Magnetic Fields at the Supermassive Black Hole's Event Horizon in M87

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NHFP
NASA Hubble Fellowship Program

PRINCETON CENTER FOR THEORETICAL SCIENCE

Event Horizon Telescope

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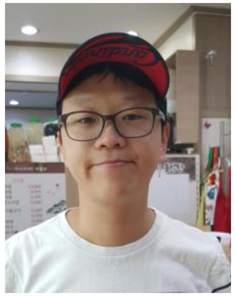

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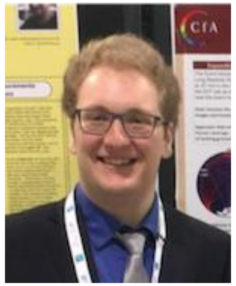

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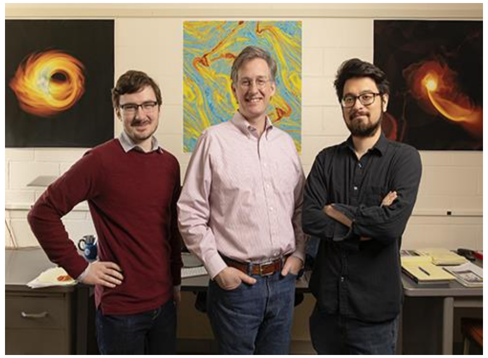

Event Horizon Telescope

M87 & M87*

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

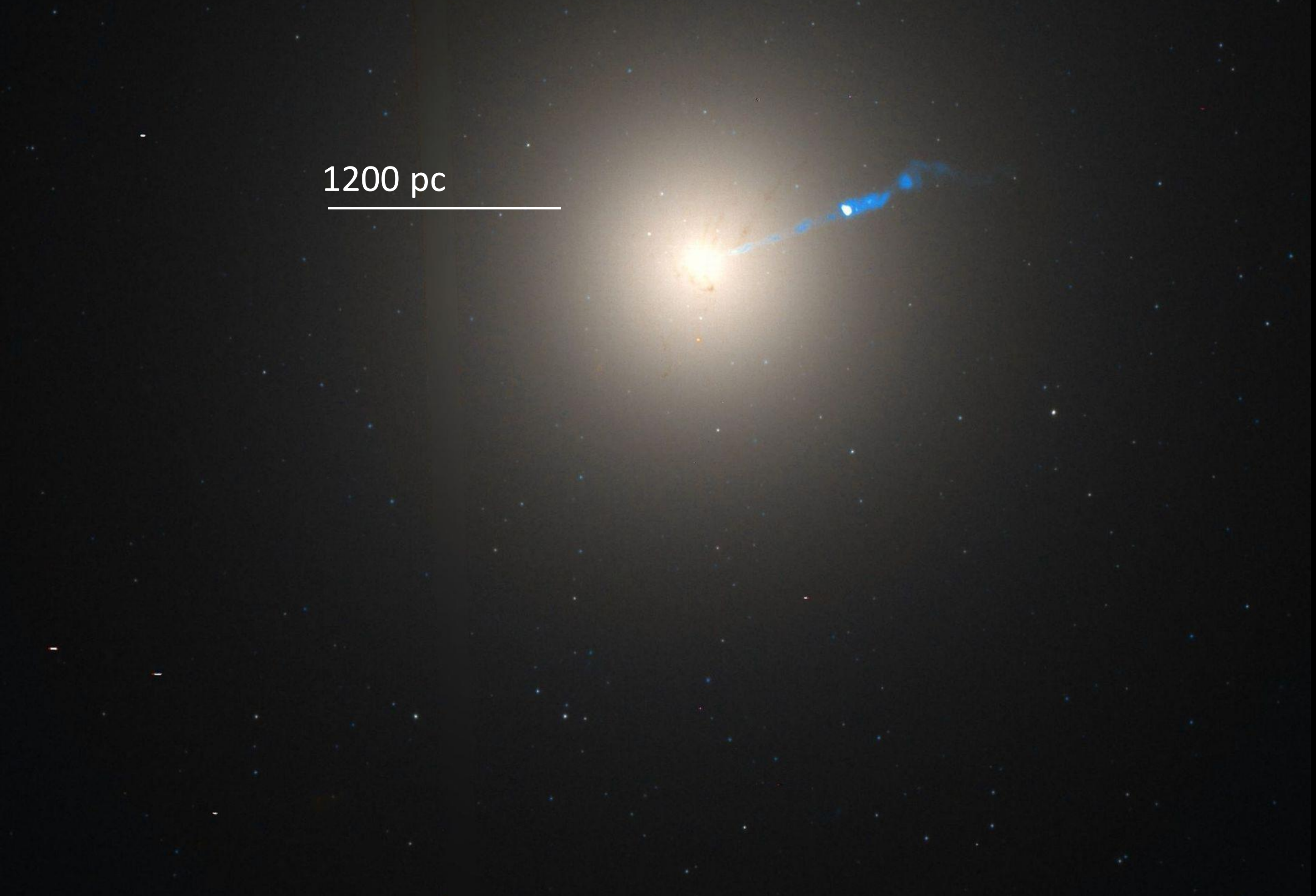

Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

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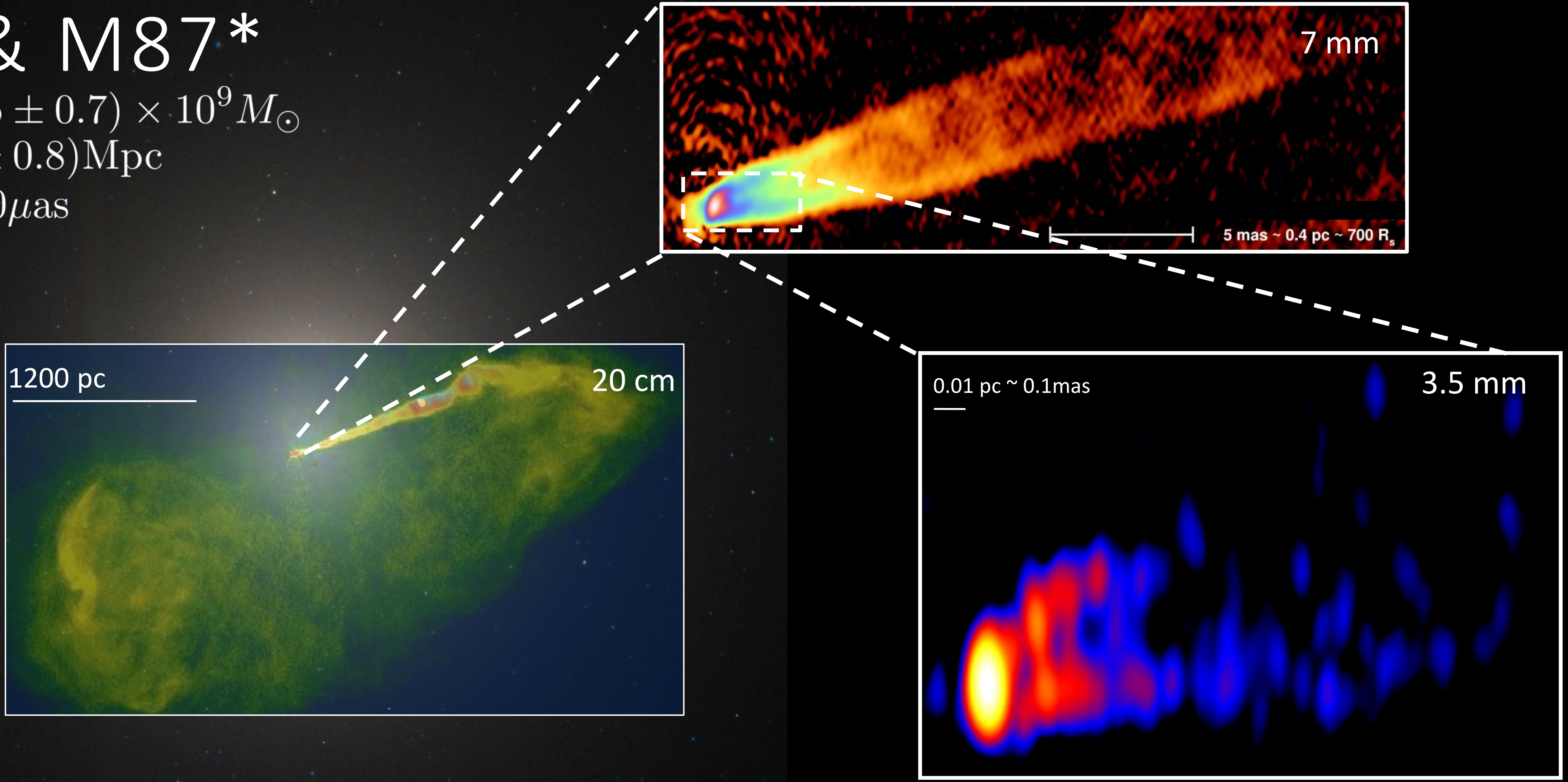

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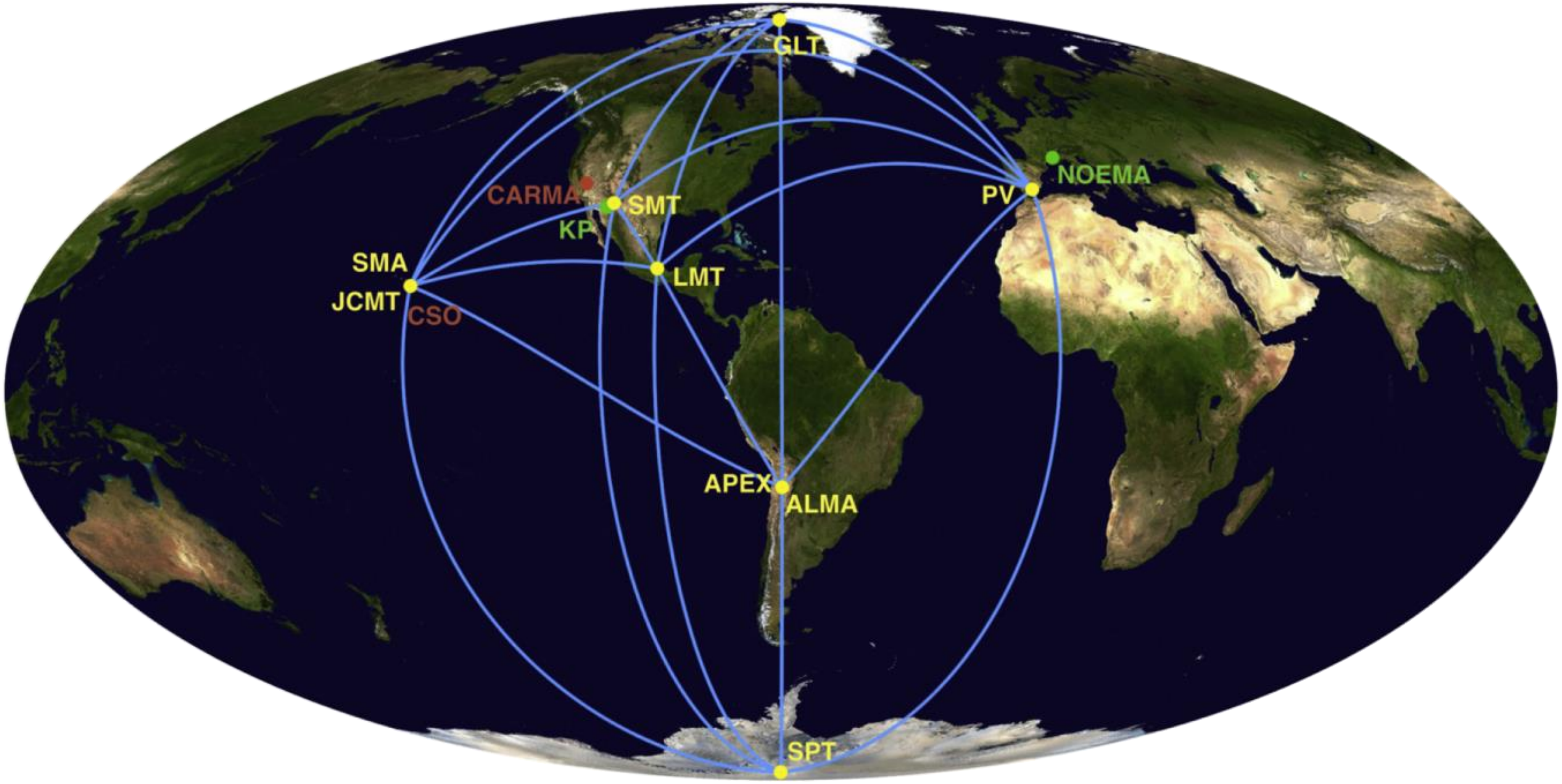
The Event Horizon Telescope



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

Image Credit:
EHT Collaboration 2019 (Paper II)

M87 & M87*

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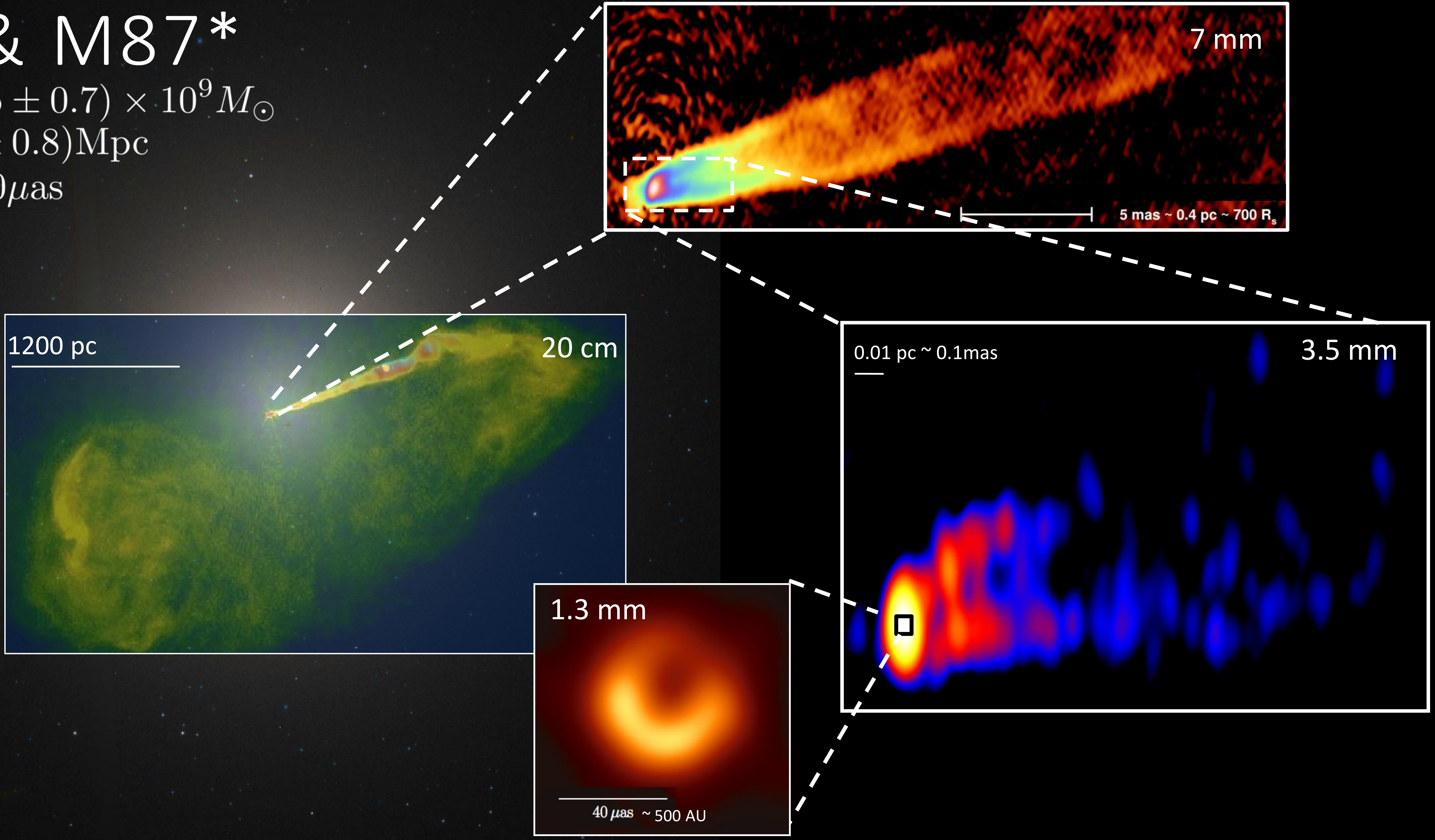

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EHT (1.3 mm)

At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Synchrotron Emission from very hot ($T \gtrsim 10^{10}\,\mathrm{K}$) plasma close to the event horizon
- Launches a powerful relativistic jet ($P_{\mathrm{jet}} \geq 10^{42}$ erg s^{-1}) outside of the galaxy

Open Questions:

- Where exactly does the emission come from?
- What is the temperature and distribution of the emitting particles?
- What is the strength and configuration of the magnetic field?

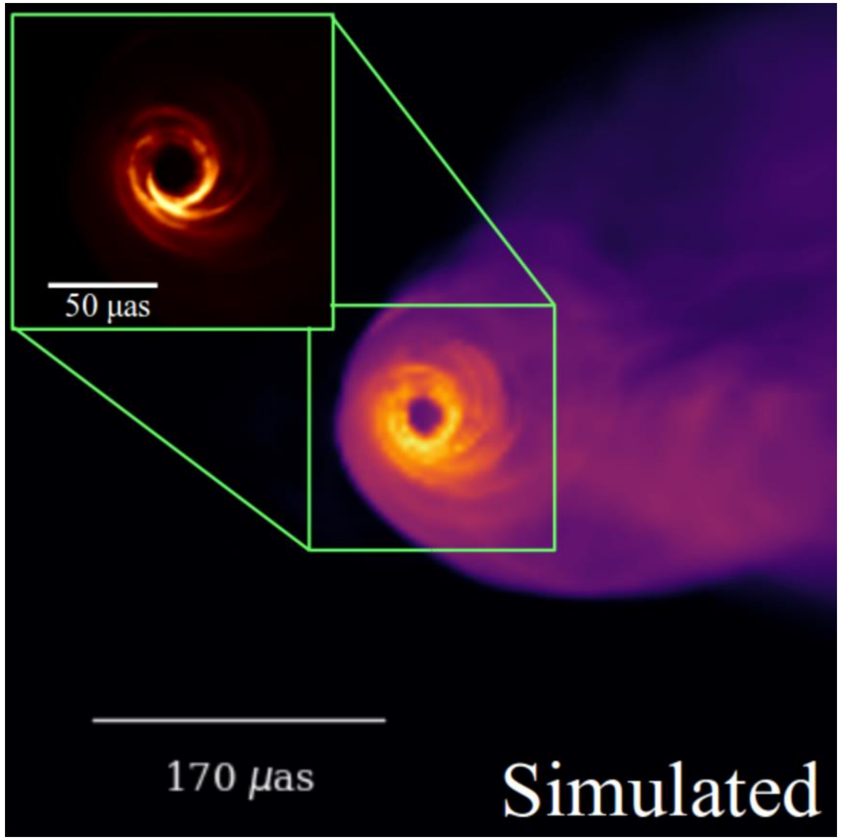
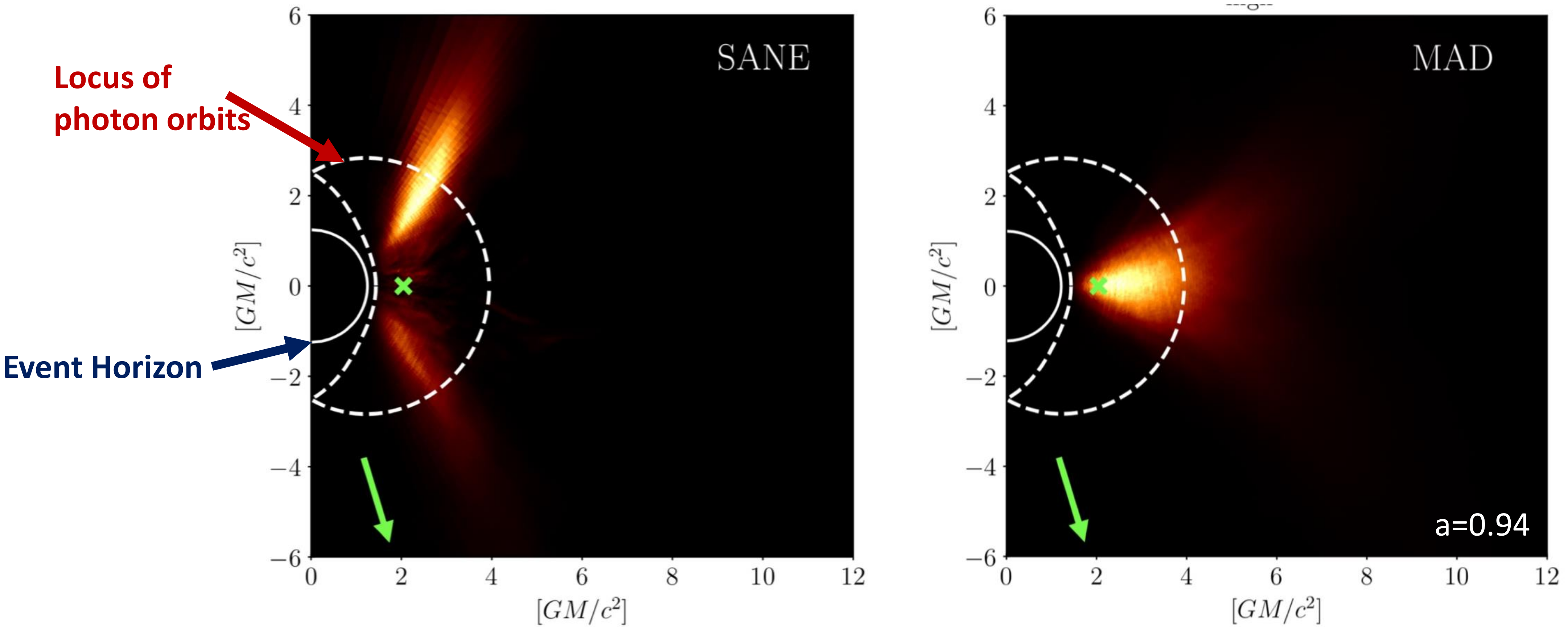


Image credit: Andrew Chael, Lindy Blackburn

Where does the emission come from?

All simulations show emission region is within a few Schwarzschild radii of the black hole, but in different spatial regions



Can we determine if emission mostly originates in inflow or outflow?
How exactly is the emission lensed by the black hole?

EHTC+ 2019, Paper V

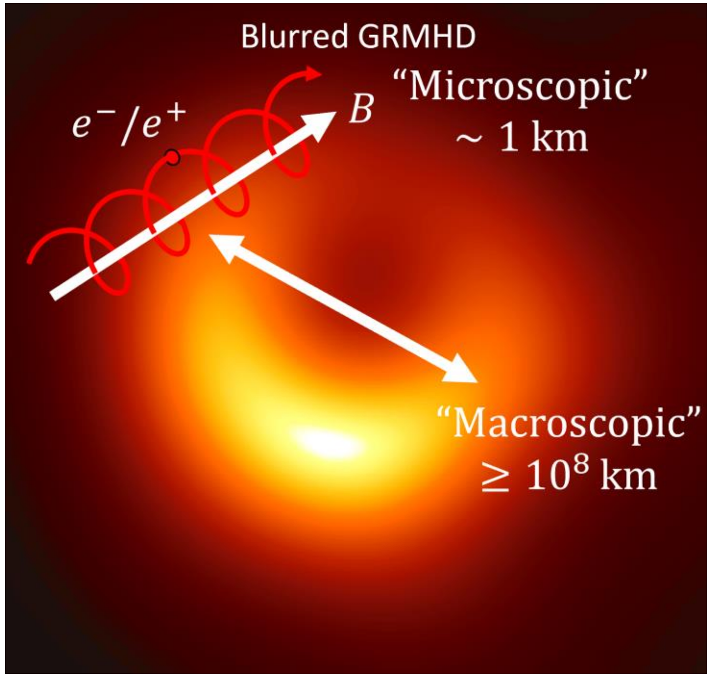
What is the distribution of emitting electrons?

