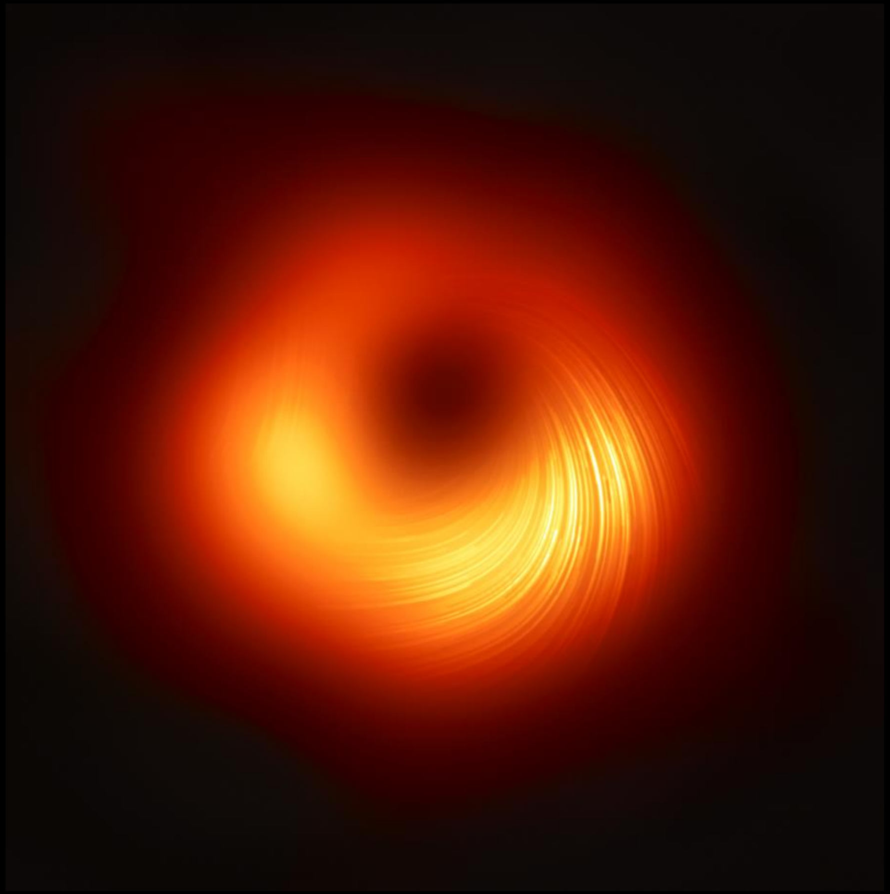
M87* in Polarized Light



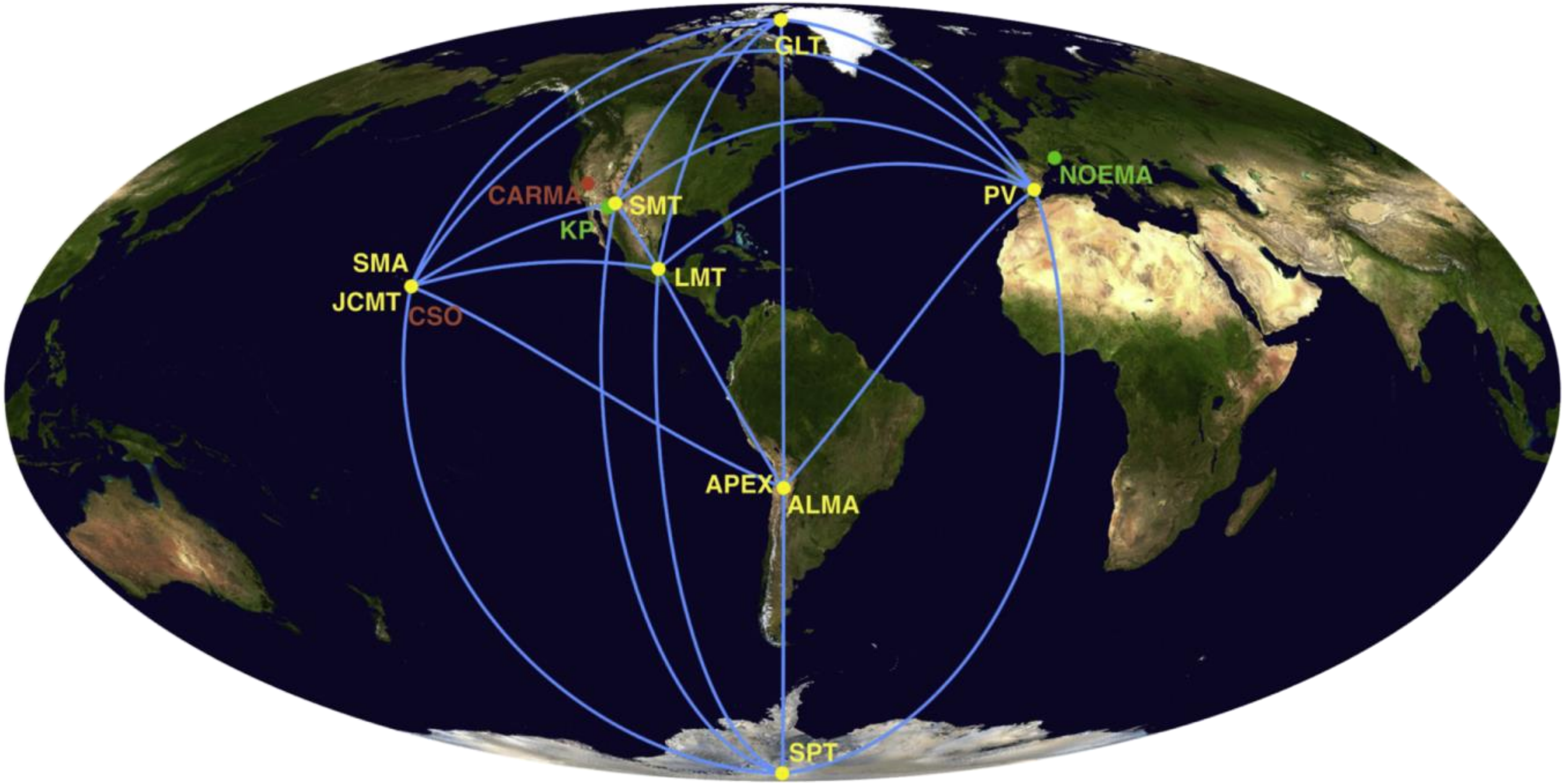
Andrew Chael
Princeton

November 15, 2023

Princeton gravity Initiative

Event Horizon Telescope

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.

Image credit: E. Traianou, MPIfR

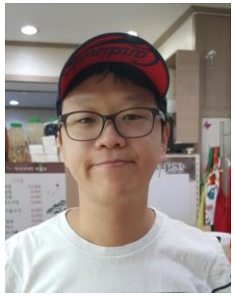
EHTC Paper VII,VIII,IX writing teams

Monika Mościbrodzka

Iván Martí-Vidal

Sara Issaoun

Jongho Park



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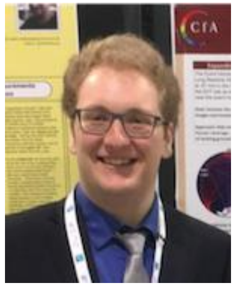

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Avery Broderick

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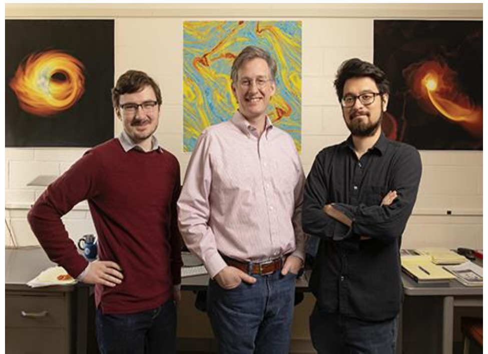
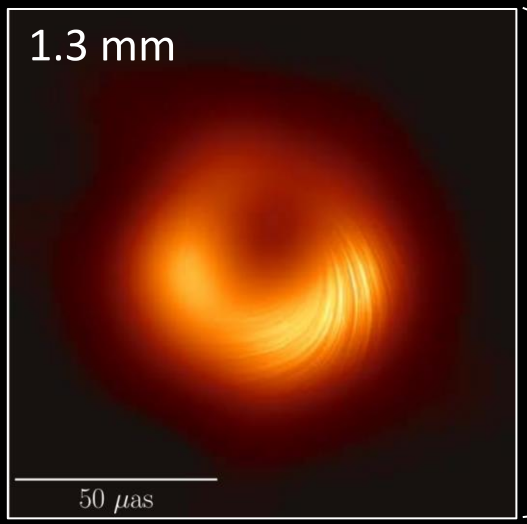
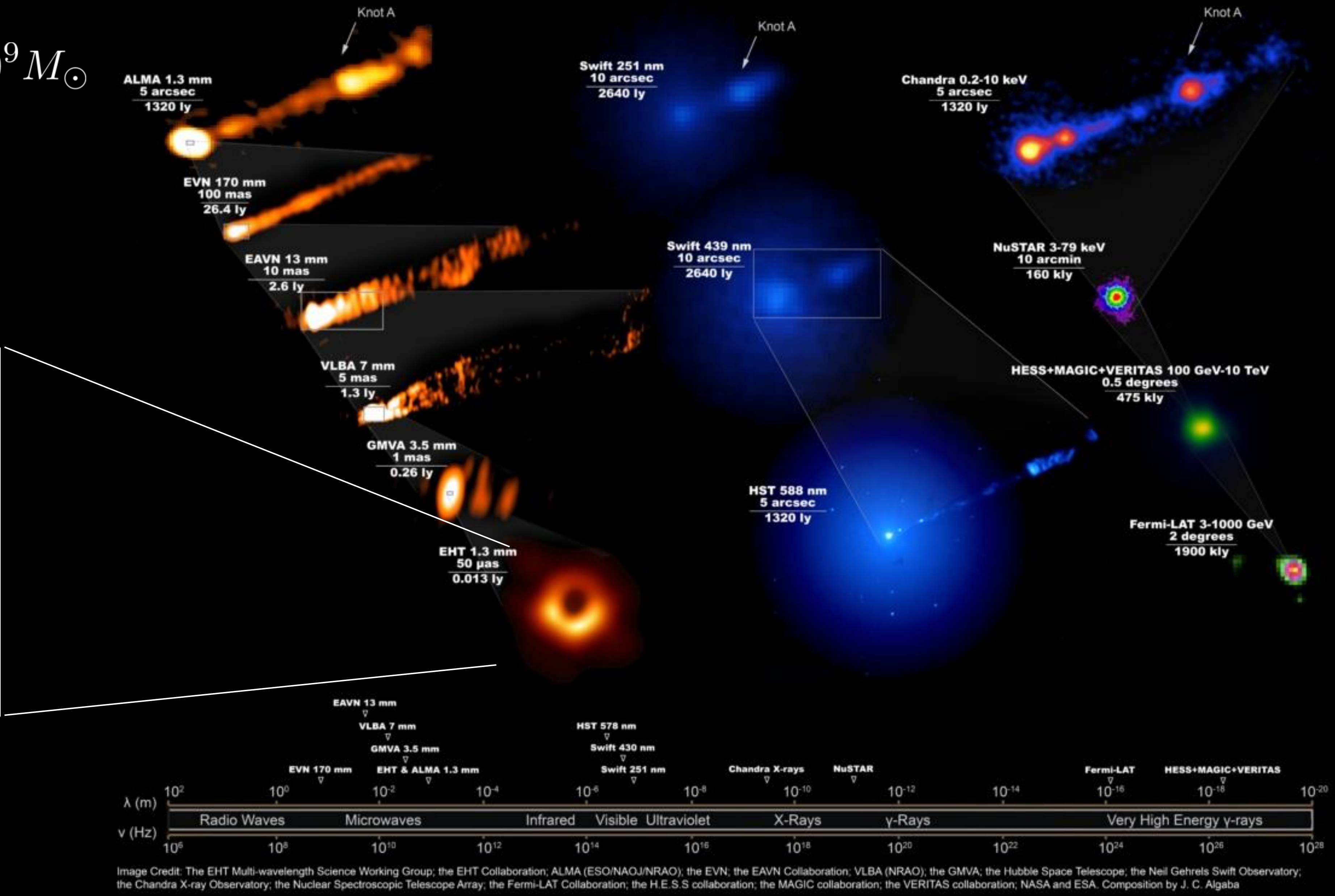


M87*

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



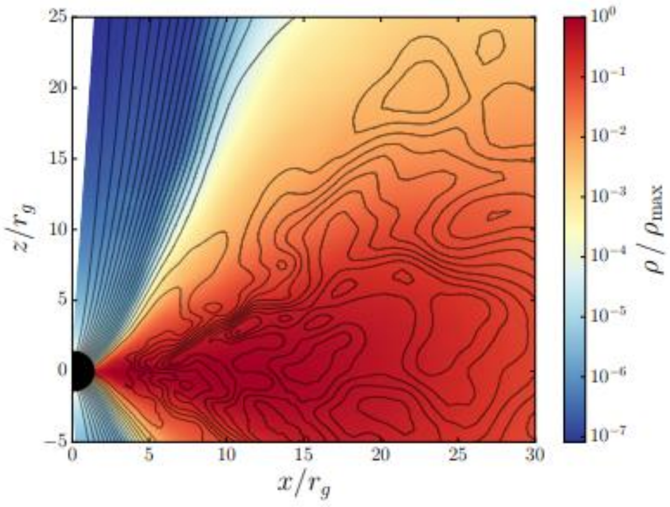


Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

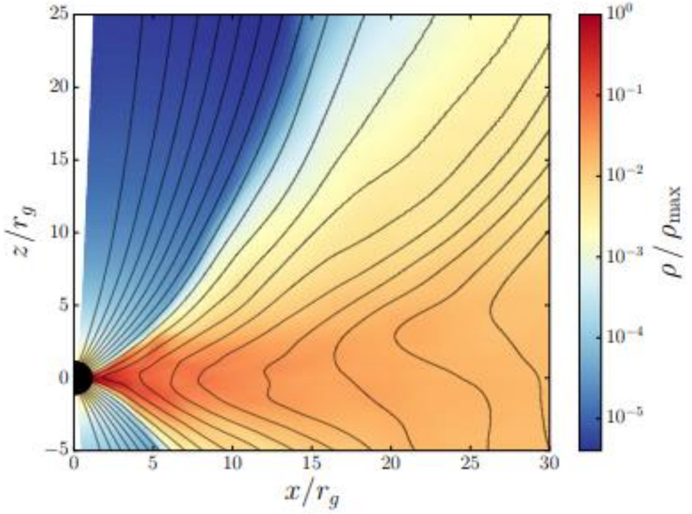
What is the magnetic field structure close to the horizon?

