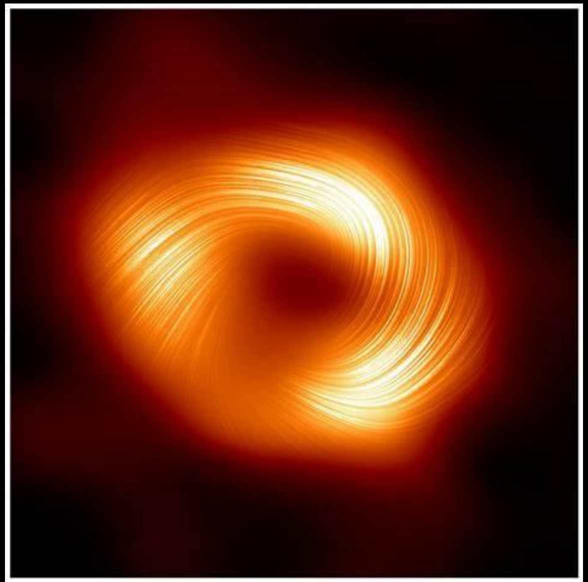
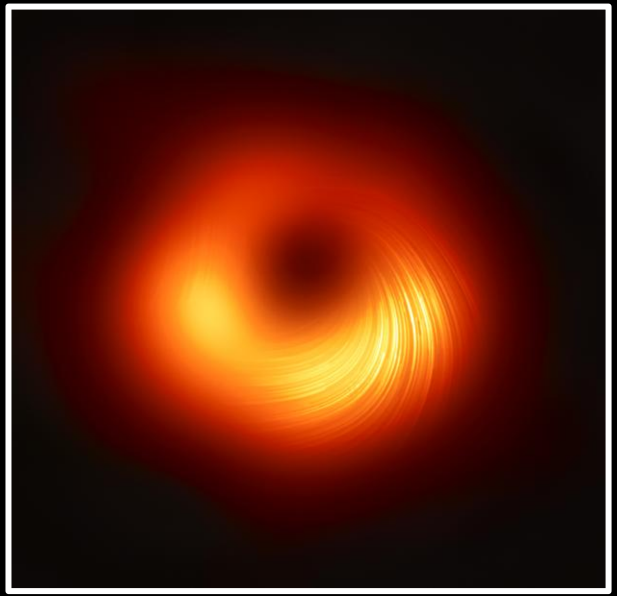
What have we learned from black hole images?

Andrew Chael
NBIA, University of Copenhagen

URSI GASS, Kraków, Poland
August 21, 2026





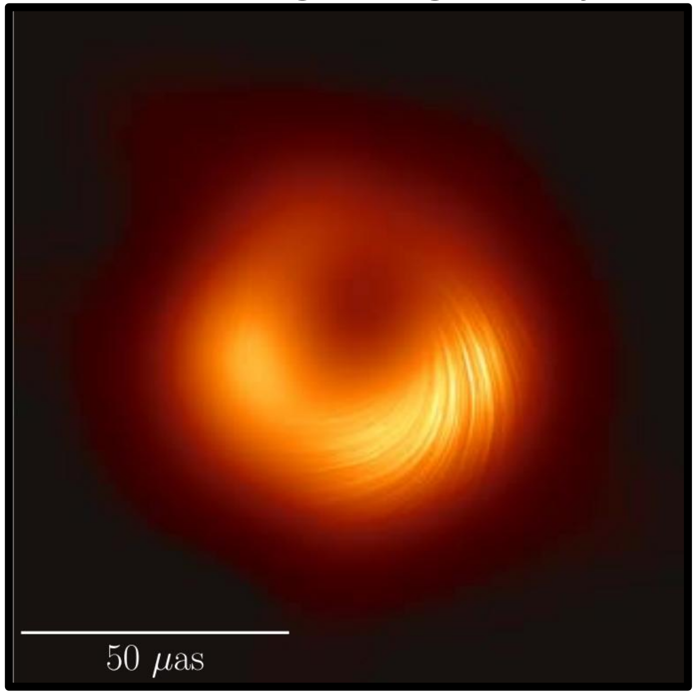
KØBENHAVNS UNIVERSITET

The Niels Bohr International Academy

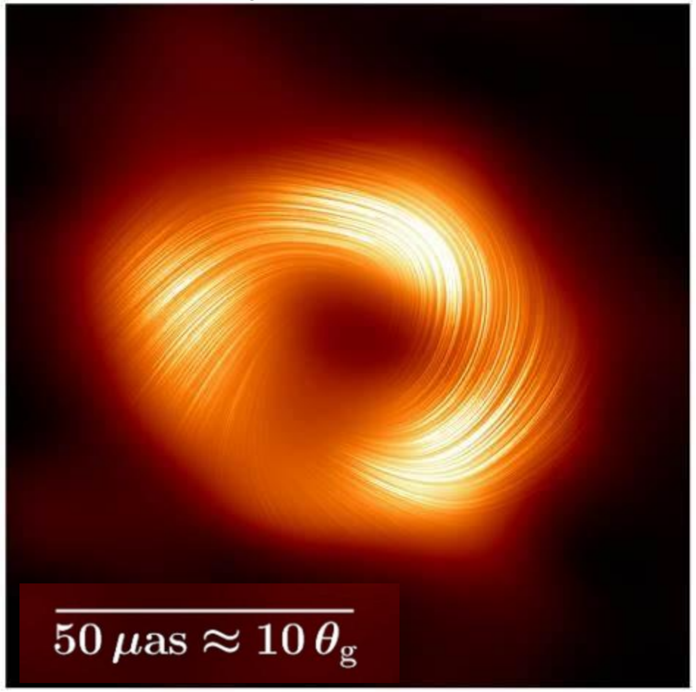
Event Horizon Telescope

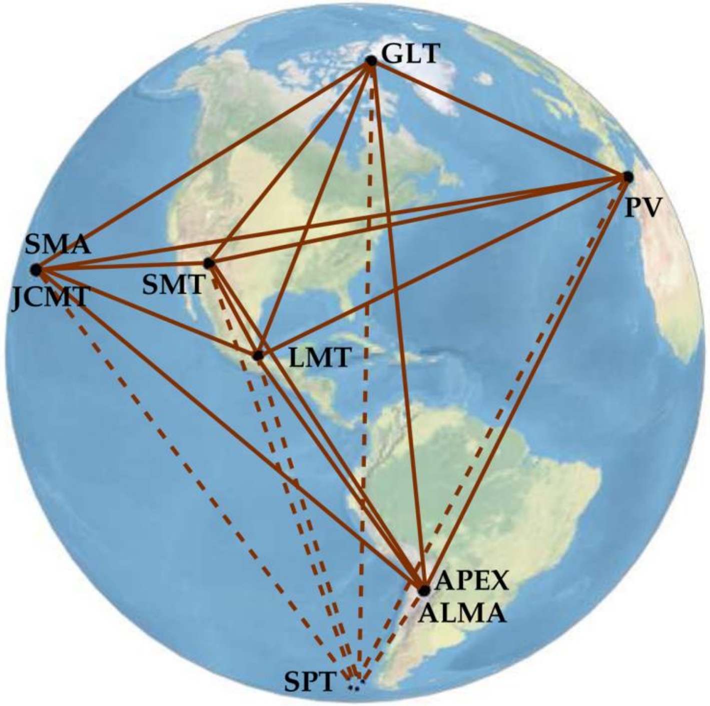
The first black hole images

M87* (EHTC 2019, 2021, 2024, 2025)
~6.5x10^9 $M_\odot$
Launches a strong extragalactic jet



Sgr A* (EHTC 2022, 2024)
~4x10^6 $M_\odot$
No obvious jet





Over three orders of magnitude in BH mass:

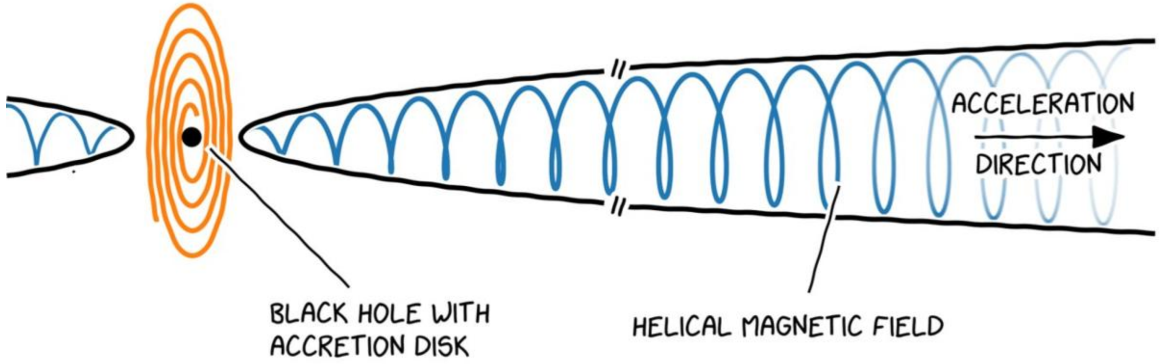
Both images feature ring-like 230 GHz emission on horizon scales (≤5 GM/c^2)

Both images are well-described by models and simulations of low-luminosity accretion: ($\dot{M} \approx 10^{-7} - 10^{-5}\dot{M}_{Edd}$)

Both images constrain our models of the accreting plasma, magnetic fields, BH mass and spin

Persistent Mysteries

- What powers extragalactic jets?
- How and where are high-energy particles accelerated near black holes?
- Can we precisely measure the black hole spin and test General Relativity?
- What is the structure and dynamics of near-horizon magnetic fields?



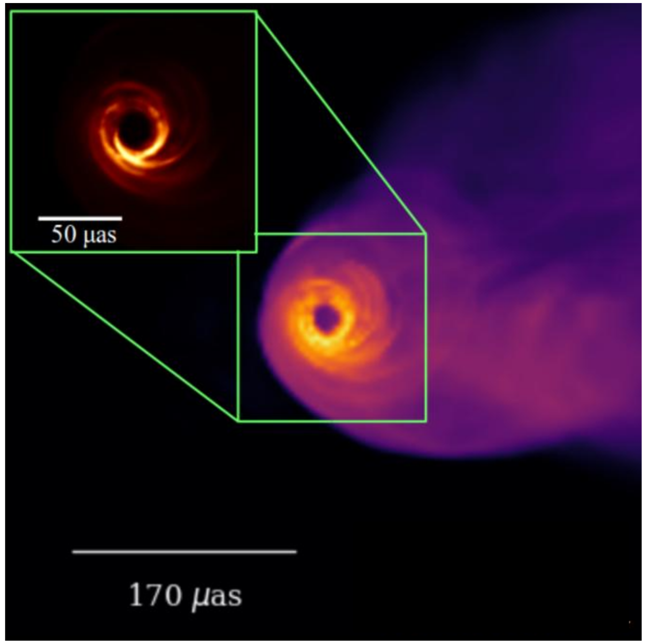


Image credits: Jan Röder, Lindy Blackburn

This talk:

1. What have we learned from the first polarized images of black holes?

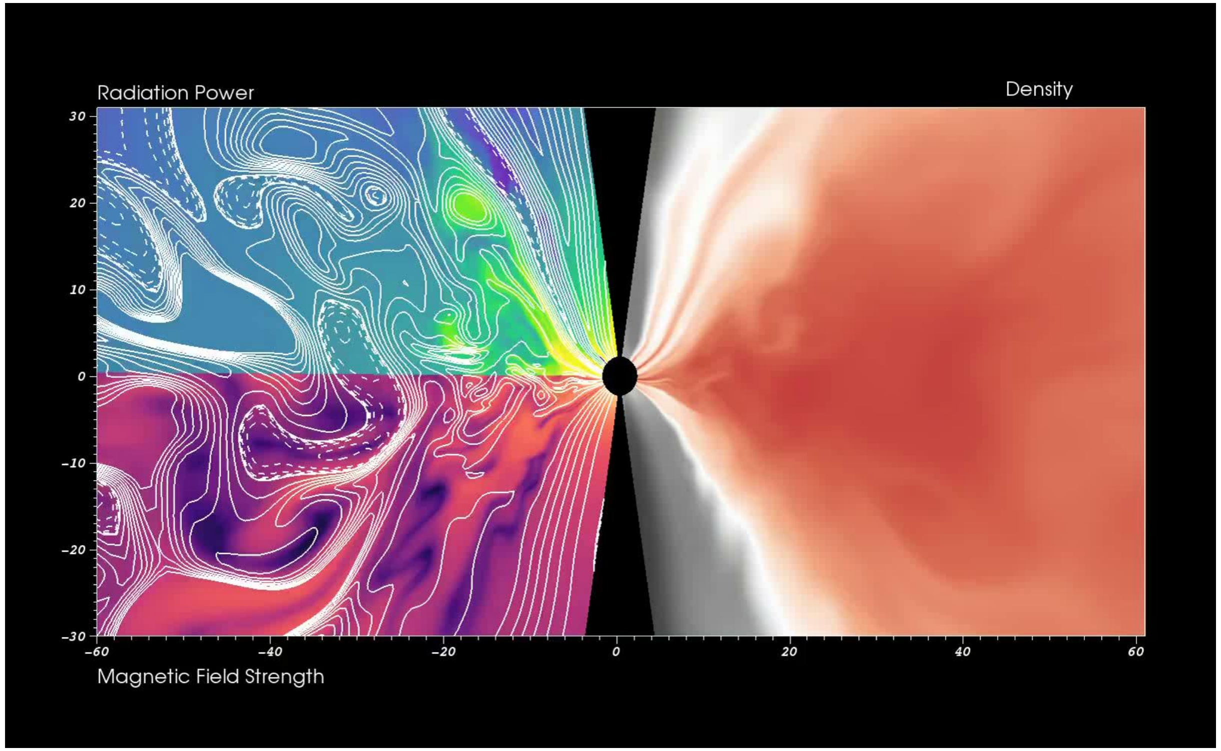
2. What can polarized EHT images tell us about how jets are launched?

3. What's next?

What have we learned from comparing polarized black hole images to simulations?

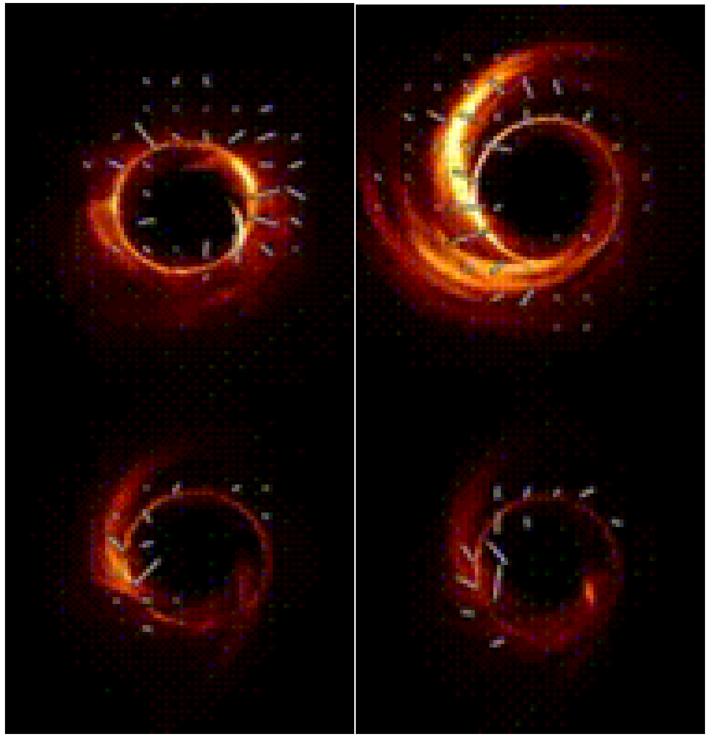
EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator); EHTC VIII, 2024

Theoretical Tools for Interpreting Black Hole Images



General Relativistic Magnetohydrodynamic (GRMHD) Simulations

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



GR Radiative Transfer

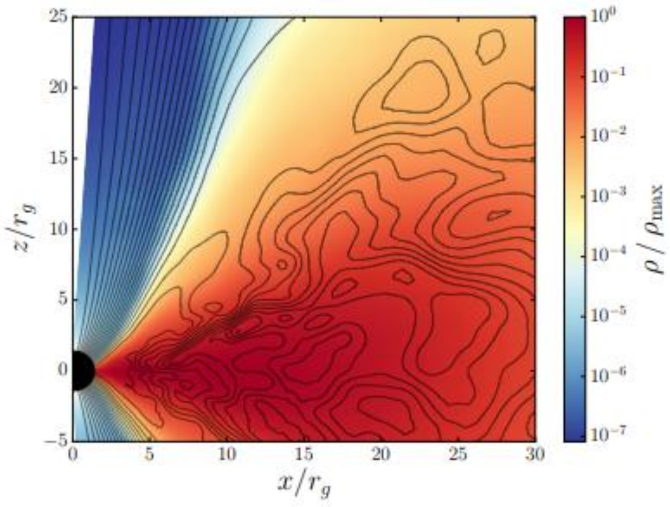
Track light rays and solves for the observed (polarized) radiation

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

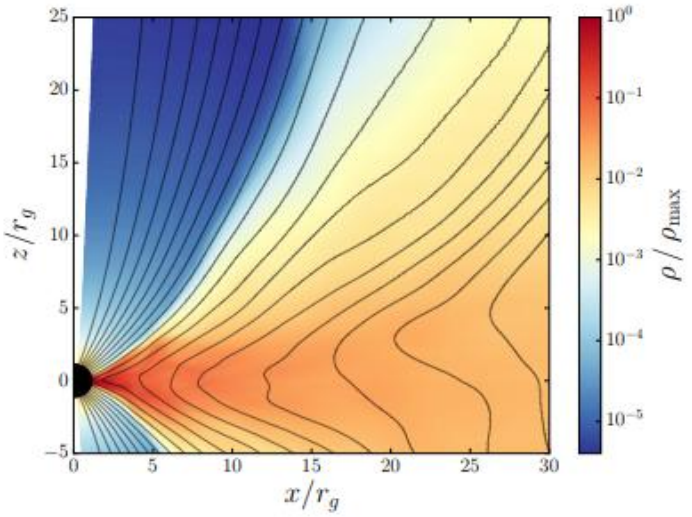
What is the magnetic field structure close to the horizon?

