# Polarization Signatures of Jet Launching on Horizon Scales

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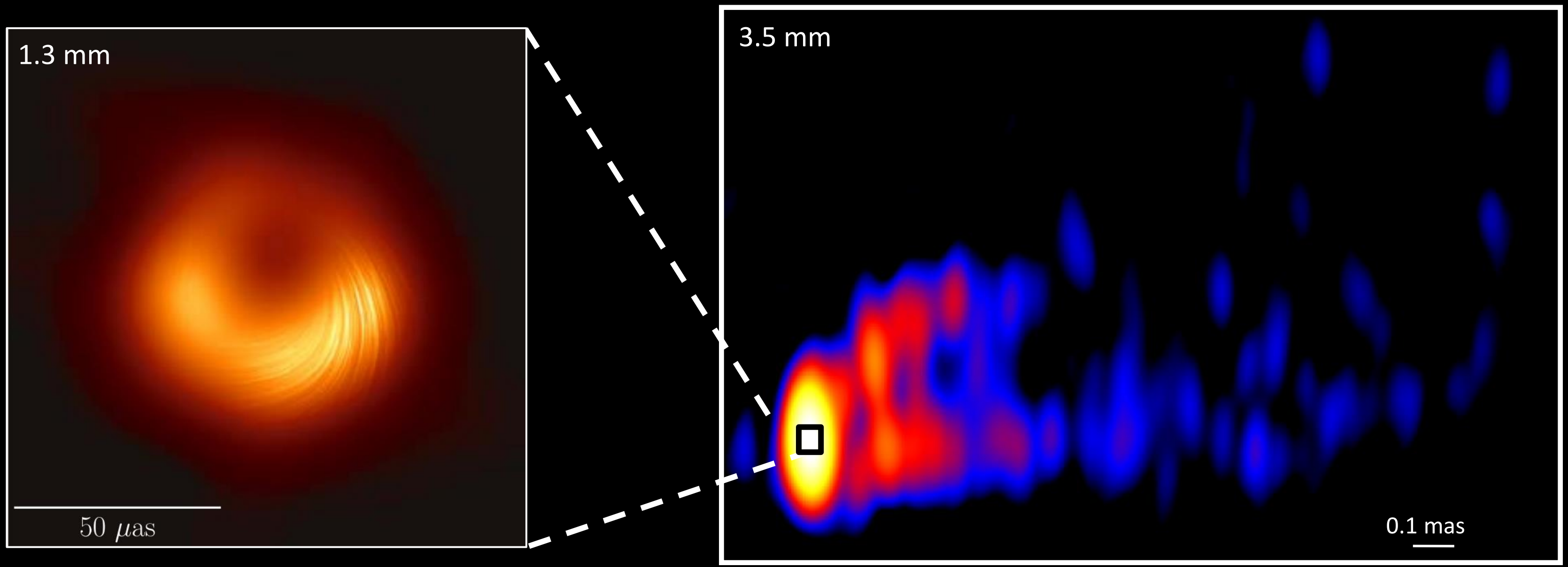
4/11/24




Princeton gravity Initiative

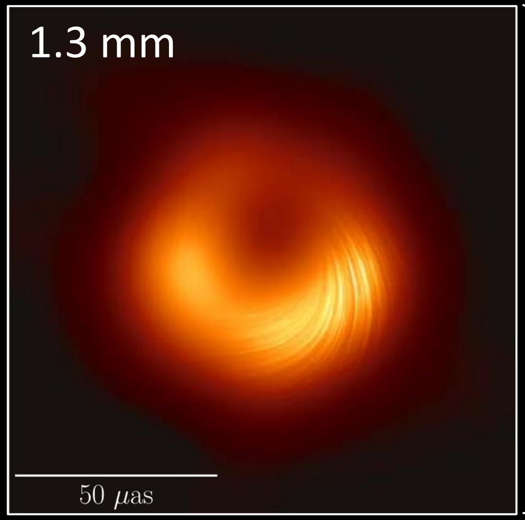
Event Horizon Telescope

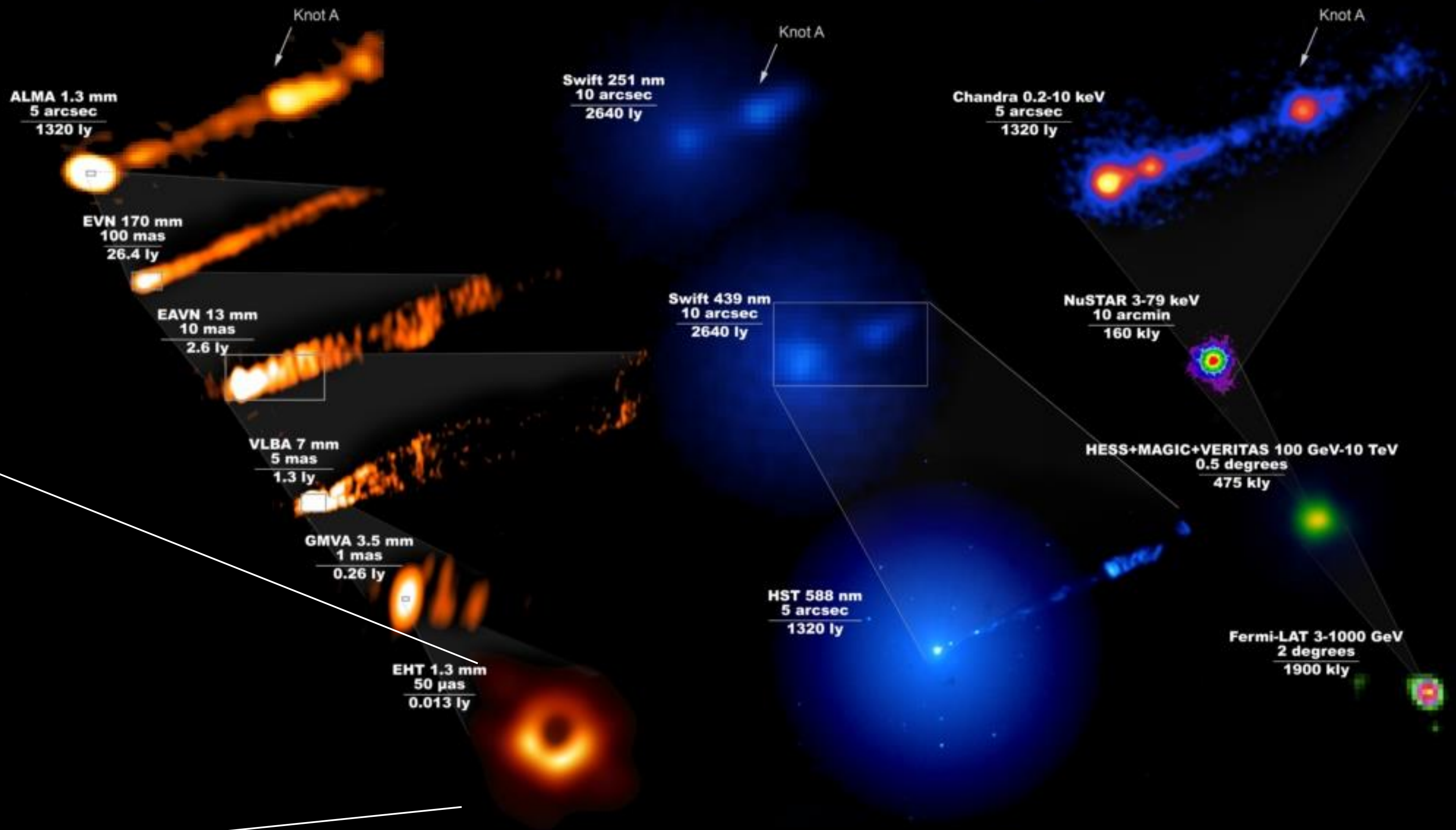
Image Credits: Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

# 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

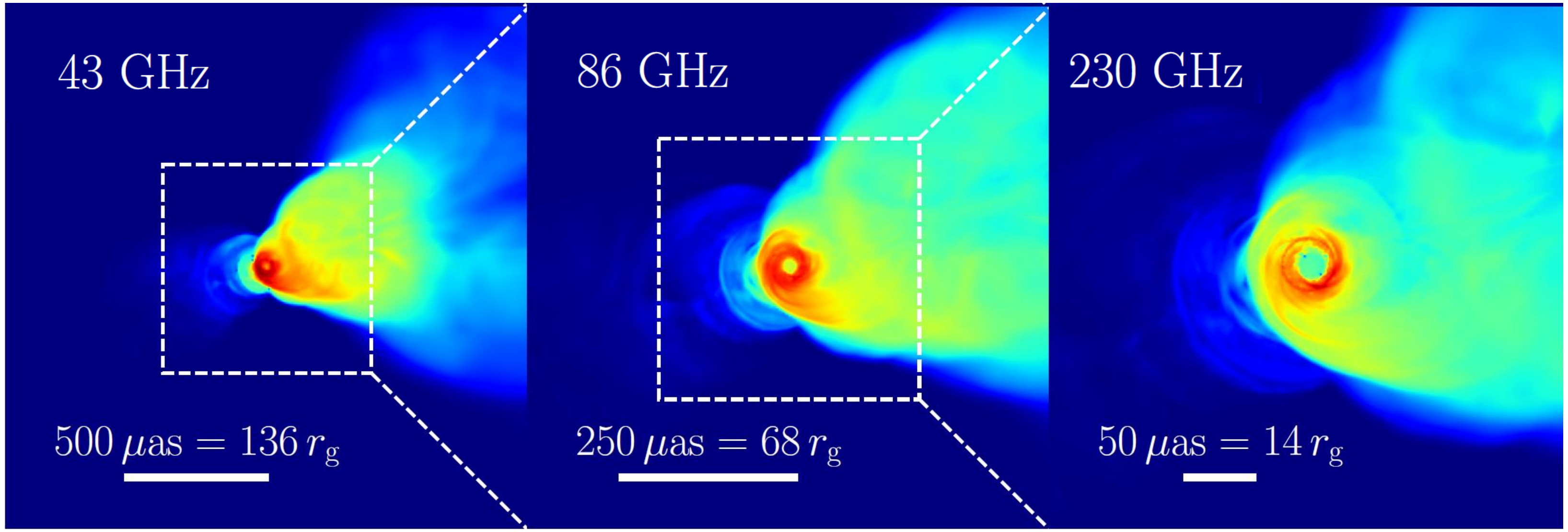
# M87's Jet in Simulations

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

- **Radiative** GRMHD simulations naturally produce the correct:

