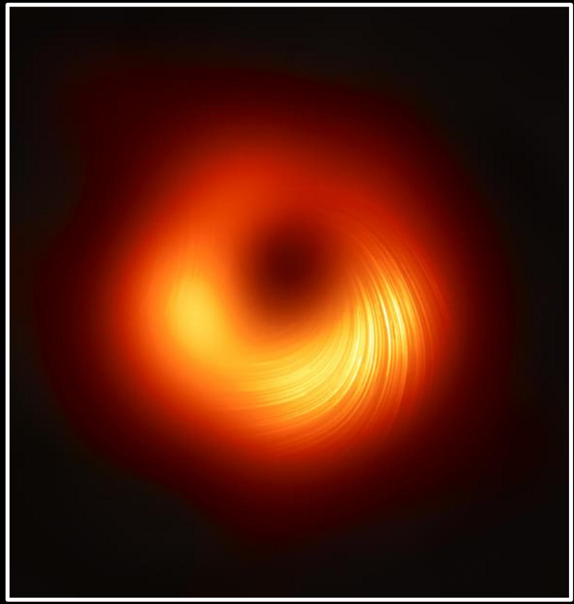
# Black Hole Images with the EHT: Features, Uncertainties, Interpretation

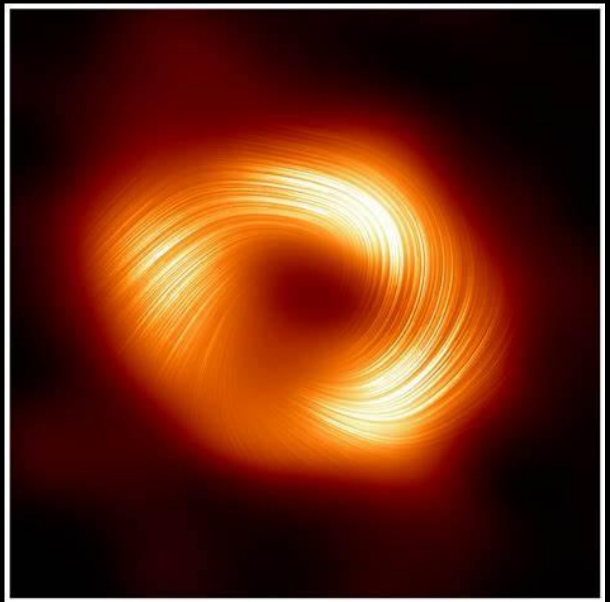

Andrew Chael

Princeton Gravity Initiative


*Black Hole Mimickers: From Theory to Observation*

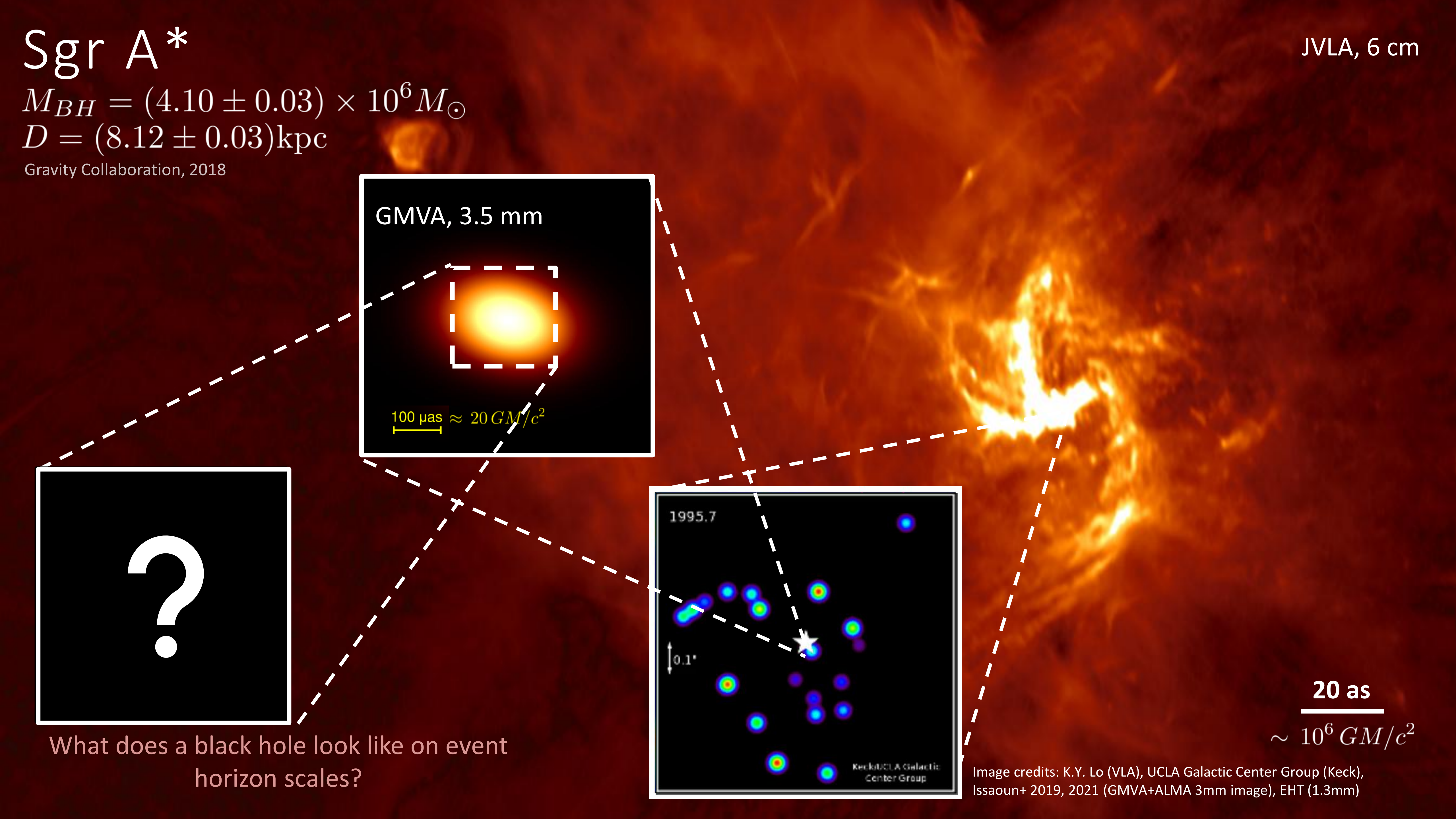
March 3, 2024





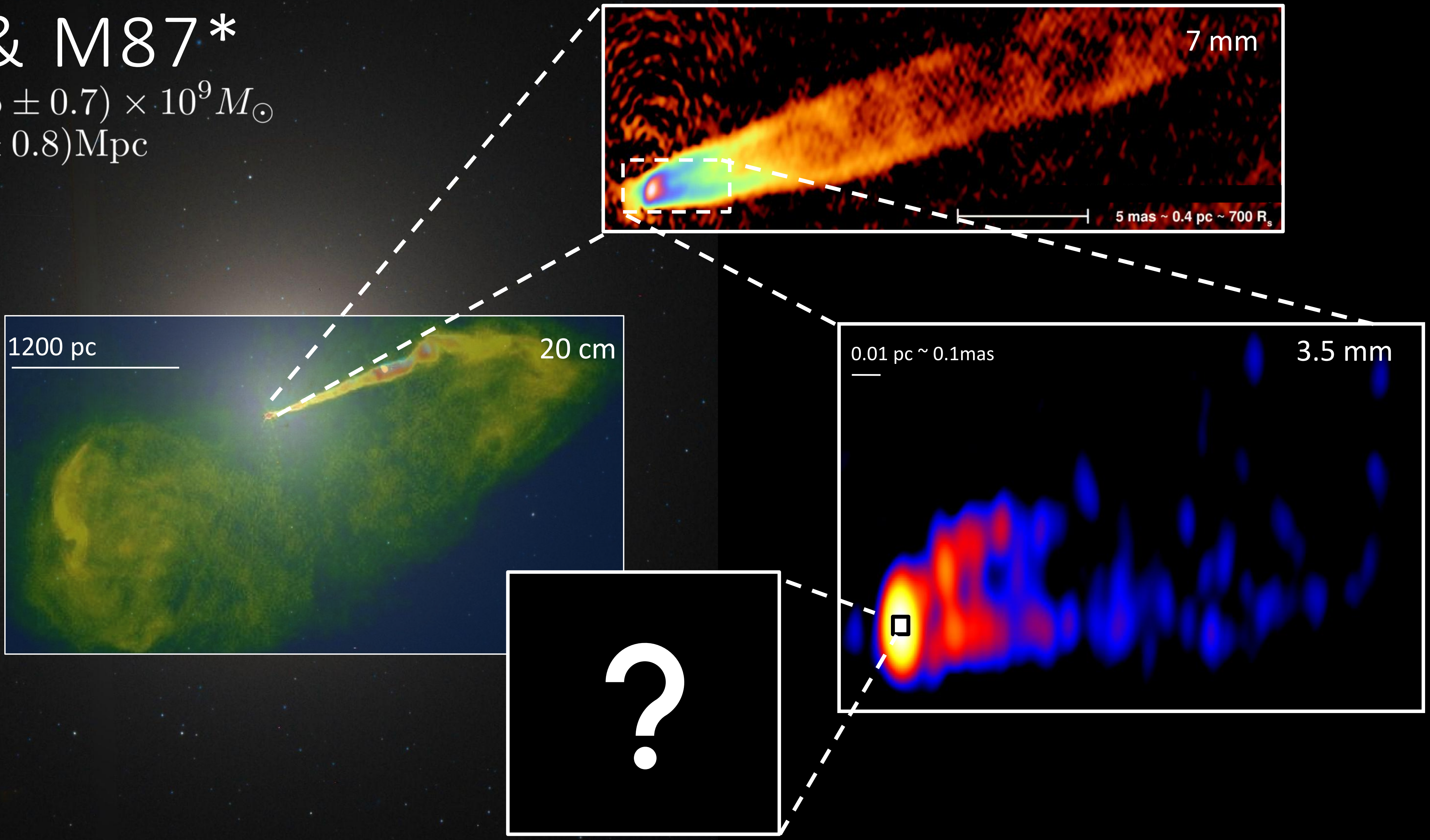
Princeton gravity Initiative

Event Horizon Telescope


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
JVLA, 6 cm
GMVA, 3.5 mm
100 μas $\approx 20\,GM/c^2$
1995.7
0.1"
20 as
$\sim 10^6\,GM/c^2$
?
What does a black hole look like on event horizon scales?
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHT (1.3mm)

# M87 & M87*

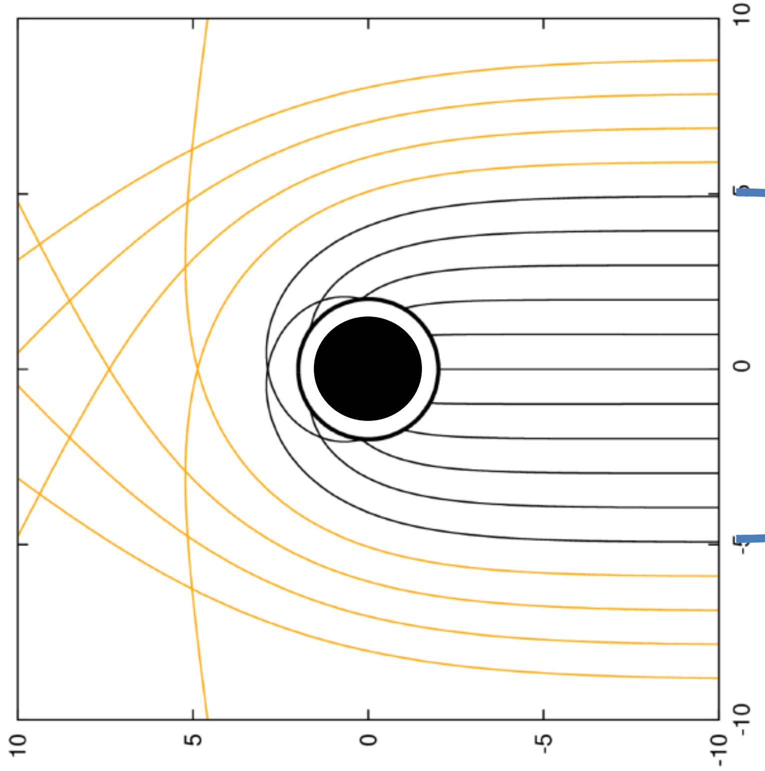
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$



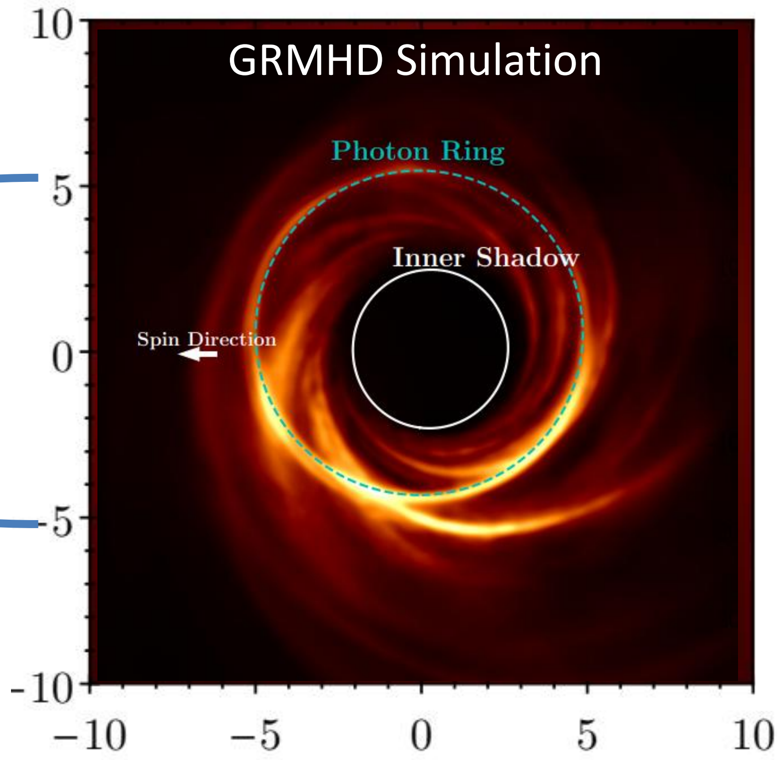

What does a *jet launching* black hole look like on event horizon scales?

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

# The Black Hole Shadow



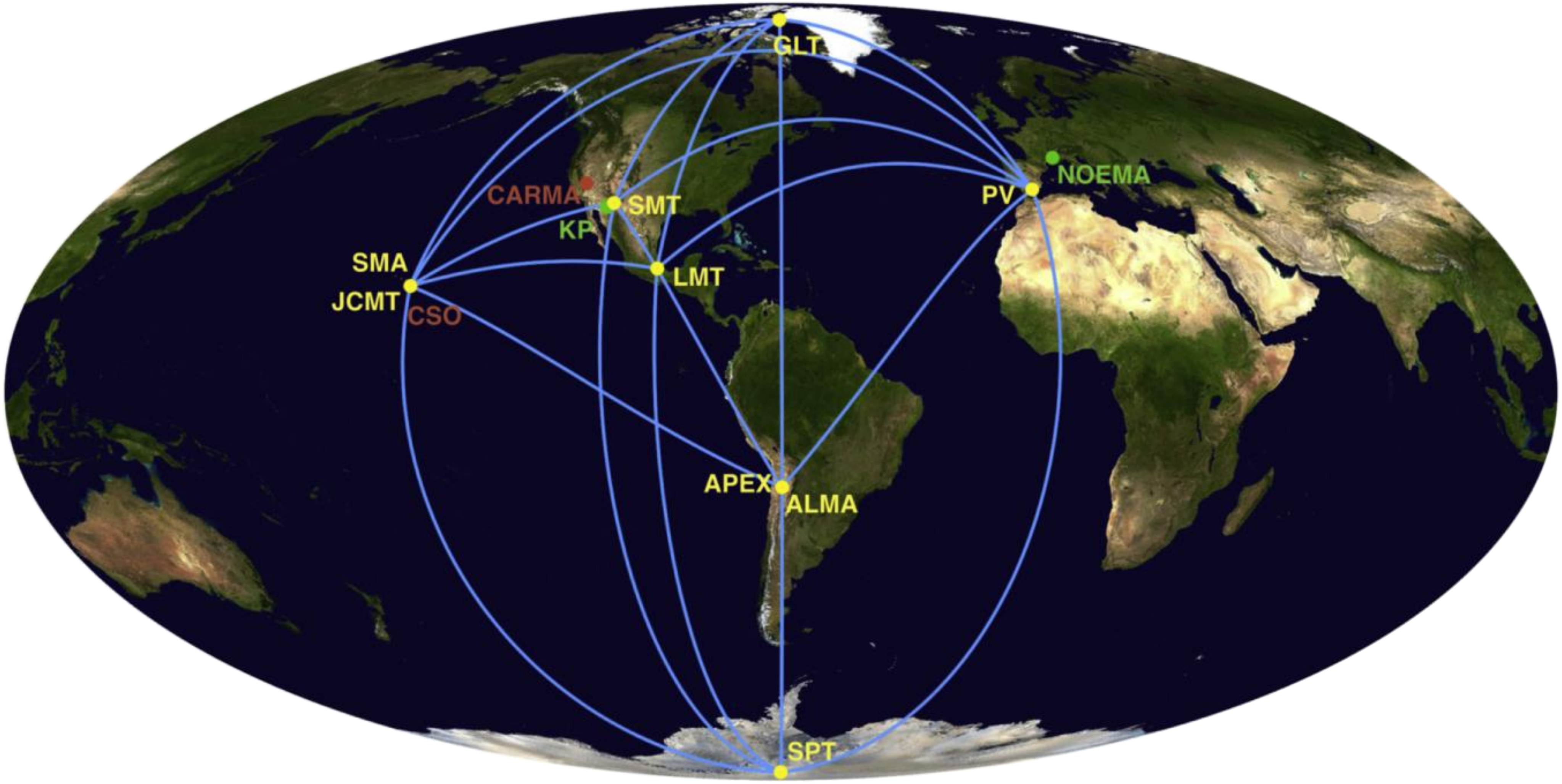
$$d_{\text{shadow}} \approx 5R_S/D$$
$$\approx 40\,\mu\text{as for M87}^*$$




Shadow sizes on the sky:
Sgr A*: 50 µas → 1.4 x $10^{-8}$ degrees
M87*: 40 µas → 1.1 x $10^{-8}$ degrees

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+ II, 2019

# M87 & M87*

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

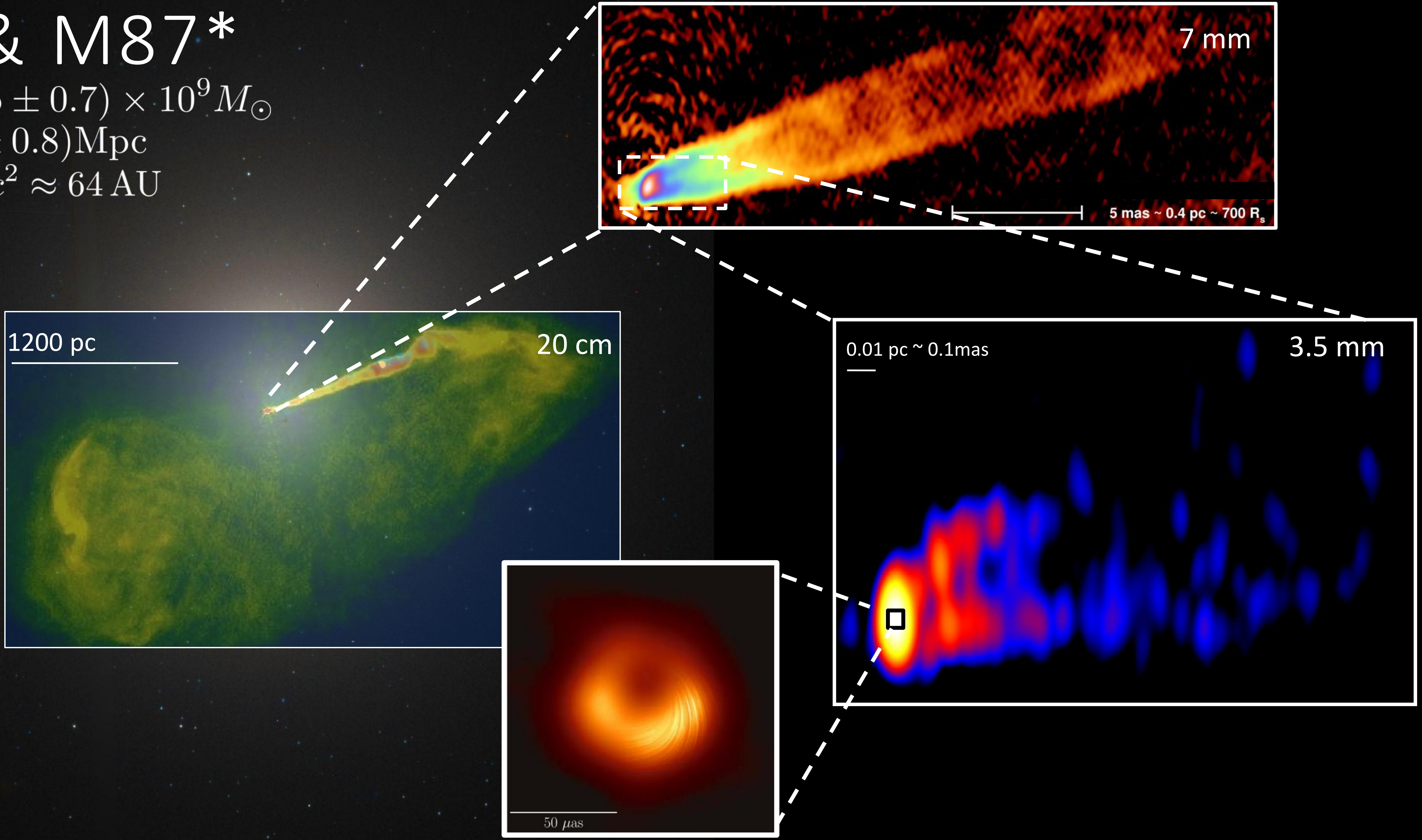
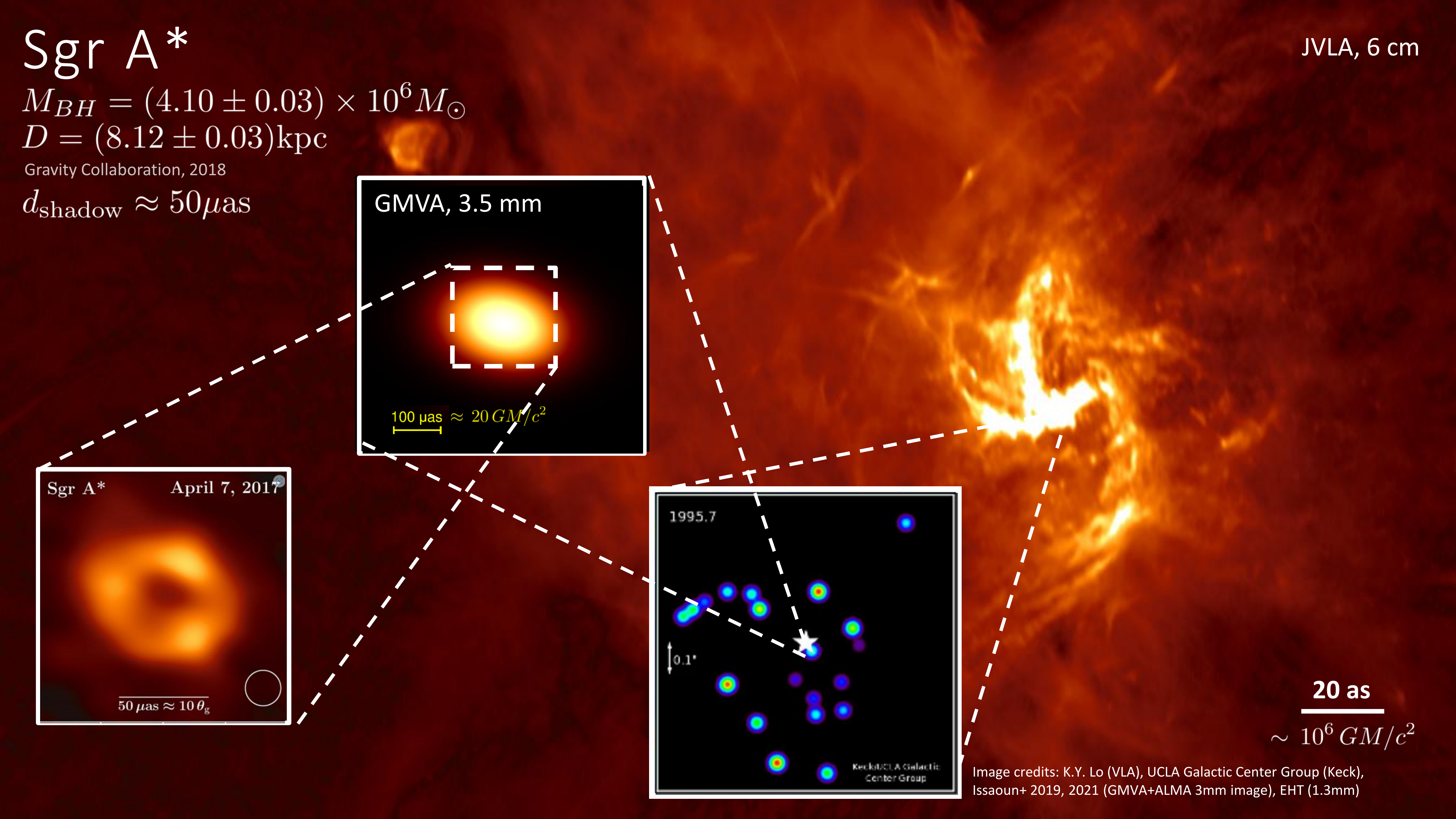



Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)


Sgr A*
$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
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Gravity Collaboration, 2018
$d_{\mathrm{shadow}} \approx 50\mu as$
JVLA, 6 cm
GMVA, 3.5 mm
100 μas $\approx 20\, GM/c^2$
Sgr A* April 7, 2017
$50\,\mu as \approx 10\,\theta_g$
1995.7
0.1"
Keck/UCLA Galactic Center Group
20 as
$\sim 10^6\, GM/c^2$
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHT (1.3mm)

# Outline

1. How does the EHT image black holes?
2. What are the main features of (polarized) black hole images?
3. What is our astrophysical interpretation of EHT images?
4. Some (biased) implications and future directions

# How do we obtain black hole images with the EHT?

# EHT: Array

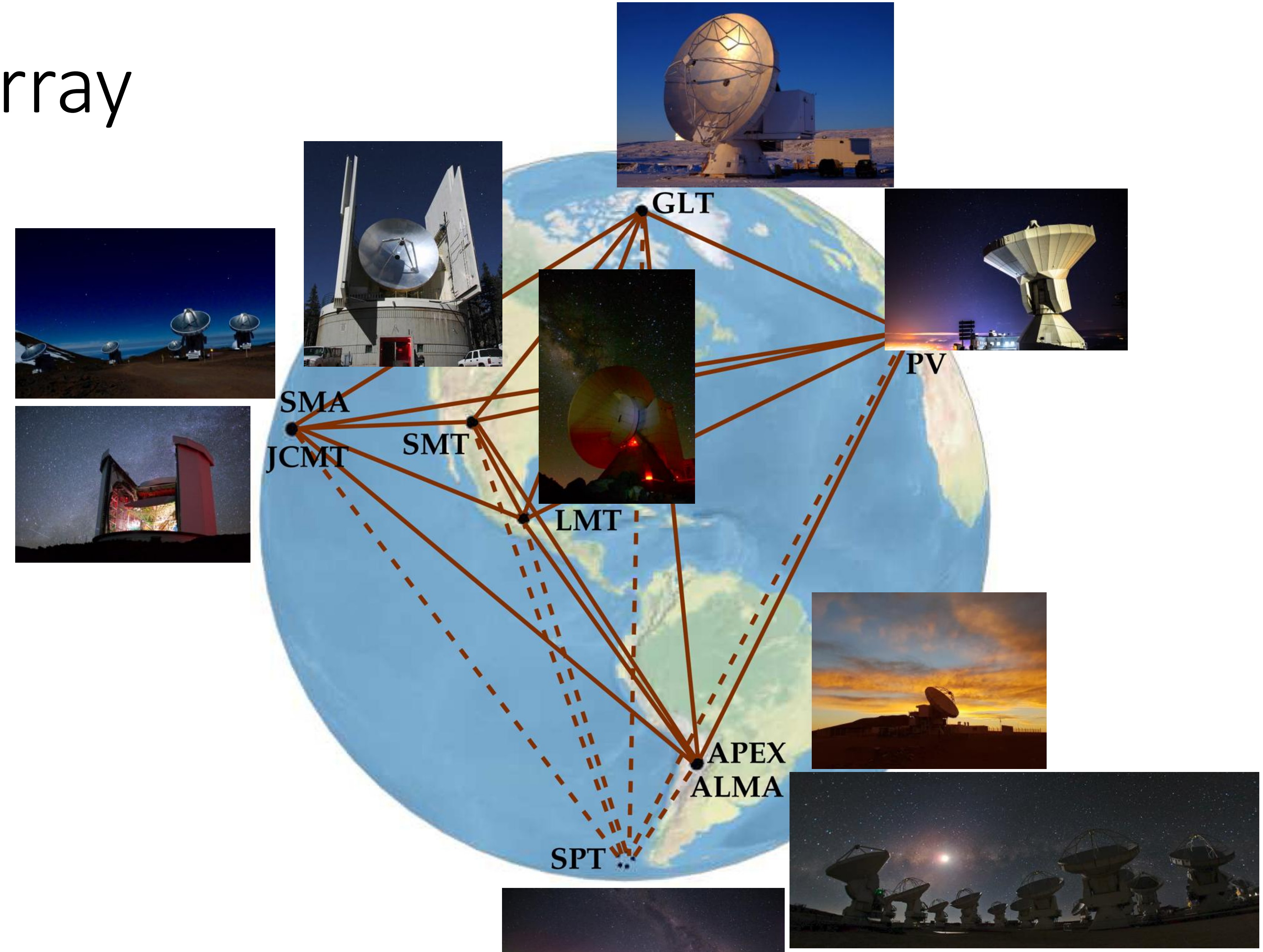



Photo Credits: EHTC 2024 I
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

# EHT: People

**300+** members

**60** institutes

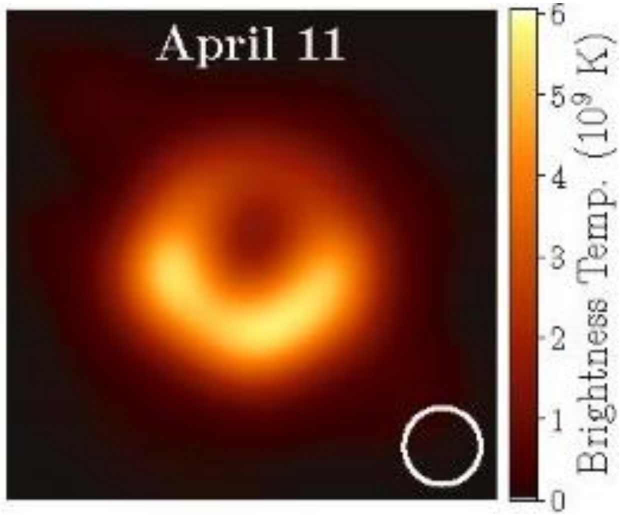
**20** countries

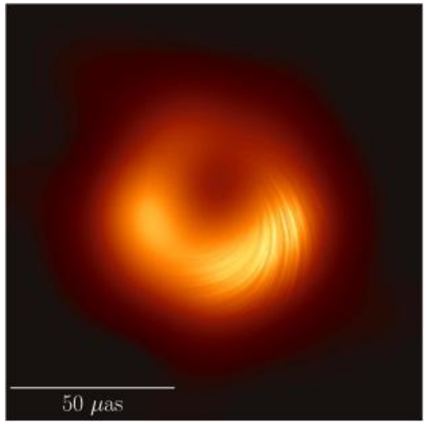
from Europe, Asia, Africa, North and South America.

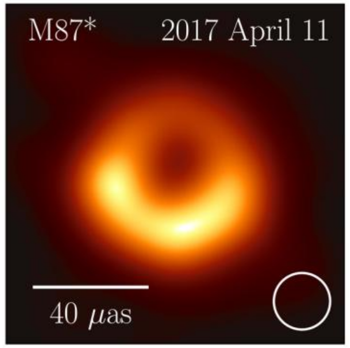
Image credit: E. Traianou

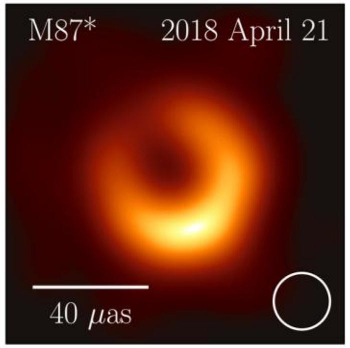
# Primary EHT Papers

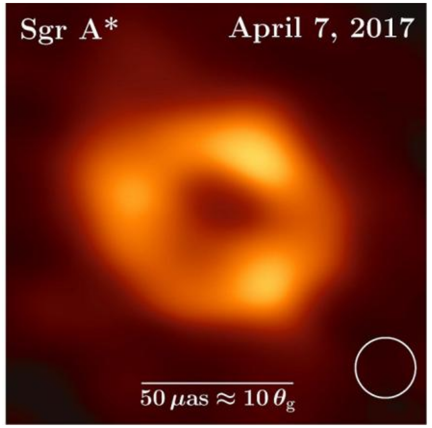
- **First M87 EHT Results I-VI [(*ApJL* 2019)]**
  - First image of a black hole and its interpretation

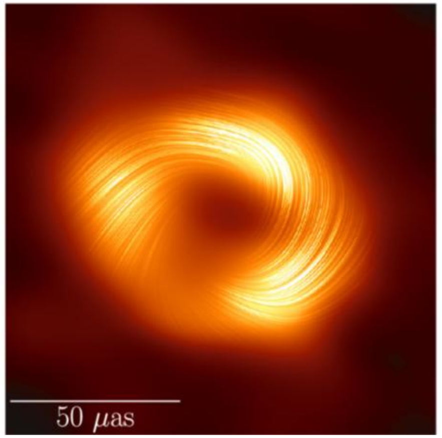


# The EHT data path

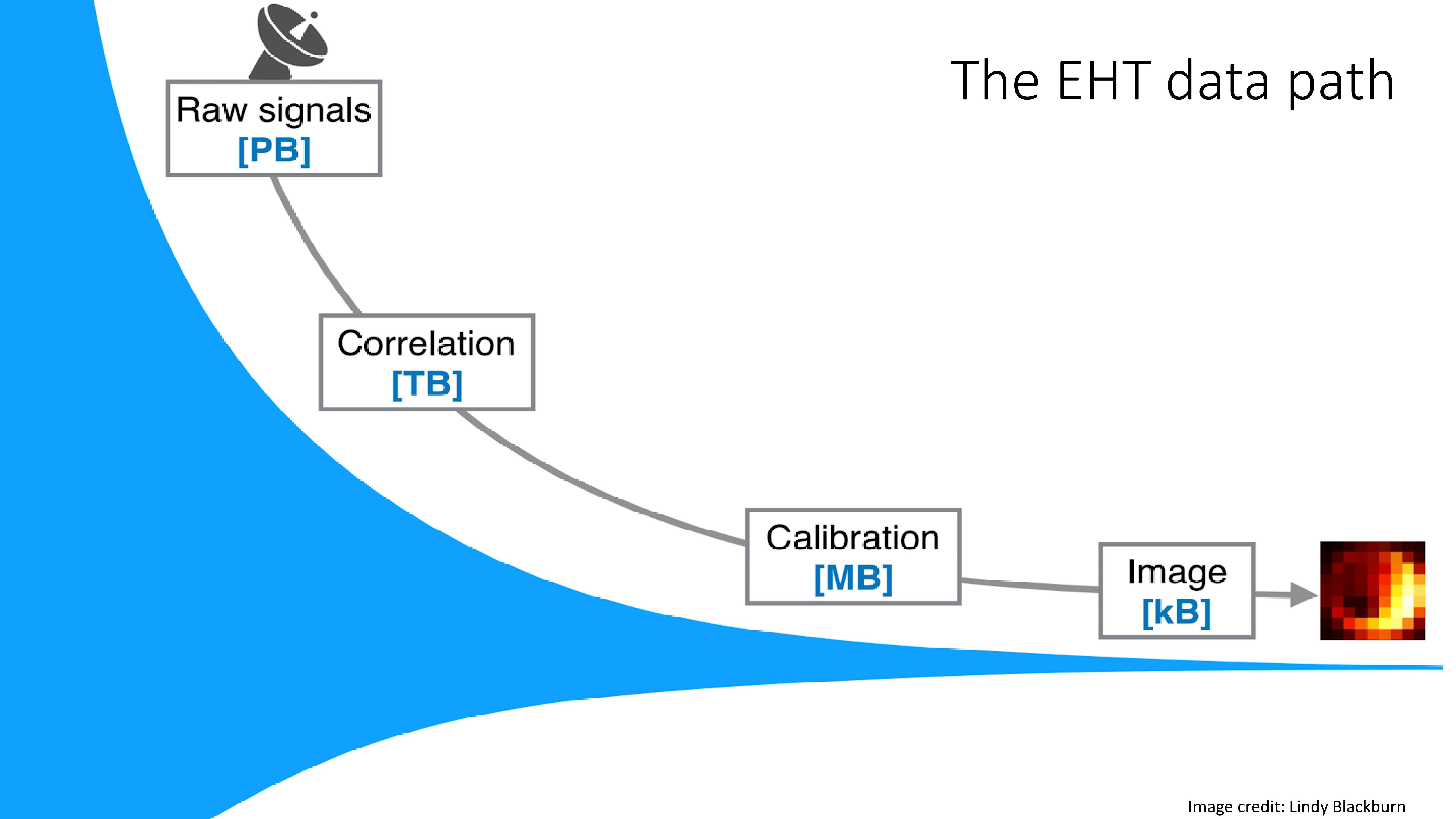
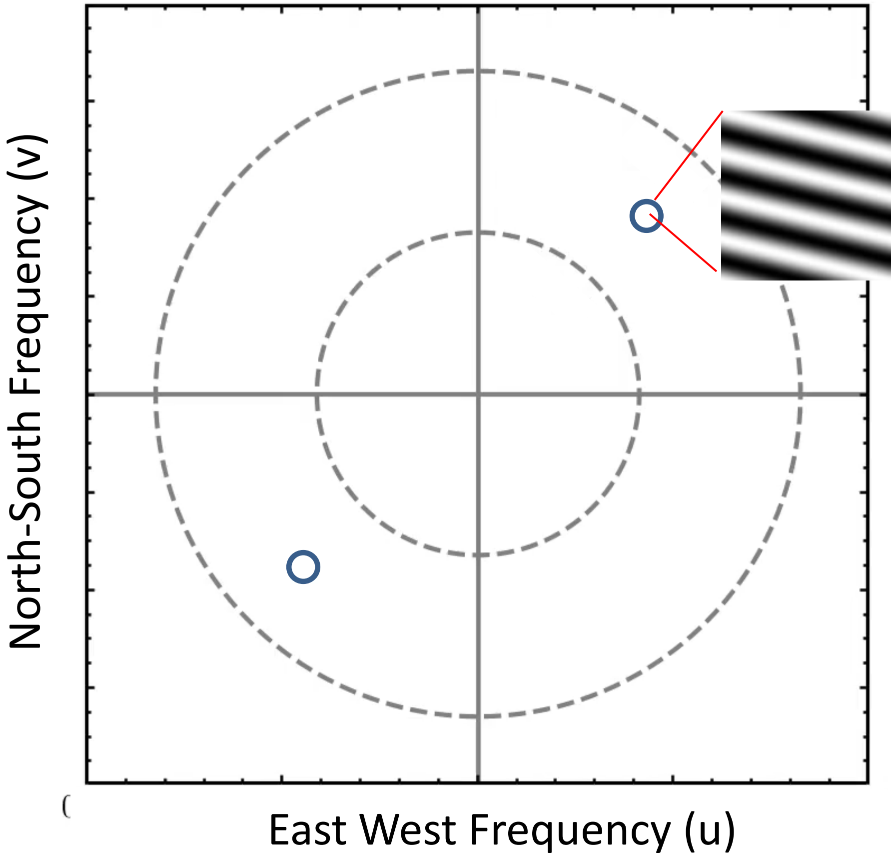



Image credit: Lindy Blackburn

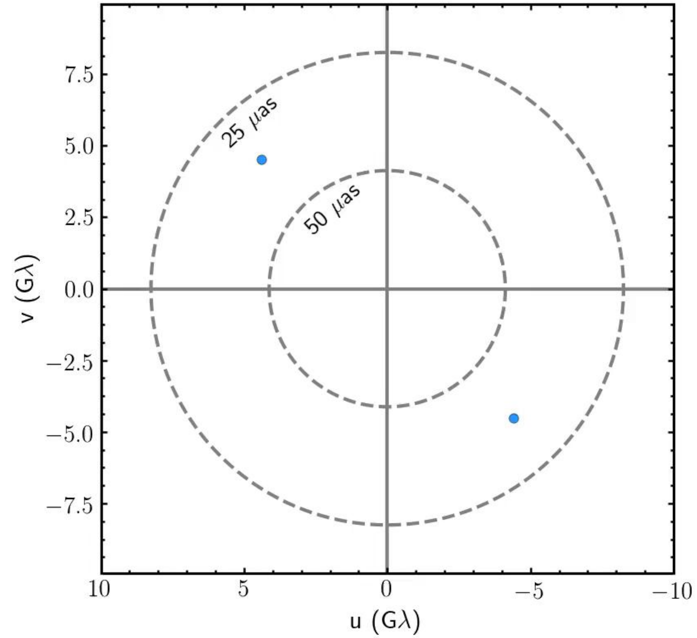
# Very Long Baseline Interferometry (VLBI)

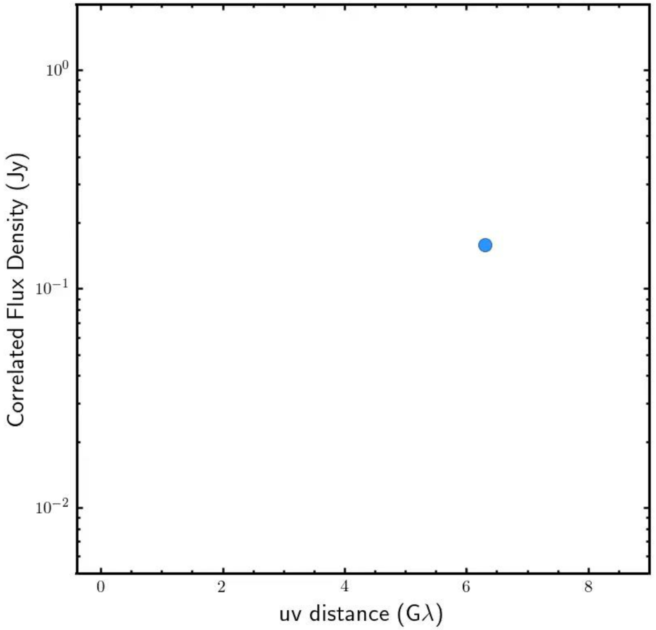



Every projected **baseline** between two telescopes provides **one Fourier component** of the image

