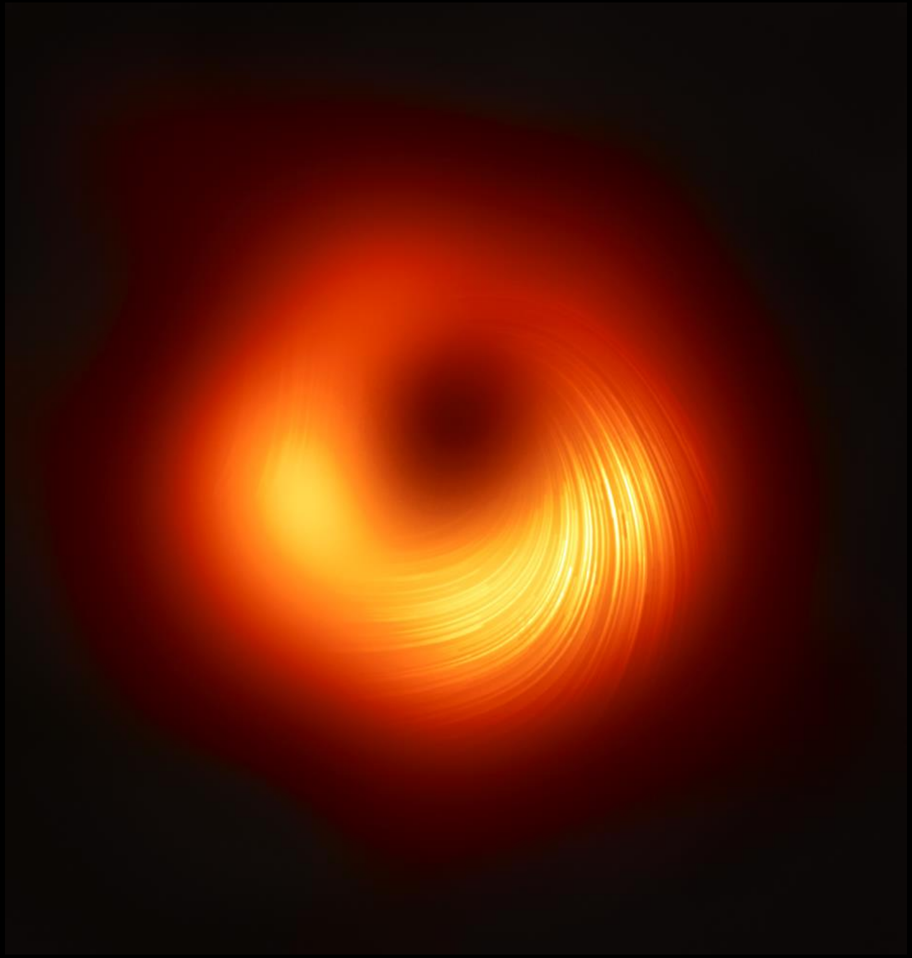
Horizon-scale polarization and magnetic fields in M87* from the EHT



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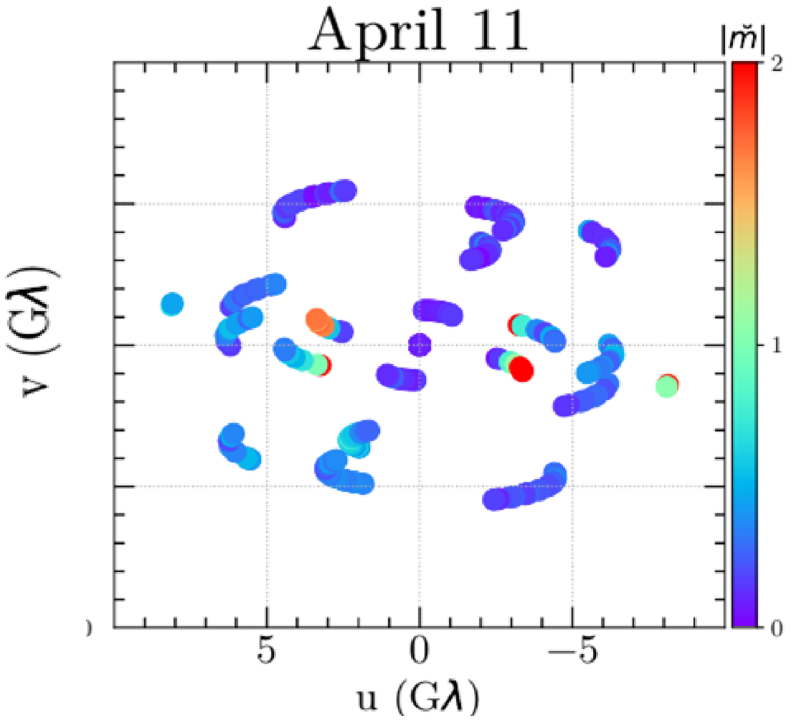
March 30, 2021

NHFP
NASA Hubble Fellowship Program
PRINCETON UNIVERSITY
Event Horizon Telescope

The EHT Collaboration

Challenges of EHT polarimetric imaging

u-*v* coverage is **sparse**: inversion of image from the data is highly unconstrained

