Polarization Signatures of Jet Launching on Horizon Scales

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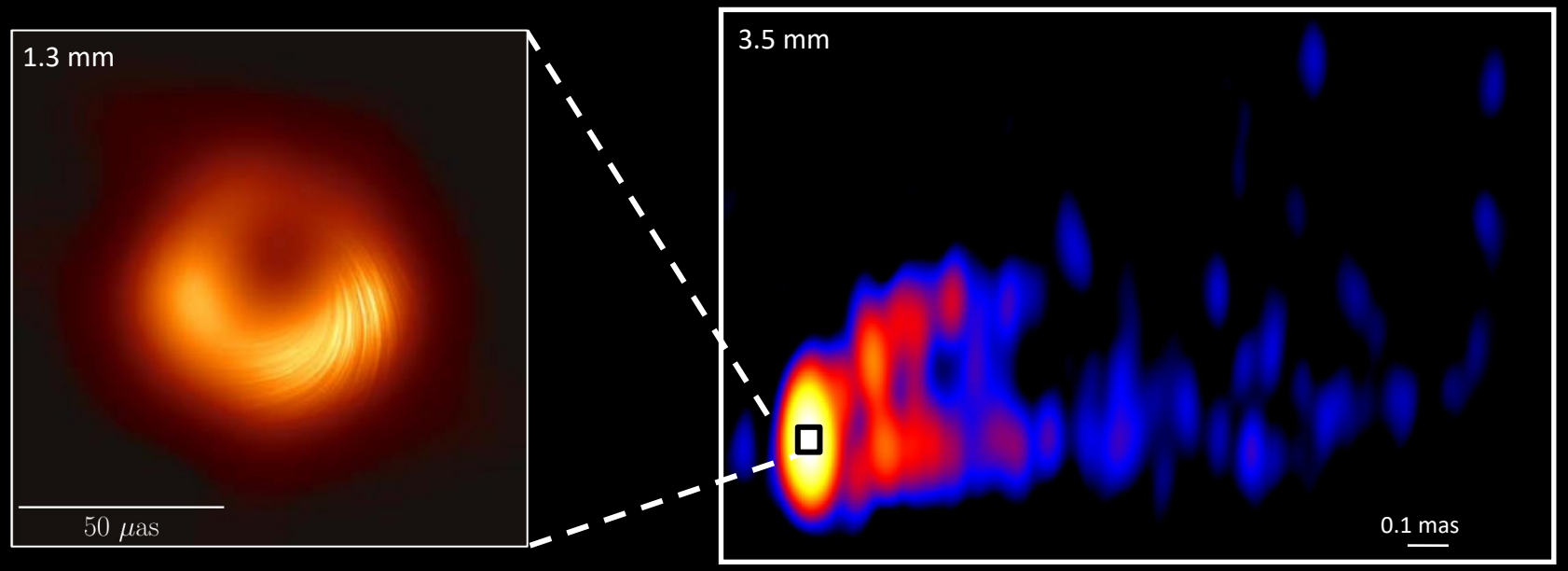
5/24/24



Princeton gravity Initiative

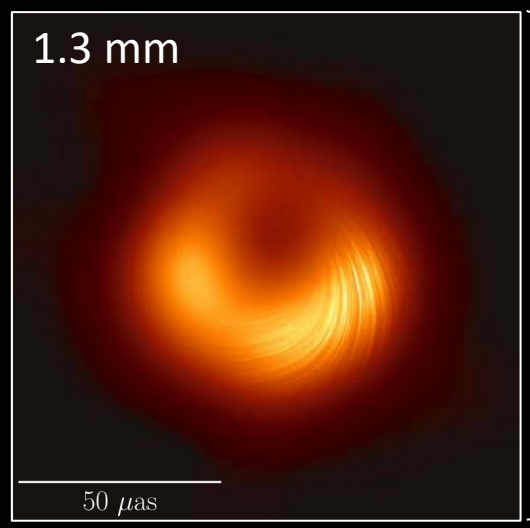
Event Horizon Telescope

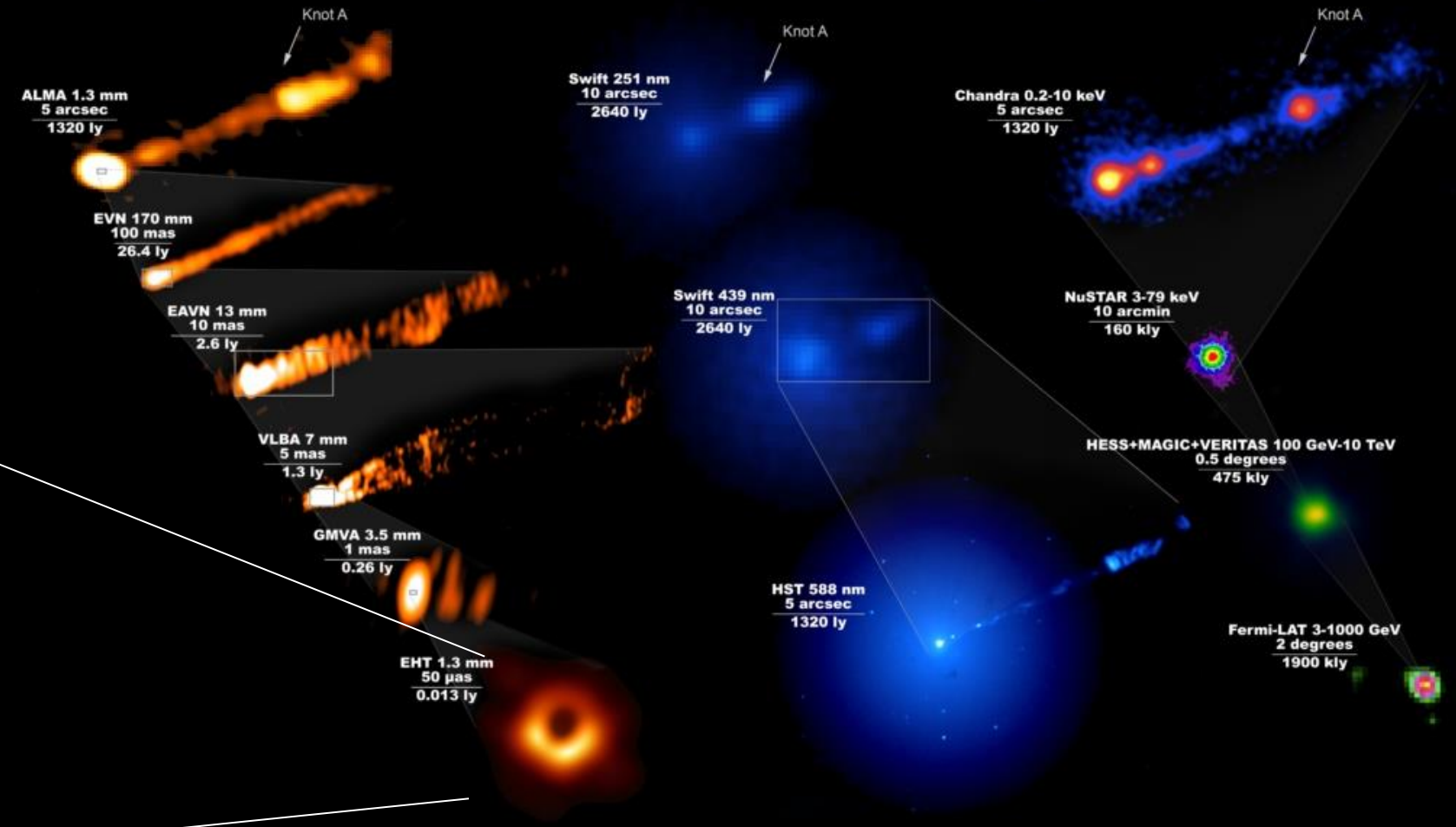
Image Credits: Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

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**?

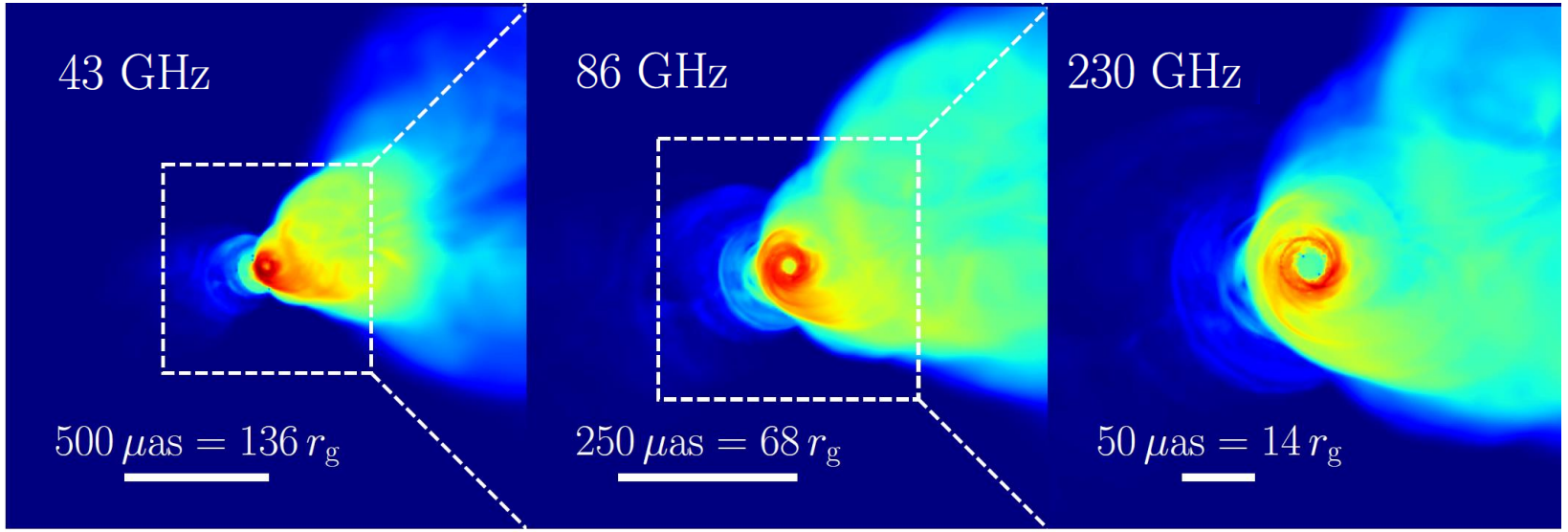
Credit: EHTC MWL+ 2021, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