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

MADs launch more powerful Blandford-Znajek jets:

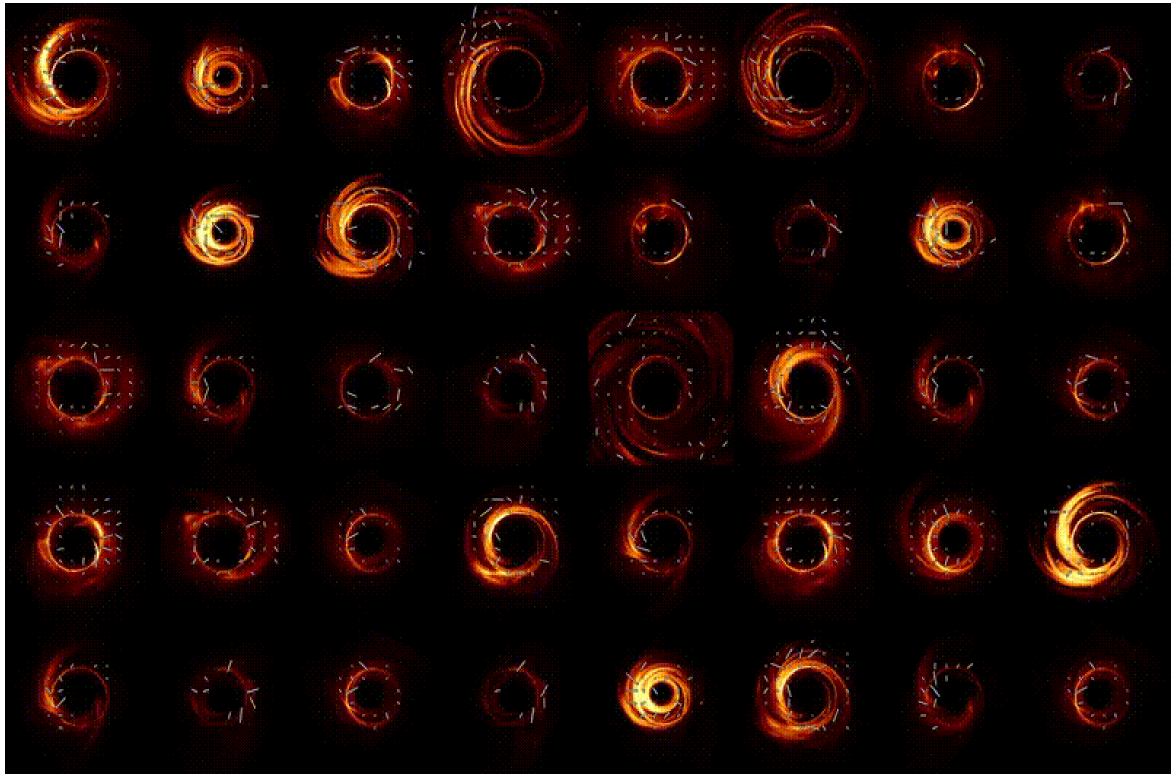
$$P_{\text{jet}} \propto \Phi_B^2 a^2$$

BH spin

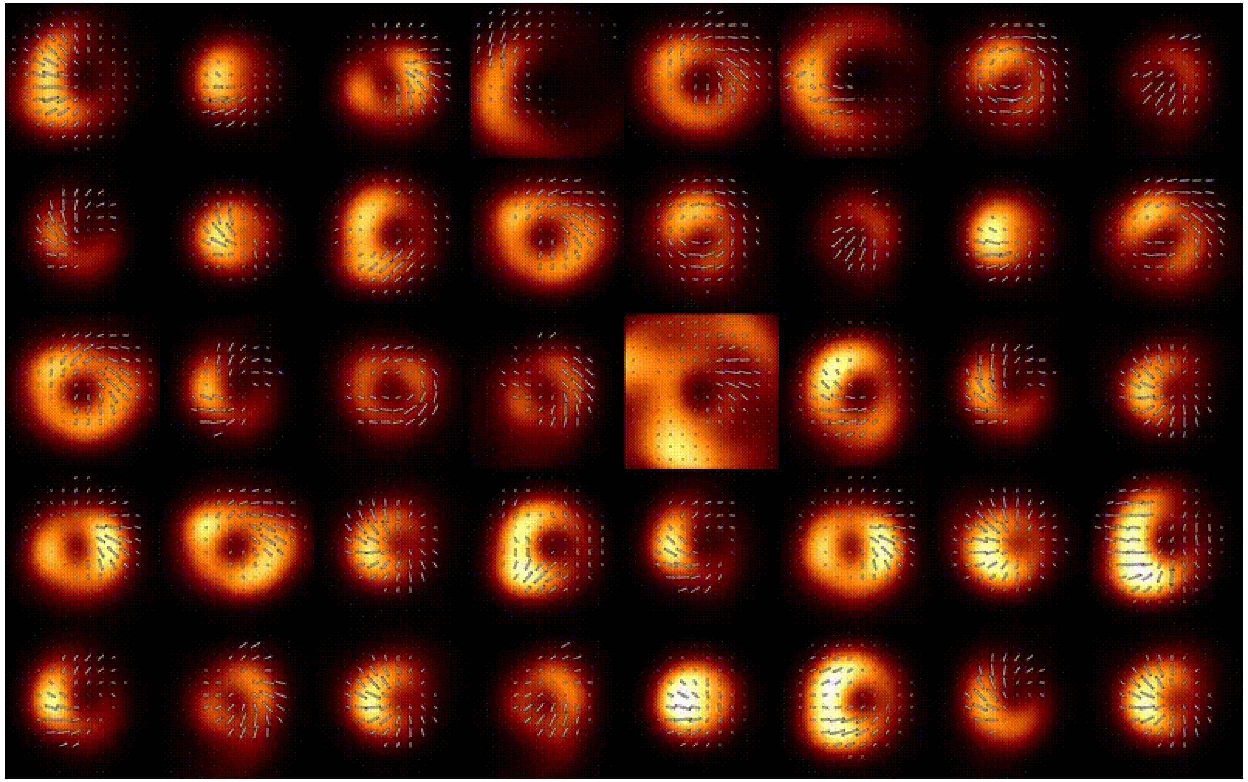
magnetic flux

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

EHT GRMHD Simulation library



native resolution



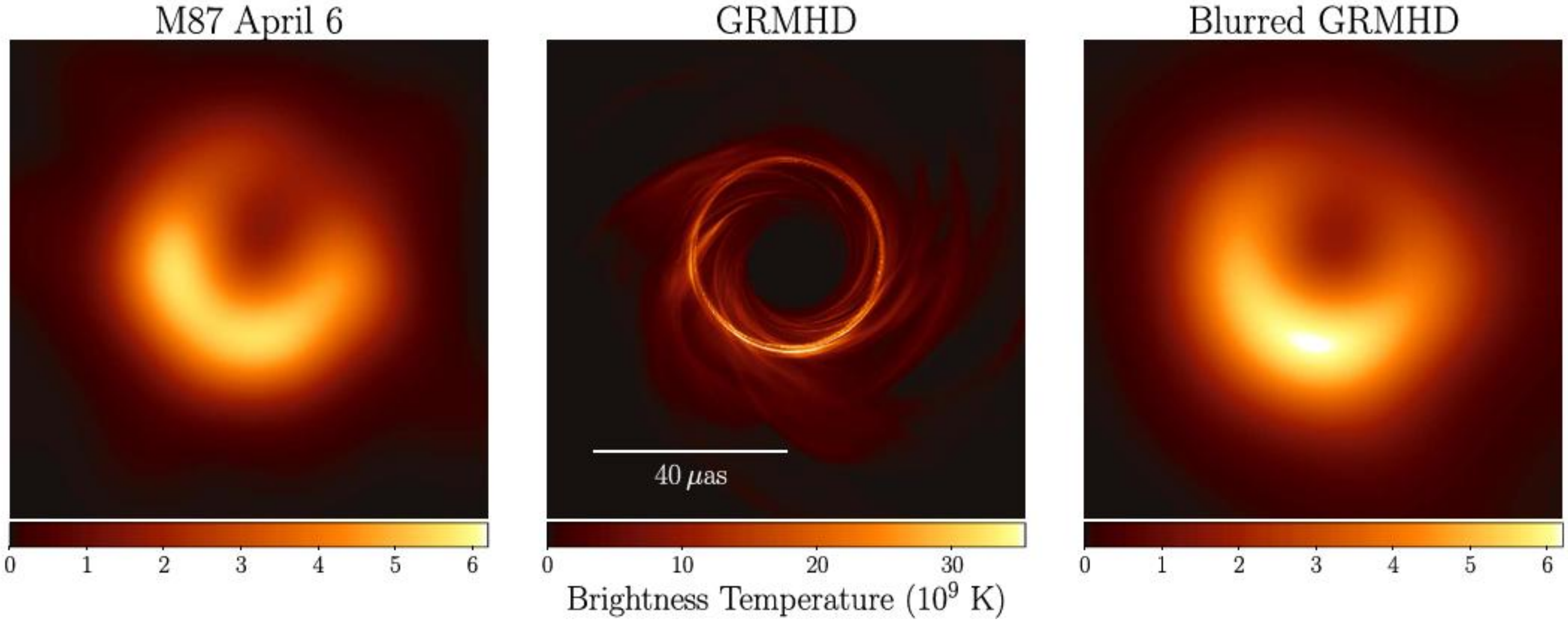
EHT resolution

Simulation survey over black hole spin and magnetic field state

Electron Temperature must be set in post-processing: $T_{\mathrm{e}} \neq T_{\mathrm{i}}$

Animation credit: Cora Prather

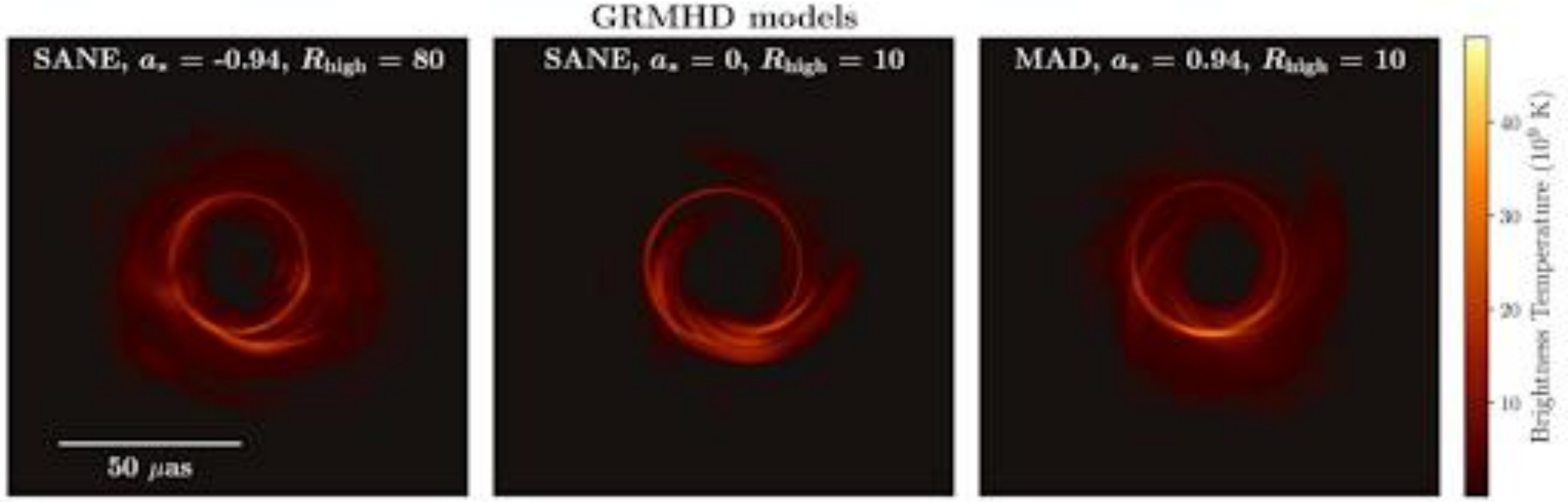
EHT Images are consistent with GRMHD Simulations



EHTC V, 2019

Scoring M87* GRMHD Simulations: before polarization

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

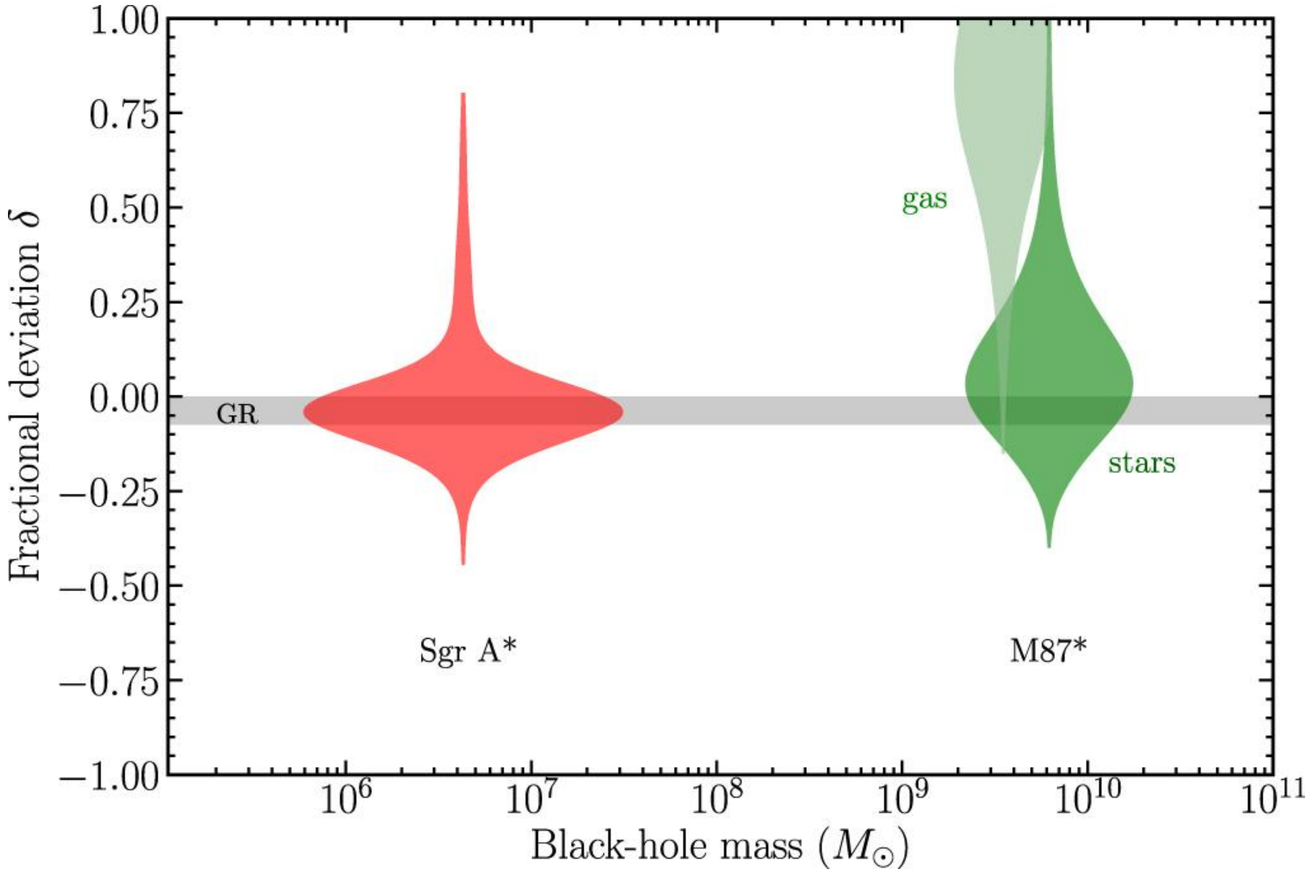


- Use **ring size** to measure black hole mass
- Use **ring asymmetry** to measure spin orientation
- Constraint on **jet power** ($\geq 10^{42}$ erg/sec) rejects all spin 0 models

EHTC V, 2019

Weighing a black hole

- Connecting EHT image ring diameter to predicted shadow size from GR requires **astrophysical** calibration
- M87* image size is consistent with previous measurements from stellar dynamics but not competing measurements from gas dynamics
- After astrophysical calibration (and assuming a stellar mass prior for M87*) both M87* and Sgr A* have image sizes consistent with GR's prediction.