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 dynamically important ones → ~10 G at the horizon for M87

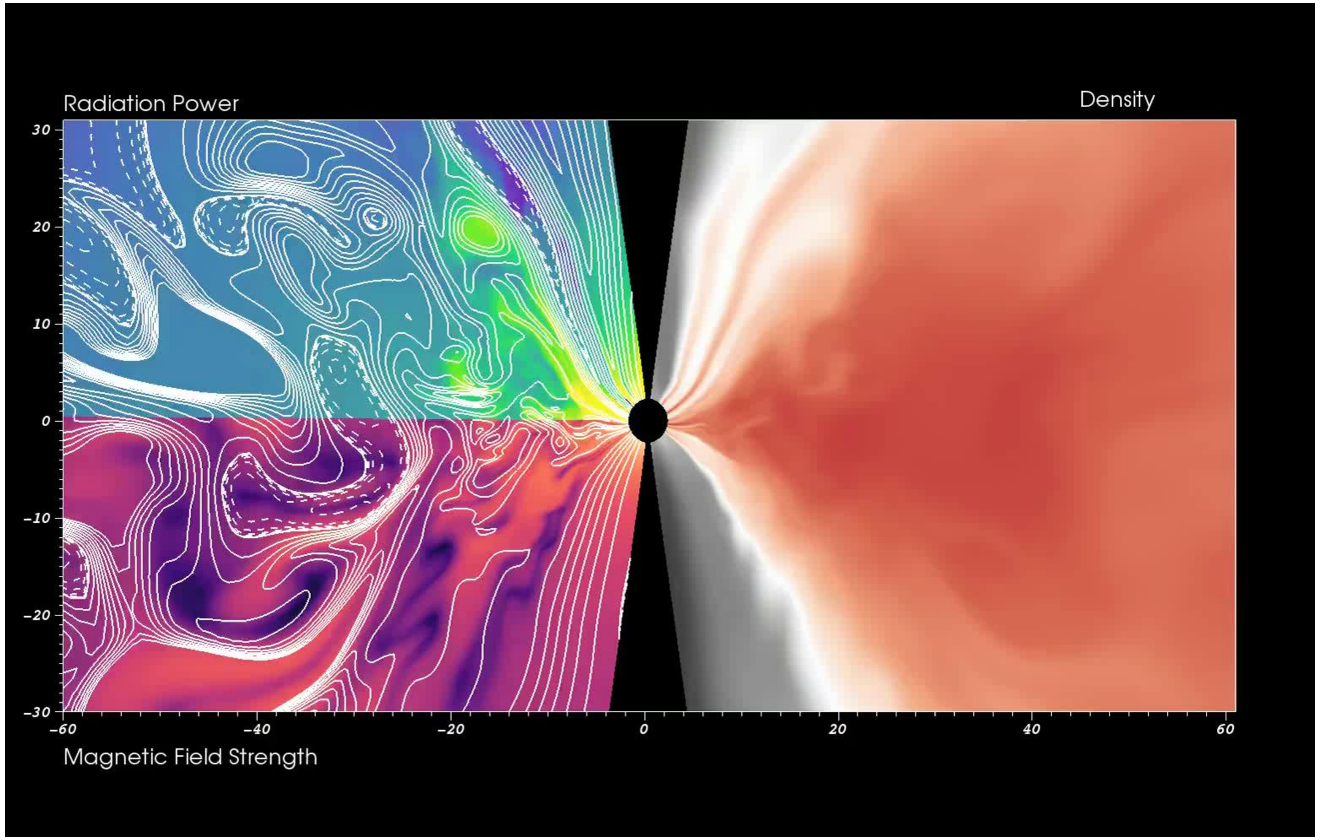
Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_B^2 a^2$

BH spin

magnetic flux

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

Interpreting Images with GRMHD Simulations

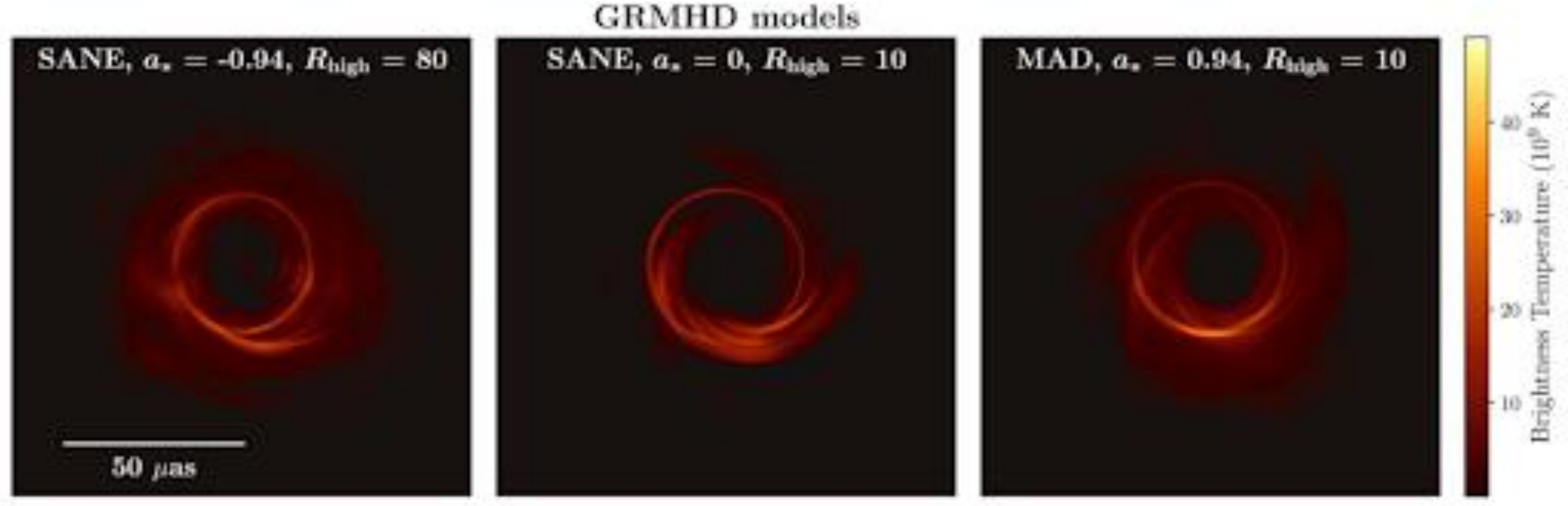


- GRMHD simulations of **radiatively inefficient disks** are the primary theoretical tool for interpreting EHT images.
- Hot ($10^{10} < T < 10^{12}$ K) , dilute ($10^4 < n < 10^7$ cm^{-3}), magnetized (1 G < |B|< 50 G) plasma naturally satisifies constraints on
  - Image brightness
  - Faraday Rotation / low linear polarization
  - Faraday Conversion / low circular polarization
- GRMHD simulations naturally **couple the accretion disk, black hole, and jet**
  - Jet launching in simulations is universal and driven by BH spin

Movie Credit: **Chael**+ 2019

Scoring 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)



- 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

Outline

1. How do we obtain a polarized image of M87* with the EHT?
2. How do we interpret the polarized image of M87*?
3. Connection between polarized images and EM energy flux

First M87 Event Horizon Telescope Results. VII. Polarization of the Ring

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

Received 2020 November 23; revised 2021 February 15; accepted 2021 February 16; published 2021 March 24

First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

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First M87 Event Horizon Telescope Results. IX. Detection of Near-horizon Circular Polarization

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

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Black Hole Polarimetry I. A Signature of Electromagnetic Energy Extraction

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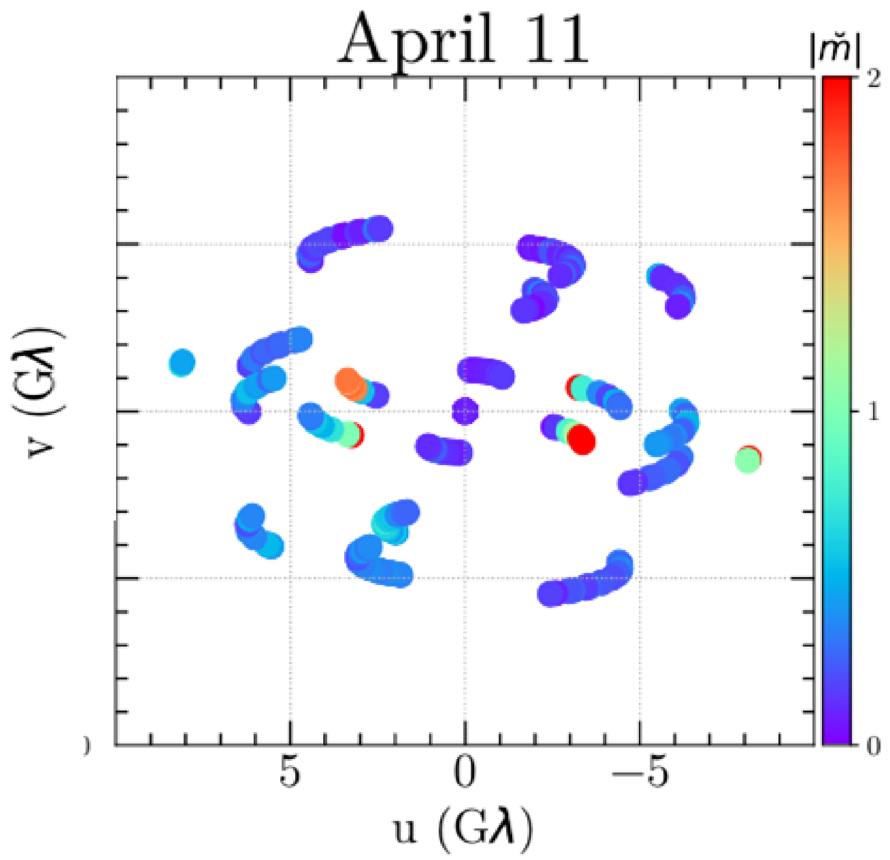
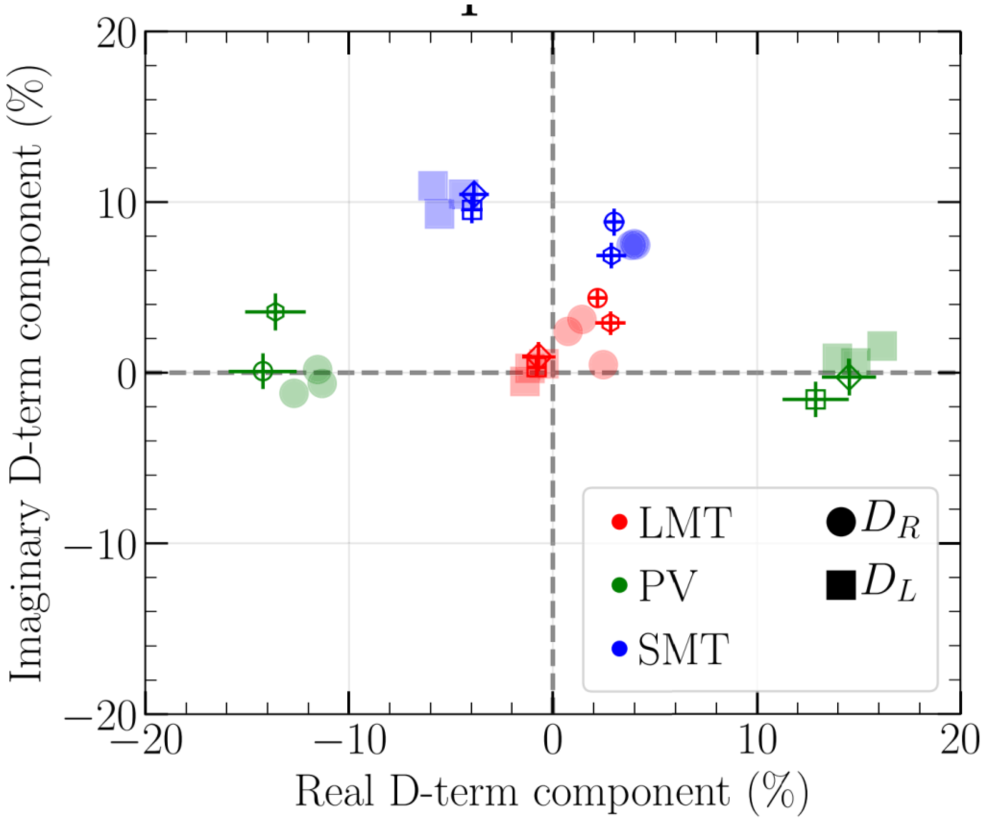
How do we obtain a polarized image of M87* with the EHT?

Two Challenges of EHT polarimetric imaging

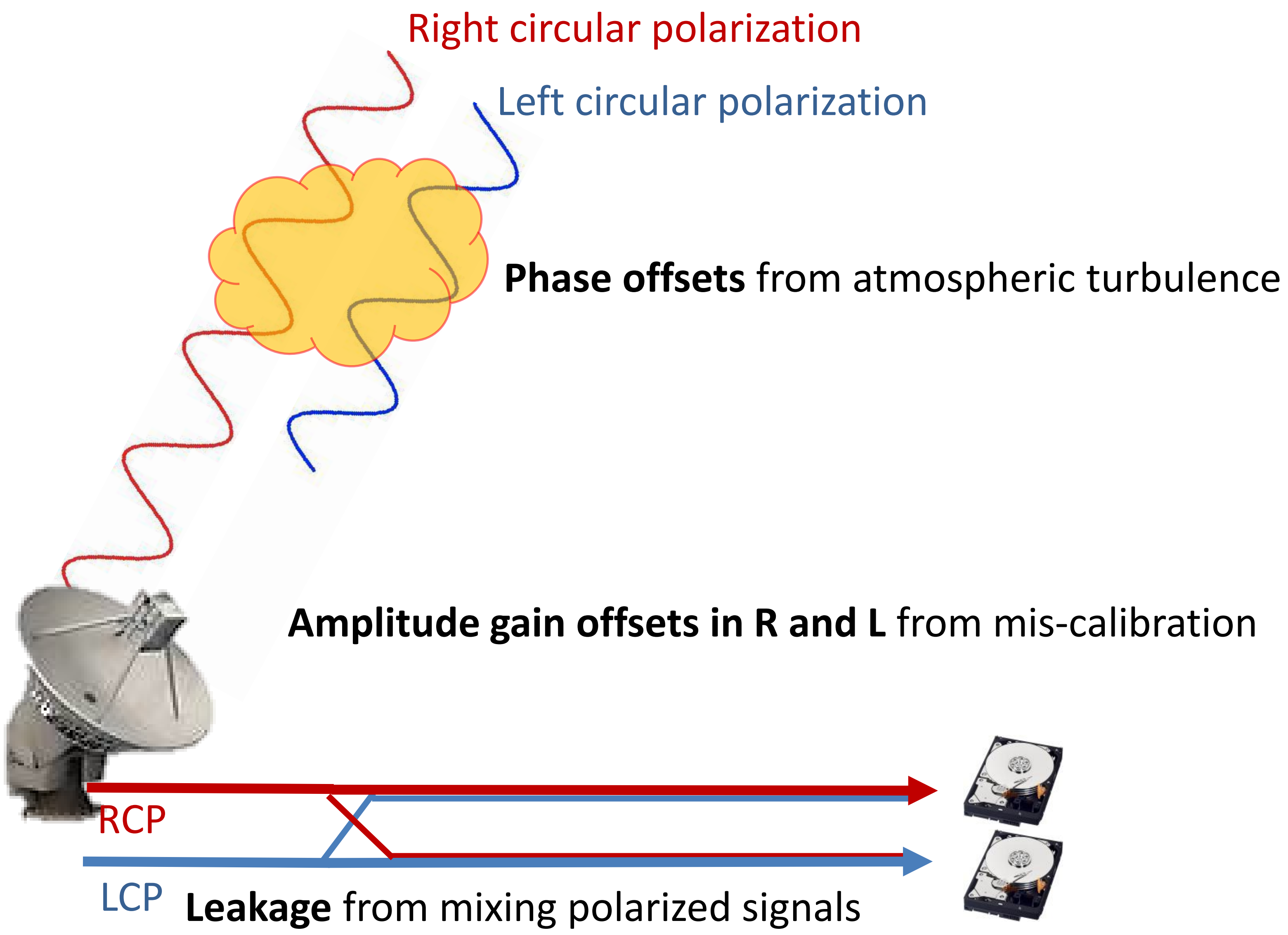
1. EHT coverage is **sparse**: inversion of image from the data is highly unconstrained



