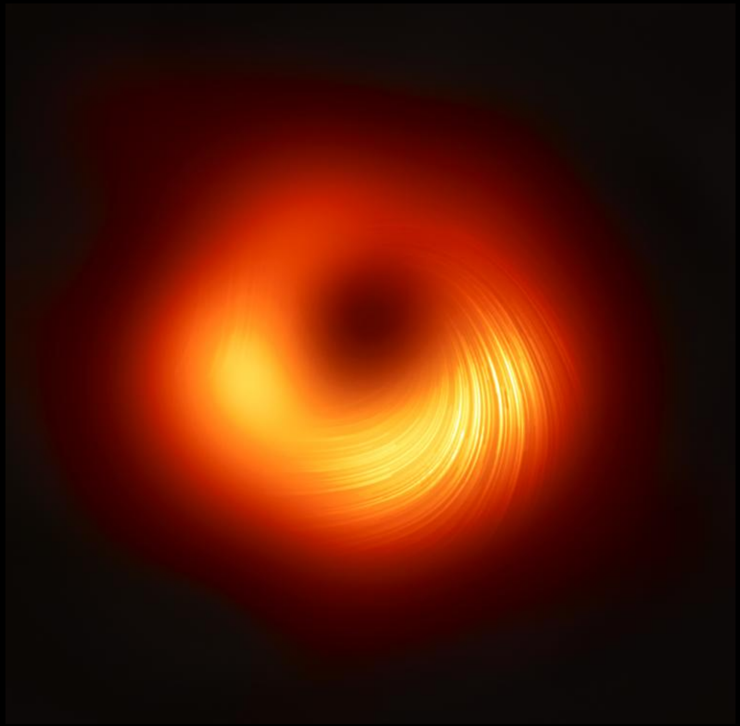
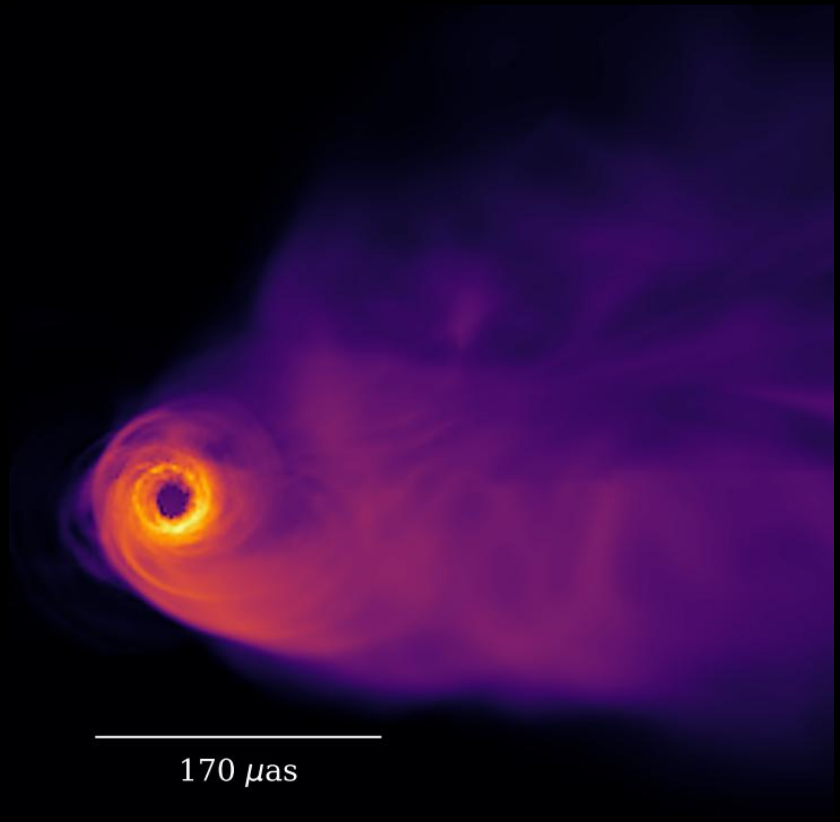
Black Hole Jet Launching Up Close

Andrew Chael
Princeton Gravity Initiative

ASIAA
March 27, 2025





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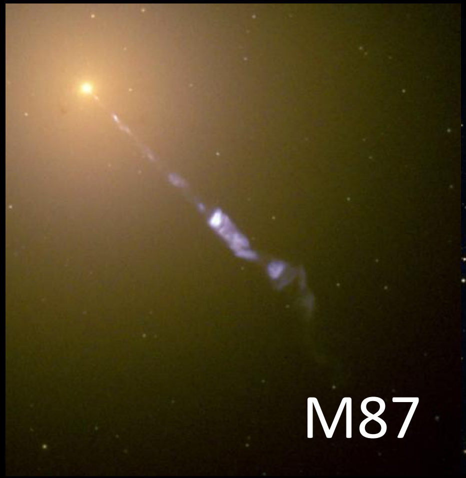
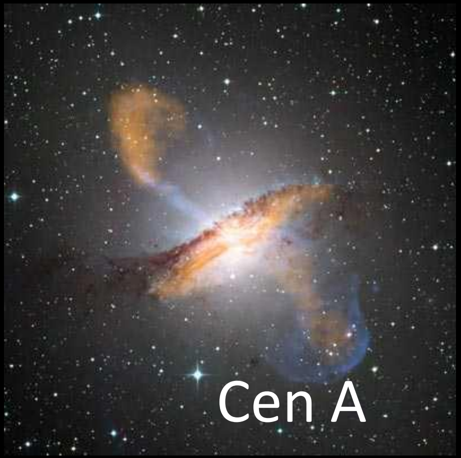
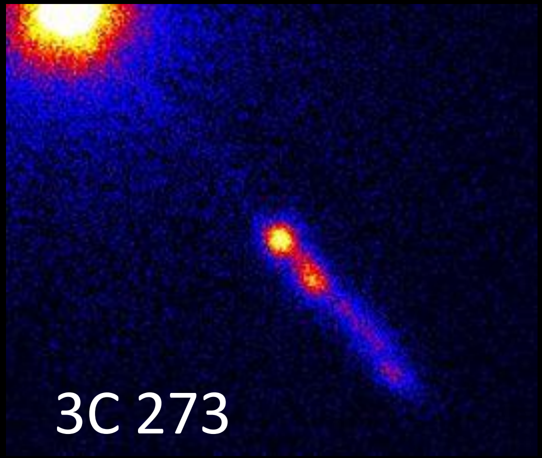
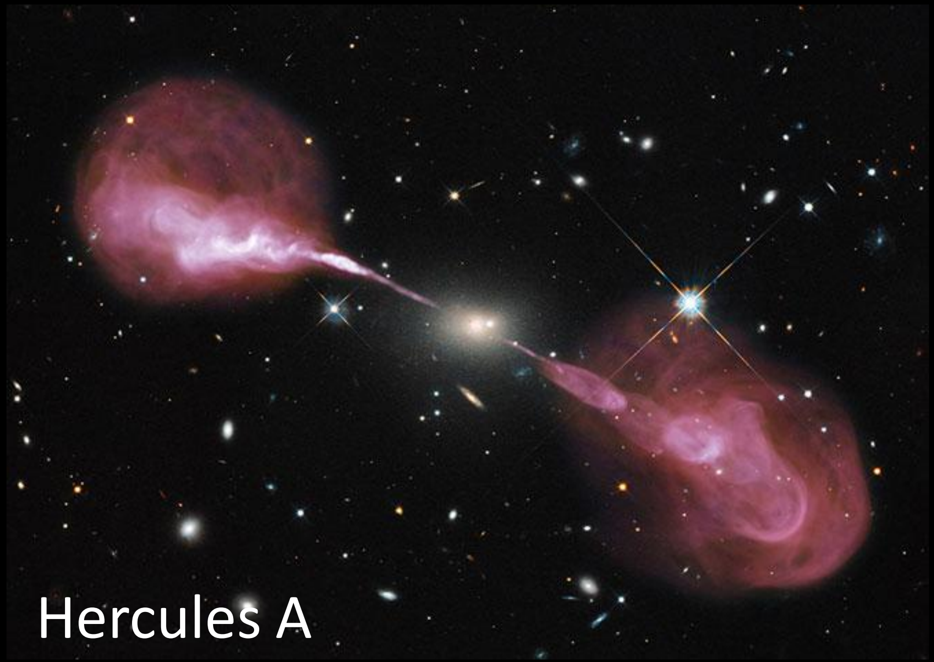
Event Horizon Telescope

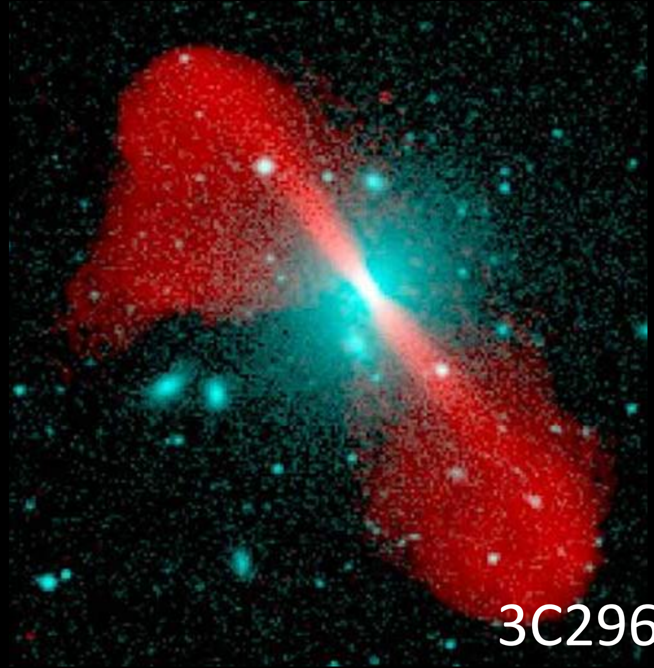
Supermassive black holes and jets are everywhere







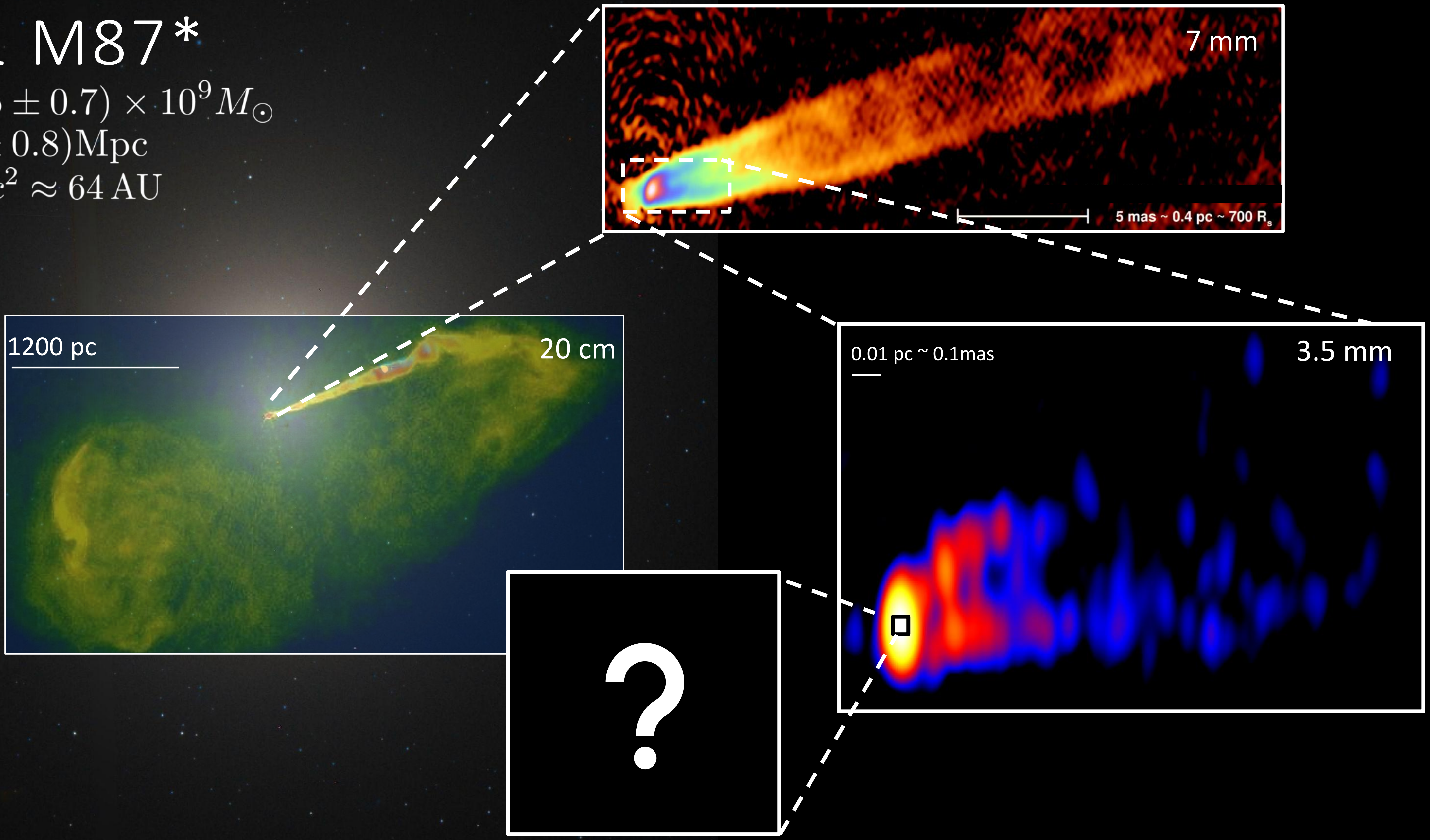




Credits: Sara Issoun, (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C293, Chandra),(Hercules A,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

M87 & M87*

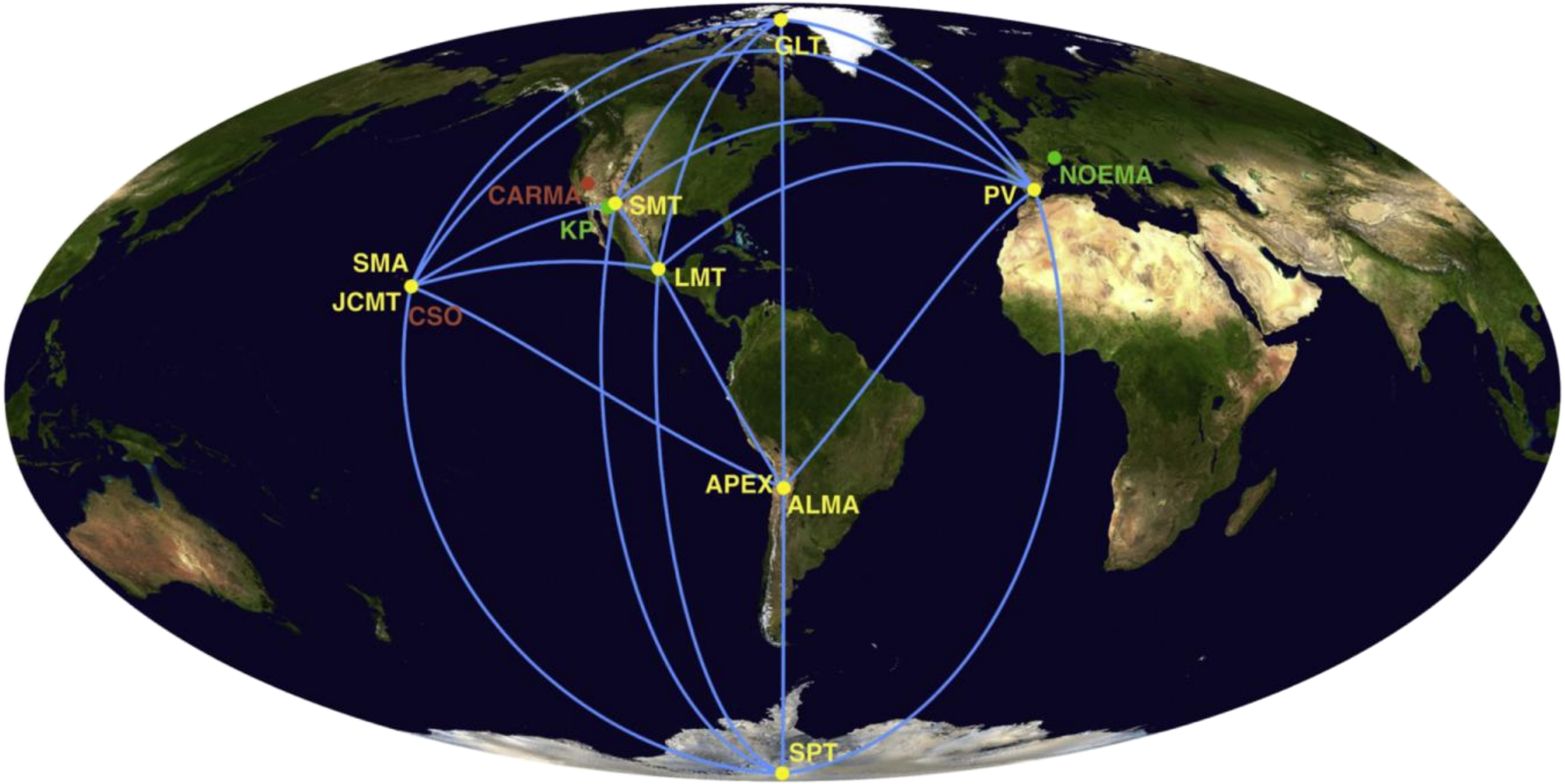
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$R_s = 2GM/c^2 \approx 64\,\mathrm{AU}$



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*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$

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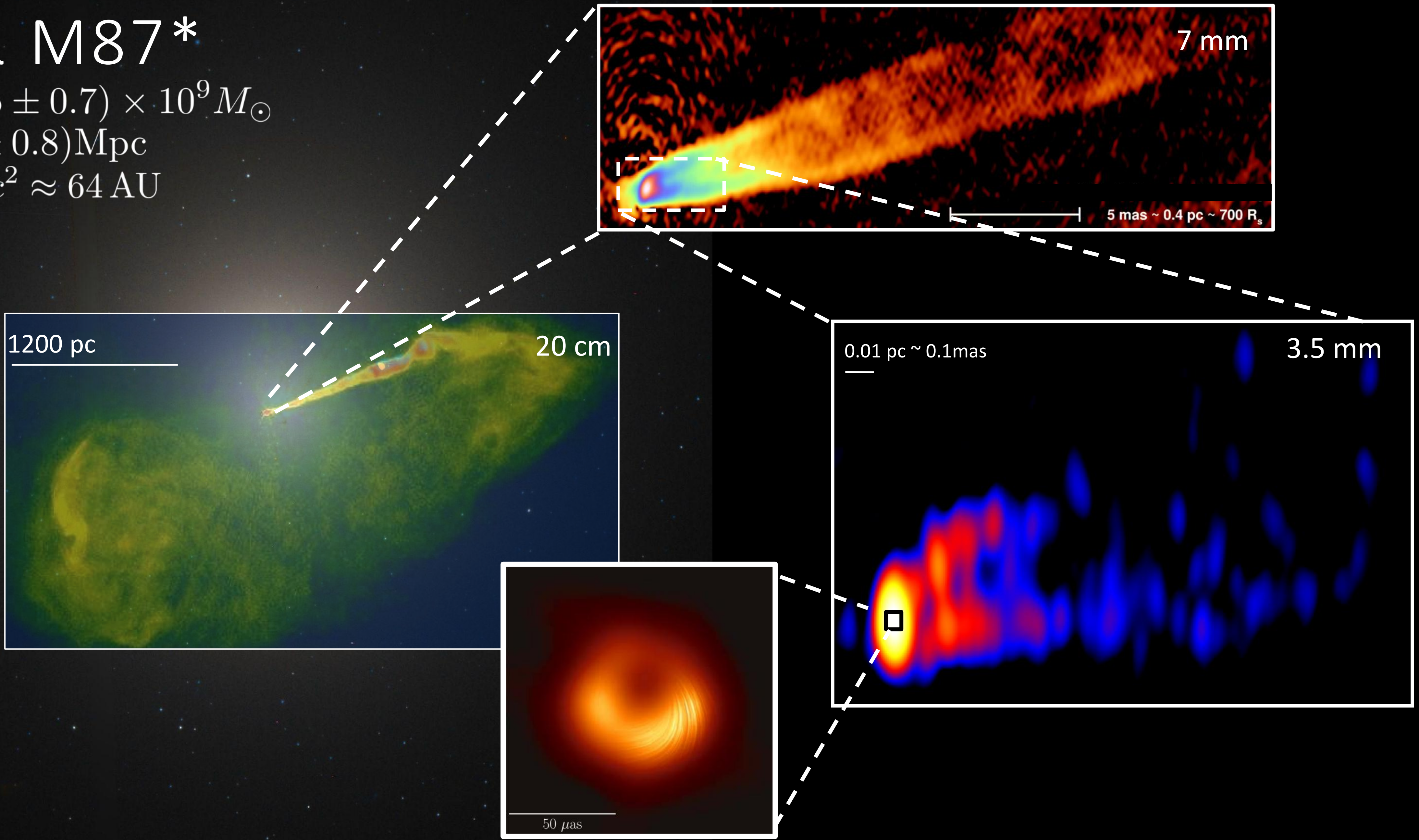
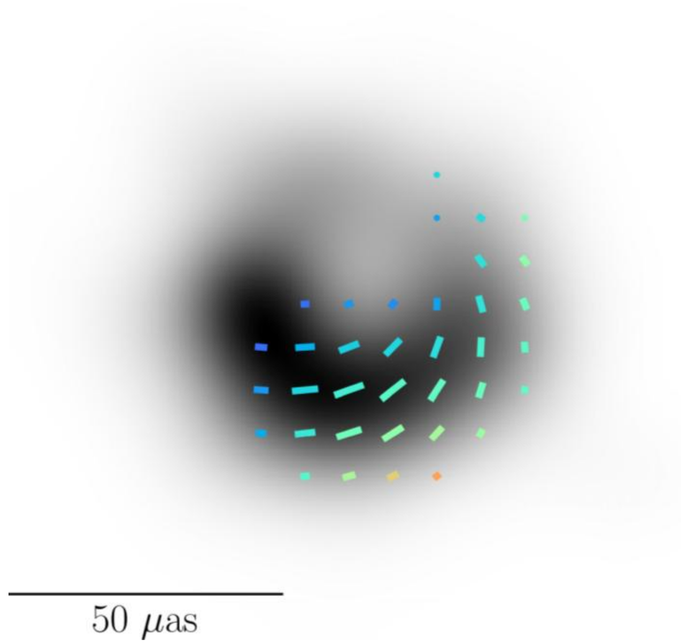
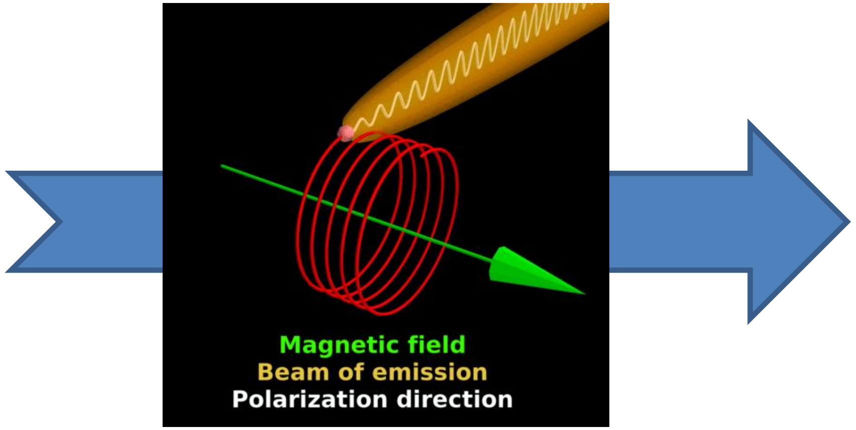


Can polarized EHT images tell us how jets are launched?

