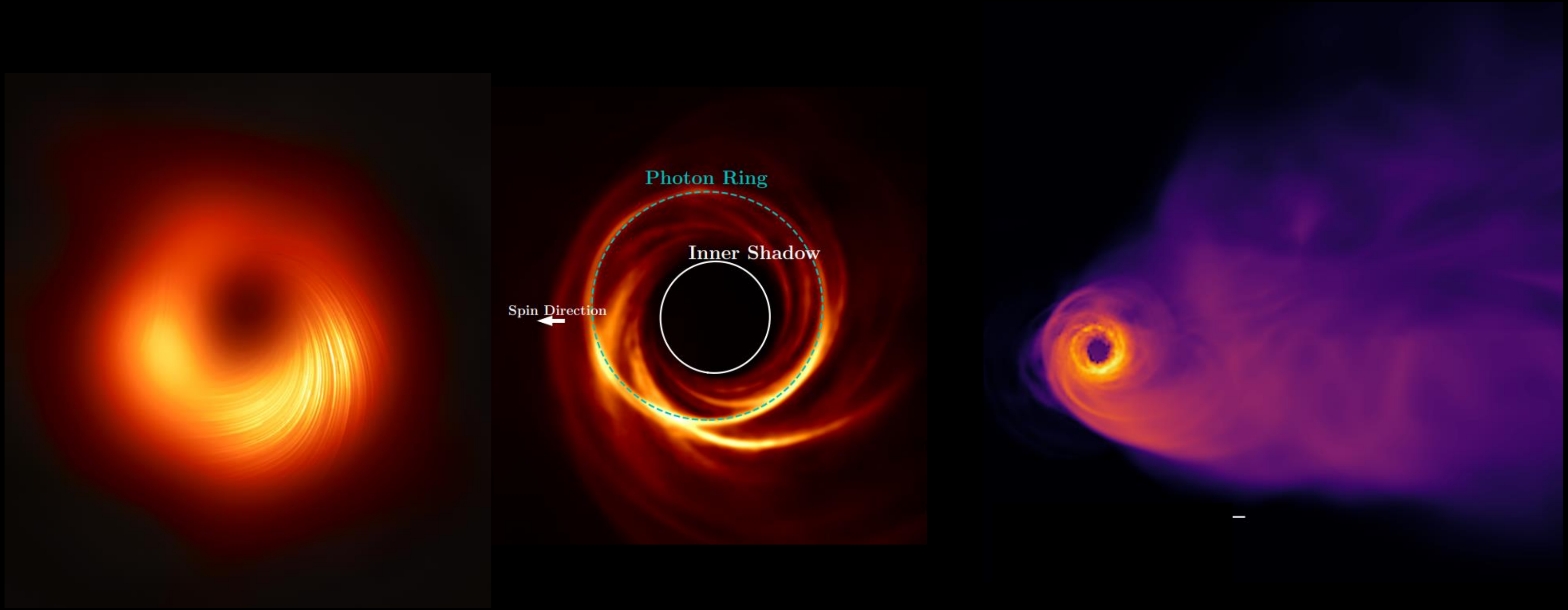
Horizon-scale images of black hole accretion and jet launching

Andrew Chael

Princeton Gravity Initiative

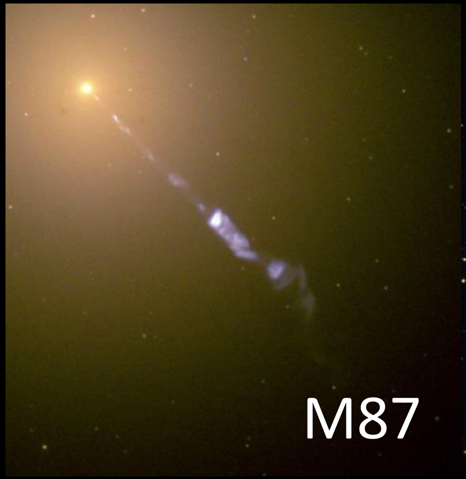
02/22/2023



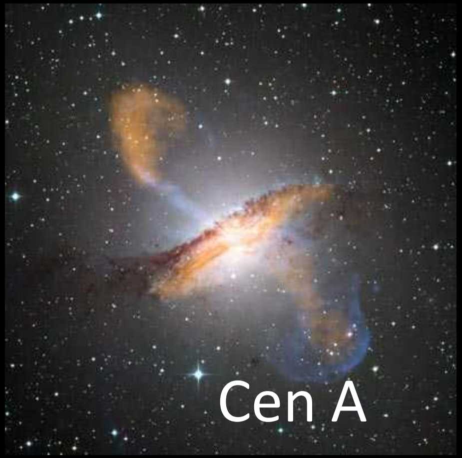
Princeton gravity Initiative

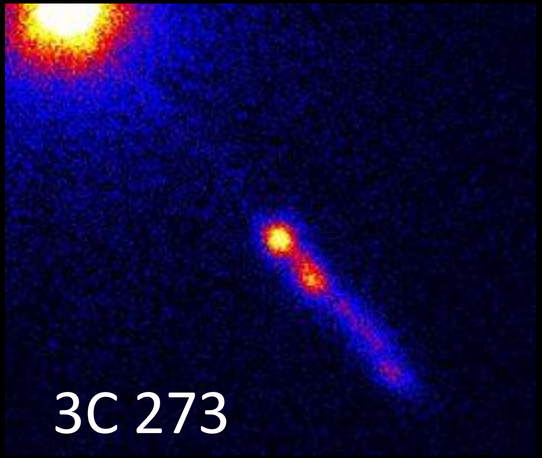
Event Horizon Telescope

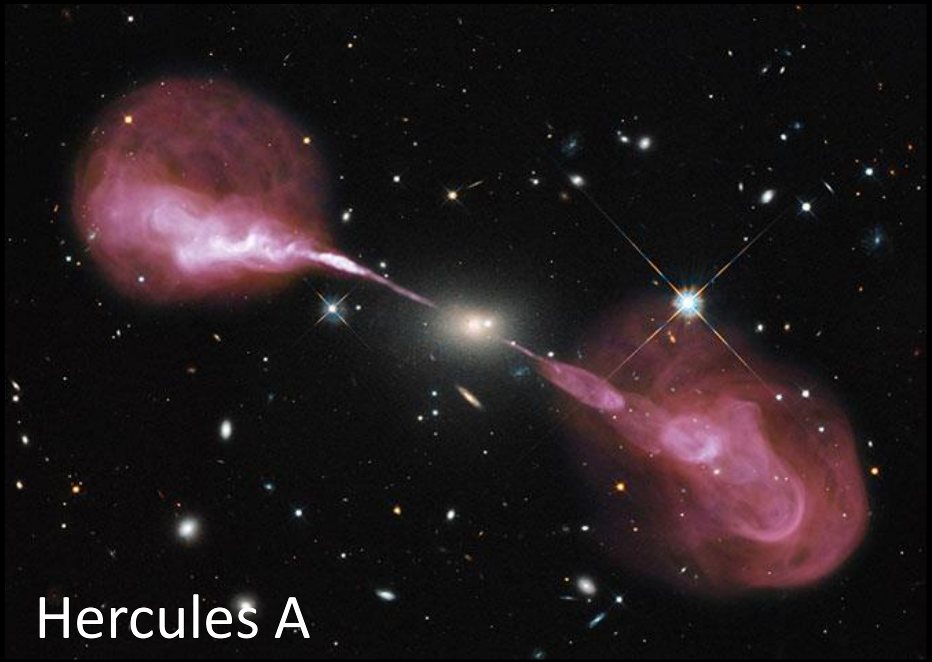
Supermassive black holes (and jets) are everywhere


M87


Cyg A

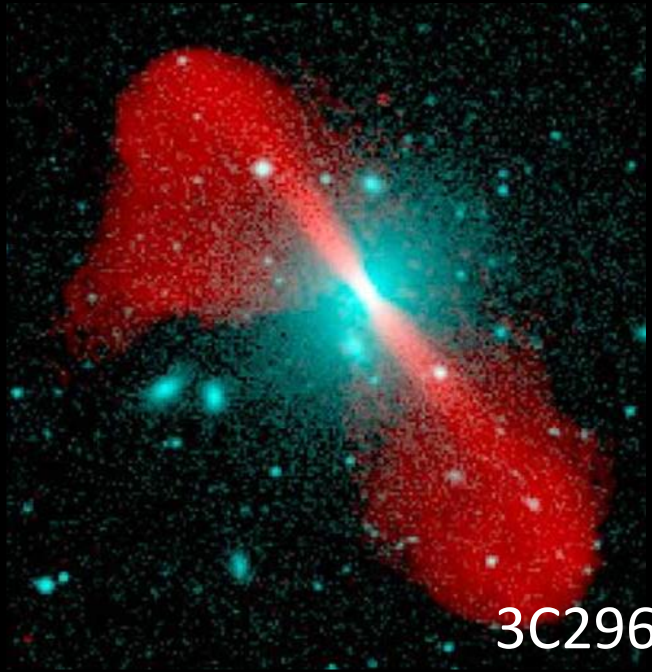

Cen A


3C 273


Hercules A


NGC 1265

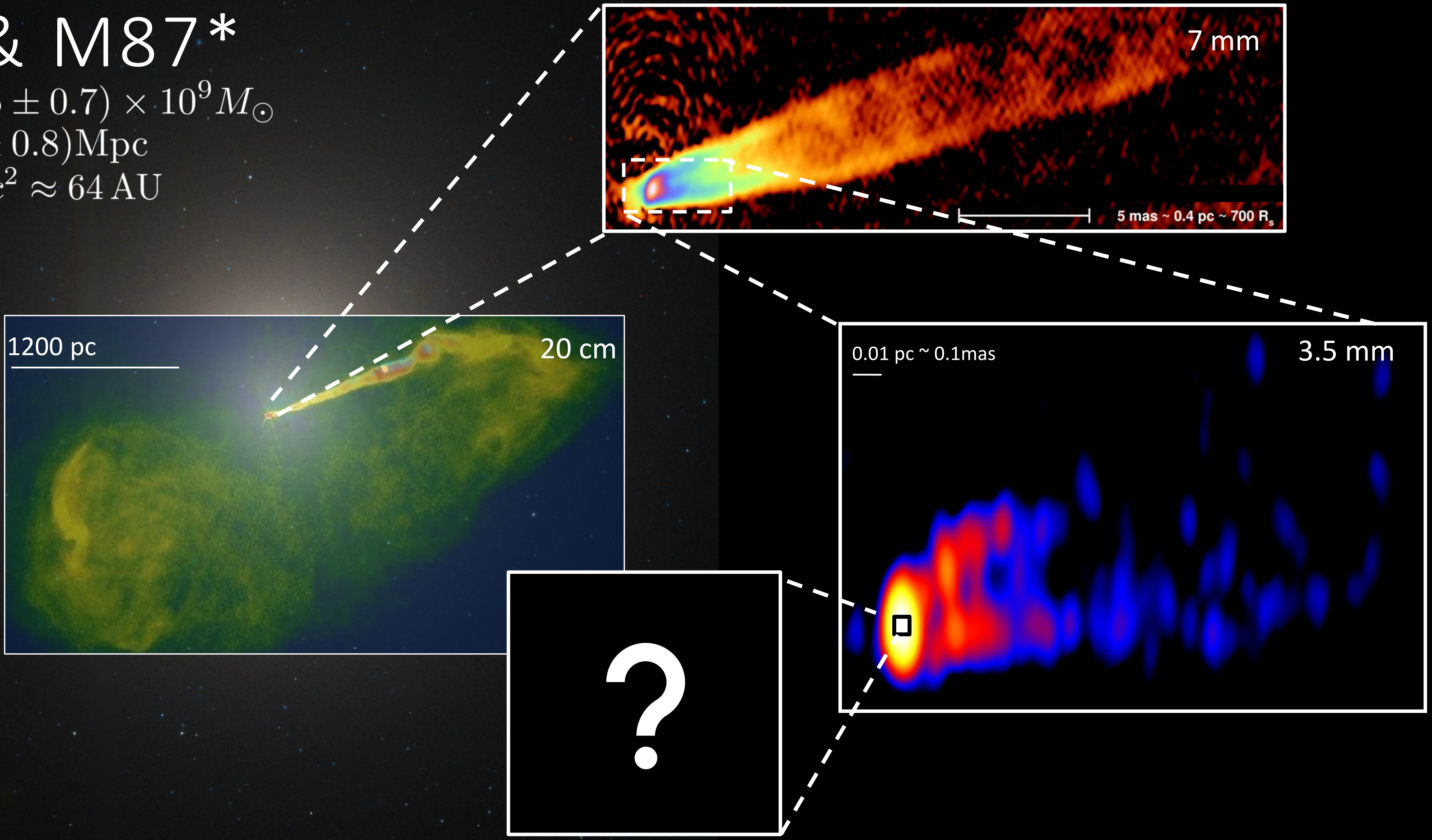
3C31


3C296

Credits: Sara Issoun, (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),(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*

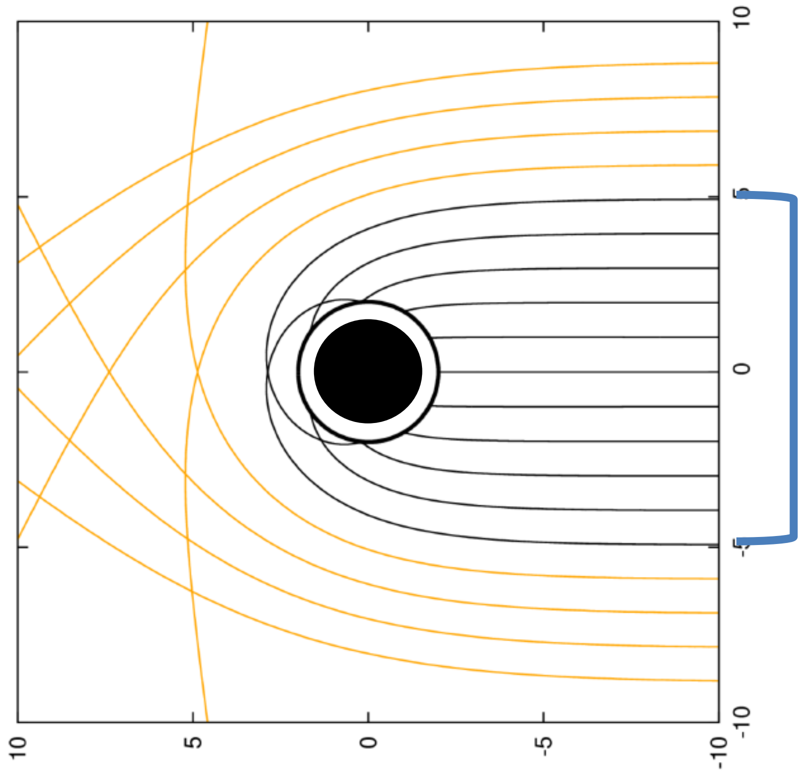
$$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$$
$$D = (16.8 \pm 0.8)\mathrm{Mpc}$$
$$R_\mathrm{s} = 2GM/c^2 \approx 64\,\mathrm{AU}$$



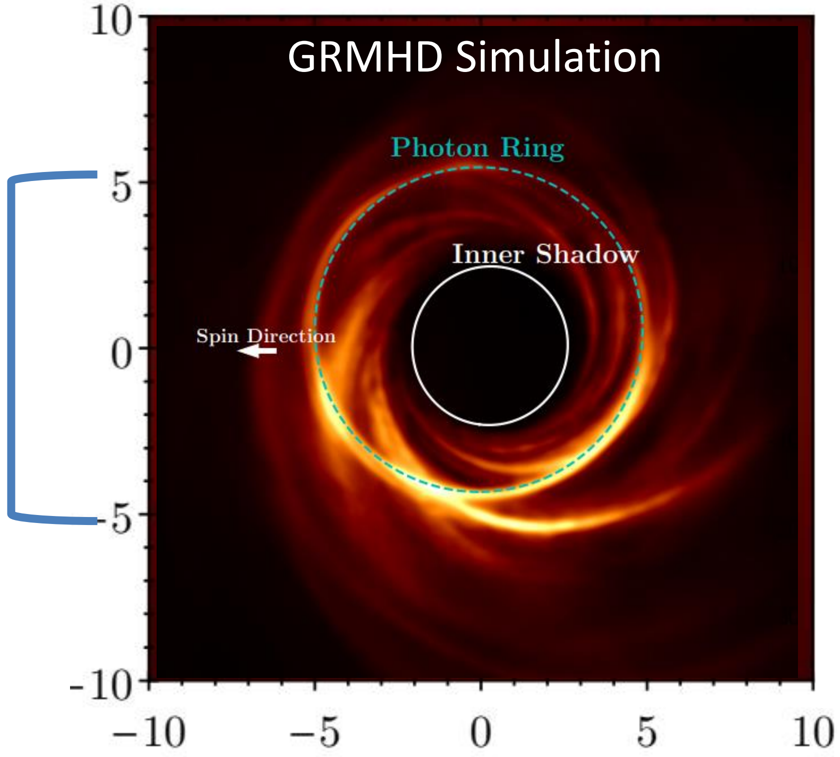
What does black hole accretion and jet launching look like at event horizon scales?

Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

The Black Hole Shadow



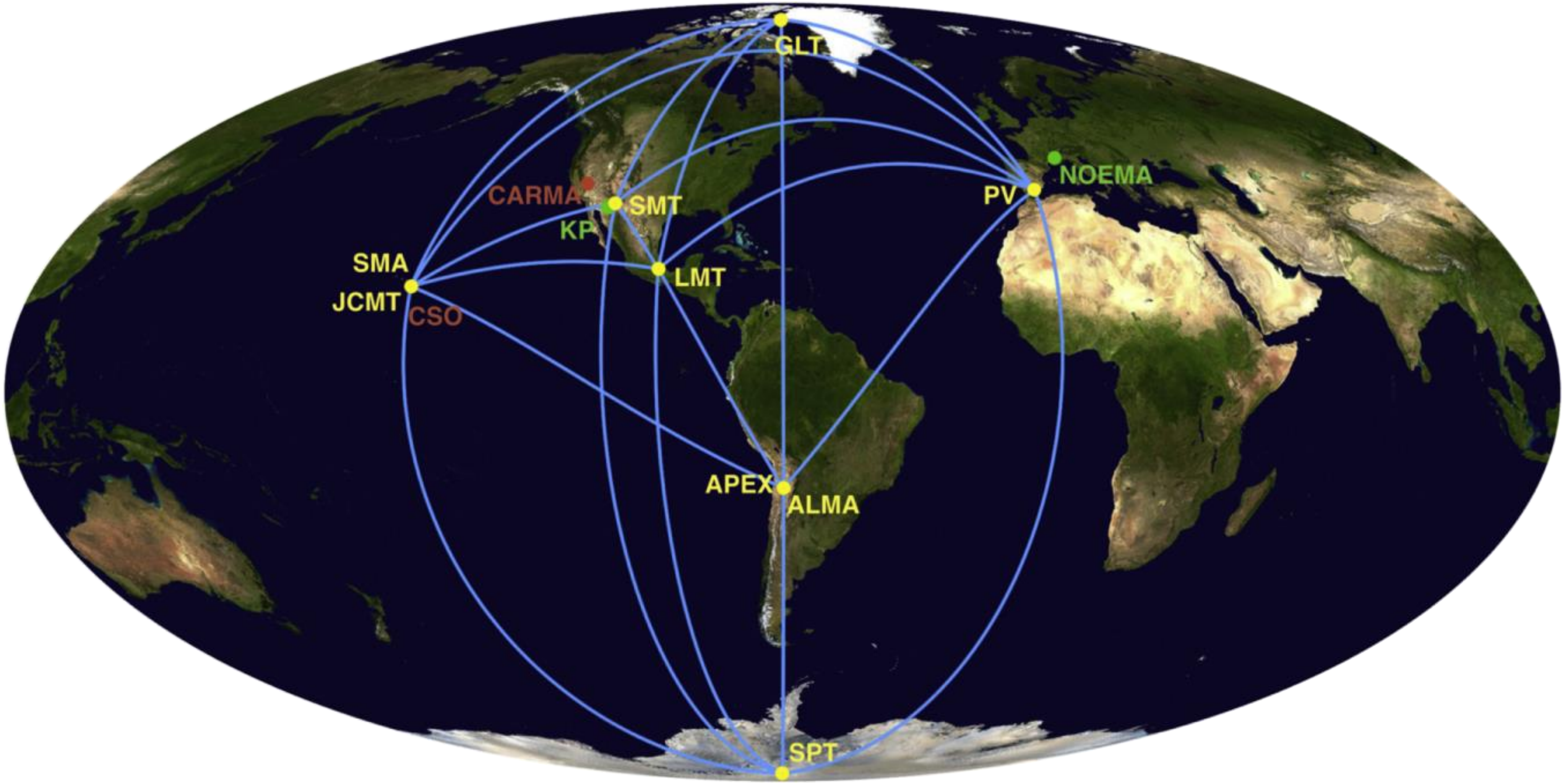
$$d_{\text{shadow}} \approx 5R_S/D$$
$$\approx 40\,\mu\text{as for M87}^*$$



- The shadow boundary **separates of rays that end on the event horizon with those that escape to infinity**

