Insights from Polarized Black Hole Images

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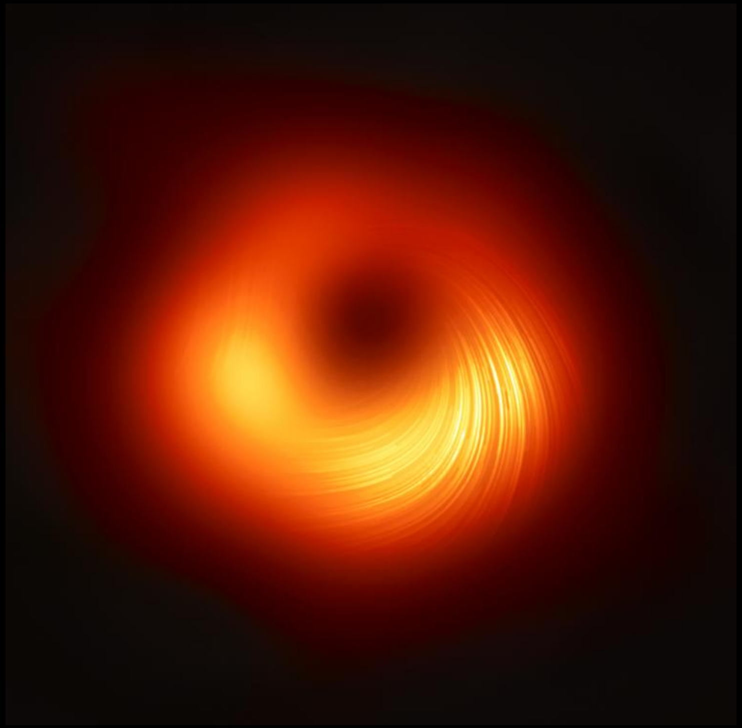
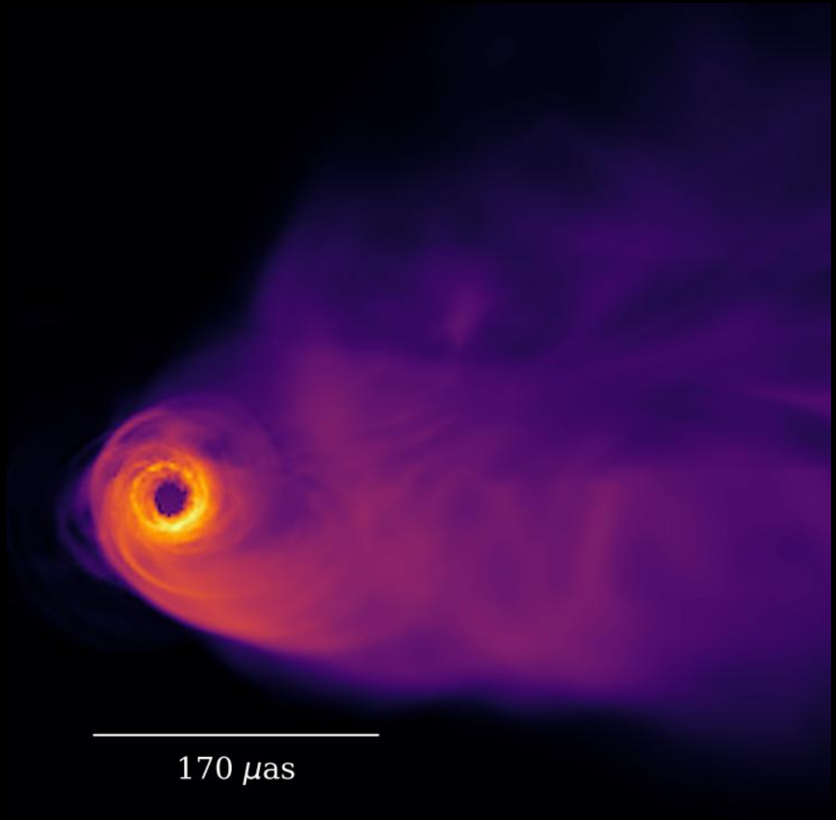
Princeton Gravity Initiative

June 12, 2025

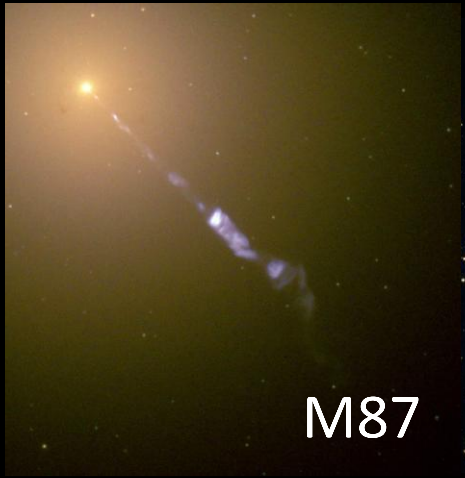




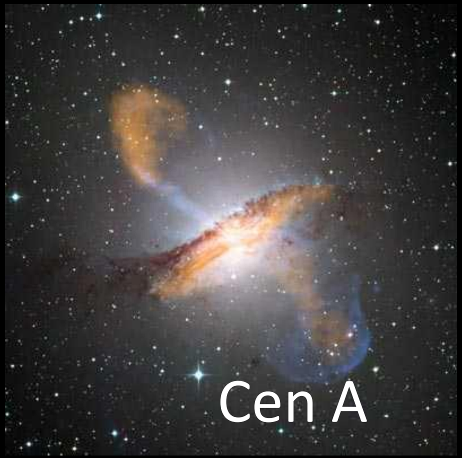
Princeton gravity Initiative

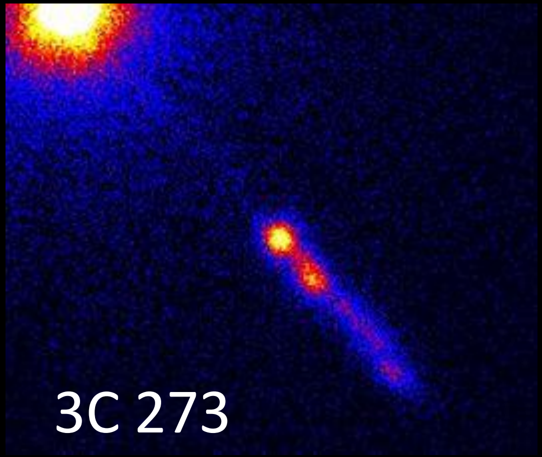
Event Horizon Telescope

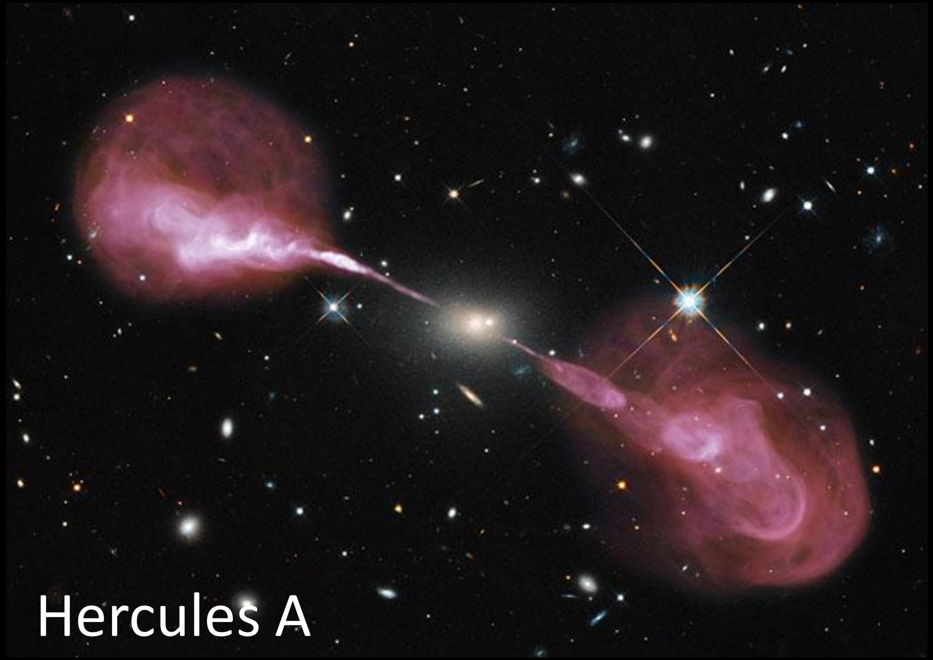
Supermassive black holes and jets are everywhere


M87


Cyg A

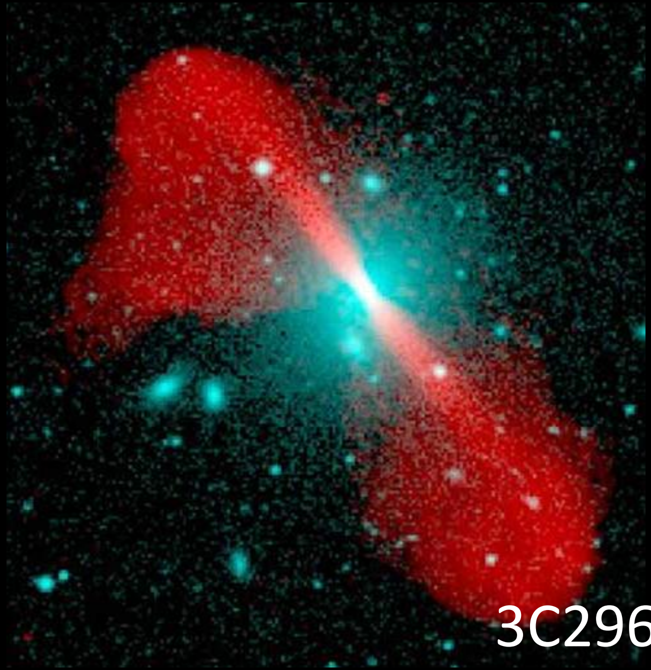

Cen A


3C 273


Hercules A


NGC 1265

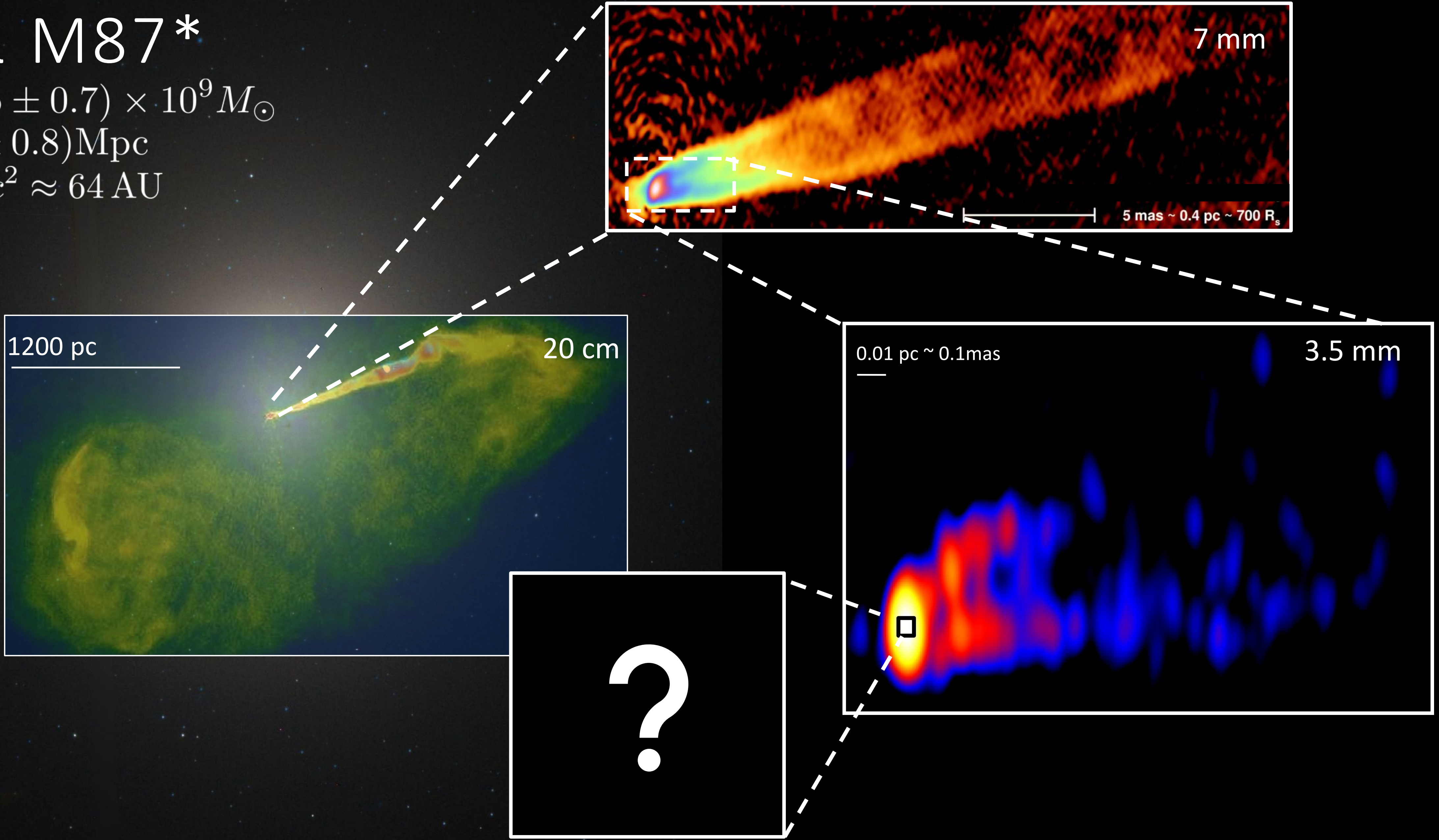
3C31


3C296

Credits: Sara Issoun, (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C293, Chandra),(Hercules A, HST/VLA),(NGC1265,M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; SDSS), (3C31, VLA), (3C296, AUI, NRAO)

M87 & M87*

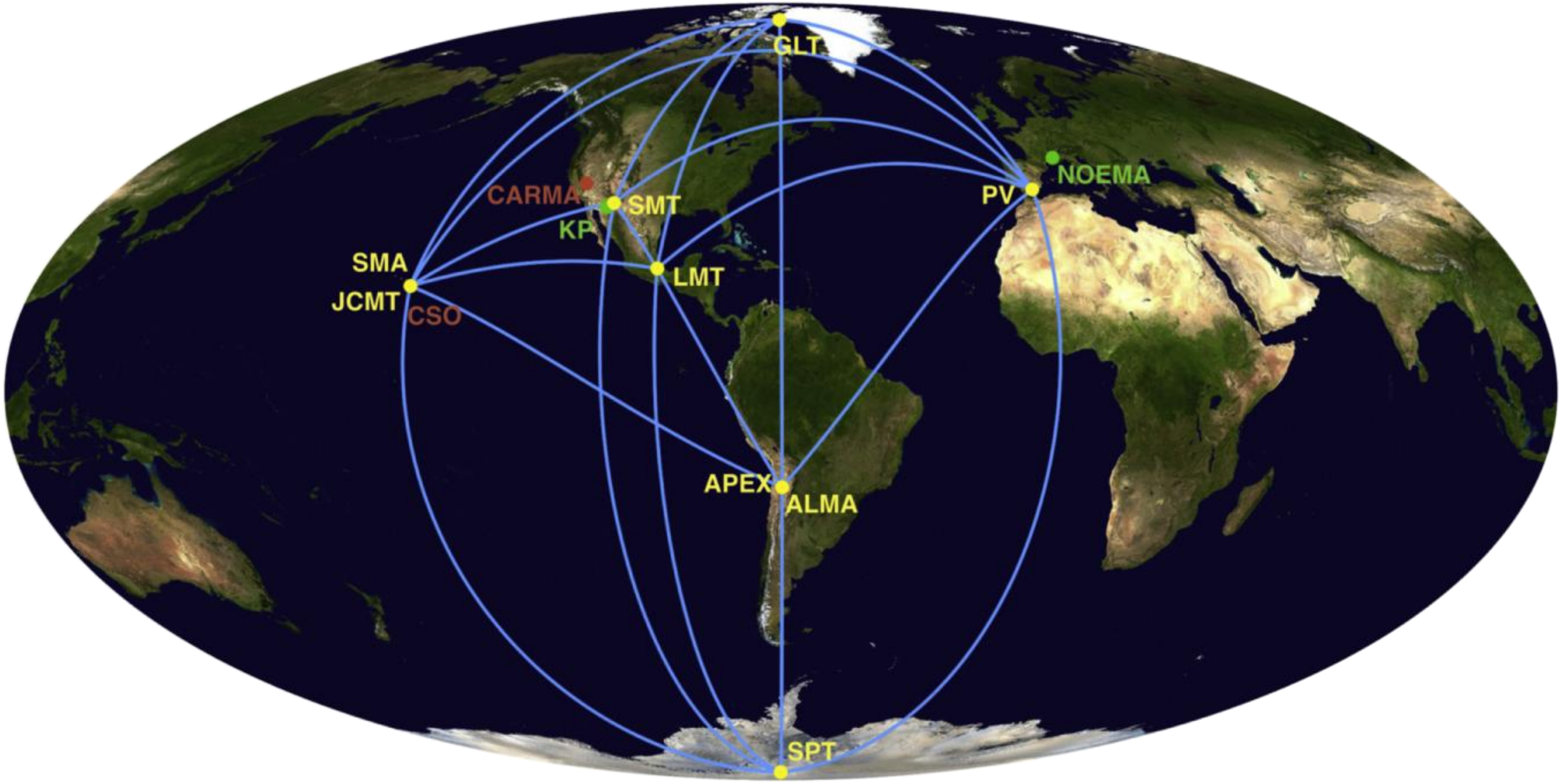
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$R_\mathrm{s} = 2GM/c^2 \approx 64\,\mathrm{AU}$



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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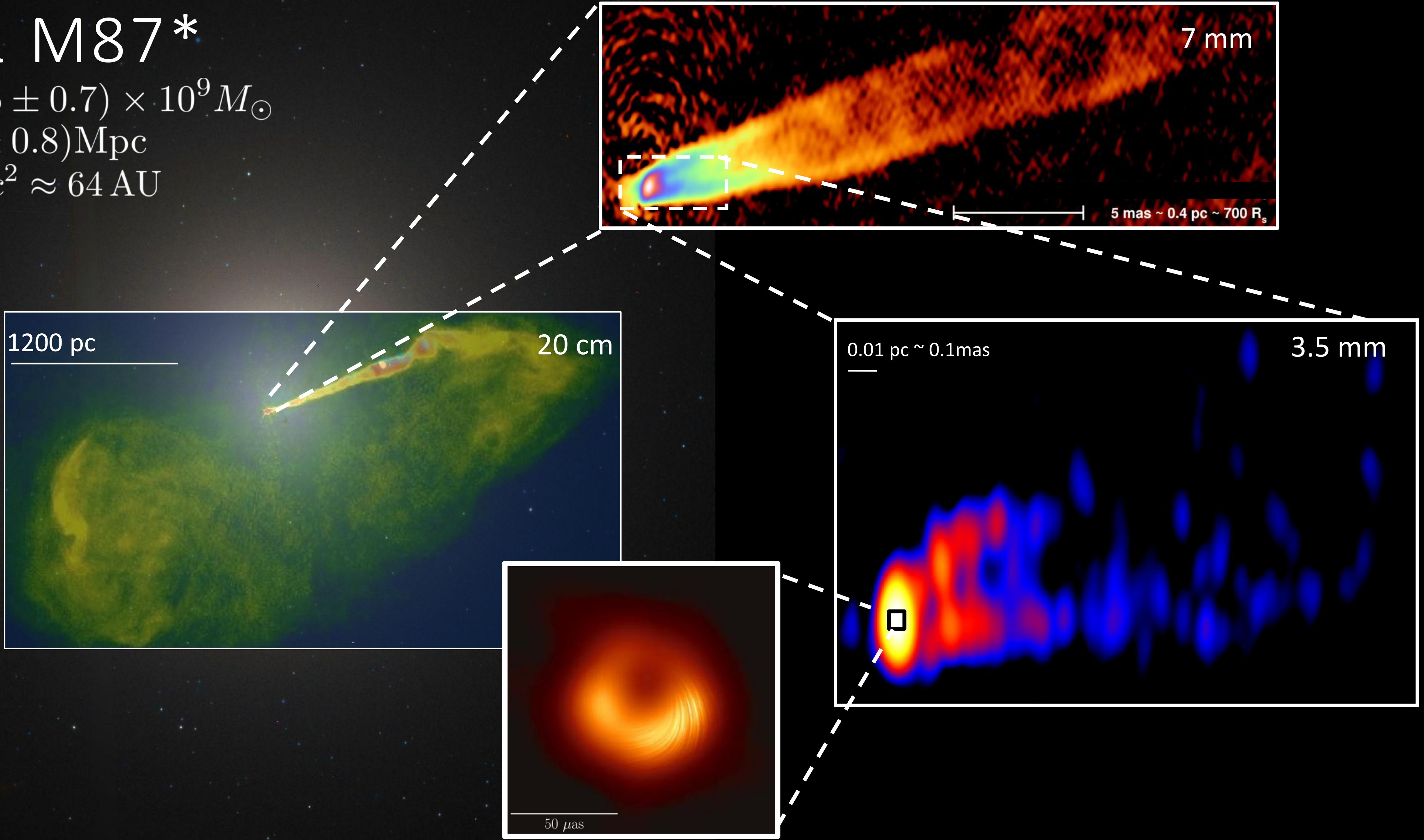
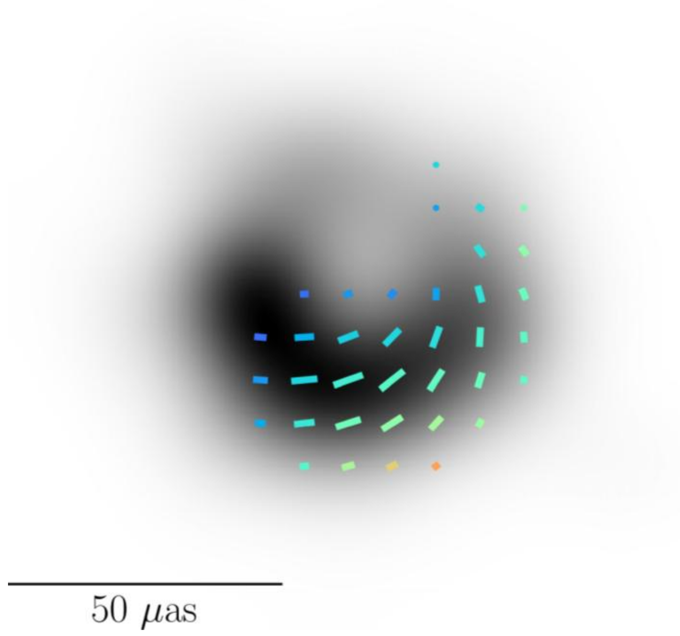
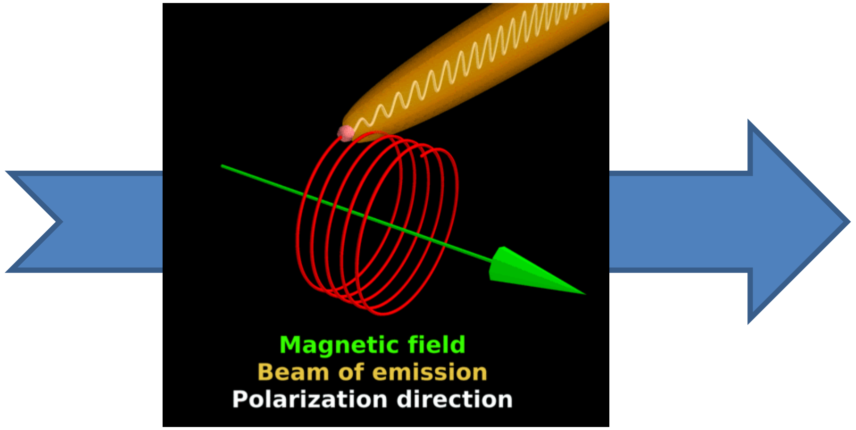


Can polarized EHT images tell us how jets are launched?