Data at each station are corrupted by unknown polarimetric **leakage** and polarization-dependent complex gain factors



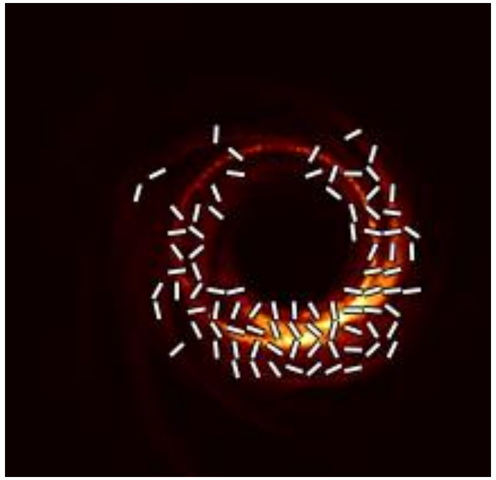
Corrupting effects at EHT stations



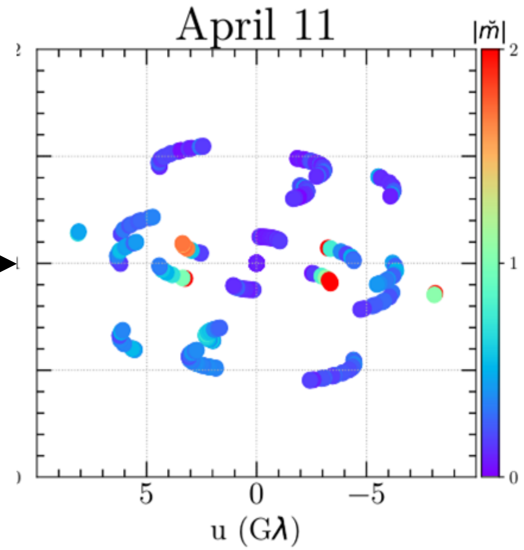
Data at each station are corrupted by unknown polarimetric **leakage** and **complex gain** factors

Solving for the Image

True Image

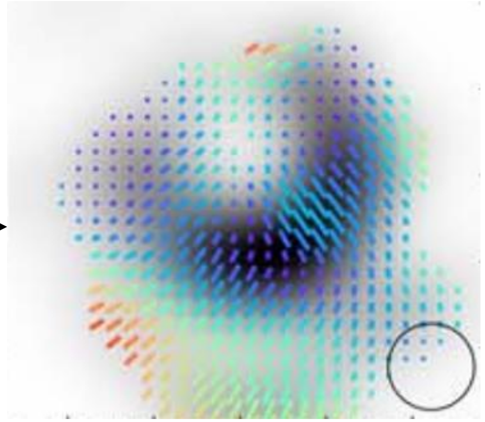


Sparse/ Corrupted Measurements



RECONSTRUCTION ALGORITHM

Reconstruction

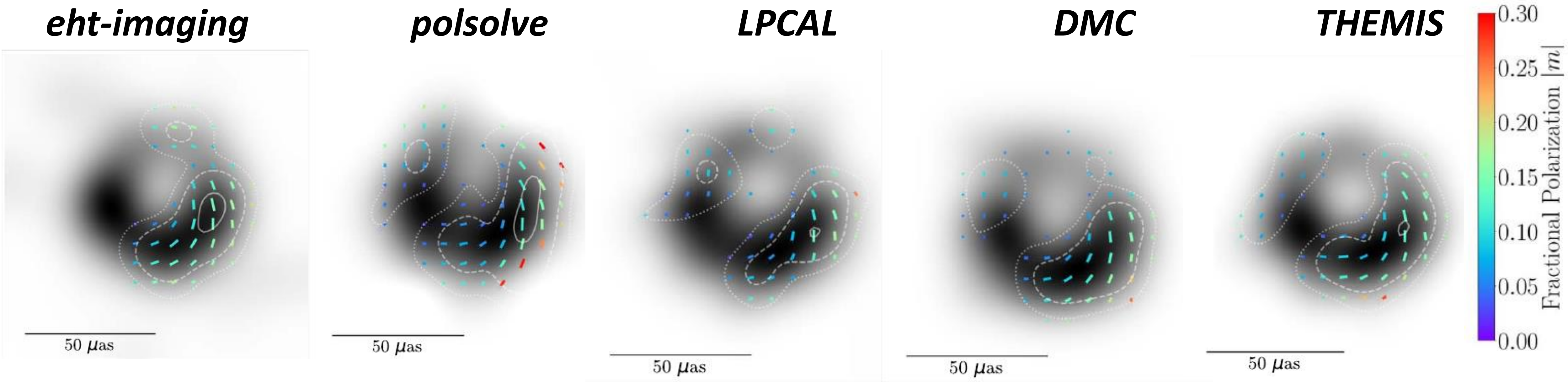


Several different types of reconstruction algorithms now used:

- **CLEAN-based**: standard and efficient, but can have difficulties on very sparse data
  - LPCAL/GPCAL (Park+ 2021) and polsolve (Marti-Vidal+ 21)
- **Regularized Maximum Likelihood w/ Gradient Descent**: fast and flexible, but lots of hyperparameters
  - eht-imaging (Chael+ 2016, 2018)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
  - Themis (Broderick+ 21), DMC (Pesce+ 21)

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

Linear Polarization Images from five vetted methods



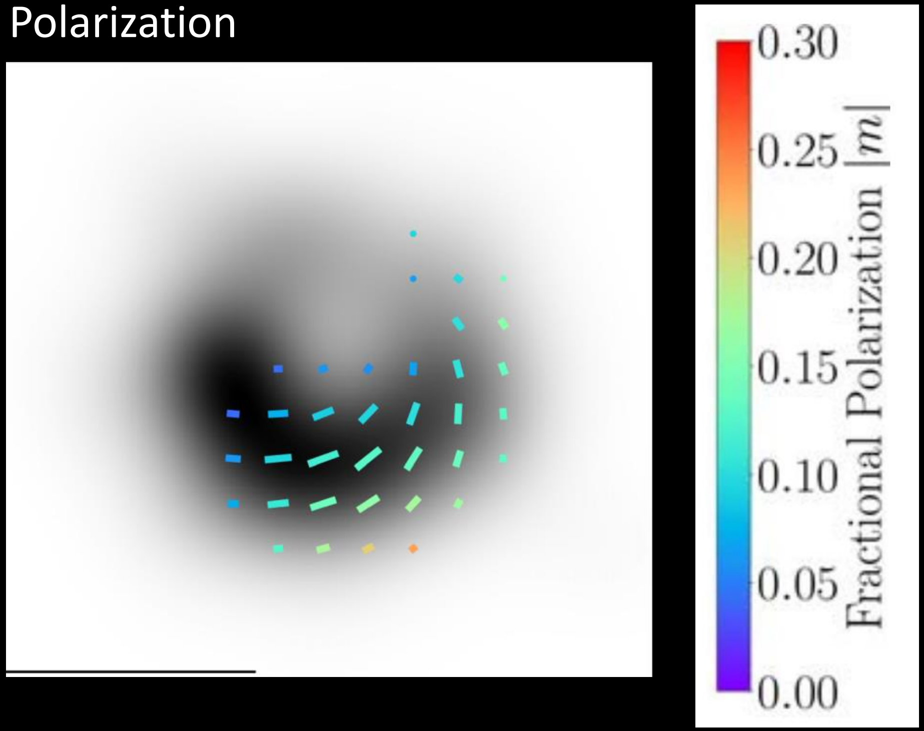
- All methods show similar polarization structure
- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **azimuthal**
- Overall level of polarization is **somewhat weak**, |m| rises to ~15 %

Credit: EHT 2021 Paper VII

M87* in **linear polarization**

Total intensity

Linear Polarization

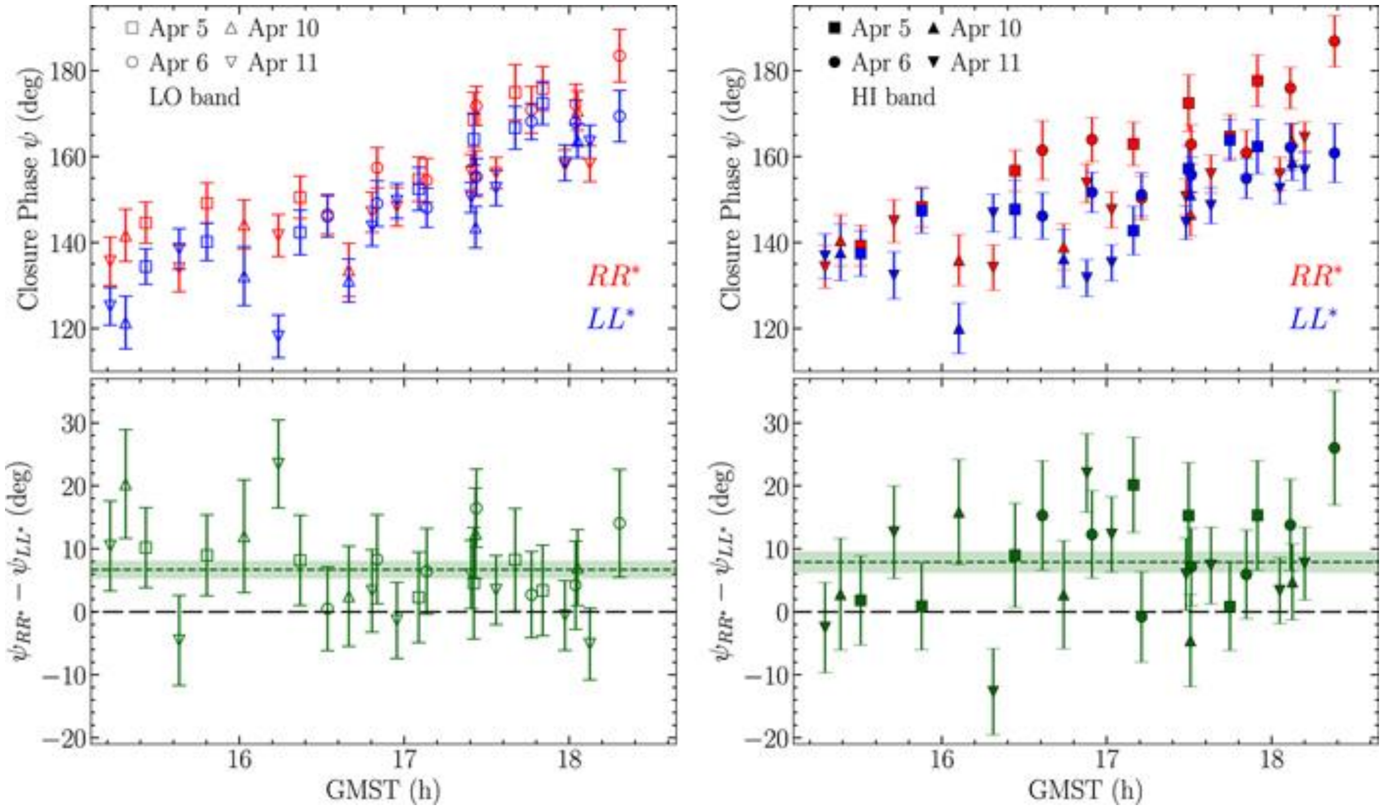


- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

EHTC+ 2021 Papers VII & VIII

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

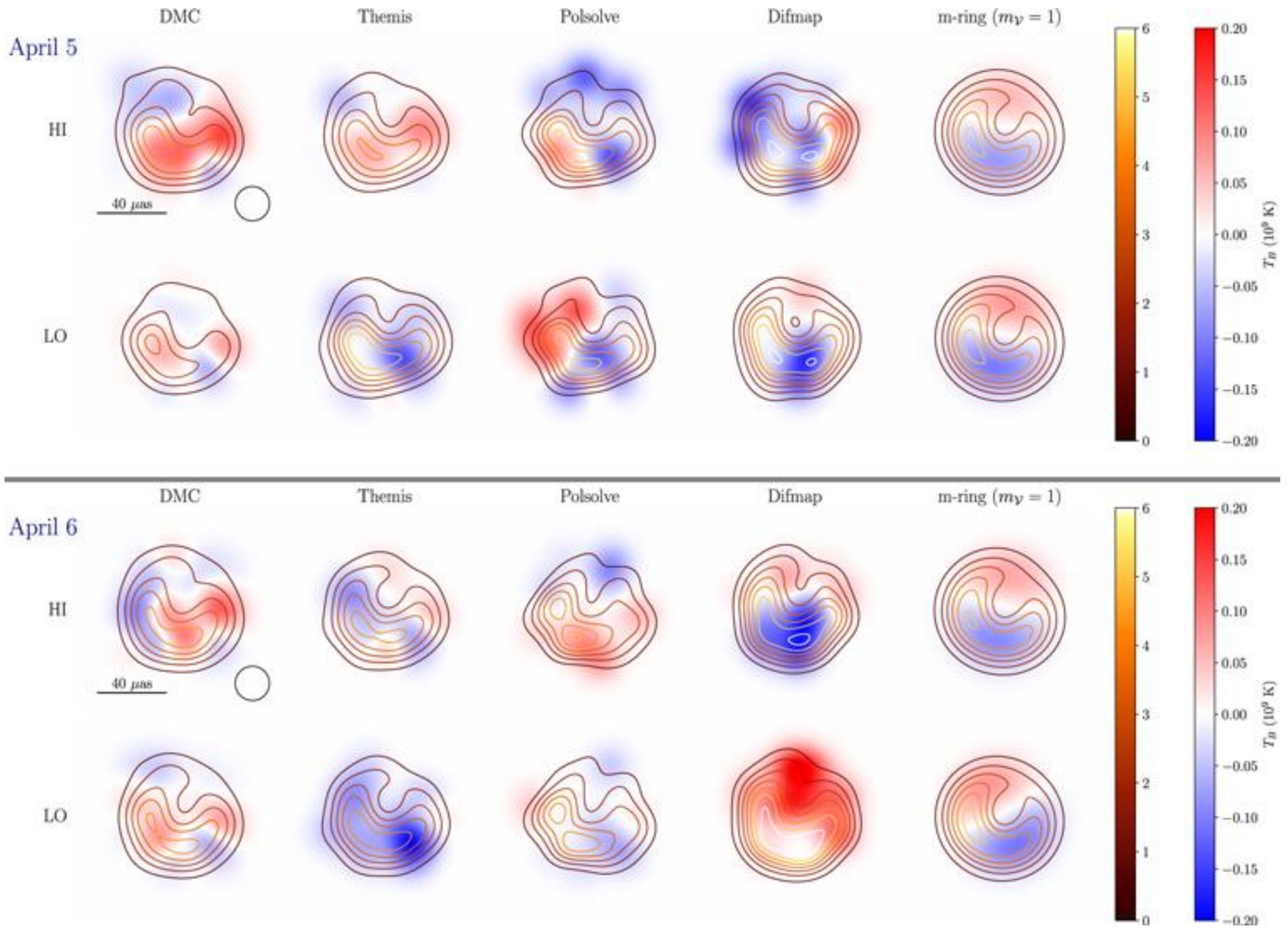
- We detect an **offset** between closure phases in the RR and LL polarizations (V=0.5(RR-LL))
- This is immune to relative gain offsets G_R / G_L
- Not seen on all triangle; upper limit of detected circular polarization in Fourier space is only 1%-10% of total intensity
- Can we constrain the image structure in circular polarization?



