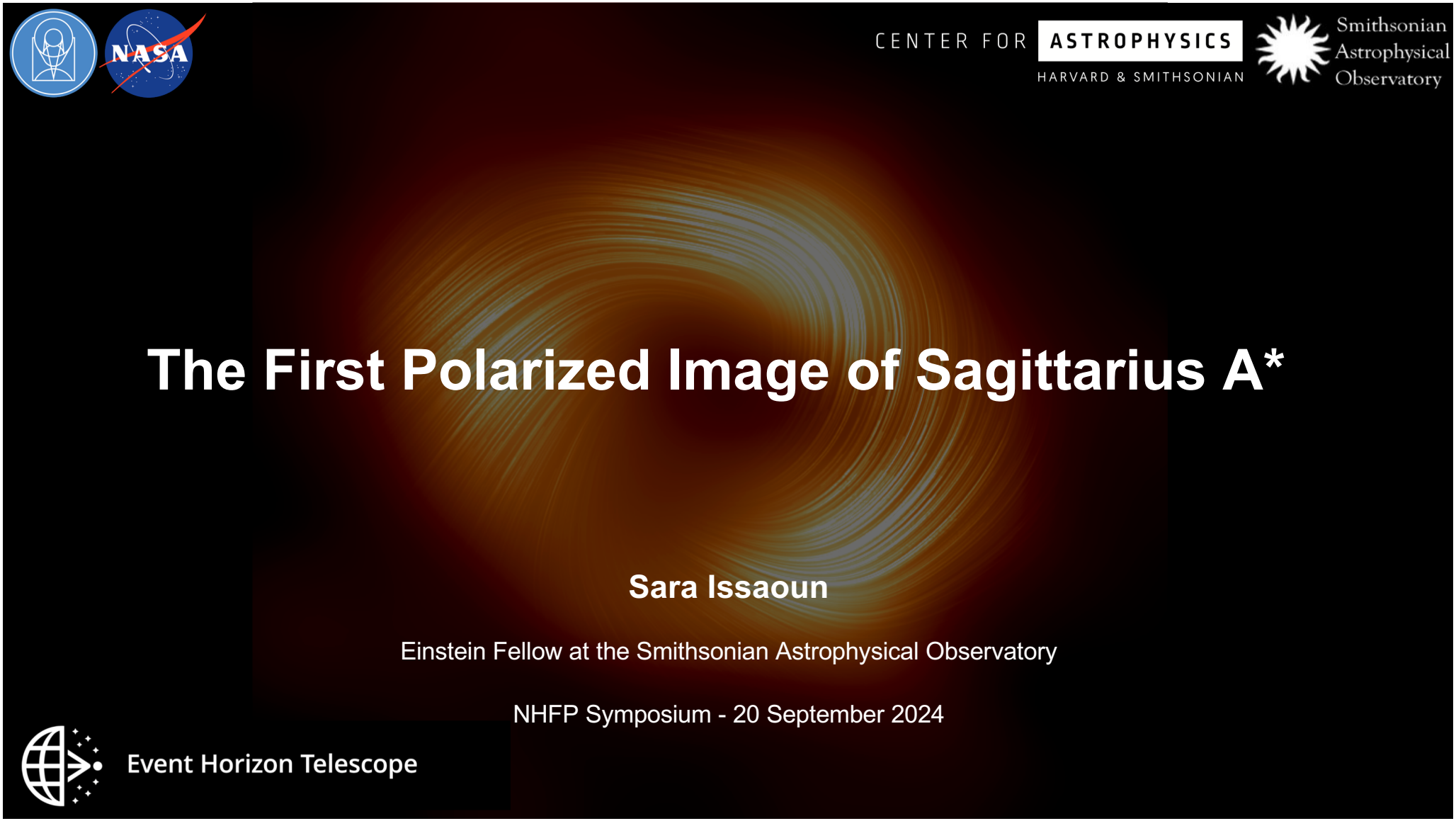


CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Smithsonian Astrophysical Observatory