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

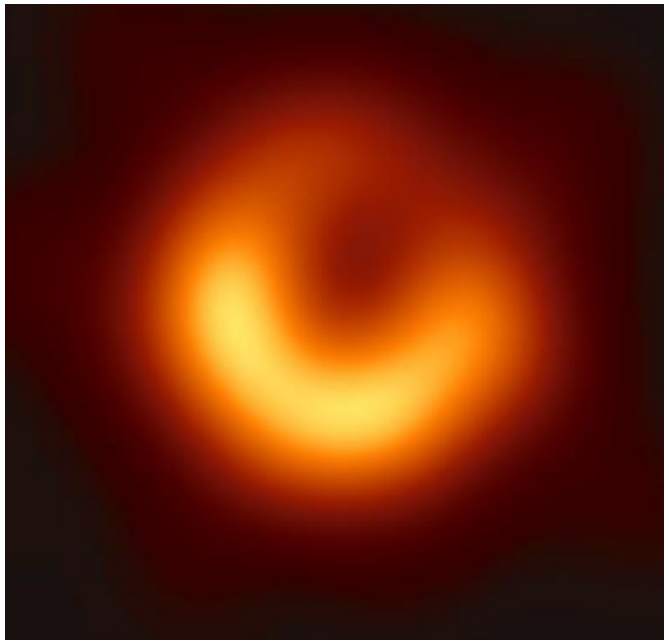
- Can we be **sure** the jet is BZ**?** What is a **physically meaningful** observation of **horizon-scale** energy flow?



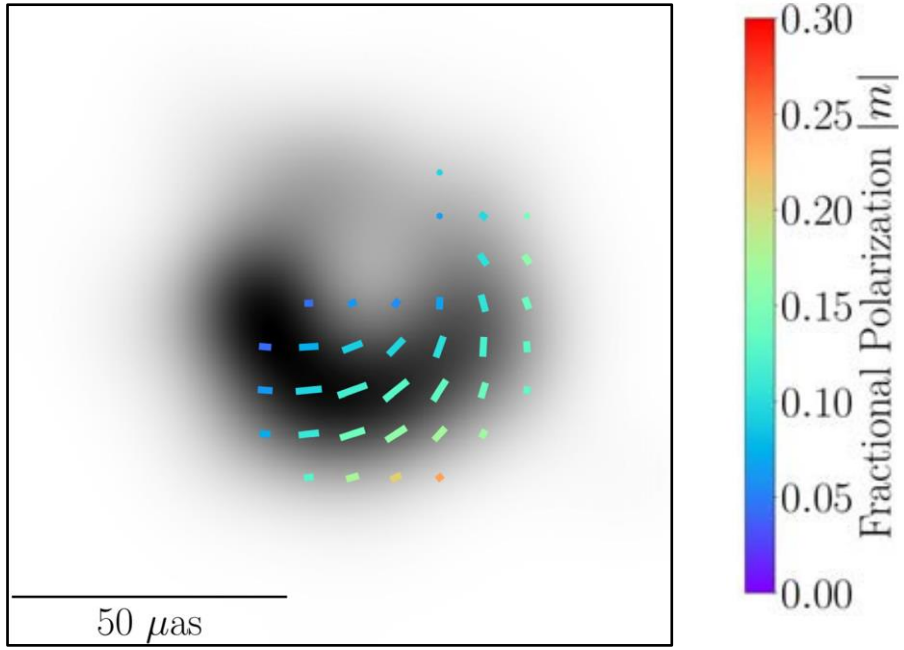
Chael+ 2019
See also: Moscibrodzka+2016, Davelaar+2019, Chatterjee+2020, Fromm+2021,Cruz-Osorio+2021….

M87* 2017 in linear polarization

Total intensity



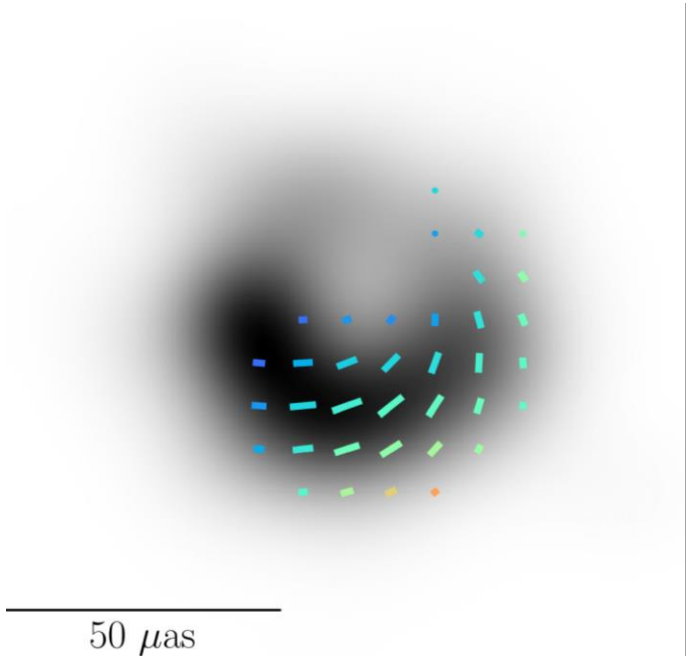
Linear Polarization

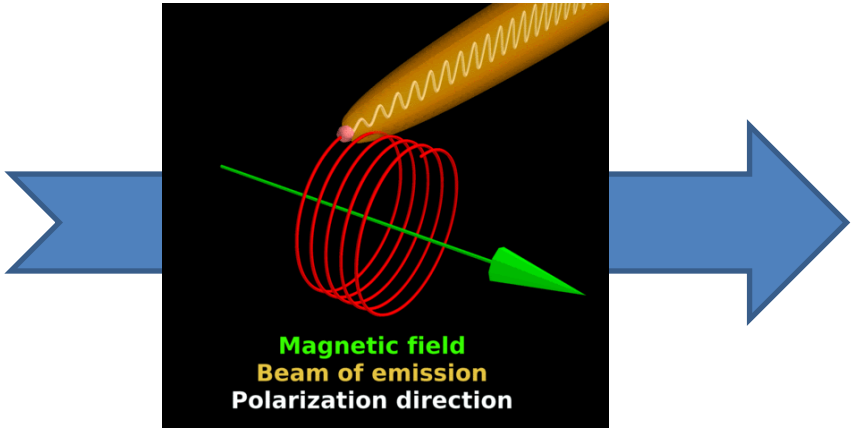


- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **weak**, ~15 %

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

Why polarization?





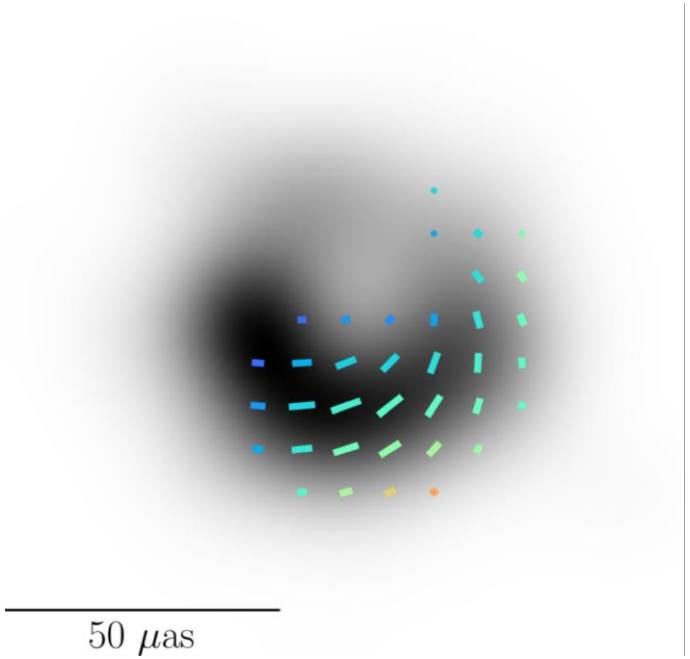
Magnetic fields in the emission region!

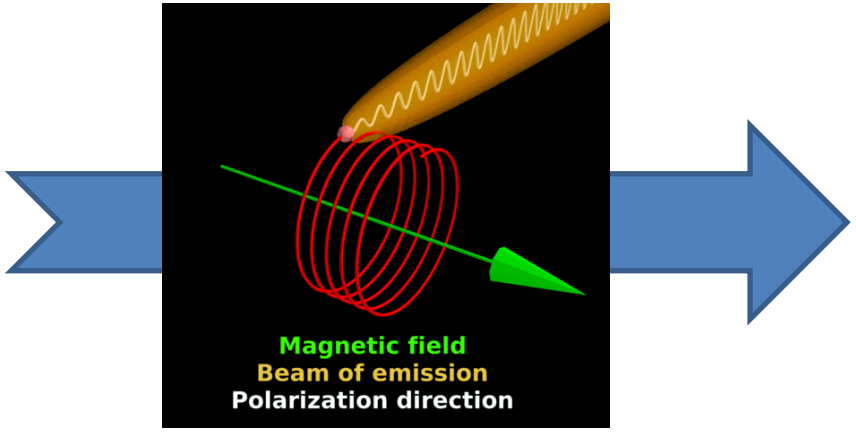
Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines

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?