Credit: EHT 20233 Paper IX

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

- Different reconstruction methods make different assumptions about how to calibrate gains, D-terms, other systematics
- Methods do not show consistent Stokes V images
  - Not consistent between days
  - Not consistent between frequency bands
- Methods show a similar overall level of |V| across the image
  - Use to place an upper limit on **<|v|> < 3.7%**

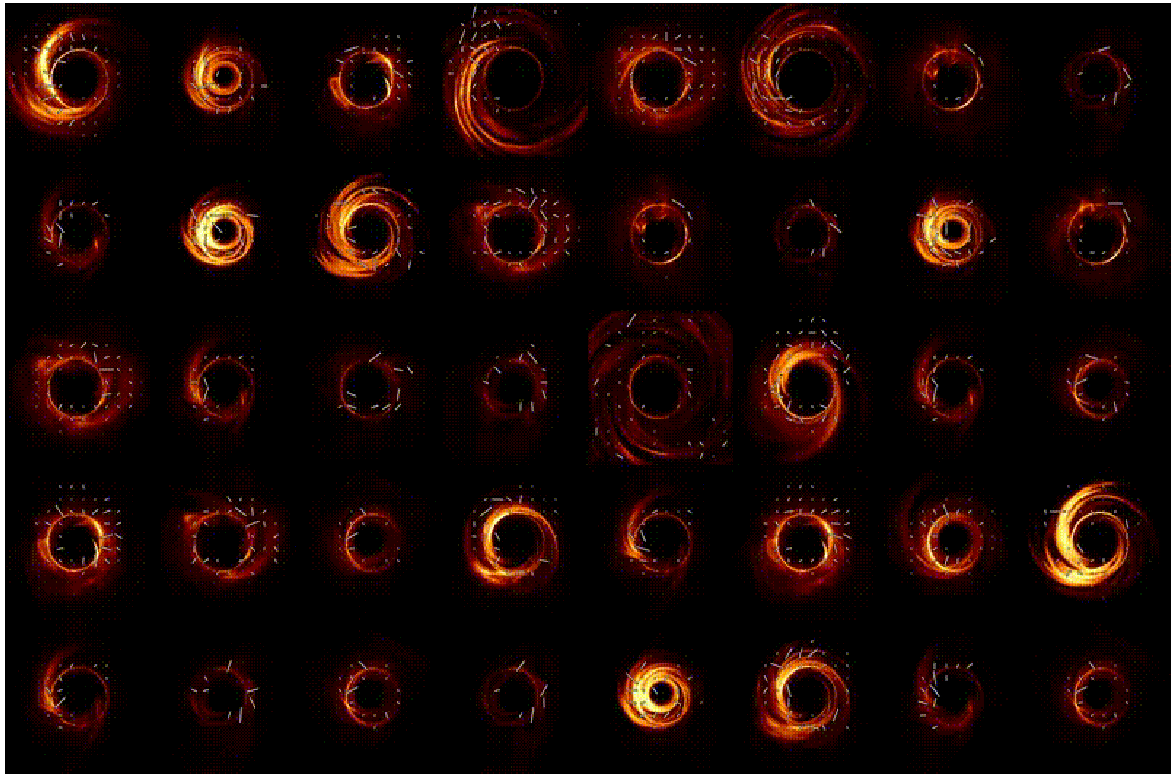


$$\langle |v| \rangle = \frac{\int |\mathcal{V}/\mathcal{I}|\, \mathcal{I}\, dA}{\int \mathcal{I}\, dA}$$ Average resolved Circular Fraction

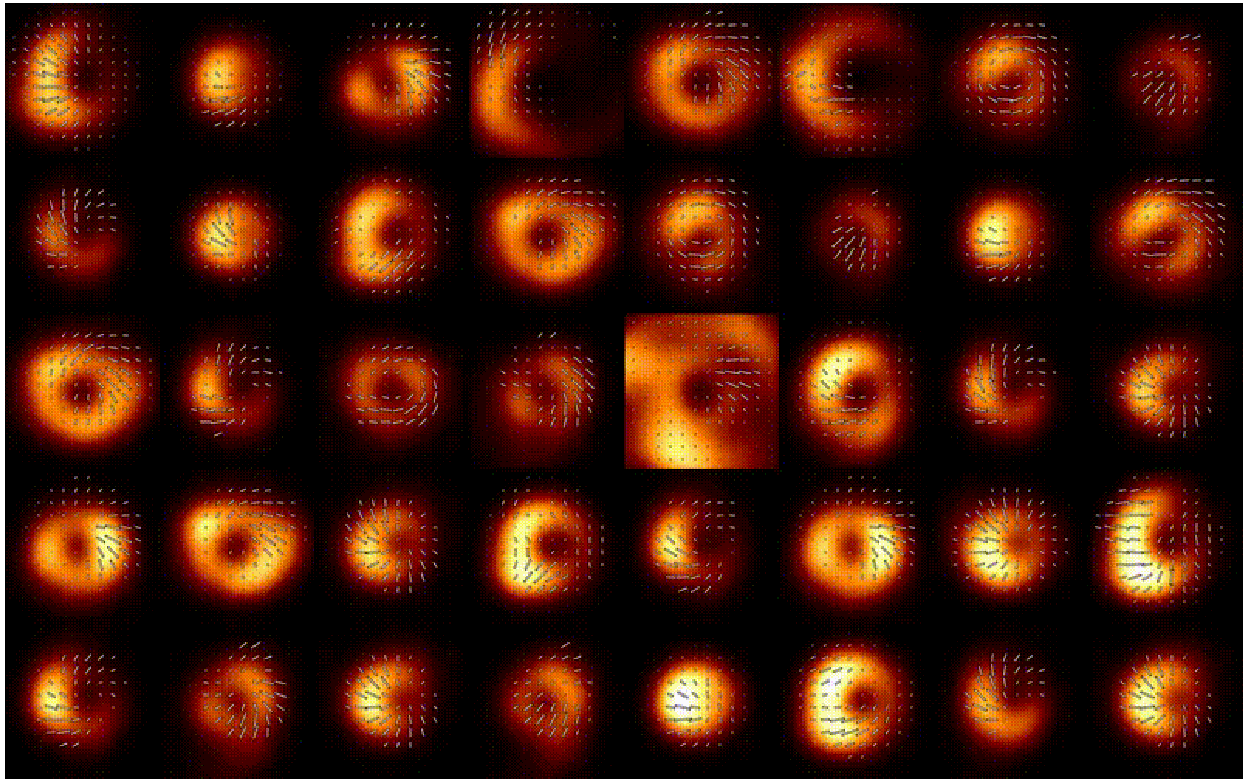
Credit: EHT 20233 Paper IX

What do the EHT’s polarization results tell us about the accretion flow?

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

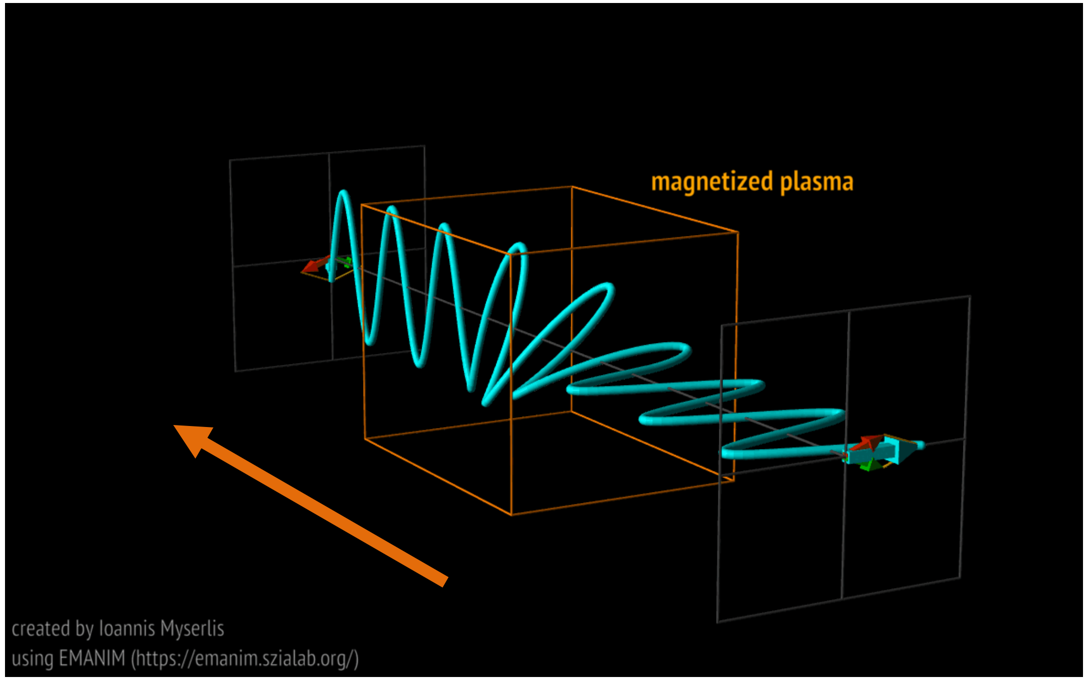
$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta^2}{1+\beta^2} + R_{\rm low}\frac{1}{1+\beta^2}$$

Two parameters set the electron temperature

Animation credit: George Wong/ Ben Prather

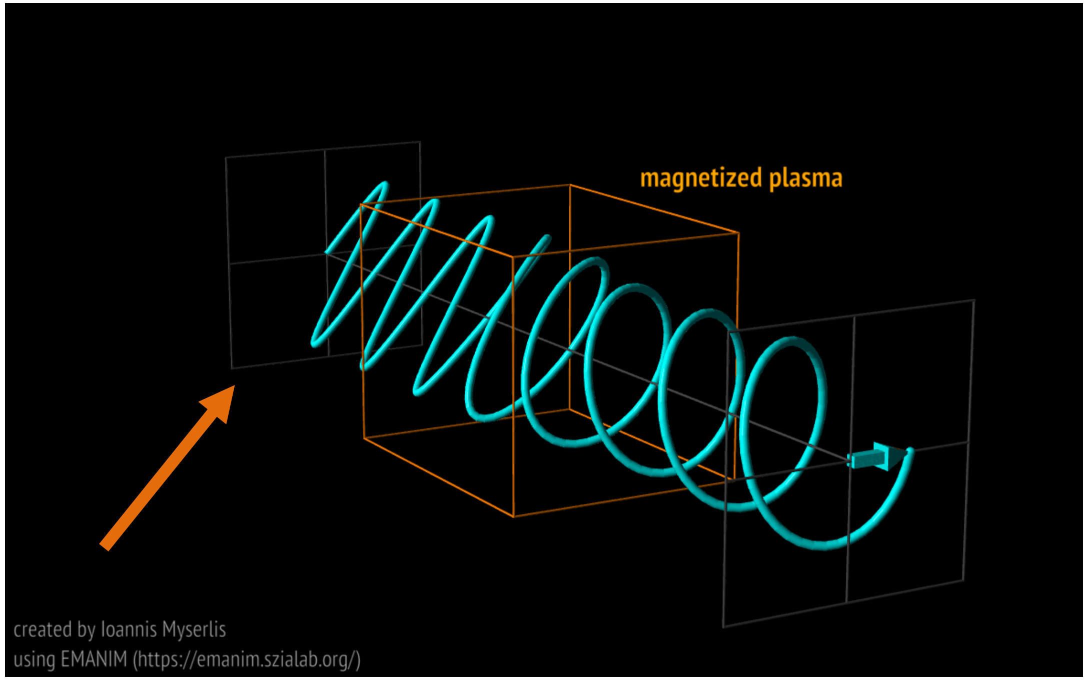
Faraday rotation and conversion are critical

Rotation



Field parallel to propagation matters

Conversion



Field parallel to linear polarization vector matters

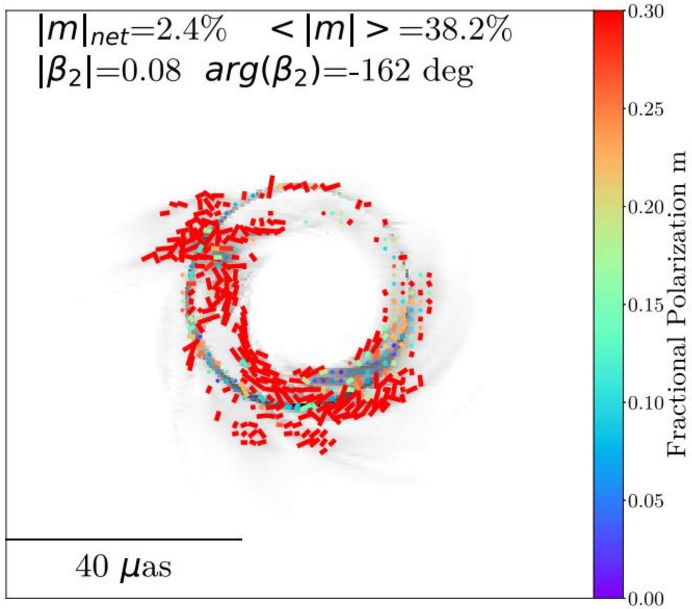
Movie credit: Ioannis Myserlis

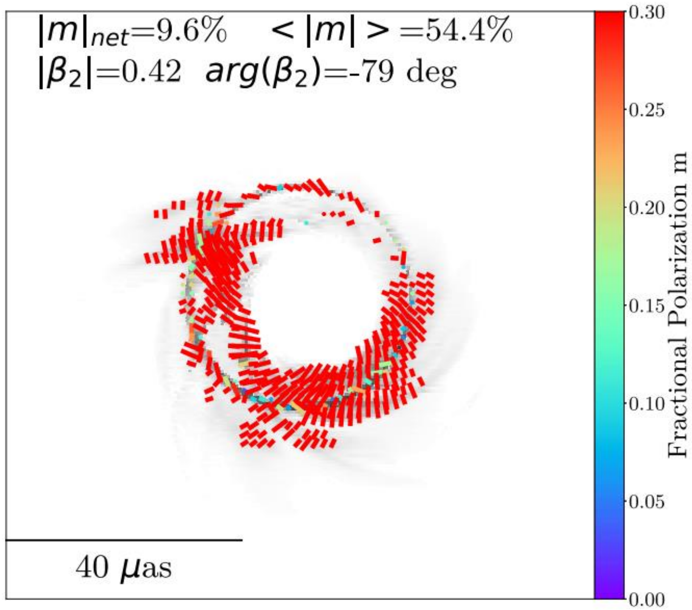
(Internal) Faraday rotation matters!

