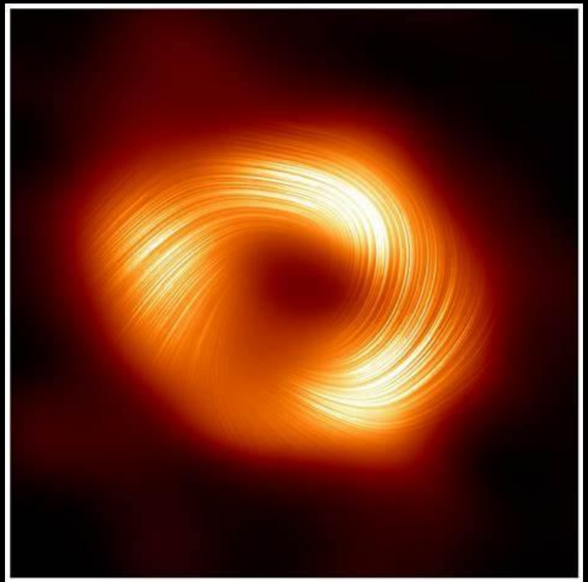
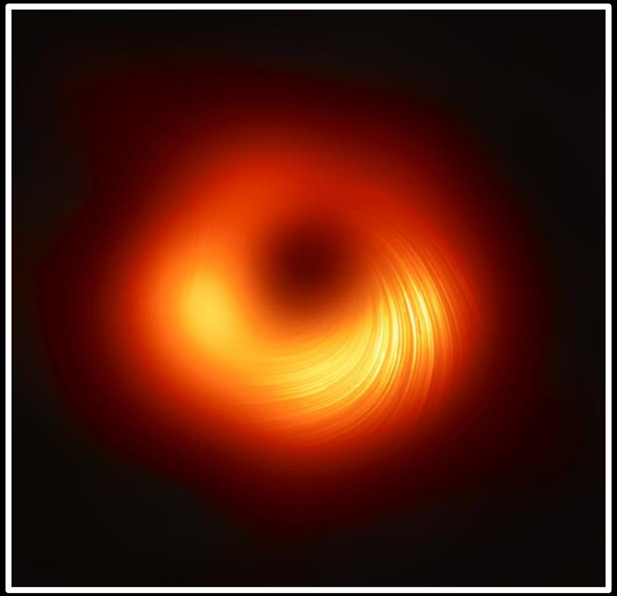
Insights from Polarized Images of Black Holes

Andrew Chael
Princeton Gravity Initiative

October 15, 2025



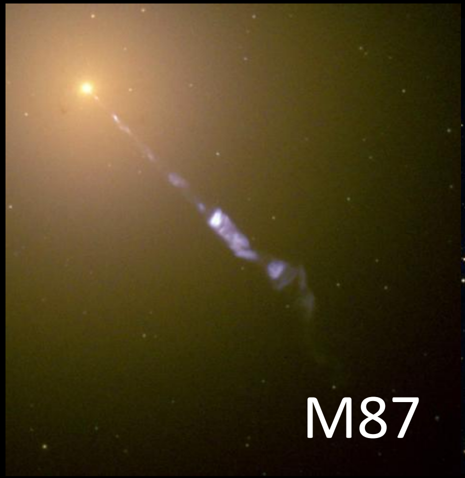


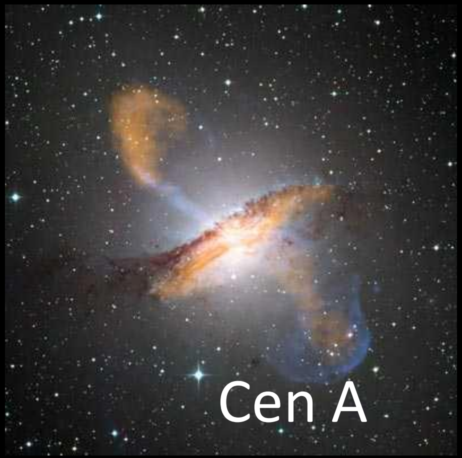
Princeton gravity Initiative

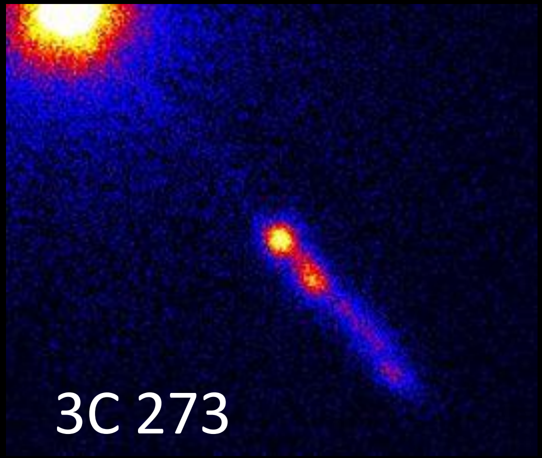
BHEX

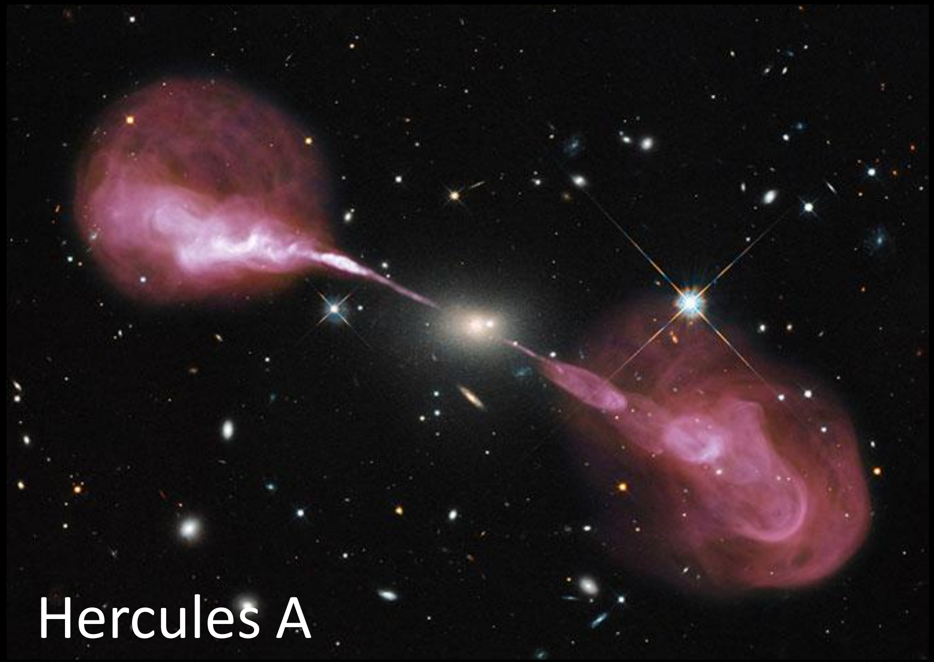
Event Horizon Telescope

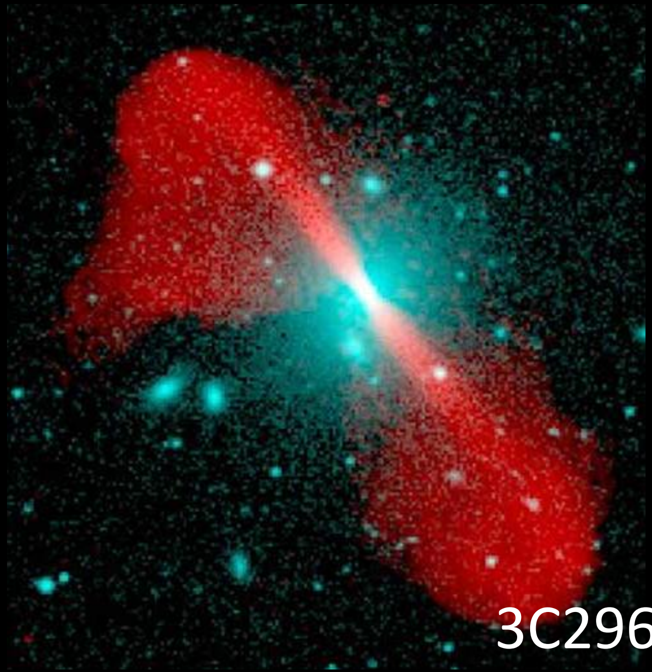
Supermassive black holes and jets are everywhere







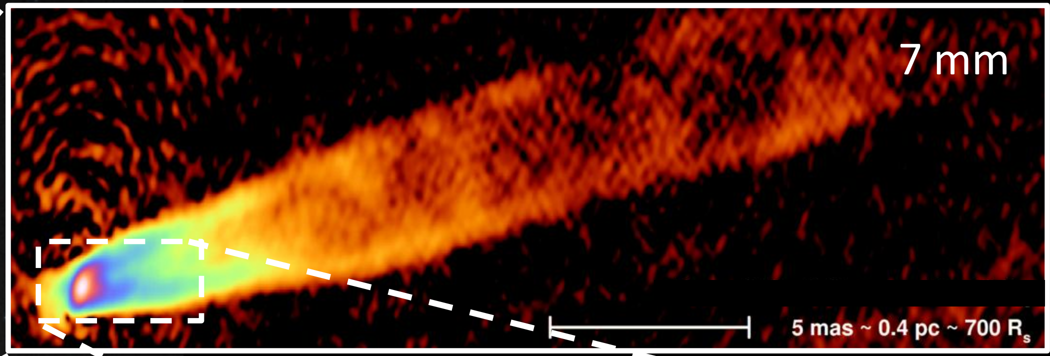


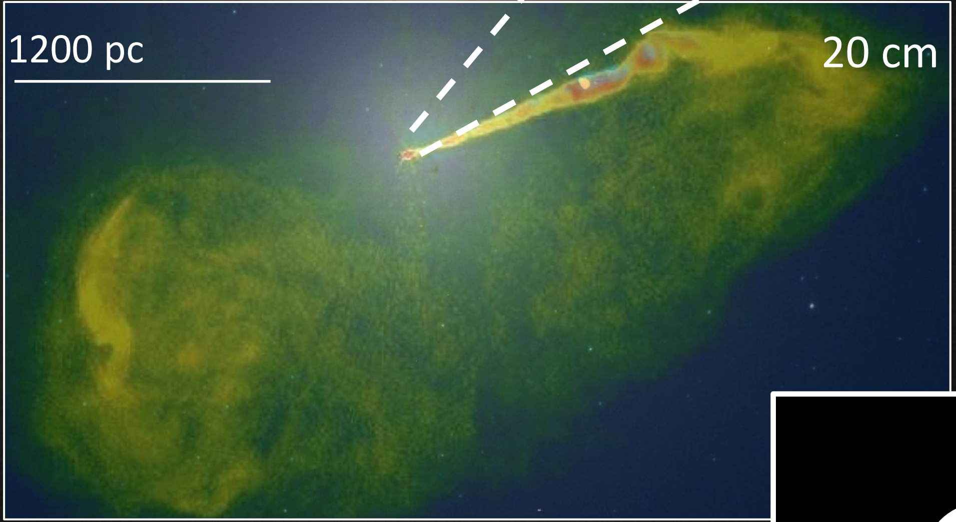


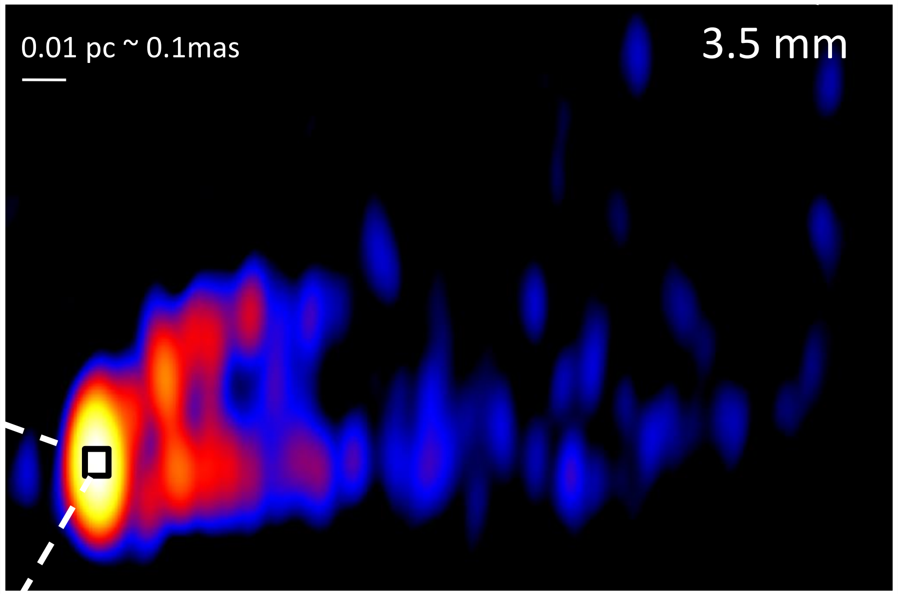
Credits: Sara Issoun, (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C293, Chandra),(Hercules A,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

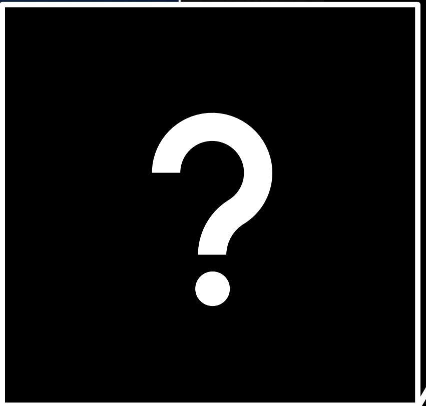
M87 & M87*

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





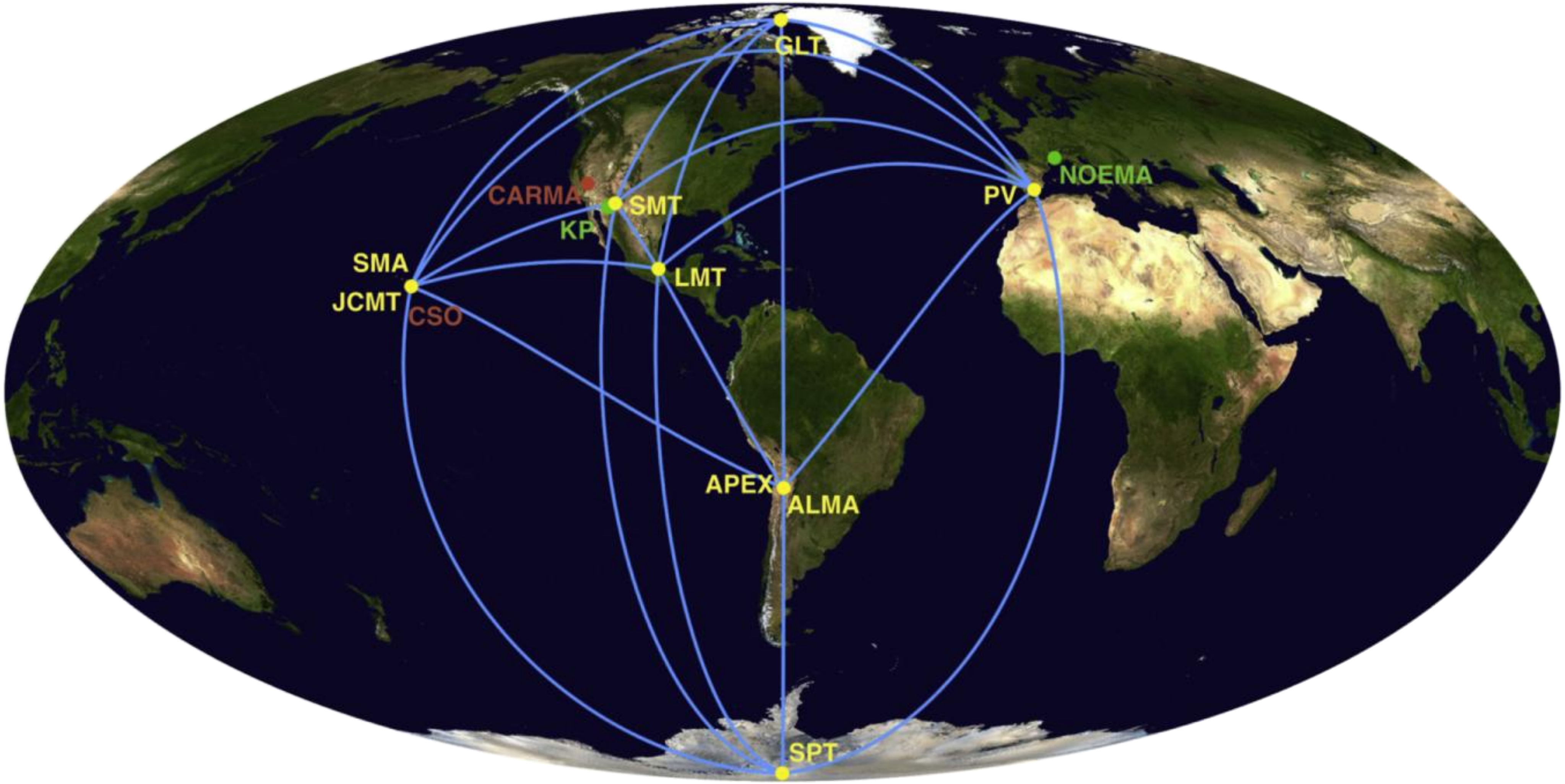




What does jet launching look like on event horizon scales?

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

The Event Horizon Telescope



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

EHTC II, 2019

M87 & M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
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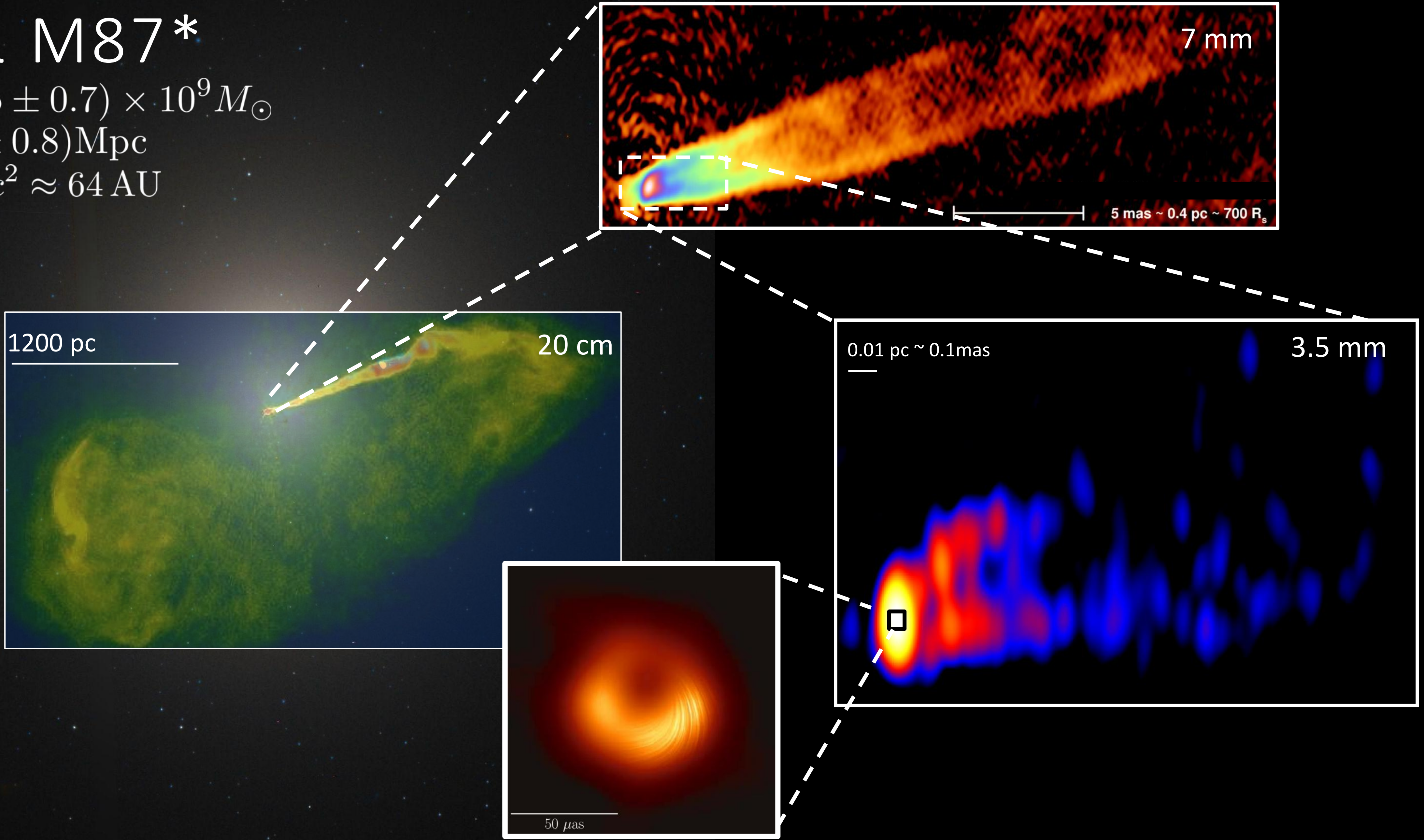


Can polarized EHT images tell us how jets are launched?

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 ($T \gtrsim 10^{10}\,\mathrm{K}$), sub-Eddington accretion flow
- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}$ erg s^{-1})
- Millimeter images from synchrotron radiation

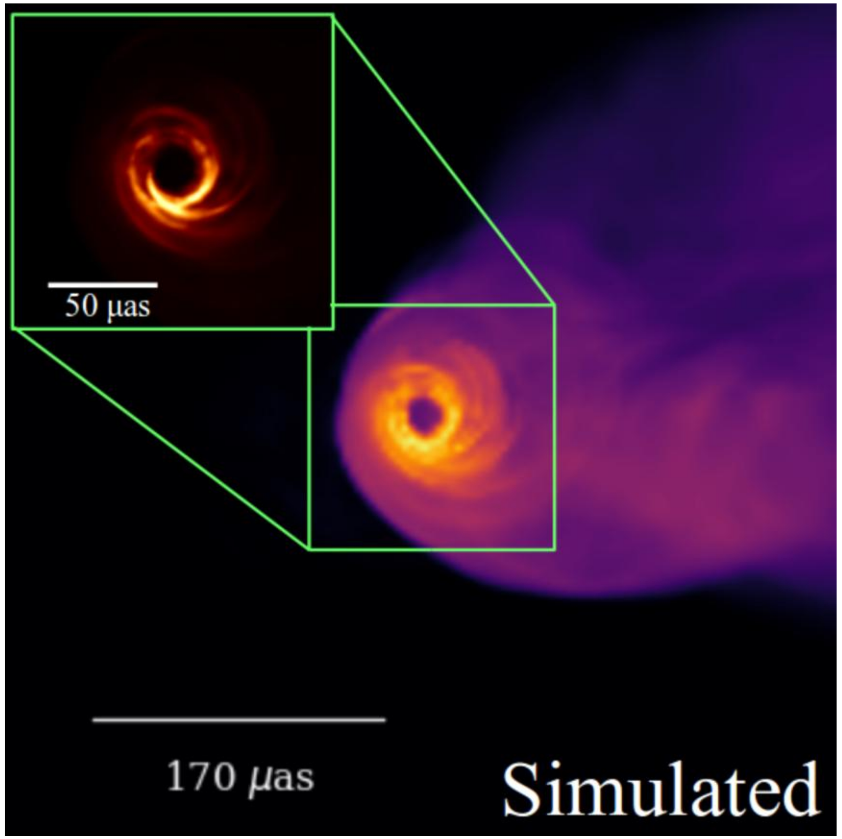
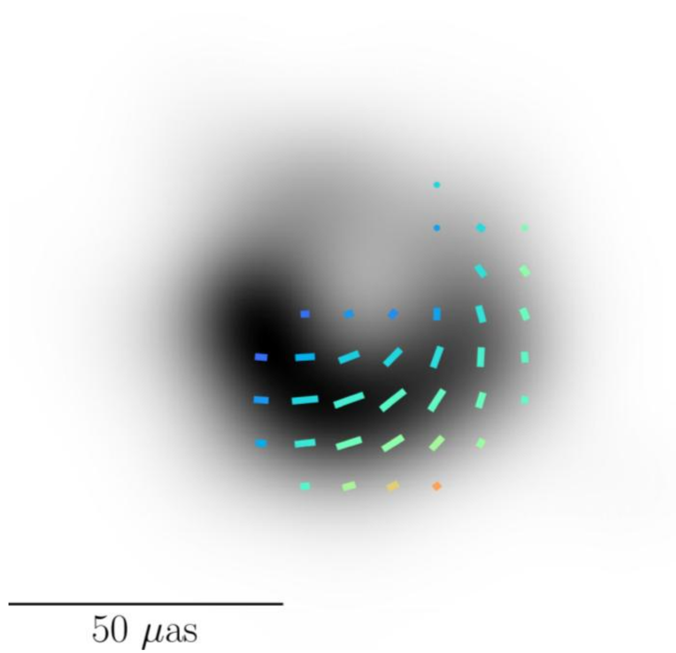
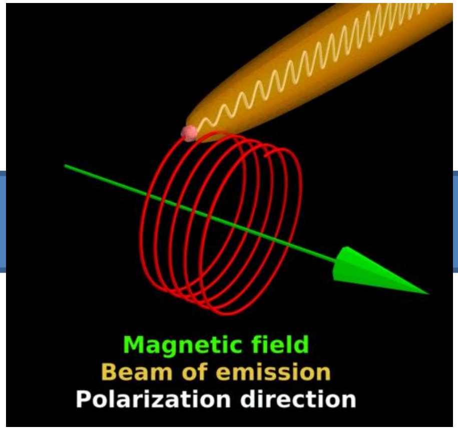


Image Credit: Blackburn+ 2019**, Chael+** 2019

Why polarization?



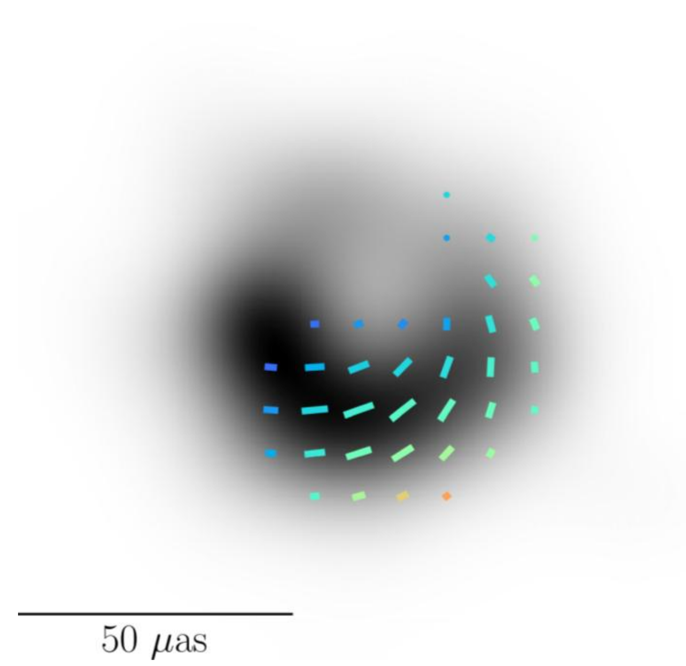


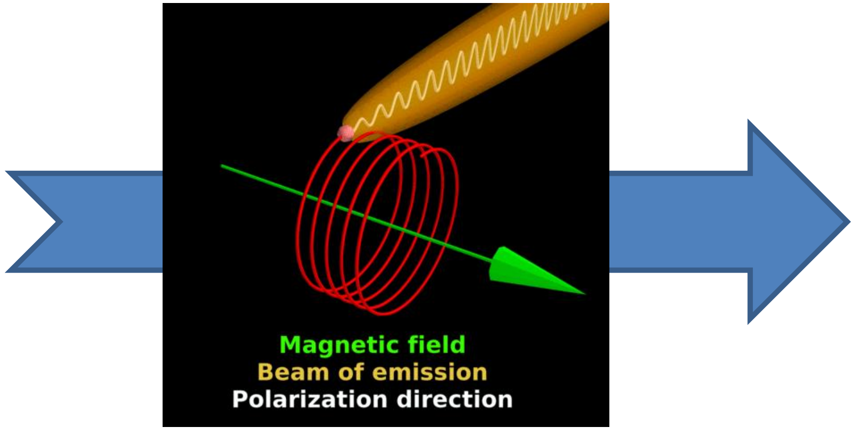
Magnetic field geometry in the emission region!

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

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

Why polarization?





