What have we learned from black hole images?

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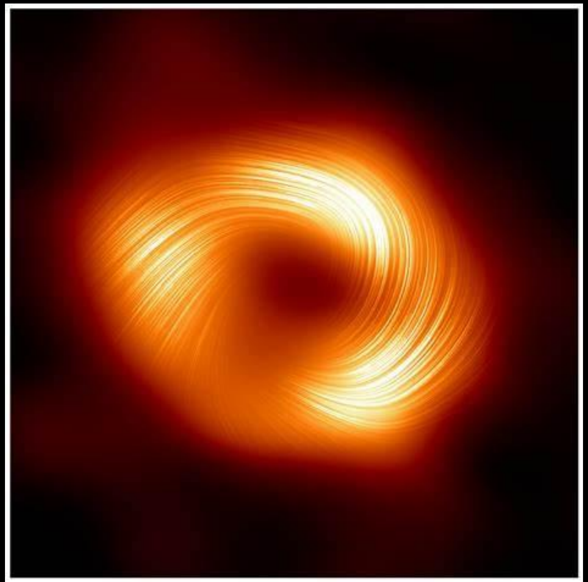
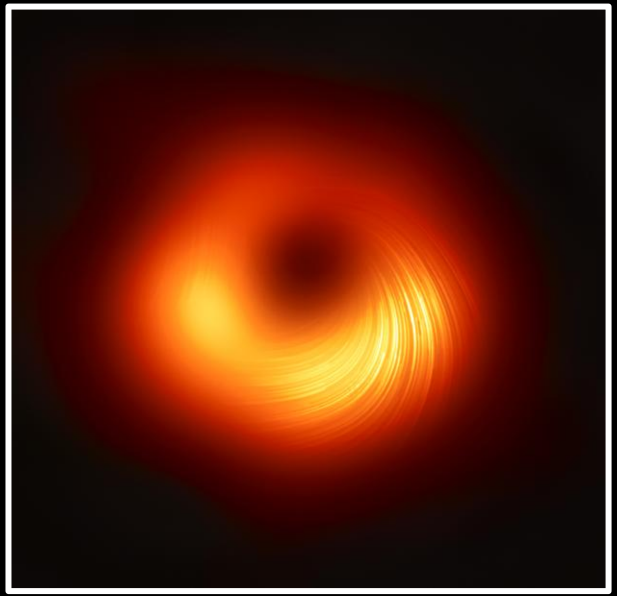
NBIA, University of Copenhagen

July 3, 2026





KØBENHAVNS UNIVERSITET

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BHEX

Event Horizon Telescope

M87 & M87*

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

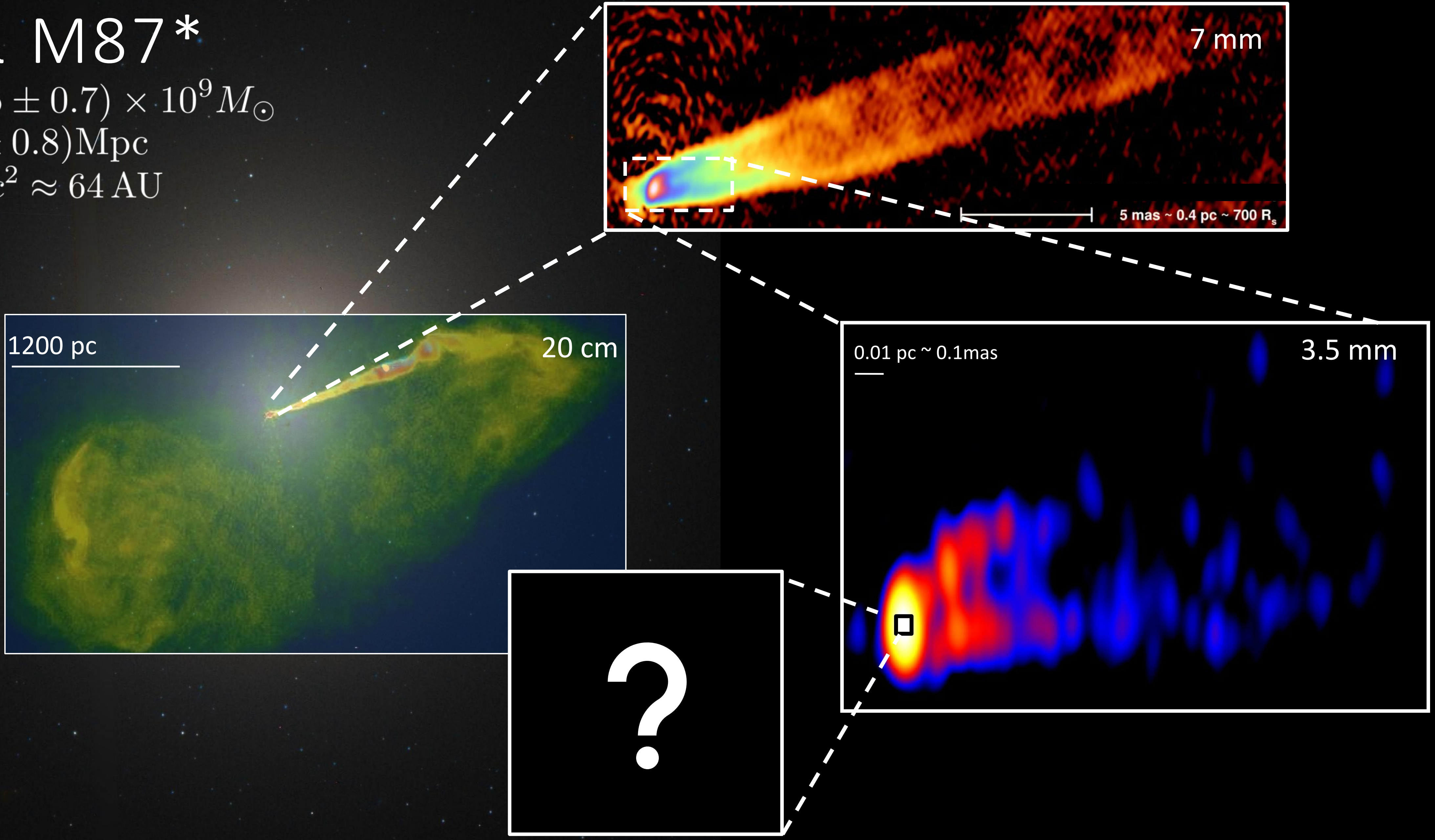
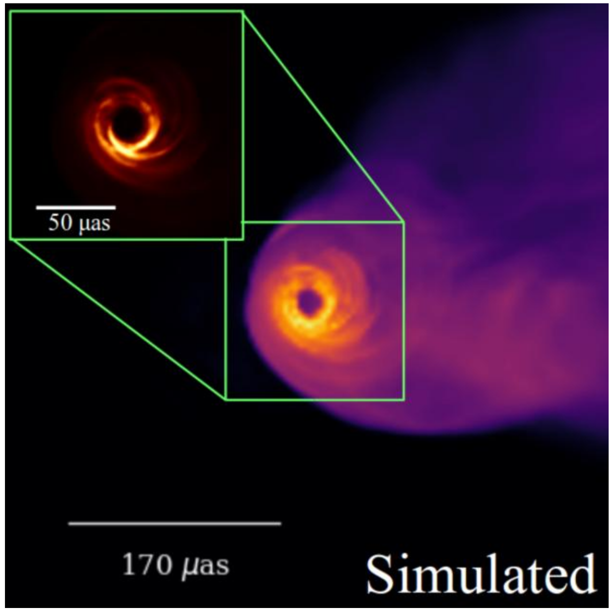


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

Persistent Mysteries of Astrophysical Jets

- We have known about jets for >100 years
- We know jets are produced by supermassive BHs and deliver energy and momentum to galactic/extragalactic scales
- We know jets contain very energetic particles and magnetic fields, and likely produce TeV-PeV neutrinos and UHECRs
- But we still do not fully understand:
  - How do strong gravity and magnetic fields work together to launch jets?
  - How are jets shaped and collimated by the near horizon environment?
  - How and where are particles accelerated close to the black hole?



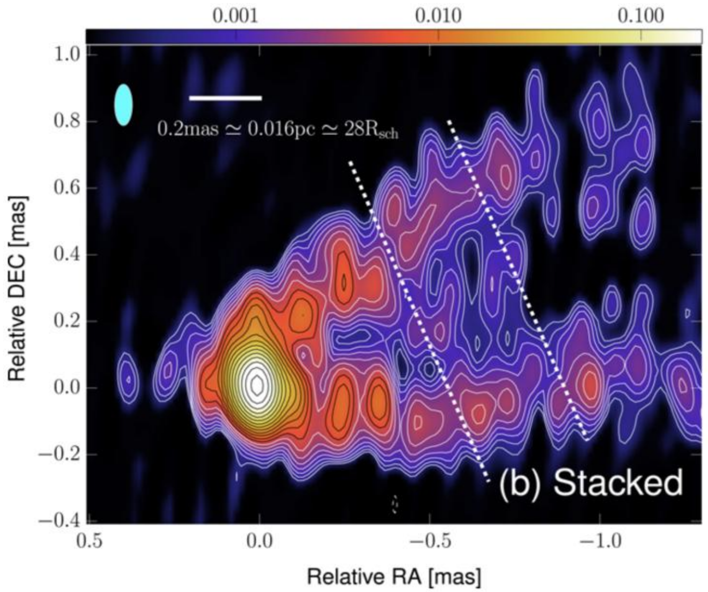
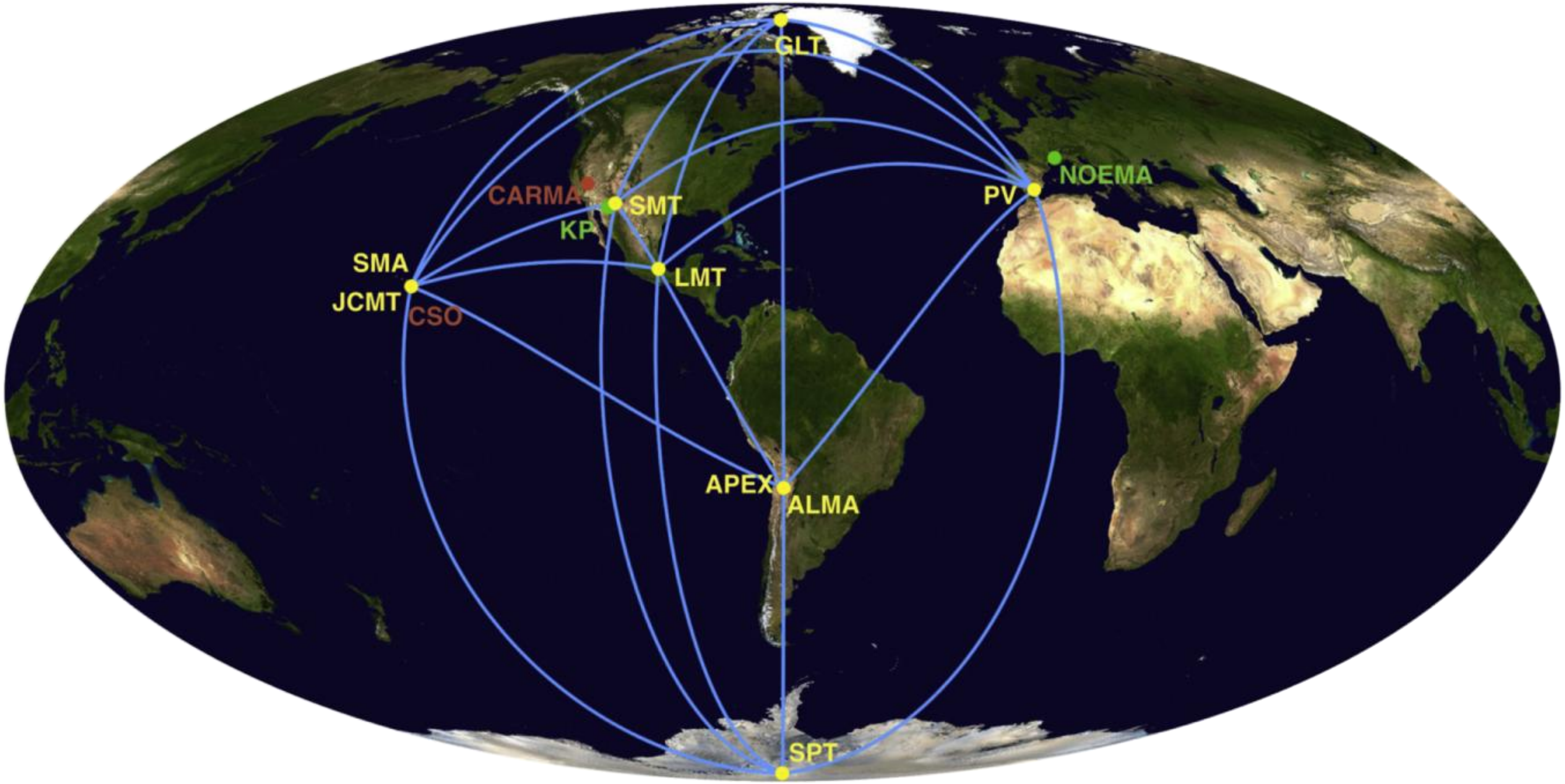


Image Credit: Blackburn+ 2019, Kim+ 2018

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

The Event Horizon Telescope Collaboration

M87 & M87*

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

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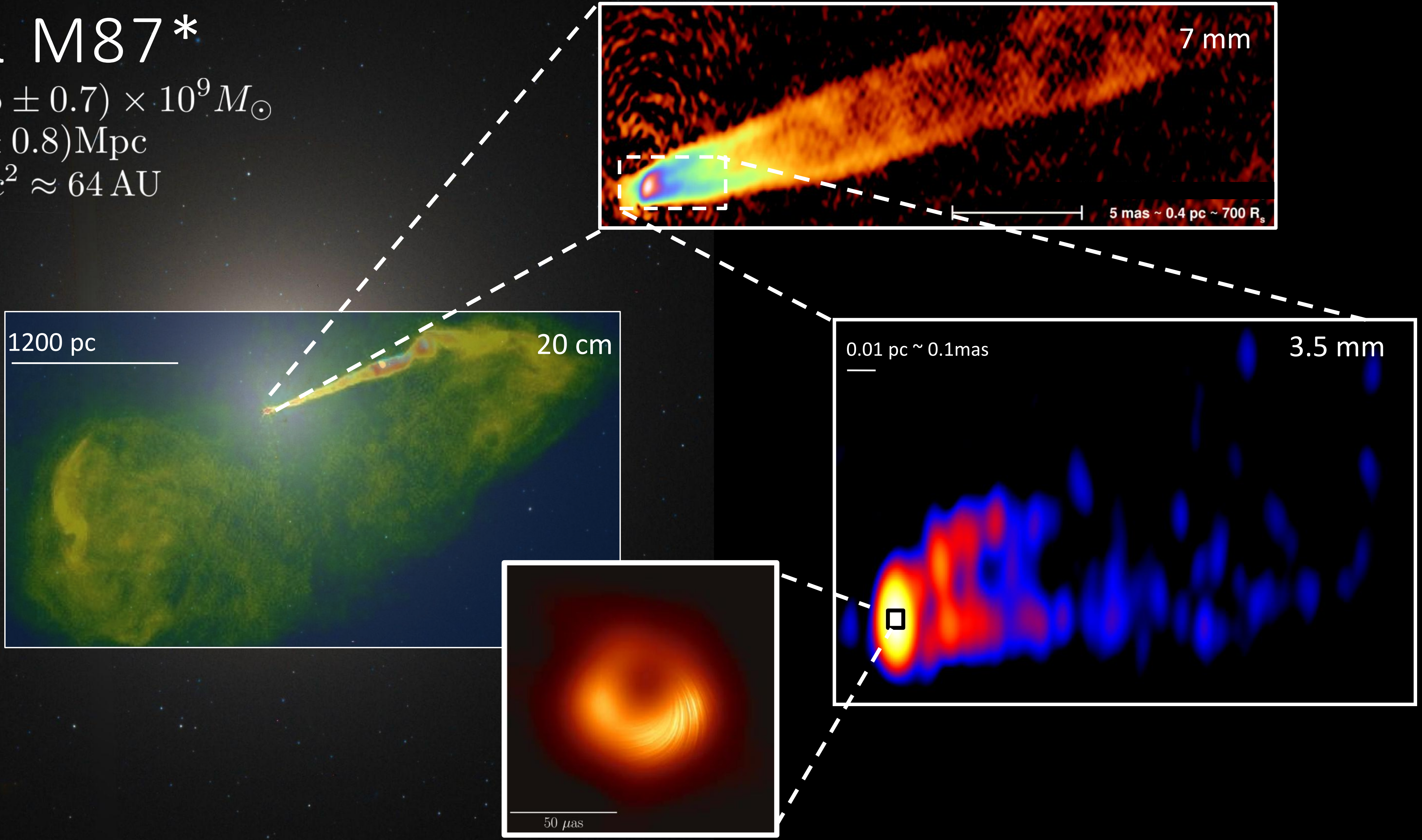
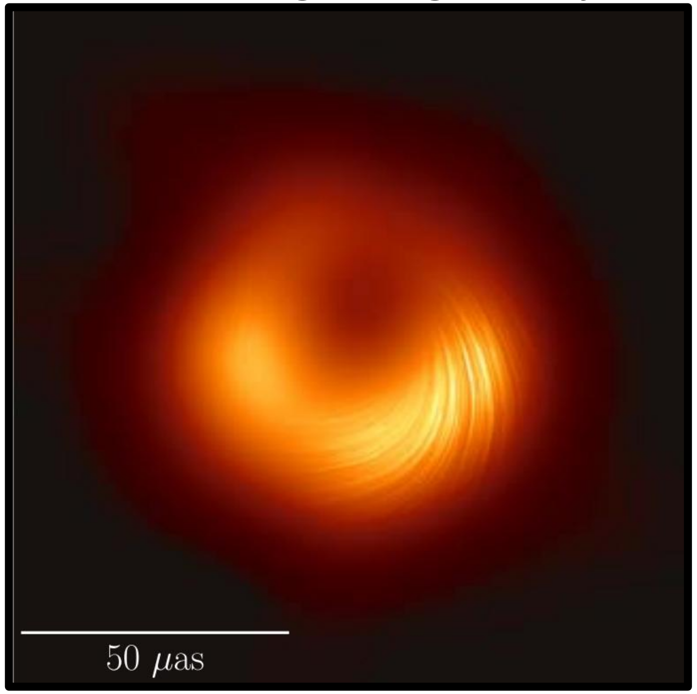


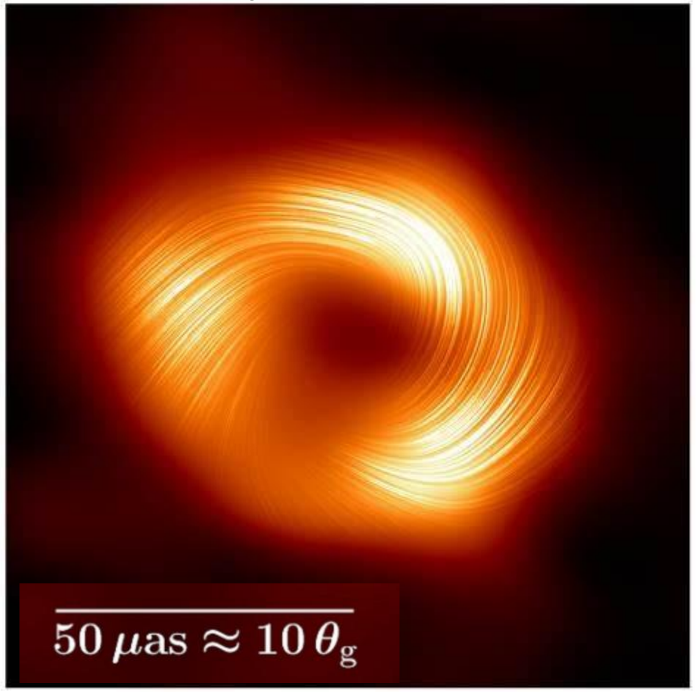
Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

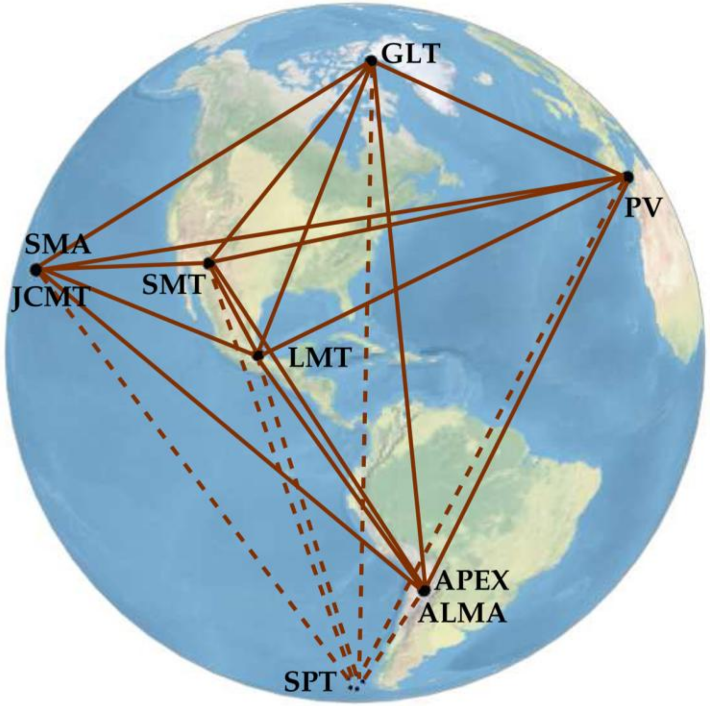
The first black hole images

M87* (EHTC 2019, 2021, 2024, 2025)
~$6.5 \times 10^9\ M_\odot$
Launches a strong extragalactic jet



Sgr A* (EHTC 2022, 2024)
~$4 \times 10^6\ M_\odot$
No obvious jet

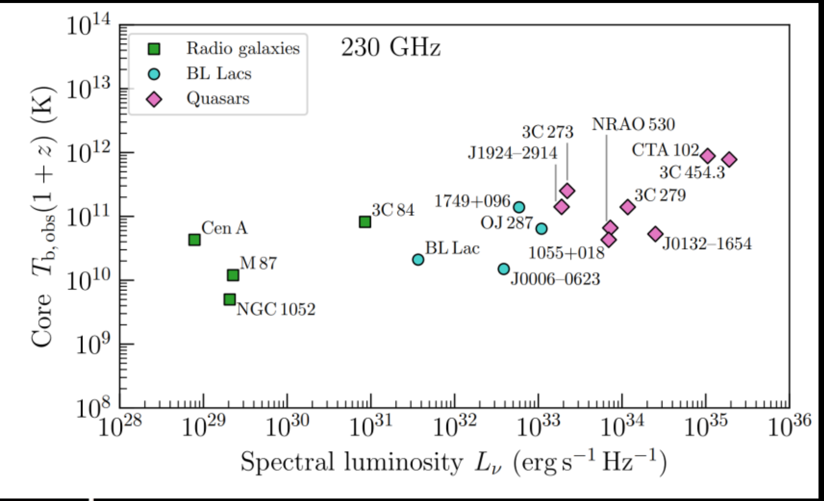




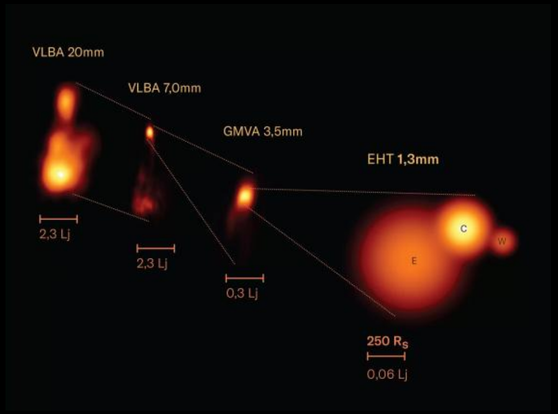
Over three orders of magnitude in BH mass:

- 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

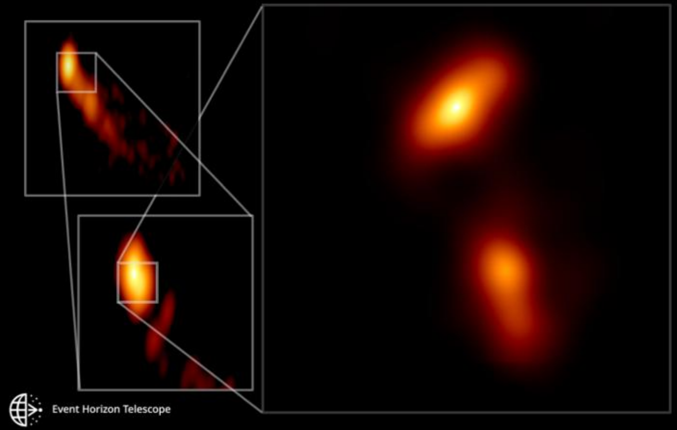
The EHT Sky



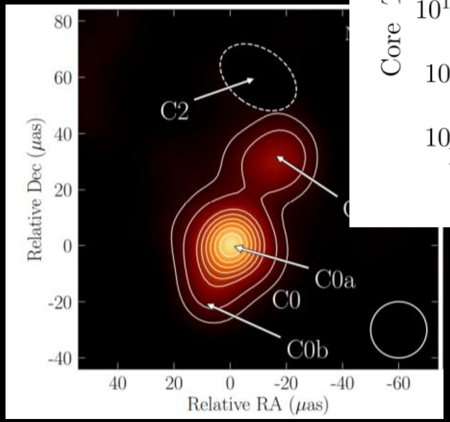
EHT Source Catalog: Röder+ 2025



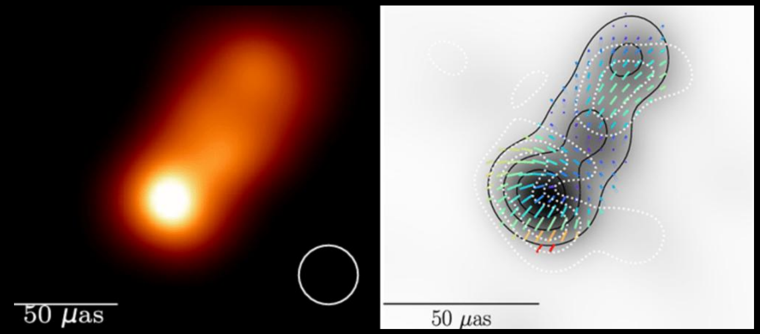
3C 84: Paraschos+ 2024



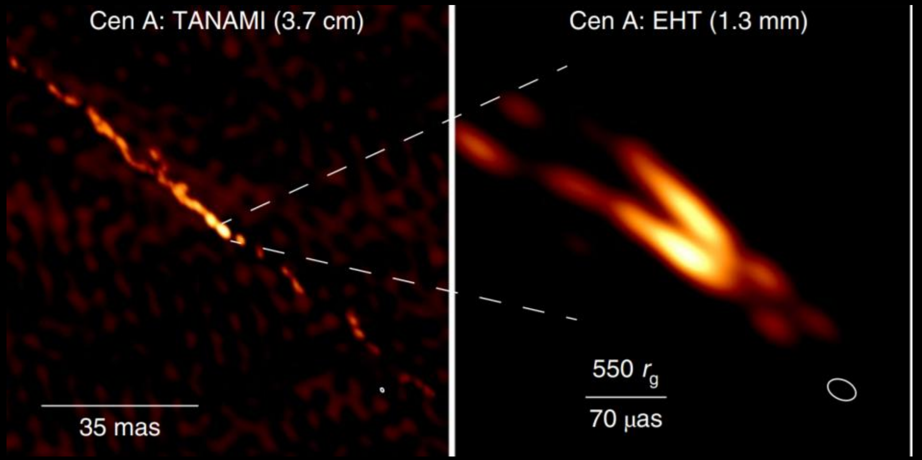
3C279: Kim+ 2020



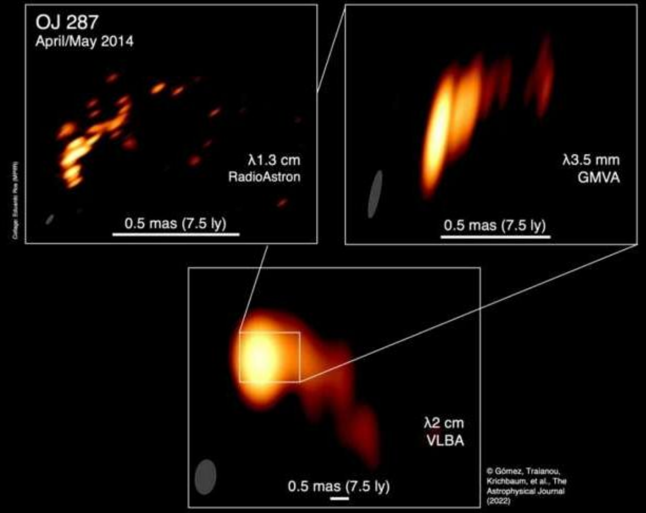
NRAO 530: Jorstad+ 2023



J1924-2914: Issaoun+ 2022



Centaurus A: Janssen+ 2020

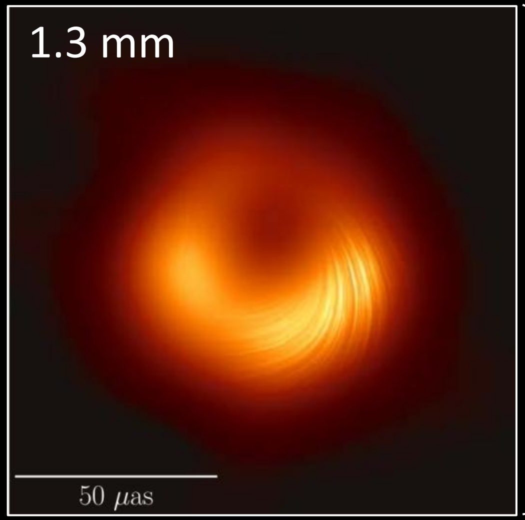


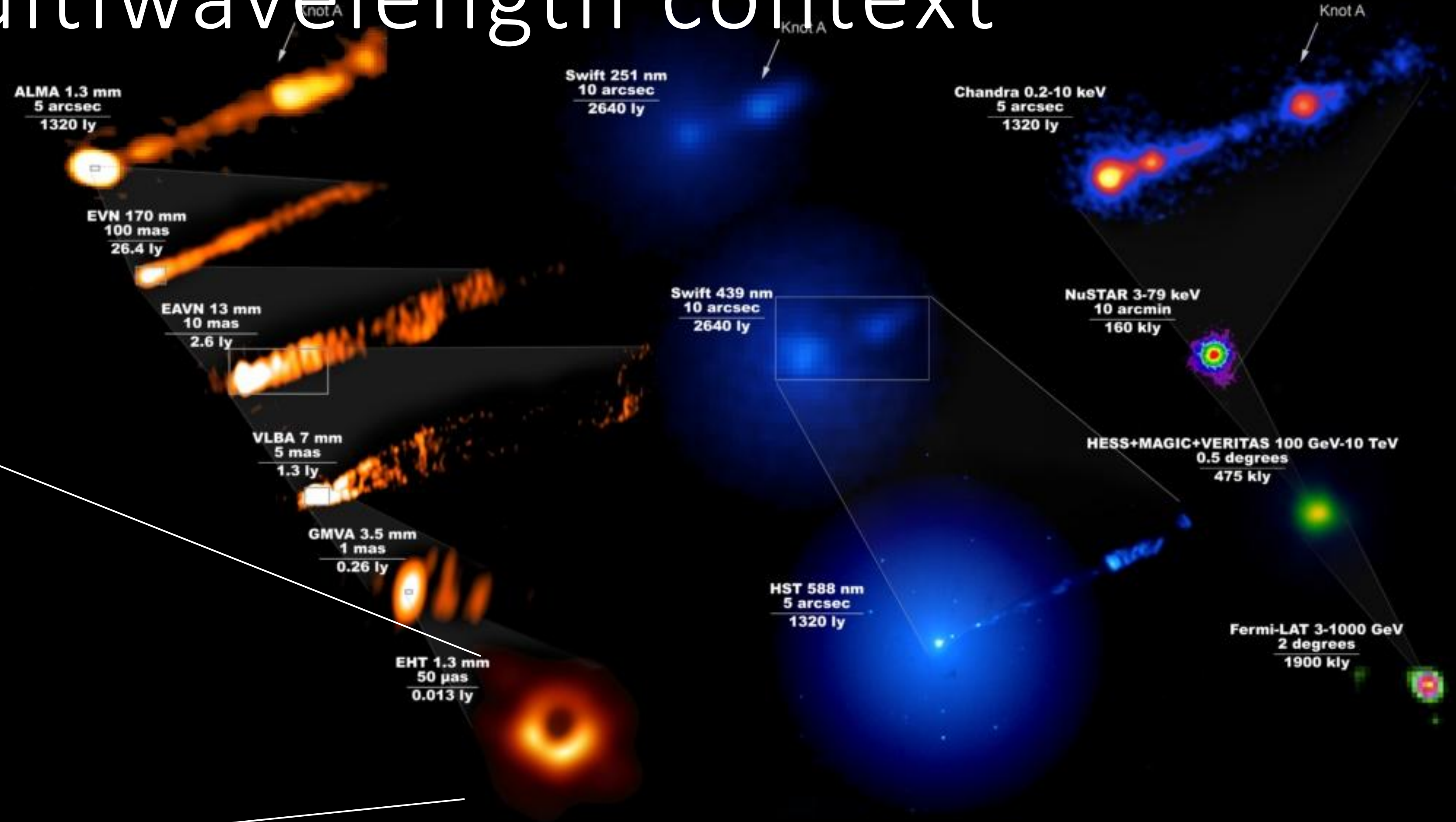
OJ 287: Traianou+ 2022

M87* in its multiwavelength context

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

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





See Sera’s talk next!

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

This talk:

1. How do we interpret black hole images?

2. What does polarization tell us about BH magnetic fields?

3. Physics from polarized BH images: jet launching, spin, particle acceleration

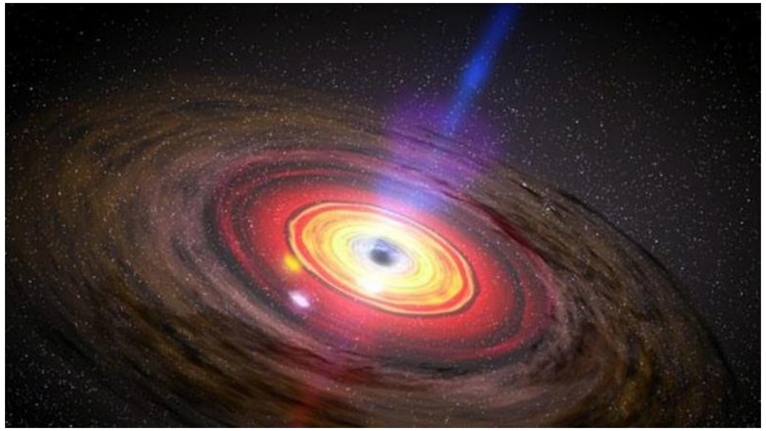
4. What’s next?

How do we compare black hole images to simulations?

EHTC V, VI 2019;
EHTC V, VI; 2022
EHTC+ 2025, 2026

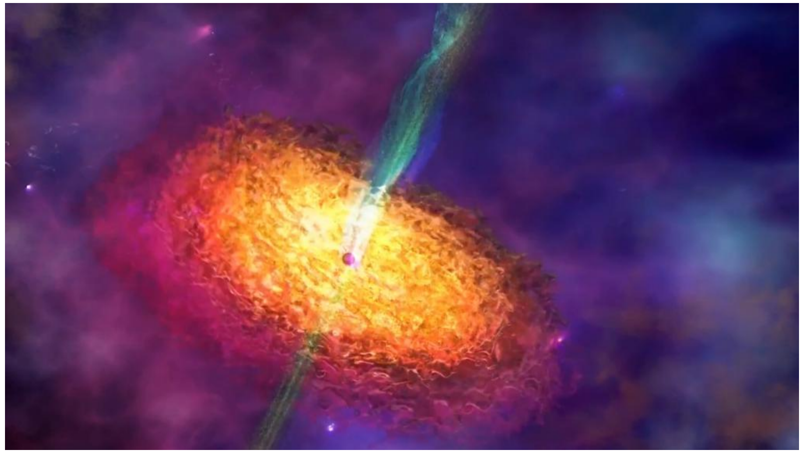
Modes of Black Hole Accretion

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



- $\dot{M}/\dot{M}_{\mathrm{Edd}} \sim 10^{-2} - 10^{-1}$
- Thin Disks
- Optically Thick & Bright
- Cool: $T \sim 10^{5}\mathrm{K}$
- Blackbody emission (+ corona, other complications)

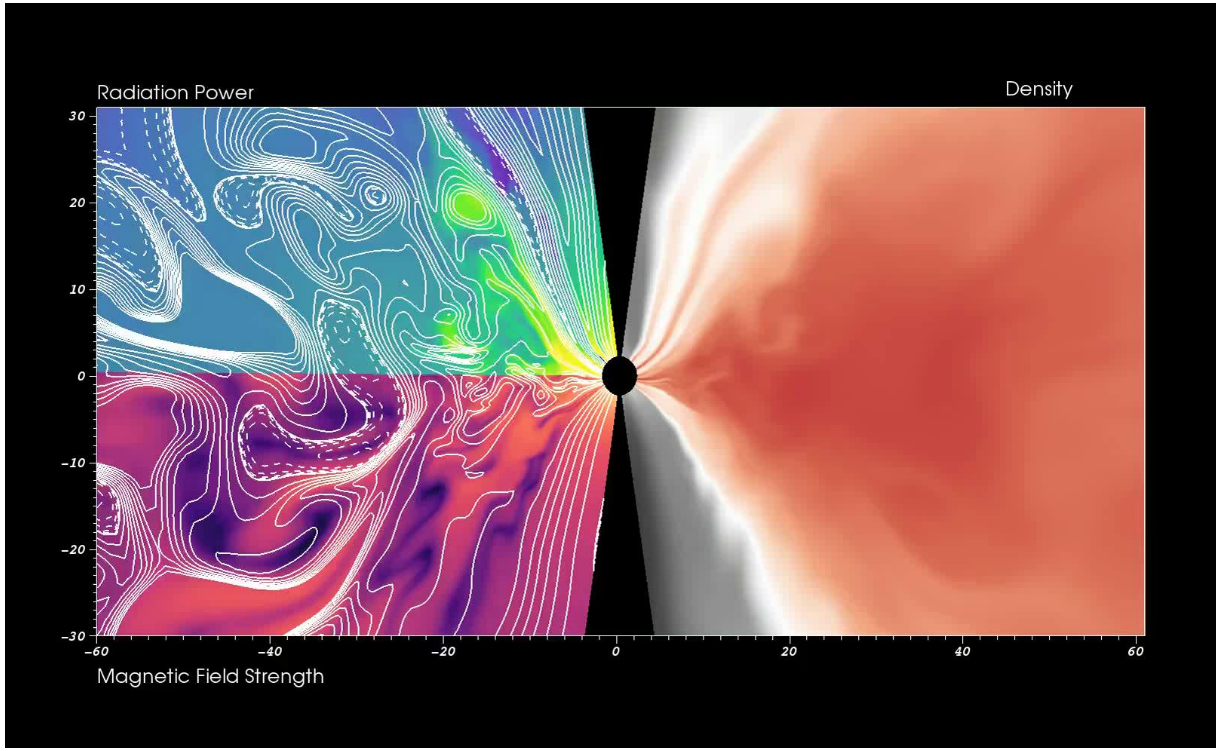
Low-Luminosity AGN (LLAGN):
Most Liberated Energy is **Advected**



- $\dot{M}/\dot{M}_{\mathrm{Edd}} \sim 10^{-7} - 10^{-5}$
- Thick Disks
- Optically Thin & Dim
- Hot: $T \gtrsim 10^{10}\mathrm{K}$
- Plasma is *collisionless* and not in equilibrium

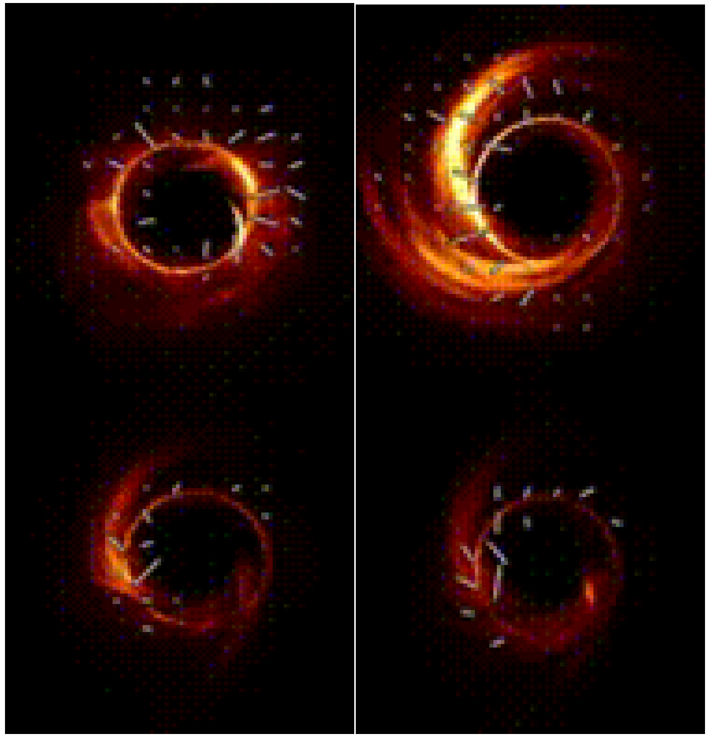
Image credits: NASA/NSF

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

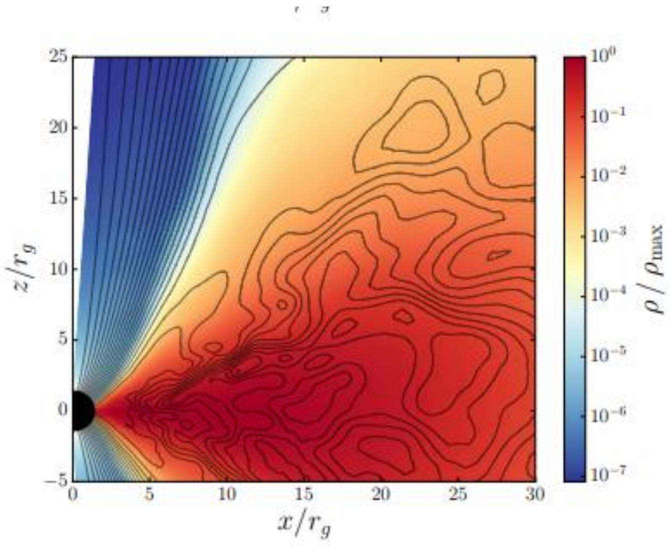
Track light rays and solves for the observed (polarized) radiation

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

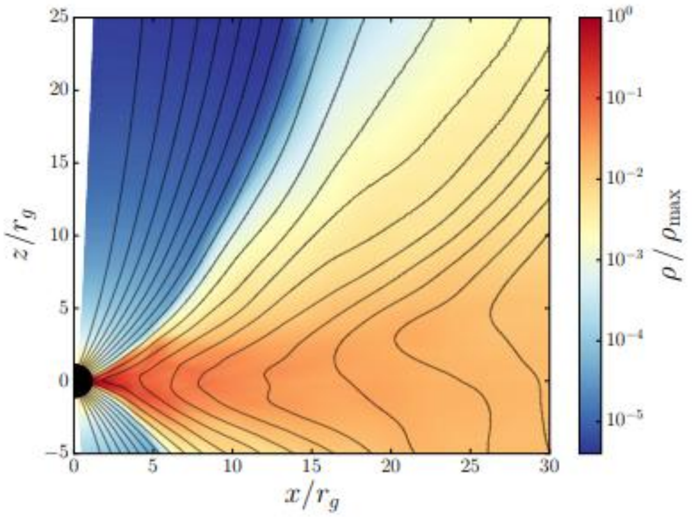
What is the magnetic field structure close to the horizon?

