Black Hole Energy Extraction in Polarized Images

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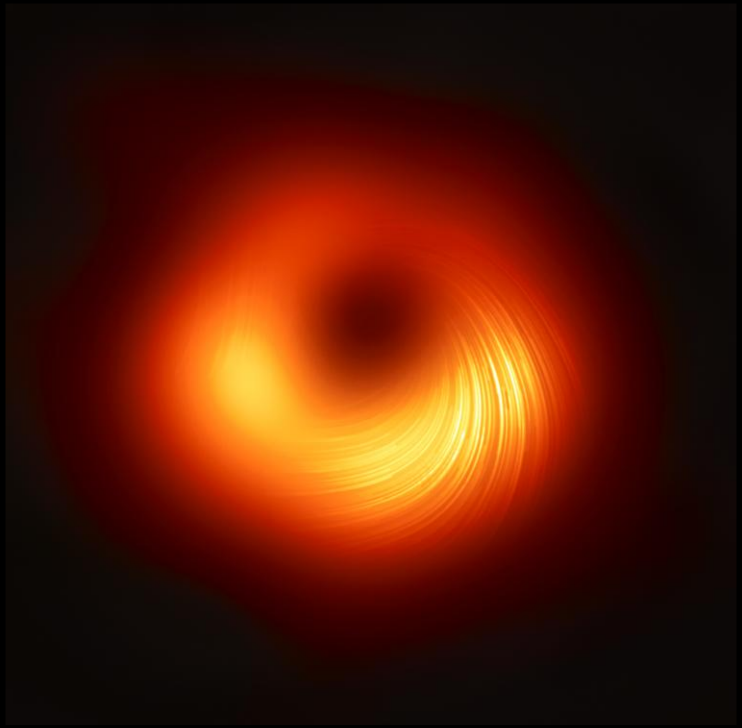
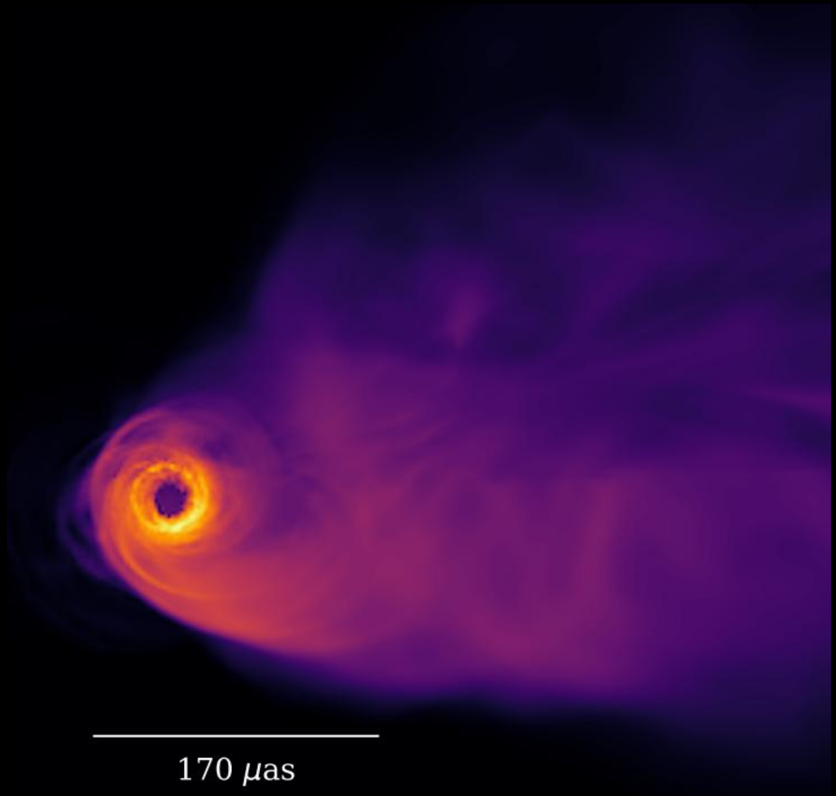
Princeton Gravity Initiative

April 24, 2025



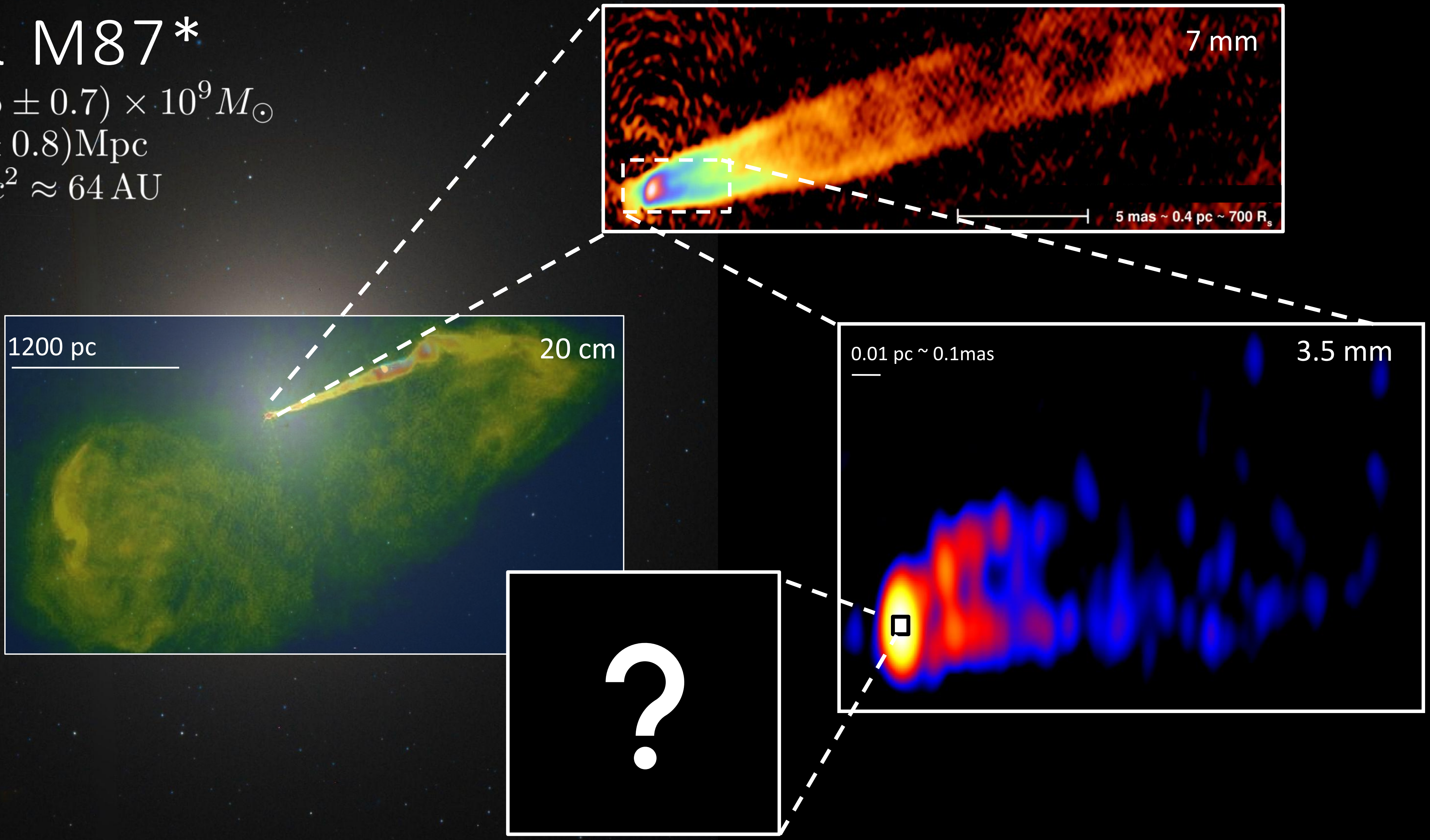


Princeton gravity Initiative

Event Horizon Telescope

M87 & M87*

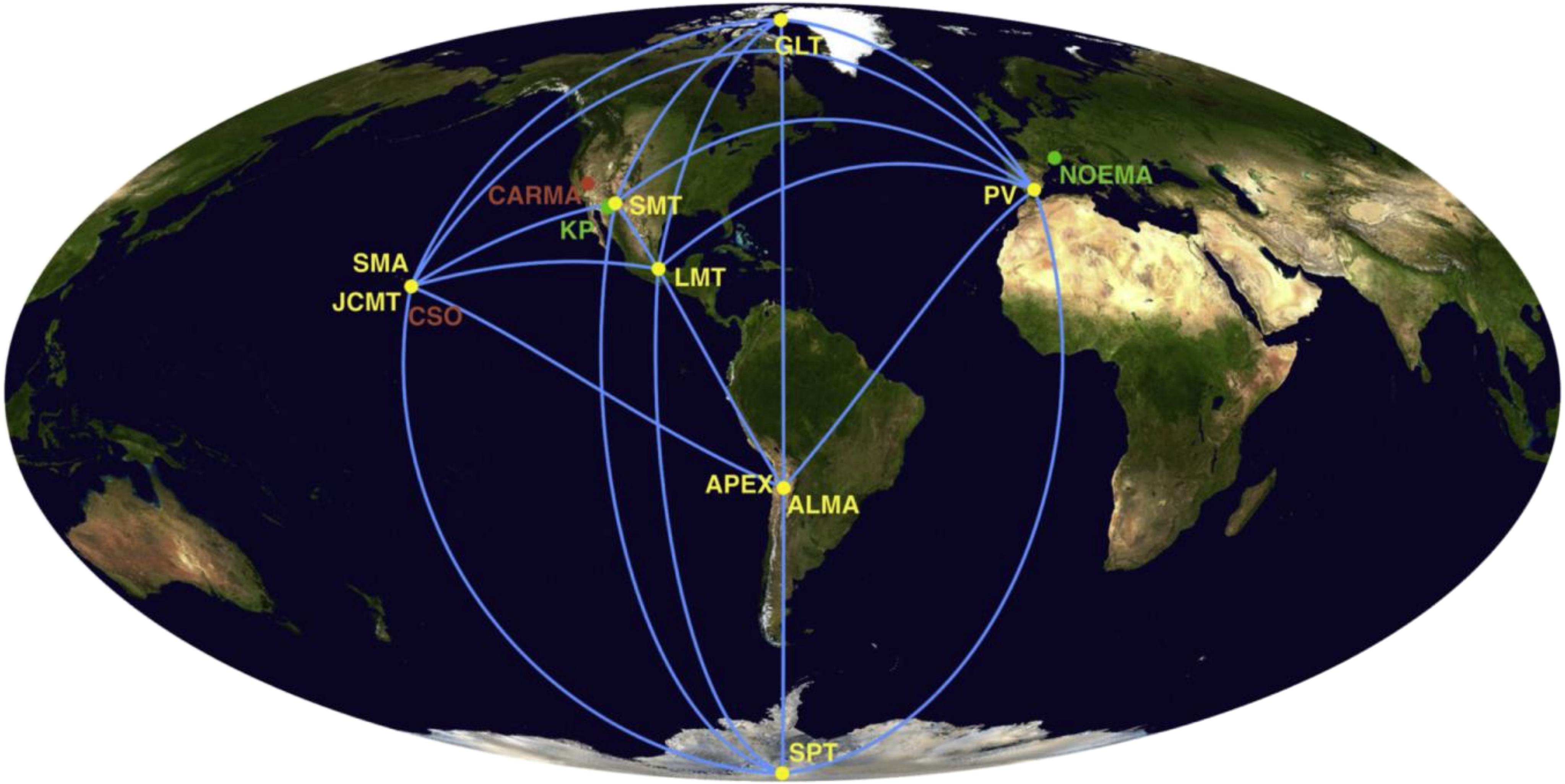
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$R_\mathrm{s} = 2GM/c^2 \approx 64\,\mathrm{AU}$



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*

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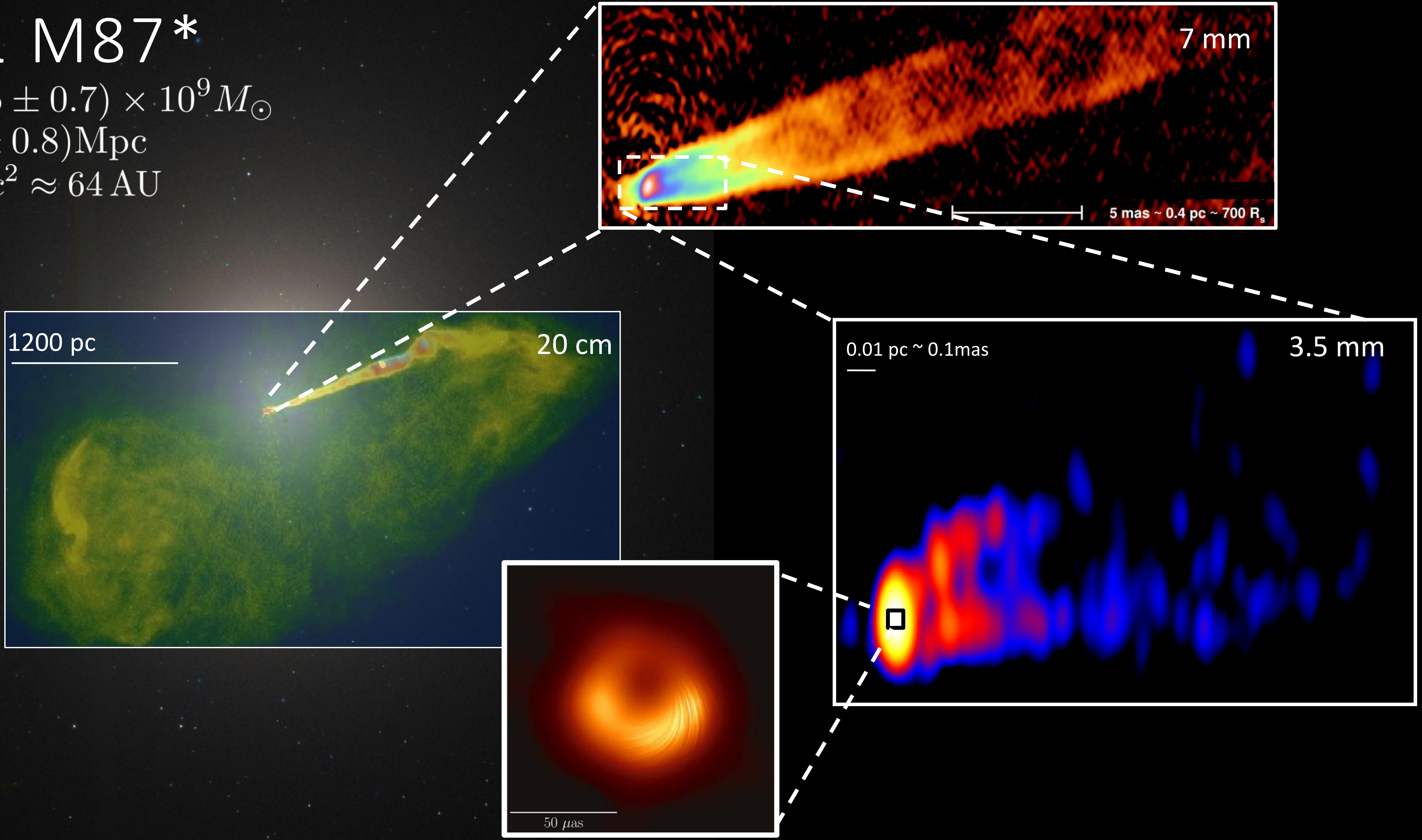
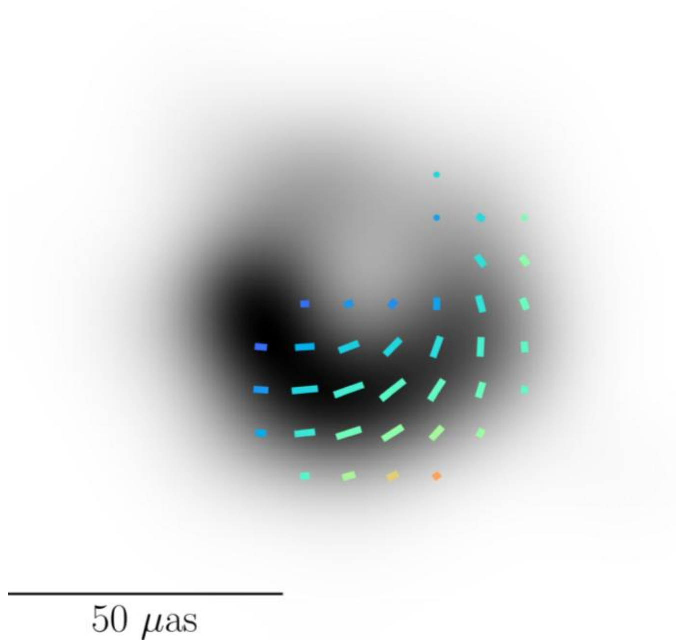
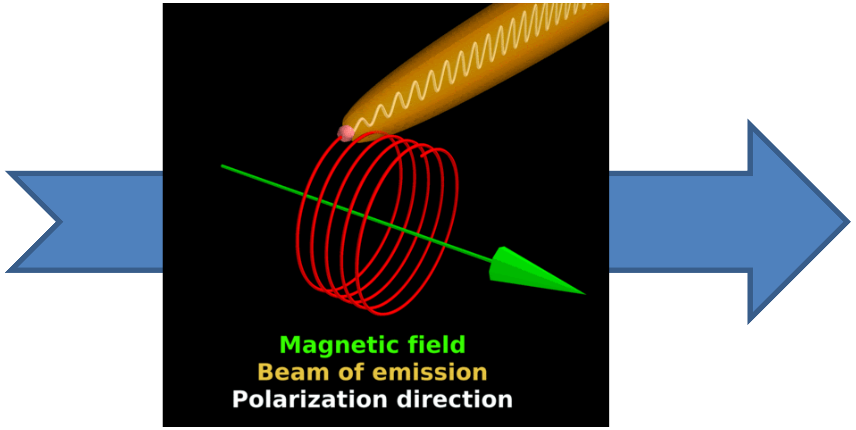


Can polarized EHT images tell us how jets are launched?

