Title: Spin Signatures in VLBI Images of Supermassive Black Hole Accretion Flows

Speakers: Daniel Palumbo

Series: Strong Gravity

Date: January 19, 2023 - 1:00 PM

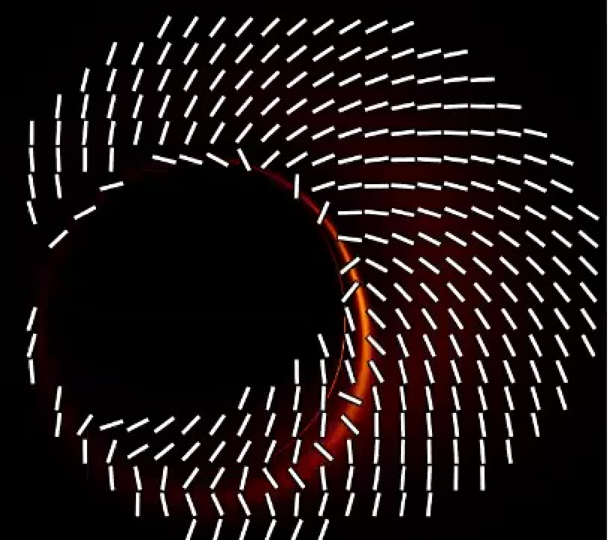
URL: https://pirsa.org/23010104

Abstract: The Event Horizon Telescope has released total intensity images of the Messier 87* and Sagittarius A* accretion flows; polarized images have been released for M 87*, and are imminent for Sgr A*. These images are a rich source of theoretical constraints on the black hole accretion flow system, but a trustworthy measurement of either black hole's spin remains elusive. Spin nonetheless remains a high priority, as the black hole angular momentum is deeply linked to mechanisms of energy extraction and galactic co-evolution. In my talk, I will discuss my work on providing theoretical traction on supermassive black hole spin, and will review the state of spin measurements using existing and future EHT data, including measurements of the black hole photon ring, inference of near-horizon magnetic field structure, and next-generation spacetime/emissivity inference codes.

Zoom: https://pitp.zoom.us/j/95355525128?pwd=blczM1ZUMGs5RmNxMVNCV3hlRDA4UT09

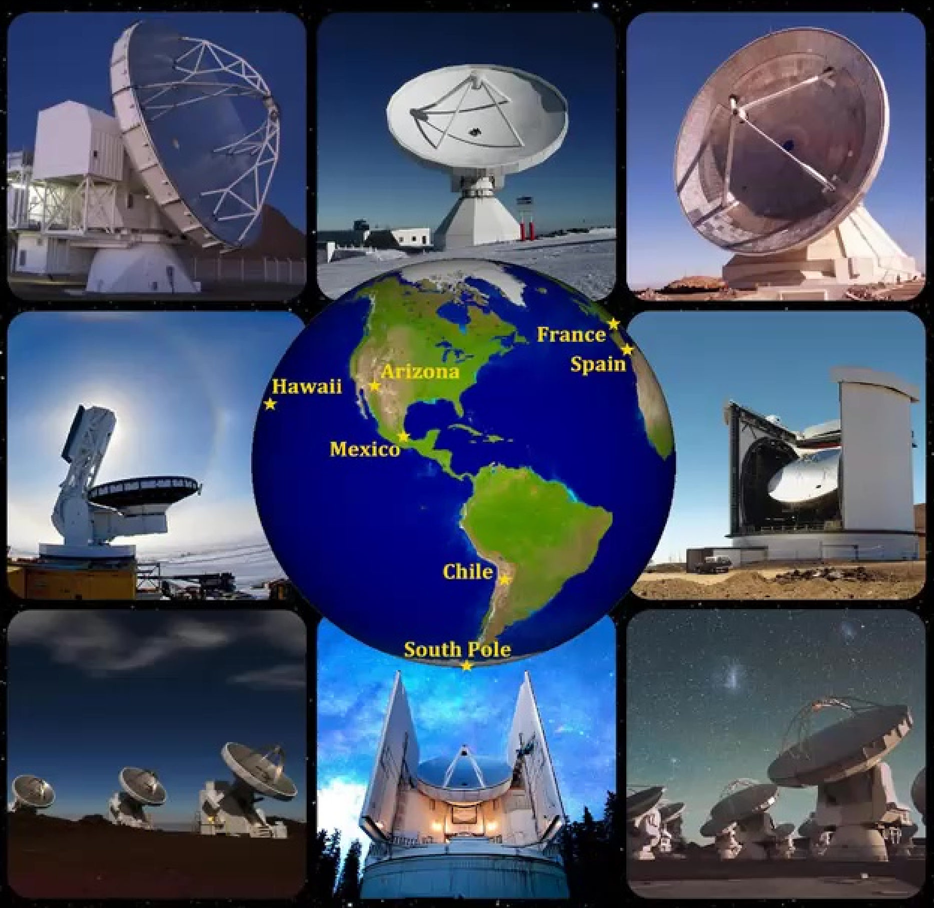
Spin Signatures in VLBI Images of Supermassive Black Hole Accretion Flows