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

Magnetic fields are weak and turbulent



"SANE"



"MAD" - Magnetically Arrested Disk

Strong, coherent magnetic fields build up on the horizon

MADs launch more powerful Blandford-Znajek jets:

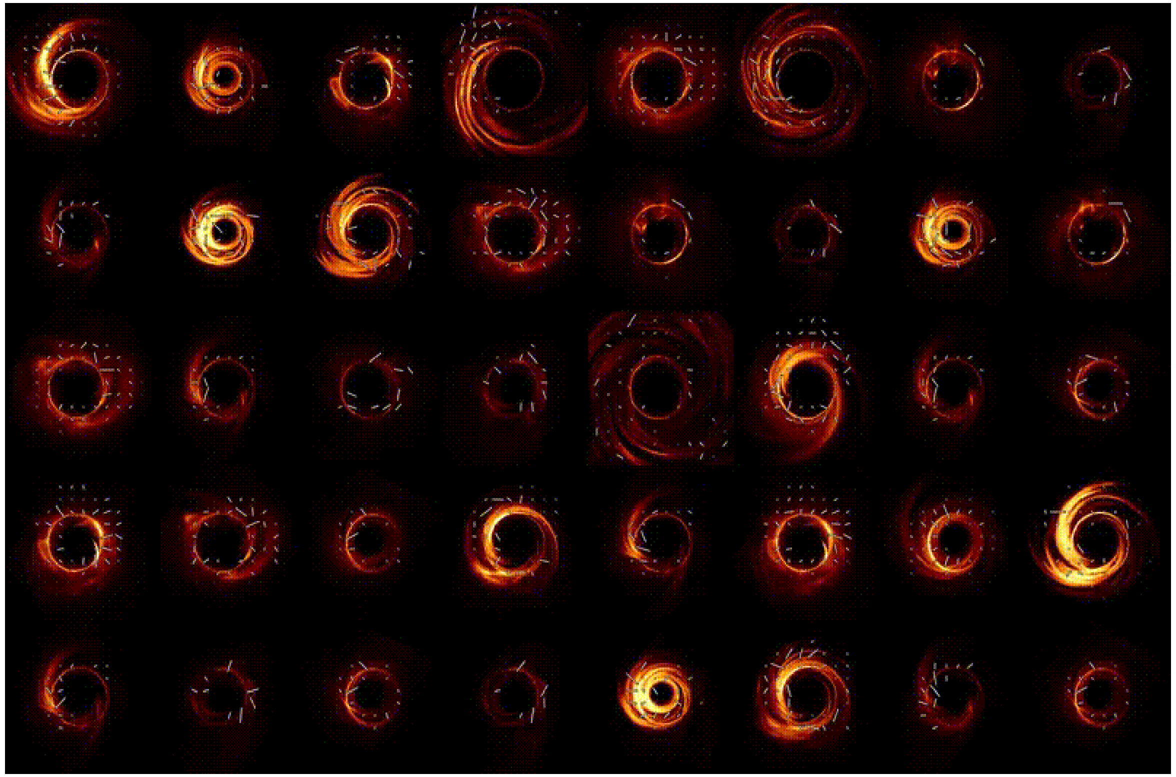
$$P_{\rm jet} \propto \Phi_B^2 a^2$$

BH spin

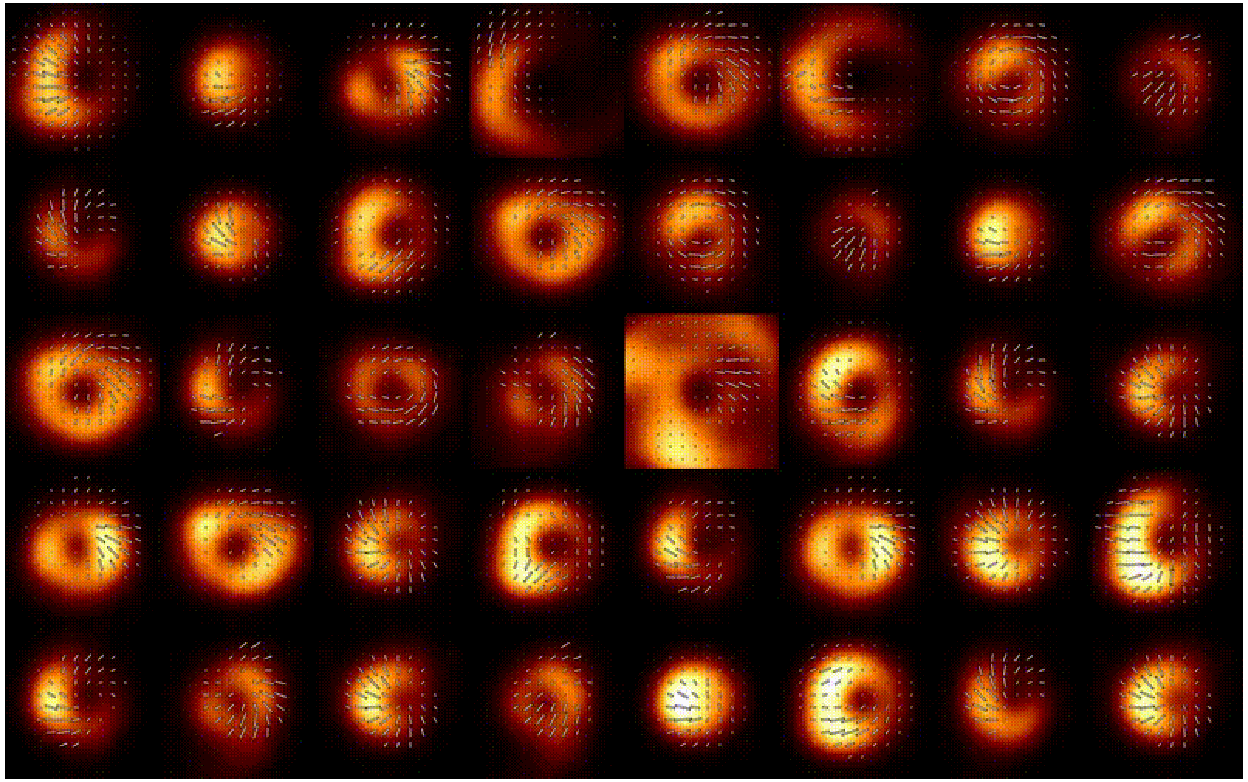
magnetic flux

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

EHT GRMHD Simulation library



native resolution



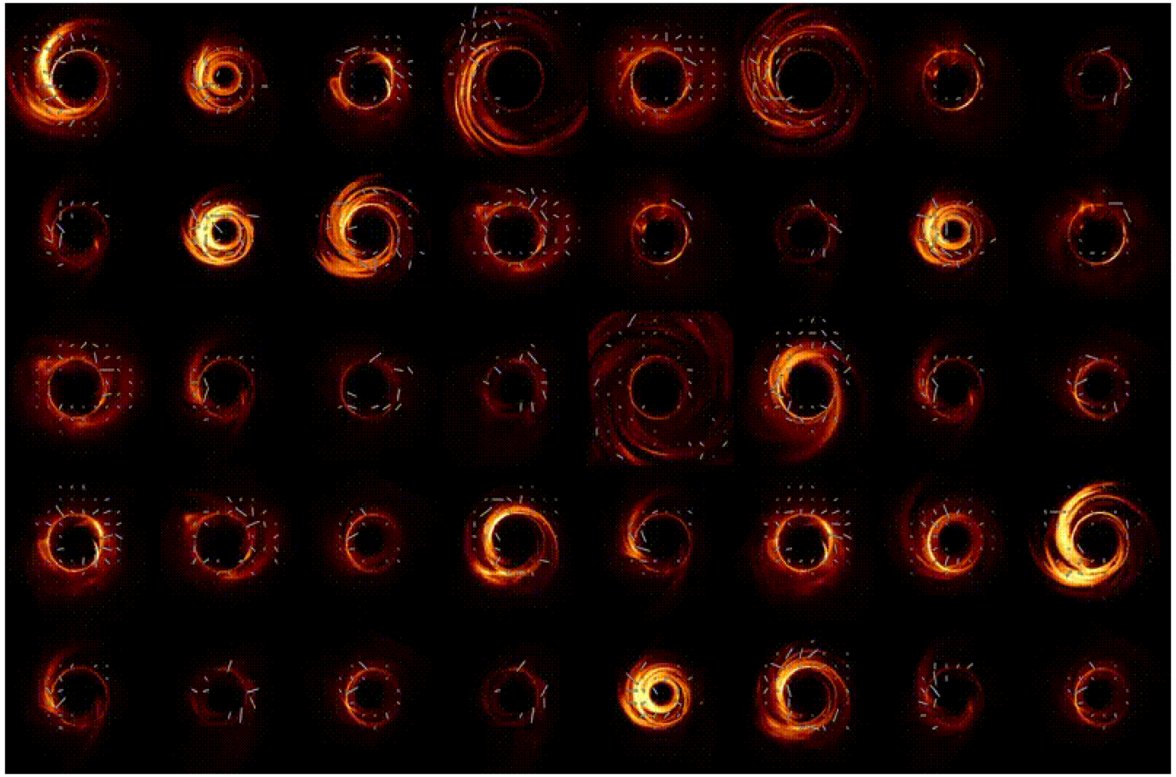
EHT resolution

Simulation survey over black hole spin and magnetic field state

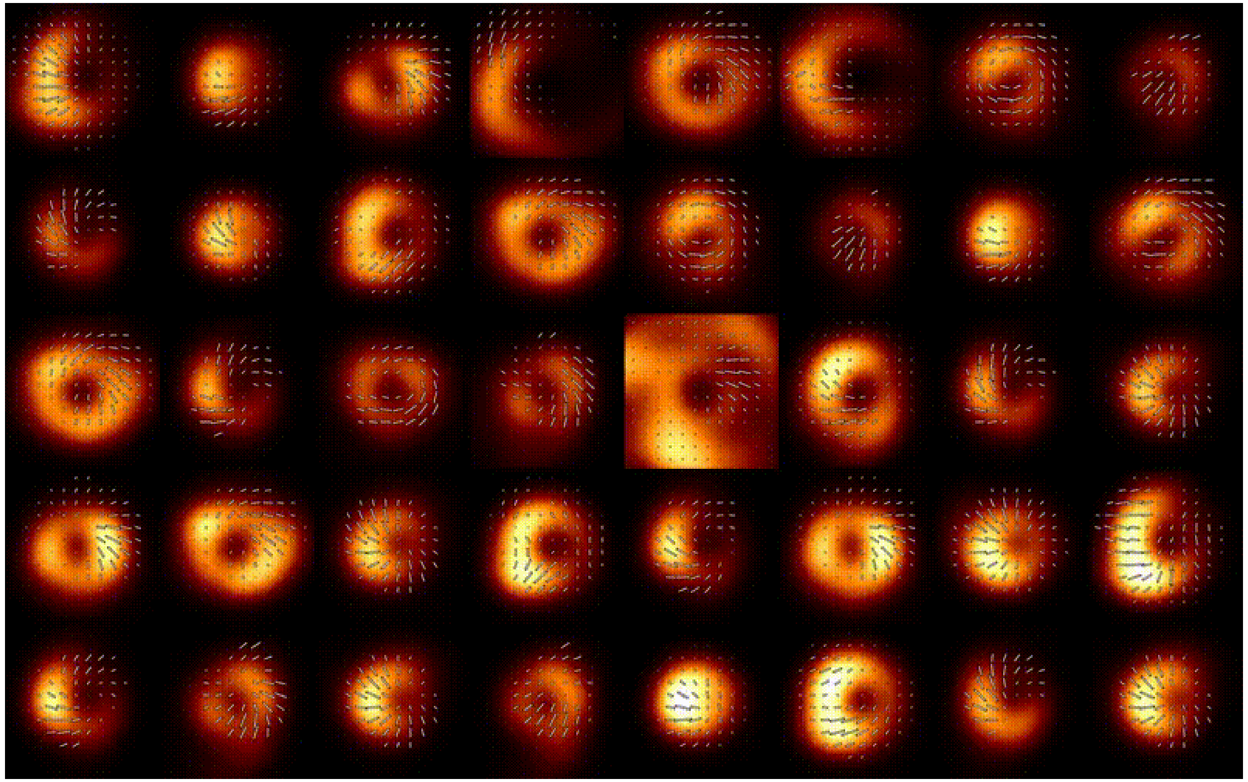
Electron Temperature must be set in post-processing: $T_{\rm e} \neq T_{\rm i}$

Animation credit: Cora Prather

EHT GRMHD Simulation library



native resolution



EHT resolution

R-β model from Moscibrodzka et al. 2016

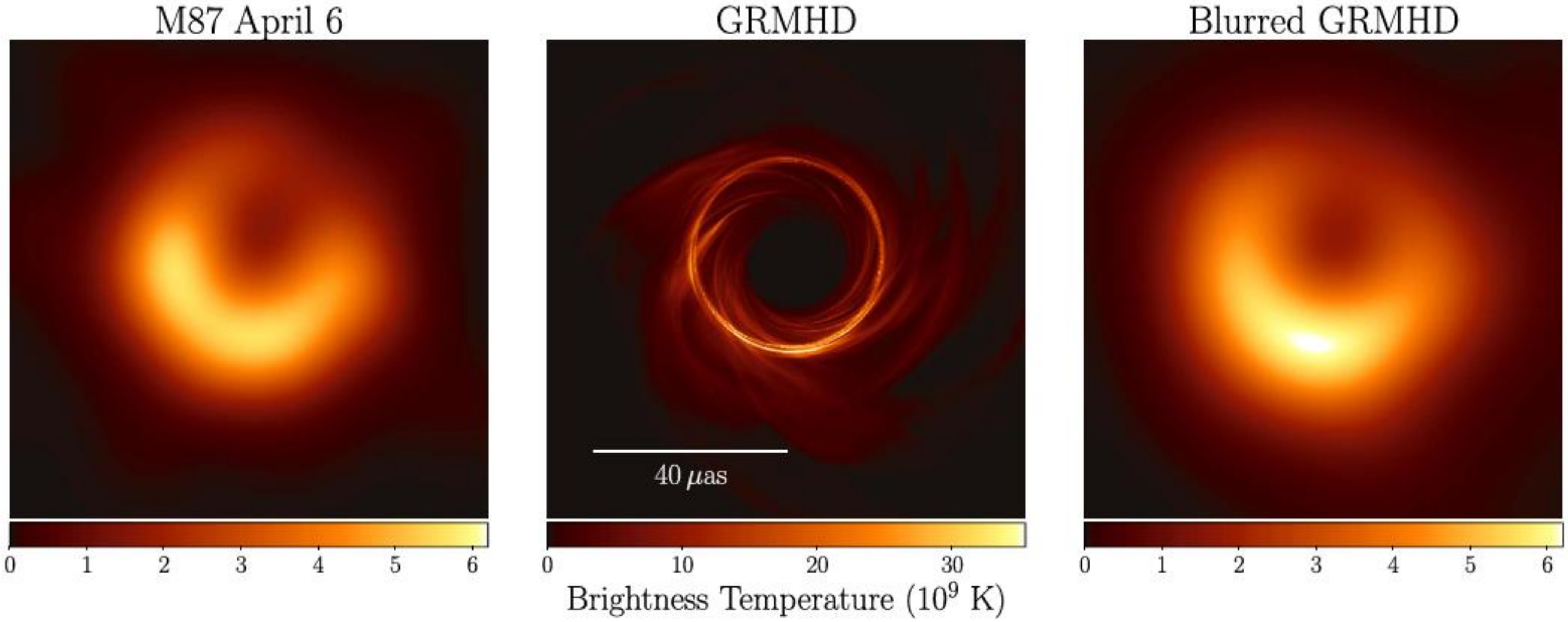
Motivated by gyrokinetic calculations of plasma heating
(e.g. Howes+ 2010, Kawazura+ 2020)

$$R = \frac{T_i}{T_e} = R_{\rm high}\,\frac{\beta^2}{1+\beta^2} + R_{\rm low}\,\frac{1}{1+\beta^2}$$

$$\beta = p_{\rm gas}/p_{\rm mag}$$

Animation credit: Cora Prather

EHT Images are consistent with GRMHD Simulations



EHTC V, 2019

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*

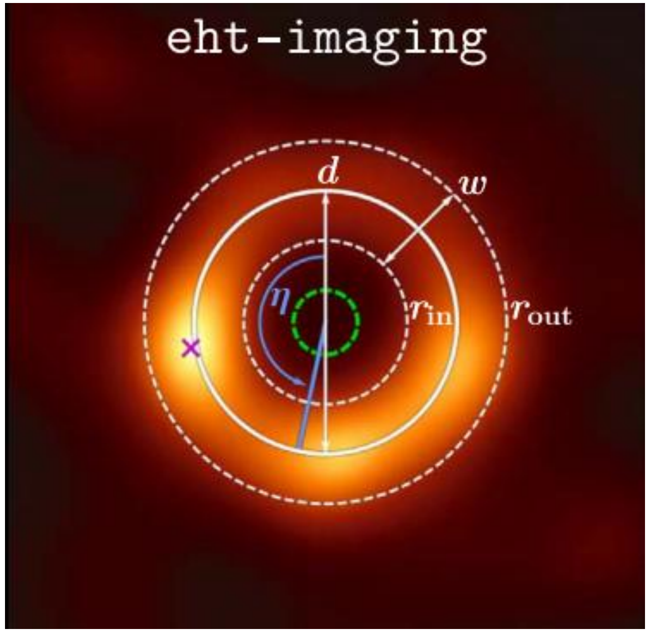
- For **M87* (2017+2018):**
  - Diameter, asymmetry, and PA are best measured

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

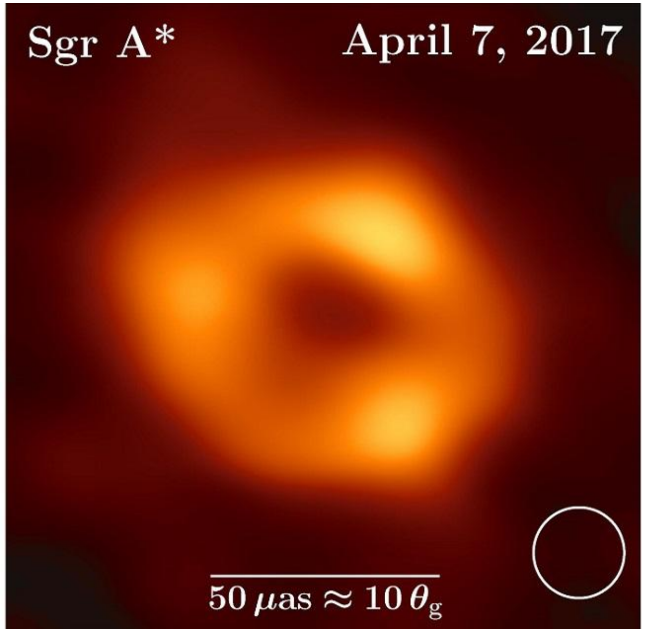
- For **Sgr A* (2018):**
  - Diameter and width are best measured

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

M87*



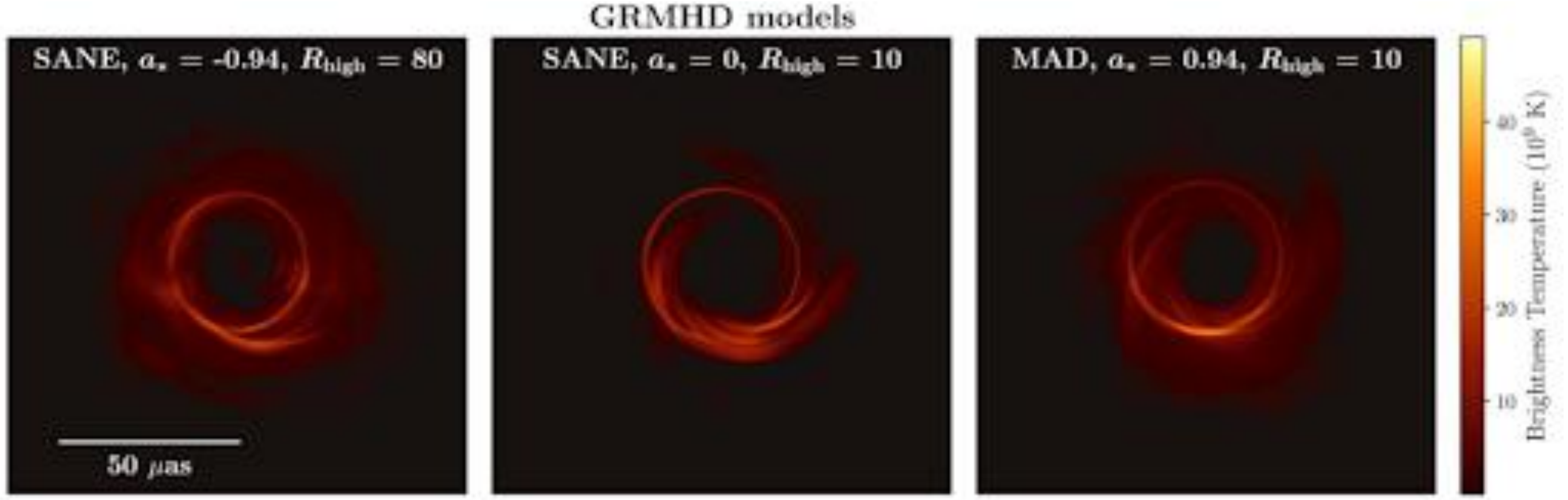
Sgr A*



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

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** (≥ 10^{42} erg/sec) rejects all spin 0 models

EHTC V, 2019

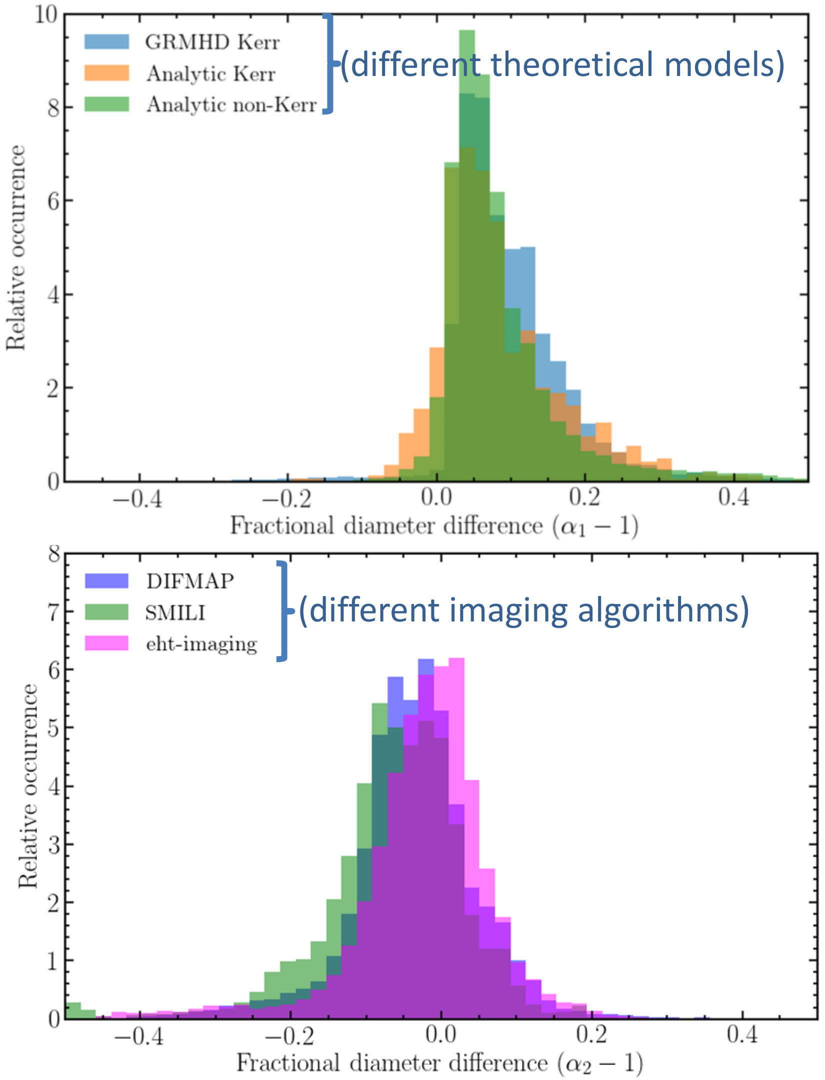
Weighing a Black Hole Image

- The black hole mass is proportional to the ring diameter with an **empirically-derived calibration coefficient** α ≠ 1:

$$\theta_g = \frac{d}{\alpha\, 6\sqrt{3}}$$

- We decompose α into an **observational part** and a **theory part** (EHTC+ 2022 VI):
  - **α_1:** bias between peak emission and theoretical shadow diameter in simulations
  - **α_2:** bias between true image diameter and that recovered by EHT in synthetic data tests

Sgr A* α-calibration pipelines:



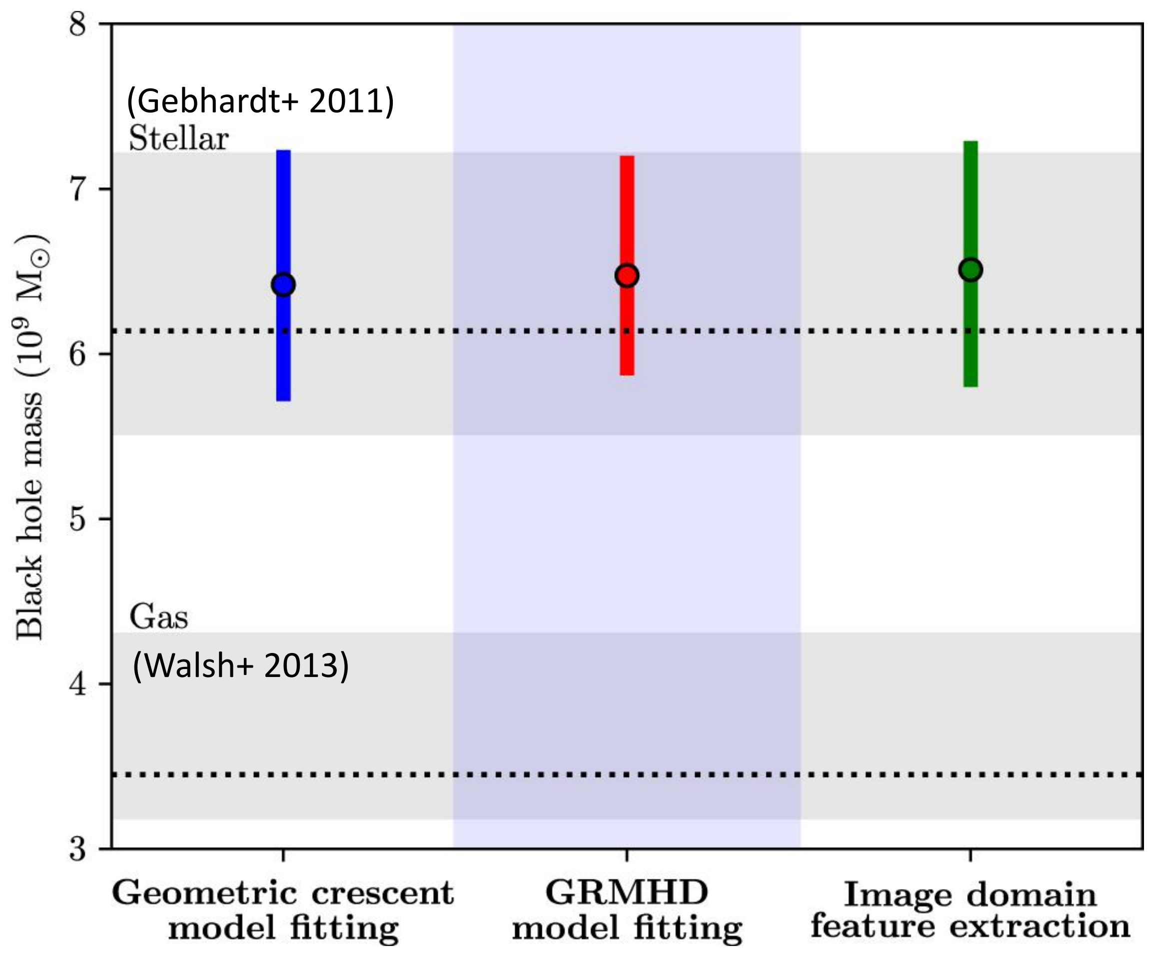
EHTC+ 2022 IV,VI

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

Mass Results from three methods

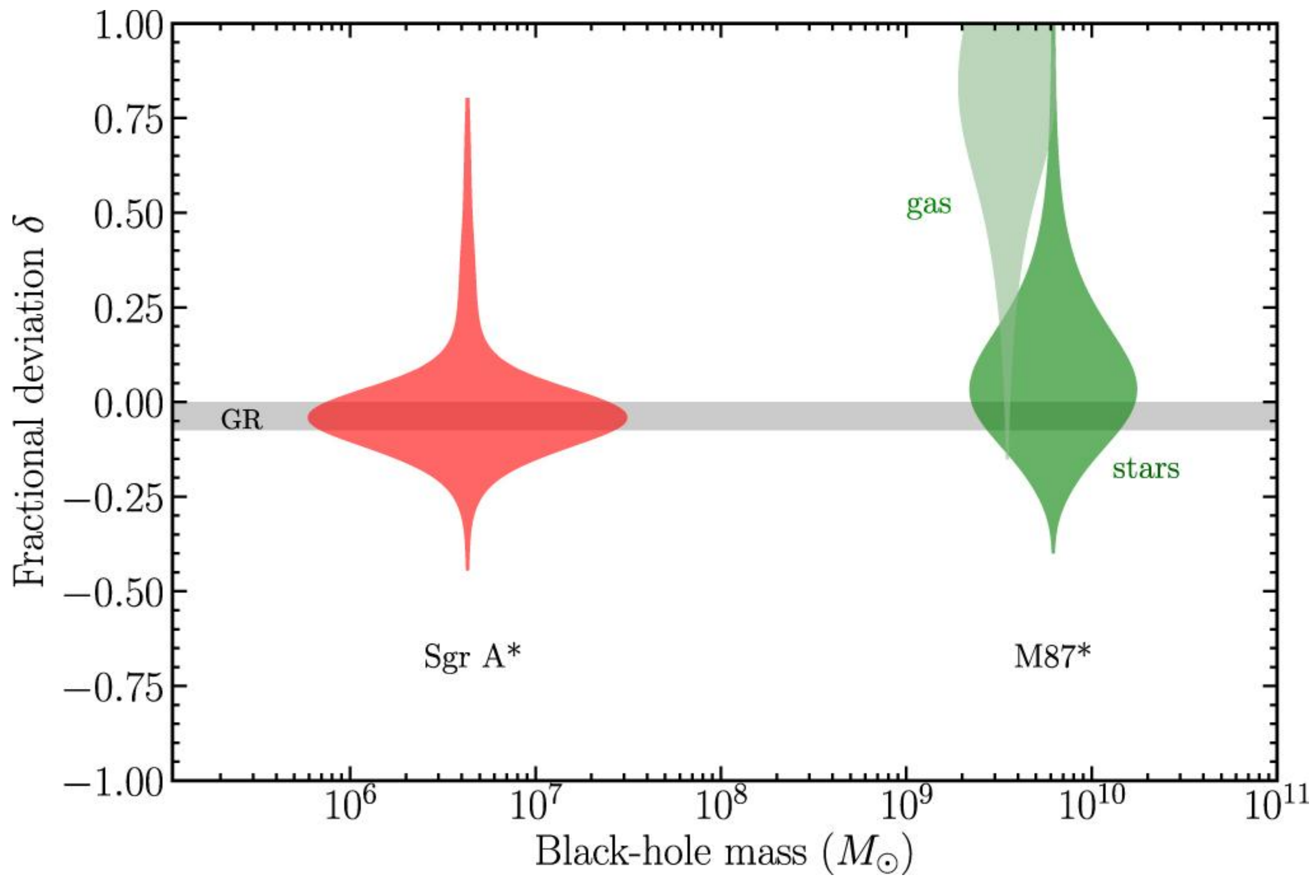


$$M = (6.2 \pm 0.7) \times 10^9 M_\odot$$

EHT Collaboration 2019 (Paper VI), EHTC+ 2025

Weighing a black hole

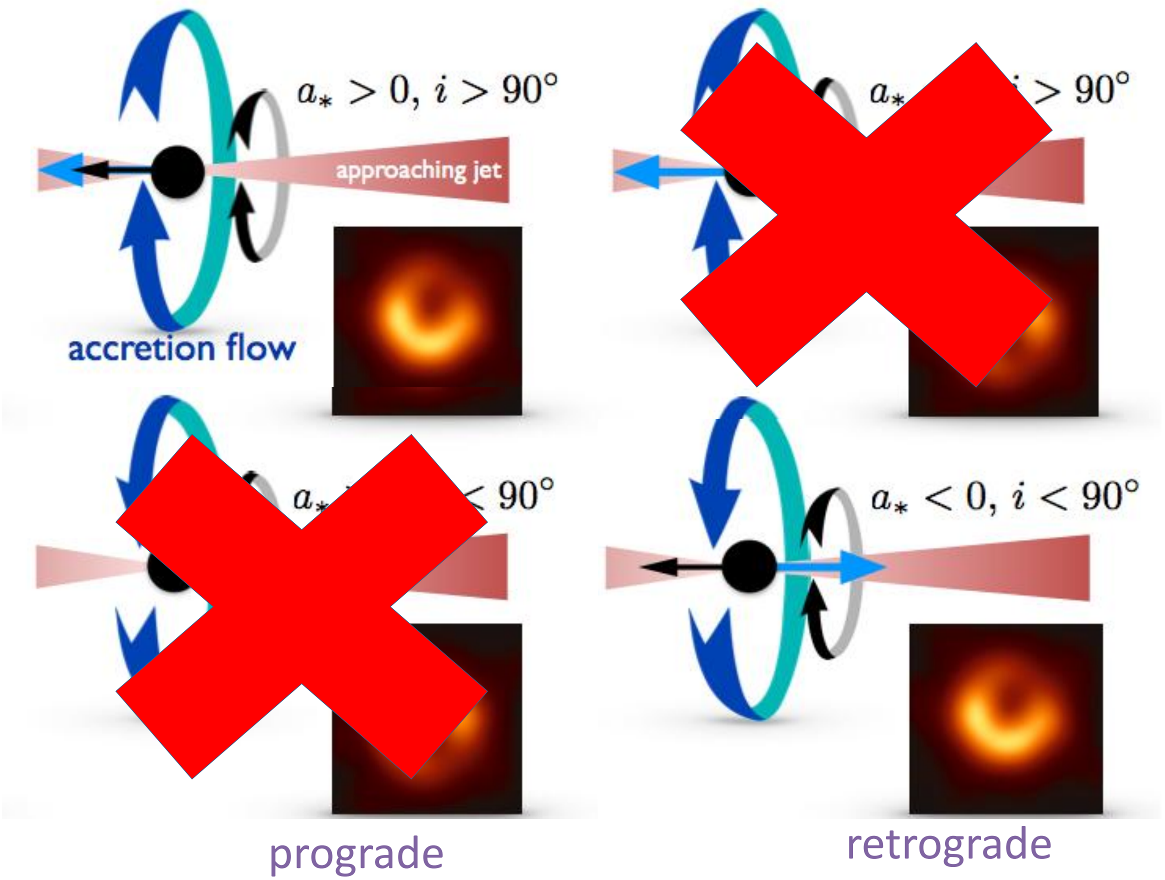
- Connecting EHT image ring diameter to predicted shadow size from GR requires **astrophysical** calibration
- M87* image size is consistent with previous measurements from stellar dynamics but not competing measurements from gas dynamics
- After astrophysical calibration (and assuming a stellar mass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

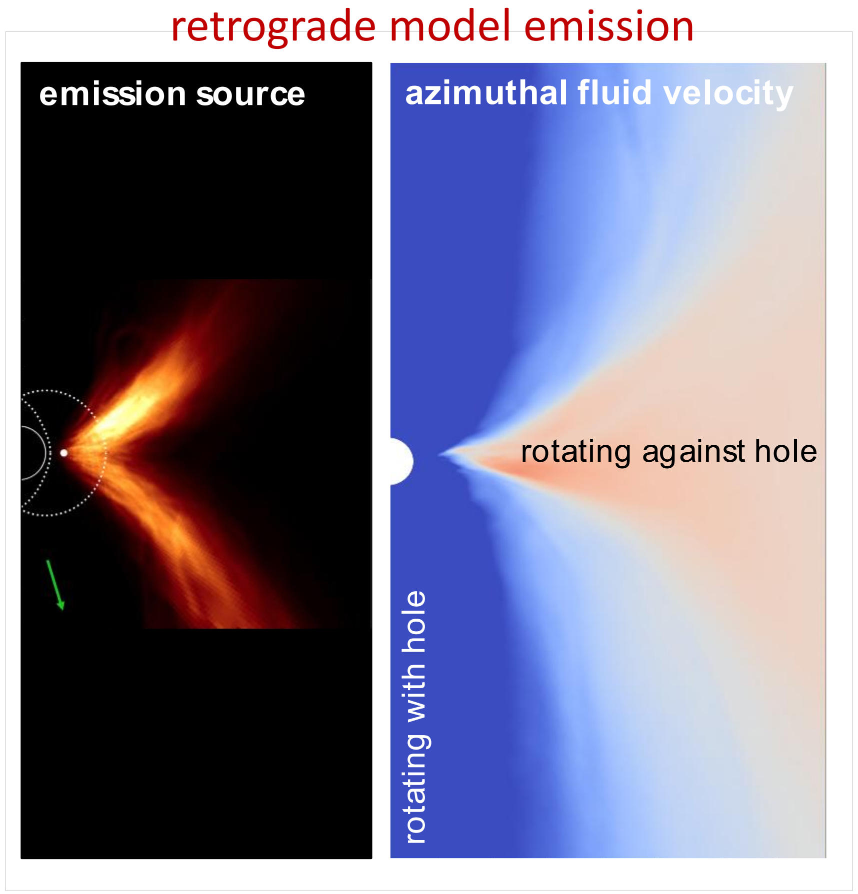


EHT Collaboration 2022 (Paper I)

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

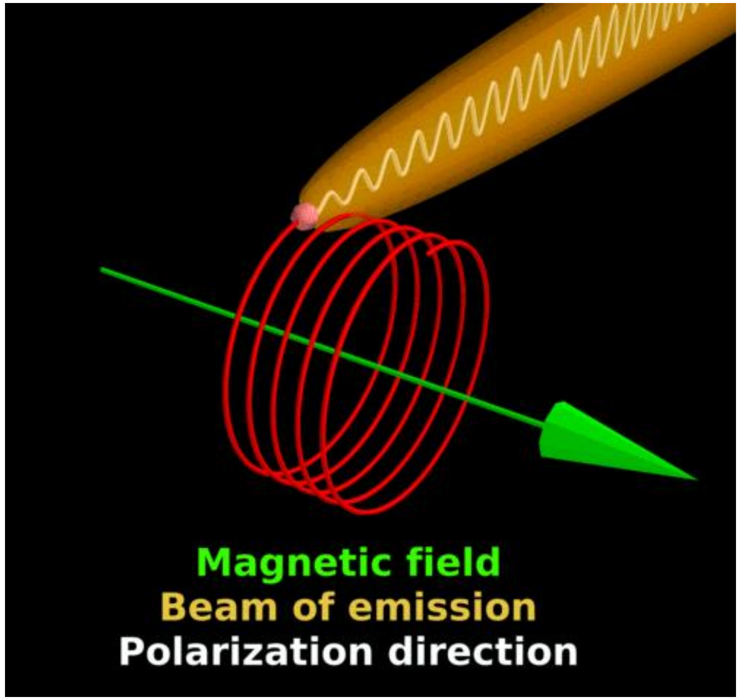
Spin > 0 is required to produce jet power, but spin magnitude is otherwise unconstrained

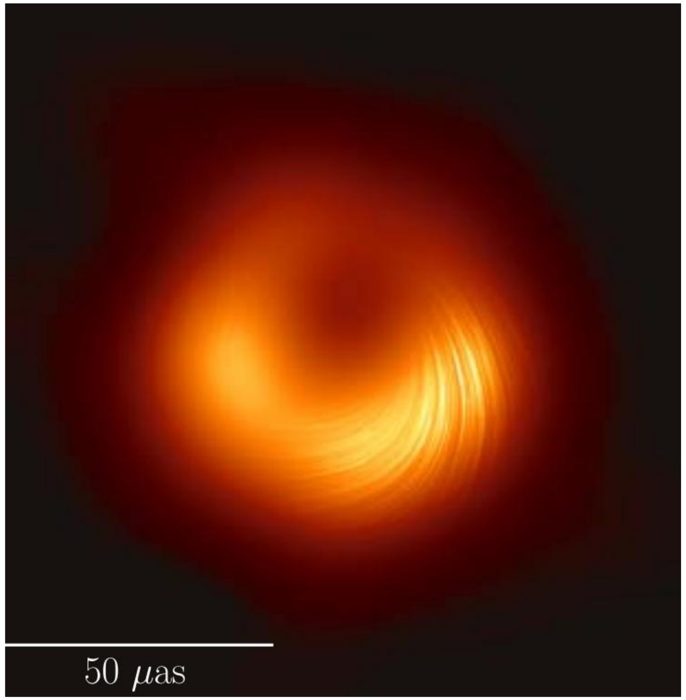
EHTC V, 2019, Wong+ 2021

What do *polarized* images of M87* and Sgr A* tell us about black hole magnetic fields?

EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
EHTC VIII, 2023
EHTC+ 2025

Why polarization?



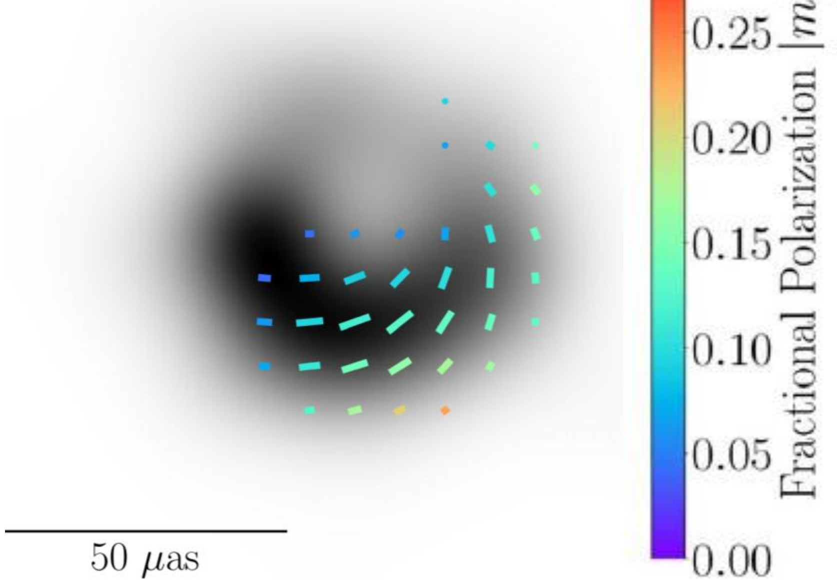


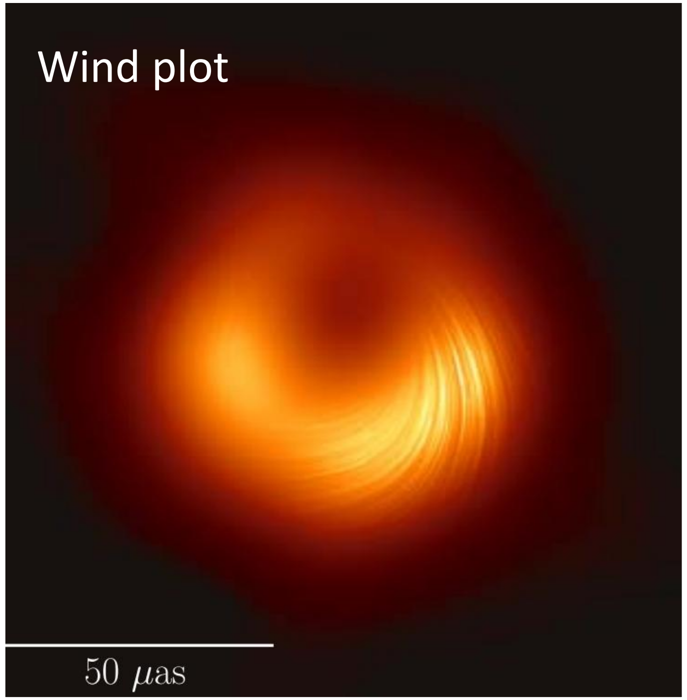
- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines
- Polarization **transport** is sensitive to the magnetic field, plasma, and spacetime
- Polarization images **highly constrain near-horizon astrophysics**

EHTC VII, VIII 2021; EHTC IX, 2023 (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

M87* in Polarized Light

Tick plot





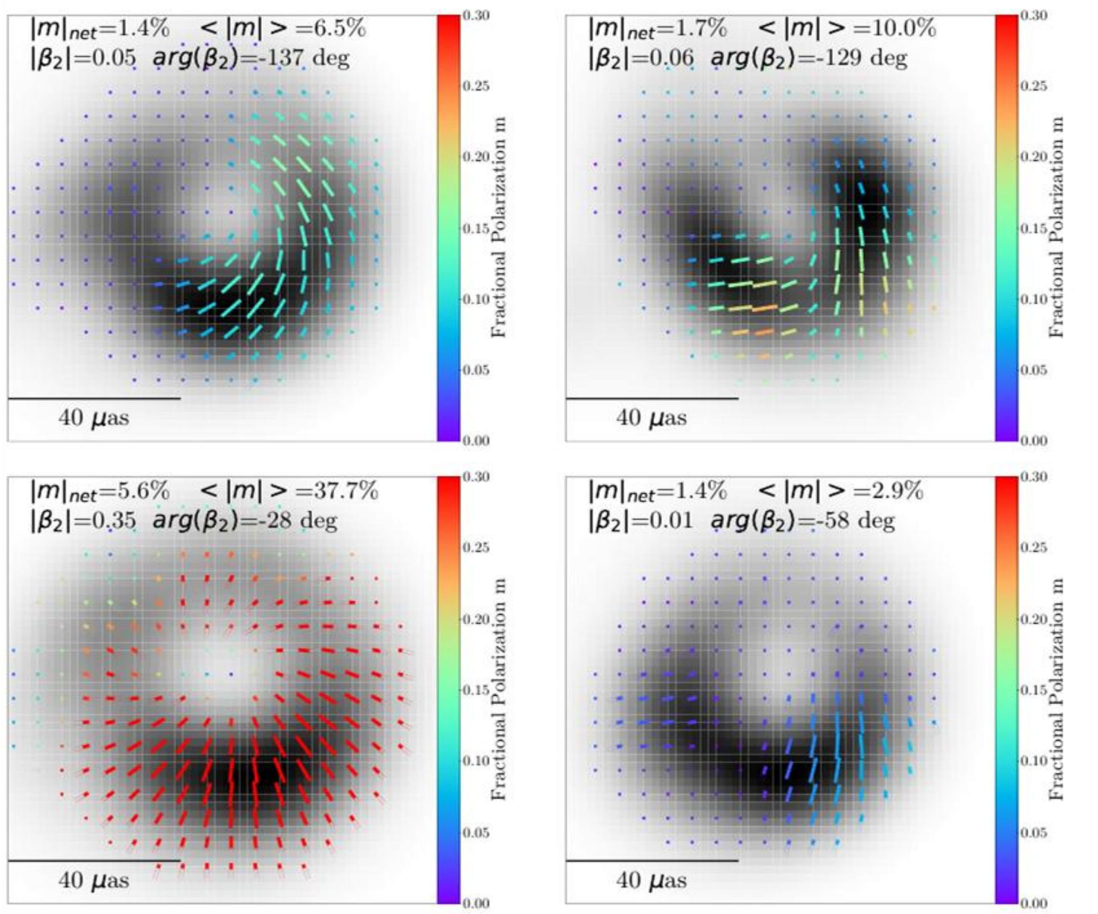
Polarization structure in M87* is predominantly **helical and weak**, (|m| ~10 %)

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

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)

Summarizing an image: Polarization

Unresolved polarization fraction

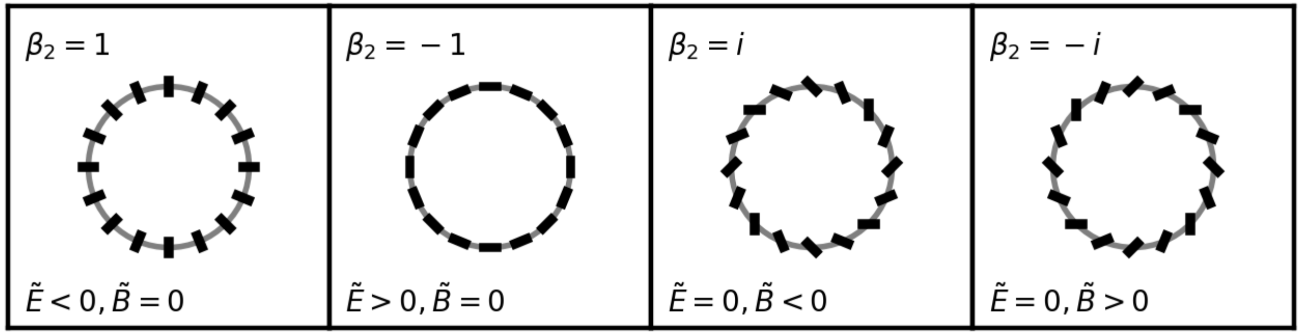
$$|m|_{\mathrm{net}} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$$

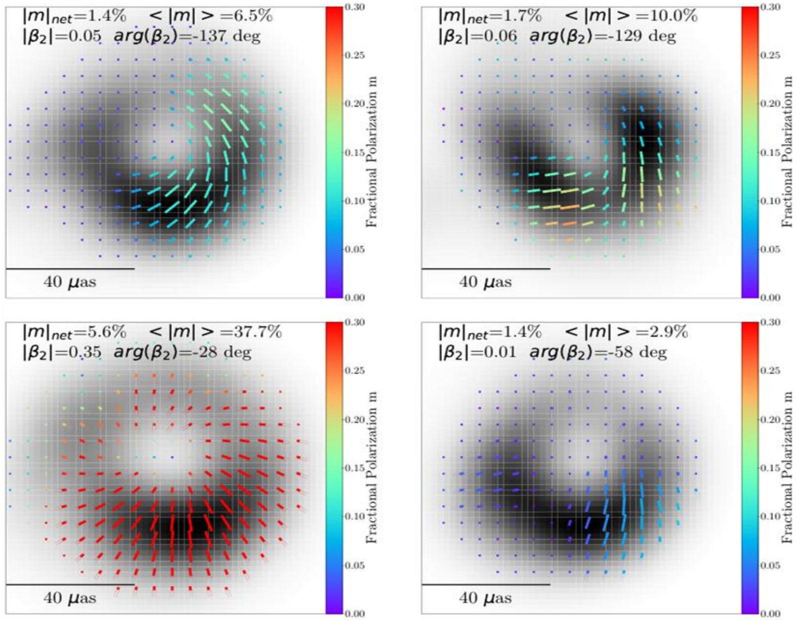
Average resolved polarization fraction

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

Azimuthal structure: 2^{nd} Fourier mode

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





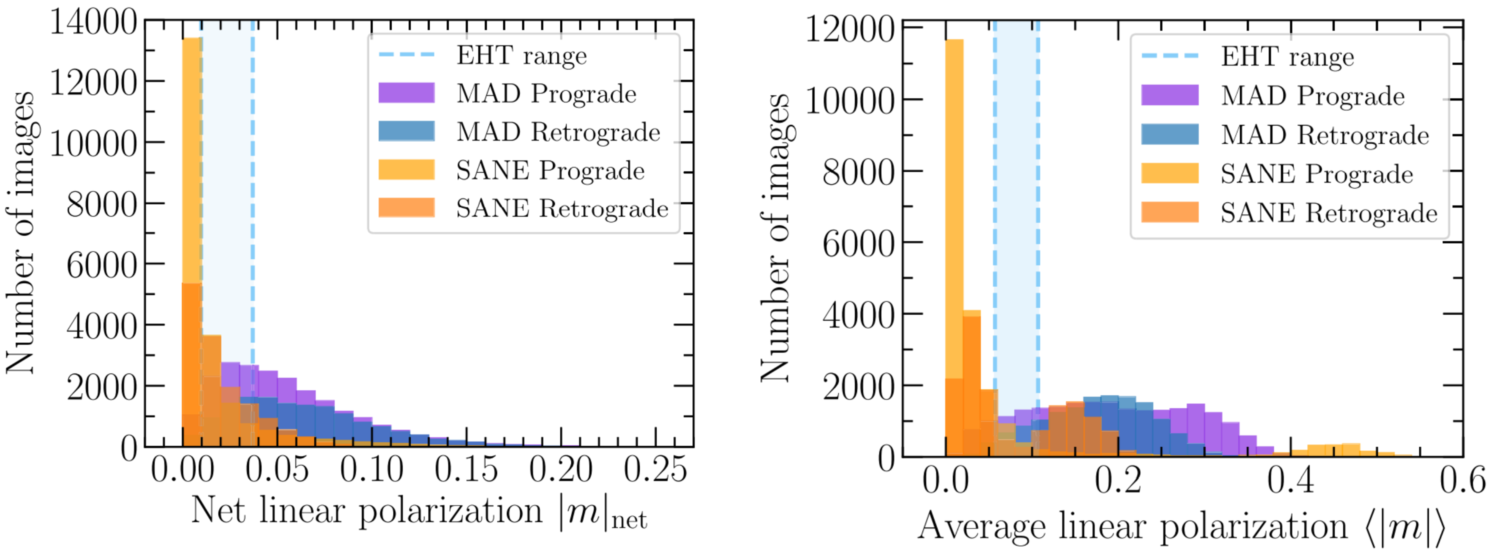
Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

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

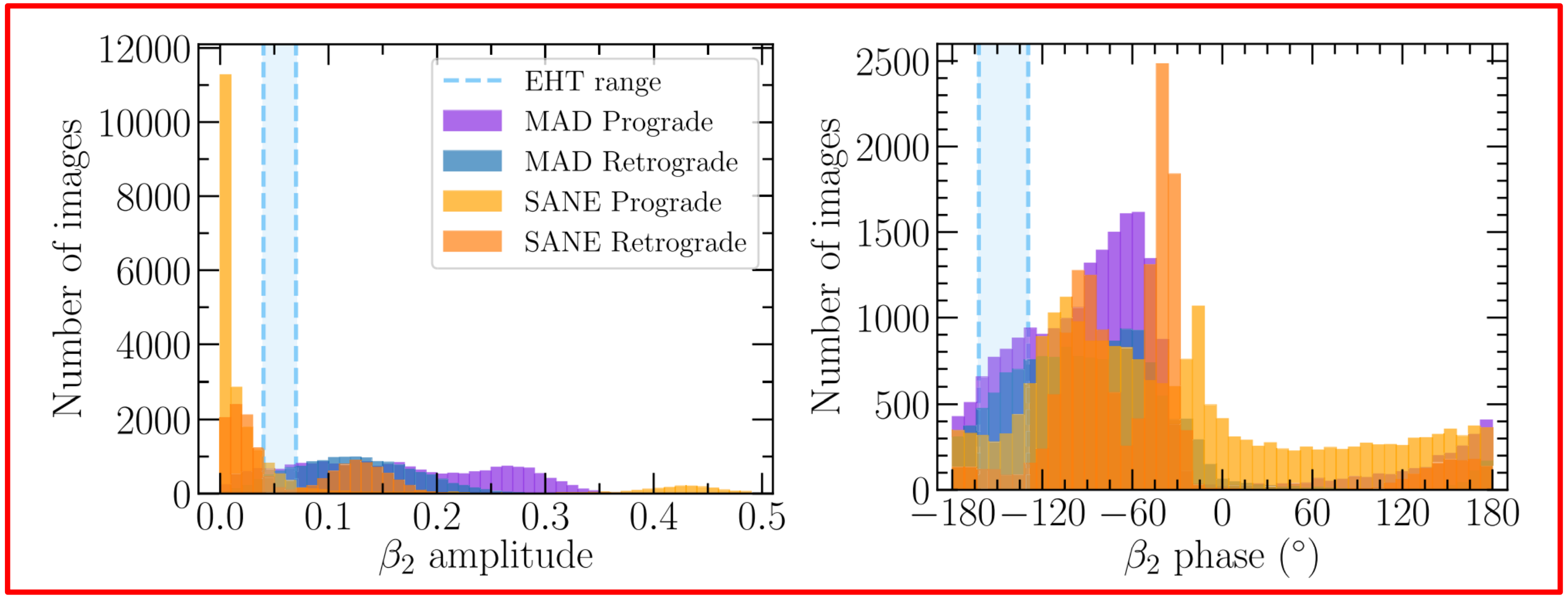
EHTC VII,VIII, 2021 (**Chael**, paper coordinator)
EHTC IX, 2023 (**Chael**, paper coordinator)

Scoring M87 simulations with linear polarization

Unresolved and **resolved** linear polarization fractions

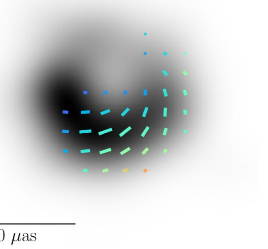


Azimuthal structure
2nd Fourier mode



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

Scoring M87* simulations with polarization



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

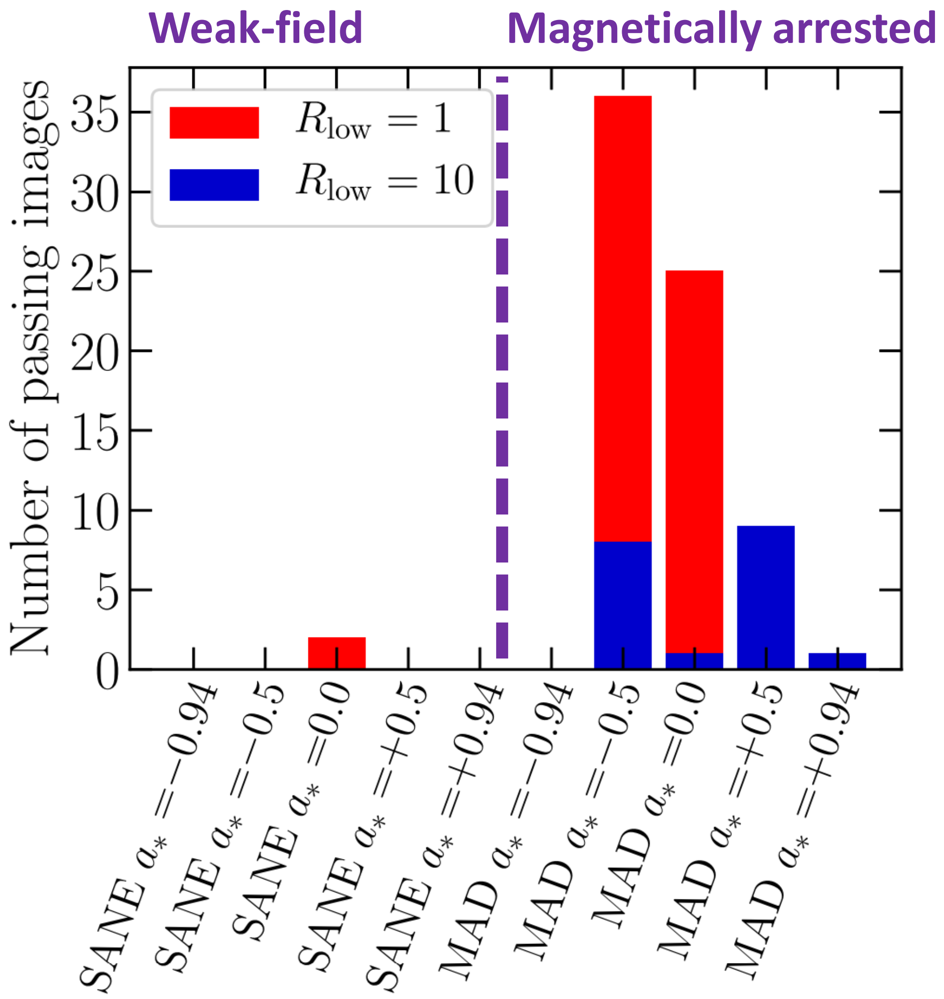
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude from passing models w/o polarization:

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

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

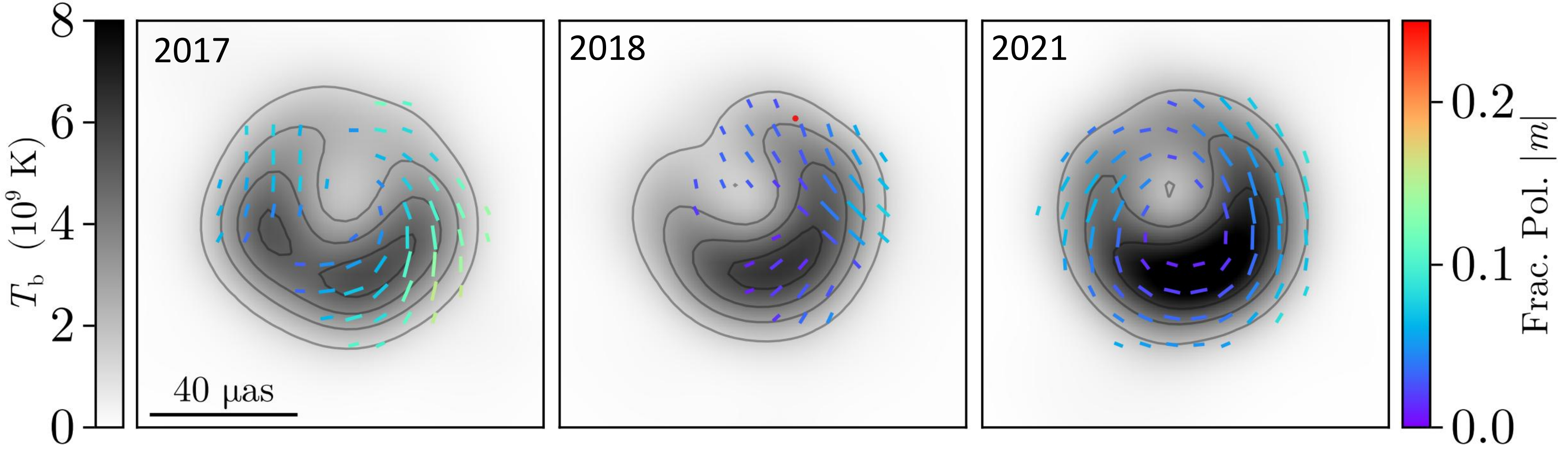
$$T_e \simeq (5 - 40) \times 10^{10}\ \mathrm{K}$$
$$|B| \simeq (7 - 30)\ \mathrm{G}$$

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



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

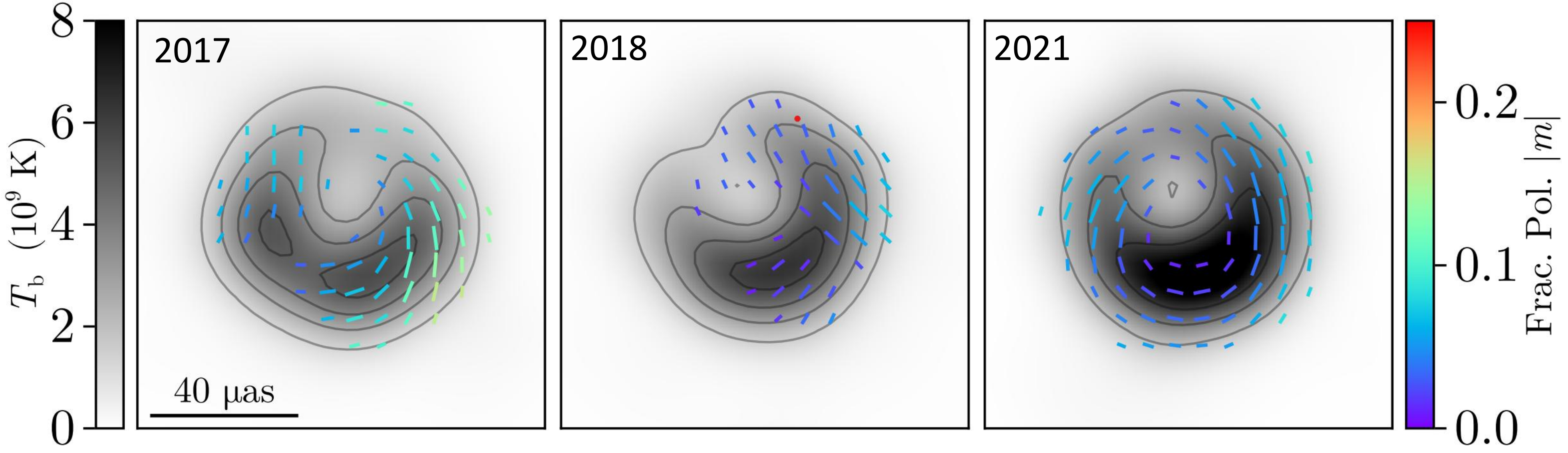
Surprising Polarization Variability in M87* over 3 years



- EHT observations show a consistent horizon-scale ring structure in M87* **over 4,000 t_g**
- Image quality is improving from EHT observations performed with a **more complete array** (including Greenland Telescope)
- Ring diameter is consistent over three years

EHTC+ 2019, 2022, 2024, 2025

Surprising Polarization Variability in M87* over 3 years



- Polarization structure shifts and fractional polarization is **significantly lower** in 2018-2021 (3%) than 2017 (~10%)
  - Does this challenge the magnetically arrested interpretation?

- This degree of variability is difficult to explain in simulation models (MAD or SANE)
  - Do we need to modify initial conditions / plasma feeding?

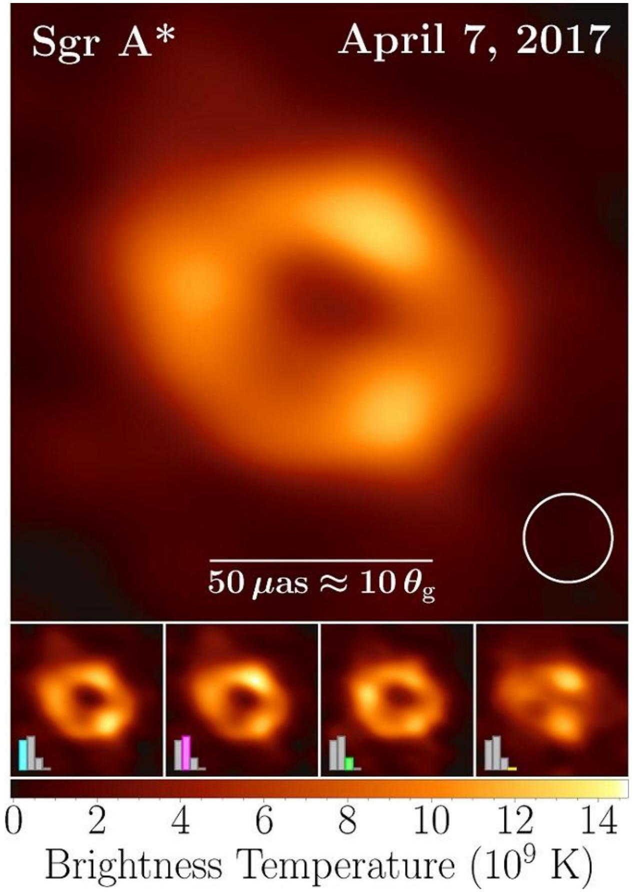
EHTC+ 2019, 2022, 2024, 2025

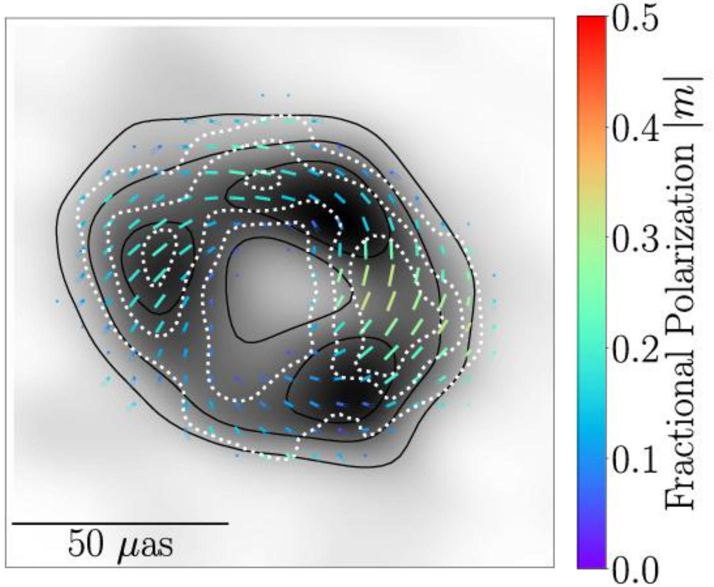
Sgr A* in Polarization

- Imaging Sgr A* is more challenging than M87 due to rapid sub-hour **variability** and **interstellar scattering**.

- Sgr A* images do not currently constrain the ring position angle or asymmetry
  → face on orientation?

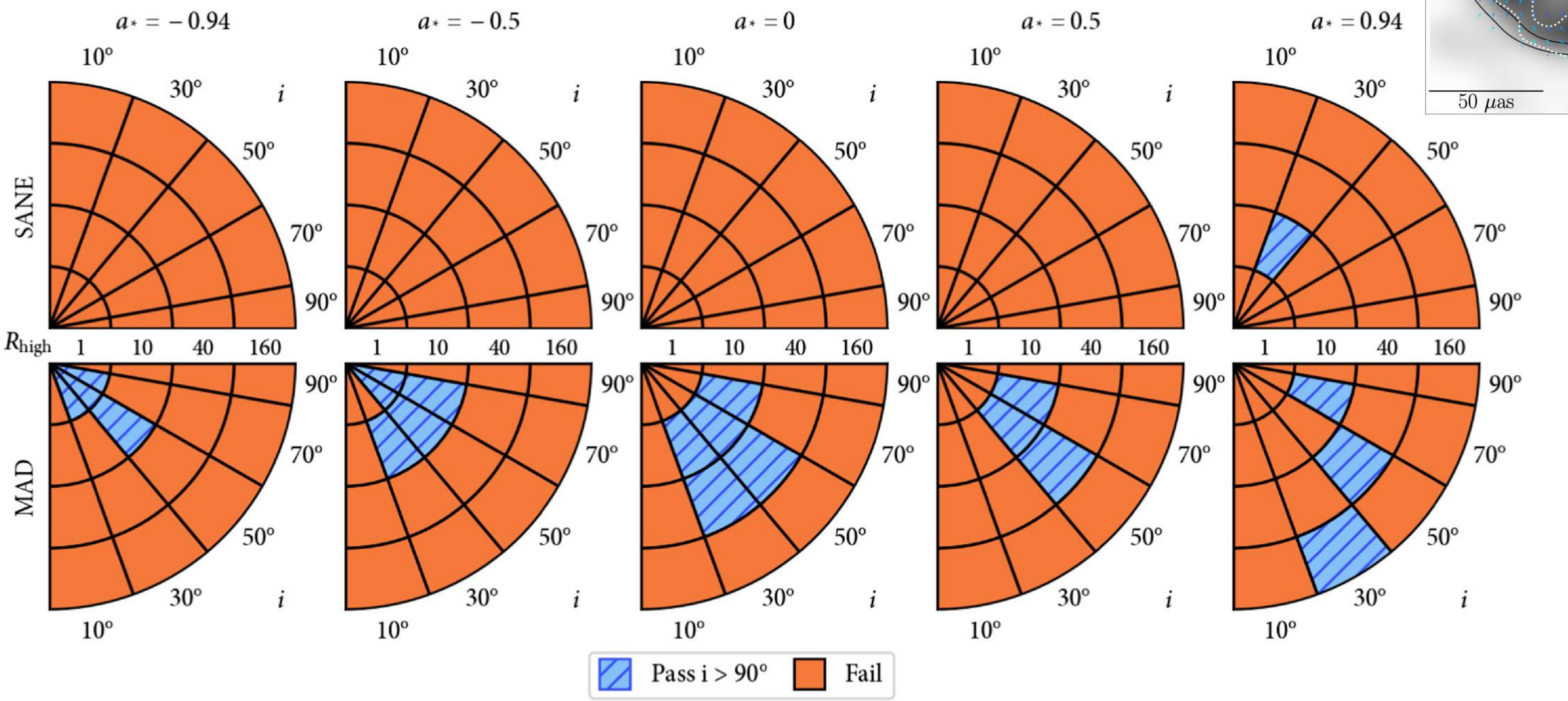
- Sgr A* is **more polarized** (≈30%) than M87*, and it shows a similar **helical linear polarization pattern**.

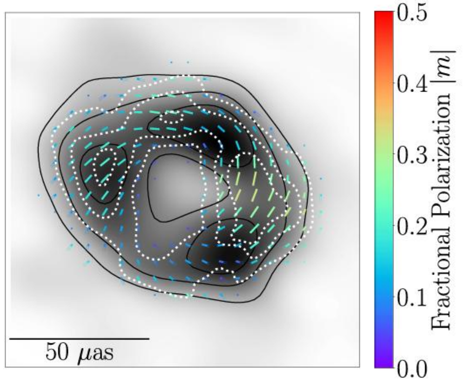




EHTC I, 2022; EHTC VII, 2024 **Chael**, paper writing team)

Sgr A* Polarization Constraints



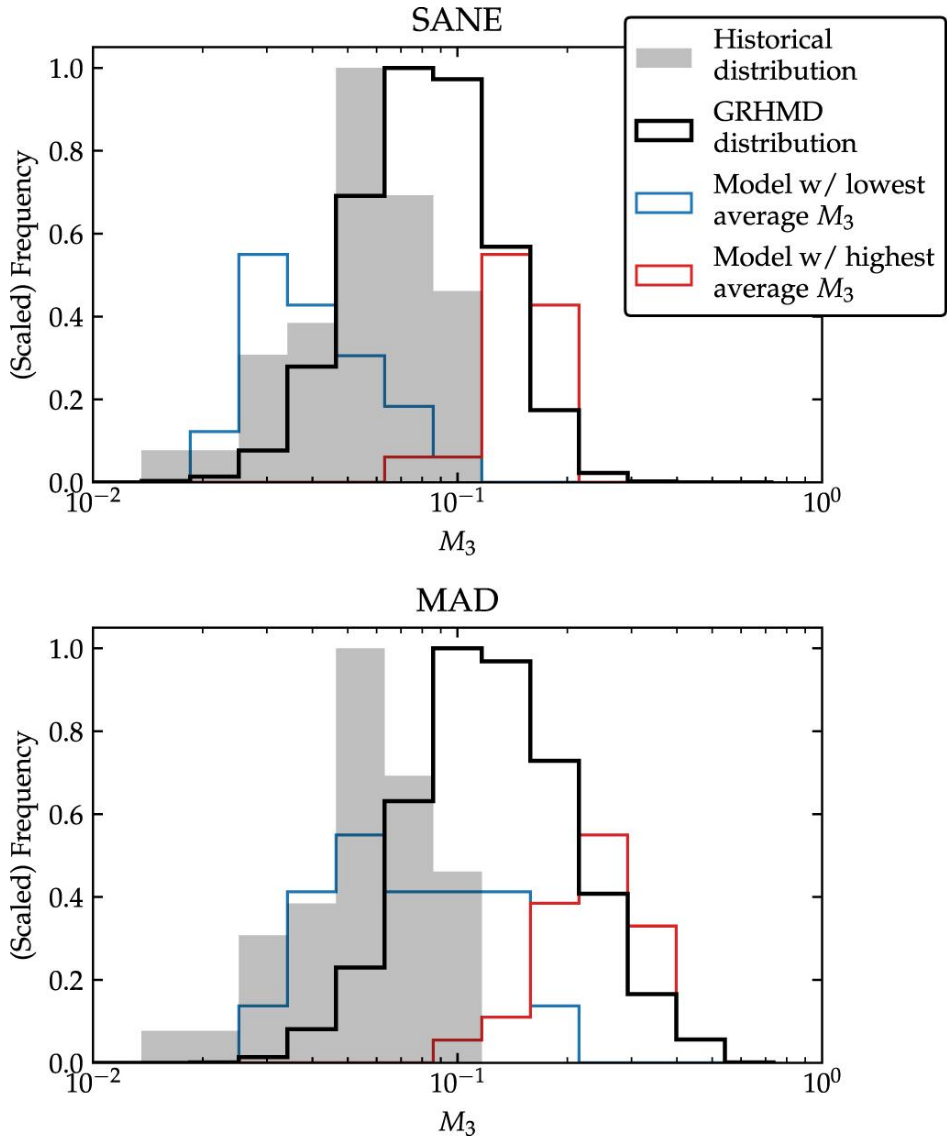


- For any model to pass requires **Faraday de-rotation.**
- Passing models all must spin **clockwise**, consistent with NIR & submm flare inferences (GRAVITY+ 2018, Wielgus+ 2022)
- **One high spin MAD model survives** both multi-wavelength and polarization cuts
  - If Sgr A* is magnetically arrested, why is there no obvious jet?