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

Why polarization?



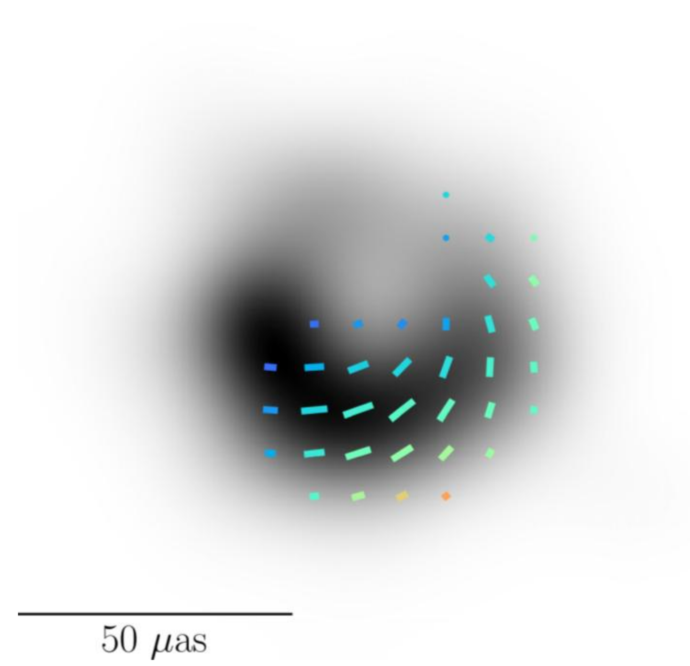


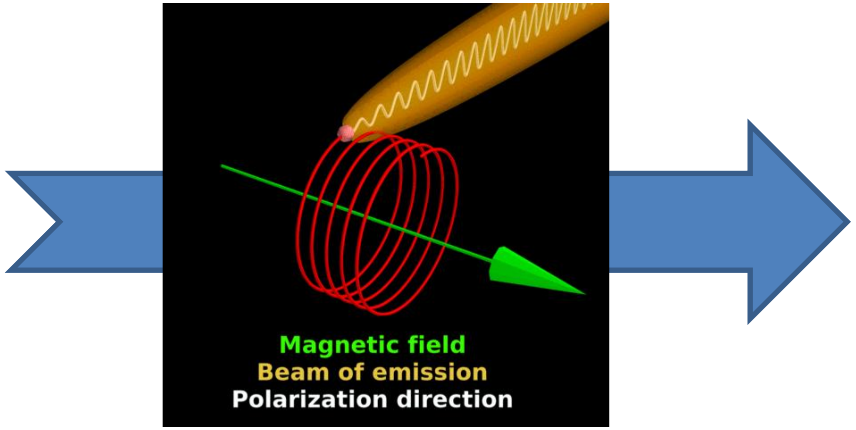
Magnetic field geometry in the emission region!

- 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 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

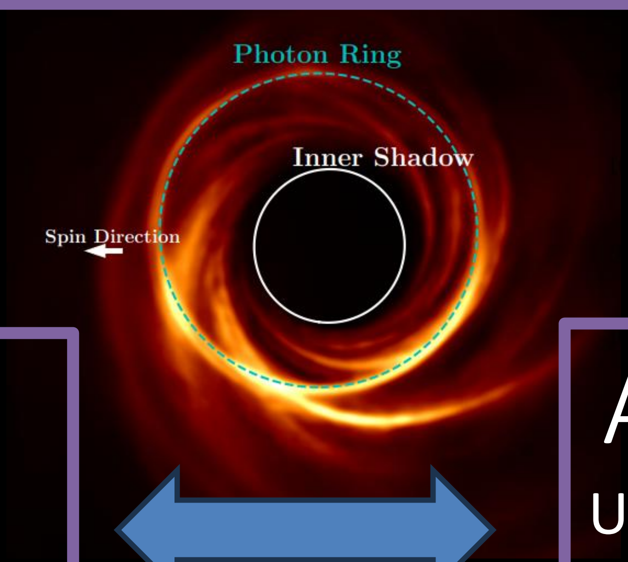
This talk:

1. How do we make *polarized* images of black holes with the EHT?
2. What did we learn from the first polarized image of M87*?
3. How can we better simulate the black hole-jet connection?
4. What can polarized EHT images tell us about jet launching?

My Research

Simulations

Using complex physics+ computers to predict near-horizon images



Imaging

Using data to map near-horizon emission in space, time, polarization, and energy

Analytic Models

Understanding key features of BH images and data with simplified physics

How did we obtain the first polarized image of a black hole?

EHTC VII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
2105.01169, 2311.10976

EHT: Array

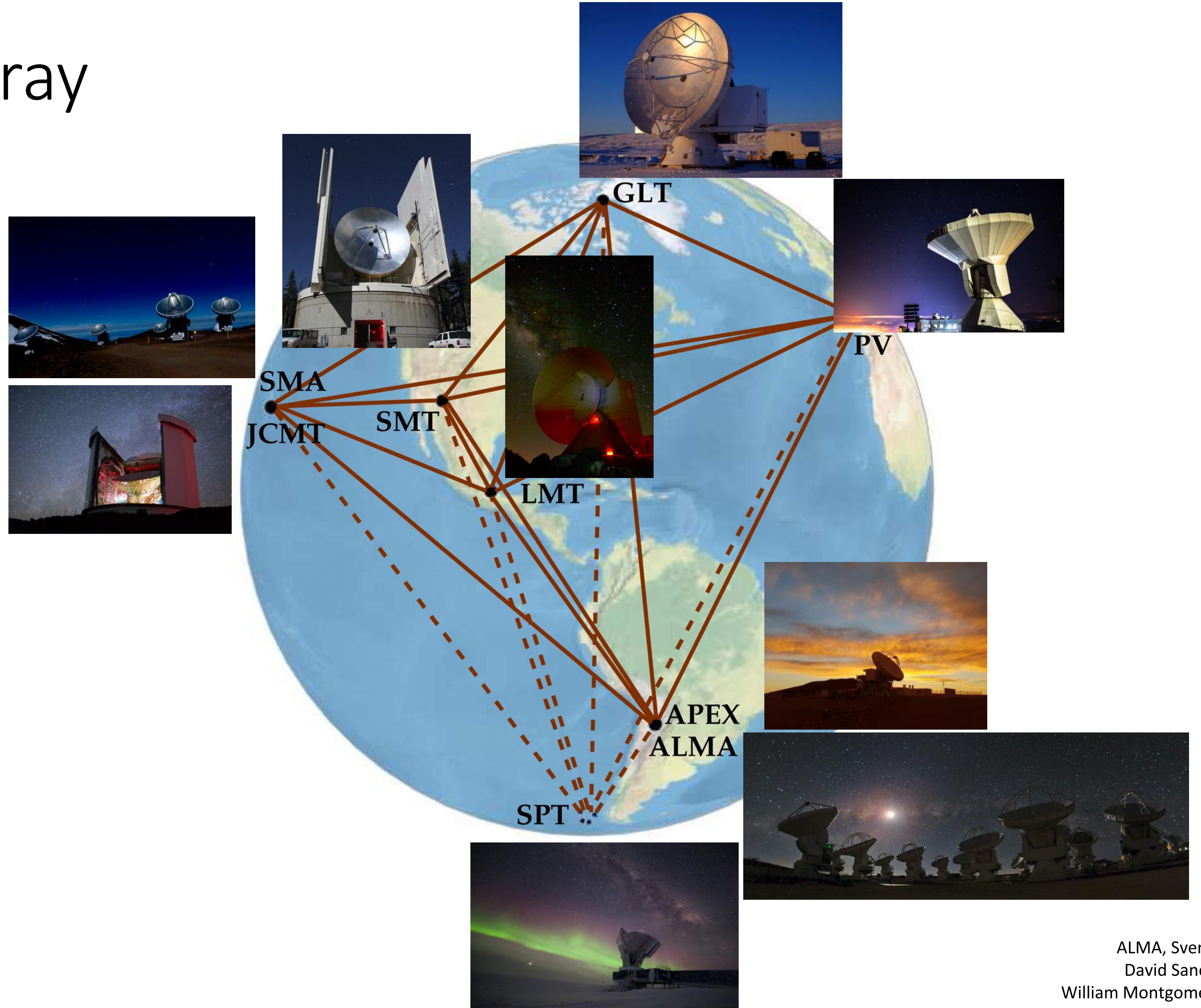


Photo Credits: EHTC I, 2024
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

EHT: People

300+ members

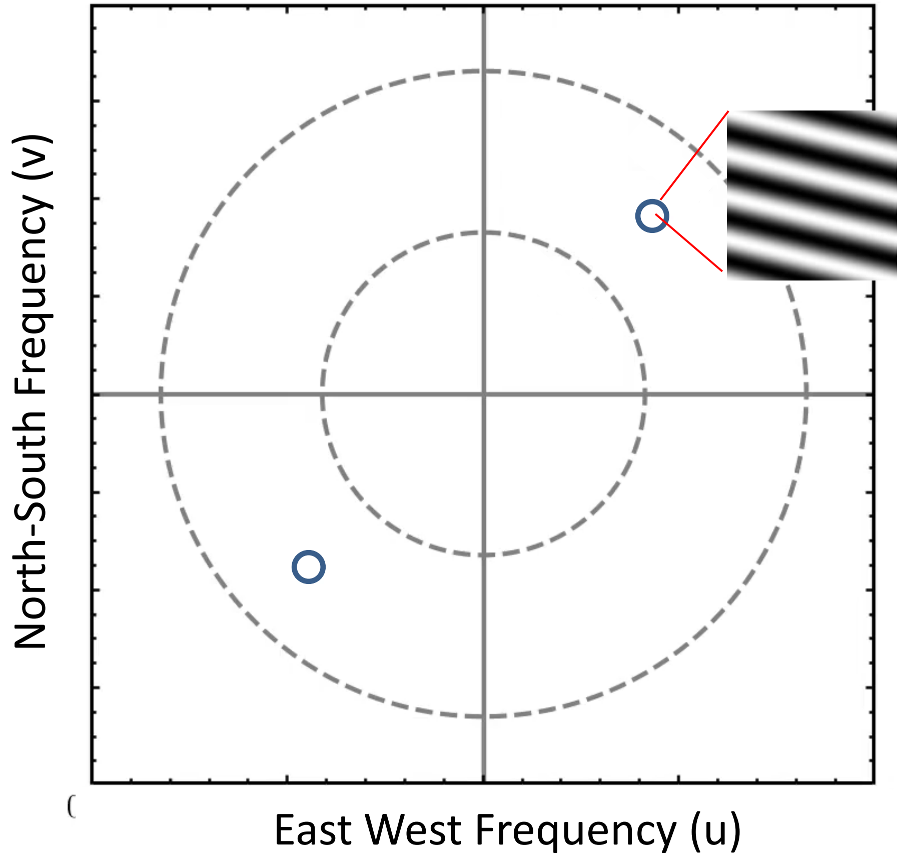
60 institutes

20 countries

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

Image credit: E. Traianou

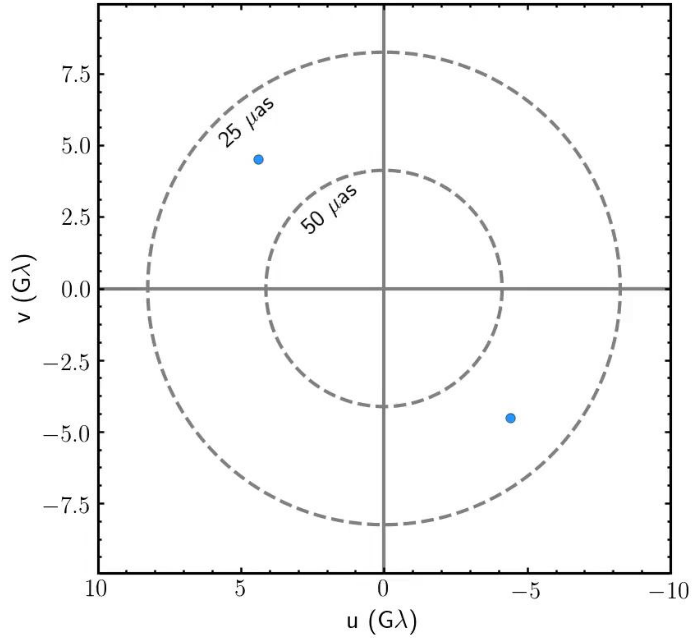
Very Long Baseline Interferometry (VLBI)

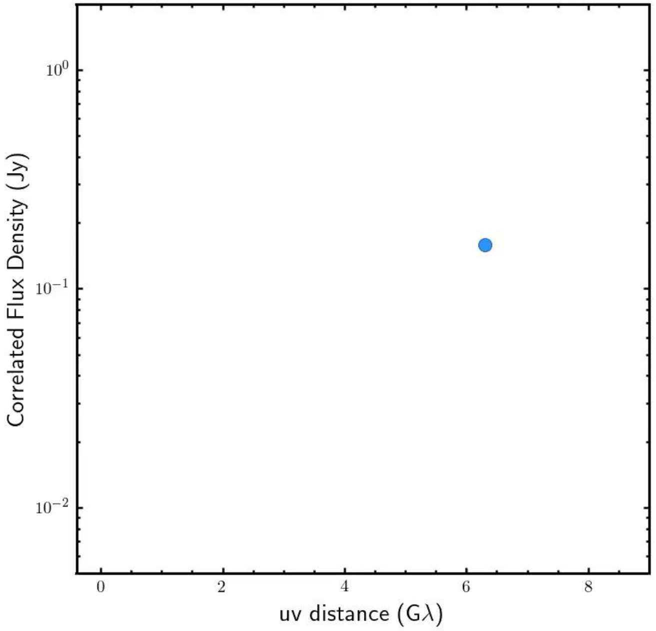


Every projected **baseline** between two telescopes provides **one Fourier component** of the image

movie credit: Katie Bouman

Very Long Baseline Interferometry (VLBI)

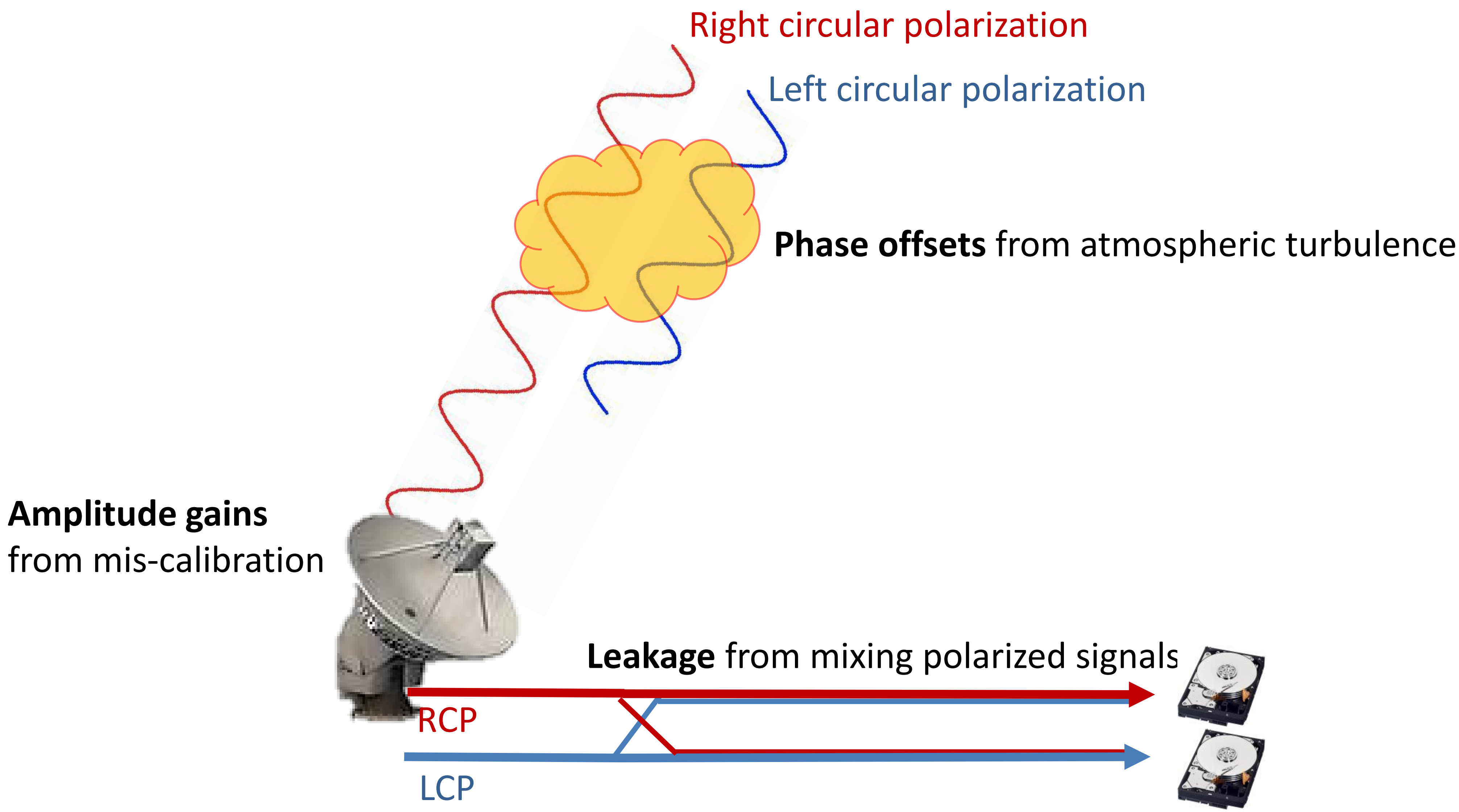




EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

movie credit: Daniel Palumbo

Challenges of near-horizon imaging

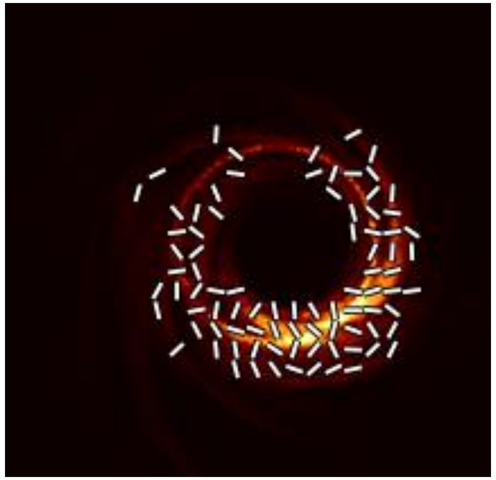


Data at each station are corrupted by unknown **gain and leakage** systematics

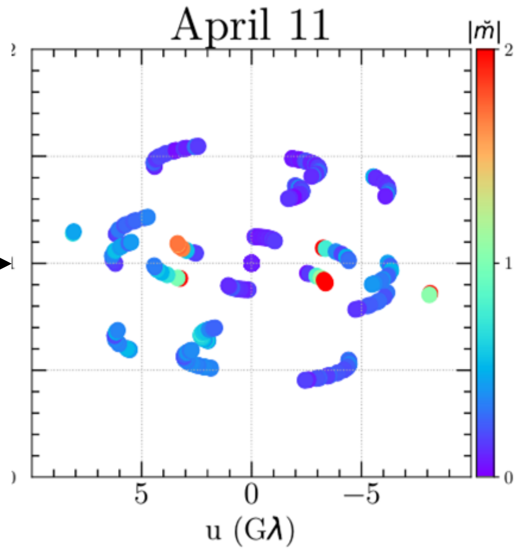
Animation credit: Andrew Chael

Solving for the Image

True Image

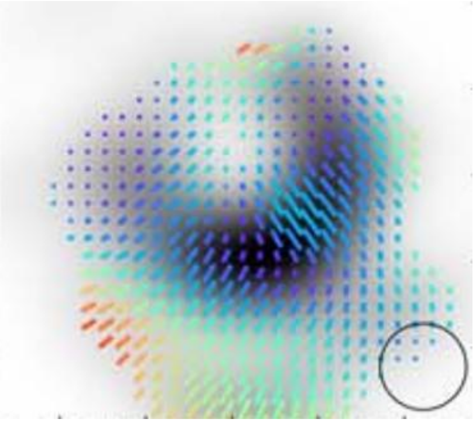


Sparse & Corrupted Measurements



RECONSTRUCTION ALGORITHM

Reconstruction



Several different types of reconstruction algorithms:

- **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, 2023), SMILI (Akiyama+ 2017)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
  - Themis (Broderick+ 21), DMC (Pesce+ 21), Comrade (Tiede+ 2022)

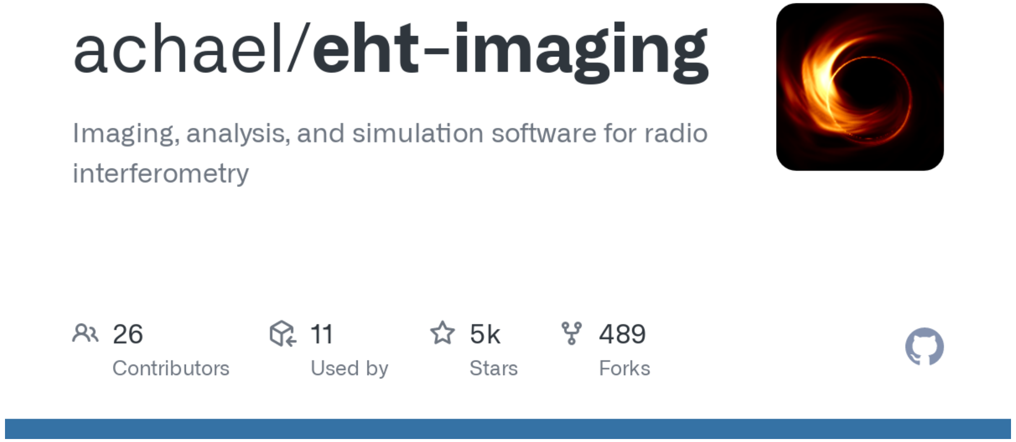
credit: Katie Bouman, Andrew Chael, EHTC VII, 2021

The **eht-imaging** software library

- python toolkit for **analyzing, simulating,** and **imaging** interferometric data

- A flexible framework for developing new tools:
  - dynamical imaging (Johnson+ 2017)
  - **multi-frequency imaging (Chael+ 2023a)**
  - geometric modeling (Roelofs+ 2023)