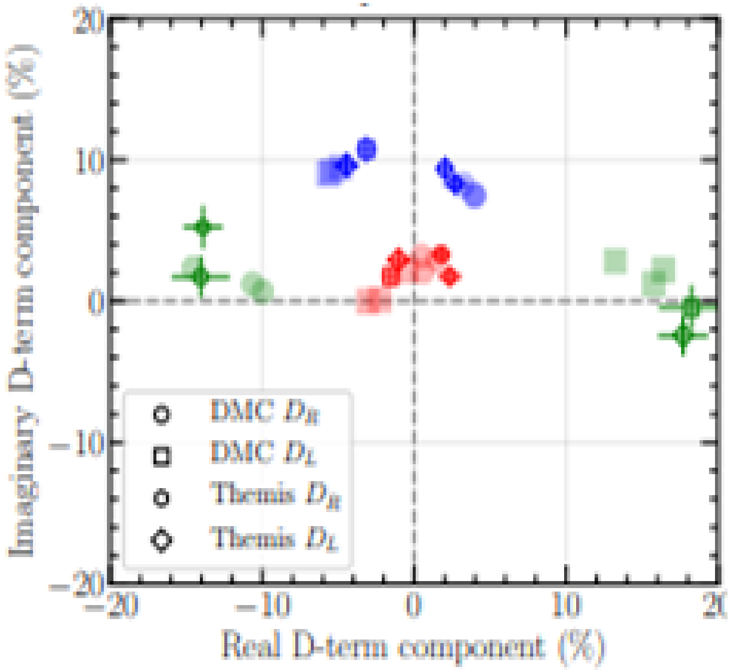


$$\tilde{I}(u,v) = \int I(x,y)e^{-2\pi i(xu+yv)}\,dx\,dy$$

$$\tilde{Q}(u,v) = \int Q(x,y)e^{-2\pi i(xu+yv)}\,dx\,dy$$

$$\tilde{U}(u,v) = \int U(x,y)e^{-2\pi i(xu+yv)}\,dx\,dy$$

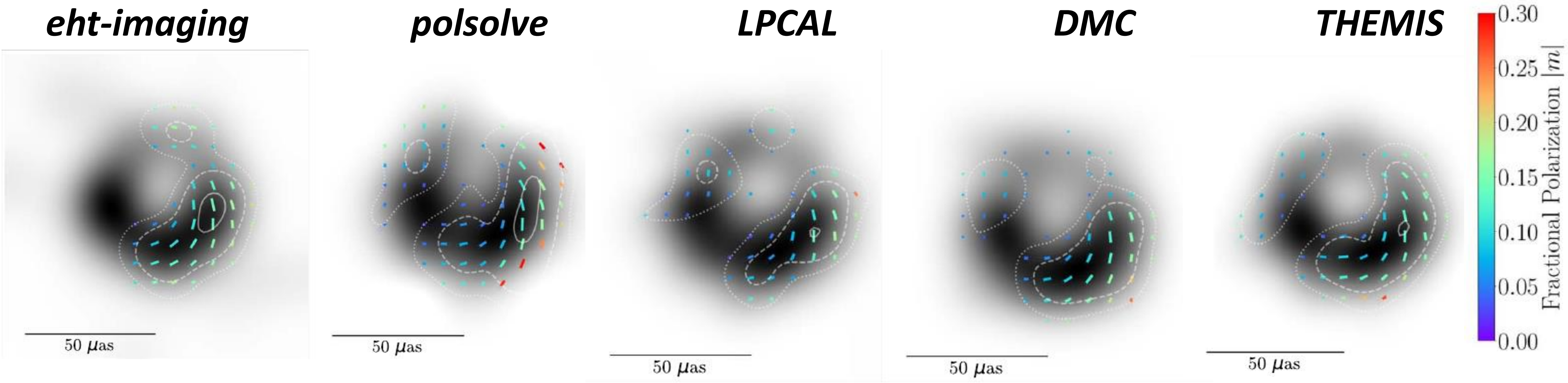
Polarimetric **leakage** (and complex gains) at each station are **unknown**



Need to solve for terms in telescope Jones matrices **at the same time** as the image structure

$$\boldsymbol{J} = \boldsymbol{G}\boldsymbol{D}\Phi = \begin{pmatrix} G_R & 0 \\ 0 & G_L \end{pmatrix}\begin{pmatrix} 1 & D_R \\ D_L & 1 \end{pmatrix}\begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}.$$

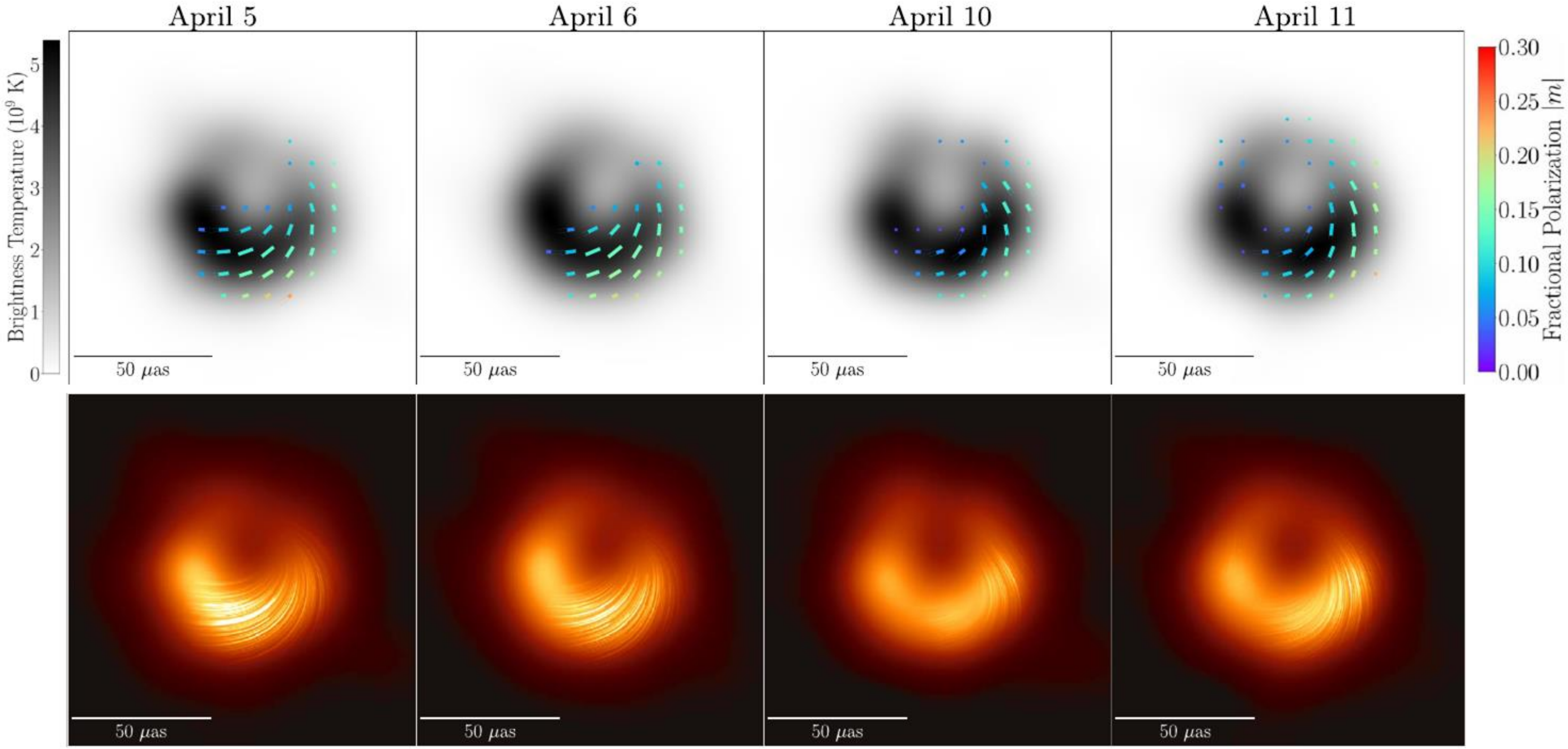
Images for **April 11** from five vetted methods



- Methods include CLEAN-based calibration algorithms (polsolve/LPCAL), gradient descent optimization (eht-imaging), and full Bayseian posterior sampling (DMC/Themis)
- All methods show similar polarization structure
- Polarized in the South-West part
- Overall weak polarization, |m| rises to ~15 %
- Contours: 20, 10, 5 μJy/μas^2