Daniel Palumbo
Strong Gravity Seminar
January 19, 2023



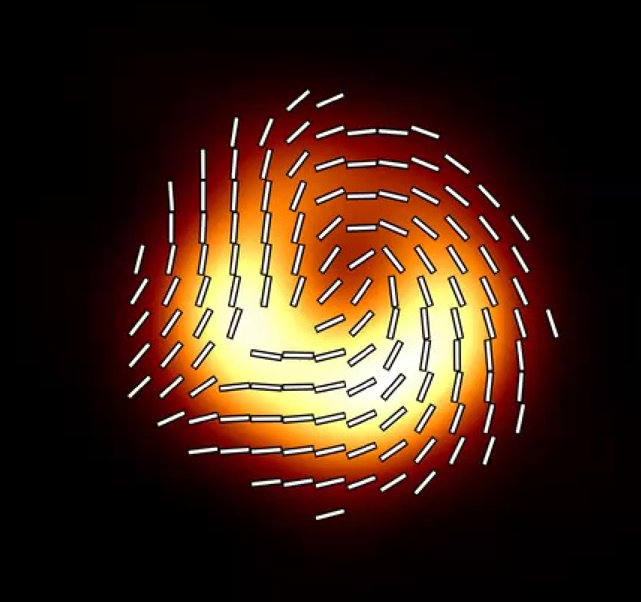
The Event Horizon Telescope

- A global network of radio observatories
- ~400 members around the world
- Decades in the making, largely repurposed/refurbished existing telescopes



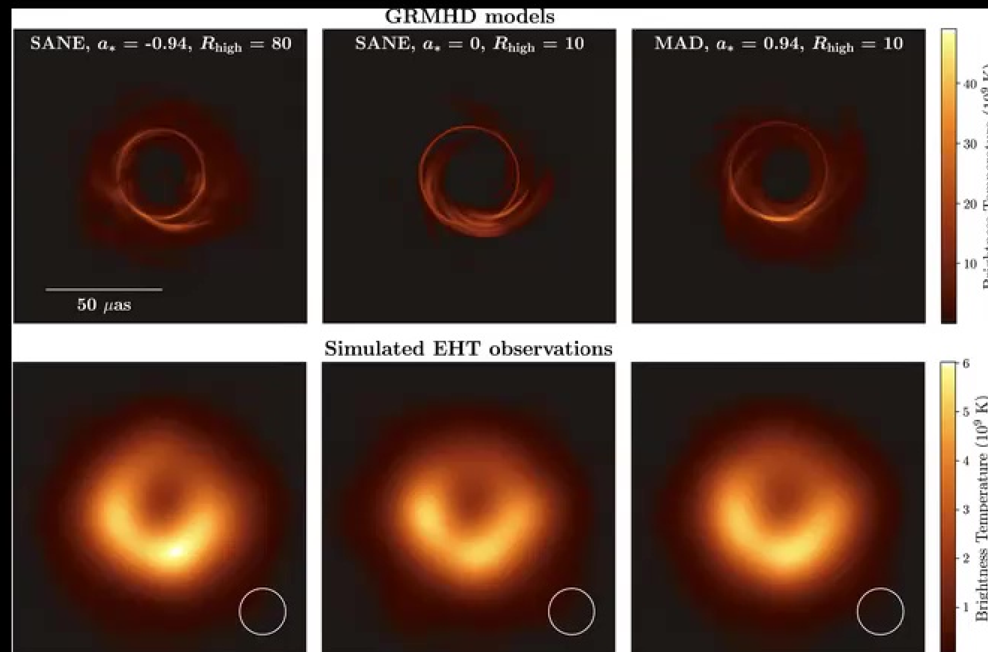
What is the EHT for?

- Taking the first-ever pictures of black holes!



What have we learned? What remains to be learned?

- We infer from GRMHD that M 87* and Sgr A* have masses consistent with prior measurements from other methods



EHTC I

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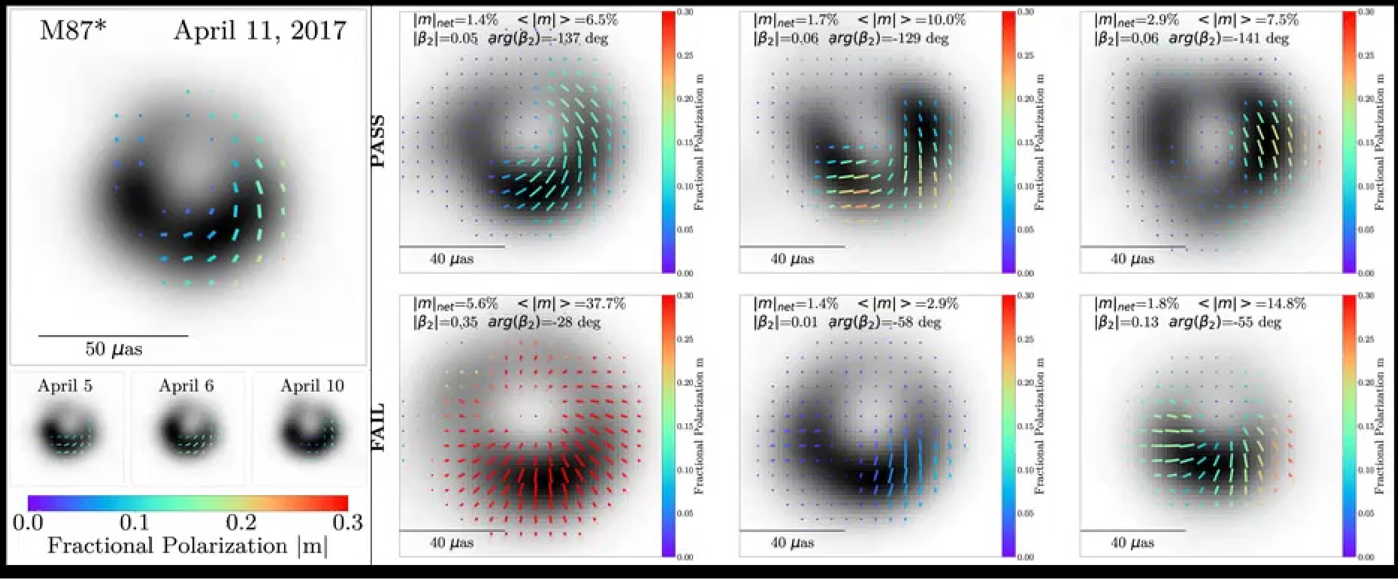
- We notice a preference in model comparisons for dynamically important magnetic fields in the accretion flow



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- Our models resemble actual black holes, but we know our models aren't good enough
- We believe our results much more when simple, universal physical arguments back up the detailed GRMHD comparisons
- My focus: building tools/experiments that connect messy astrophysical measurements to fundamental physical properties, now and in the next generation EHT
  - The next holy grail: spin

Why spin?