movie credit: Katie Bouman

# Very Long Baseline Interferometry (VLBI)



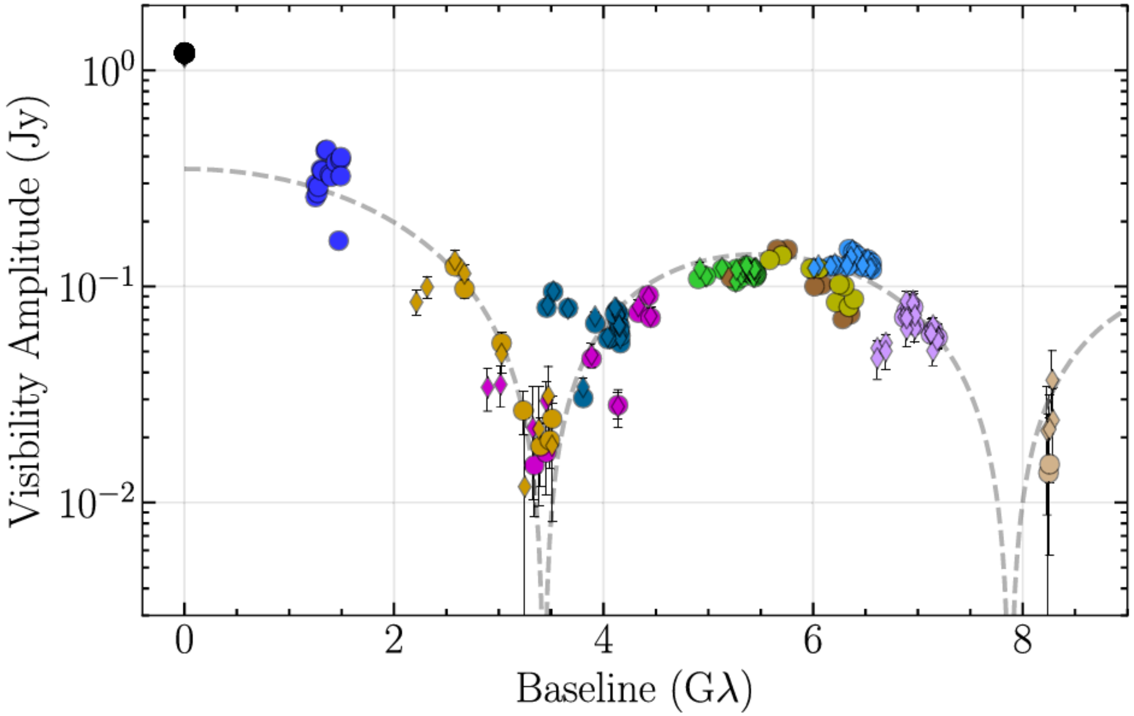




EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

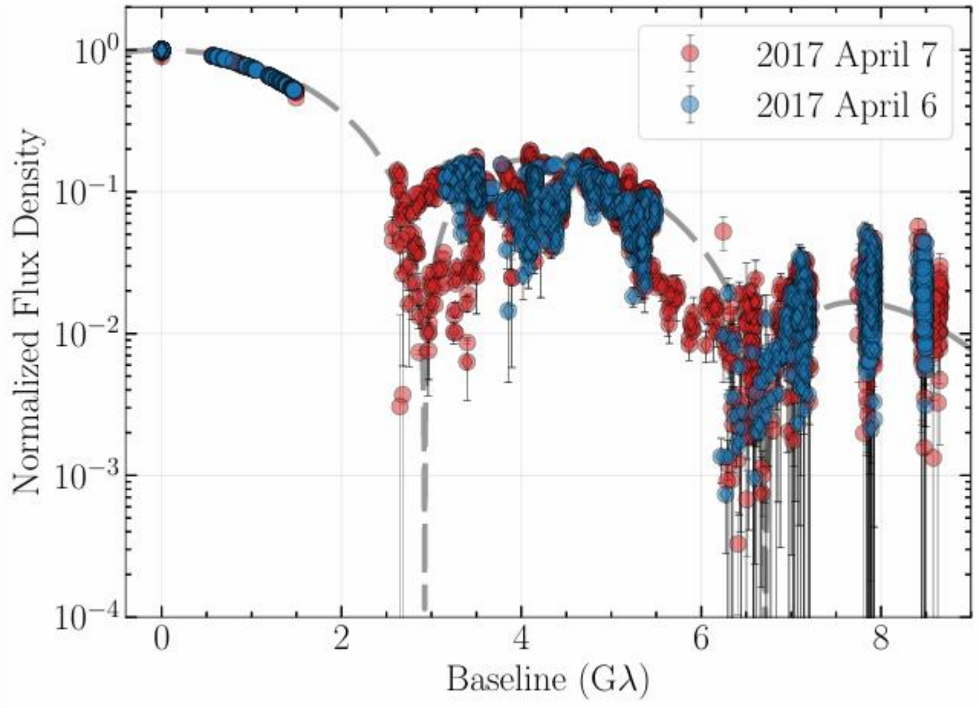
movie credit: Daniel Palumbo

# EHT Data Suggests Ring Structure

**M87***

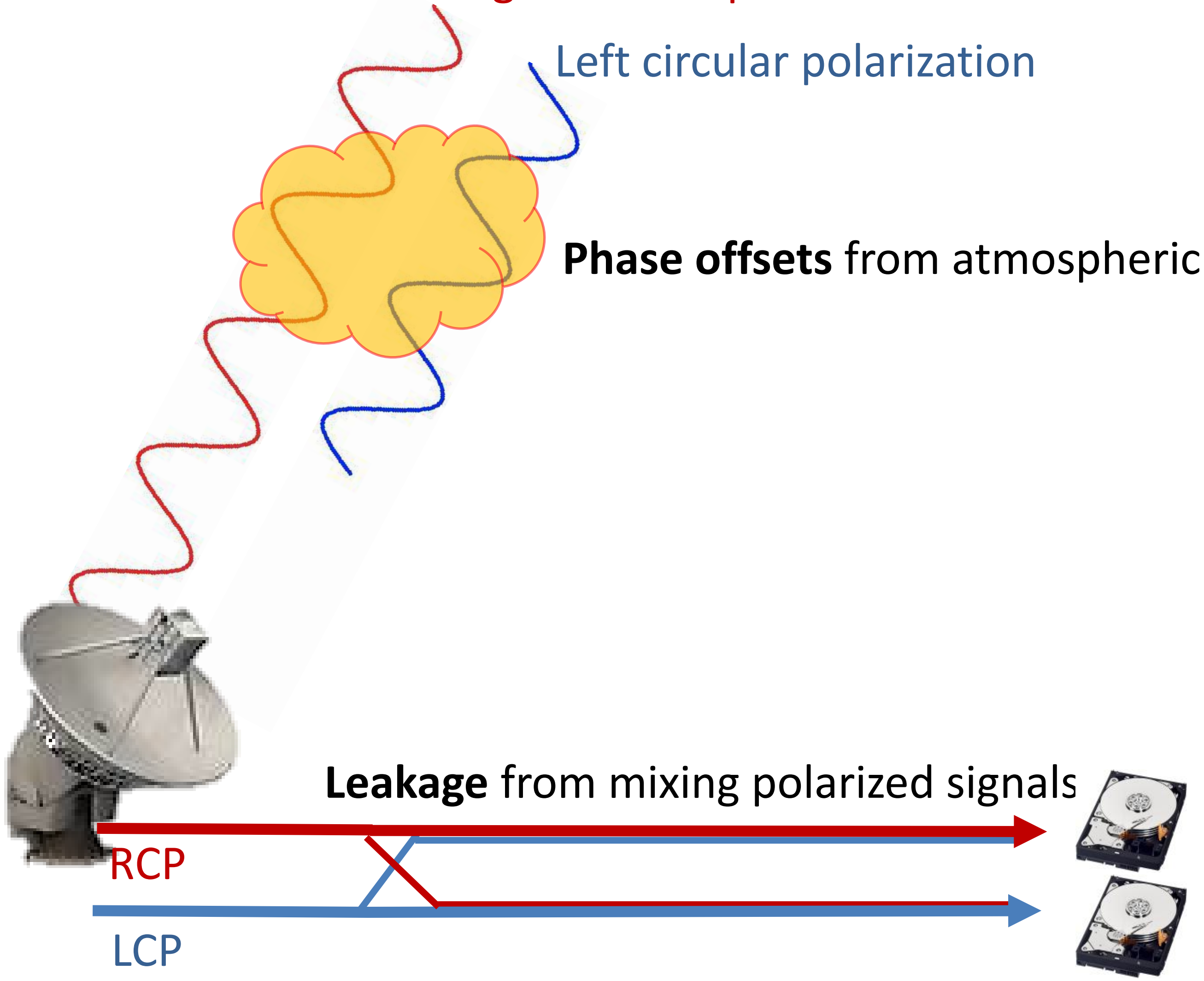



**Sgr A***




EHTC I, 2019; EHTC II, 2022

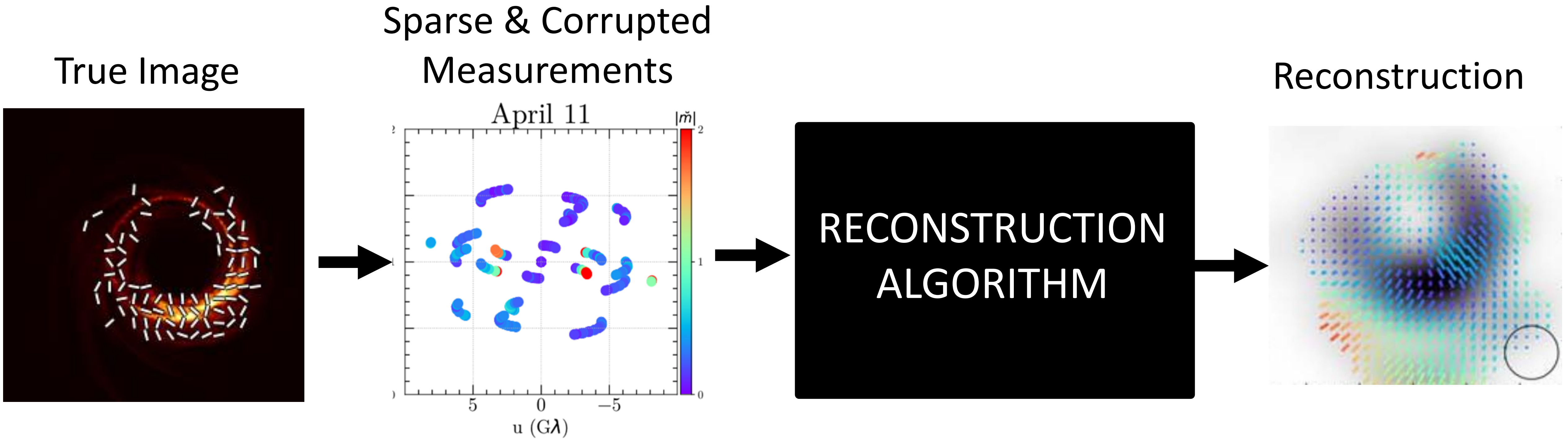
# Challenges of near-horizon imaging




Data at each station are corrupted by unknown **gain and leakage** systematics

Animation credit: Andrew Chael

# Solving for the Image



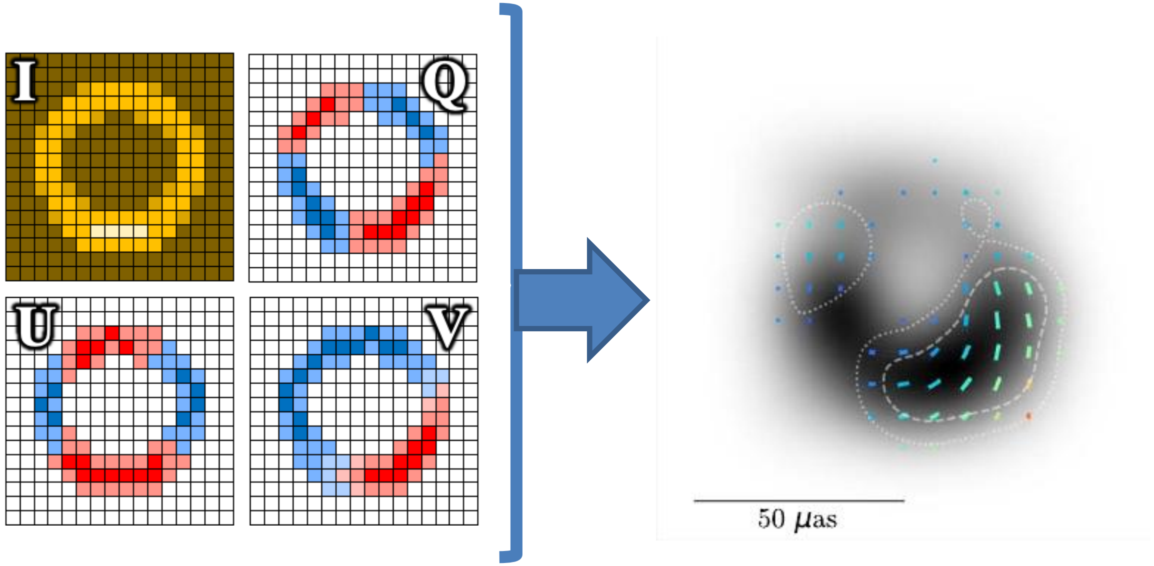

Several different types of reconstruction algorithms:

- **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 w/ Gradient Descent**: fast and flexible, but lots of hyperparameters
    - eht-imaging (Chael+ 2016, 2018, 2023), SMILI (Akiyama+ 2017)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
    - Themis (Broderick+ 21), DMC (Pesce+ 21), Comrade (Tiede+ 2022)

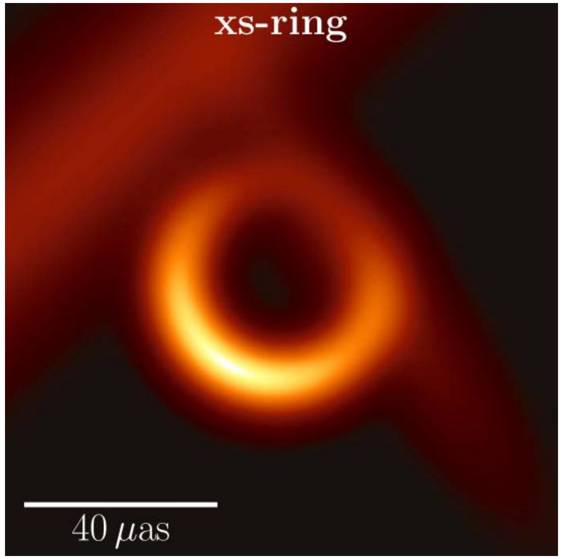
credit: Katie Bouman, Andrew Chael, EHTC VII, 2021

# Solving for the Image

**Images**: solve for pixels




**Geometric models**: solve for shapes




We compare results extensively across methods to **ensure reliability and avoid overfitting**

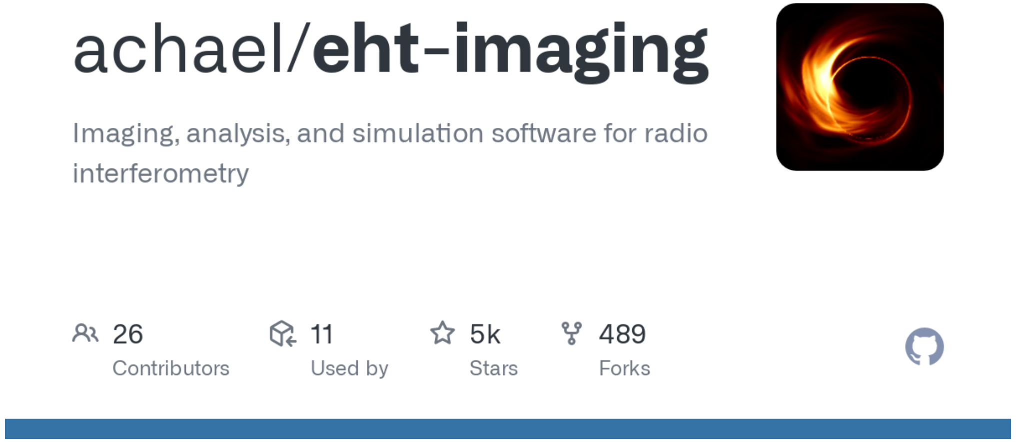
slide credit: Dom Pesce, EHTC VI, 2019

# The **eht-imaging** software library

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

- A flexible framework for developing new tools:
  - dynamical imaging (Johnson+ 2017)
  - **multi-frequency imaging (Chael+ 2023a)**
  - geometric modeling (Roelofs+ 2023)

- Uses:
  - All EHT results to date
  - Next-generation EHT design
  - Imaging & analysis from VLBA, GMVA, ALMA, RadioAstron…



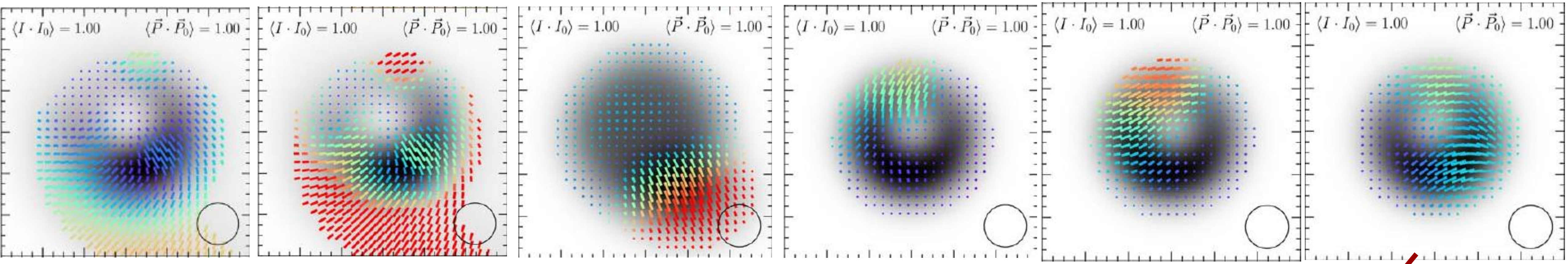

https://github.com/achael/eht-imaging

`pip install ehtim`

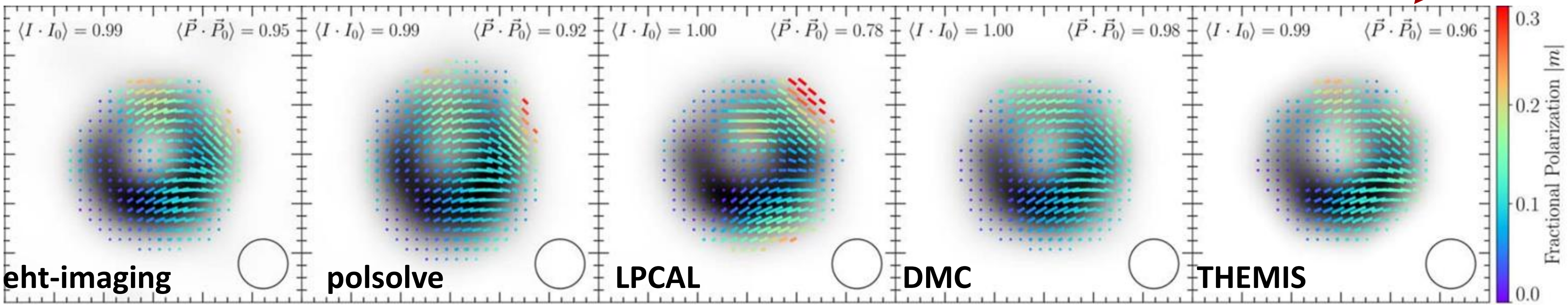
**Chael+** 2016, 2018a, 2023a

# Testing our methods with synthetic data

Six different polarized source models

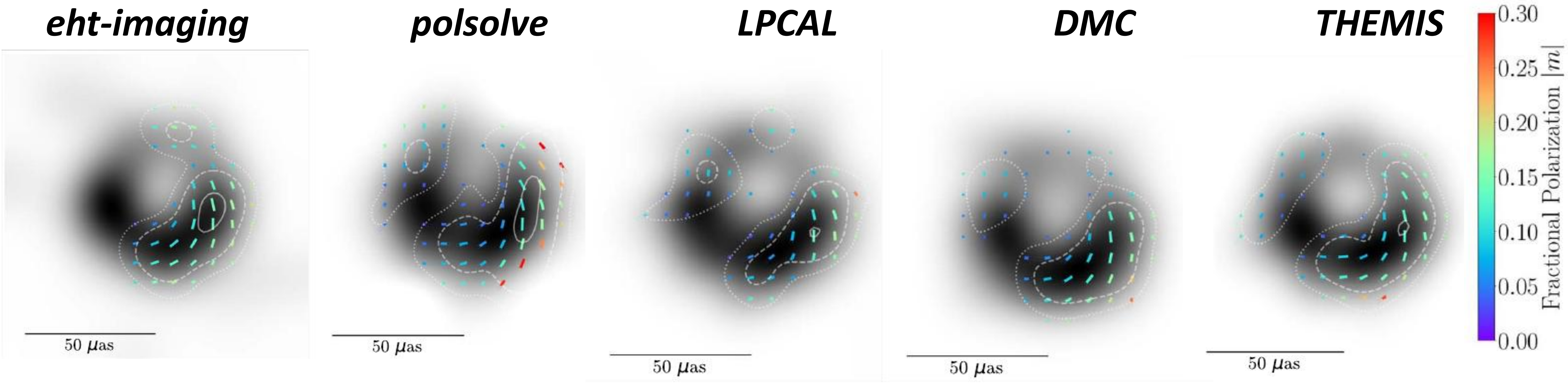



Example reconstructions of Model 6 using **5 distinct methods**




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

# Cross-comparison across methods

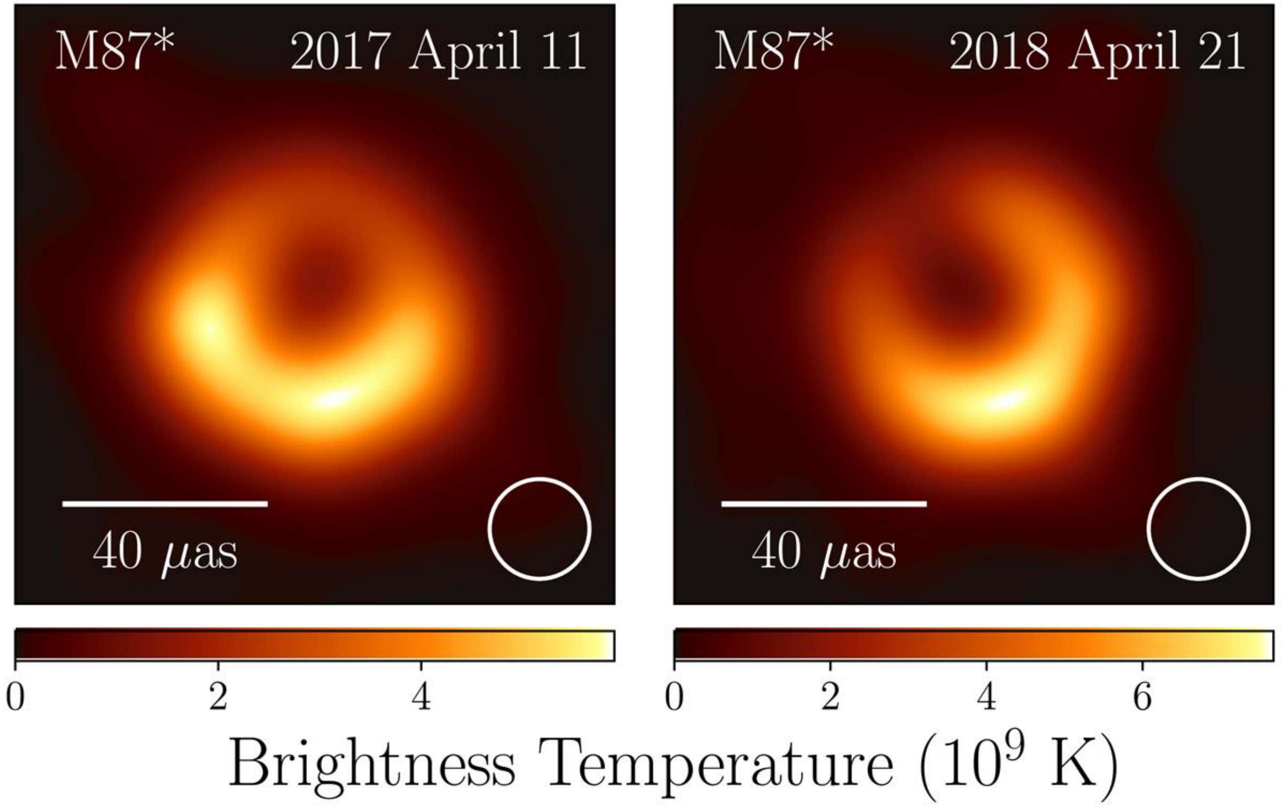



- All methods show similar total intensity and polarization structure at 20 µas resolution
- Consistent ring diameter (~40 µas) and asymmetry (south)
- Polarization structure is predominantly **helical and weak**, (|m| ~15 %)

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

# M87: Image persistance across years

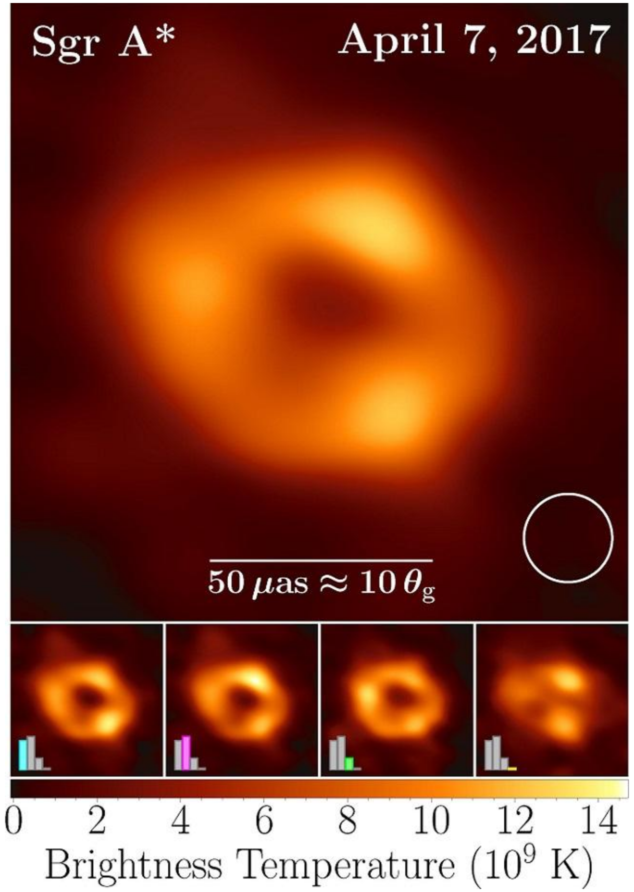
- 2018 observations show consistent horizon-scale structure in M87* **1000 gravitational timescales later.**
- Observations performed with a **more complete array** (including Greenland Telescope)
- Image **diameter is consistent** but brightness **position angle shifts**
- Stay tuned for more soon….

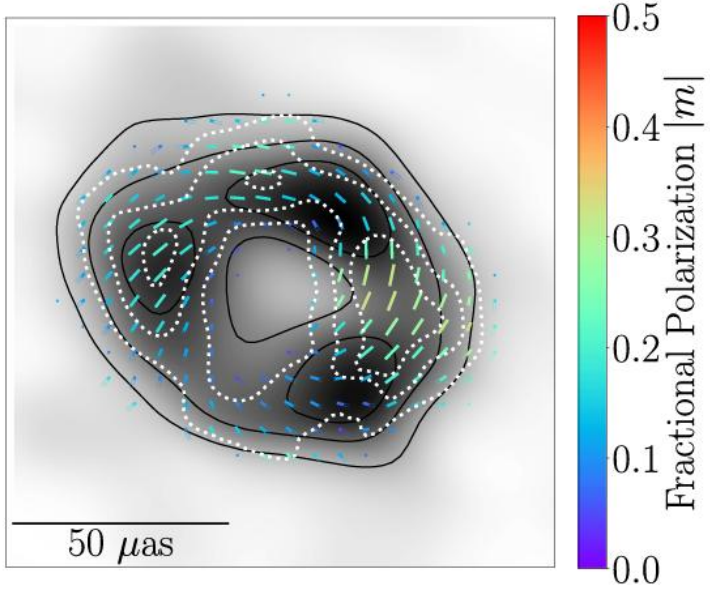



EHTC I, 2024

# Sgr A*

- Imaging Sgr A* is more challenging than M87 due to rapid sub-hour **variability** and **interstellar scattering**.
- Sgr A* images predominantly (but not uniquely) show a **≈50μas diameter ring.**
- Sgr A* images do not currently constrain the ring position angle
- Sgr A* is **more polarized** (≈30%) than M87*, and it shows a similar **helical linear polarization pattern**.



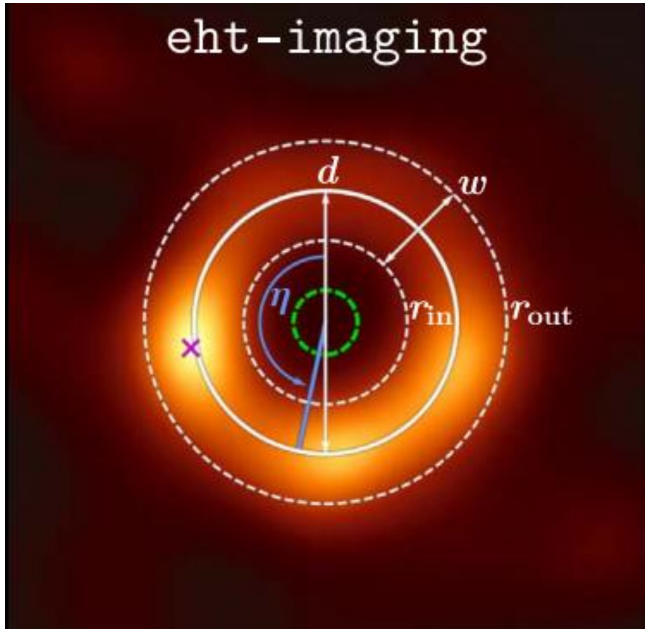



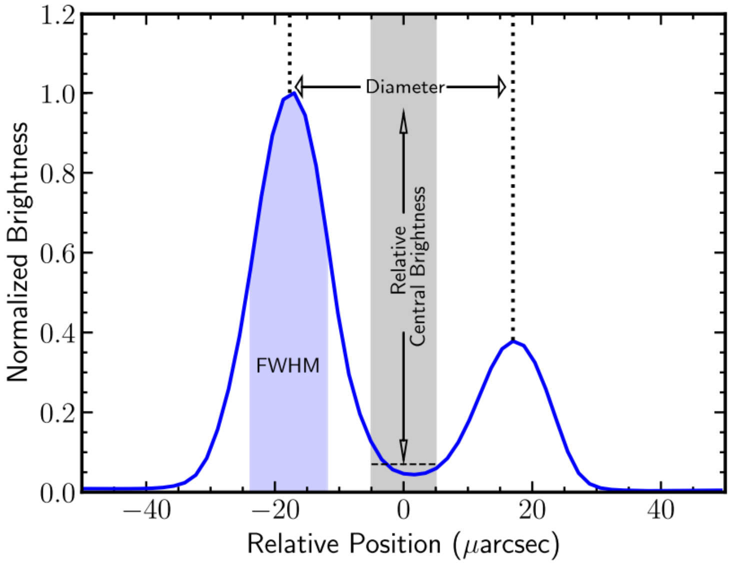

EHTC I, 2022; EHTC VII, 2024 **Chael**, paper writing team)

# What are the main features of (polarized) EHT images?

# Summarizing an image:  Total Intensity

- **Total Intensity Image Metrics**
  - Ring diameter *d*
  - Ring width *w*
  - Ring asymmetry *A*
  - Ring position angle *η*
  - Relative central brightness $f_c$
- For **M87*:**
  - Diameter and PA are best measured
- For **Sgr A*:**
  - Diameter and width are best measured

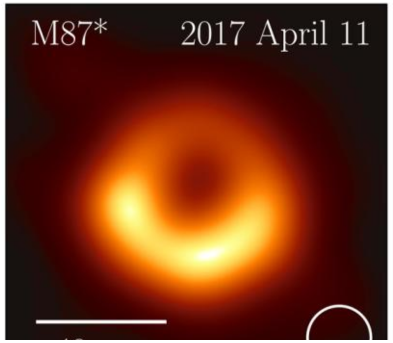


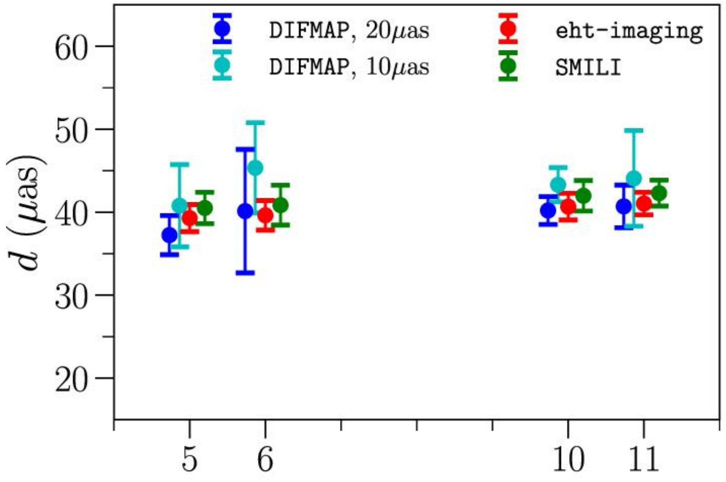

**summary statistics** defined in EHT papers represent quantities we confidence in measuring
provide a **natural point of comparison for new theoretical models** to existing data