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

~~Ma d geor n the er on!~~

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

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

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

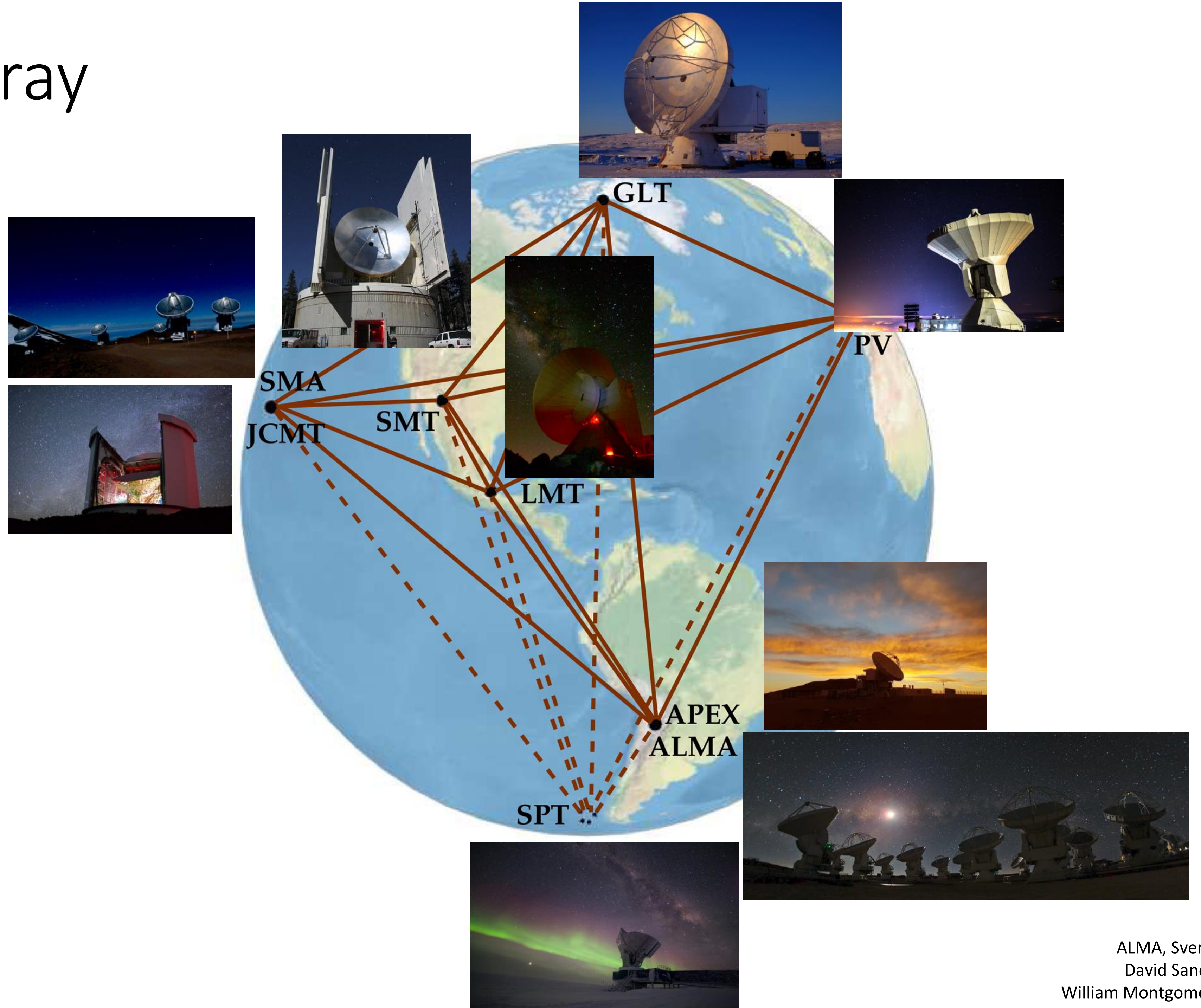


Photo Credits: EHTC I, 2024
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

EHT: People

300+ members

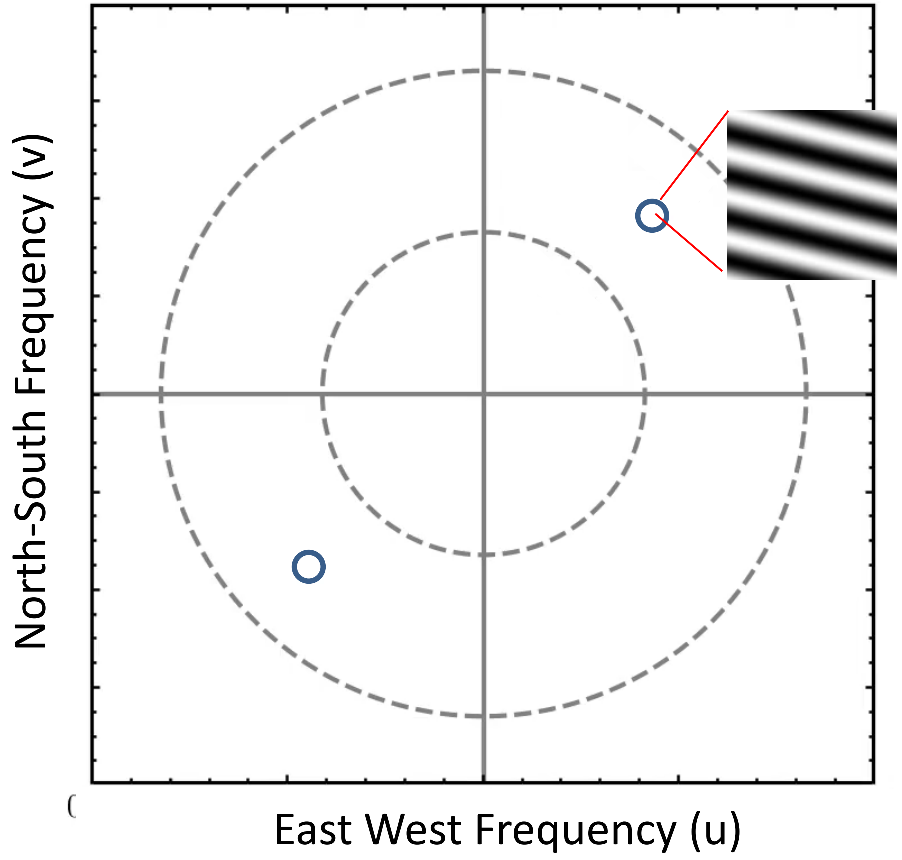
60 institutes

20 countries

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

Image credit: E. Traianou

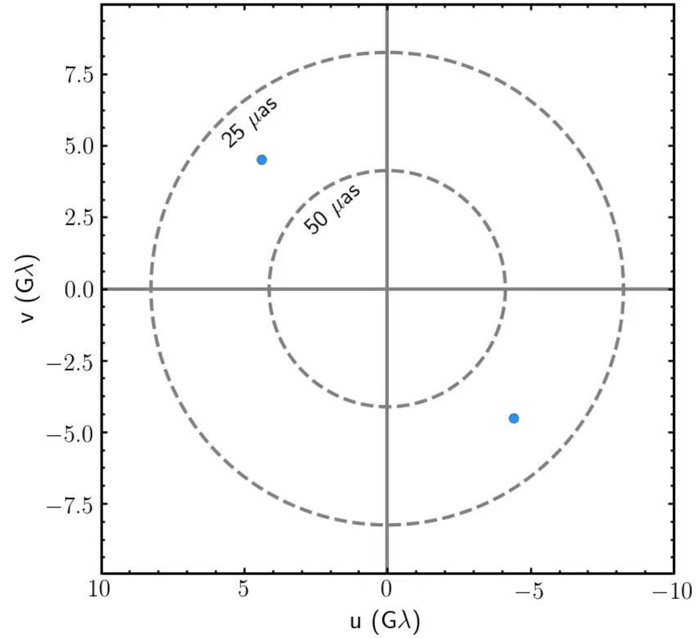
Very Long Baseline Interferometry (VLBI)

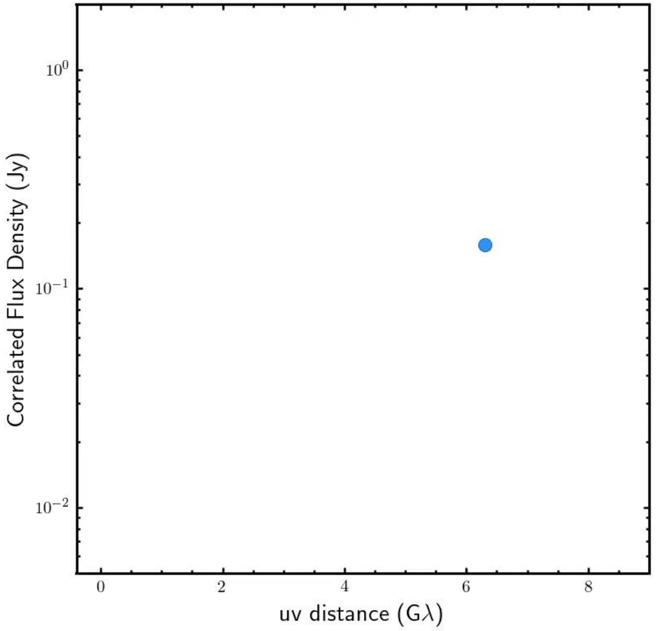


Every projected **baseline** between two telescopes provides **one Fourier component** of the image

movie credit: Katie Bouman

Very Long Baseline Interferometry (VLBI)

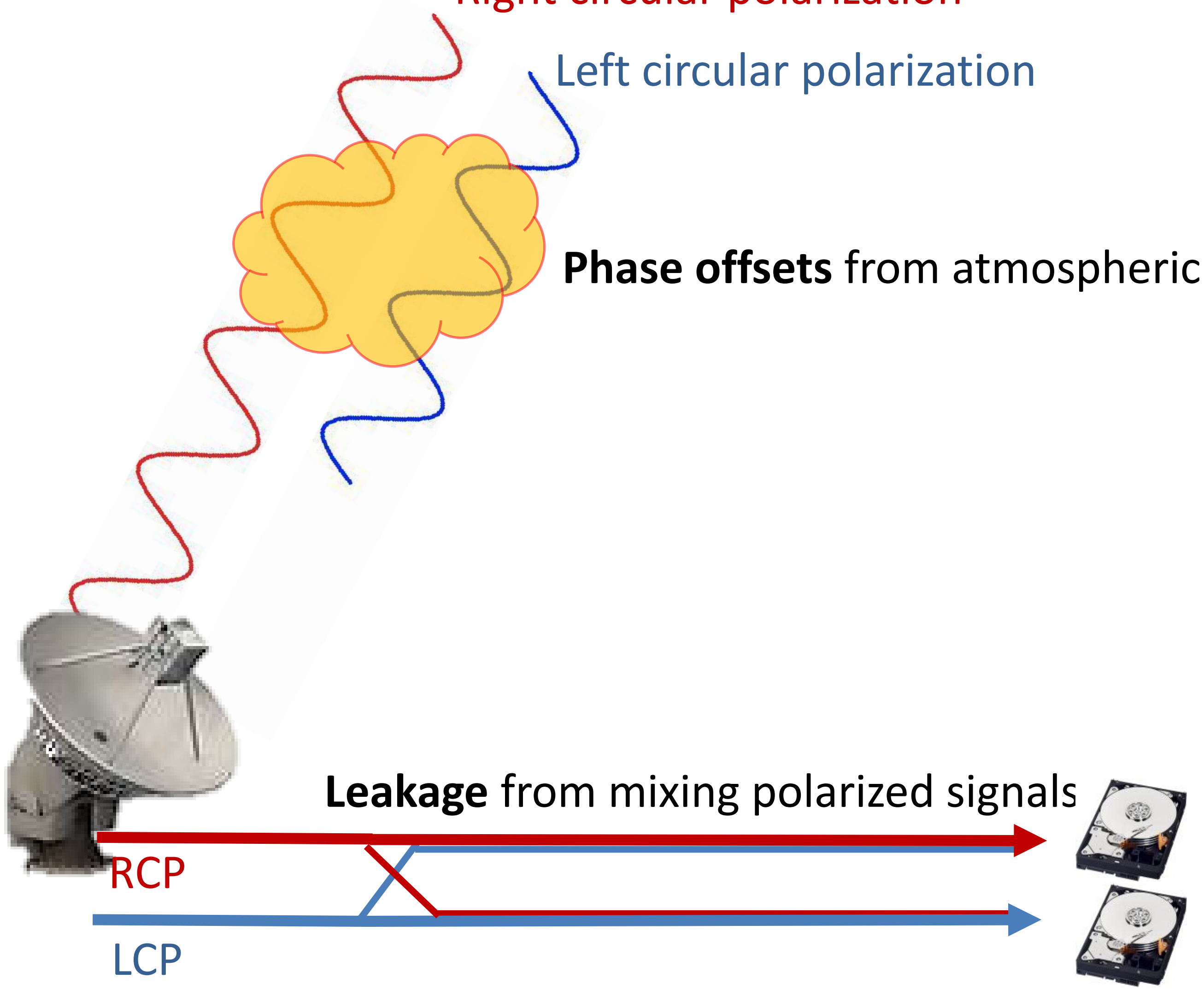




EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

movie credit: Daniel Palumbo

Challenges of near-horizon imaging

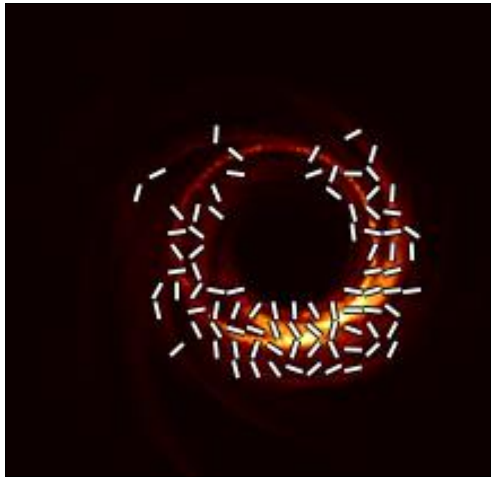


Data at each station are corrupted by unknown **gain and leakage** systematics

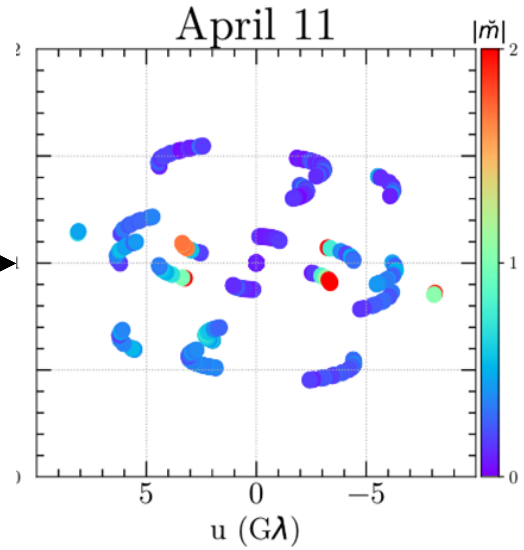
Animation credit: Andrew Chael

Solving for the Image

True Image

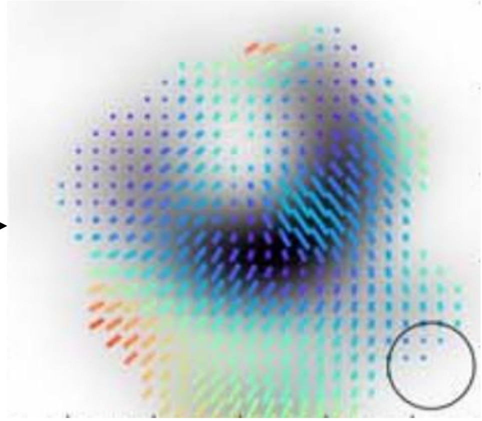


Sparse & Corrupted Measurements



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 polsolve (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)

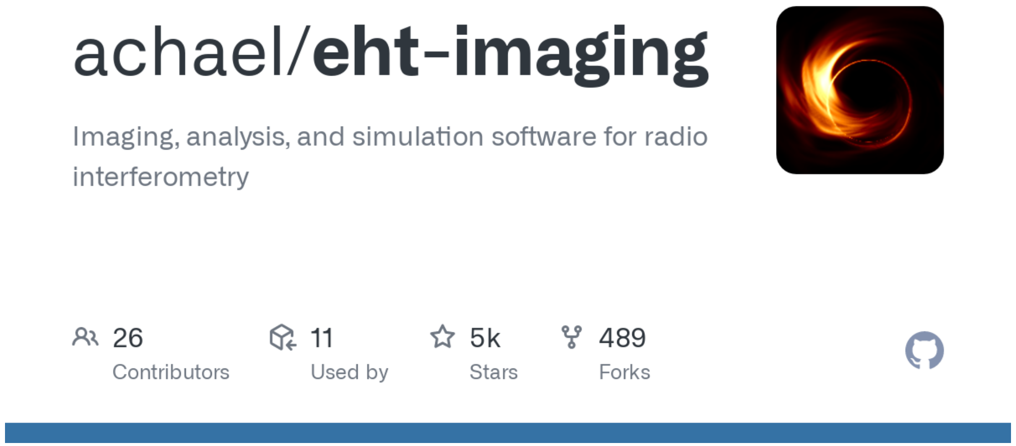
credit: Katie Bouman, Andrew Chael, EHTC VII, 2021

