Dynamic Black Hole Magnetic Fields Revealed by the Event Horizon Telescope

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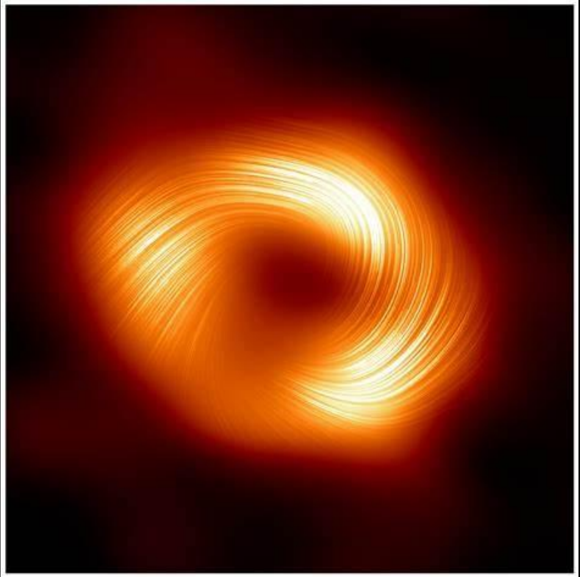
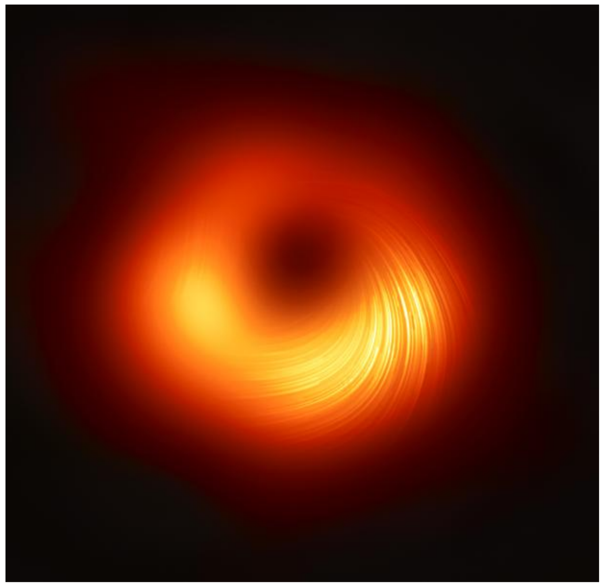
NBIA, University of Copenhagen

July 8, 2026



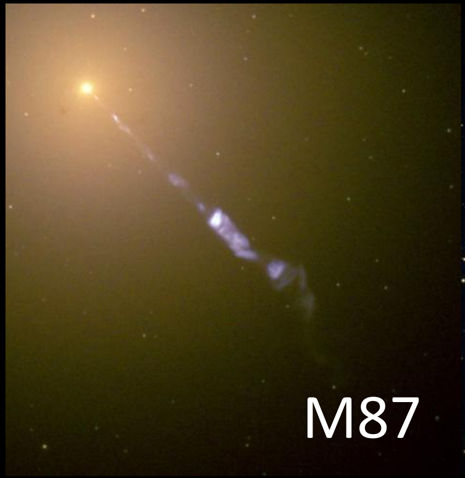


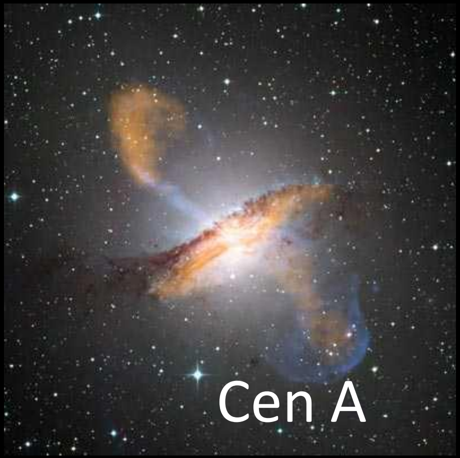
KØBENHAVNS UNIVERSITET

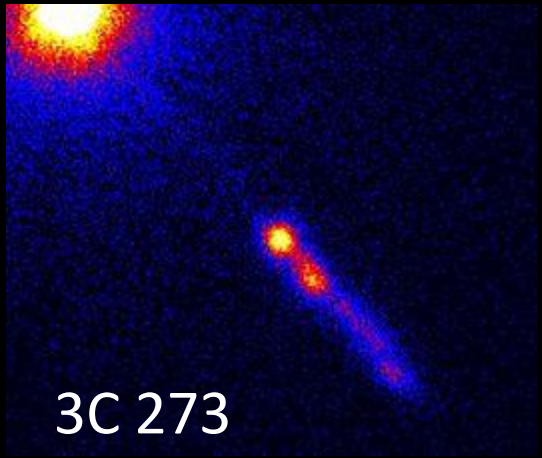
The Niels Bohr International Academy

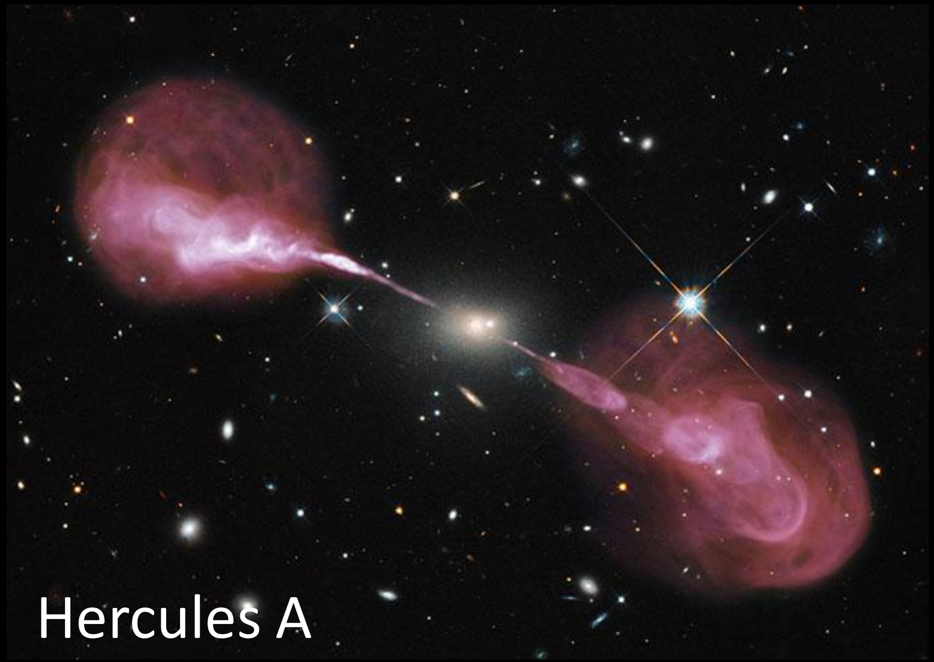
Event Horizon Telescope

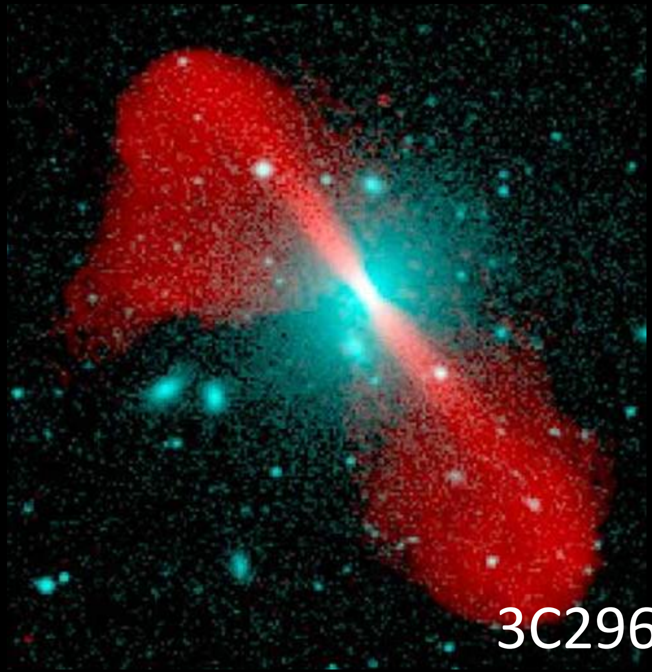
Supermassive black holes and jets are everywhere











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*

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

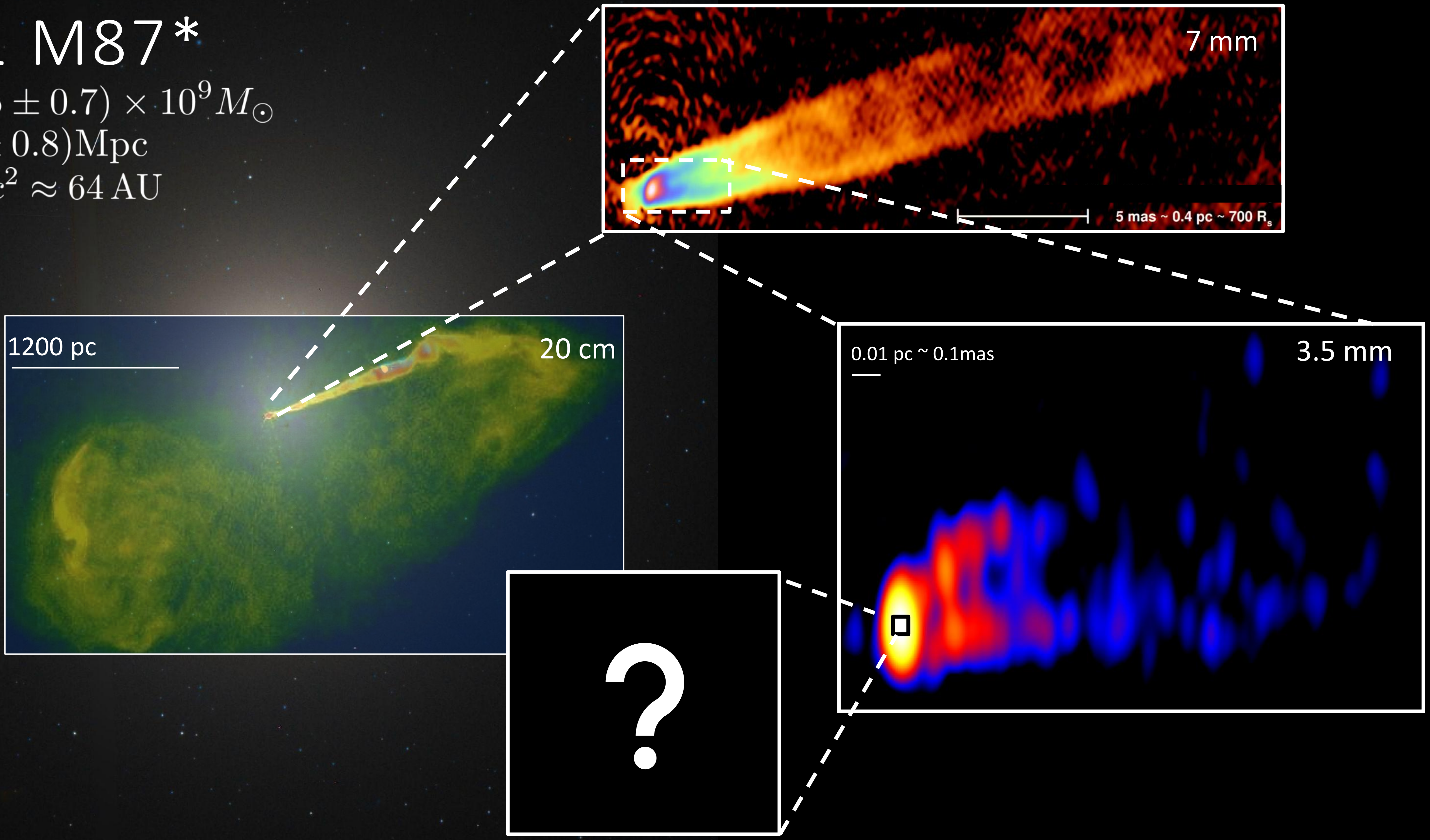
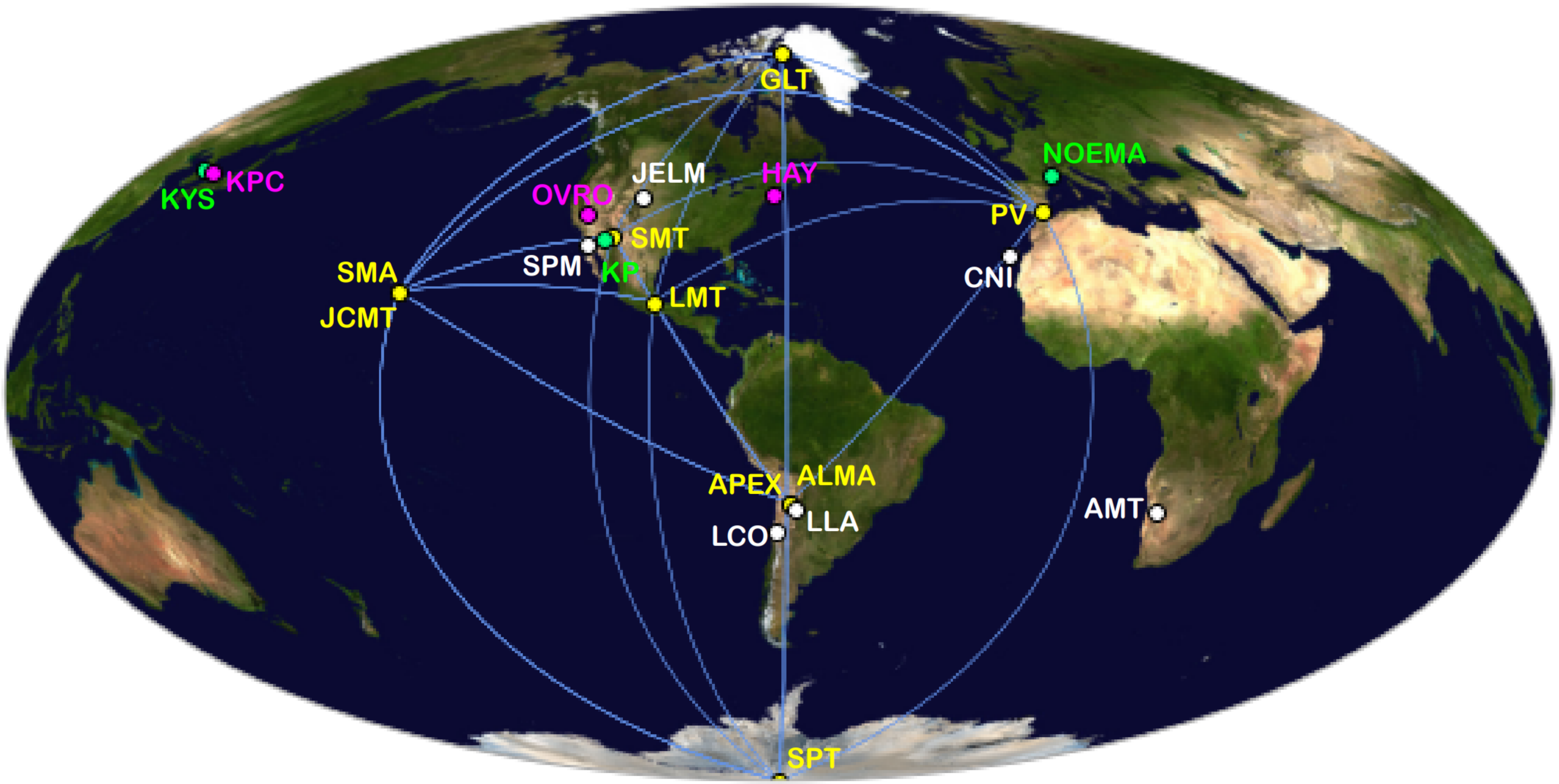


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

The Event Horizon Telescope



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

EHTC+ 2025

M87 & M87*

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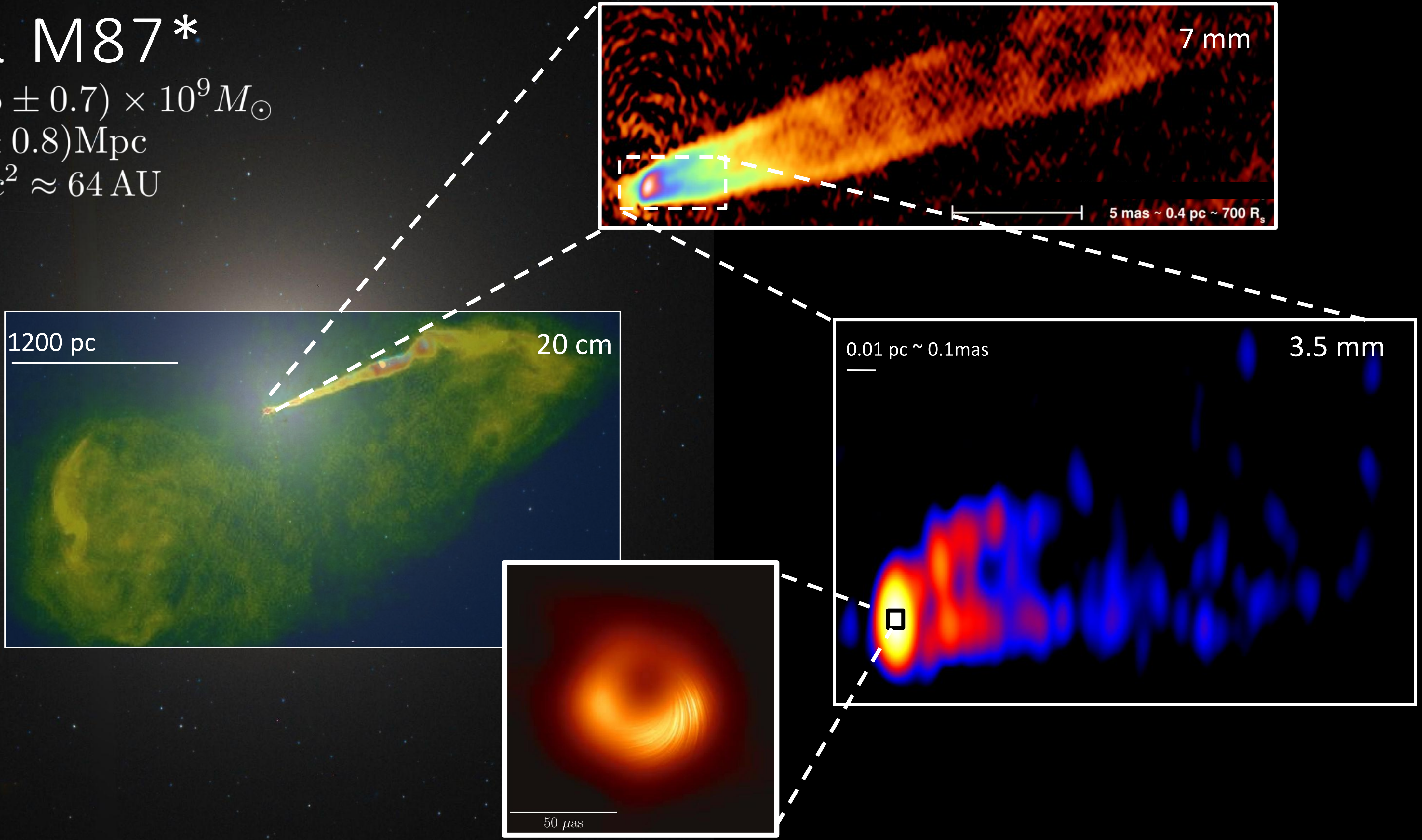