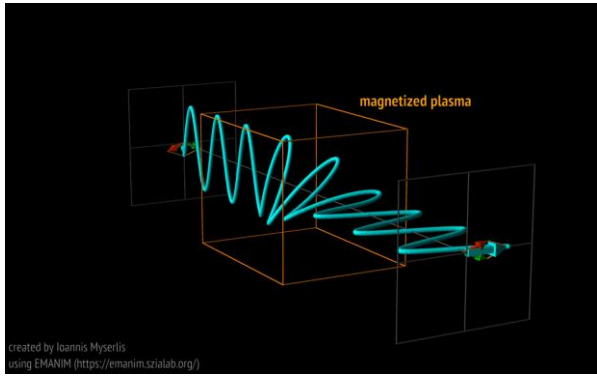




GR and Faraday effects make the situation in M87* more complicated!

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

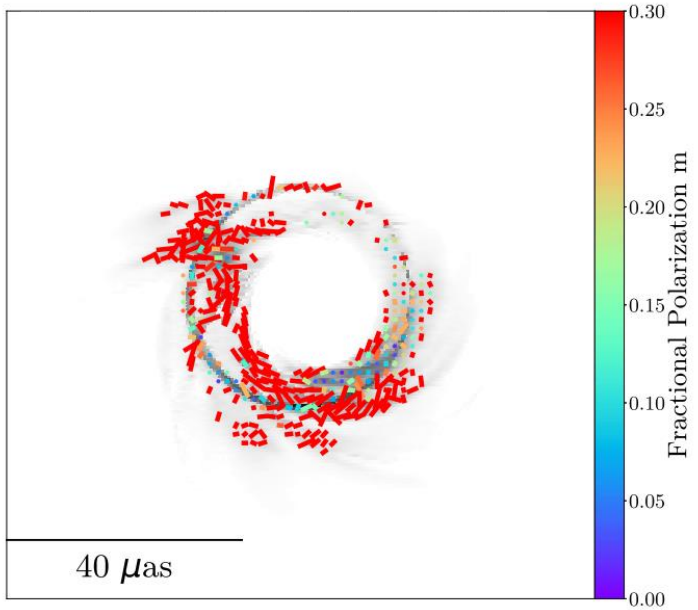
Faraday Rotation is important!

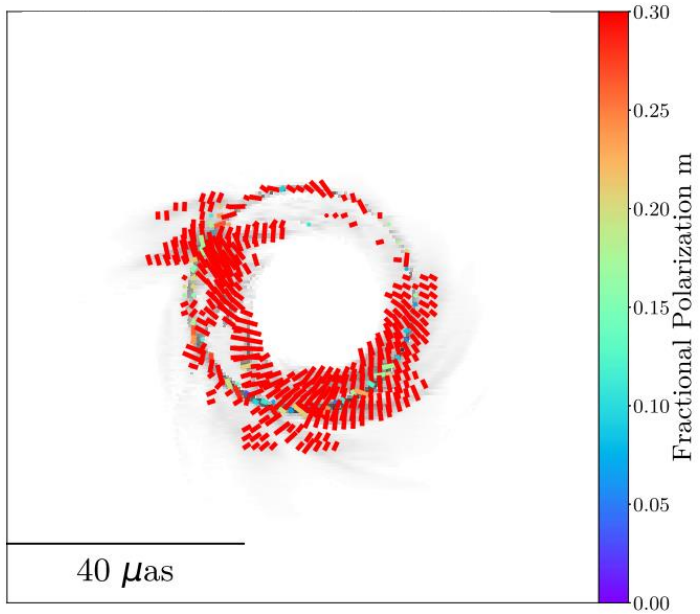


With rotation

Without rotation

‘infinite’ resolution

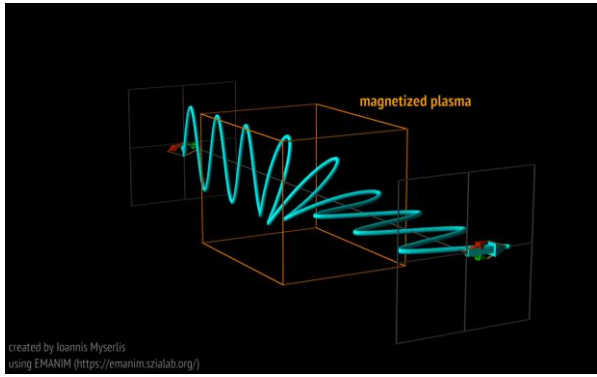




- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

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

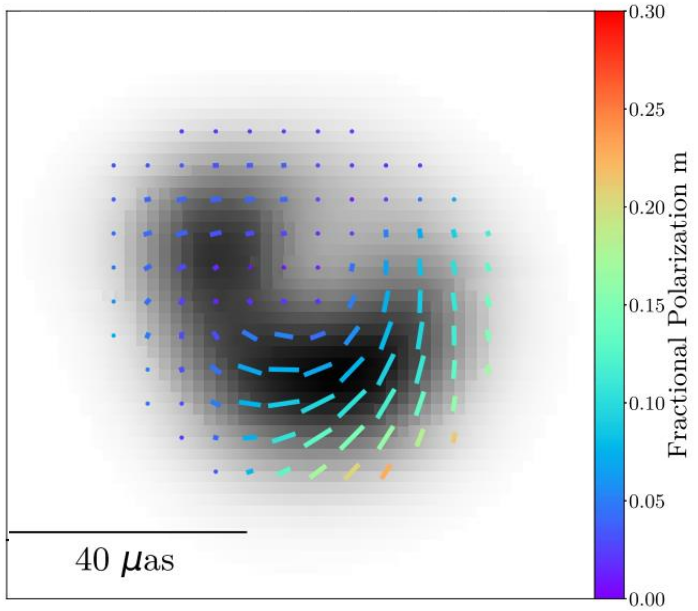
Faraday Rotation is important!

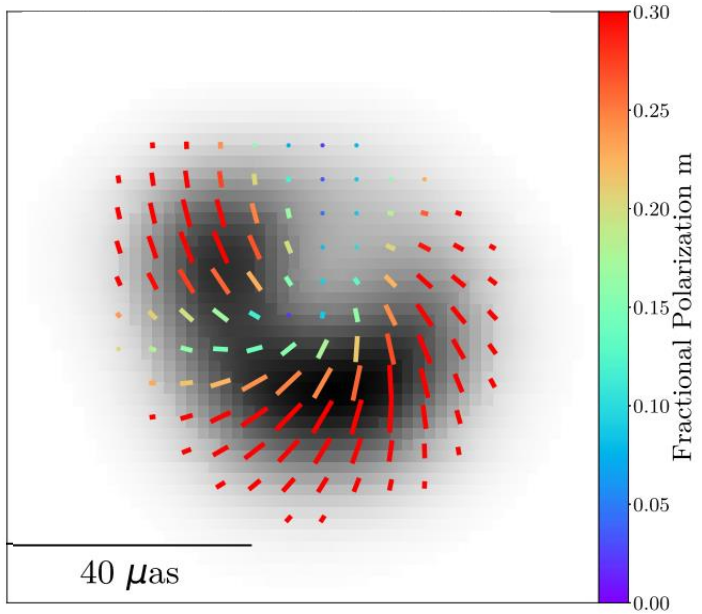


With rotation

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)

Scoring simulations with polarization: Results

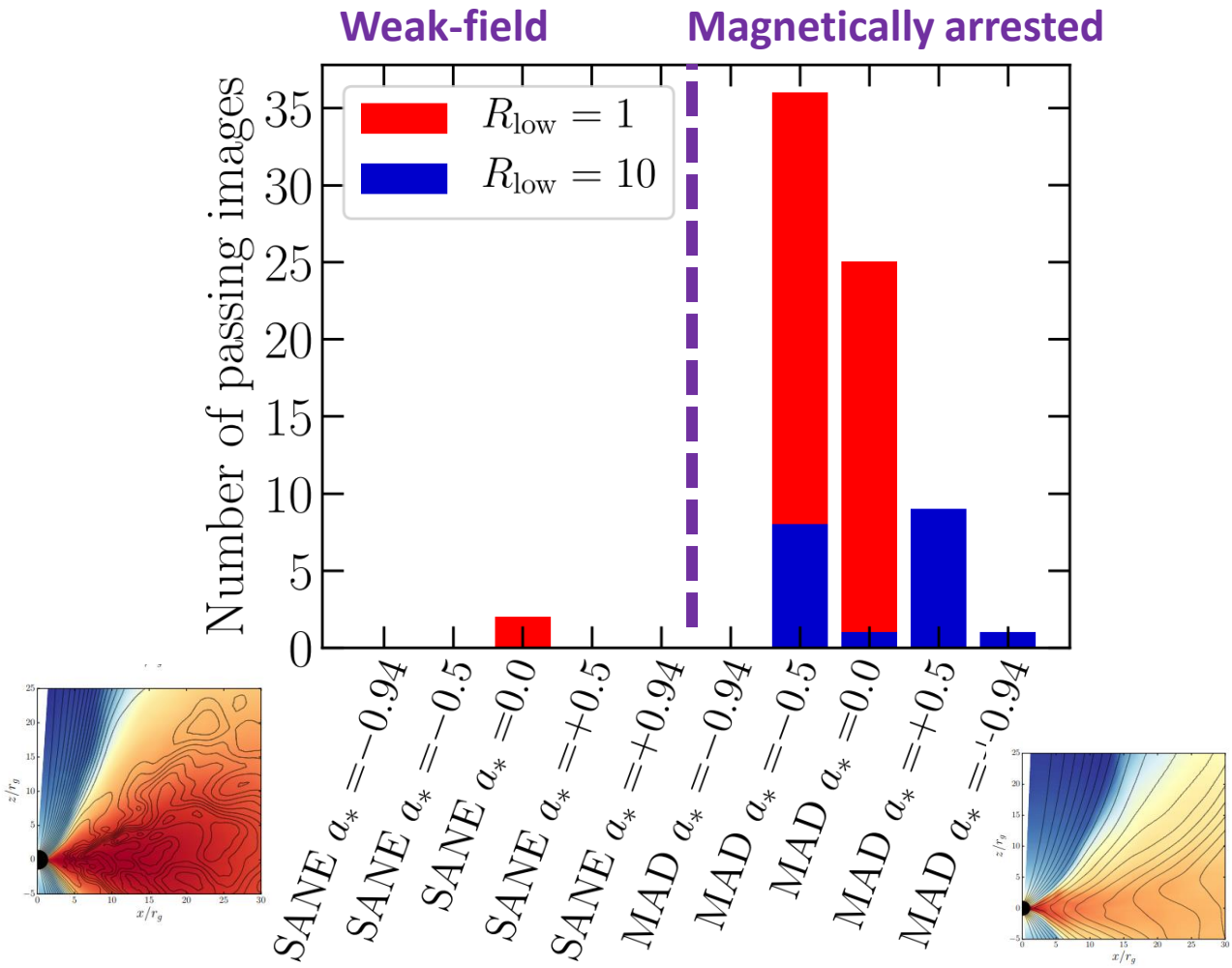
- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**