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

Why polarization?



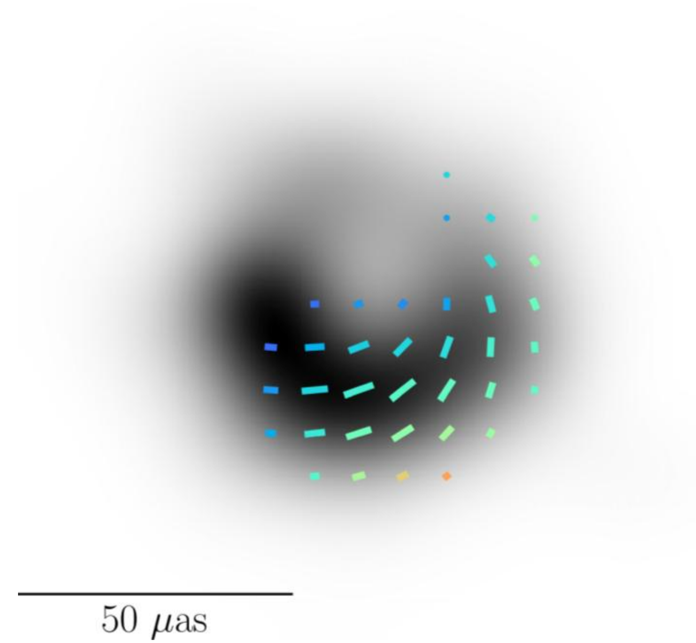


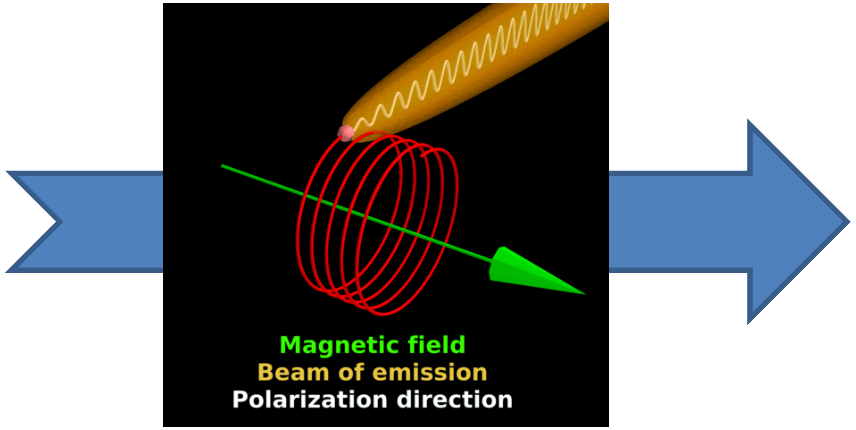
Magnetic field geometry in the emission region!

- 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!

- 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. What did we learn from comparing first polarized images of black holes to simulations?

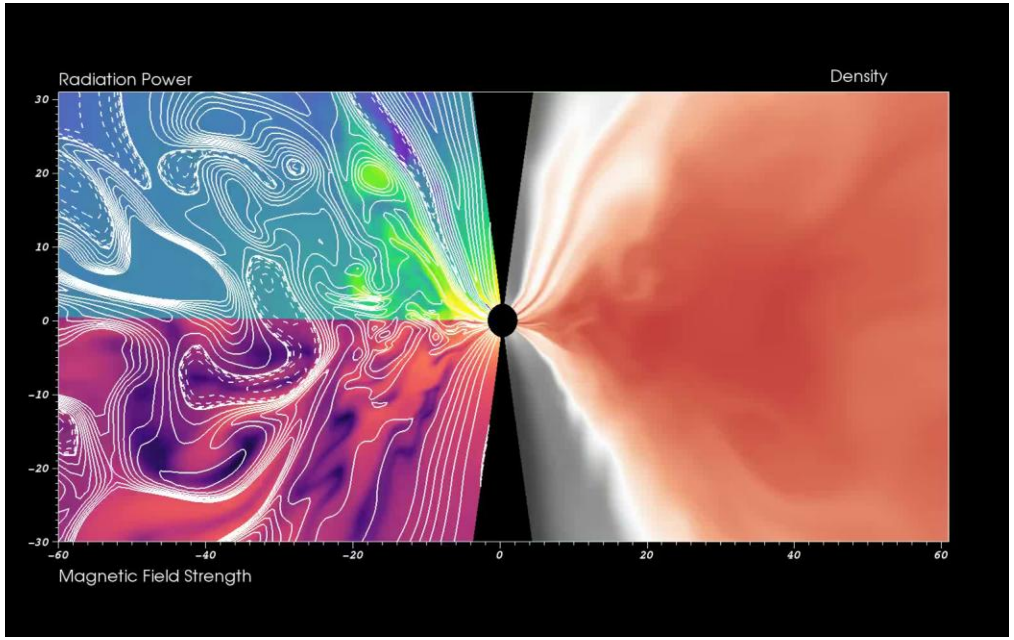
2. What can polarized EHT images tell us about jet launching?

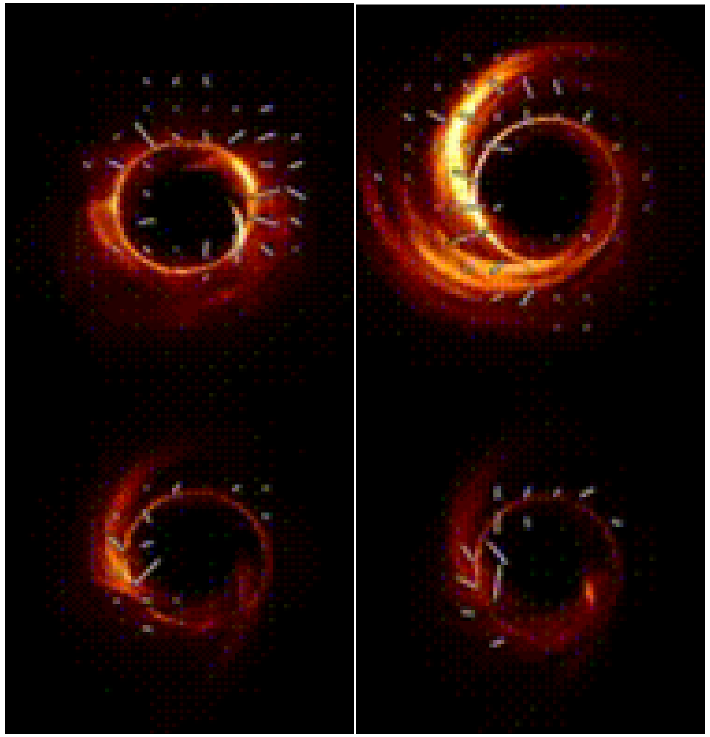
3. What’s next?

What did we learn 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

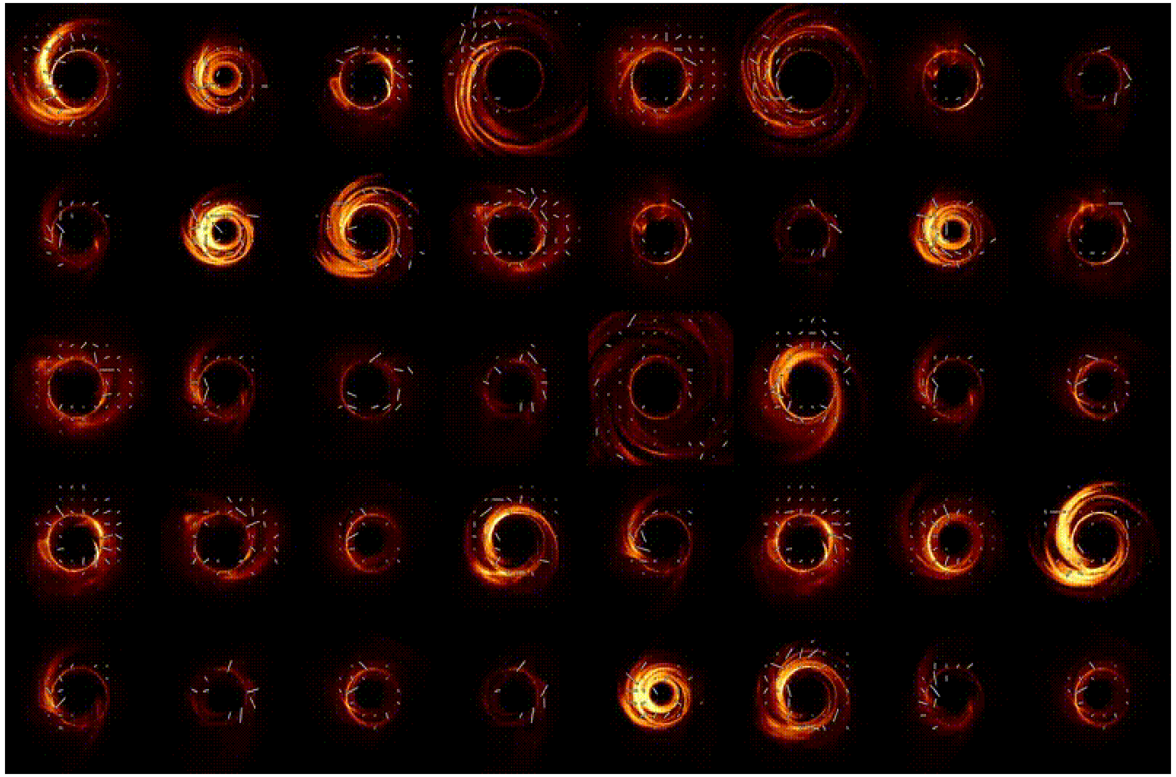
Solve coupled equations of plasma dynamics and magnetic field for low-luminosity accretion in Kerr spacetime

GR Radiative Transfer

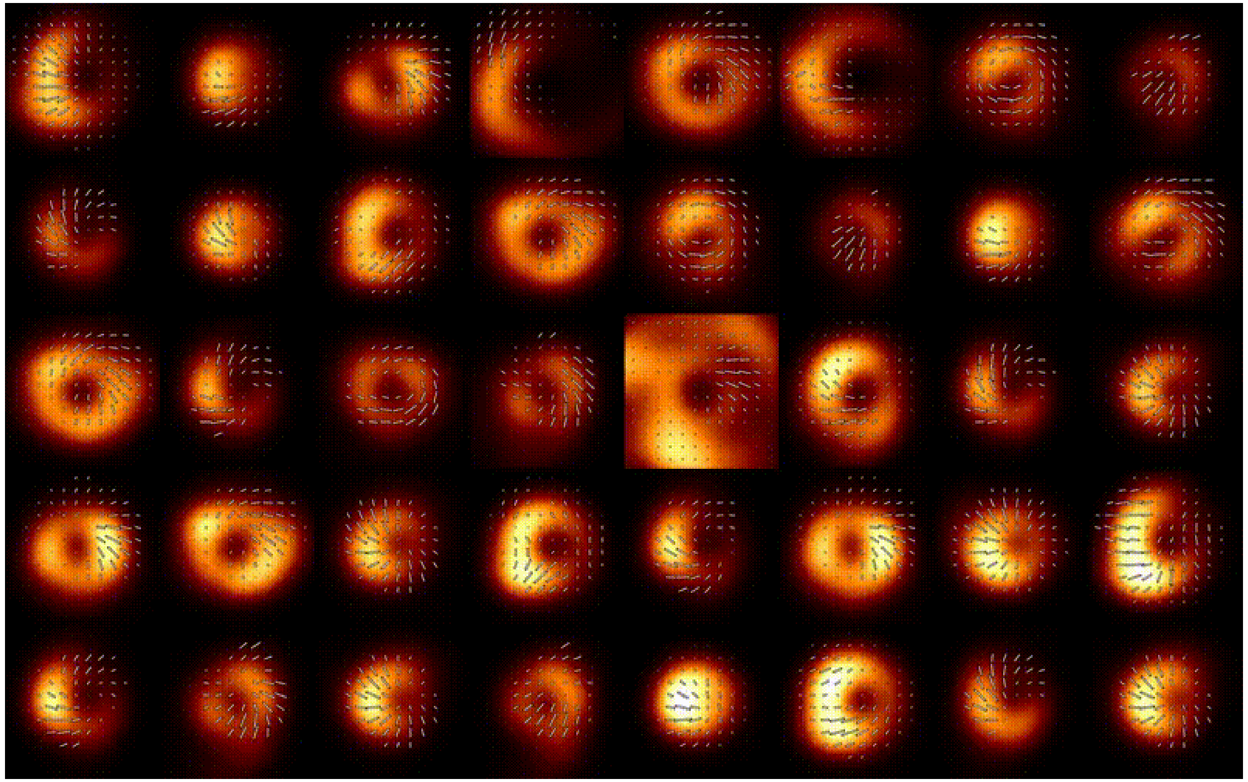
Track light rays and solves for the polarized radiation (including Faraday effects)

Movie Credits: **Chael**+ 2019, 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

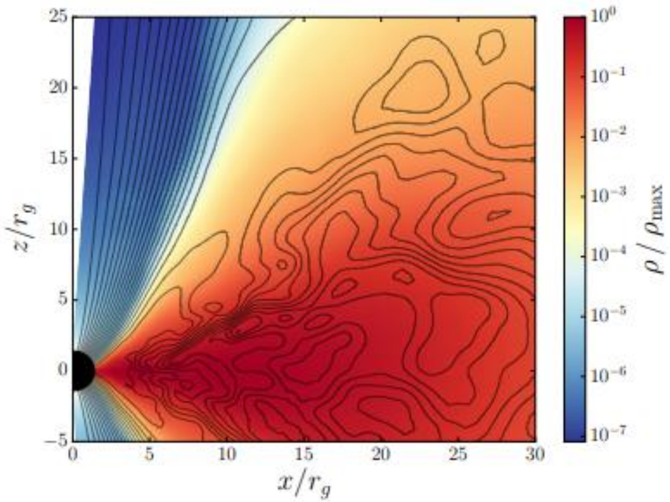
$$\boxed{T_{\mathrm{e}} \neq T_{\mathrm{i}} \neq T_{\mathrm{gas}}}$$

Animation credit: George Wong/ Ben Prather

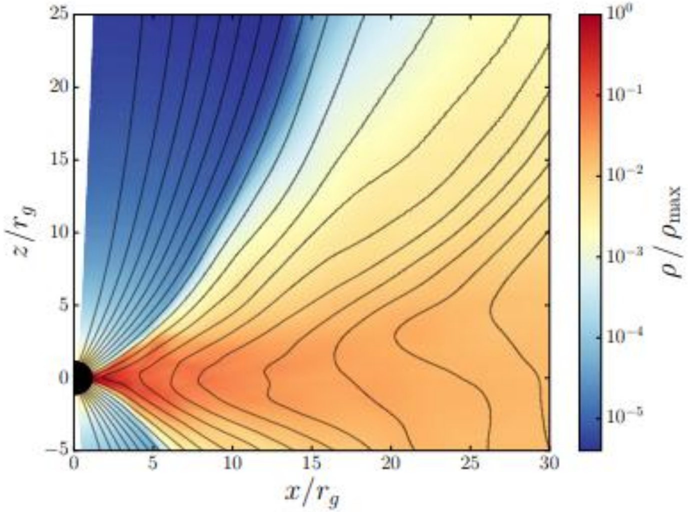
What is the magnetic field structure close to the horizon?