Image Credits: HST(Optical), NRAO (VLA),
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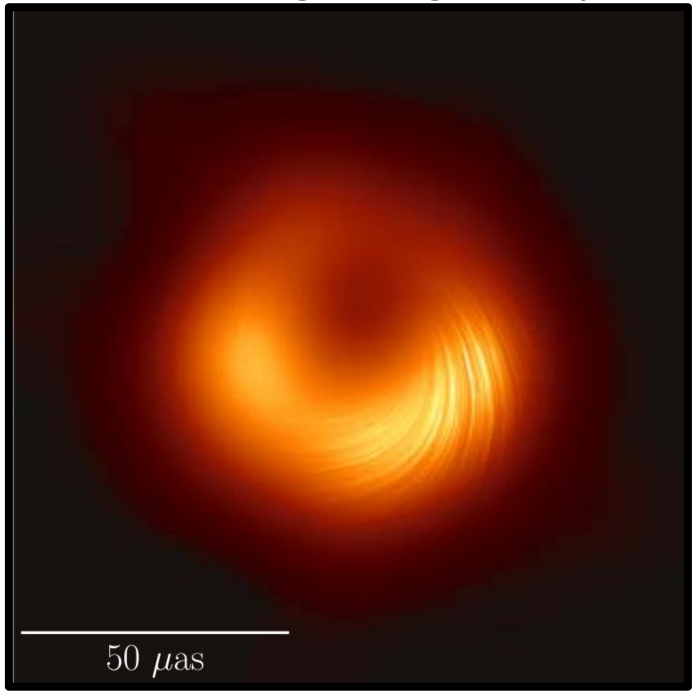
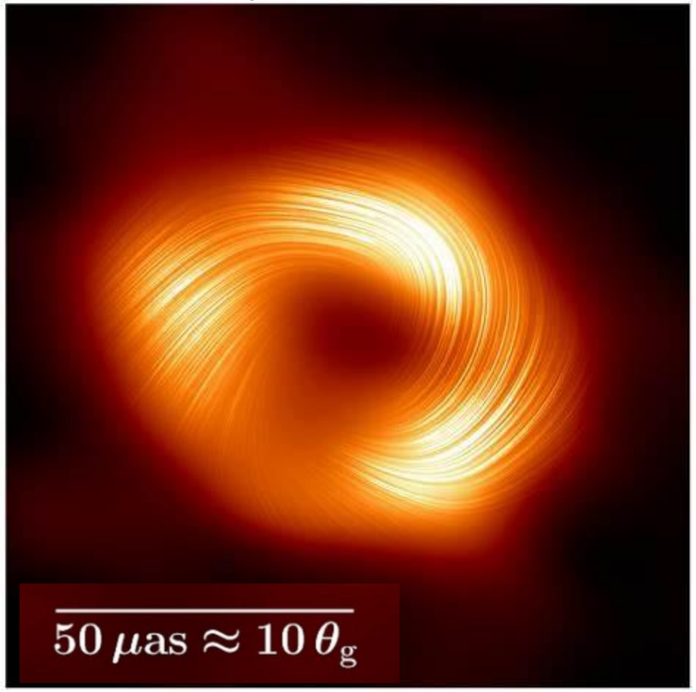
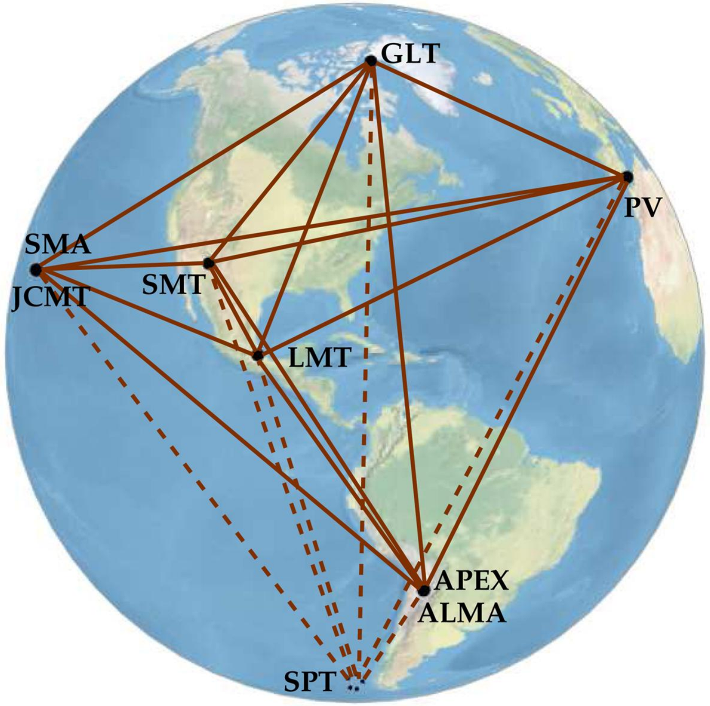
The first black hole images

M87* (EHTC 2019, 2021, 2024, 2025)
~6.5x10^9 $M_\odot$
Launches a strong extragalactic jet



Sgr A* (EHTC 2022, 2024)
~4x10^6 $M_\odot$
No obvious jet

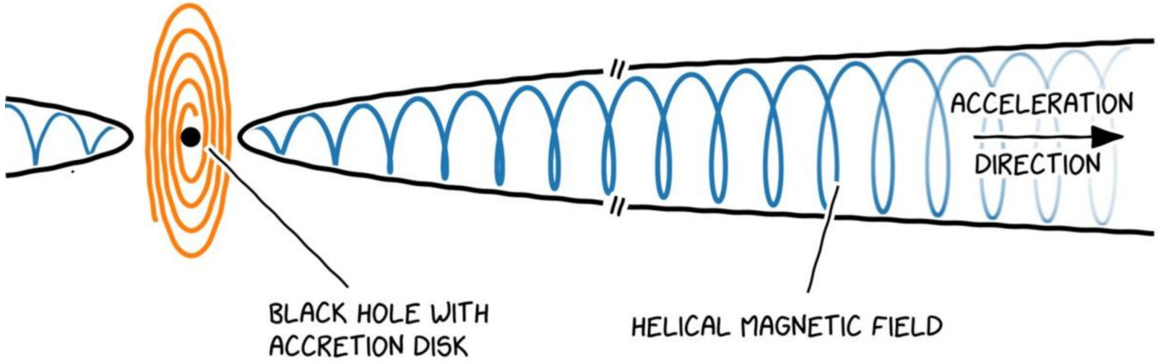




Over three orders of magnitude in BH mass:

- Both images feature ring-like 230 GHz emission on horizon scales (≤5 GM/c^2)
- Both images are well-described by models and simulations of low-luminosity accretion: ($\dot{M} \approx 10^{-7} - 10^{-5}\dot{M}_{Edd}$)
- Both images constrain our models of the accreting plasma, magnetic fields, BH mass and spin

Persistent Mysteries



- What powers the extragalactic jet?
- What accelerates particles that light up the spacetime?
- Can we precisely measure the black hole spin and test General Relativity?
- What is the structure and dynamics of near-horizon magnetic fields?

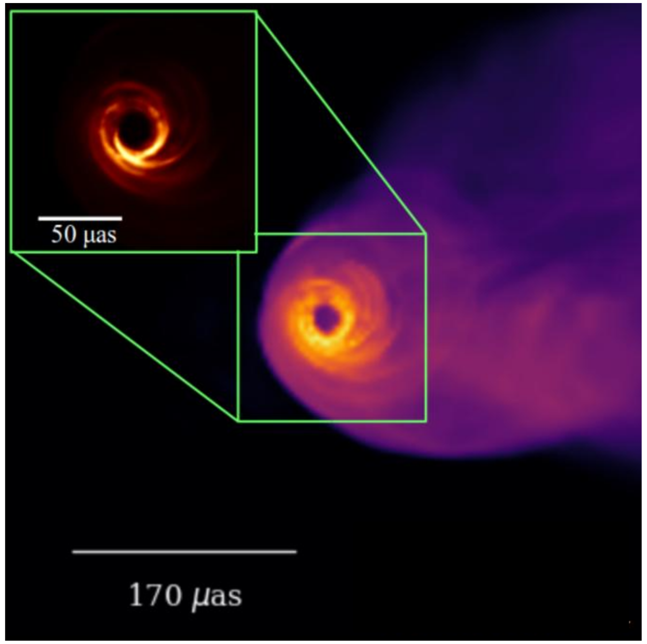


Image credits: Jan Roder, Lindy Blackburn

This talk:

1. How do we make polarized images of black holes?

2. What have we learned from comparing polarized images of black holes to simulations?

3. What's next?

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

EHTC VII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator);
EHTC VII 2024; EHTC 2025

EHT: Array

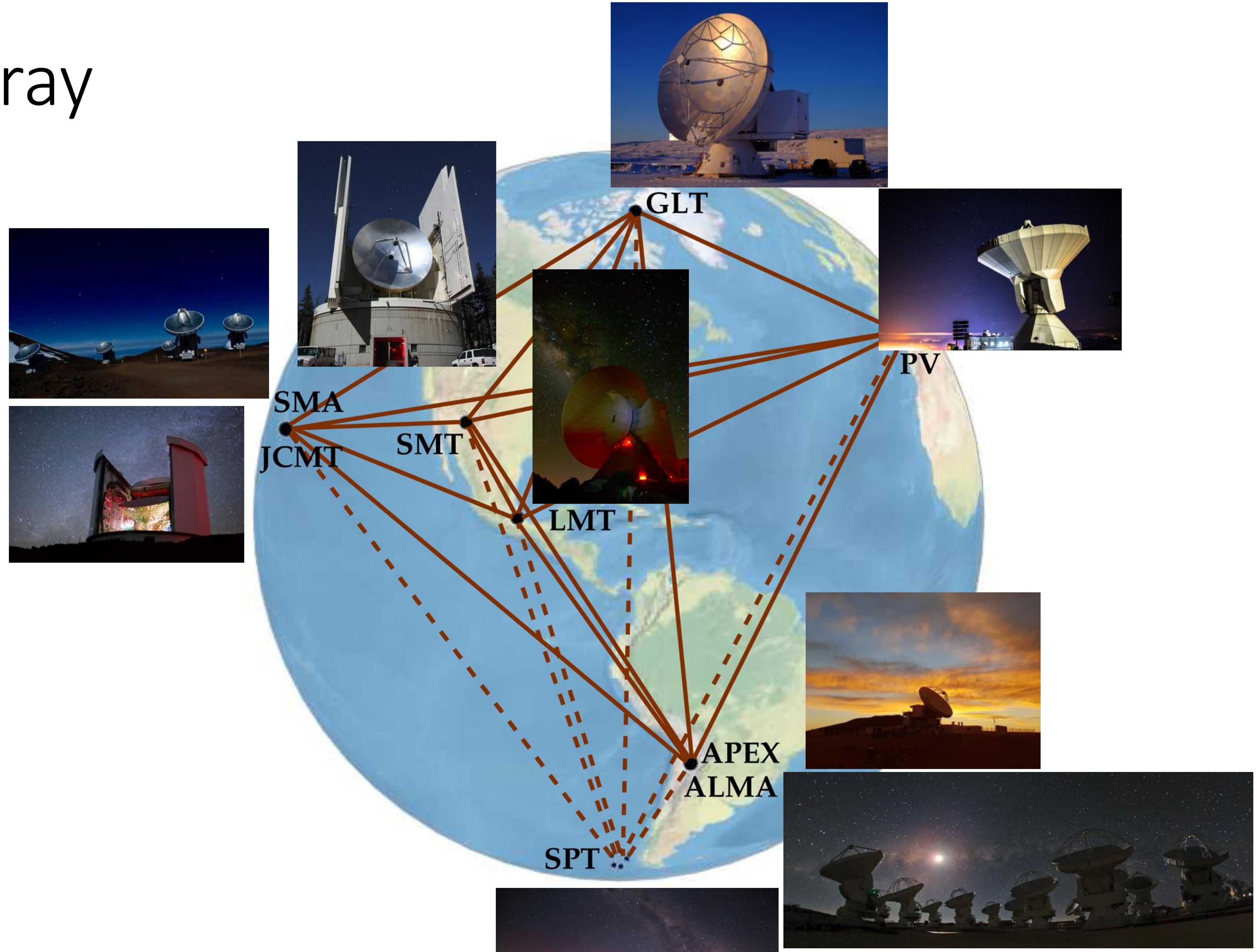
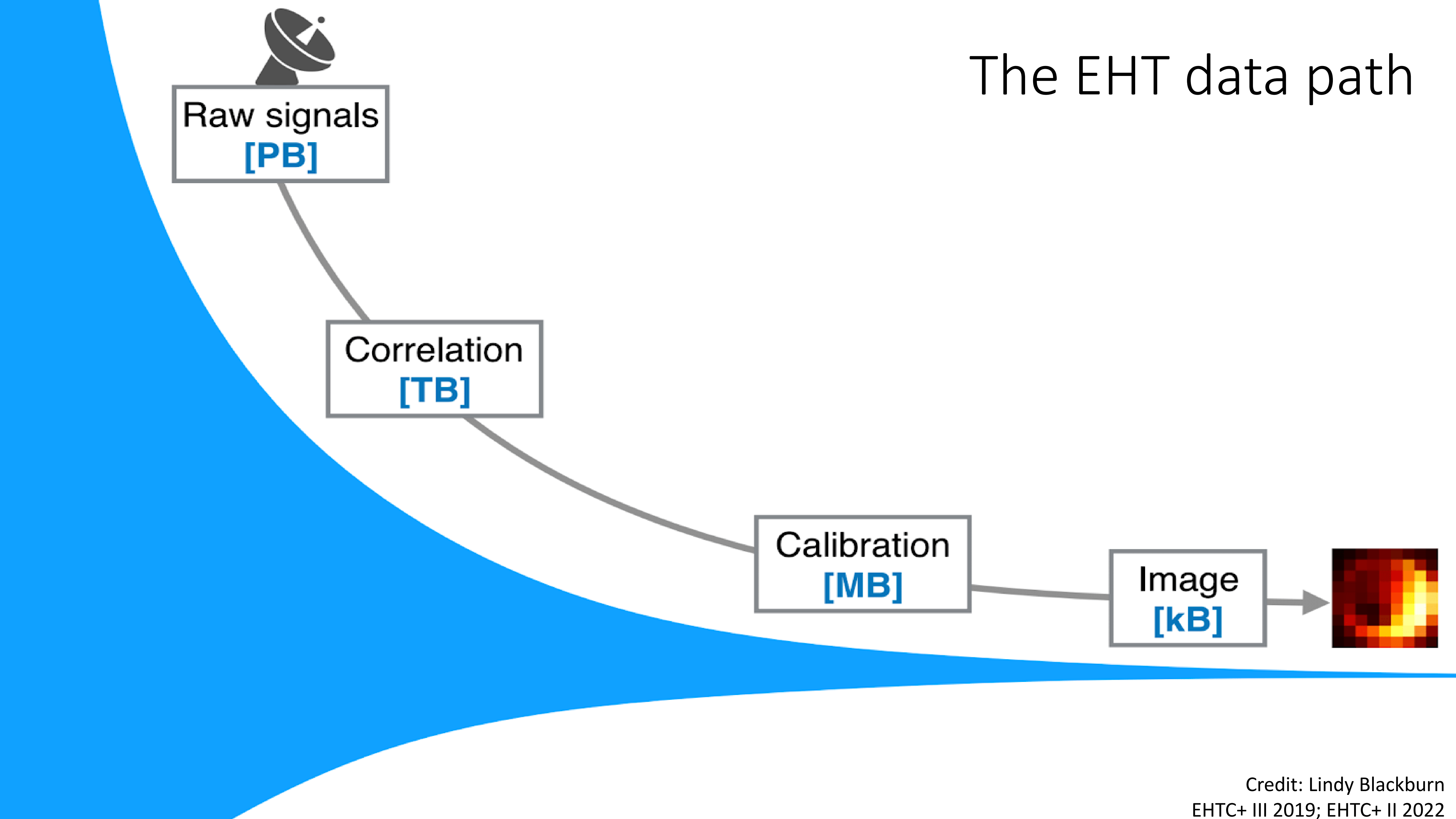


Photo Credits: EHTC I, 2024
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

EHT: People

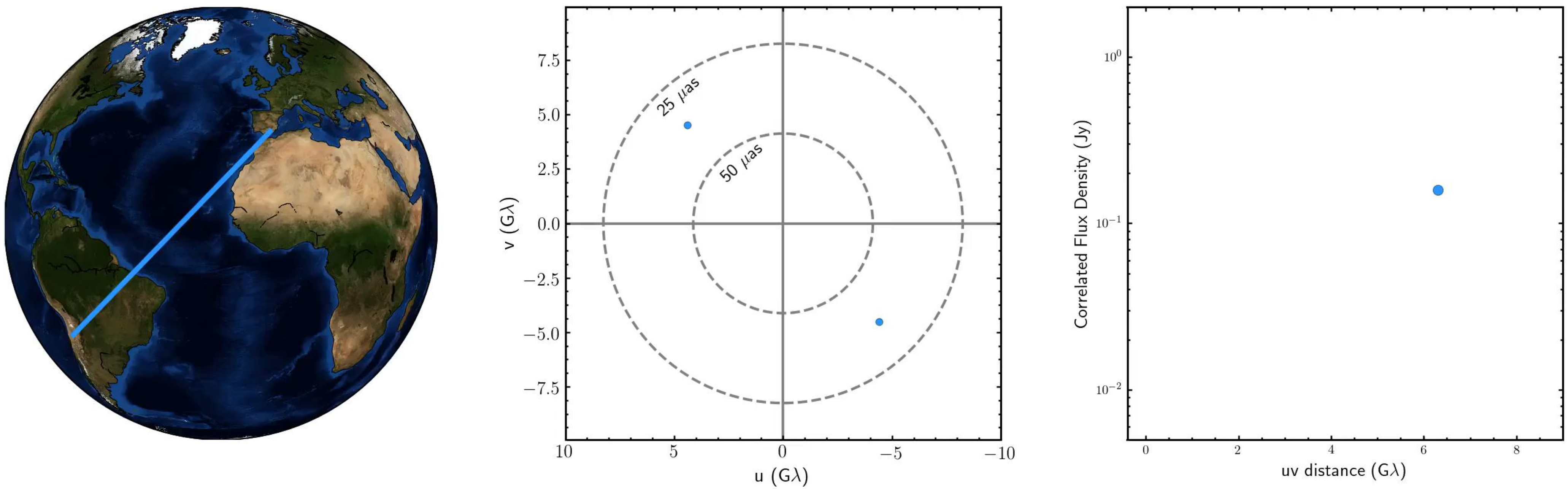

Event Horizon Telescope Collaboration Meeting
Seoul, Korea | June 21-26, 2026

The EHT data path



Credit: Lindy Blackburn
EHTC+ III 2019; EHTC+ II 2022

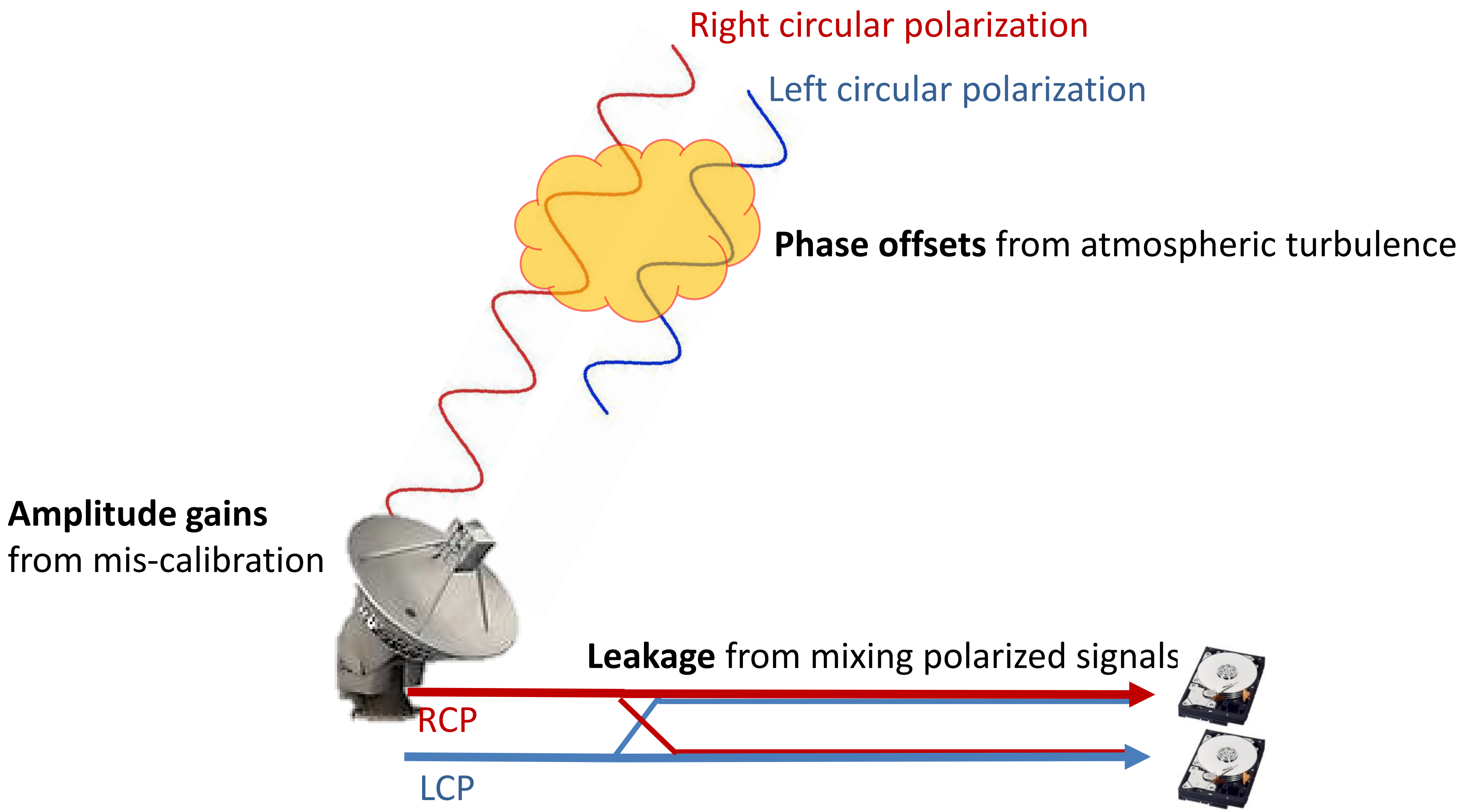
Very Long Baseline Interferometry (VLBI)



