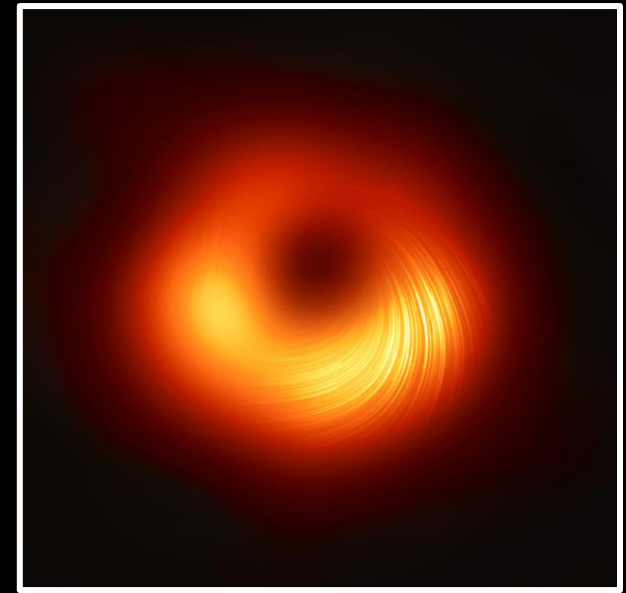
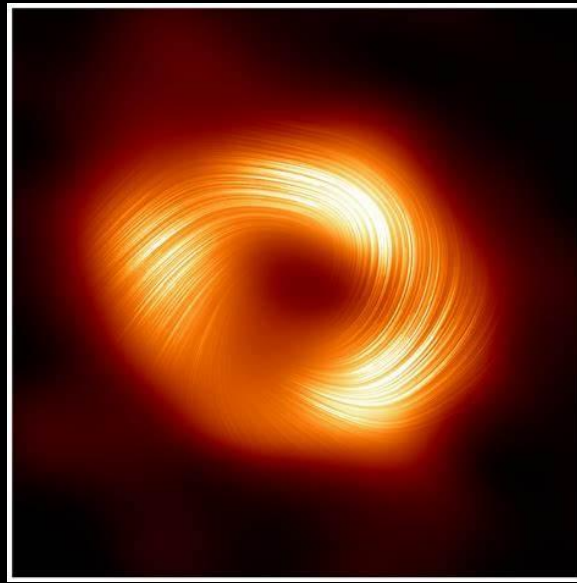


Polarized Images of Black Holes

Andrew Chael

NBIA, University of Copenhagen

April 29, 2026

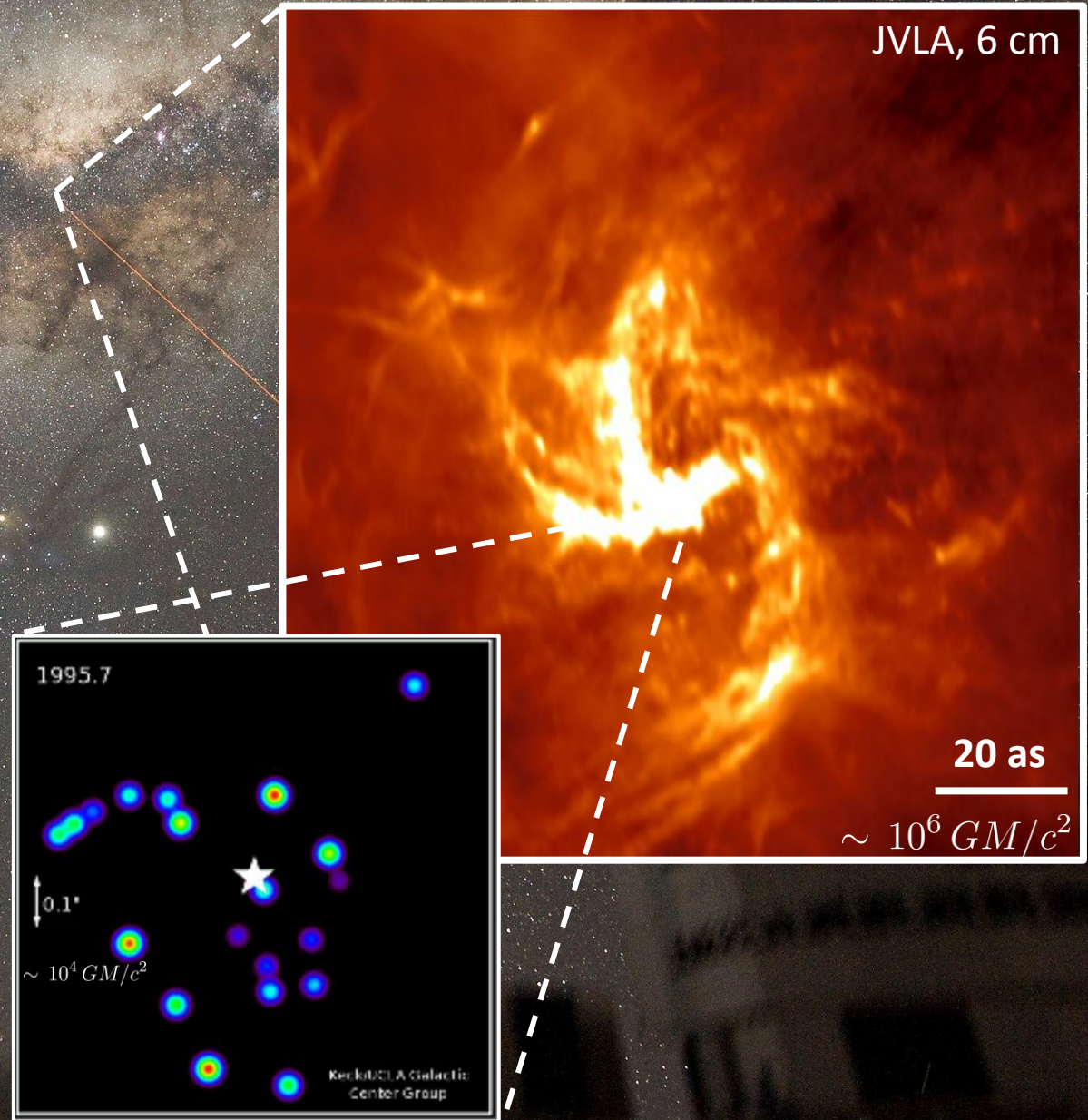


The Niels Bohr
International Academy

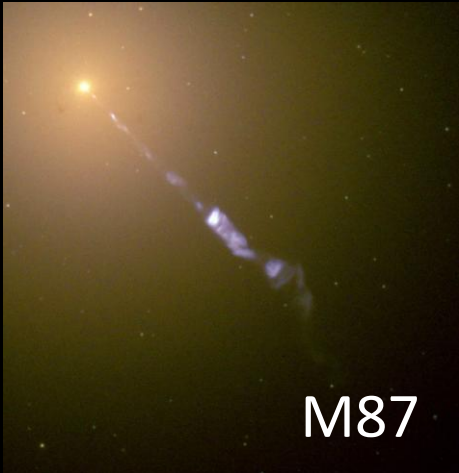


Event Horizon Telescope

At Our Galaxy's Center



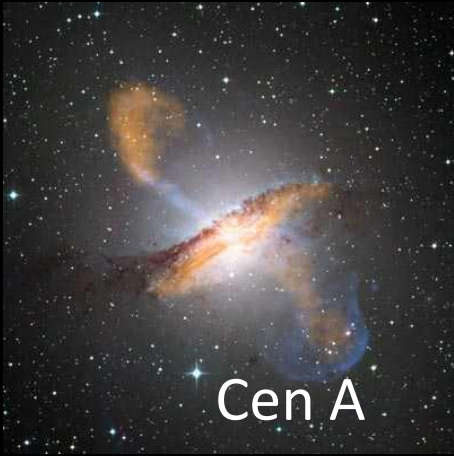
Supermassive black holes and jets are everywhere



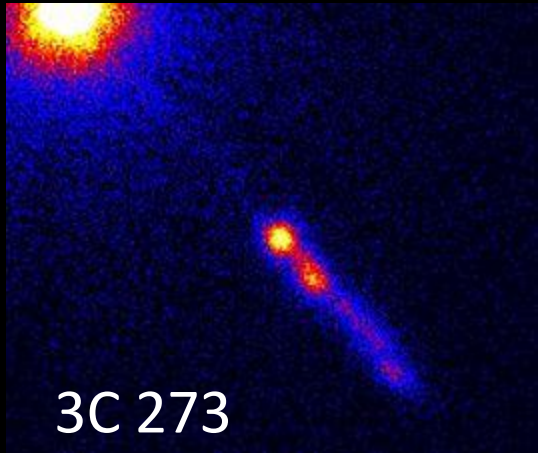
M87



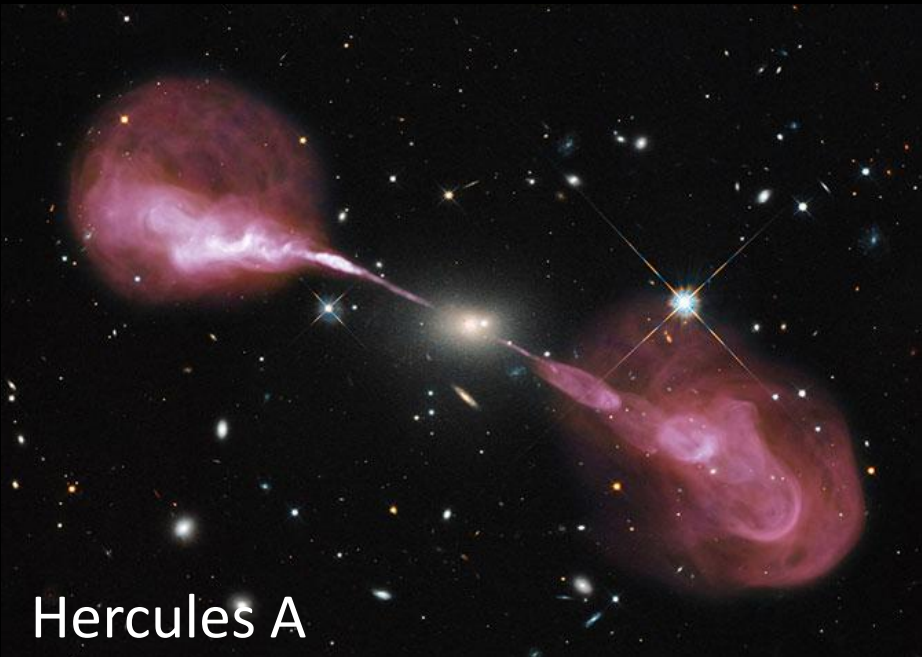
Cyg A



Cen A



3C 273



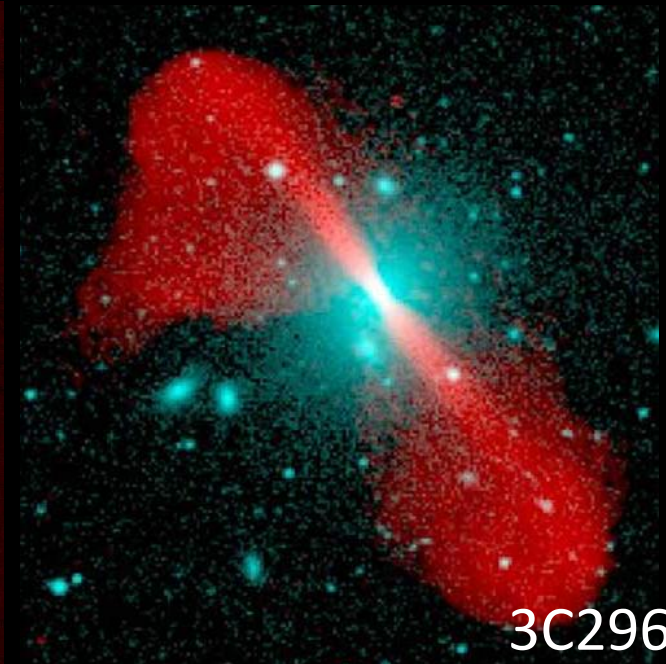
Hercules A



NGC 1265



3C31



3C296

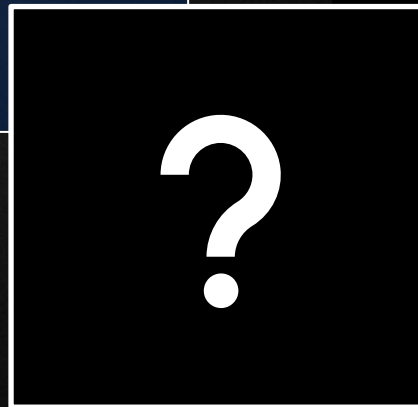
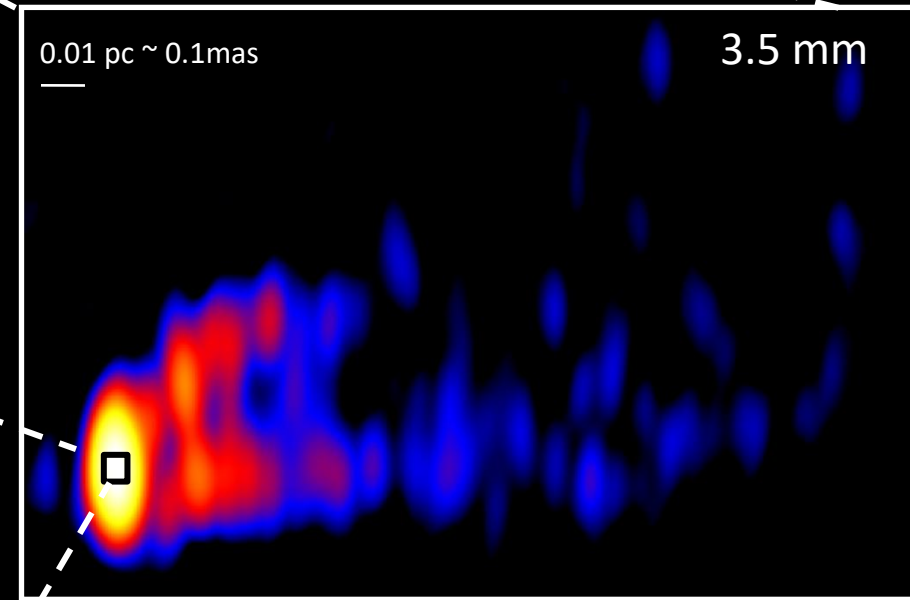
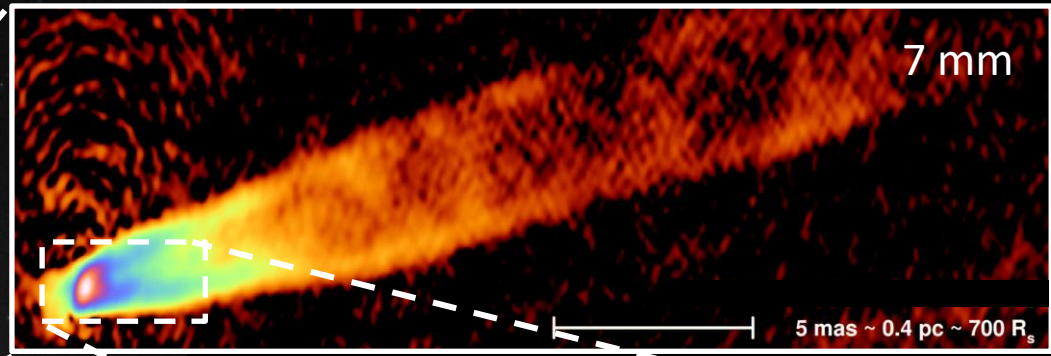
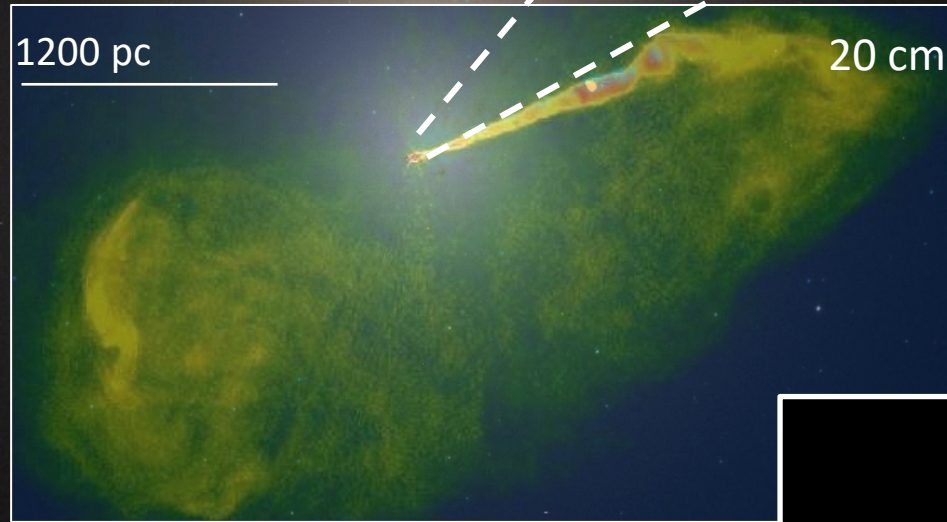
Credits: Sara Issoun, (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A. Weiss et al. (Submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey), (3C293, Chandra), (Hercules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

M87 & M87*

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

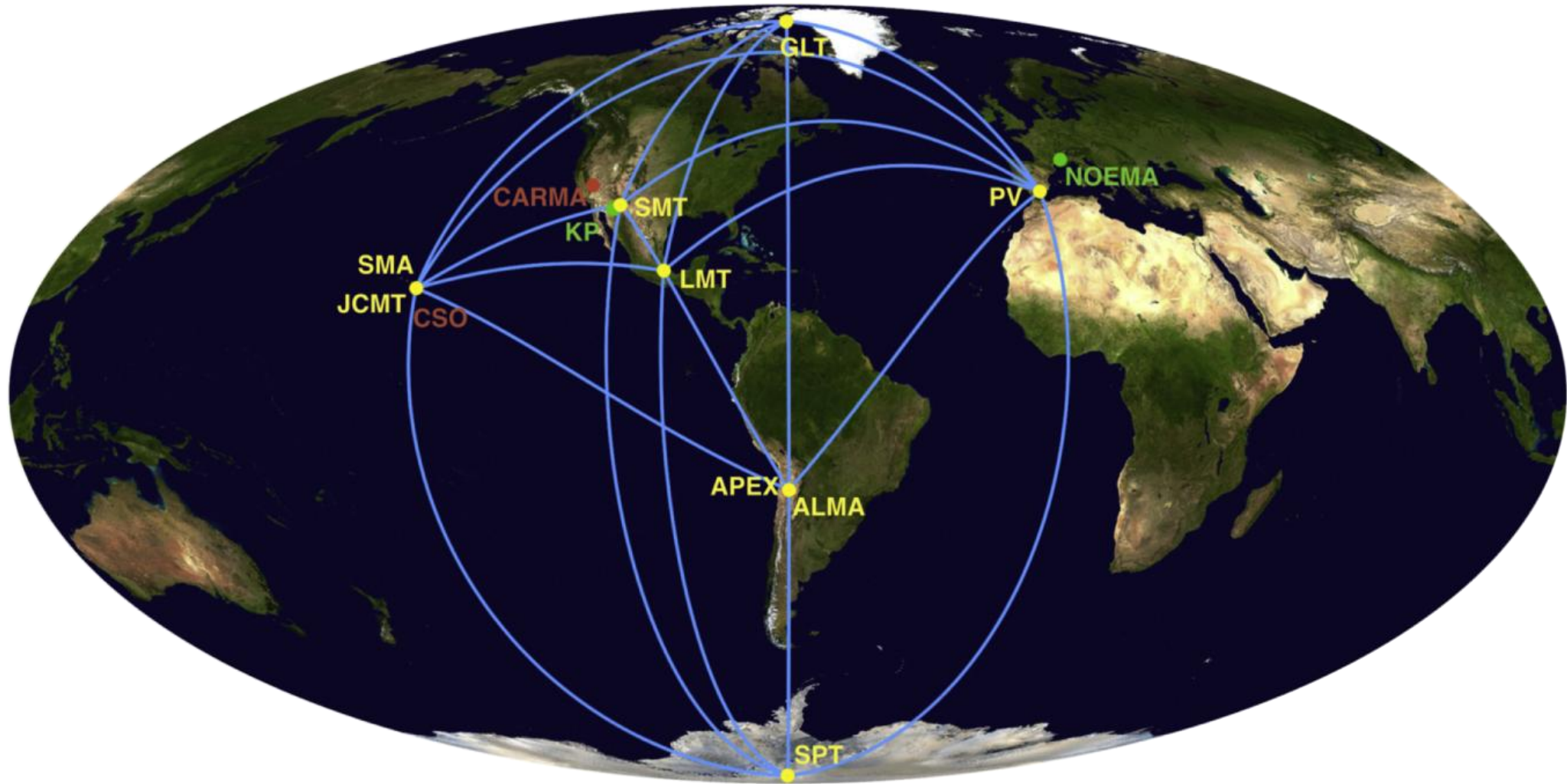
$$D = (16.8 \pm 0.8) \text{Mpc}$$

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



What does jet launching look like on event horizon scales?

The Event Horizon Telescope



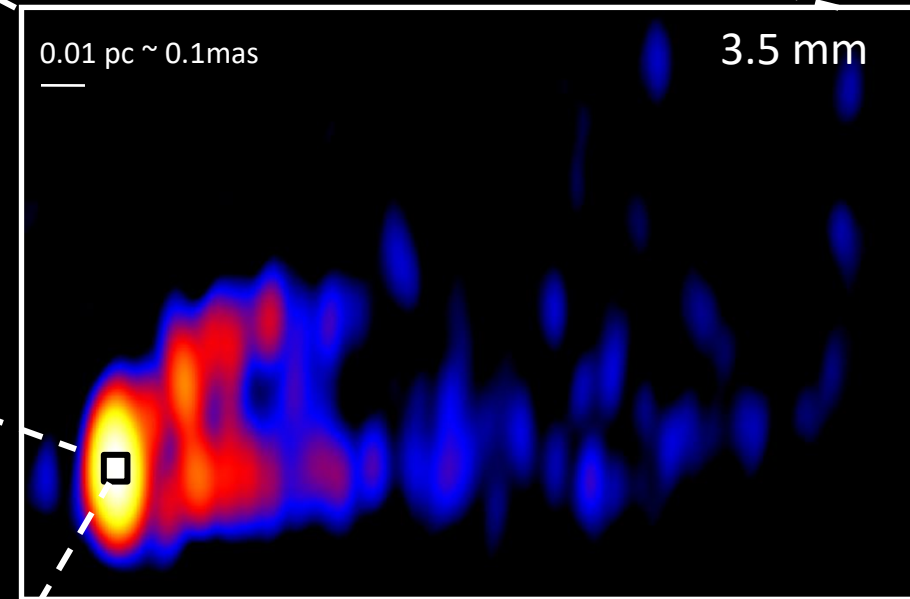
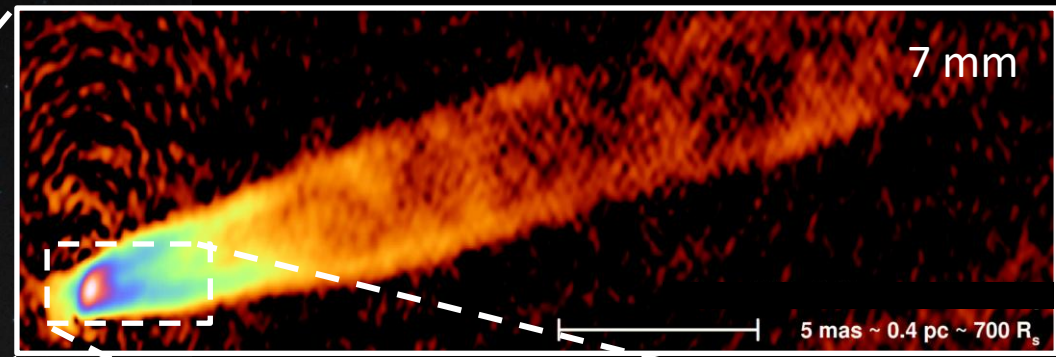
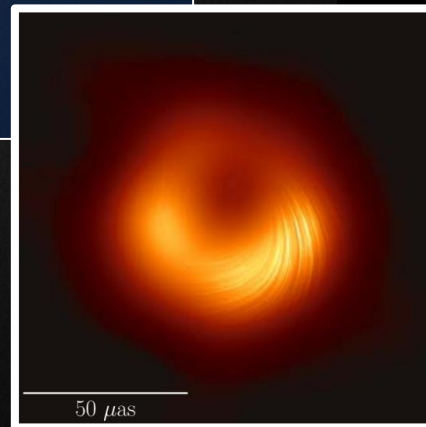
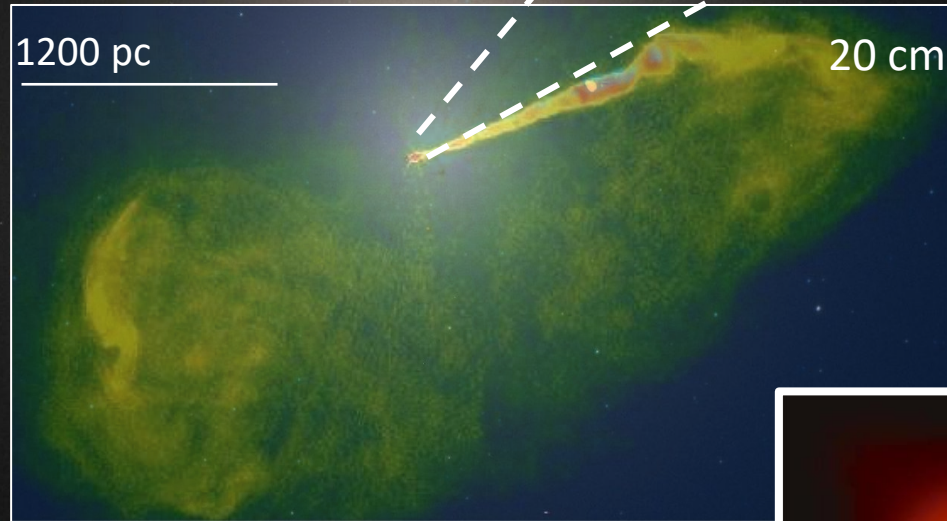
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3 \text{ mm}}{1.3 \times 10^{10} \text{ mm}} \approx 20 \mu\text{as}$$

M87 & M87*

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

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

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

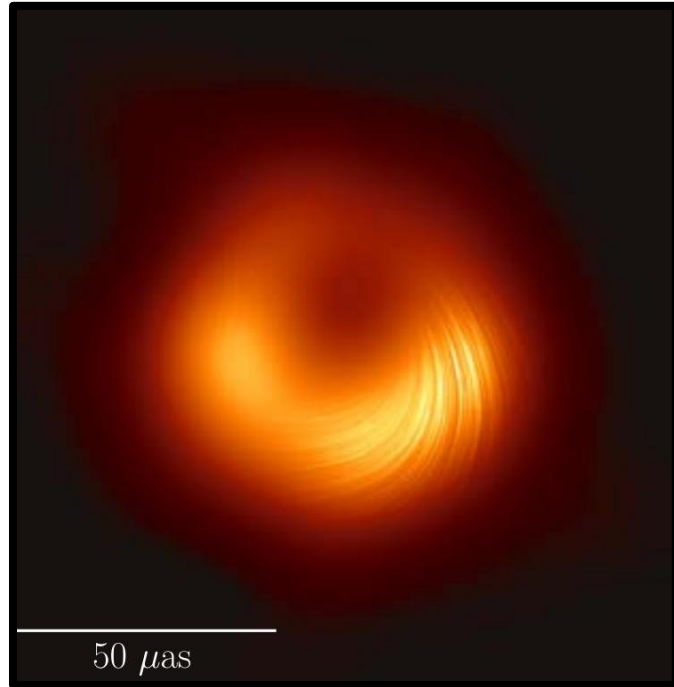


Can polarized EHT images tell us how jets are launched?

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

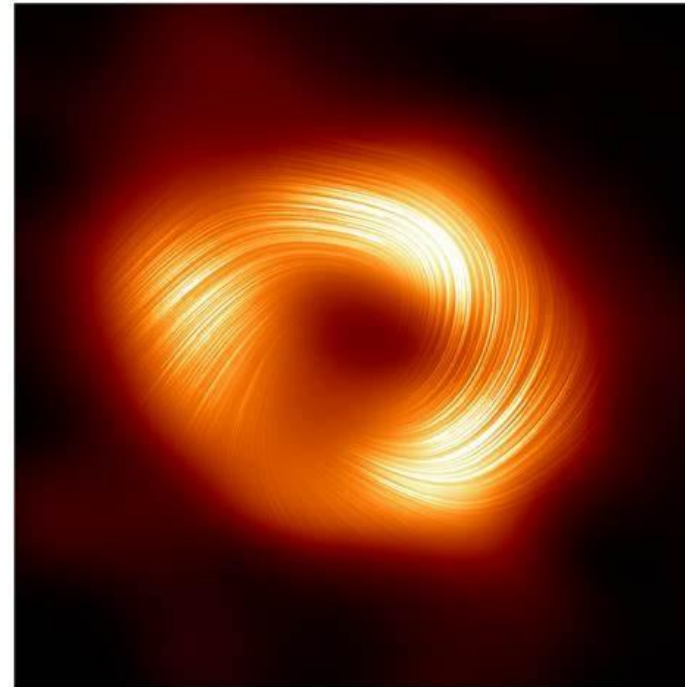
What have we learned from black hole images?

