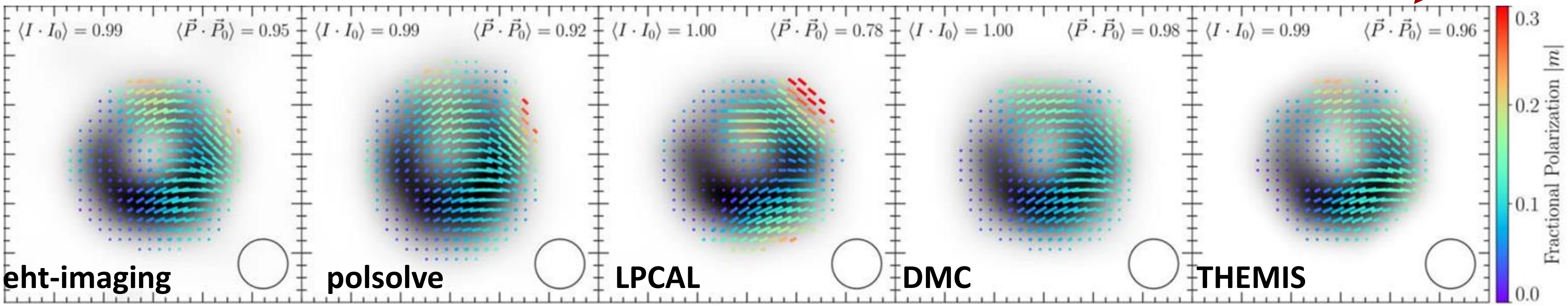
credit: Katie Bouman, Andrew Chael,
EHTC 2021, Paper VII

Testing our methods with synthetic data

We tested six different source models

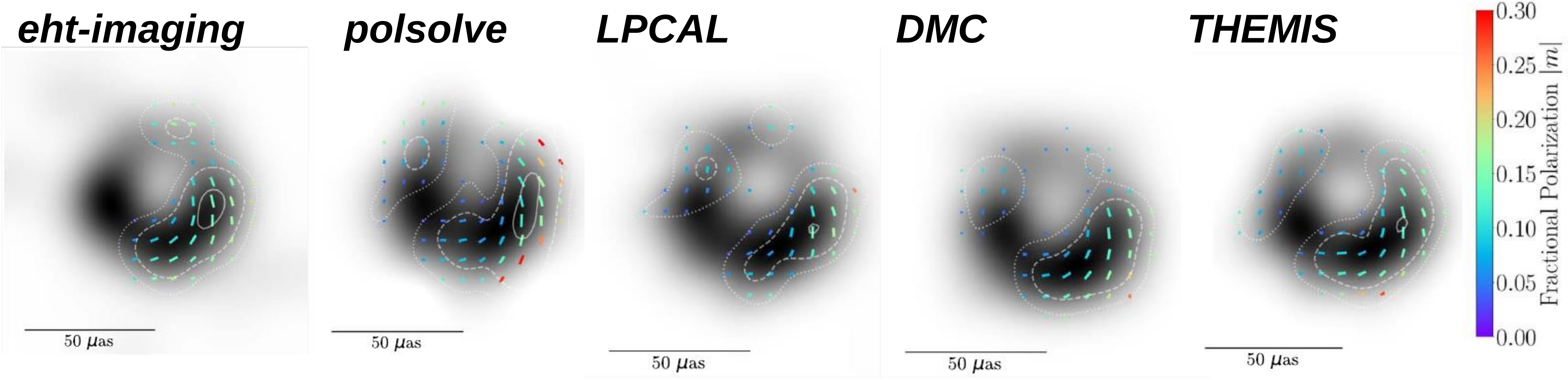


Example reconstructions of Model 6 using **5 distinct methods**



EHTC 2021, Paper VI

Images of M87* from five vetted methods



eht-imaging ***polsolve*** ***LPCAL*** ***DMC*** ***THEMIS***

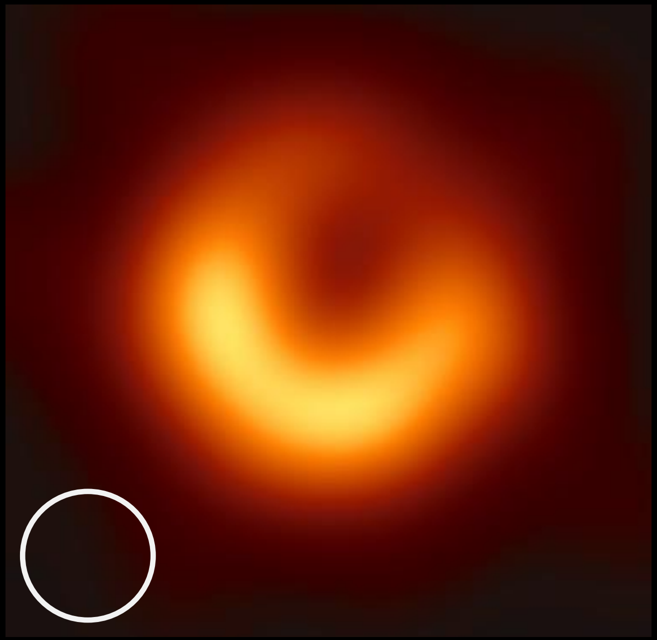
- All methods show similar polarization structure
- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **azimuthal**
- Overall level of polarization is **somewhat weak**, (|m| rises to ~15 %)

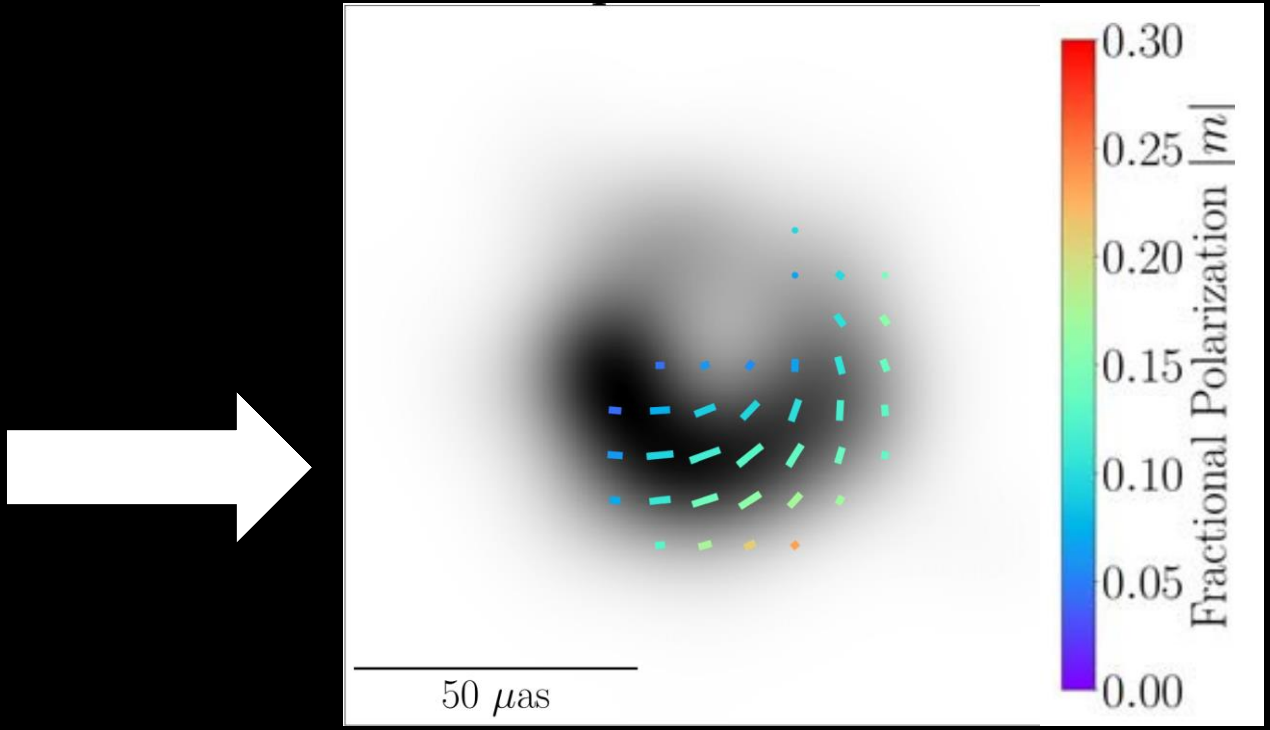
Credit: EHTC+ 2021, Paper VII

What do we learn from polarimetric images of M87*?

Total intensity

Linear Polarization



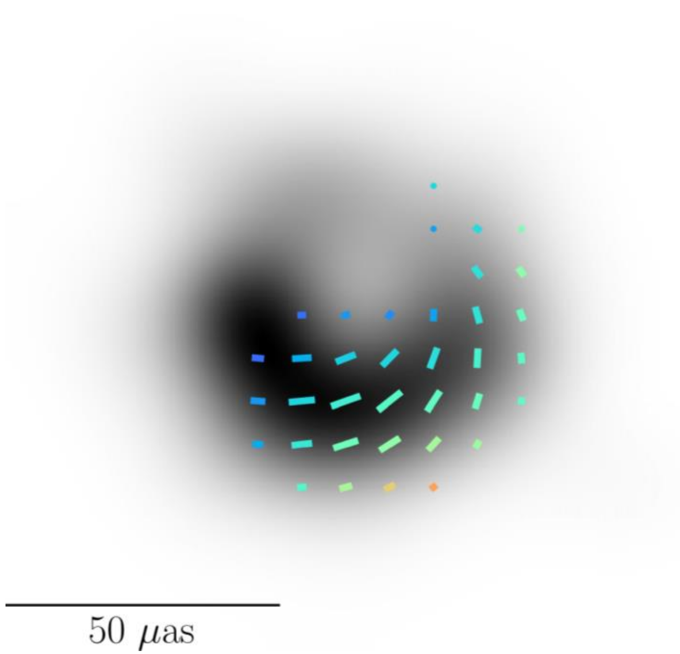


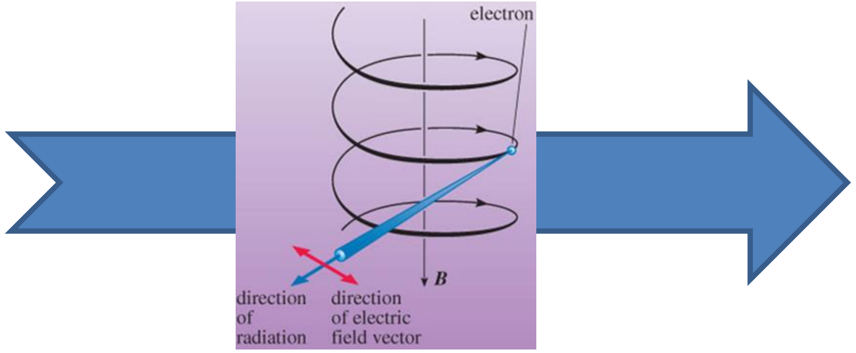
EHT Paper V (2019)
- Accretion flow is hot and dilute
- BH spin vector pointed away
- **Many simulation models fit the data**

EHT Paper VIII (2021)
- Constrains the nature of the BH magnetic fields

EHTC+ Paper VII (2021)

Synchrotron polarization traces magnetic fields



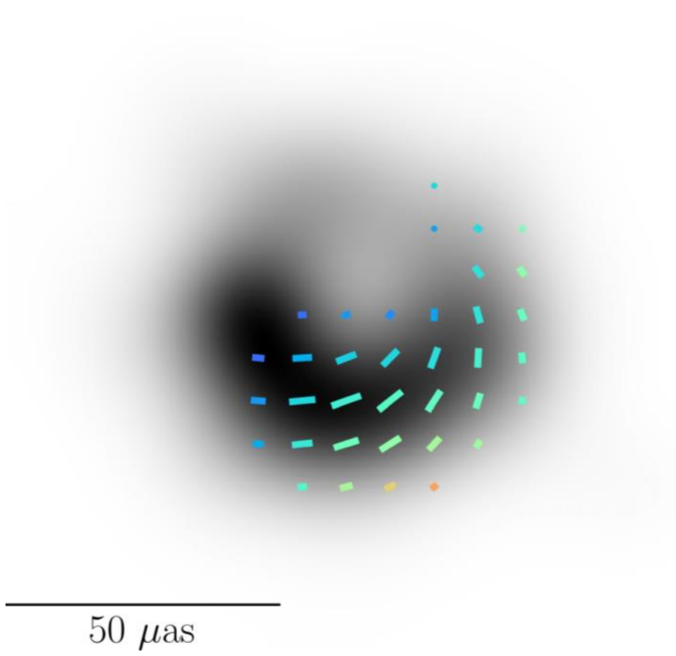


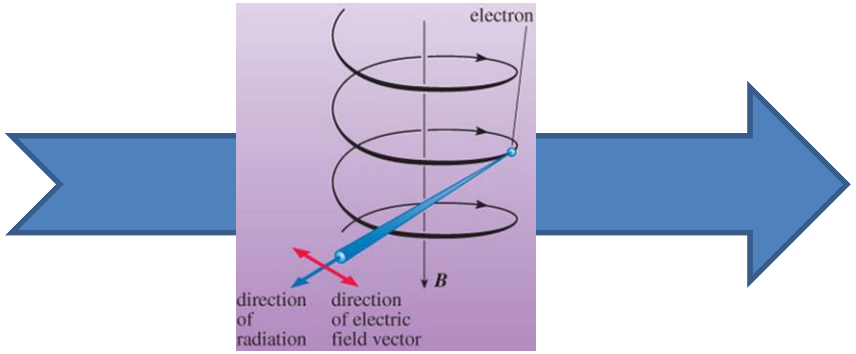
Magnetic field directions in the emission region!

Synchrotron radiation is emitted with polarization **perpendicular** to the magnetic field line

Image credit: EHTC VIII 2021, Open University

Synchrotron polarization traces magnetic fields





~~Magnetic field directions in the emission region!~~

Relativity and Faraday effects make the situation in M87* more complicated!

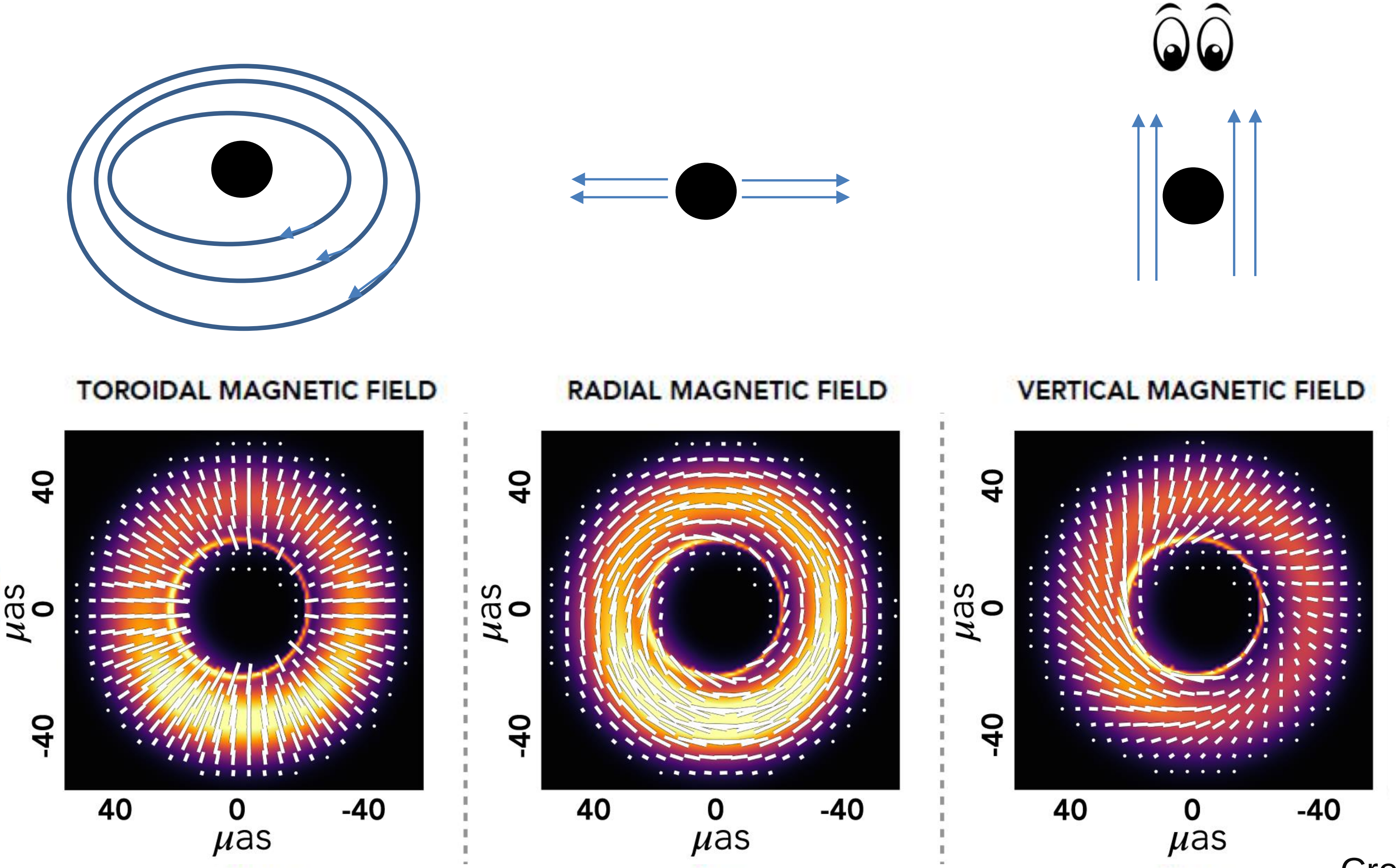
Image credit: EHTC VIII 2021, Open University

Light bending matters

3 simple models, viewed face on

Field structure

Observed image

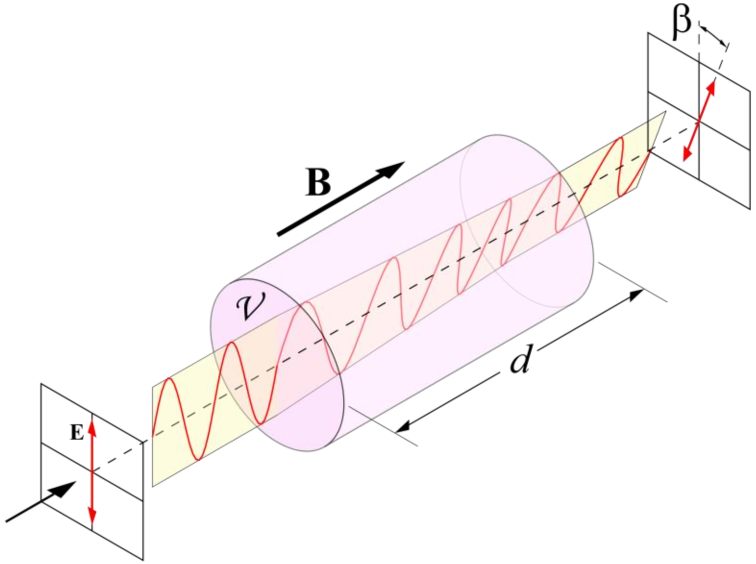


Vertical field scenario would be **unpolarized** without bent photon trajectories!

