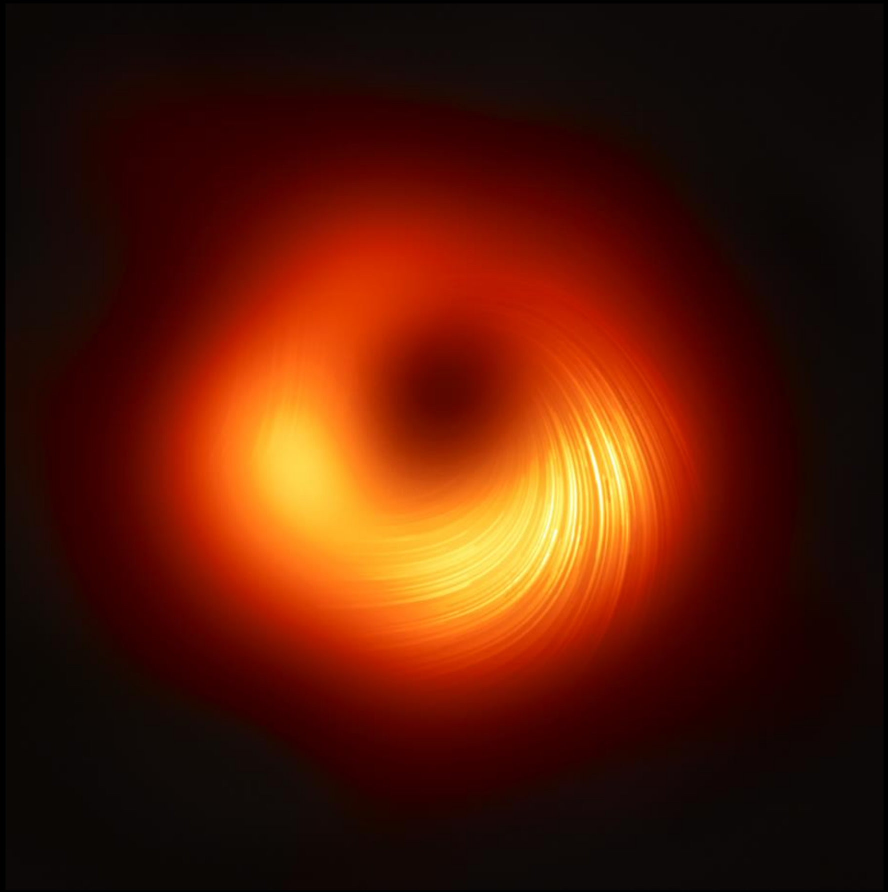
Black Holes in Polarized Light



Andrew Chael
Princeton Gravity Initiative

December 12, 2023

Princeton gravity Initiative

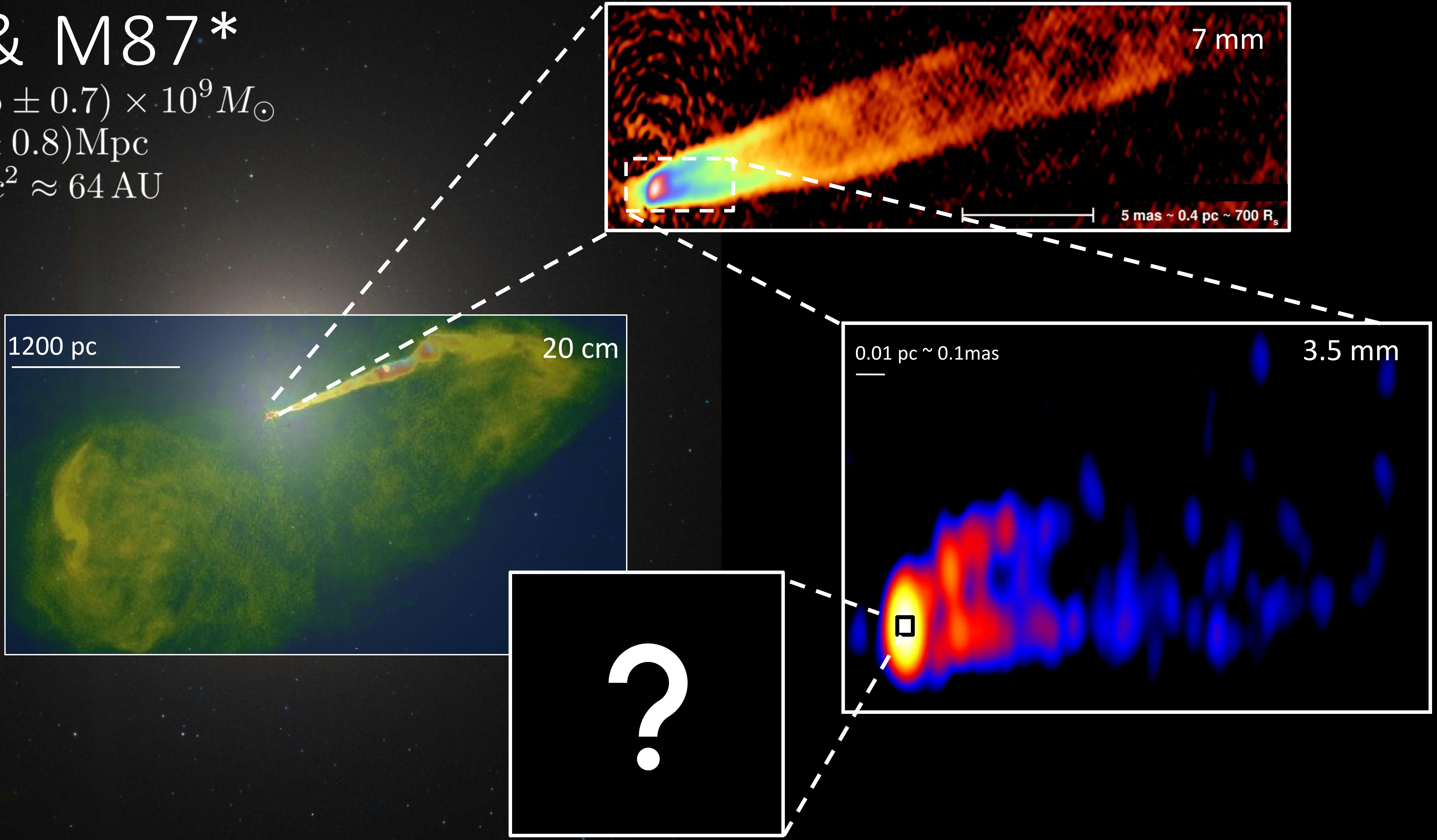
Event Horizon Telescope

M87 & M87*

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

$D = (16.8 \pm 0.8)\mathrm{Mpc}$

$R_s = 2GM/c^2 \approx 64\,\mathrm{AU}$



What does jet launching look like on event horizon scales?

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

M87 & M87*

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

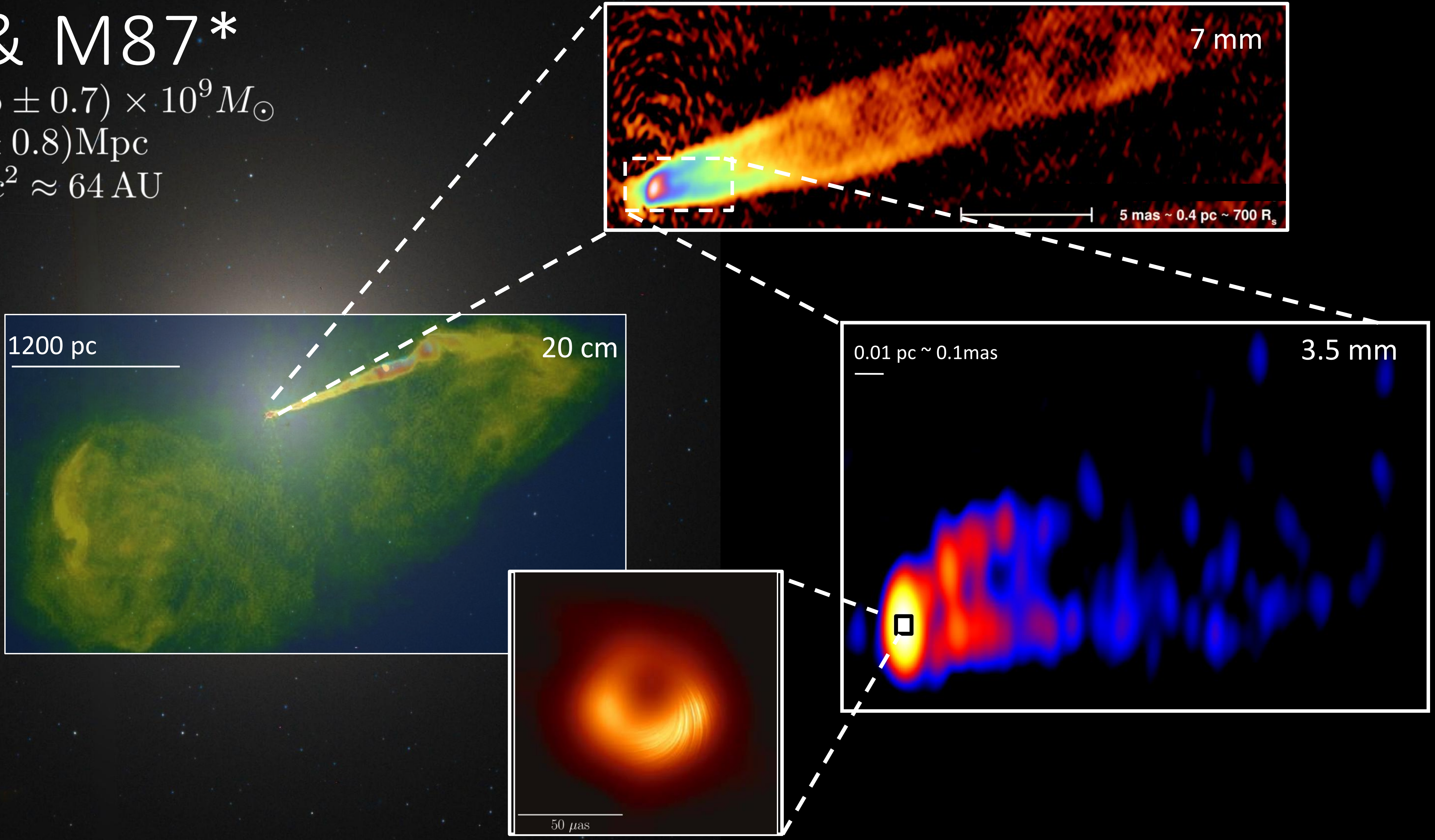
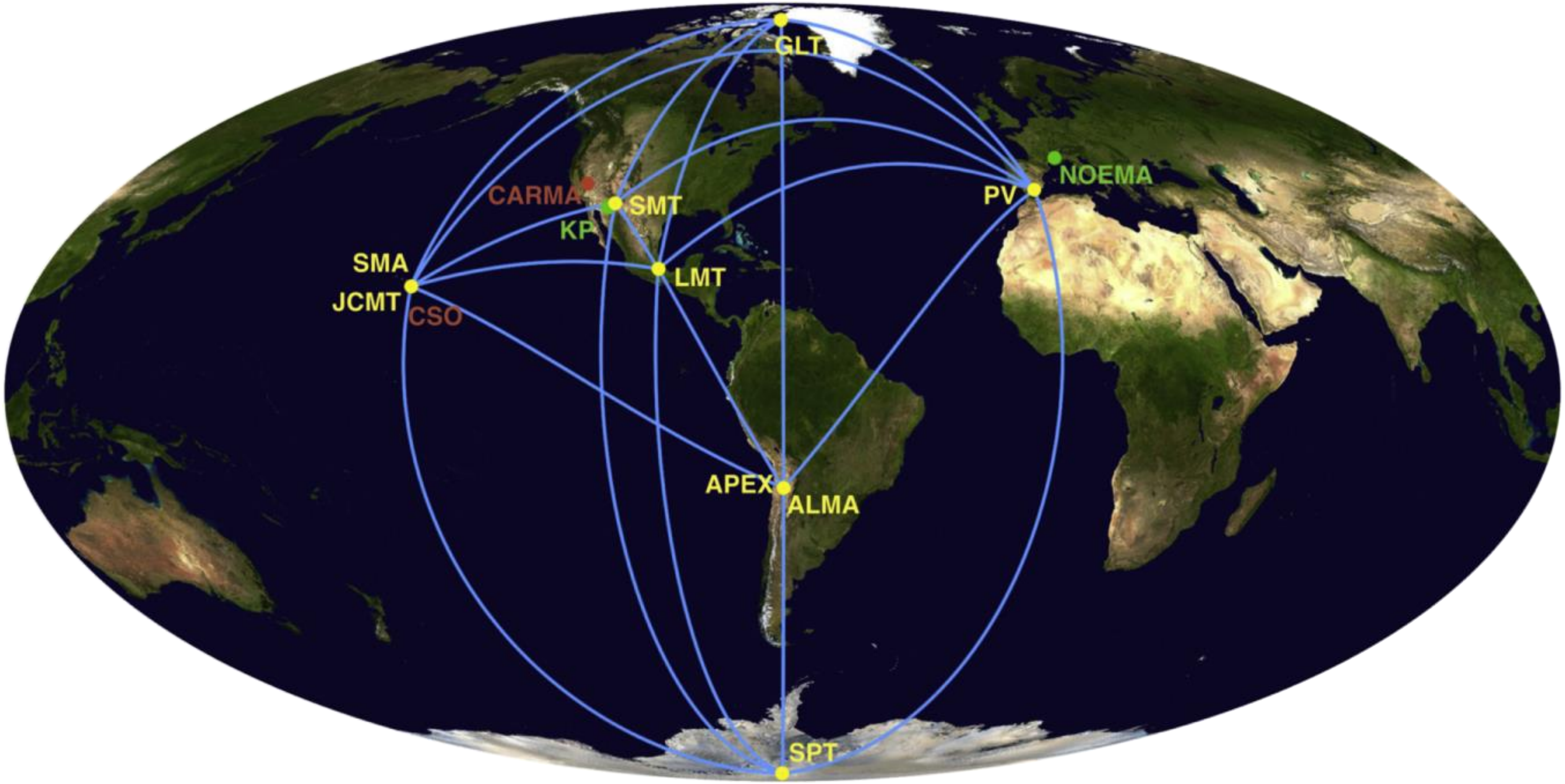


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

The Event Horizon Telescope: Instrument



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

EHTC+ 2019, Paper II

The Event Horizon Telescope: People

300+ members

60 institutes

20 countries

from Europe, Asia, Africa,
North and South America.

Image credit: E. Traianou, MPIfR

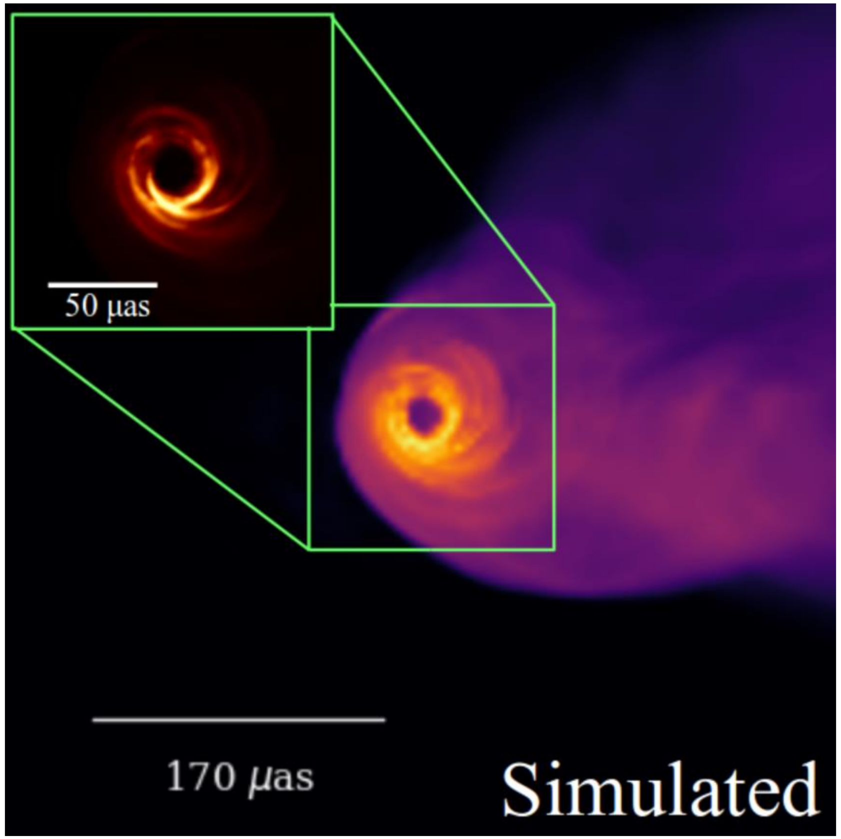
At the heart of M87…

What we know:

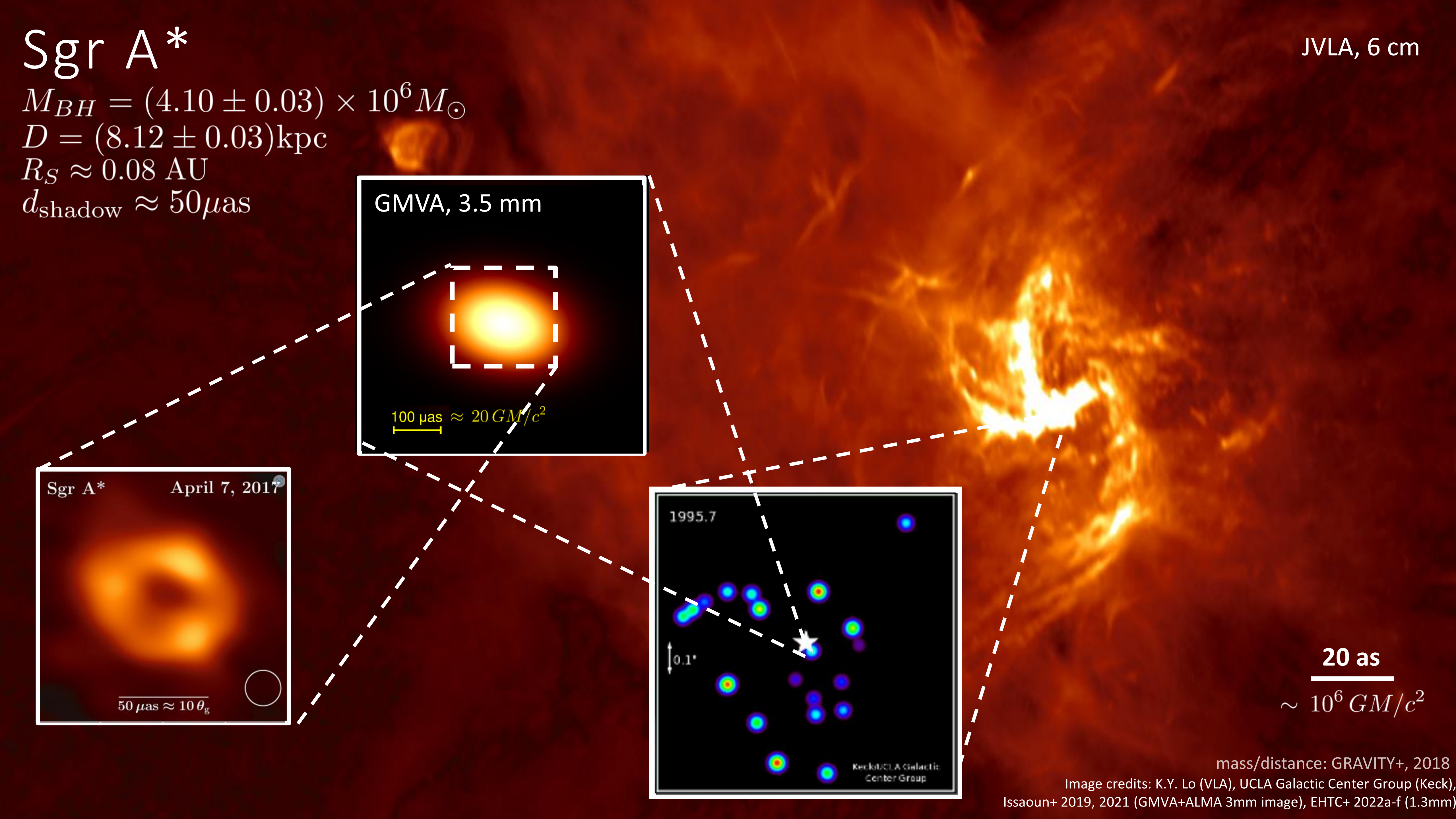
- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Hot ($T \gtrsim 10^{10}\,\mathrm{K}$), sub-Eddington accretion flow emitting synchrotron radiation
- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}\ \mathrm{erg\ s^{-1}}$)

Questions I think about:

- Is the jet launched by extracting BH spin energy?
  - What is the strength and geometry of the magnetic field?
- How can we perform precise tests of gravity?
  - What will we see with upgraded EHT observations?
- What small-scale plasma physics accelerates electrons and lights up the flow?
  - What powers X-ray/ γ -ray flares in Sgr A* and M87*?

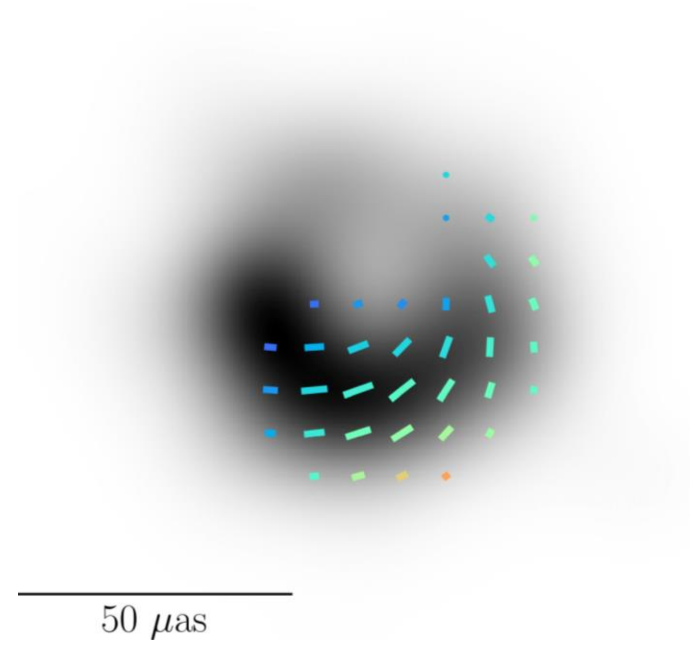


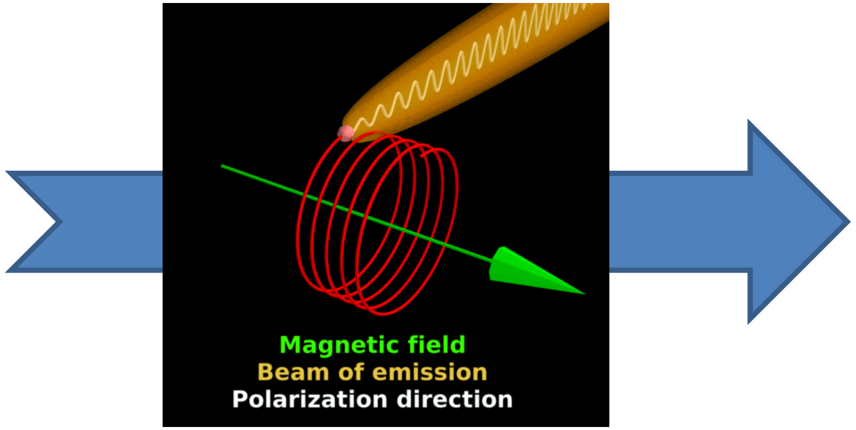
Blackburn+ 2019, **Chael+** 2019



Sgr A*
$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
$D = (8.12 \pm 0.03)\mathrm{kpc}$
$R_S \approx 0.08$ AU
$d_{\mathrm{shadow}} \approx 50\mu\mathrm{as}$
JVLA, 6 cm
GMVA, 3.5 mm
100 µas $\approx 20\,GM/c^2$
Sgr A*
April 7, 2017
$50\,\mu\mathrm{as} \approx 10\,\theta_g$
1995.7
0.1"
Keck/UCLA Galactic Center Group
20 as
$\sim 10^6\,GM/c^2$
mass/distance: GRAVITY+, 2018
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHTC+ 2022a-f (1.3mm)

Why polarization?





Magnetic field geometry in the emission region!

Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines

Polarization **transport** effects are sensitive to magnetic field and plasma parameters

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Outline

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

2. How do we interpret the polarized image of M87*?

3. Connection between polarized images and EM energy flux

First M87 Event Horizon Telescope Results. VII. Polarization of the Ring

The Event Horizon Telescope Collaboration

(See the end matter for the full list of authors.)

Received 2020 November 23; revised 2021 February 15; accepted 2021 February 16; published 2021 March 24

First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon

The Event Horizon Telescope Collaboration

(See the end matter for the full list of authors.)

Received 2020 December 2; revised 2021 February 3; accepted 2021 February 8; published 2021 March 24

First M87 Event Horizon Telescope Results. IX. Detection of Near-horizon Circular Polarization

The Event Horizon Telescope Collaboration

(See the end matter for the full list of authors.)

Received 2023 June 19; revised 2023 September 5; accepted 2023 September 12; published 2023 November 8

Black Hole Polarimetry I. A Signature of Electromagnetic Energy Extraction

Andrew Chael[1], Alexandru Lupsasca[2], George N. Wong[1,3], and Eliot Quataert[1,4]

[1] Princeton Gravity Initiative, Princeton University, Princeton, NJ 08544, USA; achael@princeton.edu

[2] Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37212, USA

[3] School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA

[4] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Received 2023 July 12; revised 2023 August 11; accepted 2023 September 11; published 2023 November 14

ArXiv: 2105.01169; 2105.01173; 2311.10976; 2307.06372

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

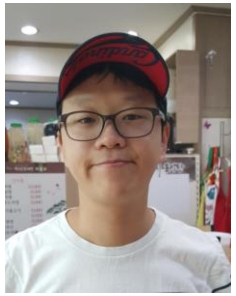
EHTC Paper VII,VIII,IX writing teams

Monika Mościbrodzka

Iván Martí-Vidal

Sara Issaoun

Jongho Park



Maciek Wielgus

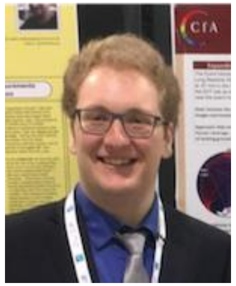
Angelo Ricarte

Jason Dexter

Andrew Chael

Alejandra Jiménez-Rosales

Daniel Palumbo



Dom Pesce

John Wardle

Svetlana Jorstad

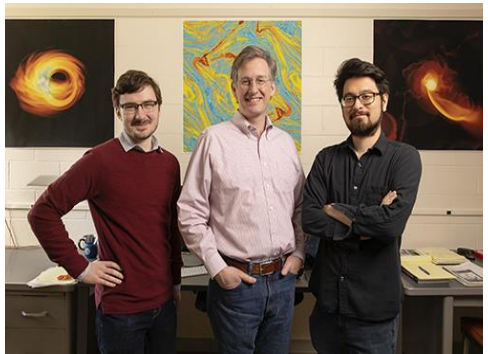
Ioannis Myserlis

Freek Roelofs

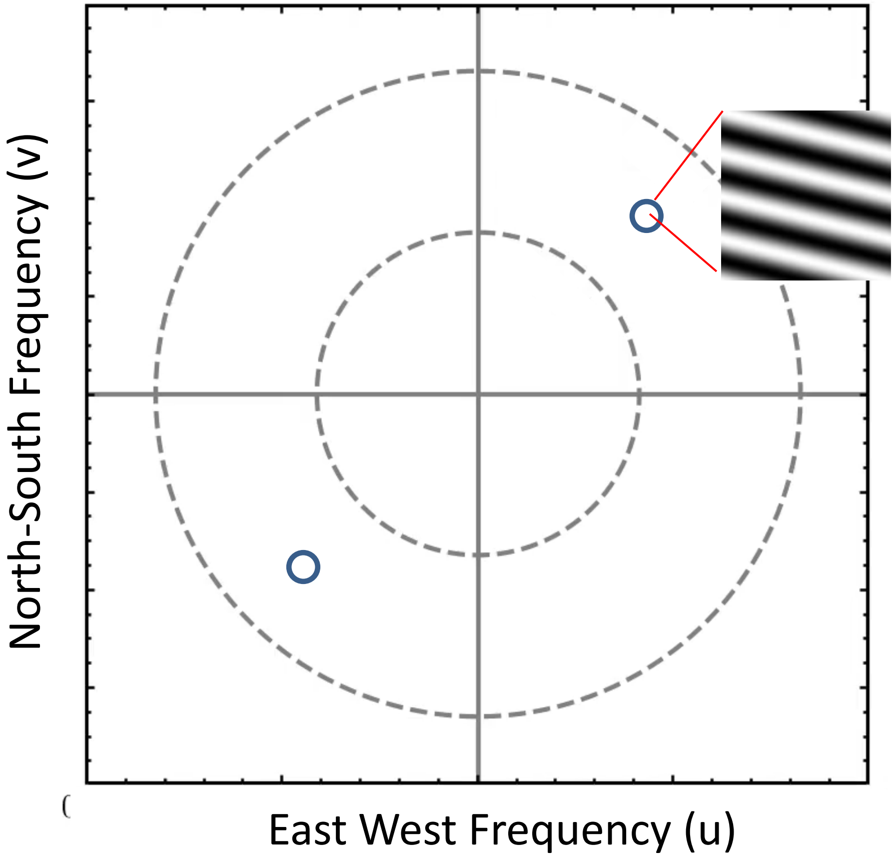
Abhishek Joshi

Avery Broderick

Ben Prather, Charles Gammie, George Wong



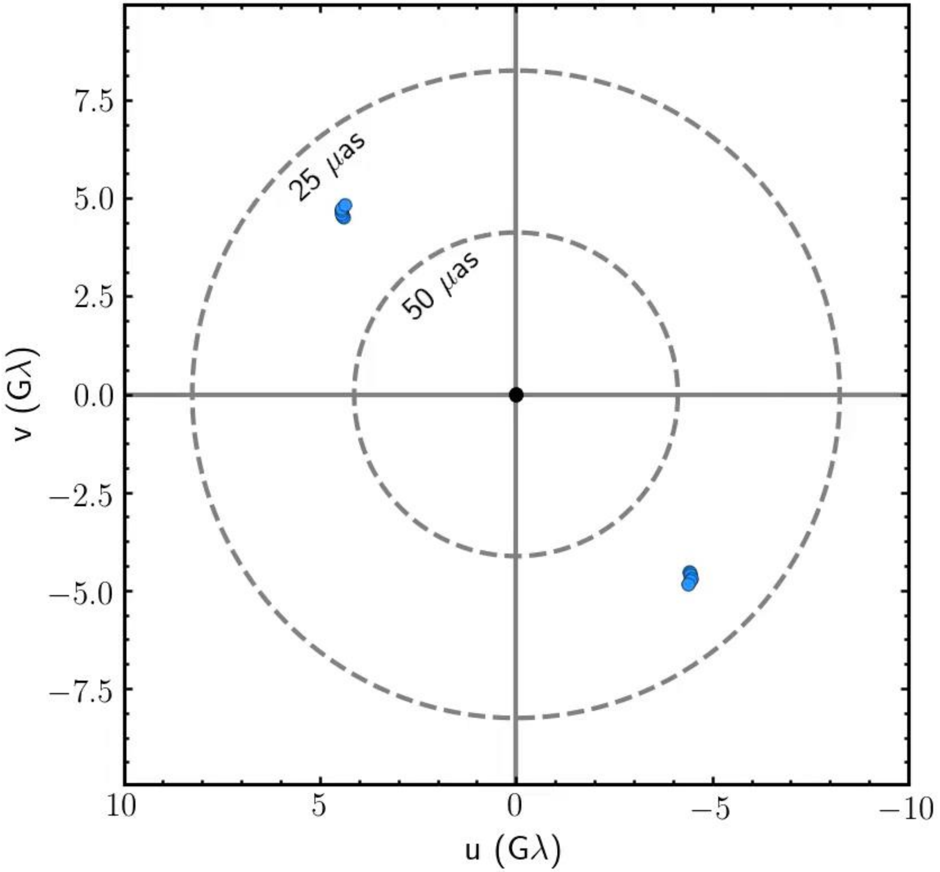
Very Long Baseline Interferometry (VLBI)



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

movie credit: Katie Bouman

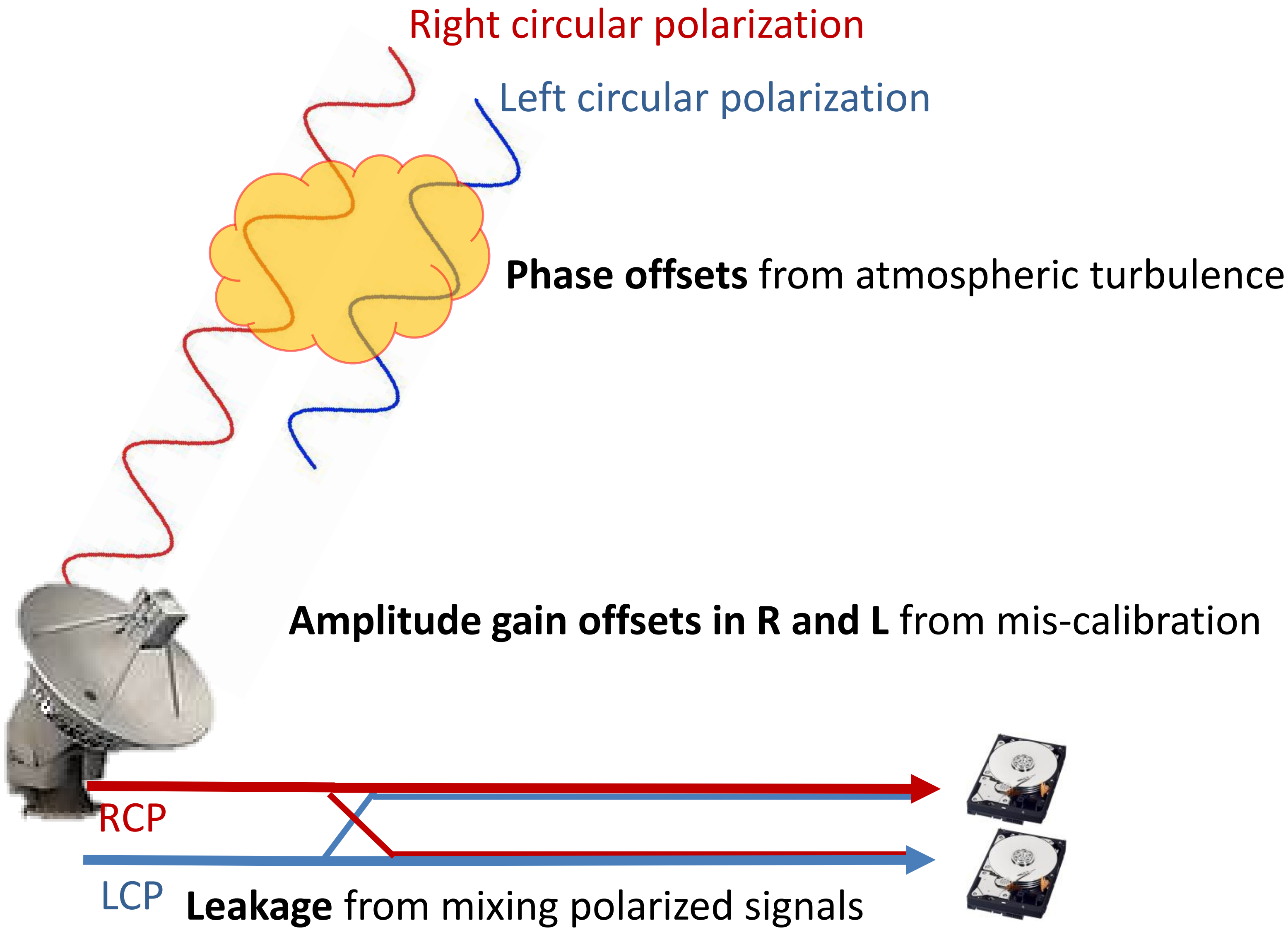
Very Long Baseline Interferometry (VLBI)