M87 – One of the Largest Black Holes



6 **billion** solar masses
Larger than Pluto's orbit
Launches a strong jet

Sgr A* – Our Galactic Center



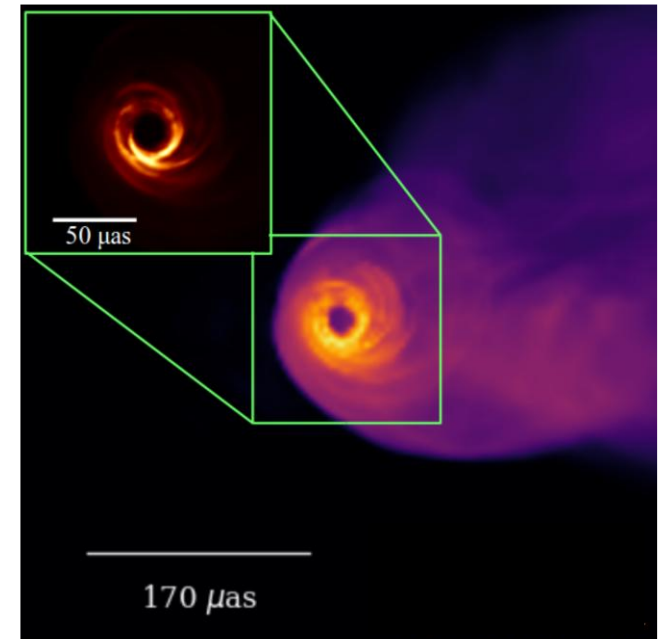
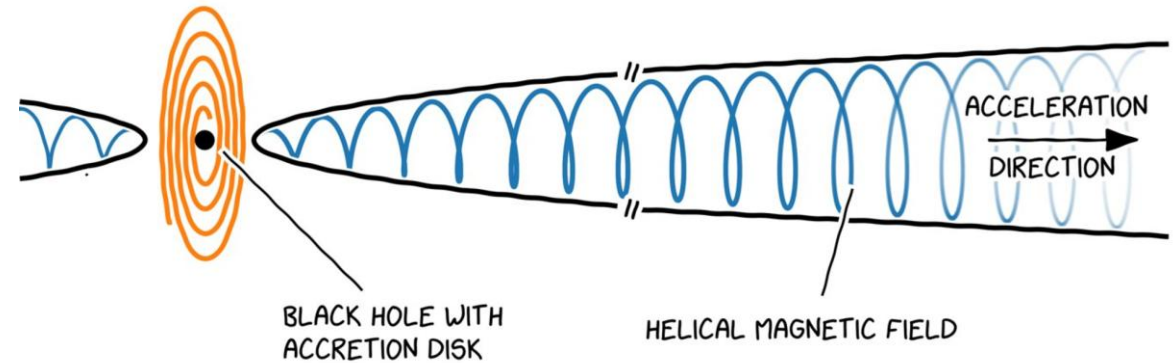
4 million solar masses
Smaller than Mercury's orbit
No obvious jet

Both imaged black holes are:

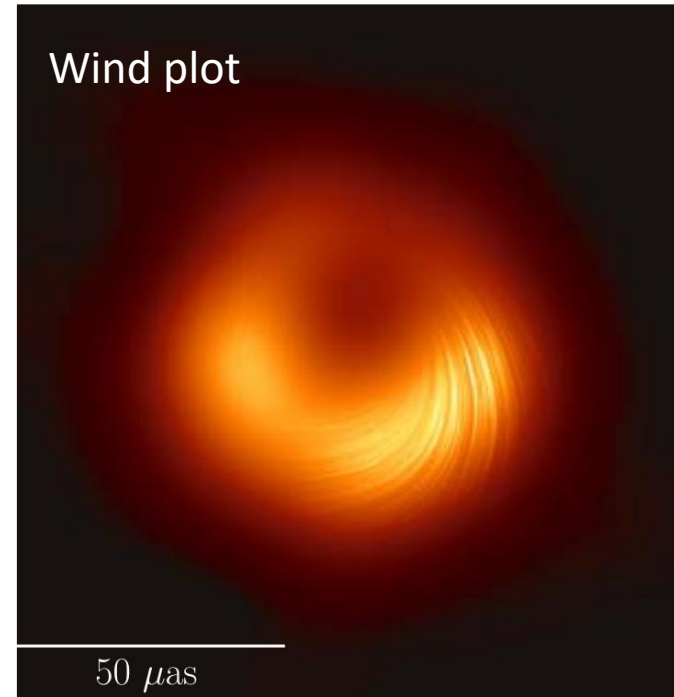
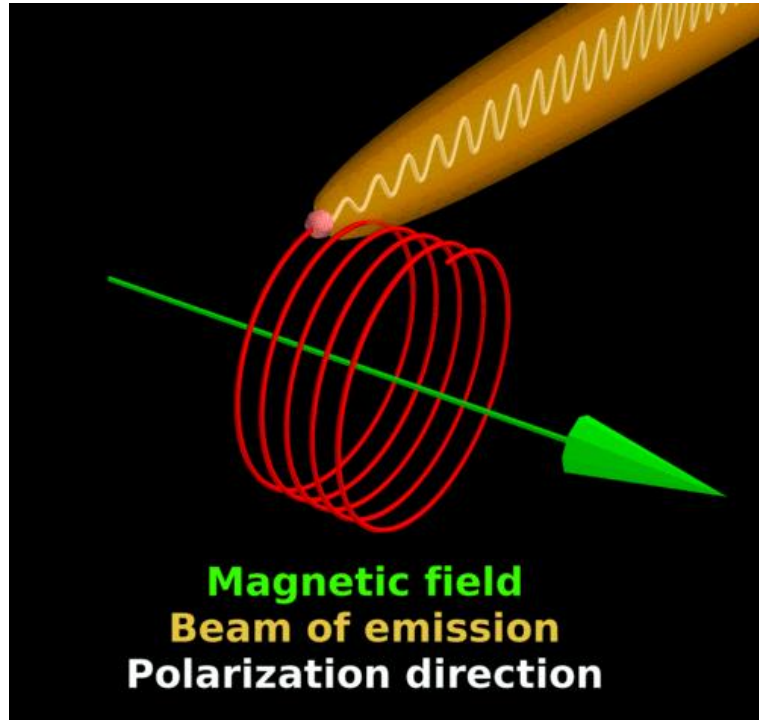
- resolved on event horizon scales
- well-described by accretion theory and General Relativity
- surrounded by strong, coherent magnetic fields

Persistent Mysteries

- What powers the extragalactic jet?
 - the large-scale accretion disk?
 - the spin of the black hole itself?
- What accelerates particles that light up the spacetime?
- Can we precisely measure the black hole spin and test General Relativity?



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**

This talk:

1. How do we make polarized images of black holes?
2. What have we learned from comparing polarized images of black holes to simulations?
3. What can polarized black hole images tell us about jet launching?
4. What's next?

How did we obtain the first polarized image of a black hole?

EHTC VII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
[2105.01169](#), [2311.10976](#)

EHT: Array

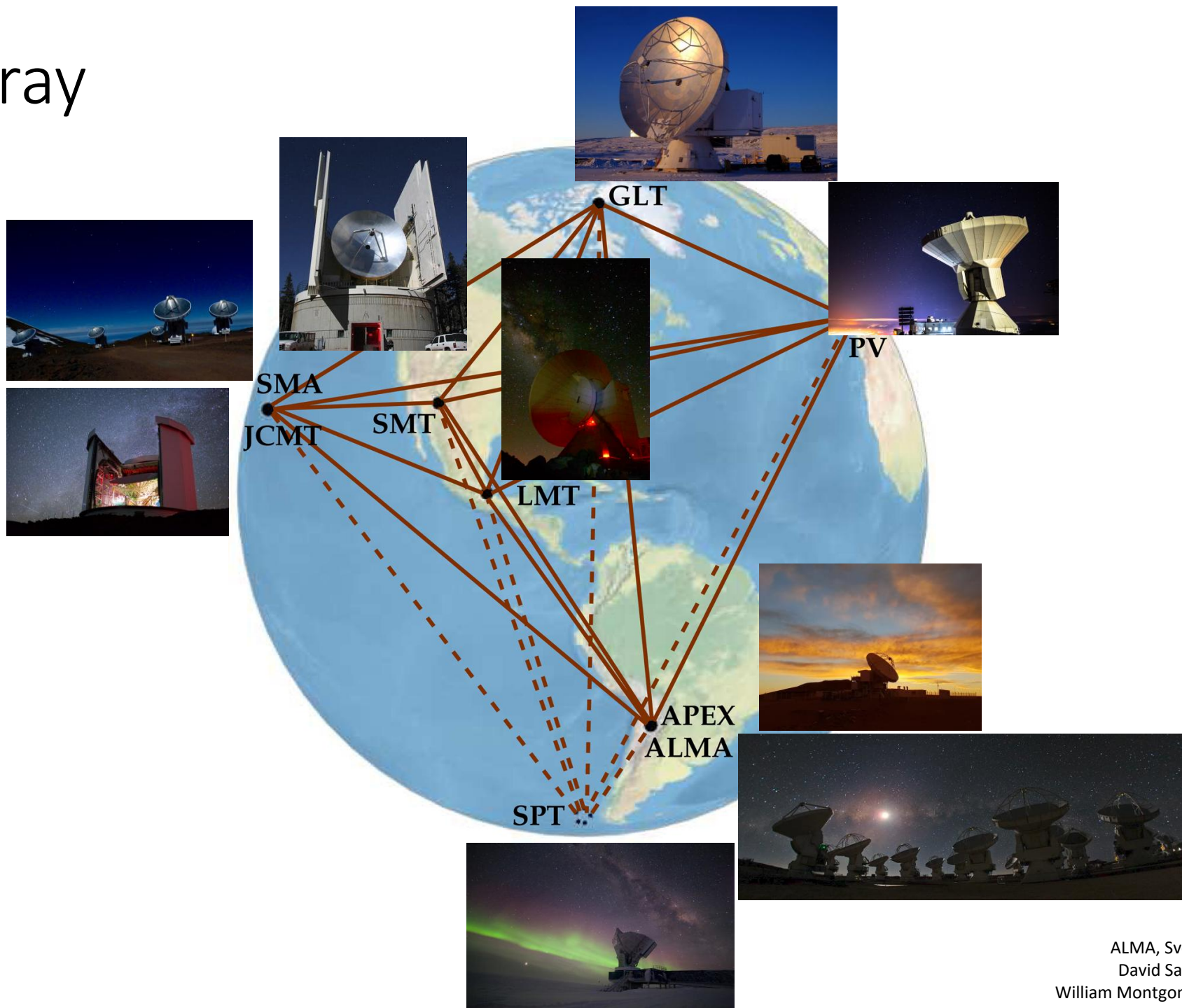


Photo Credits: EHTC I, 2024
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

EHT: People



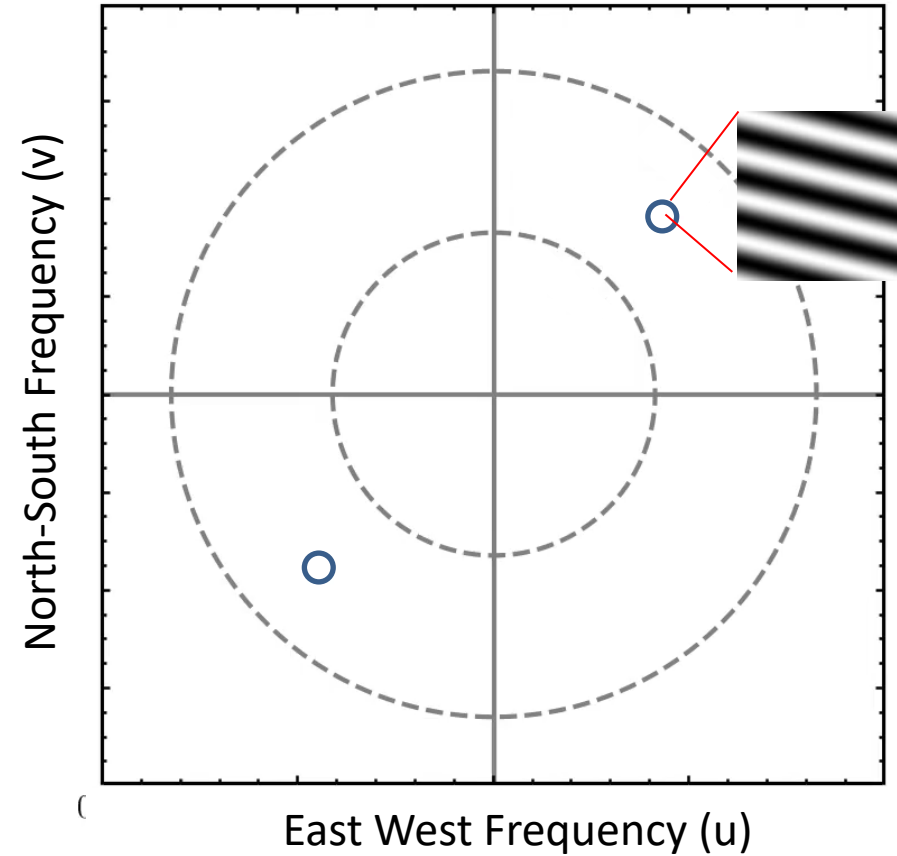
300+ members

60 institutes

20 countries

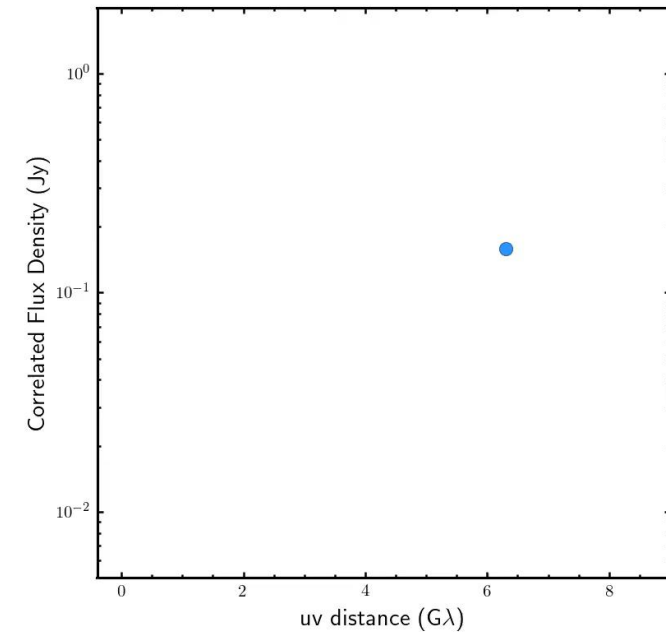
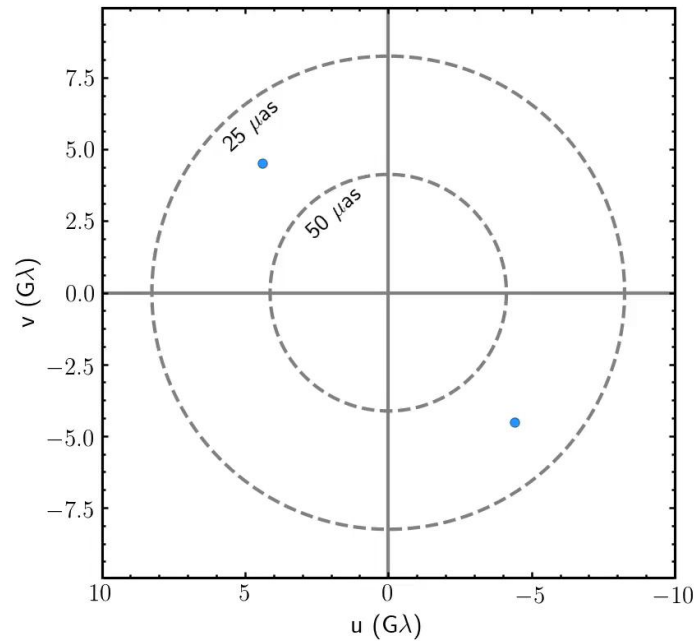
from Europe, Asia, Africa,
North and South America.

Very Long Baseline Interferometry (VLBI)



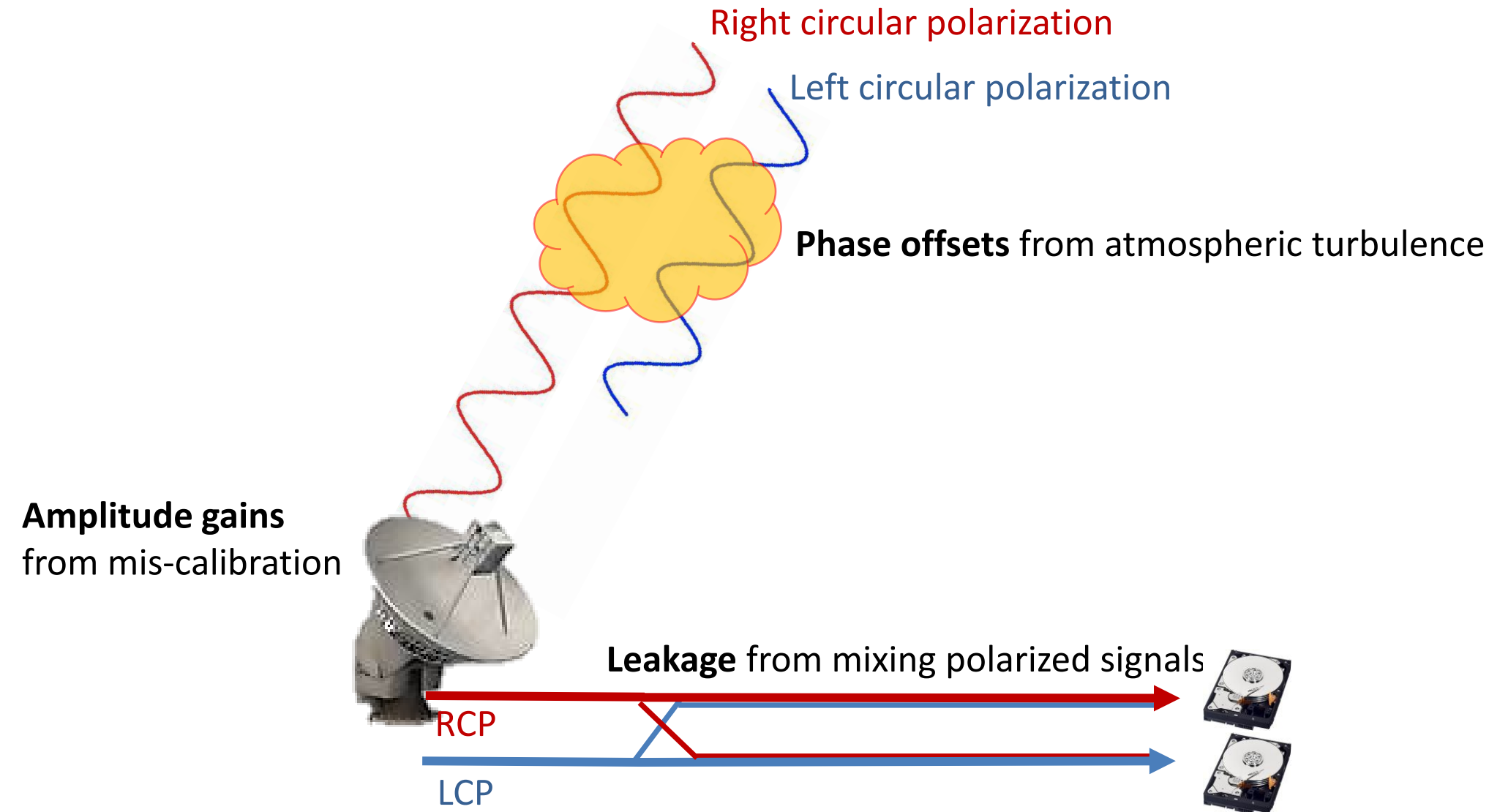
Every projected **baseline** between two telescopes provides **one Fourier component** of the image

Very Long Baseline Interferometry (VLBI)



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

Challenges of near-horizon imaging



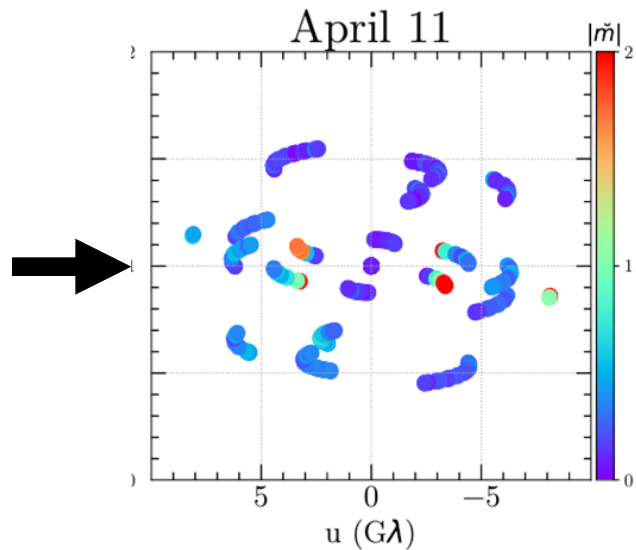
Data at each station are corrupted by unknown **gain and leakage** systematics

Solving for the Image

True Image

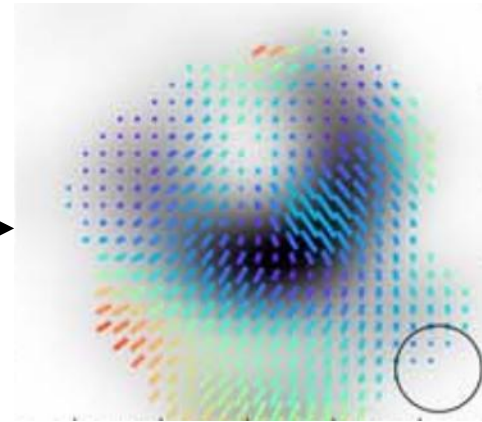


Sparse & Corrupted Measurements



RECONSTRUCTION
ALGORITHM

Reconstruction



Several different types of reconstruction algorithms:

- **CLEAN-based**: standard and efficient, but can have difficulties on very sparse data
 - LPCAL/GPCAL (Park+ 2021) and polysolve (Marti-Vidal+ 21)
- **Regularized Maximum Likelihood w/ Gradient Descent**: fast and flexible, but lots of hyperparameters
 - eht-imaging (Chael+ 2016, 2018, 2023), SMILI (Akiyama+ 2017)
- **Bayesian MCMC posterior exploration**: fully characterizes uncertainty, but expensive
 - Themis (Broderick+ 21), DMC (Pesce+ 21), Comrade (Tiede+ 2022)

The **eht-imaging** software library

- python toolkit for **analyzing, simulating, and imaging** interferometric data
- A flexible framework for developing new tools:
 - dynamical imaging (Johnson+ 2017)
 - **multi-frequency imaging (Chael+ 2023a)**
 - geometric modeling (Roelofs+ 2023)
- Uses:
 - All EHT results to date
 - Next-generation EHT design
 - Imaging & analysis from VLBA, GMVA, ALMA, RadioAstron...

achael/**eht-imaging**

Imaging, analysis, and simulation software for radio interferometry



26

Contributors

11

Used by

5k

Stars

489

Forks

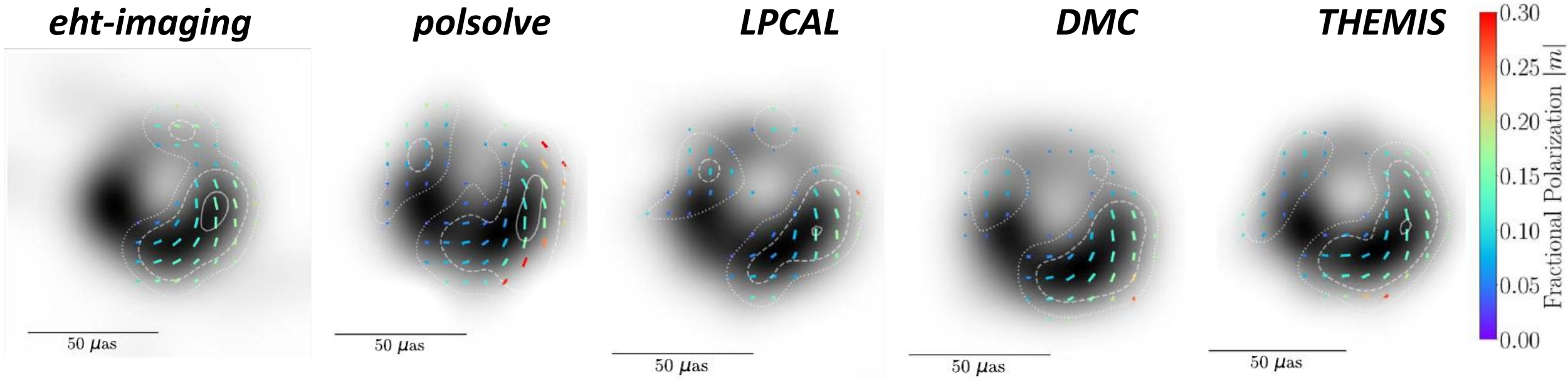


<https://github.com/achael/eht-imaging>

```
pip install ehtim
```

Chael+ 2016, 2018a, 2023a
ALMA Partnership+ 2015

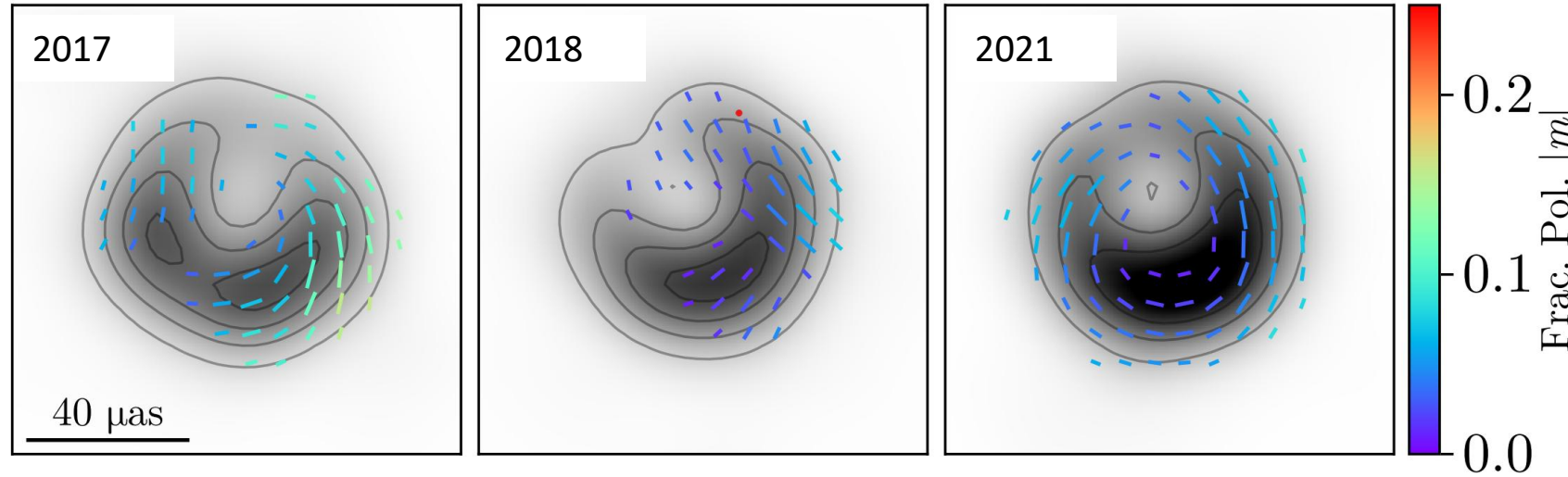
First polarized Images of M87 from 5 methods



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

Three Years of Horizon-Scale Structure in M87

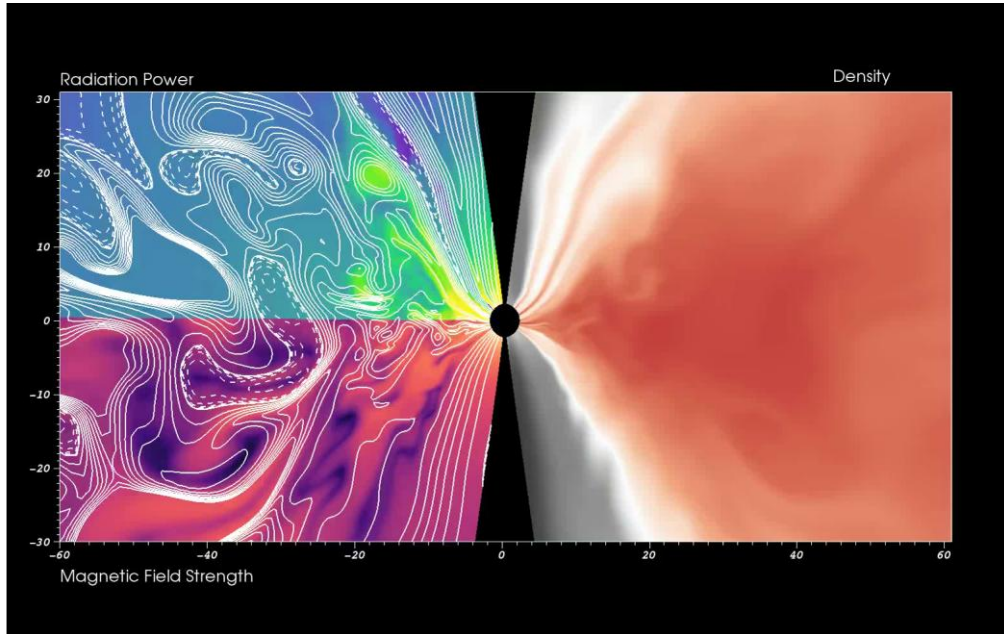
- EHT observations show a consistent horizon-scale ring structure in M87* **over 4,000 gravitational timescales**
- Image quality is improving from EHT observations performed with a **more complete array** (including Greenland Telescope)
- Image diameter is consistent but brightness position angle shifts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



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

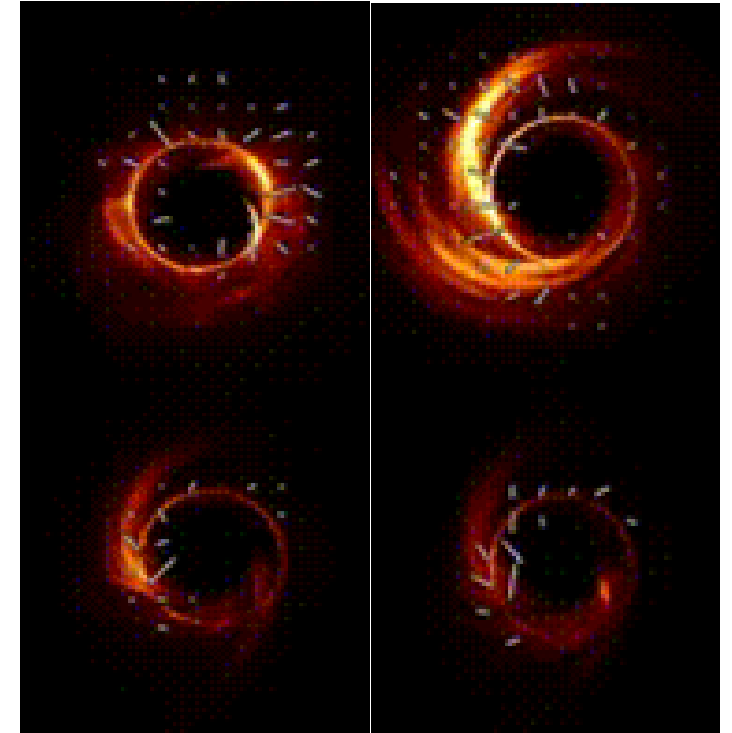
EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
[2105.01173](#), [2311.10976](#)