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

Why polarization?



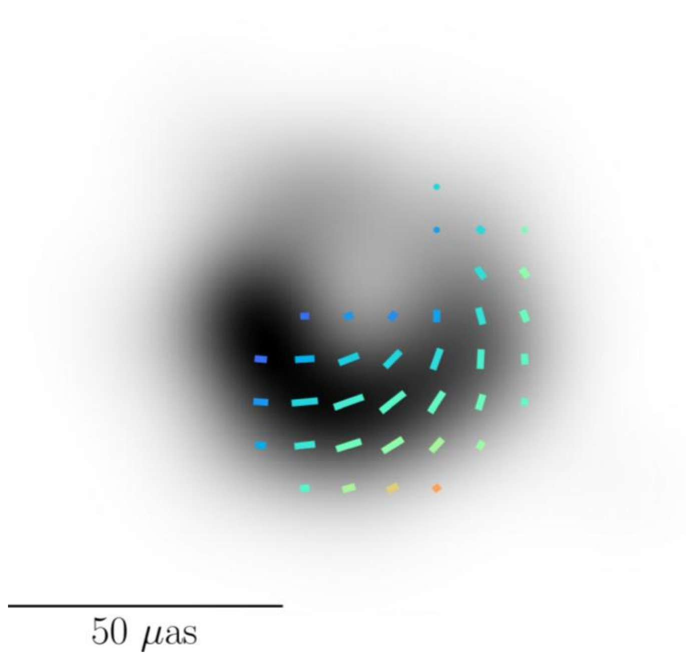


Magnetic field geometry in the emission region!

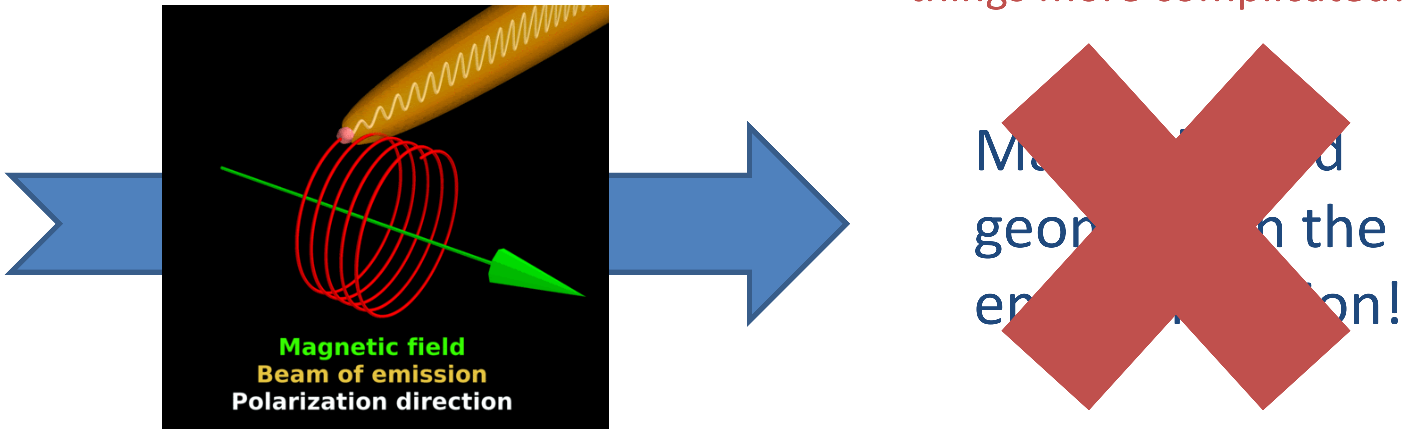
- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines

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?

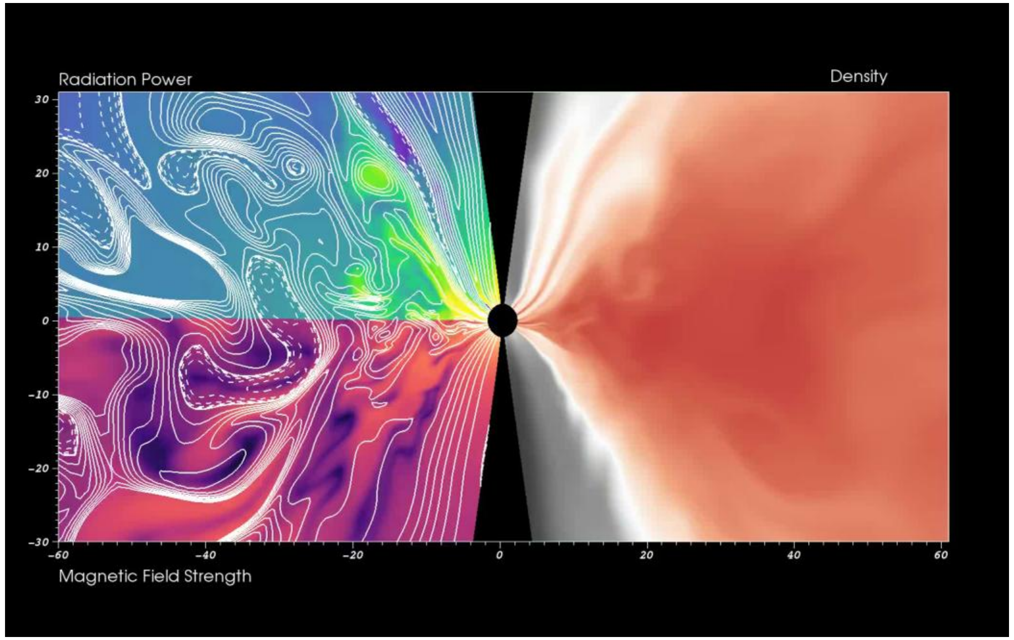
2. What can polarized EHT images tell us about jet launching?

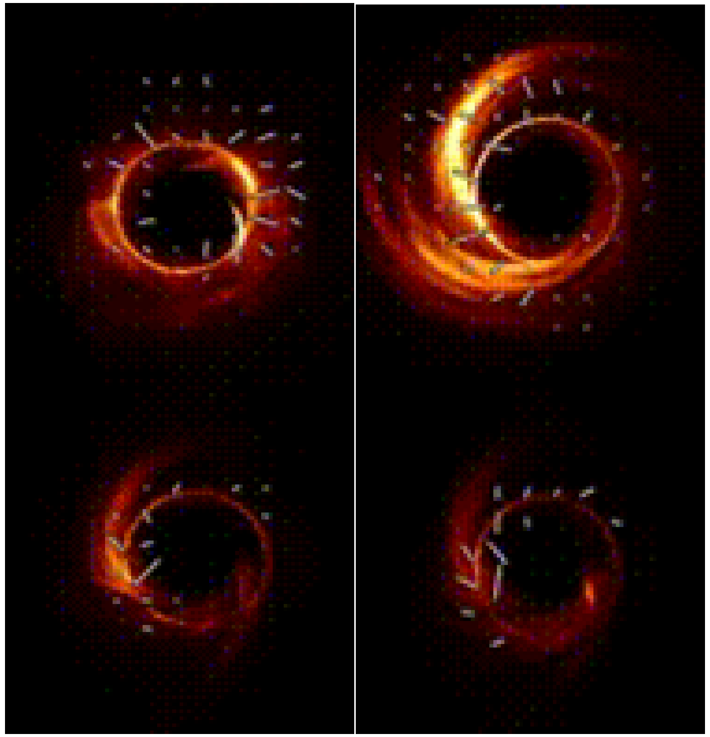
3. What’s next?

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

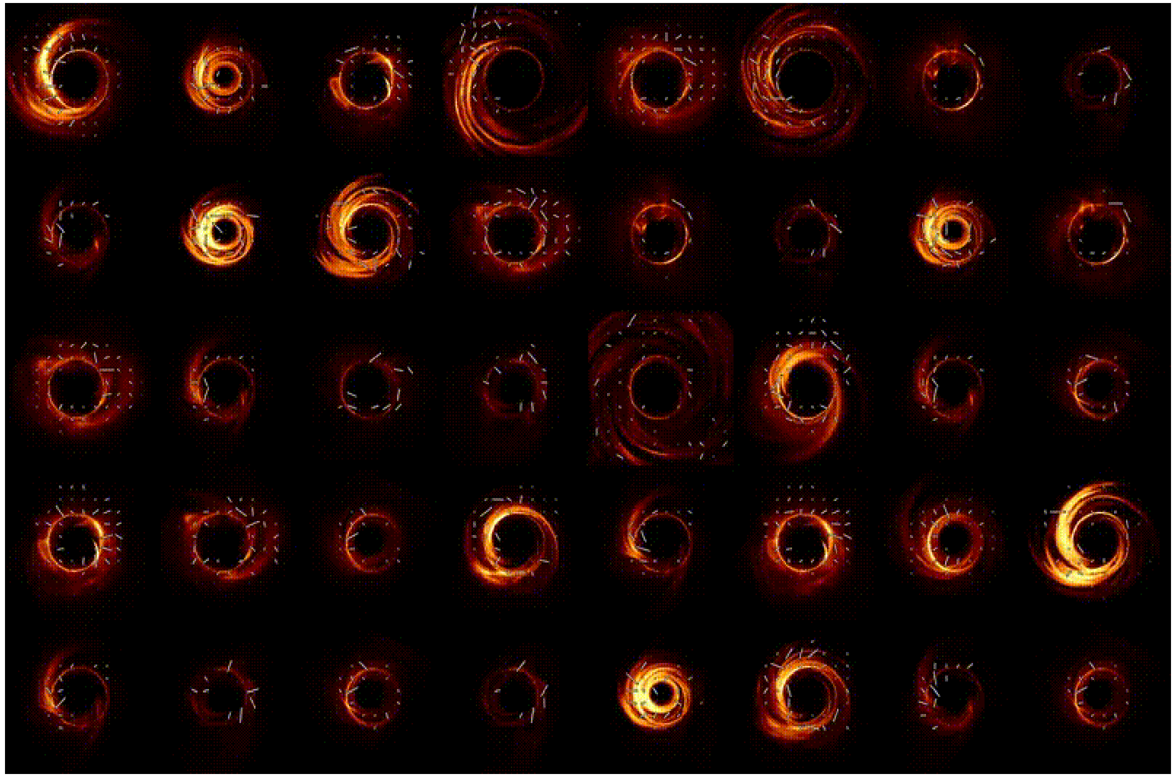
Solve coupled equations of plasma dynamics and magnetic field for low-luminosity accretion in Kerr spacetime

GR Radiative Transfer

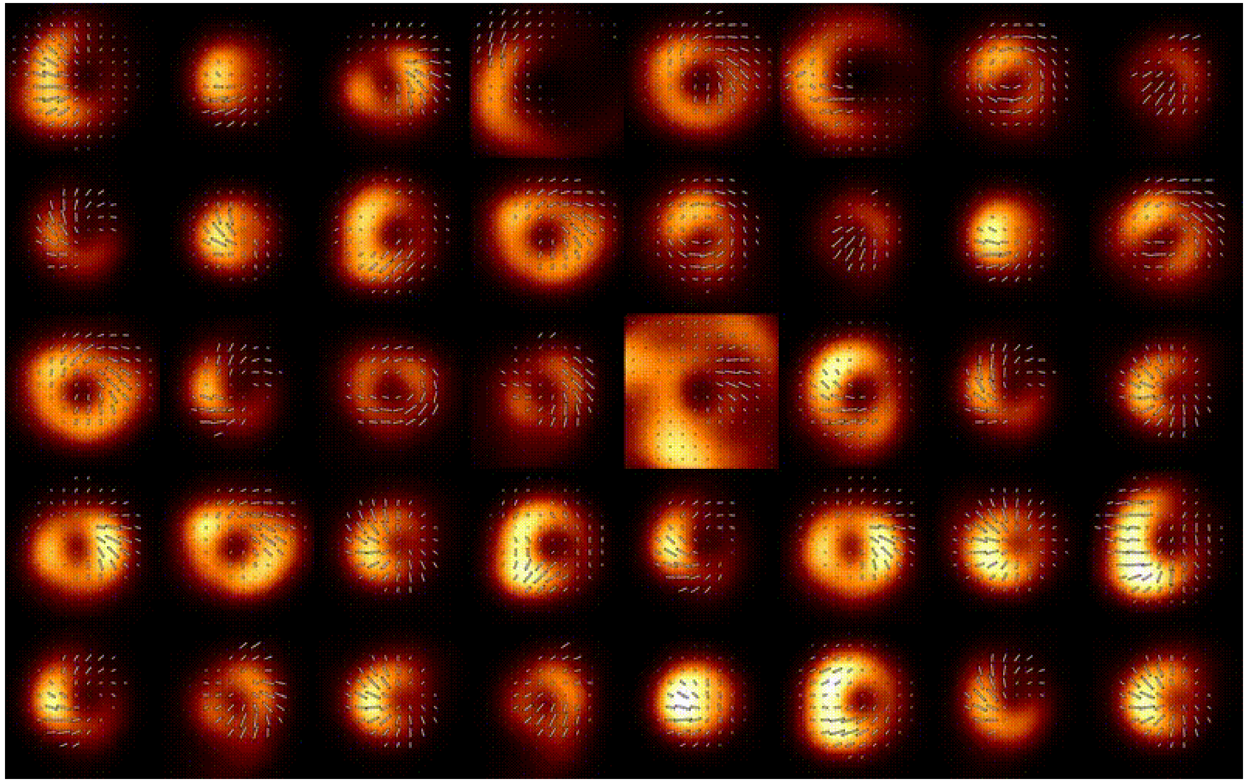
Track light rays and solves for the polarized radiation (including Faraday effects)

Movie Credits: **Chael**+ 2019 (left), 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

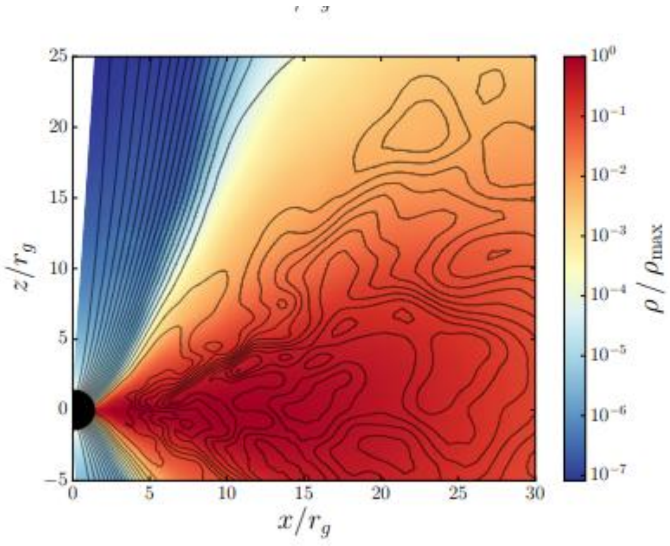
$$\boxed{T_\mathrm{e} \neq T_\mathrm{i} \neq T_\mathrm{gas}}$$

Animation credit: Ben Prather

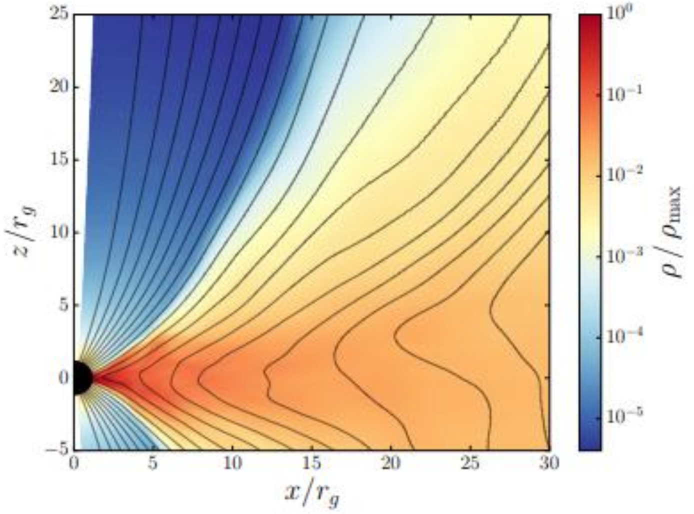
What is the magnetic field structure close to the horizon?

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

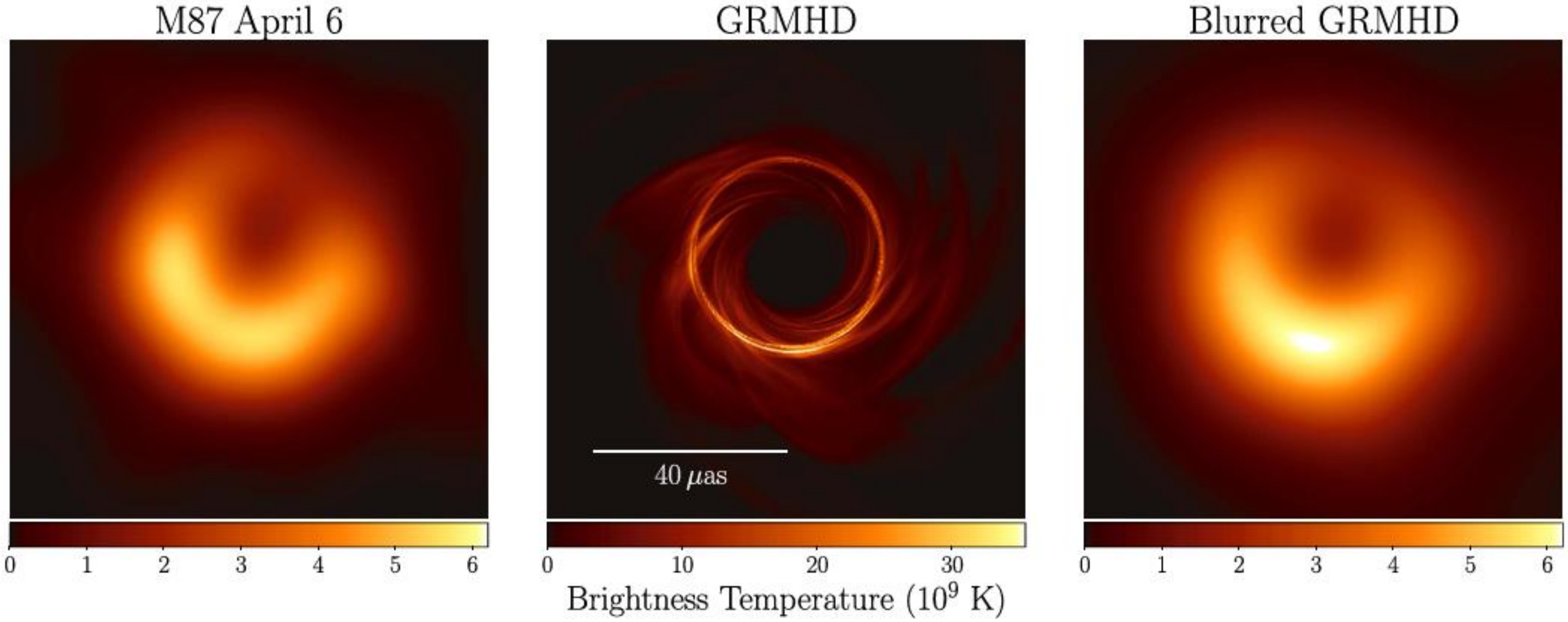
BH spin

magnetic flux

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012

Image credit: Riordan+ 2017

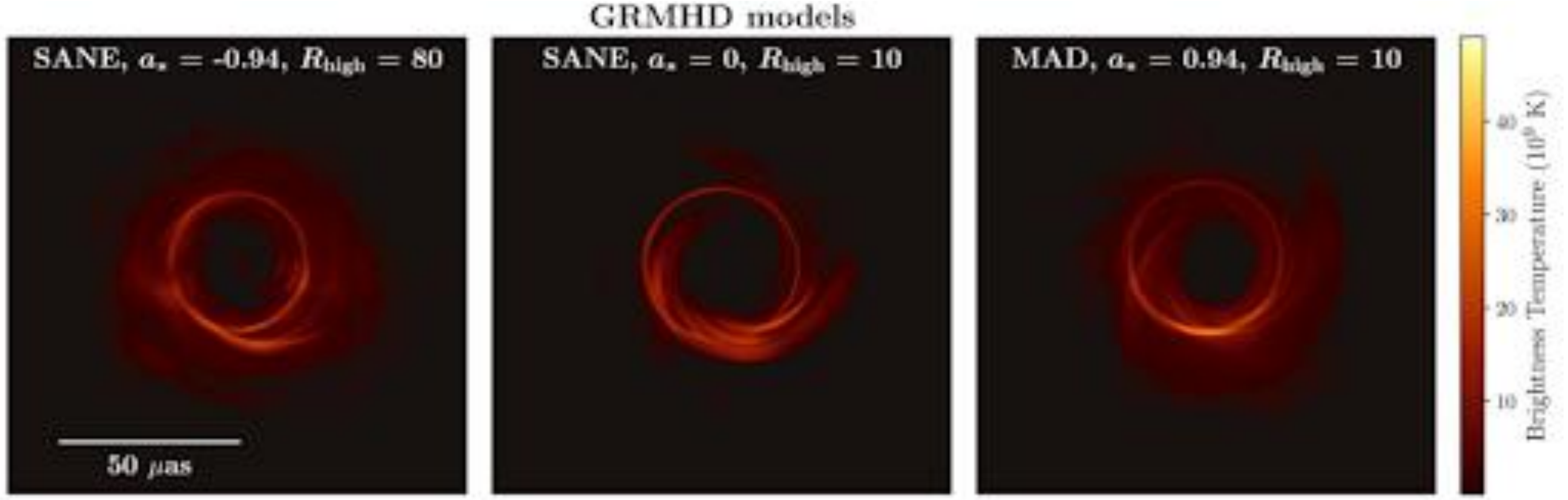
EHT Images are consistent with GRMHD/LLAGN Picture