- Coulomb coupling between ions and electrons is **inefficient**:

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

- The electron temperature is sensitive to radiative **cooling** and microscale **heating** processes
    - several options for the heating mechanism
      e.g. magnetic reconnection, Landau damping

- A big source of uncertainty in simulations, which don't resolve heating directly.



Huge scale separation
in hot accretion flows

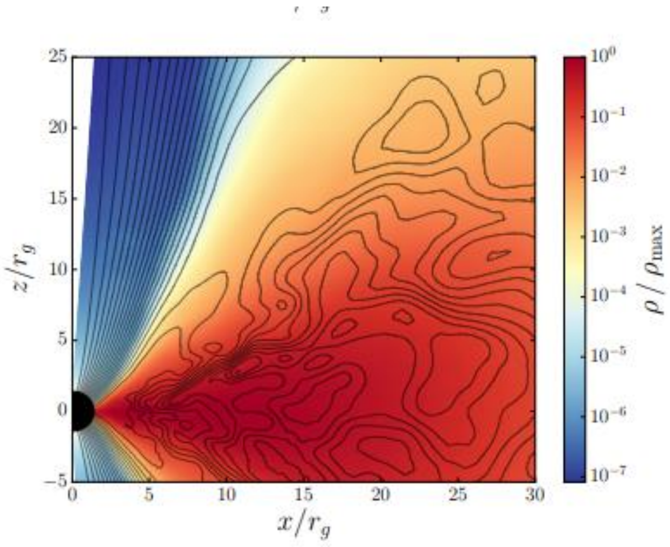
e.g. Mahadevan 1998
reconnection heating: e.g. Rowan+ 2017, Werner+ 2018. Turbulent damping: e.g. Howes 2010

Image credit: Bart Ripperda

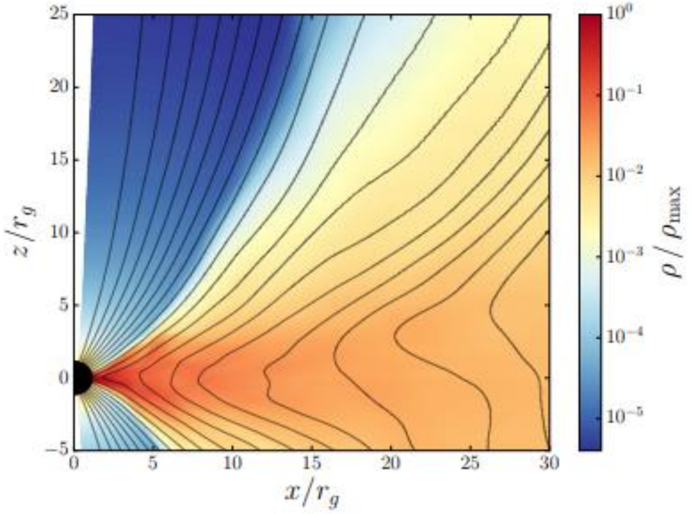
What is the magnetic field structure?

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 dynamically important ones → ~10 G at the horizon for M87

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

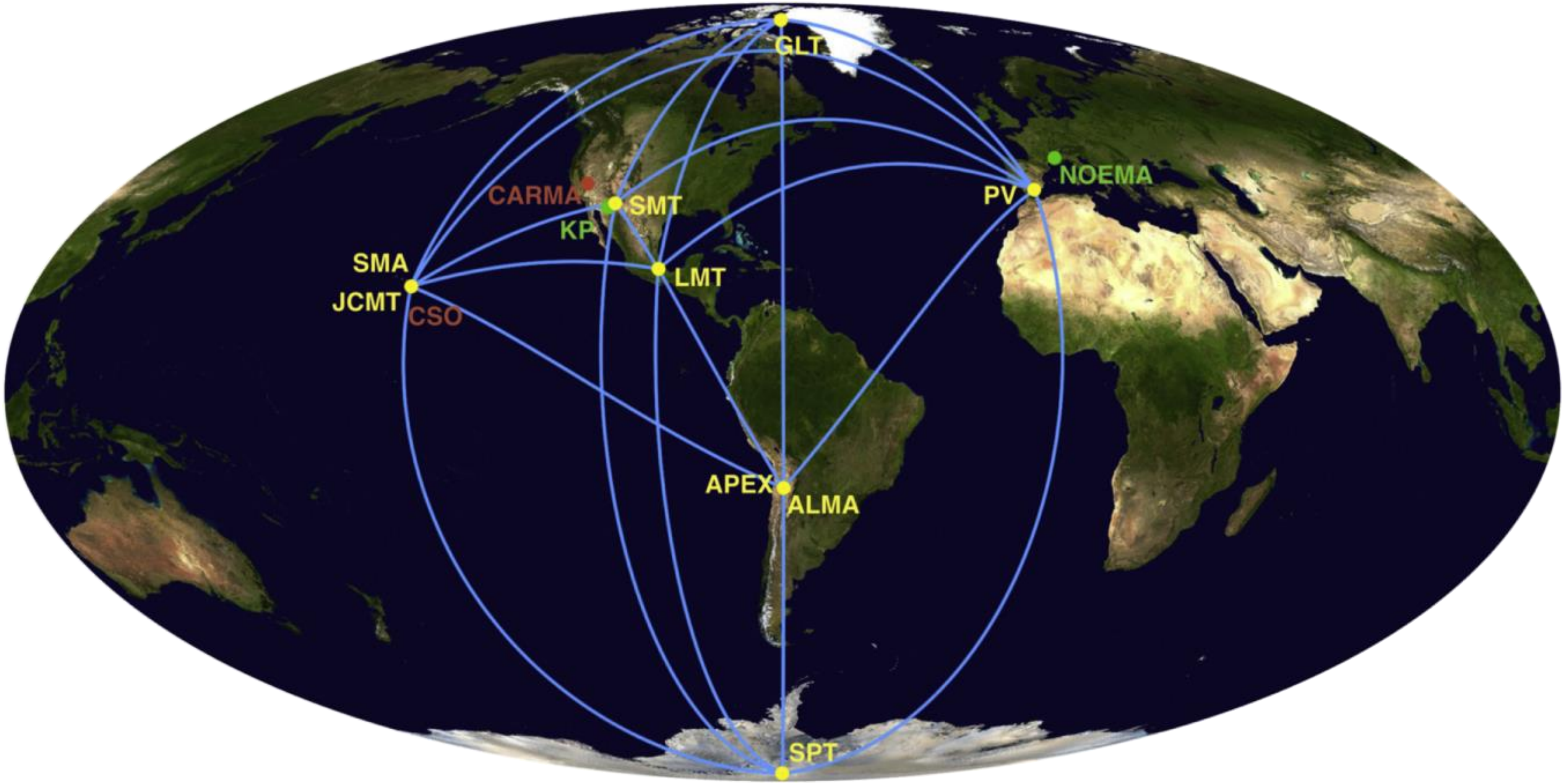
BH spin

magnetic flux

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

Image credit: Riordan+ 2017

The Event Horizon Telescope

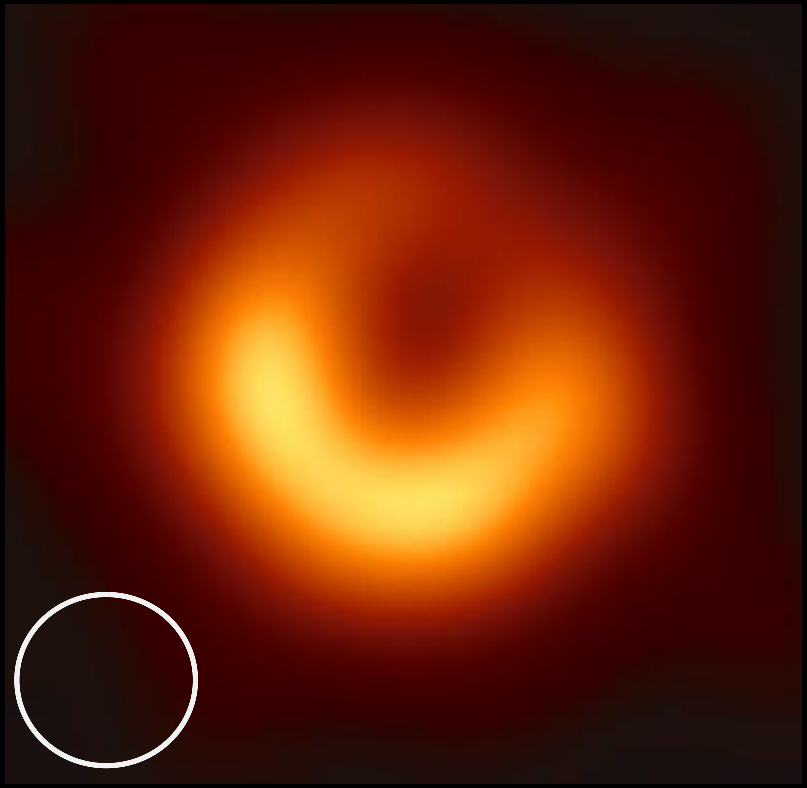


All EHT telescopes can detect and record the **polarization** of light from M87*

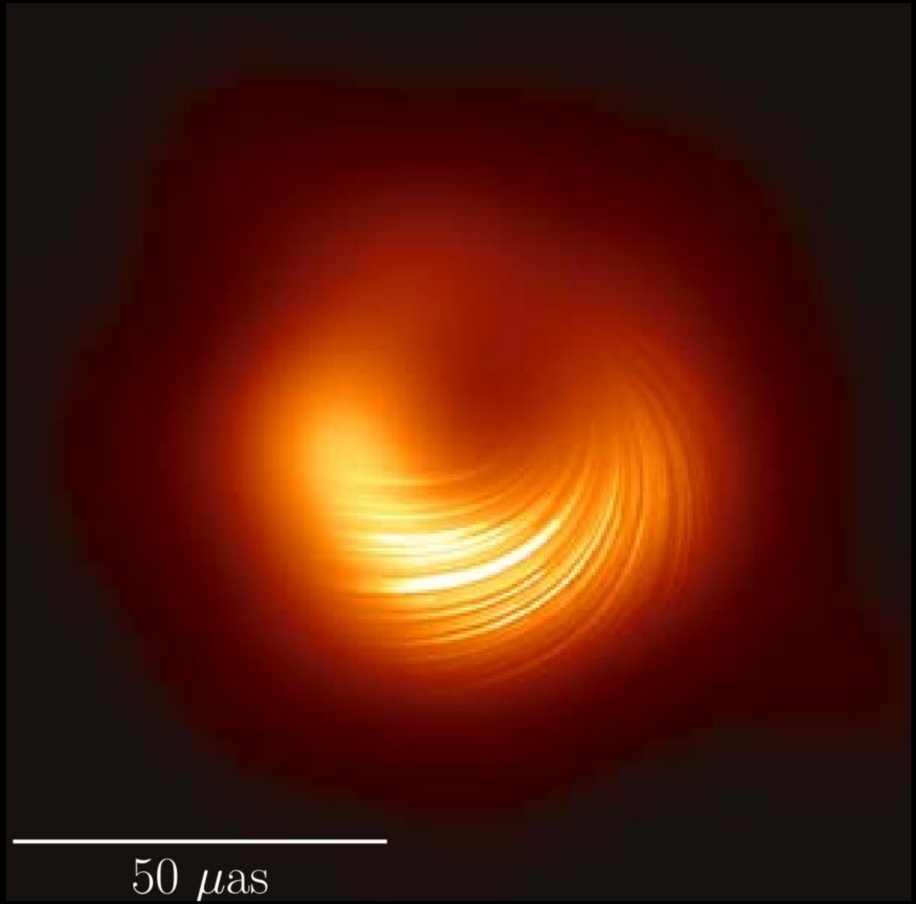
Image Credit:
EHT Collaboration 2019 (Paper II)

M87* in linear polarization

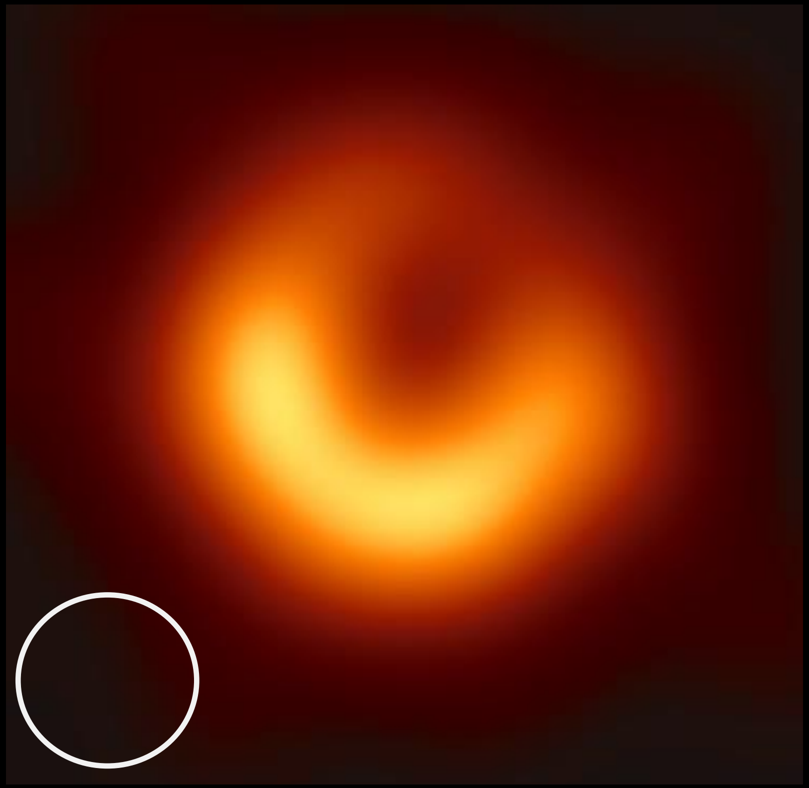
Total intensity



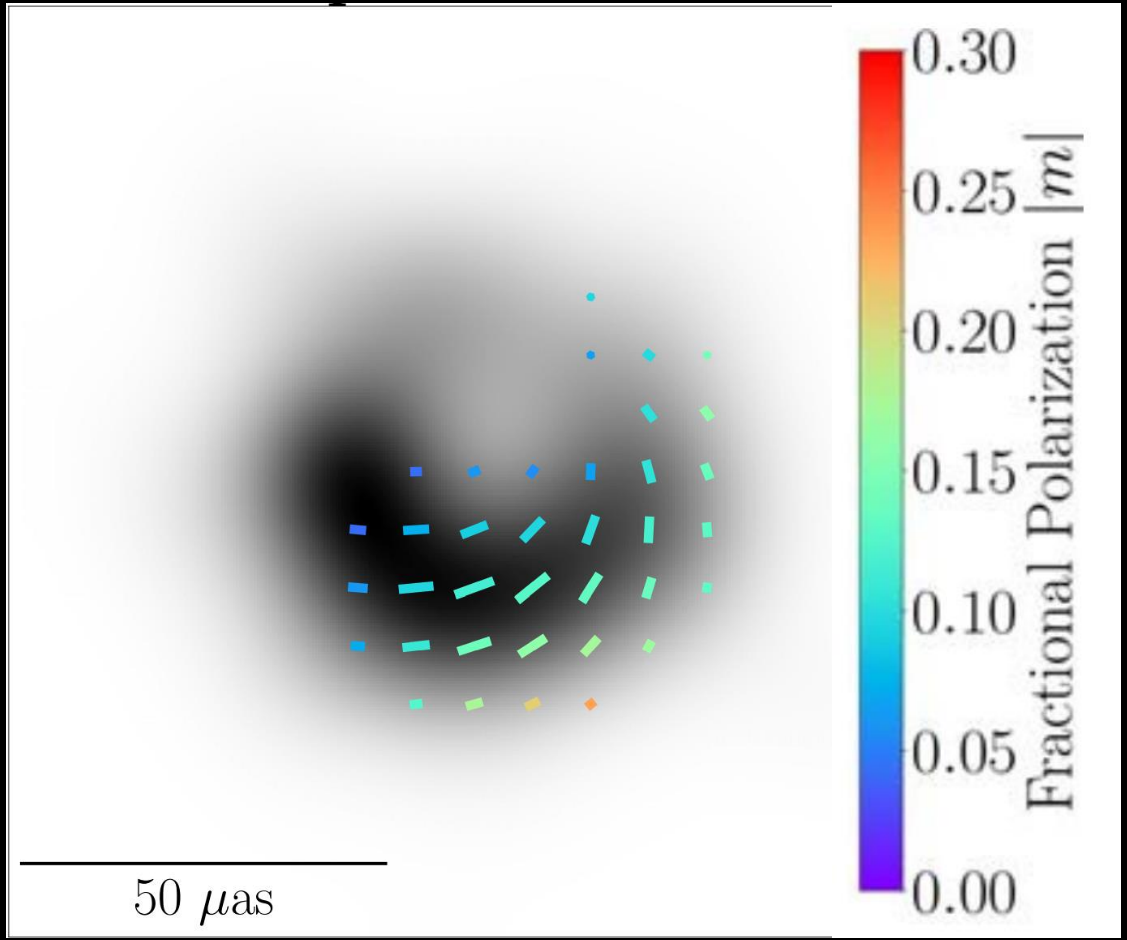
Linear Polarization



Total intensity



Linear Polarization



Outline

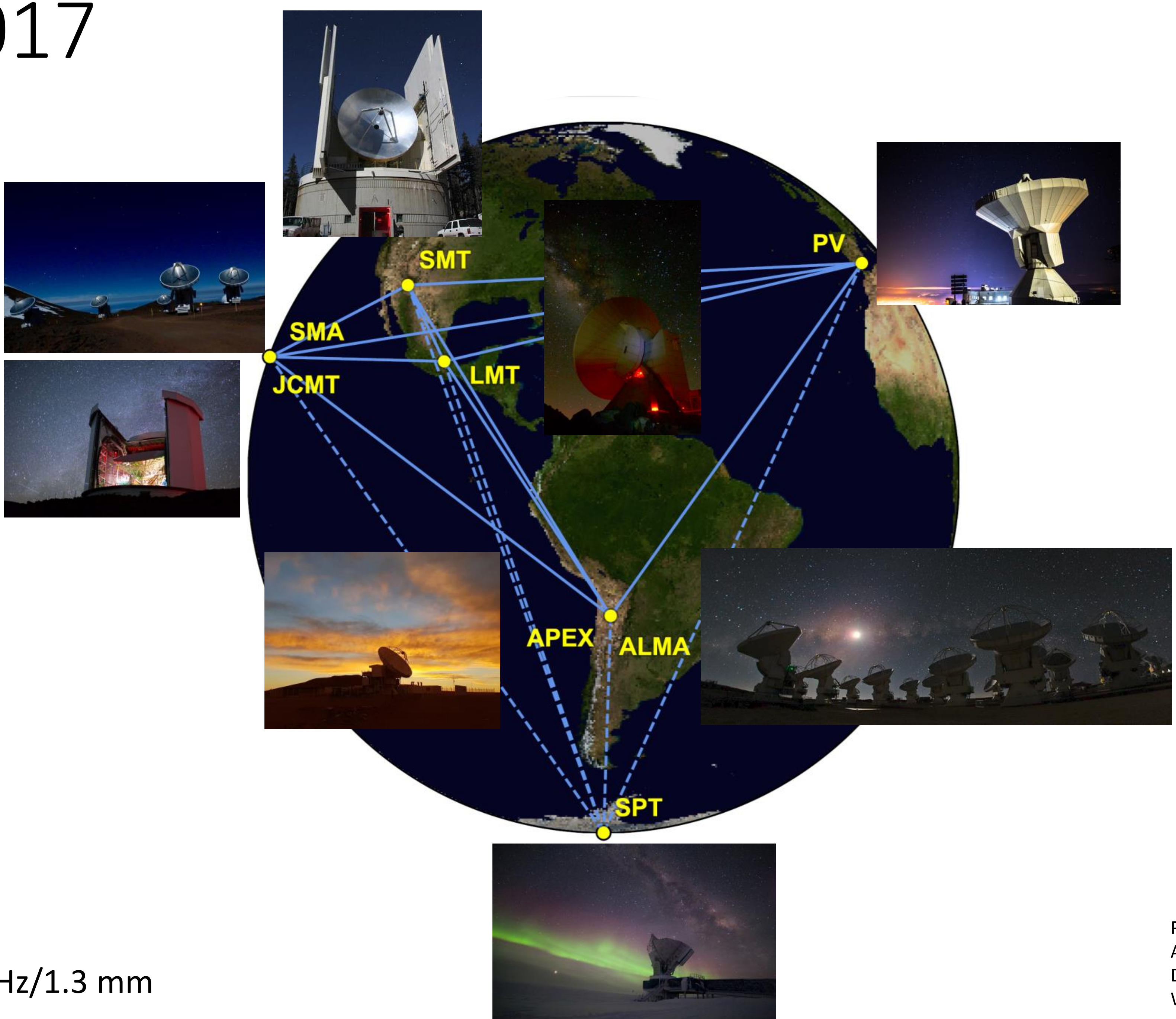
1. How do we obtain a polarized image of M87* with the EHT?

2. What does this image tell us about the magnetic fields near the supermassive black hole?

3. What's next?

How do we obtain a polarized image of M87* with the EHT?