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

movie credit: Daniel Palumbo

Challenges of near-horizon imaging

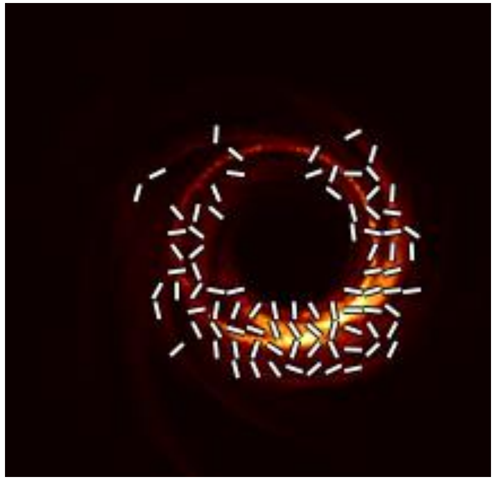


Data at each station are corrupted by unknown **gain and leakage** systematics

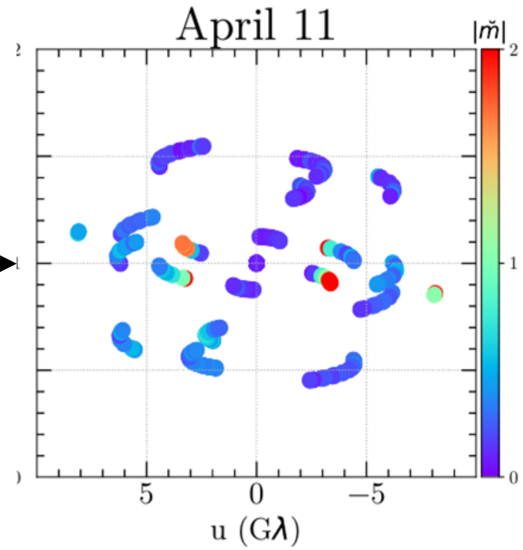
Animation credit: Andrew Chael

Solving for the Image: Algorithm Cross-Validation

True Image

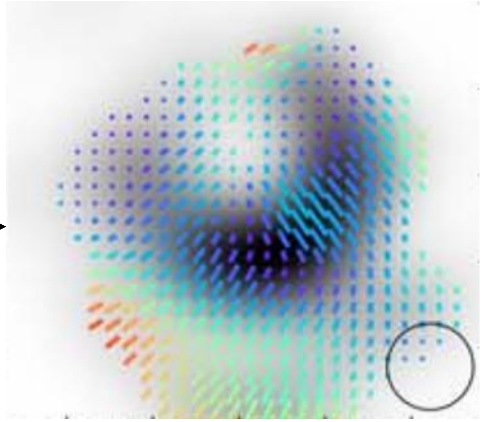


Sparse & Corrupted Measurements



RECONSTRUCTION ALGORITHM

Reconstruction

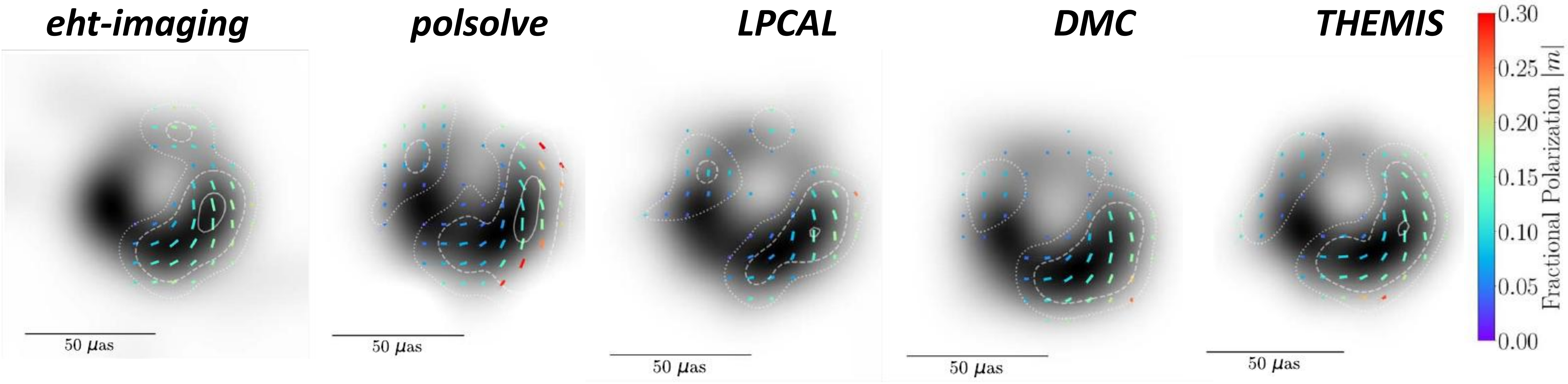


Several different types of reconstruction algorithms:

- **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, 2025)

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

First polarized Images of M87 from 5 methods

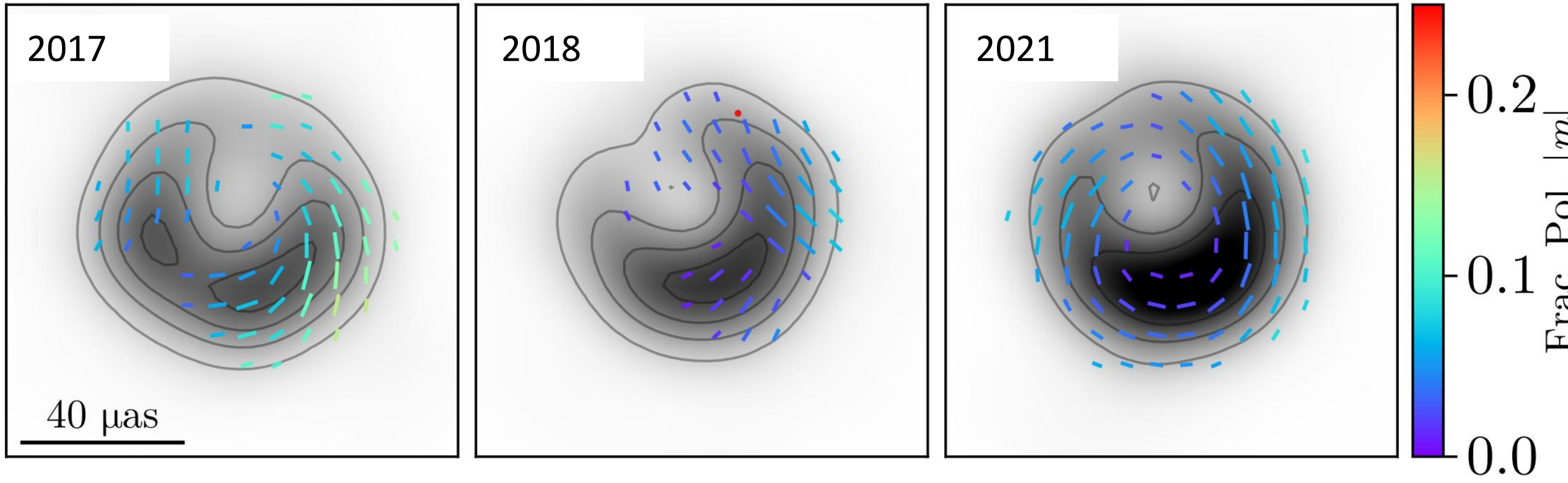


- All methods show similar total intensity and polarization structure at 20 μas resolution
- Consistent ring diameter (~40 μas) and asymmetry (south)
- Polarization structure is predominantly **helical and weak**, (|m| ~10 %)

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

Three Years of Horizon-Scale Structure in M87

- EHT observations show a consistent horizon-scale ring structure in M87* **over 4,000 gravitational timescales**
- Image quality is improving from EHT observations performed with a **more complete array** (including Greenland Telescope)
- Image diameter is consistent but brightness position angle shifts
- Polarization structure shifts and fractional polarization is **lower** in 2018-2021 (3%) than 2017 (~10%)



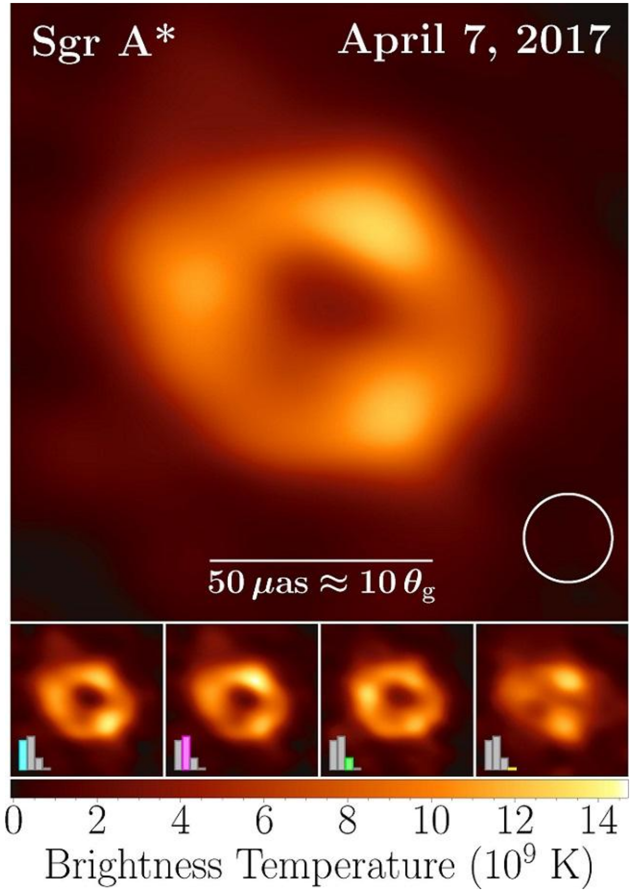
EHTC 2019, 2022, 2024, 2025
doi: [10.1051/0004-6361/202555855](10.1051/0004-6361/202555855)

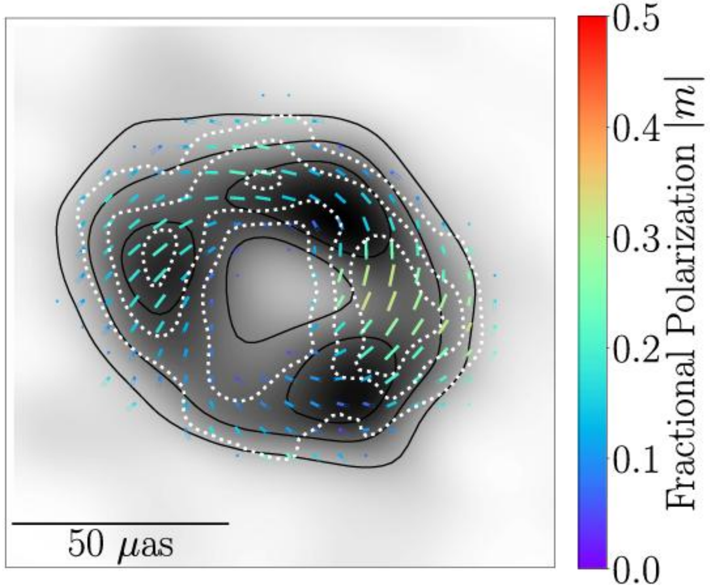
Sgr A* in Polarization

- Imaging Sgr A* is more challenging than M87 due to rapid sub-hour **variability** and **interstellar scattering**.

- Sgr A* images do not currently constrain the ring position angle or asymmetry
  → face on orientation?

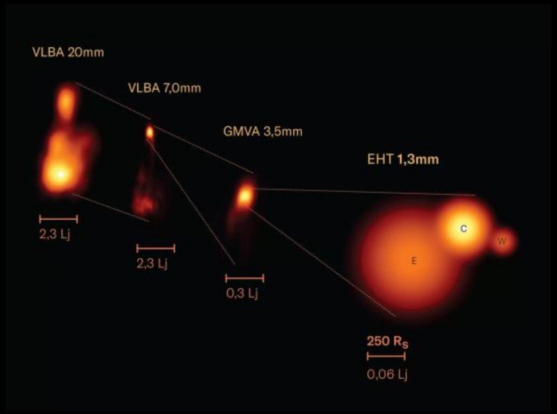
- Sgr A* is **more polarized** (≈30%) than M87*, and it shows a similar **helical linear polarization pattern**.



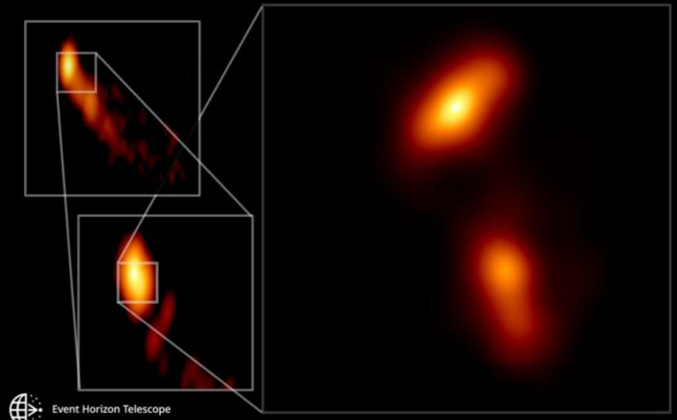


EHTC I, 2022; EHTC VII, 2024 **Chael**, paper writing team)

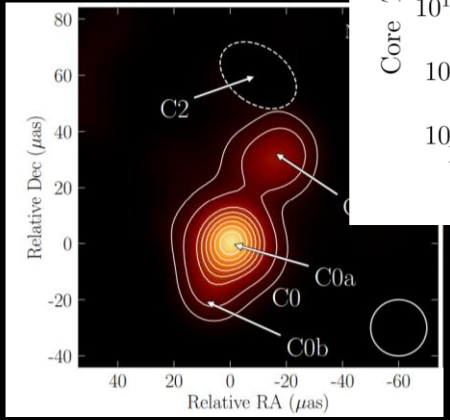
The EHT Sky



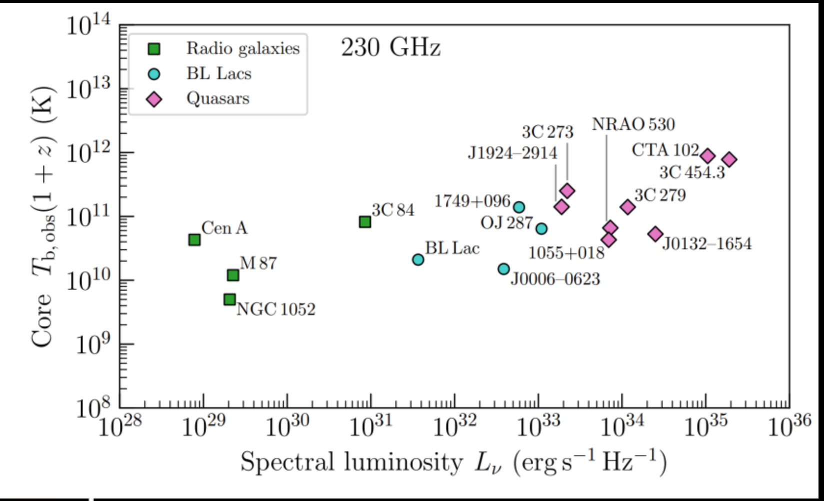
3C 84: Paraschos+ 2024



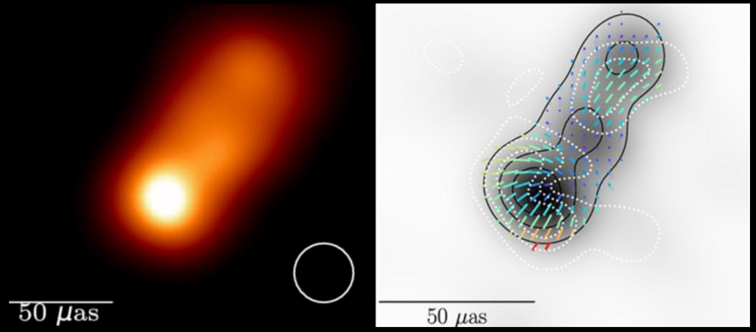
3C279: Kim+ 2020



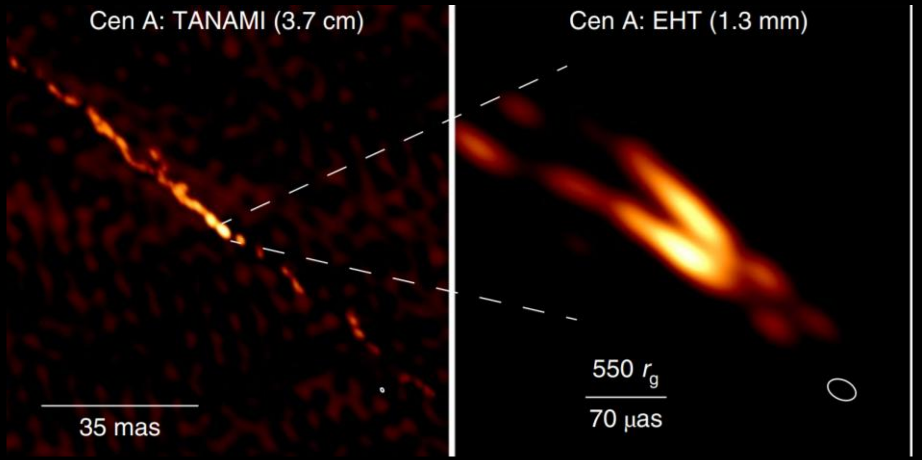
NRAO 530: Jorstad+ 2023



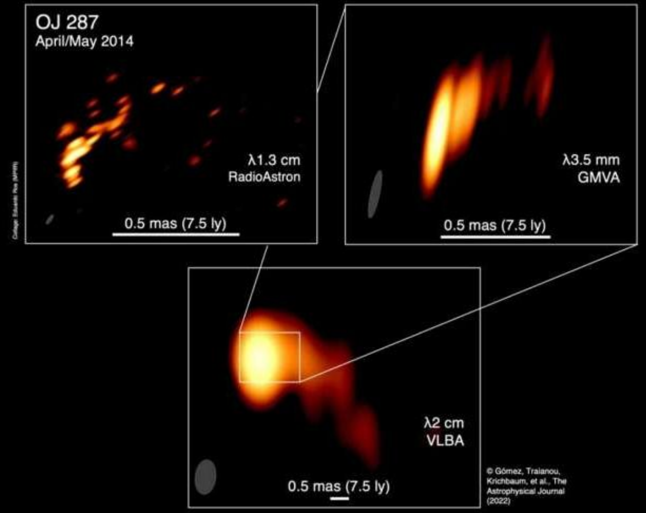
EHT Source Catalog: Röder+ 2025



J1924-2914: Issaoun+ 2022



Centaurus A: Janssen+ 2020

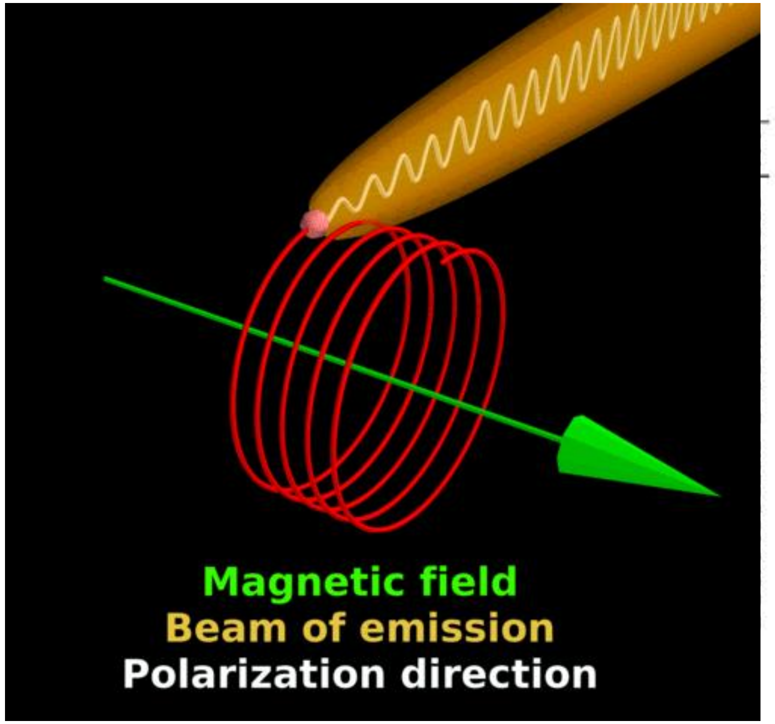


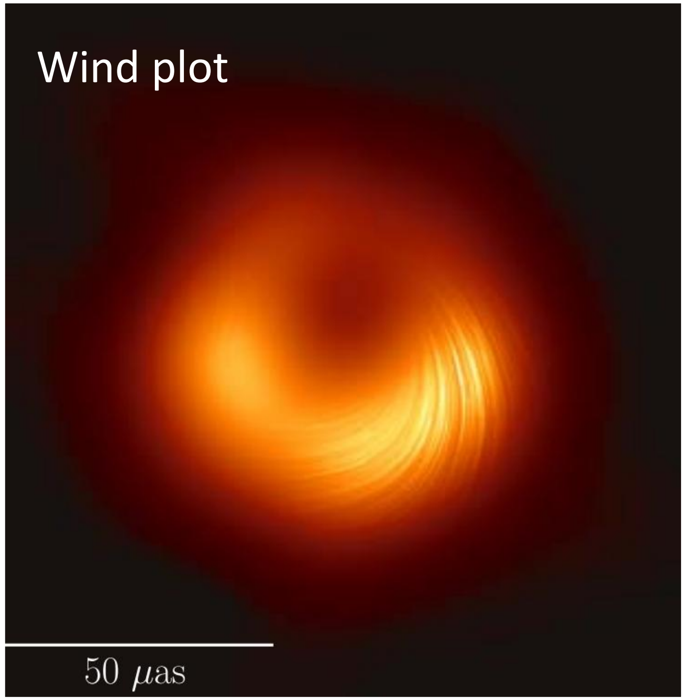
OJ 287: Traianou+ 2022

What have we learned from comparing polarized black hole images to simulations?

EHTC VIII, 2021; EHTC IX, 2023 (**Chael**, paper coordinator); EHTC VIII, 2024

Why polarization?

