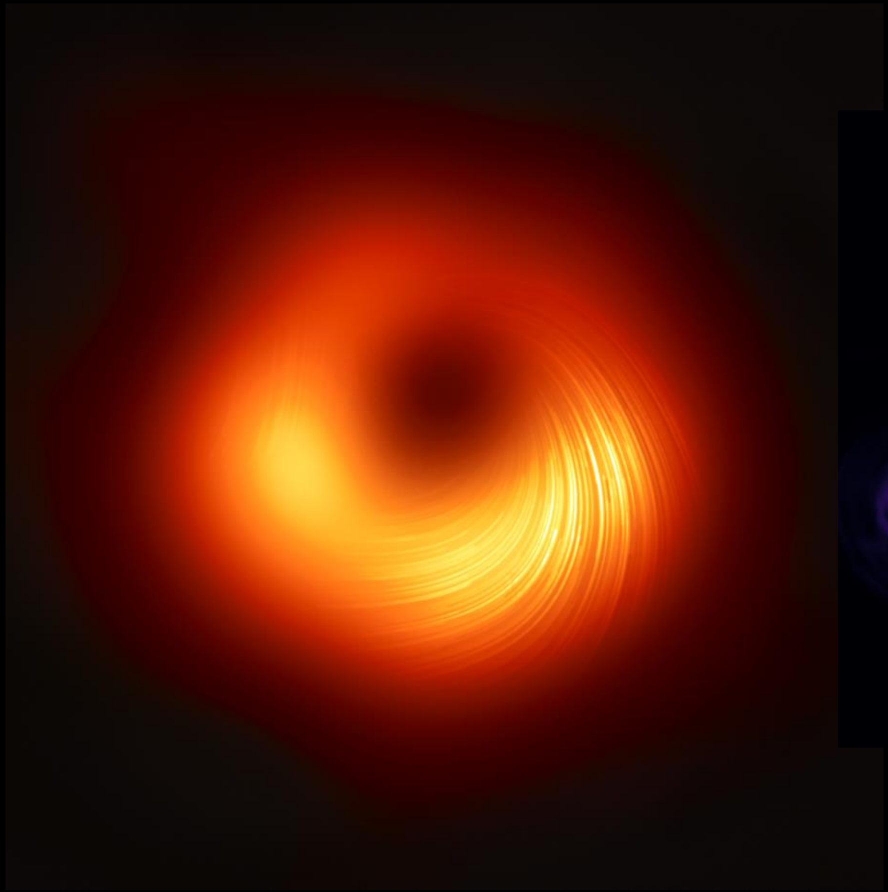
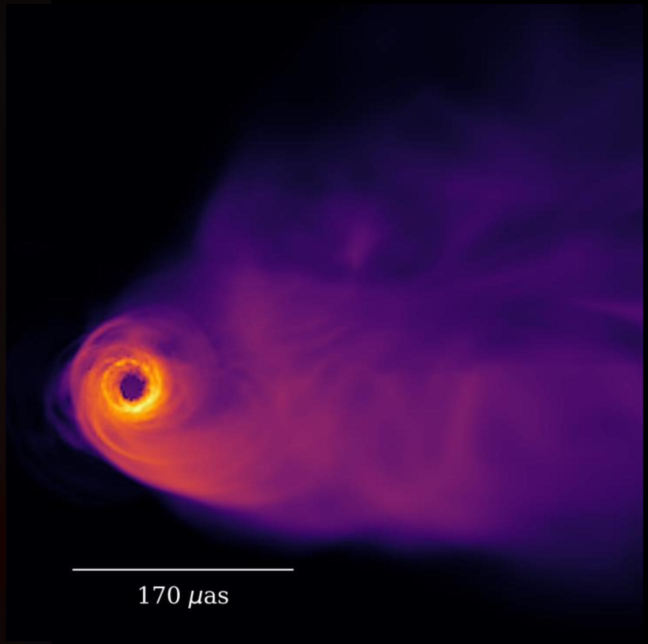
Black hole jet launching up close

Andrew Chael
Princeton Gravity Initiative
3/18/24





Princeton gravity Initiative

Event Horizon Telescope

M87 & M87*

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

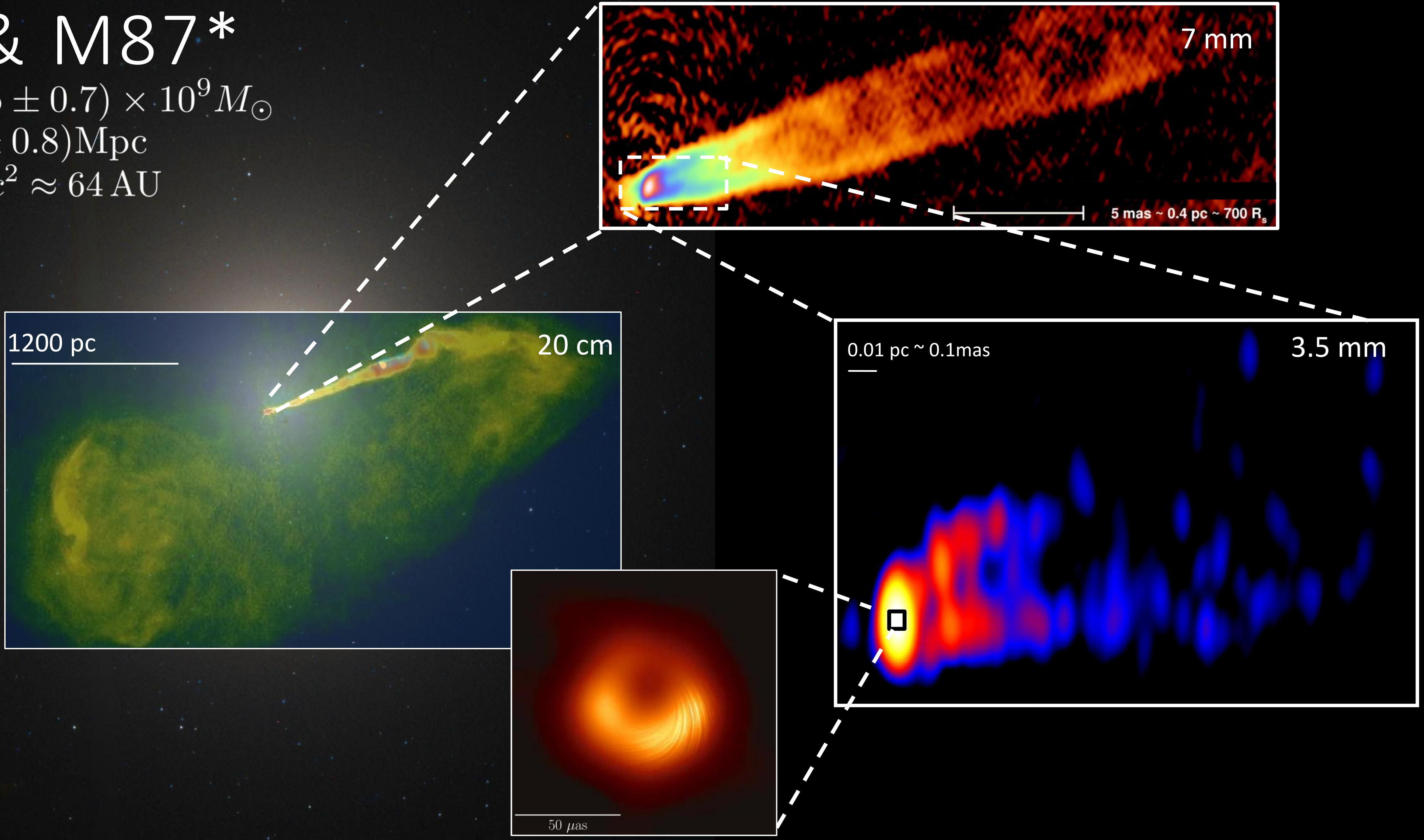
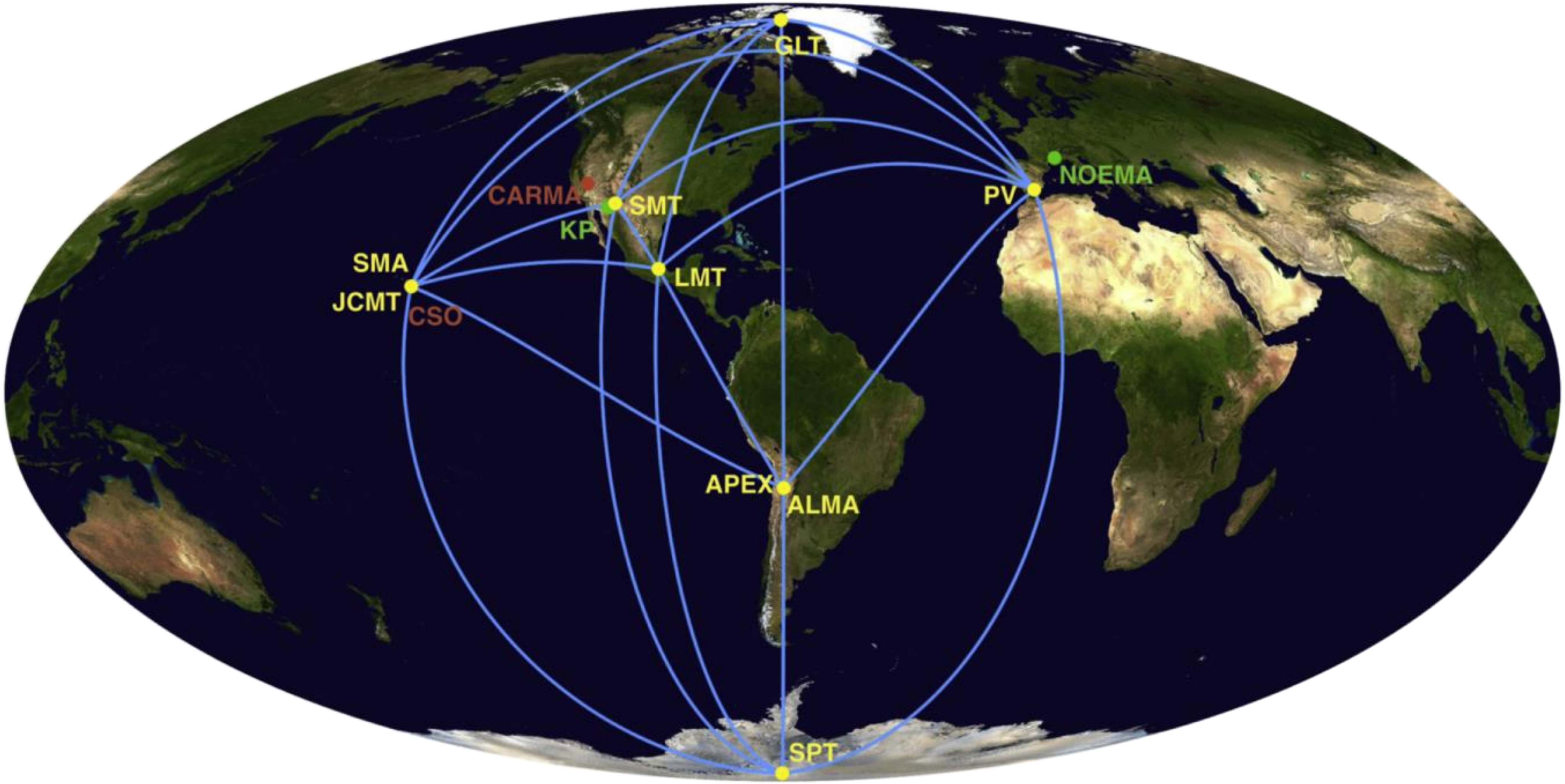


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

The Event Horizon Telescope: Instrument



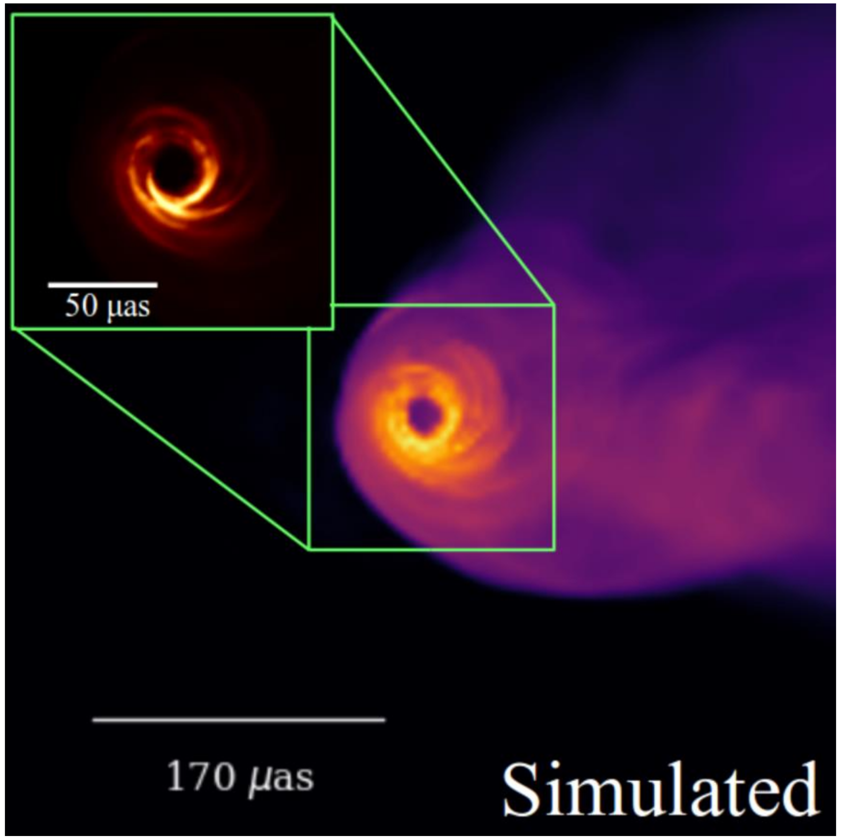
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

EHTC+ 2019, Paper II

At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Hot ($T \gtrsim 10^{10}$ K), sub-Eddington accretion flow
- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}$ erg s^{-1})
- Millimeter images from synchrotron radiation



Questions I think about:

- Is the jet launched by extracting BH spin energy?
  - What is the strength and geometry of the magnetic field?
- How can we perform precise tests of gravity?
  - How will these improve with upgraded EHT observations?
- What plasma processes accelerates electrons and lights up the flow?
  - What powers X-ray/ γ -ray flares in Sgr A* and M87*?

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

This talk:

1. What did we learn from the first *polarized* images of the M87* black hole?

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

3. How can we better simulate the black hole-jet connection?

The Event Horizon Telescope: People

300+ members

60 institutes

20 countries

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

What did we learn from the first *polarized* images of the M87* black hole?

EHTC+ 2021a,b , EHTC+ 2023 (**Chael**, paper coordinator)
2105.01169, 2105.01173, 2311.10976

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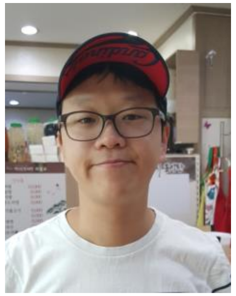

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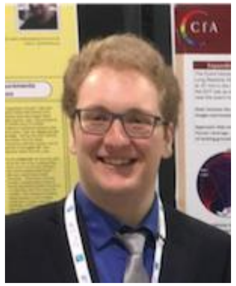

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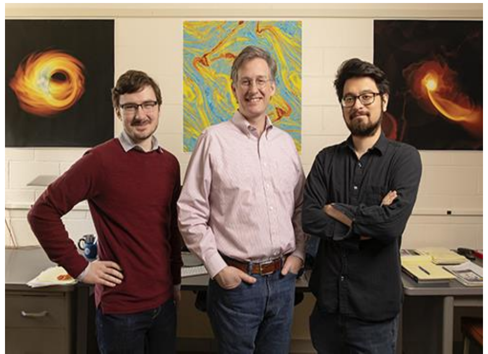
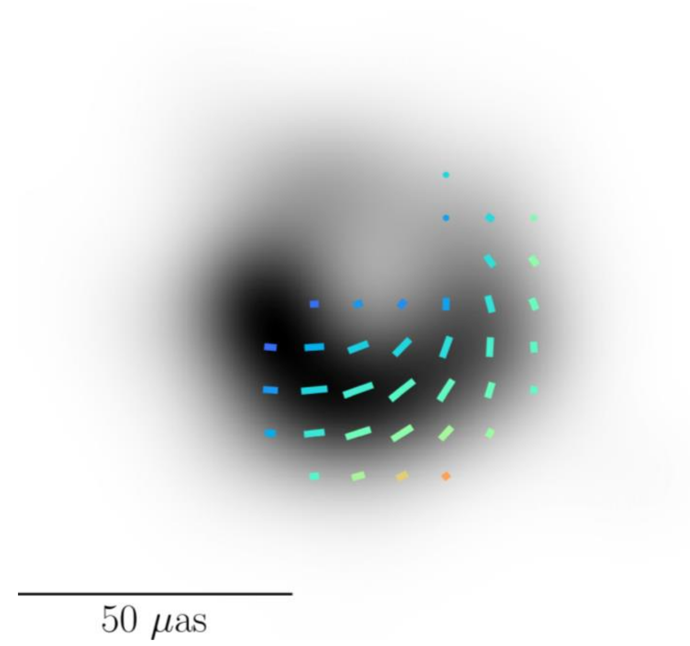
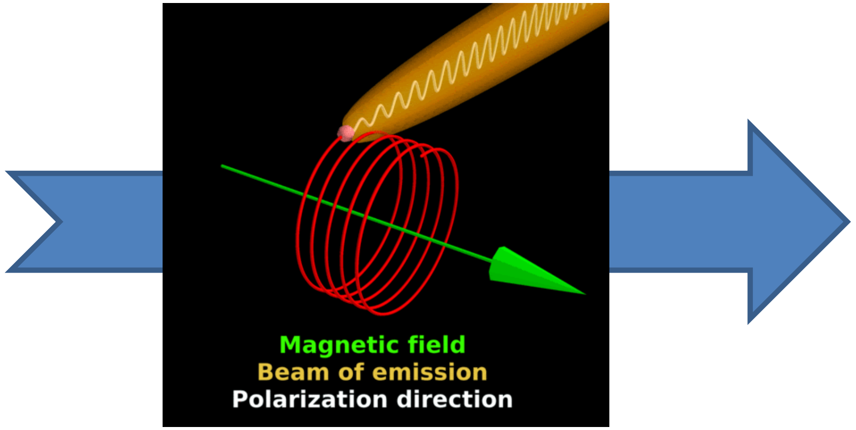


Why polarization?