Image credit: Keiichi Asada (left), Narayan+ 2019, **Chael+** 2021

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*

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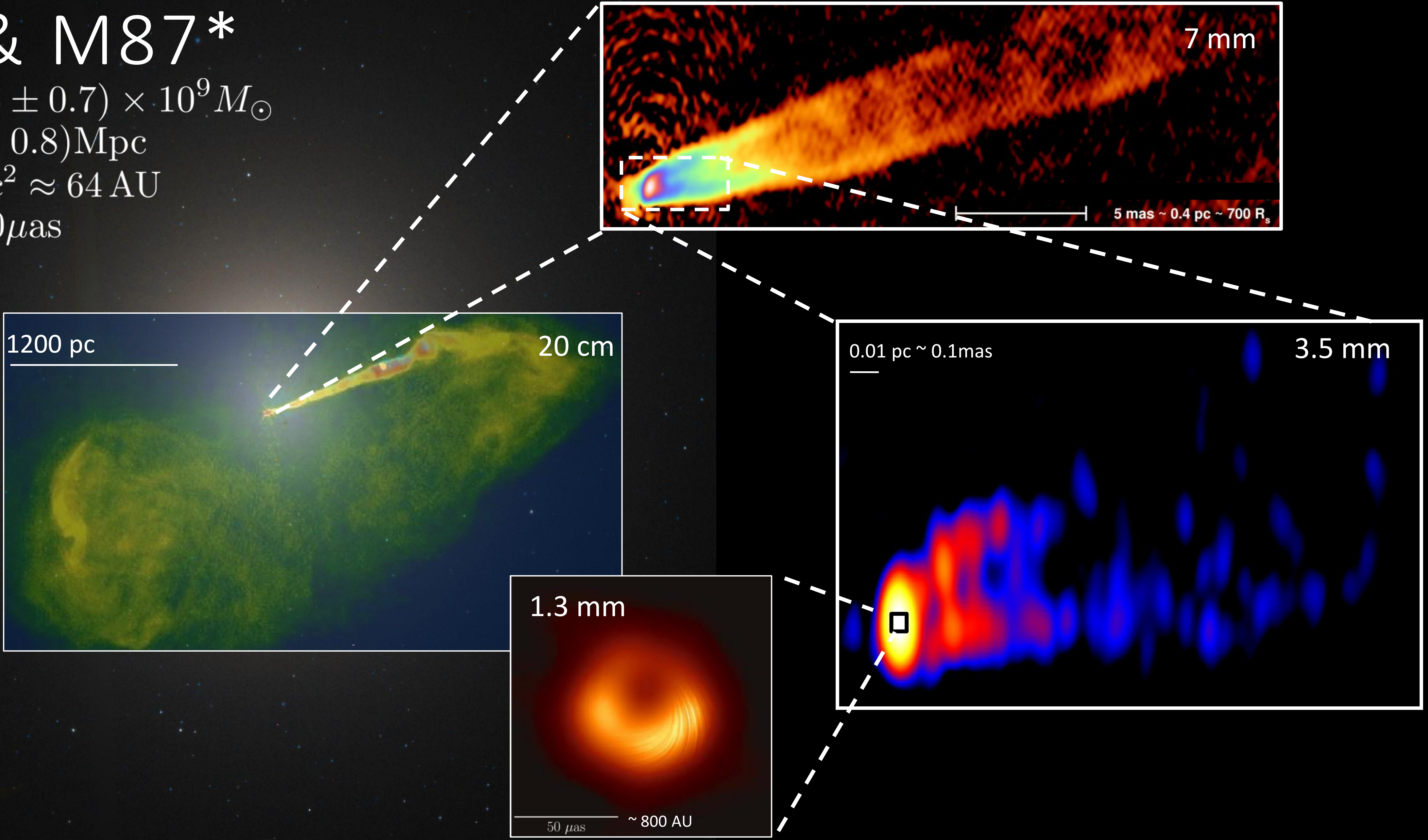
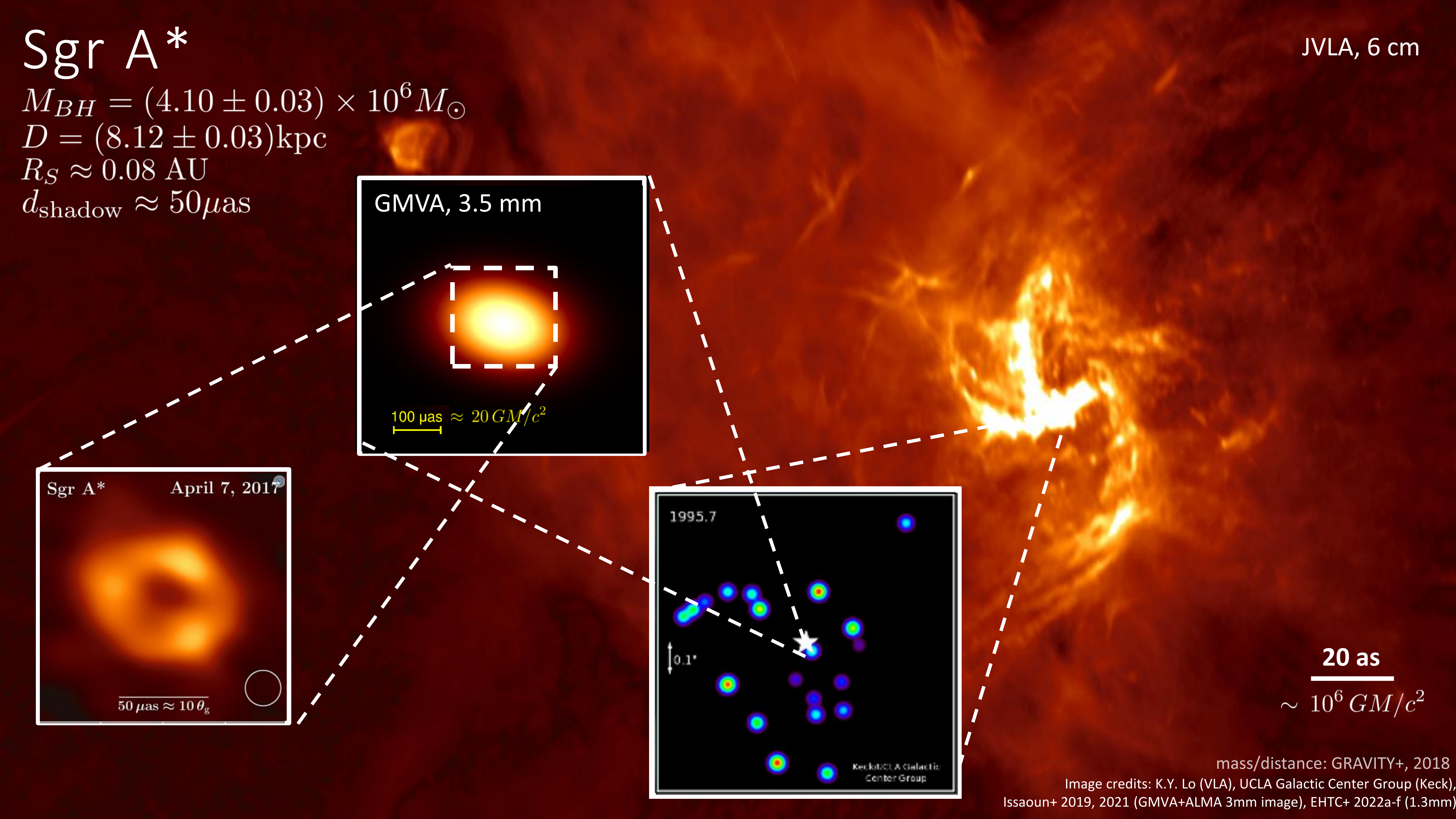


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

Sgr A*

$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
$D = (8.12 \pm 0.03)\mathrm{kpc}$
$R_S \approx 0.08$ AU
$d_{\mathrm{shadow}} \approx 50\mu as$



mass/distance: GRAVITY+, 2018

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

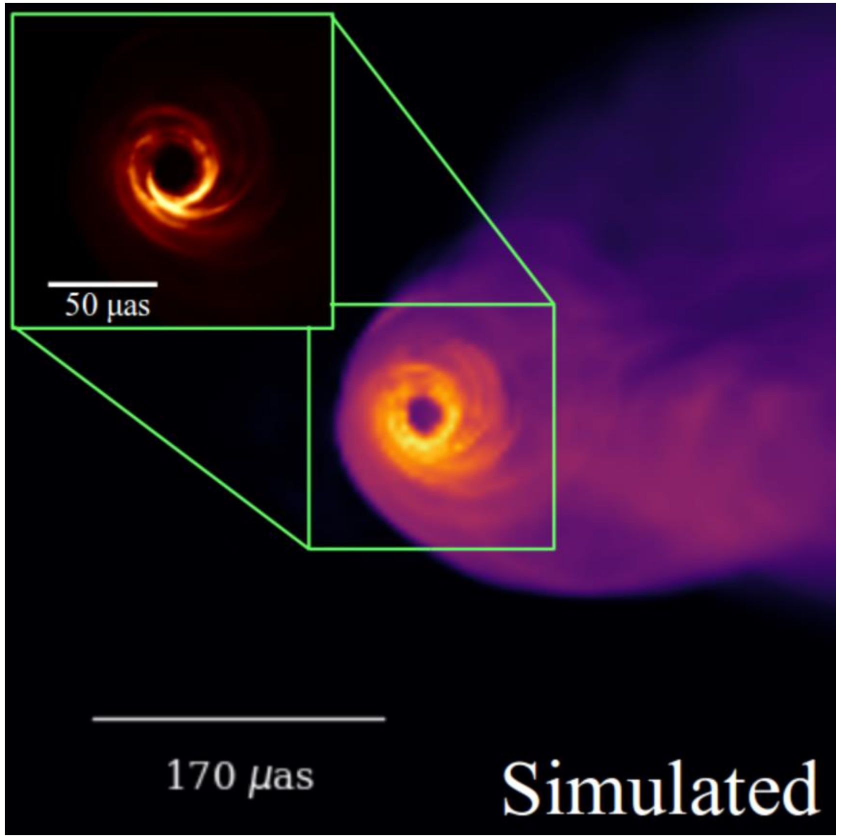
At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^{9} M_{\odot}$
- Hot ($T \gtrsim 10^{10}\,\mathrm{K}$), sub-Eddington accretion flow emitting synchrotron radiation
- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}\ \mathrm{erg\ s^{-1}}$)

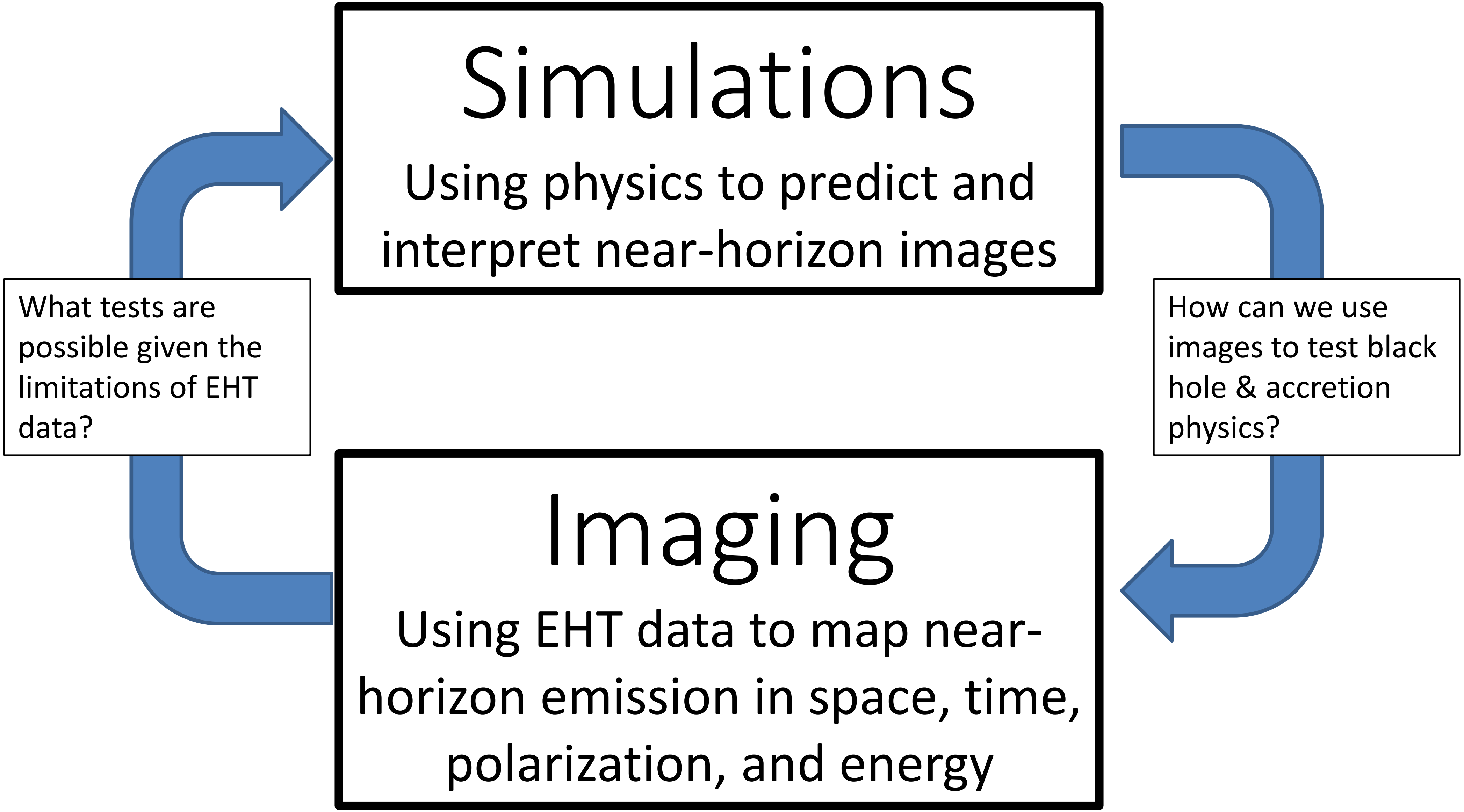
Questions I think about:

- Is the jet launched by extracting BH spin energy?
  - What is the strength and geometry of the magnetic field?
- How can we perform precise tests of gravity?
  - What will we see with upgraded EHT observations?
- What small-scale plasma physics accelerates electrons and lights up the flow?
  - What powers X-ray/ γ -ray flares in Sgr A* and M87*?



Blackburn+ 2019, **Chael+** 2019

My Research



Simulations

Using physics to predict and interpret near-horizon images

How can we use images to test black hole & accretion physics?

Imaging

Using EHT data to map near-horizon emission in space, time, polarization, and energy

What tests are possible given the limitations of EHT data?

This talk:

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

Outline:

1. How do we make resolved images of supermassive black holes?
2. What have we learned from near-horizon images?
3. What could we see next?

This talk:

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

Takeaways:

1. Near-horizon imaging required **new algorithms**
    - These techniques have wide applicability in interferometry
2. Polarization is the key for near-horizon astrophysics
    - Polarized images of M87* show its accretion is **magnetically arrested**
3. We are just getting started in what we can learn from resolved black hole images
    - Future EHT observations will reveal the **jet base** and **inner shadow**

The Event Horizon Telescope: People

300+ members

60 institutes

20 countries

from Europe, Asia, Africa,
North and South America.

Image credit: E. Traianou, MPIfR

Part I:
How do we make resolved images of supermassive black holes?

Chael+ 2016, 2018a, 2023
EHTC+ 2019 Paper IV, 2022 Paper VII (**Chael**, paper coordinator)
arXiv: 1605.06156, 1803.07088, 2210.12226, 1906.11241, 2105.01169

EHT 2017 Observations

Observation run day three

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

The EHT data path

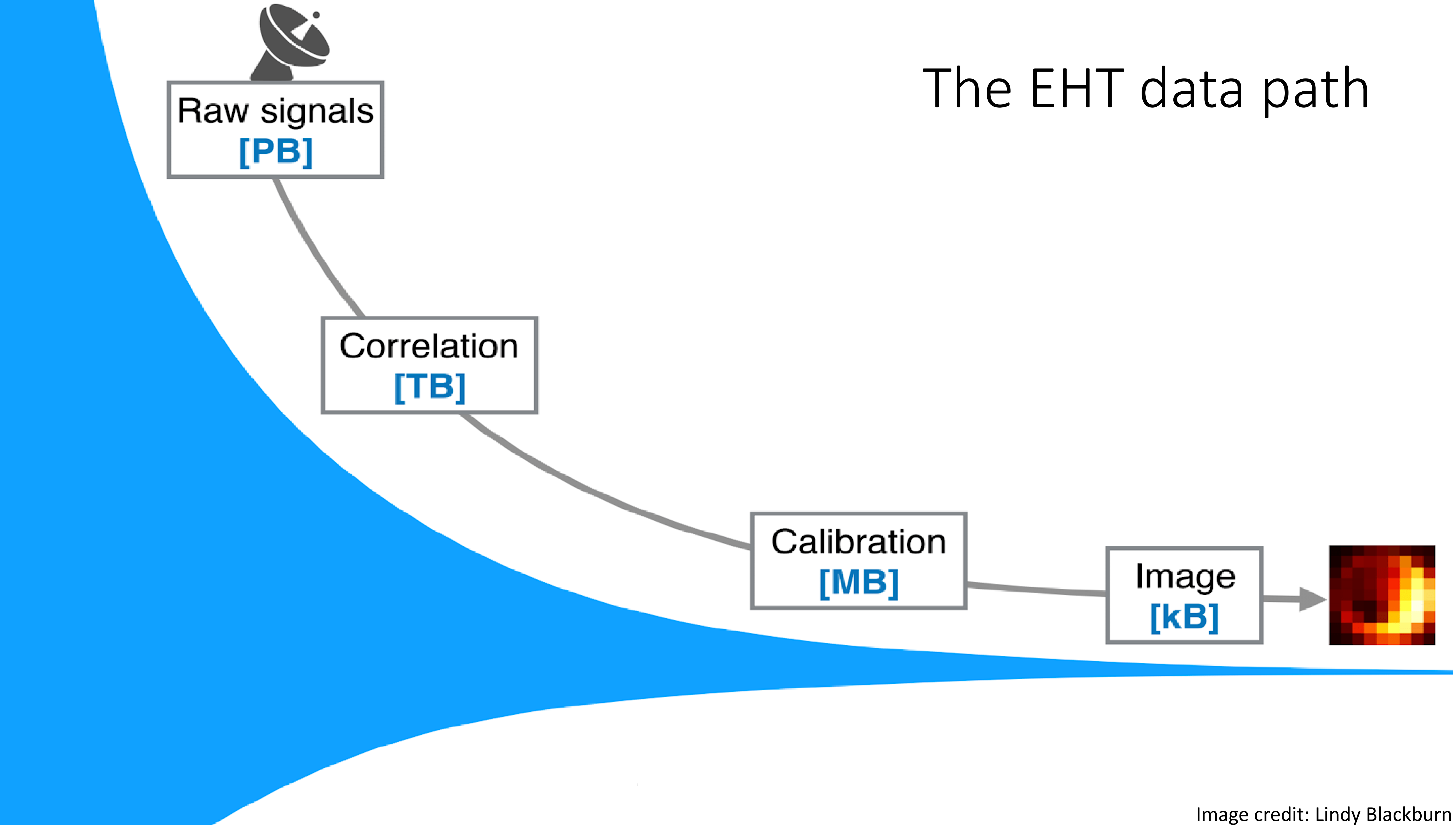
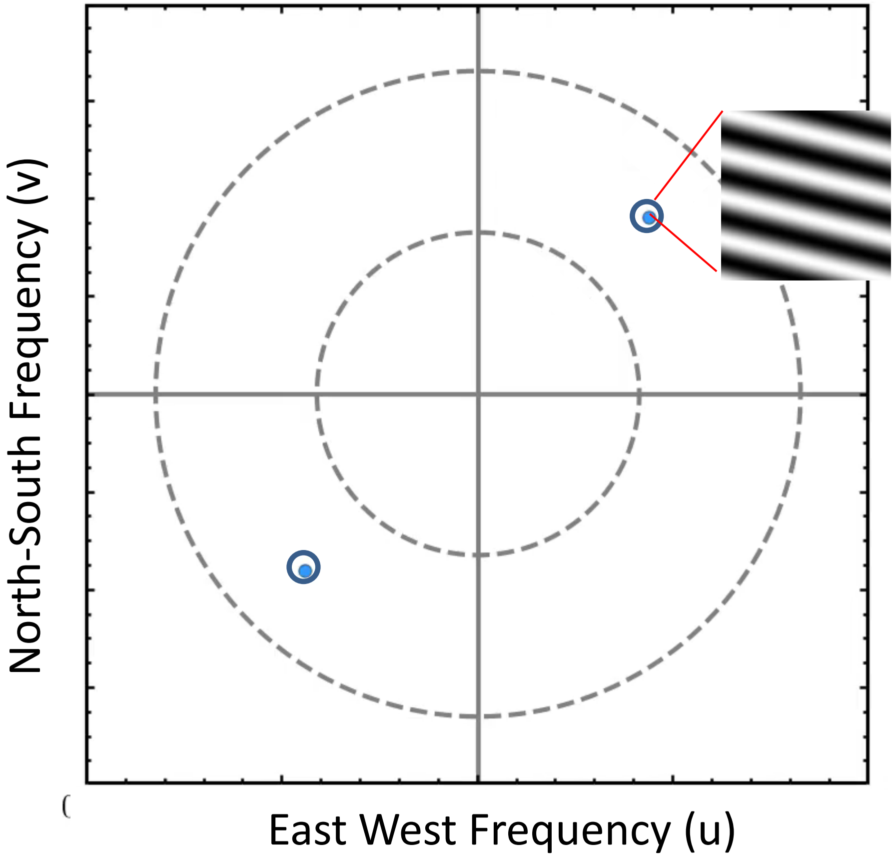