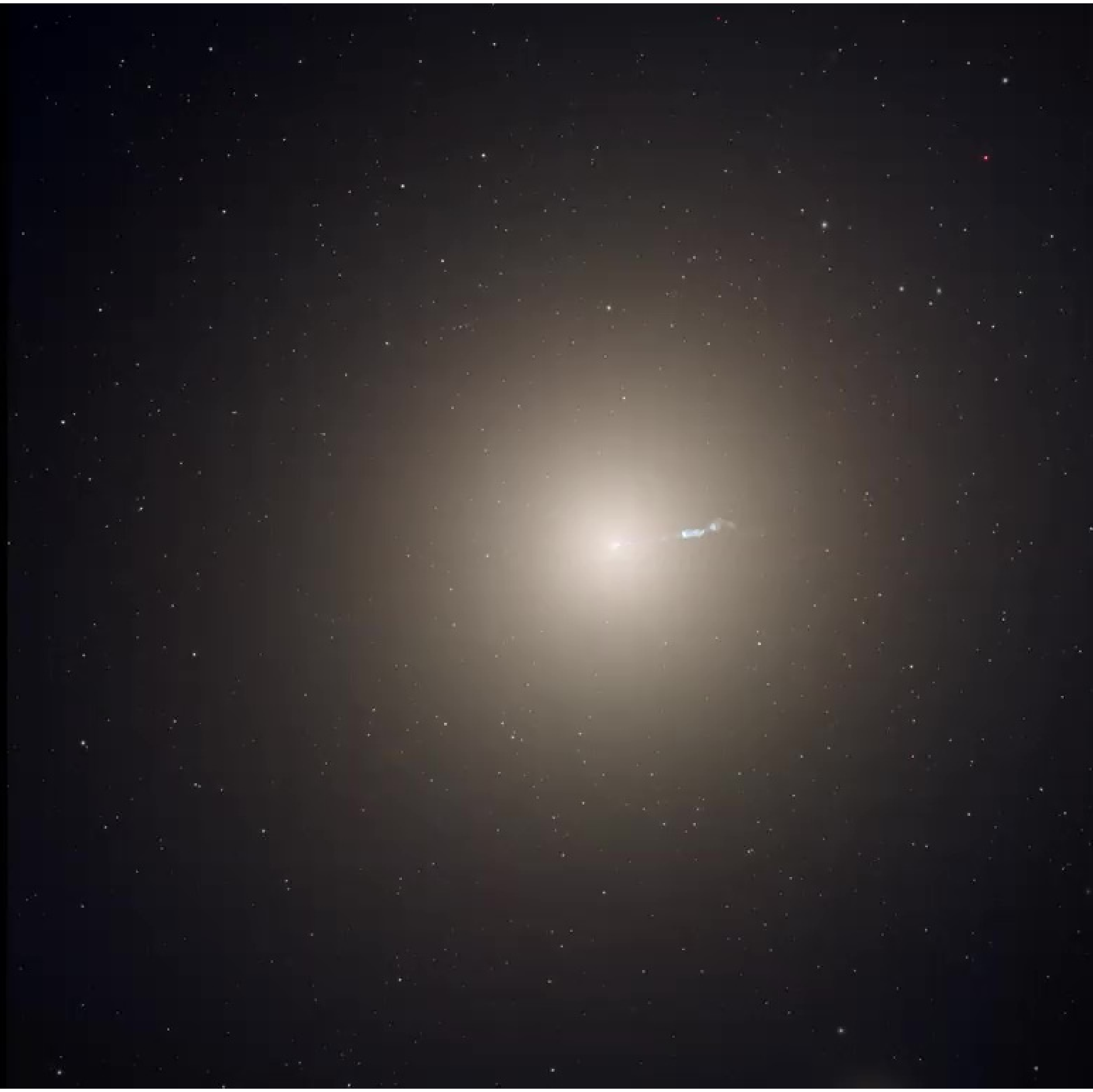
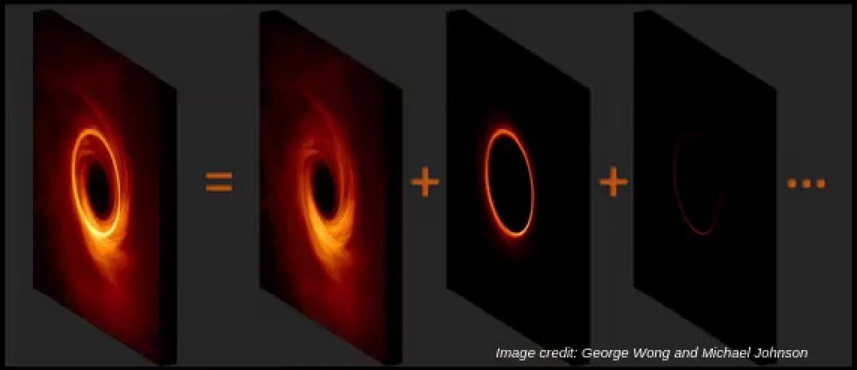