Credit: EHTC 2021 Paper VIII
Jiménez-Rosales+ 2018, Narayan+ 2021

Faraday rotation matters!

- Light propagation in a plasma **rotates** the plane of polarization



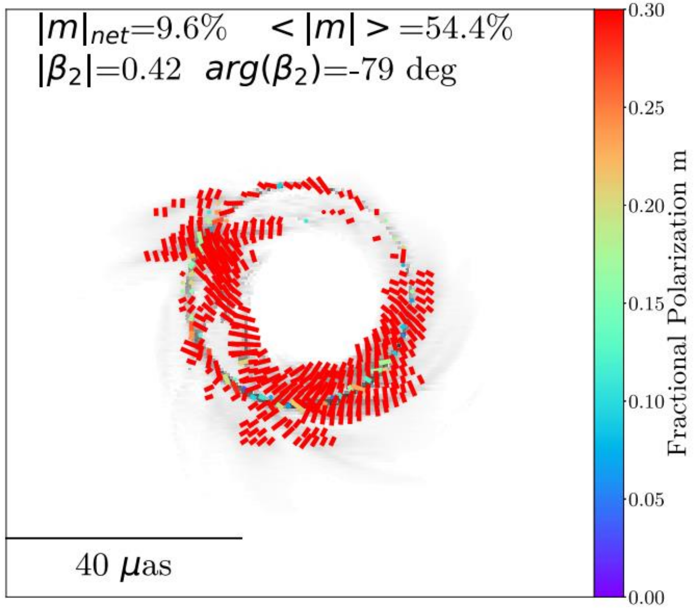
- ‘Internal’ vs ‘External’ Faraday rotation:
  - **External →** rotation is far from the source, polarization rotated by same angle everywhere
  - **Internal →** rotation is inside emitting source, image regions rotated by different amounts

Image credit: Wikipedia

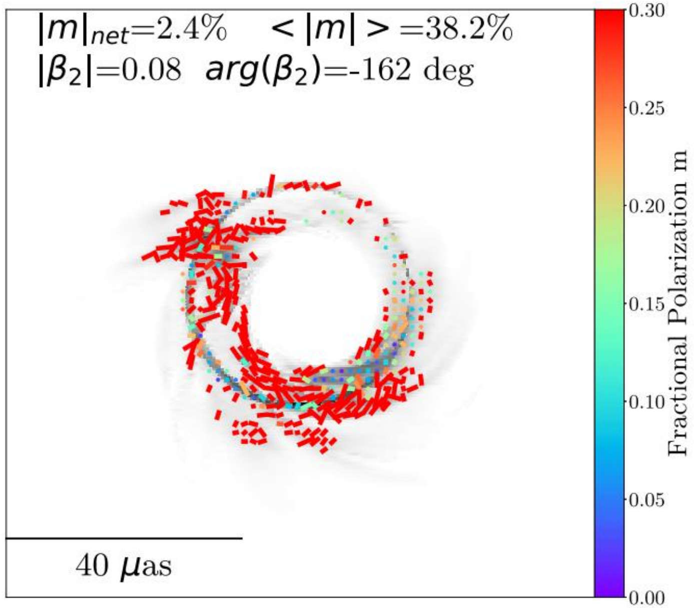
(Internal) Faraday rotation matters!

‘infinite’ resolution

Without rotation



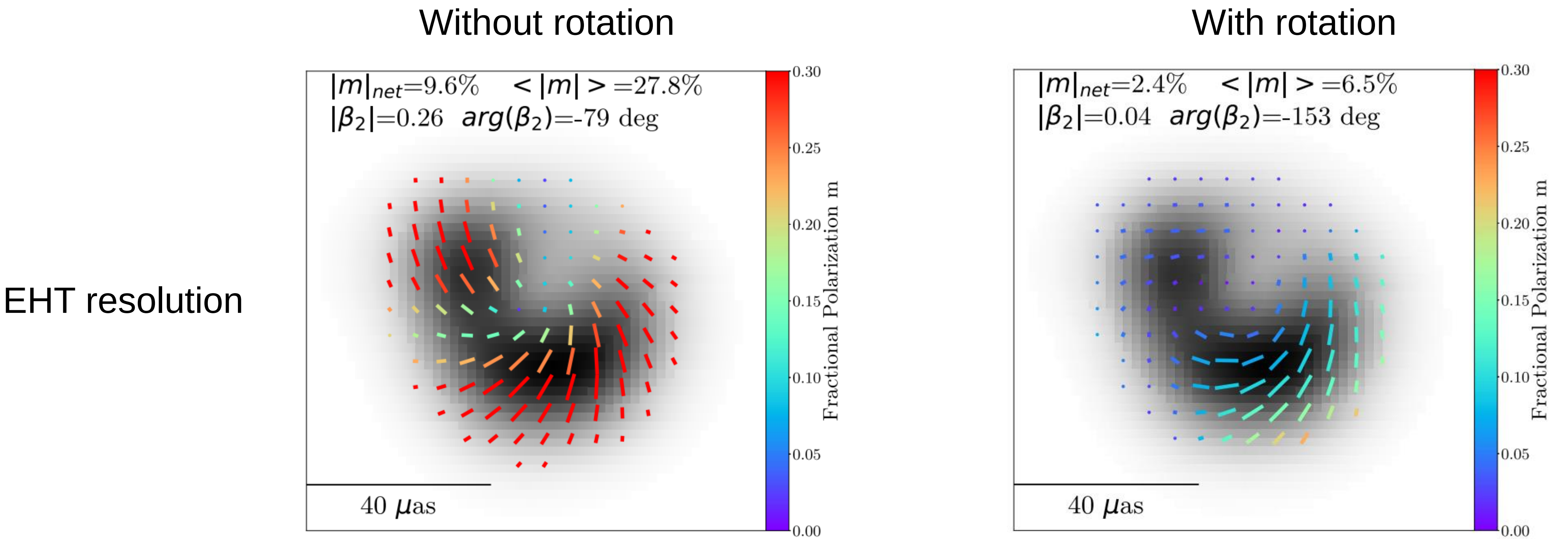
With rotation



- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

Credit: EHTC 2021 Paper VIII

(Internal) Faraday rotation matters!



- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **depolarizes** the image when blurred to EHT resolution

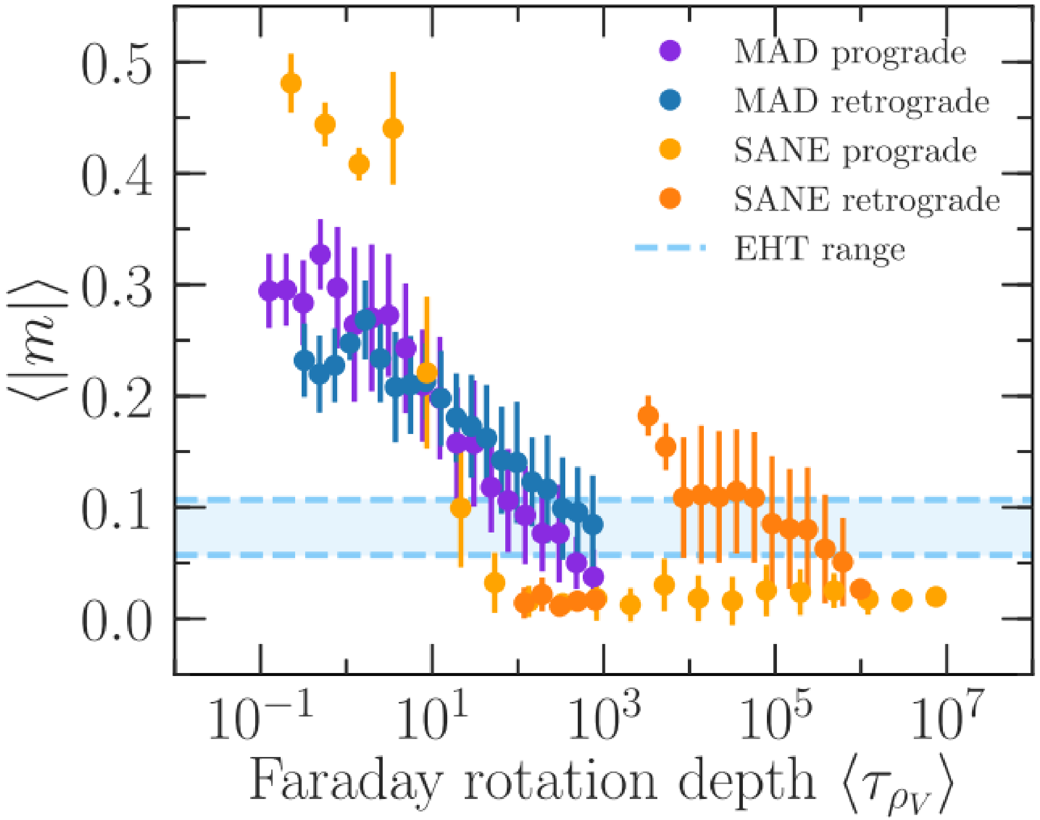
Credit: EHTC 2021 Paper VIII

(Internal) Faraday rotation matters!

- Faraday rotation on **small scales**
  → **scrambles** polarization vectors
  → **depolarizes** the image blurred to EHT resolution

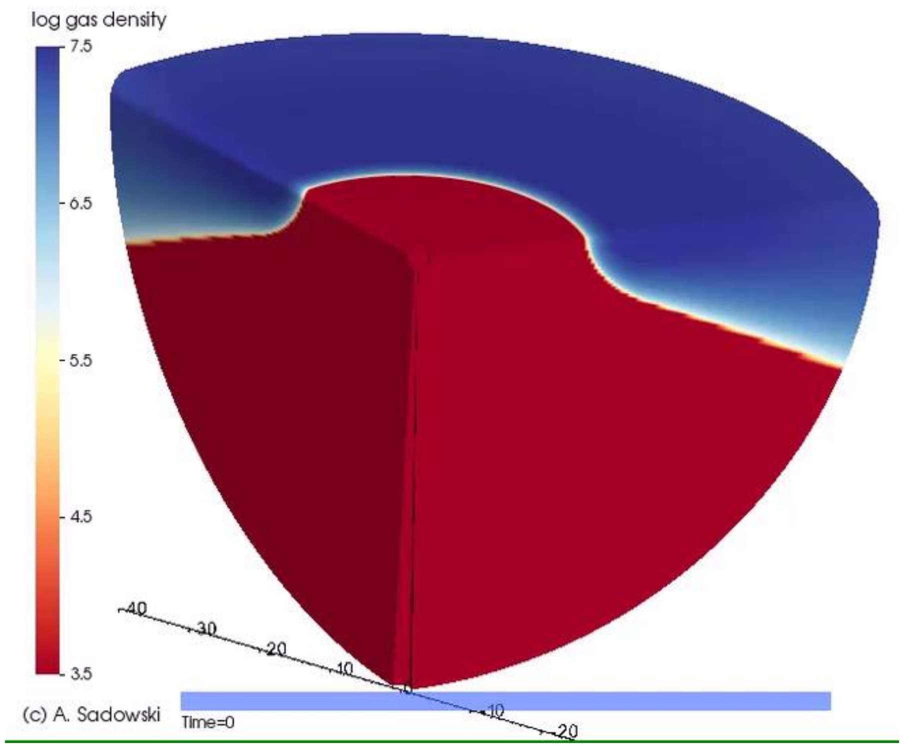
- In our simulations, only significant internal Faraday rotation can produce the low observed fractional polarization

- This means the plasma is not electron-positron!



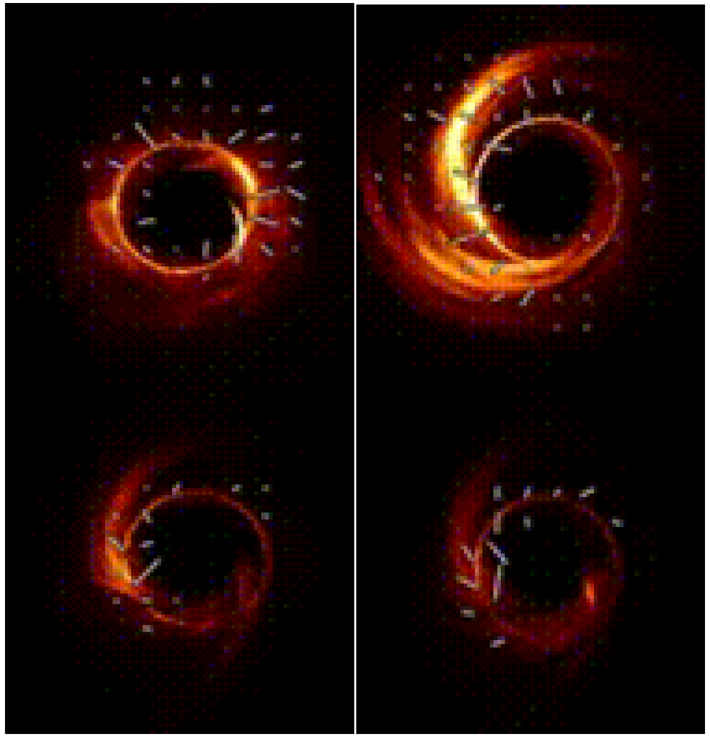
Credit: EHTC 2021 Paper VIII

Theoretical Tools for Interpreting Black Hole Images



General **R**elativistic **M**agneto**H**ydro**D**ynamic (GRMHD) simulations

Solves coupled equations of fluid dynamics and magnetic field in Kerr spacetime

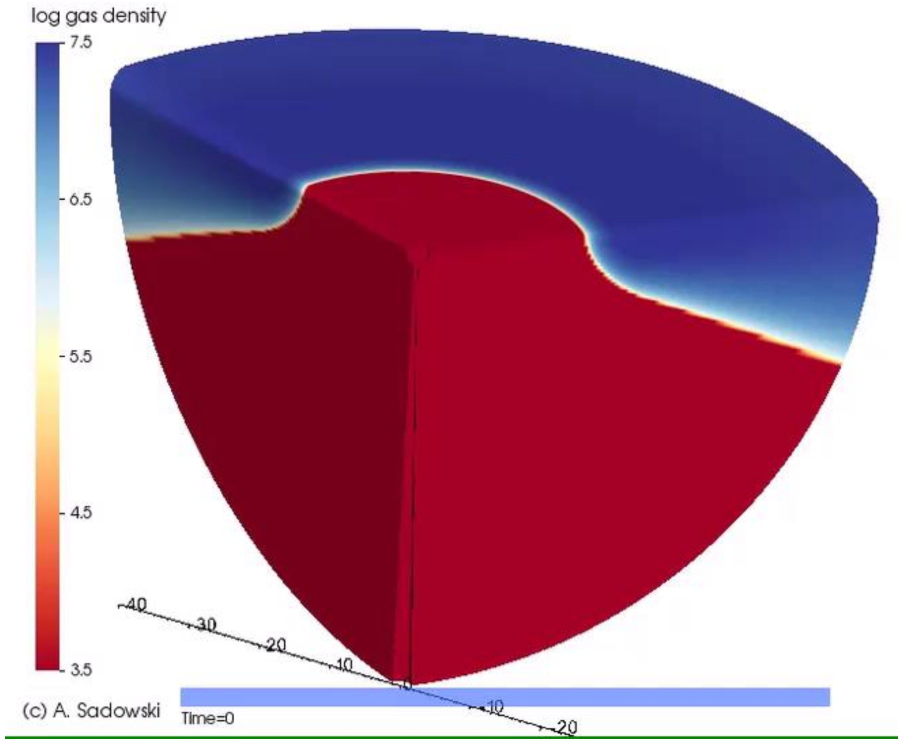


General **R**elativistic **R**ay **T**racing (GRRT)

Tracks light rays and solves for the polarized radiation (including light bending and Faraday rotation)

Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather (right)

Why GRMHD Simulations?