Credit: EHT 2021 Paper VII

Fiducial **Method-Averaged Images**



Credit: EHT 2021 Paper VII

Polarimetric image metrics

Unresolved polarization fraction

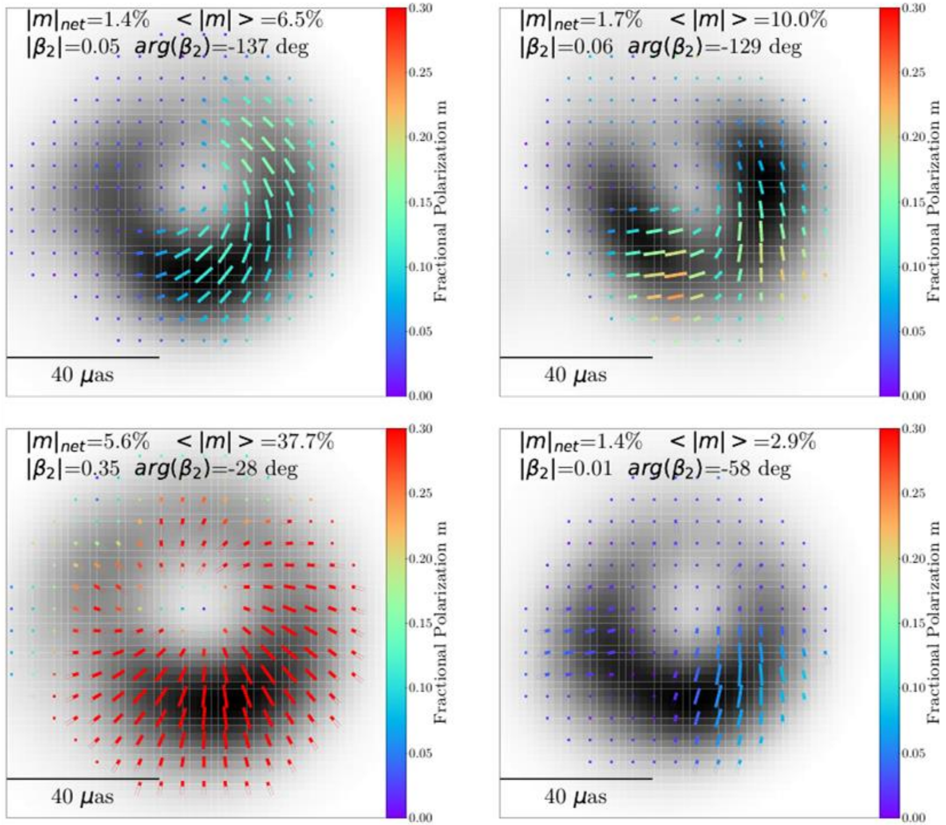
$$|m|_{\rm net} = \frac{\sqrt{(\sum_i Q_i)^2 + (\sum_i U_i)^2}}{\sum_i I_i}$$

Average resolved polarization fraction

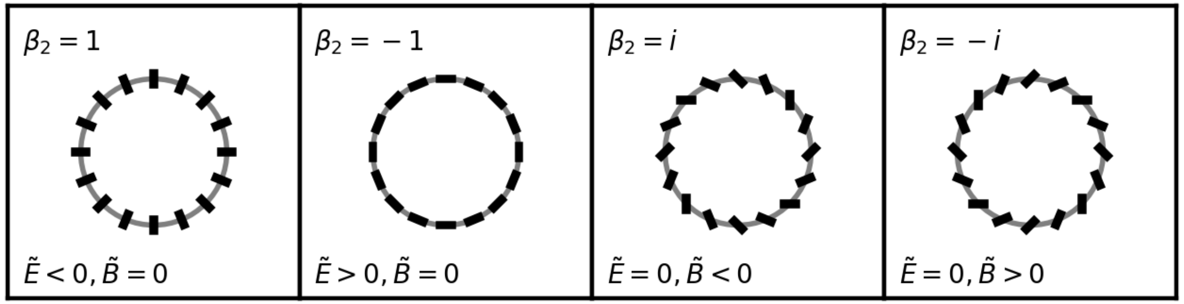
$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Azimuthal structure 2^{nd} Fourier mode

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



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



Palumbo+ 2020, EHTC+2021

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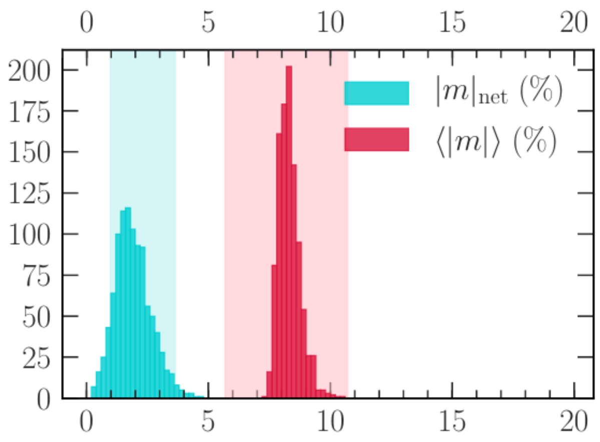
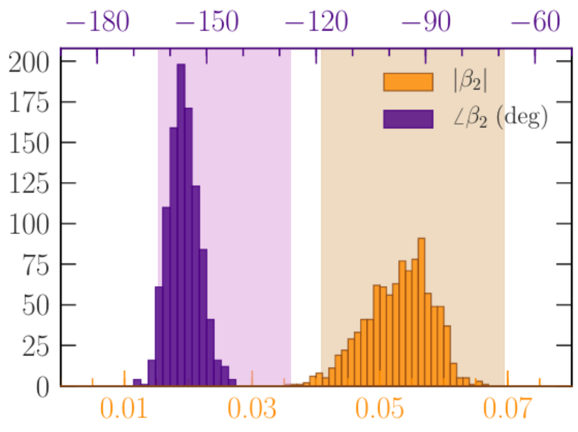




We explore the **distributions** of these metrics for each method sampling different D-term calibration solutions

We define a final **range** for each parameter that accounts for systematic uncertainty among imaging methods

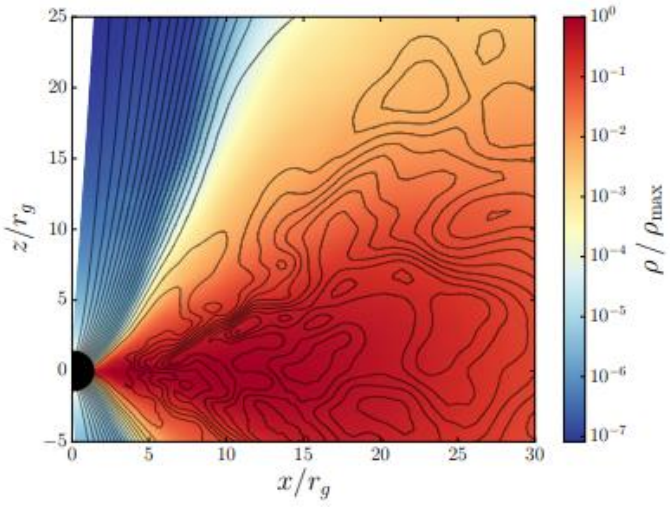
Parameter	Min	Max
$\|m\|_{\rm net}$	1.0%	3.7%
$\langle\|m\|\rangle$	5.7%	10.7%
$\|\beta_2\|$	0.04	0.07
$\angle\beta_2$	− 163°	− 127°