- 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

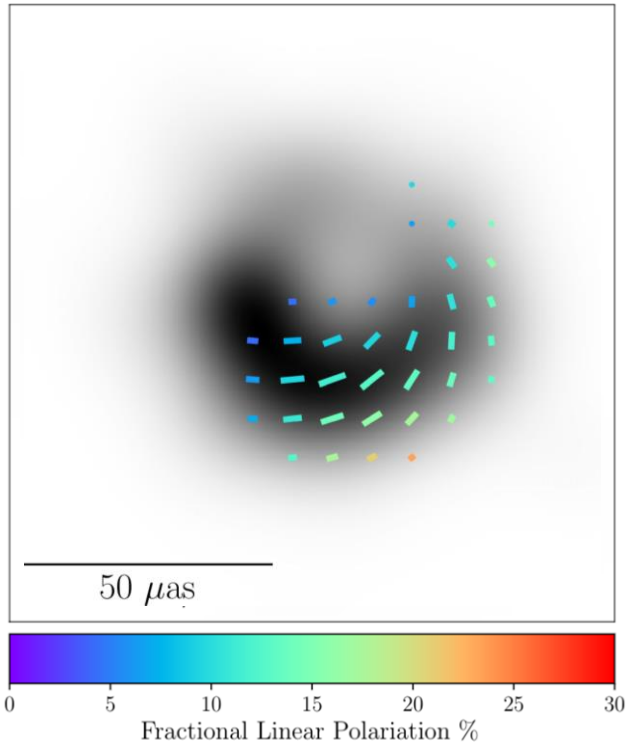


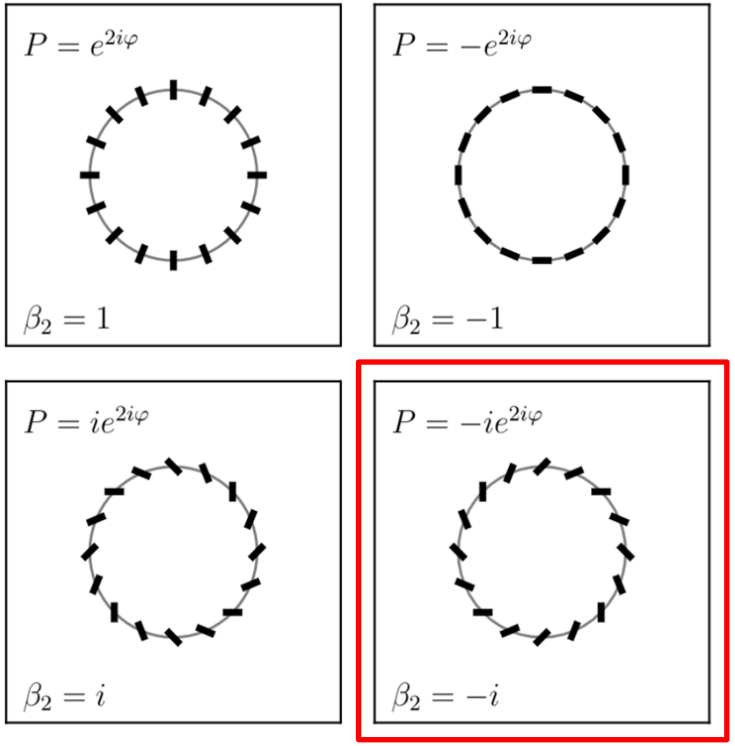
Credit: EHT 2021 Paper VIII, 2023 Paper IX (**Chael**, paper coordinator), Riordan+2017

Can we connect the polarized image of M87* on horizon scales to energy flow & jet launching?

Chael, Lupsasca, Wong & Quataert 2023
arXiv: 2307.06372

Polarized Images of M87* and horizon-scale energy flow

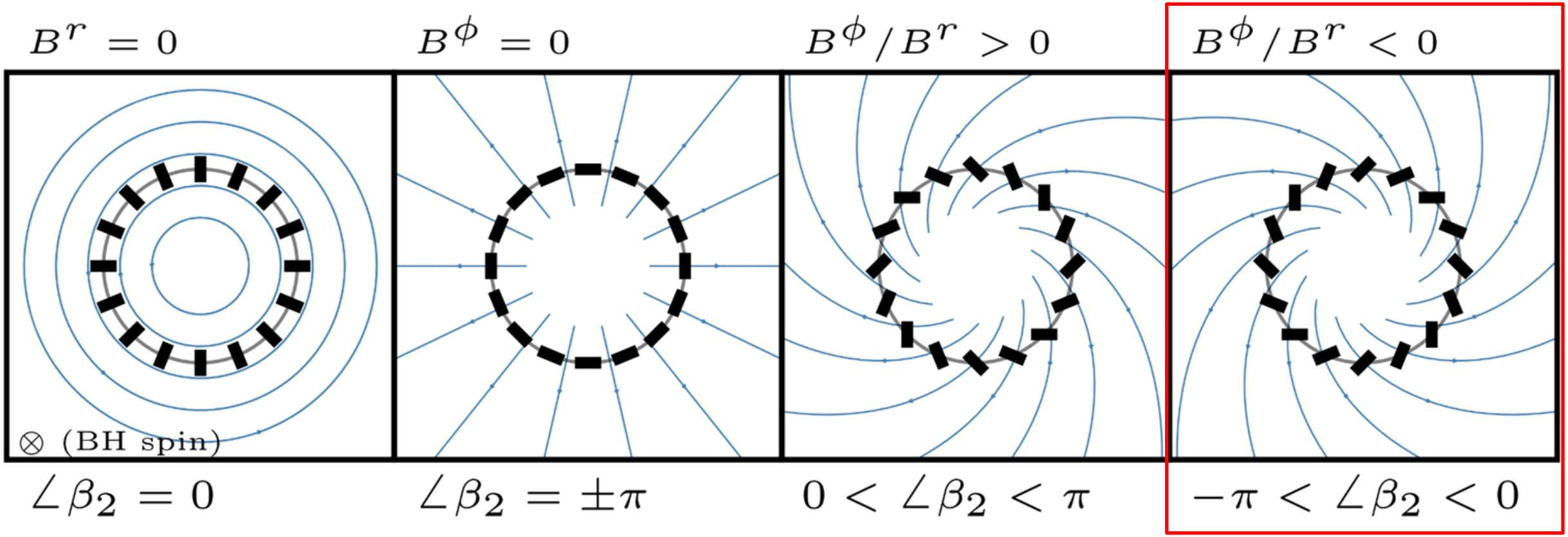




- The polarization spiral's **2nd Fourier mode** (β_2: Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

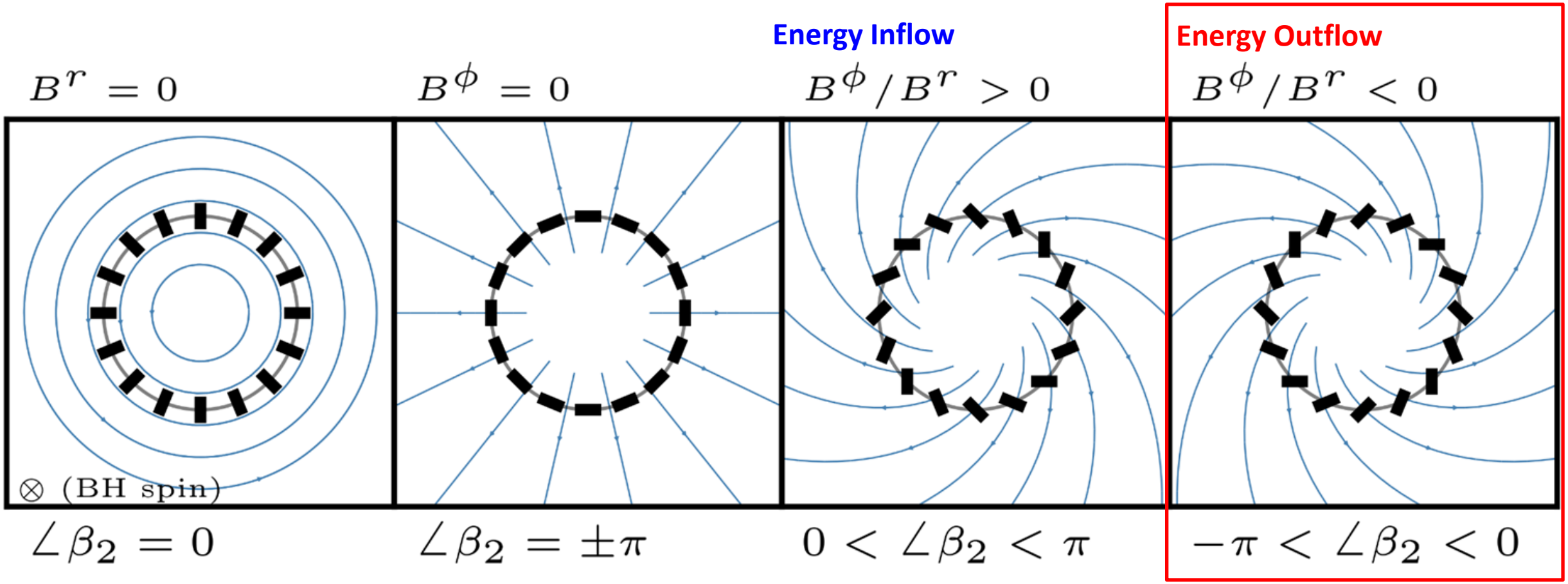
Cartoon model: $\arg(\beta_2)$ is connected to the pitch angle B^ϕ / B^r