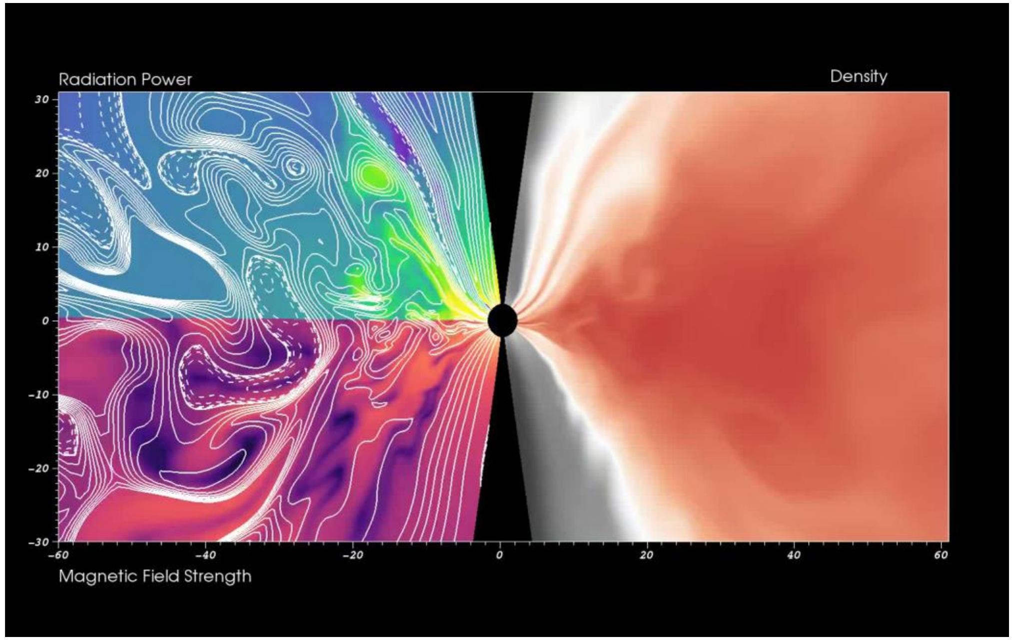
Magnetic fields in the emission region!

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

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

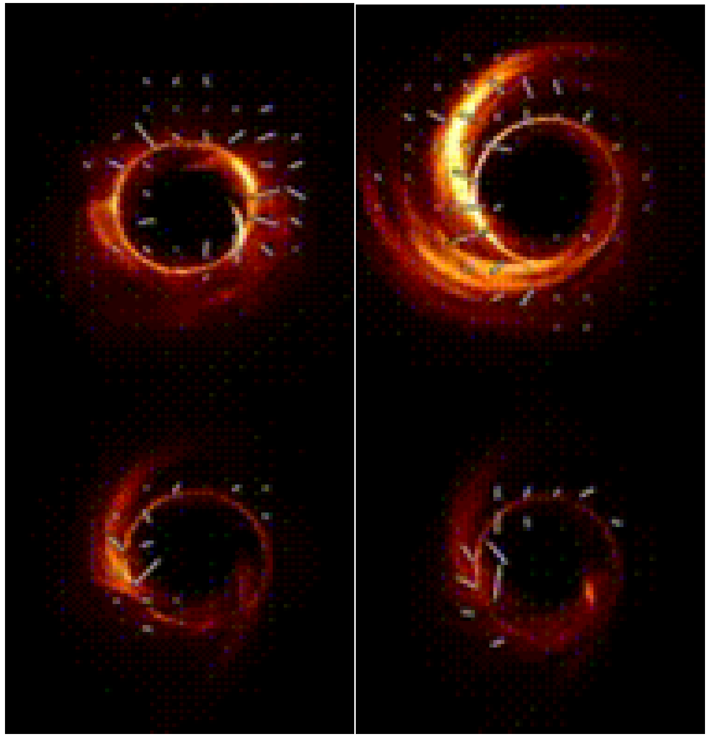
EHTC+ 2021 VII & VIII, EHTC+2023 IX (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Theoretical Tools for Interpreting Black Hole Images



General Relativistic Magnetohydrodynamic (GRMHD) Simulations

Solve coupled equations of plasma dynamics and magnetic field in Kerr spacetime



GR Radiative Transfer

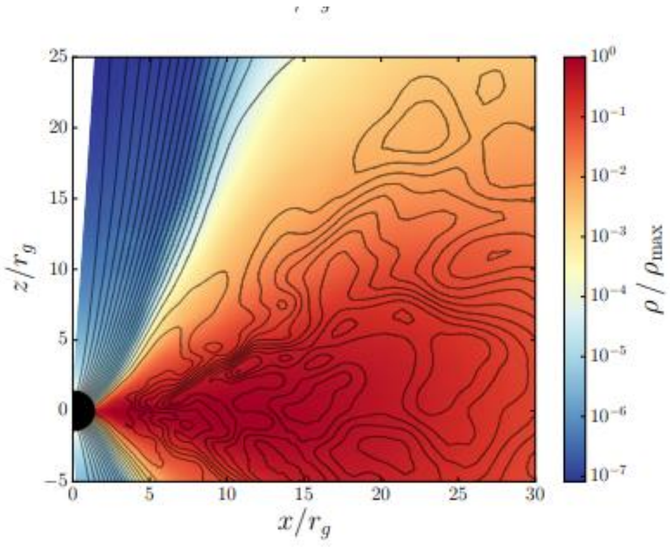
Track light rays and solves for the polarized radiation (including Faraday effects)

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

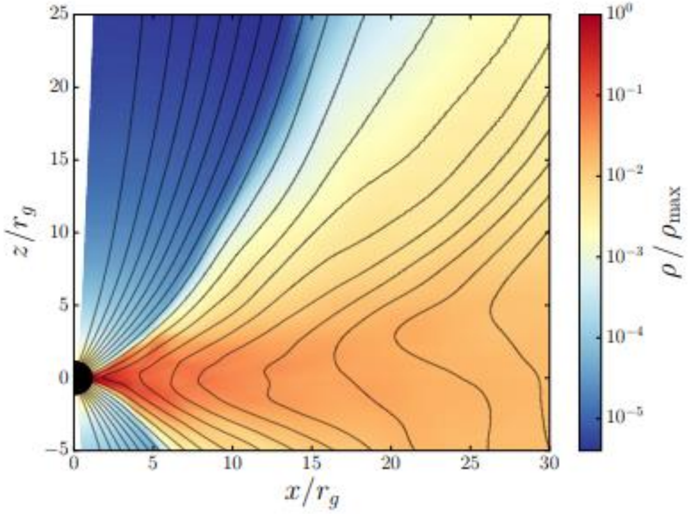
What is the magnetic field structure close to the horizon?

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

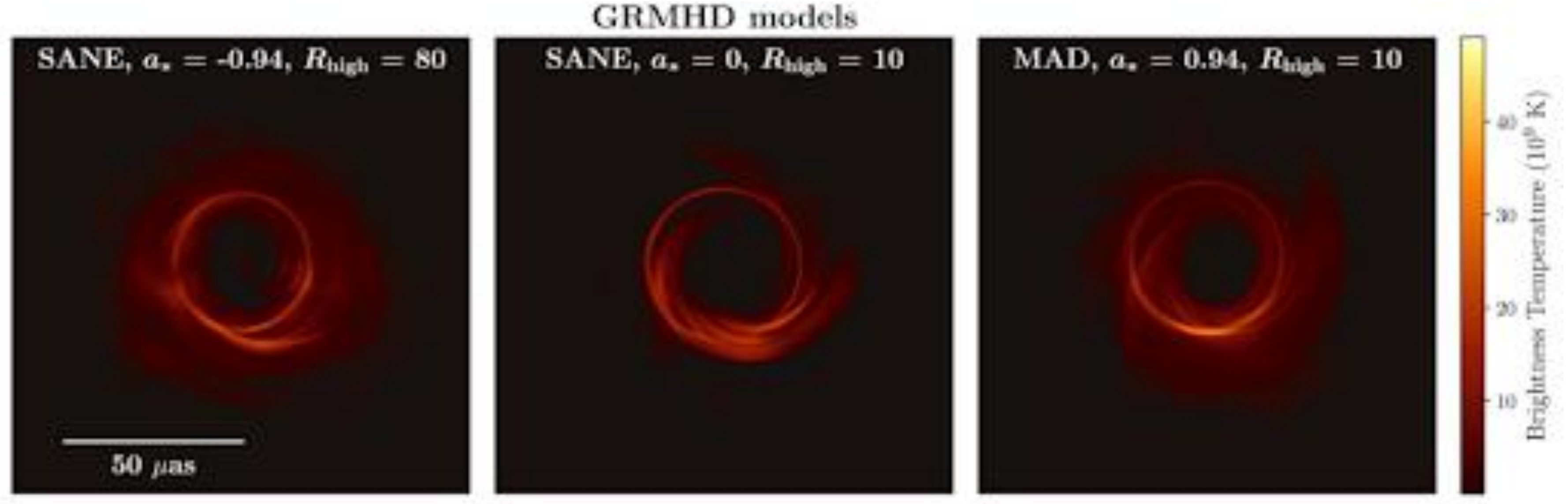
BH spin

magnetic flux

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

Scoring GRMHD Simulations: before polarization

- **Most simulation models can be made to fit total intensity observations alone** by tweaking free parameters

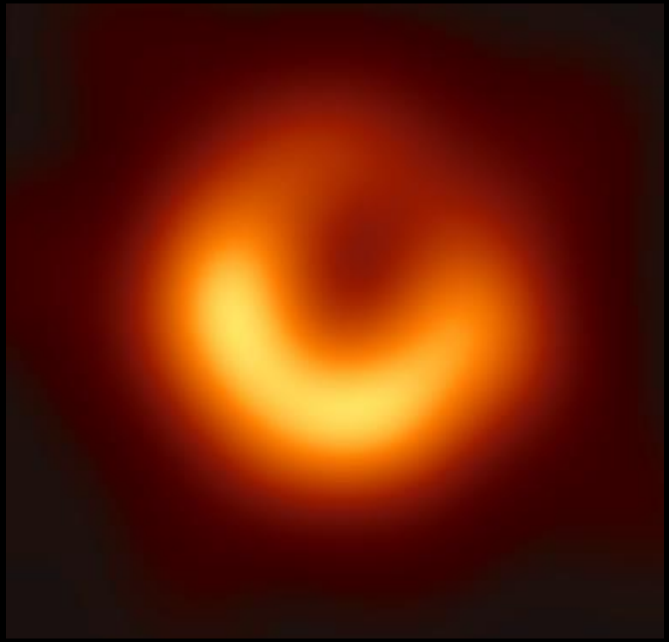


- An additional constraint on **jet power** (≥ 10^{42} erg/sec) rejects all spin 0 models
- Can we do better with polarization?

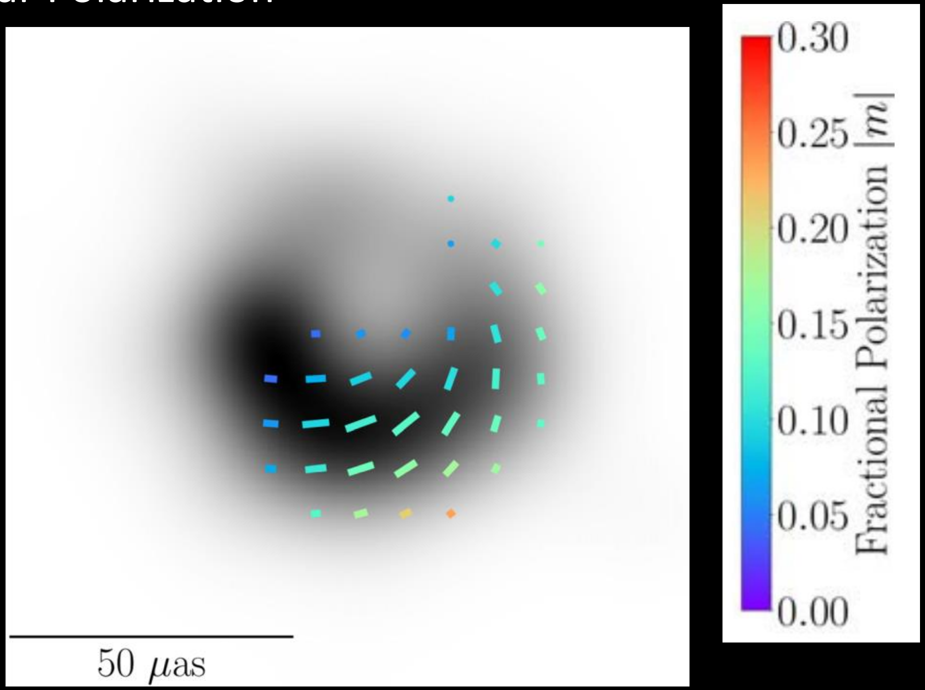
EHTC+ Paper V, 2019

M87* in **linear polarization**

Total intensity



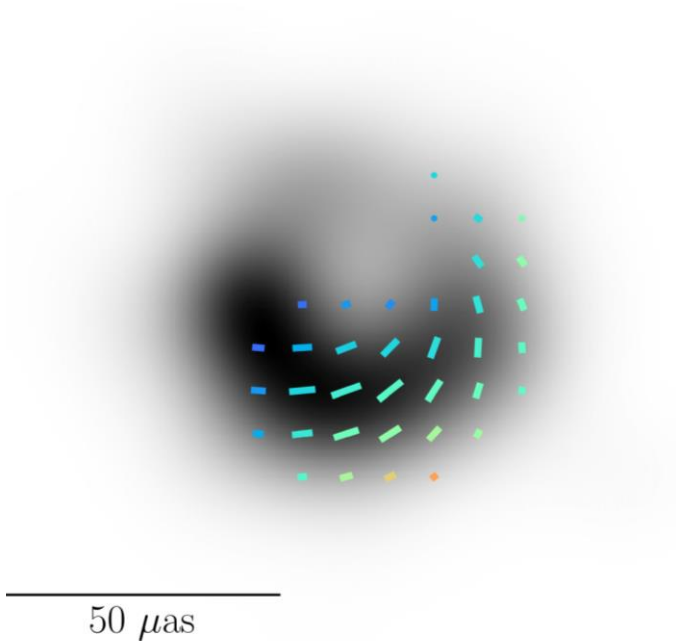
Linear Polarization

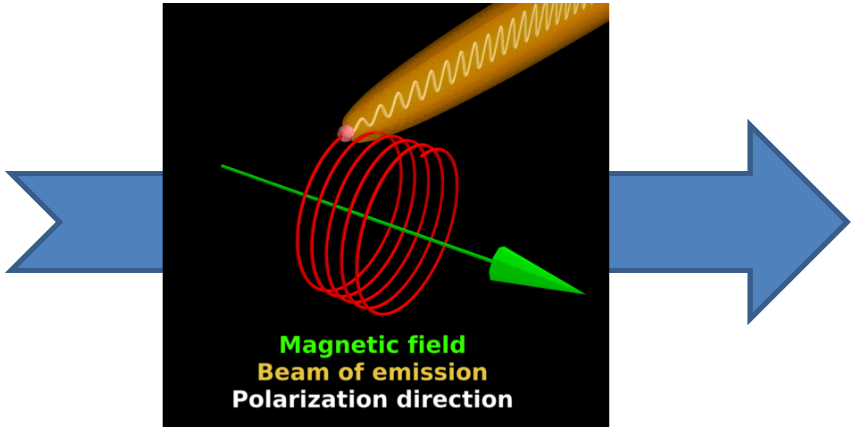


- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

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

Synchrotron polarization traces magnetic fields?

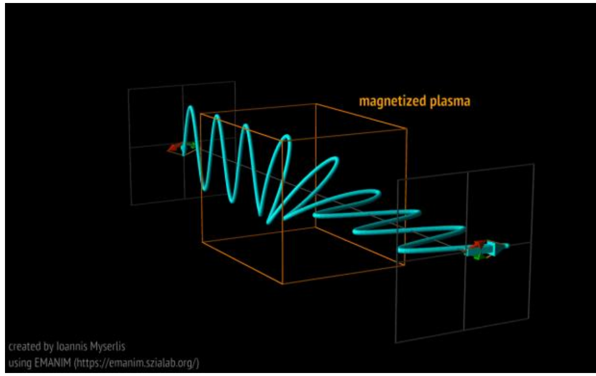




GR and Faraday effects make the situation in M87* more complicated!