EHT 2017



Imaging at 230 GHz/1.3 mm

Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

EHT 2017 Observations

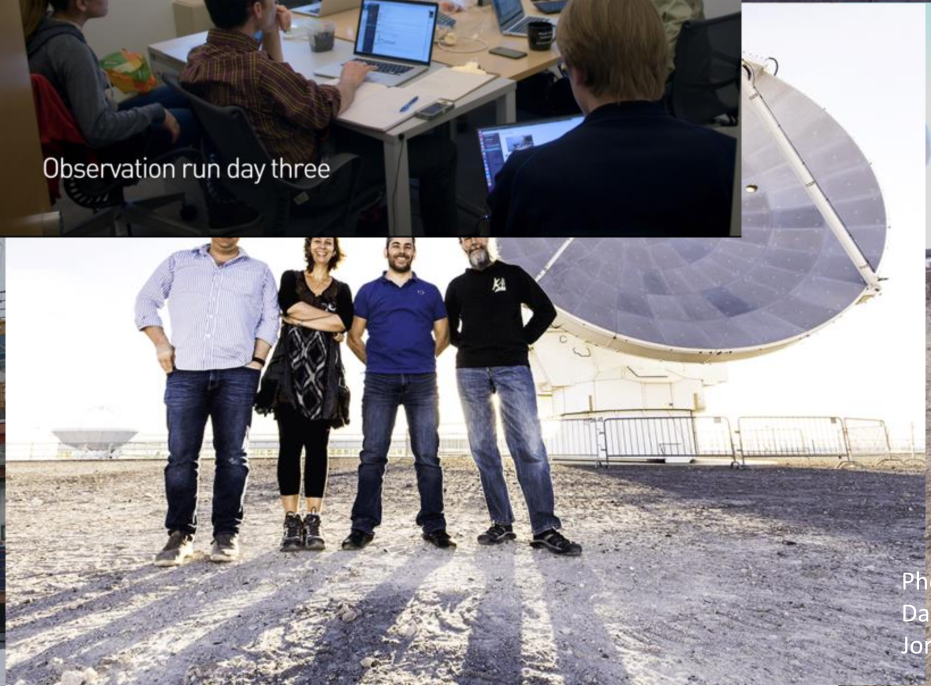
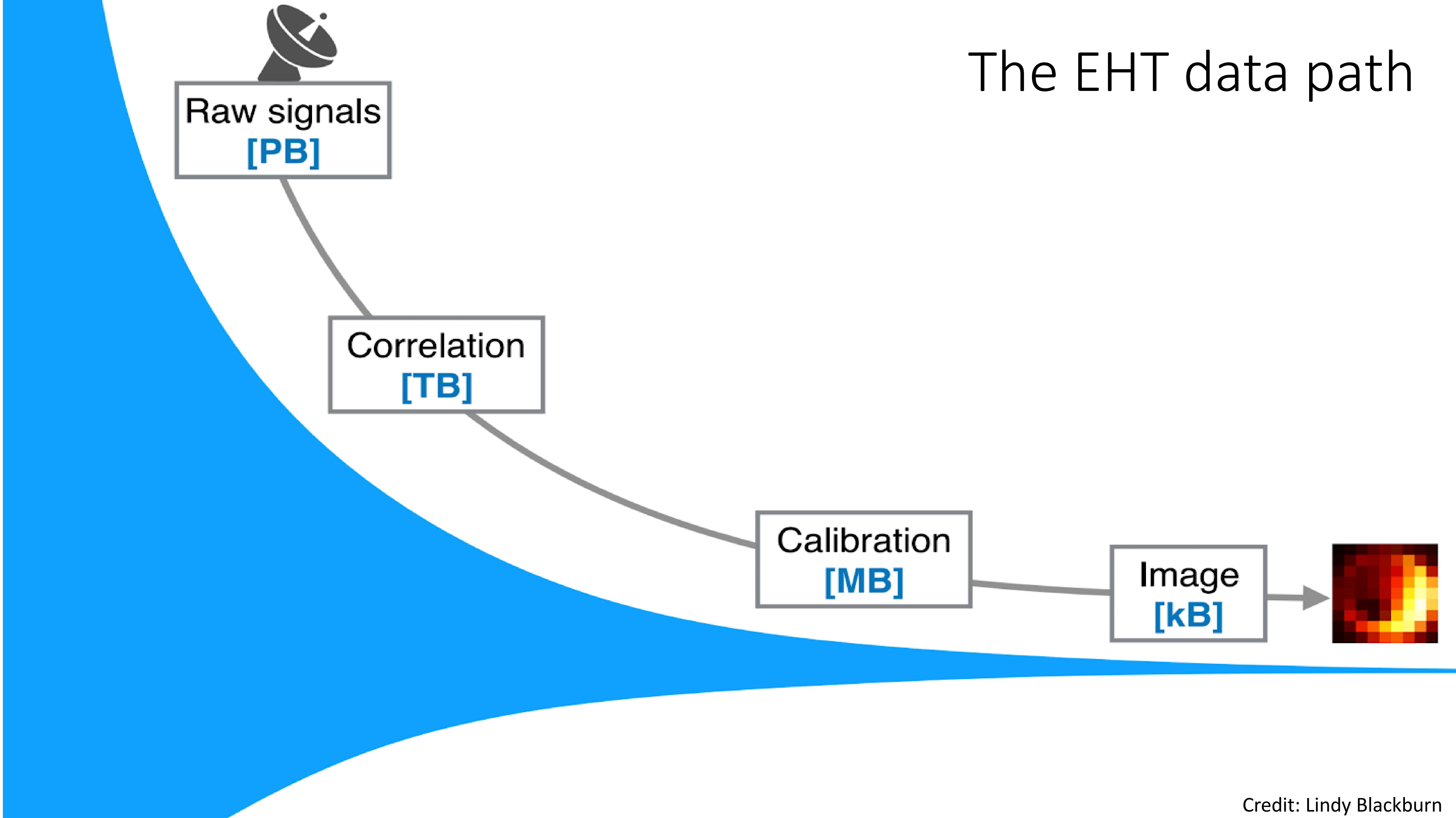


Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

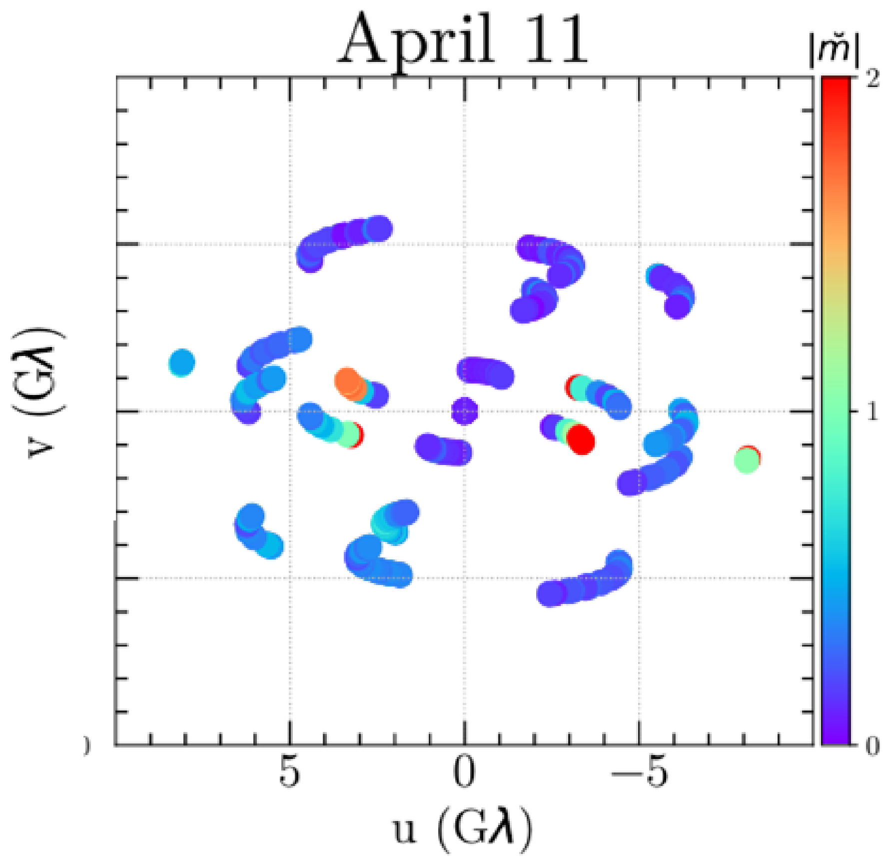
The EHT data path



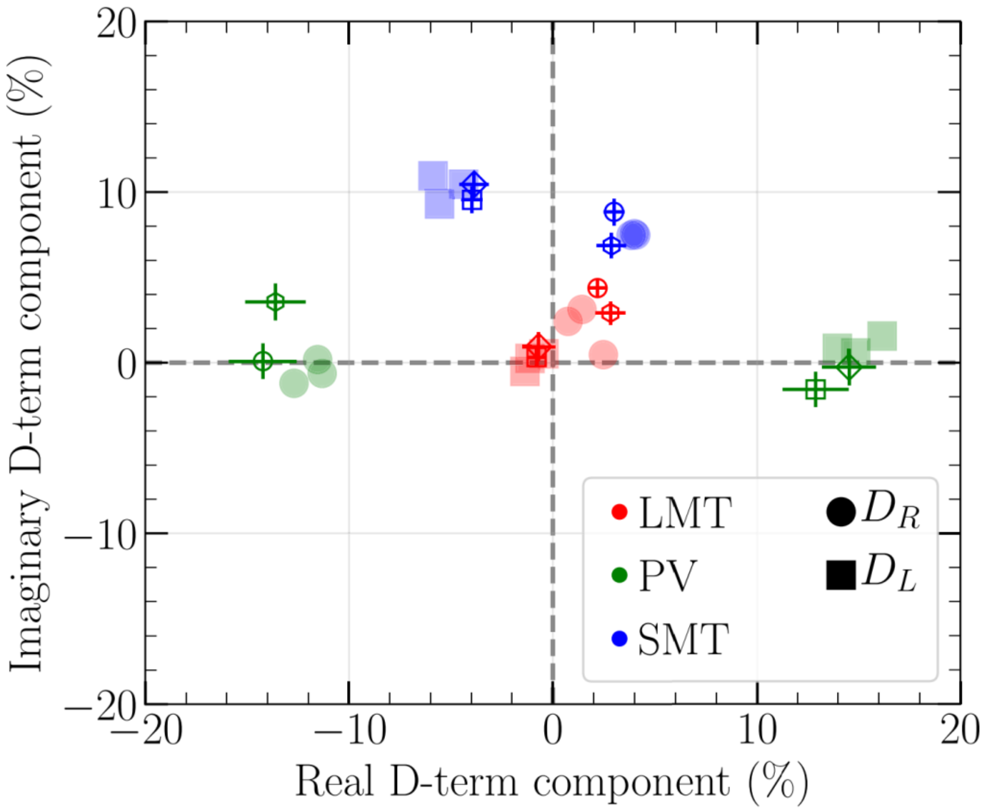
Credit: Lindy Blackburn

Two Challenges of EHT polarimetric imaging

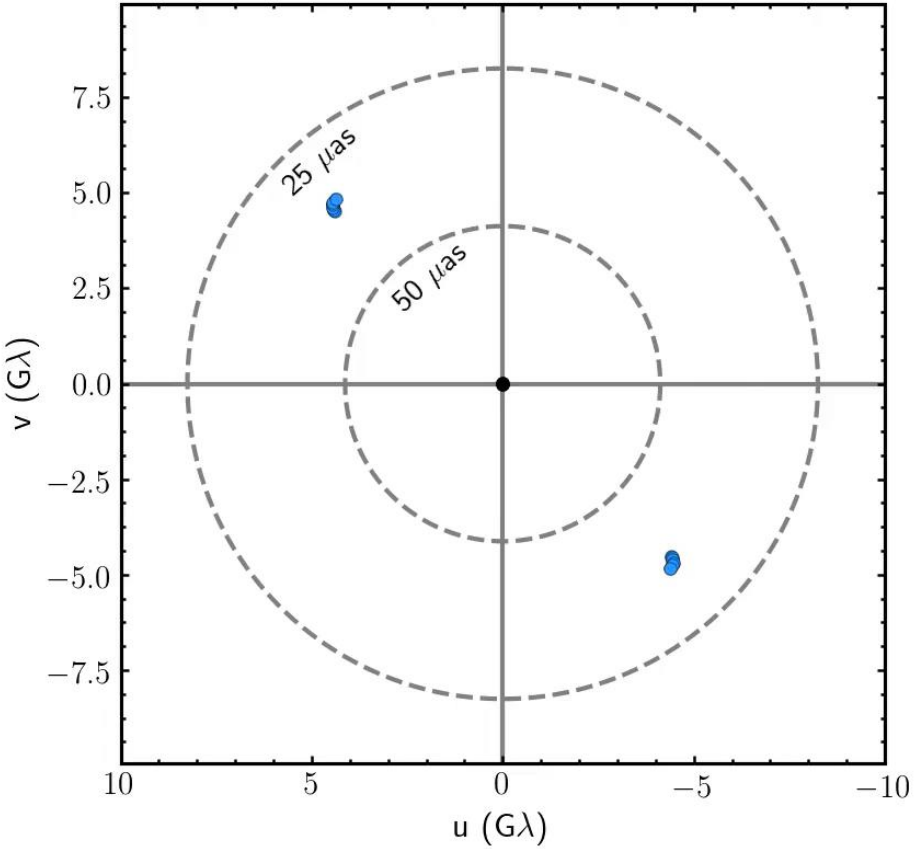
1. EHT coverage is **sparse**: inversion of image from the data is highly unconstrained



Data at each station are corrupted by unknown polarimetric **leakage** and complex gain factors



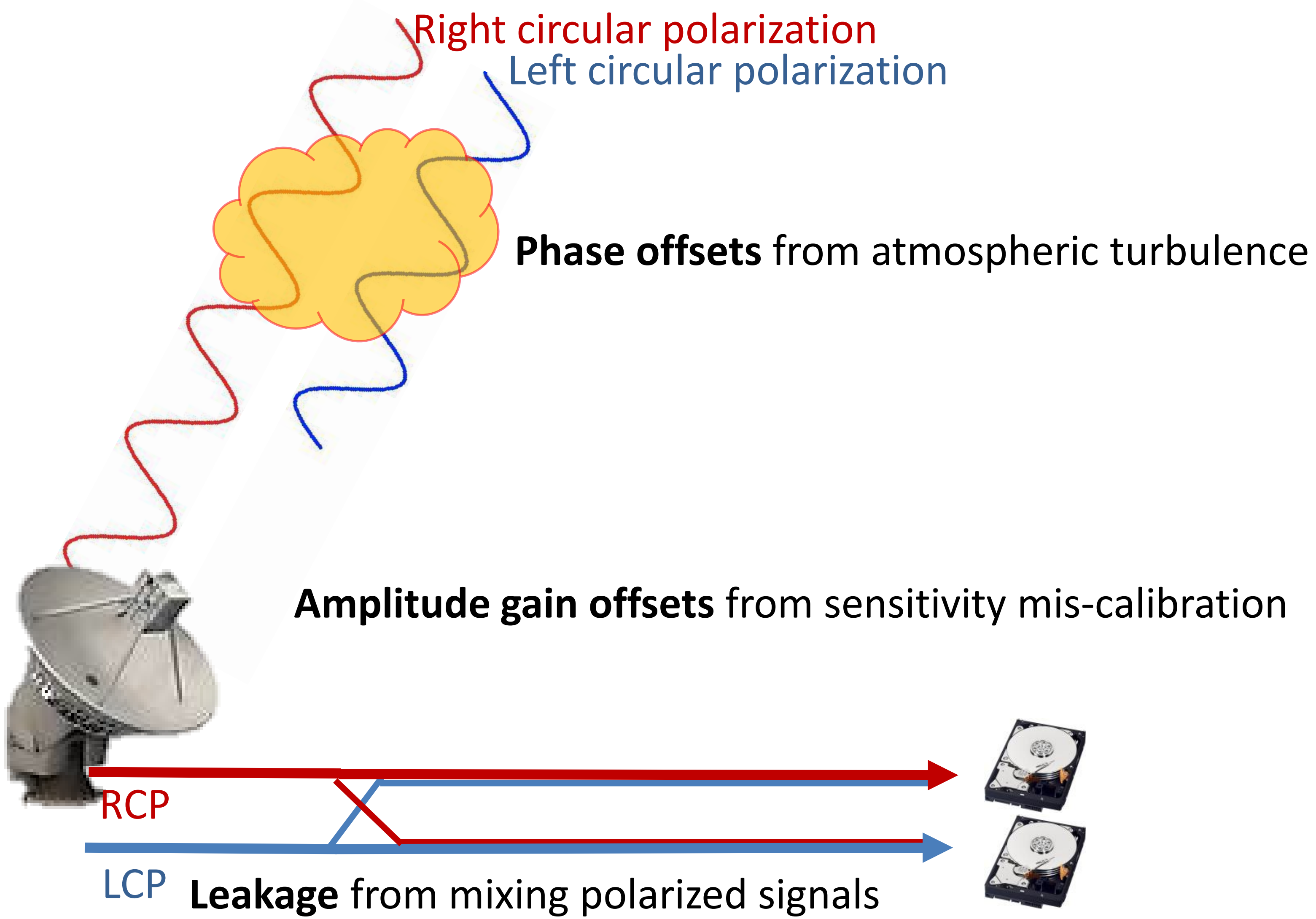
Very Long Baseline Interferometry (VLBI)



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

credit: Katie Bouman, Daniel Palumbo

Corrupting effects at EHT stations



Data at each station are corrupted by unknown polarimetric **leakage** and complex gain factors

Correcting for polarimetric leakage

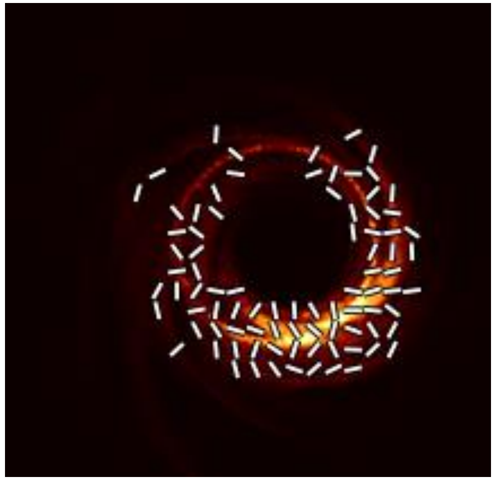
Leakage mixes right- and left- circular components of the polarization
The amount of leakage depends on complex **D-terms** at each station

$$\begin{pmatrix} R_1R_2^* & R_1L_2^* \\ L_1R_2^* & L_1L_2^* \end{pmatrix} \rightarrow \begin{pmatrix} 1 & D_{R,1} \\ D_{L,1} & 1 \end{pmatrix} \begin{pmatrix} R_1R_2^* & R_1L_2^* \\ L_1R_2^* & L_1L_2^* \end{pmatrix} \begin{pmatrix} 1 & D_{L,1}^* \\ D_{R,1}^* & 1 \end{pmatrix}$$

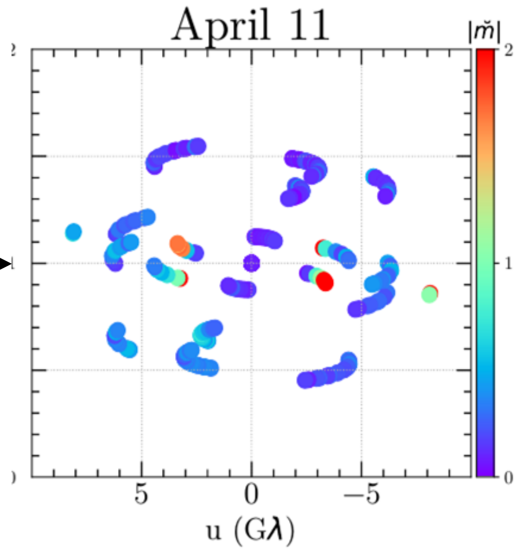
We don't know the station D-terms in advance (there are no good EHT calibration sources!), so we have to solve for them **at the same time as we solve for the image structure**

Solving for the Image

True Image

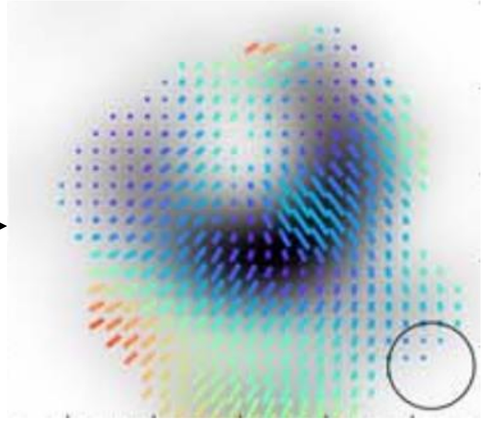


Sparse/ Corrupted Measurements



RECONSTRUCTION ALGORITHM

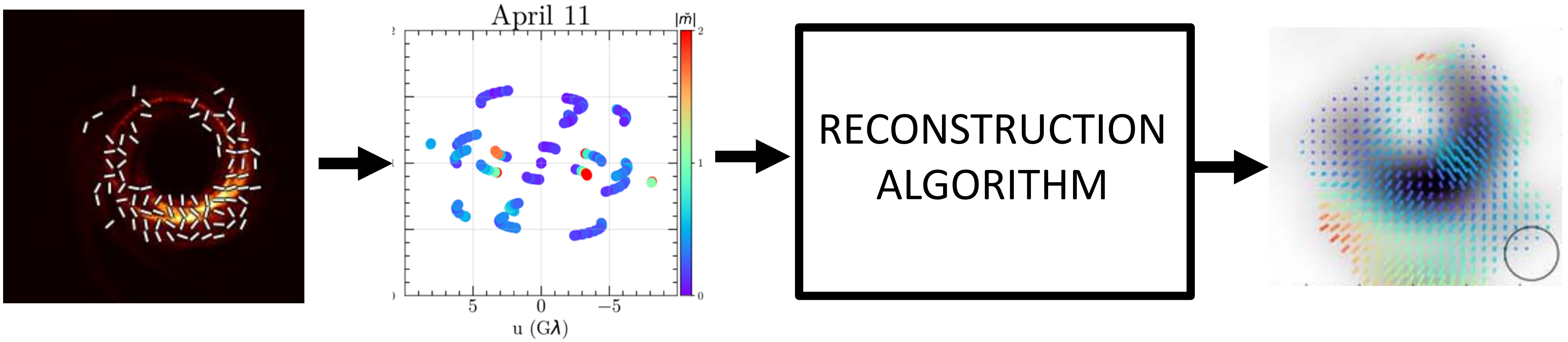
Reconstruction



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

Solving for the Image

True Image | Sparse/ Corrupted Measurements | Reconstruction

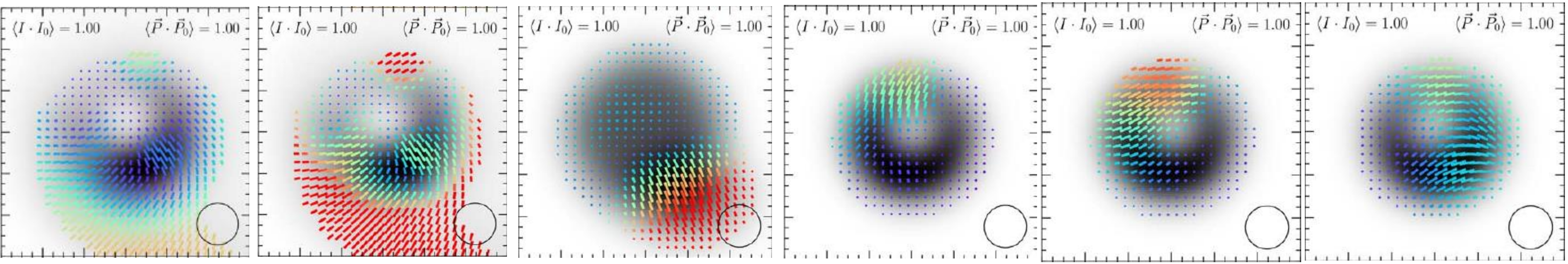


Several different types of reconstruction algorithms now used:

- **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)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
  - Themis (Broderick+ 21), DMC (Pesce+ 21)

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

Testing our methods with synthetic data



Low polarization simulation

High polarization simulation

Simple disk with high polarization offset

Simple crescent models with patterns of low and high polarization

Synthetic data are corrupted with realistic instrumental effects, including polarization leakage

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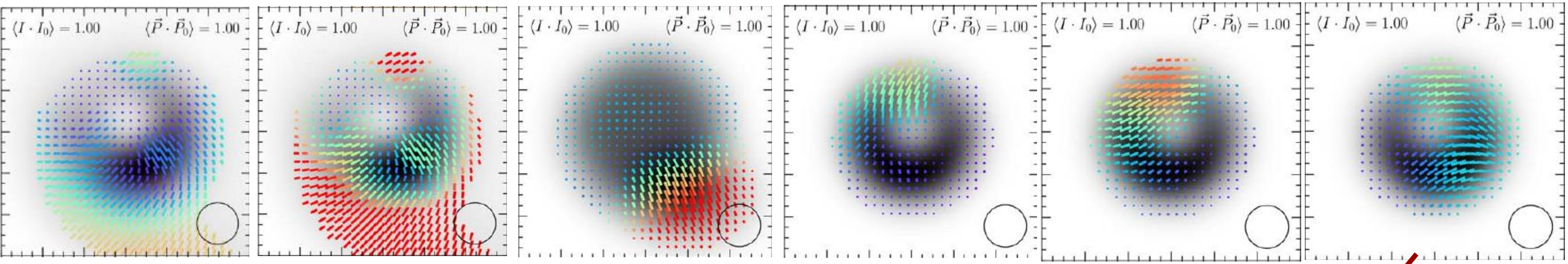
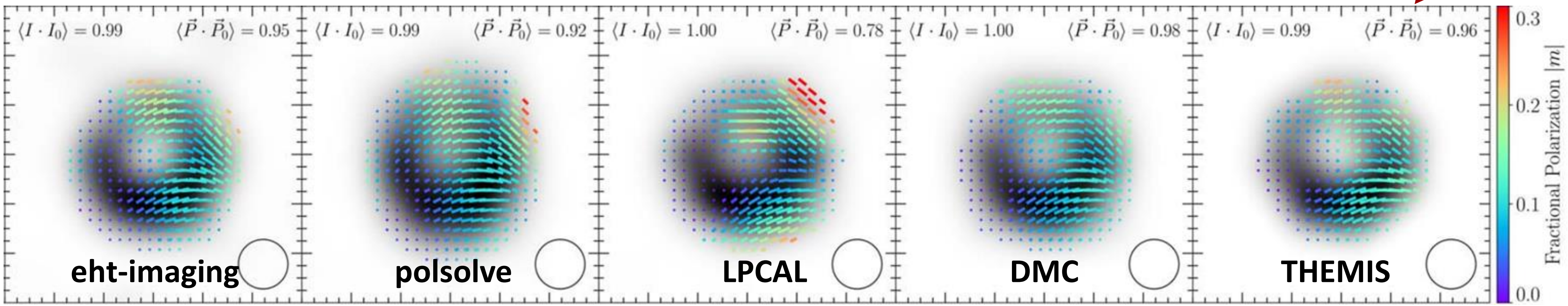
Testing our methods with synthetic data: Image recovery