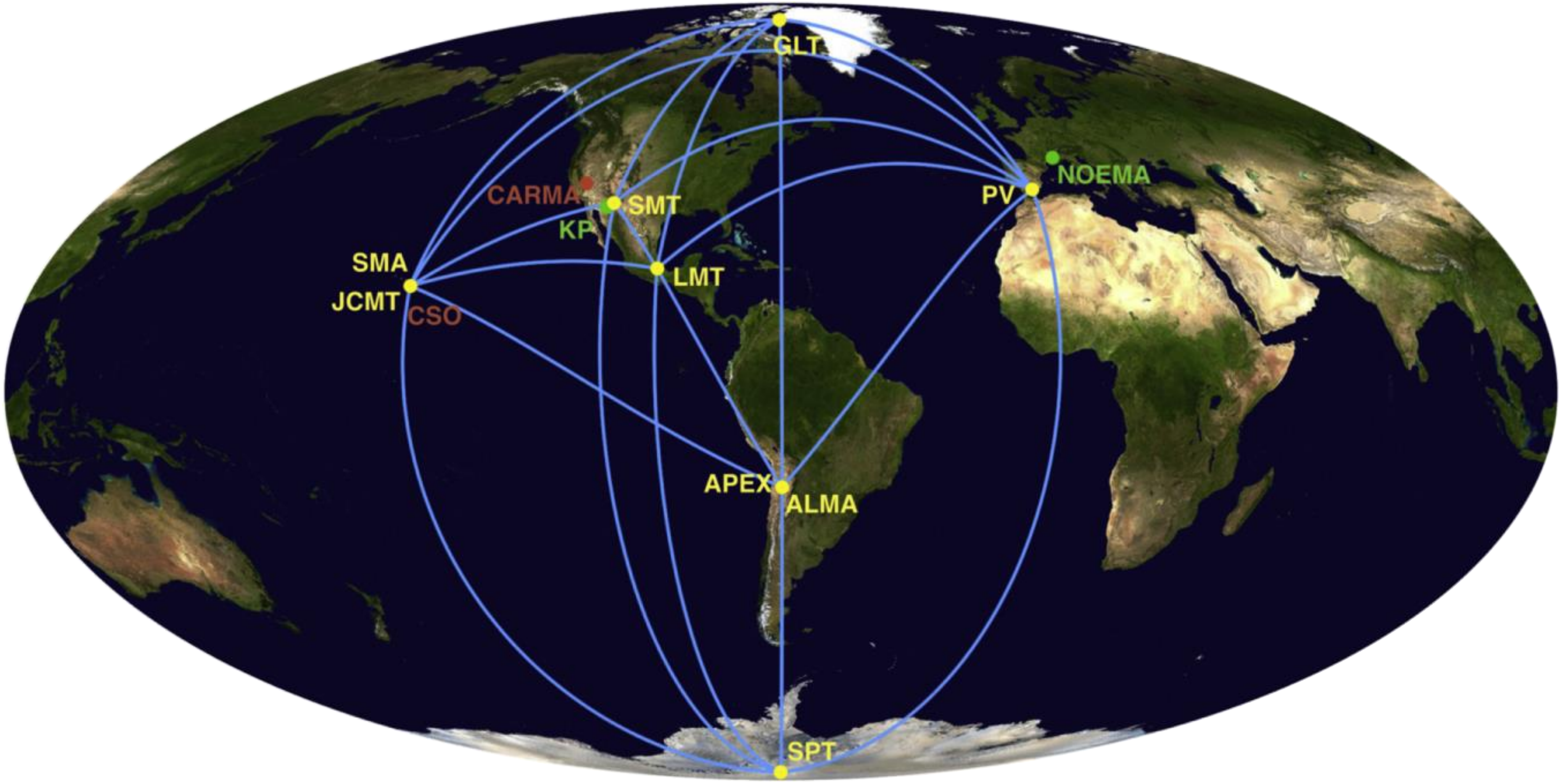
  - jet power
  - wide opening angle
  - core-shift

- Can we be **sure** the jet is BZ**?** What is a **physically meaningful** observation of **horizon-scale** energy flow?




**Chael**+ 2019

# The Event Horizon Telescope: Instrument




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

EHTC+ 2019, Paper II

# The Event Horizon Telescope: People

**300+** members

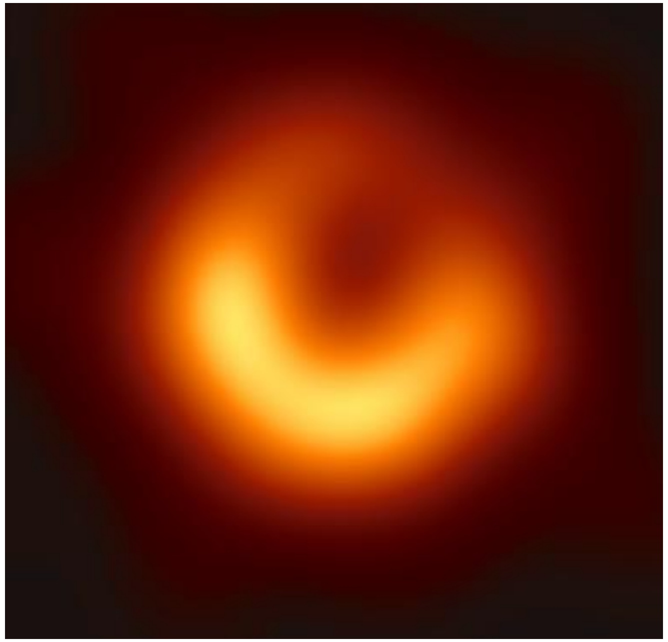
**60** institutes

**20** countries

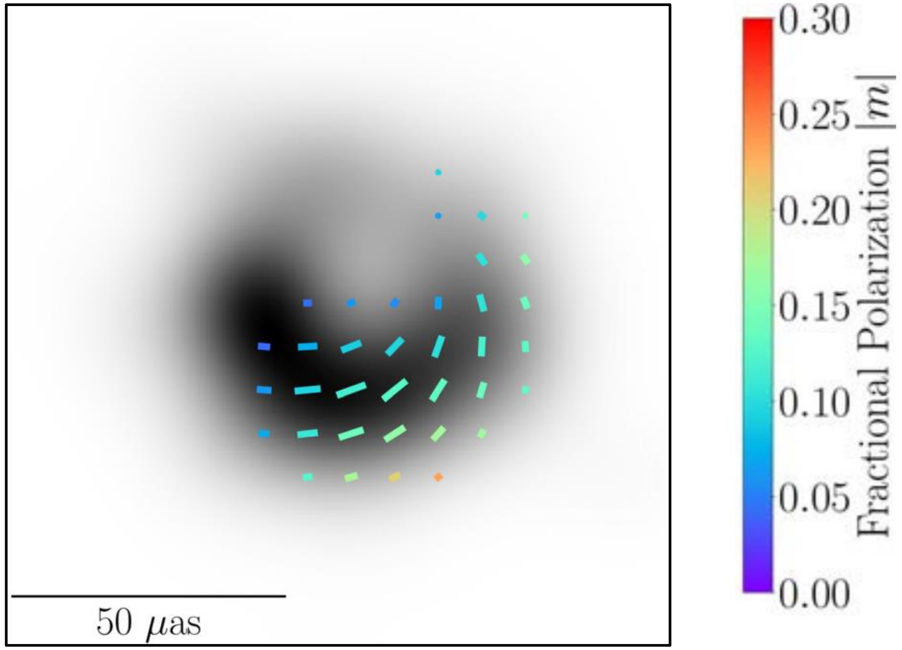
from Europe, Asia, Africa,
North and South America.

