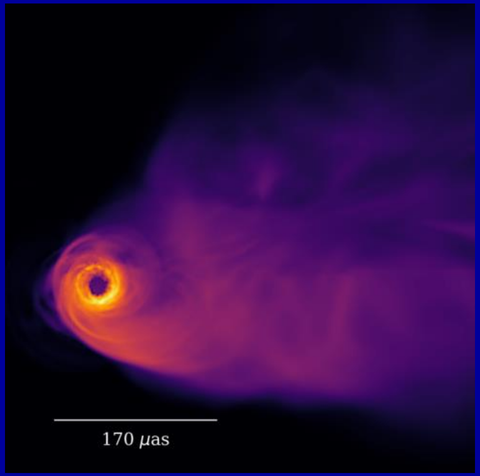
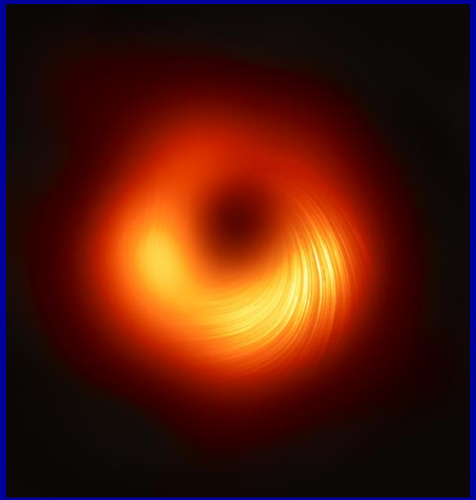
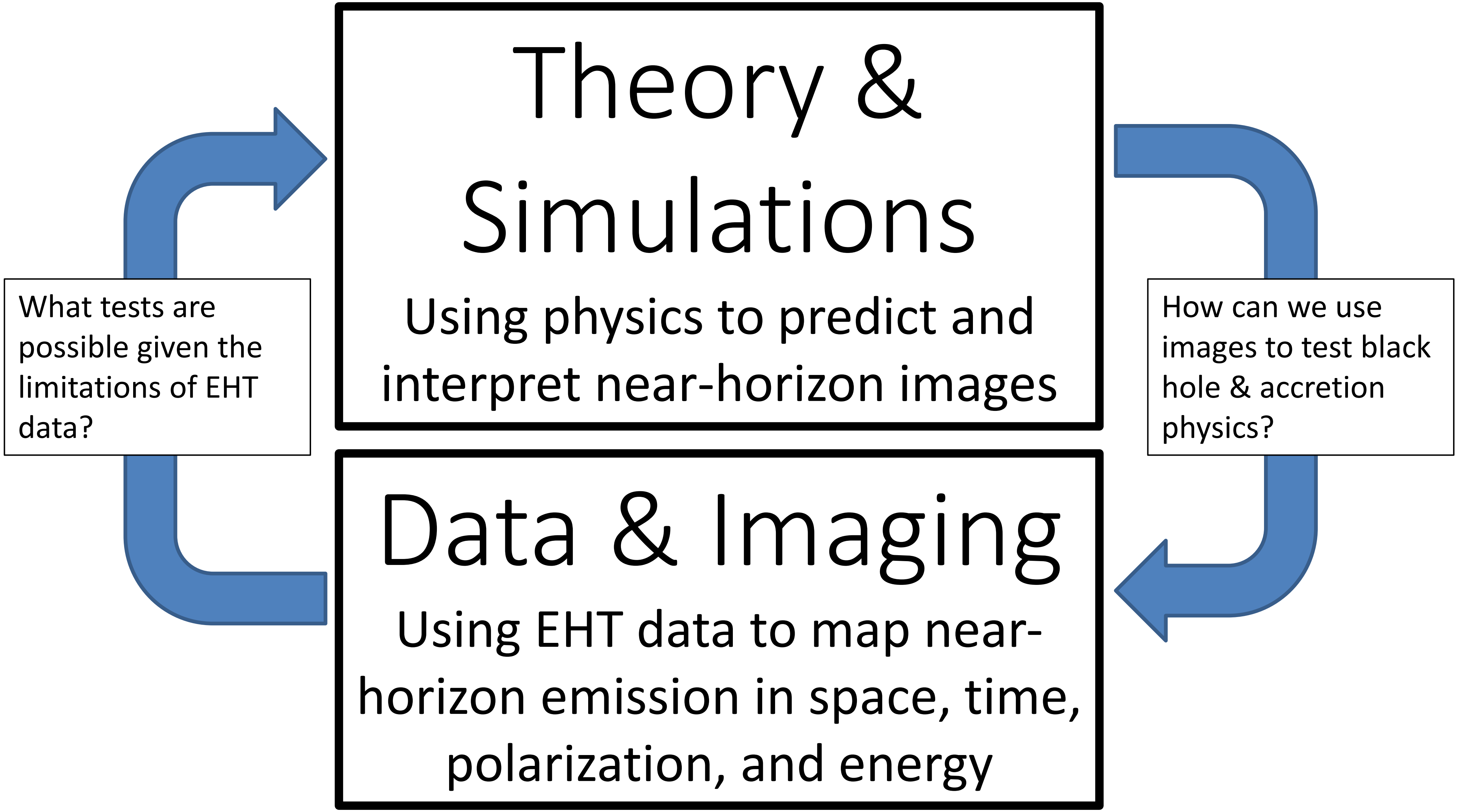



The Event Horizon and Beyond
Celebrating 50 years of Narayan

# *Simulating and Imaging Black Hole Accretion Flows*


Andrew Chael
Princeton Gravity Intitative
06/13/24





Theory & Simulations
Using physics to predict and interpret near-horizon images
How can we use images to test black hole & accretion physics?
Data & Imaging
Using EHT data to map near-horizon emission in space, time, polarization, and energy
What tests are possible given the limitations of EHT data?

# Imaging

# Ramesh laid the groundwork for EHT imaging techniques in the 80s

**Reconstruction of a polarized brightness distribution by the maximum entropy method**

R. Nityananda and R. Narayan
Raman Research Institute, Bangalore-560080, India

Received June 23, accepted September 23, 1982

*Ann. Rev. Astron. Astrophys. 1986. 24 : 127–70*

MAXIMUM ENTROPY IMAGE RESTORATION IN ASTRONOMY[1]

*Ramesh Narayan*
Steward Observatory, University of Arizona, Tucson, Arizona 85721

*Rajaram Nityananda*
Raman Research Institute, Bangalore 560080, India

J. Astrophys. Astr. (1982) 3, 419–450

**Maximum Entropy Image Reconstruction—A Practical Non-Information-Theoretic Approach**

Rajaram Nityananda and Ramesh Narayan
*Raman Research Institute, Bangalore 560080*

Received 1982 April 28; accepted 1982 September 27

HIGH-RESOLUTION LINEAR POLARIMETRIC IMAGING FOR THE EVENT HORIZON TELESCOPE

Andrew A. Chael[1], Michael D. Johnson[1], Ramesh Narayan[1], Sheperd S. Doeleman[1,2], John F. C. Wardle[3], and Katherine L. Bouman[4]
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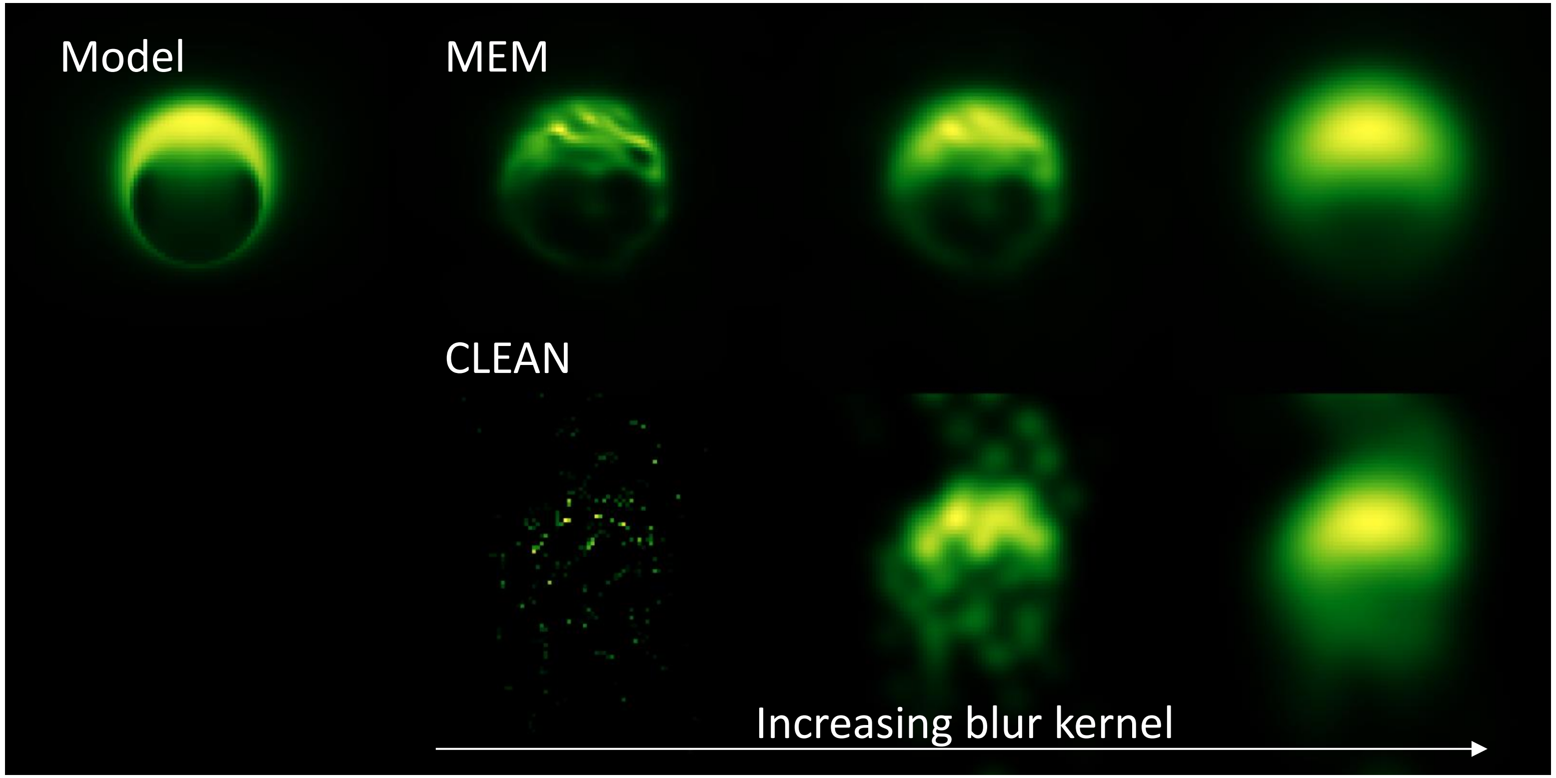
*Received 2015 December 4; revised 2016 June 8; accepted 2016 July 6; published 2016 September 14*

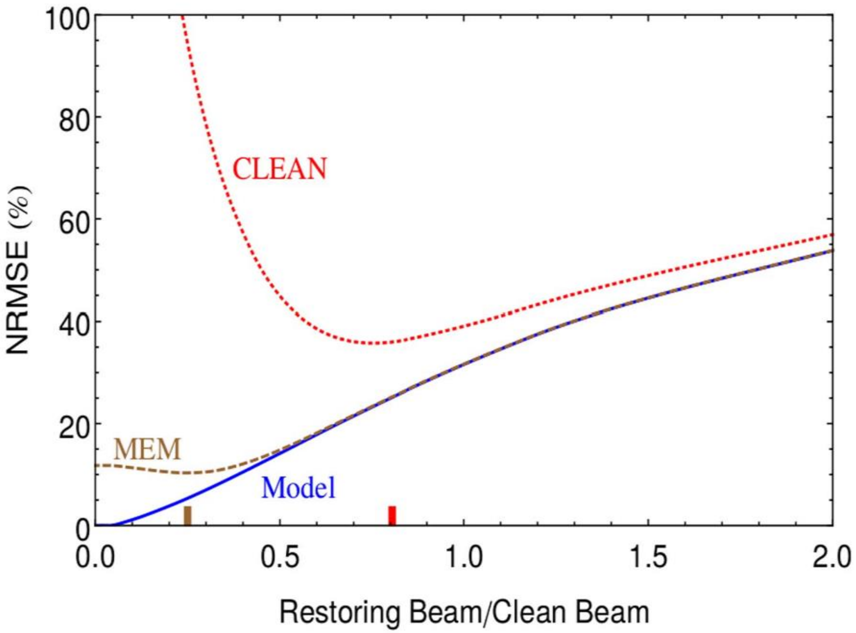
ABSTRACT

Images of the linear polarizations of synchrotron radiation around active galactic nuclei (AGNs) highlight their projected magnetic field lines and provide key data for understanding the physics of accretion and outflow from supermassive black holes. The highest-resolution polarimetric images of AGNs are produced with Very Long Baseline Interferometry (VLBI). Because VLBI incompletely samples the Fourier transform of the source image, any image reconstruction that fills in unmeasured spatial frequencies will not be unique and reconstruction algorithms are required. In this paper, we explore some extensions of the Maximum Entropy Method (MEM) to linear polarimetric VLBI imaging. In contrast to previous work, our polarimetric MEM algorithm combines a Stokes $I$ imager that only uses bispectrum measurements that are immune to atmospheric phase corruption, with a joint Stokes $Q$ and $U$ imager that operates on robust polarimetric ratios. We demonstrate the effectiveness of our technique on 7 and 3 mm wavelength quasar observations from the VLBA and simulated 1.3 mm Event Horizon Telescope observations of Sgr A$^*$ and M87. Consistent with past studies, we find that polarimetric MEM can produce superior resolution compared to the standard CLEAN algorithm, when imaging smooth and compact source distributions. As an imaging framework, MEM is highly adaptable, allowing a range of constraints on polarization structure. Polarimetric MEM is thus an attractive choice for image reconstruction with the EHT.

*Key words:* black hole physics – Galaxy: center – techniques: high angular resolution – techniques: image processing – techniques: interferometric