- 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:

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

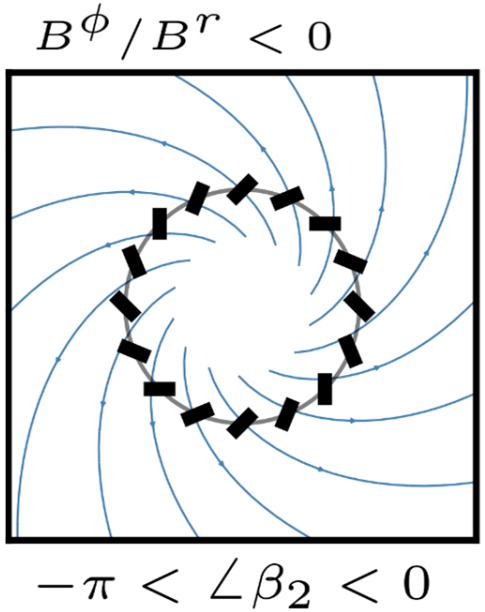
Ω_F: fieldline angular speed

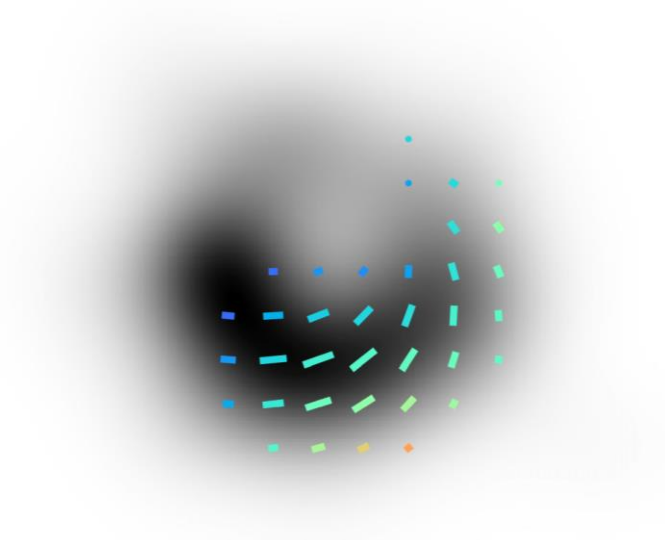
$\Delta \sin^2\theta \geq 0$

Chael+ 2023b

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

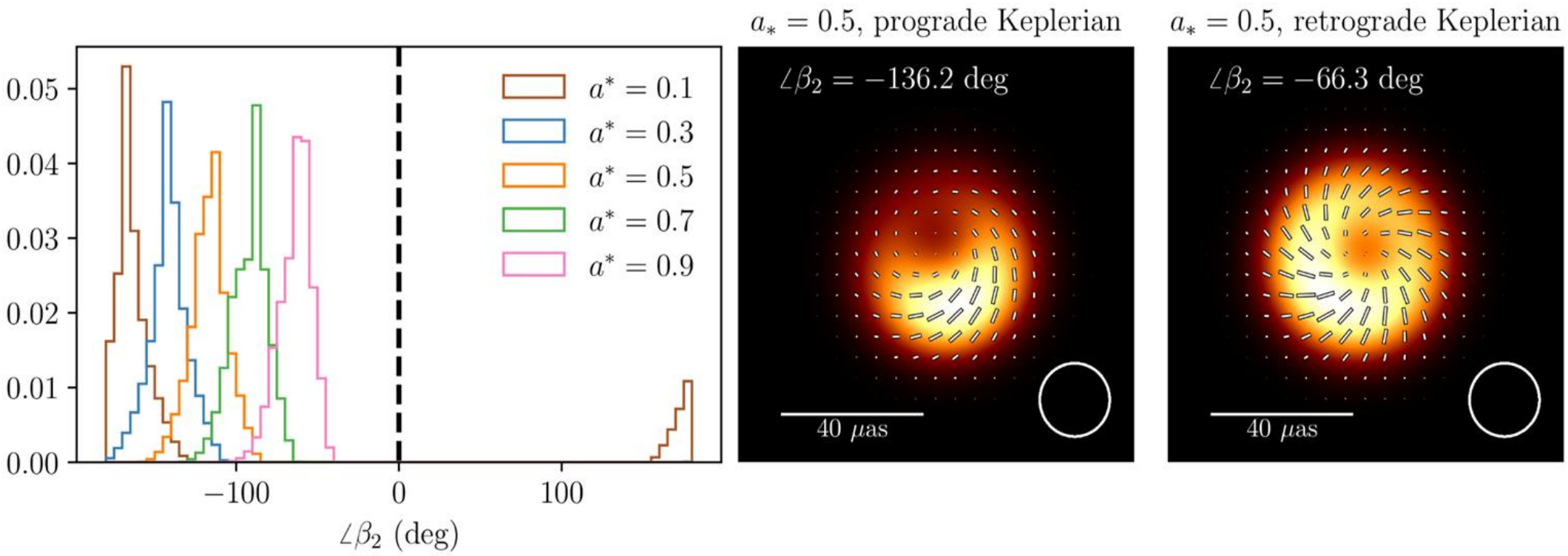
- The sign of $\arg(\beta_2)$ is directly connected to the direction of Poynting flux, assuming we know the sign of Ω_F
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy is outflowing in M87***
- This inference requires we assume fieldlines **co-rotate** with the 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 semi-analytic models of M87*



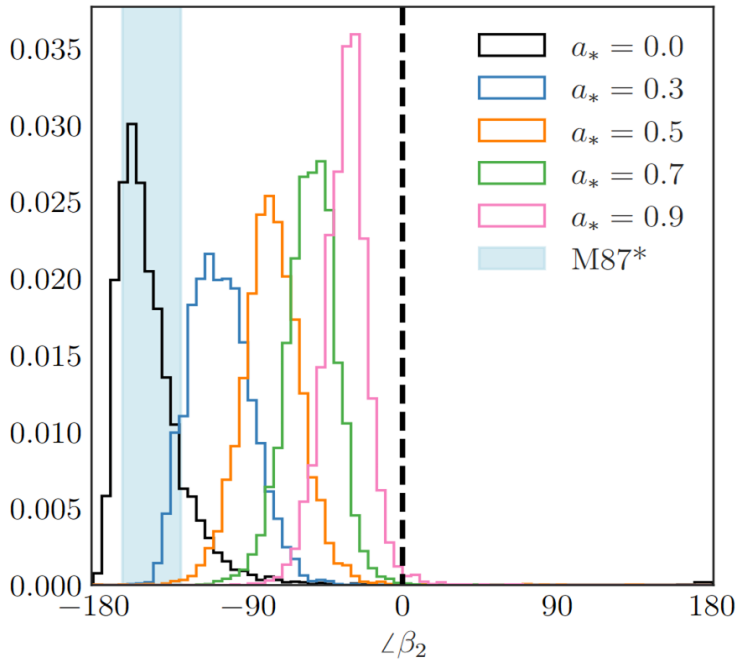
- We fix magnetic fields to the BZ monopole solution (with energy outflow)
- The black hole spin direction is fixed into the sky
- We explore many models for the velocity of the emitting fluid

Chael+ 2023b

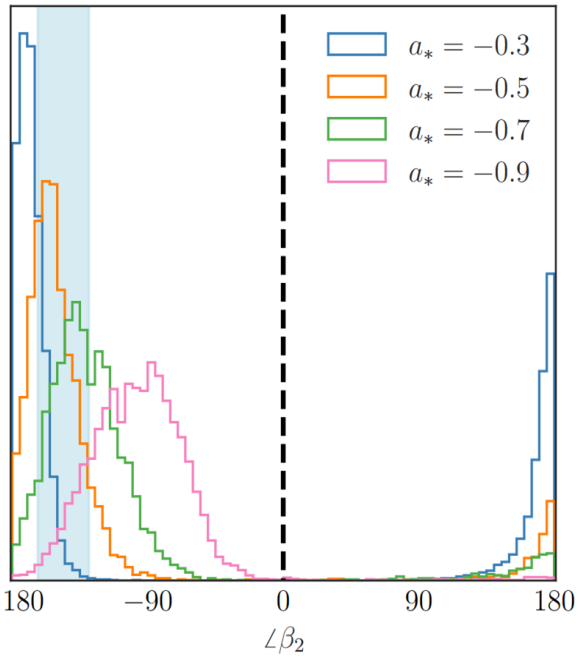
$\arg(\beta_2)$ in MAD **GRMHD simulations** of M87*