The First Polarized Image of Sagittarius A*

Sara Issaoun

Einstein Fellow at the Smithsonian Astrophysical Observatory

NHFP Symposium - 20 September 2024

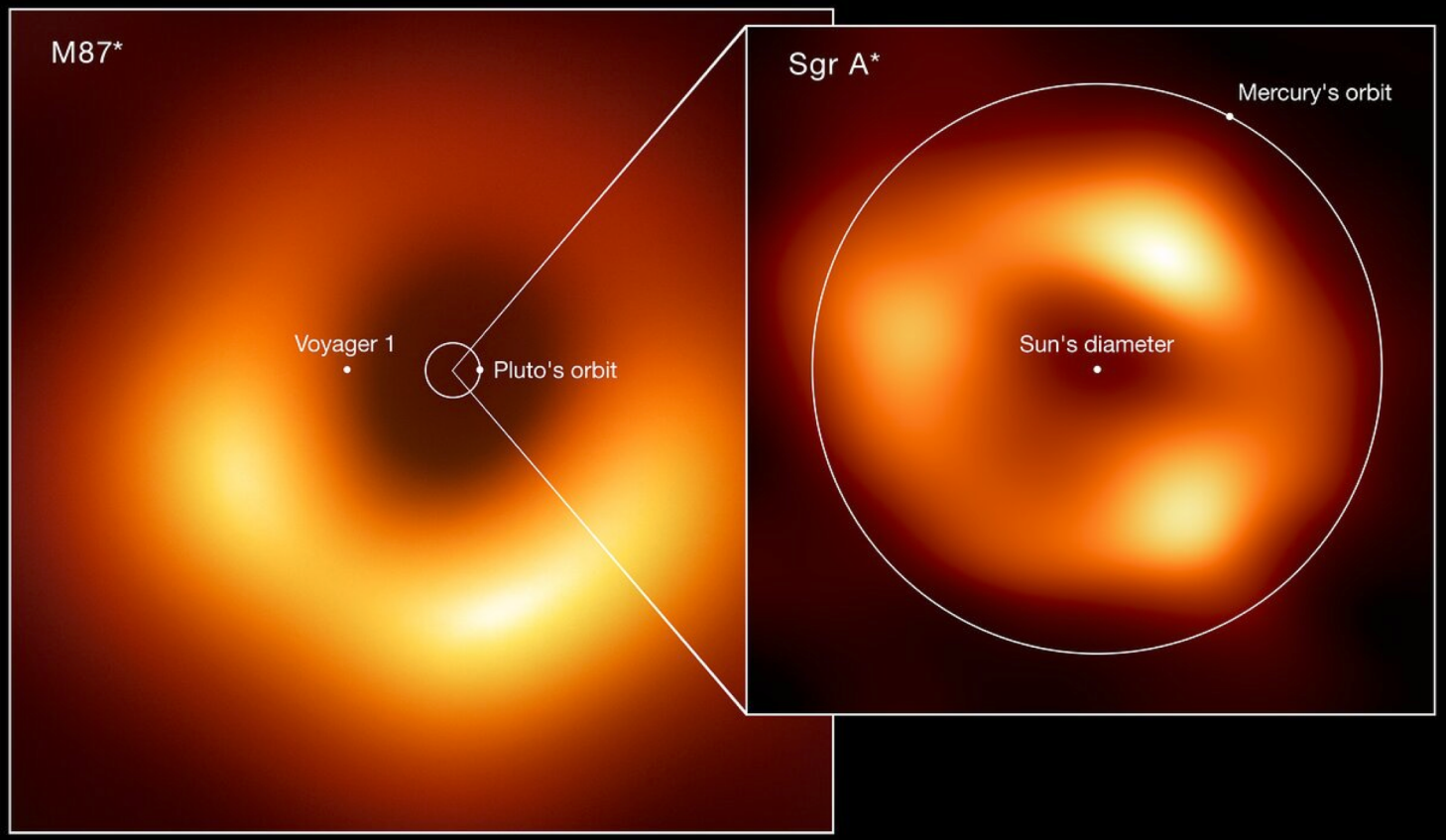
Event Horizon Telescope

A Tale of Two Black Holes

55 million light-years away from us
6.5 billion solar masses

27 thousand light-years away from us
4 million solar masses

A Tale of Two Black Holes

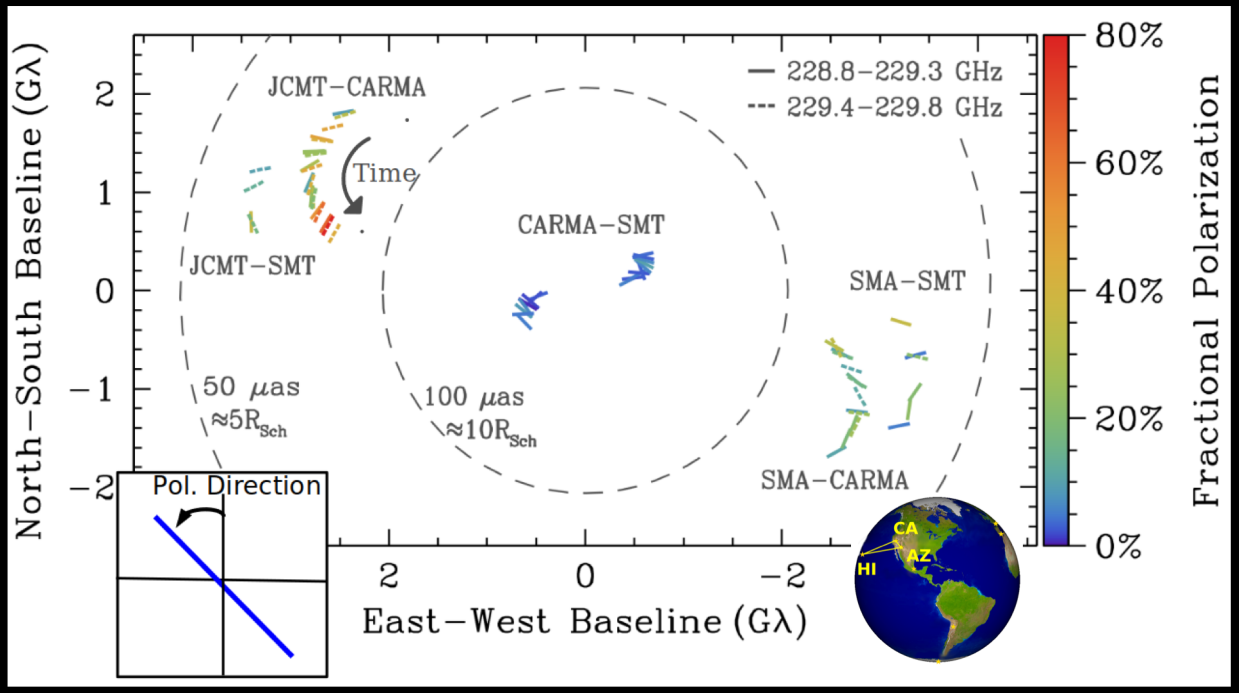


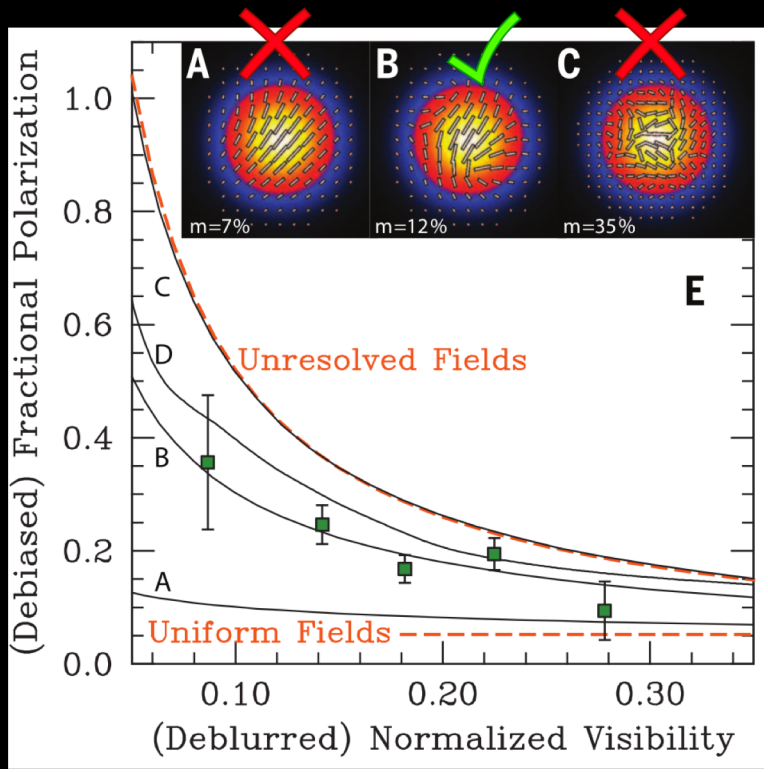
Visualization by L. Medeiros, IAS/ xkcd

The Polarization of Sgr A*: Historical Context

Proto-EHT results (2013) are the only observations that resolve the polarization of Sgr A* at any wavelength!

- Strong polarization on long baselines (>100% interferometric fractional polarization)
- Asymmetric polarization implies spatial changes in the polarization direction





The Polarization of Sgr A*: Historical Context

Polarimetric observations have provided some of the most significant breakthroughs for studies of Sgr A* over the past few decades:

- Decisive in establishing Sgr A* as an extremely underfed black hole
- Best window into the variability of Sgr A*
- Multiple lines of evidence for persistent, partially ordered magnetic fields near Sgr A*

Unlike M87*, there are almost no previous polarimetric measurements of Sgr A* using VLBI!

EHT 2017 Sgr A* Campaign

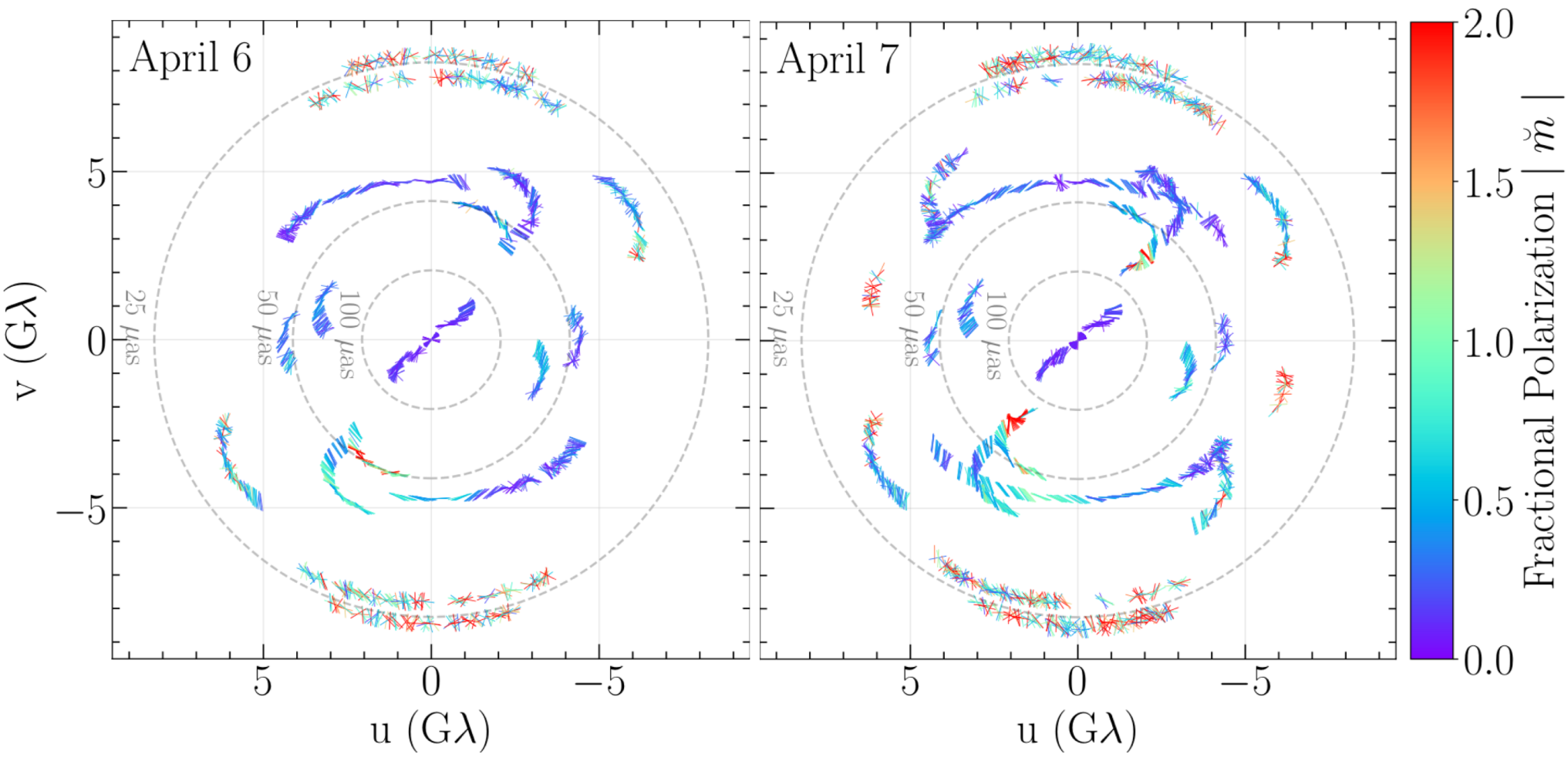
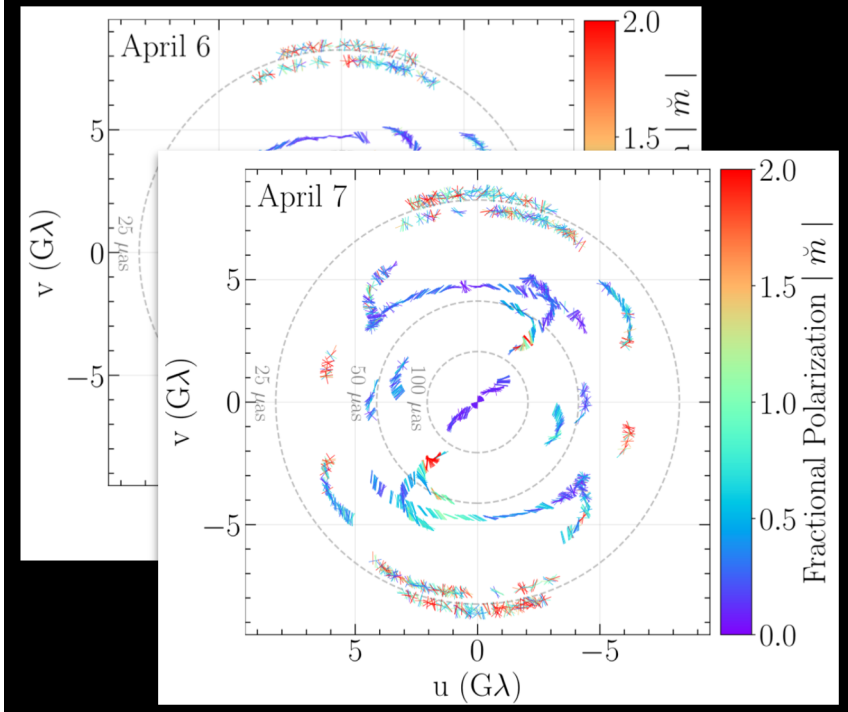


Image Reconstruction Methods: Diversity and Redundancy

$$I(\mathbf{x}) \propto \iint e^{2\pi i \mathbf{u}\cdot\mathbf{x}} V(\mathbf{u})\, d^2u$$