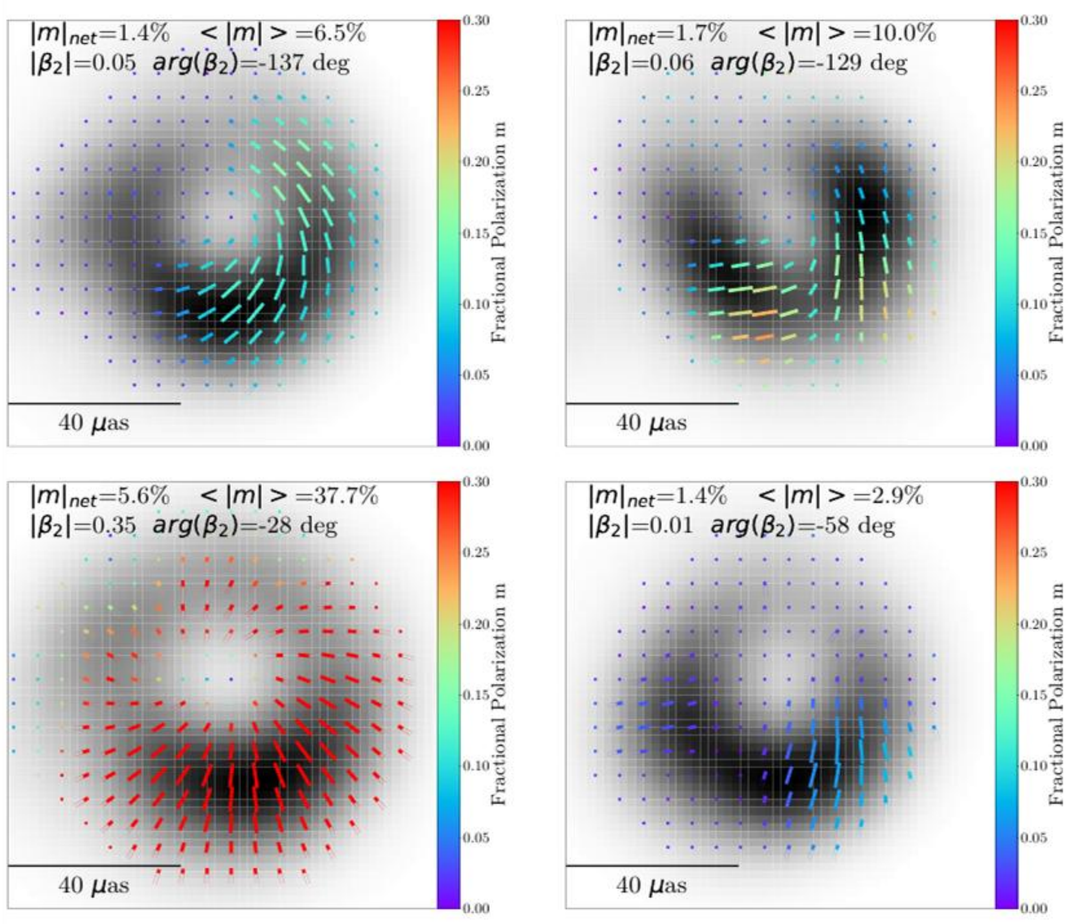


EHT Collaboration 2022 (Paper I)

Polarization is the key for near-horizon astrophysics

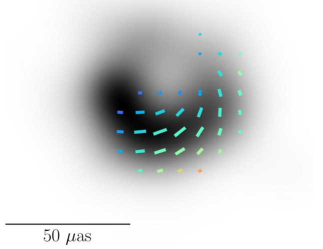
- Synchrotron radiation emits linear polarization oriented **perpendicular** to magnetic field lines
- Polarization transport is sensitive to the **magnetic field, plasma, and spacetime.**
- Simulation polarization images show many different structures:
  - **strongly** or **weakly** polarized
  - patterns that are **radial** or **helical**

Simulation Polarization Images



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

Scoring M87* simulations with polarization



- Scoring M87 2017 observations with multiple approaches all strongly favor a **magnetically arrested accretion flow**

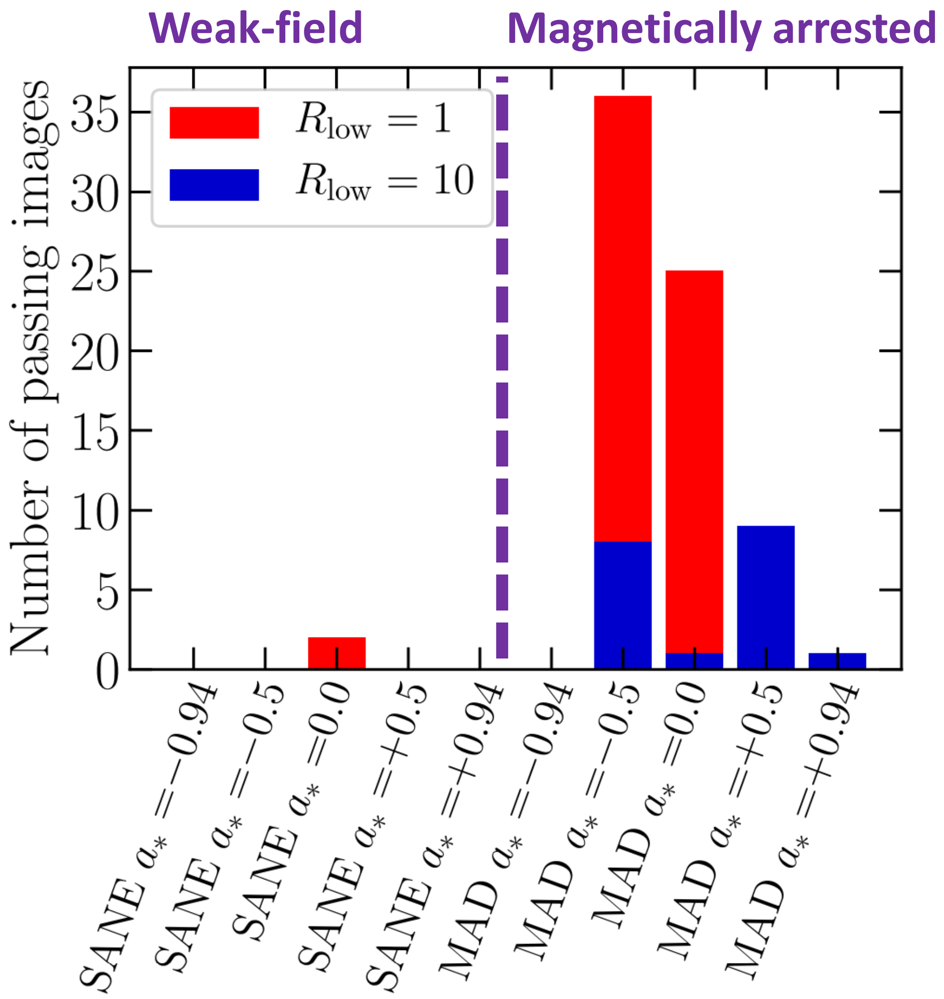
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude from passing models w/o polarization:

$$\dot{M} = 2 - 15 \times 10^{-6} \dot{M}_{\mathrm{Edd}}$$

- …and the near-horizon magnetic field and temperature.

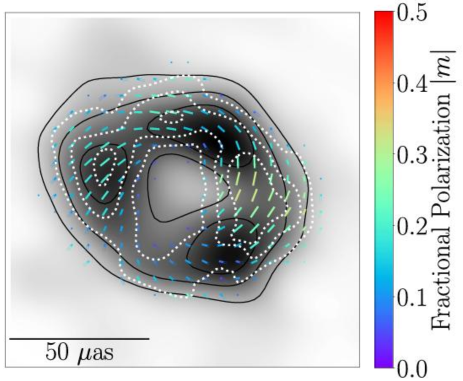
$$T_e \simeq (5 - 40) \times 10^{10}\ \mathrm{K}$$
$$|B| \simeq (7 - 30)\ \mathrm{G}$$

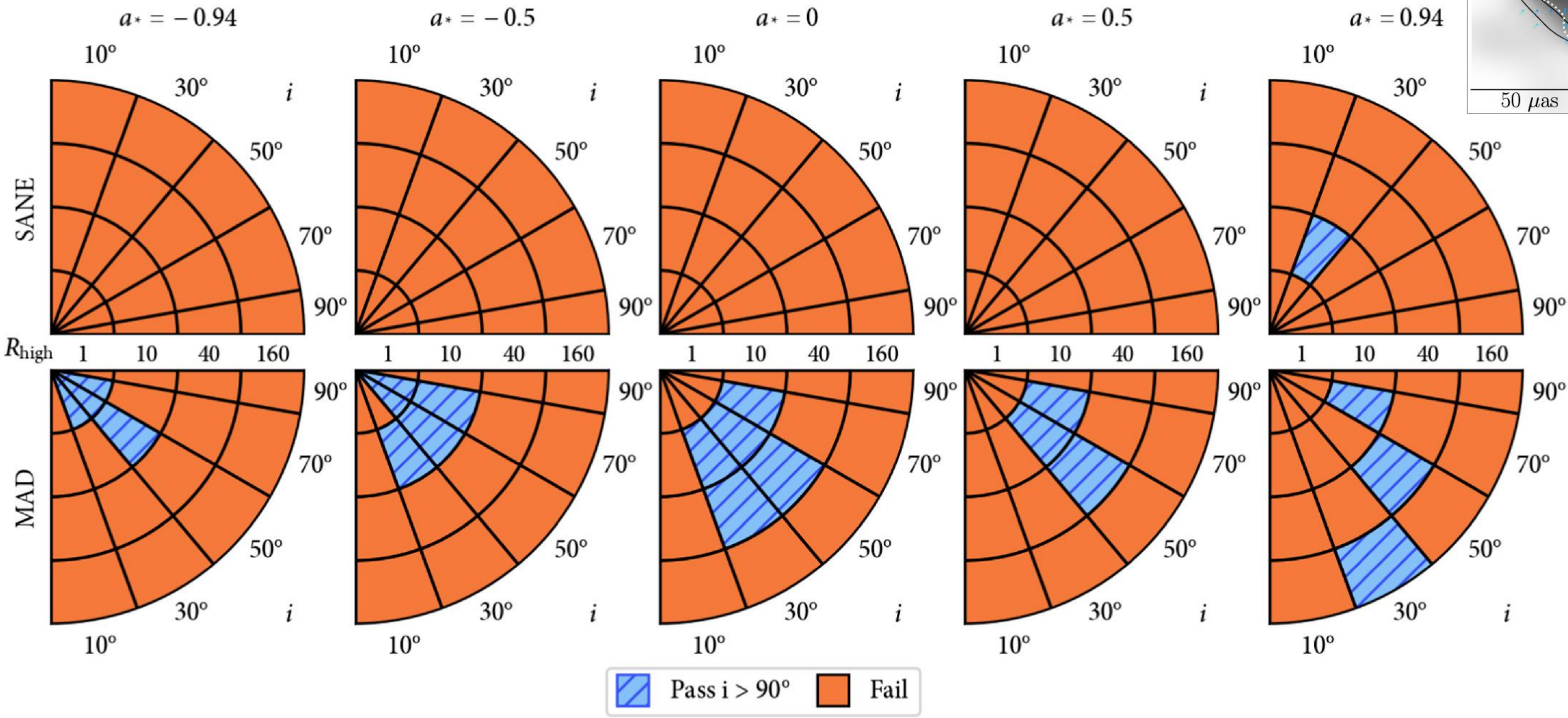
- Strong magnetic fields more easily launch BZ jets at all values of BH spin



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

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
  - If Sgr A* is magnetically arrested, why is there no obvious jet?

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

What can polarized images tell us about jet launching?

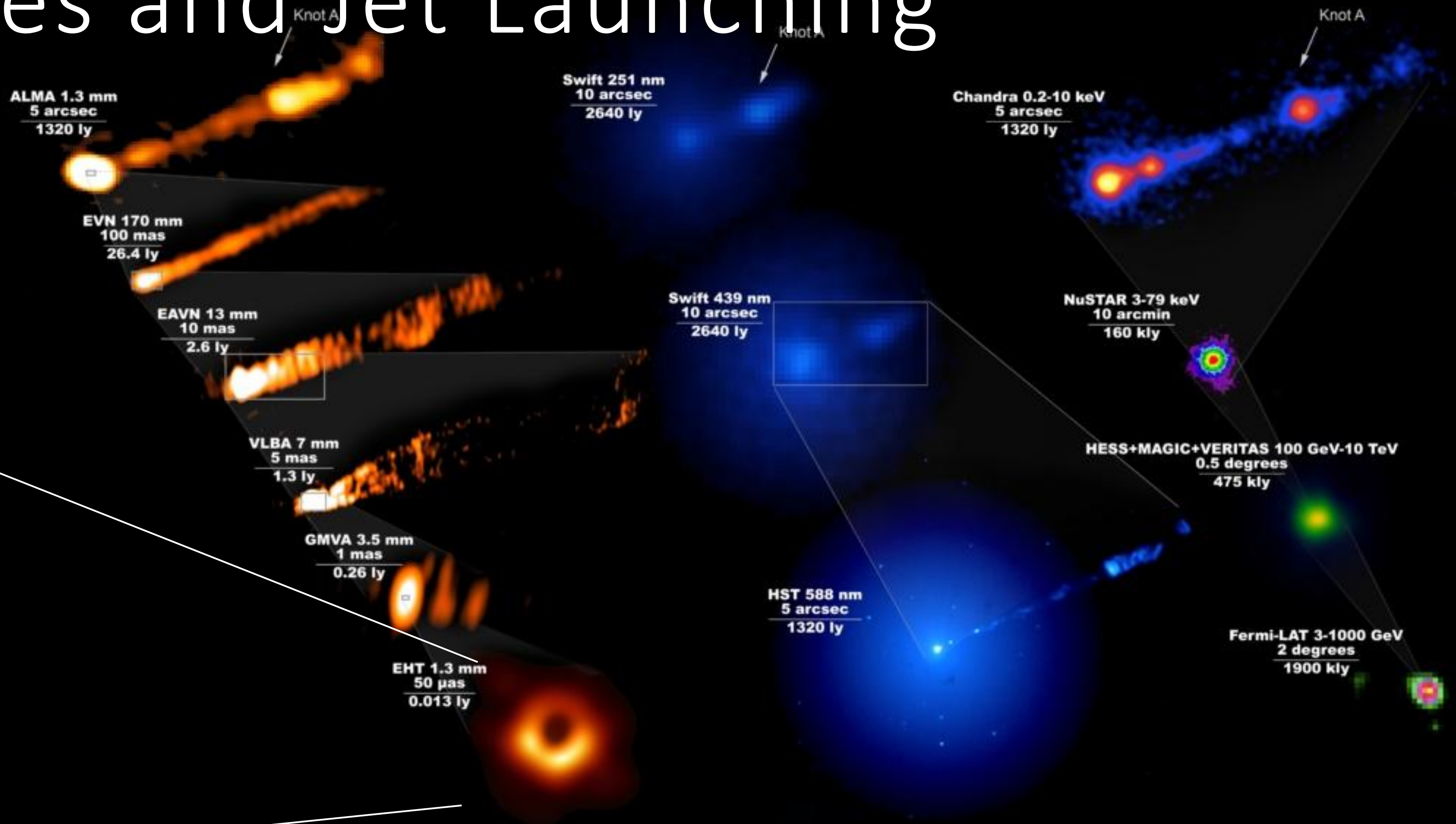
Chael+ 2023; Wong+ 2025, EHTC+ 2025

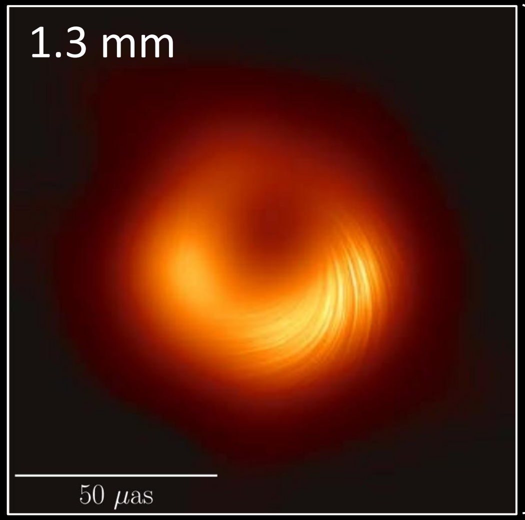
2307.06372, 2509.22639

Polarized Images and Jet Launching

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

P_{jet} is 10^{42}-10^{45} erg/s



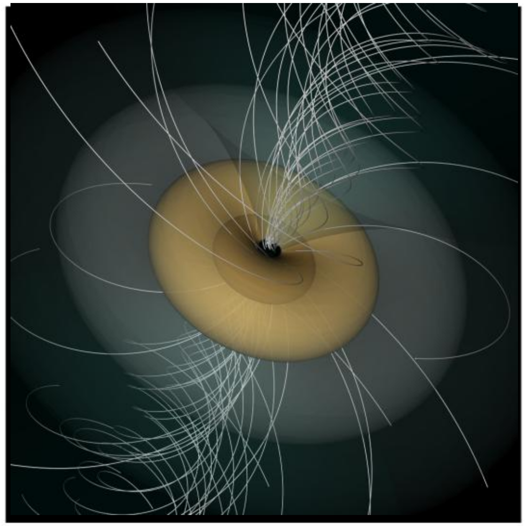


Jets are thought to be powered by black hole spin energy extracted via magnetic fields (Blandford & Znajek 1977)
Polarized images probe black hole energy extraction **on horizon scales** (e.g. Chael+ 2023).