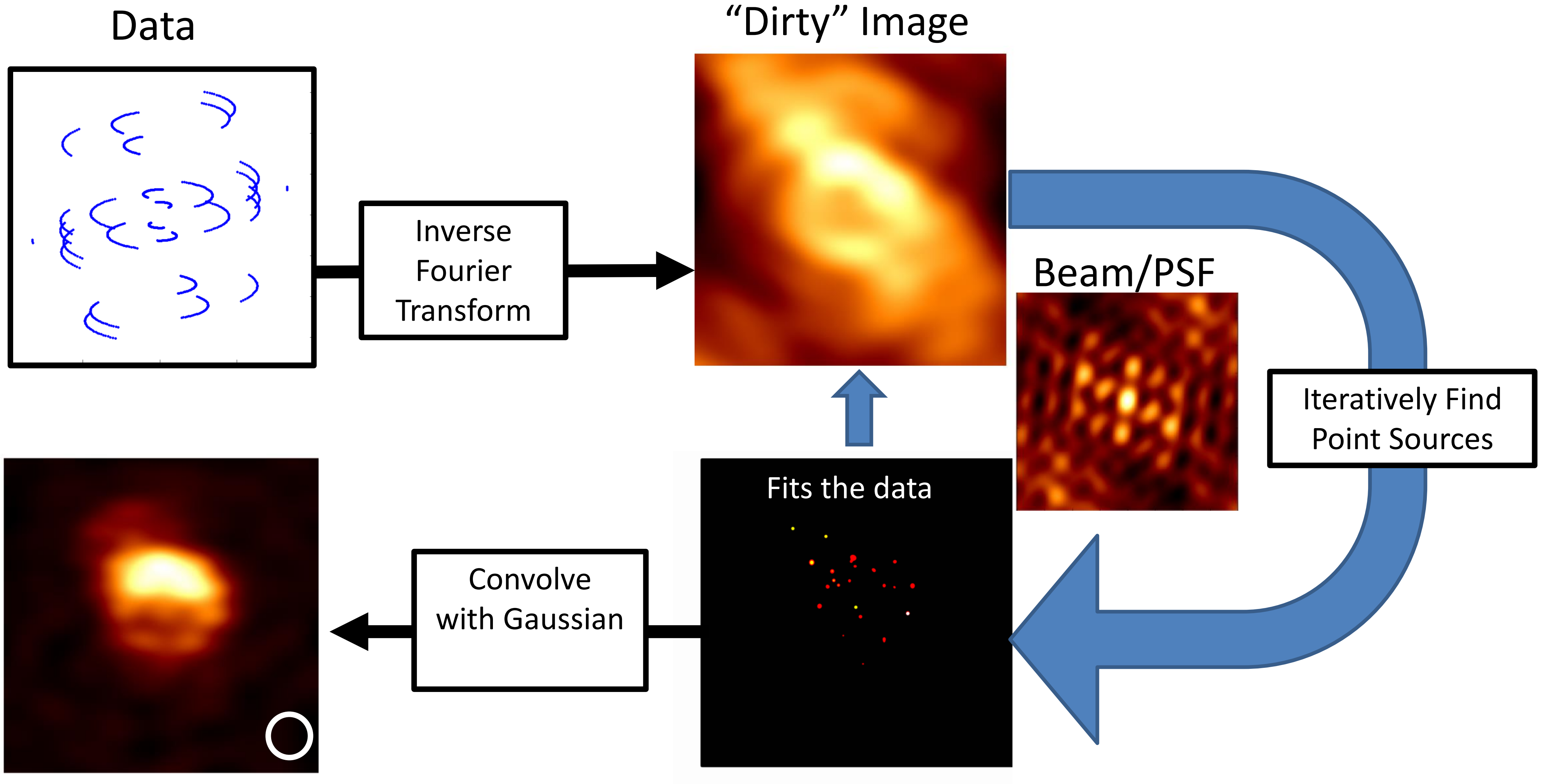
# Maximum Entropy for the EHT



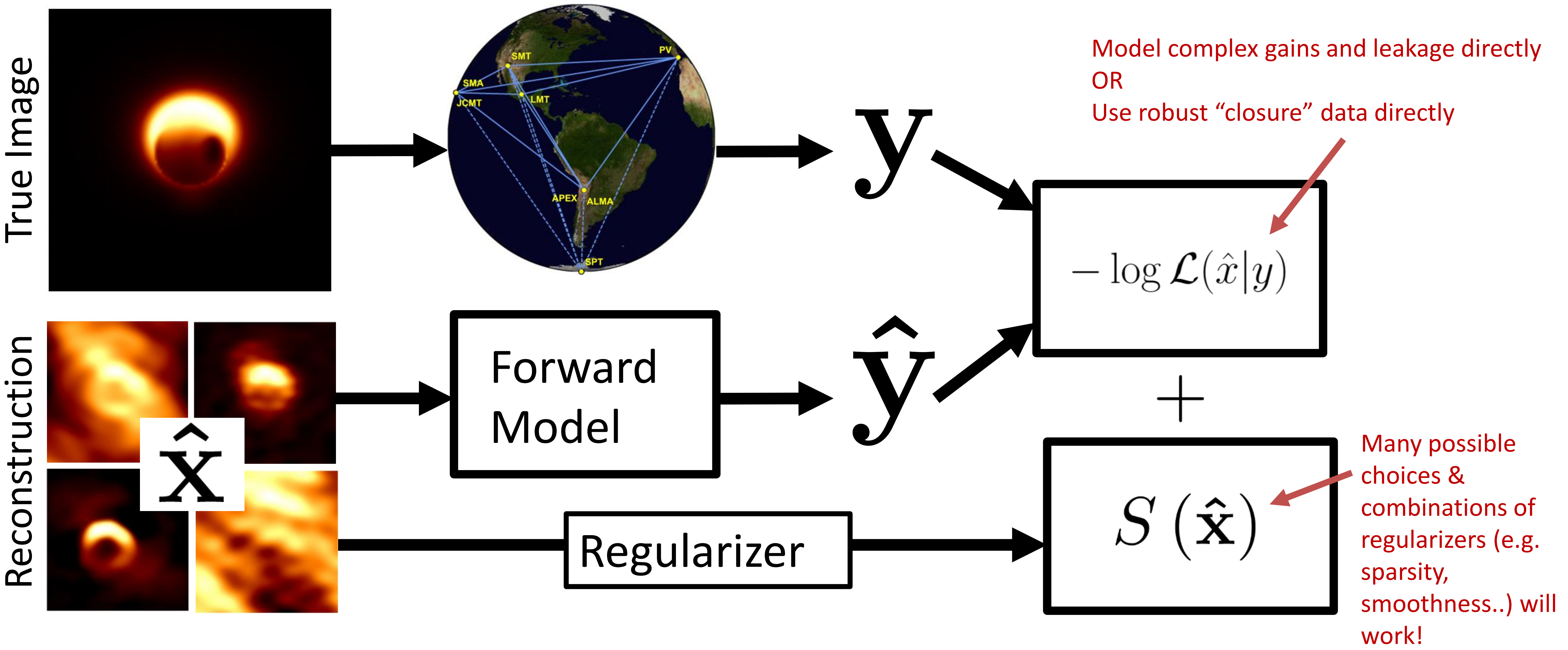




**Chael,** Johnson, Narayan**+** 2016

# Traditional Approach: CLEAN



# Regularized Maximum Likelihood

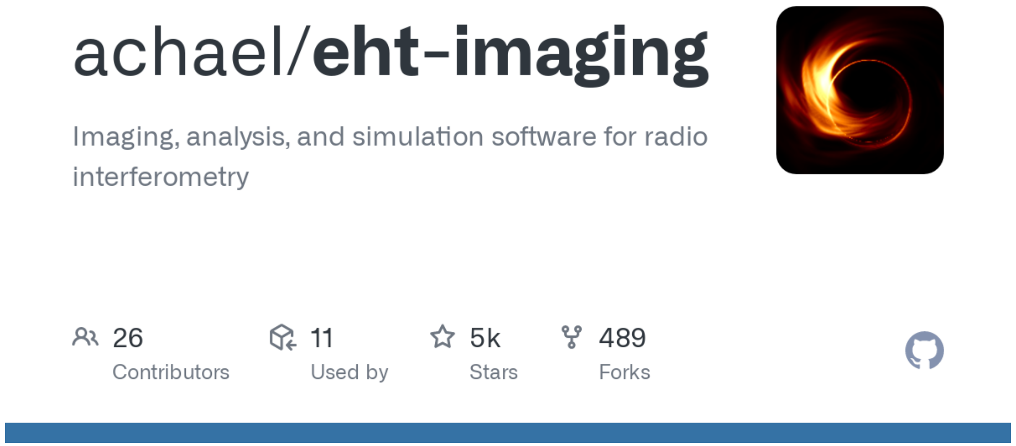


# The **eht-imaging** software library

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

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

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




[https://github.com/achael/eht-imaging](https://github.com/achael/eht-imaging)