EHTC IV, VI 2019 (**Chael**, paper writing team)
EHTC IV, 2022

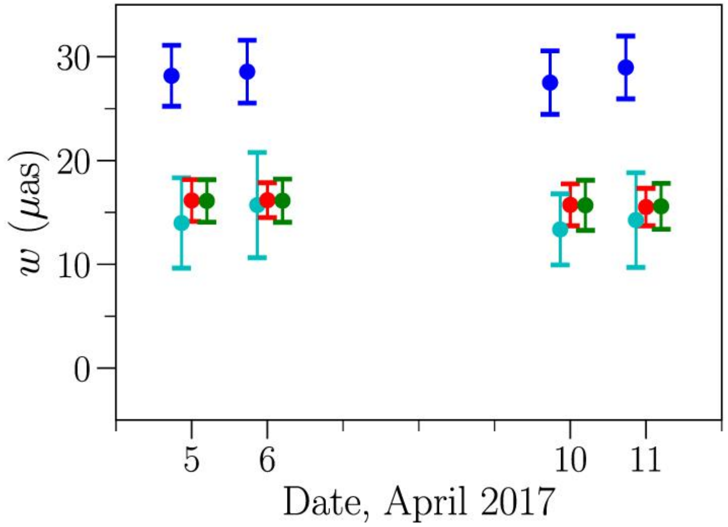
# M87 Ring Properties (2017)

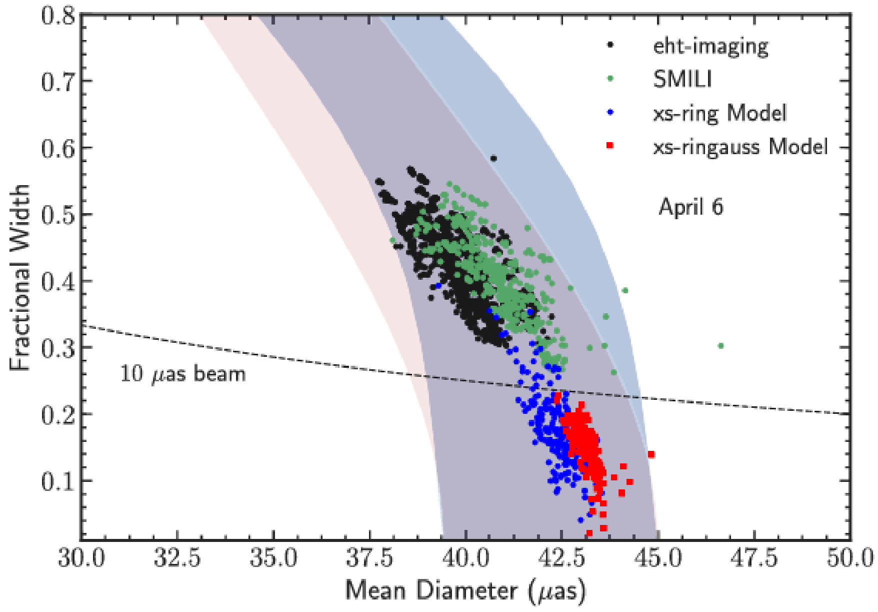



Diameter




Width



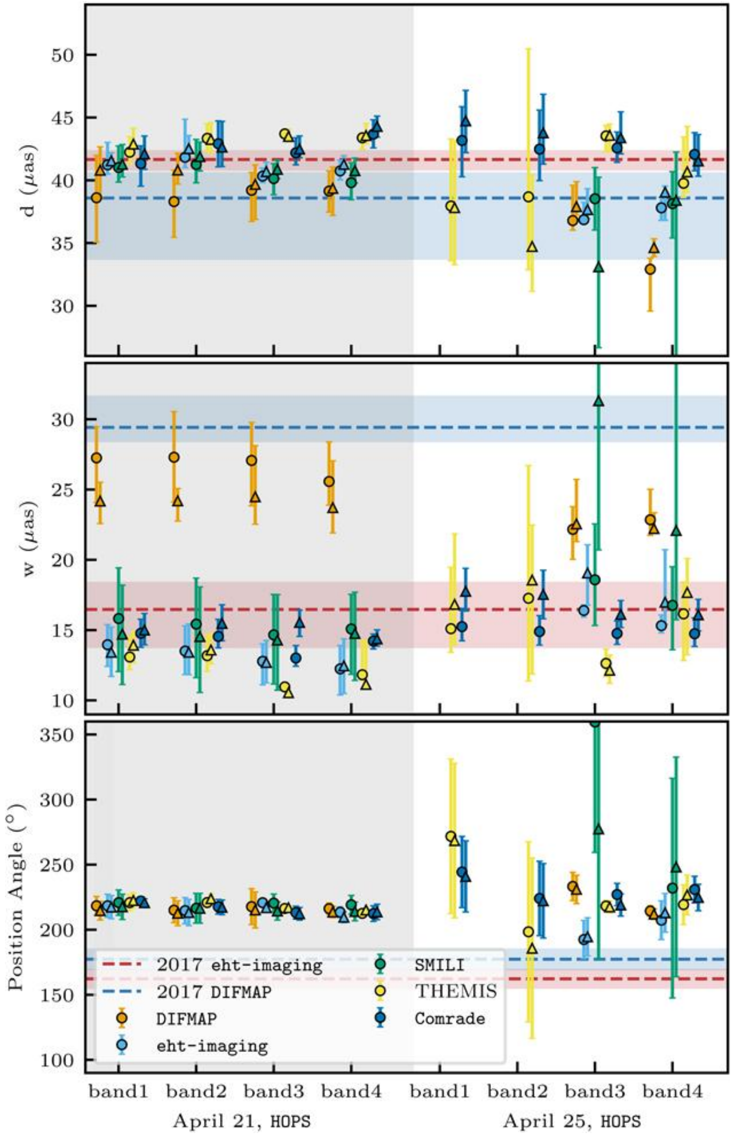



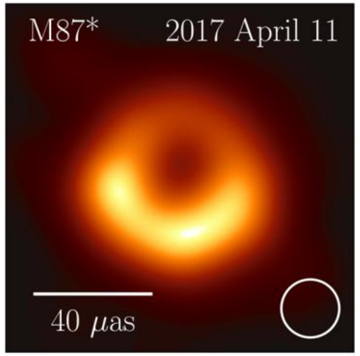

- Diameter $d \approx 41\ \mu\mathrm{as}$ is consistent across time and method
- The width is **resolution dependent**, and is at best an upper limit.
- Orientation angle shows tentative $\approx 20^{\circ}$CCW shift from April 5 – 11, 2017

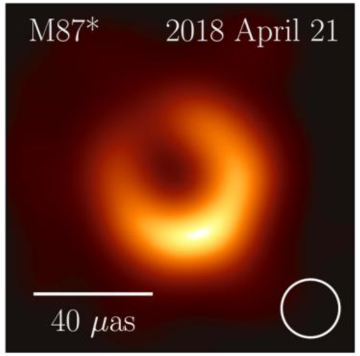
EHTC IV, VI 2019 (**Chael**, paper writing team)

# M87* Ring Properties (2017-2018)

- M87* Ring diameter is consistent from year-to $d = 42 \pm 3\,\mu\mathrm{as}$
- M87* ring width is resolution-dependent: $w/d < 0.5$
- M87* ring position angle shows a 30 degree shift counterclockwise from 2017 to 2018.

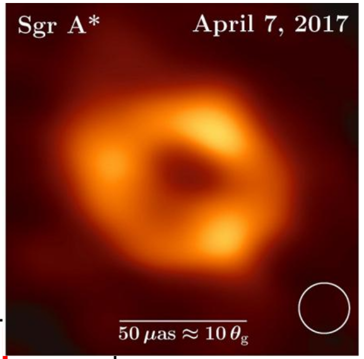


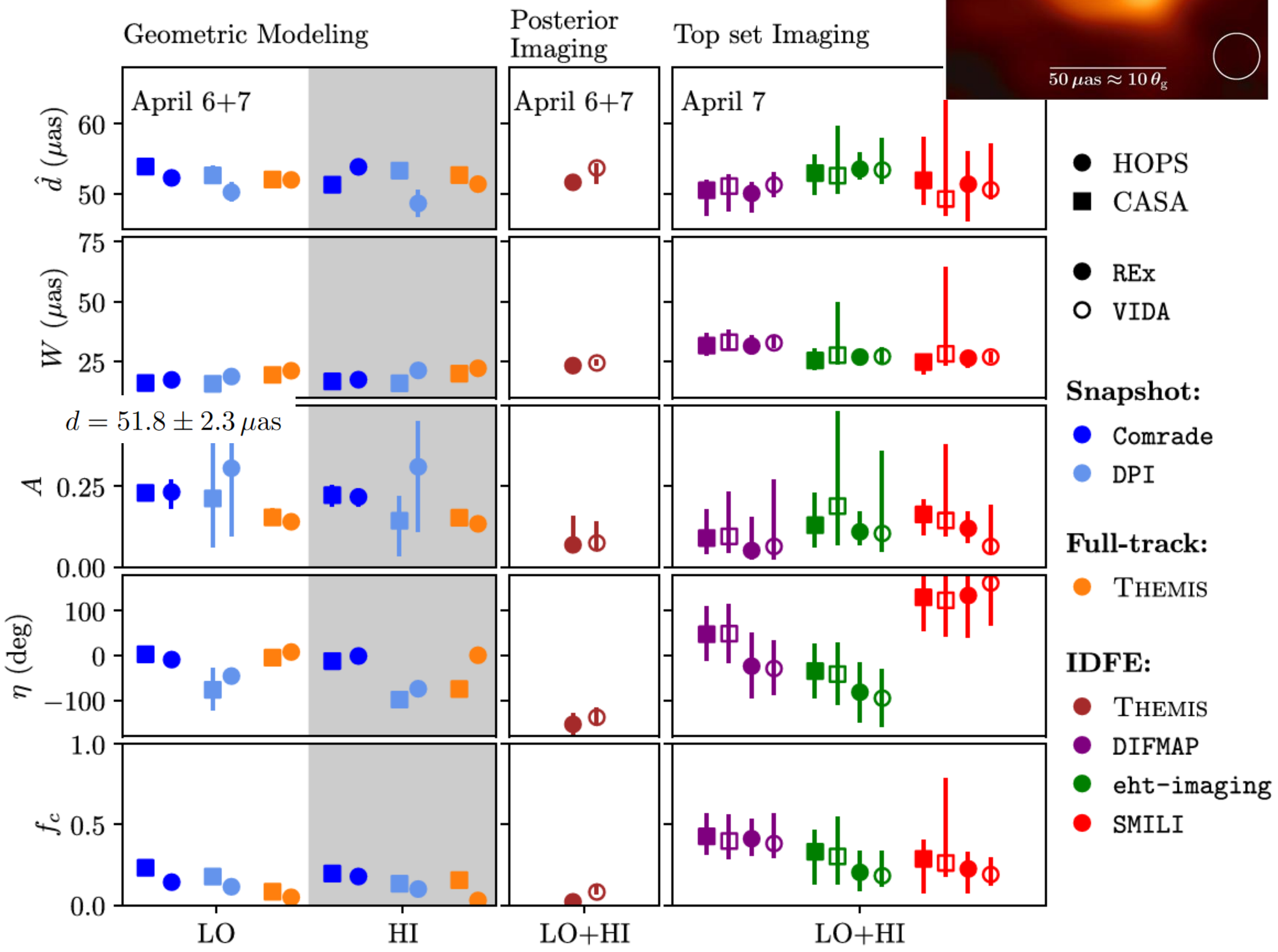




EHTC I, 2024

# Sgr A* EHT image metrics




- Sgr A* ring diameter is well measured and consistent with $4.3 \times 10^6$ solar mass black hole at the Galactic Center: $d = 51.8 \pm 2.3\, \mu\text{as}$
- Sgr A* ring width is better resolved and consistently recovered across methods: $w/d = 0.3 - 0.5$
- Sgr A* ring asymmetry is not consistently recovered.




EHTC IV, 2022

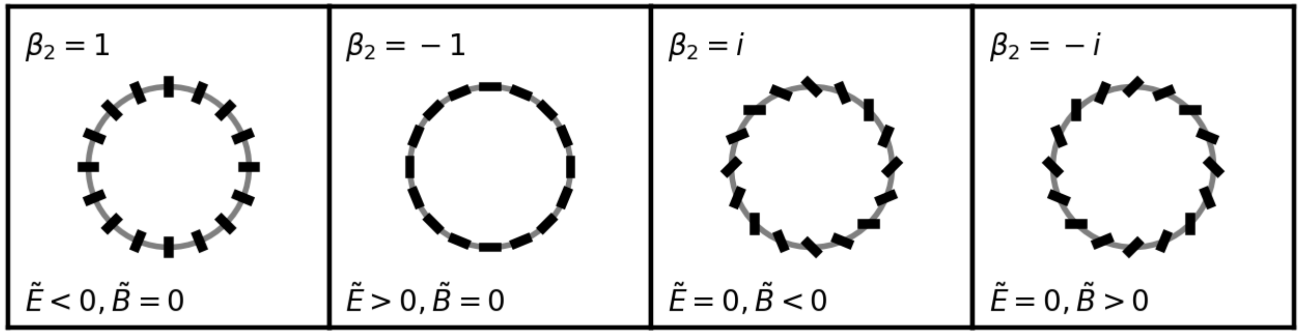
# Summarizing an image:  Polarization

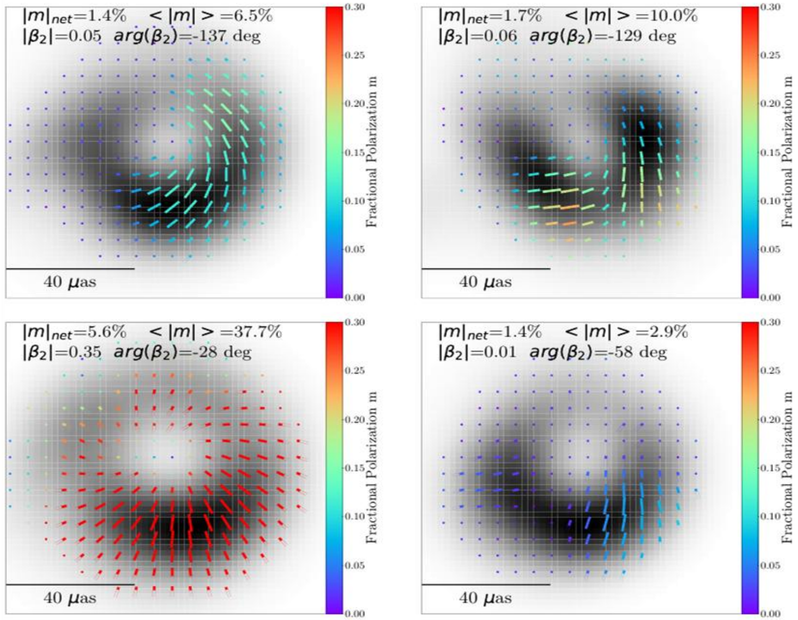
**Unresolved and Resolved** polarization fractions

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

**Azimuthal structure**
2nd Fourier mode

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



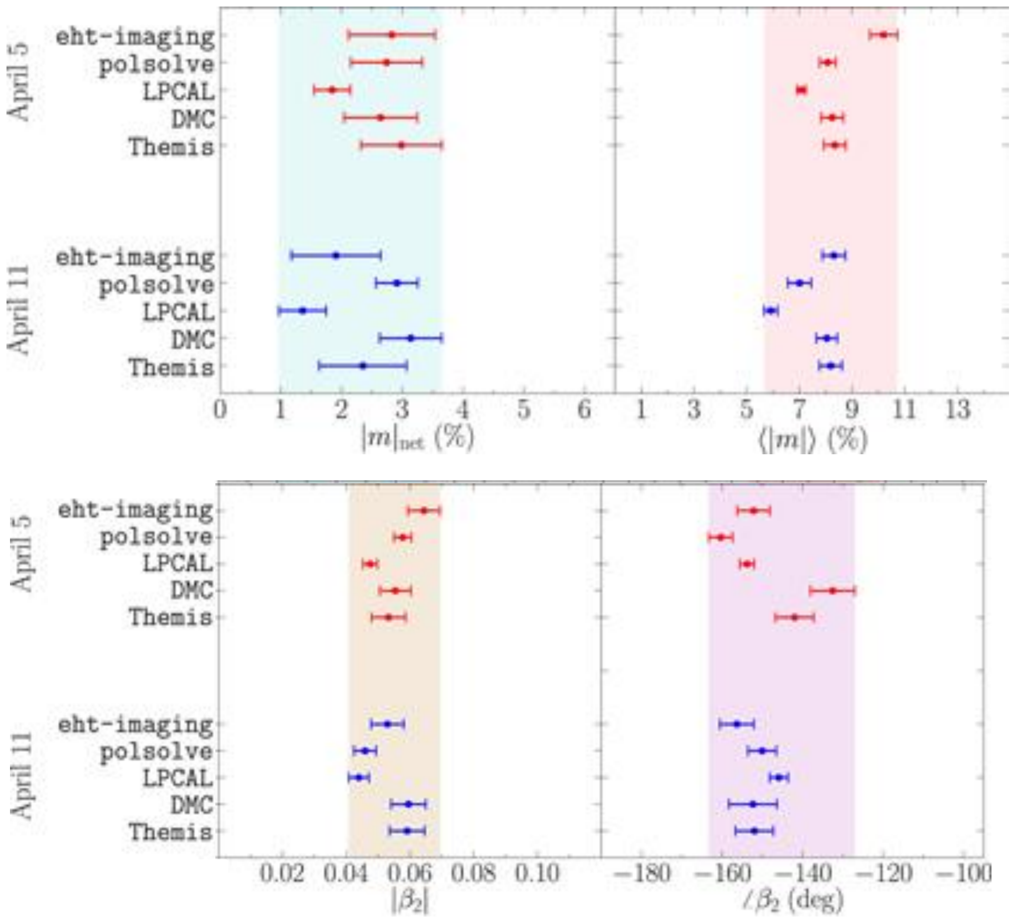

Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

**Circular polarization is marginally detected (EHTC 2023,2024) and may be constraining in the future!**

EHTC VII,VIII, 2021 (**Chael**, paper coordinator)
EHTC IX, 2023 (**Chael**, paper coordinator)

# Summarizing an image: comparing methods

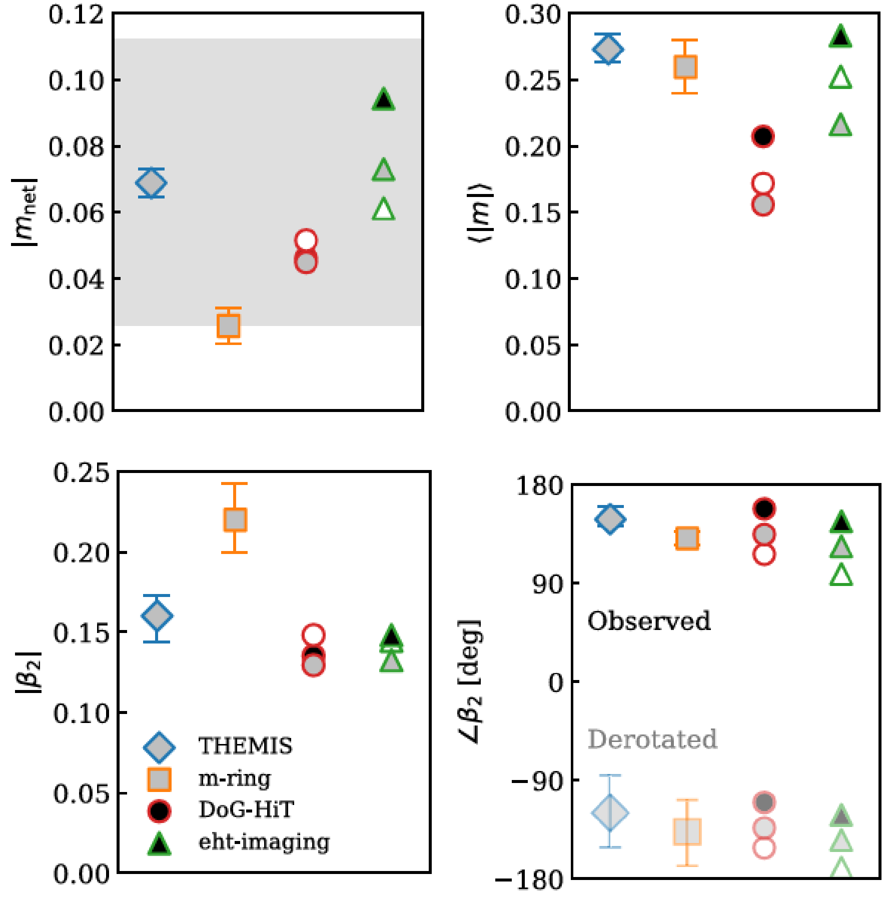
**M87 Linear polarimetric metrics**




**Unresolved and resolved linear polarization fraction**

**Polarization \`helicity\`**

**Sgr A* Linear polarimetric metrics**




Sgr A* is **more polarized** than M87*: $\langle|m|\rangle = 26 \pm 2\%$ vs $\langle|m|\rangle = 8 \pm 3\%$

Both Sgr A* and M87 have the **same sign of arg($\beta_2$)** after Faraday de-rotation

EHTC VII,VIII, 2021 (**Chael**, paper coordinator)
EHTC IX, 2023 (**Chael**, paper coordinator)
EHTC VII, 2024 (**Chael**, paper writing team)