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…

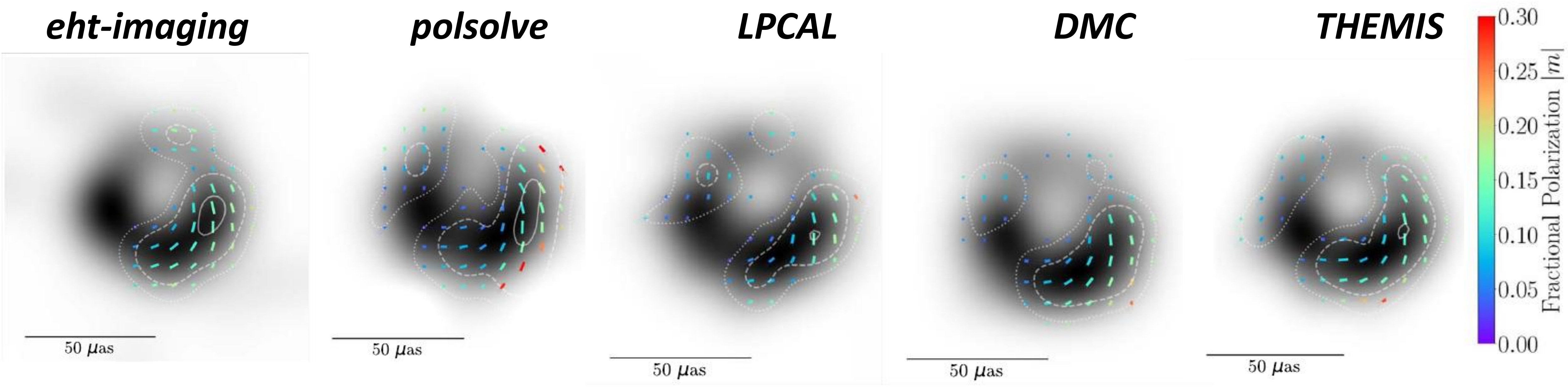


https://github.com/achael/eht-imaging

```
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 (~40 μas) and asymmetry (south)
- Polarization structure is predominantly **helical and weak**, (|m| ~10 %)

EHTC VII, 2021 (**Chael**, paper writing team)

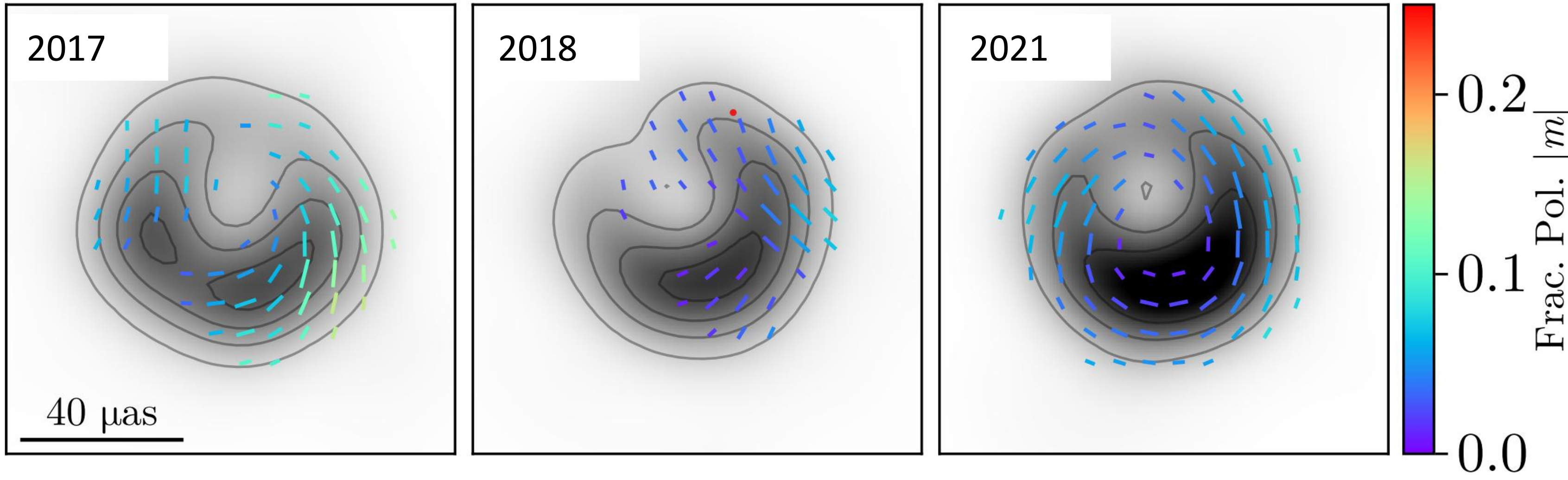
Three Years of Horizon-Scale Structure in M87

- 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%)

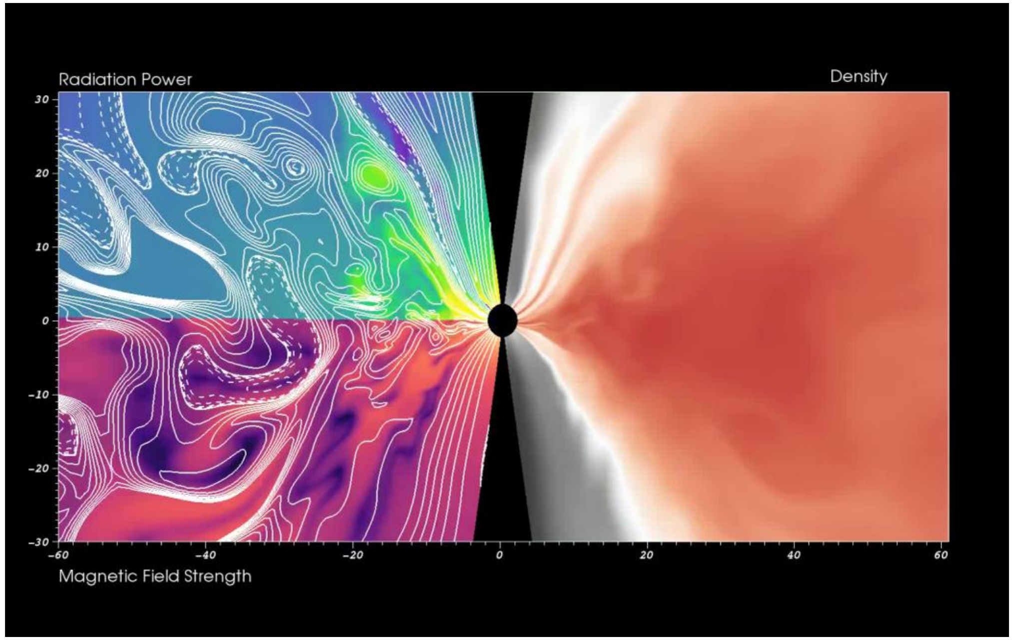


EHTC 2019, 2022, 2024, 2025
doi: 10.1051/0004-6361/202555855

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

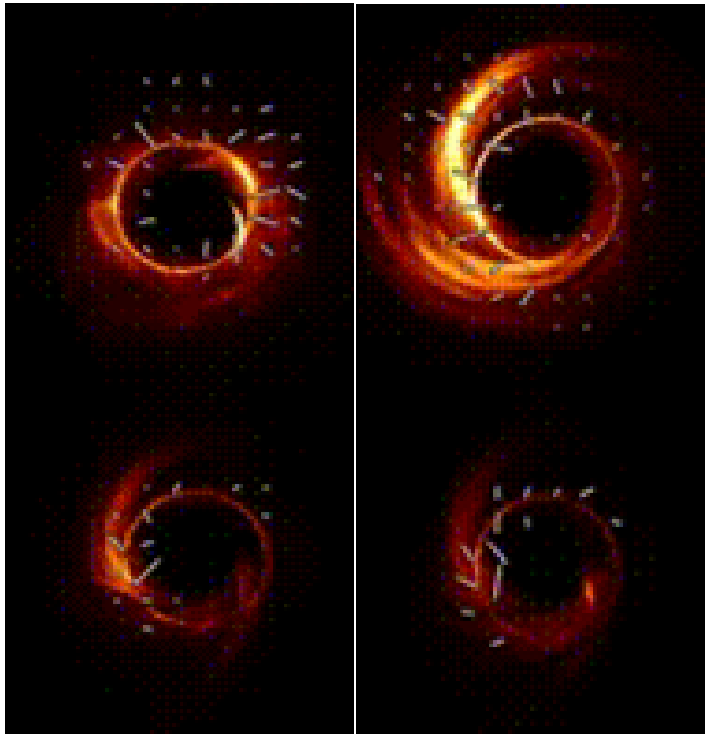
EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
2105.01173, 2311.10976

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

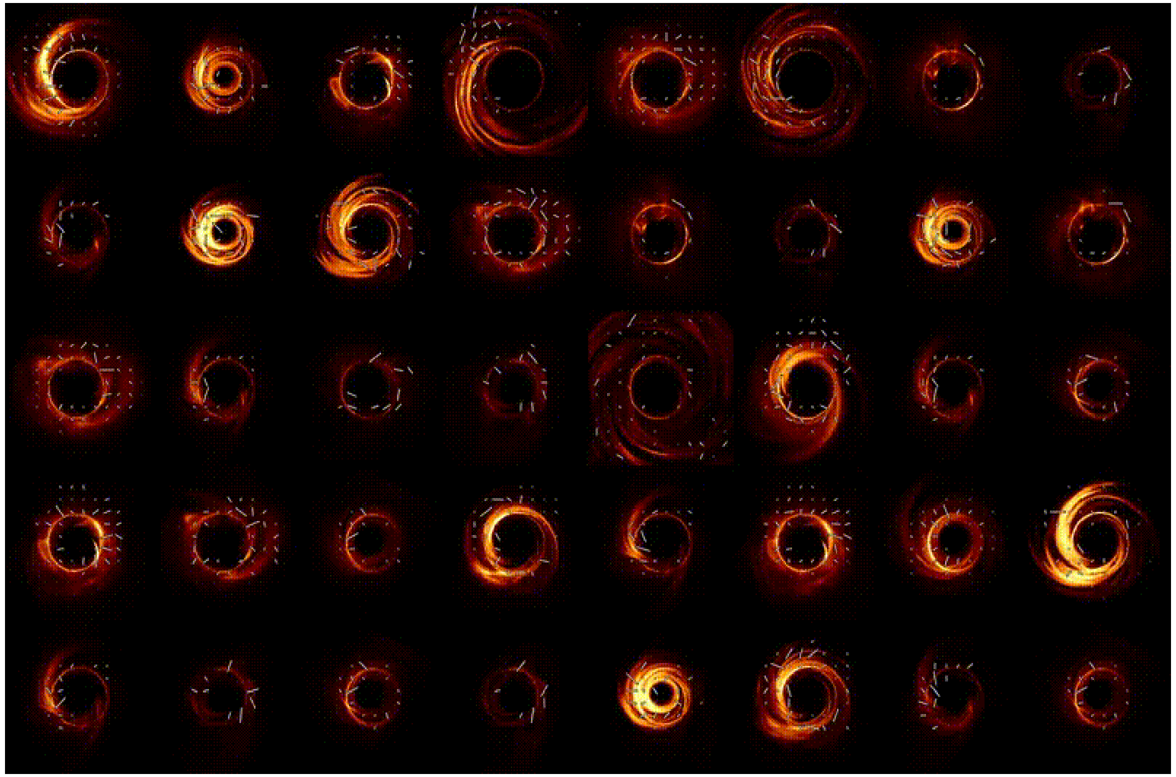


GR Radiative Transfer

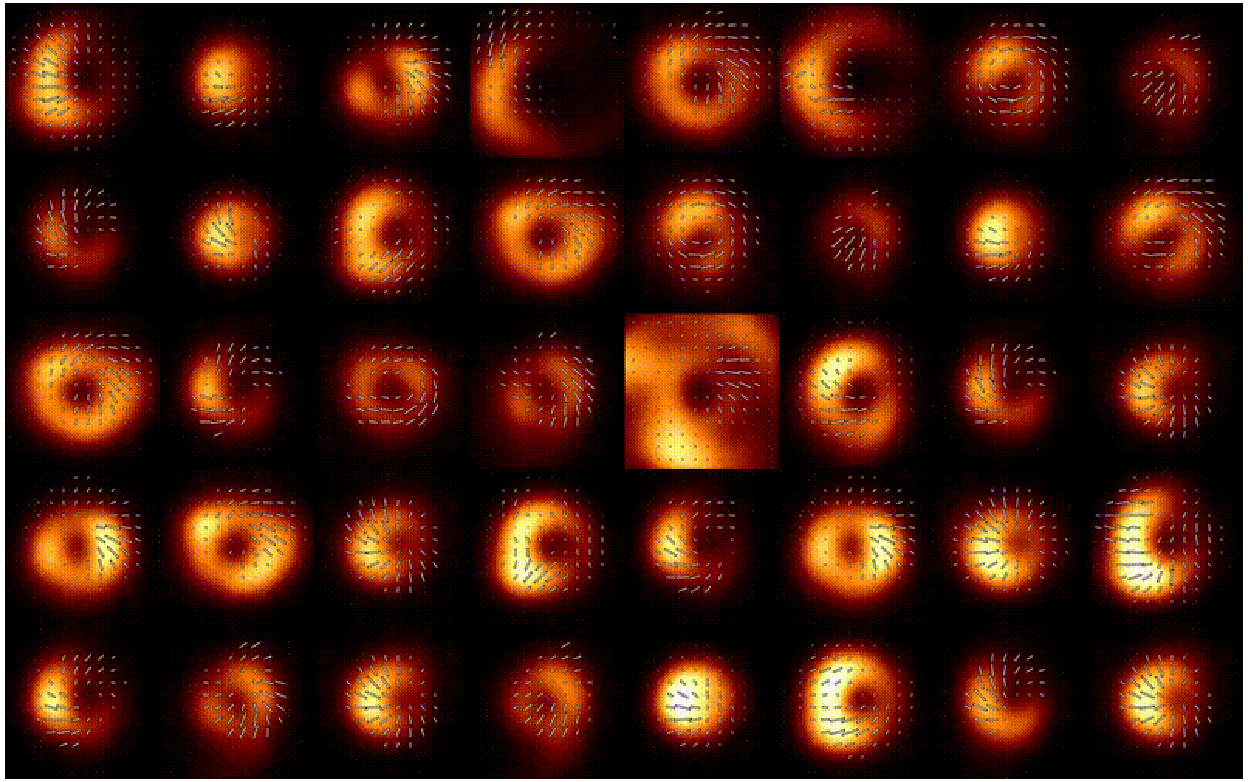
Track light rays and solves for the polarized radiation (including Faraday effects)

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

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

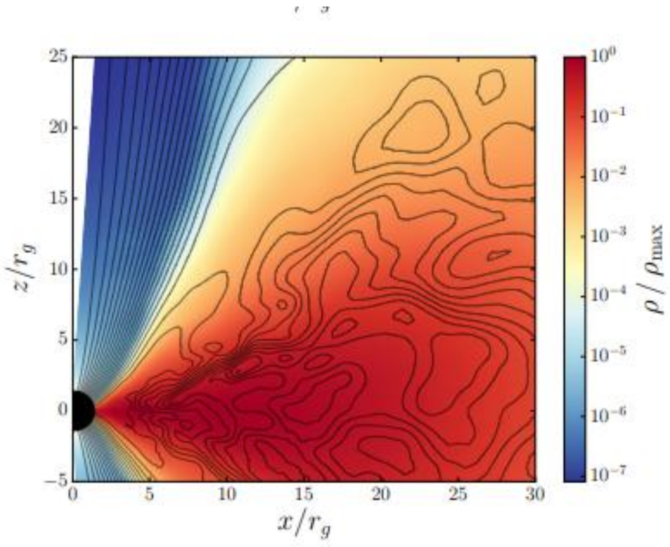
$$T_e \neq T_i$$

Animation credit: Ben Prather

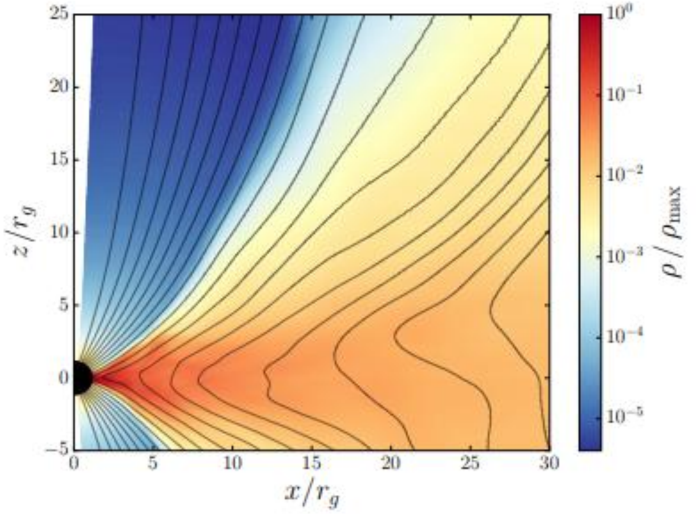
What is the magnetic field structure close to the horizon?

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

Magnetic fields are weak and turbulent



“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:

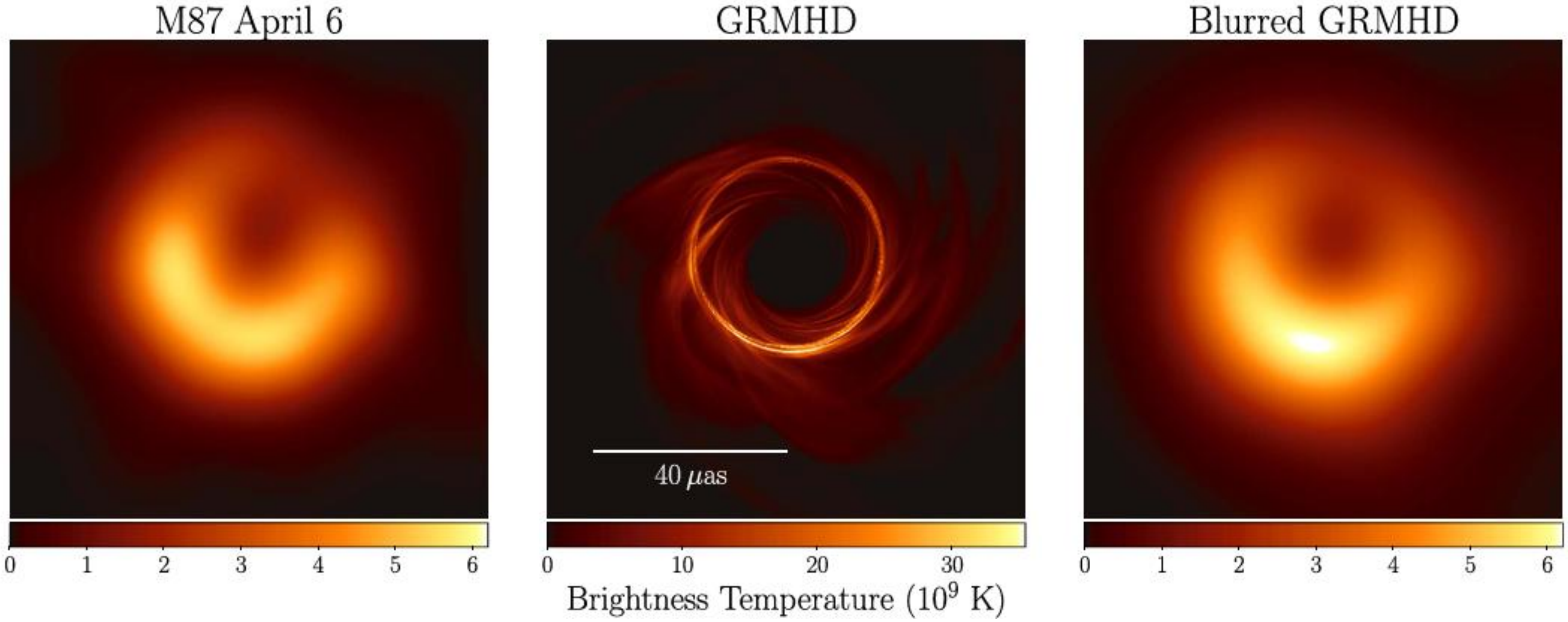
$$P_{\rm jet} \propto \Phi_B^2 a^2$$

BH spin

magnetic flux

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

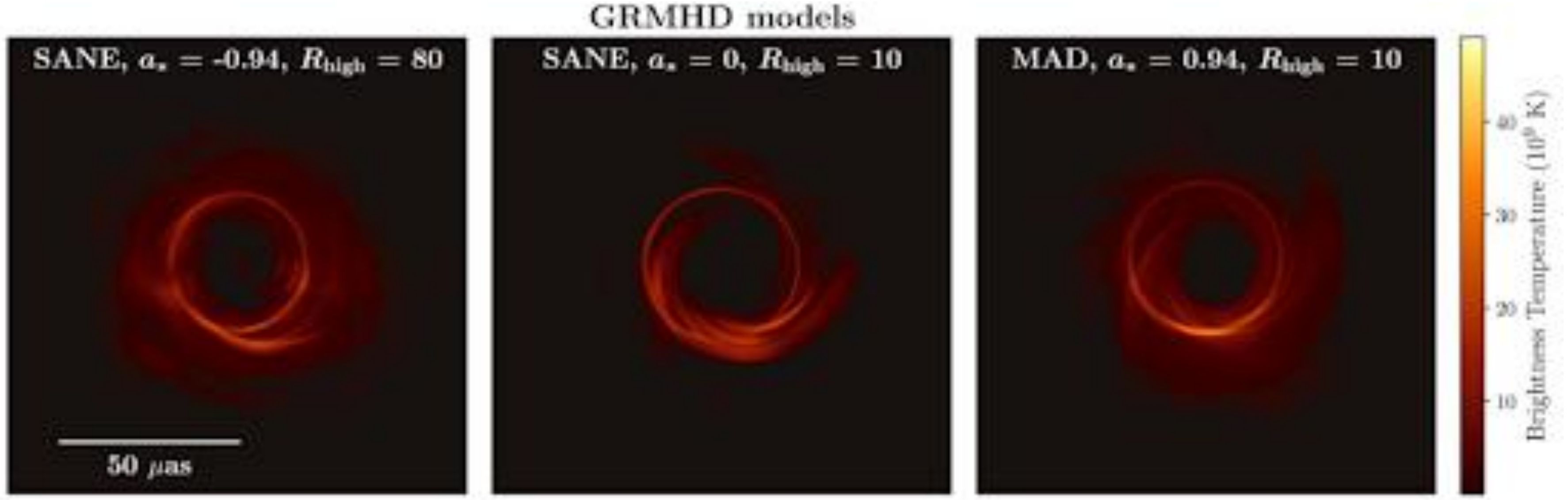
EHT Images are consistent with the GRMHD Picture



EHTC V, 2019

Scoring M87* GRMHD Simulations: before polarization

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



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

EHTC V, 2019

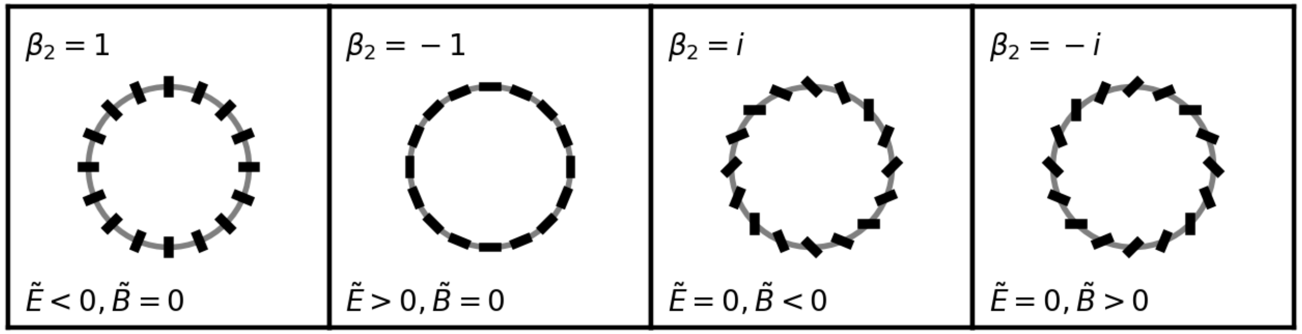
Summarizing an image: Polarization

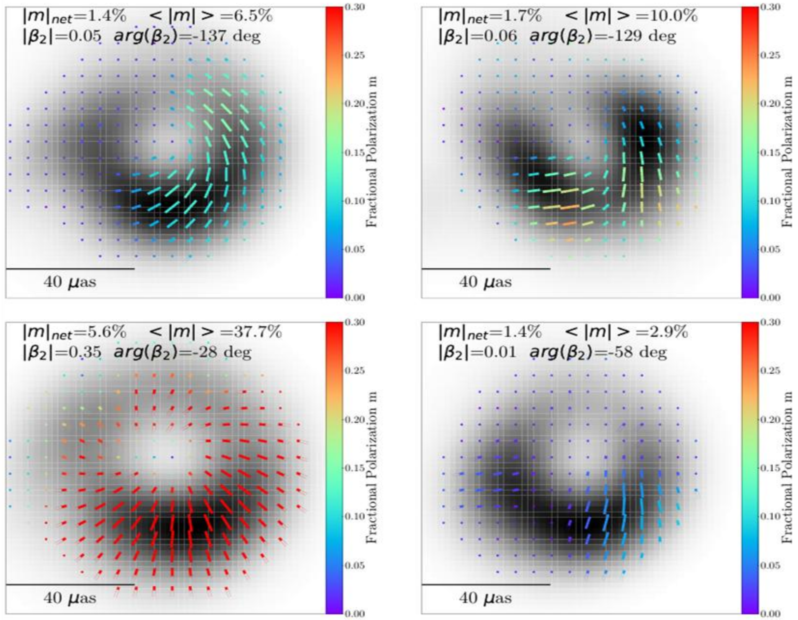
Unresolved and **Resolved** polarization fractions

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

Azimuthal Structure
2nd Fourier mode

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

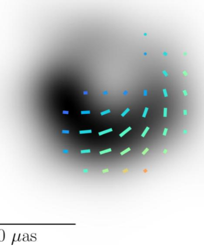




Simulation images can be **strongly** or **weakly** polarized:
with **patterns** that are radial/toroidal/helical

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

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:

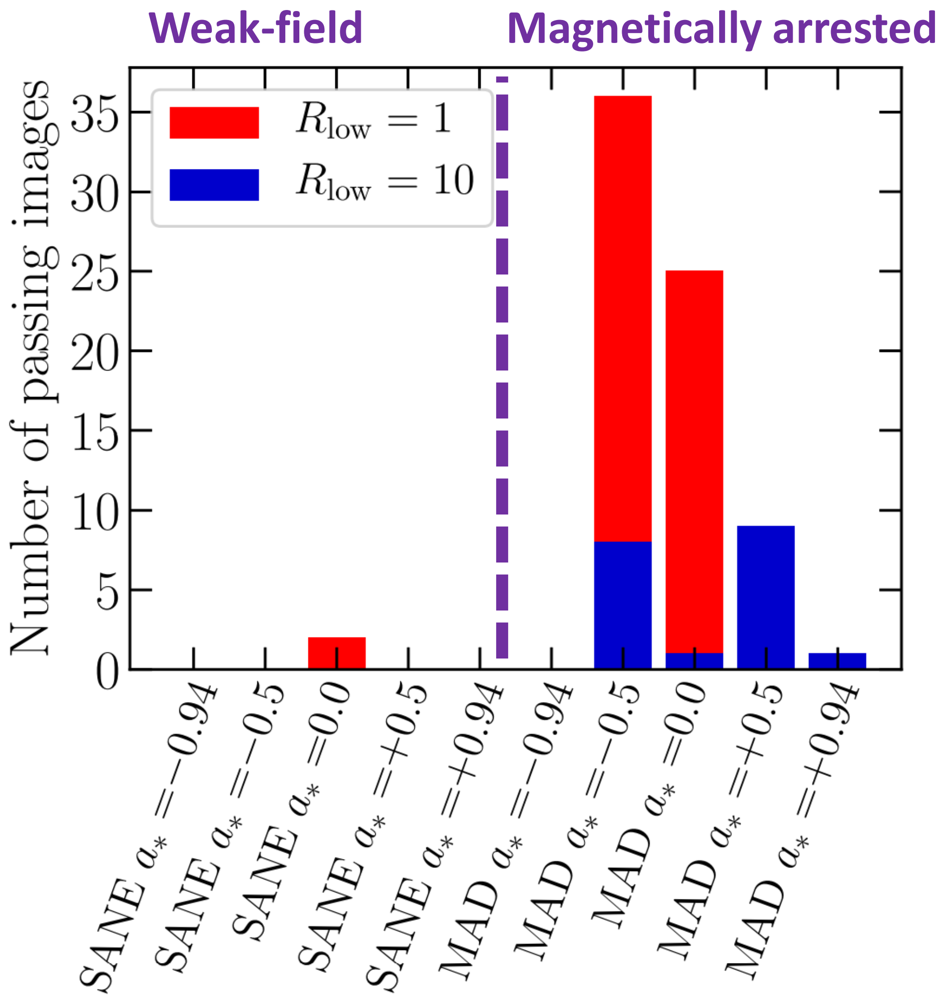
$$\dot{M} \simeq (3-20)\times 10^{-4} M_\odot\ \mathrm{yr}^{-1}$$
$$\left(\dot{M}_{\rm Edd} = 137 M_\odot\ \mathrm{yr}^{-1}\right)$$

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

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

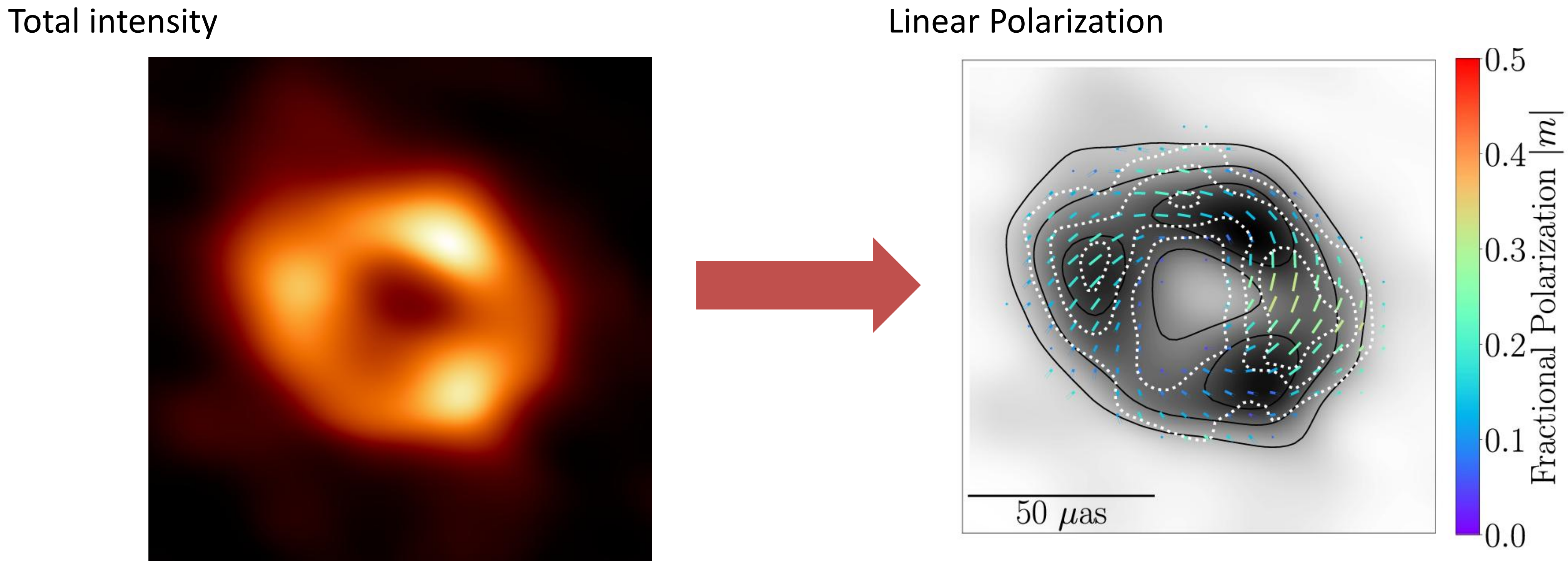
- Strong magnetic fields more easily launch BZ jets at all values of BH spin

- Do new EHT polarization measurements change this picture? Stay tuned!



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

Sgr A* in linear polarization



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

EHTC+ 2024 VII, VIII

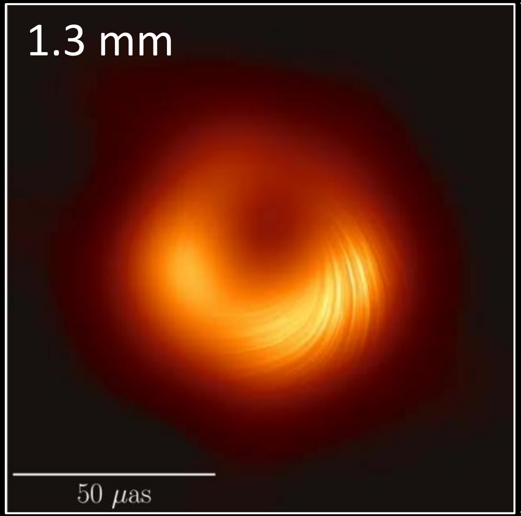
What can a polarized image of M87* tell us about energy flow & jet launching?

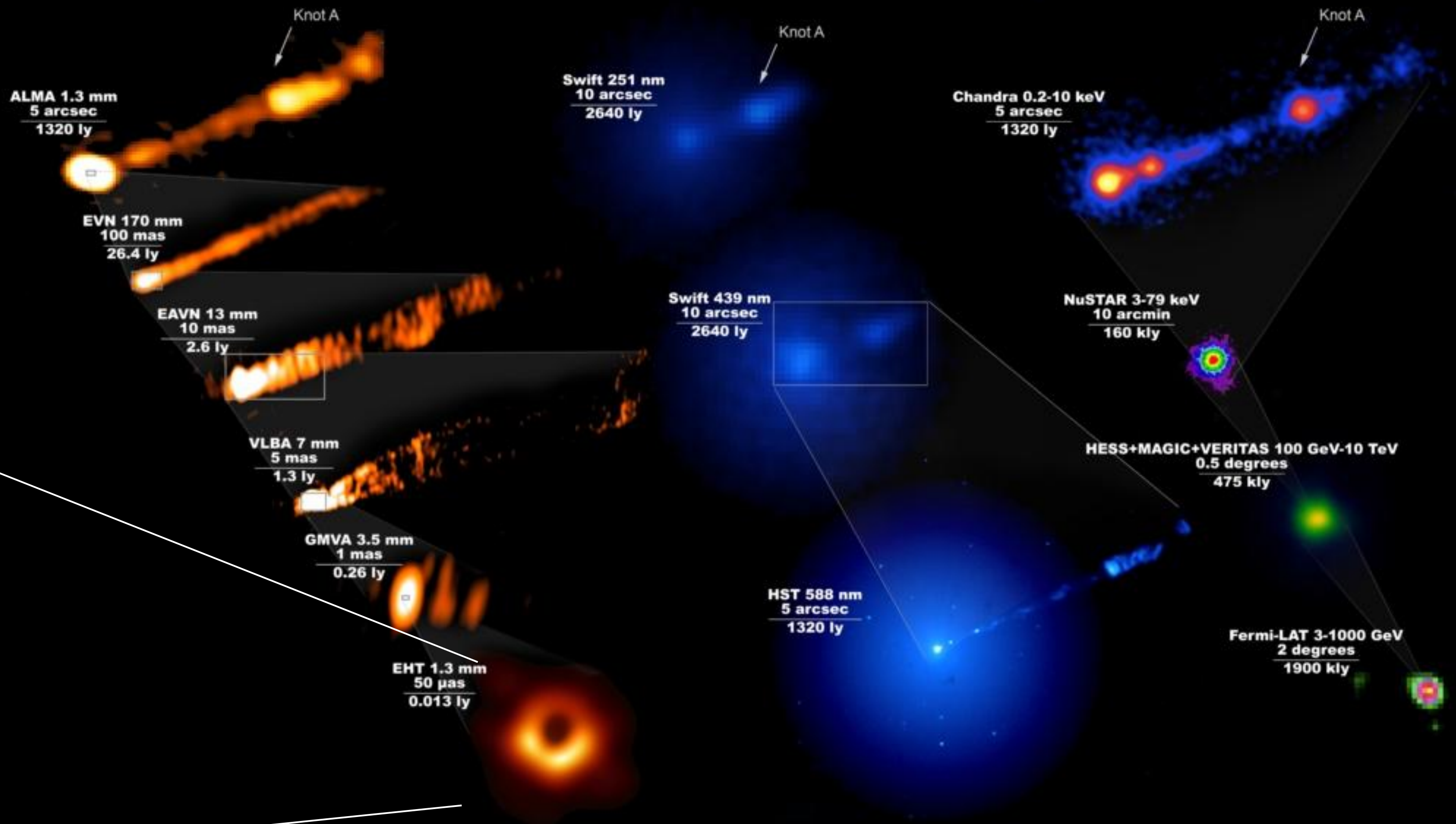
Chael+ 2023, Chael 2025
2307.06372, 2501.12448

M87*

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