Theoretical Tools for Interpreting Black Hole Images



General Relativistic Magnetohydrodynamic (GRMHD) Simulations

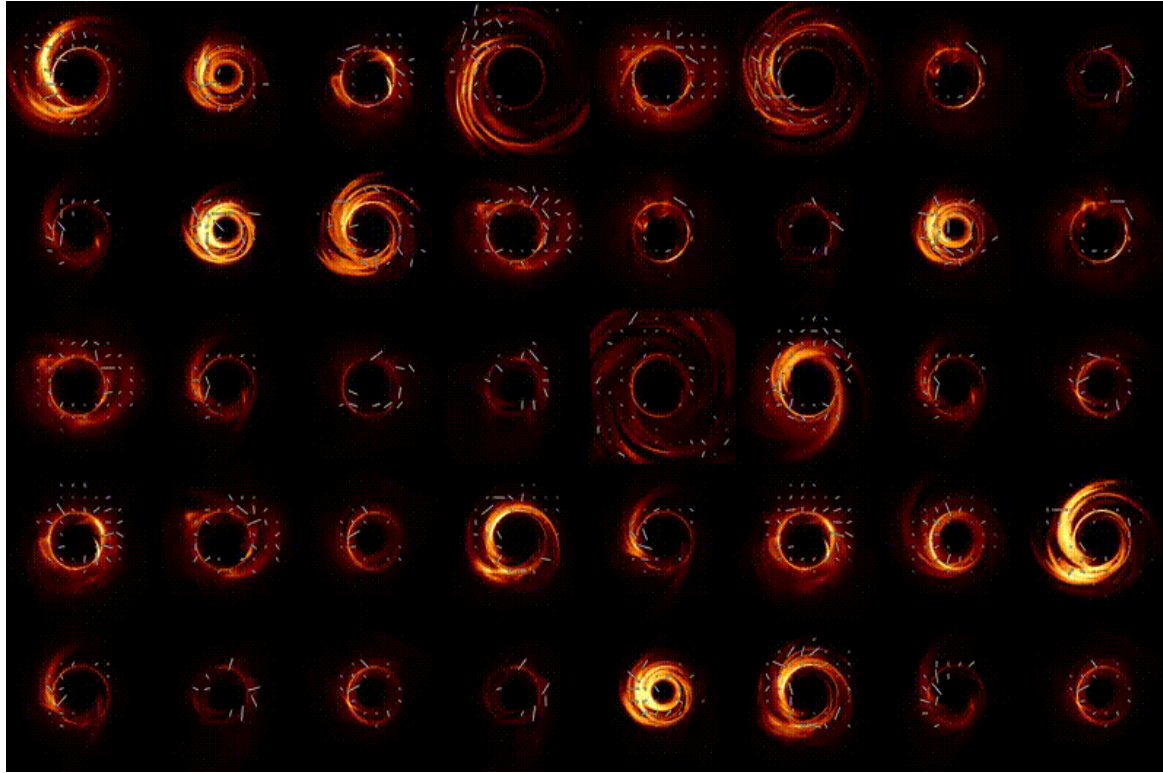
Solve coupled equations of plasma dynamics and magnetic field for low-luminosity accretion in Kerr spacetime



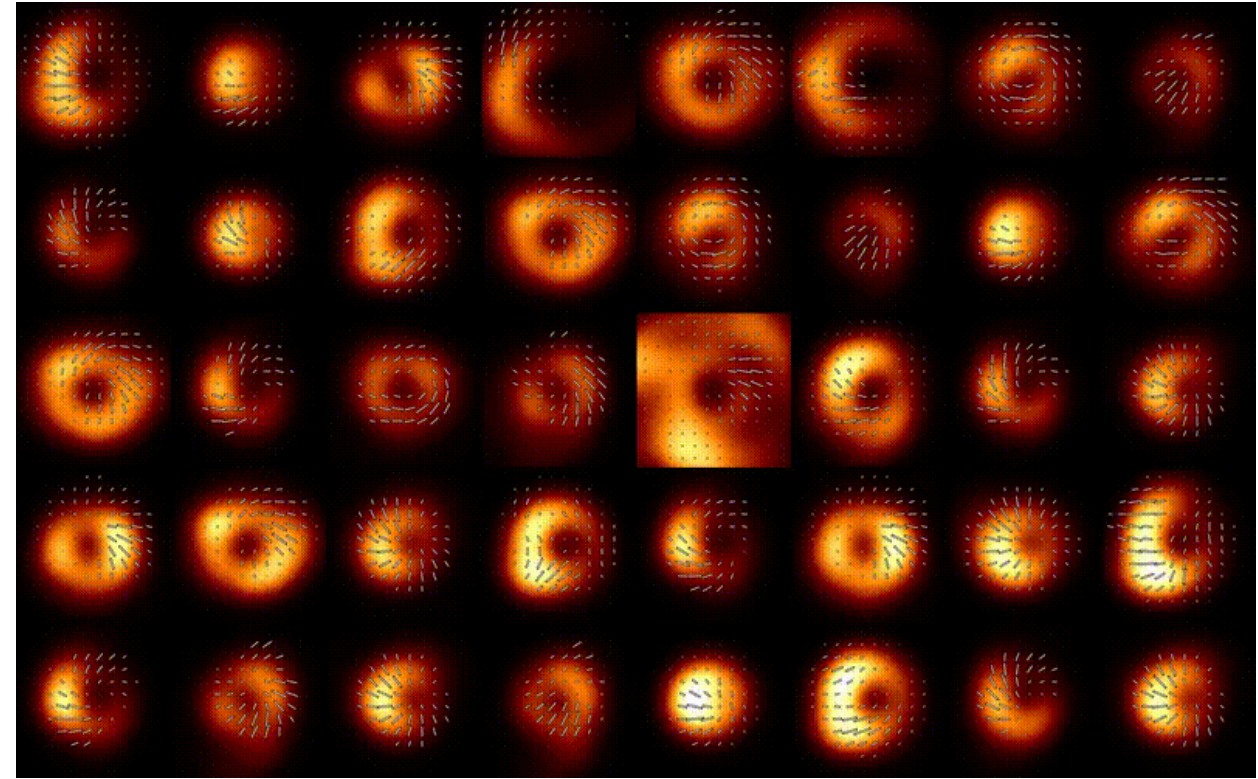
GR Radiative Transfer

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)

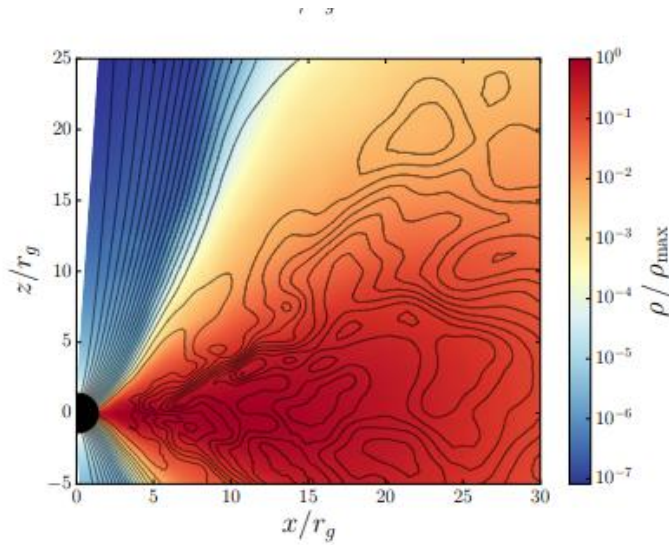
Two-temperature plasma model from Moscibrodzka et al. 2016

$$T_e \neq T_i$$

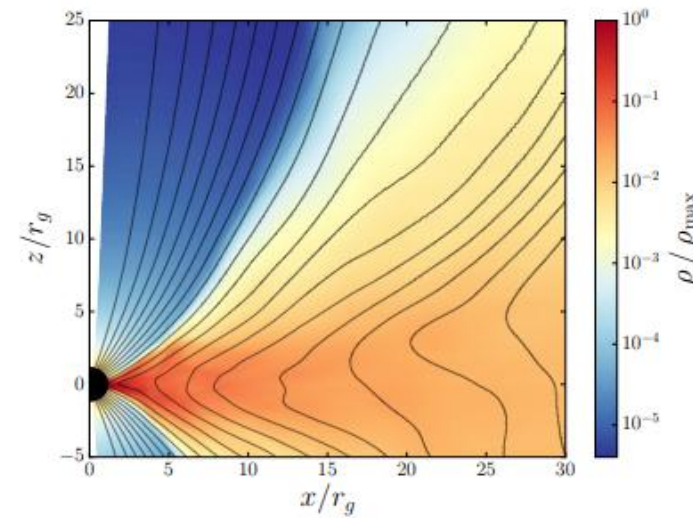
What is the magnetic field structure close to the horizon?

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

**Magnetic fields
are weak and
turbulent**



“SANE”



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

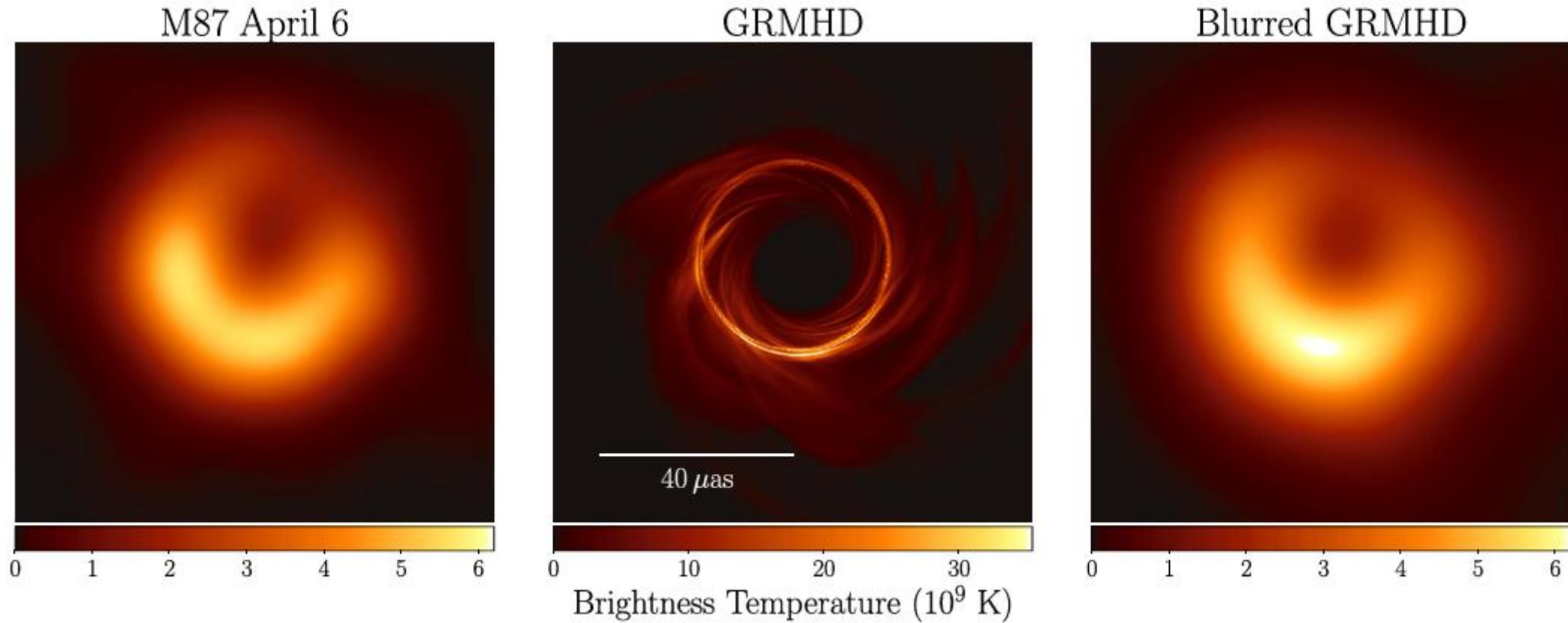
“MAD” - Magnetically Arrested Disk

MADs launch more powerful Blandford-Znajek jets:

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

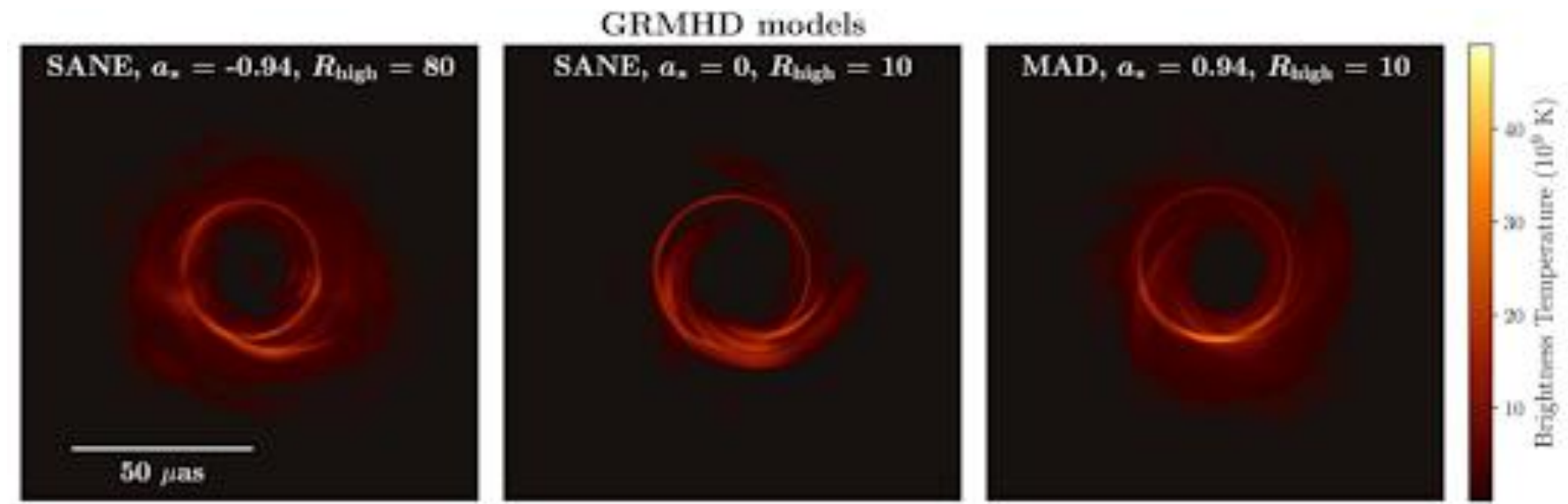
magnetic flux BH spin

EHT Images are consistent with GRMHD Simulations



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)**

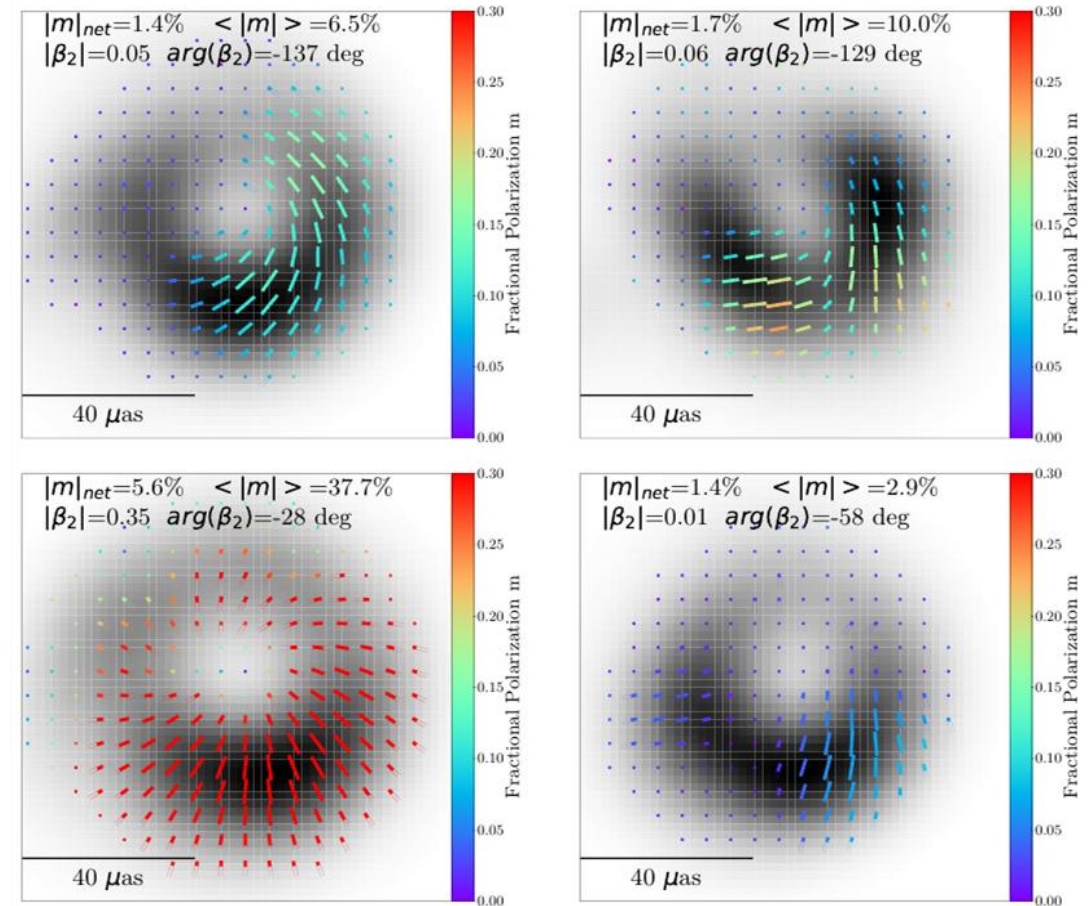


- Image asymmetry $\rightarrow$ black hole spin vector faces away from Earth
- An additional constraint on **jet power** ($\geq 10^{42}$ erg/sec) rejects all spin 0 models
- Can we do better with polarization?

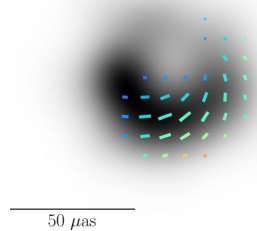
Polarization is the key for learning more

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

Simulation Polarization Images



Scoring M87* simulations with polarization



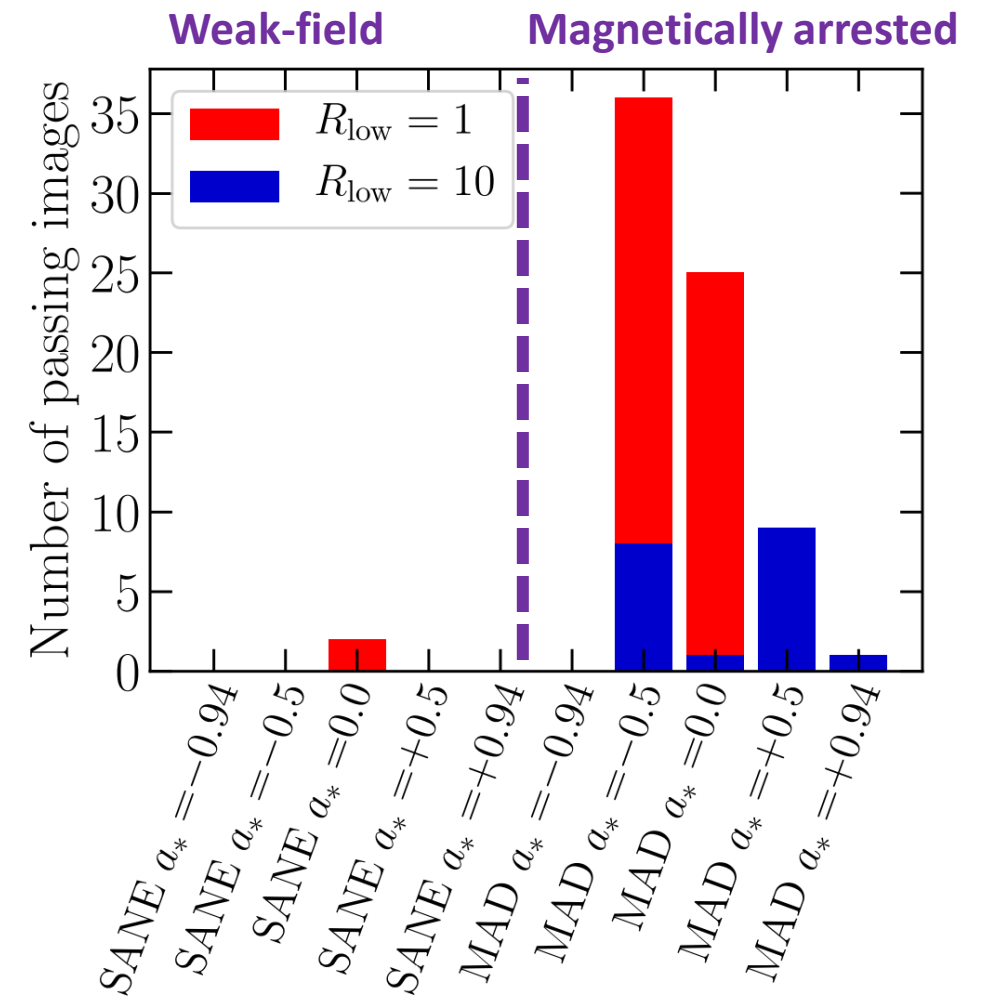
- Scoring 2017 observations with multiple approaches all **strongly favor a magnetically arrested accretion flow**
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

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

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

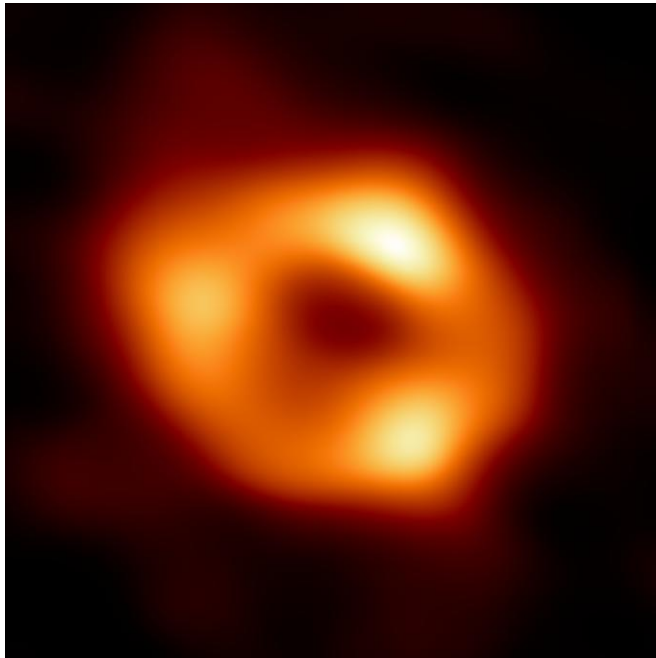
$$T_e \simeq (5 - 40) \times 10^{10} \text{ K}$$
$$|B| \simeq (7 - 30) \text{ G}$$

- Strong magnetic fields more easily launch BZ jets at all values of BH spin
- Do new EHT polarization measurements change this picture? Stay tuned!

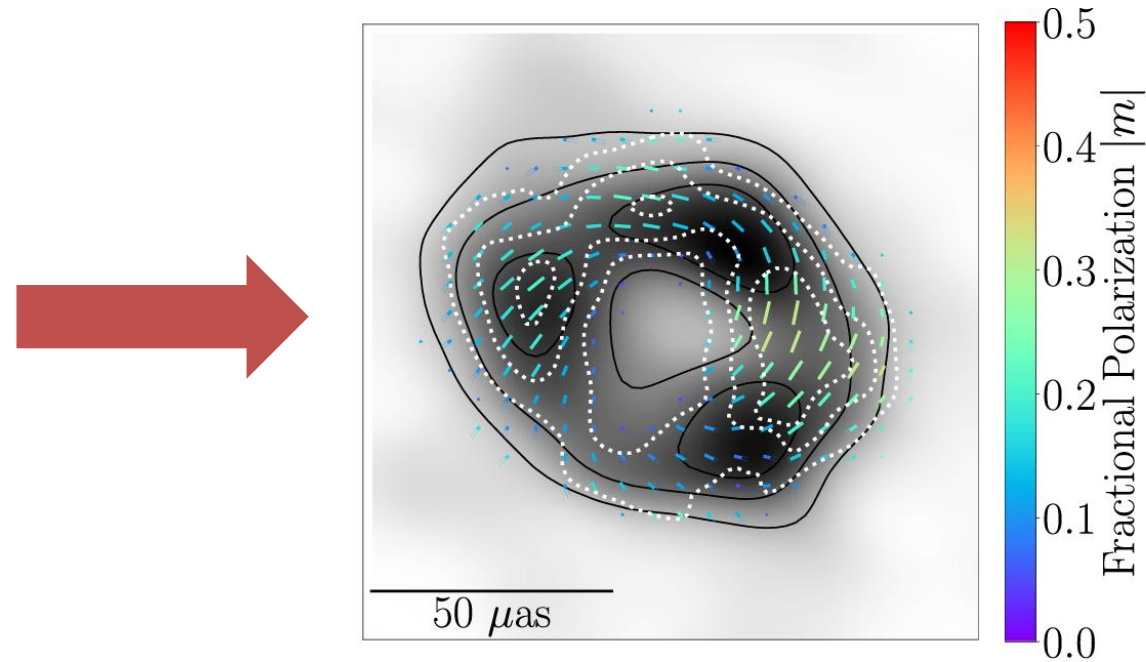


Sgr A* in linear polarization

Total intensity



Linear Polarization



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

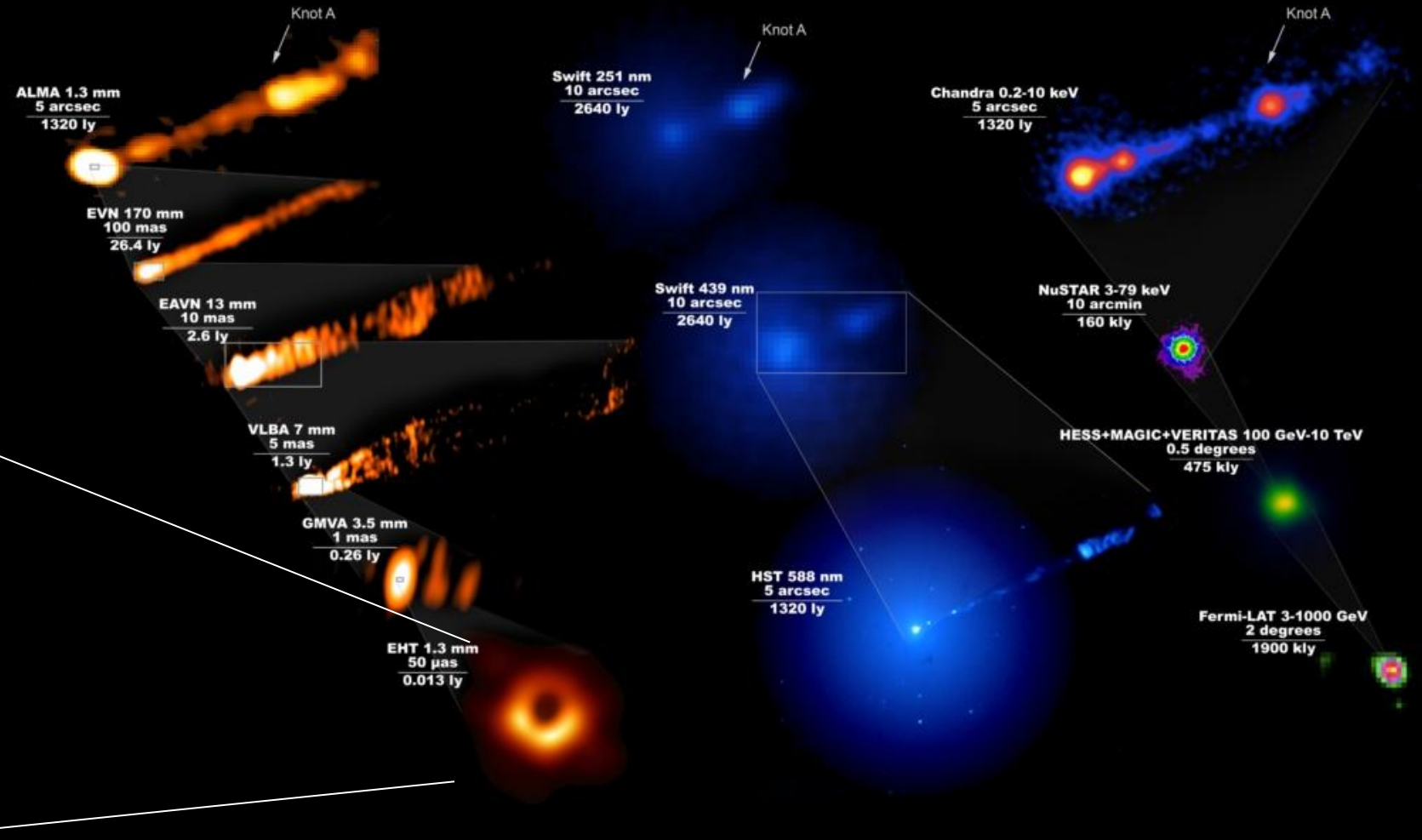
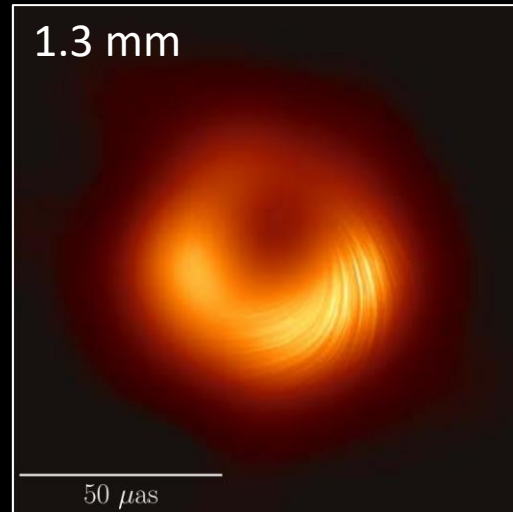
What can a polarized image of M87* tell us about energy flow & jet launching?