# EHT Multi-wavelength partners

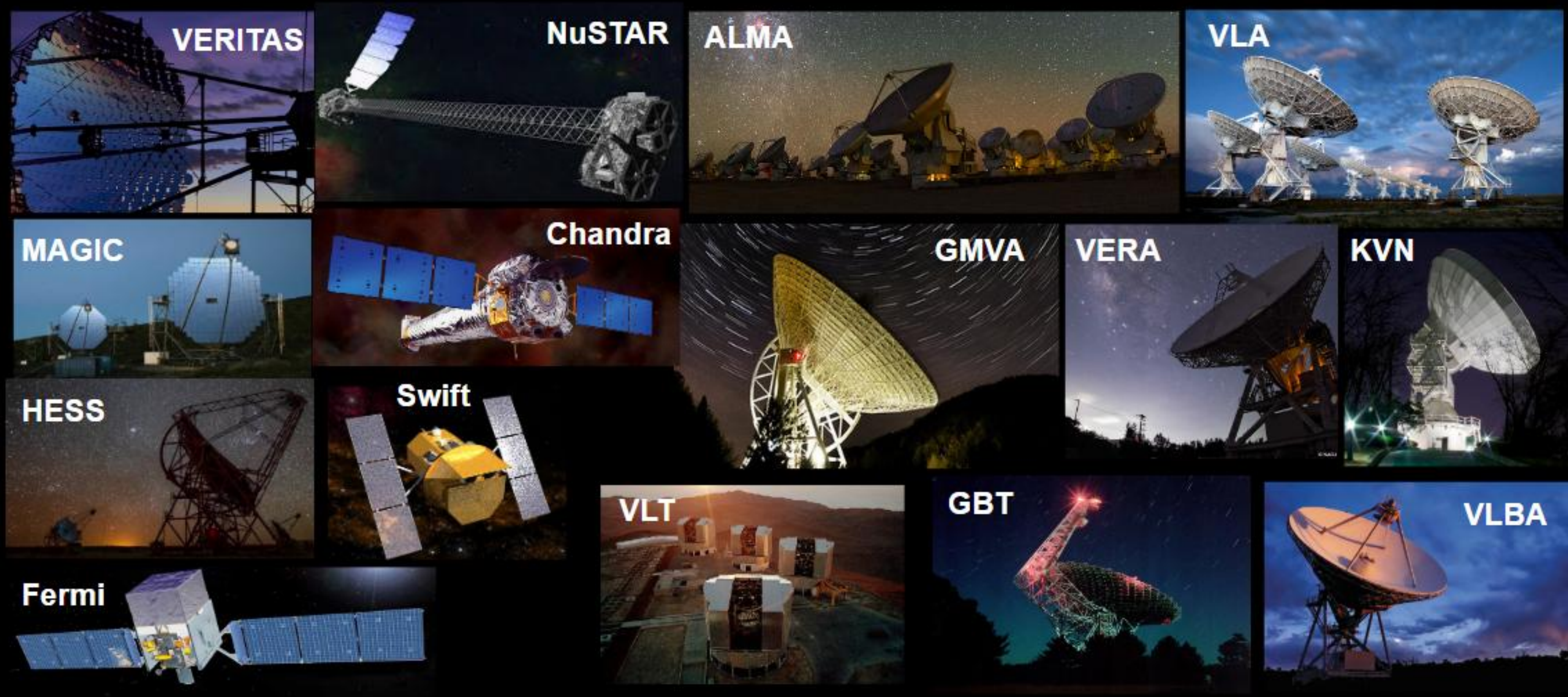


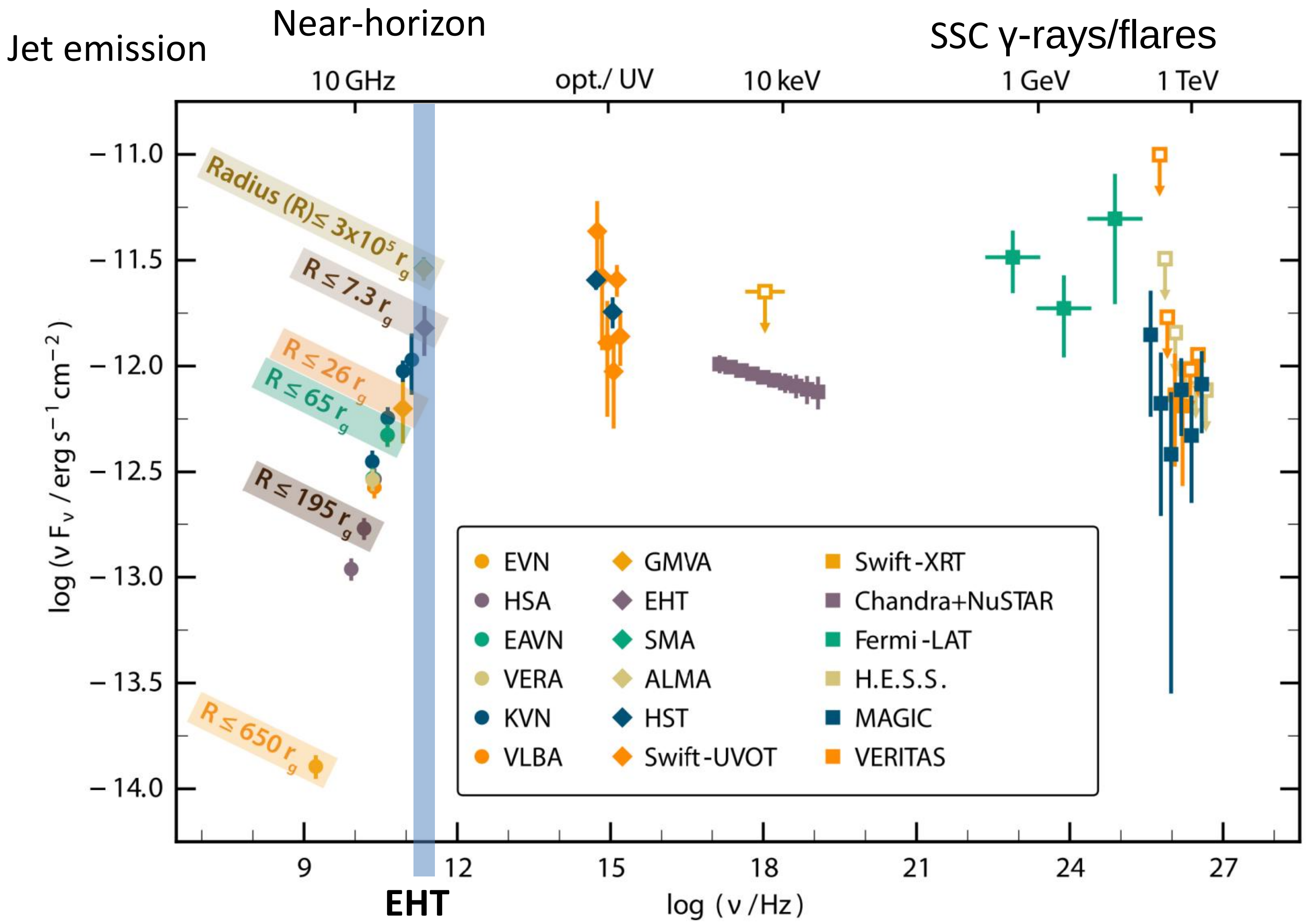

*Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken*

Slide credit: Sara Issaoun

# M87 simultaneous SED

EHTC MWL WG 2021 compiled comprehensive, simultaneous SED

- Multiple emission zones are necessary to explain the SED
- Unclear where high-energy emission originates




**M87 EHT model comparison includes jet power and X-ray luminosity lower limits**

EHTC MWG+ 2021

# Sgr A* SED

**Sub-mm Peak**

-Optically thin synchrotron from **near-horizon emission**

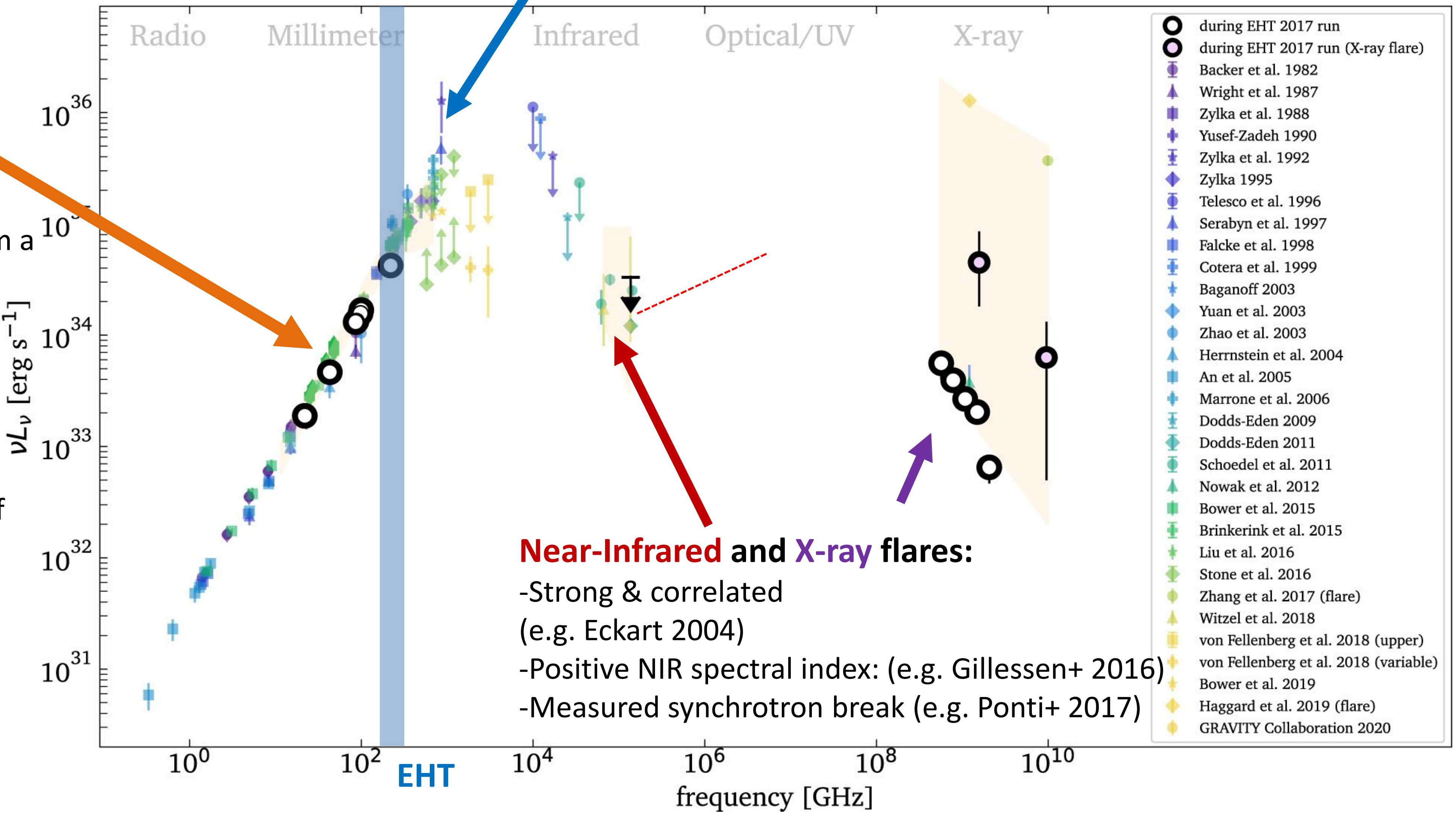
**Larger Scales:**

**Flat Radio Spectrum:**

-self-absorbed synchrotron from a thick accretion disk? (e.g. Narayan+ 1995)

-a large-scale outflow? (e.g. Falcke & Markoff 2000)

-Nonthermal electrons? (e.g. Ozel+ 2000)




**Near-Infrared and X-ray flares:**

-Strong & correlated (e.g. Eckart 2004)

-Positive NIR spectral index: (e.g. Gillessen+ 2016)

-Measured synchrotron break (e.g. Ponti+ 2017)

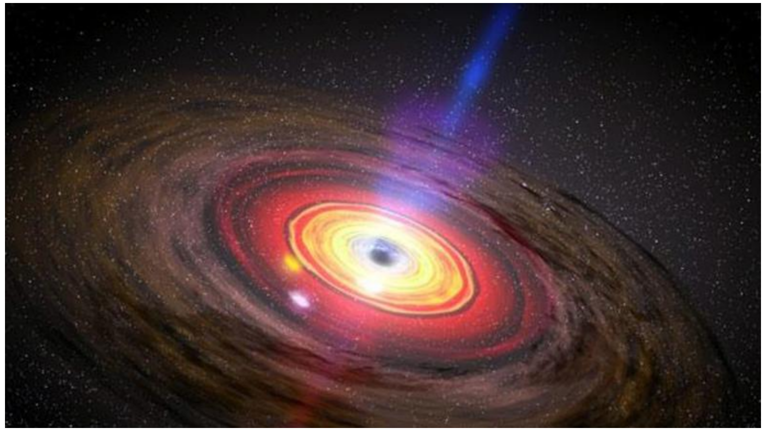
**Sgr A* EHT model comparison considers 86 GHz luminosity & source size, NIR and X-ray luminosity**

EHTC+ II, 2022

# What do EHT images tell us about the black hole environment?

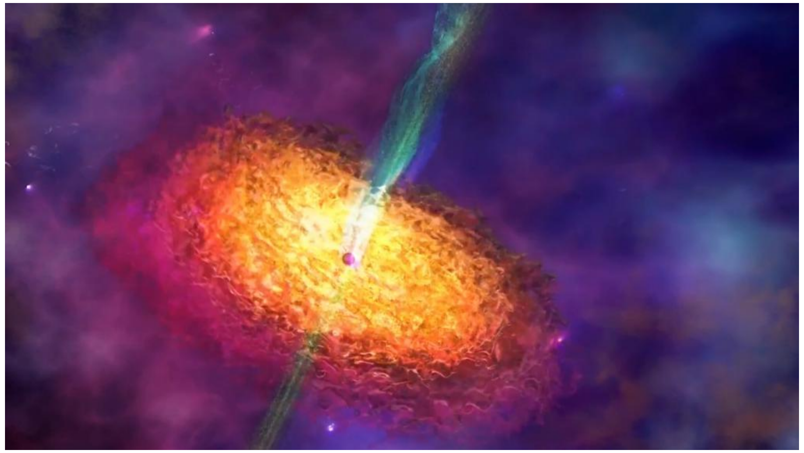
# Modes of Black Hole Accretion

Bright Active Galactic Nuclei (AGN):
Most Liberated Energy is **Radiated**



- Thin Disks
- High Luminosity & Near-Eddington Accretion Rate
- Optically Thick & Bright

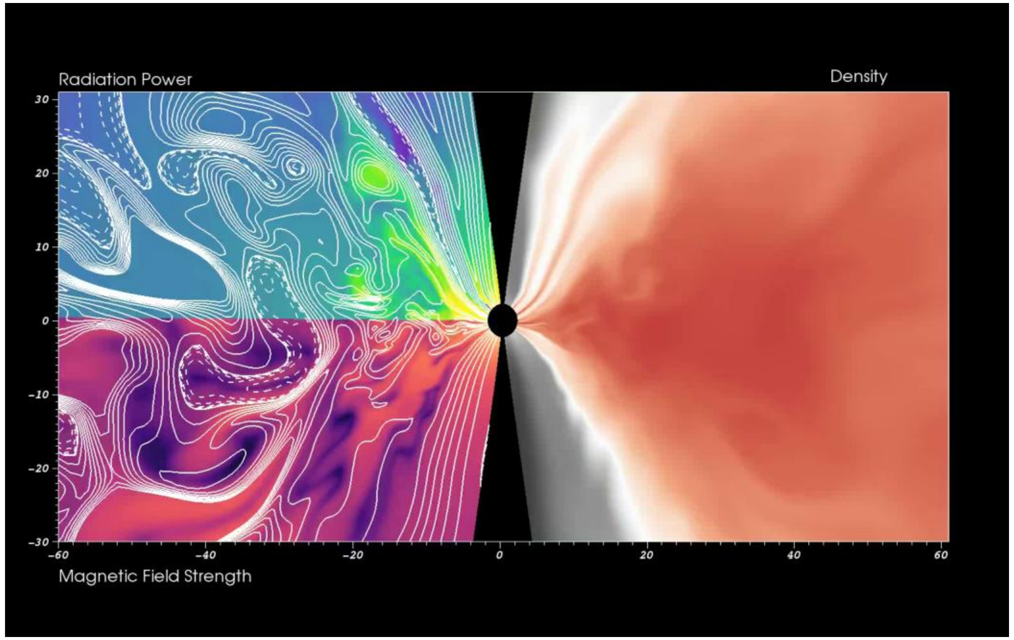
Low-Luminosity AGN (LLAGN):
Most Liberated Energy is **Advected**



- Thick Disks
- Low accretion rate/Luminosity
- Optically Thin & Dim
- Hot: $T \gtrsim 10^{10}\,\mathrm{K}$
- Plasma is *collisionless*/not in equilibrium

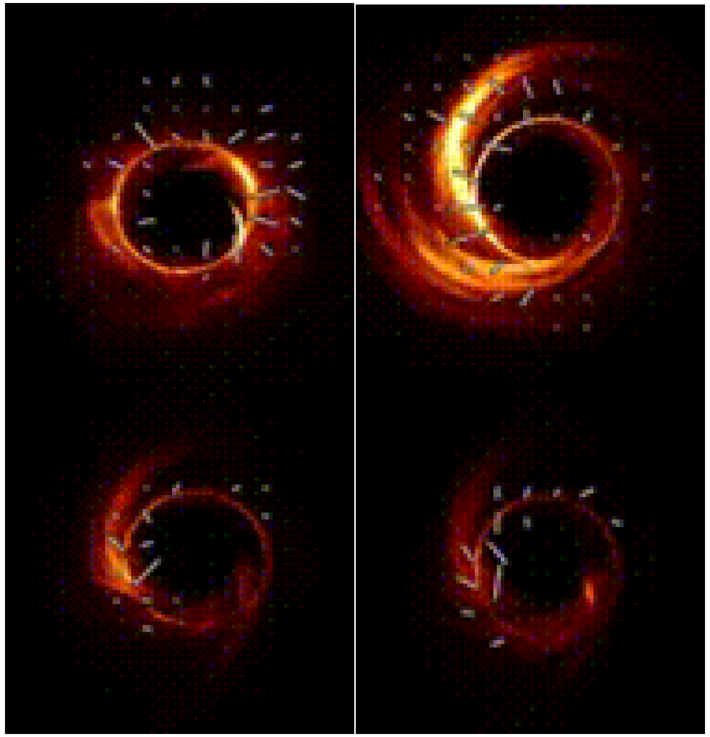
Image credits: NASA/NSF

# Theoretical Tools for Interpreting Black Hole Images




**General Relativistic Magnetohydrodynamic (GRMHD) Simulations**

Solves coupled equations of plasma dynamics and magnetic field for low-luminosity accretion in Kerr spacetime

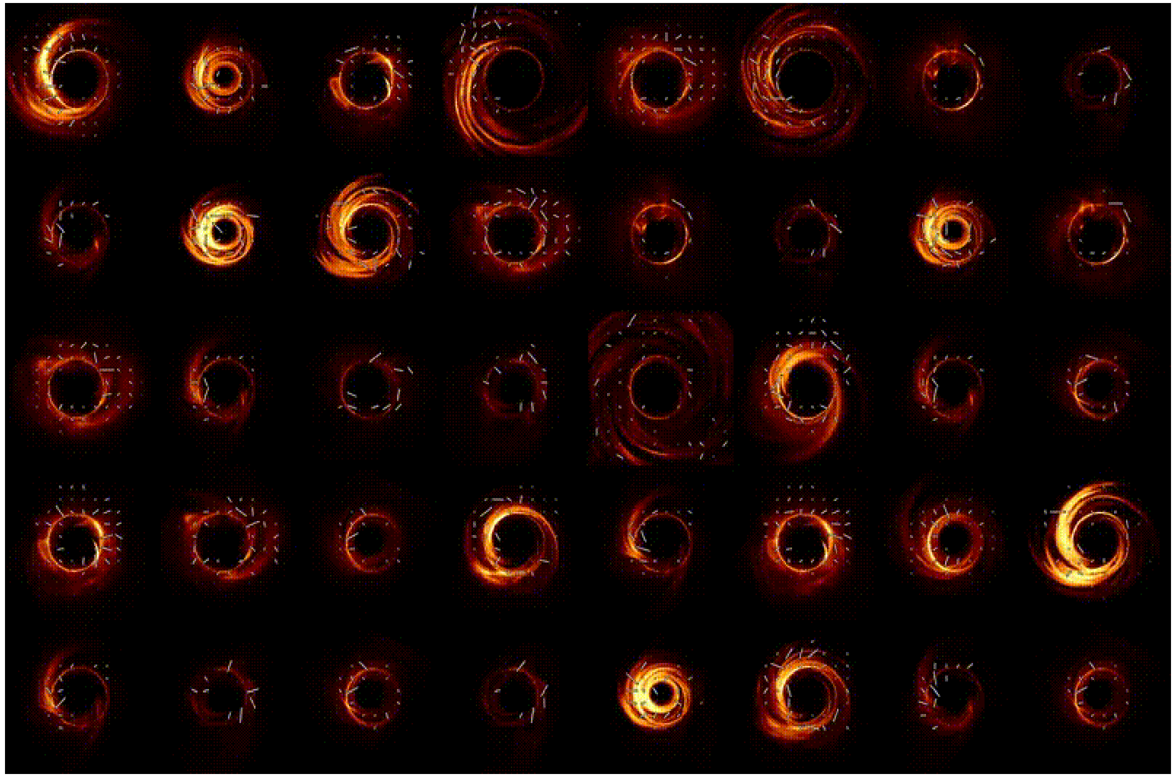


**GR Radiative Transfer**

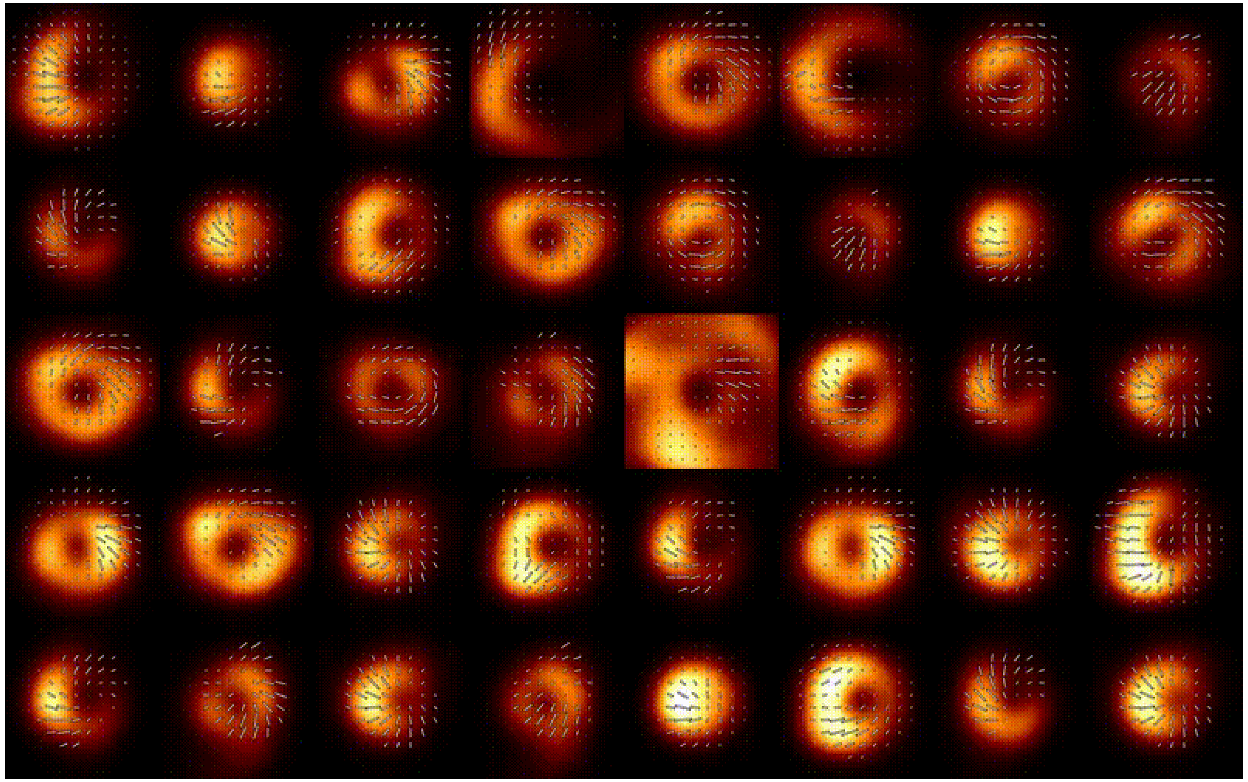
Tracks light rays and solves for the polarized radiation (including Faraday effects)

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

# GRMHD Simulation library



native resolution



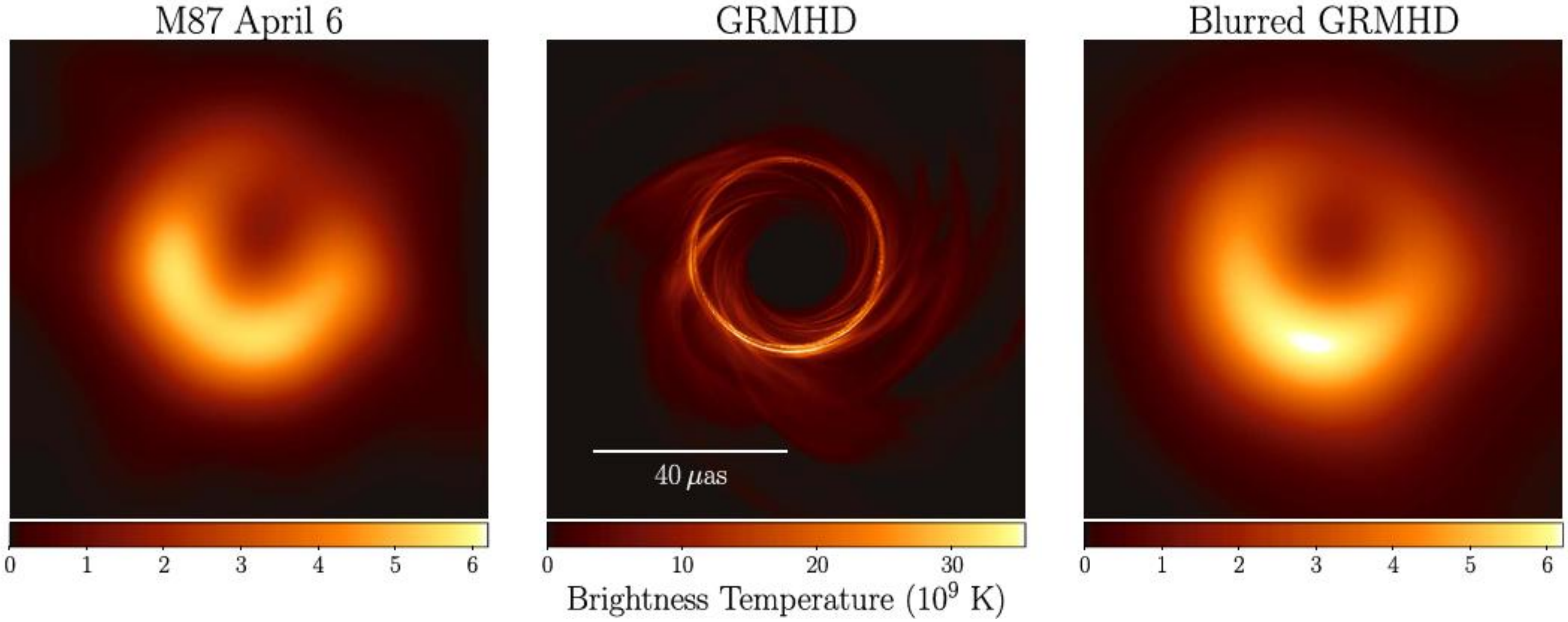
EHT resolution

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

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

Animation credit: George Wong/ Ben Prather

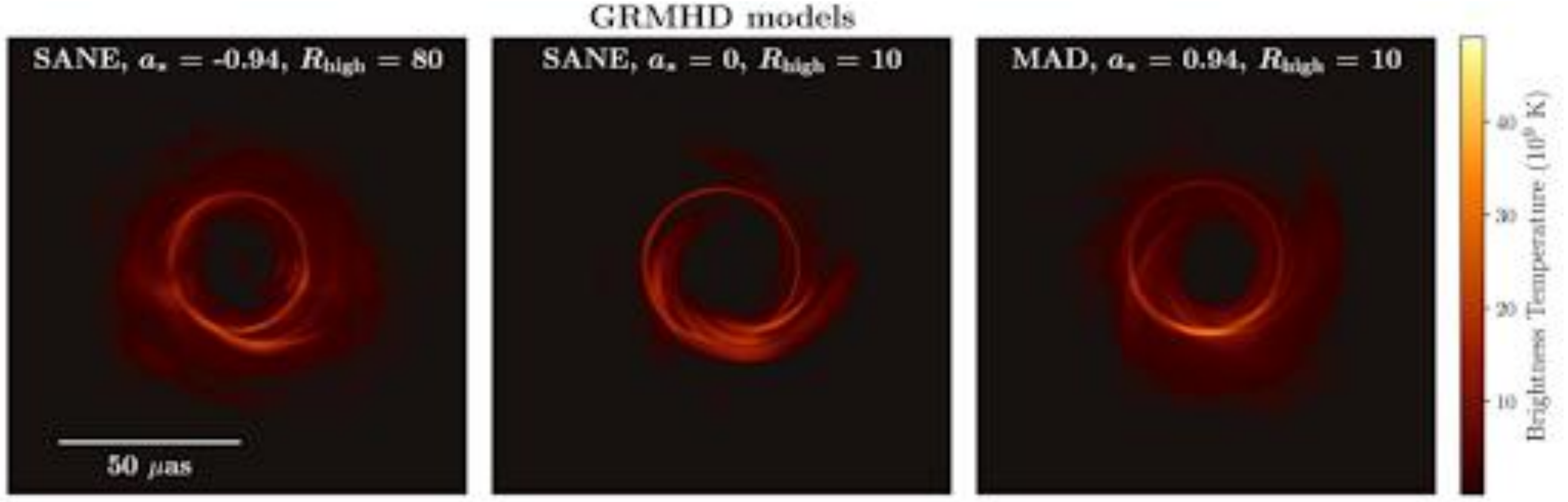
# EHT Images are **Immediately** Consistent with LLAGN Picture




