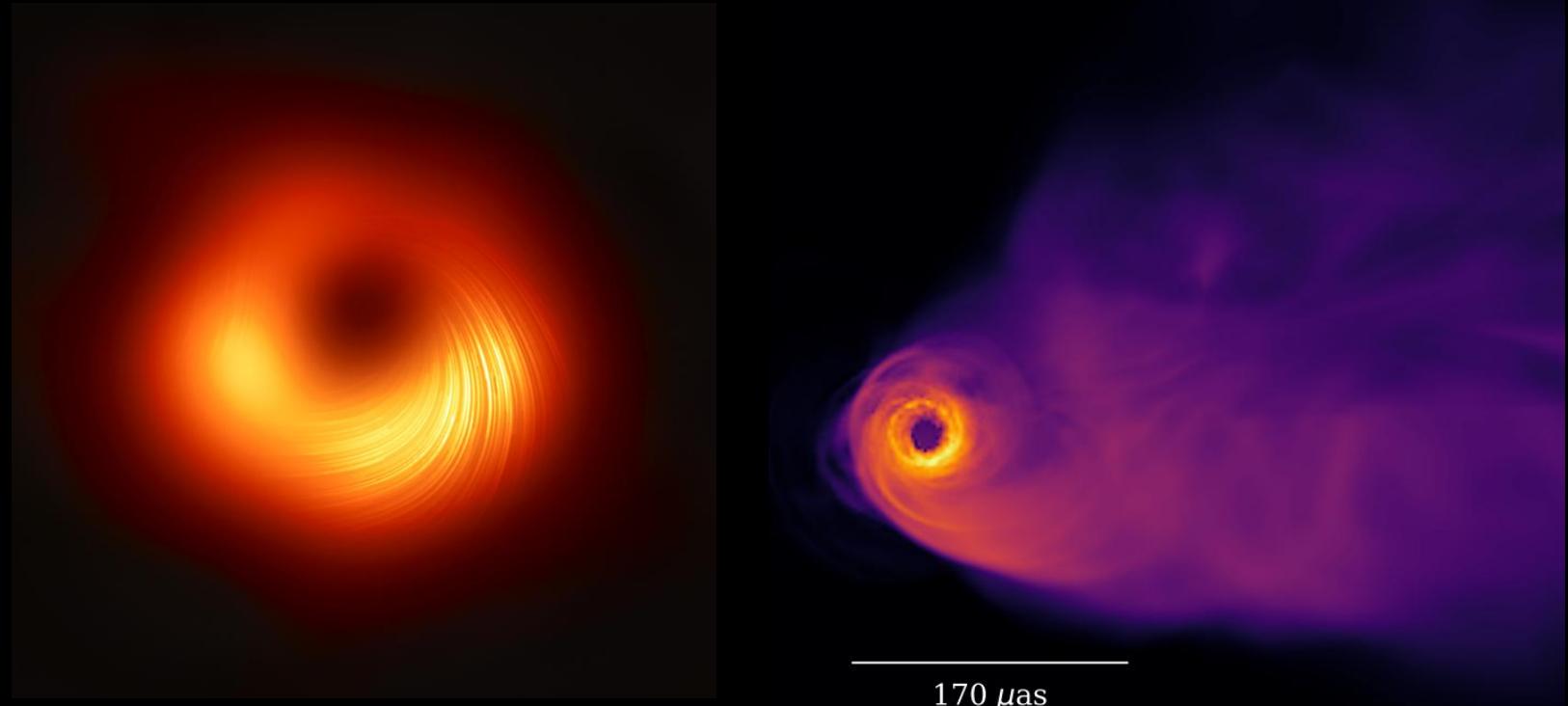


Insights from Polarized Black Hole Images

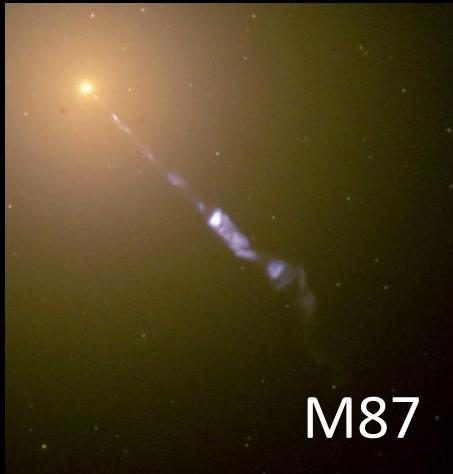
Andrew Chael
Princeton Gravity Initiative

ITC Colloquium
September 25, 2025



Event Horizon Telescope

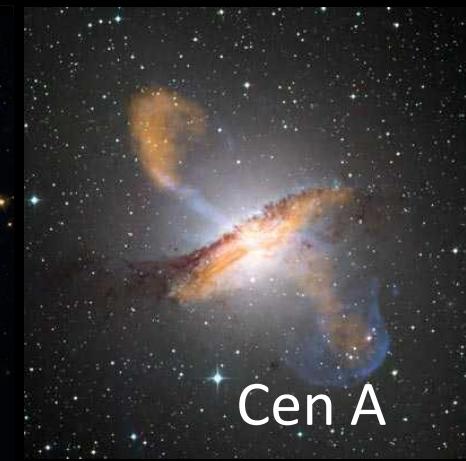
Supermassive black holes and jets are everywhere



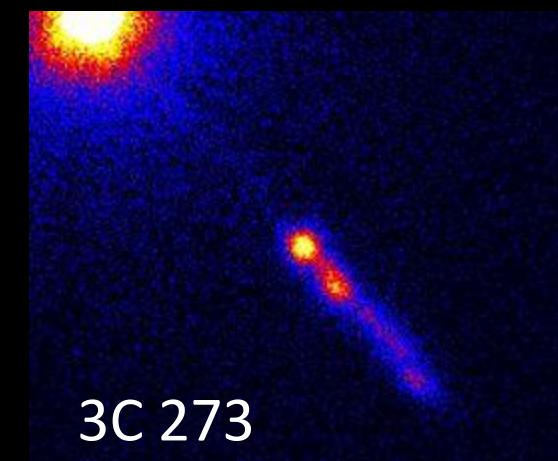
M87



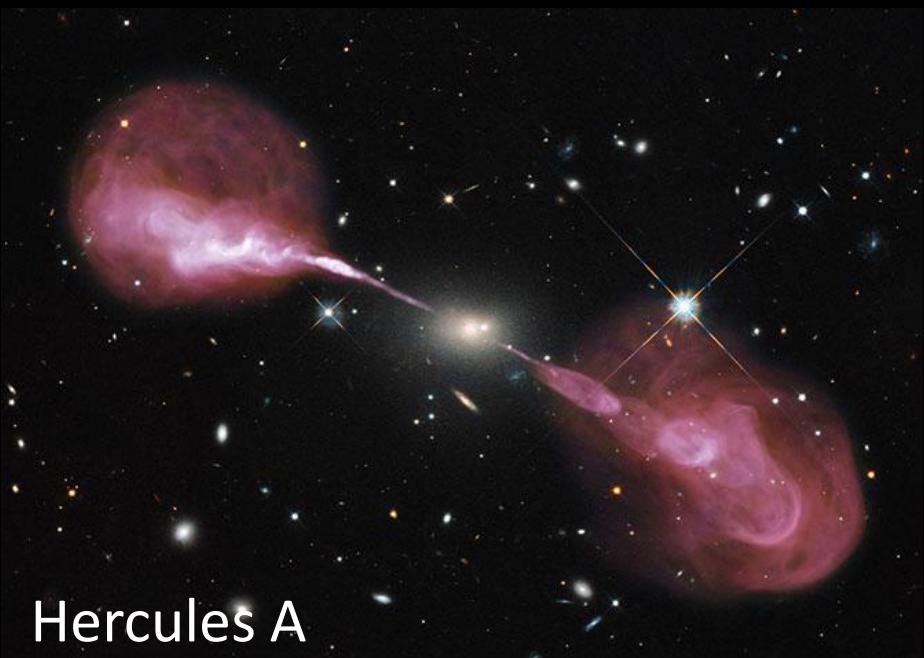
Cyg A



Cen A



3C 273



Hercules A

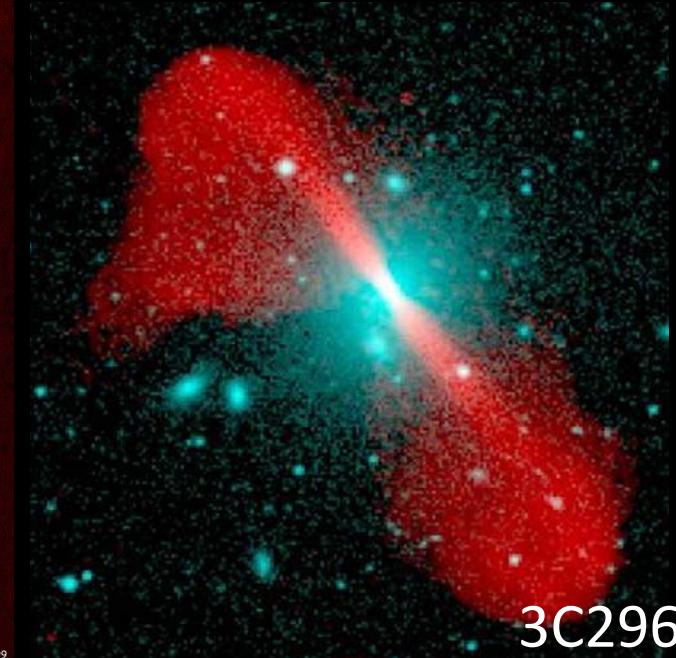


NGC 1265



3C31

Copyright (c) NRAO/AUI 1999



3C296

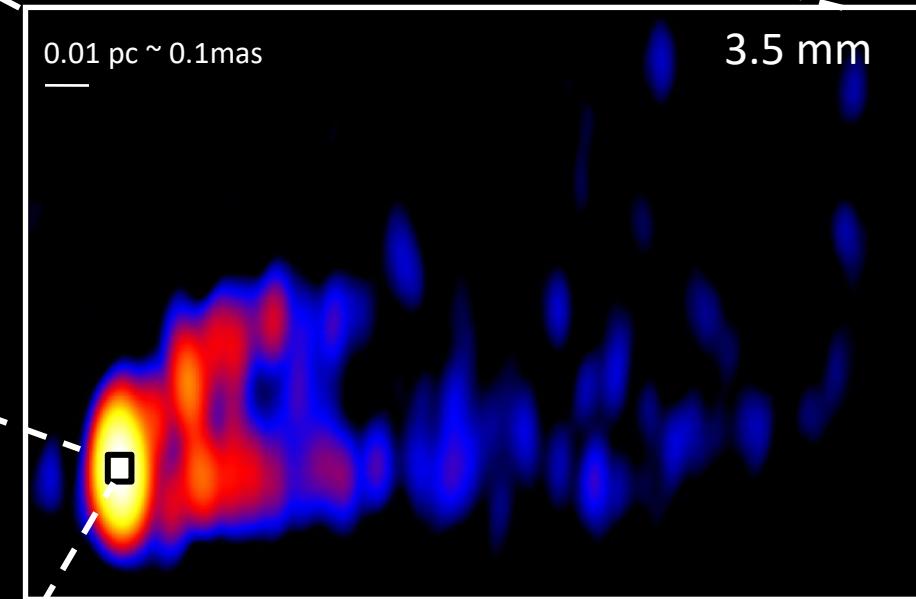
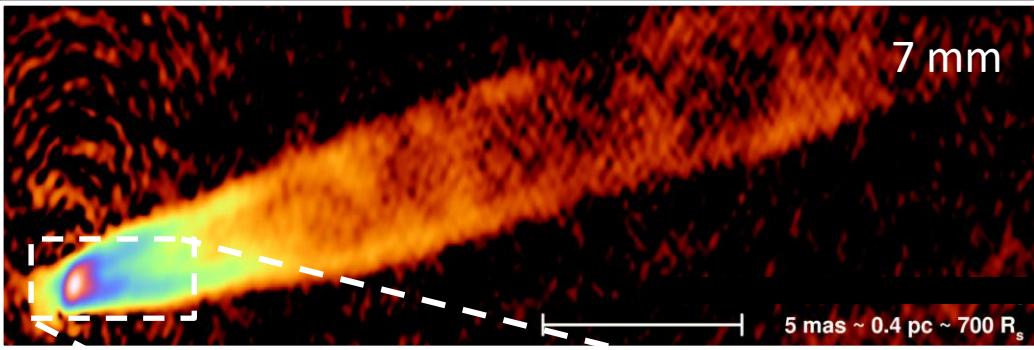
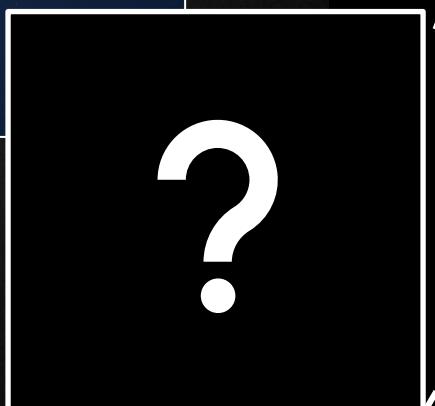
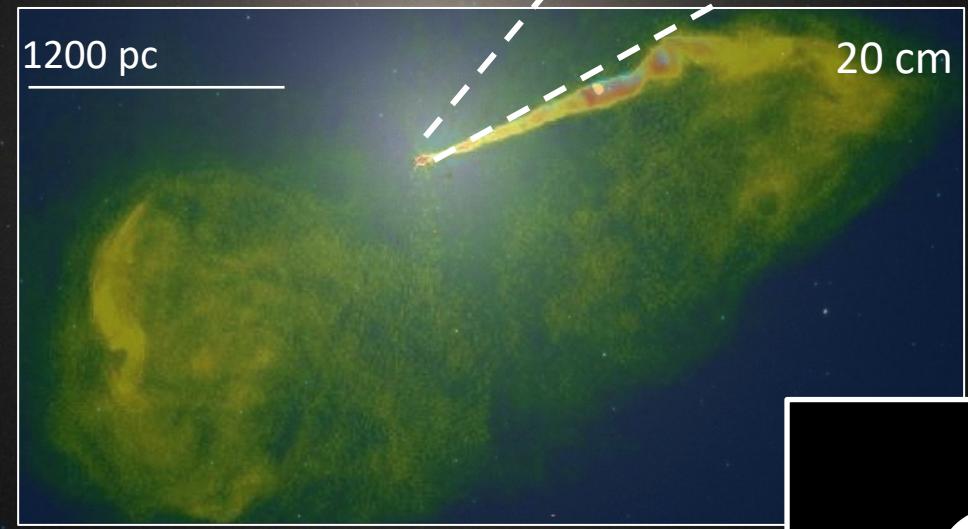
Credits: Sara Issoun, (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A)), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NF; Sloan Digital Sky Survey), (3C293, Chandra), (Hercules A, HST/VLA), (NGC1265, M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NF; SDSS), (3C31, VLA), (3C296, AUI, NRAO)

M87 & M87*

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

$$D = (16.8 \pm 0.8) \text{ Mpc}$$

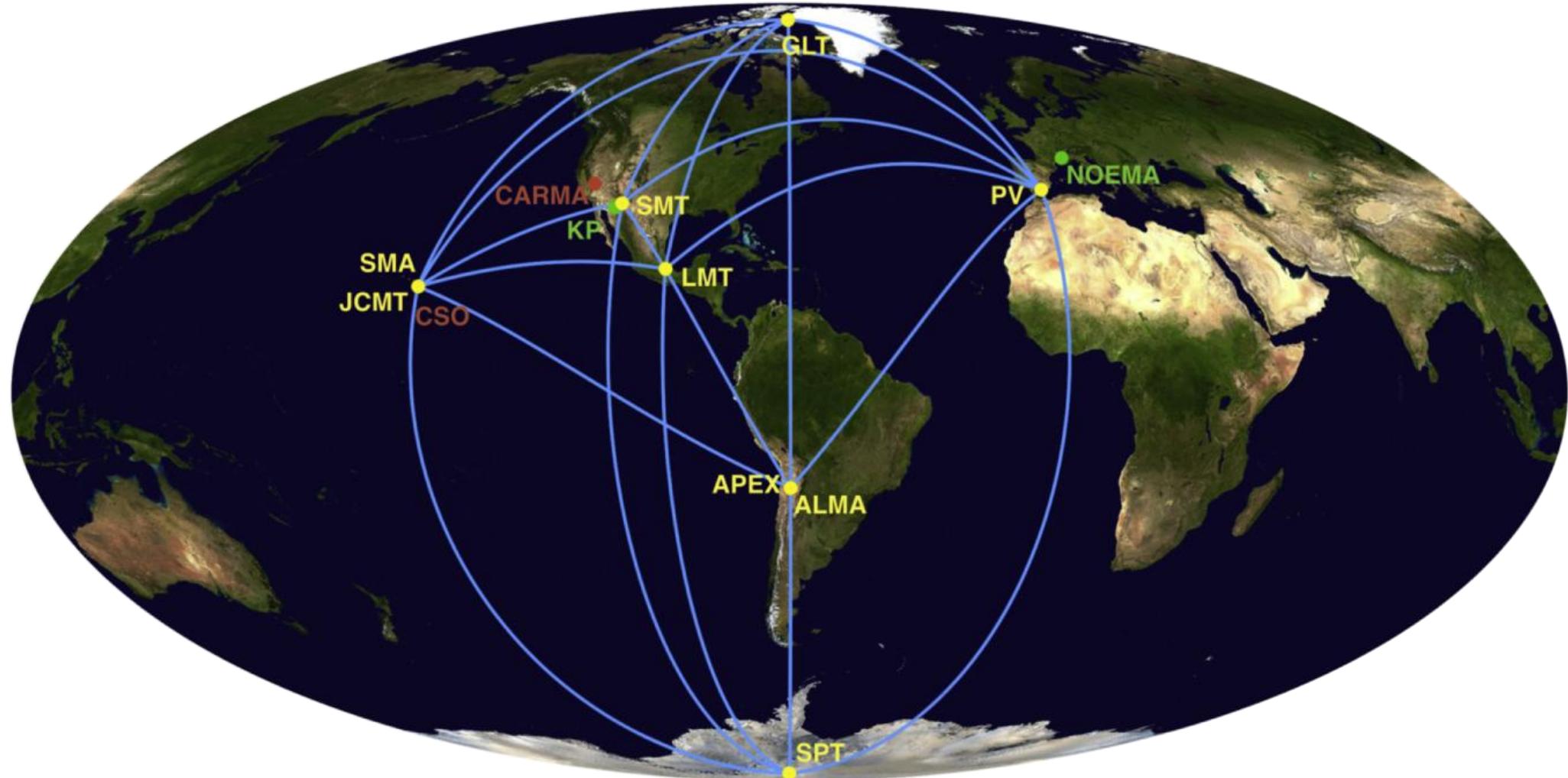
$$R_s = 2GM/c^2 \approx 64 \text{ AU}$$



What does jet launching look like on event horizon scales?

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

The Event Horizon Telescope



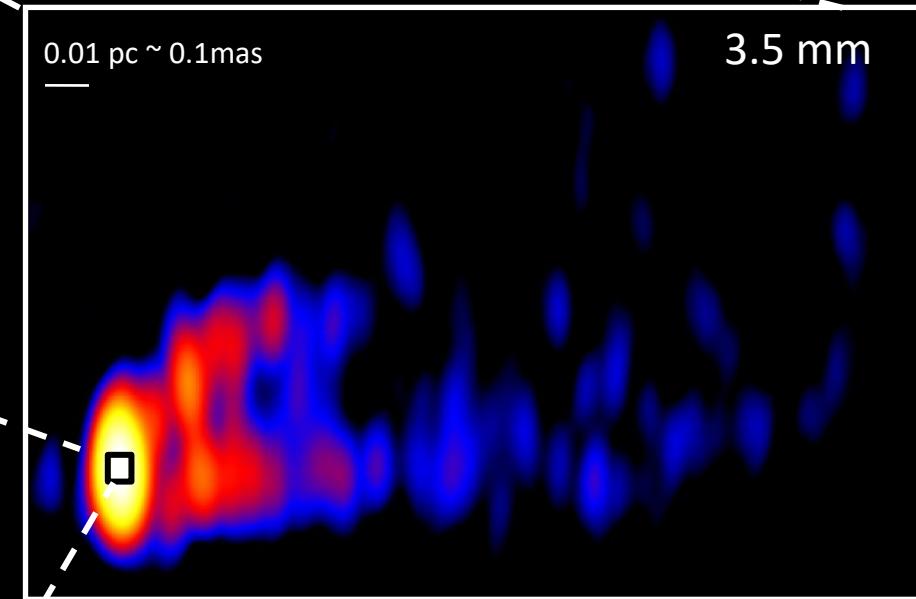
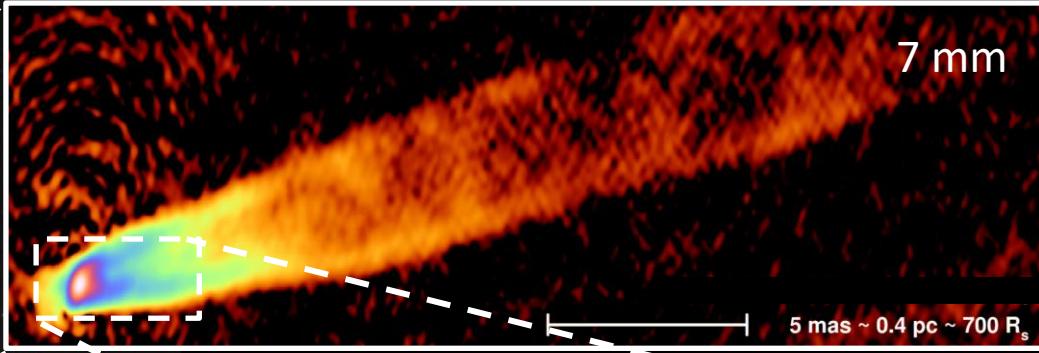
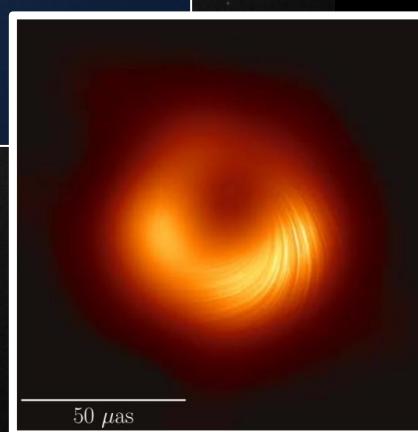
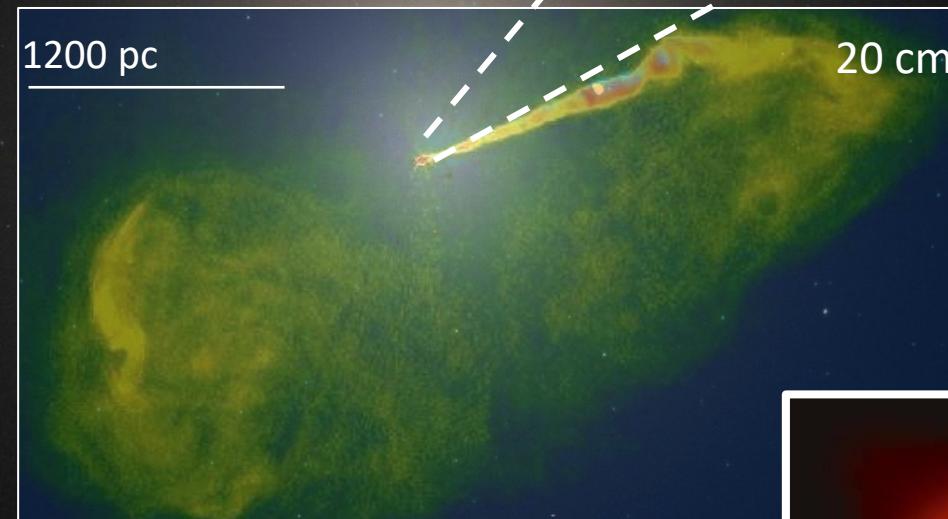
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3 \text{ mm}}{1.3 \times 10^{10} \text{ mm}} \approx 20 \mu\text{as}$$

M87 & M87*

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

$$D = (16.8 \pm 0.8) \text{ Mpc}$$

$$R_s = 2GM/c^2 \approx 64 \text{ AU}$$



Can polarized EHT images tell us how jets are launched?

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

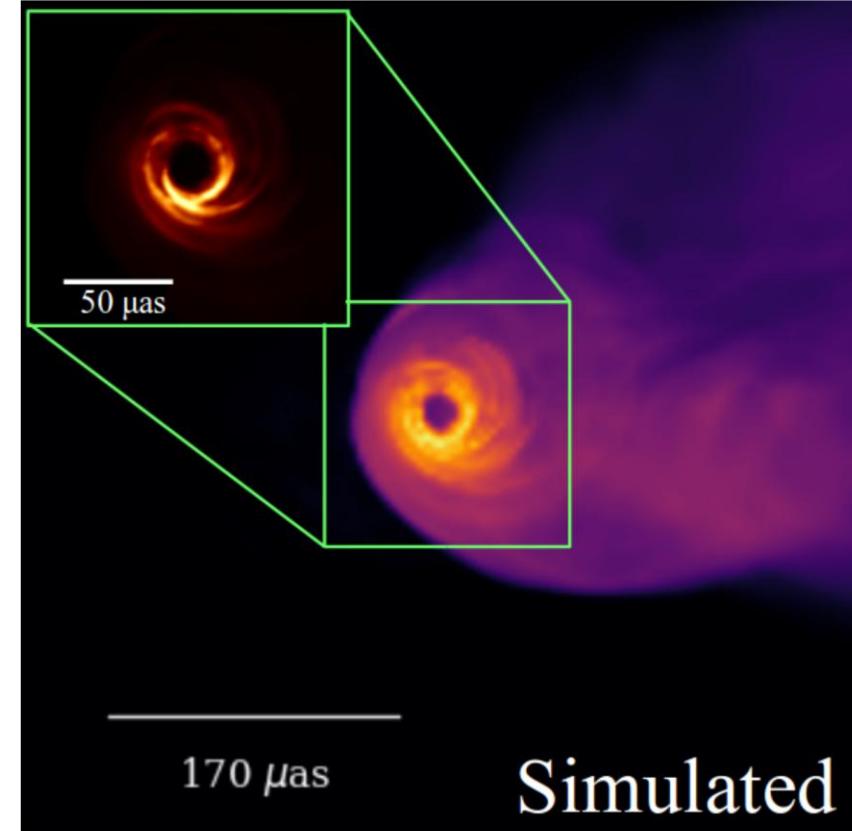
At the heart of M87...

What we know:

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

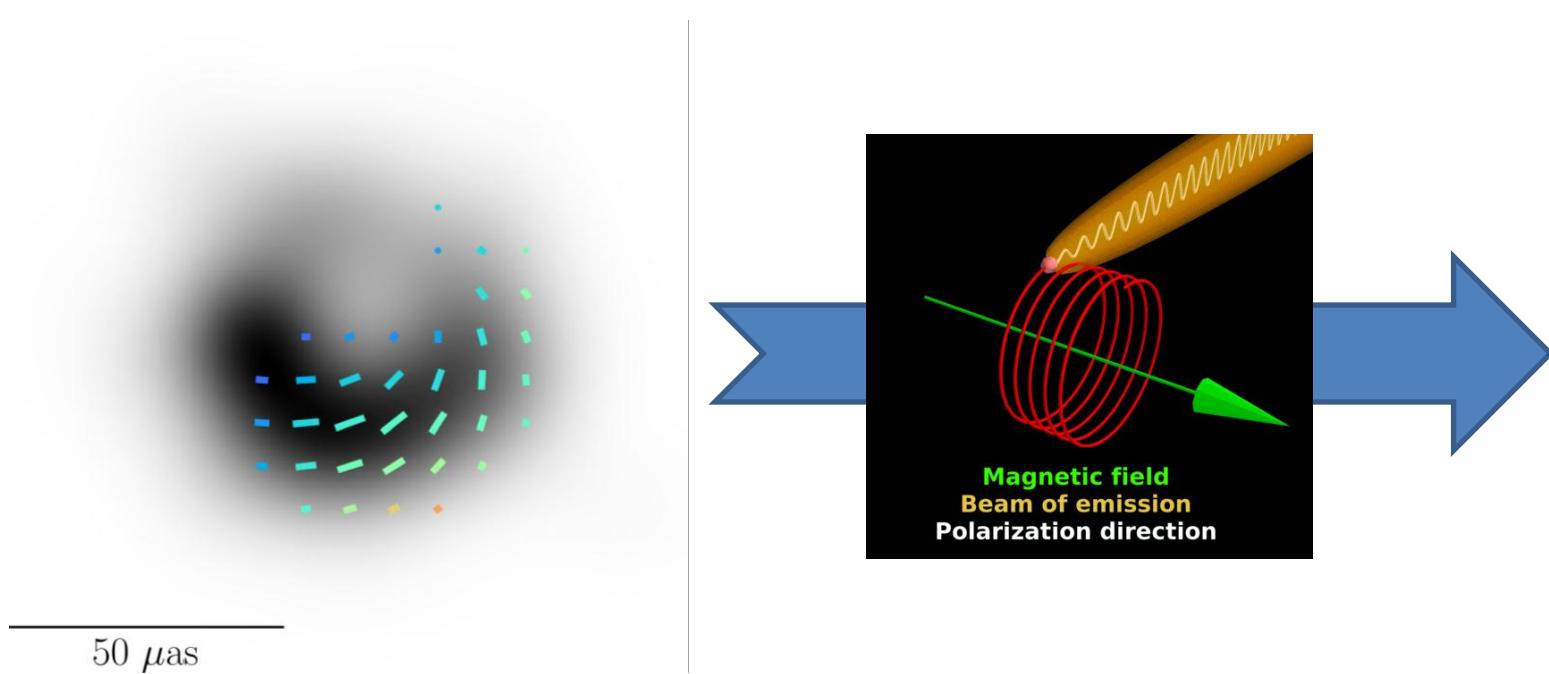
Questions I think about:

- Are jets launched by extracting BH spin energy?
 - What is the spin of the black hole?
 - What is the strength and geometry of the magnetic field?
- How can we perform precise tests of gravity?
 - How will these improve with upgraded EHT observations?
- What plasma processes accelerates electrons and lights up the flow?
 - What powers X-ray/ γ -ray flares in Sgr A* and M87*?



Simulated

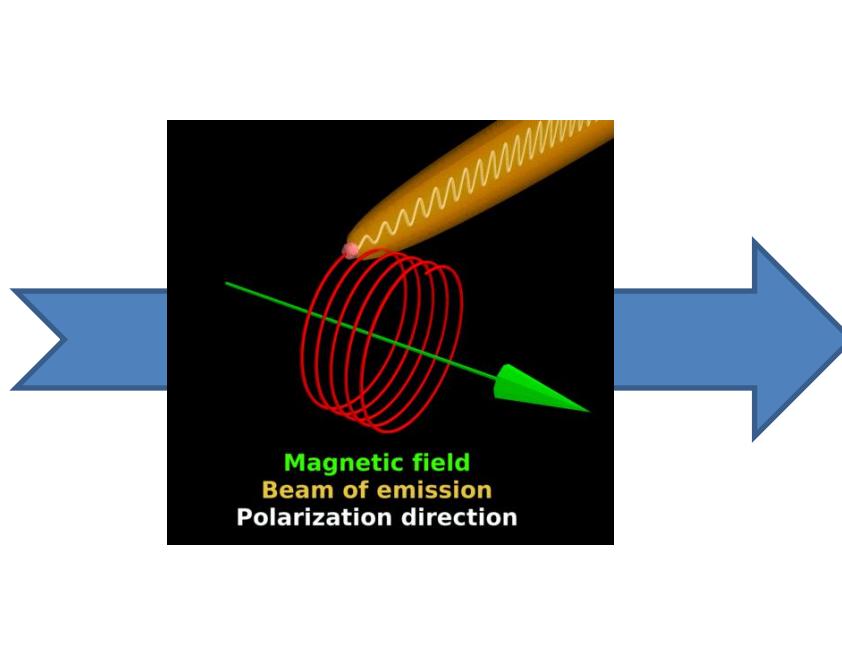
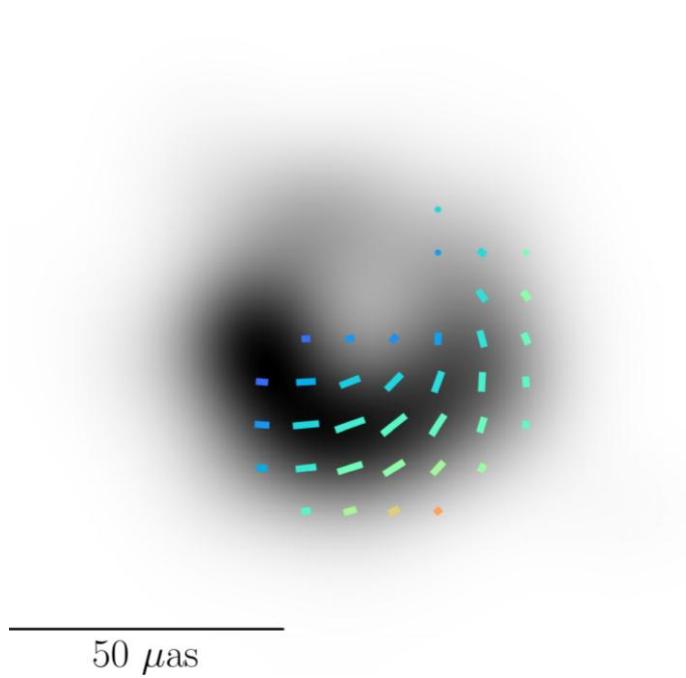
Why polarization?