Image credit: Lindy Blackburn

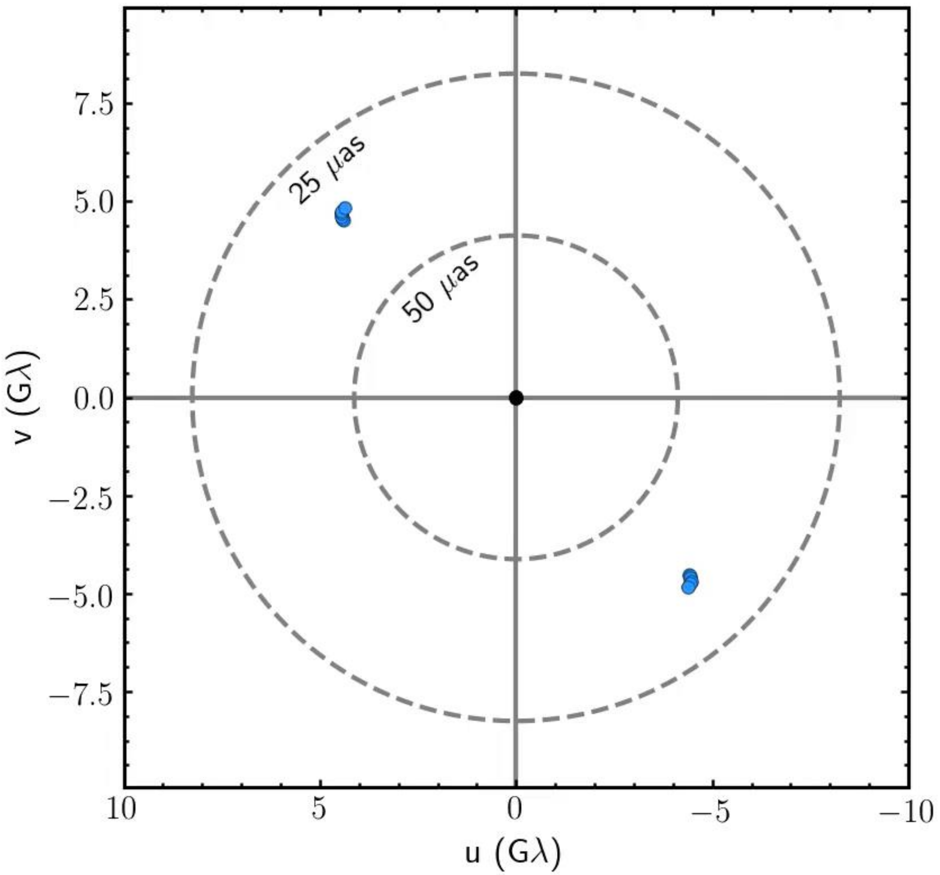
Very Long Baseline Interferometry (VLBI)



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

movie credit: Katie Bouman

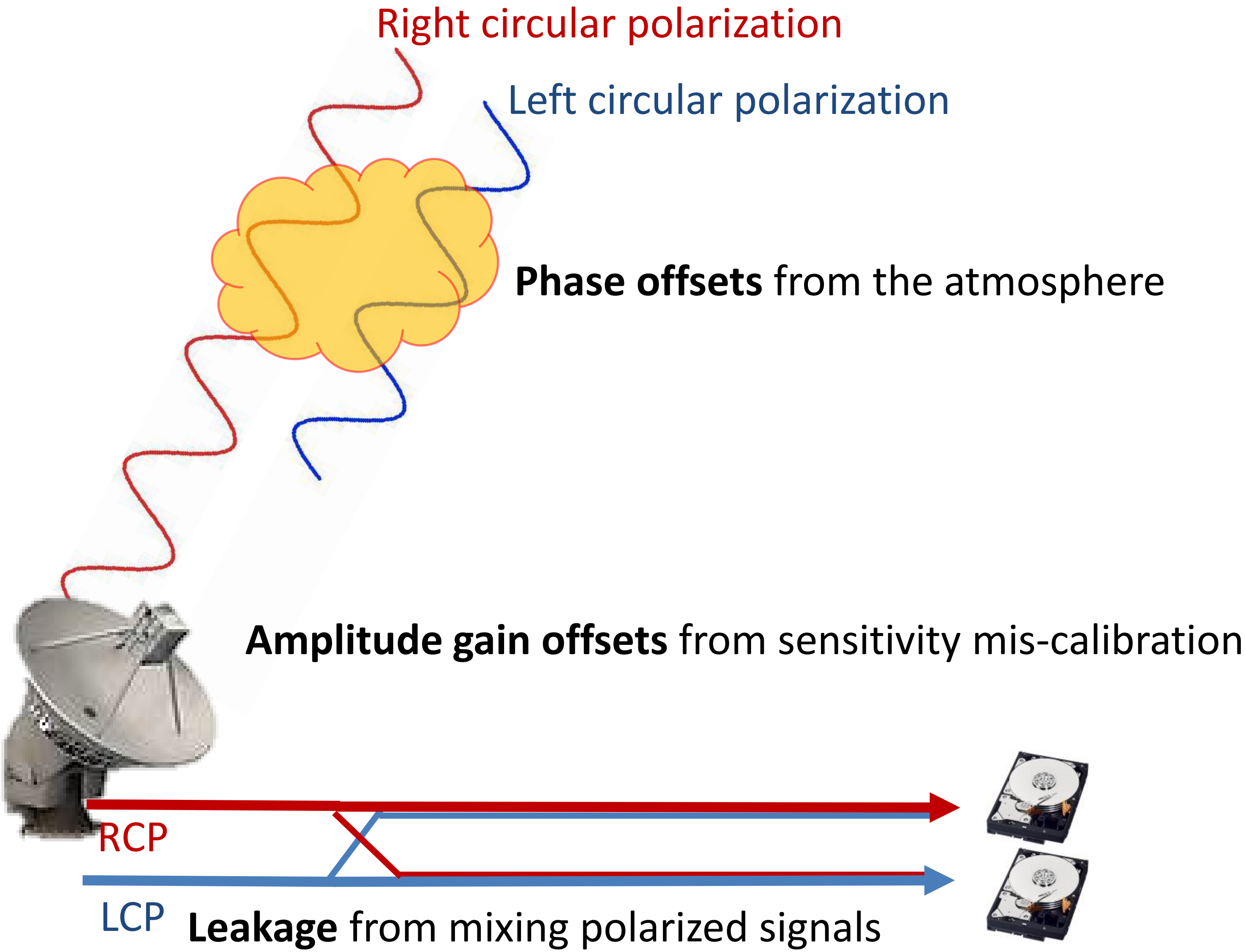
Very Long Baseline Interferometry (VLBI)



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

movie credit: Daniel Palumbo

Challenges of near-horizon imaging



Right circular polarization

Left circular polarization

Phase offsets from the atmosphere

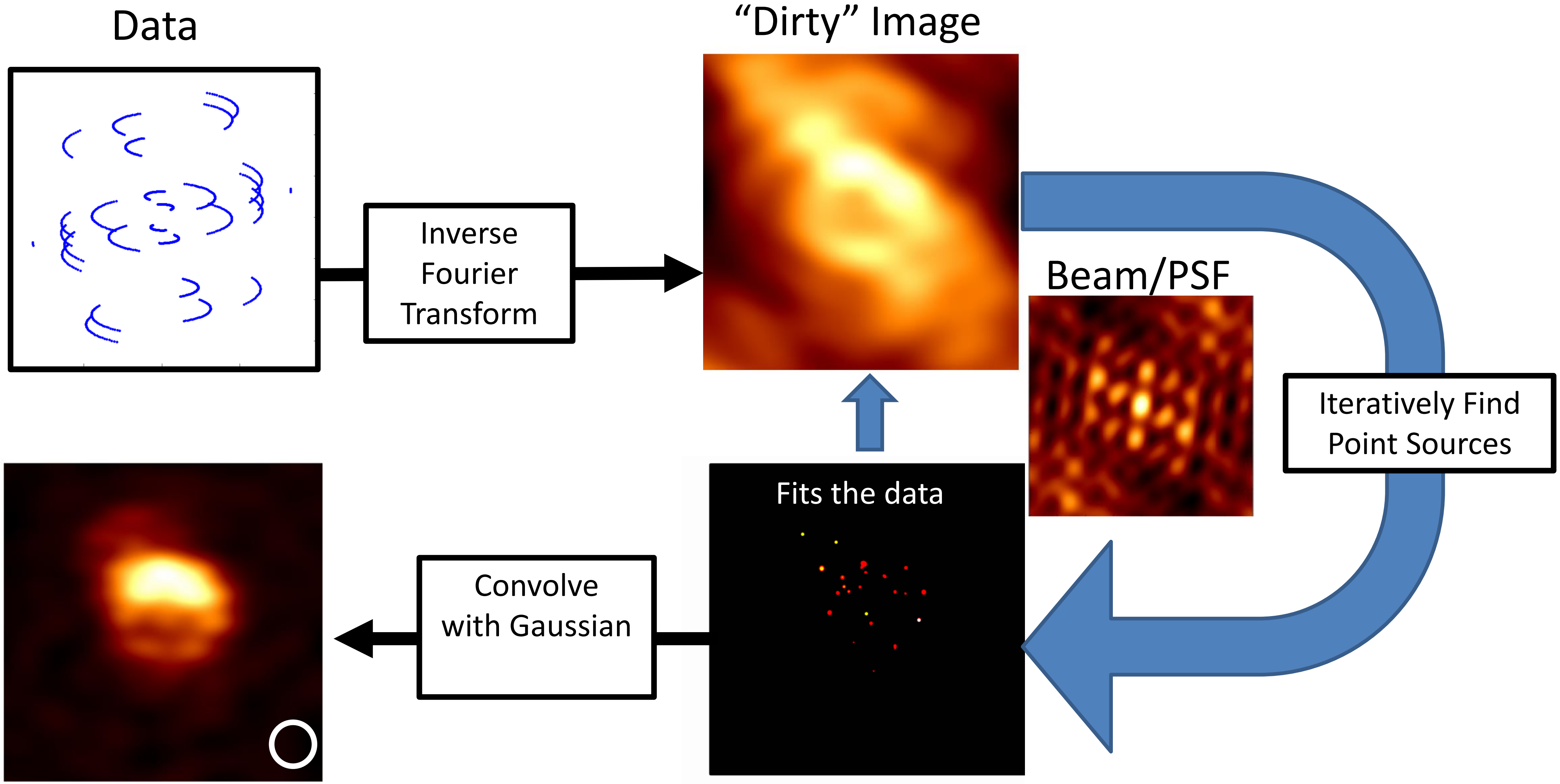
Amplitude gain offsets from sensitivity mis-calibration

RCP

LCP

Leakage from mixing polarized signals

Traditional Approach: CLEAN



Data

Inverse Fourier Transform

"Dirty" Image

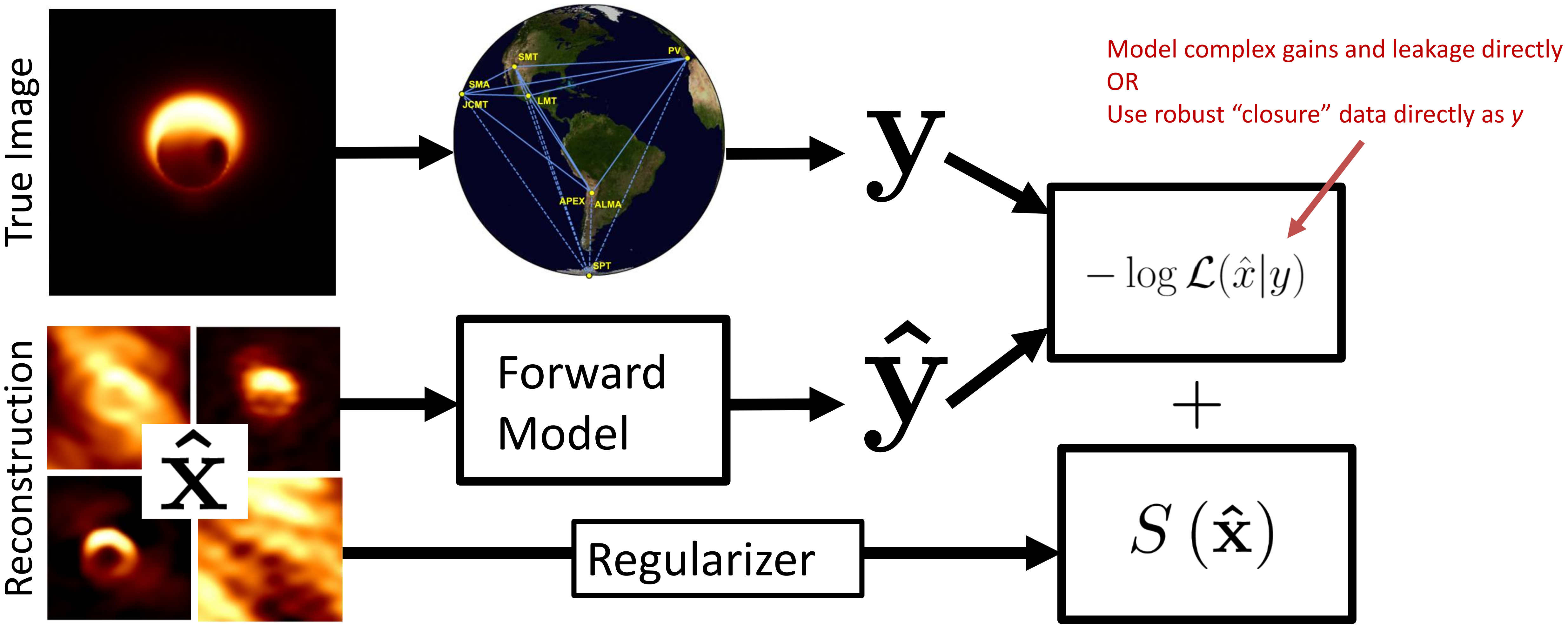
Beam/PSF

Iteratively Find Point Sources

Fits the data

Convolve with Gaussian

Regularized Maximum Likelihood



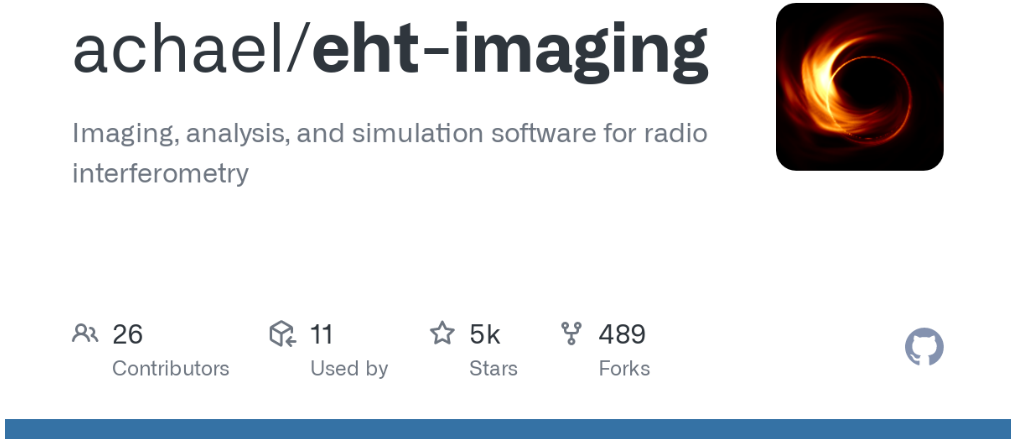
Model complex gains and leakage directly
OR
Use robust “closure” data directly as *y*

The **`eht-imaging`** software library

- Large python toolkit for **analyzing, plotting, simulating,** and **imaging** interferometric data

- Flexible framework for developing tools:
  - polarimetric imaging, dynamical imaging, **multi-frequency imaging**, geometric modeling

- Uses:
  - All EHT imaging results to date
  - EHT calibration software
  - Forecasting from simulations
  - Imaging & analysis from VLBA, GMVA, ALMA….



achael/**eht-imaging**

Imaging, analysis, and simulation software for radio interferometry

26	11	5k	489
Contributors	Used by	Stars	Forks

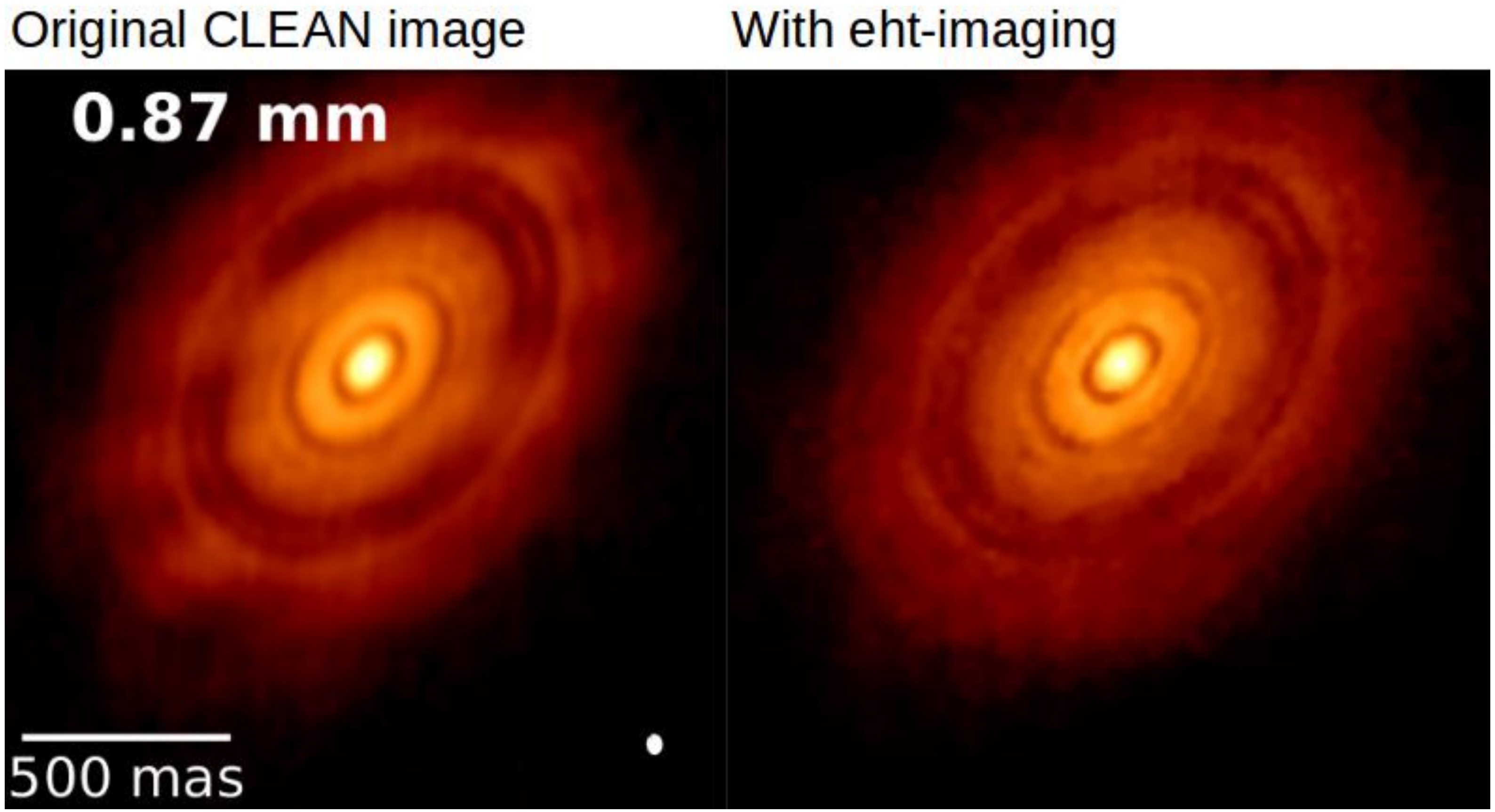
https://github.com/achael/eht-imaging

`pip install ehtim`

Chael+ 2016, 2018a, 2023

New imaging techniques have wide applicability!