# M87* in linear polarization

Total intensity



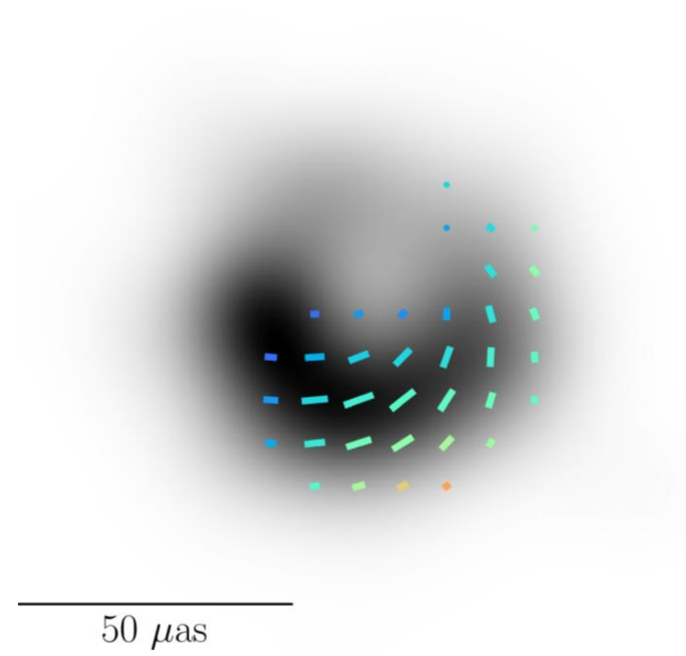
Linear Polarization

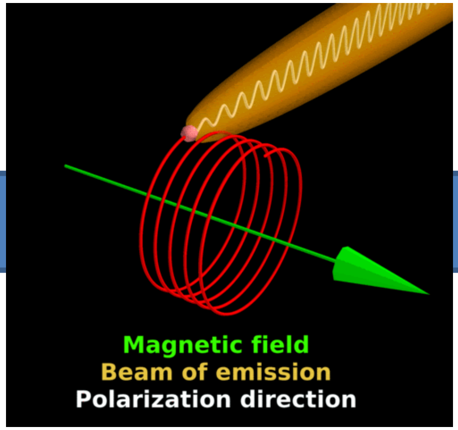



- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **weak**, ~15 %

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

# Why polarization?



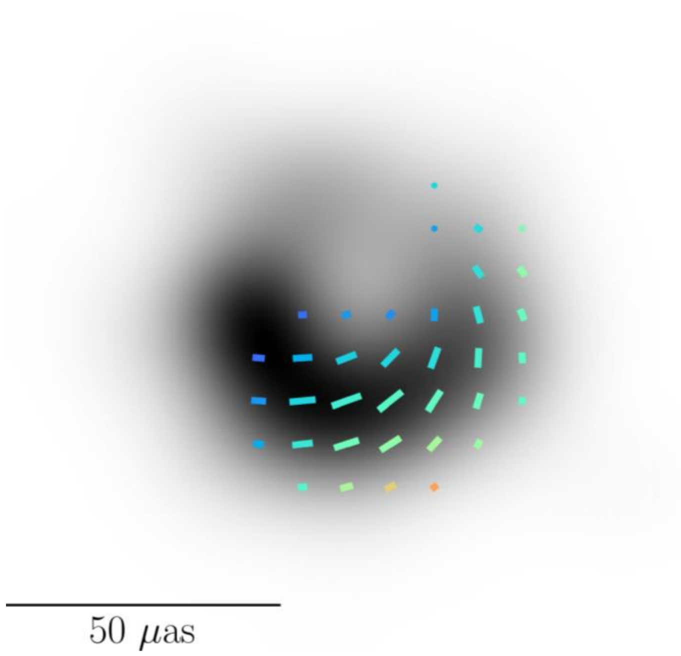

Magnetic fields in the emission region!

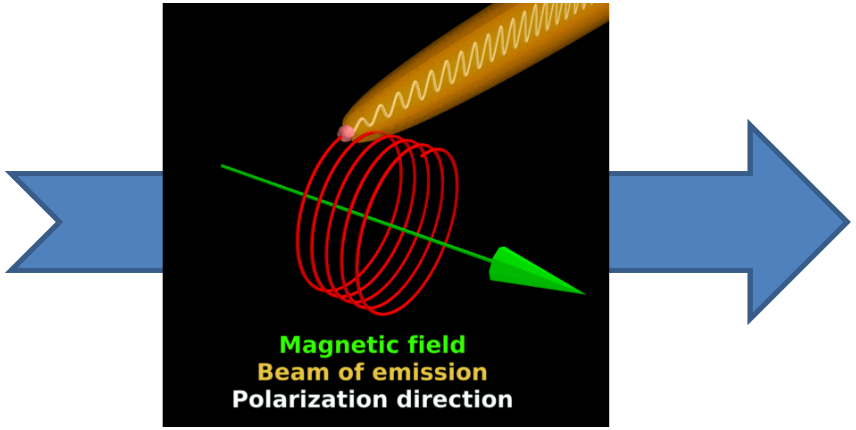
Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines

Polarization **transport** is sensitive to the magnetic field, plasma, and spacetime

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

# Synchrotron polarization traces magnetic fields?



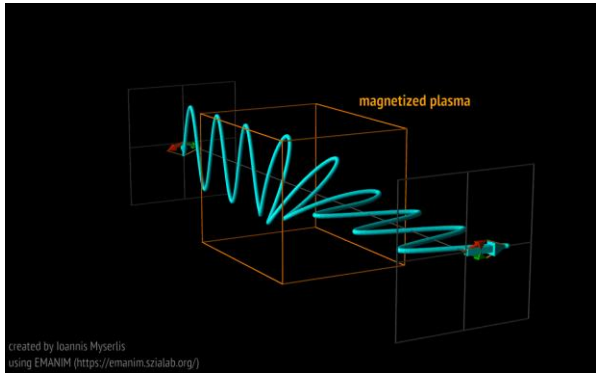




Ma d
direc n the
em ion!

**GR and Faraday effects make the situation in M87* more complicated!**

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

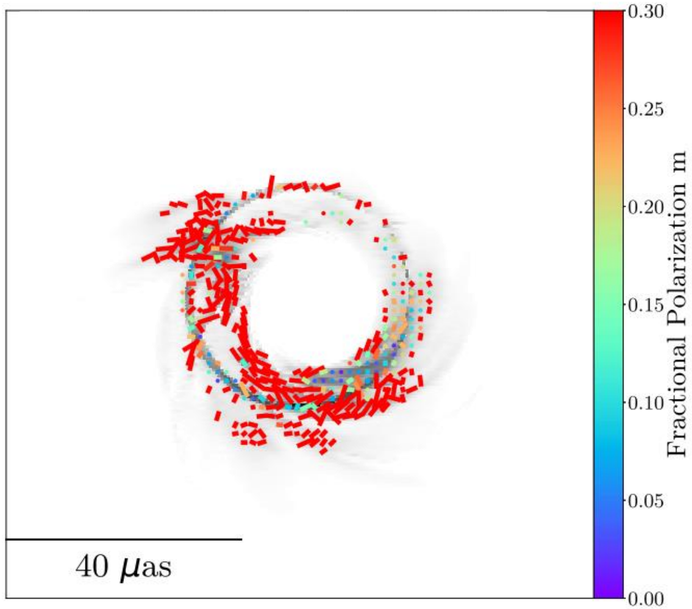
# Faraday Rotation is important!

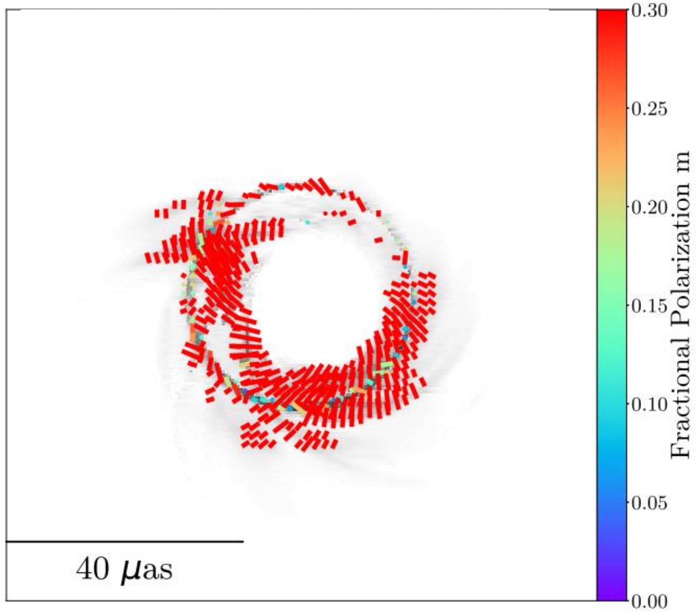



With rotation

Without rotation

'infinite' resolution

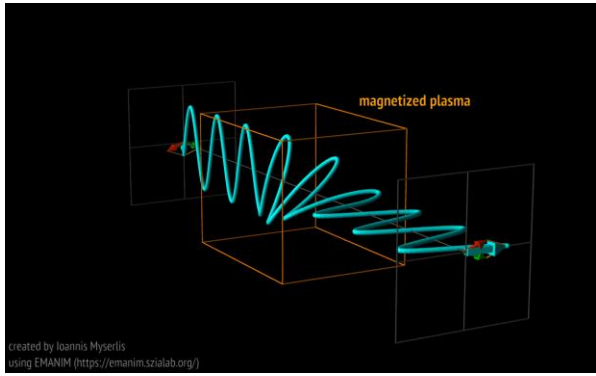



- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

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

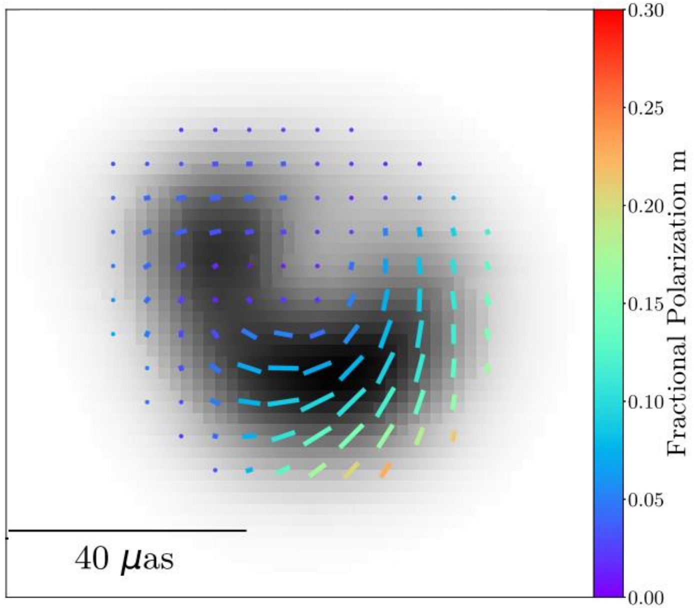
# Faraday Rotation is important!