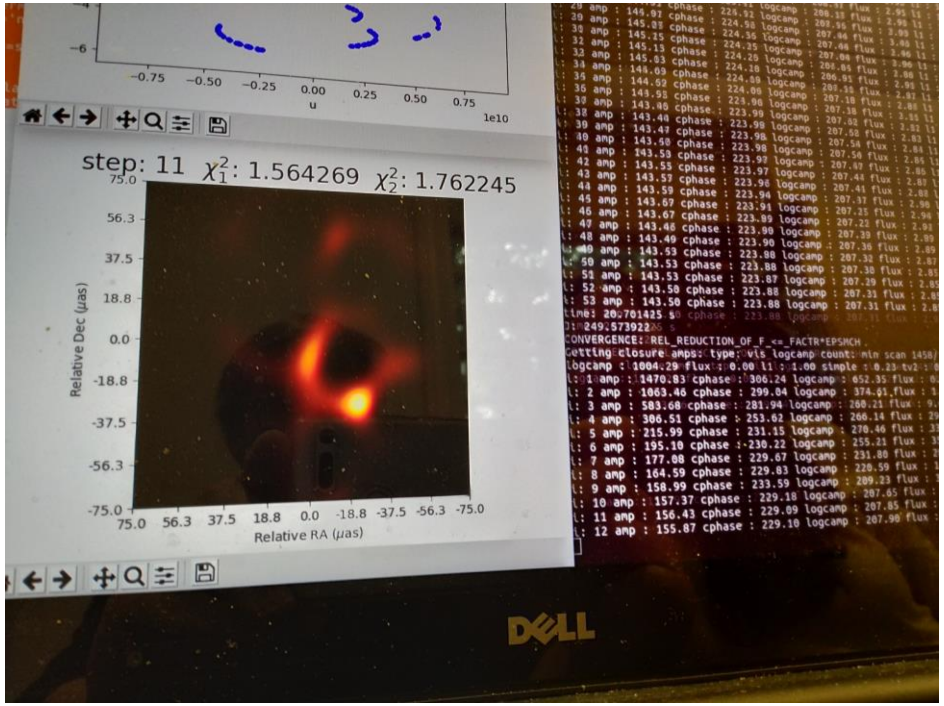
```
pip install ehtim
```

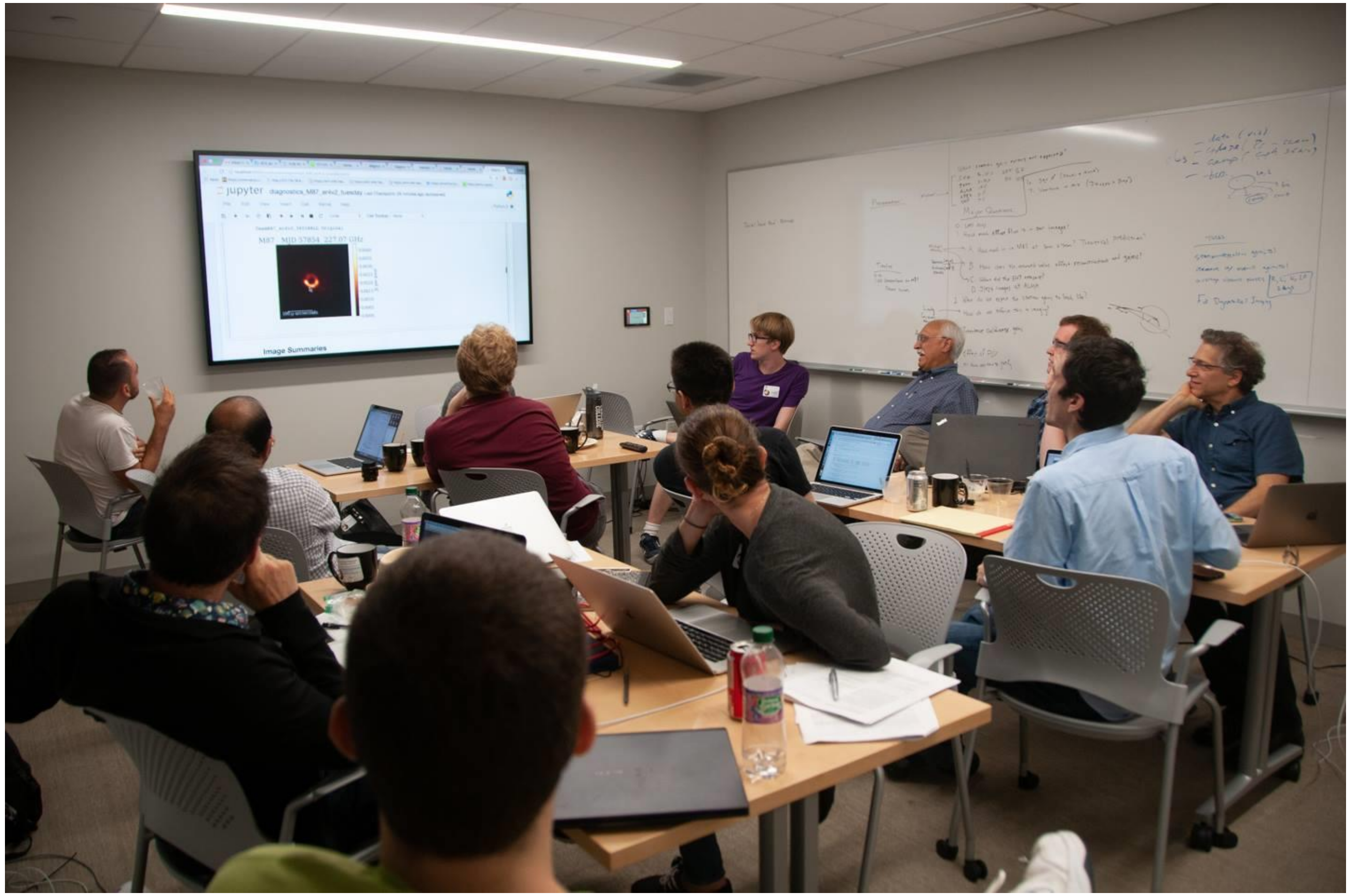
**Chael+** 2016, 2018a, 2023a

# EHT 2017 Observations

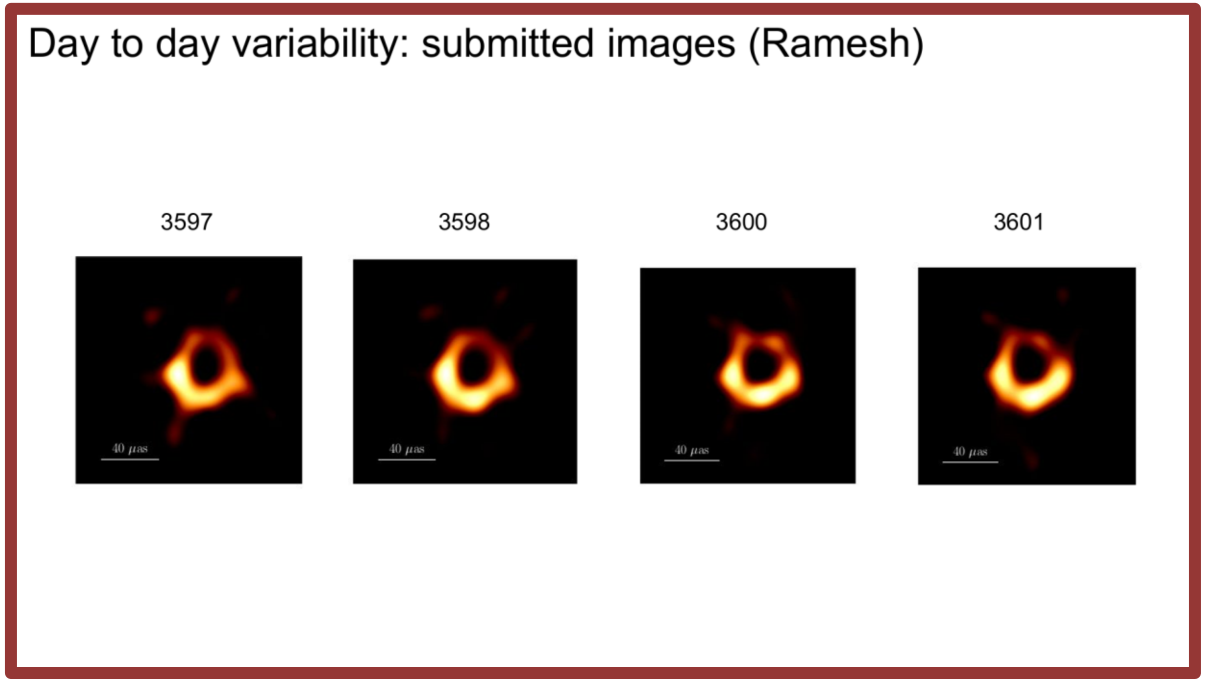

Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

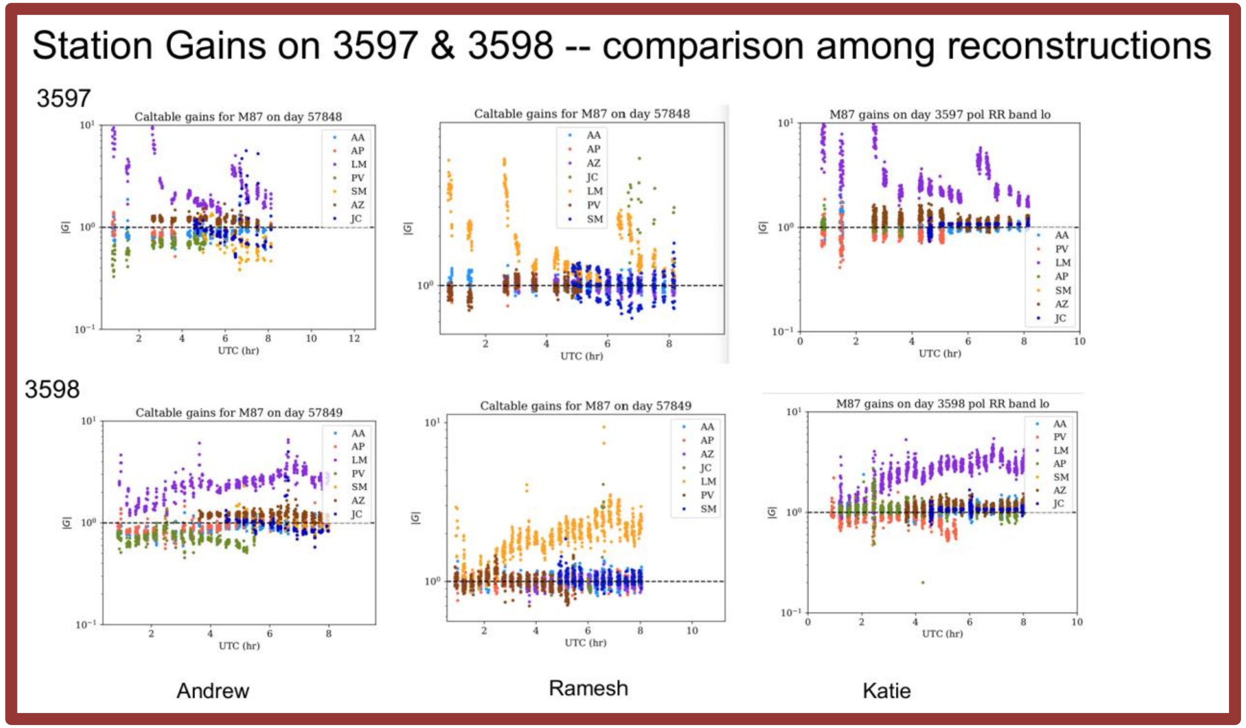
# Blind Imaging/EHT Imaging Workshop



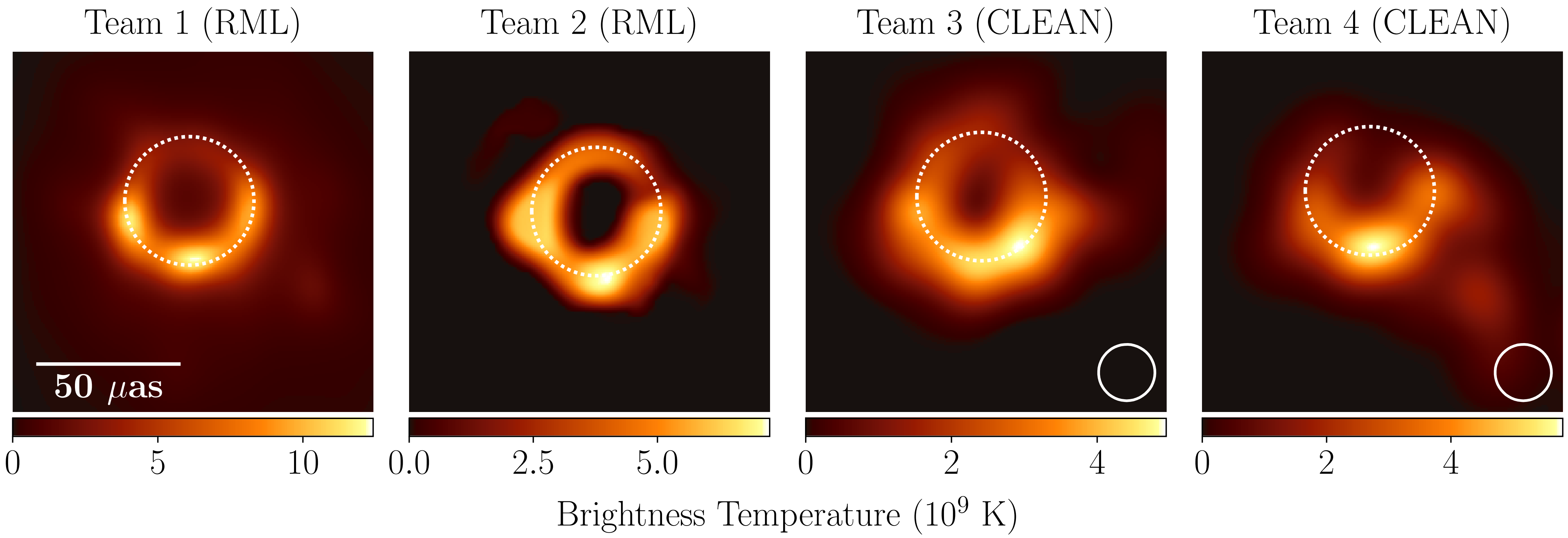
# Slides from 2018 Imaging Workshop



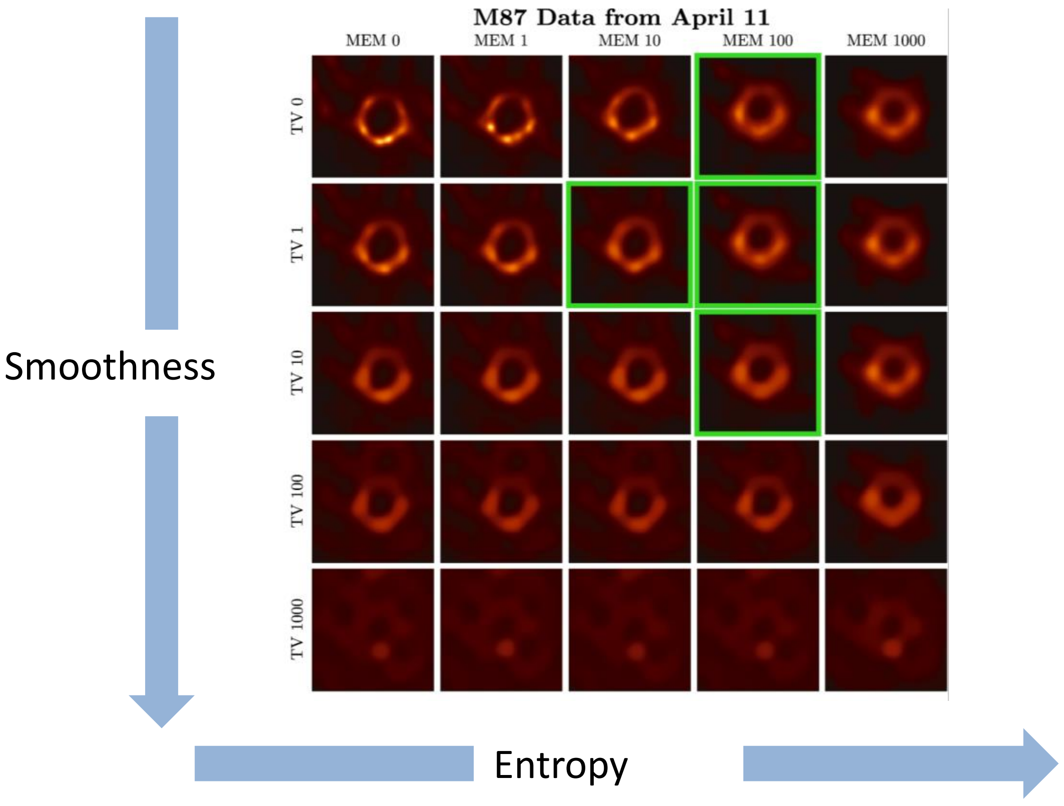

Slide Credit: Ramesh Narayan

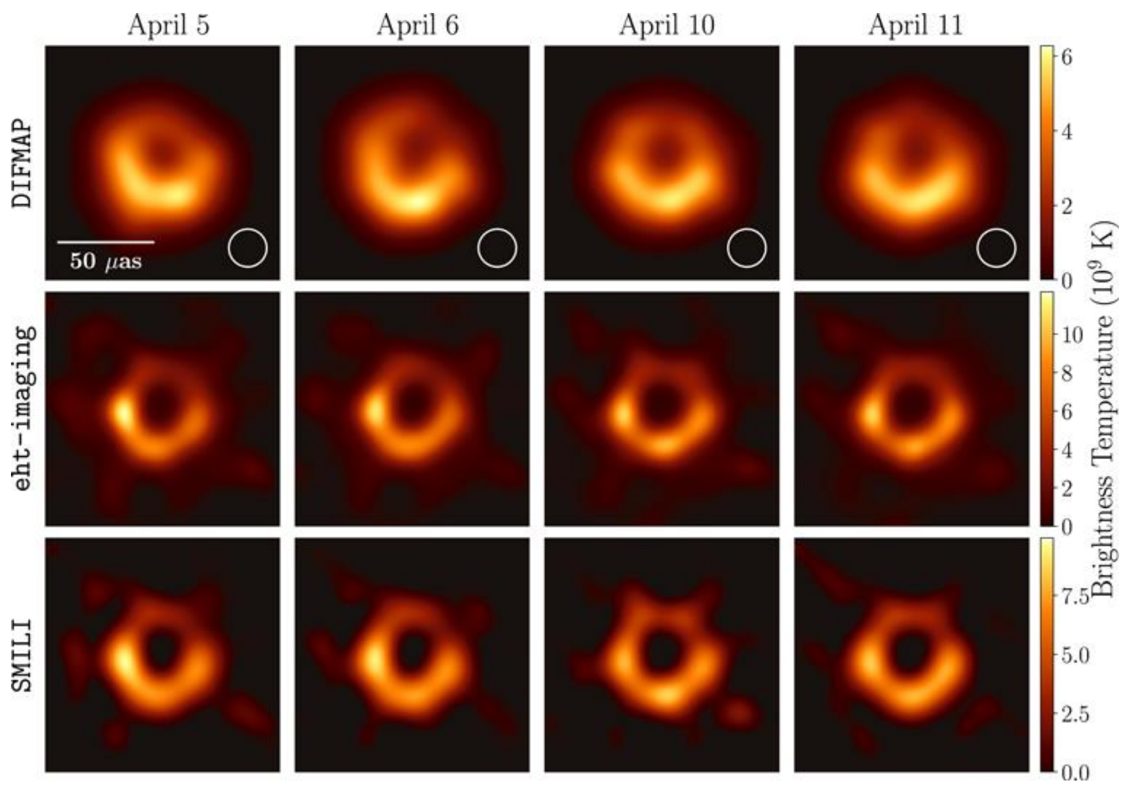
# Blind Imaging Results




EHTC+ 2019 Paper IV (**Chael,** paper writing team)

# Validation and Parameter Surveys



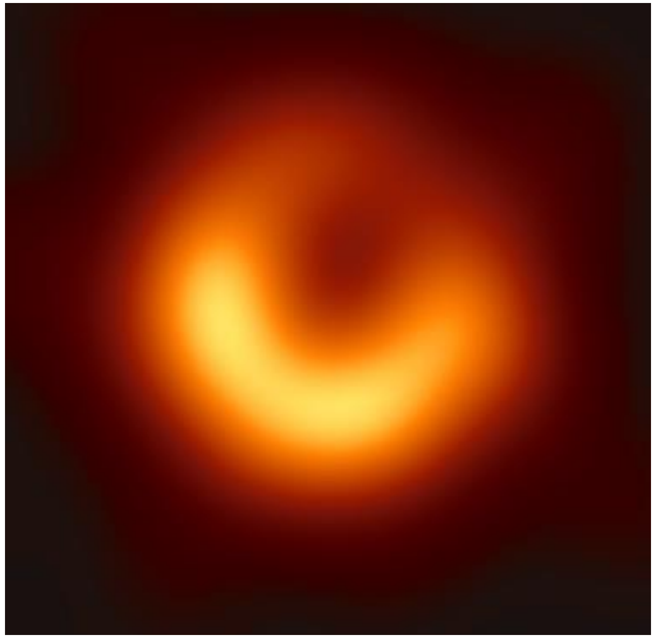




Final EHT 2017 M87* images

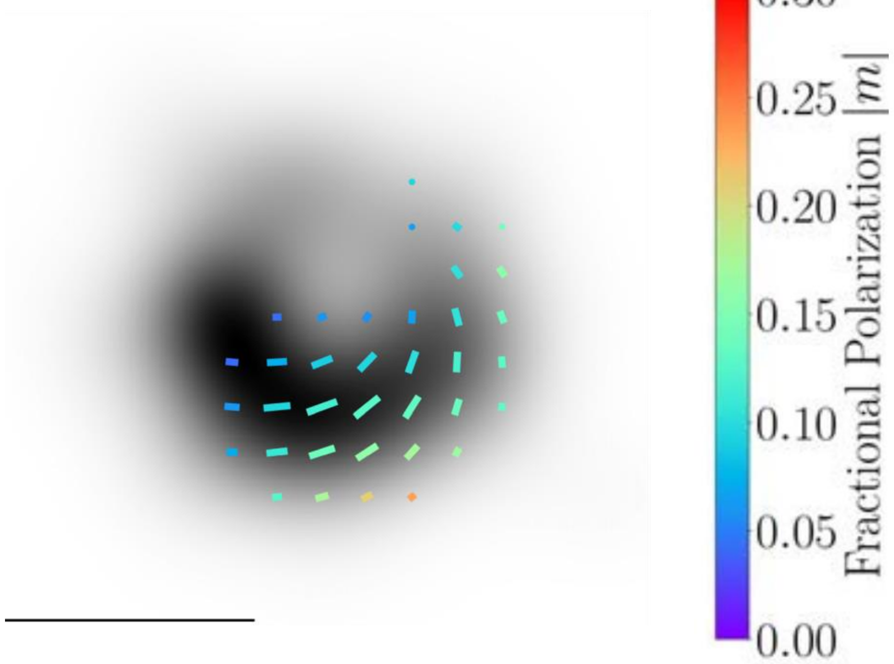
EHTC+ 2019 Paper IV (**Chael,** paper writing team)

# M87* in Polarizaiton

Total intensity



Linear Polarization

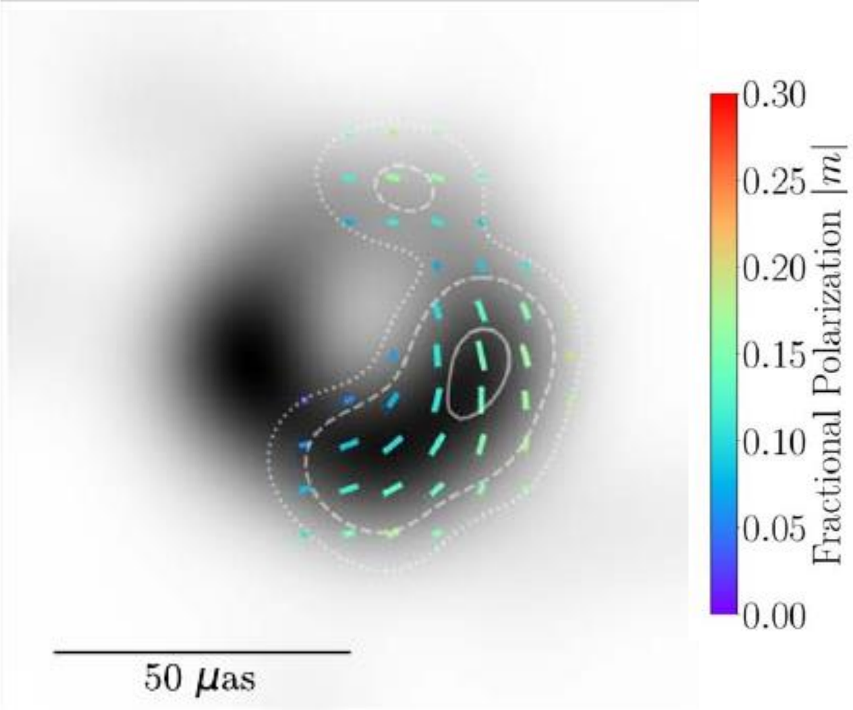



- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

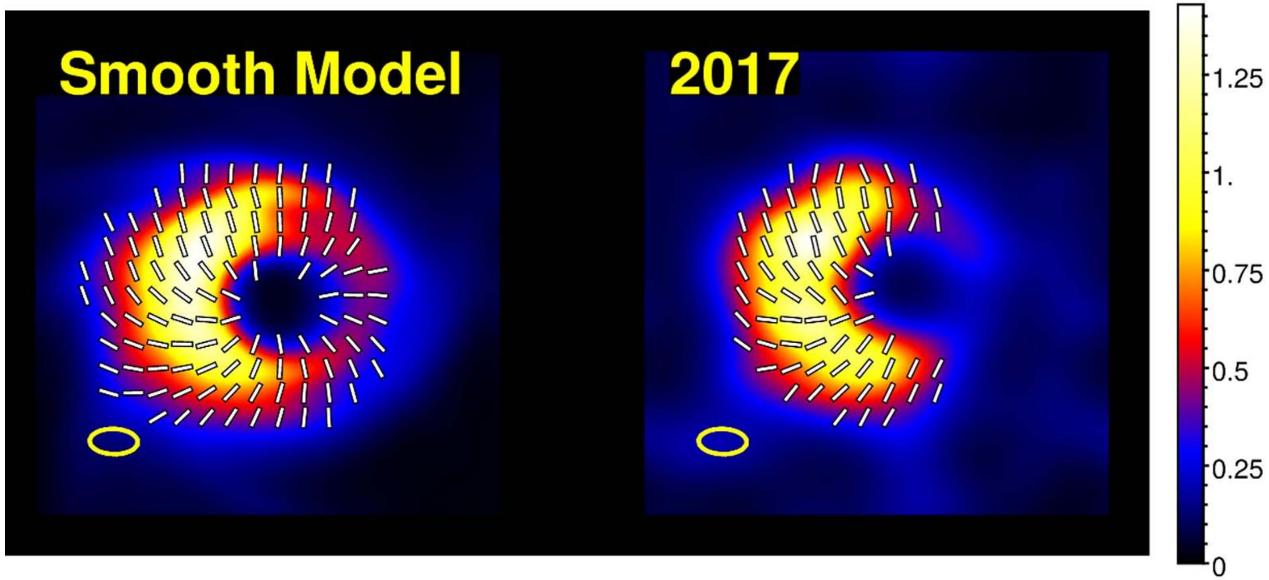
EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)