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

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.
- MAD simulations are ***nearly all* too variable** when compared with long-duration light curves.
- Possible resolutions:
  - extended emission,
  - two-temperature modeling (e.g. Chan+ 2024, Salas+ 2024),
  - initial conditions/feeding (e.g. Wong+ in prep)



EHTC V, 2022

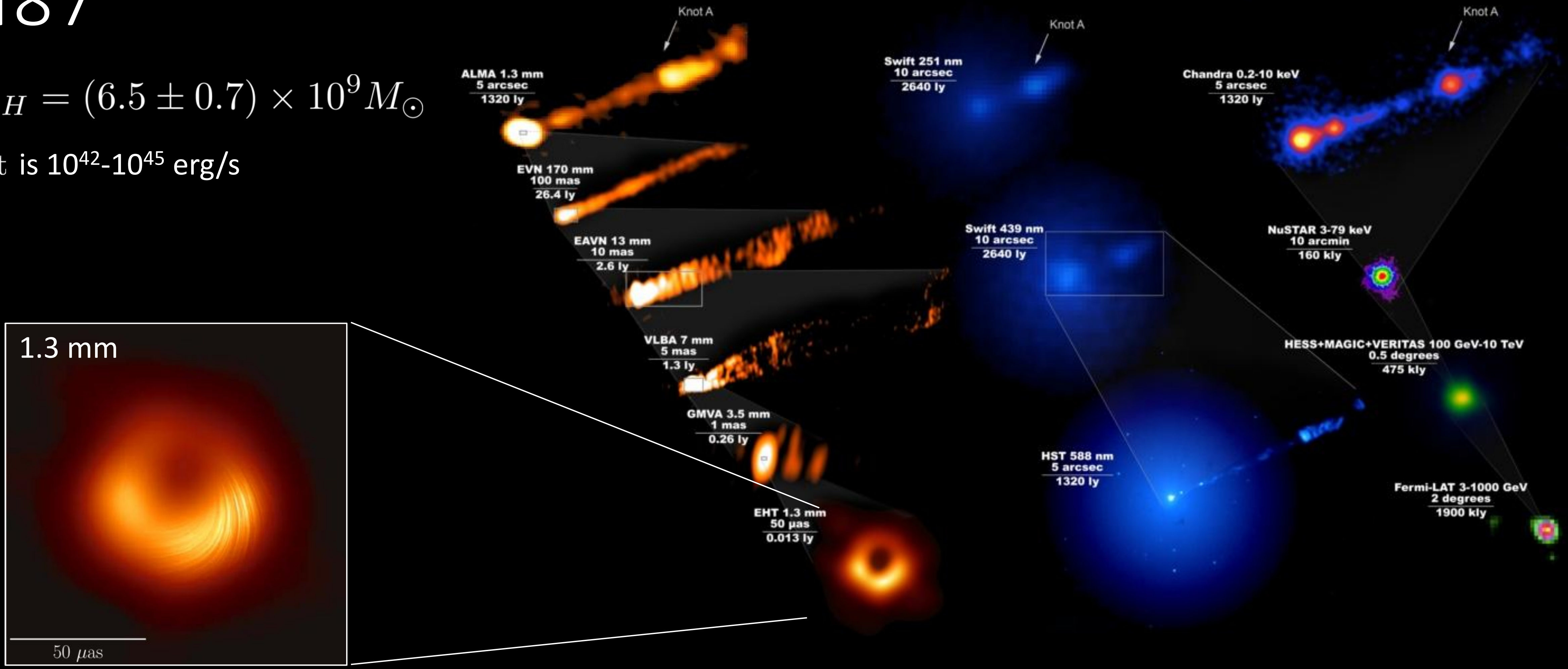
More physics from polarized images: jet launching, spin, and particle heating

Chael+ 2023, Chael 2025, Wong+ 2025, Chael+ 2026

M87*

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

$P_{\rm jet}$ 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)
Can we probe black hole energy extraction **on horizon scales**?

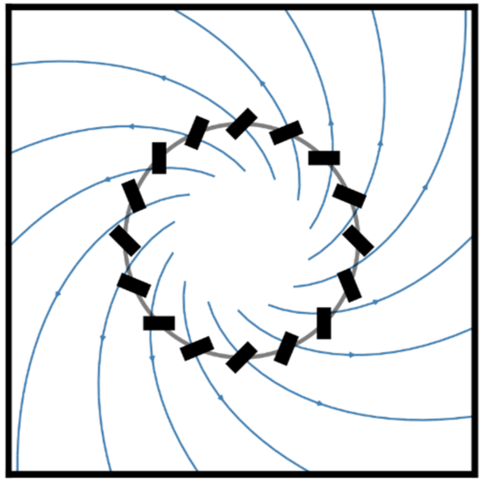
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Near-horizon polarization is connected to the **electromagnetic energy flux**

- In simple analytic models, the sign of $\angle\beta_2$ is directly connected to the direction of Poynting flux, assuming we know the sign of the angular velocity Ω_F
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy outflow in M87***
- Does this simple argument hold up in **simulations?**

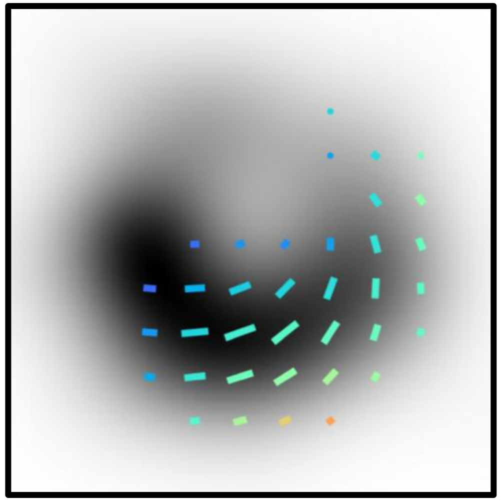
Cartoon Model

$B^\phi / B^r < 0$



$-\pi < \angle\beta_2 < 0$

M87*



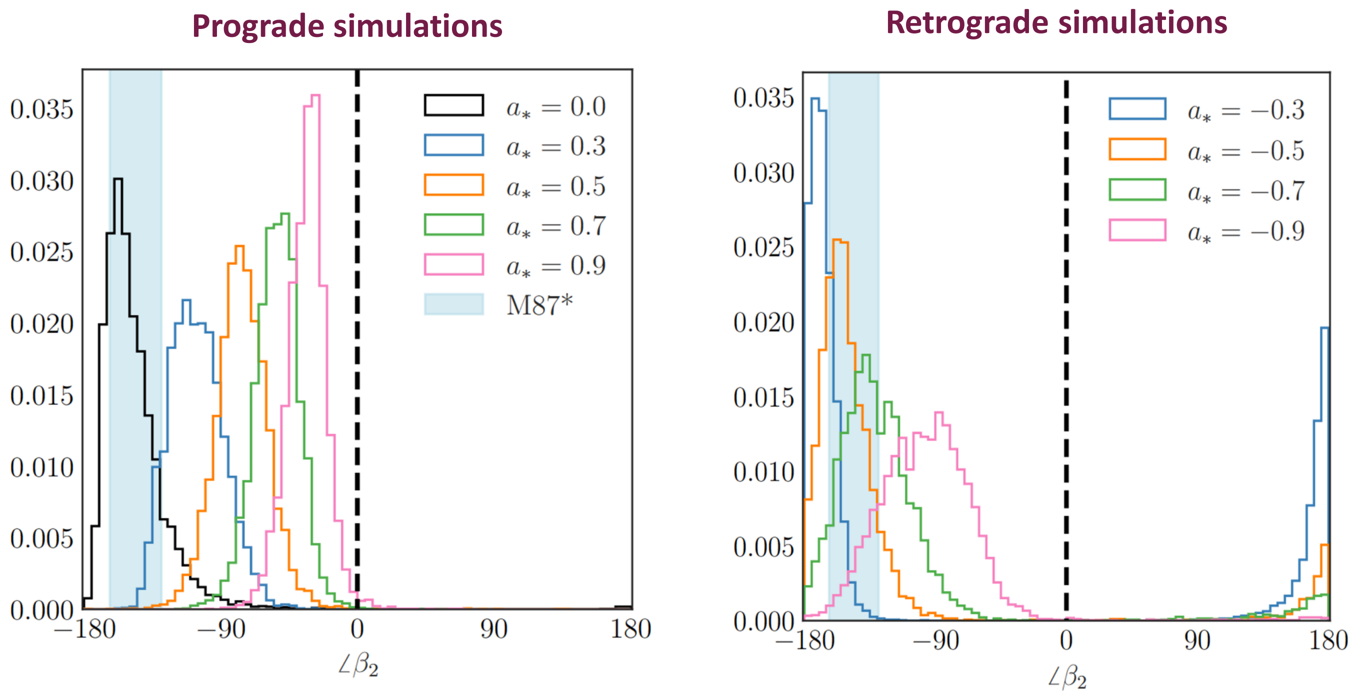
GRMHD Poynting flux

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

EHTC+ 2021 VII, **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

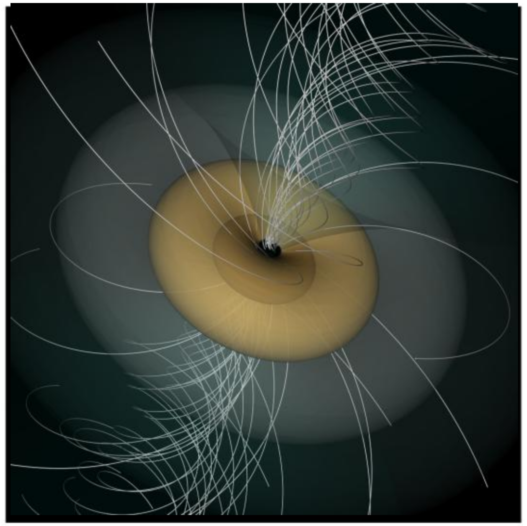


BH spin axis is into the plane of the sky in all simulation images (EHTC+V)

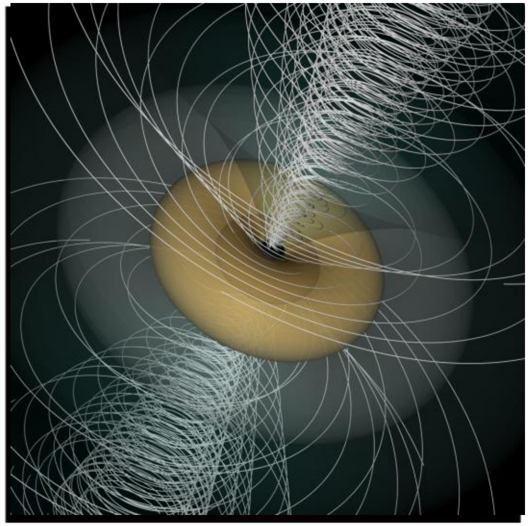
Chael+ 2023b, simulations from Narayan+2022

Polarized images are **spin dependent**

Low Spin



High Spin



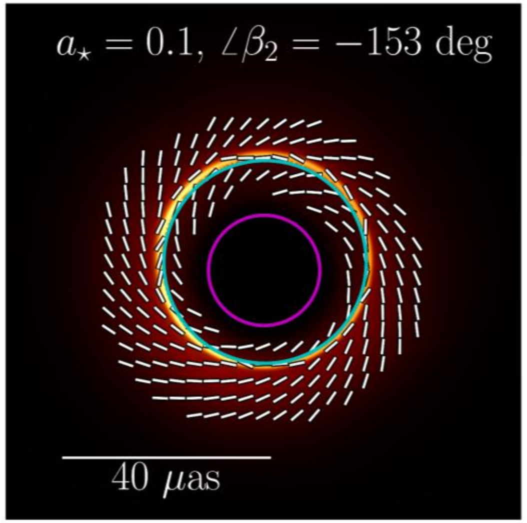
- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power

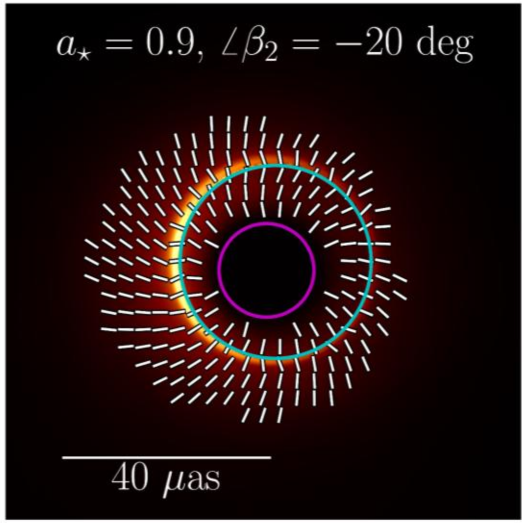
Chael+ 2023b**; Chael** 2025**;** Wong+2025

Polarized images are **spin dependent**

Low Spin

High Spin





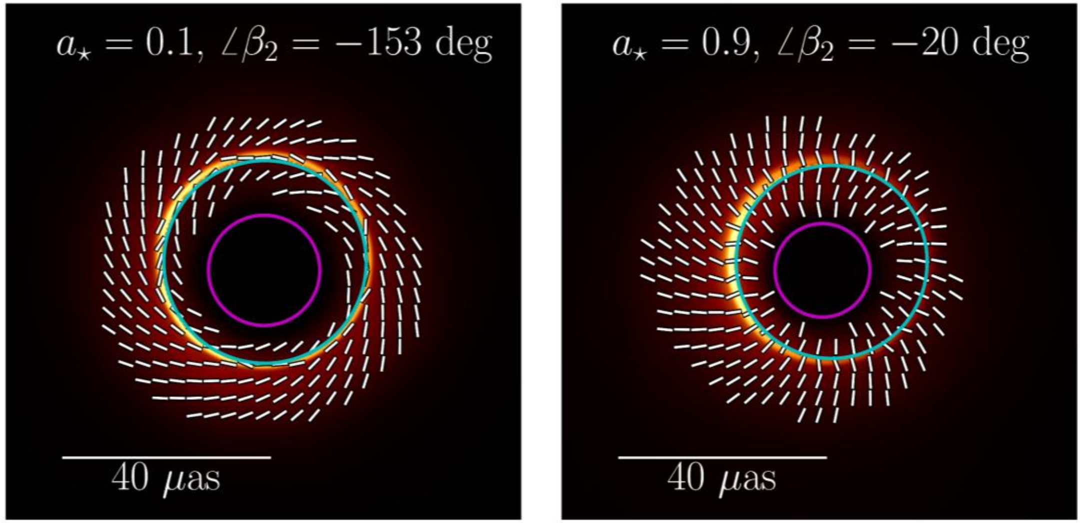
- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

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

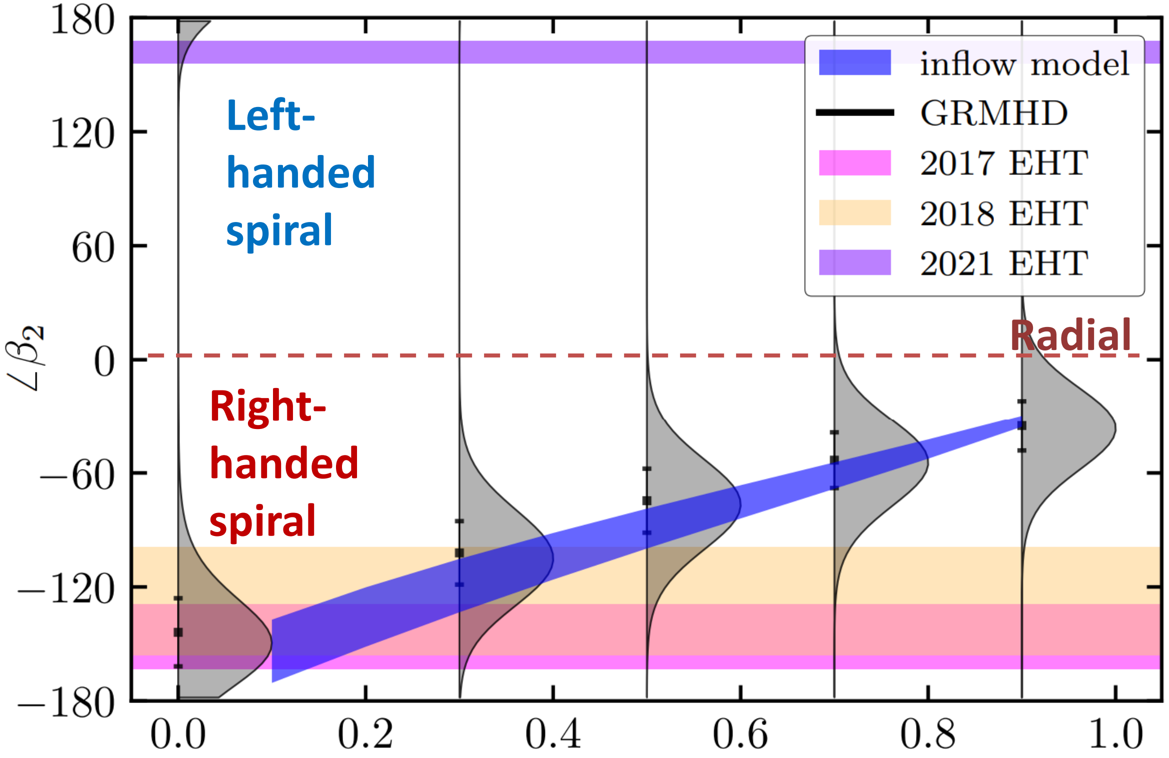
Polarized images are **spin dependent**

Low Spin

High Spin



M87*

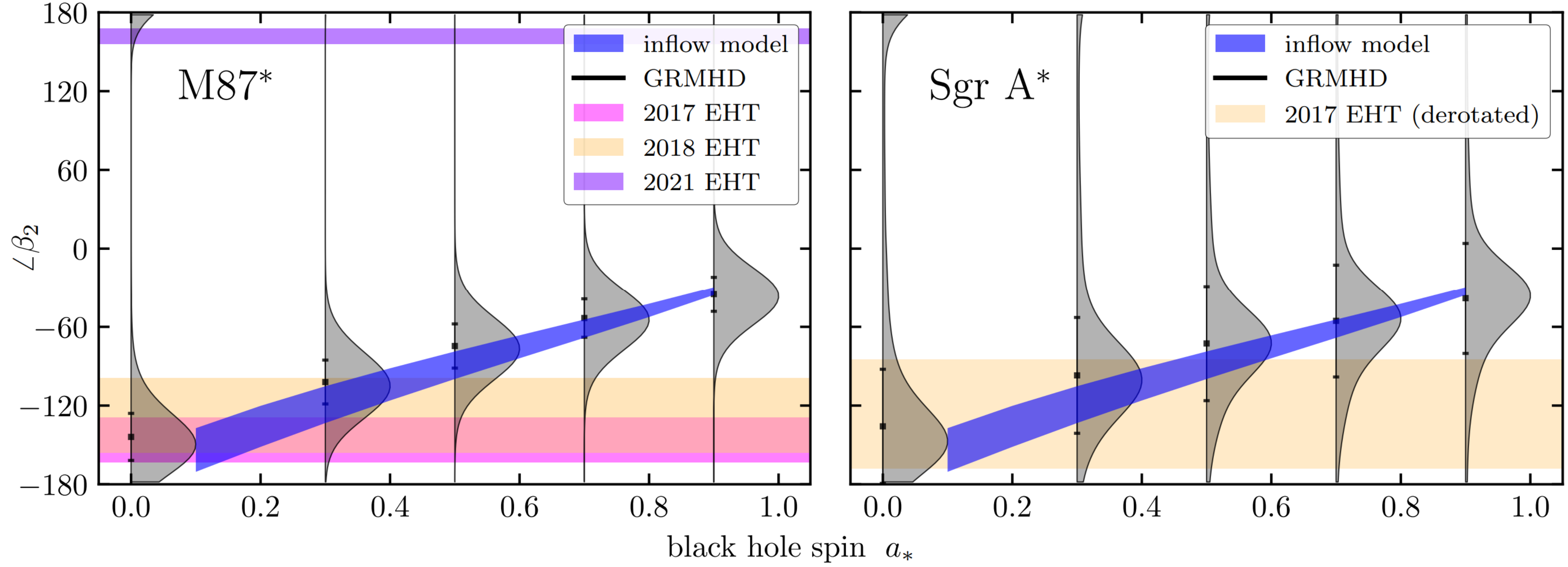


- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
  - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)

- 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

Polarized images are **spin dependent**

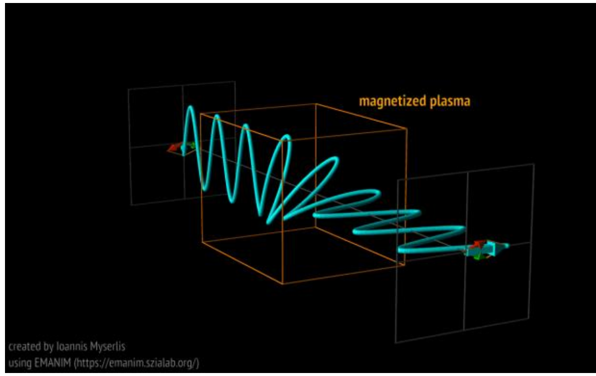


- Sgr A* polarization is consistent with energy outflow **if** the BH rotates clockwise
  - NIR flares (GRAVITY+ 2018) and ALMA mm light curves (Wielgus+ 2022) all rotate **clockwise**
- Sgr A* spin is not well constrained by EVPA pattern alone
  - combined EHT+MW constraints prefer high spin (EHTC+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

Polarimetric spin measurements are possible!

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

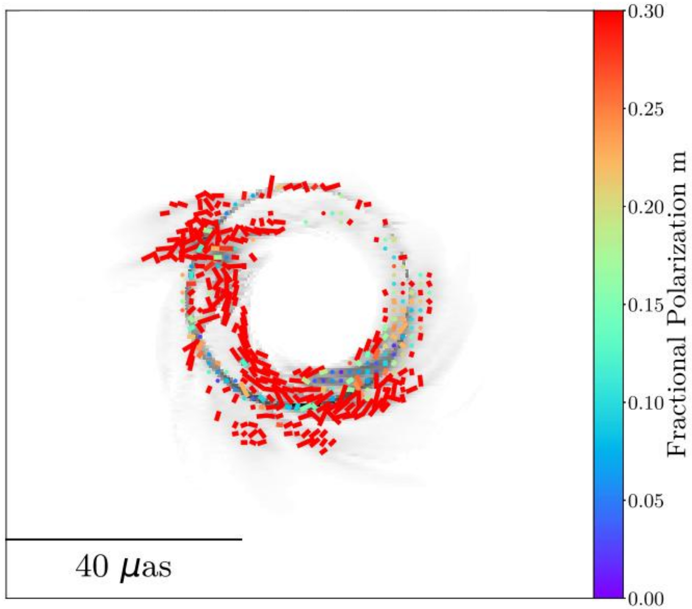
Faraday Rotation depolarizes BH images

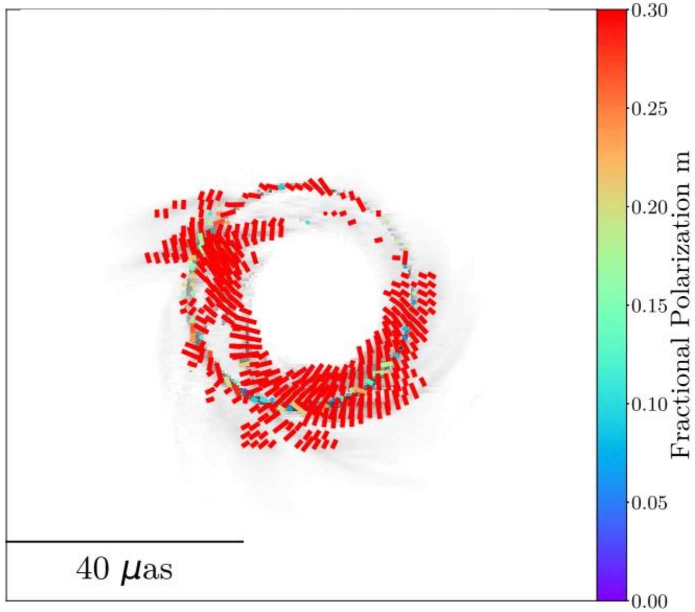


With Faraday

Without Faraday

'infinite' resolution

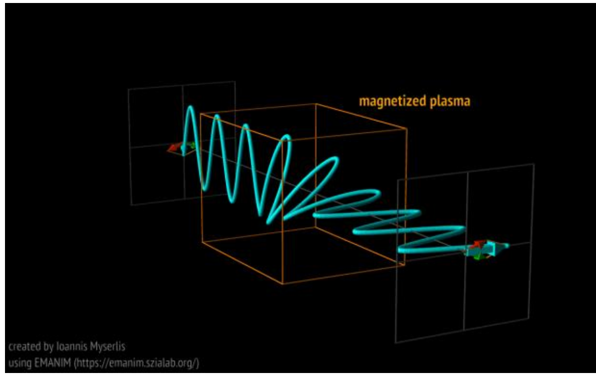




- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales

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

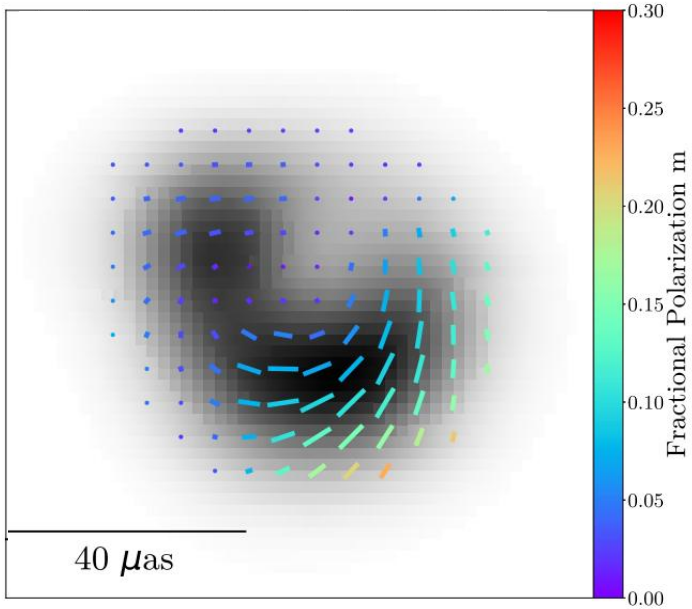
Faraday Rotation depolarizes BH images

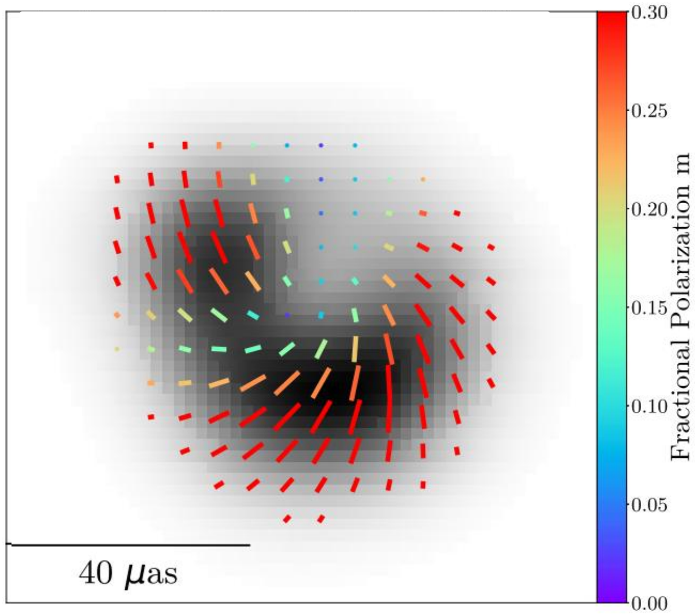


With Faraday

Without Faraday

EHT resolution



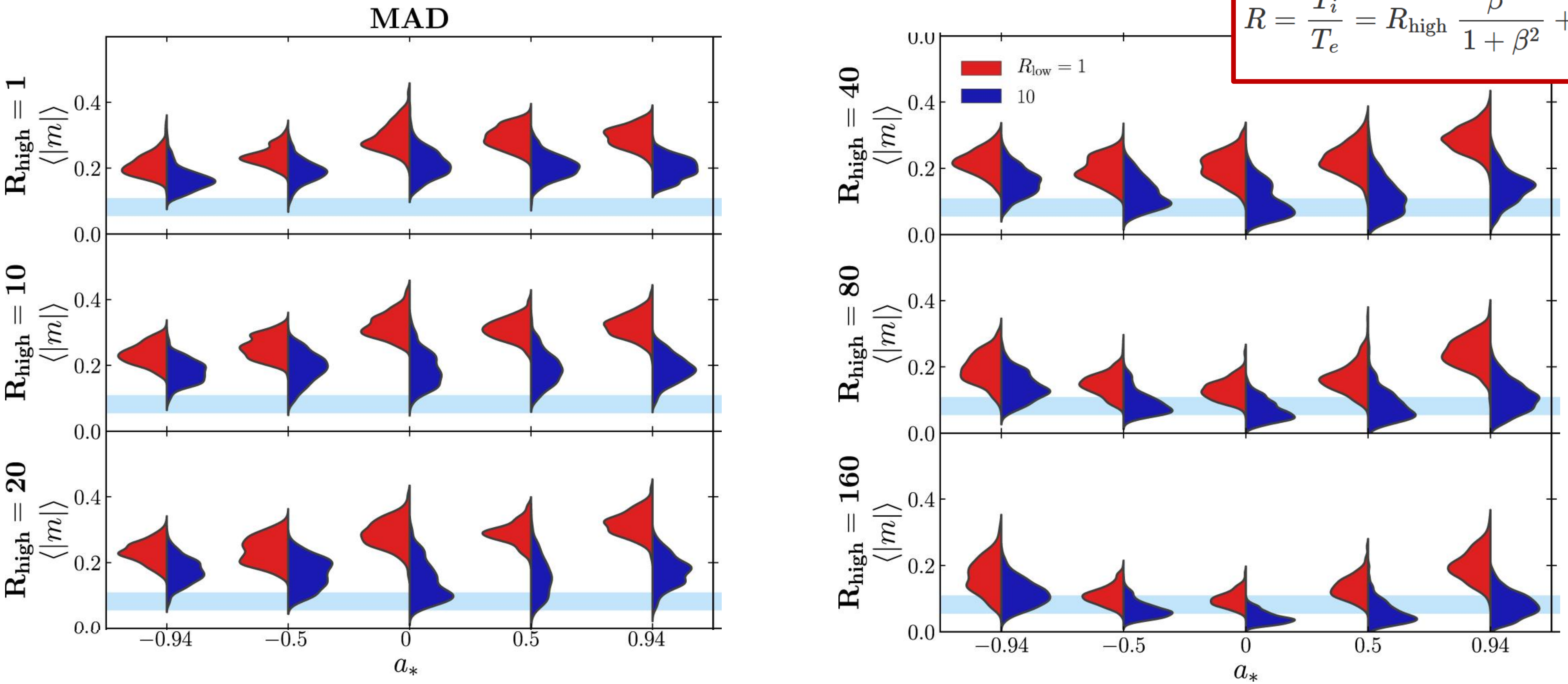


- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from **colder electrons** is necessary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

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

Constraints on the electron temperature

$$R = \frac{T_i}{T_e} = R_{\mathrm{high}} \frac{\beta^2}{1+\beta^2} + R_{\mathrm{low}} \frac{1}{1+\beta^2}$$

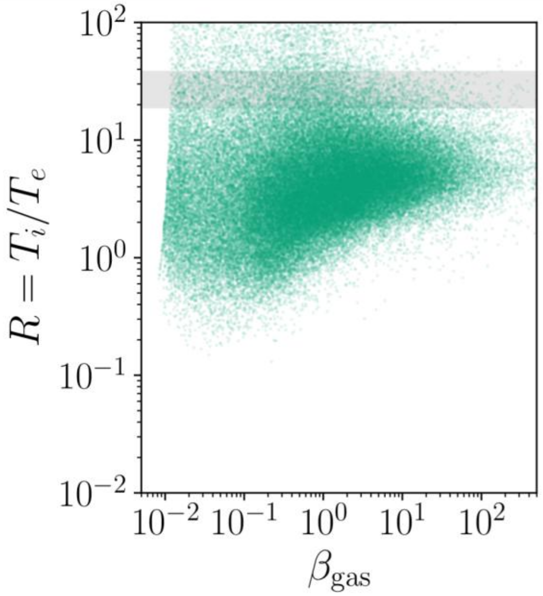


- We need low electron temperatures (large R_{high}) to produce the low polarization fraction in M87* from Faraday rotation (EHTC+ 2021 VII, Qiu+ 2023, Janssen+ 2025)

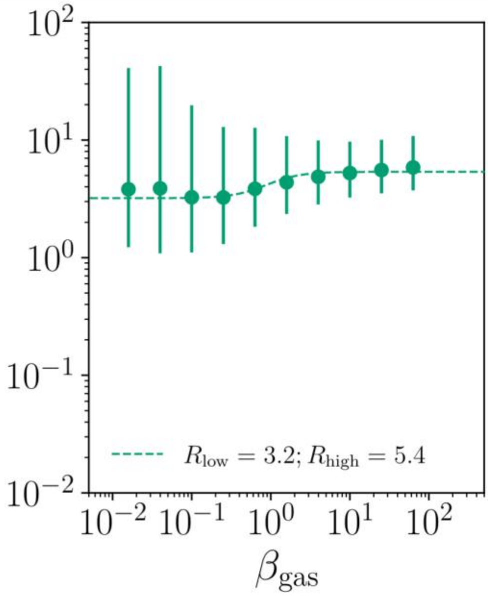
EHTC+ 2021, Moscibrodzka+ 2016

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

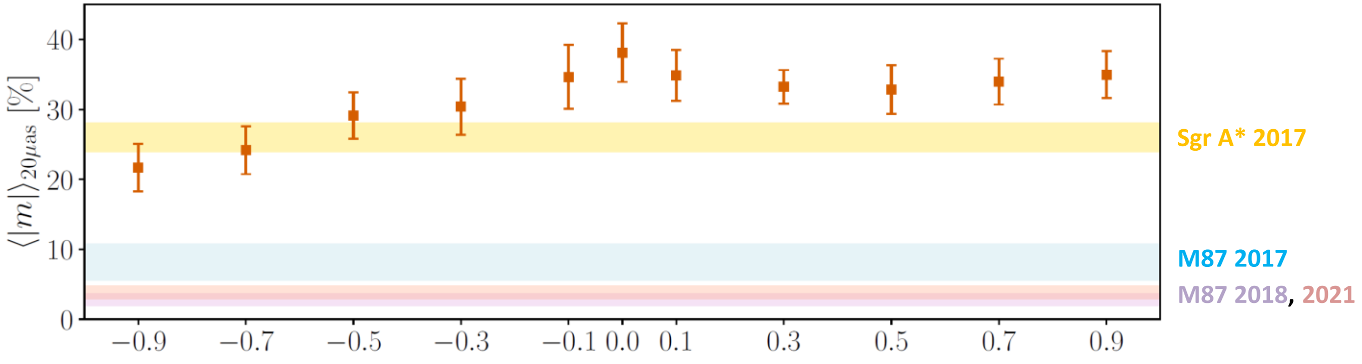
Ion-to-electron temp ratio



Effective R-β model



EHT-scale polarization fraction

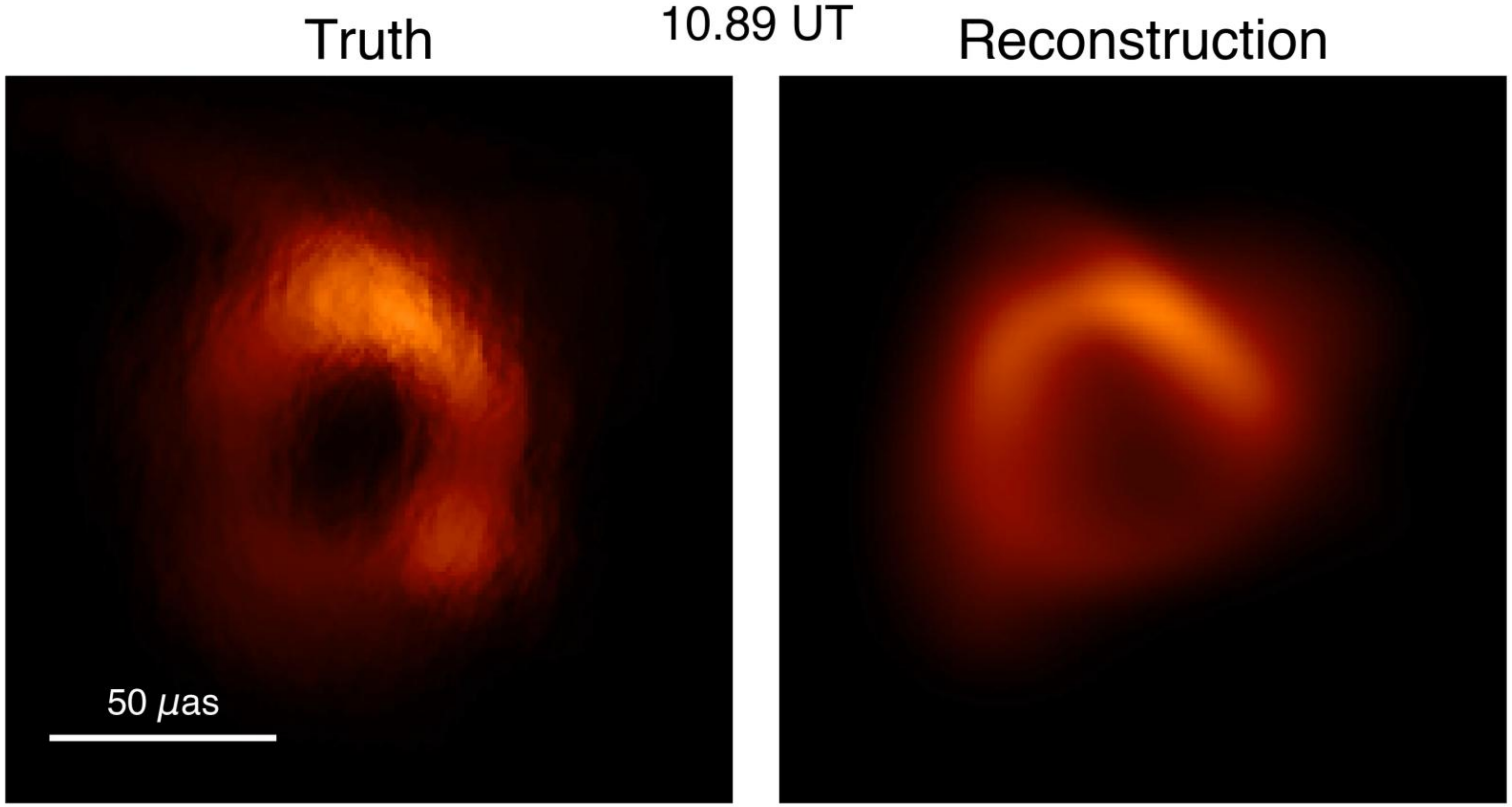


- EHT **postprocessing** prefers **cold electrons (**T_i ~ 100x T_e) to sufficiently depolarize the image (EHTC+ 2021)
- Radiative, two-temperature GRMHD (e.g. Sadowski+ 2017) solves for electron and ion temperatures self consistently with subgrid heating & cooling physics
- 2T sims prefers more modest 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

Next Steps for Horizon-Scale Black Hole Astrophysics

Sgr A* Dynamics: Horizon-scale motion

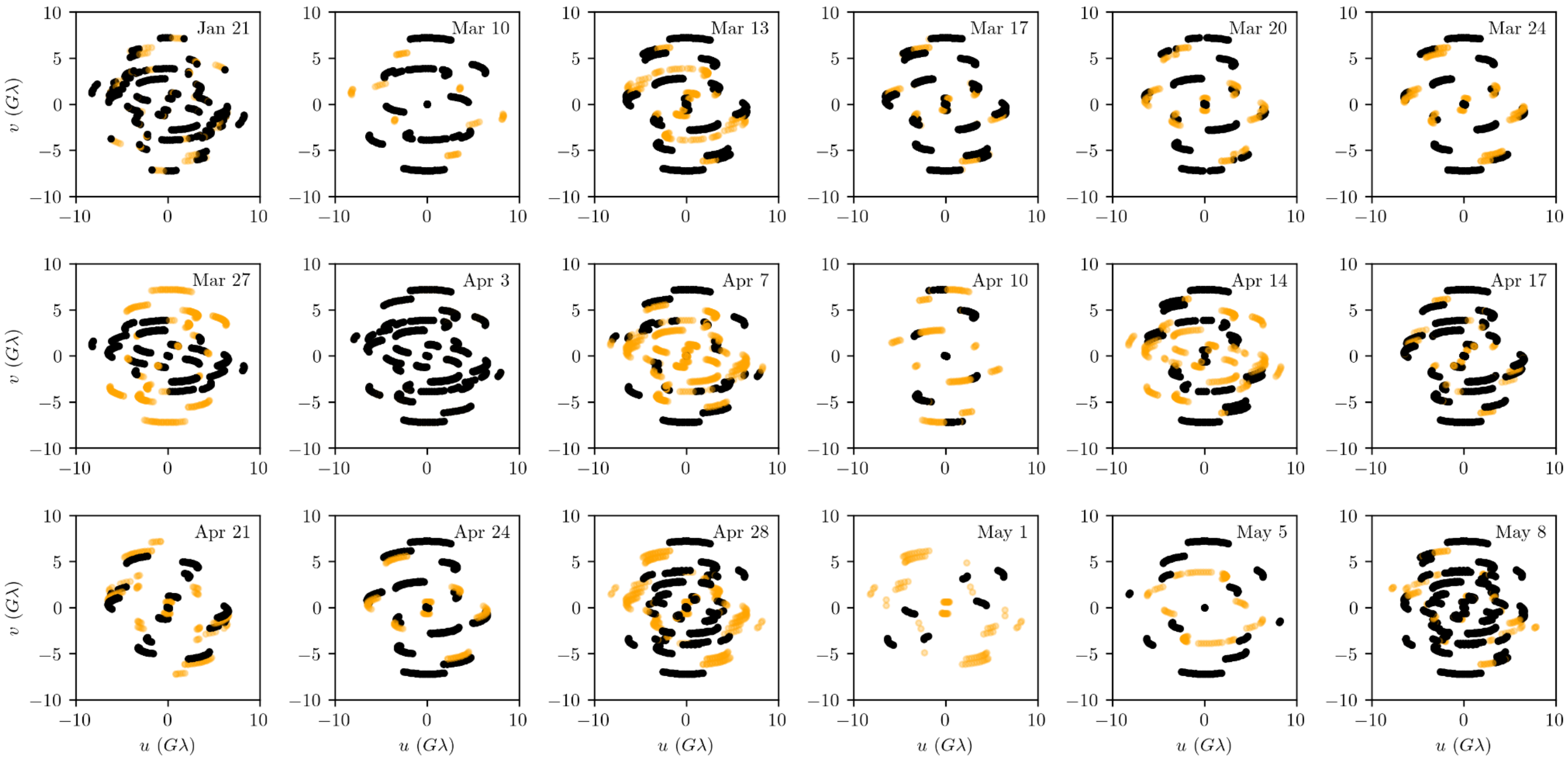


- GRAVITY near-infrared observations (GRAVITY Collab+ 2018, 2023) and unresolved ALMA observations (Wielgus+ 2022) suggest coherent clockwise motion on ~5 rg scales associated with Sgr A* flares.