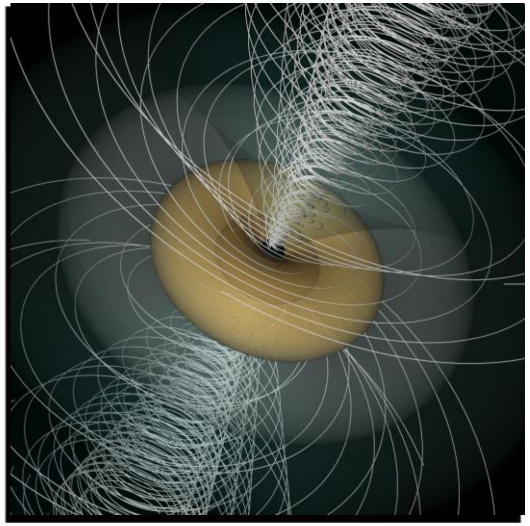
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Polarized images are **spin dependent**

Low Spin



High Spin



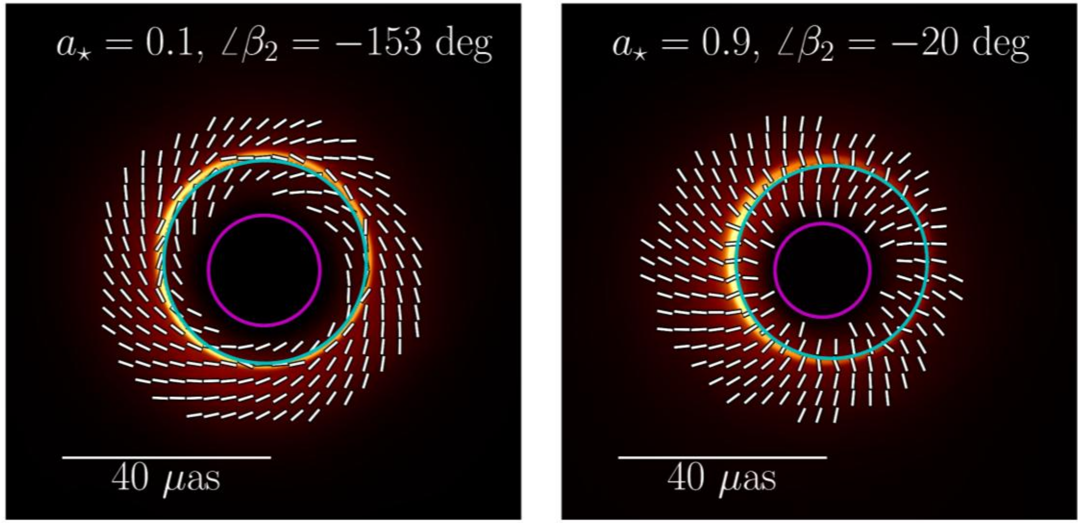
- Black hole spin **winds up magnetic fields**, with a constant sense of pitch angle $B^{\phi}/B^{r} < 0$
  - The inferred pitch angle in EHT 2017, 2018 images is consistent with energy **outflow**
- Increasing field wind-up with spin
  - increases the BZ jet power

Chael+ 2023b**; Chael** 2025**;** Wong+2025

Polarized images are **spin dependent**

Low Spin

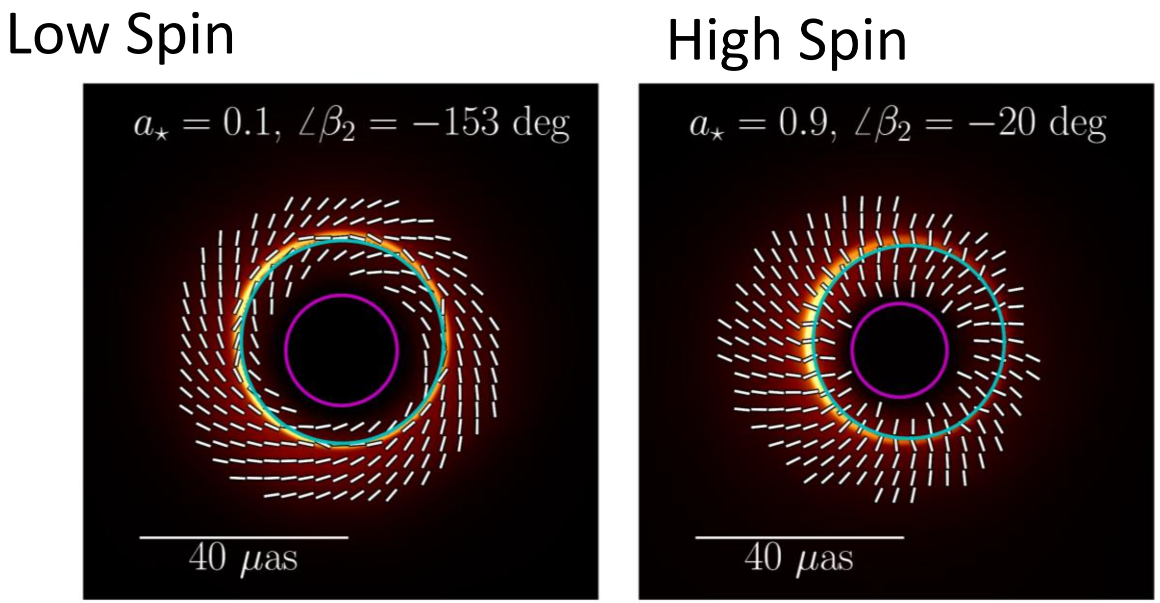
High Spin

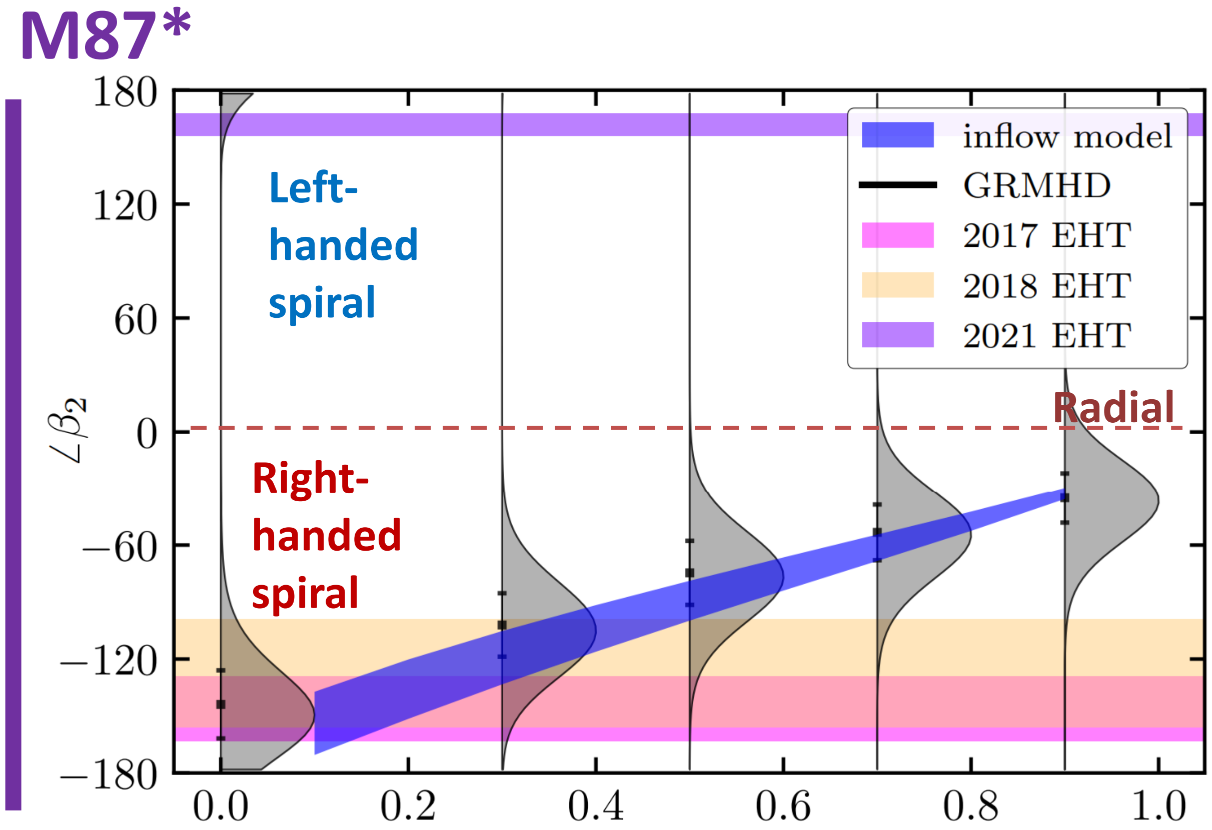


- Black hole spin **winds up magnetic fields**, with a constant sense of pitch angle $B^\phi / B^r < 0$
  - The inferred pitch angle in EHT 2017, 2018 images is consistent with energy **outflow**
- Increasing field wind-up with spin
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

Chael+ 2023b; **Chael** 2025; Wong+2025

Polarized images are **spin dependent**



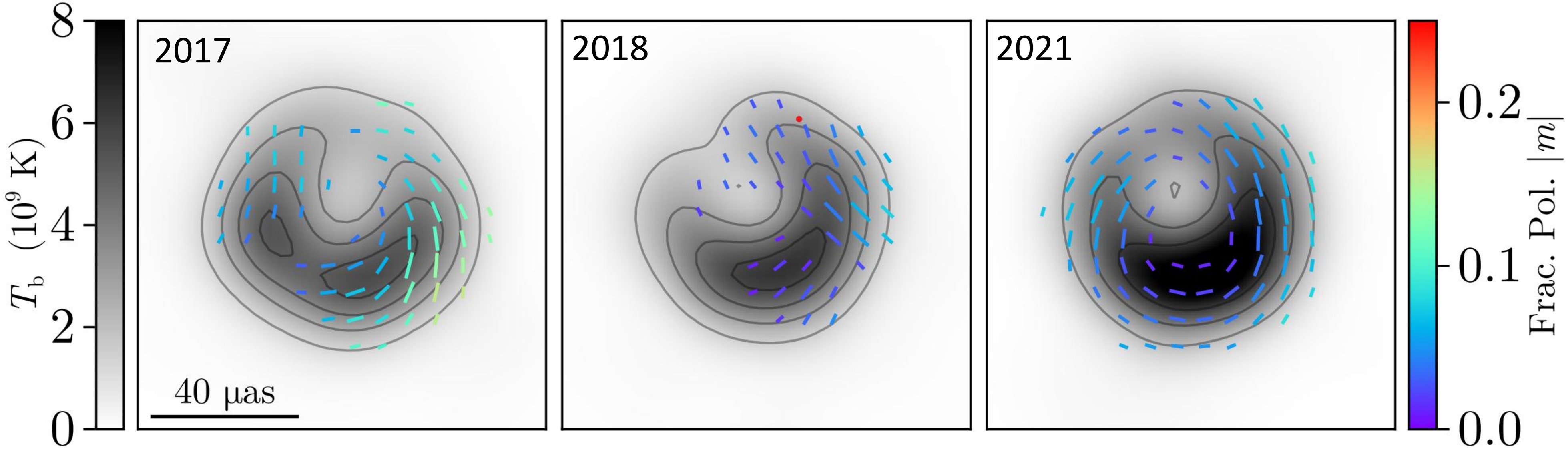


- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
    - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)

- The shift in β_2 in 2021 is mysterious
    - Change in Faraday rotation? Change in accretion state/plasma feeding?

Chael+ 2023b; **Chael** 2025; Wong+2025

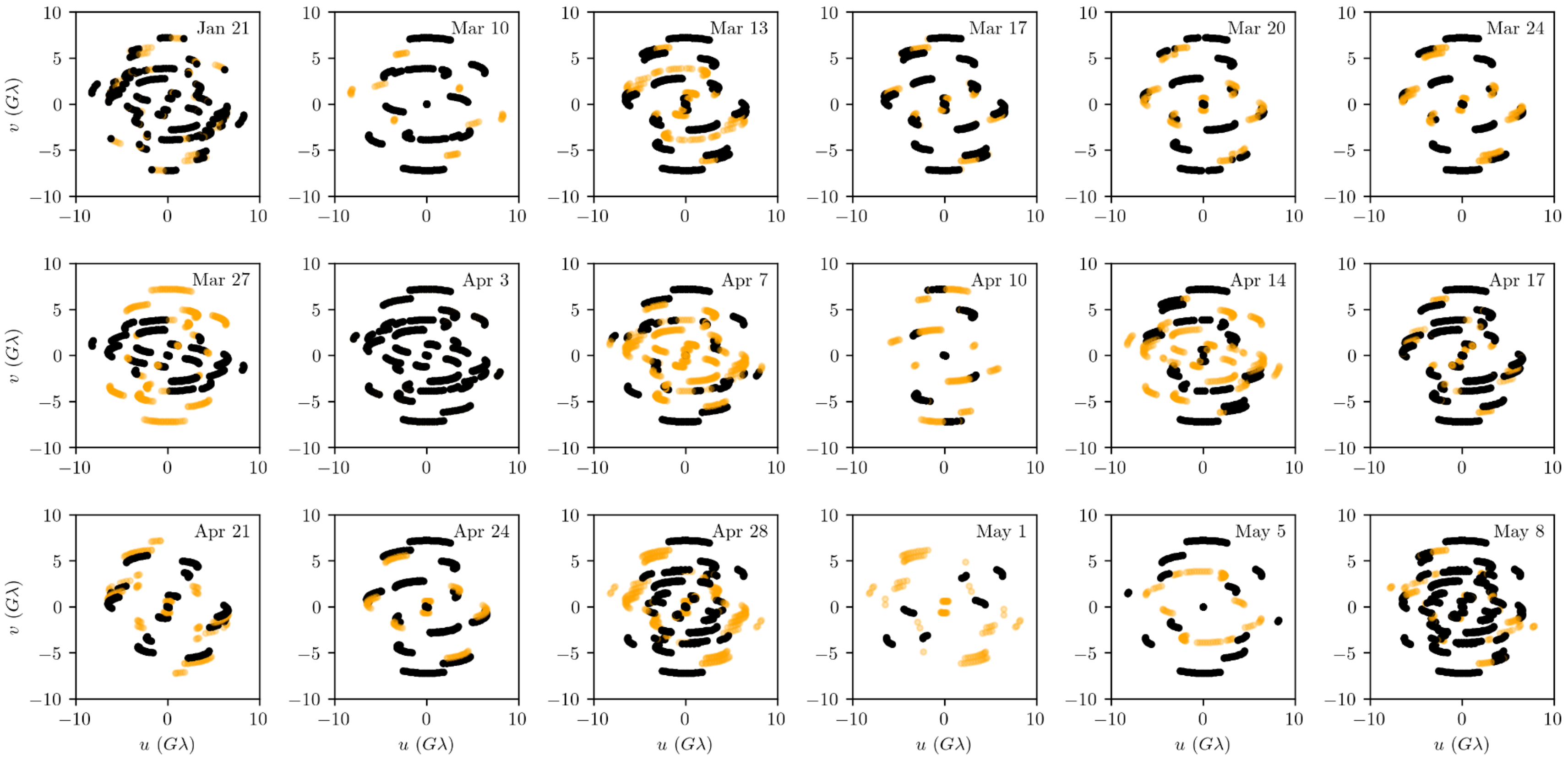
Surprising Polarization Variability in M87* over 3 years



- EHT observations show a stable total intensity ring in M87* **over 4,000 t_g**
- Polarization structure and fraction changes substantially over the 3 epochs
  - Does this variability challenge the magnetically arrested interpretation?
- This degree of variability is difficult to explain in all simulation models (MAD or SANE)
  - Do we need to improve our understanding of large-scale plasma feeding?

EHTC+ 2019, 2022, 2024, 2025

M87* Dynamics: MOVIE campaign



- EHT just wrapped up 2-month "MOVIE" campaign of biweekly imaging observations of M87*
- First regularly-sampled probe of horizon-scale variability covering unexplored **intermediate** timescales

Image credit: Boris Georgiev

Next Steps
for Horizon-Scale Black Hole Astrophysics

How can we determine the jet power source?

By zooming **out**..

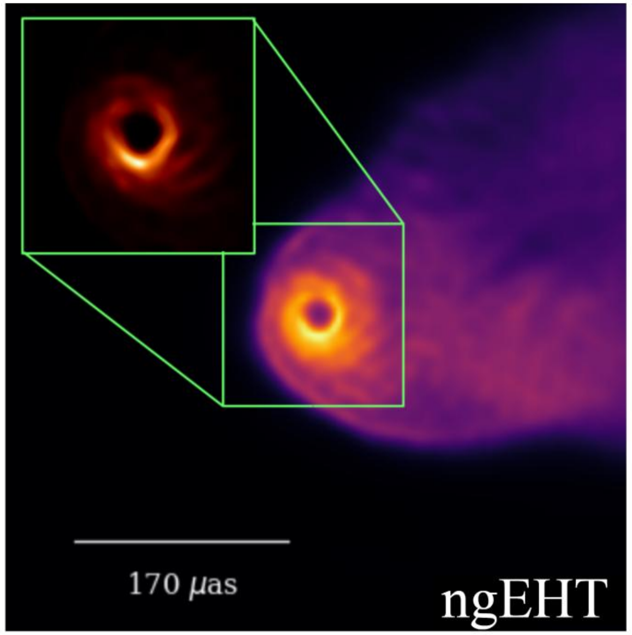


Image the connection between the BH and the low-brightness extended jet in polarization and **high dynamic range**

By zooming **in**..