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

movie credit: Daniel Palumbo

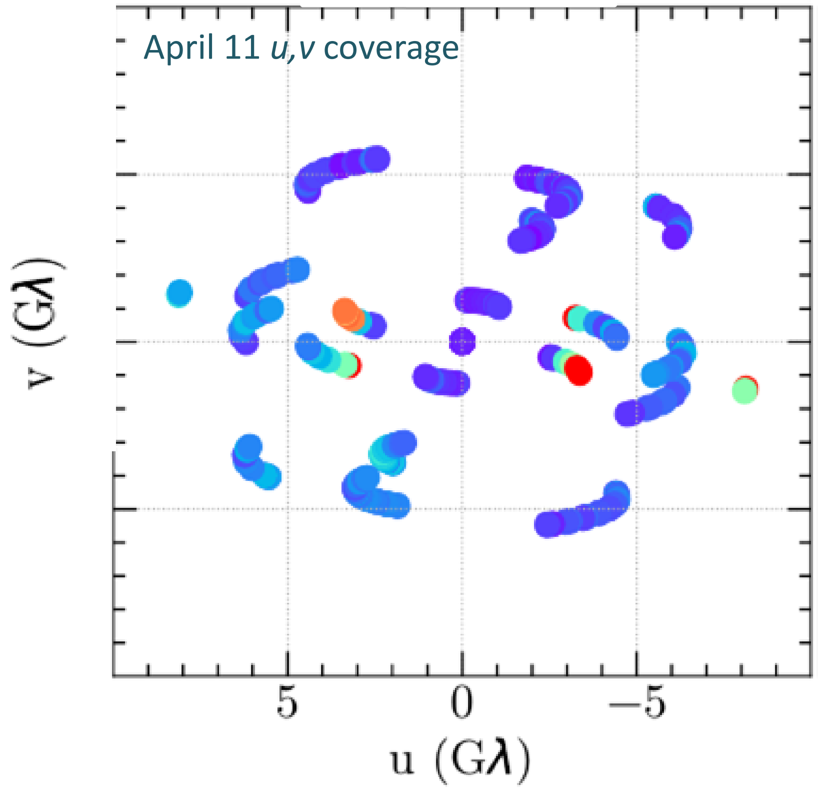
Challenges of near-horizon imaging



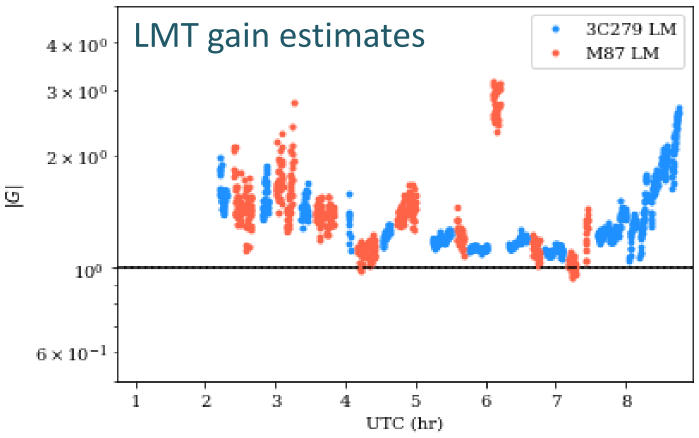
Data at each station are corrupted by unknown polarimetric **leakage** and **complex gain** factors

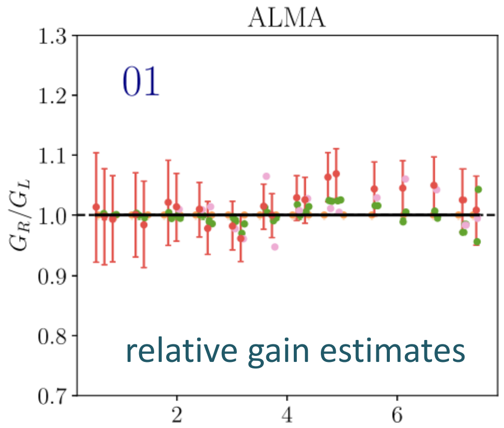
Challenges of near-horizon imaging

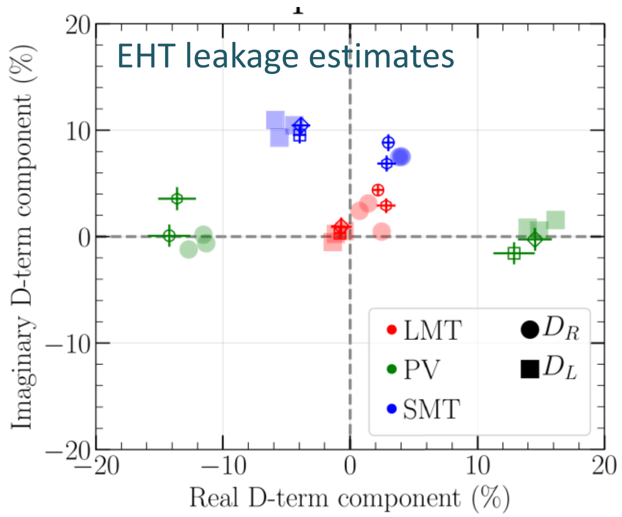
EHT coverage is **sparse**: inversion of image from the data is unconstrained



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



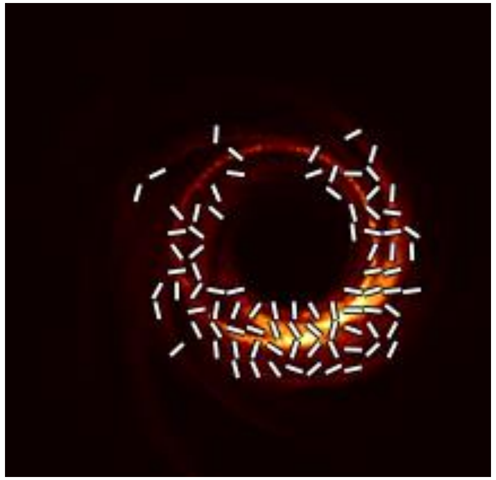




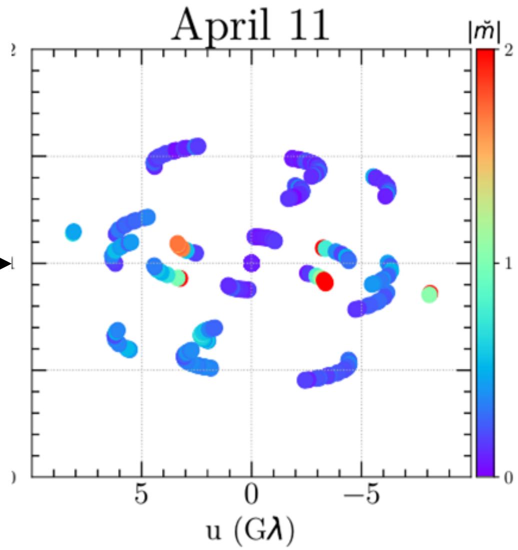
EHTC+ 2019 Paper IV, 2022 Paper VII, 2023 Paper IX (**Chael**, paper coordinator/writing

Solving for the Image

True Image

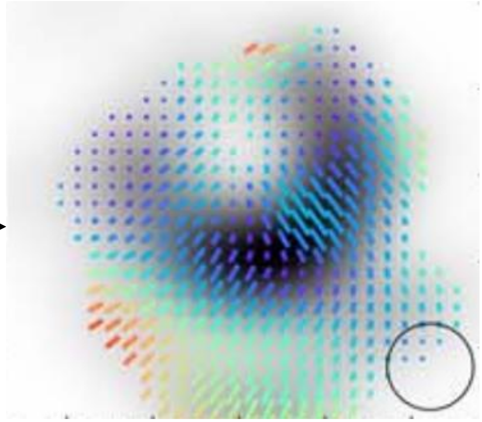


Sparse/ Corrupted Measurements



RECONSTRUCTION ALGORITHM

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)

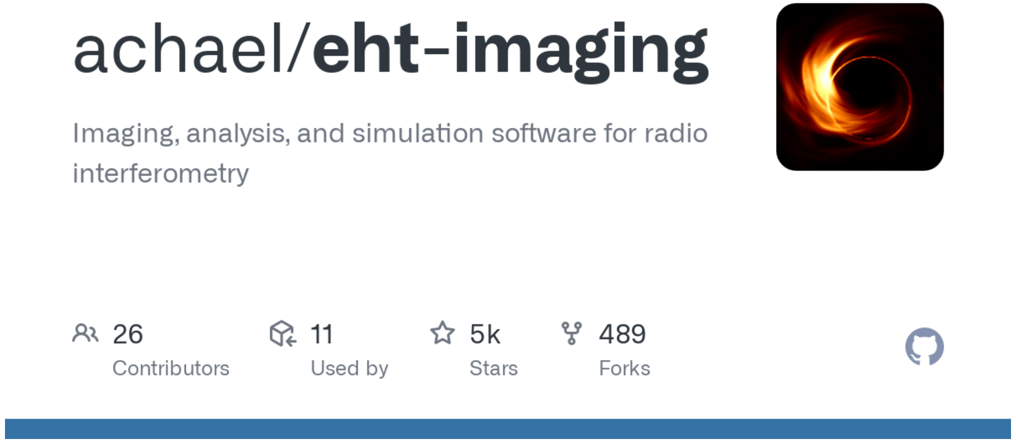
credit: Katie Bouman, Andrew Chael, EHTC 2021, Paper VII

The **`eht-imaging`** software library

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

- Flexible framework for developing tools:
    - polarimetric imaging, dynamical imaging, **multi-frequency imaging**, geometric modeling

- Uses:
    - All EHT imaging results to date
    - EHT calibration software
    - Forecasting from simulations
    - Imaging & analysis from VLBA, GMVA, ALMA….

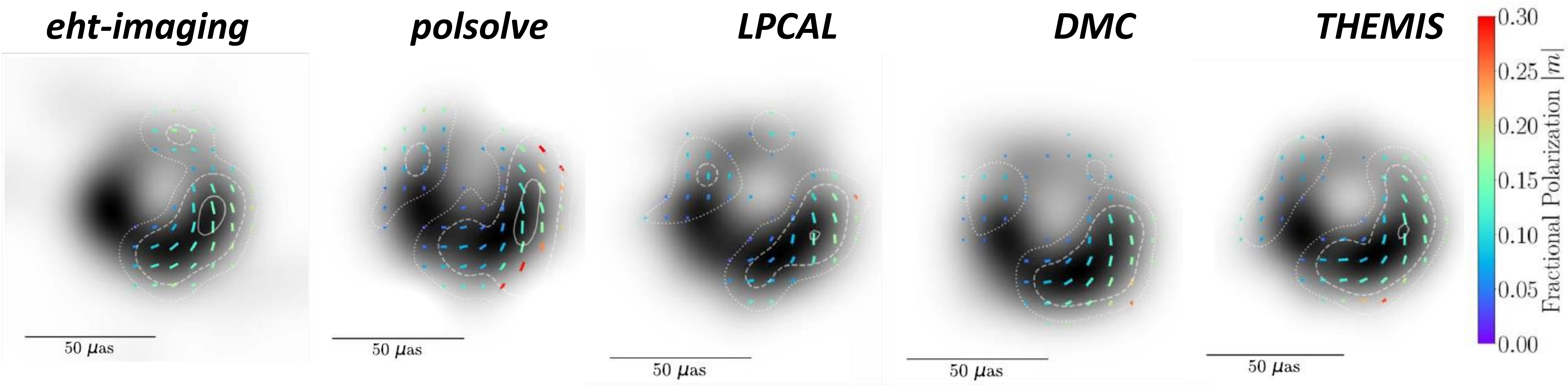


https://github.com/achael/eht-imaging

`pip install ehtim`

Chael+ 2016, 2018a, 2023

Linear Polarization Images from five vetted methods



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

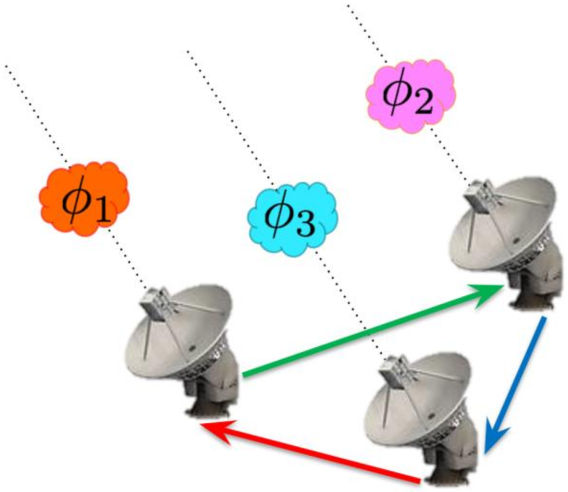
EHTC+ 2021 Paper VII (**Chael**, paper writing team)

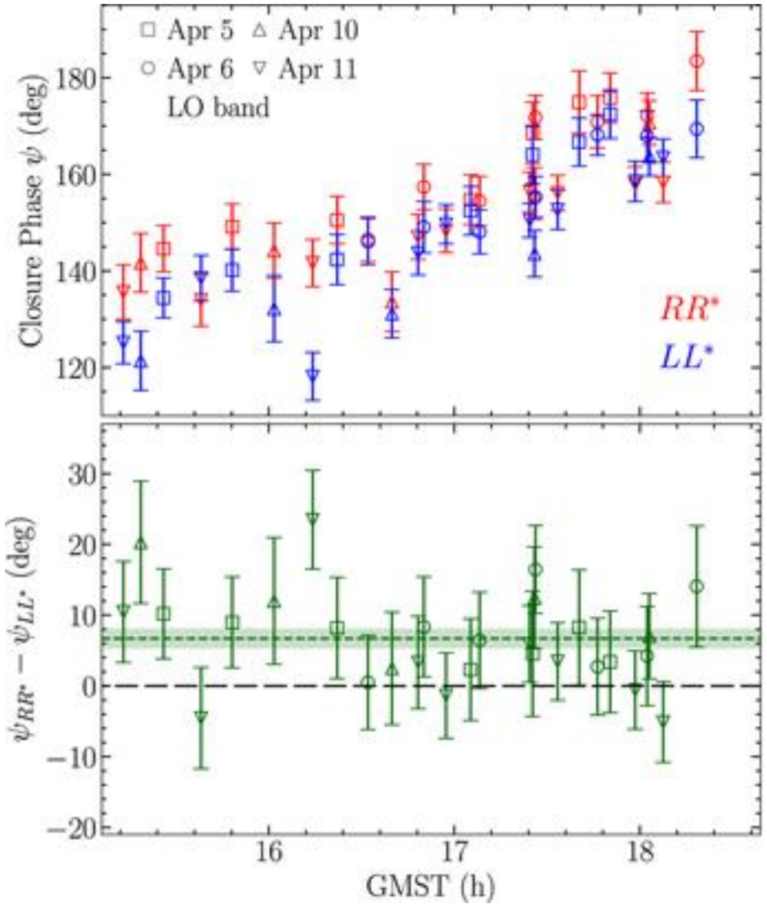
Horizon-Scale **circular polarization** is unambiguously detected by the EHT

- We detect an **offset** between **closure phases** in the RR and LL polarizations (V=0.5(RR-LL))

- This is immune to relative gain offsets G_R / G_L

- Can we constrain the image structure in circular polarization?