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

M87*

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

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



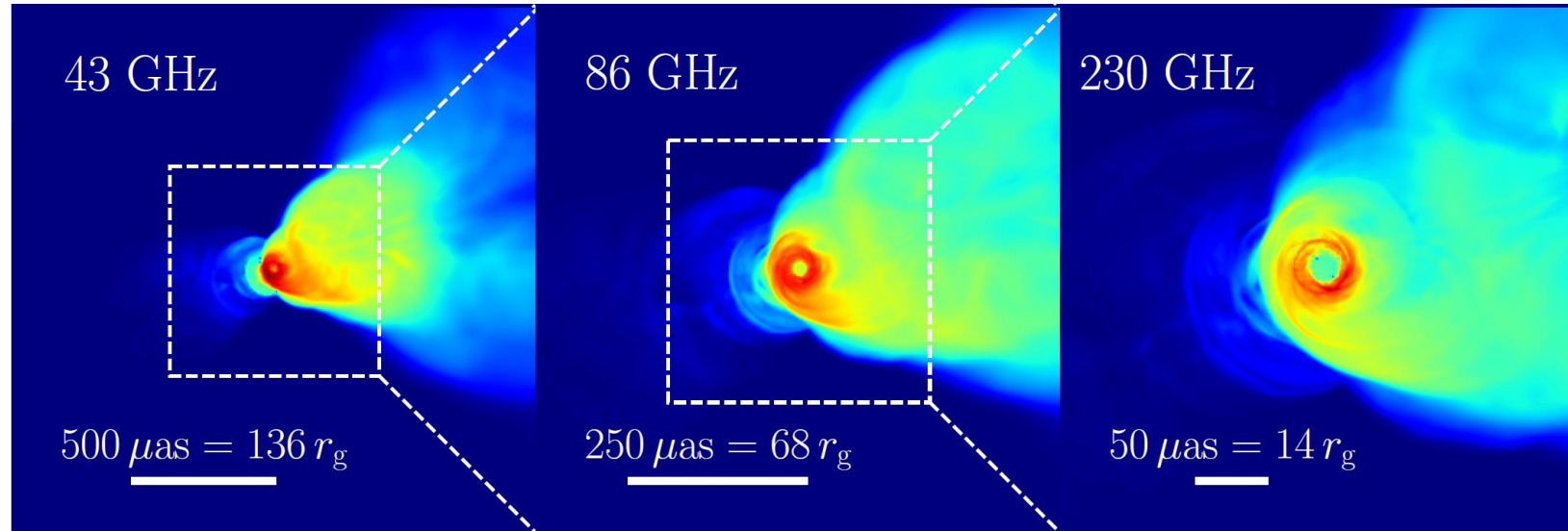
Jets are thought to be powered by black hole spin energy extracted via magnetic fields (Blandford & Znajek 1977)
Is it possible to observe black hole energy extraction **on horizon scales**?

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)

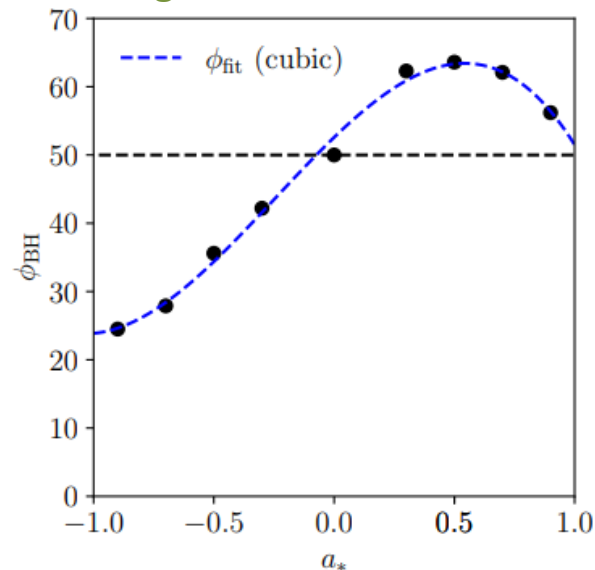
- Simulations (e.g. Chael+ 2019, 2025) naturally produce:
 - observed jet power
 - observed wide opening angle
 - observed core-shift
- Can we be **sure**? What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?



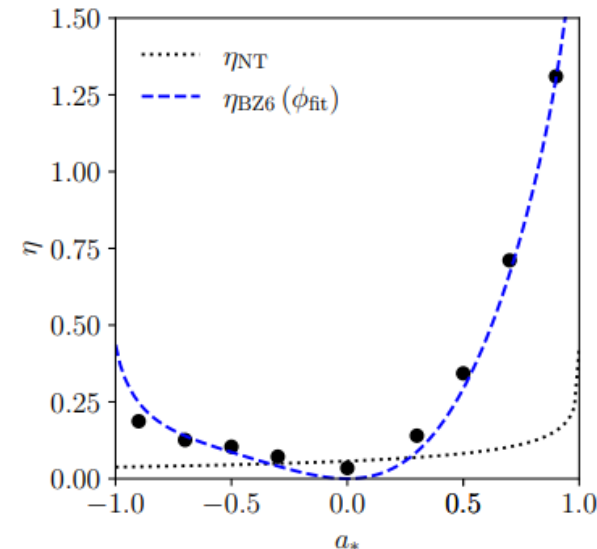
Jets in simulations are spin powered

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

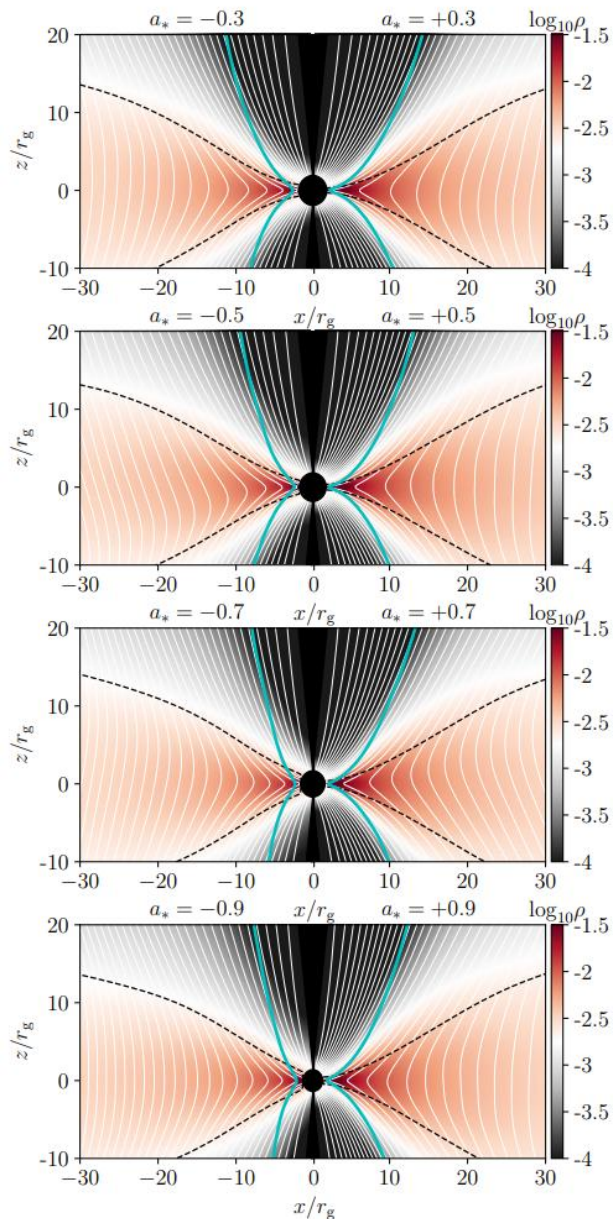
Magnetic flux through the horizon



Jet efficiency



BH spin

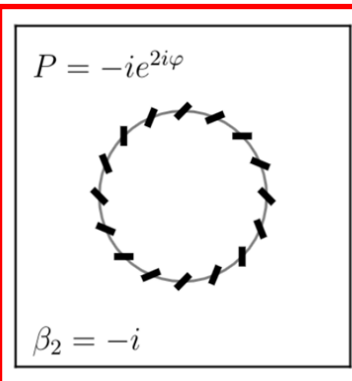
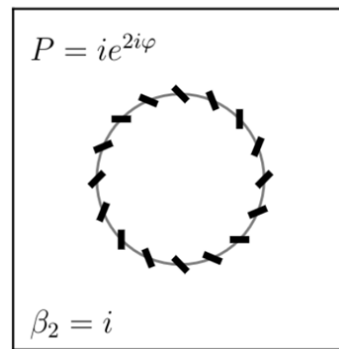
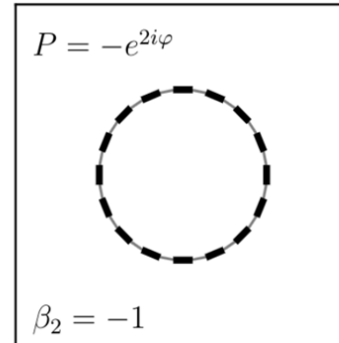
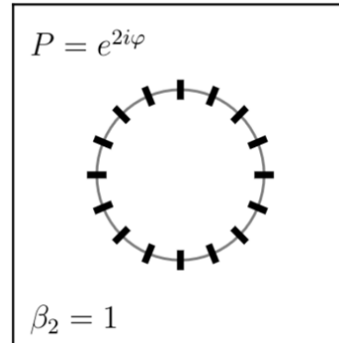
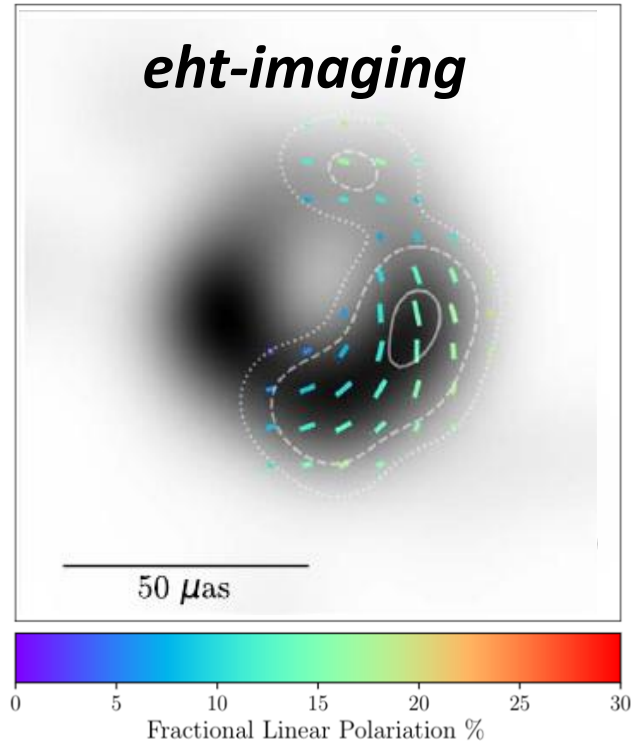


Time- and azimuth-averaged simulation data

R. Narayan, A. Chael + 2022

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

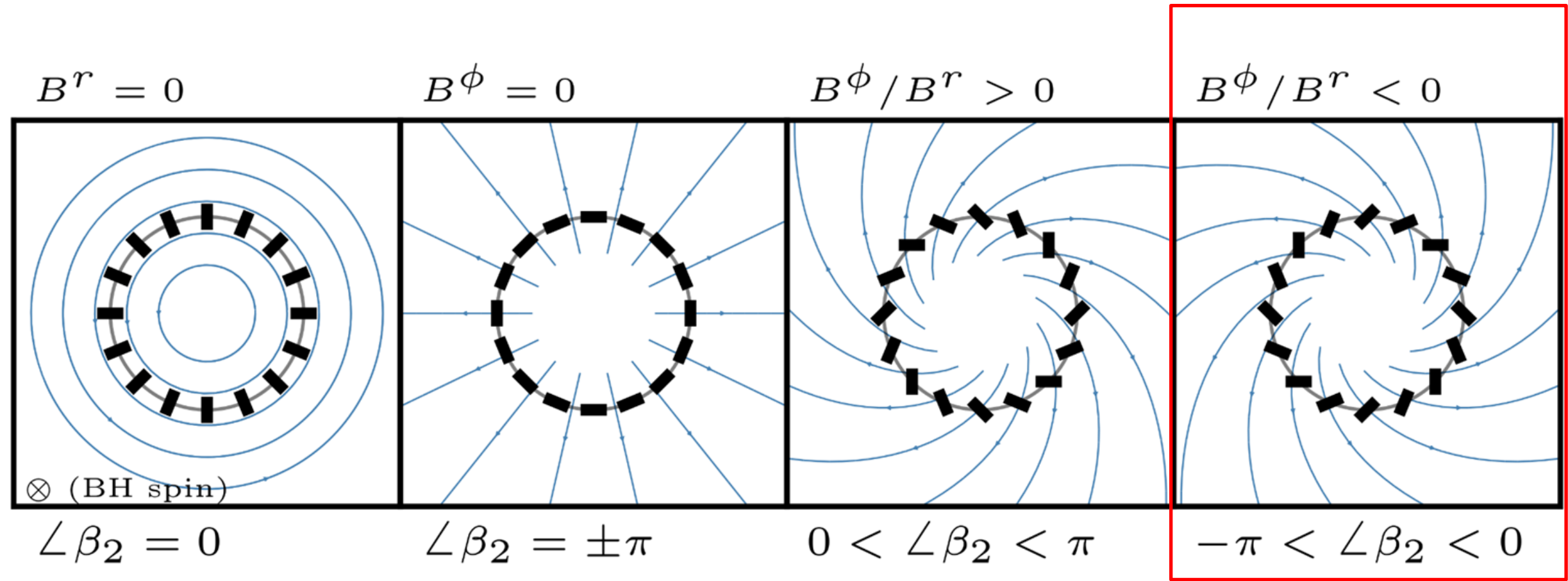
Polarized Images of M87* and horizon-scale energy flow



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

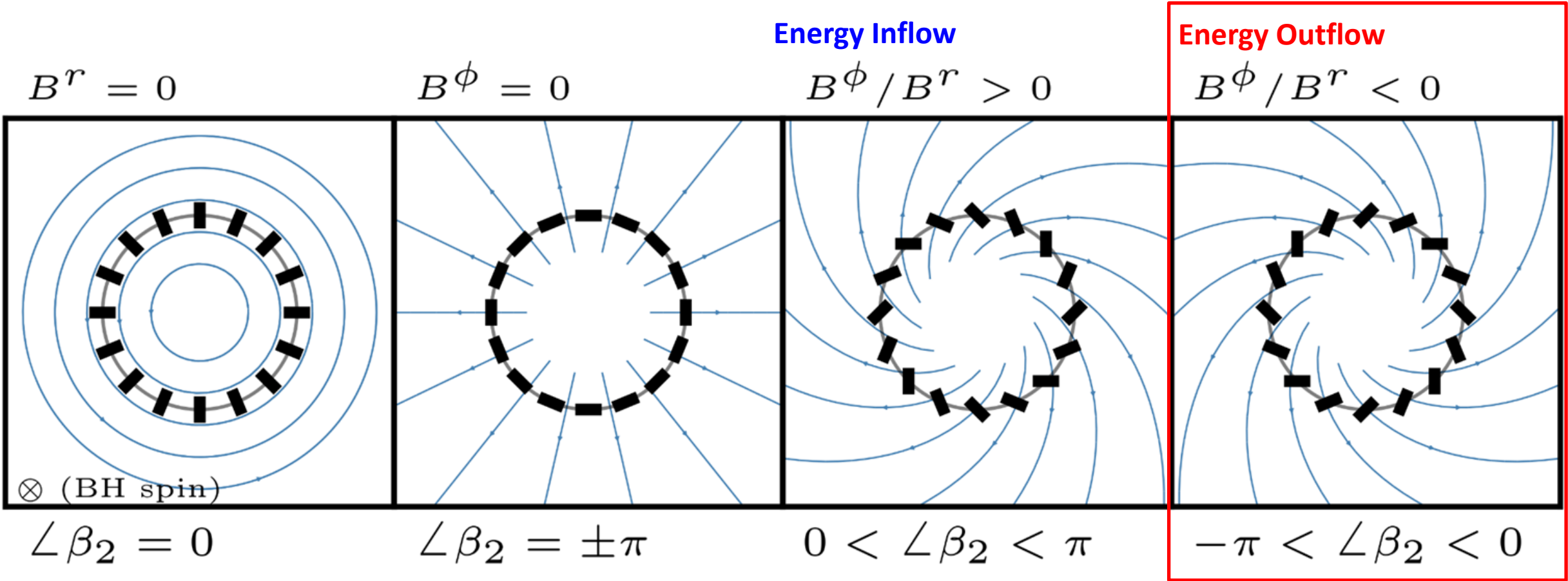
- The polarization spiral's 2nd Fourier mode (β_2 : Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret β_2 **physically**?

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

Horizon-scale polarization tracks the direction of energy flux



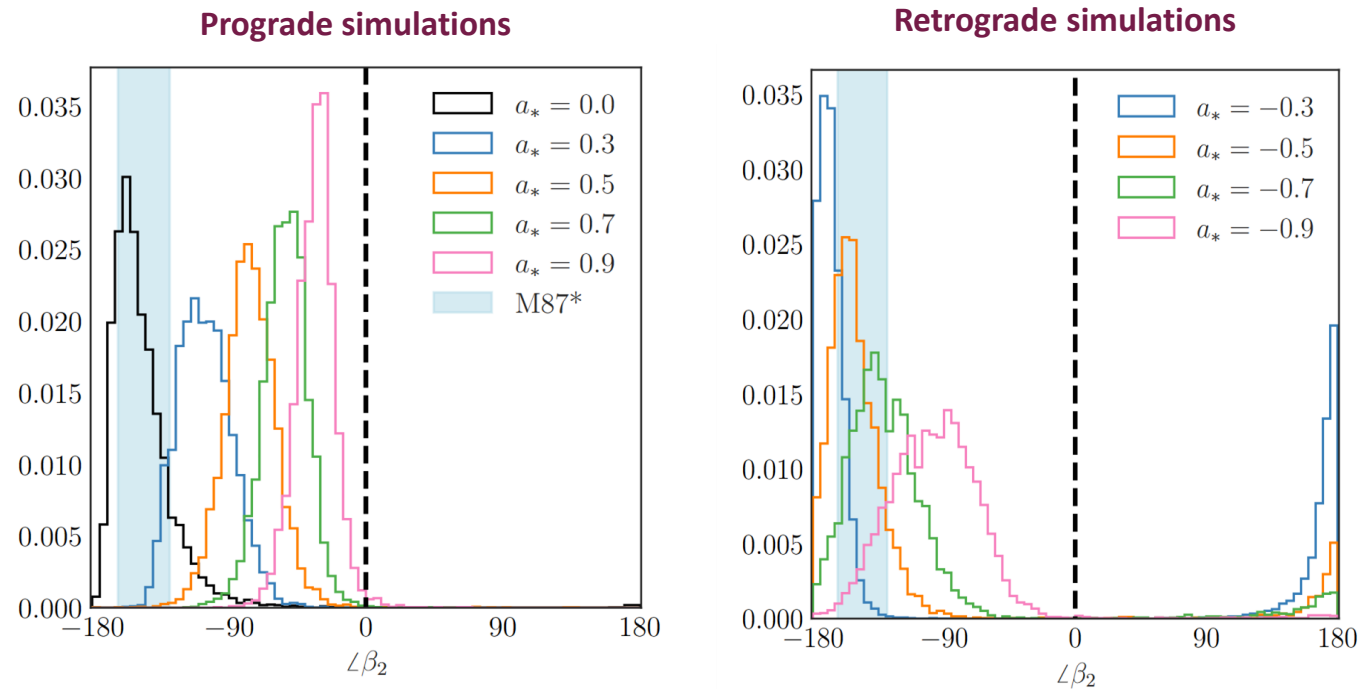
The direction of radial Poynting flux in GRMHD is set determined by B^ϕ / B^r :

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

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

Does β_2 measure the direction of energy flux in simulations?

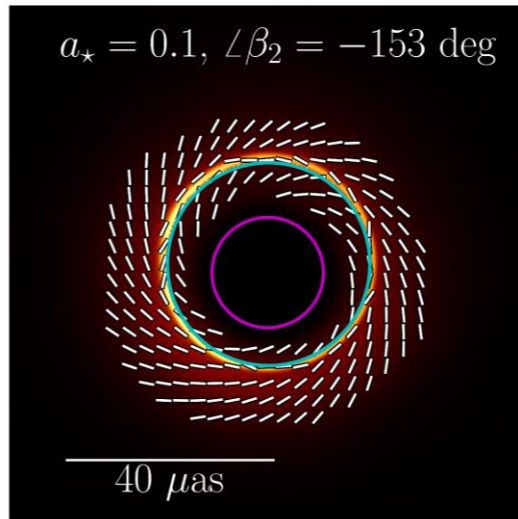
- Almost all 230 GHz images from MAD simulations have $\angle\beta_2 < 0$, consistent with the measured energy outflow in the simulations.
- **M87*'s horizon-scale polarization in 2017 is consistent with outflowing electromagnetic energy at radii $r \lesssim 5r_g$**
- $\angle\beta_2$ in simulations has a strong dependence on spin



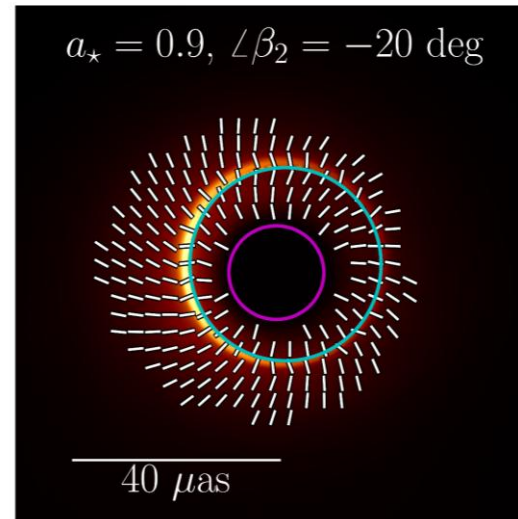
BH spin axis is into the plane of the sky in all simulation images (EHTC+V)

Polarized images are **spin dependent**

Low Spin



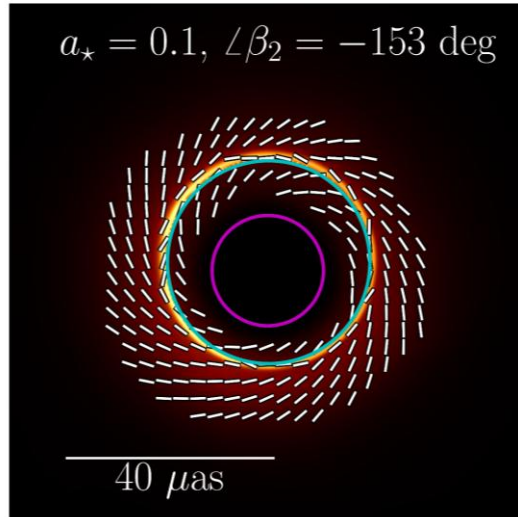
High Spin



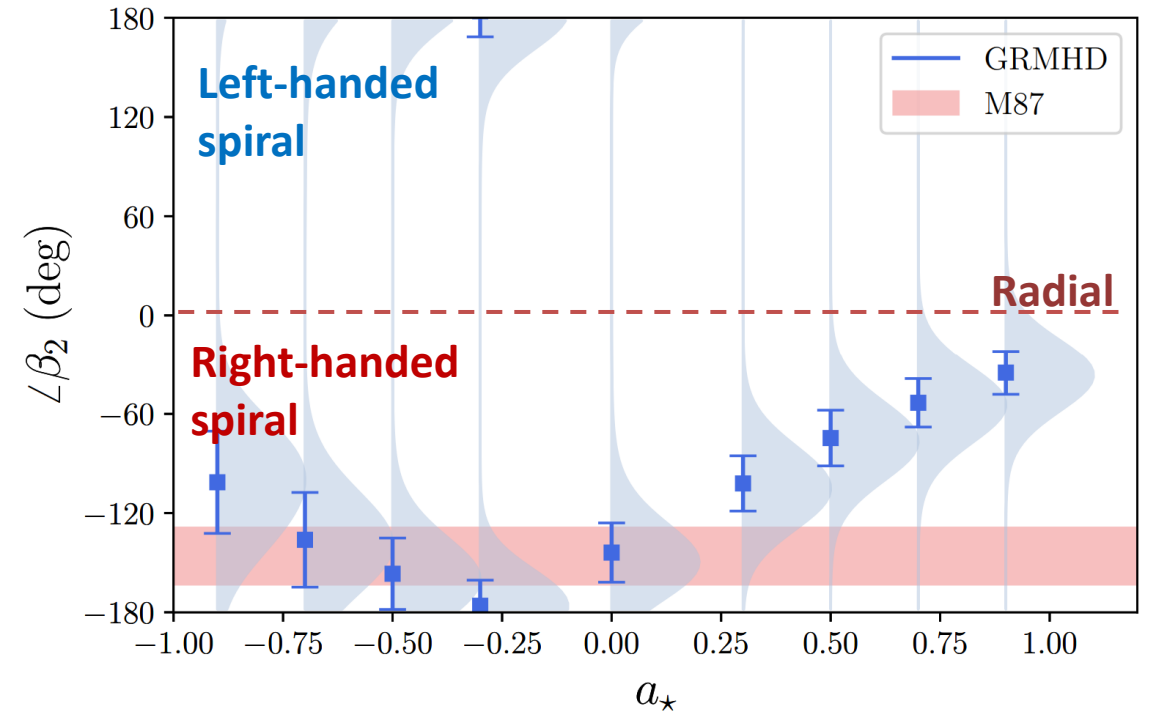
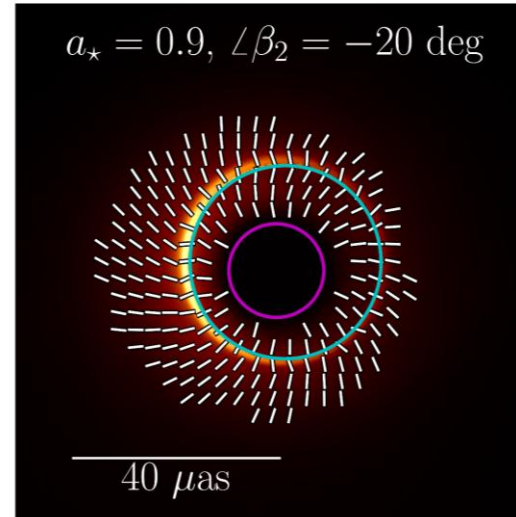
- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi} / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
 - increases the BZ jet power
 - makes the observed polarization pattern more radial

M87*'s Polarization may constrain spin

Low Spin



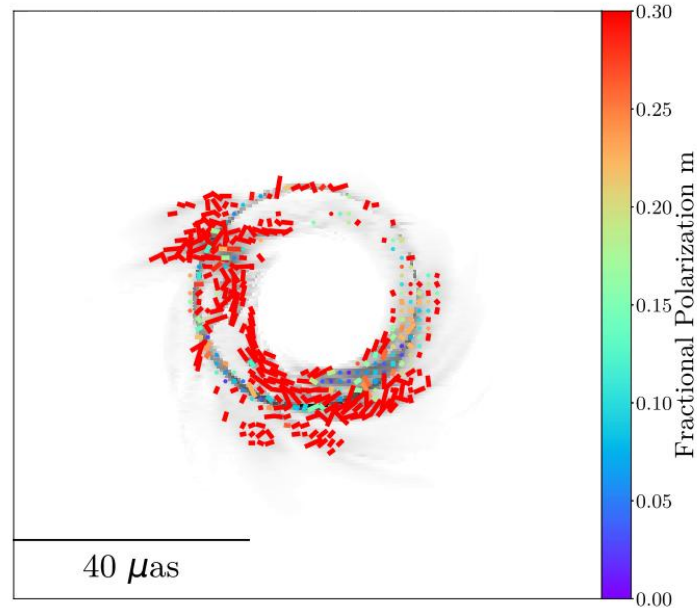
High Spin



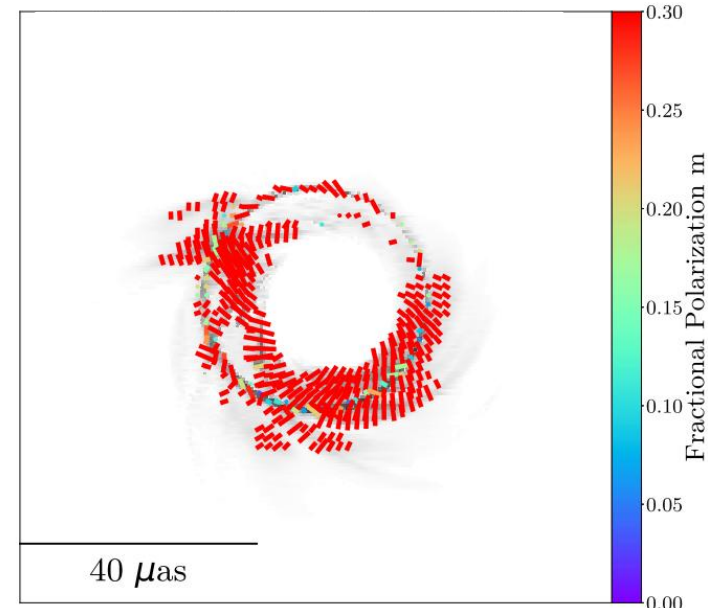
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin** (see also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)
- More work is needed to understand if these conclusions are robust to Faraday rotation and temporal variability!

What about Faraday Rotation?