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

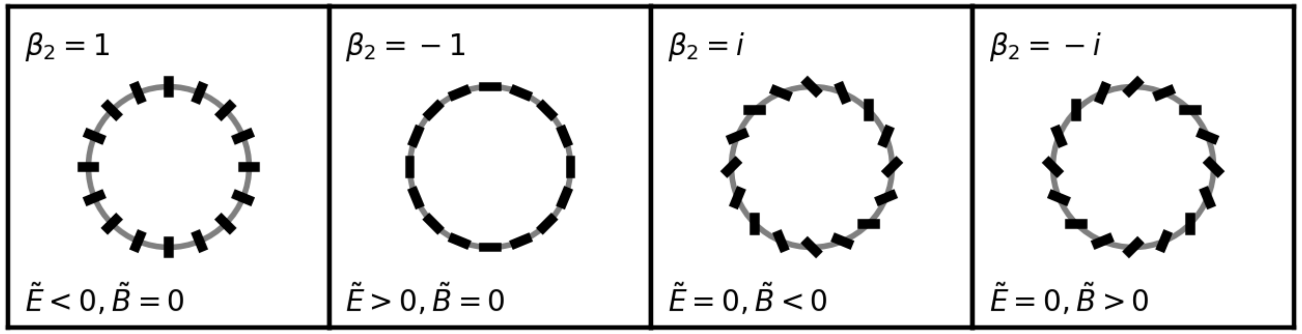
Summarizing an image: Polarization

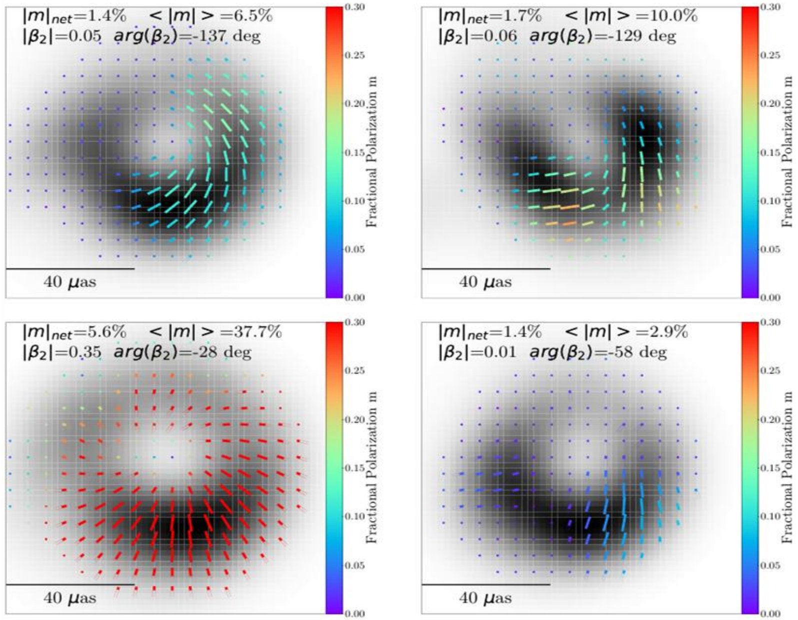
Unresolved and Resolved polarization fractions

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

Azimuthal structure
2nd Fourier mode

$$\beta_2 = \frac{1}{I_{\rm ring}} \int\limits_{\rho_{\rm min}}^{\rho_{\rm max}} \int\limits_{0}^{2\pi} P(\rho,\varphi)\, e^{-2i\varphi}\; \rho\, d\varphi\, d\rho$$

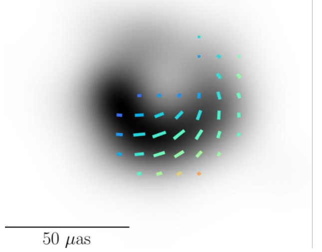




Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

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:

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

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

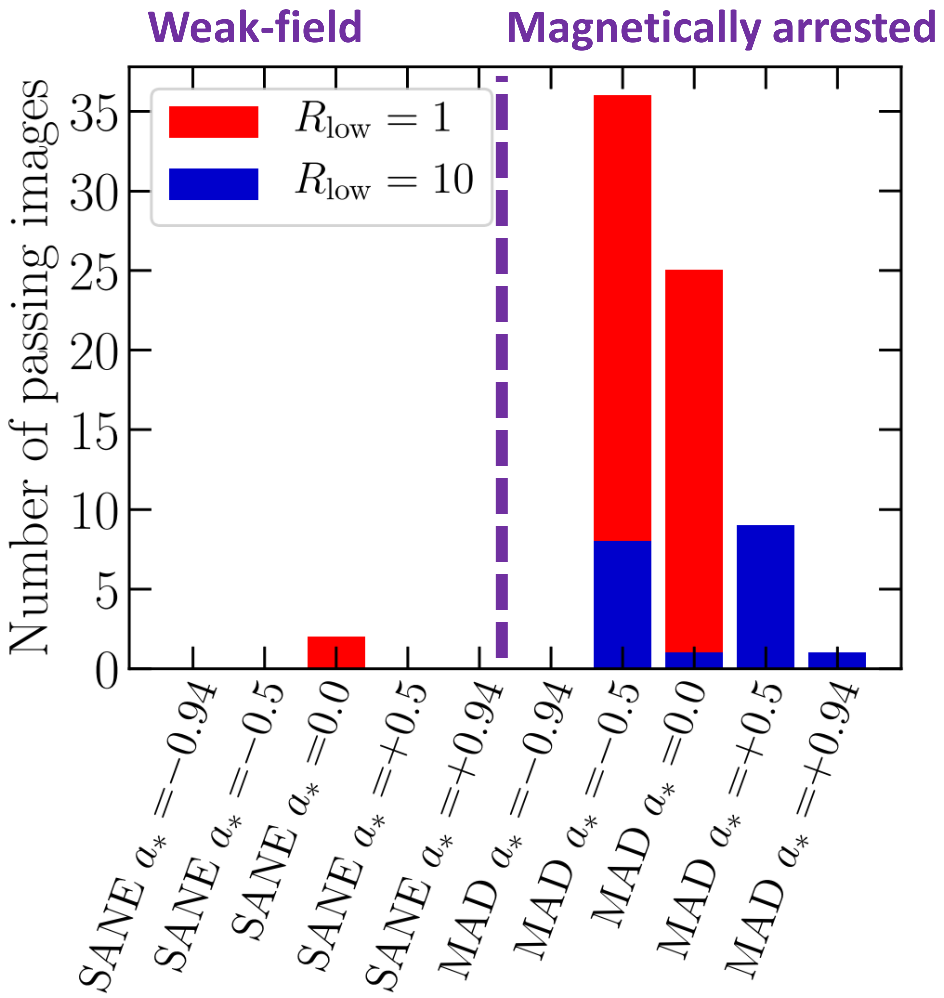
- Parameters from passing models agree with analytic model estimates:

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

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

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

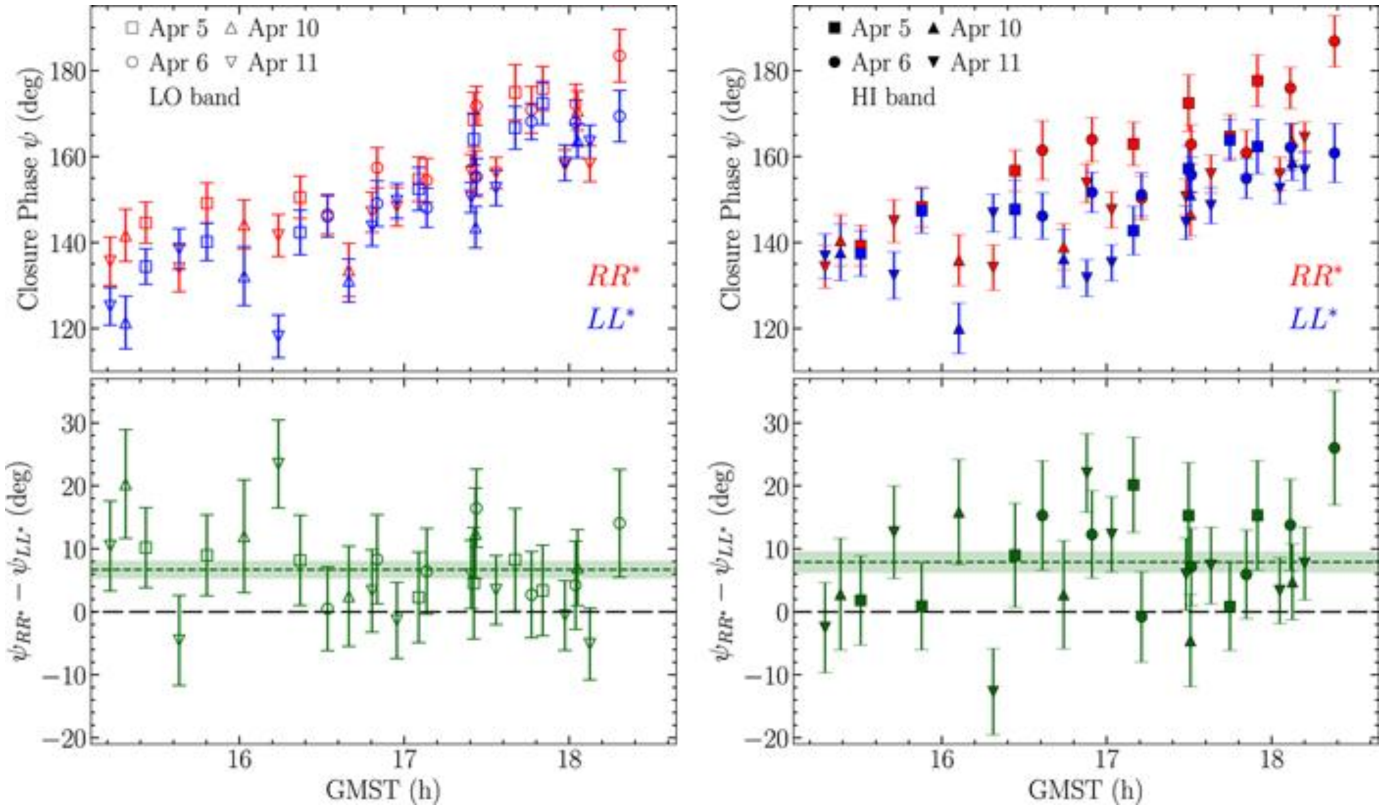
- Strong magnetic fields more easily launch Blandford-Znajek jets!



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

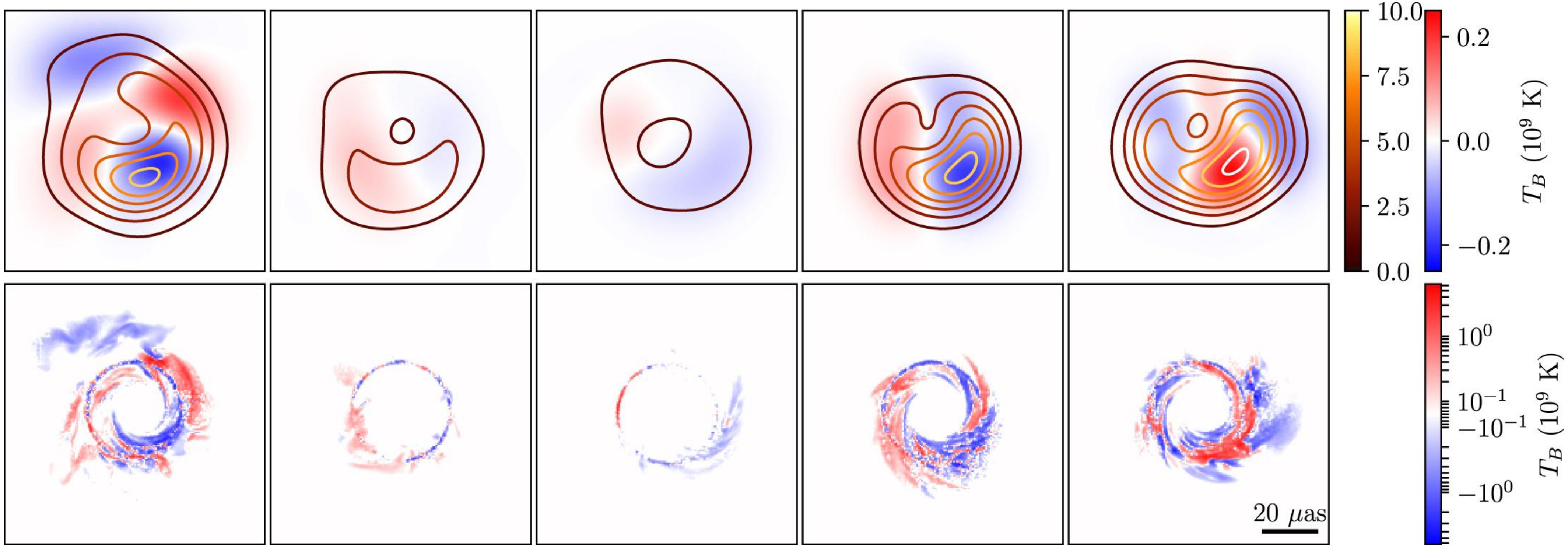
Horizon-Scale **circular polarization** is unambiguously detected by the EHT

- We detect an **offset** between robust **closure phases** in the RR and LL polarizations in both M87* and Sgr A*.
- Clear evidence of modest circular polarization in black hole images.
- Limited sensitivity and systematic gain uncertainty means we **cannot currently constrain the image structure** in circular polarization.



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

Passing simulations have **diverse circular polarization images**

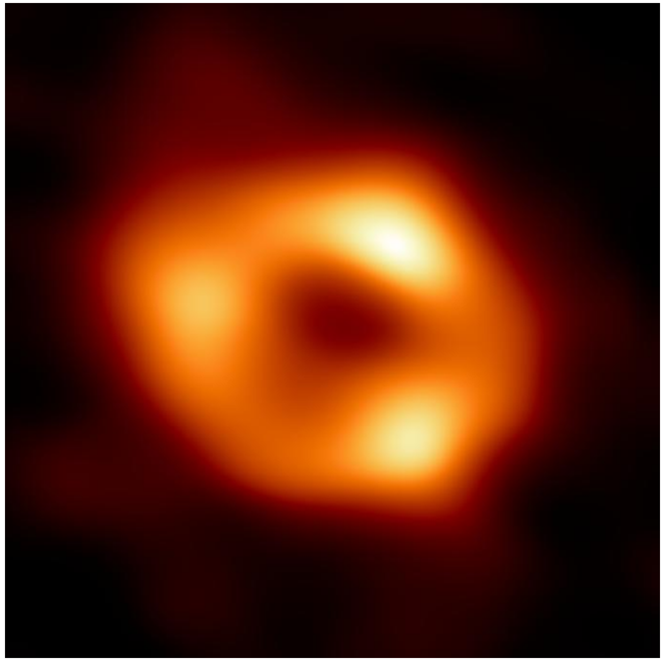


Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

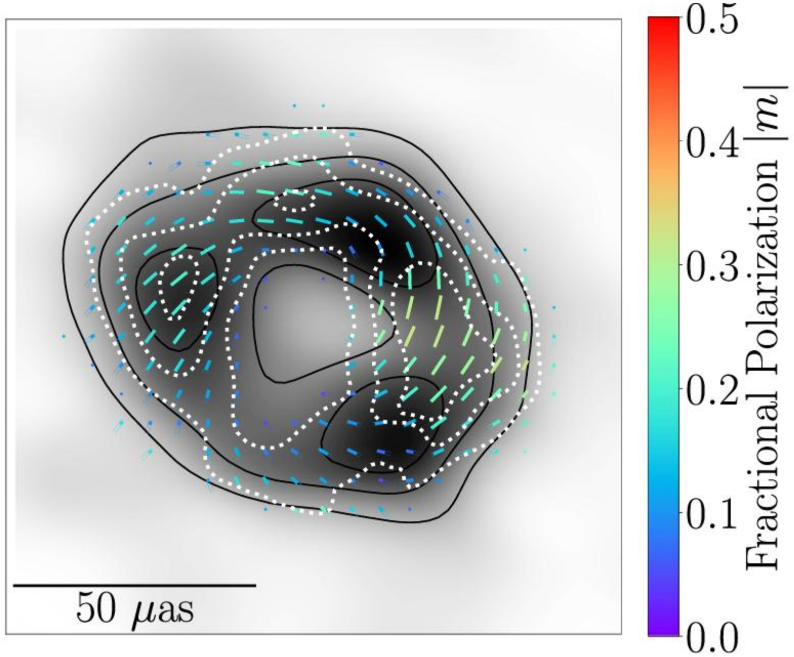
Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)
Ricarte+ 2021

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

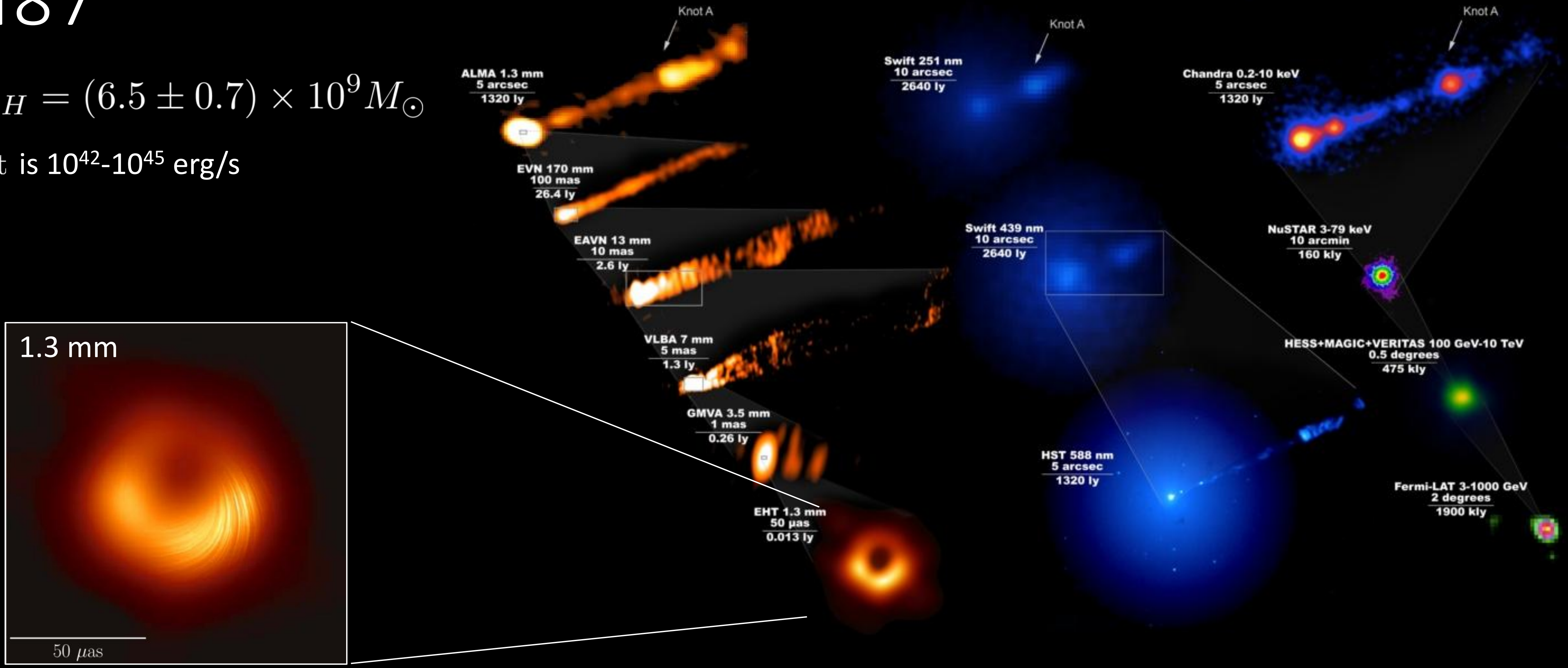
What can a polarized image of M87* tell us about energy flow & jet launching?

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**?

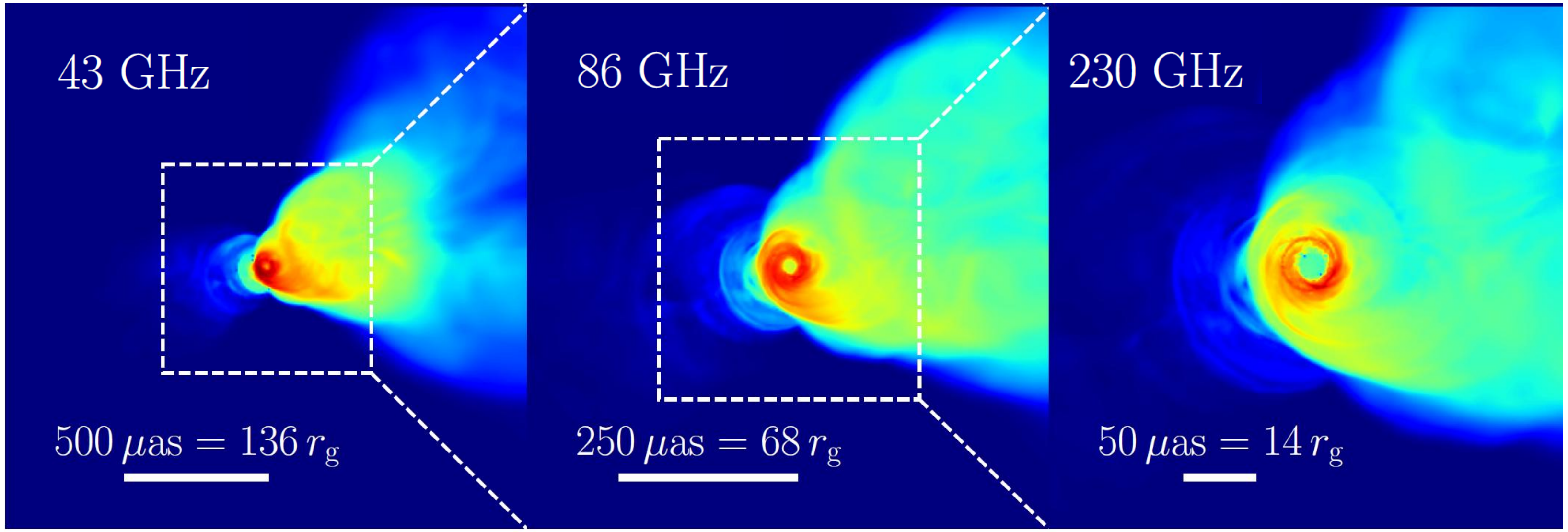
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

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?