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





Jets are thought to be powered by black hole spin energy extracted via magnetic fields (Blandford & Znajek 1977)

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

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

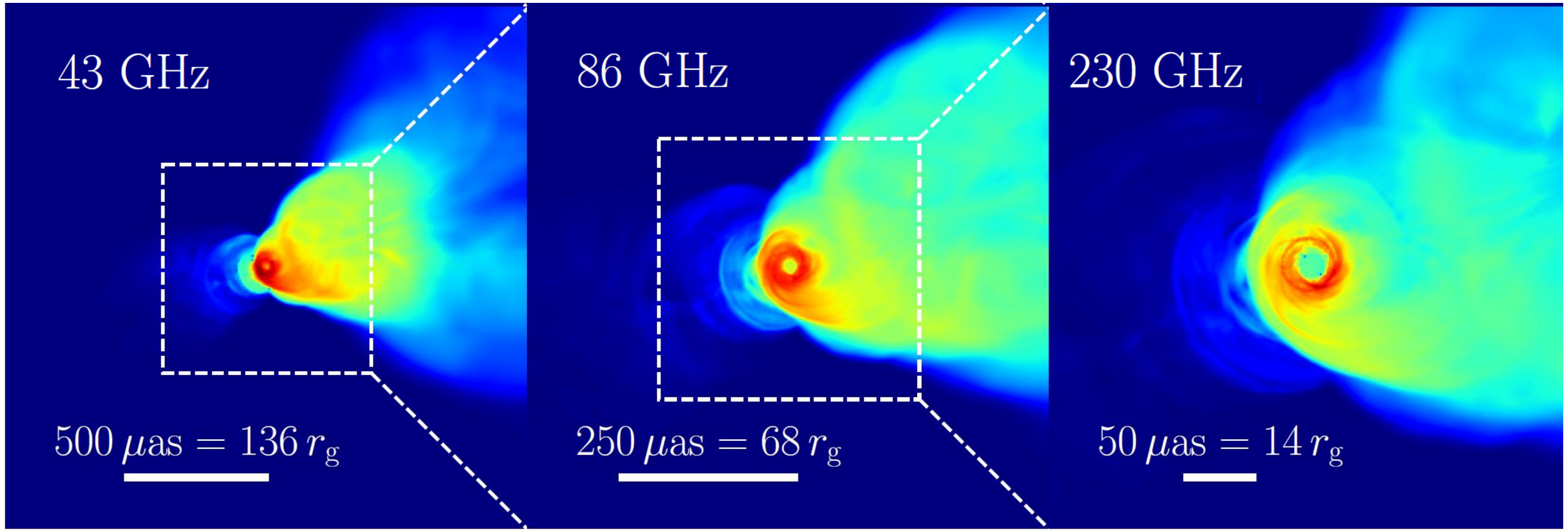
M87 Jets in GRMHD Simulations

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

- Simulations (e.g. Chael+ 2019, 2025) naturally produce:

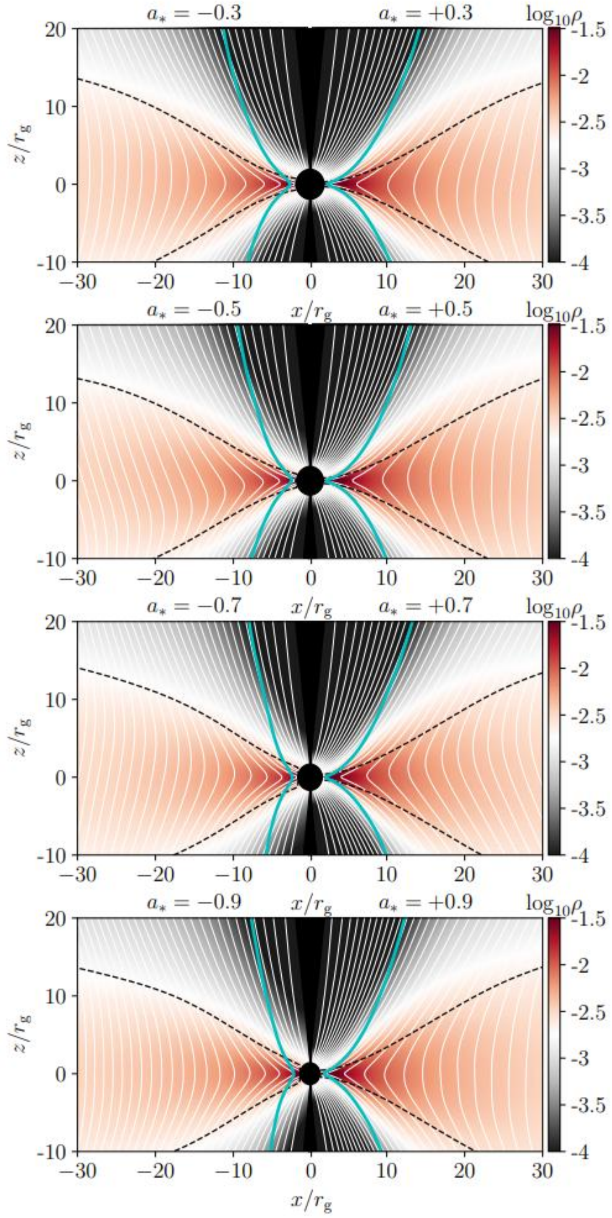
  - observed jet power
  - observed wide opening angle
  - observed core-shift

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



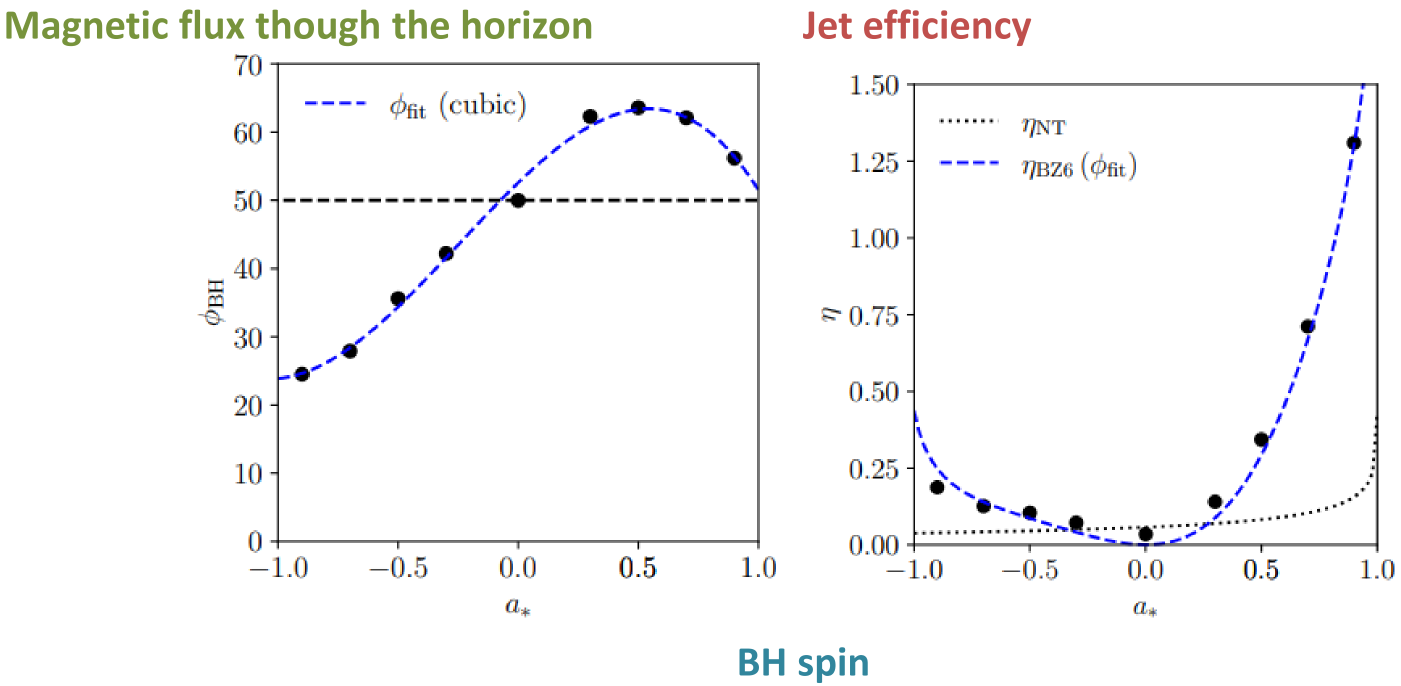
Chael+ 2019

Jets in MADs are Blandford-Znajek



Time-and azimuth-averaged simulation data

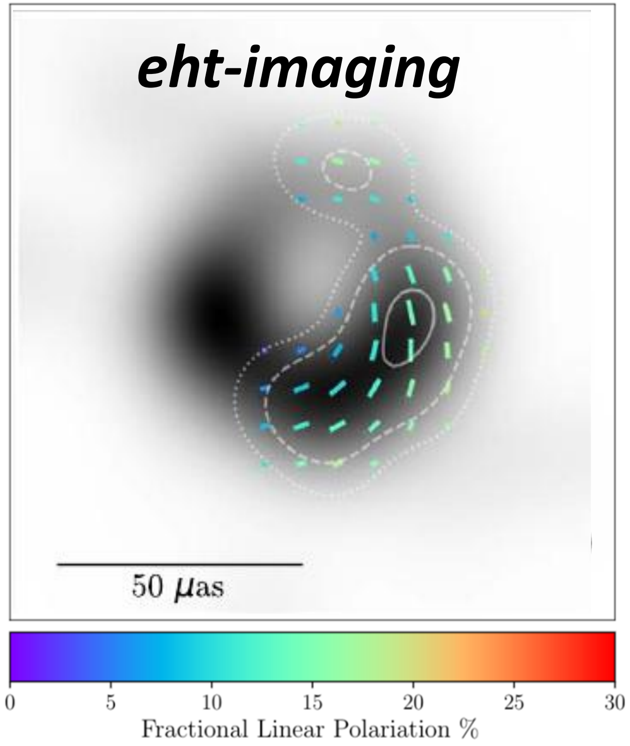
Jet power follows BZ prediction in 8 very-long-duration simulations (10^5 t_g) of magnetically arrested accretion

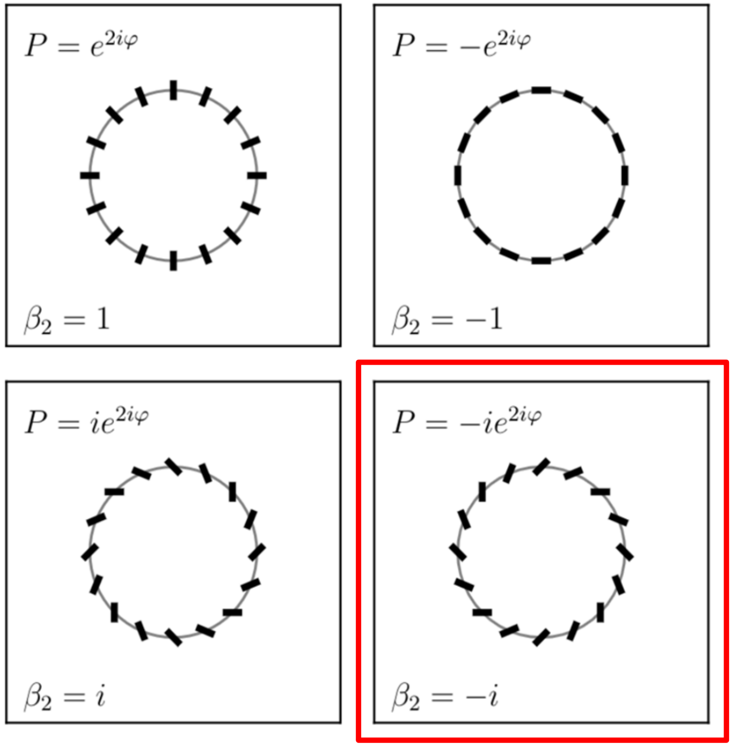


R. Narayan, **A. Chael +** 2022

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

Polarized Images of M87* and horizon-scale energy flow

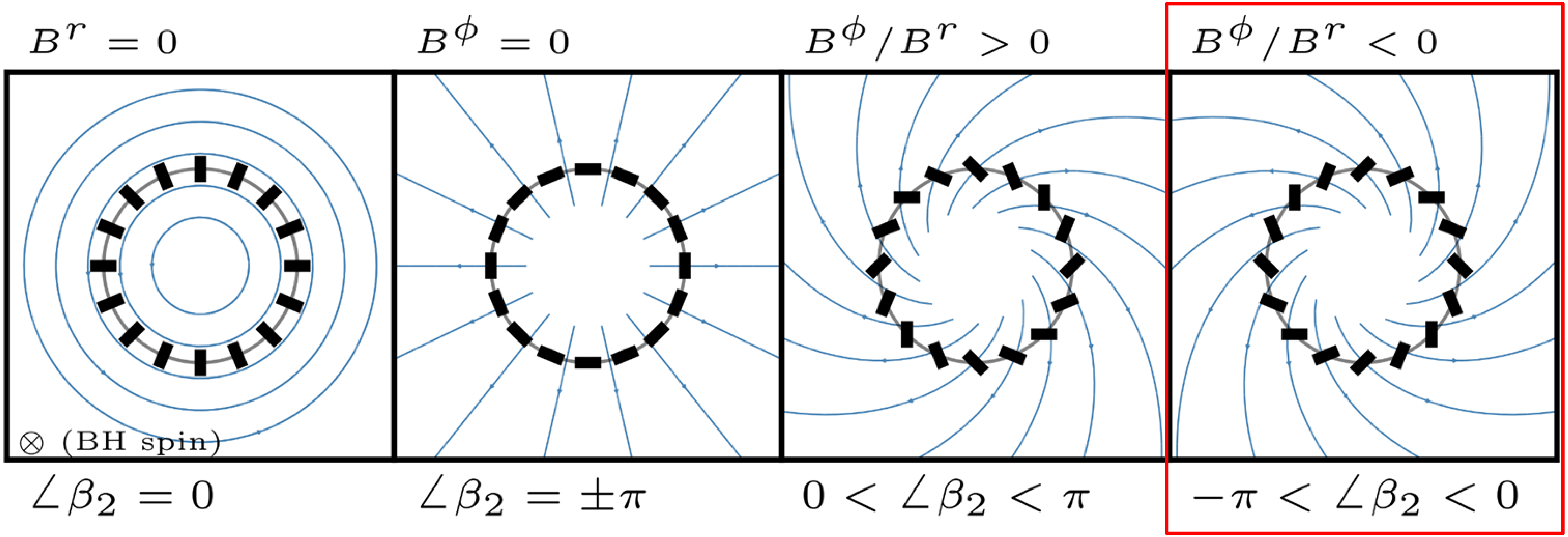




- The polarization spiral's 2nd Fourier mode ($\boldsymbol{\beta_2}$: Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

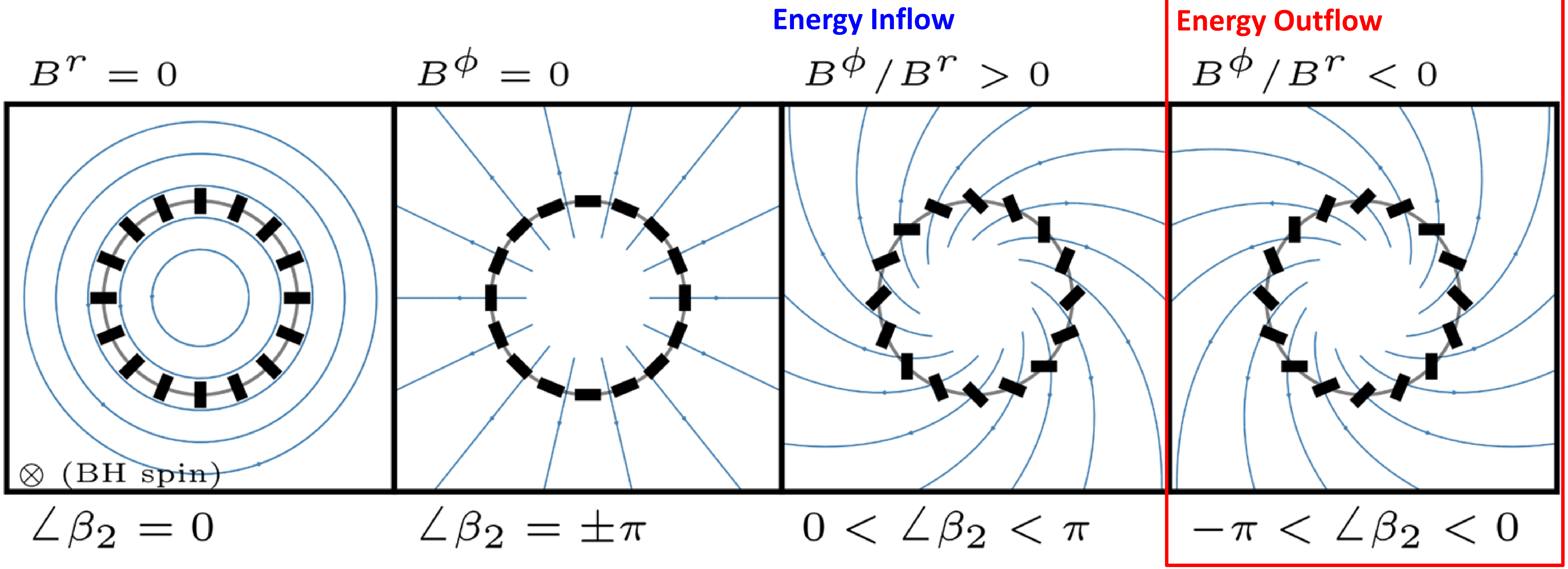
Cartoon model: β_2 is connected to the field pitch angle



- 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)

Chael+ 2023b

BZ model: β_2 is connected to the **electromagnetic energy flux**



Radial Poynting Flux:

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

fieldline angular speed

Chael+ 2023b

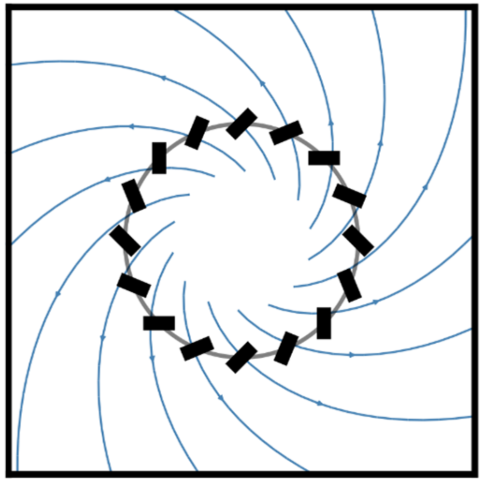
Near-horizon polarization is connected to the **electromagnetic energy flux**

- In simple BZ models, the sign of arg(β_2) is directly connected to the direction of Poynting flux, assuming we know the sign of Ω

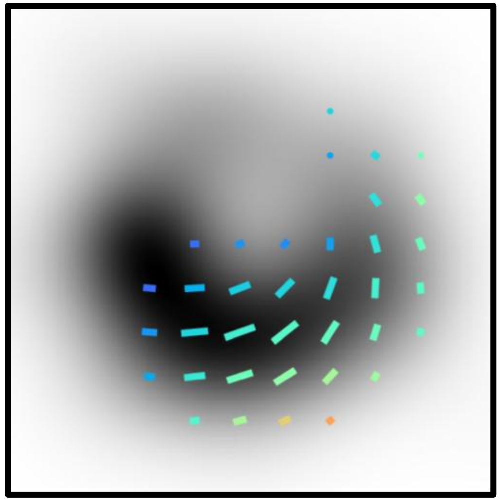
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy outflow in M87***

- Does this simple argument hold up in **more complicated models** of M87*?

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



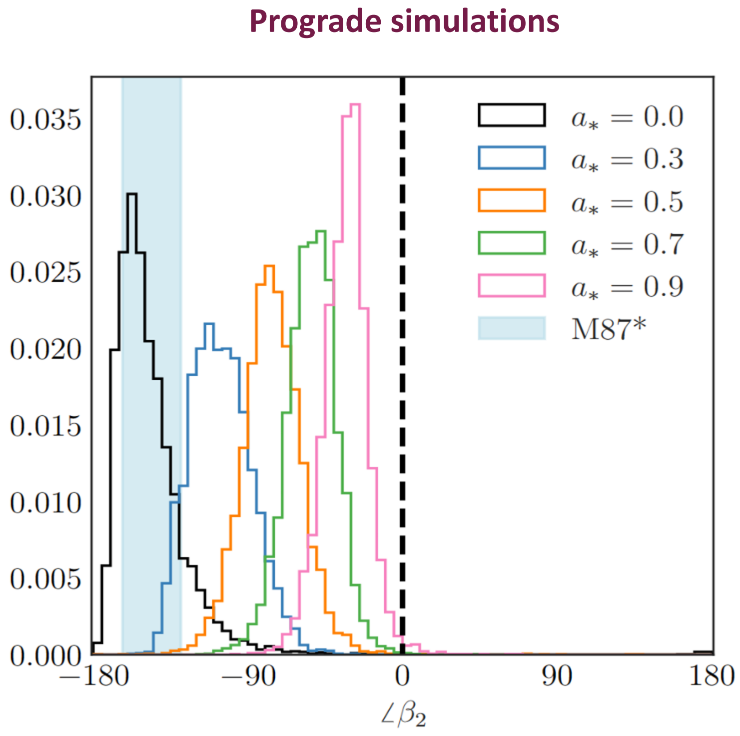
$-\pi < \angle\beta_2 < 0$

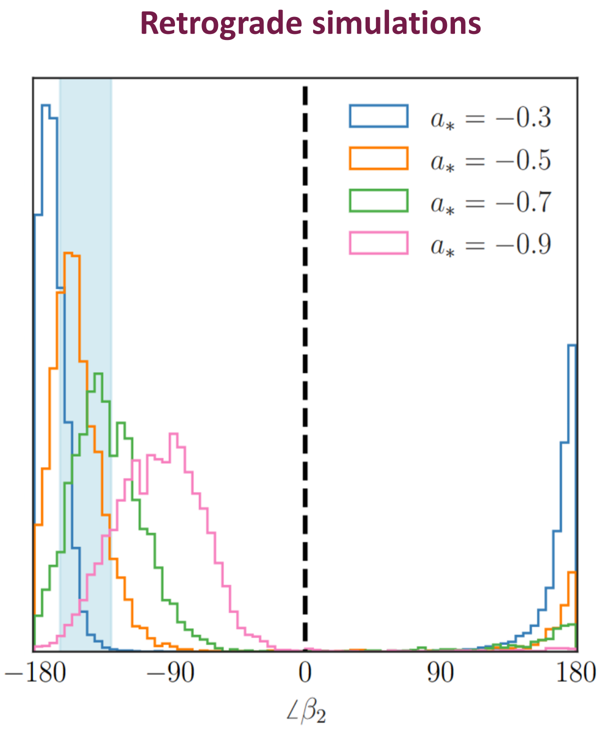


EHTC+ 2021 VII, **Chael**+ 2023b

β_2 in MAD **GRMHD simulations** of M87*

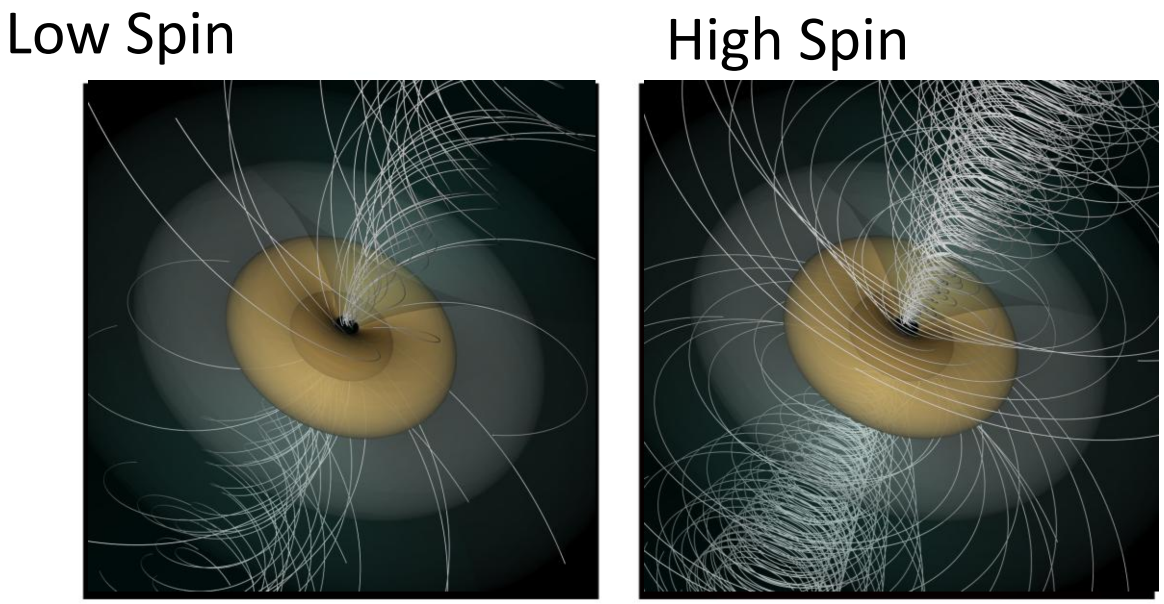
- 1600 simulated EHT-resolution M87* images from MAD simulations (Narayan+ 2022)
- Almost all 230 GHz simulation images have **negative arg(β_2)** consistent with the measured energy outflow in the simulations
- arg(β_2) has the **same dependence on spin** as in a BZ monopole model, despite effects of turbulence, non-equatorial emission, and Faraday rotation.





Chael+ 2023b

Polarized images are **spin dependent**

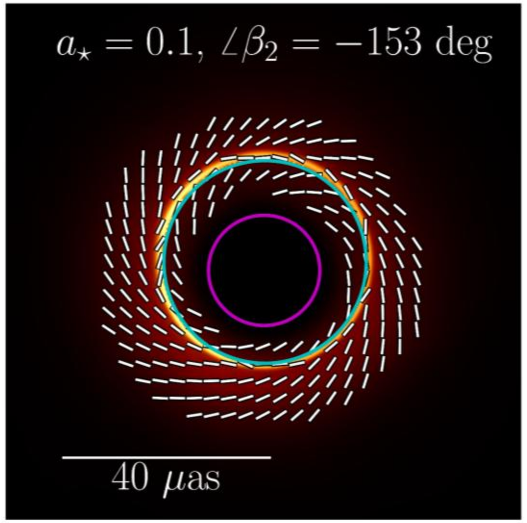


- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power

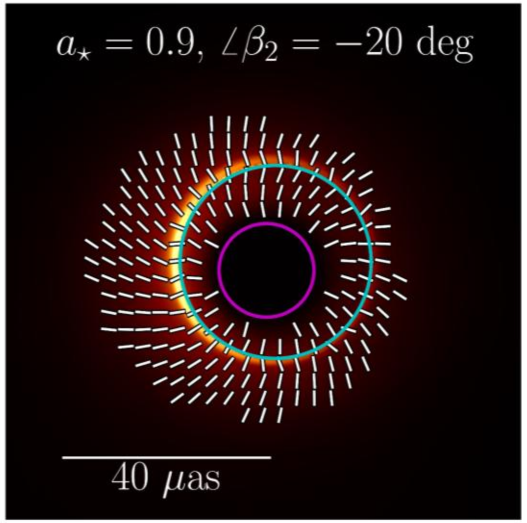
Chael+ 2023b**; Chael** 2025**;** Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

Polarized images are **spin dependent**

Low Spin



High Spin

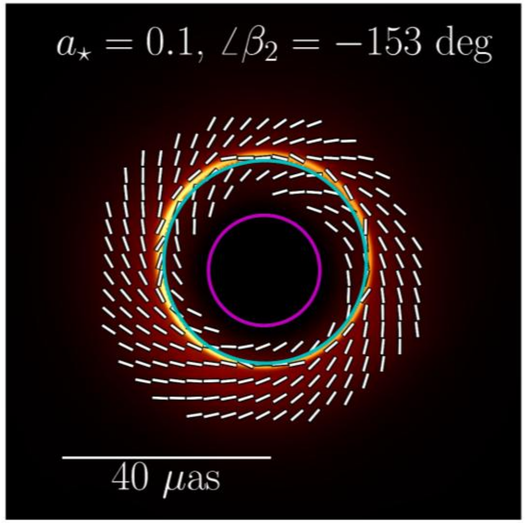


- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

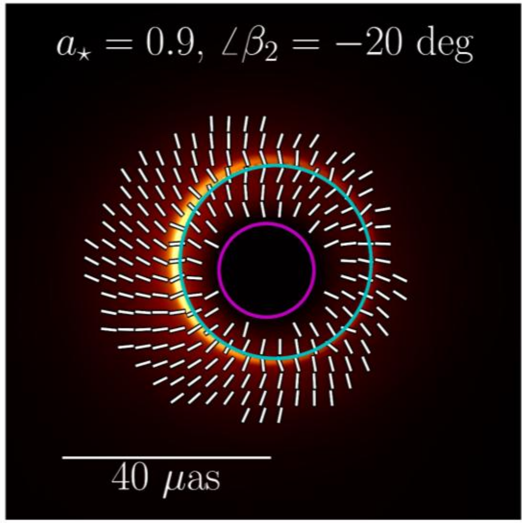
Chael+ 2023b**; Chael** 2025; Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

Polarized images are **spin dependent**

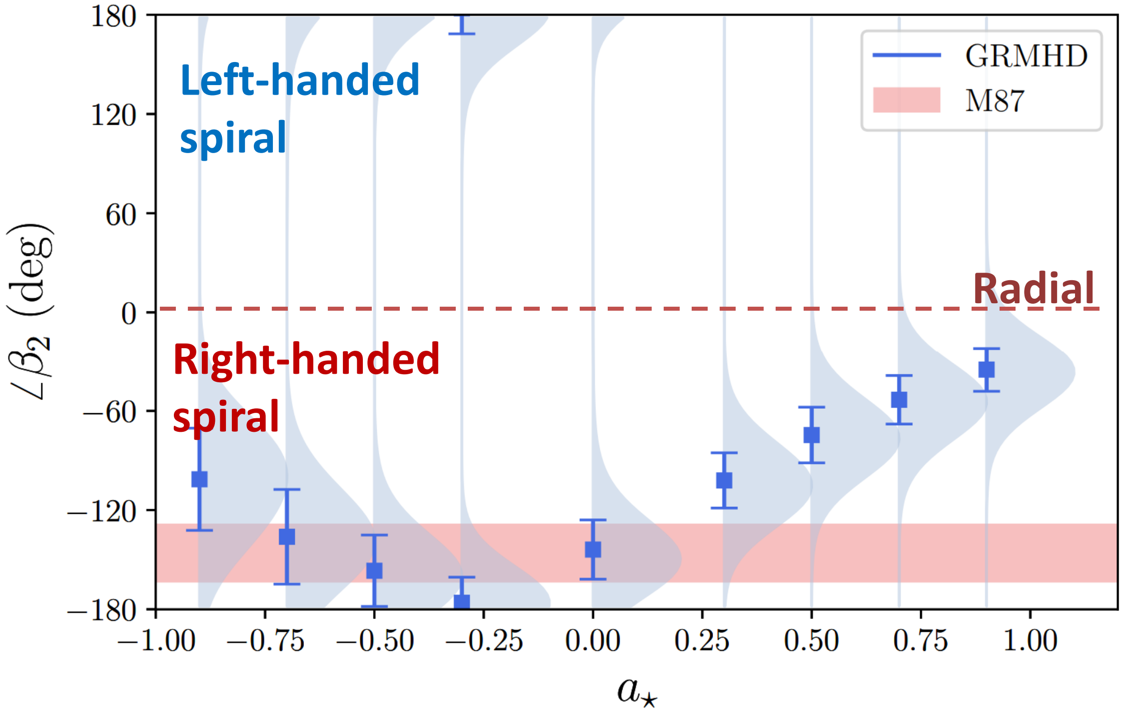