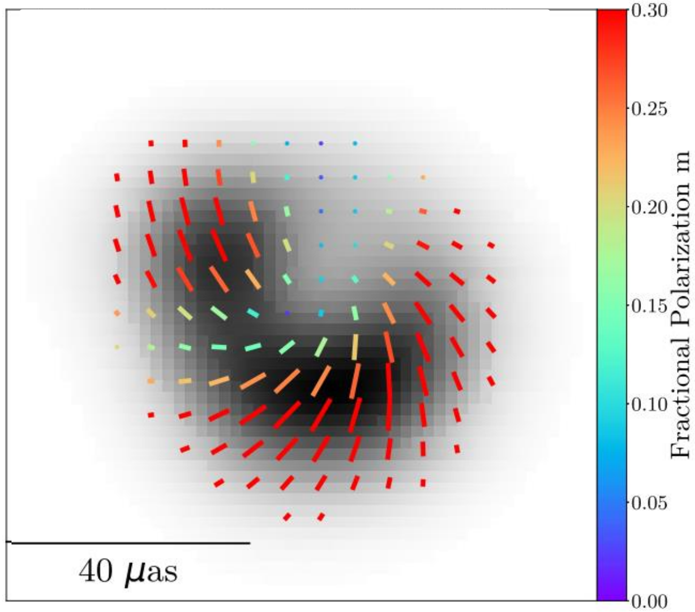



With rotation

Without rotation

EHT resolution

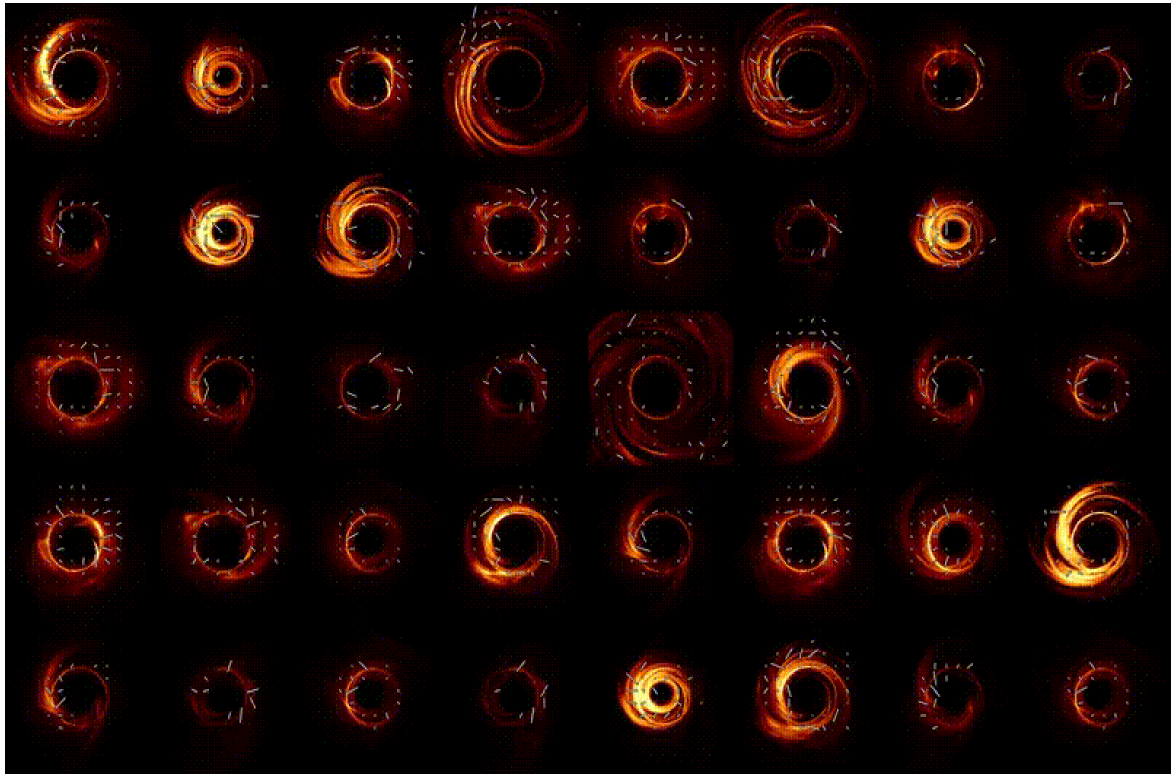


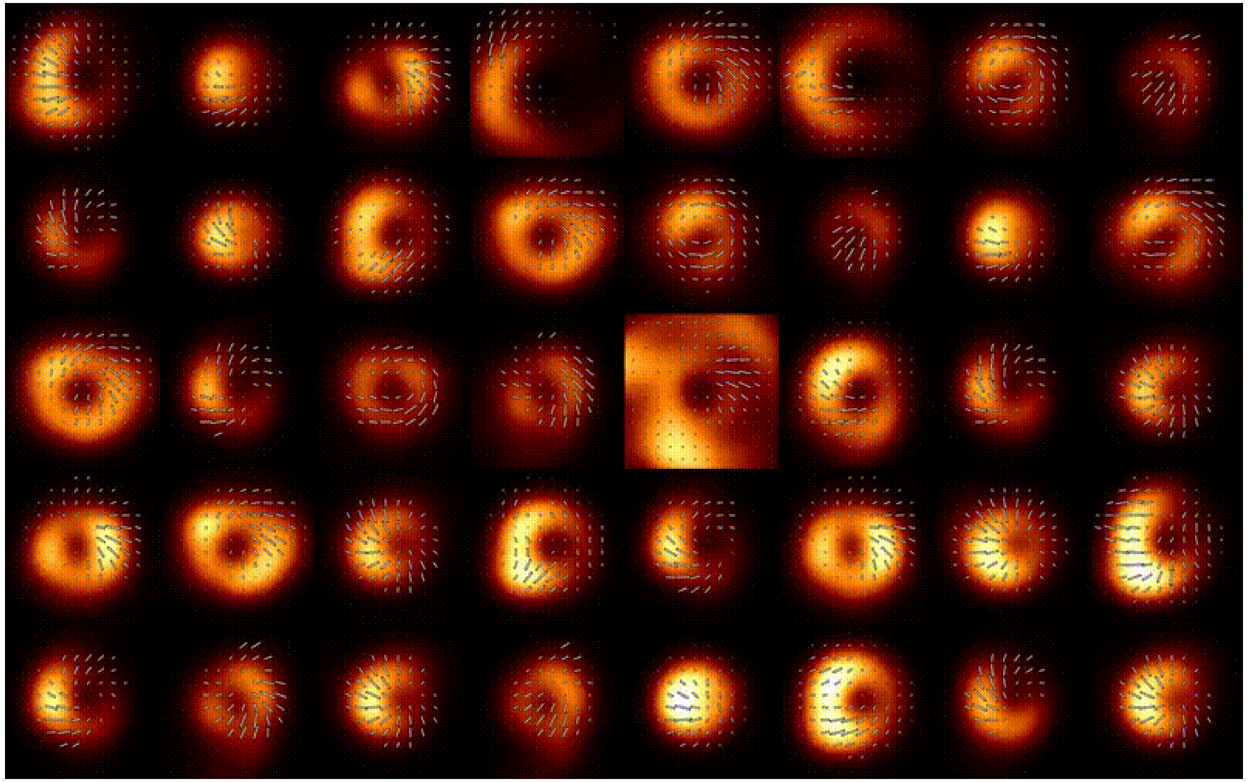

- Significant Faraday rotation on small scales
  → **scrambles** polarization directions
  → **depolarization** of the image when blurred to EHT resolution
  → **rotates** the pattern when blurred to EHT resolution

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

# GRMHD Simulation library
# 2 field states, 5 spins, >180k images



native resolution



EHT resolution

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

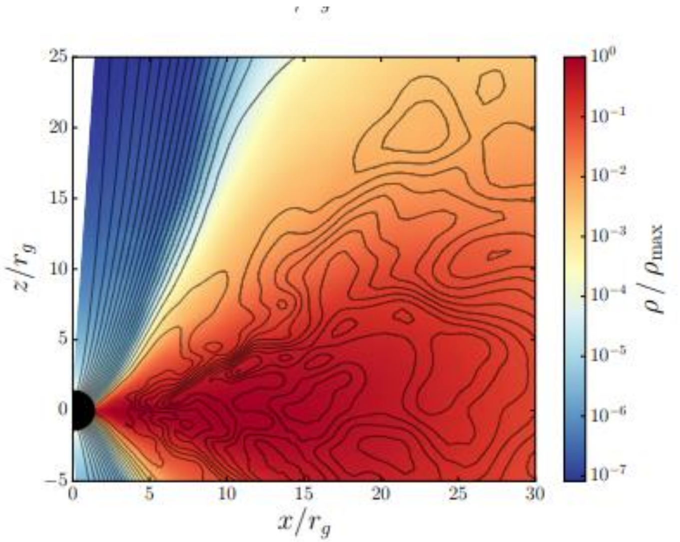
$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta^2}{1+\beta^2} + R_{\rm low}\frac{1}{1+\beta^2}$$