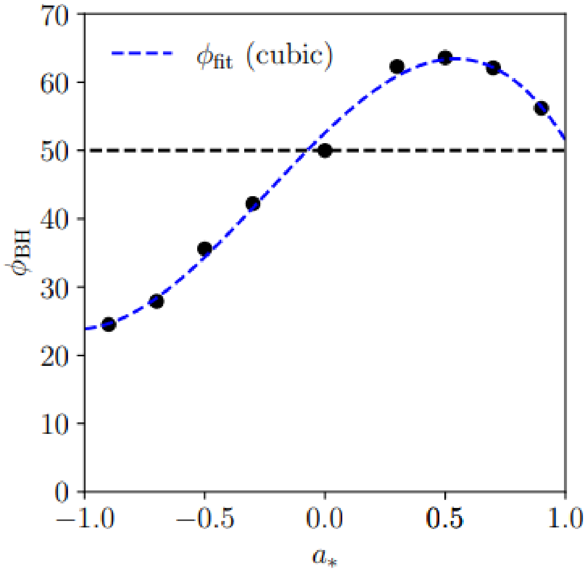


Chael+ 2019

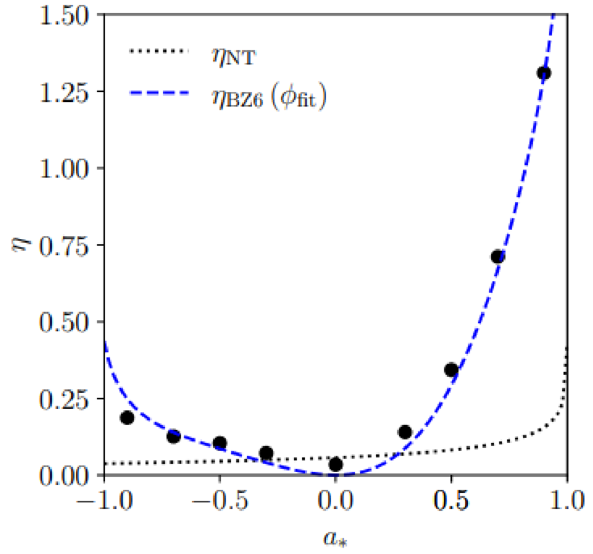
Jets in MADs are Blandford-Znajek

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

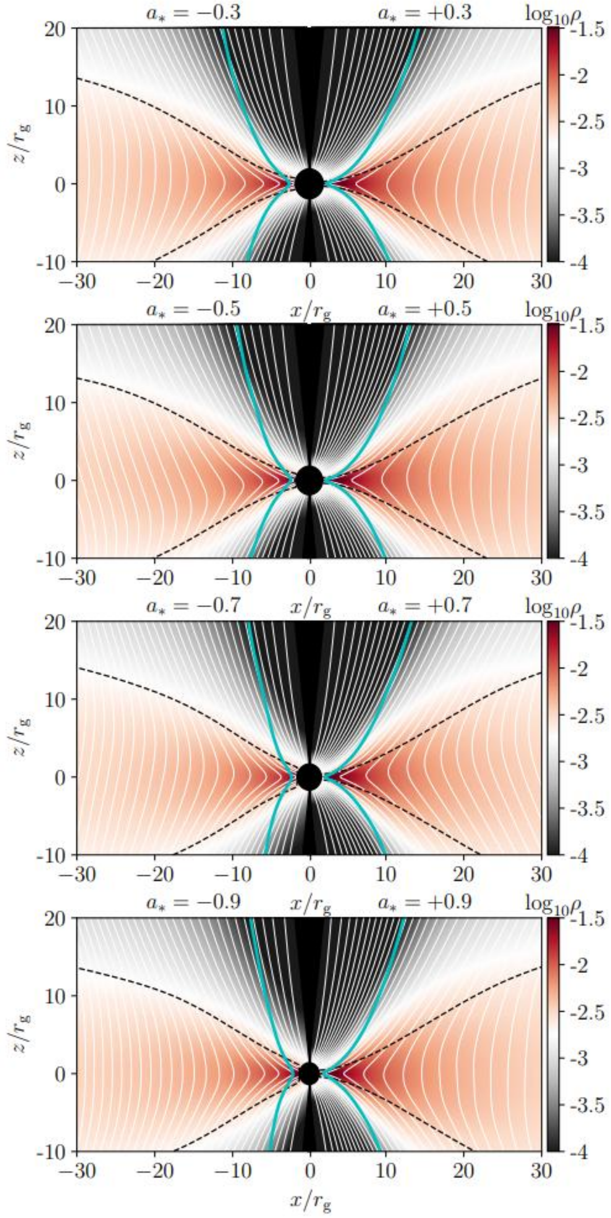
Magnetic flux though the horizon



Jet efficiency



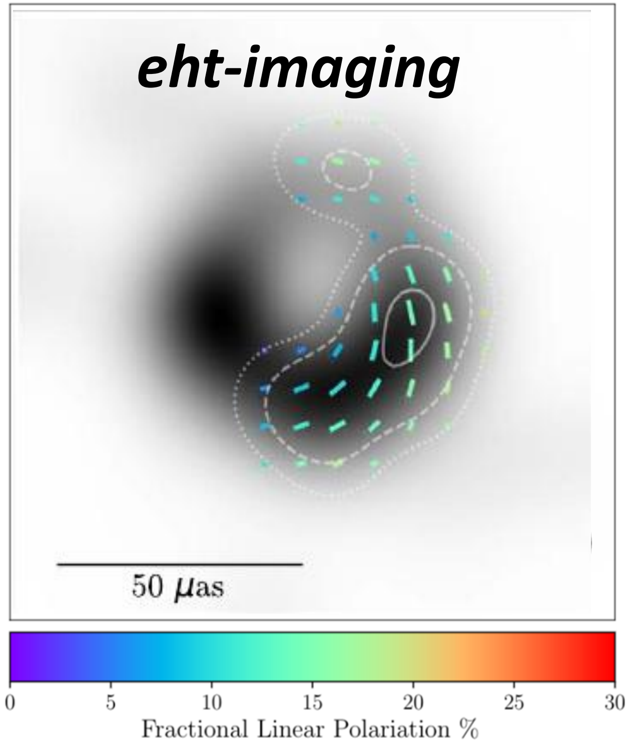
BH spin

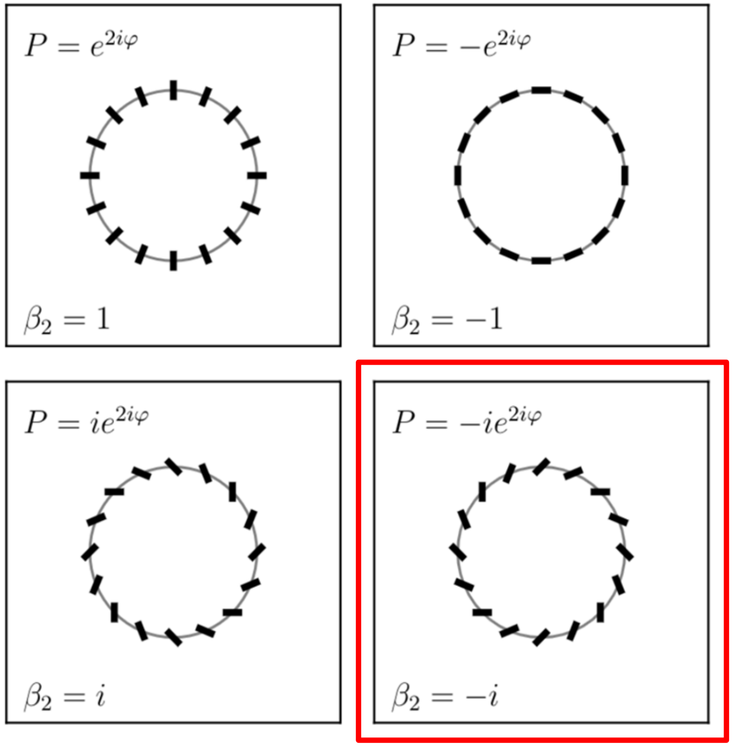


Time-and azimuth-averaged simulation data

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

Polarized Images of M87* and horizon-scale energy flow

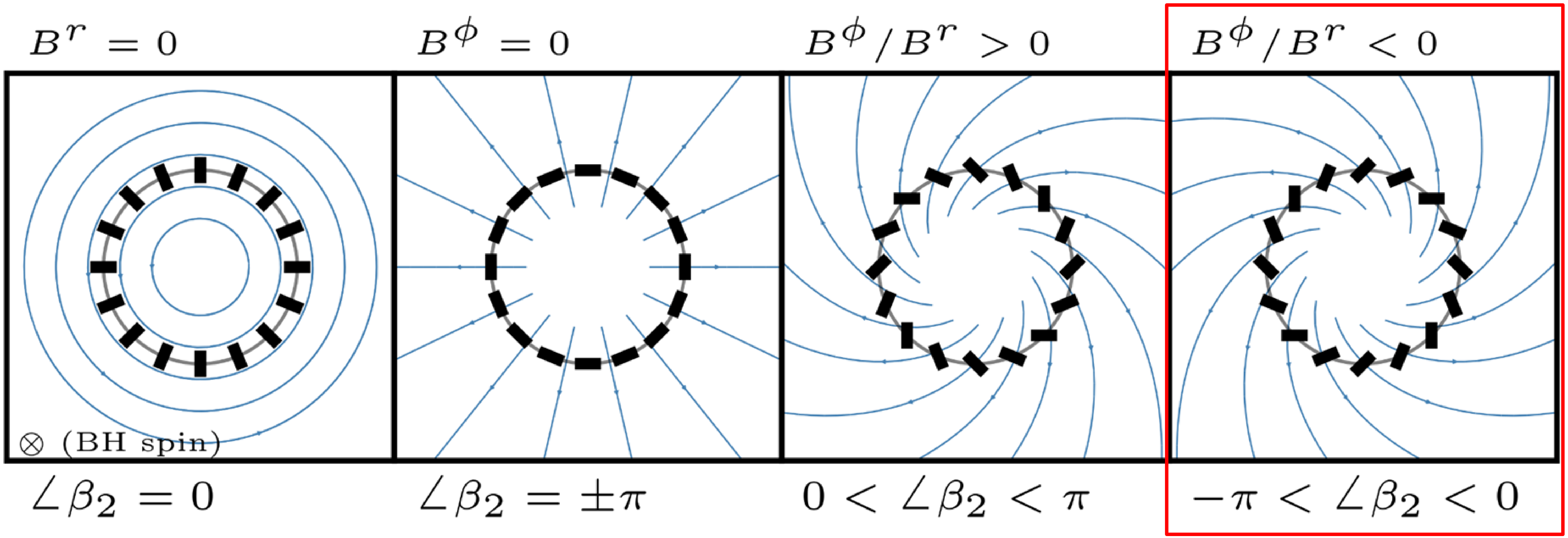




- The polarization spiral's 2nd Fourier mode ($\boldsymbol{\beta_2}$: Palumbo+ 2020) is the **most constraining** image feature
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

Cartoon model: β_2 is connected to the field pitch angle



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

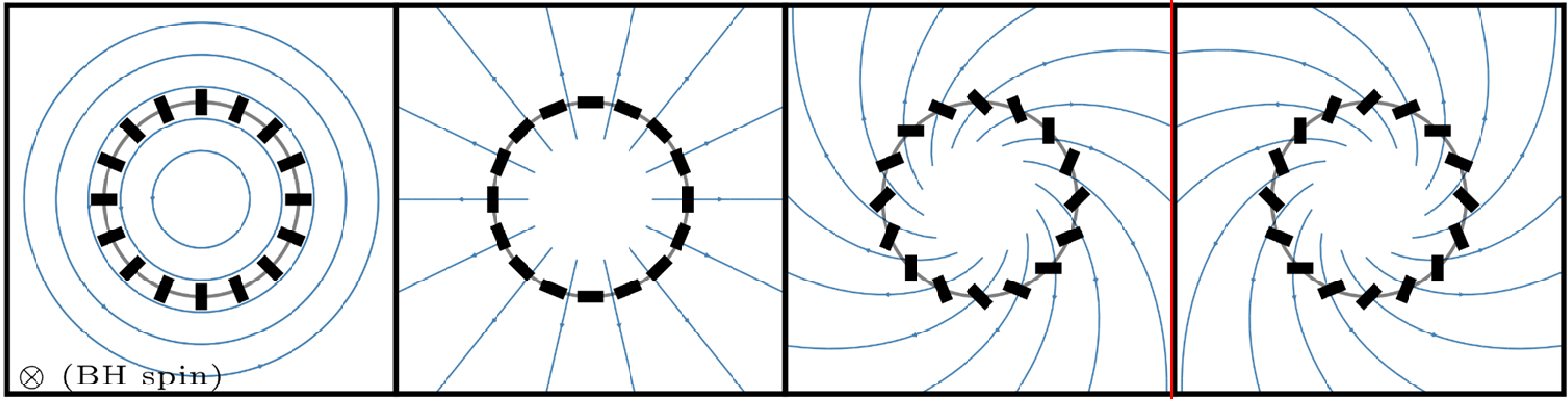
Chael+ 2023b

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

Energy Inflow

Energy Outflow

$B^r = 0$ | $B^\phi = 0$ | $B^\phi / B^r > 0$ | $B^\phi / B^r < 0$



$\angle\beta_2 = 0$ | $\angle\beta_2 = \pm\pi$ | $0 < \angle\beta_2 < \pi$ | $-\pi < \angle\beta_2 < 0$

Radial Poynting flux in Boyer-Lindquist coordinates:

$$\mathcal{J}^r_{\mathcal{E}} = -T^r{}_{t\,\mathrm{EM}} = -B^r B^\phi \underset{\substack{\uparrow \\ \text{fieldline angular speed}}}{\Omega_F} \Delta \sin^2\theta$$

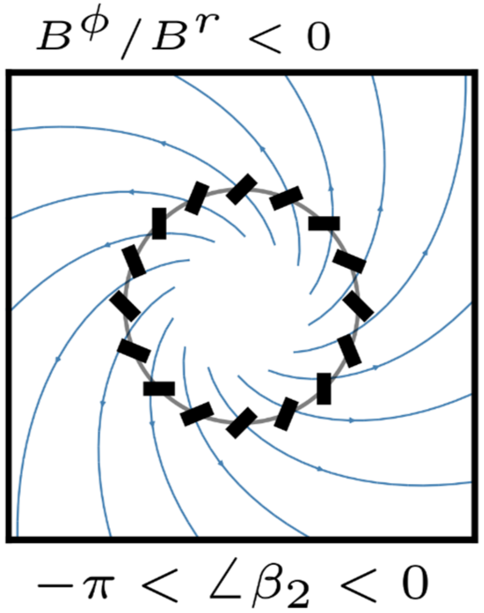
Chael+ 2023b

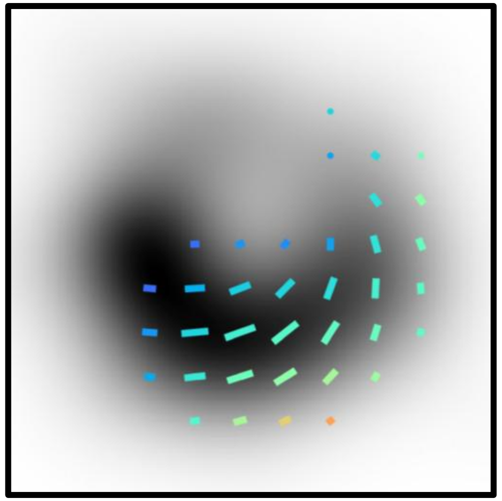
Near-horizon polarization is connected to the **electromagnetic energy flux**

- 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***

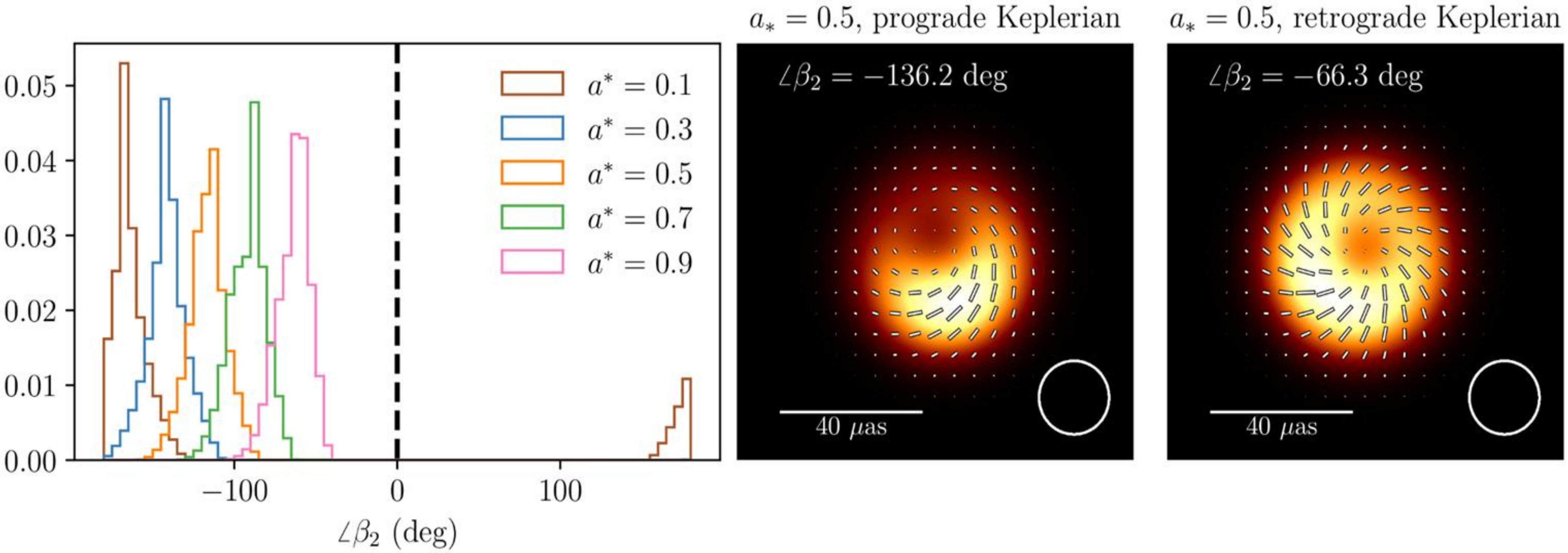
- Does this simple argument hold up in **more complicated models** of M87*?





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

β_2 in semi-analytic models of M87*



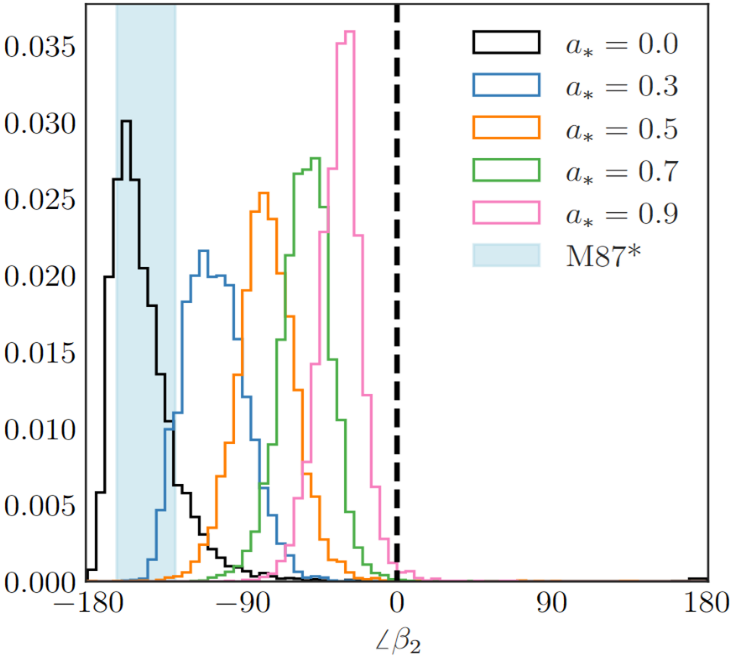
- We fix magnetic fields to the force-free BZ monopole solution (with energy outflow)
- We explore many models for the velocity of the emitting fluid
- Changes in fluid velocity do not significantly affect sign of arg(β_2) or trend with BH spin

Chael+ 2023b

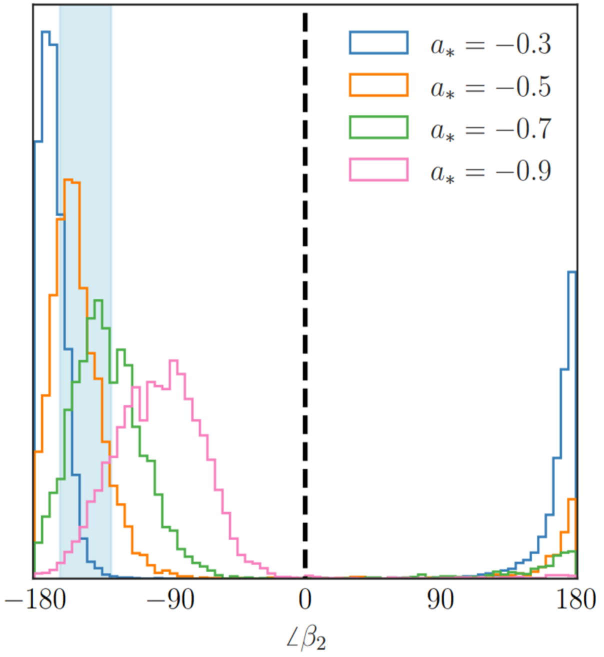
β_2 in MAD **GRMHD simulations** of M87*

- 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.

Prograde simulations

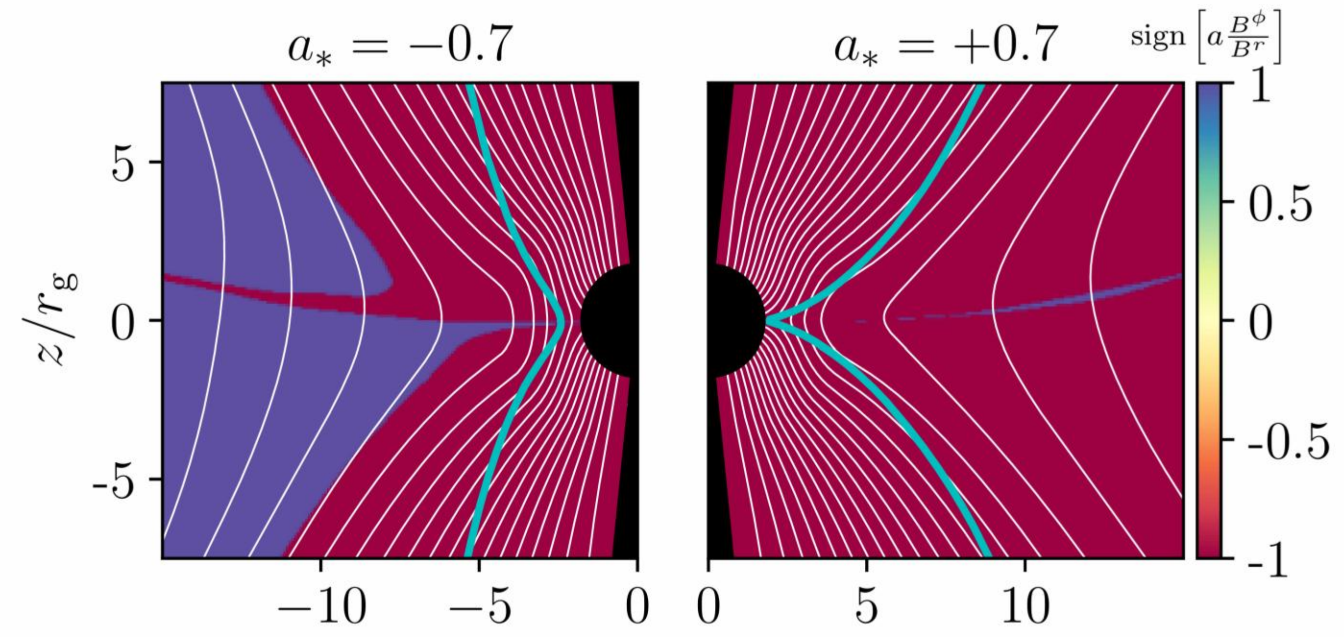


Retrograde simulations



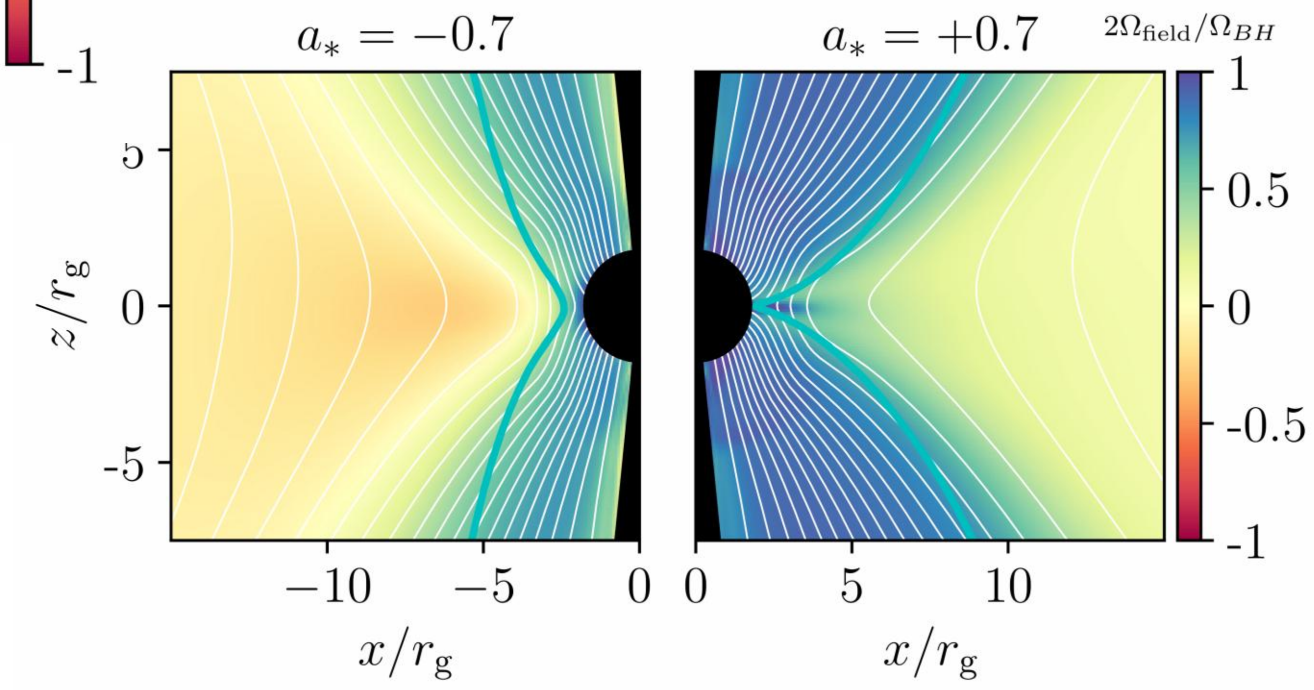
Chael+ 2023b

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



Sign of magnetic field pitch angle

Field-line angular speed



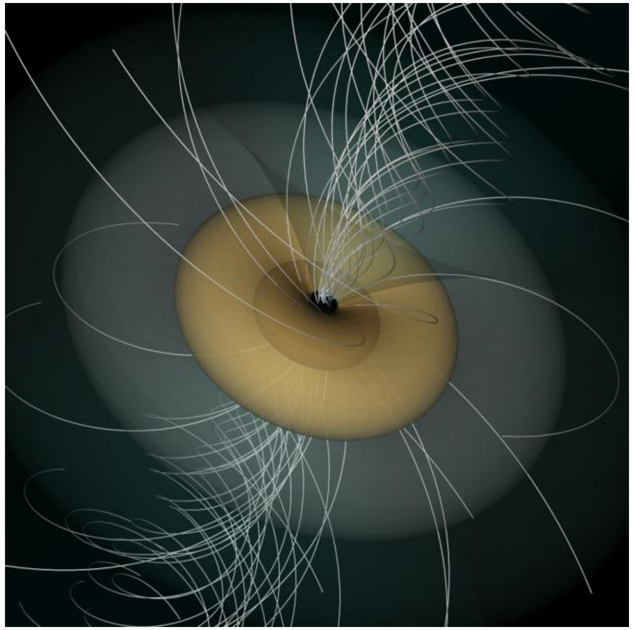
Even in **retrograde** simulations, field-lines in the 230 GHz emission region **co-rotate** with the black hole and have a negative B^ϕ / B^r