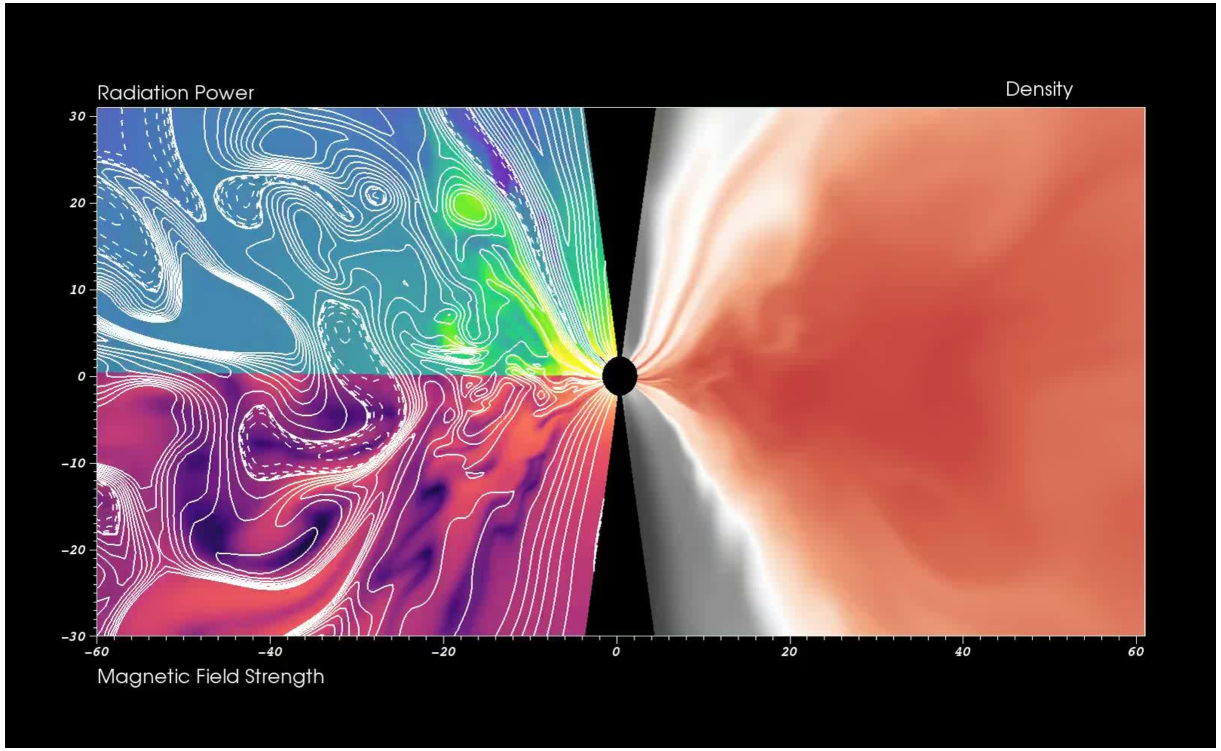




- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines
- Polarization **transport** is sensitive to the magnetic field, plasma, and spacetime
- Polarization images **highly constrain near-horizon astrophysics**

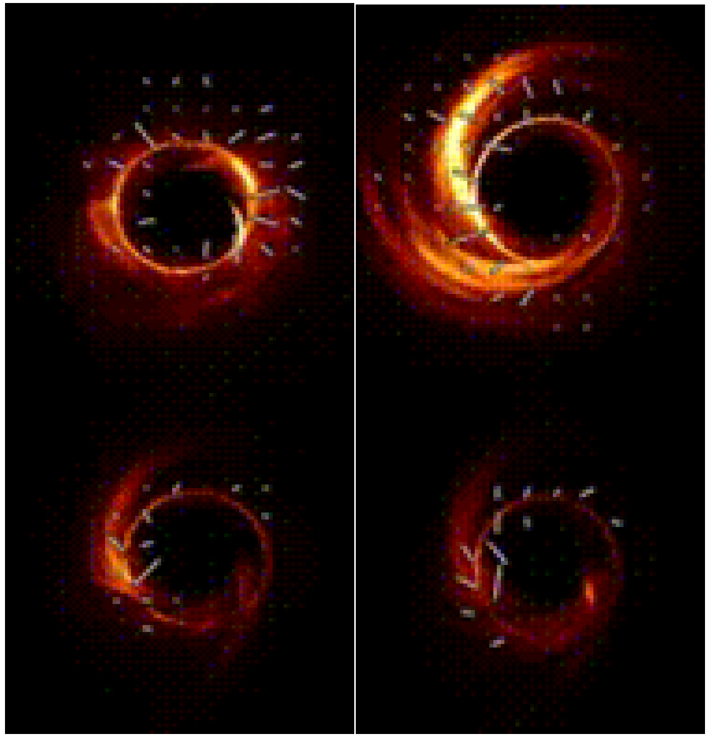
EHTC VII, VIII 2021; EHTC IX, 2023 (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

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

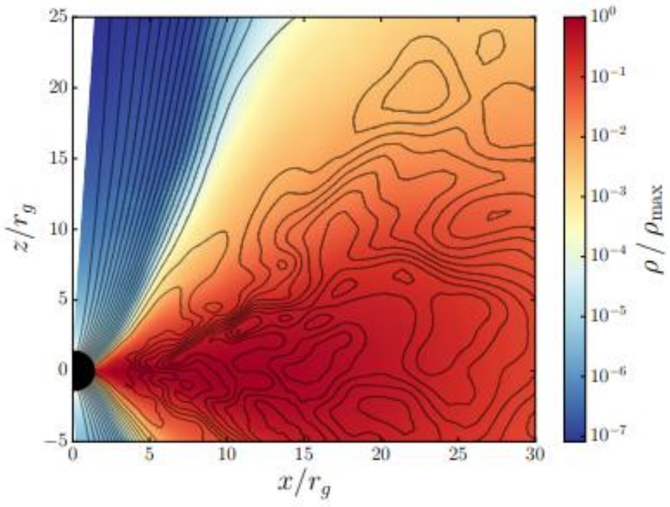
Track light rays and solves for the observed (polarized) radiation

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

What is the magnetic field structure close to the horizon?

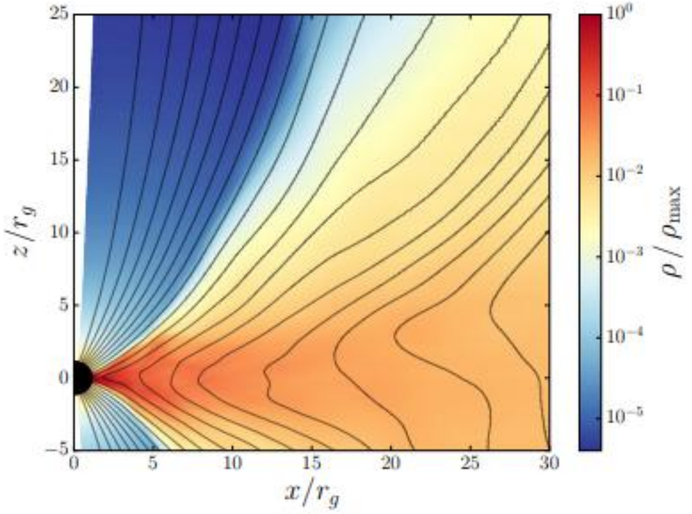
Two accretion states that depend on the accumulated magnetic flux on horizon

Magnetic fields are weak and turbulent



“SANE”

Strong, coherent magnetic fields build up on the horizon



“MAD” - Magnetically Arrested Disk

MADs launch more powerful Blandford-Znajek jets:

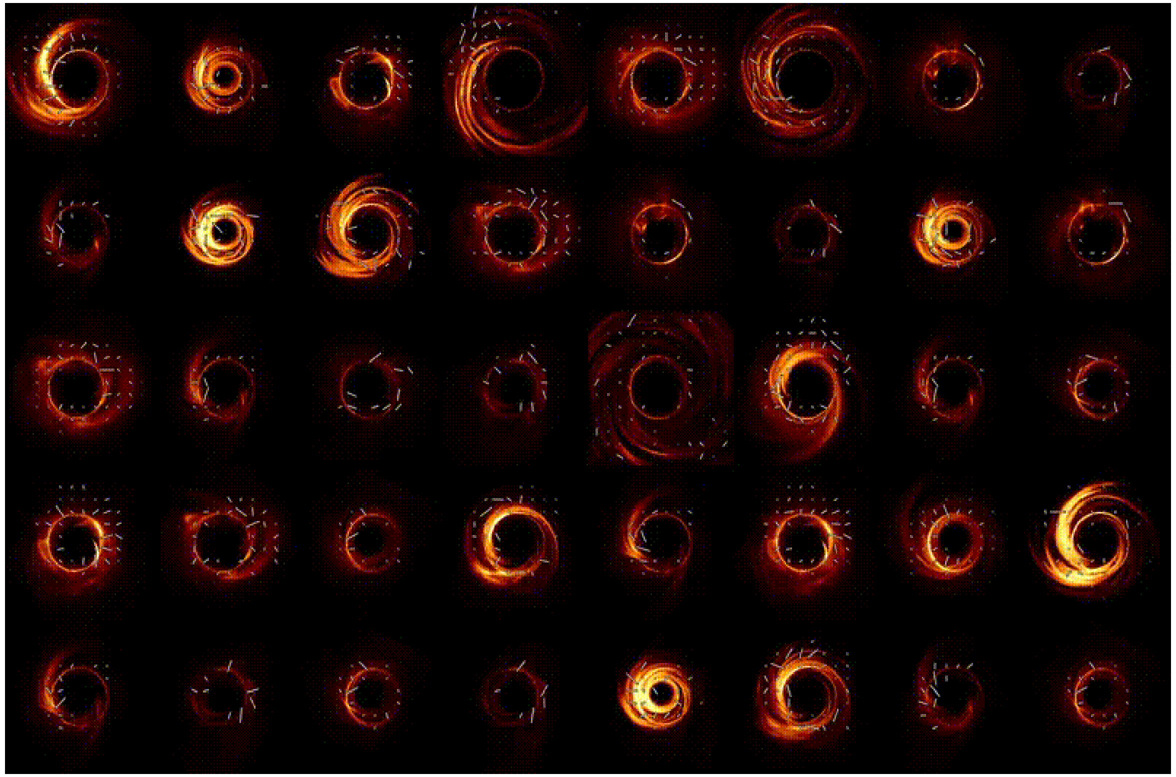
$$P_{\rm jet} \propto \Phi_B^2 a^2$$

BH spin

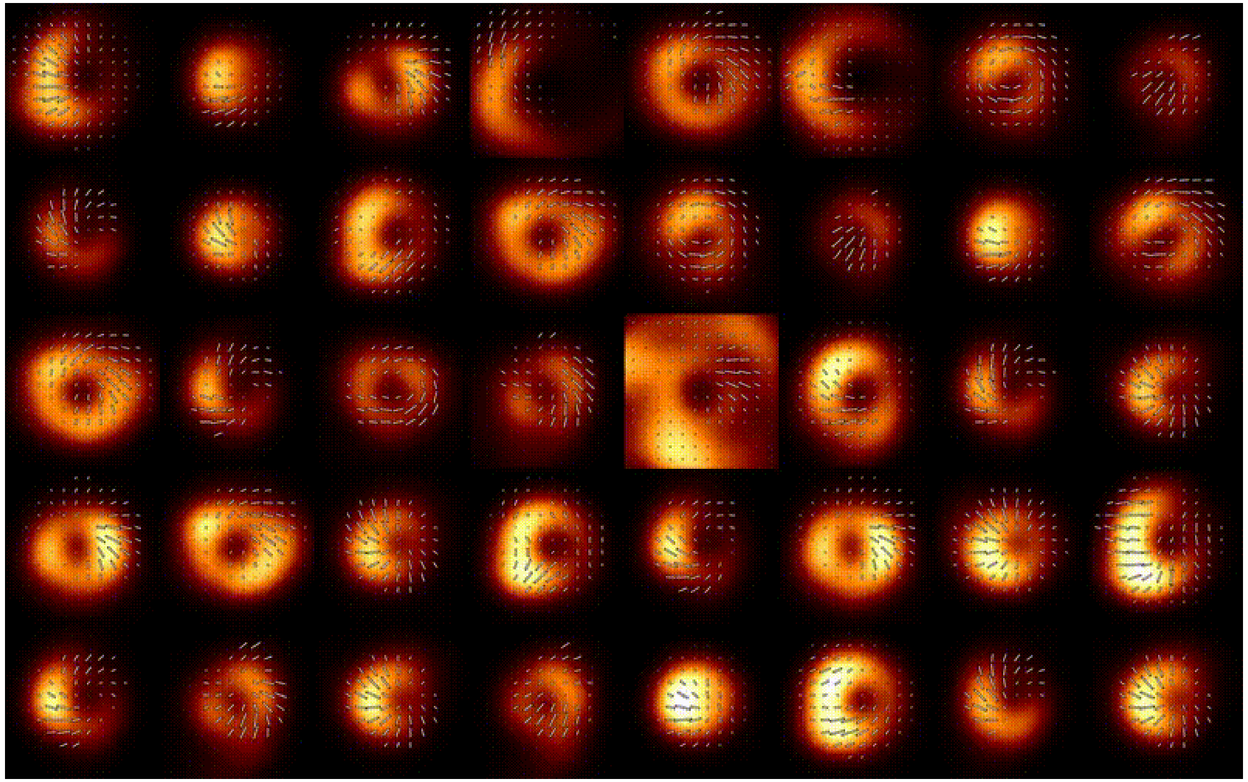
magnetic flux

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

EHT GRMHD Simulation library



native resolution



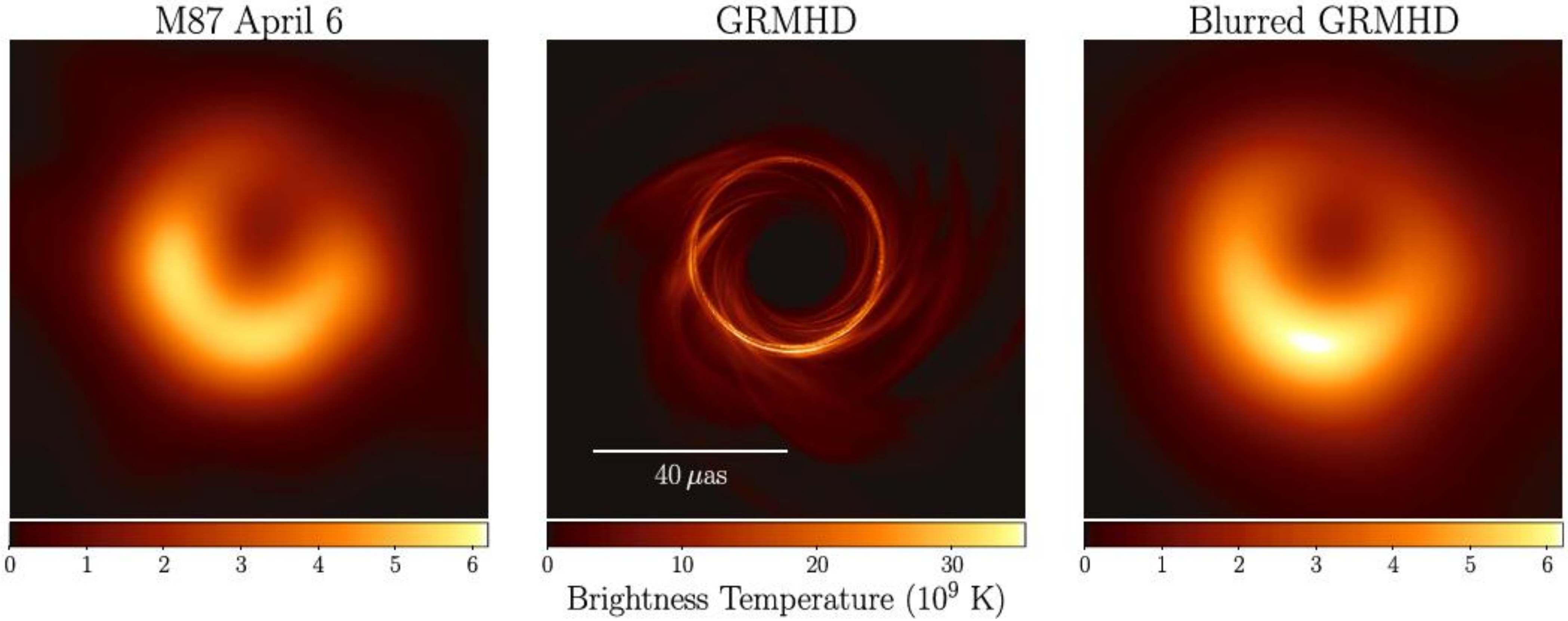
EHT resolution

Simulation survey over black hole spin and magnetic field state

Electron Temperature must be set in post-processing: $T_{\rm e} \neq T_{\rm i}$

Animation credit: Cora Prather

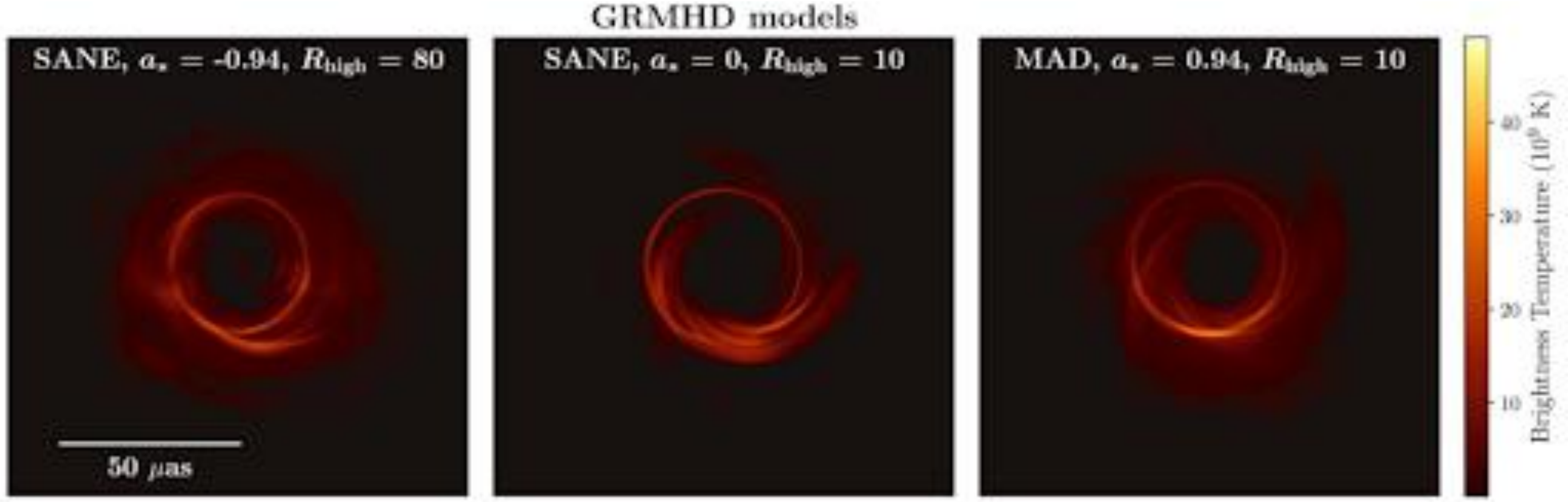
EHT Images are consistent with GRMHD Simulations



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)



- Use **ring size** to measure black hole mass
- Use **ring asymmetry** to measure spin orientation
- Constraint on **jet power** (≥ 10^{42} erg/sec) rejects all spin 0 models

EHTC V, 2019

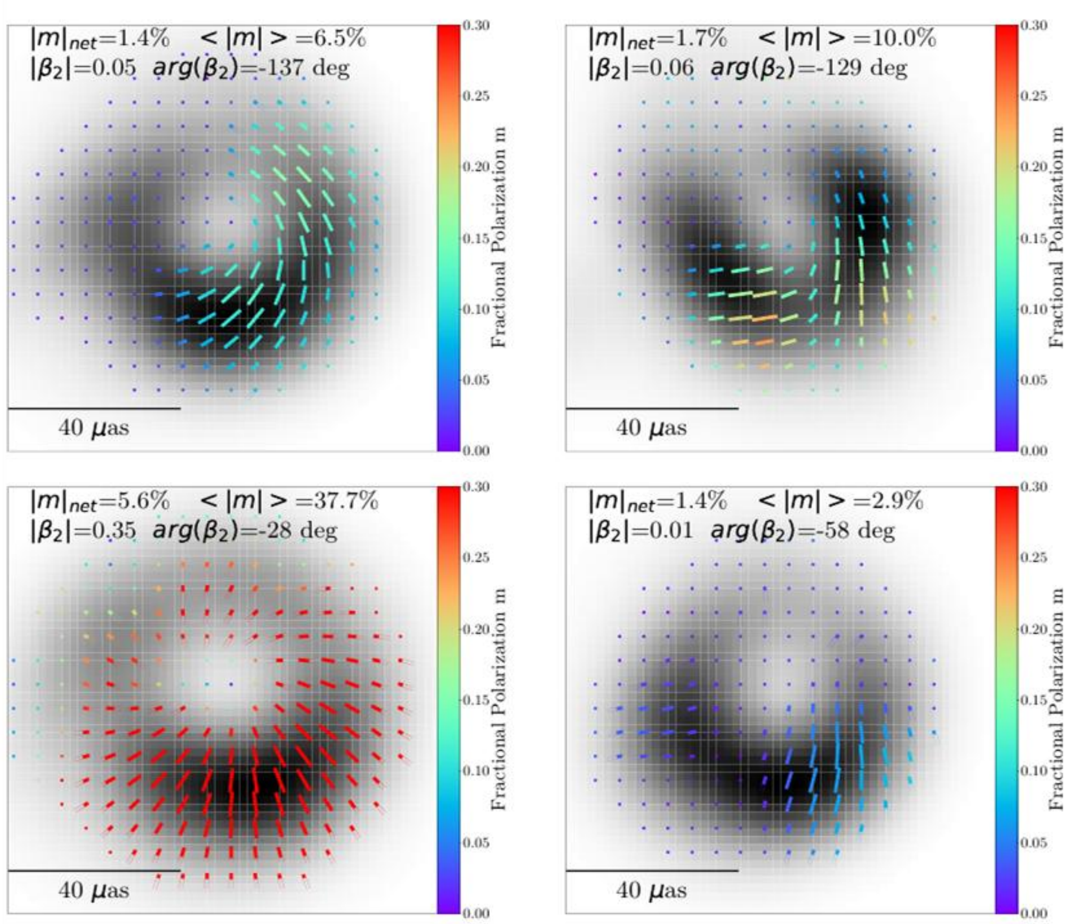
Polarization is the key for near-horizon astrophysics