# M87* in Polarizaiton

M87* 2017 from
**eht-imaging**




Chael+ 2016 image of a MAD Simulation (from Jason Dexter)

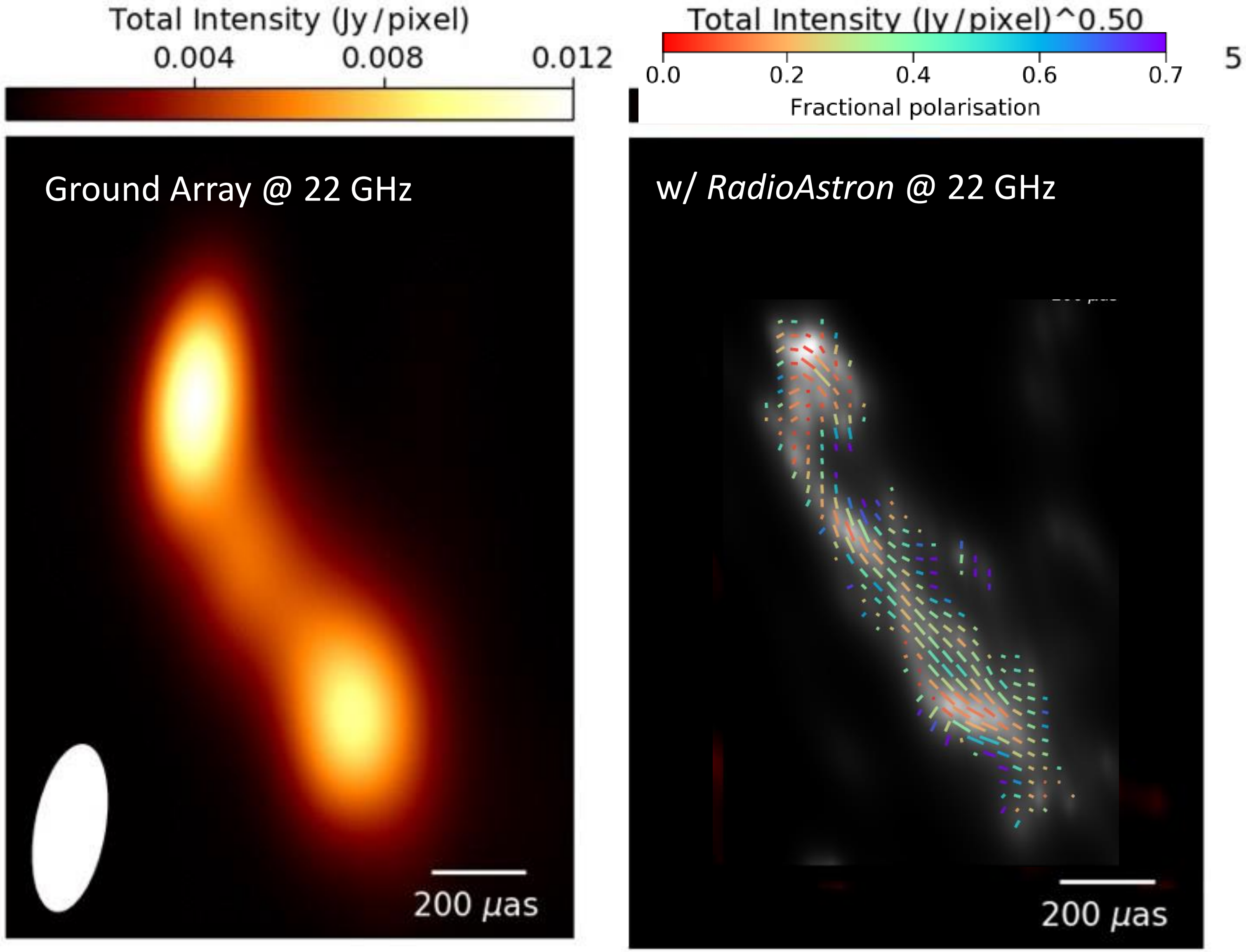



EHTC+ 2021 Paper VII (**Chael**, paper writing team)
**Chael**, Johnson, Narayan+ 2016

# EHT imaging techniques have wide applicability!

## 3C279 with *RadioAstron*

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



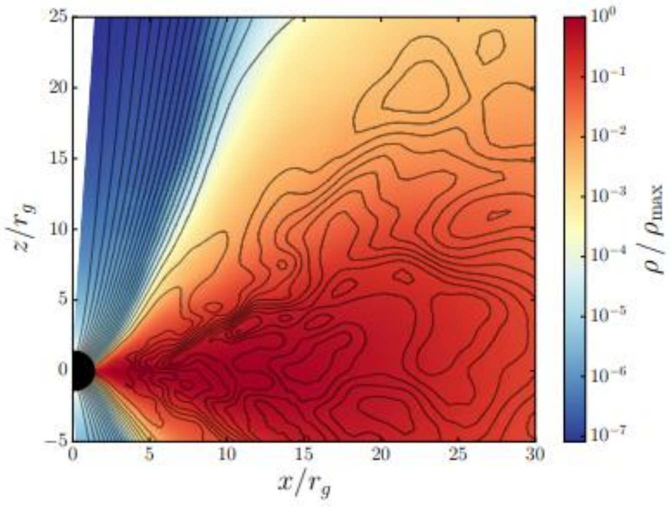

Fuentes et al, 2023

# Simulations (and analytics)

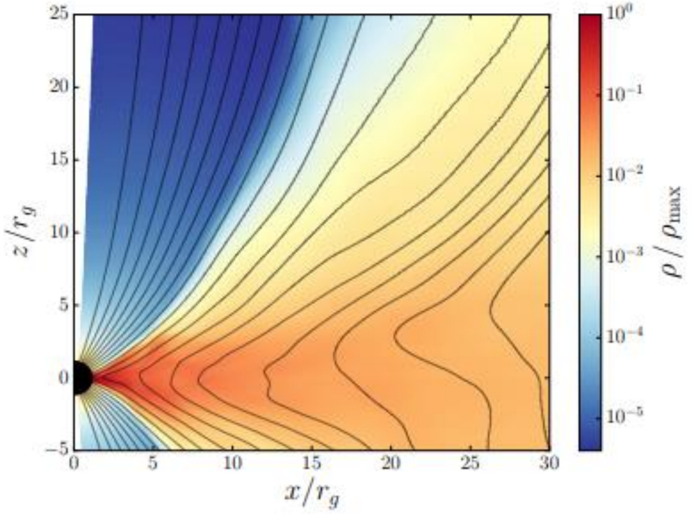
# What is the magnetic field structure close to the horizon?

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

**Magnetic fields are weak and turbulent**




"SANE"




"MAD" - Magnetically Arrested Disk

**Strong, coherent magnetic fields build up on the horizon**

Note: 'strong' fields mean dynamically important ones → ~10 G at the horizon for M87

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

**BH spin**

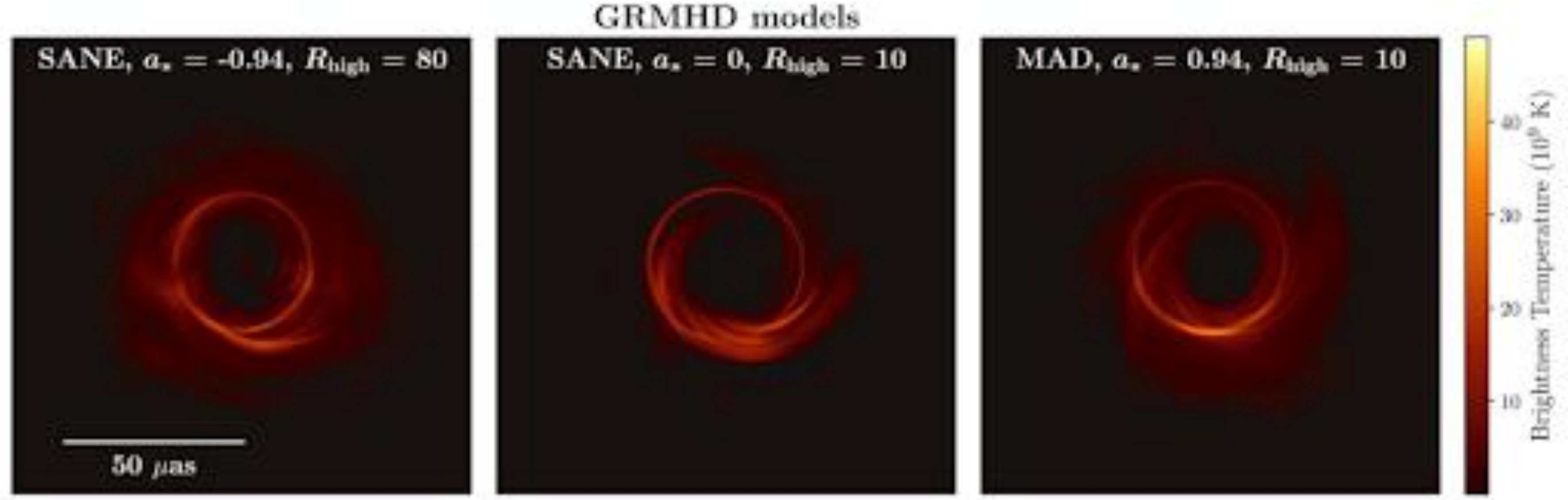
**magnetic flux**

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

Image credit: Riordan+ 2017

# Scoring 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)




- 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**

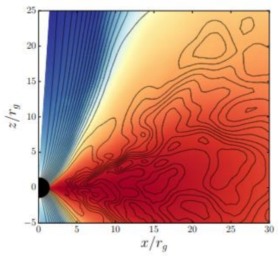
- Scoring simulations against EHT polarization image with multiple approaches **all strongly favor a magnetically arrested accretion flow**

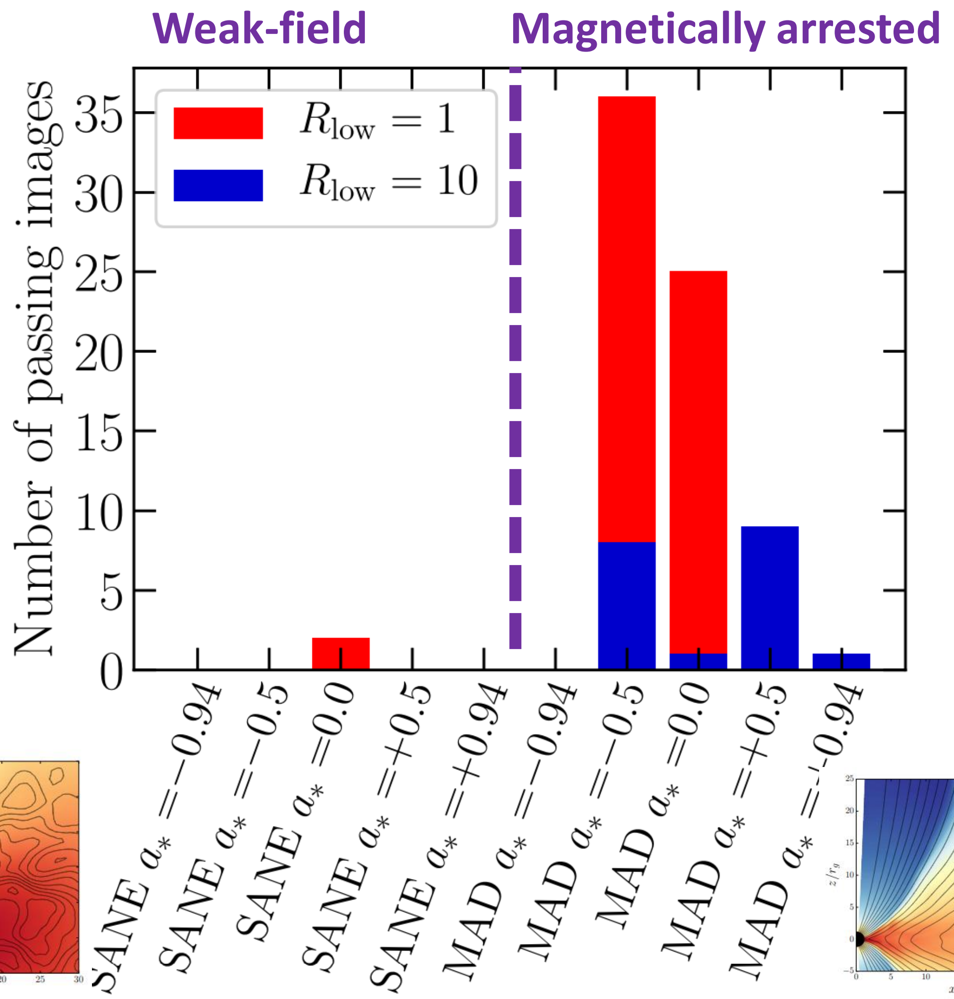
- Implications for accretion and jet launching:
  - We constrain M87*'s allowed accretion rate by 2 orders of magnitude:

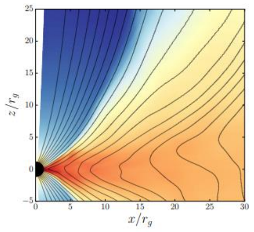
$$\dot{M} \simeq (3 - 20) \times 10^{-4} M_\odot \ \mathrm{yr}^{-1}$$

$$\left(\dot{M}_{\mathrm{Edd}} = 137 M_\odot \ \mathrm{yr}^{-1}\right)$$

  - Radiative efficiency ~1%

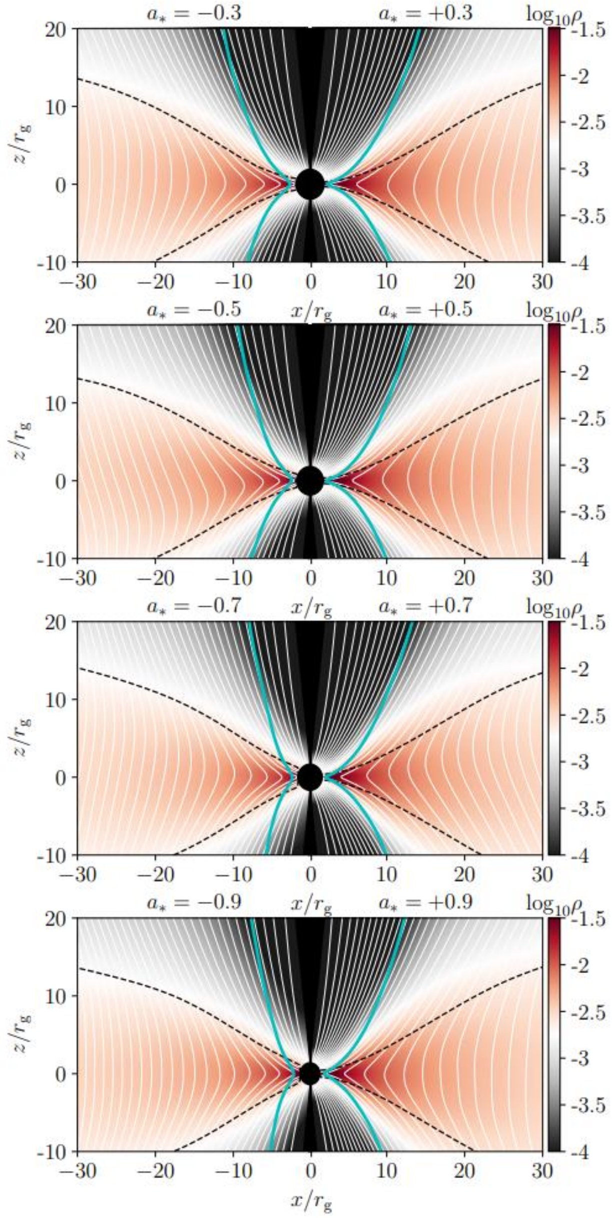




Credit: EHT 2021 Paper VIII, 2023 Paper IX (**Chael**, paper coordinator), Riordan+2017