Example reconstruction of Model 6 using **5 distinct methods**



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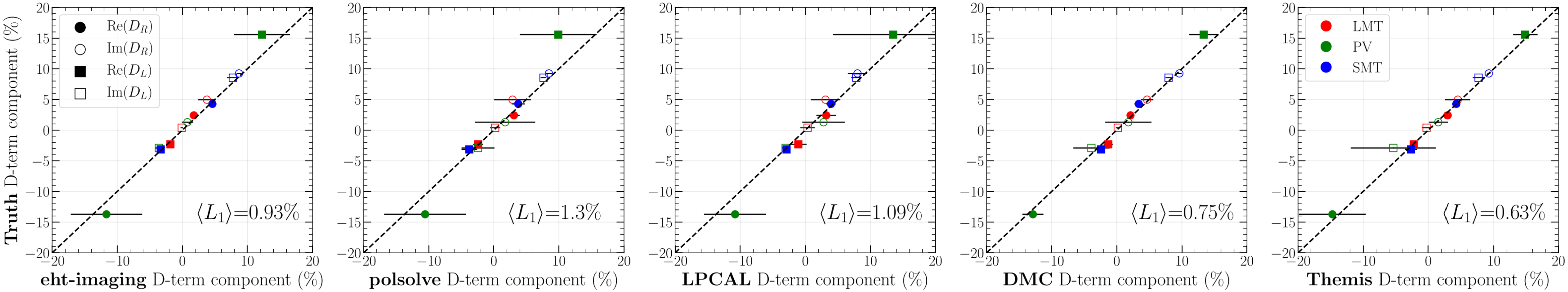
Testing our methods with synthetic data: D-term recovery



All methods can accurately solve for station D-terms in the synthetic data

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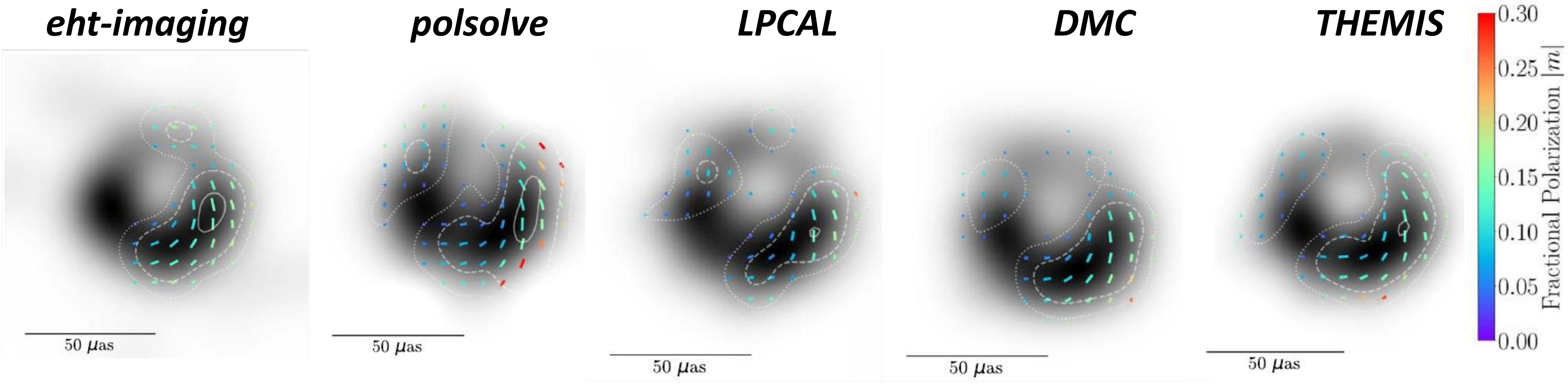
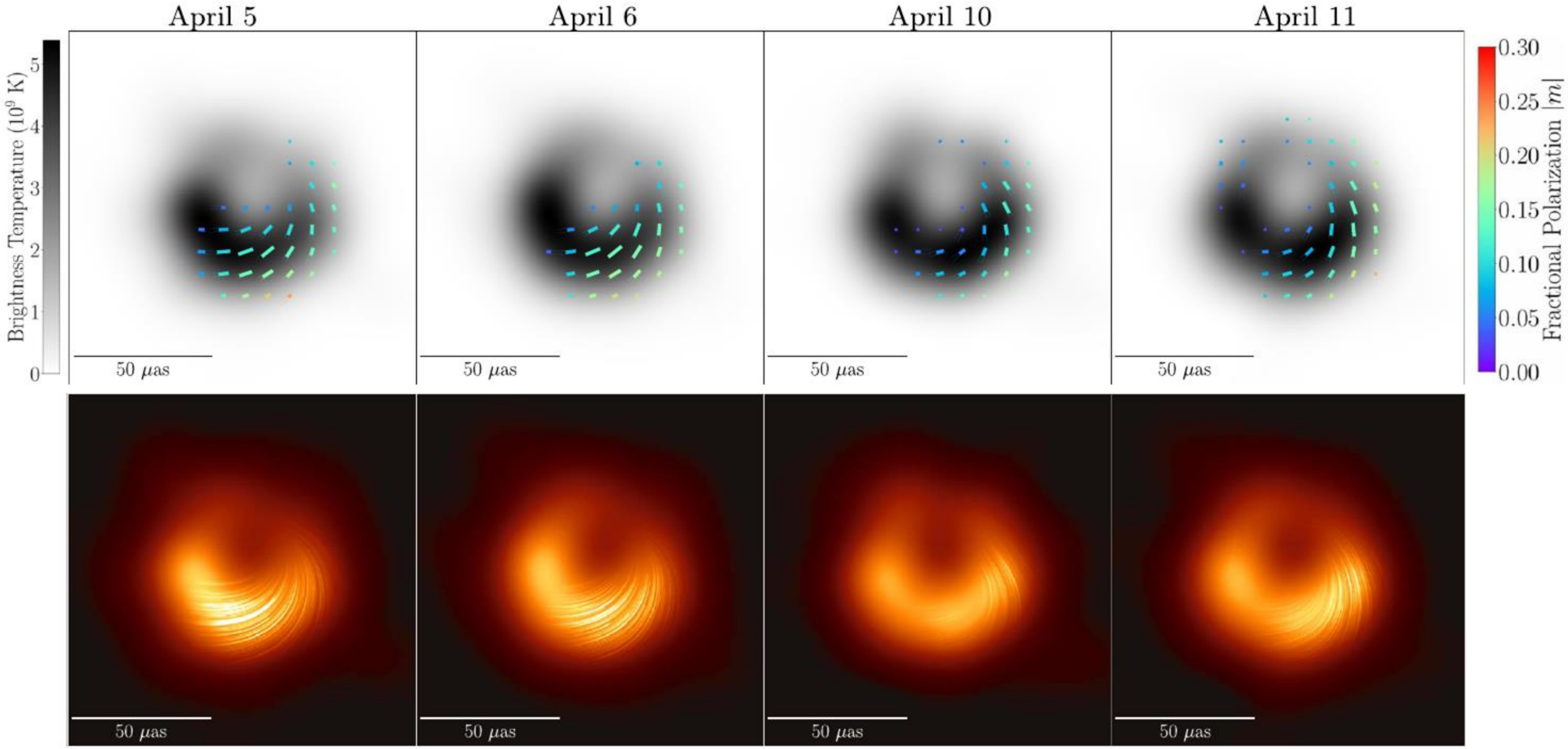
Images for **April 11** from five vetted methods



- All methods show similar polarization structure
- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **azimuthal**
- Overall level of polarization is **somewhat weak**, |m| rises to ~15 %

Credit: EHT 2021 Paper VII

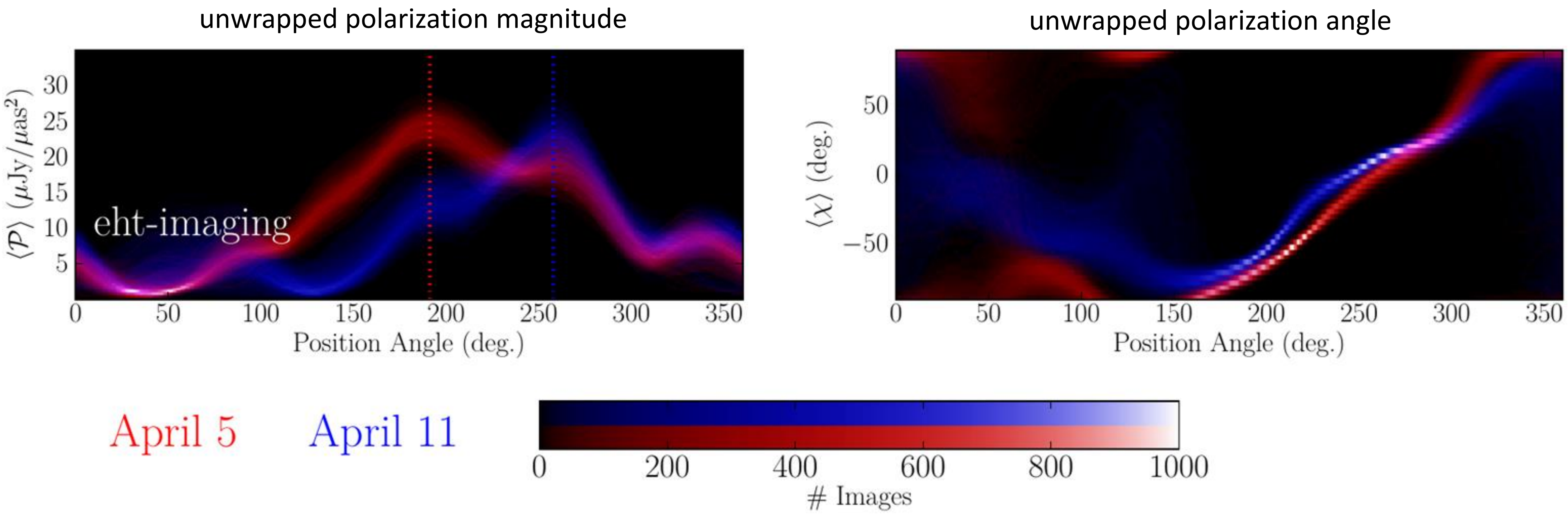
Fiducial **Method-Averaged Images**



Consistent overall structure, but **hints of time-variability** over the week of observations?

Credit: EHT 2021 Paper VII

Azimuthal profiles of the polarized image

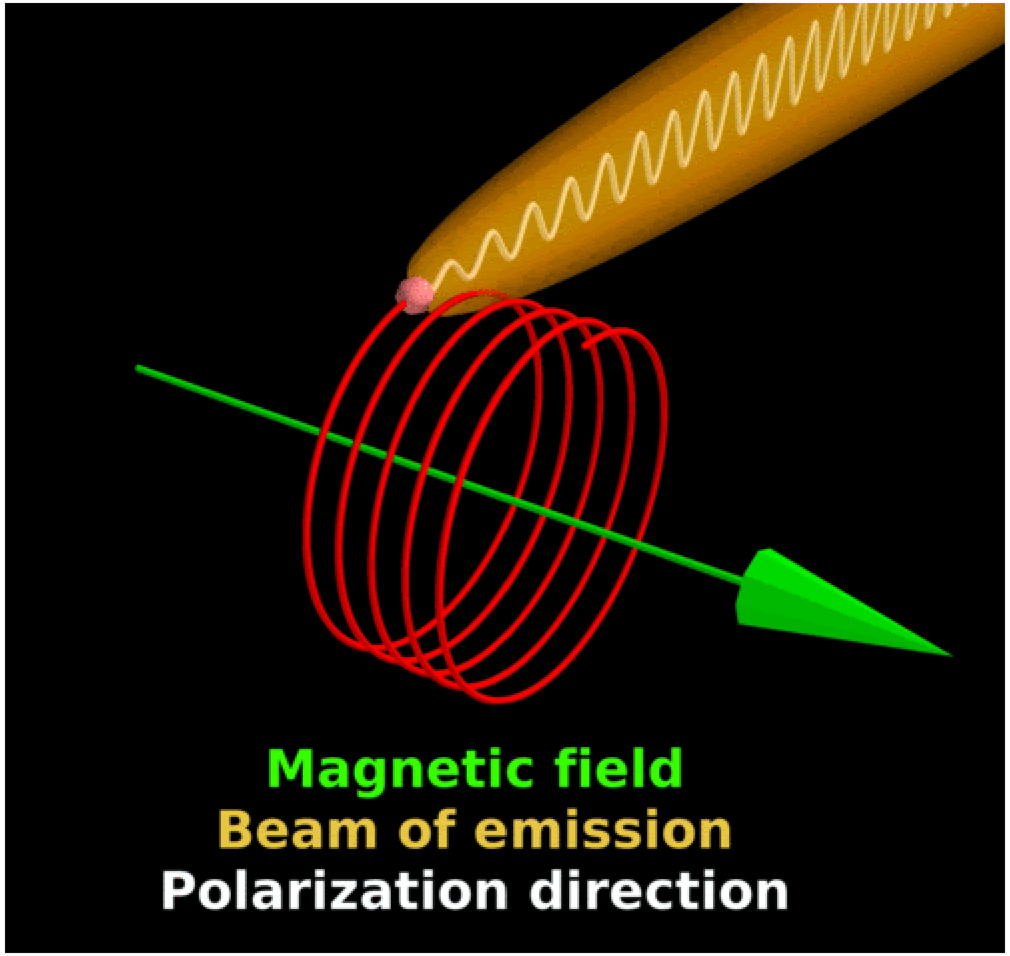


An apparent change in the position angle of the polarization brightness peak from April 5 to April 11

Credit: EHT 2021 Paper VII

What does this image tell us about magnetic fields near the supermassive black hole?

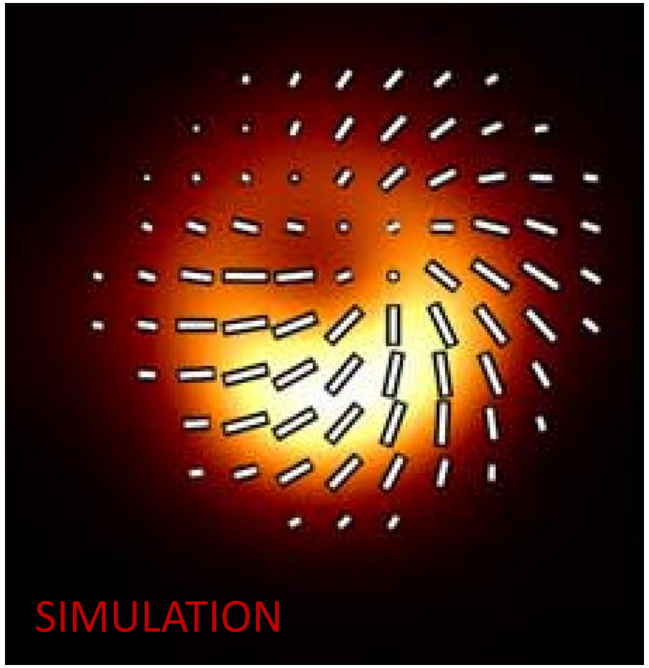
Synchrotron polarization traces magnetic fields

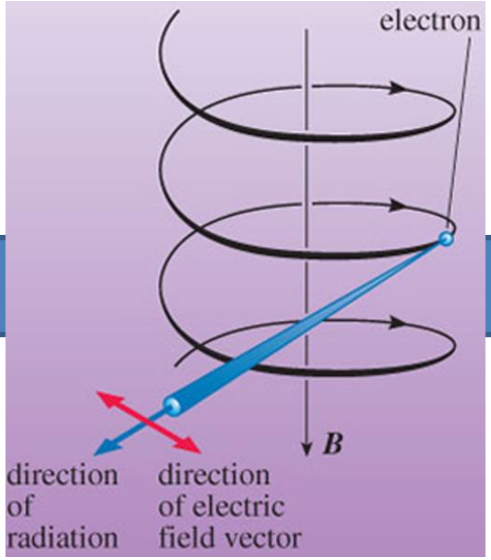


Synchrotron radiation is emitted with polarization **perpendicular** to the magnetic field line

Movie credit: Ivan Marti-Vidal

Synchrotron polarization traces magnetic fields



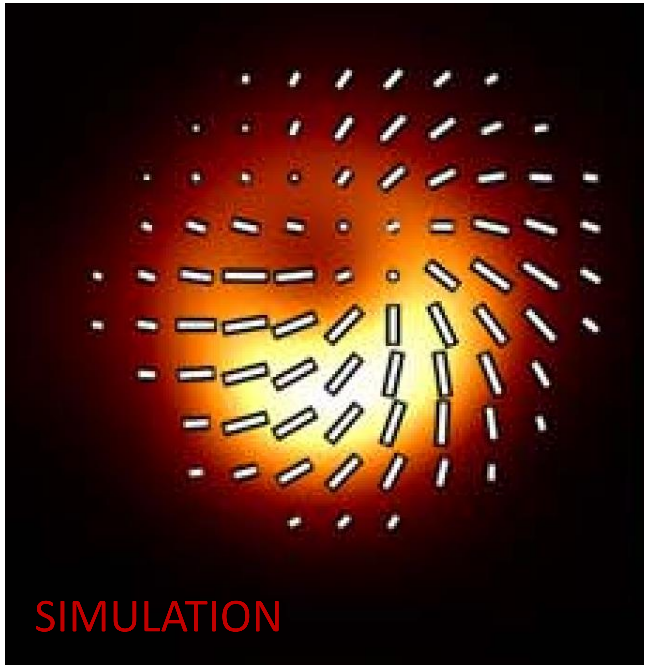


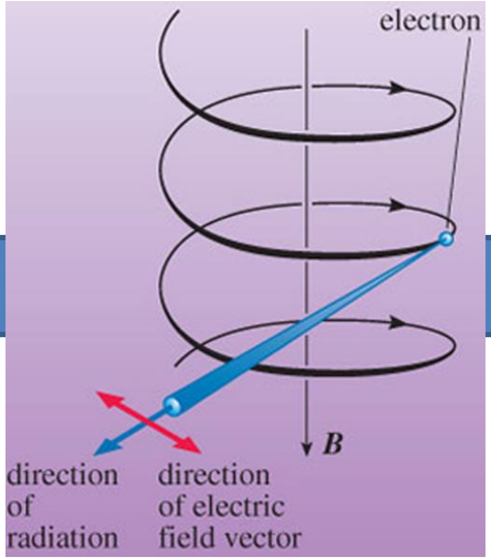
Magnetic field directions in the emission region!

Synchrotron radiation is emitted with polarization **perpendicular** to the magnetic field line

Image credit: EHTC VIII 2021, Open University

Synchrotron polarization traces magnetic fields





Magnet ield
directio n the
emissi n gion!

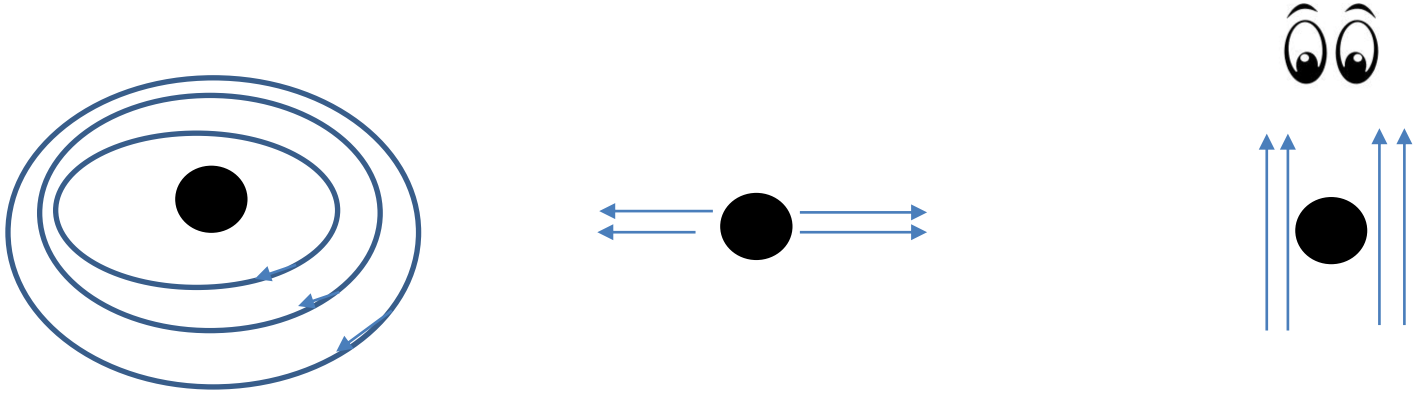
Relativity and Faraday effects make the situation in M87* more complicated!

Image credit: EHTC VIII 2021,
Open University

Relativity matters!

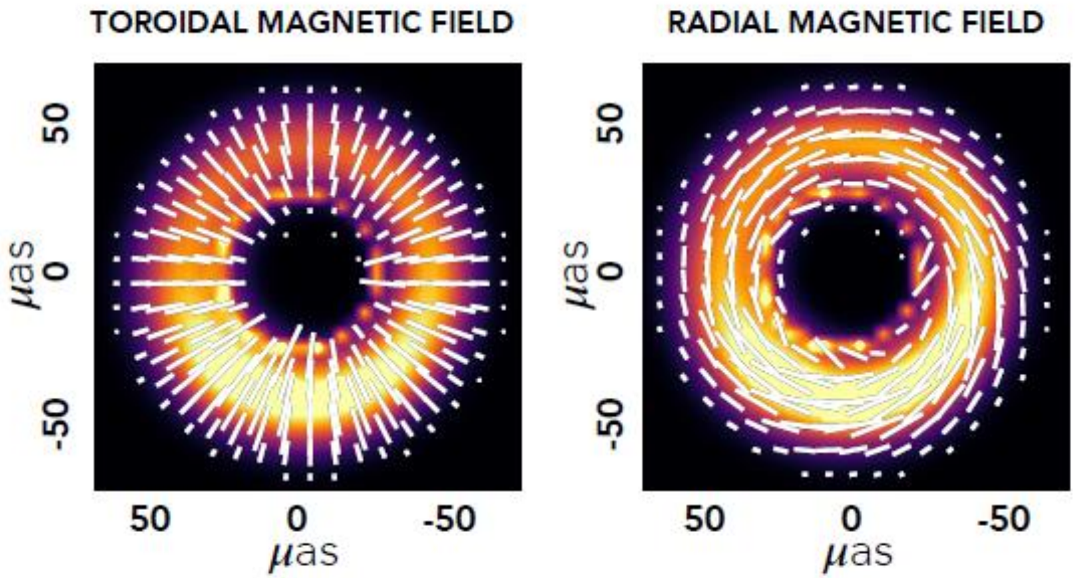
3 simple models, viewed face on

Field structure



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

Observed image



Credit: EHTC 2021 Paper VIII
Jiménez-Rosales+ 2018

Relativity matters!