Low Spin



High Spin



M87*

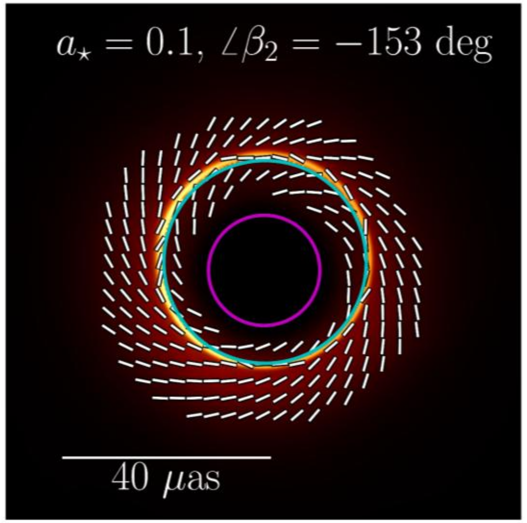


- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
  - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)

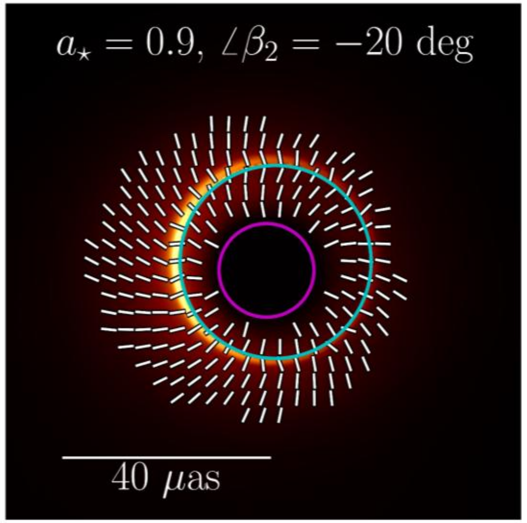
Chael+ 2023b; **Chael** 2025; Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

Polarized images are **spin dependent**

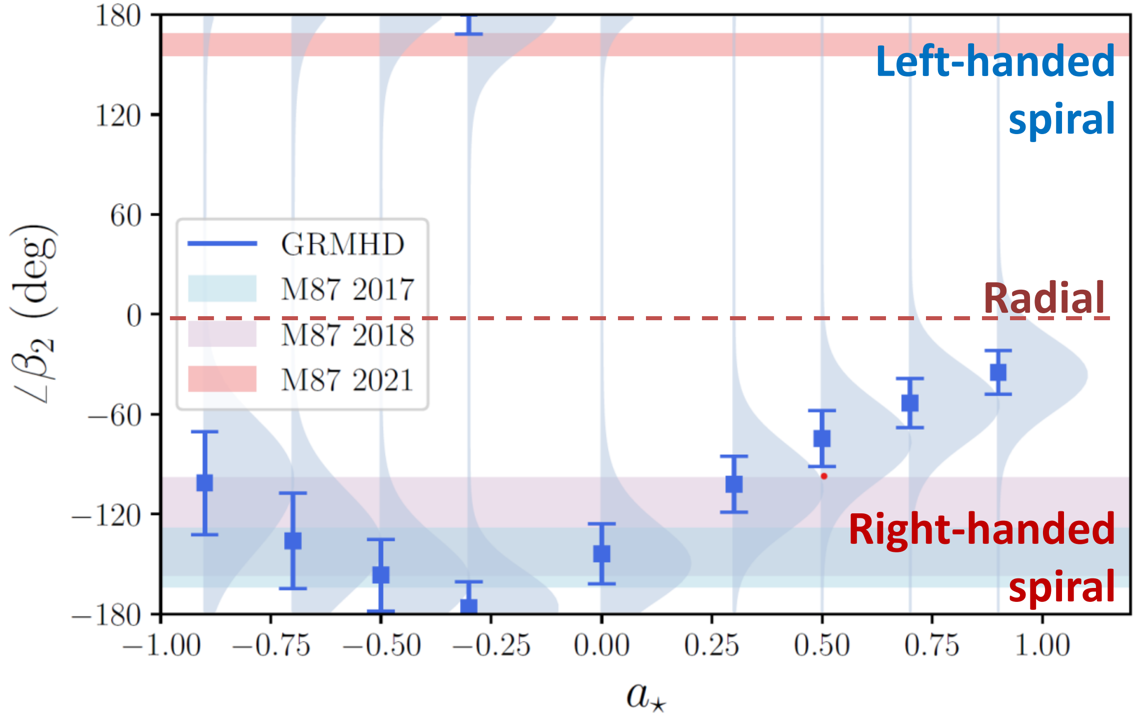
Low Spin



High Spin



M87*

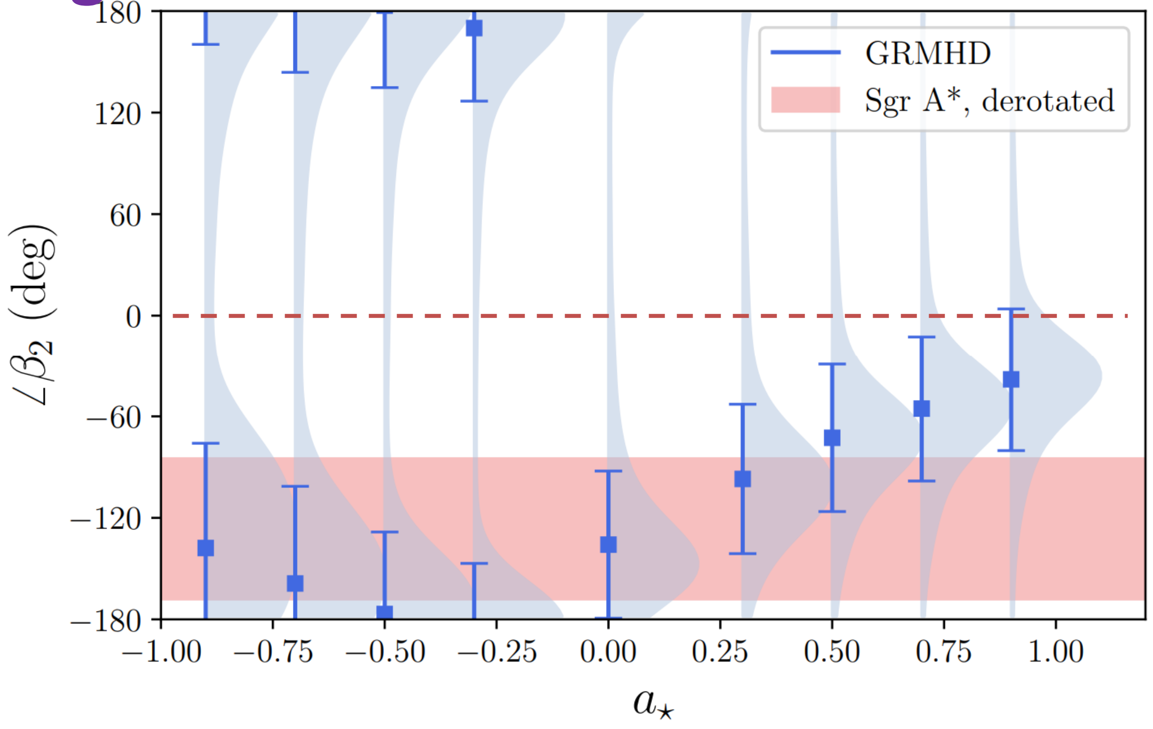


- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
  - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)
- **The shift in arg(β_2)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

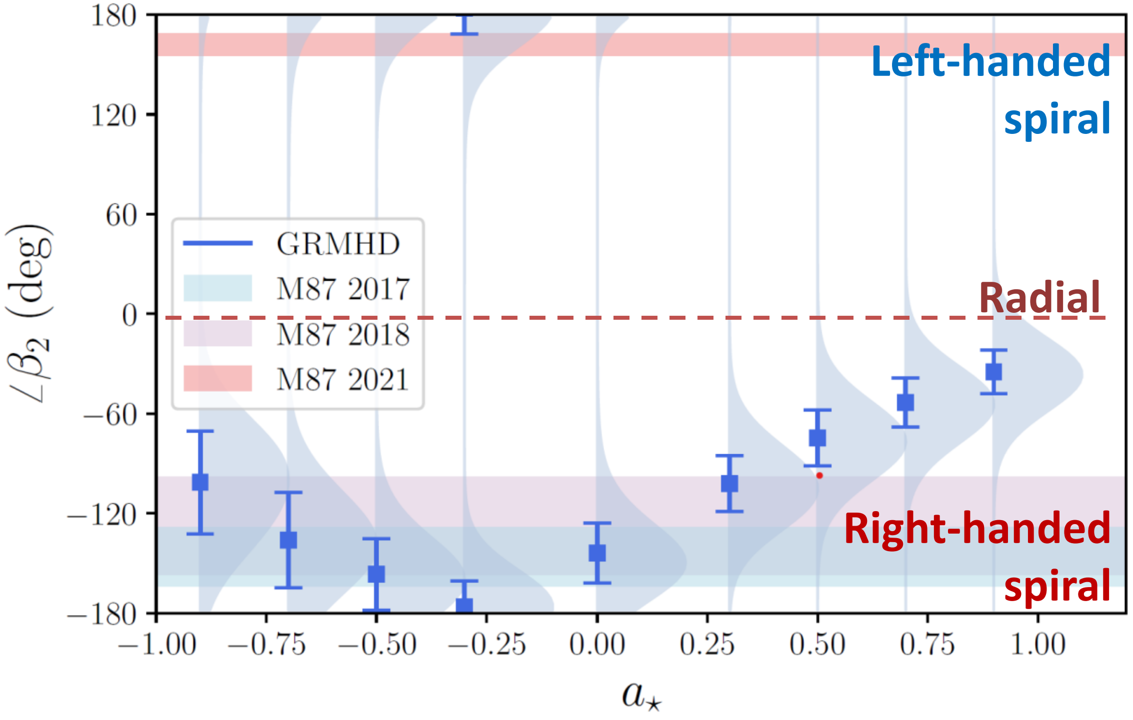
Chael+ 2023b; **Chael** 2025; Wong, **Chael**+ in prep
β_2 from Palumbo+ 2020
Simulations from Narayan+ 2022

Polarized images are **spin dependent**

Sgr A*



M87*

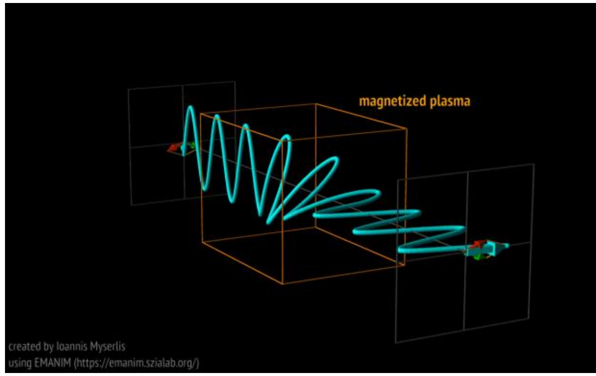


- Sgr A* polarization is consistent with energy outflow **if** the BH rotates clockwise
  - NIR flares (GRAVITY+ 2018) and ALMA mm lightcurves (Wielgus+ 2022) all rotate **clockwise**
- Sgr A* spin is not well constrained by EVPA pattern alone
  - combined EHT+MW constraints prefer high spin (EHTC+ VIII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

Polarimetric spin measurements are possible and will get better!

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

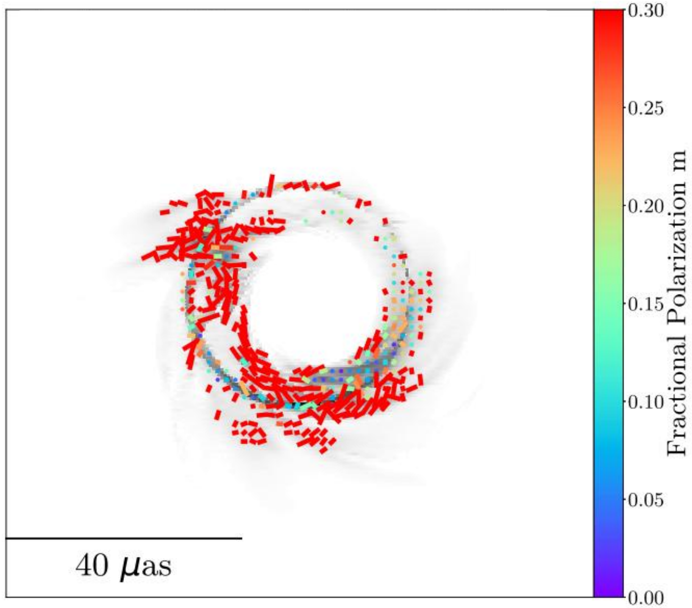
What about **Faraday Rotation**?

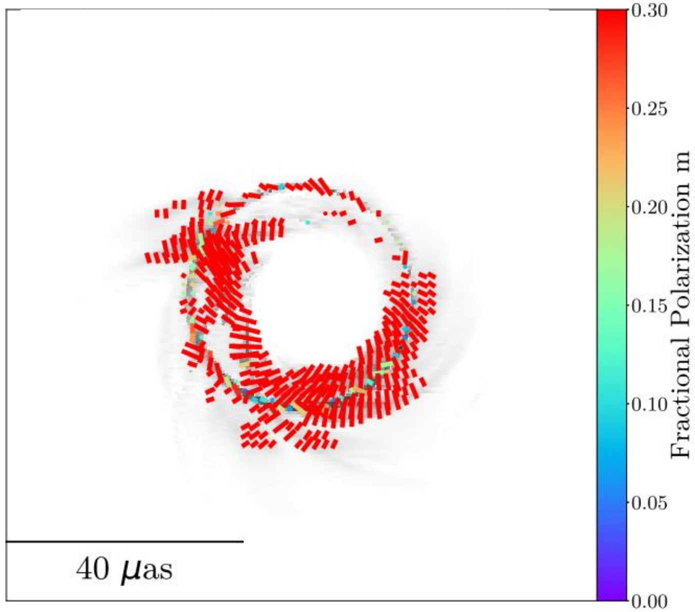


With Faraday

Without Faraday

'infinite' resolution

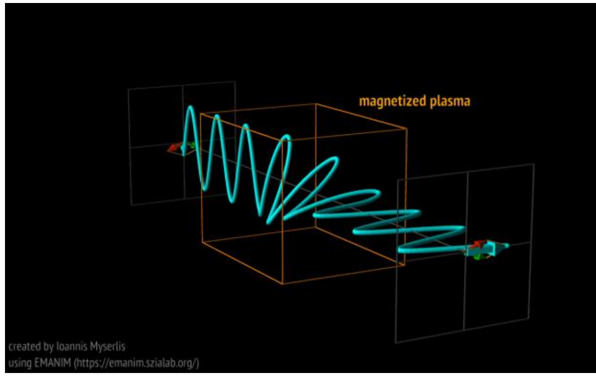




- Significant Faraday rotation on different scales
  → **Scrambles** polarization vectors on small scales

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

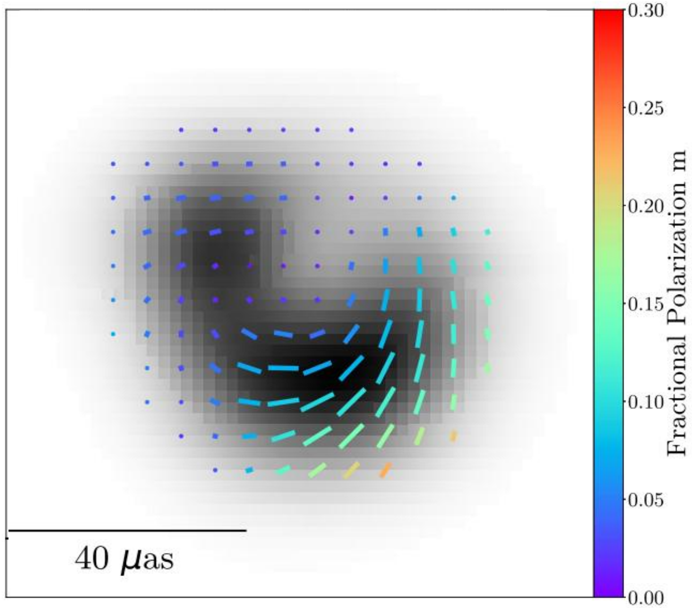
What about **Faraday Rotation**?

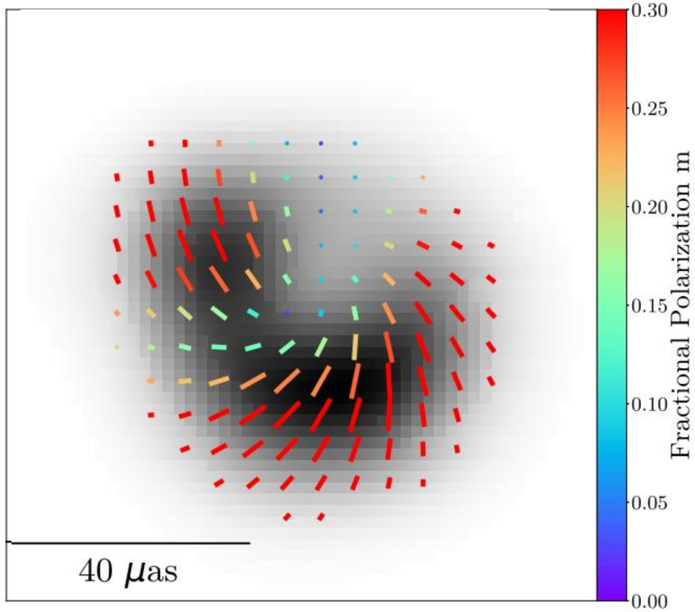


With Faraday

Without Faraday

EHT resolution



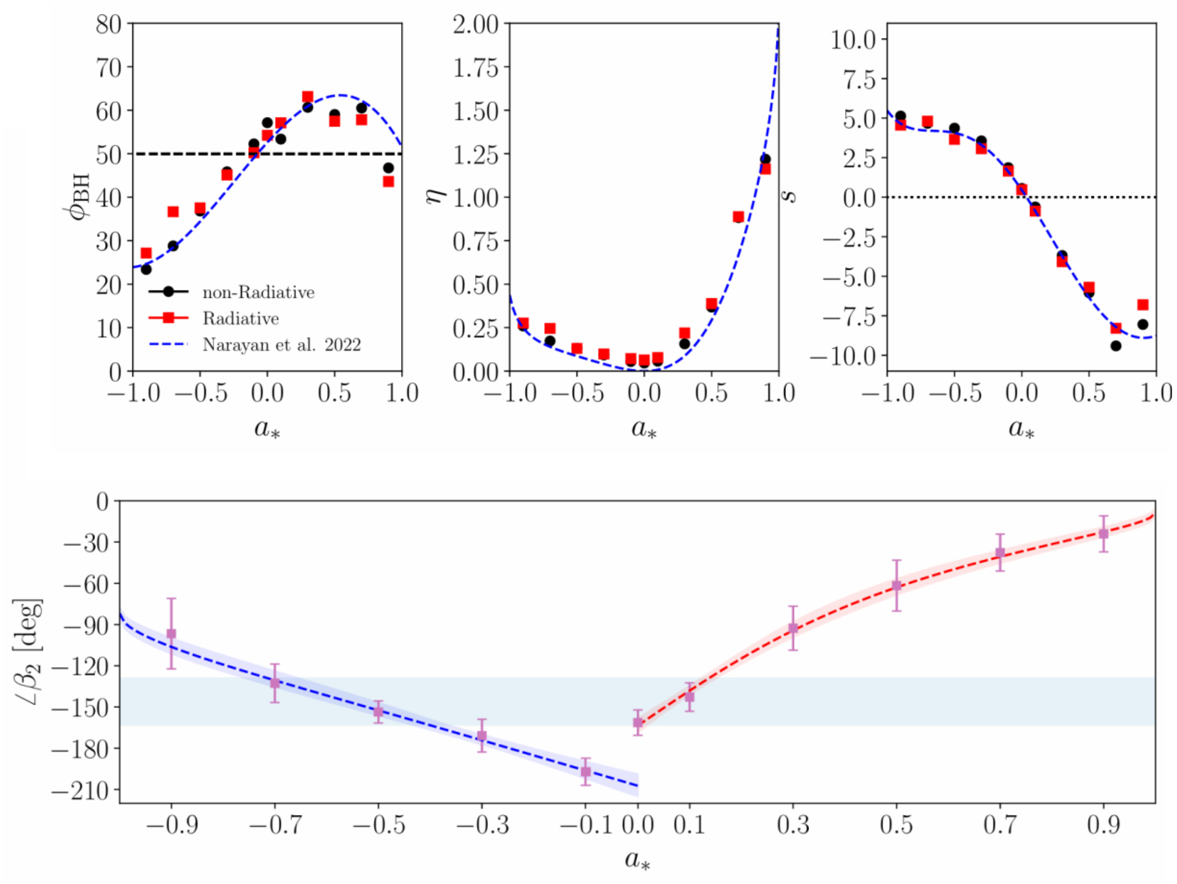


- Significant Faraday rotation on different scales
  - → **Scrambles** polarization vectors on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from **colder electrons** is necessary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

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

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

Aside: Radiative Simulations Have Similar Jets…



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

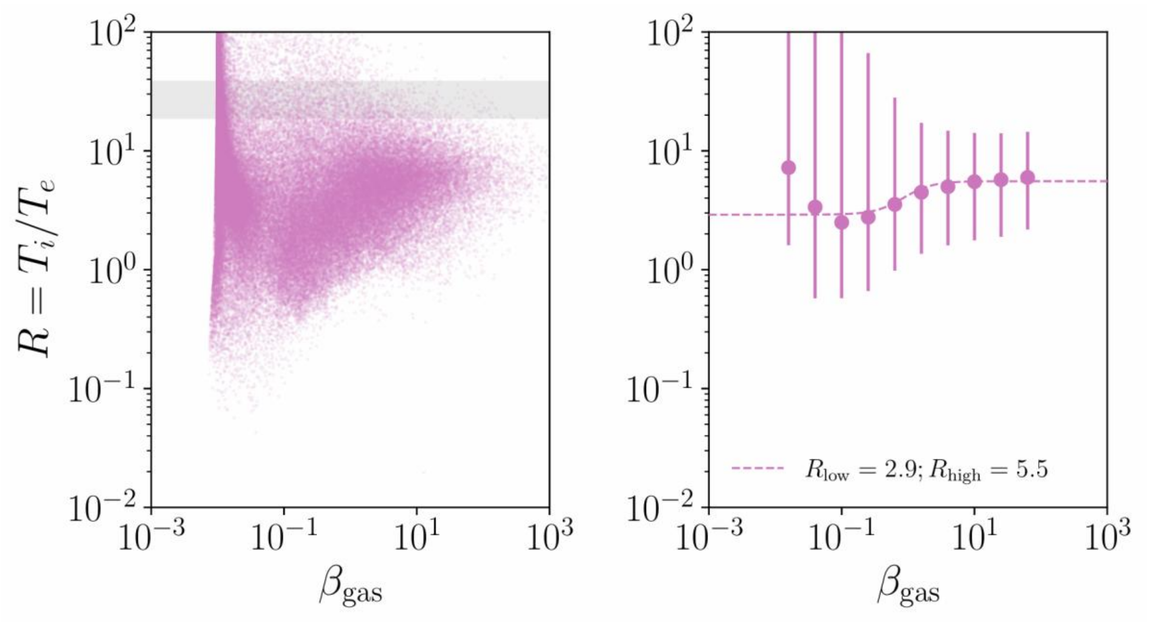
$$T_{\rm e} \neq T_{\rm i}$$

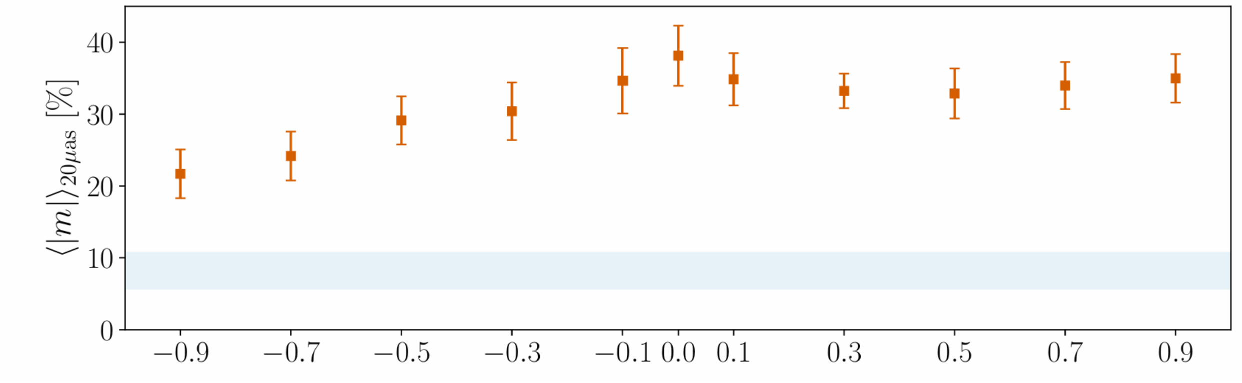
- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** (e.g. Ressler+2015,17, Chael+ 2018,19)

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

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

…but electrons are too hot!





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

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

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**..

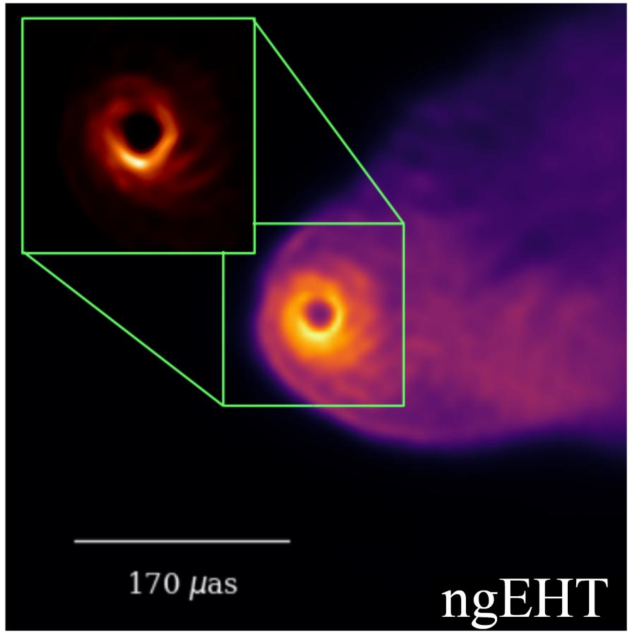


Image the connection between the BH and the low-brightness extended jet in **high dynamic range** with the **next-generation EHT (ngEHT)**

By zooming **in**..

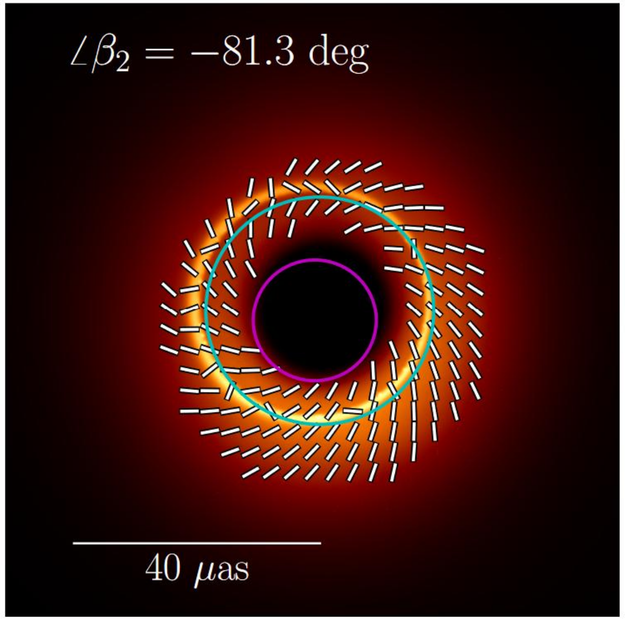
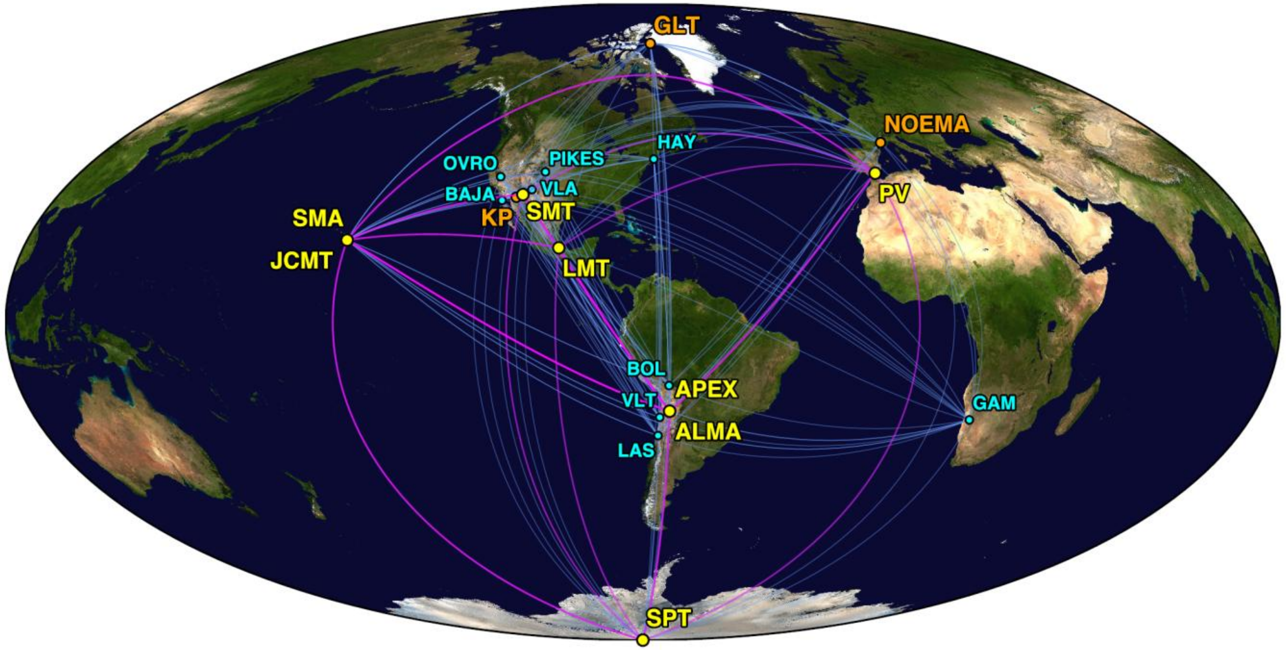
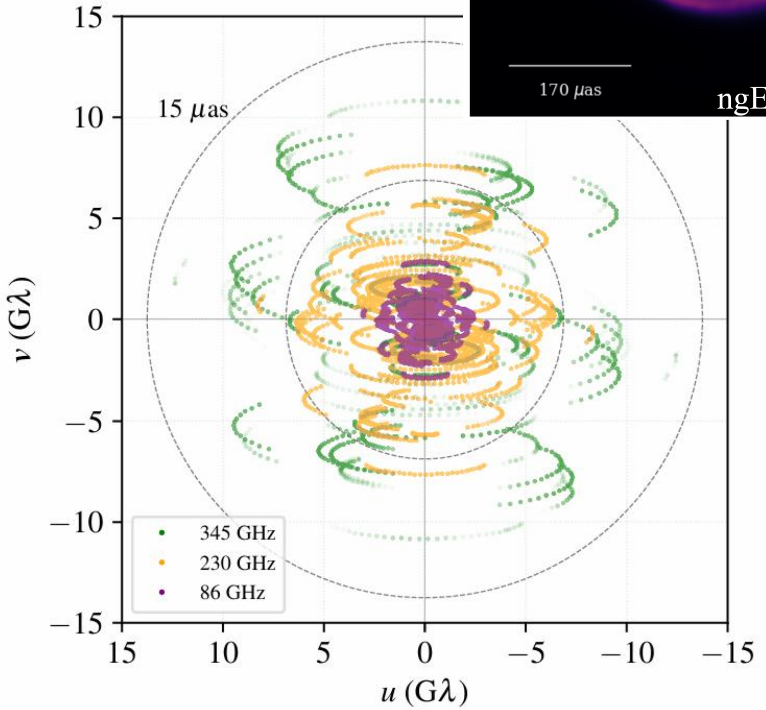
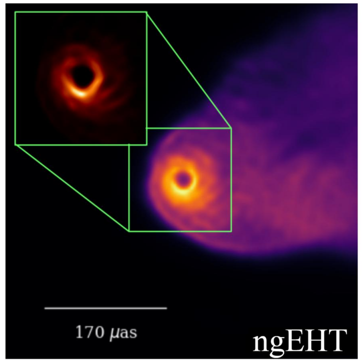


Image field lines close to the event horizon in **high resolution** with the **Black Hole Explorer (BHEX)**