EHTC 2021, Paper VII

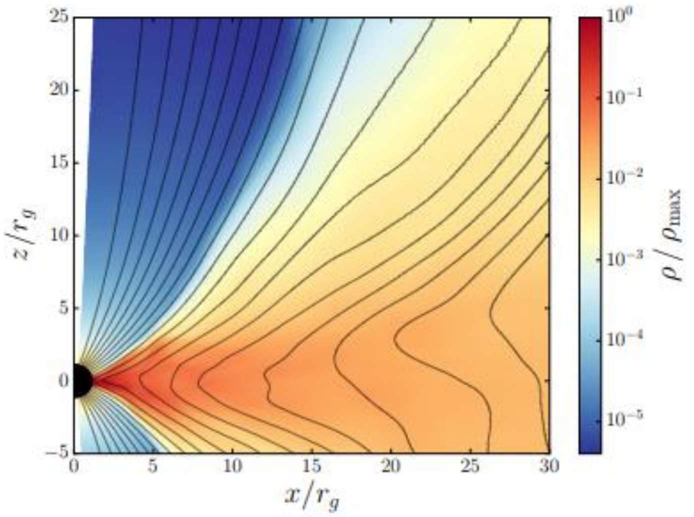
What do the images say about the near-horizon magnetic field structure?

General Relativistic Magnetohydrodynamic (GRMHD) Simulations
show two accretion states that depend on the accumulated magnetic flux on horizon

Magnetic fields are weak and turbulent



“SANE”



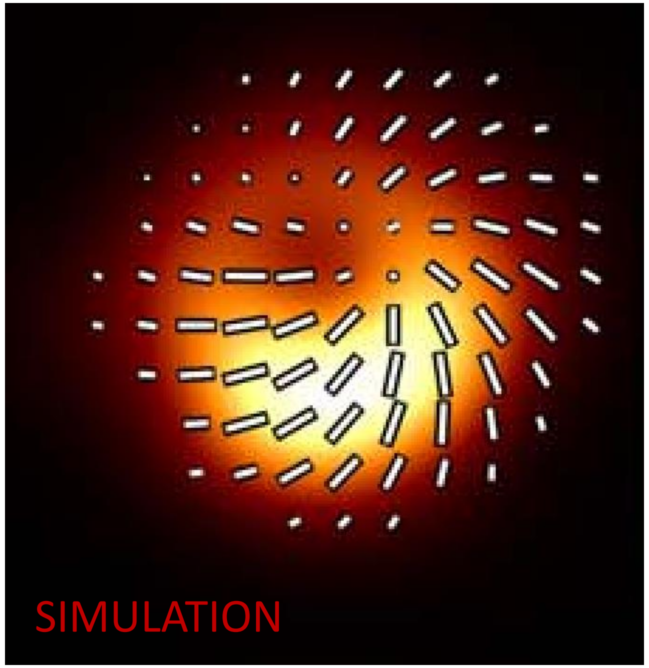
Strong, coherent magnetic fields build up on the horizon

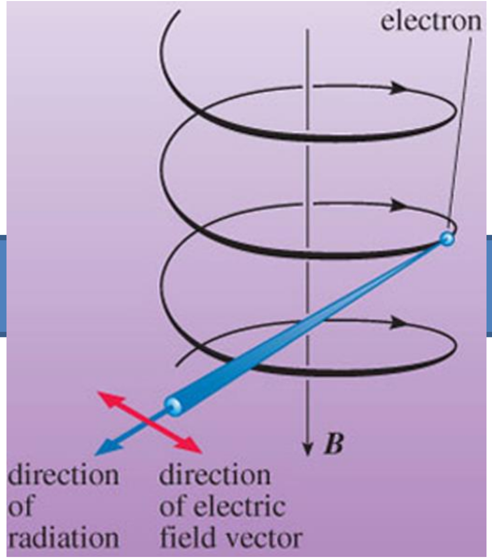
“MAD”
Magnetically Arrested Disk

Note: ‘strong’ fields mean dynamically important ones – still only ~10 G at the horizon for M87

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

Synchrotron polarization traces magnetic fields

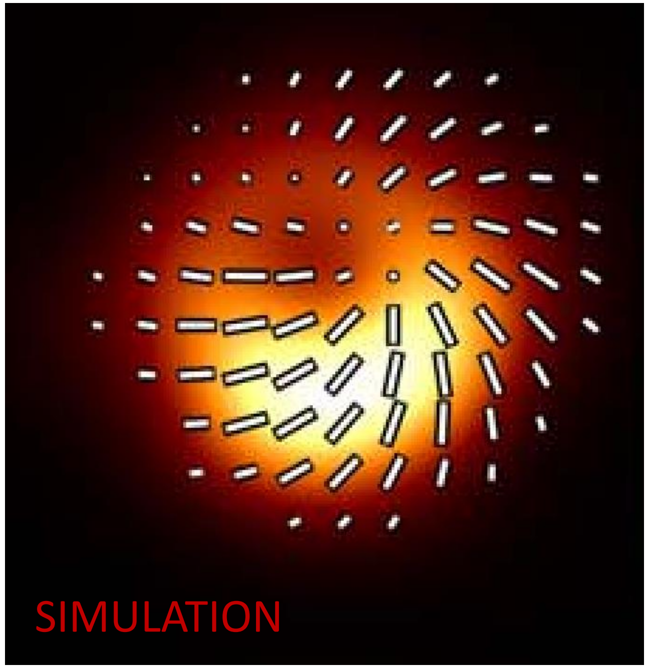


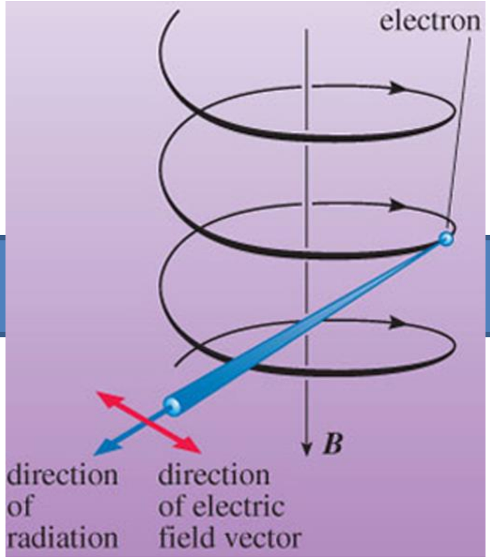


Magnetic field directions in the emission region!