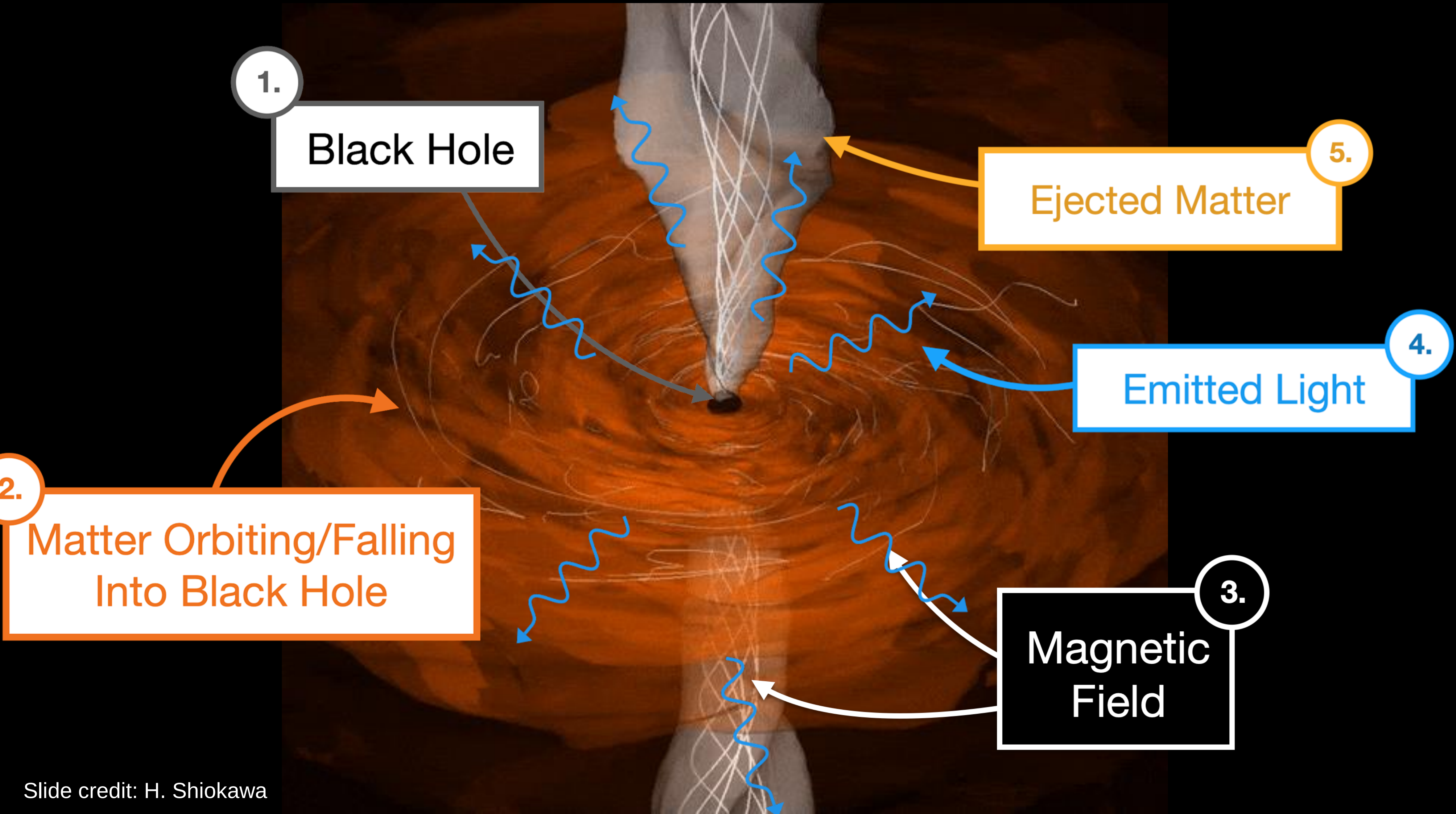
General **R**elativistic **M**agneto**H**ydro**D**ynamics
Solves the coupled equations of fluid and magnetic field in Kerr spacetime

- GRMHD Simulations are a primary theoretical tool for investigating the physics of accretion and jet launching near supermassive black holes and interpreting EHT images.

- GRMHD simulations naturally **couple the accretion disk, black hole, and jet**
  - Jet launching is universal and driven by BH spin

- GRMHD Simulations are naturally **turbulent** and **dynamic**
  - we know source variability is a critical feature of Sgr A* and M87

Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather (right)



1. **Black Hole**

2. **Matter Orbiting/Falling Into Black Hole**

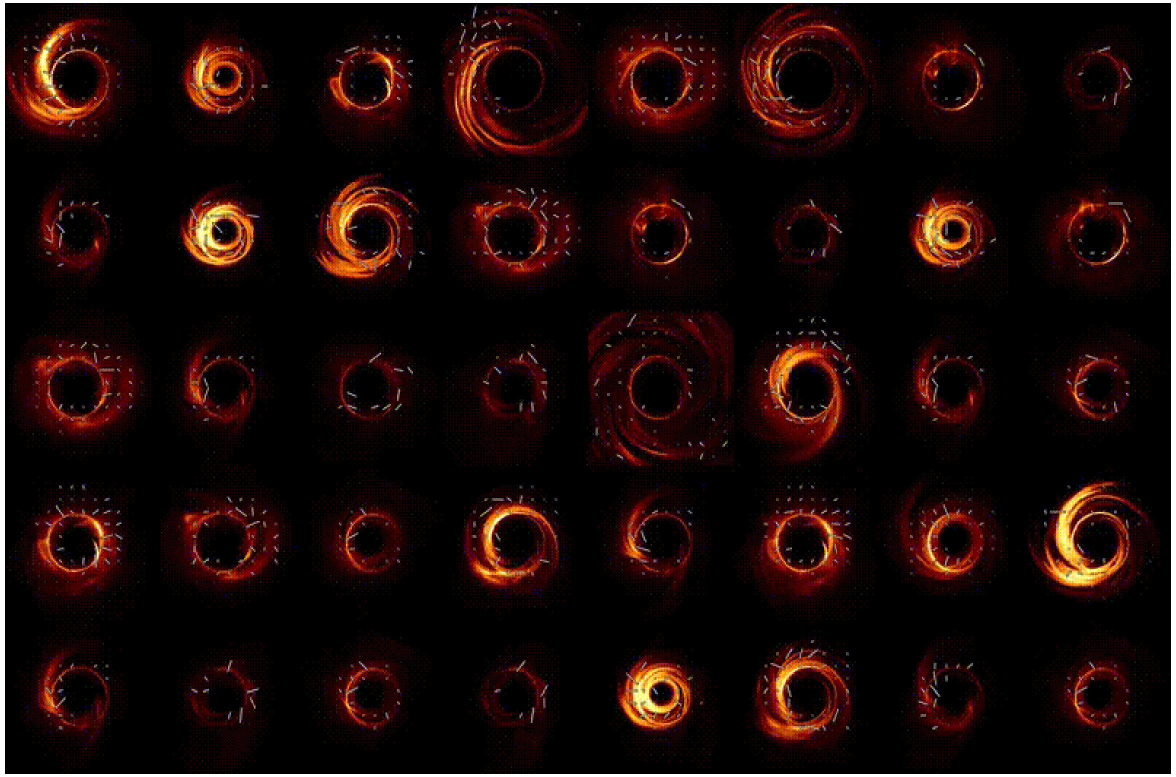
3. **Magnetic Field**

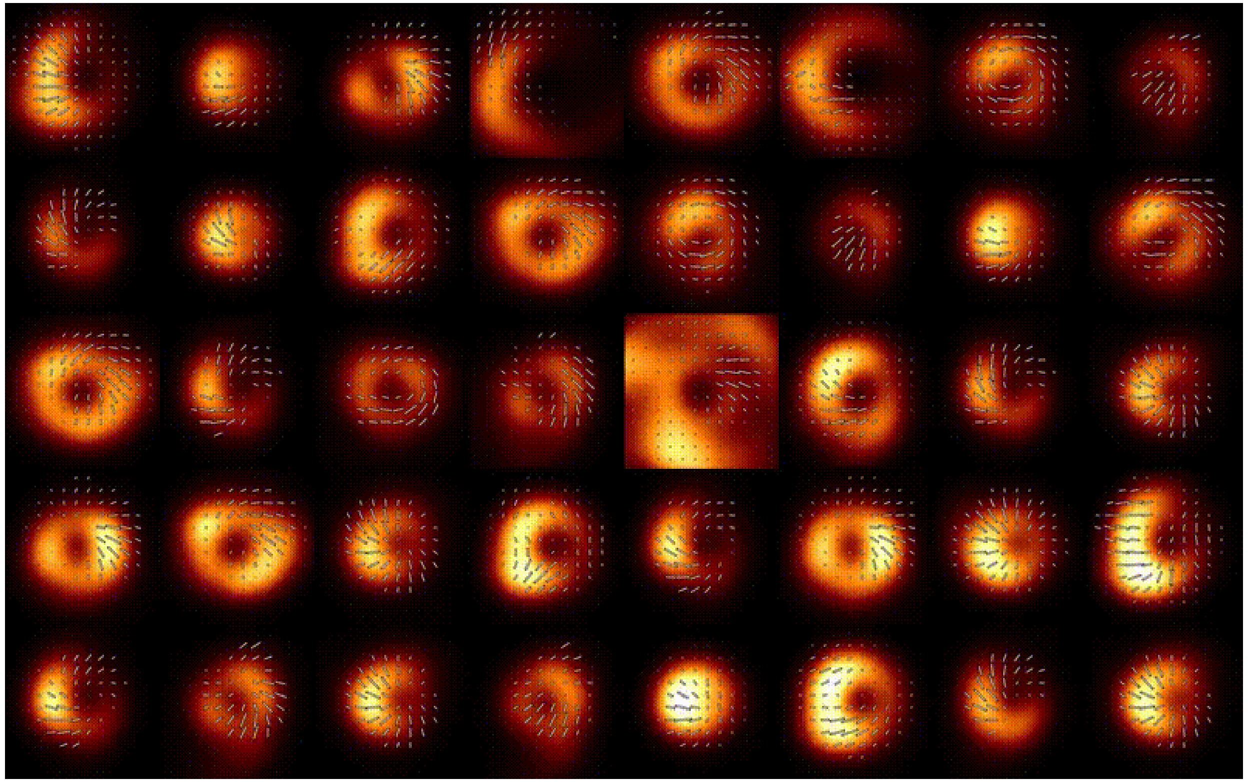
4. **Emitted Light**

5. **Ejected Matter**

Slide credit: H. Shiokawa

GRMHD Simulation library
2 field states, 5 BH spins, 72k images


native resolution


EHT resolution

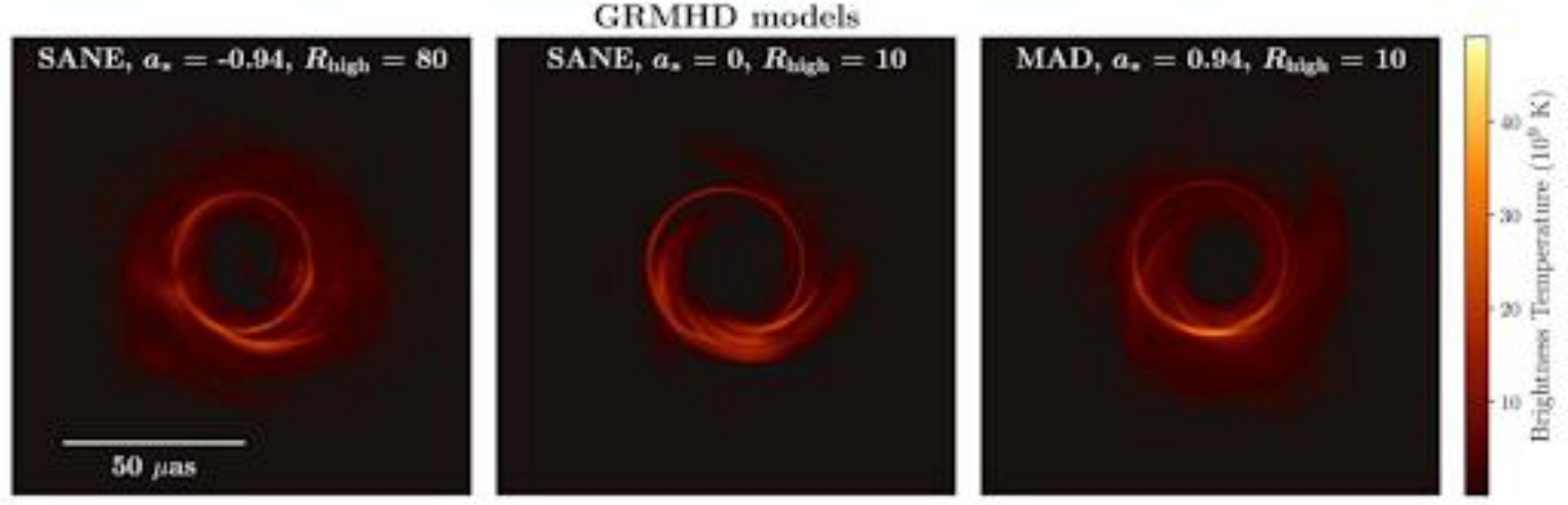
Images modeled with the ipole GRRT code (Moscibrodzka & Gammie 2018)
Two-temperature plasma model from Moscibrodzka et al. 2016

Animation credit: George Wong/ Ben Prather

Scoring GRMHD Simulations: before polarization

(EHTC+ 2019, Paper V)

- **Most simulation models can be made to fit total intensity observations alone** by tweaking free parameters (mass, PA, total flux density)



- An additional constraint on **jet power** (≥ 10^{42} erg/sec) rejects all spin 0 models
- Can we do better with polarization?

EHTC+ Paper V, 2019

Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

$$|m|_{\mathrm{net}} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$$

Unresolved circular polarization fraction (ALMA)

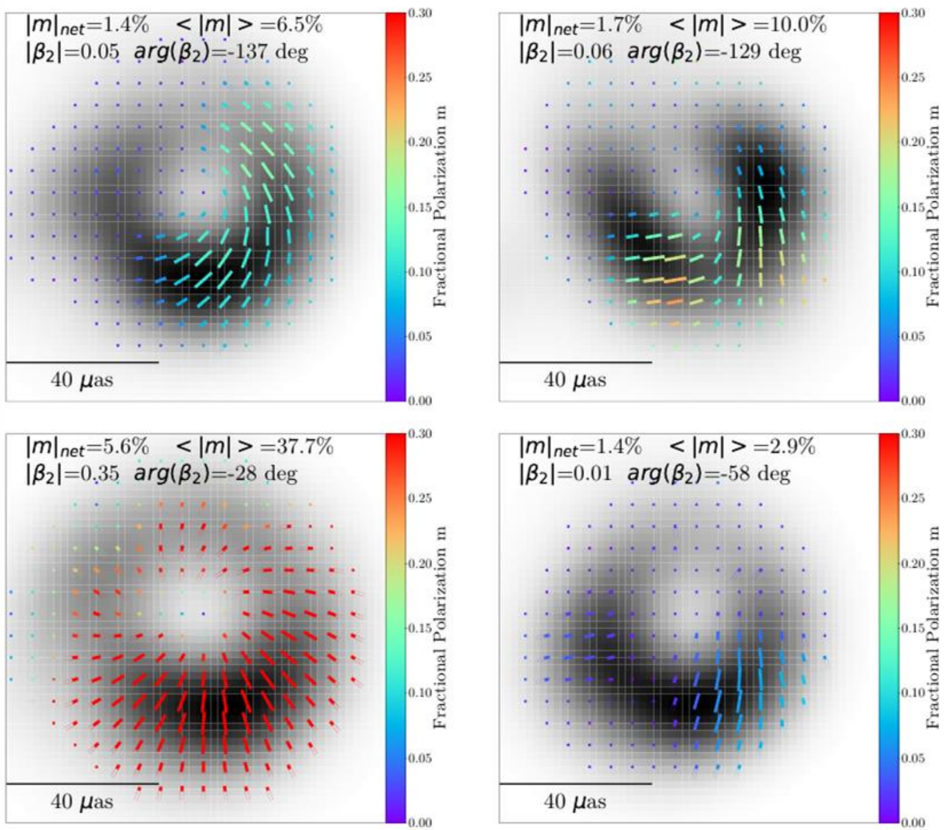
$$|v|_{\mathrm{net}} = \frac{\left|\sum_i V_i\right|}{\sum_i I_i}$$

Average resolved polarization fraction

$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Azimuthal structure
2nd Fourier mode

$$\beta_2 = \frac{1}{I_{\mathrm{ring}}} \int\limits_{\rho_{\min}}^{\rho_{\max}} \int\limits_{0}^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\; \rho\, d\varphi\, d\rho$$

