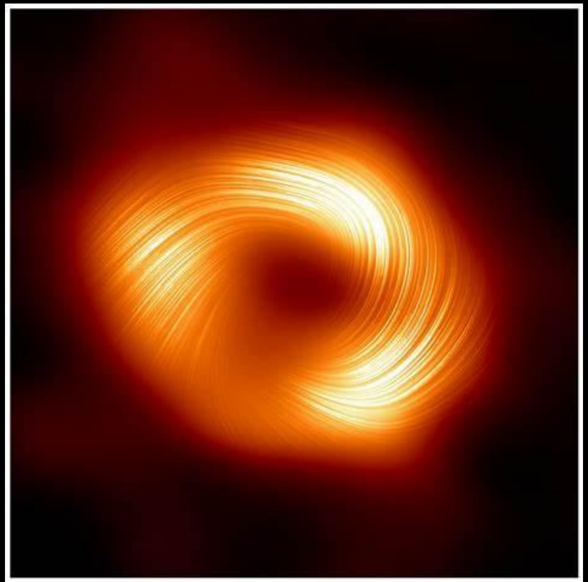
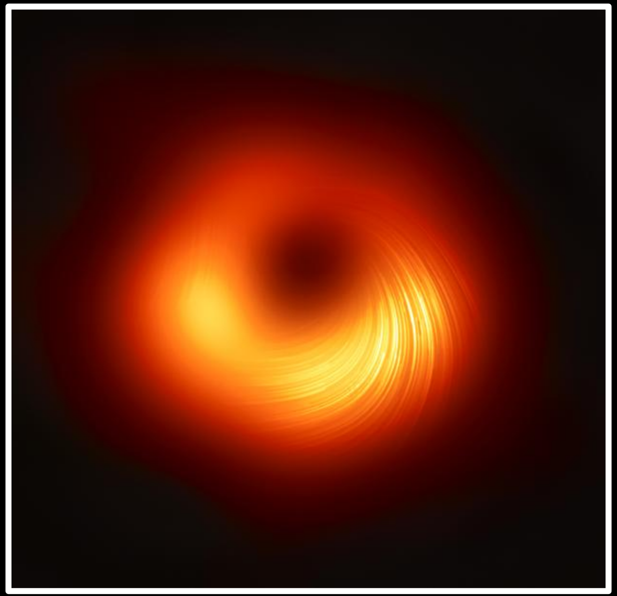
What can we learn from polarized images of black holes?

Andrew Chael
NBIA

March 23, 2026





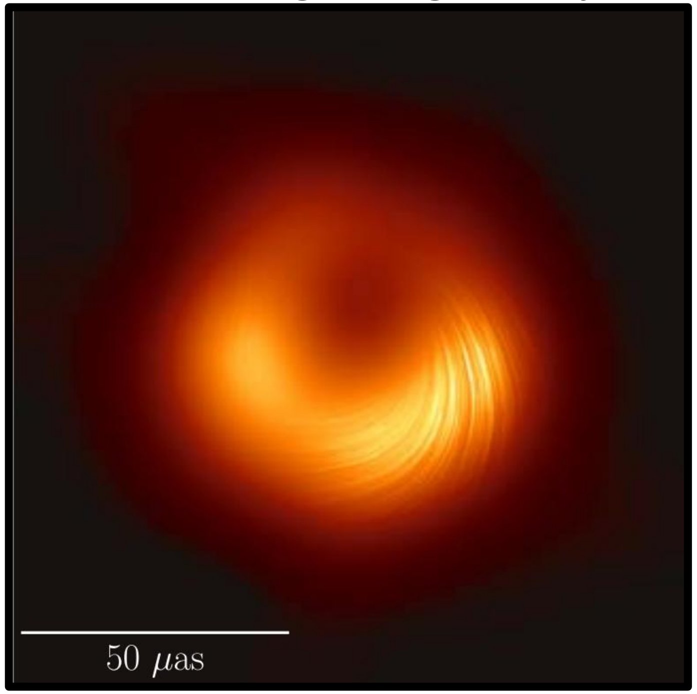
The Niels Bohr International Academy

BHEX

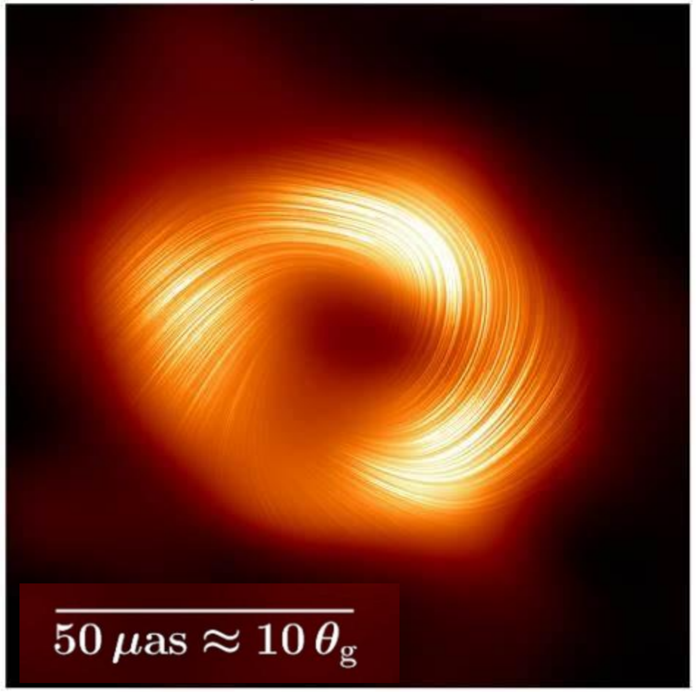
Event Horizon Telescope

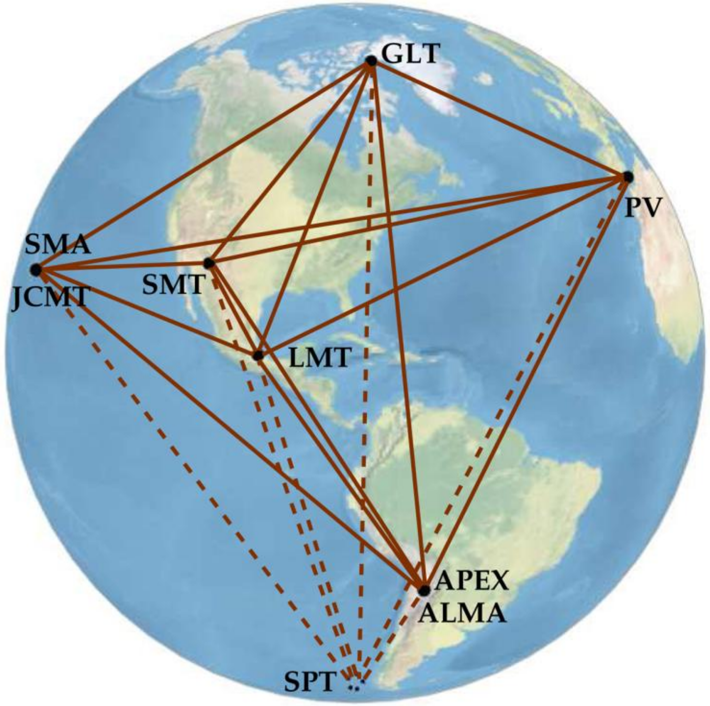
The first black hole images

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





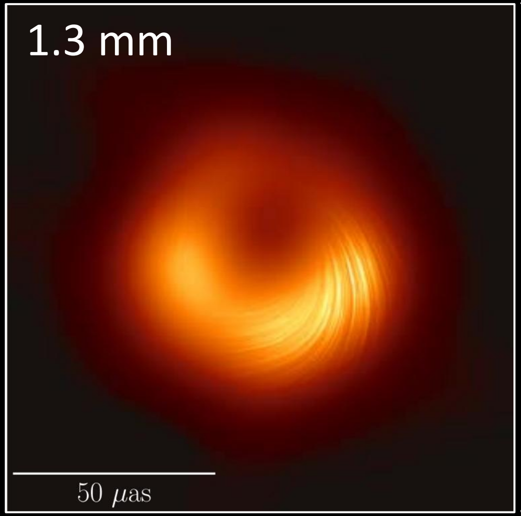
Over three orders of magnitude in BH mass:

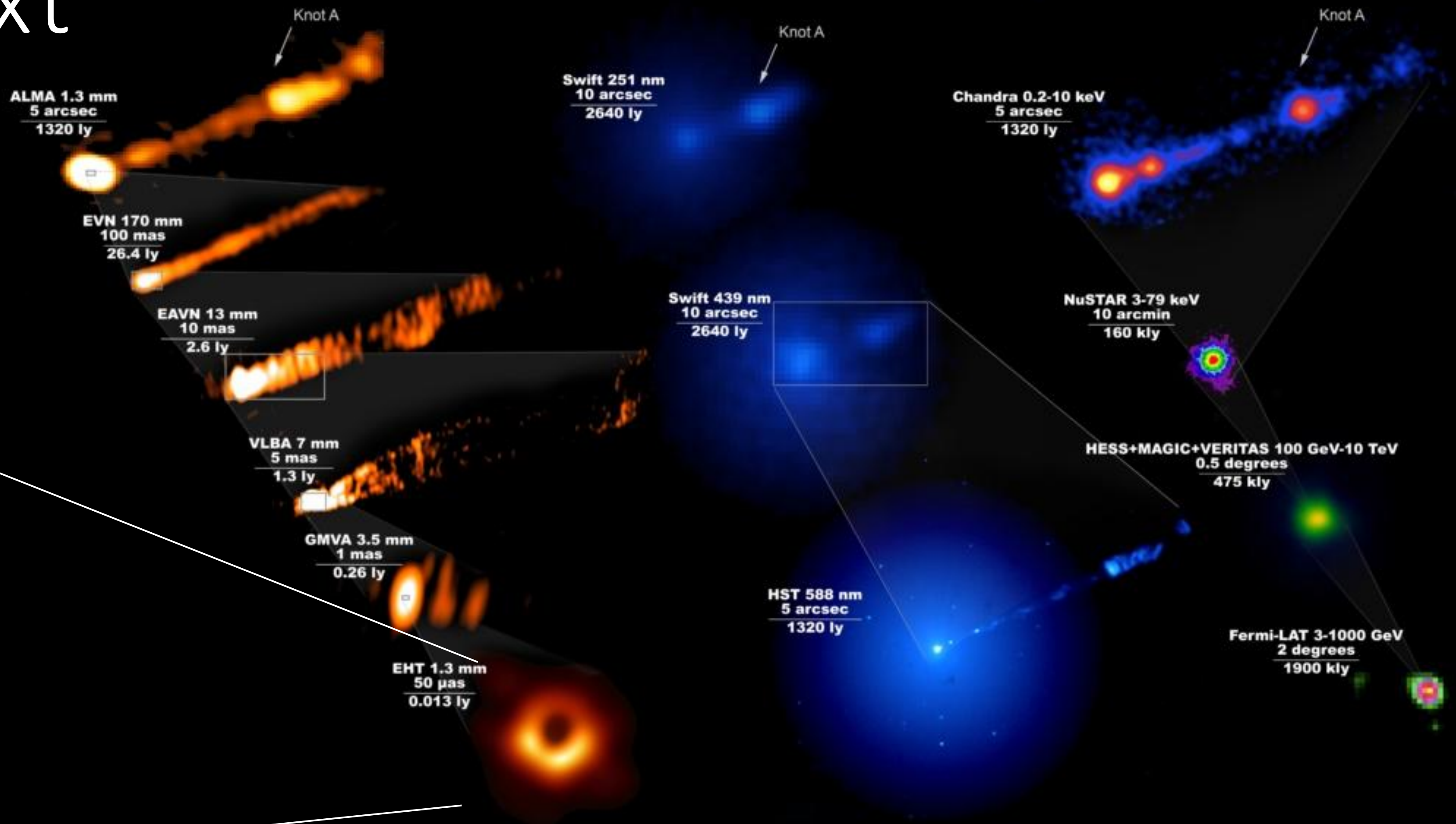
- Both images feature ring-like 230 GHz emission on horizon scales (≤5 GM/c^2)
- Both images are well-described by models and simulations of low-luminosity accretion: ($\dot{M} \approx 10^{-7} - 10^{-5}\dot{M}_{Edd}$)
- Both images constrain our models of the accreting plasma, magnetic fields, BH mass and spin

M87* in context

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

$P_{\rm jet} \sim 10^{42} - 10^{45}$ erg/s





Jets may be launched by magnetic fields extracting black hole spin energy (Blandford & Znajek 1977)

Is it possible to observe black hole energy extraction **on horizon scales**?