Image credit: EHTC VIII 2021, Open University

Synchrotron polarization traces magnetic fields





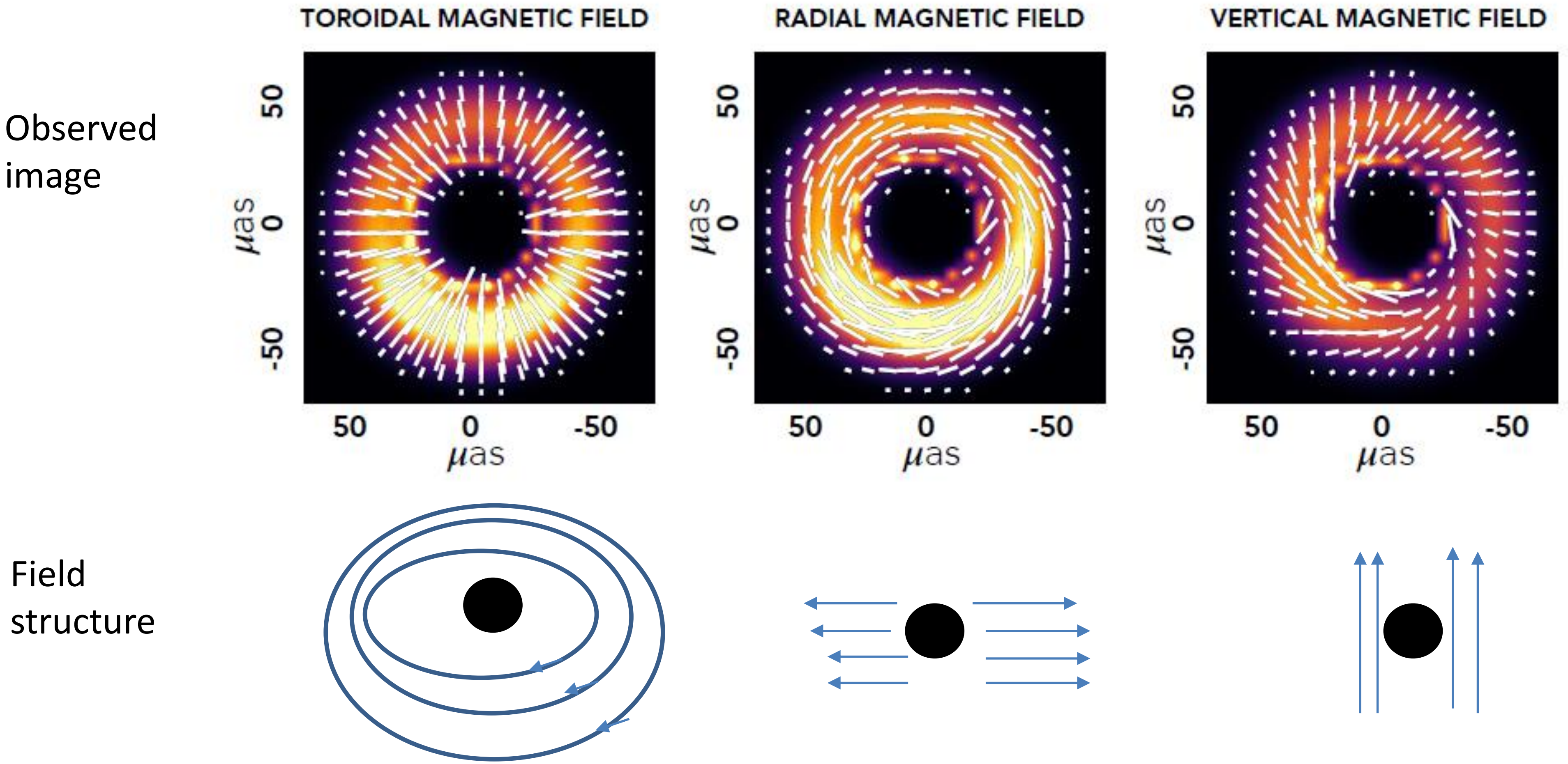
Magnetic field direction in the emission region!

GR and Faraday effects make the situation in M87* much more complicated!

Image credit: EHTC VIII 2021, Open University

Relativity matters!