- Uses:
  - All EHT results to date
  - Next-generation EHT design
  - Imaging & analysis from VLBA, GMVA, ALMA, RadioAstron…



https://github.com/achael/eht-imaging

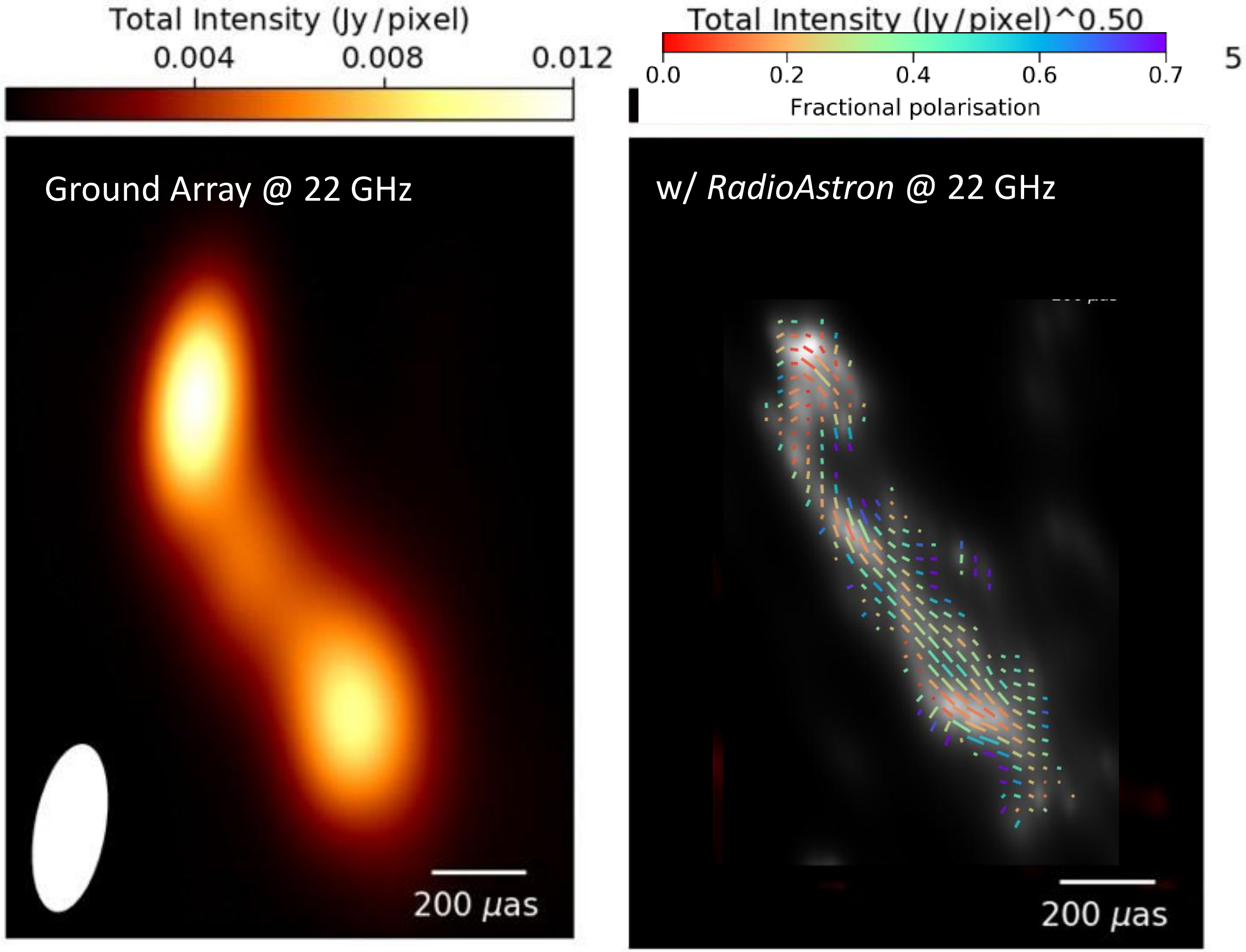
`pip install ehtim`

Chael+ 2016, 2018a, 2023a

New EHT imaging techniques have wide applicability!

3C279 with *RadioAstron*

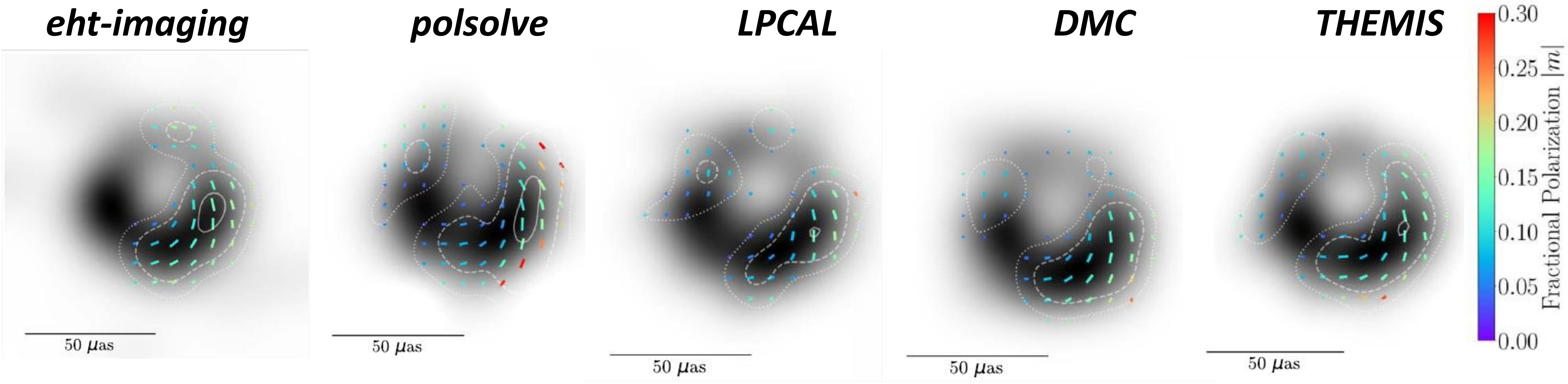
- At 22 GHz (1.3 cm) observed in 2014
- Space baselines to *RadioAstron* supported by a ground array of 23 antennas
- Reconstruction with **eht-imaging**.



Antonio Fuentes

Fuentes et al, 2023

Polarized Images of M87 from 5 methods

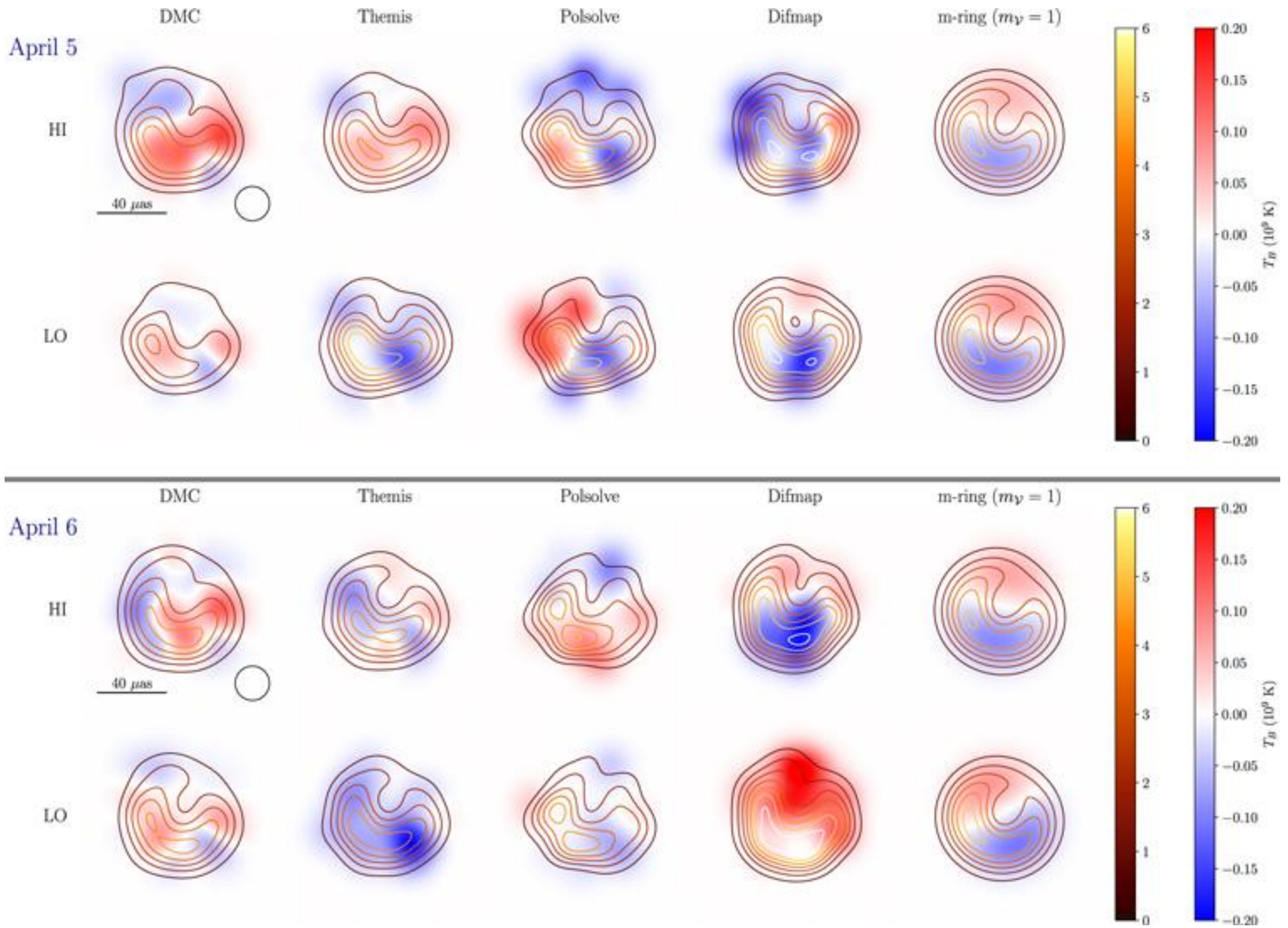


- All methods show similar total intensity and polarization structure at 20 μas resolution
- Consistent ring diameter (~40 μas) and asymmetry (south)
- Polarization structure is predominantly **helical and weak**, (|m| ~15 %)

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

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

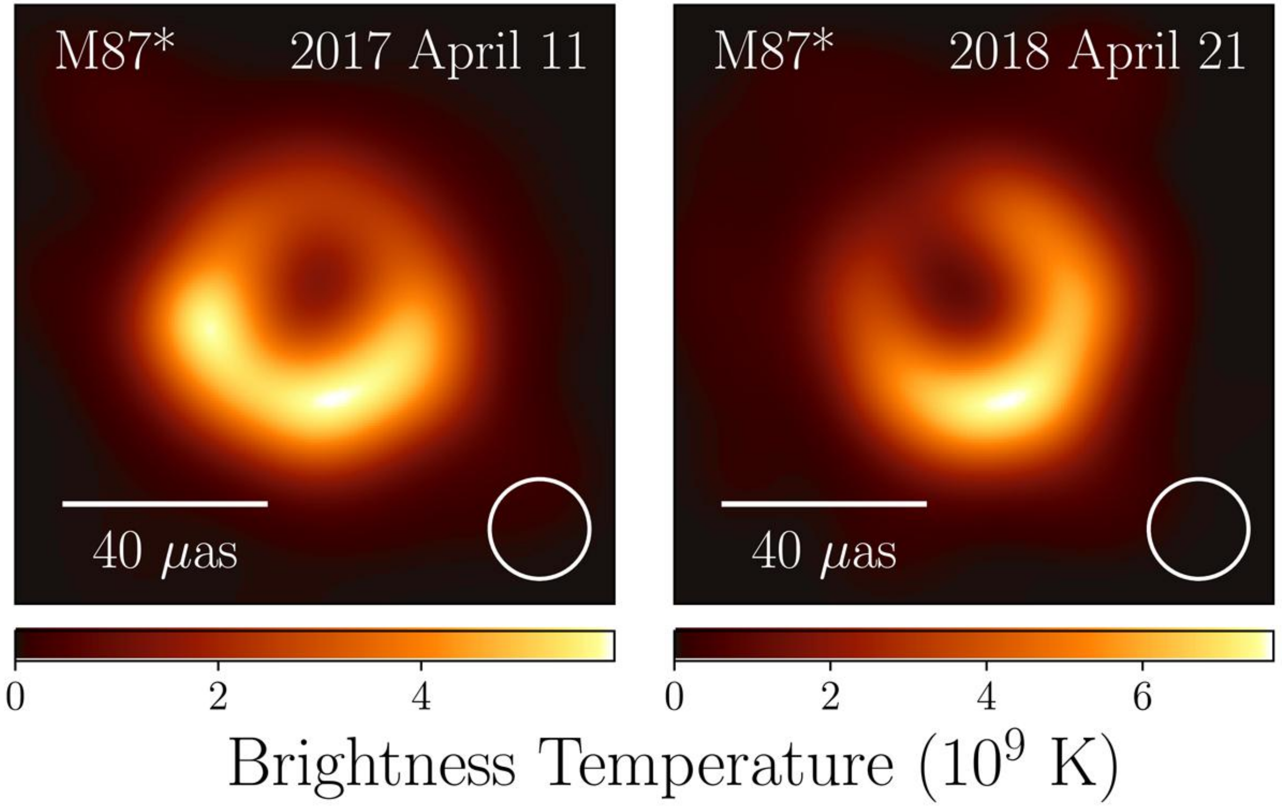
- EHT **unambiguously detects** circular polarization in M87*
- Different methods do not show consistent circular polarization images
  - between days
  - between frequency bands
- We place an upper limit: $\langle |v| \rangle$ **< 3.7%**
- **Future observations will be more sensitive!**



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

M87: Image persistance across years

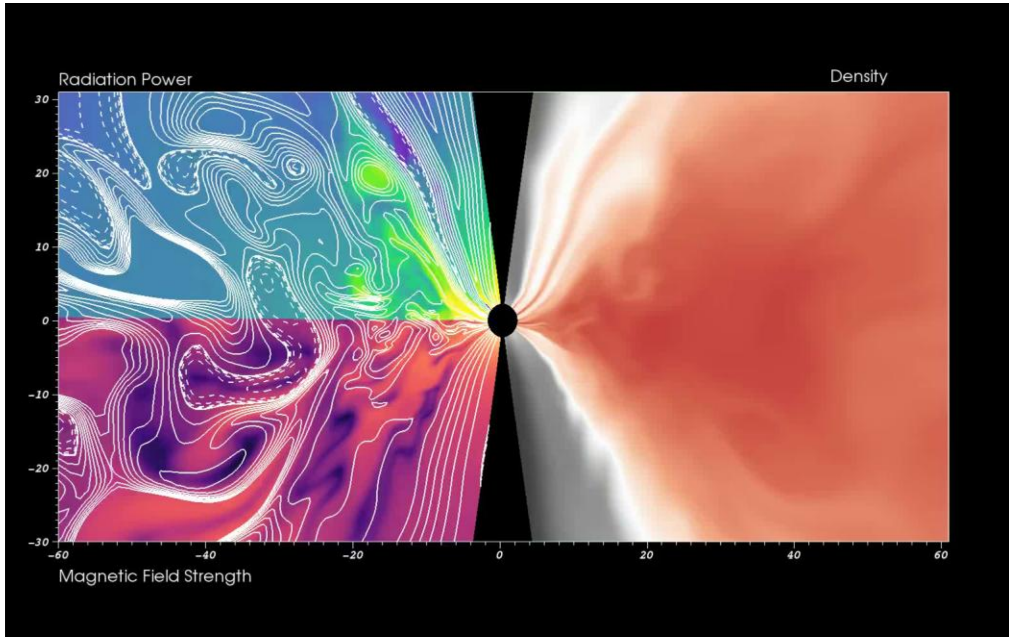
- 2018 observations show consistent horizon-scale structure in M87* **1000 gravitational timescales later.**
- Observations performed with a **more complete array** (including Greenland Telescope)
- Image **diameter is consistent** but brightness **position angle shifts**
- Stay tuned for more soon….



What did we learn from comparing polarized images of M87* to simulations?

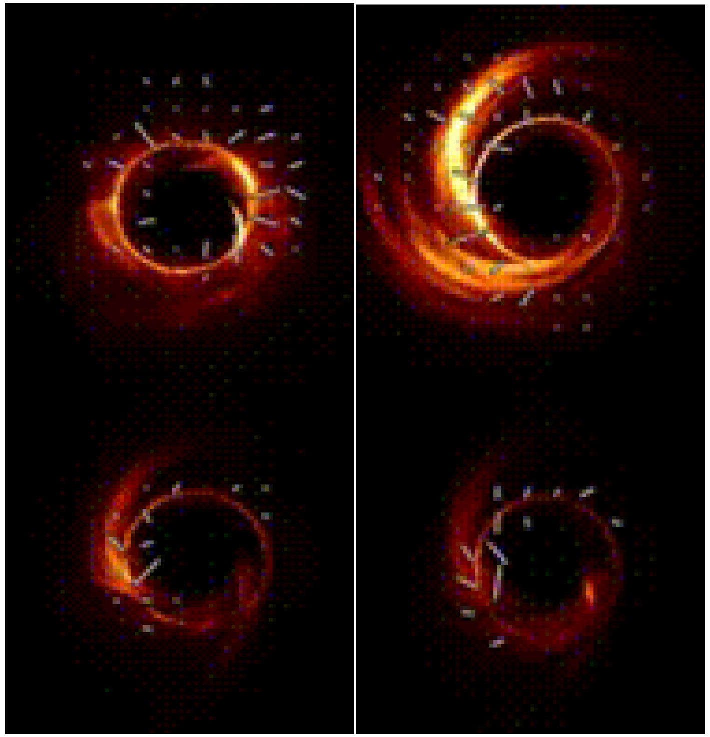
EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator)
2105.01173, 2311.10976

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

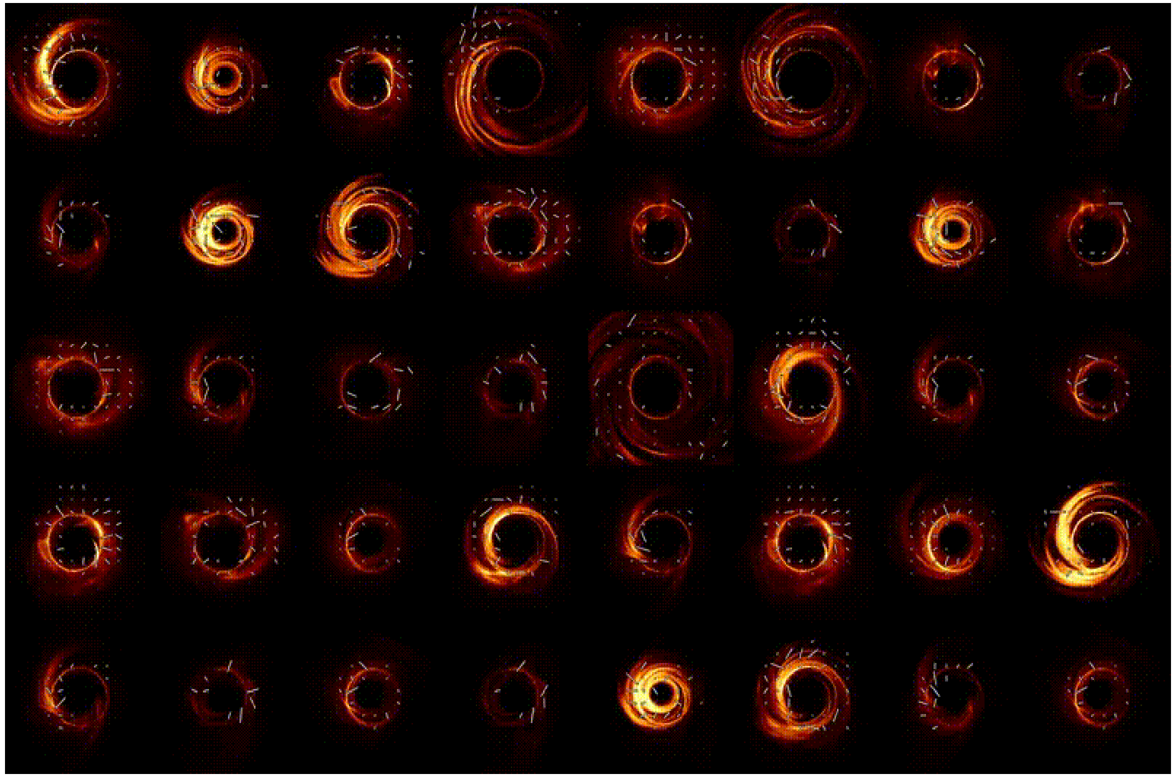


GR Radiative Transfer

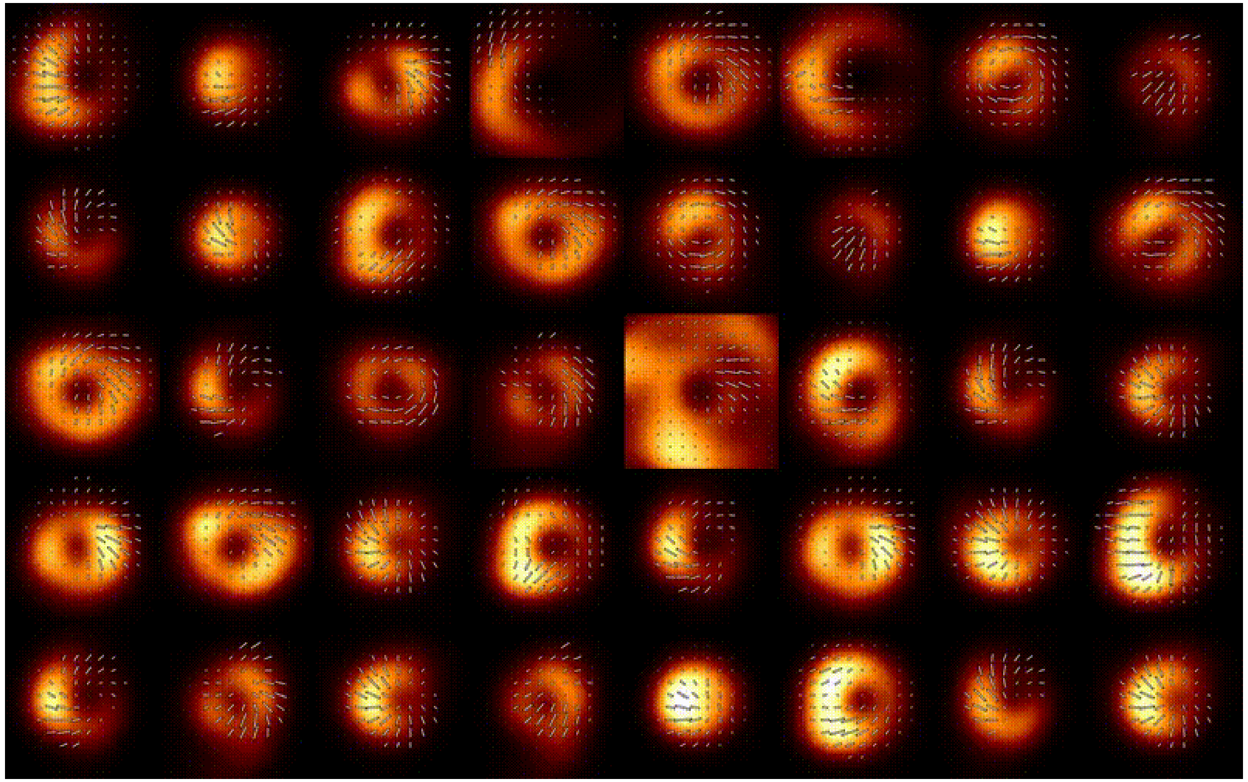
Track light rays and solves for the polarized radiation (including Faraday effects)

Movie Credits: **Chael**+ 2019, 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

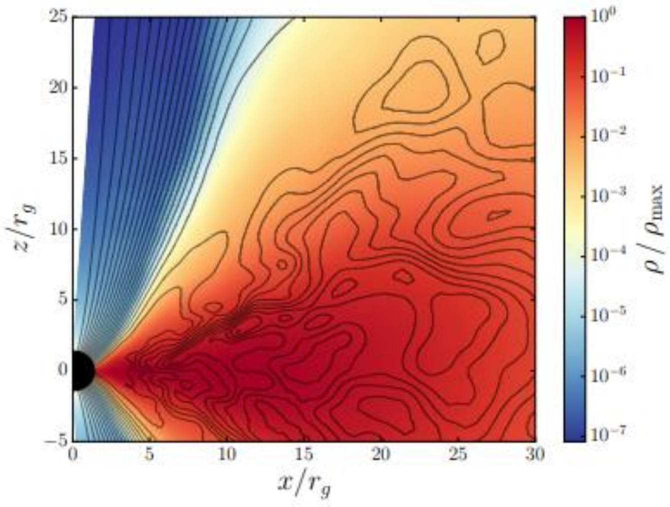
$$T_{\rm e} \neq T_{\rm i} \neq T_{\rm gas}$$

Animation credit: George Wong/ Ben Prather

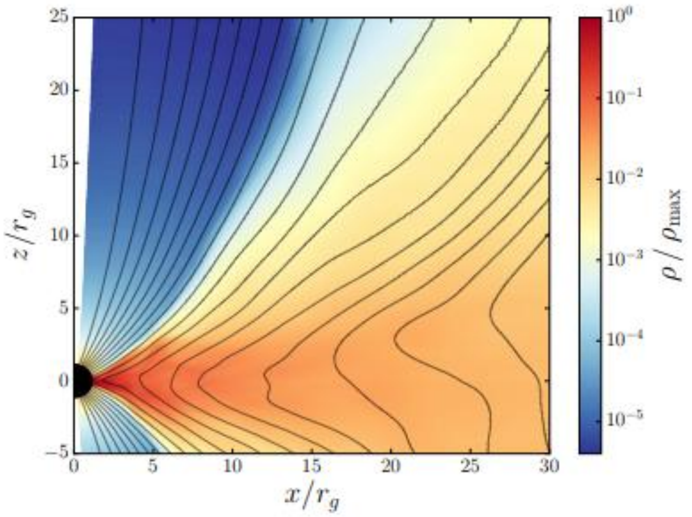
What is the magnetic field structure close to the horizon?