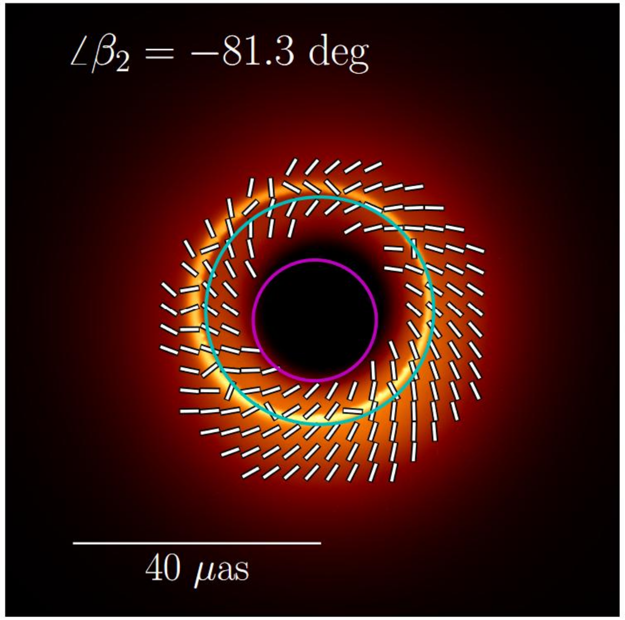


Image field lines close to the event horizon in **high resolution**

The future of near-horizon observations

Extended & next-generation EHT

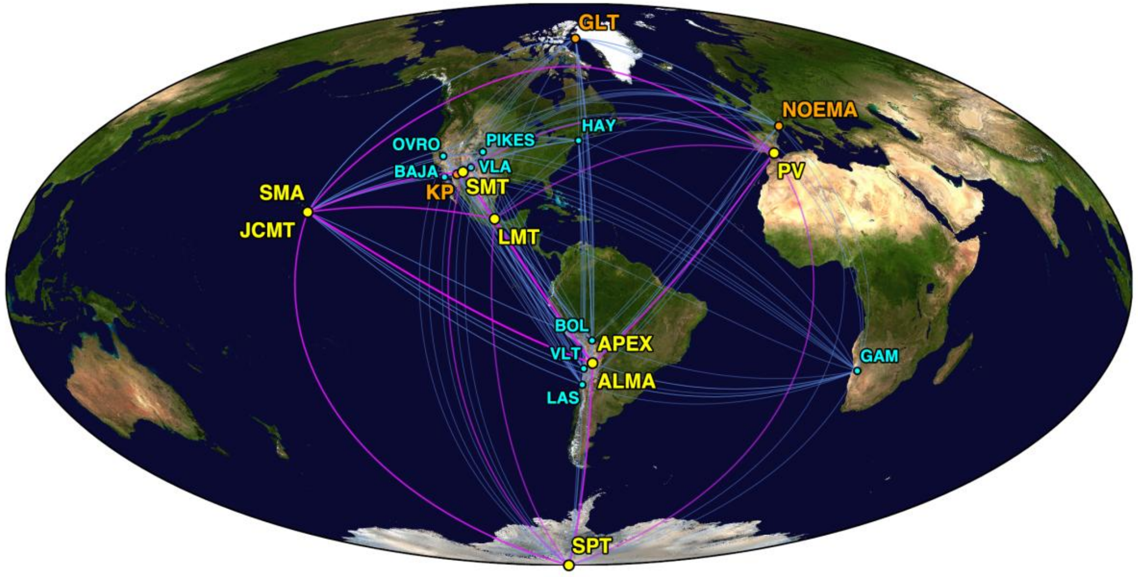


Image black holes and their jets in **multiple frequencies** and **high dynamic range**

Black Hole Explorer (BHEX)

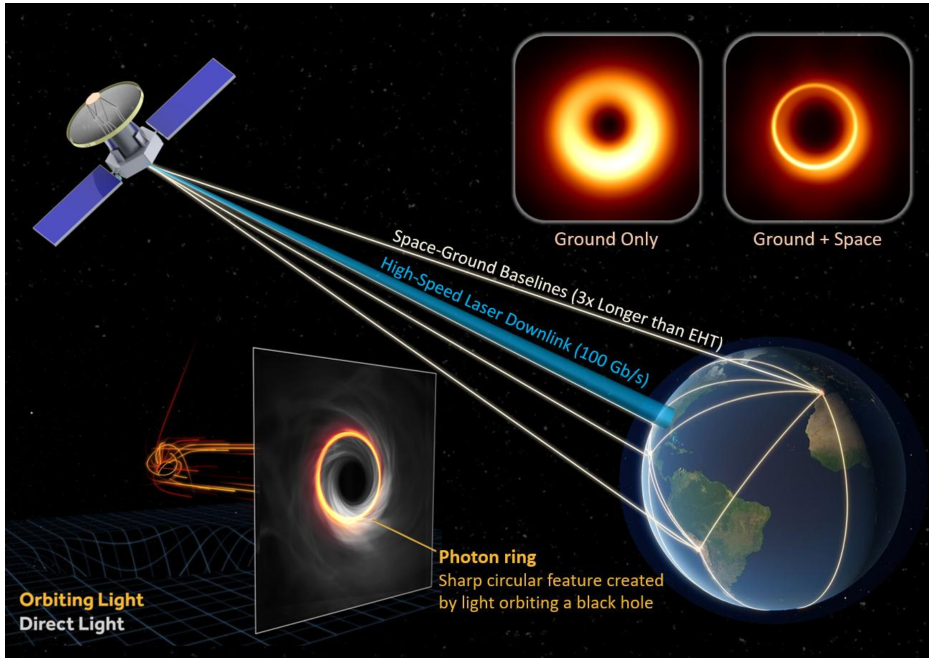
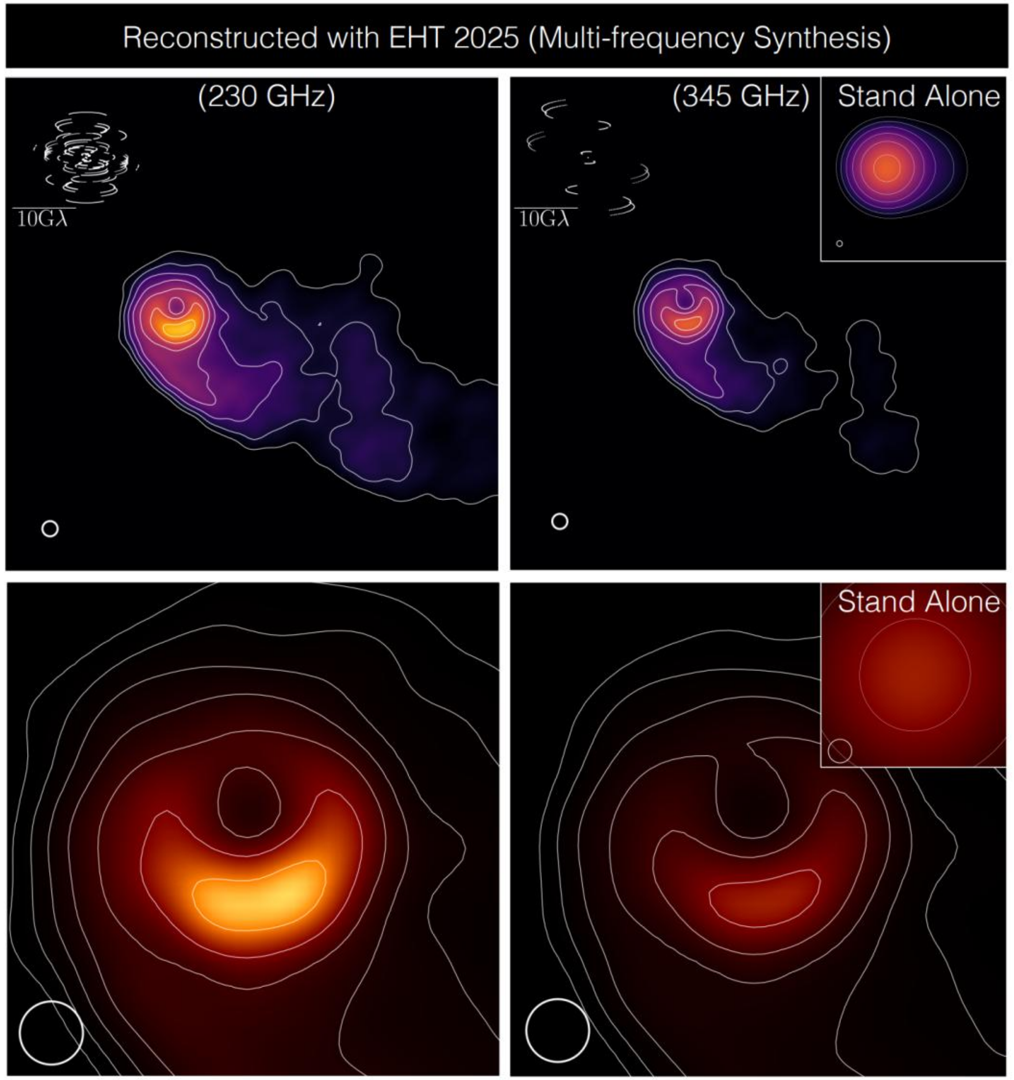


Image **extreme gravitational lensing** and dozens of new black holes **in high resolution**

See EHTC+ 2024 (2410.02986); Johnson+ 2024 (2406.12917)

Pushing the VLBI Frequency Frontier with FPT

- EHT baselines have detected fringes at 345 GHz – highest ever for VLBI (Raymond+ 2024)
- Frequency phase transfer (FPT) of phase solutions can substantially improve 345 GHz coverage (Pesce+ 2024 , Issaoun+ 2025)
- With observations at multiple frequencies, we can directly constrain Faraday rotation and better probe the intrinsic magnetic field in high resolution



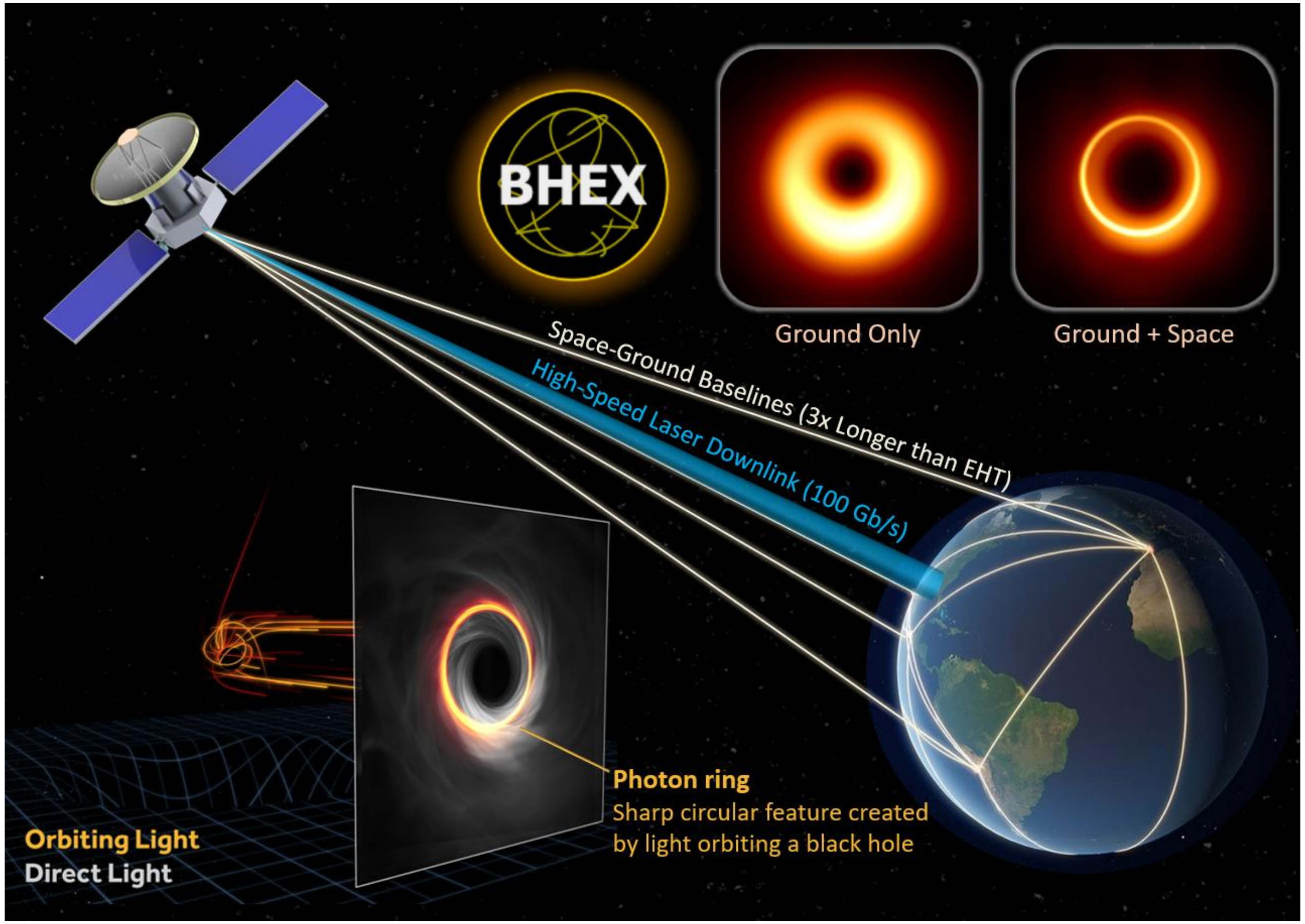
Raymond+ 2024, Pesce+ 2024, EHTC+ 2025

Expanding the EHT's lens: the Black Hole Explorer

Earth-Space millimeter VLBI

- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground mmVLBI network & pioneers optical laser downlink
- Targeting next NASA SMEX call (~September 9!)

See talk this afternoon

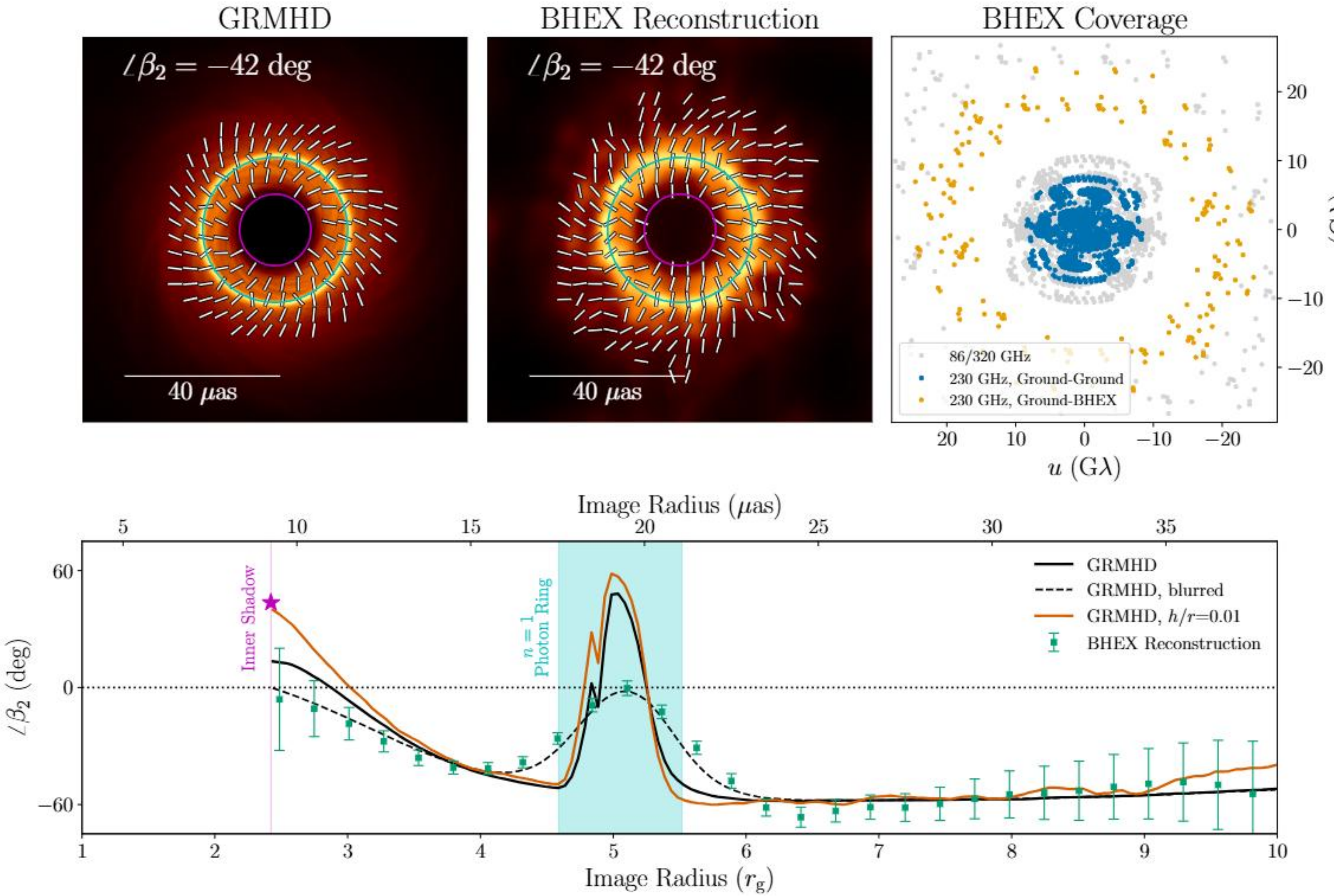


blackholeexplorer.org

BHEX will probe horizon-threading magnetic field lines

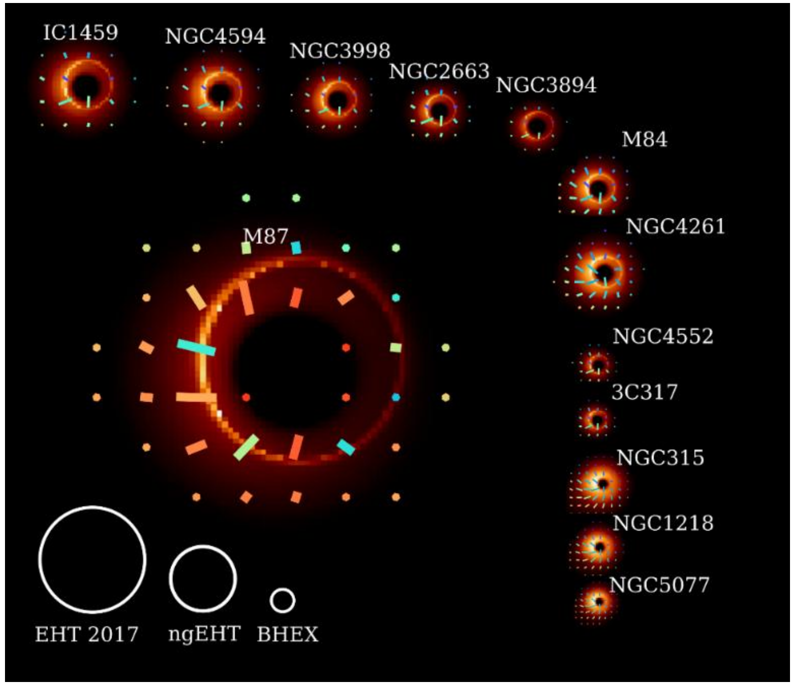
- Polarization evolves rapidly toward the horizon due to both **frame dragging** and **parallel transport** (Chael+ 2026)