EHTC+ VIII 2021 (**Chael**, paper coordinator)
Animation credit: Ben Prather

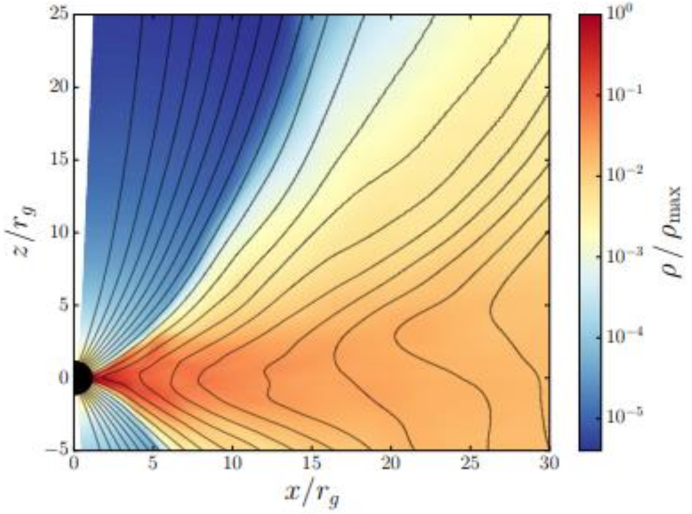
# What is the magnetic field structure close to the horizon?

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**

'Strong' fields mean dynamically important ones → ~10-100 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

# Scoring simulations with polarization: Results

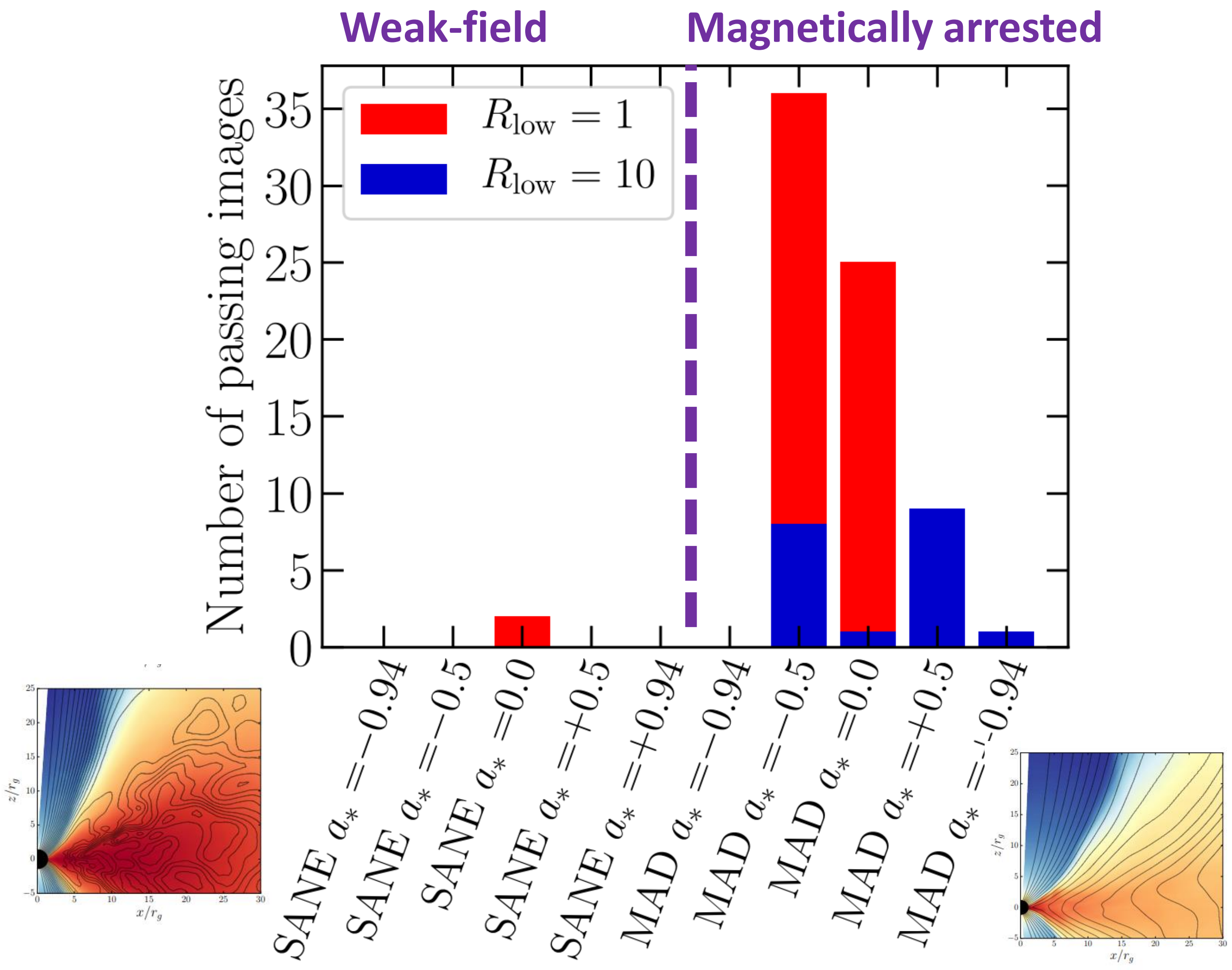
- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**

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

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

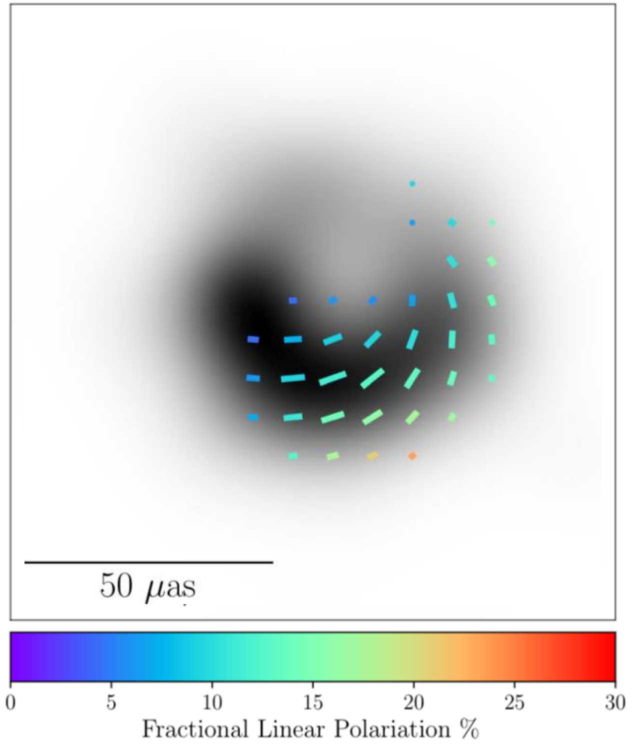
$$\left(\dot{M}_{\mathrm{Edd}} = 137 M_\odot\ \mathrm{yr}^{-1}\right)$$

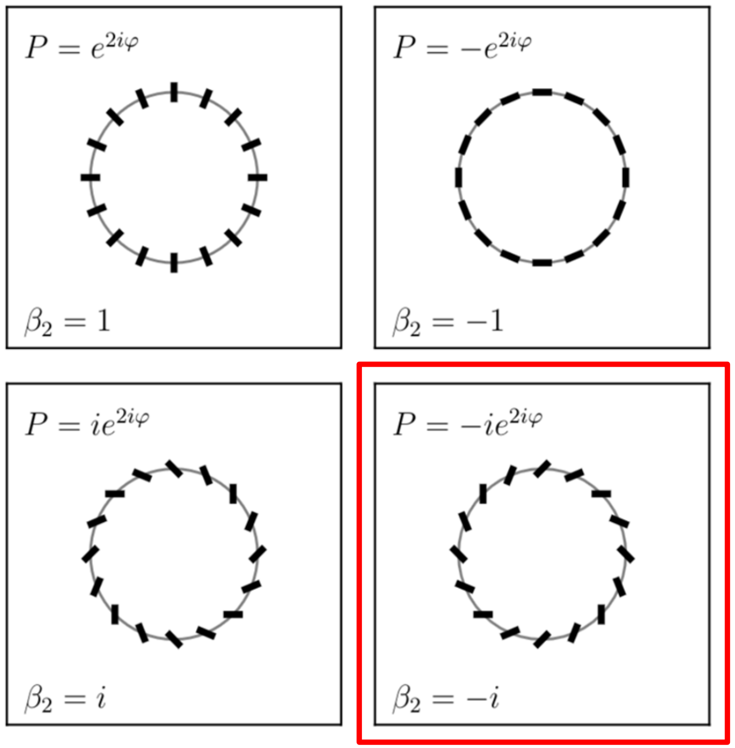
- Strong fields **more easily launch jets** at lower values of BH spin




Credit: EHT 2021 Paper VIII, 2023 Paper IX (**Chael**, paper coordinator), Riordan+2017