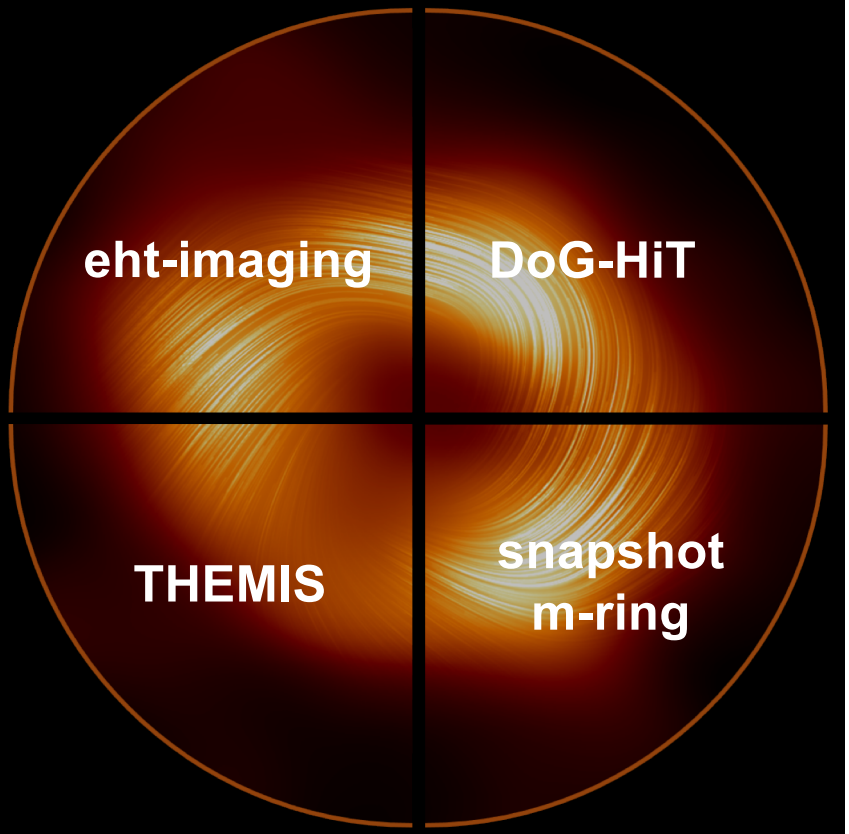


Image Reconstruction Methods: Diversity and Redundancy

eht-imaging	Pixel basis	Stokes I self-cal'd $(\mathrm{CP}, \mathrm{CA}, \lvert\mathrm{V}\rvert)$	Stokes Q,U $(RL^*, \breve{m})$	Stokes V $(RR^* - LL^*)$	Pre-marg. variability	RML+survey
DoG-HiT	Wavelet basis	Stokes I self-cal'd $(\mathrm{CP}, \mathrm{CA})$	Stokes Q,U D-term fit (RL^*)	Stokes V $(RR^* - LL^*)$	Post-marg. variability	RML+survey
THEMIS	Splined raster basis	Stokes I,Q,U,V self-cal'd, D-term fit (RR^*, LL^*, RL^*, LR^*)			Pre-marg. variability	Posterior exploration
snapshot m-ring	m-ring model	Stokes I,Q,U,V $(\mathrm{CP}, \mathrm{CA}, \breve{m})$			Post-marg. variability	Posterior exploration

Image Reconstruction Methods: Diversity and Redundancy

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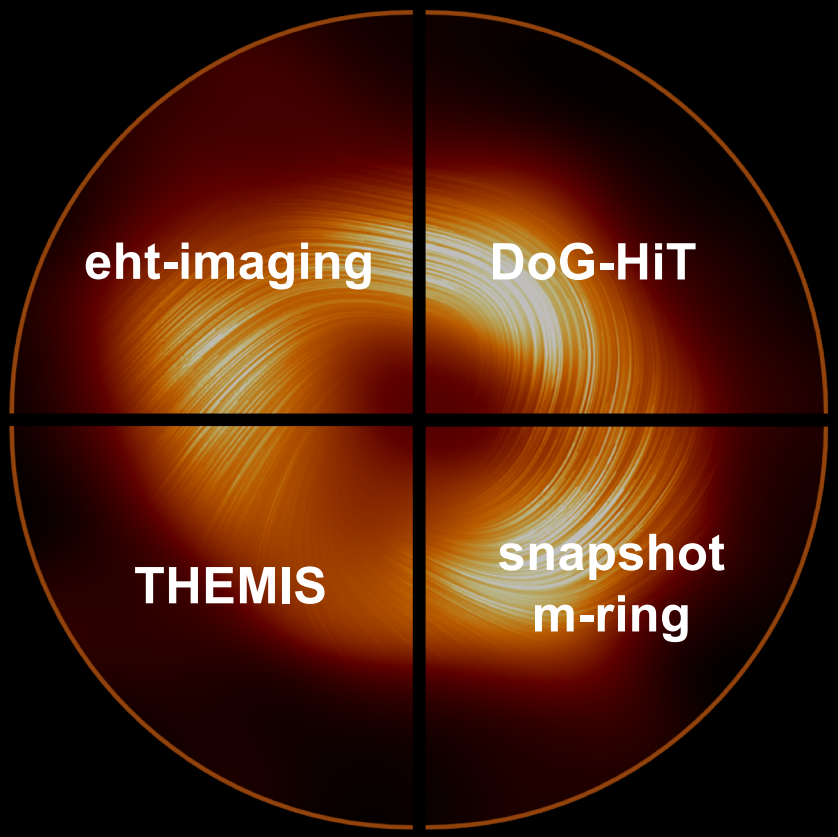
Image Reconstruction Methods: Diversity and Redundancy



Many methods with:

- Different assumptions about the image
- Different data products
- Different variability mitigation
- Different image products

Wherein they agree:

Signals on the sky,
not artifacts of the analysis.

Understanding our images

Data calibration

Step 1

Blind imaging in independent teams

Step 2

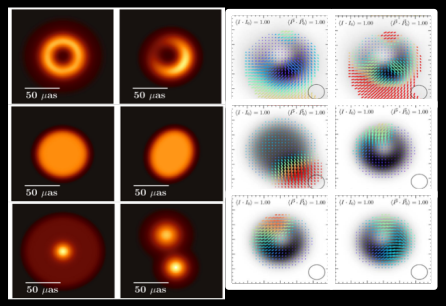
Pipeline building per independent software