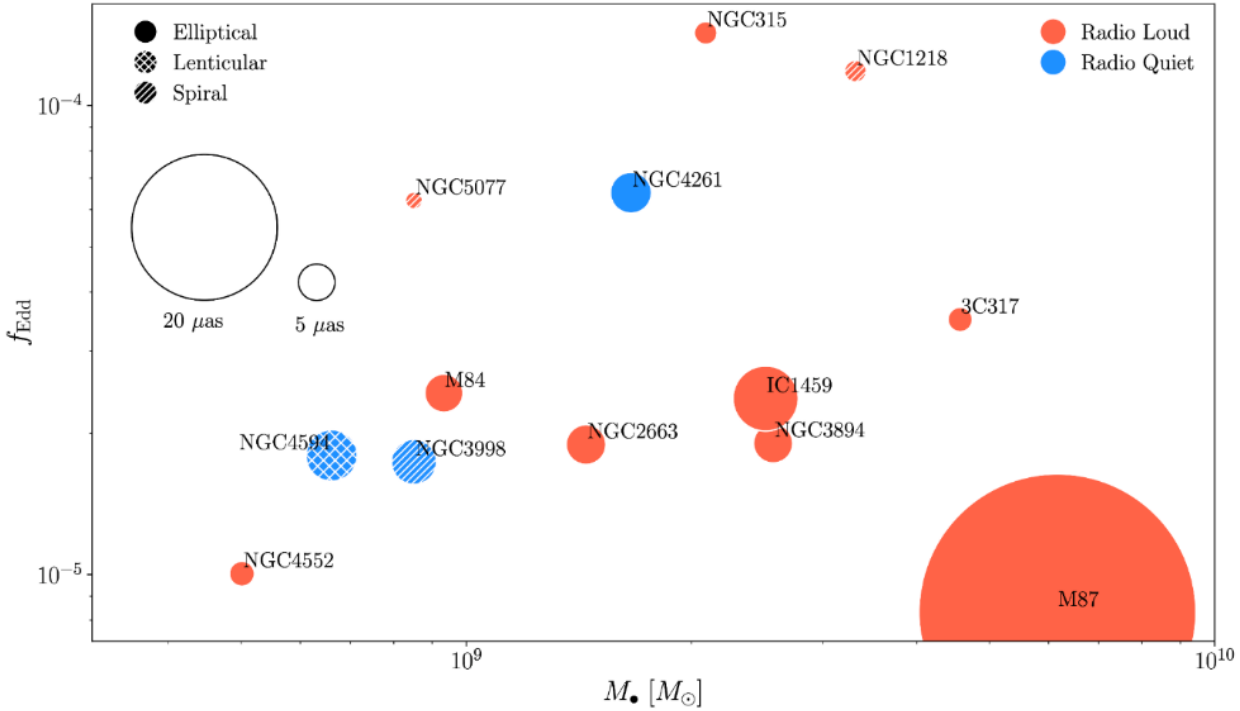
- **BHEX + EHT have the resolution to observe this evolution,** directly probing field lines that extract energy from the black hole



Chael+ 2026, [2606.12518](2606.12518)

A Horizon-Scale Sample of Low-Luminosity AGN with BHEX





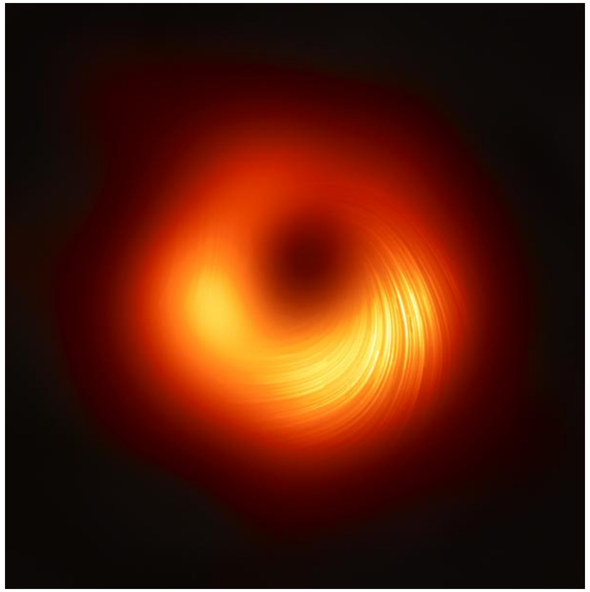
BHEX will increase the sample size of resolved black hole horizons from 2 to >10

BHEX will determine how the near-horizon black hole environment changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties

Zhang, Ricarte+ 2024; Akiyama+ 2026
See ETHER Sample; e.g. Pesce+ 2022, Ramakrishnan+ 2023, Nair+ 2024

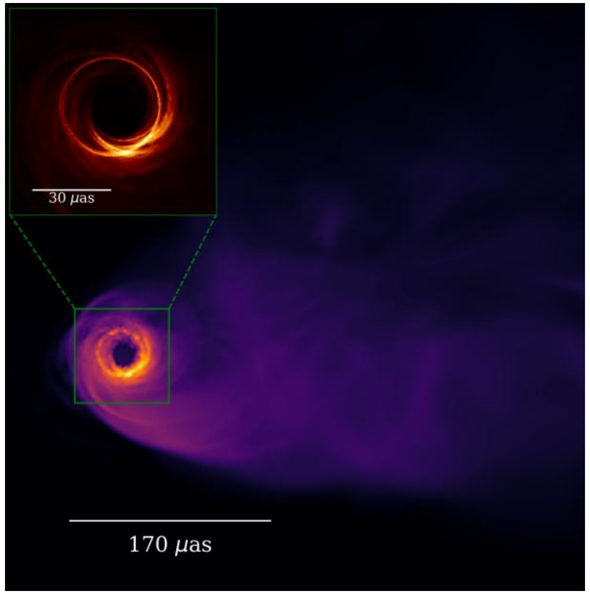
Takeaways…

1. **Near-horizon images are largely consistent** with our picture of low-luminosity accretion from simulations
2. **Polarization is the key** for constraining near-horizon magnetic fields and jet launching
3. **Future ground and space-based VLBI observations** will directly probe the black hole-jet connection at the horizon scale



…and more questions

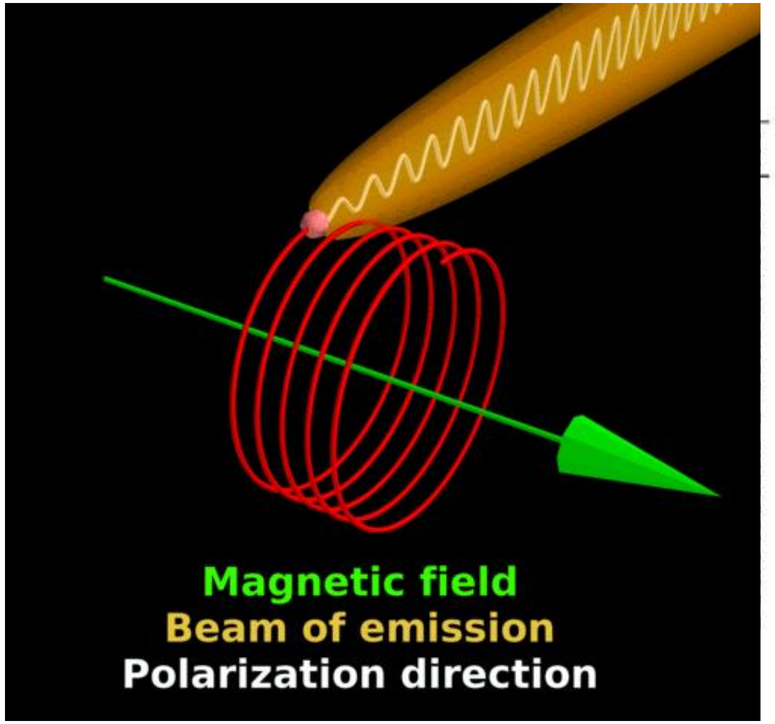
- Can we improve our simulations to account for unexpected variability observed at the horizon scale?
- What powers flares in Sgr A* and M87* and can we directly connect horizon-scale observations to multiwavelength constrains?
- What can future earth- and space-VLBI observations tell us about near-horizon physics in supermassive black holes beyond Sgr A* and M87*?

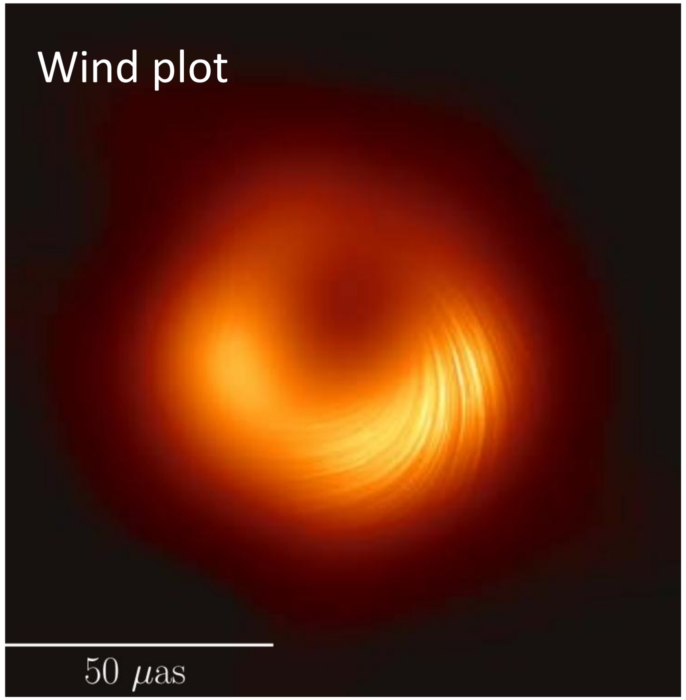


EHT VII, 2021; **Chael** 2025

Backup Slides

Why polarization?





- 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; EHTC IX, 2023 (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Comparing Black Hole Image Features to Simulations

- **EHT recovers size & shape information with multiple pipelines**
  - Independent imaging methods
  - Independent geometric modeling approaches

- **EHT Image Metrics**
  - Ring diameter *d*
  - Ring width *w*
  - Ring asymmetry *A*
  - Ring position angle *η*

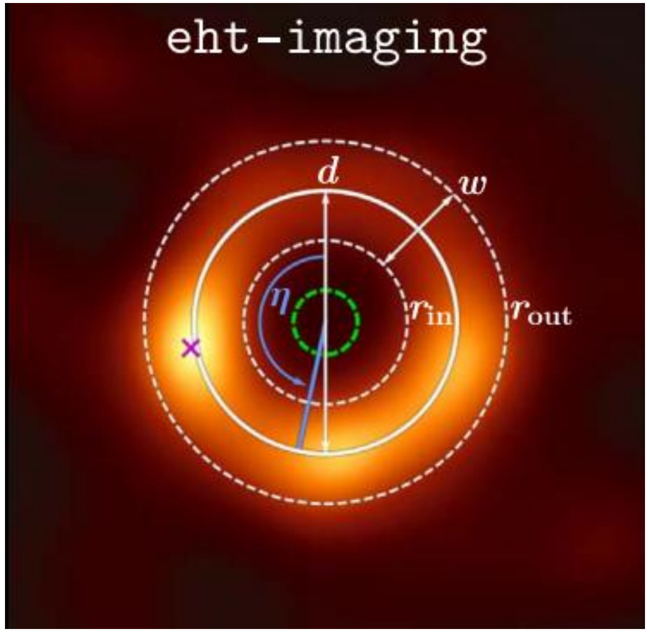
- For **M87* (2017+2018):**
  - Diameter, asymmetry, and PA are best measured

$$d = 42 \pm 3\,\mu\text{as}$$

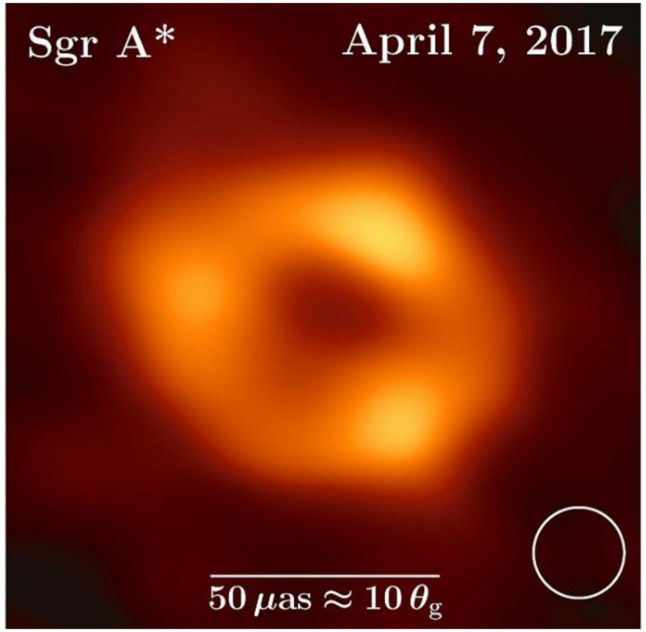
- For **Sgr A* (2018):**
  - Diameter and width are best measured

$$d = 51.8 \pm 2.3\,\mu\text{as}$$

M87*



Sgr A*



EHTC IV 2019 (**Chael**, paper coordinator)
EHTC+ VI, 2019, EHTC+ IV, VI 2022, EHTC+ 2024, 2025

Summarizing an image: Polarization

Unresolved
polarization fraction

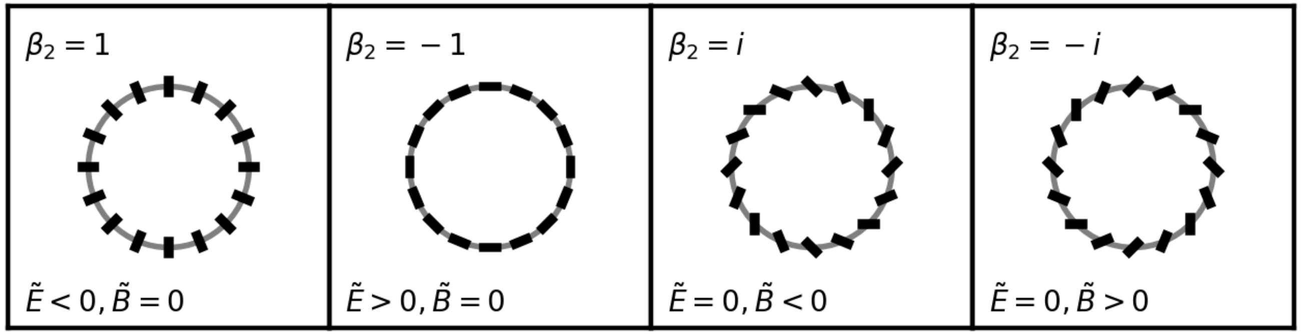
$$|m|_{\rm net} = \frac{\sqrt{(\sum_i Q_i)^2 + (\sum_i U_i)^2}}{\sum_i I_i}$$

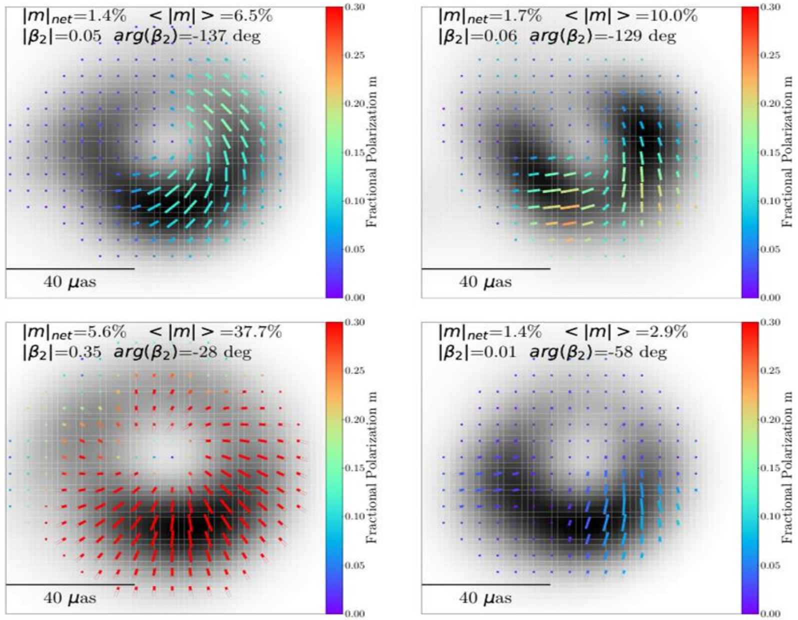
Average resolved
polarization fraction

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

Azimuthal structure:
2nd Fourier mode

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





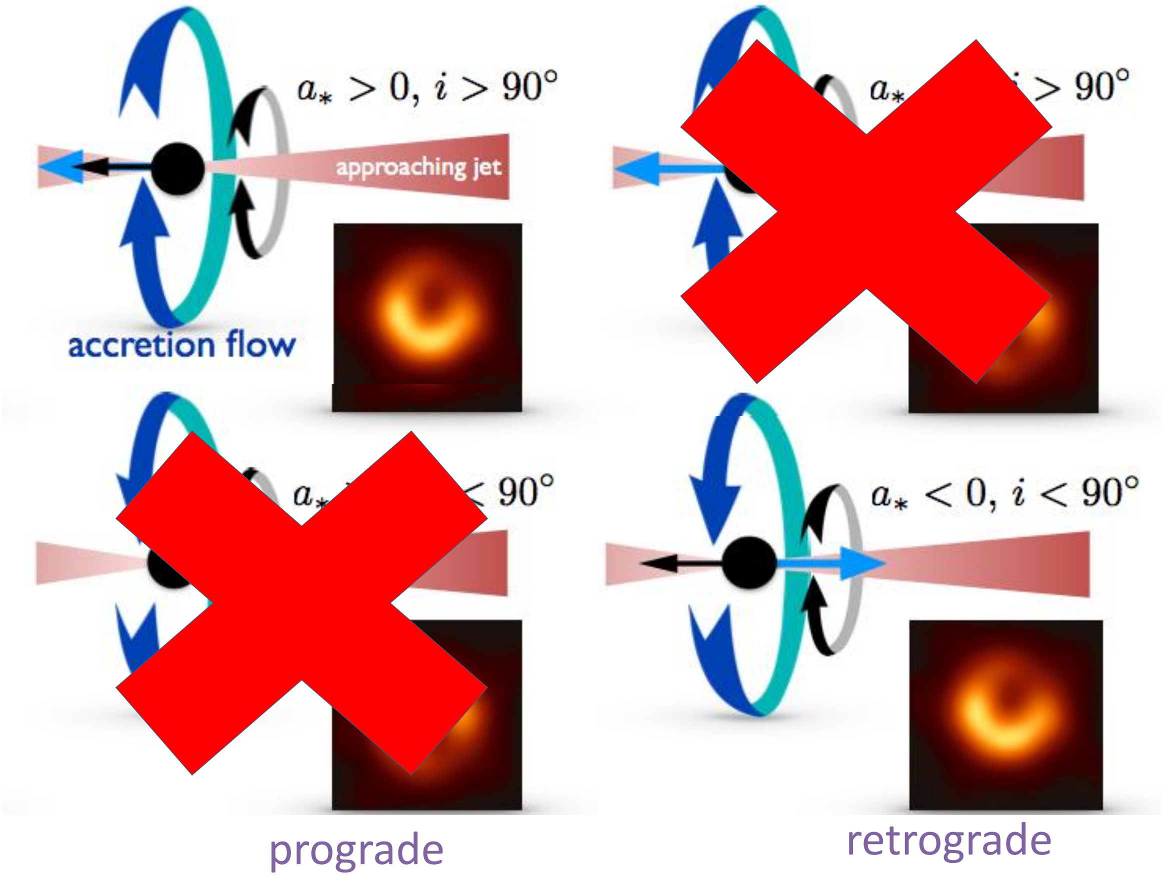
Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