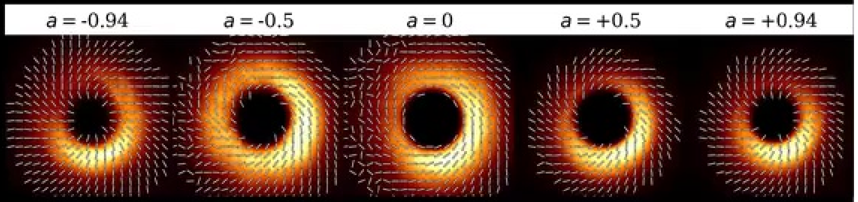
Image: Hubble

Outline - spin as the centerpiece of future EHT science

- The black hole photon ring



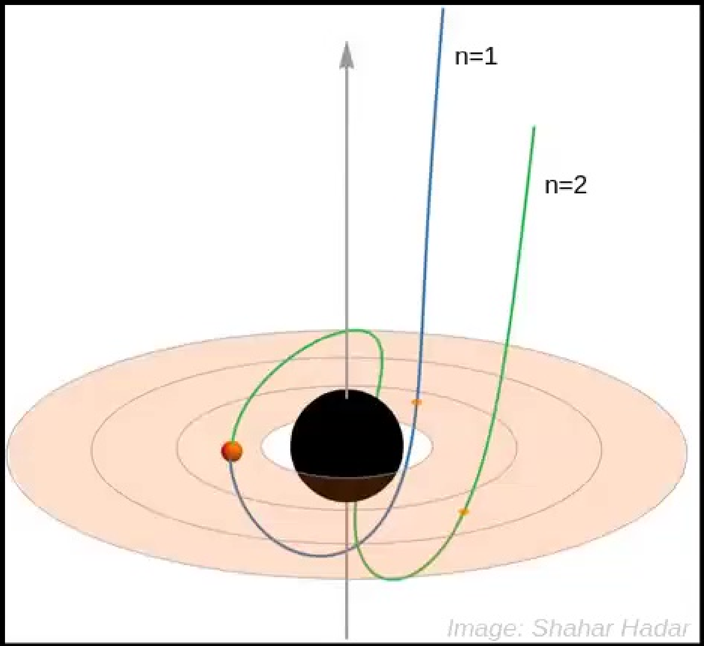
- Polarization spirals



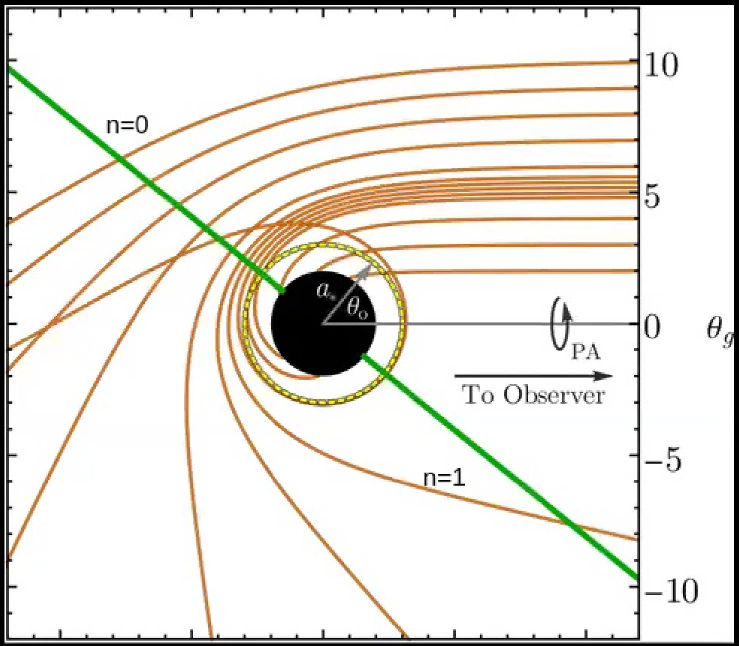
- Rapid semi-analytic model fitting of the accretion flow