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

This talk:

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

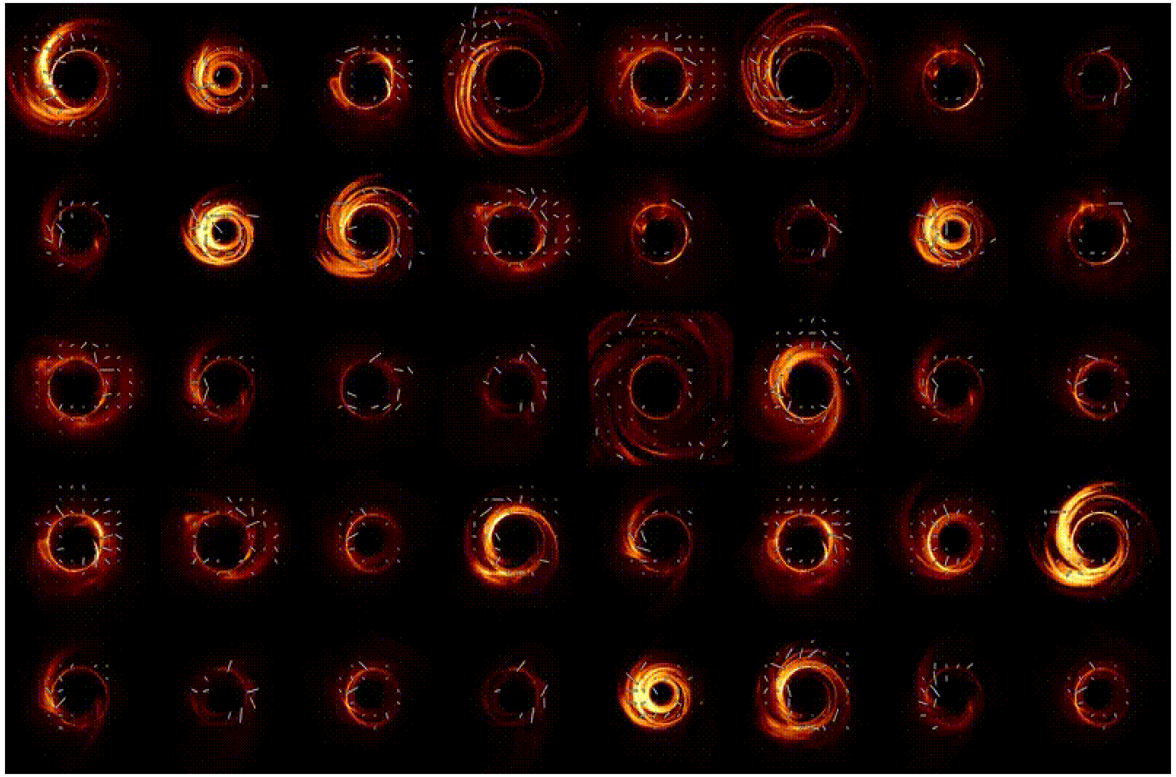
2. What can polarized EHT images tell us about how jets are launched?

3. What’s next?

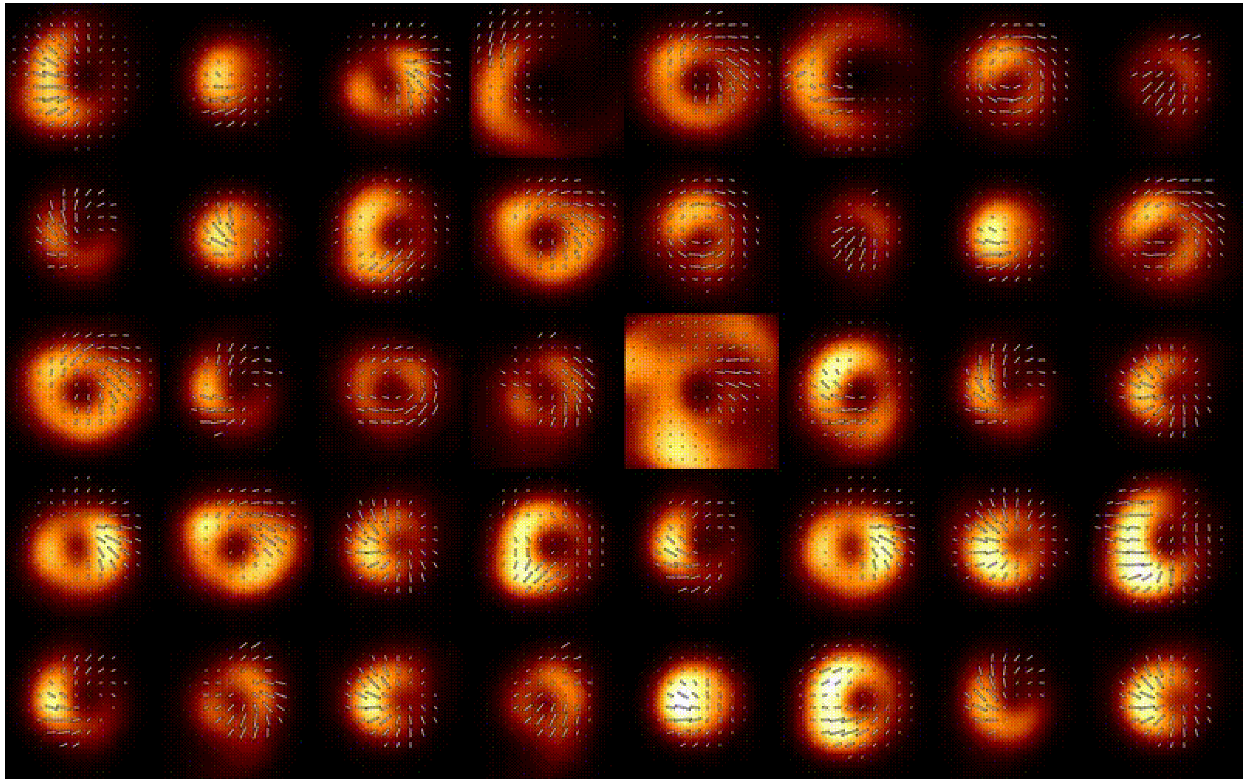
What did we learn from comparing polarized images of M87* to simulations?

EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
2105.01173, 2311.10976

GRMHD Simulation libraries



native resolution



EHT resolution

We need an electron temperature model to predict the observed emission (typically from Moscibrodzka et al. 2016)

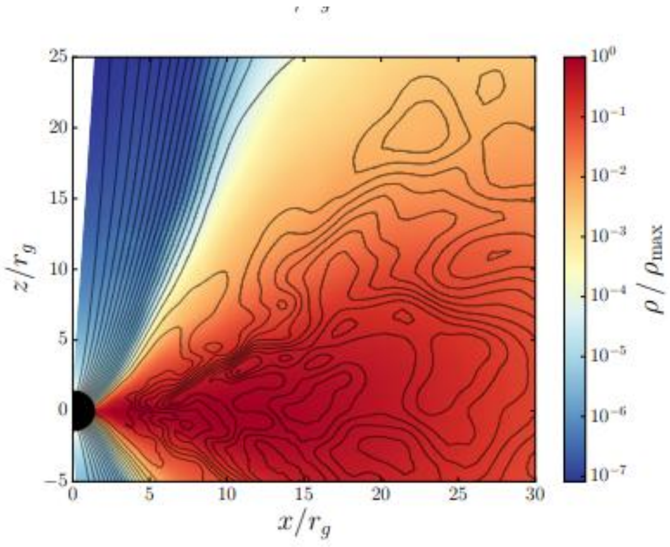
$$T_{\rm e} \neq T_{\rm i} \neq T_{\rm gas}$$

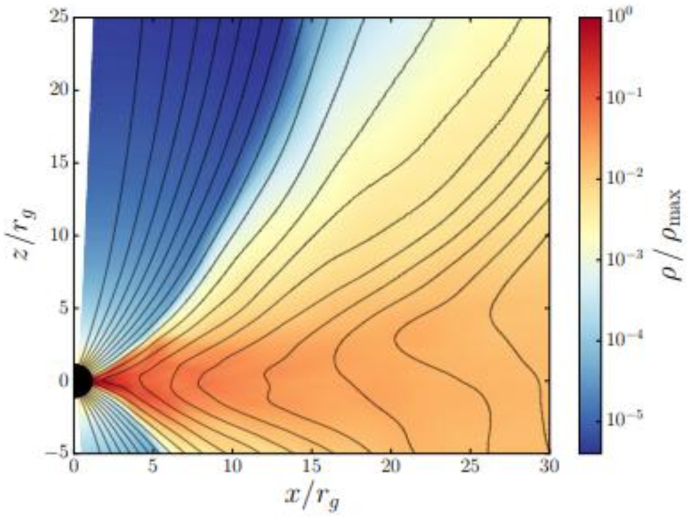
Animation credit: George Wong/ Cora Prather

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





Strong, coherent magnetic fields build up on the horizon

"SANE"

"MAD" - Magnetically Arrested Disk

MADs launch more powerful Blandford-Znajek jets:

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

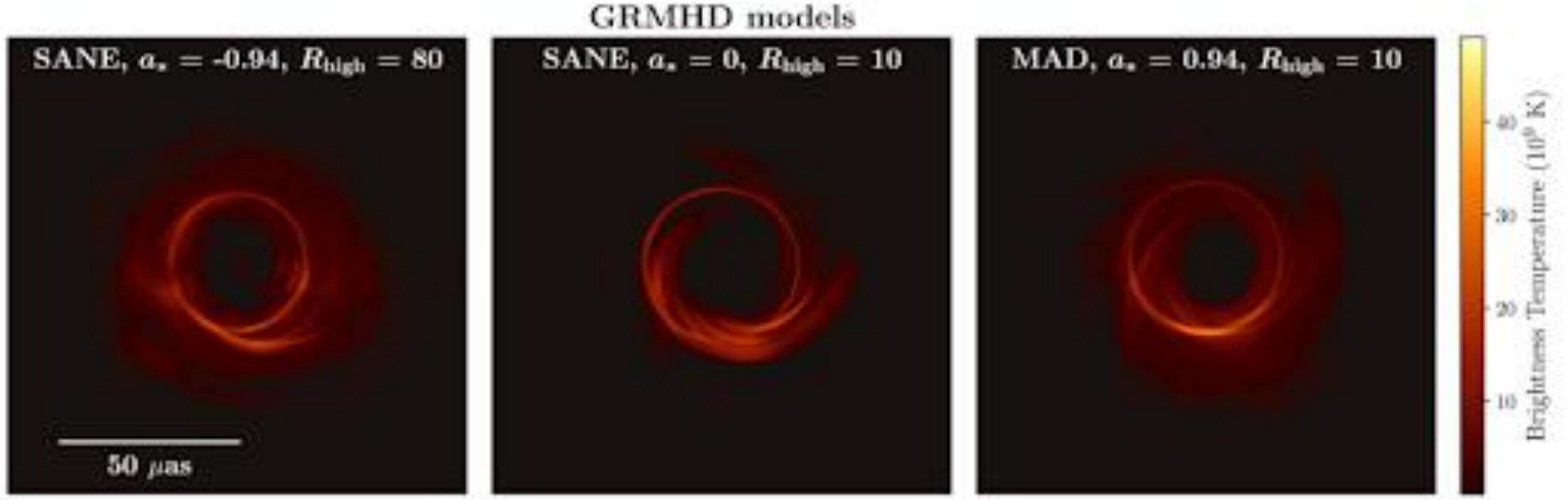
BH spin

magnetic flux

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

Comparing M87* images to GRMHD before polarization

- **Most simulation models can describe total intensity observations** by tweaking free parameters (mass, PA, total flux density)



- Image asymmetry → black hole spin vector faces away from Earth (plasma rotates clockwise)

EHTC V, 2019

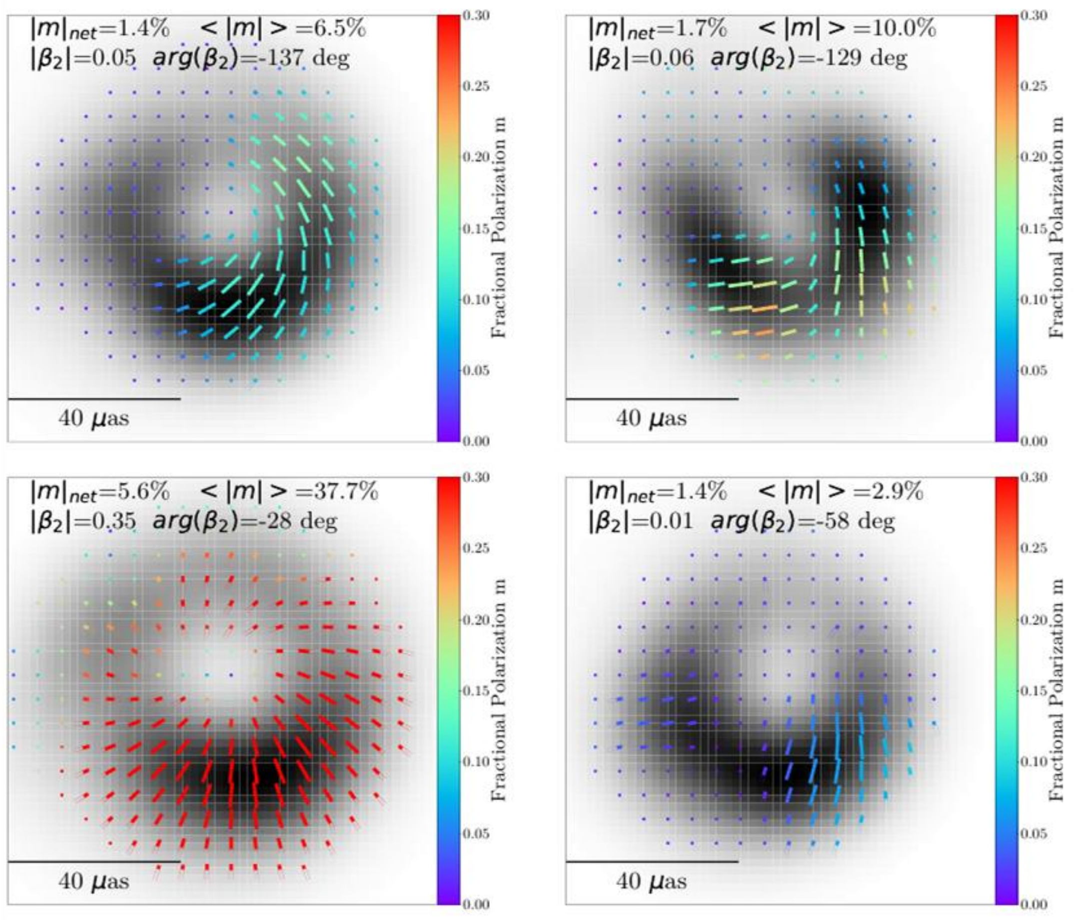
Polarization is the key for learning more

- Synchrotron radiation emits linear polarization oriented **perpendicular** to magnetic field lines

- Polarization transport is sensitive to the **magnetic field, plasma, and spacetime.**