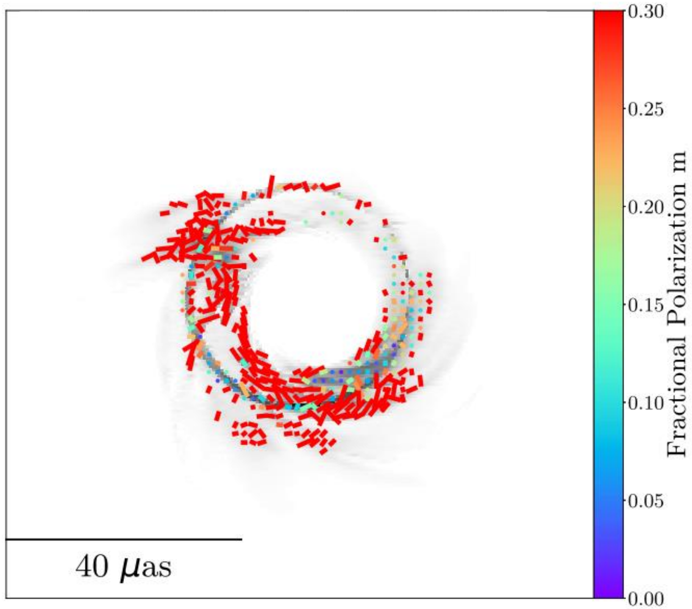
EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Faraday Rotation is important!

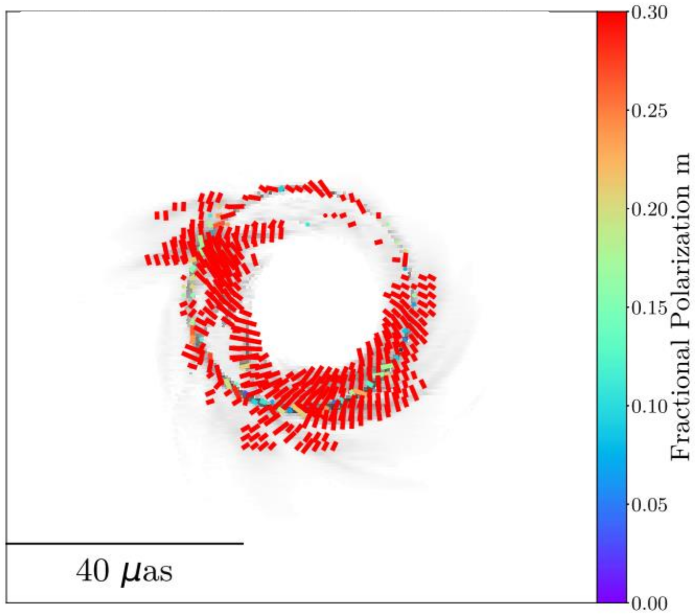


'infinite' resolution

With rotation



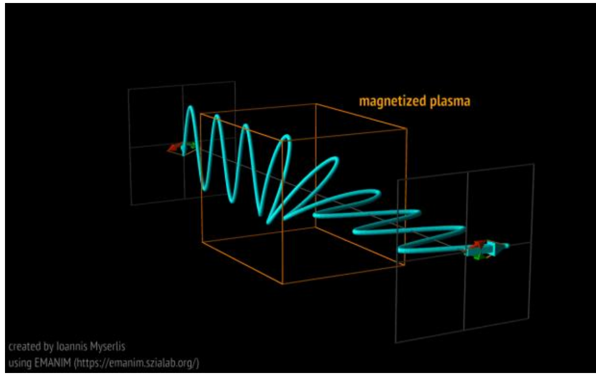
Without rotation



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

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

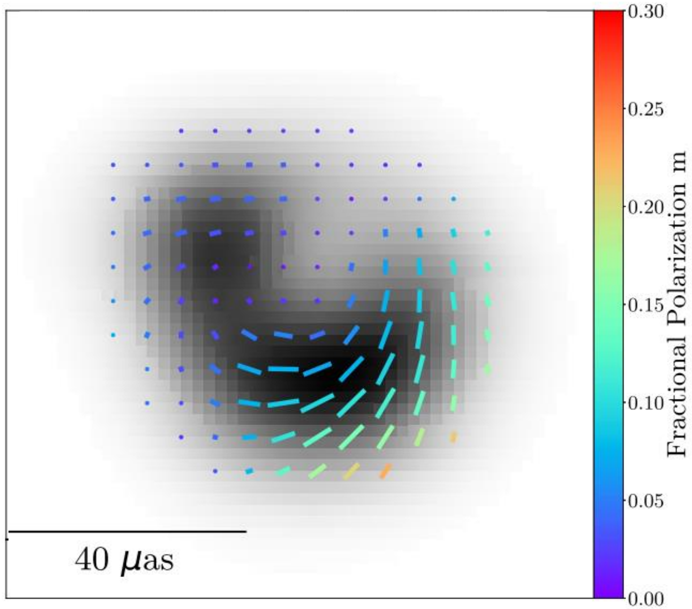
Faraday Rotation is important!

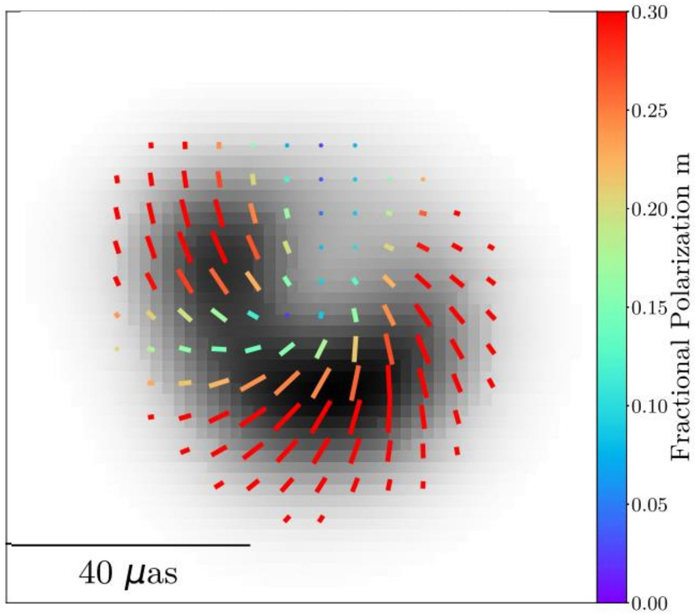


With rotation

Without rotation

EHT resolution

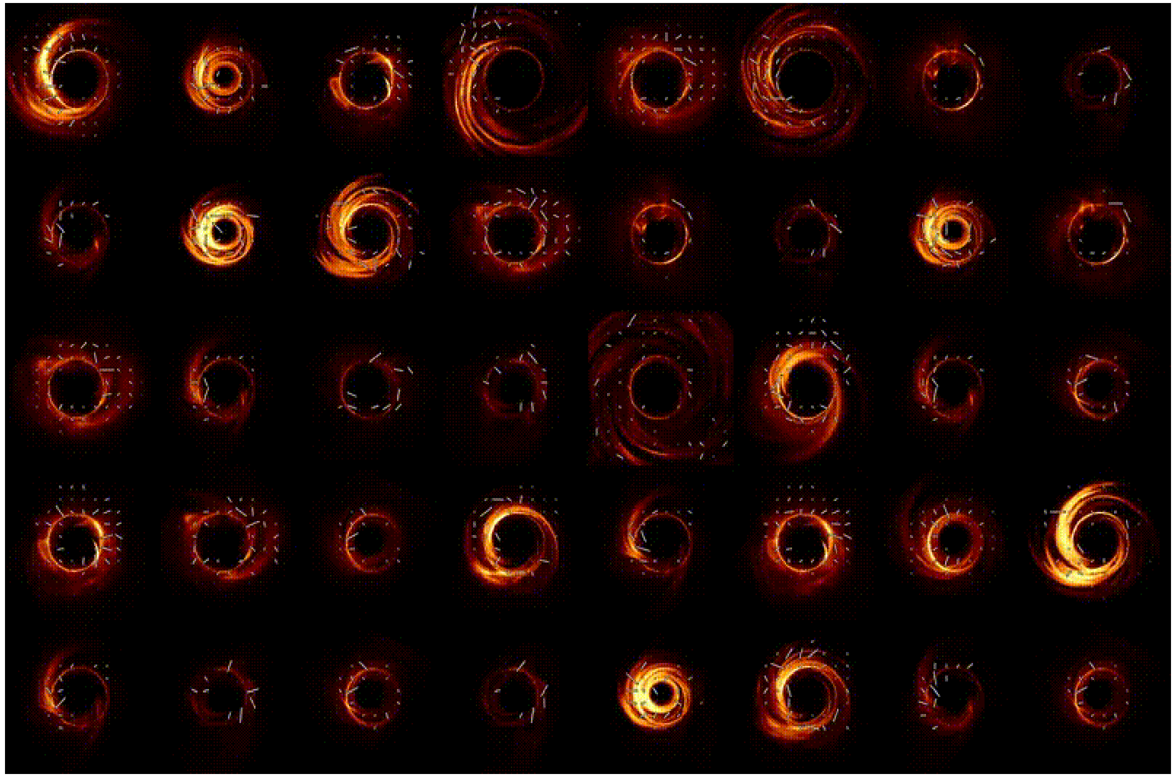




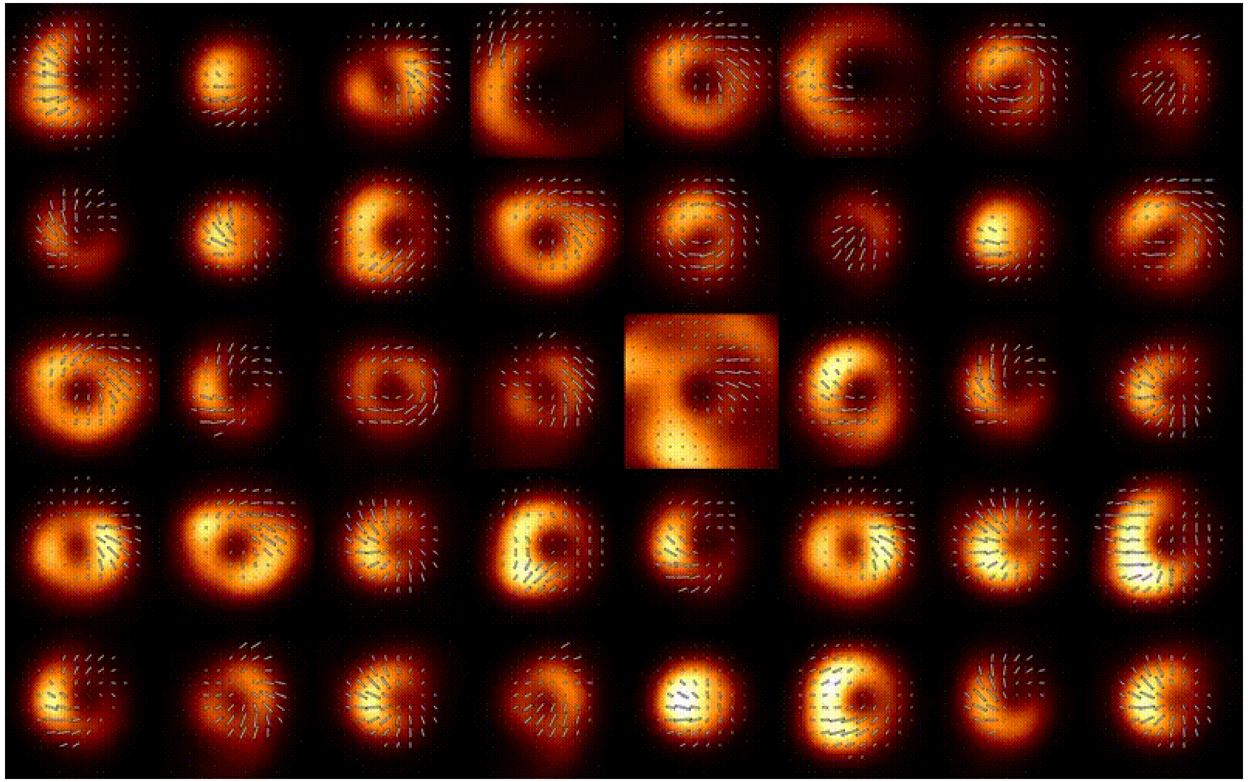
- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **depolarization** of the image when blurred to EHT resolution
  - → **rotates** the pattern when blurred to EHT resolution

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

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

Animation credit: Ben Prather

Scoring simulations with polarization: Image metrics

Azimuthal Linear structure
2[nd] mode (Palumbo+ 2020)

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

Unresolved linear polarization fraction

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

Unresolved circular polarization fraction (from ALMA)

$$|v|_{\rm net} = \frac{|\sum_i V_i|}{\sum_i I_i}$$

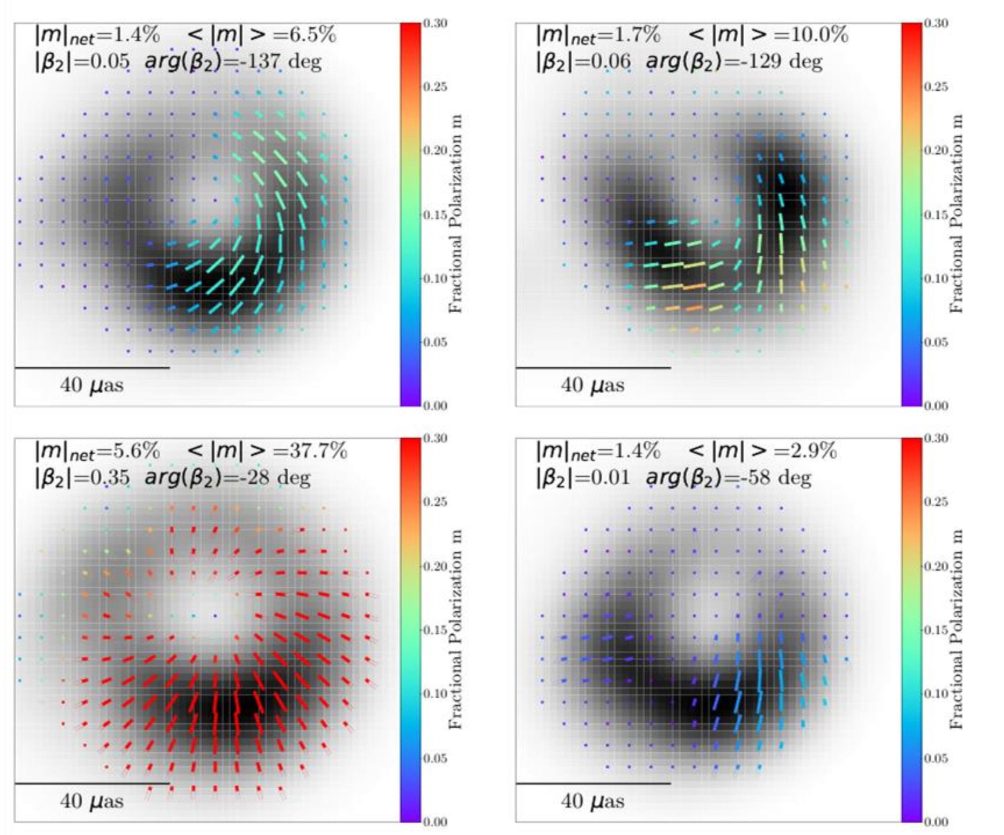
Average resolved linear fraction

$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Average resolved circular fraction

$$\langle |v| \rangle = \frac{\sum_i |V_i / I_i|}{\sum_i I_i}$$

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



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

Scoring simulations with polarization: Image metrics

Azimuthal Linear structure
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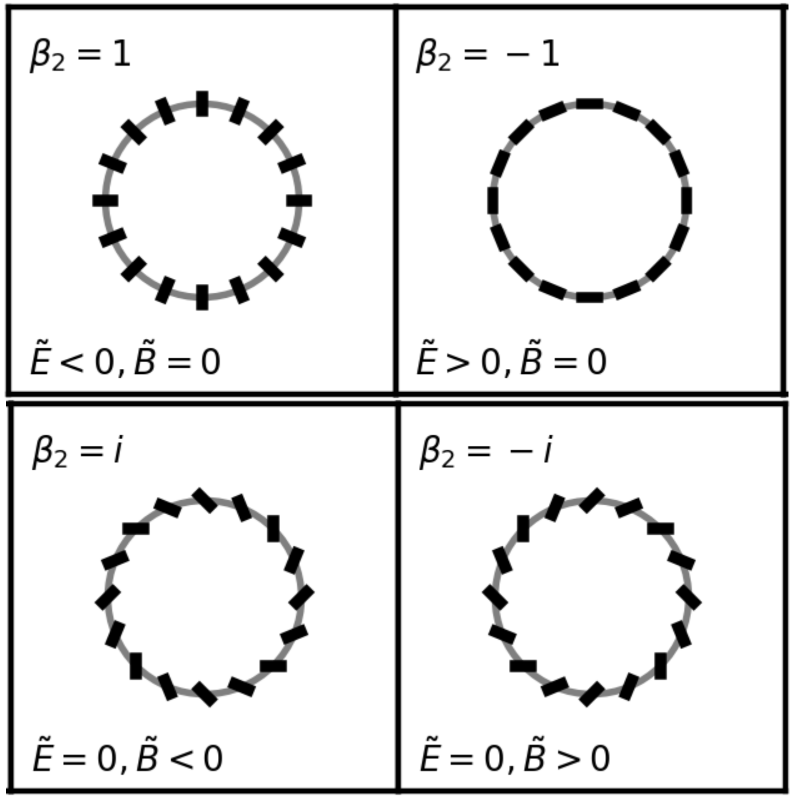
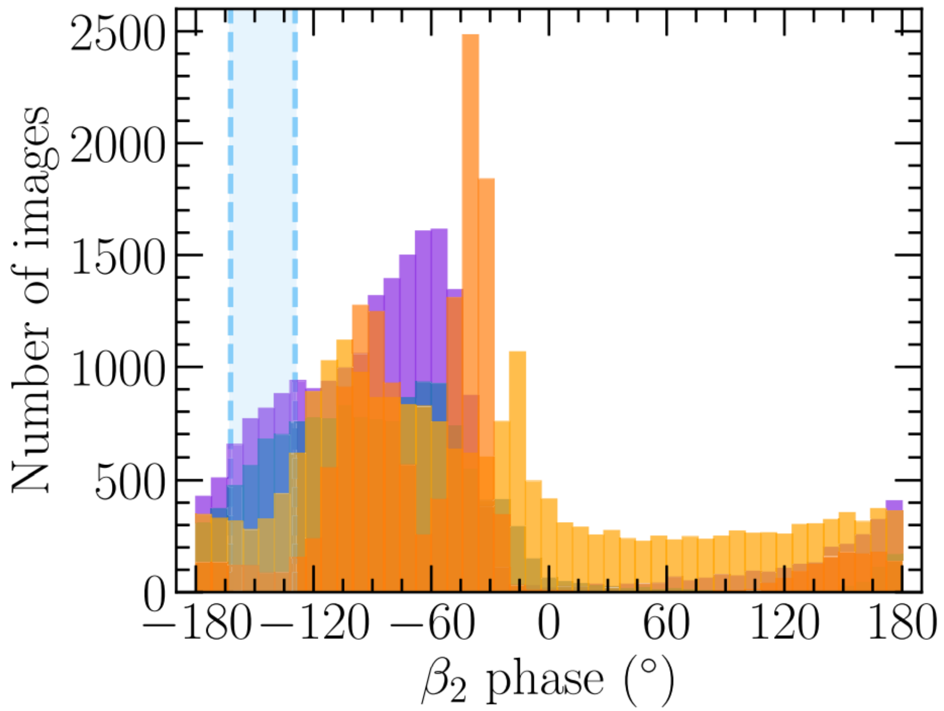