# Polarized Images of M87* and horizon-scale energy flow

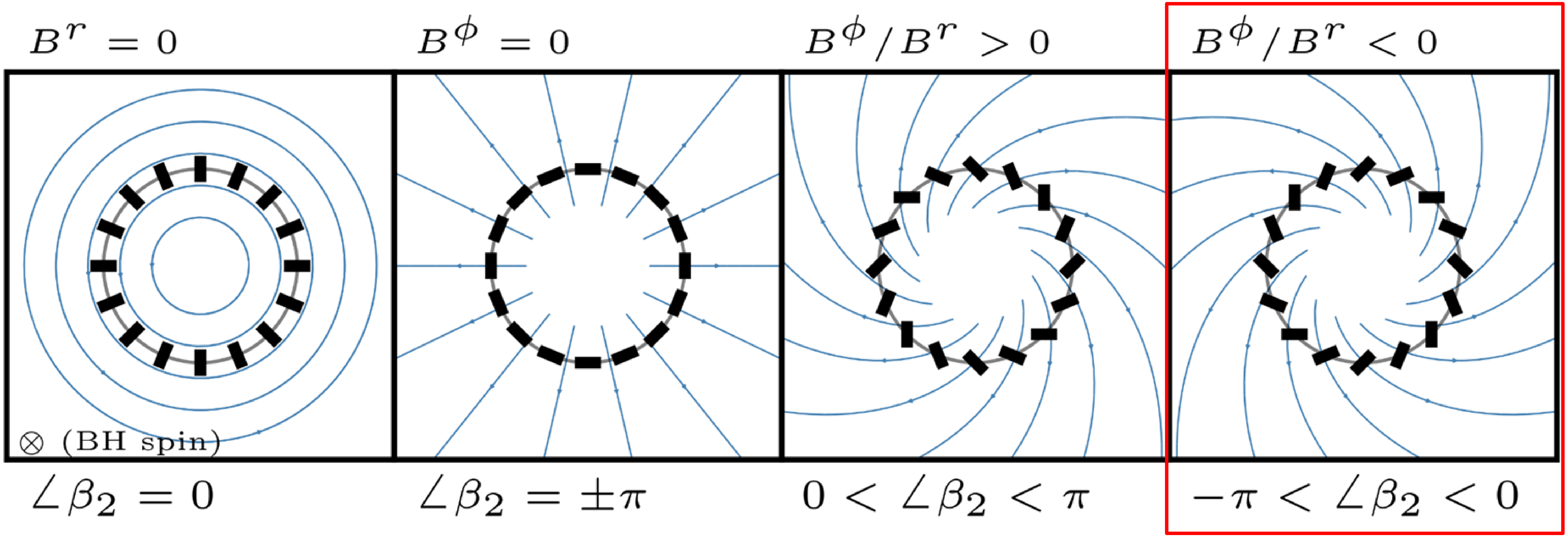



- The polarization spiral's **2nd Fourier mode** ($\beta_2$: Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

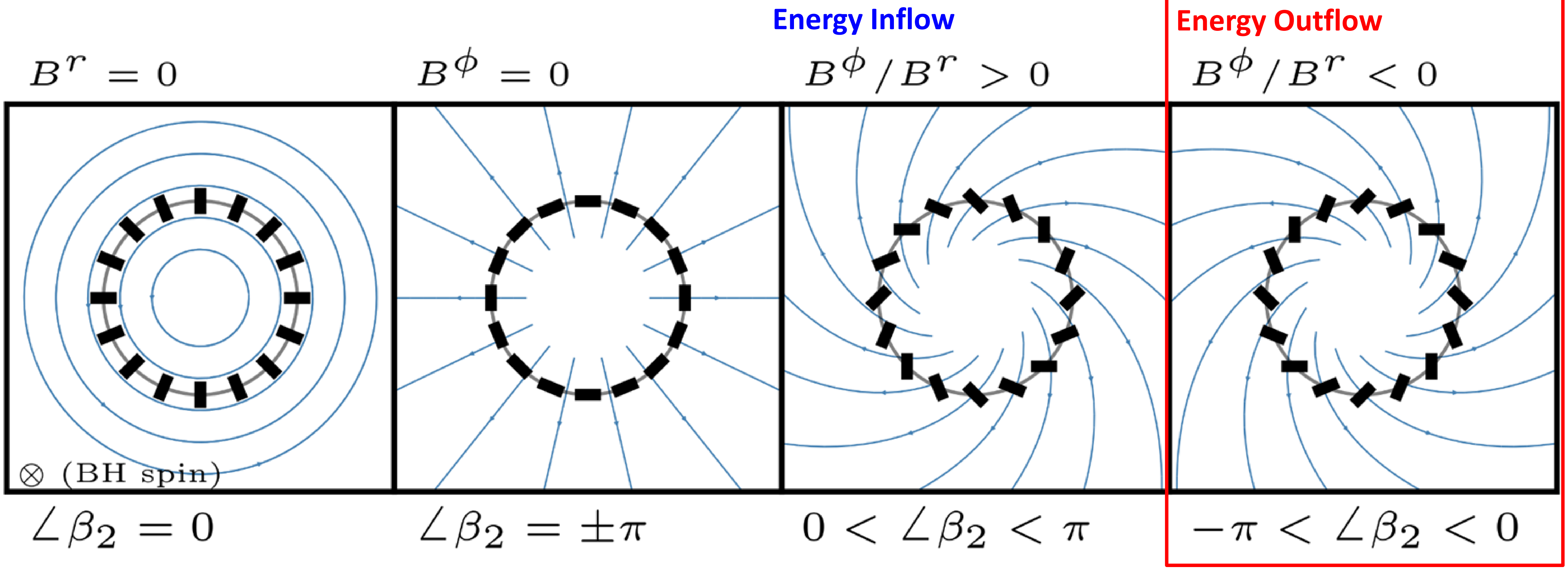
# Cartoon model: arg($\beta_2$) is connected to the pitch angle $B^\phi / B^r$




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

**Chael**+ 2023b

# $\arg(\beta_2)$ is connected to the **electromagnetic energy flux**




**Radial Poynting flux in Boyer-Lindquist coordinates:**

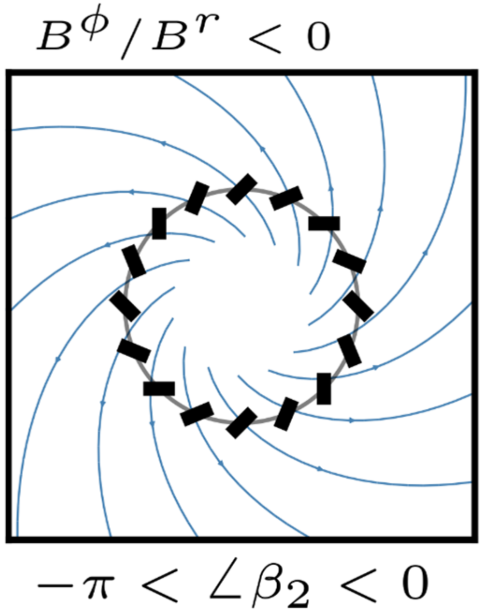
$$\mathcal{J}^r_{\mathcal{E}} = -T^r_{\ t\ \mathrm{EM}} = -B^r B^\phi \Omega_F \underbrace{\Delta \sin^2\theta}_{\geq 0}$$

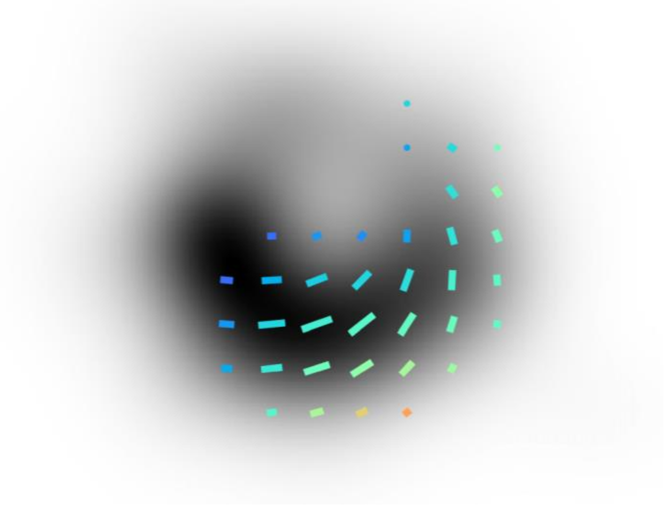
fieldline angular speed

Chael+ 2023b

# $\arg(\beta_2)$ is connected to the **electromagnetic energy flux**

- The sign of $\arg(\beta_2)$ is directly connected to the direction of Poynting flux, assuming we know the sign of $\Omega_F$
- Ignoring Faraday effects, **the EHT's measurement of $\beta_2$ implies electromagnetic energy is outflowing in M87***
- This inference requires we assume fieldlines **co-rotate** with the emitting plasma in a **clockwise** sense
- Does this simple argument hold up in **more complicated models**?