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

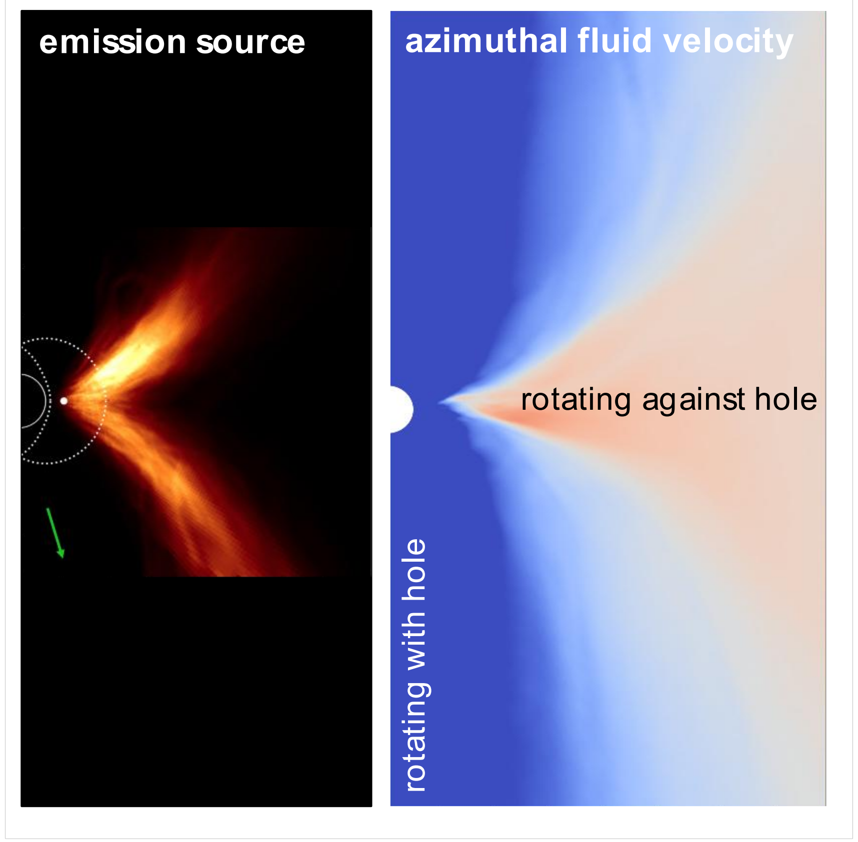
EHTC VII,VIII, 2021 (**Chael**, paper coordinator)
EHTC IX, 2023 (**Chael**, paper coordinator)

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)



retrograde model emission



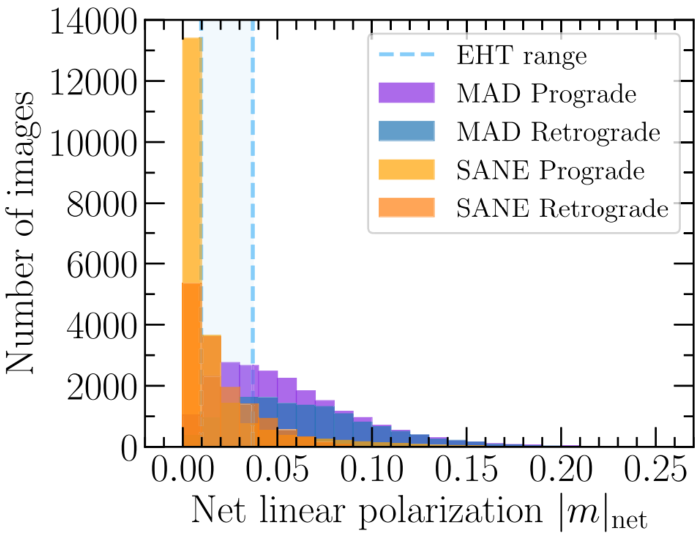
BH spin-away (**clockwise rotation**) models are strongly favored for M87

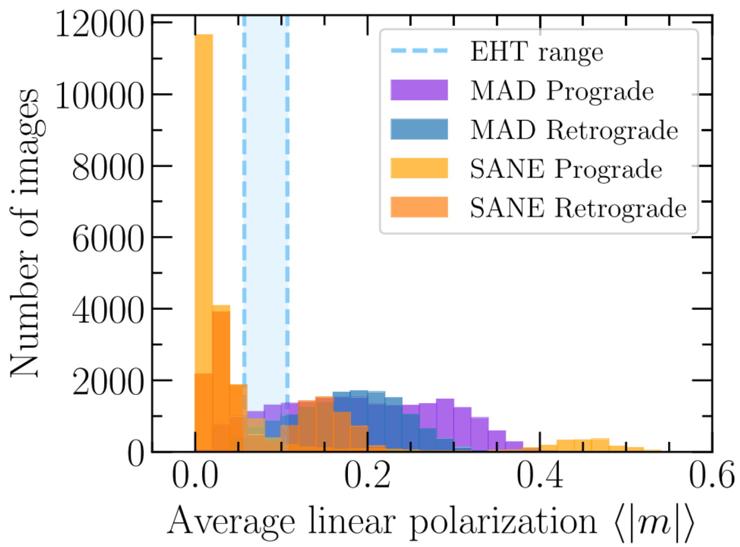
Spin > 0 is required to produce jet power, but spin magnitude is otherwise unconstrained

EHTC V, 2019, Wong+ 2021

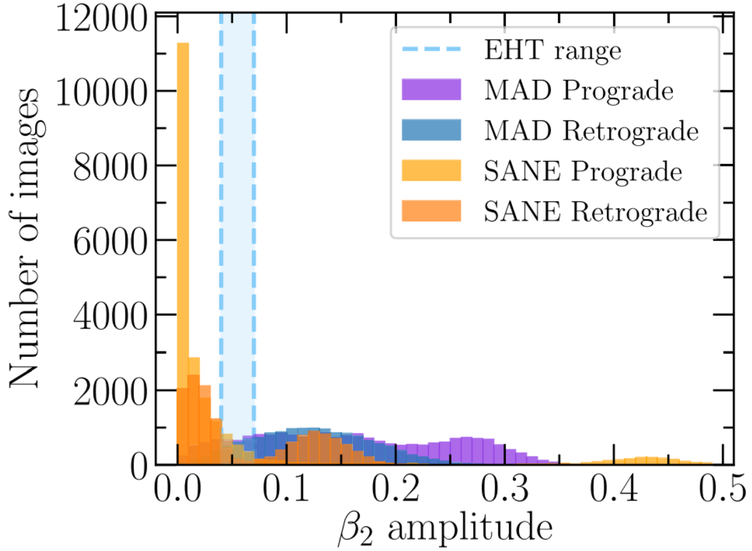
Scoring M87 simulations with linear polarization

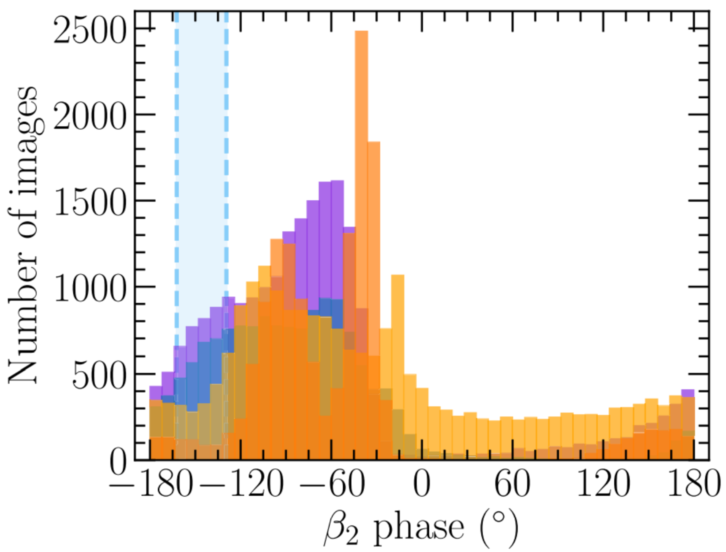
Unresolved and **resolved** linear polarization fractions





Azimuthal structure
2nd Fourier mode





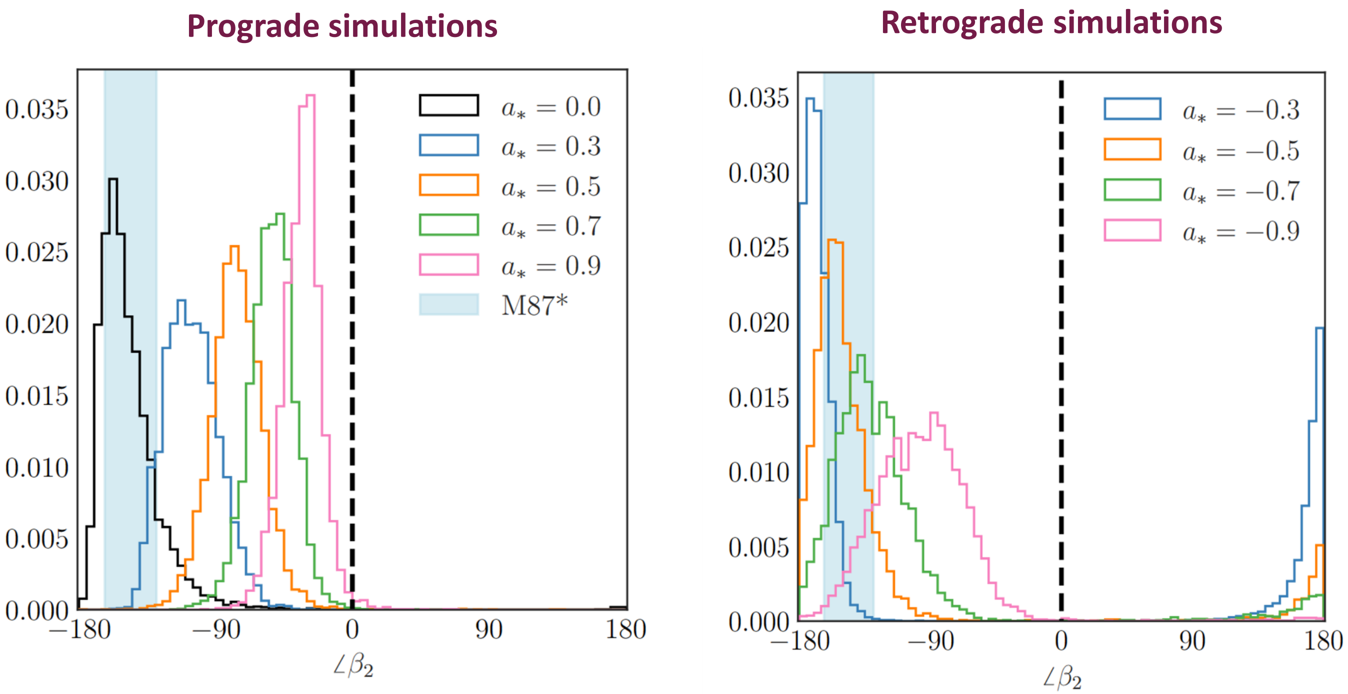
EHTC VIII, 2021 (**Chael**, paper coordinator)

Does β_2 measure the direction of energy flux in simulations?

- Almost all 230 GHz images from MAD simulations have $\angle\boldsymbol{\beta_2} < \mathbf{0}$, consistent with the measured energy outflow in the simulations.

- **M87*'s horizon-scale polarization in 2017 is consistent with outflowing electromagnetic energy at radii $\boldsymbol{r \lesssim 5r_g}$**

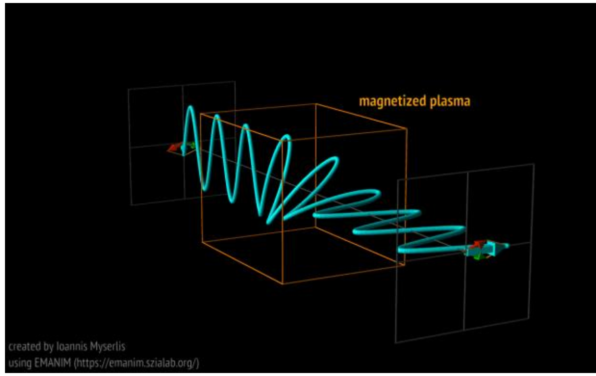
- $\angle\beta_2$ in simulations has a strong dependence on spin



BH spin axis is into the plane of the sky in all simulation images (EHTC+V)

Chael+ 2023b, simulations from Narayan+2022

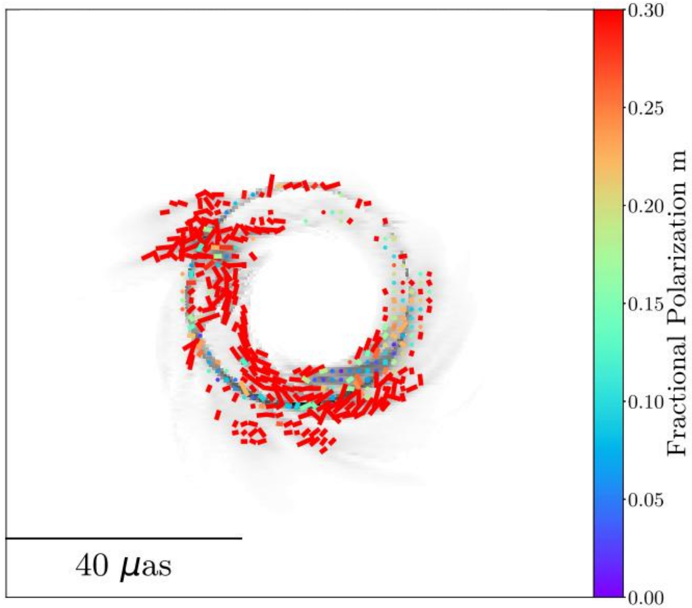
Faraday Rotation depolarizes BH images

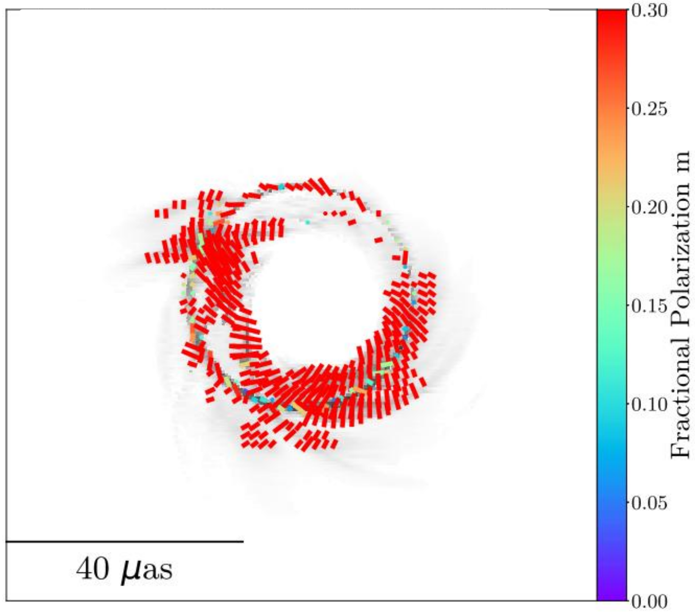


With Faraday

Without Faraday

'infinite' resolution

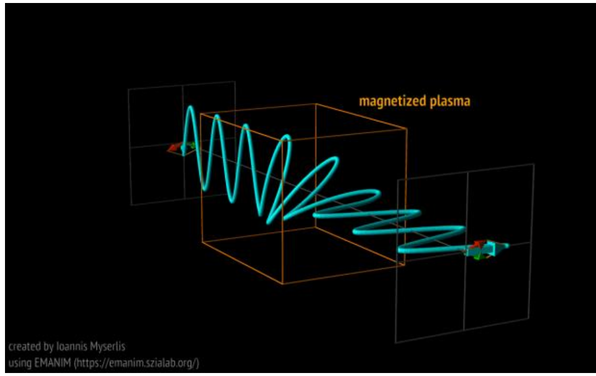




- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales

Credit: EHT 2021 Paper VIII (**Chael**, paper coordinator)