Credit: EHT 2021 Paper VIII, 2023 Paper IX (**Chael**, paper coordinator)

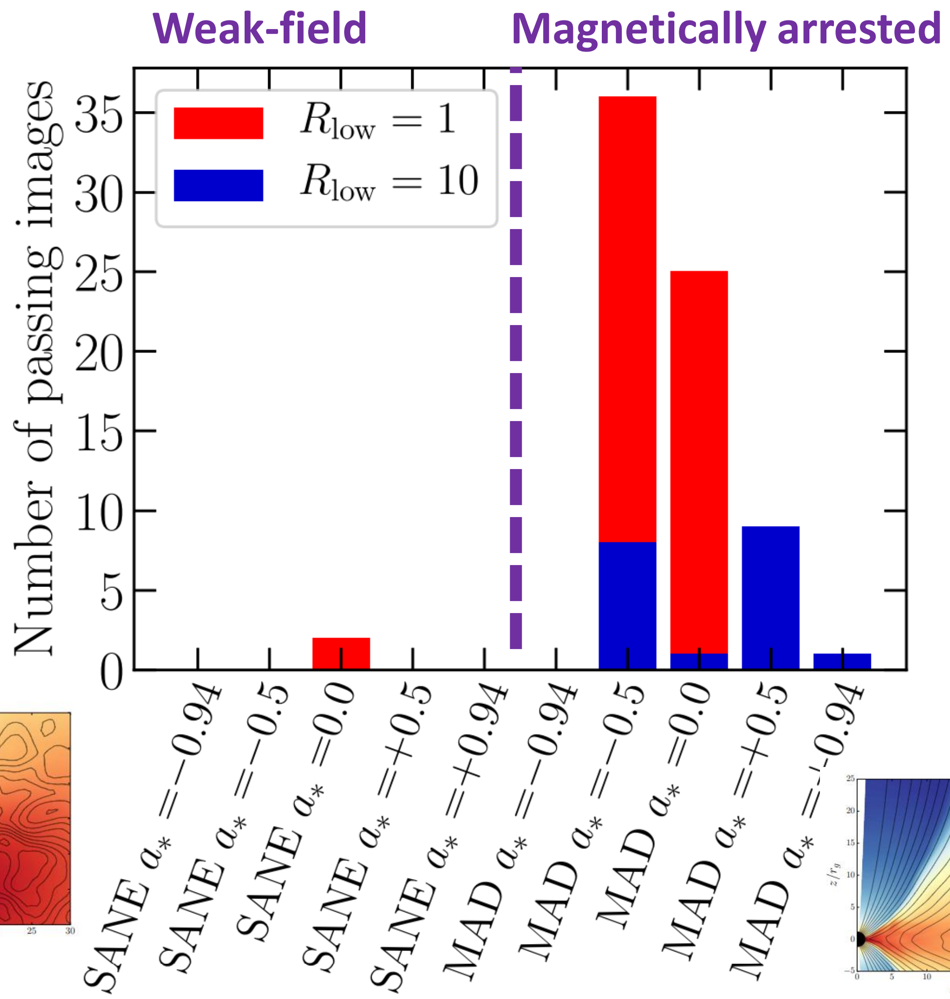
Scoring simulations with polarization: Results

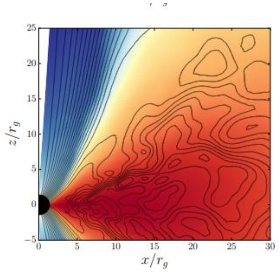
- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**

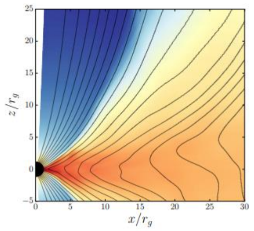
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

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

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



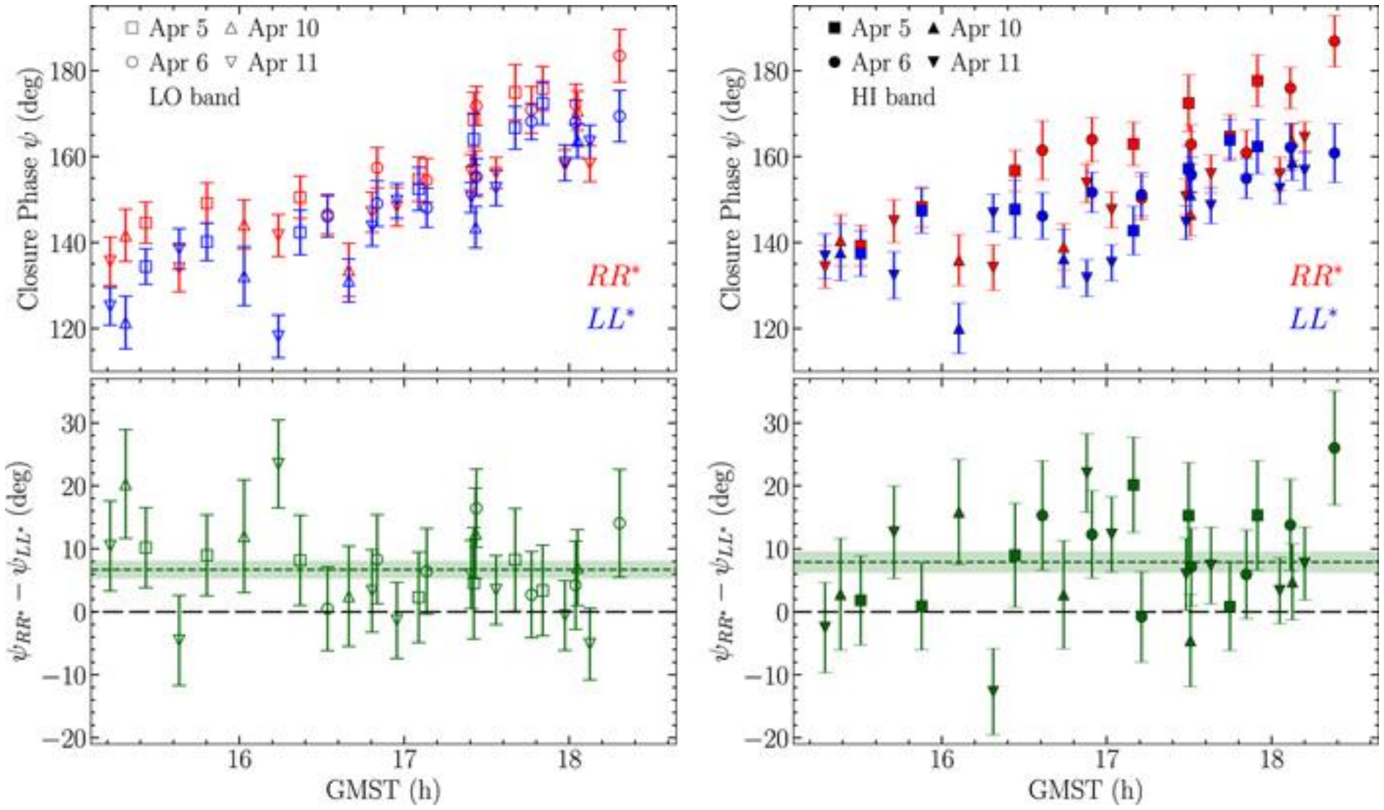




Credit: EHT 2021 Paper VIII, 2023 Paper IX (**Chael**, paper coordinator), Riordan+2017

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

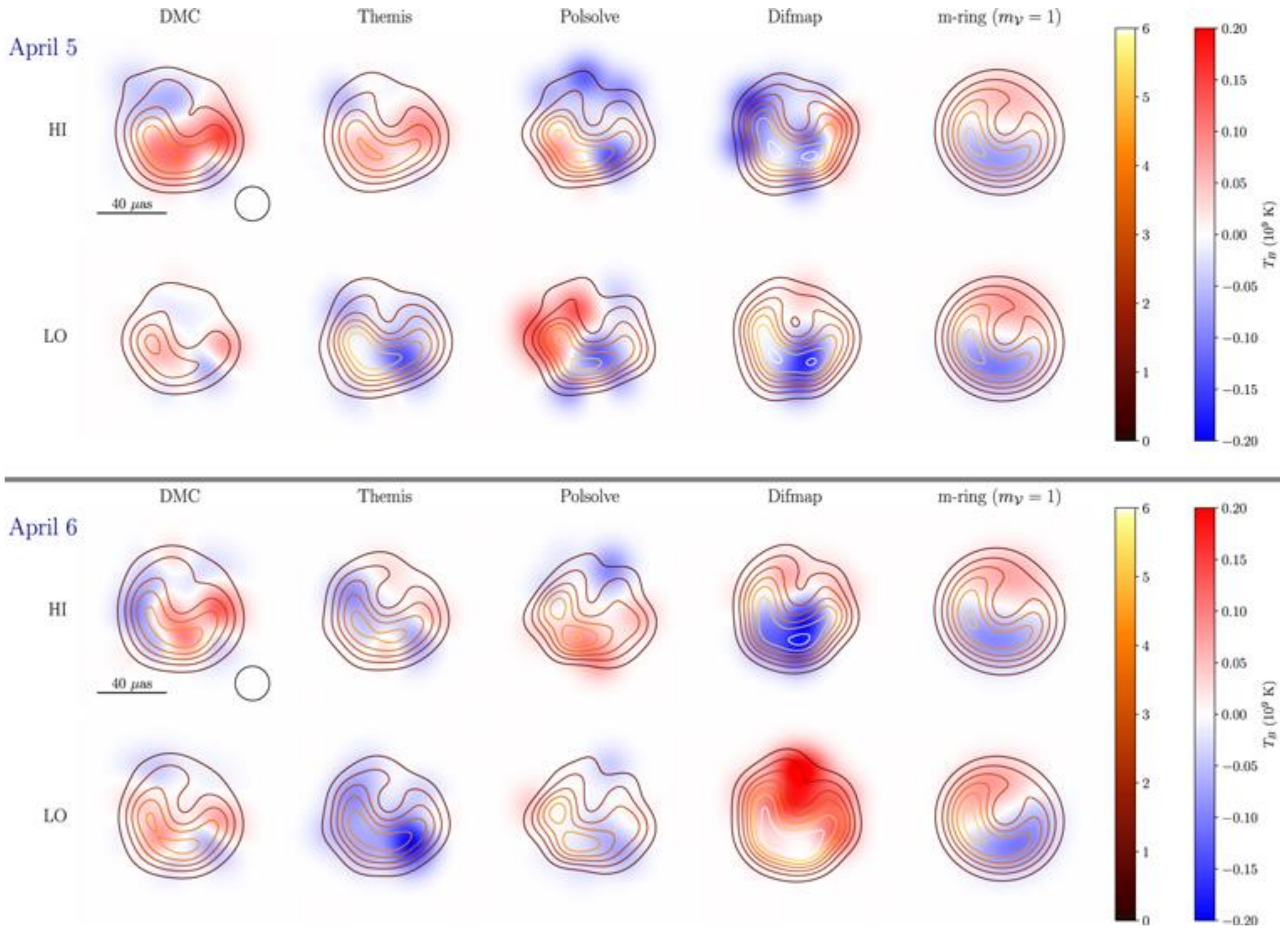
- We detect an **offset** between closure phases in the RR and LL polarization data.
- This signal is immune to atmospheric phase corruption and relative gain offsets G_R / G_L



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

Horizon-Scale circular polarization *images* are **not** robustly recovered

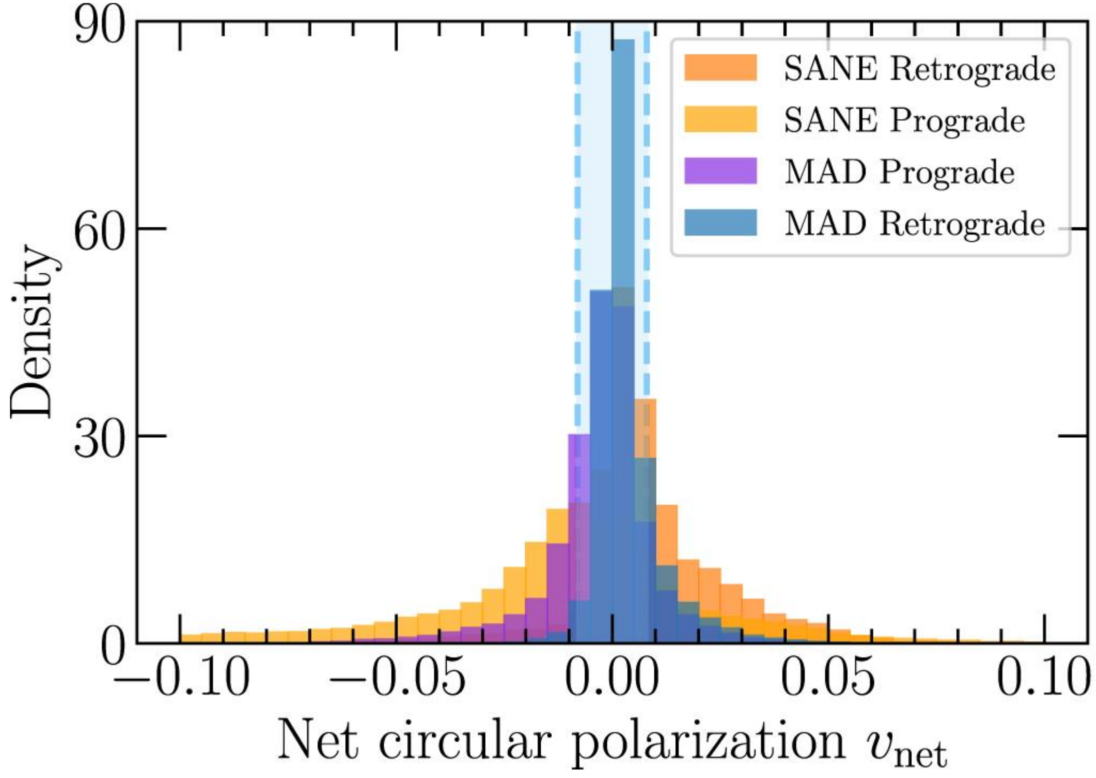
- Circular polarization in M87* is **10x weaker** than linear
- Different methods do not show consistent circular polarization images
  - between days
  - between frequency bands
- We place an upper limit:
  $\langle |v| \rangle$ **< 3.7%**
- **Future observations will be more sensitive!**

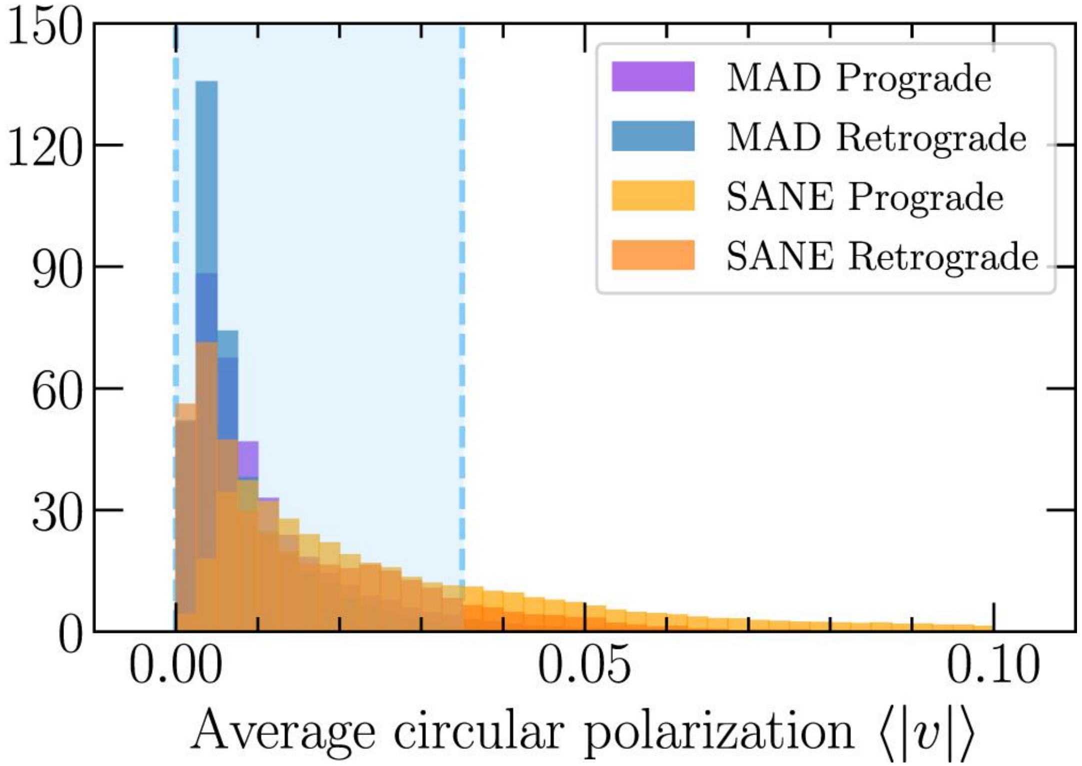


$$\langle |v| \rangle = \frac{\int |\mathcal{V}/\mathcal{I}|\, \mathcal{I}\, dA}{\int \mathcal{I}\, dA}$$