HL Tau with ALMA



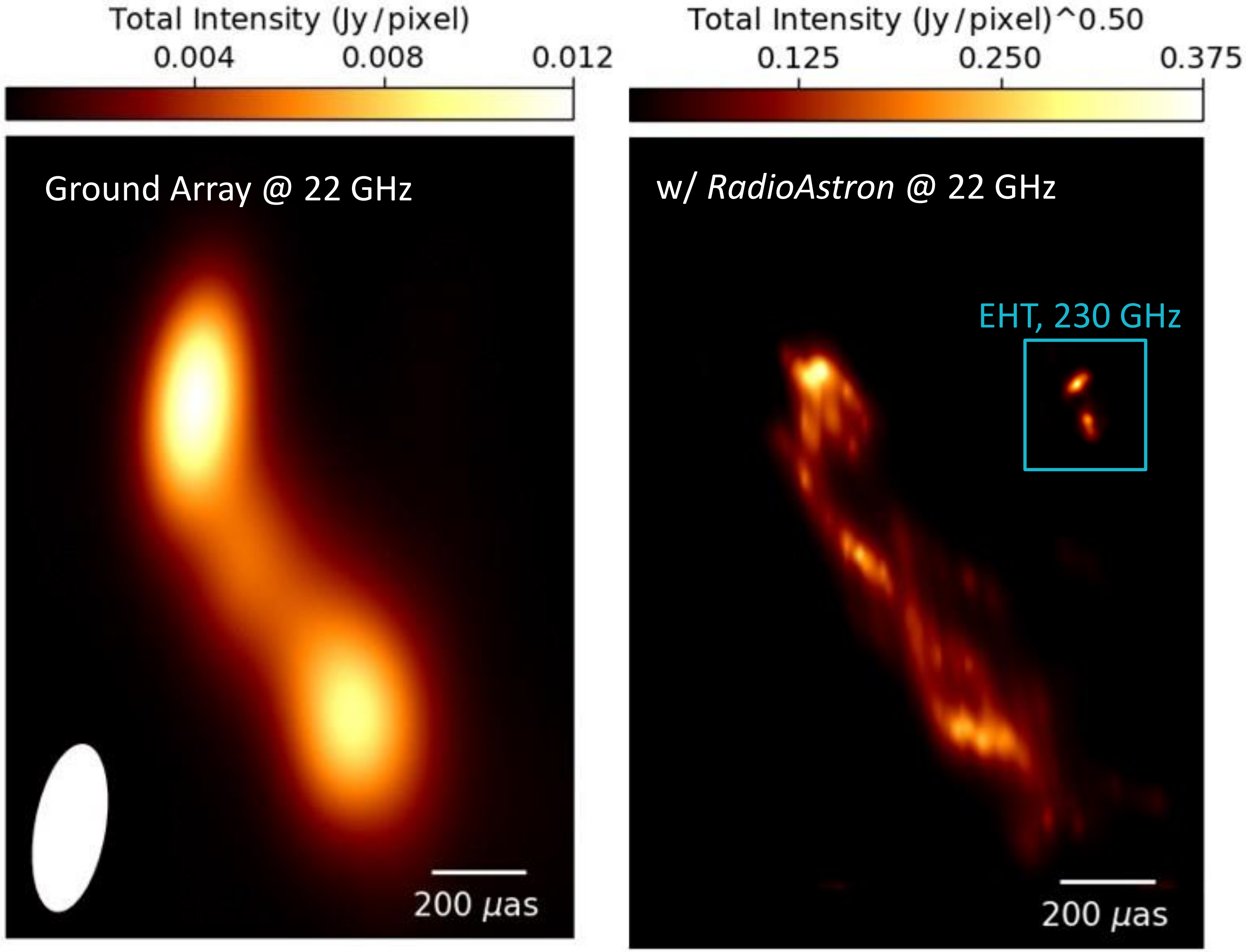
Chael+ 2018a

Data & CLEAN image: ALMA Partnership+ 2015

New imaging techniques have wide applicability!

3C279 with *RadioAstron*

- At 22 GHz (1.3 cm) observed in 2014
- Space baselines to *RadioAstron* supported by a ground array of 23 antennas
- Reconstruction with **eht-imaging**.

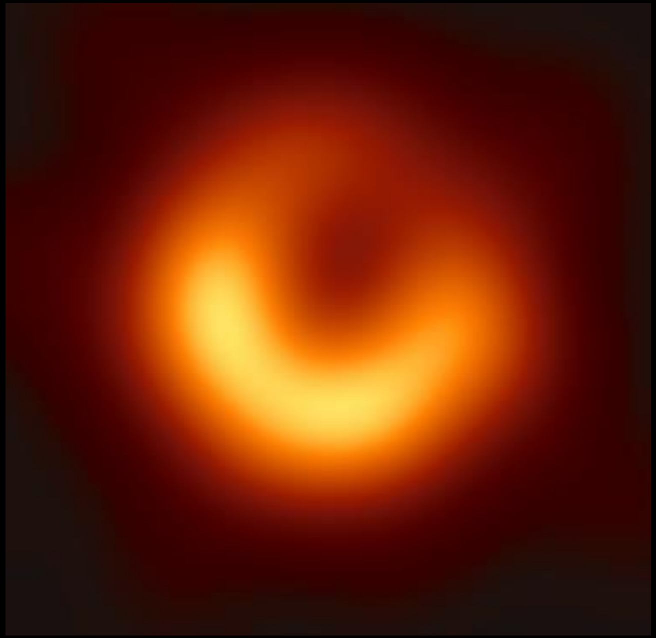


Antonio Fuentes

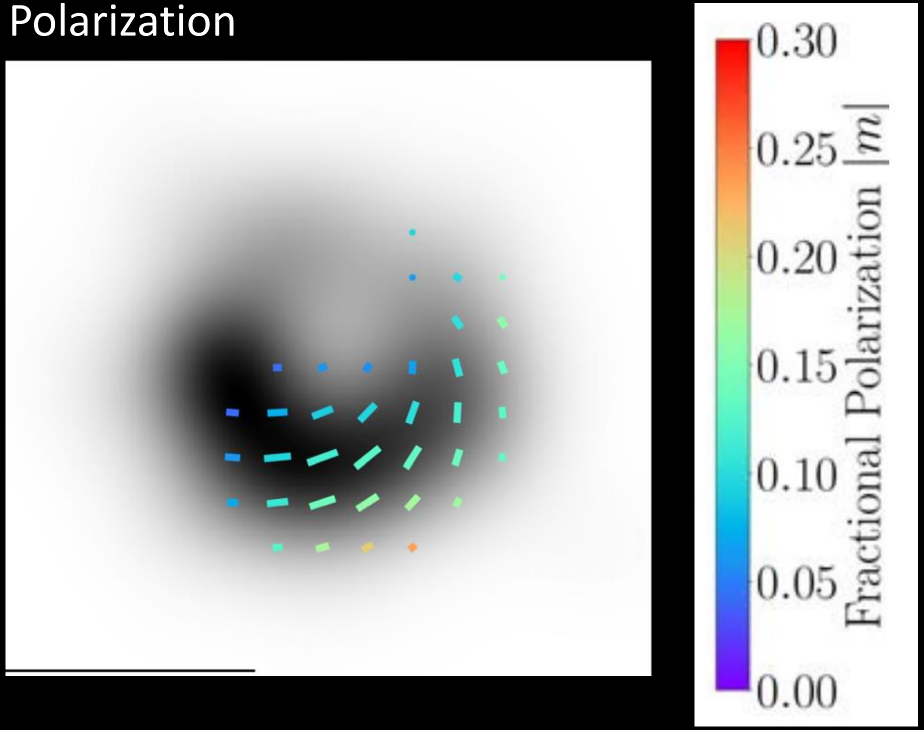
Fuentes et al, submitted preprint: https://www.researchsquare.com/article/rs-1449452/v1

Polarimetric images of M87*

Total intensity



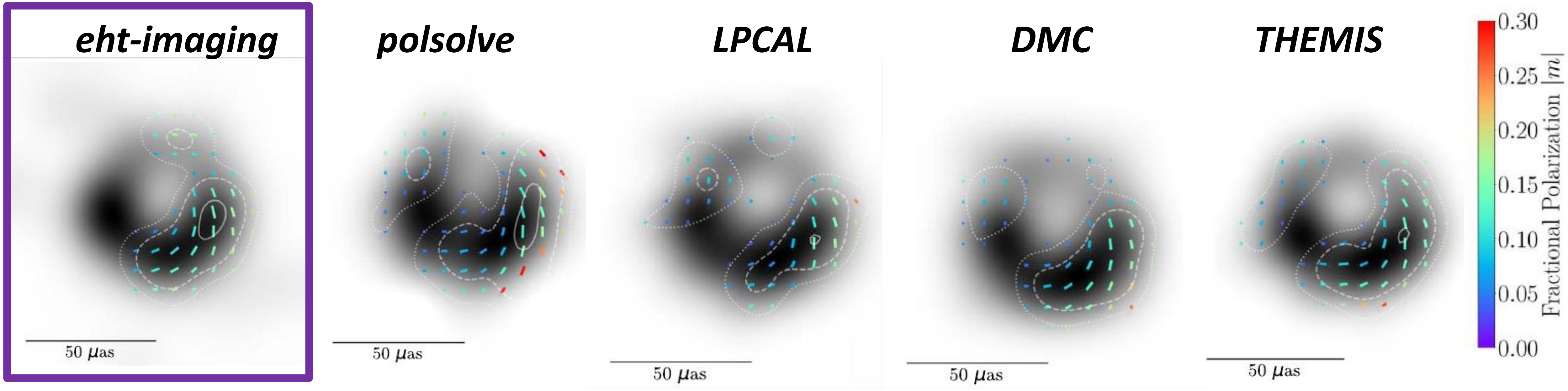
Linear Polarization



- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)

Validation is essential: use multiple methods



EHTC+ 2021 Paper VII (**Chael**, paper writing team)

Part II:
What have we learned from near-horizon images?

EHTC+ 2021, Paper VII & VIII (**Chael**, paper coordinator)
arXiv:2105.01169, 2105.01173

EHTC Polarization team (Paper VII-VIII)

coordinators

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Iván Martí-Vidal

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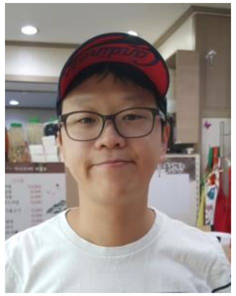
Sara Issaoun

Jongho Park

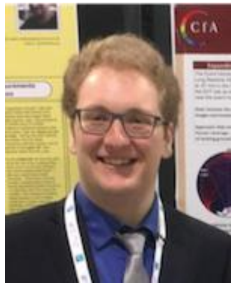


Maciek Wielgus

Angelo Ricarte

Alejandra Jiménez-Rosales

Daniel Palumbo



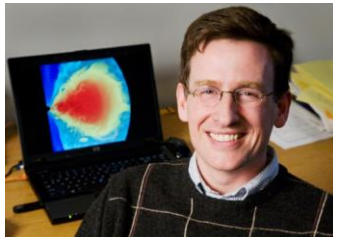
Dom Pesce

John Wardle

Avery Broderick

Ben Prather

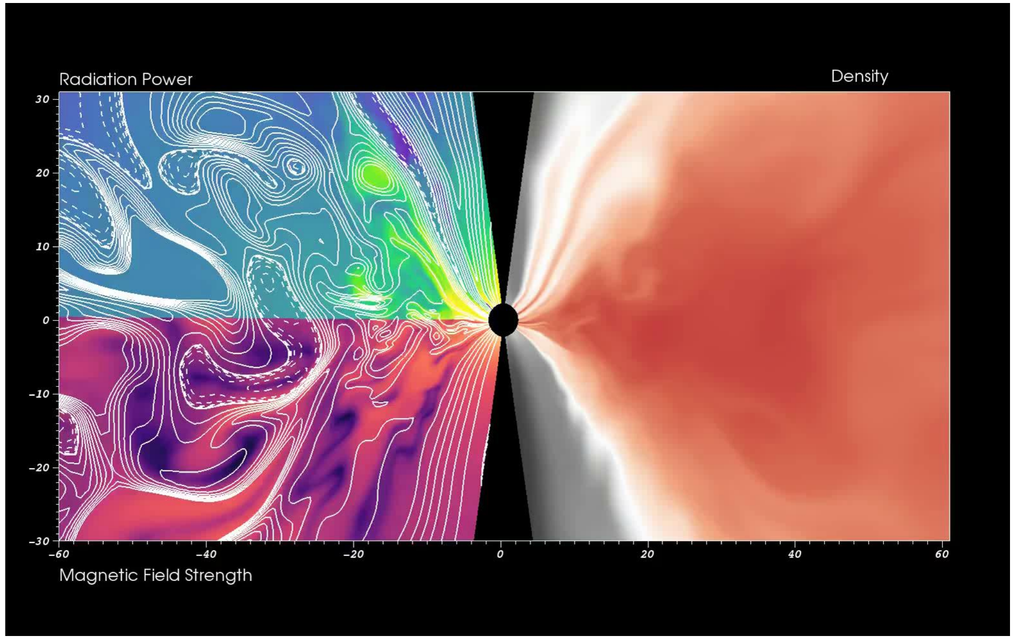
Charles Gammie

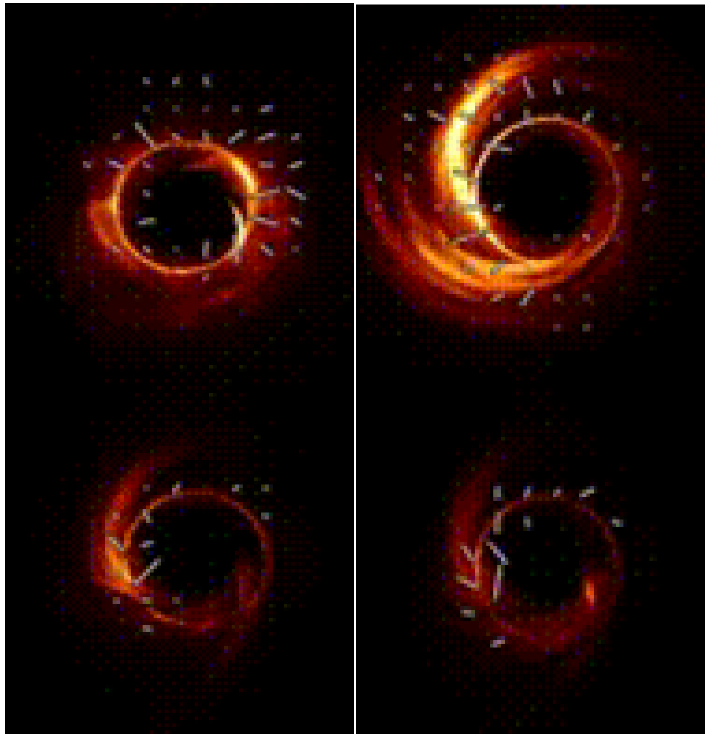


George Wong

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator)
ArXiv: 2105.01169, 2105.01173

Theoretical Tools for Interpreting Black Hole Images





GRMHD Simulations

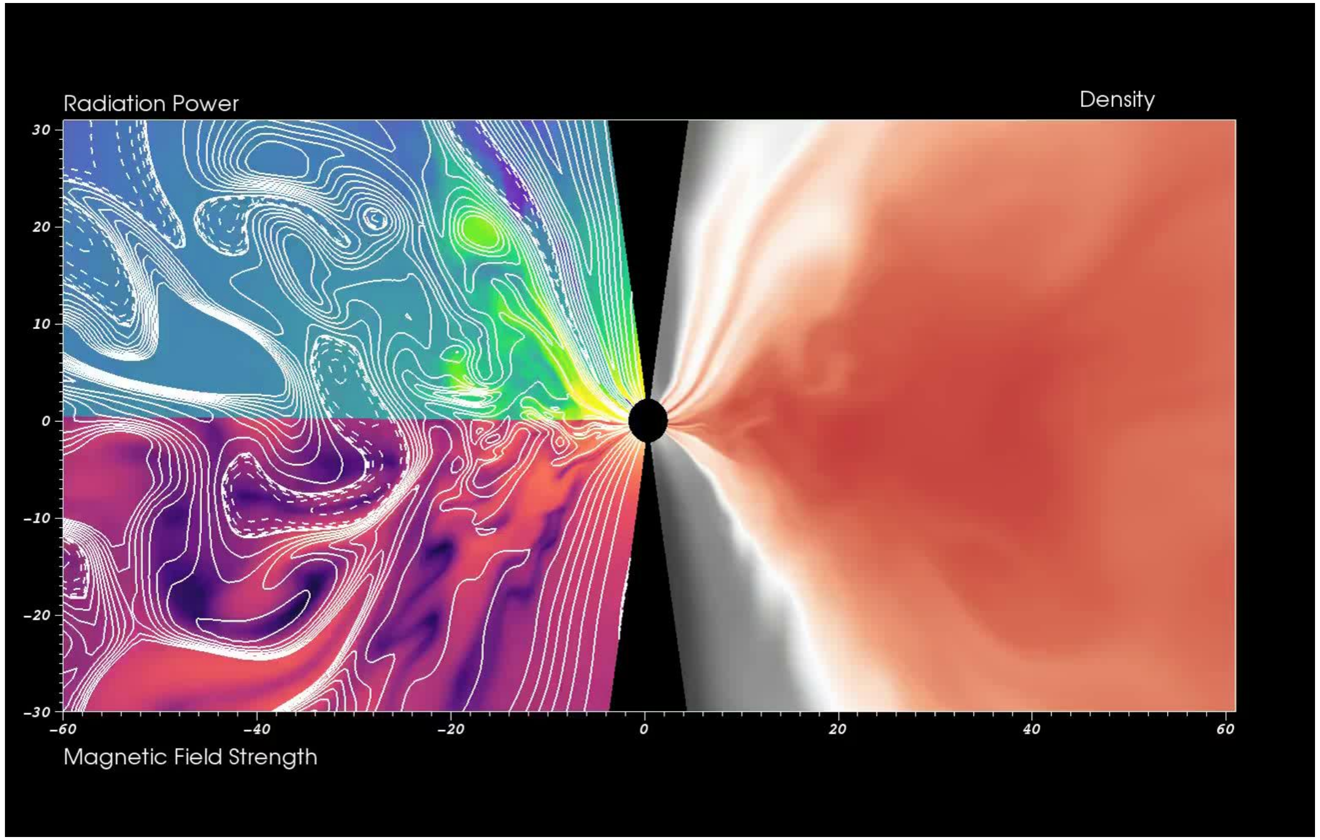
Solves coupled equations of plasma dynamics and magnetic field in Kerr spacetime

GR Radiative Transfer

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

Movie Credits: **Chael**+ 2019, Ben Prather (right)

Interpreting Images with GRMHD Simulations



- **G**eneral **R**elativistic **M**agneto**H**ydro**D**ynamic simulations solve the coupled equations of plasma and magnetic fields in the Kerr spacetime

- GRMHD simulations are the primary theoretical tool for interpreting EHT images.

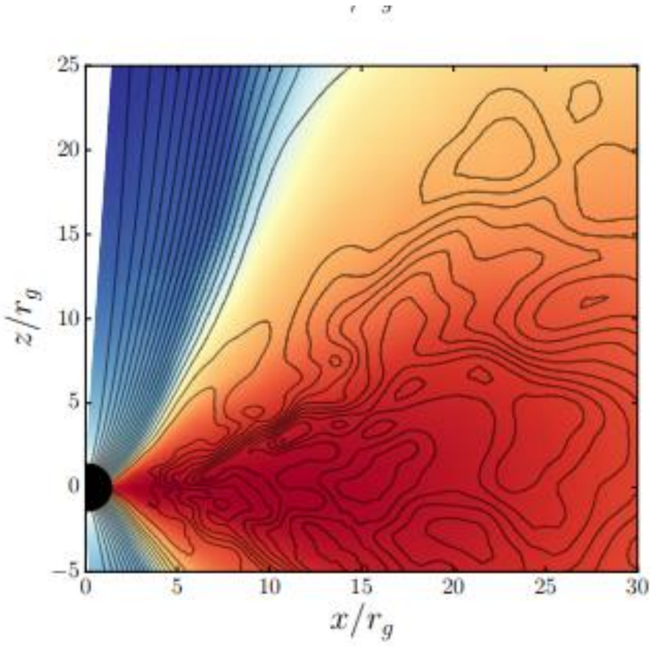
- GRMHD simulations naturally **couple the accretion disk, black hole, and jet**
  - Jet launching in simulations is universal and driven by BH spin

Movie Credit: **Chael**+ 2019

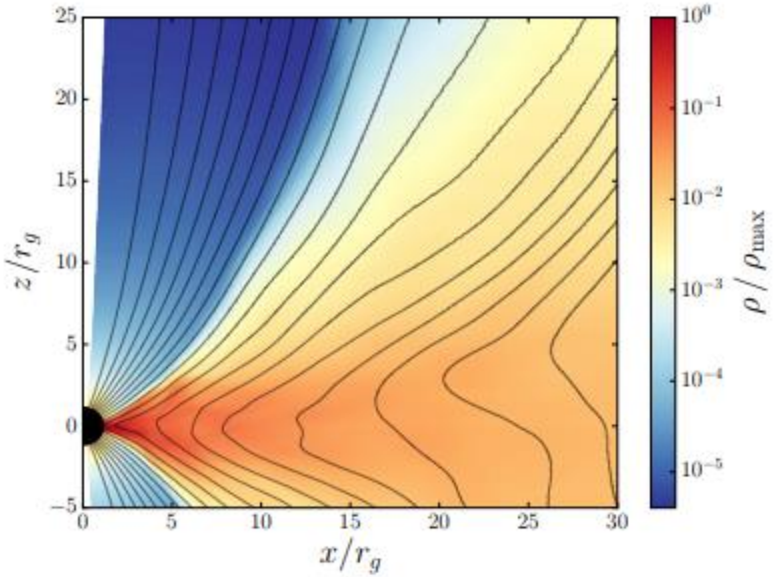
Magnetic field structure in sub-Eddington accretion

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

- **Magnetic fields are weak and turbulent**
- **Angular Momentum transport is local (MRI)**



“Standard and Normal”



Magnetically Arrested

- **Strong, coherent magnetic fields build up on the horizon**
- **Angular momentum transport is global (winds)**