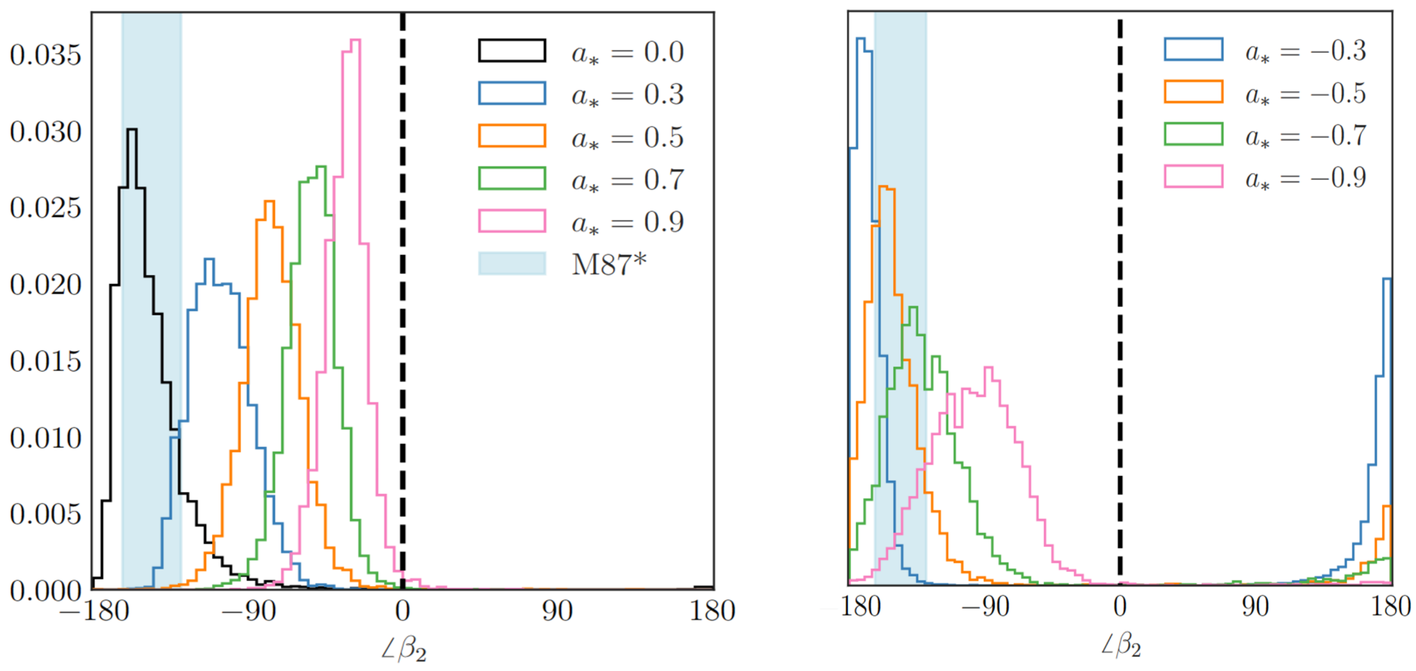
EHTC+ 2021 VII, **Chael**+ 2023b

# $\arg(\beta_2)$ in MAD **GRMHD simulations** of M87*?

- 1600 simulated EHT-resolution M87* images from MAD simulations (Narayan+ 2022)
- Almost all 230 GHz simulation images have **negative** $\arg(\beta_2)$ consistent with the measured energy outflow in the simulations
- $\arg(\beta_2)$ has the **same qualitative dependence on spin** as in a simple BZ monopole model!

Prograde simulations

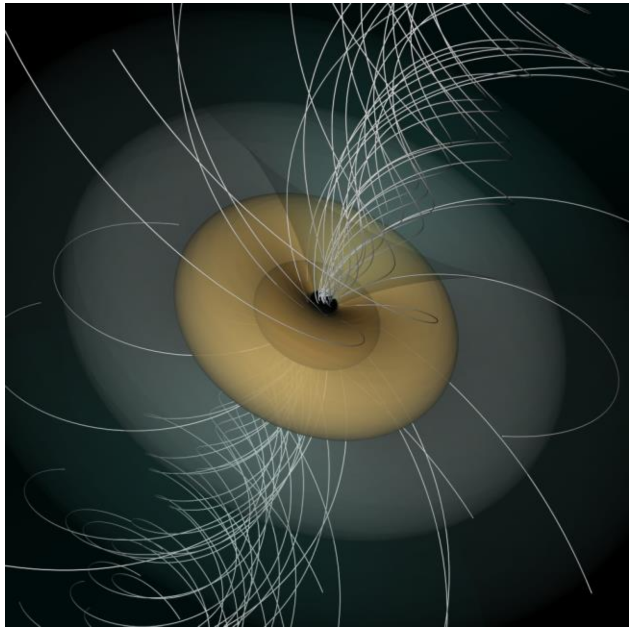
Retrograde simulations



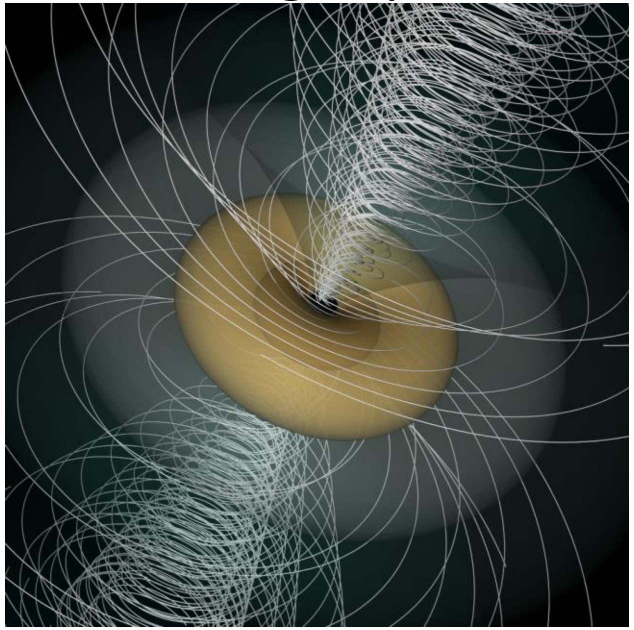

**Chael**+ 2023b

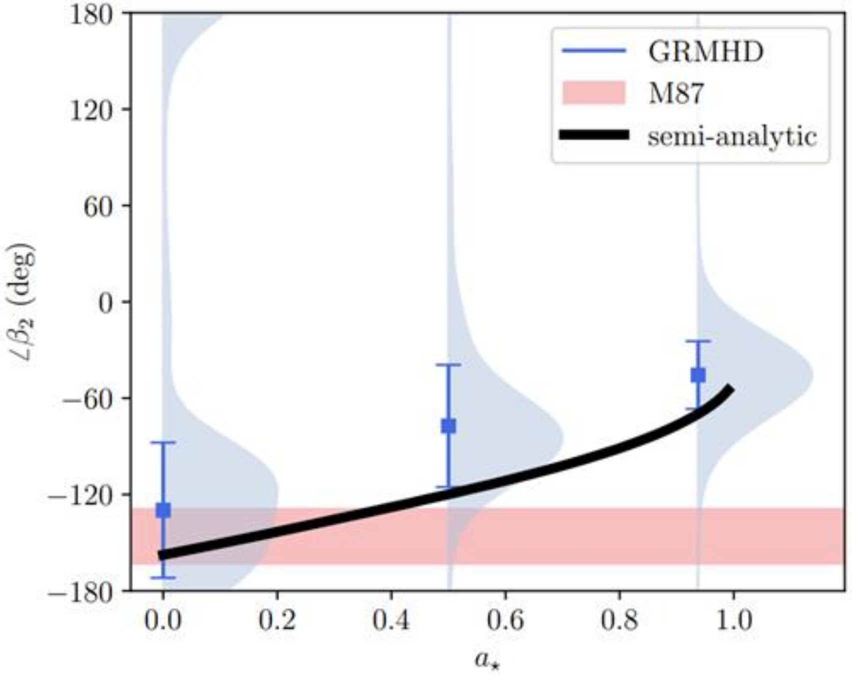
# Polarized images are **spin dependent**

Low Spin



High Spin

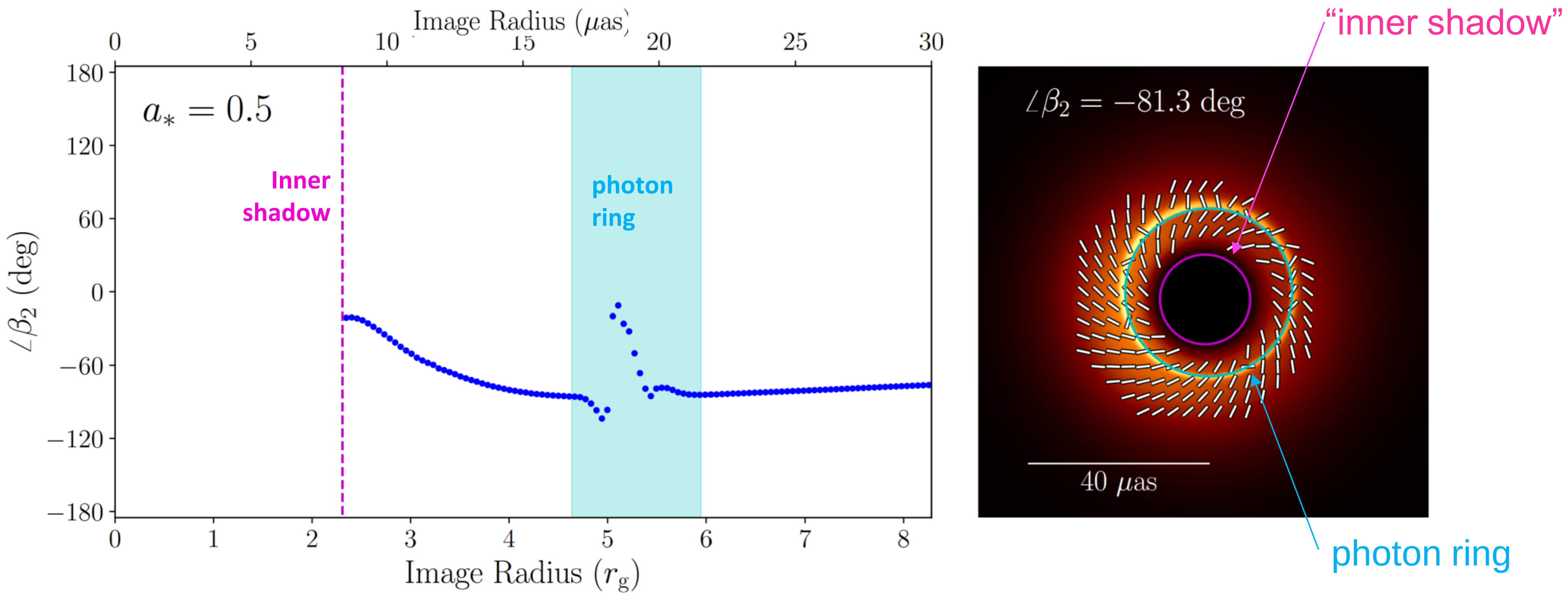





- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - and makes the observed polarization pattern more radial