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

GRMHD simulations naturally produce low circular polarization



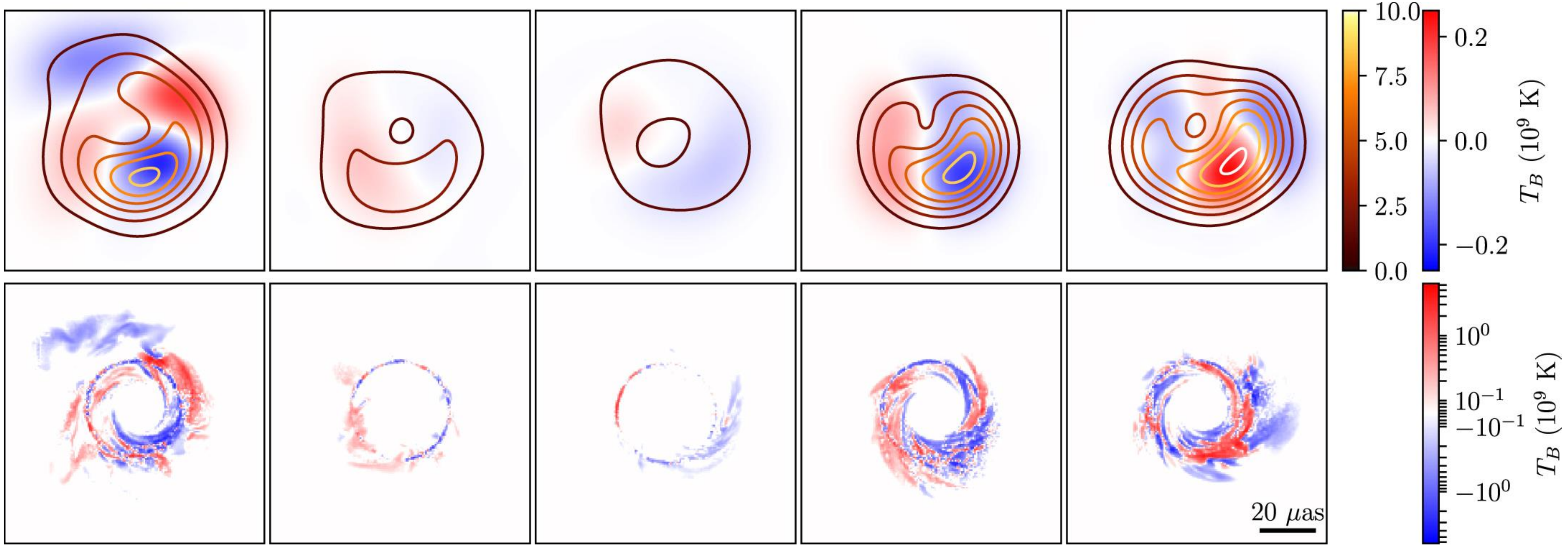


$$v_{\rm net} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

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

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

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

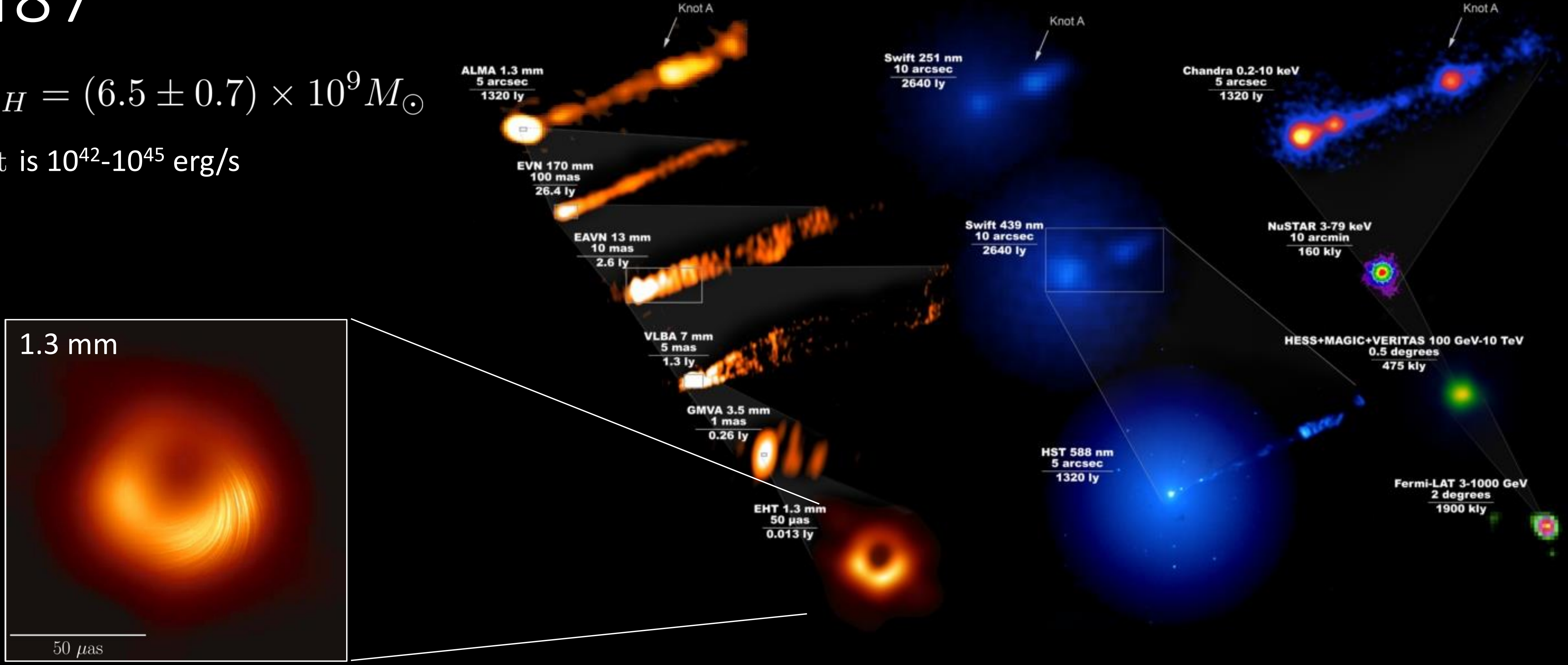
Can we connect the polarized image of M87* on horizon scales to energy flow & jet launching?

Chael, Lupsasca, Wong & Quataert 2023
2307.06372

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**?

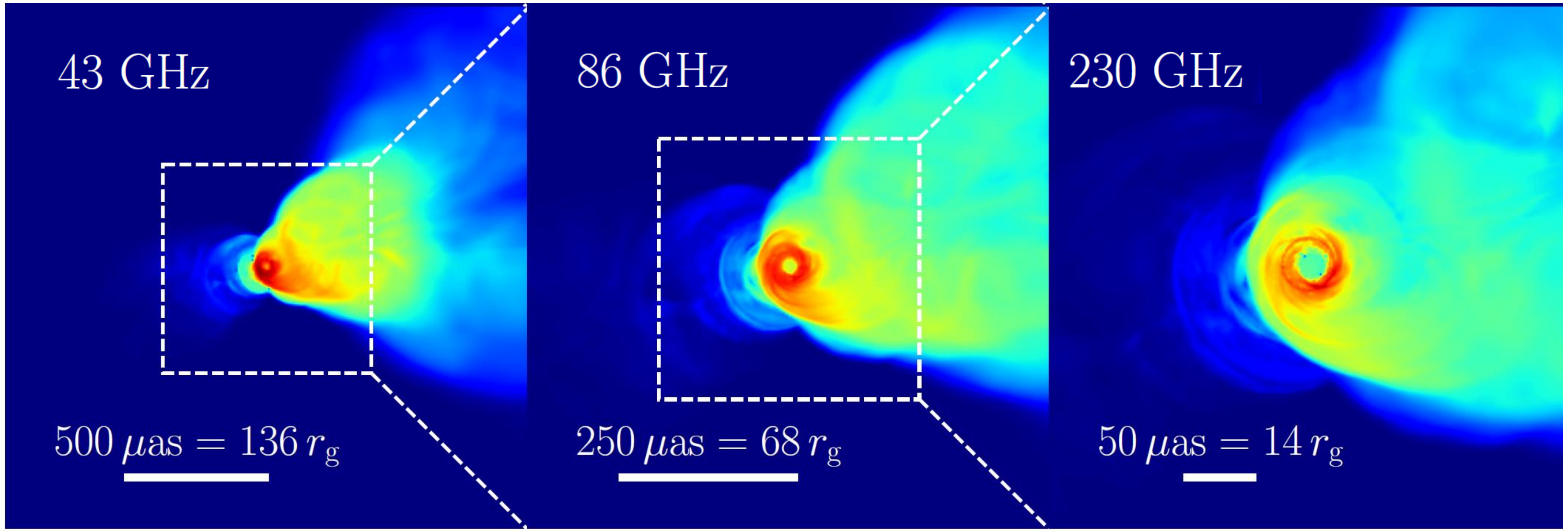
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

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)

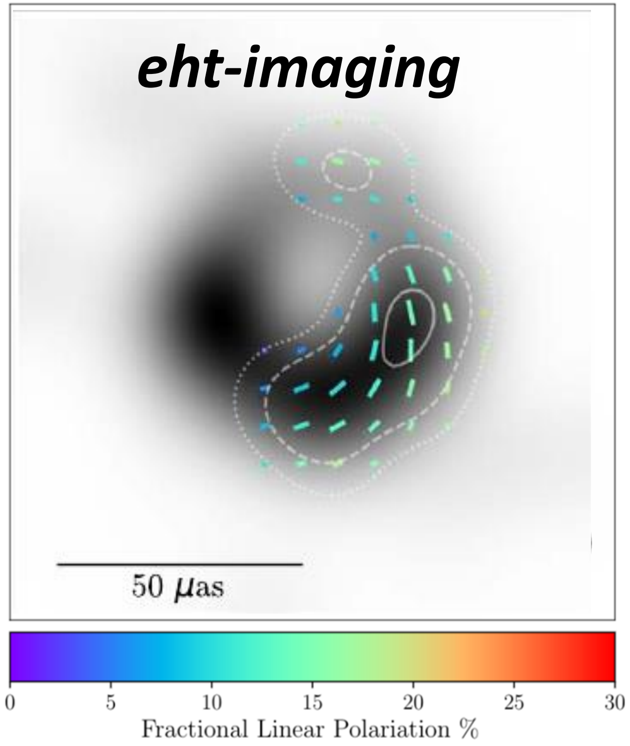
- **Radiative** simulations (Chael+ 2019) naturally produce:
  - A jet power in measured range
  - observed wide opening angle
  - observed core-shift

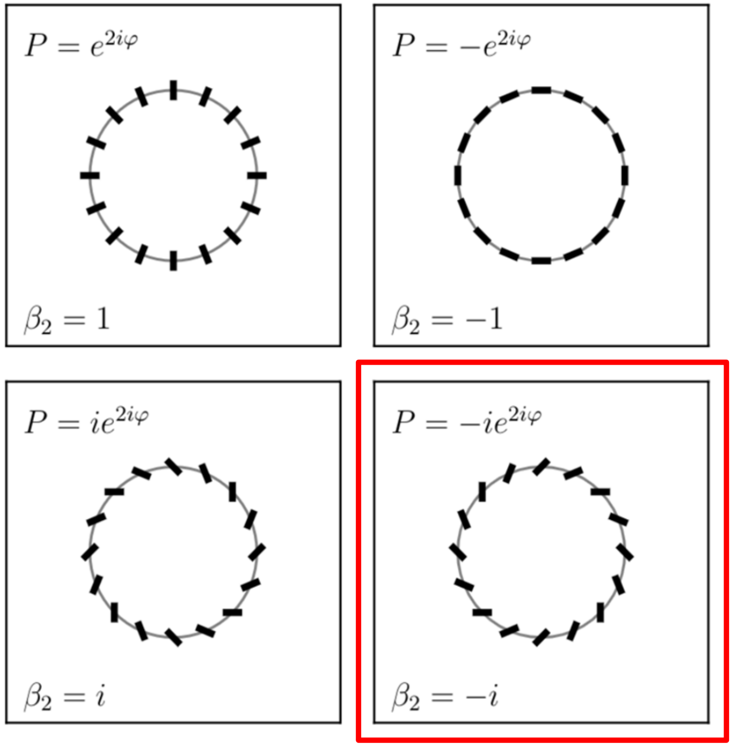
- Can we be **sure?** What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?



Chael+ 2019

Polarized Images of M87* and horizon-scale energy flow

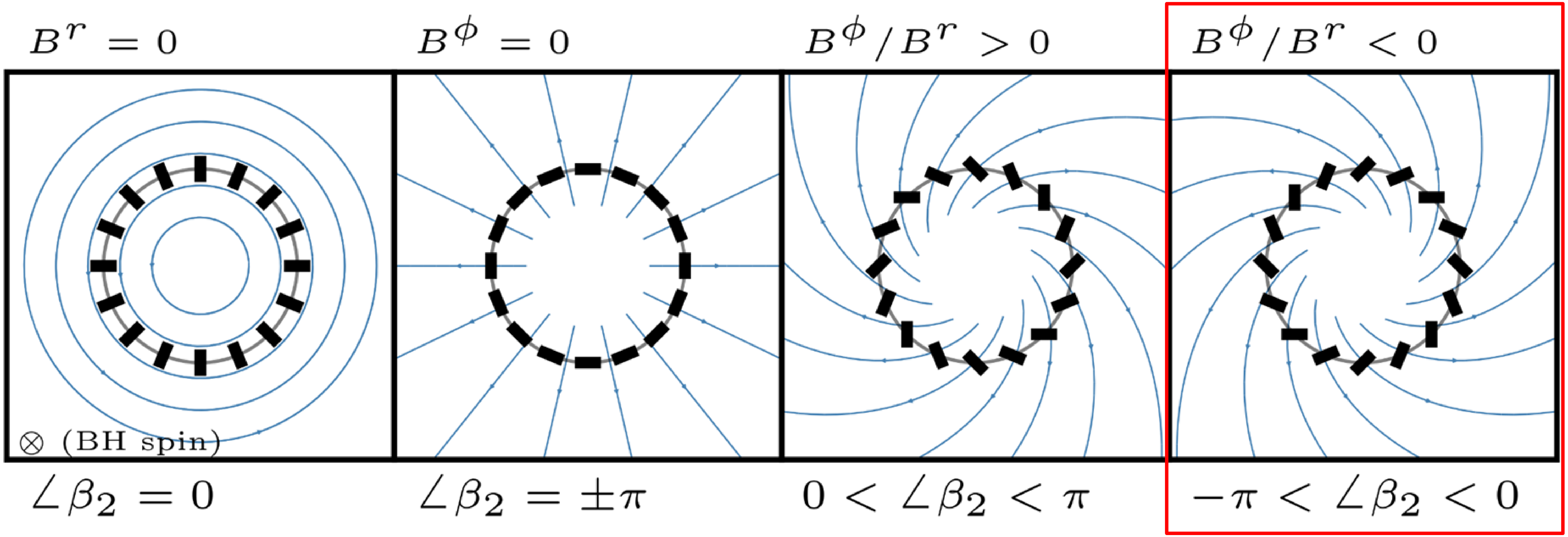




- The polarization spiral's 2nd Fourier mode (**β_2**: Palumbo+ 2020) is the **most constraining** feature for simulation scoring
- Can we interpret **β_2 physically**?