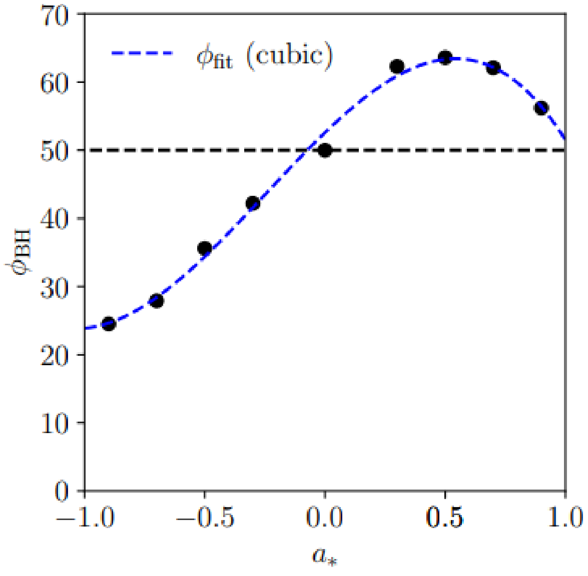
# Jets in MADs are BZ



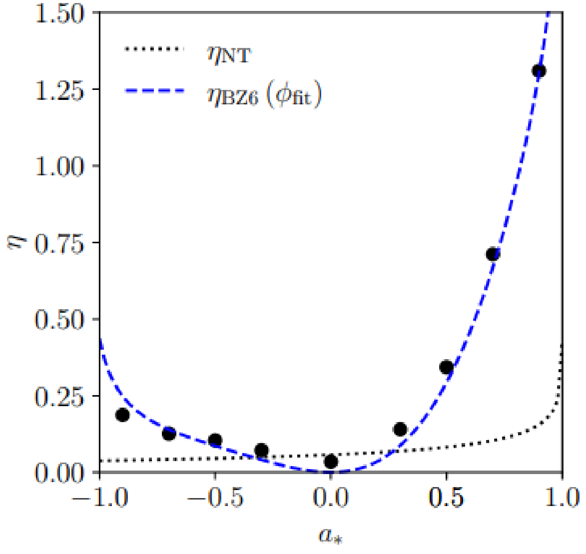

Time-and azimuth-averaged simulation data

- We see agreement with BZ jet power prediction in 8 v**ery-long-duration simulations** ($10^5$ $t_g$) of magnetically arrested accretion

Magnetic flux though the horizon




Jet efficiency

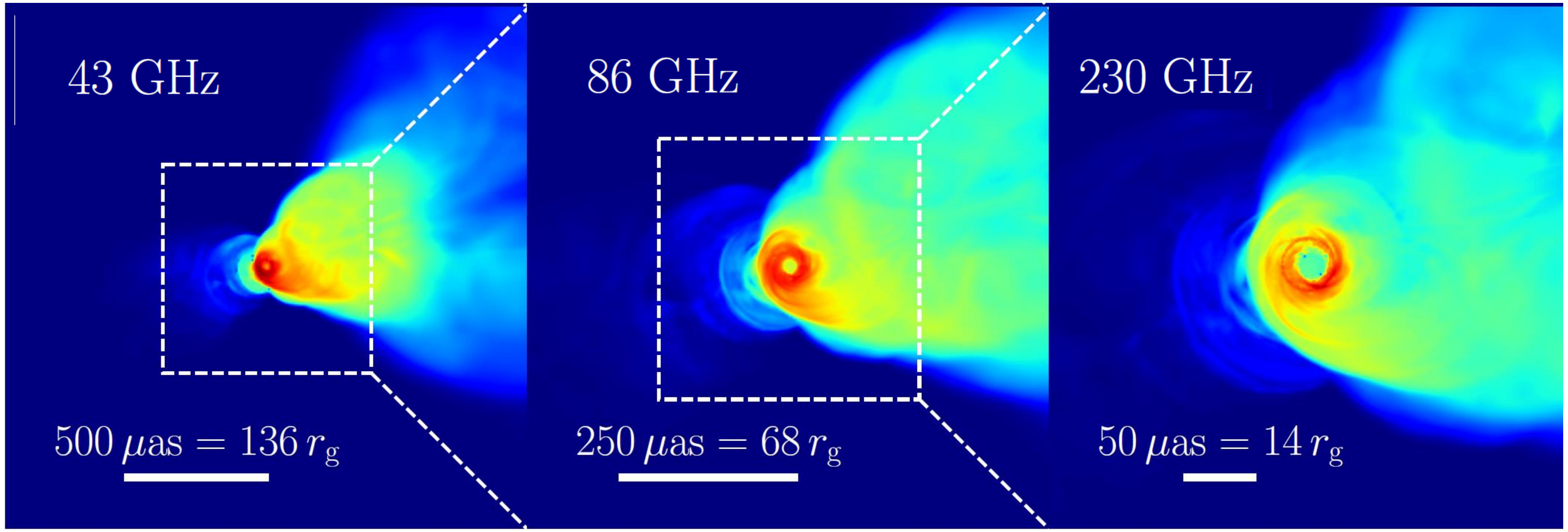


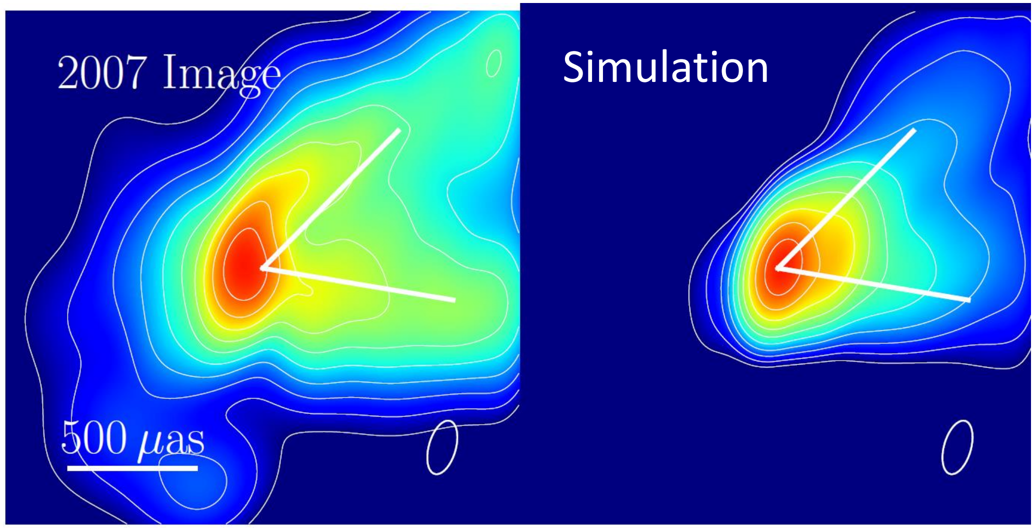

BH spin

R. Narayan, **A. Chael**, K. Chatterjee, A. Ricarte, B. Curd, 2021

# M87 Jets in GRRMHD Simulations

- **Radiative, Two-Temperature, MAD** simulations (Chael+ 2019) naturally produce:
  - A jet power in measured range
  - observed wide opening angle
  - observed core-shift

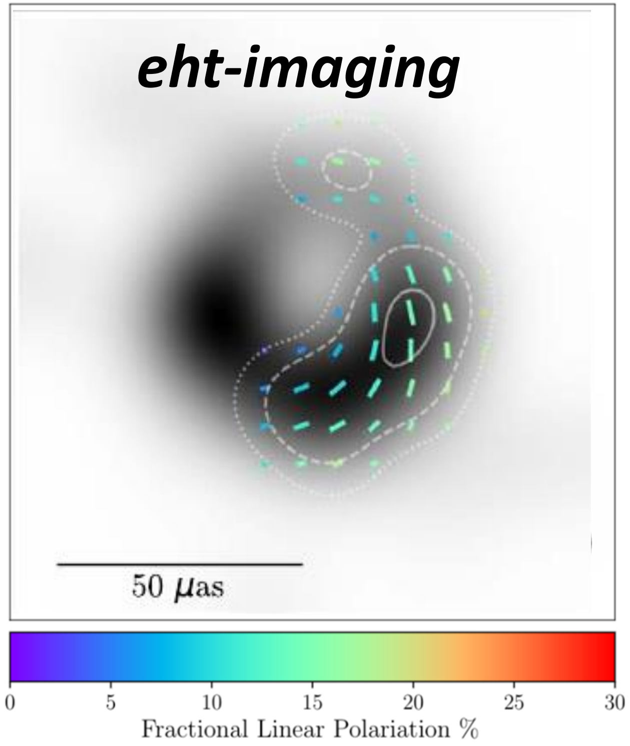


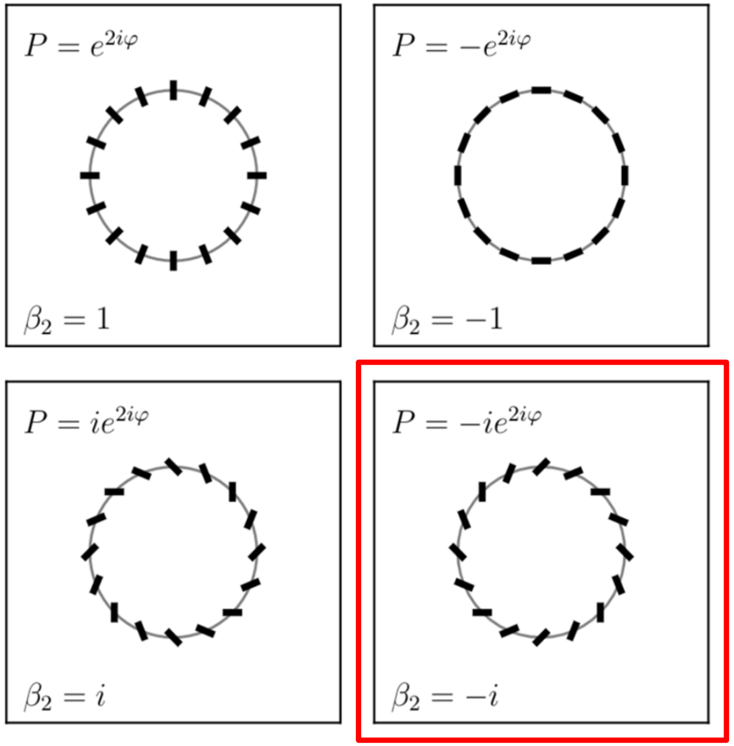




- Can we be **sure** M87’s jet is BZ**?** What is a **physically meaningful** observation of **horizon-scale** energy flow from a black hole?

**Chael**+ 2019

# Polarized Images of M87* and horizon-scale energy flow



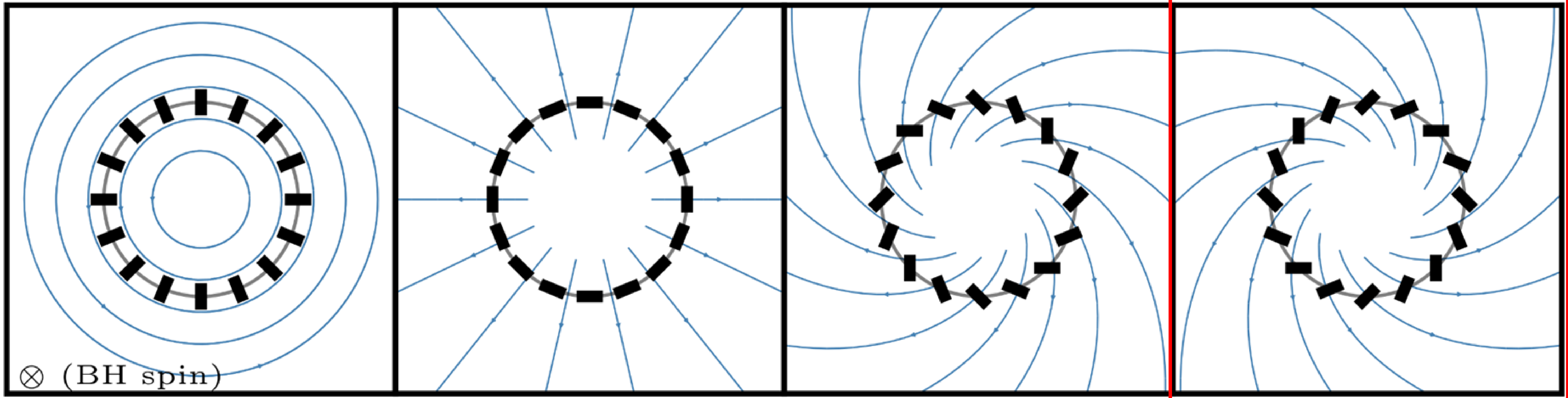

- The polarization spiral's 2nd Fourier mode (**$\beta_2$**: Palumbo+ 2020) is the **most constraining** feature for simulation scoring
- Can we interpret **$\beta_2$** **physically**?

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

# $\arg(\beta_2)$ is connected to the **electromagnetic energy flux**

**Energy Inflow** **Energy Outflow**

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




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

**Trailing field geometry is a key prediction of BZ**

## Radial Poynting flux in Boyer-Lindquist coordinates:

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

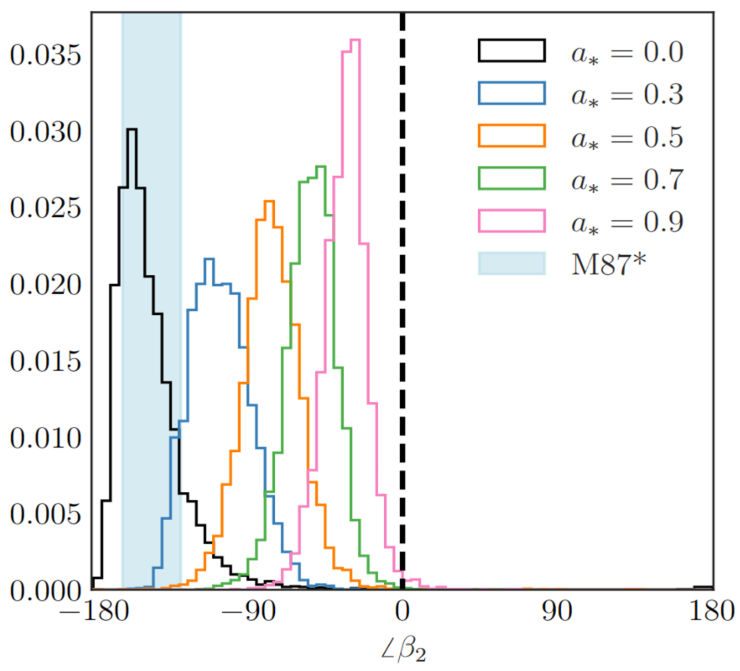
fieldline angular speed

Chael+ 2023b

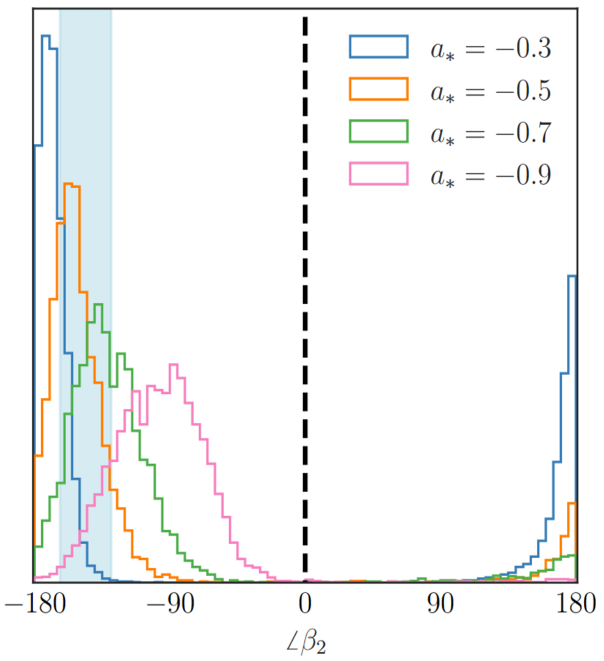
# $\arg(\beta_2)$ in MAD **GRMHD simulations** of M87*?