Magnetic field
geometry in the
emission region!

- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines

Why polarization?



GR light bending, aberration, and Faraday rotation make things more complicated!

~~Movie credit: Ivan Martí-Vidal
geometry on the emission!~~

- 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**

This talk:

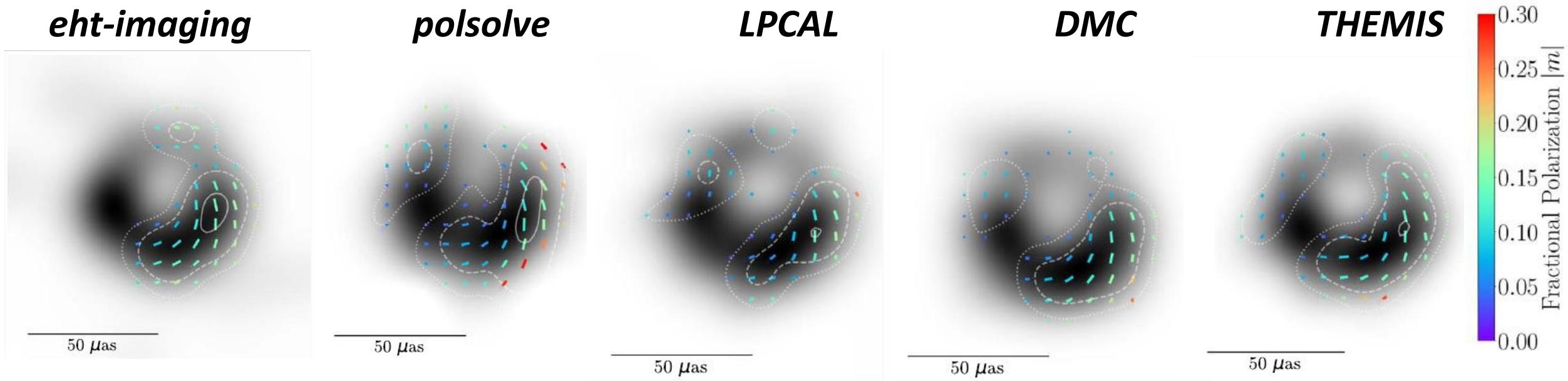
1. What have we learned from comparing first polarized images of black holes to simulations?
2. What can polarized EHT images tell us about jet launching?
3. What's next?

What have we learned from comparing polarized images of M87* to simulations?

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

[2105.01173](#), [2311.10976](#)

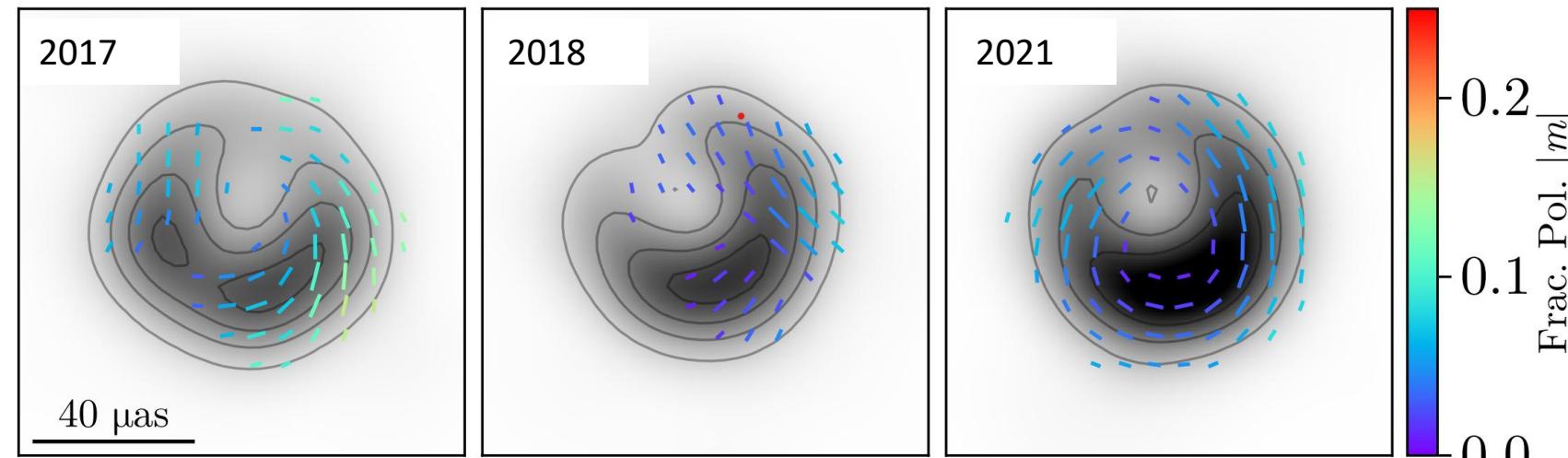
Polarized Images of M87 from 5 methods in 2017



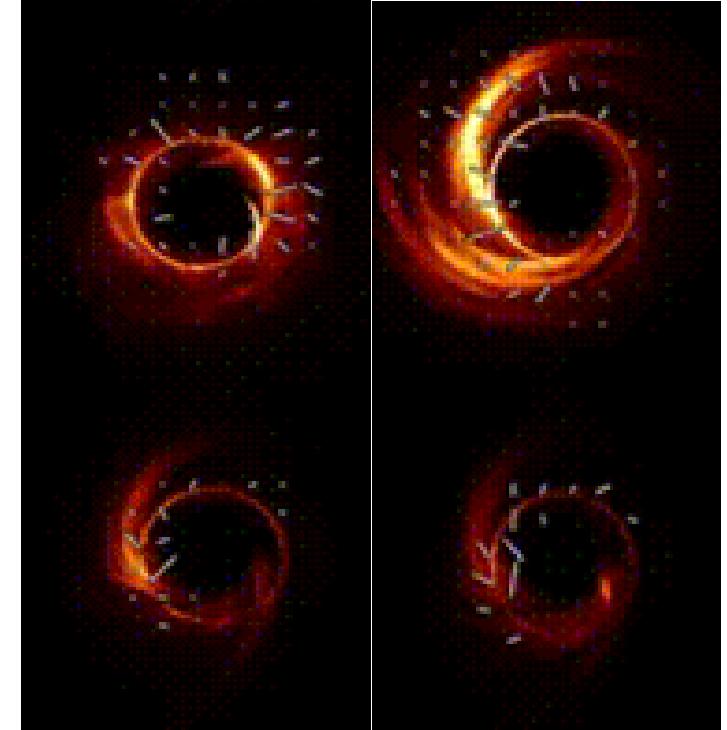
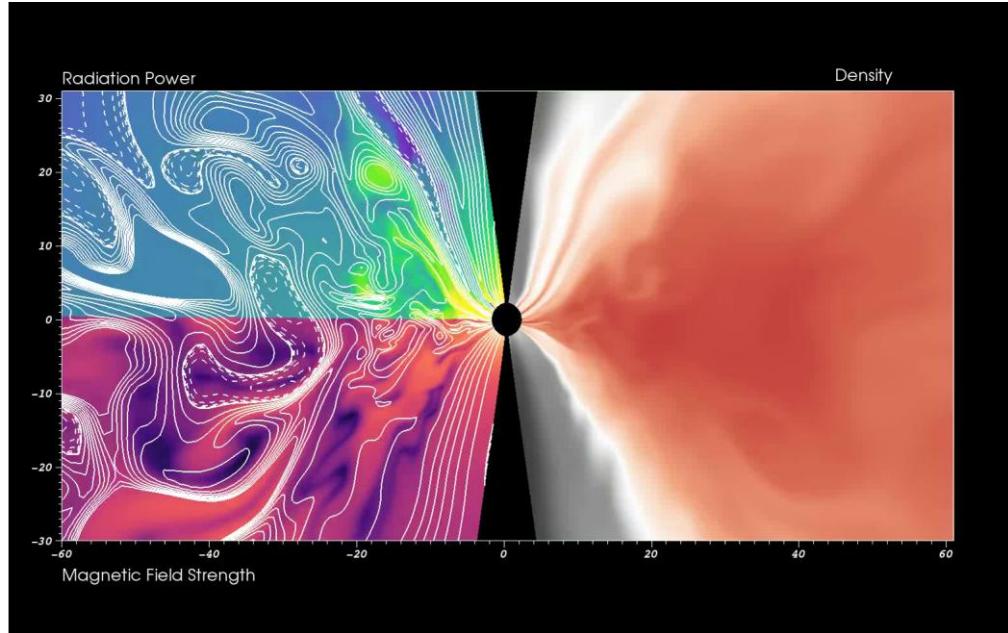
- All methods show similar total intensity and polarization structure at 20 μ as resolution
- Consistent ring diameter (\sim 40 μ as) and asymmetry (south)
- Polarization structure is predominantly **helical and weak**, ($|m| \sim$ 10 %)

Three Years of Horizon-Scale Structure in M87

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



Theoretical Tools for Interpreting Black Hole Images



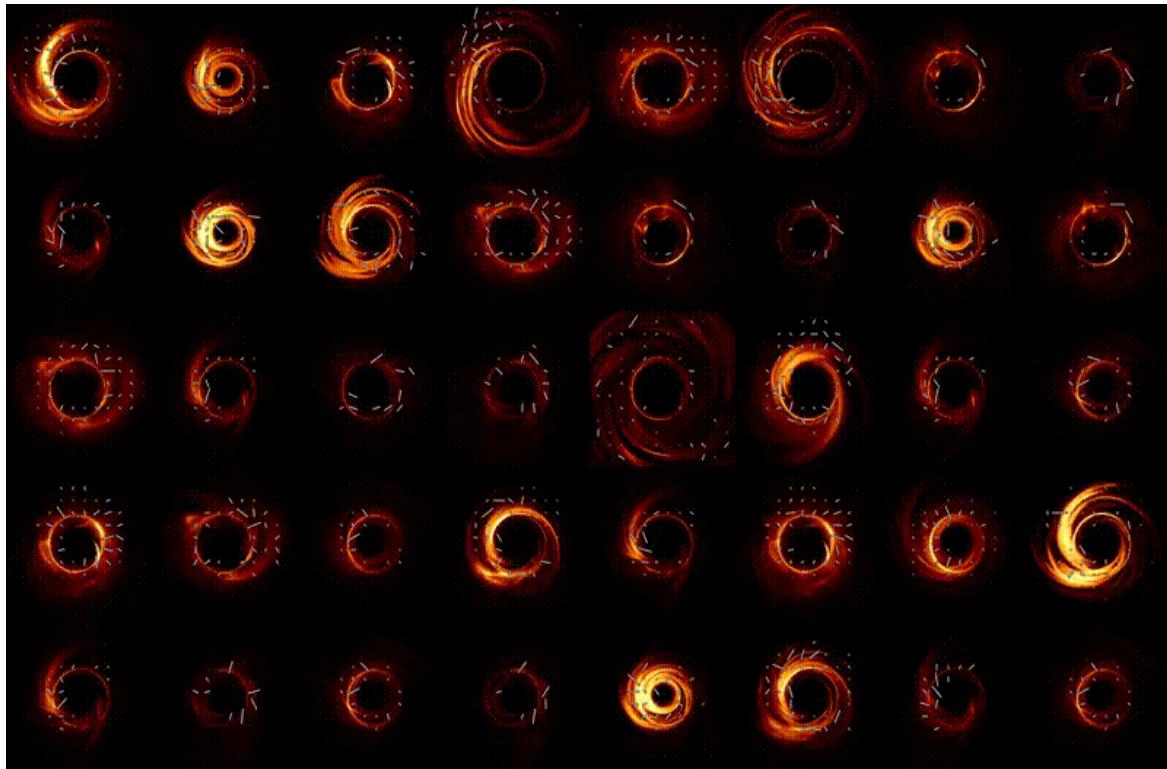
General Relativistic Magnetohydrodynamic (GRMHD) Simulations

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

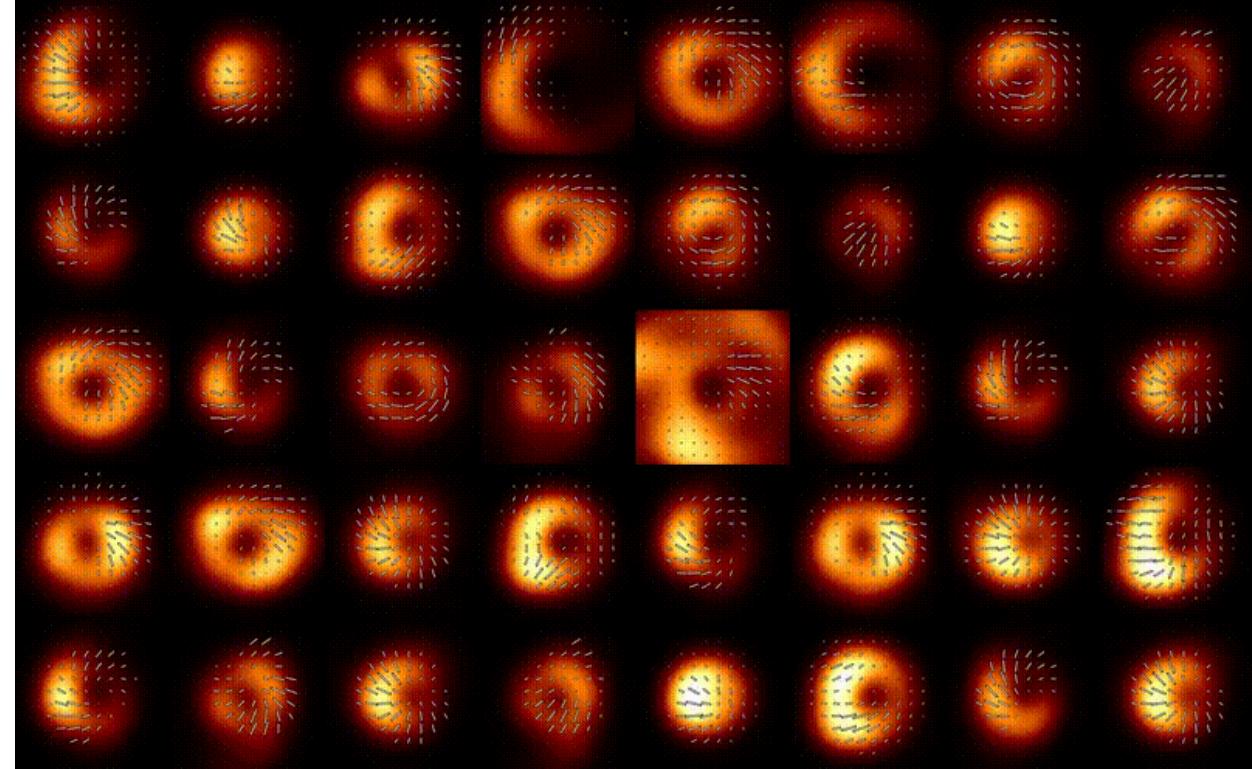
GR Radiative Transfer

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

GRMHD Simulation library



native resolution



EHT resolution

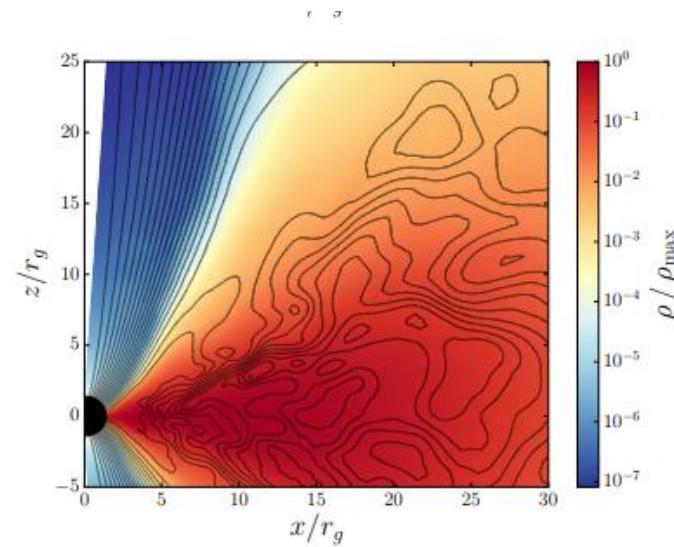
Images modeled with the ipole GRRT code (Moscibrodzka & Gammie 2018)
Two-temperature plasma model from Moscibrodzka et al. 2016

$$T_e \neq T_i \neq T_{\text{gas}}$$

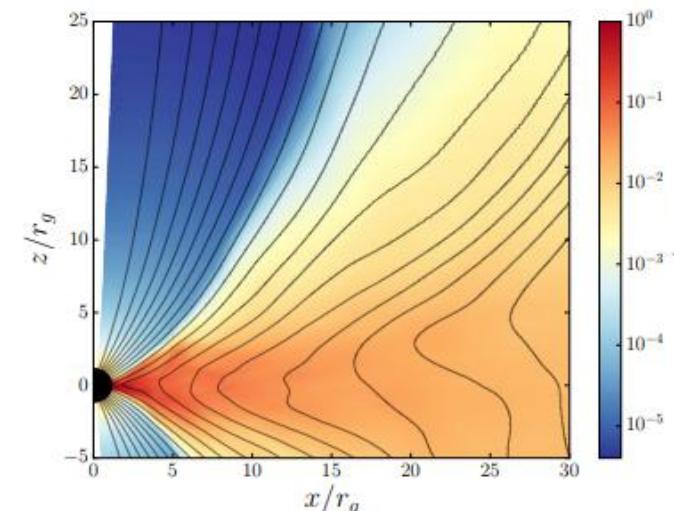
What is the magnetic field structure close to the horizon?

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

Blandford-Znajek (1977) Magnetic fields extract BH spin energy to launch jets:

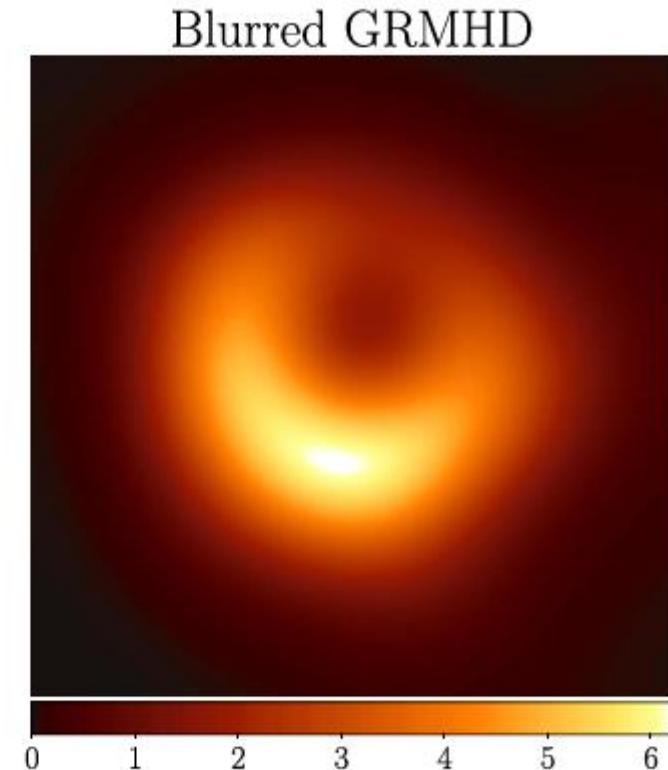
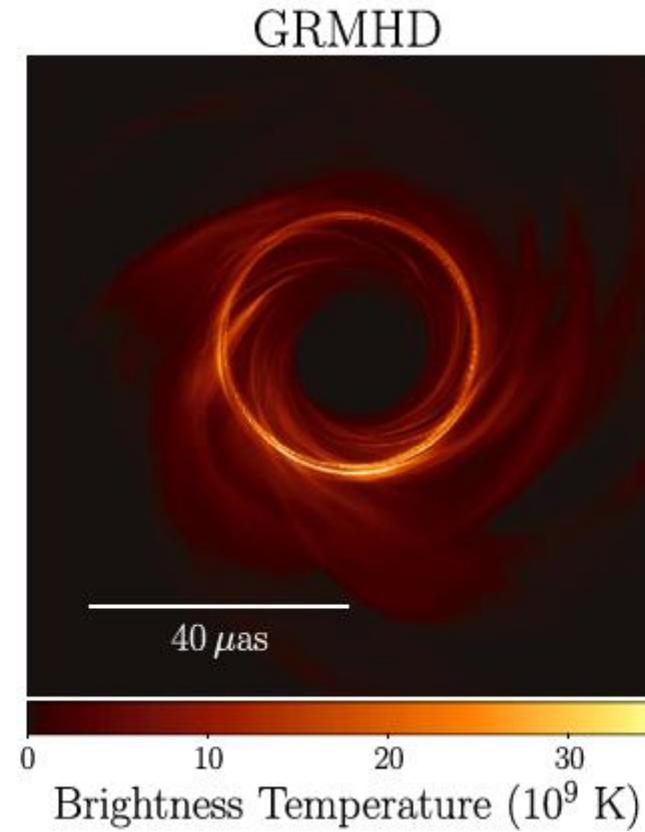
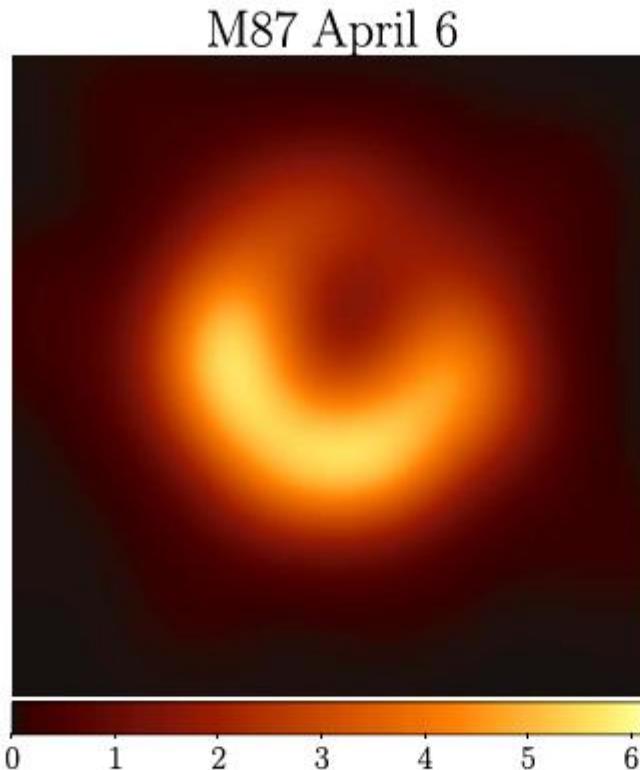
$$P_{\text{jet}} \propto \Phi_B^2 a^2$$

BH spin
magnetic flux

Igumenshchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012

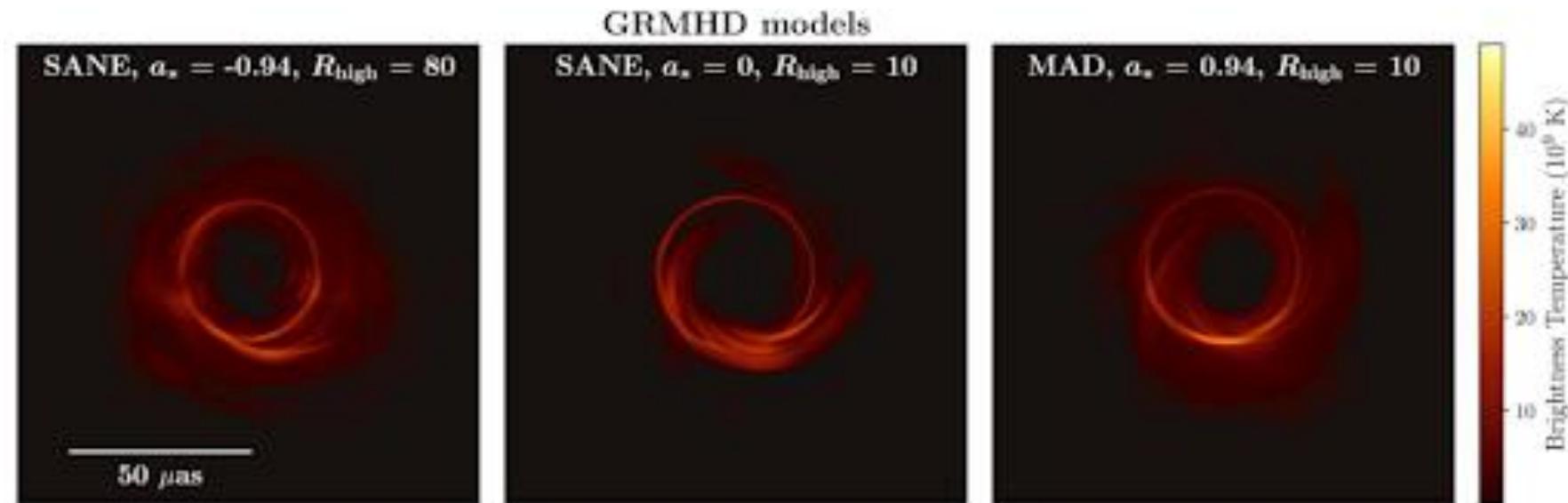
Image credit: Riordan+ 2017

EHT Images are consistent with GRMHD/LLAGN Picture



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)**



- Image asymmetry → black hole spin vector faces away from Earth
- An additional constraint on **jet power** ($\geq 10^{42} \text{ erg/sec}$) rejects all spin 0 models
- Can we do better with polarization?

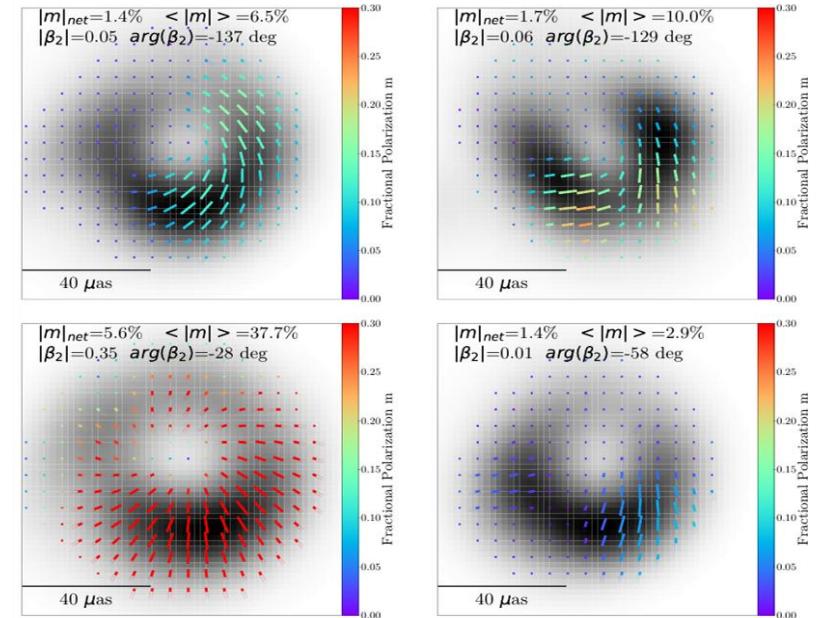
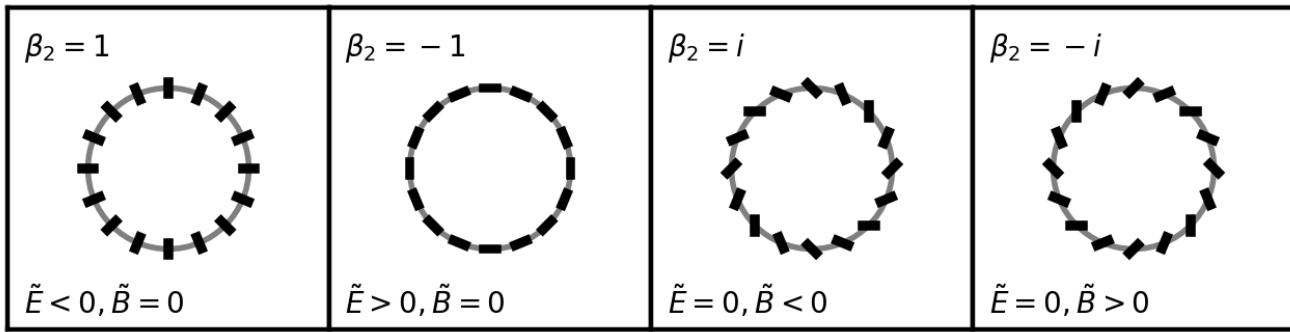
Summarizing an image: Polarization

Unresolved and Resolved polarization fractions

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

**Azimuthal structure
2nd Fourier mode**

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



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

Scoring M87* simulations with polarization

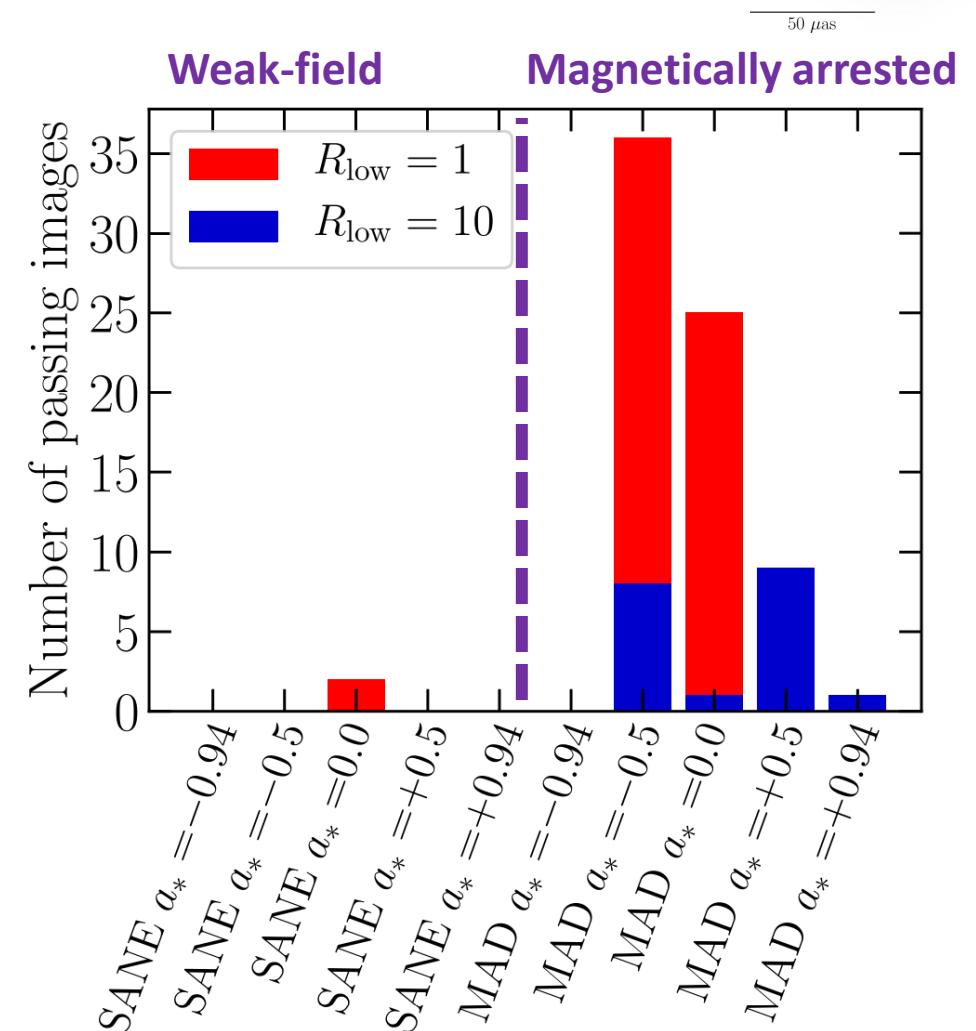
- Scoring 2017 observations with multiple approaches **all strongly favor a magnetically arrested accretion flow**
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

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

- Parameters from passing models agree with analytic model estimates:

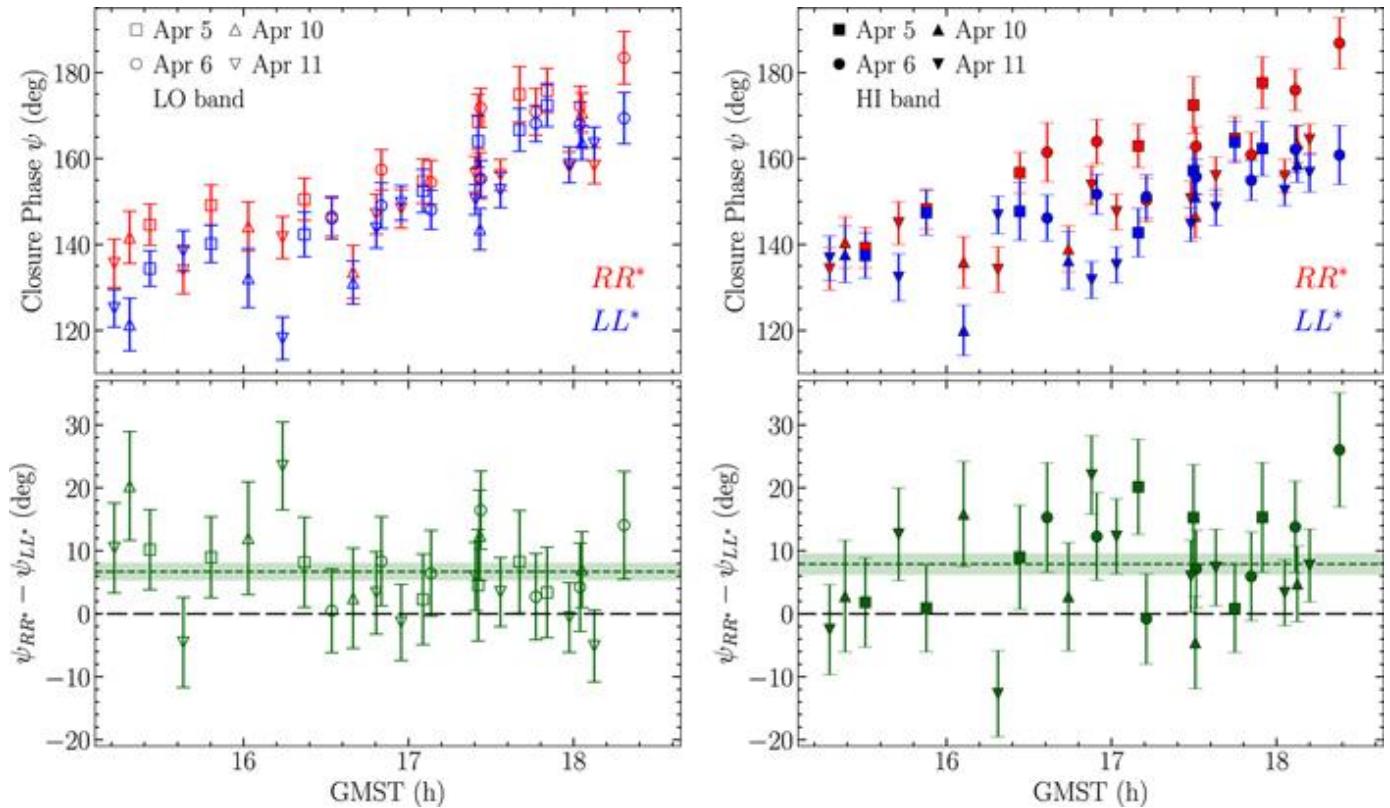
$$T_e \simeq (5 - 40) \times 10^{10} \text{ K}$$
$$|B| \simeq (7 - 30) \text{ G}$$
$$n \sim 10^{4-5} \text{ cm}^{-3}$$

- Strong magnetic fields more easily launch BZ jets!
- Do new EHT polarization measurements change this picture? Stay tuned!