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

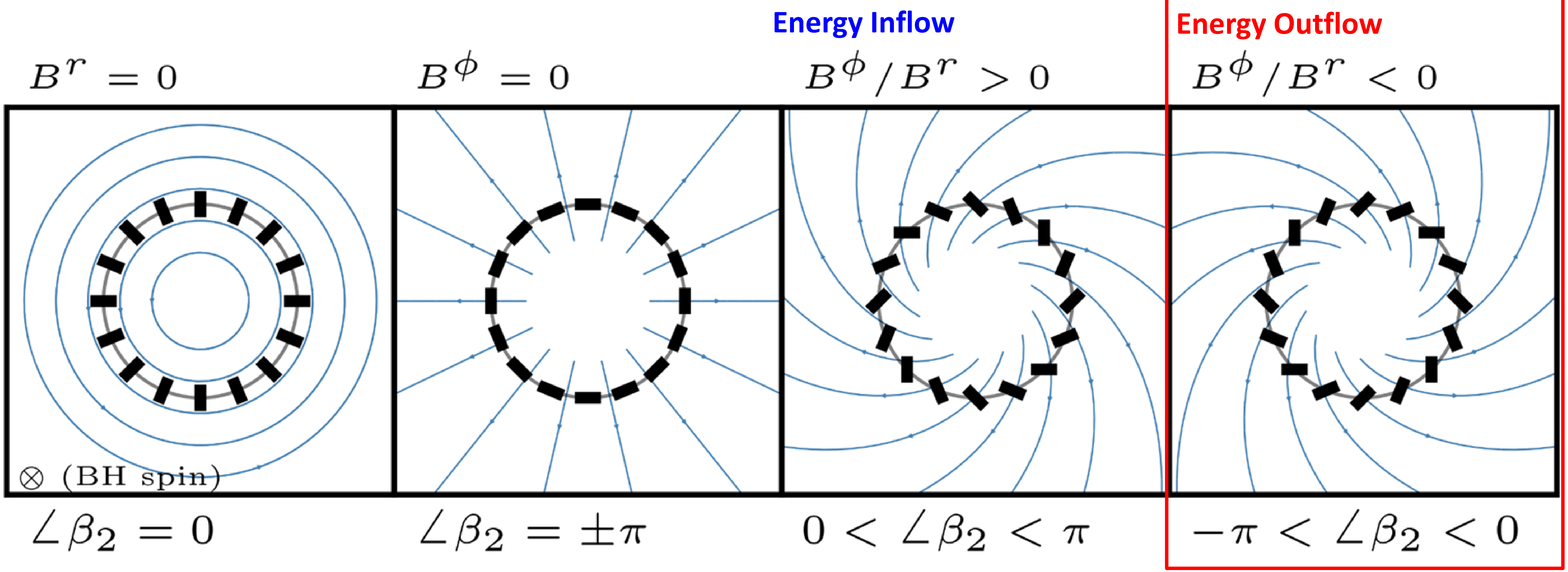
Cartoon model: arg(β_2) is connected to the pitch angle B^ϕ/B^r



- 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

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



Radial Poynting flux in Boyer-Lindquist coordinates:

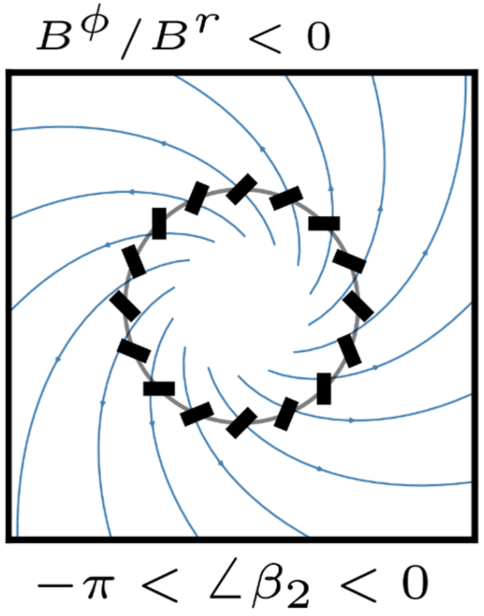
$$\mathcal{J}^r_{\mathcal{E}} = -T^r_{\ t\ \mathrm{EM}} = -B^r B^\phi\, \Omega_F\, \Delta \sin^2\theta$$

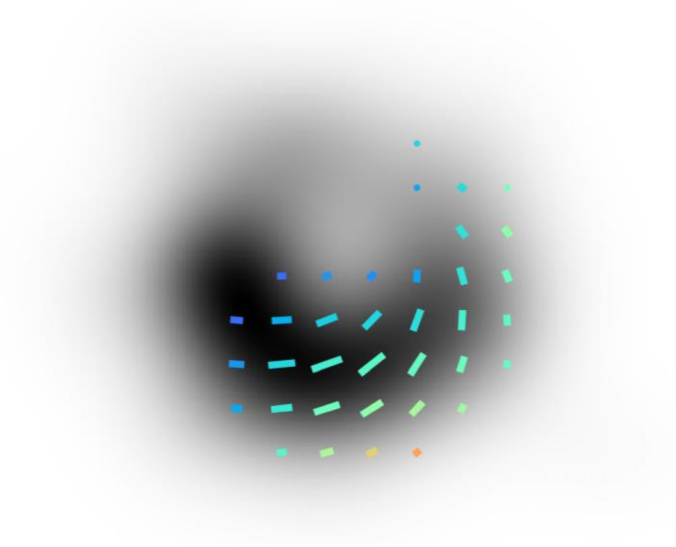
fieldline angular speed

Chael+ 2023b

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

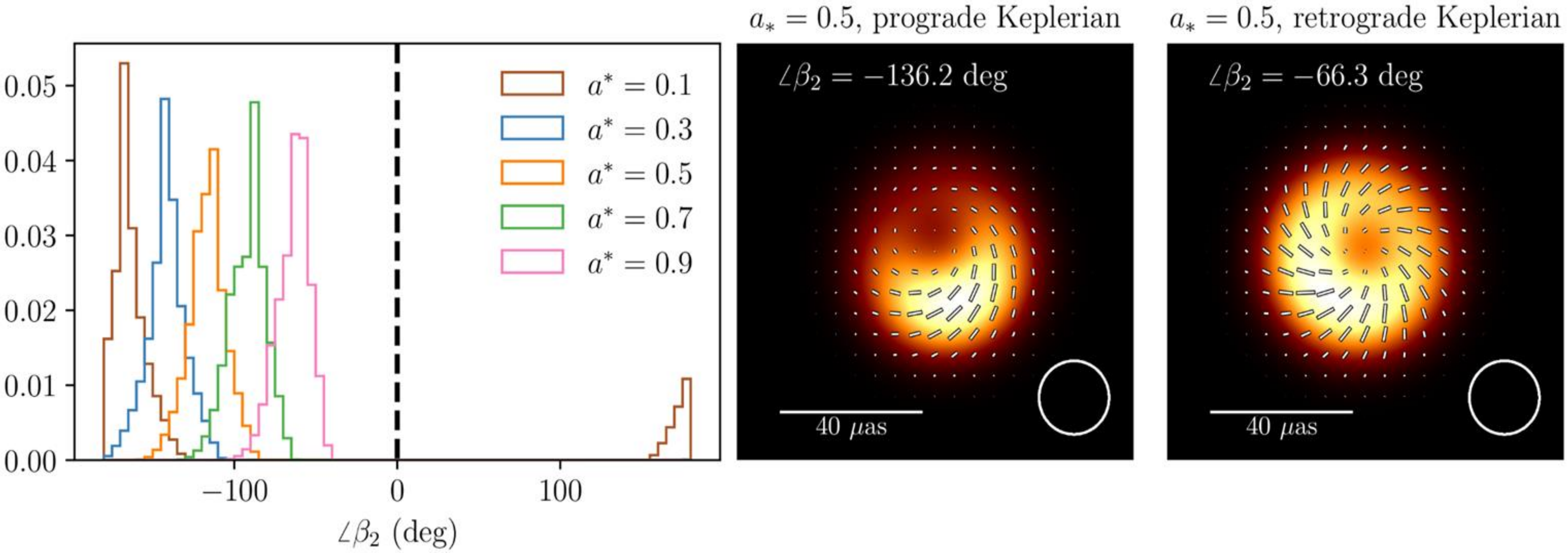
- The sign of $\arg(\beta_2)$ is directly connected to the direction of Poynting flux, assuming we know the sign of Ω
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy outflow in M87***
- This inference requires we assume fieldlines **co-rotate** with the emitting plasma (the angular velocity vector is into the sky)
- Does this simple argument hold up in **more complicated models** of M87*?





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

arg(β_2) in semi-analytic models of M87*

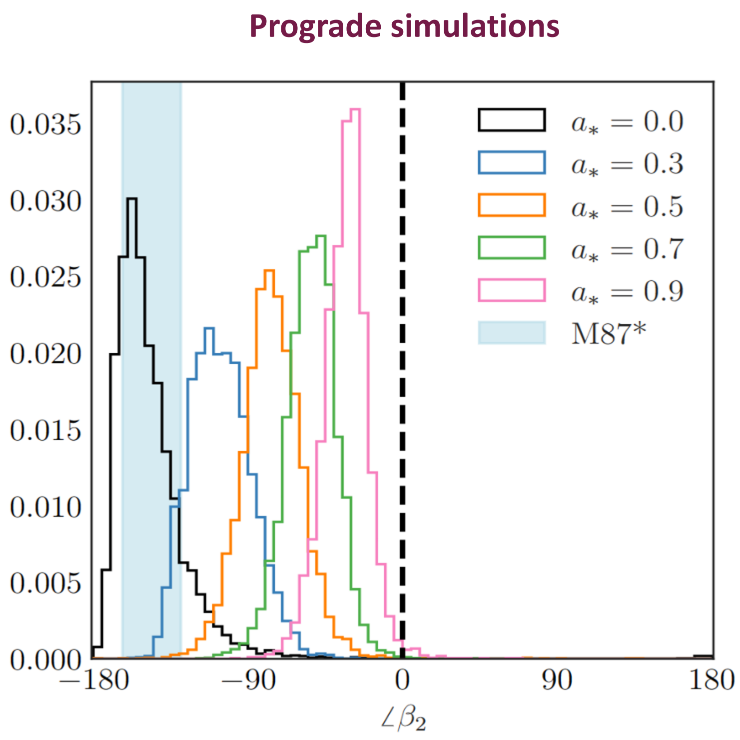


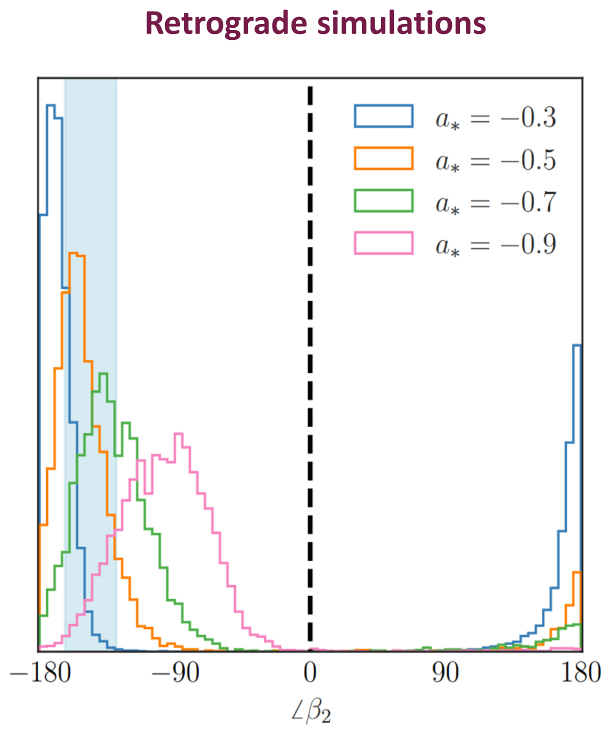
- We fix magnetic fields to the BZ monopole solution (with energy outflow)
- The black hole spin direction is fixed into the sky
- We explore many models for the velocity of the emitting fluid

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 the BZ monopole model





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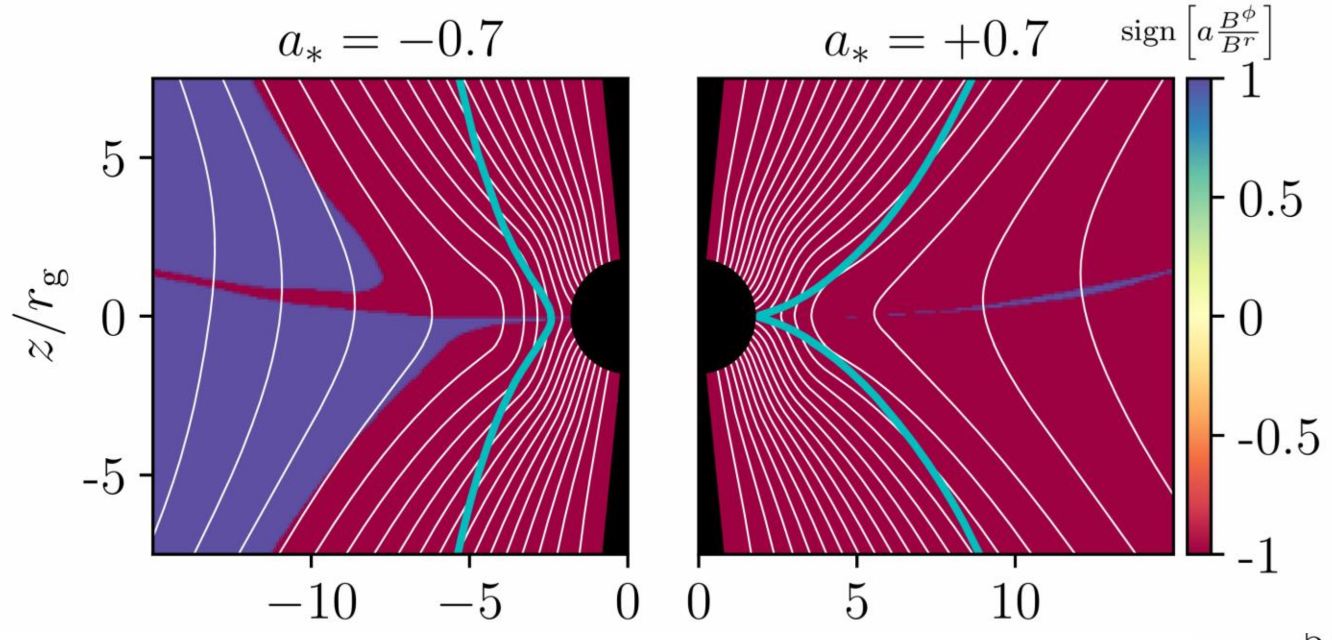
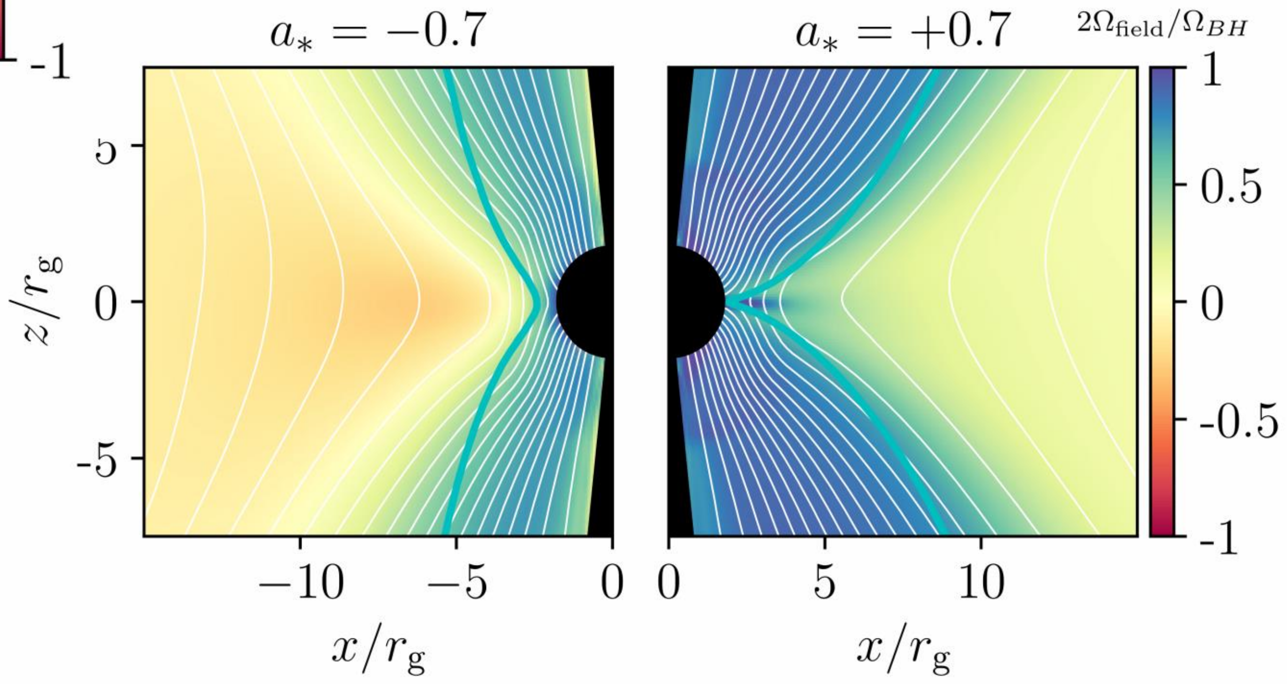
In GRMHD, energy-extracting fieldlines set arg(β_2)