Note: ‘strong’ fields → ~10 G at the horizon for M87

Blandford-Znajek (1977): $P_{\text{jet}} \propto \Phi_B^2 a^2$

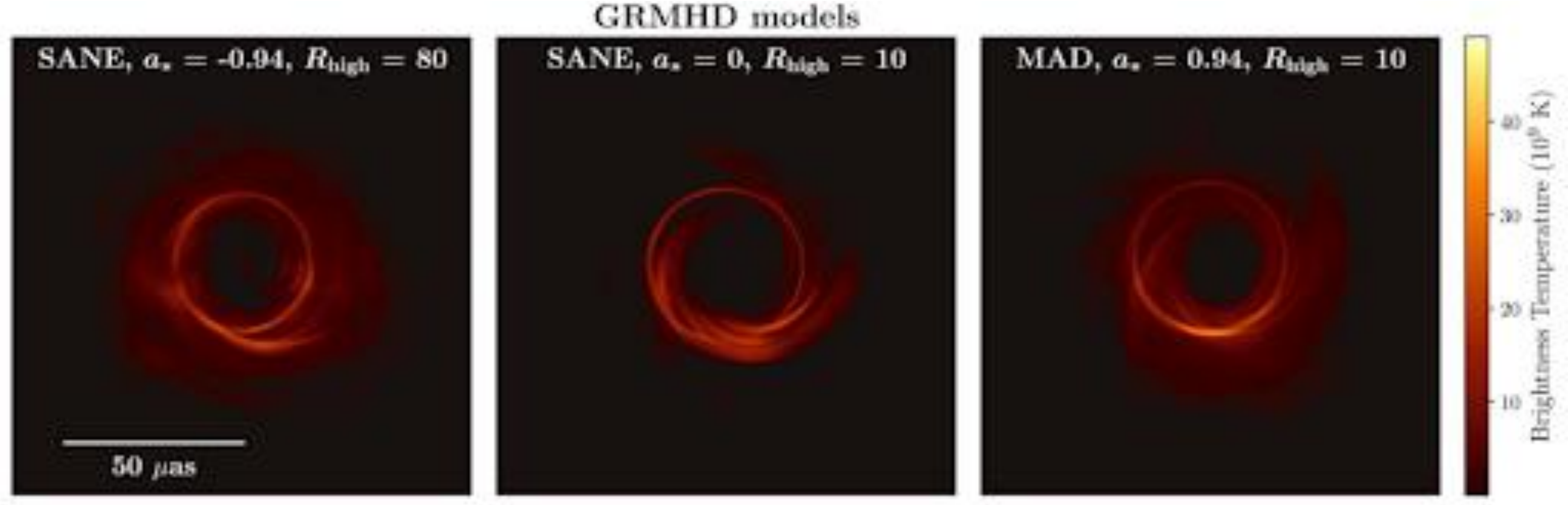
BH spin

magnetic flux

e.g. Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: Riordan+ 2017

Scoring GRMHD Simulations: before polarization

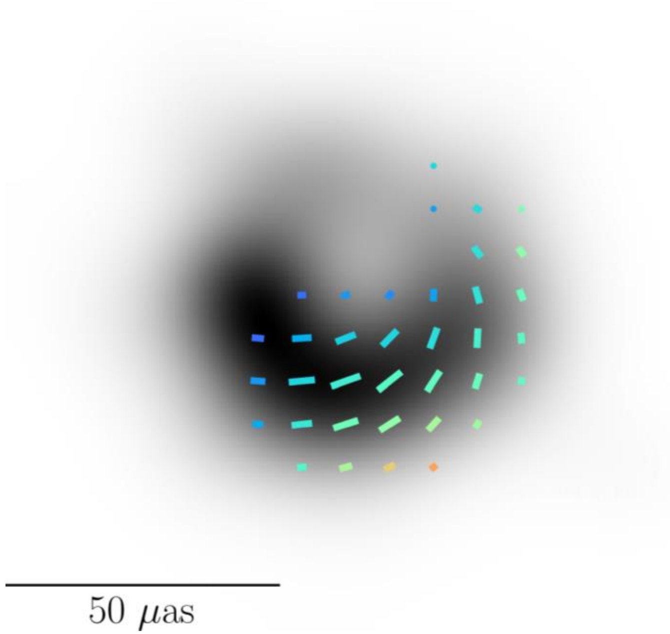
- **Most simulation models can be made to fit total intensity observations alone** by tweaking free parameters (BH mass, position angle)

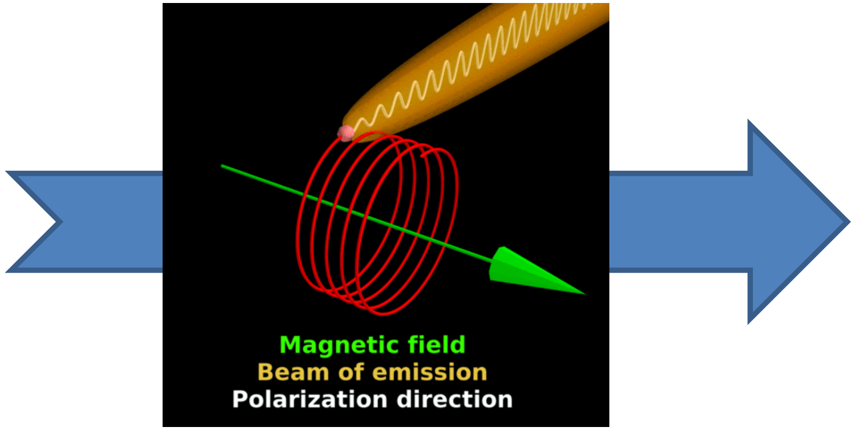


- Can we do better with polarization?

EHTC+ 2019, Paper V

Synchrotron polarization traces magnetic fields



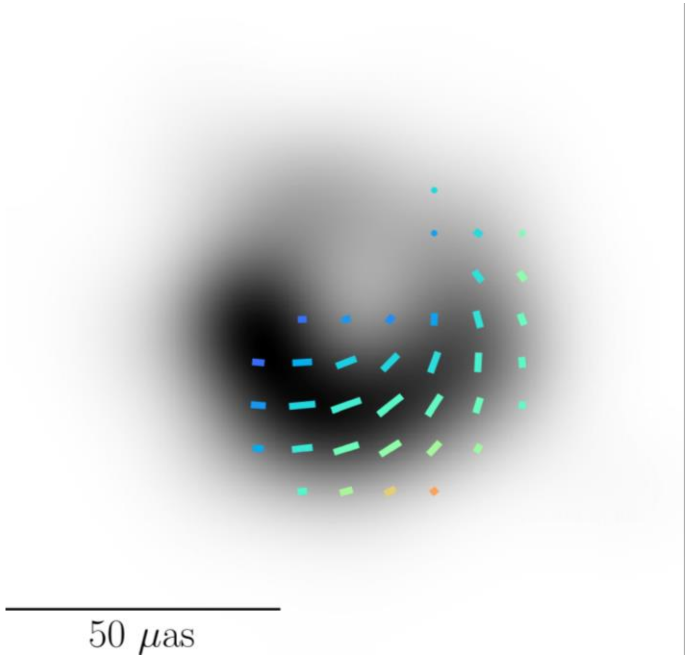


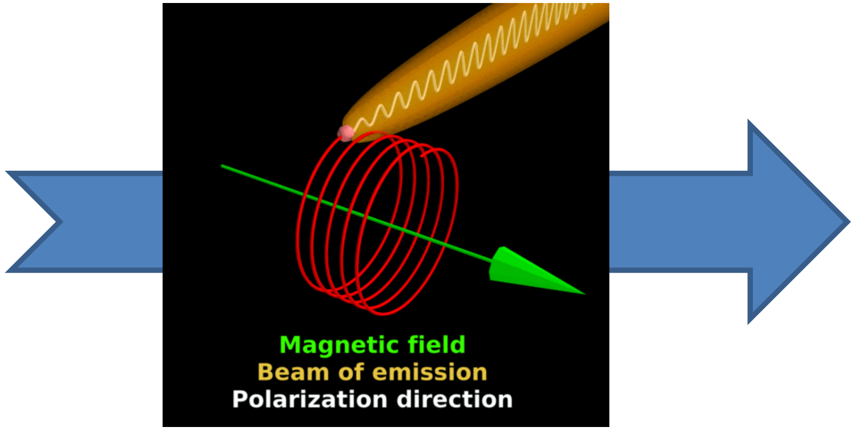
Magnetic field geometry in the emission region!

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

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Synchrotron polarization traces magnetic fields





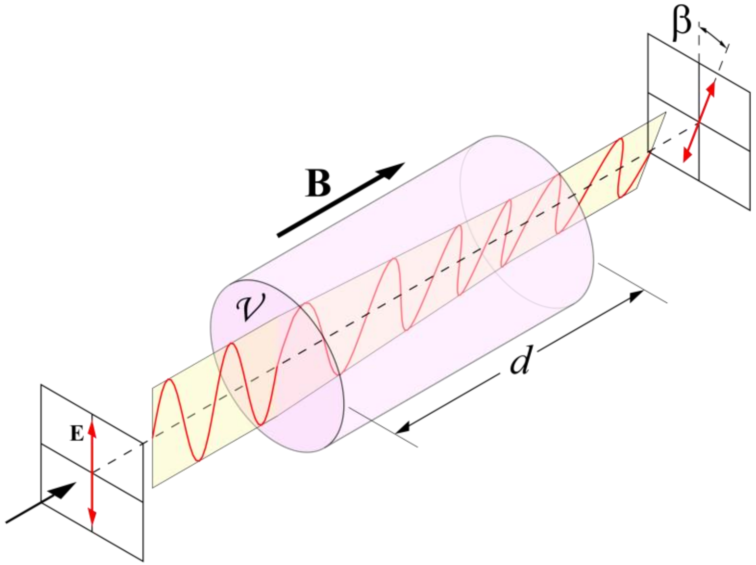
Ma d
direc n the
em ion!

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

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Faraday rotation matters!

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



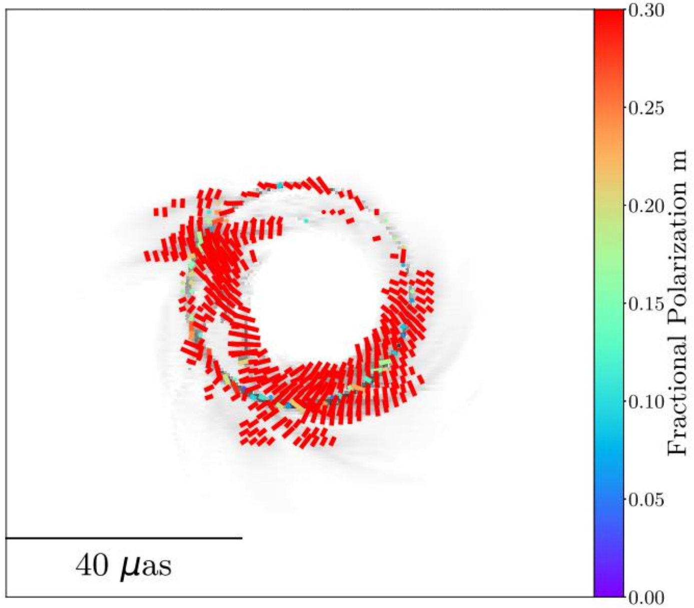
- ‘Internal’ vs ‘External’ Faraday rotation:
  - **External** → rotation is far from the source, polarization rotated by same angle everywhere
  - **Internal** → rotation is inside emitting source, image regions rotated by different amounts

Image credit: Wikipedia

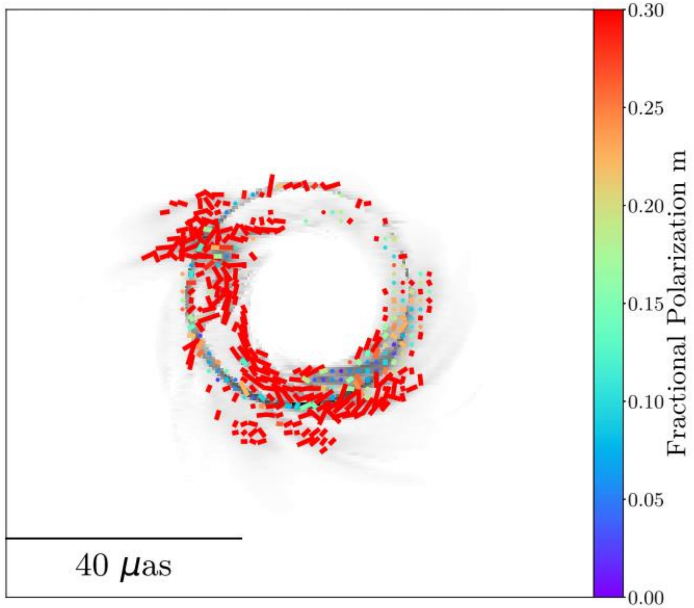
(Internal) Faraday rotation matters!

'infinite' resolution

Without Faraday rotation



With Faraday rotation



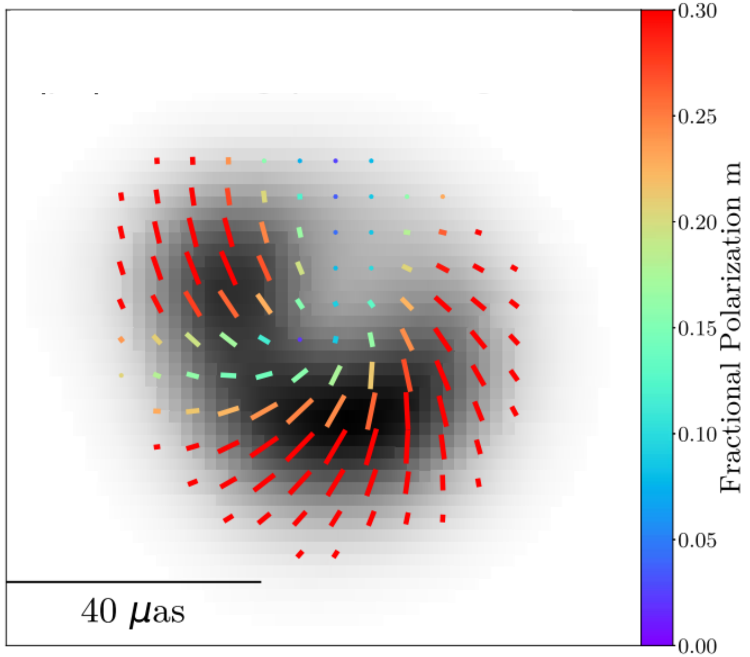
- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

Credit: EHTC 2021 Paper VIII

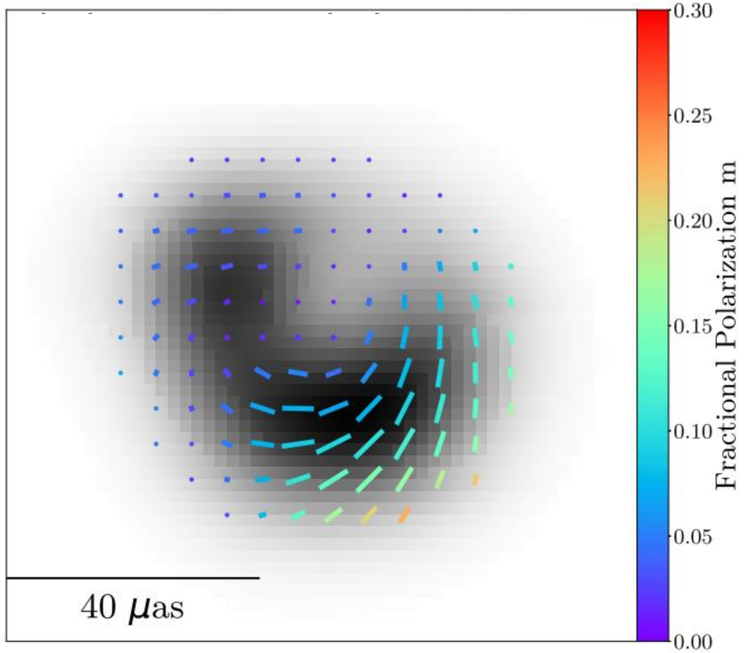
(Internal) Faraday rotation matters!

at EHT resolution

Without Faraday rotation



With Faraday rotation

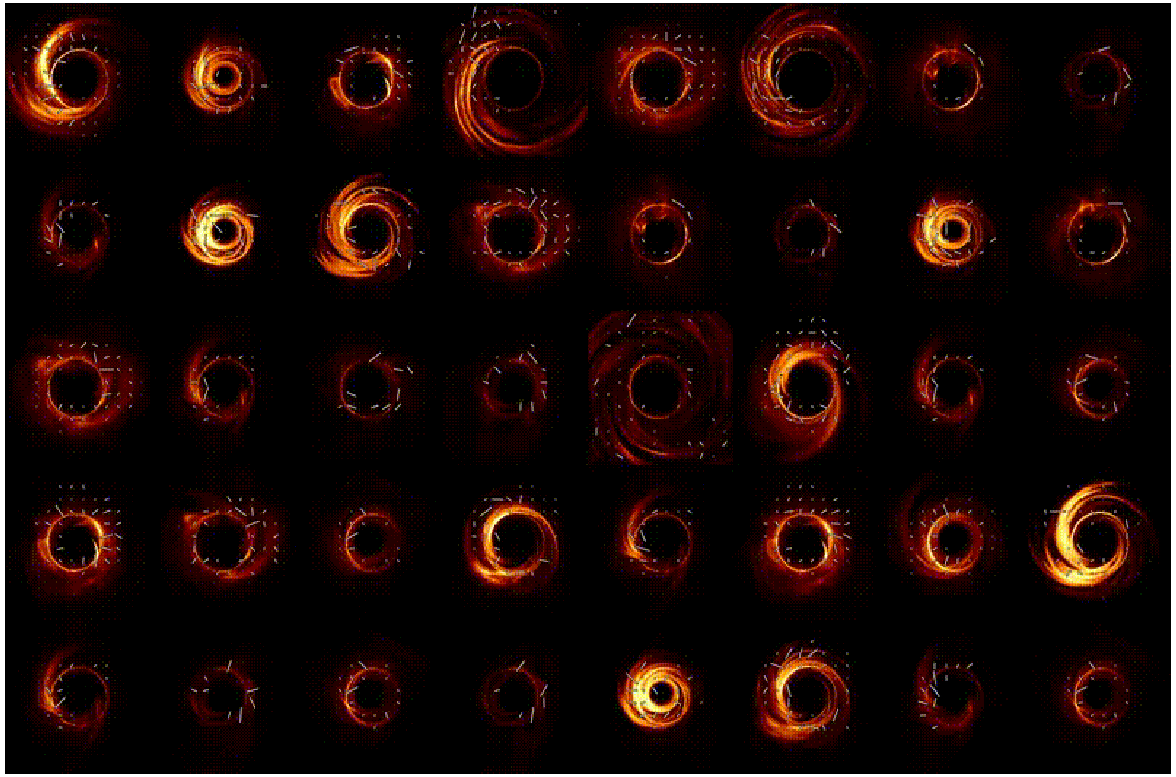


- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **depolarizes and rotates** the image when blurred to EHT resolution

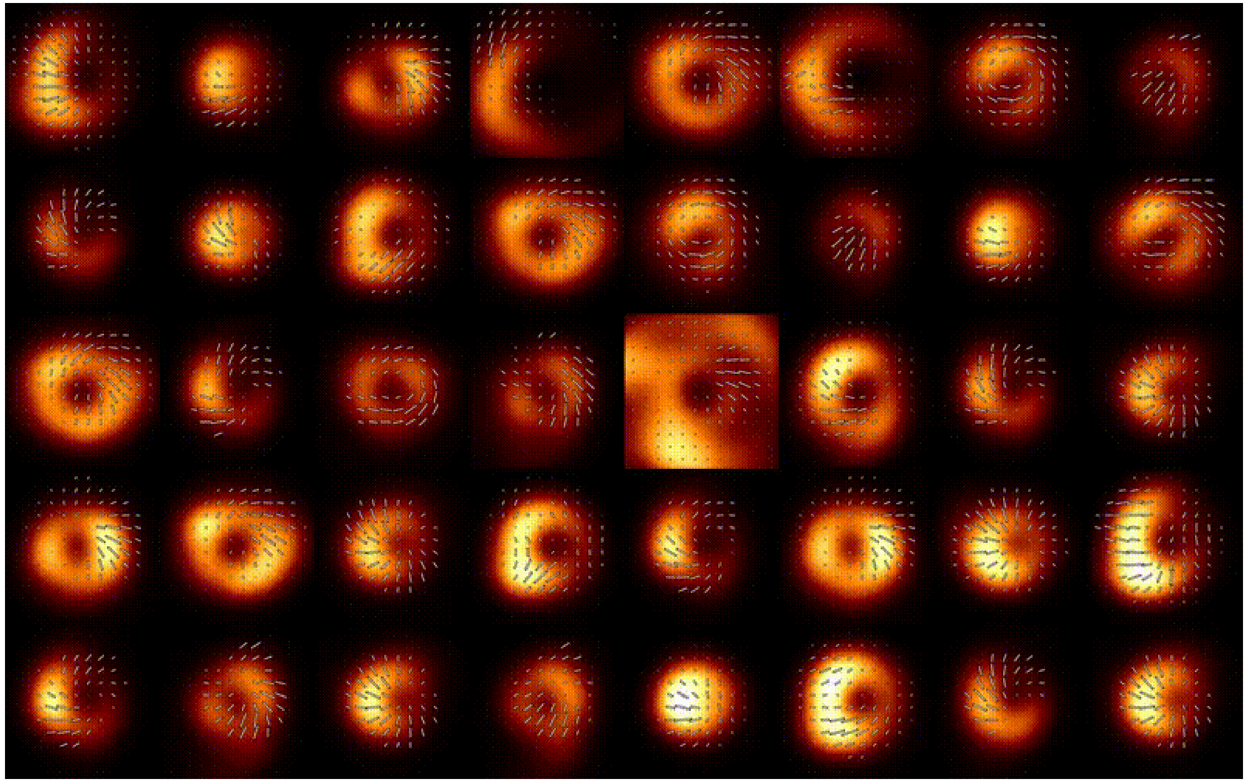
    This means the emitting plasma is not (completely) made of pairs!