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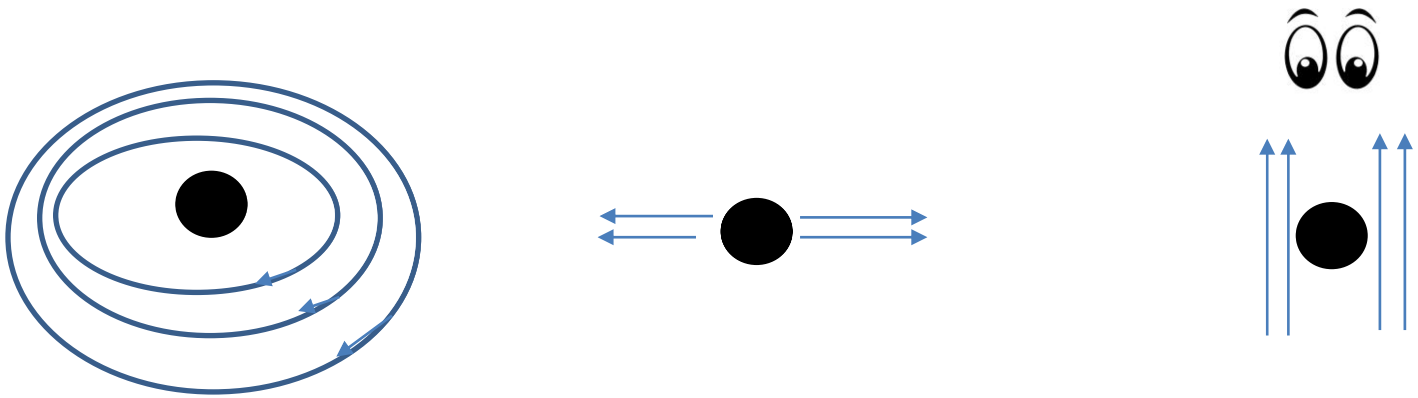

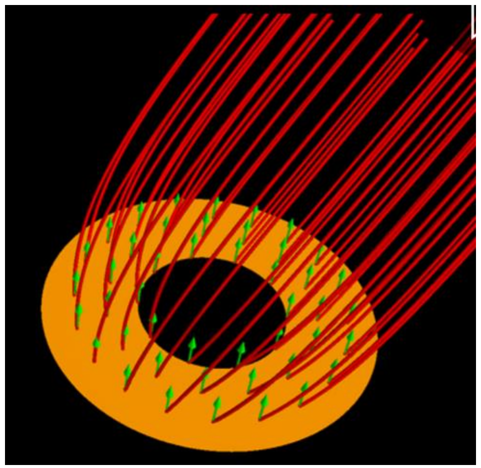

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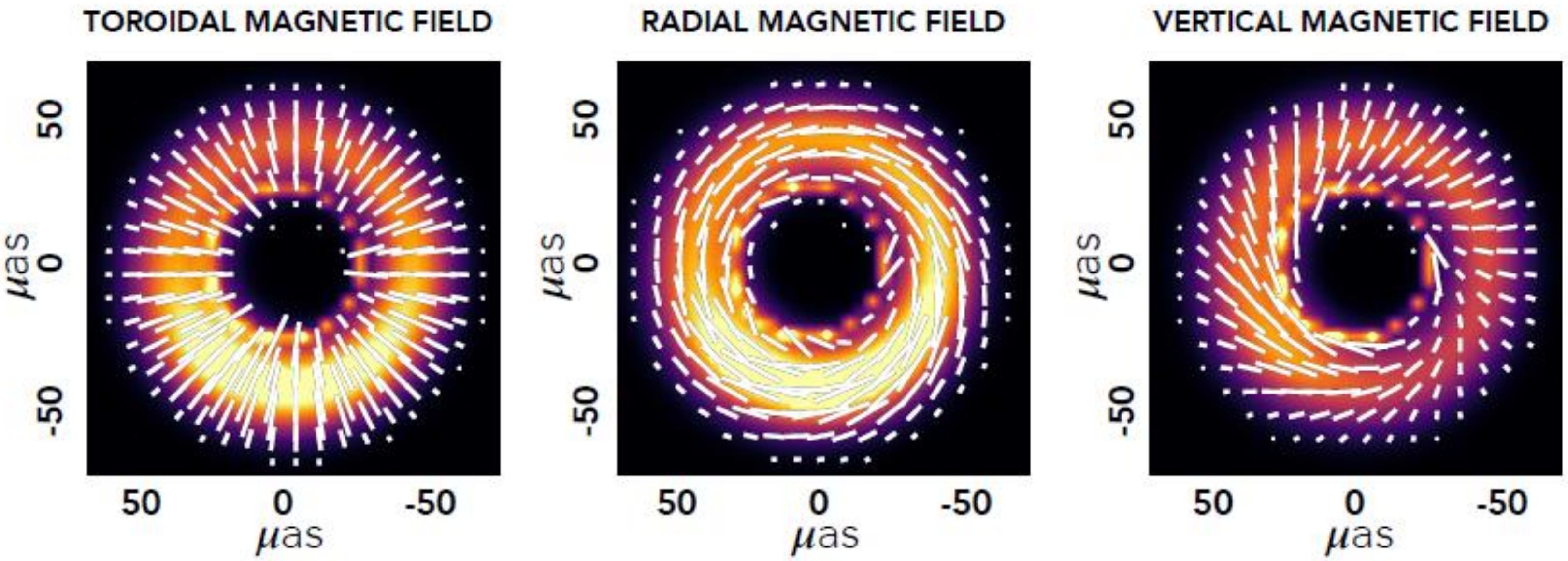
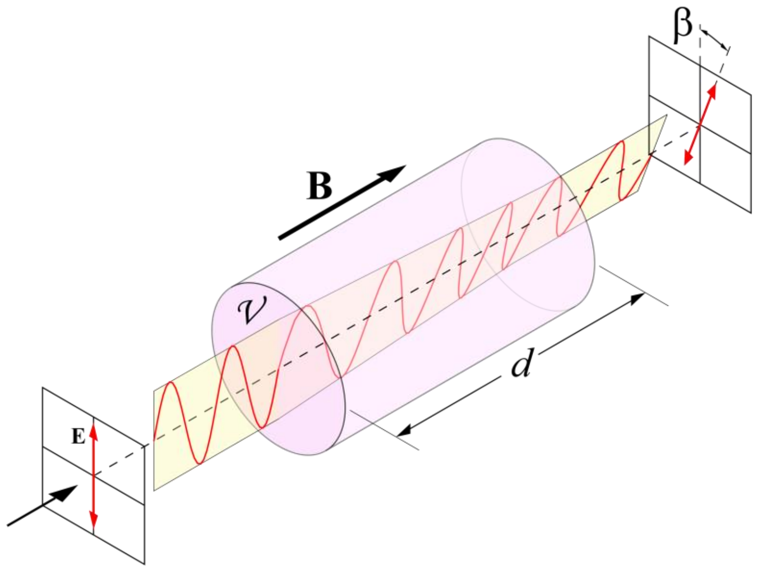


Credit: EHTC 2021 Paper VIII
Jiménez-Rosales+ 2018
Ivan Marti-Vidal

Faraday rotation matters!

- Light propagation in a plasma **rotates** the plane of polarization



- 'Internal' vs 'External' Faraday rotation:
  - **External** → rotation is far from the source, polarization rotated by same angle everywhere
  - **Internal** → rotation is inside emitting source, different image regions rotated by different amounts

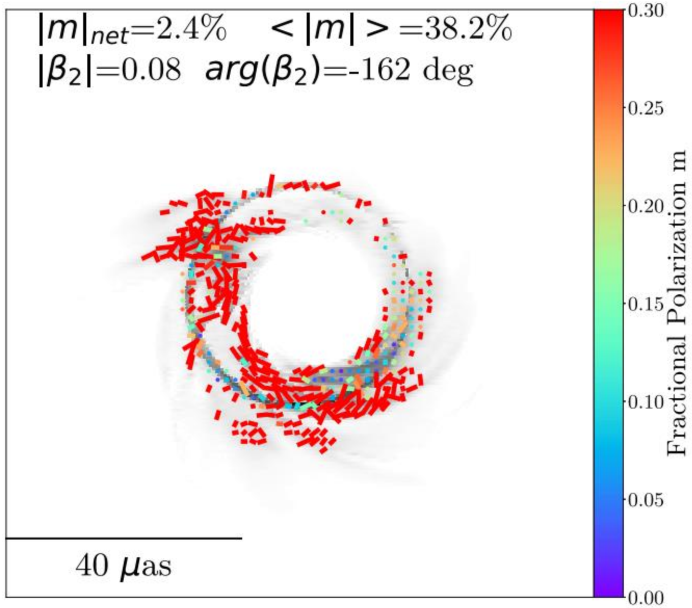
Image credit: Wikipedia

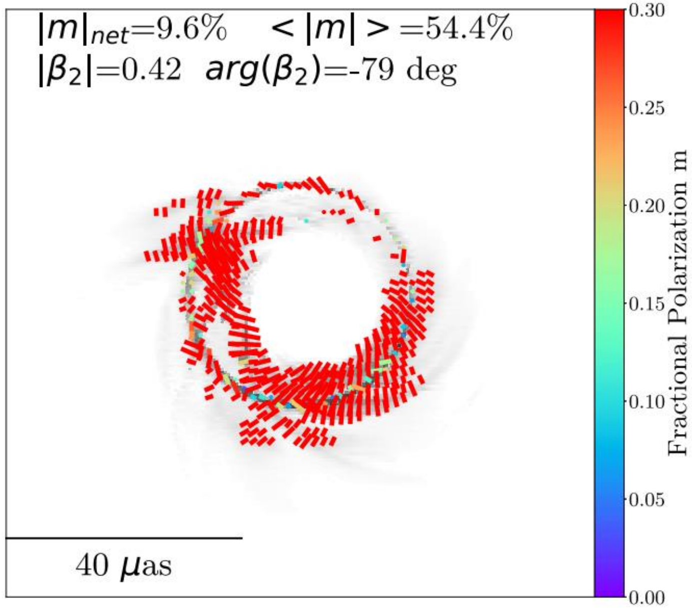
(Internal) Faraday rotation matters!

With rotation

Without rotation

'infinite' resolution



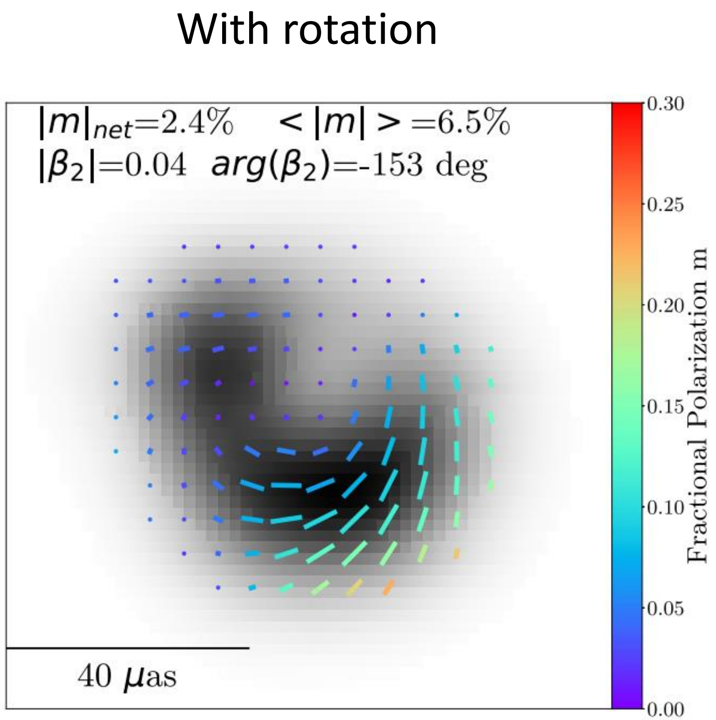


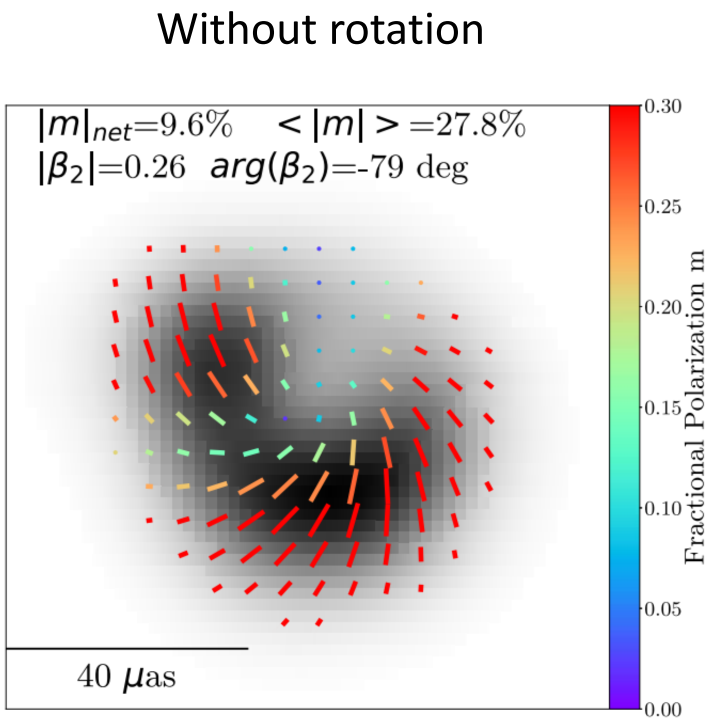
- Significant Faraday rotation on small scales
  → **scrambles** polarization directions
  → **depolarization** of the image when blurred to EHT resolution
  → **overall rotation** of the pattern when blurred to EHT resolution

Credit: EHTC 2021 Paper VIII

(Internal) Faraday rotation matters!

EHT resolution





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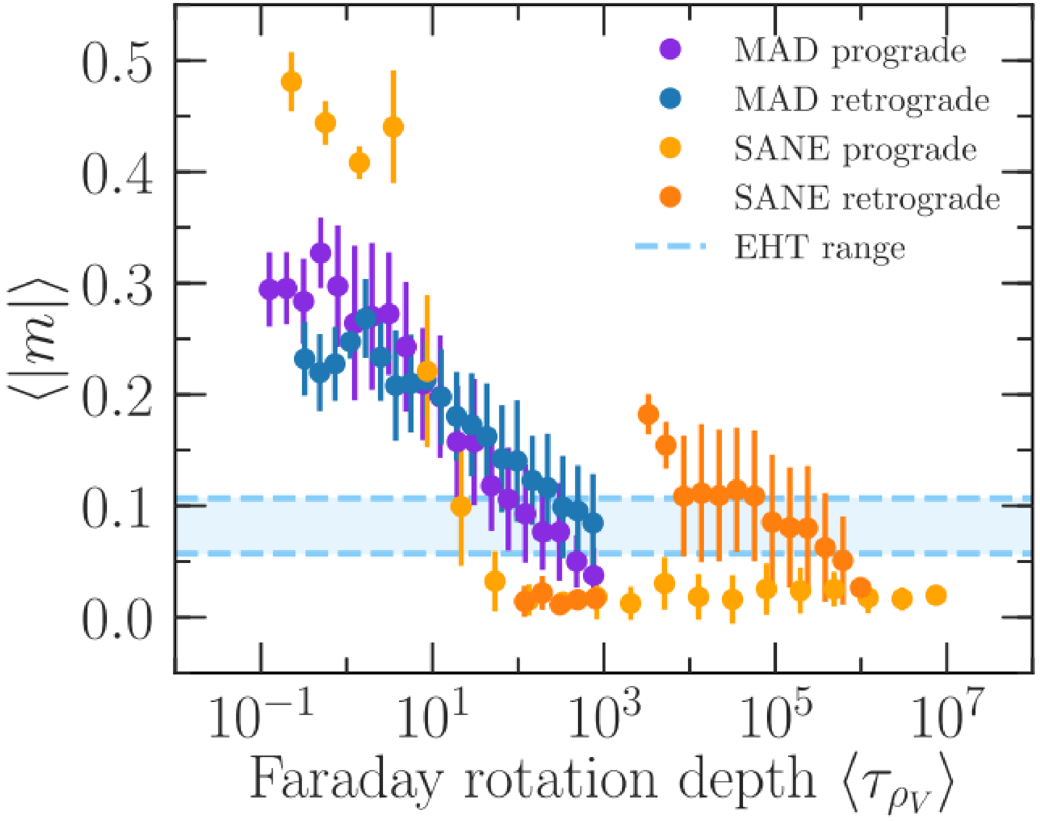
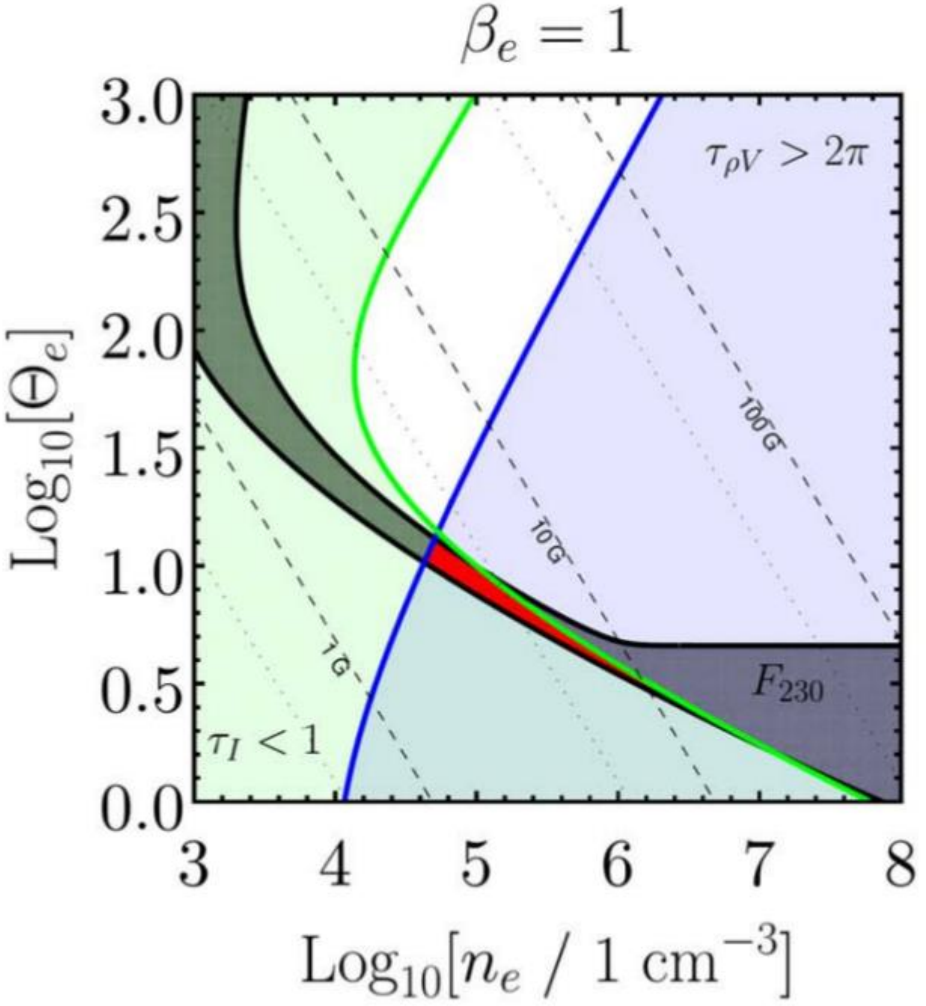
  → **depolarization** of the image when blurred to EHT resolution
  → **overall rotation** of the pattern when blurred to EHT resolution

- In simulations, only significant internal Faraday rotation can produce the low fractional polarization we observe



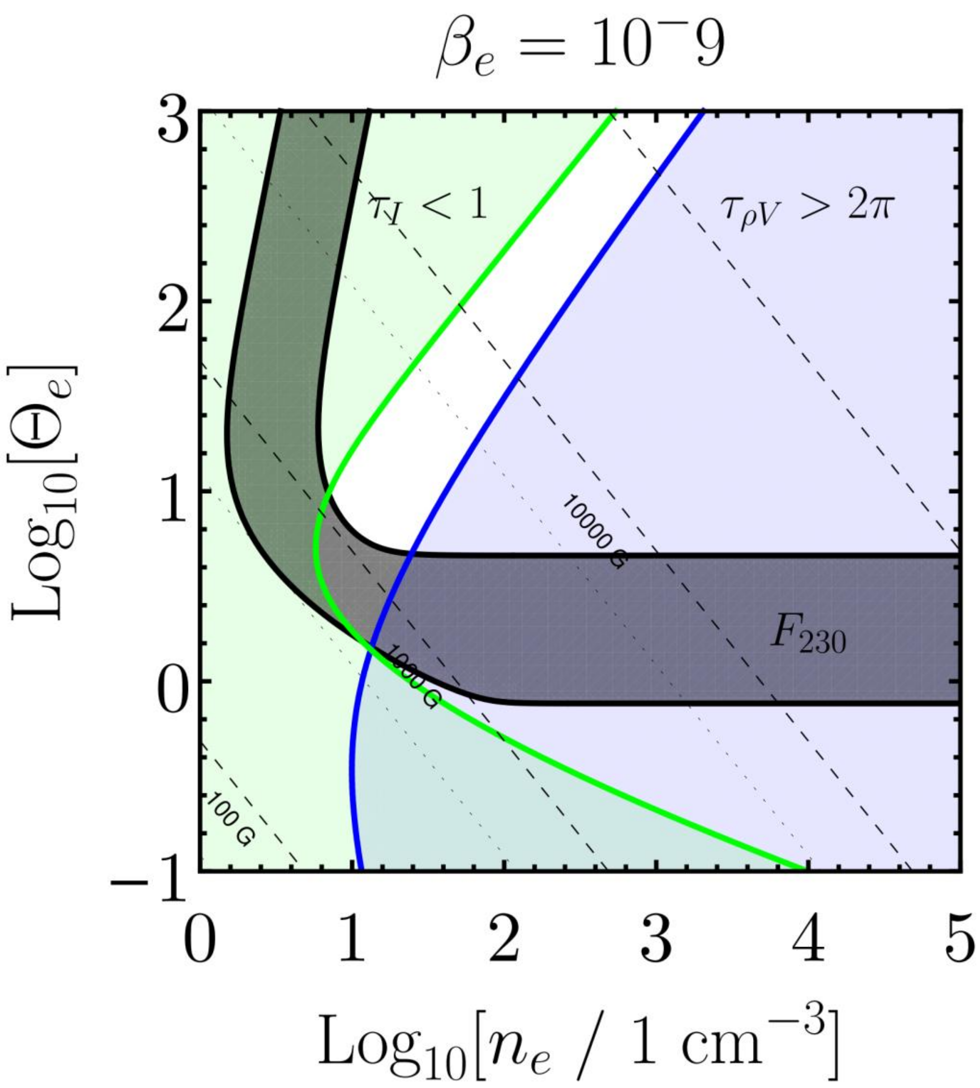
Credit: EHTC 2021 Paper VIII
Jimenez-Rosales+ 2018

Faraday rotation constrains the plasma parameters: Simple one-zone model



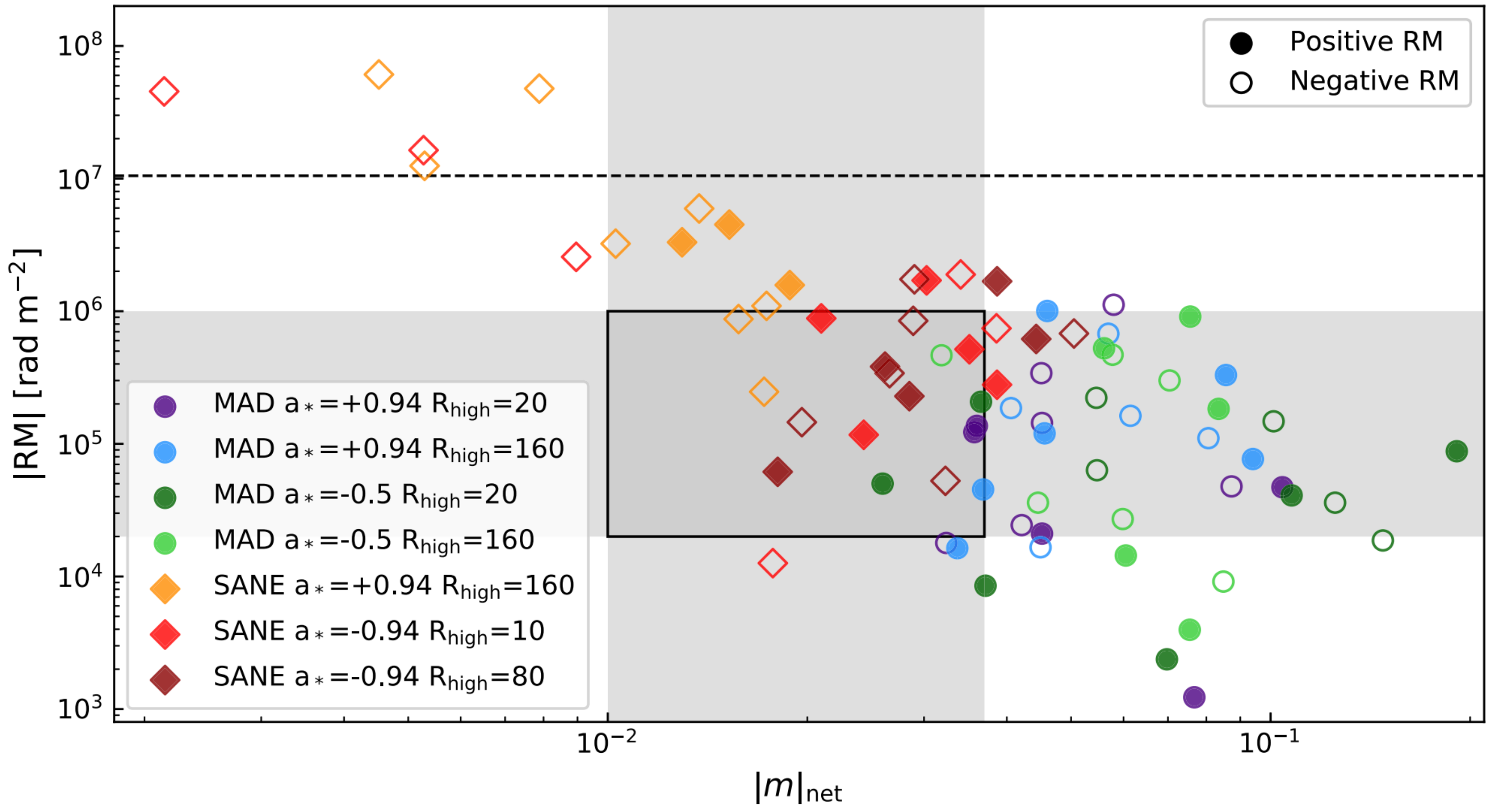
- Isothermal sphere model: no GR or SR effects
- Demand that the emission satisfy 3 constraints:
  - Optically thin
  - Faraday thick
  - Total flux density in EHT range for M87
- Constrains the electron temperature, number density, and magnetic field strength:
  - $10^{10} < T < 1.2\text{x}10^{11}$ K
  - $10^4 < n < 10^7$ cm^{-3}
  - $1 < |B| < 30$ G
- Density is most sensitive to β (magnetic pressure/gas pressure) assumed in the model