Sign of magnetic field pitch angle

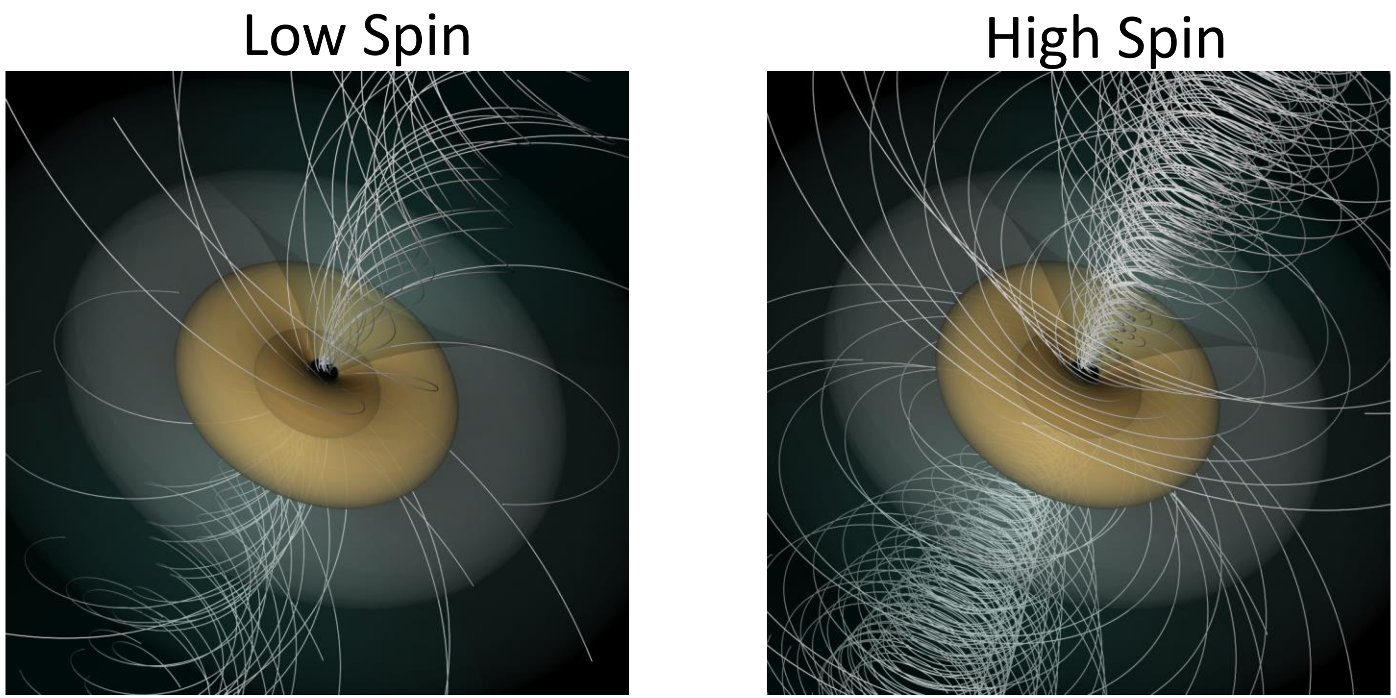
Field-line angular speed

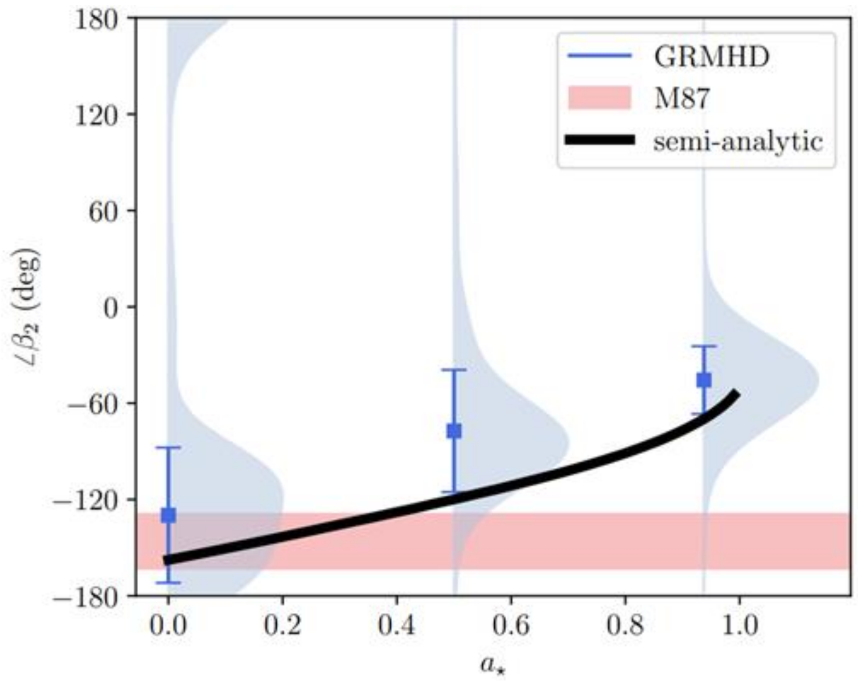


Even in **retrograde** simulations, field-lines in the 230 GHz emission region usually co-rotate with the black hole and have a negative B^ϕ / B^r

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

Polarized images are **spin dependent**

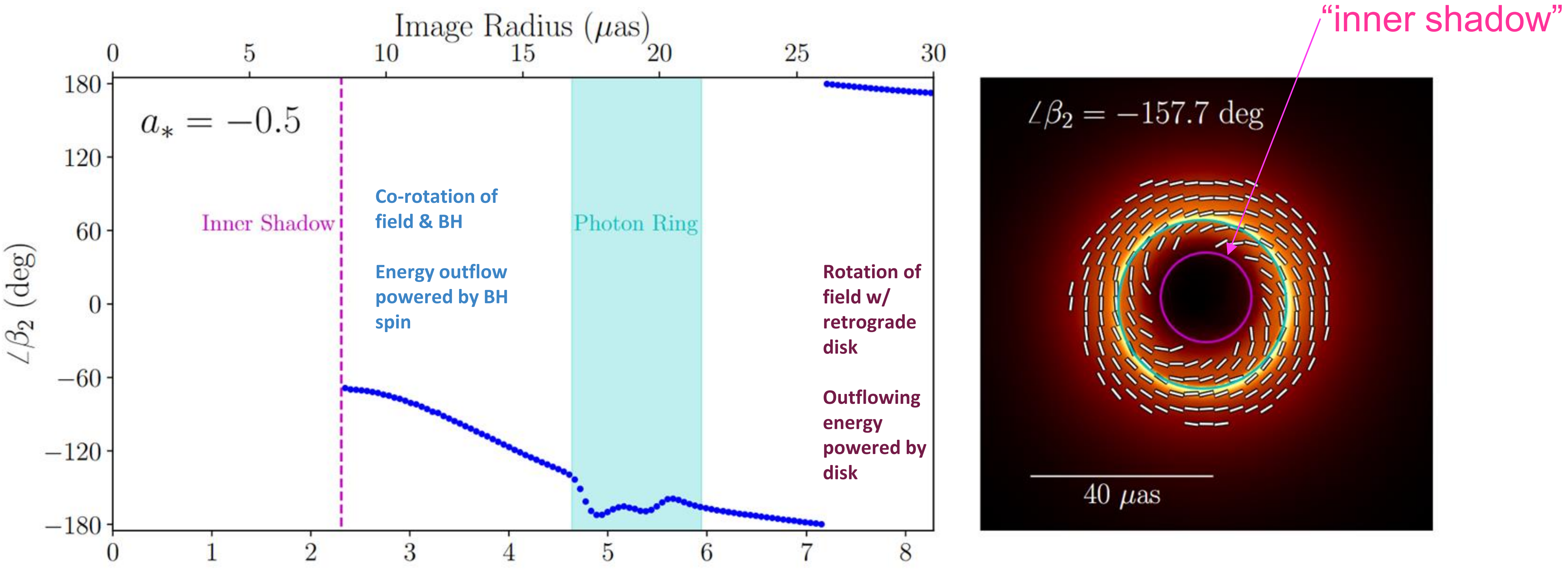




- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the Poynting flux (BZ jet power)
  - makes the observed polarization pattern more radial

Image credit: George Wong

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

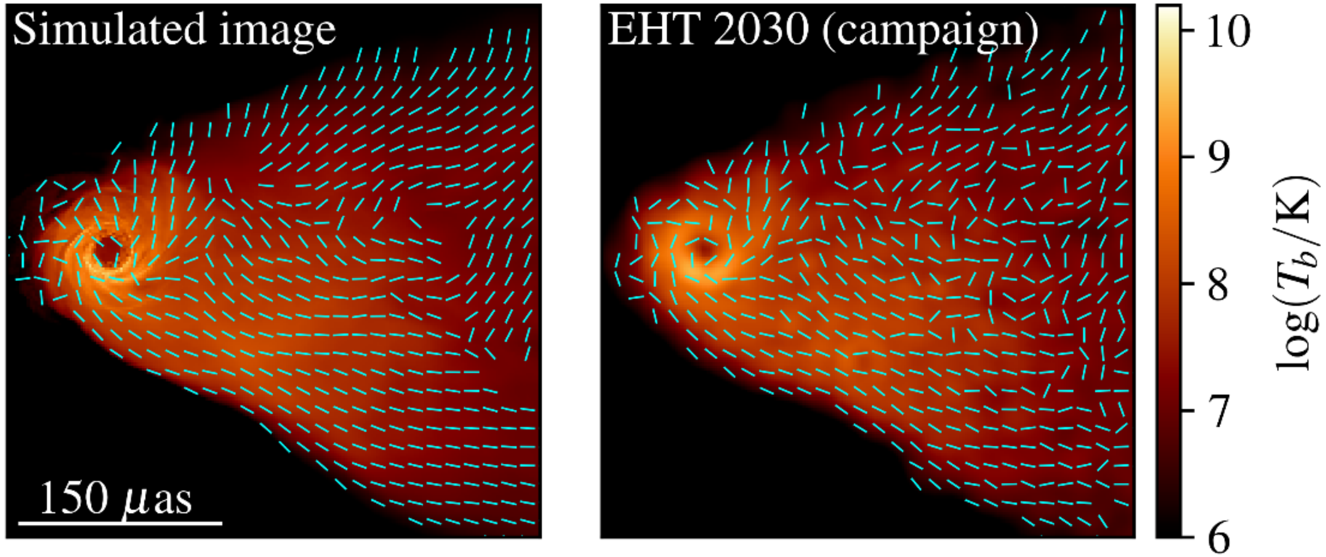


- Measuring polarization as a function of radius **probes energy flow at different scales**

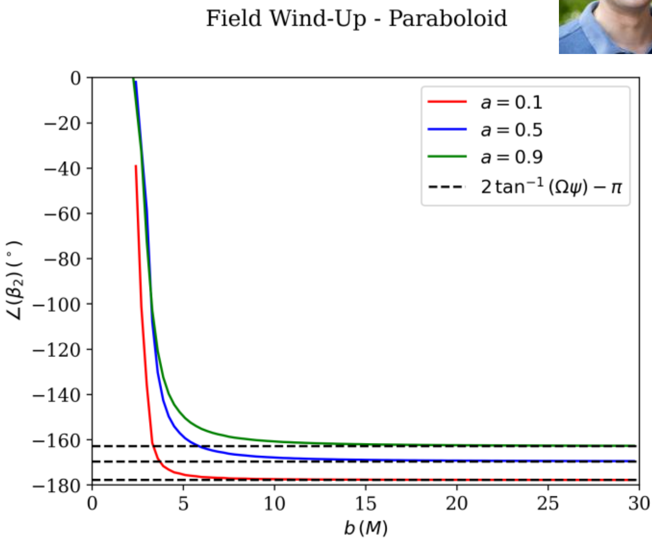
- Both simple BZ models and GRMHD simulations make a strong prediction
    - $\arg(\beta_2)$ evolves rapidly close to the **inner shadow** as fields are **wound up by spin**

Chael+ 2023b, (also Ricarte+ 2022)

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



Ongoing work by 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

How can we better simulate the black hole-jet connection?

Chael in prep

Difficulties with GRMHD Simulations at high magnetization

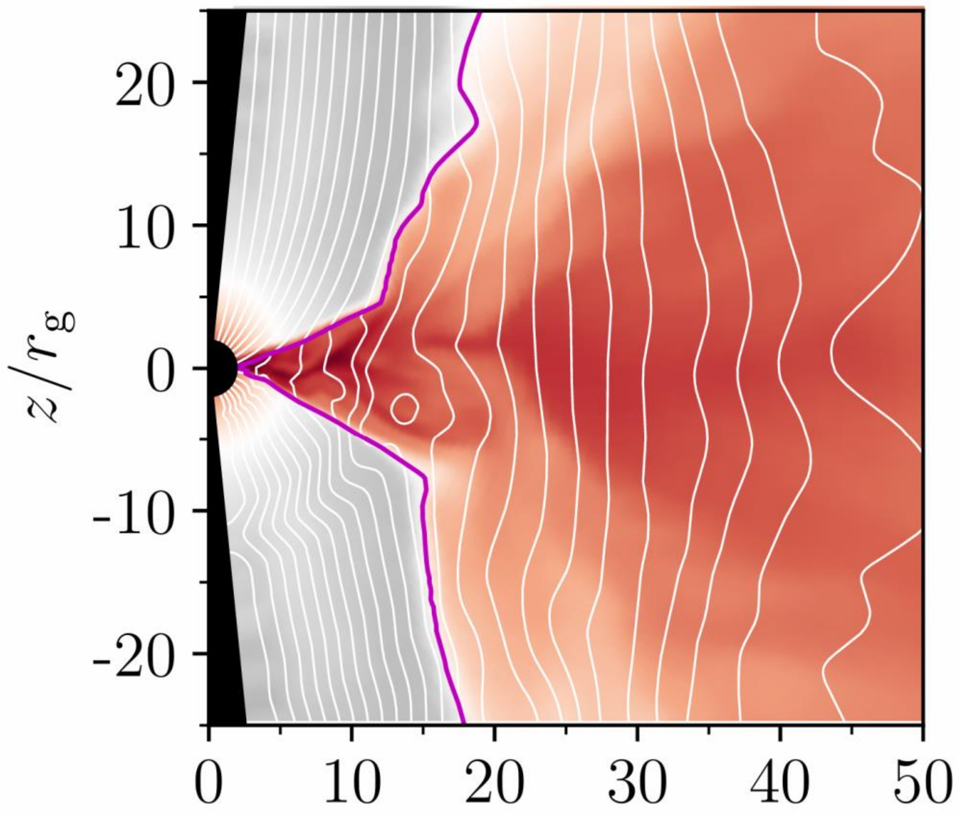
- GRMHD codes conserve the total stress energy tensor, composed of matter and electromagnetic parts:

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

- In the limit $\sigma \gg 1$, numerical codes struggle to recover the fluid quantities from the conserved stress-energy and the simulation can crash

- GRMHD codes introduce density ‘floors’ for stability

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



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

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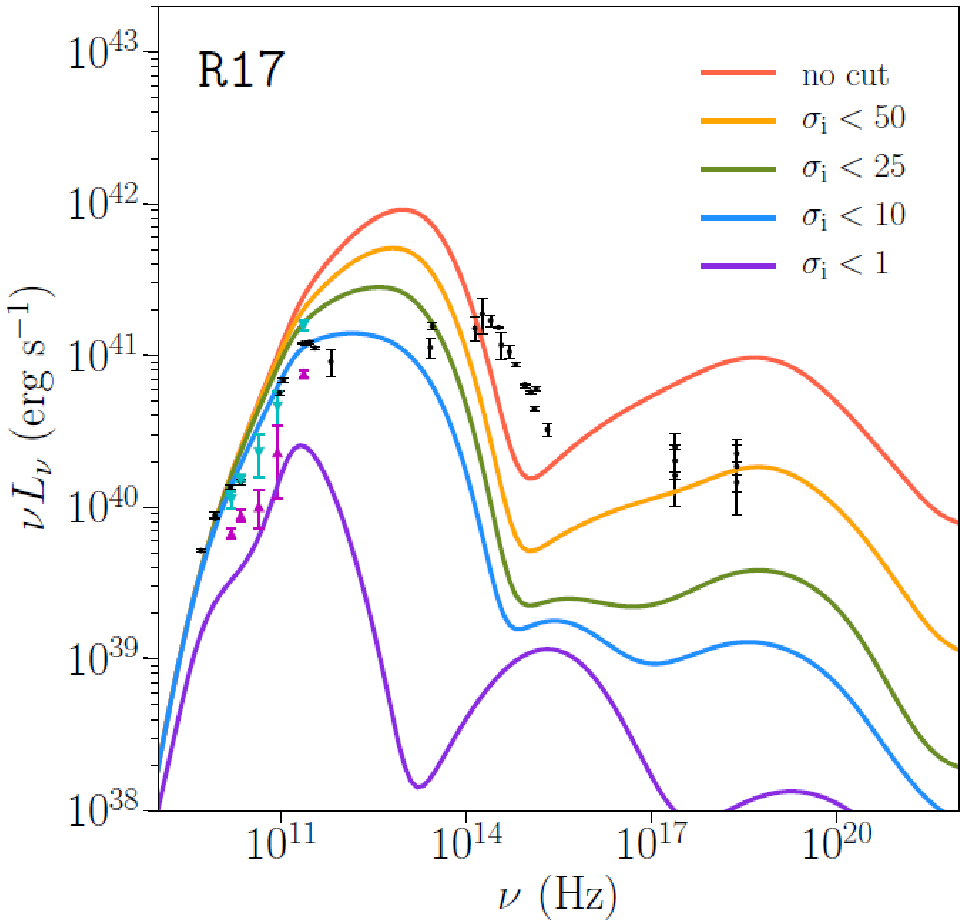
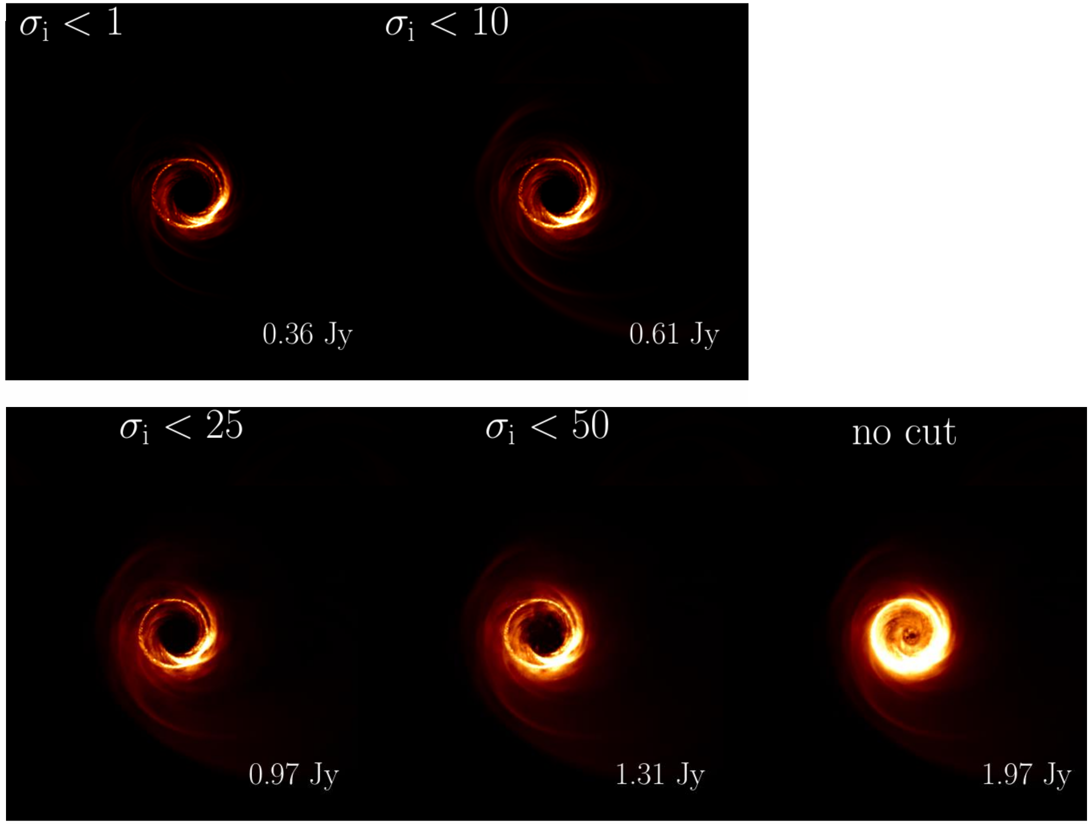
Choosing "σ cut" is a major uncertainty in simulated images





Chael+ 2019

Hybrid GRMHD+Force Free Simulations

- When $\sigma \gg 1$, GRMHD dynamics may approximated by the force-free equations:

$$\nabla_\mu T^{\mu\nu}_{\rm EM} = J_\mu F^{\mu\nu} = 0.$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

- The evolution of the field-parallel velocity, fluid density, and fluid energy density are **decoupled** from the evolution of the EM field in the force-free region

- **Goal**: Can modify a GRMHD code to:
  - Transition to force-free evolution in high-magnetization region?
  - Remove the requirement for density floors?
  - Without major code modifications?