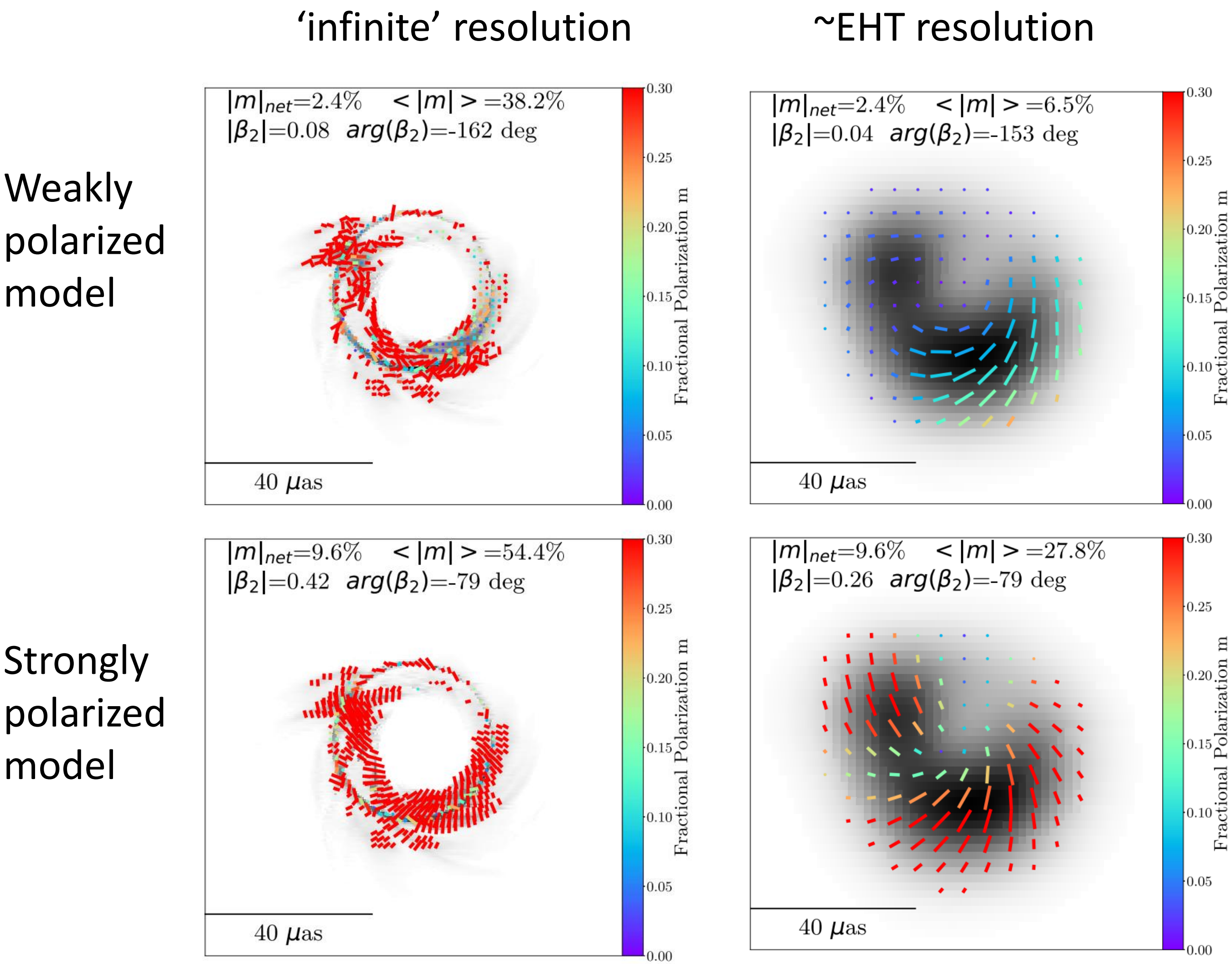
3 simple models, viewed face on



Vertical field scenario would be **unpolarized** without bent photon trajectories!

Credit: EHTC+ VIII 2021
Jiménez-Rosales+ 2018

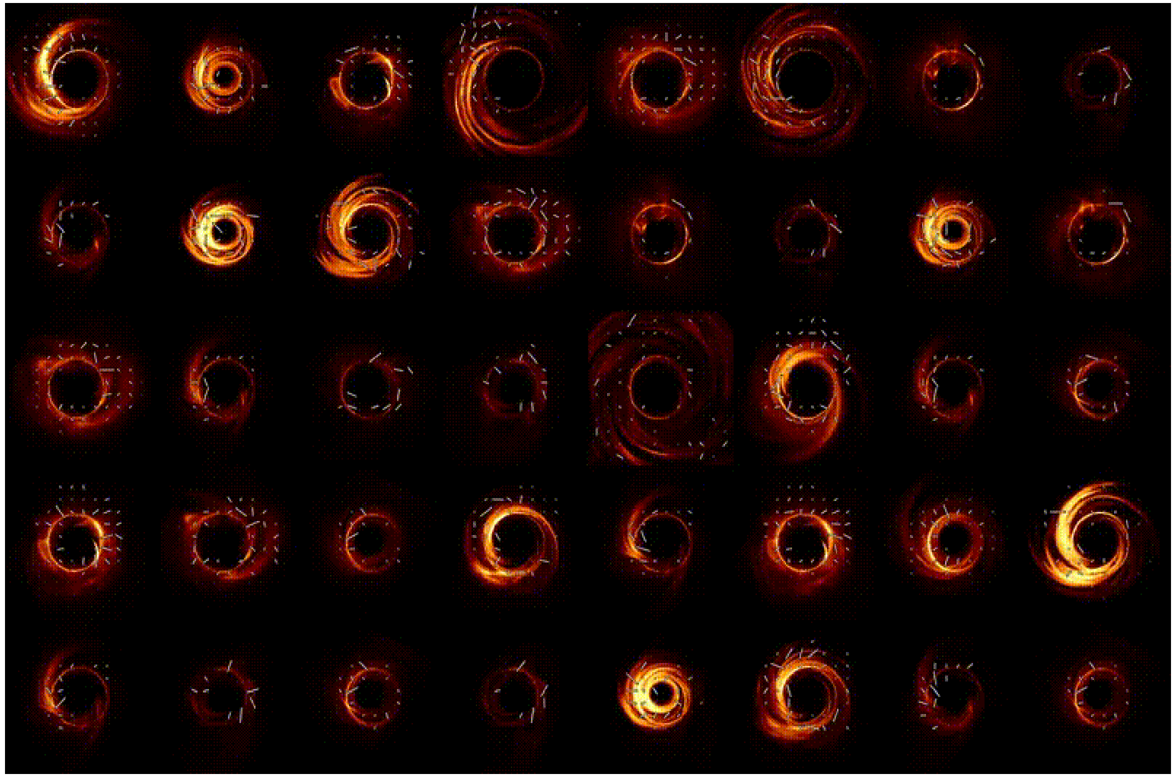
Faraday rotation matters!



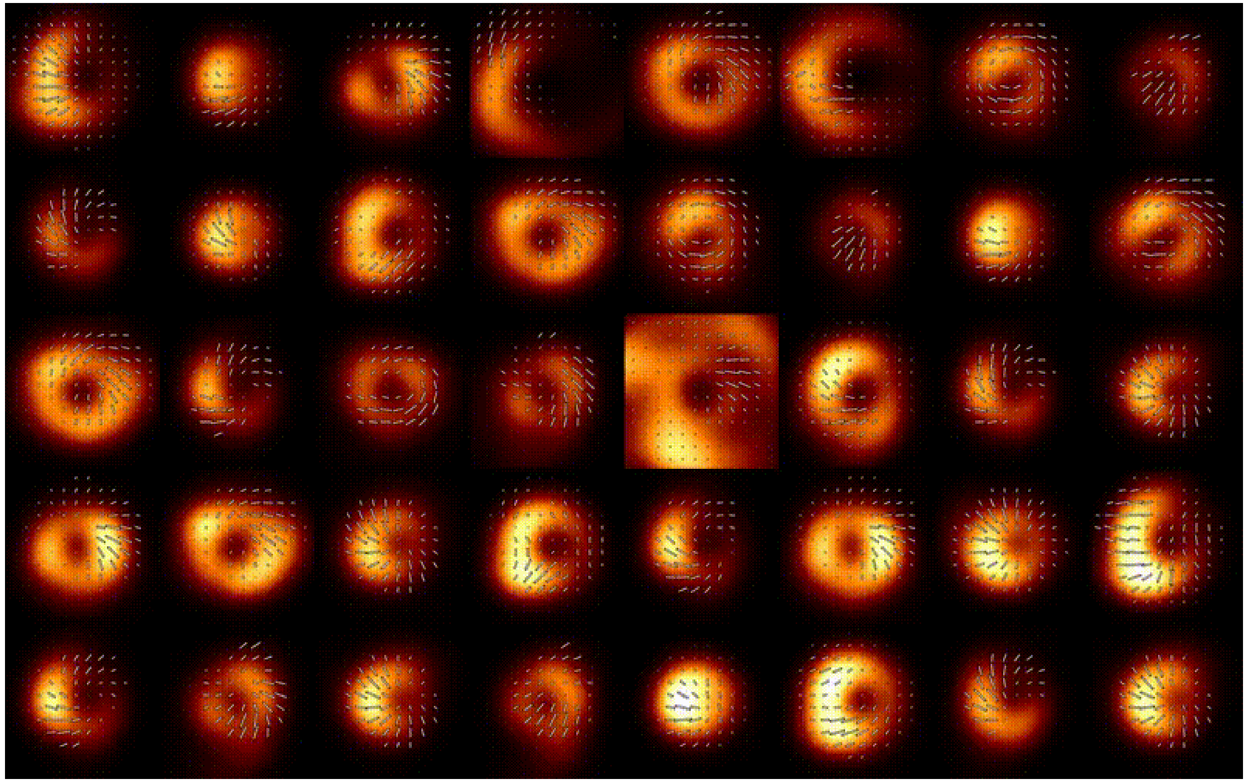
- Significant Faraday rotation on scales smaller than the EHT beam → scrambled polarization directions → depolarization of the image observed by the EHT

- Faraday rotation strength is a direct probe of the plasma parameters (density/temperature/B-field).