- 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

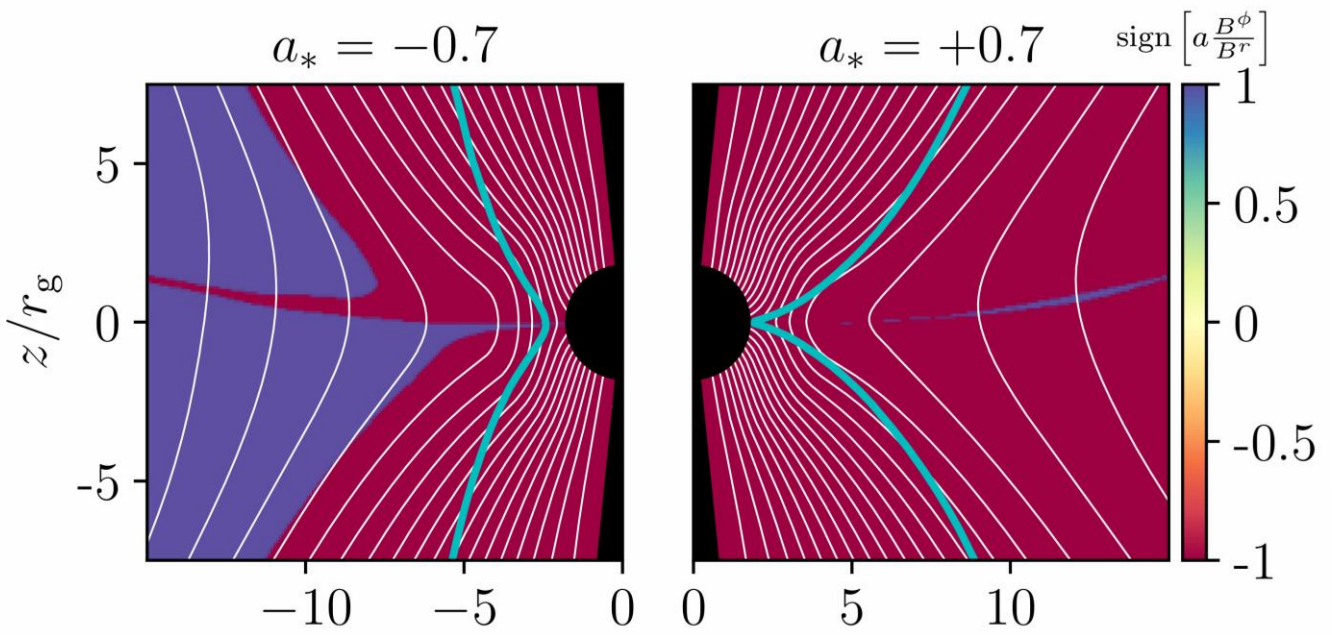


Retrograde simulations



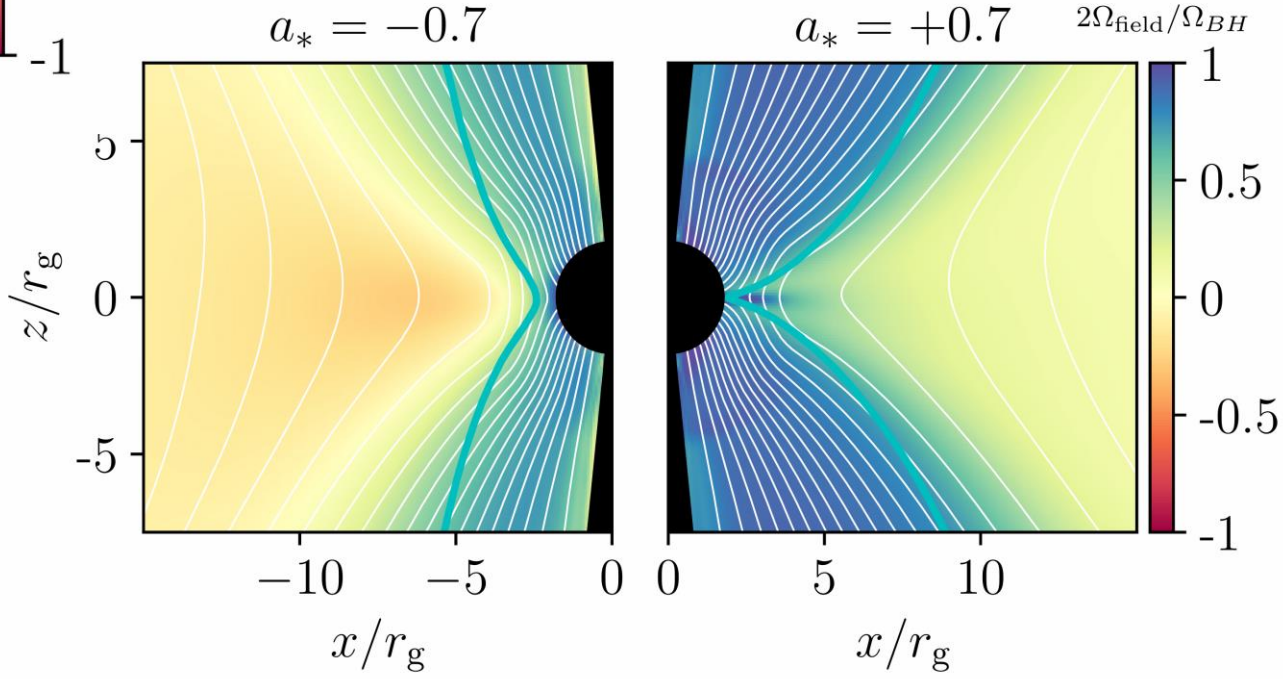
Chael+ 2023b

In GRMHD, energy-extracting fieldlines set arg(β_2)



Sign of magnetic field pitch angle

Field-line angular speed

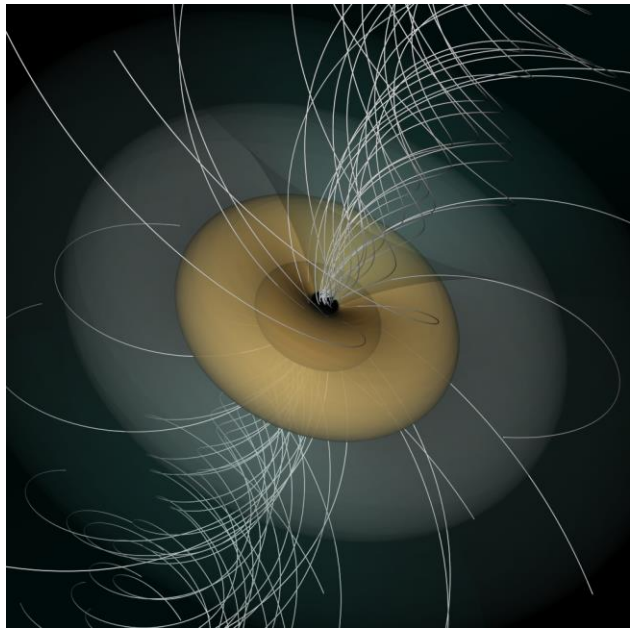


Even in **retrograde** simulations, field-lines in the 230 GHz emission region usually co-rotate with the black hole and have a negative B^ϕ / B^r

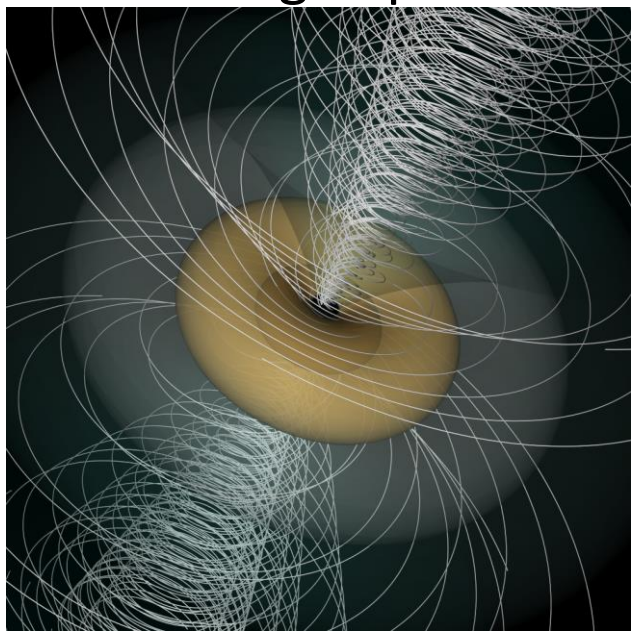
Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022, Wong+ 2021