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

Note: 'strong' fields mean ~10 G at the horizon for M87*

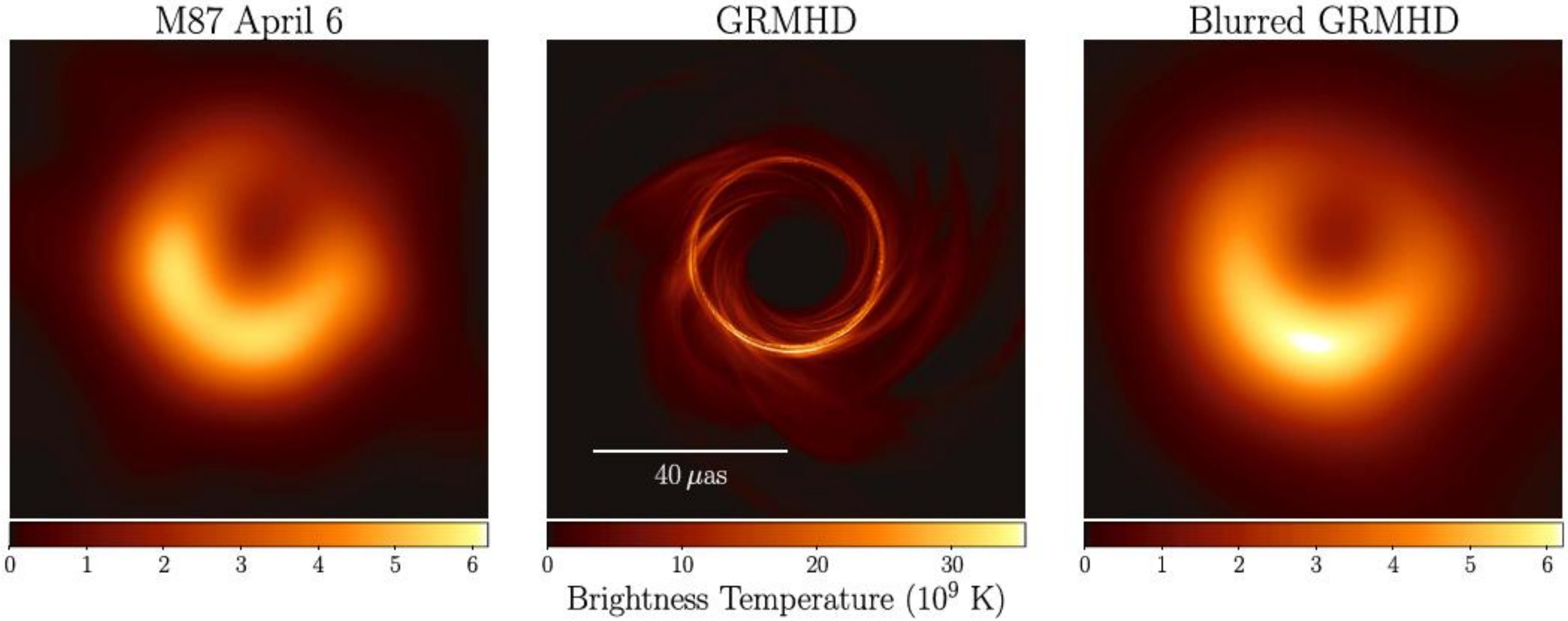
Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_B^2 a^2$

BH spin

magnetic flux

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

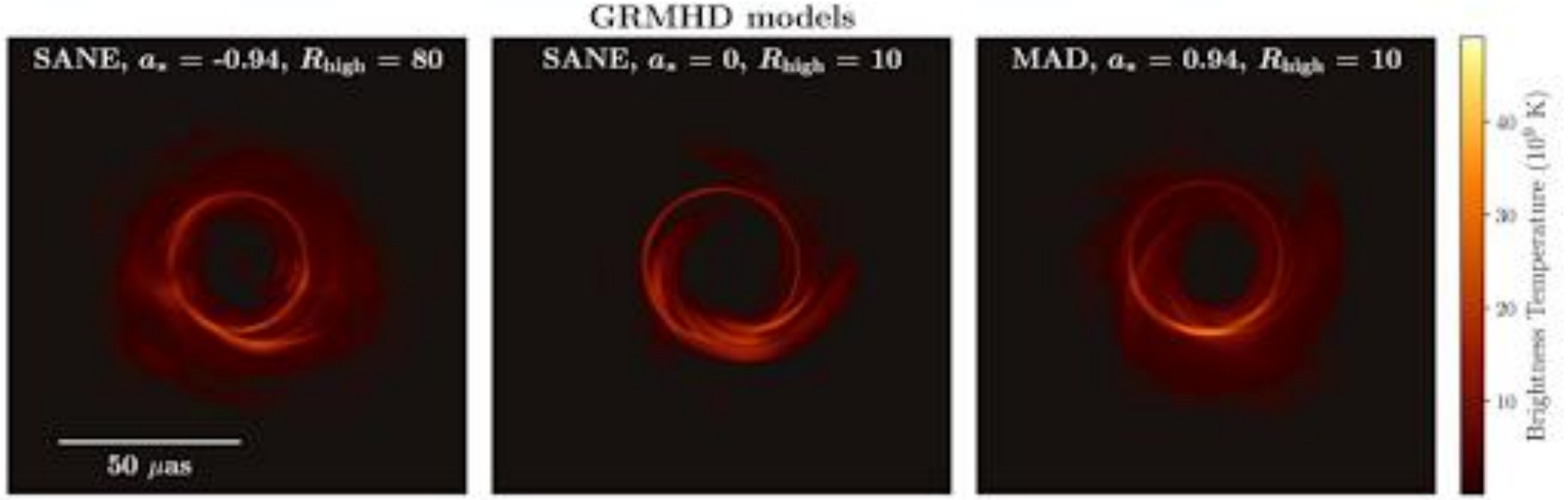
EHT Images are consistent with GRMHD/LLAGN Picture



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

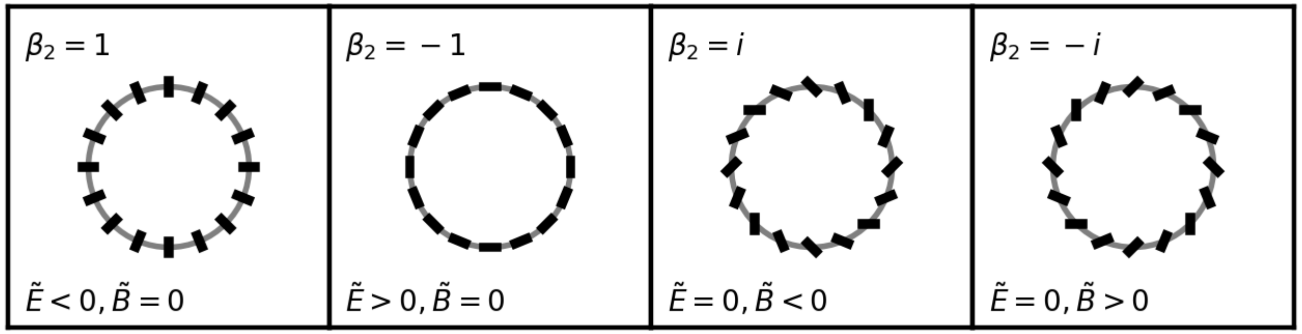
Summarizing an image: Polarization

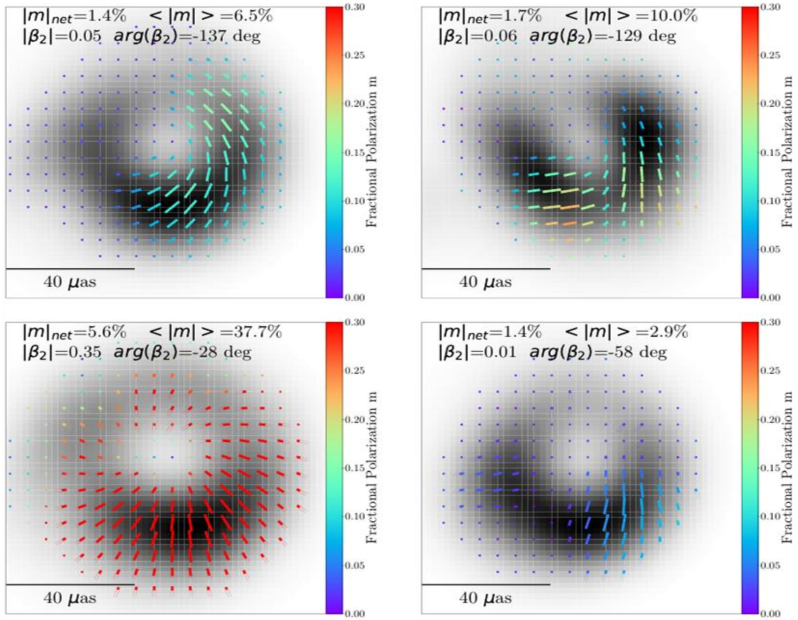
Unresolved and Resolved polarization fractions

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

Azimuthal structure
2nd Fourier mode

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

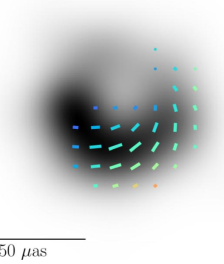




Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

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

Scoring M87* simulations with polarization



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

- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

$$\dot{M} \simeq (3 - 20) \times 10^{-4} M_\odot \ \mathrm{yr}^{-1}$$

$$\left(\dot{M}_{\mathrm{Edd}} = 137 M_\odot \ \mathrm{yr}^{-1}\right)$$

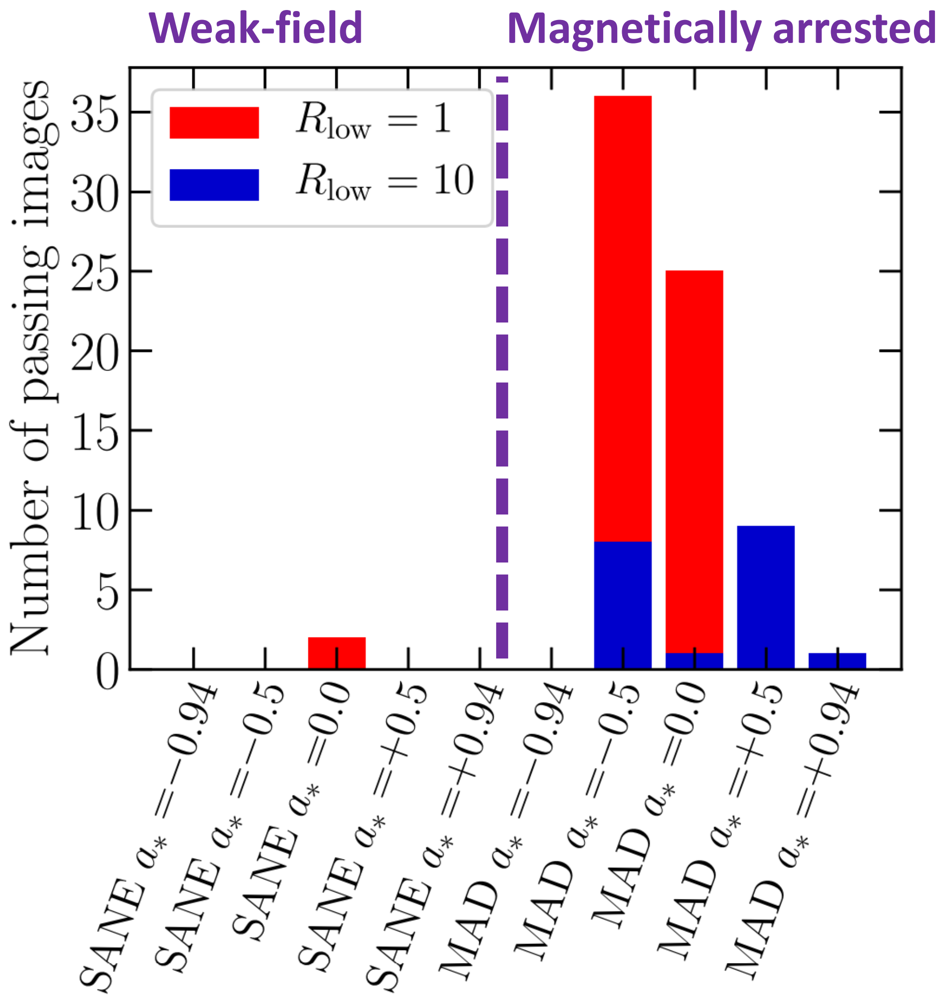
- Parameters from passing models agree with analytic model estimates:

$$T_e \simeq (5 - 40) \times 10^{10} \ \mathrm{K}$$

$$|B| \simeq (7 - 30) \ \mathrm{G}$$

$$n \sim 10^{4-5} \ \mathrm{cm}^{-3}$$

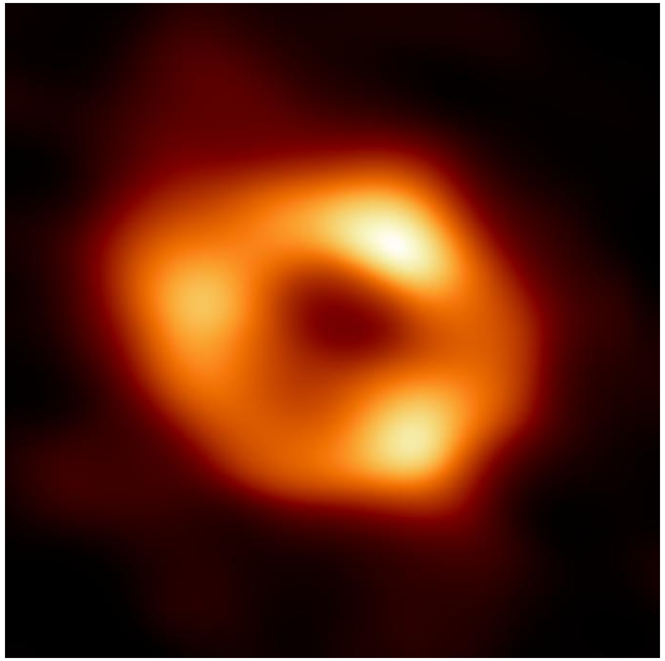
- Strong magnetic fields more easily launch Blandford-Znajek jets!



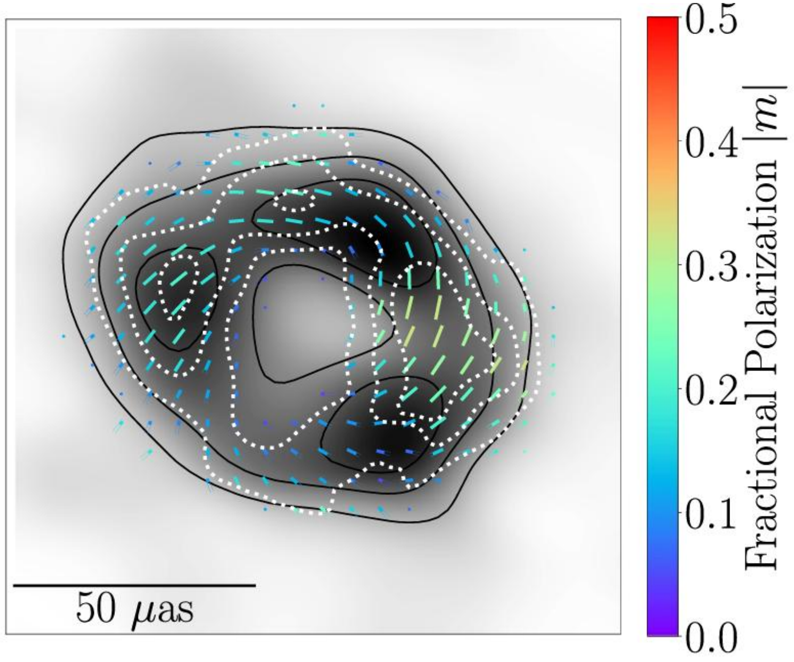
EHTC 2021 VIII, 2023 IX (**Chael**, paper coordinator)

Aside: Sgr A* in linear polarization

Total intensity



Linear Polarization



- Polarization fraction is **higher** than M87
- β_2 is consistent with **clockwise rotation** measured in NIR flares
- MAD simulations also preferred – ***where is the jet?***

EHTC+ 2024 VII, VIII

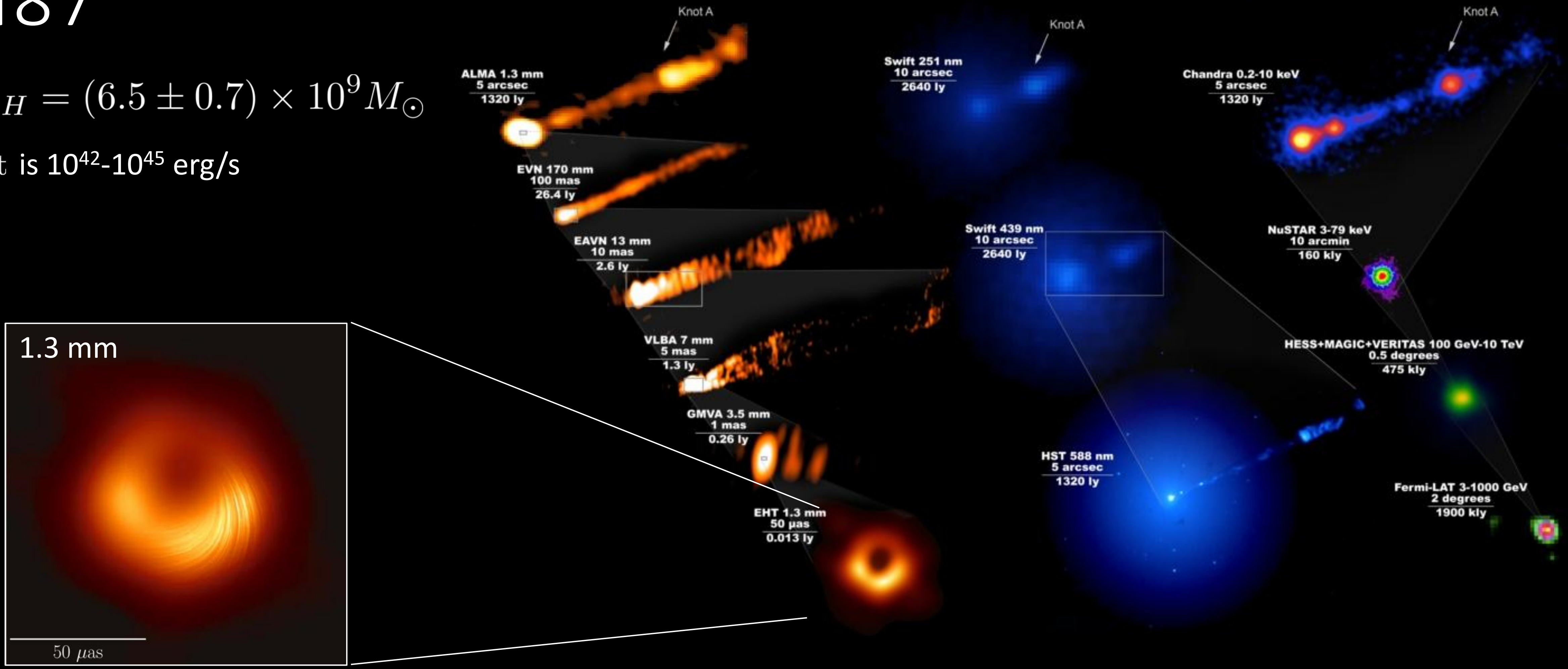
What can a polarized image of M87* tell us about energy flow & jet launching?