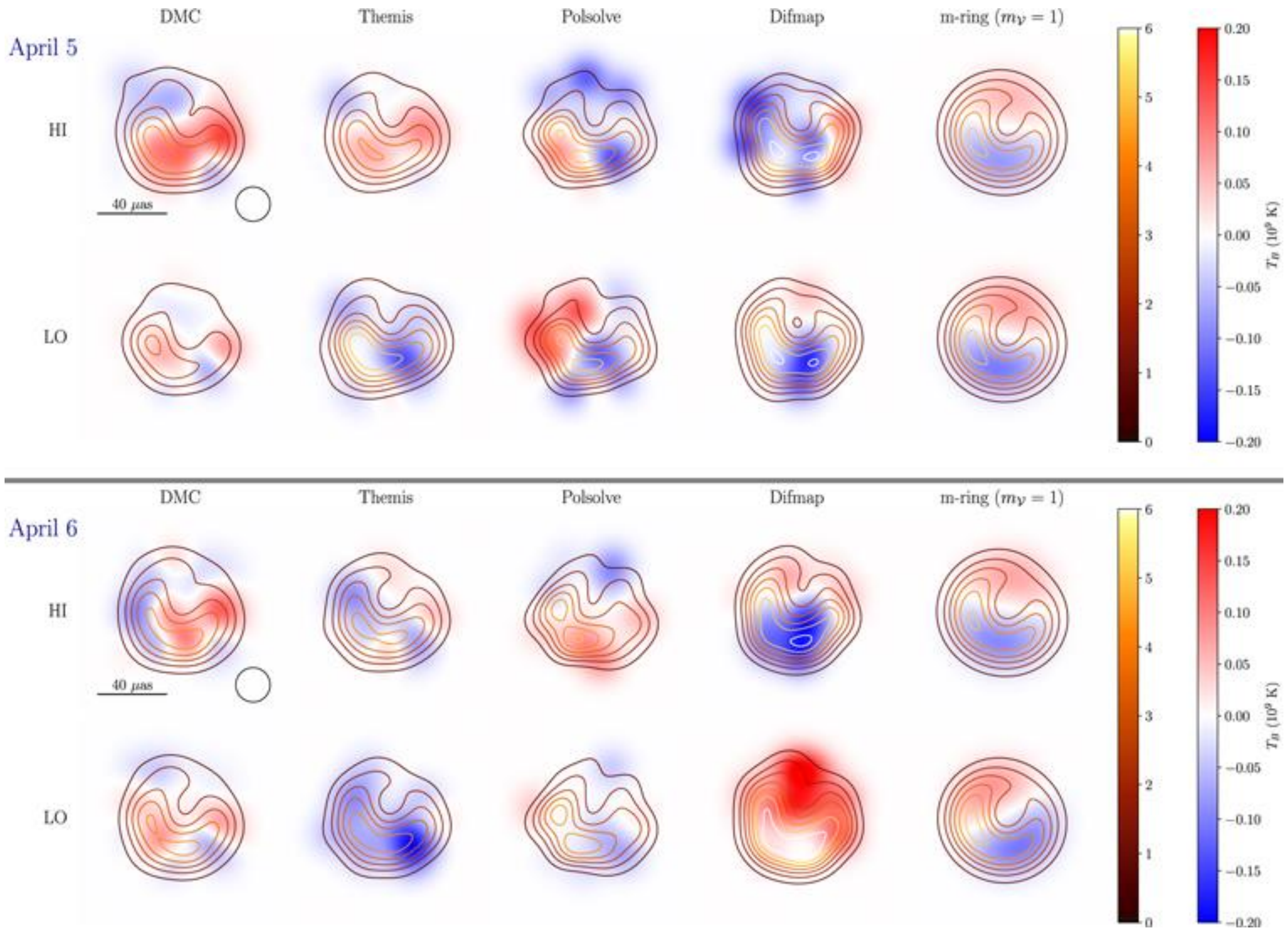
Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)

Horizon-Scale circular polarization *images* are **not** robustly recovered

- Different reconstruction methods make different assumptions about how to calibrate gains, D-terms, other systematics

- Methods do not show consistent Stokes V images
  - Not consistent between days
  - Not consistent between frequency bands

- We place an upper limit **<|v|> < 3.7%**



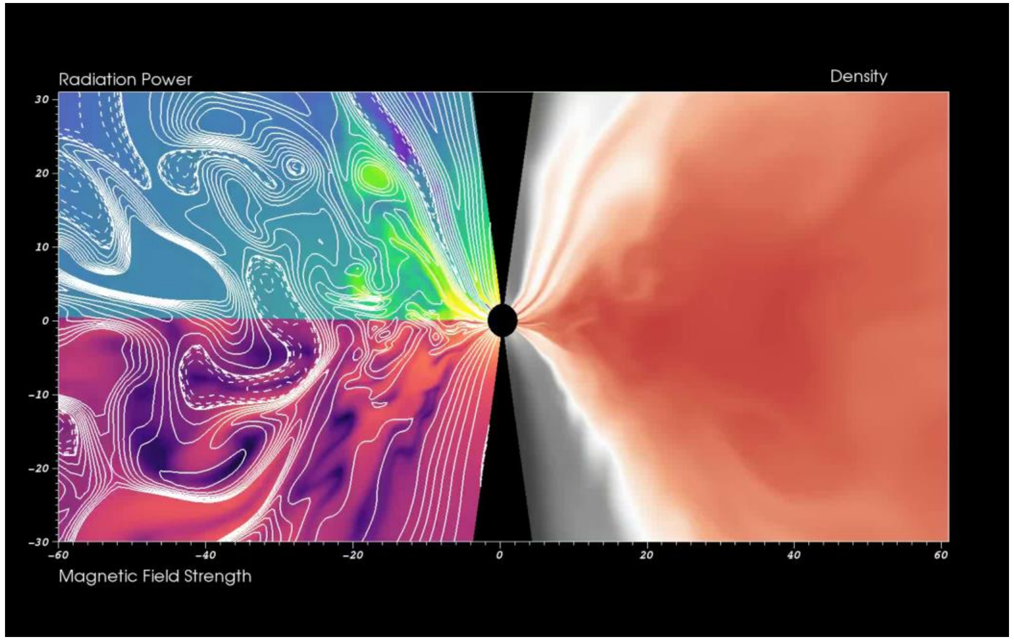
$$\langle|v|\rangle = \frac{\int |\mathcal{V}/\mathcal{I}|\,\mathcal{I}\,dA}{\int \mathcal{I}\,dA}$$

Average resolved Circular Fraction

Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)

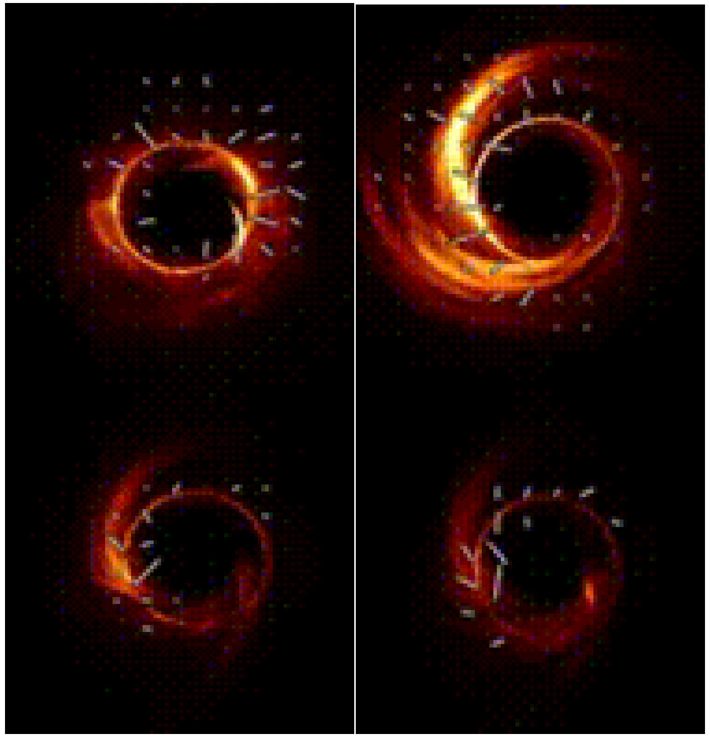
What do the EHT’s polarization results tell us about the accretion flow?

Theoretical Tools for Interpreting Black Hole Images



General Relativistic Magnetohydrodynamic (GRMHD) Simulations

Solves coupled equations of plasma dynamics and magnetic field in Kerr spacetime



GR Radiative Transfer

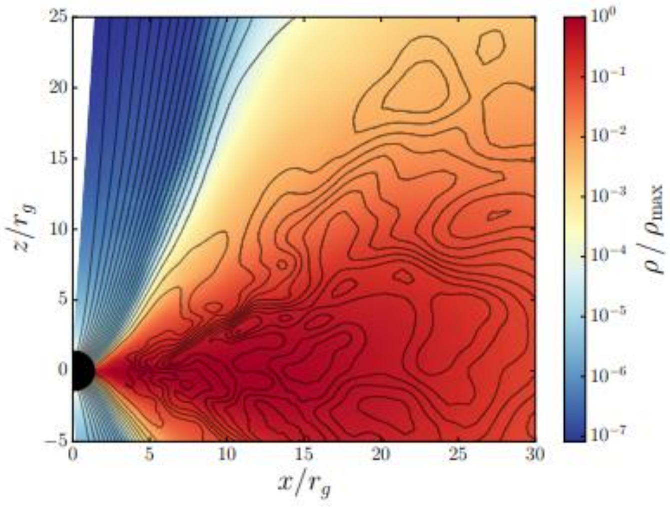
Tracks light rays and solves for the polarized radiation (including Faraday effects)

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

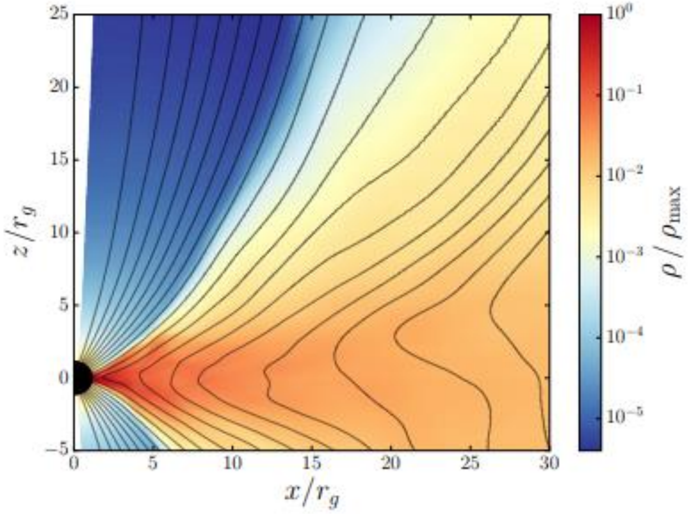
What is the magnetic field structure close to the horizon?

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

Magnetic fields are weak and turbulent



"SANE"



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

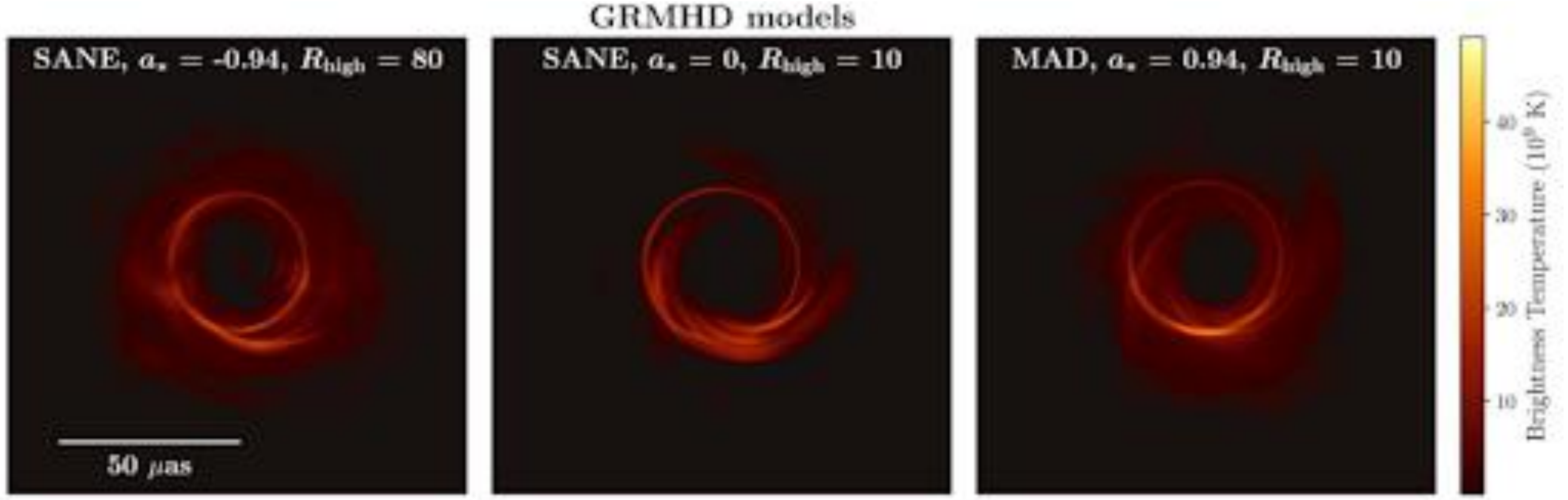
BH spin

magnetic flux

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

Scoring GRMHD Simulations: before polarization

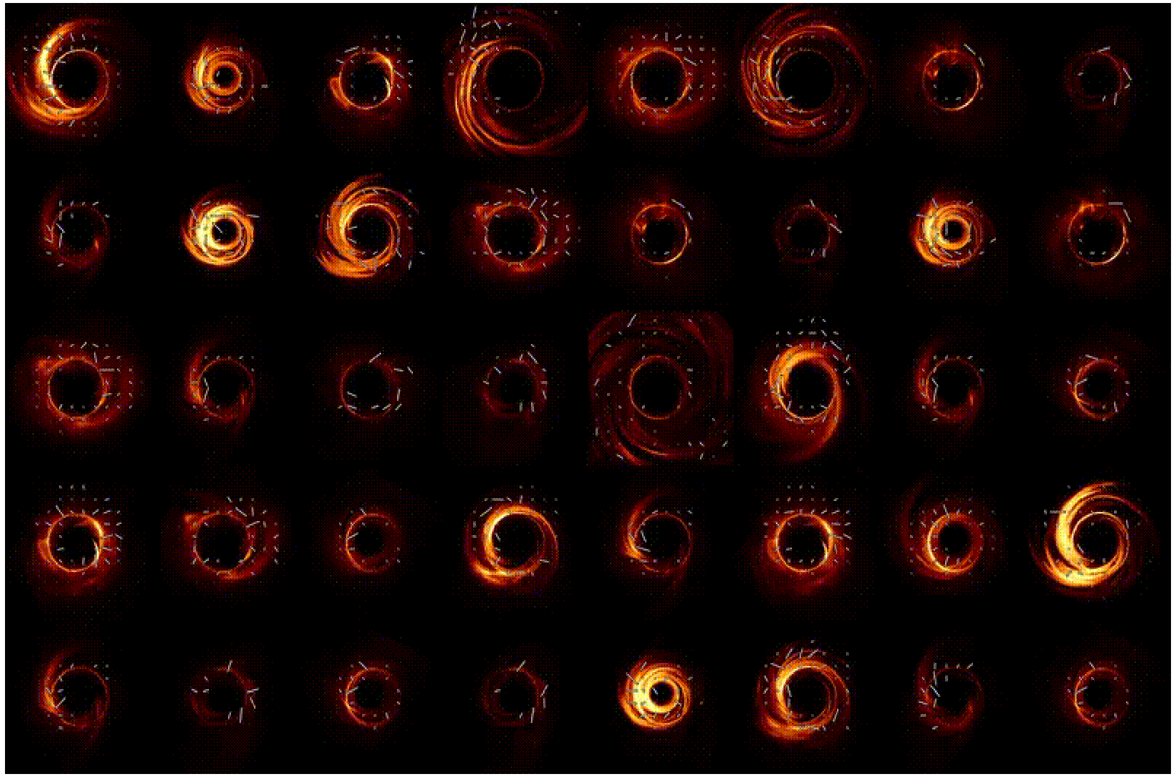
- **Most simulation models can be made to fit total intensity observations alone** by tweaking free parameters (mass, PA, total flux density)



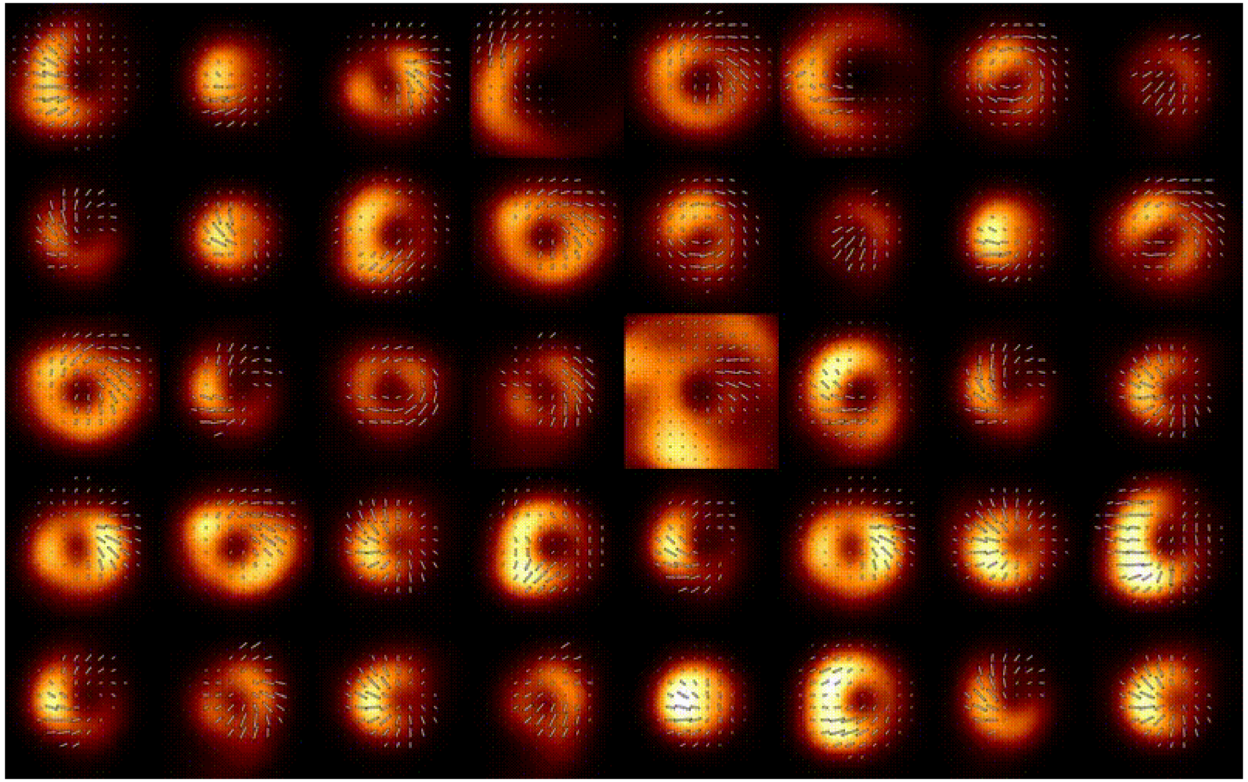
- An additional constraint on **jet power** ($\geq 10^{42}$ erg/sec) rejects all spin 0 models
- Can we do better with polarization?