Black holes lens light around them; disks produce rings

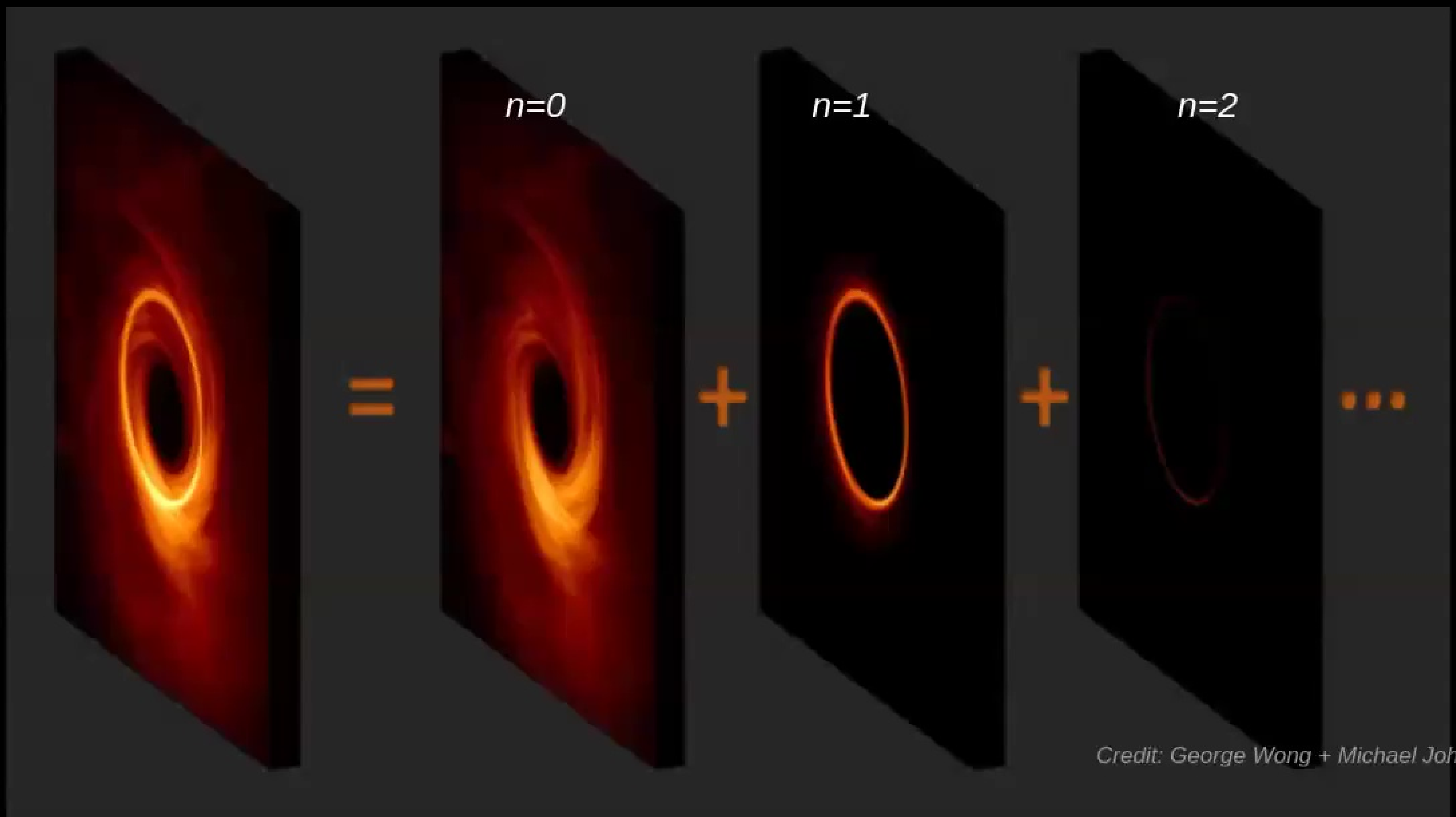
"Forwards:" Any point in space has an infinite number of light paths connecting to the observer; these paths correspond to increasing numbers of windings around the black hole.