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*

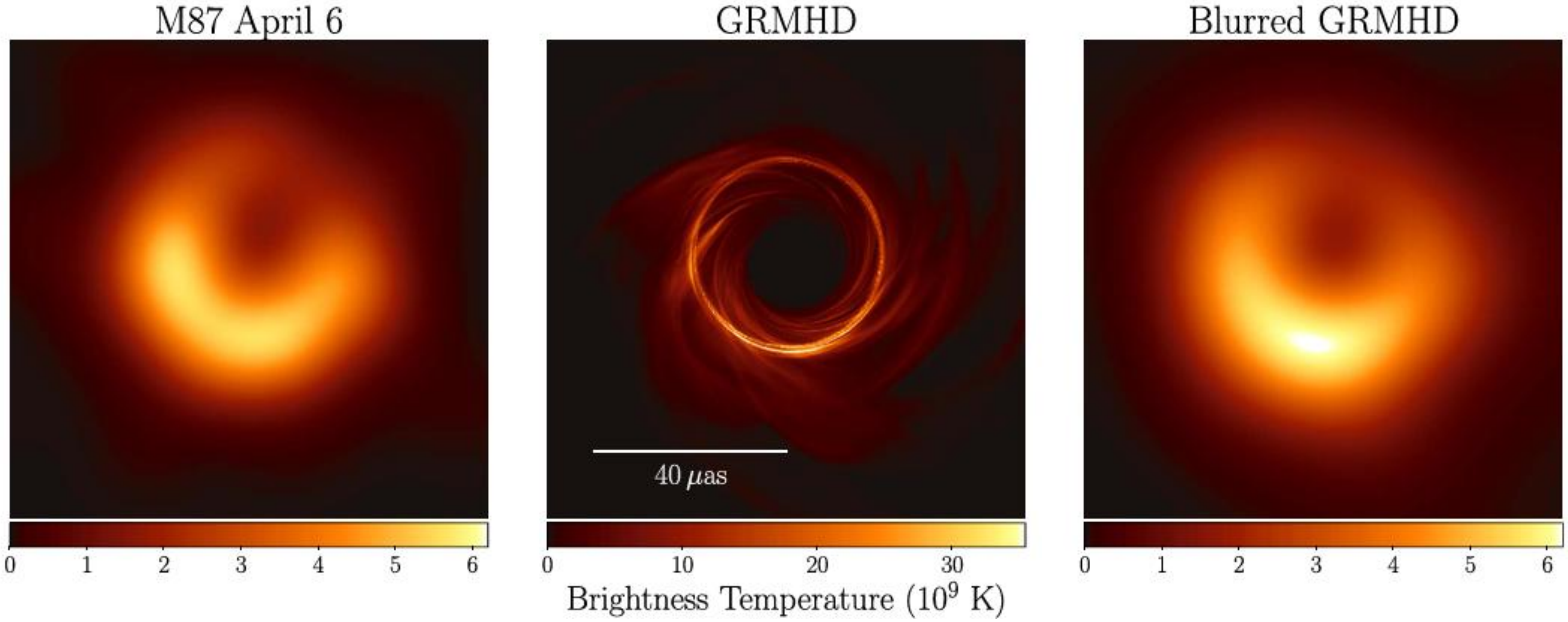
Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_B^2 a^2$

BH spin

magnetic flux

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

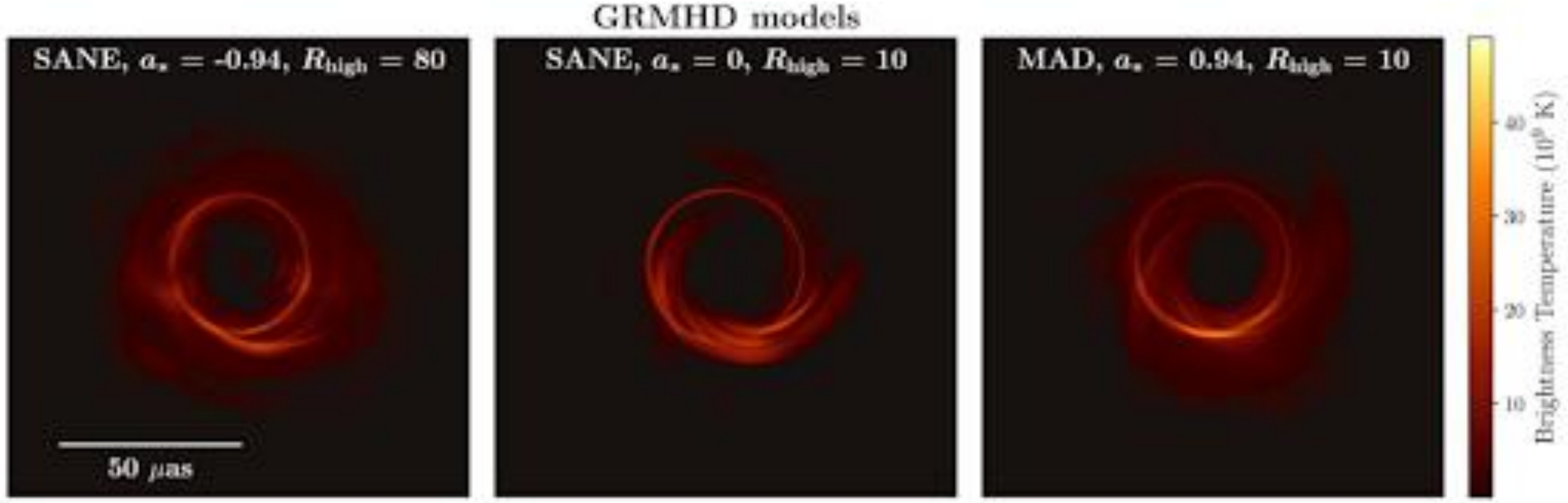
EHT Images are consistent with GRMHD/LLAGN Picture



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

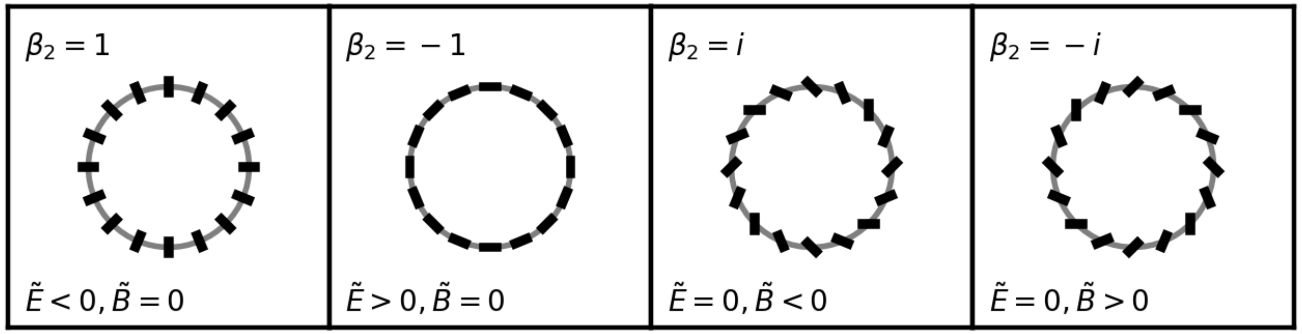
Summarizing an image: Polarization

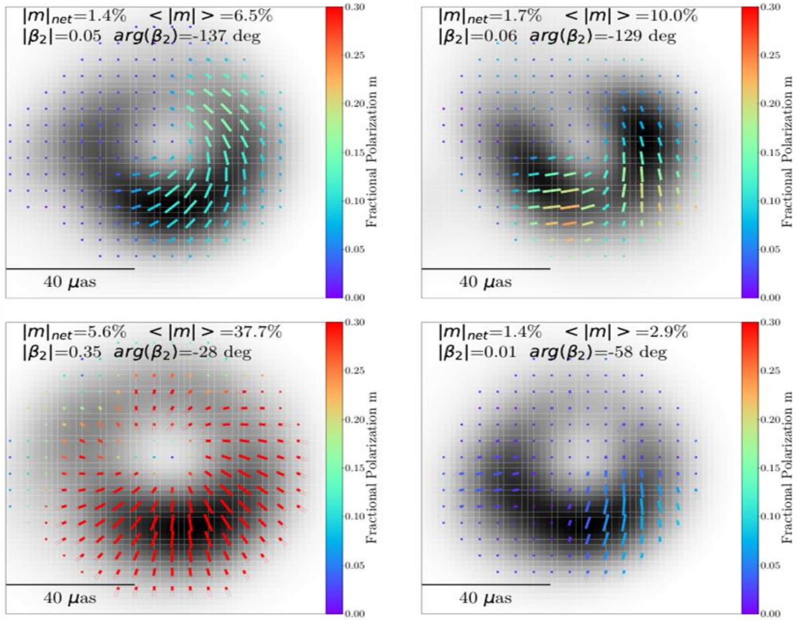
Unresolved and Resolved polarization fractions

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

Azimuthal structure
2nd Fourier mode

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

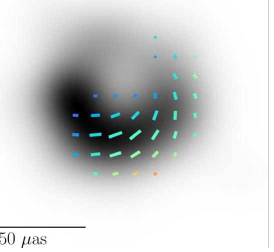




Simulation images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

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**

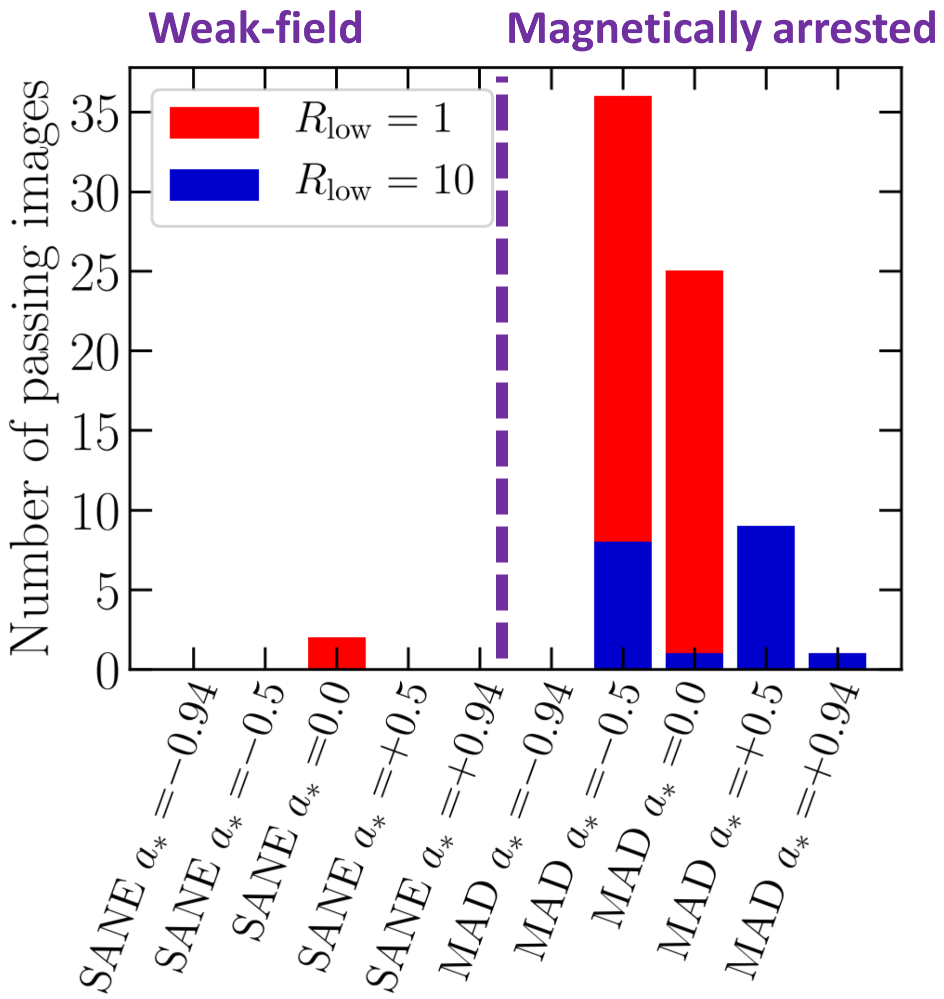
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

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

- Parameters from passing models agree with analytic model estimates:

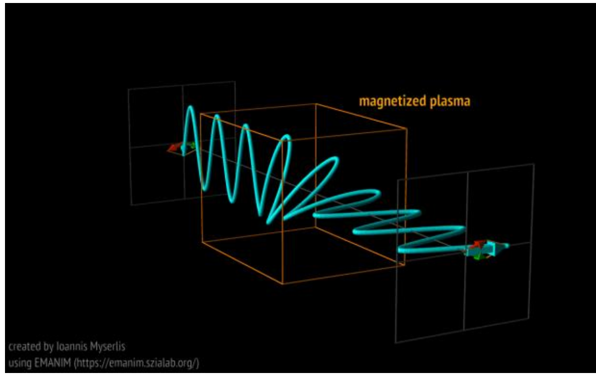
$$T_e \simeq (5-40)\times 10^{10}\ \mathrm{K}$$
$$|B| \simeq (7-30)\ \mathrm{G}$$
$$n \sim 10^{4-5}\ \mathrm{cm}^{-3}$$

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



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

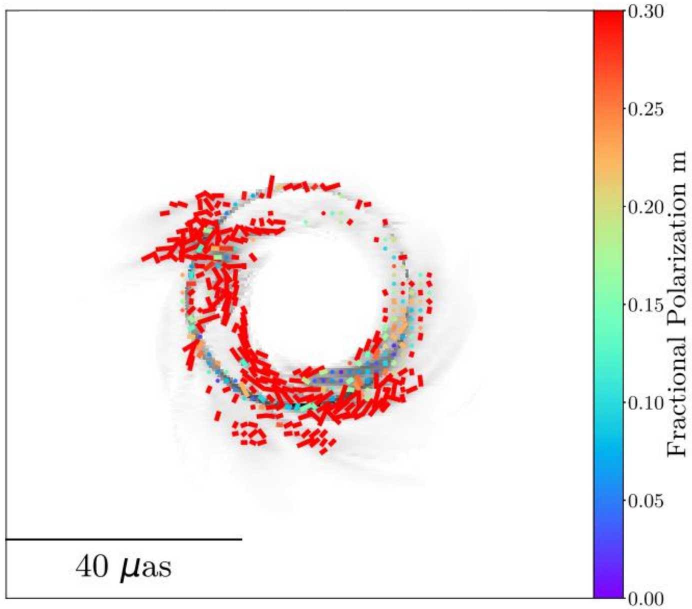
Faraday Rotation is important!

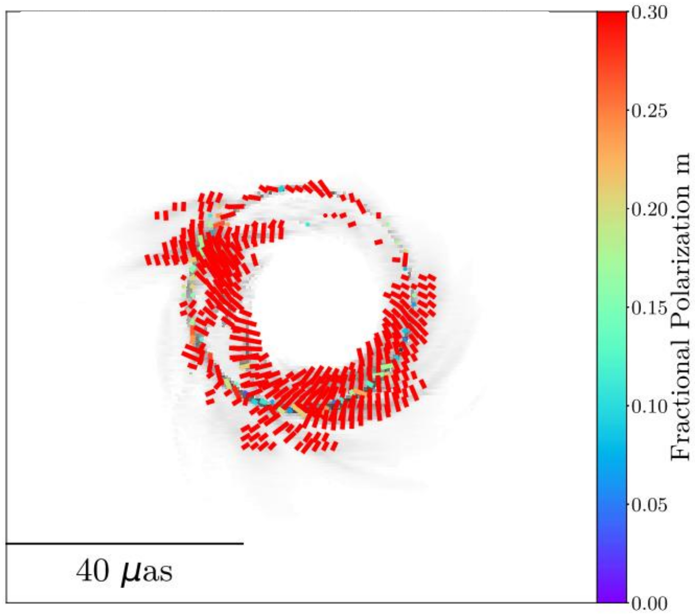


With rotation

Without rotation

'infinite' resolution

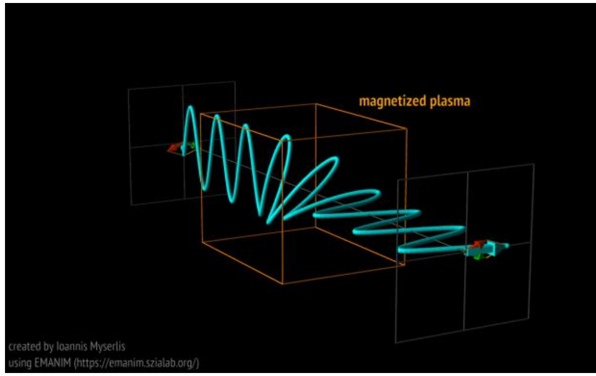




- Significant Faraday rotation on small scales
  → **scrambles** polarization directions

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

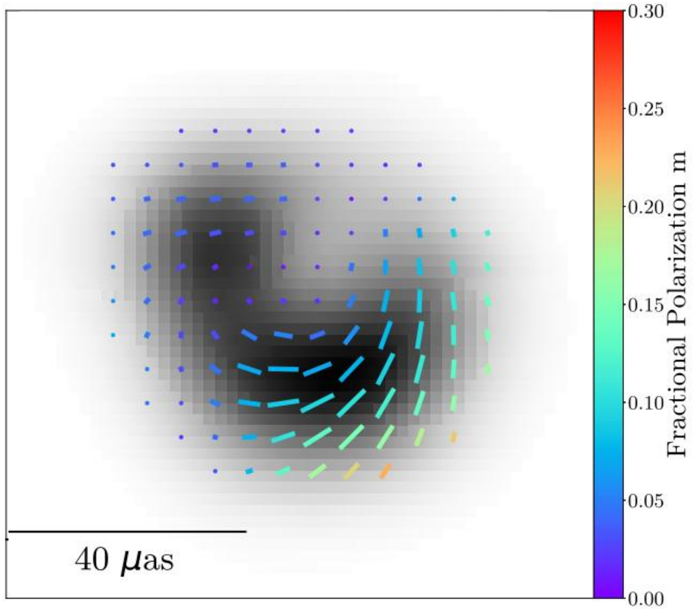
Faraday Rotation is important!