EHTC+ Paper V, 2019

GRMHD Simulation library



native resolution



EHT resolution

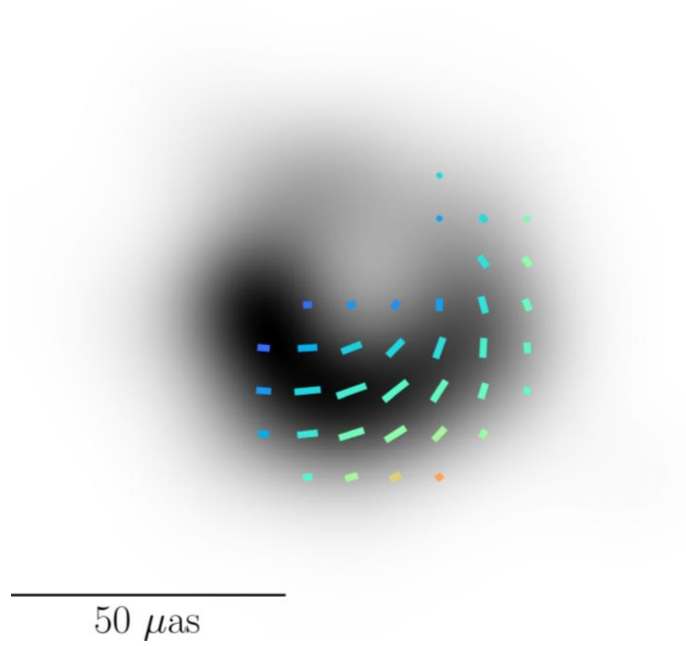
Images modeled with the ipole GRRT code (Moscibrodzka & Gammie 2018)
Two-temperature plasma model from Moscibrodzka et al. 2016

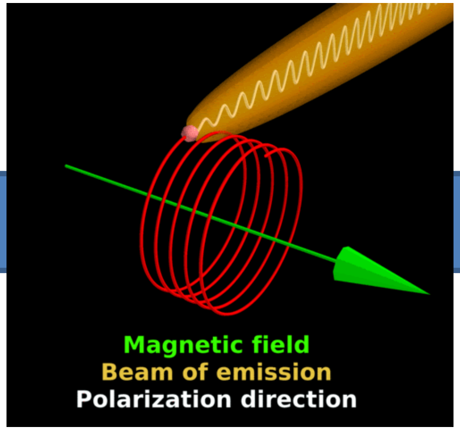
$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta^2}{1+\beta^2} + R_{\rm low}\frac{1}{1+\beta^2}$$

Two parameters set the electron temperature

Animation credit: George Wong/ Ben Prather

Synchrotron polarization traces magnetic fields?



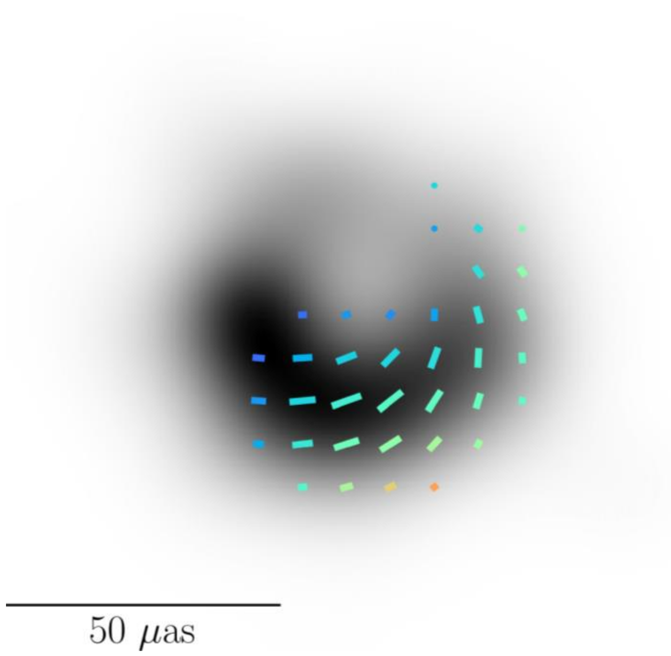


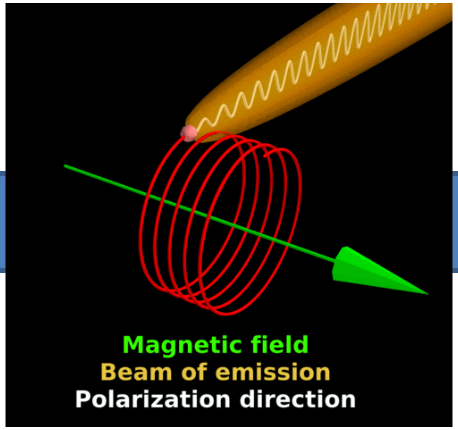
Magnetic field geometry in the emission region!

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

EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

Synchrotron polarization traces magnetic fields?





Ma d
direc n the
em ion!

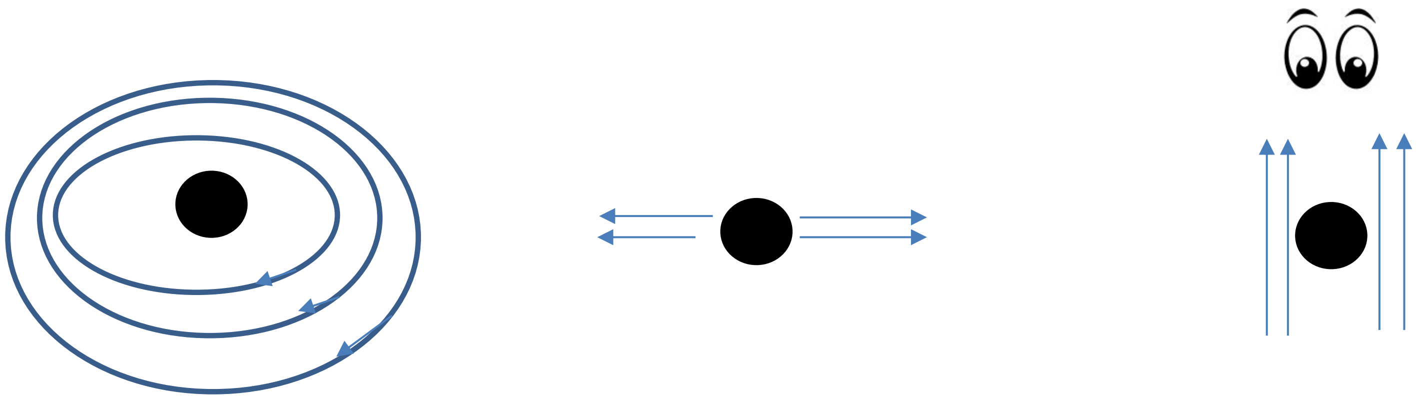
GR and Faraday effects make the situation in M87* more complicated!

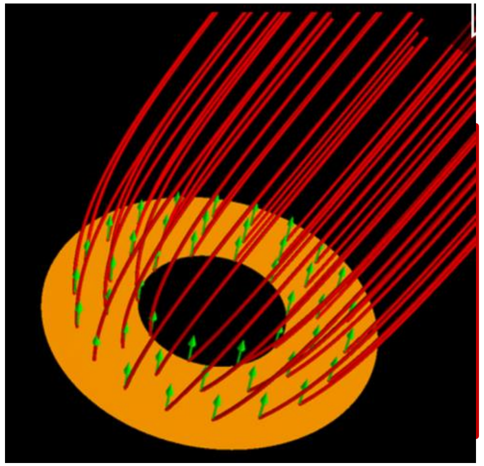
EHTC+ 2021 Papers VII & VIII (**Chael**, paper coordinator/writing team)
Movie Credit: Ivan Marti-Vidal

GR light bending and parallel transport matter!

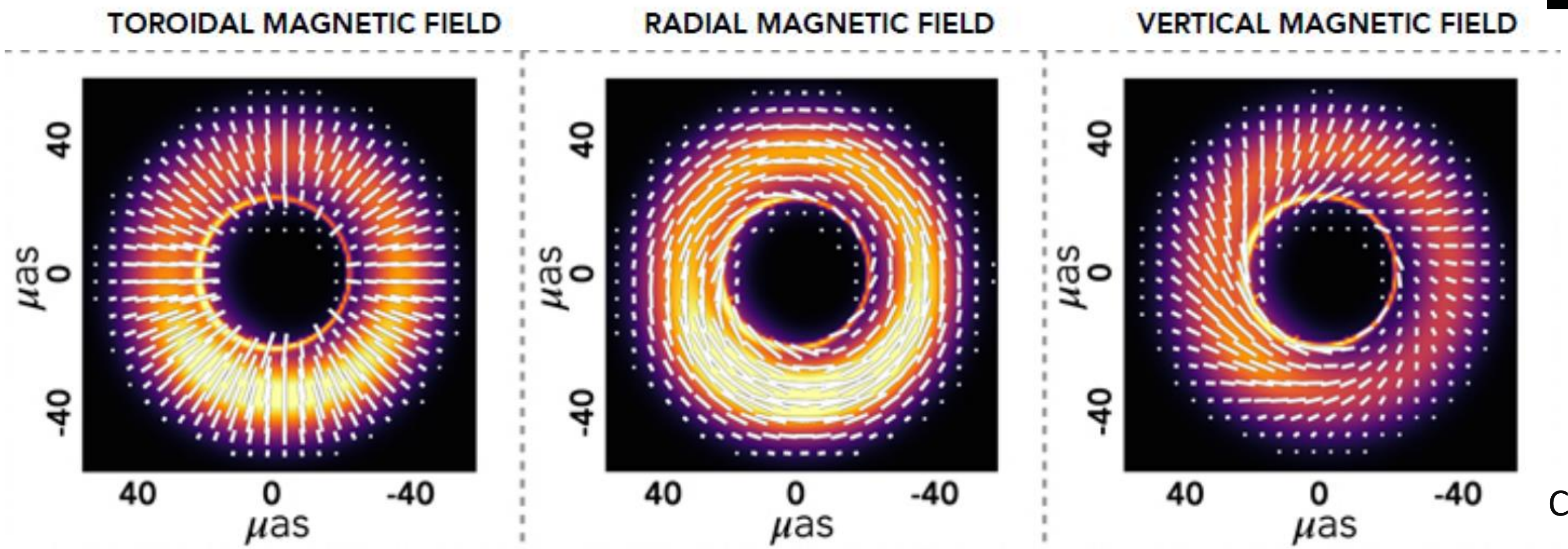
3 simple models, viewed face on

Field structure





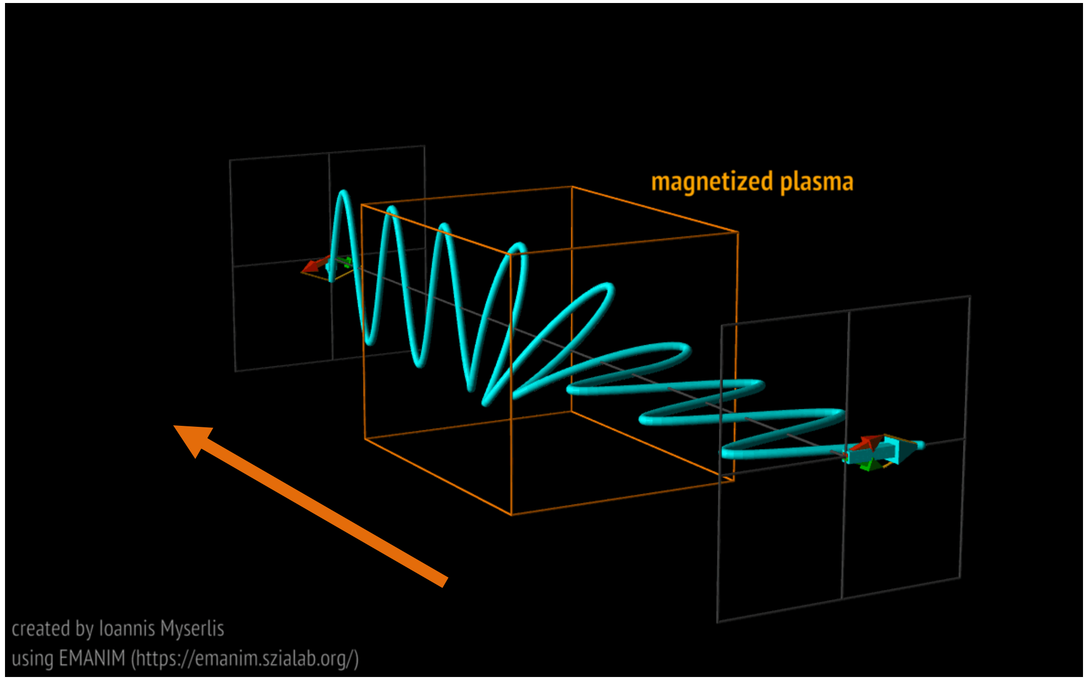
Observed image



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

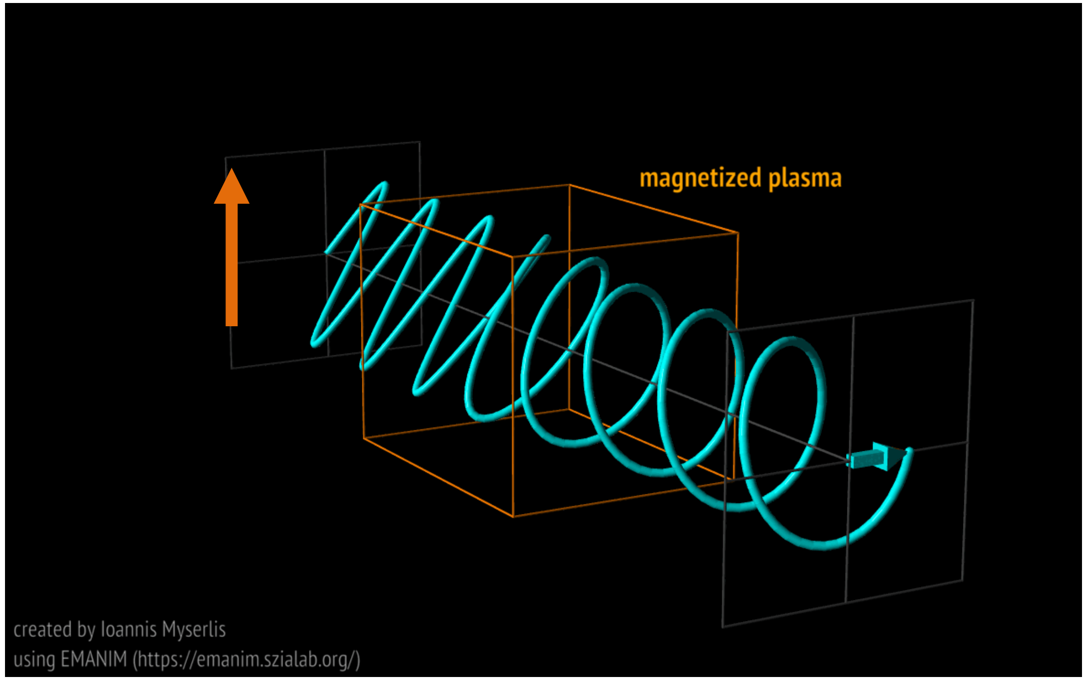
Faraday rotation and conversion are critical