Faraday rotation constrains the plasma parameters: Simple one-zone model



- Isothermal sphere model: no GR or SR effects
- Demand that the emission satisfy 3 constraints:
  - Optically thin
  - Faraday thick
  - Total flux density in EHT range for M87
- This model disfavors very strong (kG) fields, where the emission would have to be optically thick to be Faraday thick

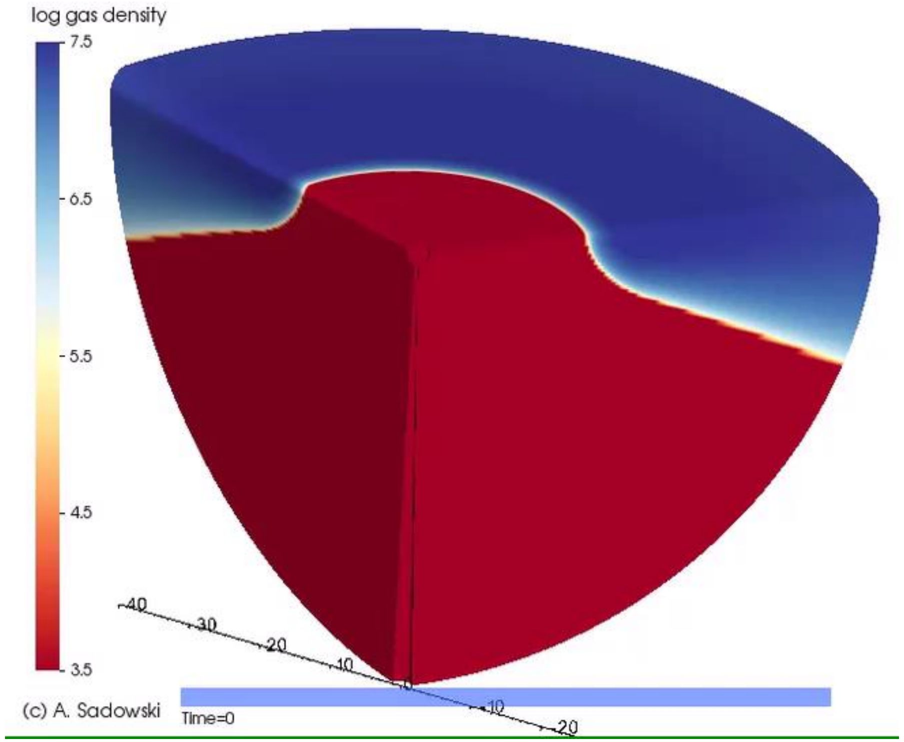
GRMHD simulations can explain observed **net** RM **internally**



Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

Credit: EHTC 2021 Paper VIII
Angelo Ricarte

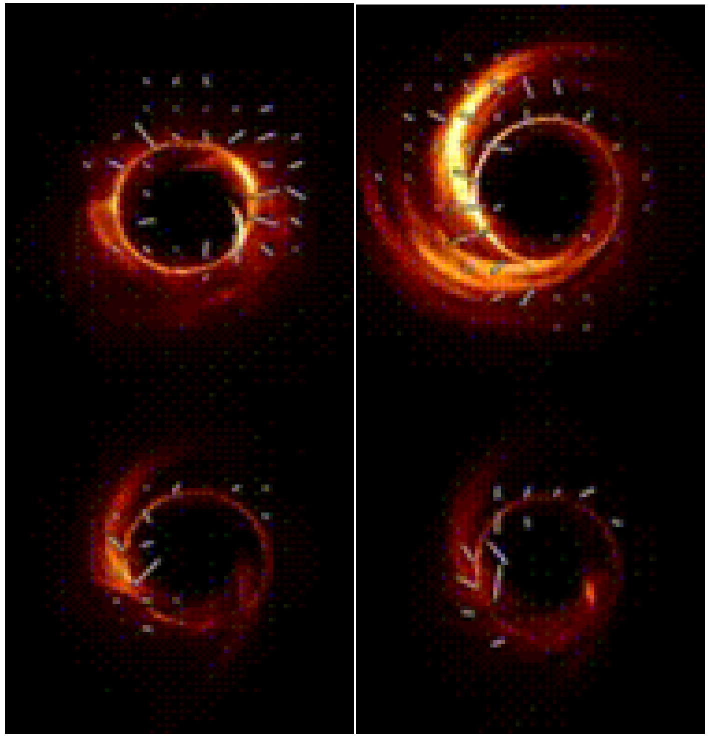
General Relativistic MagnetoHydroDynamic (GRMHD) simulations



Solves coupled equations of plasma and magnetic field in Kerr spacetime

$T_e?$

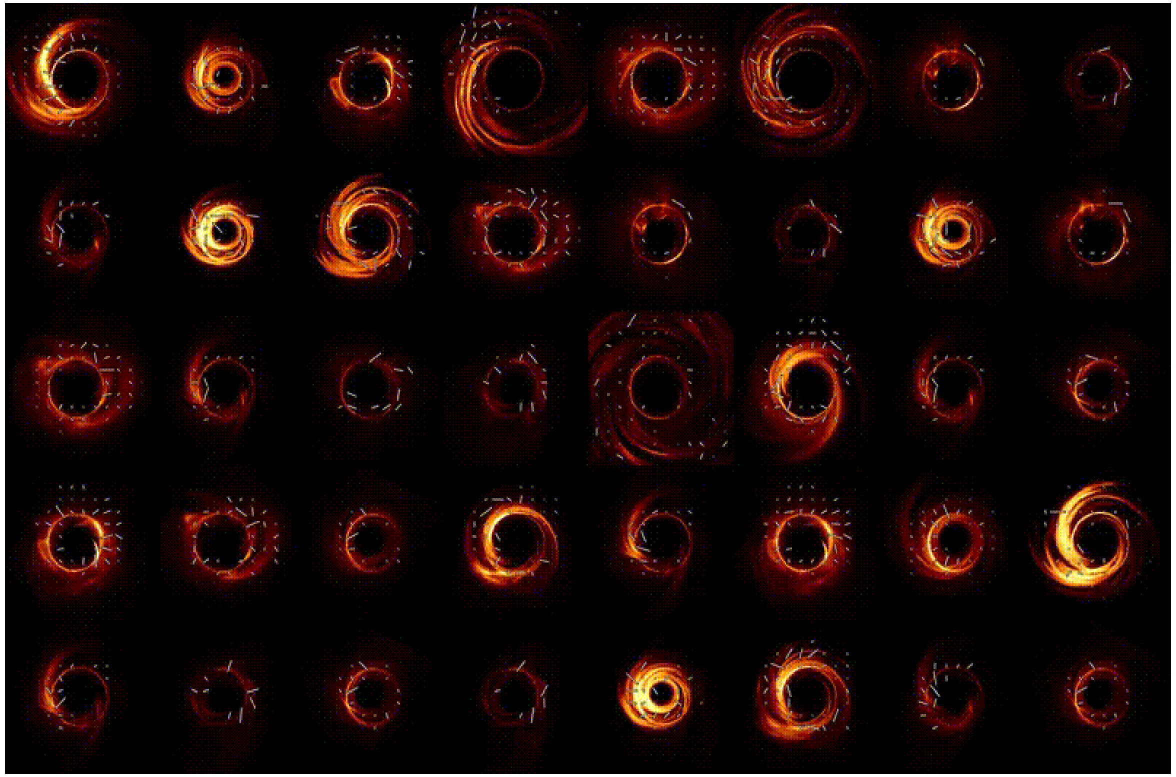
General Relativistic Ray Tracing (GRRT)



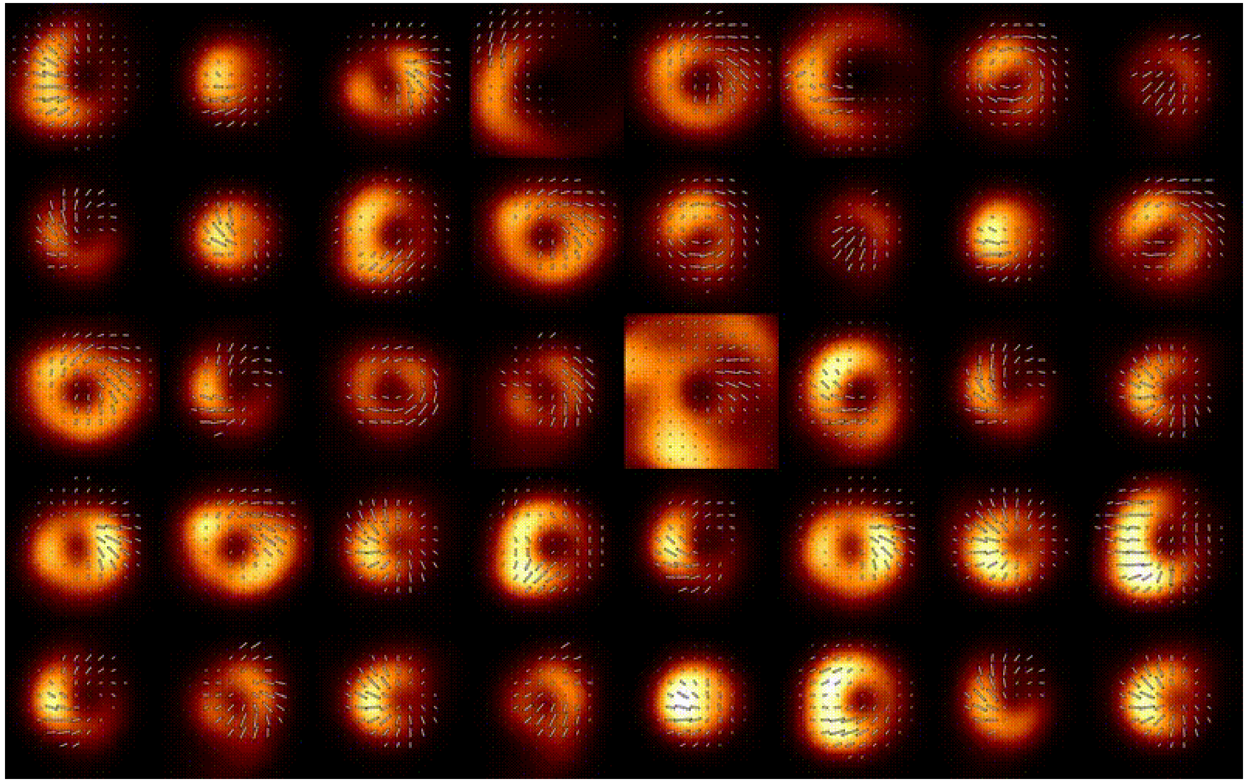
Tracks light rays and solves for the polarized radiation (incl. parallel transport and Faraday rotation)

Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather (right)

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

$$\frac{T_i}{T_e} = R_{\text{high}} \frac{\beta^2}{1+\beta^2} + R_{\text{low}} \frac{1}{1+\beta^2}$$

Two parameters set the electron temperature

Animation credit: George Wong/ Ben Prather

Key quantities in simulations of M87

1. Spacetime geometry: M, a
   - -Liberating potential energy heats the plasma.
   - -Extraction of spin energy can form jets

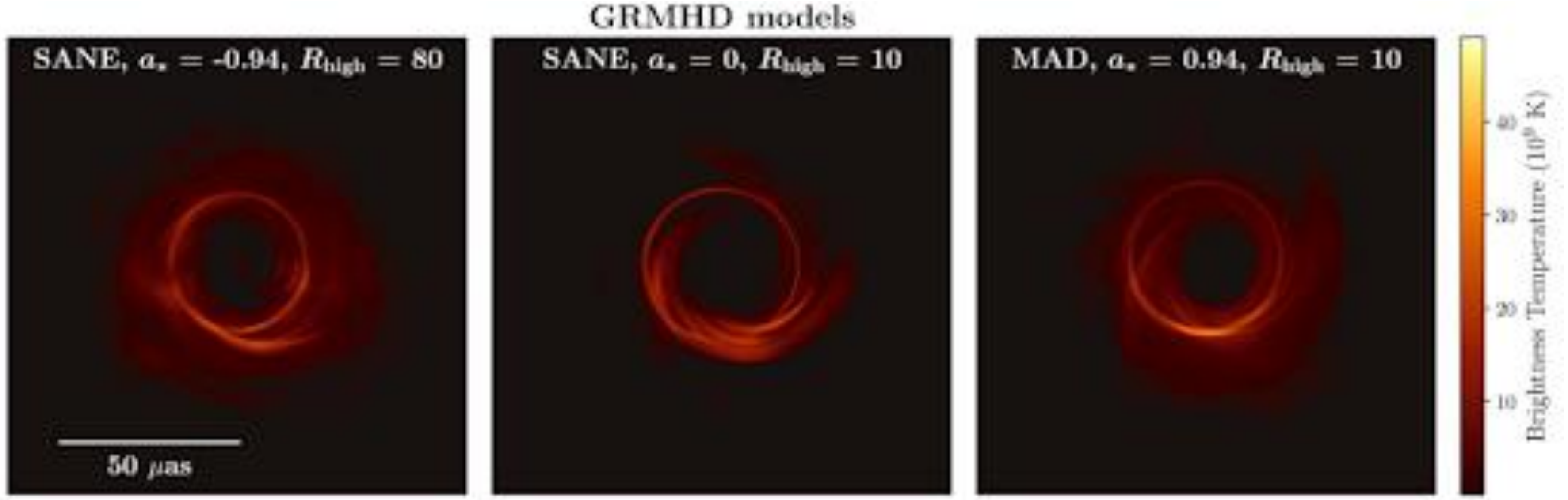
2. Accretion and magnetic field: $\dot{M}, \Phi_B$
   - - Is the B-field weak and turbulent or strong & coherent?
   - - How quickly does the black hole accrete matter?

3. Electron distribution function: $T_e, n_e(\gamma)$
   - -What plasma processes set the electron temperature?
   - -Is there a nonthermal population?

Scoring GRMHD Simulations: before polarization

(EHTC 2019, Paper V)

- **Most simulation models can be made to fit total intensity observations alone** by tweaking free parameters (mass, PA, total flux density)



- An additional constraint on **jet power** (≥ 10^{42} erg/sec) rejects all spin 0 models
- Can we do better with polarization?

EHTC+ Paper V, 2019

Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

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

Unresolved circular polarization fraction (from ALMA)

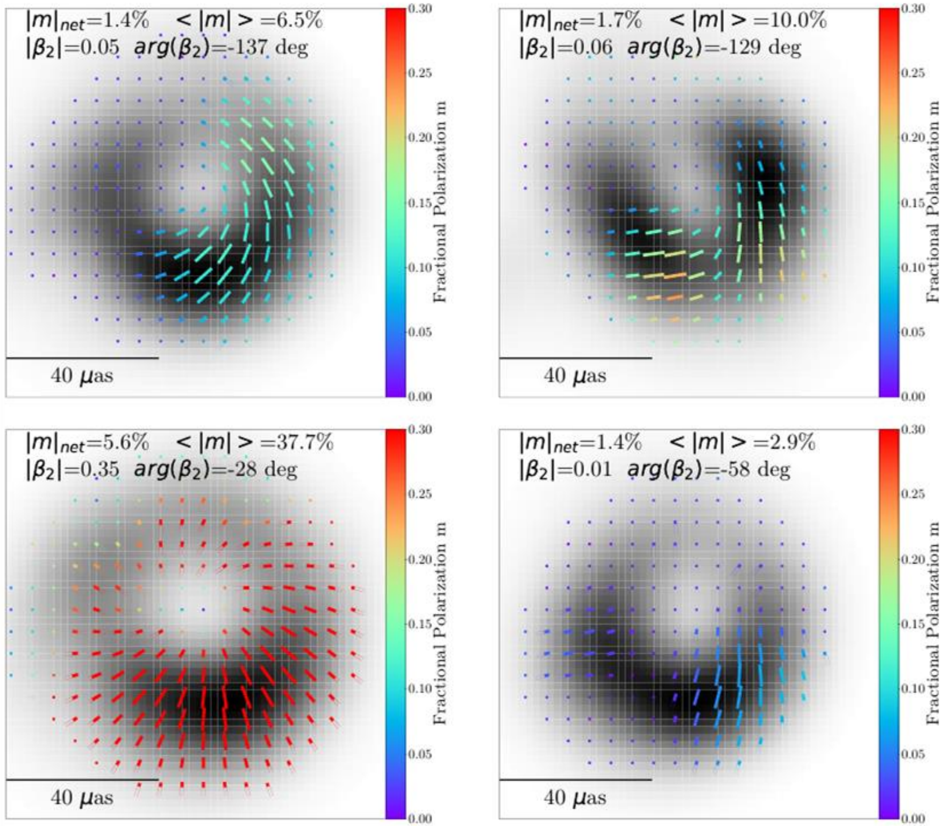
$$|v|_{\rm net} = \frac{\left|\sum_i V_i\right|}{\sum_i I_i}$$

Average resolved polarization fraction

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

Azimuthal structure 2nd 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

EHTC+2021

Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

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

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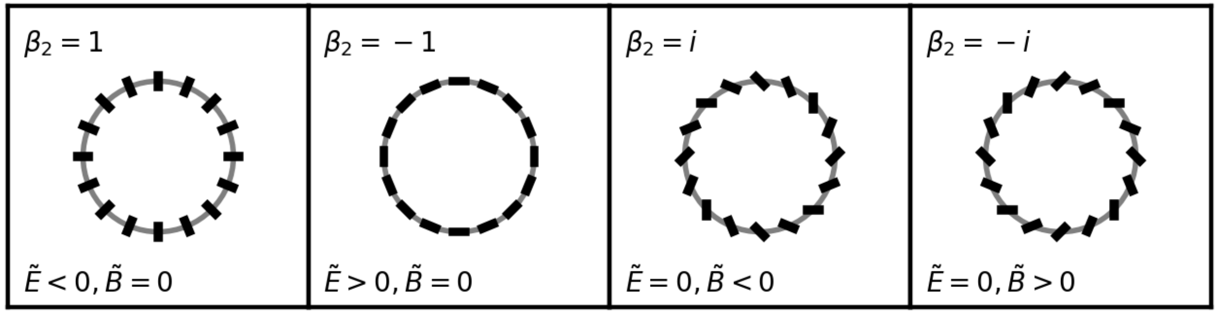
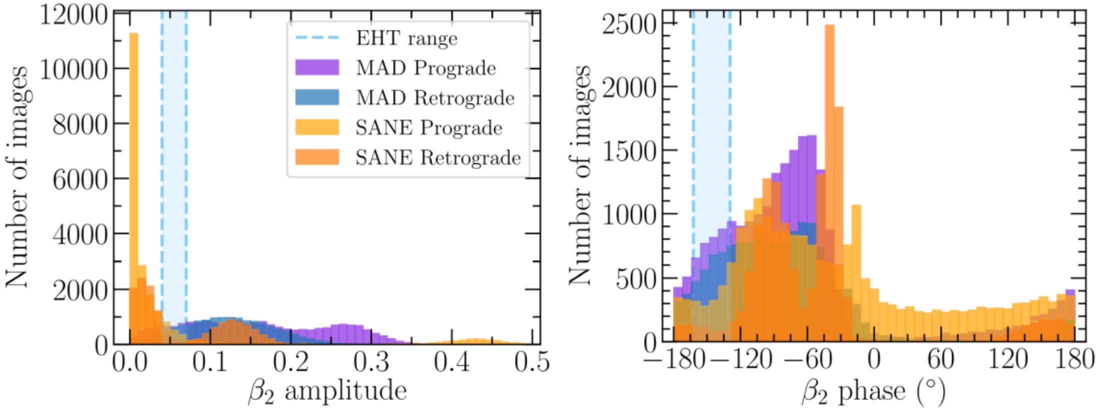
Azimuthal structure
2nd mode

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





2nd azimuthal mode is a strong discriminator of accretion states (Palumbo+ 2020)
Equivalent to E- or B- mode of the polarization pattern

EHTC+2021
Palumbo+ 2020

Scoring simulations with polarization: Image metrics

Unresolved linear polarization fraction

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

Unresolved circular polarization fraction (from ALMA)

$$|v|_{\rm net} = \frac{|\sum_i V_i|}{\sum_i I_i}$$

Average resolved polarization fraction

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

Azimuthal structure 2nd Fourier mode

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

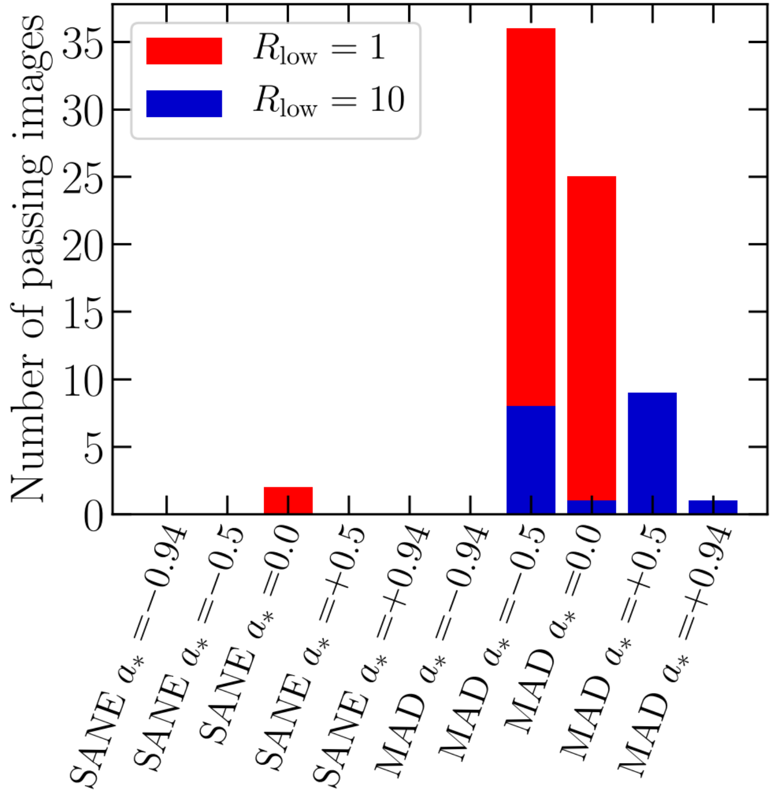
We define an acceptable **range for each parameter** that accounts for systematic uncertainty in D-term and image reconstruction among methods

Parameter	Min	Max
$\lvert m\rvert_{\rm net}$	1.0%	3.7%
$\lvert v\rvert_{\rm net}$	0	0.8%
$\langle \lvert m\rvert \rangle$	5.7%	10.7%
$\lvert\beta_2\rvert$	0.04	0.07
$\angle\beta_2$	−163 deg	−129 deg