GRMHD Simulation library
2 field states, 5 spins, 72k images



native resolution



EHT resolution

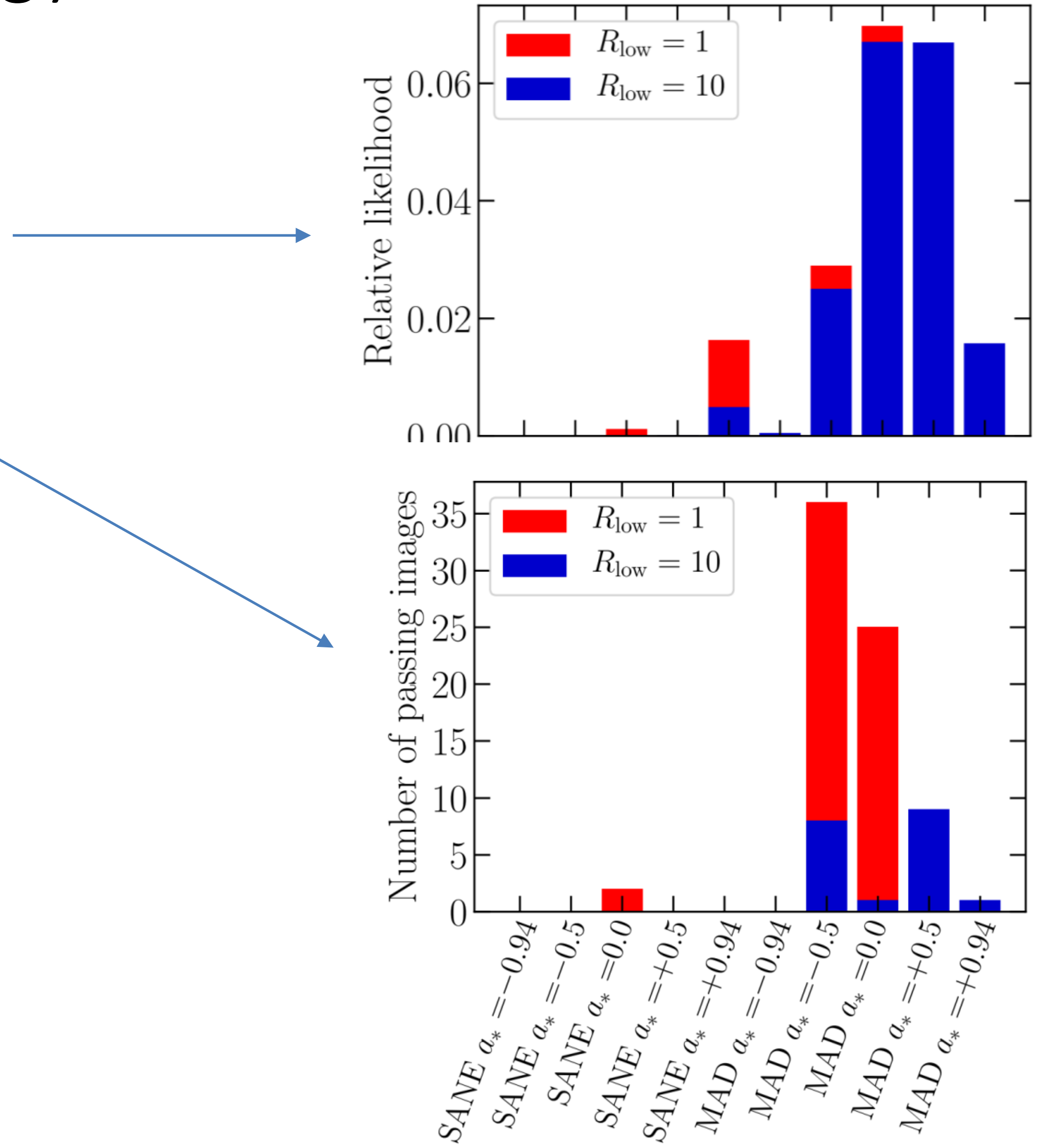
Images modeled with the ipole GRRT code (Moscibrodzka & Gammie 2018)

Two-temperature plasma model from Moscibrodzka et al. 2016 $R = \frac{T_i}{T_e} = R_{\mathrm{high}} \frac{\beta^2}{1+\beta^2} + R_{\mathrm{low}} \frac{1}{1+\beta^2}$

Animation credit: George Wong

GRMHD simulation scoring shows a strong preference for magnetically arrested disks in M87

- Two scoring approaches:
  - 'joint' (construct a likelihood comparing to mean simulation values, assuming parameters are independent).
  - 'simultaneous' (demand individual images satisfy all image constraints at once)
- **Both approaches strongly favor magnetically arrested simulations**
- The two approaches differ in other details (especially in which electron heating parameters they favor).
- An additional constraint on the jet power rejects all surviving non-MAD simulations (and all spin-zero simulations)