Step 3

Image validation

Feedback on data quality

Synthetic Models

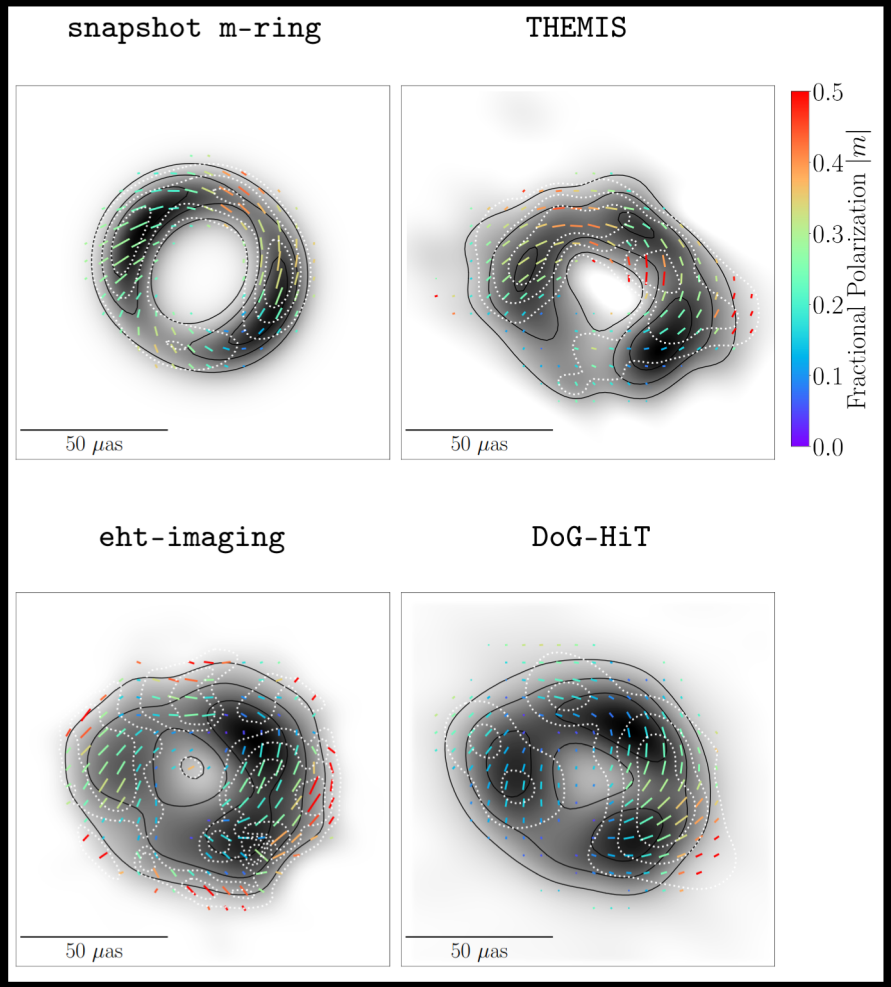


Goodness of fit to data

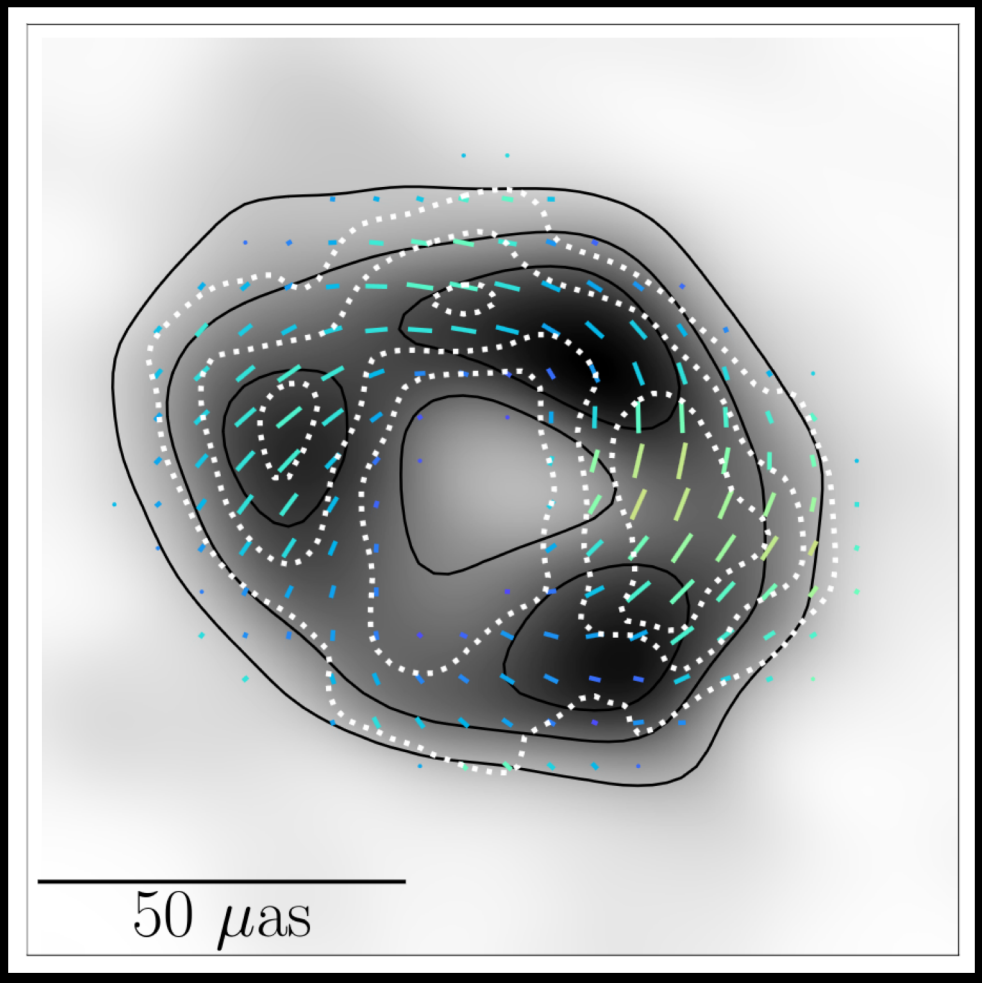
Consistency with calibrator analysis

Structure robustness

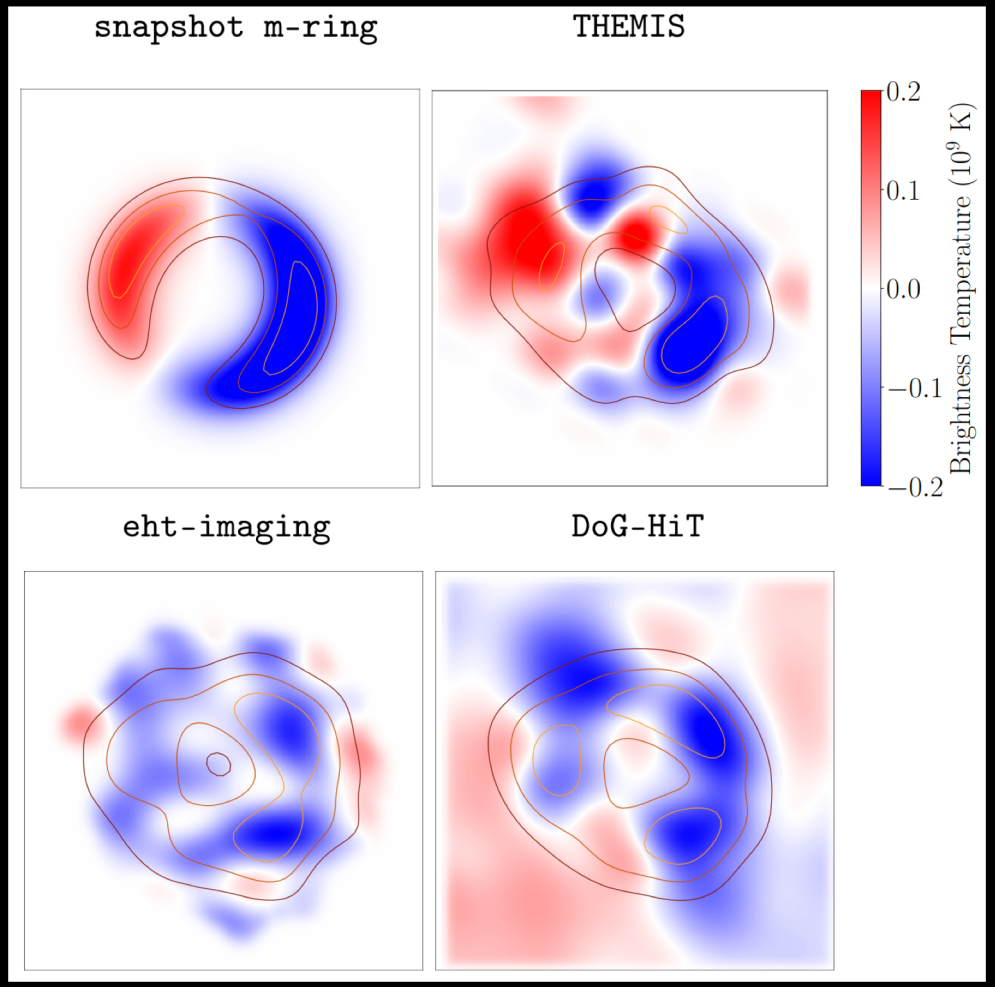
Real Data: Linear Polarization Images



Method-average



Real Data: Circular Polarization Images



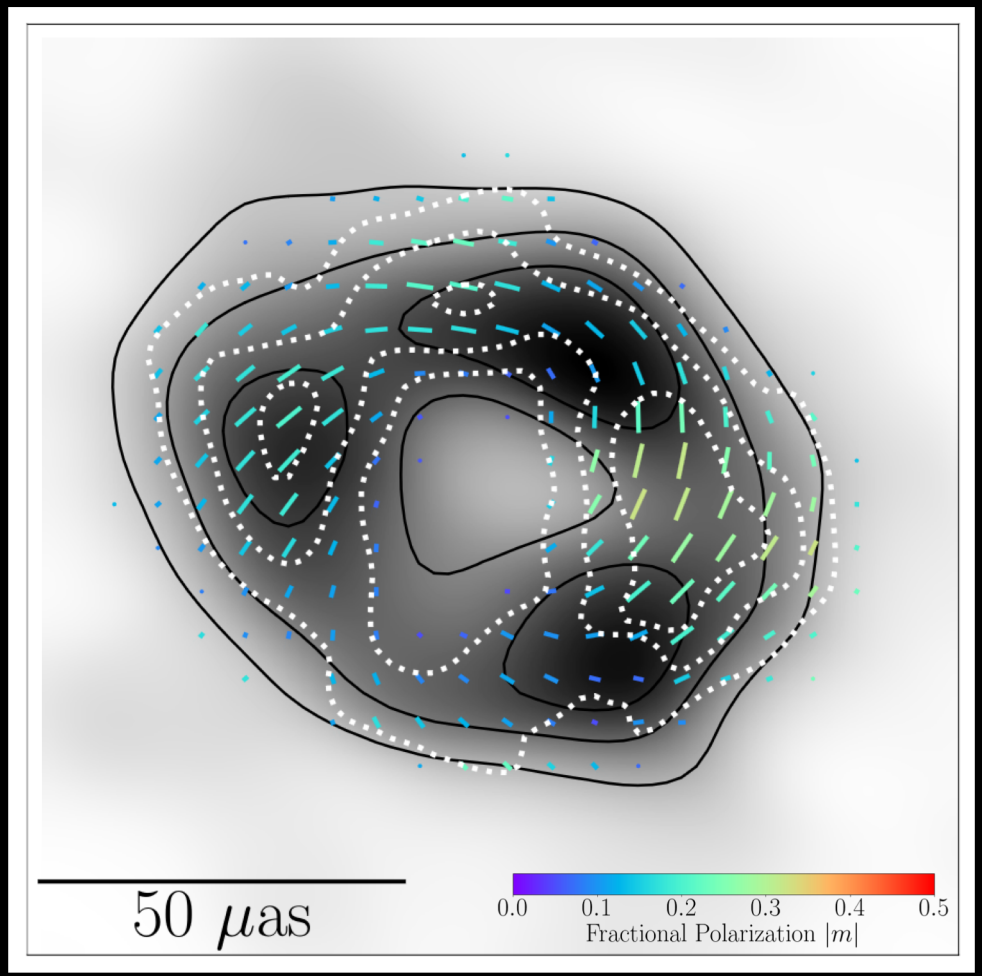
All methods reconstruct negative circular polarization on the West side of the emission ring

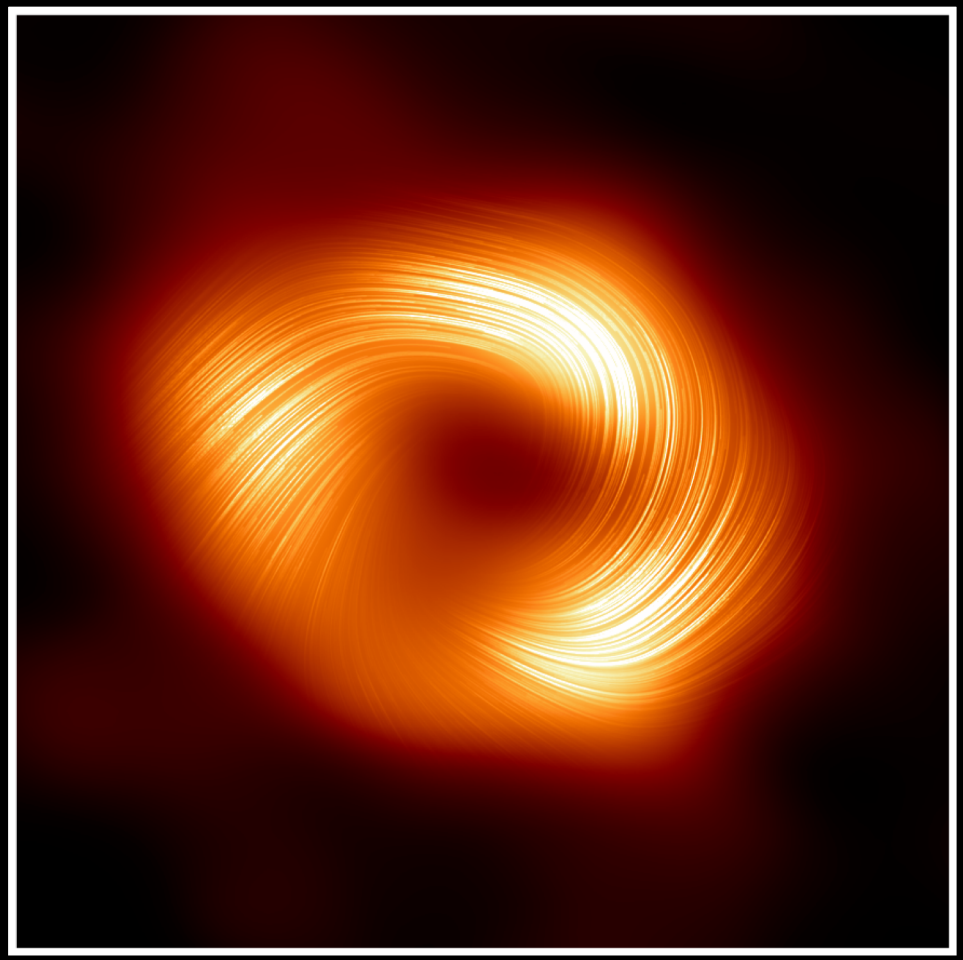
Both THEMIS and m-ring modeling find an East-West dipole structure