- 1600 simulated EHT-resolution M87* images from MAD simulations (Narayan+ 2022)
- Almost all 230 GHz simulation images have **negative $\arg(\beta_2)$** consistent with the measured energy outflow in the simulations
- $\arg(\beta_2)$ has the **same qualitative dependence on spin** as in the BZ monopole model

**Prograde simulations**

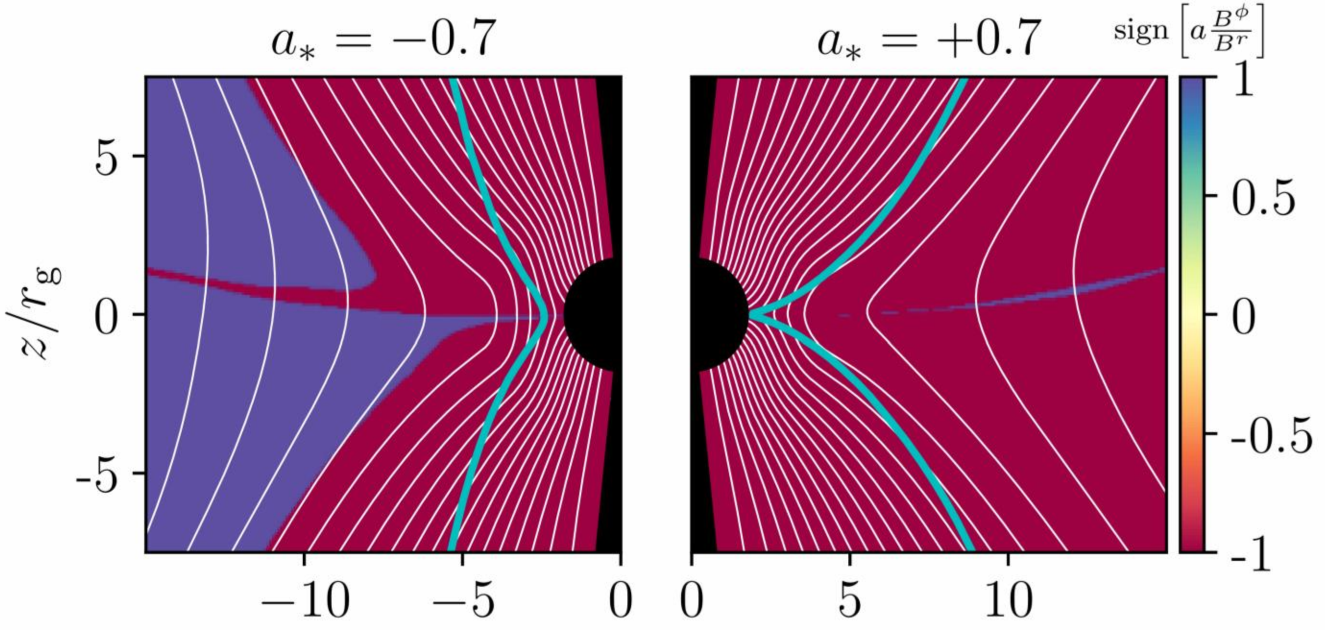



**Retrograde simulations**



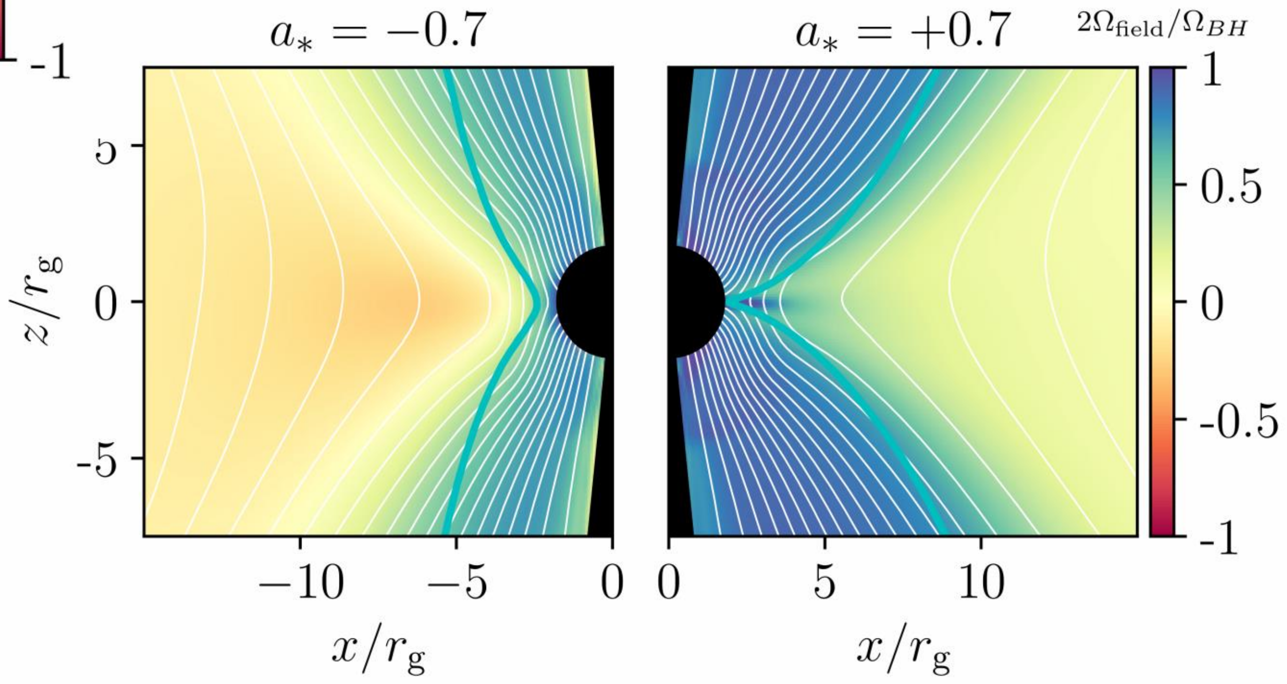

**Chael**+ 2023b

# In GRMHD, energy-extracting fieldlines set $\arg(\beta_2)$




Sign of magnetic field pitch angle

Field-line angular speed



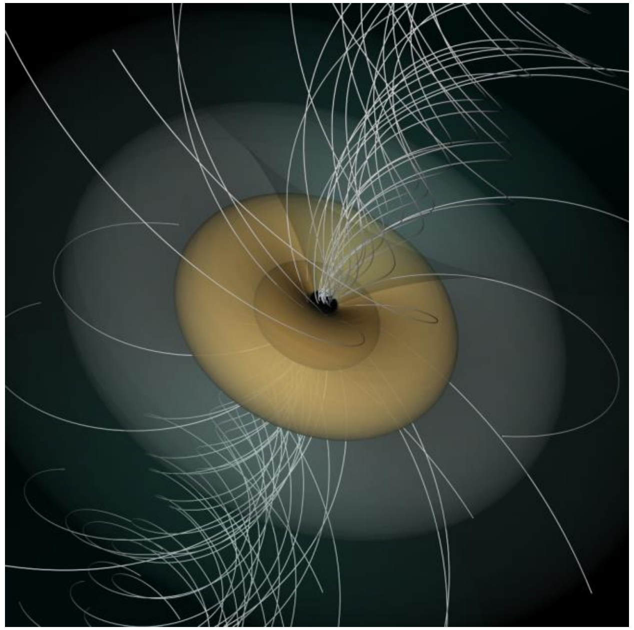

Even in **retrograde** simulations, field-lines in the 230 GHz emission region **co-rotate** with the black hole and have a negative $B^\phi$ / $B^r$

**Chael**+ 2023

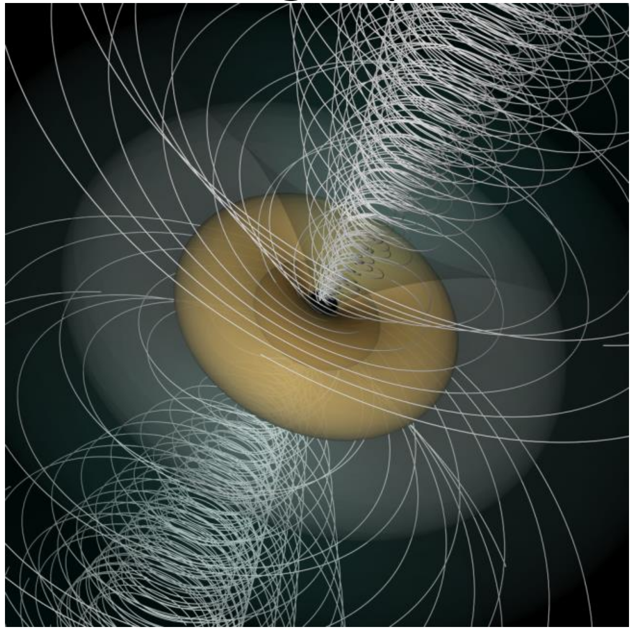
Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022, Wong+ 2021

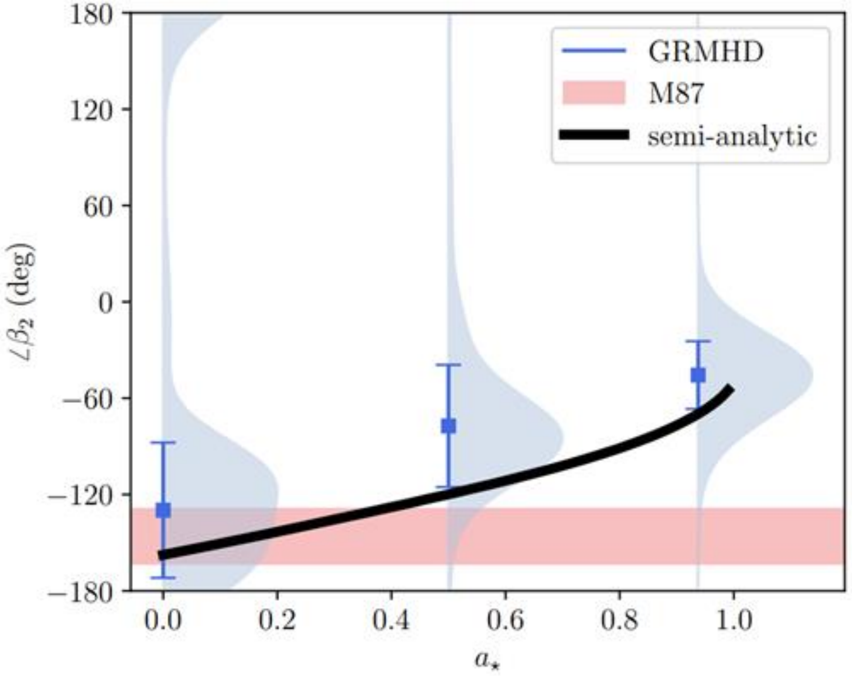
# Polarized images are **spin dependent**

Low Spin



High Spin

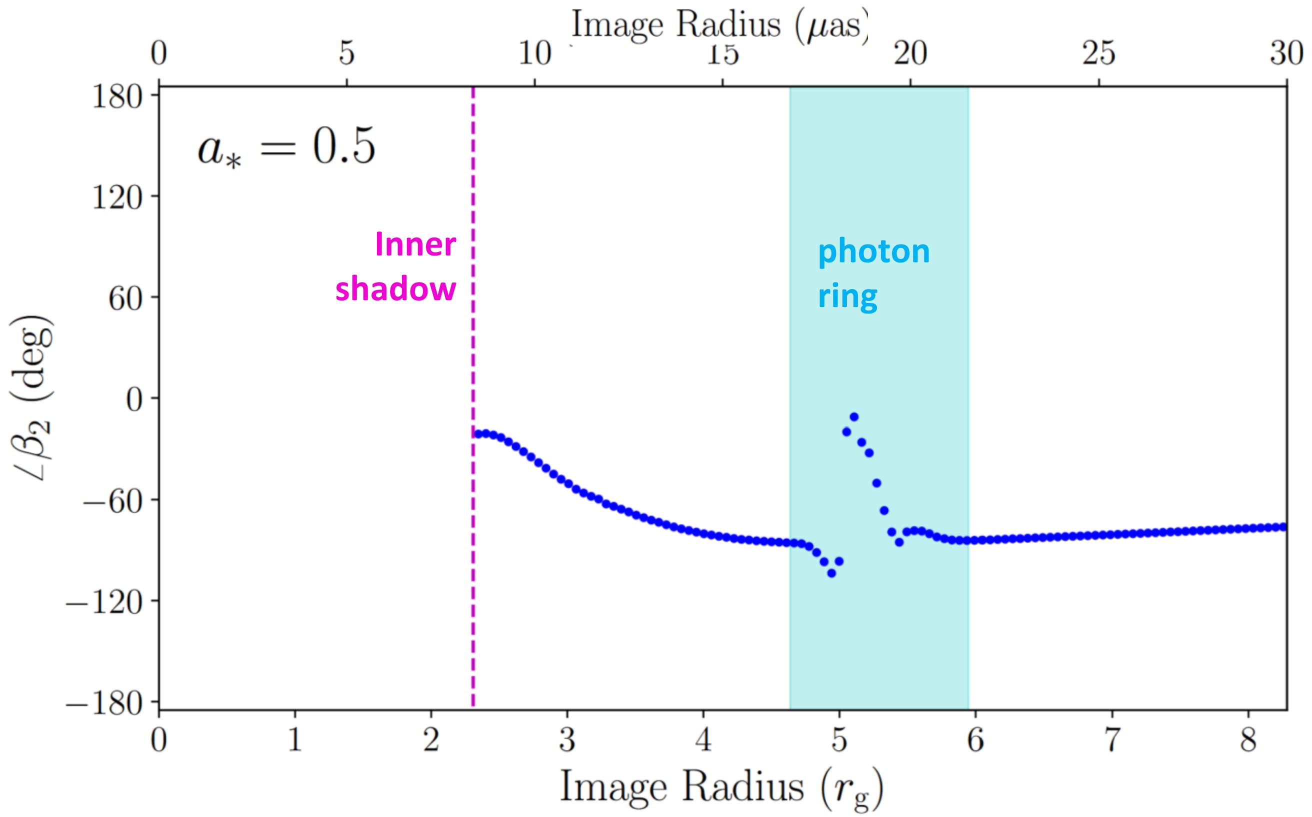


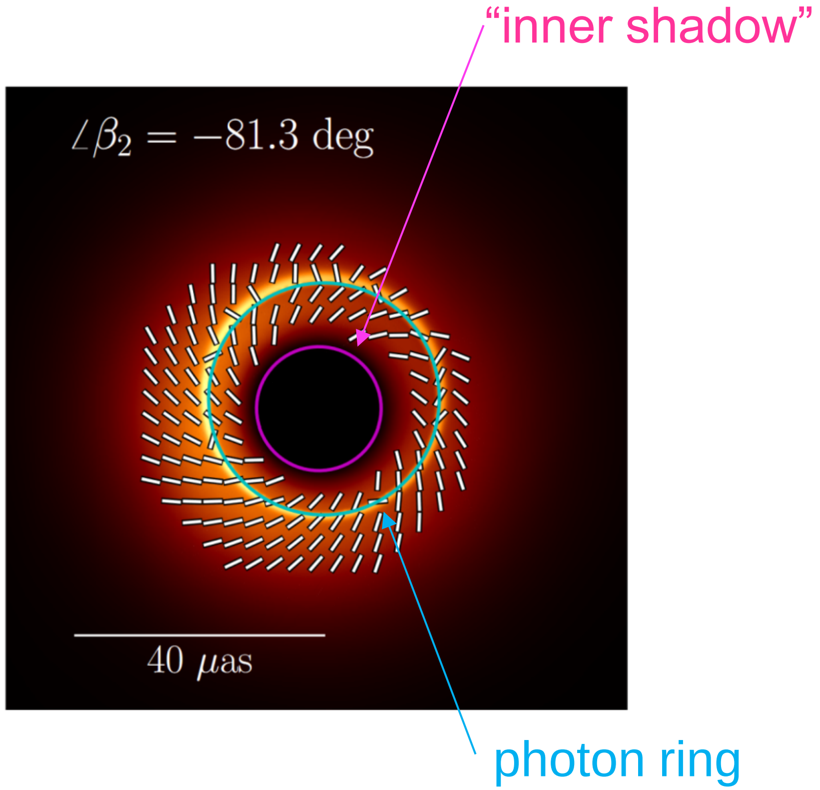



- Black hole **spin winds up initially radial fields**, but always so that $B^{\phi}/B^{r} < 0$
- The field pitch angle **increases with spin**
- Increased field winding
  - increases the Poynting flux (BZ jet power)
  - makes the observed polarization pattern more radial