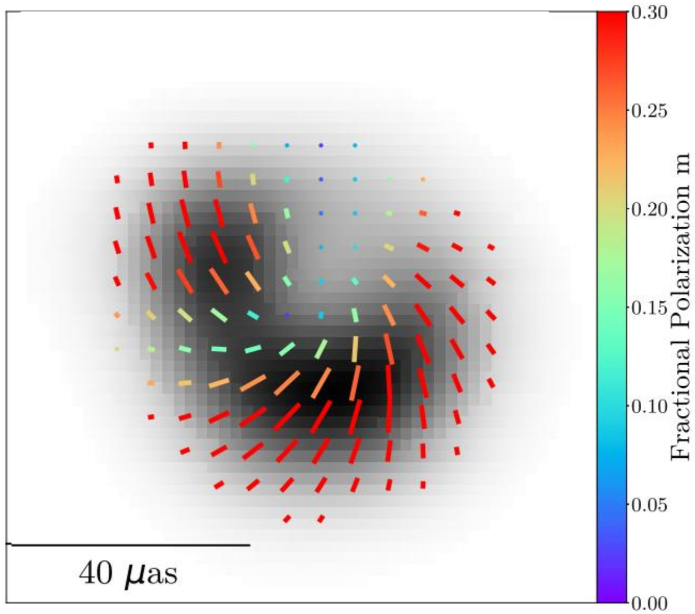


With rotation

Without rotation

EHT resolution

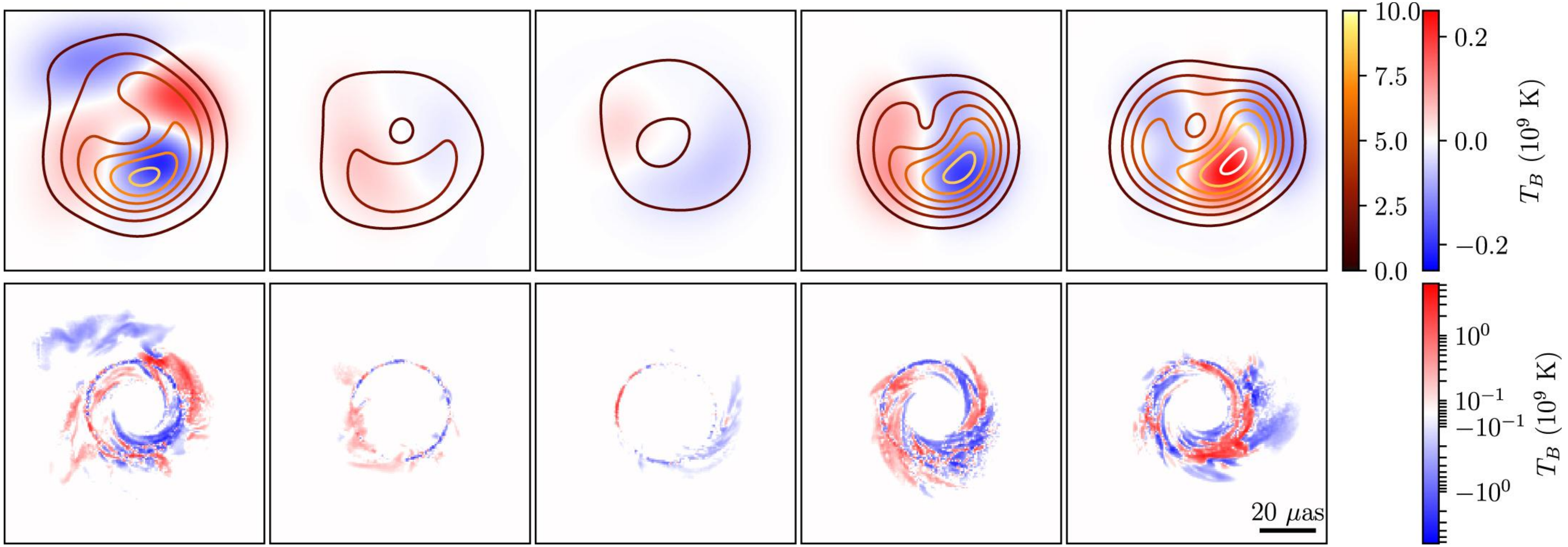




- Significant Faraday rotation on small scales
  - → **scrambles** polarization directions
  - → **Depolarizes** the image when blurred to EHT resolution
  - → **rotates** the pattern when blurred to EHT resolution
- Internal Faraday rotation is necessary to depolarize MAD models

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

Passing simulations have diverse circular polarization images

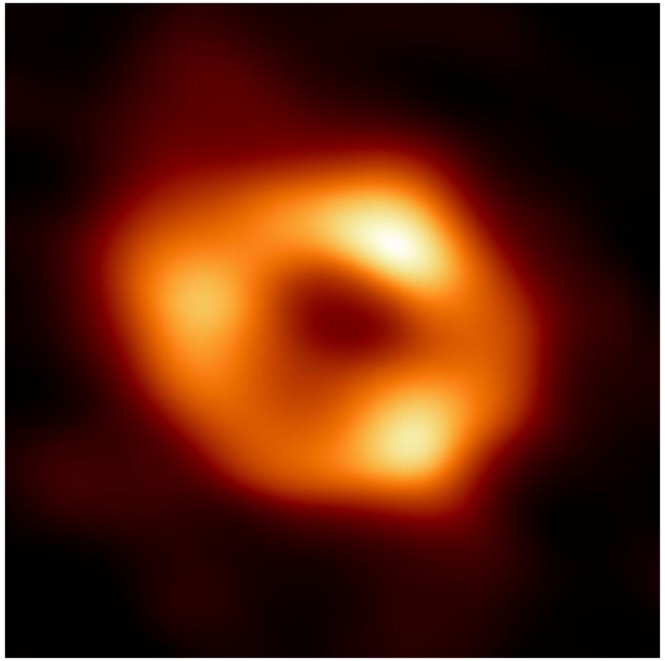


Detecting the Stokes V image structure with more sensitive observations will constrain models further.
Need more theoretical work to understand these morphologies!

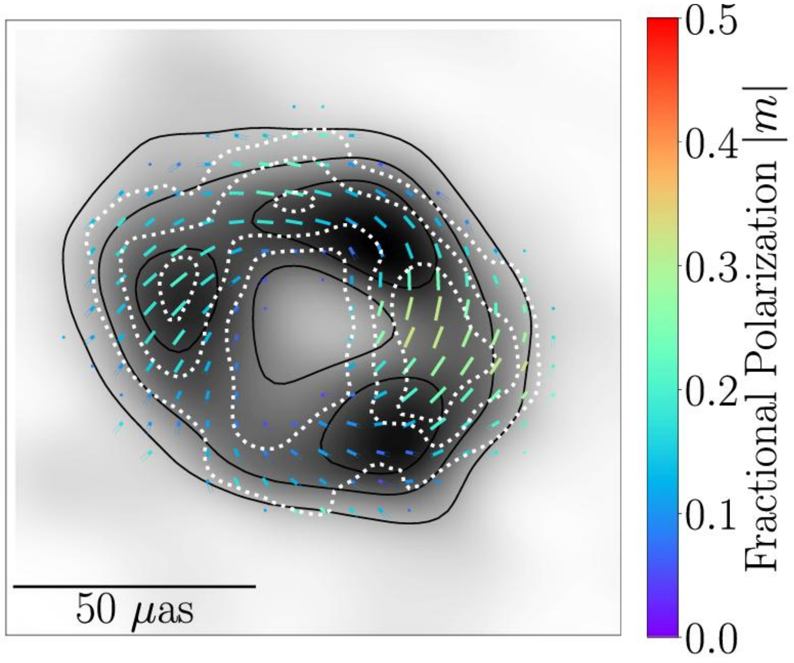
Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)
Ricarte+ 2021

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

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:

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

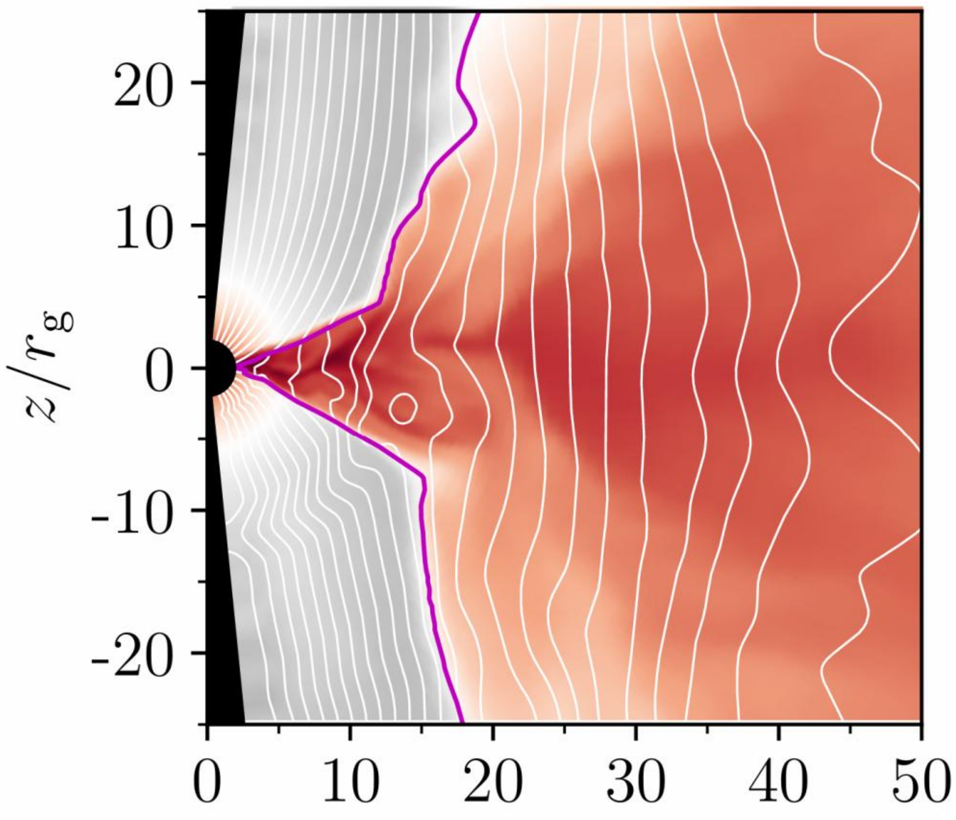
- The ratio of magnetic energy to rest-mass energy is defined:

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

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

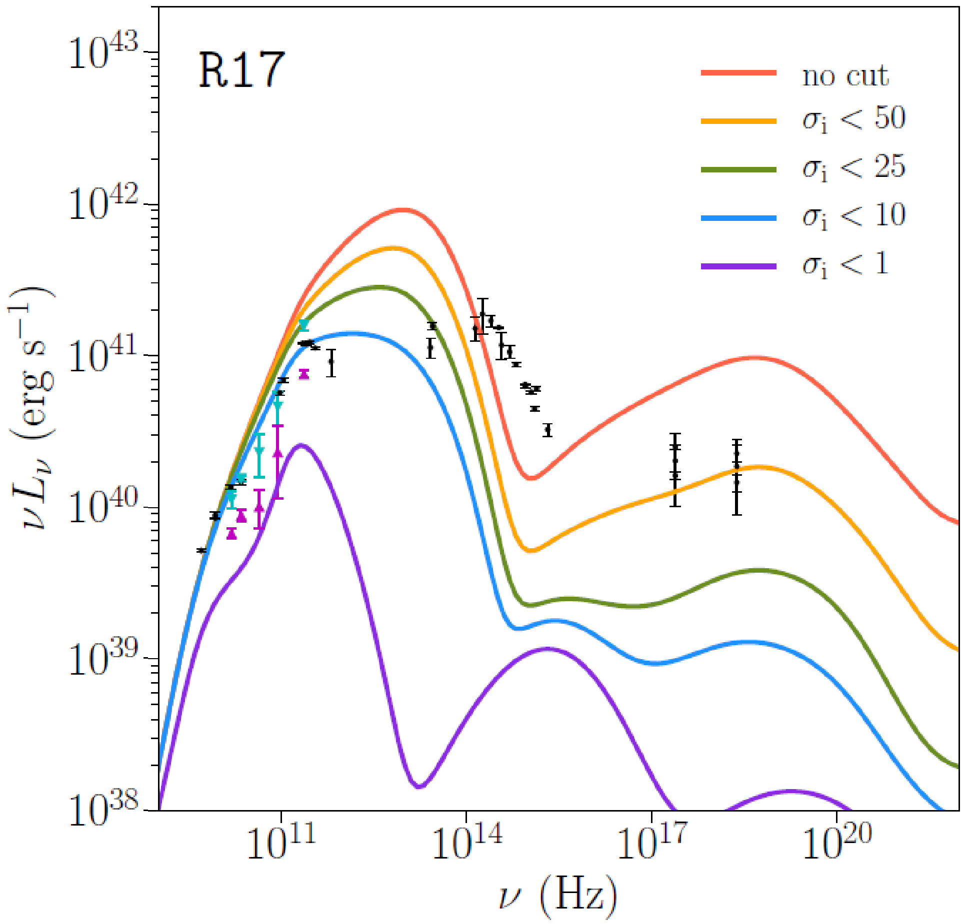
- GRMHD codes introduce density ‘floors’ for stability

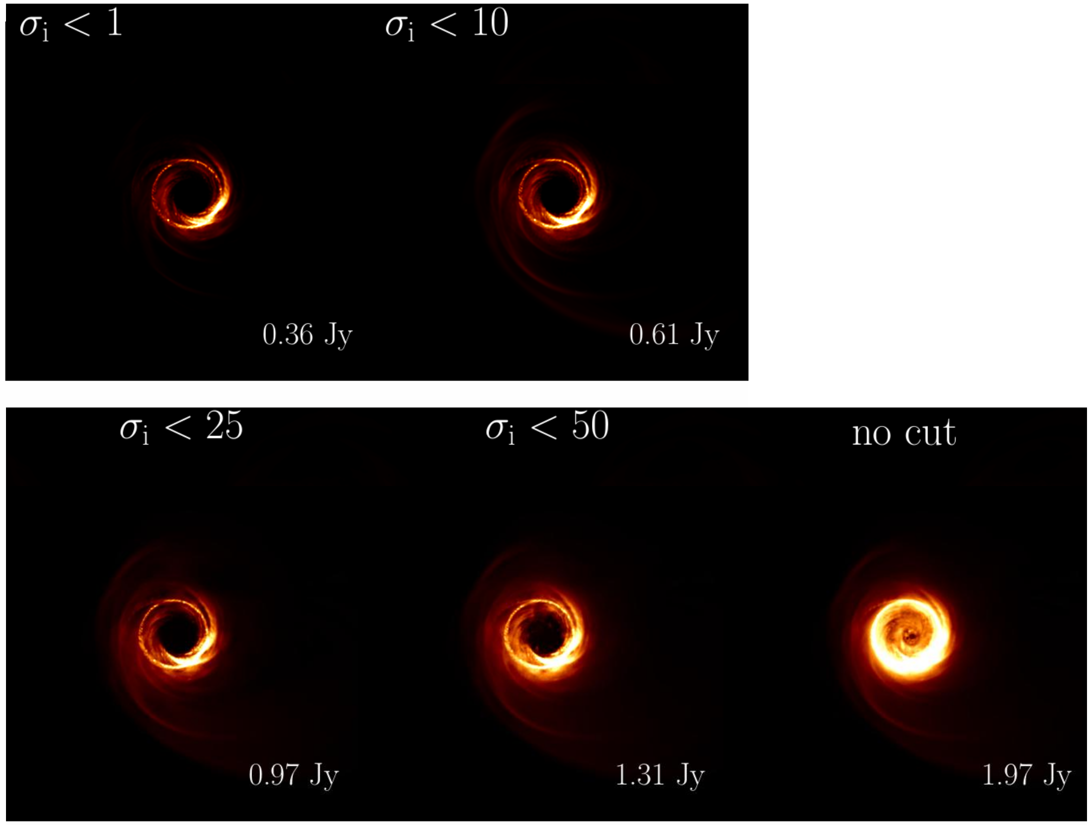
$$\sigma < \sigma_{\max}$$



Chael 2024

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





Chael+ 2019

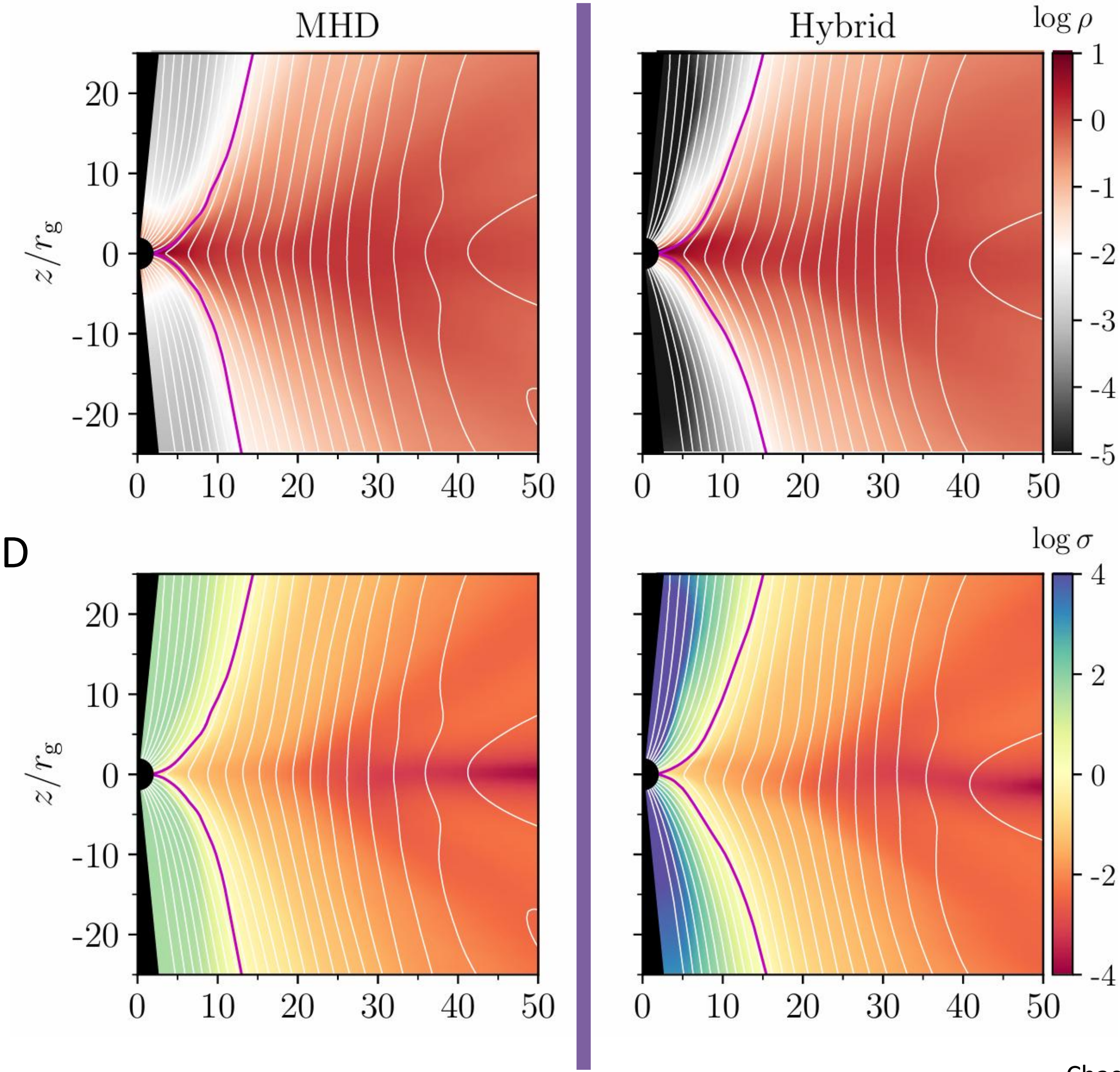
A New Hybrid GRMHD + Force-Free Code

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

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

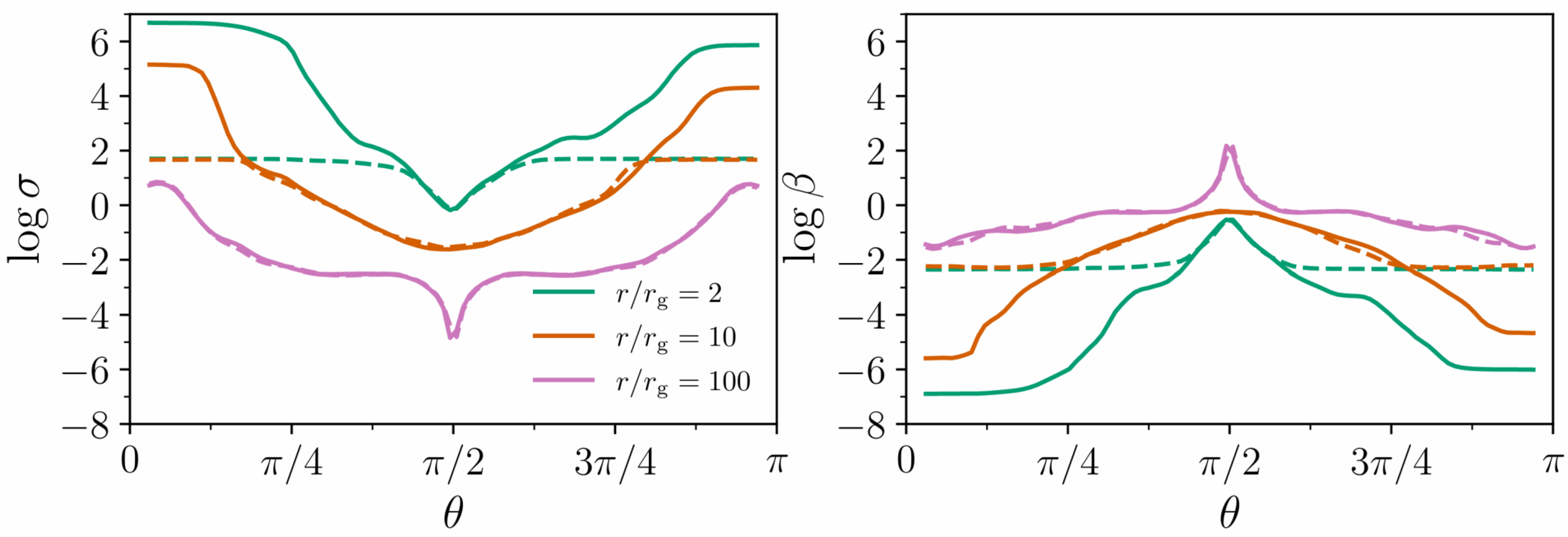
- electromagnetic fields evolve with **no back-reaction**
- field-parallel velocity determined from GRMHD limit
- **gas evolved adiabatically** in fixed background

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



Chael 2024

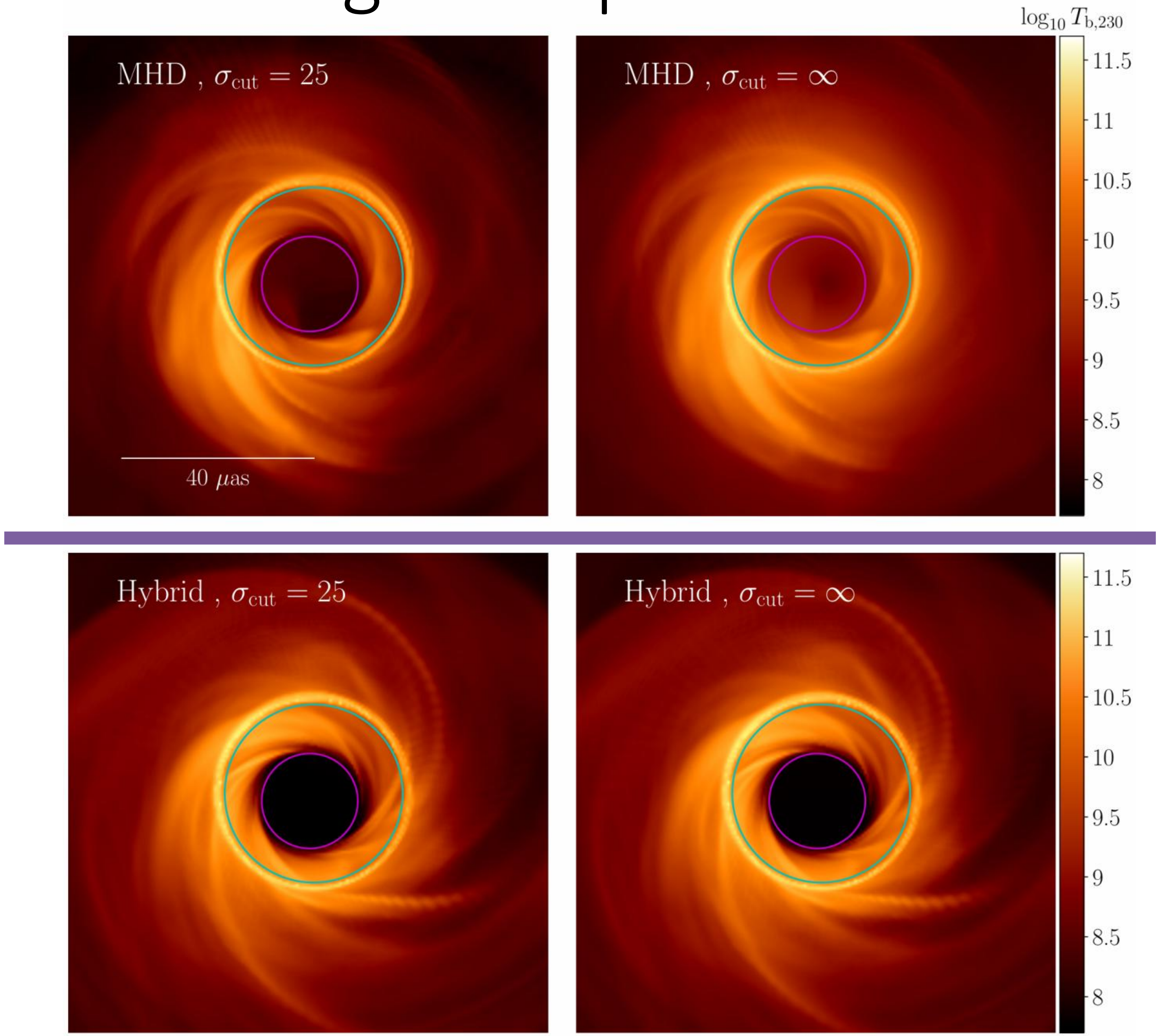
Comparing standard GRMHD and Hybrid GRMHD+FF