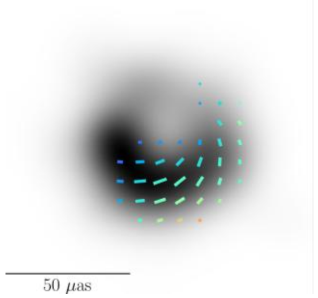
- Simulation polarization images show many different structures:
  - **strongly** or **weakly** polarized
  - patterns that are **radial** or **helical**

Simulation Polarization Images



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

Scoring M87* simulations with polarization

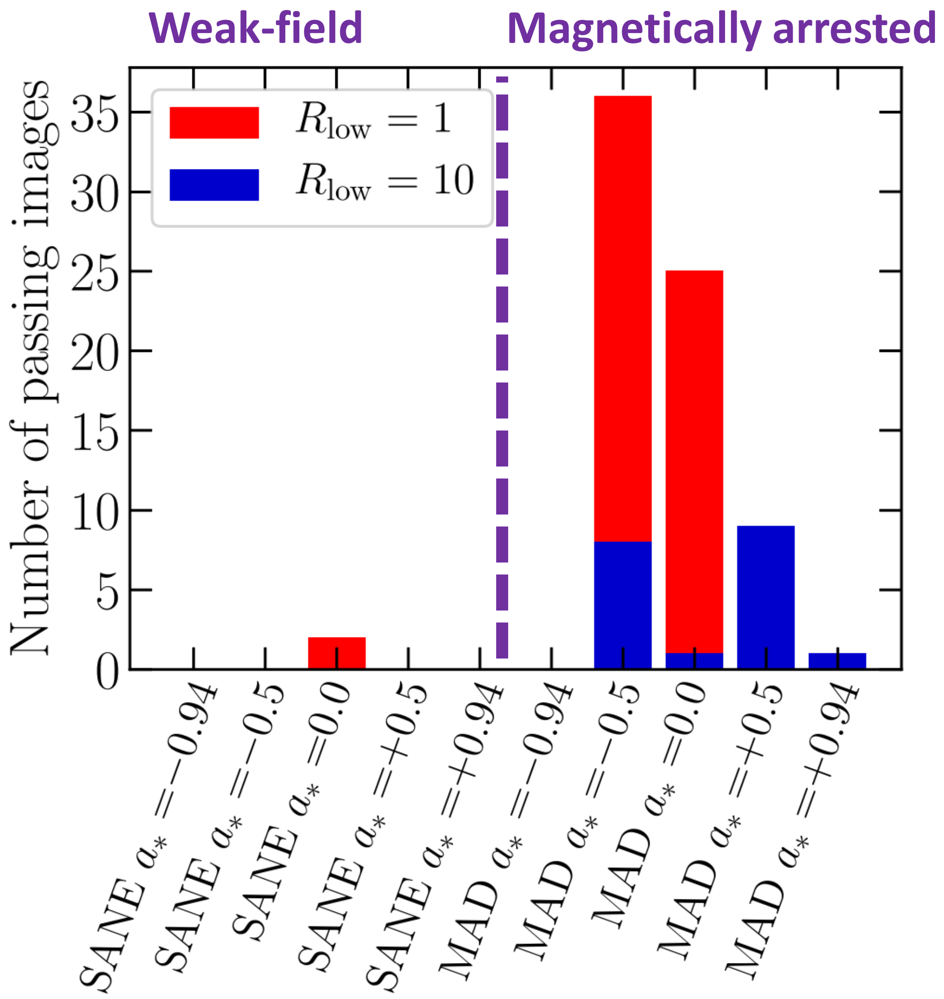


- Scoring simulations against EHT 2017 data with multiple approaches **all strongly favor a magnetically arrested accretion flow**

- Plasma parameters from passing simulations agree with analytic model estimates:

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

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



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

What can a polarized image of M87* tell us about energy flow near the horizon?

Chael+ 2023; Wong, Chael+ 2025

2307.06372, 2509.22639

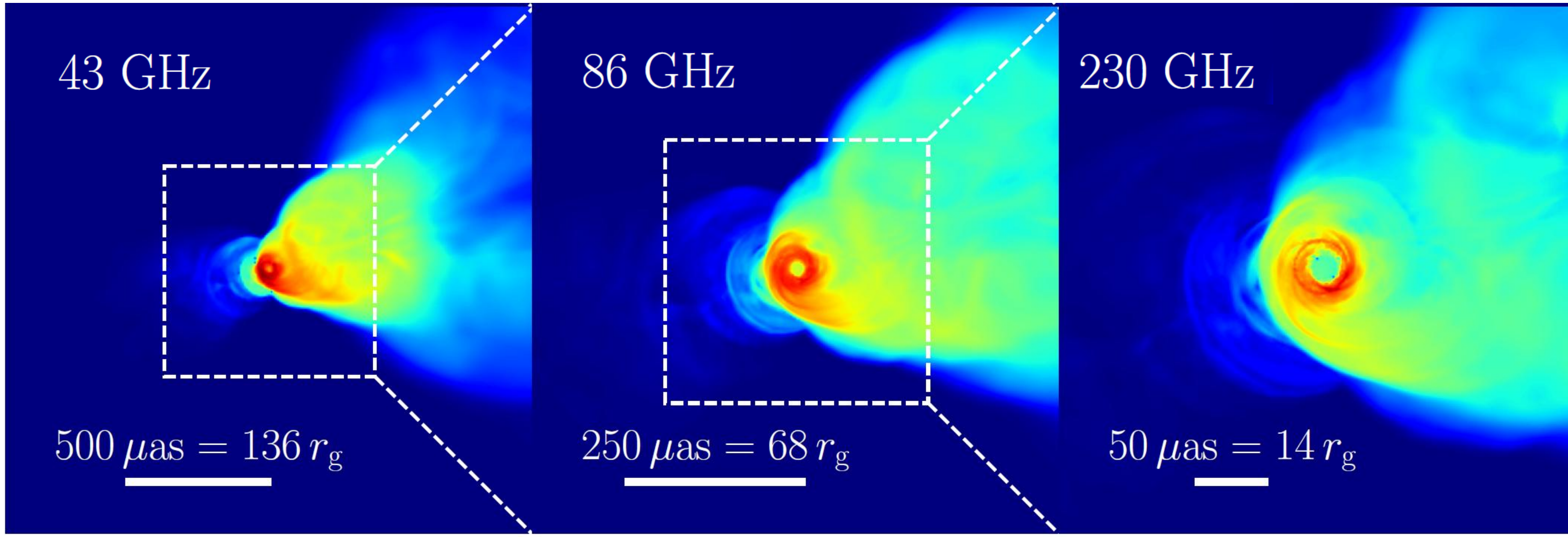
M87 Jets in GRMHD Simulations

- Jets from magnetically arrested GRMHD simulations **are powered by black hole spin** (e.g. McKinney & Gammie 2004, Tchekhovskoy+ 2012, EHTC+ 2019, Narayan+ 2022)

- Radiative simulations of M87*'s jet (Chael+ 2019, 2025) naturally produce:

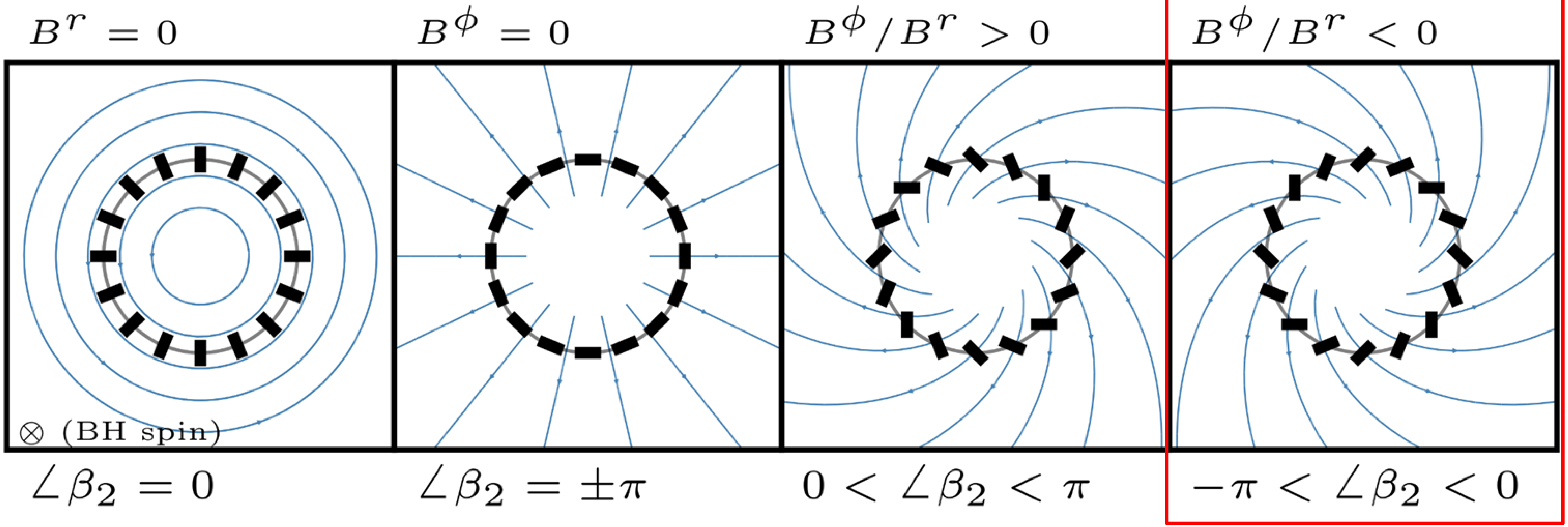
    - A jet power in the measured range
    - The observed wide opening angle
    - The observed core-shift

- Can we be **sure** M87's jet is spin powered? What is a **physically meaningful** observation of **horizon-scale** energy flow?



Chael+ 2019

Horizon-scale polarization tracks the **magnetic pitch angle**

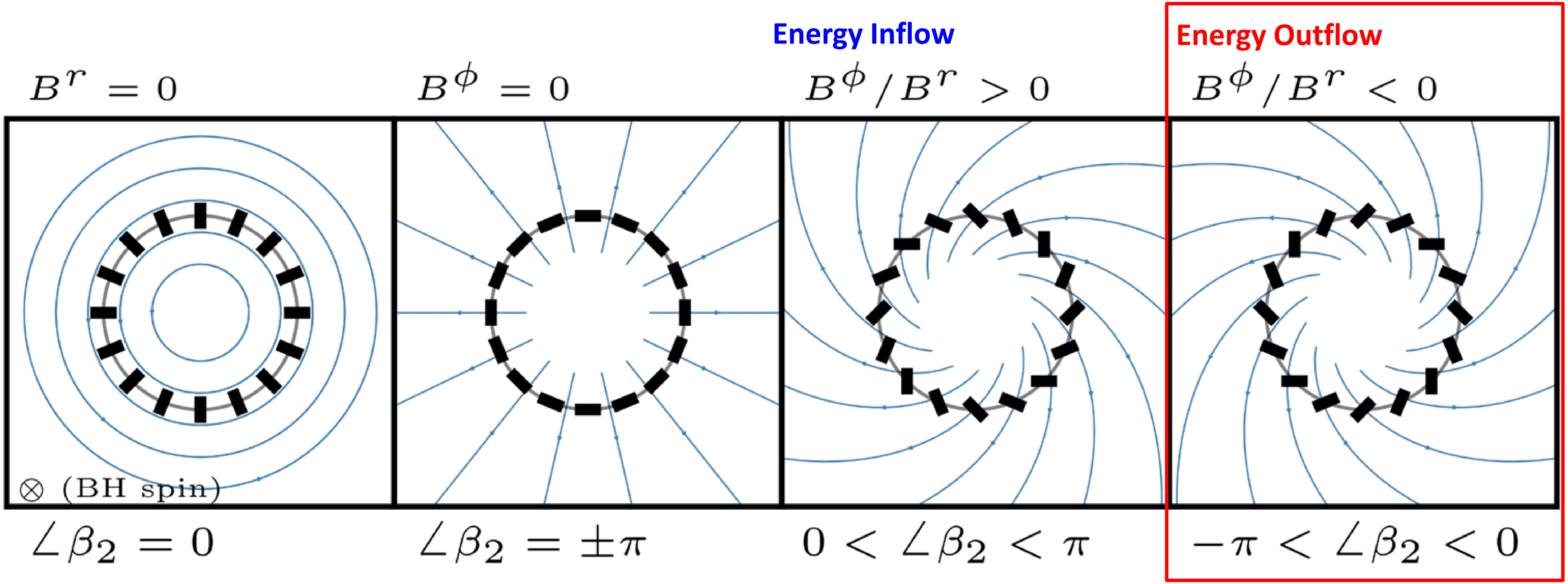


- The β_2 statistic encodes the direction of the polarization spiral (Palumbo+ 2020)
- In the simplest model (equatorial emission, no Faraday, no GR), the observed sign of $\angle\beta_2$ determines the sign of B^ϕ/B^r

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

Palumbo+ 2020, **Chael**+ 2023b

Horizon-scale polarization tracks the **direction of energy flux**



The direction of radial Poynting flux in GRMHD is set determined by B^ϕ/B^r :

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

- Our coordinate axis is **into the screen,** so $\Omega_F > 0$ means **clockwise** rotation (EHT Paper V, 2019)