Rotation



Field parallel to propagation matters

Conversion



Field in plane of linear polarization vector matters

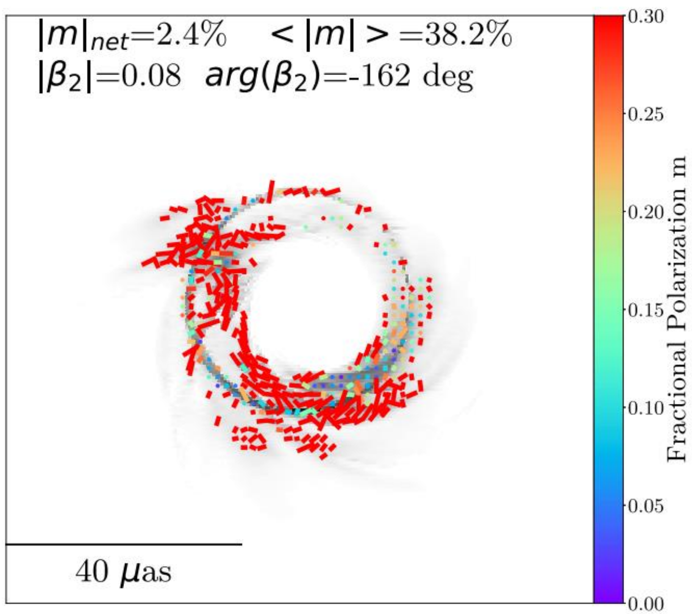
Movie credit: Ioannis Myserlis

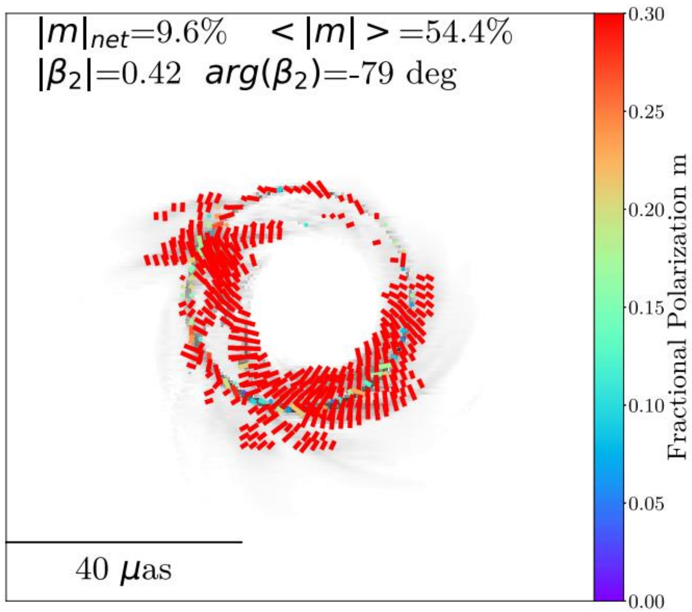
Internal Faraday rotation

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

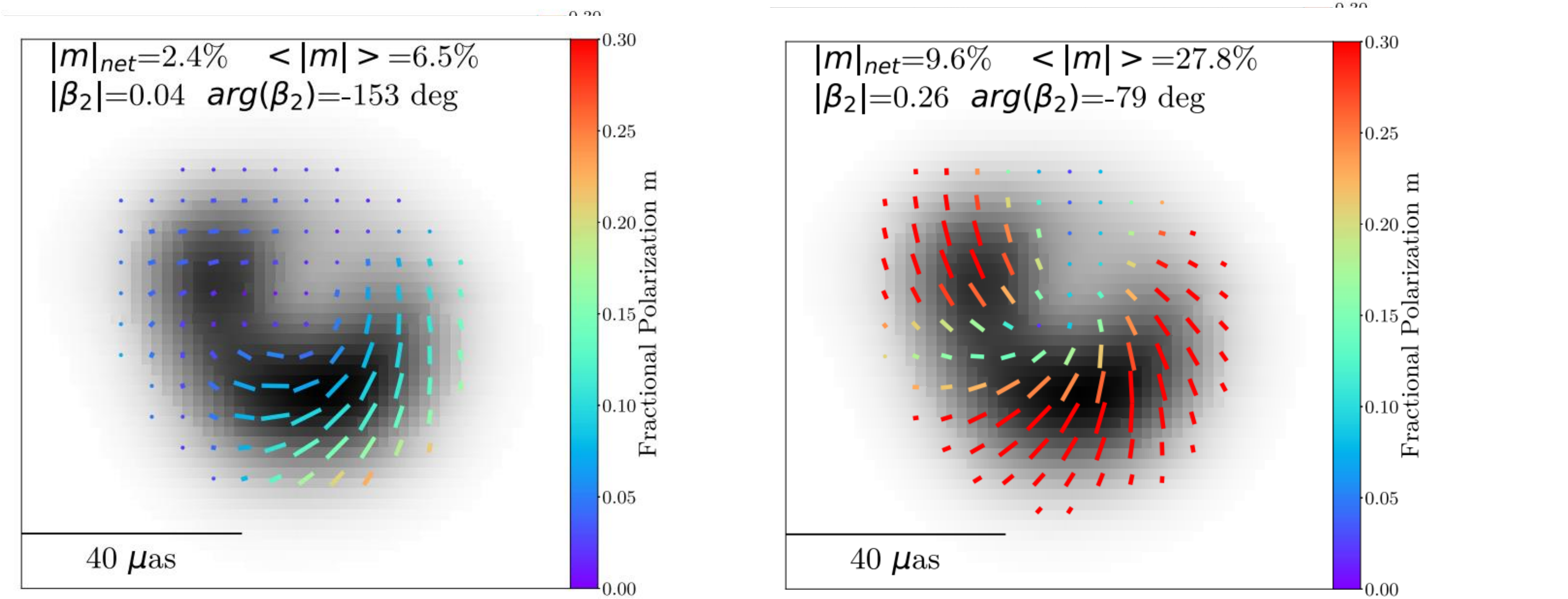
Credit: EHT 2021 Paper VIII (**Chael**, paper coordinator)

Internal Faraday rotation

With rotation

Without rotation

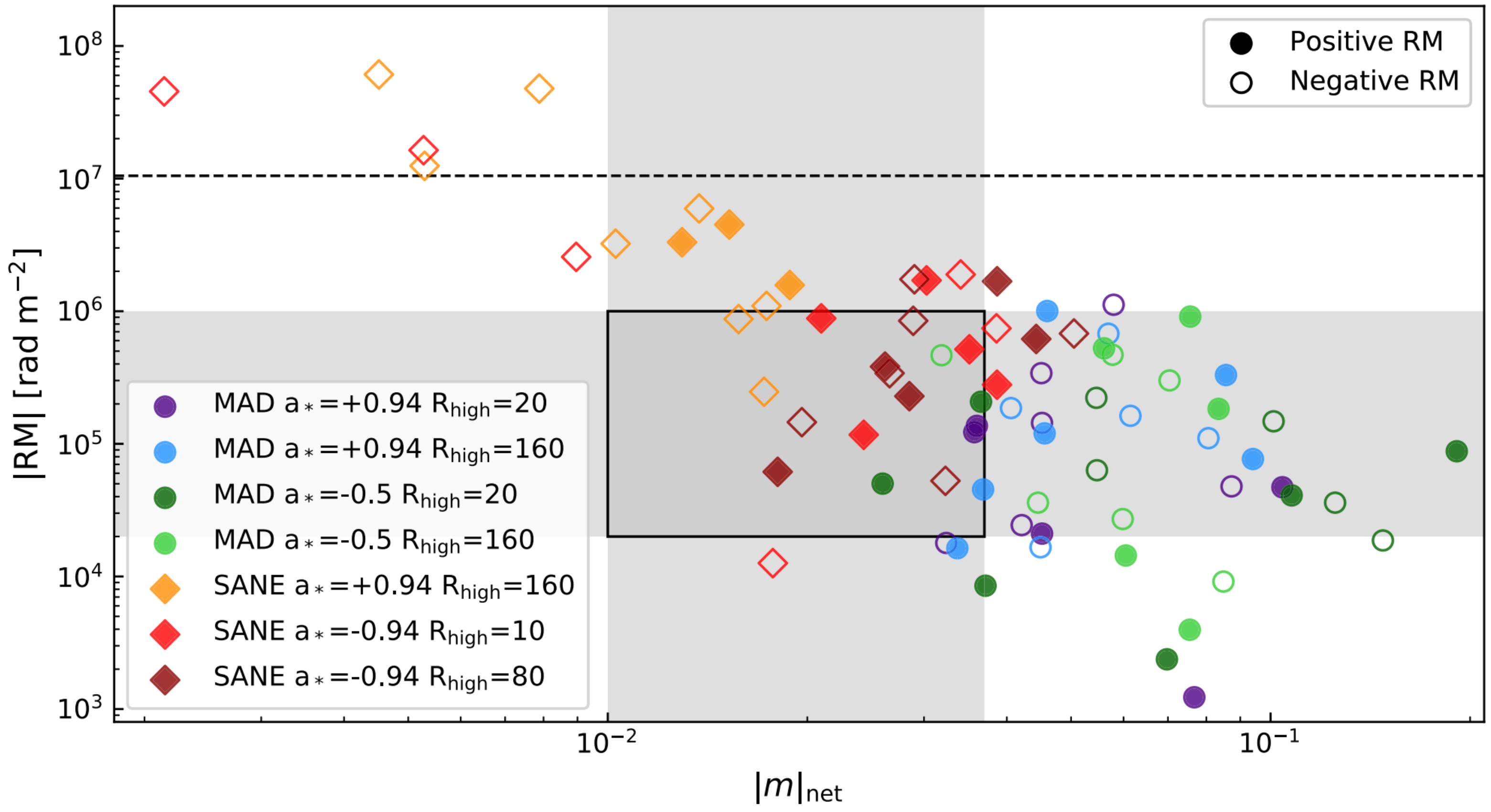
EHT resolution



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

GRMHD simulations can explain M87's Rotation Measure

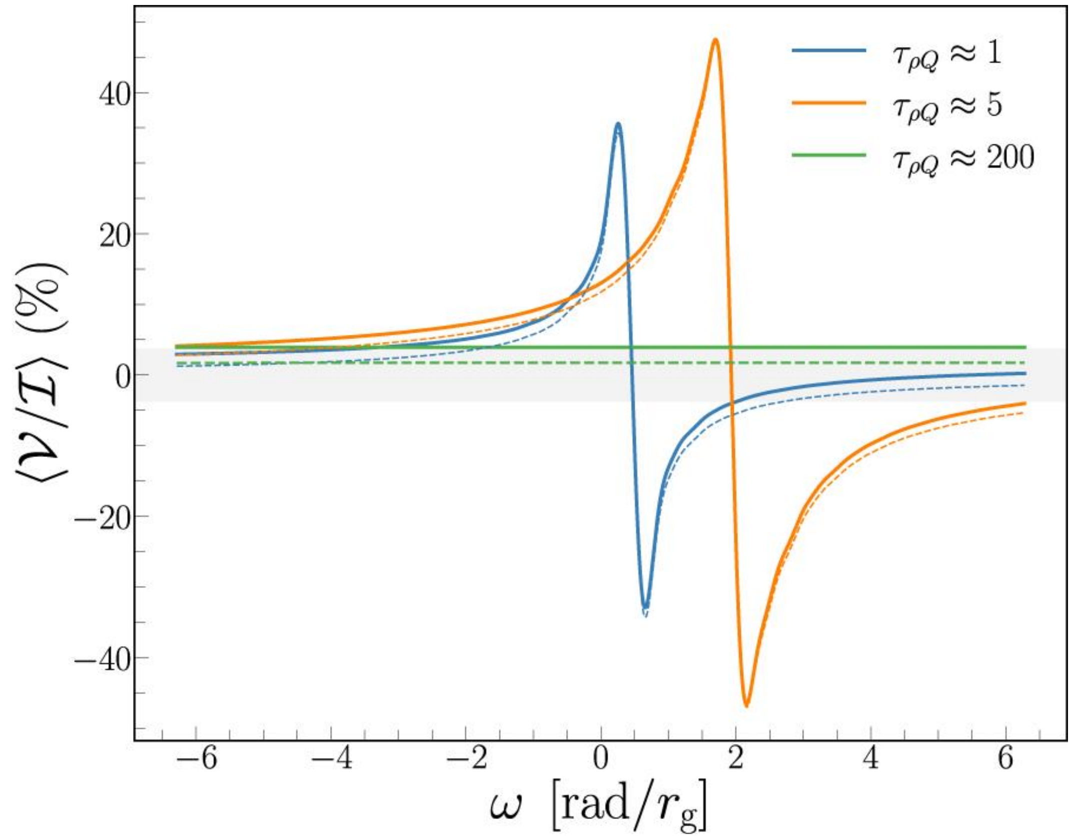


Important in future work to use simultaneous observations on larger scales to better constrain contributions of internal and any external Faraday rotation.

Credit: EHTC 2021 Paper VIII
Angelo Ricarte

Most circular polarization is produced by **conversion**

- One-zone models and GRMHD simulations both confirm conversion is the dominant source of circular polarization in favored models
- In a uniform field geometry, Faraday conversion will typically produce more circular than linear polarization
- The interplay of conversion, rotation, and changing magnetic field direction along the line of sight determines the level and sign of circular polarization



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 linear fraction

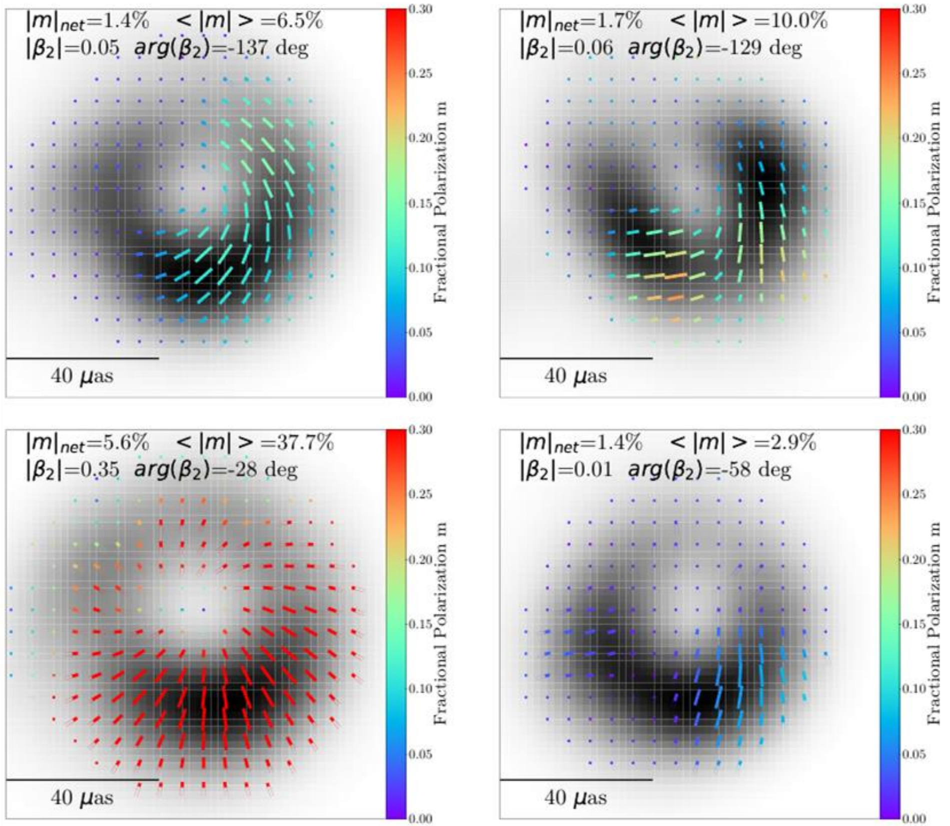
$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Average resolved circular fraction

$$\langle |v| \rangle = \frac{\sum_i |V_i / I_i|}{\sum_i I_i}$$

Azimuthal Linear structure
2nd mode (Palumbo+ 2020)

$$\beta_2 = \frac{1}{I_{\rm ring}} \int\limits_{\rho_{\rm min}}^{\rho_{\rm max}} \int\limits_{0}^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\ \rho\, d\varphi\, d\rho$$



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

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

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)

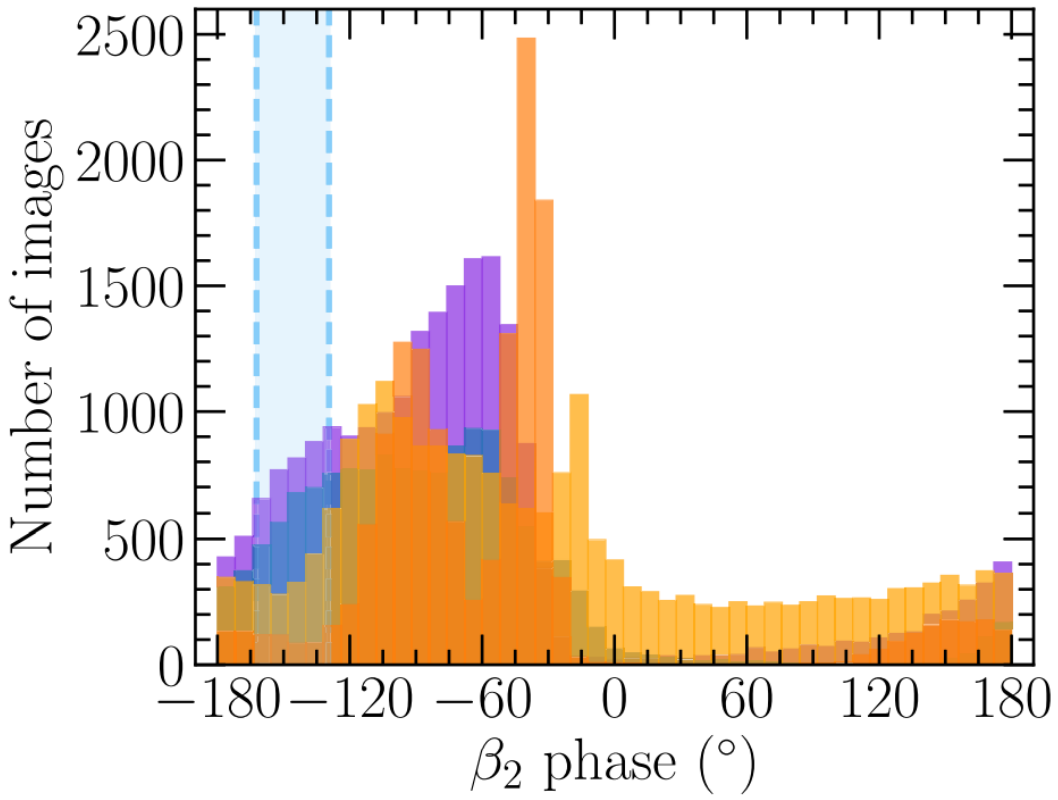
$$|v|_{\rm net} = \frac{\left|\sum_i V_i\right|}{\sum_i I_i}$$