EHTC+2021, Paper VII, VIII

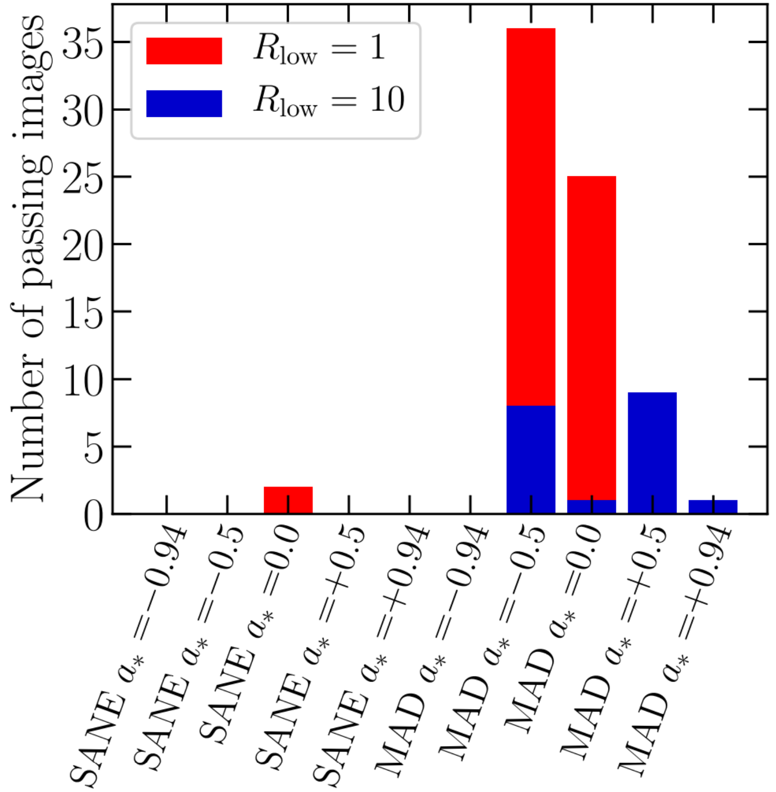
Polarimetric simulation scoring

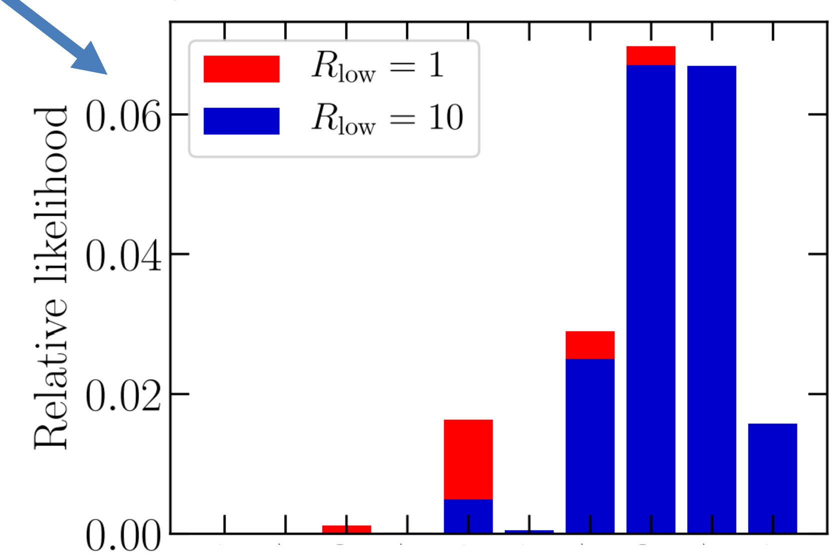
- Two scoring approaches:
  - **‘simultaneous’** (demand individual images satisfy all image constraints at once)
  - Only 73 / 72,000 images satisfy all constraints simultaneously!
  - All but 2 of the passing images are from MAD simulations



Polarimetric simulation scoring

- Two scoring approaches:
  - **'simultaneous'** (demand individual images satisfy all image constraints at once)
  - **'joint'** (compute a likelihood comparing distance between measured quantities and simulation mean with the simulation variance)
- **Both approaches strongly favor magnetically arrested (MAD) simulations**
- The two approaches differ 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

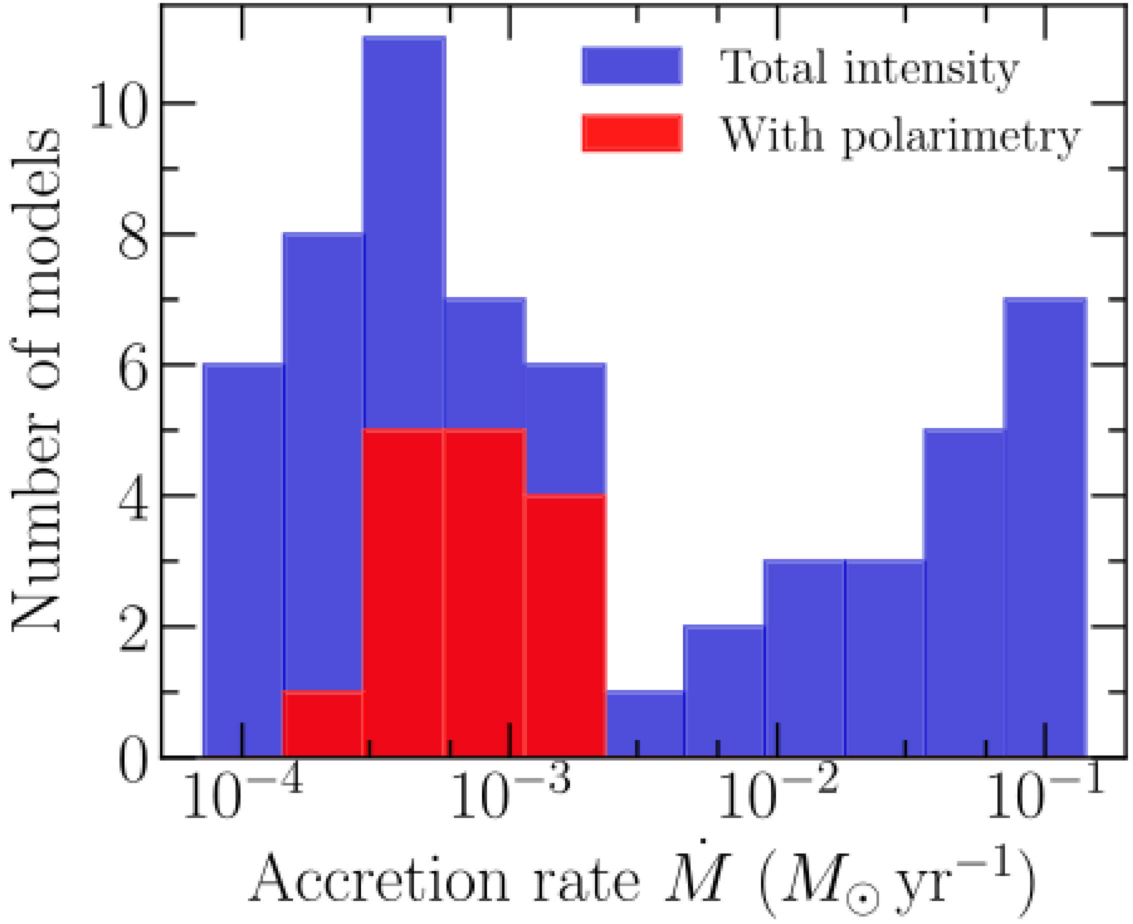
- Surviving models significantly tighten constraints on accretion rate from total intensity results:

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

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

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

- Radiative efficiency ~1%
  - Cooling is important!

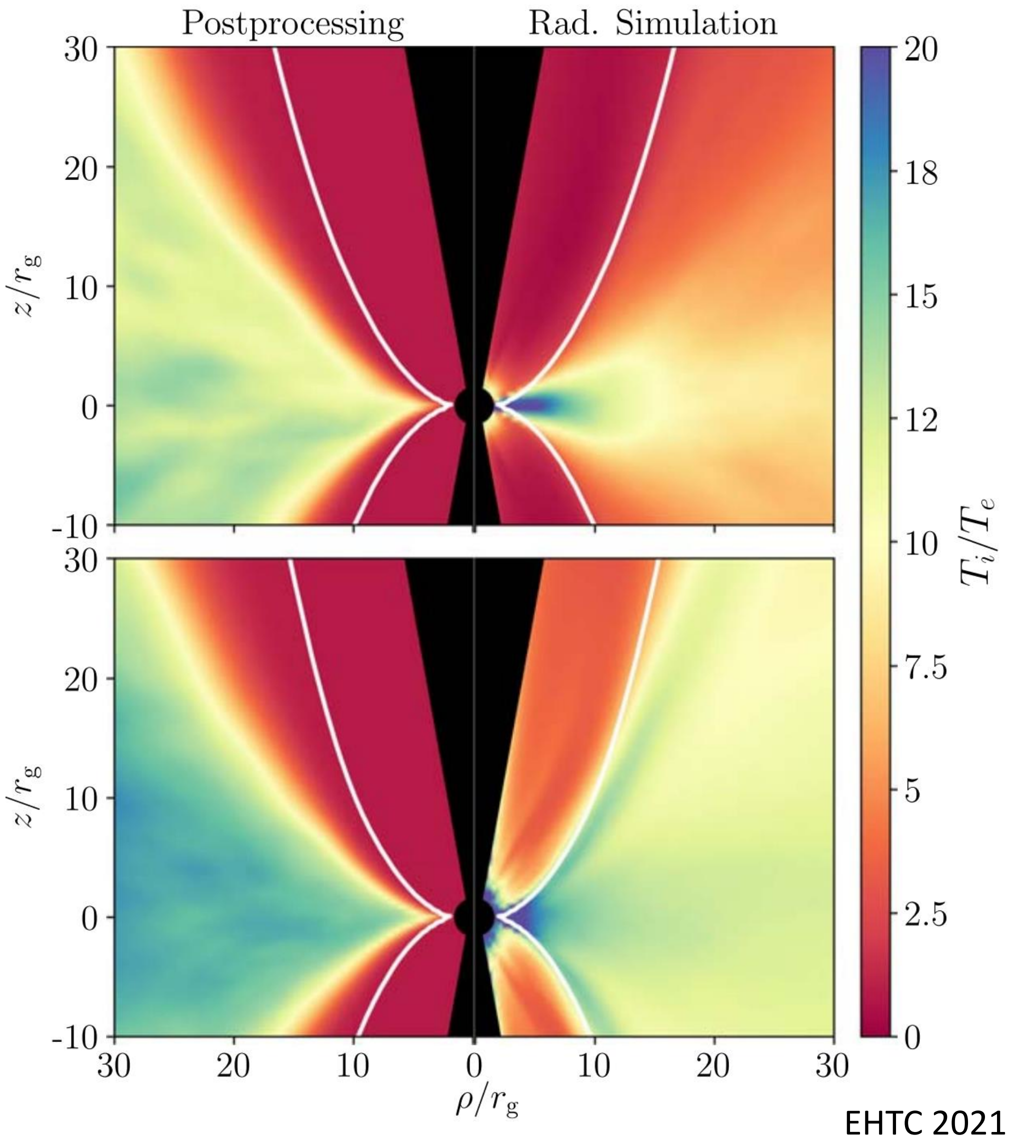


Next Steps

Electron Heating/Acceleration/Cooling

- Current simulation has one prescription for determining electron temperature from simulation data, coarsely sampled.
    - Different scoring methods disagree on preferred parameters.
    - Can we constrain these parameters or do we need better models?

- Can radiative simulations help?
    - Self-consistently evolve electron temperatures under cooling/electron heating
    - Computationally expensive, and limited by available plasma models



e.g. Ressler+ 2015,17 Sadowski+ 2017, Chael+ 2018, Dexter+ 2020, Ball 2016, Davelaar 2019

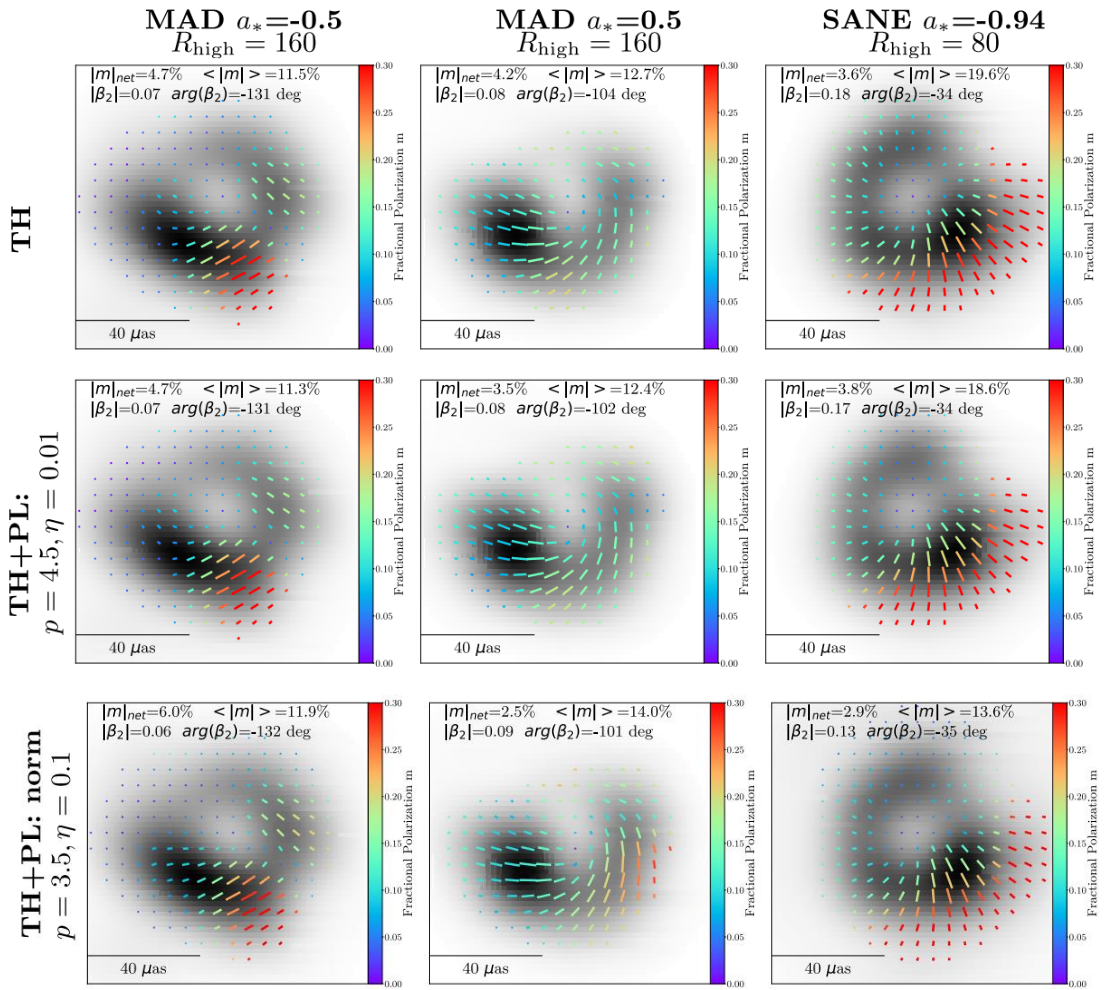
EHTC 2021 Paper VIII
Chael+ 2021

Electron Heating/Acceleration/Cooling

- Current simulation has one prescription for determining electron temperature from simulation data, coarsely sampled.
  - Different scoring methods disagree on preferred parameters.
  - Can we constrain these parameters or do we need better models?

- Can radiative simulations help?
  - Self-consistently evolve electron temperatures under cooling/electron heating
  - Computationally expensive, and limited by available plasma models

- Nonthermal electrons?
  - We explored several extensions with a nonthermal tail to the EDF
  - Does not change preference for MADs, but does add order ~unity uncertainty to accretion rate

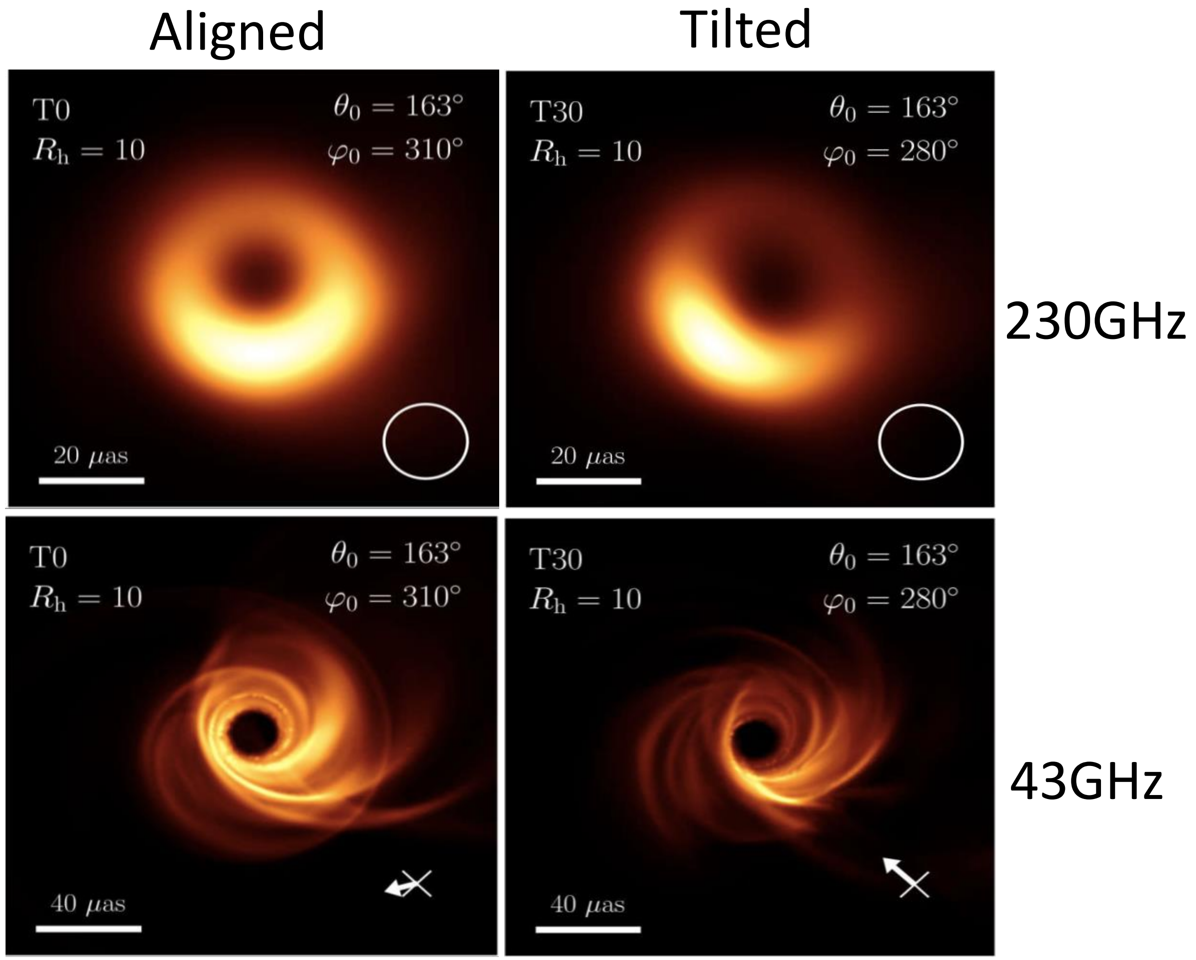


e.g. Ressler+ 2015,17 Sadowski+ 2017, Chael+ 2018, Dexter+ 2020, Ball 2016, Davelaar 2019

EHTC 2021 Paper VIII

Tilted disks

- All EHT library simulations have disk angular momentum **parallel/antiparallel** to BH spin axis
- In tilted-disk simulations, **lensing** of the inner disk/jet base can result in quite different 230 GHz images even though 43 GHz jet images are similar
- Need a library of tilted disk systems!