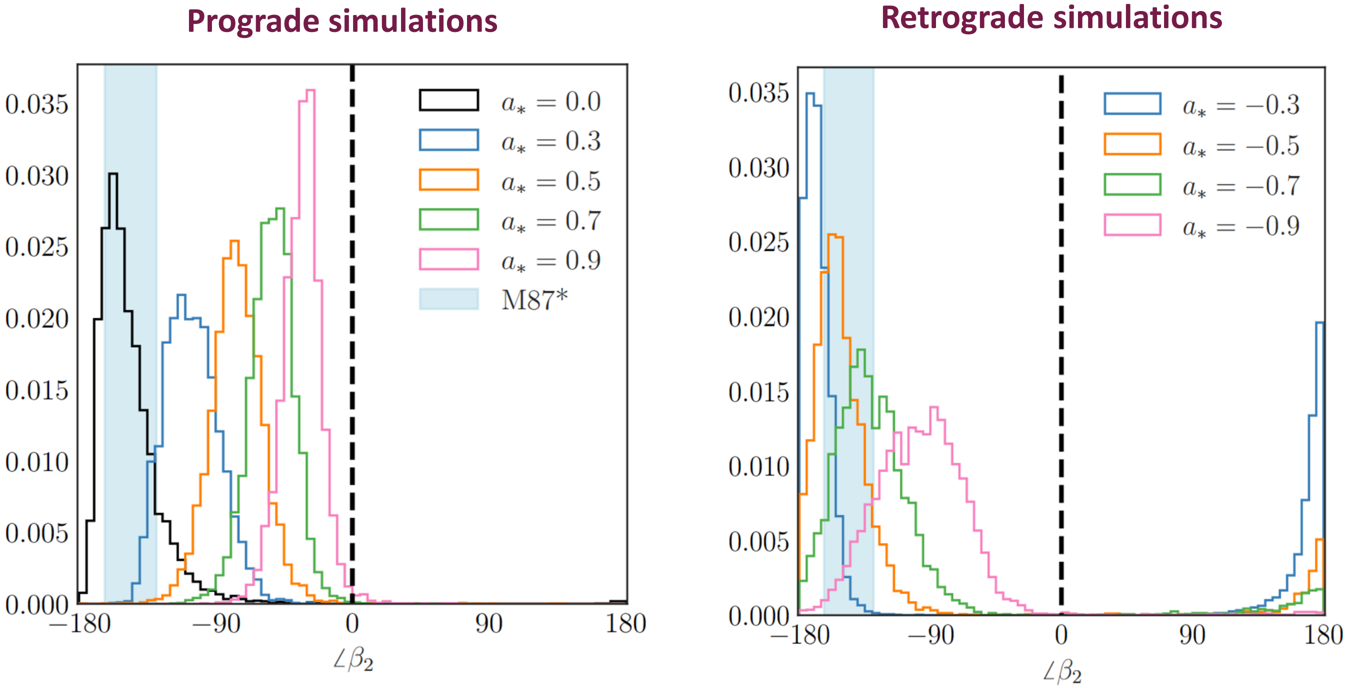
Chael+ 2023b

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



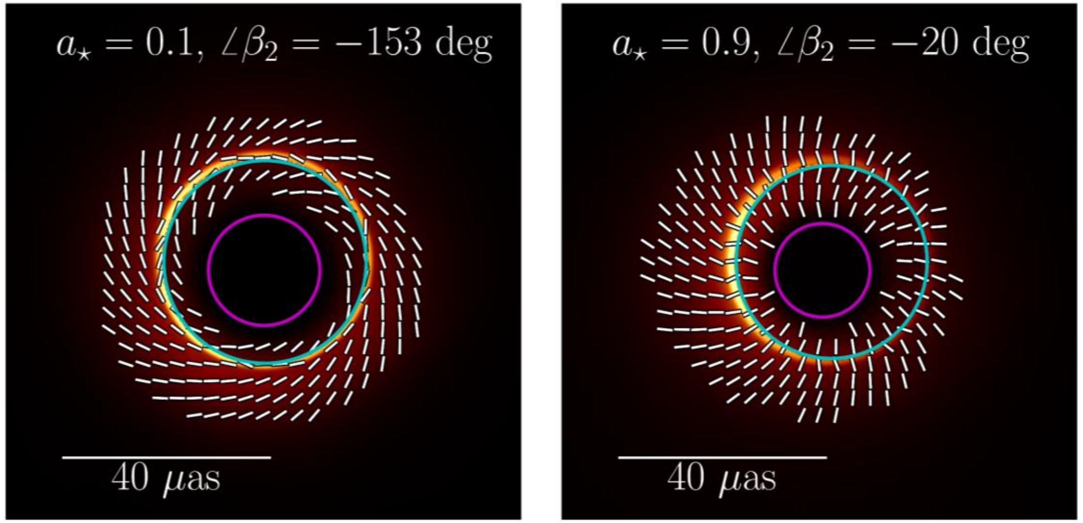
BH spin axis is into the plane of the sky in all simulation images (EHTC+V)

Chael+ 2023b, simulations from Narayan+2022

Polarized images are **spin dependent**

Low Spin

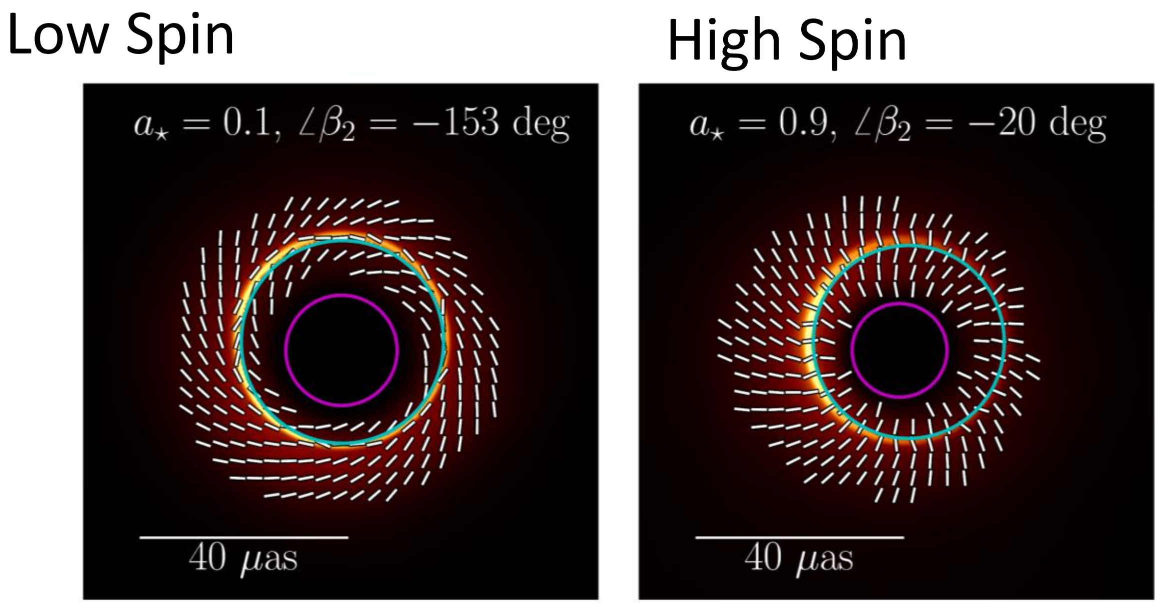
High Spin

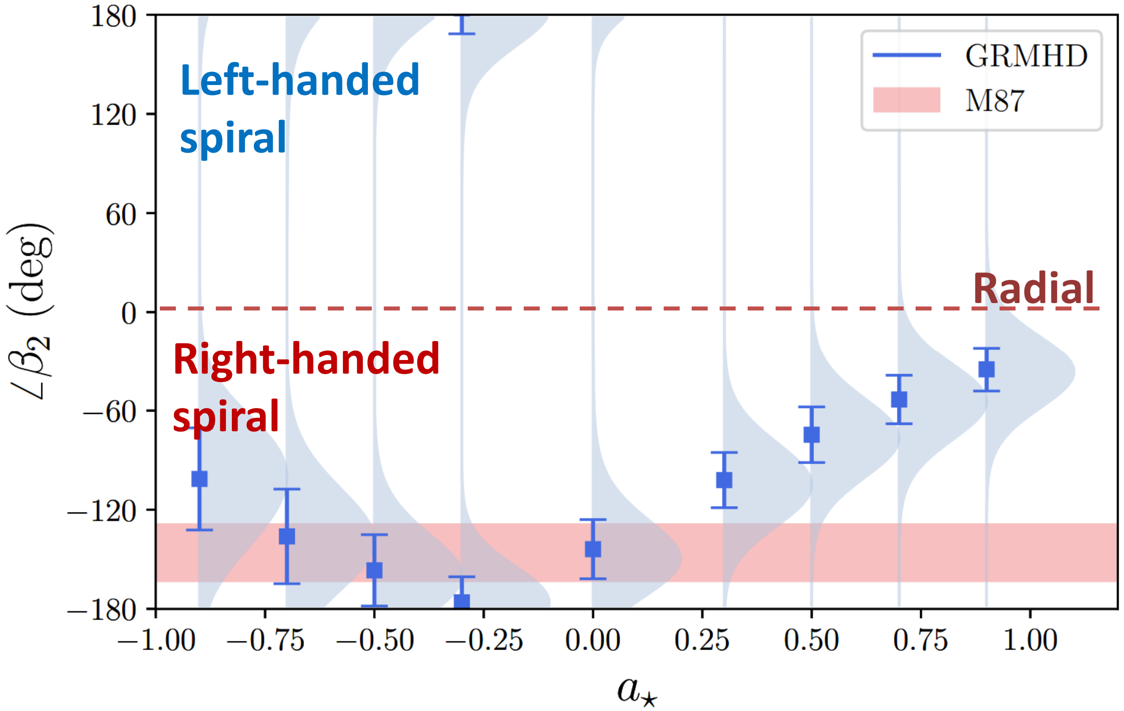


- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

Chael+ 2023b**;** Wong, **Chael**+ 2025
Simulations from Narayan+ 2022

M87*'s Polarization may constrain spin





- 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)
- More work is needed to understand if these conclusions are robust to Faraday rotation and temporal variability!

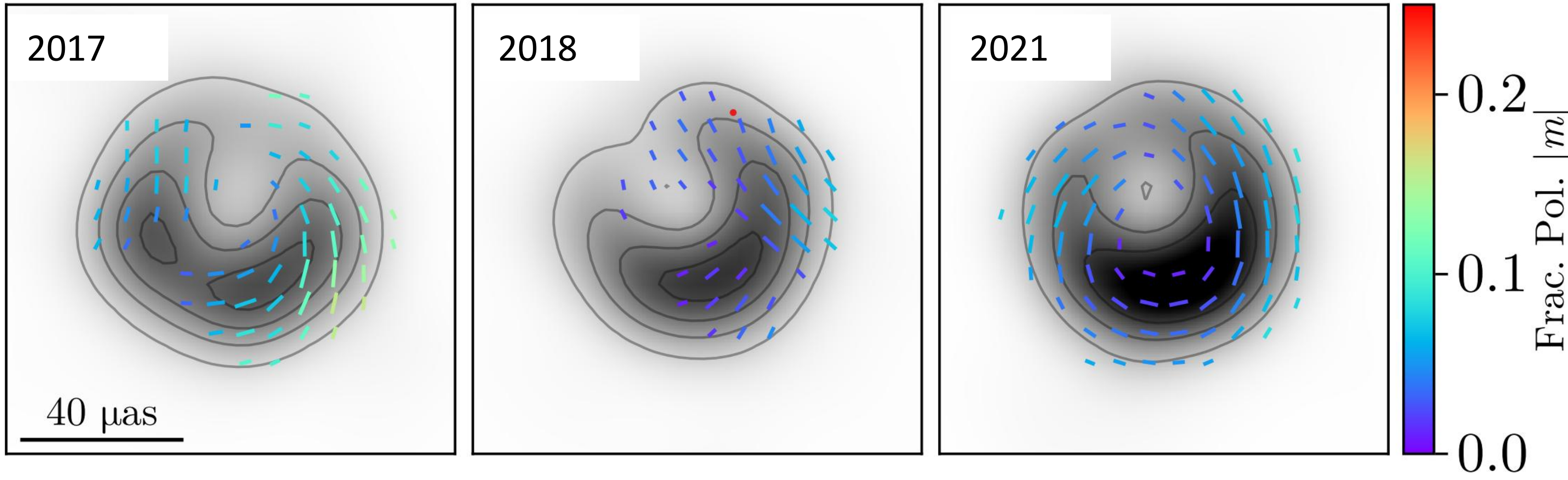
Chael+ 2023b; Wong, **Chael**+ 2025
Simulations from Narayan+ 2022

Next steps for determining the jet power source

Gelles+ 2025,2026, Chael+ in prep.
2410.00954, 2601.13307

Can we understand the M87*’s evolving polarization over time?

- EHT observations show a consistent horizon-scale ring structure in M87* **over 4,000 gravitational timescales** from 2017-2021
- Image quality is improving from EHT observations performed with a **more complete array** (including Greenland Telescope)
- **Polarization** structure changes and fractional polarization is **lower** in 2018-2021 (3%) than 2017 (~10%)
- **Stay tuned!**



EHTC + 2025
doi: 10.1051/0004-6361/202555855

How can we determine the jet power source?

By zooming **out**..

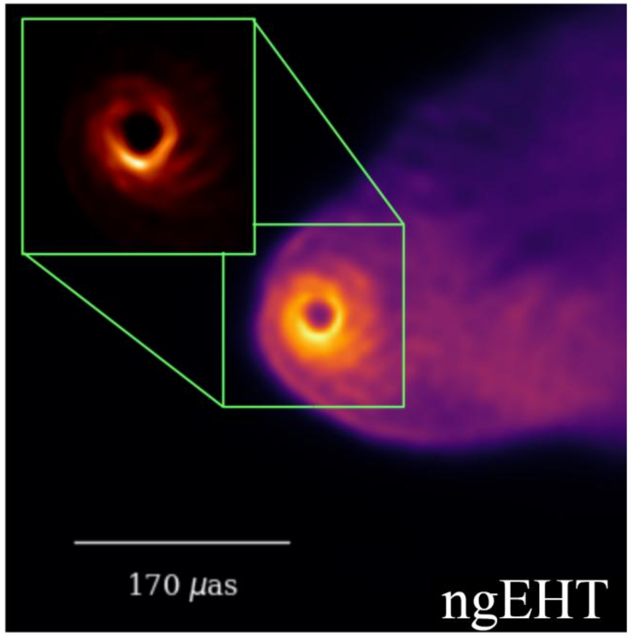


Image the connection between the BH and the low-brightness extended jet in polarization and **high dynamic range**

By zooming **in**..