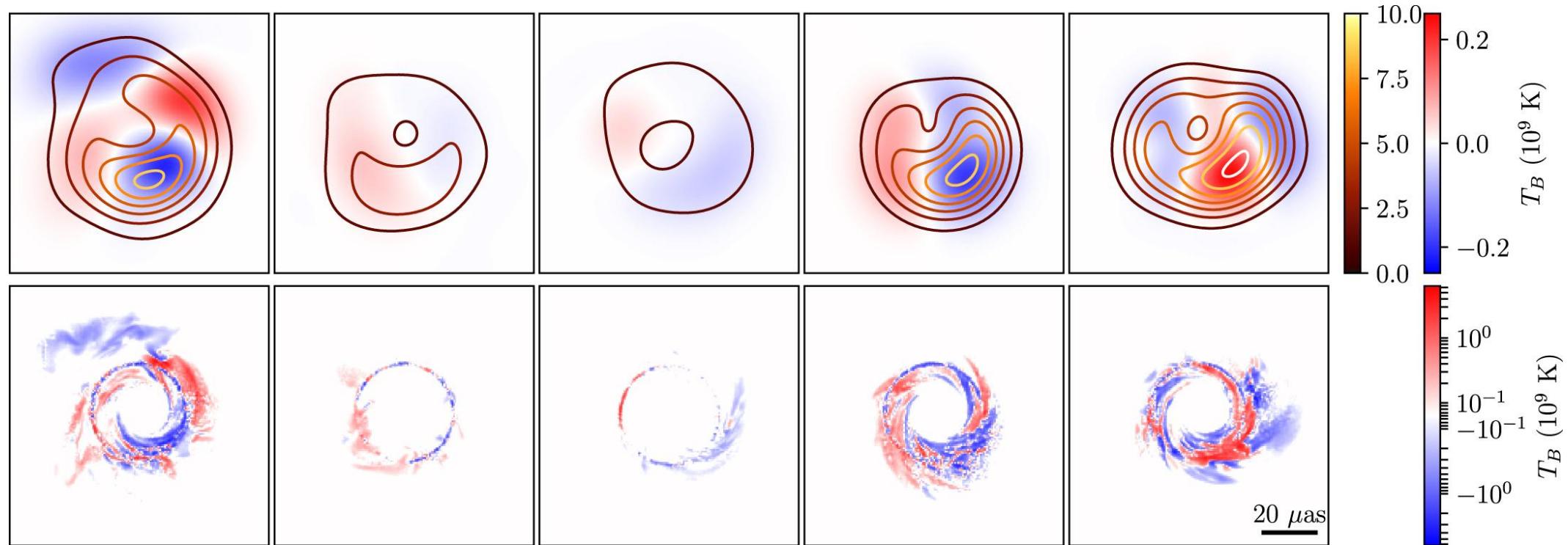


Horizon-Scale circular polarization is unambiguously detected by the EHT

- 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.



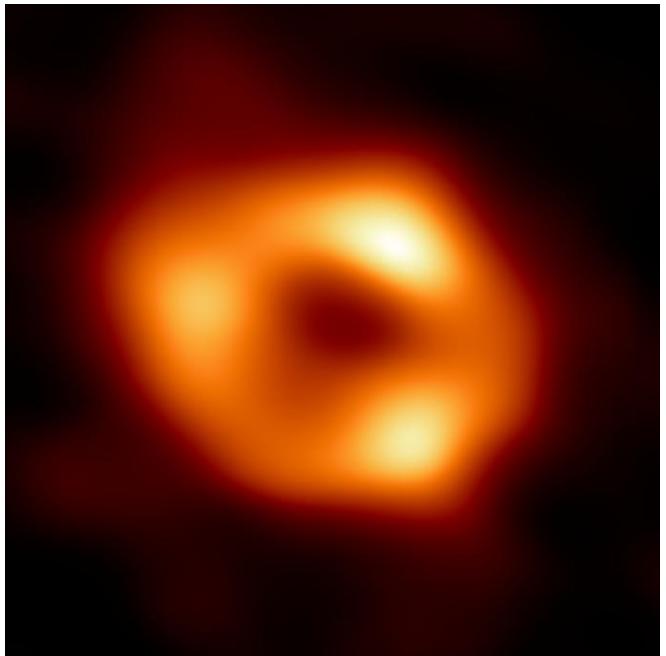
Passing simulations have diverse circular polarization images



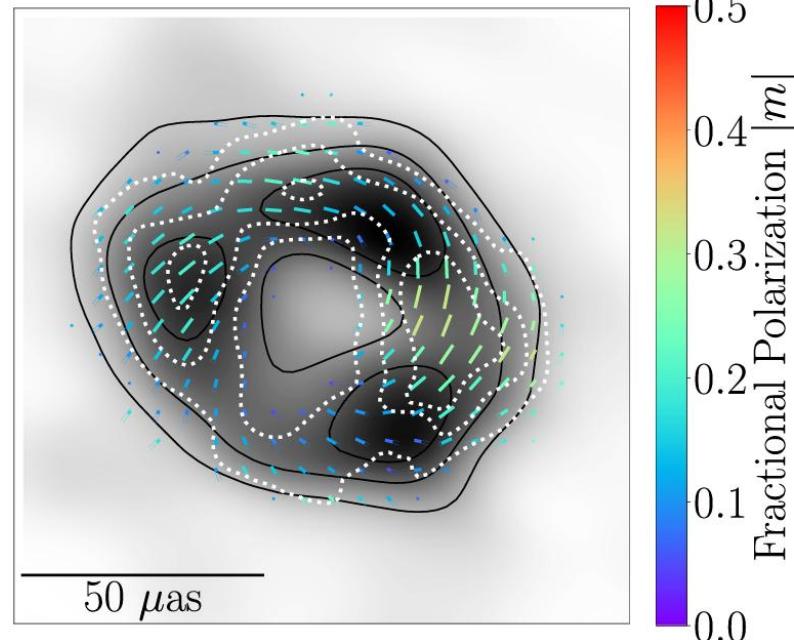
Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

Sgr A* in linear polarization

Total intensity



Linear Polarization



- Polarization fraction is **higher** than in M87 ($\sim 25\%$)
- β_2 is consistent with **clockwise rotation** measured in NIR flares
- MAD simulations also preferred – **where is the jet?**

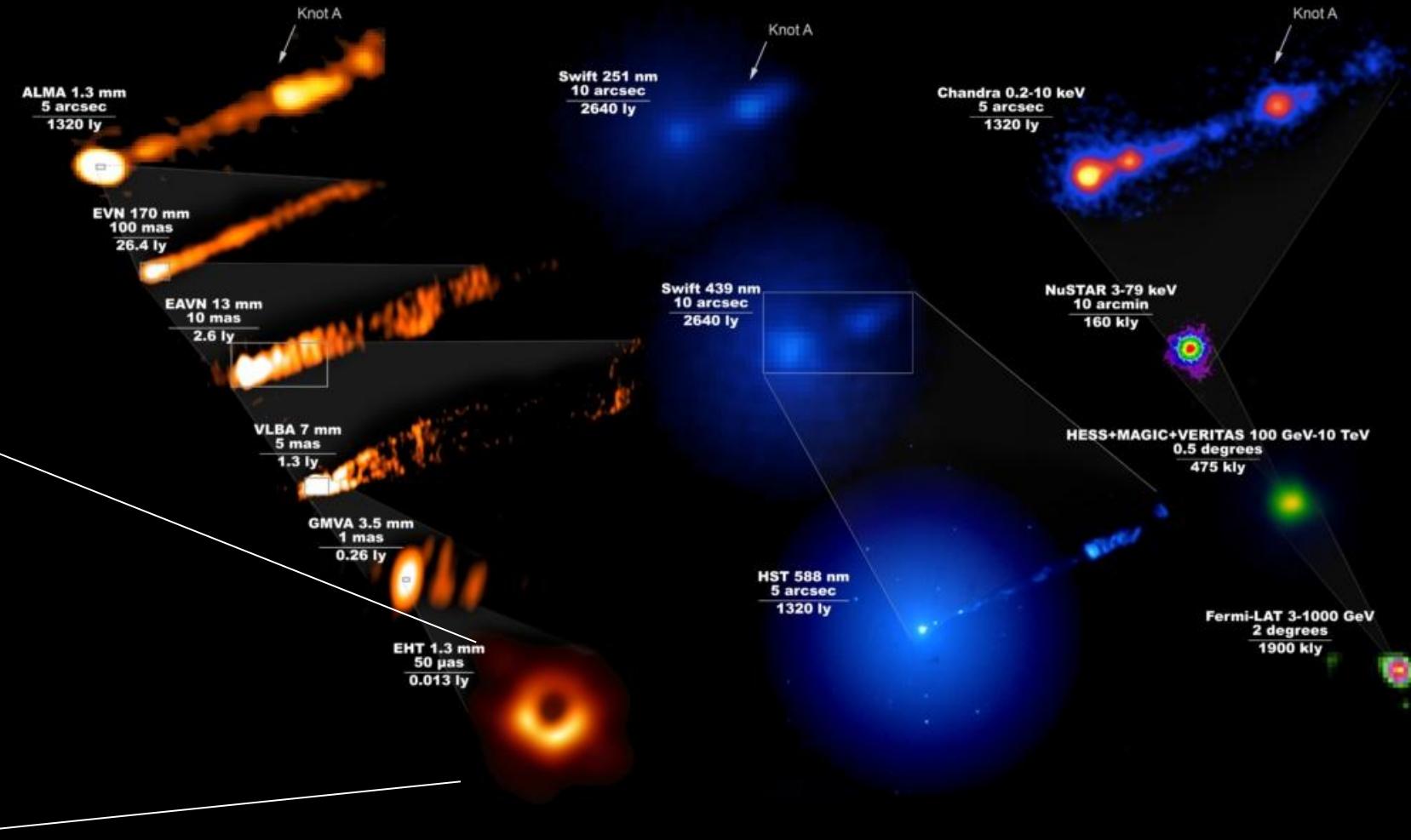
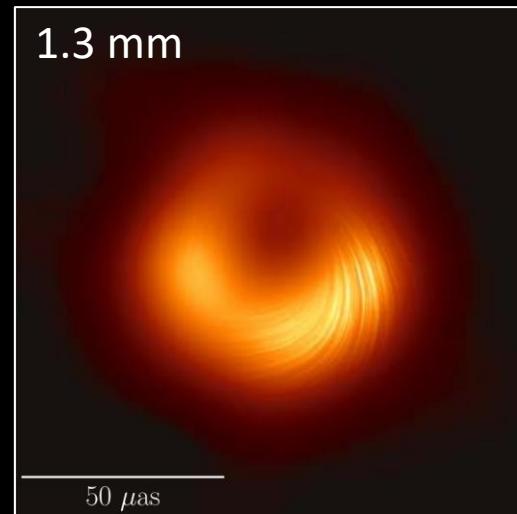
What can a polarized image of M87* tell us
about energy flow & jet launching?

Chael+ 2023, Chael 2025
[2307.06372](#), [2501.12448](#)

M87*

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

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



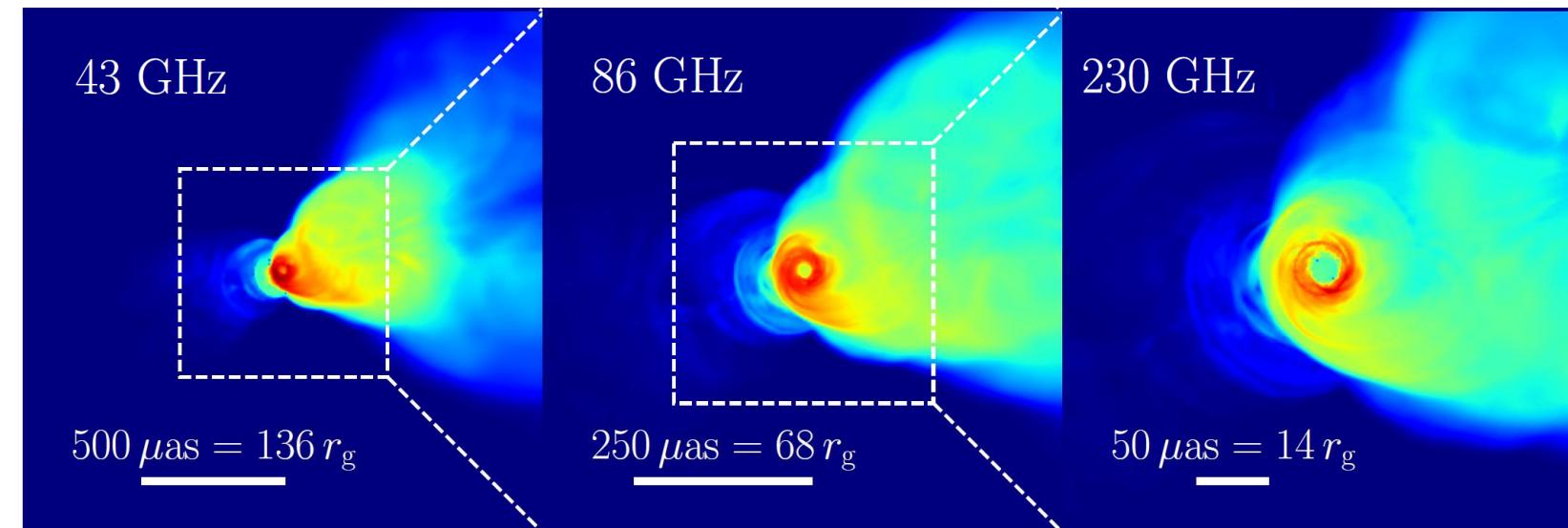
Jets are thought to be powered by black hole spin energy extracted via magnetic fields (Blandford & Znajek 1977)
Is it possible to observe black hole energy extraction **on horizon scales?**

M87 Jets in GRMHD Simulations

- Jets from magnetically arrested GRMHD simulations **are powered by black hole spin**

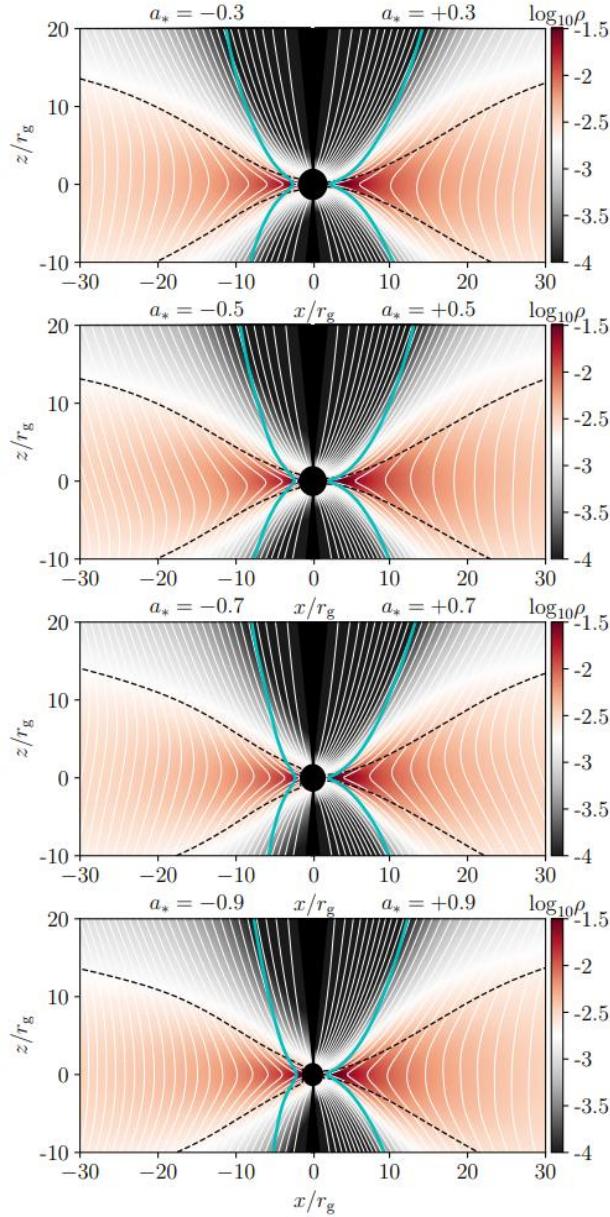
(e.g. McKinney & Gammie 2004,
Tchekhovskoy+ 2012, EHTC+ 2019, Narayan+
2022)

- Radiative** simulations (Chael+ 2019, 2025) naturally produce:
 - A jet power in measured range
 - observed wide opening angle
 - observed core-shift



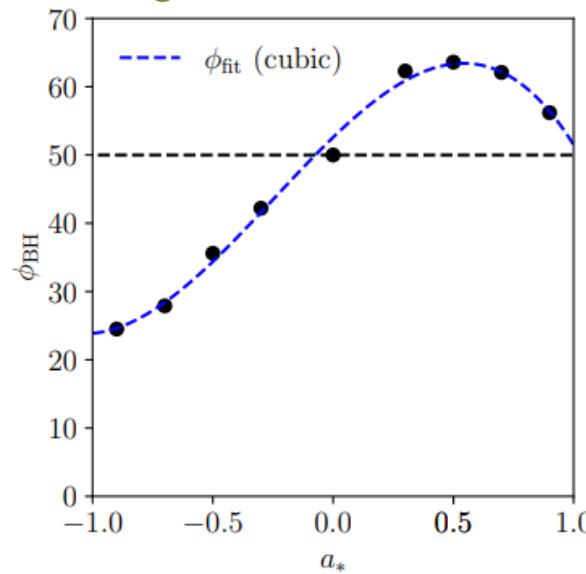
- Can we be **sure**? What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?

Jets in MADs are Blandford-Znajek

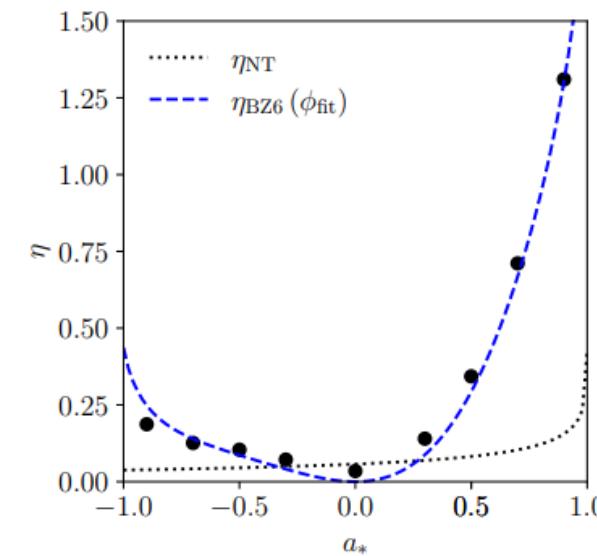


Jet power follows BZ prediction in 8 very-long-duration simulations
($10^5 t_g$) of magnetically arrested accretion

Magnetic flux though the horizon

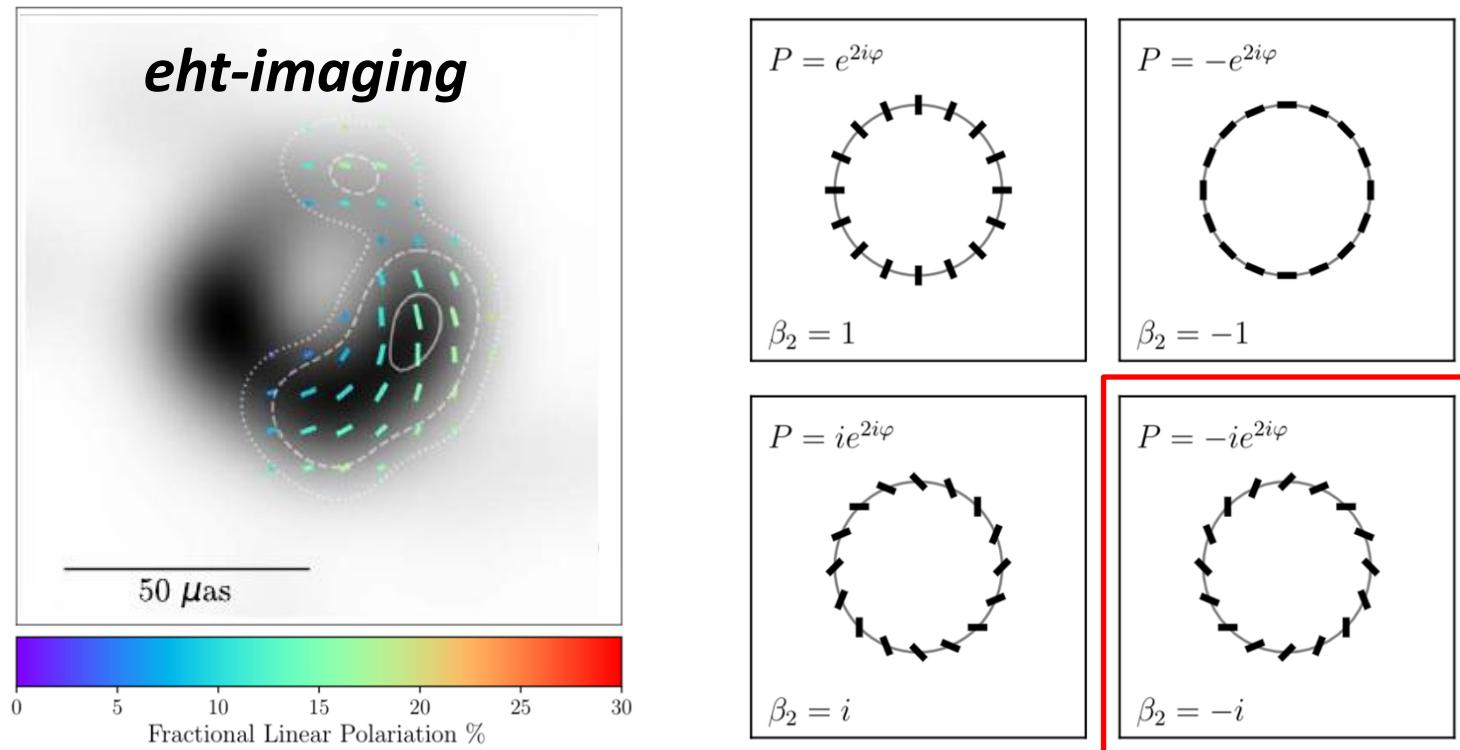


Jet efficiency



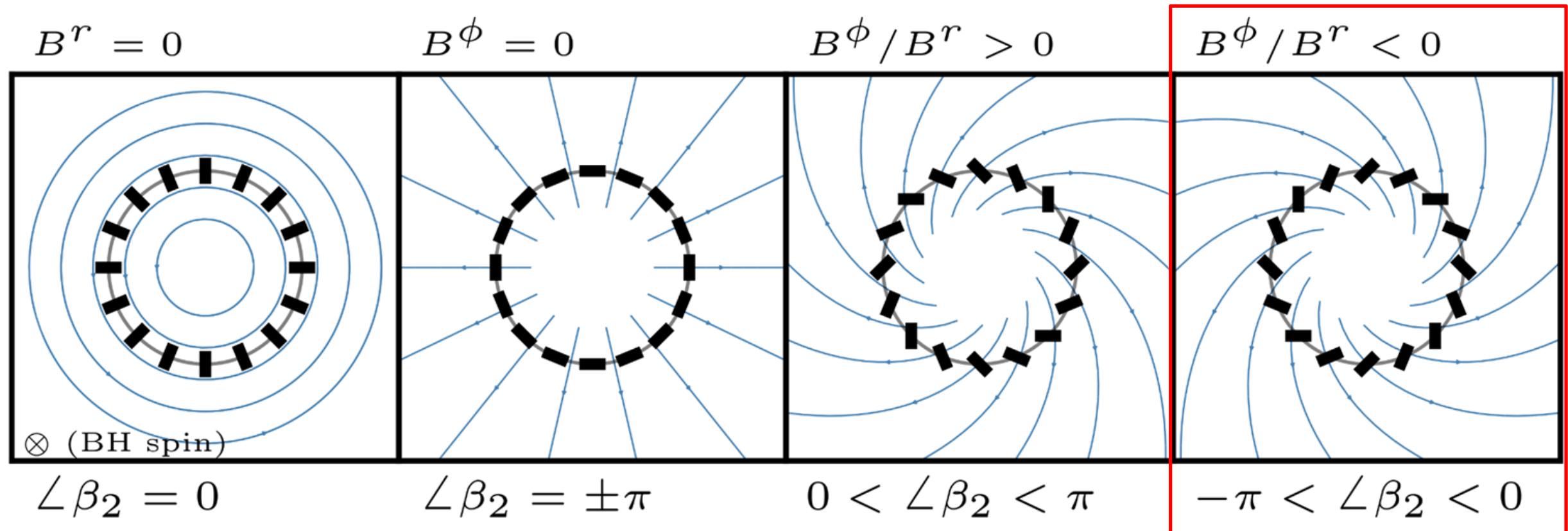
BH spin

Polarized Images of M87* and horizon-scale energy flow



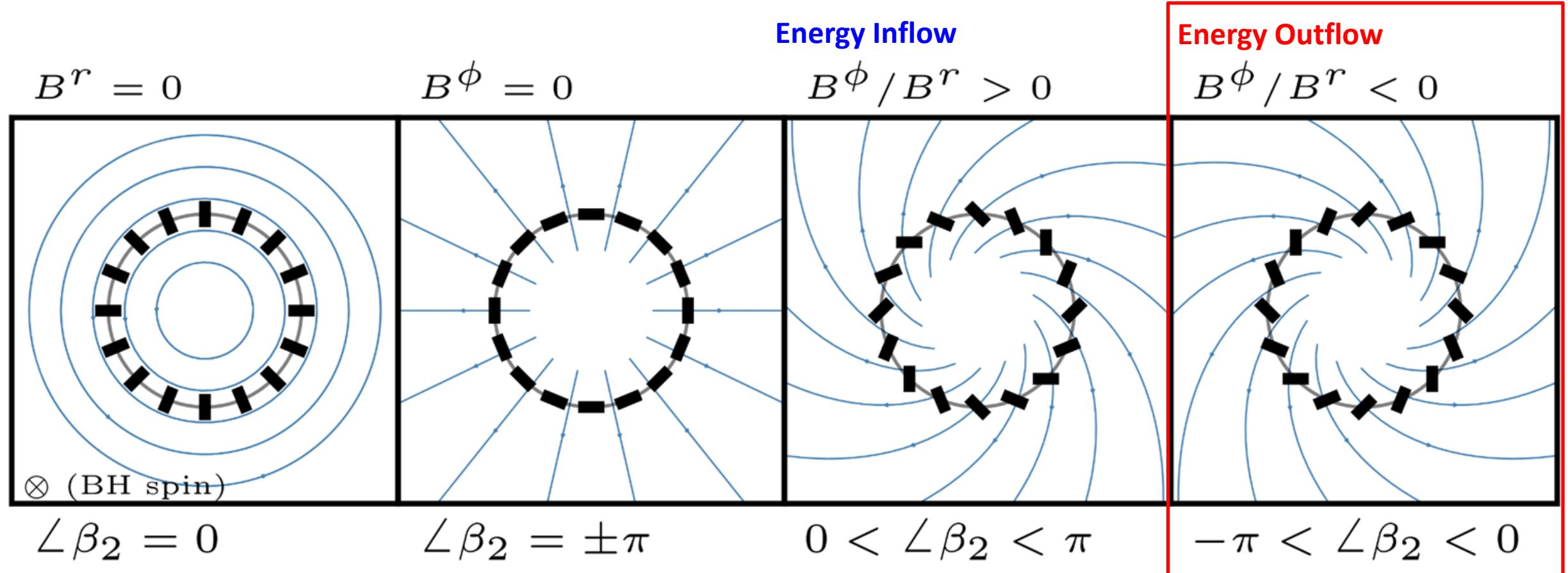
- The polarization spiral's 2nd Fourier mode (β_2 : Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret β_2 **physically**?