Overall preference for simple circular polarization structures

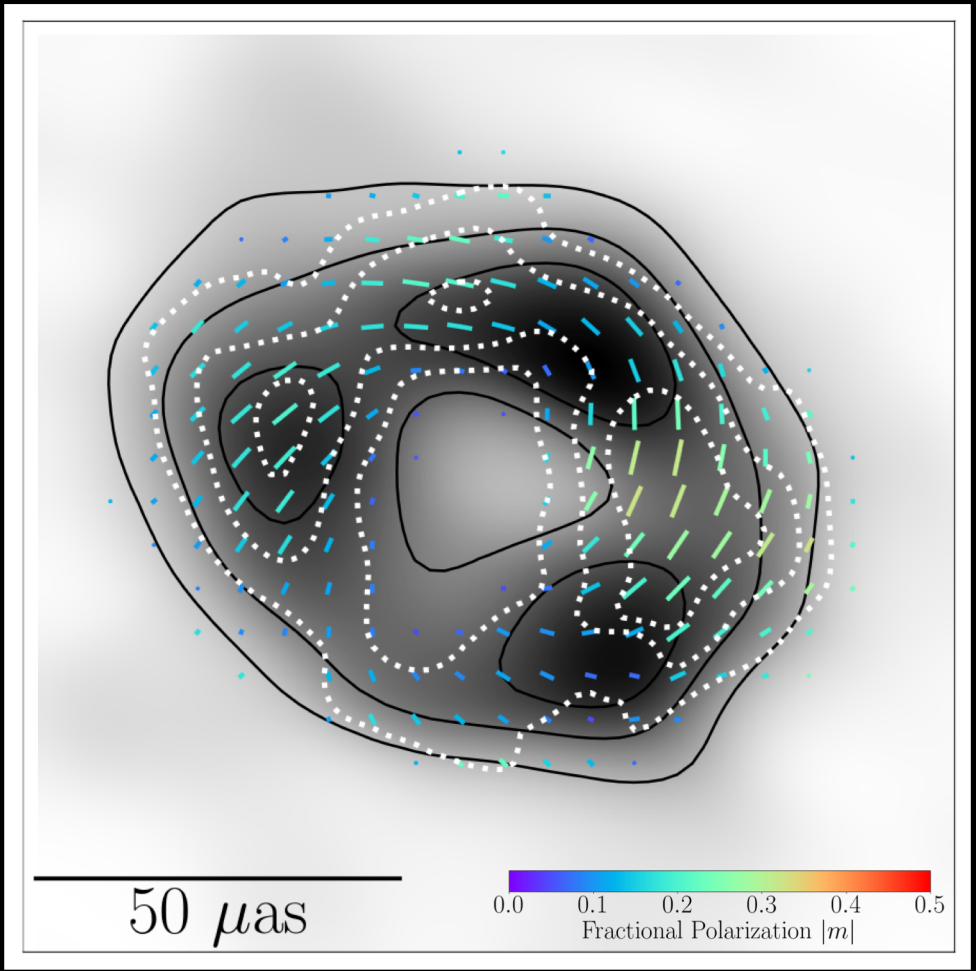
The circular polarization structure is more uncertain than the linear polarization structure

This is Sagittarius A*!



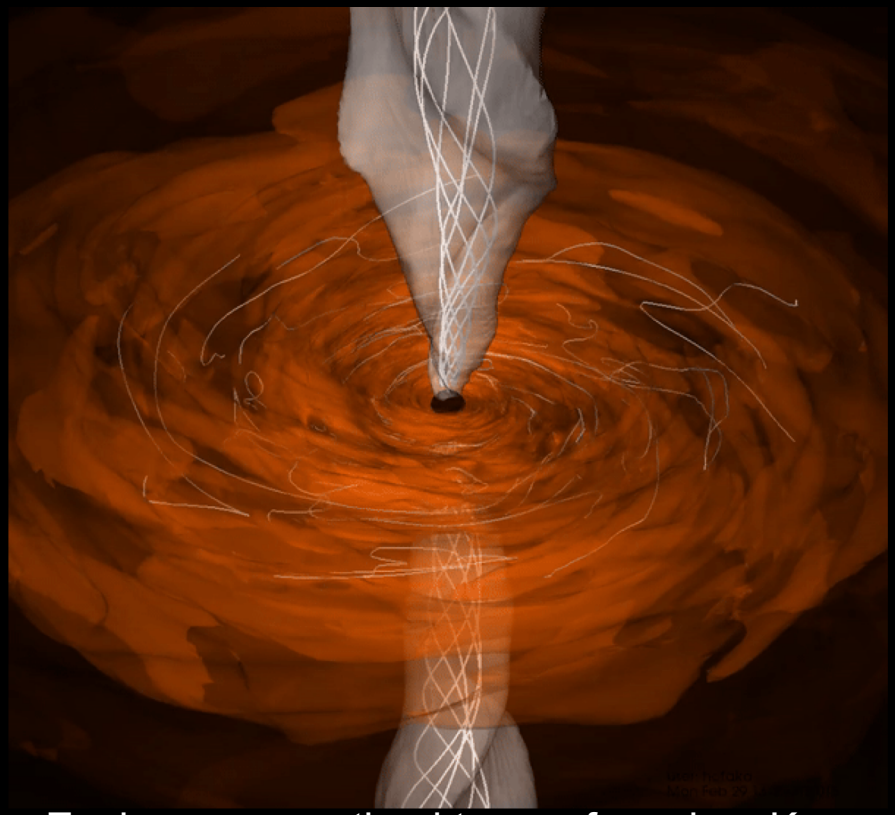


What are we looking at?



- Very low accretion rate implies puffy hot accretion flow.
- **Synchrotron radiation**: intrinsically polarized, tracing magnetic field
- Non-polarized image already preferred models that were (i) non-zero spin, (ii) relatively face-on, and (iii) strongly magnetized (EHTC et al. 2022a-f).
- **New**: large polarization fraction with rotational symmetry.

General Relativistic Magnetohydrodynamics (GRMHD)

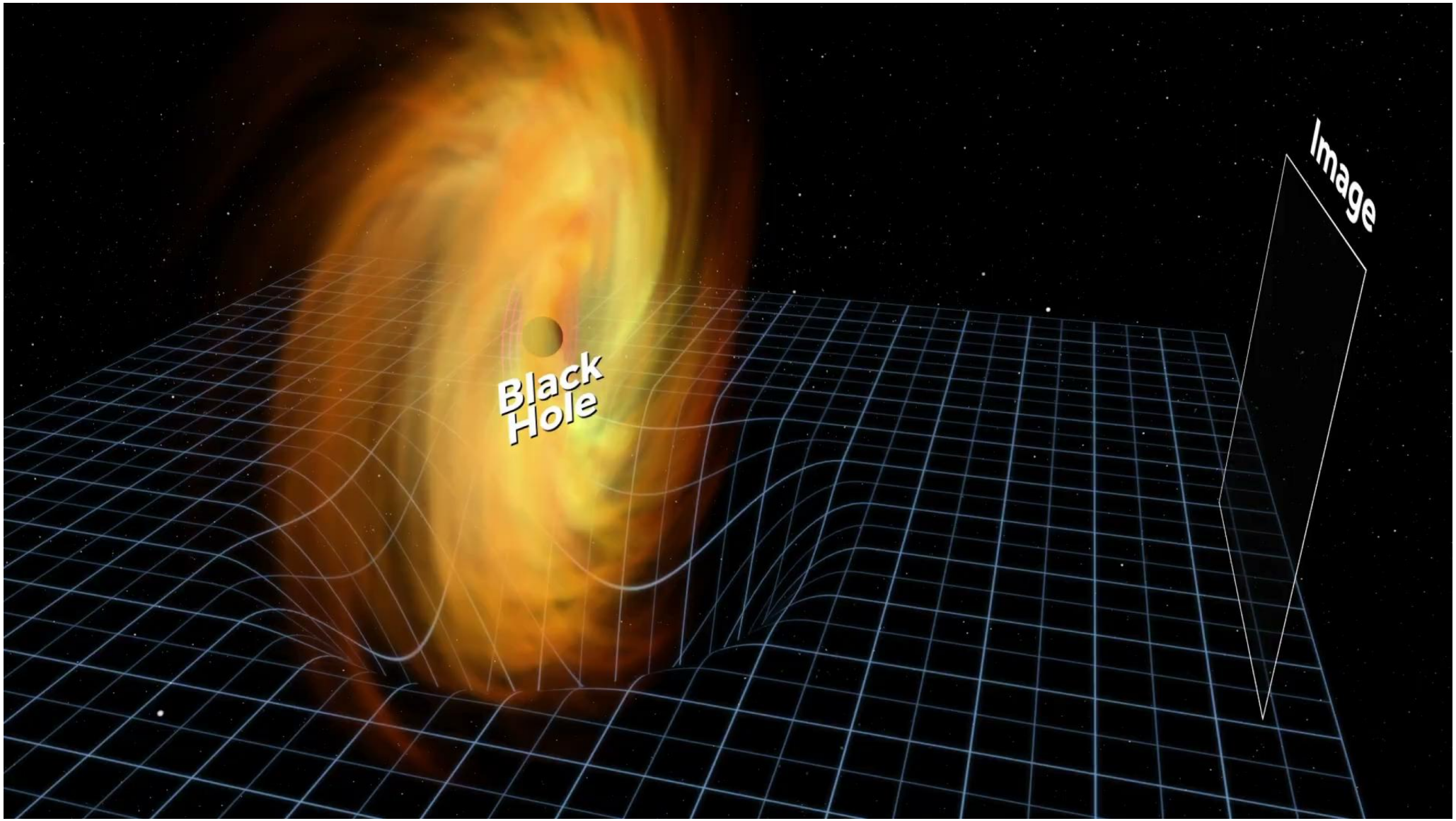


Evolve a magnetized torus of gas in a Kerr spacetime of a given spin.