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



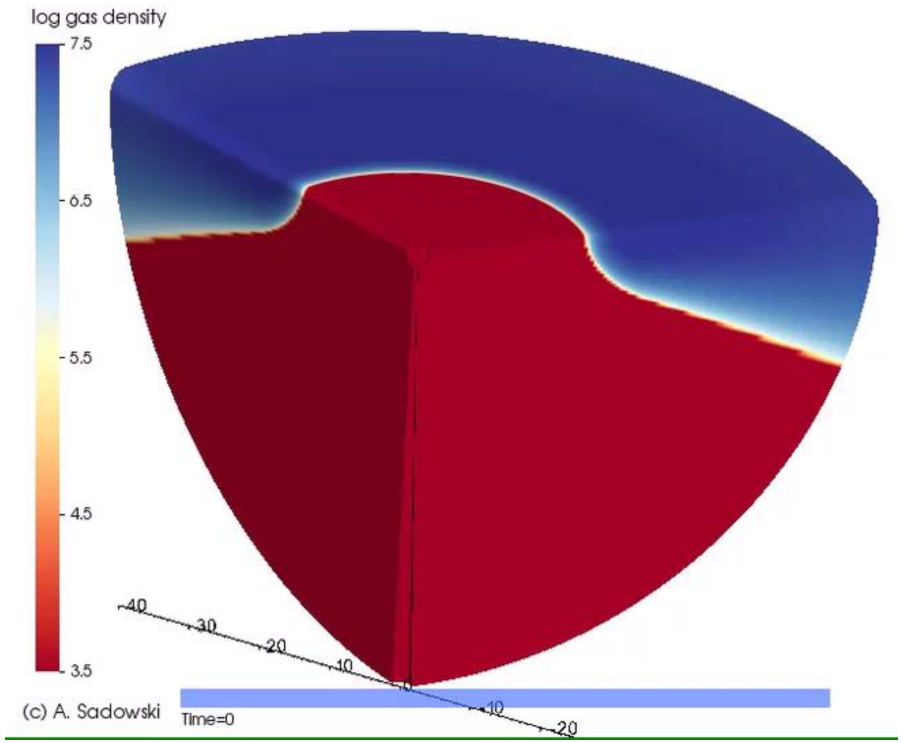
In standard GRMHD, foreground jet emission fills in the shadow region unless we have a cut on σ in radiative transfer

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

Chael+ in prep

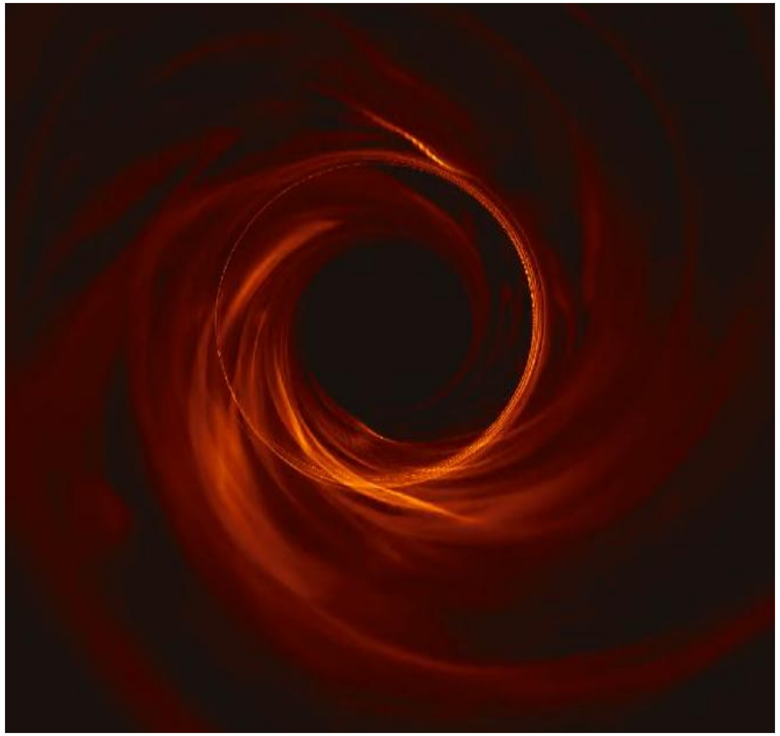
MAD Simulation Uncertainties: Electron Temperature

GRMHD



T_e?

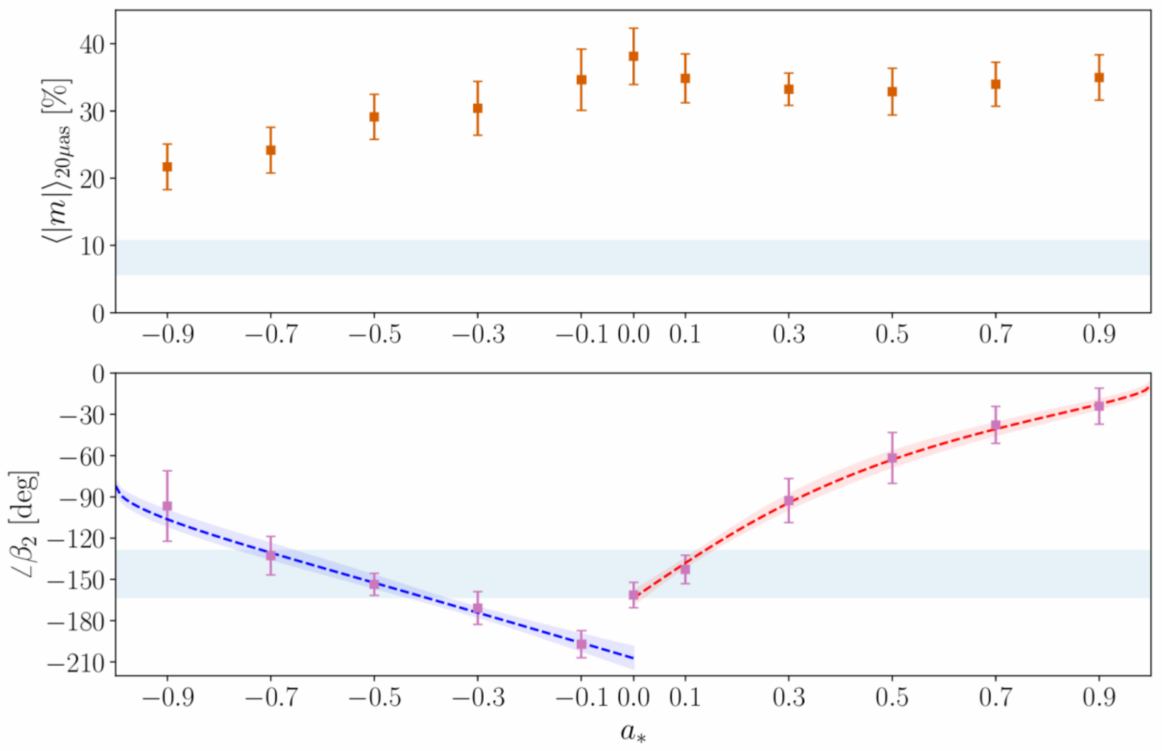
GRRT



- Traditional GRMHD simulations assign the electron temperature in post-processing
- *Two-temperature* simulations can solve directly for the electron temperature, assuming an underlying model of plasma heating

Movie Credits: Aleksander Sądowski, EHTC V, 2019

How do we produce sufficiently cold electrons?



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

$$T_e \neq T_i$$

- EHT analysis fixes T_e locally in **postprocessing** and seems to prefer electrons T_i ~ 100x T_e to sufficiently depolarize the image in MAD simulations.
- 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

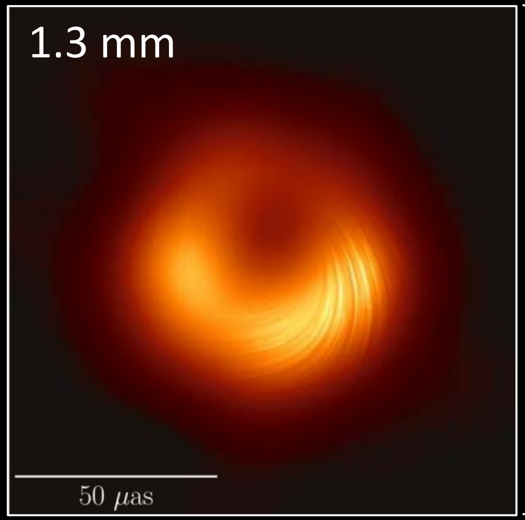
What can a polarized image of M87* tell us about energy flow & jet launching?

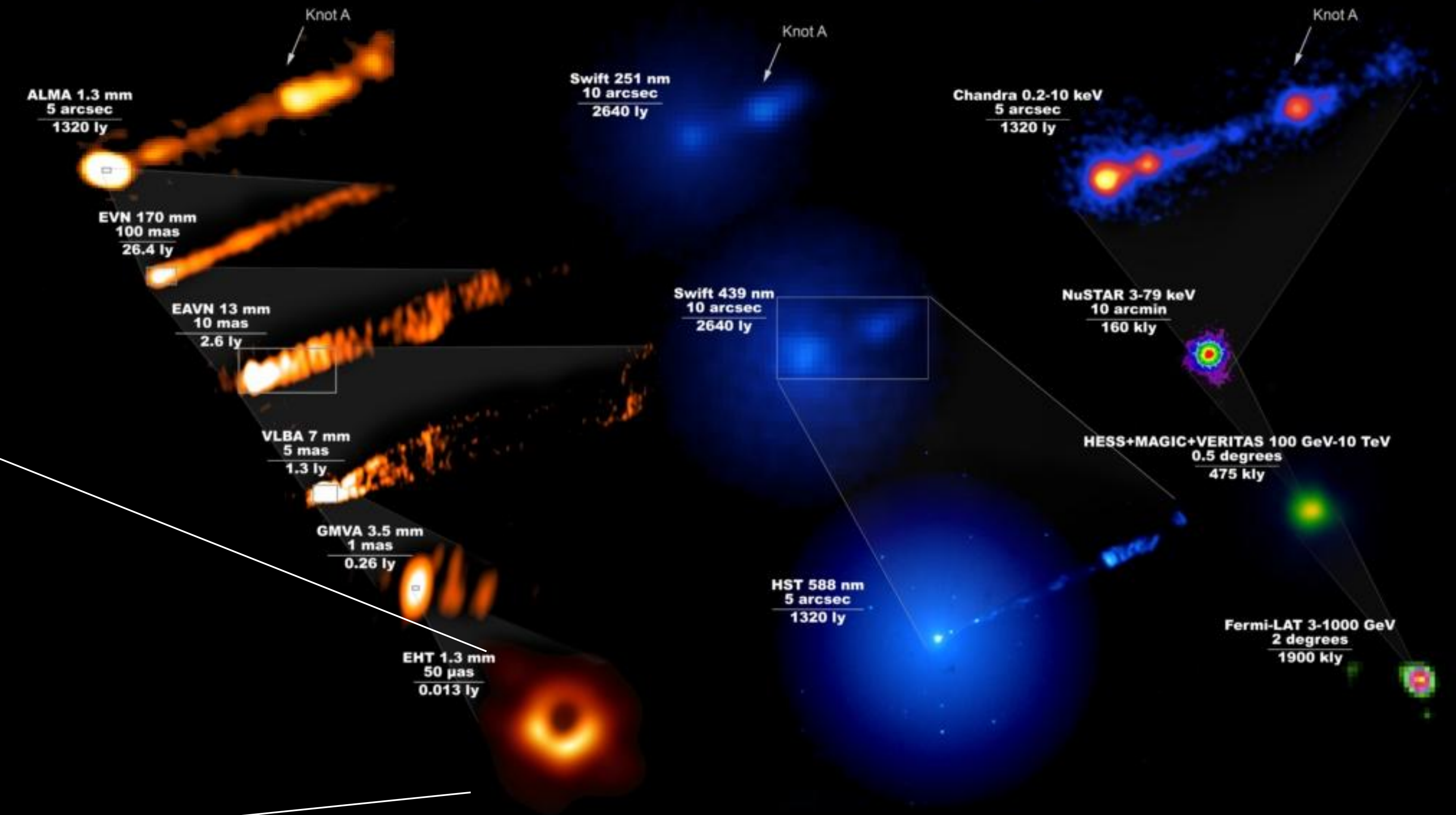
Chael+ 2023, Gelles+ 2025, Chael+ in prep.
2307.06372, 2410.00954

M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$

P_{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

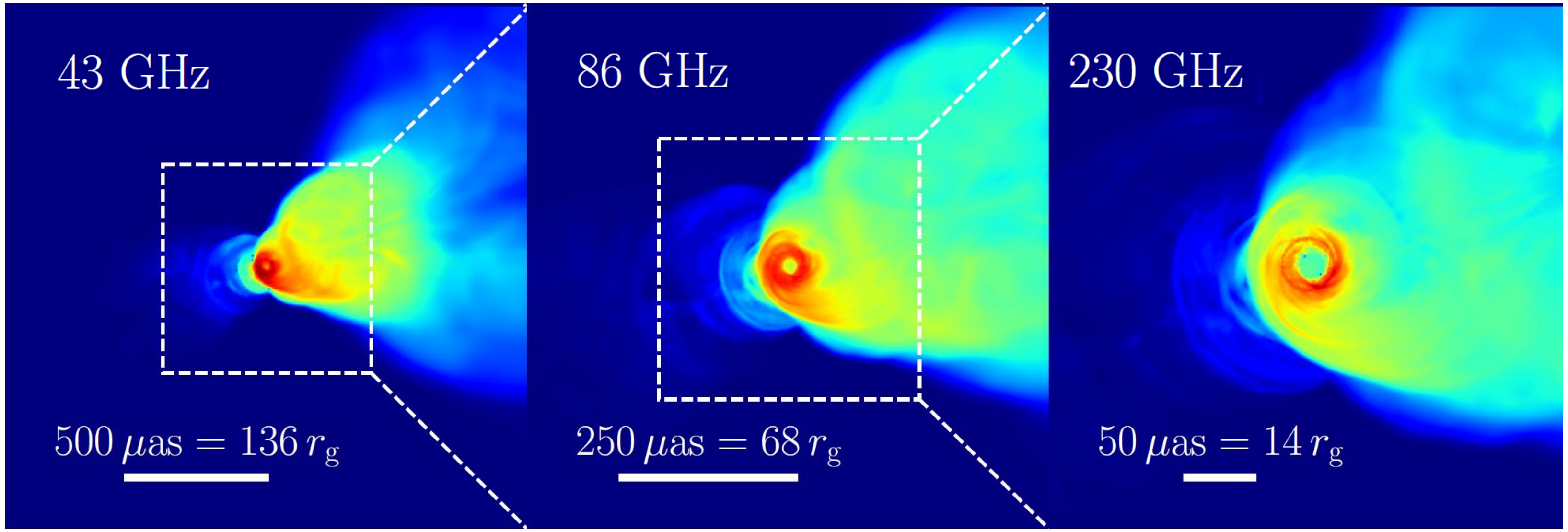
M87 Jets in GRMHD Simulations

- 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:

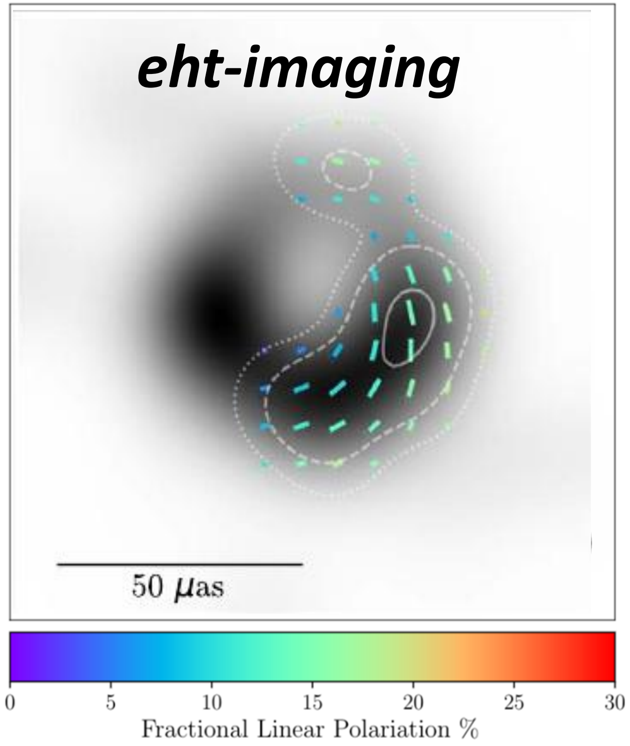
  - A jet power in measured range
  - observed wide opening angle
  - observed core-shift

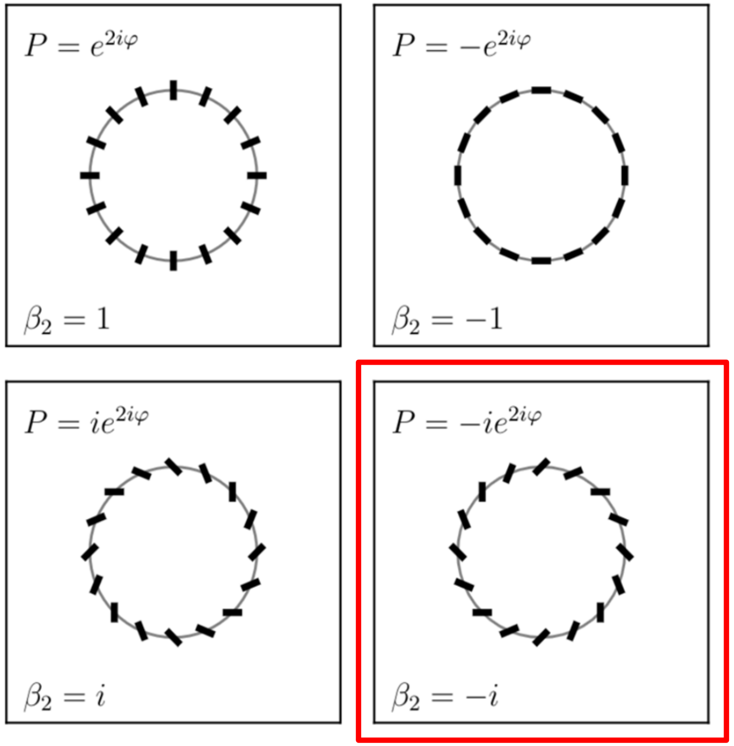
- Can we be **sure?** What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?



Chael+ 2019

Polarized Images of M87* and horizon-scale energy flow

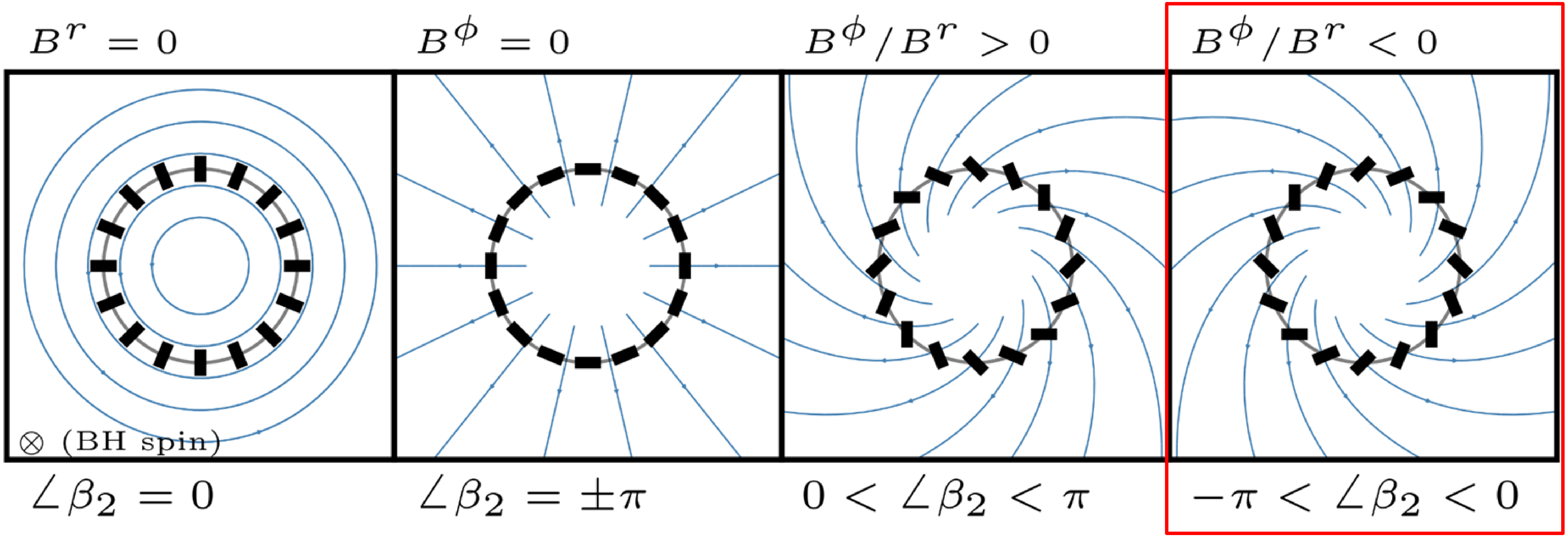




- The polarization spiral's 2nd Fourier mode ($\boldsymbol{\beta_2}$: Palumbo+ 2020) is the **most constraining** feature
- Can we interpret $\boldsymbol{\beta_2}$ **physically**?