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

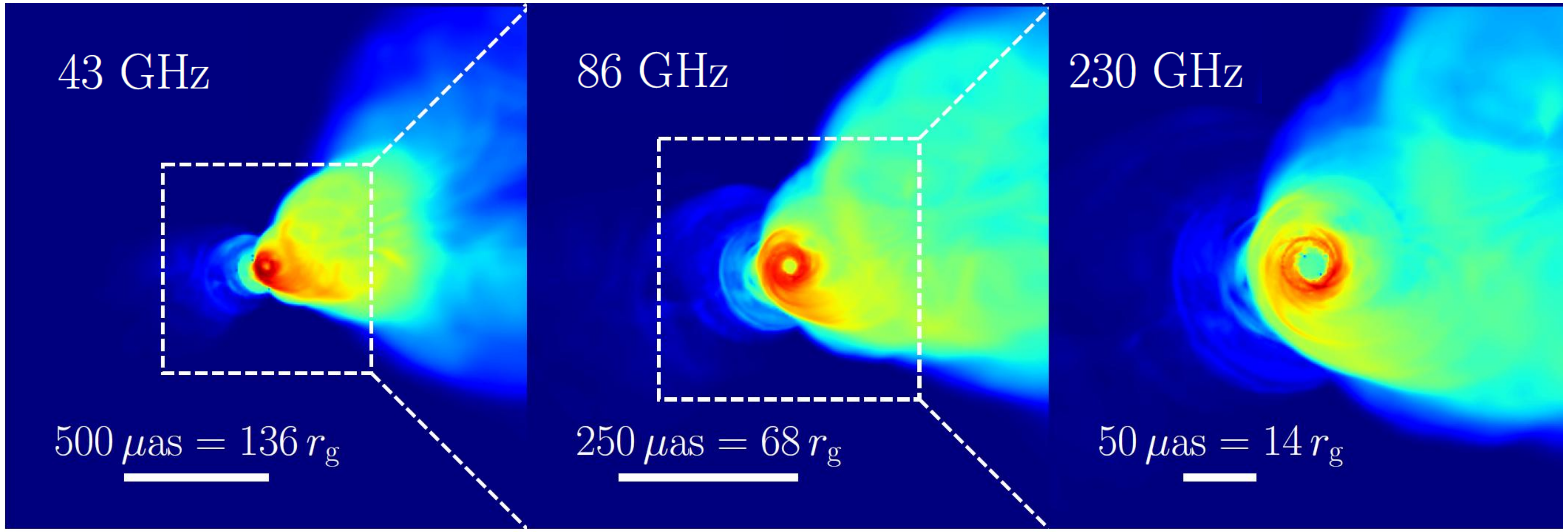
M87 Jets in GRMHD Simulations

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

- **Radiative** simulations (Chael+ 2019, 2025) naturally produce:

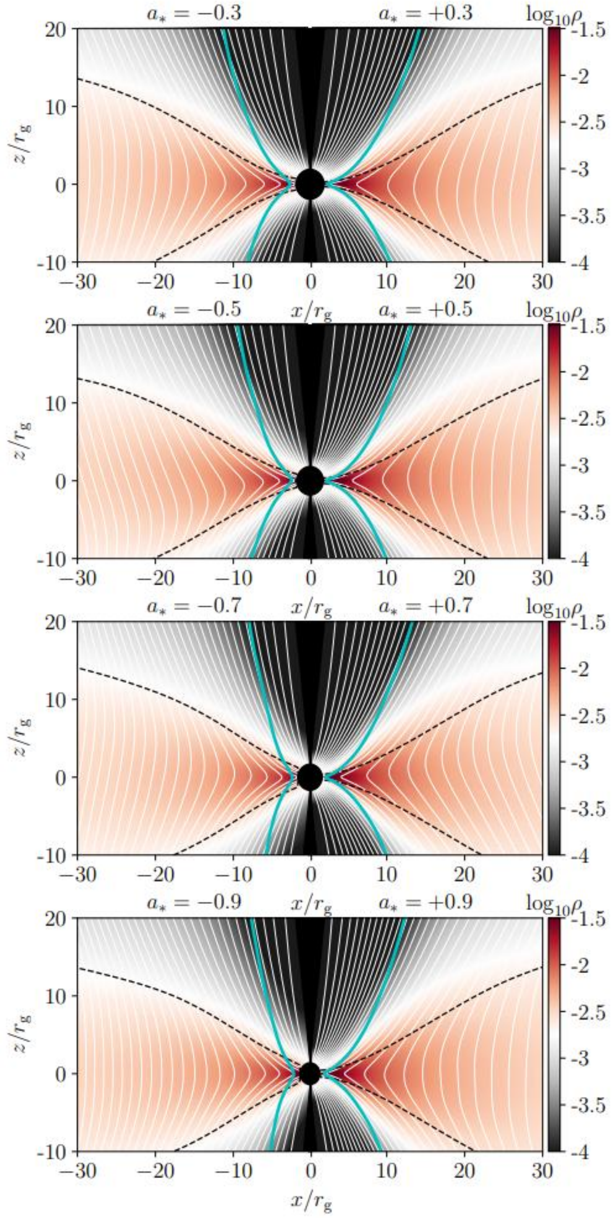
  - A jet power in measured range
  - observed wide opening angle
  - observed core-shift

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



Chael+ 2019

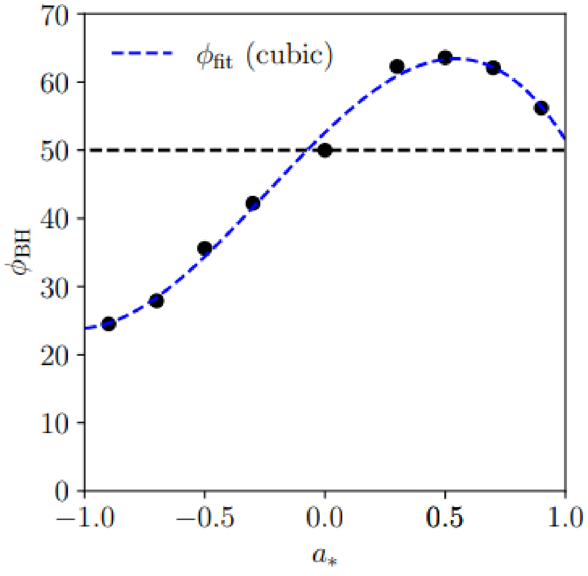
Jets in MADs are Blandford-Znajek



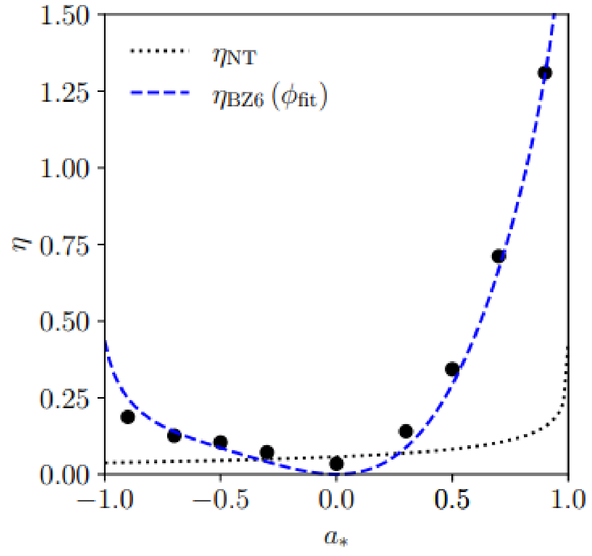
Time-and azimuth-averaged simulation data

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

Magnetic flux though the horizon



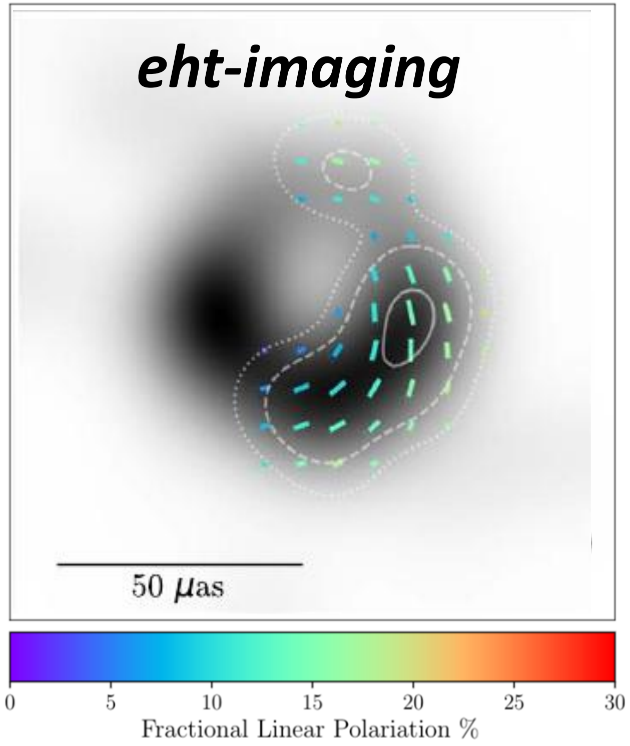
Jet efficiency

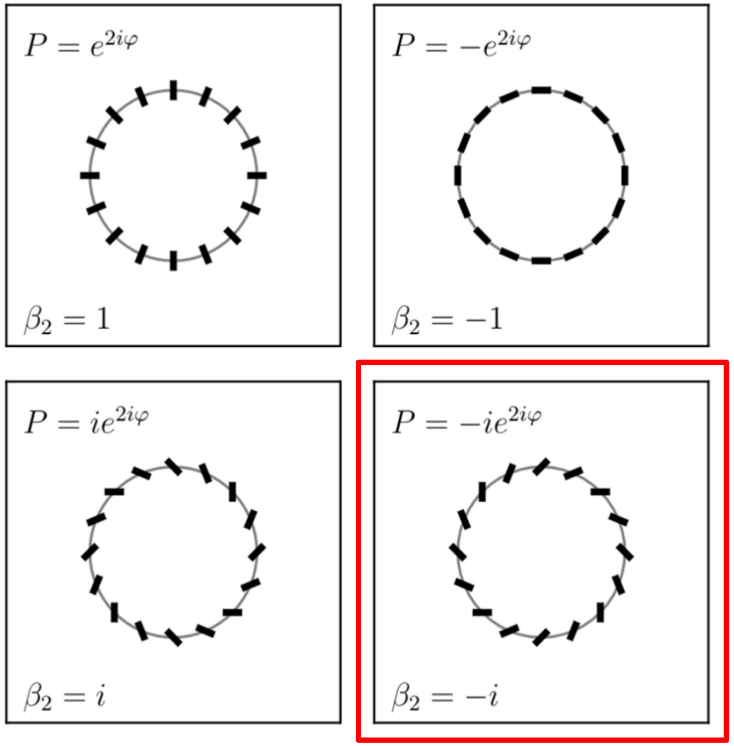


BH spin

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

Polarized Images of M87* and horizon-scale energy flow

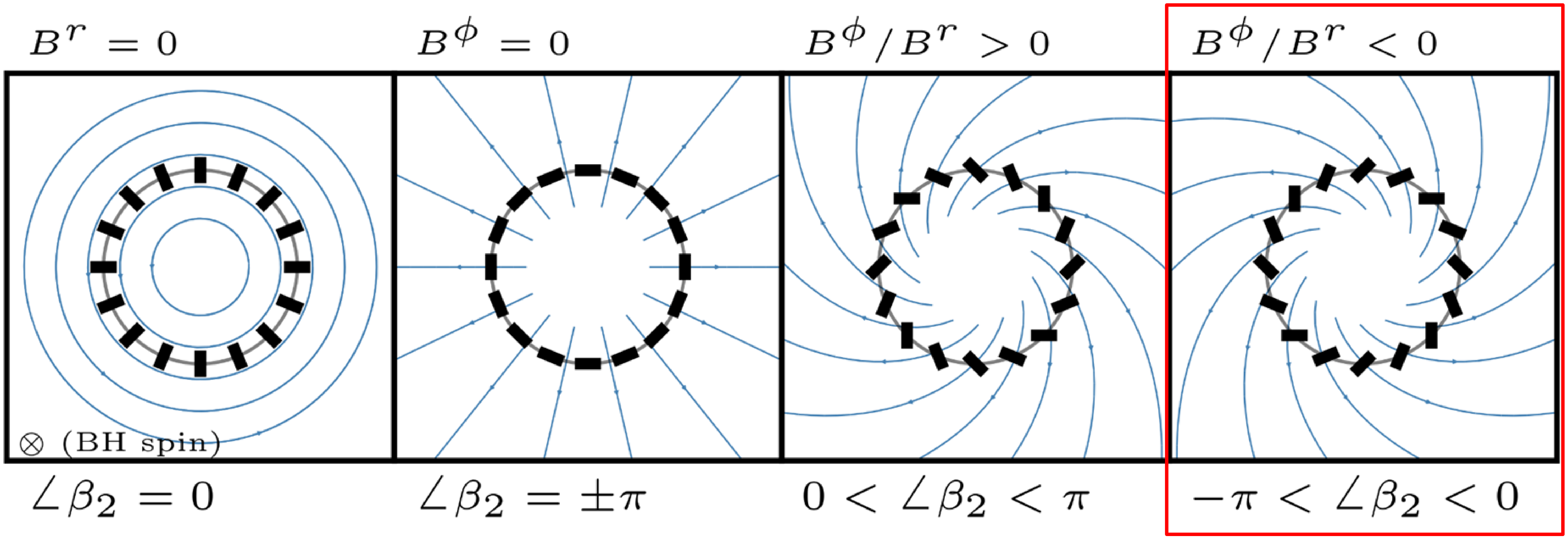




- The polarization spiral's 2nd Fourier mode (**β_2**: Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret **β_2 physically**?