Cartoon model: β_2 is connected to the field pitch angle



- Face on fields, no Faraday rotation, no optical depth, no relativistic parallel transport or abberation
- Coordinate axis points **into the sky** (EHT Paper V, 2019)

BZ model: β_2 is connected to the electromagnetic energy flux



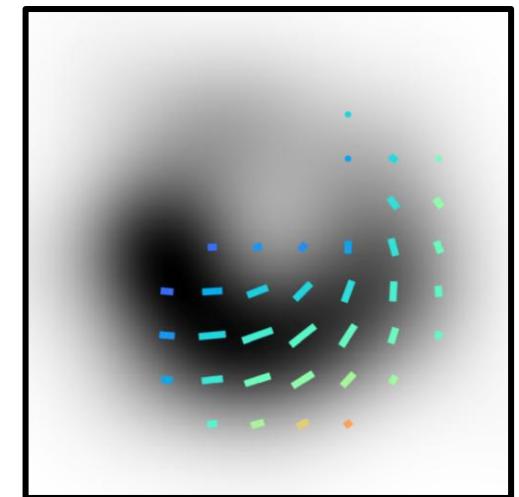
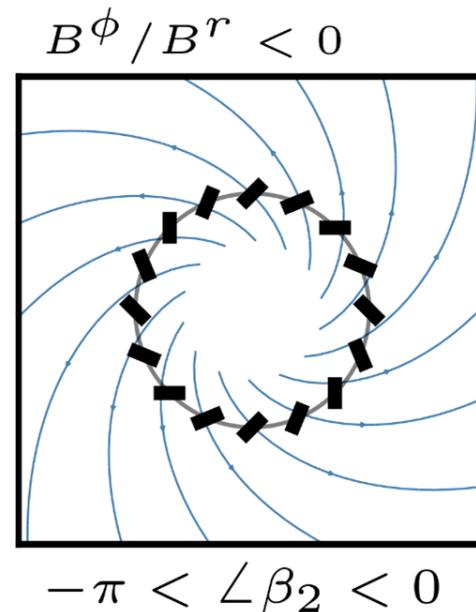
Radial Poynting Flux:

$$\mathcal{J}_E^r = -T_{t \text{ EM}}^r = -B^r B^\phi \Omega_F \Delta \sin^2 \theta.$$

↑
 fieldline angular speed

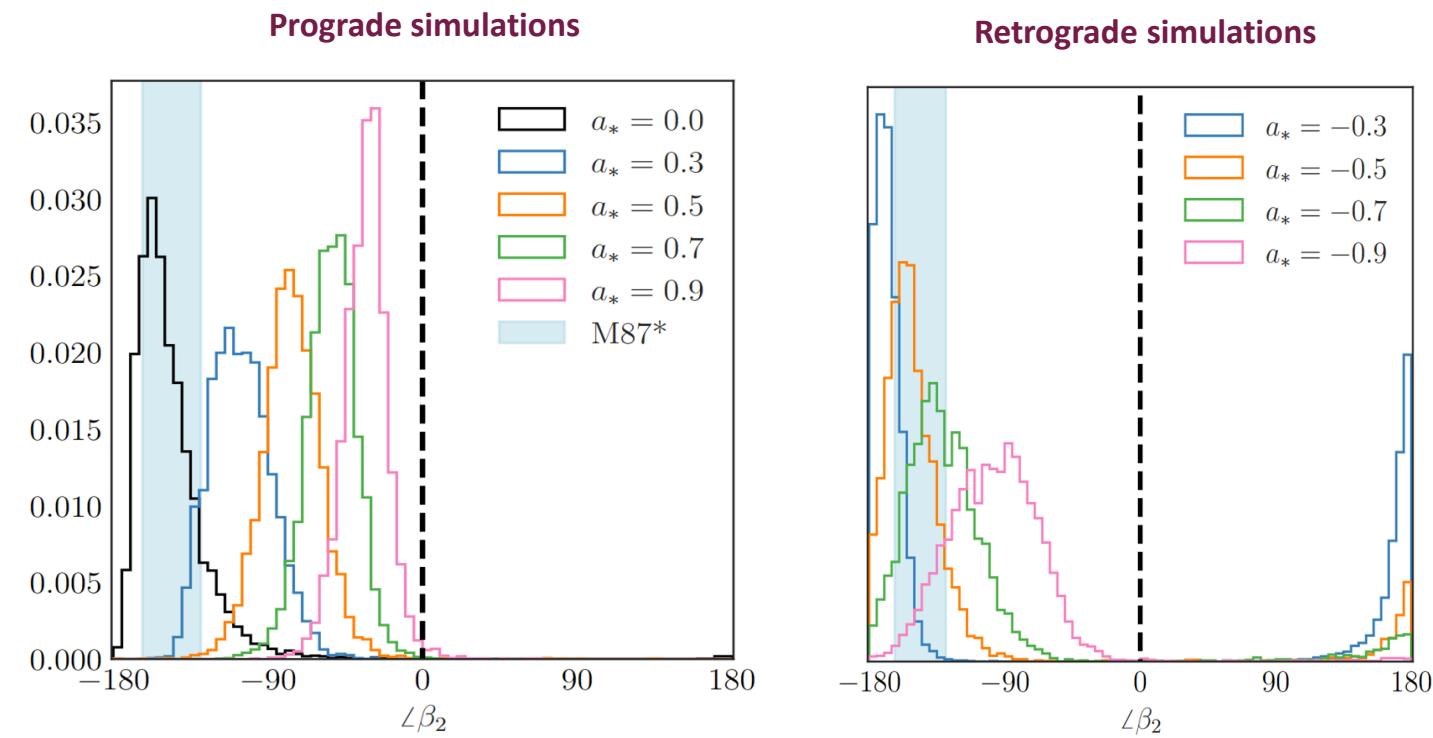
Near-horizon polarization is connected to the electromagnetic energy flux

- In simple BZ models, the sign of $\arg(\beta_2)$ is directly connected to the direction of Poynting flux, assuming we know the sign of Ω
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy outflow in M87***
- Does this simple argument hold up in **more complicated models** of M87*?

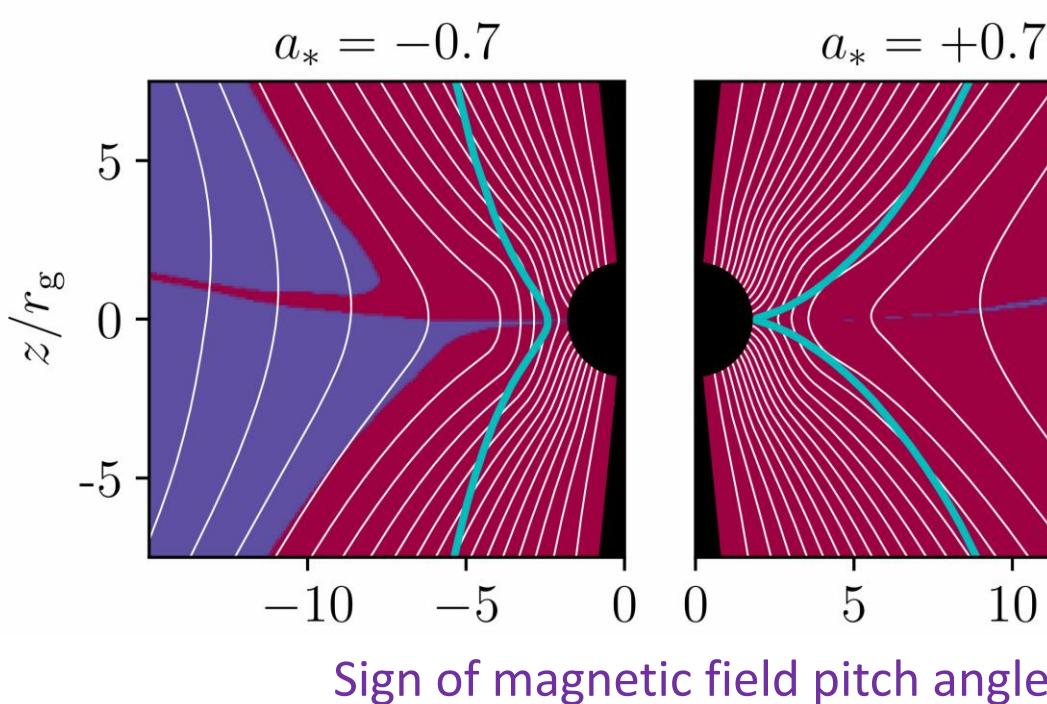


β_2 in MAD GRMHD simulations of M87*

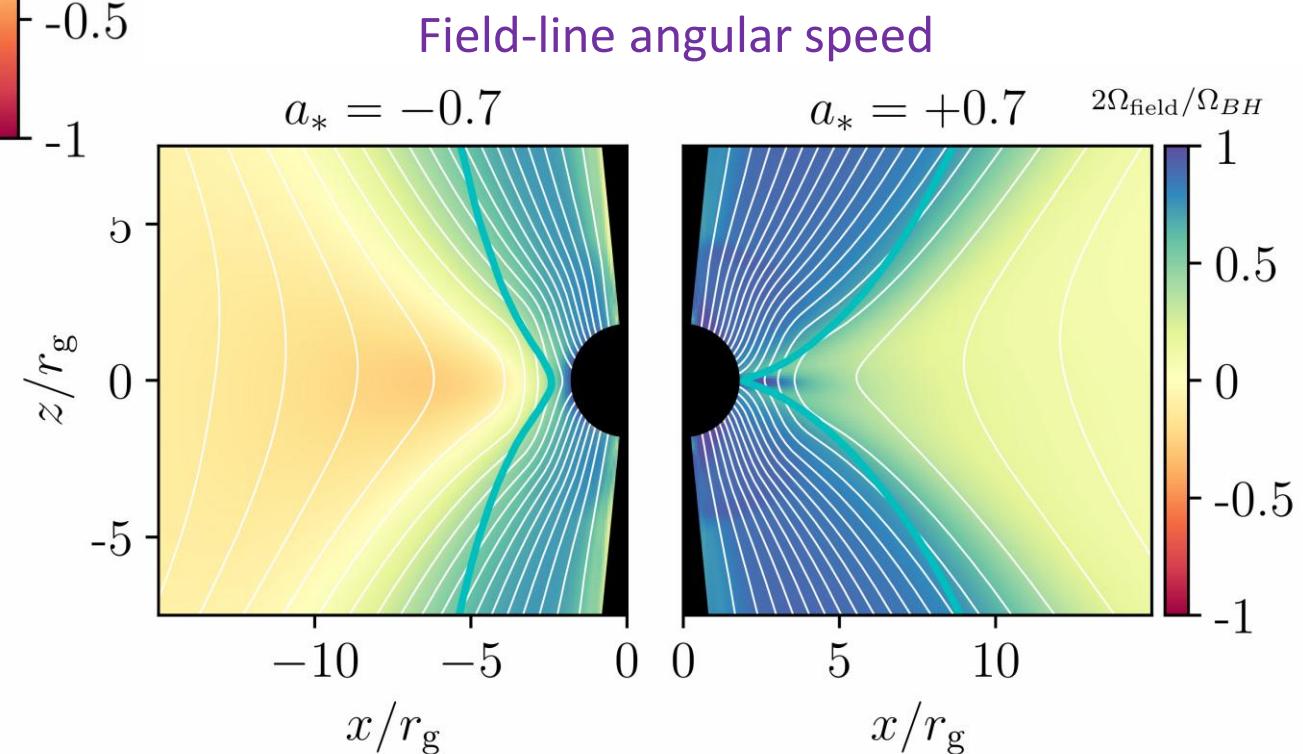
- 1600 simulated EHT-resolution M87* images from MAD simulations (Narayan+ 2022)
- Almost all 230 GHz simulation images have **negative $\arg(\beta_2)$** consistent with the measured energy outflow in the simulations
- $\arg(\beta_2)$ has the **same qualitative dependence on spin** as in the BZ monopole model, despite effects of turbulence, non-equatorial emission, and Faraday rotation.



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



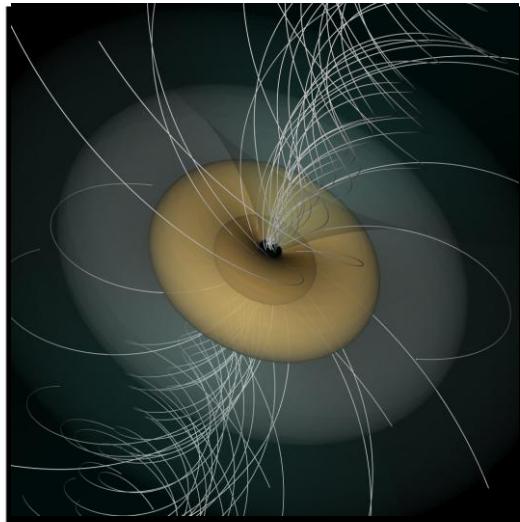
Sign of magnetic field pitch angle



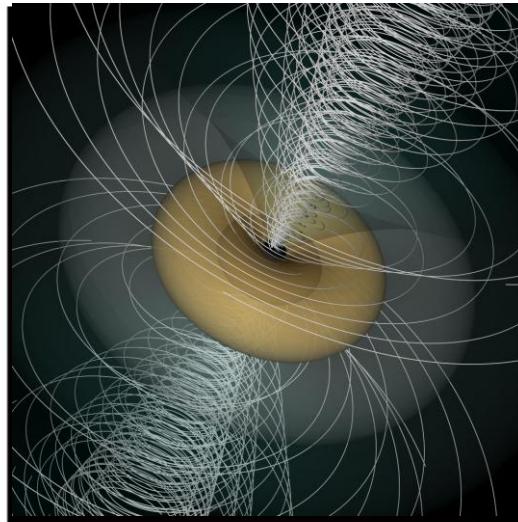
Even in **retrograde** simulations, field-lines in the 230 GHz emission region **co-rotate** with the black hole and have a negative B^ϕ / B^r

Polarized images are spin dependent

Low Spin



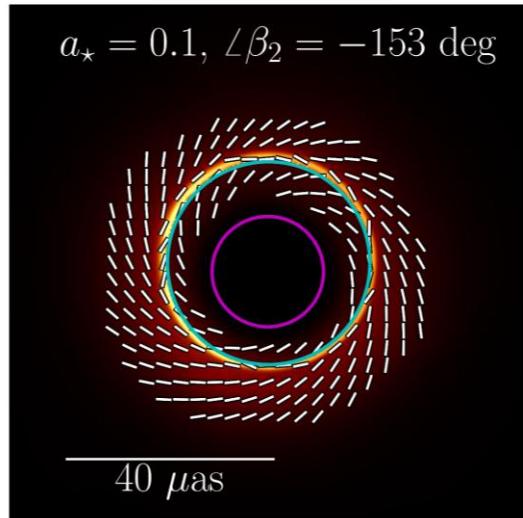
High Spin



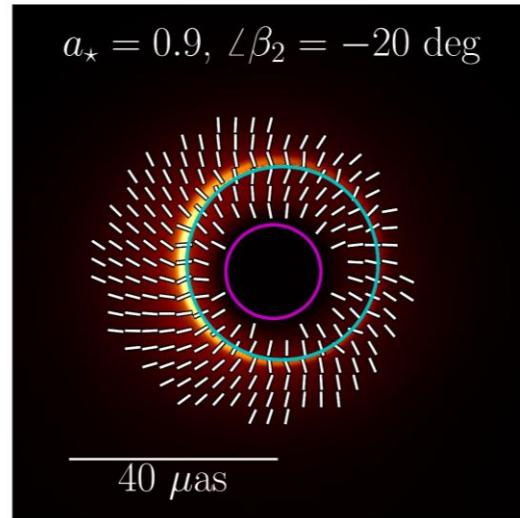
- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
 - increases the BZ jet power

Polarized images are spin dependent

Low Spin



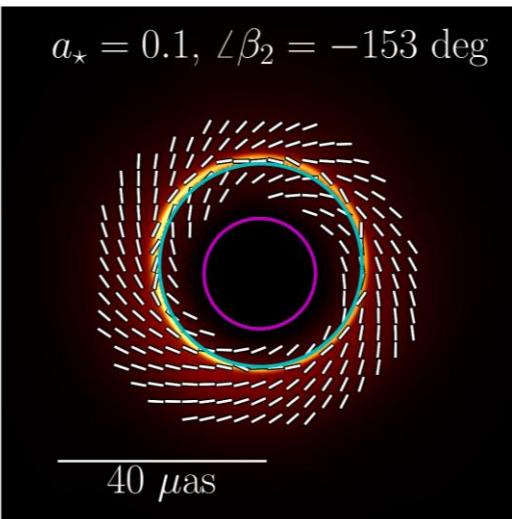
High Spin



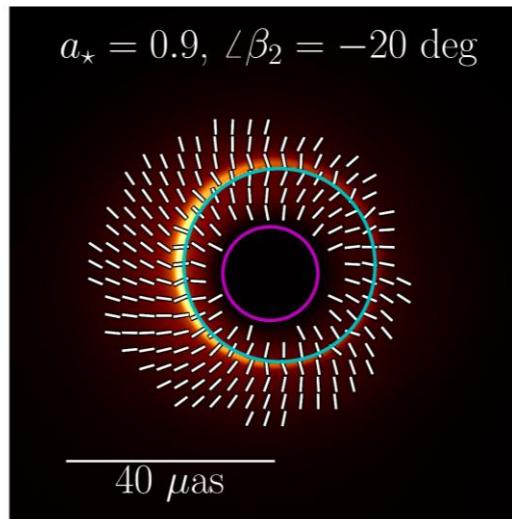
- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
 - increases the BZ jet power
 - makes the observed polarization pattern more radial

Polarized images are spin dependent

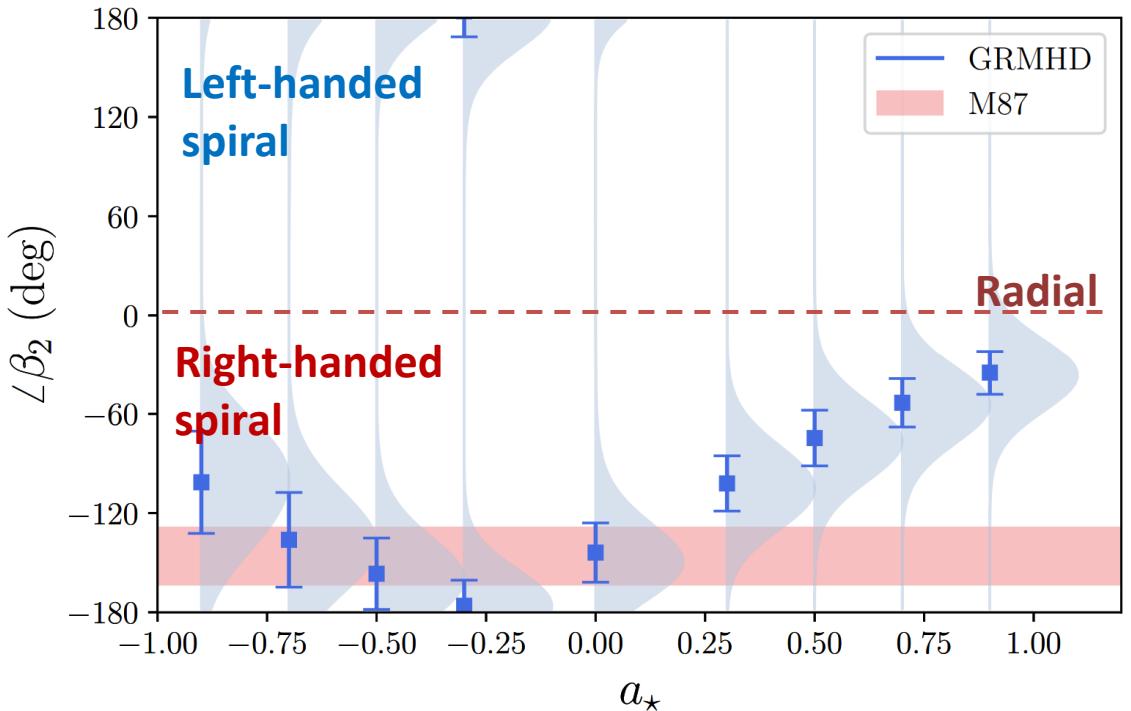
Low Spin



High Spin



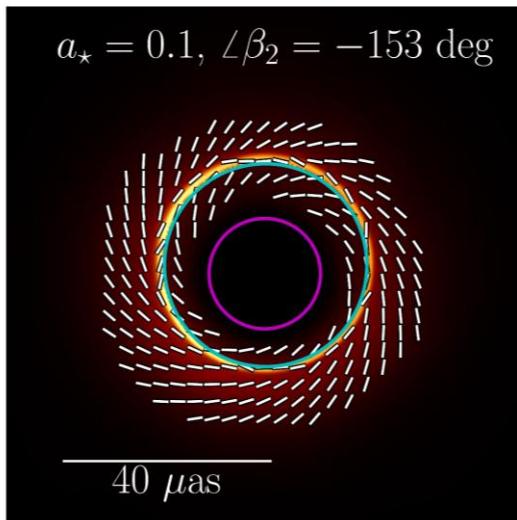
M87*



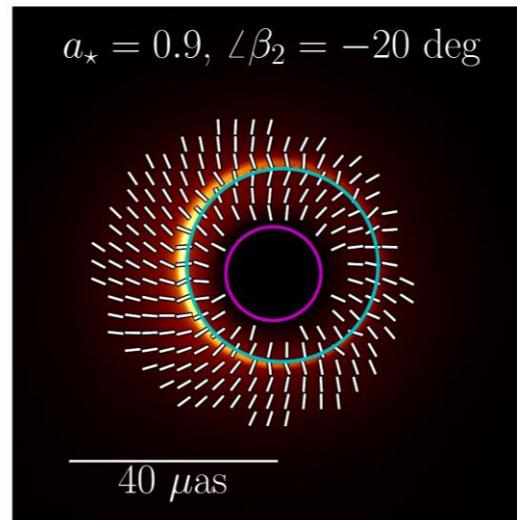
- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise BH rotation**
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
 - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)

Polarized images are spin dependent

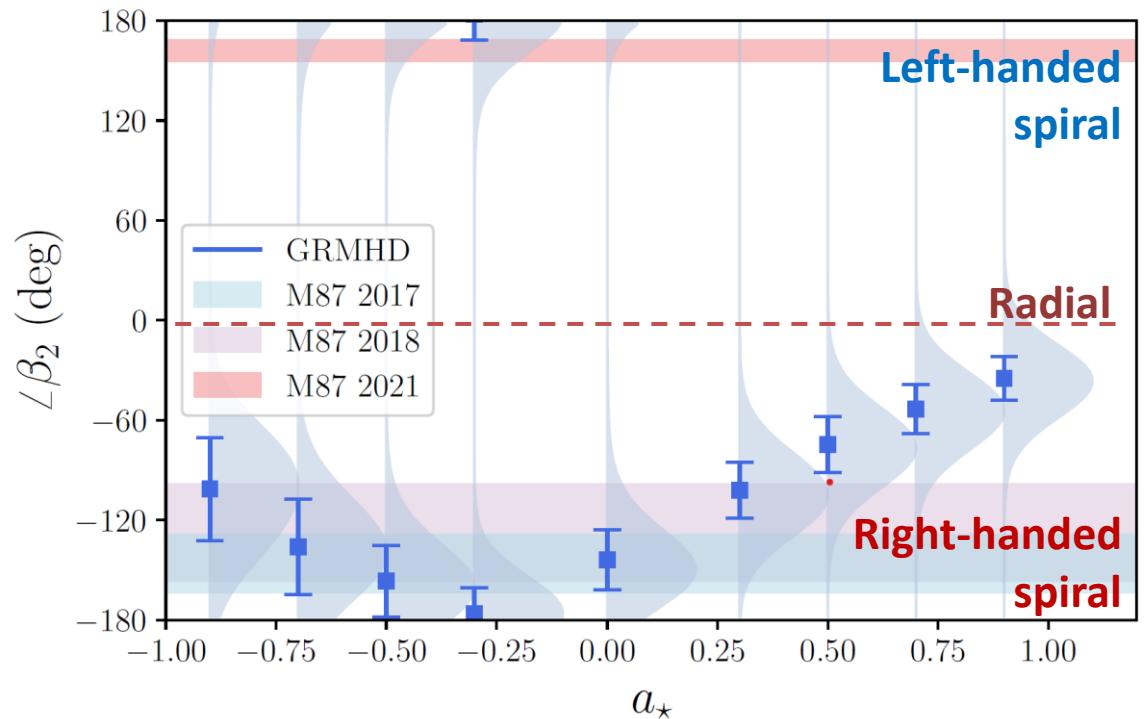
Low Spin



High Spin

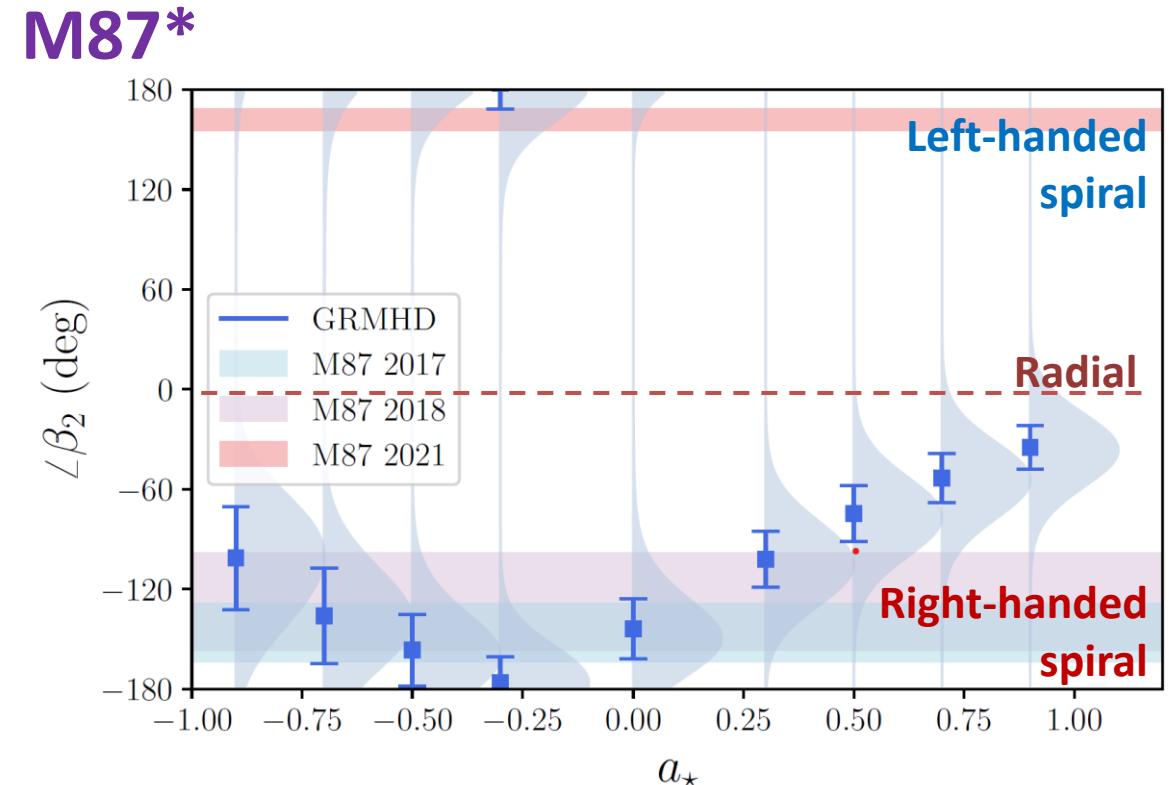
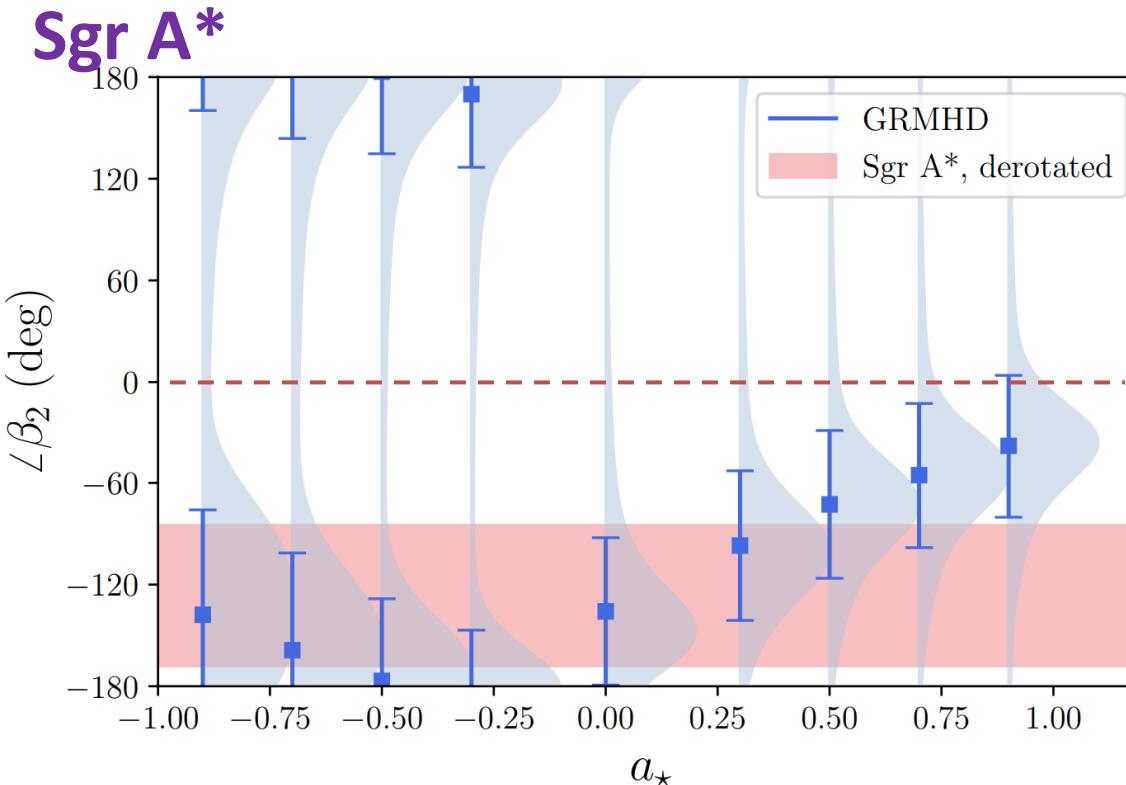


M87*



- 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)
- **Change in sign in $\arg(\beta_2)$ 2021 is mysterious**
 - Retrograde spin?
 - Change in external Faraday screen?

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 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!**

Next steps for determining the BH spin and jet power source

Gelles+ 2025, Chael+ in prep.

[2410.00954](#)

How can we determine the jet power source?

By zooming **out**..

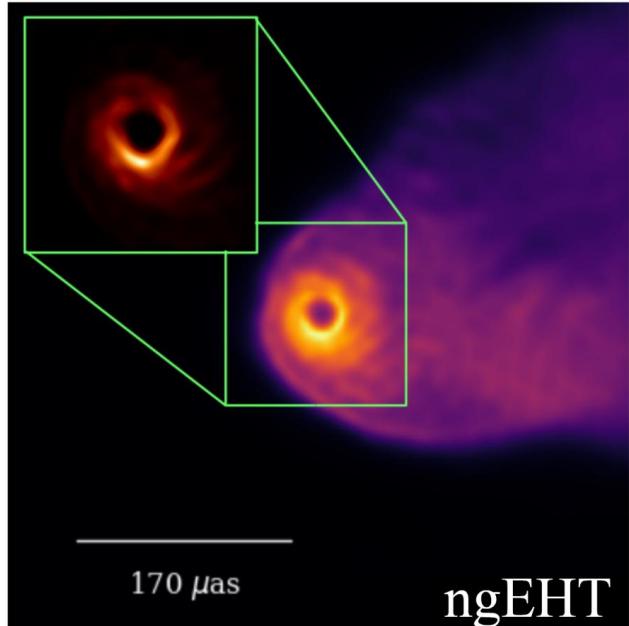


Image the connection between the BH and the low-brightness extended jet in **high dynamic range** with the **next-generation EHT (ngEHT)**

By zooming **in**..