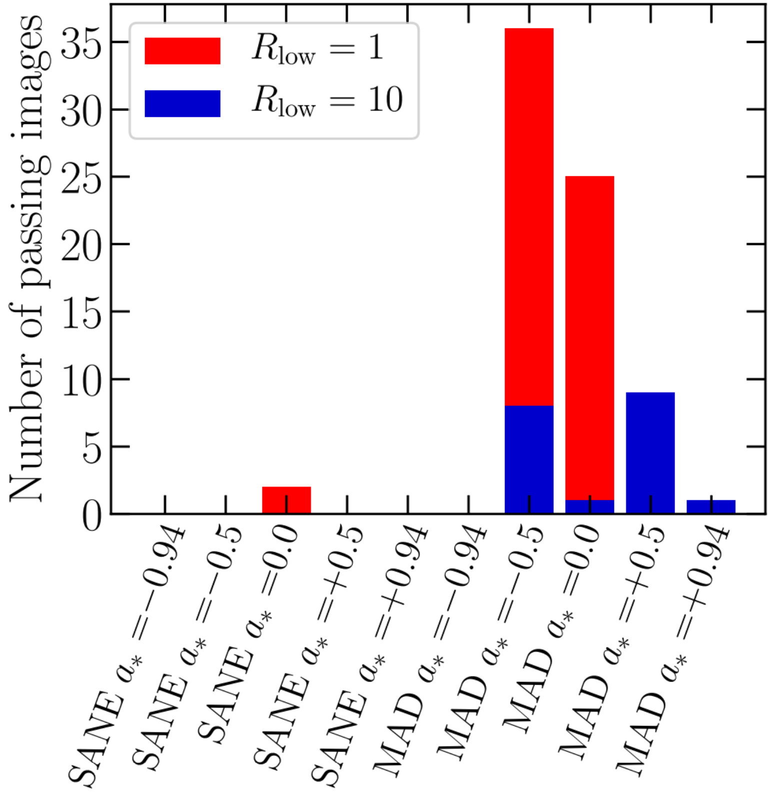


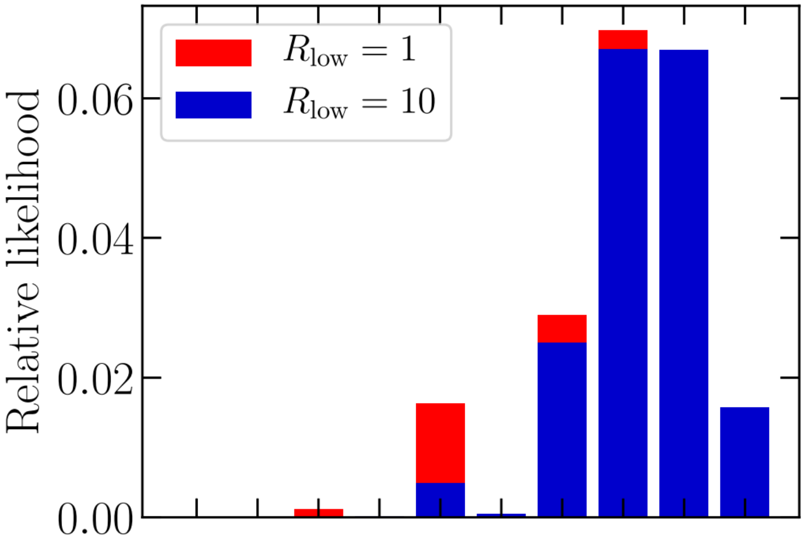
GRMHD images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

EHTC+ 2021 Paper VIII

Polarimetric simulation scoring

- Two scoring approaches:
  - **‘simultaneous’** (demand individual images satisfy all image constraints at once)
  - **‘joint’** (compute a likelihood comparing distance between measured quantities and simulation mean with the simulation variance)
- **Both approaches strongly favor a magnetically arrested accretion flow**
- The two approaches favor different prescriptions for the electron heating physics.
- Adding a constraint on the jet power rejects **all** simulations that are not magnetically arrested



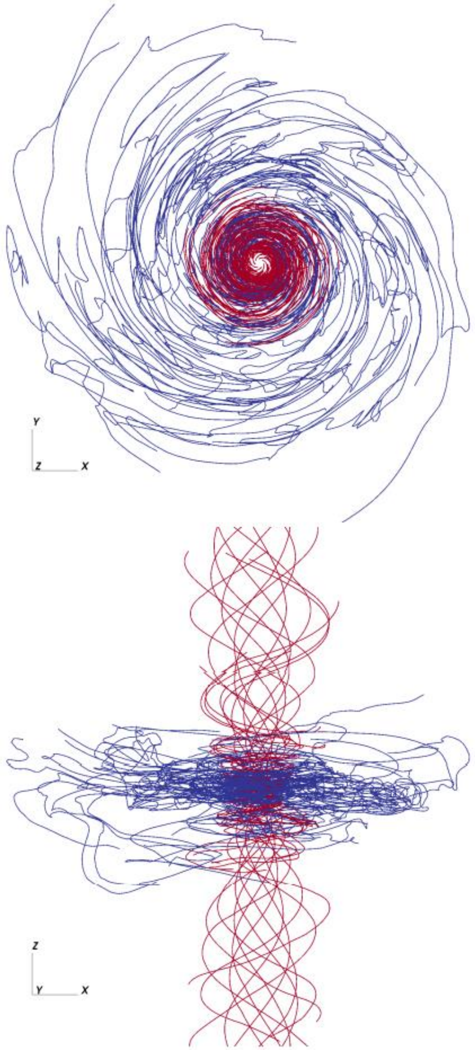


EHTC+ 2021 Paper VIII

Simulation field structure in 3D

Fields in magnetically arrested disk (MAD) simulations have a stronger vertical component. The jet carries more power and is wider

MAD



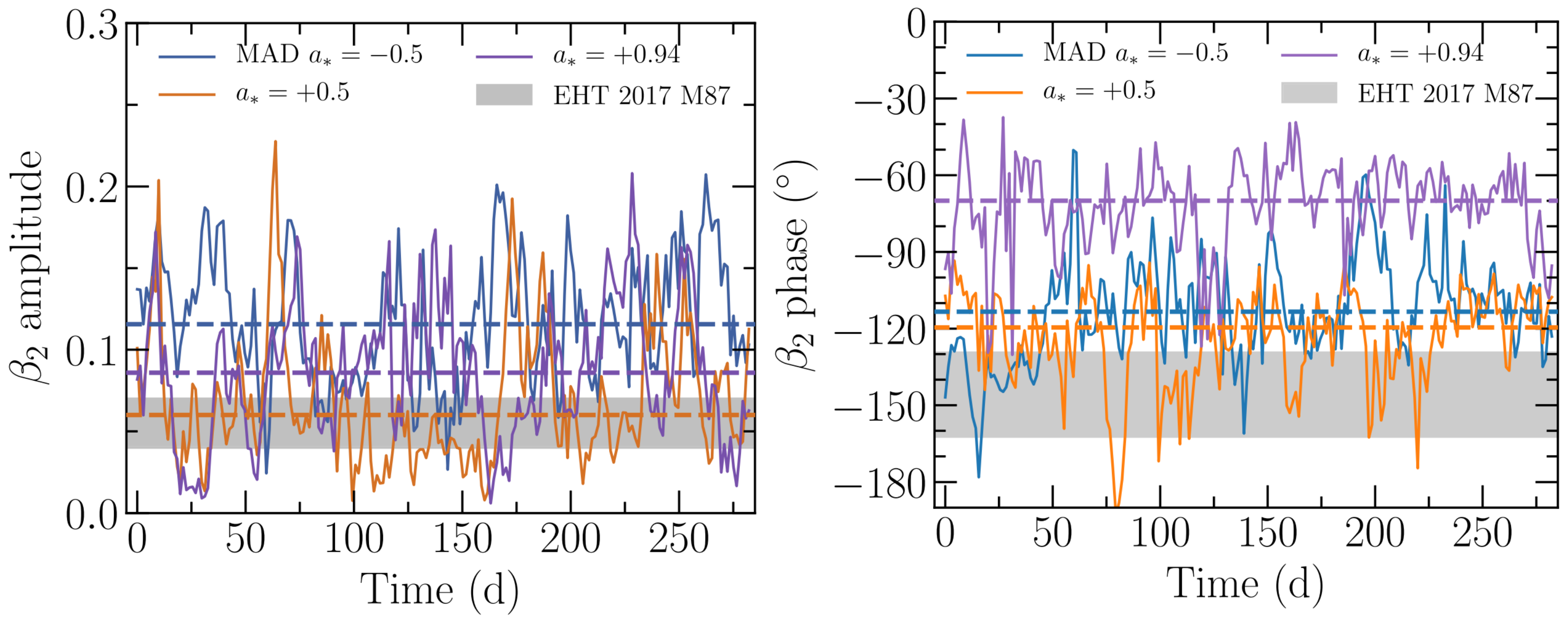
SANE

Fields in “SANE” simulations still have a helical jet, but the disk fields are relatively toroidal.

(both with spin a=0.94)
Image Credit: Angelo Ricarte

Polarization: Next Steps

A next step: Polarization is *variable*

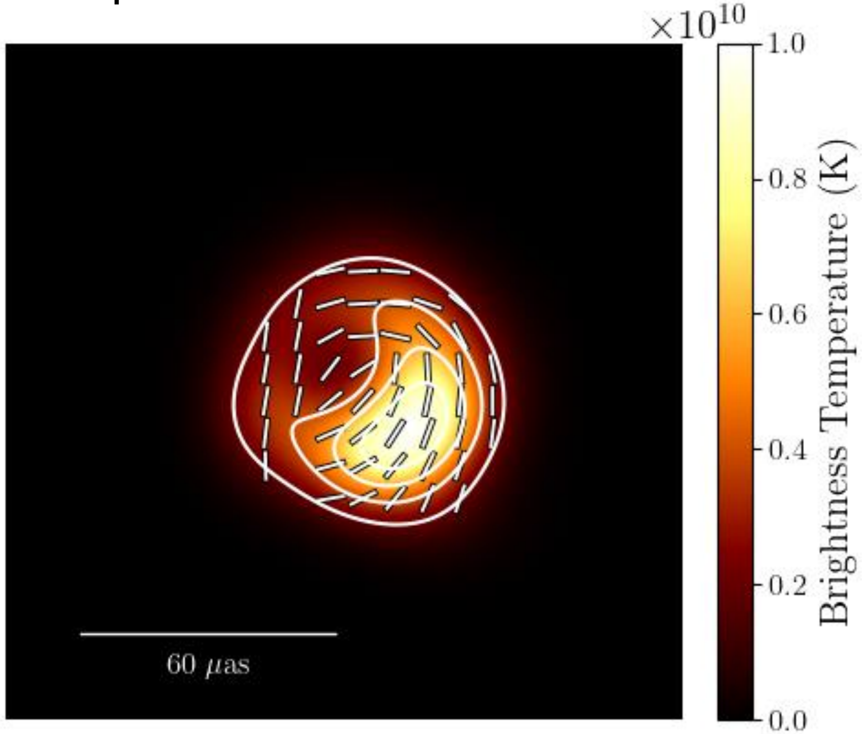


- If our picture is right, future EHT observations should see **strong variability on week-month timescales** in all our measured quantities
- More measurements should further tighten our constraints, and may require us to expand our space of models

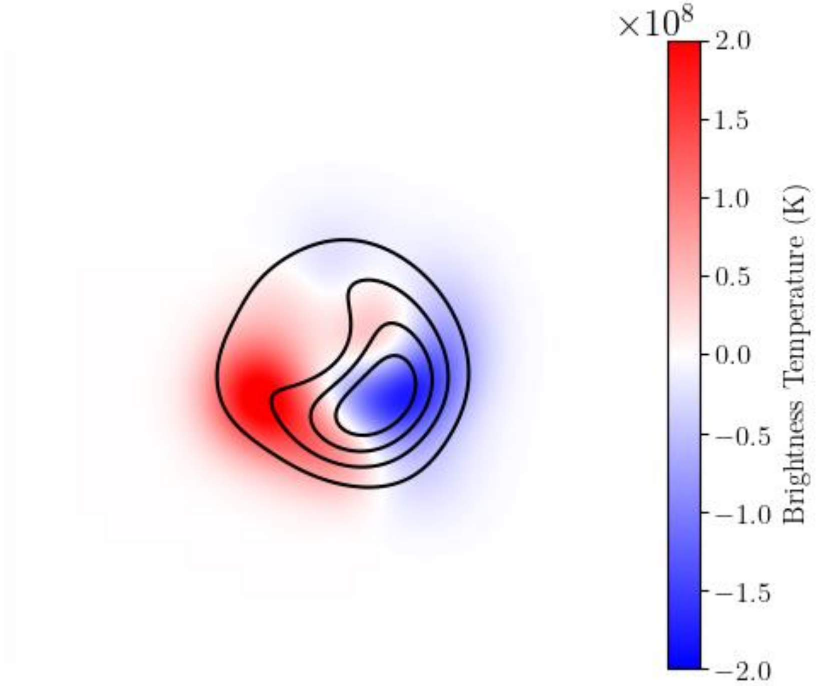
EHTC 2021, Paper VIII

A next step: Circular Polarization

Linear polarization

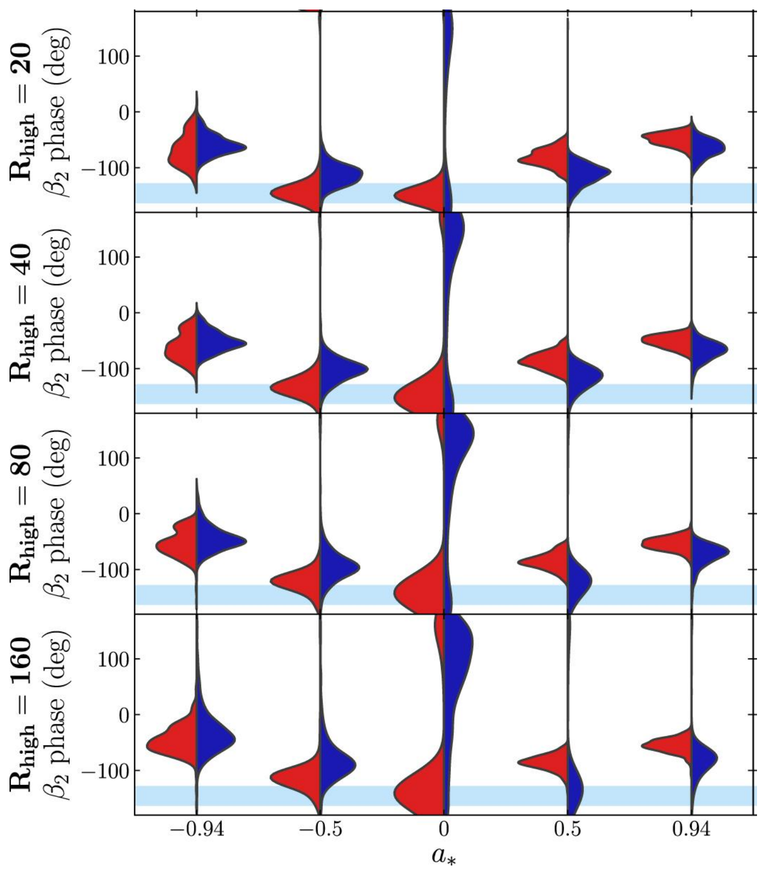


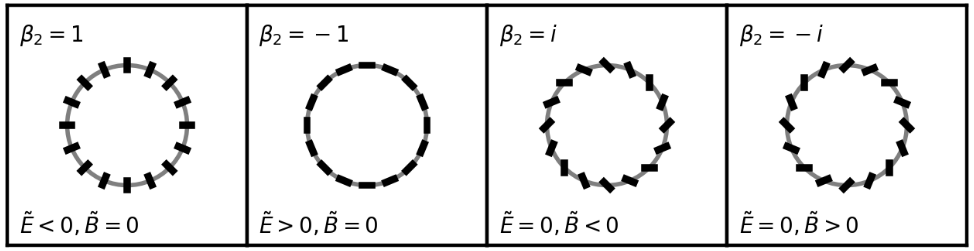
Circular polarization



- EHT data sensitive to linear and circular polarization
- Circular polarization in models can better constrain plasma properties, including particle composition
- Unfortunately, models predict very low circular polarization <~3% which may be beyond EHT’s current ability to image
- Stay tuned!

A next step: Understanding Spin Dependence





- In limited sample of MAD simulations, there seems to be a mild dependence of the β_2 phase with BH spin

- Is this intrinsic to something about the spacetime affecting the, B-field geometry or is it dependent on astrophysical details?

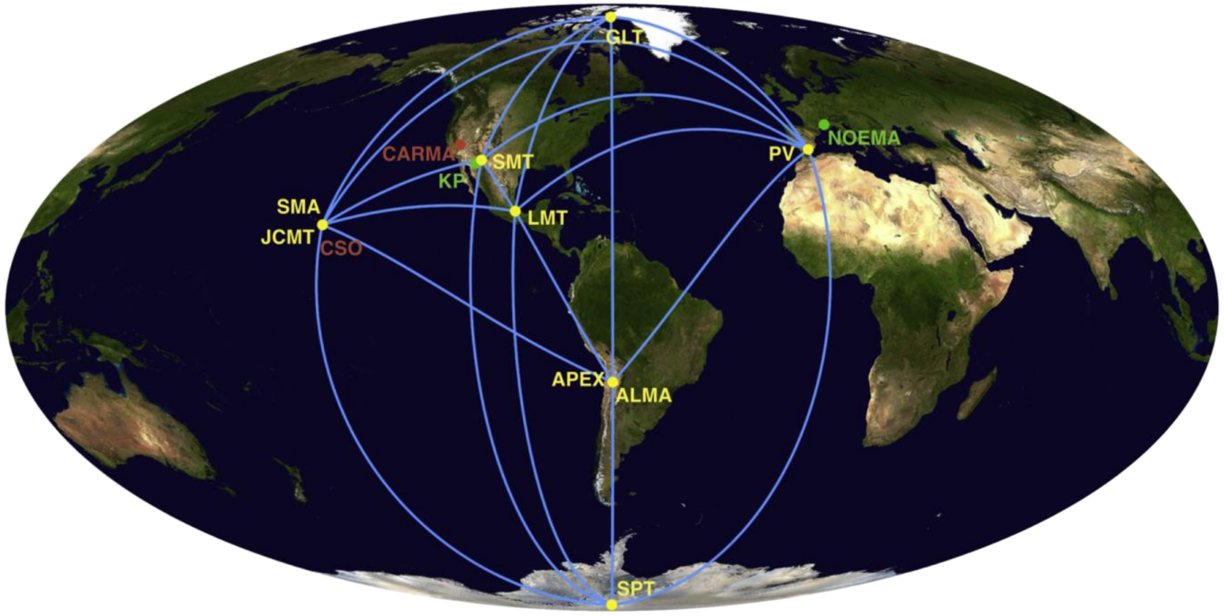
- Work in progress!