Image credit: George Wong

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

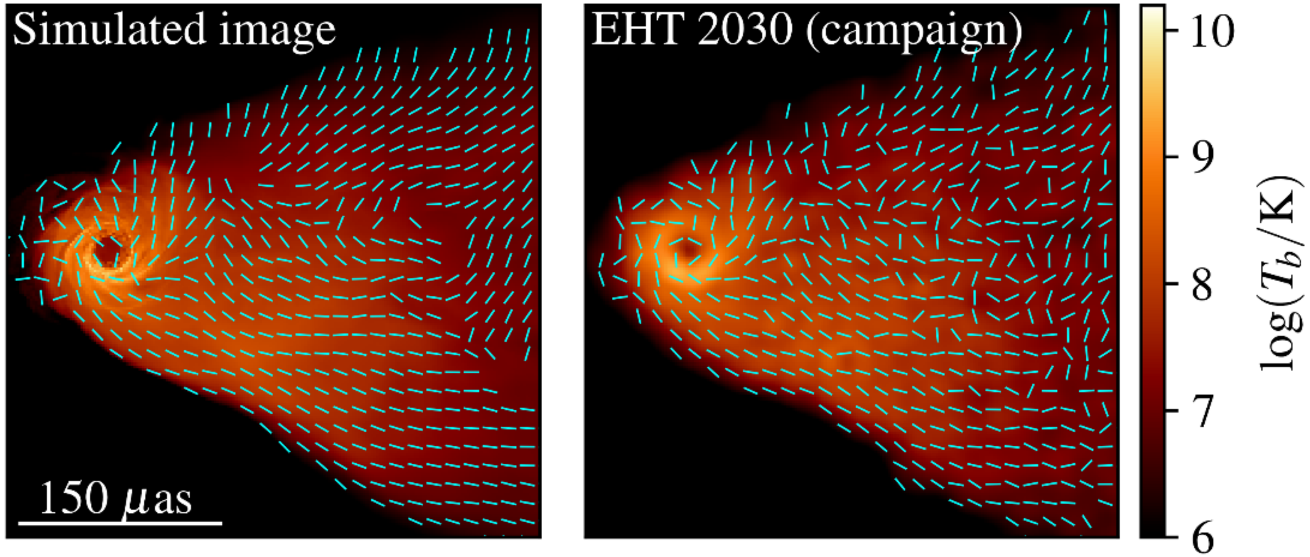



- Measuring polarization as a function of radius **probes energy flow at different scales**

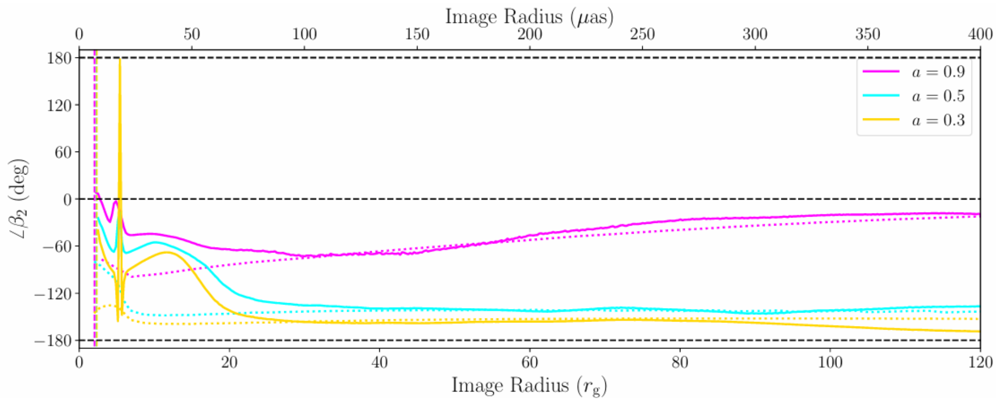
- Both simple models and GRMHD simulations make a strong prediction
  - arg($\beta_2$) evolves rapidly close to the horizon as the rest frame fields become more azimuthal from **GR frame dragging**

**Chael**+ 2023b, (also Ricarte+ 2022)

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




Ongoing work with Zack Gelles (Princeton)

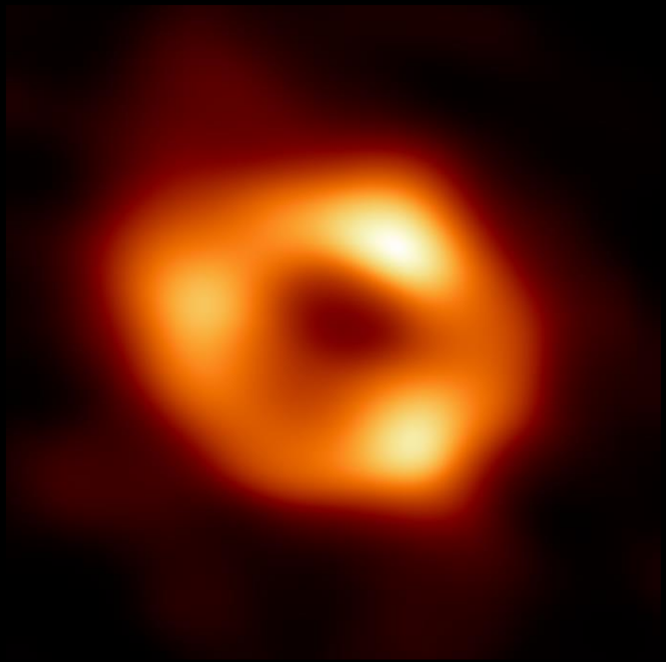



- New telescope sites & larger bandwidth will enhance EHT's **dynamic range**
  - These will illuminate both the **BH-jet connection**
- These new observations will require new theoretical models and simulations to fully interpret
  - Can we directly measure energy flow **from the horizon through the jet base?**

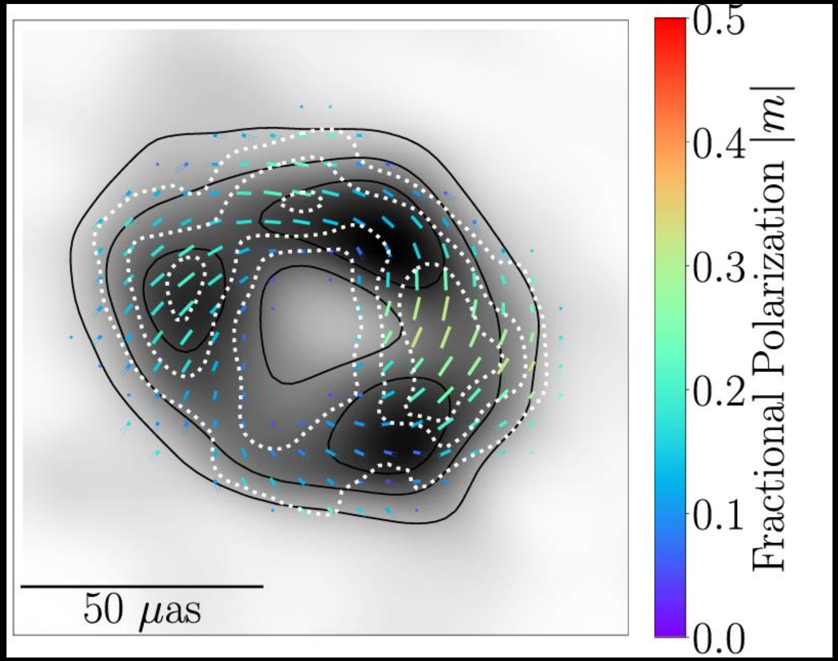
**Chael**+ 2019, 2023b
Image Credit: Paul Tiede, Dom Pesce, Zack Gelles

# Aside: Sgr A* in linear polarization

Total intensity



Linear Polarization




- Polarization fraction is **higher** than M87
- $\beta_2$ is consistent with **clockwise rotation** measured in NIR flares
- MAD simulations prefeerred – **where is the jet?**

EHTC+ 2024 VII, VIII

# Takeaways:

- EHT observations of M87* and Sgr A* in polarization are our most constraining probes of near-horizon magnetic fields and extragalactic jet launching at the central engine

- EHT polarization data singles out magnetically arrested accretion disk models:
  - The magnetic field is dynamically important at the event horizon in M87* and Sgr A*

- The azimuthal structure of the linear polarization in M87* is **consistent with outward Poynting flux**
  - To use polarization to test the BZ mechanism for black hole energy extraction, we will need to track polarization on **multiple scales**