EHTC V, 2019

# Scoring M87* GRMHD Simulations: before polarizatio

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

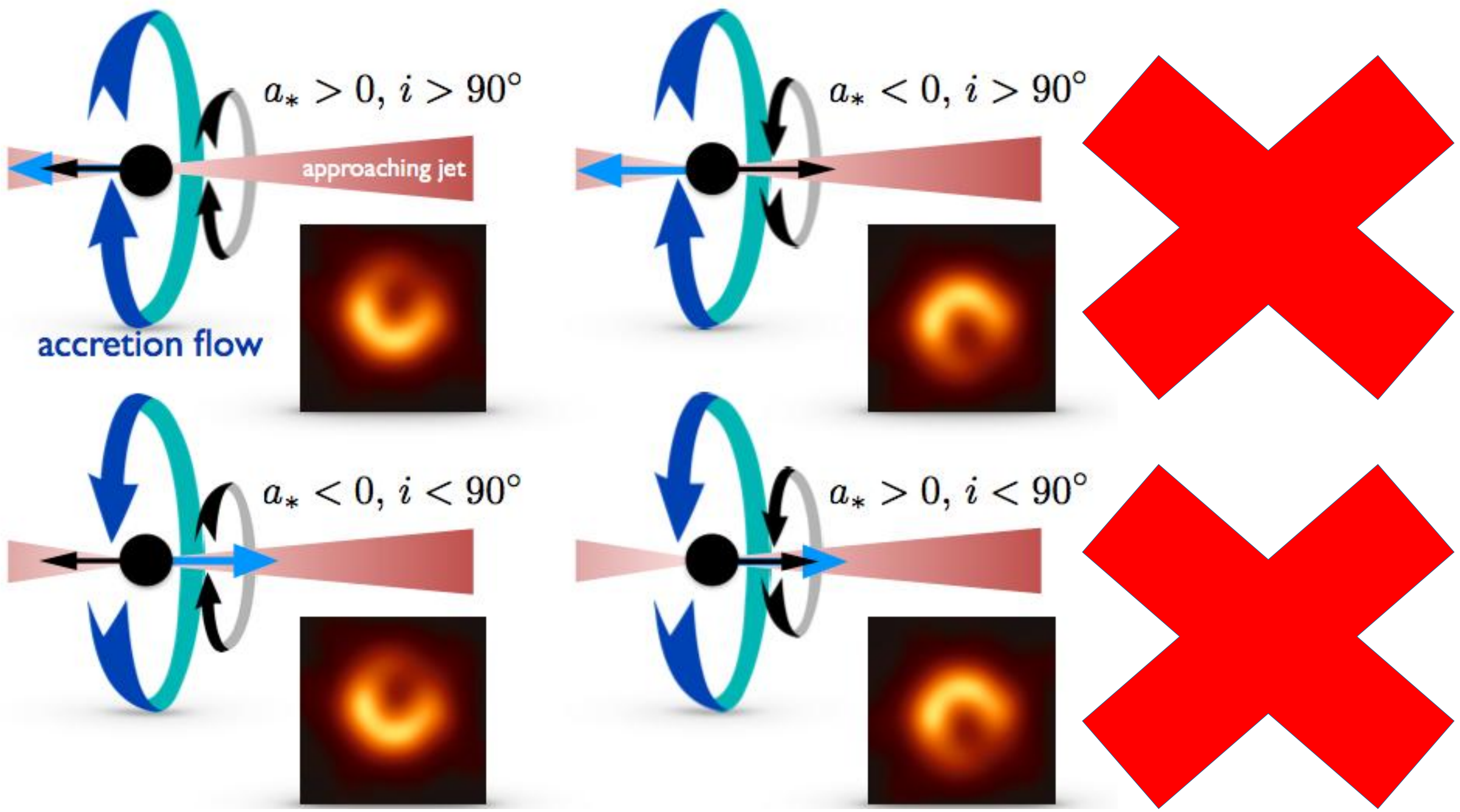



- An additional constraint on **jet power** (≥ $10^{42}$ erg/sec) rejects all spin 0 models
- Can we do better with polarization?

EHTC V, 2019

# Ring Asymmetry and Black Hole Spin

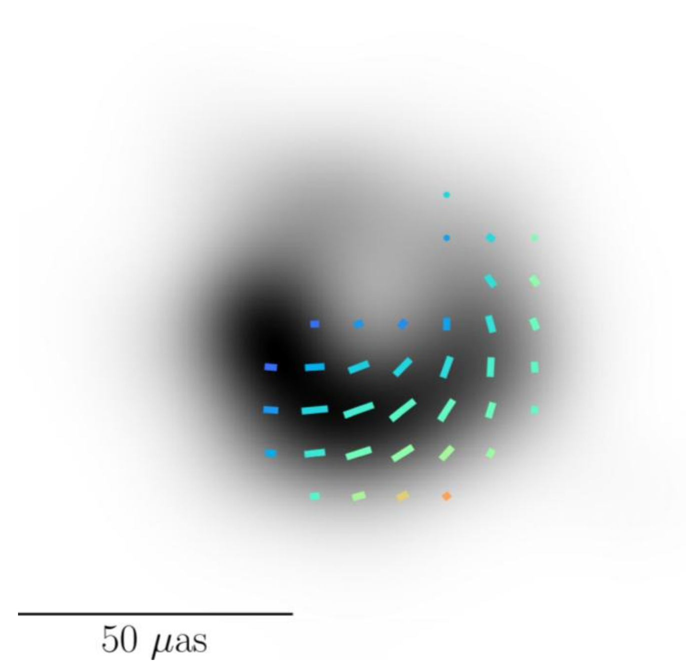
The **BH angular momentum**, not the **disk angular momentum** determines the image orientation in models with nonzero spin (see Wong+ 21)

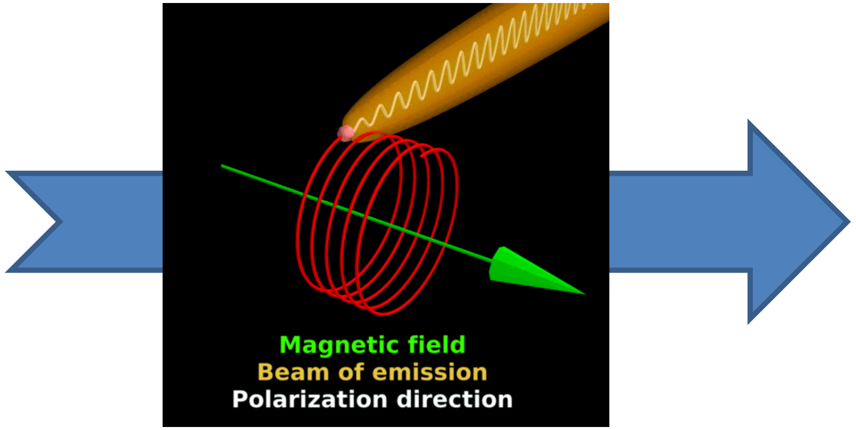



BH spin-away (**clockwise rotation**) models are strongly favored for M87

EHTC V, 2019

# Why polarization?




Magnetic field geometry in the emission region!

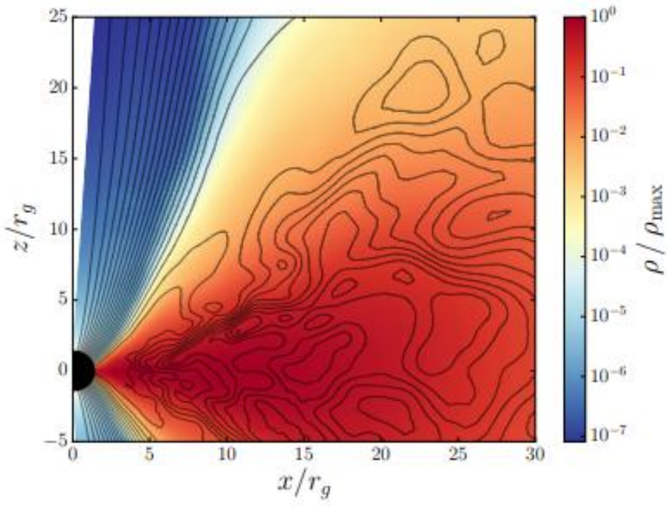
- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines
- Polarization **transport** is sensitive to the magnetic field, plasma, and spacetime
- Polarization images highly constrain near-horizon astrophysics

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

# What is the magnetic field structure close to the horizon?

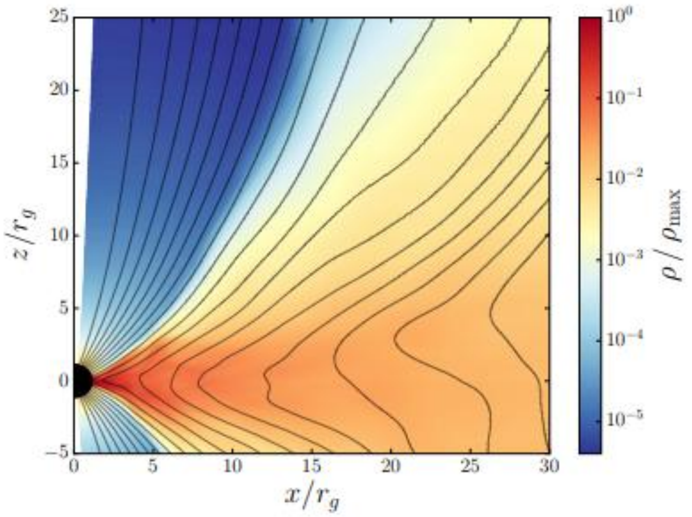
Two accretion states that depend on the accumulated magnetic flux on horizon

**Magnetic fields are weak and turbulent**




"SANE"

**Strong, coherent magnetic fields build up on the horizon**




"MAD" - Magnetically Arrested Disk

Note: 'strong' fields mean ~10 G at the horizon for M87*

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

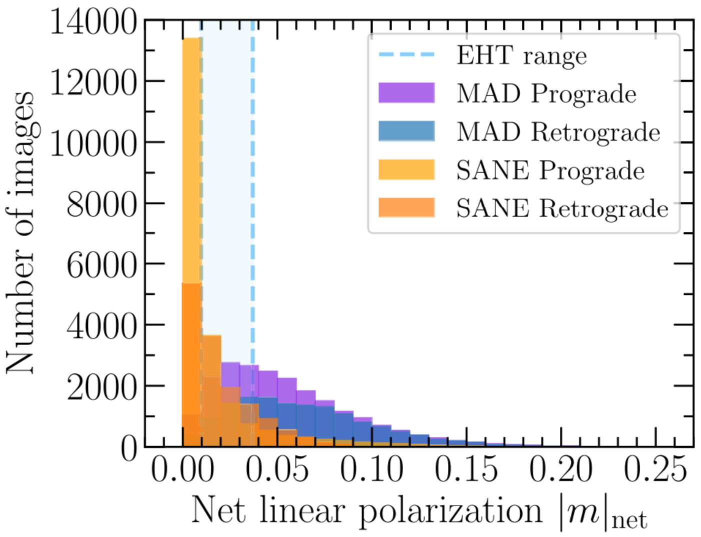
**BH spin**

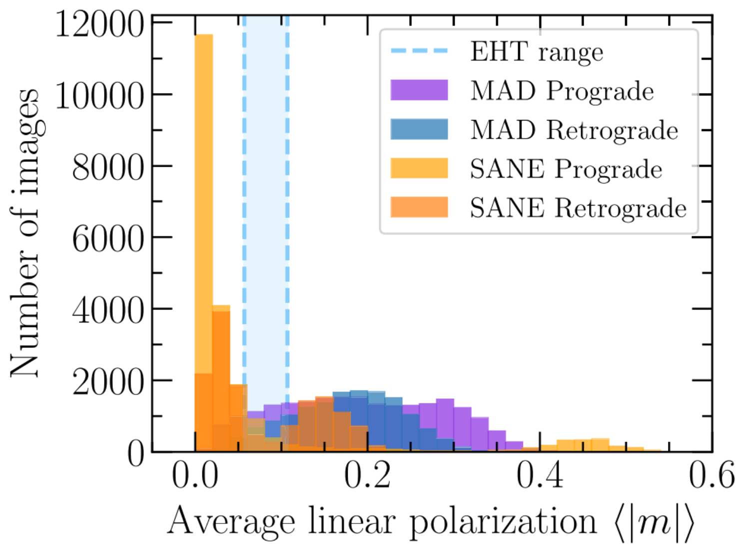
**magnetic flux**

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: Riordan+ 2017

# Scoring M87 simulations with linear polarization

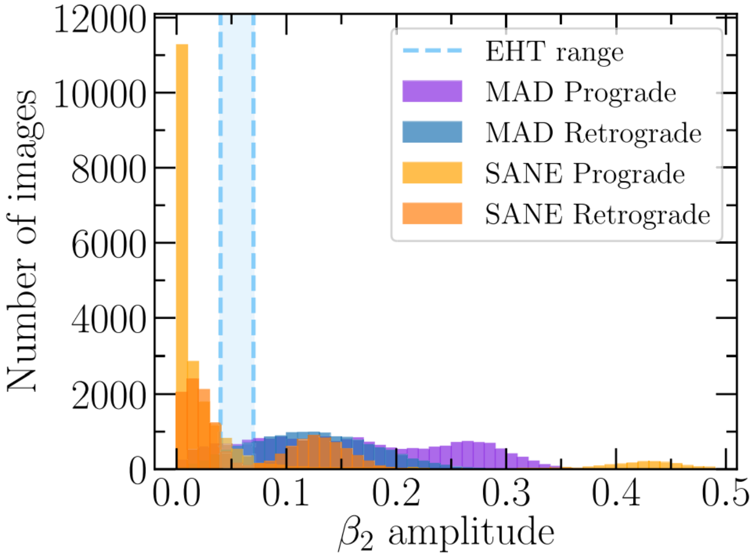
**Unresolved** and **resolved** linear polarization fractions

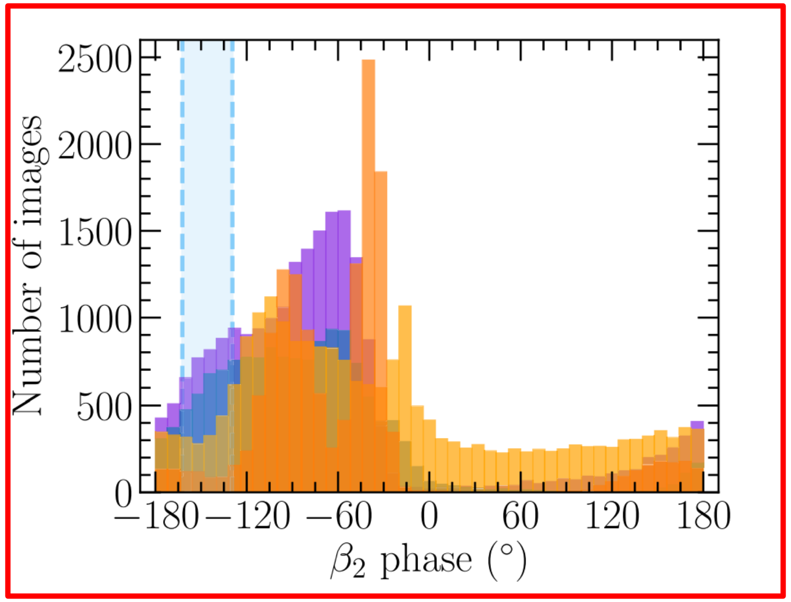



**Azimuthal structure**

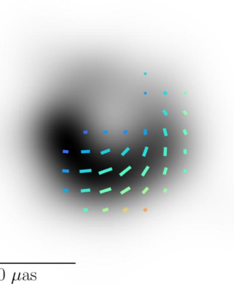
2nd Fourier mode




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

# Scoring M87* simulations with polarization




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

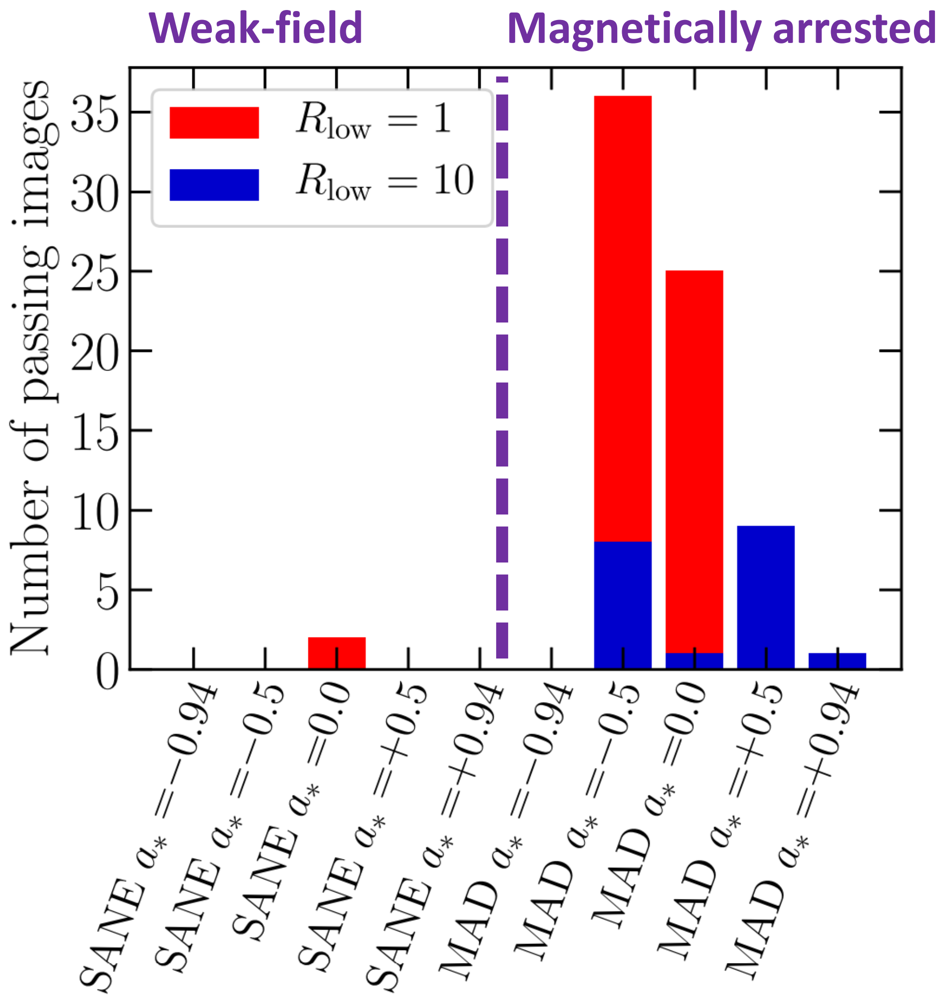
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

$$\dot{M} \simeq (3 - 20) \times 10^{-4} M_\odot \text{ yr}^{-1}$$
$$\left(\dot{M}_{\text{Edd}} = 137 M_\odot \text{ yr}^{-1}\right)$$

- Parameters from passing models agree with one-zone estimates:

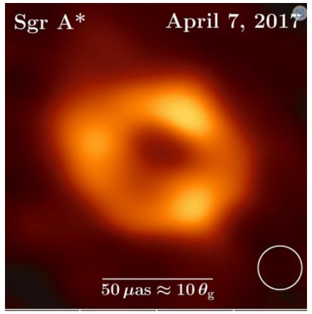
$$T_e \simeq (5 - 40) \times 10^{10} \text{ K}$$
$$|B| \simeq (7 - 30) \text{ G}$$
$$n \sim 10^{4-5} \text{ cm}^{-3}$$

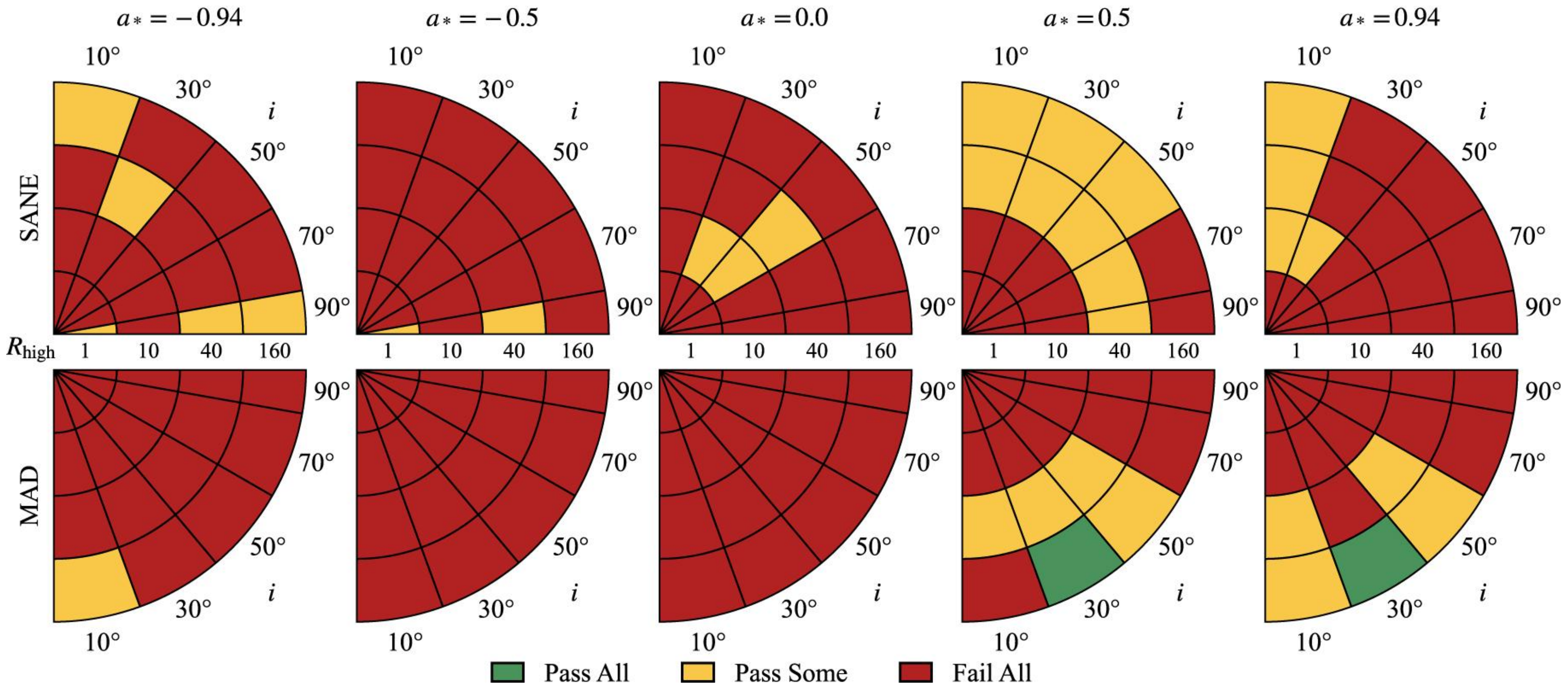
- Strong magnetic fields more easily launch Blandford-Znajek jets!