- Long-term effort to use EHT data to constrain intra-observation motion: see talk by Rohan Dahale later today!

Image credit: Rohan Dahale

M87* Dynamics: MOVIE campaign

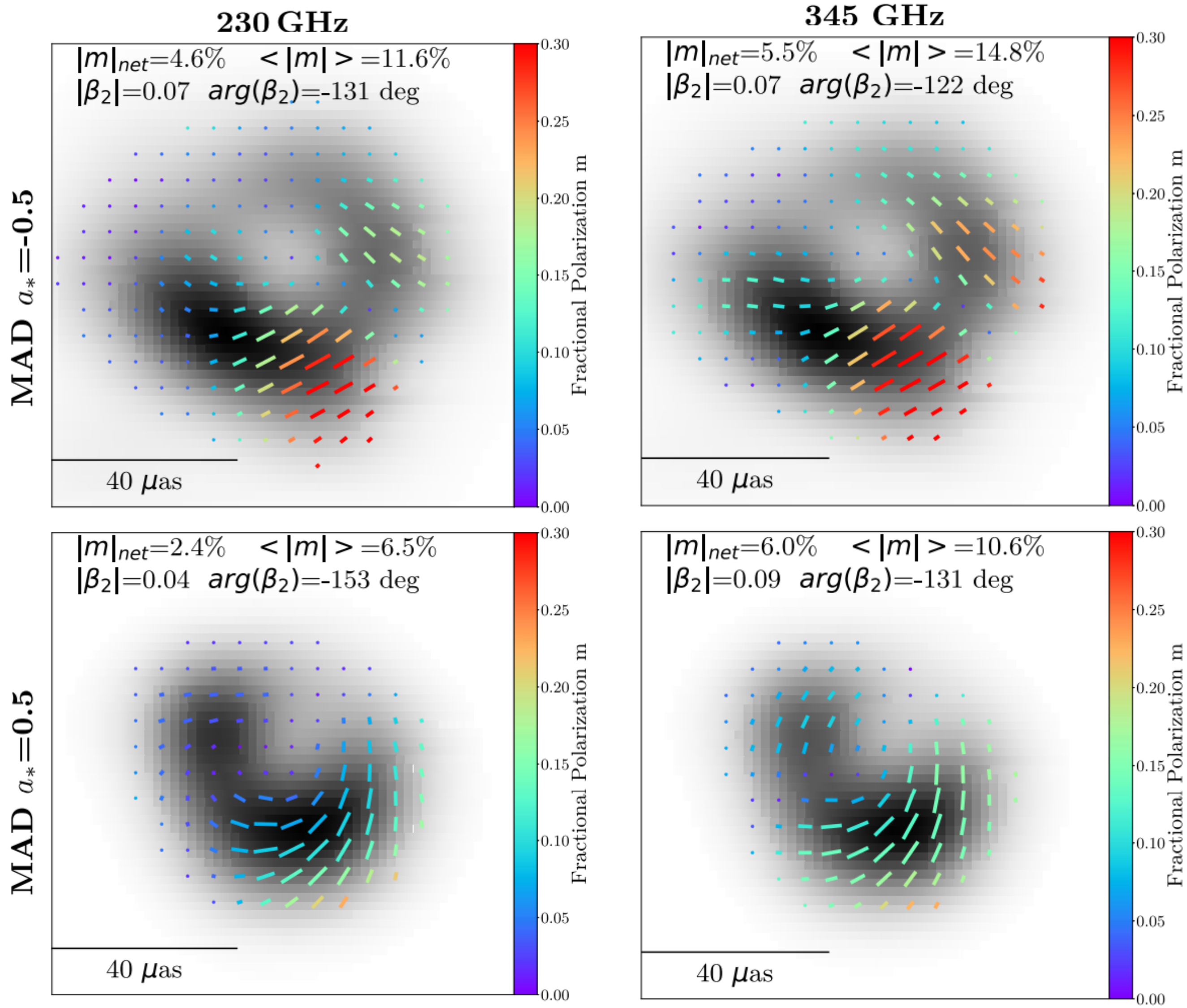


- M87*'s near-horizon variability has been probed on ~day and ~year timescales, but intermediate timescales are unexplored
- EHT just wrapped up 2-month "MOVIE" campaign of biweekly imaging observations of M87*
- See talk by Boris Georgiev later today!

Image credit: Boris Georgiev

Pushing the VLBI Frequency Frontier

- 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



EHTC 2021, Paper VIII

The future of near-horizon observations

Extended & next-generation EHT

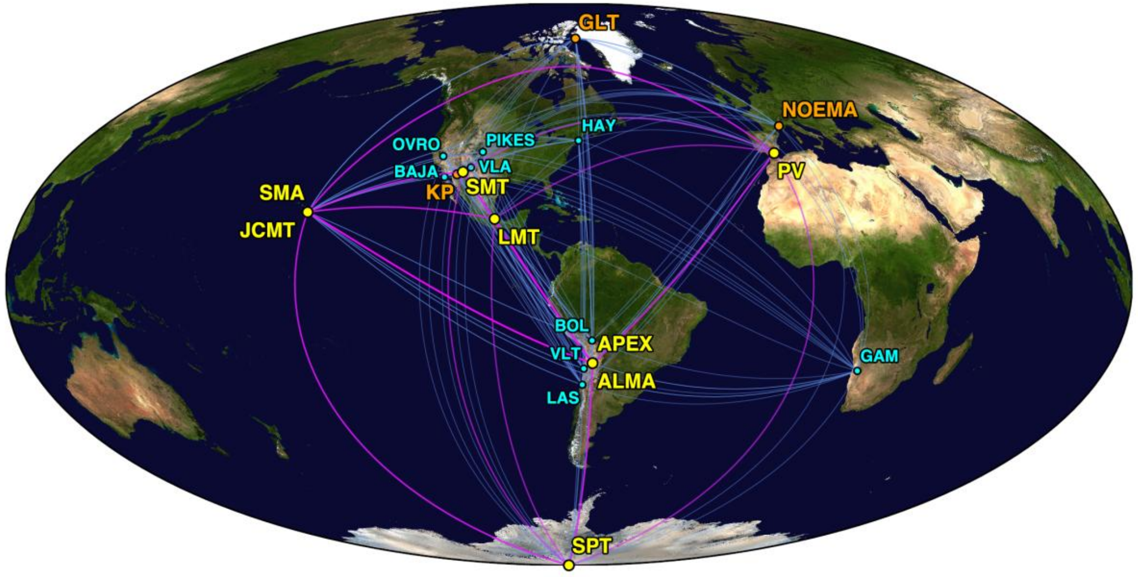


Image black holes and their jets in **multiple frequencies** and **high dynamic range**

Black Hole Explorer (BHEX)

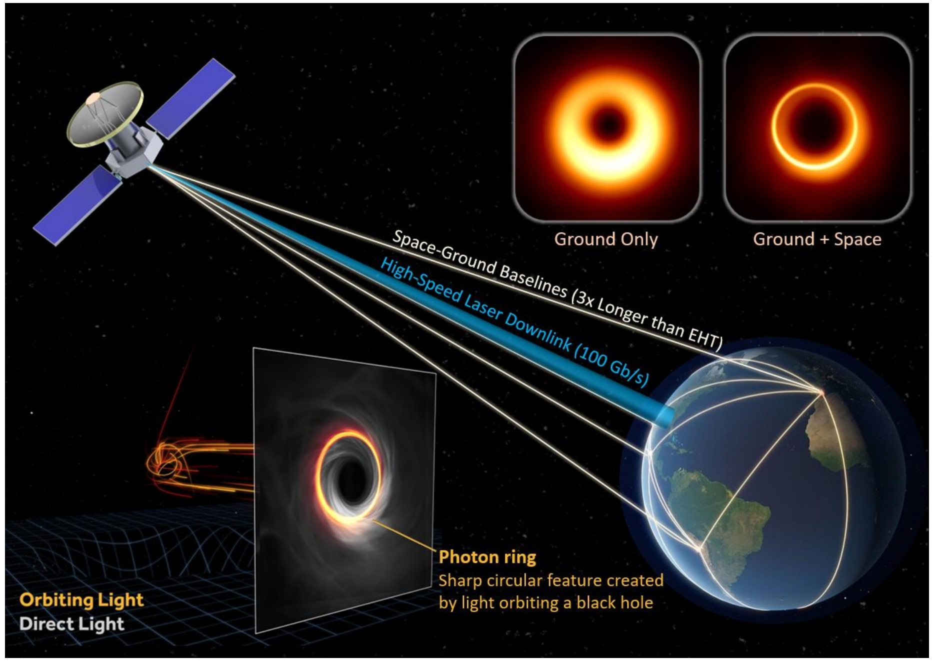


Image **extreme gravitational lensing** and dozens of new black holes **in high resolution**

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

How can we determine the jet power source?

By zooming **out**..

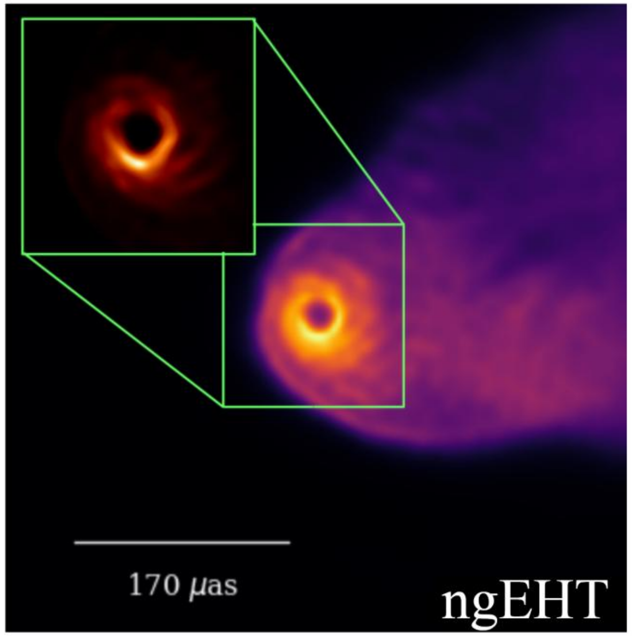


Image the connection between the BH and the low-brightness extended jet in polarization and **high dynamic range**

By zooming **in**..

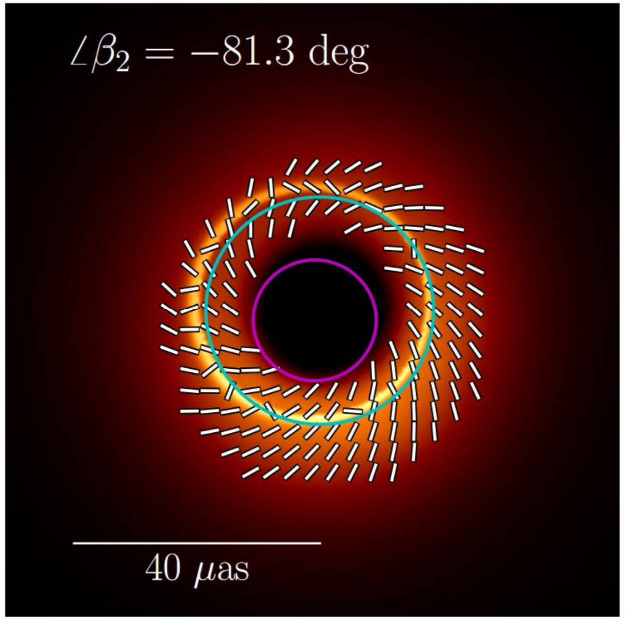
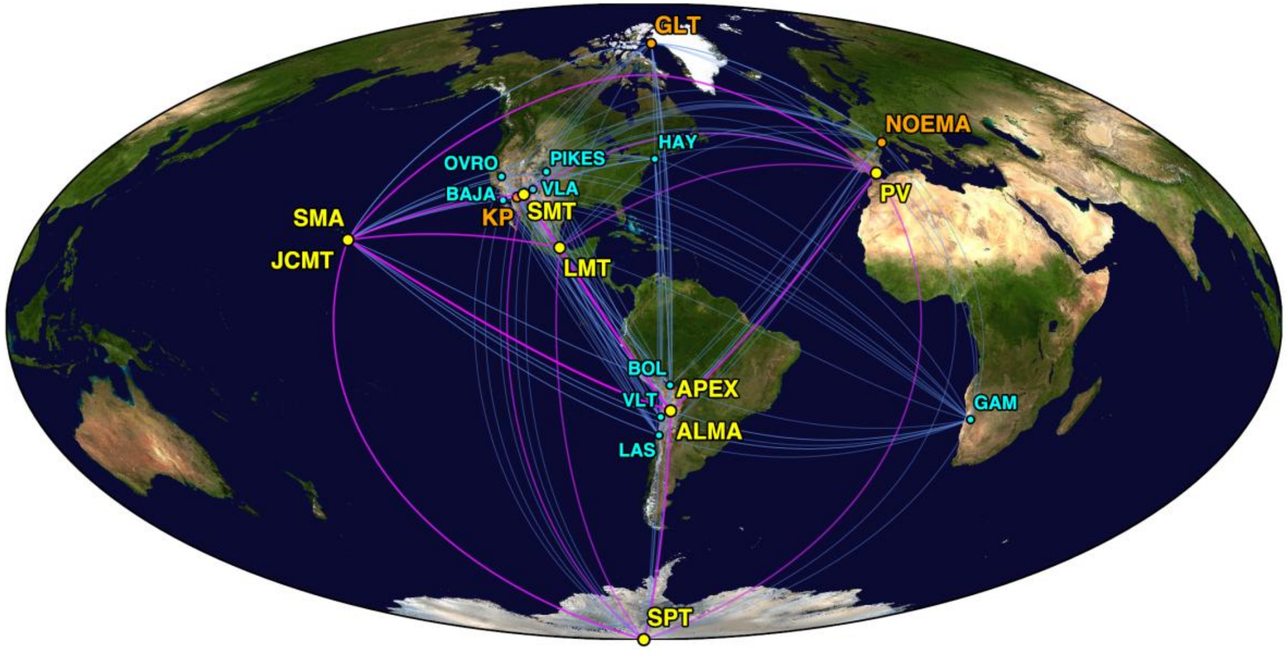
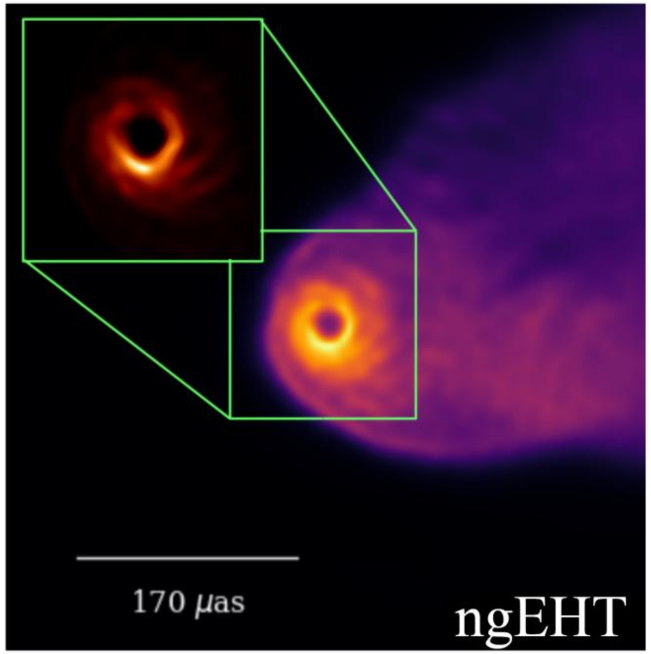


Image field lines close to the event horizon in **high resolution**

Filling in the EHT's lens: new ground sites

ngEHT concept (Doeleman+ 2023)





Increased coverage from new sites and observing frequencies will map out the black hole-jet connection and improve time resolution in Sgr A*

2017: Observations at 6 distinct sites
2018: Observations at 7 sites (+ GLT)
2021: Observations at 9 sites (+ Kitt Peak & NOEMA)
2024: 345 GHz observations
2030s: new sites in Tenerife (TEA), Namibia (AMT)….

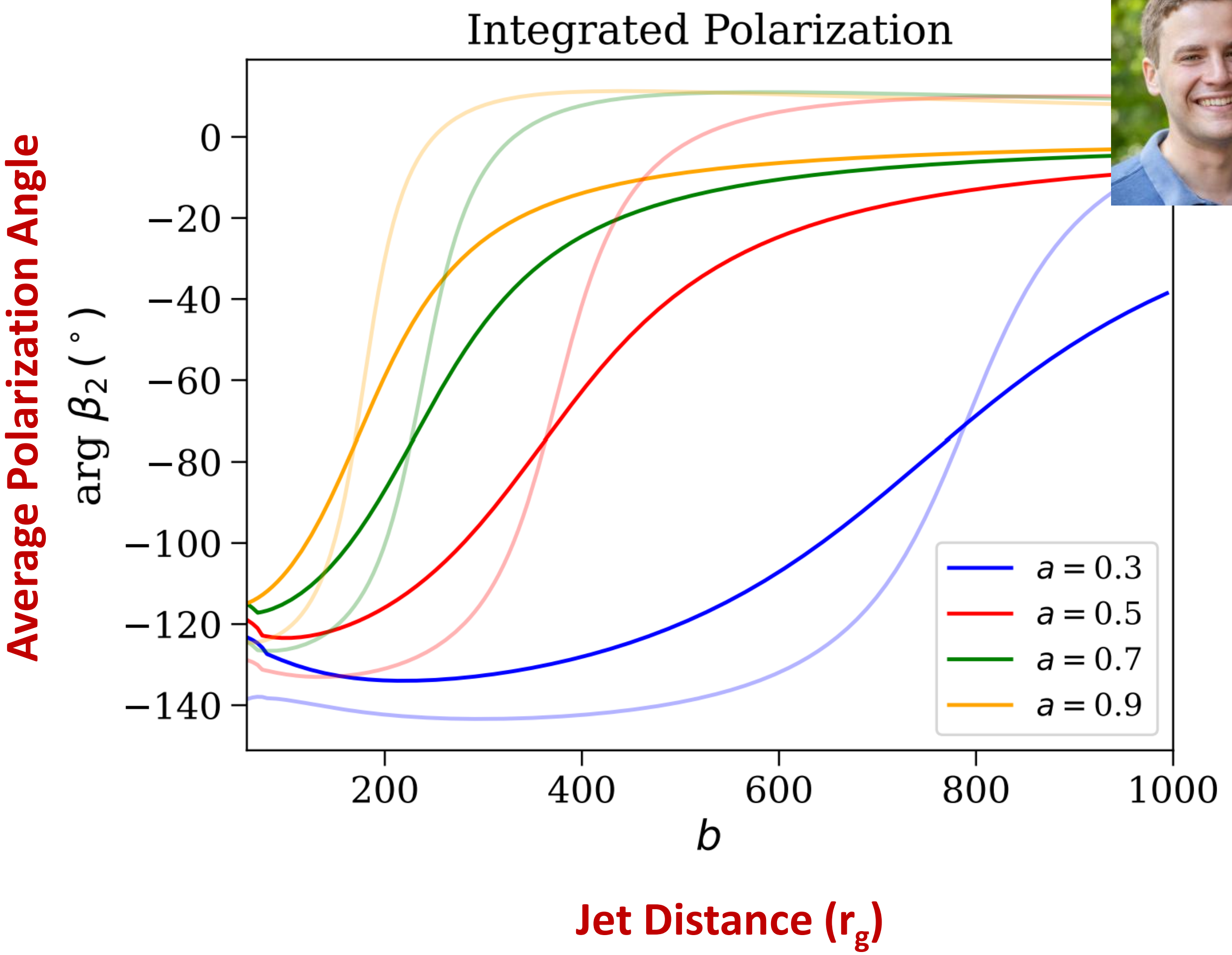
$$N_{\mathrm{obs}} = \binom{N_{\mathrm{sites}}}{2} \propto N_{\mathrm{sites}}^2$$

Image credits: Blackburn+ 2019, Doeleman+ 2023

High Dynamic Range Jet Polarimetry Constrains BH spin

See poster by Zack Gelles!
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)



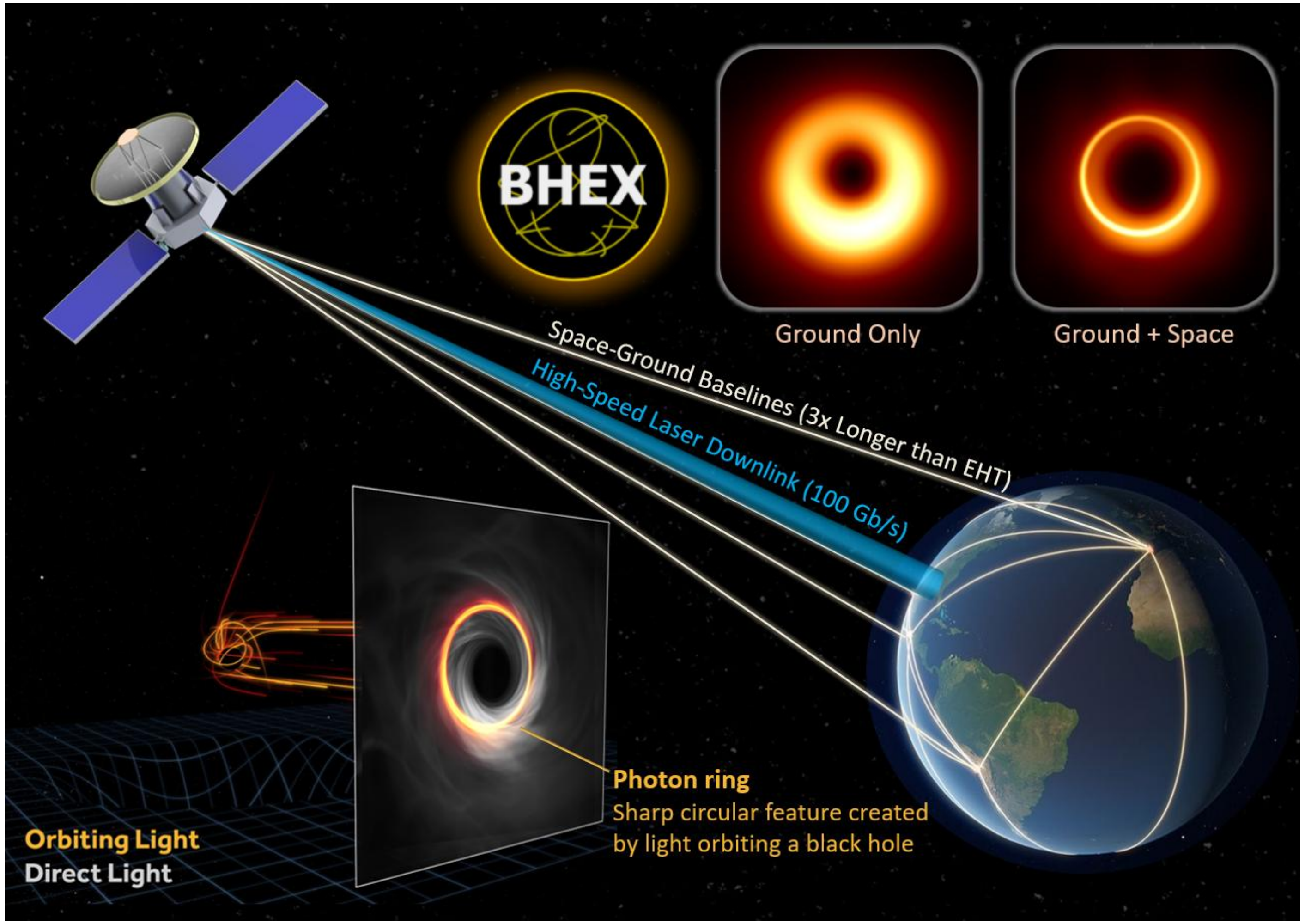
Gelles+ 25, Gelles+ 26

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 (~70 days!)

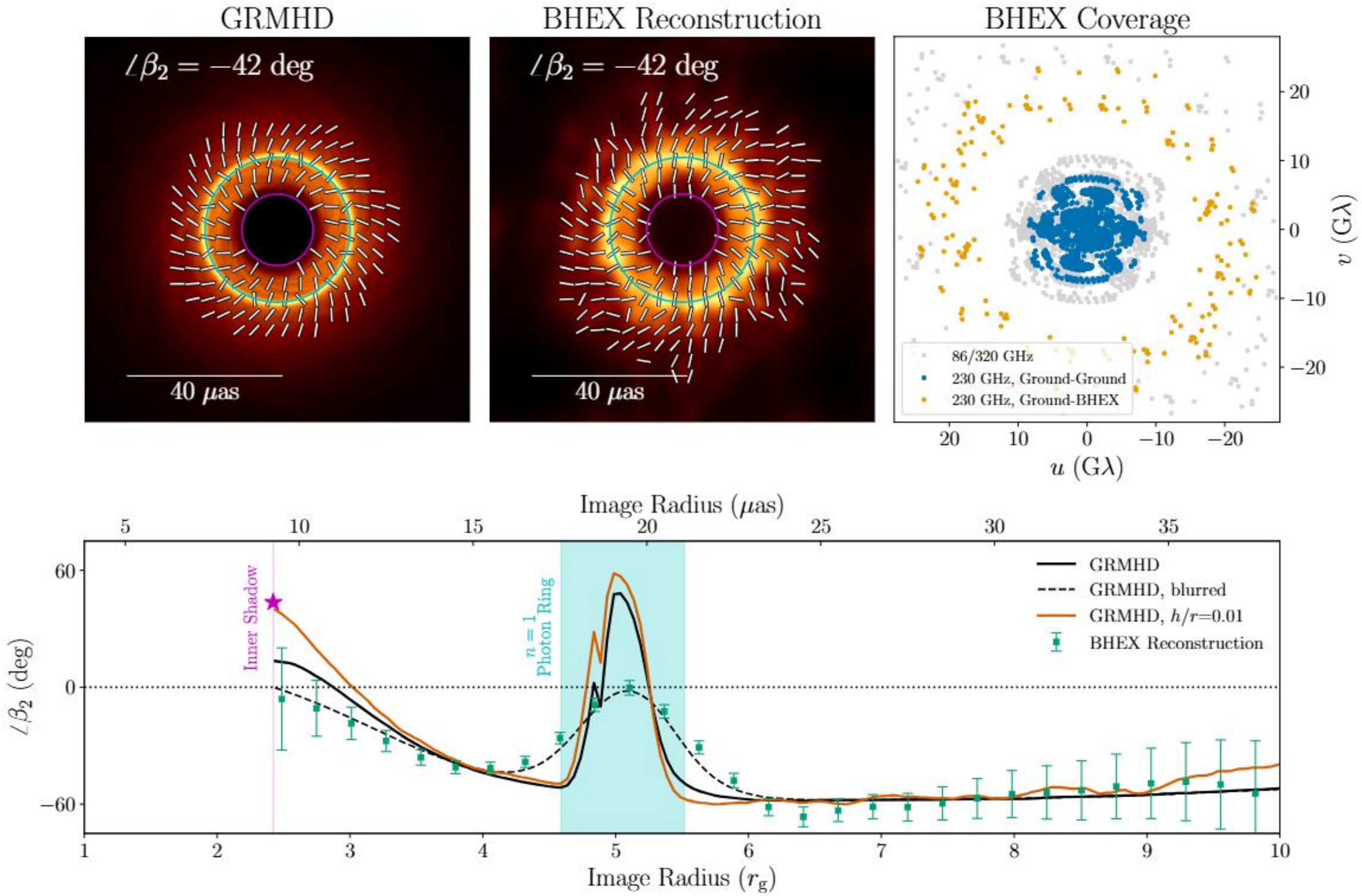
See upcoming talk by Michael Johnson



BHEX will probe horizon-threading magnetic field lines

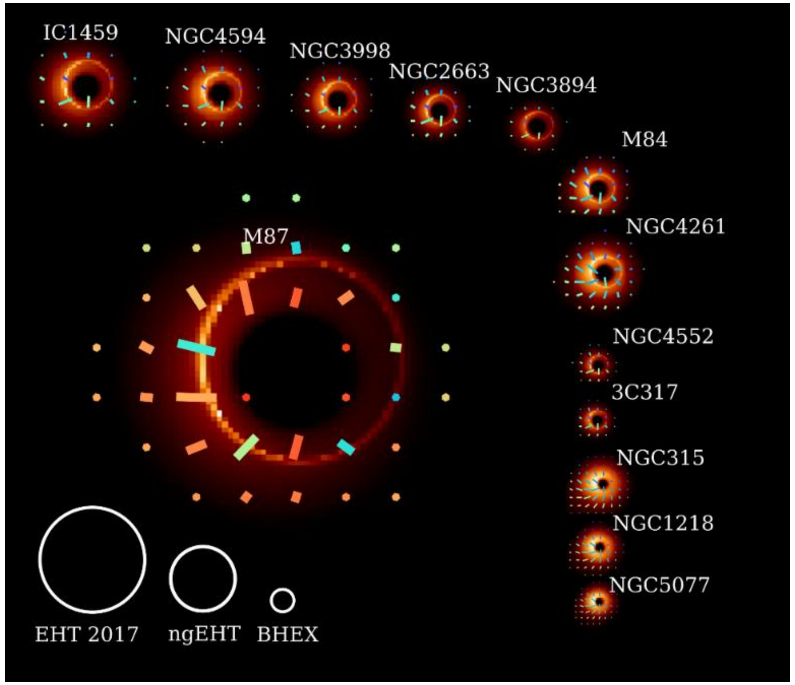
- Polarization evolves rapidly toward the unique horizon value due to both **frame dragging** and **parallel transport** (Chael+ 2026)

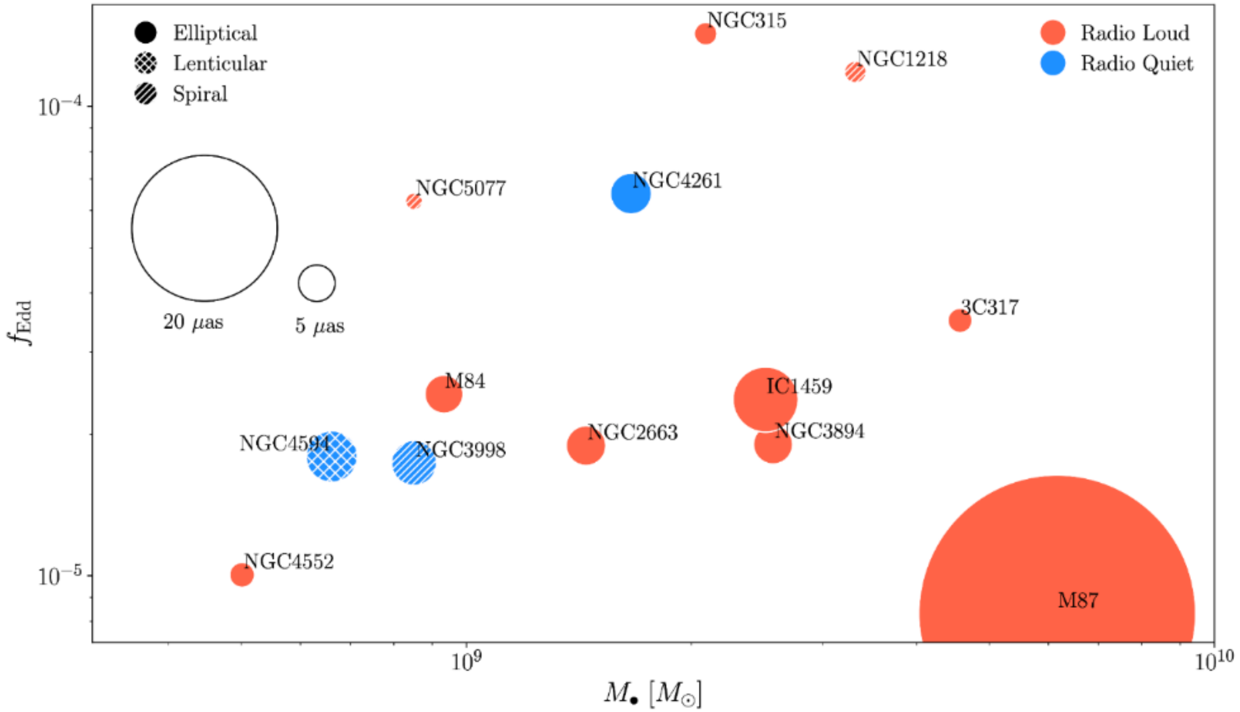
- **BHEX + EHT can obtain the resolution to observe this evolution,** directly probing field lines that penetrate the ergosphere and extract energy from the black hole



Chael+ 2026

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

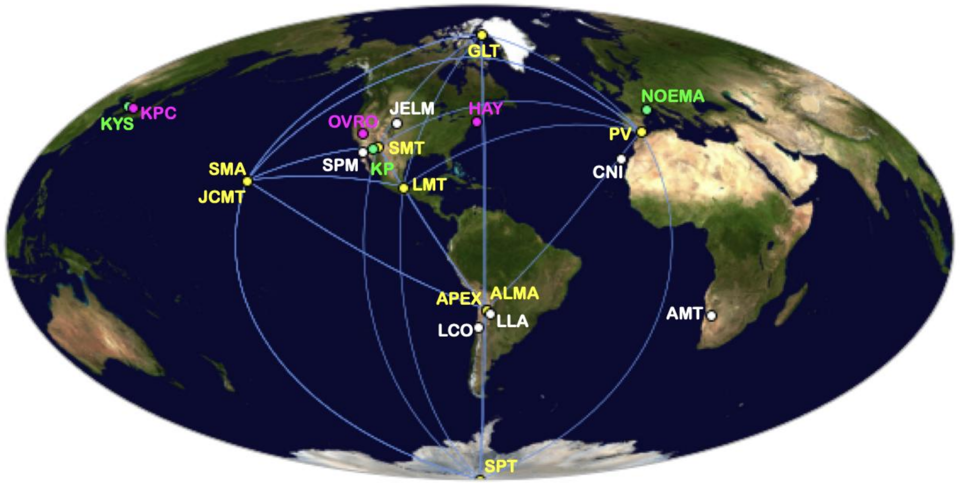
BHEX will determine how the near-horizon black hole environment changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties

Zhang, Ricarte+ 2024

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

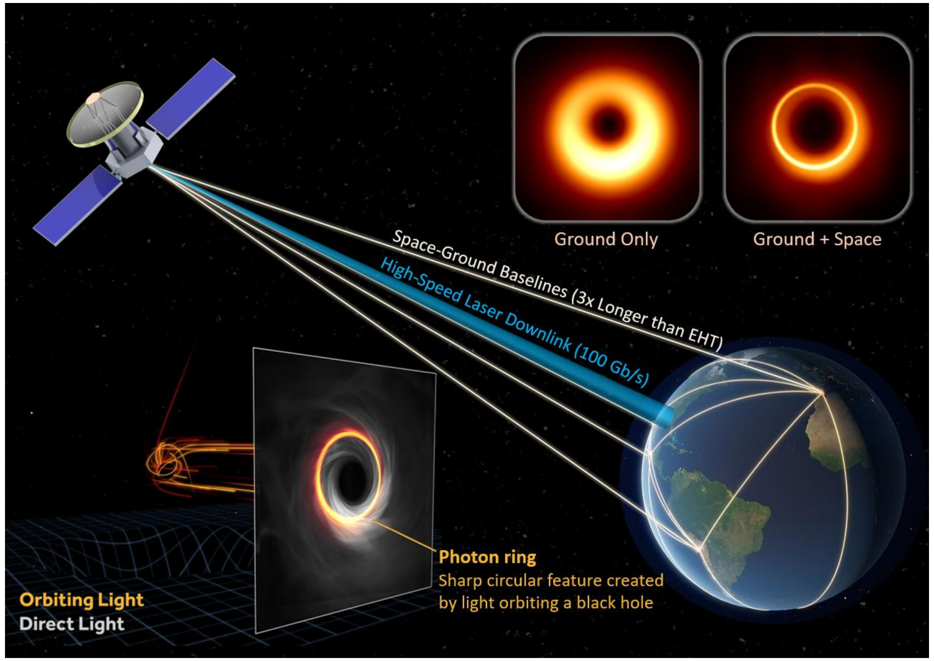
The future of near-horizon black hole astrophysics

Expanded ground-based EHT array



- Expand all EHT sites to multi-frequency observing and add 4-5 new stations (e.g. Doeleman+ 2023)
- 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)

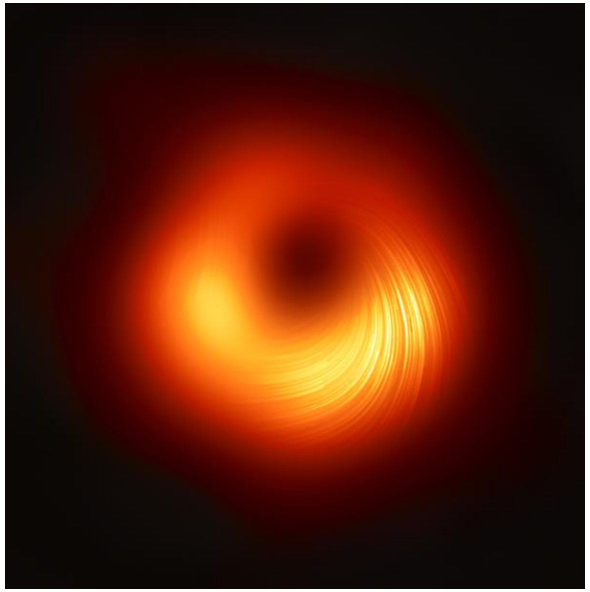


- NASA SMEX proposal for a mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to ~12 (Zhang+ 2024)

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

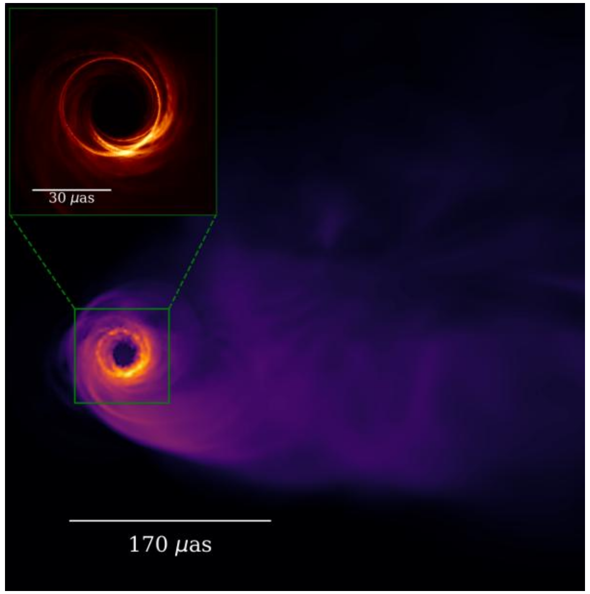
Takeaways…

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 astrophysics
3. EHT polarization images are consistent with **magnetically arrested accretion** and **outward electromagnetic energy flux**
4. **Future ground and space-based VLBI observations** will directly probe the black hole-jet connection at the horizon scale



…and more questions

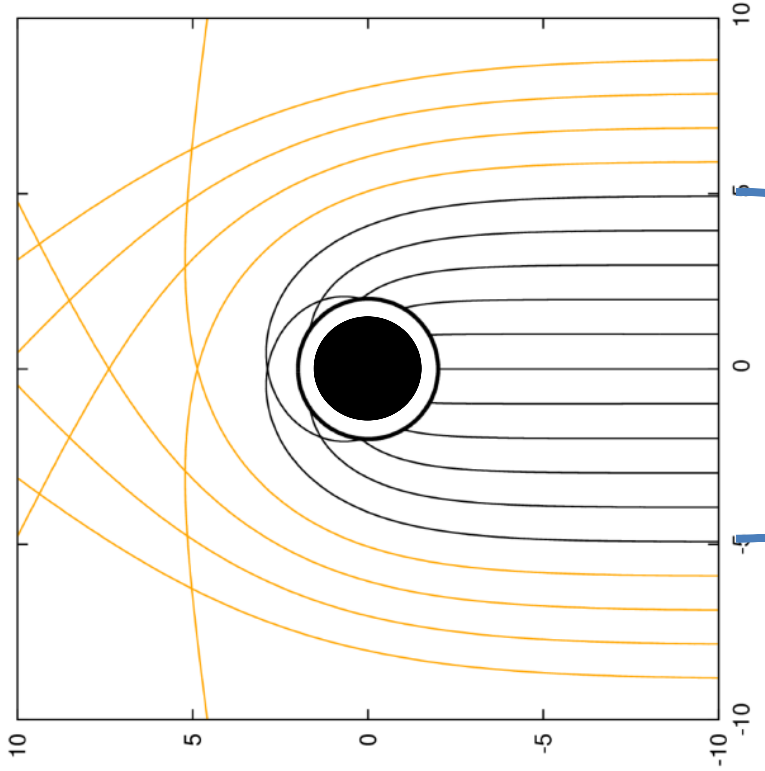
- How do we explain the preference for cool electrons in M87 and Sgr A*?
- Can we improve our simulations to account for the unexpected variability properties at the horizon scale?
- What powers flares in Sgr A* and M87* and can we directly connect horizon-scale observations to multiwavelegth constrains?
- What can EHT/BHEX observation tell us about near-horizon physics in supermassive black holes beyond Sgr A* and M87*?