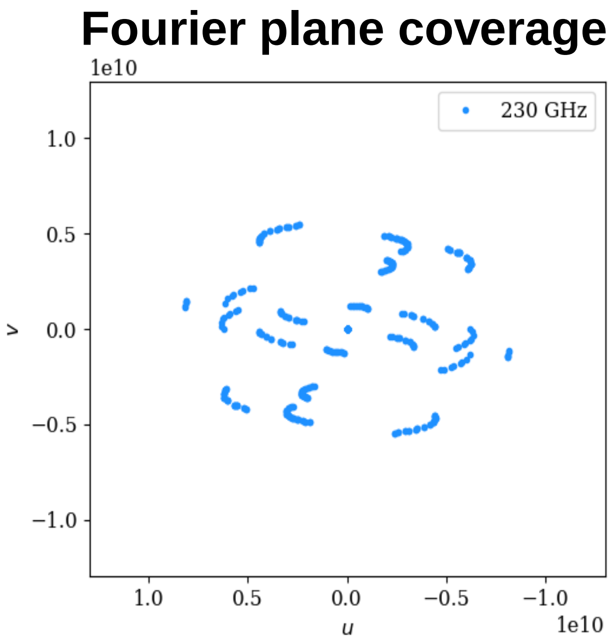
Palumbo, Wong, Prather 2020
EHTC+ VIII 2021

Part II:
What will we see in next-generation images?

Chael+ 2021
arXiv: 2106.00683

EHT observations in the last 5 years

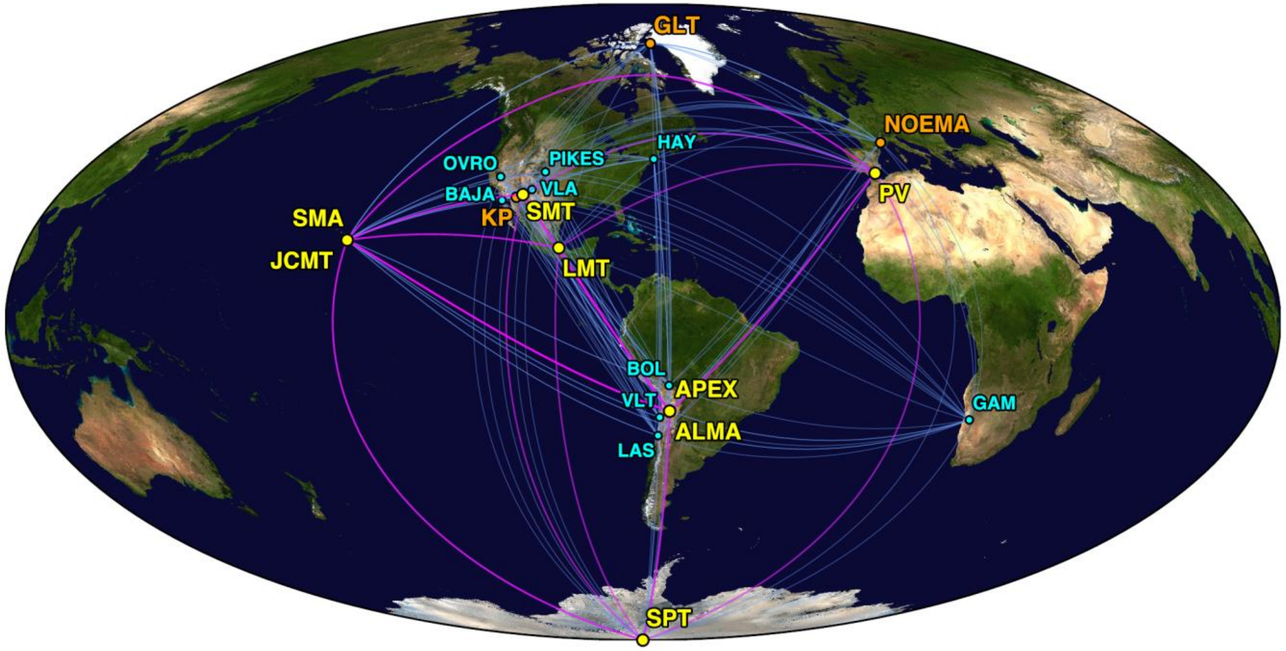



Fourier plane coverage

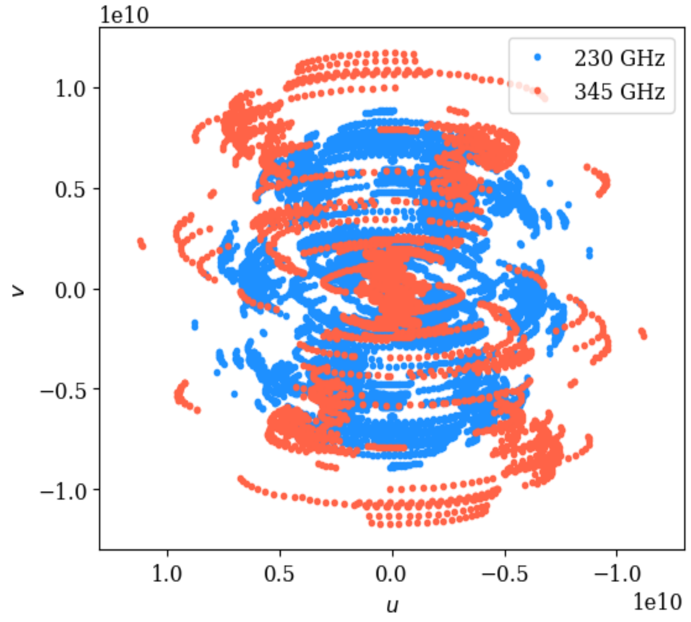
2017: Observations at 6 distinct sites
2018: Observations at 7 sites (+ GLT)
2019-2020: no observations
2021: Observations at 9 sites (+ Kitt Peak & NOEMA)

$$N_{\text{obs}} = \binom{N_{\text{sites}}}{2} \propto N_{\text{sites}}^2$$

A next-generation EHT (ngEHT)



Fourier plane coverage

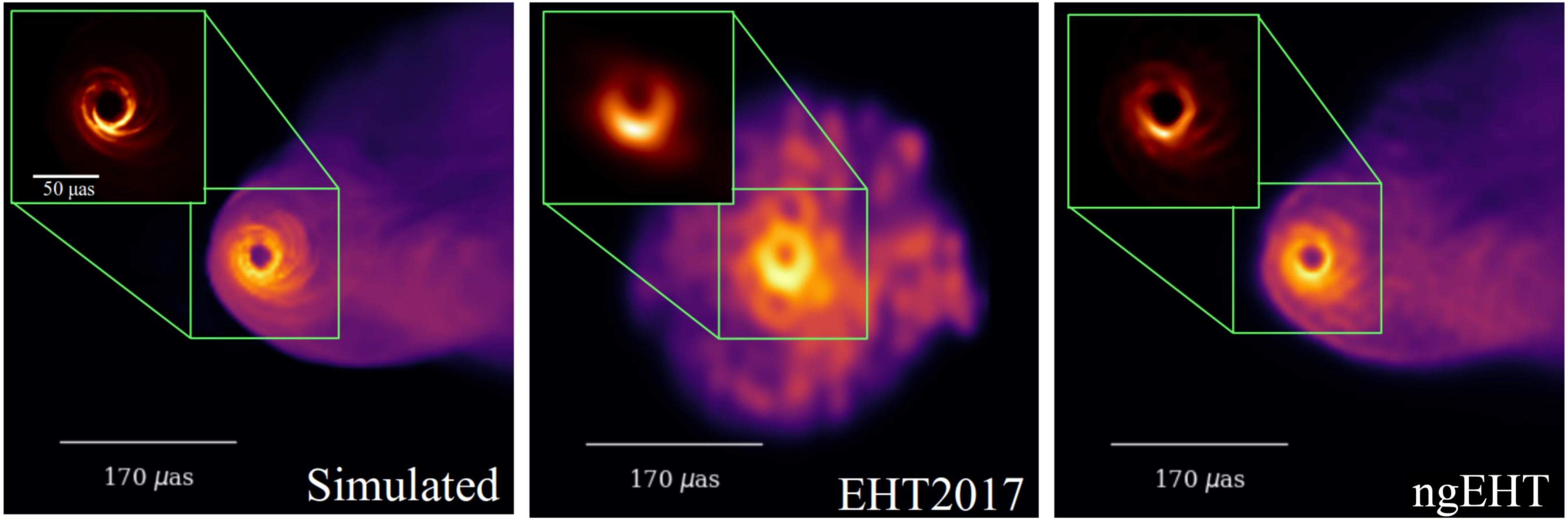


Adding 345 GHz will increase **resolution**

Increased (u,v) filling from new sites in ngEHT will enhance **dynamic range**

See the EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)

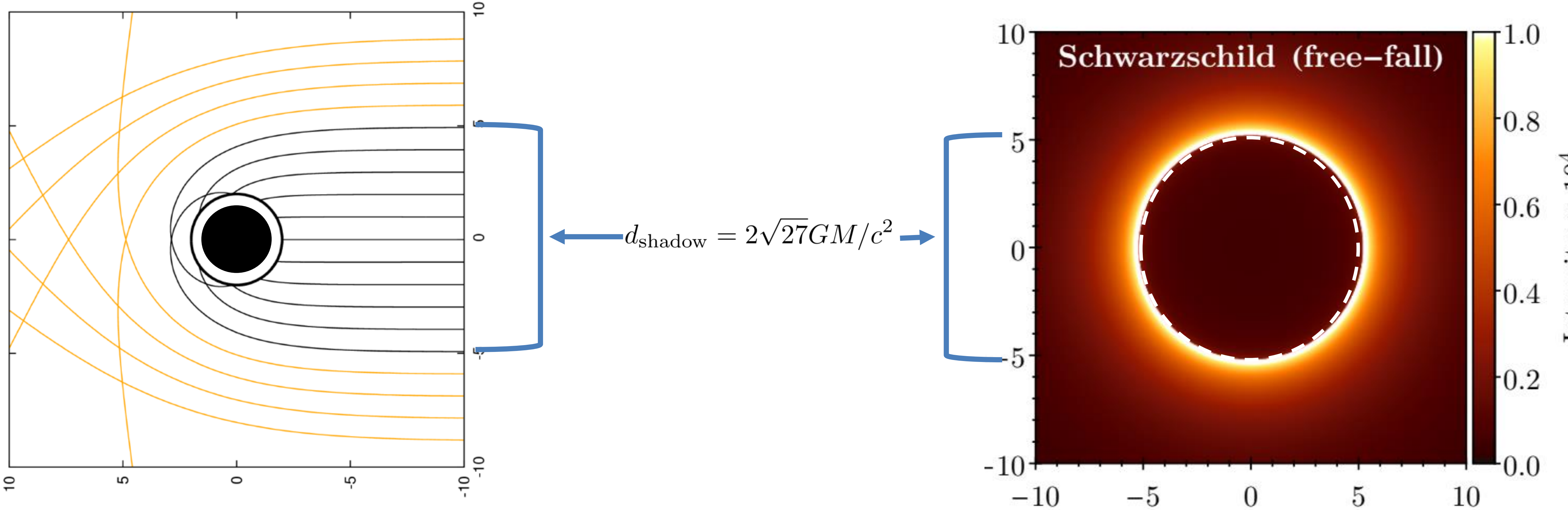
ngEHT: a high dynamic range black hole imager



- Increased (u,v) filling from new telescope sites in ngEHT will enhance image **dynamic range** from ~10 (EHT2017) to > 1000.
- High dynamic range images will illuminate the **BH-jet connection**
- High dynamic range images may also **reveal the 'inner shadow' feature**

See EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)
Simulation credit: Chael+ 2019

Black hole image formation: The Shadow

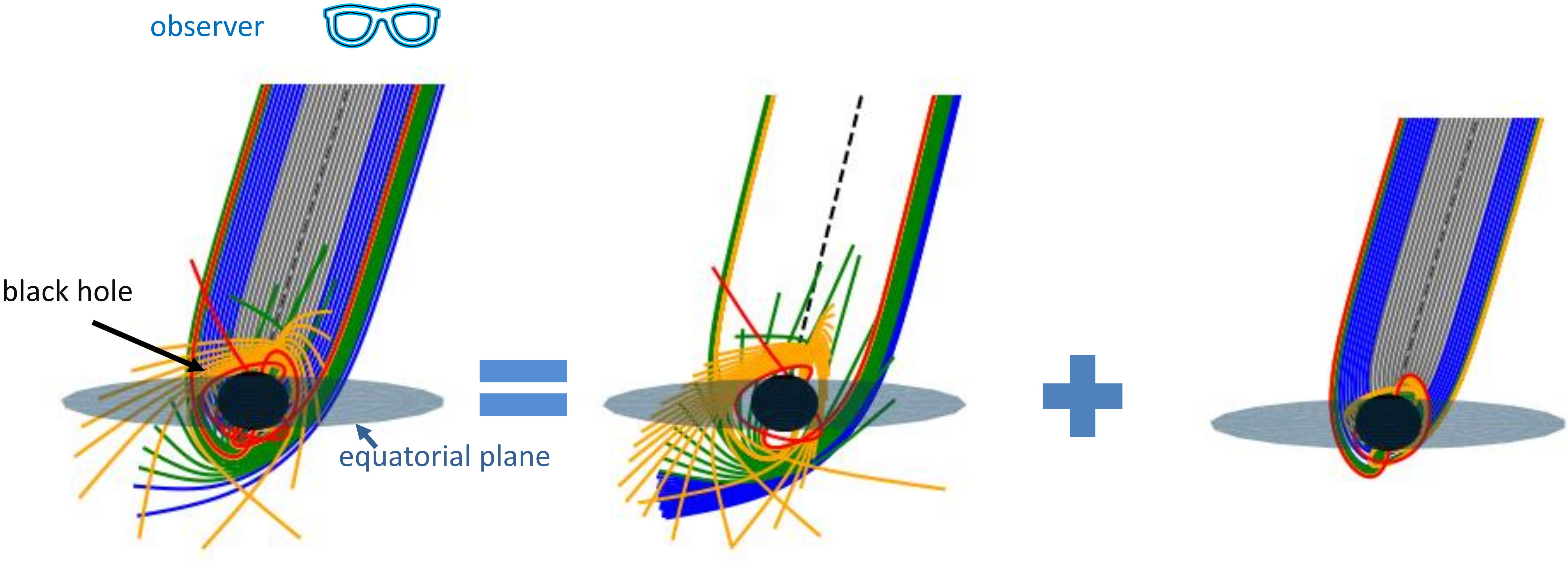


$$d_{\rm shadow} = 2\sqrt{27}GM/c^2$$

- The ‘critical curve’ on the image **separates of rays that end on the event horizon with those that escape to infinity**
- The interior of the critical curve is the ‘black hole shadow’, where all rays end on the horizon
- The shadow is prominent as an image feature when the emission is **spherically symmetric and optically thin**

Image credit: Keiichi Asada
Narayan+ 2019 (also Falcke+ 2000, many others)