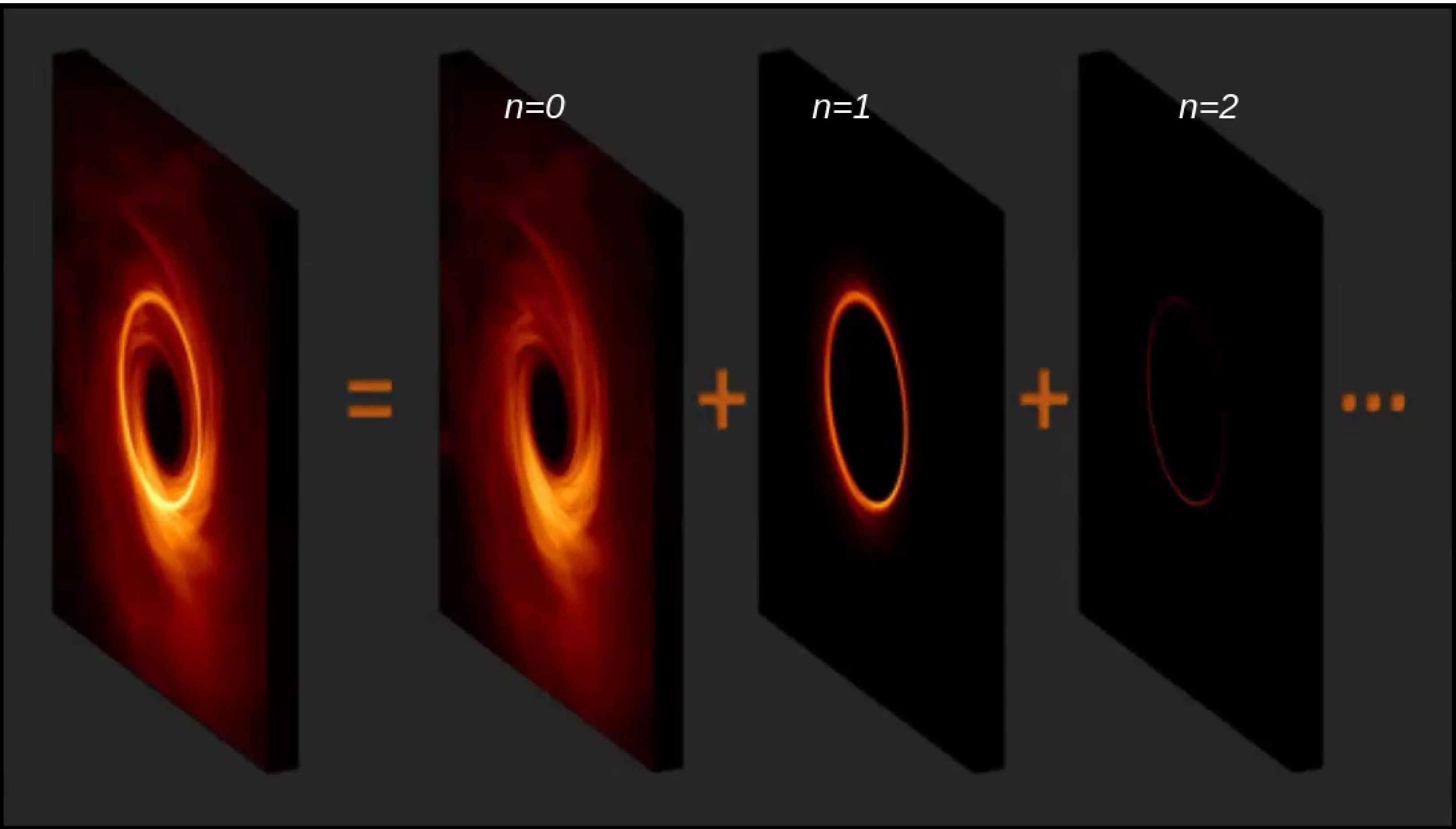


"Backwards:" A point on the observer image corresponds to a single photon path, which might intersect a plane around the black hole any number of times (increasing exponentially towards the critical curve).



We observe an infinite* sum of lensed images

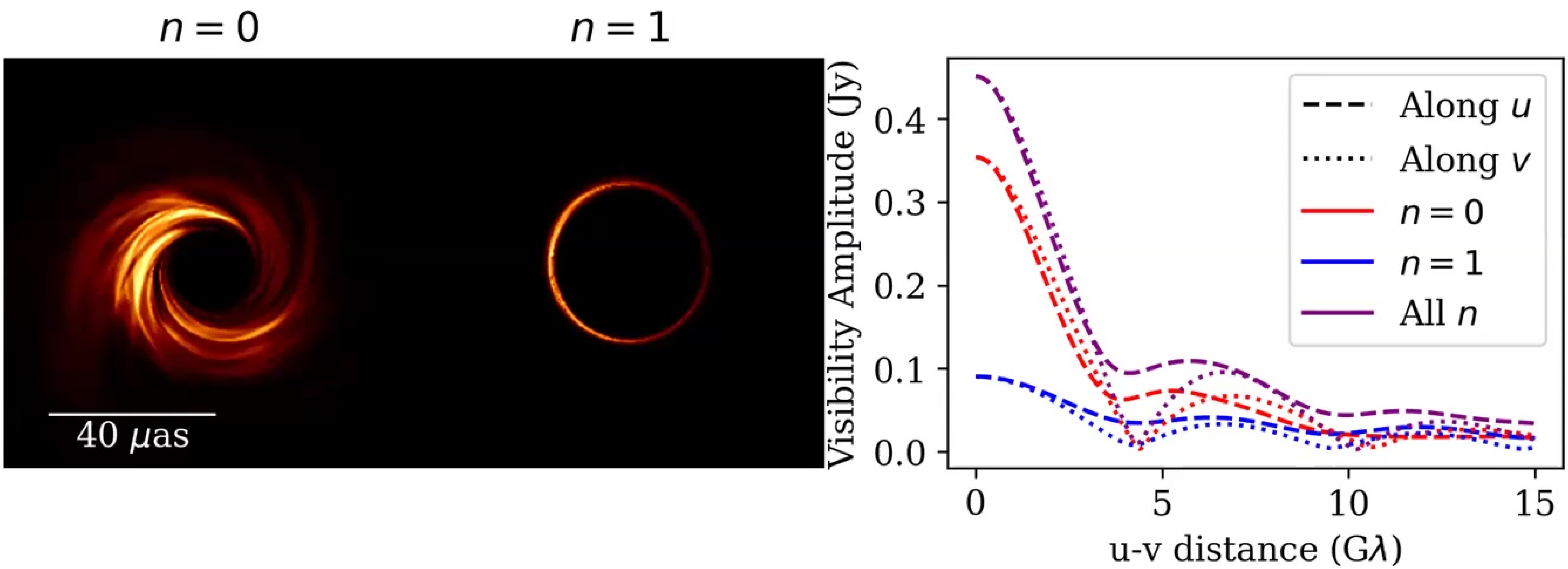




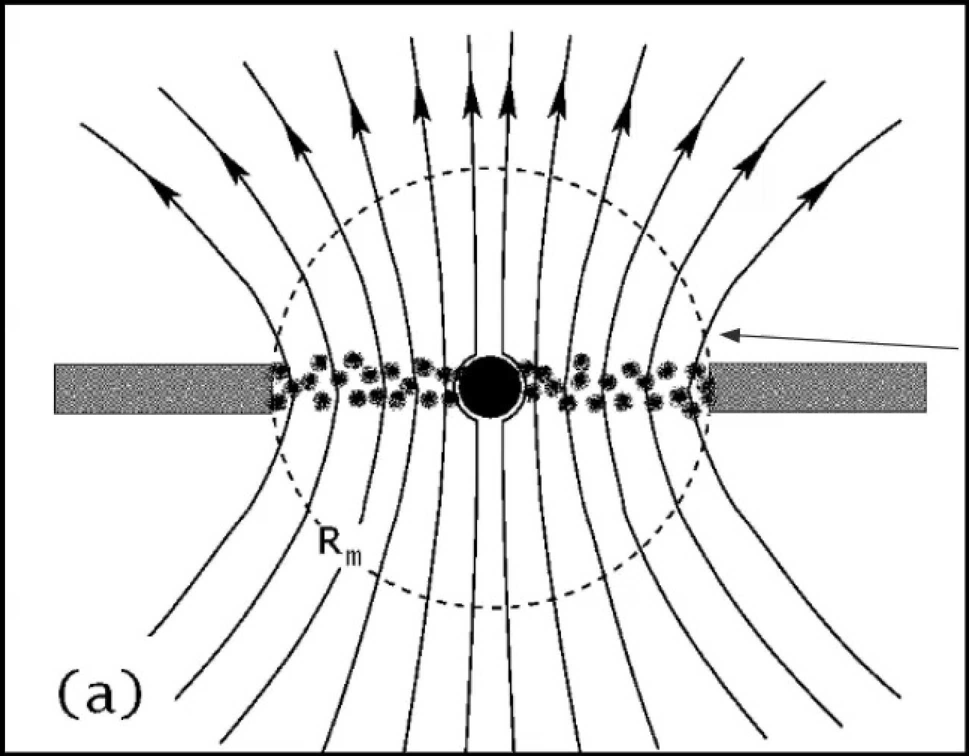
The Photon Ring is an absolute ruler in an otherwise highly degenerate problem

- Only mass (M/D), spin, and inclination shape the critical curve

Why worry about the photon ring for the EHT?