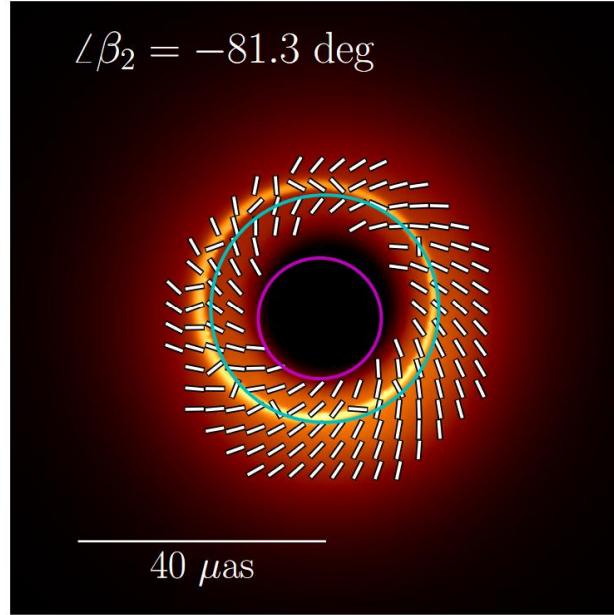
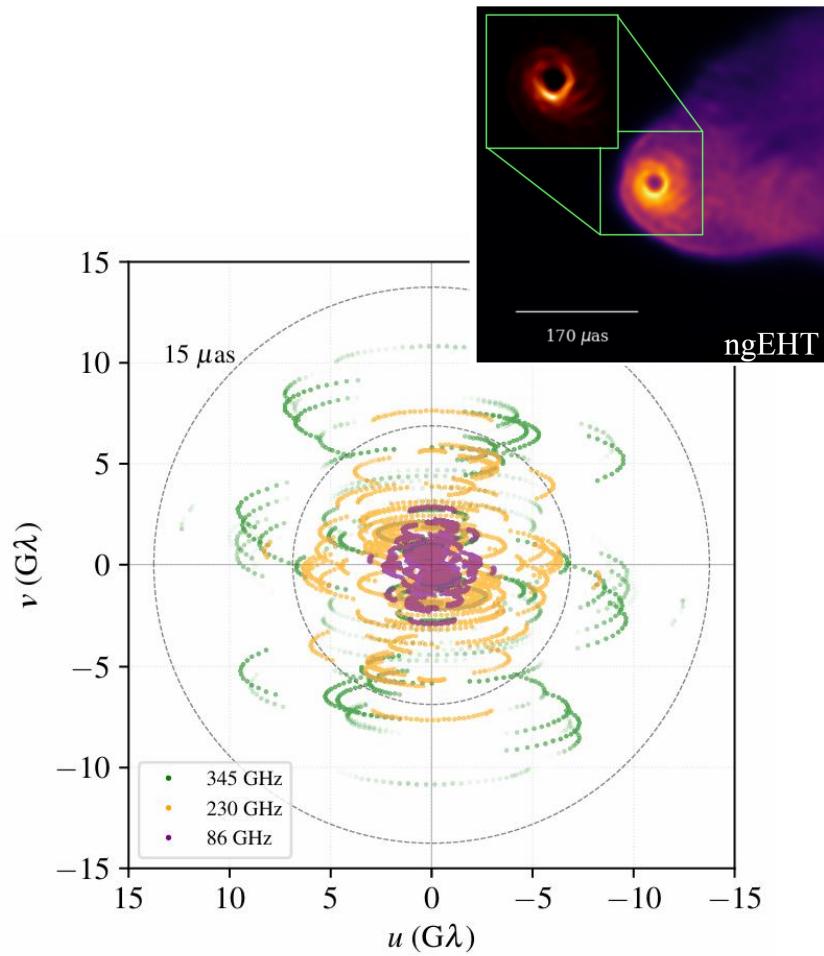
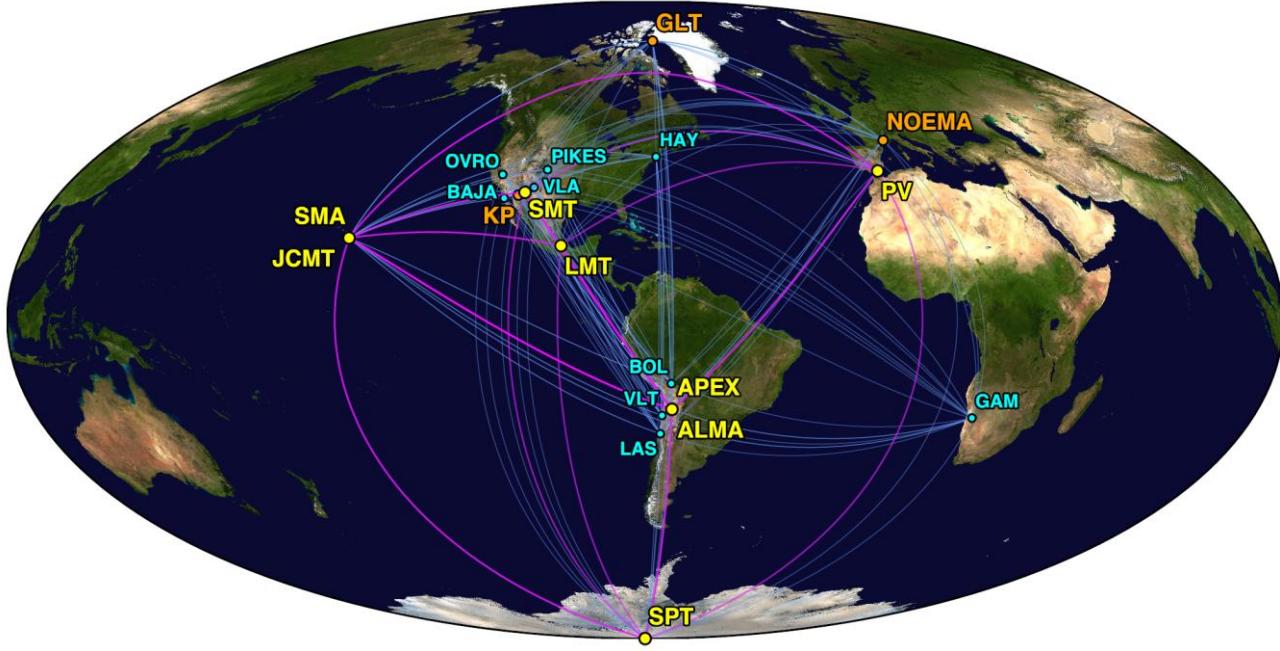


Image field lines close to the event horizon in **high resolution** with the **Black Hole Explorer (BHEX)**

The next-generation EHT (ngEHT)



Increased coverage from new sites and observing frequencies in ngEHT will enhance **dynamic range**

2017: Observations at 6 distinct sites

2018: Observations at 7 sites (+ GLT)

2021-22: Observations at 9 sites (+ Kitt Peak & NOEMA)

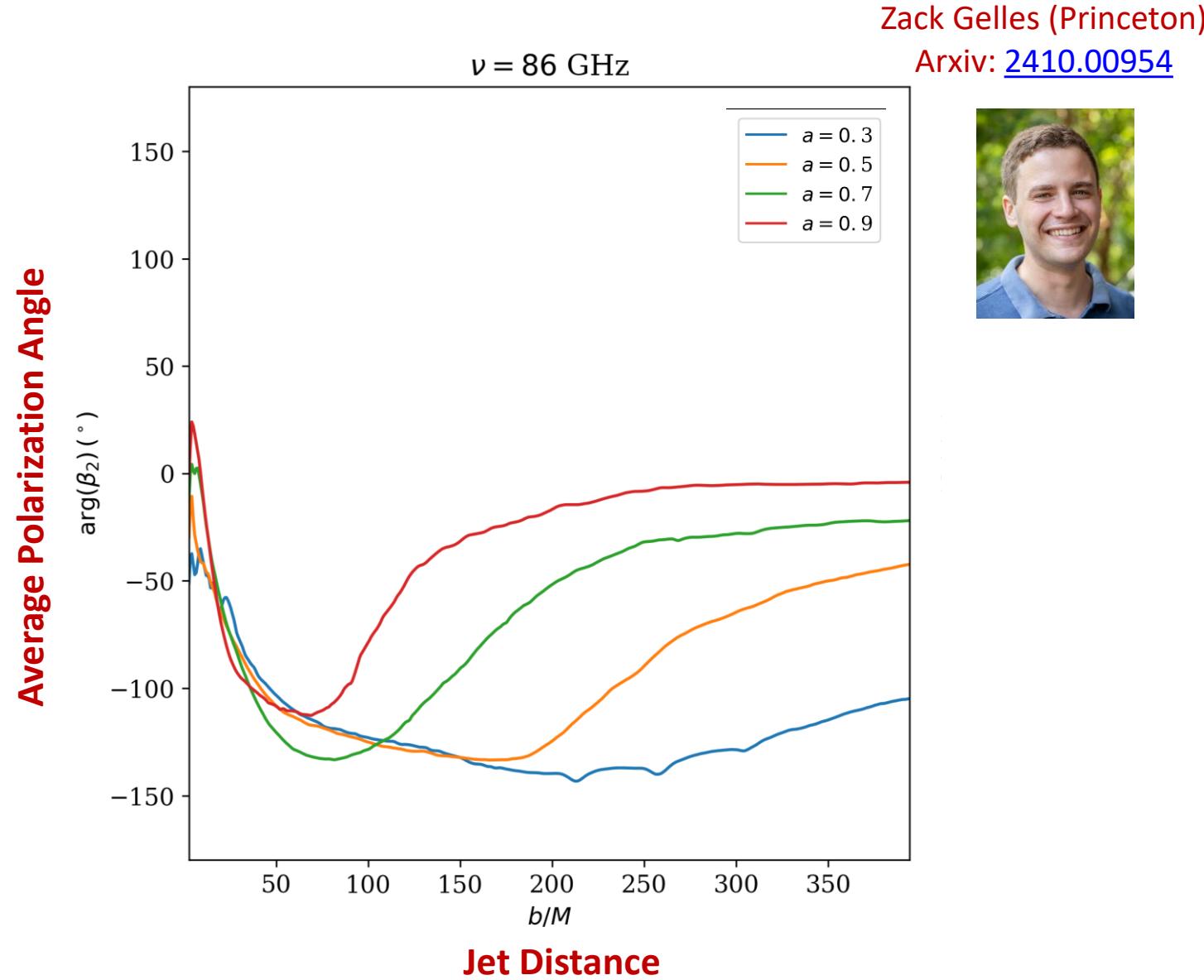
2024-25: 230+345 GHz observations

2030s: tri-band observations at 14 sites

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

BHEX will see polarimetric signatures of jet launching: *zooming out*

- Measuring polarization as a function of radius **probes energy flow at different scales** (Chael+ 2023)
- For Blandford-Znajek launched jets (as in GRMHD simulations) higher BH spin winds up magnetic fields closer to the jet base
- Polarization of BZ jets has a **strong signature of spin at the light cylinder** (Gelles+ 2025, Gelles in prep)



BHEX will see polarimetric signatures of jet launching:
zooming out

Zack Gelles (Princeton)
Arxiv: [2410.00954](https://arxiv.org/abs/2410.00954)

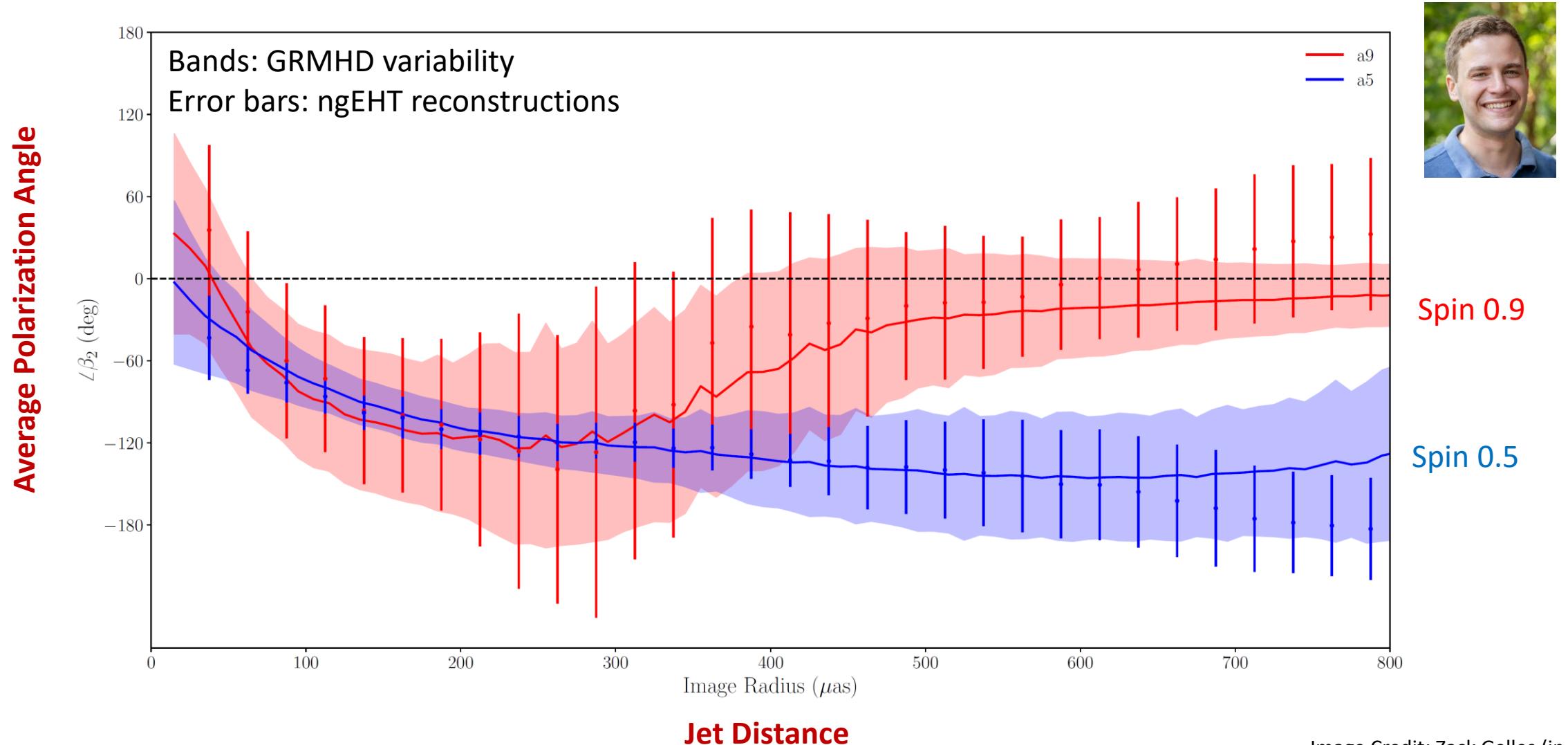


Image Credit: Zack Gelles (in prep)

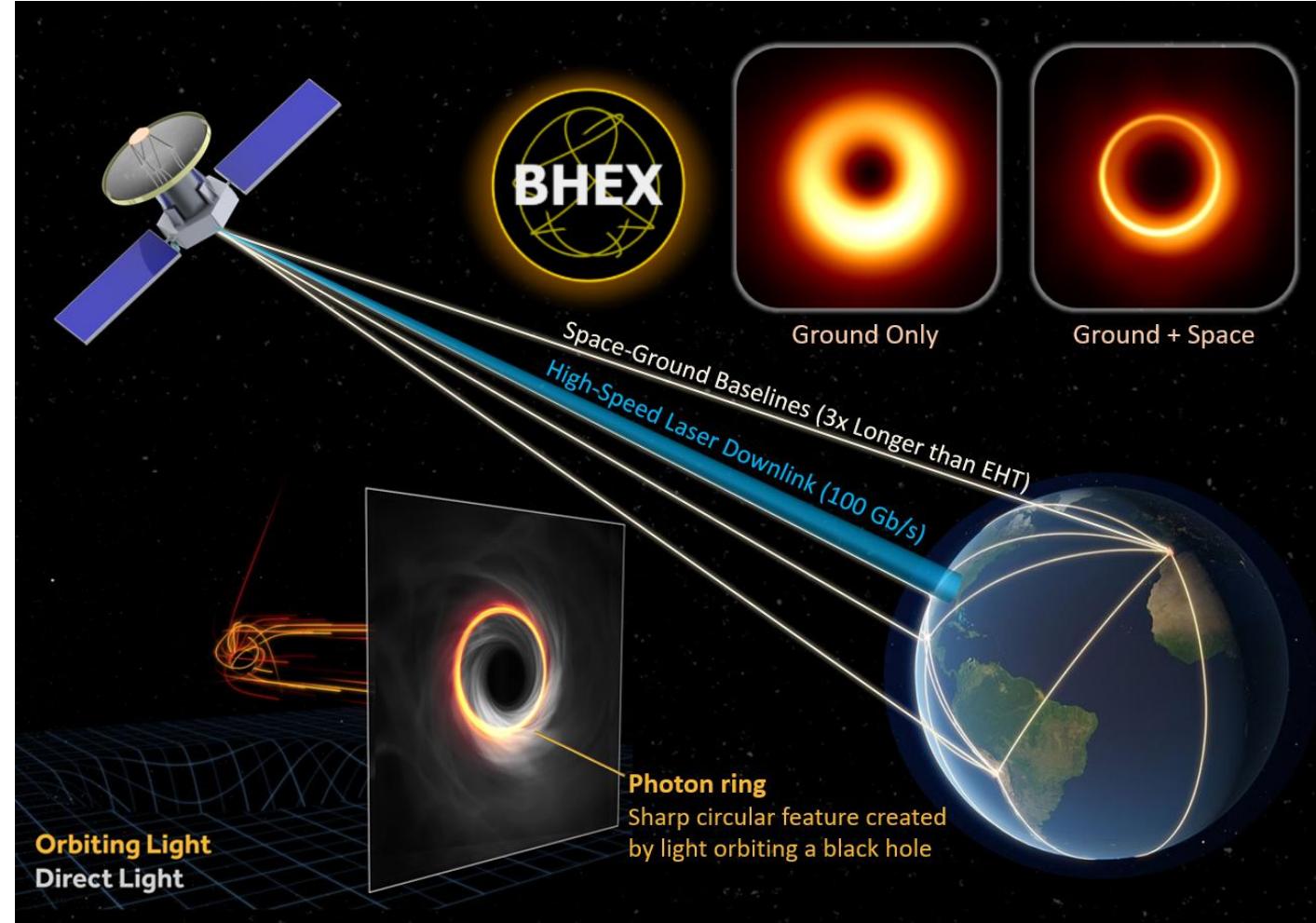
Going Further: The Black Hole Explorer (BHEX)

Earth-Space millimeter VLBI

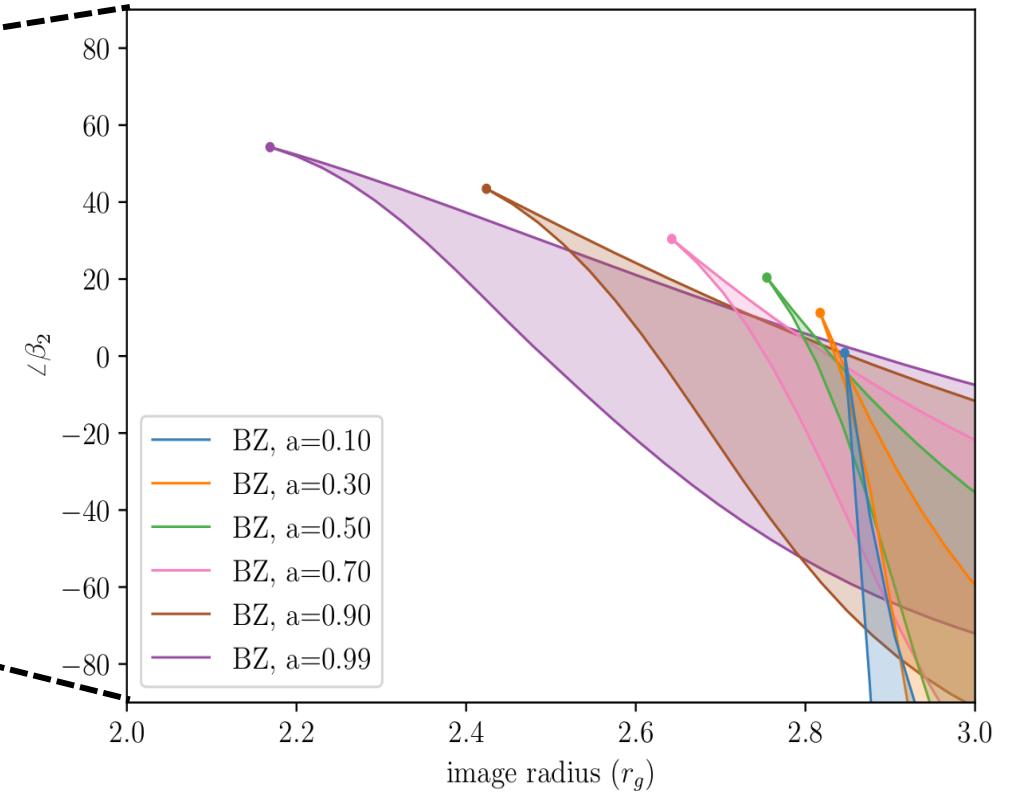
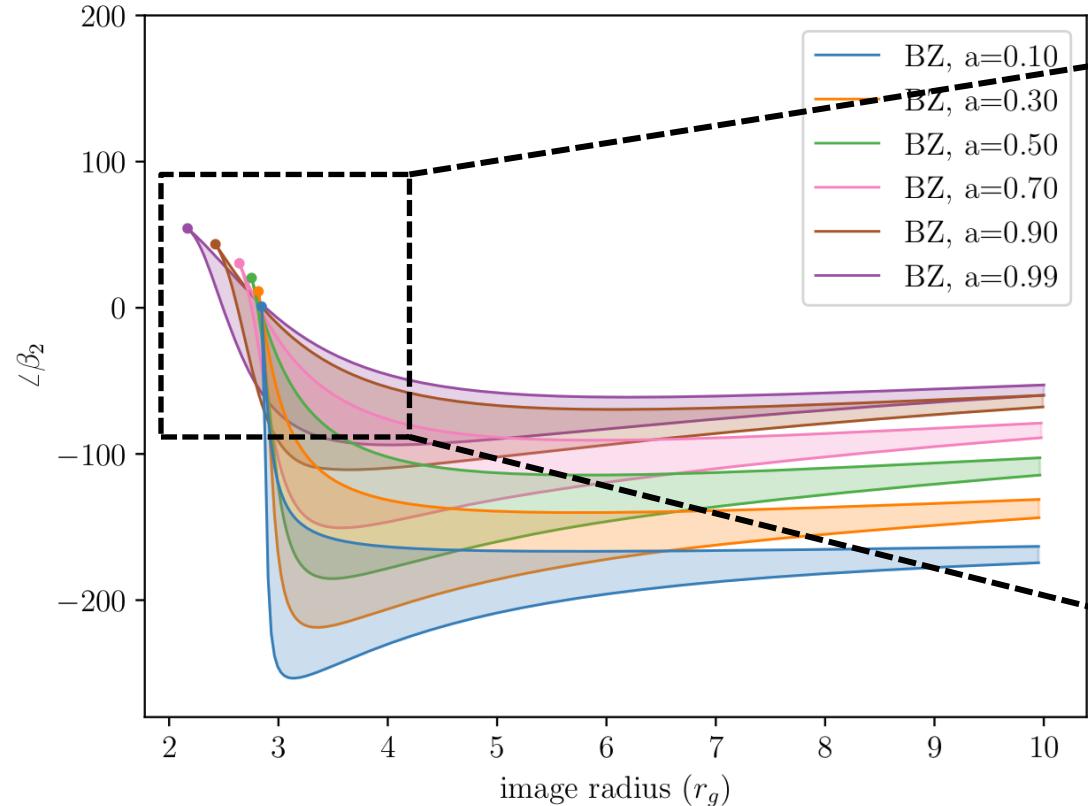
- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground mmVLBI network & pioneers optical laser downlink
- Targeting next NASA SMEX call

BHEX Science Goals

1. Discover and measures a black hole's photon ring
2. Reveal the shadows of >10 supermassive black holes
3. Constrain jet launching & acceleration on horizon → parsec scales



Universal value of the polarization angle at the horizon



In axisymmetric GRMHD models, synchrotron emission has a **value dependent only on spin and inclination** at the inner shadow (the asymptotic lensed image of the horizon; Chael+ 2021)

Universal value of EVPA at the horizon

- Axisymmetric GRMHD magnetic fields around a black hole predict a **unique** asymptotic linear polarization pattern approaching the event horizon dependent only on **spin and inclination**

$$\chi = \arctan\left(\frac{1}{z_0}\right) - \arctan\left(\frac{-\beta}{\alpha + a \sin \theta_o}\right)$$

$$z_0 = \frac{r_+ (a \sin^2 \theta - \lambda) + \nu_\theta a \cos \theta \sin \theta \sqrt{\Theta(\theta)}}{a (a \sin^2 \theta - \lambda) \cos \theta - \nu_\theta r_+ \sin \theta \sqrt{\Theta(\theta)}}$$

$$\Theta(\theta) = \eta + a^2 \cos^2 \theta - \lambda^2 / \tan^2 \theta \quad \text{Angular Potential}$$

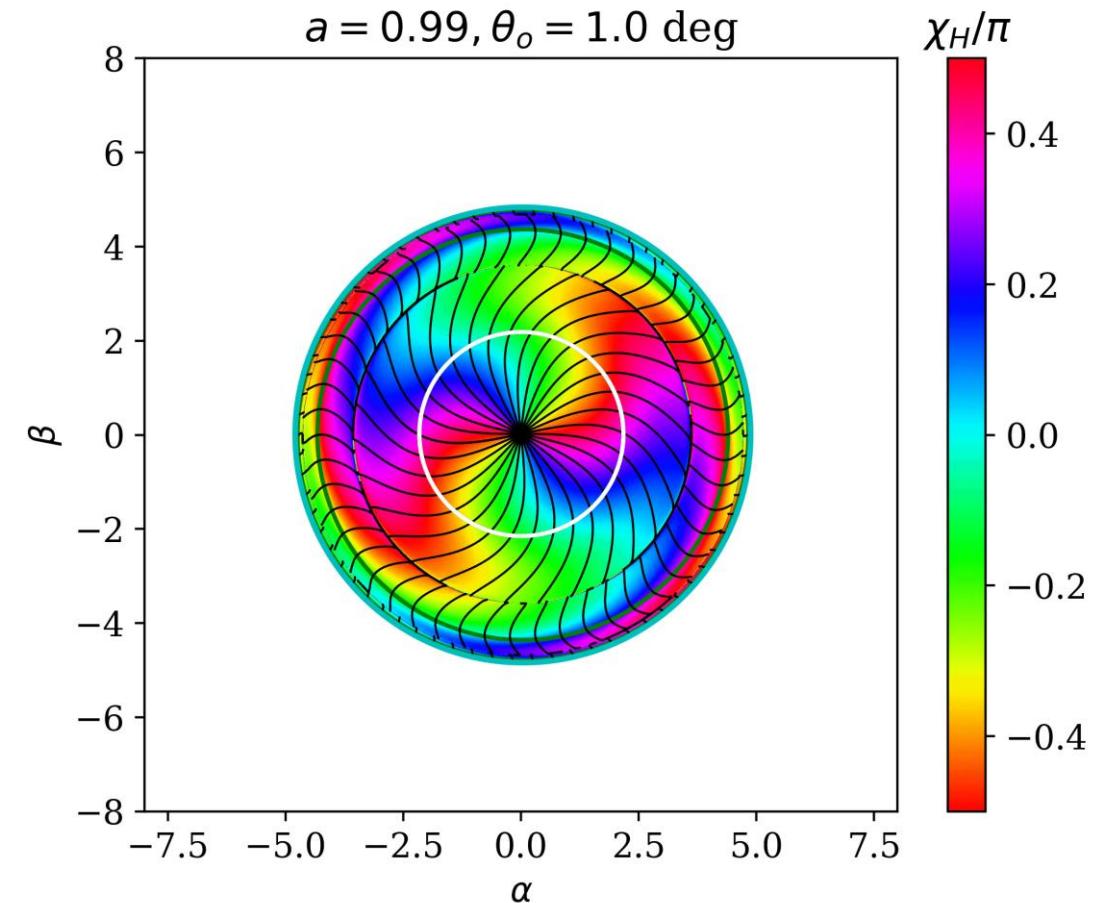
$$\lambda = -\alpha \sin \theta_o$$

$$\eta = (\alpha^2 - a^2) \cos^2 \theta_o + \beta^2$$

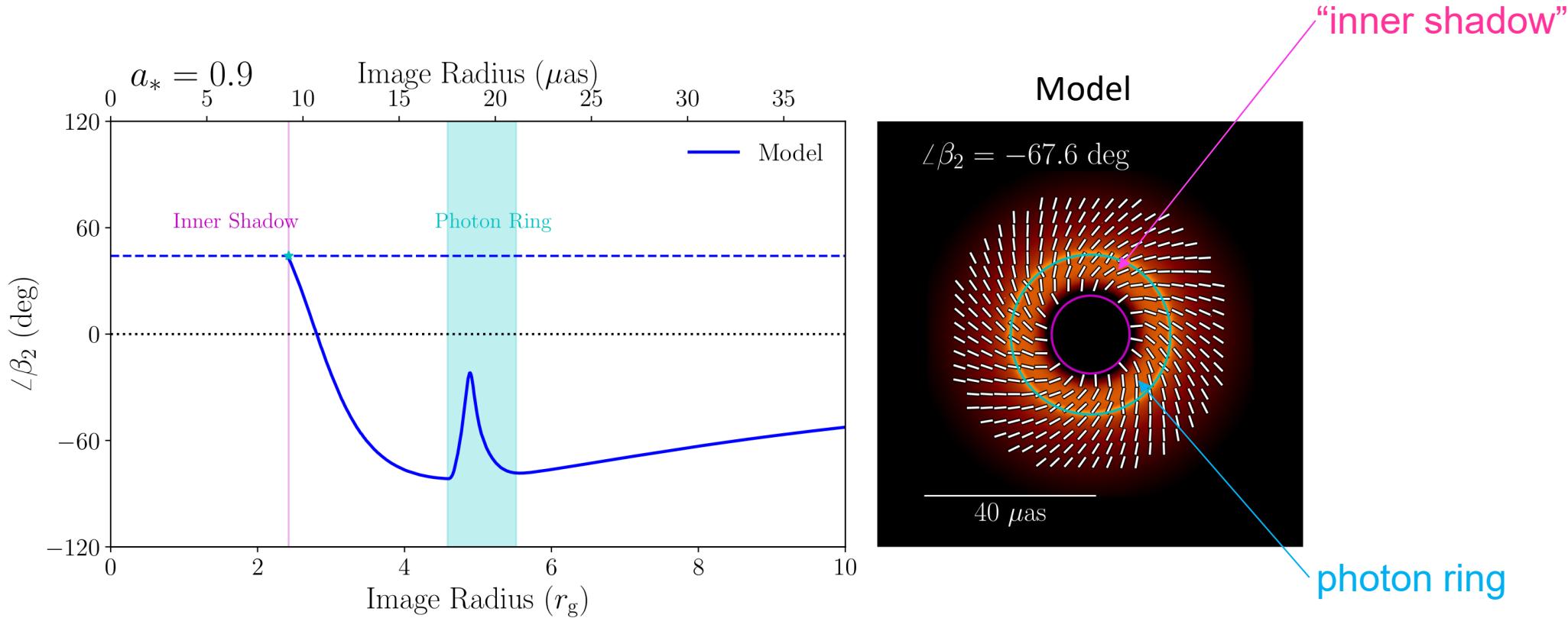
Conserved
Quantities

- For equatorial emission, viewed face-on, $\arg(\beta_2)$ approaches a simple universal horizon value:

$$\angle \beta_{2,+} \approx 2 \arctan\left(\frac{\nu_\theta a}{\sqrt{2r_+^2 + a^2}}\right)$$

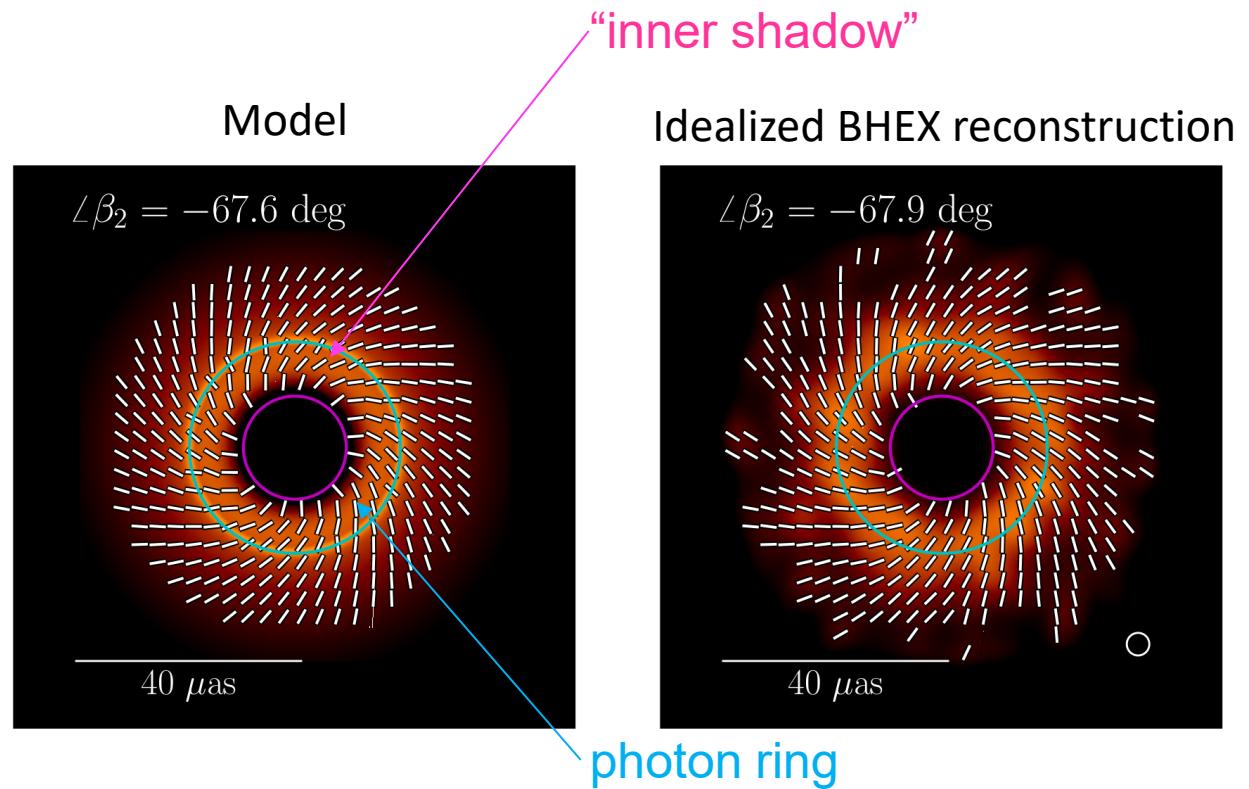
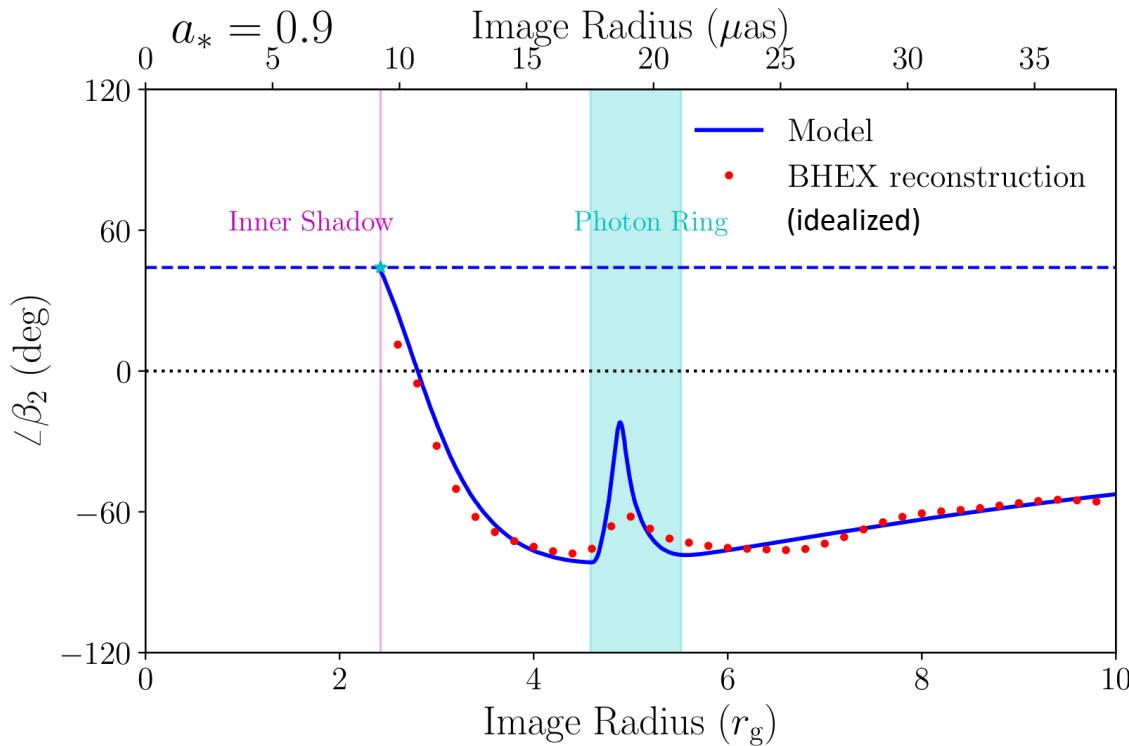