With Faraday

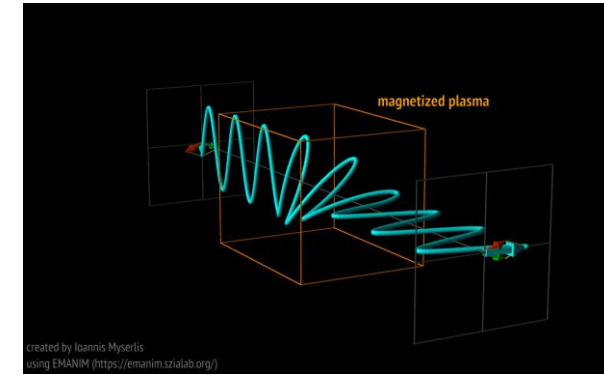


Without Faraday

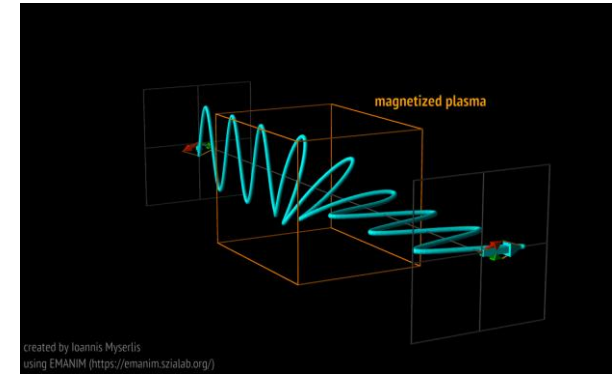


‘infinite’ resolution

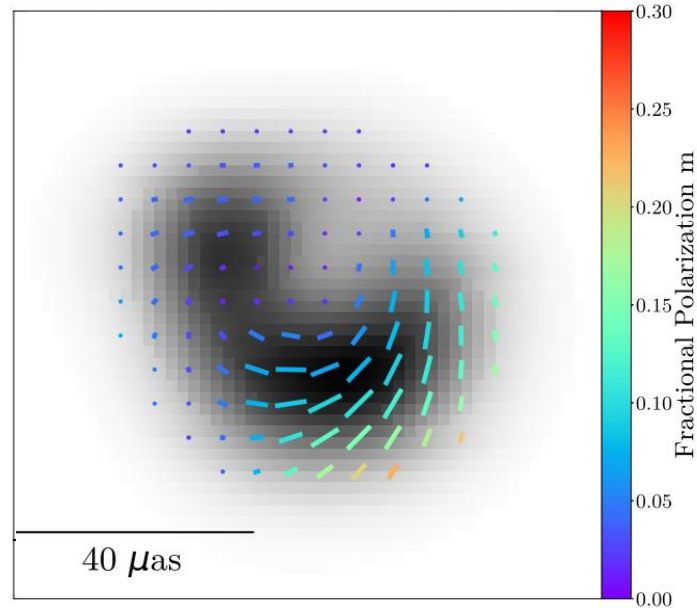
- Significant Faraday rotation on different scales
→ **Scrambles** polarization vectors on small scales



What about Faraday Rotation?

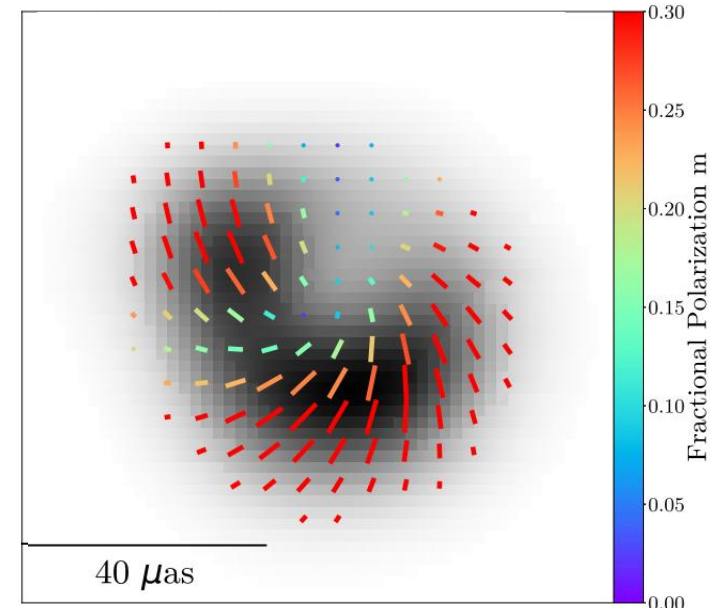


With Faraday



EHT resolution

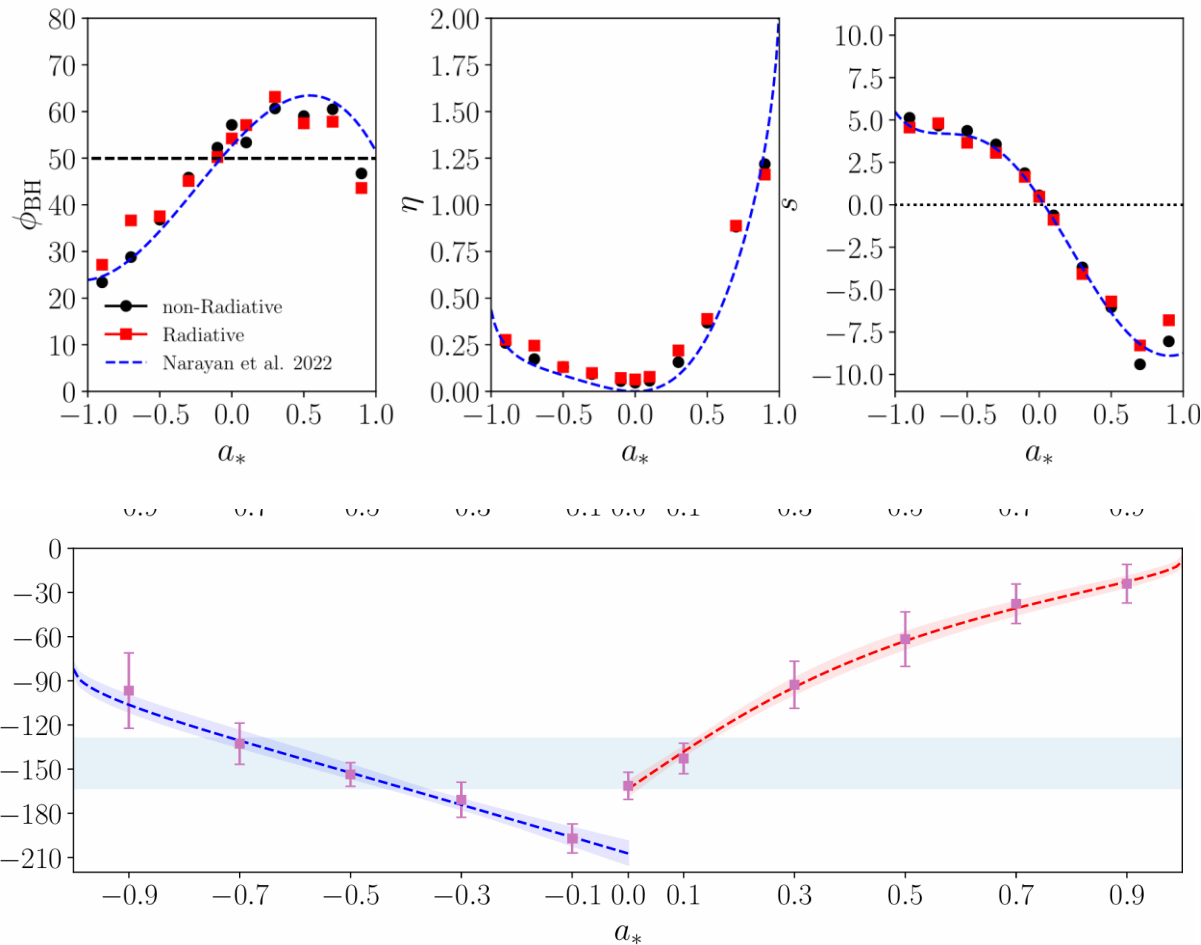
Without Faraday



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

We need **multi-frequency data** to fully account for Faraday rotation – coming soon!

Aside: Radiative Simulations Have Similar Jets...

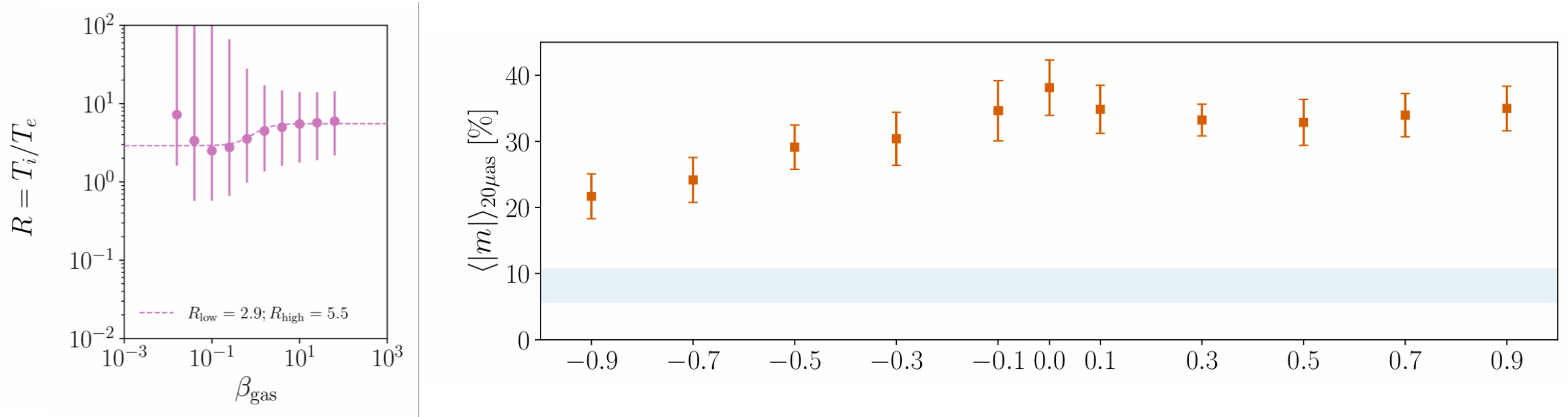


- M87* and Sgr A* have two-temperature plasmas

$$T_e \neq T_i$$

- 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 $\arg(\beta_2)$

...but electrons are too hot!



- EHT analysis seems to prefer **cold electrons** ($T_i \sim 100 \times T_e$) to sufficiently depolarize the image
- Two-temperature GRMHD includes **heating and cooling self-consistently** but prefers more modest temperature ratios (Chael 2025)
- Is there a sub-grid plasma model that will produce cold electrons?
 - Or is this a hint that we need to modify our global picture?

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**..

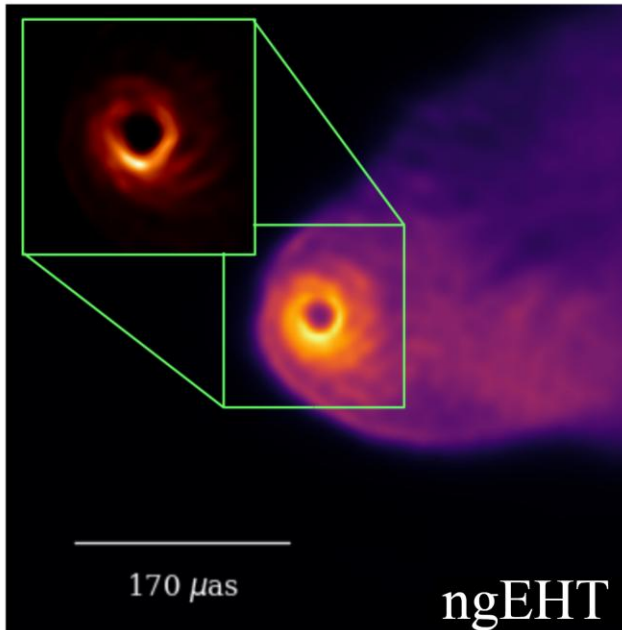


Image the connection between the BH and the low-brightness extended jet in polarization and **high dynamic range**

By zooming **in**..

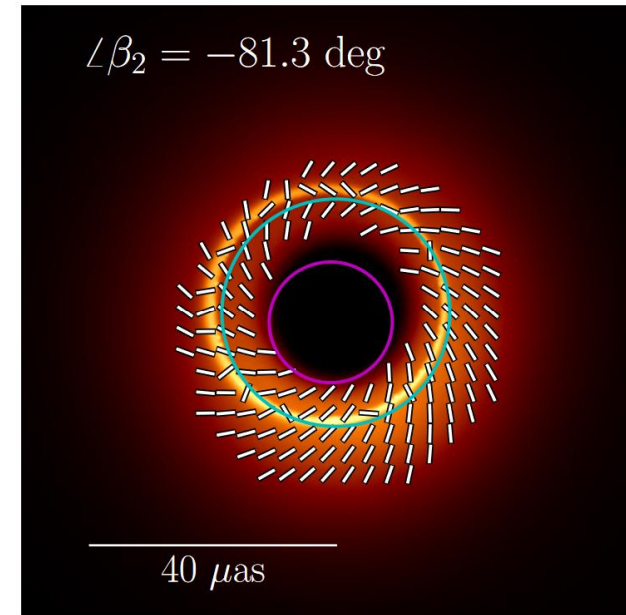


Image field lines close to the event horizon in **high resolution**

The future of near-horizon observations

Extended & next-generation EHT

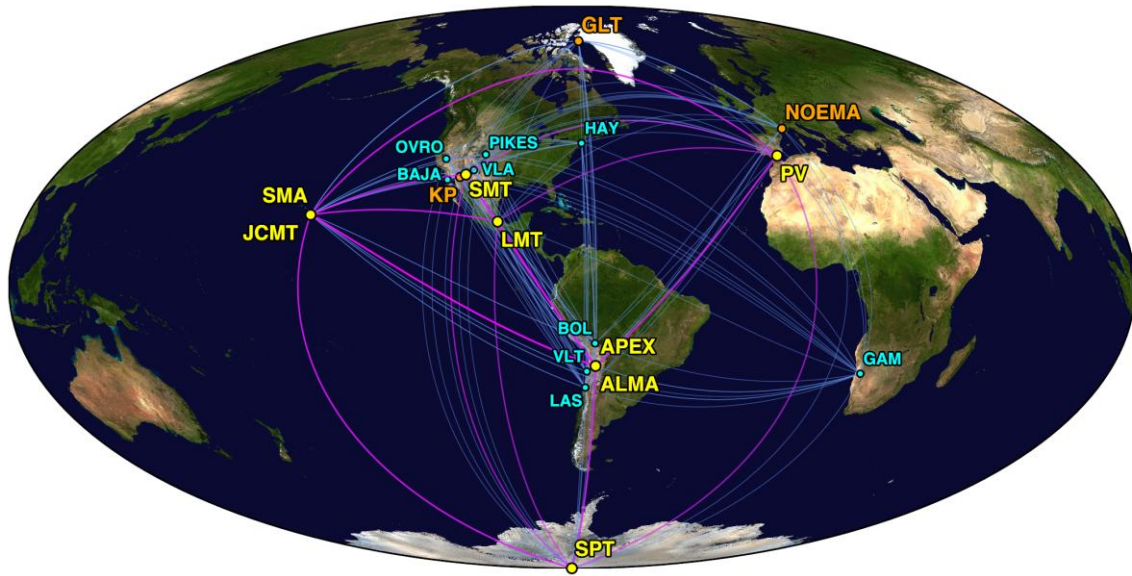


Image black holes and their jets in **multiple frequencies** and **high dynamic range**

Black Hole Explorer (BHEX)

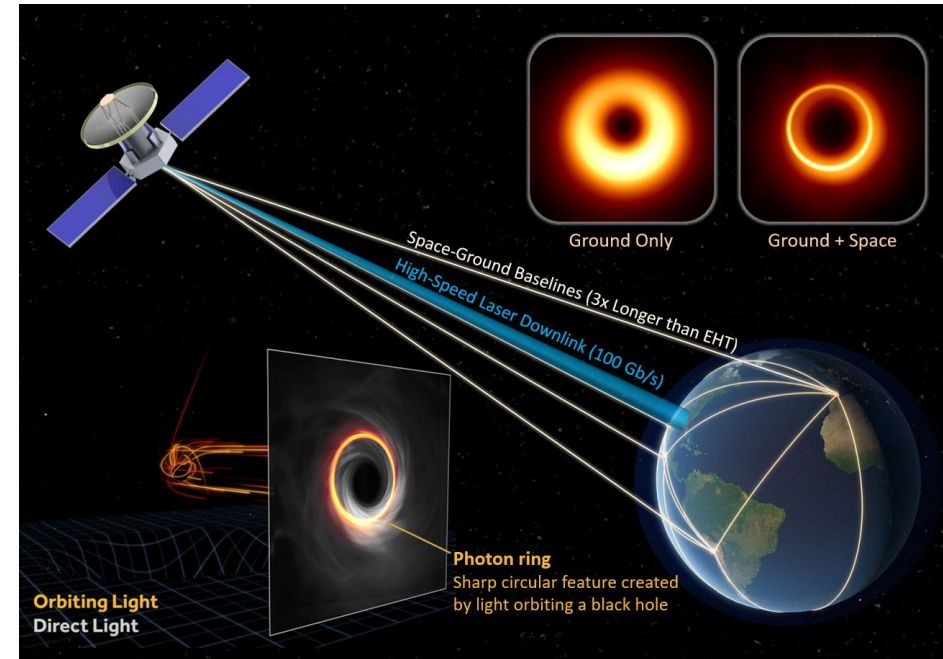
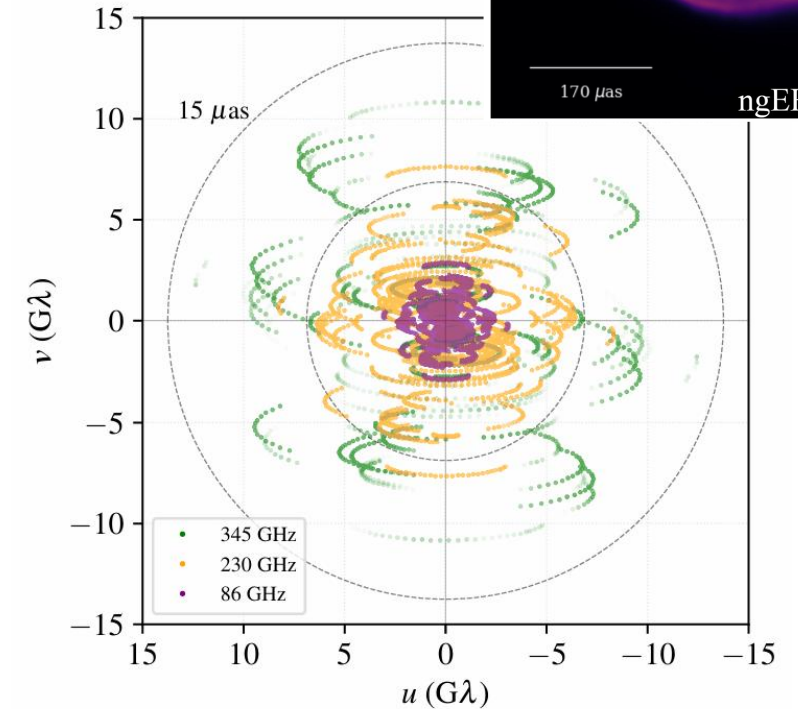
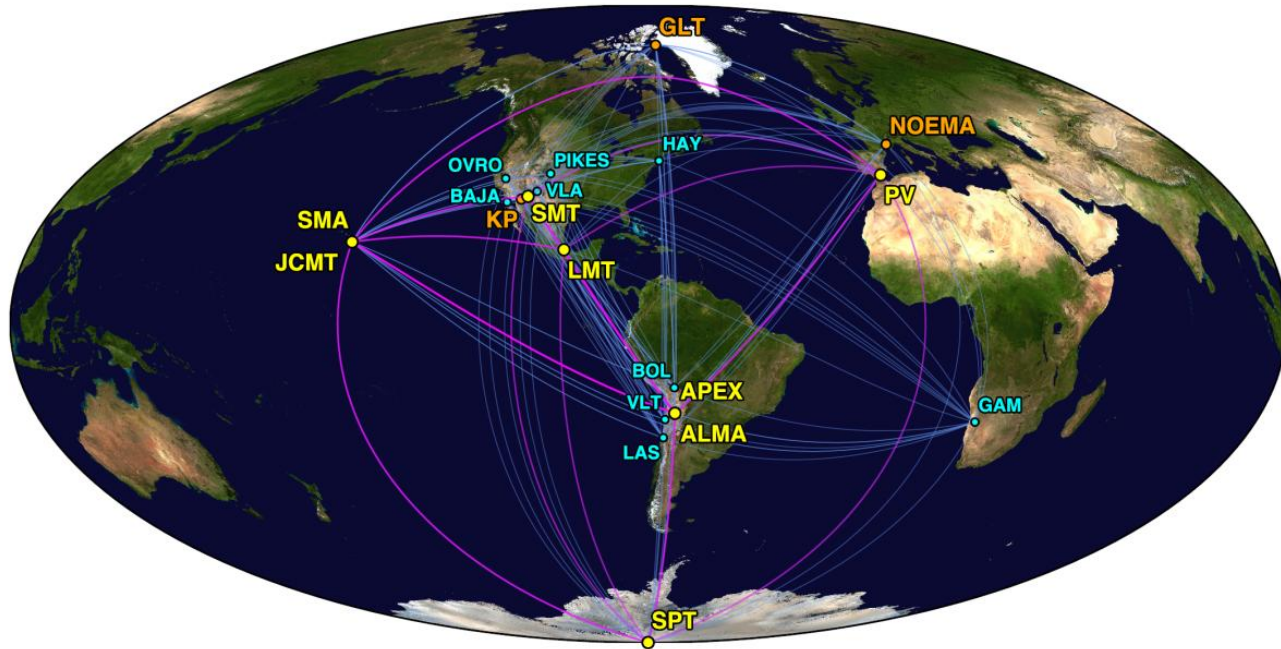


Image **extreme gravitational lensing** and dozens of new black holes in **high resolution**

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

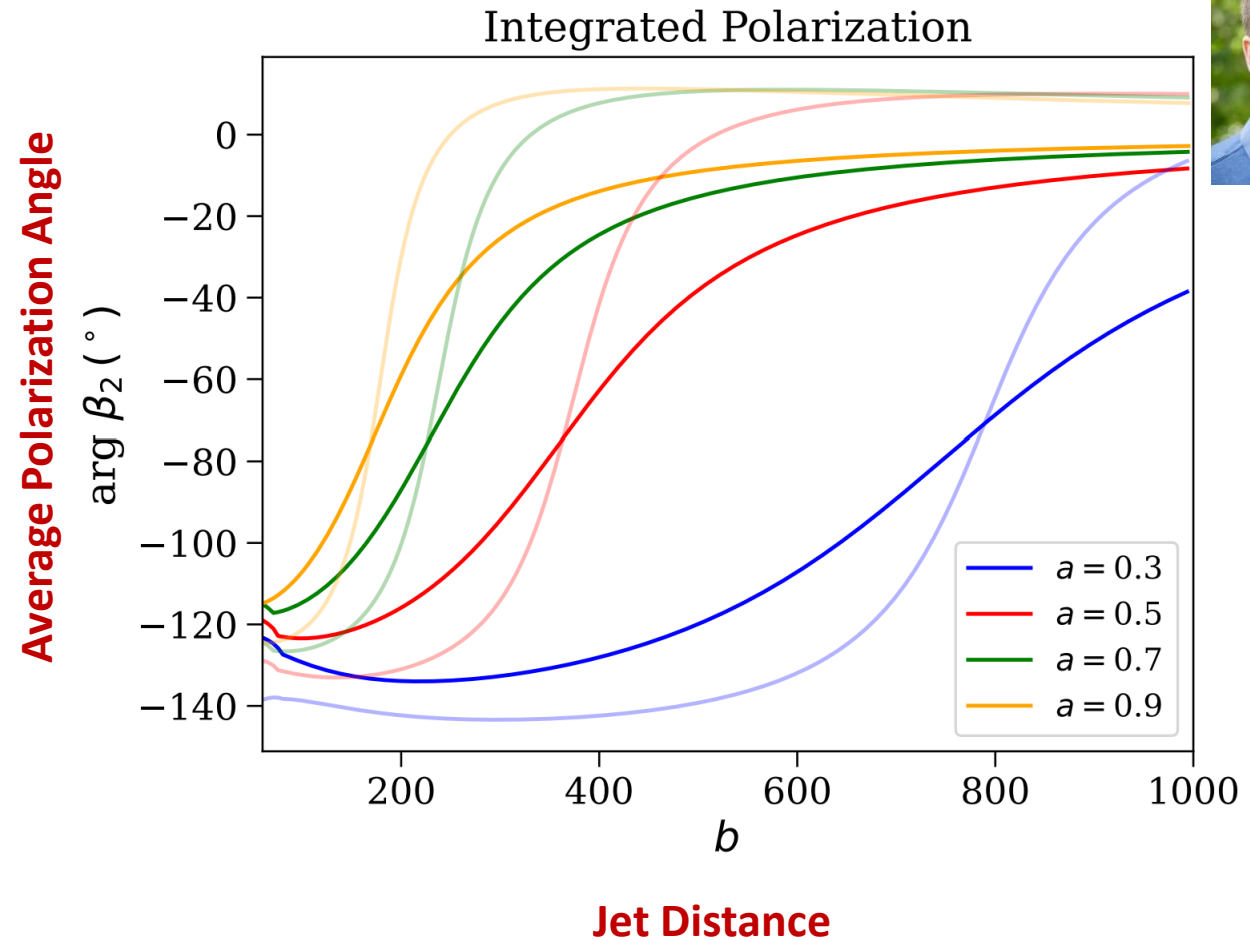
2030s: tri-band observations at 14 sites

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

EHT/ngEHT: *zooming out*

- 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)

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



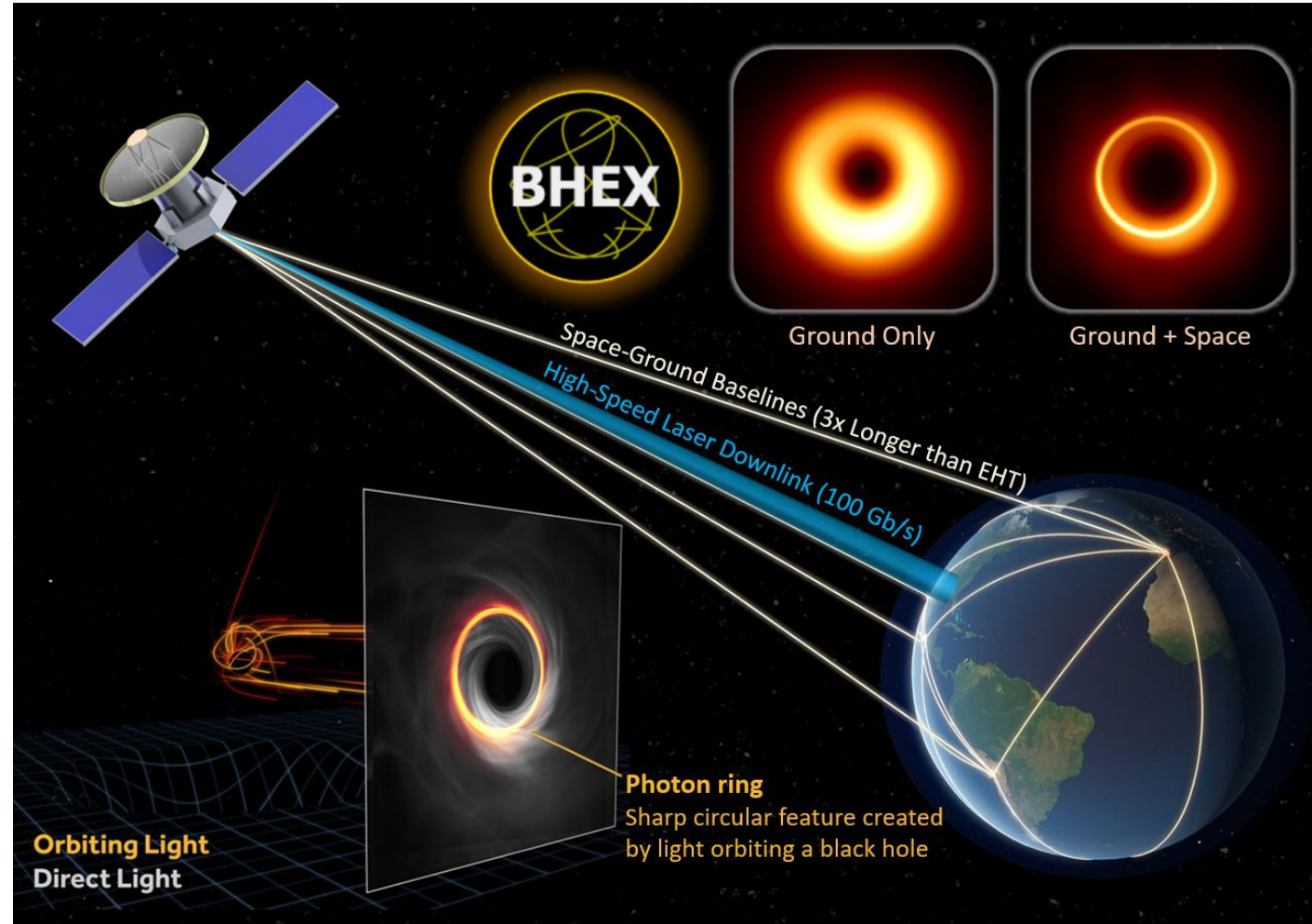
Going Further: The Black Hole Explorer (BHEX)

Earth-Space millimeter VLBI

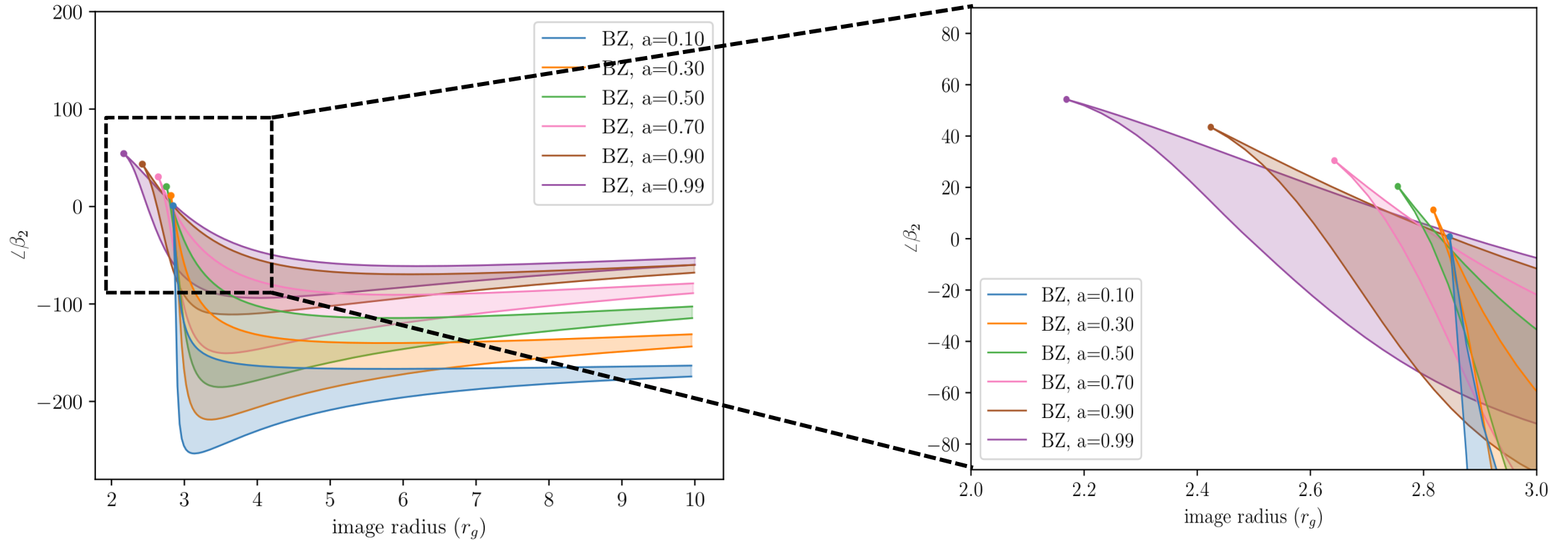
- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground mmVLBI network & pioneers optical laser downlink
- Targeting next NASA SMEX call