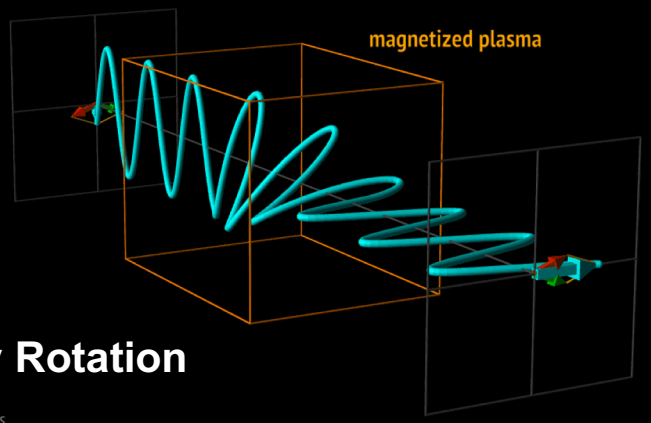
General Relativistic Ray Tracing (GRRT)

Solve null geodesic equation for trajectories, then do polarized radiative transfer.

Movies: Hotaka Shiokawa

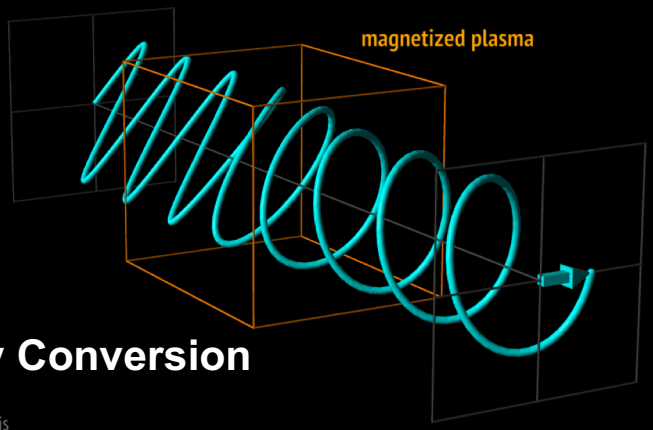

Black Hole
Image

Additional plasma effects?



Faraday Rotation

created by Ioannis Myserlis
using EMANIM (https://emanim.szialab.org/)



Faraday Conversion

created by Ioannis Myserlis
using EMANIM (https://emanim.szialab.org/)

As polarized emission travels through a magnetized plasma, it is modified by **Faraday effects**.

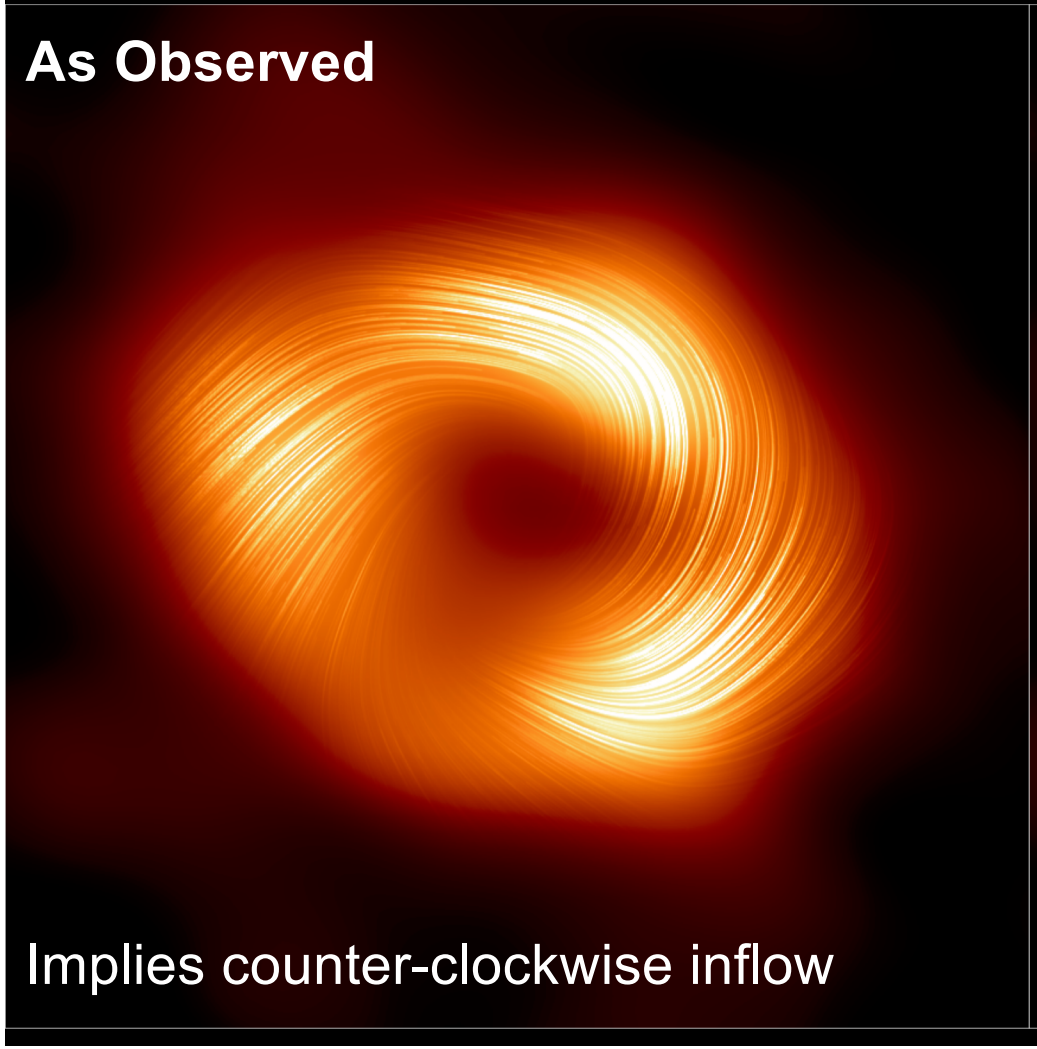
To “undo” Faraday rotation by an external screen and “derotate,” astronomers compute the **rotation measure (RM)**.

$$\mathrm{RM} = \frac{\Delta \mathrm{EVPA}}{\Delta \lambda^2}$$

For Sgr A*, we observed an RM corresponding to a 46 degree rotation (Wielgus et al. 2023). However, we’re not sure if this really corresponds to an external screen to be removed.

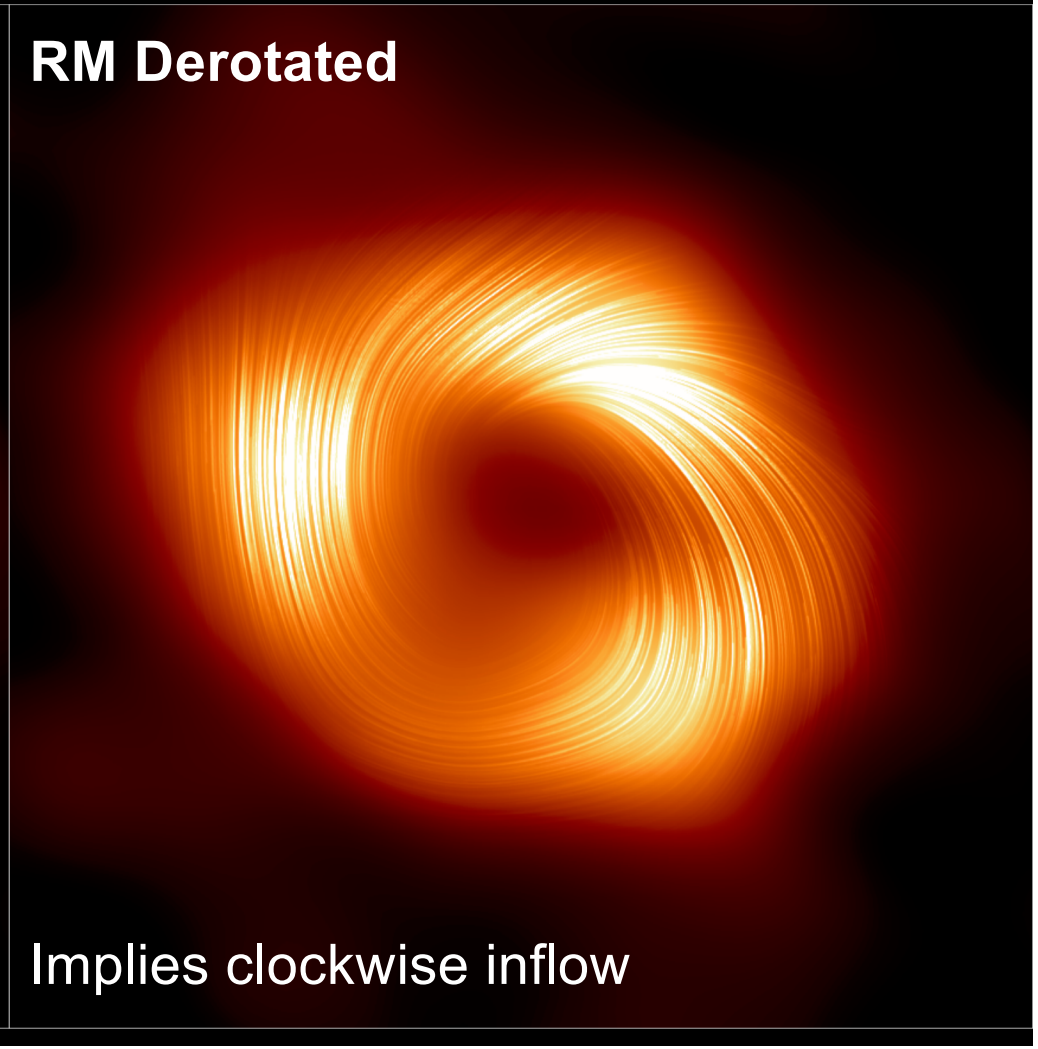
Which should we compare with the simulations?