To look for energy extraction, we need to zoom in



- $\arg(\beta_2)$ evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
 - strong evolution of $\arg(\beta_2)$ close to the horizon is predicted by both simple BZ models and GRMHD

To look for energy extraction, we need to zoom in

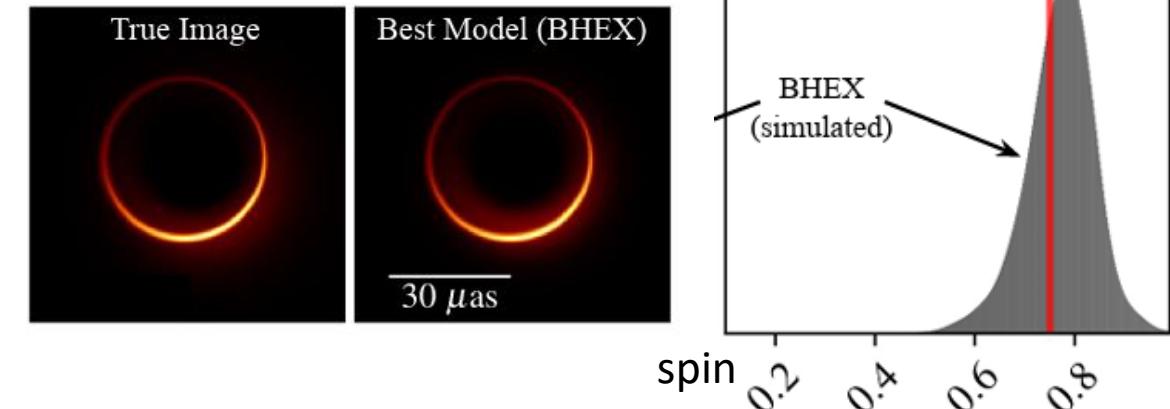


- $\arg(\beta_2)$ evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
 - strong evolution of $\arg(\beta_2)$ close to the horizon is predicted by both simple BZ models and GRMHD
- **BHEX + EHT can obtain the resolution to observe this evolution**
 - Directly probing field lines that penetrate the ergosphere and approach the horizon

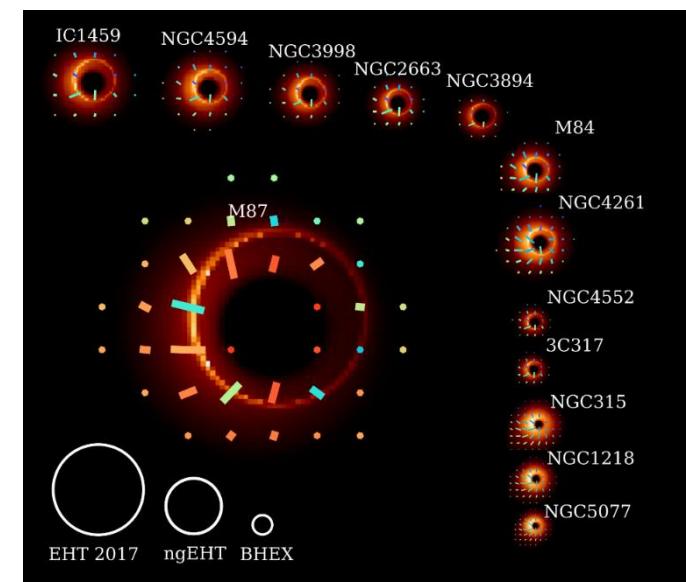
BHEX photon ring Spin Measurements can calibrate polarimetric spin relations

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

M87 Photon ring measurements

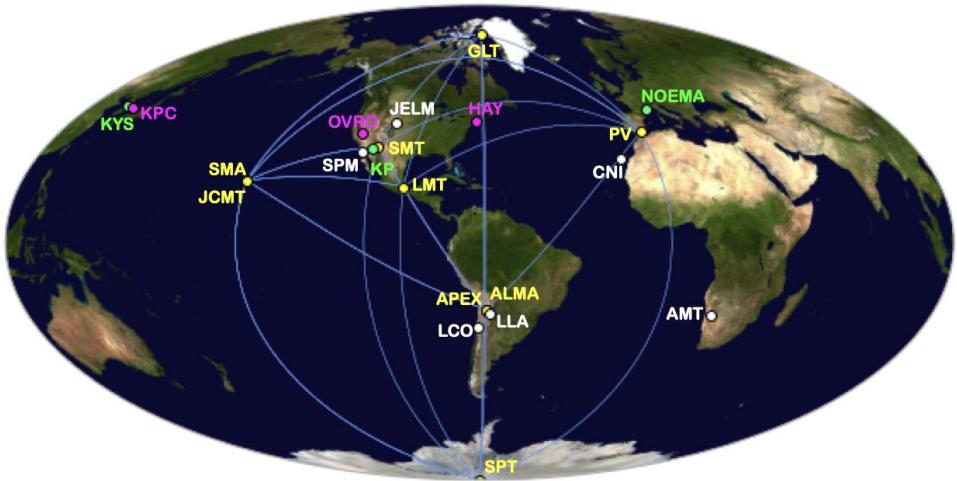


Horizon-resolvable sources with BHEX



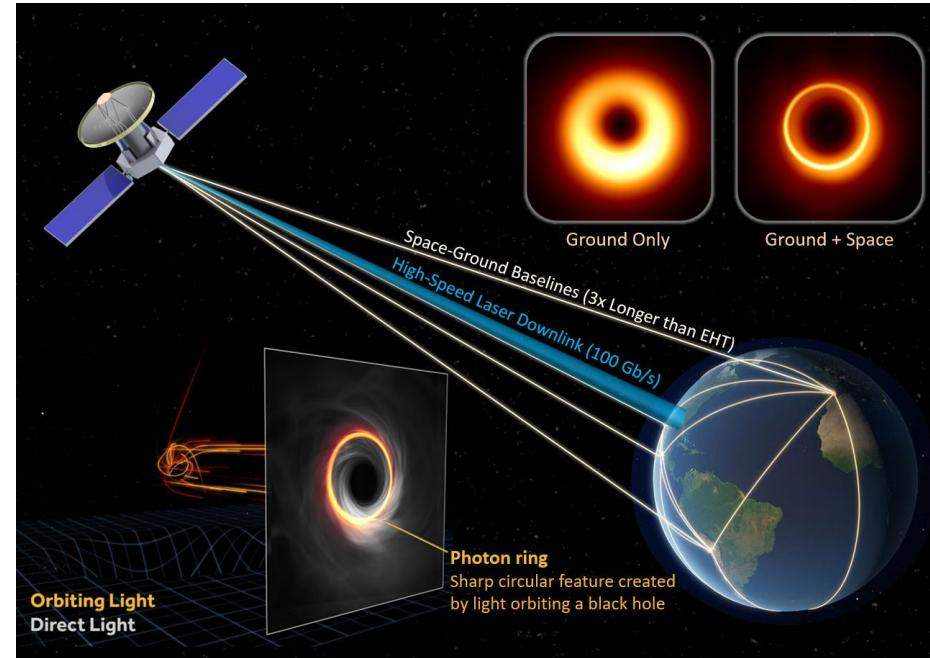
The future of near-horizon black hole astrophysics

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](#))
- Make movies of Sgr A* and resolve black hole flares

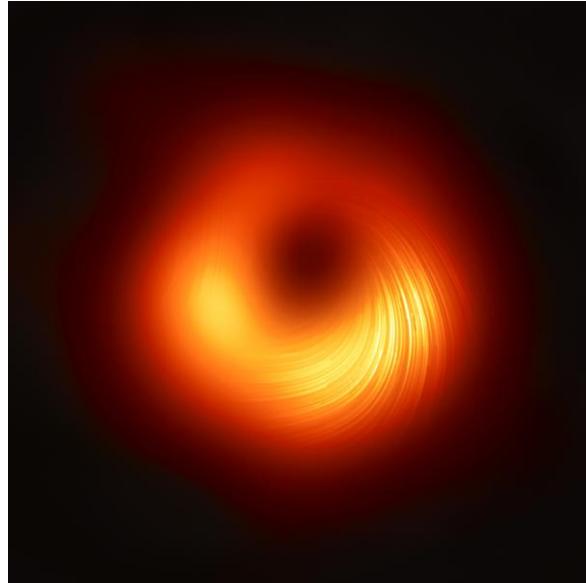
Space VLBI / Black Hole Explorer (BHEX)



- 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)

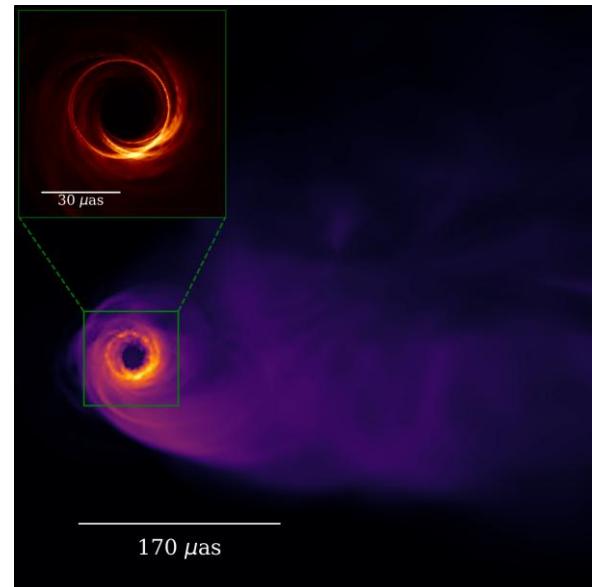
Takeaways...

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



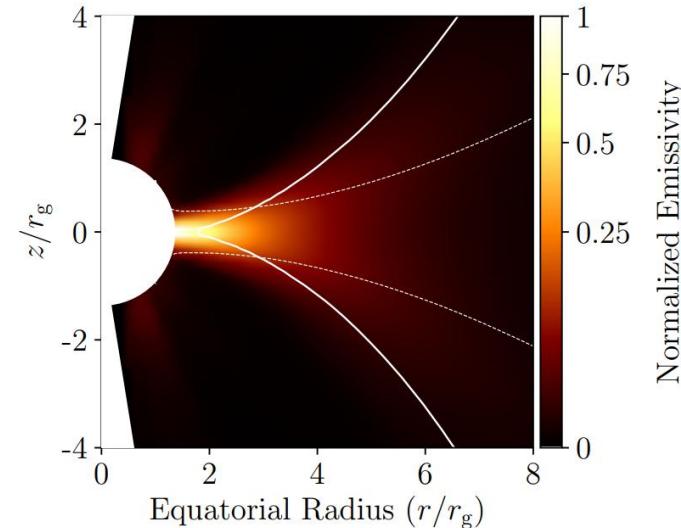
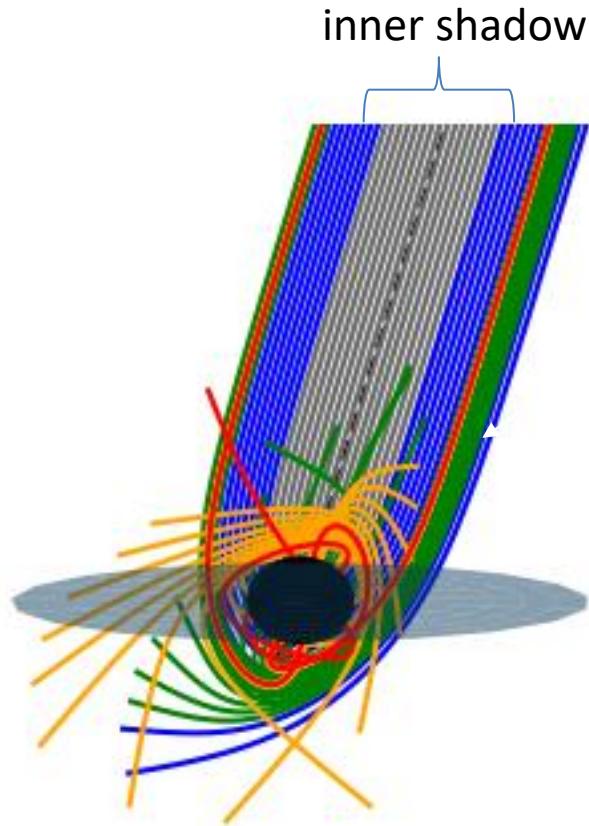
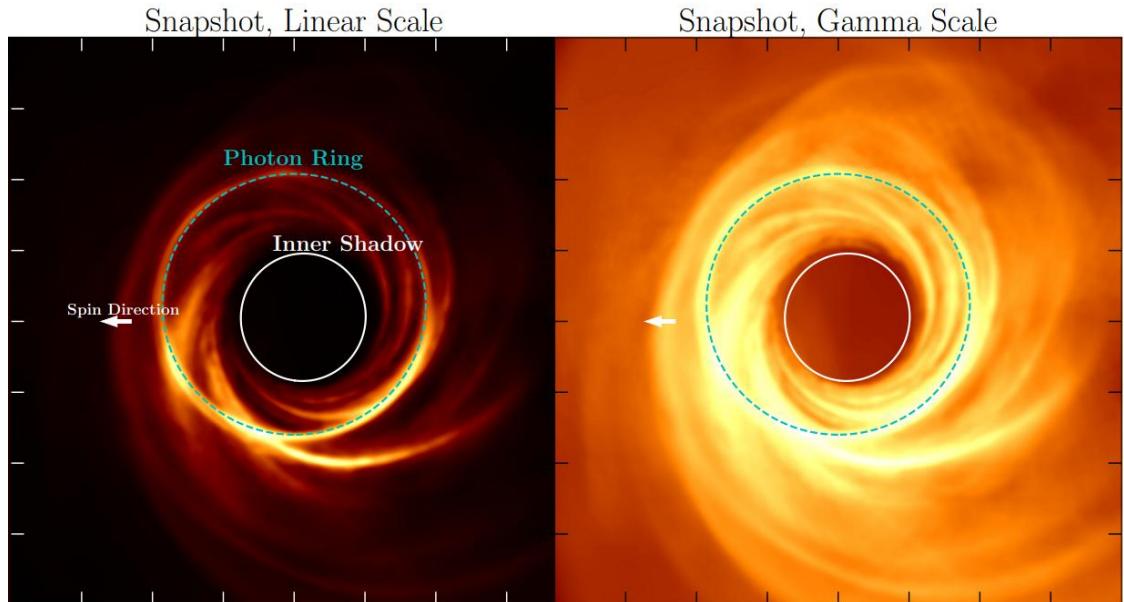
...and more questions

- What plasma physics sets the temperature/distribution of the electrons?
- What powers flares in Sgr A* and M87*?
- What can EHT/BHEX observation tell us about near-horizon physics in supermassive black holes beyond Sgr A* and M87*?



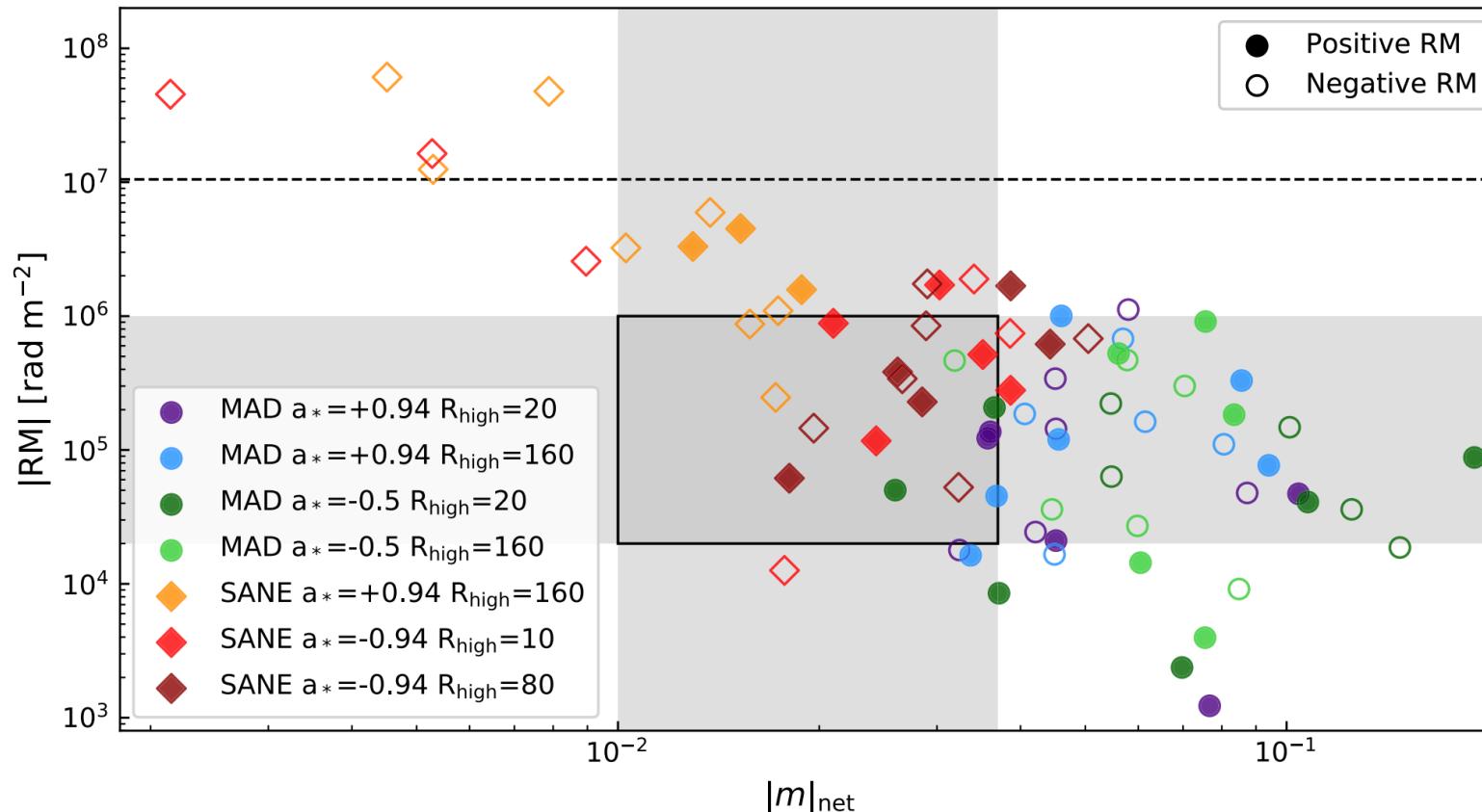
backup slides

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



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

GRMHD simulations can explain M87's Rotation Measure

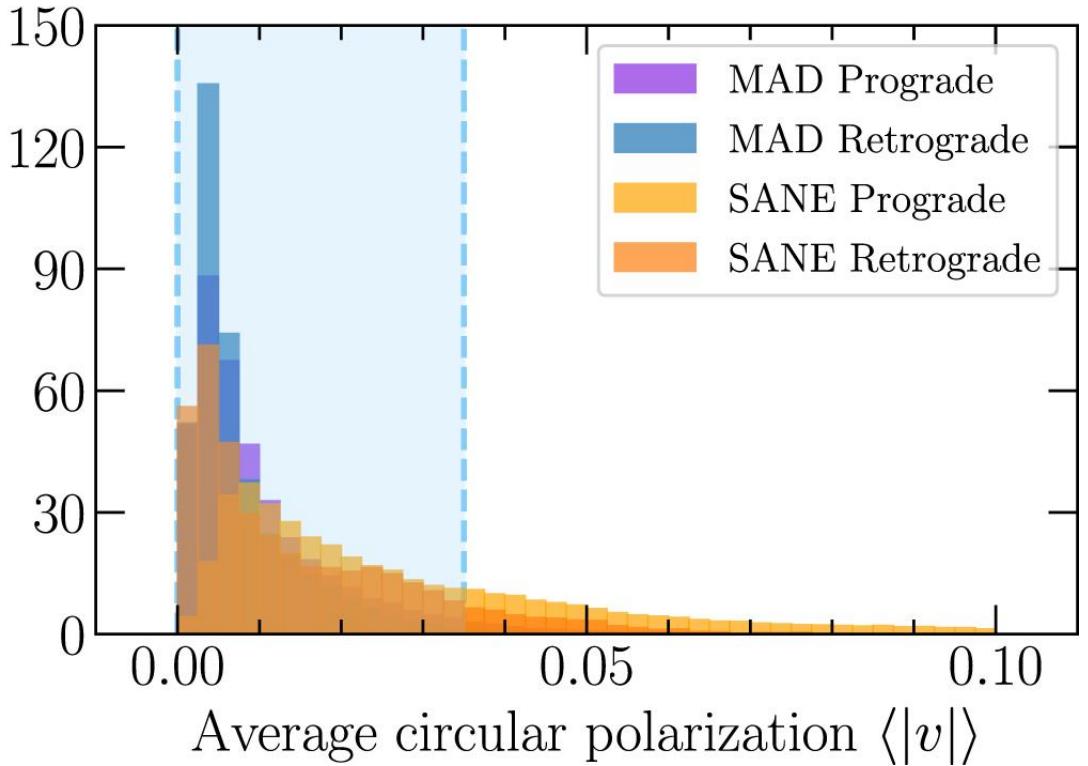
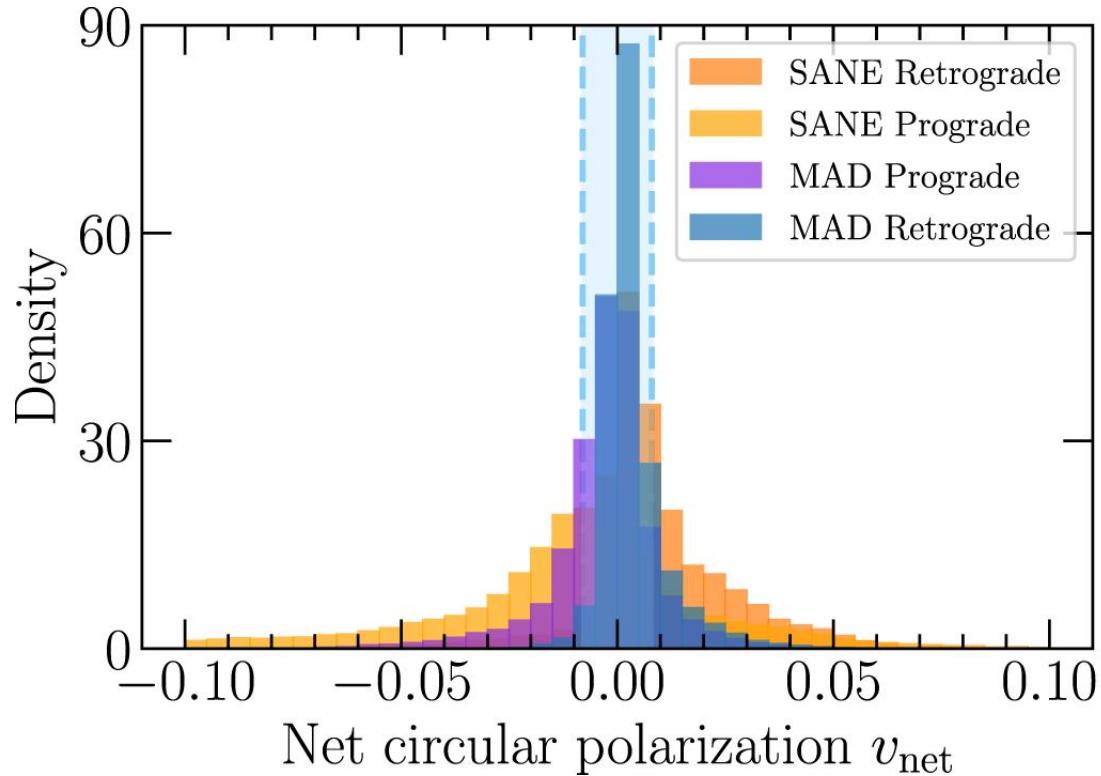


Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

Credit: EHTC 2021 Paper VIII

Angelo Ricarte

GRMHD simulations naturally produce low circular polarization

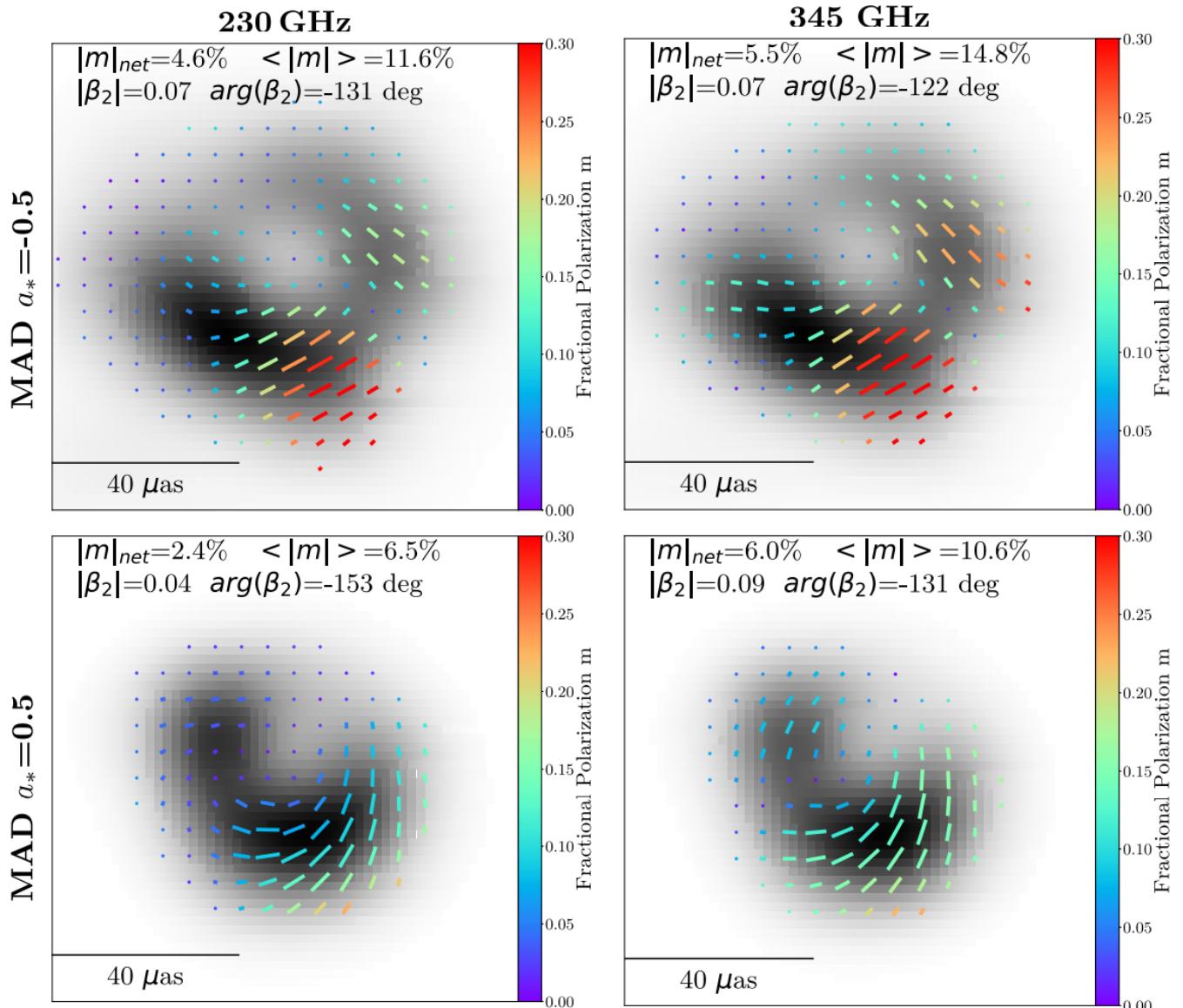


$$v_{\text{net}} = \frac{\int \mathcal{V} dA}{\int \mathcal{I} dA}.$$

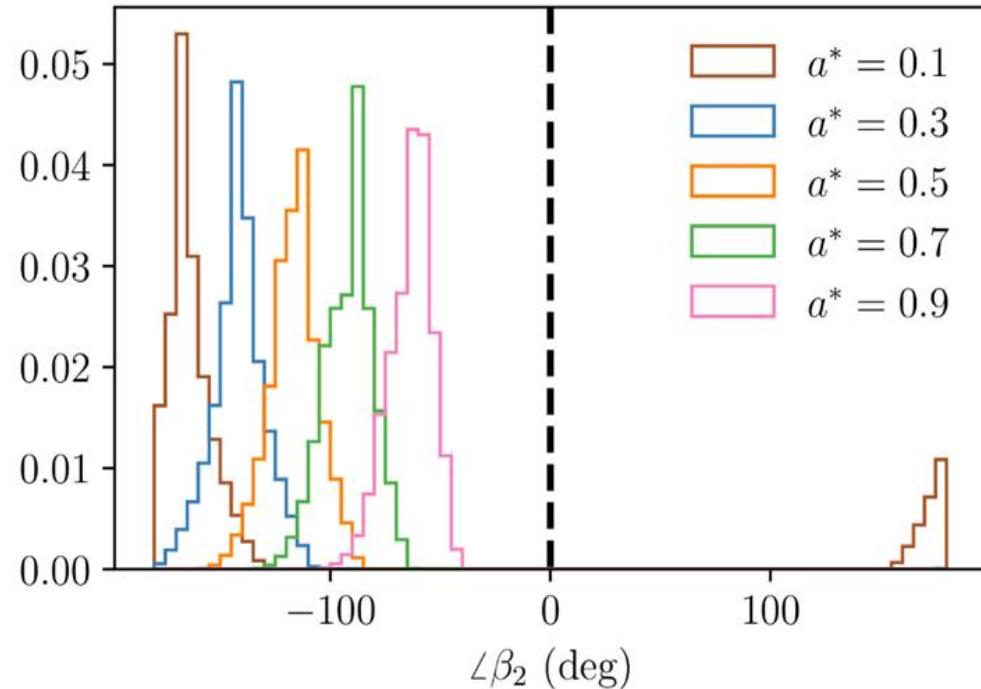
$$\langle |v| \rangle = \frac{\int |\mathcal{V}/\mathcal{I}| \mathcal{I} dA}{\int \mathcal{I} dA},$$

Higher frequencies

- Future EHT campaigns will observe at 345 GHz
- If our picture is right, we should see weaker Faraday rotation and **stronger polarization**
- With observations at multiple frequencies, we can directly map Faraday rotation and further constrain our models