Image credit: George Wong

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



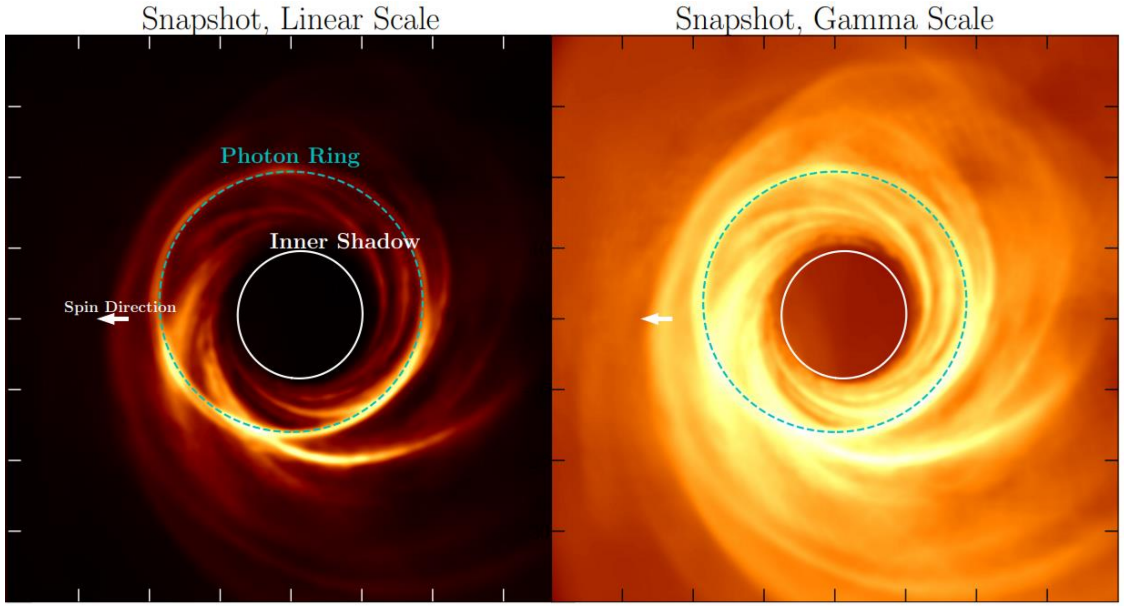



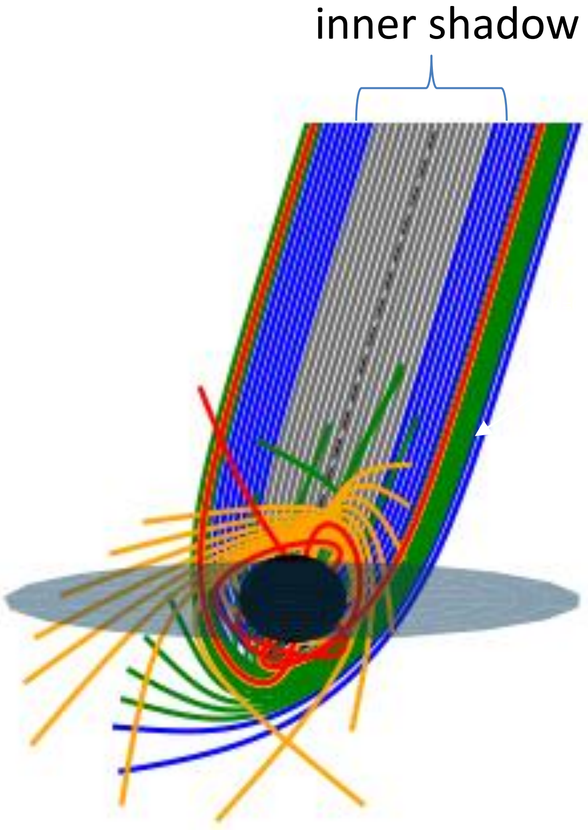

- Measuring polarization as a function of radius **probes energy flow at different scales**

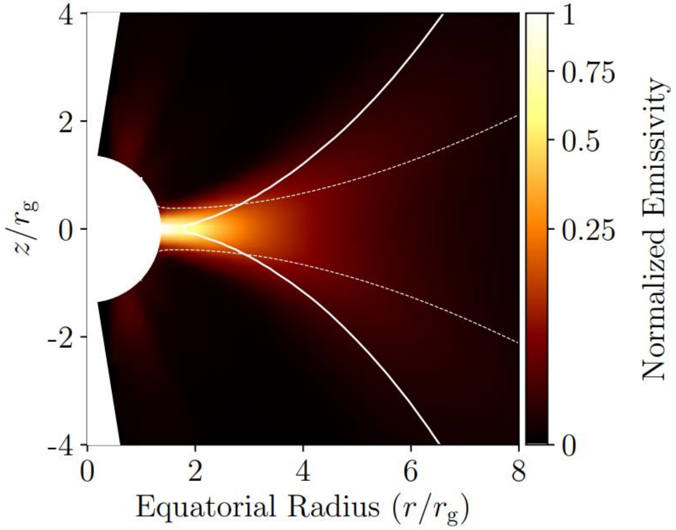
- Both simple models and GRMHD simulations make a strong prediction
  - arg($\beta_2$) evolves rapidly close to the horizon as the rest frame fields become more azimuthal from **GR frame dragging**

**Chael**+ 2023b, (also Ricarte+ 2022)

# Aside: Inner shadow is a generic prediction of MAD simulations



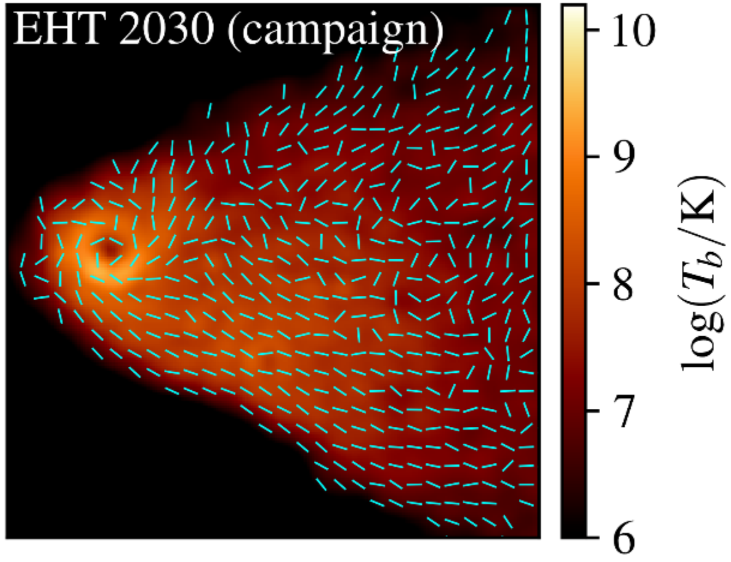



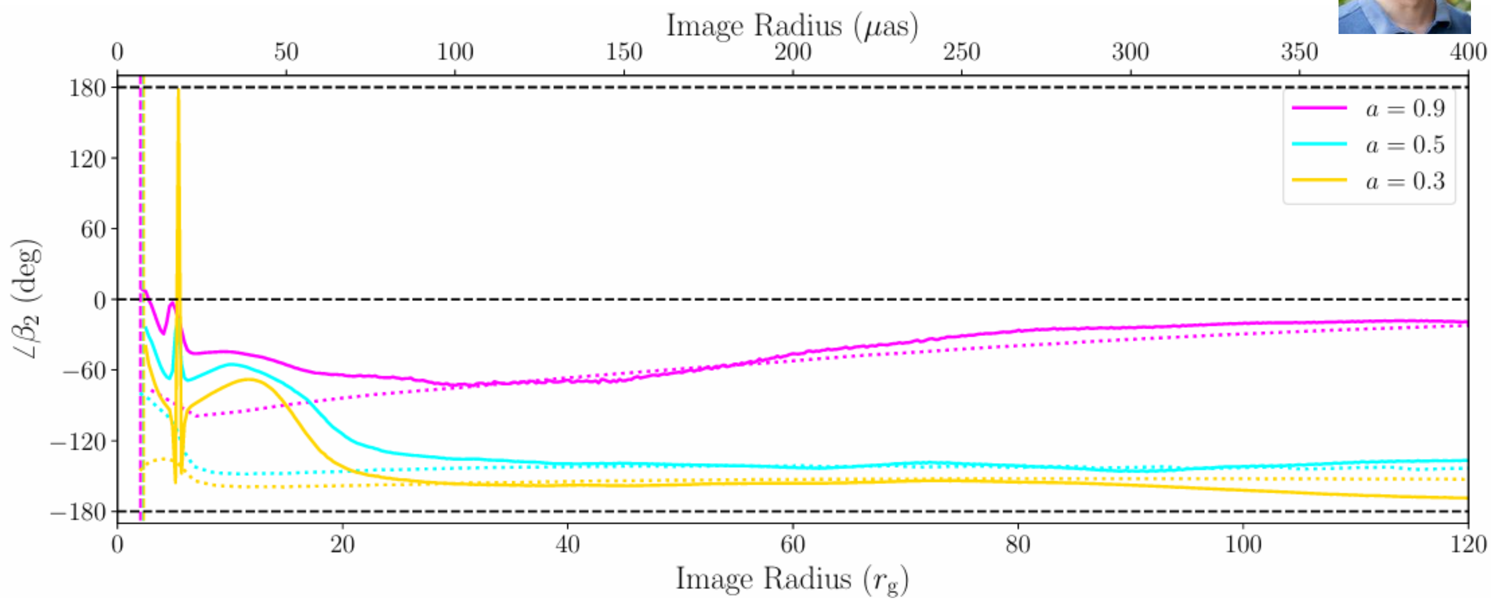

- The **inner shadow is visible in simulations**; its edge **approaches** the **lensed position of the event horizon**
- MADs have thin / nearly equatorial emission regions close to the horizon
- Redshift increases near the horizon → the inner shadow is **most visible at high dynamic range**

**Chael**+ 2021

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



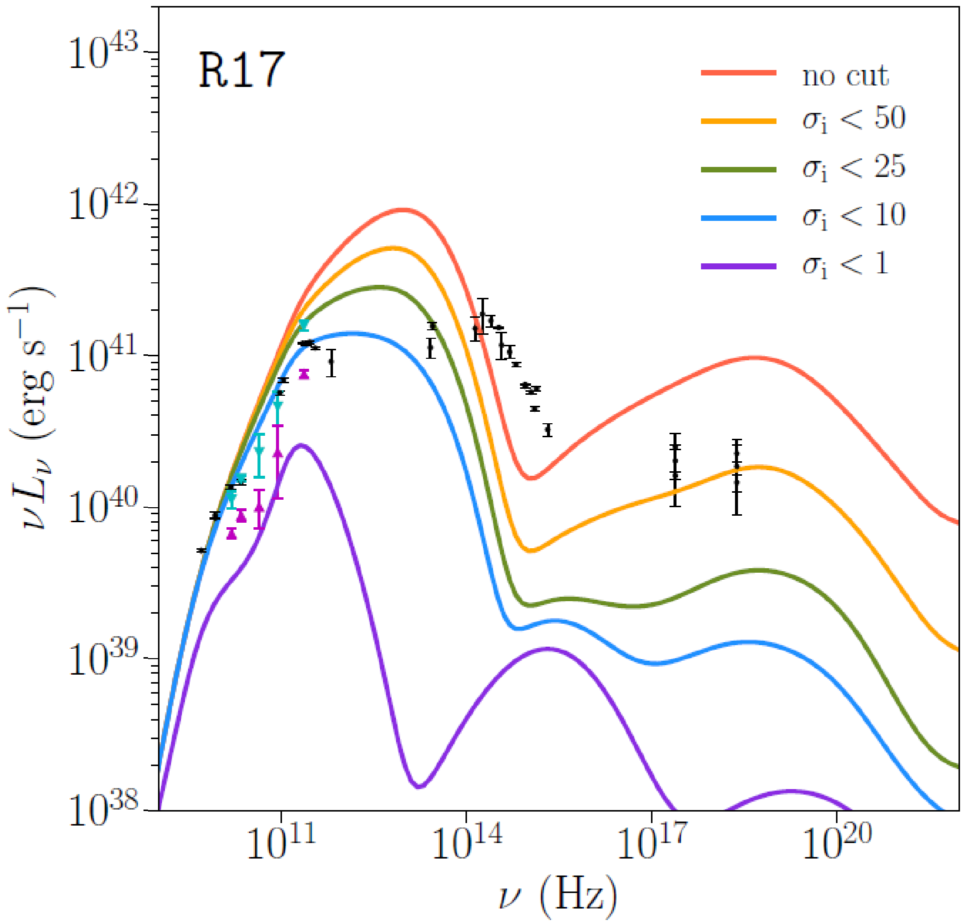

Ongoing work with Zack Gelles (Princeton)

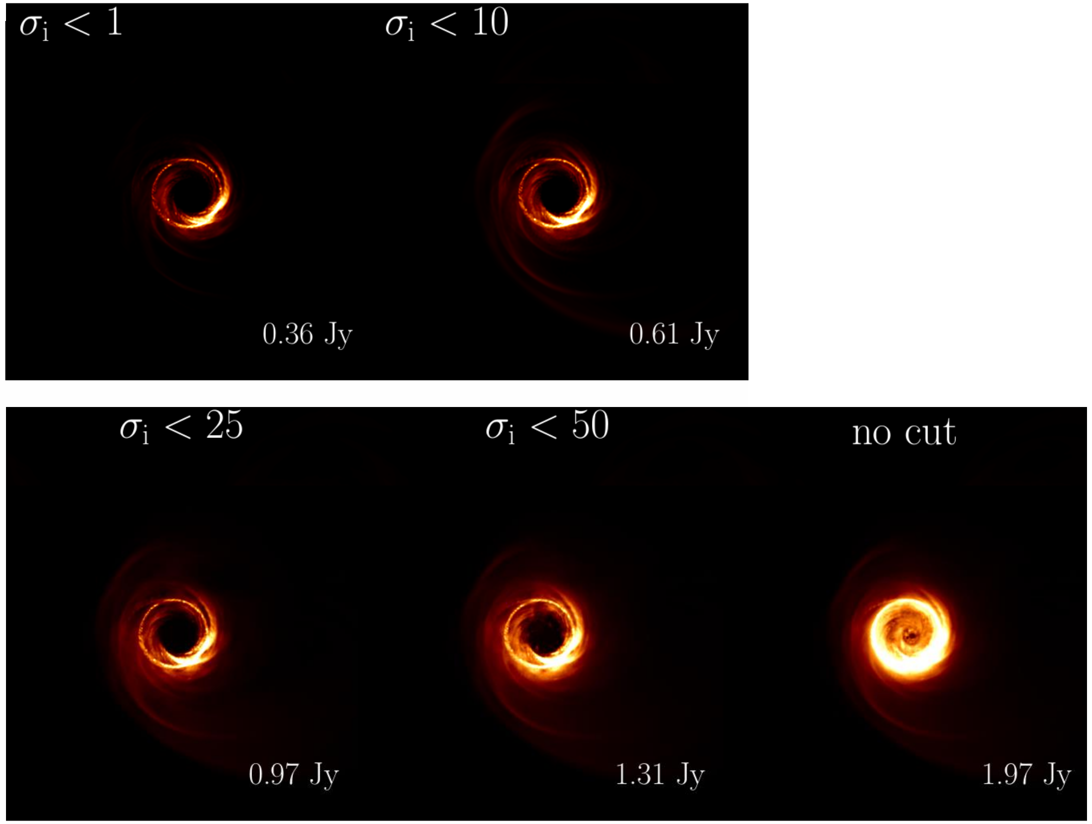



- New telescope sites & larger bandwidth will enhance EHT's **dynamic range**
  - These will illuminate both the **BH-jet connection**
- These new observations will require new theoretical models and simulations to fully interpret
  - Can we directly measure energy flow **from the horizon through the jet base?**