- Synchrotron radiation emits linear polarization oriented **perpendicular** to magnetic field lines

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

- Simulation polarization images show many different structures:
  - **strongly** or **weakly** polarized
  - patterns that are **radial** or **helical**

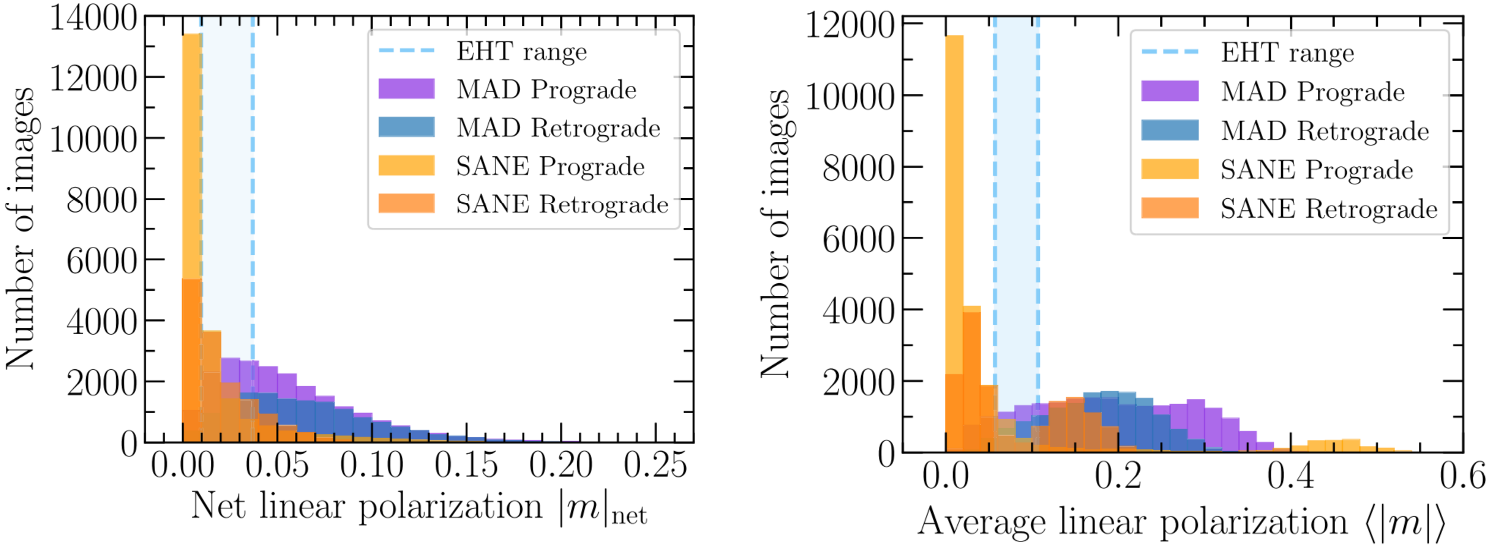
Simulation Polarization Images



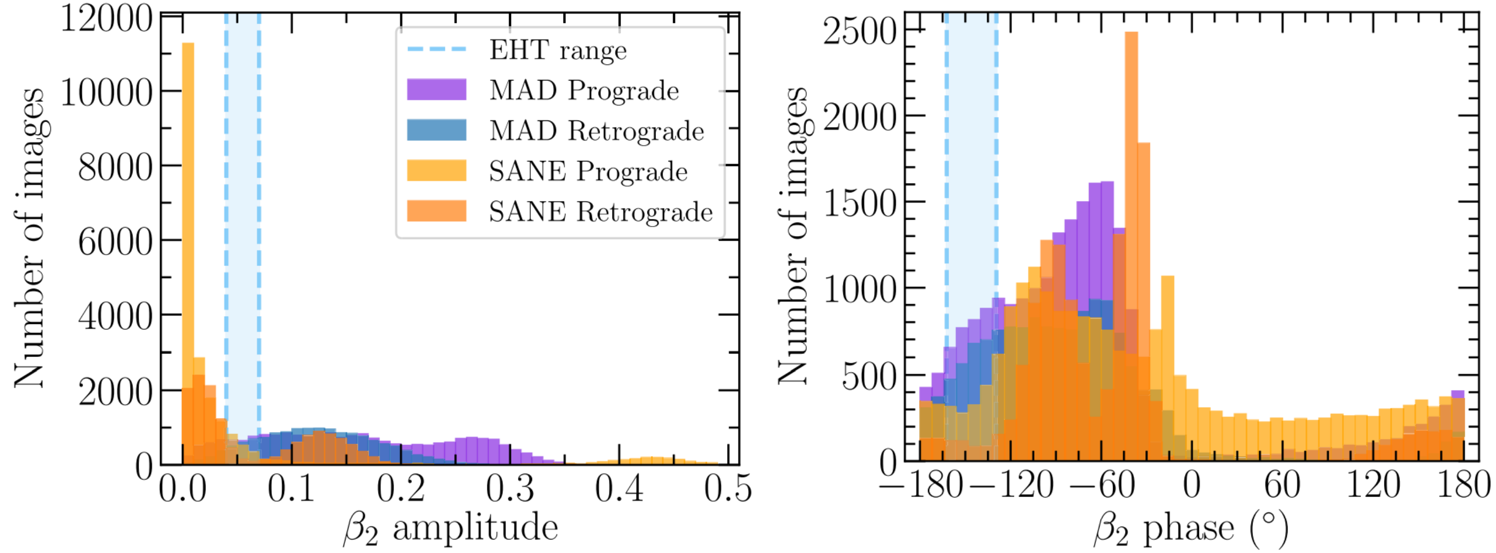
EHTC+ VII, VIII 2021 (**Chael**, paper coordinator)

Scoring M87 simulations with linear polarization

Unresolved and **resolved** linear polarization fractions

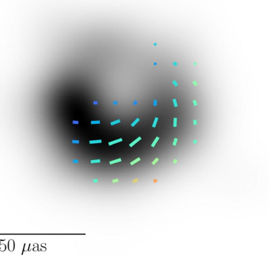


Azimuthal structure
2nd Fourier mode



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

Scoring M87* simulations with polarization



- Scoring M87 2017 observations with multiple approaches all strongly favor a **magnetically arrested accretion flow**

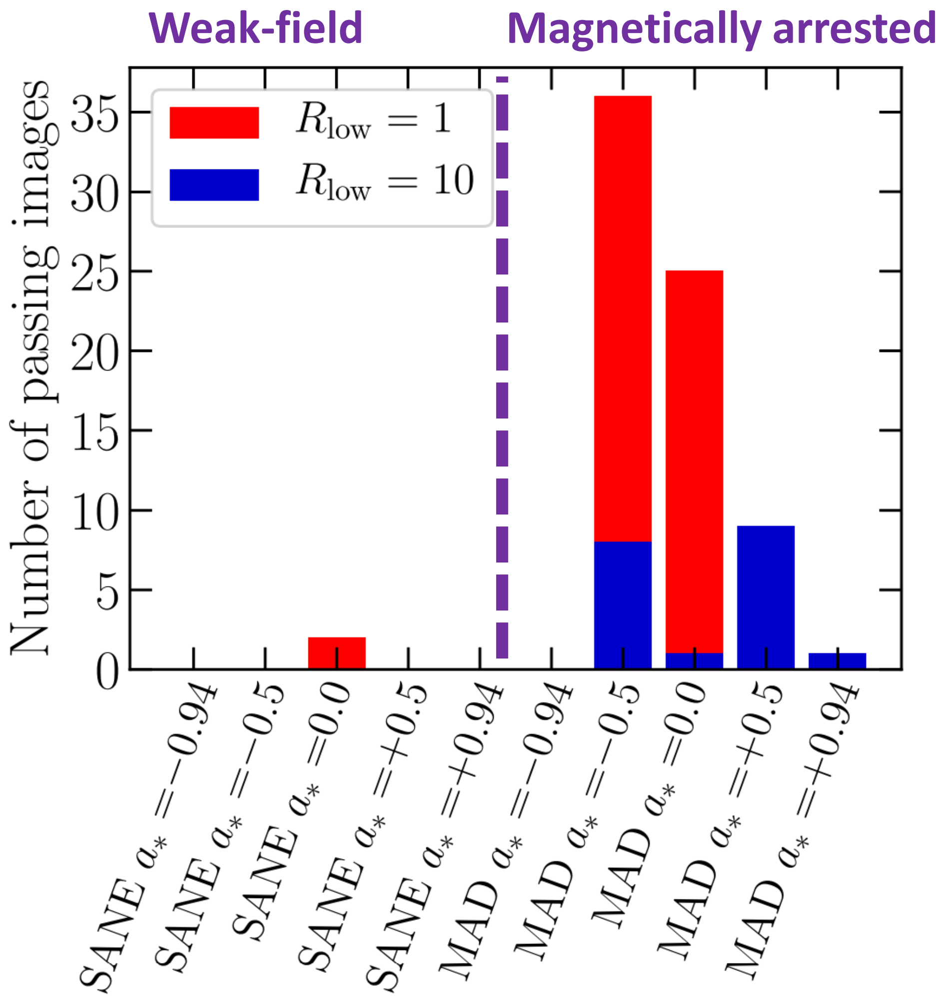
- We constrain M87*'s allowed accretion rate by 2 orders of magnitude from passing models w/o polarization:

$$\dot{M} = 2 - 15 \times 10^{-6} \dot{M}_{\text{Edd}}$$

- …and the near-horizon magnetic field and temperature.

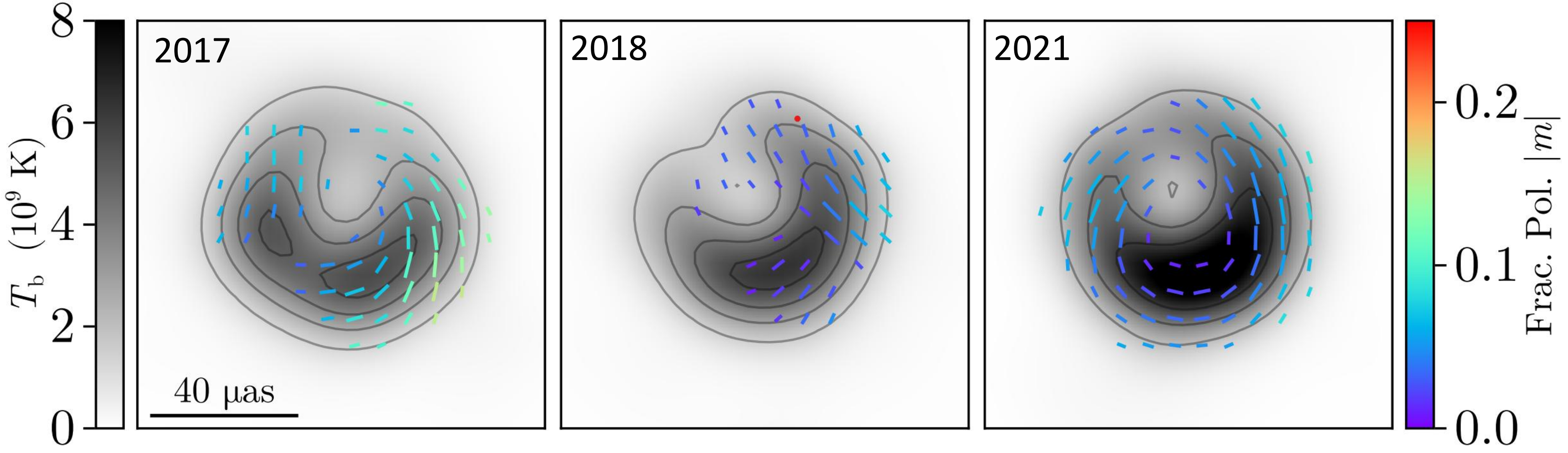
$$T_e \simeq (5 - 40) \times 10^{10}\ \text{K}$$
$$|B| \simeq (7 - 30)\ \text{G}$$

- Strong magnetic fields more easily launch BZ jets at all values of BH spin



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

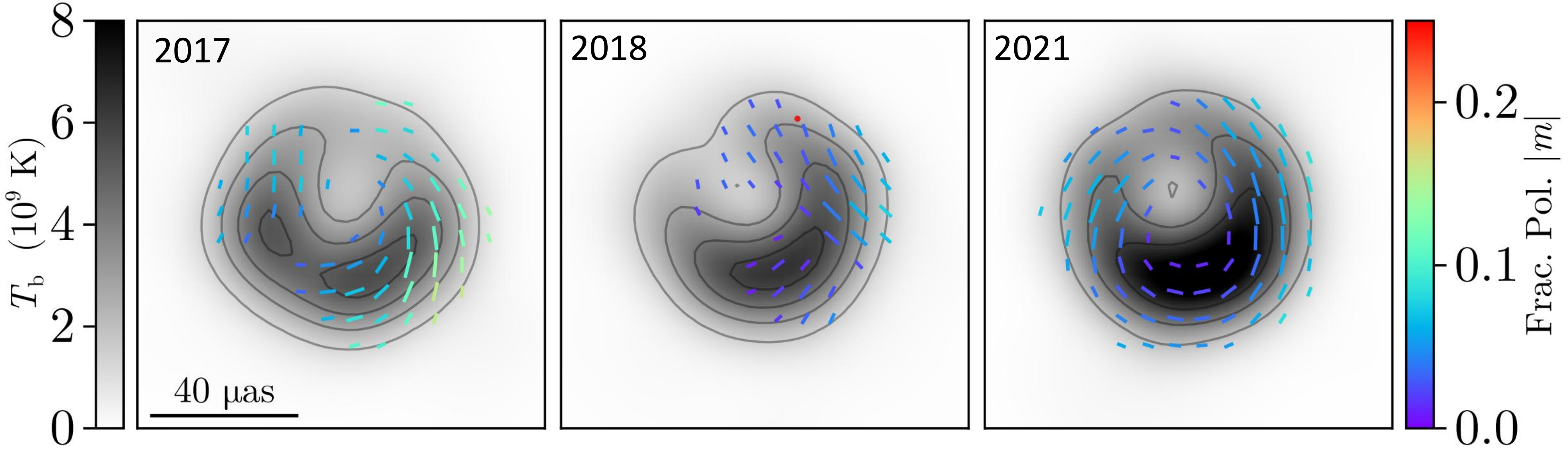
Surprising Polarization Variability in M87* over 3 years



- EHT observations show a consistent horizon-scale ring structure in M87* **over 4,000 t_g**
- Image quality is improving from EHT observations performed with a **more complete array** (including Greenland Telescope)
- Ring diameter is consistent over three years

EHTC+ 2019, 2022, 2024, 2025

Surprising Polarization Variability in M87* over 3 years

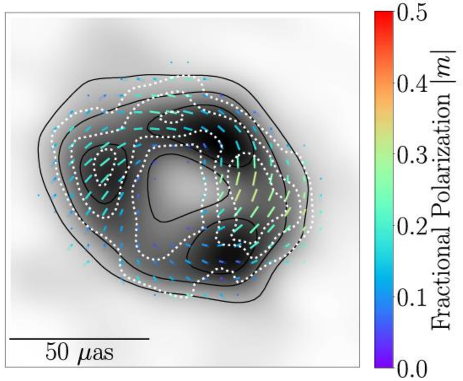


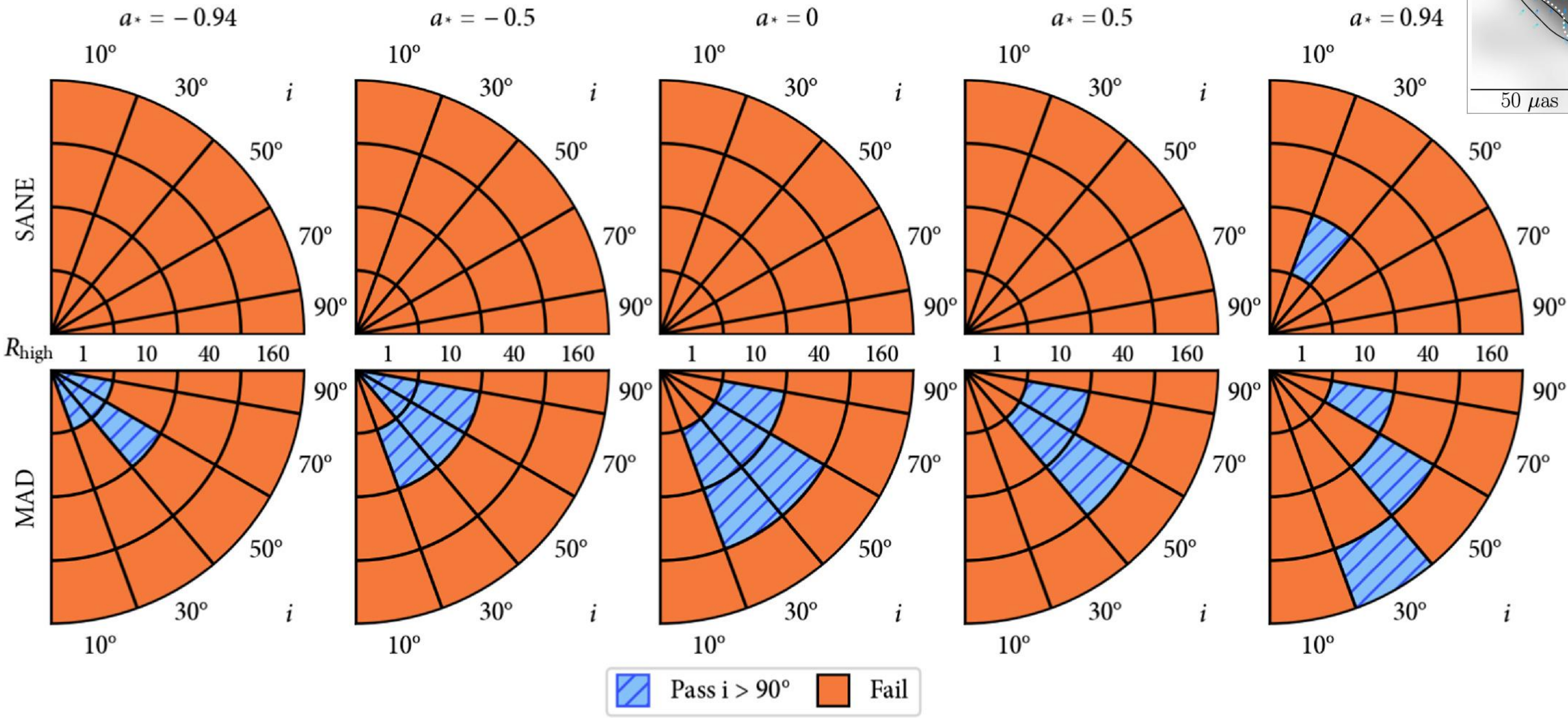
- Polarization structure shifts and fractional polarization is **significantly lower** in 2018-2021 (3%) than 2017 (~10%)
  - Does this challenge the magnetically arrested interpretation?

- This degree of variability is difficult to explain in simulation models (MAD or SANE)
  - Do we need to modify initial conditions / plasma feeding?

EHTC+ 2019, 2022, 2024, 2025

Sgr A* Polarization Constraints





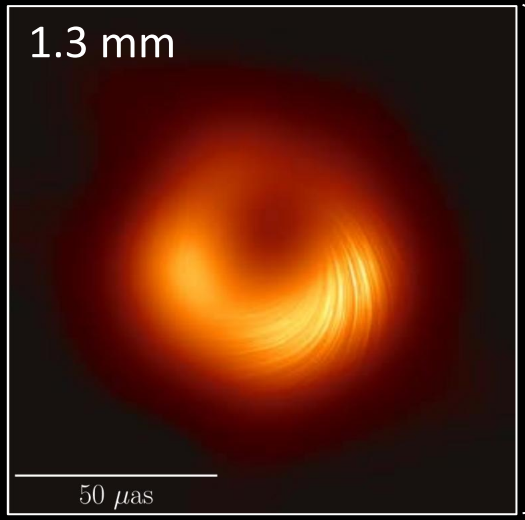
- For any model to pass requires **Faraday de-rotation.**
- Passing models all must spin **clockwise**, consistent with NIR & submm flare inferences (GRAVITY+ 2018, Wielgus+ 2022)
- **One high spin MAD model survives** both multi-wavelength and polarization cuts
  - If Sgr A* is magnetically arrested, why is there no obvious jet?