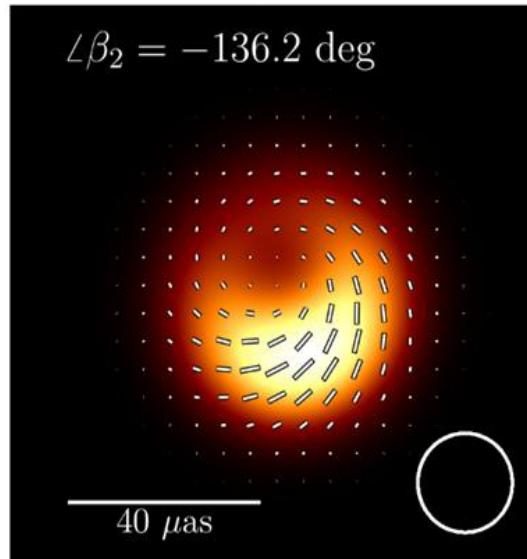


β_2 in semi-analytic models of M87*



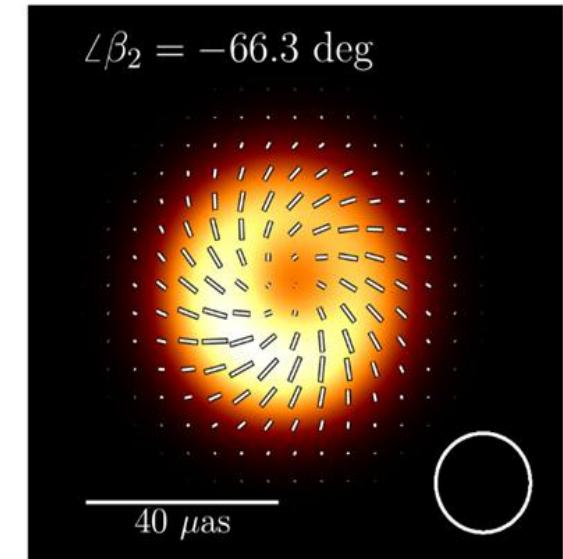
$a_* = 0.5$, prograde Keplerian

$$\angle \beta_2 = -136.2 \text{ deg}$$



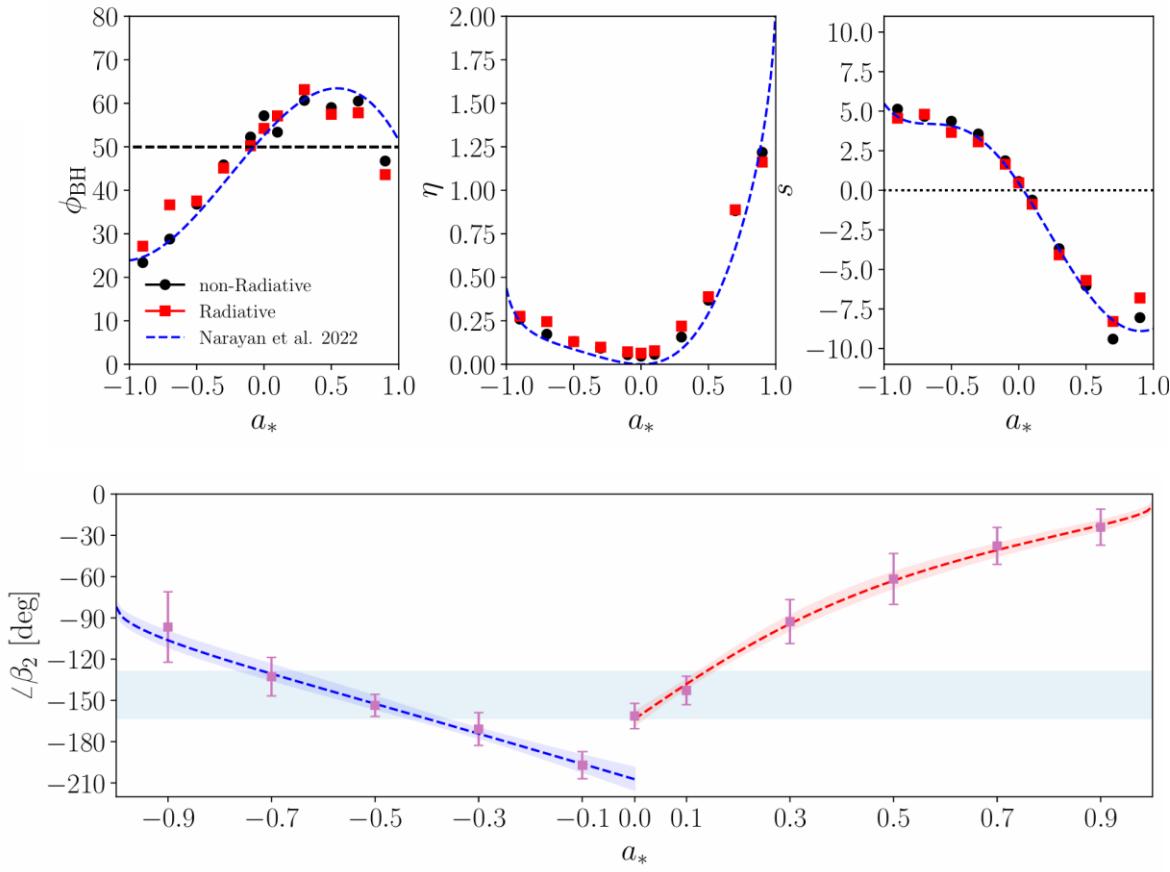
$a_* = 0.5$, retrograde Keplerian

$$\angle \beta_2 = -66.3 \text{ deg}$$



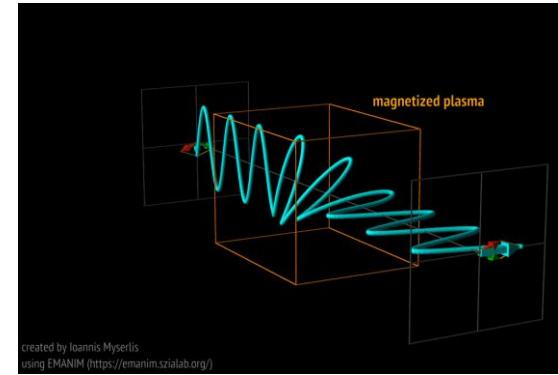
- We fix magnetic fields to the force-free BZ monopole solution (with energy outflow)
- We explore many models for the velocity of the emitting fluid
- Changes in fluid velocity do not significantly affect sign of $\arg(\beta_2)$ or trend with BH spin

Aside: Radiative Simulations Have Similar Jets...



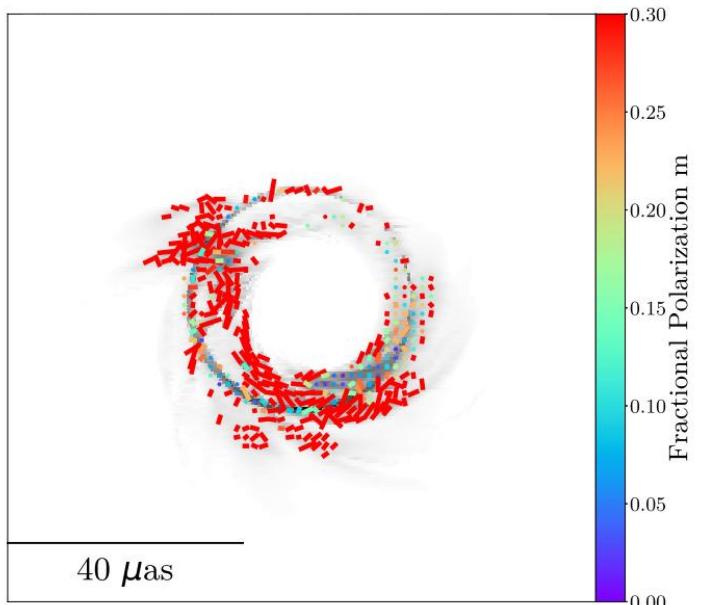
- M87* and Sgr A* have two-temperature plasmas
 $T_e \neq T_i$
- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** (e.g. Ressler+2015,17, Chael+ 2018,19)
- M87* has a radiative efficiency of $\sim 10\%$ (EHTC+ 2021, Chael+ 2025), but radiative feedback does not significantly change global jet/disk properties or $\arg(\beta_2)$

What about Faraday Rotation?

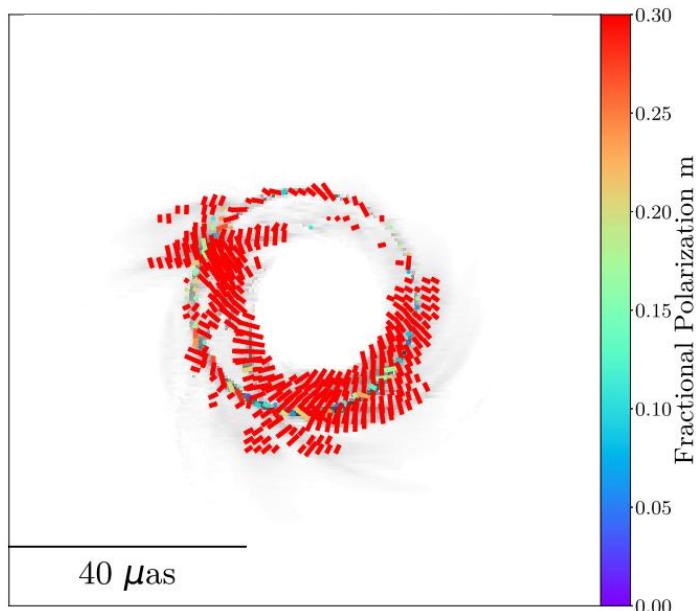


'infinite' resolution

With Faraday

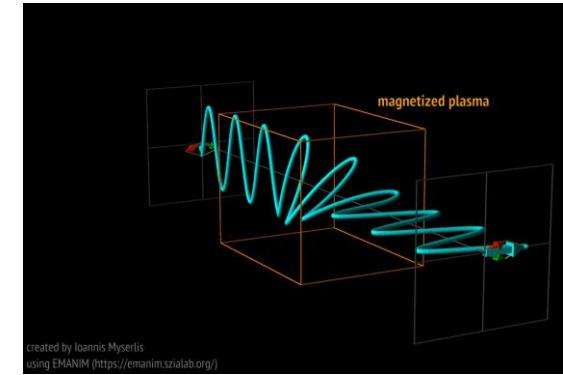


Without Faraday



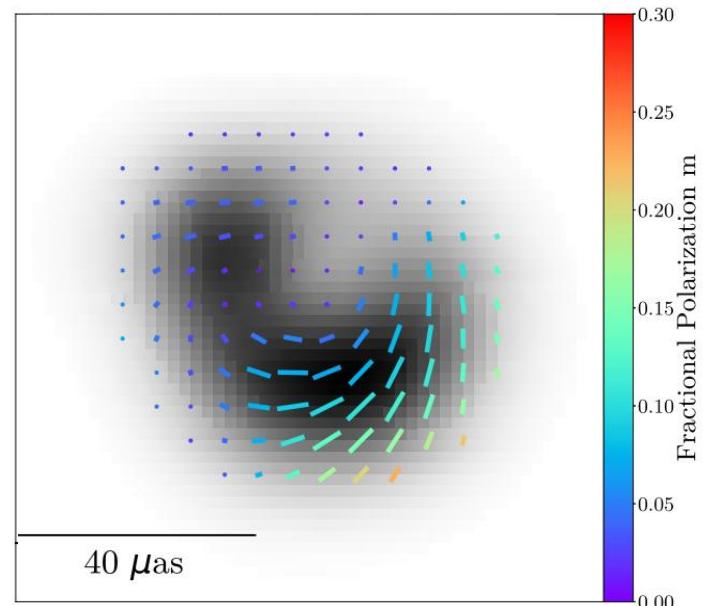
- Significant Faraday rotation on small scales
 - **Rotates** the overall polarization pattern at EHT resolution
 - **Scrambles** polarization vectors on small scales

What about Faraday Rotation?

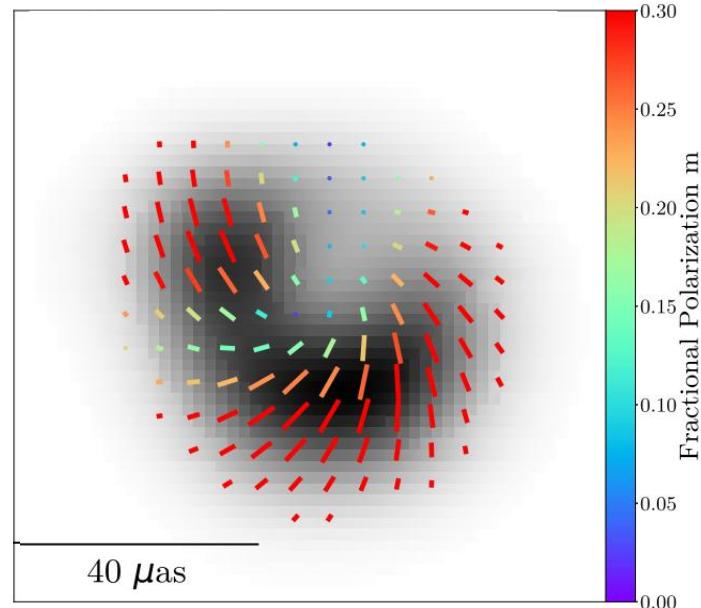


EHT resolution

With Faraday

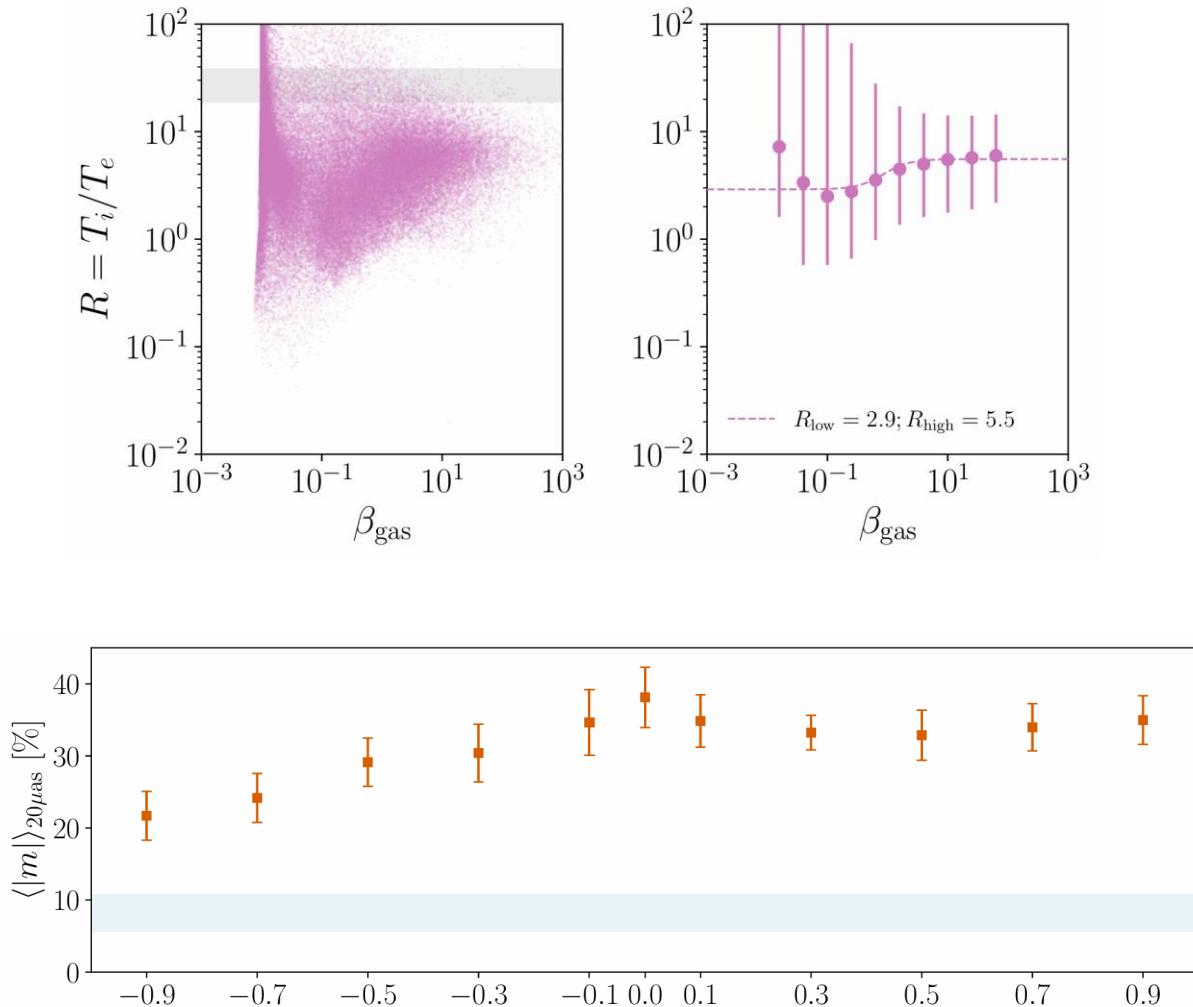


Without Faraday



- 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

...but electrons are too hot!

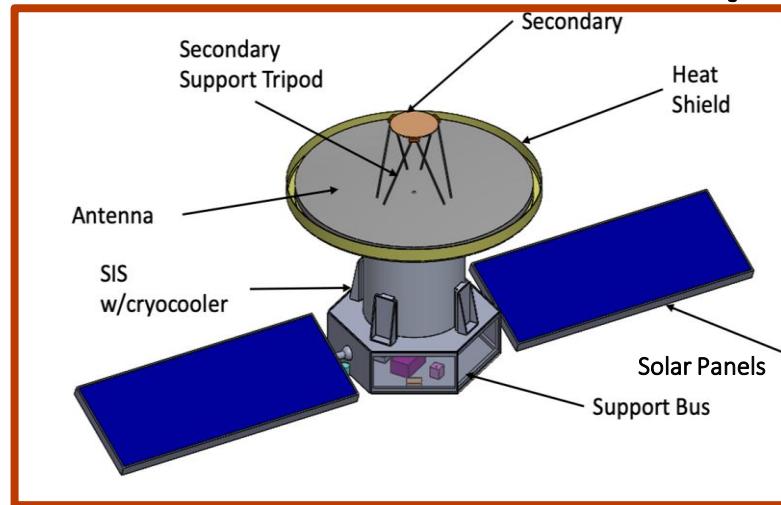


- EHT analysis fixes T_e locally in **postprocessing** and seems to prefer **cold electrons** ($T_i \sim 100x T_e$) to sufficiently depolarize the image
- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** but prefer more modest temperature ratios (Chael 2025)
- Is there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

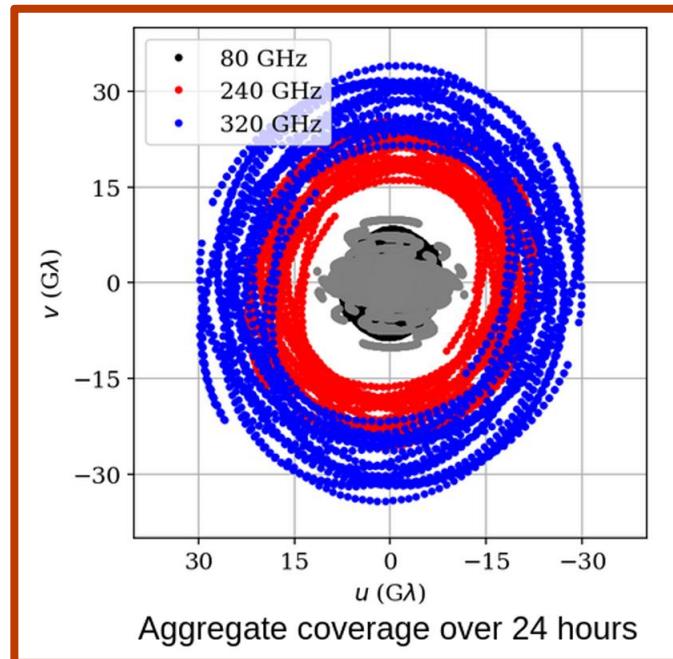
The Black Hole Explorer (BHEX)



Spacecraft



Example M87 $u-v$ coverage

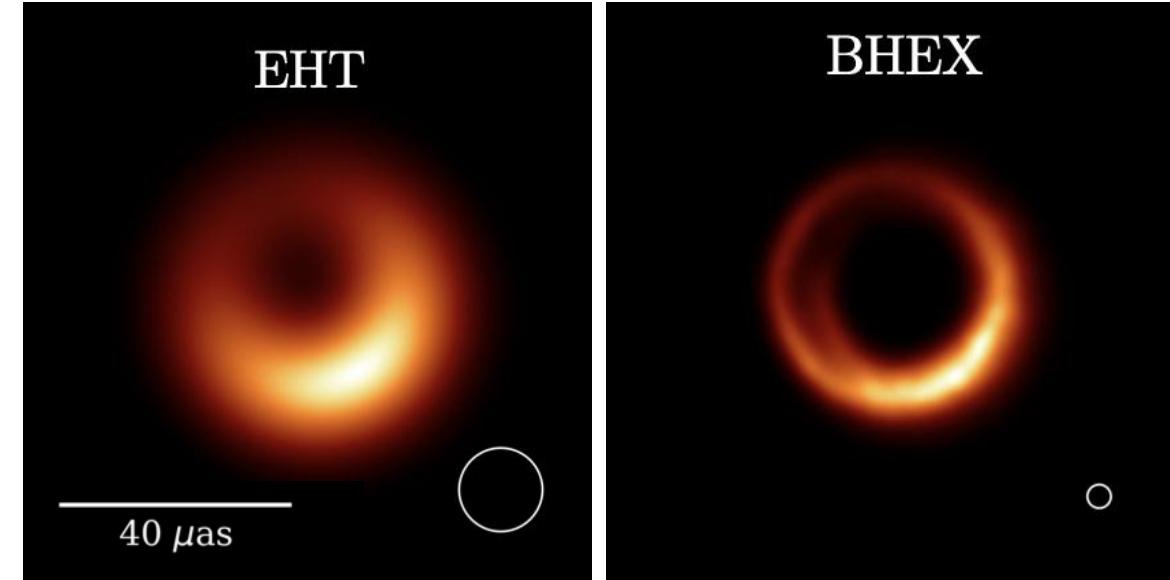
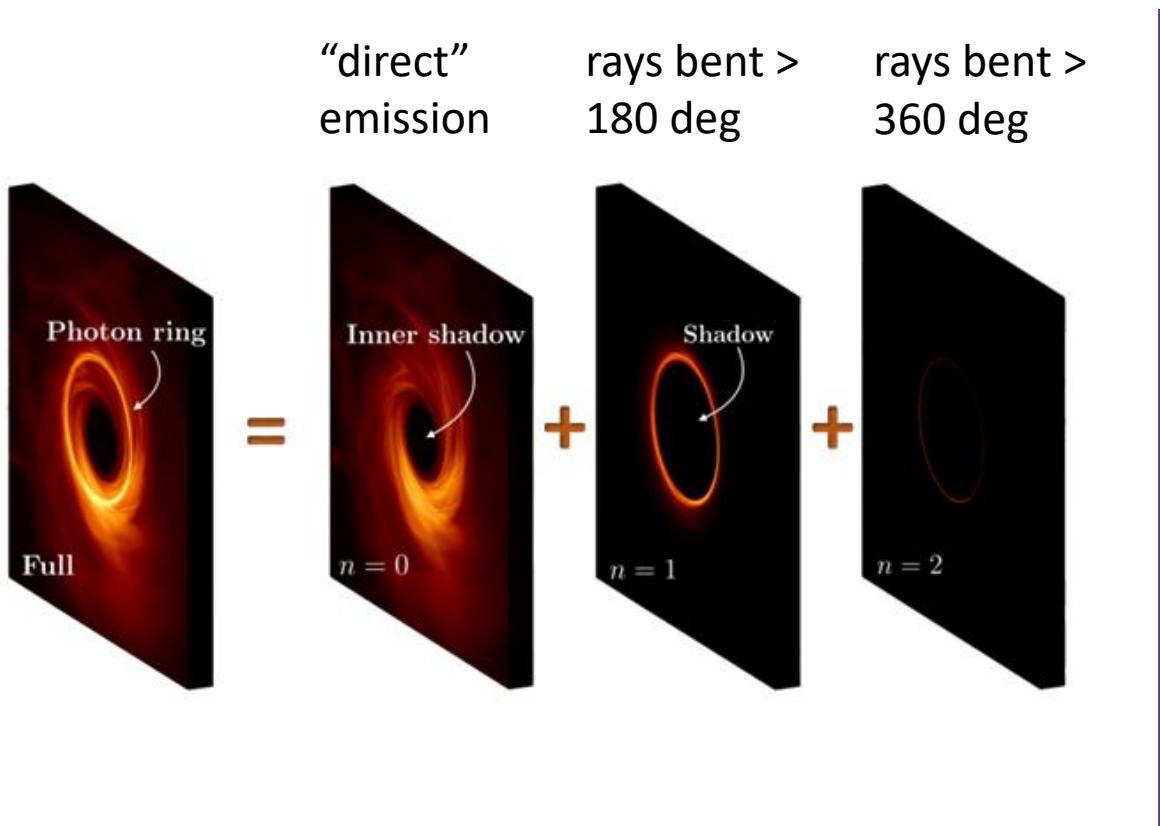


Mission Parameters

- 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

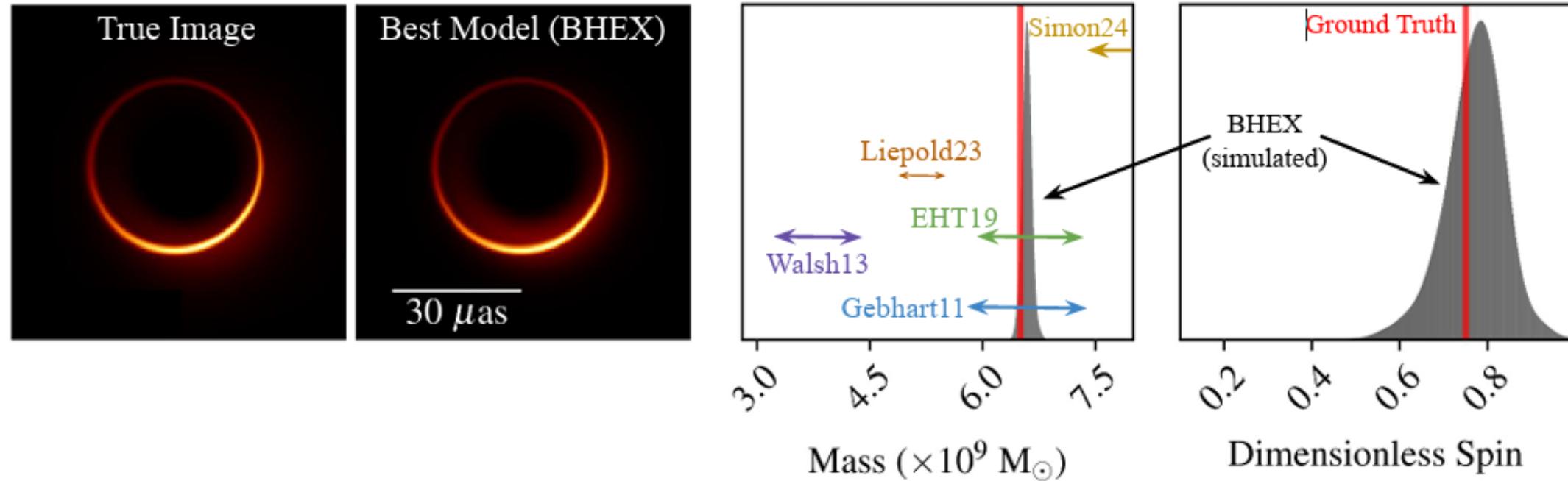
- Targeting next NASA SMEX call
- Fact Sheet: blackholeexplorer.org/fact-sheet
- Series of SPIE papers: arXiv [2406.12917](https://arxiv.org/abs/2406.12917)
- Open science plenary calls every month
 - We are always interested in new ideas for BHEX jet science!
 - Particularly potential multi-wavelength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

Direct Photon Ring Mass & Spin Measurements with BHEX



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

Direct Photon Ring Mass/Spin Measurements with BHEX

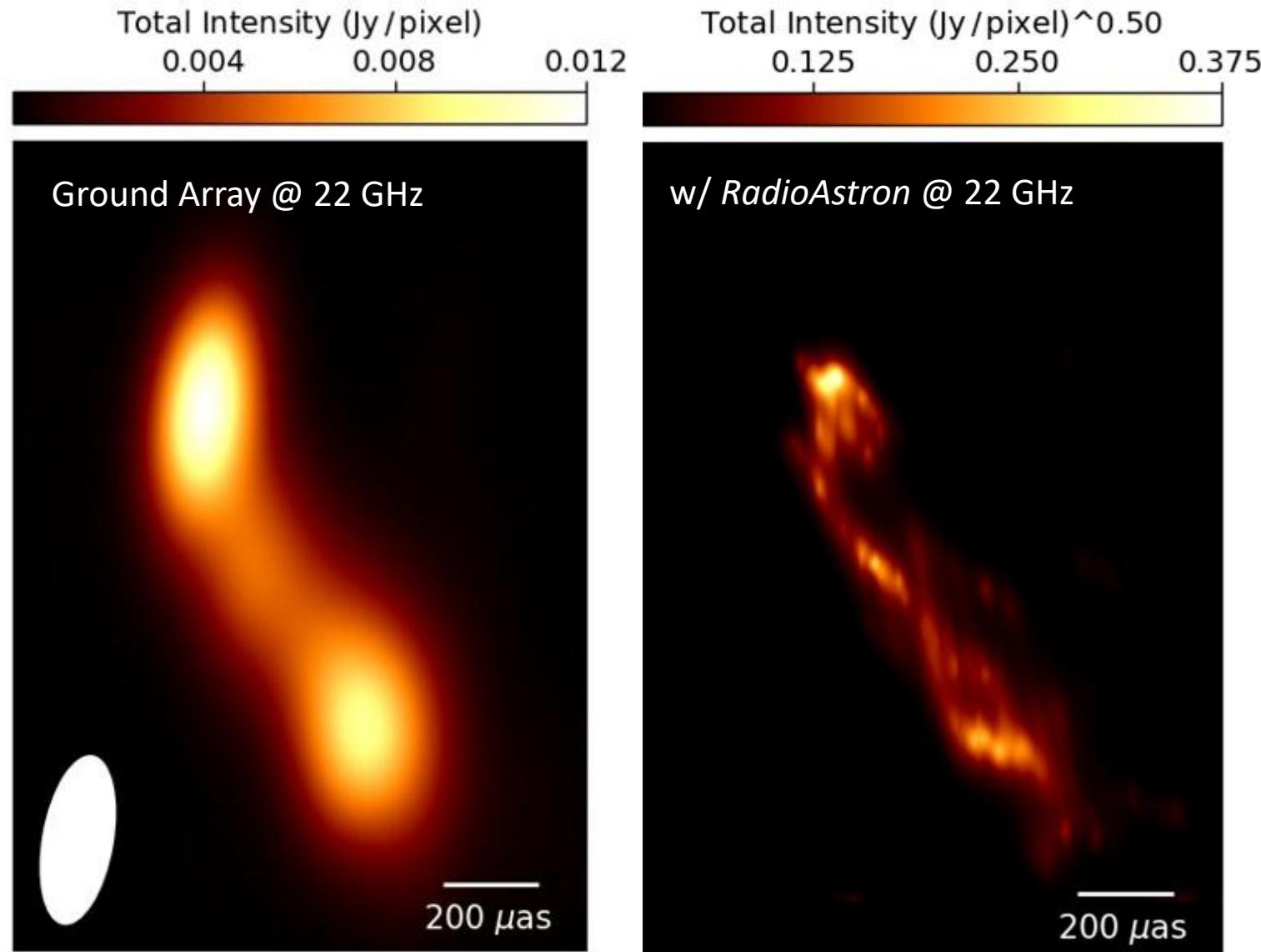


By comparing strongly-lensed and direct emission ring size and shape, BHEX will constrain Sgr A* and M87*'s **spin to ~10% and mass to ~1%**