EHTC+ 2021 Paper VIII (**Chael**, paper coordinator)

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



“infinite” resolution



EHT resolution

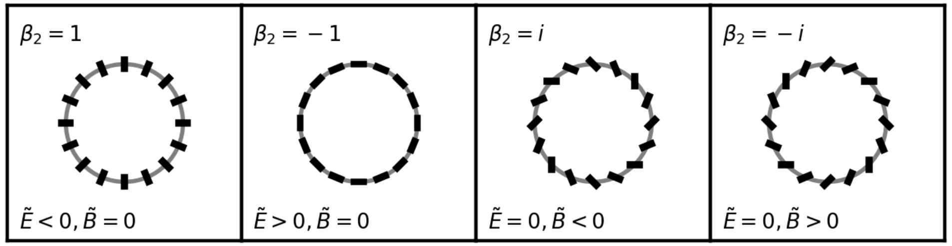
Light-bending and Faraday effects are built in (`ipole` code, Mościbrodzka et al. 2016)

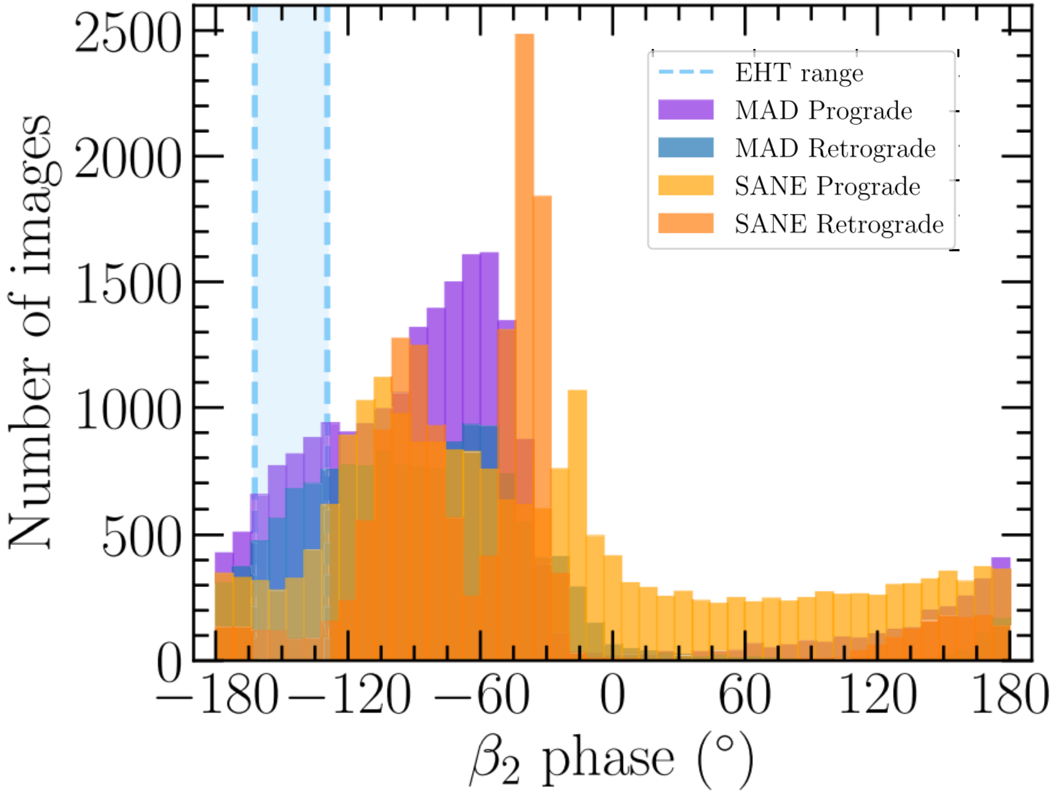
EHTC+ 2021 Paper VIII (**Chael**, paper coordinator)
Animation Credit: Ben Prather

Scoring a polarized image

- We compare EHT images to GRMHD images using several summary statistics
- These metrics include the total and average polarization fraction
- The **most constraining metric** is the 2nd Fourier coefficient characterizing the azimuthal structure:

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho,\varphi)\, e^{-2i\varphi}\; \rho\, d\varphi\, d\rho$$





Palumbo+ 2020
EHTC+ 2021 Paper VIII (**Chael**, paper coordinator)

Polarimetric simulation scoring

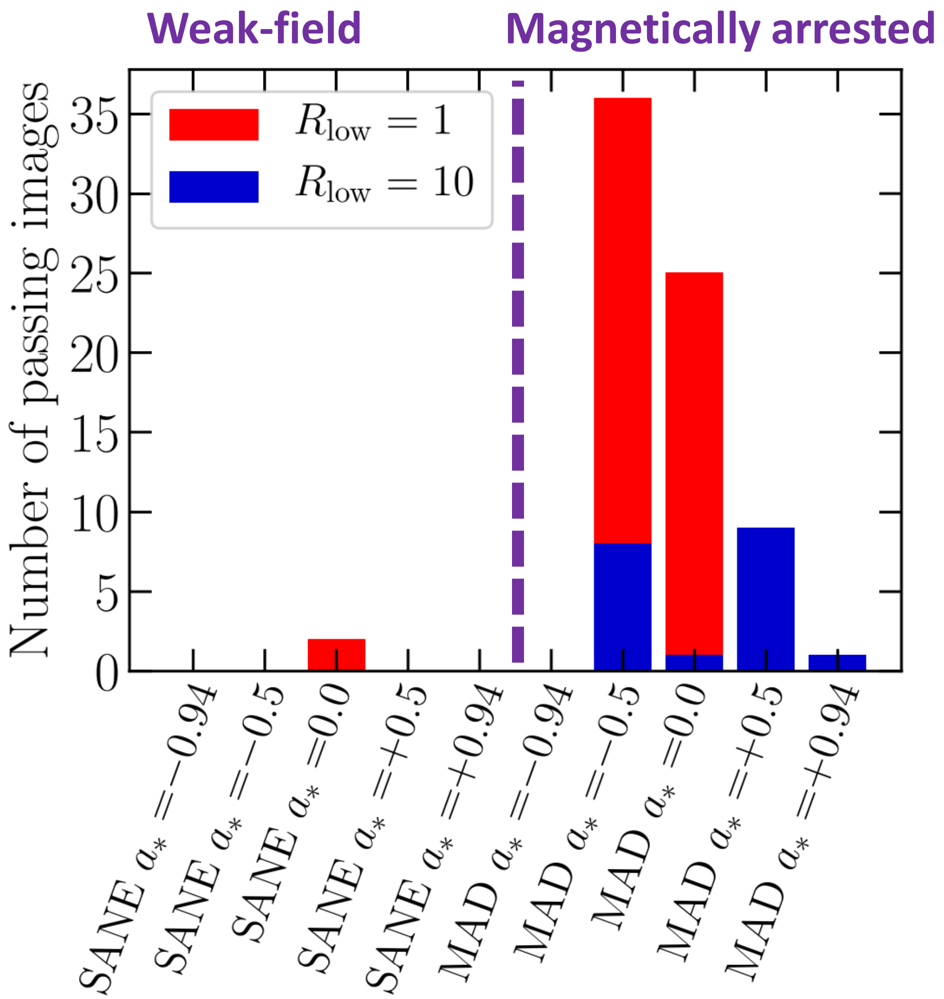
- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**

- Implications for accretion and jet launching:
  - Narrows M87*’s allowed accretion rate by 2 orders of magnitude:

$$\dot{M} \simeq (3-20) \times 10^{-4} M_{\odot}\ \mathrm{yr}^{-1}$$

$$\left(\dot{M}_{\mathrm{Edd}} = 137 M_{\odot}\ \mathrm{yr}^{-1}\right)$$

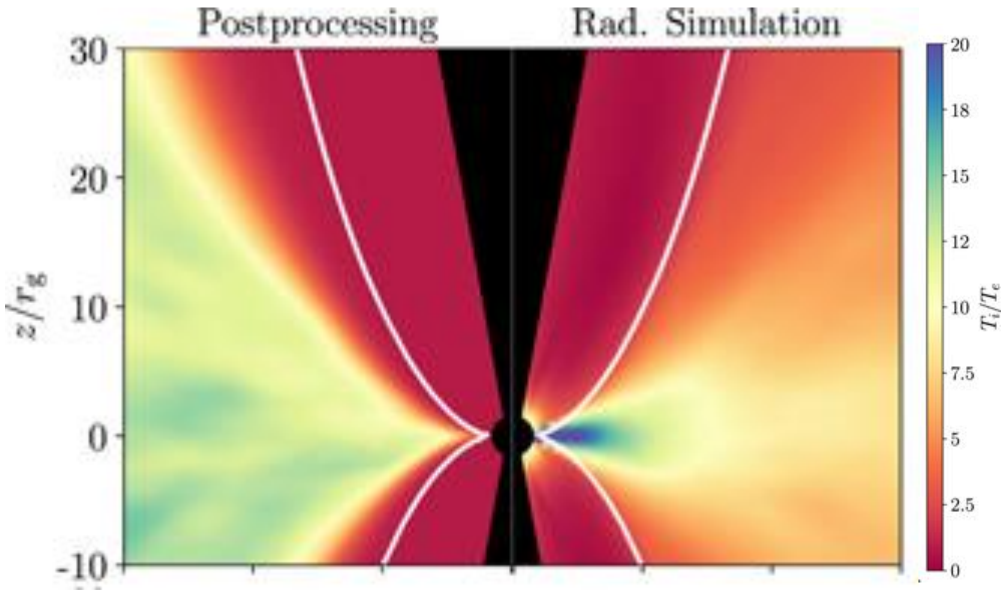
  - Strong fields **more easily launch jets** at lower values of BH spin



EHTC+ 2021 Paper VIII (**Chael**, paper coordinator)

Electron Heating and Cooling

ion-to-electron temperature ratio



Simulations with radiation & heating can produce very different emission profiles than are found in postprocessing techniques!

- M87* and Sgr A* have two-temperature plasmas

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

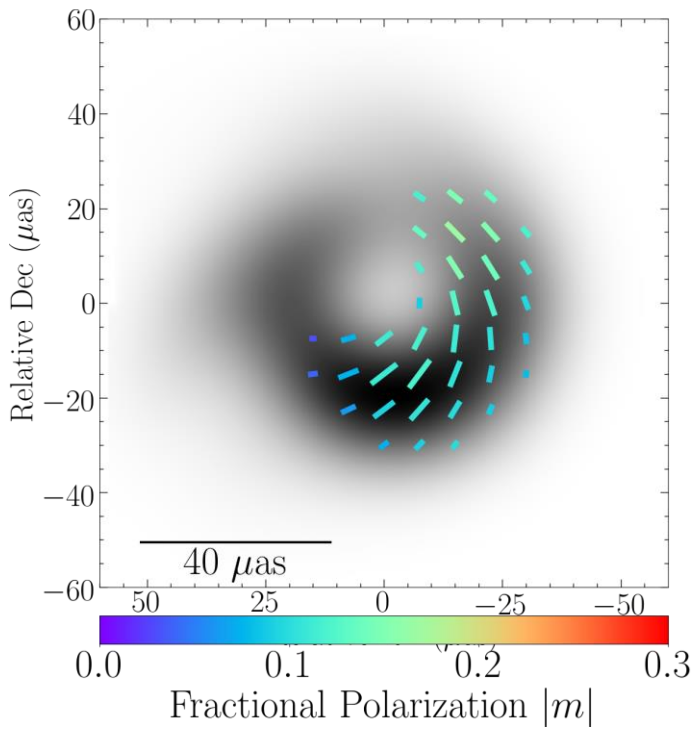
- EHT analysis fixes T_e locally in **postprocessing:**
  - **Major uncertainty** in EHT analysis
  - Most GRMHD simulations **don't produce bright jets!**

- Radiative, Two-Temperature GRMHD includes **heating and cooling self-consistently**:
  - Sub-grid plasma heating model still uncertain

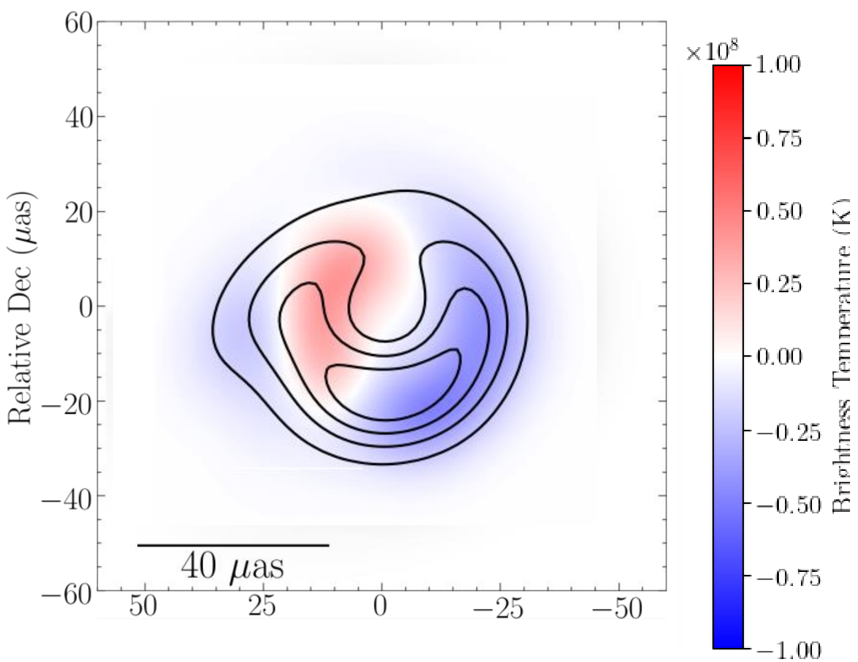
Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019, 2023 (in prep),** Dexter+ 2020,2021, Mizuno+ 2021

Very Soon: Circular Polarization

Linear polarization (simulation)



Circular polarization (simulation)



- Circular polarization in models can better constrain plasma properties, including particle composition
- Stay tuned!

EHTC Paper IX in prep (**Chael**, coordinator)

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

Chael+2019, 2021, 2023
arXiv: 1810.01983, 2106.00683, 2210.12226

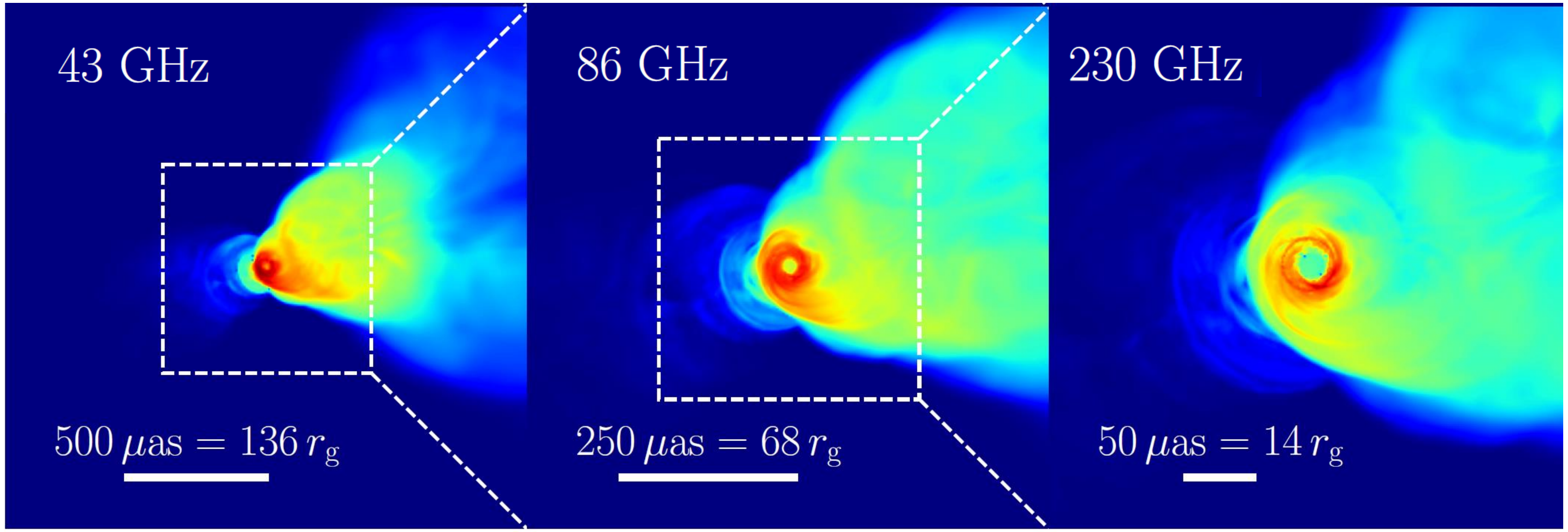
M87 Jets from two-temperature Simulations

Jets from magnetically arrested **two-temperature** simulations naturally produce:

- jet power in measured range
- observed wide opening angle
- observed core-shift

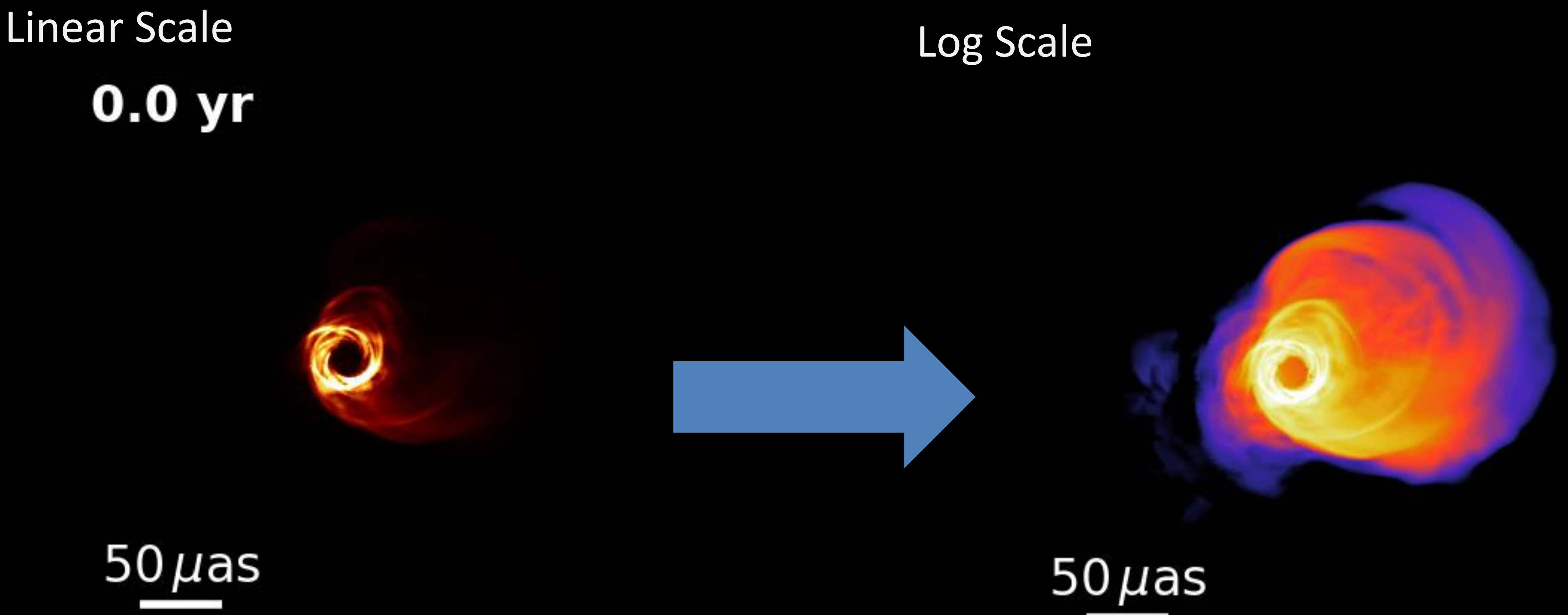
The observed limb-brightening is hard to reproduce

- Nonthermal distributions?