Chael+ 2023

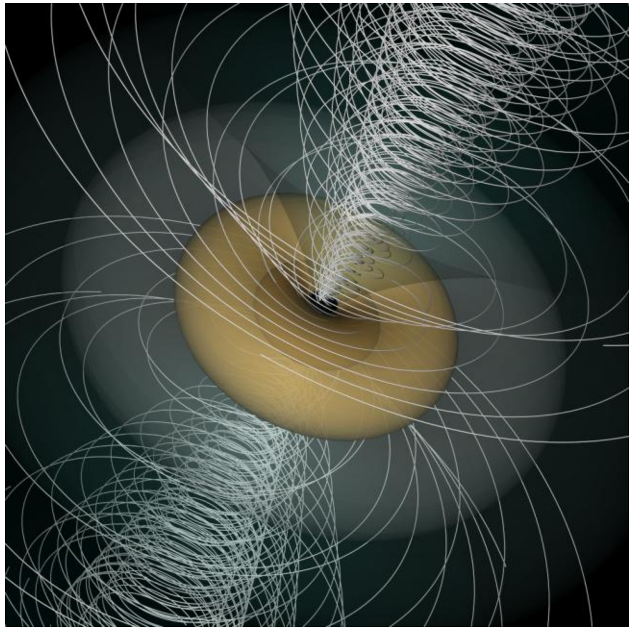
Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022, Wong+ 2021

Polarized images are **spin dependent**

Low Spin



High Spin

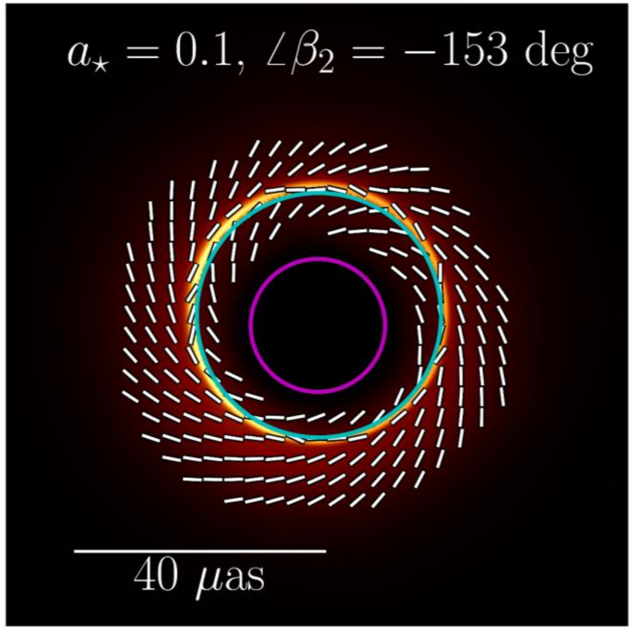


- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
    - increases the Poynting flux (BZ jet power)

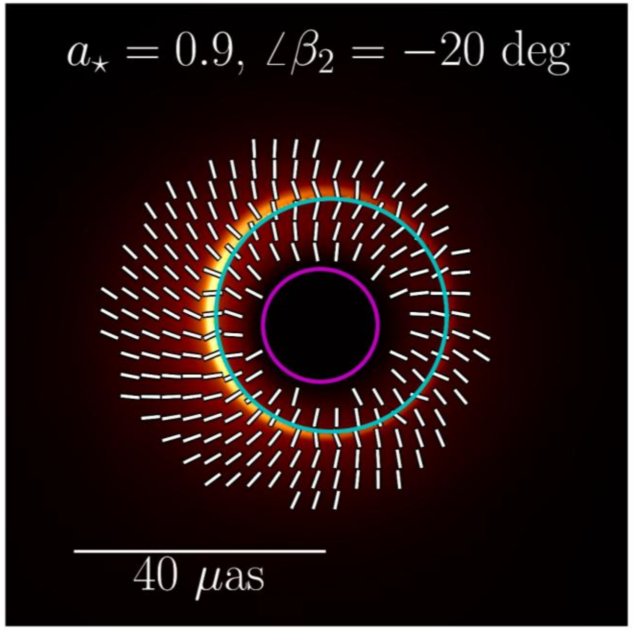
Image credit: George Wong

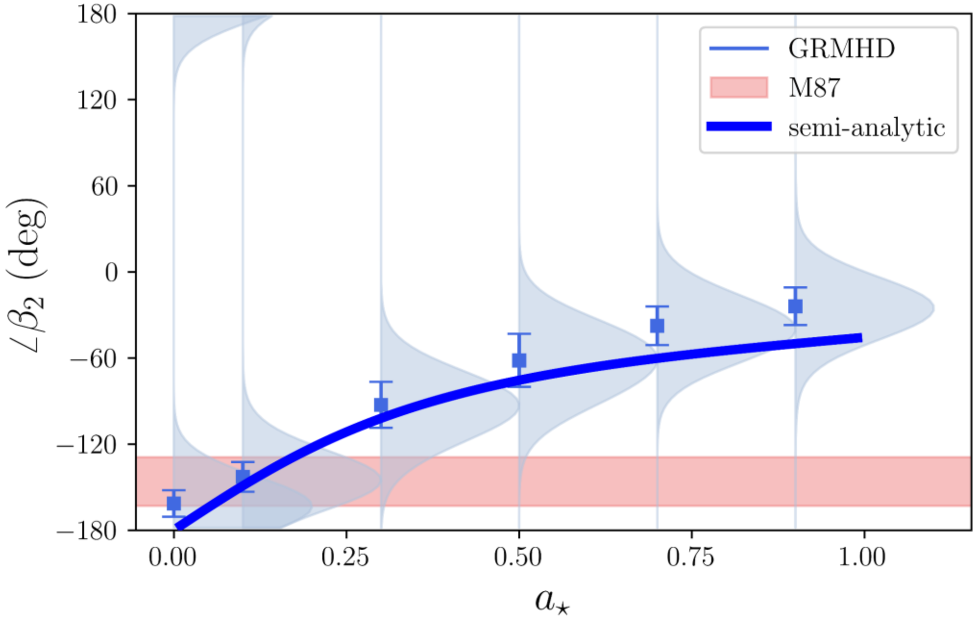
Polarized images are **spin dependent**

Low Spin



High Spin

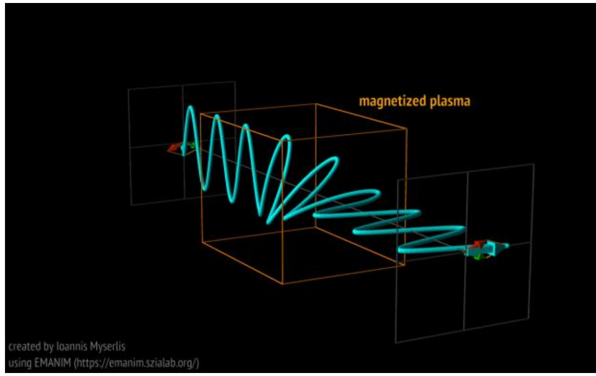




- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the Poynting flux (BZ jet power)
  - makes the observed polarization pattern more radial

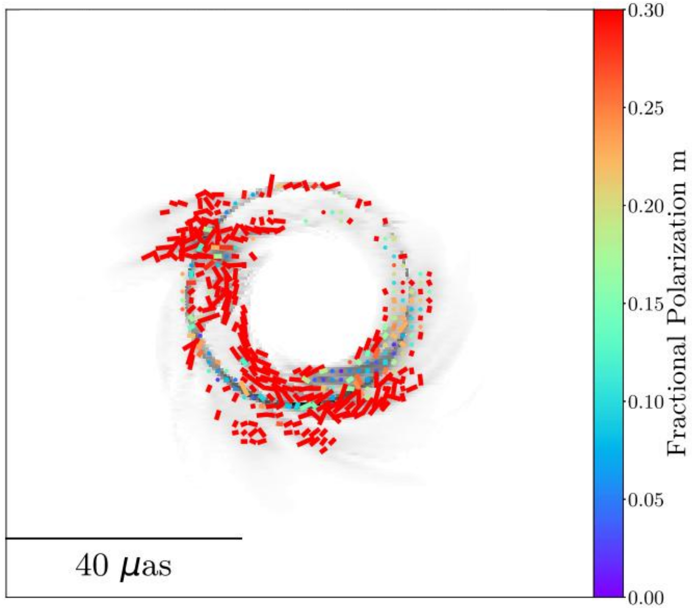
Chael+2023

What about **Faraday Rotation**?

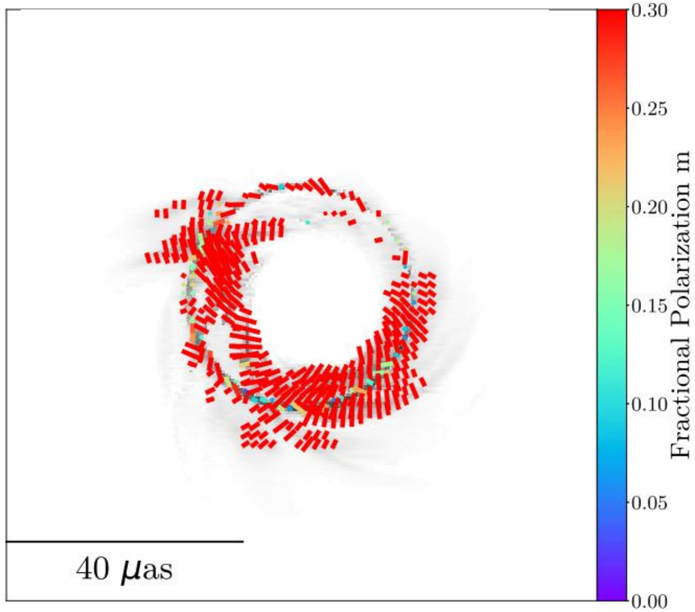


‘infinite’ resolution

With Faraday



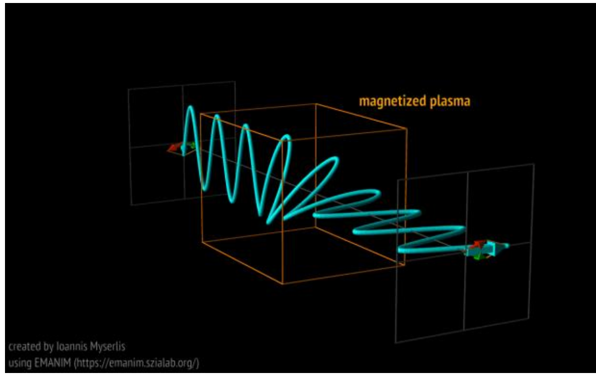
Without Faraday



- Significant Faraday rotation on small scales
  → **Rotates** the overall polarization pattern at EHT resolution
  → **Scrambles** polarization vectors on small scales

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

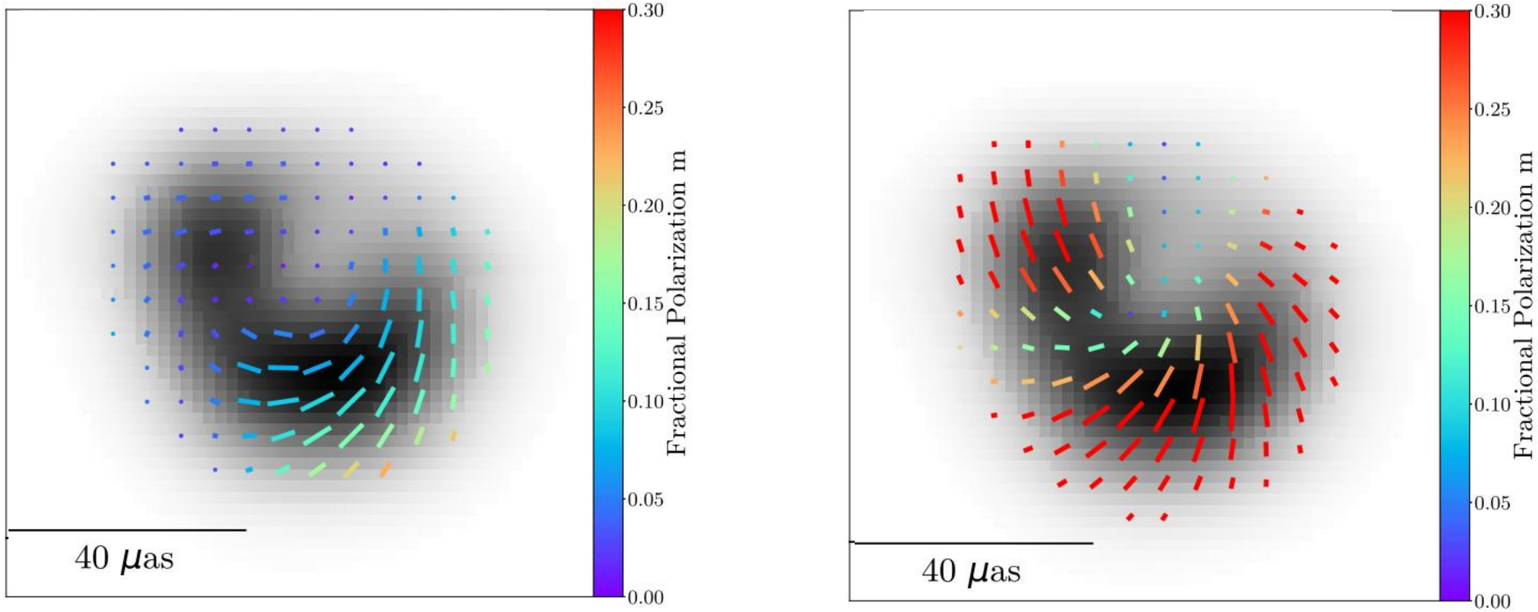
What about **Faraday Rotation**?



With Faraday

Without Faraday

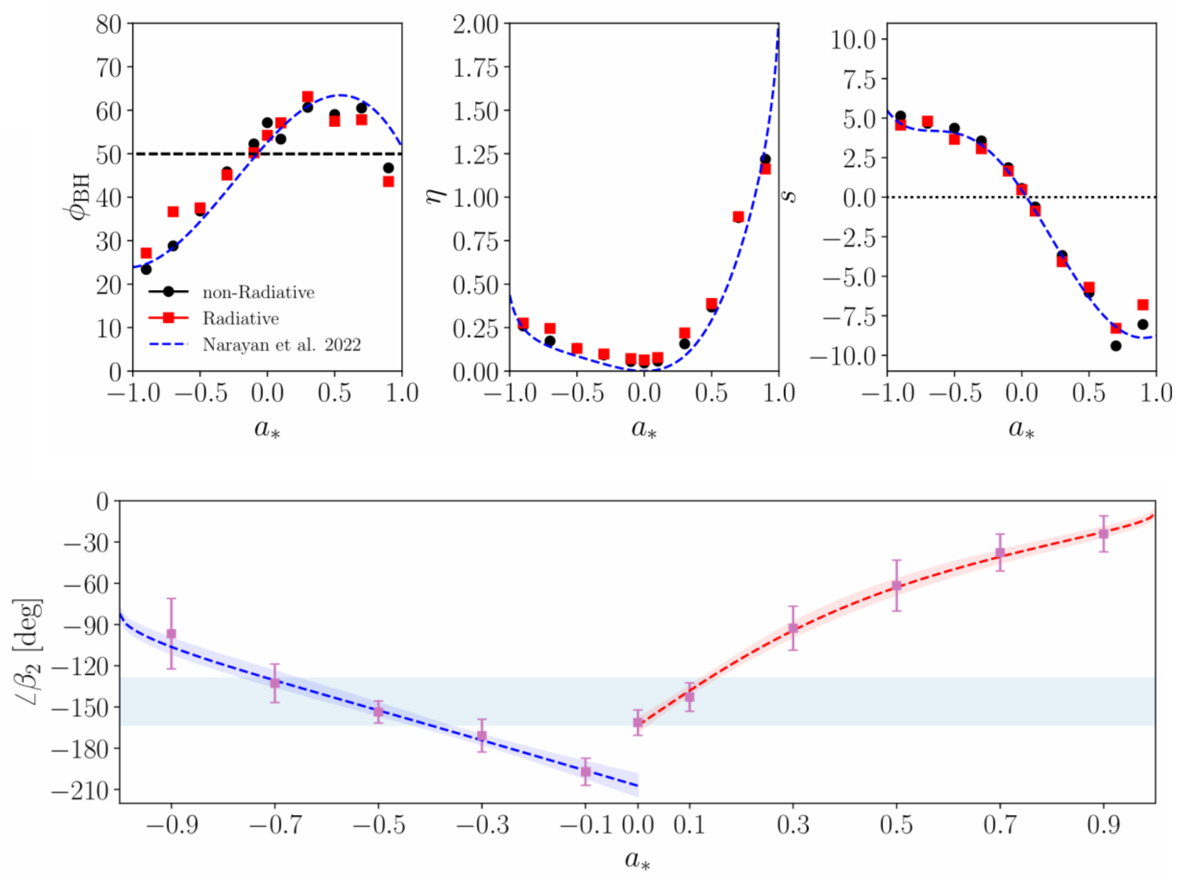
EHT resolution



- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from **colder electrons** is necessary to depolarize MAD models

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

Aside: Radiative Simulations Have Similar Jets…



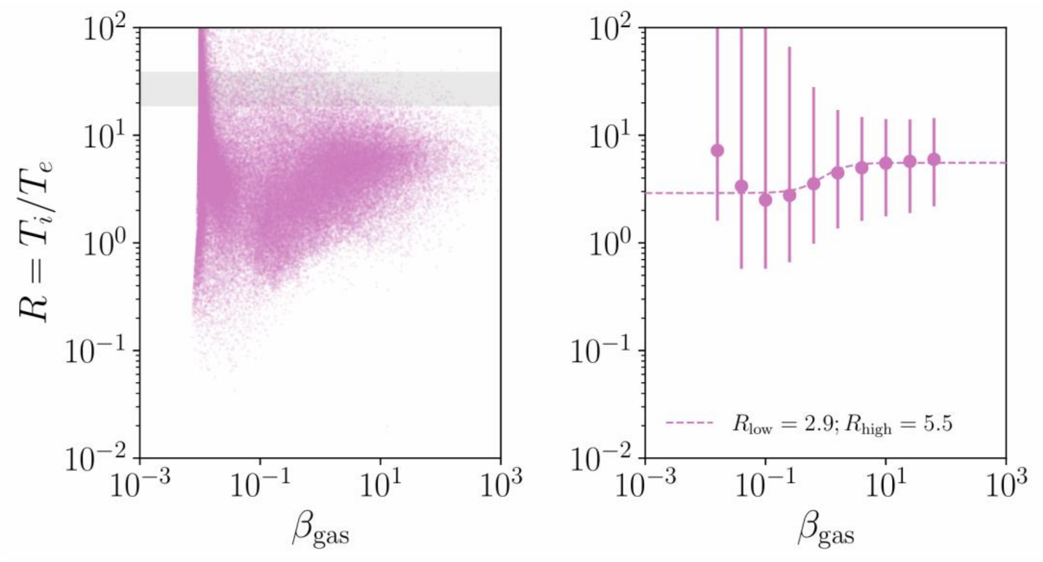
- M87* and Sgr A* have two-temperature plasmas

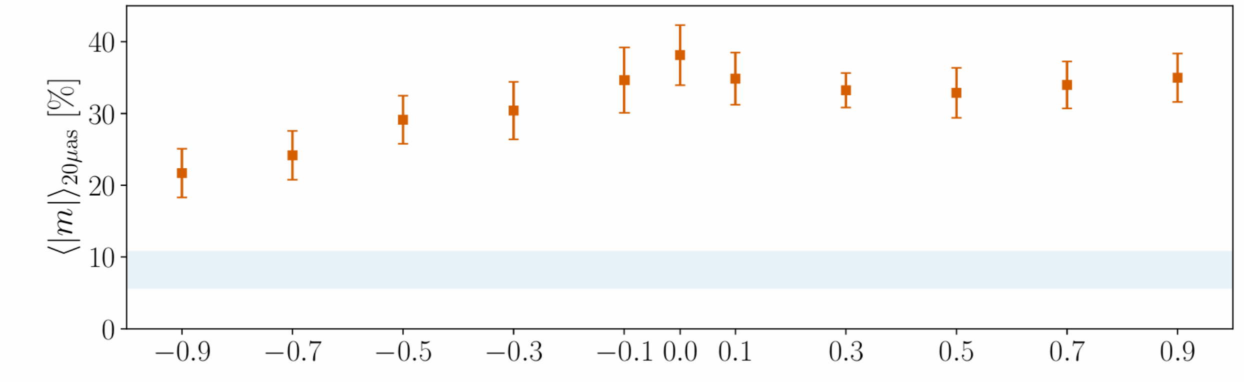
$$T_{\rm e} \neq T_{\rm i}$$

- 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 $T_{\rm e}$ locally in **postprocessing** and seems to prefer **cold electrons (**T_i ~ 100x T_e **)** to sufficiently depolarize the image
- 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**..