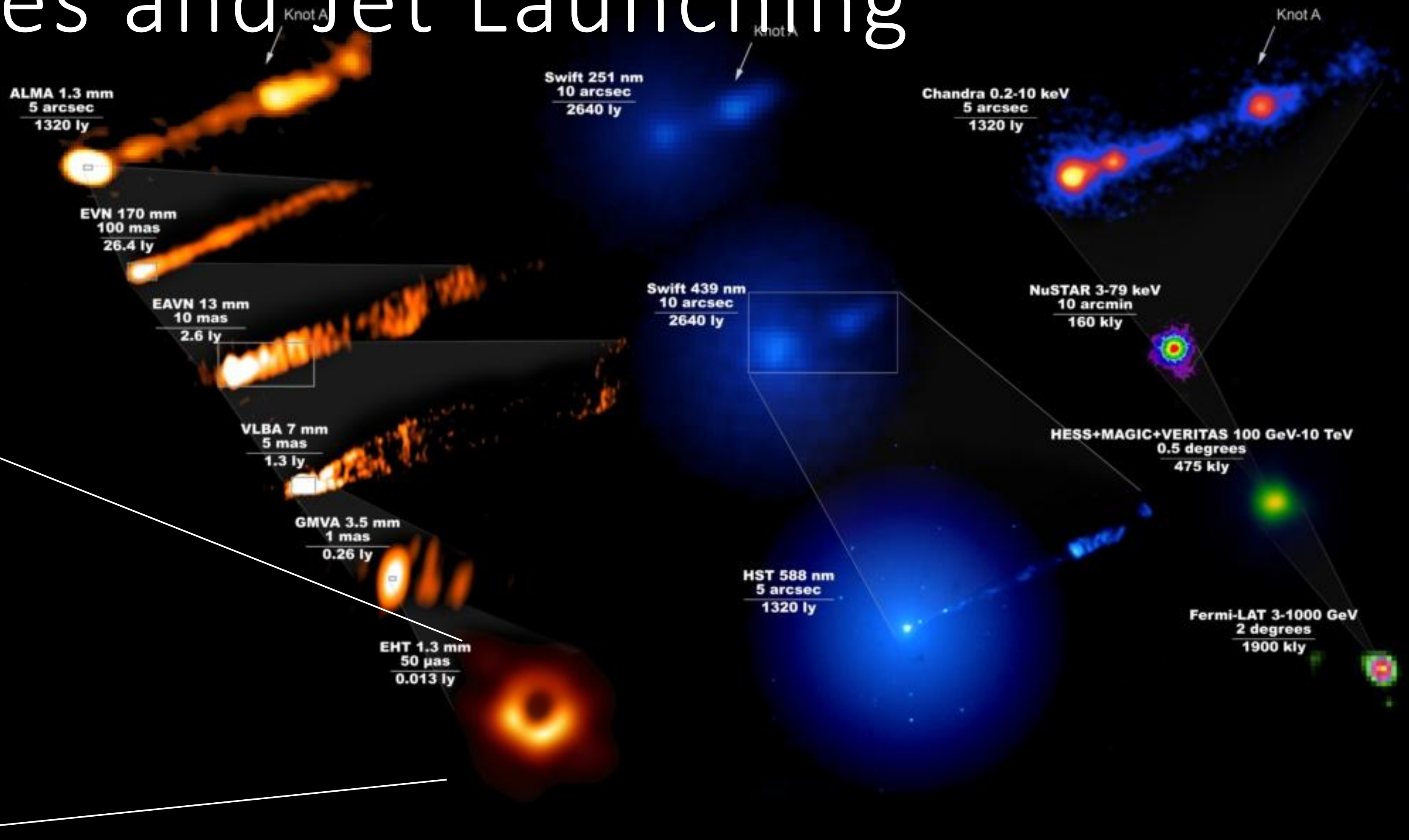
EHT VIII, 2024 (**Chael**, paper writing team)

Polarized Images and Jet Launching

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

$P_{\rm jet}$ is 10^{42}-10^{45} erg/s





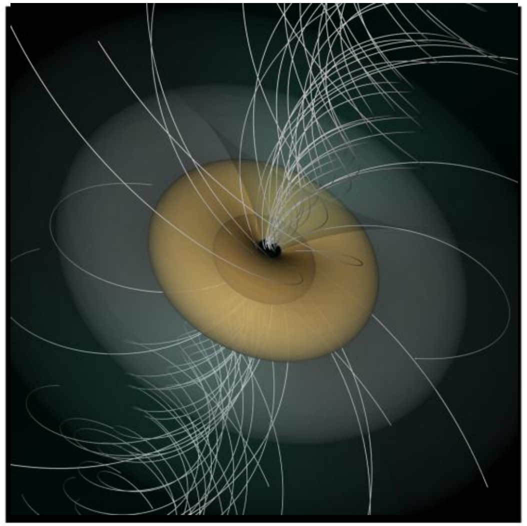
Jets are thought to be powered by black hole spin energy extracted via magnetic fields (Blandford & Znajek 1977)

Polarized images probe black hole energy extraction **on horizon scales** (e.g. Chael+ 2023).

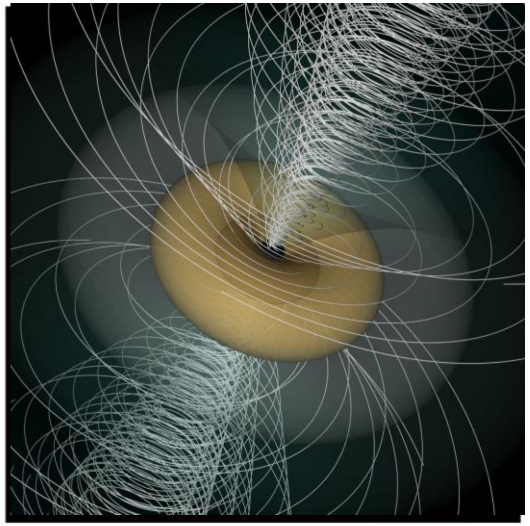
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Polarized images are **spin dependent**

Low Spin



High Spin

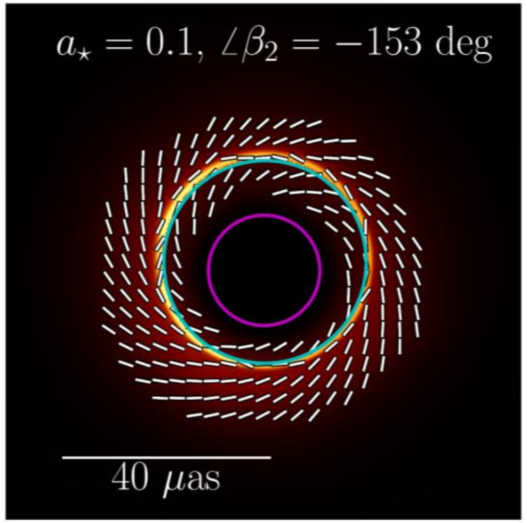


- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power

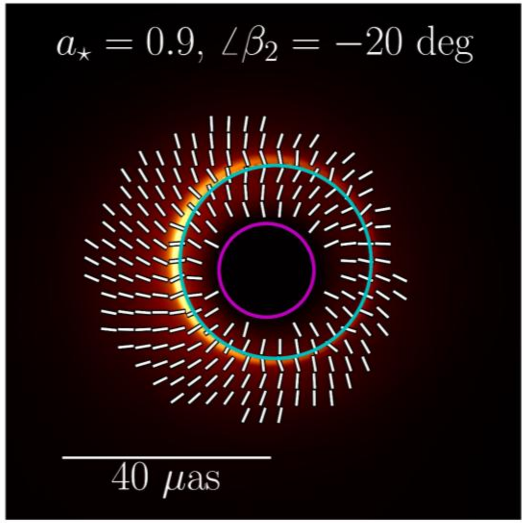
Chael+ 2023b**; Chael** 2025**;** Wong+2025

Polarized images are **spin dependent**

Low Spin



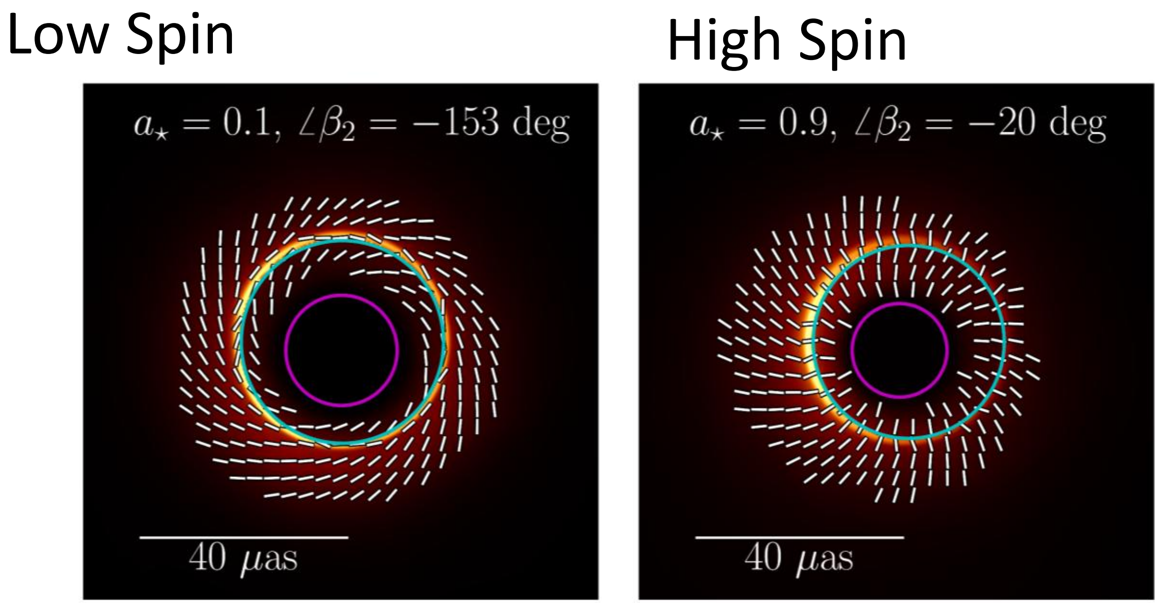
High Spin

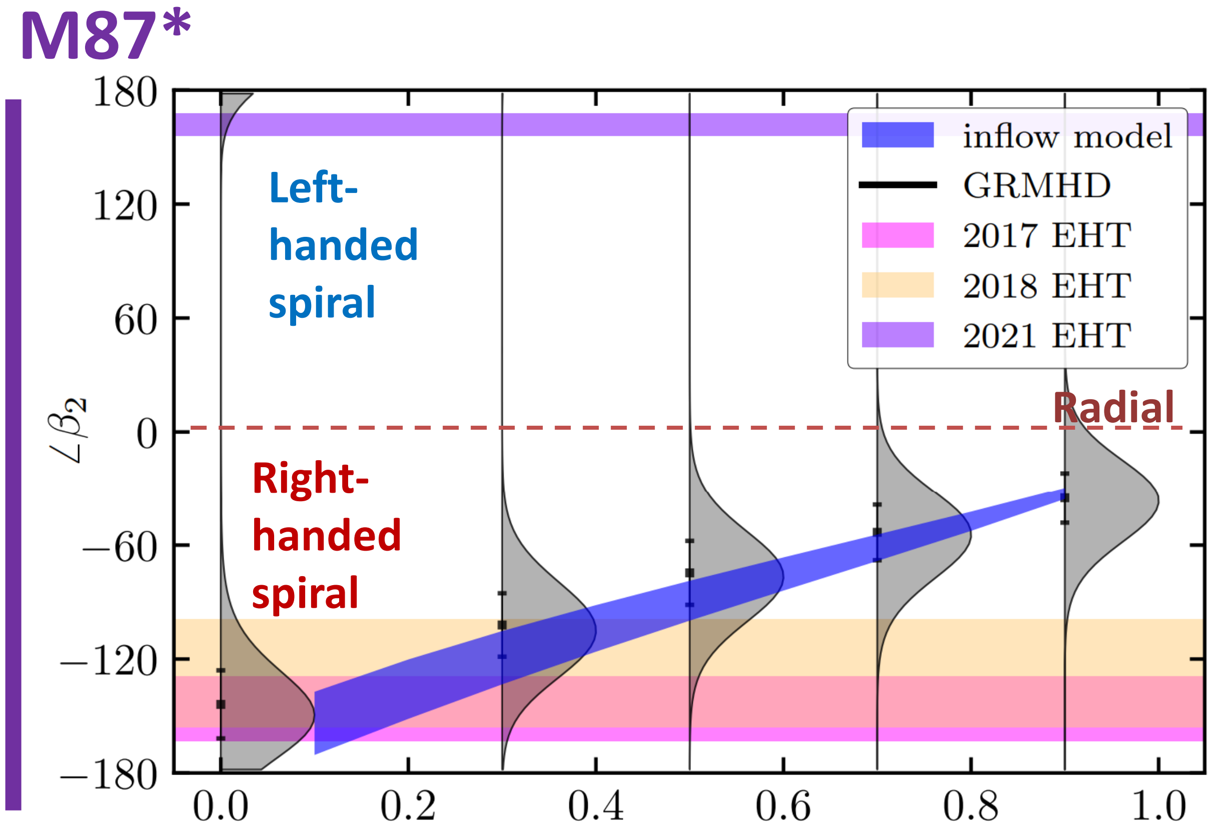


- Black hole **spin winds up initially radial fields**, but always so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the BZ jet power
  - makes the observed polarization pattern more radial

Chael+ 2023b; **Chael** 2025; Wong+2025

Polarized images are **spin dependent**



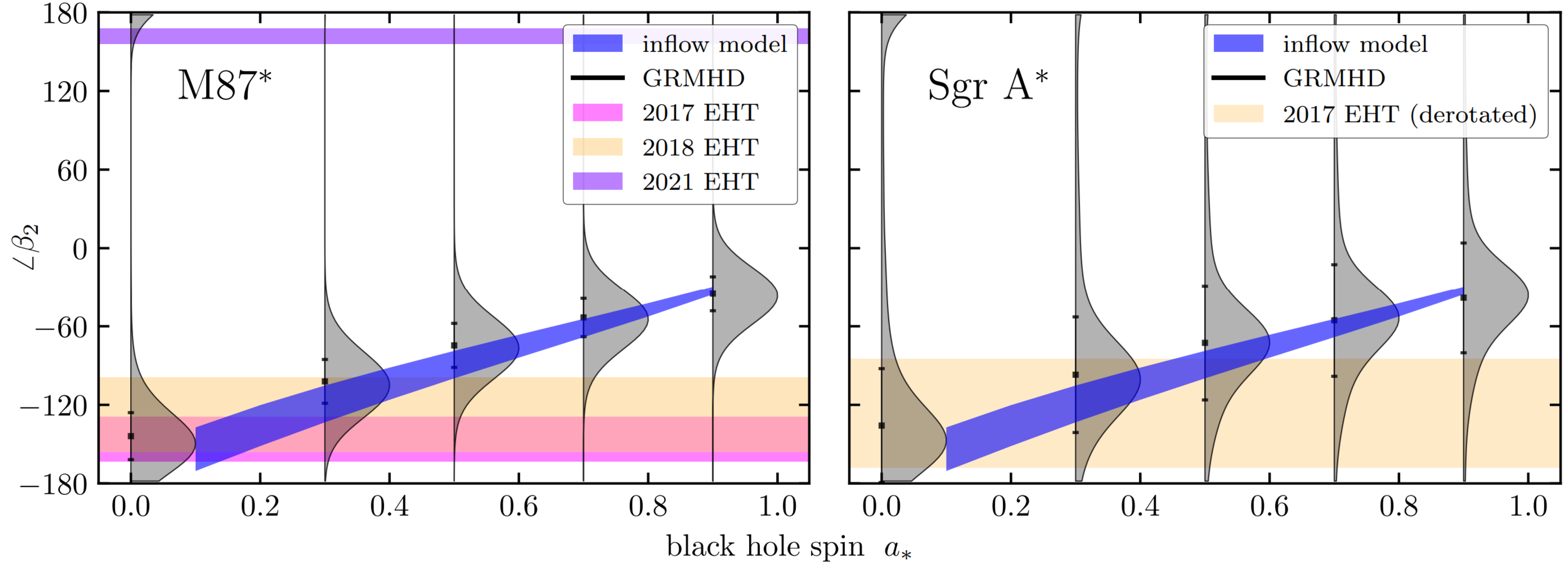


- M87* polarization in 2017 and 2018 is **consistent with energy outflow** for inferred **clockwise** BH rotation
- M87* polarization in 2017 and 2018 EVPA patterns are most consistent with **low or moderate, retrograde spin**
  - (See also Qiu+ 2023, Chang+ 2024, Janssen+ 2025)

- The shift in β_2 in 2021 is mysterious
  - Change in Faraday rotation? Change in accretion state/plasma feeding?

Chael+ 2023b; **Chael** 2025; Wong+2025

Polarized images are **spin dependent**



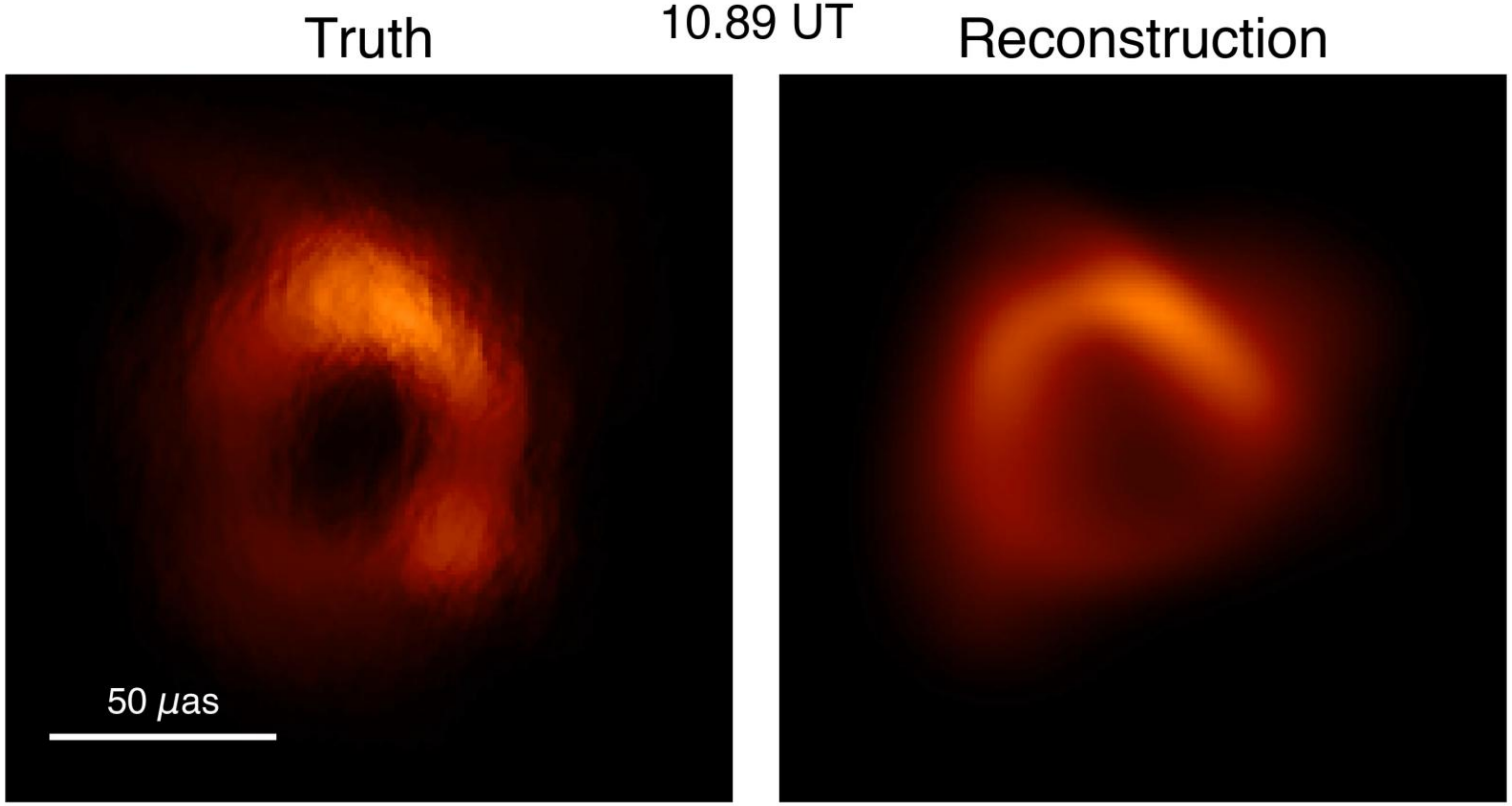
- Sgr A* polarization is consistent with energy outflow **if** the BH rotates clockwise
  - NIR flares (GRAVITY+ 2018) and ALMA mm light curves (Wielgus+ 2022) all rotate **clockwise**
- Sgr A* spin is not well constrained by EVPA pattern alone
  - combined EHT+MW constraints prefer high spin (EHTC+ VIII 2024)

Polarimetric spin measurements are possible!