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

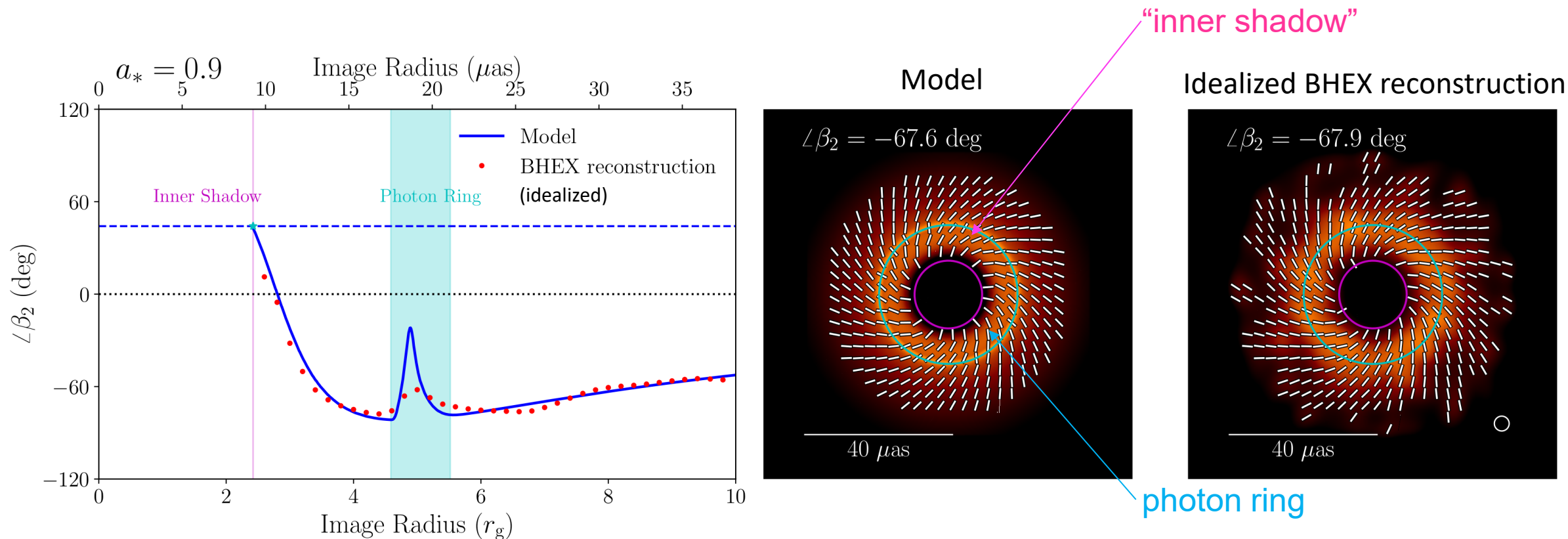


BHEX: *zooming in*



- 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)

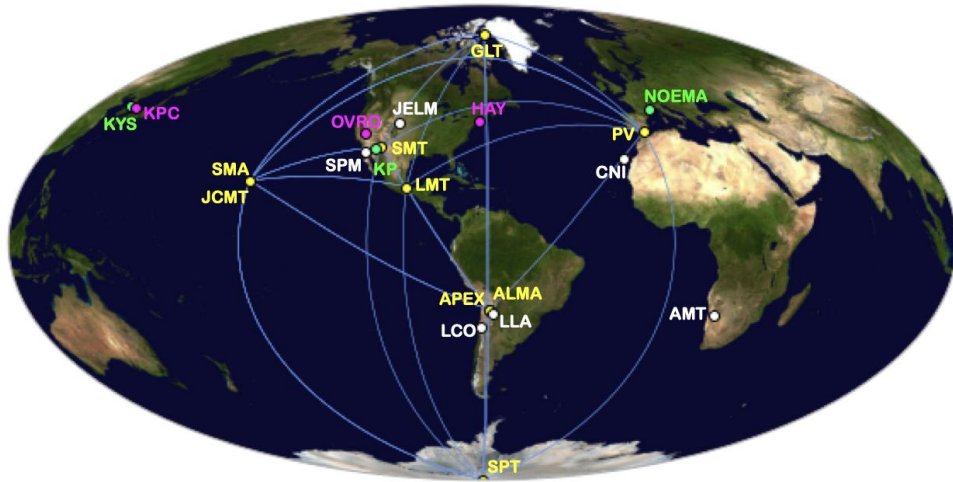
BHEX: *zooming in*



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

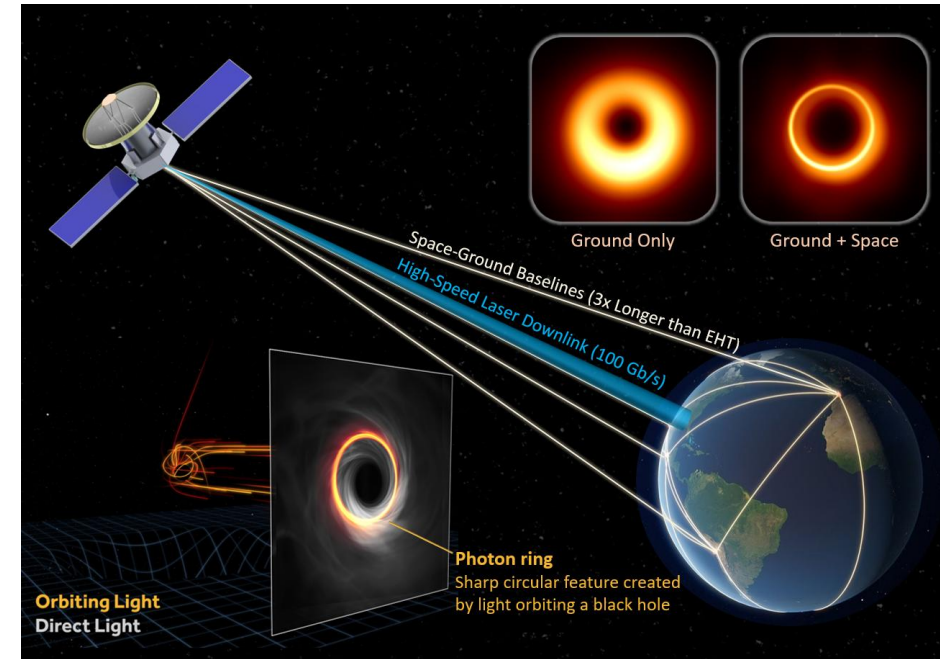
The future of near-horizon black hole astrophysics

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)



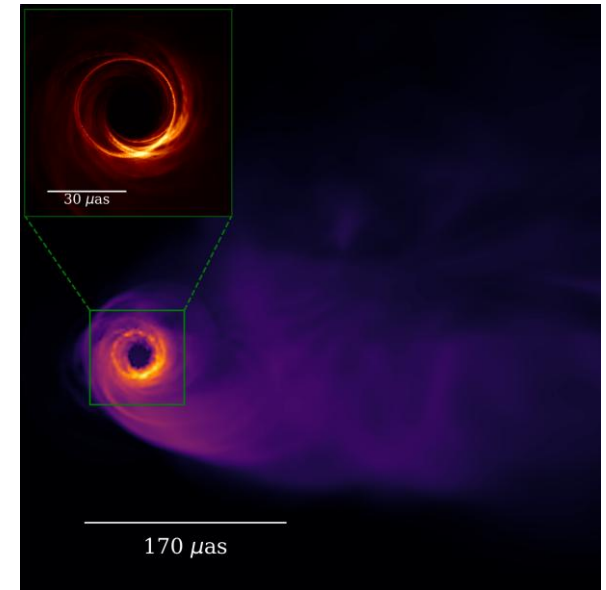
- NASA SMEX proposal for a mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to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

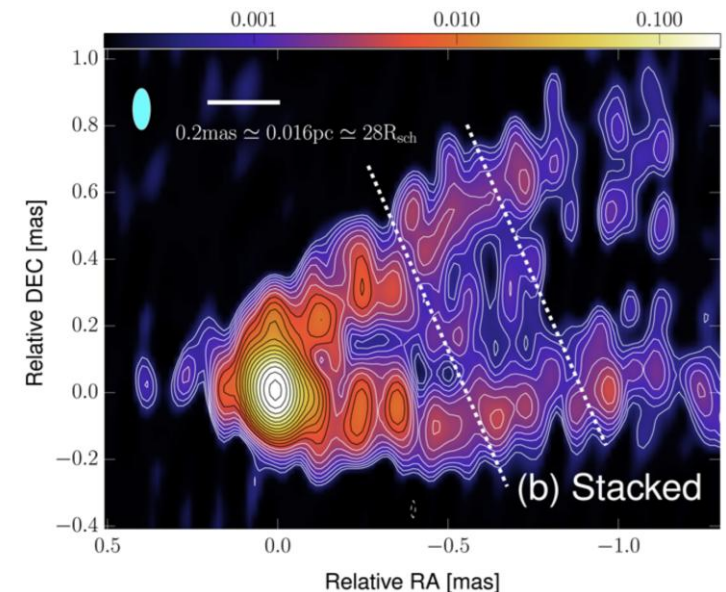
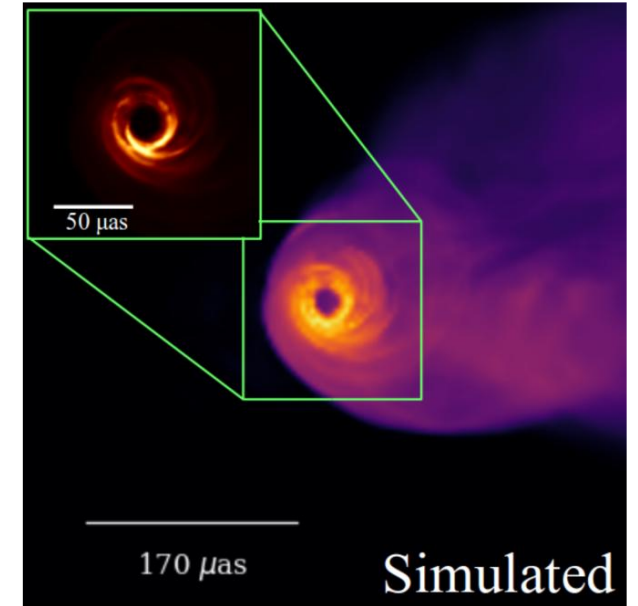
- What plasma physics sets the temperature/distribution of the electrons?
- What powers flares in Sgr A* and M87*?
- What can EHT/BHEX observation tell us about near-horizon physics in supermassive black holes beyond Sgr A* and M87*?



backup slides

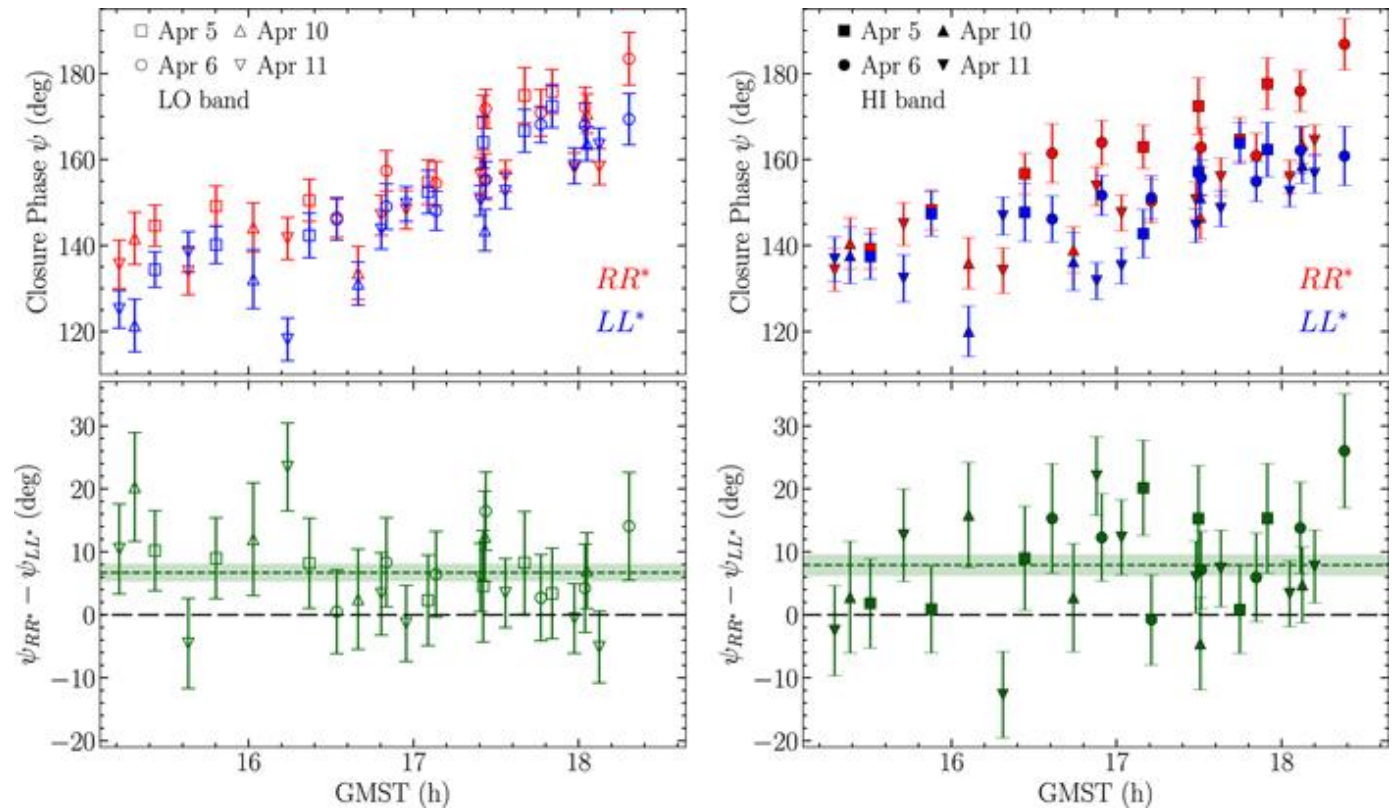
Persistent Mysteries of Astrophysical Jets

- We have known about jets for >100 years
- We know jets are produced by supermassive BHs
- We know jets are variable, relativistic, extend huge distances, contain very energetic particles and magnetic fields, and likely produce TeV-PeV neutrinos and UHECRs
- But we still do not know:
 - How are they launched?
 - How are they accelerated and collimated?
 - What particles fill jets and how are they distributed in space and energy?

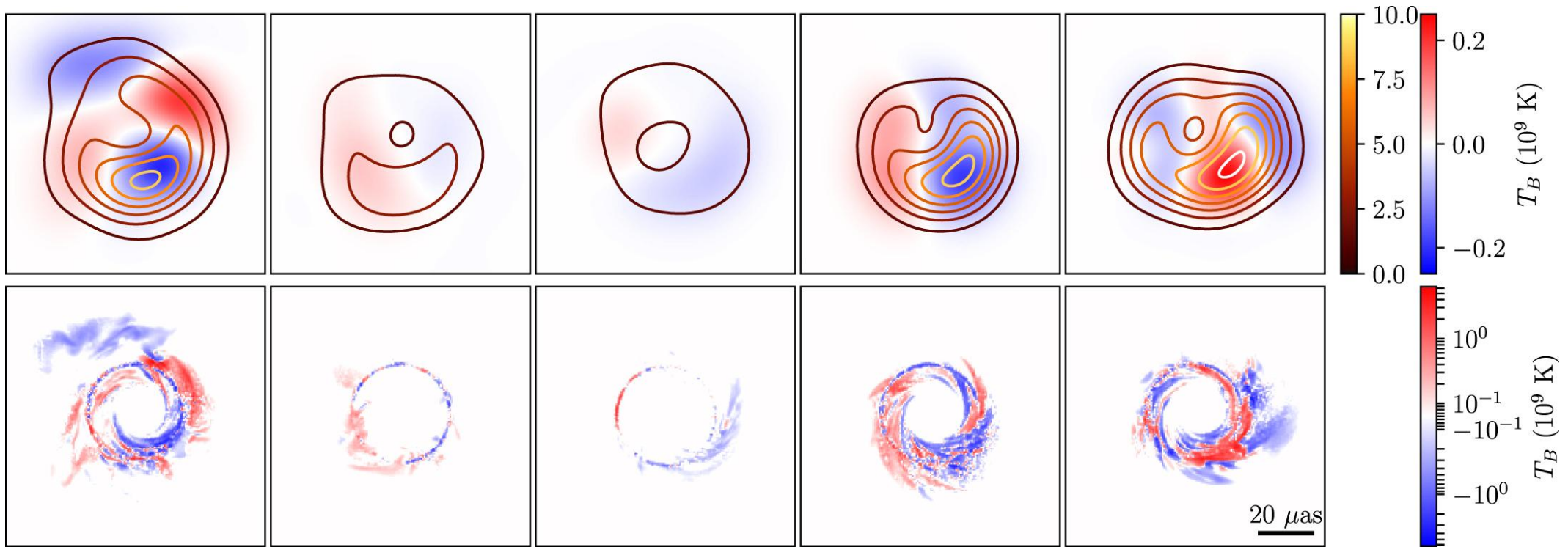


Horizon-Scale circular polarization is unambiguously detected by the EHT

- 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.

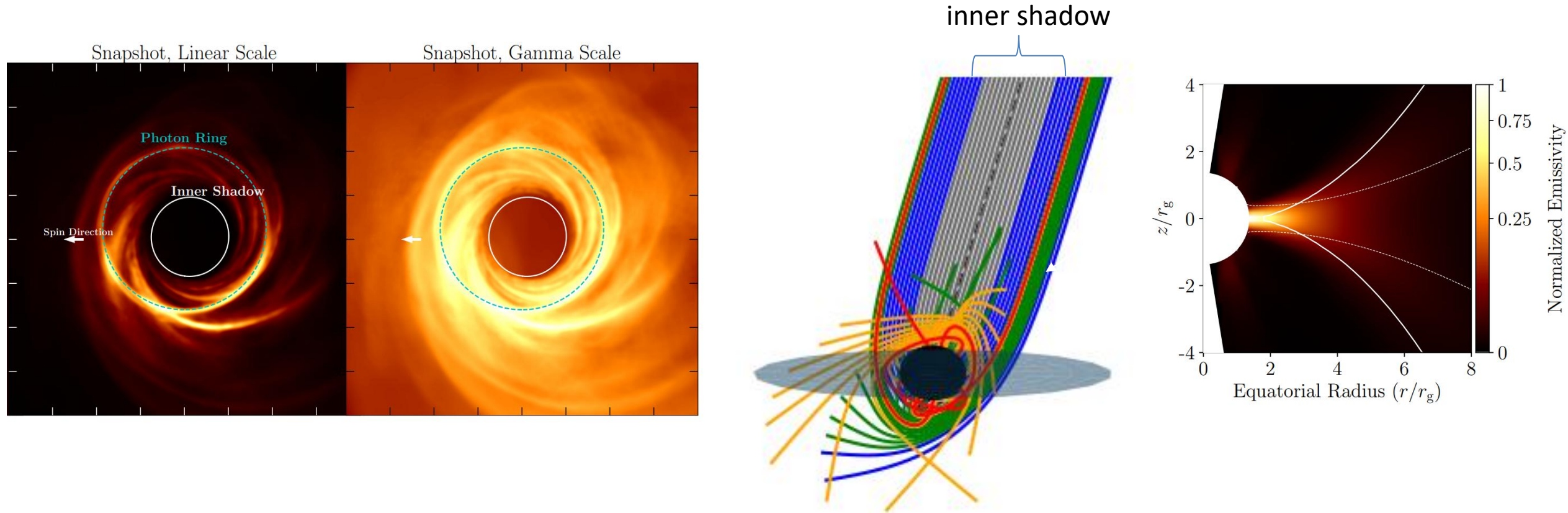


Passing simulations have diverse circular polarization images



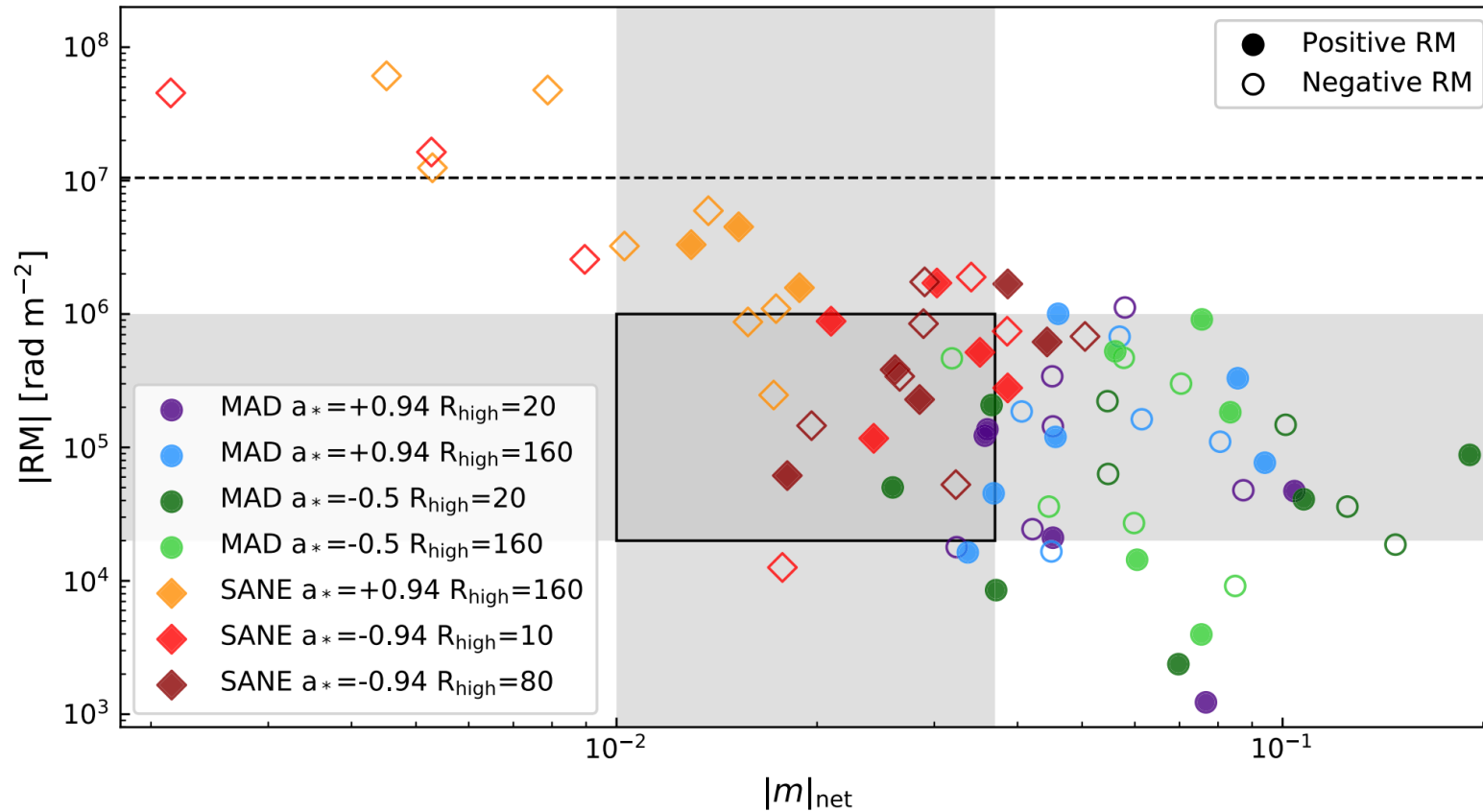
Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

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



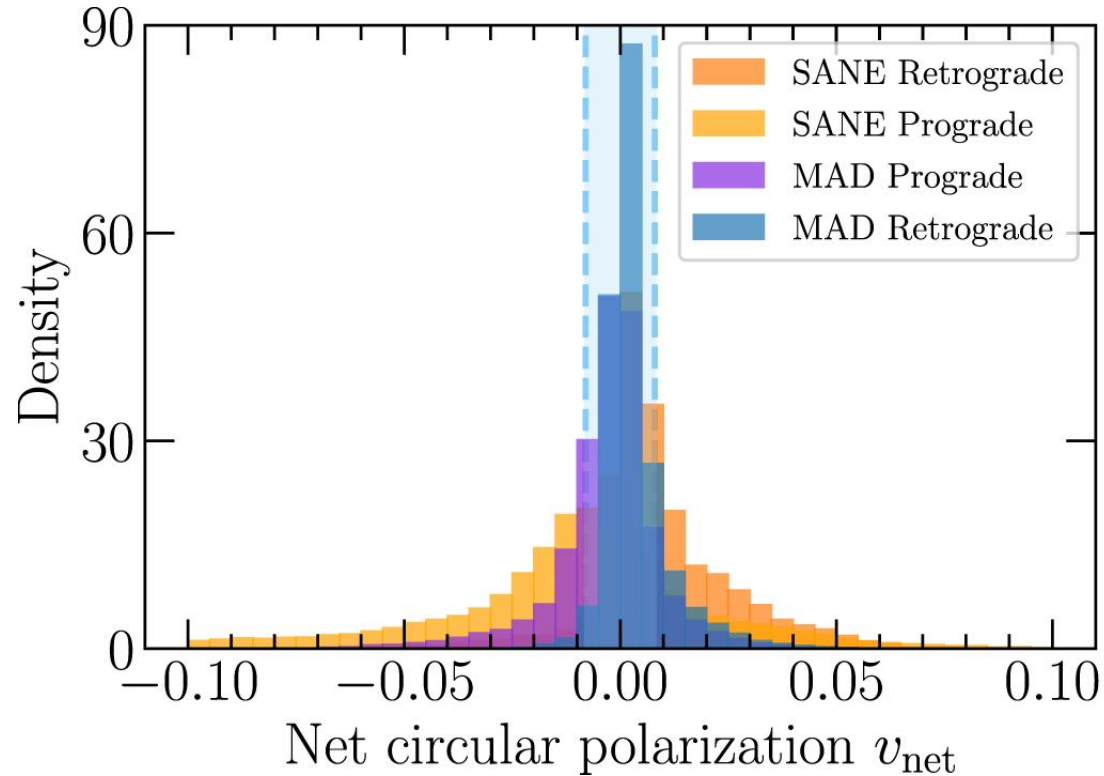
- The **inner shadow is visible in simulations**; its edge **approaches** the **lensed position of the event horizon**
- MADs have thin / nearly equatorial emission regions close to the horizon
- Redshift increases near the horizon → the inner shadow is **most visible at high dynamic range**

GRMHD simulations can explain M87's Rotation Measure

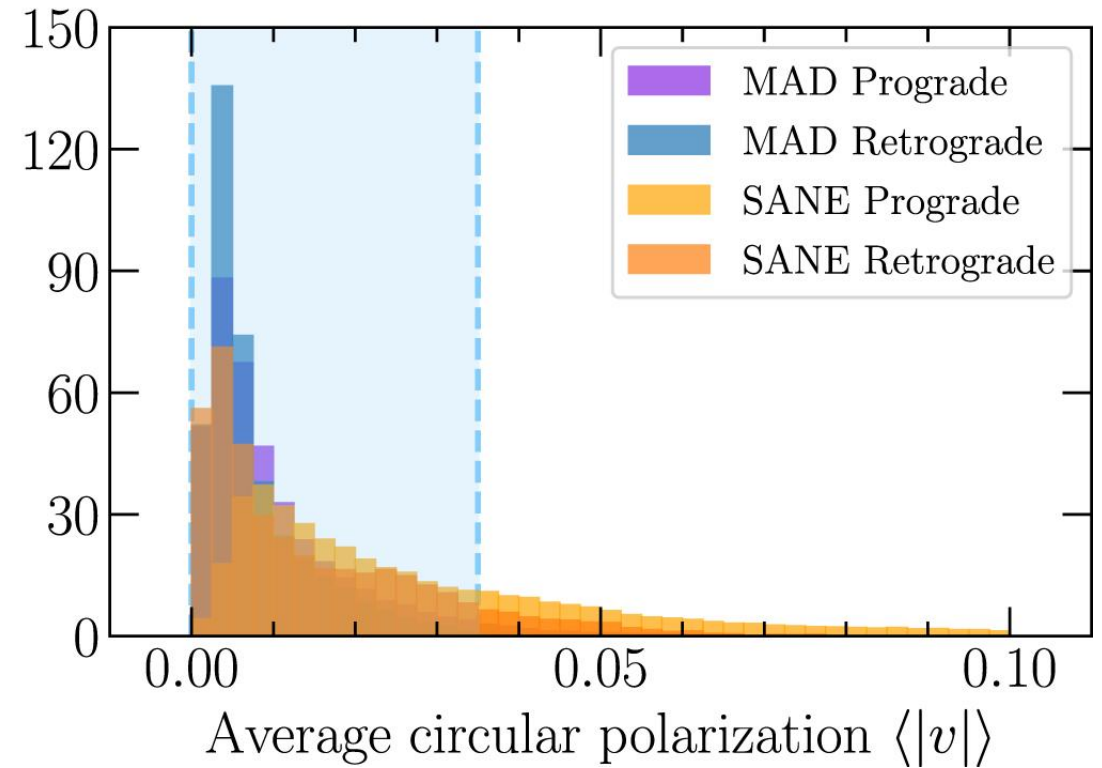


Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

GRMHD simulations naturally produce low circular polarization



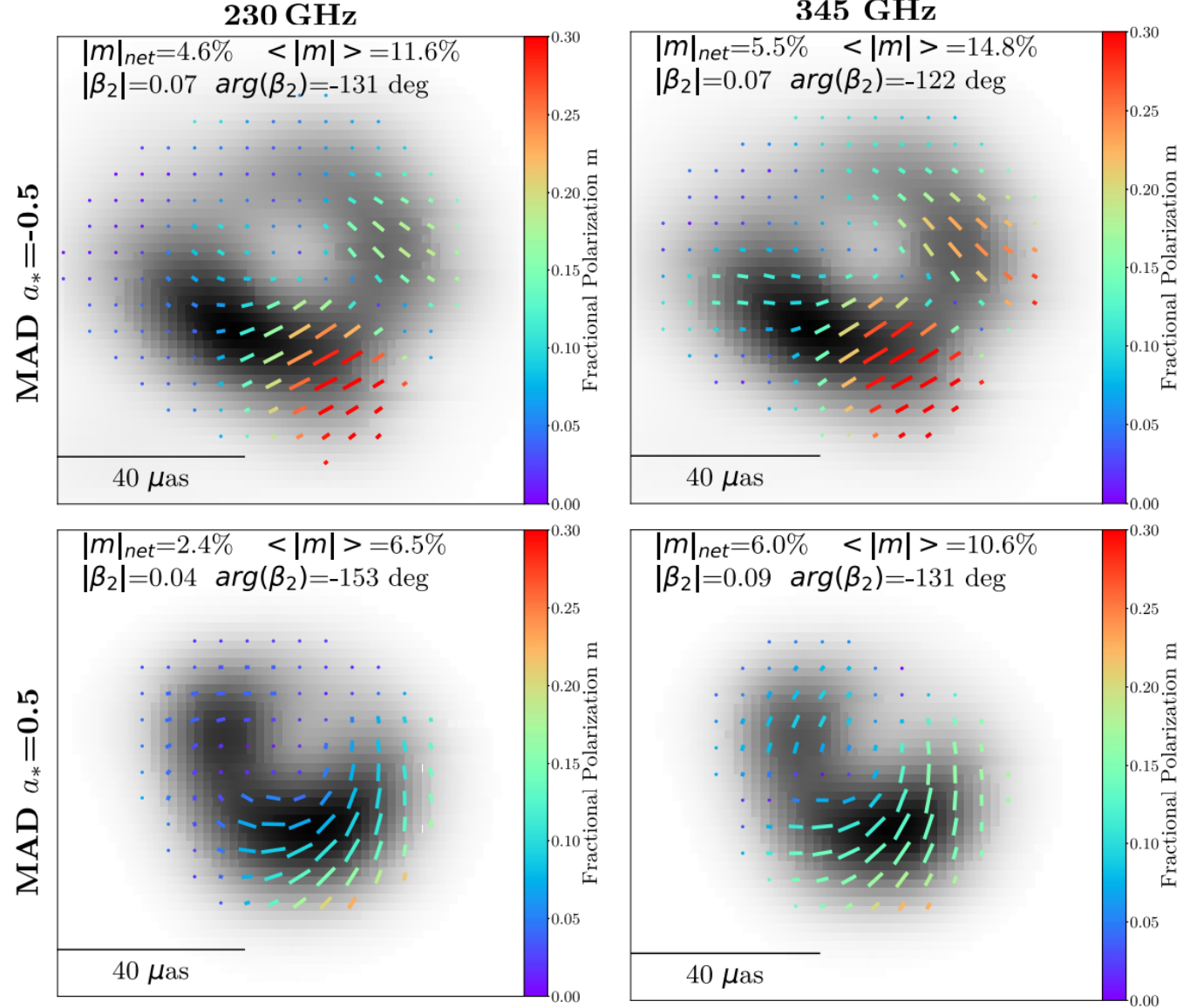
$$v_{\text{net}} = \frac{\int \mathcal{V} dA}{\int \mathcal{I} dA}.$$