Average resolved linear fraction

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

Average resolved circular fraction

$$\langle |v| \rangle = \frac{\sum_i |V_i / I_i|}{\sum_i I_i}$$



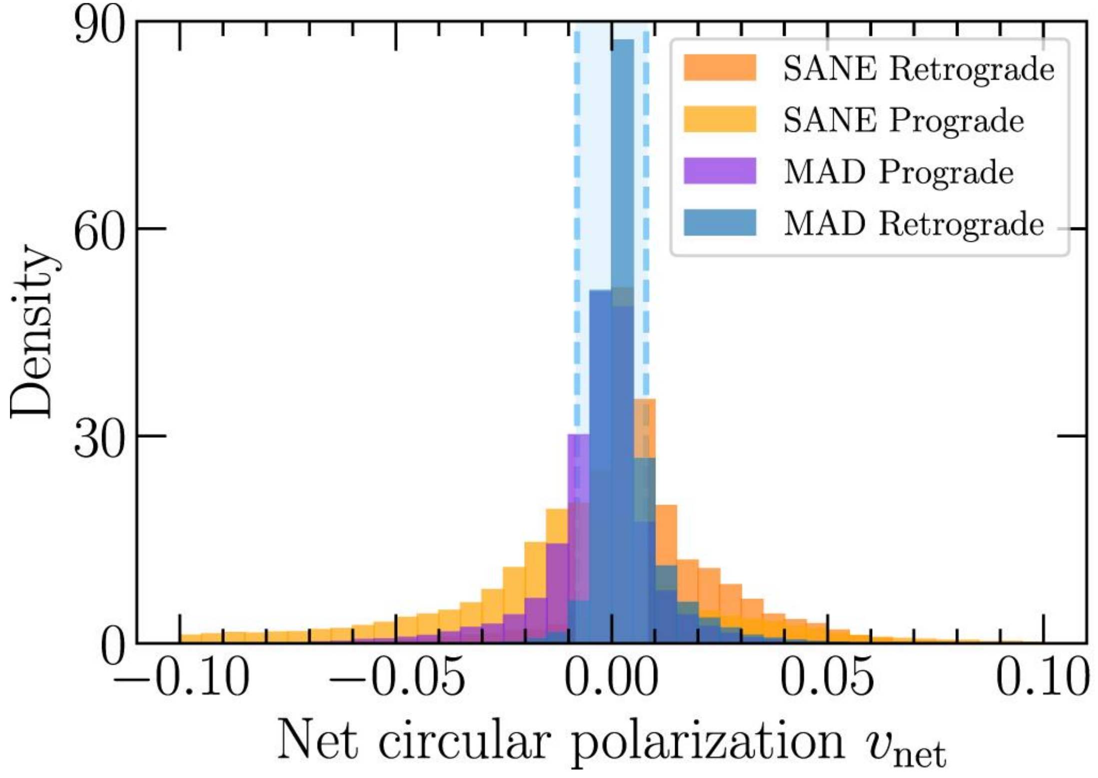
Azimuthal Linear structure 2nd mode (Palumbo+ 2020)

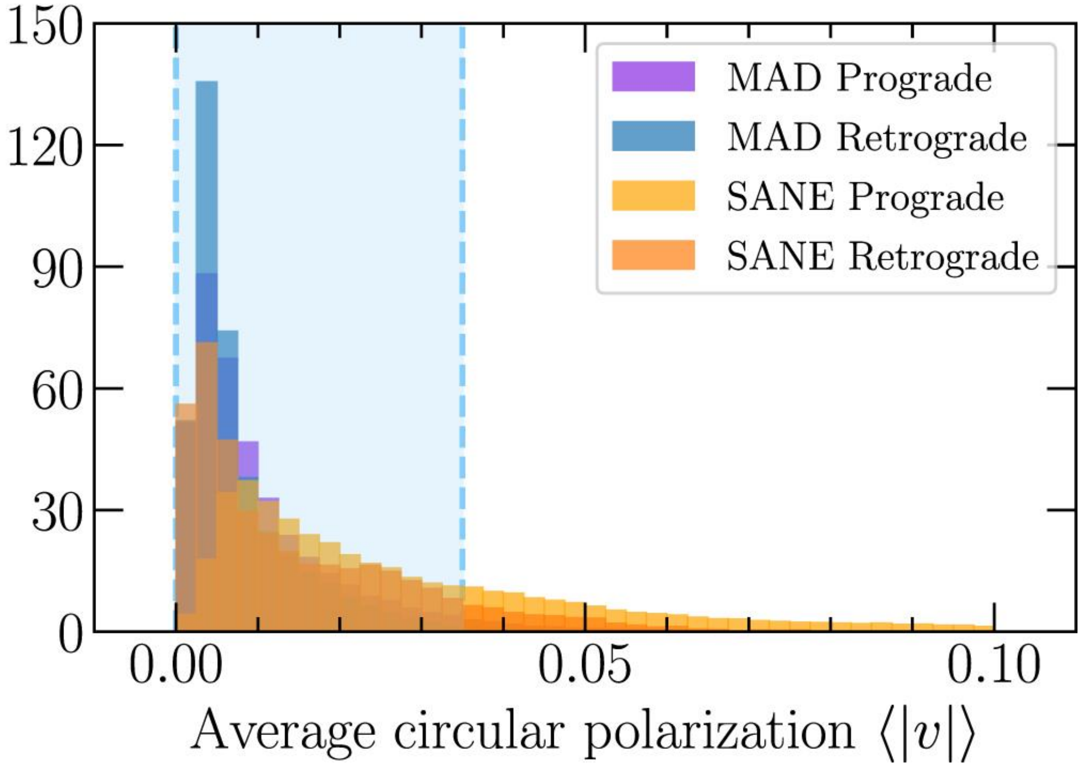
$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\ \rho\, d\varphi\, d\rho$$

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

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

GRMHD simulations naturally produce low circular polarization





$$v_{\rm net} = \frac{\int \mathcal{V}\, dA}{\int \mathcal{I}\, dA}.$$

$$\langle |v| \rangle = \frac{\int |\mathcal{V}/\mathcal{I}|\, \mathcal{I}\, dA}{\int \mathcal{I}\, dA};$$

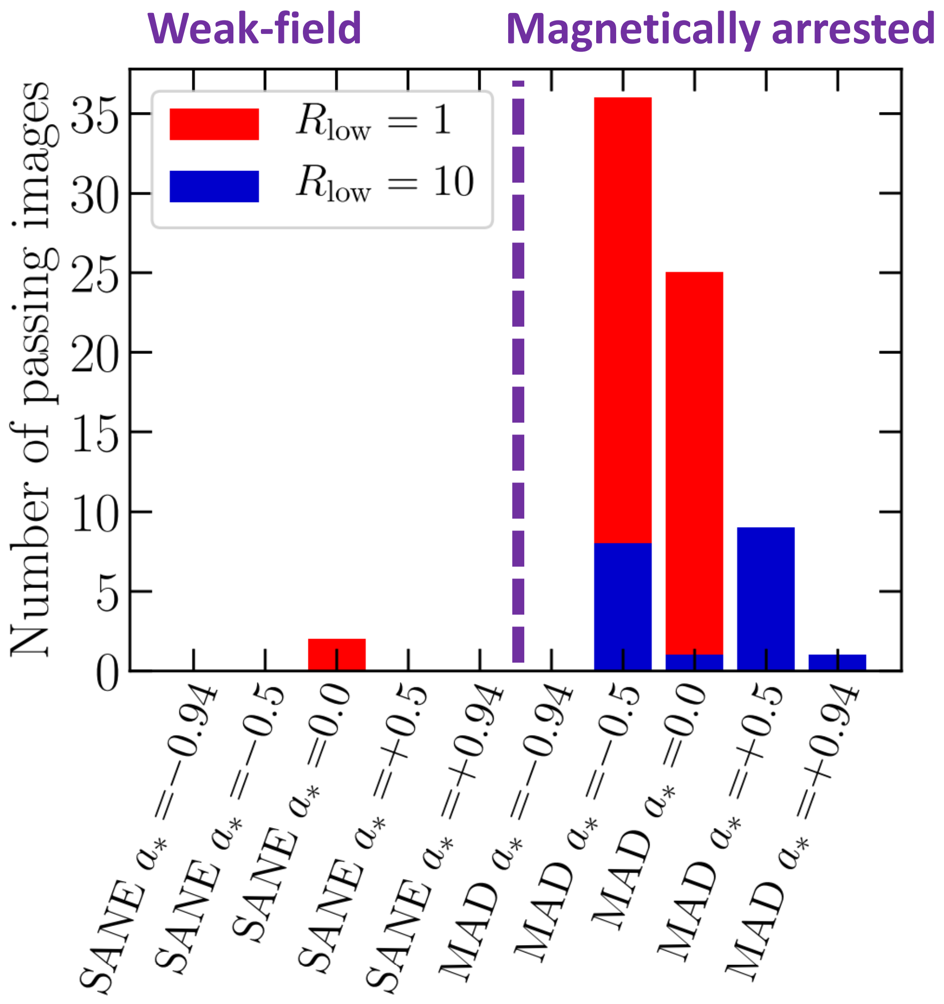
Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)

Polarimetric simulation scoring

- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**
- Implications for accretion and jet launching:
  - Narrows M87*'s allowed accretion rate by 2 orders of magnitude:

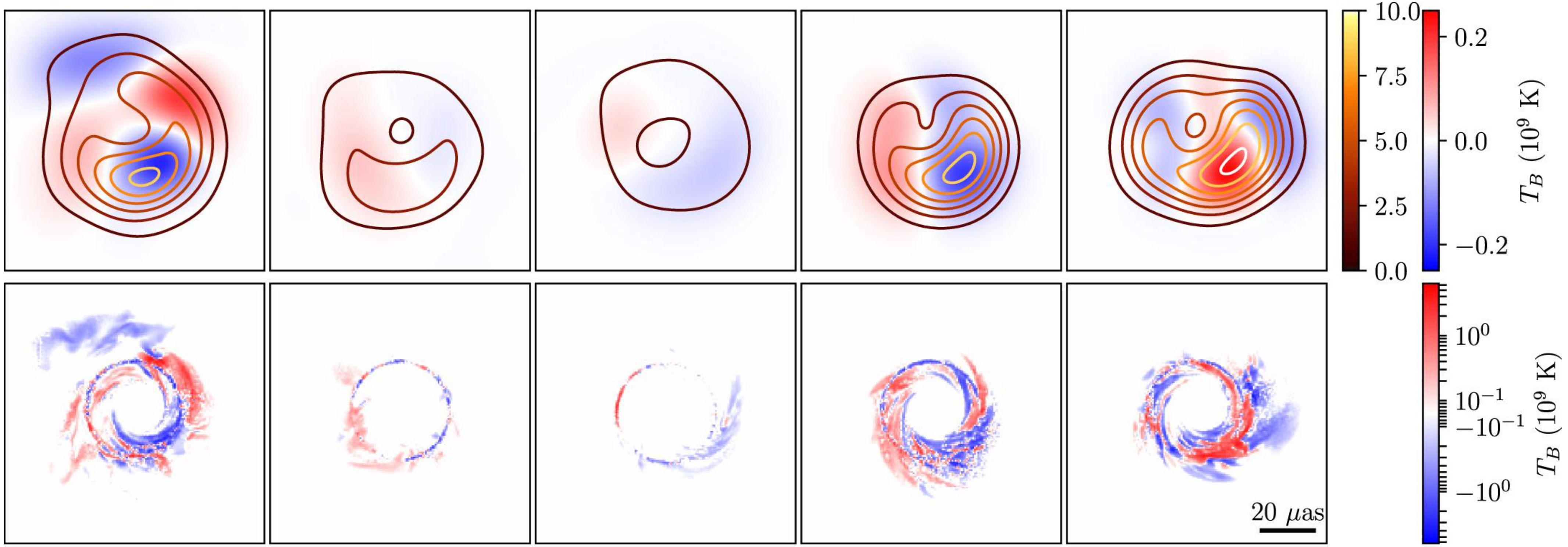
$$\dot{M} \simeq (3 - 20) \times 10^{-4} M_\odot \text{ yr}^{-1}$$
$$\left(\dot{M}_{\rm Edd} = 137 M_\odot \text{ yr}^{-1}\right)$$

  - Strong fields **more easily launch jets** at lower values of BH spin



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

Passing simulations have diverse circular polarization images



Detecting the Stokes V image structure with more sensitive observations will constrain our models further
Need more theoretical work to understand these morphologies!

Credit: EHT 2023 Paper IX (**Chael**, paper coordinator)
Ricarte+ 2021

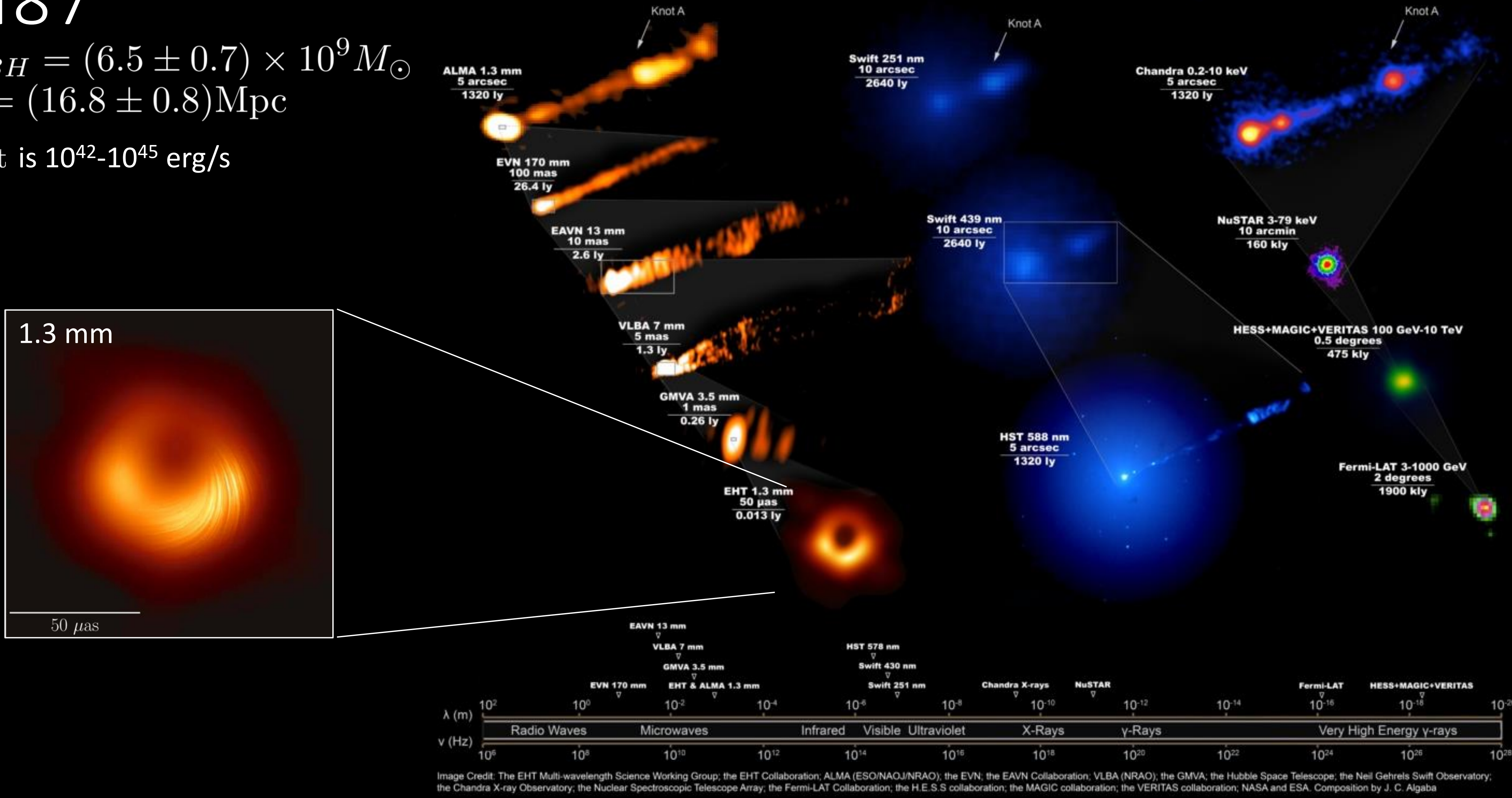
Connecting EHT images to electromagnetic energy flow

Chael, Lupsasca, Wong, Quataert 2023

2307.06372

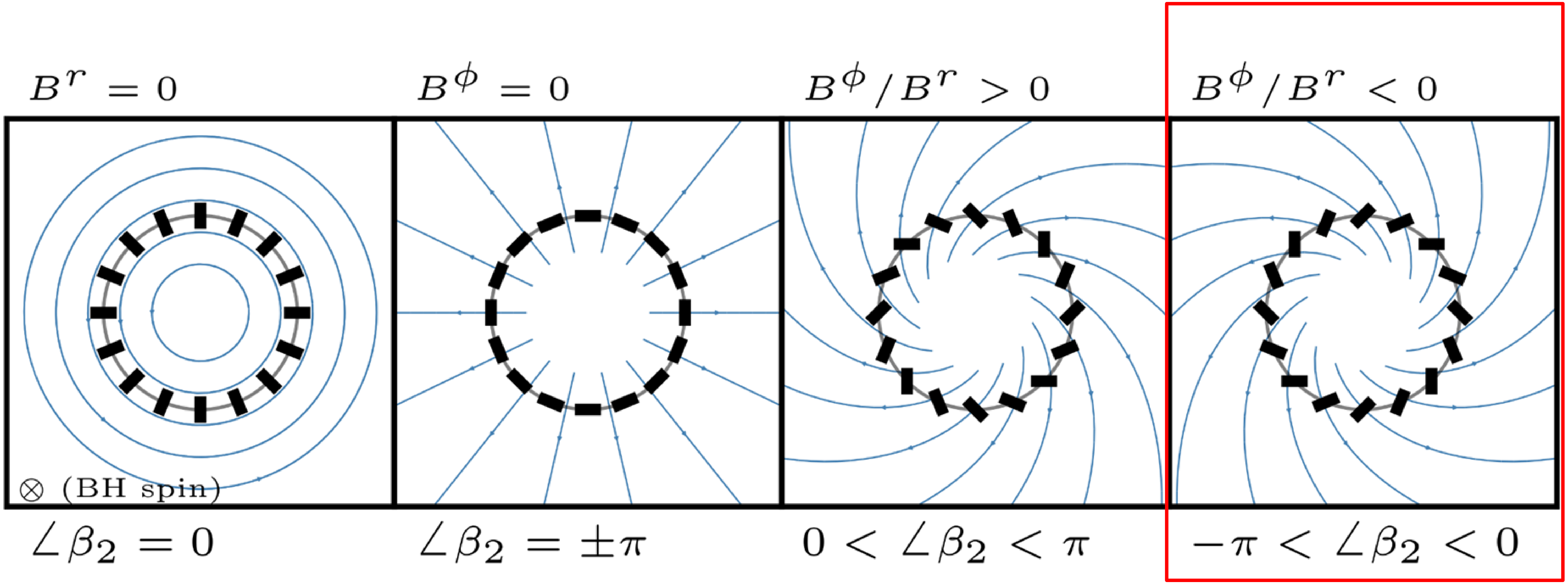
M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$P_{\rm jet}$ is 10^{42}-10^{45} erg/s