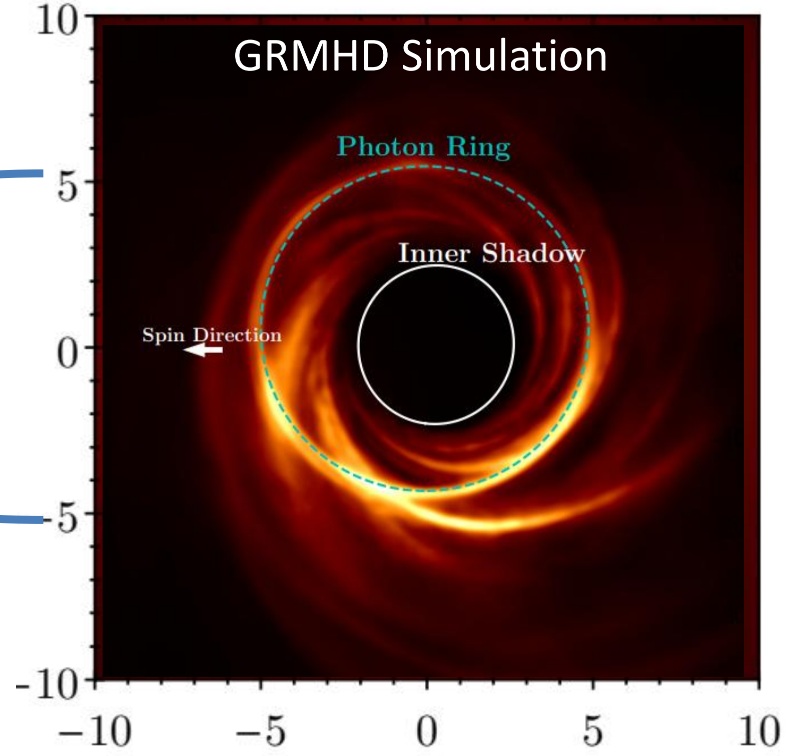
EHT VII, 2021; **Chael** 2025

backup slides

The Black Hole Shadow



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



Shadow sizes on the sky:

Sgr A*: ~50 μas

M87*: ~40 μas

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

EHT Multi-wavelength partners

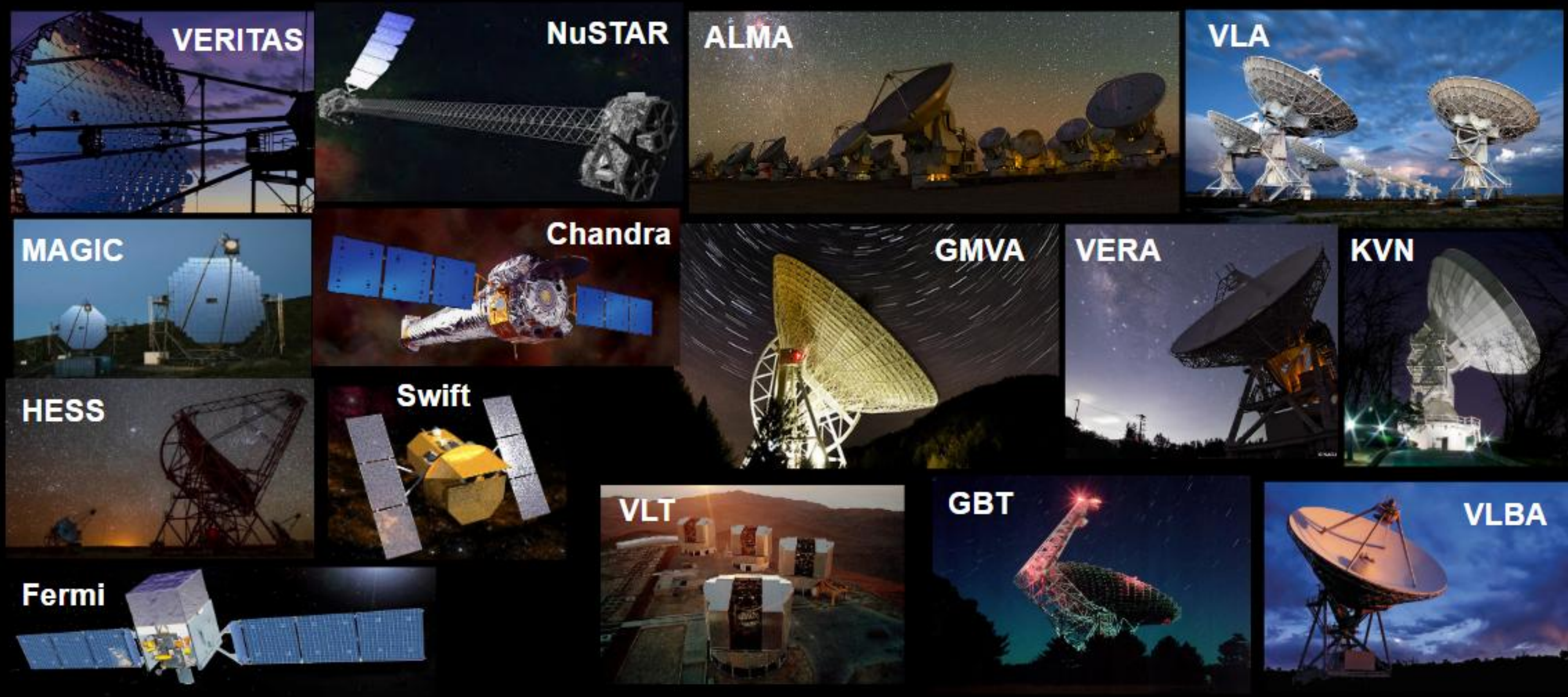


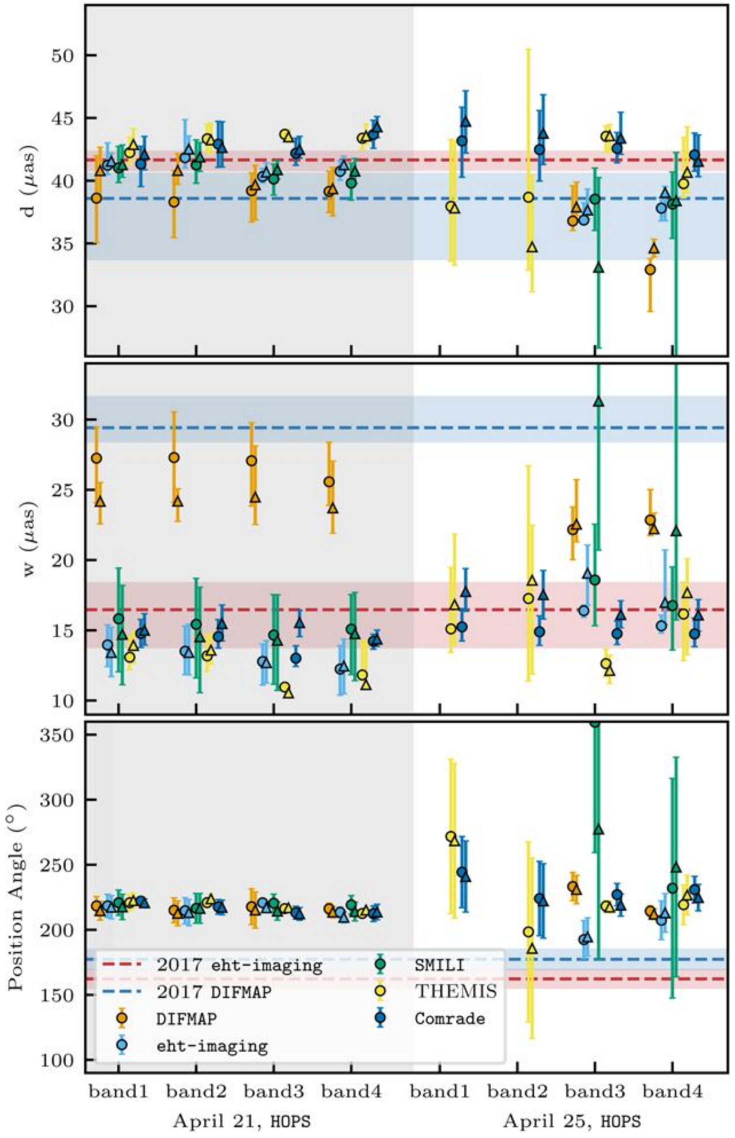
Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

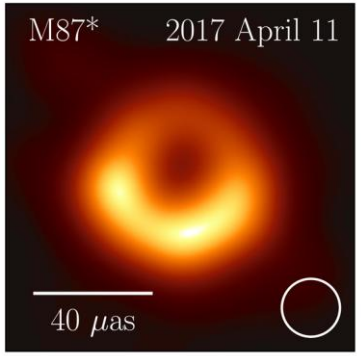
Slide credit: Sara Issaoun

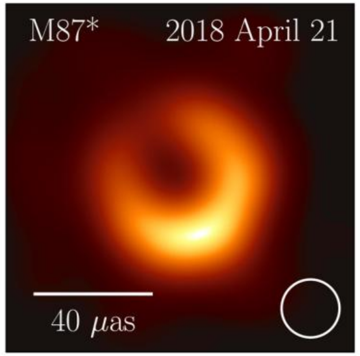
M87* Ring Properties (2017-2018)

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

UPDATE





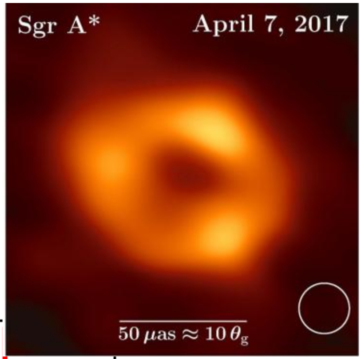


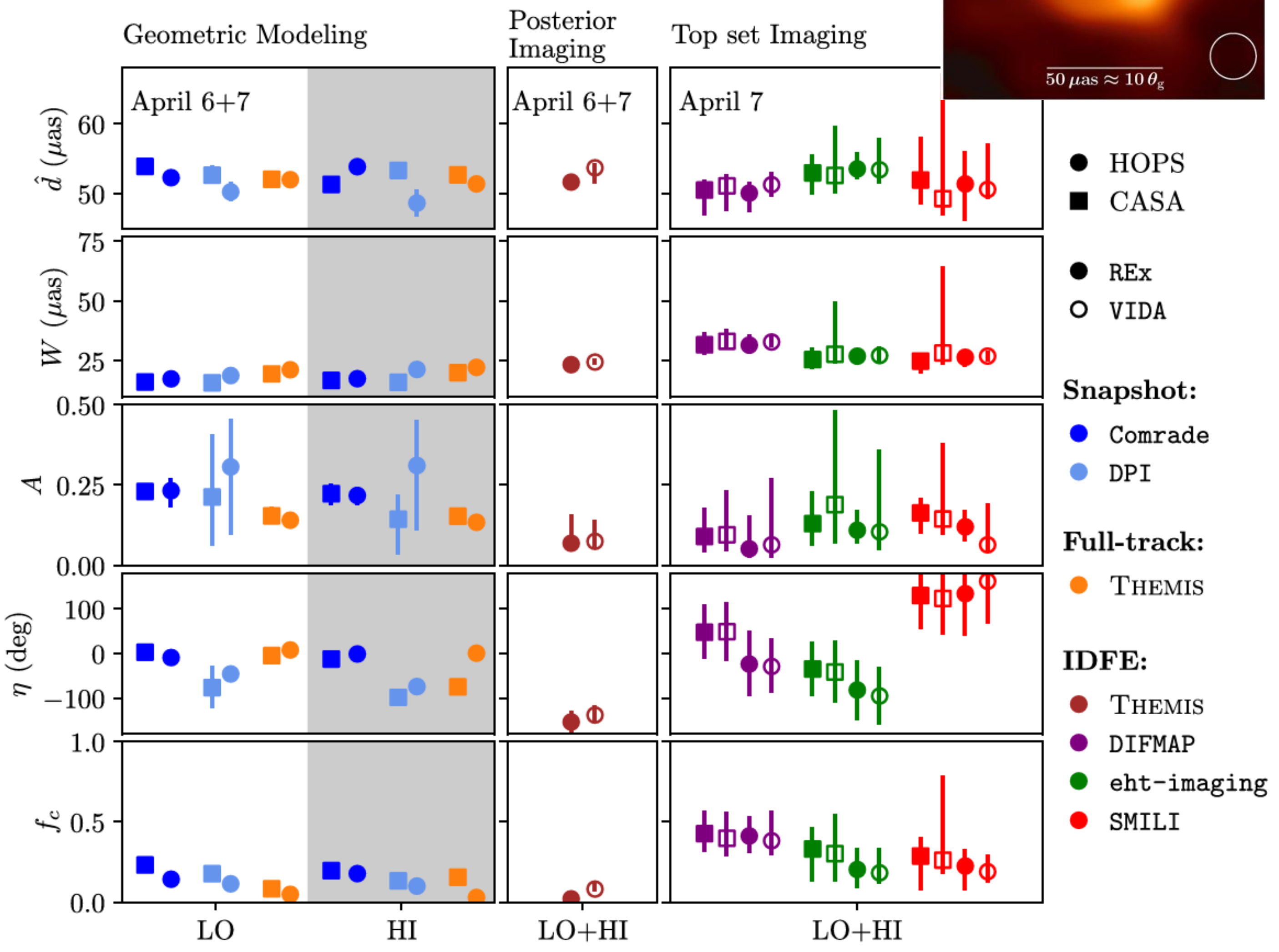
Sgr A* Ring properties

- Sgr A* ring diameter is well measured and consistent with 4.3 x 10^6 solar mass black hole at the Galactic Center: $d = 51.8 \pm 2.3\,\mu\mathrm{as}$

- Sgr A* ring width is better resolved than M87* and is consistently recovered across methods: $w/d = 0.3 - 0.5$

- Sgr A* ring asymmetry/position angle are not consistently recovered.



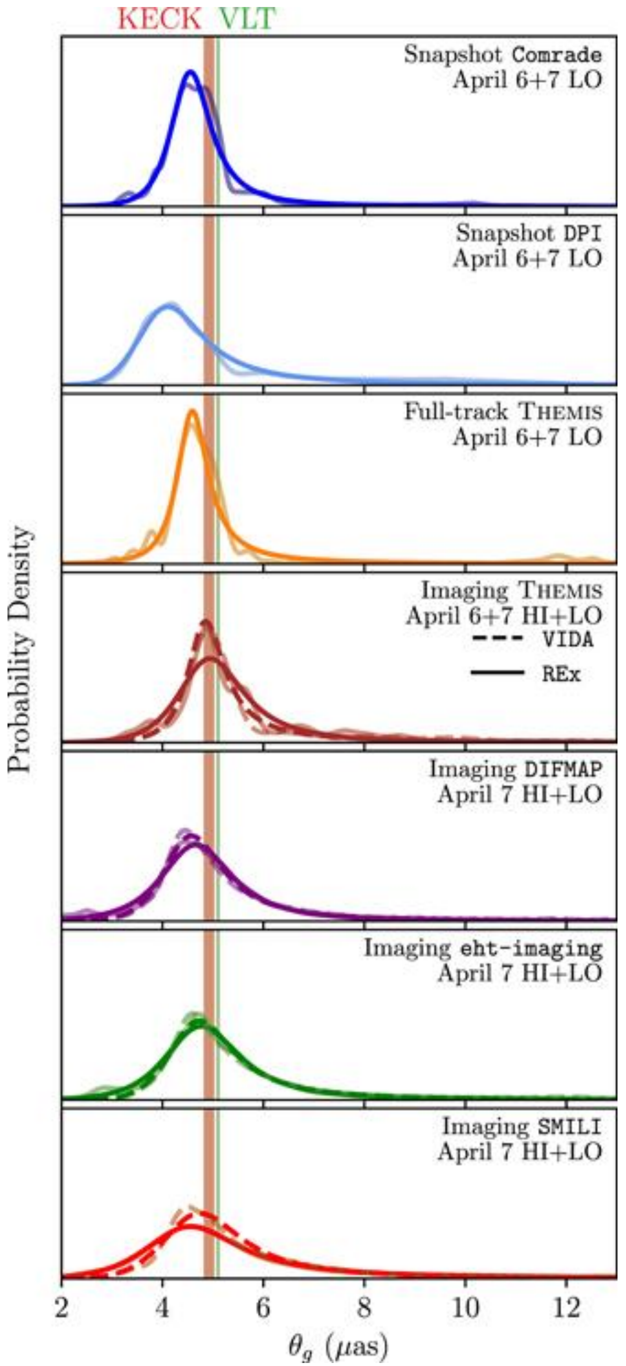


EHTC IV, 2022

EHT Mass Measurements

Sgr A* (EHTC+ 2022 IV,VI)

- $\theta_g = 4.8^{+1.4}_{-0.7} \mu$as (from all pipelines)
- $M = 4.0^{+1.1}_{-0.6} \times 10^6 M_\odot$ (using distance measurement from Reid+ 2019)
- Consistent with measurements from stellar orbits (Do+2019, GRAVITY+ 2020), but 25x less precise
- Less precise than M87* EHT mass because of increased uncertainty in α from unknown inclination



Independent Sgr A* imaging and modeling pipelines

EHT Mass Measurements

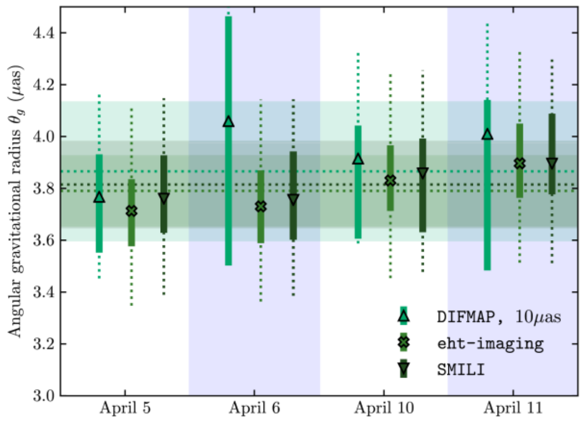
Sgr A* (EHTC+ 2022 IV,VI)

- $\theta_g = 4.8^{+1.4}_{-0.7} \mu$as (from all pipelines)
- $M = 4.0^{+1.1}_{-0.6} \times 10^6 M_{\odot}$ (using distance measurement from Reid+ 2019)
- Consistent with measurements from stellar orbits (Do+2019, GRAVITY+ 2020), but 25x less precise
- Less precise than M87* EHT mass because of increased uncertainty in α from unknown inclination

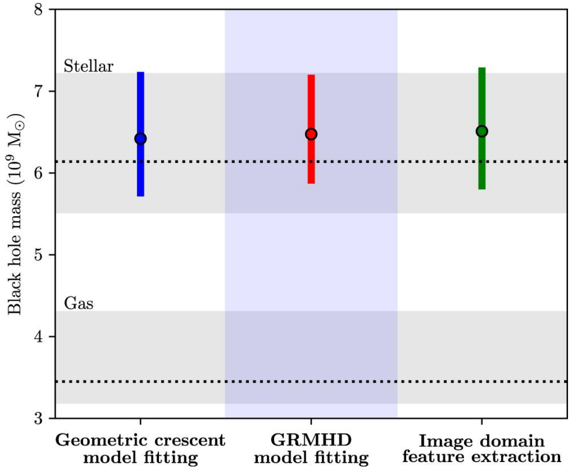
M87* (EHTC+ 2019 IV,VI, EHTC+ 2025)

- $\theta_g = 3.62^{+0.41}_{-0.34} \mu$as (from combined 2017, 2018 GRMHD fits)
- $M = 6.16^{+0.71}_{-0.57} \times 10^9 M_{\odot}$ (using distance measurements from Bird+ 2010, Blakeslee+2009, Cantiello+ 2018)
- Consistent with some mass measurements (Gebhart+2011) but in tension/inconsistent with others (Walsh+2013, Liepold+2023, Simon+2024)

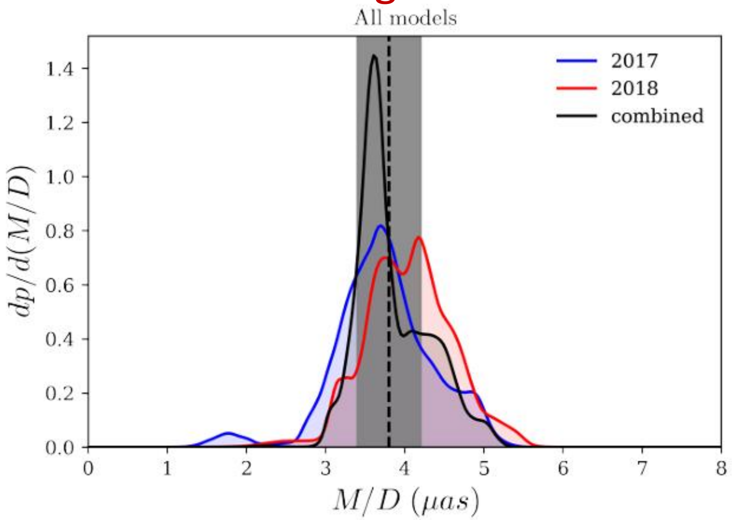
2017 M87 imaging pipelines



2017 M87 all pipeline masses



2-year M87 GRMHD fitting:

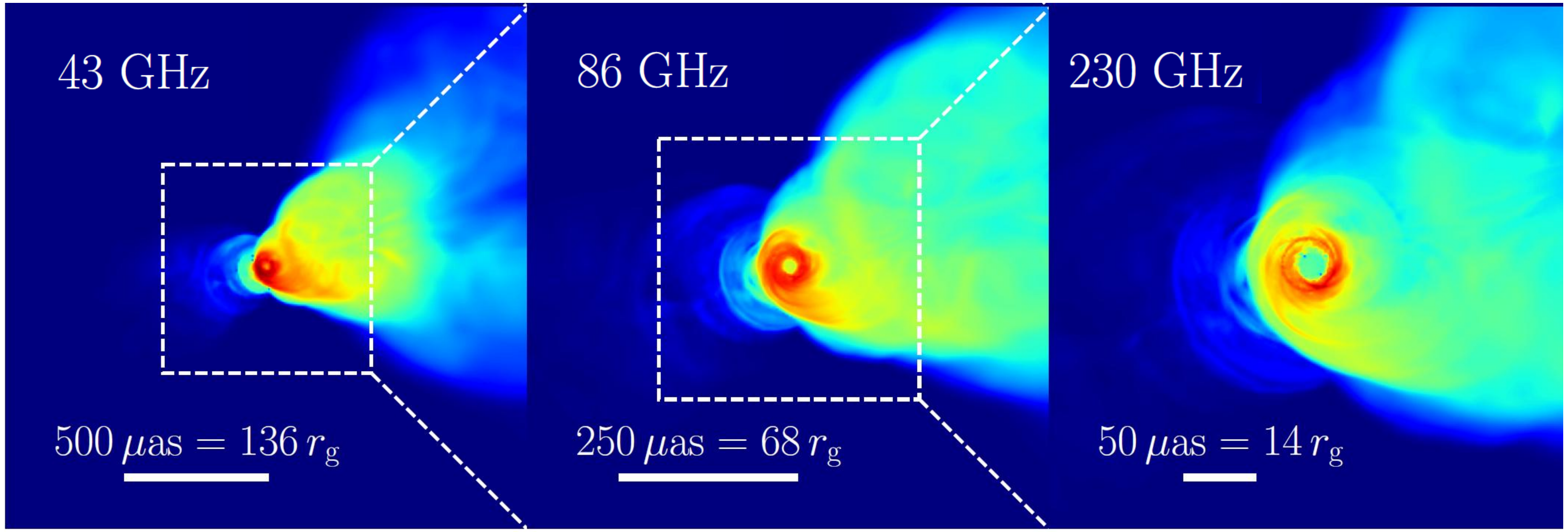


M87 Jets in GRMHD Simulations

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

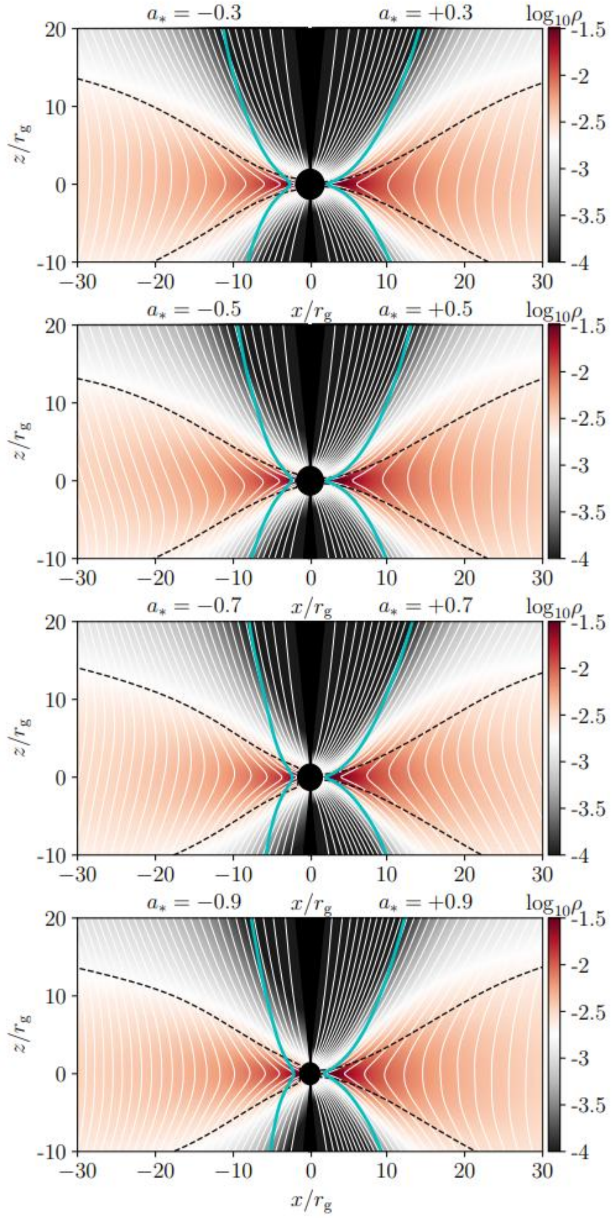
- Simulations (e.g. Chael+ 2019, 2025) naturally produce:
  - observed jet power
  - observed wide opening angle
  - observed core-shift

- Can we be **sure?** What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?



Chael+ 2019

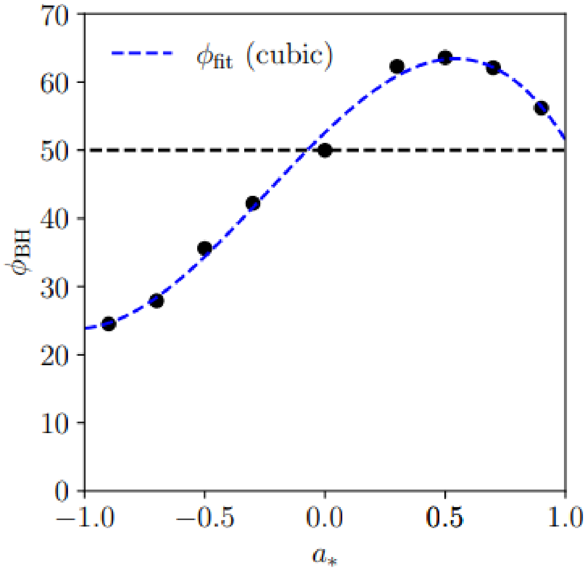
Jets in simulations are spin powered



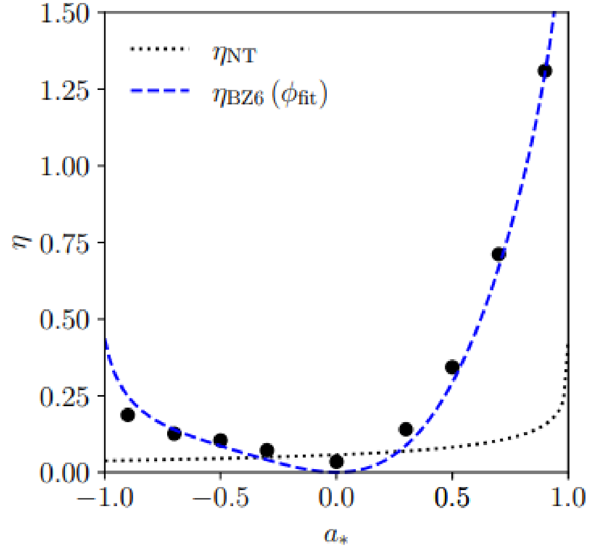
Time-and azimuth-averaged simulation data

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

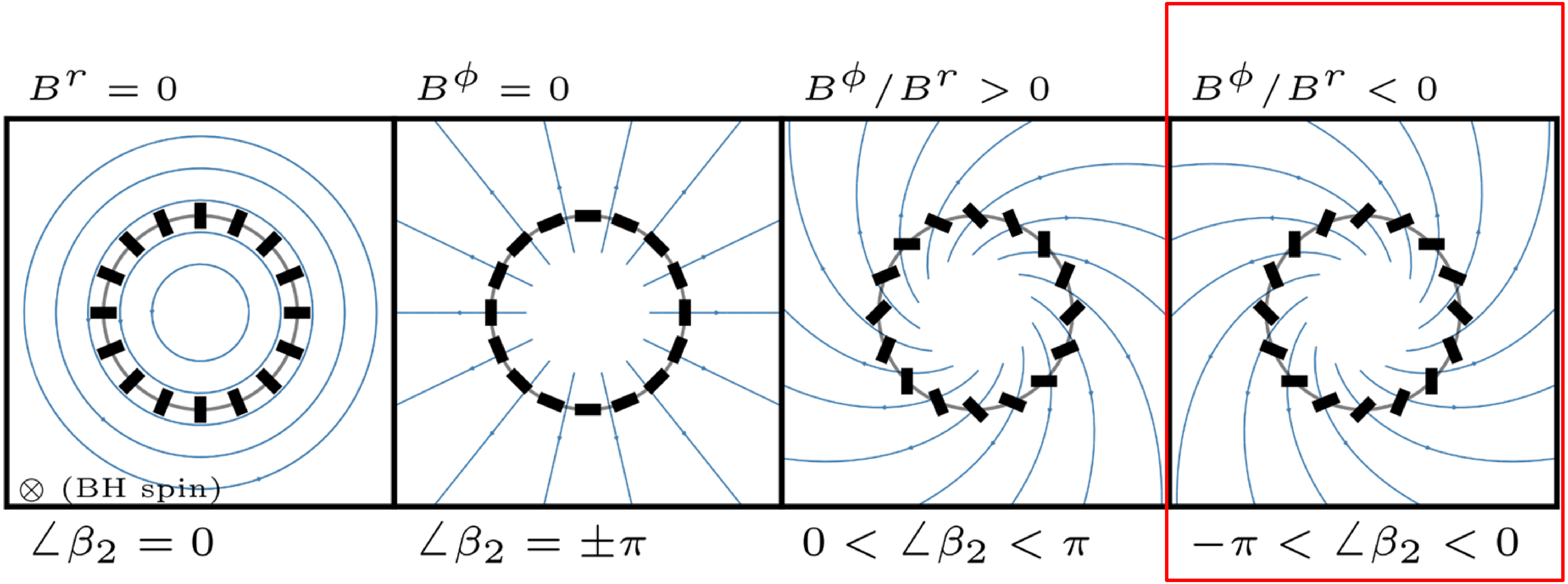


BH spin

R. Narayan, **A. Chael +** 2022

Tchekhovskoy+ 2012, Lowell+ 2023, Ricarte+ 2023, Guo+ 2025

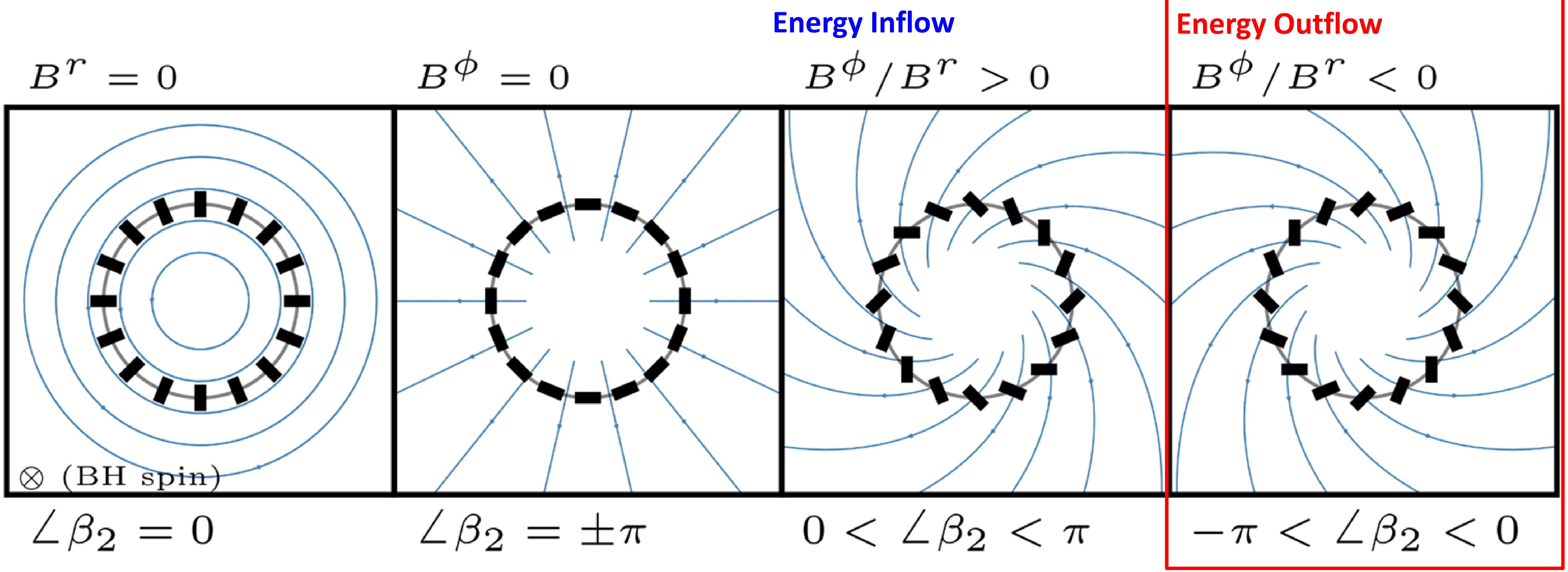
Horizon-scale polarization tracks the **magnetic pitch angle**