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

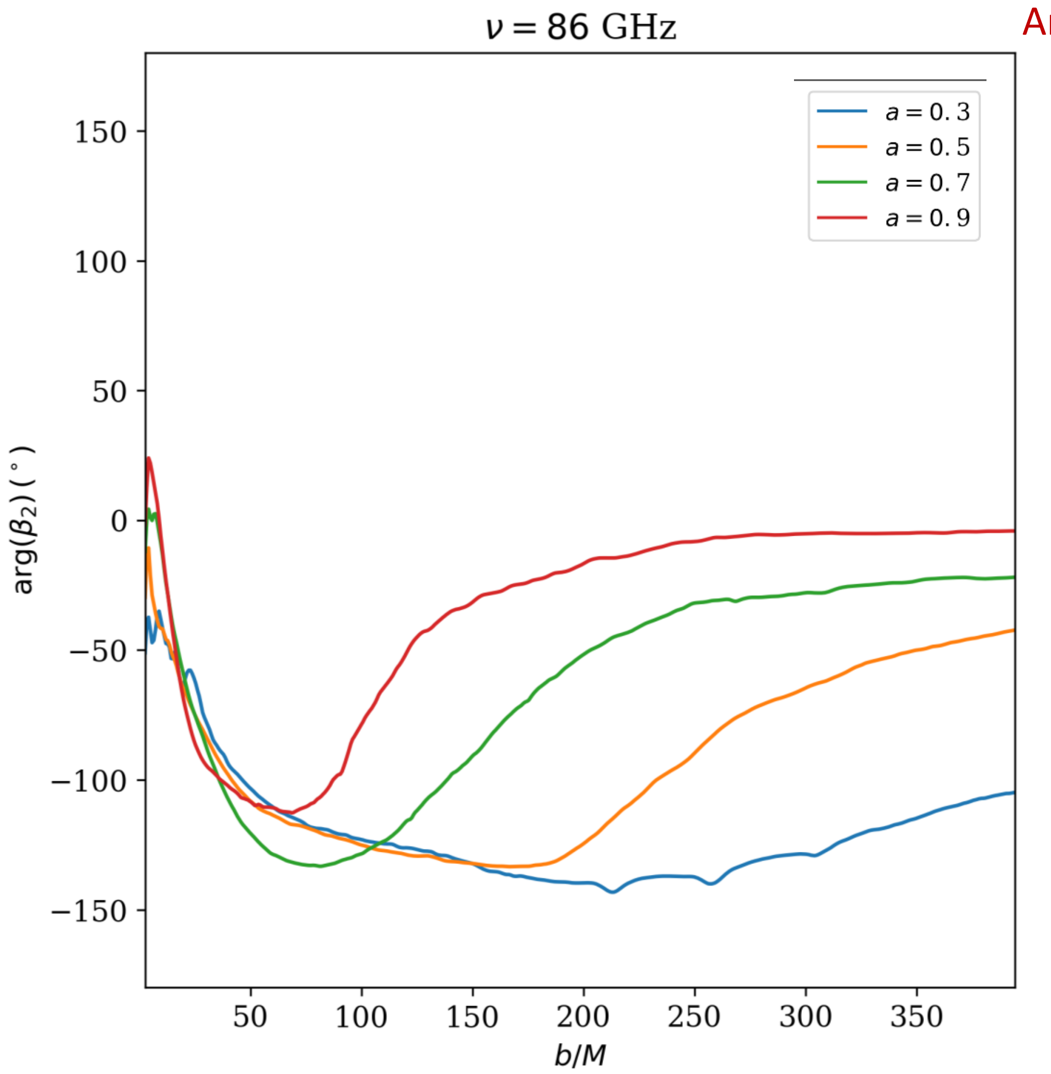
$$N_{\rm obs} = \binom{N_{\rm sites}}{2} \propto N_{\rm sites}^2$$

Doeleman+ 2023

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)

Average Polarization Angle



Jet Distance

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

Image Credit: Zack Gelles

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

Zack Gelles (Princeton)
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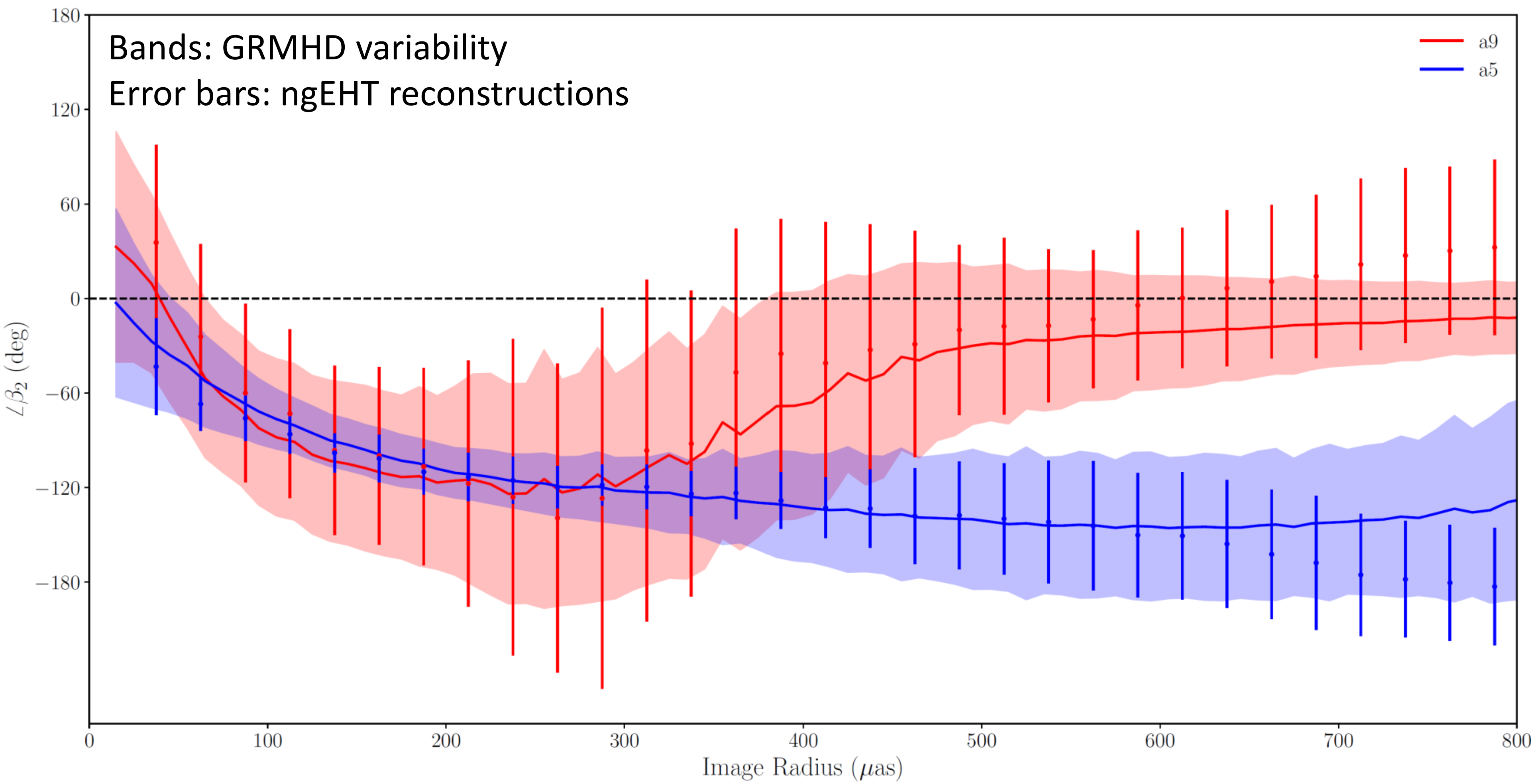
Average Polarization Angle



Spin 0.9

Spin 0.5

Jet Distance

Image Credit: Zack Gelles (in prep)

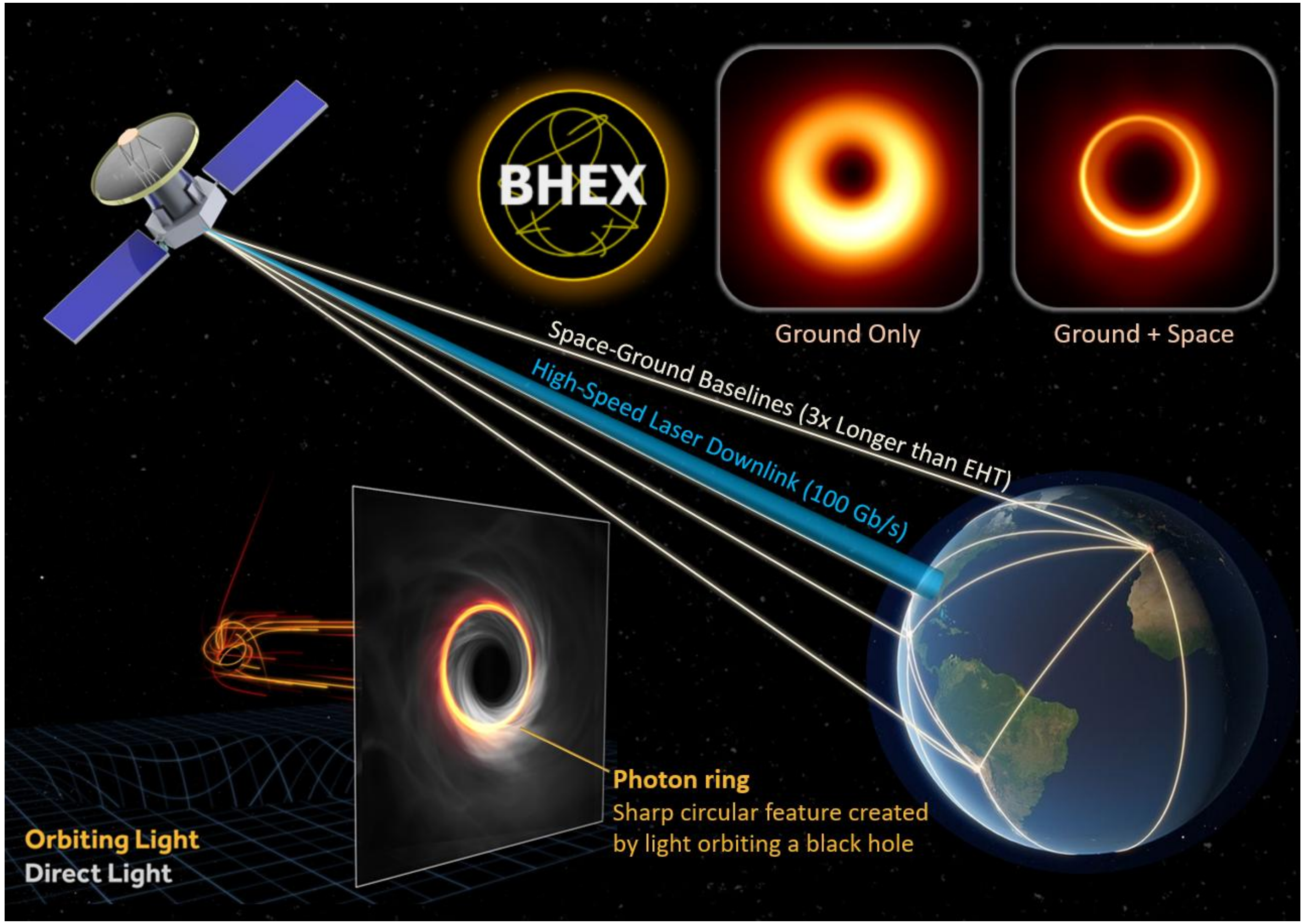
Going Further: The Black Hole Explorer (BHEX)

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

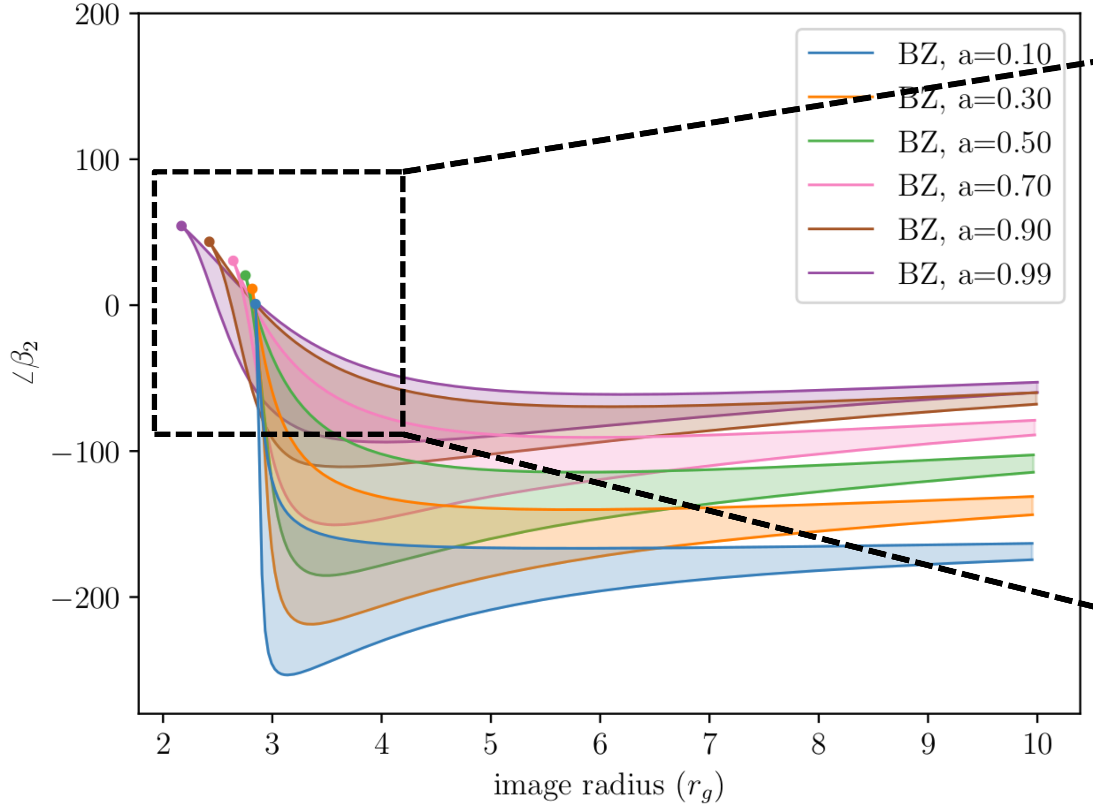
BHEX Science Goals

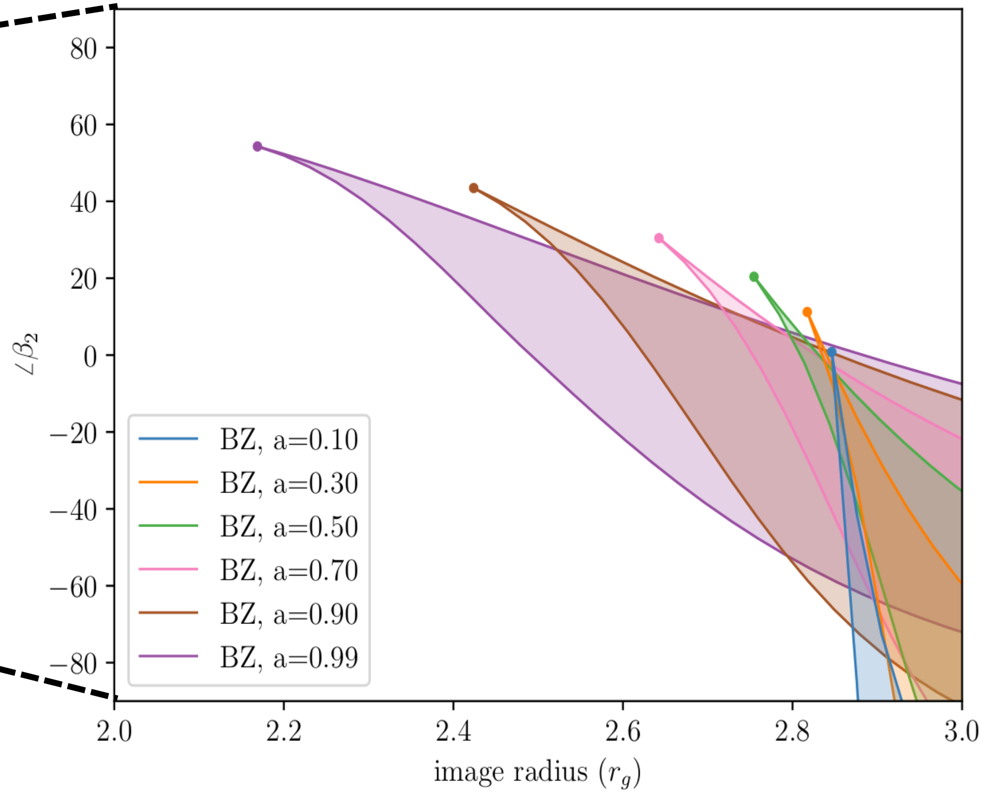
1. Discover and measures a black hole's photon ring
2. Reveal the shadows of >10 supermassive black holes
3. Constrain jet launching & acceleration on horizon → parsec scales



blackholeexplorer.org

Universal value of the polarization angle at the horizon

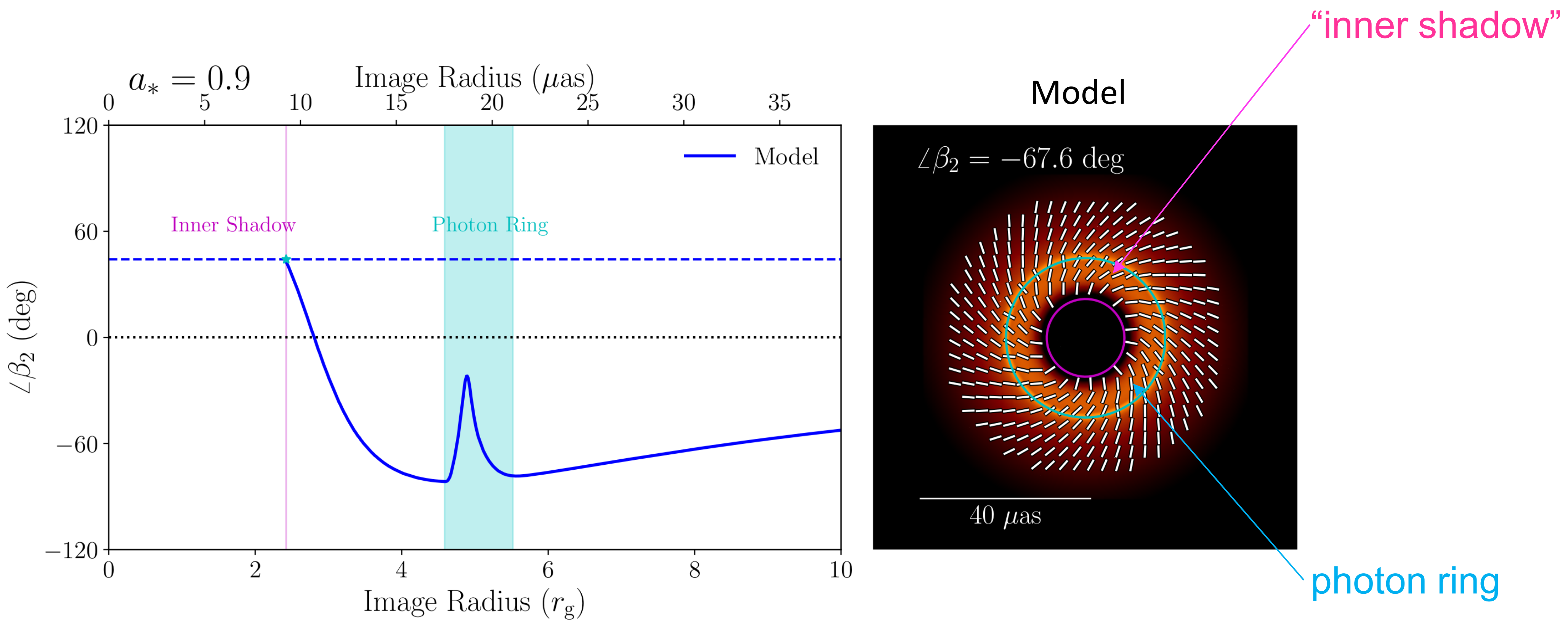




In axisymmetric GRMHD models, synchrotron emission has a **value dependent only on spin and inclination** at the inner shadow (the asymptotic lensed image of the horizon; Chael+ 2021)

Hou+ 2025, Lupsasca, Chael+ in prep

To look for energy extraction, we need to zoom **in**



- arg(β_2) evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - strong evolution of arg(β_2) close to the horizon is predicted by both simple BZ models and GRMHD

Chael+ 2023b

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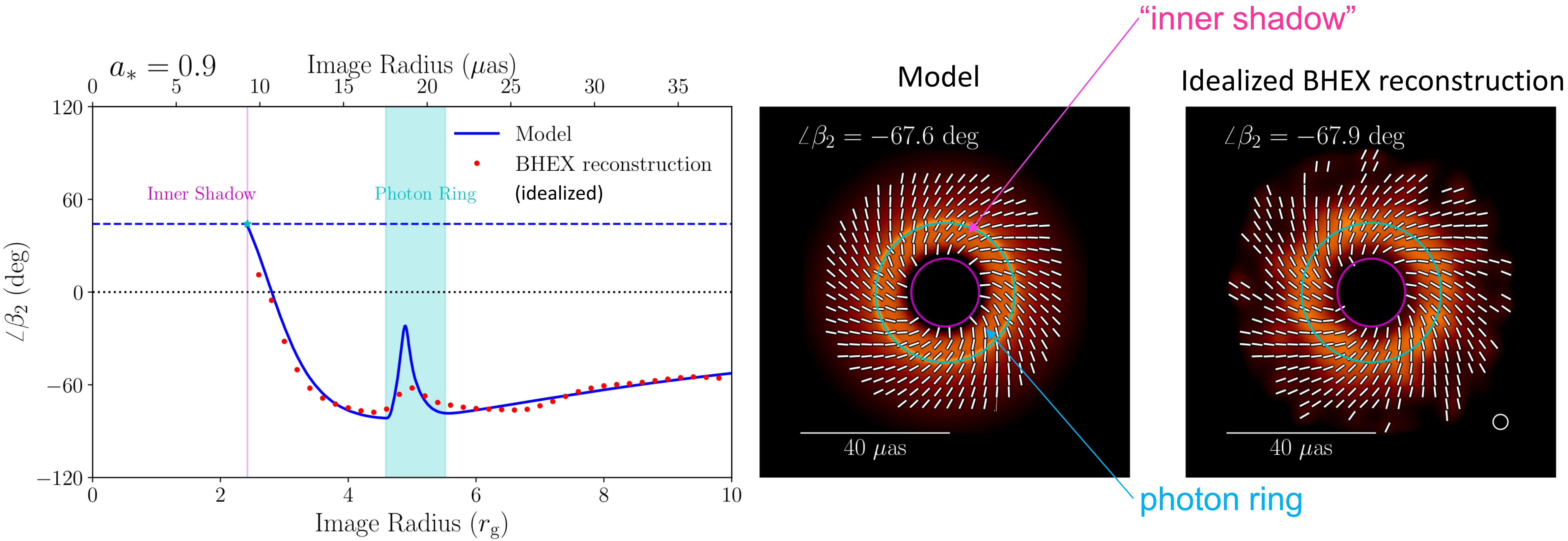


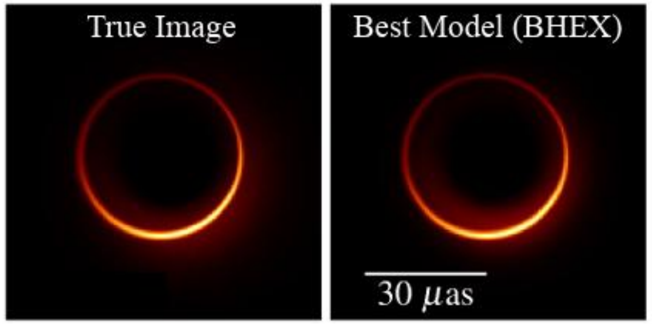
- arg(β_2) evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
    - strong evolution of arg(β_2) close to the horizon is predicted by both simple BZ models and GRMHD
- **BHEX + EHT can obtain the resolution to observe this evolution**
    - Directly probing field lines that penetrate the ergosphere and approach the horizon

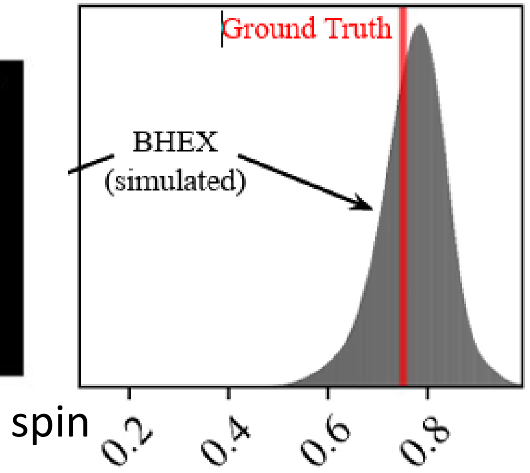
Chael+ 2023b

BHEX photon ring Spin Measurements can calibrate polarimetric spin relations

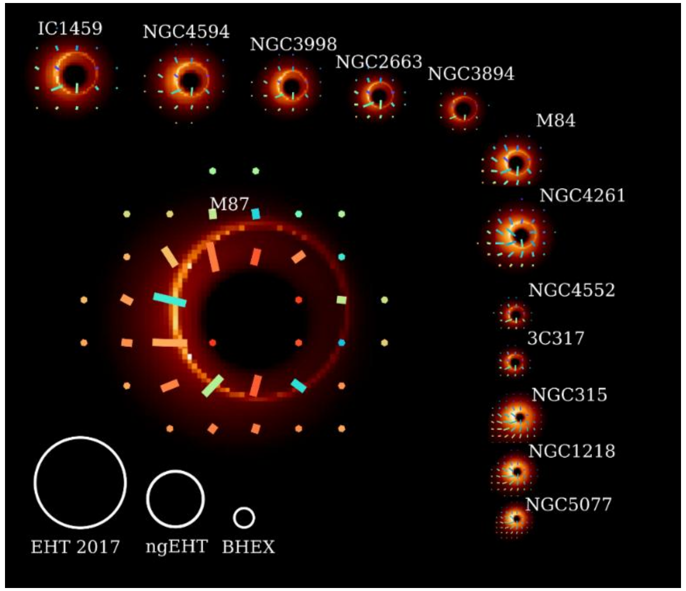
- By comparing strongly-lensed and direct emission ring size and shape, BHEX will constrain Sgr A* and M87*'s **spin to ~10%** and **mass to ~1%**
- Direct photon ring spin measurements will help **calibrate** measurements from near-horizon polarimetry
- BHEX will make >10 horizon-scale measurements of mass (from the size of the emission region) and spin (from magnetic field helicity)

M87 Photon ring measurements





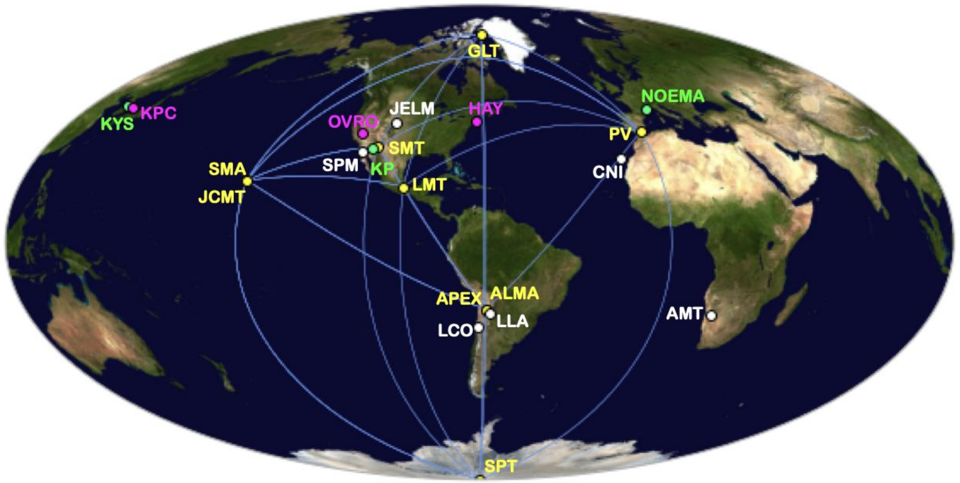
Horizon-resolvable sources with BHEX



Johnson+ 2020, Johnson+ 2024, Lupsasca+ 2024, Zhang+ 2024

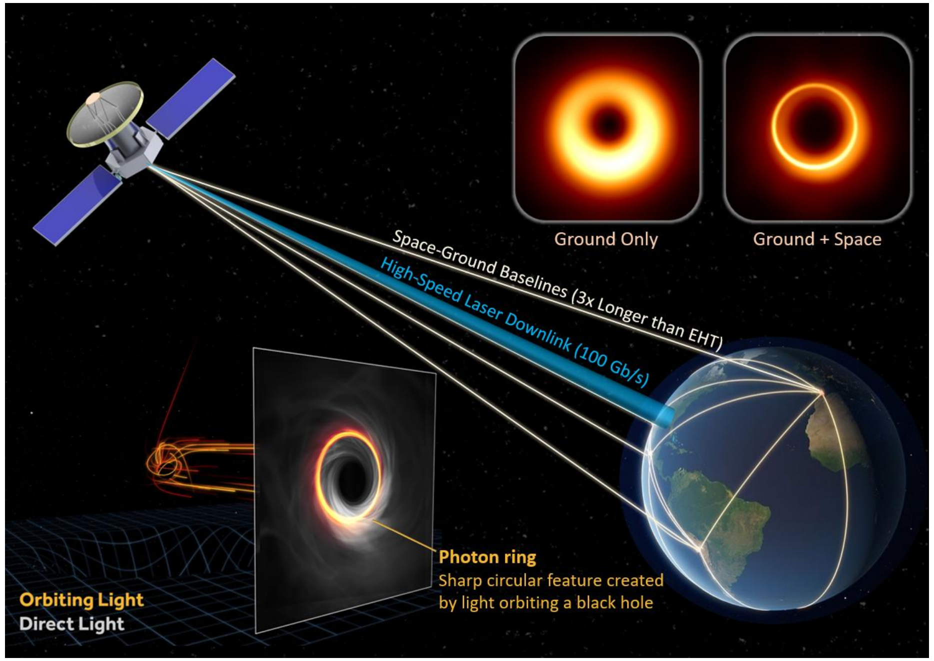
The future of near-horizon black hole astrophysics

Expanded ground-based EHT array



- Expand all EHT sites to multi-frequency observing and add 4-5 new stations (e.g. Doeleman+ 2023)
- Image black holes and jets in high dynamic range at multiple frequencies
- Probe jet launching from horizon to hundreds of Schwarzschild radii (see e.g. Gelles+ 2024: [2410.00954](2410.00954))
- Make movies of Sgr A* and resolve black hole flares

Space VLBI / Black Hole Explorer (BHEX)

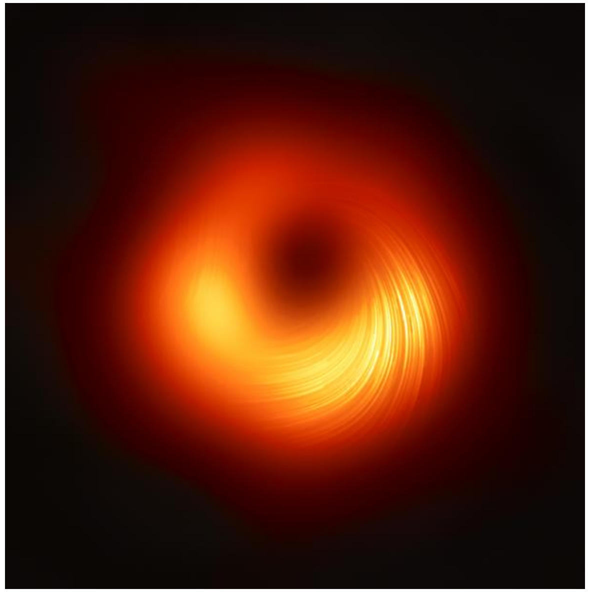