Chael+ 2023b; **Chael** 2025; Wong+2025

Next Steps
for Horizon-Scale Black Hole Astrophysics

Sgr A* Dynamics: Horizon-scale motion

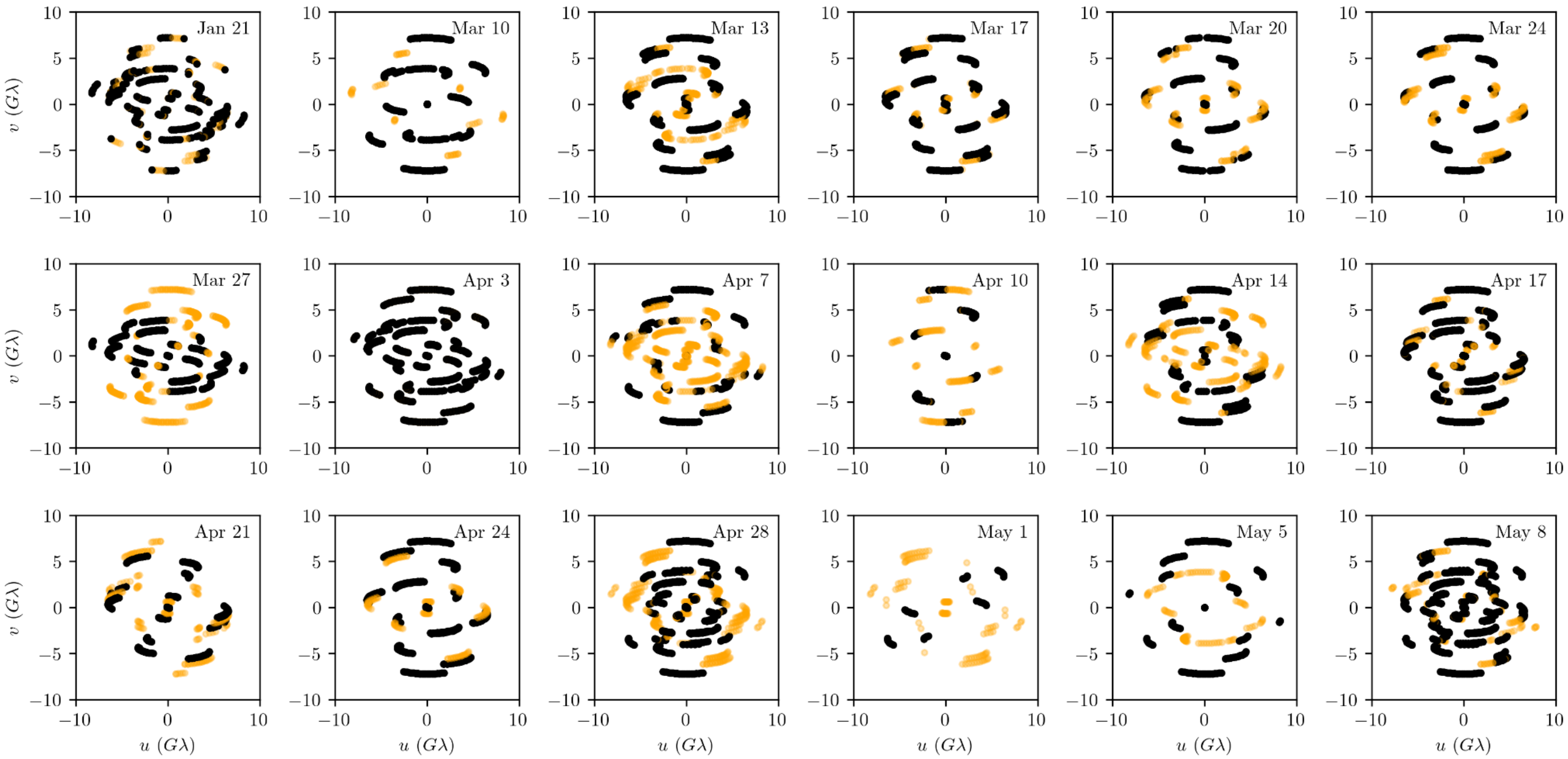


- GRAVITY near-infrared observations (GRAVITY Collab+ 2018, 2023) and unresolved ALMA observations (Wielgus+ 2022) suggest coherent clockwise motion on ~5 rg scales associated with Sgr A* flares.

- Long-term effort to use EHT data to constrain intra-observation motion.

Image credit: Rohan Dahale

M87* Dynamics: MOVIE campaign

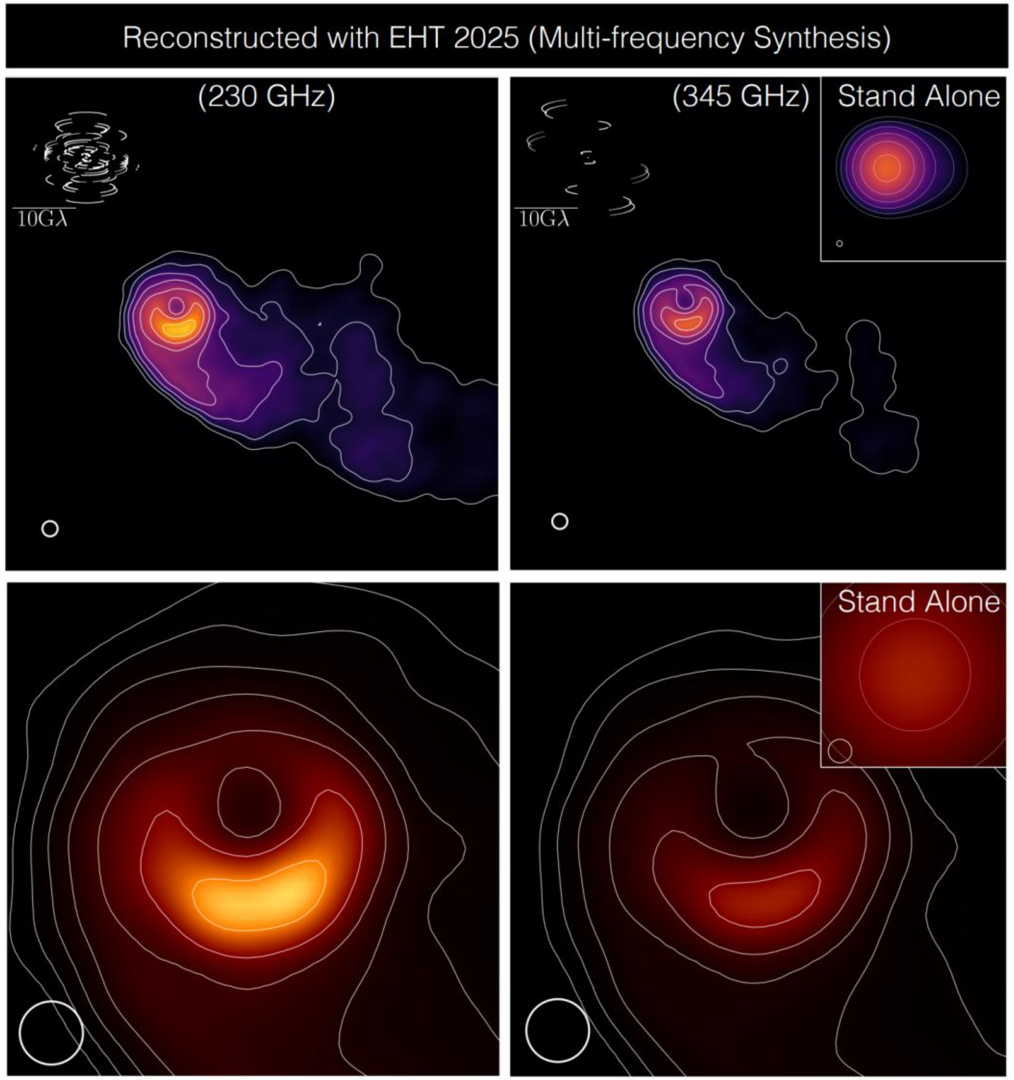


- M87*'s near-horizon variability has been probed on ~day and ~year timescales, but intermediate timescales are unexplored
- EHT just wrapped up 2-month "MOVIE" campaign of biweekly imaging observations of M87*

Image credit: Boris Georgiev

Pushing the VLBI Frequency Frontier

- EHT baselines have detected fringes at 345 GHz – highest ever for VLBI (Raymond+ 2024)
- Frequency phase transfer (FPT) of phase solutions can substantially improve 345 GHz coverage (Pesce+ 2024 , Issaoun+ 2025)
- With observations at multiple frequencies, we can directly constrain Faraday rotation and better probe the intrinsic magnetic field in high resolution



Raymond+ 2024, Pesce+ 2024, EHTC+ 2025

How can we determine the jet power source?

By zooming **out**..

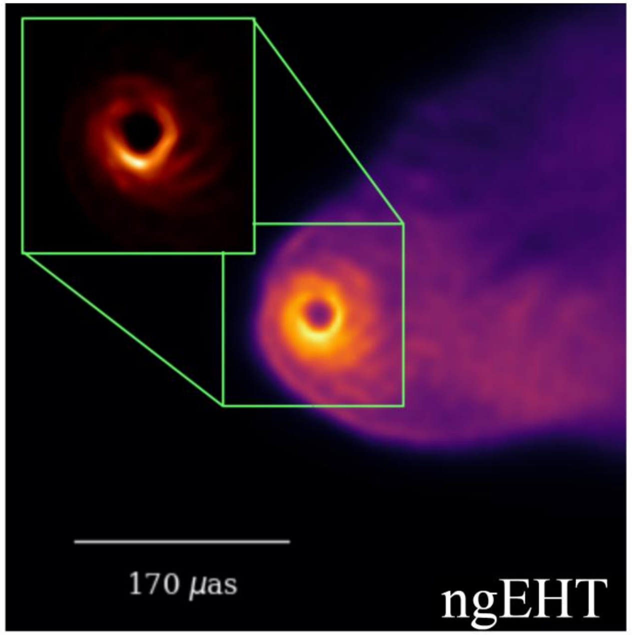


Image the connection between the BH and the low-brightness extended jet in polarization and **high dynamic range**

By zooming **in**..

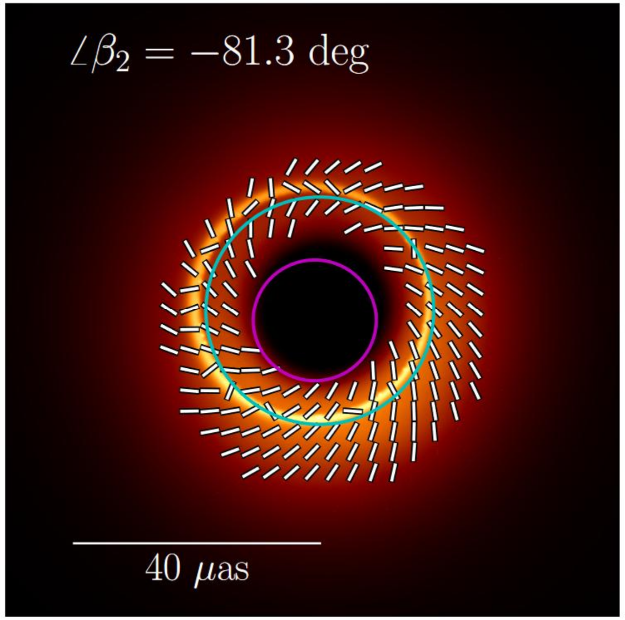


Image field lines close to the event horizon in **high resolution**

The future of near-horizon observations

Extended & next-generation EHT

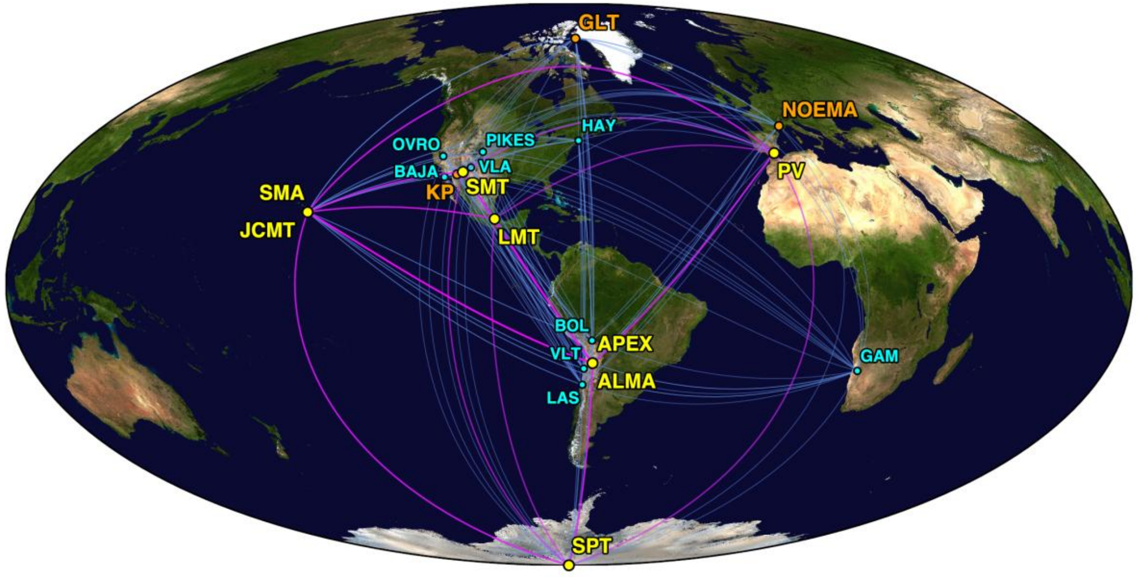


Image black holes and their jets in **multiple frequencies** and **high dynamic range**

Black Hole Explorer (BHEX)

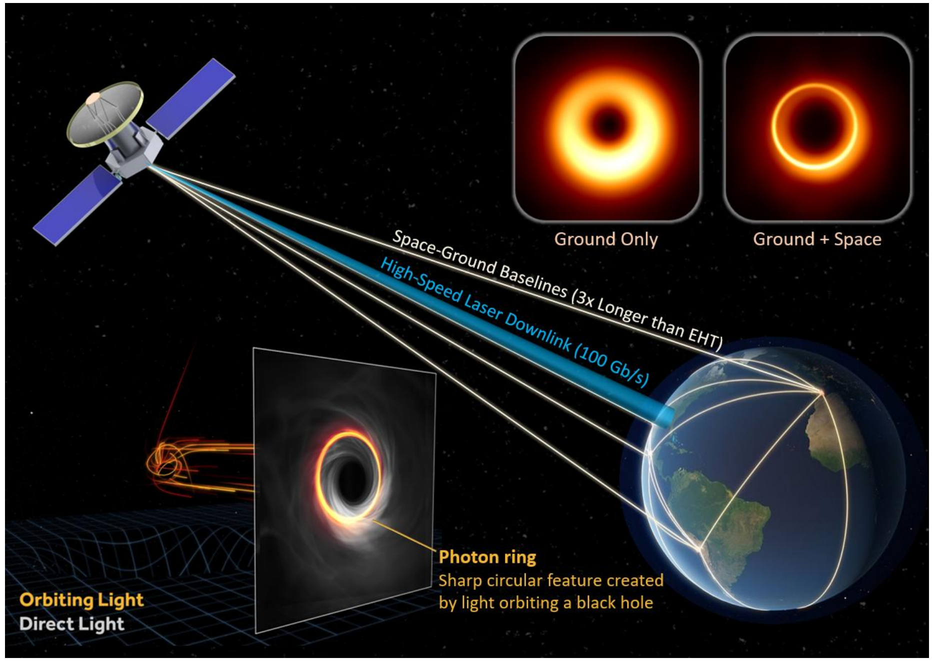
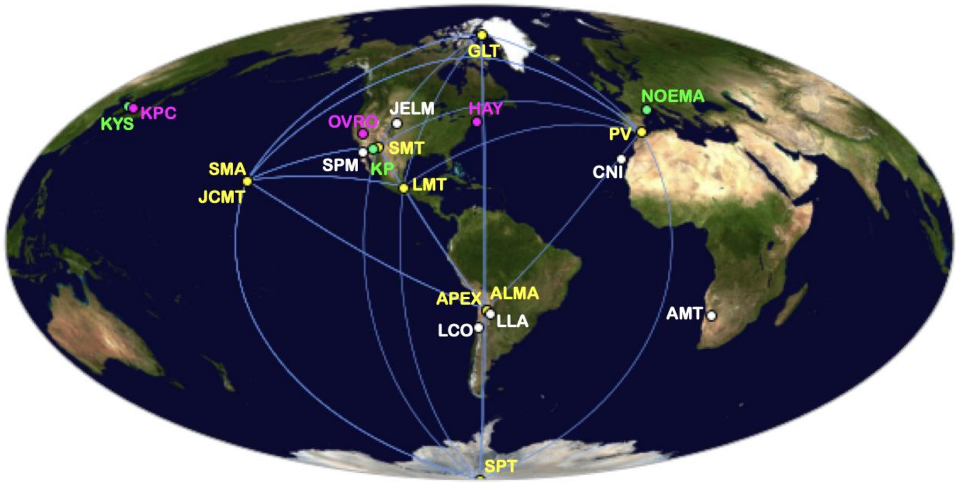


Image **extreme gravitational lensing** and dozens of new black holes **in high resolution**

See EHTC+ 2024 (2410.02986); Johnson+ 2024 (2406.12917)

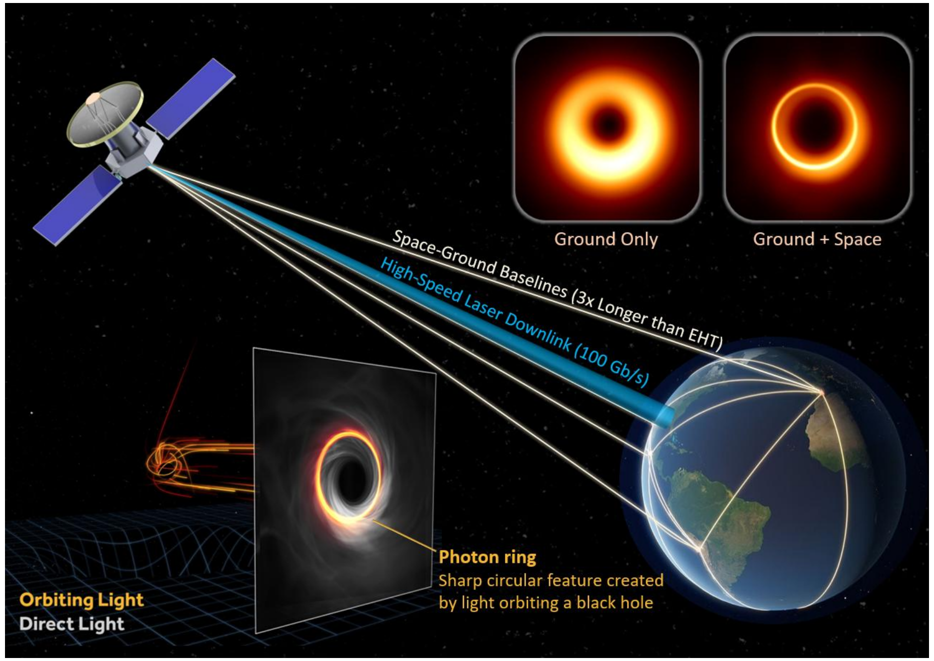
The future of near-horizon black hole astrophysics

Expanded ground-based EHT array



- Expand all EHT sites to multi-frequency observing and add new sites in Tenerife (TEA), Namibia (AMT) ….
- Image black holes and jets in high dynamic range at multiple frequencies
- Probe jet launching from horizon to hundreds of Schwarzschild radii (see e.g. Gelles+ 2024**:** 2410.00954)
- Make movies of Sgr A* and resolve black hole flares

Space VLBI / Black Hole Explorer (BHEX)

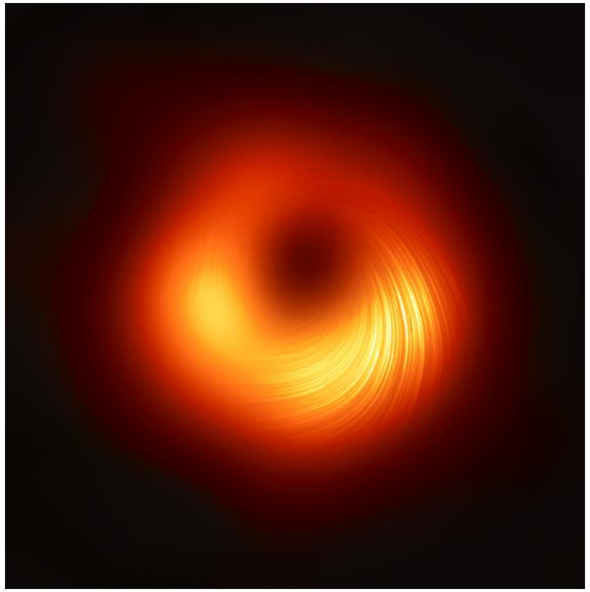


- A mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to ~12 (Zhang+ 2024)
- Also: SHARP and SHAPREx (Roelofs+ 2026)

See Doeleman+ 2023, EHTC+ 2024 (2410.02986); Johnson+ 2024 (2406.12917)

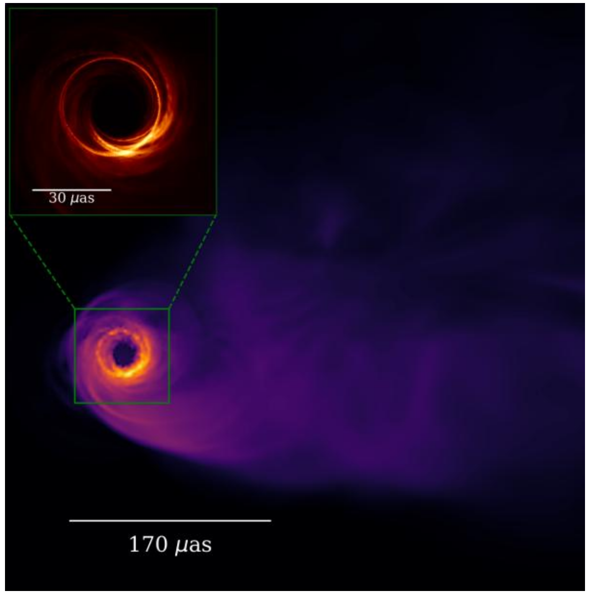
Takeaways…

1. **Near-horizon images are largely consistent** with our picture of low-luminosity accretion from simulations
2. **Polarization is the key** for constraining near-horizon magnetic fields and jet launching
3. **Future ground and space-based VLBI observations** will directly probe the black hole-jet connection at the horizon scale