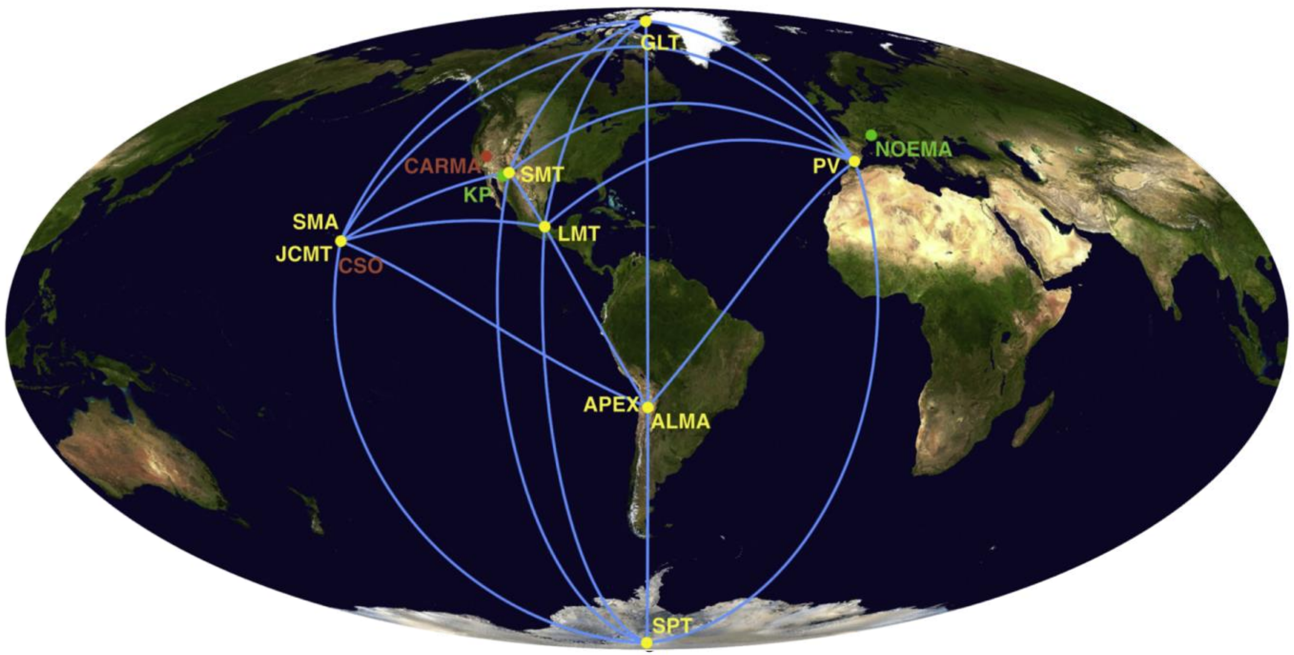
Chael+ 2019

The black hole-jet connection at 230 GHz

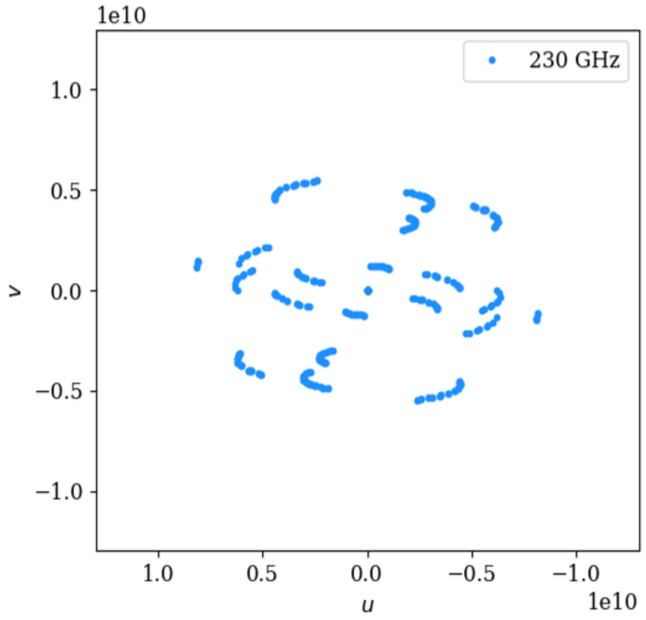


Chael+ 2019

2017 EHT observations



Fourier plane coverage

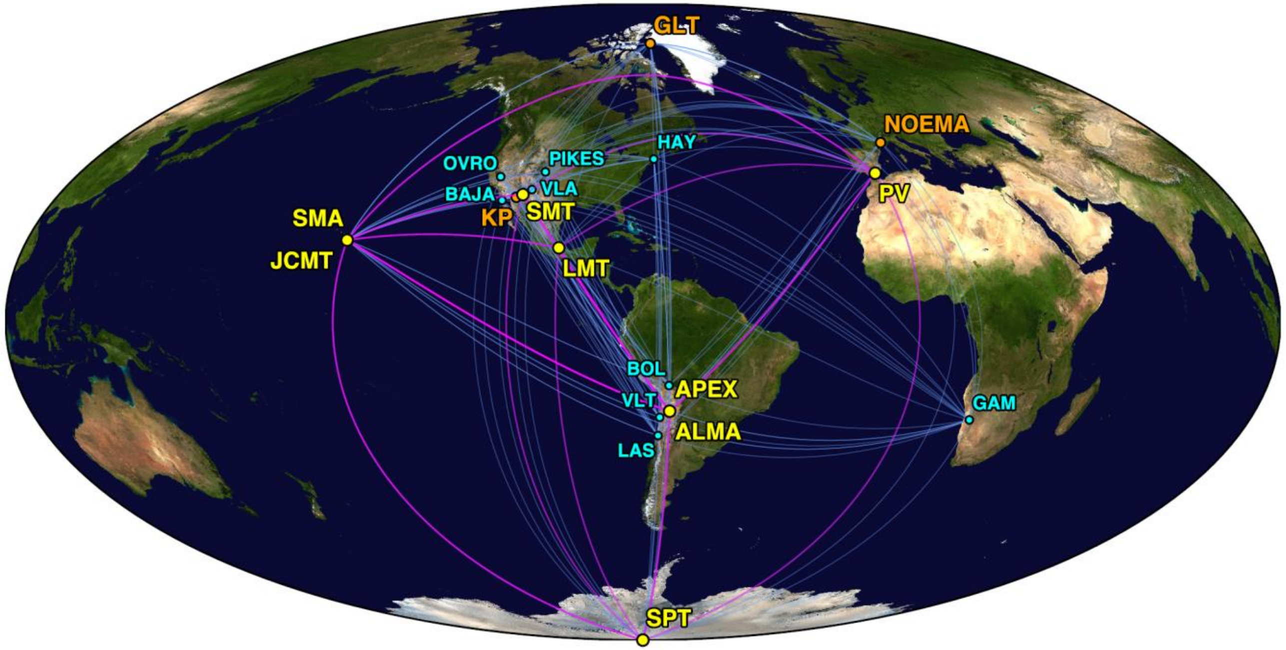


Adding 345 GHz will increase **resolution**

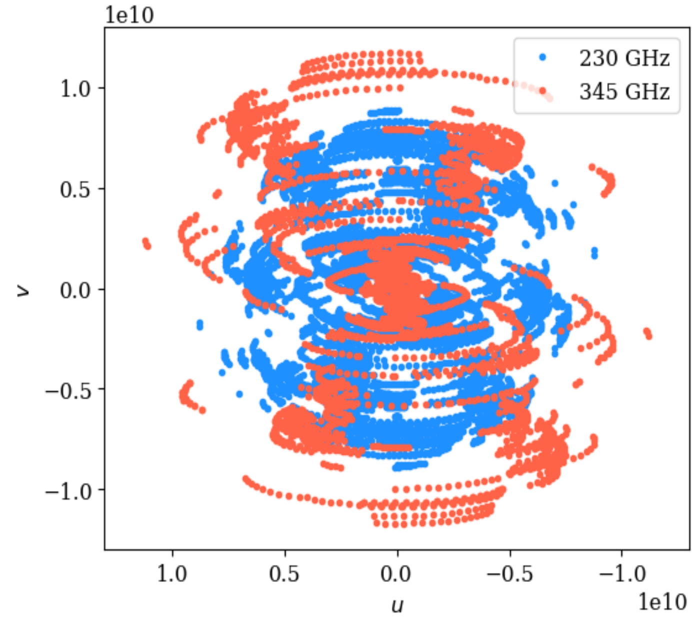
Increased (u,v) filling from new sites in ngEHT will enhance **dynamic range**

EHTC+ Paper II, 2019

The next-generation EHT (ngEHT)



Fourier plane coverage



Adding 345 GHz will increase **resolution**

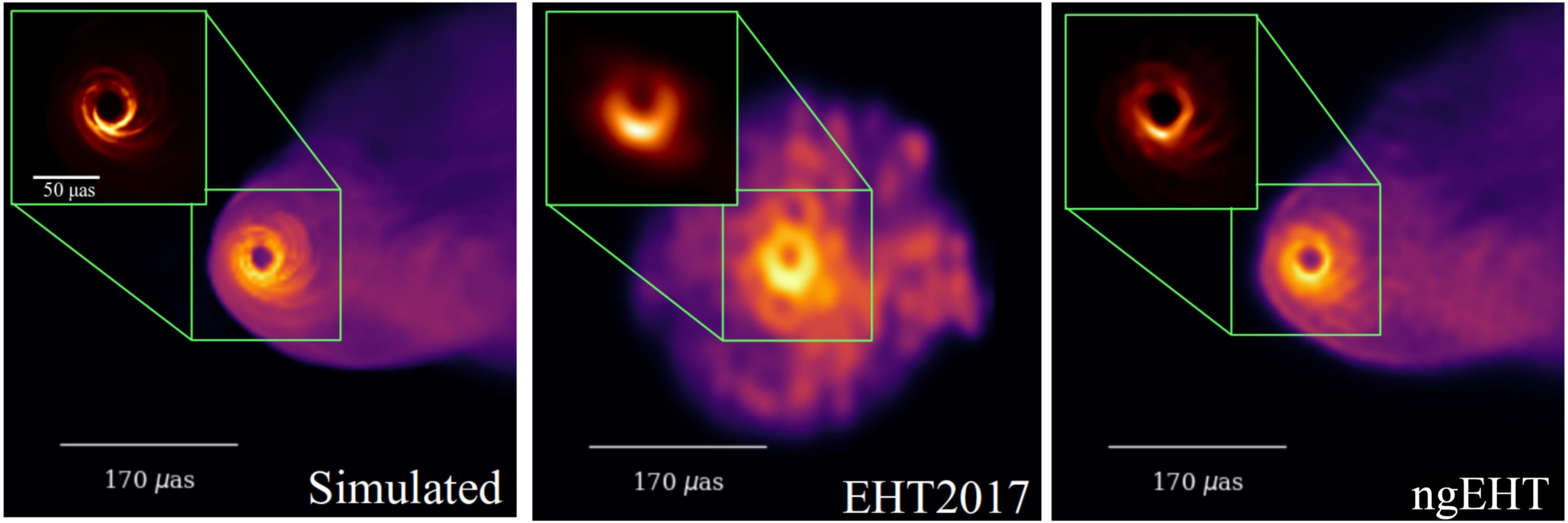
Increased (u,v) filling from new sites in ngEHT will enhance **dynamic range**

2017: Observations at 6 distinct sites
2018: Observations at 7 sites (+ GLT)
2021-2022: Observations at 9 sites (+ Kitt Peak & NOEMA)

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

EHT Ground Astro2020 APC White Paper
(Blackburn+ 2019; arXiv:1909.01411)

ngEHT: a high dynamic range black hole imager

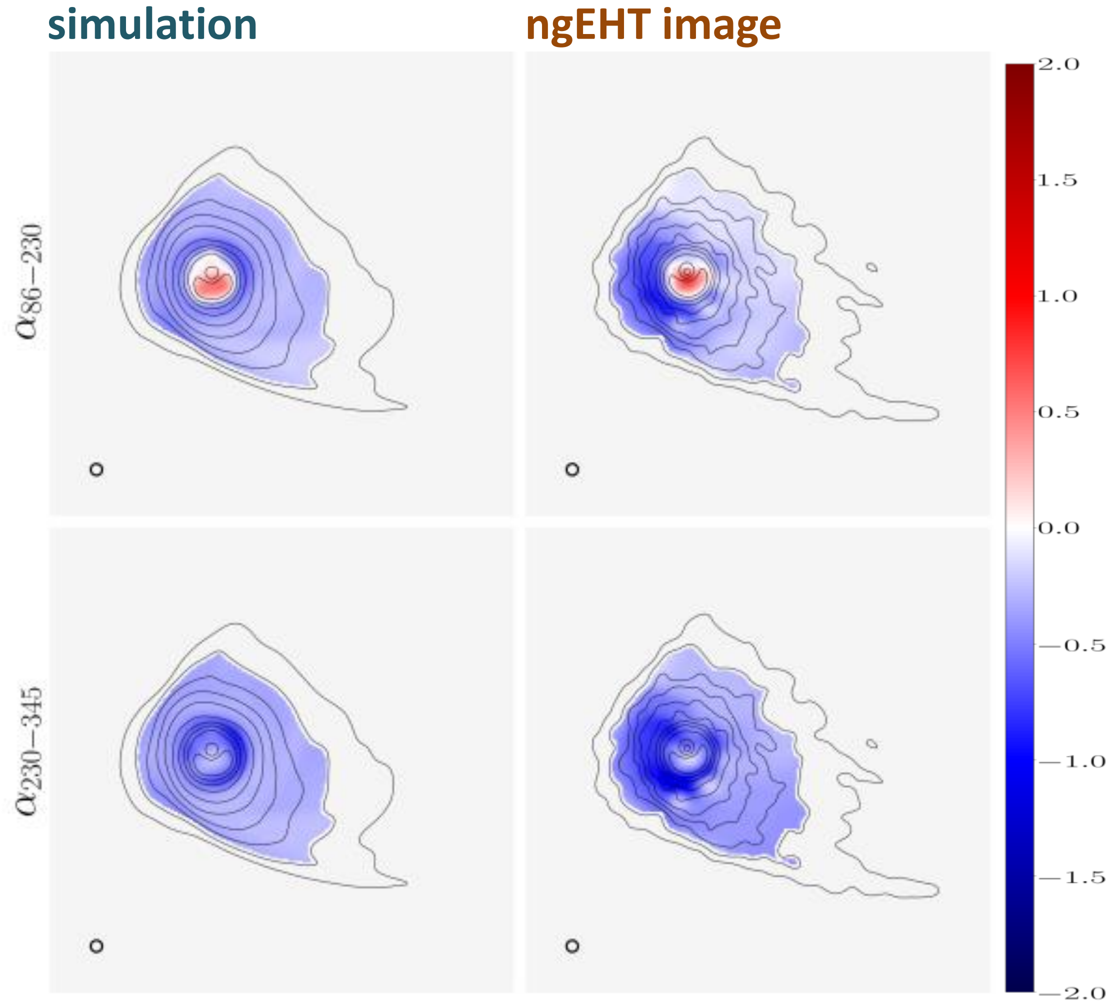


- Increased (*u,v*) filling from new telescope sites in ngEHT will enhance image **dynamic range**
  - High dynamic range images will illuminate the **BH-jet connection**
  - High dynamic range images may also reveal the **'inner shadow'**

Figure: Blackburn+ 2019
Simulation & Imaging: **Chael**+ 2019

Multifrequency near-horizon imaging with the ngEHT

Spectral Index Reconstruction

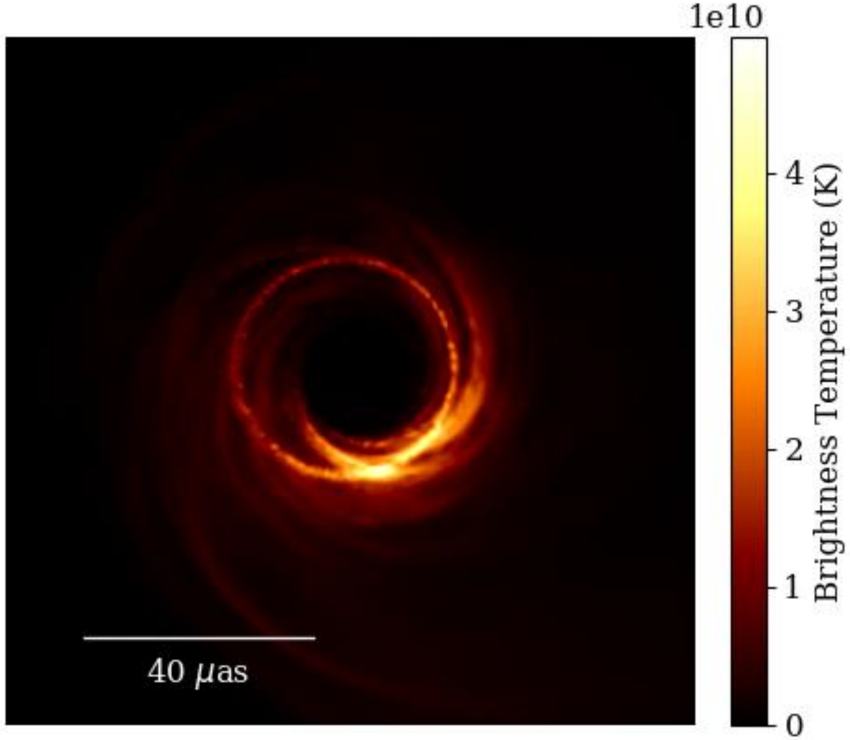


Multi-frequency ngEHT images can probe the **electron temperature and distribution function** in the disk, jet, and interface

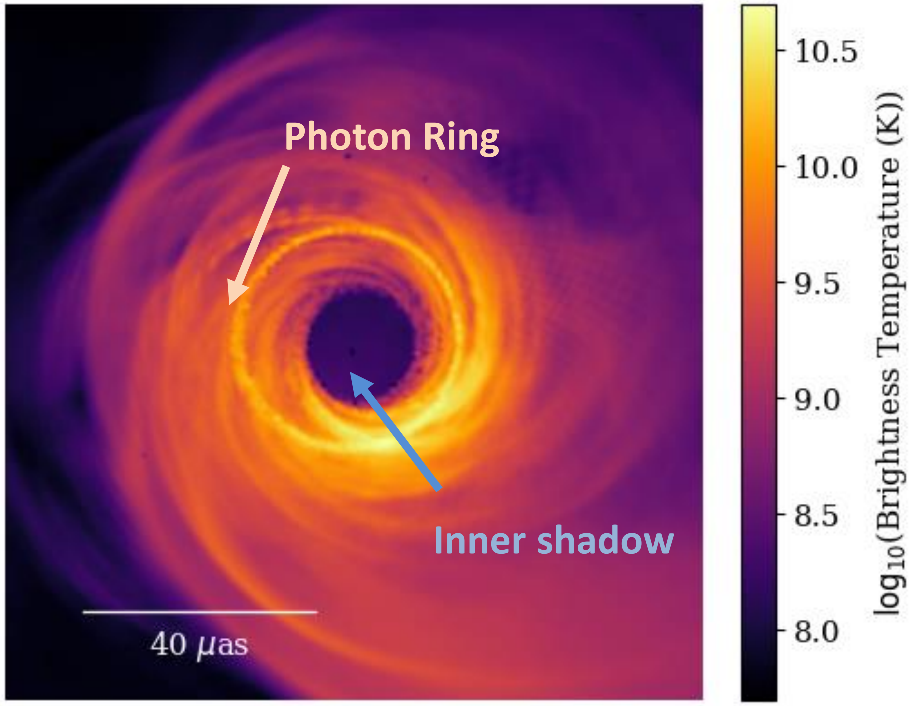
Chael+ 2023
Simulation: Mizuno+ 2021

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

High-dynamic-range near the horizon: the inner shadow



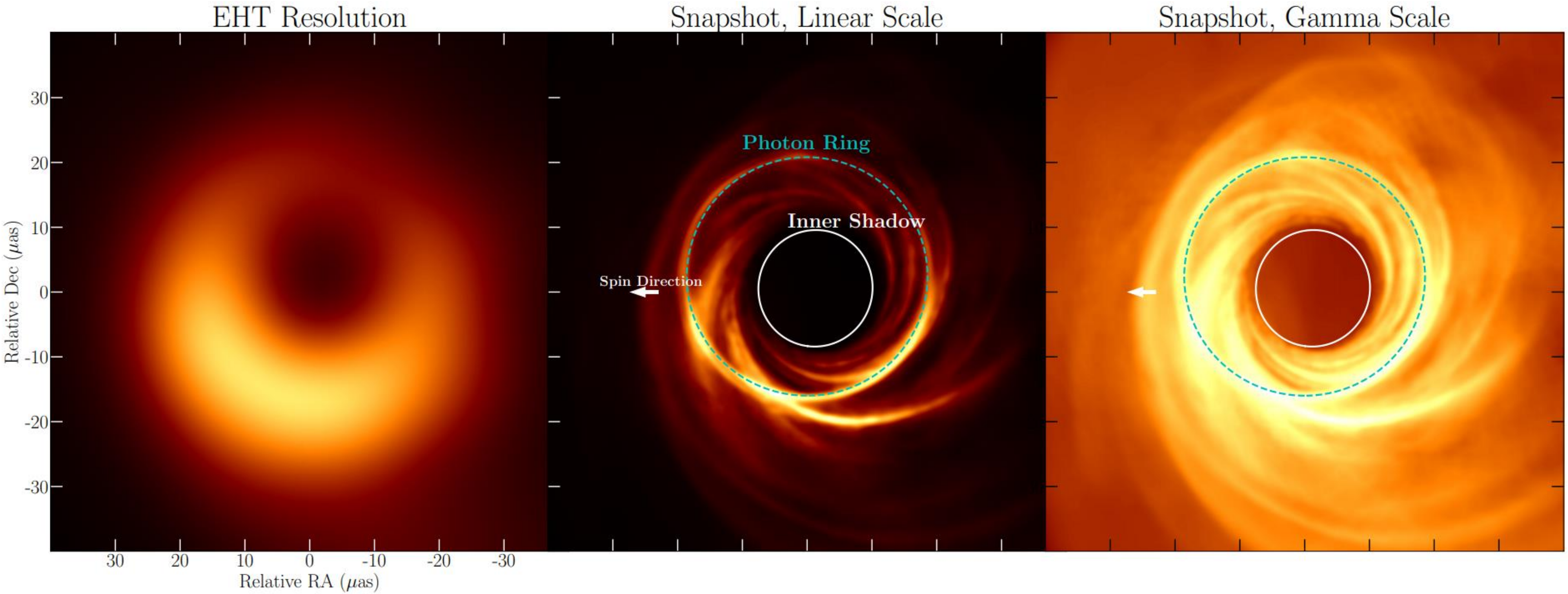
Linear scale



Log scale

Chael+ 2021, arXiv 2106.00683

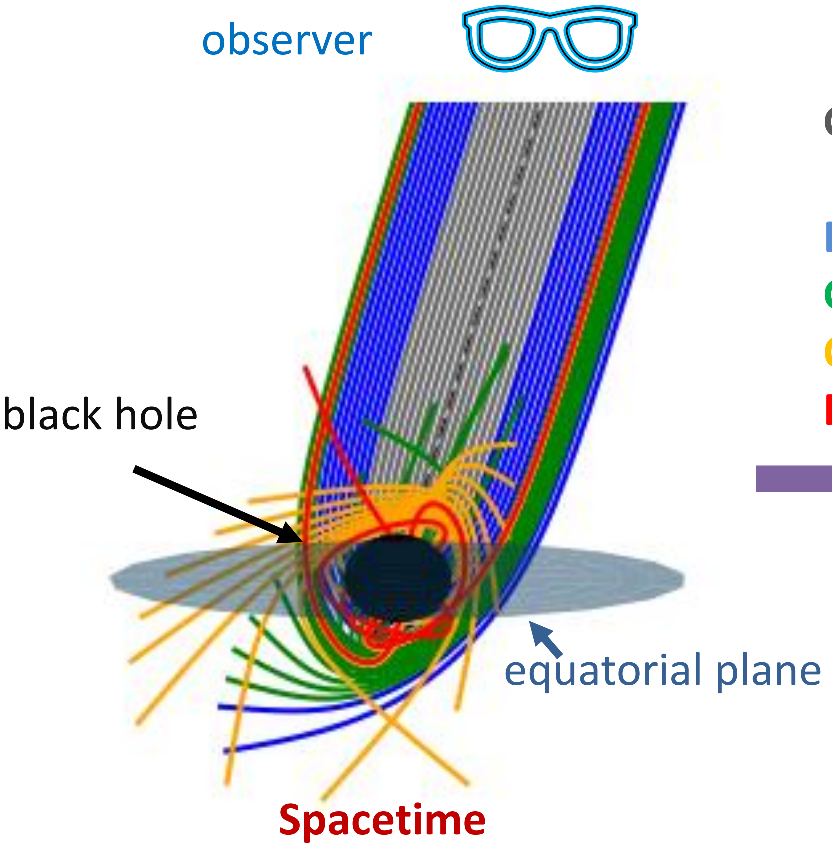
Inner shadow in magnetically arrested simulation images