**Chael**+ 2019, 2023b
Image Credit: Paul Tiede, Dom Pesce, Zack Gelles

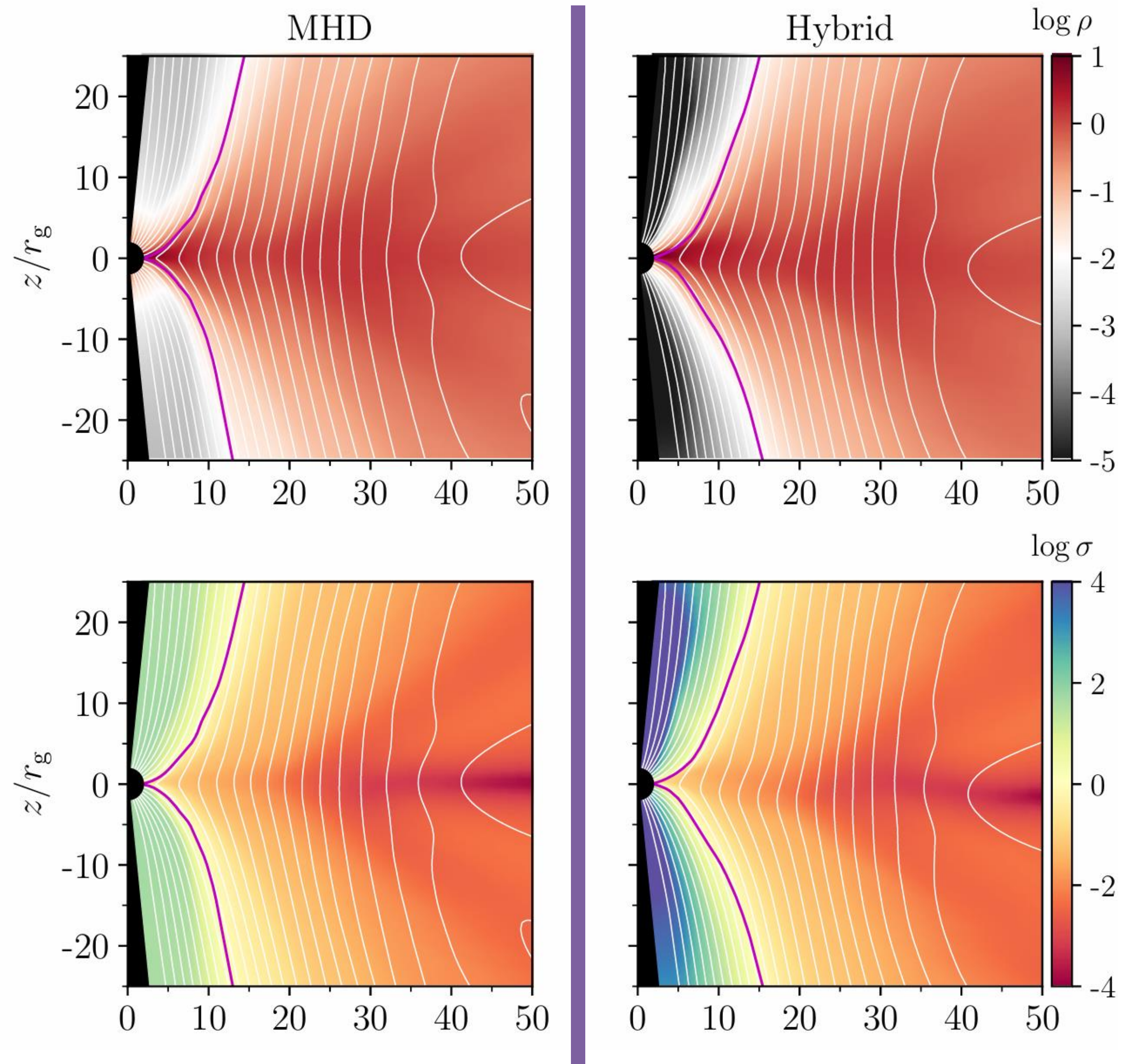
# MAD Simulation uncertainties: High-Magnetization Regions

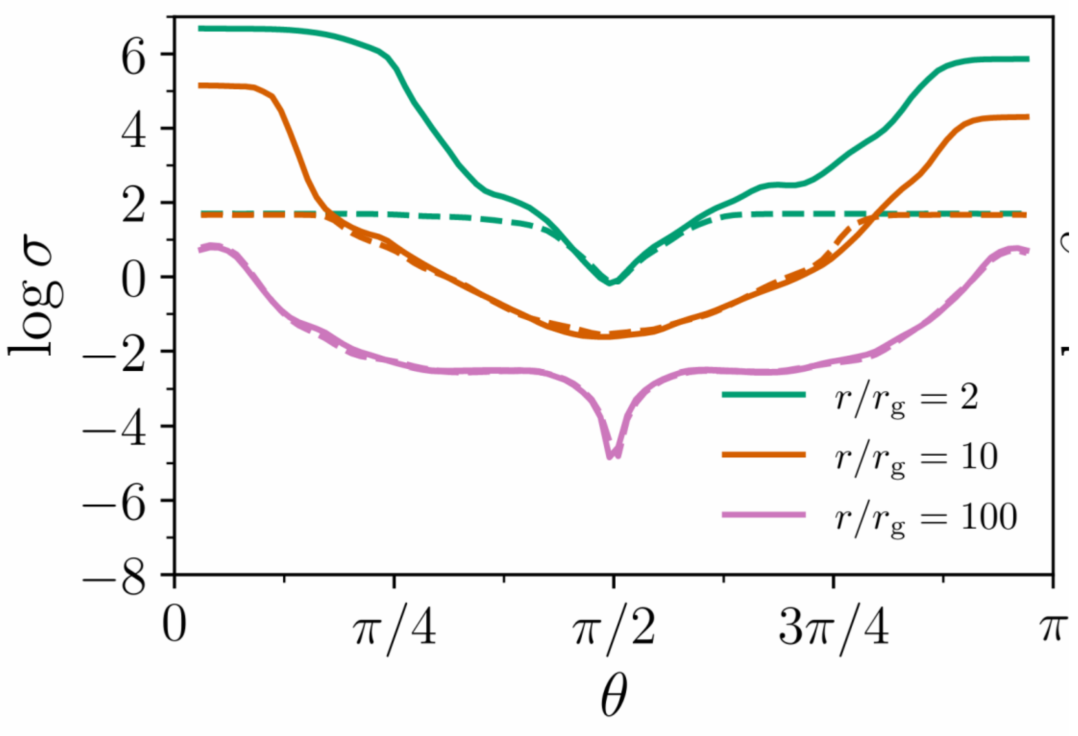



Chael+ 2019

# Evolving the jet with hybrid GRMHD+Force-Free

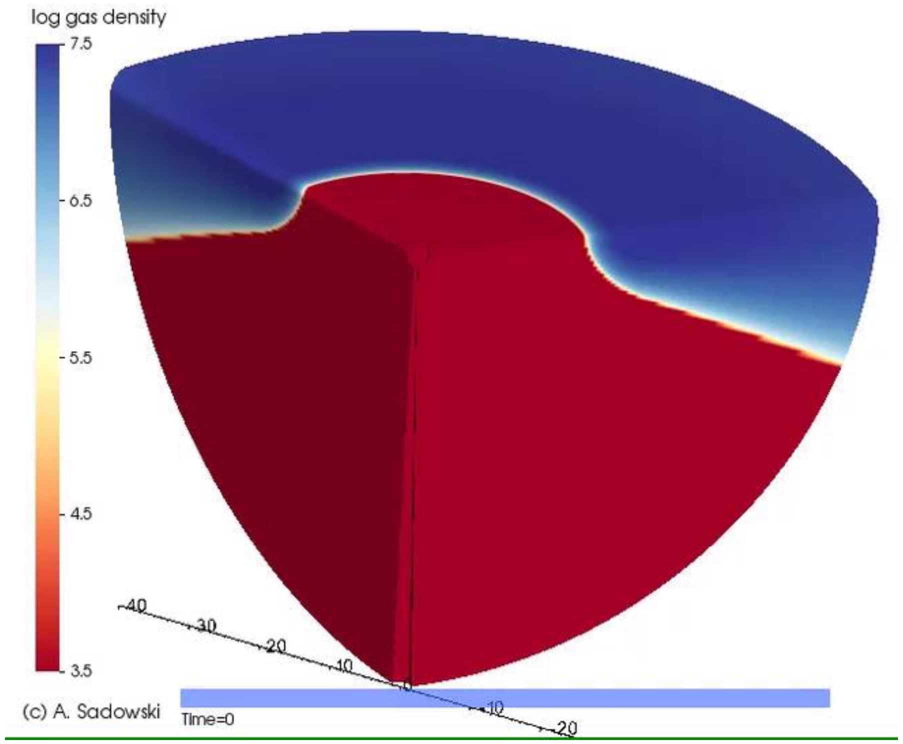



Chael 2024

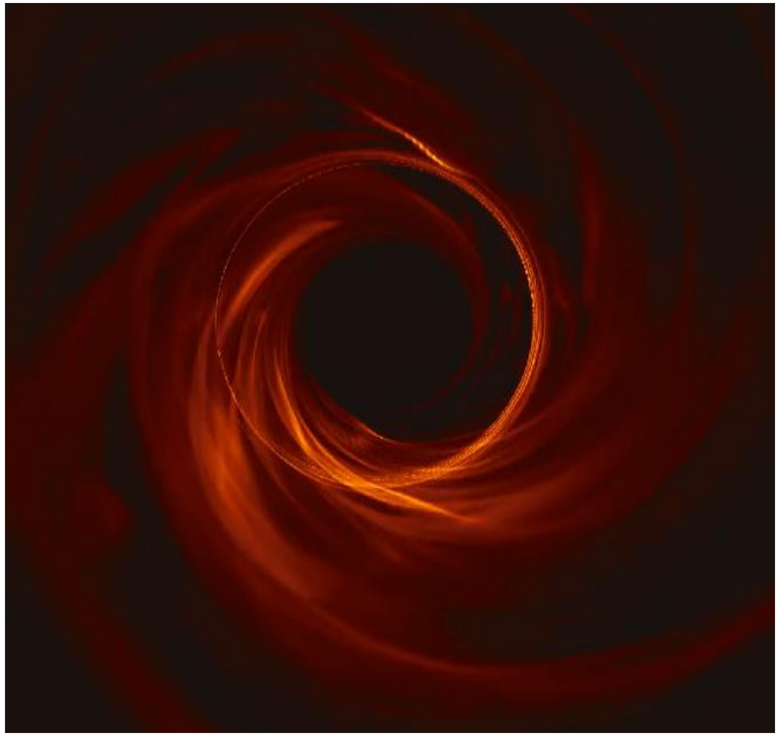
# MAD Simulation Uncertainties: Electron Temperature

GRMHD




$T_e$?

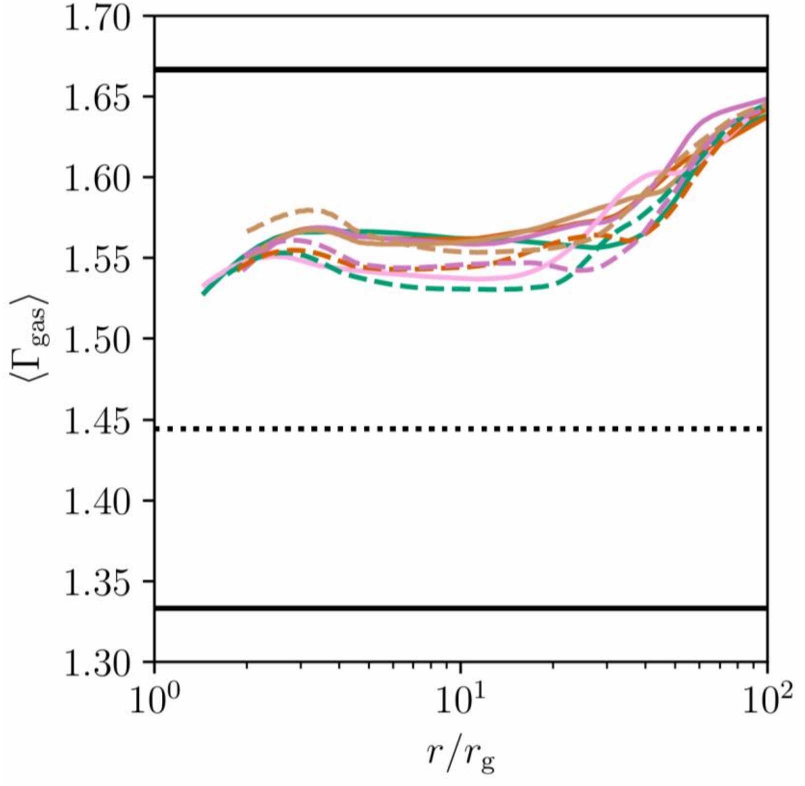
GRRT



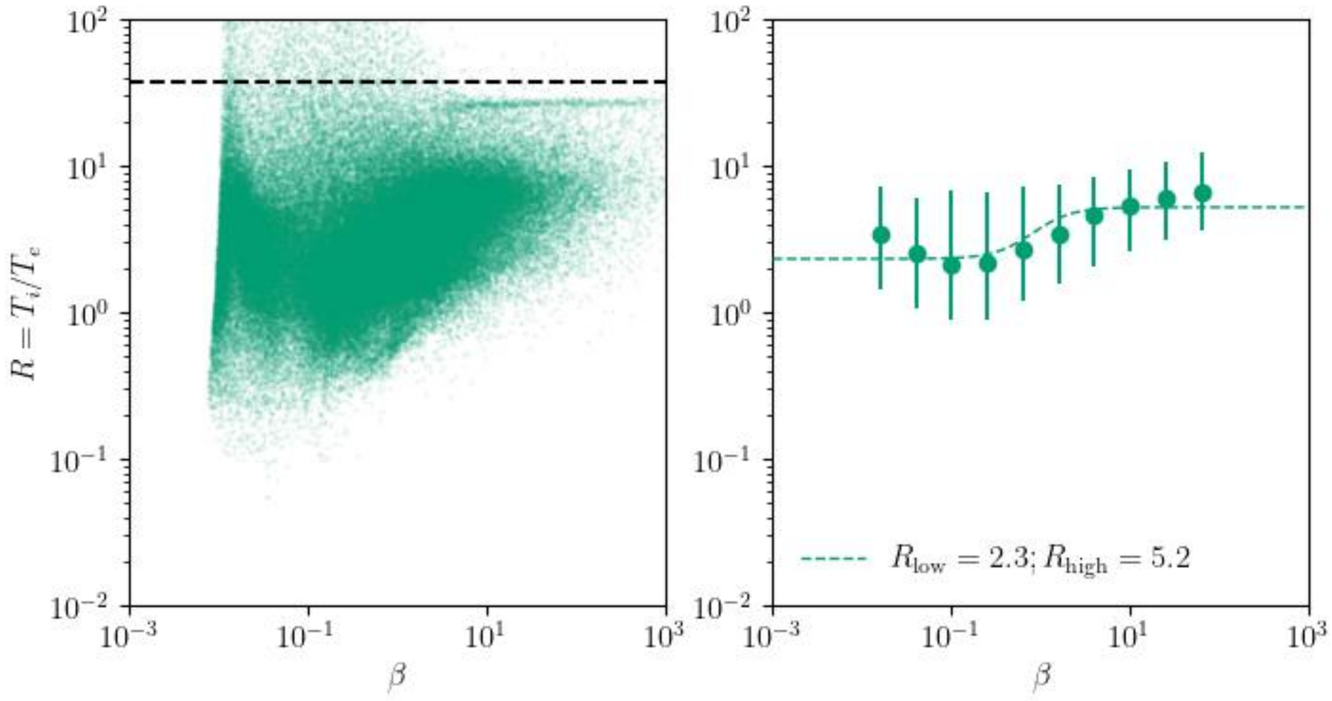
Movie Credits: Aleksander Sądowski,
EHT Collaboration 2019 (Paper V)

# New Survey of 2-T, radiative GRMHD

Adiabatic Index




Ion-to-electron temperature ratio




Between 4/3 and 13/9!

Lower Rhigh/ higher Rlow than typically used! (but a lot of scatter)

Chael in prep

# Takeaways:

- The EHT has imaged M87* and Sgr A* in full polarization: Ramesh’s work was critical for developing the suite of imaging & analysis methods we have today

- EHT linear polarization images show **~20% polarization** with an **azimuthal pattern** of polarization angles at 20 microarcsec scales. Circular polarization on these scales is **<4%**

- The EHT images can be used to constrain GRMHD simulation models of the emission region:
    - M87* and Sgr A* **are** MAD

- The azimuthal structure of the linear polarization in M87* is consistent with outward Poynting flux
    - Simple model prediction is upheld in a library of GRMHD simulation images.

- Electron temperature uncertainties and high-sigma regions remain big challenges for connecting GRMHD images to data
    - Hybrid GRMHD+FF and 2T simulations can help!