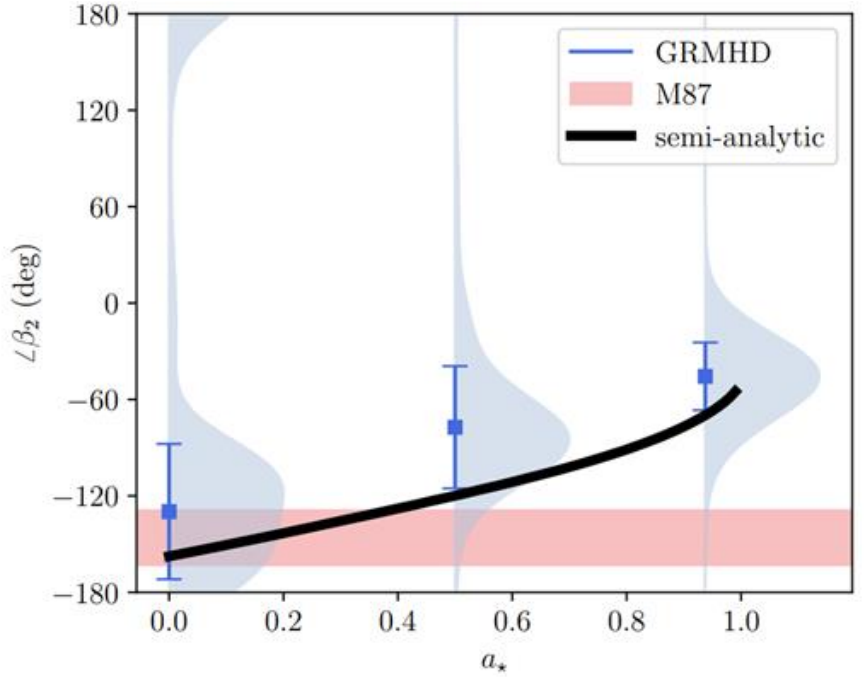
Polarized images are **spin dependent**

Low Spin



High Spin

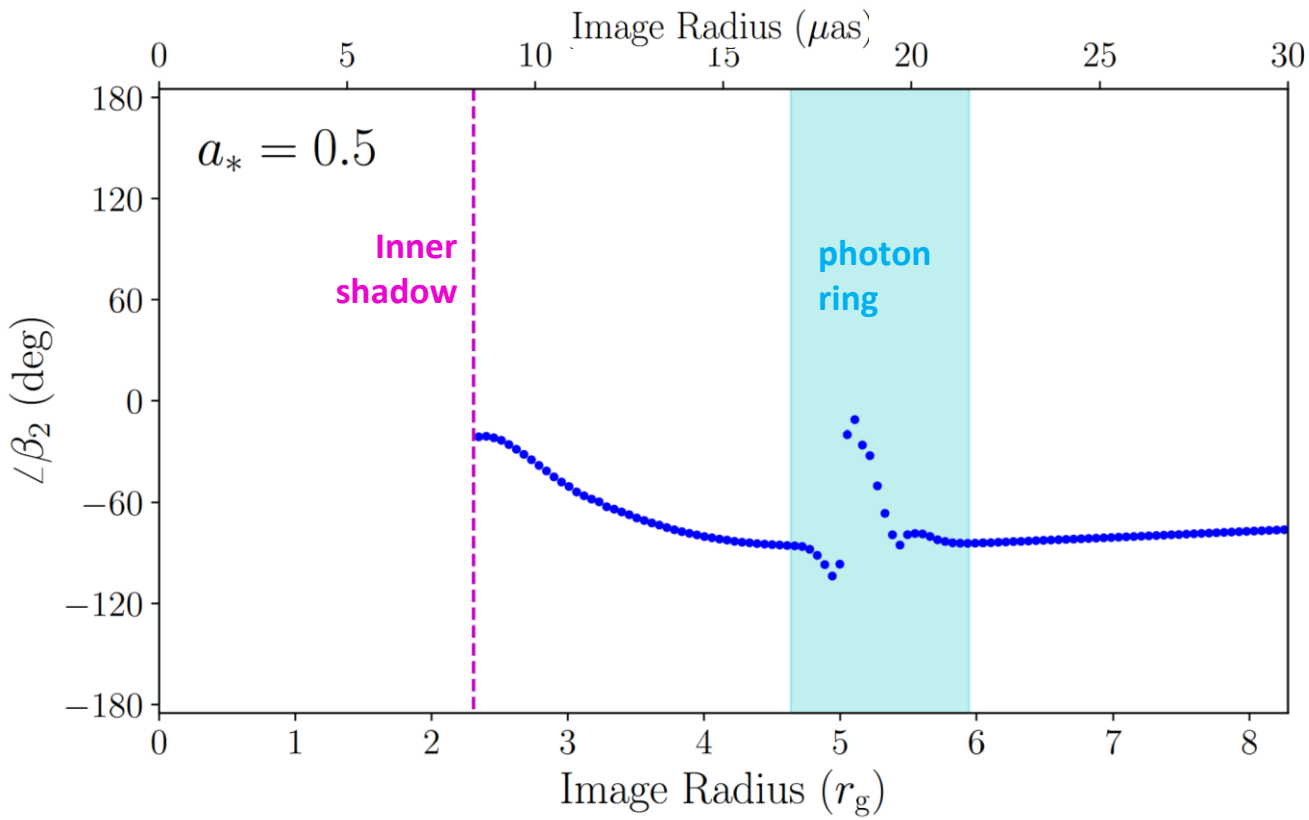


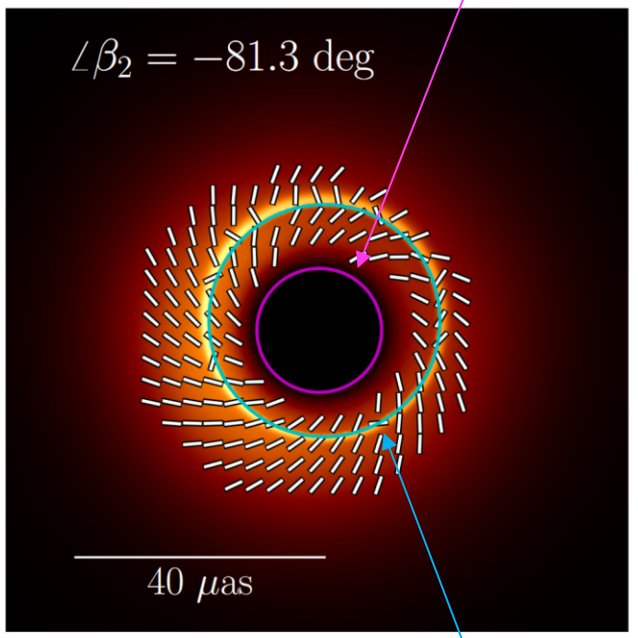


- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - and makes the observed polarization pattern more radial

Image credit: George Wong

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





"inner shadow"

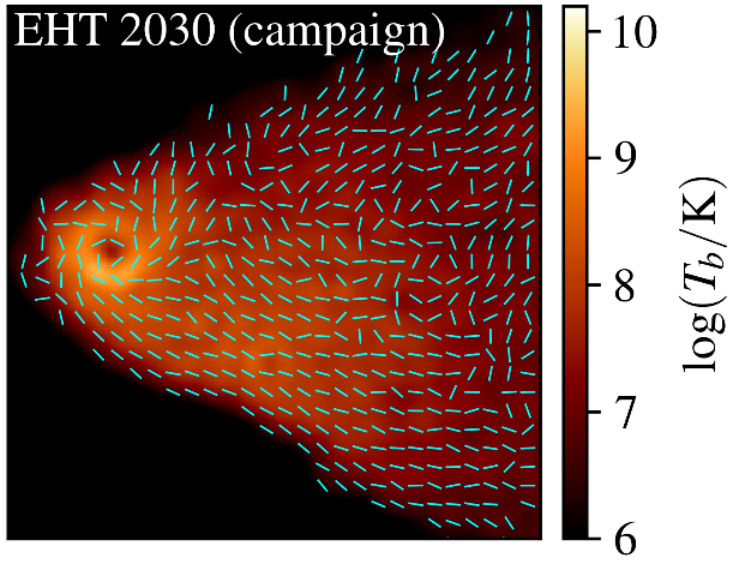
photon ring

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

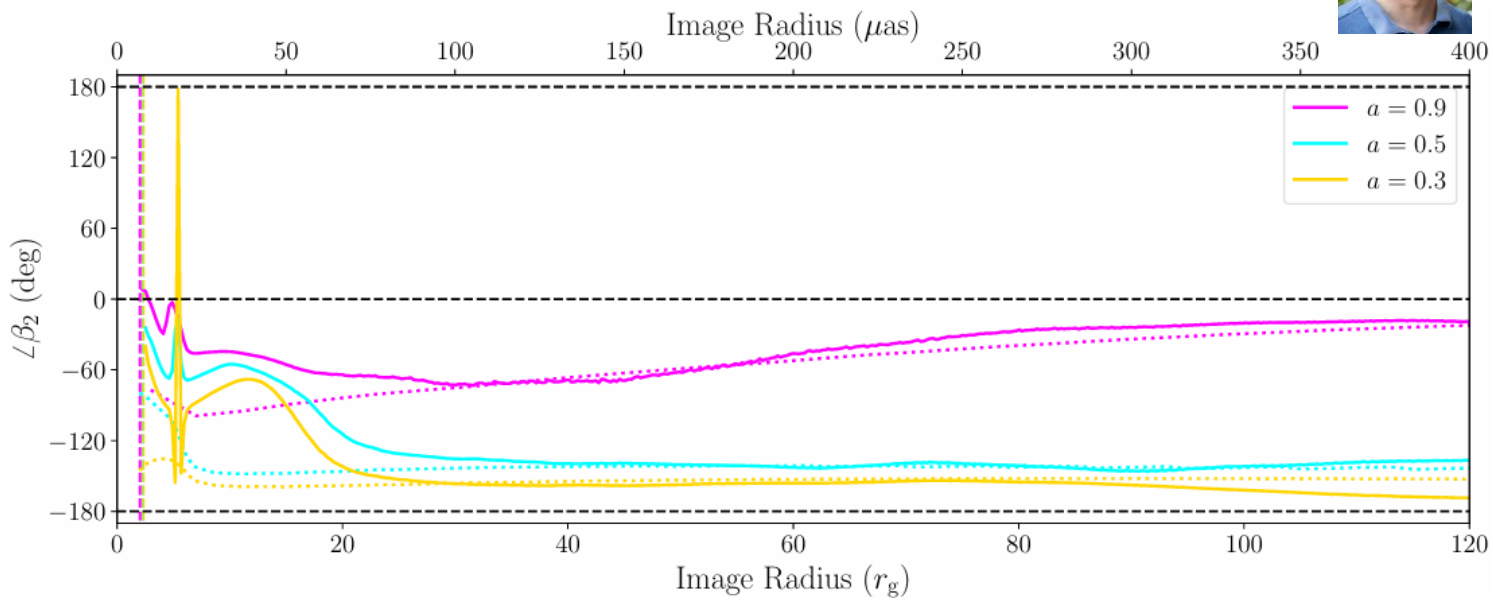
- Both simple models and GRMHD simulations make a strong prediction
  - arg(β_2) evolves rapidly close to the horizon as the rest frame fields become more azimuthal from **GR frame dragging**

Chael+ 2023b, (also Ricarte+ 2022)

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



Ongoing work with Zack Gelles (Princeton)