- The inner shadow is **lensed image of the equatorial event horizon**
- Redshift means the edge of the inner shadow in real images only asymptotically approaches the horizon
- the correspondence becomes better at higher dynamic range

Chael+ 2021

Black hole image substructure: photon rings and the inner shadow



Gray – never cross the equatorial plane,
form the **'inner shadow'**

Blue – cross once (direct image)

Green – cross twice (1st photon ring)

Orange – cross 3x (2nd photon ring)

Red – cross 4x (3rd photon ring)

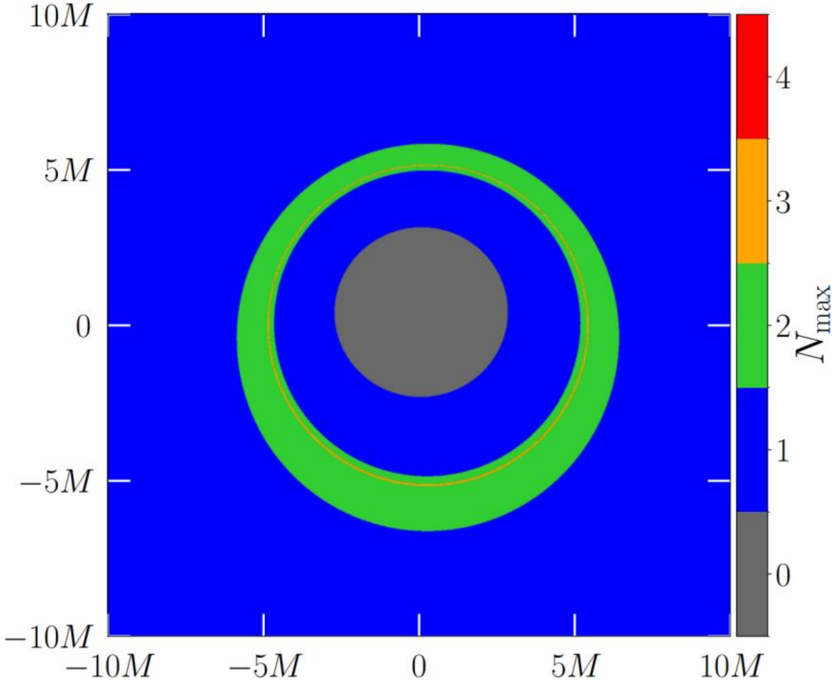
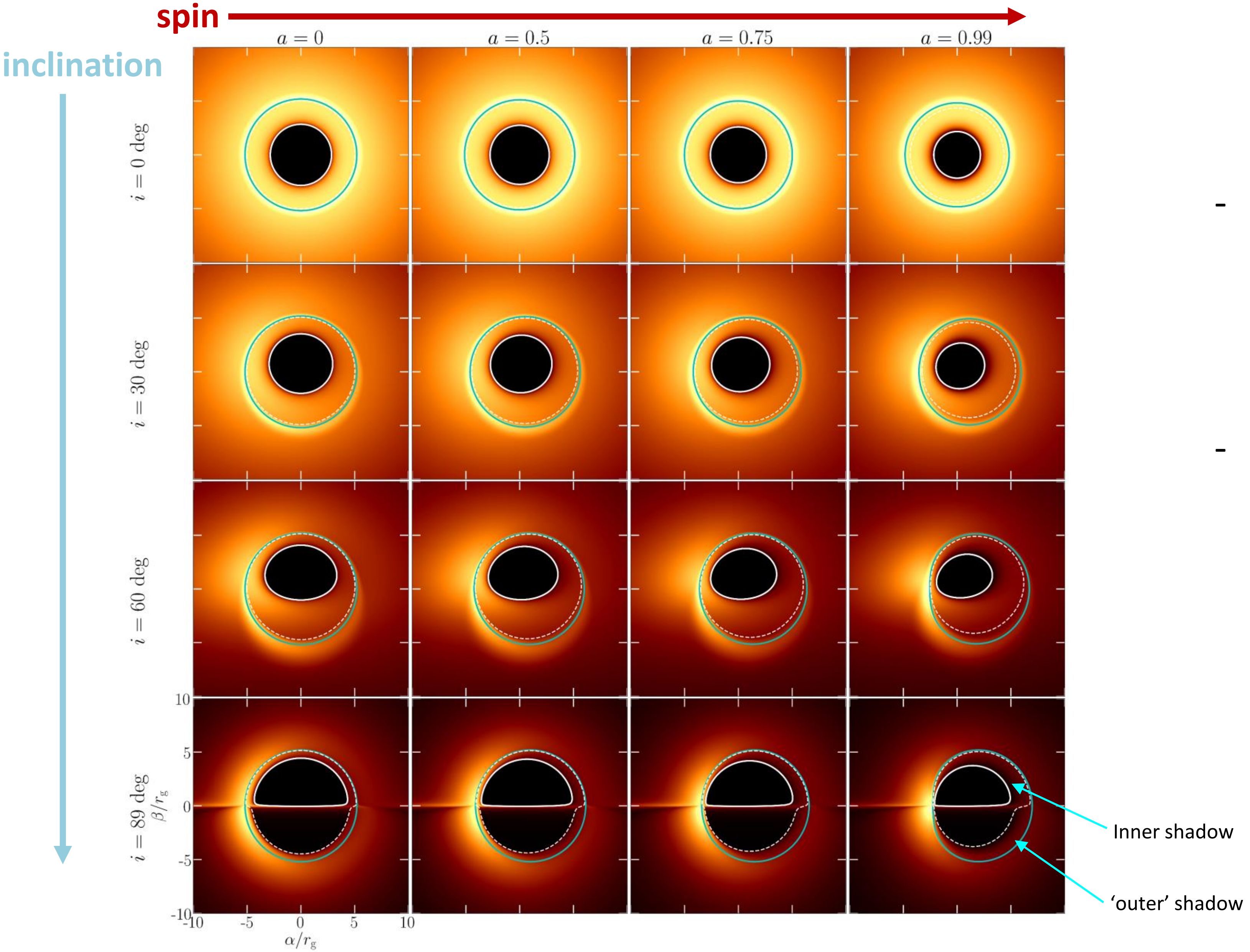


Image plane

Chael+ 2021, Levis+ 2022

Plots from my code **`kgeo`**: https://github.com/achael/kgeo

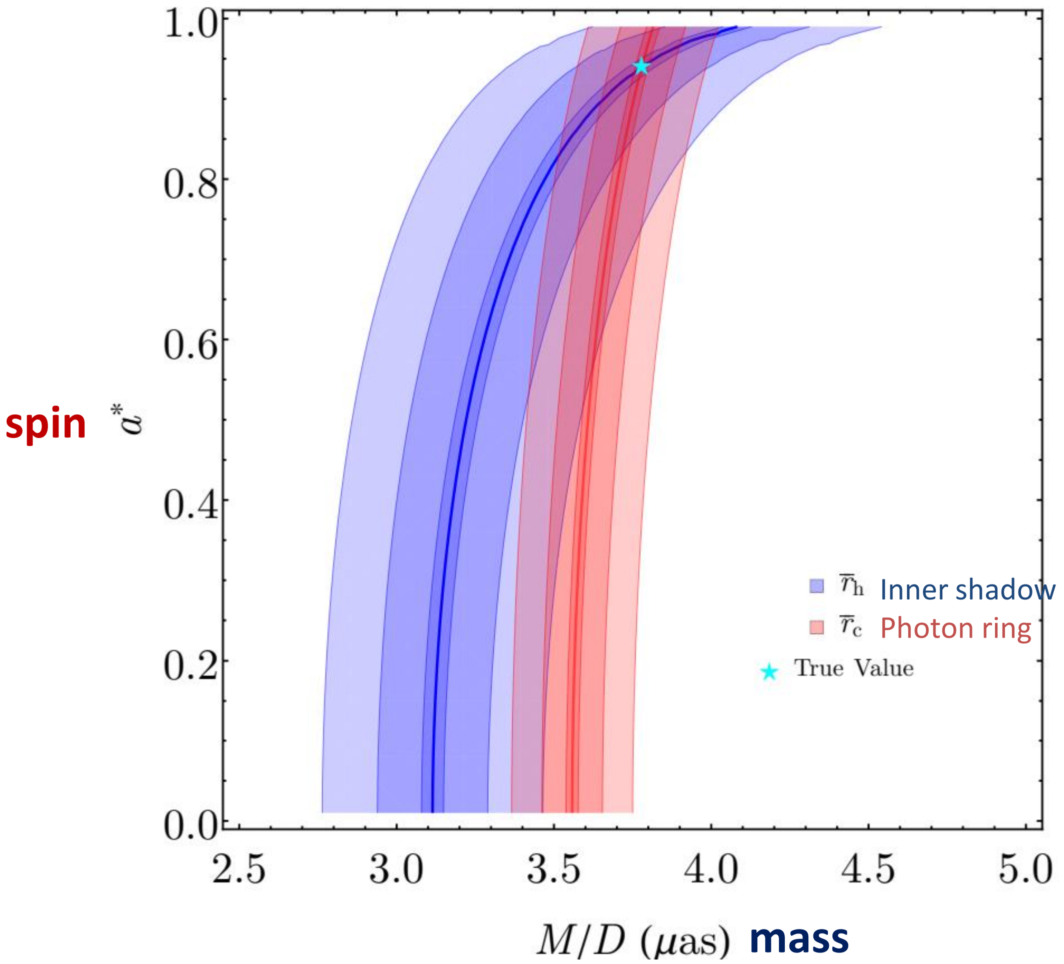
Inner shadow images provide another probe of spacetime



- 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 the photon ring / "outer" shadow

Chael+ 2021

Inner shadow images provide another probe of spacetime



Toy example of determining mass and spin with inner shadow (blue) and photon ring (red) radius measurements for **M87***

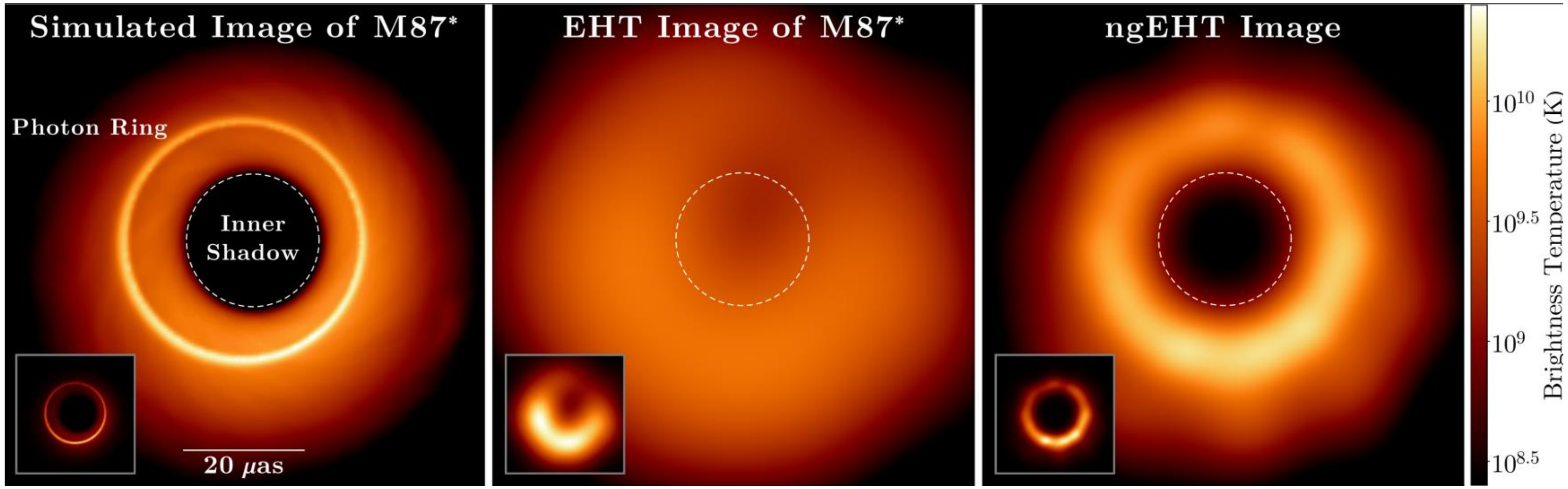
(bands represent measurement uncertainties of 0.1, 0.5, 1 uas)

With **two** curves in the image (the inner shadow and photon ring), we can measure **relative sizes** (and positions), removing degenercies in estimating mass & spin

Chael+ 2021

ngEHT should detect the inner shadow

- New fast, GPU-accelerated Bayesian imaging code comrade (Paul Tiede, CfA)
- **Imaging algorithms can detect the inner shadow in ngEHT data** – analytic modeling may constrain its shape more precisely



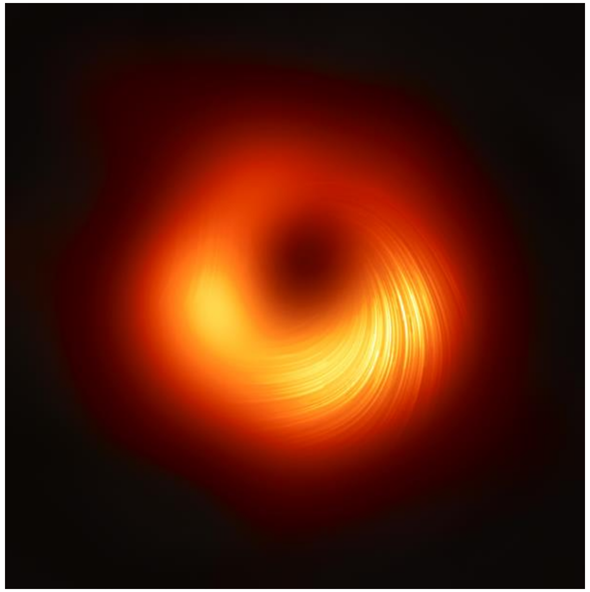
https://github.com/ptiede/Comrade.jl

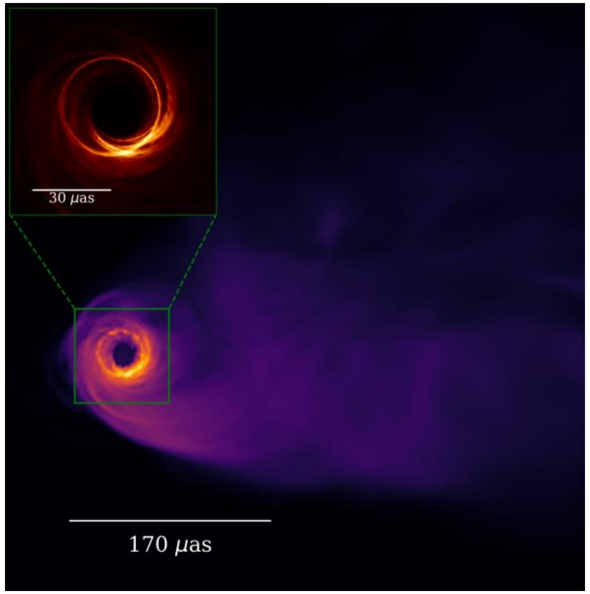
Image credit: Paul Tiede

Conclusion:
The future of black hole imaging is bright

Takeaways…

1. Near-horizon imaging required advances in **algorithms and validation**
    - New techniques have wide applicability to interferometry
2. **Polarization** is the key for near-horizon astrophysics
    - Polarized images strongly constrain the field structure at M87*'s jet base -> the accretion disk is magnetically arrested
3. **We are just getting started** in what we can learn from black hole images
    - Interpreting images of the **black hole-jet connection** will require radiative simulations that correctly light up the jet
    - The ngEHT should see the black hole's **inner shadow**, significantly strengthening EHT spacetime measurements





EHTC+ 2021 Paper VII, **Chael+**2019,2021

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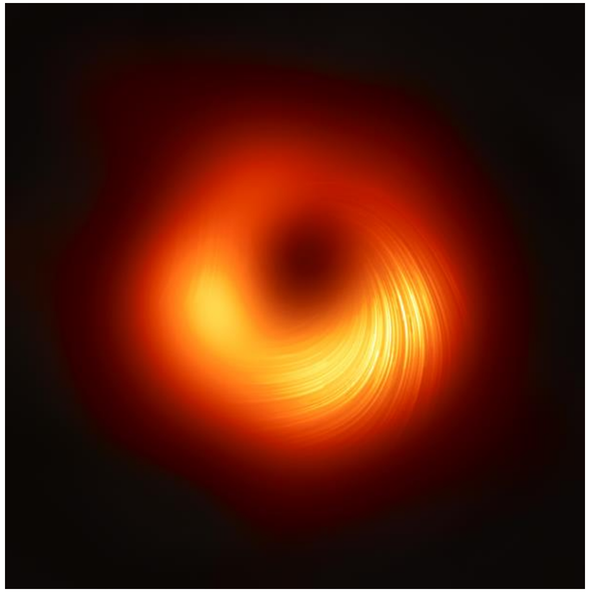
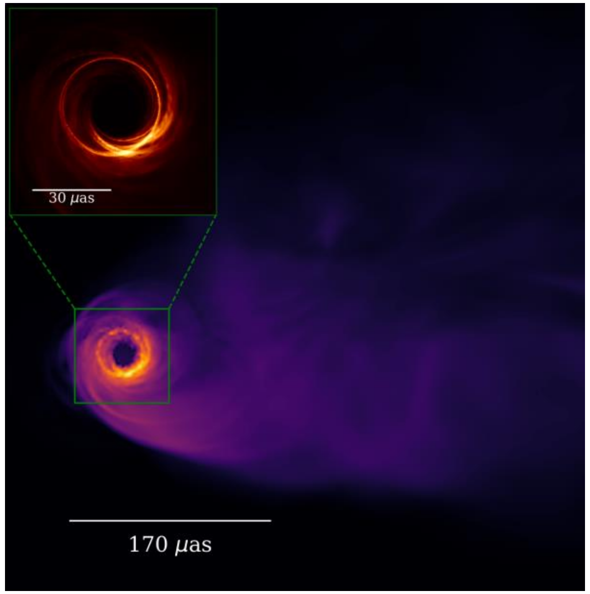


…and more questions

- Can we measure black hole energy extraction in M87*?
- What plasma physics sets the temperature/distribution of the electrons?
- What powers flares in Sgr A* and M87*?
- What can EHT/ngEHT observation tell us about the near-horizon environments of supermassive black holes beyond Sgr A* and M87*?



EHTC+ 2021 Paper VII, **Chael+**2019,2021