As Observed



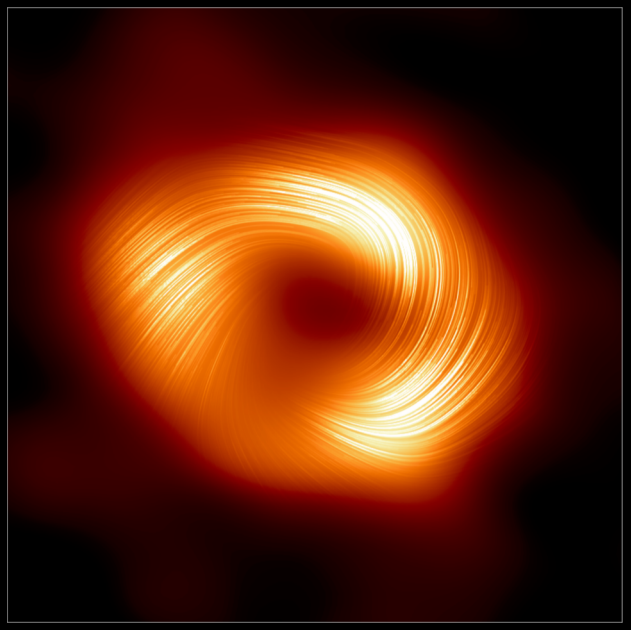
Implies counter-clockwise inflow

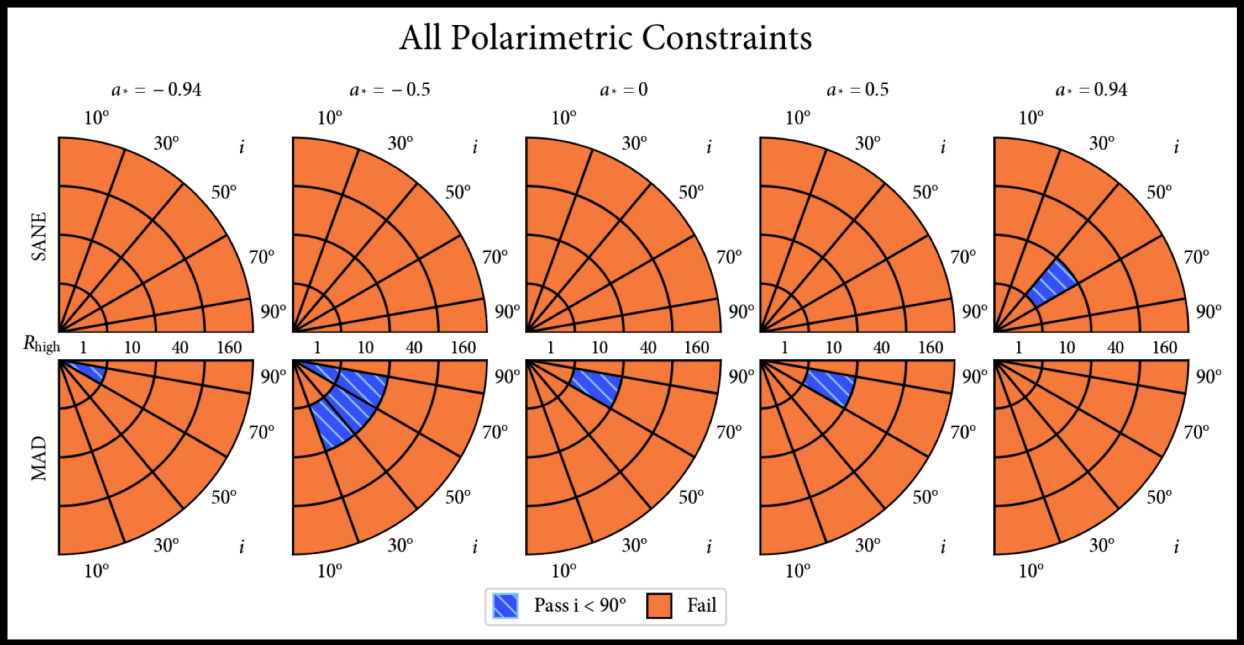
RM Derotated



Implies clockwise inflow

Combined Constraints: Without derotation



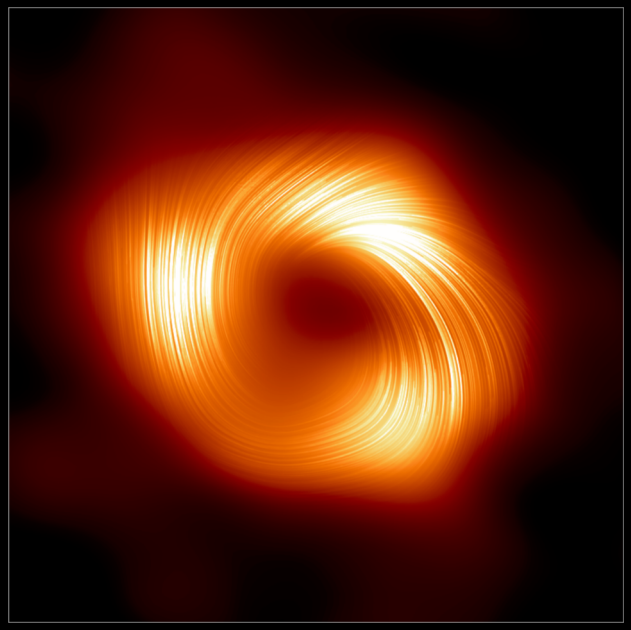


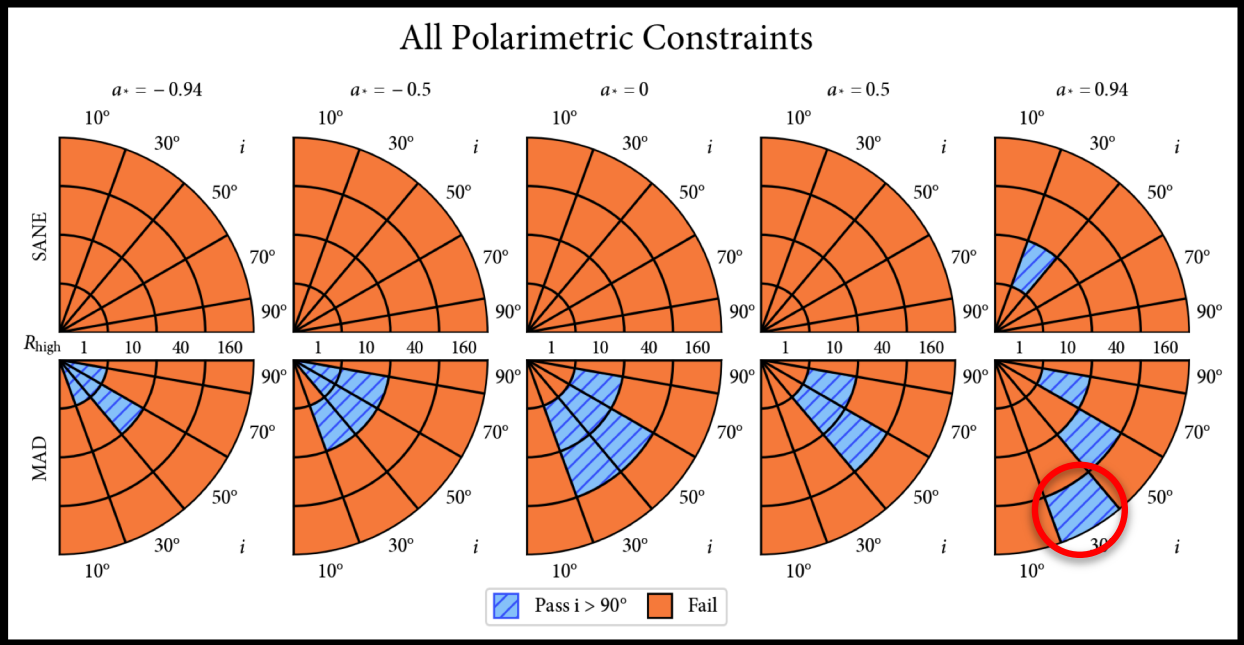
Preferred models are:

- Moderate inclination
- Rotating **counterclockwise**
- Mostly MAD

- **Inconsistent** with total intensity constraints

Combined Constraints: With derotation





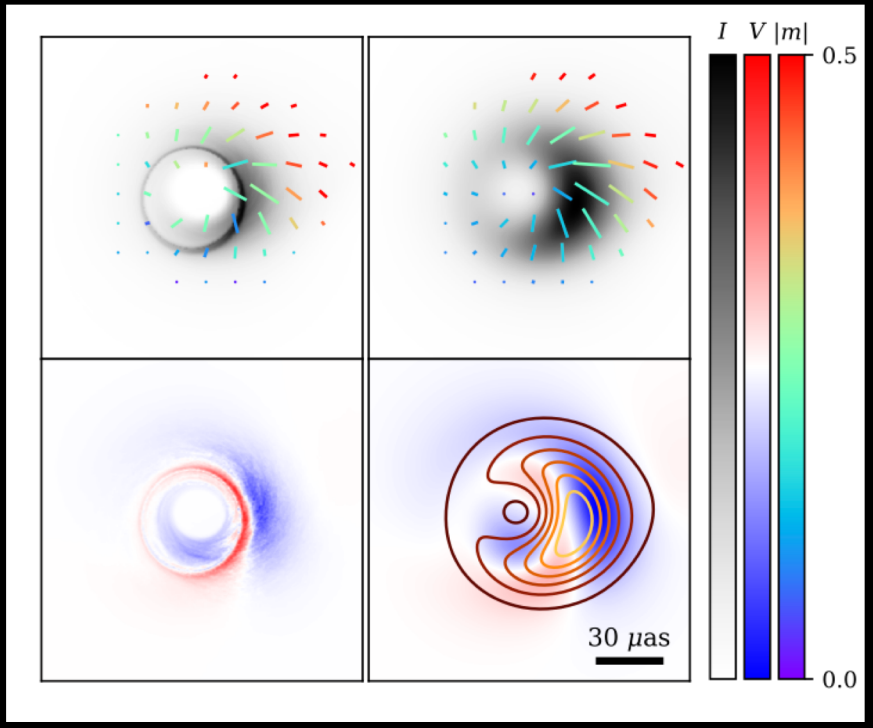
Preferred models are:

- Moderate inclination
- Rotating **clockwise**
- Mostly MAD

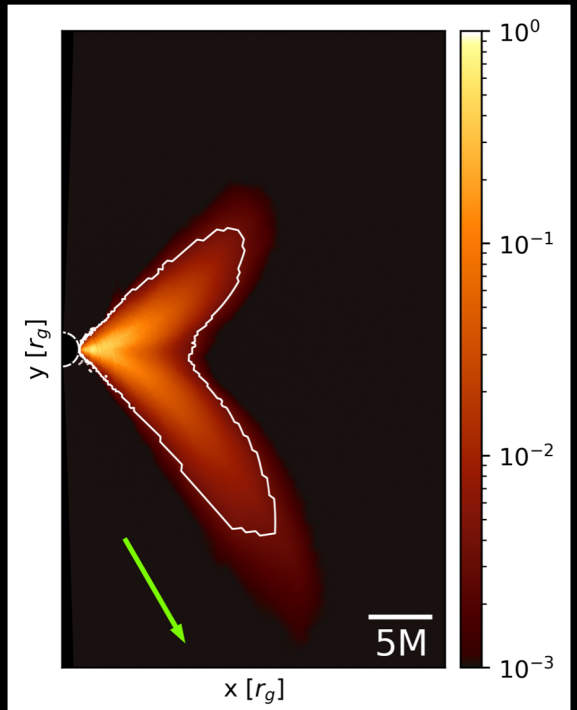
- **Consistent** with total intensity constraints

The Best-Bet Model

Time-averaged Images

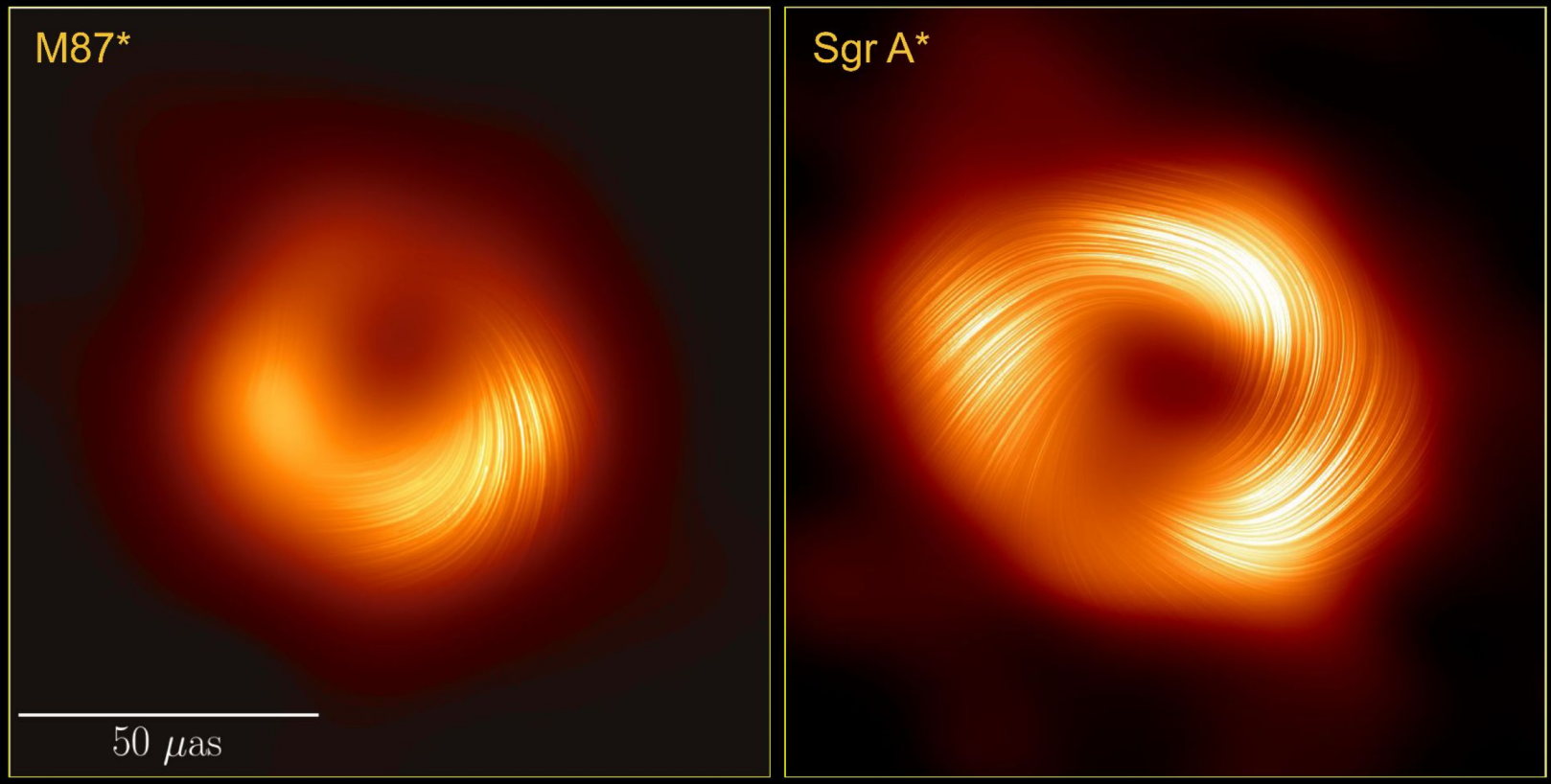


Emission Density

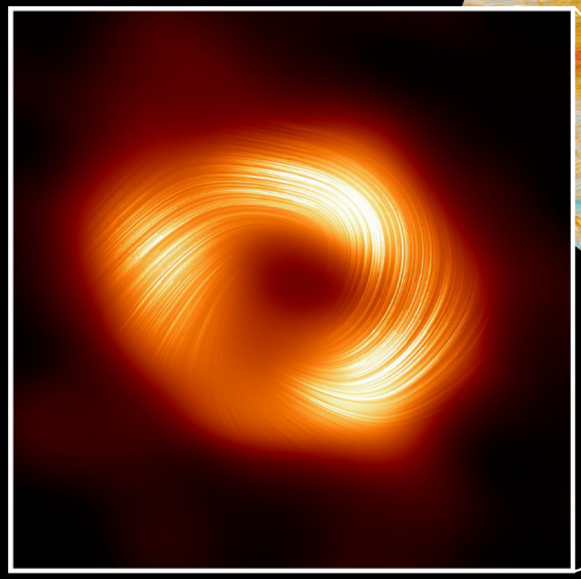


- Magnetically Arrested Disk (MAD), just like M87*. Is this universal?
- Jet is 150% efficient due to spin extraction.
- Significant emission from jet sheath.

A Tale of Two Black Holes.. in Polarization!



A polarized Milky Way

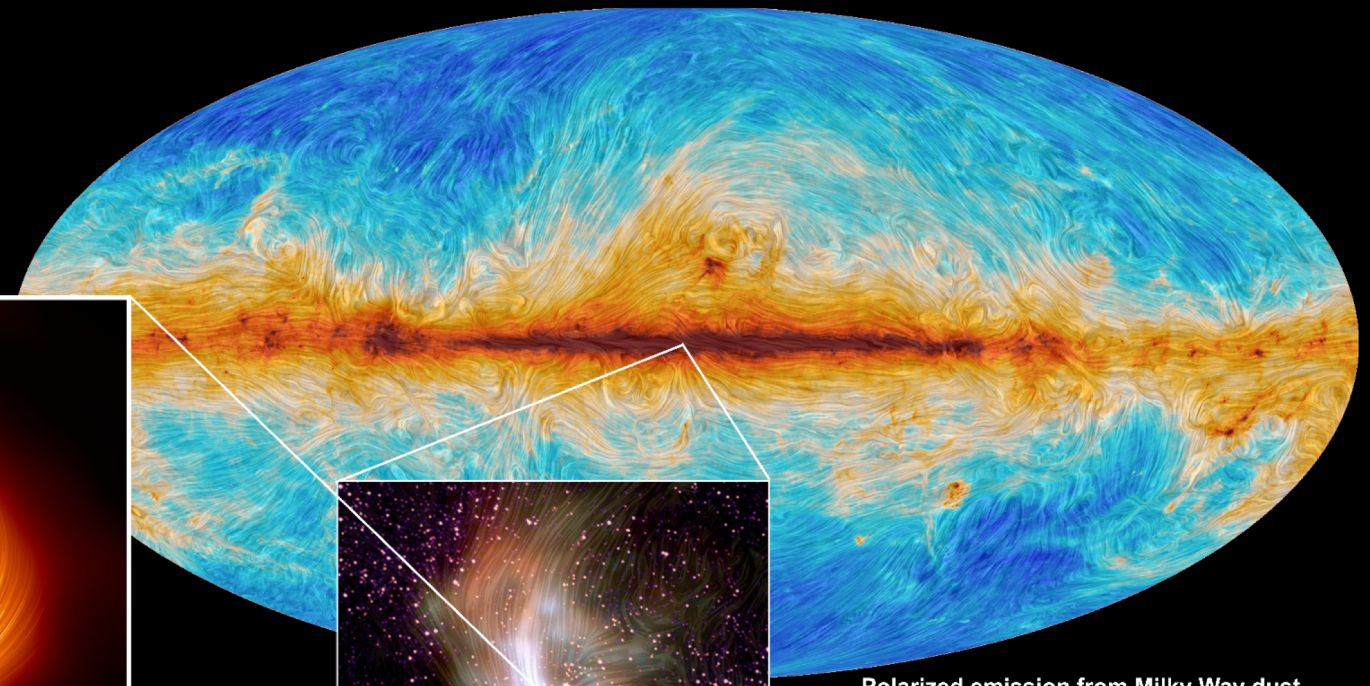


Polarized emission from plasma around our Milky Way supermassive black hole Sagittarius A*

Cr. Event Horizon Telescope Collaboration

Polarized emission from dust at the center of our Milky Way

Cr. NASA/SOFIA, NASA/Hubble Space Telescope/NICMOS.



Polarized emission from Milky Way dust

Cr. ESA and the Planck Collaboration