- NASA SMEX proposal for a mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to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

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

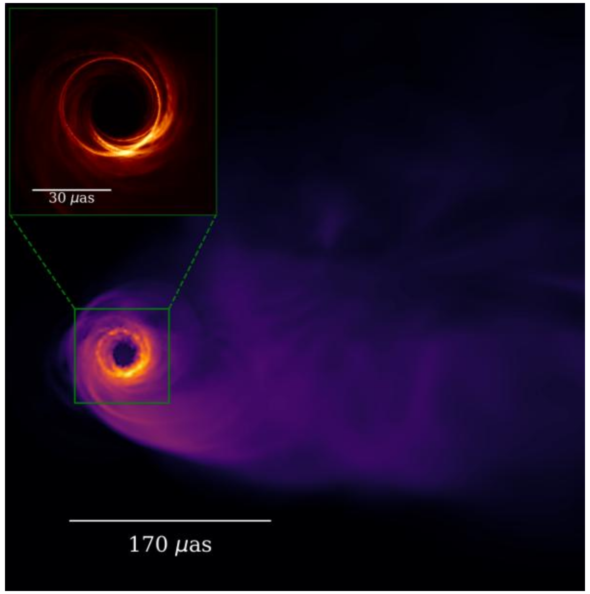
Takeaways…

1. **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*?

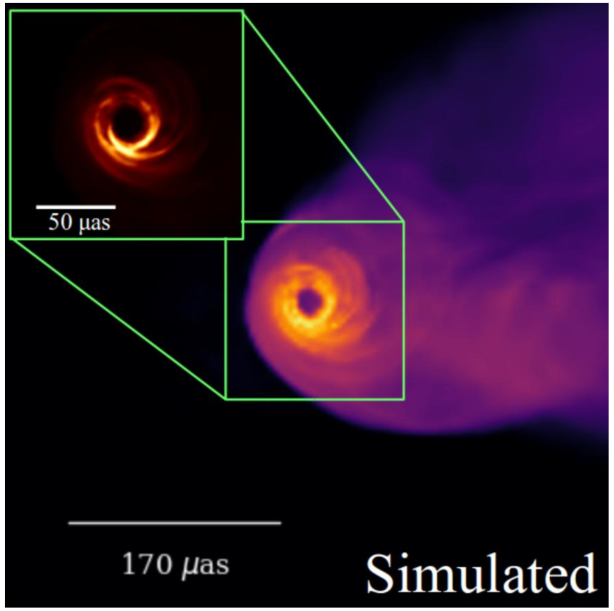


EHT VII, 2021; **Chael** 2025

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?



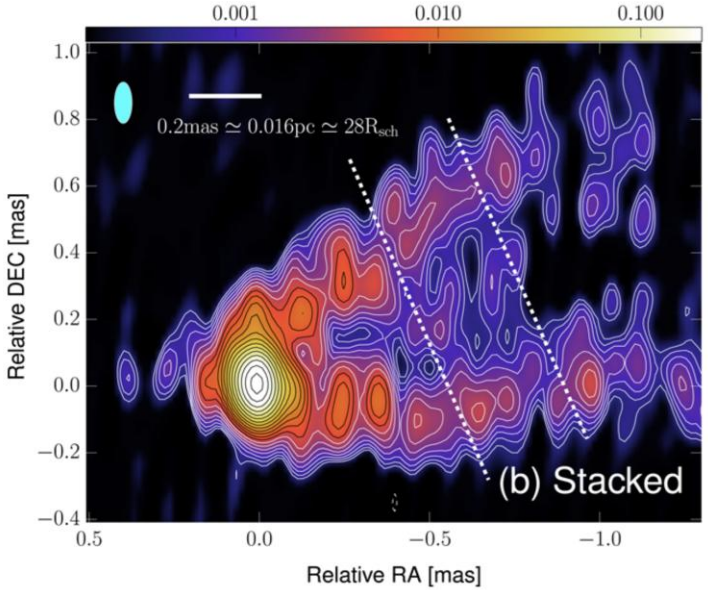
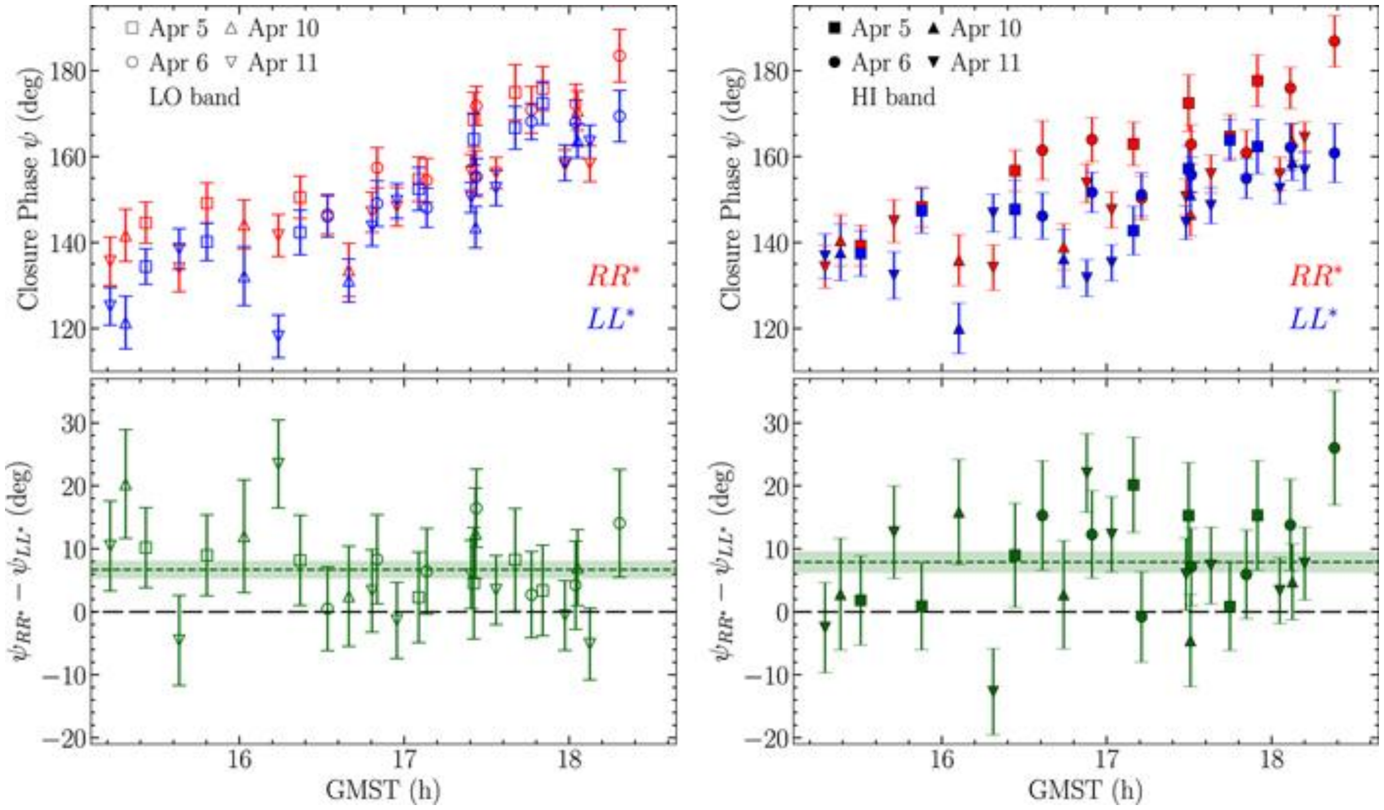


Image Credit: Blackburn+ 2019, Kim+ 2018

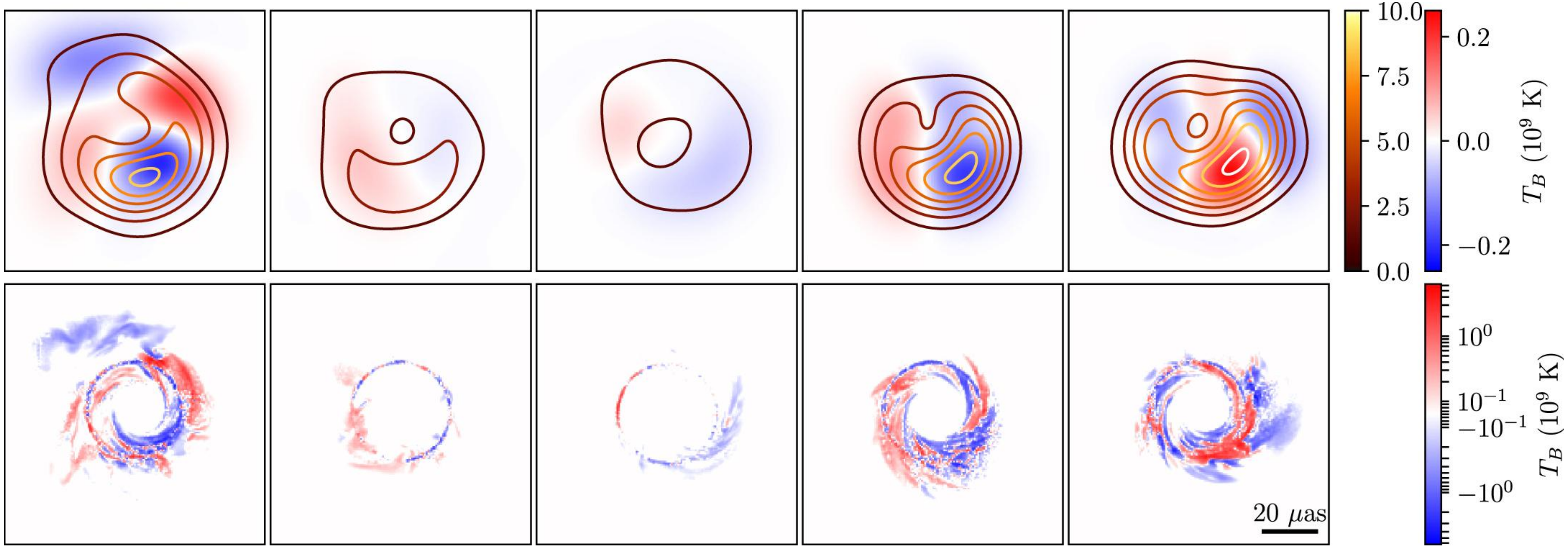
Horizon-Scale **circular polarization** is unambiguously detected by the EHT

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



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

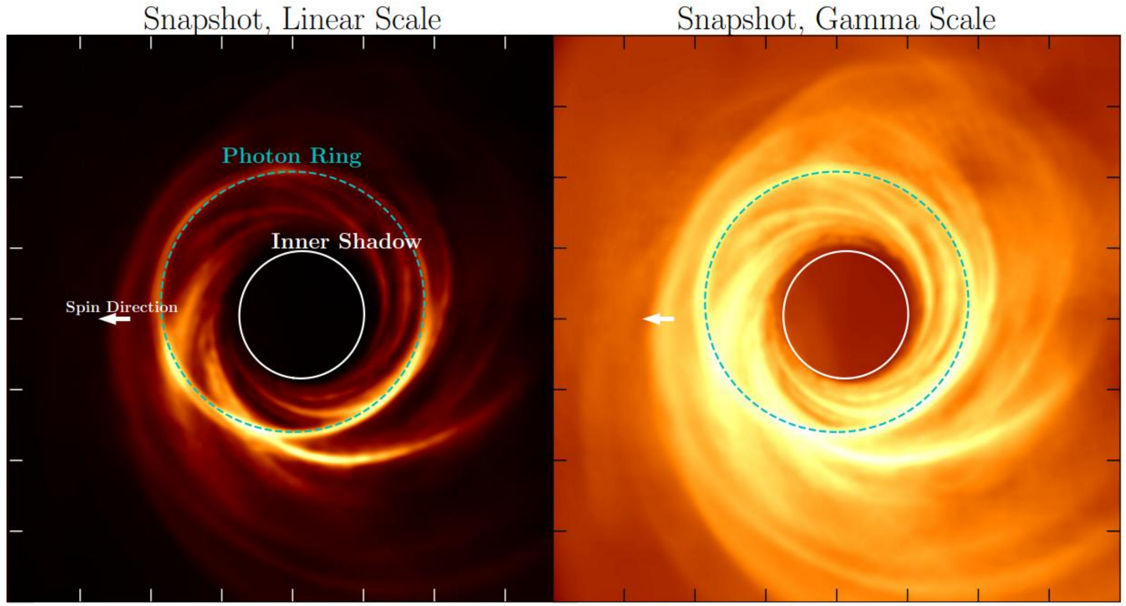
Passing simulations have **diverse circular polarization images**

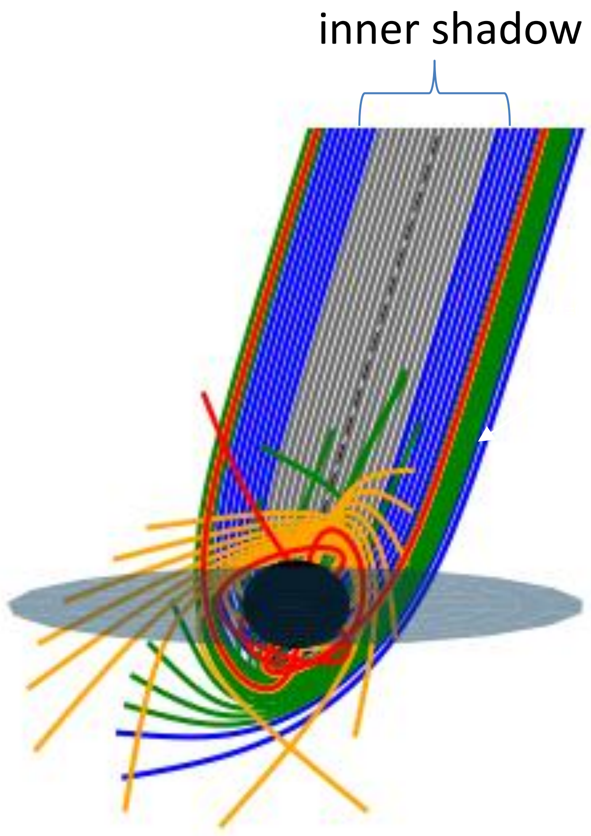


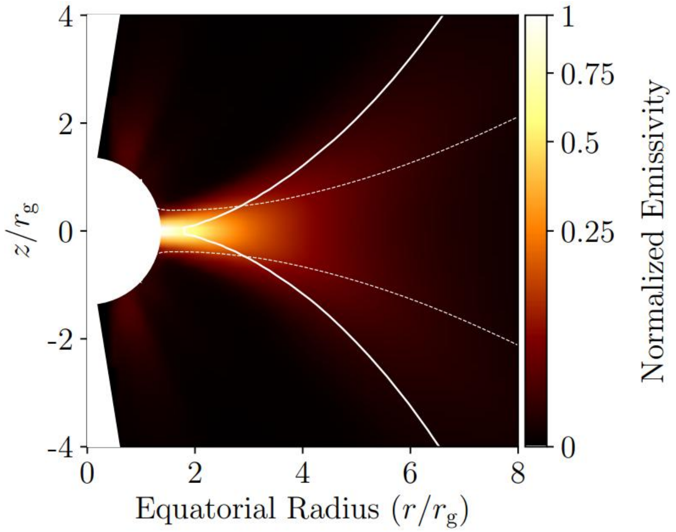
Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

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

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



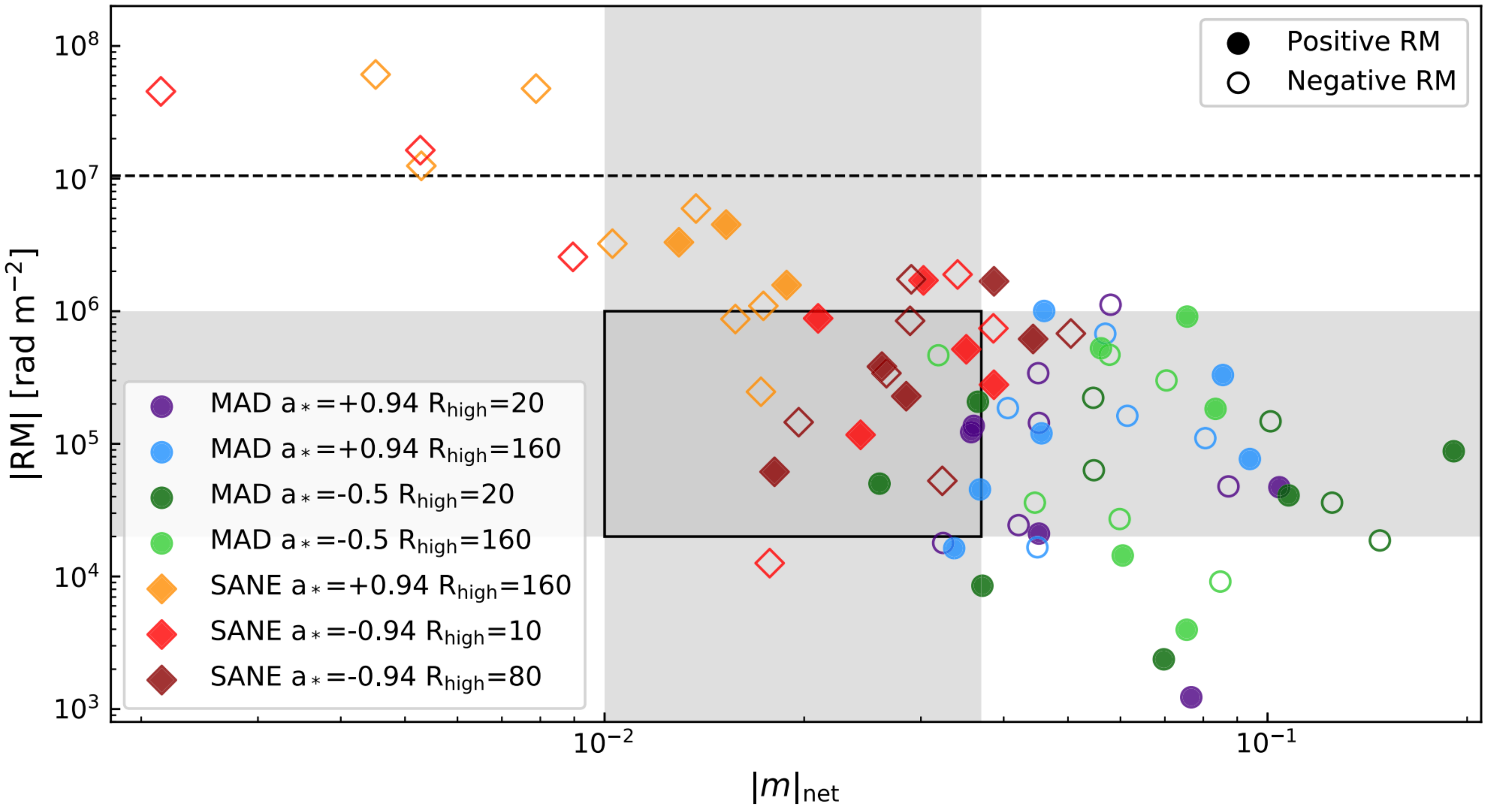




- The **inner shadow is visible in simulations**; its edge **approaches** the **lensed position of the event horizon**
- MADs have thin / nearly equatorial emission regions close to the horizon
- Redshift increases near the horizon → the inner shadow is **most visible at high dynamic range**

Chael+ 2021

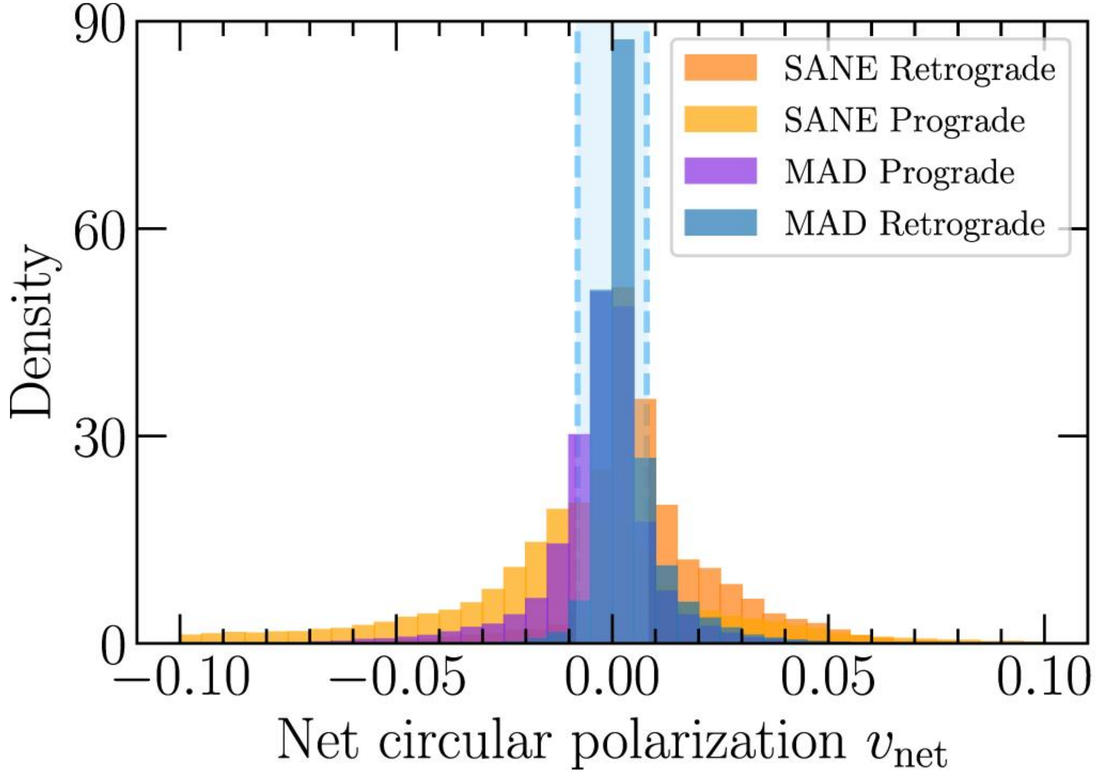
GRMHD simulations can explain M87's Rotation Measure

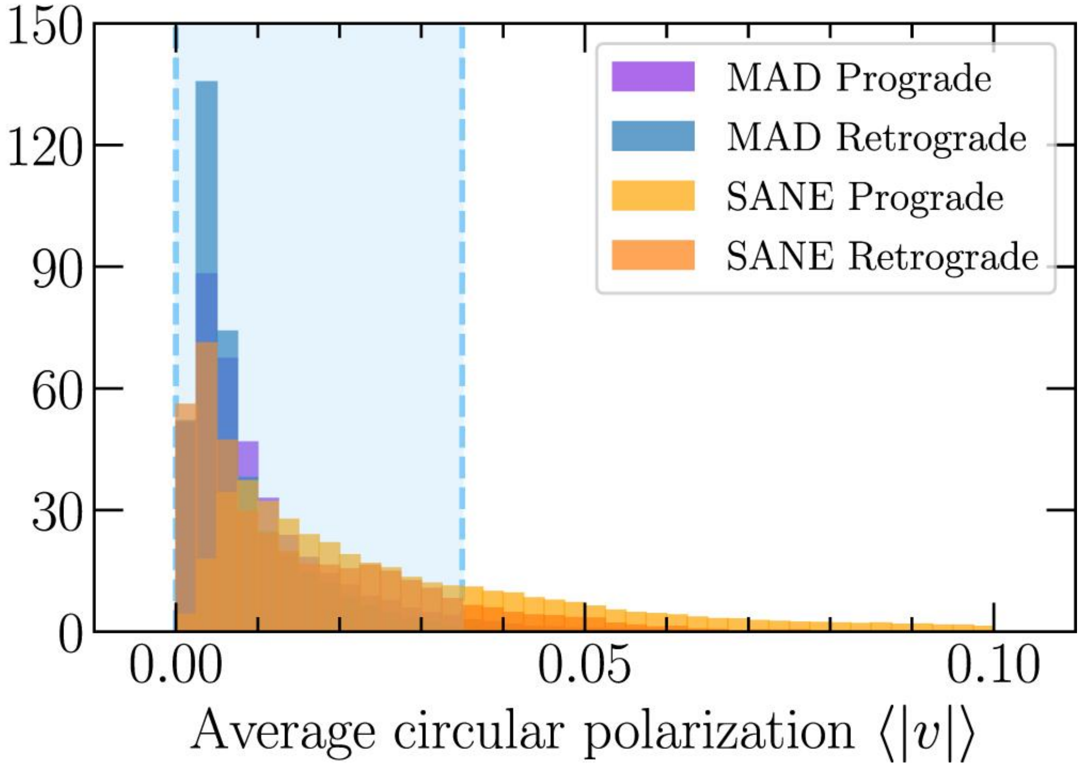


Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

Credit: EHTC 2021 Paper VIII
Angelo Ricarte

GRMHD simulations naturally produce low circular polarization





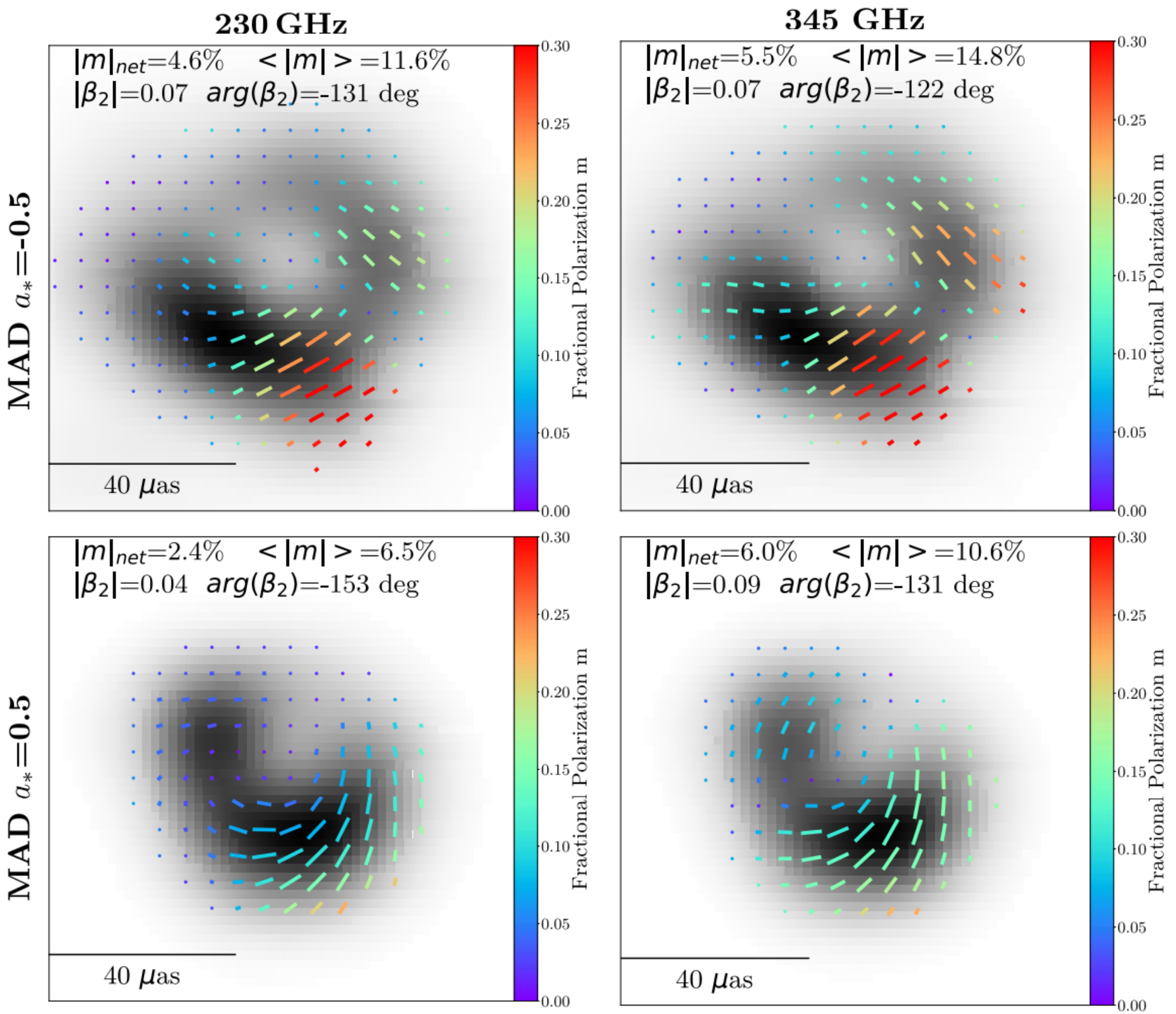
$$v_{\mathrm{net}} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

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

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

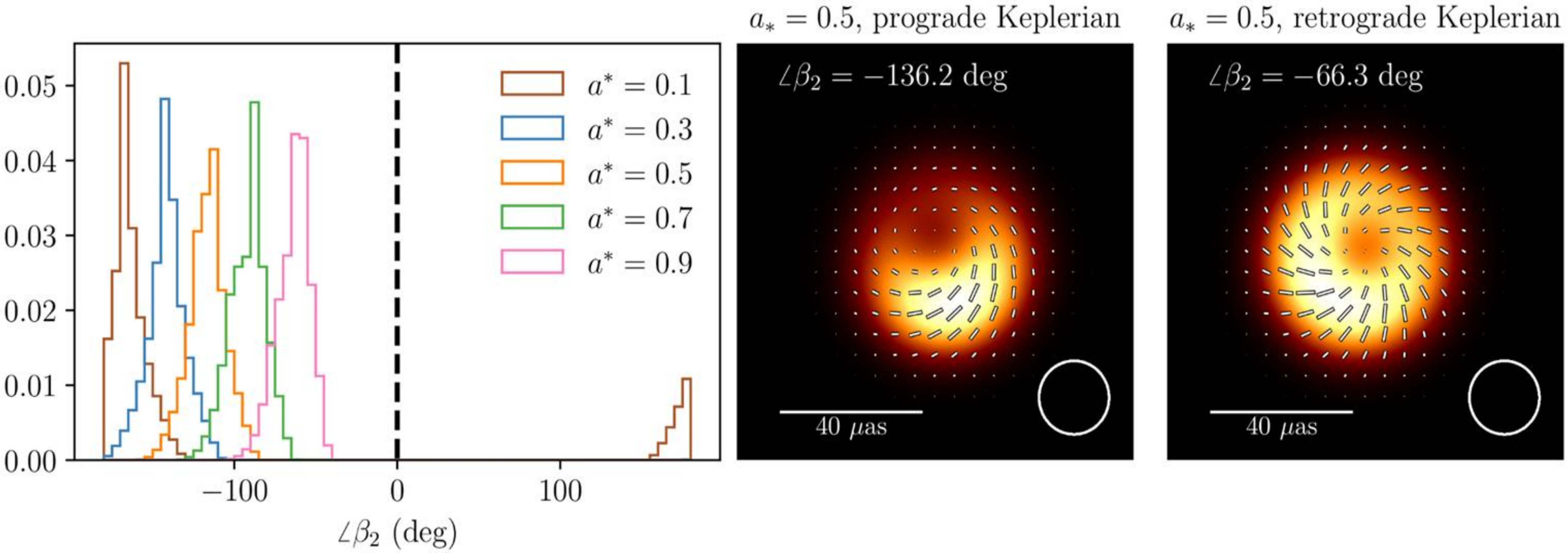
Higher frequencies

- 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



EHTC 2021, Paper VIII

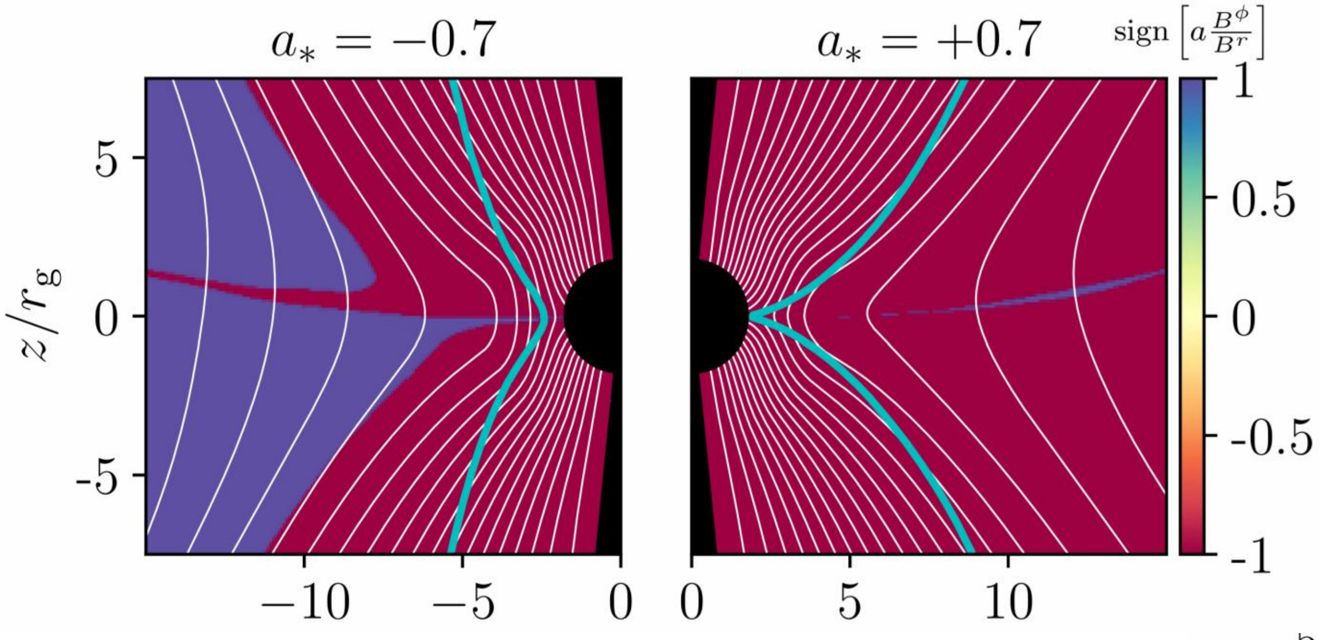
β_2 in semi-analytic models of M87*



- 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(β_2) or trend with BH spin

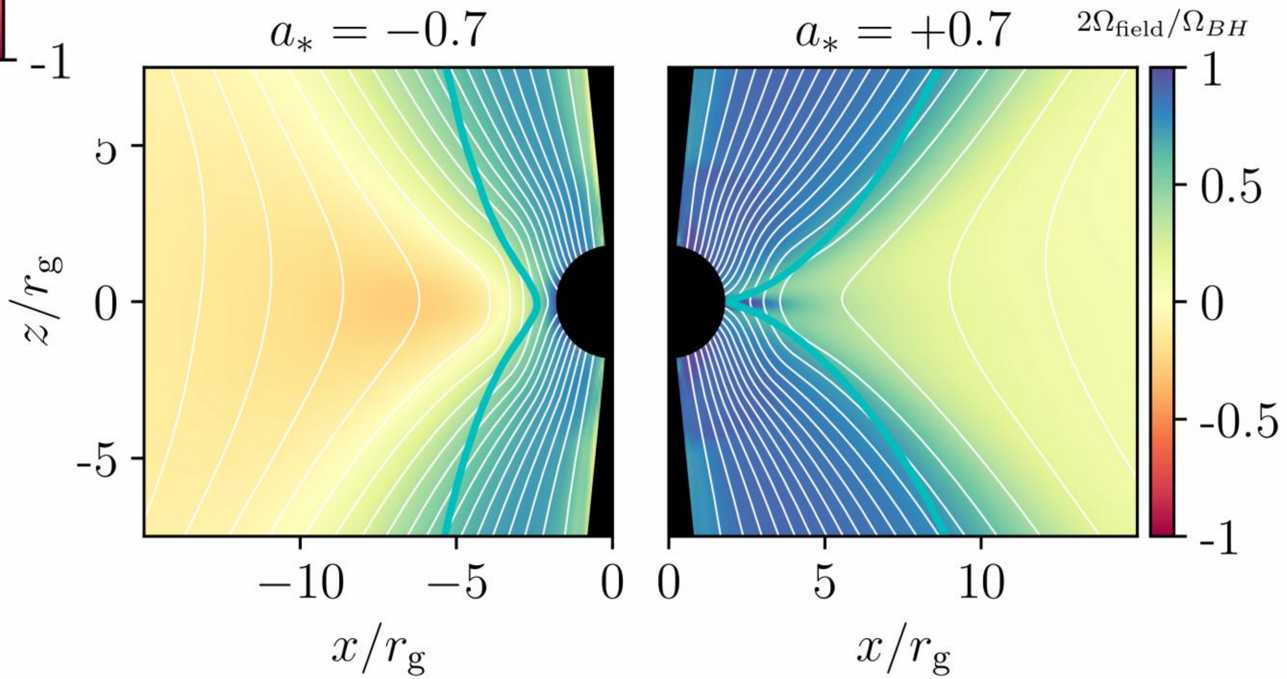
Chael+ 2023b

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



Sign of magnetic field pitch angle

Field-line angular speed



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

Chael+ 2023
Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022, Wong+ 2021

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**

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

Horizon EVPA

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

$$\Theta(\theta) = \eta + a^2\cos^2\theta - \lambda^2/\tan^2\theta$$

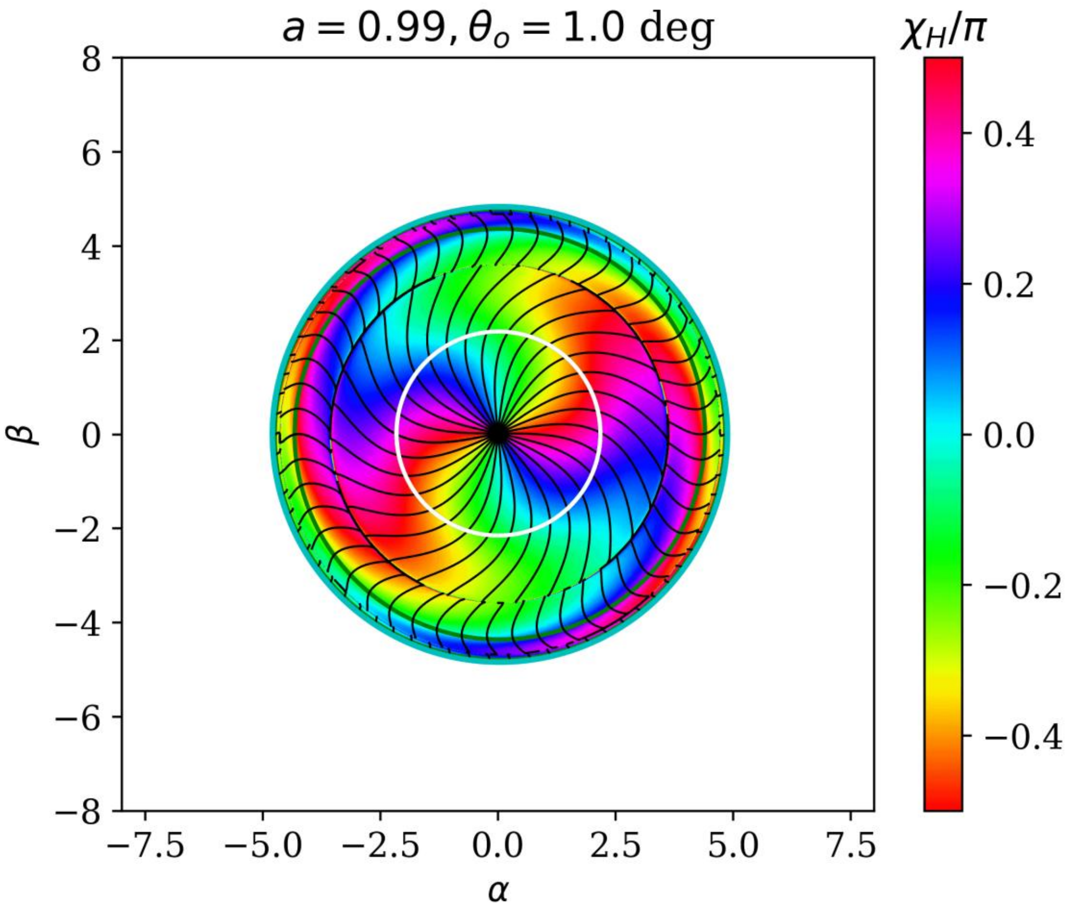
Angular Potential

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

Conserved Quantities

- For equatorial emission, viewed face-on, arg(β_2) approaches a simple universal horizon value:

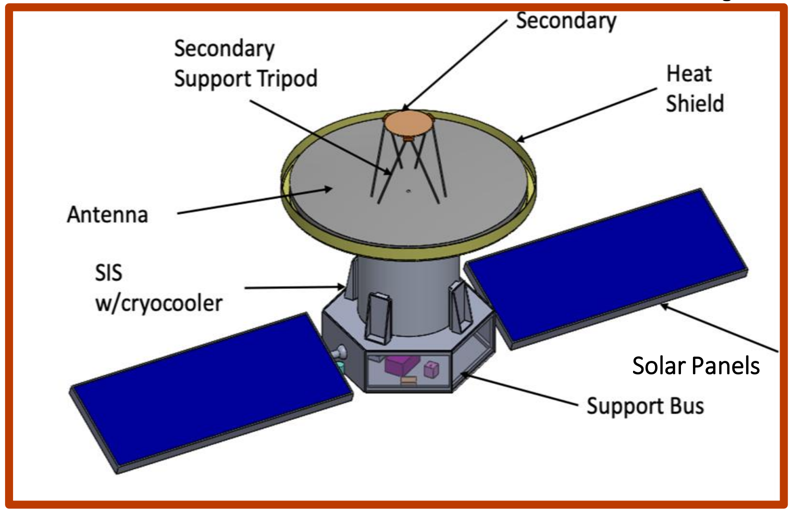
$$\angle\beta_{2,+} \approx 2\arctan\left(\frac{\nu_\theta\, a}{\sqrt{2r_+^2 + a^2}}\right)$$



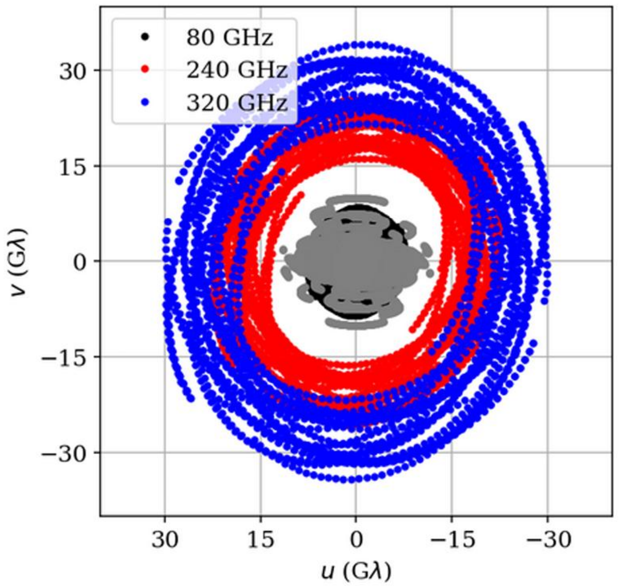
Hou+ 2025, Lupsasca+ in prep, Chael+ in prep
See also Gates+ 2018

The Black Hole Explorer (BHEX)