- 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

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

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



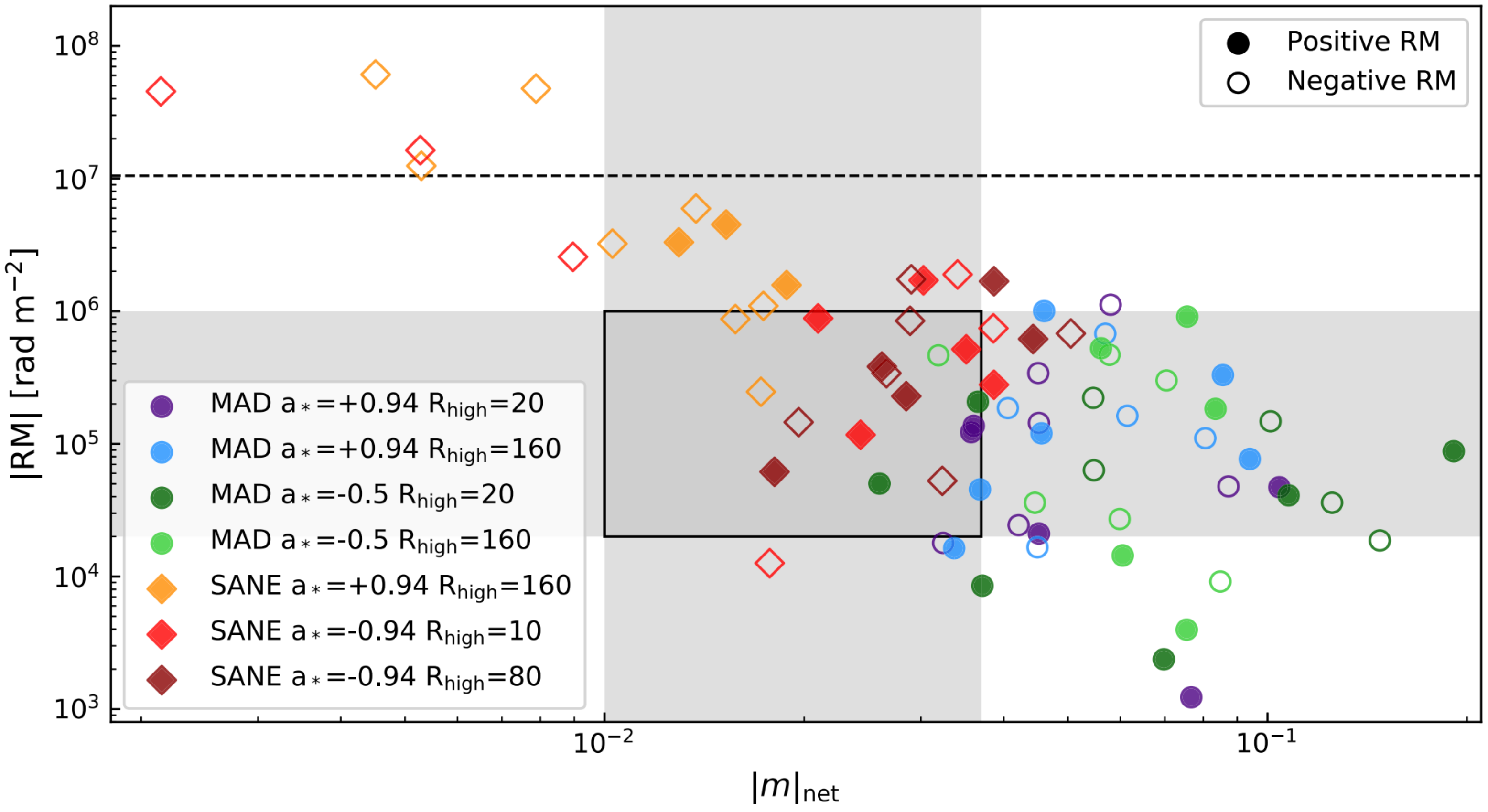
The direction of radial Poynting flux in GRMHD is set determined by B^ϕ / B^r :

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

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

Chael+ 2023b

GRMHD simulations can explain M87’s Rotation Measure



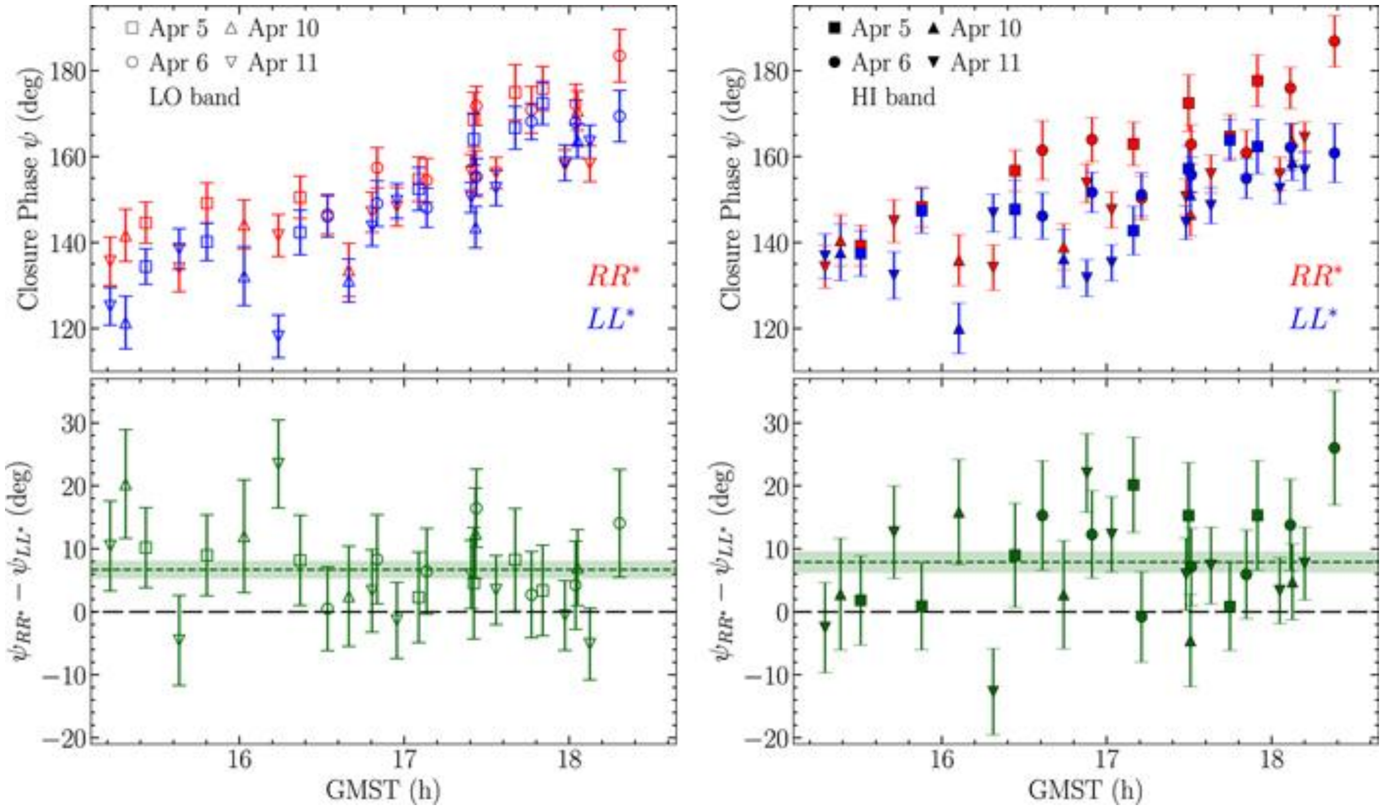
Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

Credit: EHTC 2021 Paper VIII

Angelo Ricarte

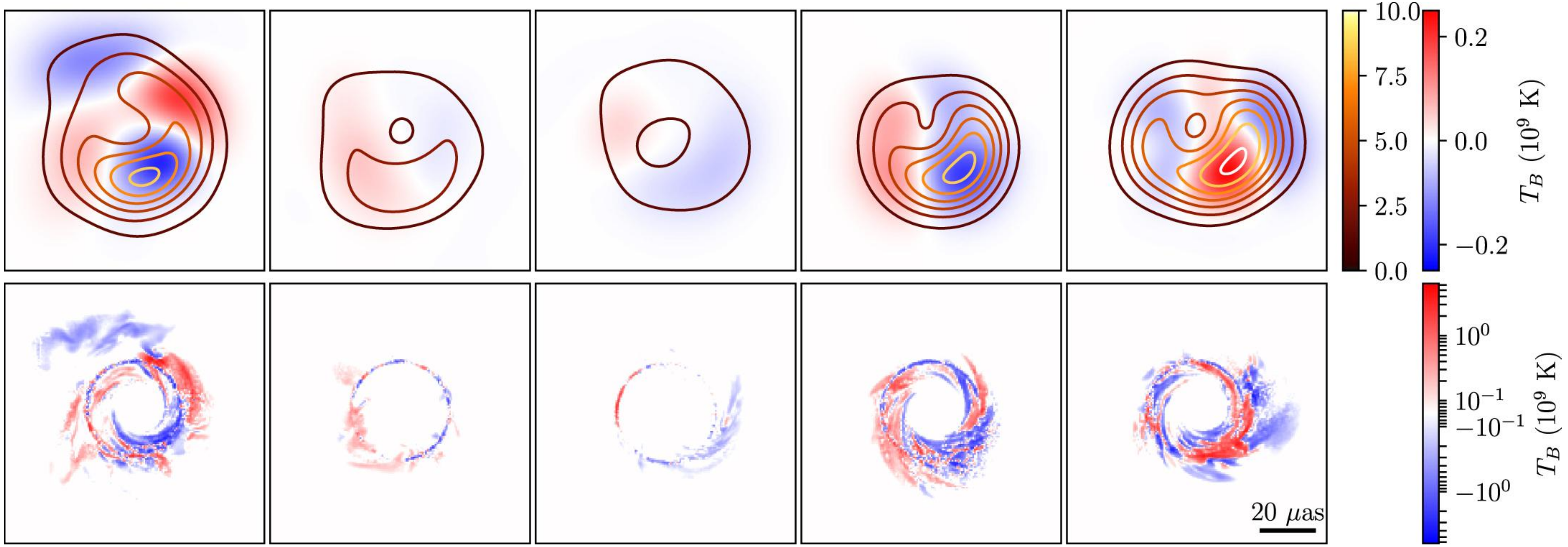
Horizon-Scale **circular polarization** is unambiguously detected by the EHT

- We detect an **offset** between robust **closure phases** in the RR and LL polarizations in both M87* and Sgr A*.
- Clear evidence of modest circular polarization in black hole images.
- Limited sensitivity and systematic gain uncertainty means we **cannot currently constrain the image structure** in circular polarization.



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

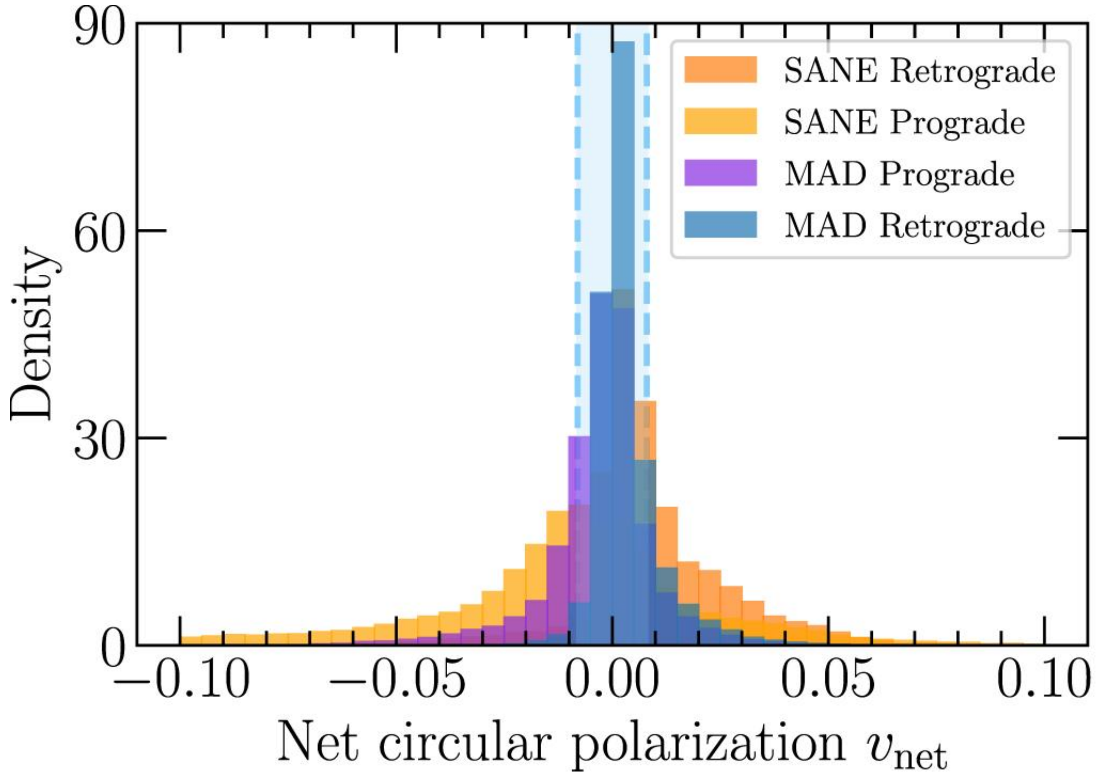
Passing simulations have **diverse circular polarization images**

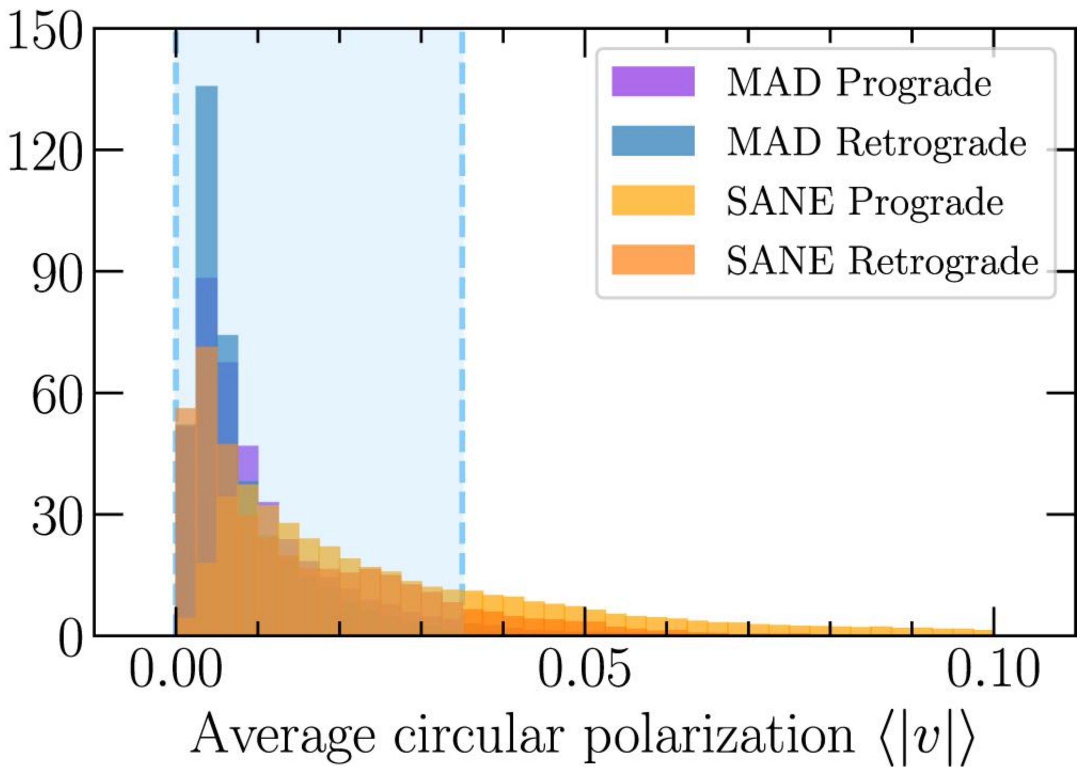


Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

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

GRMHD simulations naturally produce low circular polarization



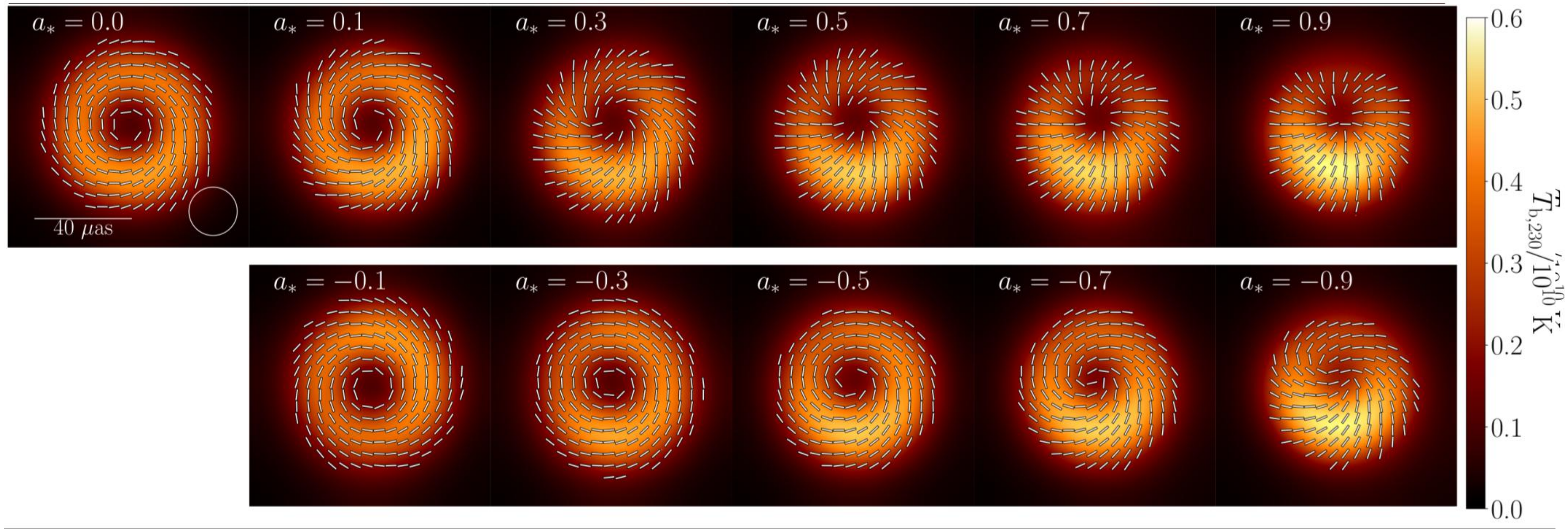


$$v_{\rm net} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

$$\langle|v|\rangle = \frac{\int |\mathcal{V}/\mathcal{I}|\, \mathcal{I}\, dA}{\int \mathcal{I}\, dA};$$

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

Connecting plasma physics to BH simulations



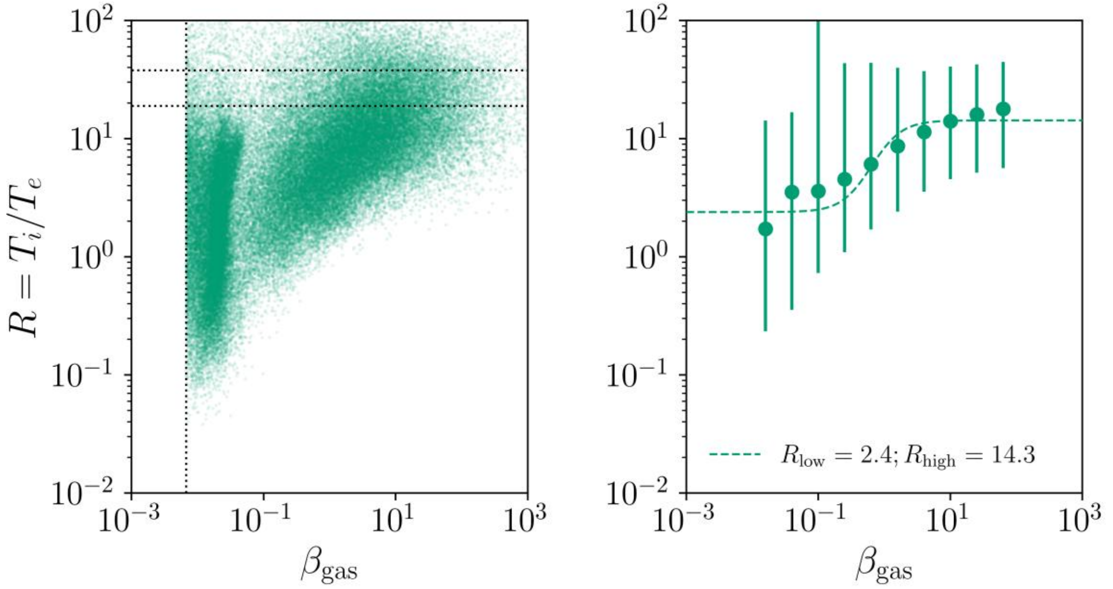
- **Two-temperature** GRMHD simulations evolve electron and ion temperatures separately, coupled to radiation and a **sub-grid model for electron-ion plasma heating**
- In Chael 2025 we conduct the first large survey of two-temperature simulations of M87* across black hole spin using a model for electron heating from Landau-damped turbulence (Kawazura+ 2019)

Chael 2025

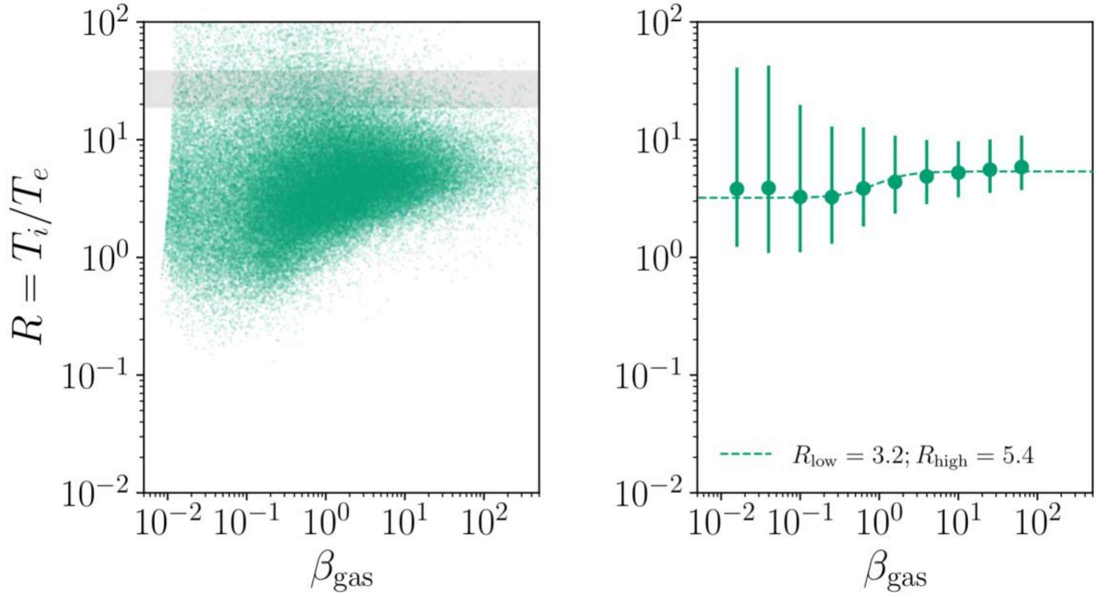
ee also: Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019,** Dexter+ 2020,2021, Mizuno+ 2021, Moscibrodzka+ 2024, Salas+ 2024

What about different plasma heating mechanisms?

Heating from Magnetic Reconnection (Rowan+ 2019; Chael+ 2019)



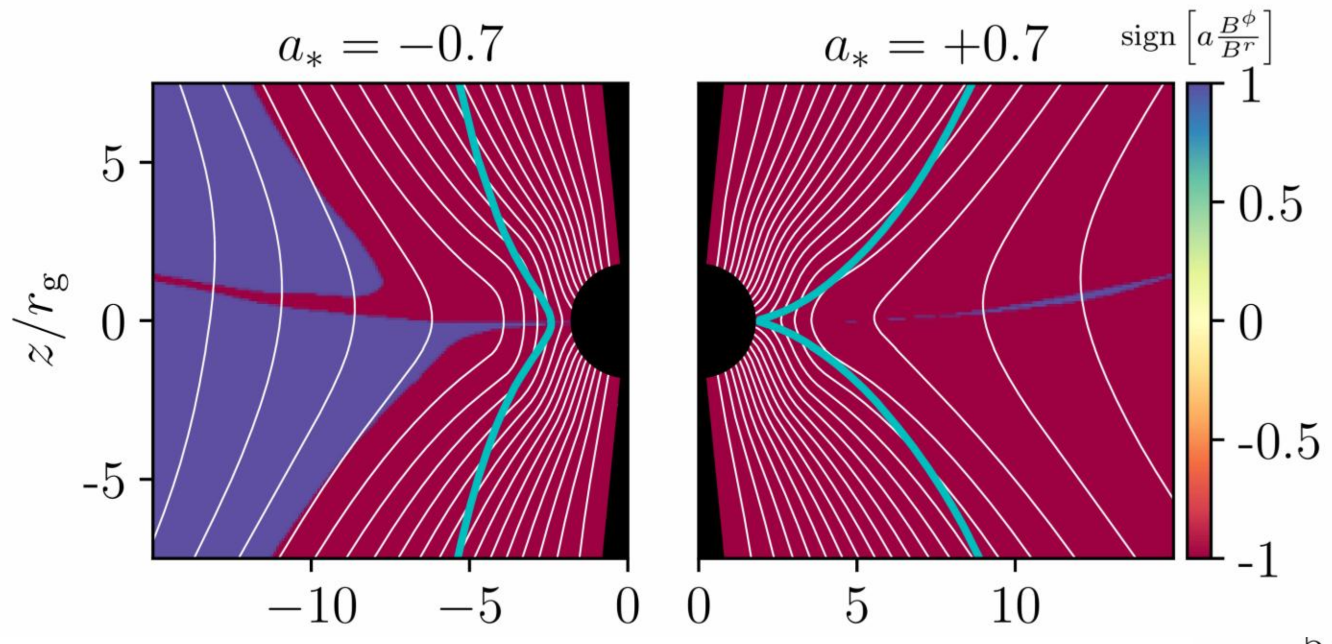
Heating from Landau Damped Turbulence (Kawazura+ 2019)



Using a sub-grid heating model based on magnetic reconnection heating produces slightly cooler electrons (*R*~15) but still not nearly cold enough to match preferred value from EHT observations (*R*>50)

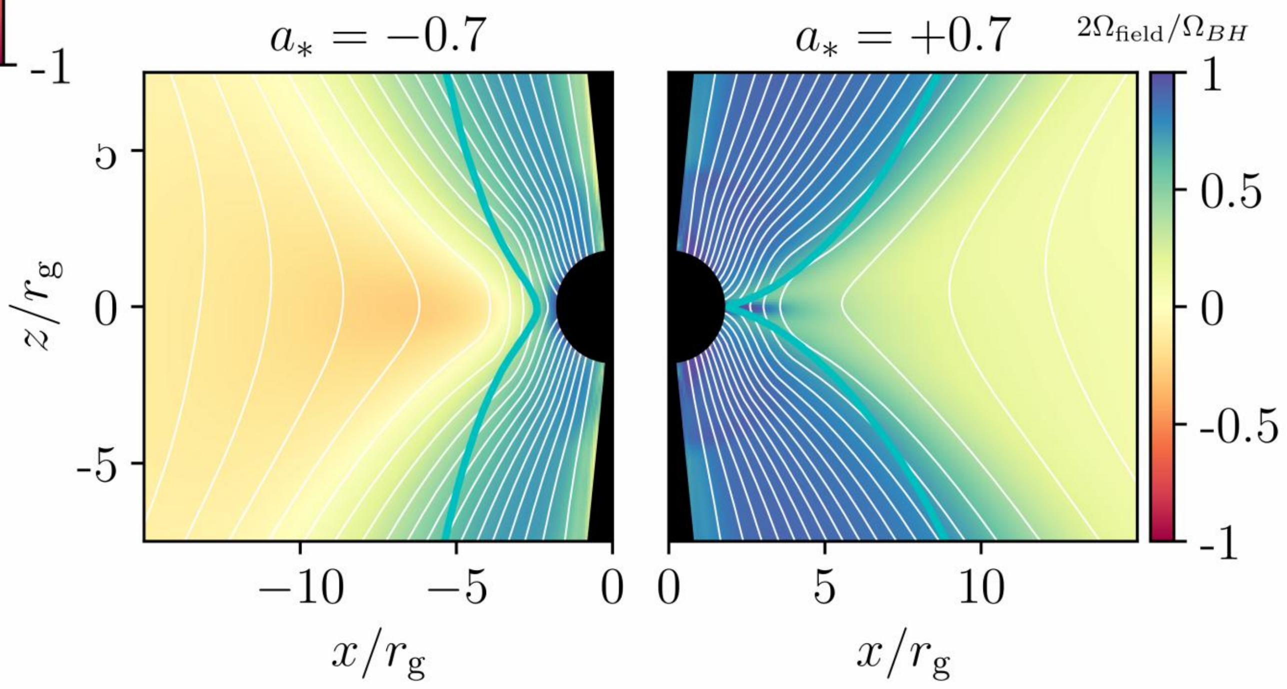
Chael+ 2019, Chael 2025

In GRMHD, energy-extracting fieldlines set $\arg(\beta_2)$



Sign of magnetic field pitch angle

Field-line angular speed



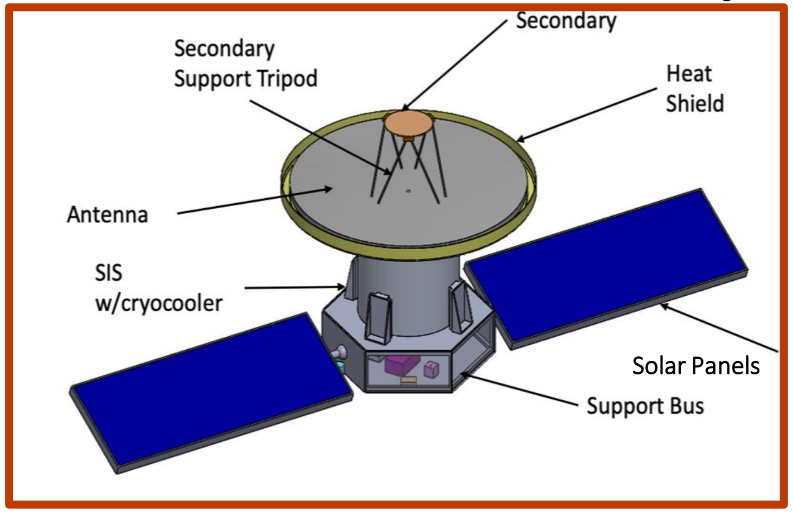
Even in **retrograde** simulations, field-lines in the 230 GHz emission region **co-rotate** with the black hole and have a negative B^ϕ / B^r

Chael+ 2023

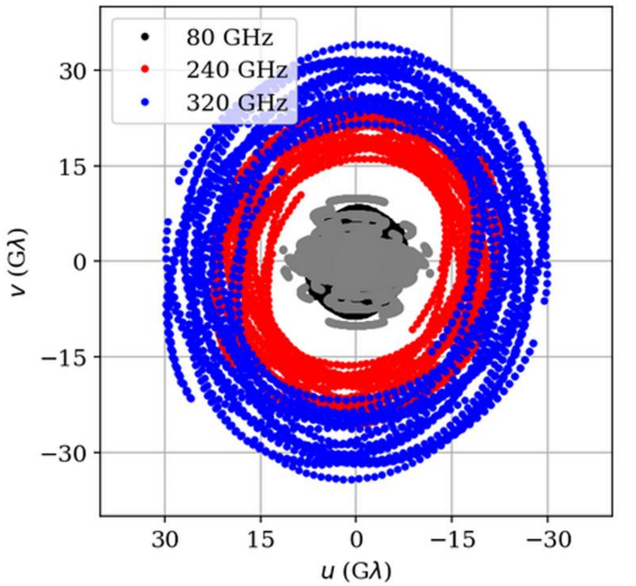
Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022, Wong+ 2021

The Black Hole Explorer (BHEX)

Spacecraft



Example M87 *u-v* coverage



Aggregate coverage over 24 hours

Figures: D. Marrone (top) / D. Palumbo (bottom)

Mission Parameters

- 3.4m Antenna, 30um surface, shaded
- Simultaneous dual-band observations (80-106 + 240-320 GHz)
- 48 GHz of sampled bandwidth (64 Gb/s)
- Orbit: ~20,000 km altitude
- Lifetime: 2+ years
- Telemetry: 100 Gbps using laser communications

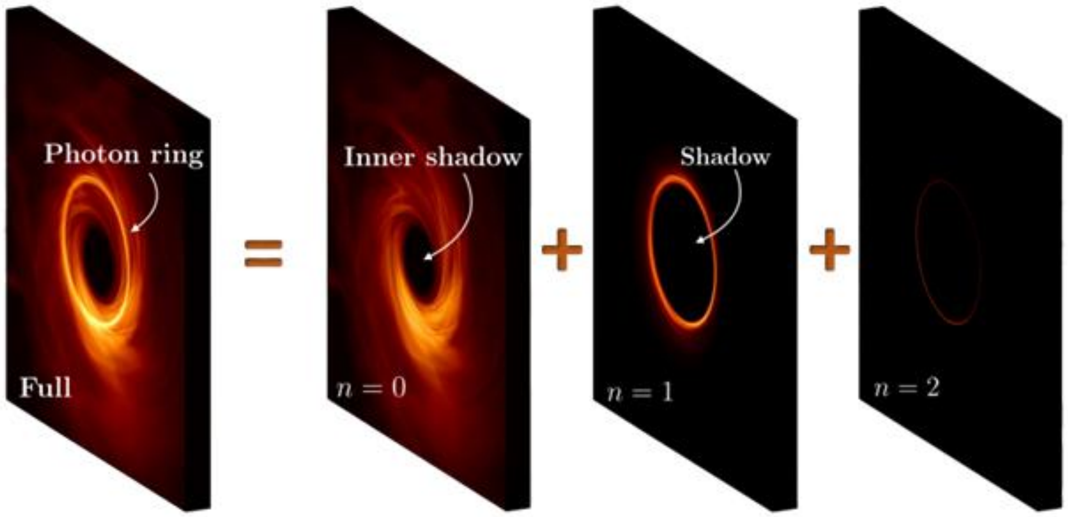
- **Targeting next NASA SMEX call**
- **Fact Sheet: blackholeexplorer.org/fact-sheet**
- **Series of SPIE papers: arXiv 2406.12917**
- **Open science plenary calls every month**
  - **We are always interested in new ideas for BHEX jet science!**
  - **Particularly potential multi-wavelength connections**

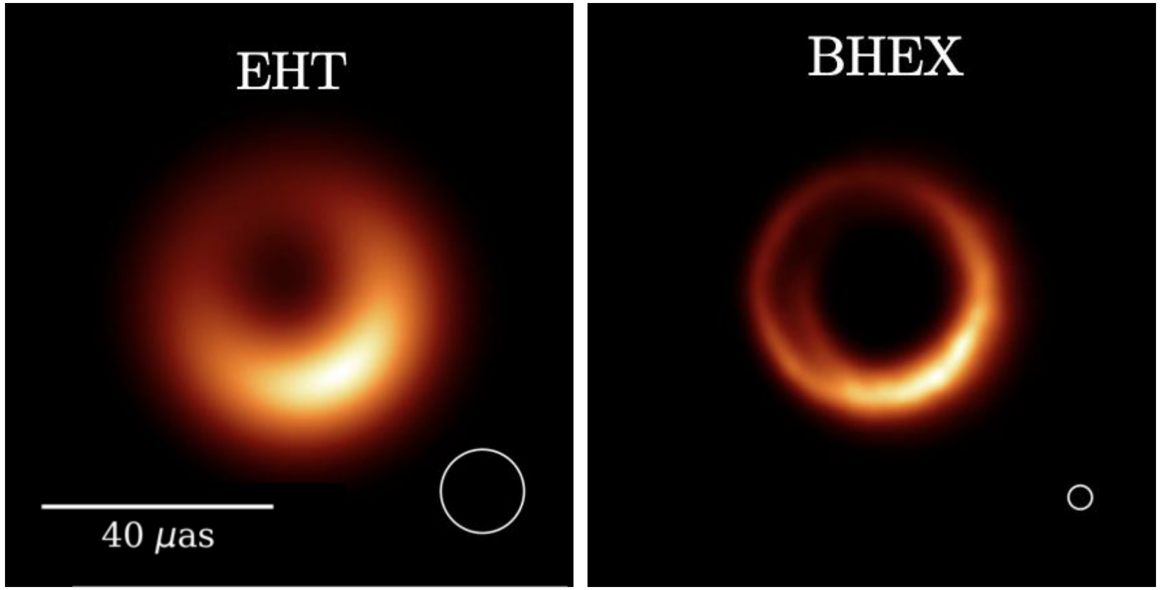
Direct Photon Ring Mass & Spin Measurements with BHEX

“direct” emission

rays Corat > 180 deg

rays Corat > 360 deg

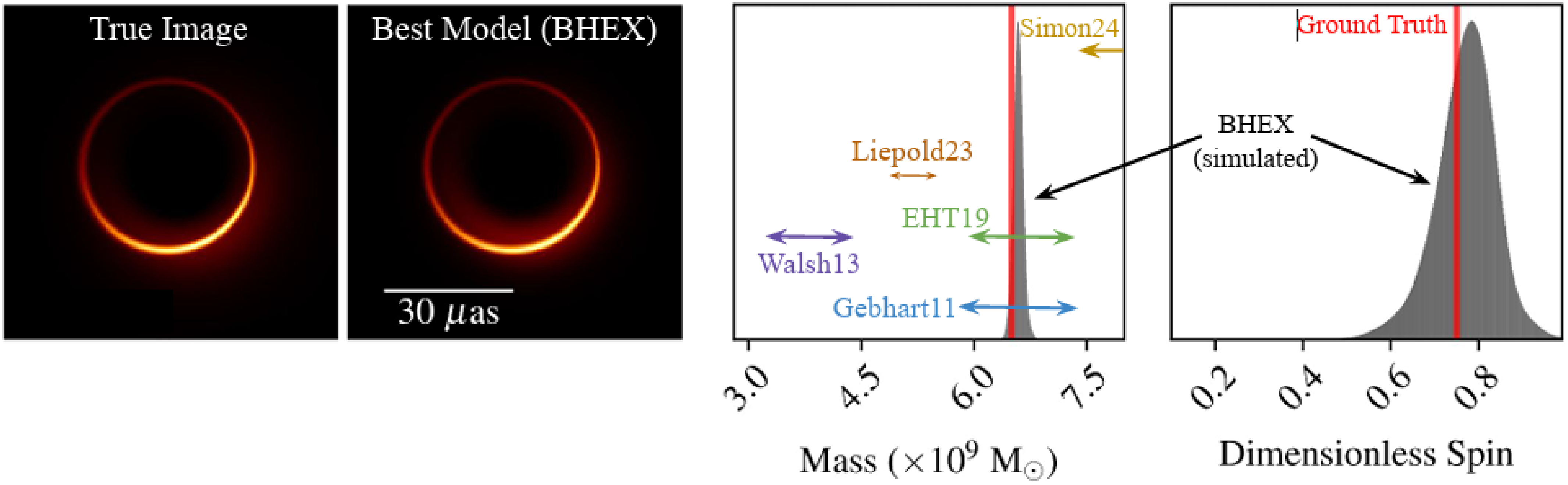




BHEX will detect and image the **photon rings** formed by **light deflected >180 degrees** in Sgr A* and M87*

Johnson+ 2020, Johnson+ 2024, Lupsasca+ 2024

Direct Photon Ring Mass/Spin Measurements with BHEX



By comparing strongly-lensed and direct emission ring size and shape, BHEX will constrain Sgr A* and M87*'s **spin to ~10%** and **mass to ~1%**

Direct photon ring spin measurements will help **calibrate** measurements from near-horizon polarimetry