EHTC 2021 VIII, 2023 IX (**Chael**, paper coordinator)

# Sgr A* non-polarization Constraints



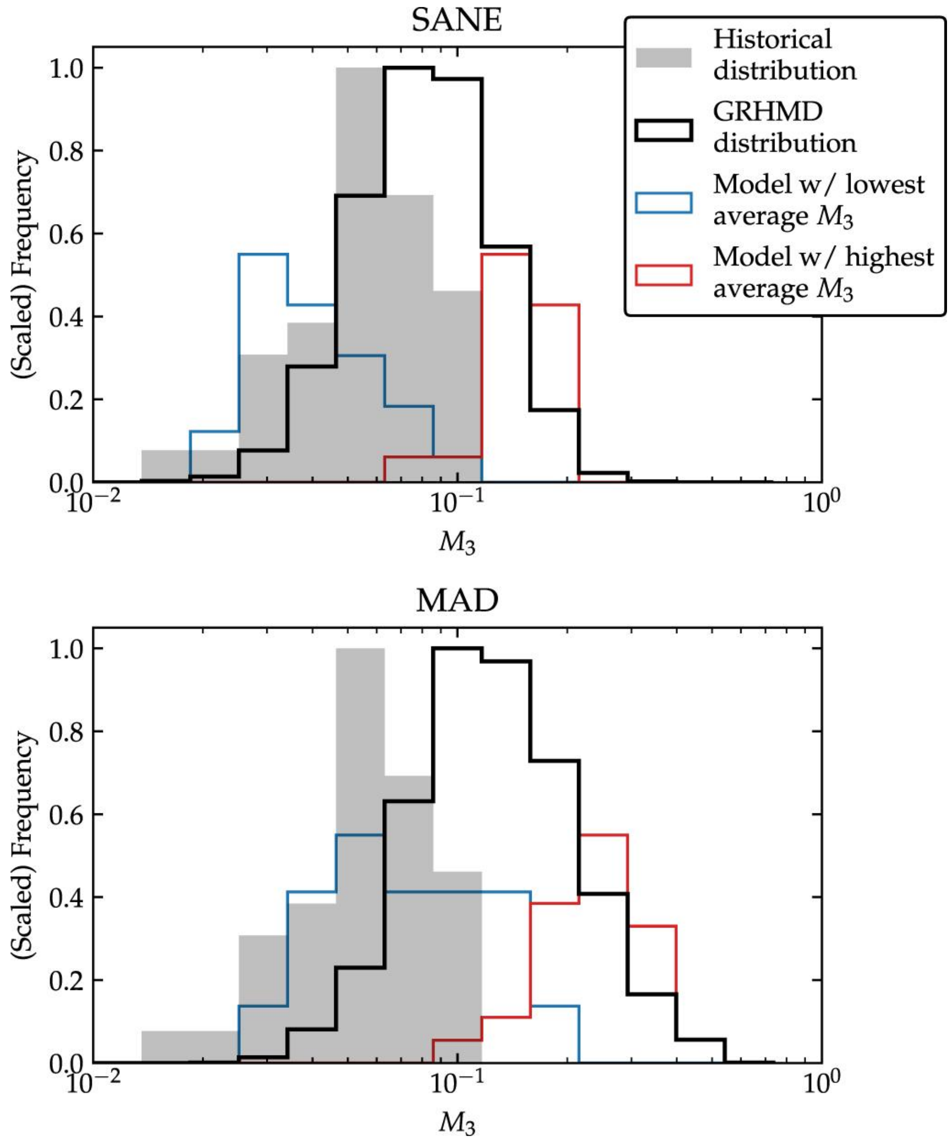




- Sgr A* models are strongly constrained by the precise mass measurement, strong multi-wavelength constraints, and resolved ring width.
- **Most passing models are MAD**
- Passing models have **low inclination**: i ≤ 30 deg

EHTC V, 2022

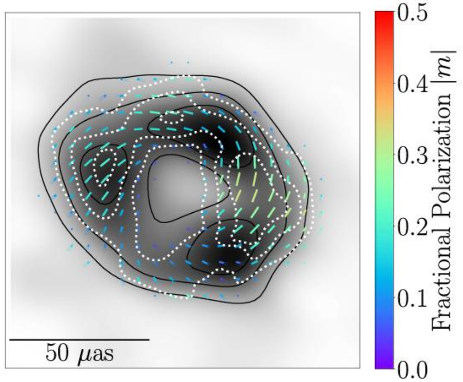
# The Sgr A* "Variability Crisis"

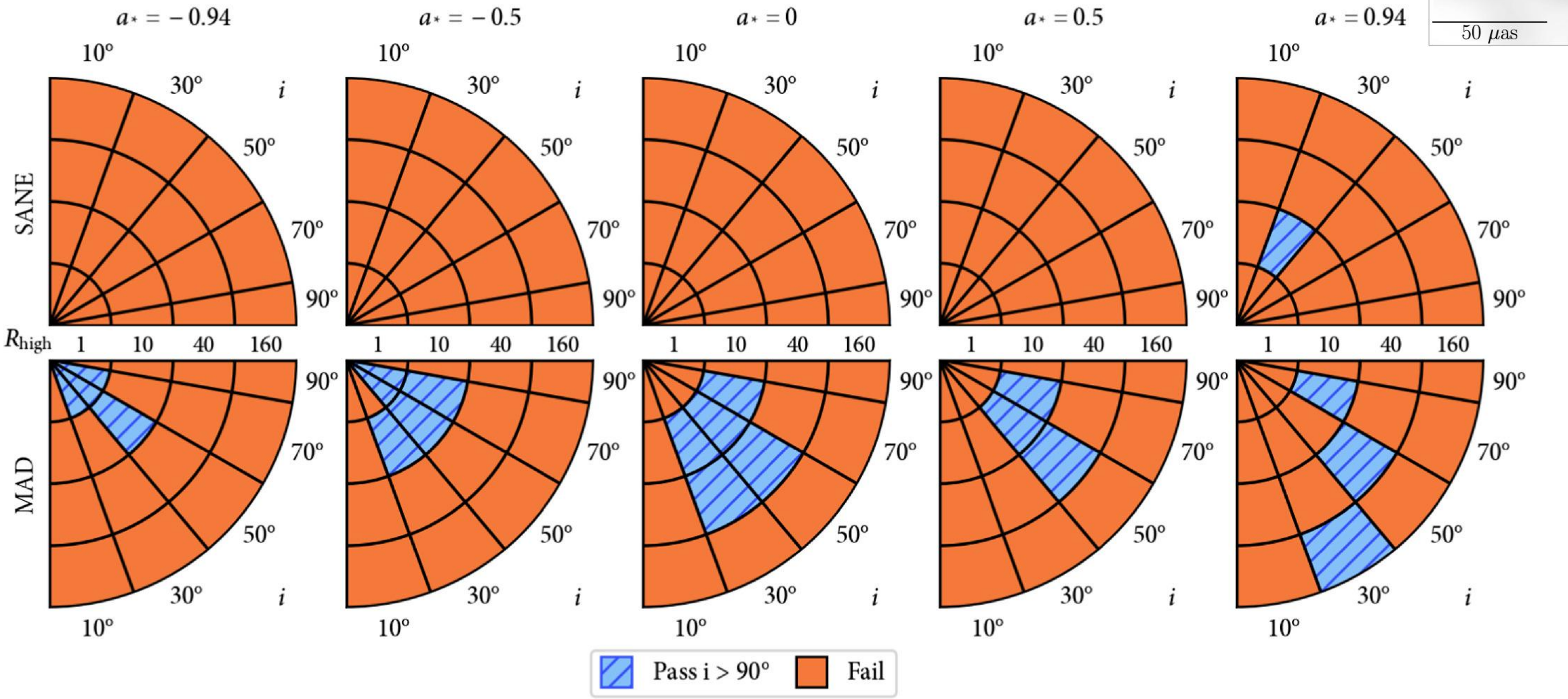
- Sgr A* has a **short gravitational timescale** (~20 sec) and is one of the most observed objects in the sky across the EM spectrum over the last few decades.
- Sgr A* simulations are ***nearly all*** **too variable** when compared with long-duration light curves.
- How big of a problem is this? Opinions differ!
- Possible resolutions: extended emission, better two-temperature modeling (e.g. Chan+ 2024) radiative cooling (e.g. Salas+2024)




EHTC V, 2022

# Sgr A* Polarization Constraints




- For any model to pass requires **Faraday de-rotation.**
- Passing models all must spin **clockwise**, consistent with NIR & submm flare inferences (GRAVITY+ 2018, Wielgus+ 2022)
- **One high spin MAD model survives** both multi-wavelength and polarization cuts

EHT VIII, 2024 (**Chael**, paper writing team)

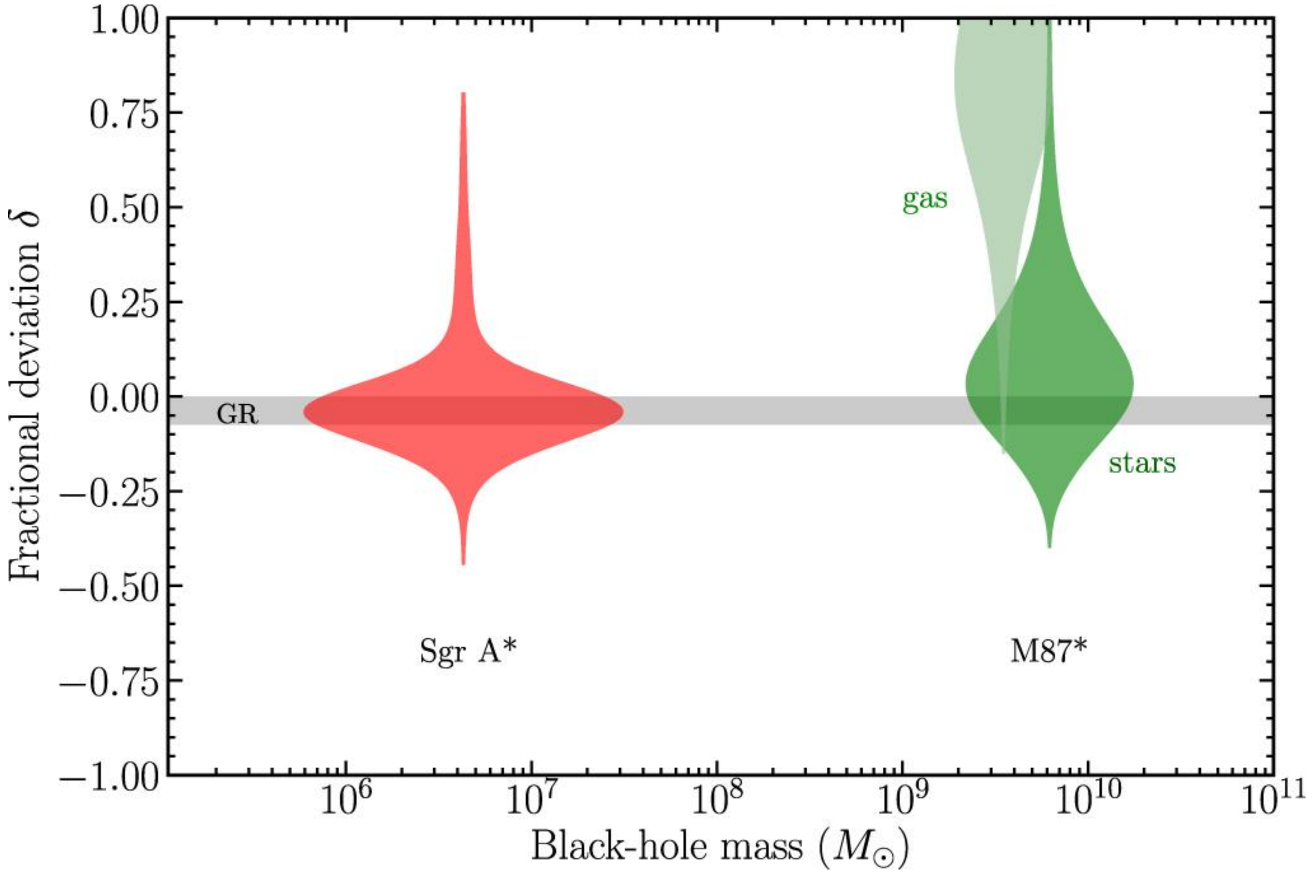
# Sgr A*and M87*: Tests of GR

- Connecting EHT image ring diameter to predicted shadow size from GR requires **astrophysical** calibration

- **Uncertainty** in diameter measurement, mass, and astrophysical source model included in distribution of the deviation parameter δ

- Both M87* and Sgr A* have image sizes consistent with GR prediction.

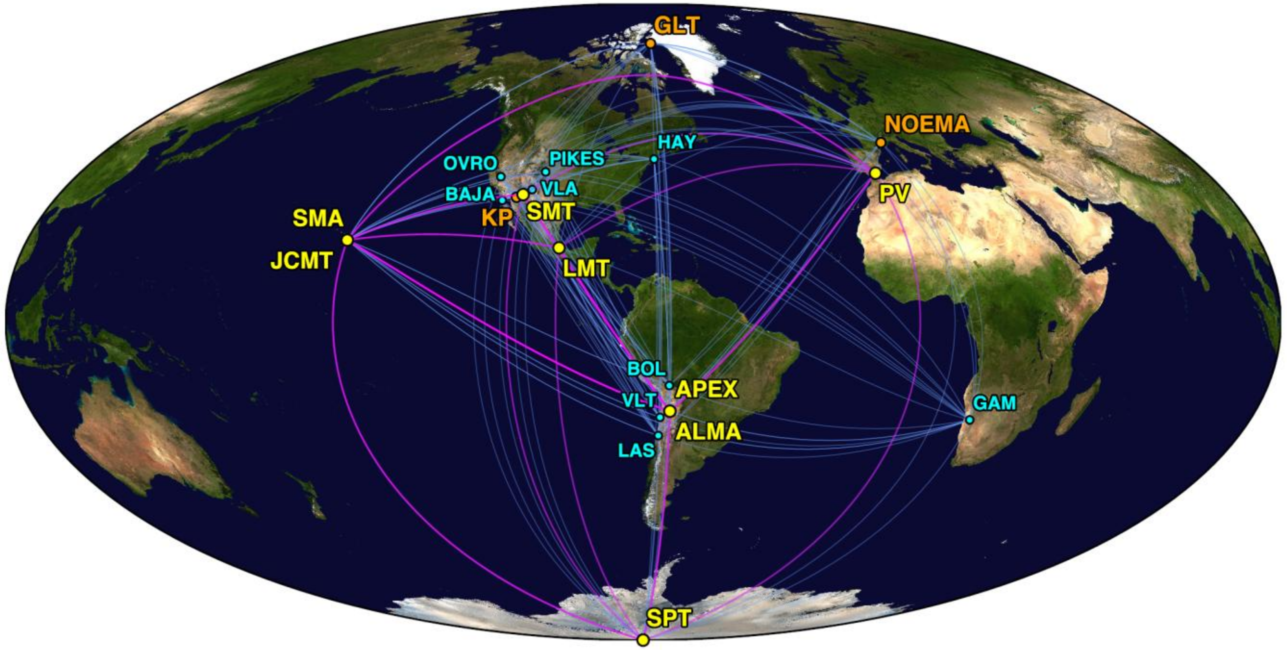
- See talk by Lia soon!

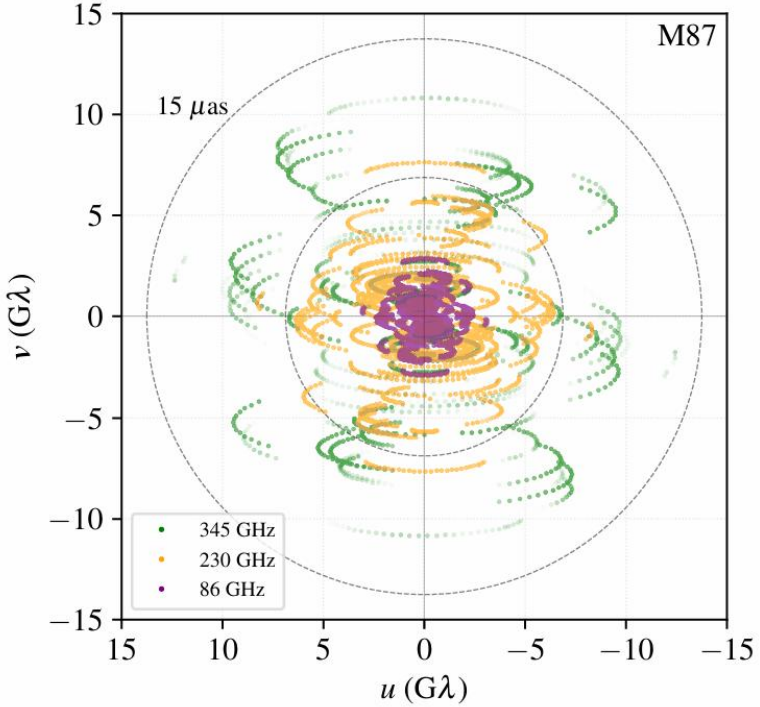



EHTC I, VI, 2022

# Some Next Steps and (biased) Implications

# EHT upgrades




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

**2017**: Observations at 6 distinct sites
**2021**: Observations at 9 sites (+ Kitt Peak & NOEMA)
**2025:** 230 and 345 GHz observations in full array
**2030+:** tri-band observations at ~14 sites?

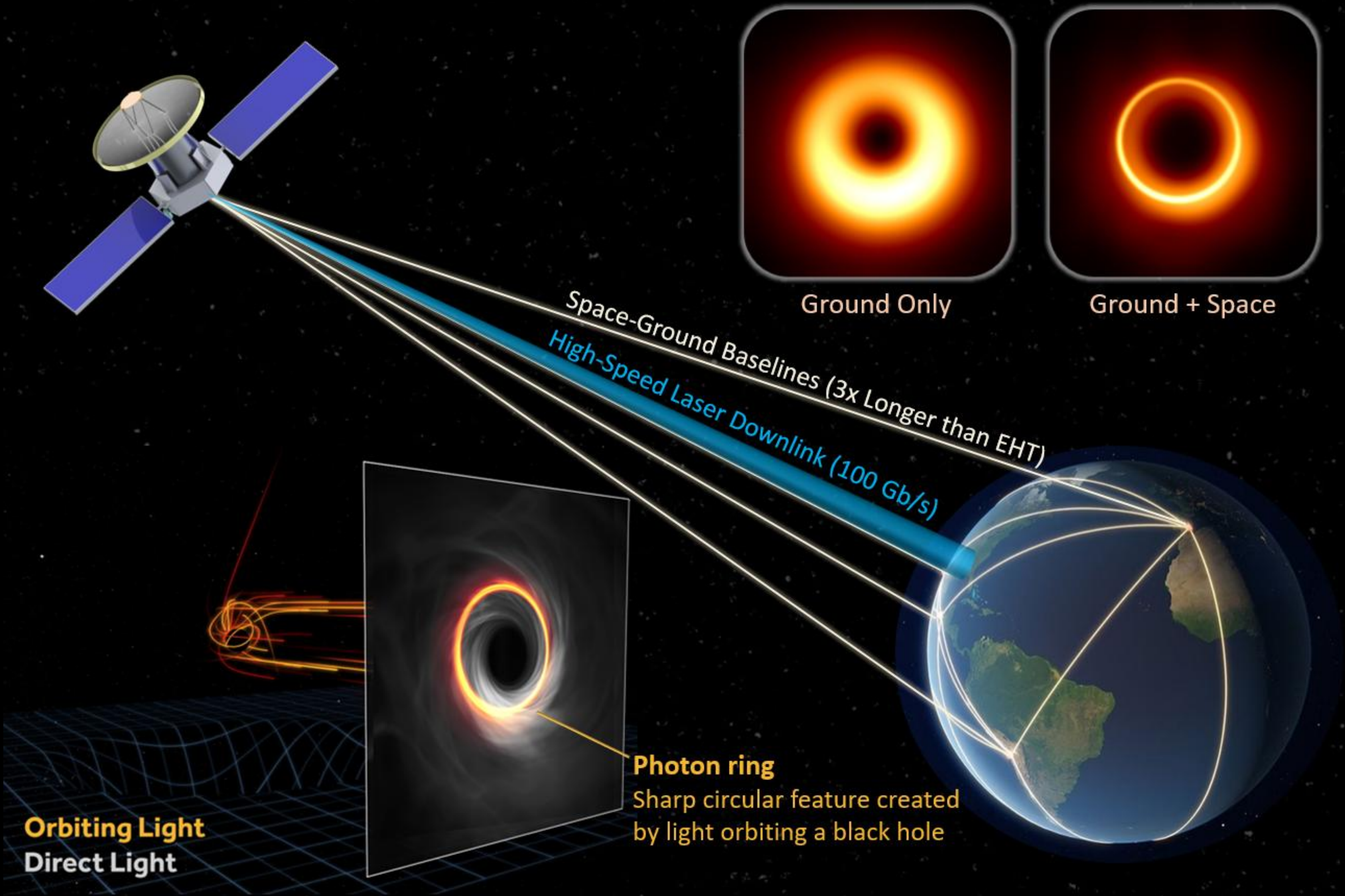
$$N_{\mathrm{obs}} = \binom{N_{\mathrm{sites}}}{2} \propto N_{\mathrm{sites}}^2$$

Doeleman+ 2023, Johnson+ 2023, EHTC+ 2024

# The Black Hole Explorer (BHEX)

**BHEX will achieve the highest angular resolution in history and reveal a black hole's "photon ring" for the first time**

- First *direct* measurement of a black hole's spin
- Opportunity to study *dozens* of black holes
- Leverages existing ground infrastructure
- Targeting a 2025 SMEX proposal
- See Wednesday talk by Alex Lupsasca!

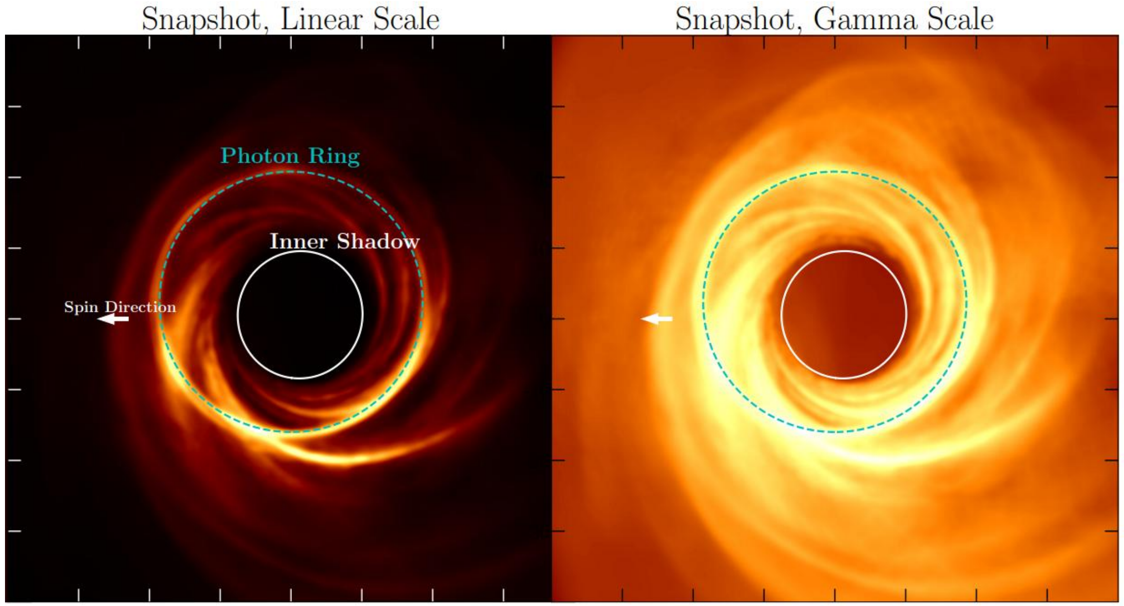


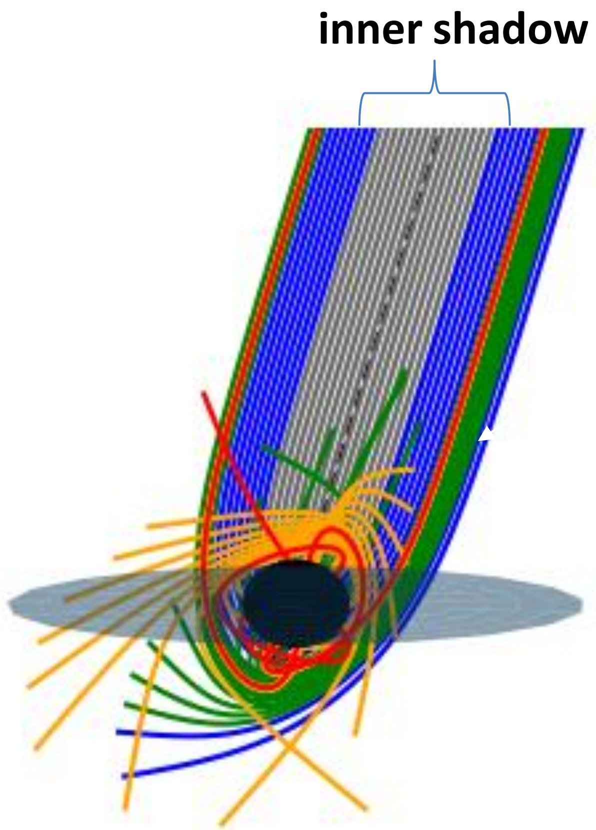

**Science Goals**

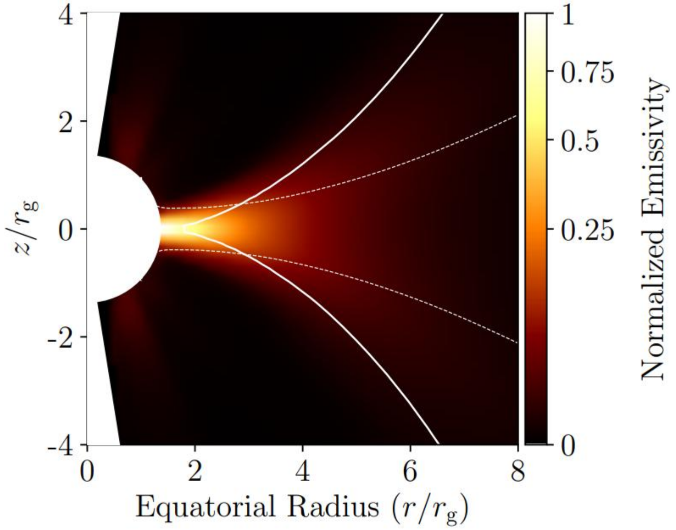
- ➢ Discover a black hole's photon ring
- ➢ Make direct measurements of a black hole's mass and spin
- ➢ Reveal the shadows of *dozens* of supermassive black holes

https://www.blackholeexplorer.org/

# The “Inner shadow” is a generic prediction of MAD simulations



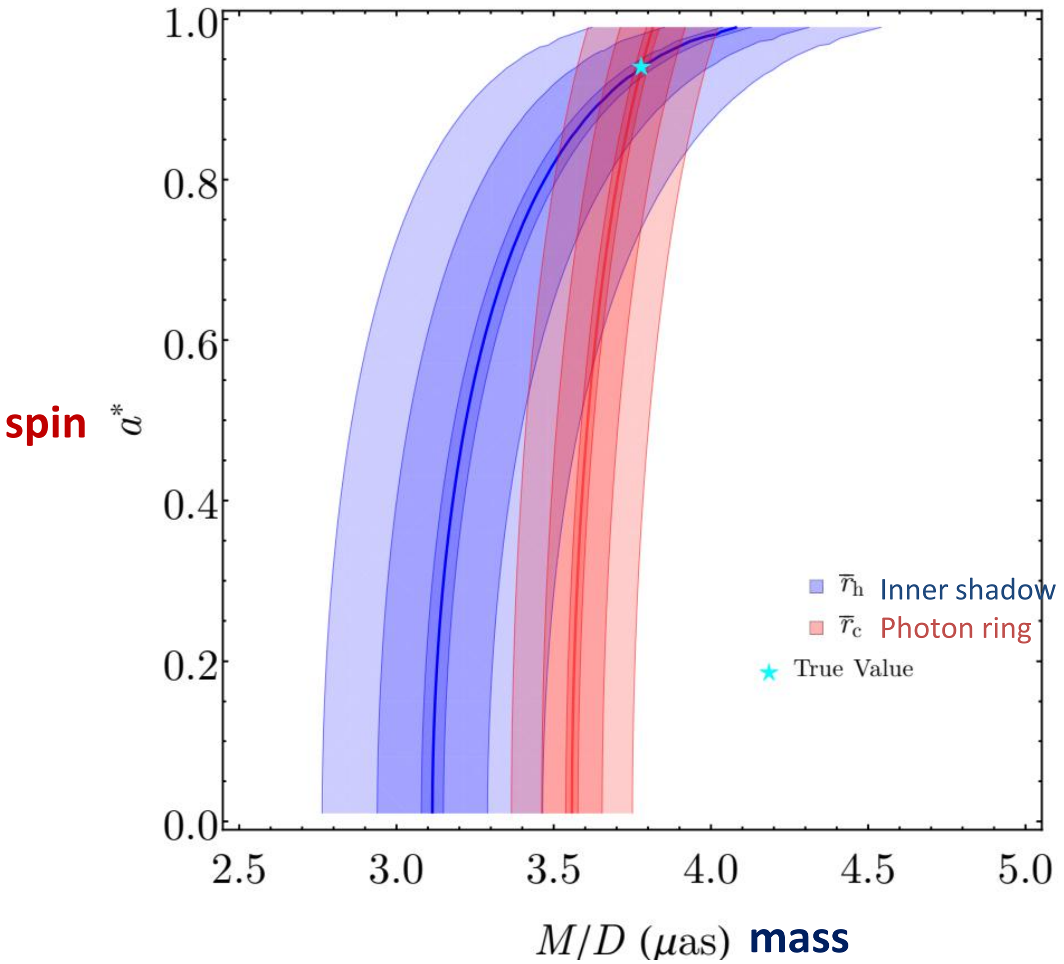




- The **inner shadow is visible in simulations**; its edge approaches the **lensed position of the event horizon**
- MADs have thin / nearly equatorial emission regions close to the horizon
- Redshift increases near the horizon → the inner shadow is **most visible at high dynamic range**