With rotation

Without rotation

‘infinite’ resolution



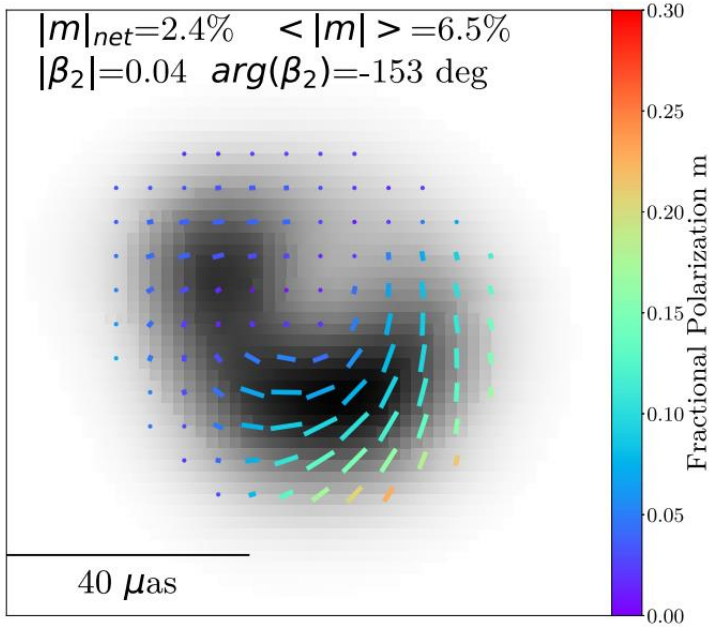


- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **depolarization** of the image when blurred to EHT resolution
  - → **overall rotation** of the pattern when blurred to EHT resolution

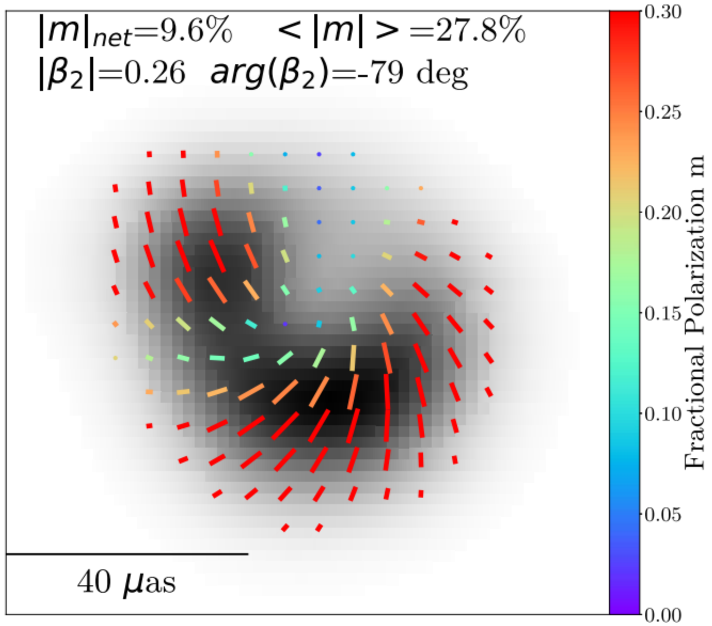
Credit: EHTC 2021 Paper VIII

(Internal) Faraday rotation matters!

With rotation



Without rotation

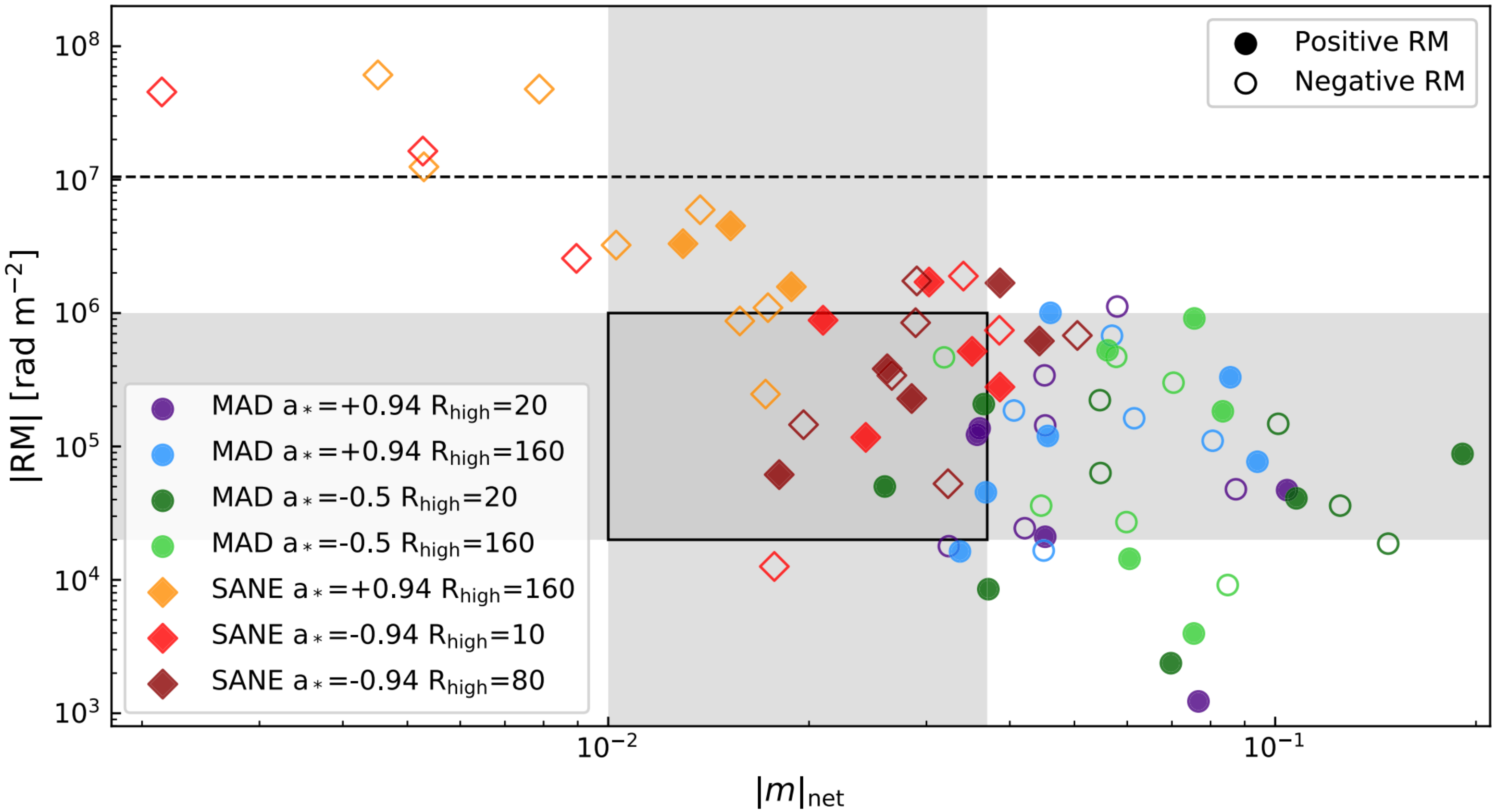


EHT resolution

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

Credit: EHTC 2021 Paper VIII

GRMHD simulations can explain M87's Rotation Measure



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

Credit: EHTC 2021 Paper VIII

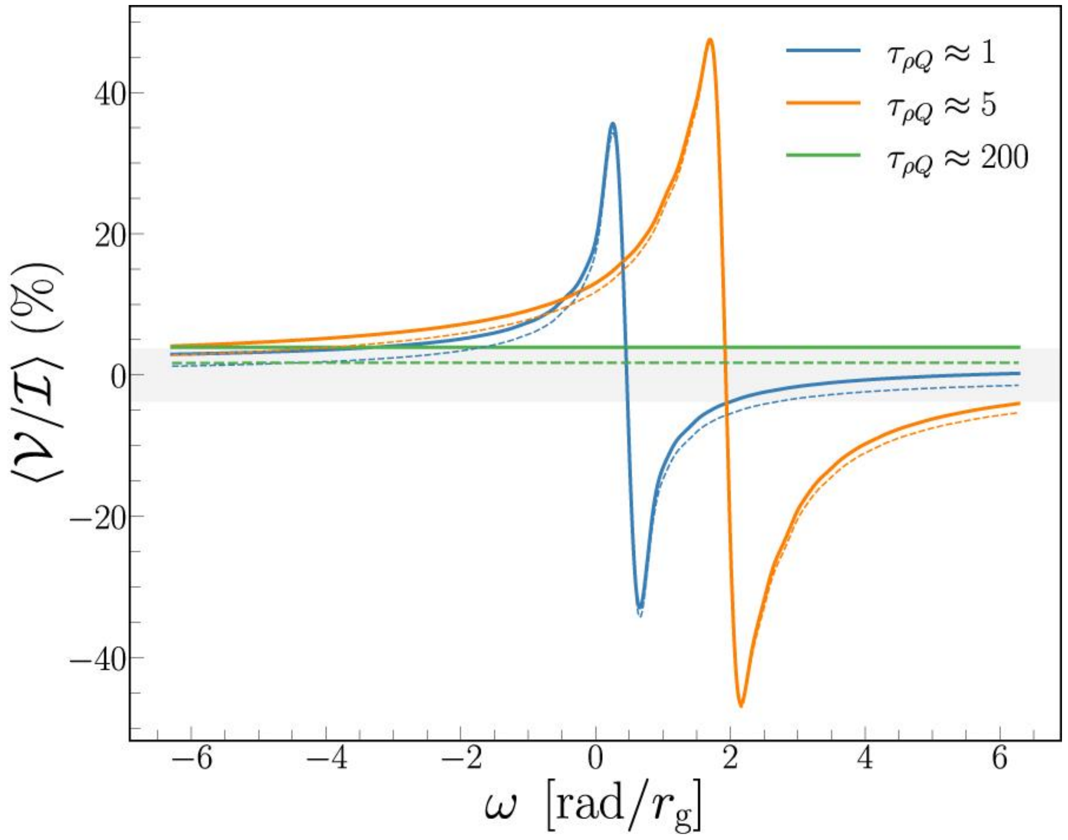
Angelo Ricarte

Most circular polarization is produced by **conversion**

- One-zone models and GRMHD simulations both confirm conversion is the dominant source of circular polarization in favored models

- In a uniform field geometry, Faraday conversion will typically produce more circular than linear polarization

- The interplay of conversion, rotation, and changing magnetic field direction along the line of sight determines the level and sign of circular polarization



Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

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

Unresolved circular polarization fraction (from ALMA)

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

Average resolved linear fraction

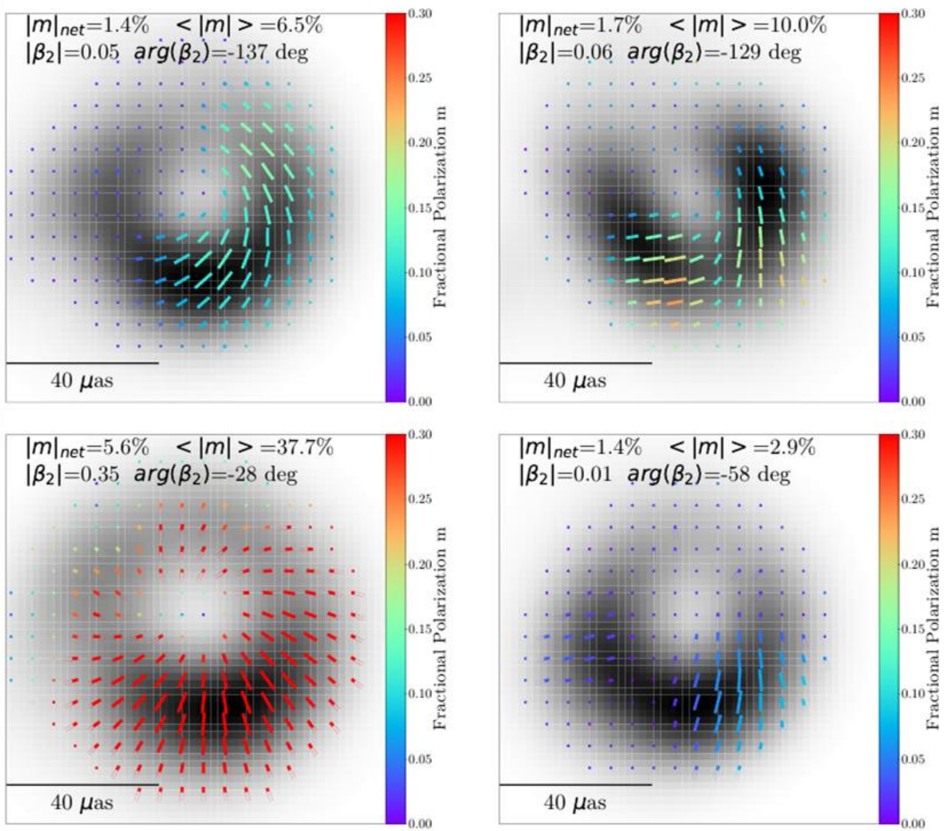
$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Average resolved circular fraction

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

Azimuthal Linear structure 2nd mode (Palumbo+ 2020)

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



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

Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

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

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

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

Azimuthal Linear structure 2nd mode (Palumbo+ 2020)

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

Table 3
Observational Constraints Applied to Our GRMHD Image Library

Parameter	Minimum	Maximum
$m_{\rm net}$	1.0%	3.7%
$v_{\rm net}$	−0.8%	0.8%
$\langle \lvert m \rvert \rangle$	5.7%	10.7%
$\lvert \beta_2 \rvert$	0.04	0.07
$\angle \beta_2$	−163°	−129°
$\langle \lvert v \rvert \rangle$ (This Work)	0	3.7%