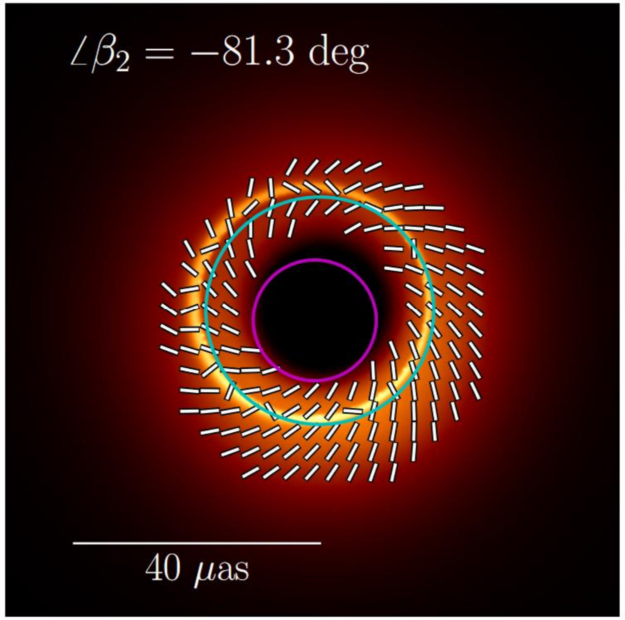


Image field lines close to the event horizon in **high resolution**

The future of near-horizon observations

Extended & next-generation EHT

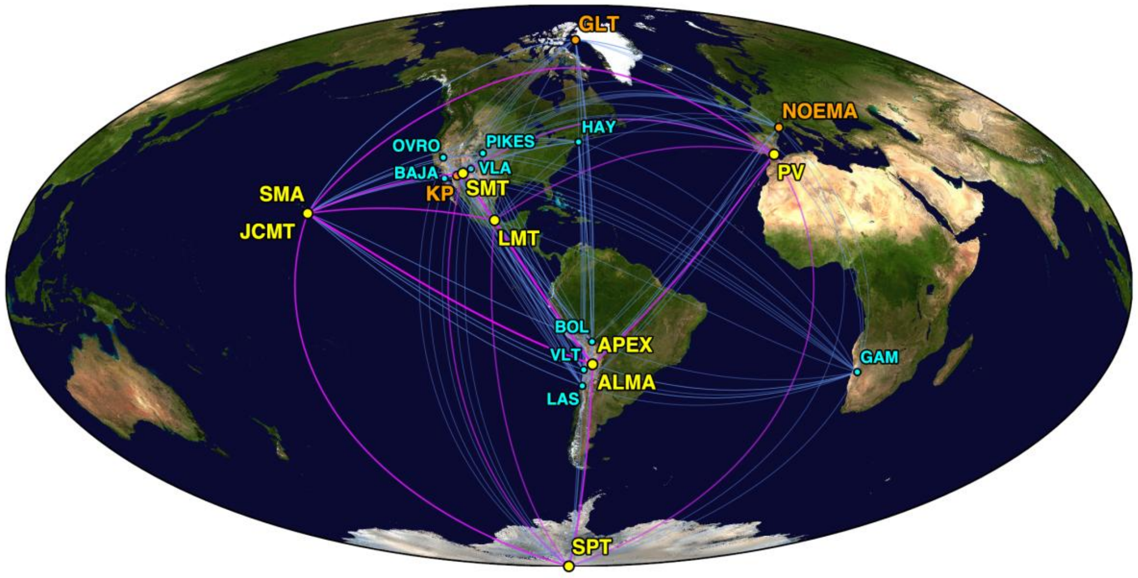


Image black holes and their jets in **multiple frequencies** and **high dynamic range**

Black Hole Explorer (BHEX)

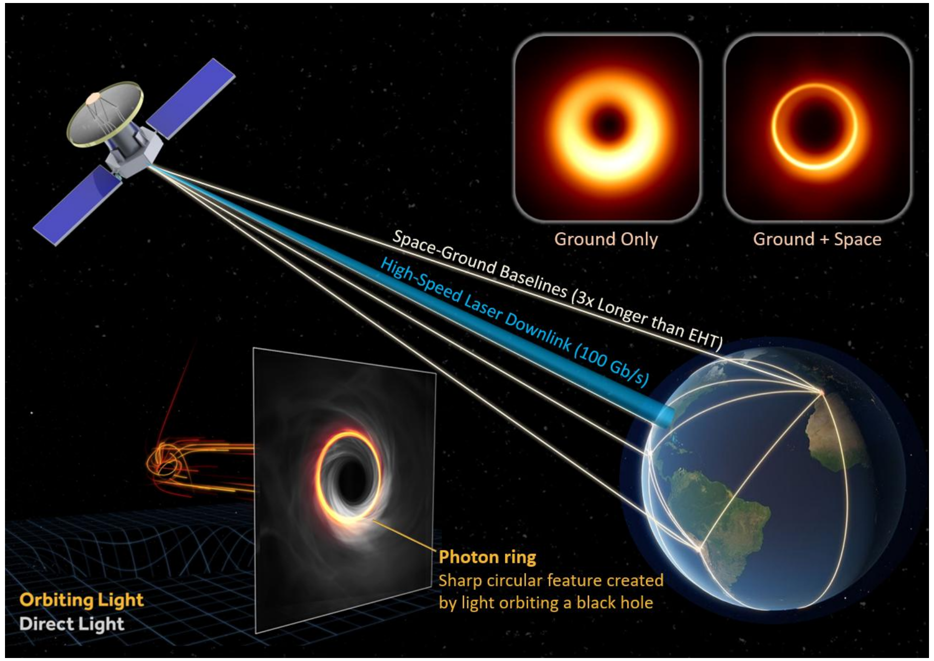


Image **extreme gravitational lensing** and dozens of new black holes **in high resolution**

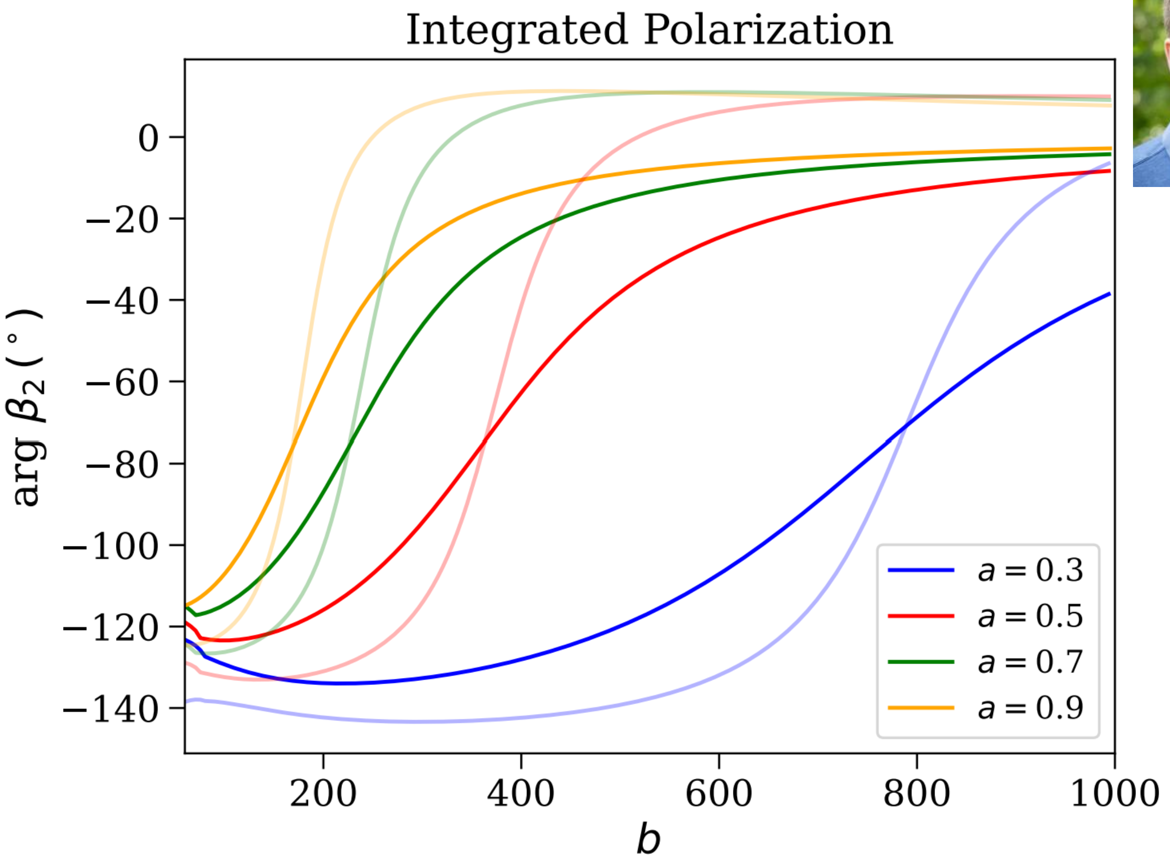
See EHTC+ 2024 (2410.02986); Johnson+ 2024 (2406.12917)

EHT/ngEHT: *zooming out*

Zack Gelles (Princeton)
Arxiv: [2410.00954](), [2601.13307]()

- EHT/ngEHT observations with high dynamic range will connect horizon-scale polarization to the extended jet
- The polarization of BZ jets has a **strong signature of spin** at the **light cylinder** (Gelles+ 2025)
- The evolution of synchrotron polarization in the jet launching region is highly sensitive to the BH spin, Lorentz factor and inclination (Gelles+ 2026)
    - See Zack's poster!

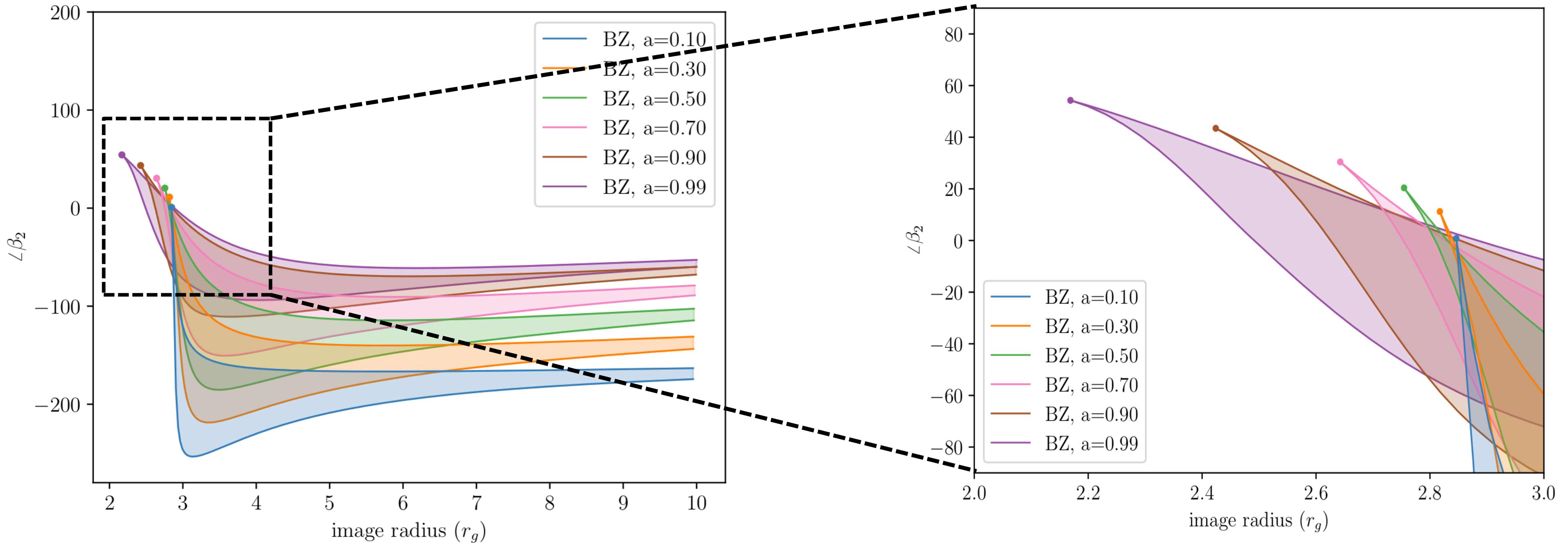
Average Polarization Angle



Jet Distance

Gelles+ 25, Gelles+ 26

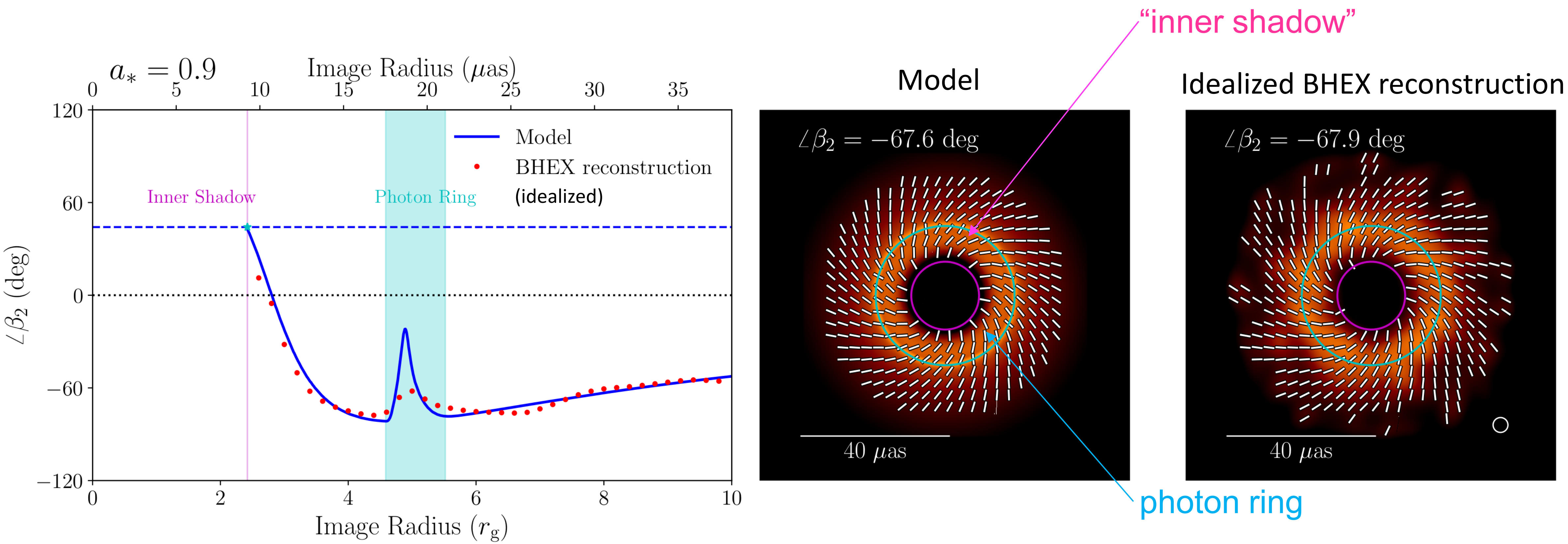
BHEX: *zooming in*



- Synchrotron radiation asymptotically close to the horizon has a **universal position angle** dependent only on the BH spin and inclination (Hou+ 25, Chael+ in prep)