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

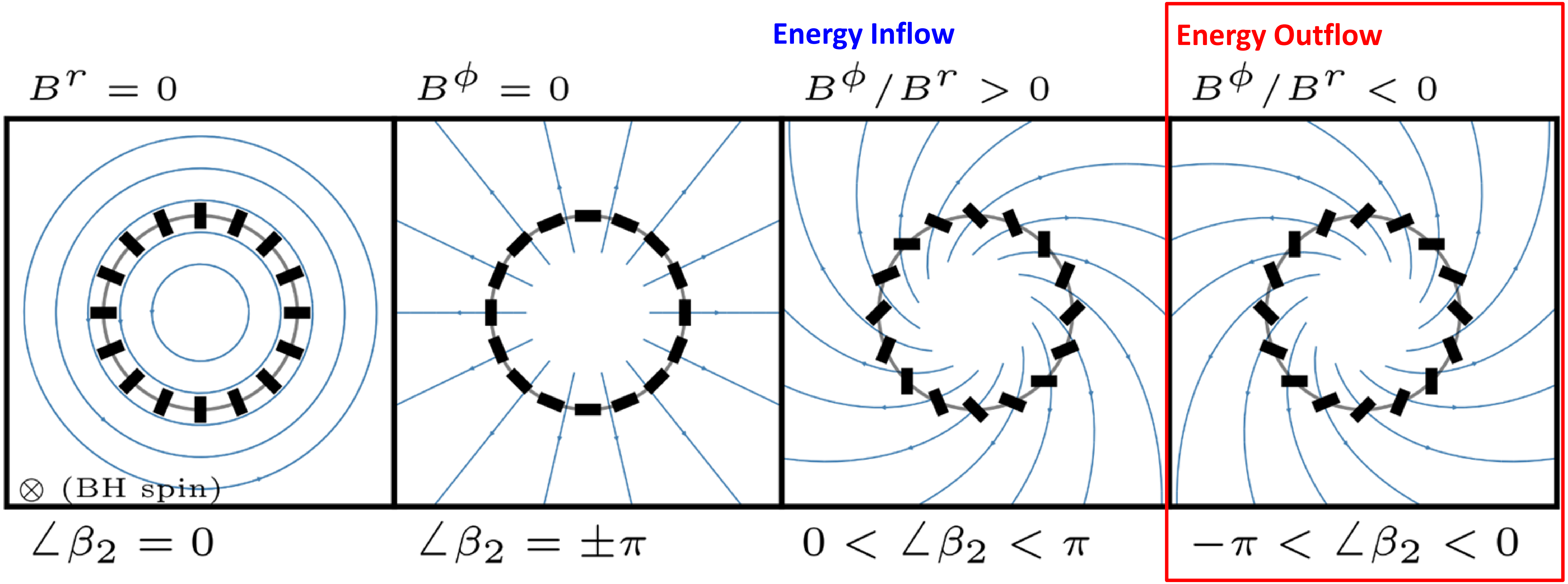
Cartoon model: β_2 is connected to the field pitch angle



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

Chael+ 2023b

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



Radial Poynting flux in Boyer-Lindquist coordinates:

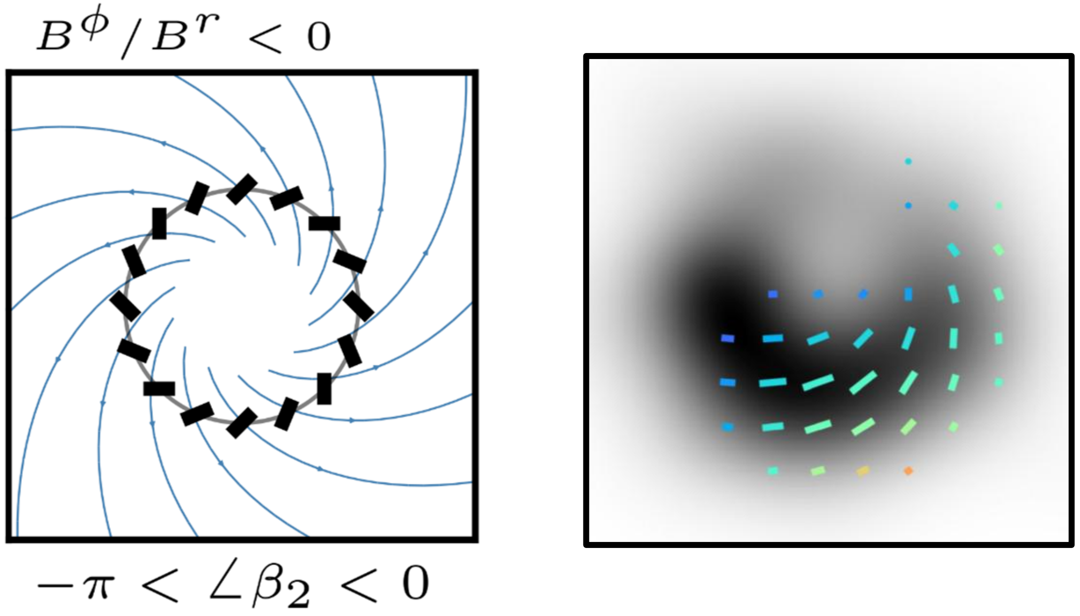
$$\mathcal{J}^r_{\mathcal{E}} = -T^r{}_{t\ \mathrm{EM}} = -B^r B^\phi \, \Omega_F \, \Delta \sin^2\theta$$

fieldline angular speed

Chael+ 2023b

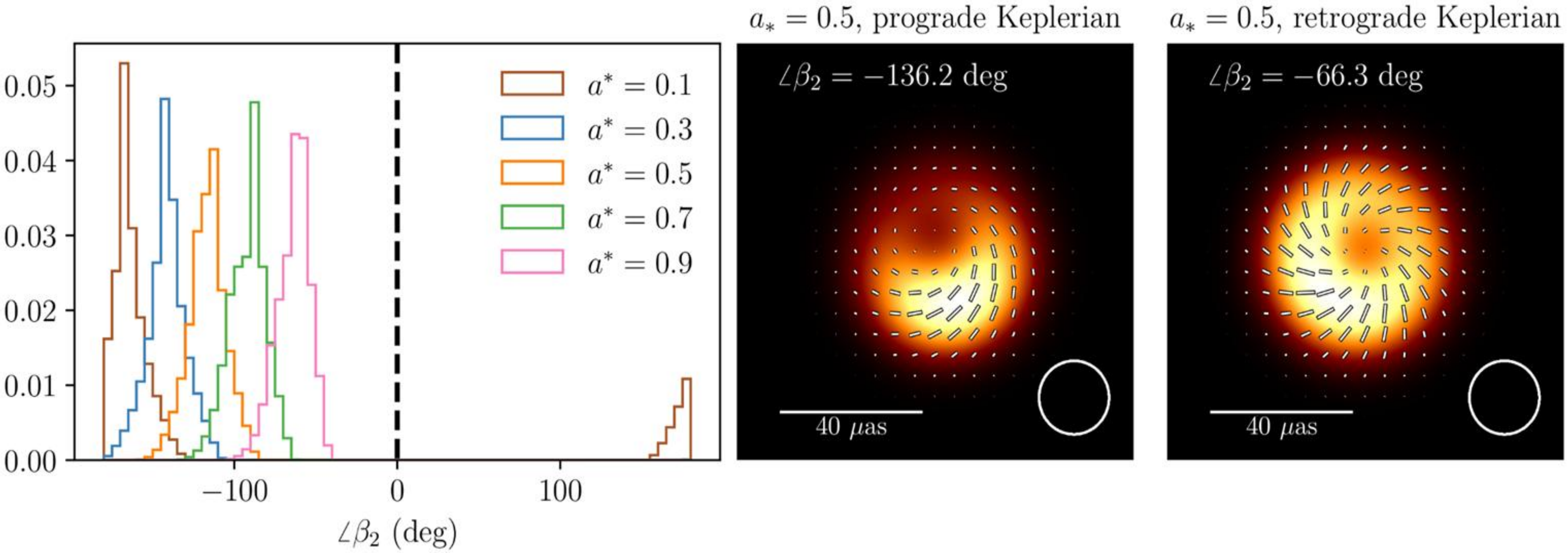
Near-horizon polarization is connected to the **electromagnetic energy flux**

- 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*?



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

β_2 in semi-analytic models of M87*

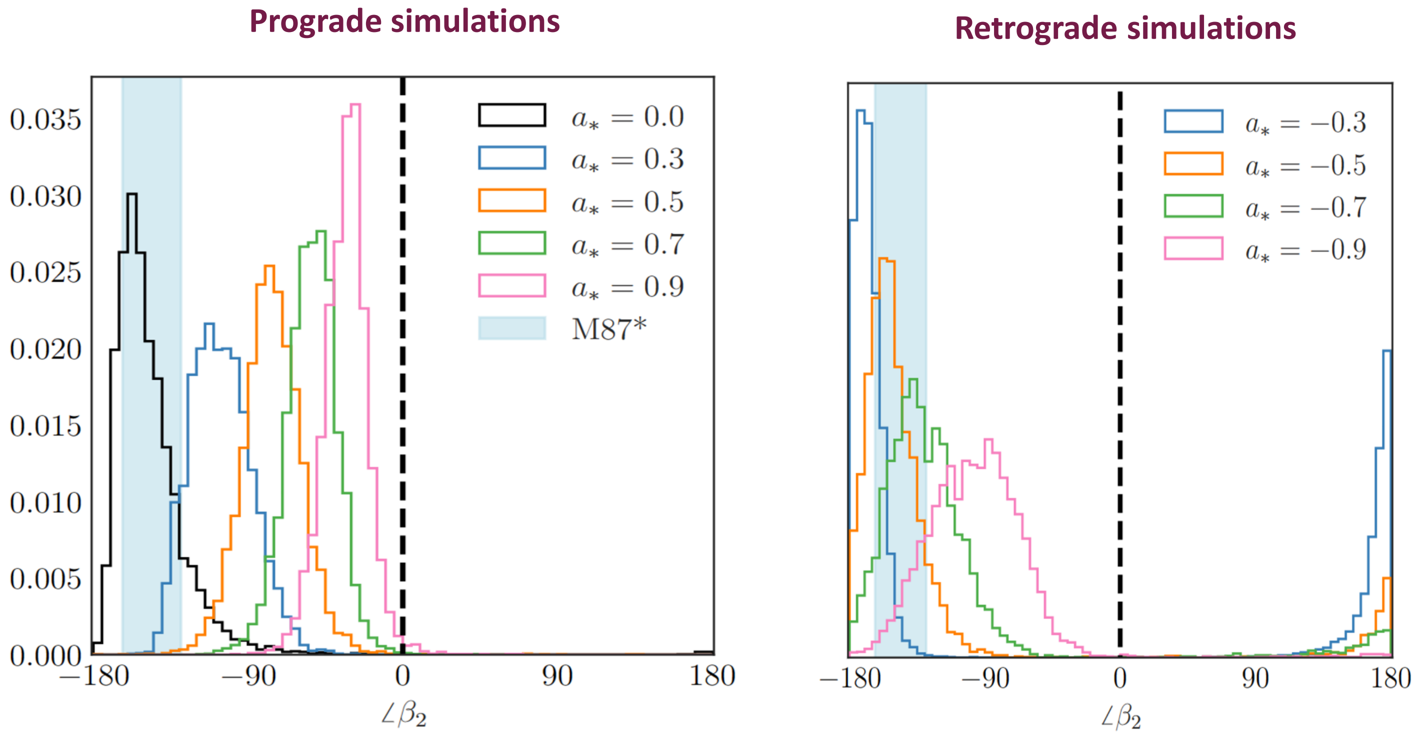


- We fix magnetic fields to the force-free BZ monopole solution (with energy outflow)
- We explore many models for the velocity of the emitting fluid
- Changes in fluid velocity do not significantly affect sign of arg(β_2) or trend with BH spin

Chael+ 2023b

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

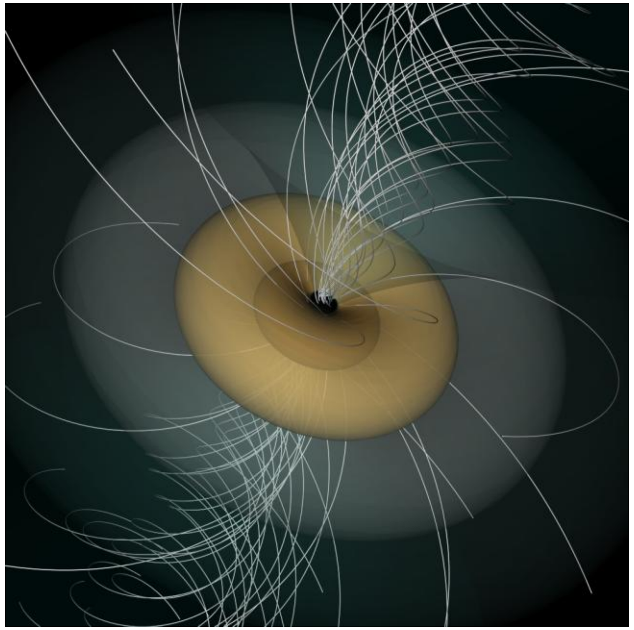
- 1600 simulated EHT-resolution M87* images from MAD simulations (Narayan+ 2022)
- Almost all 230 GHz simulation images have **negative arg(β_2)** consistent with the measured energy outflow in the simulations
- arg(β_2) has the **same qualitative dependence on spin** as in the BZ monopole model, despite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



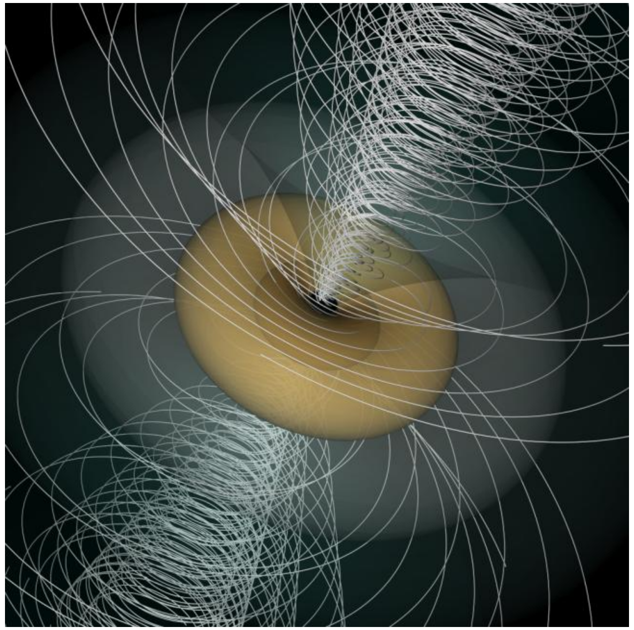
Chael+ 2023b

Polarized images are **spin dependent**

Low Spin



High Spin

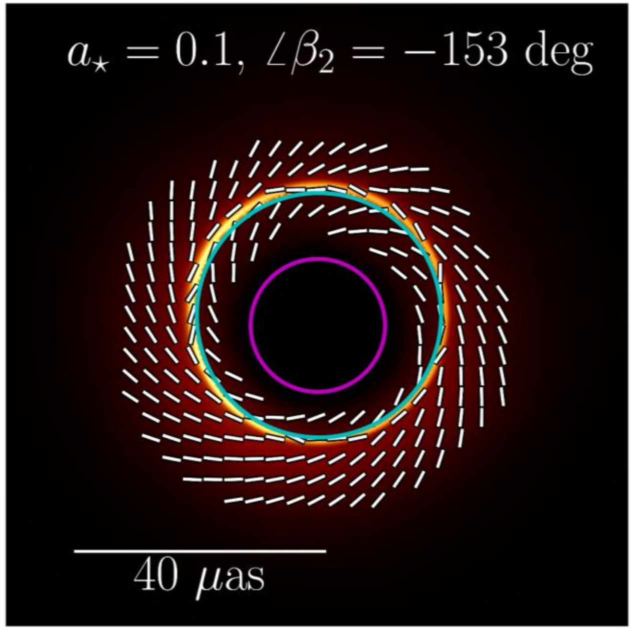


- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
    - increases the Poynting flux (BZ jet power)