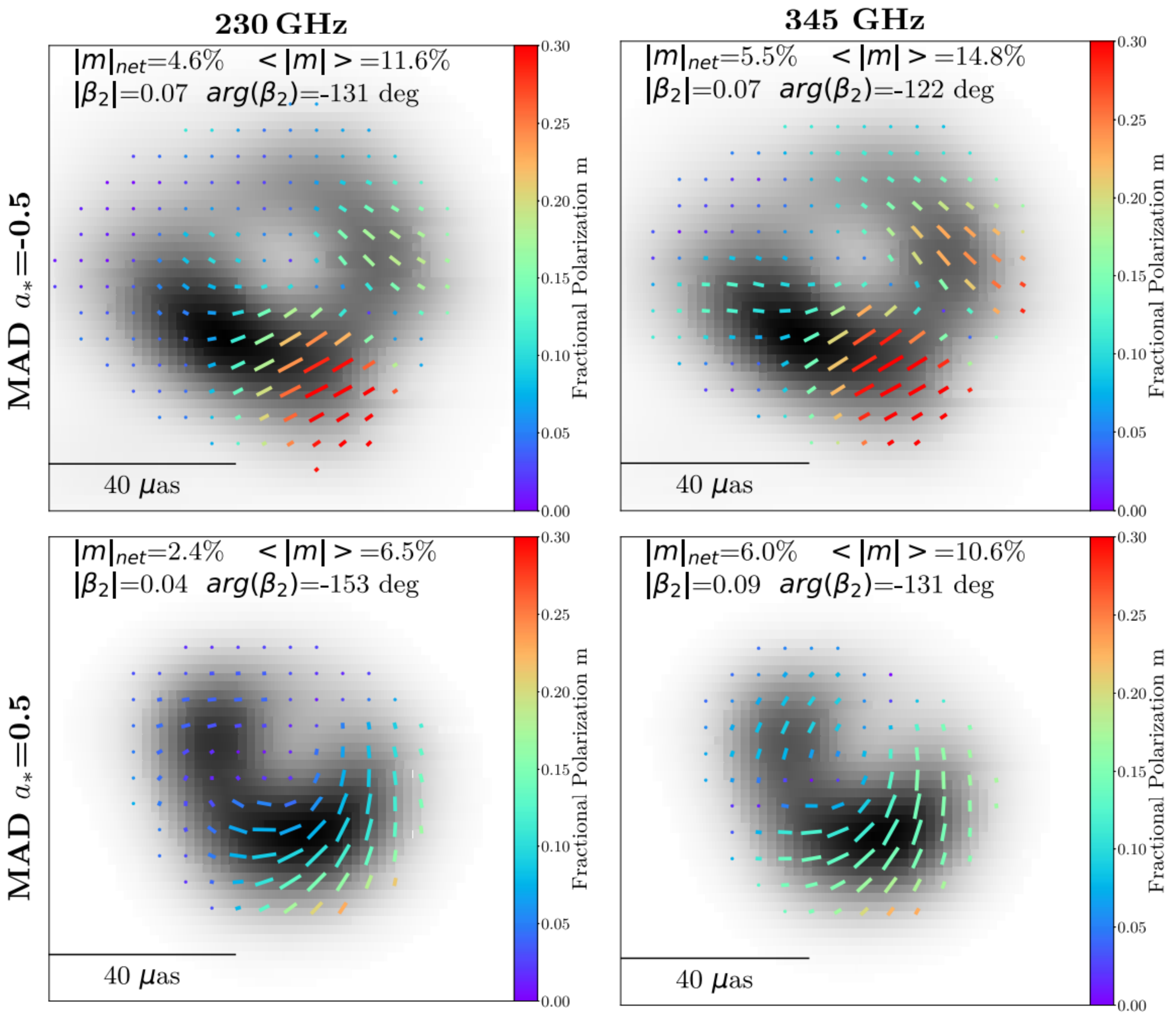


also: Fragile+07, Dexter+11, McKinney+13, Liska+18, White+19,+20

Chatterjee+20

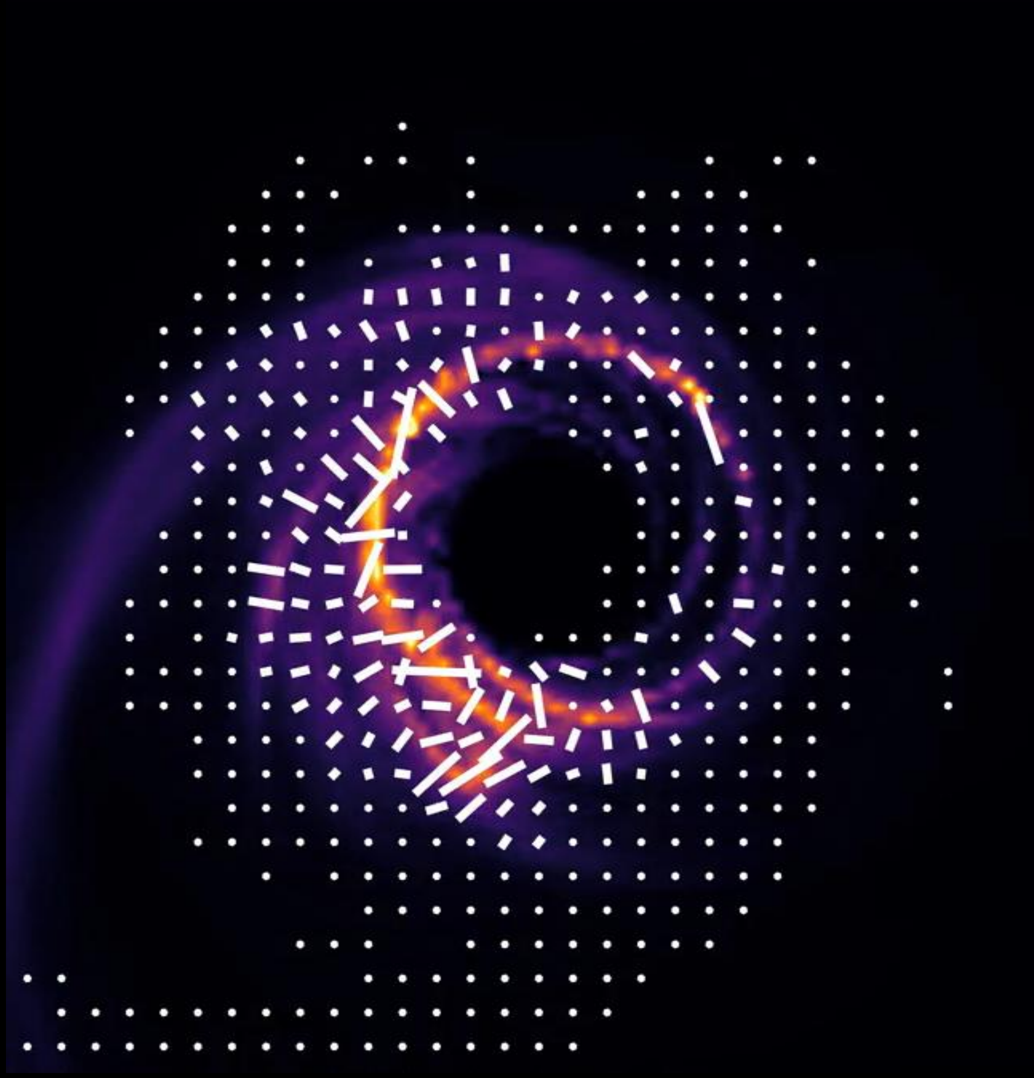
Higher frequencies

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

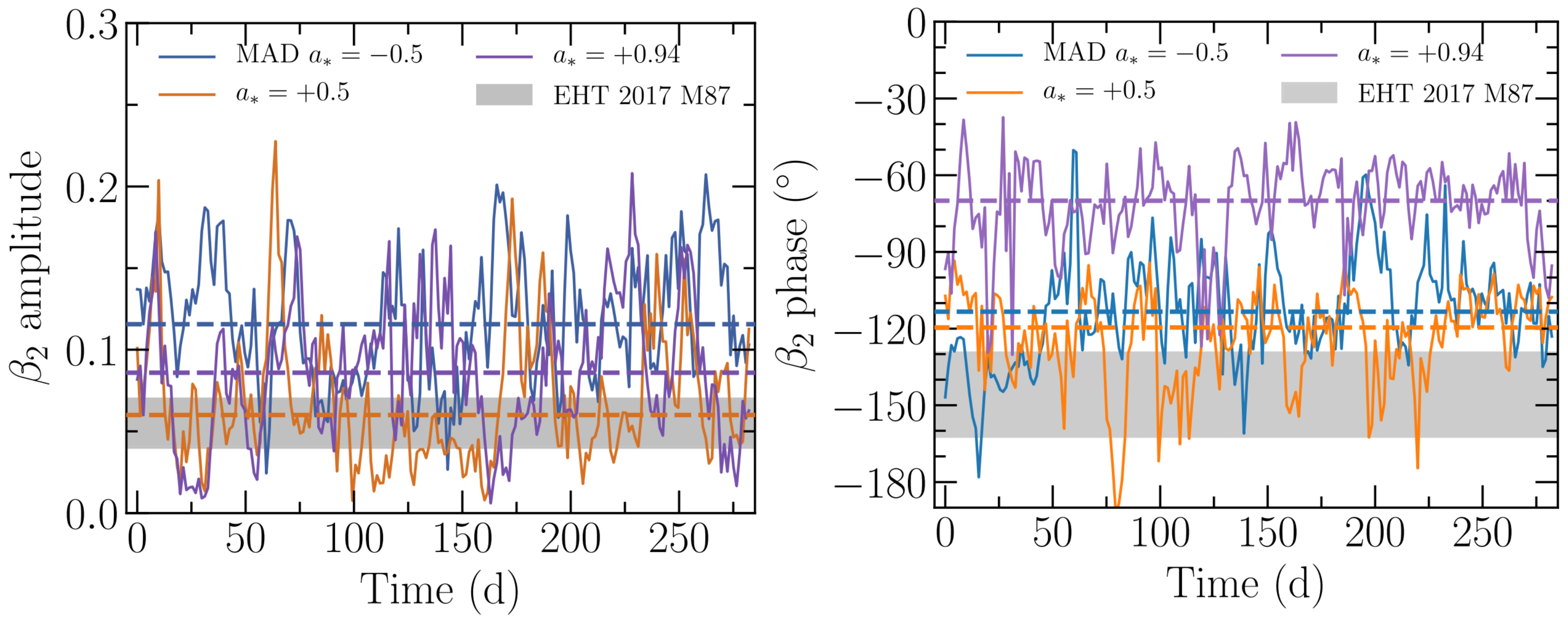


EHTC 2021, Paper VIII

Polarization is *variable*



Polarization is *variable*

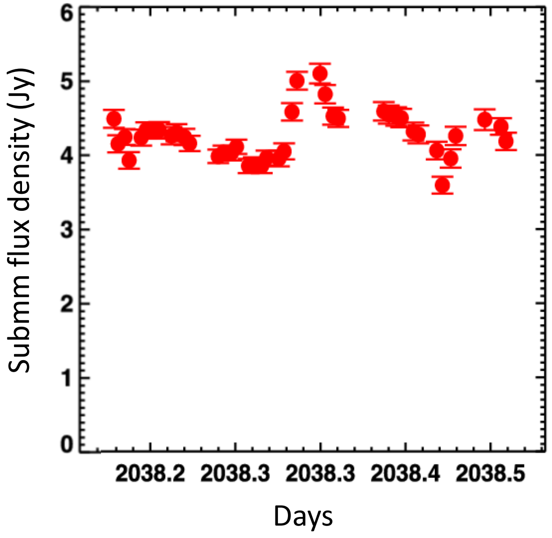


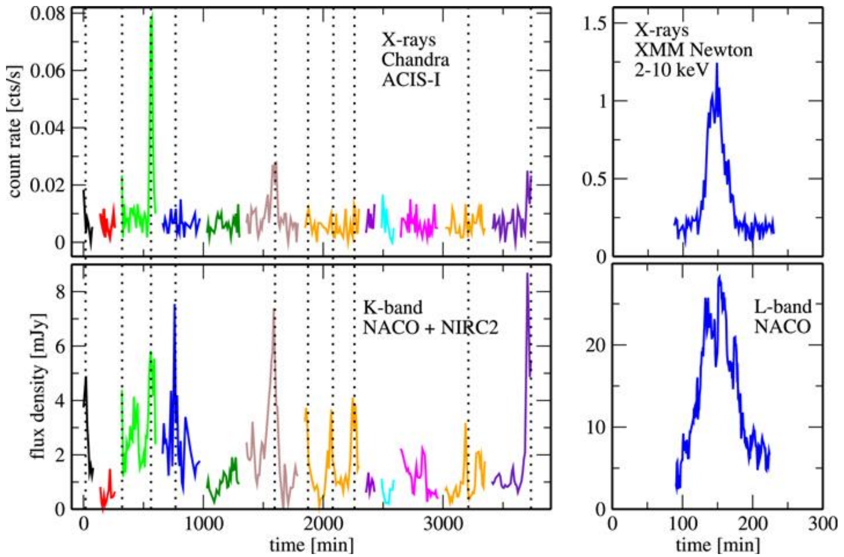
- If our picture is right, future EHT observations should see **strong variability on week-month timescales** in all our measured quantities
- More measurements should further tighten our constraints, and will probably require us to expand our space of models

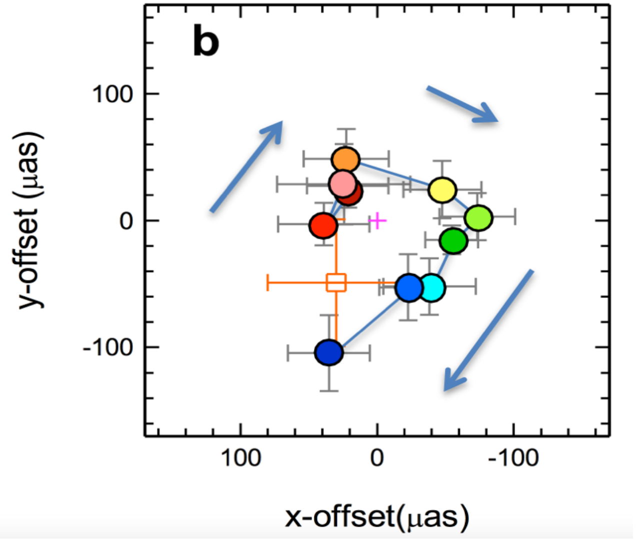
EHTC 2021, Paper VIII

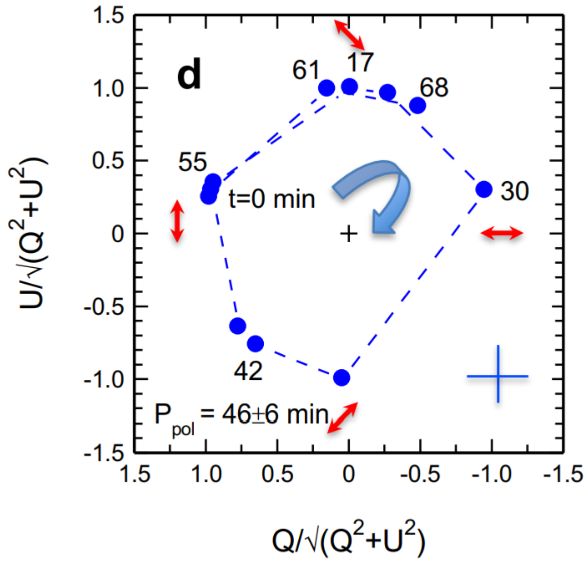
Time variability: Sgr A* Flares

- Intra-day 1.3 mm variability in Sgr A* on minute-hour timescales makes imaging very hard!









- GRAVITY NIR Interferometry: flares rotate near the horizon, and show polarization 'loops'

Marrone+2008, Dexter+2014, Fazio+ 2018, GRAVITY Collab+ 2018b

Sagittarius A* -- coming soon!

$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_{\odot}$
$D = (8.12 \pm 0.03)\text{kpc}$

Gravity Collaboration, 2018

$d_{\text{shadow}} \approx 50\mu\text{as}$

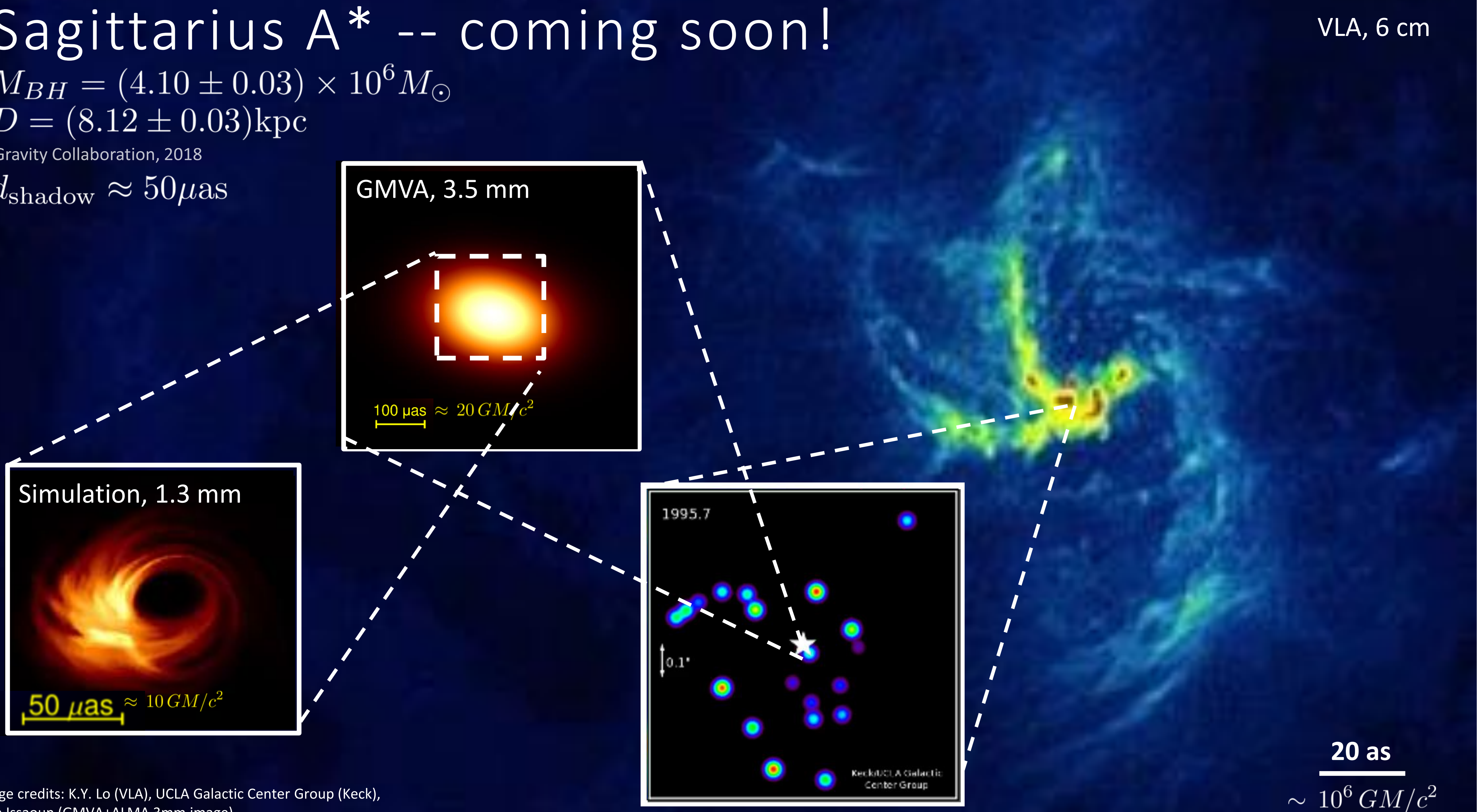
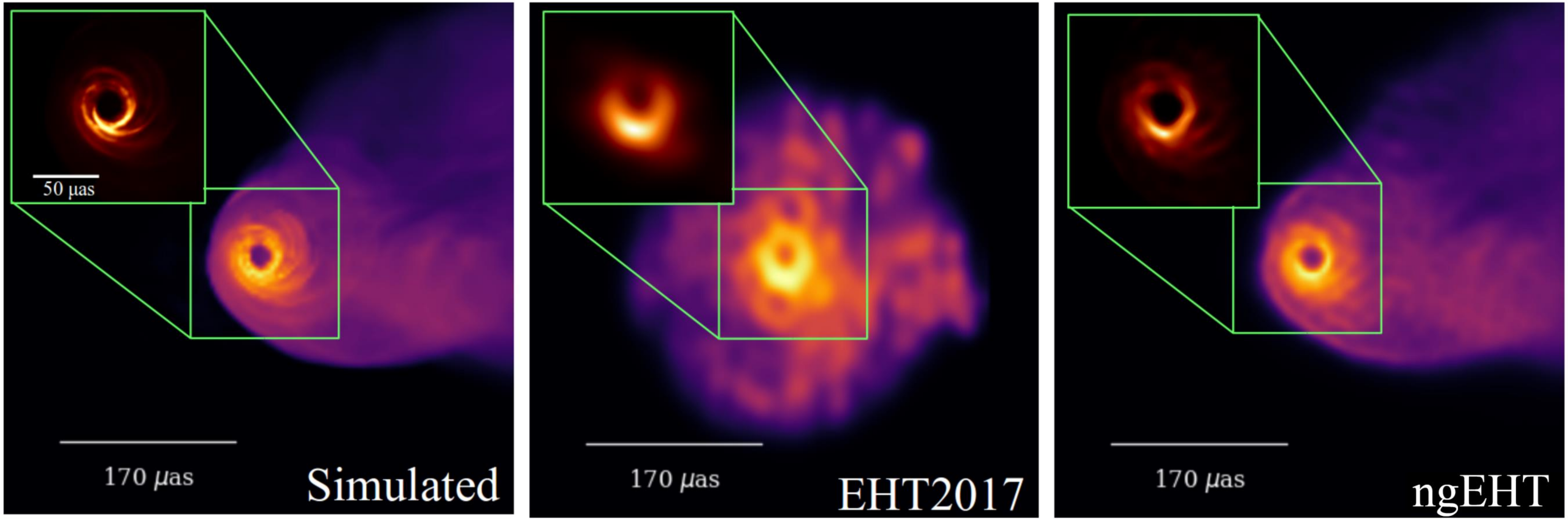


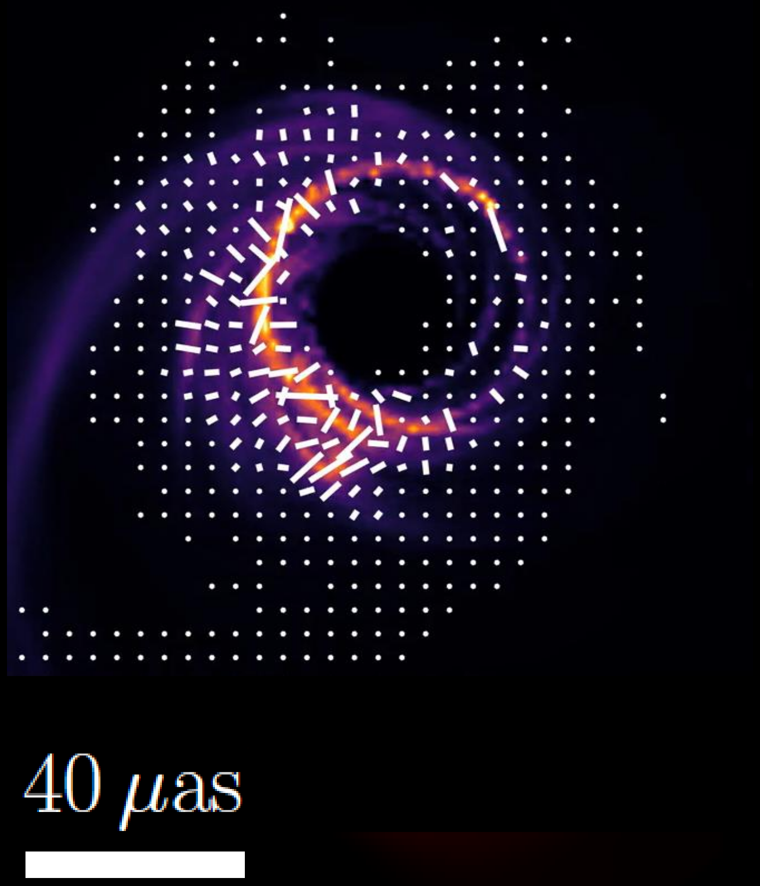
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

Connecting to Larger Scales:
ngEHT will illuminate the BH-jet connection



The current **EHT lacks <u>short</u> baselines**, which are necessary to detect extended structure.
With more dishes added to the array, we will be able to observe the **BH-jet connection** in total intensity and polarization

Image Credit: Michael Johnson
EHT Astro2020 APC White Paper
(Blackburn, Doeleman+; 1909.01411)



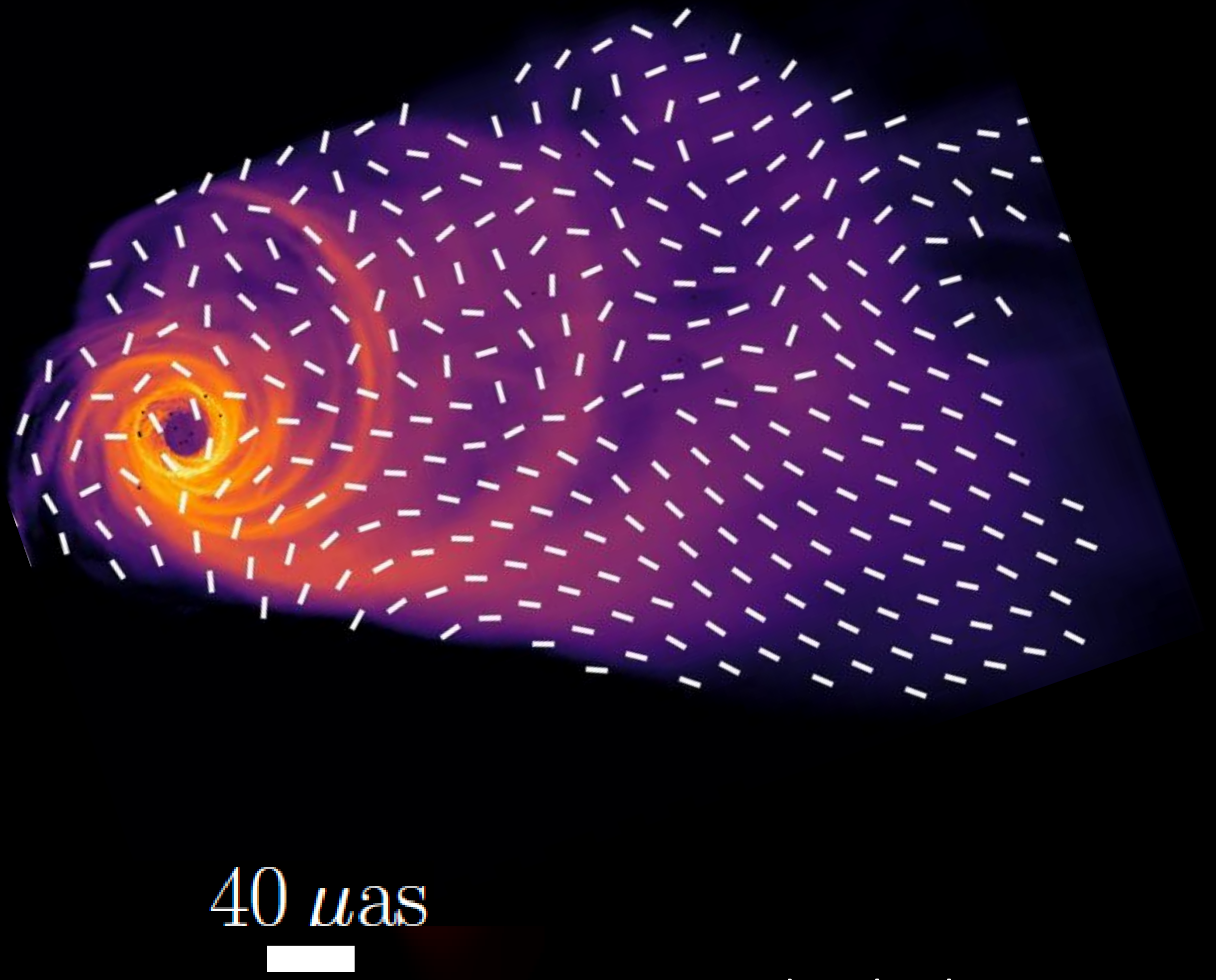


Image credit; Chael+19, Jason Dexter

Summary:

- The EHT has published the first images of the linear polarized synchrotron emission produced near the event horizon of a supermassive black hole
- Producing these images of M87 requires fitting **sparsely-sampled data with corruption** from atmospheric turbulence and polarization leakage.
  - Multiple different reconstruction methods were tested on synthetic data and used to produce conservative images
- The EHT images show **relatively weak polarization** with an **azimuthal pattern** of polarization angles
- The EHT images can be used to constrain GRMHD simulation models of the emission region:
  - self-consistently including light bending and Faraday rotation effects is important
- The polarization data singles out magnetically arrested models:
  - **the magnetic field is dynamically important at the event horizon in M87***
- Time variability and future observations will further constrain our models
  - we need to expand our model space to consider different electron distributions and tilted disks

Thank you!

PCTS workshop on polarization from black holes: May 10-13!