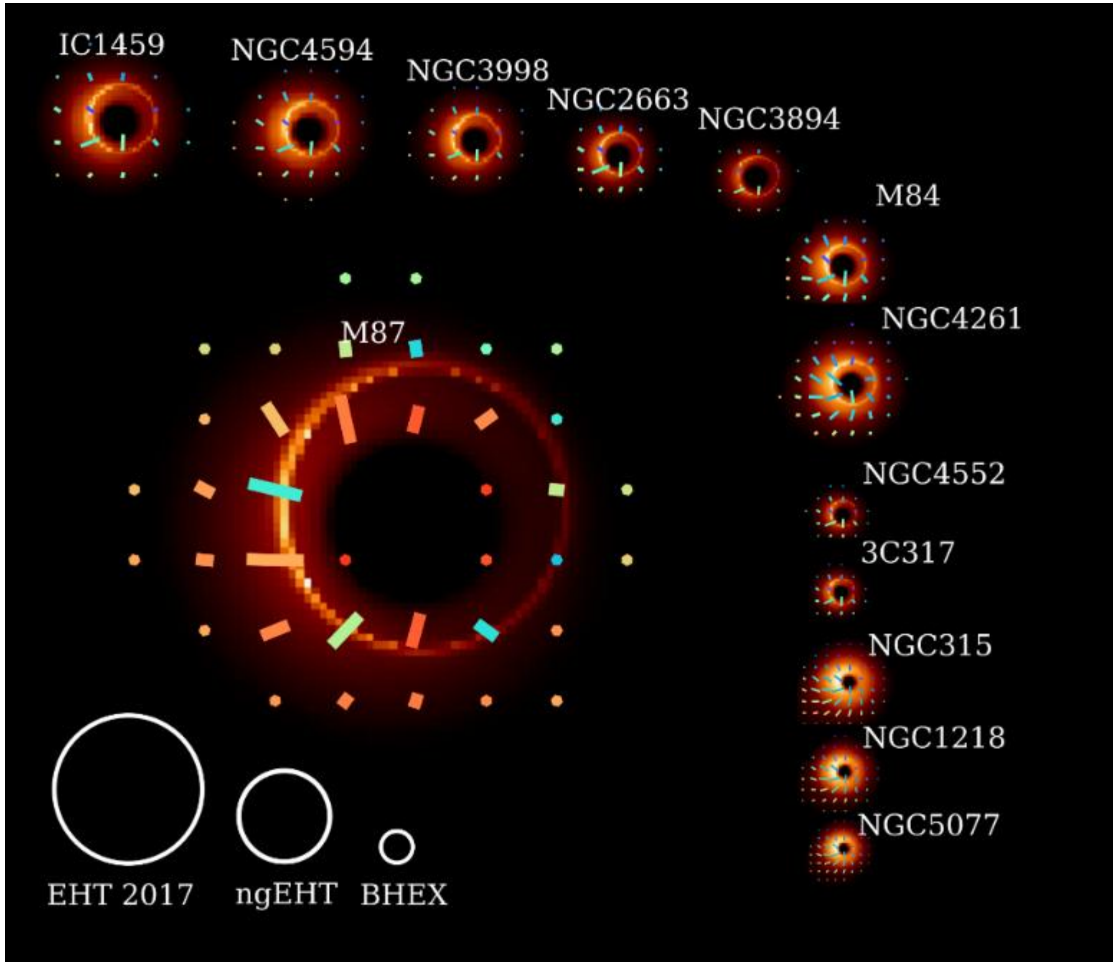
Johnson+ 2020, Johnson+ 2024, Lupsasca+ 2024

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 make >10 horizon-scale measurements of mass (from the size of the emission region) and spin (from magnetic field helicity)

- BHEX will observe how horizon-scale accretion changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties



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

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

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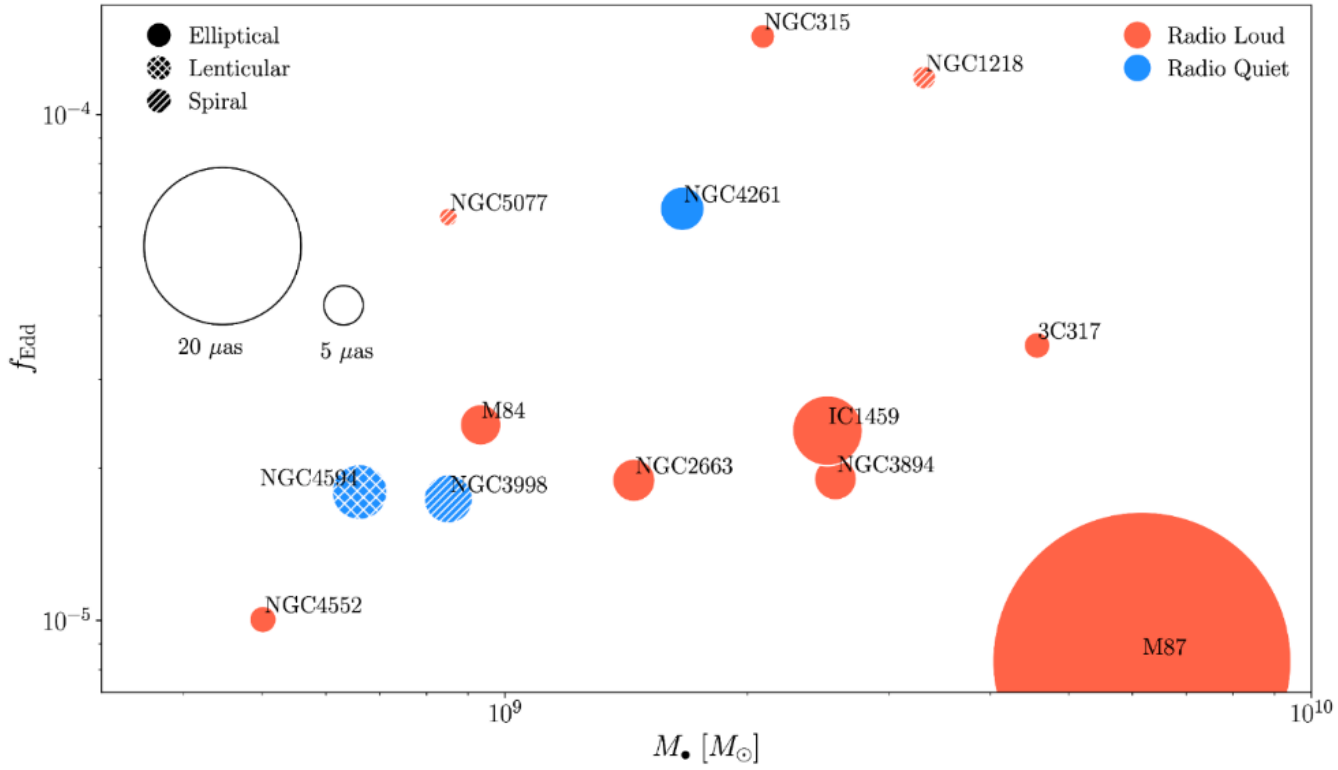
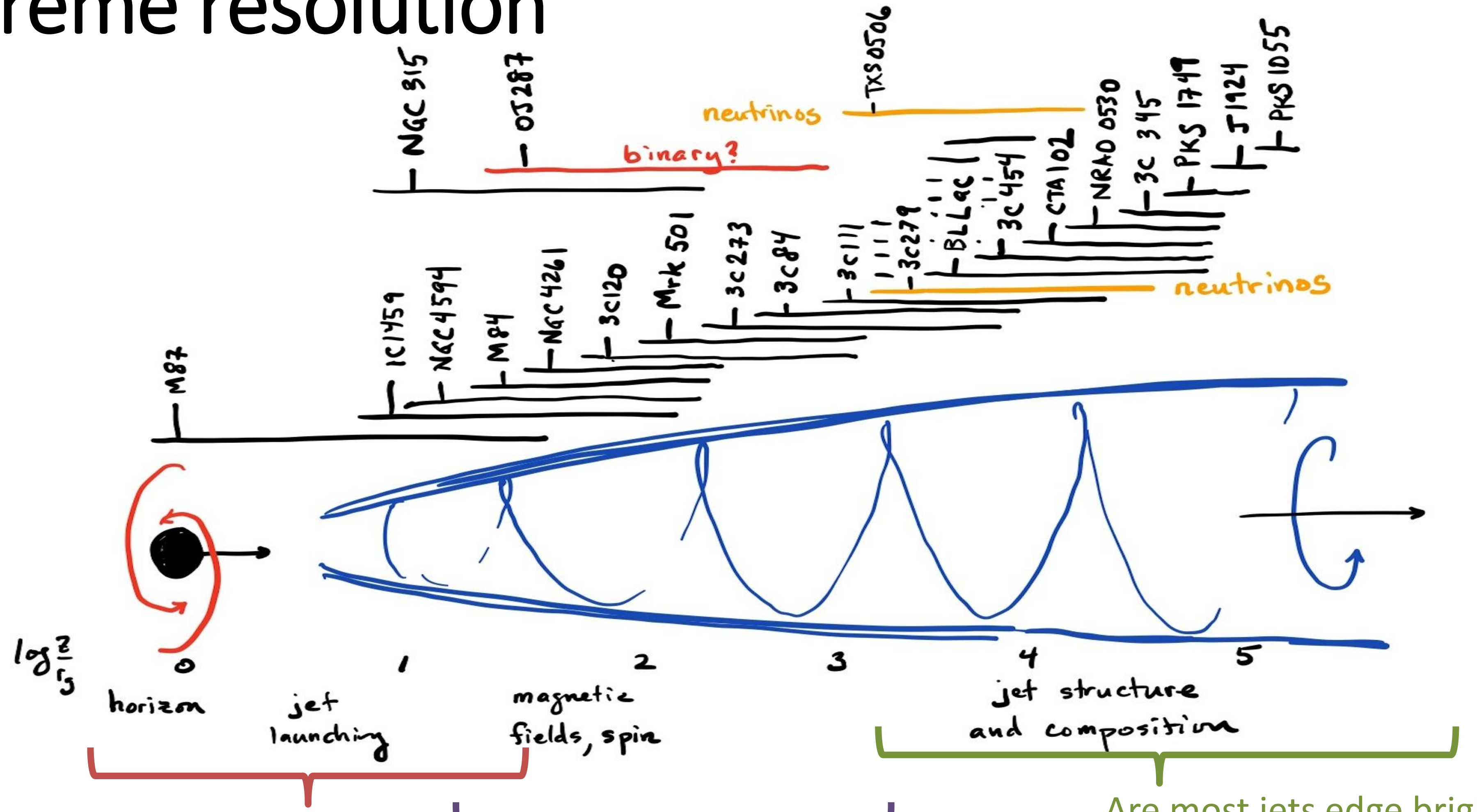


Zhang, Ricarte+ 2024
See ETHER Sample; e.g. Pesce+ 2022, Ramakrishnan+ 2023, Nair+ 2024

BHEX will observe jets on **multiple scales** with **extreme resolution**



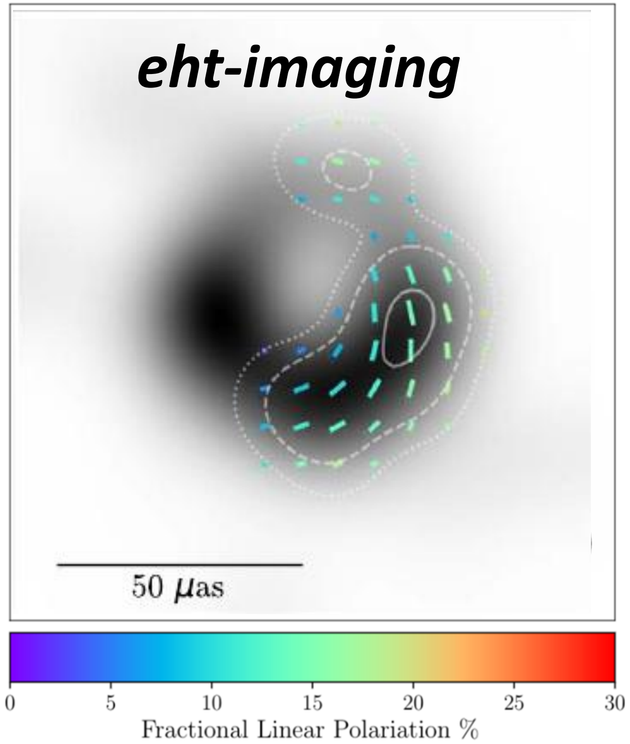
How does the jet connect to the BH? Can we observe dynamics propagate btw the accretion disk and jet?

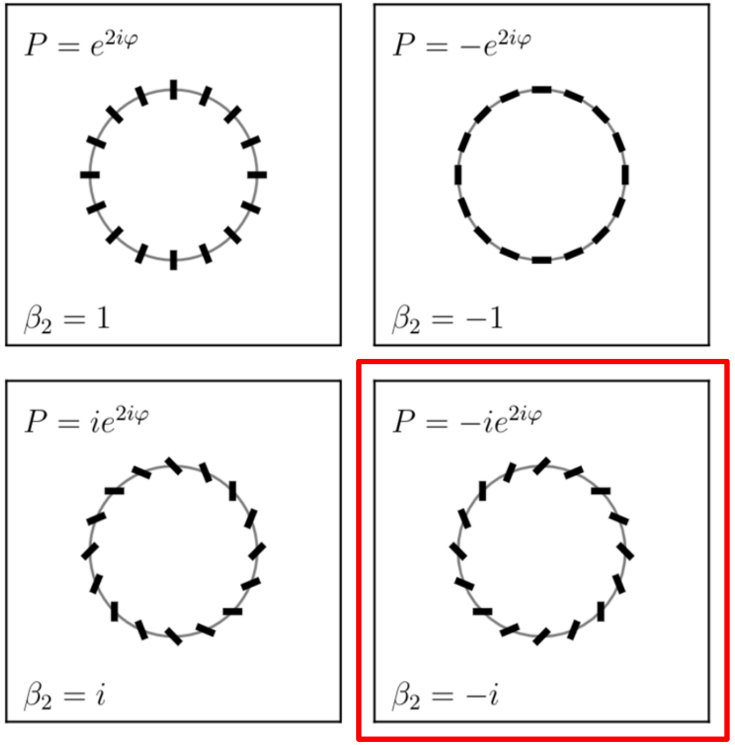
How do jets accelerate? Can we measure BH spin with jet polarimetry?

Are most jets edge brightened? Can resolved images (+polarization) constrain models of particle content/acceleration/anisotropy?

Image Credit: Charles Gammie

Polarized Images of M87* and horizon-scale energy flow





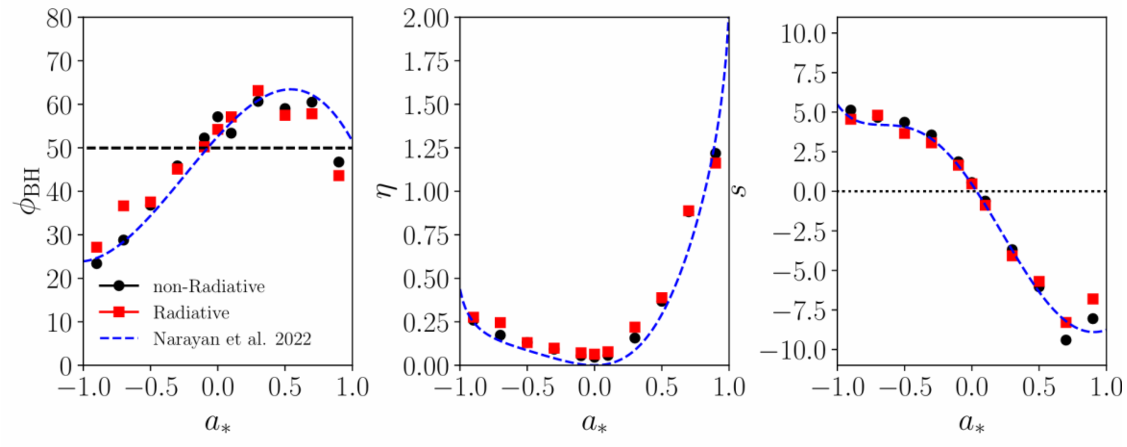
$$\beta_2 = \frac{1}{I_{\mathrm{ring}}} \int_{\rho_{\mathrm{min}}}^{\rho_{\mathrm{max}}} \int_0^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\, \rho\, d\varphi\, d\rho$$

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

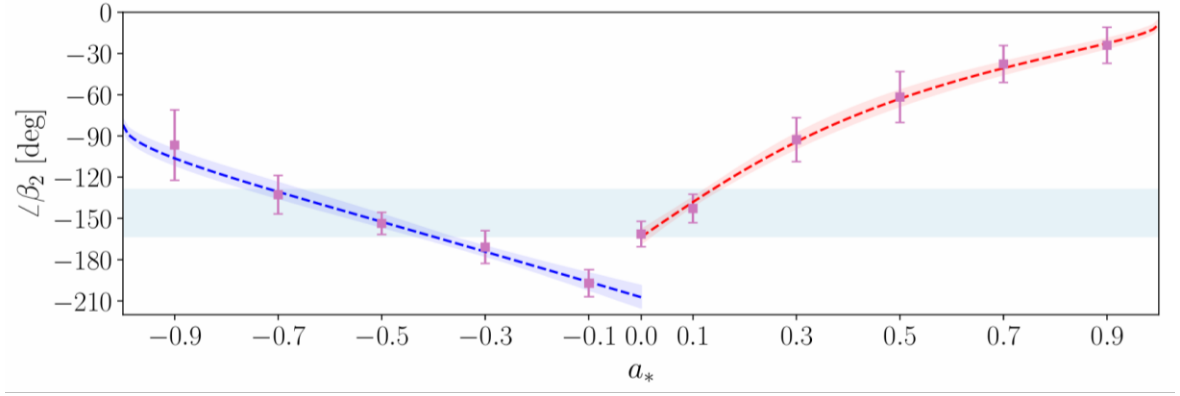
EHTC 2021 VIII (**Chael**, paper coordinator)
Palumbo+ 2020

Radiative MAD Simulations Have Similar Jets and polarization angles….

Magnetization **Jet efficiency** **BH spindown**



Average Polarization Pitch angle

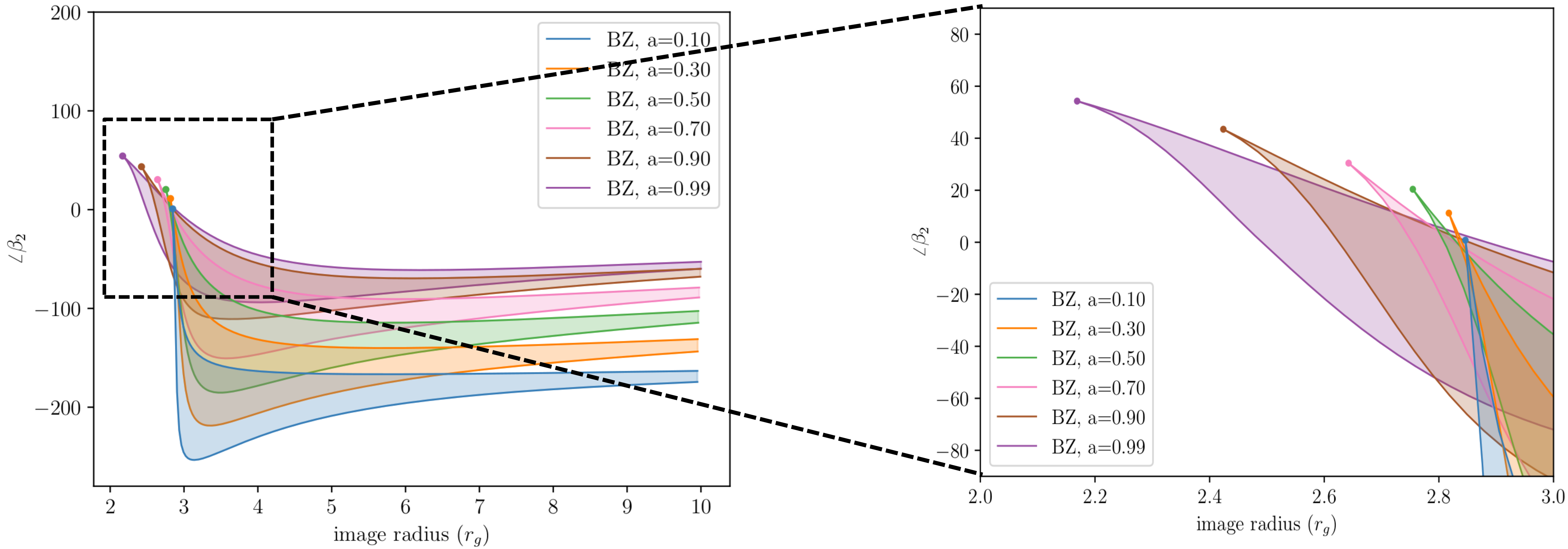


- M87* and Sgr A* have two-temperature plasmas
- EHT analysis fixes $T_{\rm e}$ locally in **postprocessing** and seems to prefer electrons T_i >50x T_e to sufficiently depolarize the image
- In radiative, two-temperature simulations, overall radiative efficiency of ~10% (EHTC+ 2021, Chael+ 2025) does not significantly change global jet or disk properties
    - or the bulk trend of polarization structure with spin arg(β_2)

Chael 2025

ee also: Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019,** Dexter+ 2020,2021, Mizuno+ 2021, Moscibrodzka+ 2024, Salas+ 2024

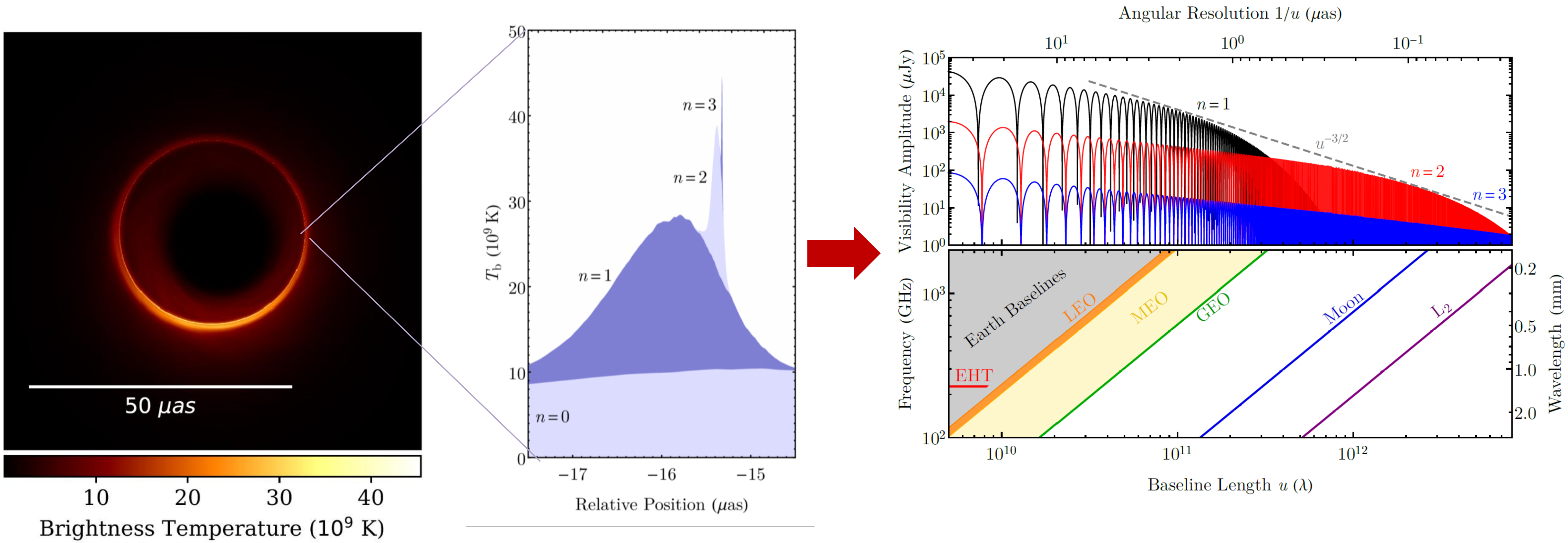
BHEX: *zooming in*



- 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

Future: Space VLBI can measure the photon ring precisely

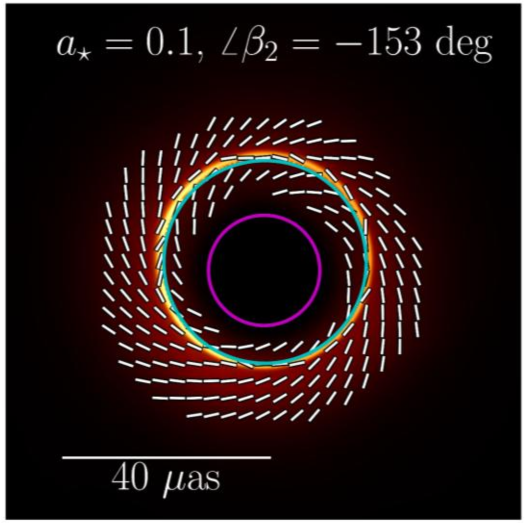


Longer and longer baselines measure narrower and narrower subrings – each from a different number of photon windings!

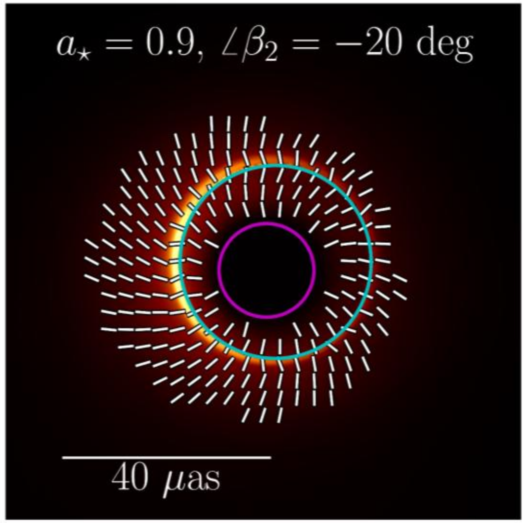
Johnson+ 2019, arXiv: 1907.04329

Polarized images are **spin dependent**

Low Spin



High Spin



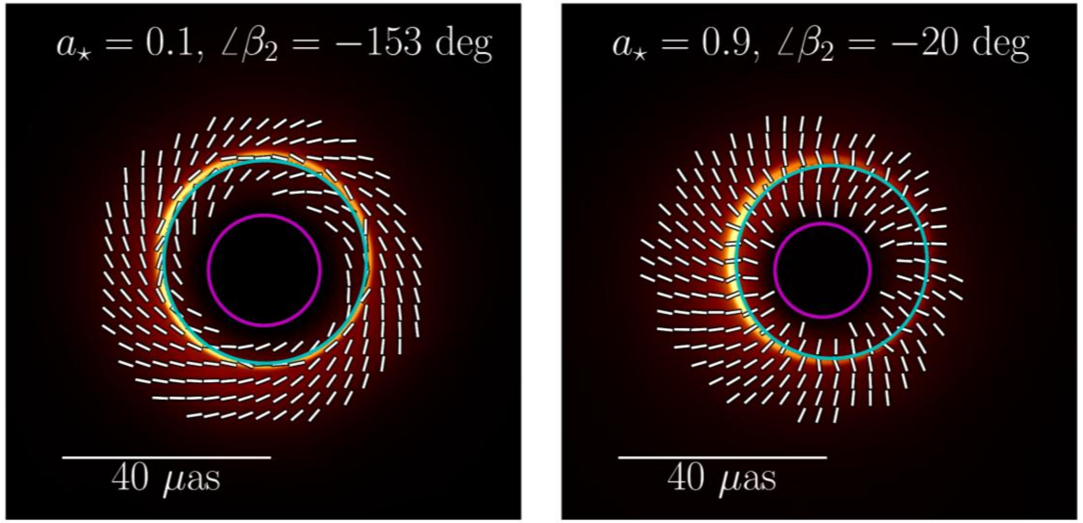
- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

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

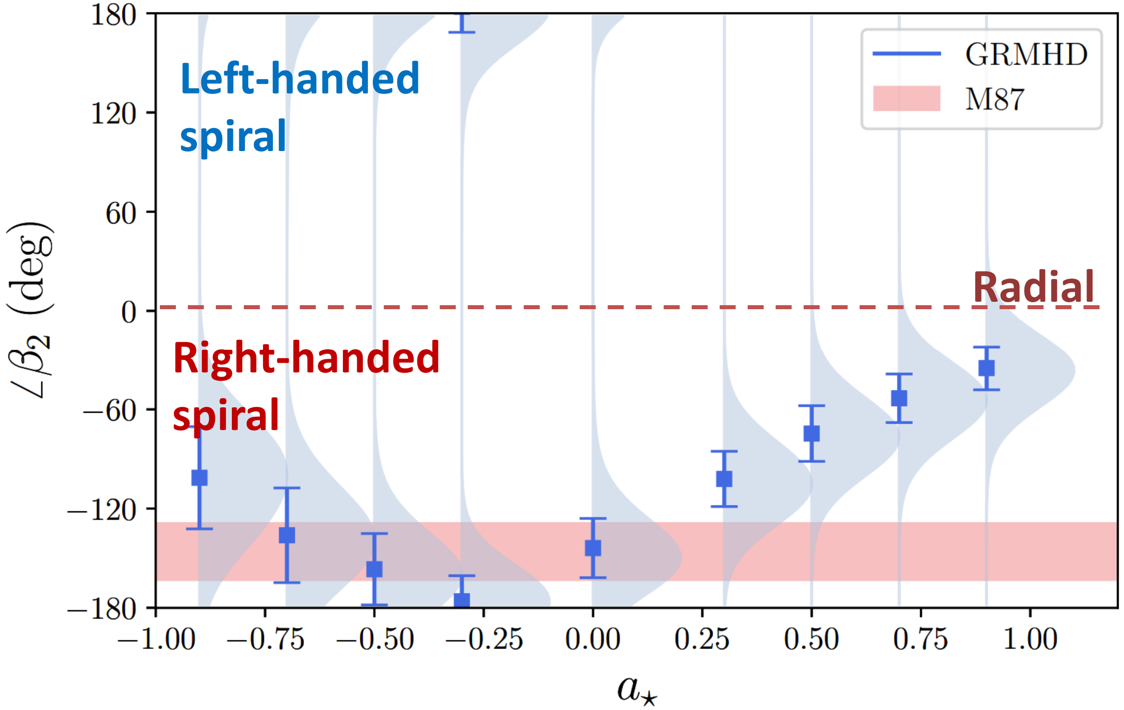
Polarized images are **spin dependent**

Low Spin

High Spin



M87*



- 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)

Chael+ 2023b; **Chael** 2025; Wong+2025
β_2 from Palumbo+ 2020
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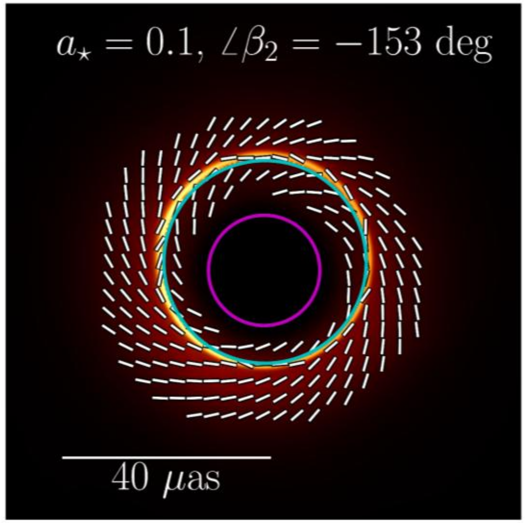
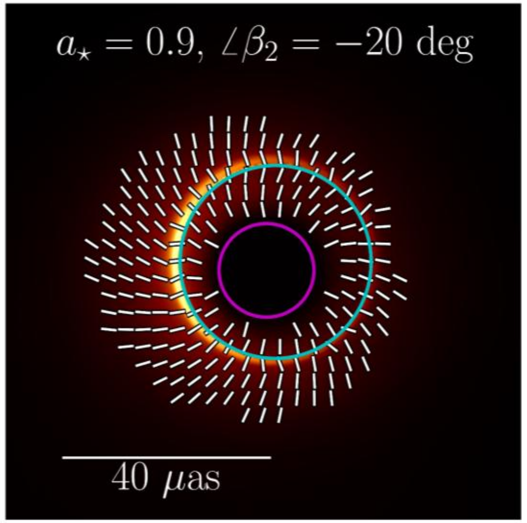
Polarized images are **spin dependent**

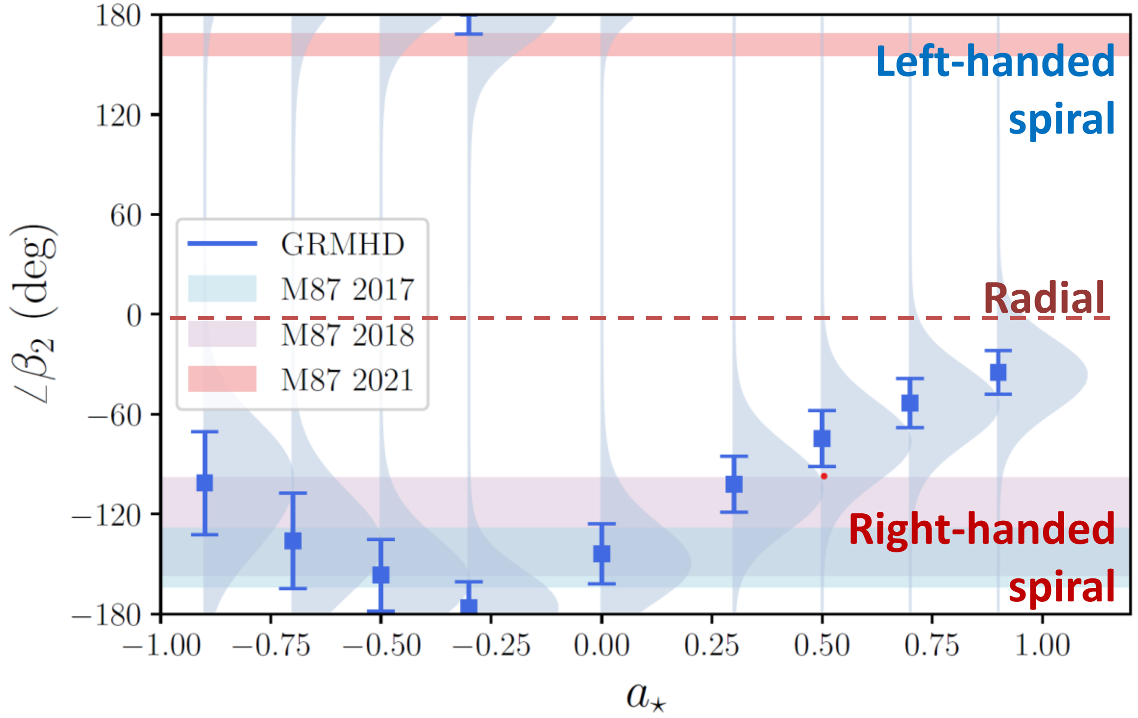
Low Spin



High Spin



M87*



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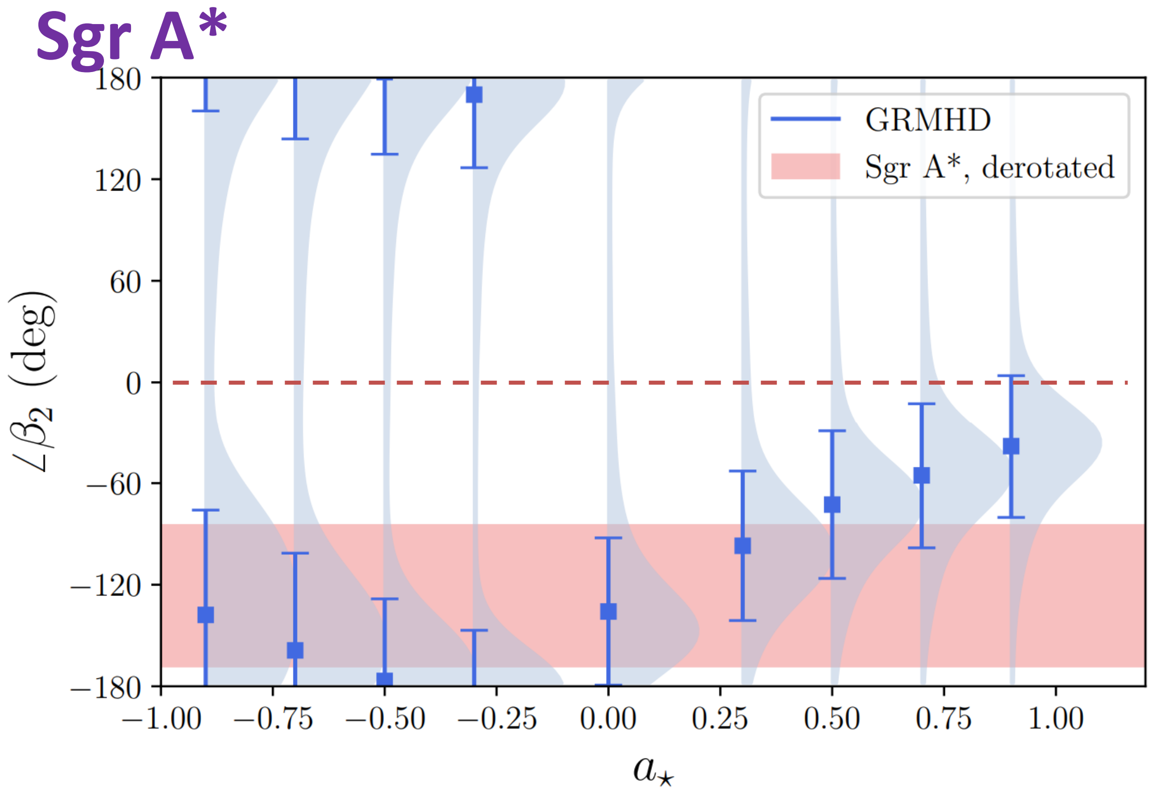
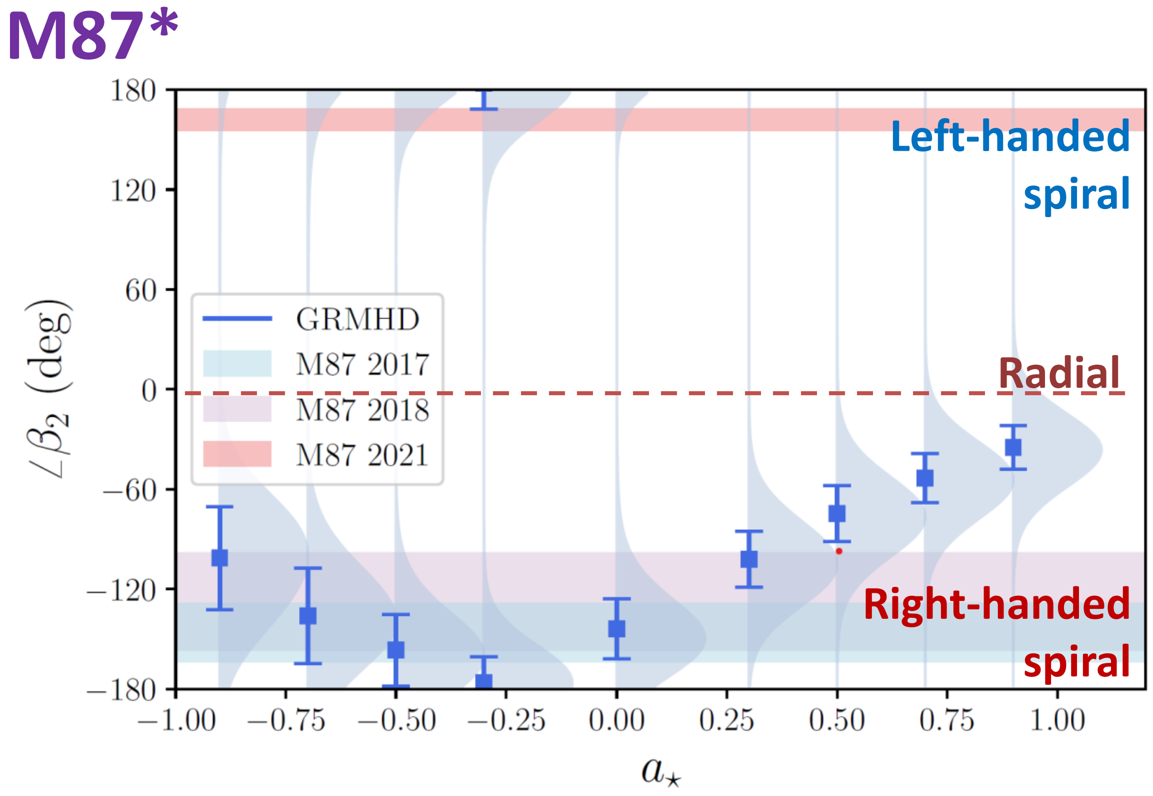
- **The shift in β_2 in 2021 is mysterious**
  - Change in Faraday rotation? Change in accretion state/plasma feeding?

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

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
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022