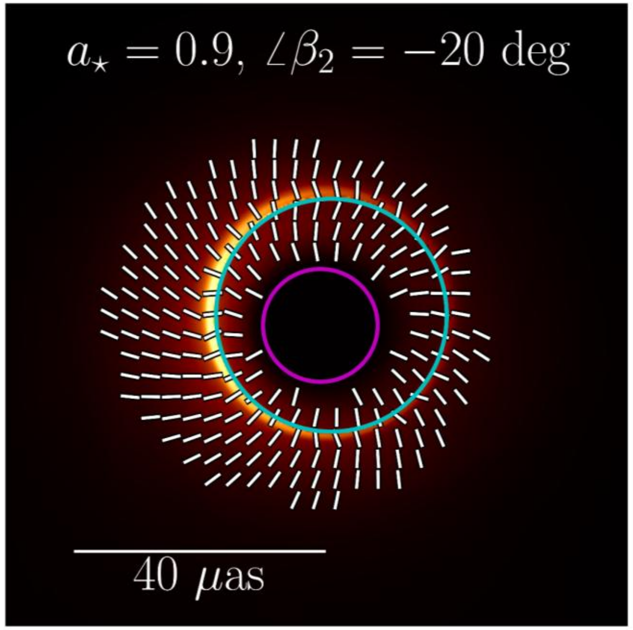
Image credit: George Wong

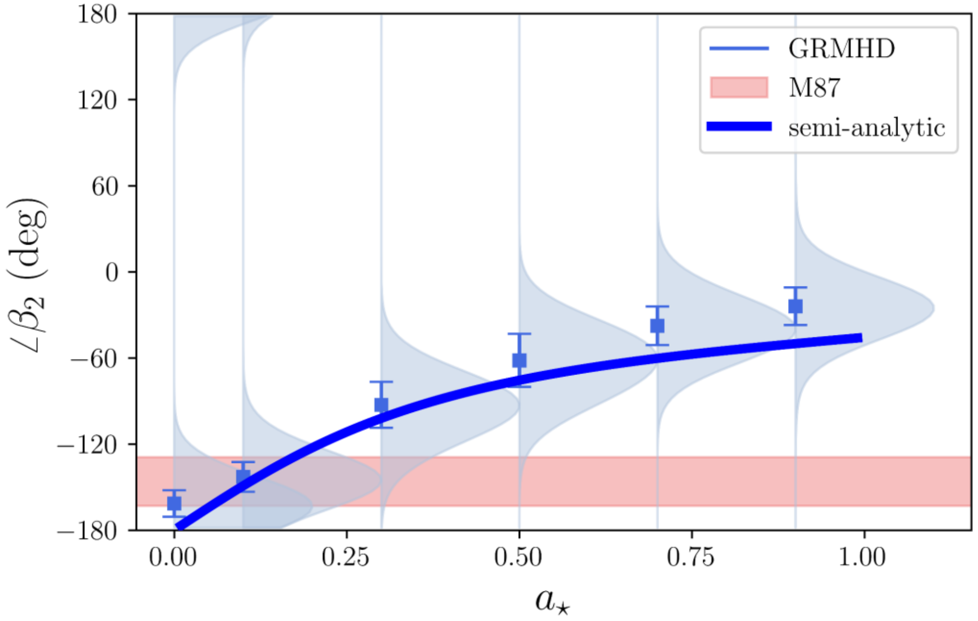
Polarized images are **spin dependent**

Low Spin



High Spin

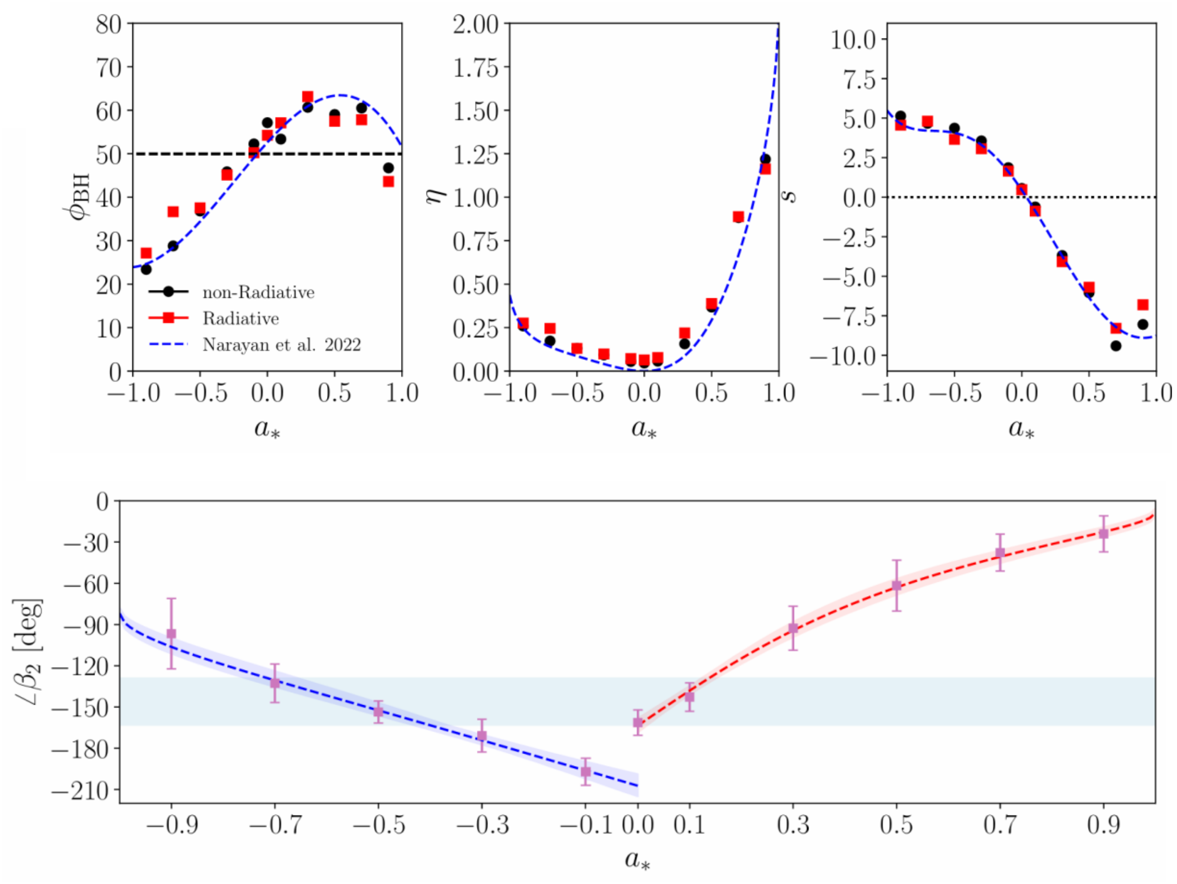




- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the Poynting flux (BZ jet power)
  - makes the observed polarization pattern more radial

Chael+2023

Aside: Radiative Simulations Have Similar Jets…



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

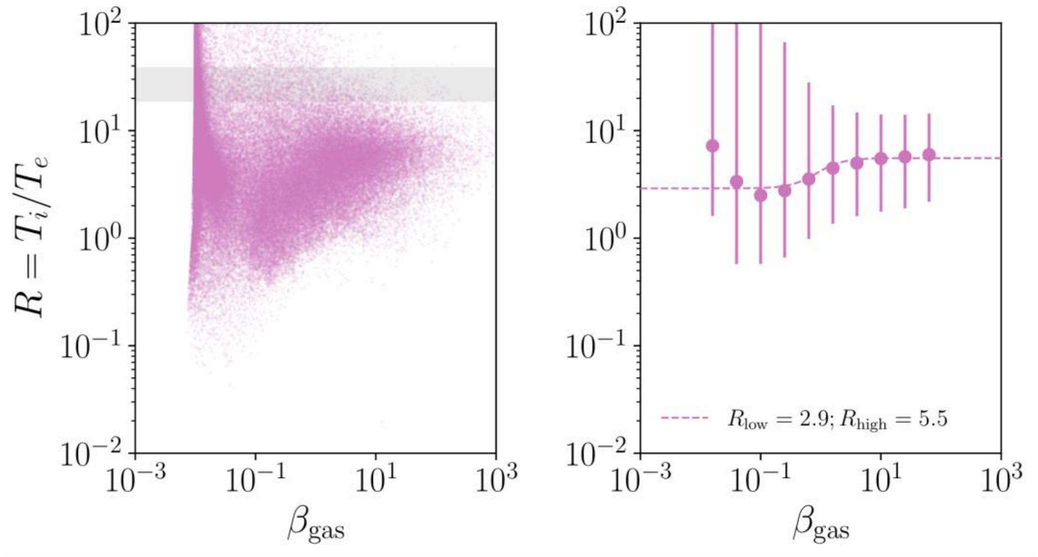
$$T_{\rm e} \neq T_{\rm i}$$

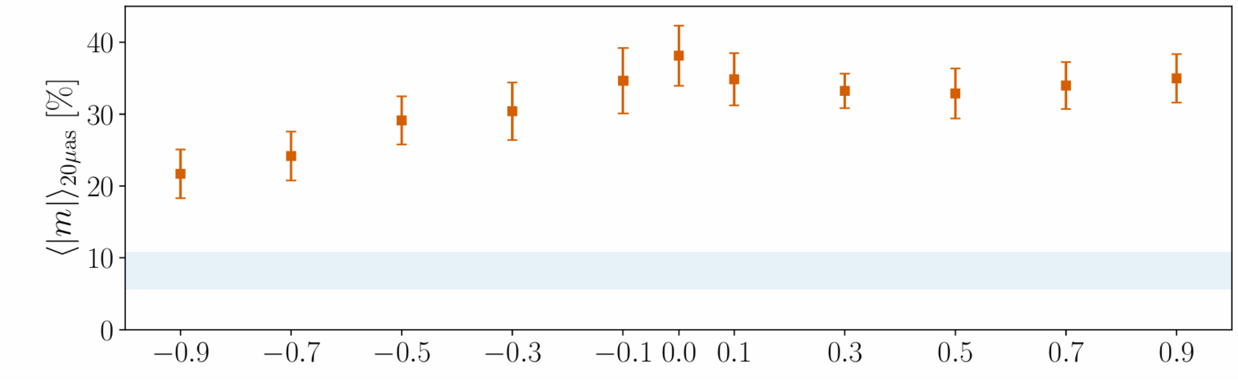
- Radiative, two-temperature GRMHD includes **heating and cooling self-consistently** (e.g. Ressler+2015,17, Chael+ 2018,19)

- 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_e locally in **postprocessing** and seems to prefer electrons T_i ~ 100x T_e to sufficiently depolarize the image in MAD simulations.
- 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 jet power source

Gelles+ 2025, Chael+ in prep.
2410.00954

How can we determine the jet power source?

By zooming **out**..

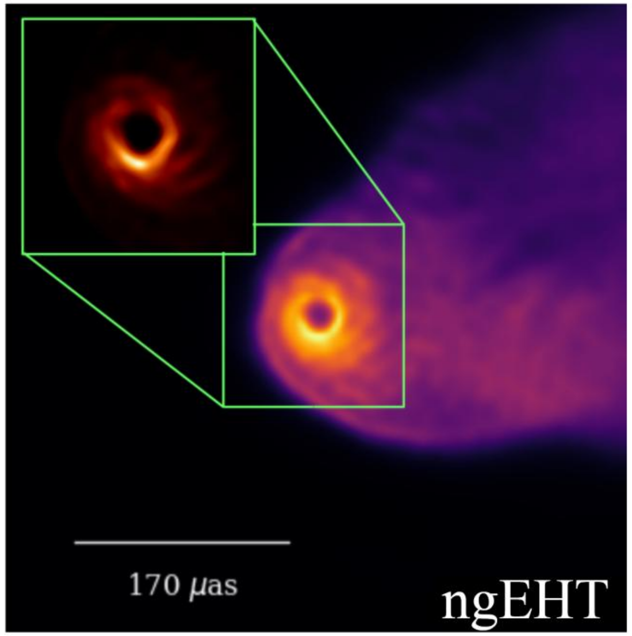


Image the connection between the BH and the low-brightness extended jet in **high dynamic range** with the **next-generation EHT (ngEHT)**

By zooming **in**..

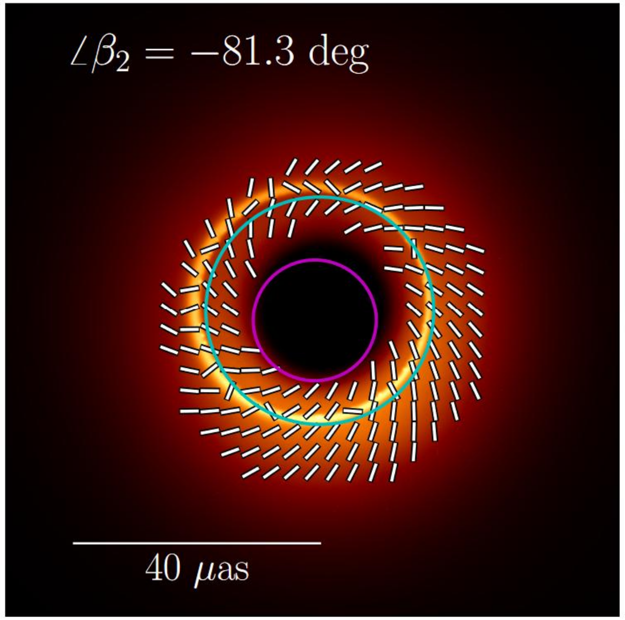
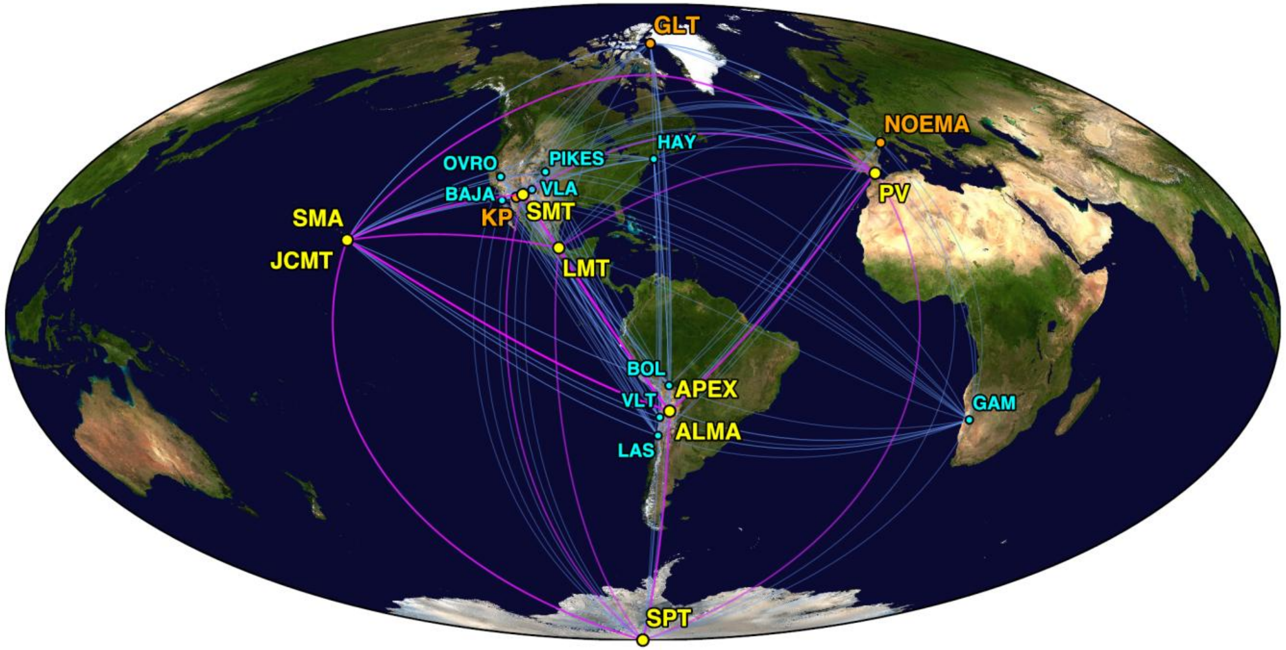
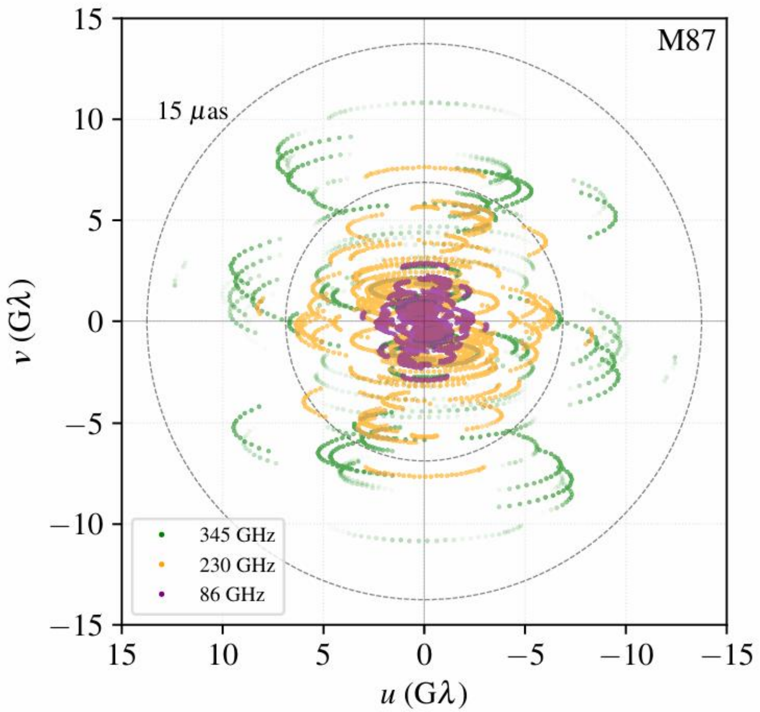


Image field lines close to the event horizon in **high resolution** with the **Black Hole Explorer (BHEX)**

The next-generation EHT (ngEHT)