Chael+ in prep

BHEX: *zooming in*



- Synchrotron radiation asymptotically close to the horizon has a **universal position angle** dependent only on the BH spin and inclination (Hou+ 25, Chael+ in prep)
- β_2 evolves rapidly toward the unique horizon value due to both **frame dragging** and **parallel transport**
- **BHEX + EHT can obtain the resolution to observe this evolution,** directly probing field lines that penetrate the ergosphere and approach the horizon

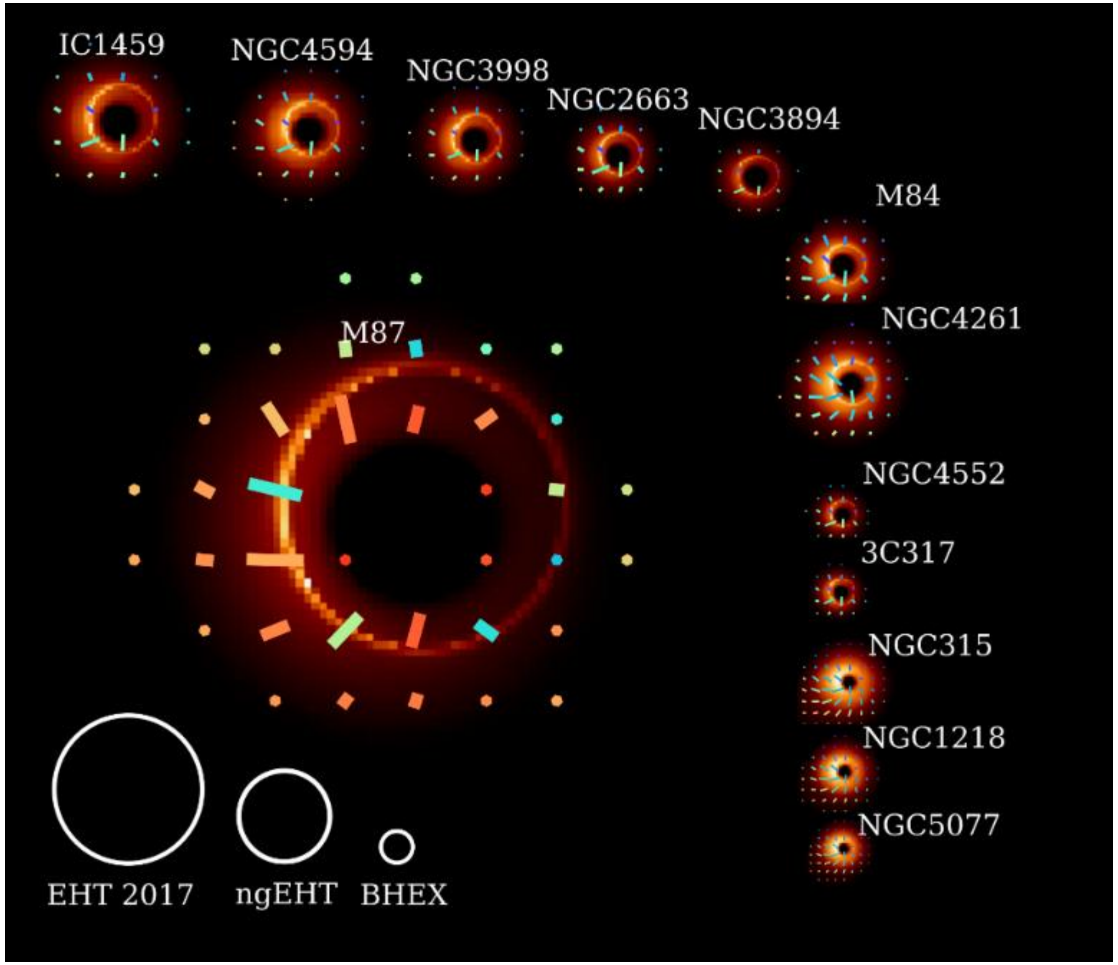
Chael+ in prep

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 and constrain their mass (from image size) and spin (from polarization)

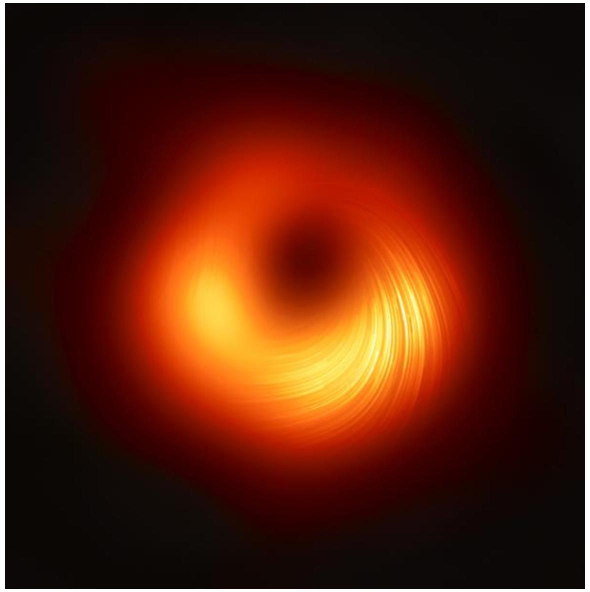
- BHEX will determine how polarized black hole images changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties

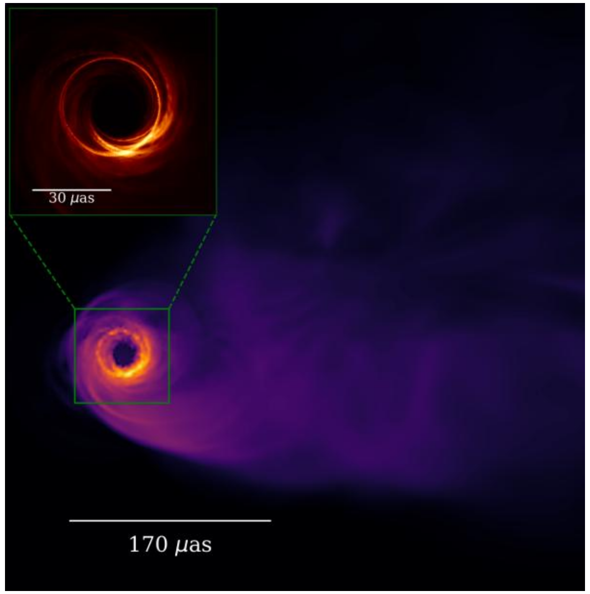
- See talk by Angelo Ricarte on Friday!



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

Takeaways





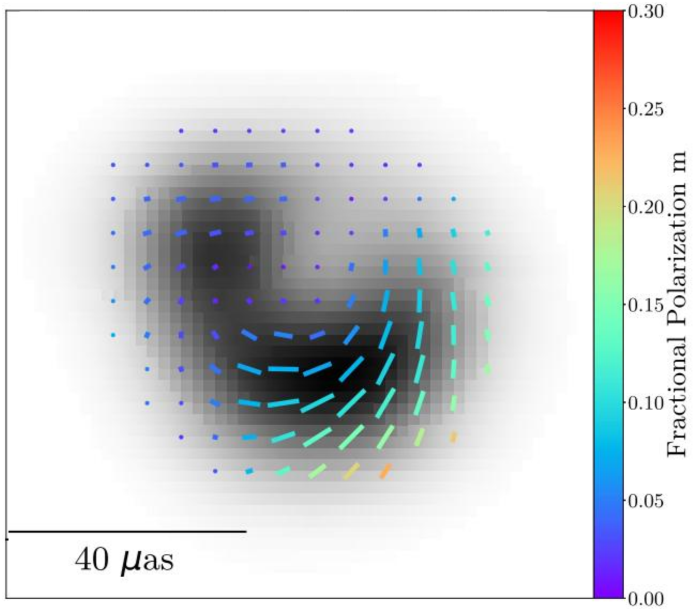
- **Polarization is the key** for constraining accretion and jet launching models with near-horizon observations
- EHT polarization images are consistent with **magnetically arrested accretion** and **outward electromagnetic energy flux**
- Near-horizon synchrotron polarization is sensitive to **black hole spin**
- **Future ground and space-based observations** with EHT, ngEHT, and BHEX will directly probe the black hole-jet connection from the horizon to parsec scales

EHT VII, 2021; **Chael** 2025

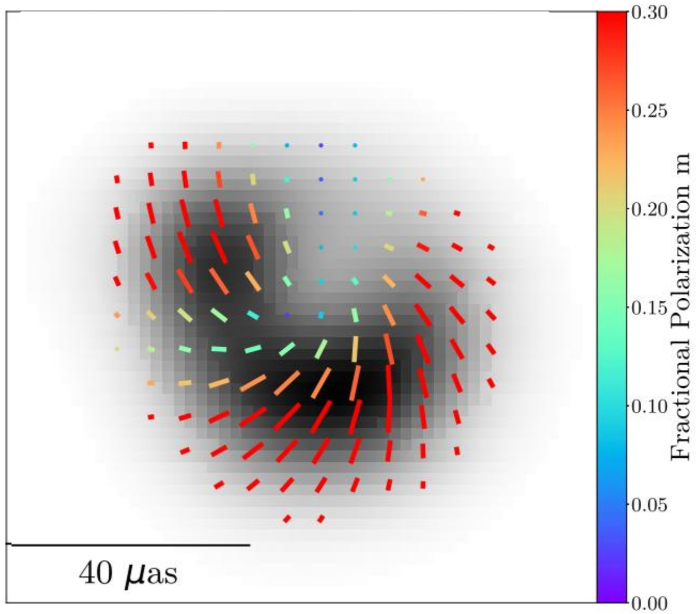
backup slides

Polarized images constrain the electron temperature

With Faraday



Without Faraday



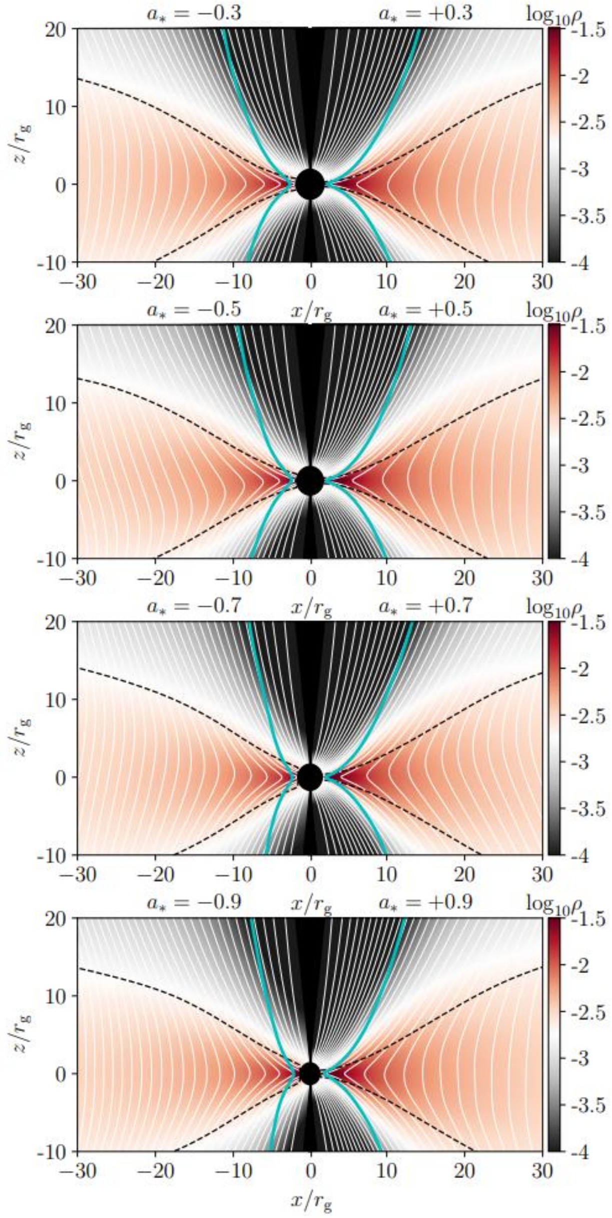
EHT resolution

- Significant **Faraday rotation** on different scales
  - → **Scrambles** polarization vectors on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from relatively **cold electrons** $(T_i/T_e \gtrsim 50)$ is necessary to depolarize MAD models

We need **multi-frequency data** to fully understand the horizon-scale Faraday rotation – coming soon!