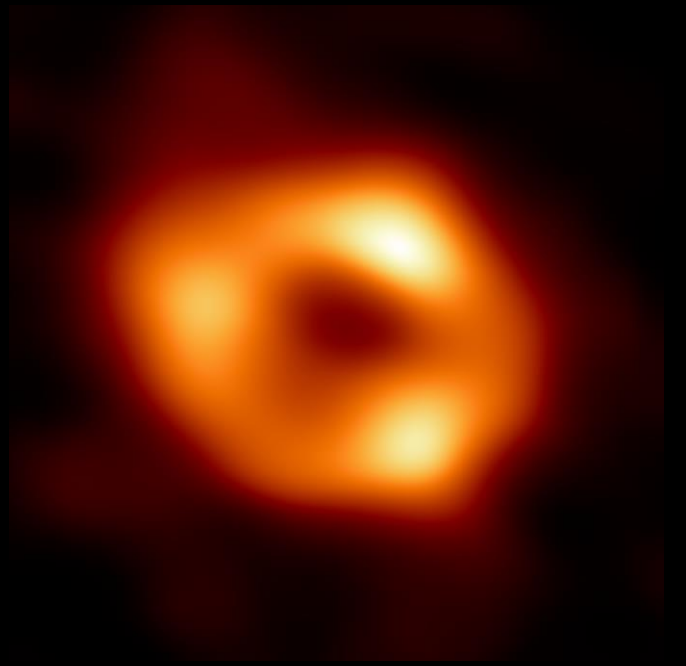
- New telescope sites & larger bandwidth will enhance EHT's **dynamic range**
  - These will illuminate both the **BH-jet connection**
- These new observations will require new theoretical models and simulations to fully interpret
  - Can we directly measure energy flow **from the horizon through the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

Chael+ 2019, 2023b

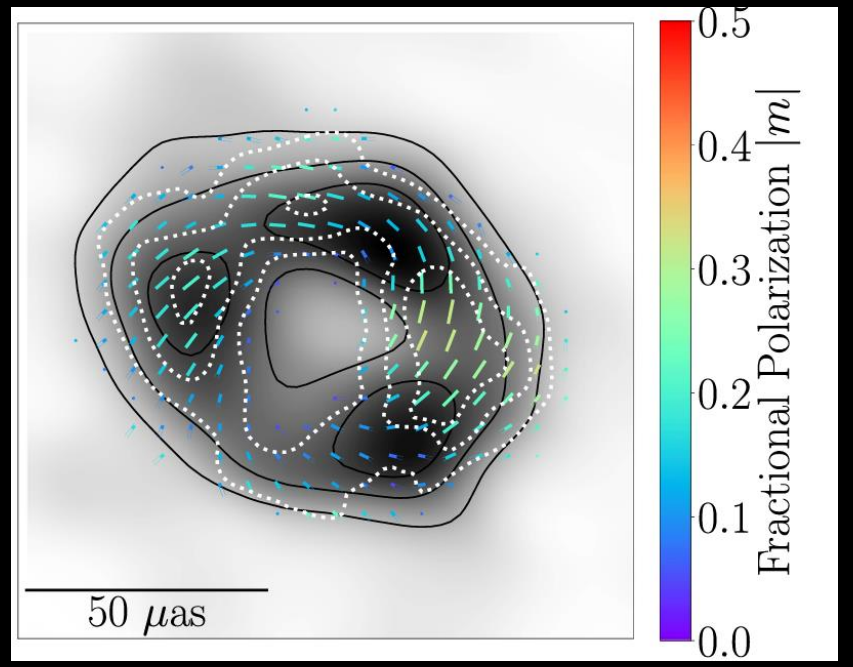
Image Credit: Paul Tiede, Dom Pesce, Zack Gelles

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
  - **only after Faraday derotation**
- MAD simulations preferred – **where is the jet?**

EHTC+ 2024 VII, VIII

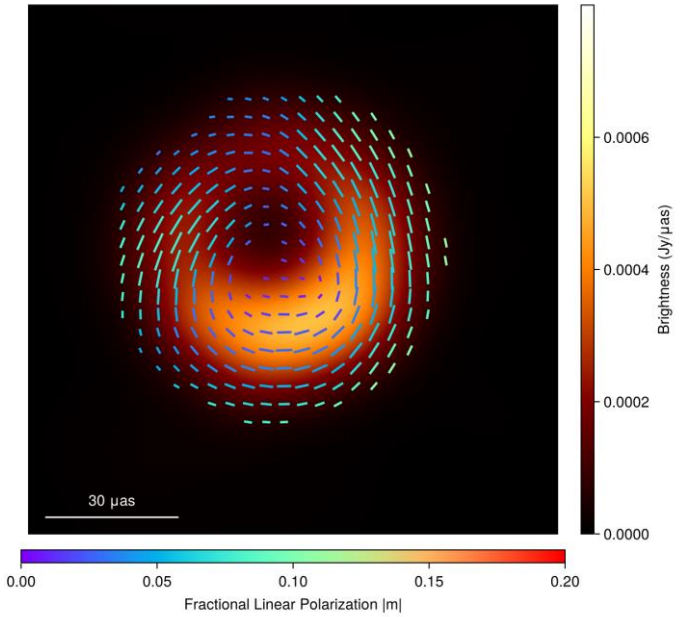
What is going on in M87 2021?

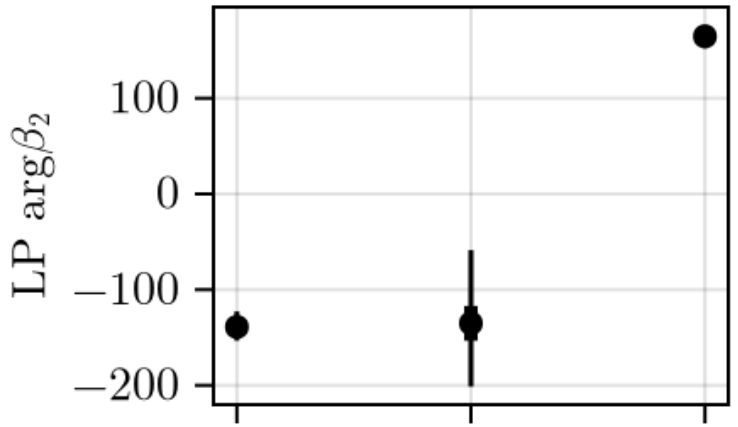
- M87 arg(β_2) **flips sign** between 2017/2018 and 2021

- This presents a challenge to the clean interpretation of arg(β_2) as a probe of Poynting flux!

- Possible explanations:
  - A large increase in Faraday rotation?
    - inside or outside the emission region?
  - A change in the location of the emission region?
    - Jet vs counterjet vs disk components?
    - Retrograde disk emission?
  - A change in the magnetic field structure?

- Understanding the flip in arg(β_2) and its variability in future years is **critical** for theoretical interpretation and for potential future use of polarimetric images for constraining jet launching





Credit: Paul Tiede/ M87 2021 Project Team

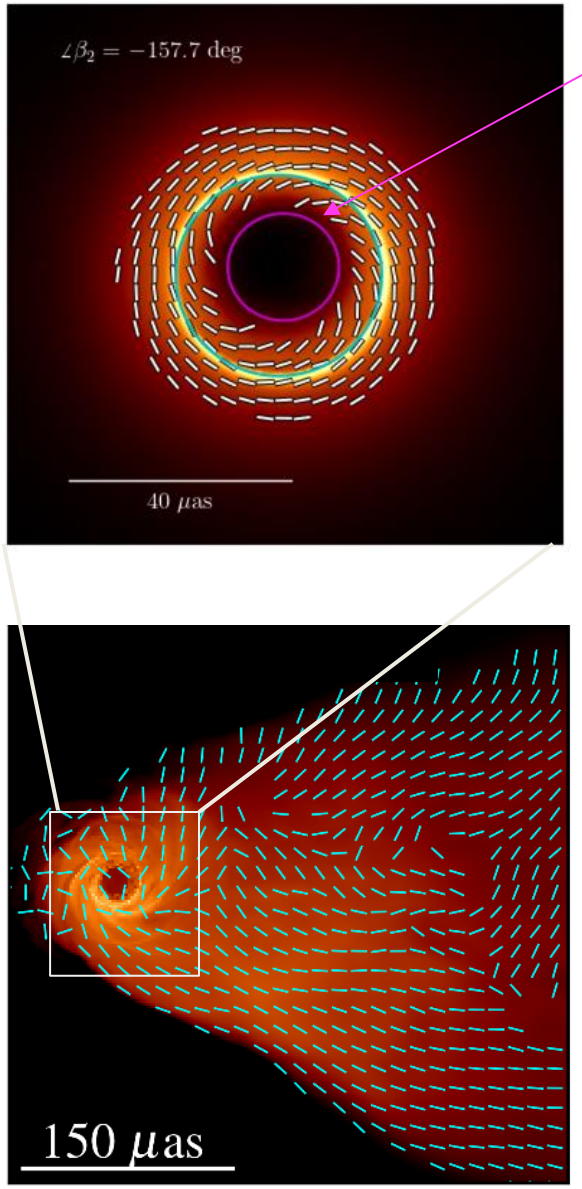
Takeaways

- Testing the BZ mechanism and directly measuring BH spin in M87* and other sources is a key science goal for the EHT's next decade

- We need **high-dynamic range, multi-frequency, polarized EHT images** to:
  - Measure polarization **down to the horizon**
  - Connect the energy flux **from horizon scales out through the jet base**

- We need **new simulation suites and analytic models** to
  - calibrate the spin-dependence of β_2
  - fully account for complicating factors (Faraday effects, field geometries, 3D structure…)

- Connecting theory and observation, we will be able to directly test the BZ mechanism for jet launching in the next several years



"inner shadow"

Goal 1: measure energy flux **down to horizon**

Goal 2: measure energy flux **out through jet base**

Chael+ 2023b