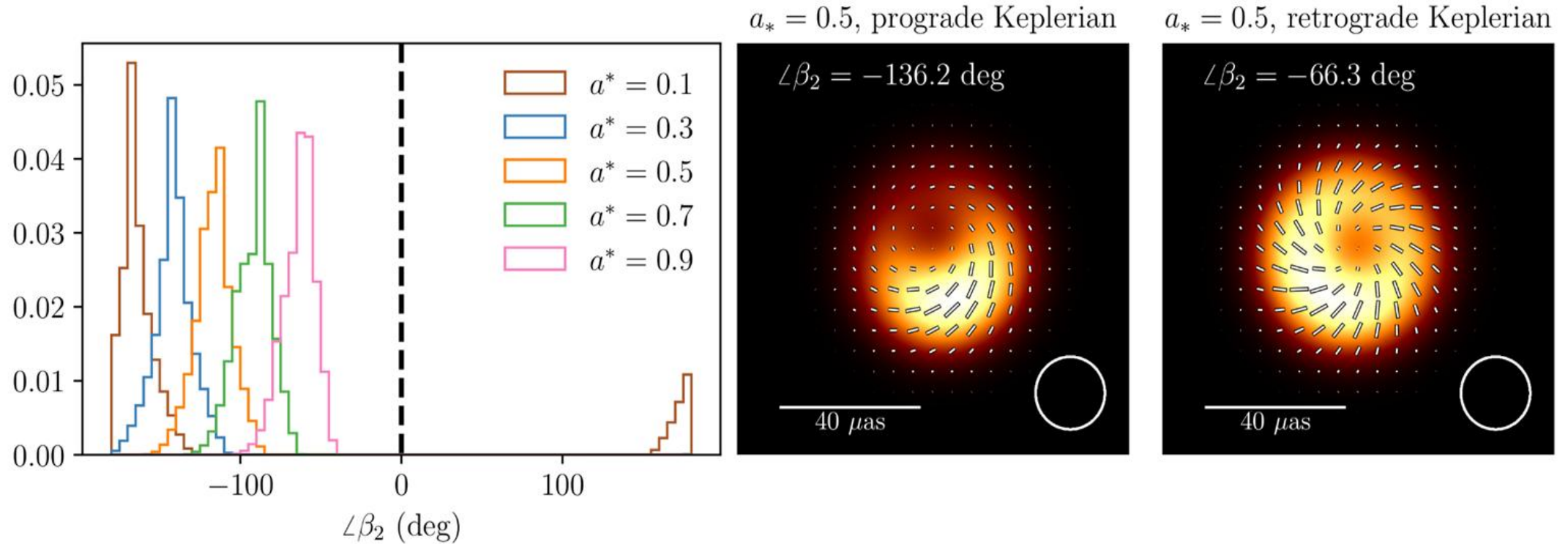
$$\langle |v| \rangle = \frac{\int |\mathcal{V}/\mathcal{I}| \mathcal{I} dA}{\int \mathcal{I} dA}.$$

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

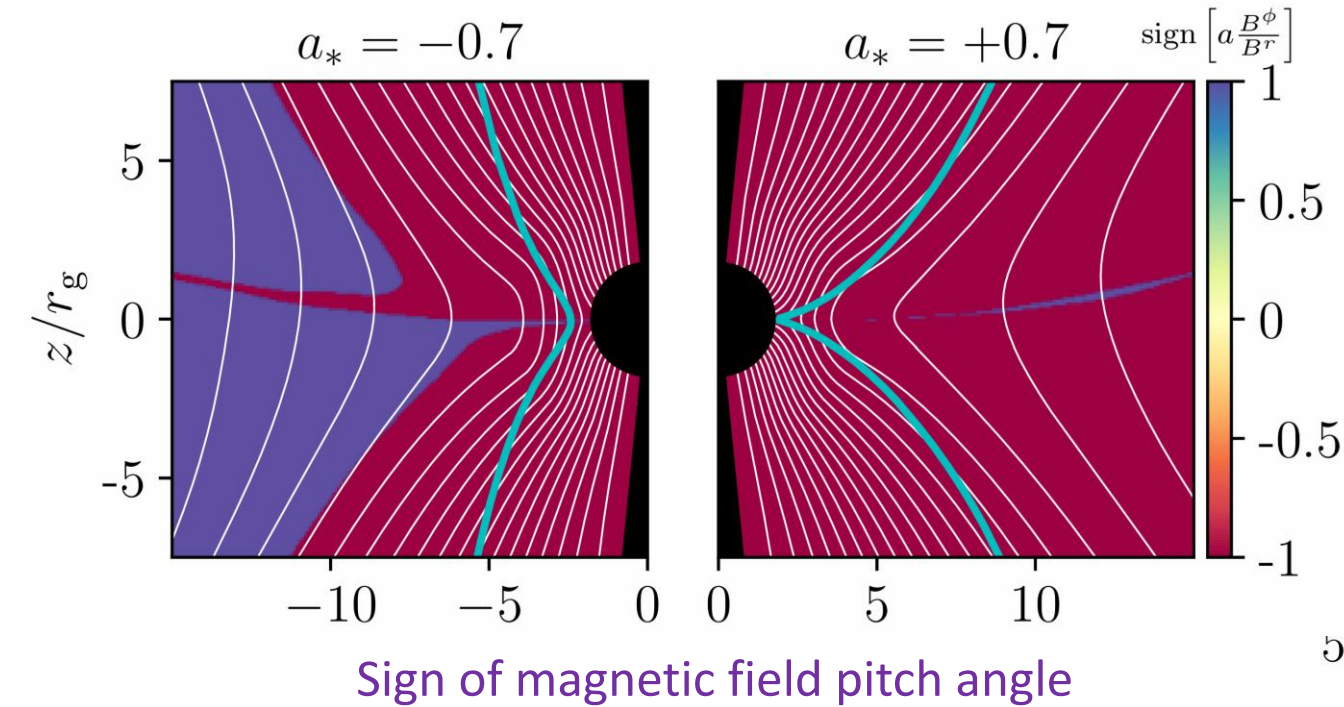


β_2 in semi-analytic models of M87*

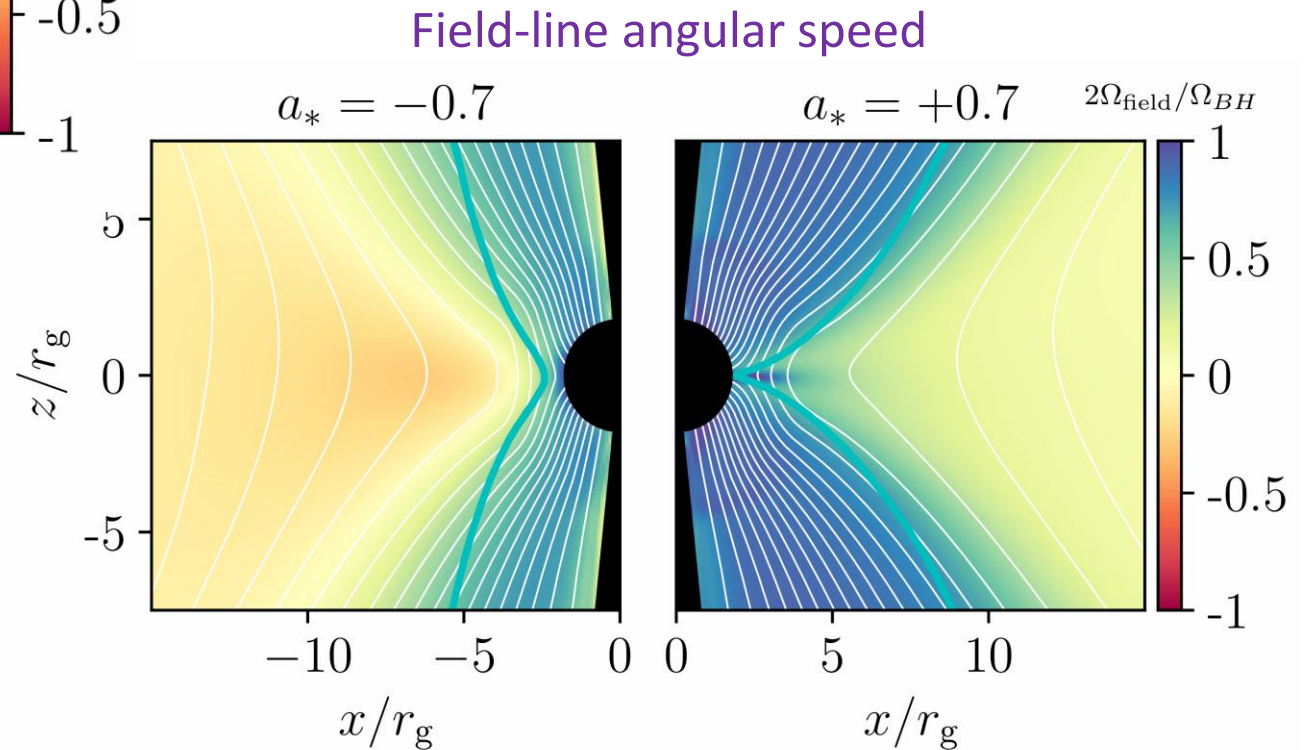


- We fix magnetic fields to the force-free BZ monopole solution (with energy outflow)
- We explore many models for the velocity of the emitting fluid
- Changes in fluid velocity do not significantly affect sign of $\arg(\beta_2)$ or trend with BH spin

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



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



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**

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

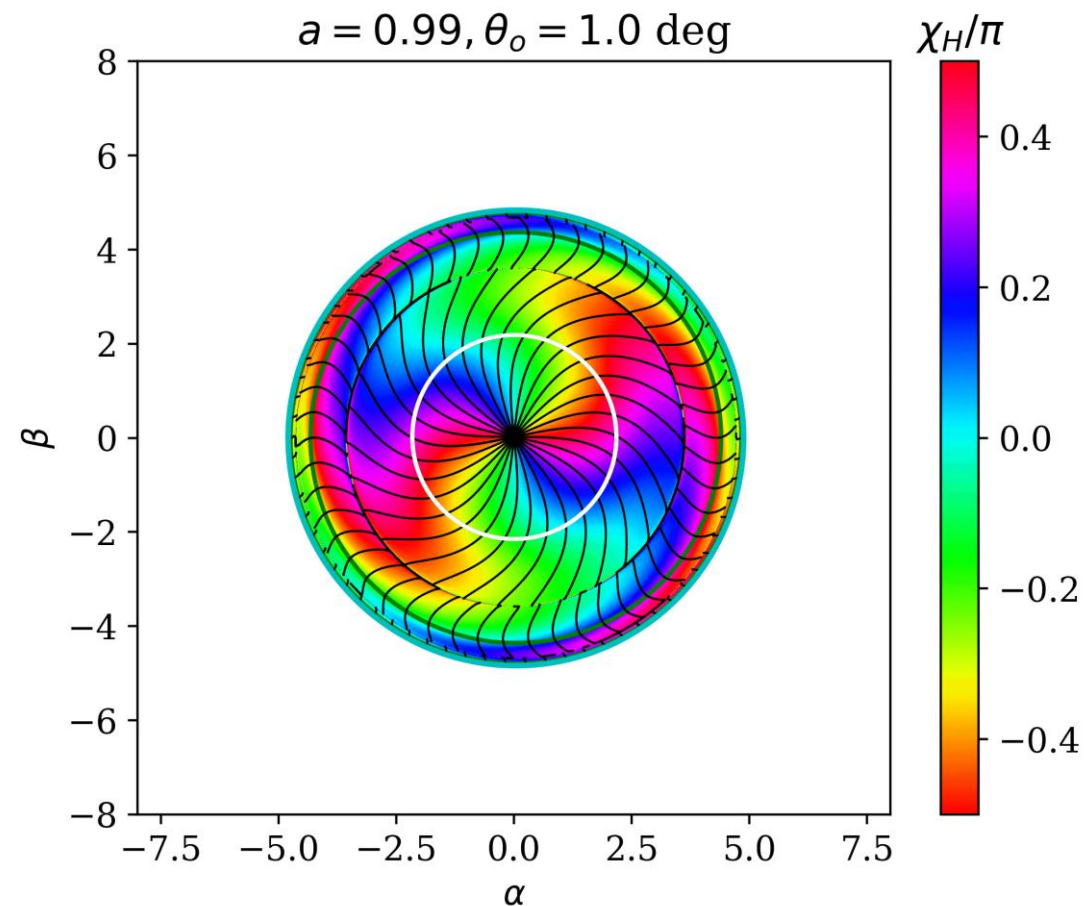
$$z_0 = \frac{r_+ (a \sin^2 \theta - \lambda) + \nu_\theta a \cos \theta \sin \theta \sqrt{\Theta(\theta)}}{a (a \sin^2 \theta - \lambda) \cos \theta - \nu_\theta r_+ \sin \theta \sqrt{\Theta(\theta)}}$$

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

$$\begin{aligned} \lambda &= -\alpha \sin \theta_o \\ \eta &= (\alpha^2 - a^2) \cos^2 \theta_o + \beta^2 \end{aligned} \quad \left. \vphantom{\begin{aligned} \lambda &= -\alpha \sin \theta_o \\ \eta &= (\alpha^2 - a^2) \cos^2 \theta_o + \beta^2 \end{aligned}} \right\} \text{Conserved Quantities}$$

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

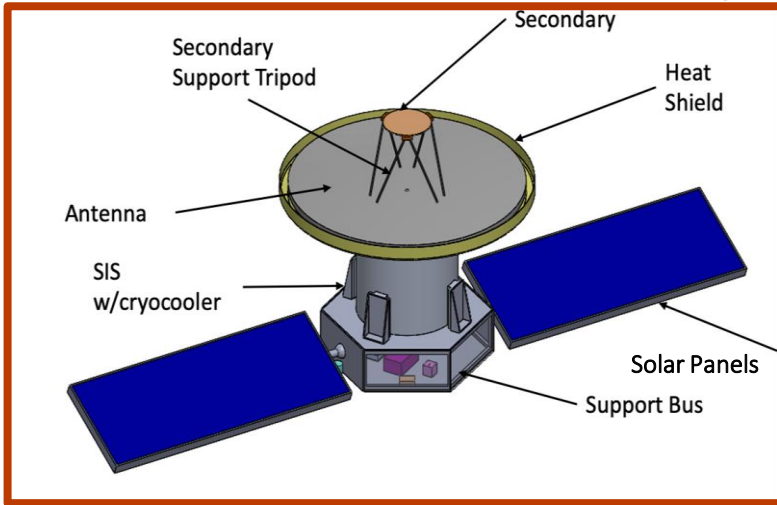
$$\angle \beta_{2,+} \approx 2 \arctan\left(\frac{\nu_\theta a}{\sqrt{2r_+^2 + a^2}}\right)$$



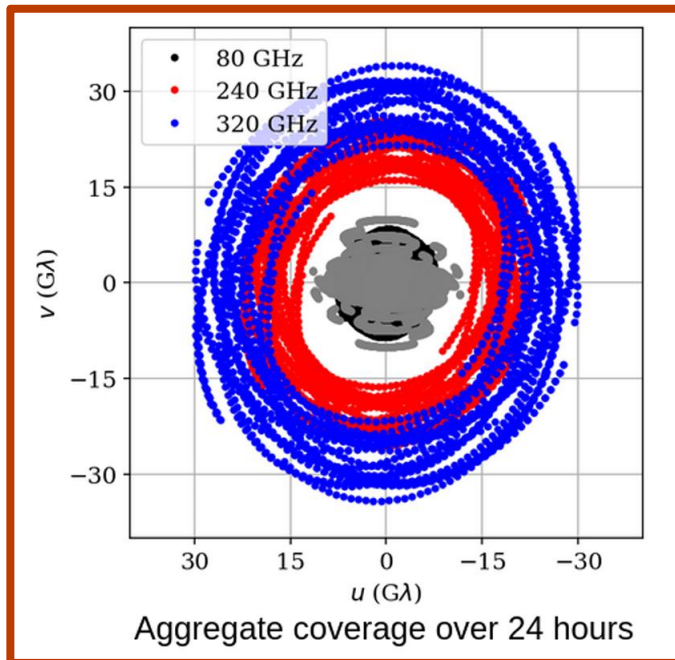
The Black Hole Explorer (BHEX)



Spacecraft



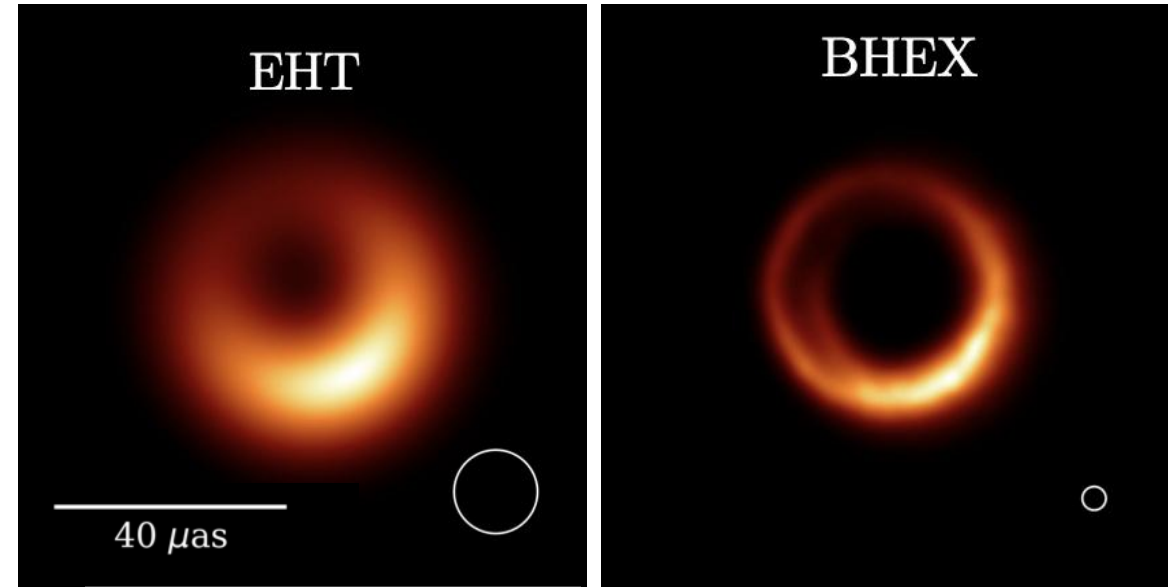
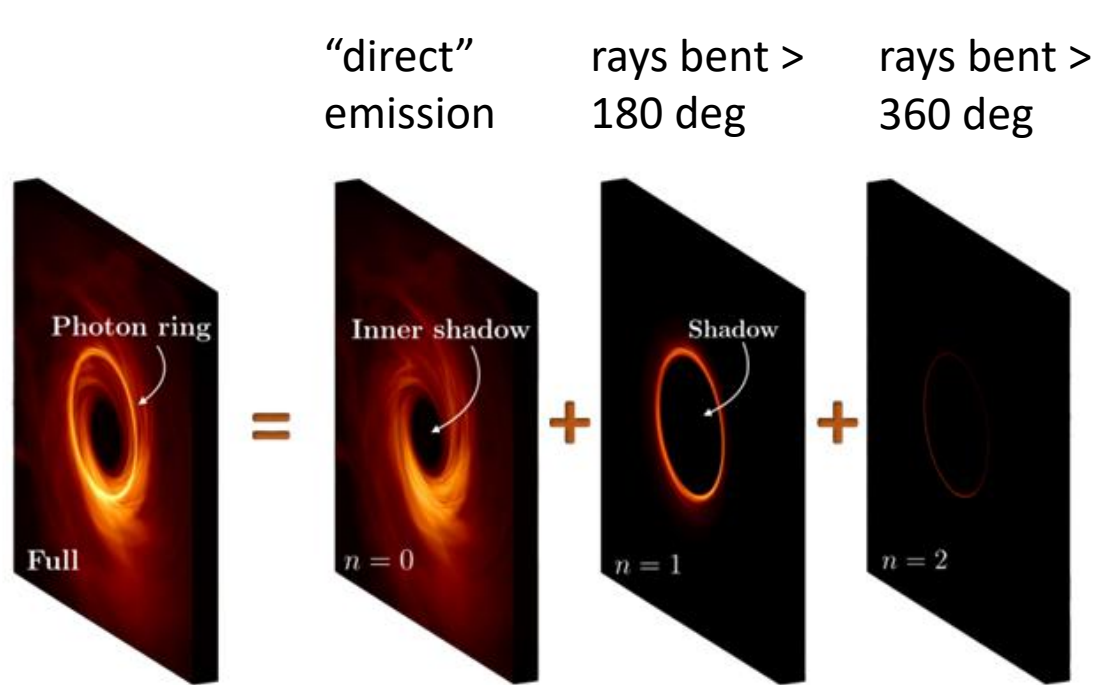
Example M87 u - v coverage



Mission Parameters

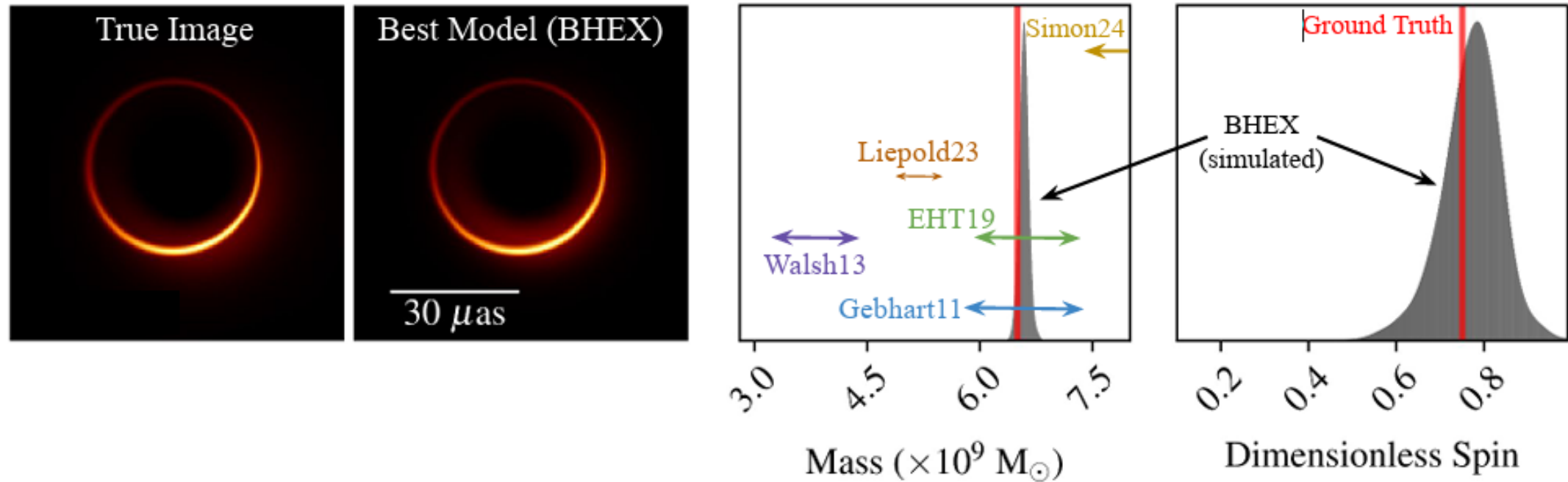
- 3.4m Antenna, 30um surface, shaded
 - Simultaneous dual-band observations (80-106 + 240-320 GHz)
 - 48 GHz of sampled bandwidth (64 Gb/s)
 - Orbit: ~20,000 km altitude
 - Lifetime: 2+ years
 - Telemetry: 100 Gbps using laser communications
-
- Targeting next NASA SMEX call
 - Fact Sheet: blackholeexplorer.org/fact-sheet
 - 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

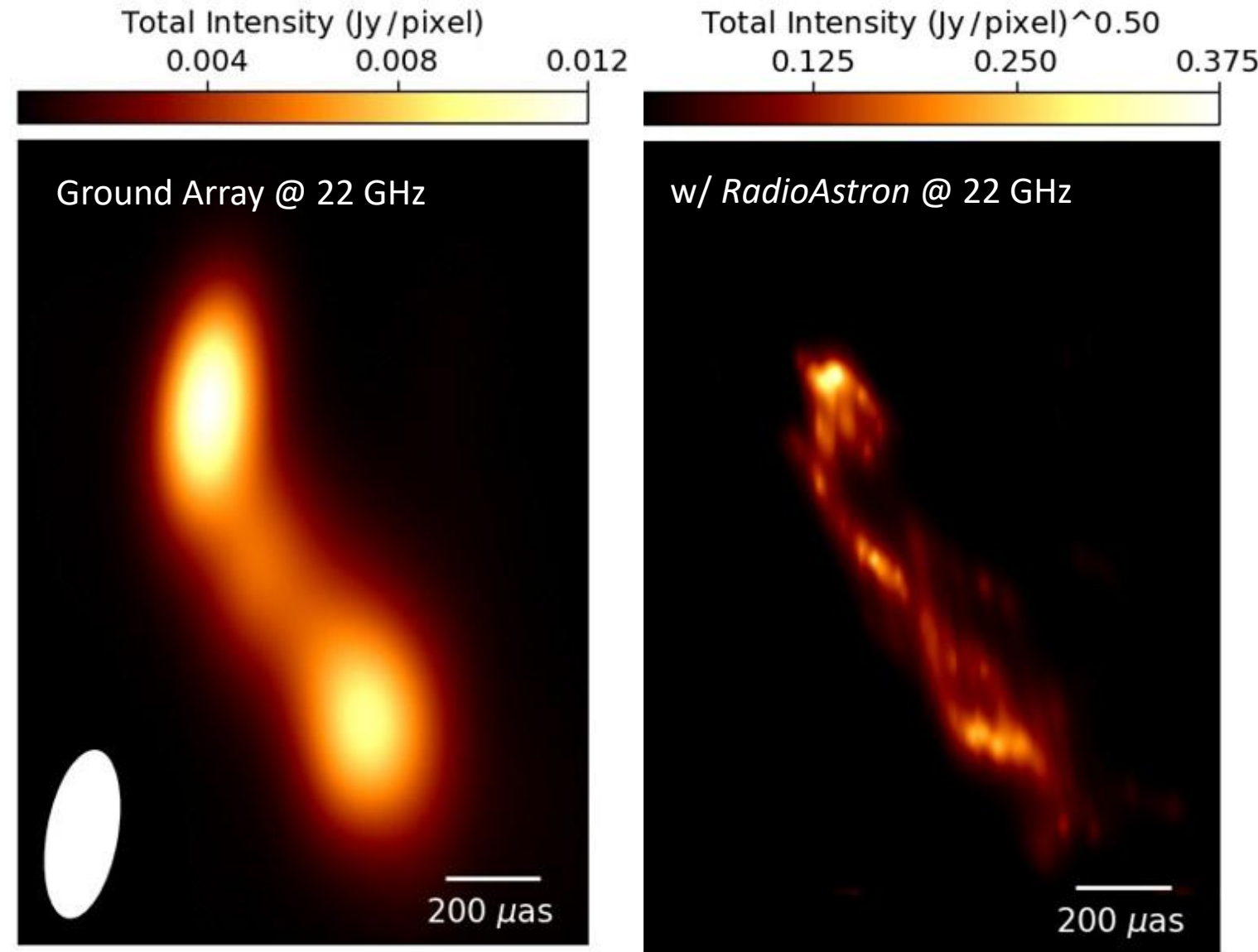


By comparing strongly-lensed and direct emission ring size and shape, BHEX will constrain Sgr A* and M87*'s **spin to ~10%** and **mass to ~1%**