Implications for M87*'s accretion

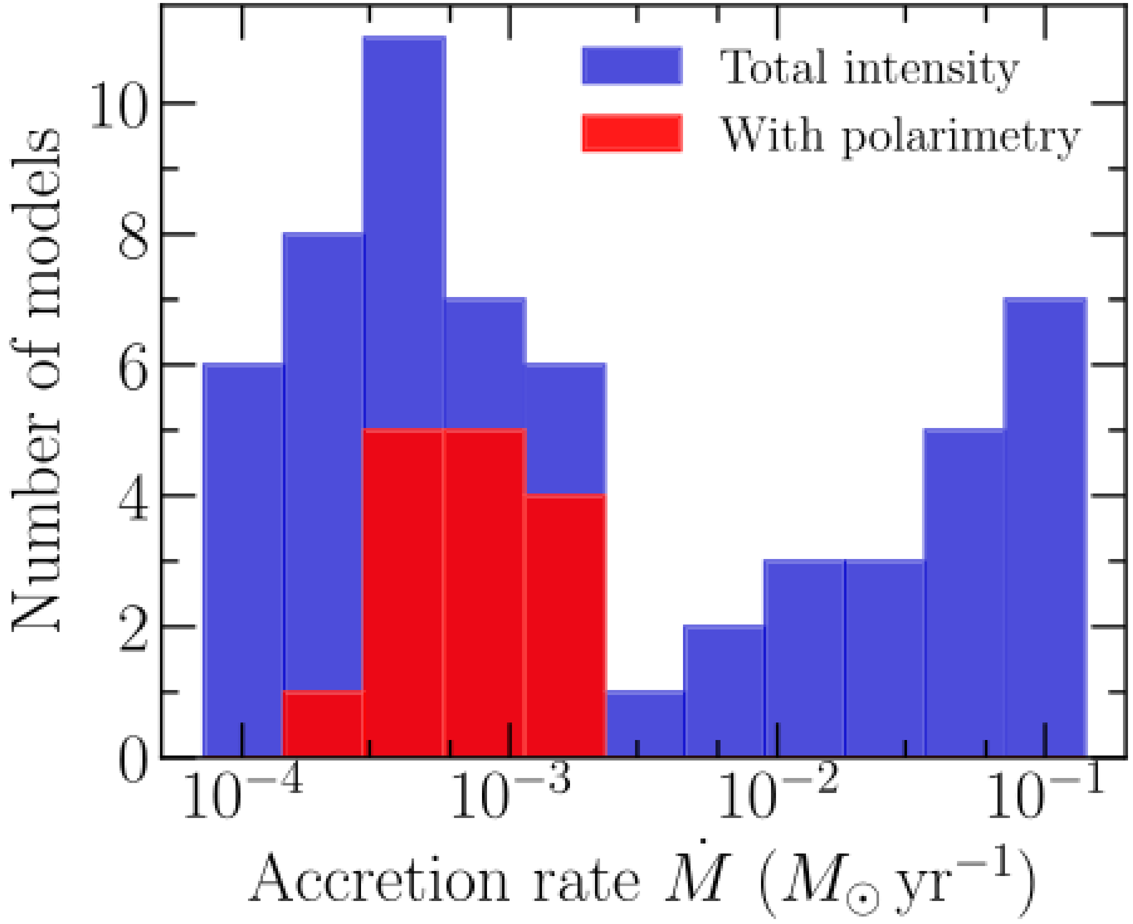
- Surviving models significantly tighten constraints on accretion rate from total intensity results:

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

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

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

- Radiative efficiency ~1%



Future:

- **Time variability**: GRMHD simulations predict variability in the polarization structure / magnitude on month-year timescales. Observing regularly will tighten these constraints

- **Model space**: need to add tilted disk models and a broader range of black hole spins and electron heating/acceleration parameters

- **Array improvements**: will allow us to connect near-horizon structure to faint jet emission at 230 GHz and connect 230 GHz to 345 GHz structure

M87

$$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$$
$$D = (16.8 \pm 0.8)\text{Mpc}$$
$$d_{\text{shadow}} \approx 40\mu\text{as}$$

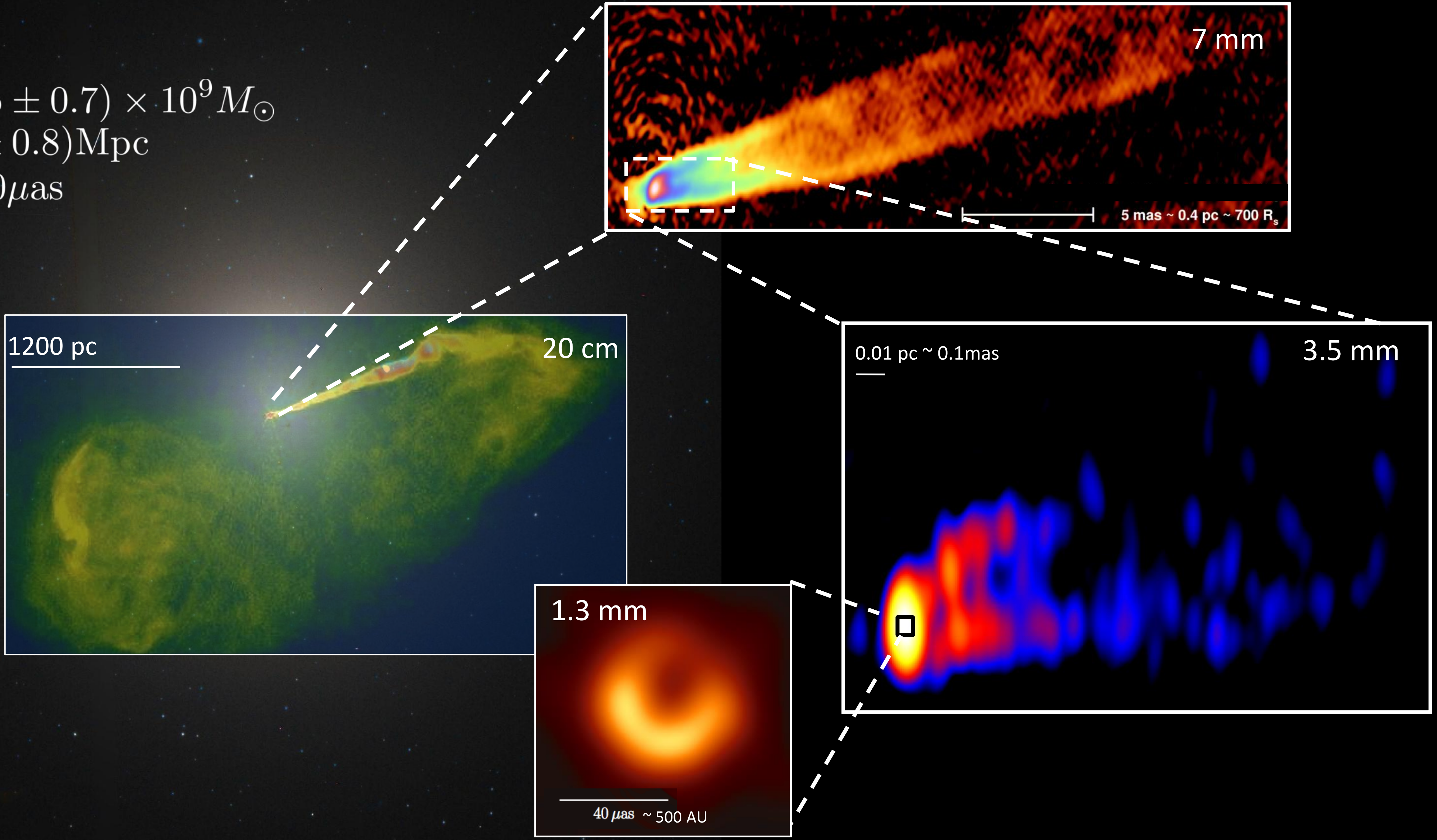


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)