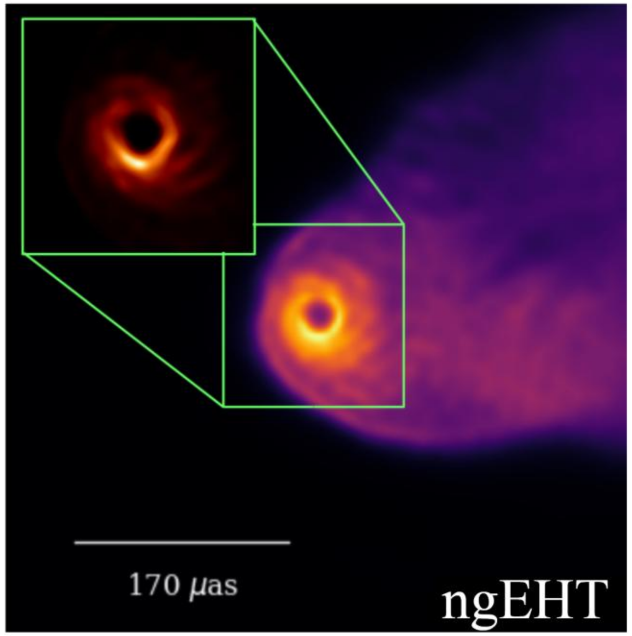


Image the connection between the BH and the low-brightness extended jet in **high dynamic range** with the **next-generation EHT (ngEHT)**

By zooming **in**..

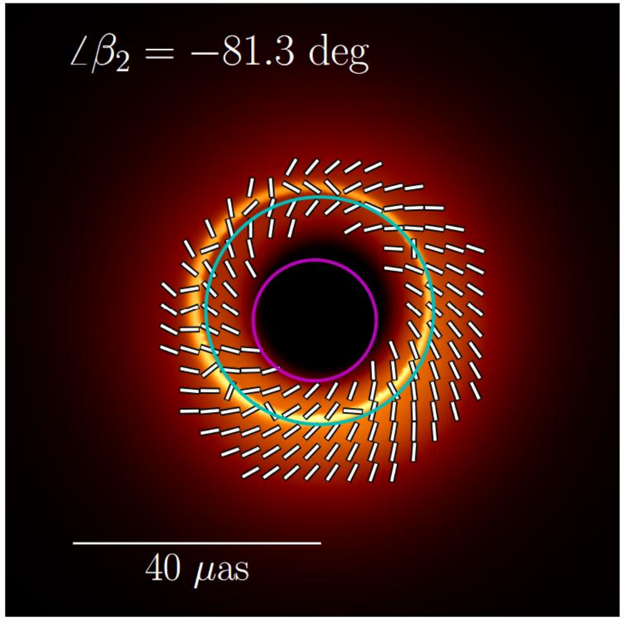
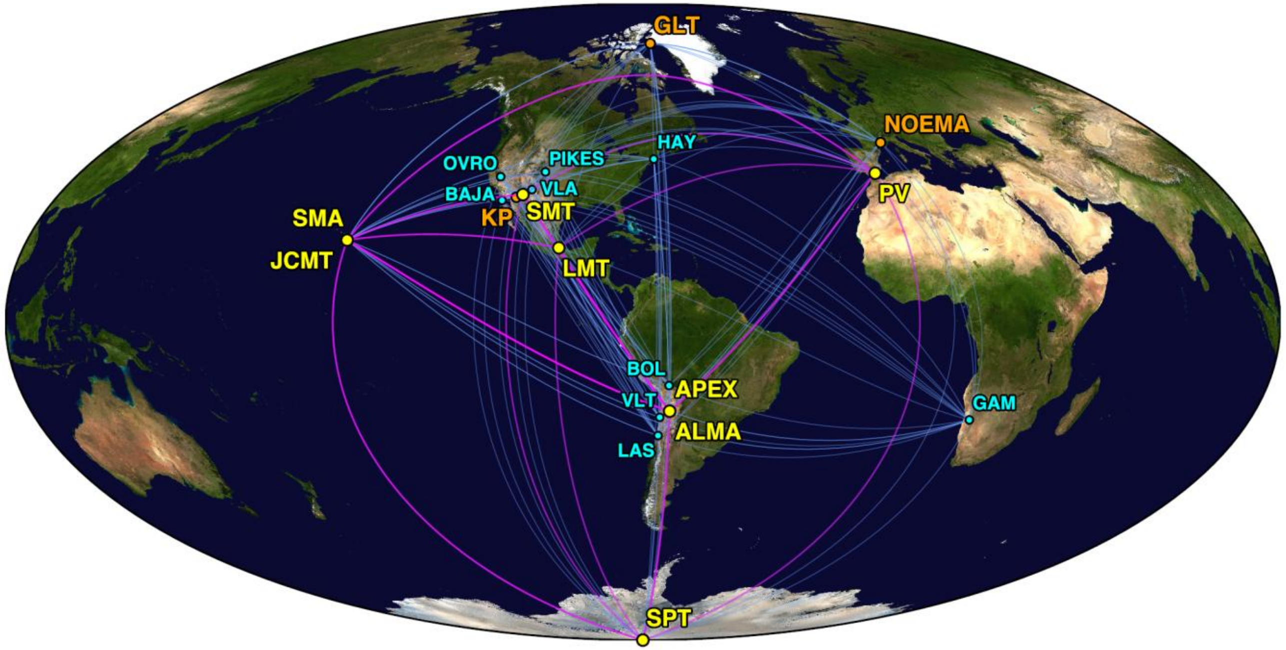
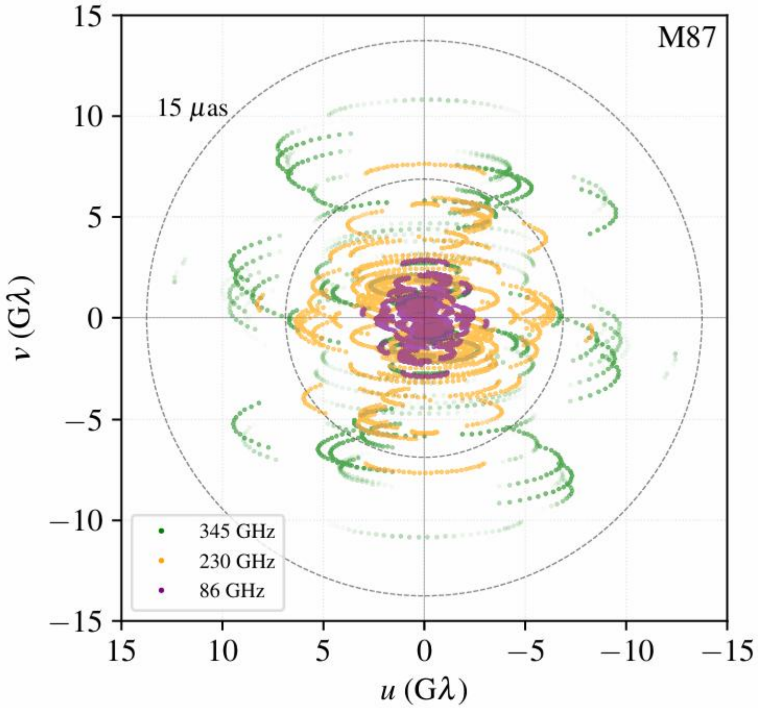


Image field lines close to the event horizon in **high resolution** with the **Black Hole Explorer (BHEX)**

The next-generation EHT (ngEHT)





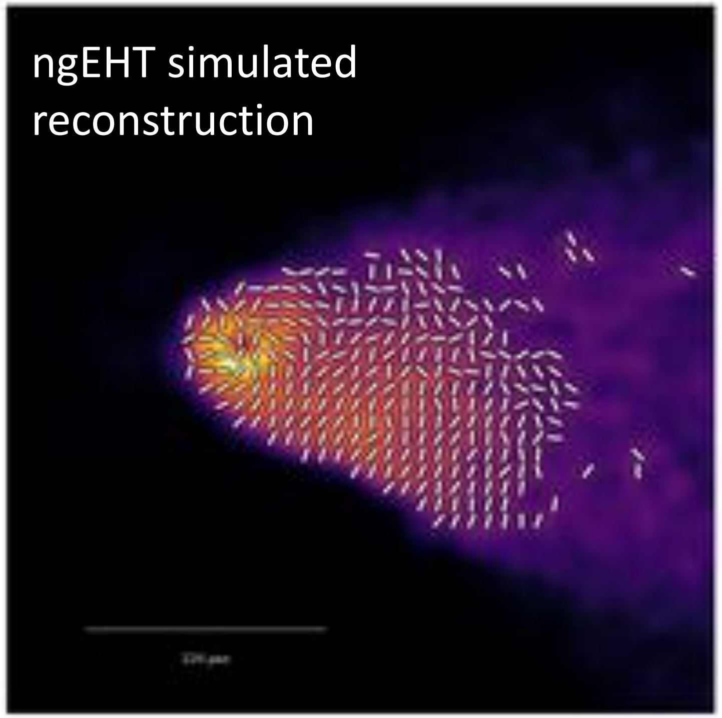
Increased coverage from new sites and observing frequencies in ngEHT will enhance **dynamic range**

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

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

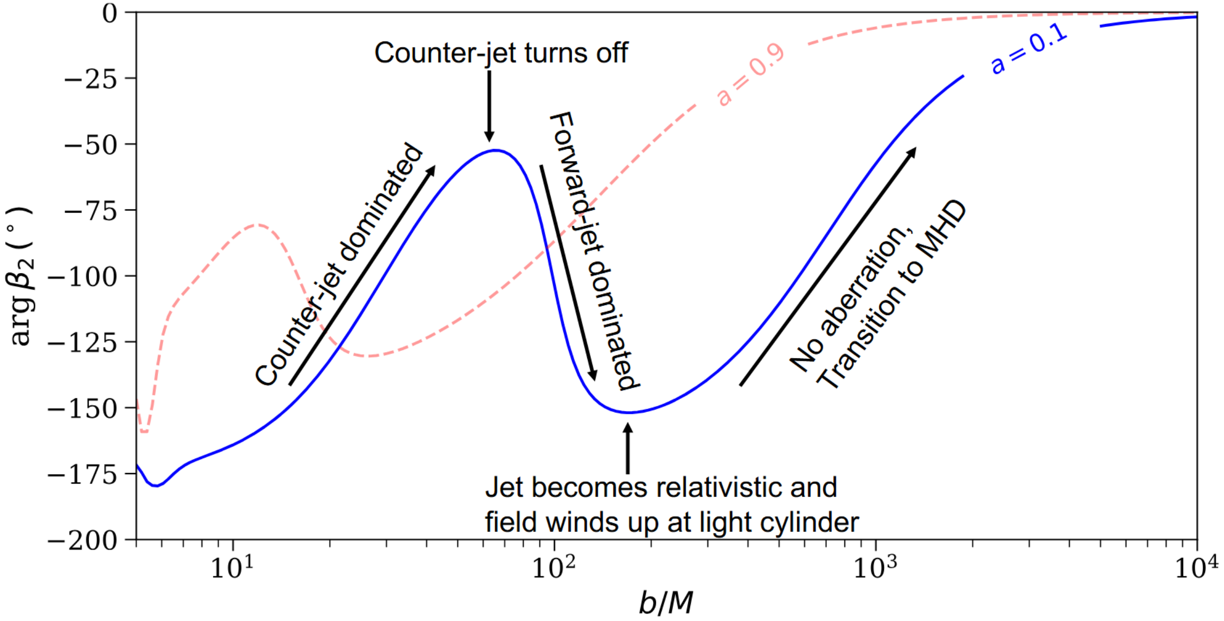
Doeleman+ 2023

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



ngEHT simulated reconstruction

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

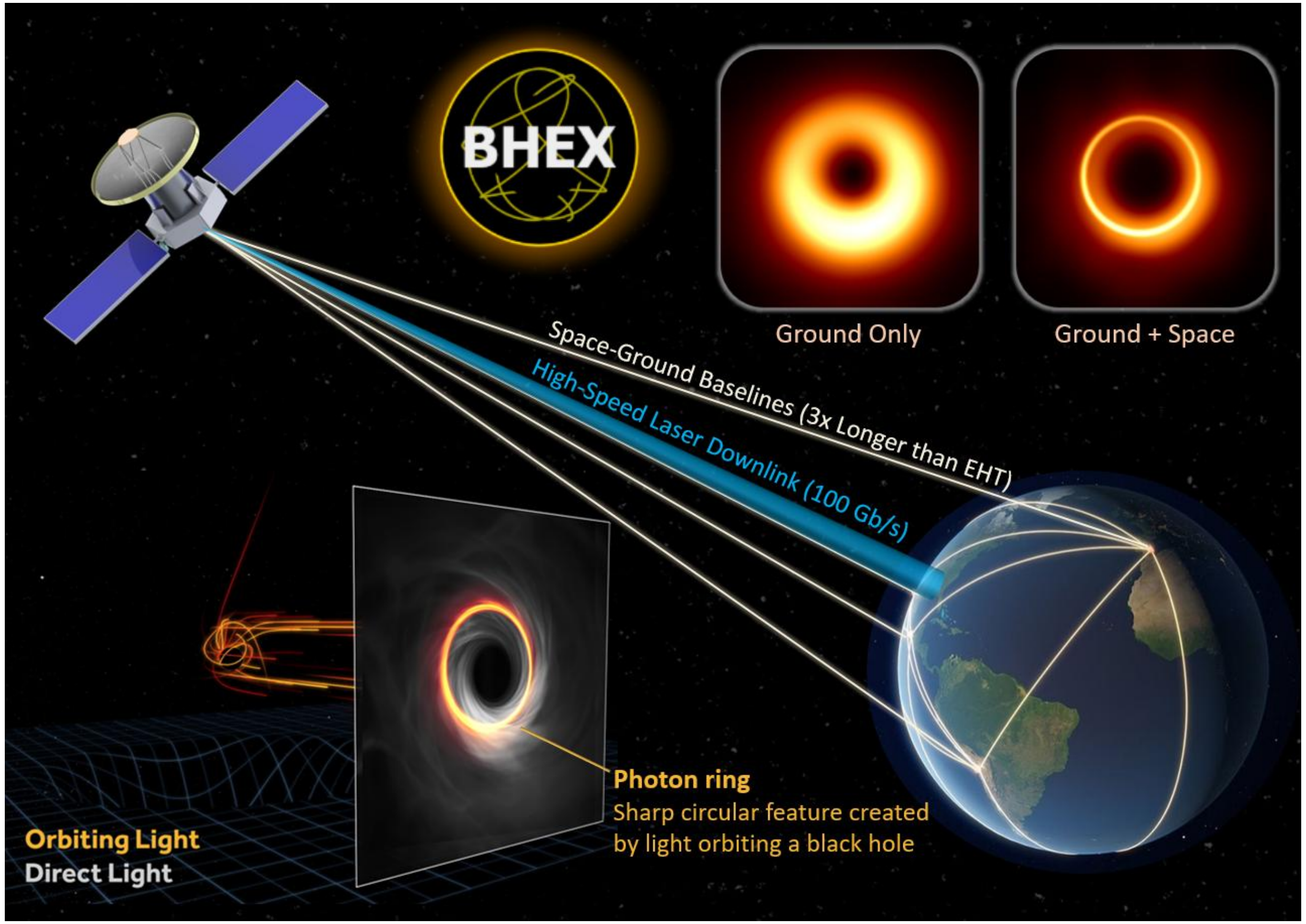
The Black Hole Explorer (BHEX)

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

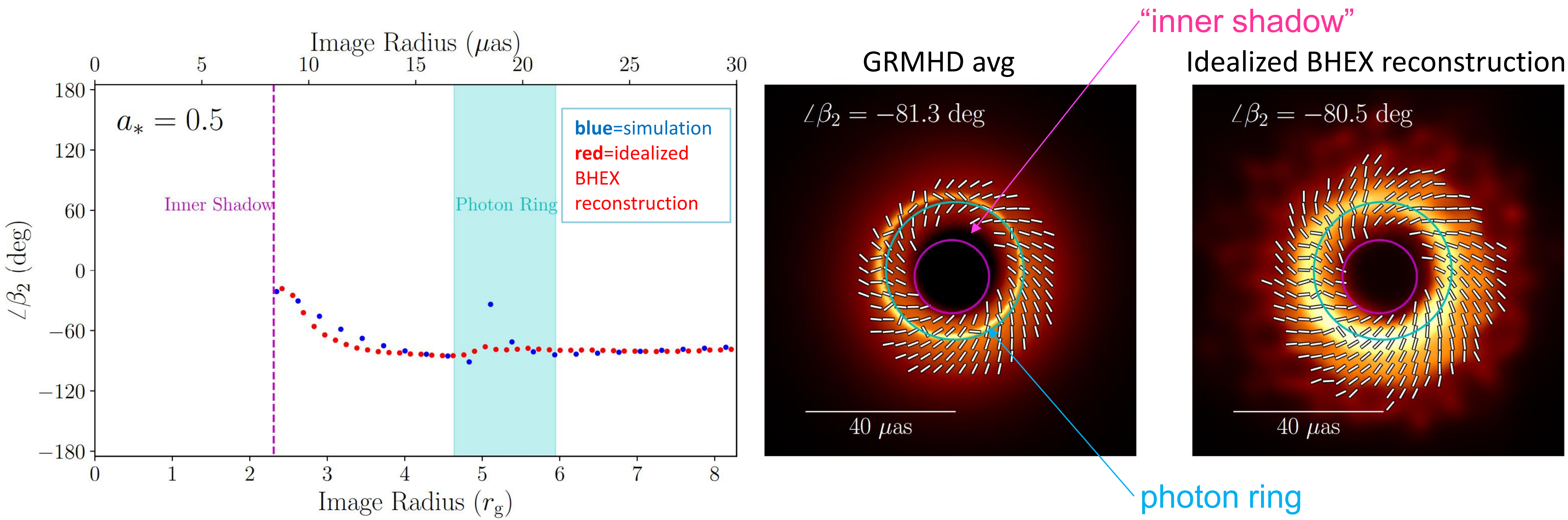
BHEX Science Goals

- 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



blackholeexplorer.org

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

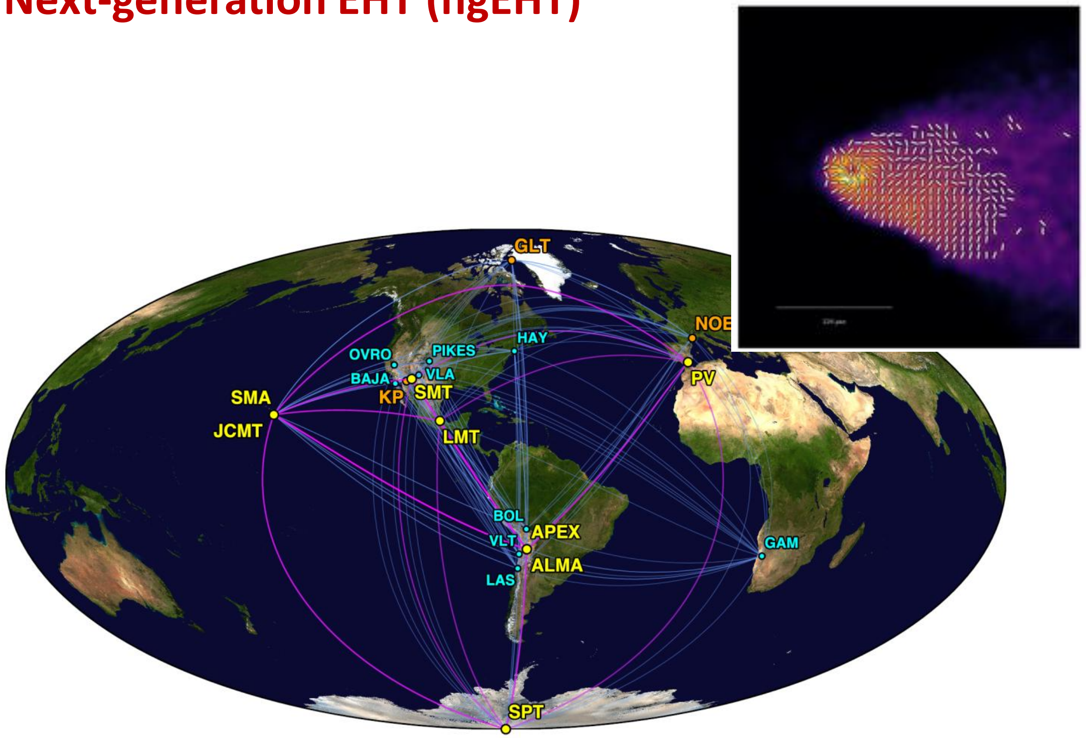


- β_2 evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - Strong evolution of arg(β_2) to the horizon is predicted by both simple BZ models and GRMHD
- **BHEX + EHT obtain the resolution to observe energy extraction at horizon scales**

Chael+ 2023b, Chael in prep

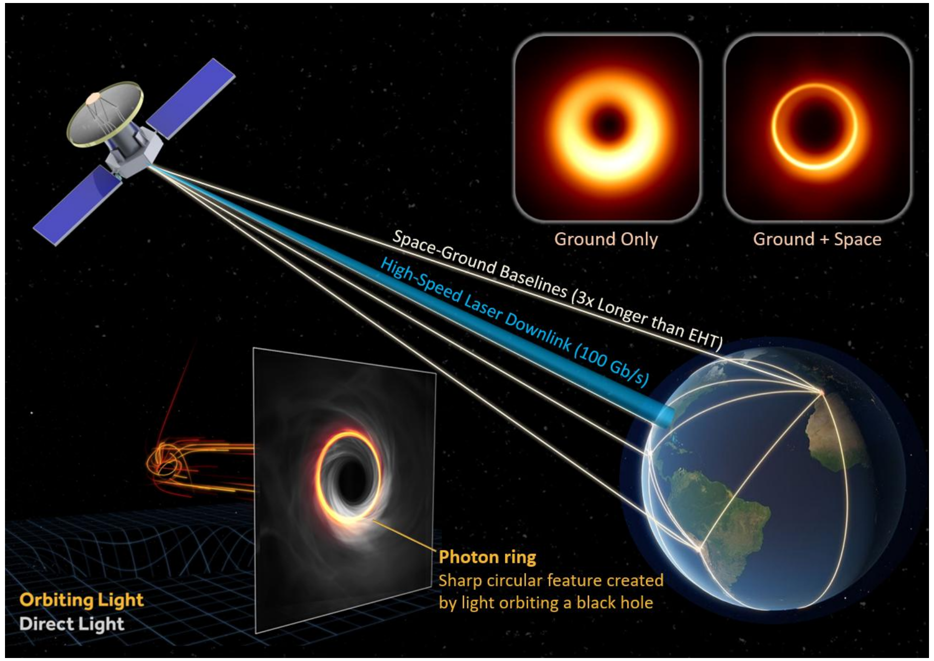
The future of near-horizon black hole astrophysics

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)

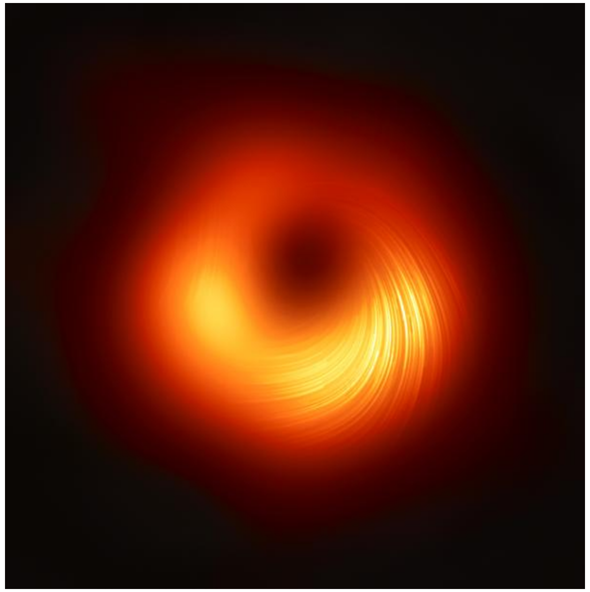
Black Hole Explorer (BHEX)



- 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)

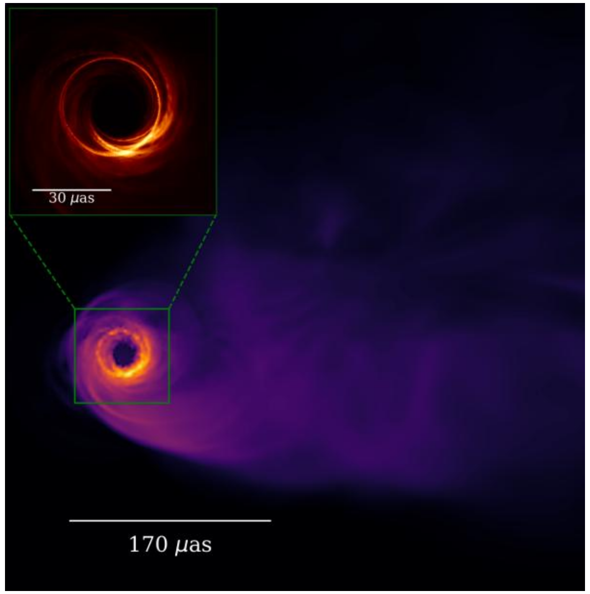
Takeaways…

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 near-horizon physics in supermassive black holes beyond Sgr A* and M87*?