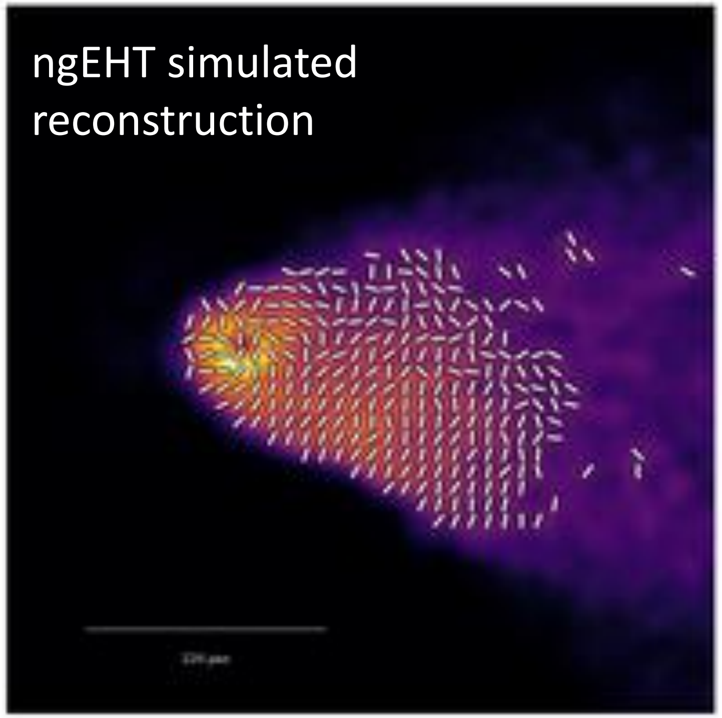
Increased coverage from new sites and observing frequencies in ngEHT will enhance **dynamic range**

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

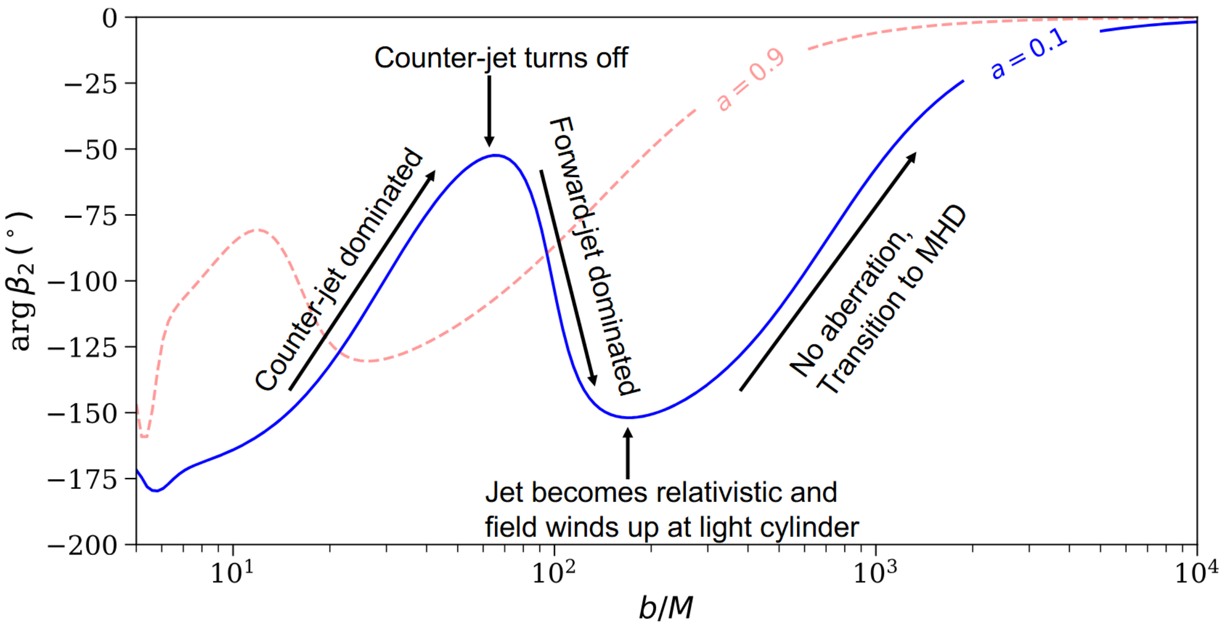
$$N_{\mathrm{obs}} = \binom{N_{\mathrm{sites}}}{2} \propto N_{\mathrm{sites}}^2$$

Doeleman+ 2023

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



Zack Gelles (Princeton)
Arxiv: [2410.00954]



- New sites & larger bandwidth will enhance EHT's **dynamic range** and **illuminate** the **BH-jet connection**
- Measuring polarization as a function of radius **probes energy flow at different scales**
- Polarization of BZ jets has a **strong signature of spin** at the **light cylinder** (Gelles, Chael, & Quataert 2025)

Chael+ 2019, 2023b
Gelles, **Chael**, Quataert+ 2025
Image Credit: Paul Tiede, Dom Pesce, Zack Gelles

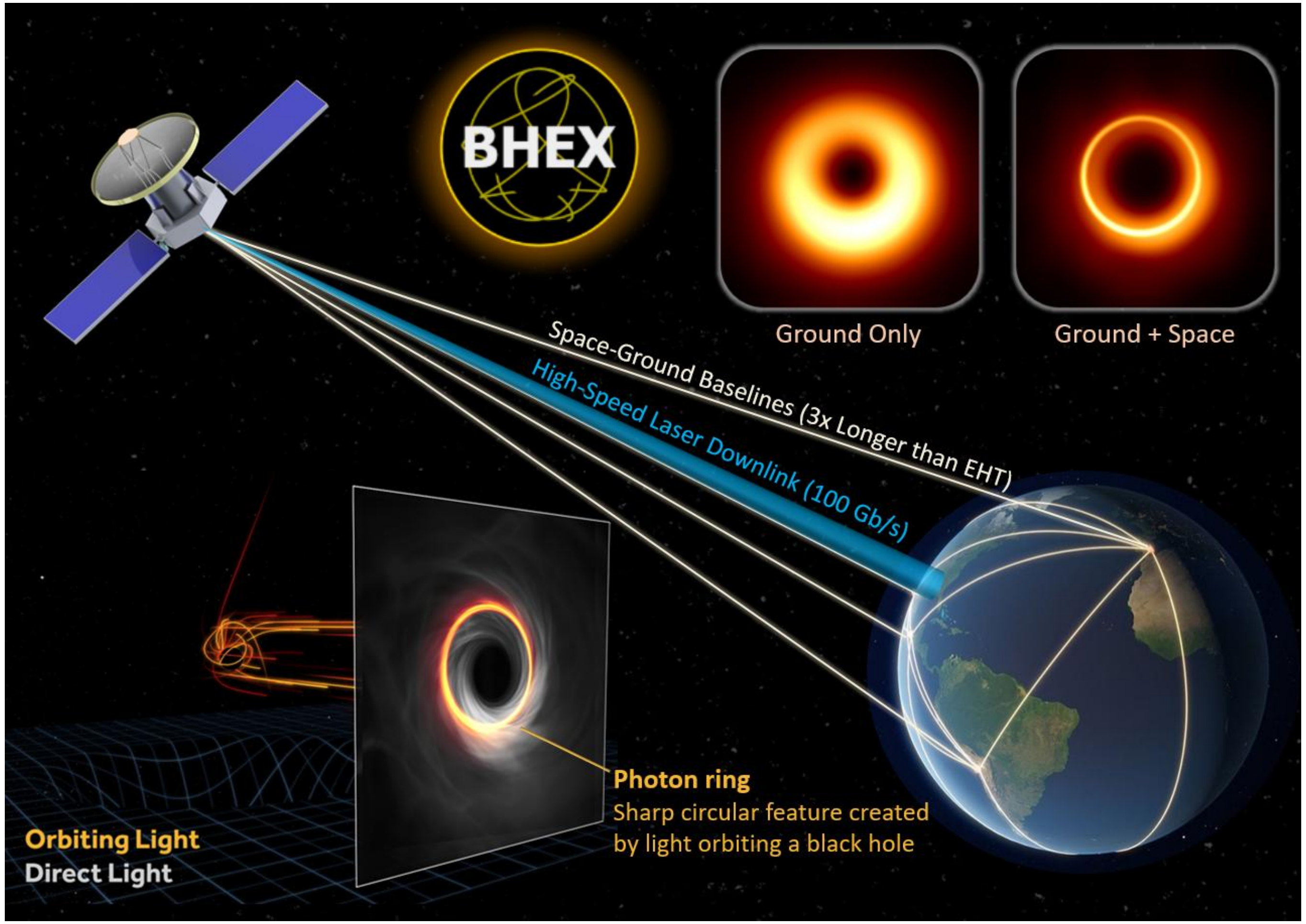
The Black Hole Explorer (BHEX)

Earth-Space VLBI at 1.3 mm

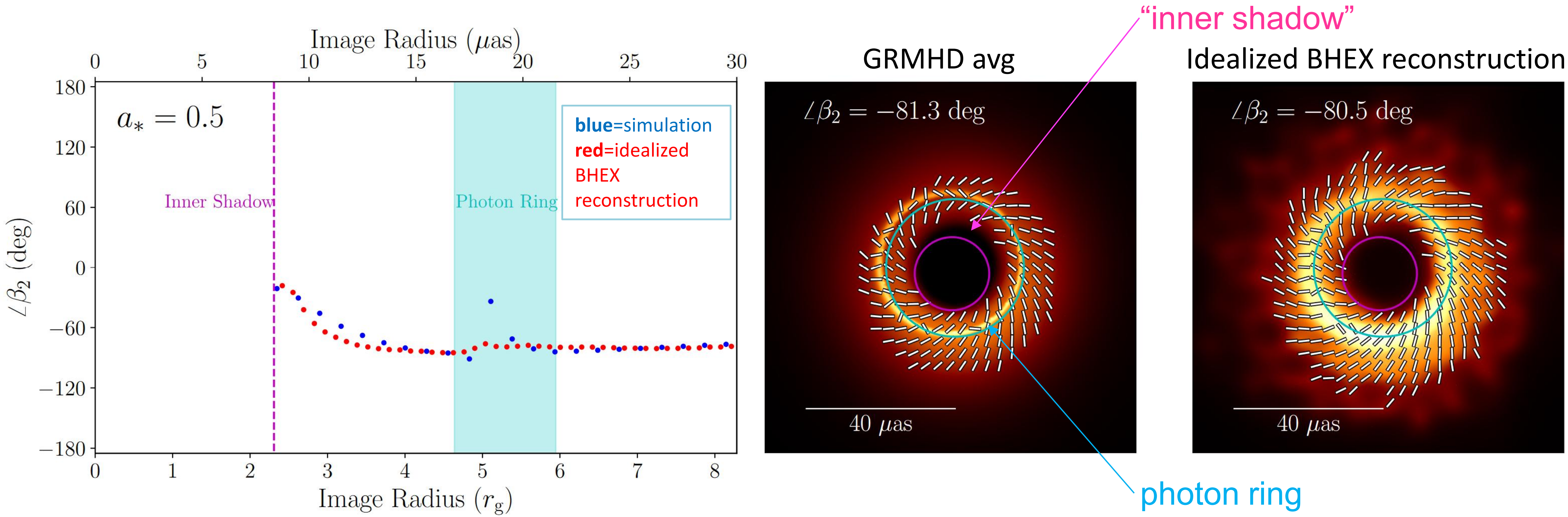
- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground infrastructure & pioneers optical laser downlink
- Targeting a 2025 SMEX proposal

BHEX Science Goals

- Discover a black hole’s photon ring
- Make direct measurements of a black hole’s mass and spin
- Reveal the shadows of *dozens* of supermassive black holes



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

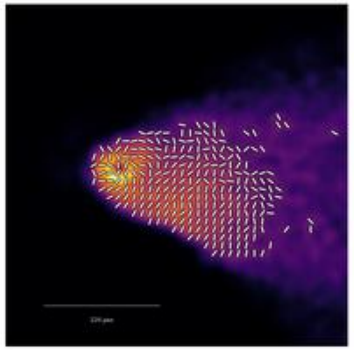


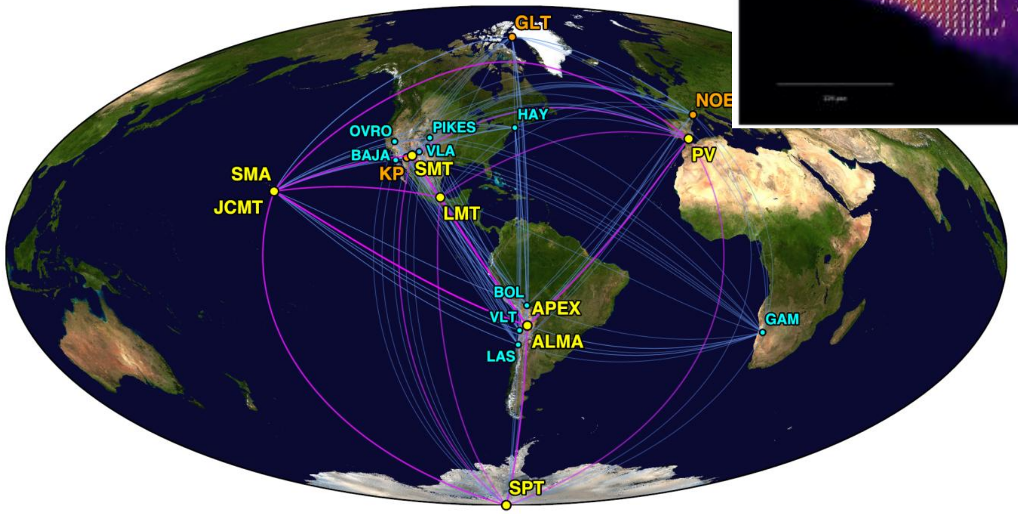
- β_2 evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - Strong evolution of arg(β_2) to the horizon is predicted by both simple BZ models and GRMHD
- **BHEX + EHT obtain the resolution to observe energy extraction at horizon scales**

Chael+ 2023b, Chael in prep

The future of near-horizon black hole astrophysics

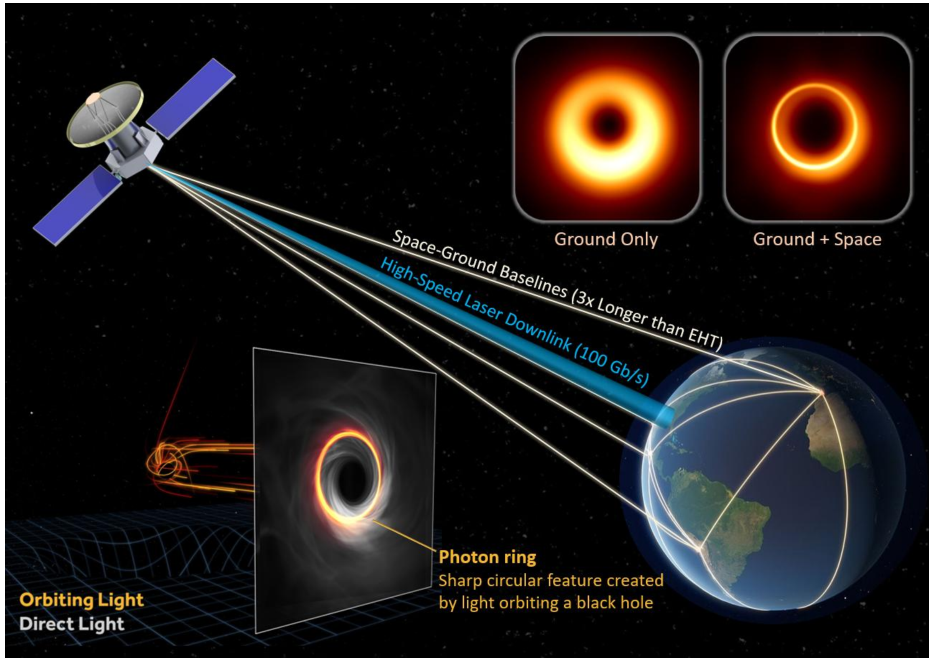
Next-generation EHT (ngEHT)





- Expand all EHT sites to multi-frequency observing and add 4-5 new stations (Doeleman+ 2023)
- Image black holes and AGN jets in **high dynamic range**
- Probe black hole jet launching from horizon to hundreds of Schwarzschild radii (Gelles+ 2025: [2410.00954]())

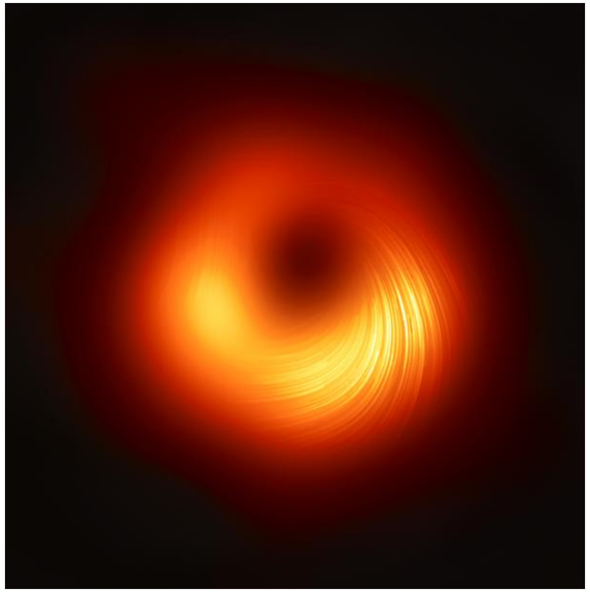
Black Hole Explorer (BHEX)



- 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)