Accretion zoology

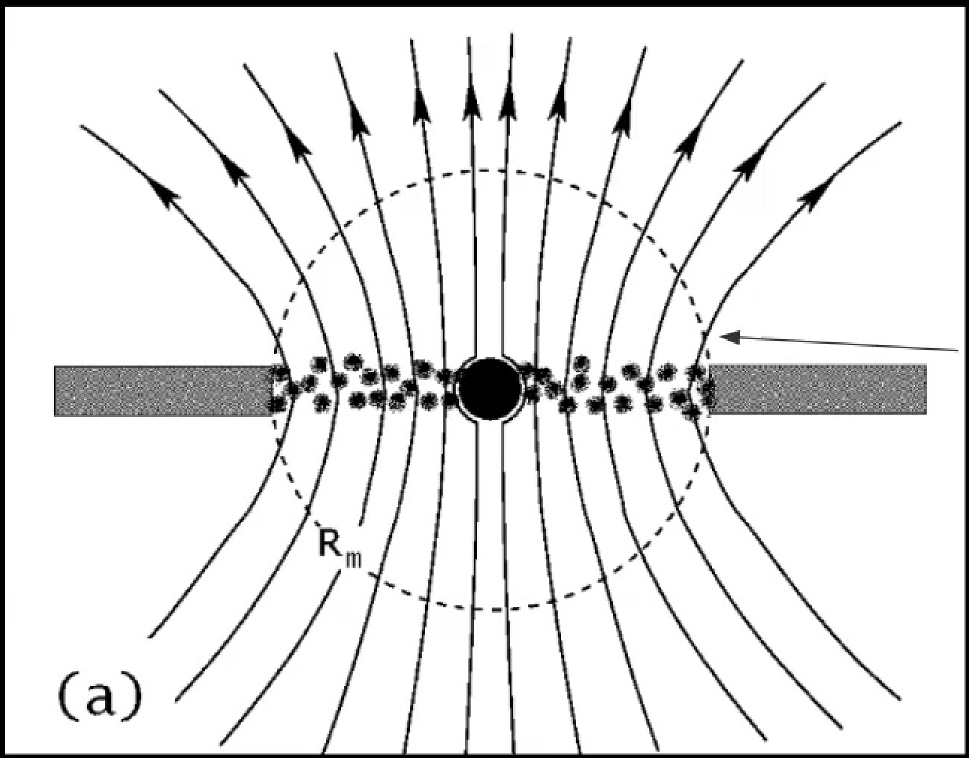


Narayan+ 2003

Standard And Normal Evolution (SANE): weaker fields, tend to “go with the flow” -> generally more disordered and toroidal fields

Magnetically Arrested Disk (MAD): strong, dynamically important fields threading the event horizon itself -> radial and vertical fields become significant