Spacecraft



Example M87 *u-v* coverage



Aggregate coverage over 24 hours

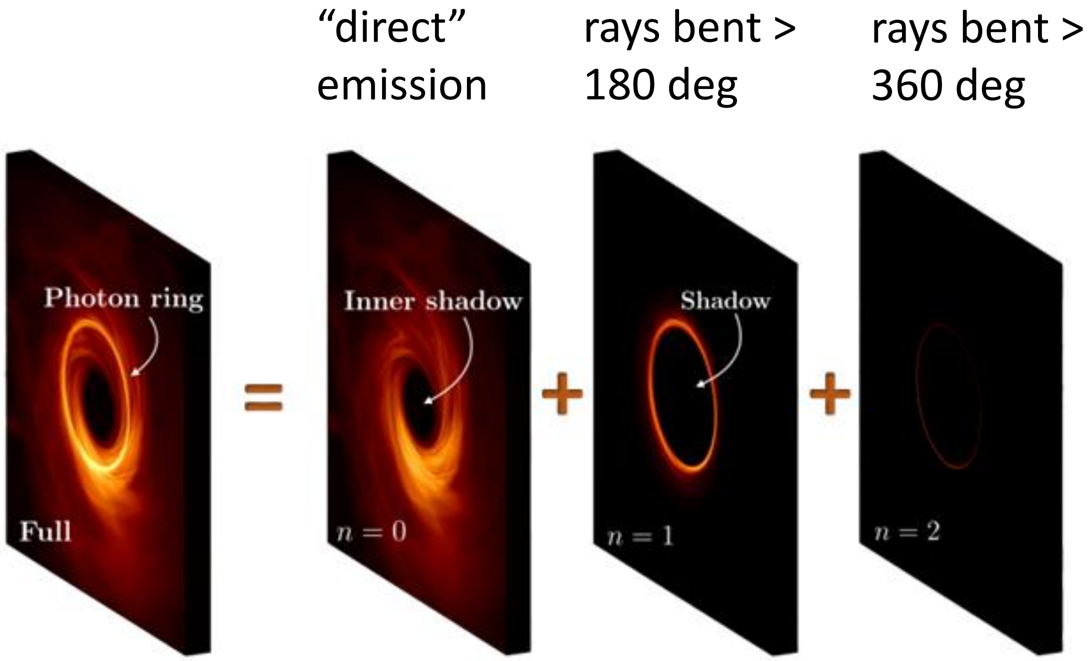
Figures: D. Marrone (top) / D. Palumbo (bottom)

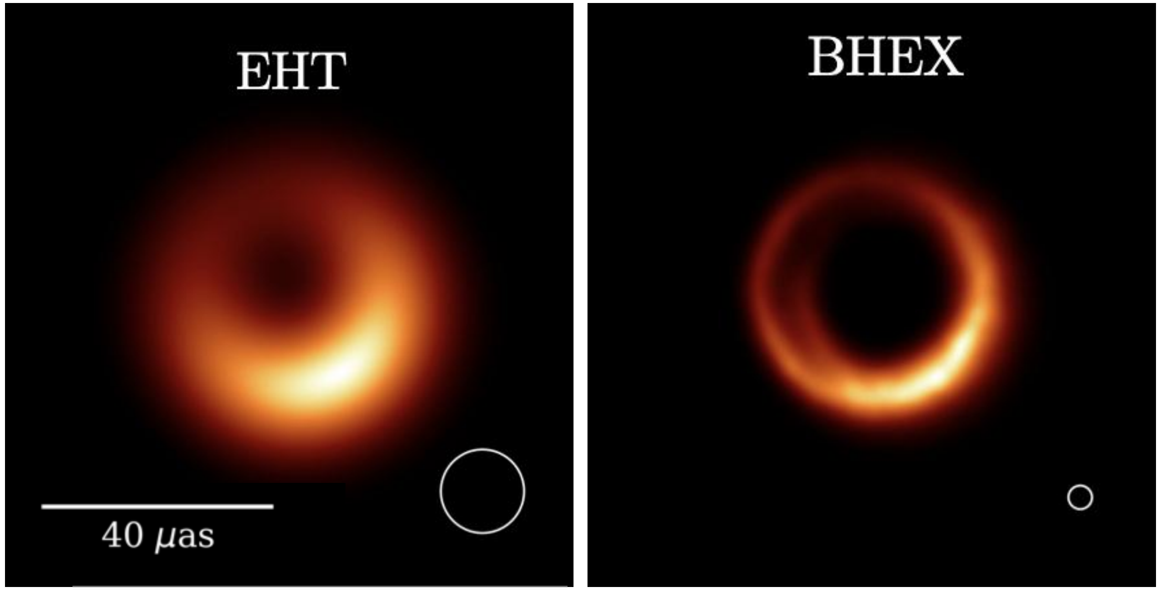
Mission Parameters

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

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

Direct Photon Ring Mass & Spin Measurements with BHEX

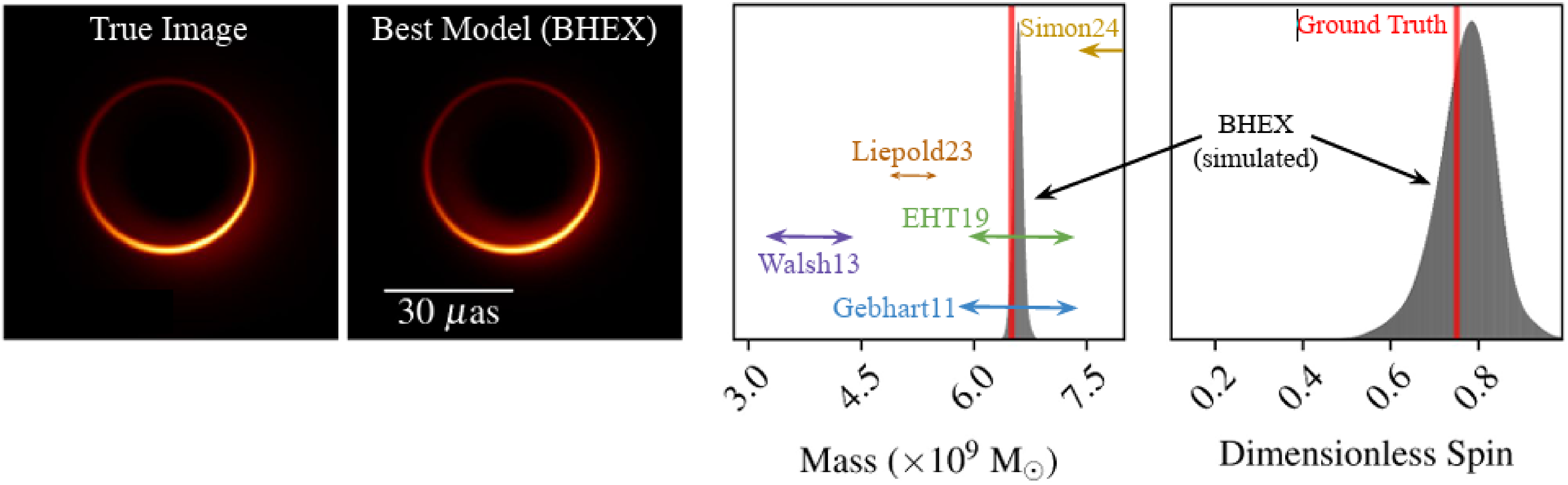




BHEX will detect and image the **photon rings** formed by **light deflected >180 degrees** in Sgr A* and M87*

Johnson+ 2020, Johnson+ 2024, Lupsasca+ 2024

Direct Photon Ring Mass/Spin Measurements with BHEX



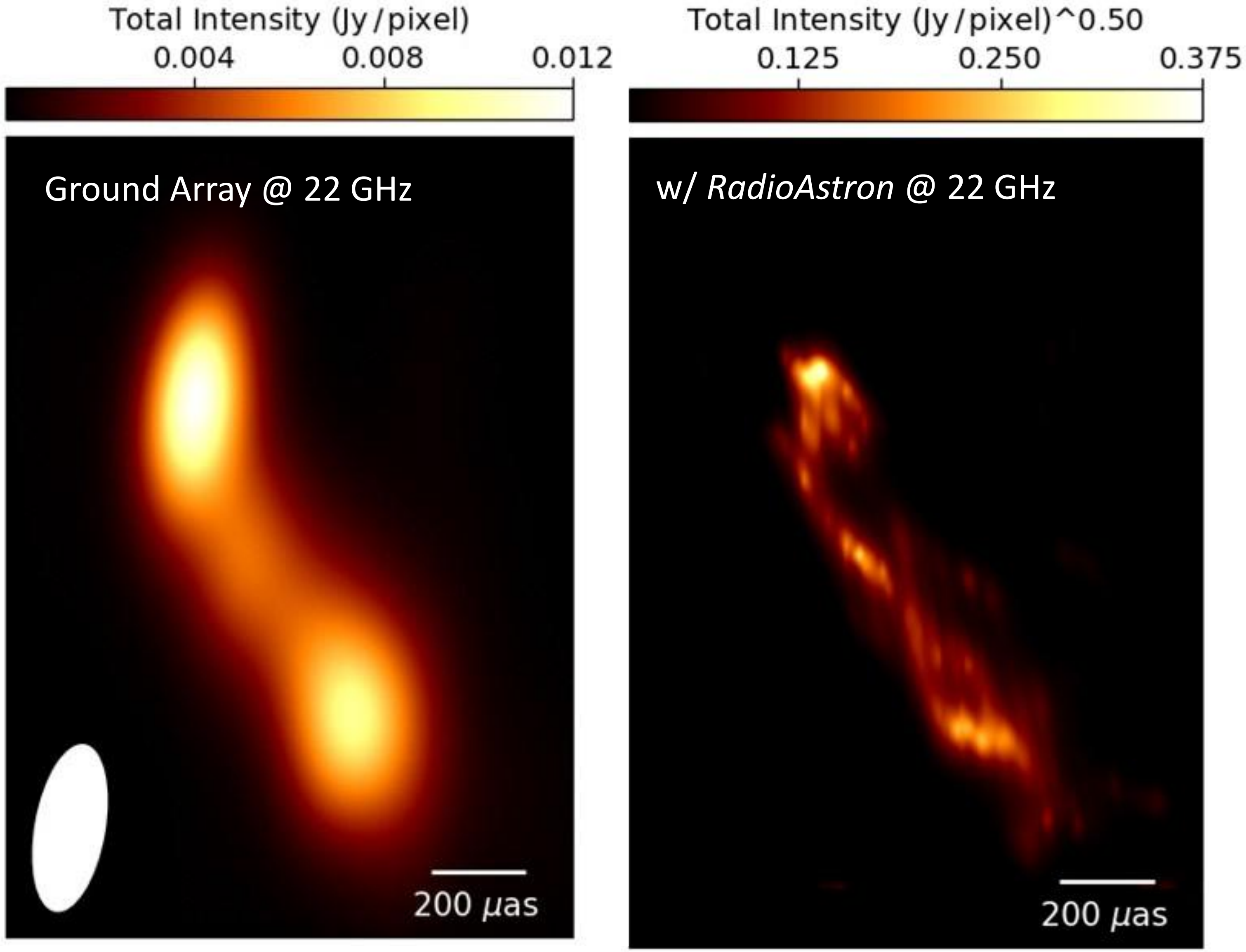
By comparing strongly-lensed and direct emission ring size and shape, BHEX will constrain Sgr A* and M87*'s **spin to ~10%** and **mass to ~1%**

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

Johnson+ 2020, Johnson+ 2024, Lupsasca+ 2024

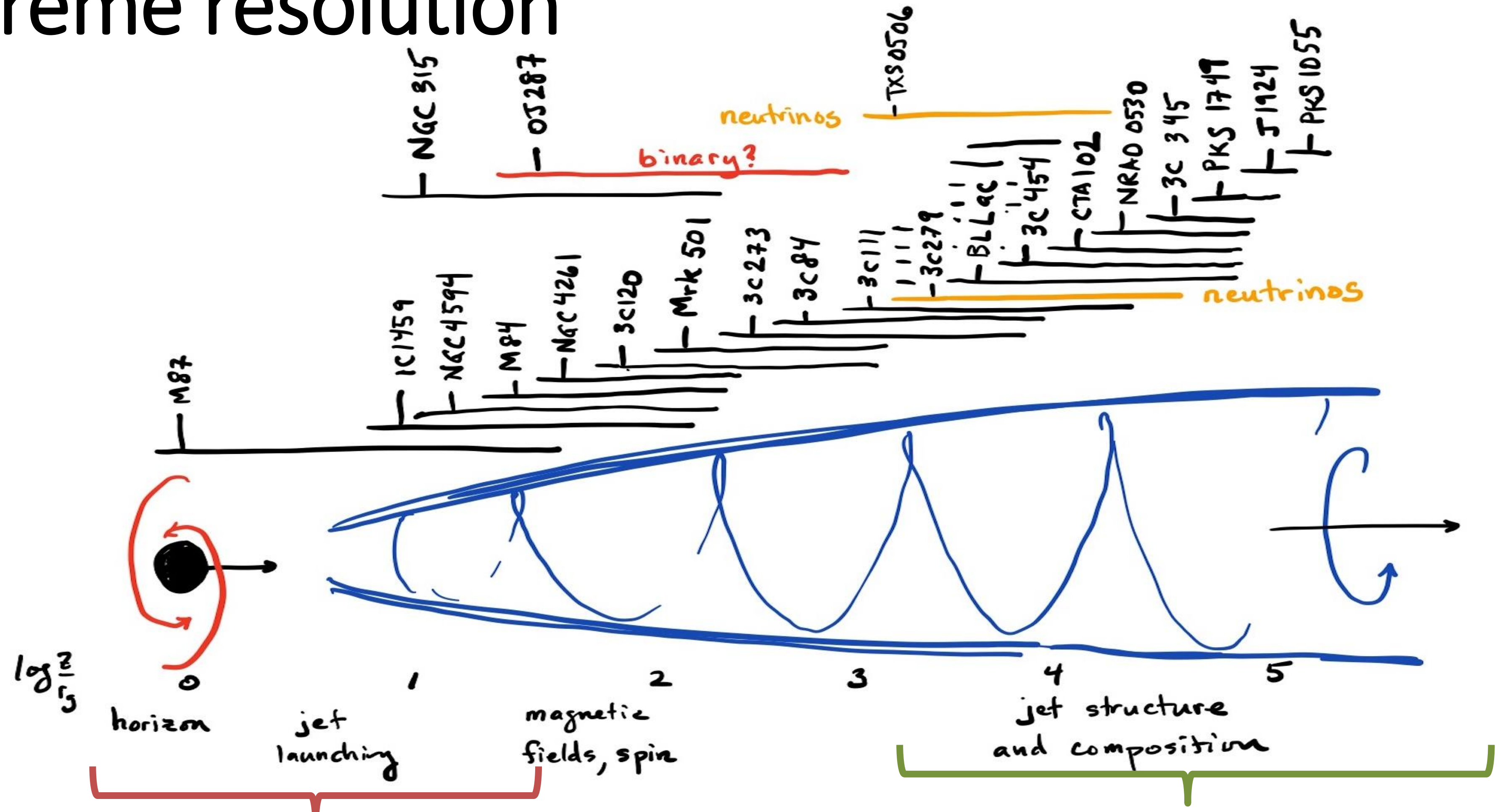
The Power of Space VLBI: 3C279 with *RadioAstron*

- 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



Fuentes et al, 2023

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



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

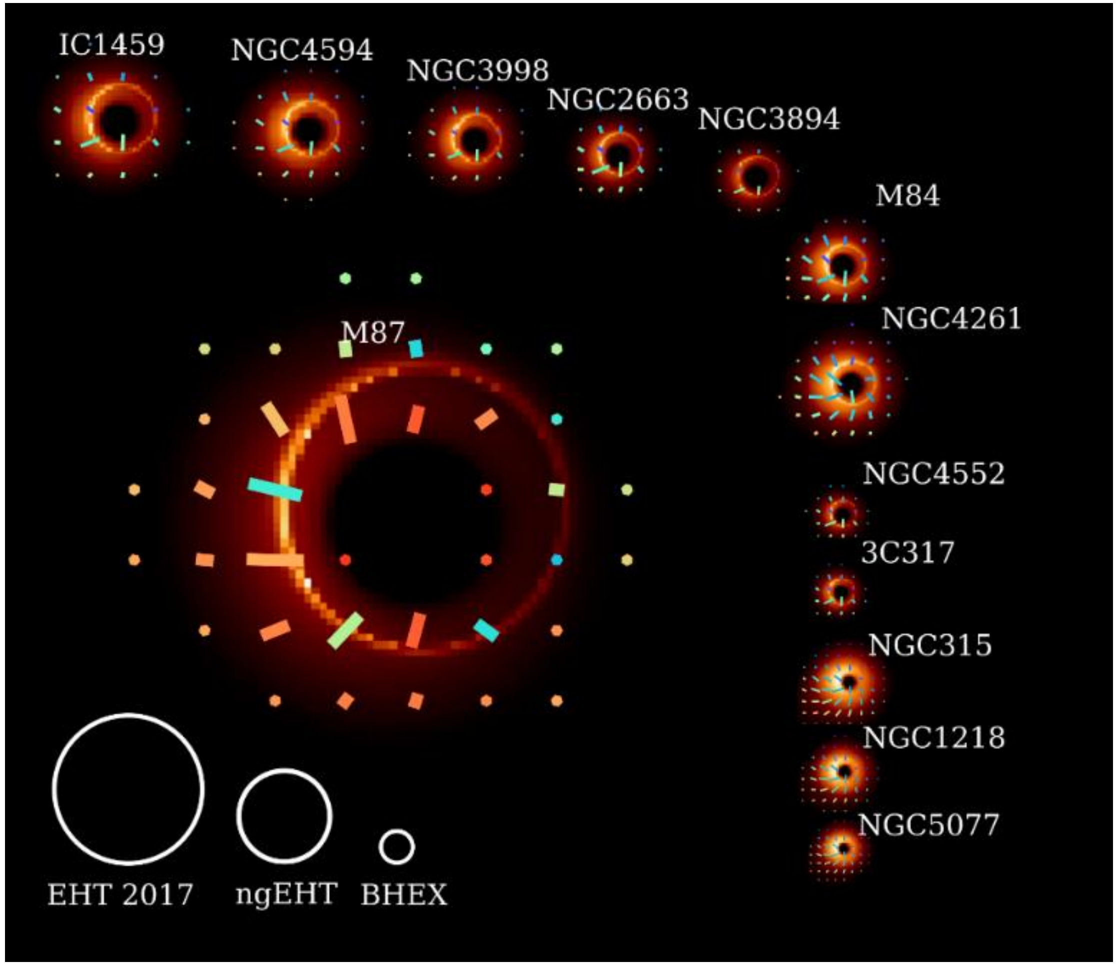
How do jets accelerate? Can we measure BH spin with jet polarimetry?

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

Image Credit: Charles Gammie

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

- BHEX will increase the sample size of resolved black hole horizons from 2 to >10
- BHEX will make >10 horizon-scale measurements of mass (from the size of the emission region) and spin (from magnetic field helicity)
- BHEX will observe how horizon-scale accretion changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties



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

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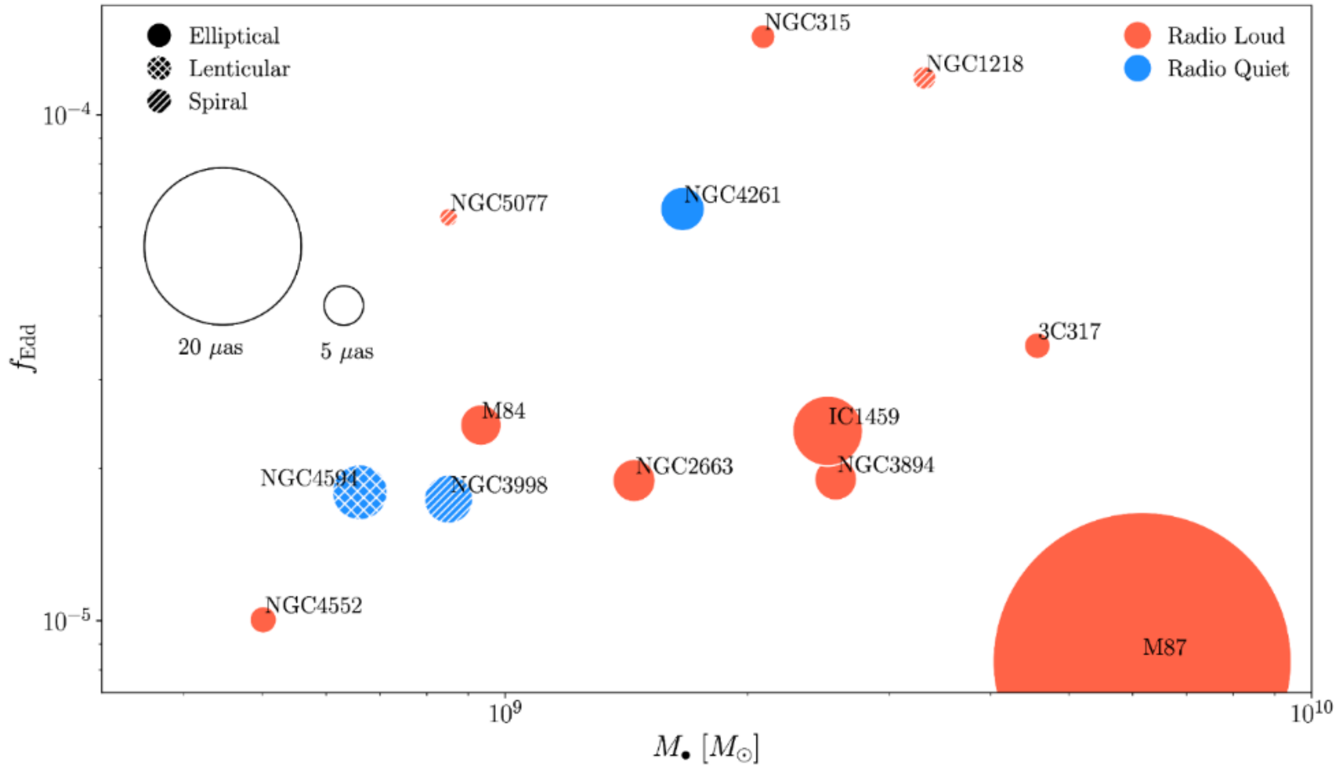


Zhang, Ricarte+ 2024

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

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:

$$\nabla_\mu \left(T^{\mu\nu}_{\mathrm{MAT}} + T^{\mu\nu}_{\mathrm{EM}}\right) = 0$$

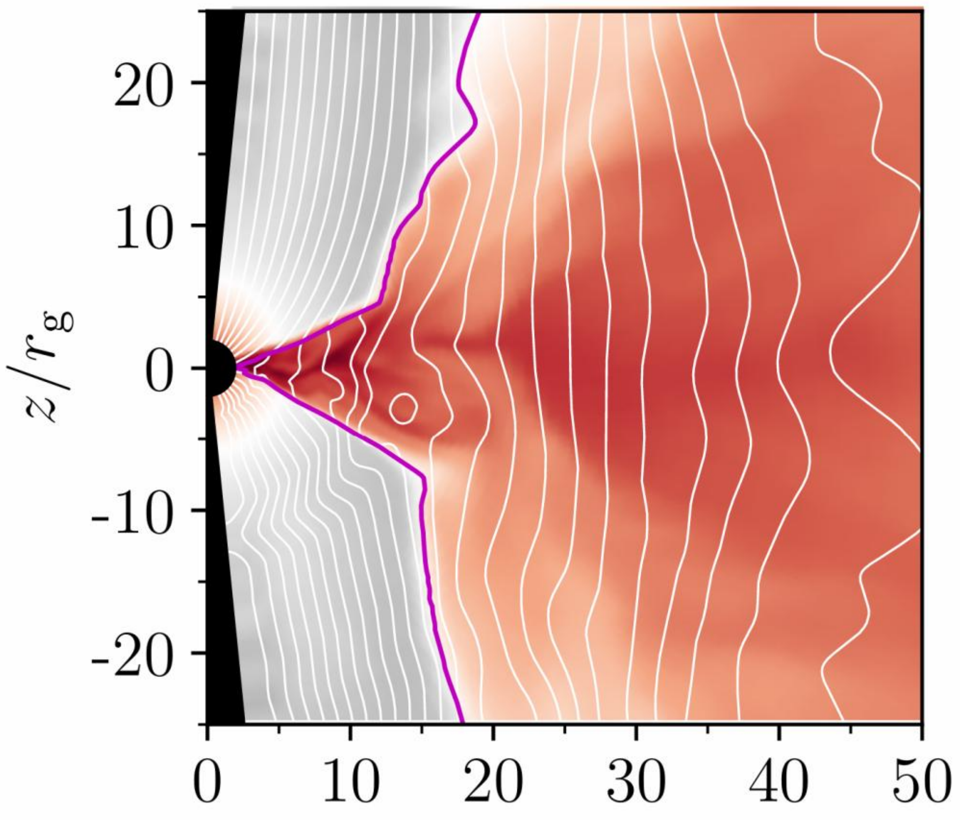
- The ratio of magnetic energy to rest-mass energy is defined:

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

- In the limit $\sigma \gg 1$, numerical codes struggle to recover fluid variables and the simulation can crash

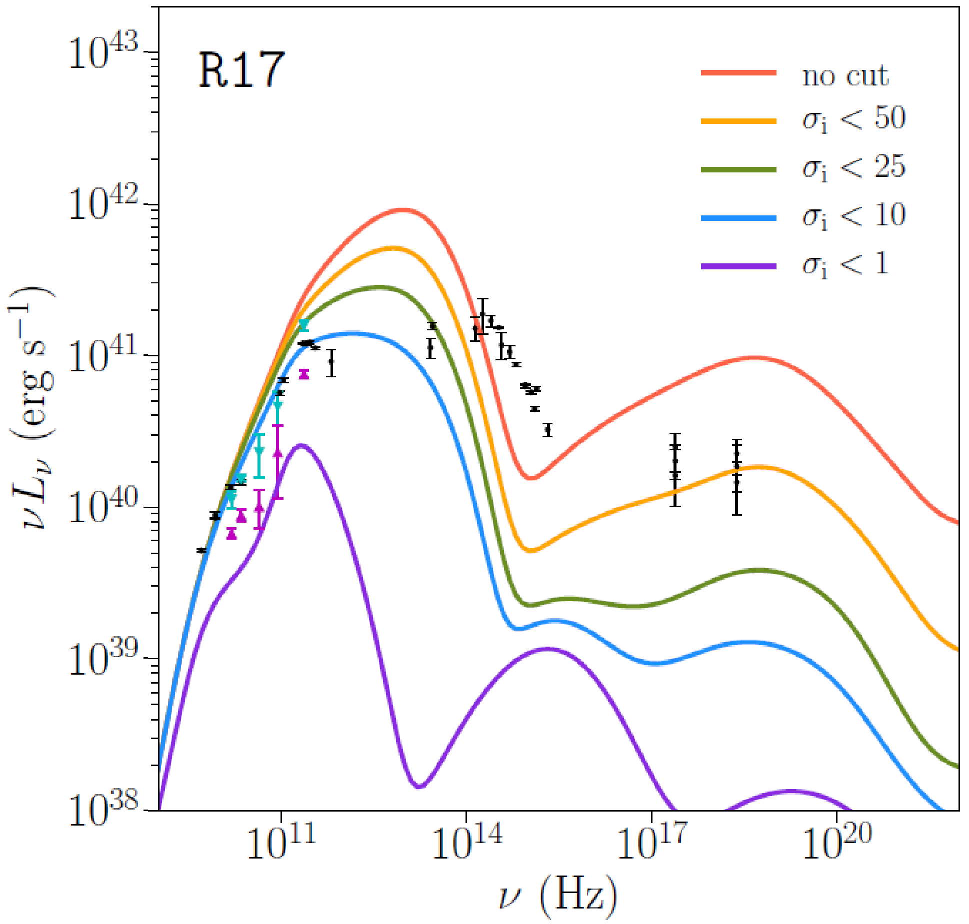
- GRMHD codes introduce density 'floors' for stability

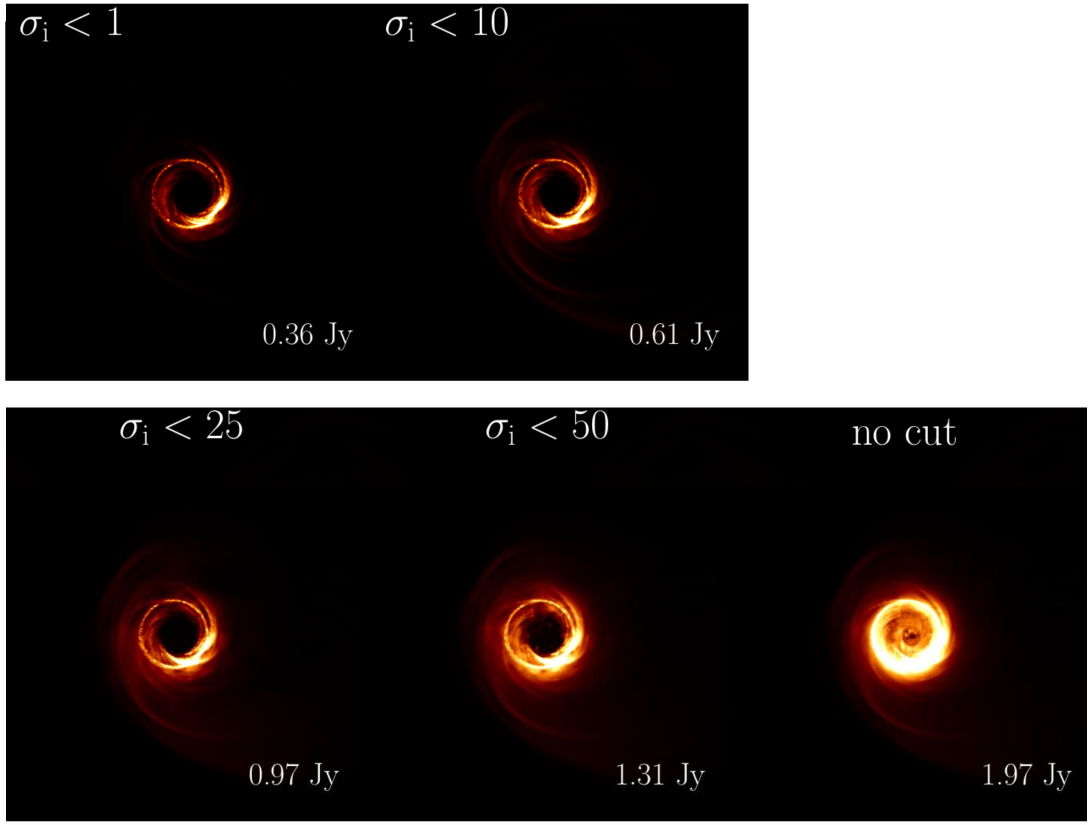
$$\sigma < \sigma_{\max}$$



Chael 2024

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





Chael+ 2019

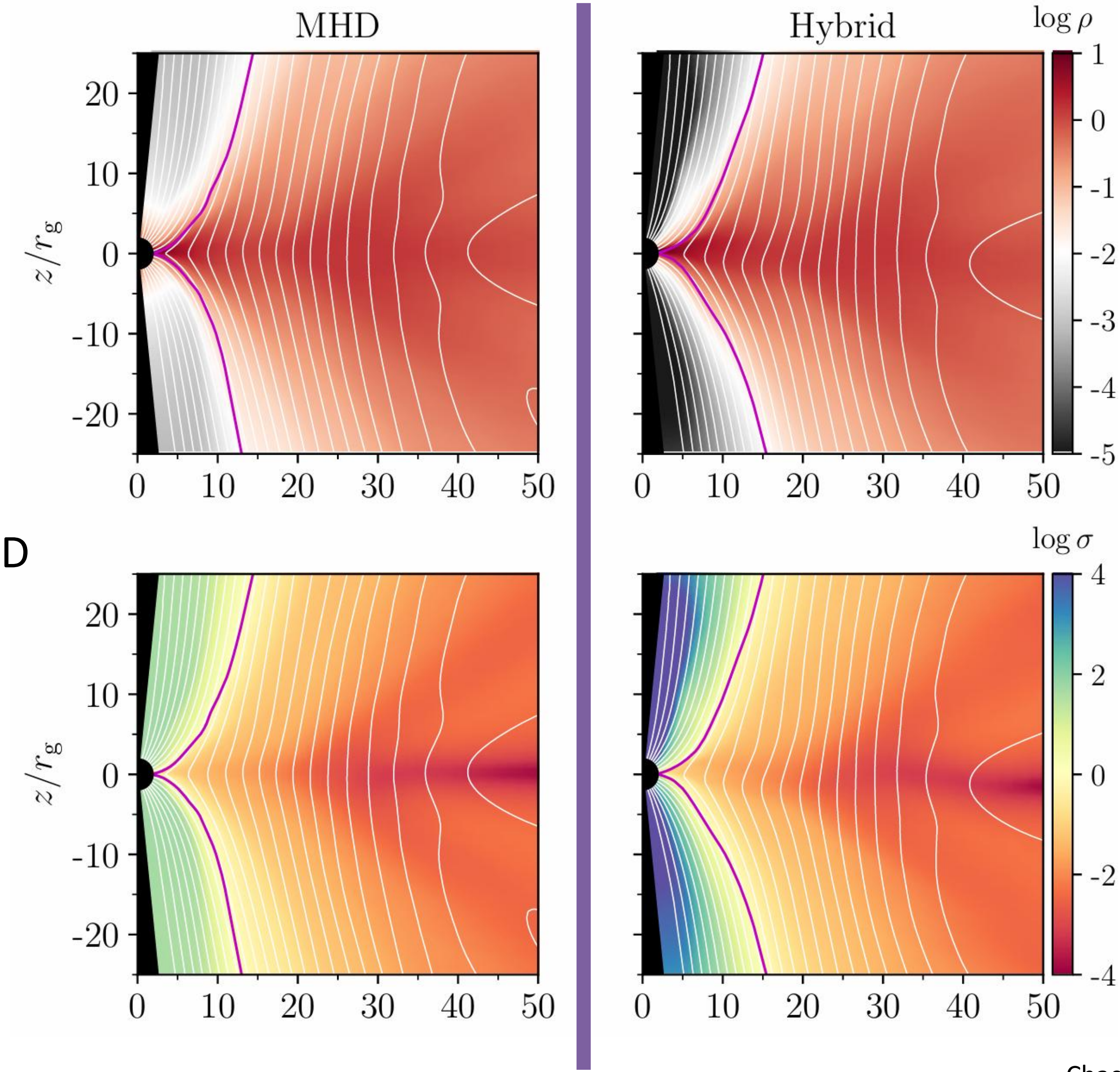
A New Hybrid GRMHD + Force-Free Code

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

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

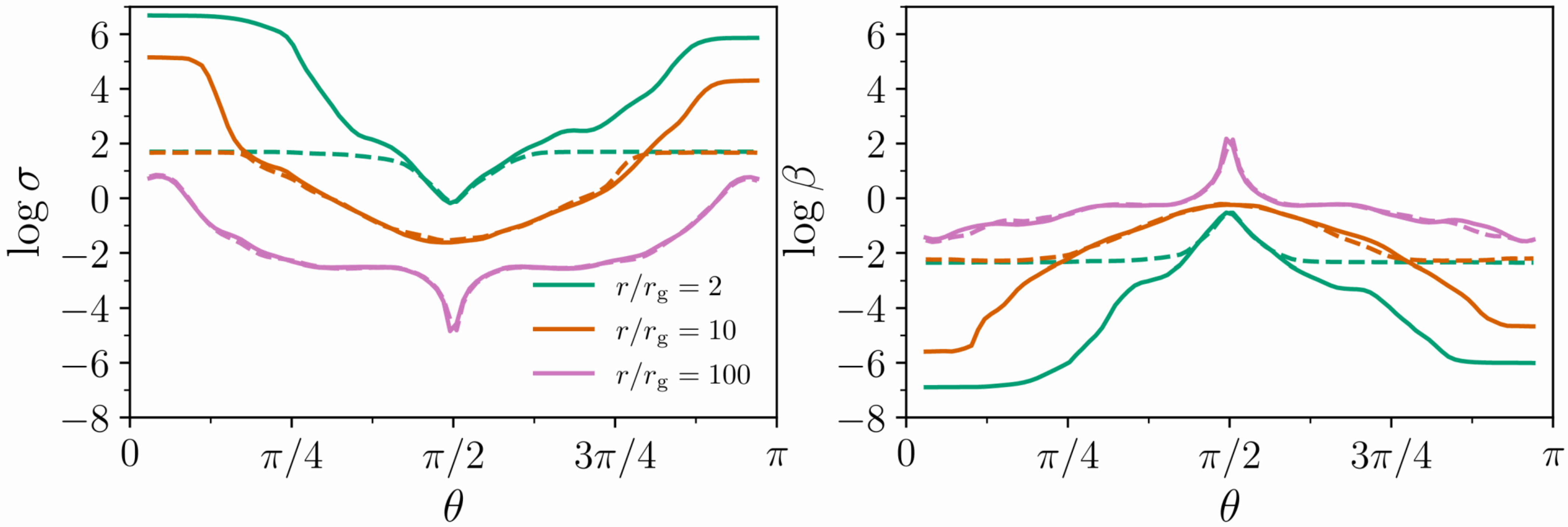
- electromagnetic fields evolve with **no back-reaction**
- field-parallel velocity determined from GRMHD limit
- **gas evolved adiabatically** in fixed background

Can transition between the schemes in ``intermediate'' σ regions



Chael 2024

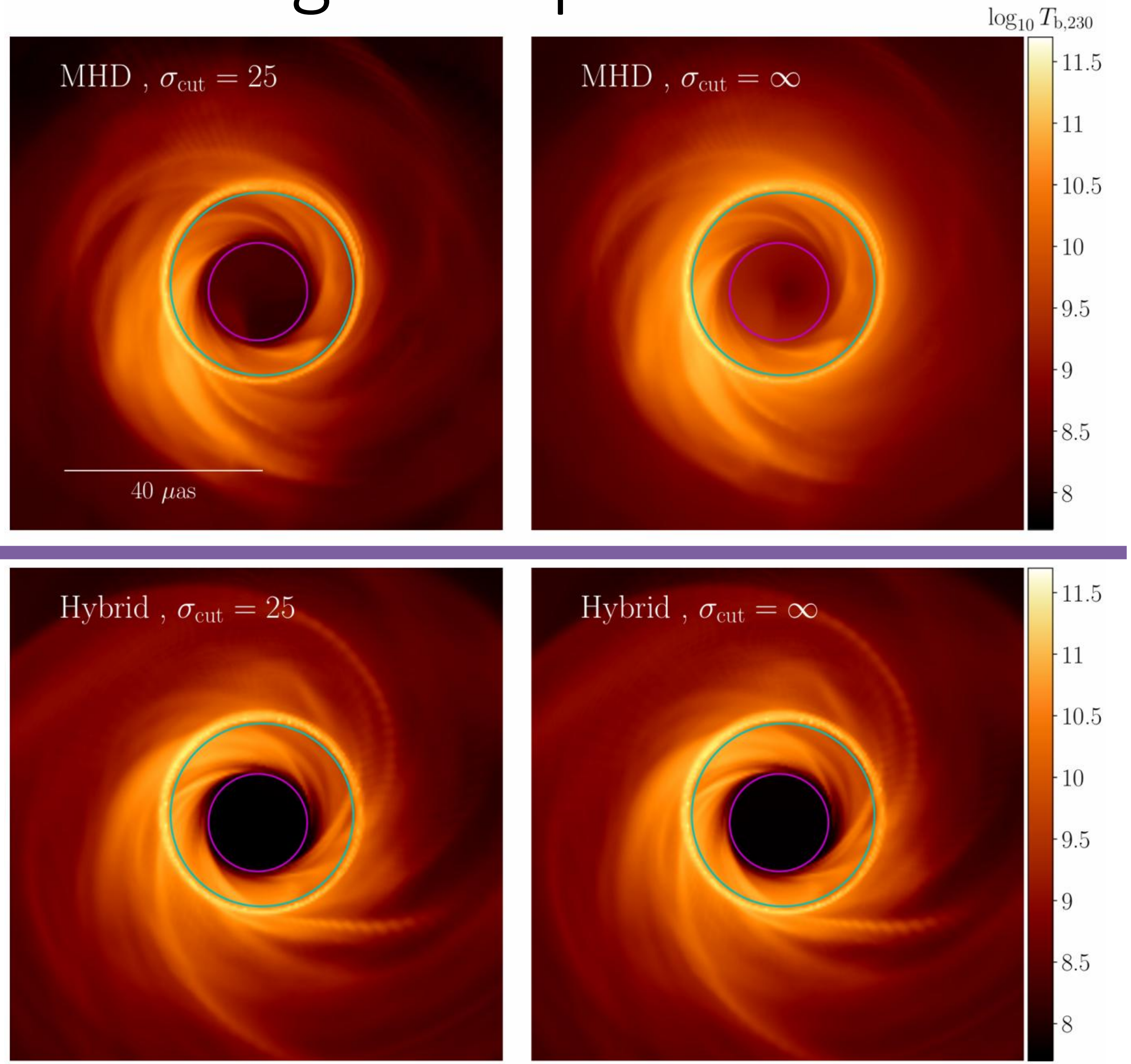
Comparing standard GRMHD and Hybrid GRMHD+FF



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

Chael+ in prep

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

Chael+ in prep