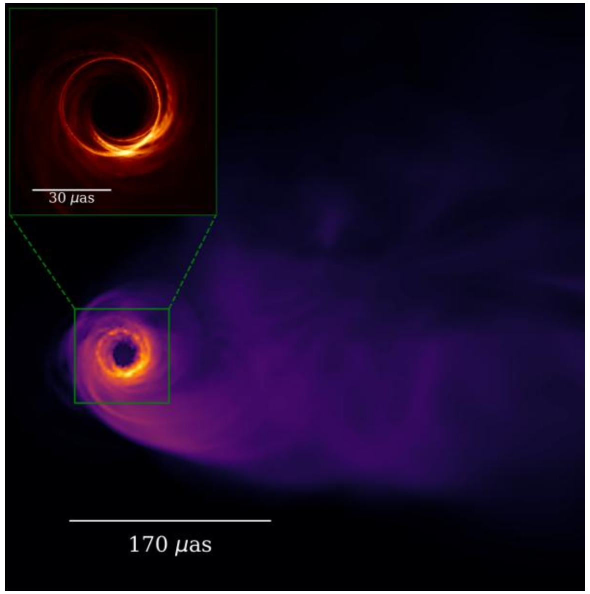
Takeaways…

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 observations** will directly probe the black hole-jet connection



…and more questions

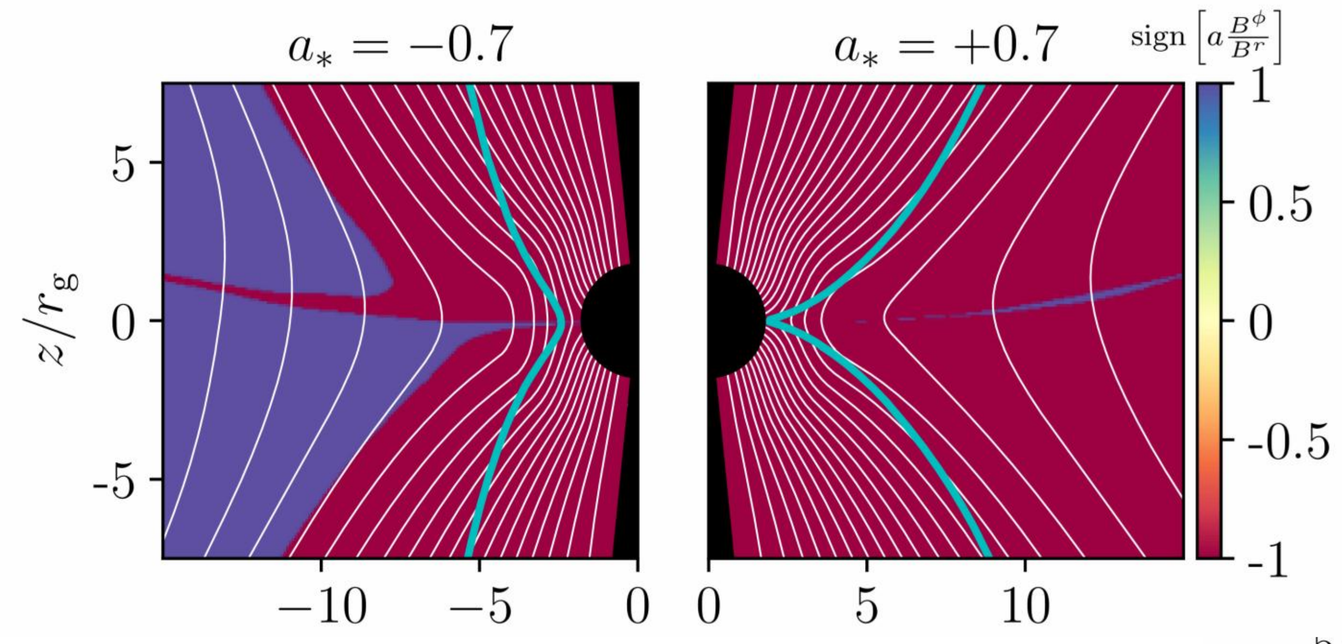
- What plasma physics sets the temperature/distribution of the electrons?
- What powers flares in Sgr A* and M87*?
- What can EHT/BHEX observation tell us about the near-horizon environments of supermassive black holes beyond Sgr A* and M87*?



EHT VII, 2021; **Chael** 2025

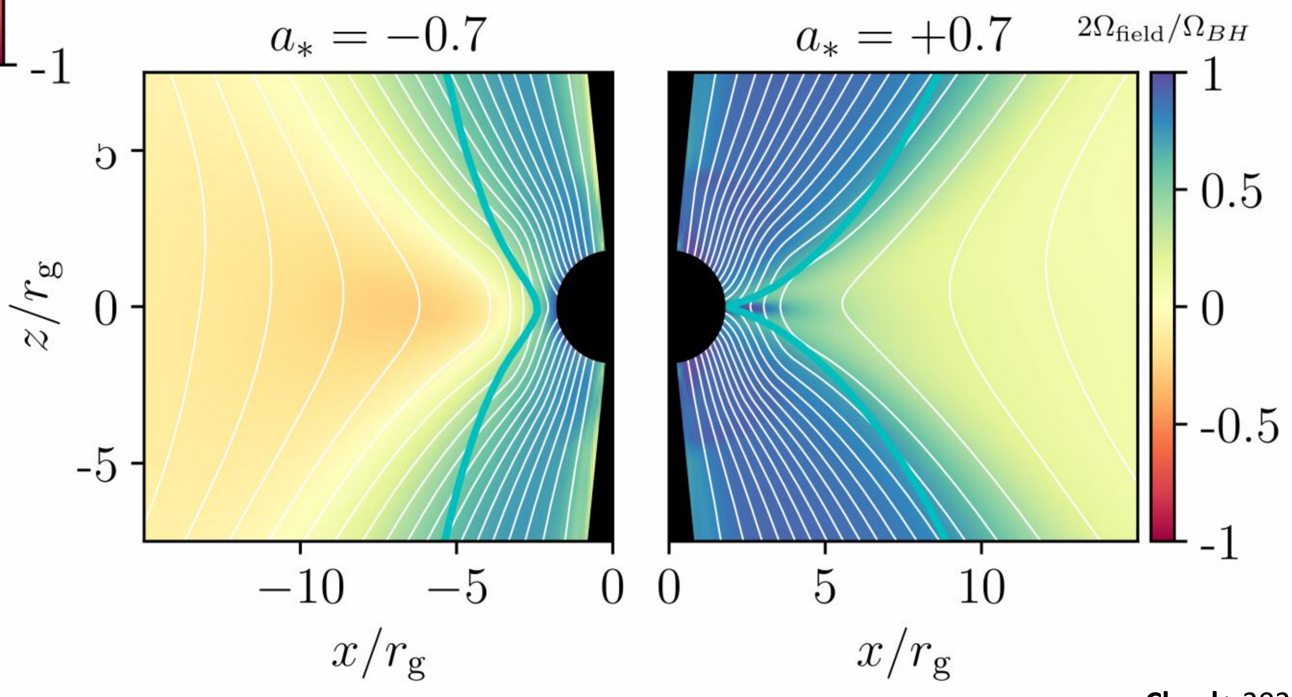
backup slides

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



Sign of magnetic field pitch angle

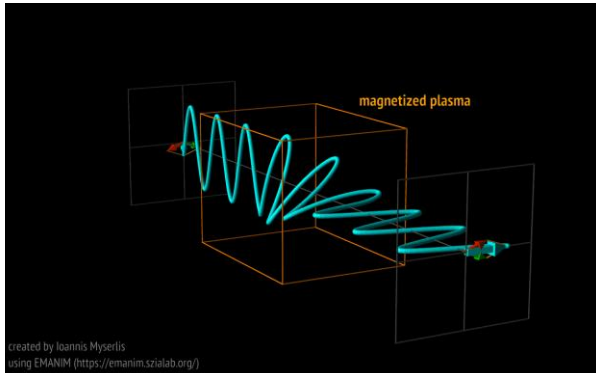
Field-line angular speed



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

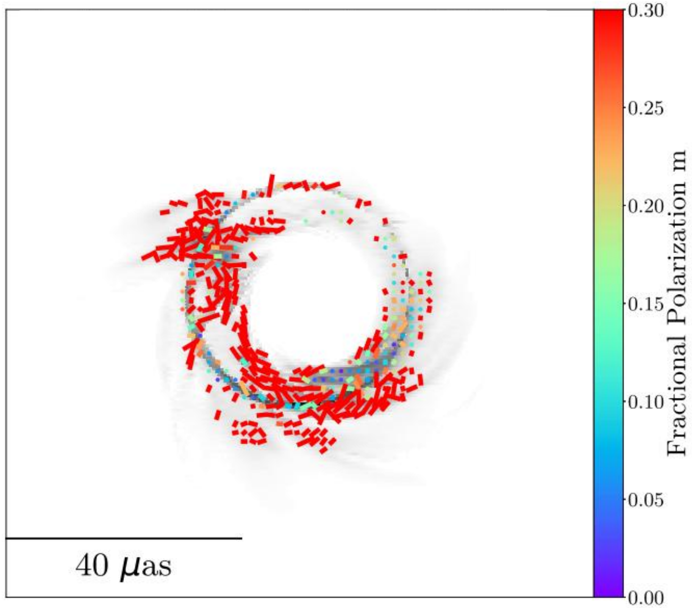
Faraday Rotation is important!

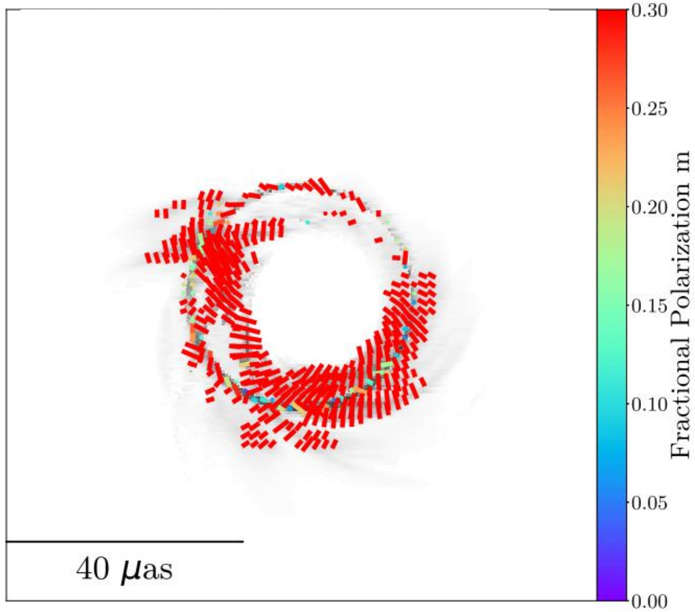


With rotation

Without rotation

'infinite' resolution

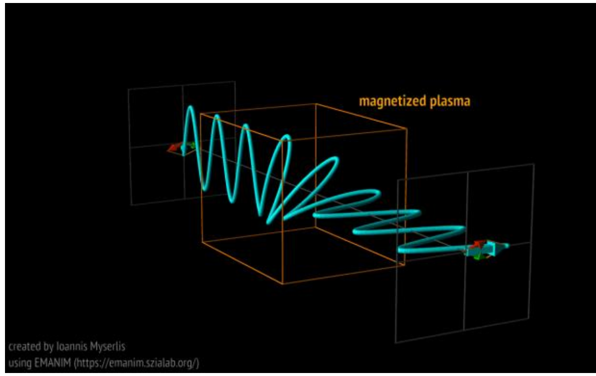




- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

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

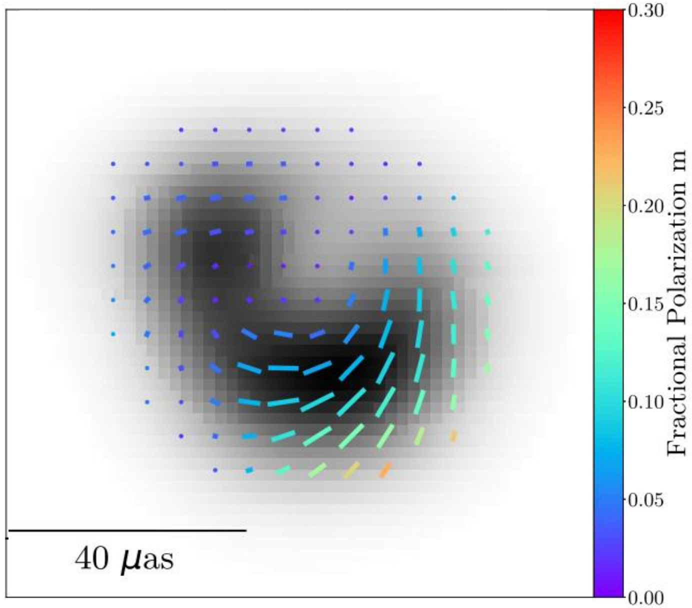
Faraday Rotation is important!

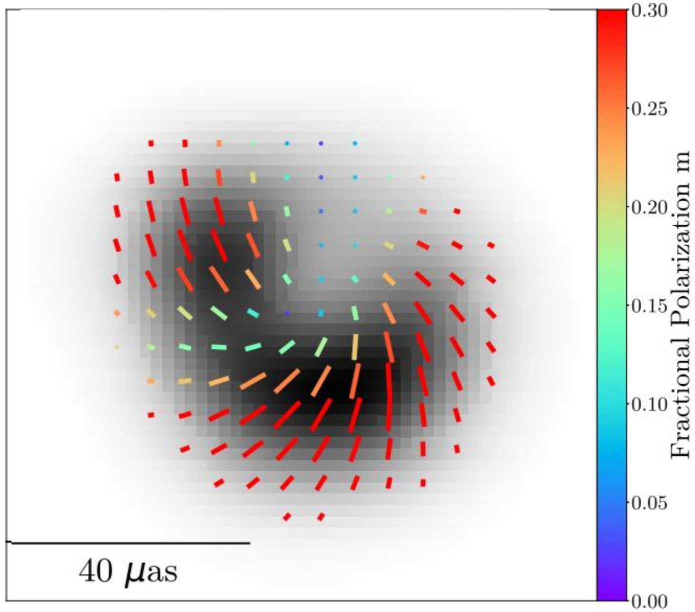


With rotation

Without rotation

EHT resolution

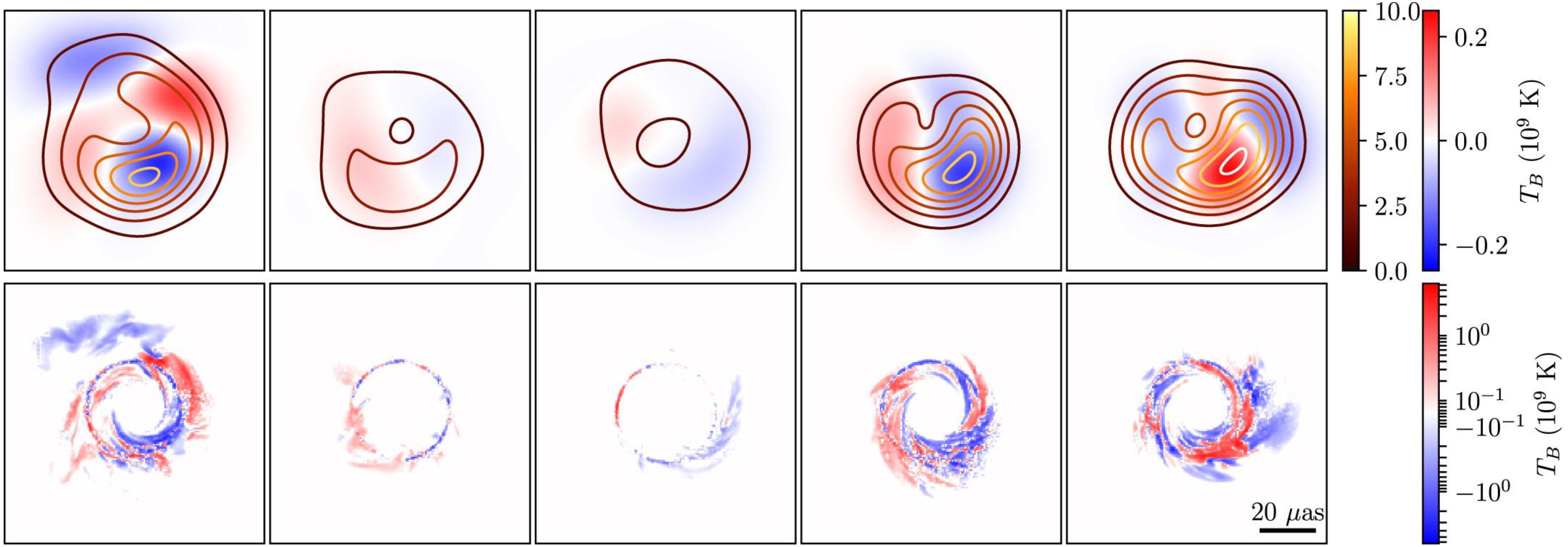




- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **Depolarizes** the image when blurred to EHT resolution
  - → **rotates** the pattern when blurred to EHT resolution
- Internal Faraday rotation is necessary to depolarize MAD models

Credit: EHT 2021 Paper VIII (**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