Black hole image formation: The Shadow



all rays

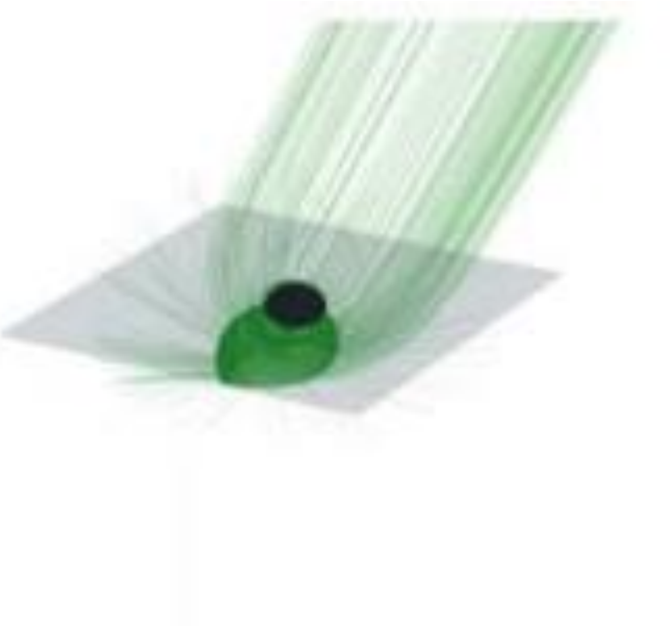
Rays that **escape to infinity**

Rays that **end up on the black hole (the shadow)**

Chael+ 2021, Levis+ 2022

Black hole image formation: Strong Lensing

These rays cross the equator **once**



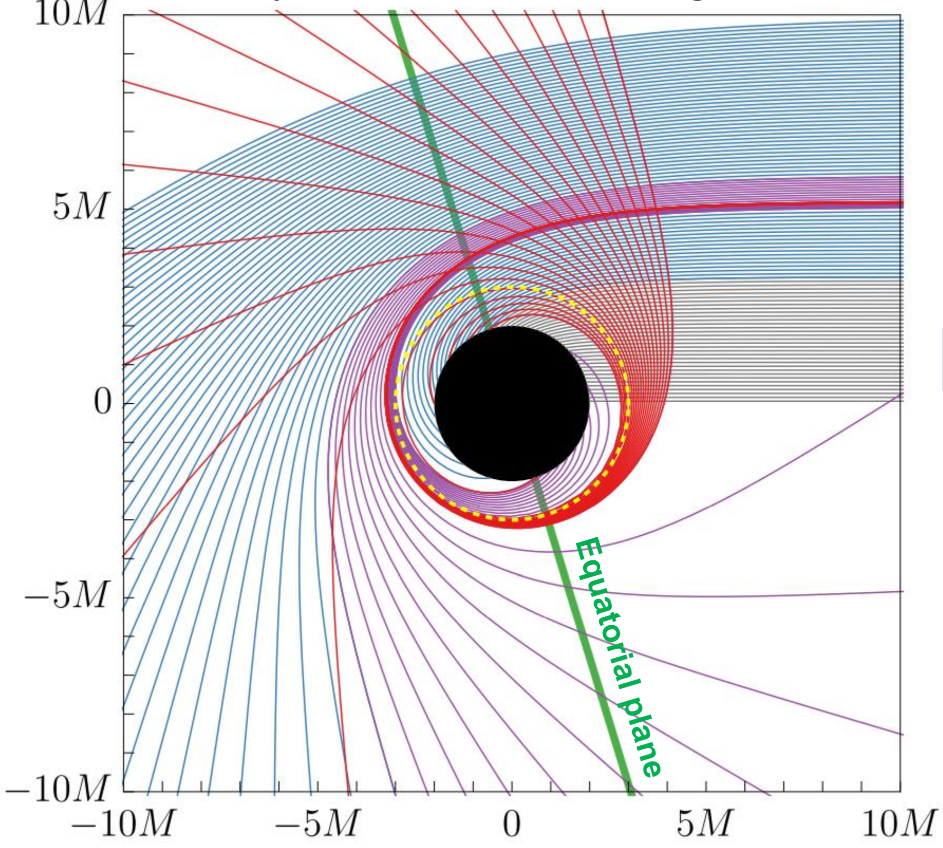
These rays cross the equator **twice**

These rays cross the equator **3x**

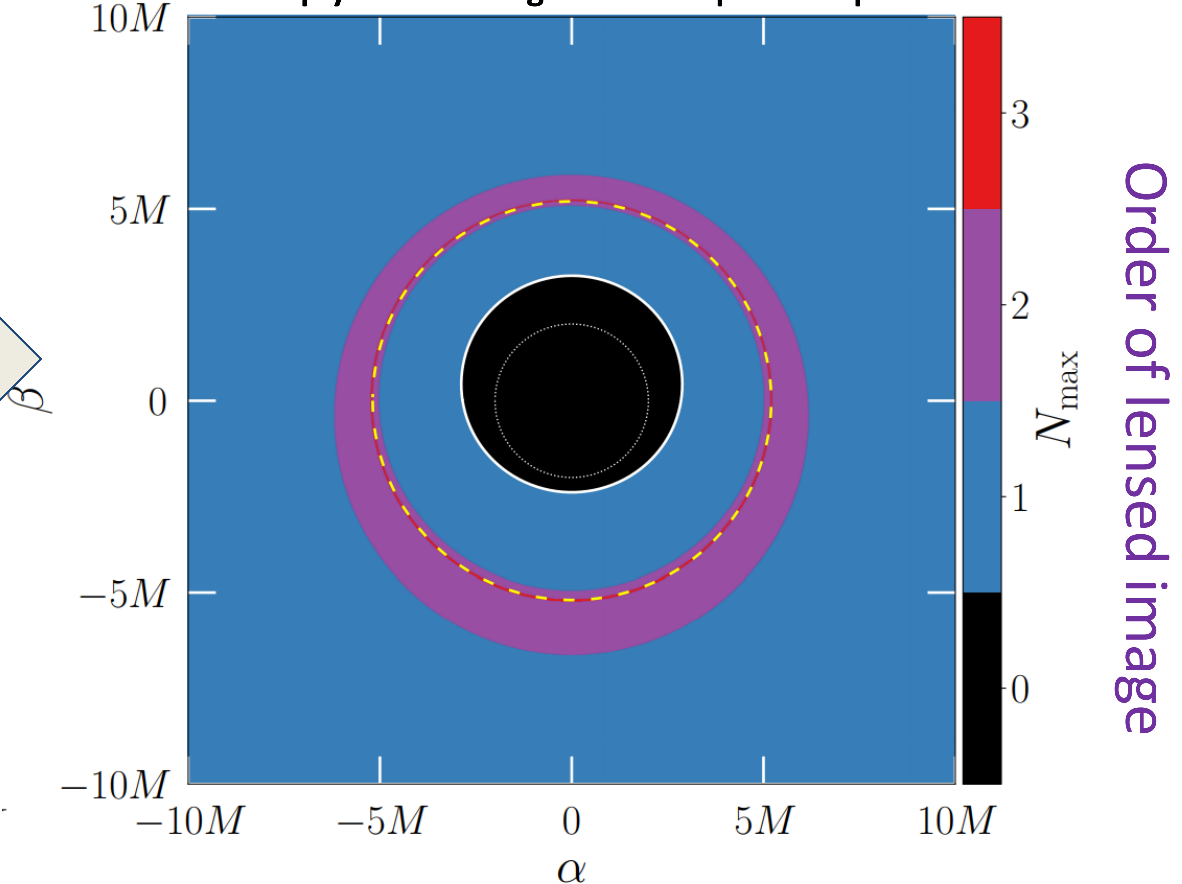
If **emission is concentrated** in the equatorial plane, we will see **multiple images**

Chael+ 2021, Levis+ 2022

Lensed images of the equatorial plane


Spin a=0, inclination i=17 deg

Observer plane


Multiply-lensed images of the equatorial plane

Multiply lensed images of the (optically thin) equatorial plane appear at the critical curve

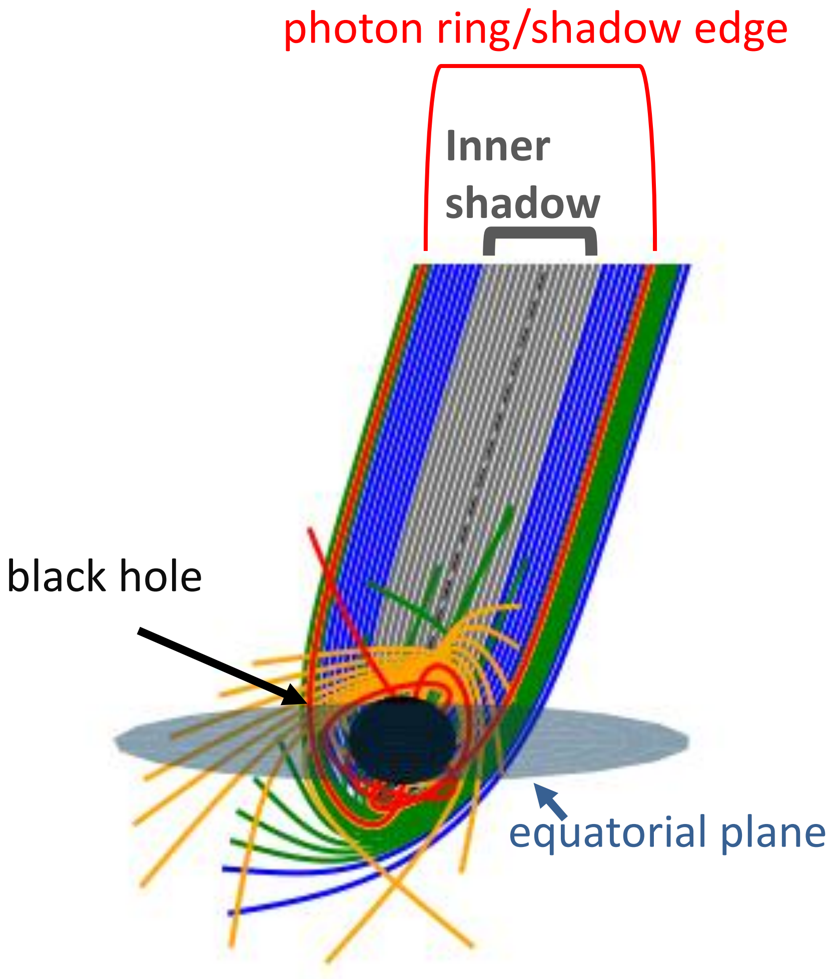
→ the brightest part of the image, or **‘photon ring’**

The direct (lensed) image of the horizon is formed by rays that never intersect the equator

→ the darkest part of the image, or **‘inner shadow’**

A. Chael, M. Johnson, A. Lupsasca
arXiv: 2106.00683
See also: Luminet 1979, Takahashi 2004, Gralla, Holz, Ward 2019, Dokuchaev 2019

Photon Rings and the Inner shadow



Gray rays – never cross the equatorial plane

- these form the **'inner shadow'**

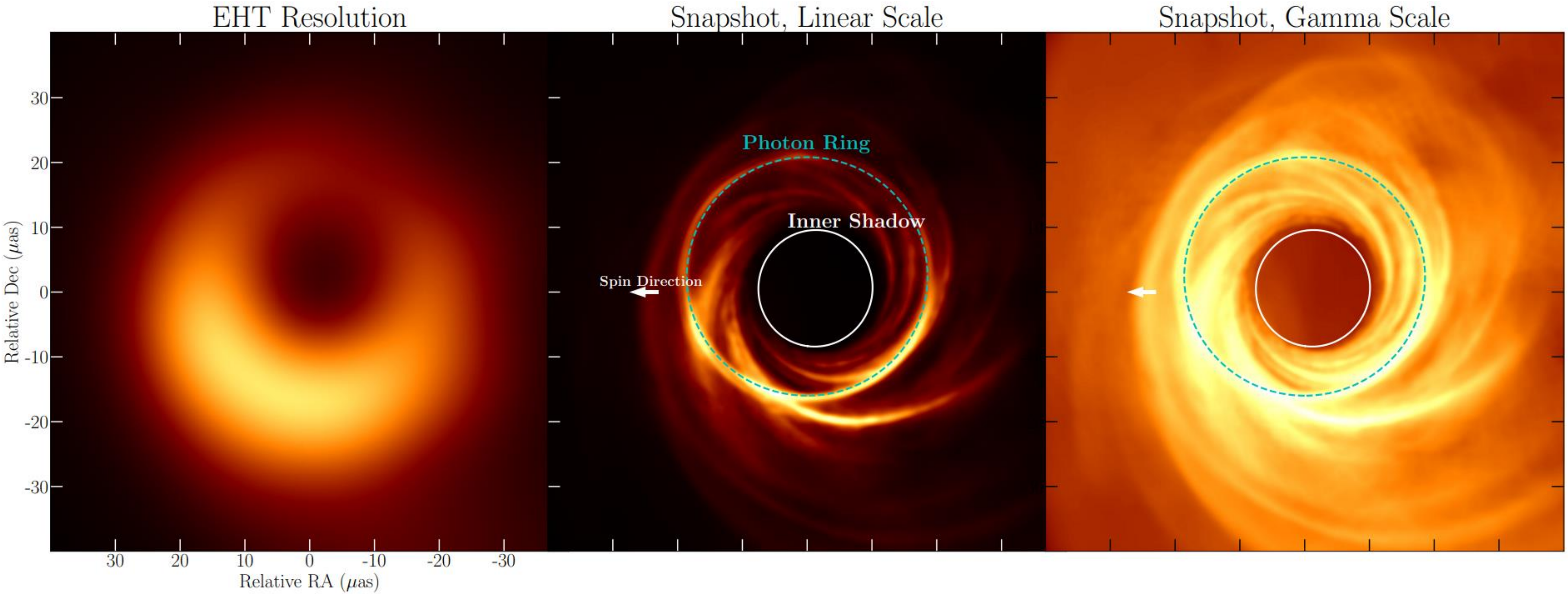
Blue rays – cross once (the direct image)

Green rays – cross twice (the first photon ring)

Orange rays – cross 3x (the second photon ring)

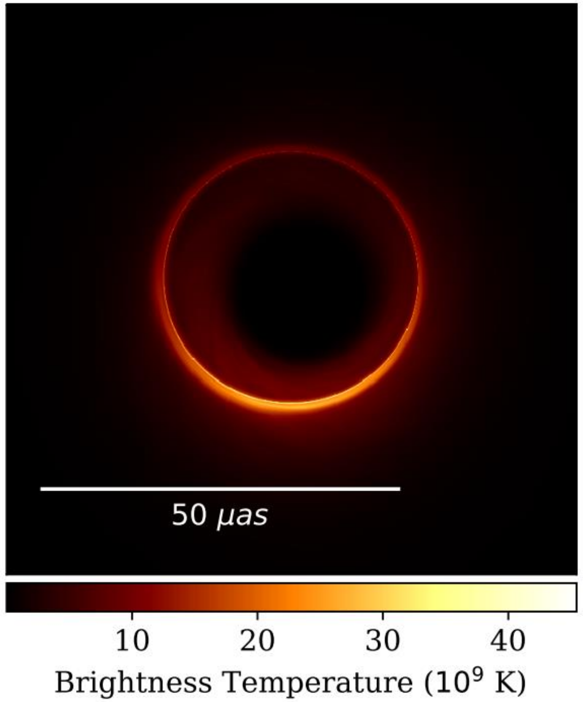
Red rays – cross 4x (the third photon ring)

Inner shadow in magnetically arrested simulation images

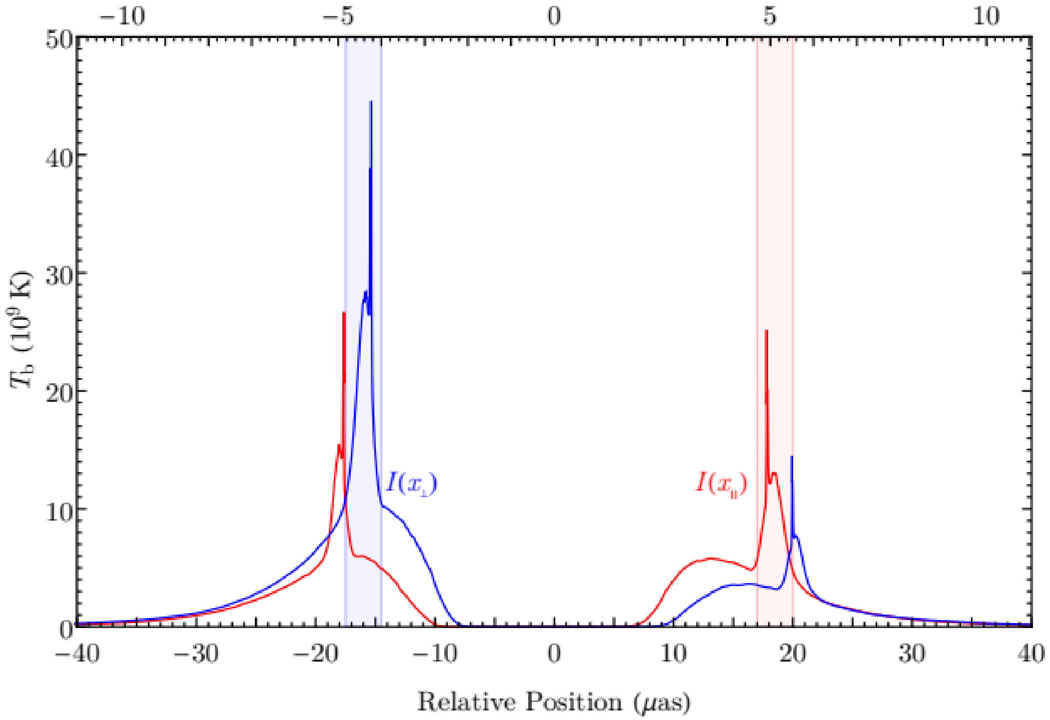


- The inner shadow is visible in simulations; its edge approaches the **lensed image of the equatorial event horizon**
- Infinite redshift at the horizon: the edge of the inner shadow only asymptotically approaches the horizon image
  → the correspondence becomes better with higher dynamic range images