**Chael**+ 2021

# Inner shadow images provide another probe of spacetime



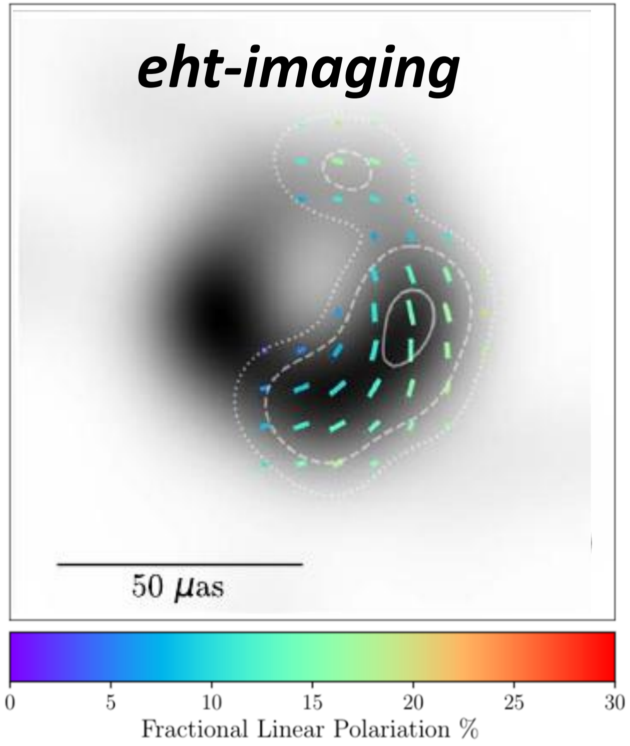

**Toy example** of determining mass and spin with inner shadow (blue) and photon ring (red) radius measurements for **M87***

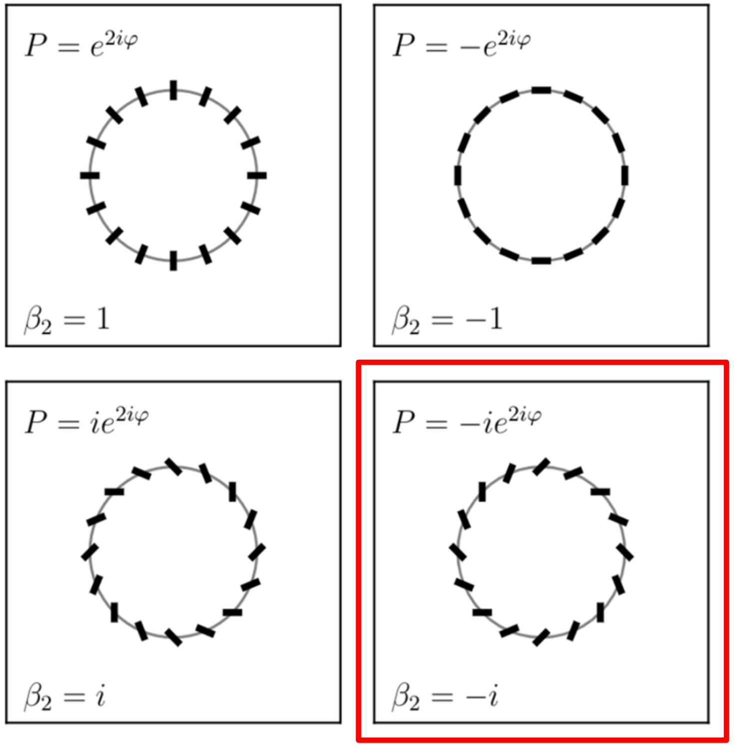
(bands represent measurement uncertainties of 0.1, 0.5, 1 uas)

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

# Polarized Images and horizon-scale energy flow



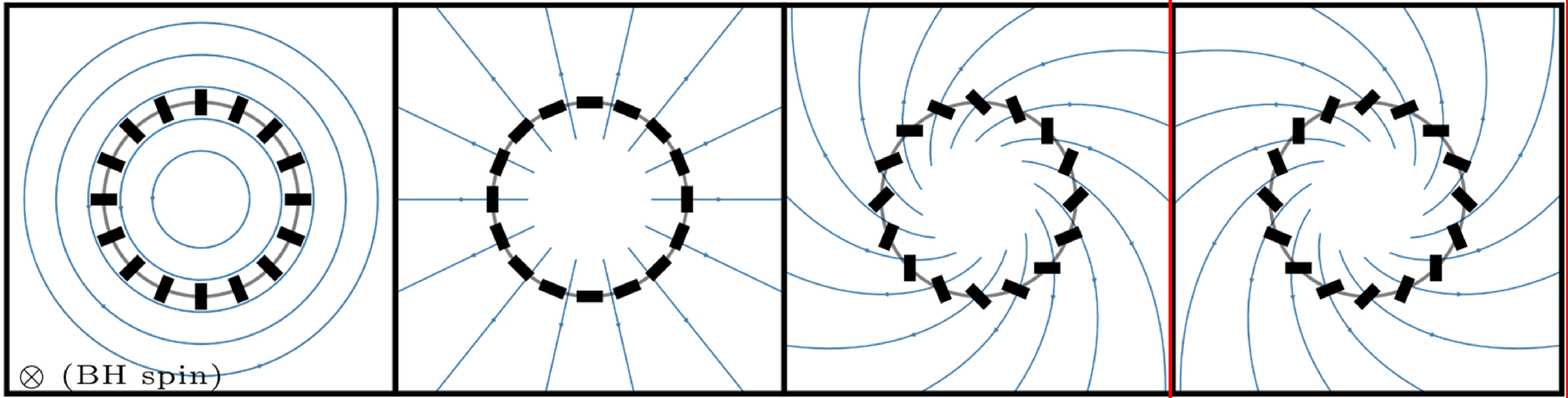

- The polarization spiral's 2nd Fourier mode ($\boldsymbol{\beta_2}$: Palumbo+ 2020) is the **most constraining** feature for GRMHD simulation scoring
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

# Polarized Images and horizon-scale energy flow

**Energy Inflow** | **Energy Outflow**

$B^r = 0$ | $B^\phi = 0$ | $B^\phi / B^r > 0$ | $B^\phi / B^r < 0$




$\angle\beta_2 = 0$ | $\angle\beta_2 = \pm\pi$ | $0 < \angle\beta_2 < \pi$ | $-\pi < \angle\beta_2 < 0$

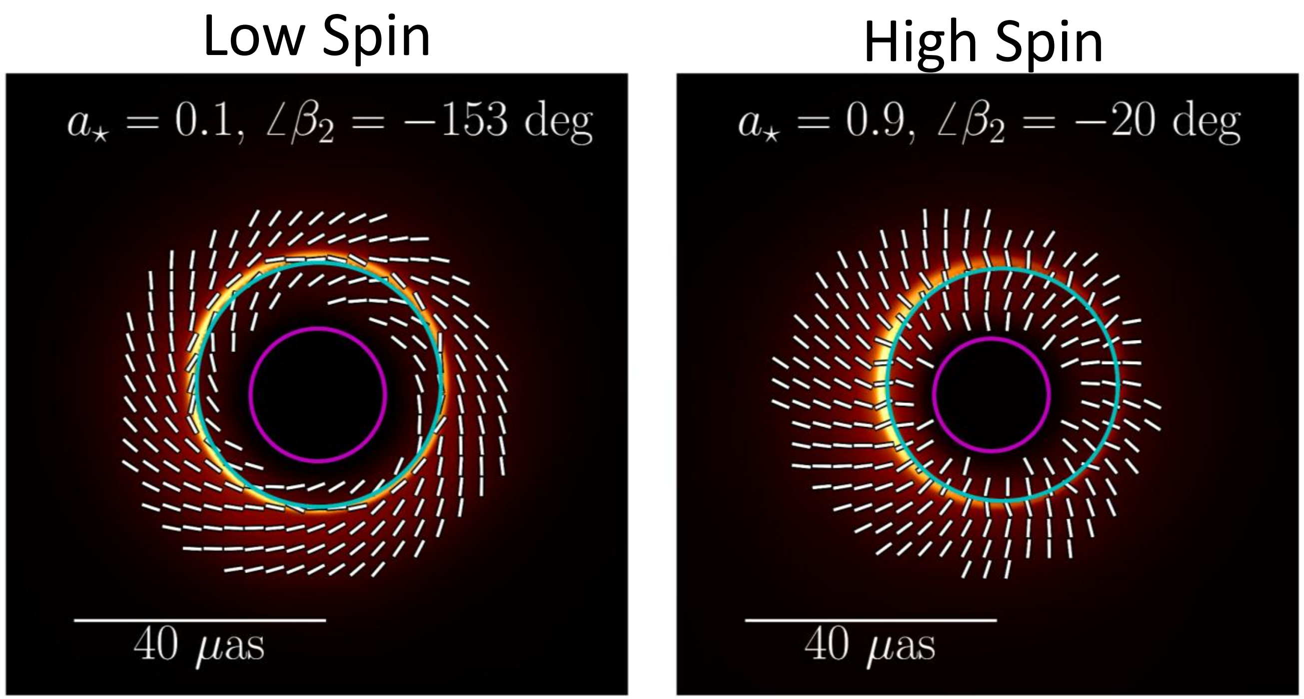
**Radial Poynting Flux:**

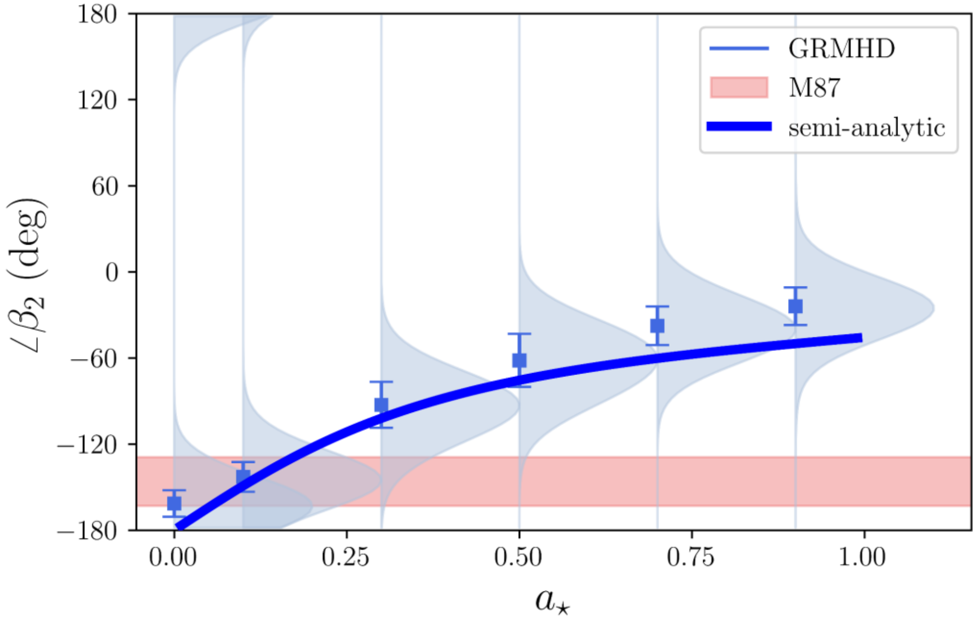
$$\mathcal{J}^r_{\mathcal{E}} = -T^r_{t\ \mathrm{EM}} = -B^r B^\phi \,\Omega_F\, \Delta \sin^2\theta$$

fieldline angular speed

Chael+ 2023b

# Polarized images are **spin dependent**

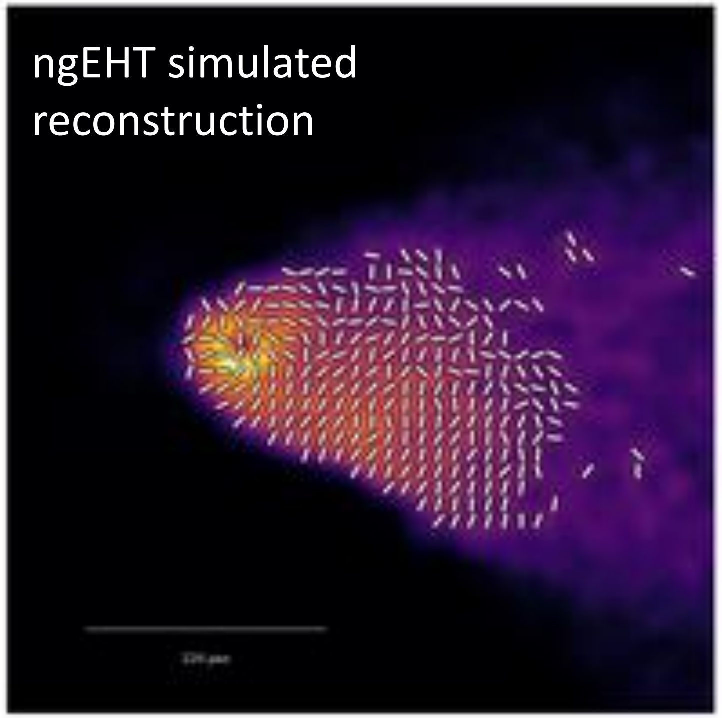


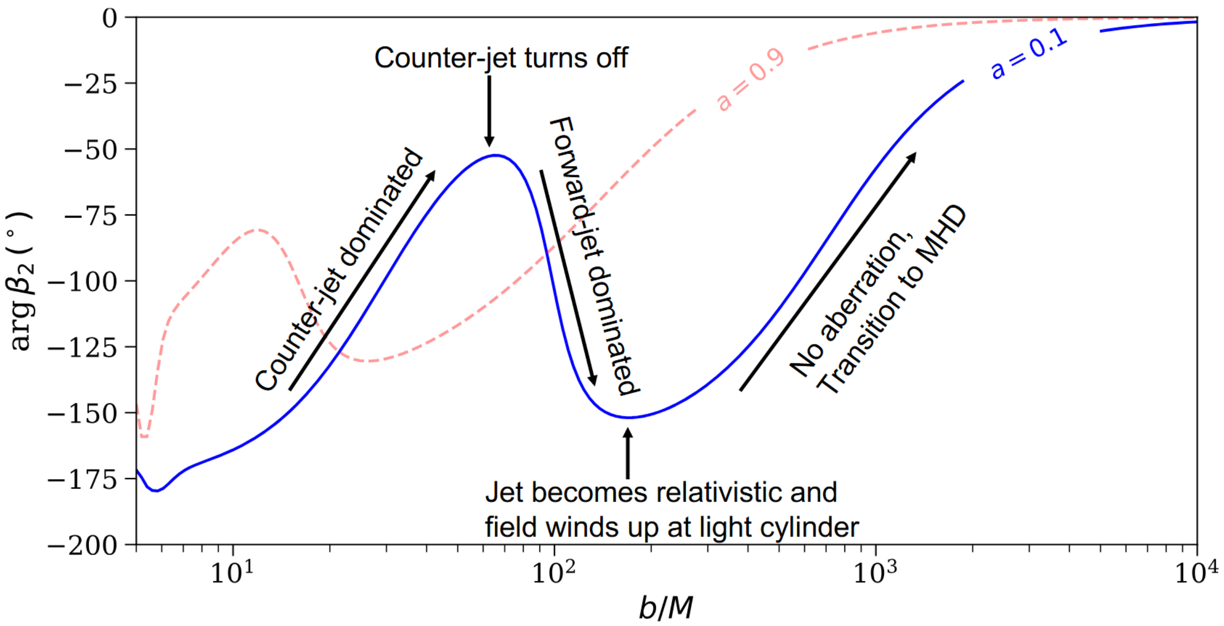




- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the Poynting flux (BZ jet power)
  - makes the observed polarization pattern more radial

**Chael** in prep

# To look for energy extraction, we need to zoom **out**



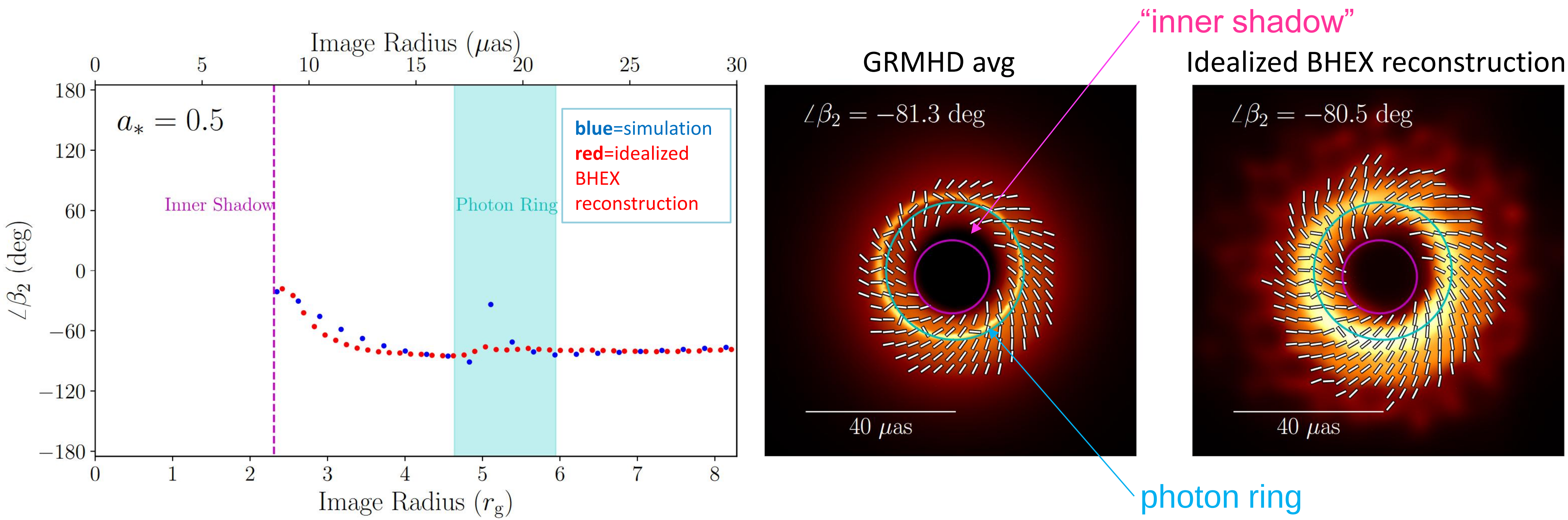




Zack Gelles (Princeton)
Arxiv: 2410.00954

- New sites & larger bandwidth will enhance EHT's **dynamic range** and **illuminate** the **BH-jet connection**
- Measuring polarization as a function of radius **probes energy flow at different scales**
- Polarization of BZ jets has a **strong signature of spin** at the **light cylinder** (Gelles, Chael, & Quataert 2025)

**Chael**+ 2019, 2023b
Gelles, **Chael**, Quataert+ 2025
Image Credit: Paul Tiede, Dom Pesce, Zack Gelles

# To look for energy extraction, we need to zoom **in**

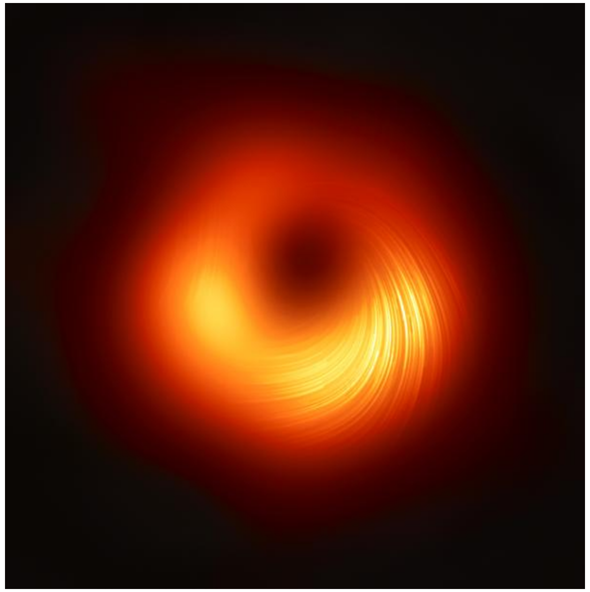



- arg($\beta_2$) evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - strong evolution of arg($\beta_2$) to the horizon is predicted by both analytic models and GRMHD
- BHEX + EHT can obtain **the dynamic range and resolution** to observe this evolution?
  - Can we trace energy-extracting field lines to <0.5$r_g$ to the horizon?

**Chael**+ 2023b

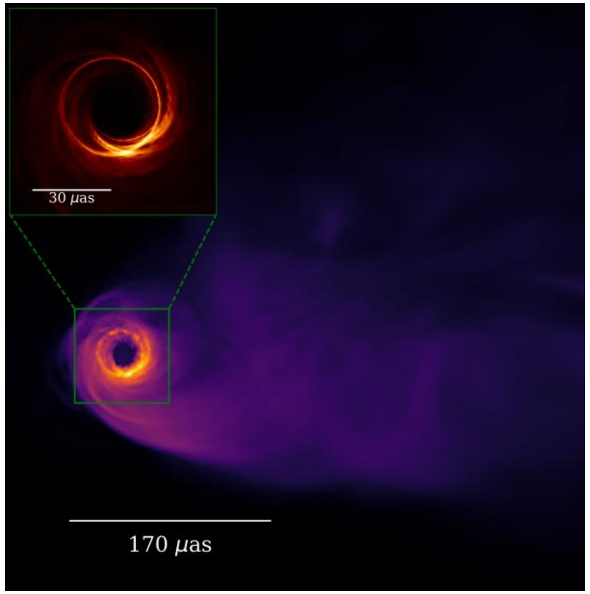
# Takeaways…

1. **Sgr A* and M87* are regularly studied on the horizon scale** in exquisite detail by the Event Horizon Telescope
2. **EHT uses multiple analysis approaches** and summary statistics to focus on the most-well constrained image features
3. **Polarization** is the key for constraining near-horizon astrophysics, and indicates that accretion in both Sgr A* and M87* is likely magnetically arrested
4. **We are just getting started** in what we can learn from black hole images



# …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/BHEX observation tell us about the near-horizon environments of supermassive black holes beyond Sgr A* and M87*?




EHT VII, 2021; **Chael** 2025