EHT VII, 2021; **Chael** 2025

backup slides

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

Chael 2024, Chael 2025
2404.01471, 2501.12448

Difficulties with GRMHD Simulations at high magnetization

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

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

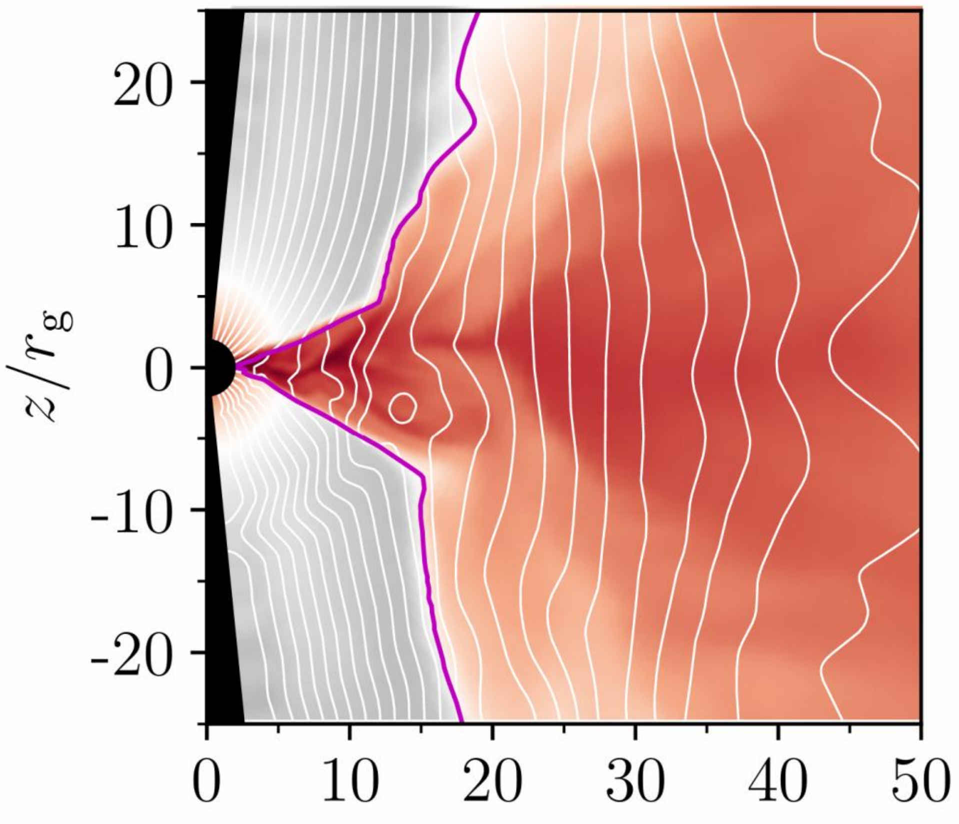
- The ratio of magnetic energy to rest-mass energy is defined:

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

- In the limit $\sigma \gg 1$, numerical codes struggle to recover fluid variables and the simulation can crash

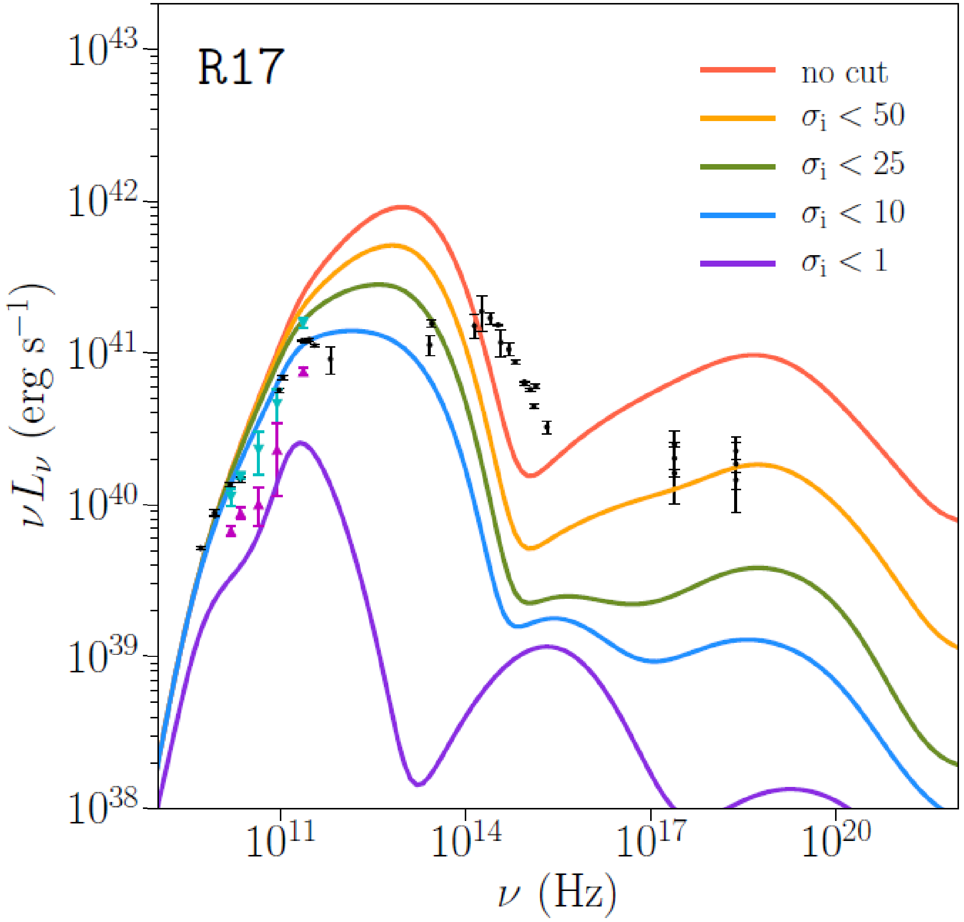
- GRMHD codes introduce density ‘floors’ for stability

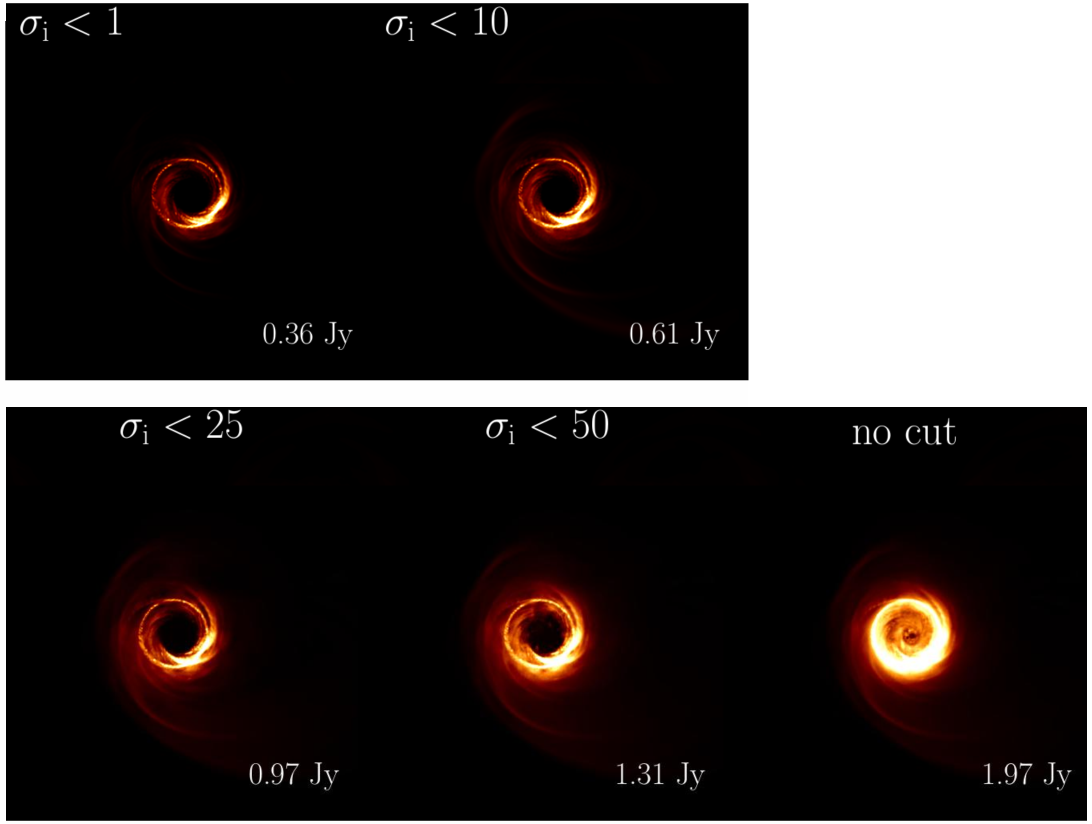
$$\sigma < \sigma_{\max}$$



Chael 2024

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





Chael+ 2019

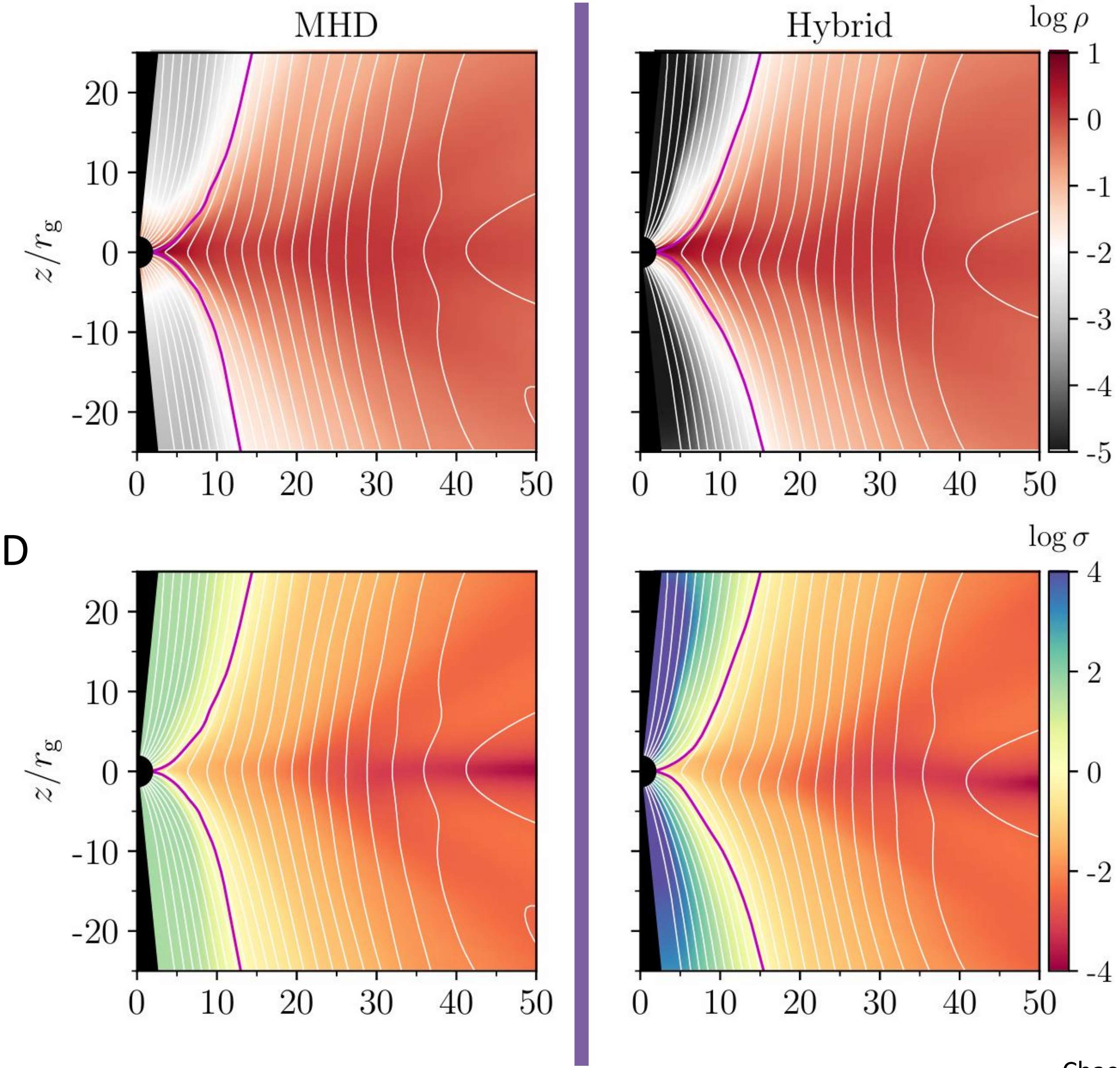
A New Hybrid GRMHD + Force-Free Code

Below $\sigma < \sigma_{\mathrm{trans}}$, use GRMHD as normal

Above $\sigma > \sigma_{\mathrm{trans}}$, use a **decoupled force-free scheme:**

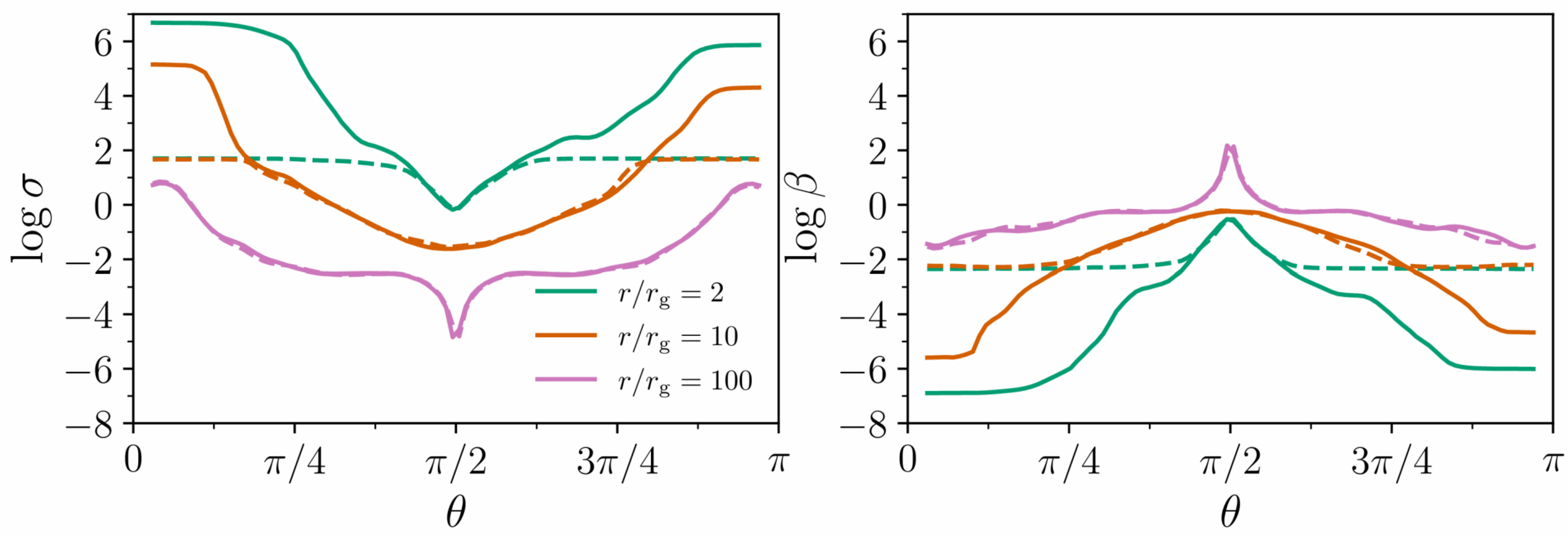
- electromagnetic fields evolve with **no back-reaction**
- field-parallel velocity determined from GRMHD limit
- **gas evolved adiabatically** in fixed background

Can transition between the schemes in ``intermediate'' σ regions



Chael 2024

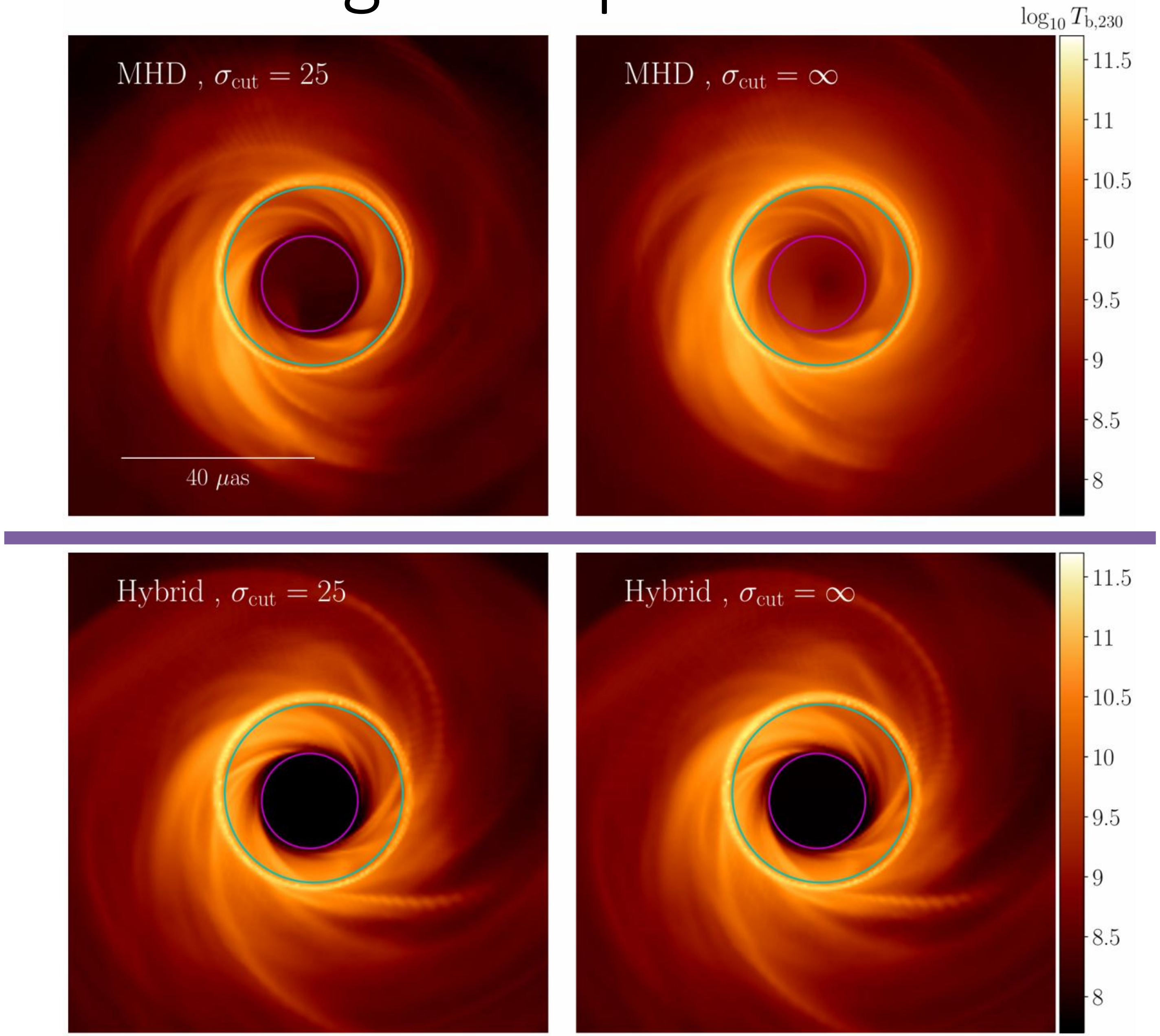
Comparing standard GRMHD and Hybrid GRMHD+FF