Chael+ in prep

A new approach for hybrid GRMHD+FF

- **One set of primitives** $\rho,\ u_{\rm int},\ \tilde{u}^i,\ B^i$ everywhere

- We evolve **two sets of conserved quantities** derived from the same primitives:

$$\underbrace{\rho u^0, B^i}_{\text{Used for both}} \qquad \underbrace{T^0_{0\ \rm tot}, T^0_{i\ \rm tot}}_{\text{Used for GRMHD}} \qquad \underbrace{T^0_{i\ \rm EM}, b^0, (\rho s)u^0}_{\text{Used for force-free}}$$

- Below $\sigma < \sigma_{\rm trans}$, invert conserved->primitive using GRMHD as normal

- Above $\sigma > \sigma_{\rm trans}$, invert conserved->primitive using a **decoupled FFE scheme**

Chael+ in prep

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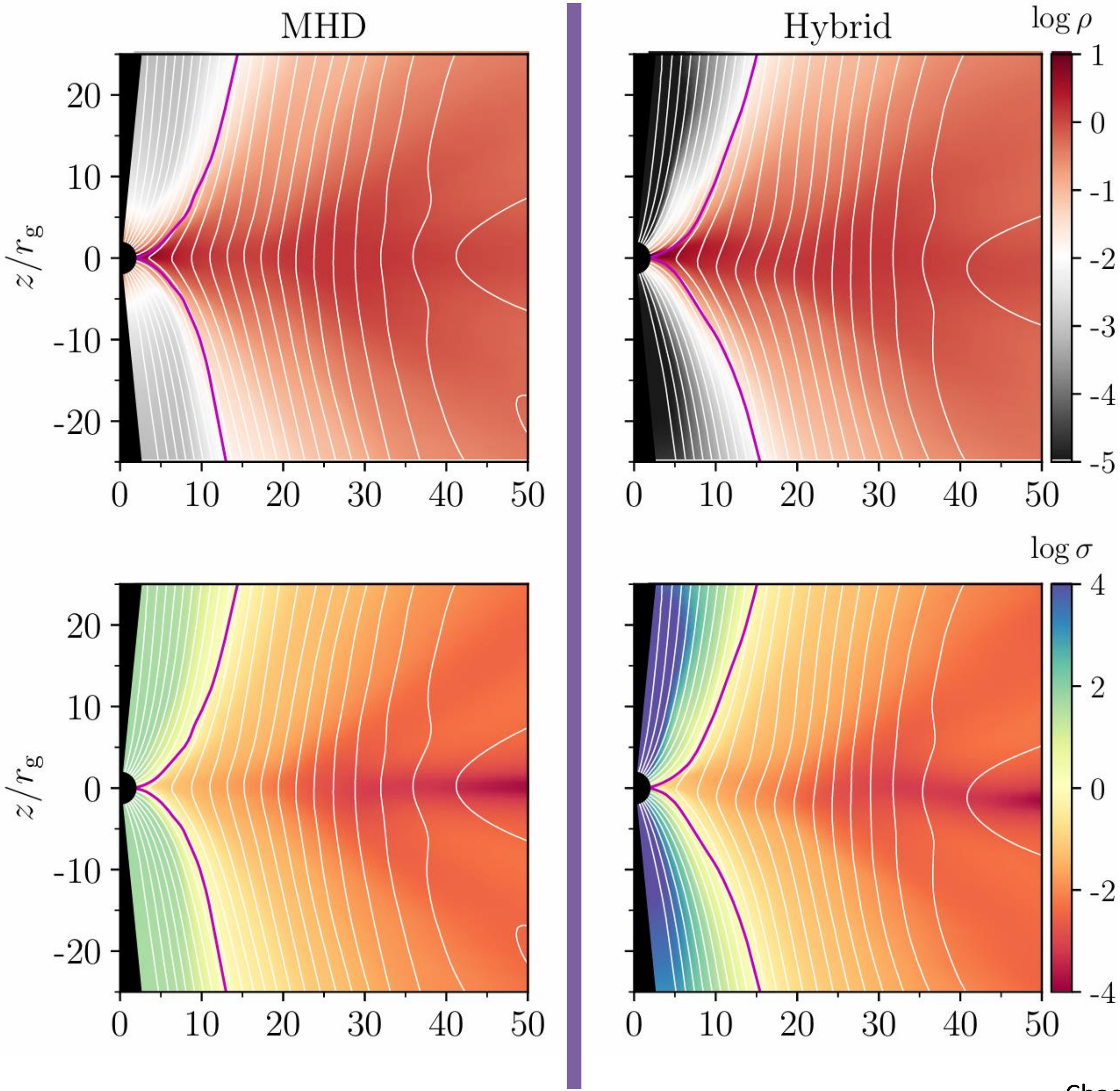
- Below $\sigma < \sigma_{\rm trans}$, invert conserved->primitive using GRMHD as normal

- Above $\sigma > \sigma_{\rm trans}$, invert conserved->primitive using a **decoupled FFE scheme**
  - based on McKinney 2006 finite volume GRFE formulation
  - Field-parallel velocity is evolved in the **cold approximation**
  - Gas energy density is evolved **adiabatically**

Chael+ in prep

Comparing standard GRMHD and Hybrid GRMHD+FF

- Spin 0.5 MAD simulations
- 160 x 128 x 96 resolution, run to t=10,000 *M*
- Run with standard GRMHD and GRMHD+FF modes
    - GRMHD: **sigma ceiling at 50**
    - Hybrid: **sigma transition at 50**



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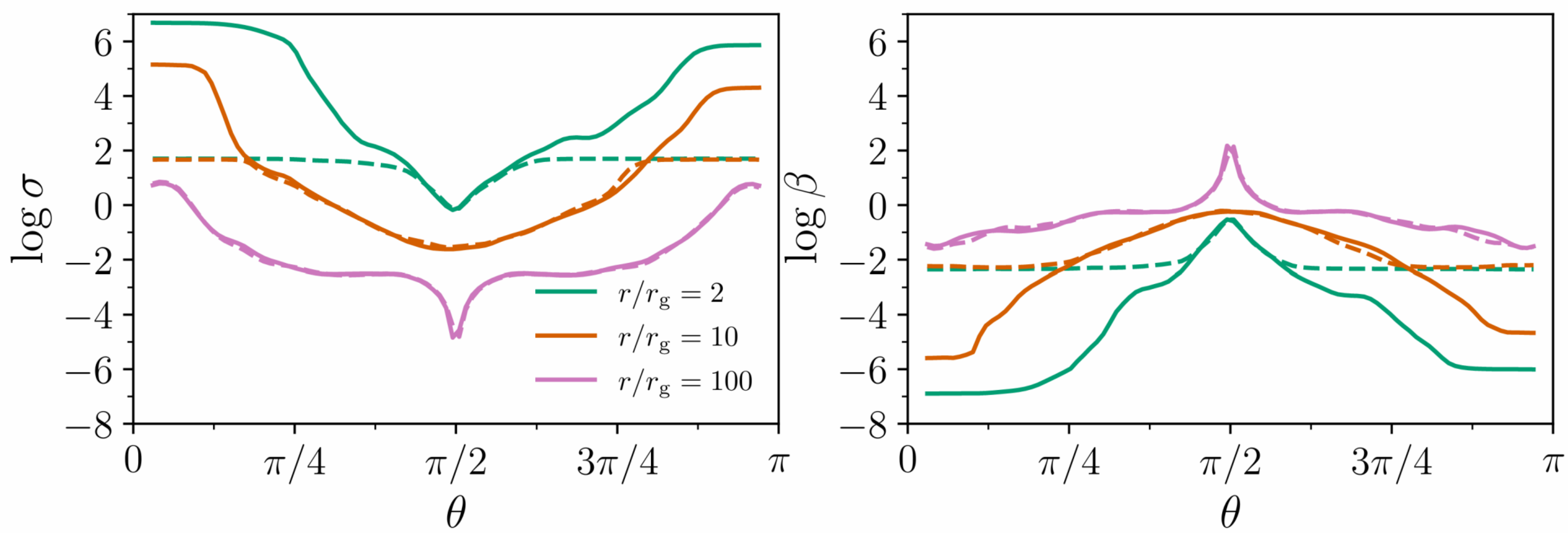
Comparing standard GRMHD and Hybrid GRMHD+FF



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

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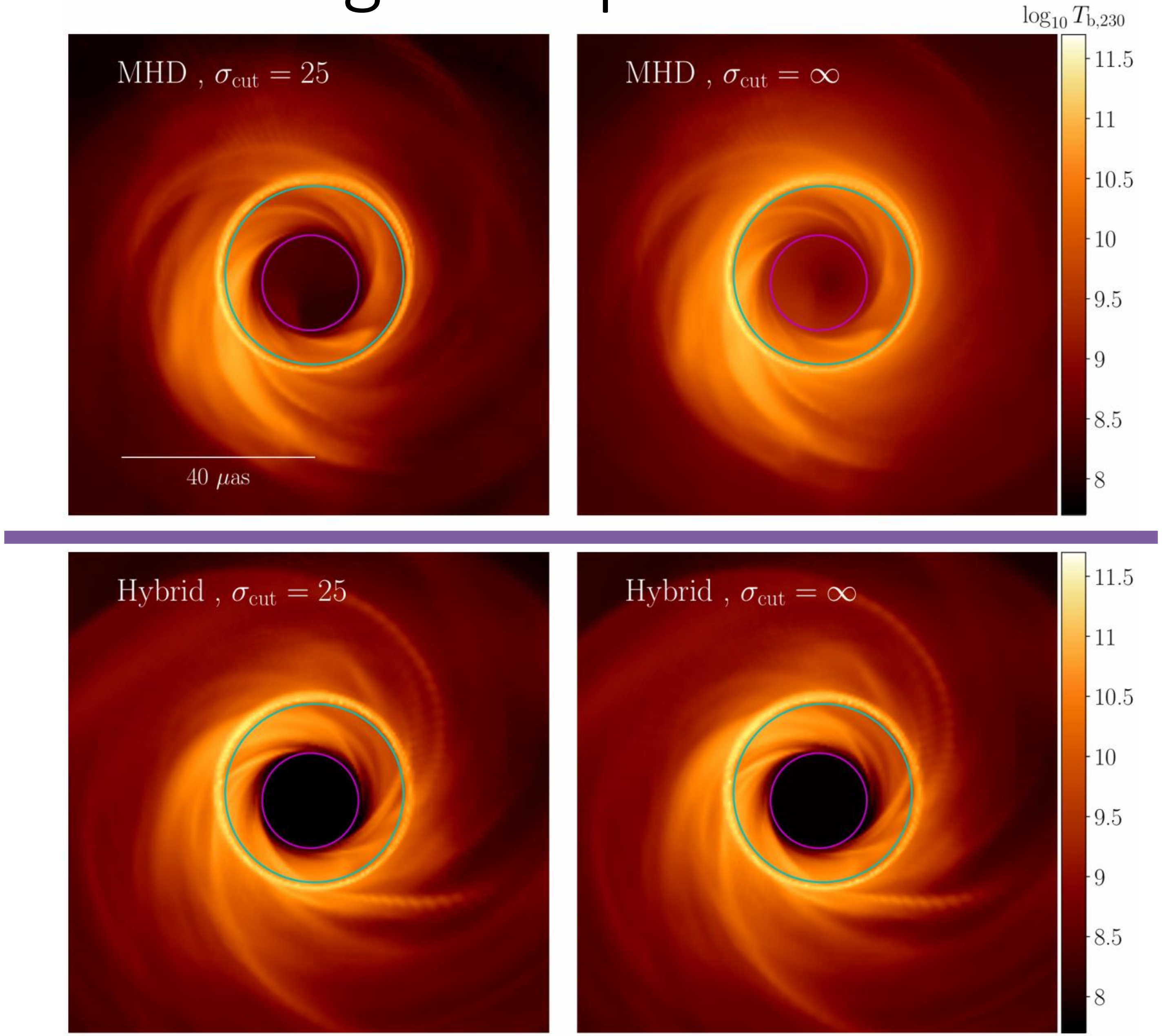
230 GHz Image comparison

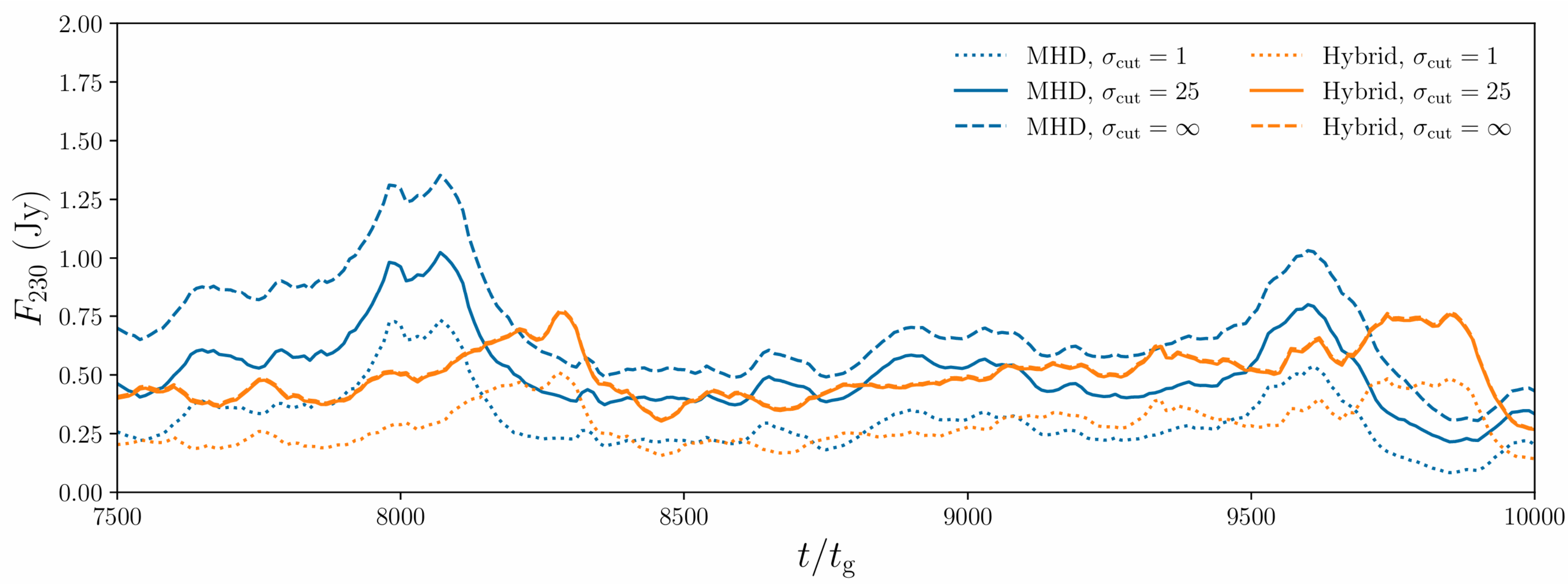


In standard GRMHD, foreground jet emission fills in the shadow region unless we have a cut on σ in radiative transfer

Hybrid simulation images look the same with and without a σ cut

Chael+ in prep

230 GHz lightcurve comparison



- Our hybrid method suppresses significant emission from high sigma region
  - **But 1<σ<25 emission is important!!**
- Is the full SED more stable to sigma cut as well? Does this method work in simulations with **radiation**?

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Takeaways:

- EHT observations of M87* in linear and circular polarization are our most constraining probes of near-horizon magnetic fields and extragalactic jet launching

- The polarization data singles out magnetically arrested GRMHD models:
  - The magnetic field is dynamically important at the event horizon in M87*

- 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 need to look at polarization on multiple scales

- New simulation techniques like hybrid GMRHD+GRFFE can help us better understand the black-hole jet connection and the power of EHT observations to measure spin and test BZ