Photon Rings



Time-averaged GRMHD

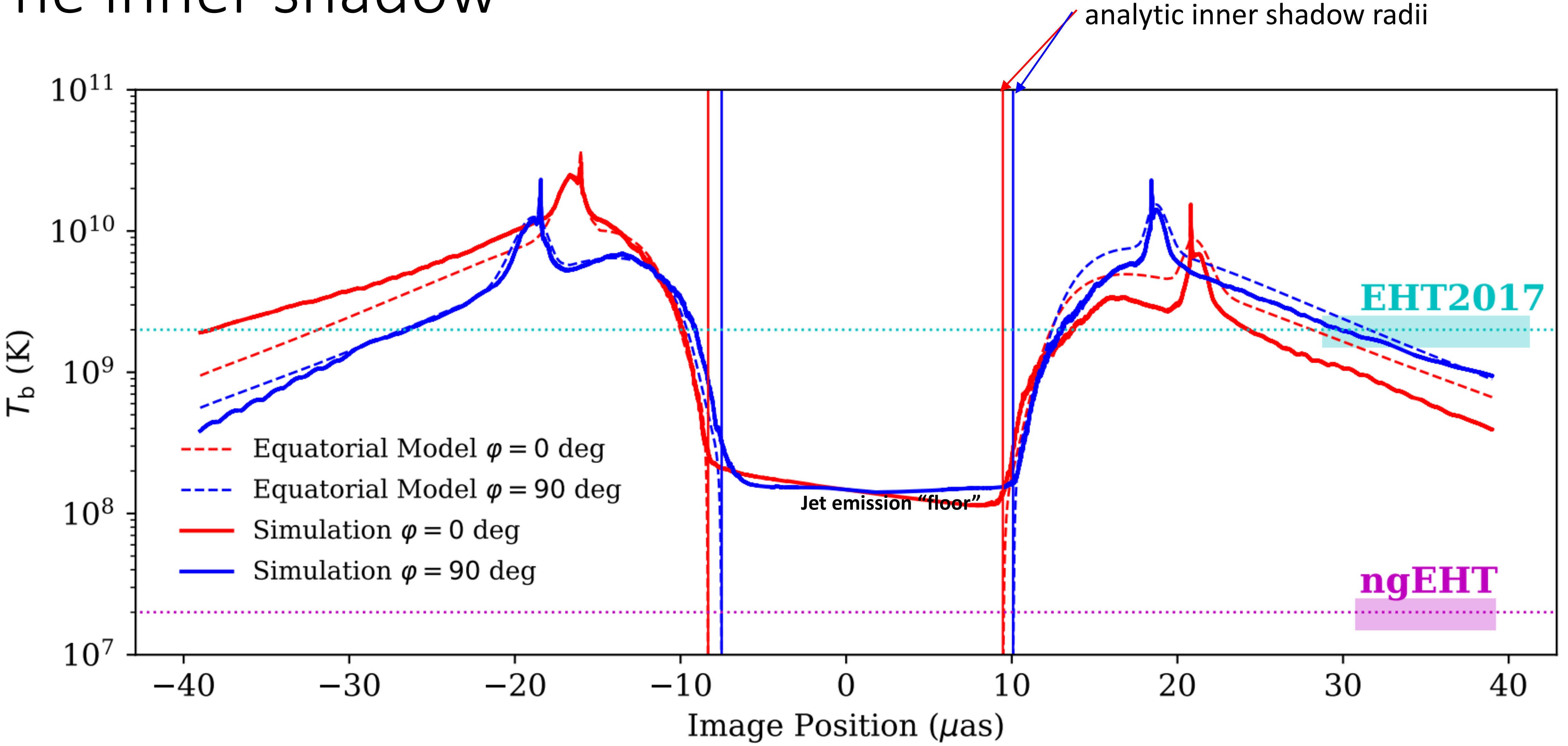


Angular slices (image)

- As geodesics wrap around the black hole multiple times, they form a **series of images** lensed into **increasingly narrow rings**
- These subrings approach the critical curve exponentially.
- Distinguishing the subrings requires a **spatially limited emission region** (e.g. emission confined to the equatorial plane)

Johnson+ 2019
Arxiv: 1907.04329

The inner shadow

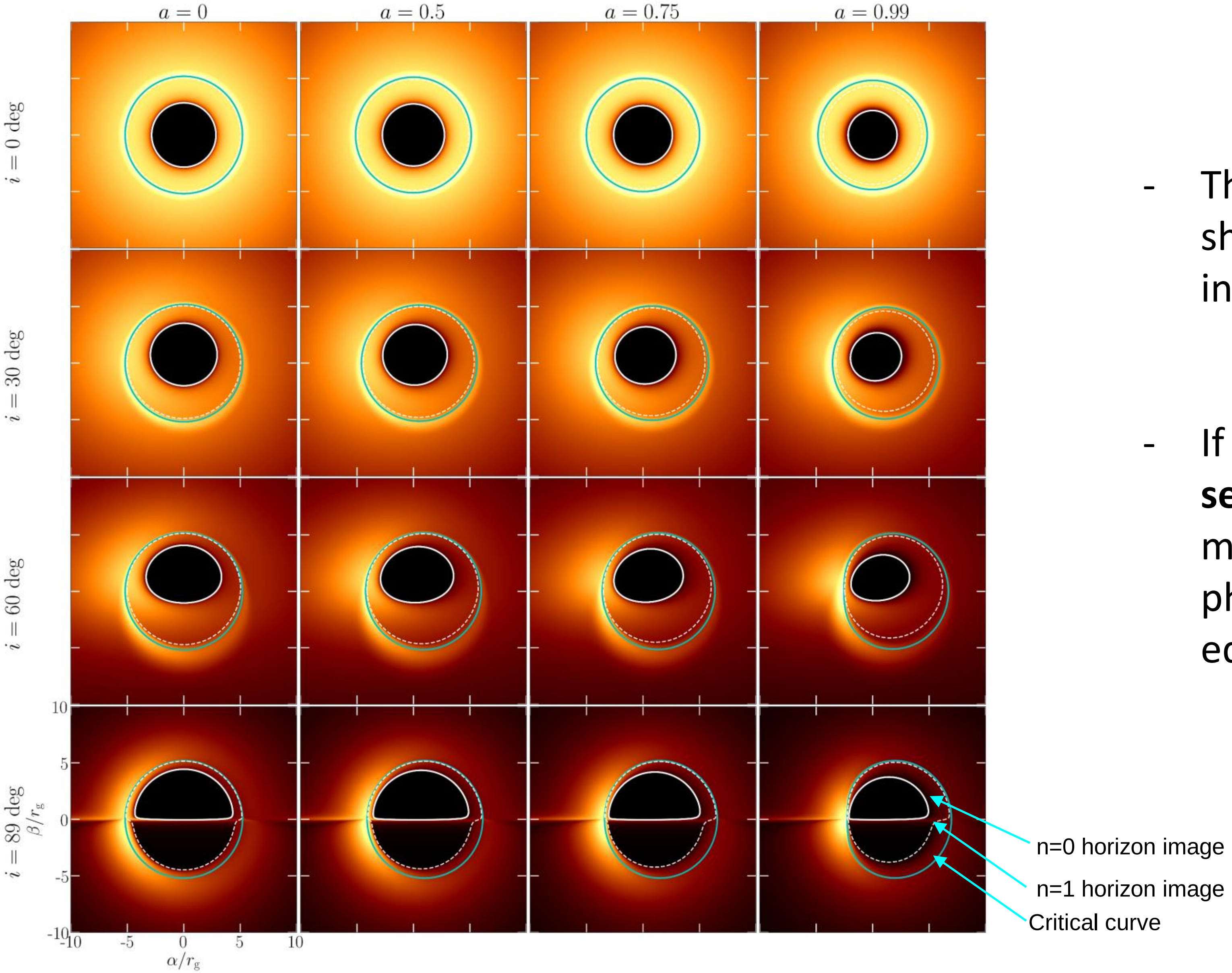

analytic inner shadow radii

Jet emission “floor”

- The inner shadow is visible in simulations; its edge approaches the **lensed image of the equatorial event horizon**
- Infinite redshift: the edge of the inner shadow only **asymptotically approaches** the horizon image

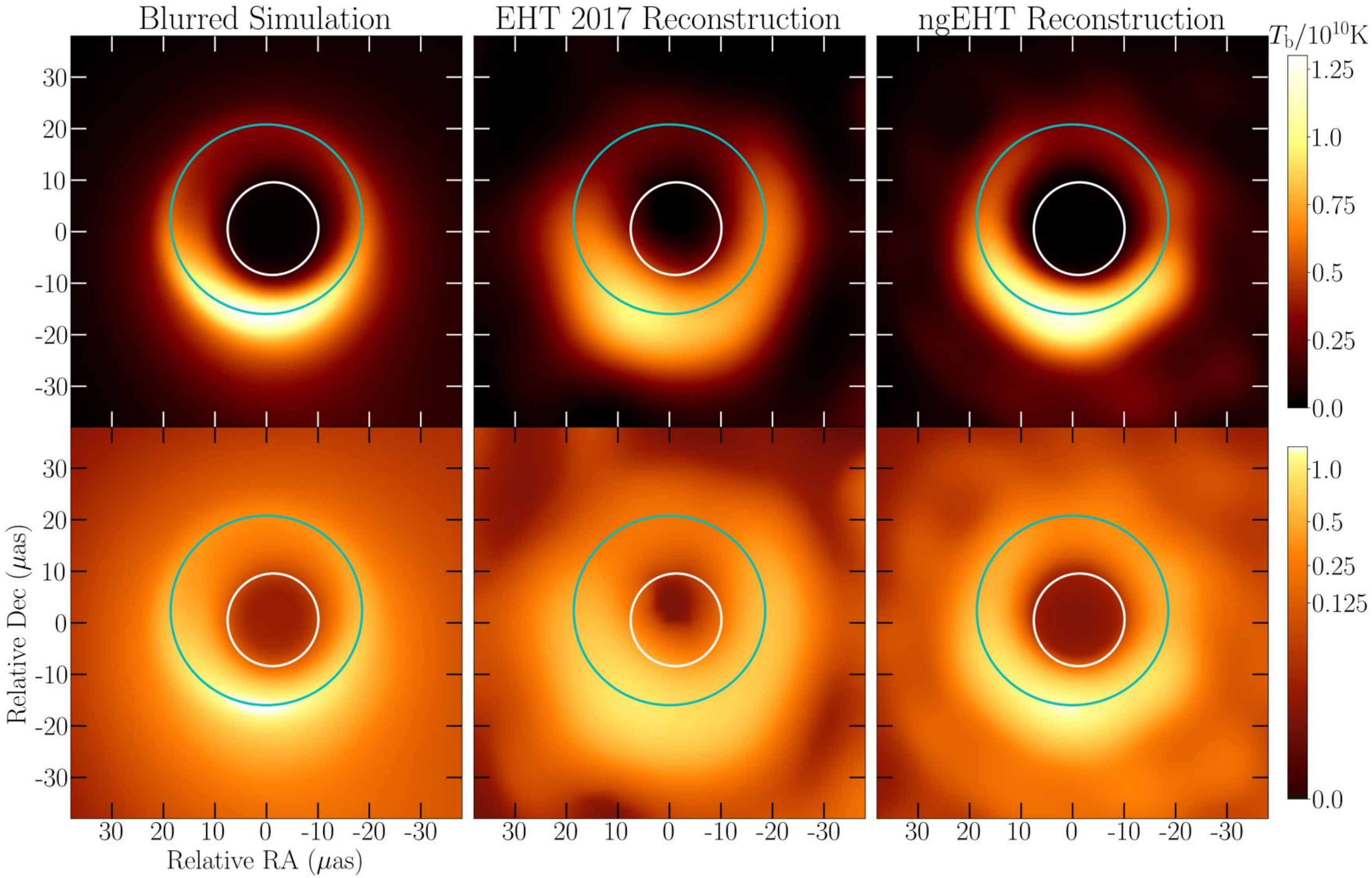
→ the correspondence becomes better with higher dynamic range

Inner shadow images provide another probe of spacetime



- The inner shadow changes in shape and size with spin and inclination
- If observable, it would provide a **second set of constraints** on the metric from observations of the photon ring / black hole shadow edge

EHT 2017 and ngEHT image reconstructions



Using eht-imaging software: https://github.com/achael/eht-imaging

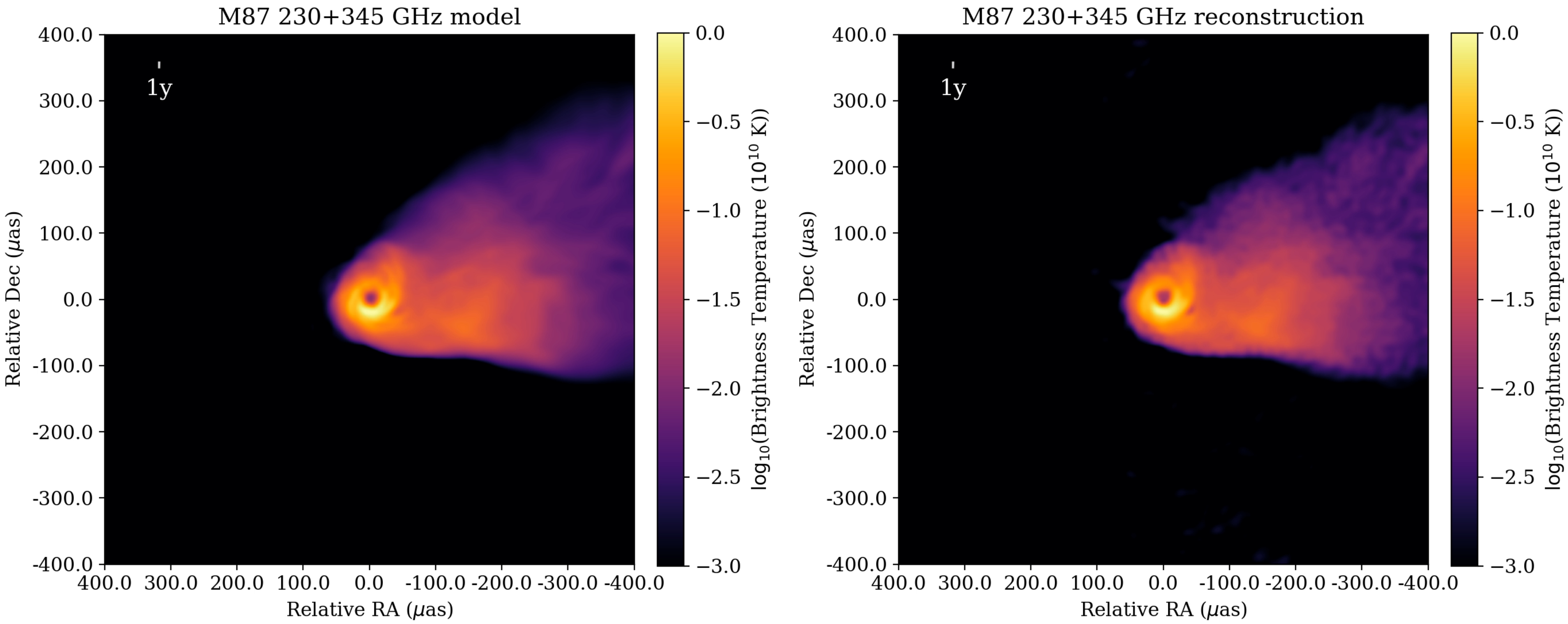
- ‘Realistic’ EHT imaging scripts using closure phases and amplitudes, but on the time-averaged image
- **Imaging algorithms can detect the inner shadow in ngEHT data** – analytic modeling may constrain its shape more precisely

Conclusion:

The future of BH imaging is bright

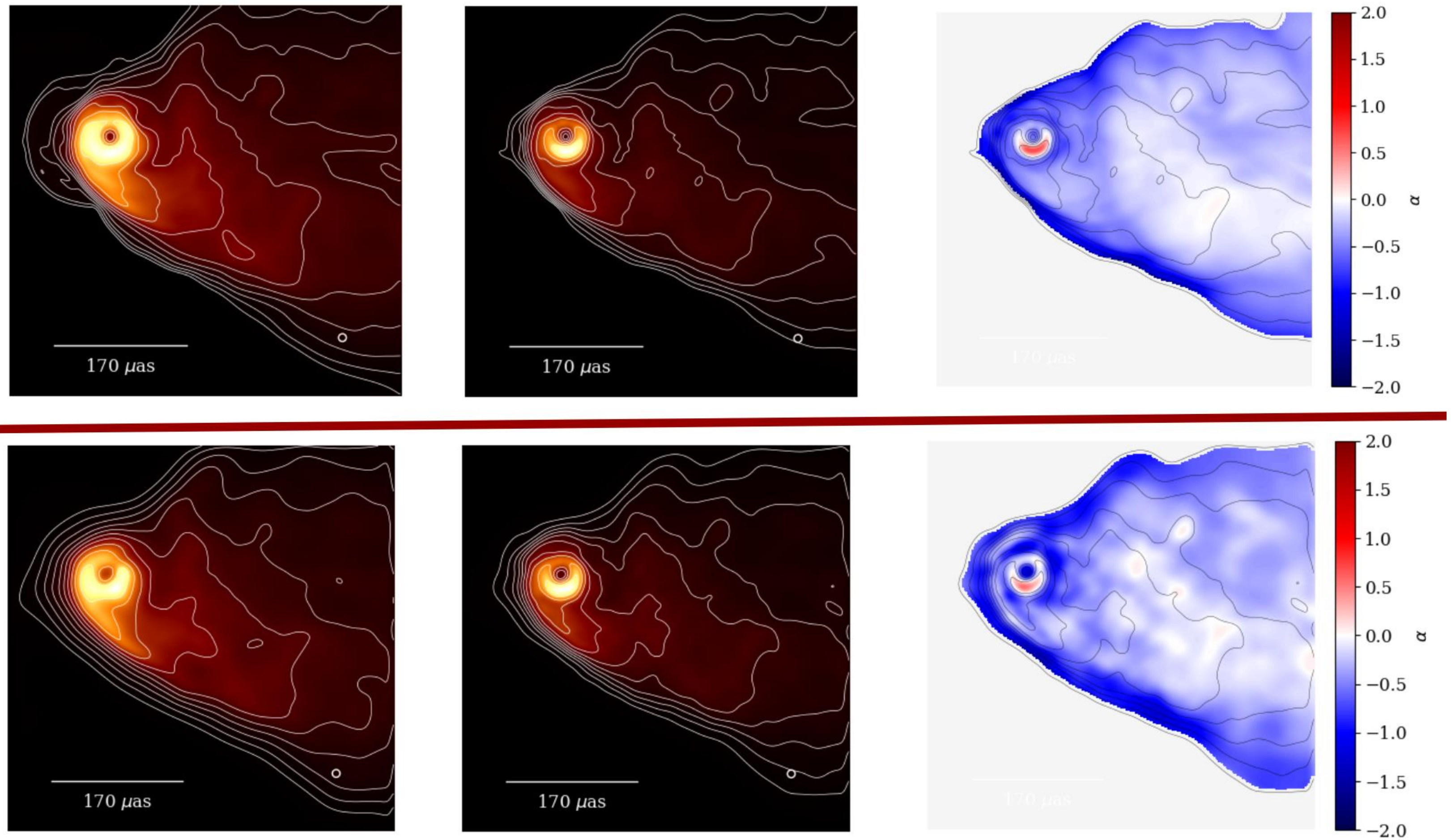
Chael+ 2021
arXiv: 2106.00683

ngEHT jet monitoring



Slide credit: Lindy Blackburn, Andrew Chael

Multifrequency BH Imaging with the ngEHT



86GHz

230GHz

Spectral index

Simulation

$$\log I_i\left(\vec{\theta}\right) = \log\left[I_0(\vec{\theta})\right] + \alpha(\vec{\theta})\log\left(\frac{\nu_i}{\nu_0}\right)$$