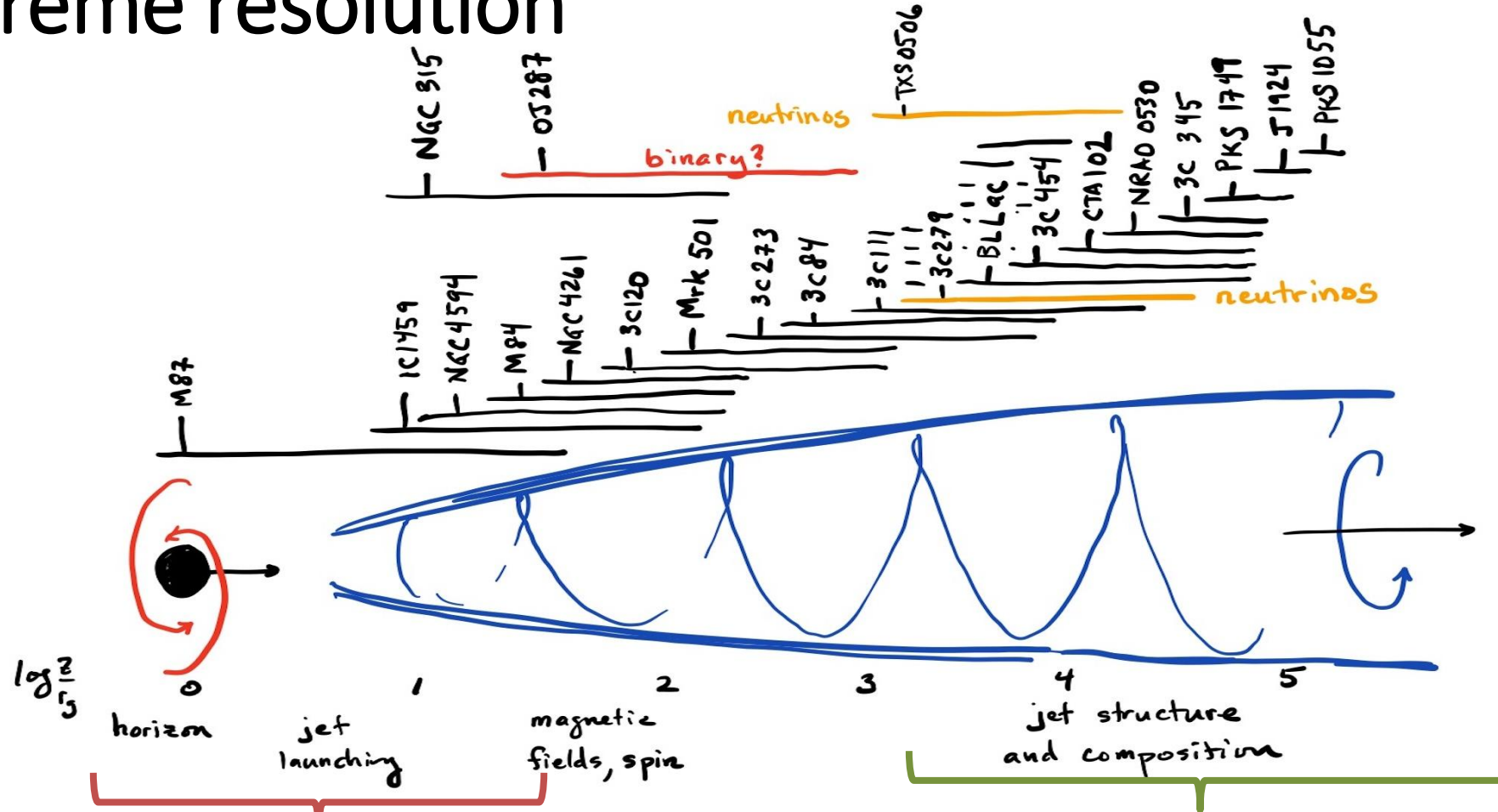
Direct photon ring spin measurements will help **calibrate** measurements from near-horizon polarimetry

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 VBLI images



BHEX will observe jets on multiple scales with extreme resolution



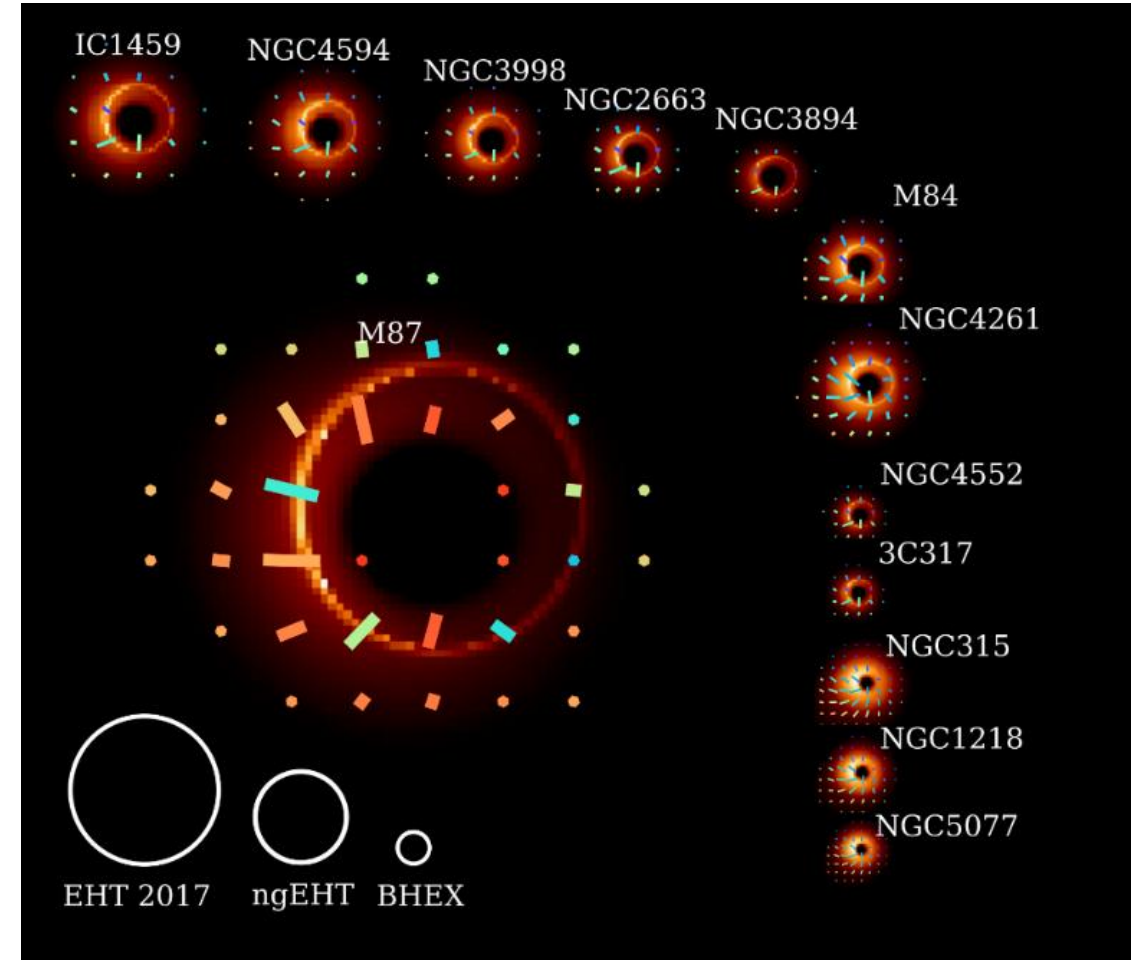
How does the jet connect to the BH?
Can we observe dynamics propagate
btw the accretion disk and jet?

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?

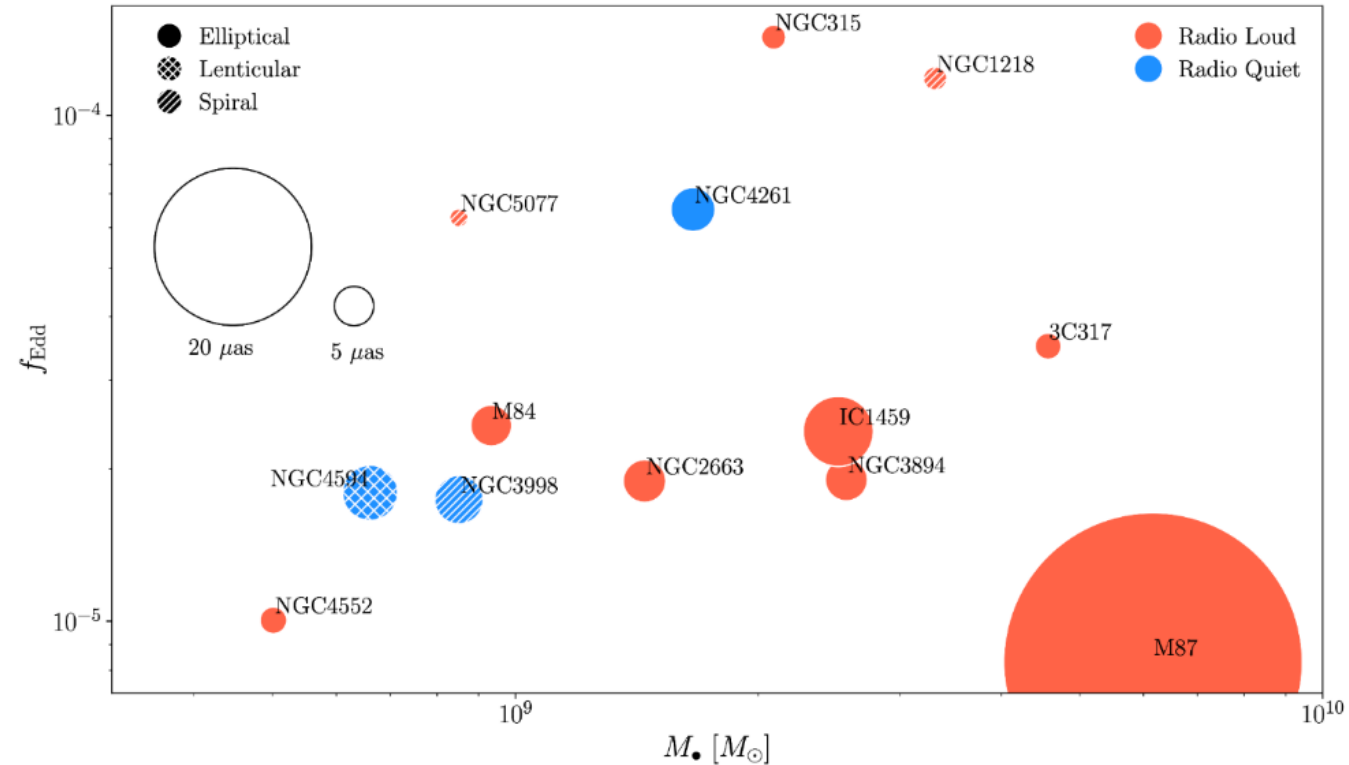
A Horizon-Scale Sample of Low-Luminosity AGN with BHEX

- 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



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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:

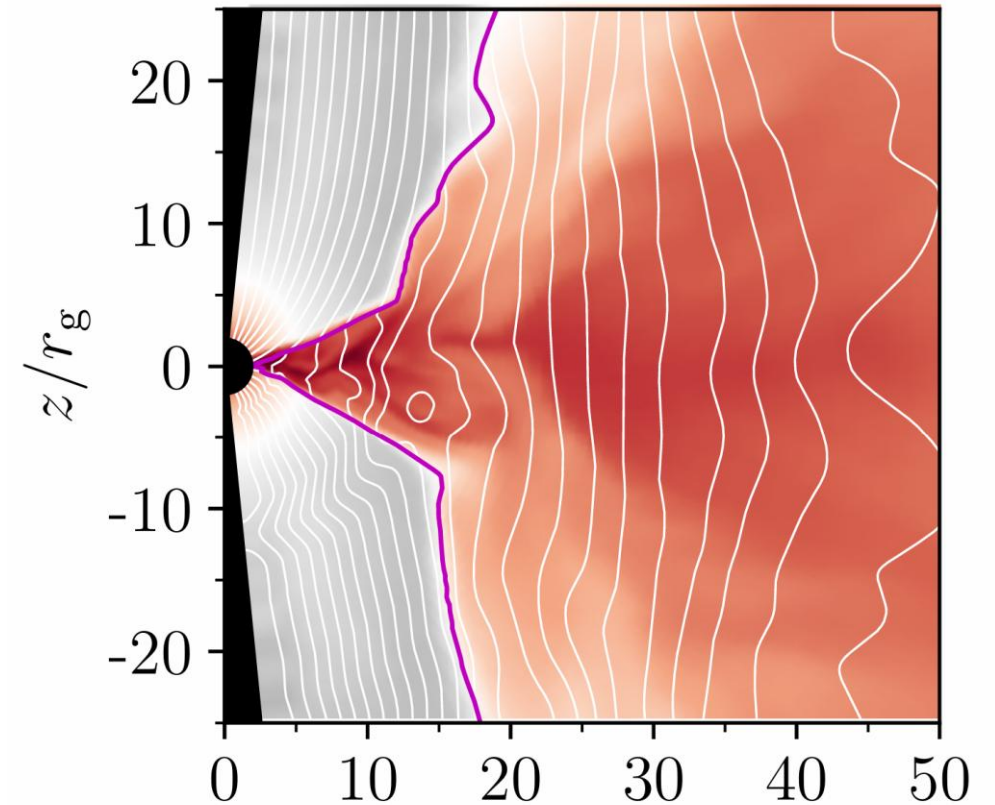
$$\nabla_{\mu} \left(T_{\text{MAT}}^{\mu\nu} + T_{\text{EM}}^{\mu\nu} \right) = 0$$

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

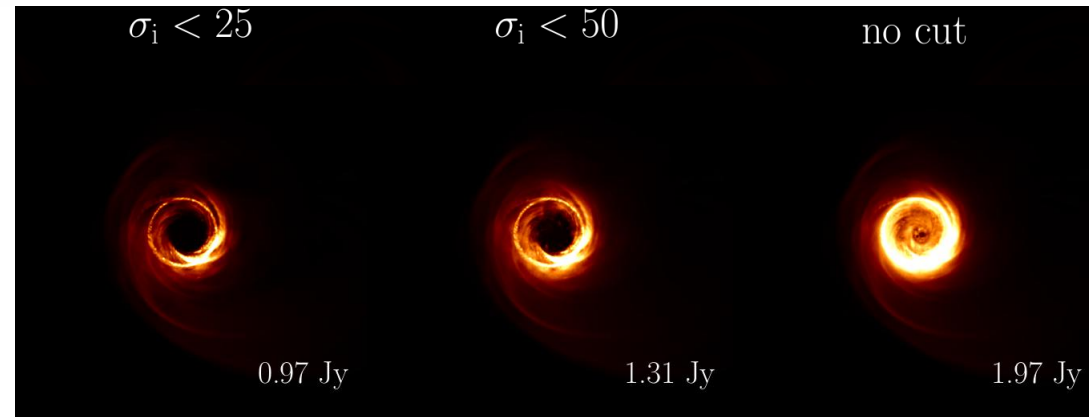
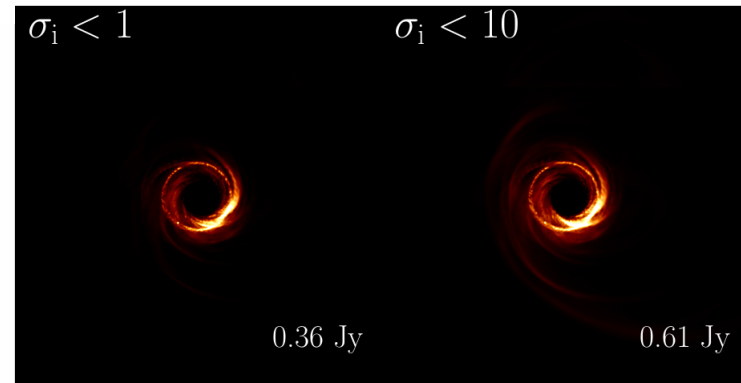
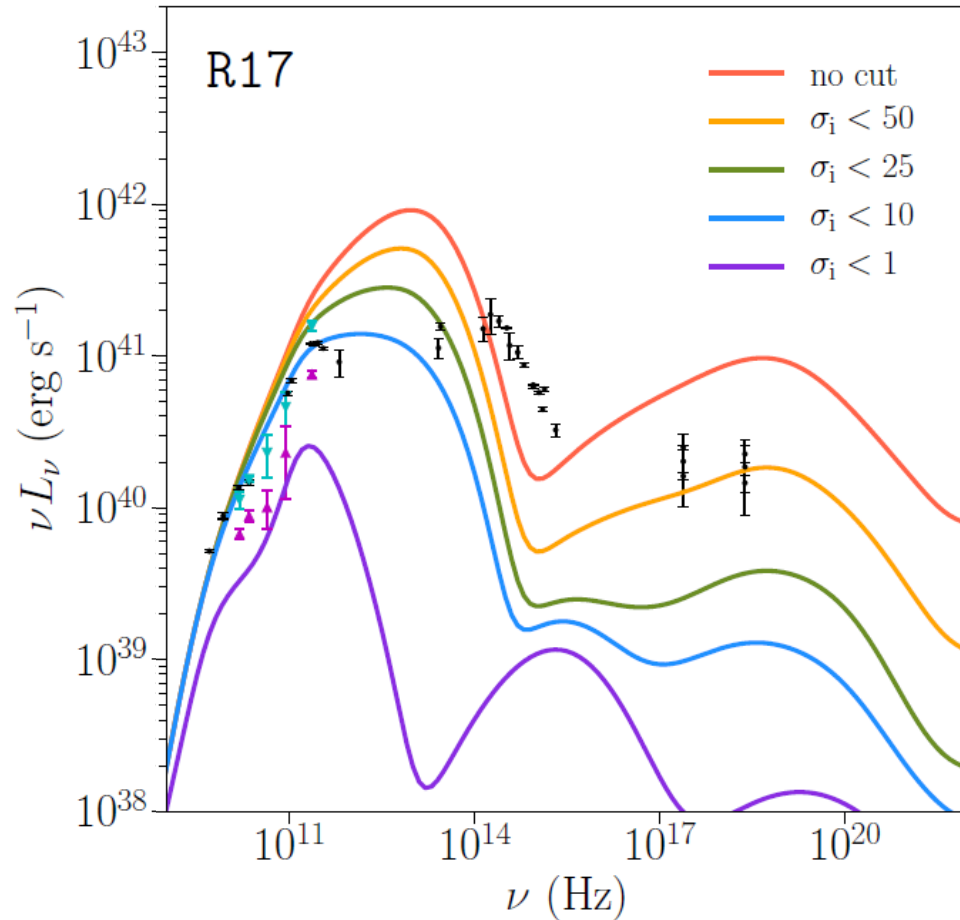
$$\sigma = b^2 / \rho$$

- 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

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



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



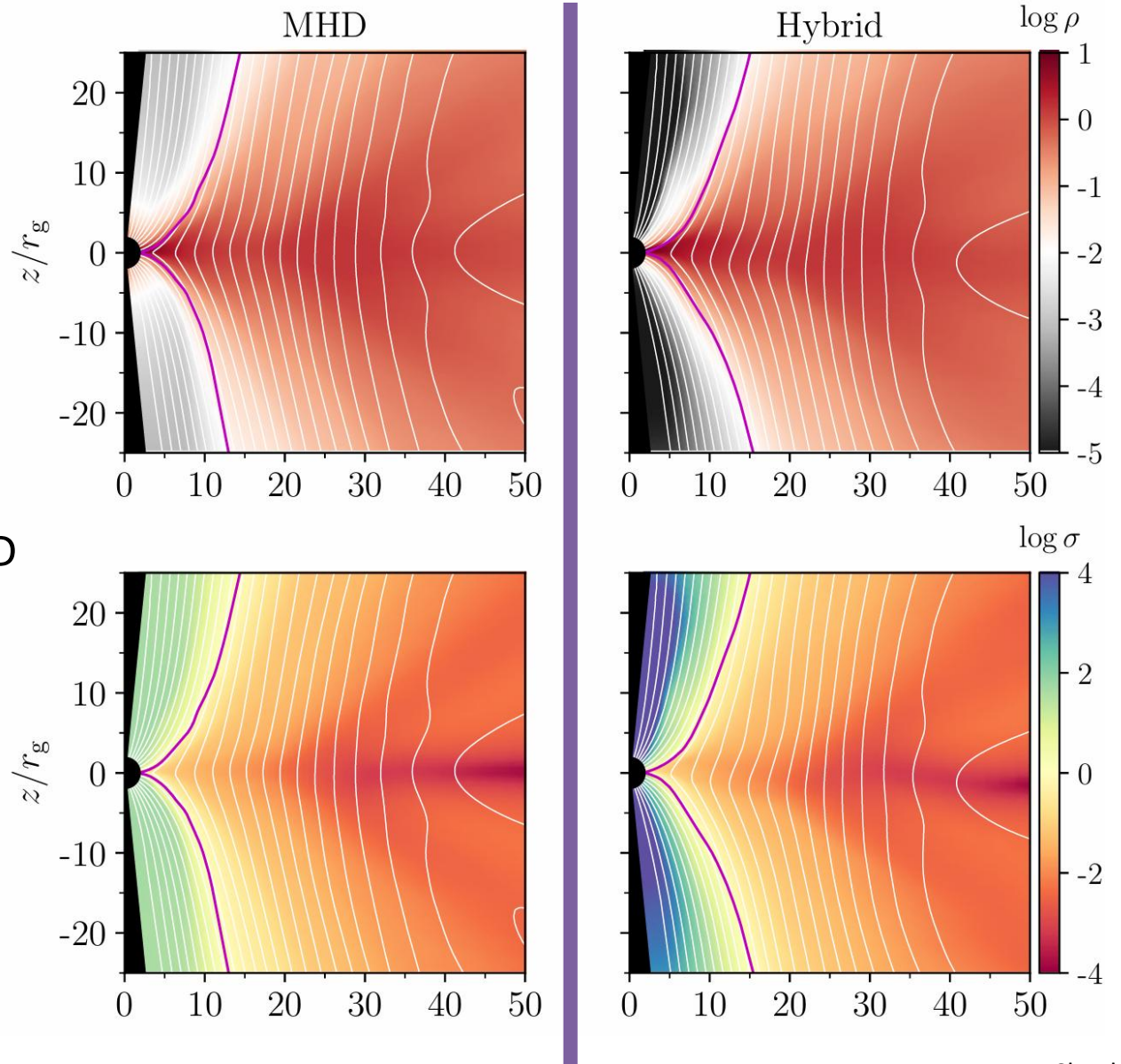
A New Hybrid GRMHD + Force-Free Code

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

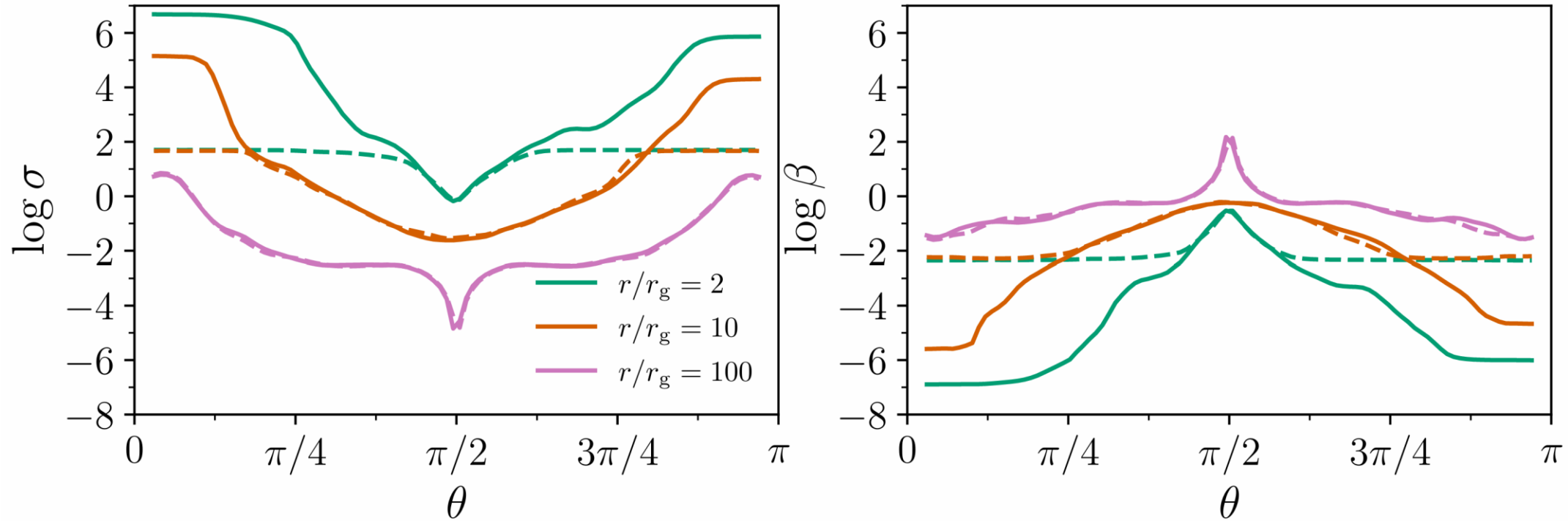
Above $\sigma > \sigma_{\text{trans}}$, use a **decoupled force-free scheme**:

- 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

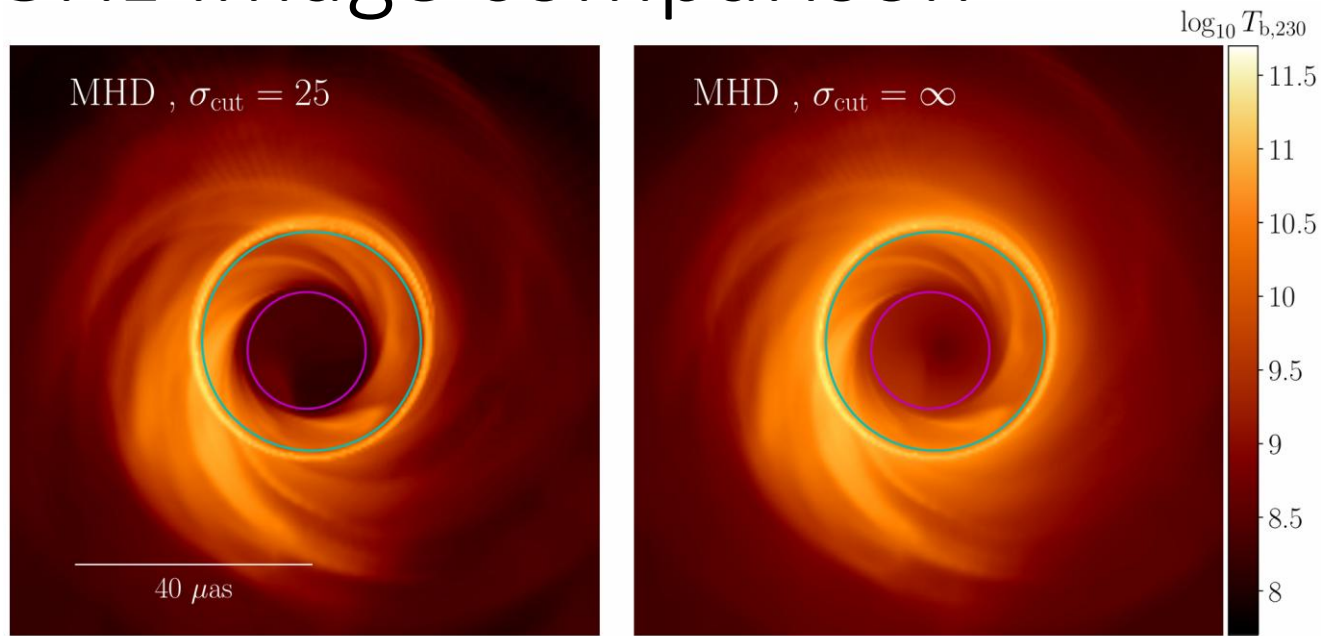


Comparing standard GRMHD and Hybrid GRMHD+FF

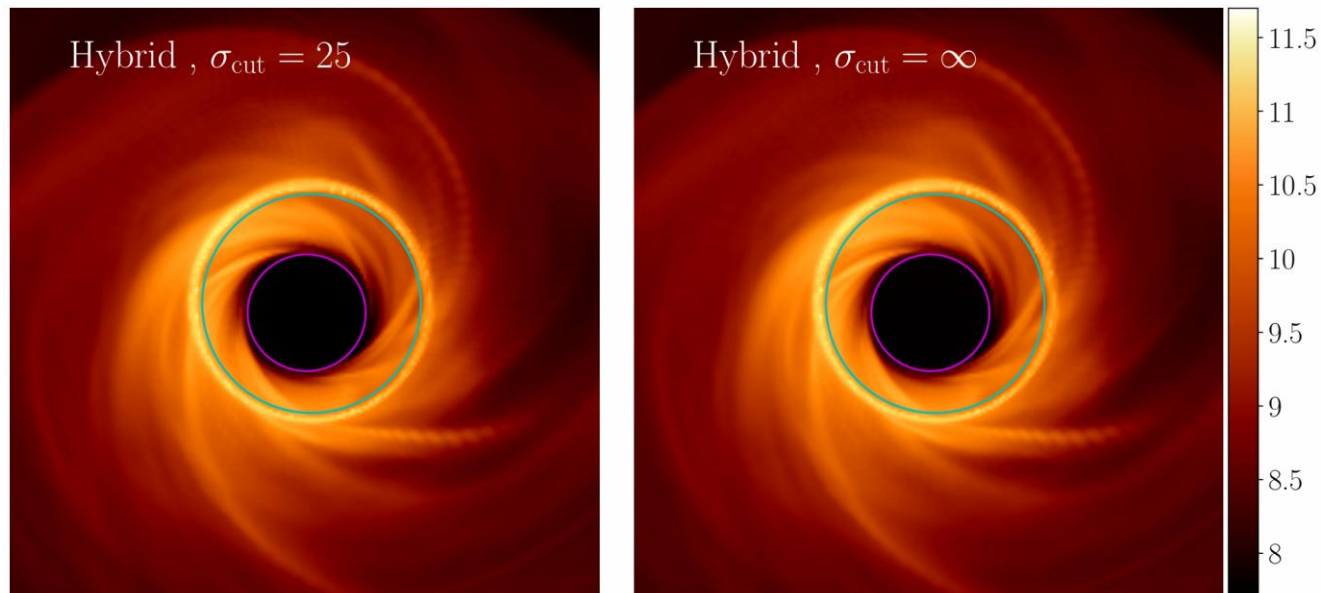


We achieve stable evolution up to $\sigma=10^6$ in the force-free jet region close to the black hole

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