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

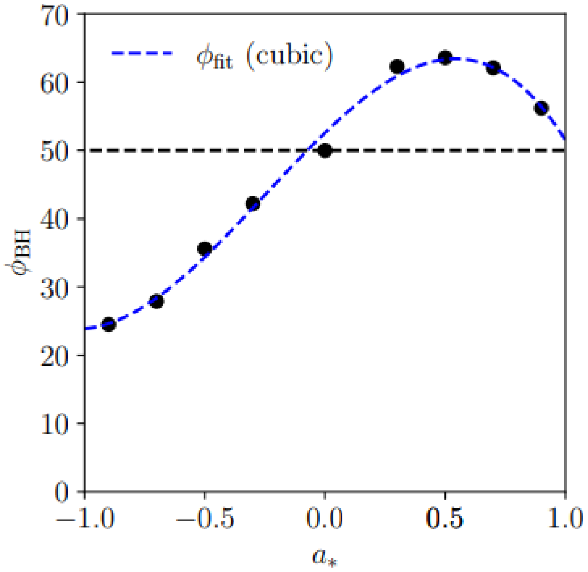
Simulation Jets are definitely Blandford-Znajek



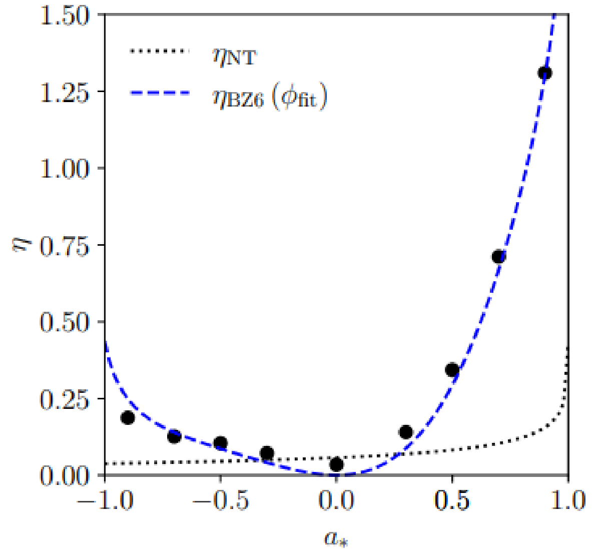
Time-and azimuth-averaged simulation data

Jet power follows BZ prediction in 8 very-long-duration simulations (10^5 t_g) of magnetically arrested accretion

Magnetic flux though the horizon



Jet efficiency

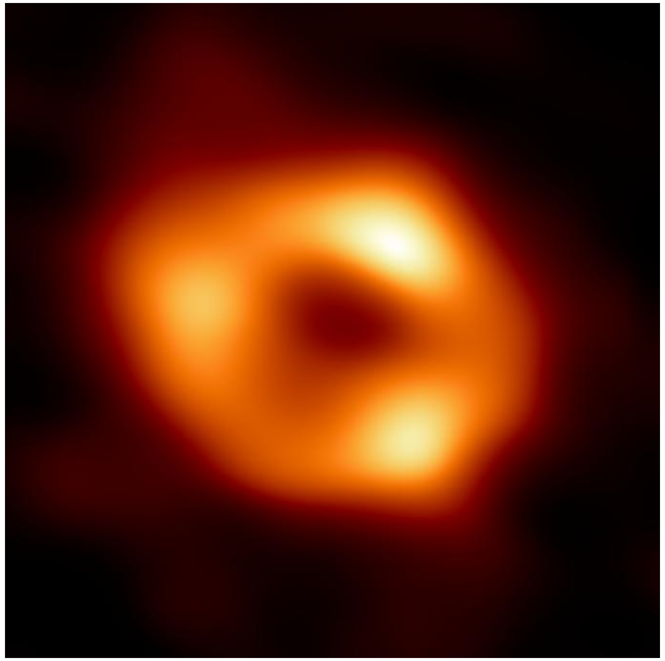


BH spin

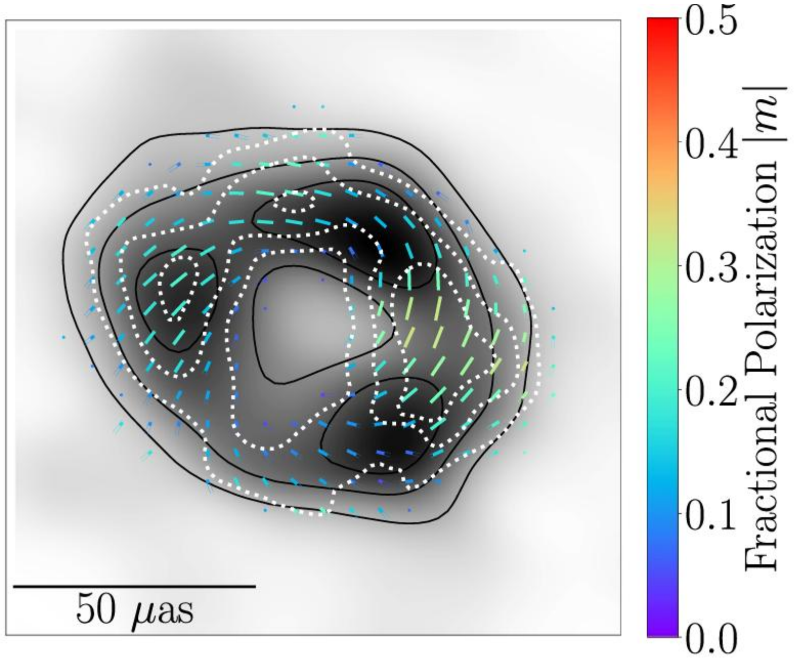
R. Narayan, **A. Chael +** 2021
Tchekhovskoy+ 2012, Lowell+ 2023, Guo+ 2025…

Sgr A* in linear polarization

Total intensity



Linear Polarization

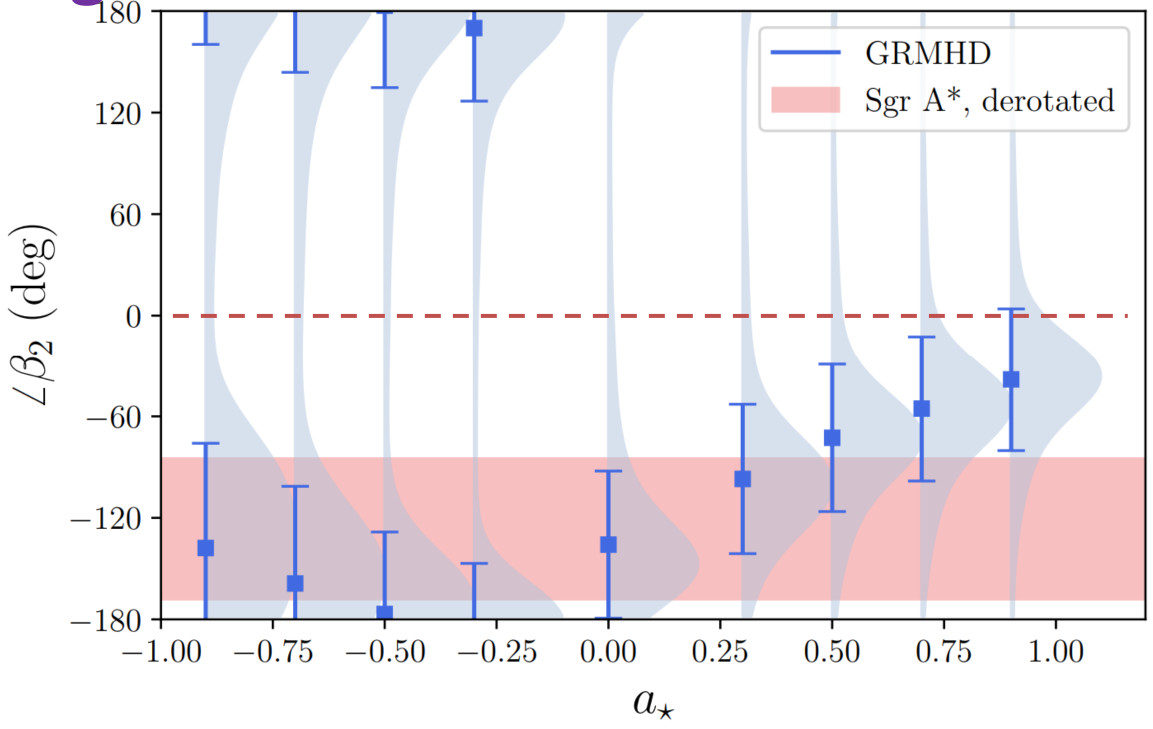


- Polarization fraction is **higher** than M87
- β_2 sign is consistent with **clockwise rotation** measured in NIR flares
- MAD simulations are preferred, but don't require very cold electrons
- **where is the jet?**

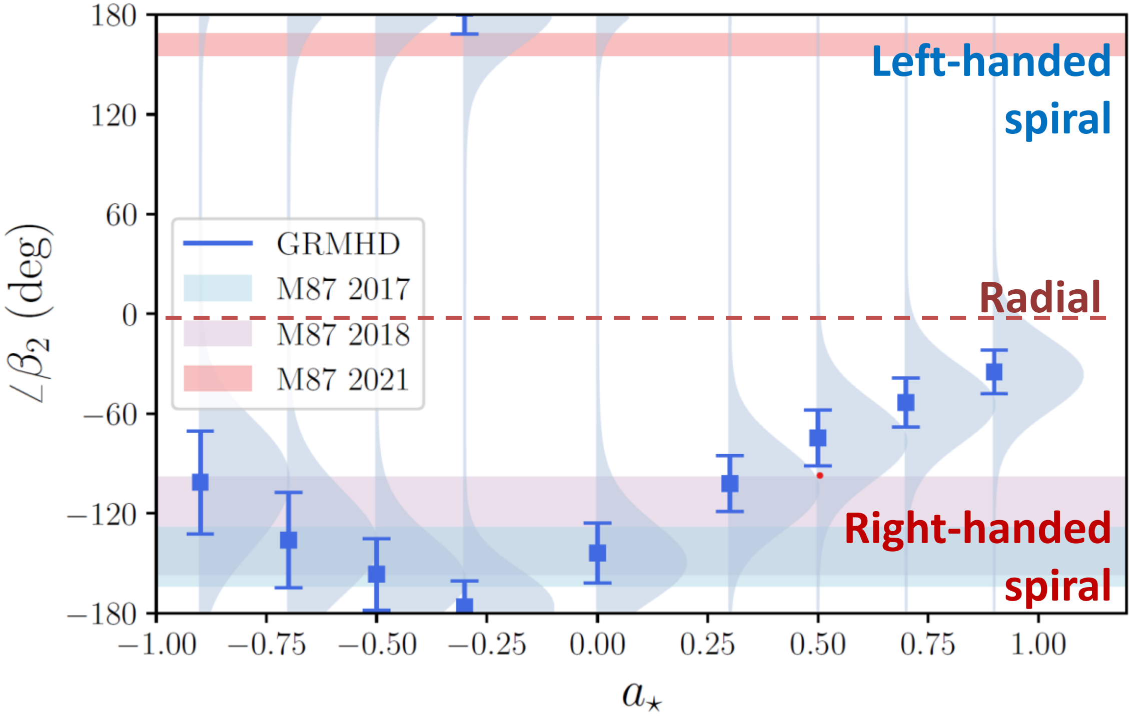
EHTC+ 2024 VII, VIII (Angelo Ricarte, paper coordinator)

Polarized images of Sgr A* are **spin dependent**

Sgr A*



M87*

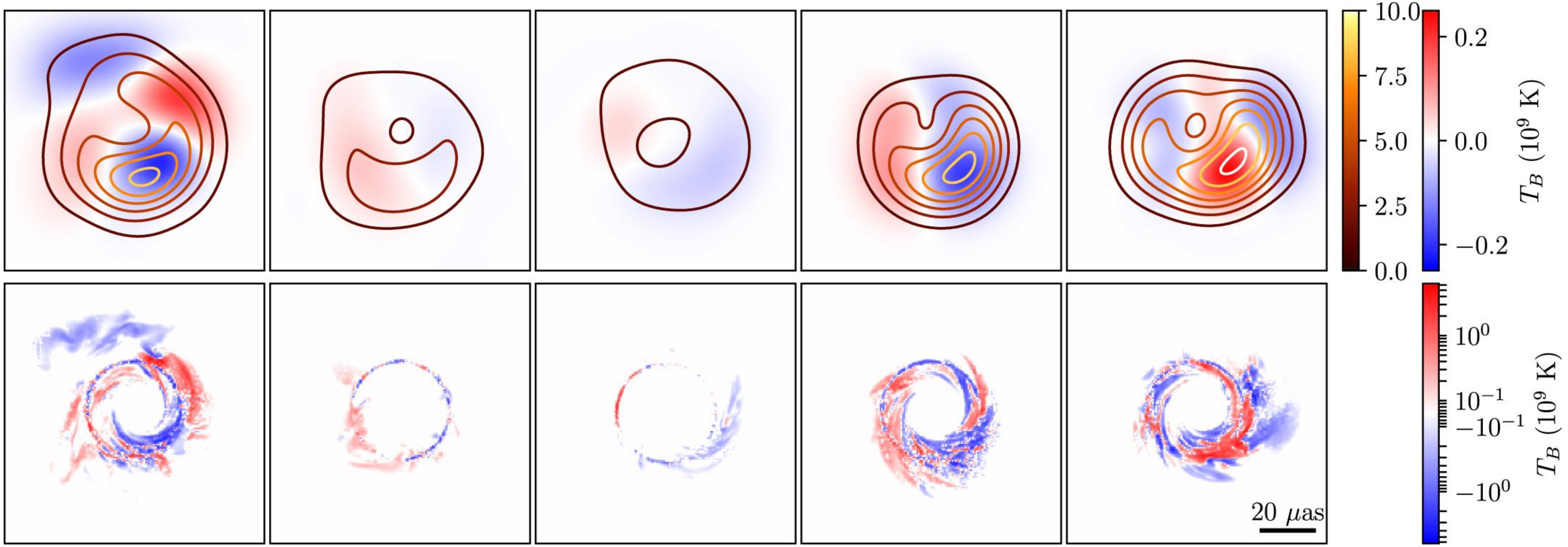


- Sgr A* polarization is consistent with energy outflow **if** the BH rotates clockwise
  - NIR flares (GRAVITY+ 2018) and ALMA mm lightcurves (Wielgus+ 2022) all rotate **clockwise**
- Sgr A* spin is not well constrained by EVPA pattern alone
  - combined EHT+MW constraints prefer high spin (EHTC+ VIII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

Polarimetric spin measurements are possible and will get better!