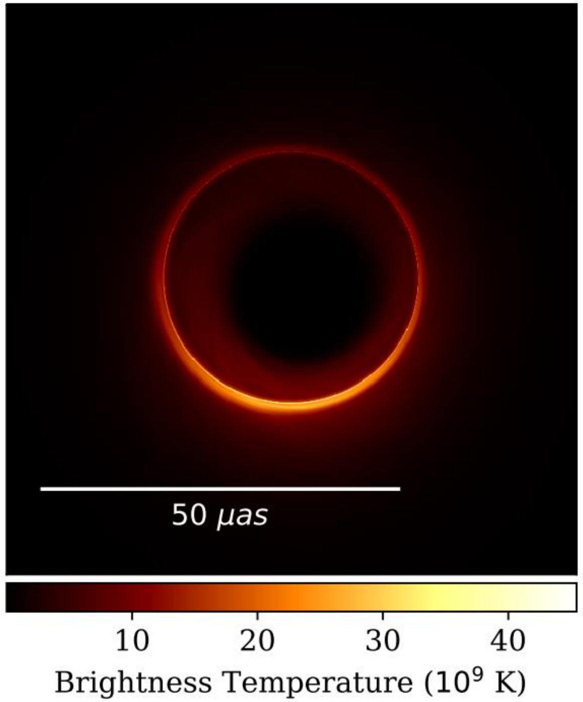
Simulated ngEHT image using **multifrequency synthesis**

Using eht-imaging software: https://github.com/achael/eht-imaging

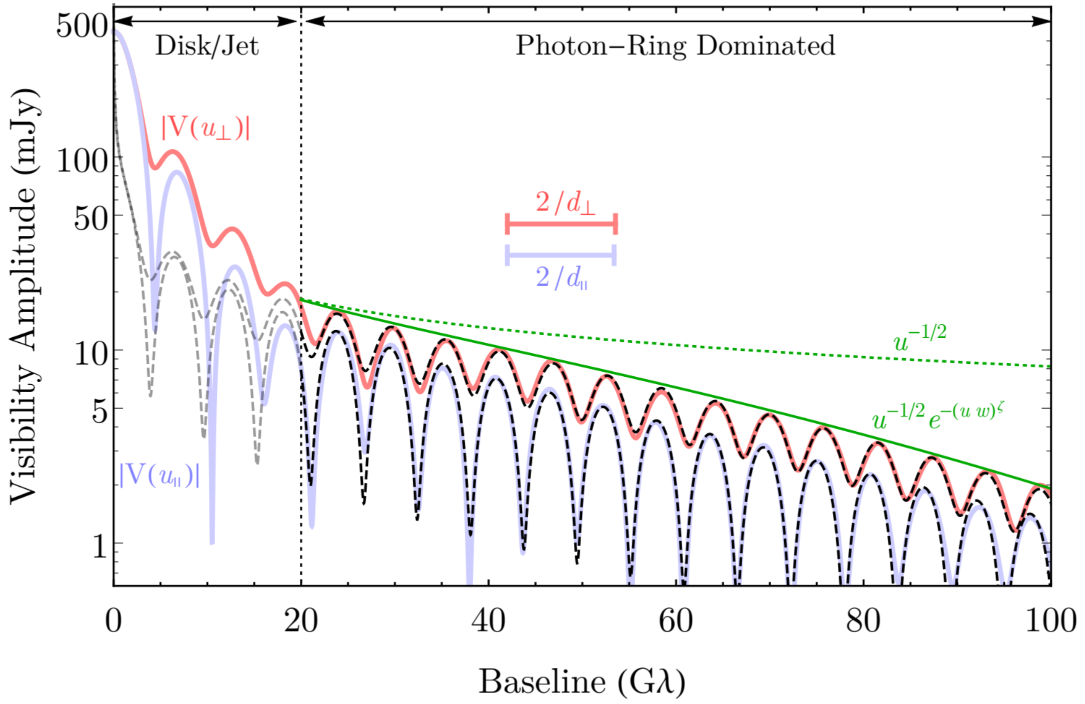
Chael+ 2022, arxiv 2210.12226

Space VLBI

Time-averaged GRMHD



Angular slices (visibility)



- A VLBI experiment with extremely long baselines (e.g. to space) could directly detect & measure the photon rings
- Even with earth-limited baselines, we might tease the photon rings out directly with sophisticated modeling

Johnson+ 2019
Arxiv: 1907.04329

Summary

1. What do polarized images of M87* tell us about the magnetic fields near the supermassive black hole?

A: Magnetic fields in M87* are strong and dynamically important:
the accretion flow is **magnetically arrested**

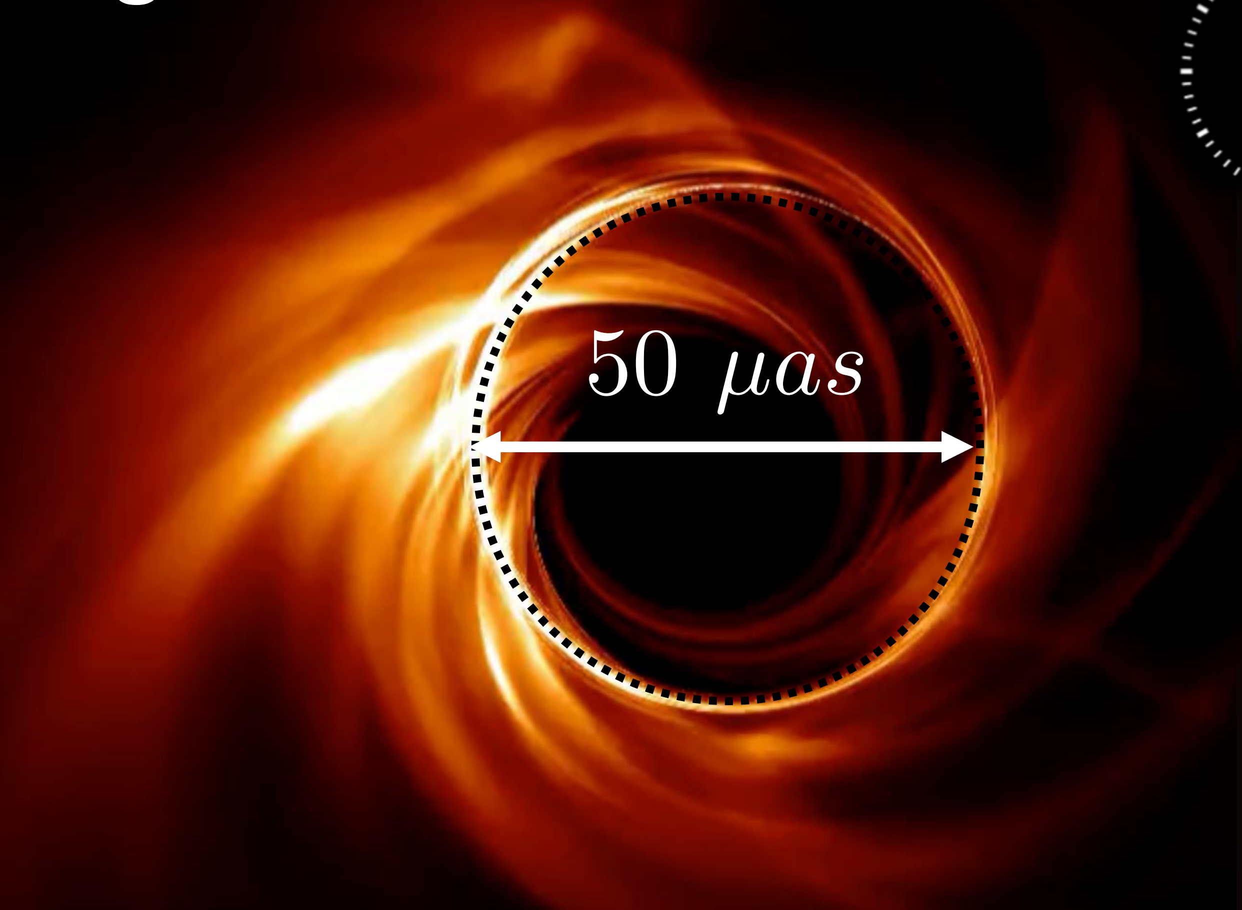
2. What might we see in M87* with a next-generation EHT array?

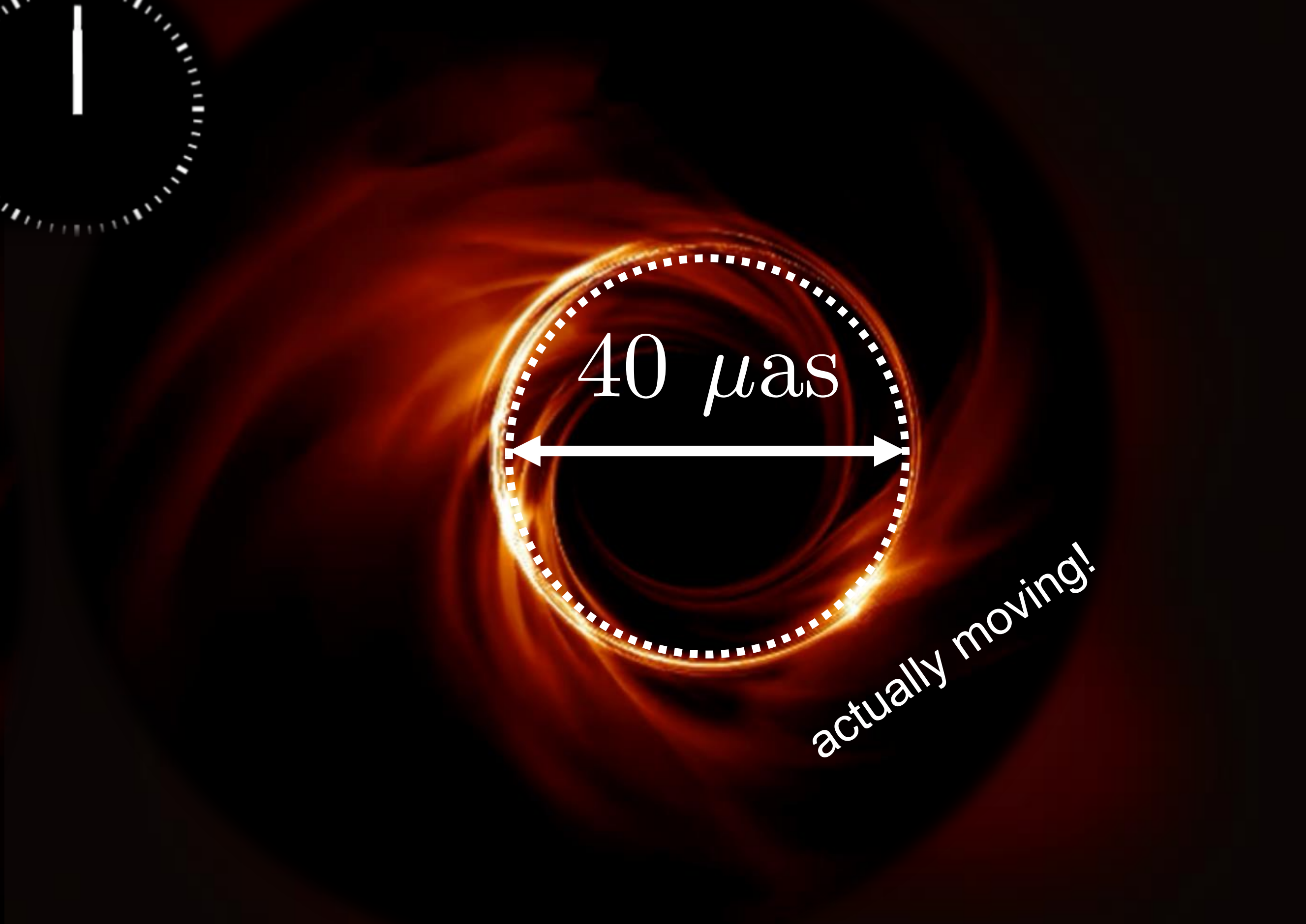
A: an “inner shadow” closely tracing the lensed event horizon and a direct
view of supermassive BH jet launching

Thank you!

Slide Credit: Katie Bouman / Calte
Simulation Credit: Abhishek Joshi

SgrA* vs M87*





Sagittarius A* (Sgr A*)

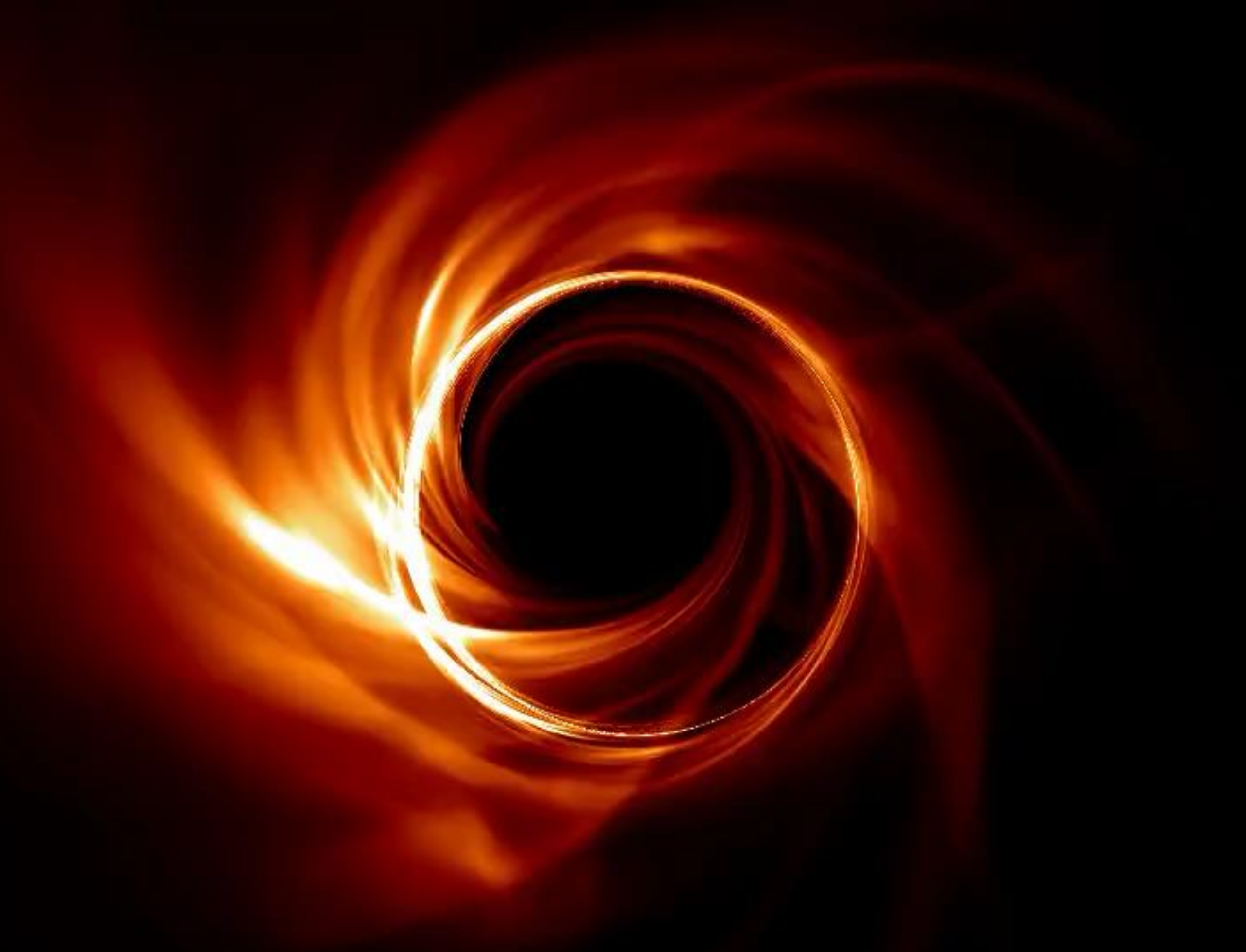
→ 27 thousand light year away
→ Smaller Than Mercury’s Orbit
→ 4-30 minutes for Gas to Orbit

M87*

→ 55 million light years away
→ Larger than Pluto’s Orbit
→ 4-30 days for Gas to Orbit

Slide Credit: Katie Bouman / Calte
Simulation Credit: Abhishek Joshi

SgrA* vs M87*



Simulation of Sgr A*

Measurements Taken
As Earth Rotates