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

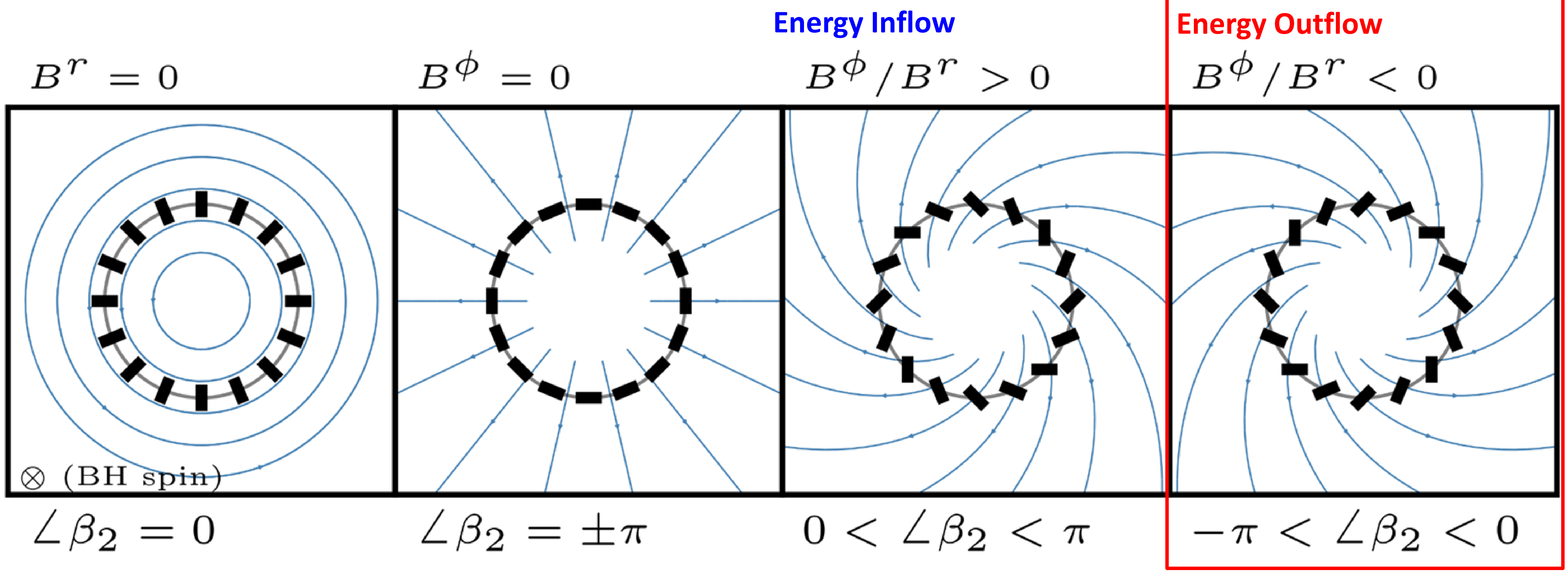
Cartoon model: β_2 is connected to the field pitch angle



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

Chael+ 2023b

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



Radial Poynting flux in Boyer-Lindquist coordinates:

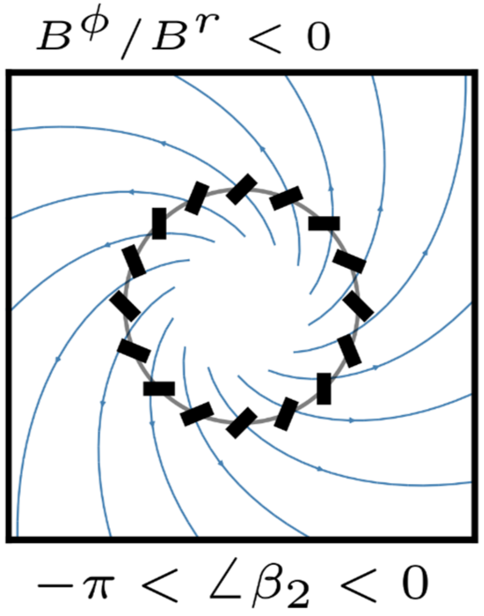
$$\mathcal{J}^r_{\mathcal{E}} = -T^r_{\ t\ \mathrm{EM}} = -B^r B^\phi \, \Omega_F \, \Delta \sin^2\theta$$

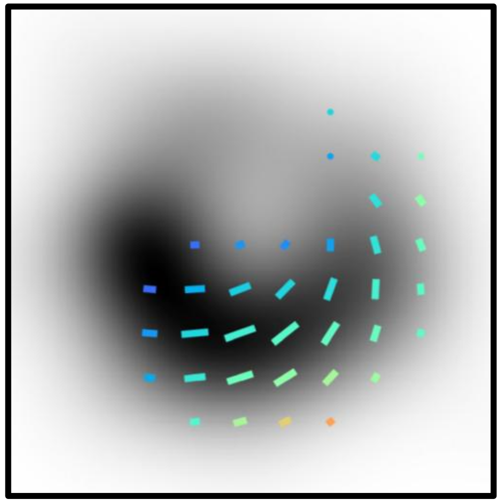
fieldline angular speed

Chael+ 2023b

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*?



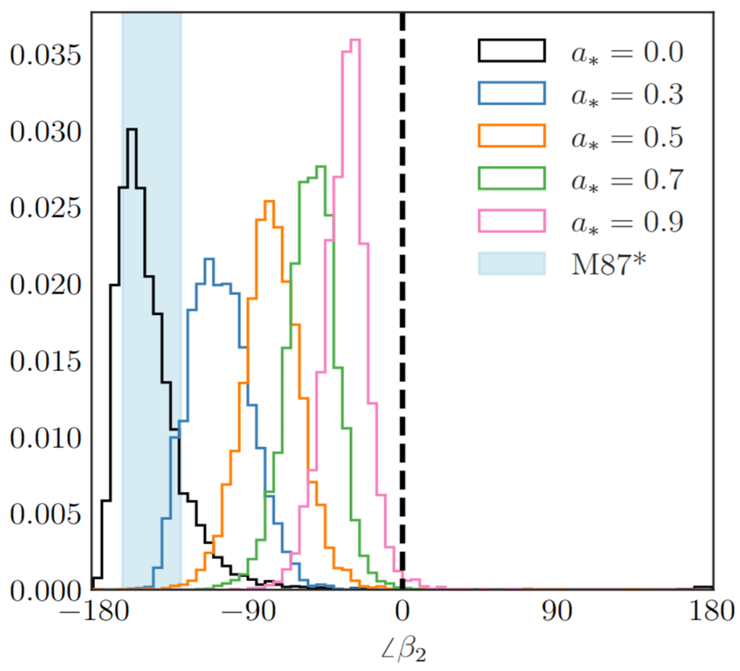


EHTC+ 2021 VII, **Chael**+ 2023b

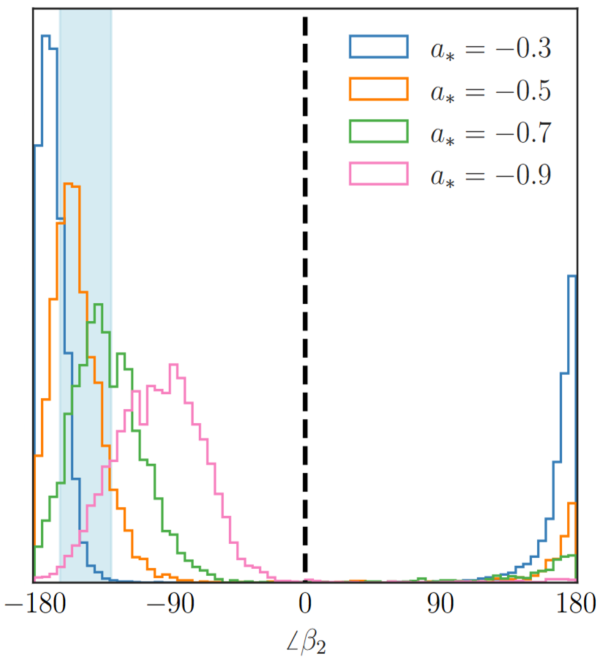
β_2 in MAD **GRMHD simulations** of M87*

- 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

Prograde simulations



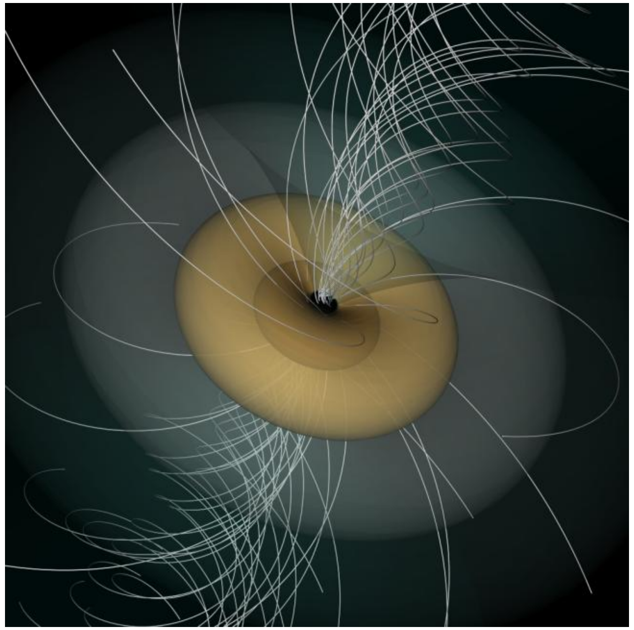
Retrograde simulations



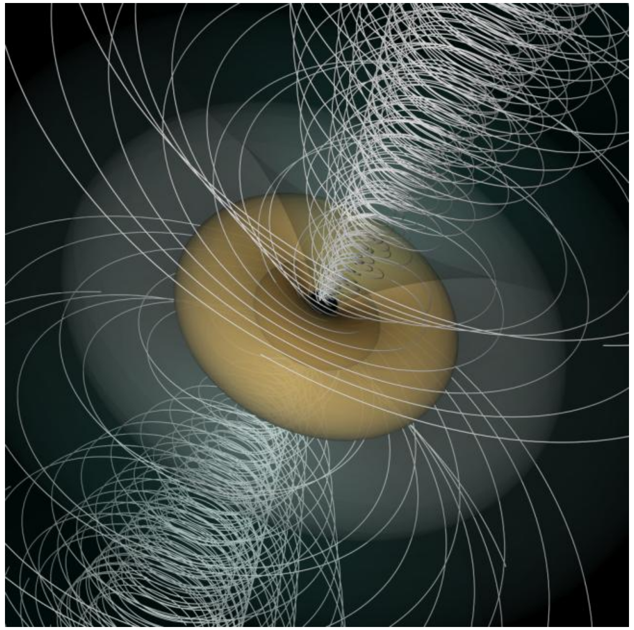
Chael+ 2023b

Polarized images are **spin dependent**

Low Spin



High Spin

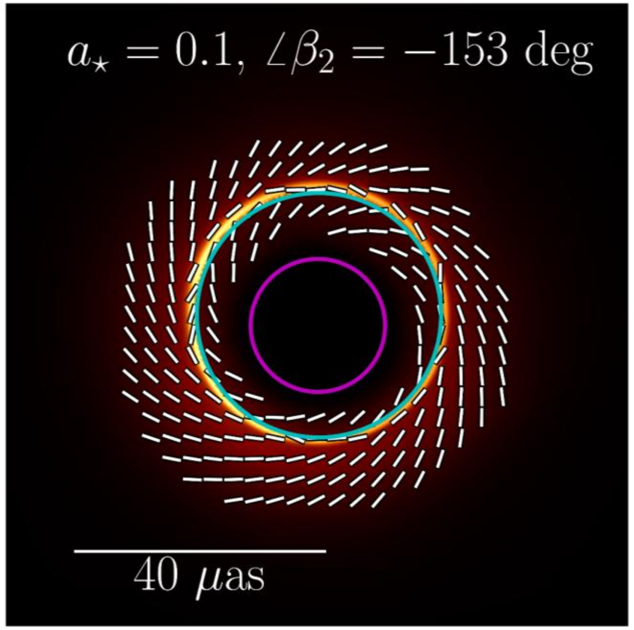


- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
    - increases the Poynting flux (BZ jet power)

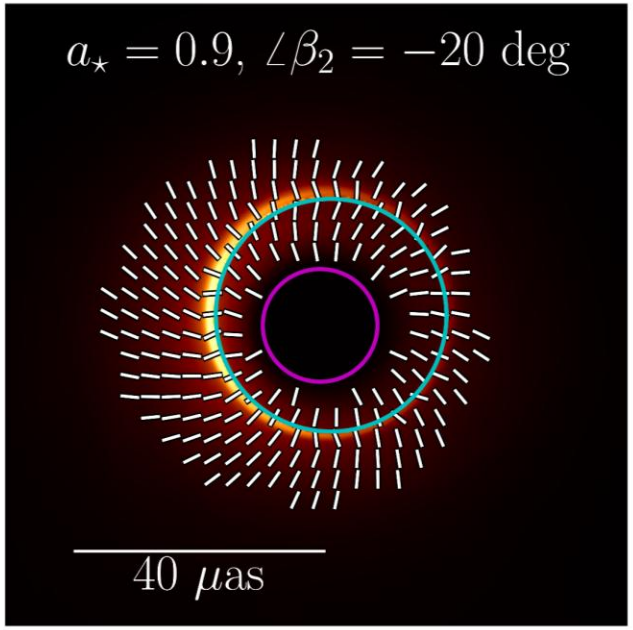
Image credit: George Wong

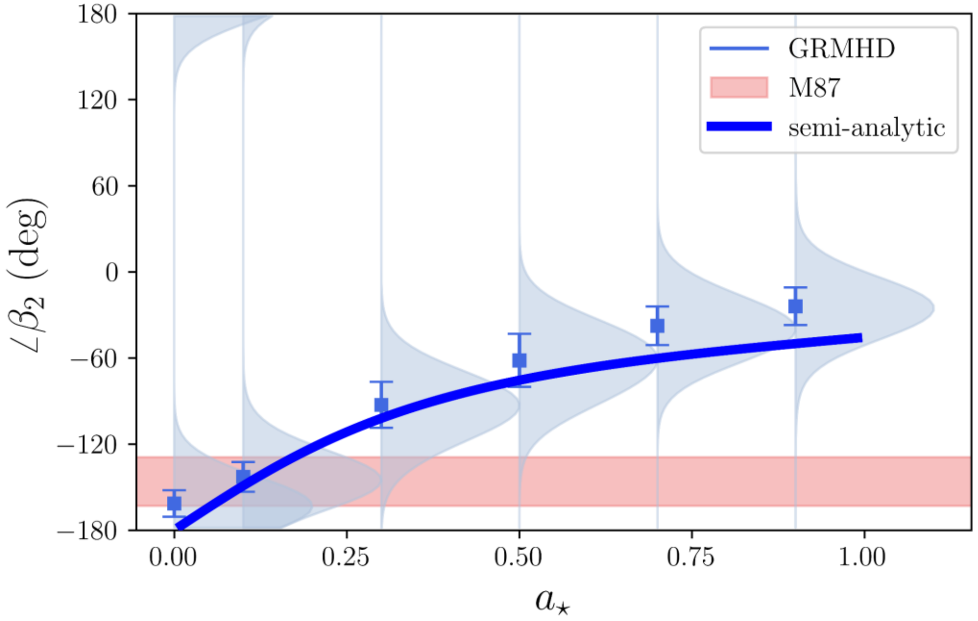
Polarized images are **spin dependent**

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

How can we determine the jet power source?

By zooming **out**..

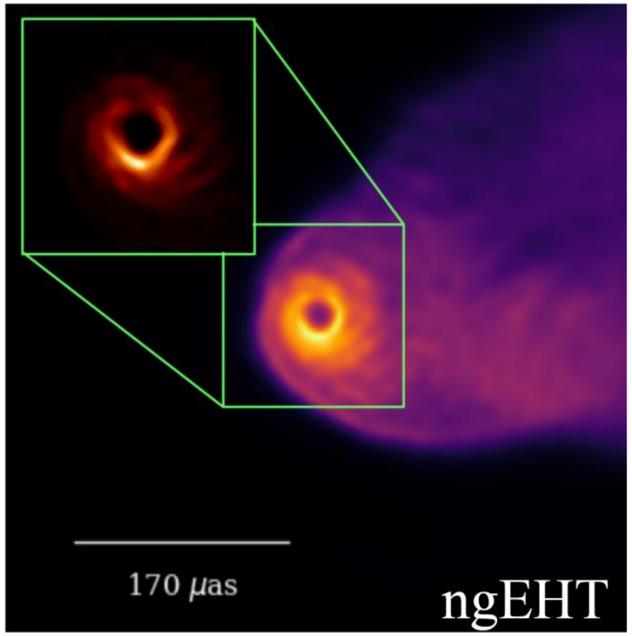


Image the connection between the BH and the low-brightness extended jet in **high dynamic range** with the **next-generation EHT (ngEHT)**

By zooming **in**..

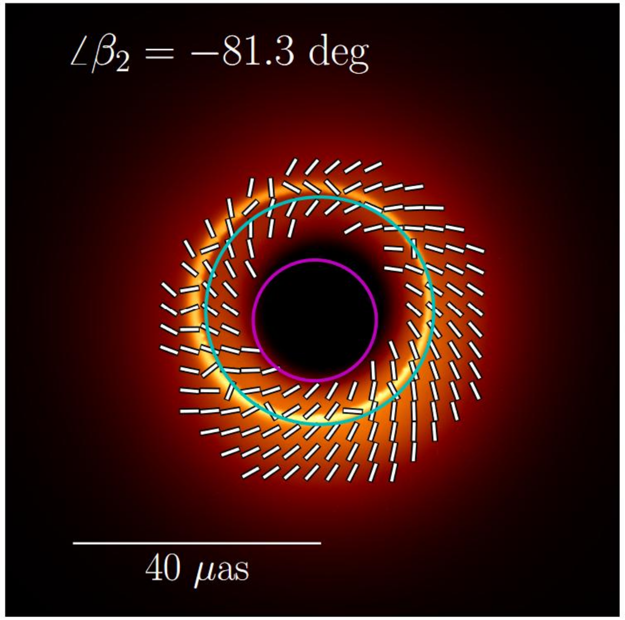
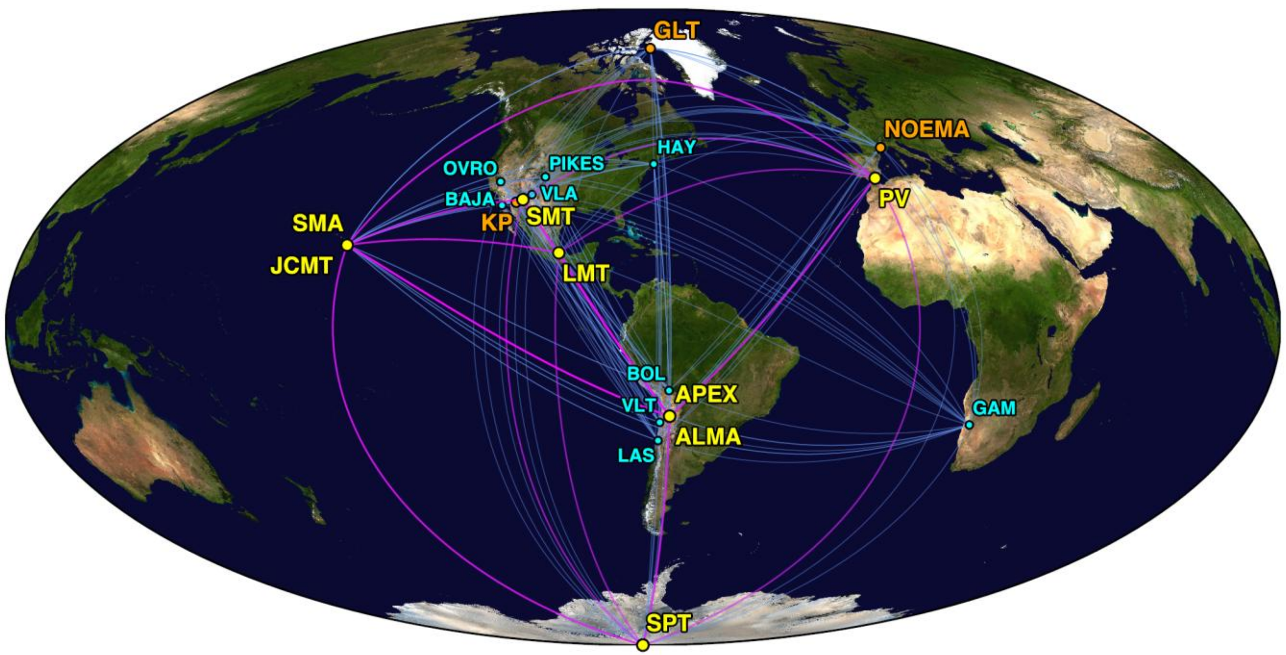
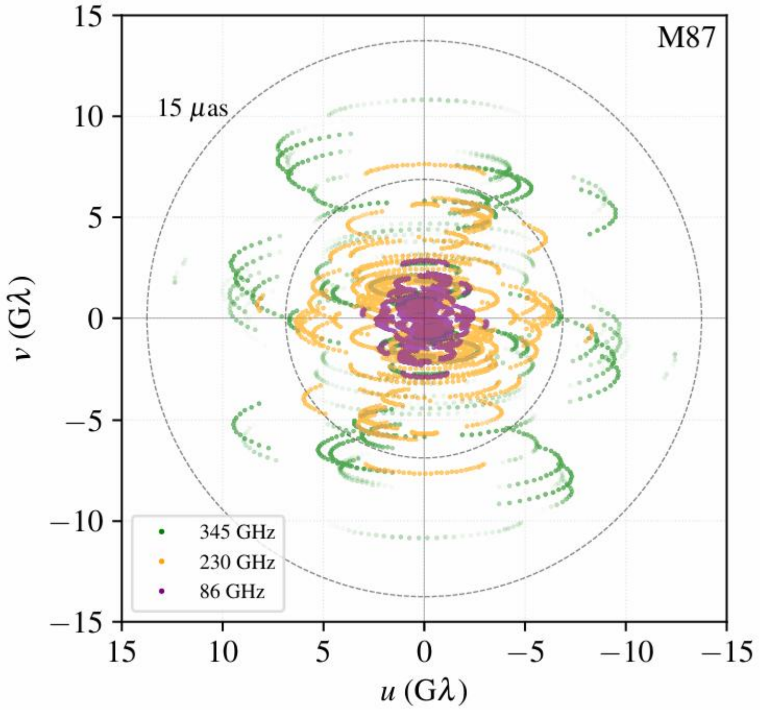


Image field lines close to the event horizon in **high resolution** with the **Black Hole Explorer (BHEX)**

The next-generation EHT (ngEHT)





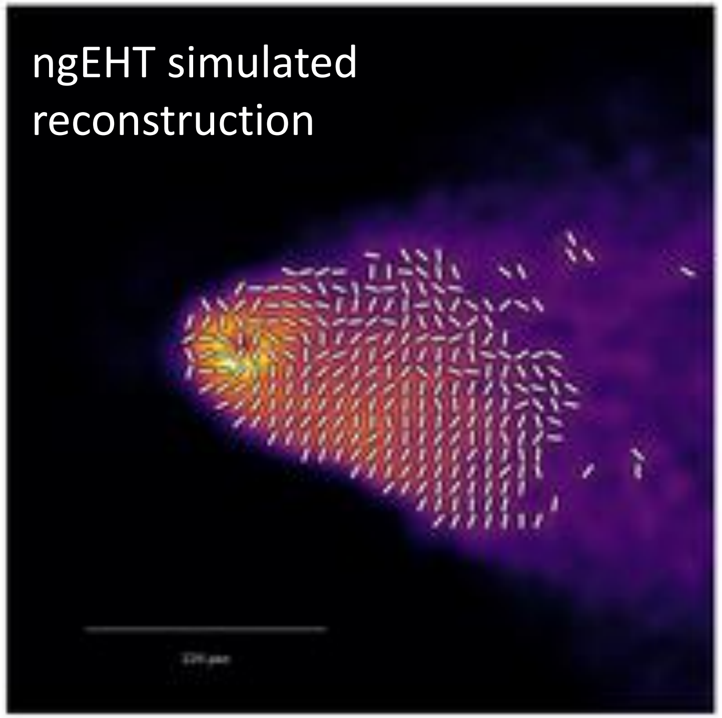
Increased coverage from new sites and observing frequencies in ngEHT will enhance **dynamic range**