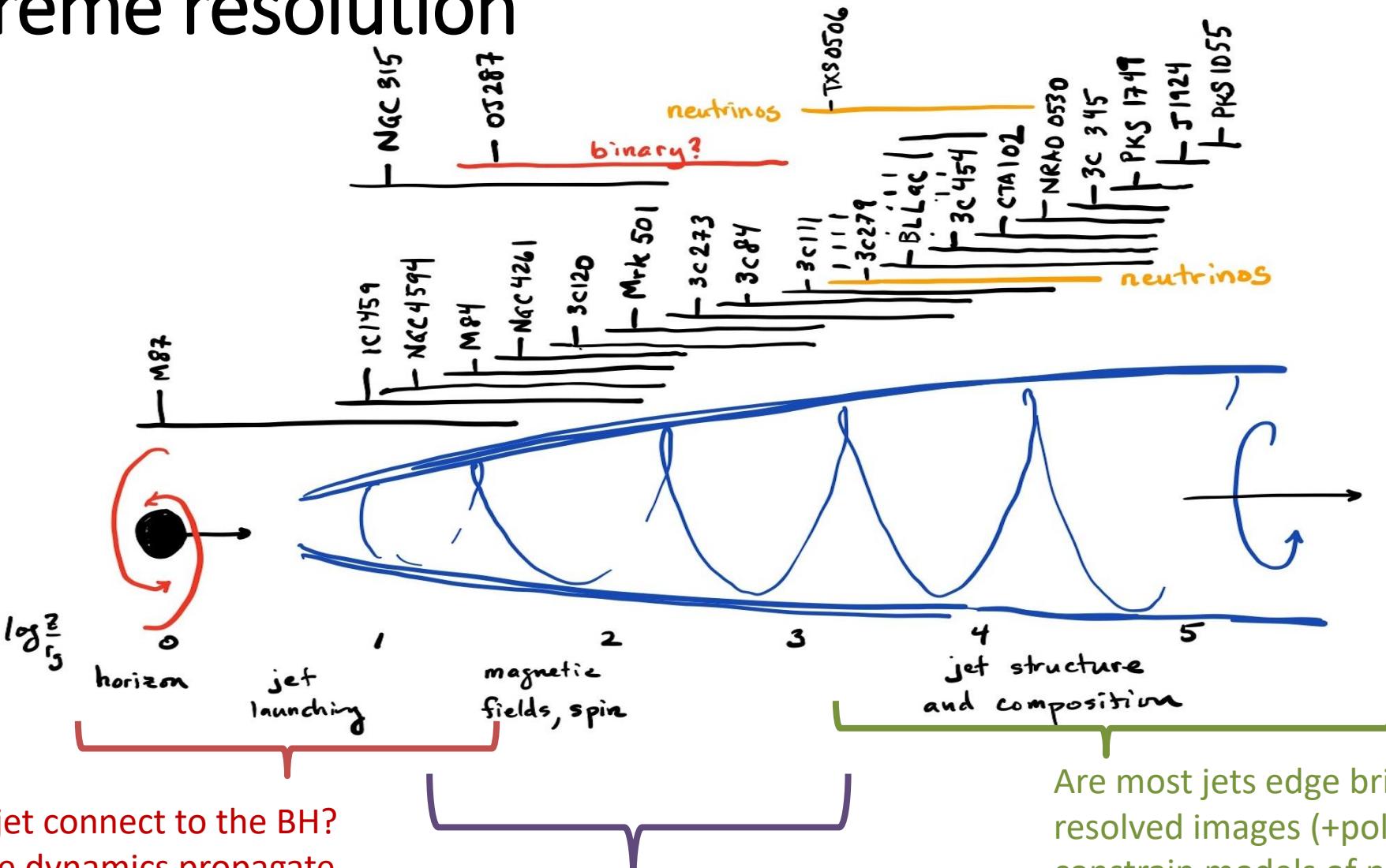
Direct photon ring spin measurements will help **calibrate** measurements from near-horizon polarimetry

The Power of Space VLBI: 3C279 with *RadioAstron*

- At 22 GHz (1.3 cm), observed in 2014
- Space baselines to *RadioAstron* supported by a ground array of 23 antennas
- Reconstruction with **eht-imaging** (Chael+ 2016,18).
- Space VLBI reveals a detailed transverse filamentary structure obscured in standard VLBI images

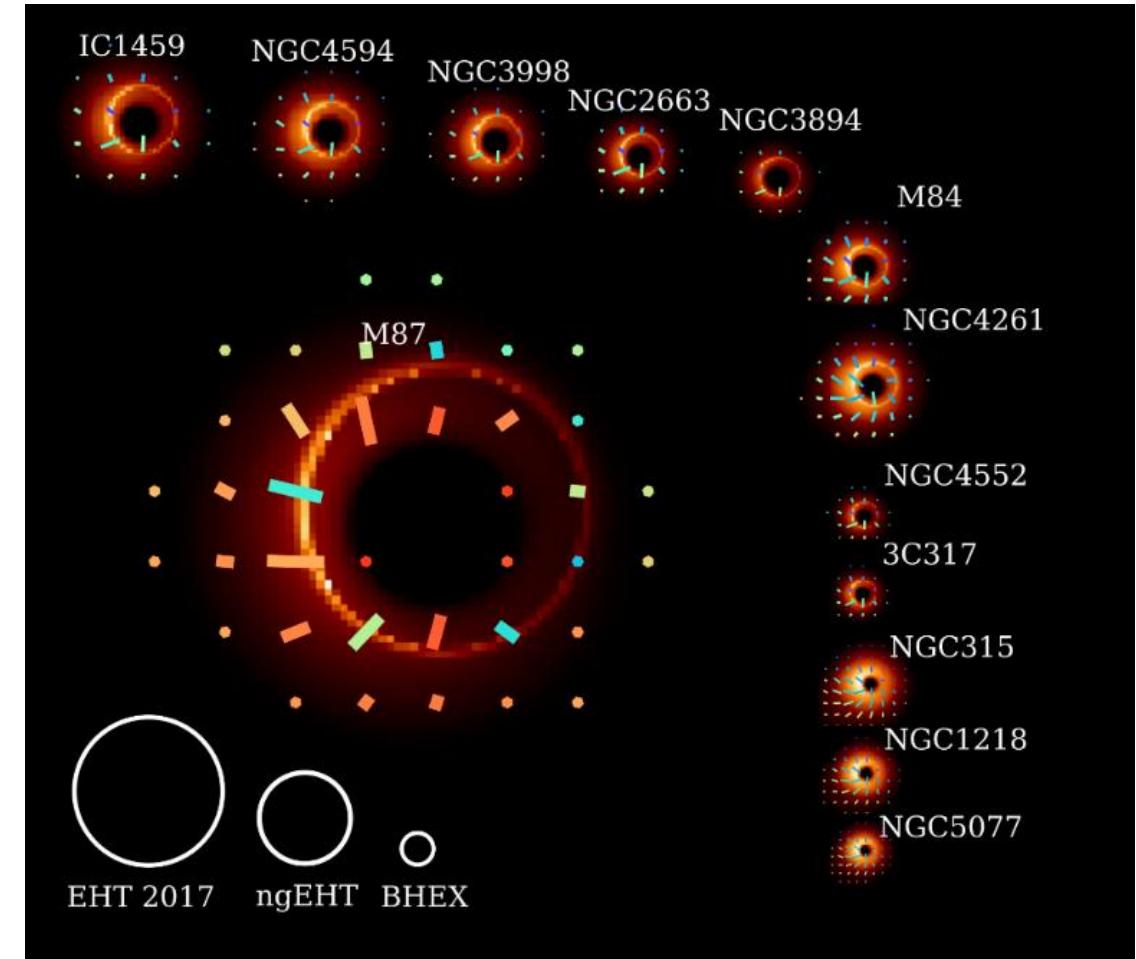


BHEX will observe jets on multiple scales with extreme resolution



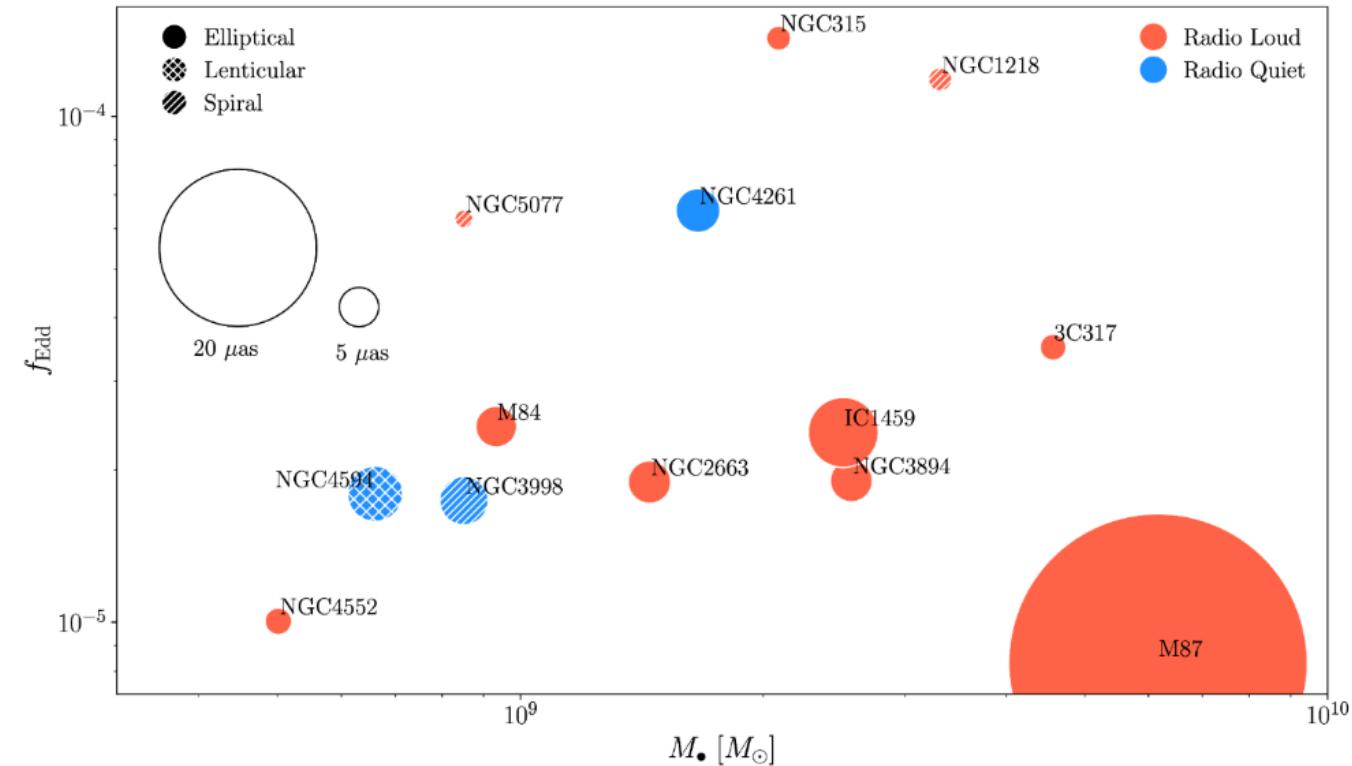
A Horizon-Scale Sample of Low-Luminosity AGN with BHEX

- 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



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



How can we better simulate the black hole-jet connection?

Chael 2024

2404.01471

Difficulties with GRMHD Simulations at high magnetization

- GRMHD codes conserve the total stress energy tensor, composed of matter and electromagnetic parts:

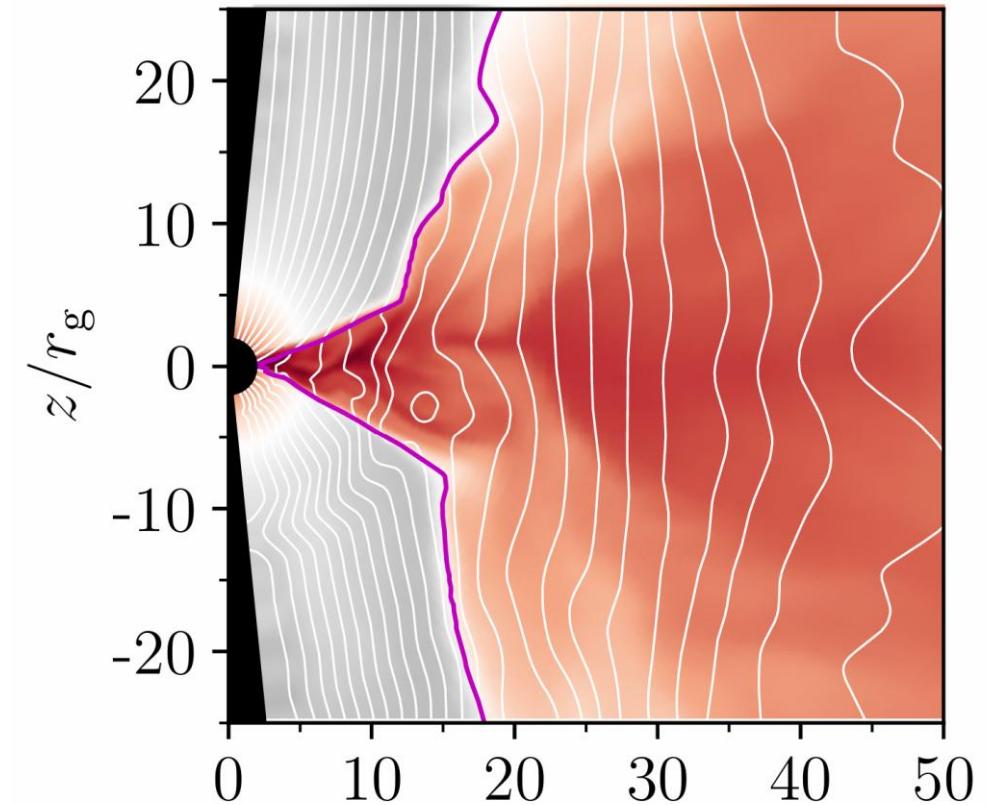
$$\nabla_\mu \left(T_{\text{MAT}}^{\mu\nu} + T_{\text{EM}}^{\mu\nu} \right) = 0$$

- The ratio of magnetic energy to rest-mass energy is defined:

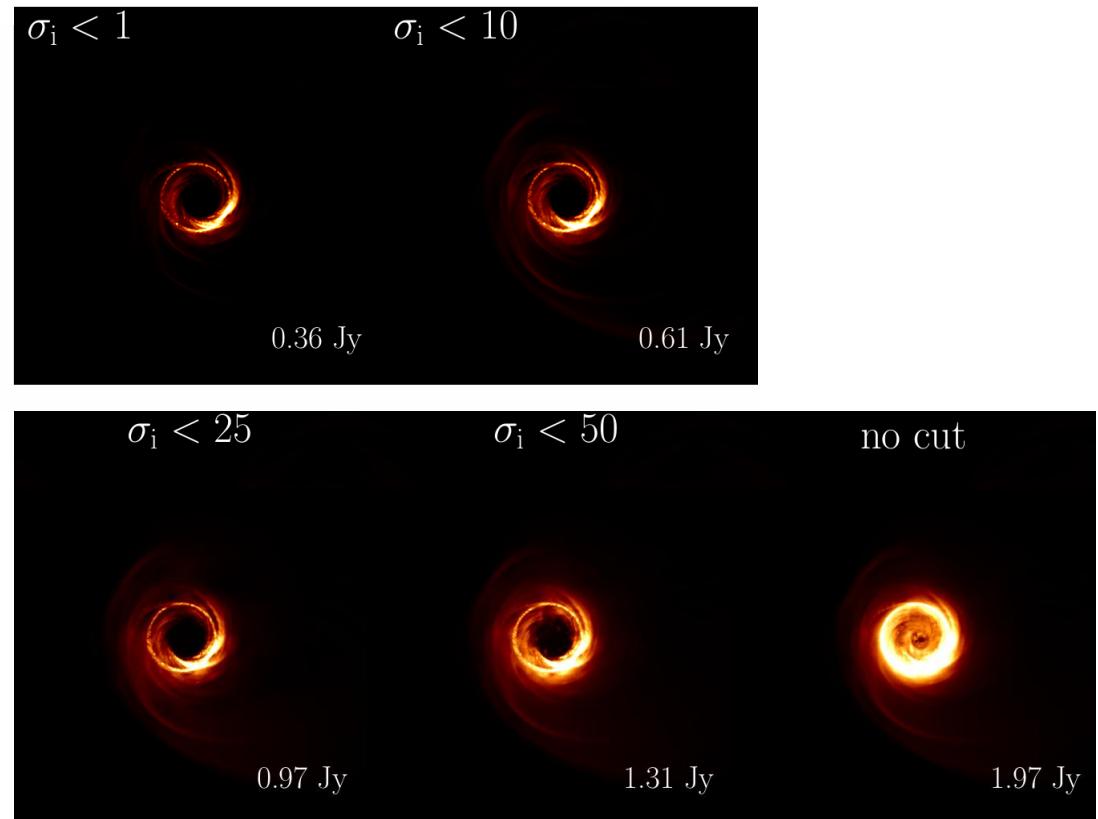
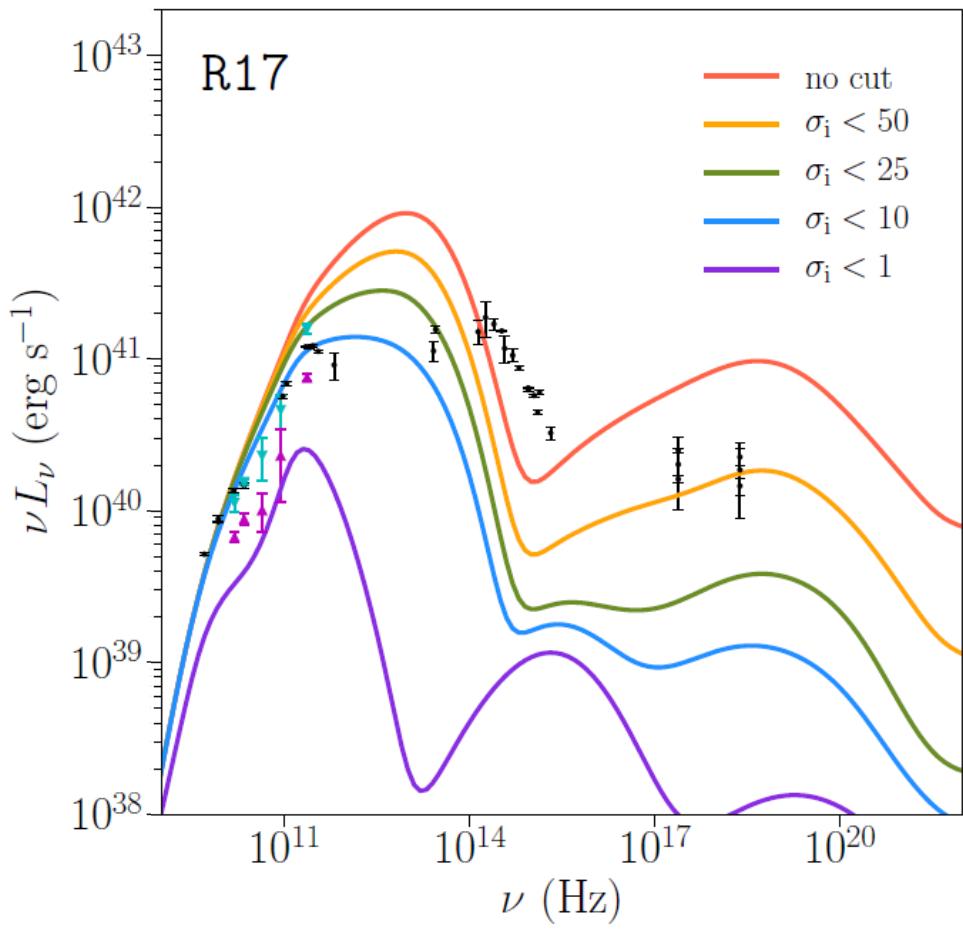
$$\sigma = b^2/\rho$$

- In the limit $\sigma \gg 1$, numerical codes struggle to recover fluid variables and the simulation can crash
- GRMHD codes introduce density ‘floors’ for stability

$$\sigma < \sigma_{\max}$$



Choosing “ σ cut” is a major uncertainty in simulated images



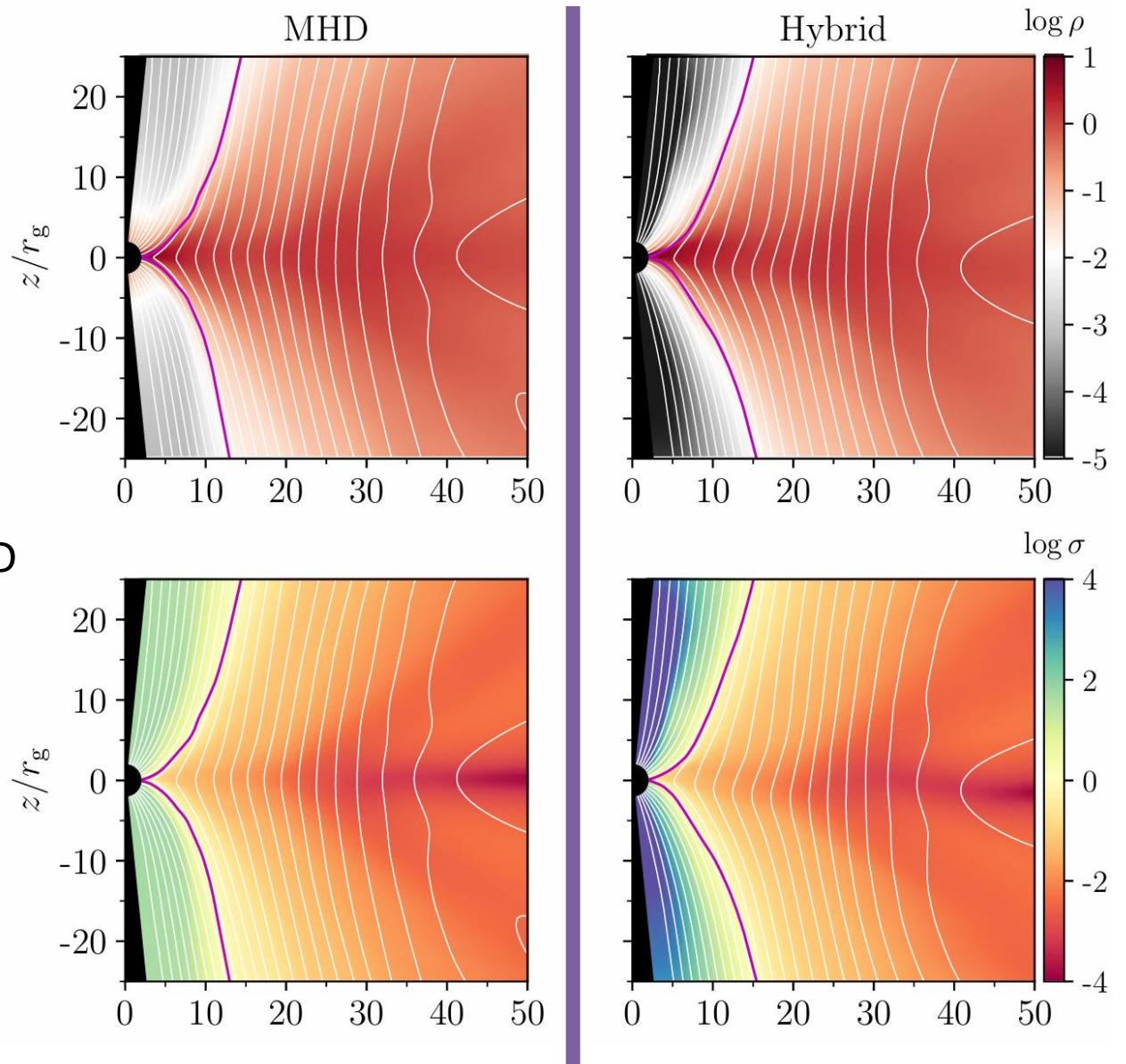
A New Hybrid GRMHD + Force-Free Code

Below $\sigma < \sigma_{\text{trans}}$, use GRMHD as normal

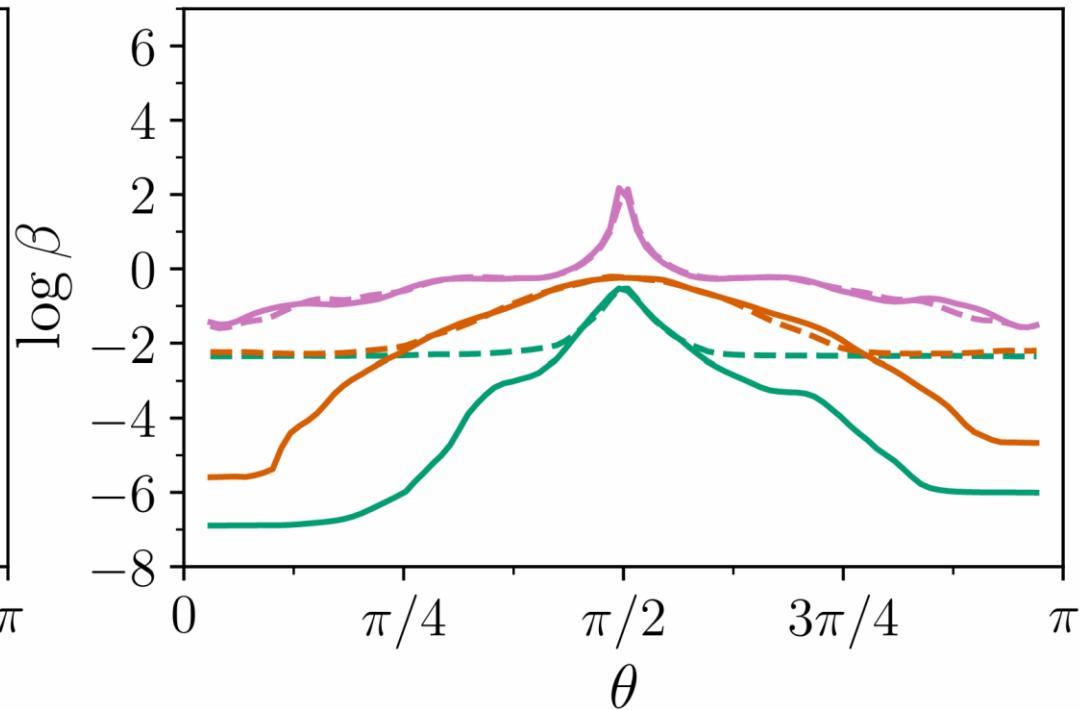
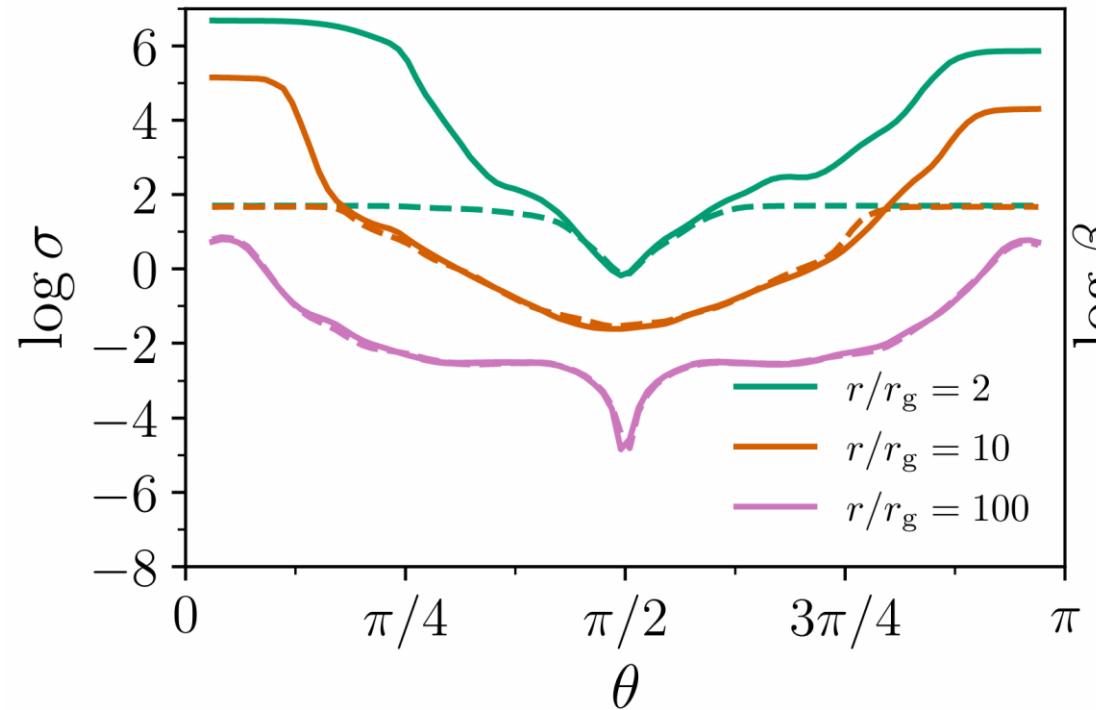
Above $\sigma > \sigma_{\text{trans}}$, use a **decoupled force-free scheme**:

- electromagnetic fields evolve with **no back-reaction**
- field-parallel velocity determined from GRMHD limit
- **gas evolved adiabatically** in fixed background

Can transition between the schemes in “intermediate” σ regions

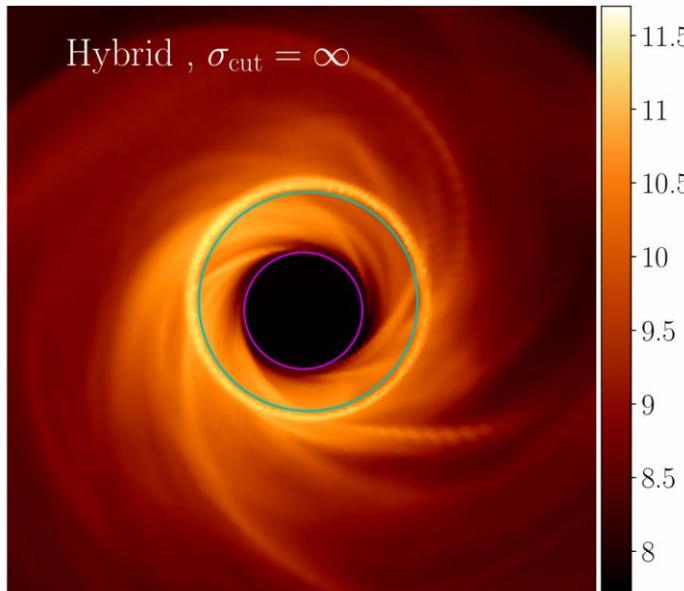
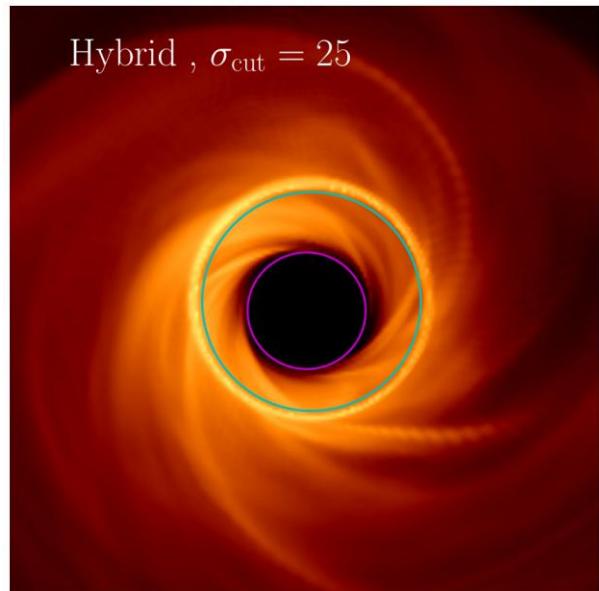
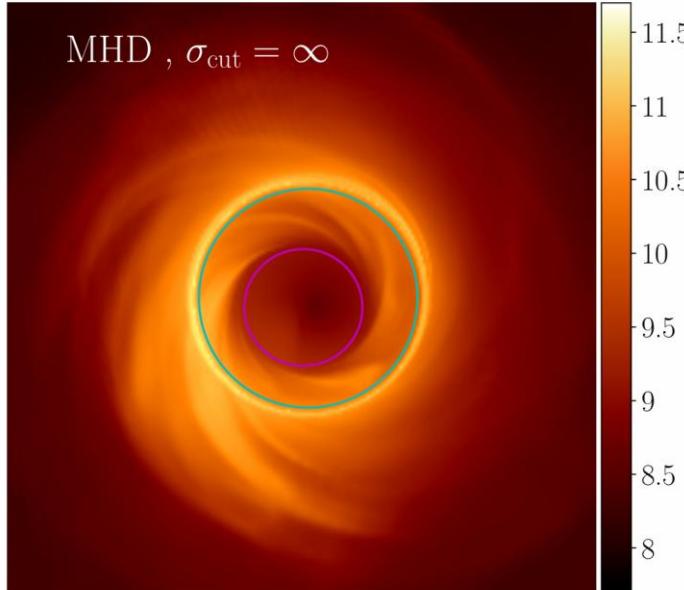
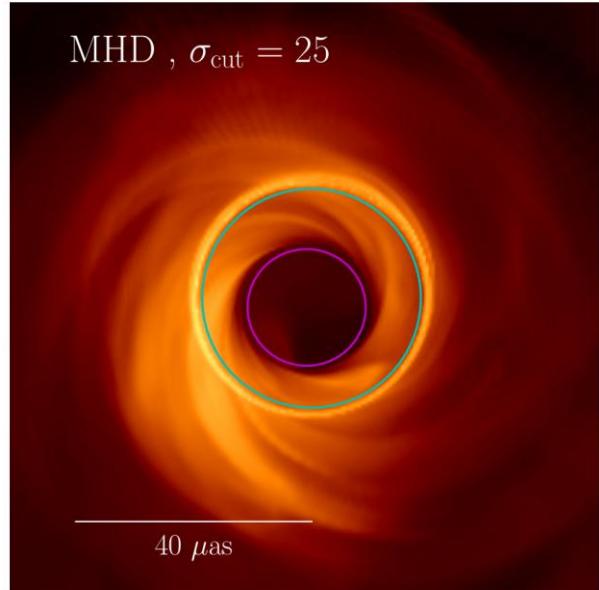


Comparing standard GRMHD and Hybrid GRMHD+FF



We achieve stable evolution up to $\sigma=10^6$ in the force-free jet region close to the black hole

230 GHz Image comparison



In standard GRMHD,
foreground jet emission fills
in the shadow region unless
we have a cut on σ in
radiative transfer

Hybrid simulation images
look the same with and
without a σ cut

**Next Steps: Comparing jet
images from traditional and
hybrid simulations**