Chael+ 2023b; **Chael** 2025; Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

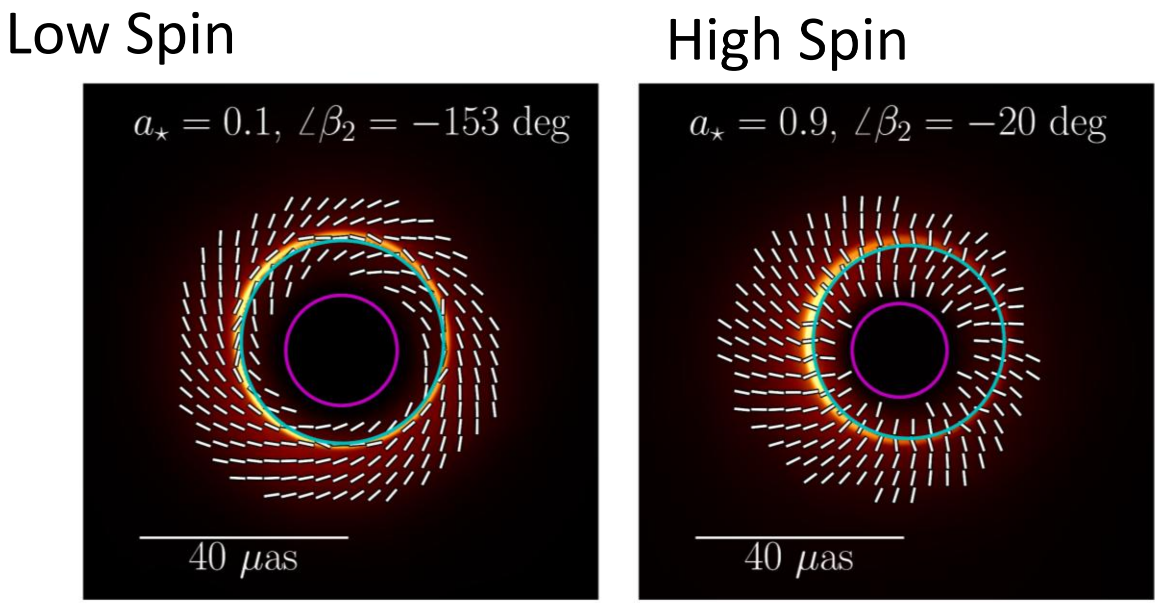
Passing simulations have diverse circular polarization images

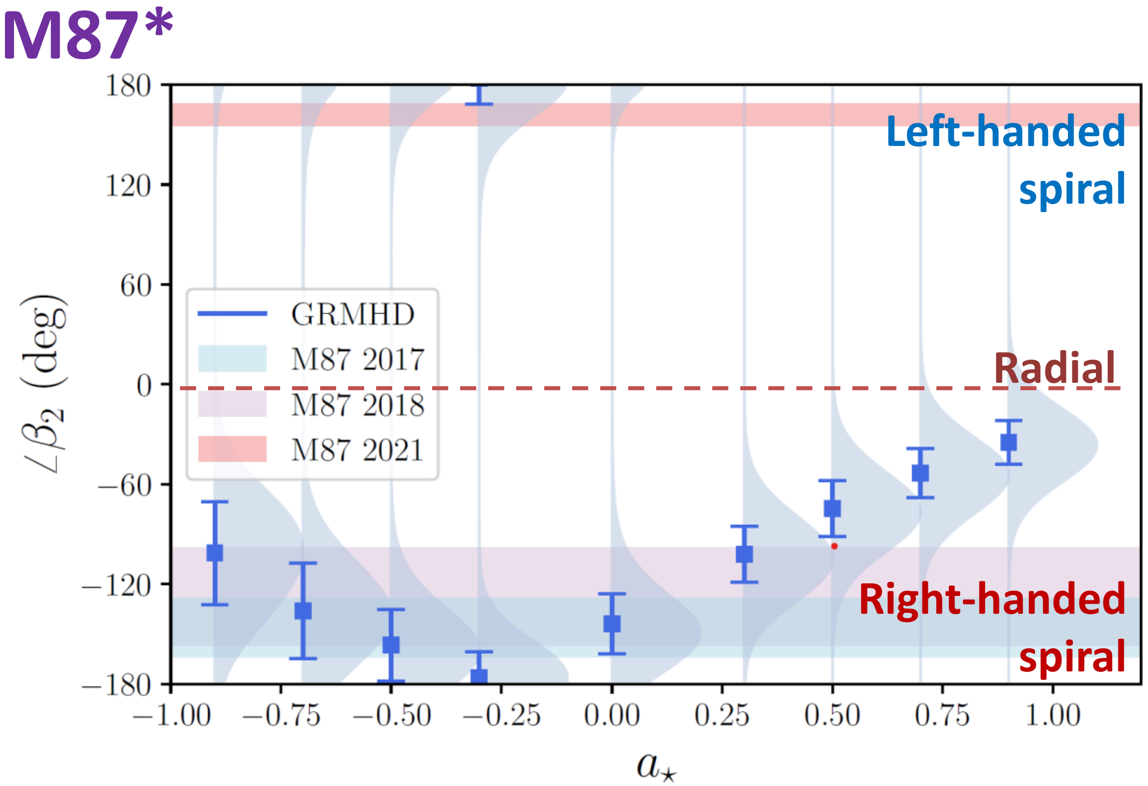


Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)
Ricarte+ 2021

M87*'s polarization over time

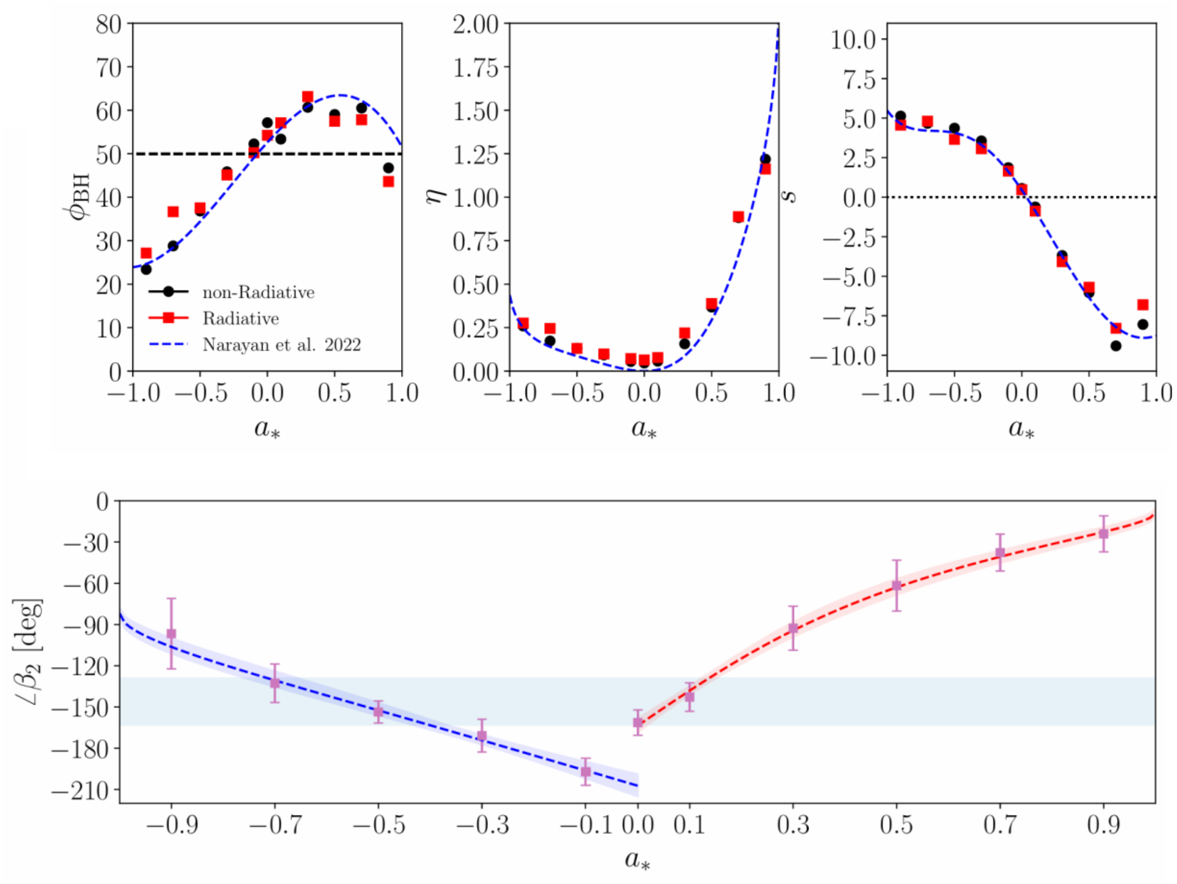




- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
  - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)
- **The shift in arg(β_2) in 2021 is mysterious**
  - Change in Faraday rotation?
  - Emission from retrograde accretion disk at larger radii?

Chael+ 2023b; **Chael** 2025; Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

Jets and Polarization in Radiative GRMHD



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

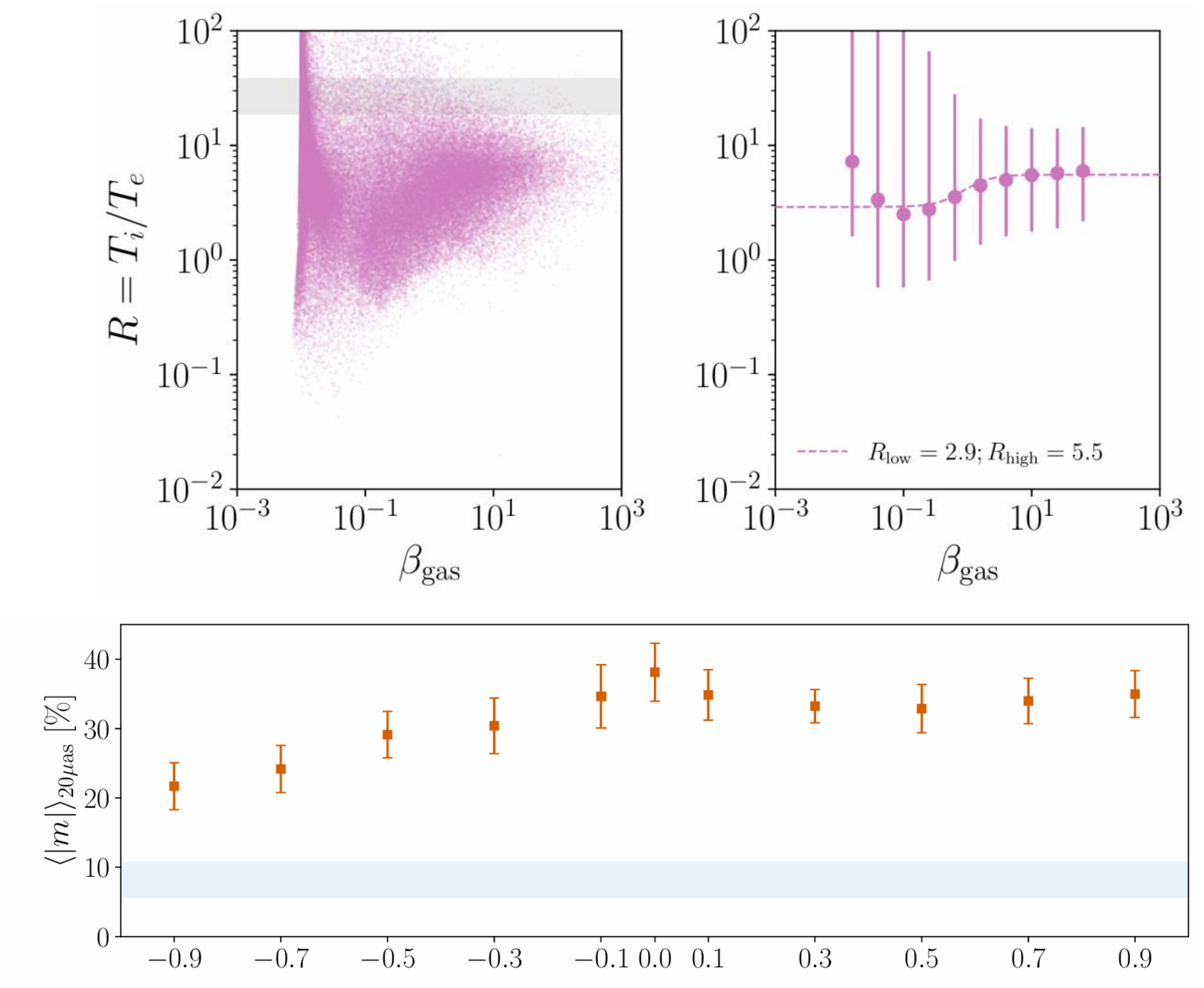
$$T_{\rm e} \neq T_{\rm i}$$

- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** (e.g. Ressler+2015,17, Chael+ 2018,19)

- M87* has a radiative efficiency of ~10% (EHTC+ 2021, Chael+ 2025), but radiative feedback does not significantly change global jet/disk properties or arg(β_2)

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

…but electrons are too hot!



- EHT analysis fixes $T_{\rm e}$ locally in **postprocessing** and seems to prefer **cold electrons** (T_i ~ 100x T_e) to sufficiently depolarize the image
- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** but prefer more modest temperature ratios (Chael 2025)
- Is there a plasma heating prescription that will produce cold electrons? Or is this a hint that we need to modify our global picture?

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