…and more questions

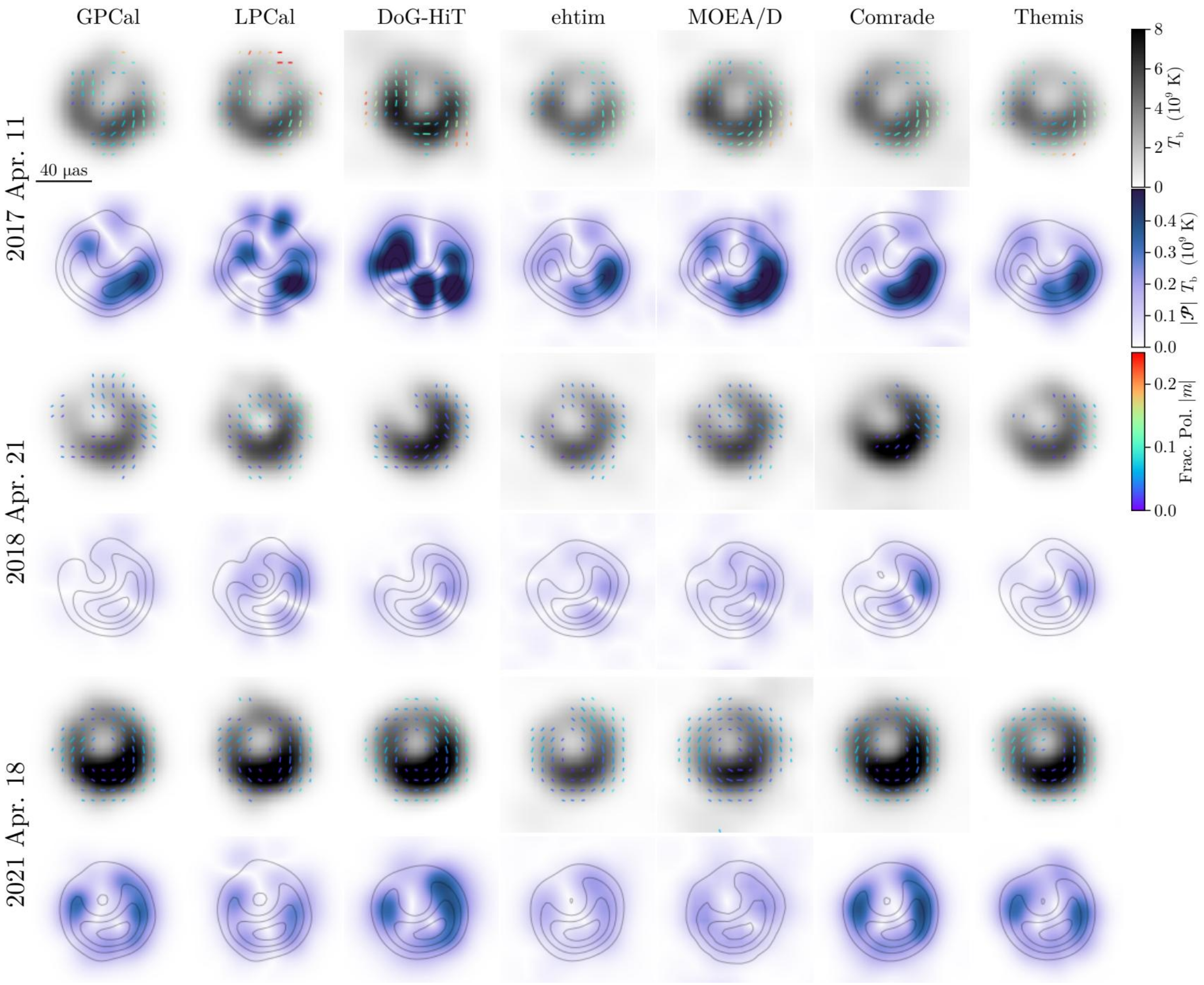
- Can we improve our simulations to account for unexpected variability observed at the horizon scale?
- What powers flares in Sgr A* and M87* and can we directly connect horizon-scale observations to multiwavelength constrains?
- What can future earth- and space-VLBI observations tell us about near-horizon physics in supermassive black holes beyond Sgr A* and M87*?



EHT VII, 2021; **Chael** 2025

Backup Slides

Individual M87* images from 2017-2021



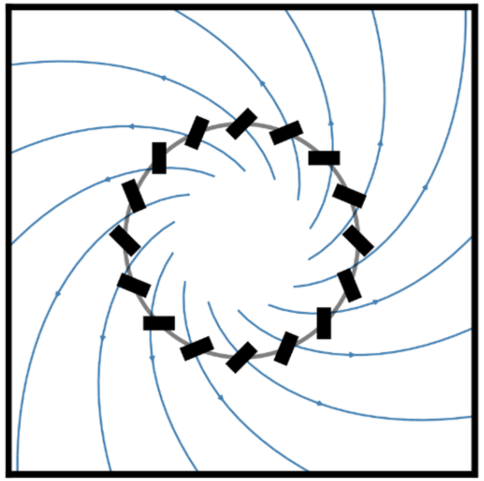
EHTC+ 2025

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

- In simple analytic models, the sign of $\angle\beta_2$ is directly connected to the direction of Poynting flux, assuming we know the sign of the angular velocity Ω_F
- Ignoring Faraday effects, **the EHT's measurement of β_2 implies electromagnetic energy outflow in M87***
- Does this simple argument hold up in **simulations?**

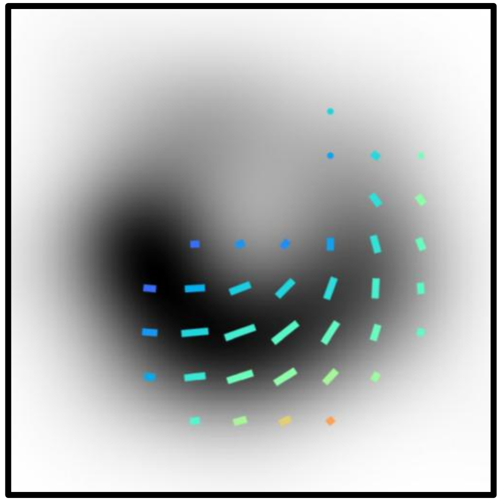
Cartoon Model

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



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

M87*



GRMHD Poynting flux

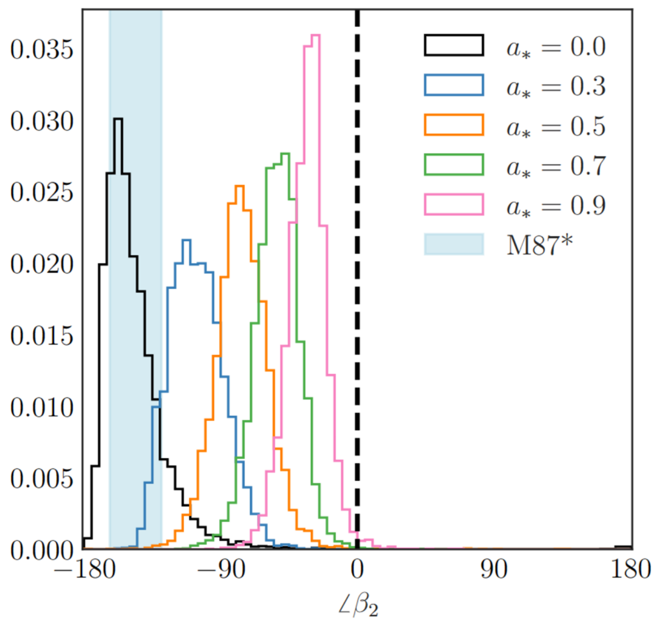
$$\mathcal{J}^r_{\mathcal{E}} = -T^r_{t\ \mathrm{EM}} = -B^r B^\phi\, \Omega_F\, \Delta \sin^2\theta$$

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

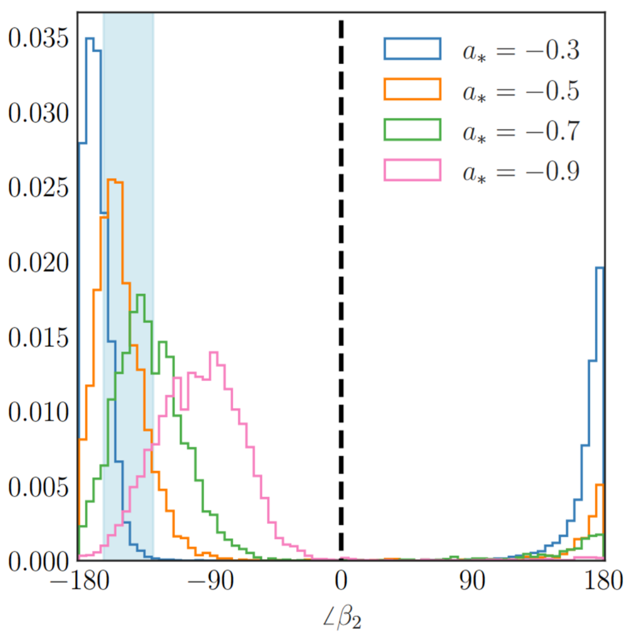
Does β_2 measure the direction of energy flux in simulations?

- Almost all 230 GHz images from MAD simulations have $\angle\boldsymbol{\beta}_2 < \mathbf{0}$, consistent with the measured energy outflow in the simulations.
- **M87*'s horizon-scale polarization in 2017 is consistent with outflowing electromagnetic energy at radii $\boldsymbol{r \lesssim 5r_g}$**
- $\angle\beta_2$ in simulations has a strong dependence on spin

Prograde simulations



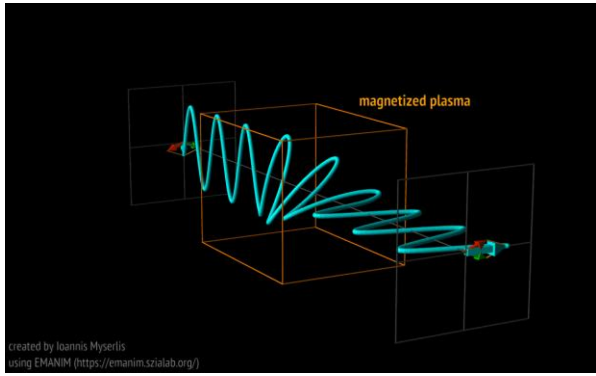
Retrograde simulations



BH spin axis is into the plane of the sky in all simulation images (EHTC+V)

Chael+ 2023b, simulations from Narayan+2022

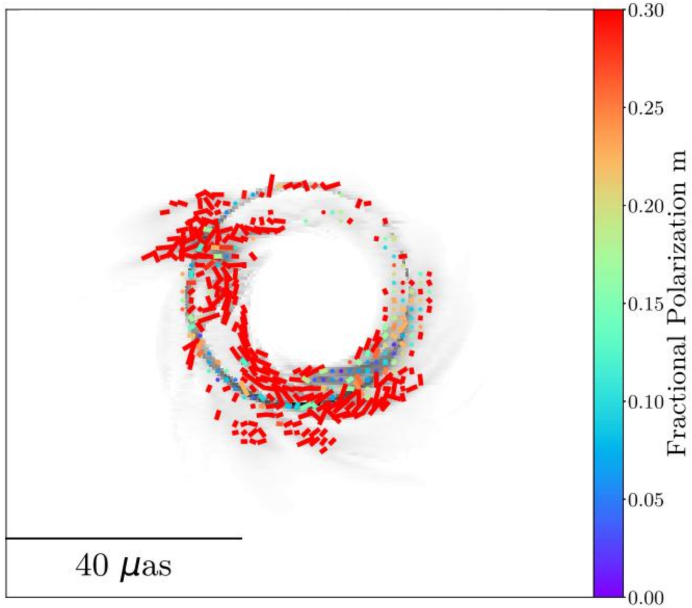
Faraday Rotation depolarizes BH images

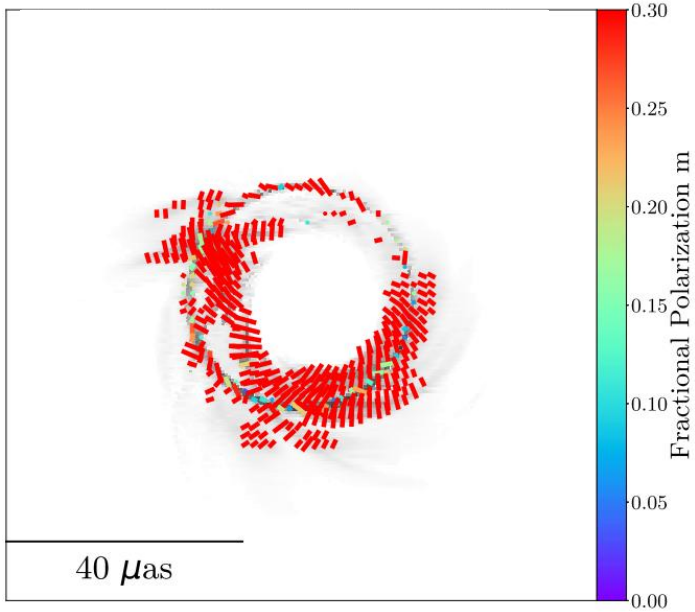


With Faraday

Without Faraday

'infinite' resolution

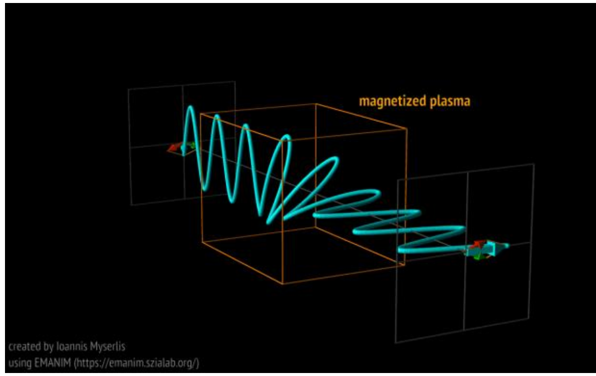




- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales

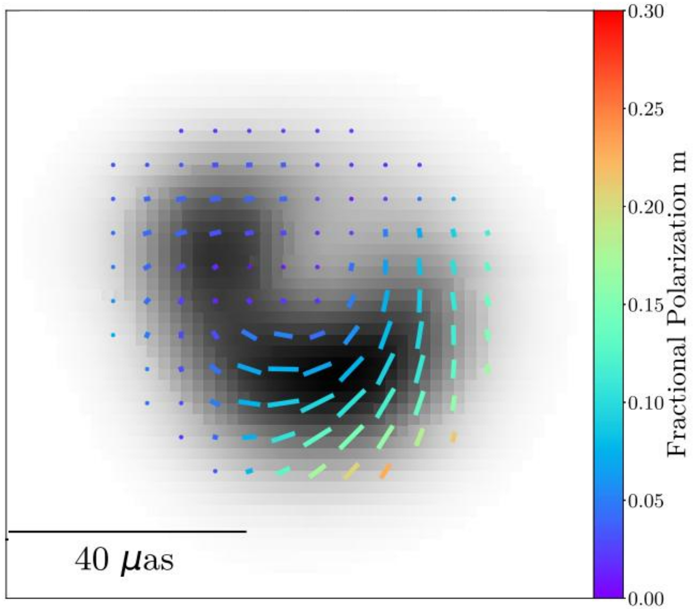
Credit: EHT 2021 Paper VIII (**Chael**, paper coordinator)

Faraday Rotation depolarizes BH images

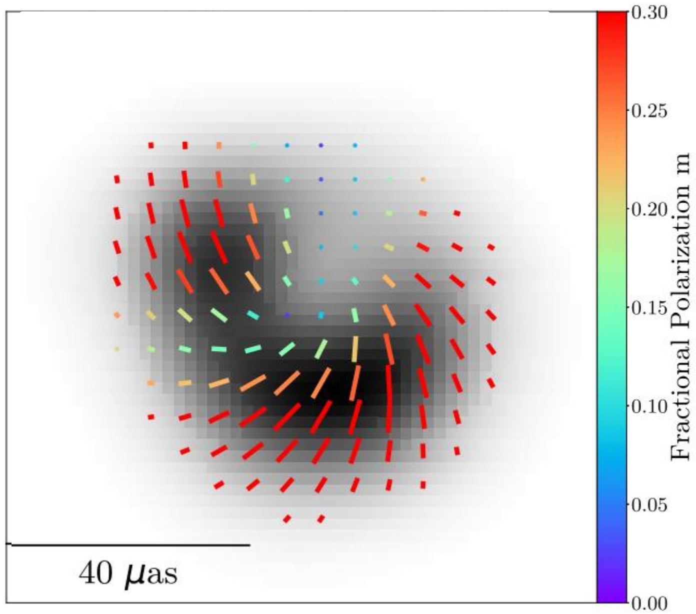


EHT resolution

With Faraday



Without Faraday

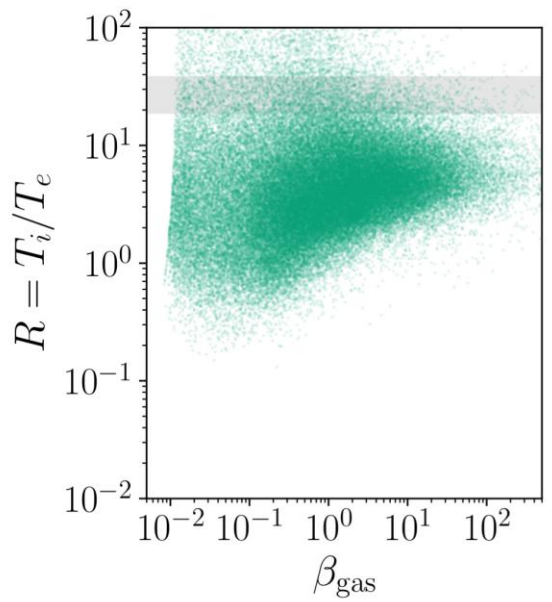


- Significant Faraday rotation on small scales
  - → **Rotates** the overall polarization pattern at EHT resolution
  - → **Scrambles** polarization vectors on small scales
  - → **Depolarizes** the image when blurred to EHT resolution
- Internal Faraday rotation from **colder electrons** is necessary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

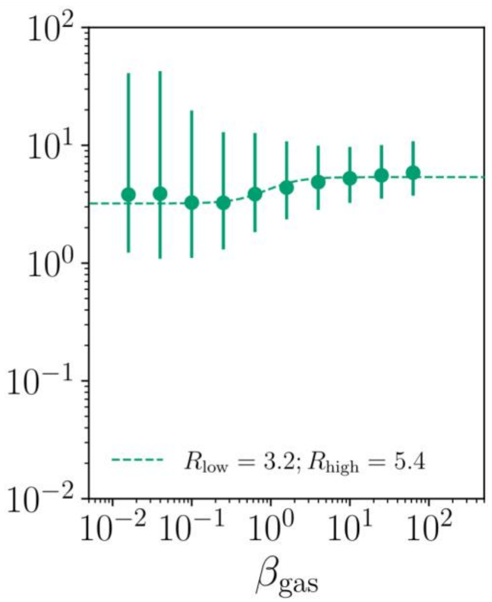
Credit: EHT 2021 Paper VIII (**Chael**, paper coordinator)

Electrons in *Radiative, Two-Temperature* Simulations are too hot!

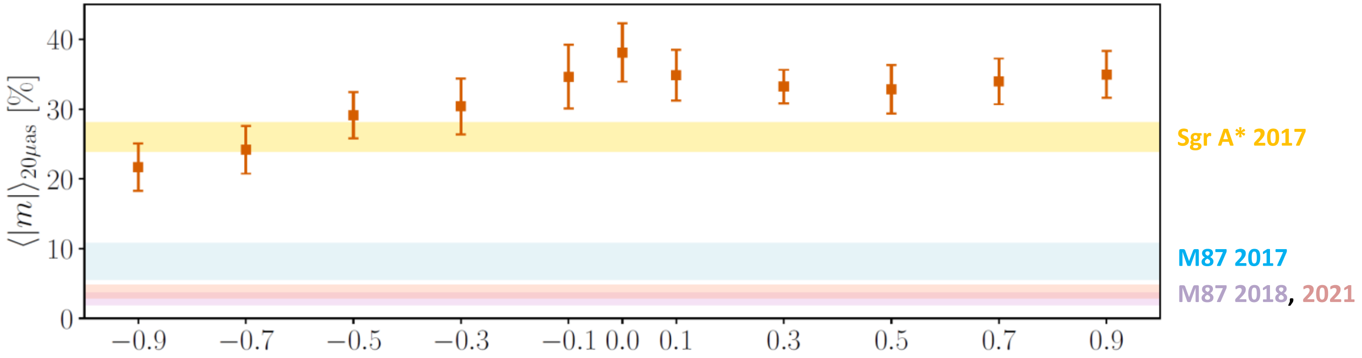
Ion-to-electron temp ratio



Effective R-β model



EHT-scale polarization fraction



- EHT **postprocessing** prefers **cold electrons** (**$T_i \sim 100x\ T_e$**) to sufficiently depolarize the image (EHTC+ 2021)
- Radiative, two-temperature GRMHD (e.g. Sadowski+ 2017) solves for electron and ion temperatures self consistently with subgrid heating & cooling physics
- 2T sims prefers more modest temperature ratios (Chael 2025)
  - **M87 images are too polarized!**
- Do we need to modify:
  - Plasma *microphysics* (electron heating: e.g. Zhdankin+ 2018, Rowan+ 2019, Kawazura+ 2020)
  - *Macroscale* feeding/initial conditions (e.g. Wong+ in prep)

see also: Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019, 2025**
Dexter+ 2020,2021, Mizuno+ 2021