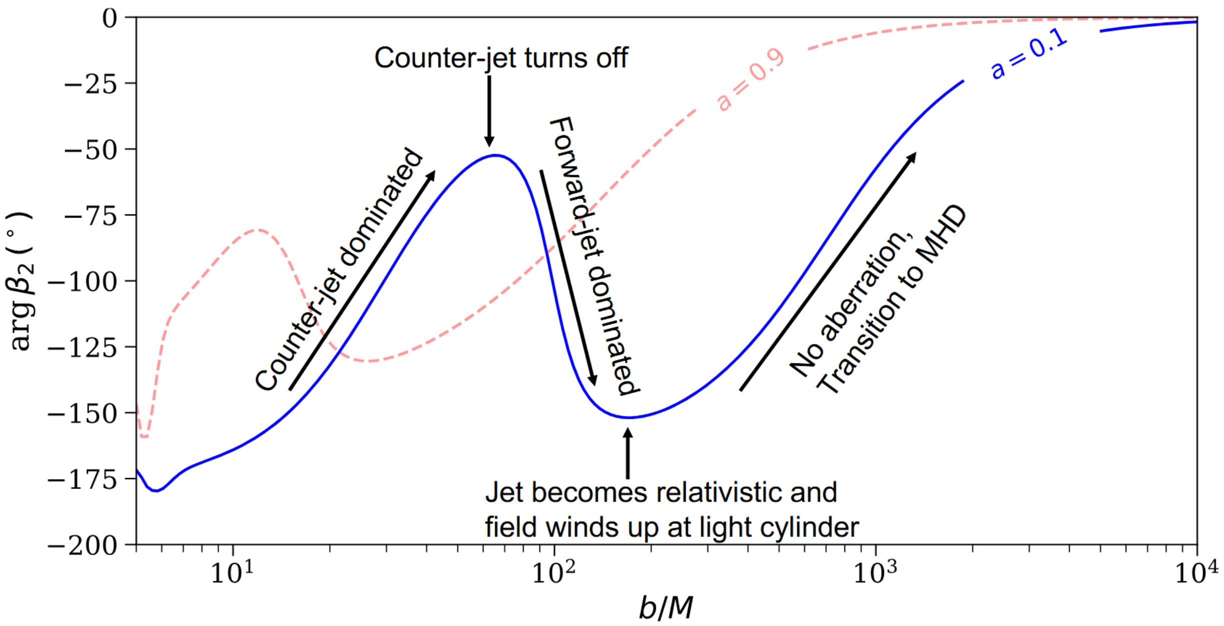
2017: Observations at 6 distinct sites
2018: Observations at 7 sites (+ GLT)
2021-22: Observations at 9 sites (+ Kitt Peak & NOEMA)
2024-25: 230+345 GHz observations
2030s: tri-band observations at 14 sites

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

Doeleman+ 2023

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





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

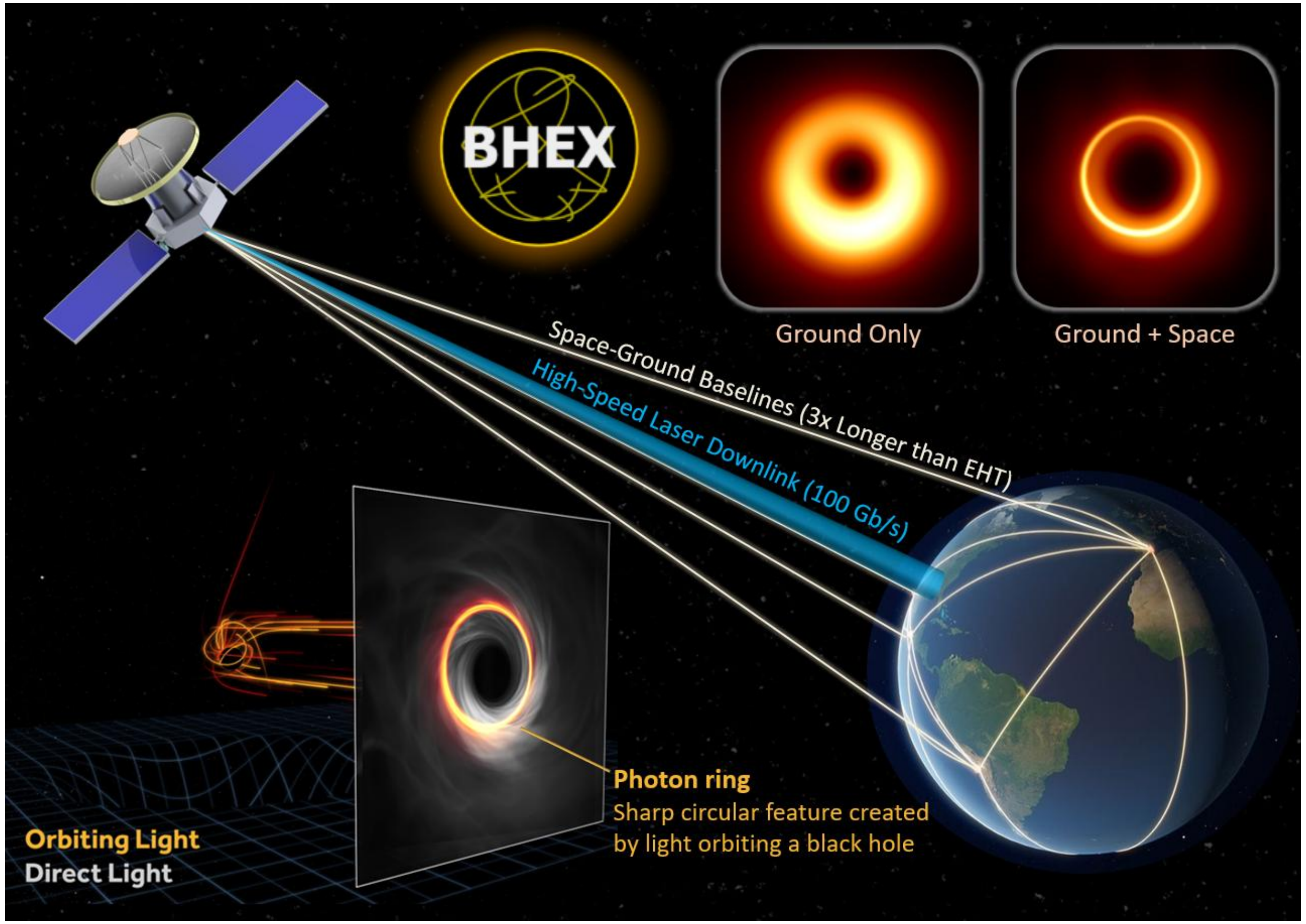
The Black Hole Explorer (BHEX)

Earth-Space VLBI at 1.3 mm

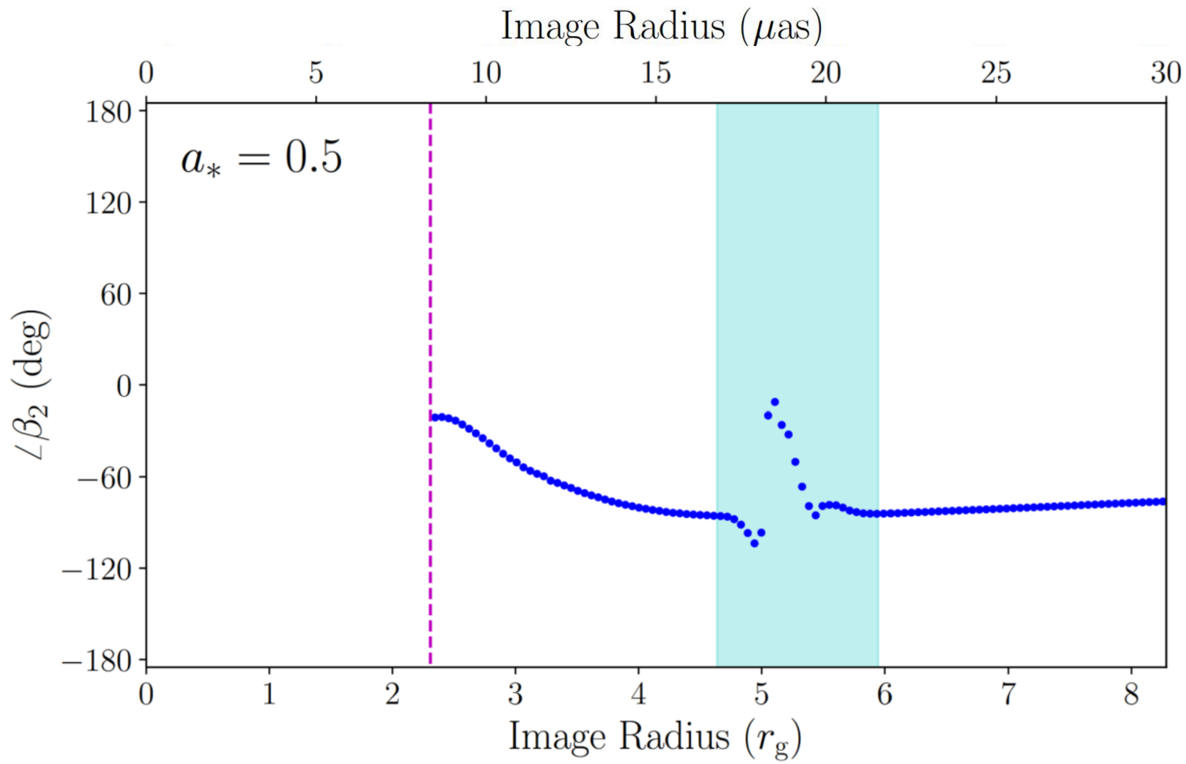
- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground infrastructure & pioneers optical laser downlink
- Targeting a 2025 SMEX proposal

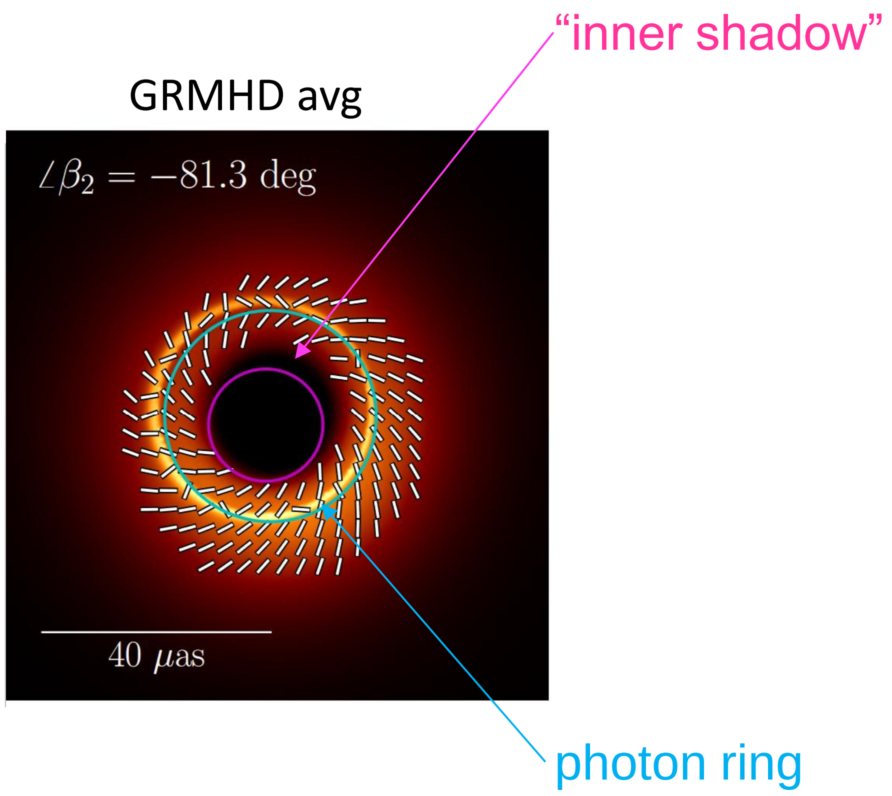
BHEX Science Goals

- 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



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

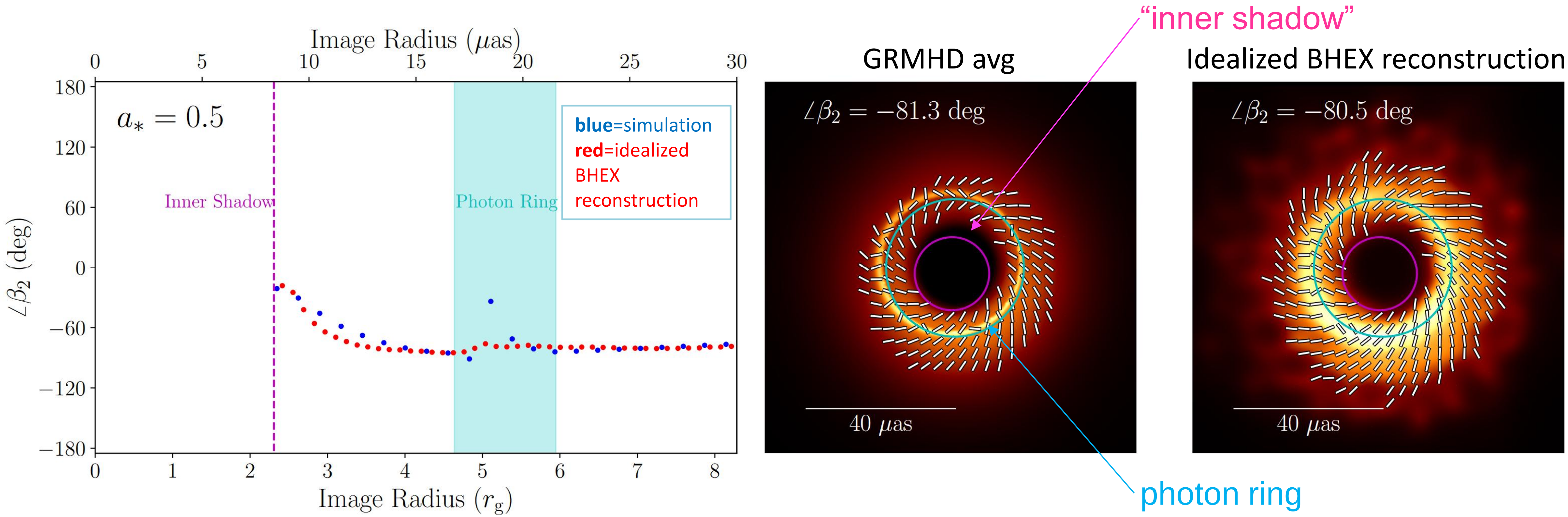




- β_2 evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - Strong evolution of arg(β_2) to the horizon is predicted by both analytic BZ models and GRMHD

Chael+ 2023b, Chael in prep

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

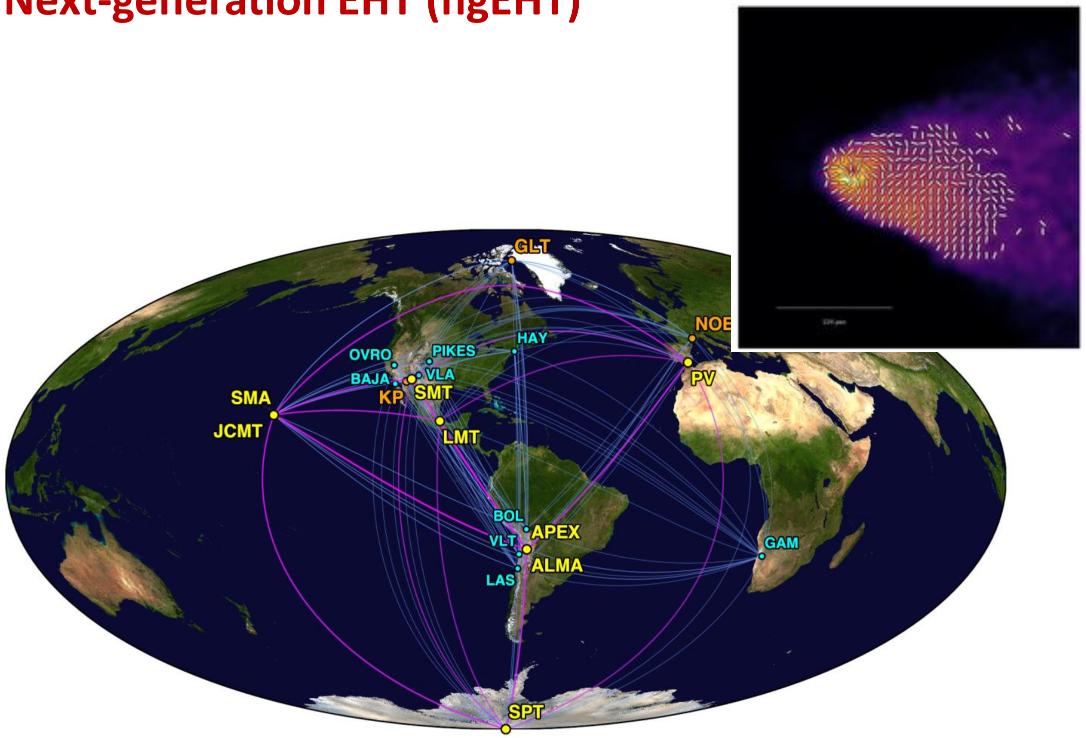


- β_2 evolves rapidly close to the horizon from both **field wind-up** and **parallel transport**
  - Strong evolution of arg(β_2) to the horizon is predicted by both simple BZ models and GRMHD
- **BHEX + EHT obtain the resolution to observe energy extraction at horizon scales**

Chael+ 2023b, Chael in prep

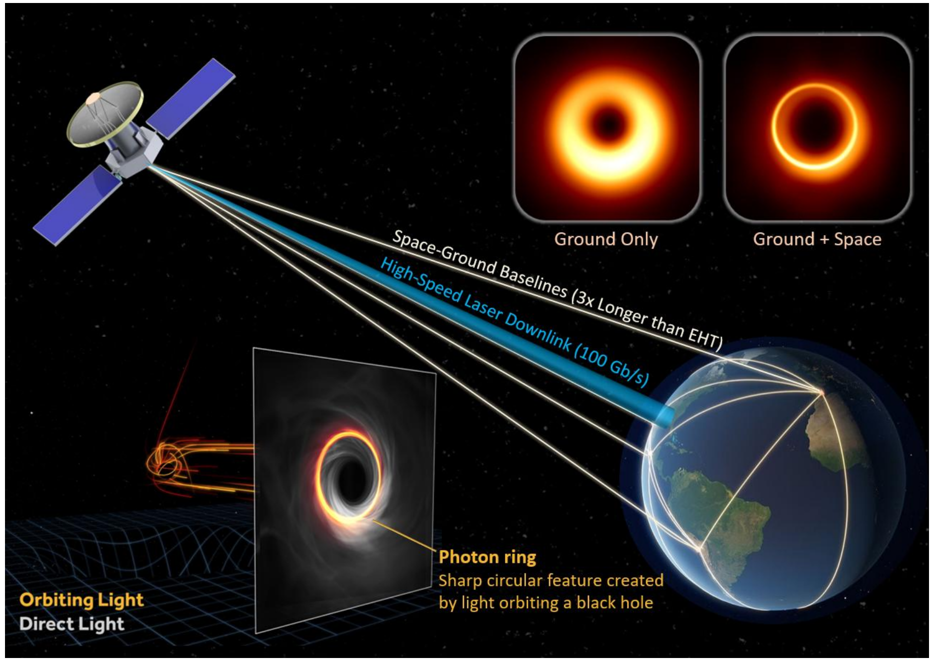
The future of near-horizon black hole astrophysics

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+ 2024: 2410.00954)

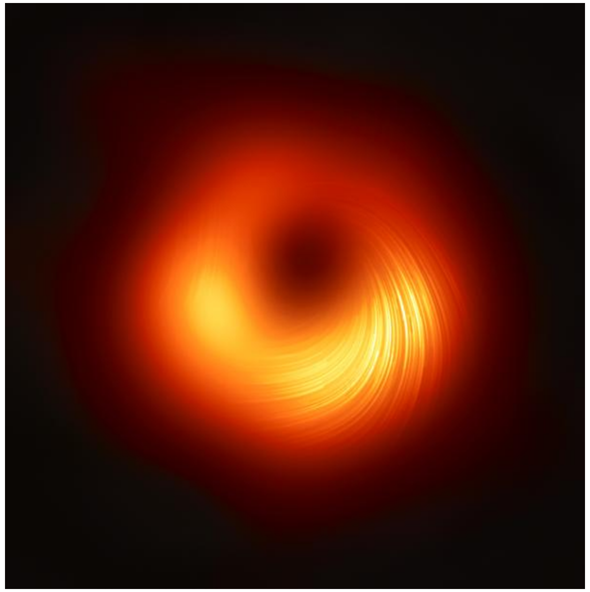
Black Hole Explorer (BHEX)

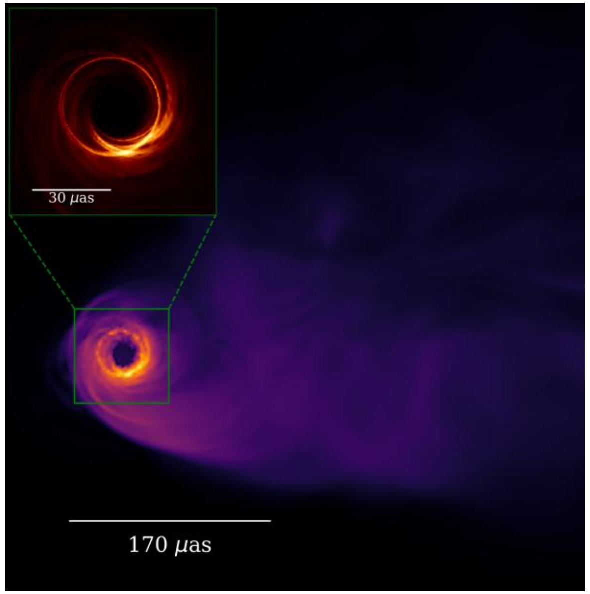


- NASA SMEX proposal for a mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to ~12 (Zhang+ 2024)

Takeaways…

1. **Polarization is the key** for constraining near-horizon astrophysics, and indicates that accretion in M87* is likely magnetically arrested
2. GRMHD simulations for interpreting EHT images can be extended with **force-free evolution and electron thermodynamics.**
3. EHT polarization images are **consistent with outward horizon-scale electromagnetic energy flux**
4. **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 the near-horizon environments of supermassive black holes beyond Sgr A* and M87*?

EHT VII, 2021; **Chael** 2025