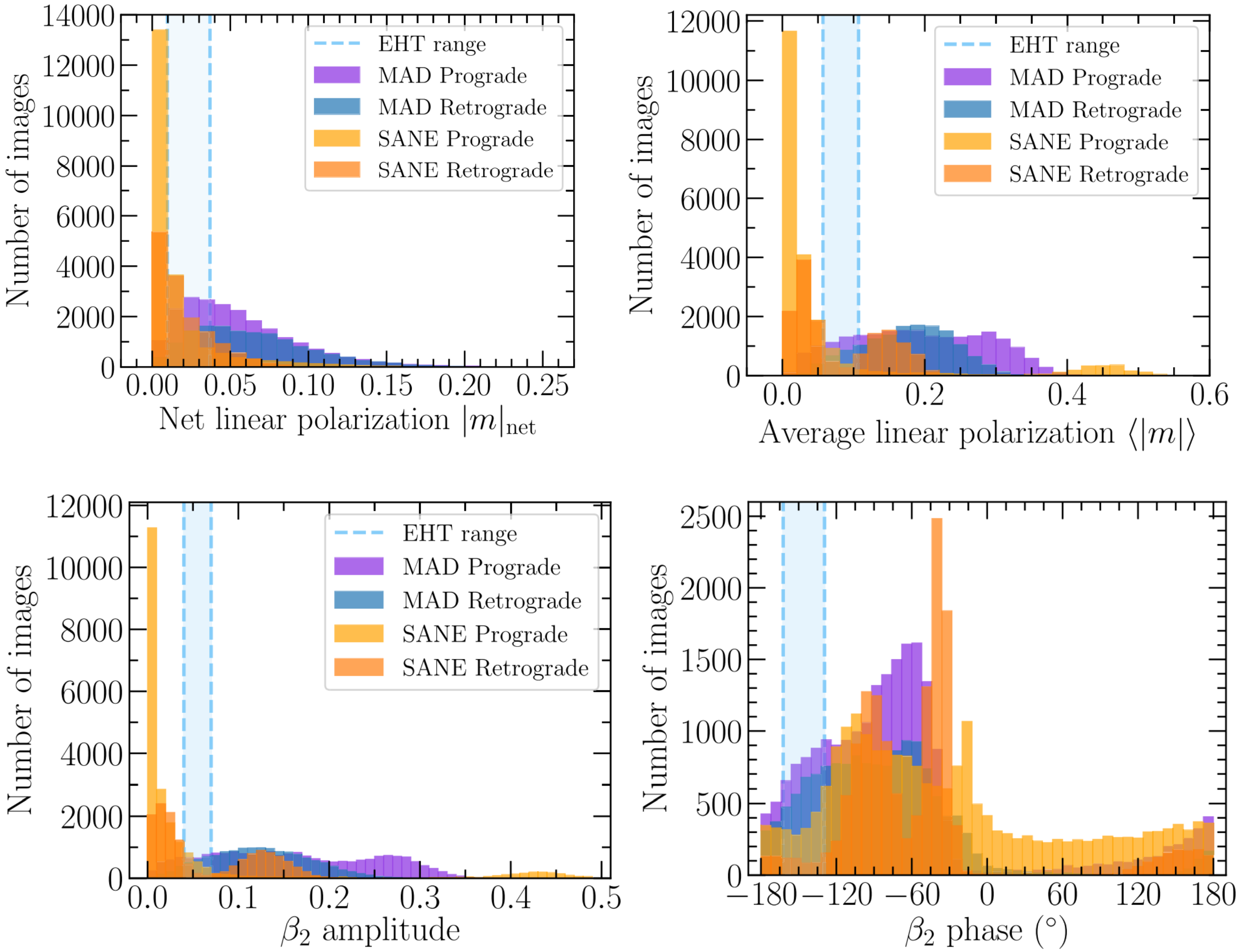
Note. Most of these constraints are inherited from Paper VII and were previously used to constrain models in Paper VIII. This work adds the new upper limit on $\langle |v| \rangle$.

EHTC+2021 VII, VIII, 2023 IX

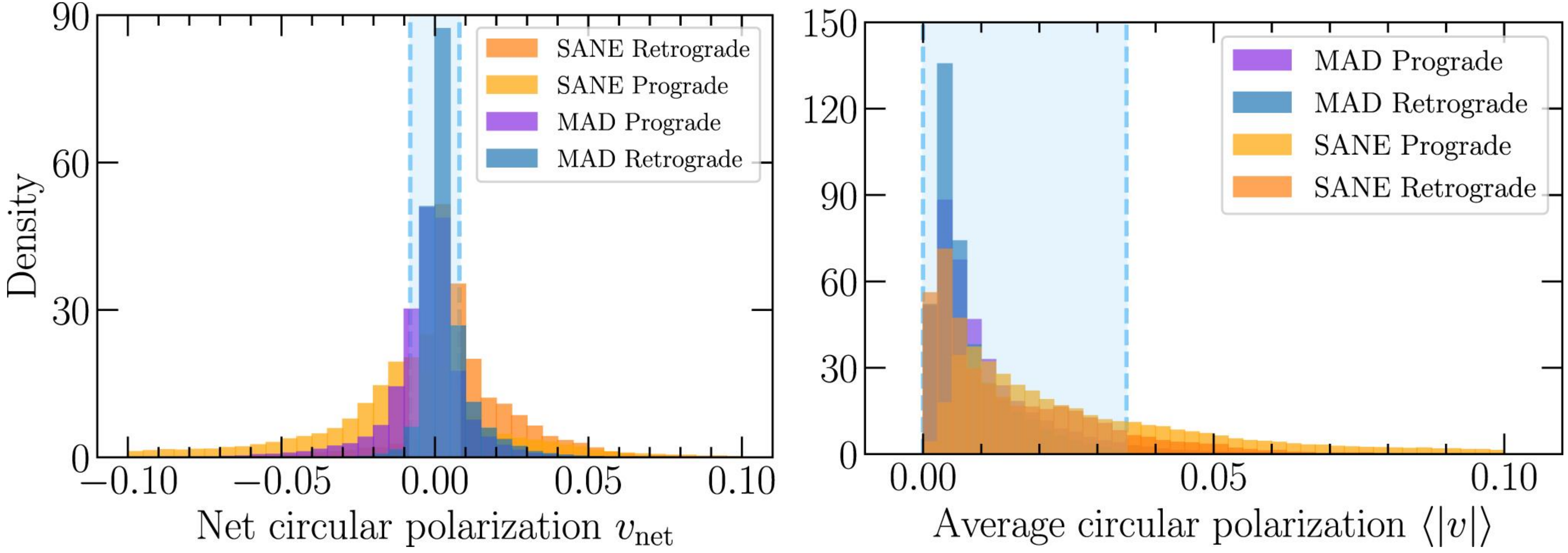
Scoring simulations with linear polarization

Unresolved and **resolved** linear polarization fractions

Azimuthal structure
2nd Fourier mode



GRMHD simulations naturally produce low circular polarization



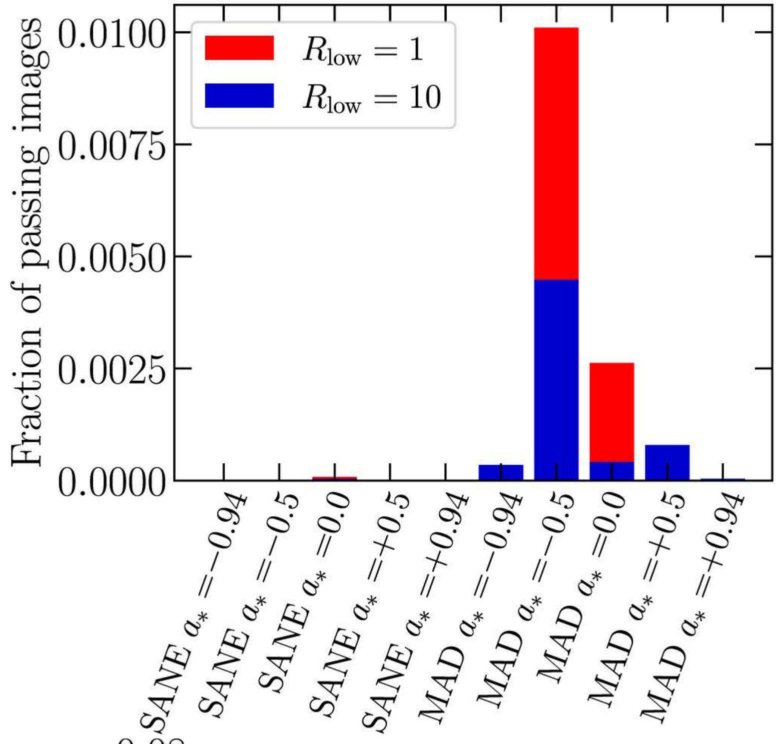
$$v_{\rm net} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

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

EHTC+2023 IX

Polarimetric simulation scoring

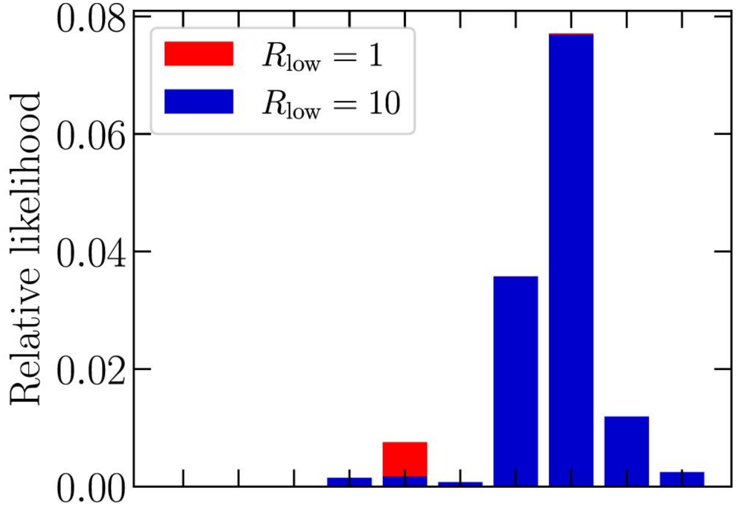
- Two scoring approaches:
  - **'simultaneous'** (demand individual images satisfy all image constraints at once)
  - **'joint'** (compute a likelihood comparing distance between measured quantities and simulation mean with the simulation variance)



- **Both approaches strongly favor magnetically arrested (MAD) simulations**

- The two approaches differ in which electron heating parameters they favor.

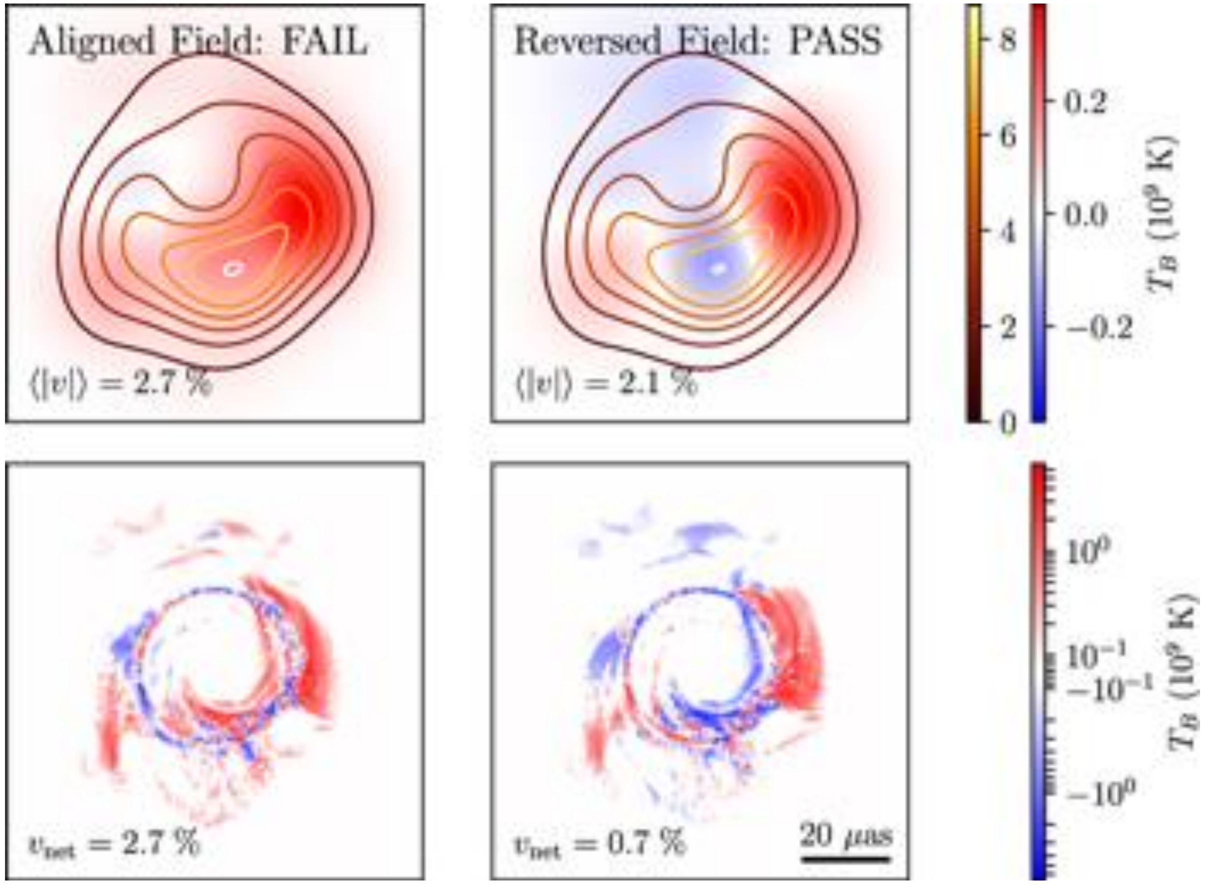
- An additional constraint on the jet power rejects all surviving non-MAD simulations (and all spin-zero simulations)



EHTC+2023 IX

Field orientation is very important!