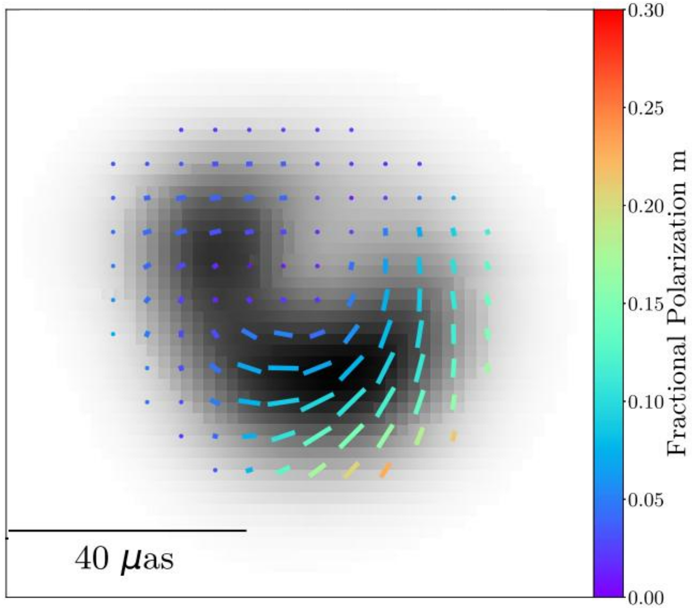
Faraday Rotation depolarizes BH images

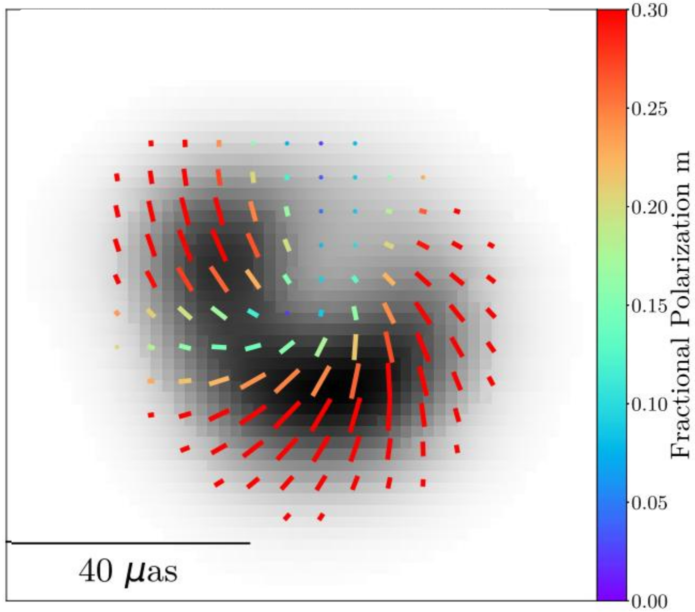


With Faraday

Without Faraday

EHT resolution



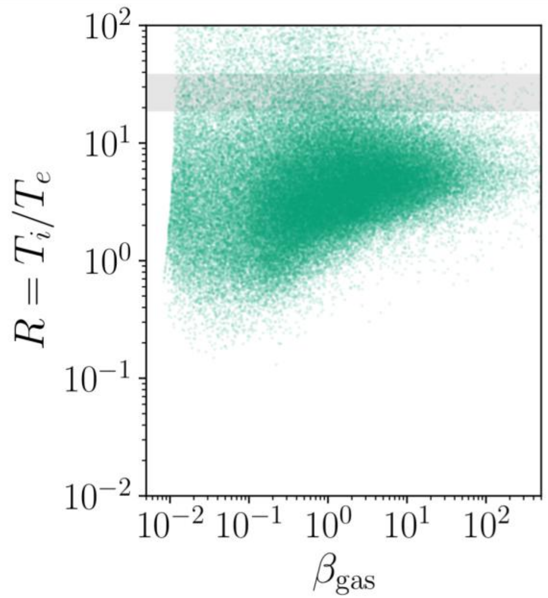


- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from **colder electrons** is necessary to depolarize MAD models

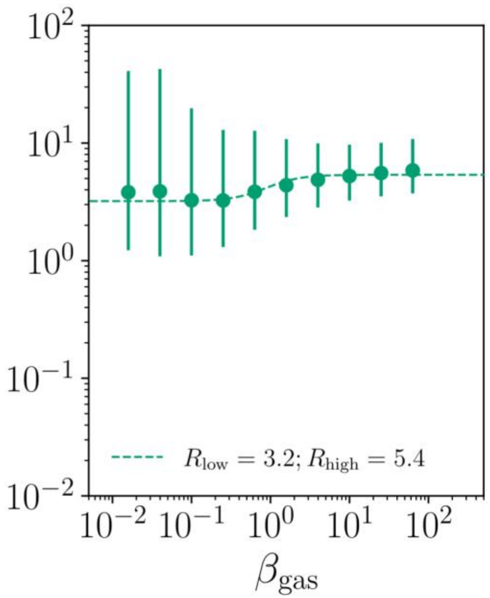
Credit: EHT 2021 Paper VIII (**Chael**, paper coordinator)

Electrons in *Radiative, Two-Temperature* Simulations are too hot!

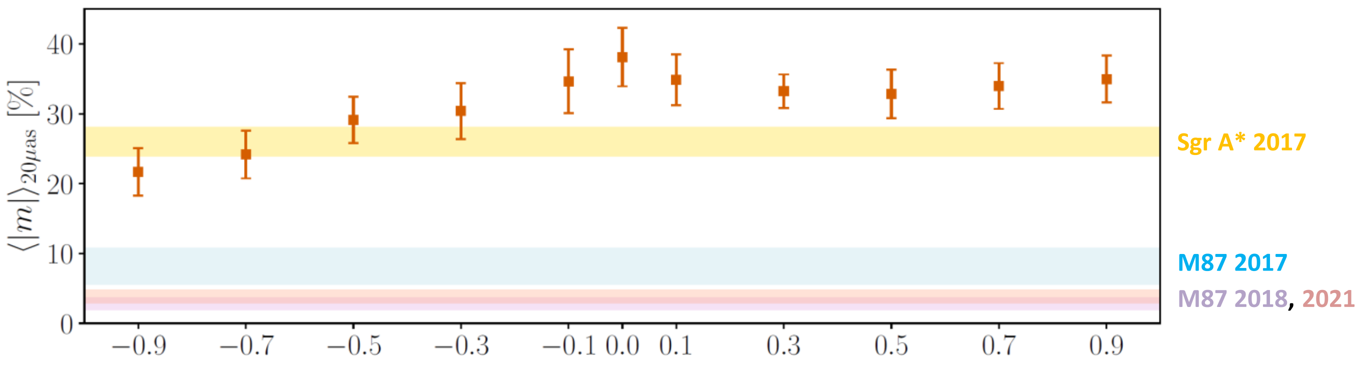
Ion-to-electron temp ratio



Effective R-β model



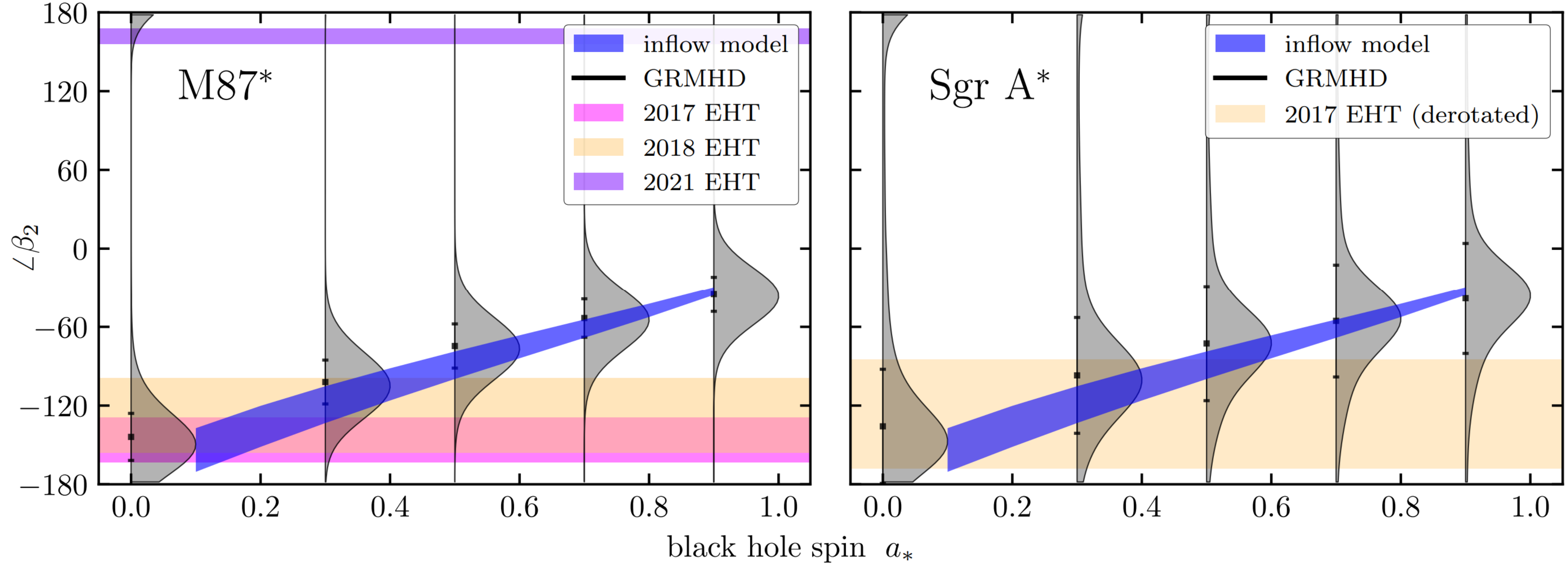
EHT-scale polarization fraction



- EHT **postprocessing** prefers **cold electrons (**T_i ~ 100x T_e) to sufficiently depolarize the image (EHTC+ 2021)
- Radiative, two-temperature GRMHD (e.g. Sadowski+ 2017) solves for electron and ion temperatures self consistently with subgrid heating & cooling physics
- 2T sims prefers more modest temperature ratios (Chael 2025)
  - **M87 images are too polarized!**
- Do we need to modify:
  - Plasma *microphysics* (electron heating: e.g. Zhdankin+ 2018, Rowan+ 2019, Kawazura+ 2020)
  - *Macroscale* feeding/initial conditions (e.g. Wong+ in prep)

see also: Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019, 2025**
Dexter+ 2020,2021, Mizuno+ 2021

Polarized images are **spin dependent**

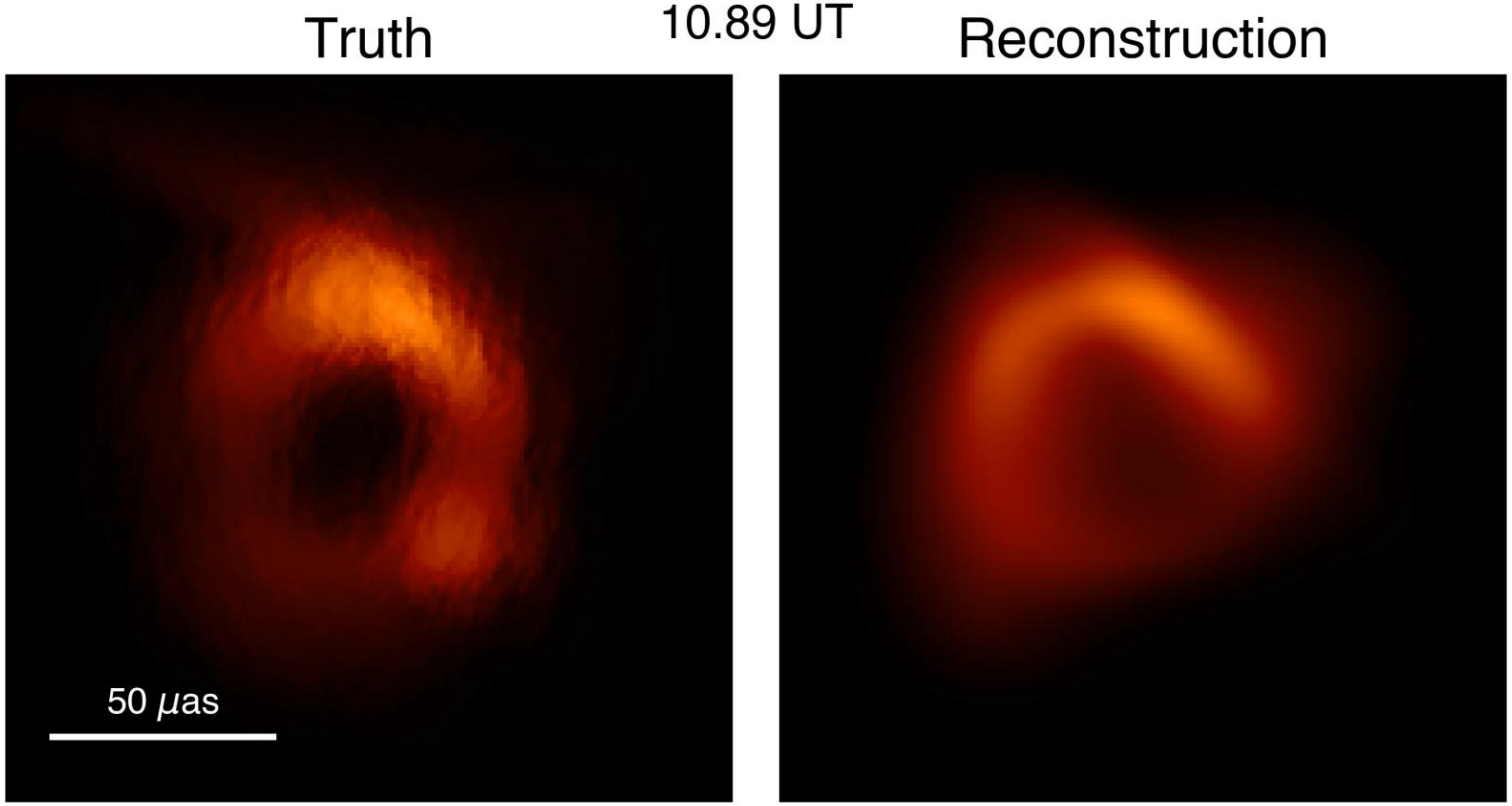


- Sgr A* polarization is consistent with energy outflow **if** the BH rotates clockwise
  - NIR flares (GRAVITY+ 2018) and ALMA mm light curves (Wielgus+ 2022) all rotate **clockwise**
- Sgr A* spin is not well constrained by EVPA pattern alone
  - combined EHT+MW constraints prefer high spin (EHTC+ VIII 2024)

Polarimetric spin measurements are possible!

Chael+ 2023b; **Chael** 2025; Wong+2025

Sgr A* Dynamics: Horizon-scale motion



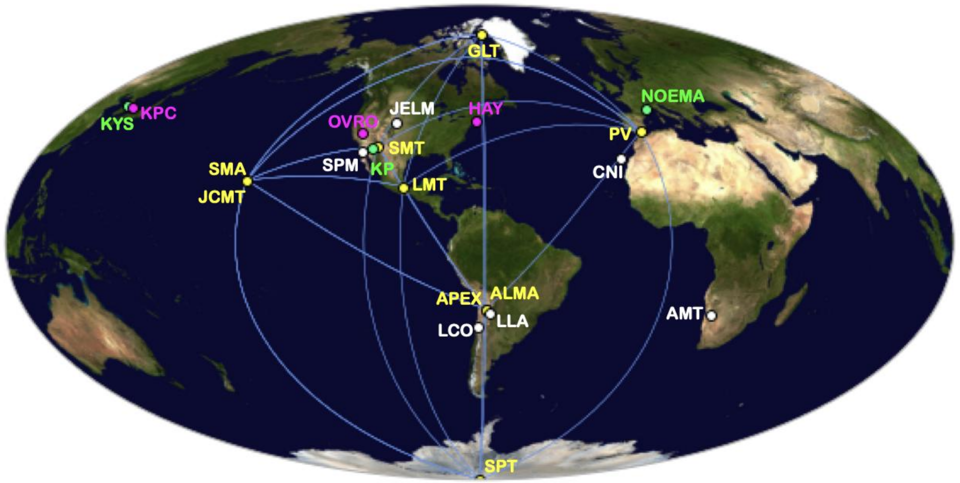
- GRAVITY near-infrared observations (GRAVITY Collab+ 2018, 2023) and unresolved ALMA observations (Wielgus+ 2022) suggest coherent clockwise motion on ~5 rg scales associated with Sgr A* flares.

- Long-term effort to use EHT data to constrain intra-observation motion.

Image credit: Rohan Dahale

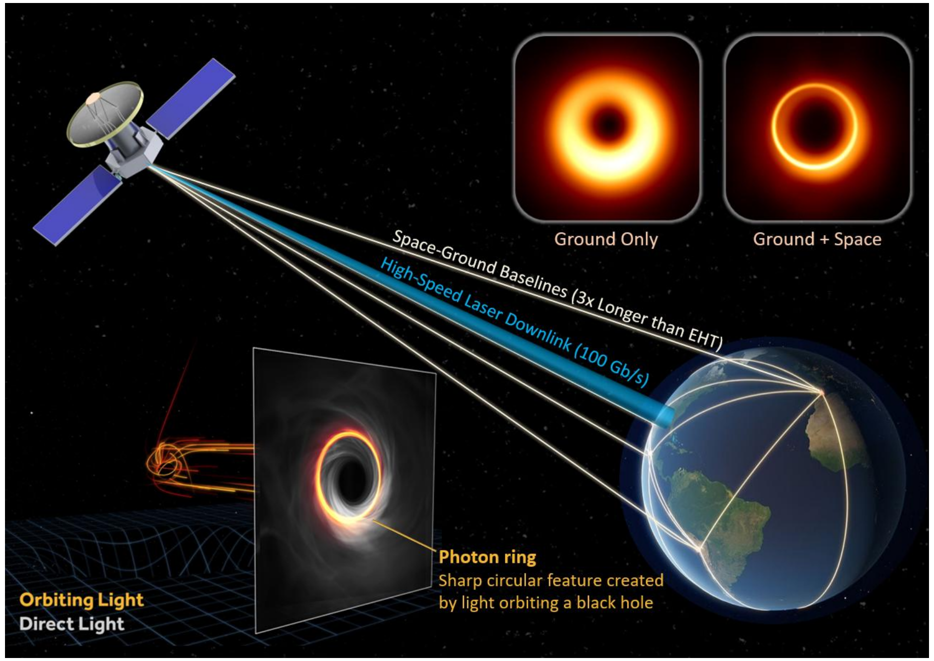
The future of near-horizon black hole astrophysics

Expanded ground-based EHT array



- Expand all EHT sites to multi-frequency observing and add new sites in Tenerife (TEA), Namibia (AMT) ….
- Image black holes and jets in high dynamic range at multiple frequencies
- Probe jet launching from horizon to hundreds of Schwarzschild radii (see e.g. Gelles+ 2024**:** [2410.00954](2410.00954))
- Make movies of Sgr A* and resolve black hole flares

Space VLBI / Black Hole Explorer (BHEX)



- A mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to ~12 (Zhang+ 2024)
- Also: SHARP and SHAPREx (Roelofs+ 2026)

See Doeleman+ 2023, EHTC+ 2024 (2410.02986); Johnson+ 2024 (2406.12917)