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

Chael+ in prep

230 GHz Image comparison

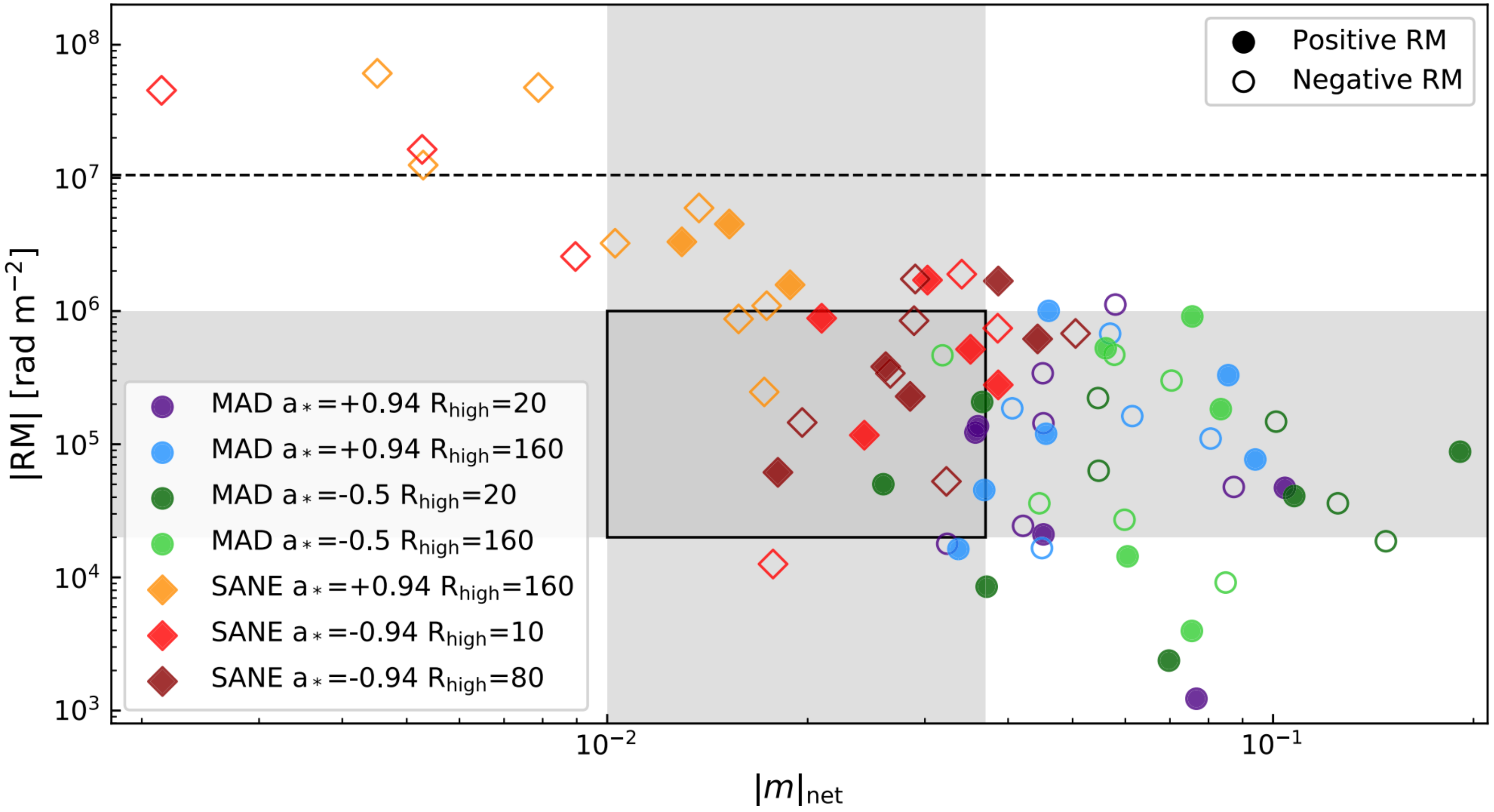


In standard GRMHD, foreground jet emission fills in the shadow region unless we have a cut on σ in radiative transfer

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

Chael+ in prep

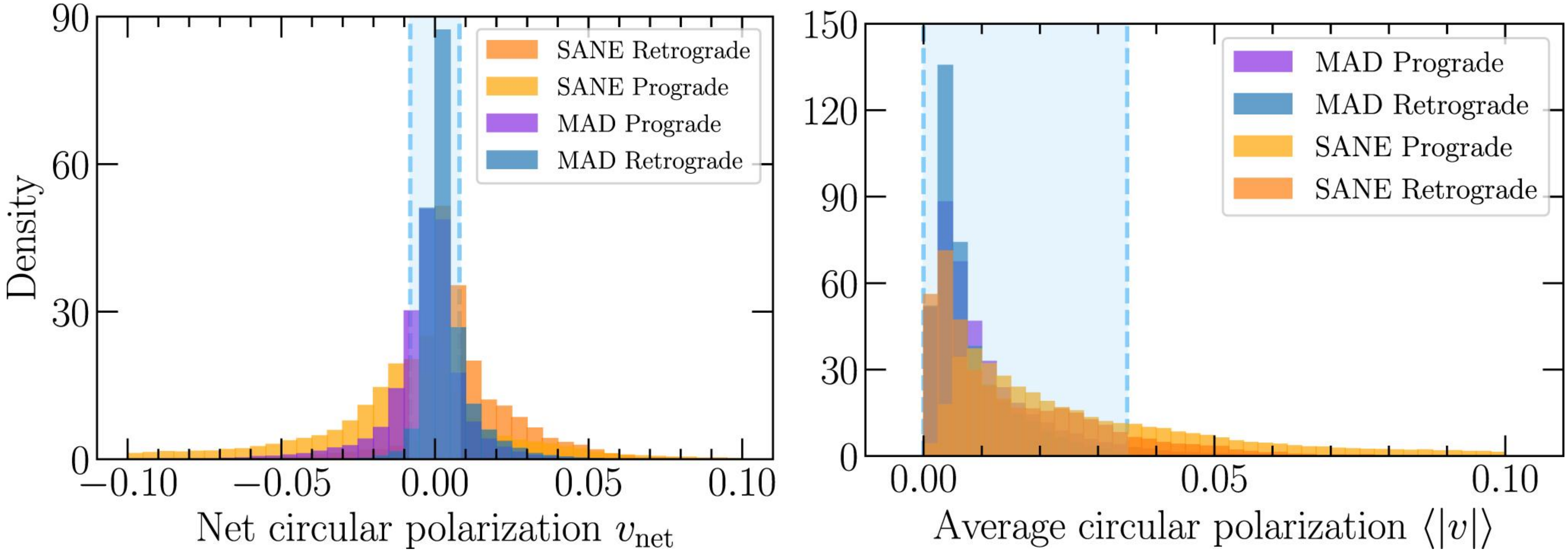
GRMHD simulations can explain M87's Rotation Measure



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

GRMHD simulations naturally produce low circular polarization



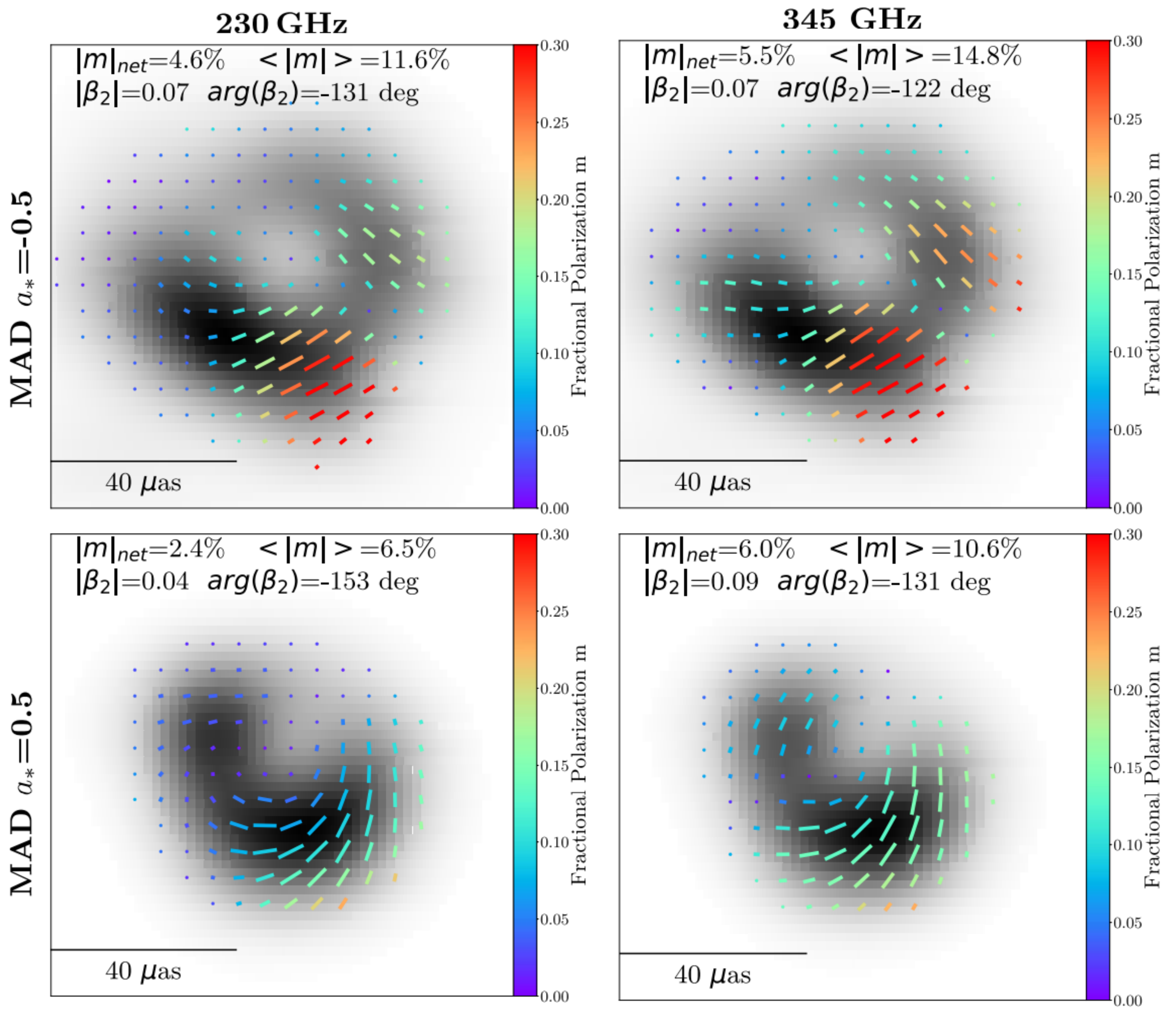
$$v_{\rm net} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

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

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

Higher frequencies

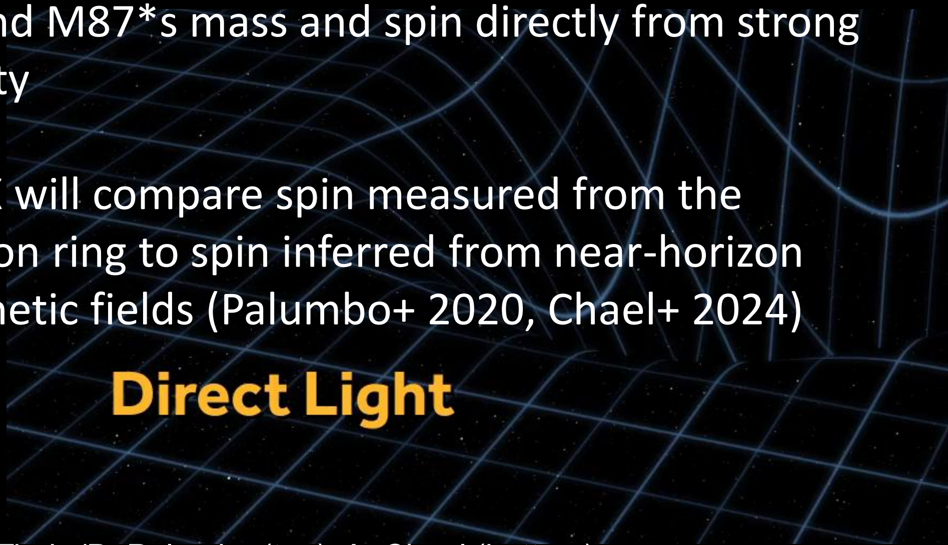
- Future EHT campaigns will observe at 345 GHz
- If our picture is right, we should see weaker Faraday rotation and **stronger polarization**
- With observations at multiple frequencies, we can directly map Faraday rotation and further constrain our models



EHTC 2021, Paper VIII

BHEX Science Area 1:
Detect Black Hole Photon Rings and Directly Measure BH Spin

- BHEX will detect and image the photon rings formed by light deflected >180 degrees in Sgr A* and M87*
- BHEX will measure the size and asymmetry of the photon rings in Sgr A* and M87* to ~1% accuracy
- BHEX will use these measurements to infer Sgr A* and M87*s mass and spin directly from strong gravity
- BHEX will compare spin measured from the photon ring to spin inferred from near-horizon magnetic fields (Palumbo+ 2020, Chael+ 2024)



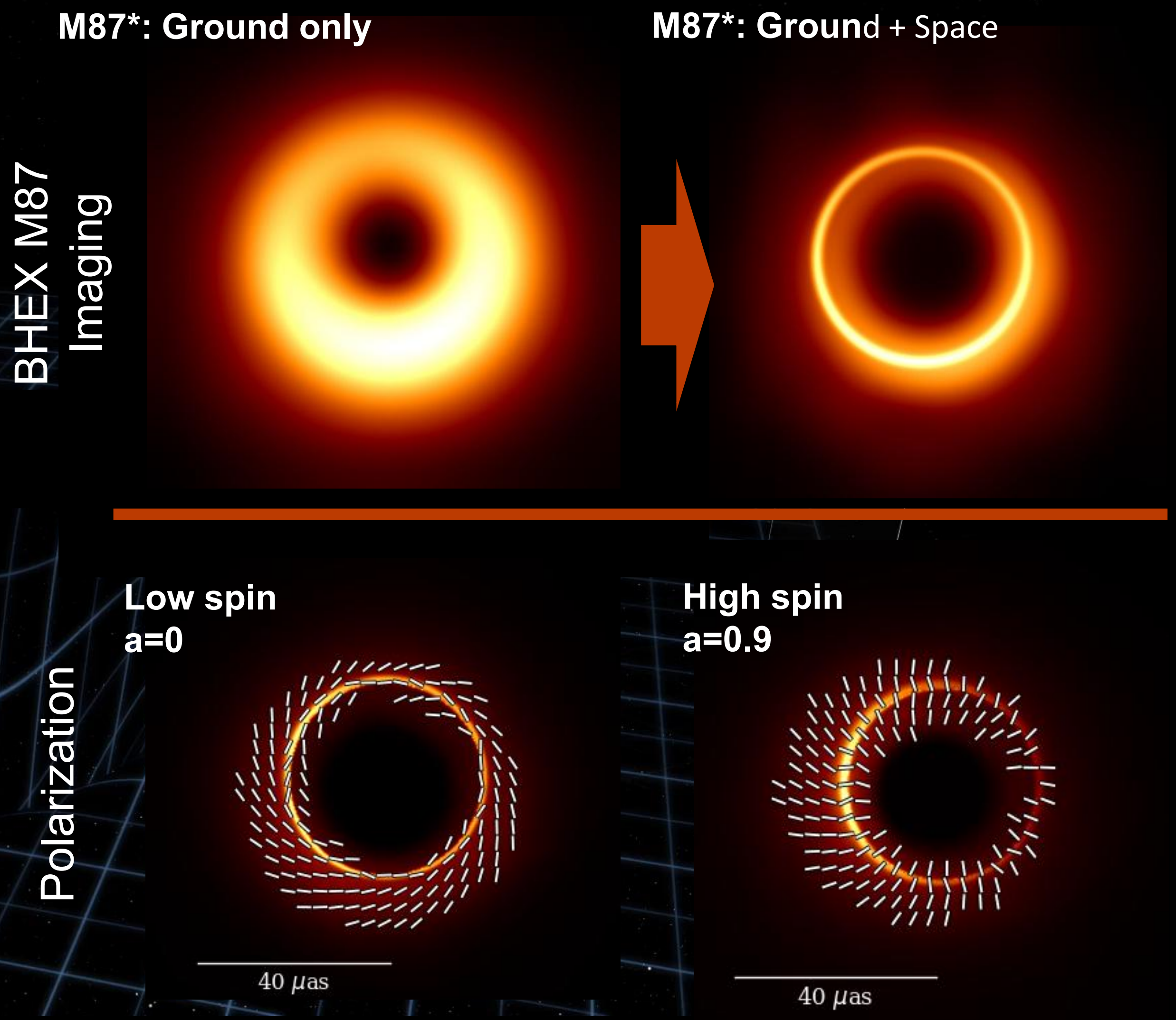
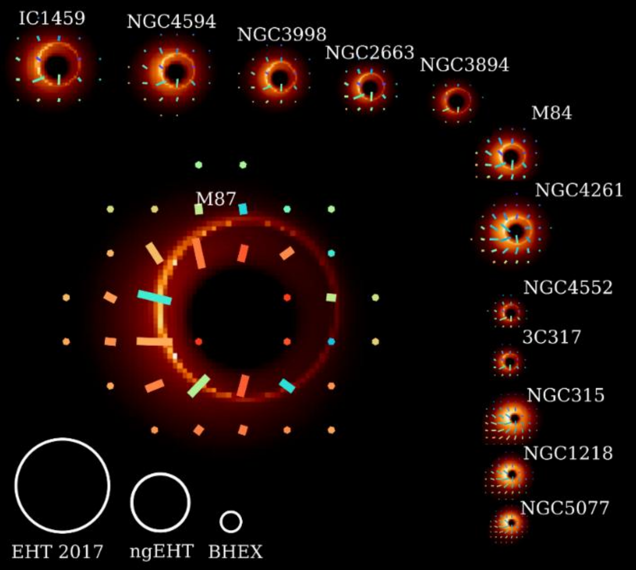


Image credits: P. Tiede/D. Palumbo (top), A. Chael (bottom)

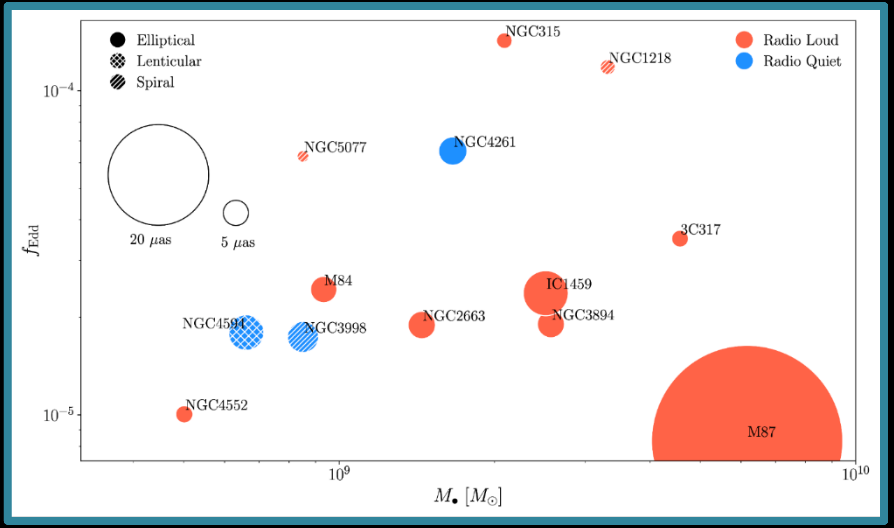
BHEX Science Area 2:
Survey Low-Luminosity AGN with Horizon-scale Resolution

- BHEX will increase the sample size of resolved black hole horizons from 2 to >10
- BHEX will make >10 horizon-scale measurements of mass (from the size of the emission region) and spin (from magnetic field helicity)
- BHEX will observe how horizon-scale accretion changes with mass, spin, accretion rate, radio-loudness, and host galaxy properties
- BHEX will probe nearby AGN with sufficient angular resolution to detect SMBH binaries at sub-pc separations

Event Horizon Targets



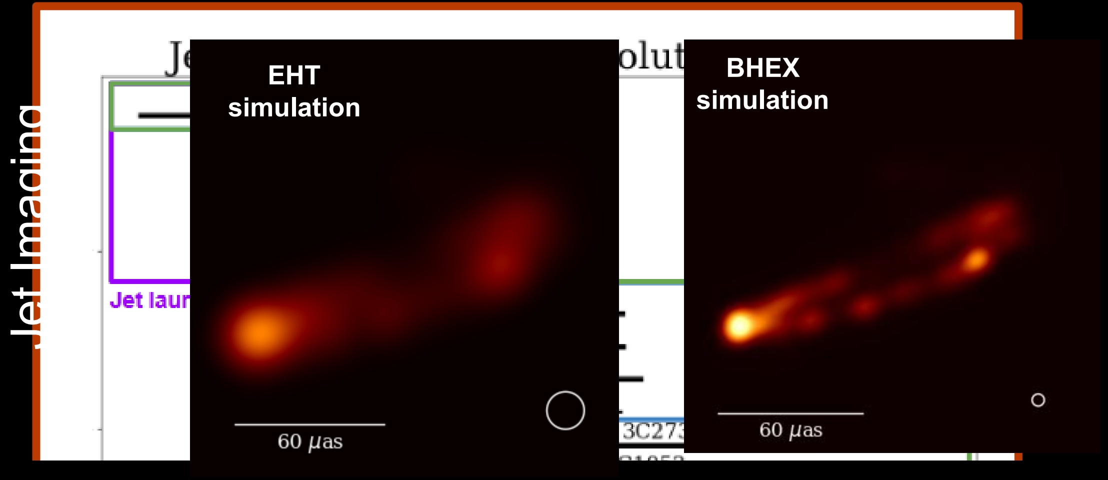
LLAGN properties

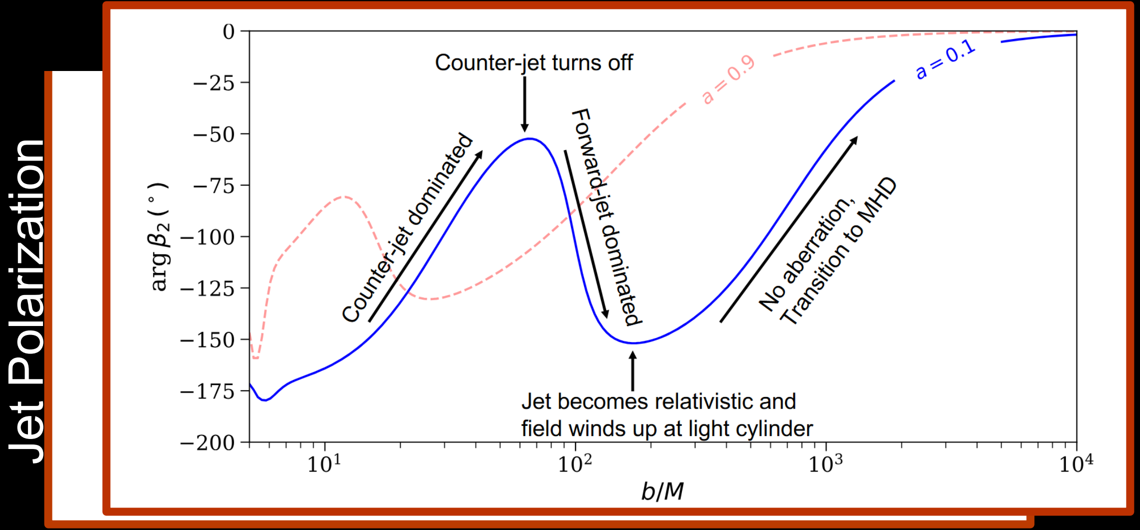


Figures: Zhang, Ricarte et al 2024

BHEX Science Area 3:
Resolving Extragalactic Jet Launching and Collimation

- BHEX will resolve longitudinal and *transverse* structure in jets from scales of 10-10,000 GM/c^2
- BHEX will determine if BH jets are universally edge brightened and probe their magnetic fields, structure, and composition on sub-pc scales
- BHEX will investigate magnetic fields at the jet light cylinder (10-500 GM/c ^{2}), which may encode BH spin (Gelles, Chael & Quataert 2024)
- BHEX will make rapid follow-up images of jets associated with high-energy neutrinos





Figures: P. Tiede (top) ; Gelles, Chael, Quataert 2024 (bottom)