- GRMHD is insensitive to the direction of the magnetic field, but polarized radiative transfer is **not**
- Changing the direction of the magnetic field changes:
  - sign of emitted V
  - direction of Faraday rotation
- images typically do not just flip sign when we reverse the field
  - circular polarization is typically produced via an interplay btw Faraday rotation and conversion,



EHTC+2023 IX

Implications for M87*'s accretion

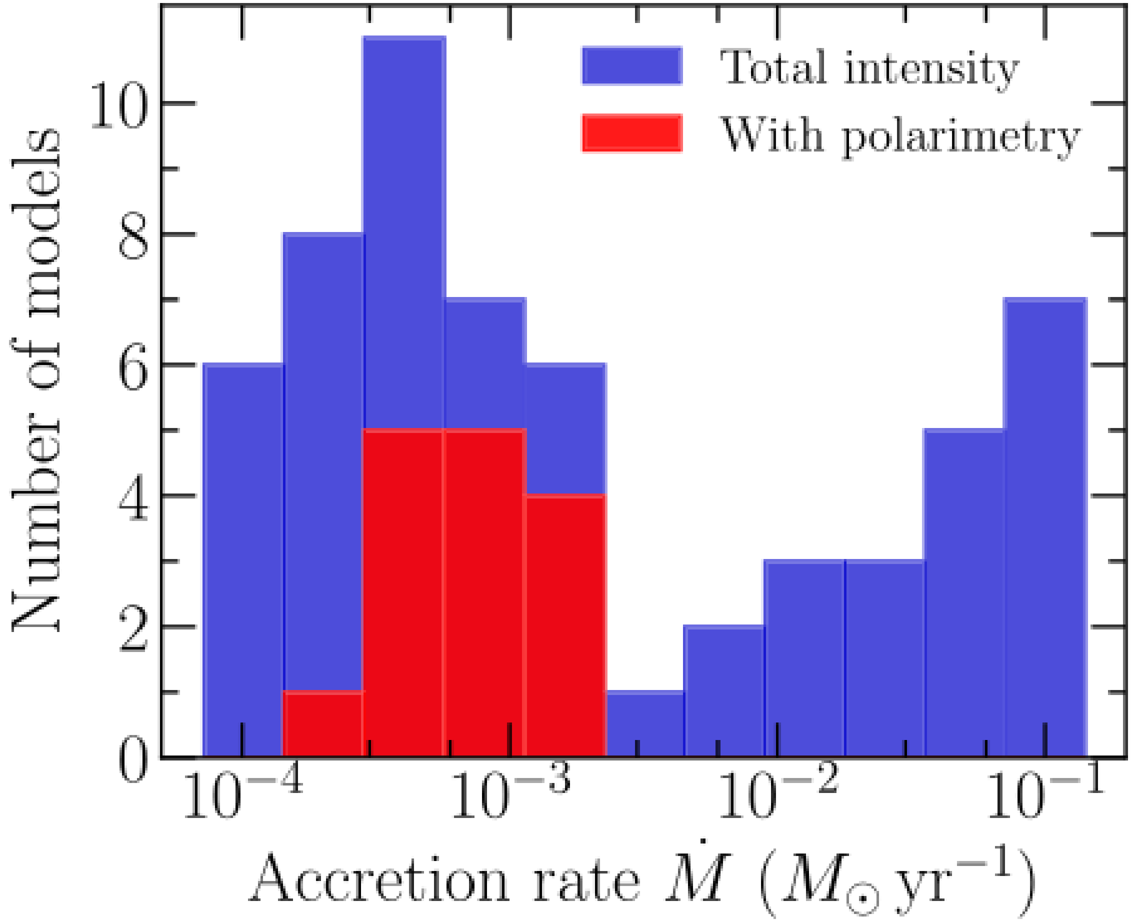
- Surviving models significantly tighten constraints on accretion rate from total intensity results:

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

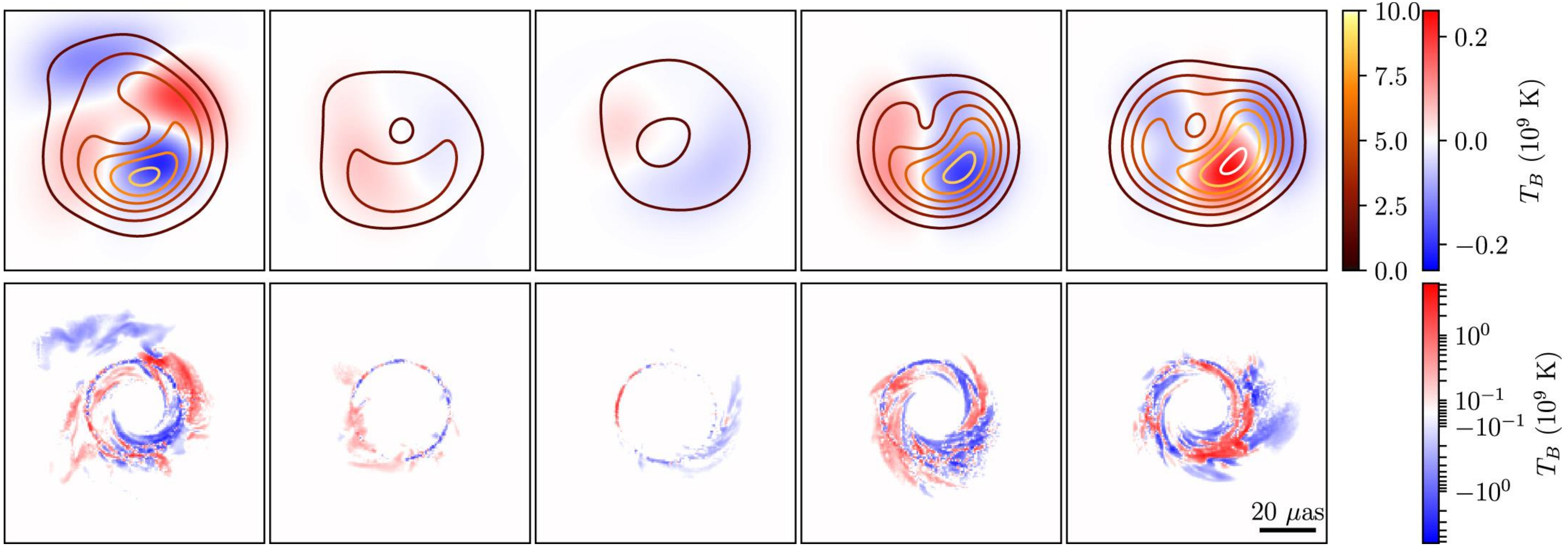
- Constrains the electron temperature, number density, and magnetic field strength (in agreement with estimates from simple one-zone models):

$$T_e \simeq (5 - 40) \times 10^{10}\ \mathrm{K}$$
$$|B| \simeq (7 - 30)\ \mathrm{G}$$
$$n \sim 10^{4-5}\ \mathrm{cm}^{-3}$$

- Radiative efficiency ~1%
  - Cooling is important!



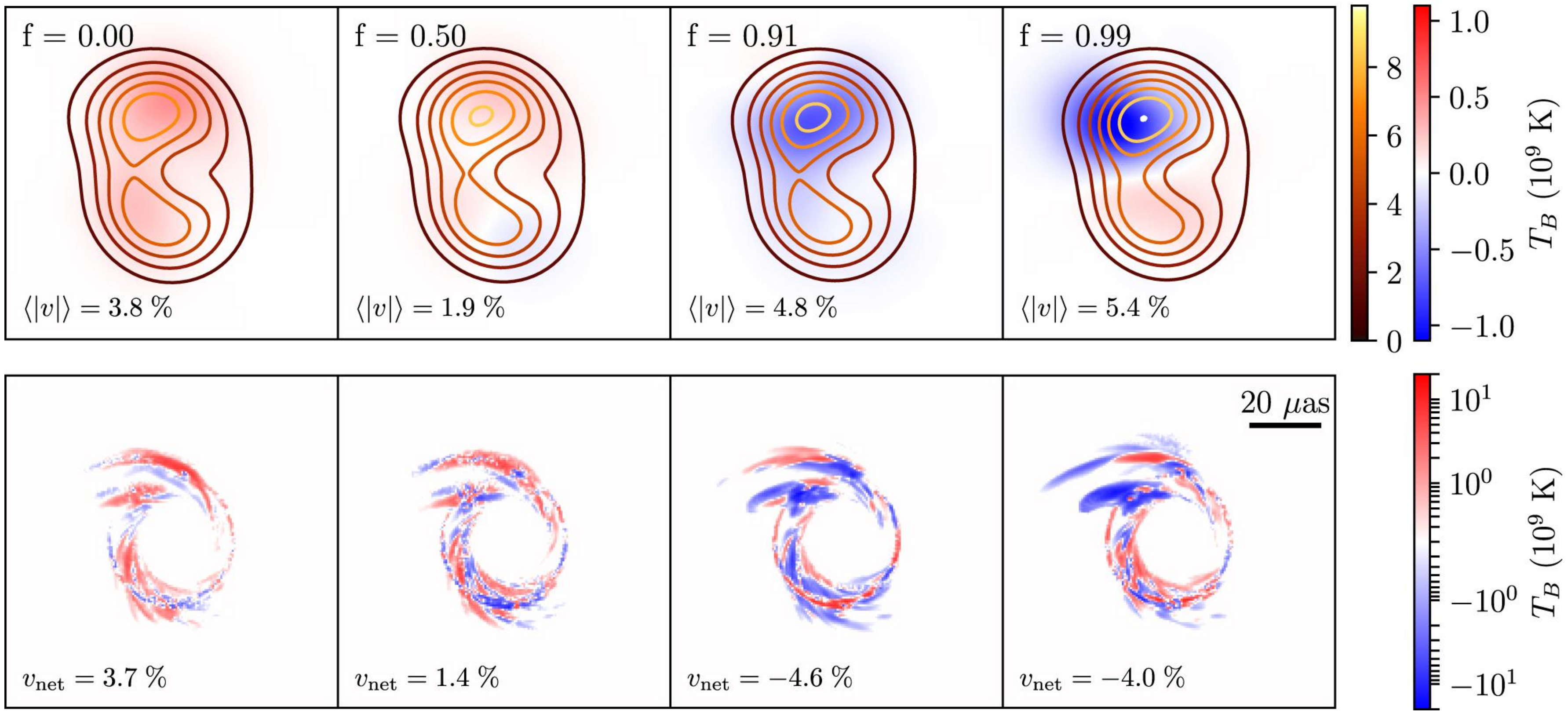
Passing simulations have diverse Stokes V morphologies



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

EHTC+2023 IX
Ricarte+ 2021

Circular Polarization is sensitive to pairs, but not in the way you might immediately think….



Conversion is the dominant source of Stokes V. It is **enhanced** by pairs
Faraday rotation is **reduced** by pairs
The interplay of these effects is complex

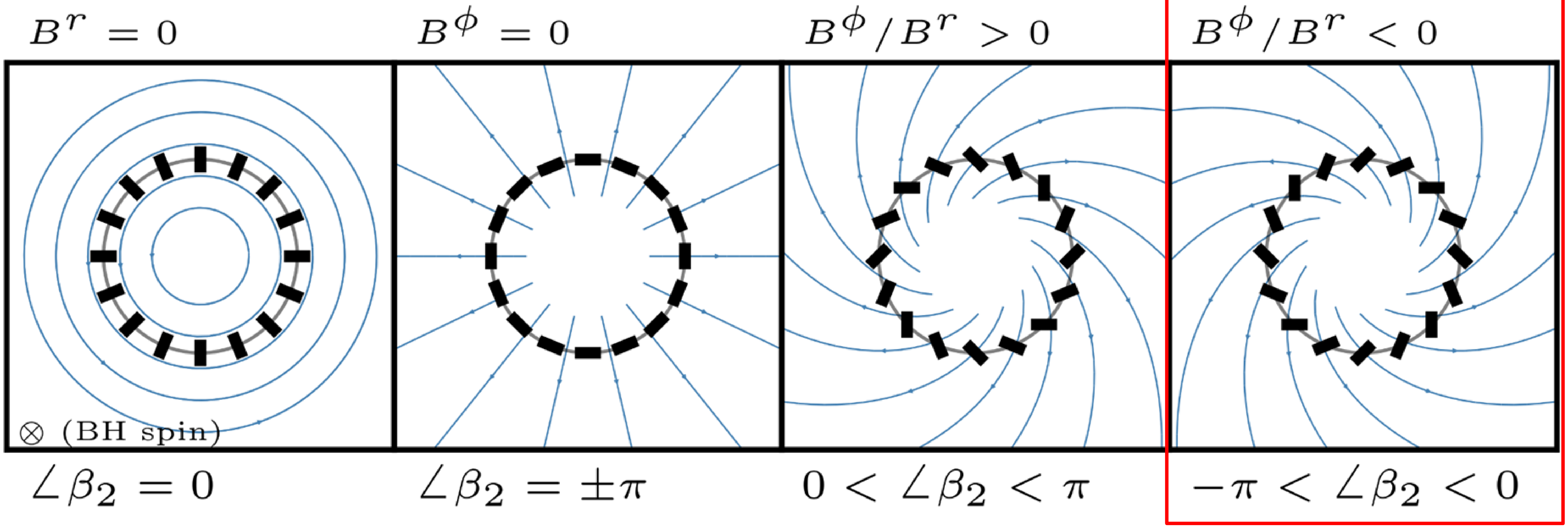
EHTC+2023 IX

Connecting EHT images to electromagnetic energy flow

Chael, Lupsasca, Wong, Quataert 2023

2307.06372

$\arg(\beta_2)$ is connected to the ratio B^ϕ / B^r



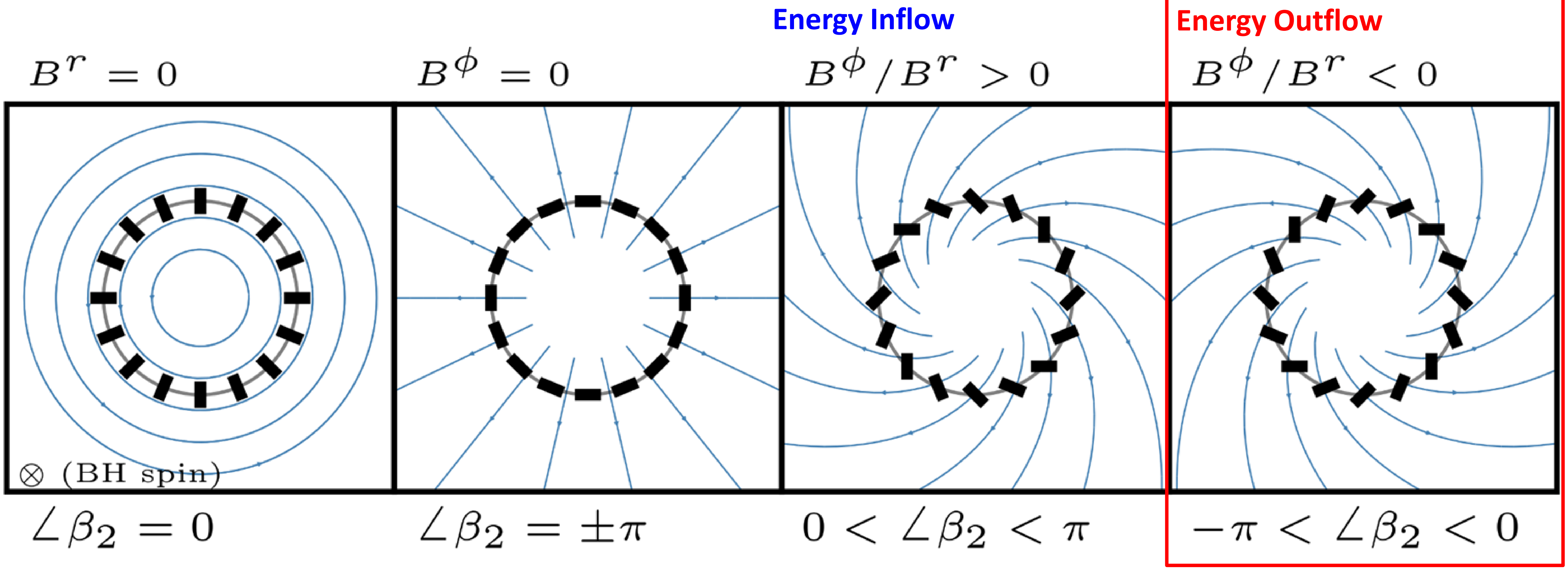
Cartoon picture:

- face on fields, no Faraday rotation, no optical depth, no relativistic parallel transport/abberation
- The BH spin is axis **into the screen** (EHT Paper V, 2019)

$$\angle\beta_2 \approx 2\arctan\left(\frac{B^r}{rB^\phi}\right) \quad \text{(observer at } \theta_o = \pi\text{)}$$

Chael+ 2023

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



Poynting flux (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+ 2023

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

- **The sign of $\arg(\beta_2)$ is connected to the direction of Poynting flux**

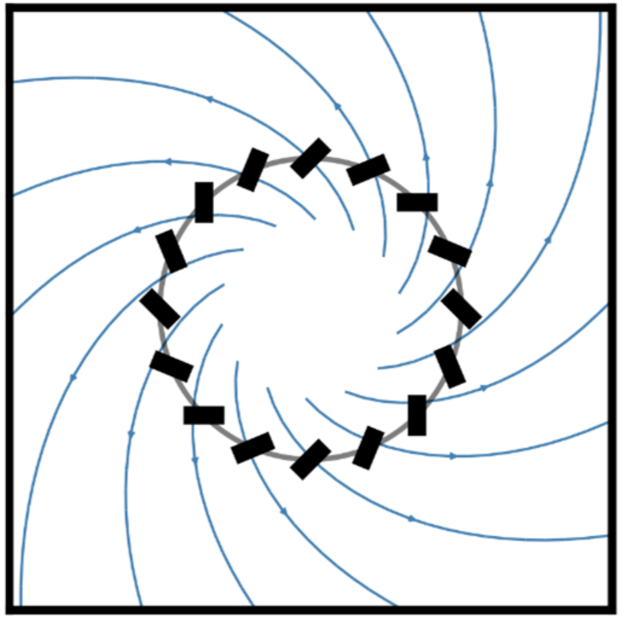
- **Ignoring Faraday effects**, The EHT's measurement
  -163 deg < $\arg(\beta_2)$ < -129 deg (Paper VII)
  implies electromagnetic energy outflow in M87*

- This inference requires we know the **rotation direction**
  - We assume fieldlines **co-rotate** with the emitting material. (the angular velocity & spin vector is into the sky)

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

Energy Outflow

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

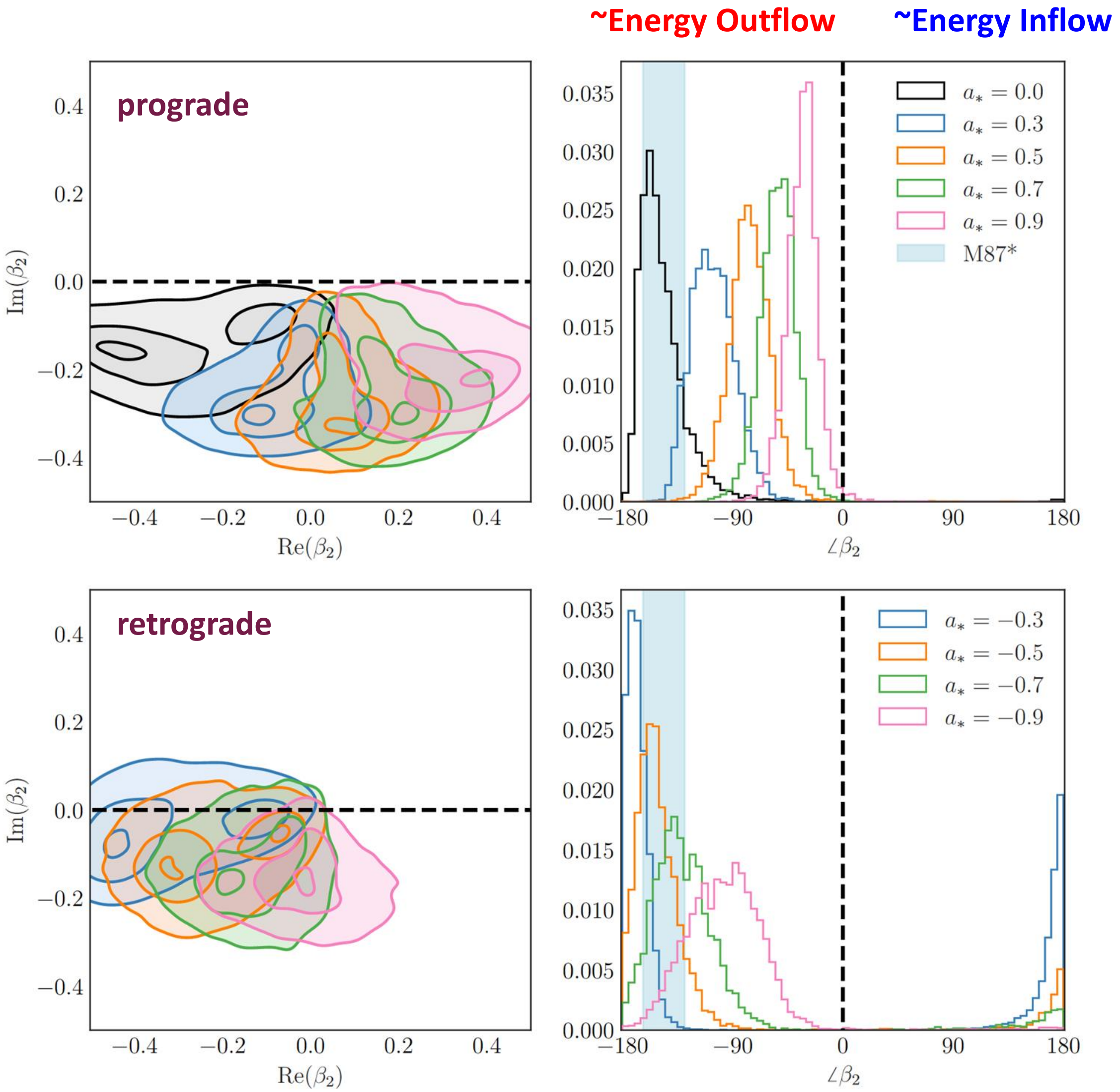


$-\pi < \angle\beta_2 < 0$

Chael+ 2023

Does the relationship between arg(β_2) and energy flux persist in **GRMHD models** of M87*?

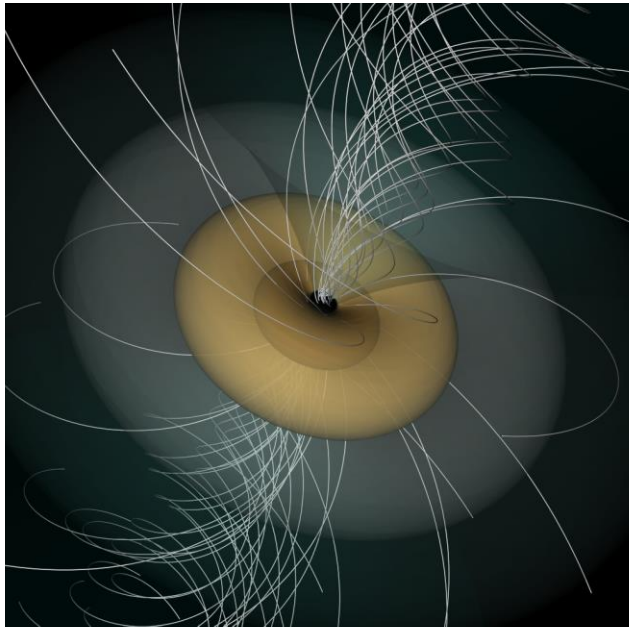
- M87* images from KORAL MAD simulations (Narayan+ 2022)
- 1600 snapshots covering different 6 different electron heating models (inclination fixed to M87* value)
- Almost all simulation images have arg(β_2) consistent with energy outflow in our simple picture
- arg(β_2) has the **same qualitative dependence on spin** as in the BZ monopole model



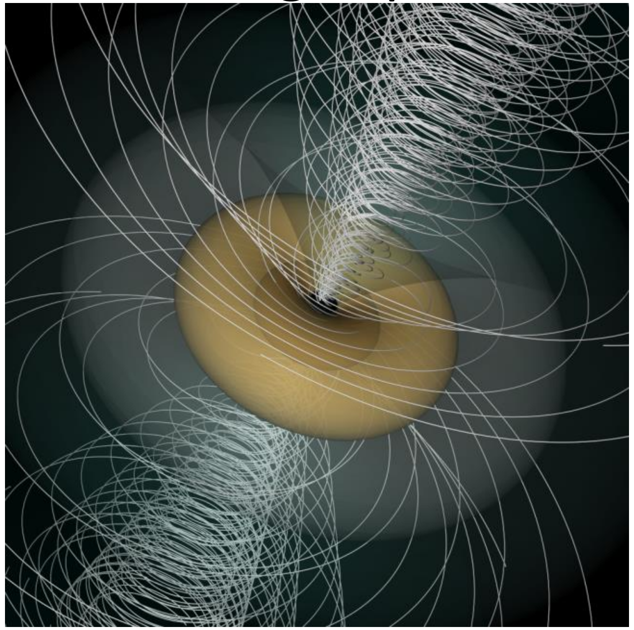
Chael+ 2023

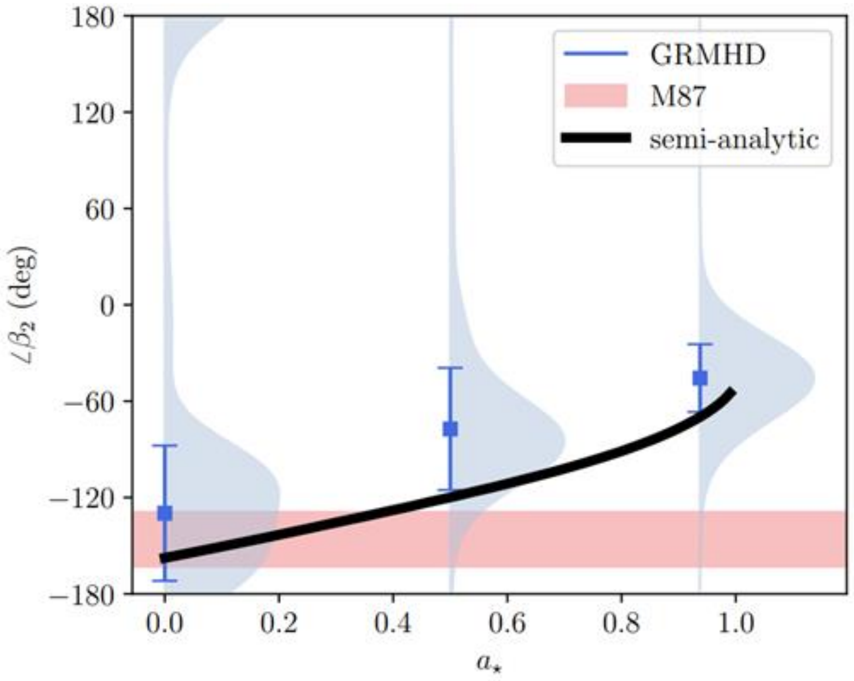
arg(β_2) has a strong dependence on BH spin in these models

Low Spin



High Spin



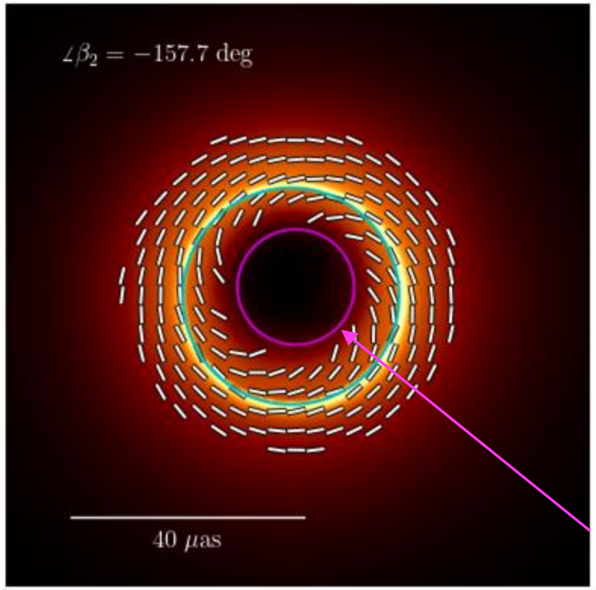


- BH **spin winds up initially radial fields**, so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding will
  - □ increase the Poynting flux (BZ jet power)
  - □ make the observed polarization more radial

Image credit: George Wong

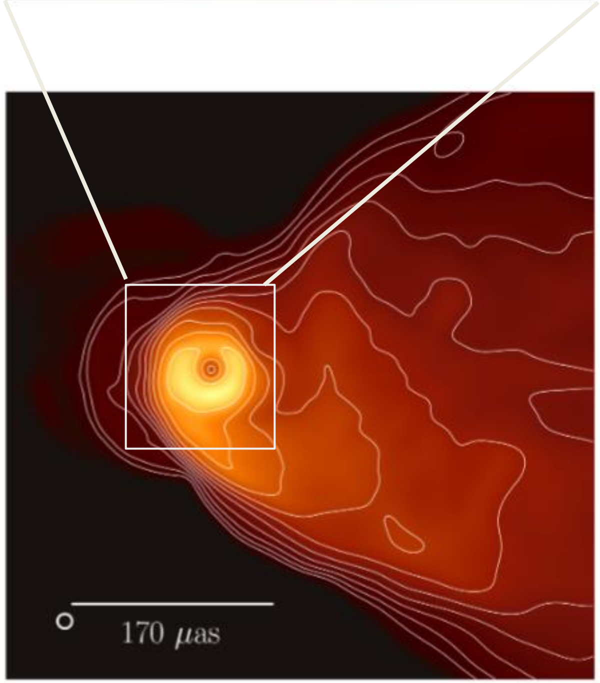
EHT/ngEHT next steps

- EHT Paper VII measurements of arg(β_2) suggest **electromagnetic outflow on scales of ~5M** in M87*.
- We can't yet be 100% sure if this energy outflow
  - is spin powered
  - or powers the large-scale jet
  - **the ngEHT could answer these questions!**
- We need **high-dynamic range, polarized ngEHT images** to:
  - Measure arg(β_2) **down to the horizon**
  - Connect the energy flux **from horizon scales out through the jet base**



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

"inner shadow"



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

Takeaways:

- The EHT has finally analyzed M87* in full polarization

- The structure of linear polarization is robustly constrained. Circular polarization is detected but the structure is not constrained.

- EHT linear polarization images show **~20% polarization** with an **azimuthal pattern** of polarization angles at 20 microarcsec scales. Circular polarization on these scales is **<4%**

- The EHT images can be used to constrain GRMHD simulation models of the emission region:
    - self-consistently including Faraday rotation and conversion effects is important

- The polarization data singles out magnetically arrested models:
    - **the magnetic field is dynamically important at the event horizon in M87***
    - These models naturally produce enough Faraday rotation to explain observed RM and low linear and circular polarization fractions

- The azimuthal structure of the linear polarization in M87* is consistent with outward Poynting flux
    - Simple model prediction is upheld in GRMHD simulation images.