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

$\arg(\beta_2)$ is connected to the ratio B^{ϕ}/B^{r}



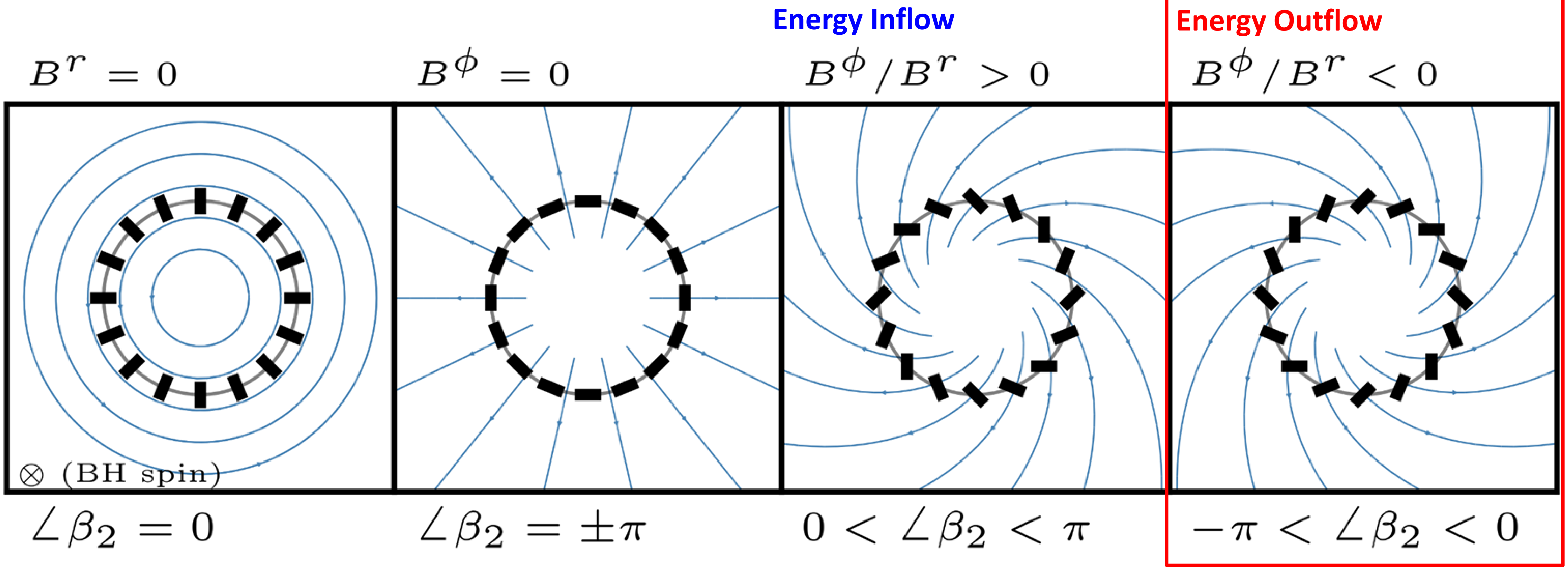
Cartoon picture:

- face on fields, no Faraday rotation, no optical depth, no relativistic parallel transport/abberation
- The BH spin is axis **into the sky** (EHT Paper V, 2019)

$$\angle\beta_2 \approx 2\arctan\left(\frac{B^r}{rB^{\phi}}\right) \quad \text{(observer at } \theta_o = \pi\text{)}$$

Chael+ 2023

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



Poynting flux (Boyer-Lindquist coordinates):

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

fieldline angular speed

Chael+ 2023

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

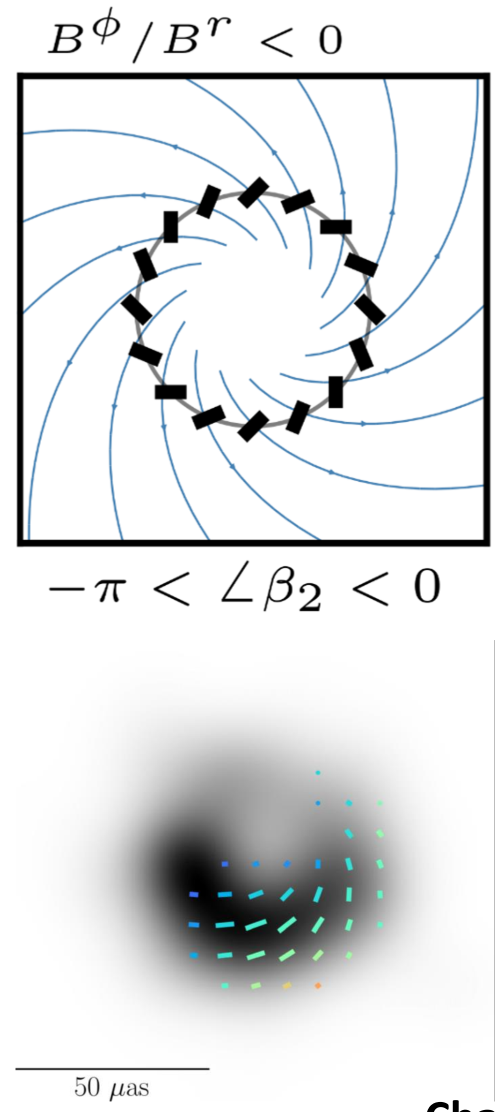
- **The sign of $\arg(\beta_2)$ is connected to the direction of Poynting flux**

- **Ignoring Faraday effects**, The EHT's measurement **implies electromagnetic energy outflow in M87***

- This inference requires we assume fieldlines **co-rotate** with the emitting plasma (the angular vector is into the sky)

- Does this simple argument hold up in **more complicated models** of M87*?

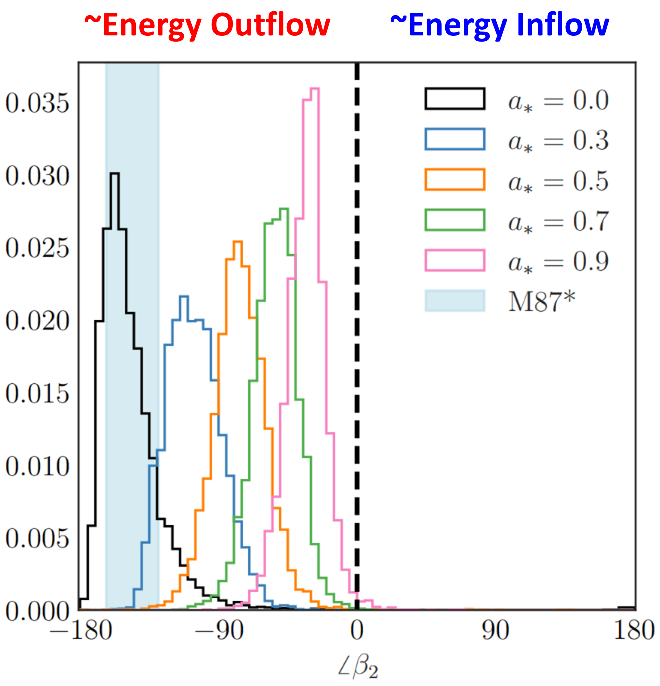
Energy Outflow



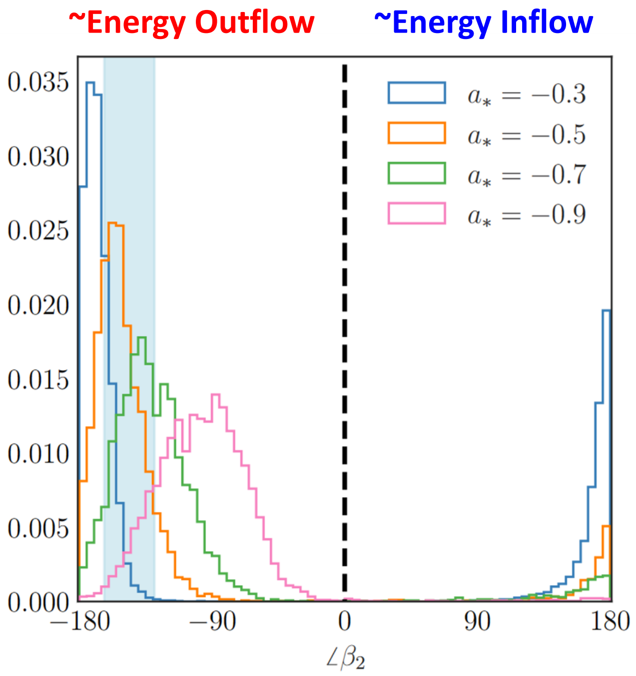
Chael+ 2023

the relationship between arg(β_2) and energy flux
st in **GRMHD models** of M87*?

- 1600 simulated M87* images from MAD simulations (Narayan+ 2022)
- Almost all simulation images have arg(β_2) consistent with energy outflow in our simple picture
- arg(β_2) has the **same qualitative dependence on spin** as in the BZ monopole model



Prograde Simulations

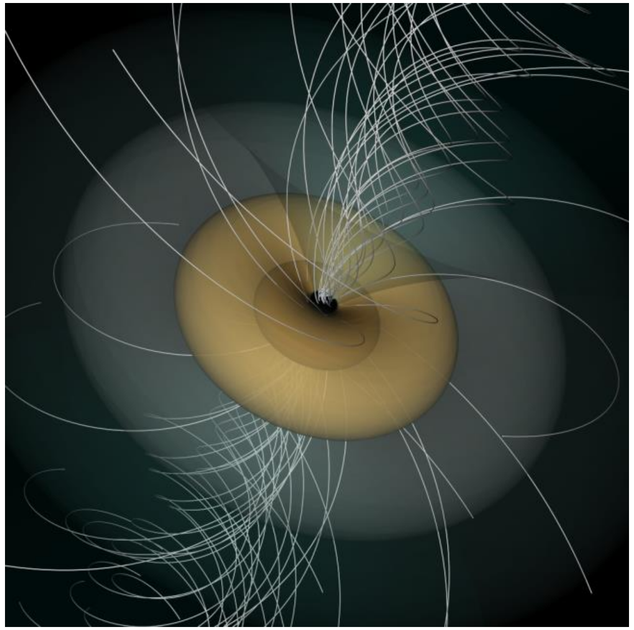


Retrograde Simulations

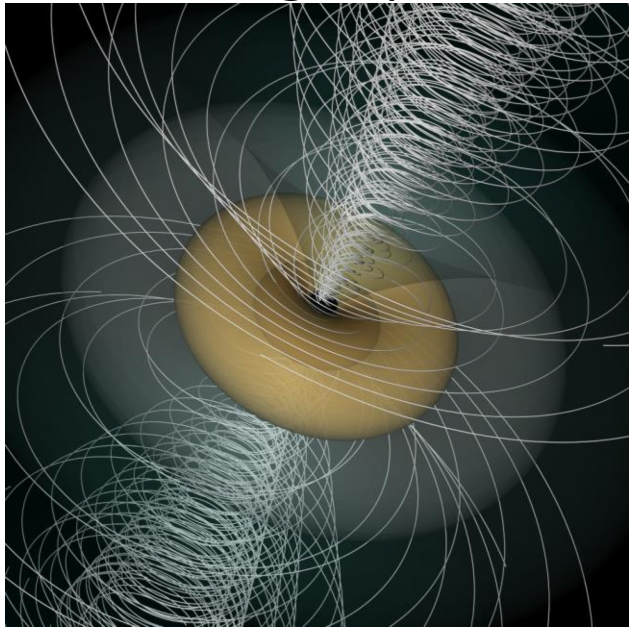
Chael+ 2023

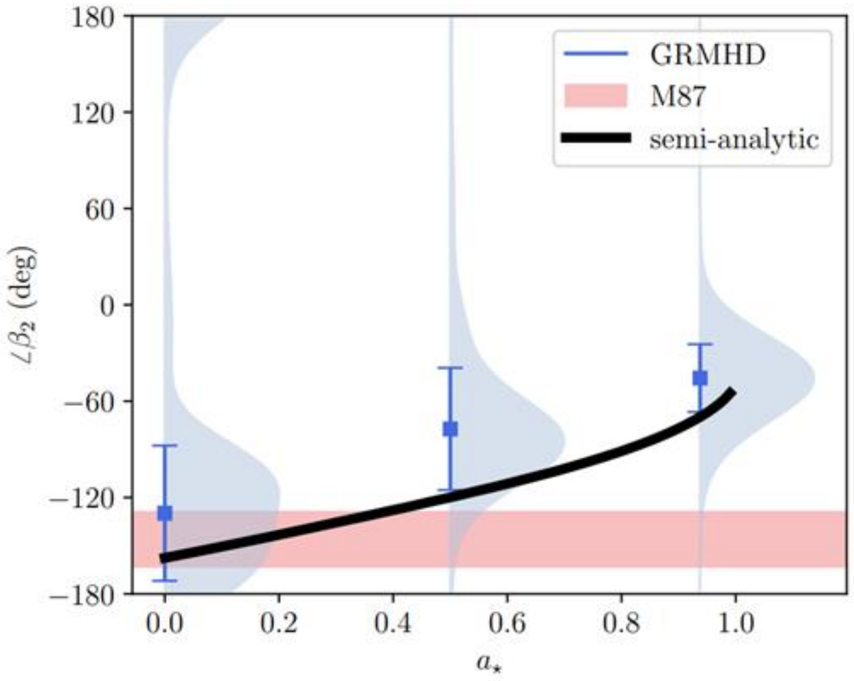
$\arg(\beta_2)$ has a strong dependence on BH spin in these models

Low Spin



High Spin



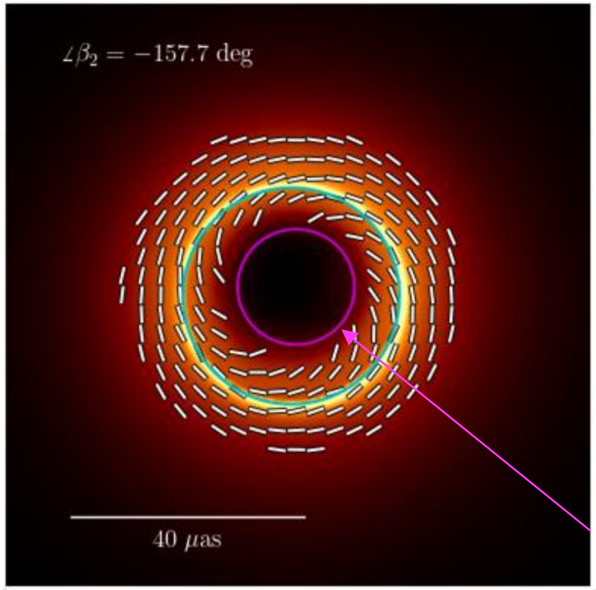


- BH **spin winds up initially radial fields**, so that $B^\phi / B^r < 0$
- The field pitch angle **increases with spin**
- Increased field winding will
  - increase the Poynting flux (BZ jet power)
  - make the observed polarization more radial

Image credit: George Wong

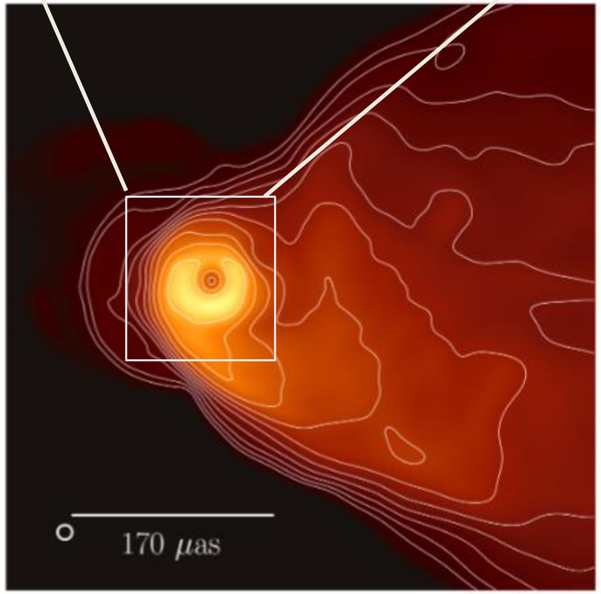
Next Steps

- EHT Paper VII measurements of arg(β_2) suggest **electromagnetic outflow on scales of ~5M** in M87*.
- We can't yet be 100% sure if this energy outflow
  - is spin powered
  - or powers the large-scale jet
  - **Future EHT observations could answer these questions!**
- We need **high-dynamic range, polarized images** to:
  - Measure arg(β_2) **down to the horizon**
  - Connect the energy flux **from horizon scales out through the jet base**



Goal 1: measure energy flux **down to horizon**

"inner shadow"



Goal 2: measure energy flux **out through jet base**

Chael+ 2021, **Chael**+ 2022

Takeaways:

- The EHT has finally analyzed M87* in full polarization
- The structure of linear polarization is robustly constrained. Circular polarization is detected but the structure is not constrained.
- 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:
    - self-consistently including Faraday rotation and conversion effects is important
- The polarization data singles out magnetically arrested models:
    - **the magnetic field is dynamically important at the event horizon in M87***
    - These models naturally produce enough Faraday rotation to explain observed RM and low linear and circular polarization fractions
- The azimuthal structure of the linear polarization in M87* is consistent with outward Poynting flux
    - Simple model prediction is upheld in GRMHD simulation images.