Accretion zoology



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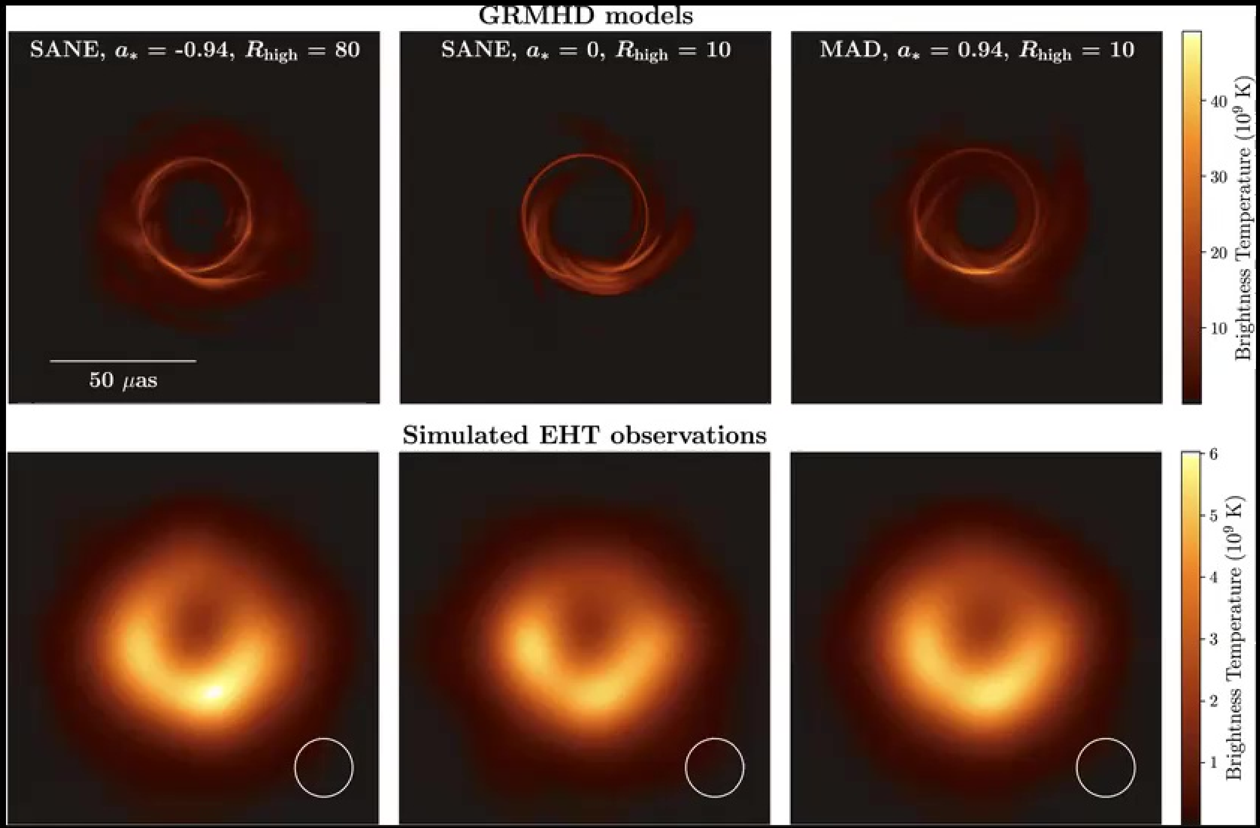
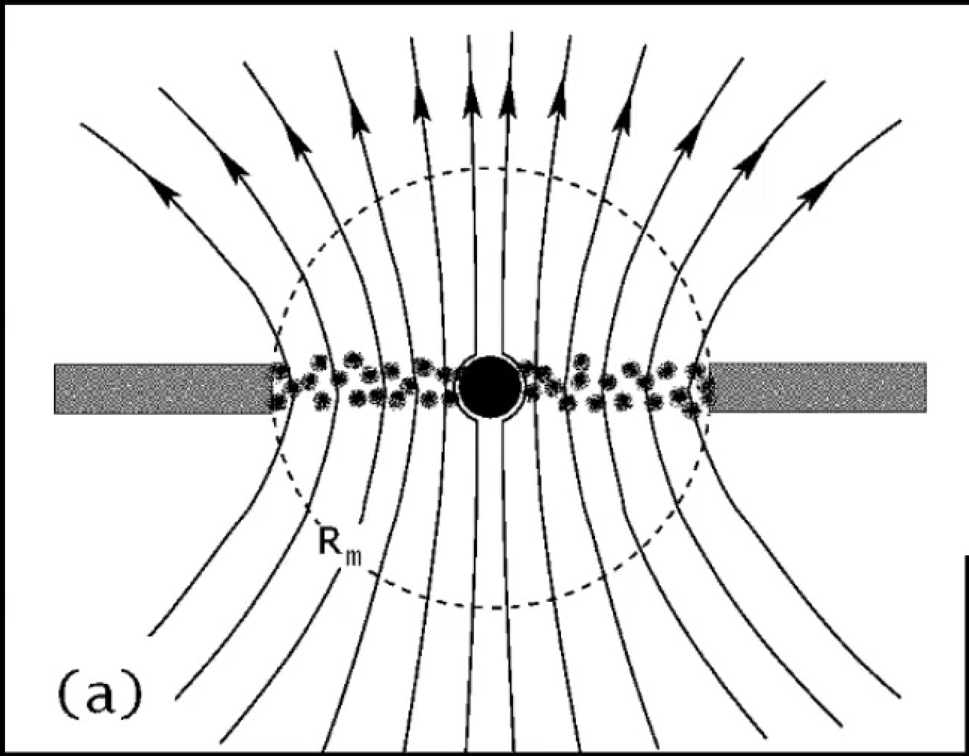
At EHT resolution, total intensity doesn't distinguish state



EHTC I, Figure 4

Black hole magnetization and synchrotron radiation



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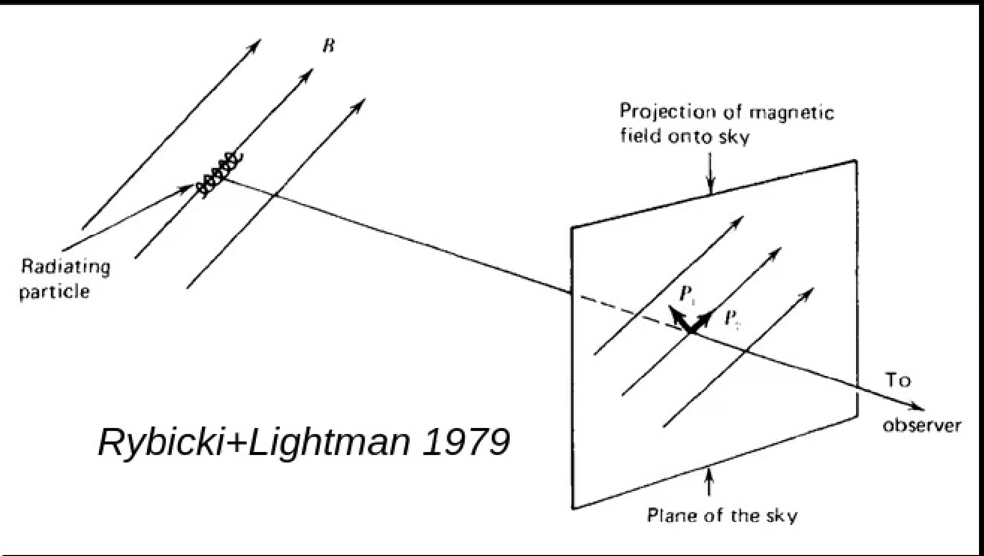
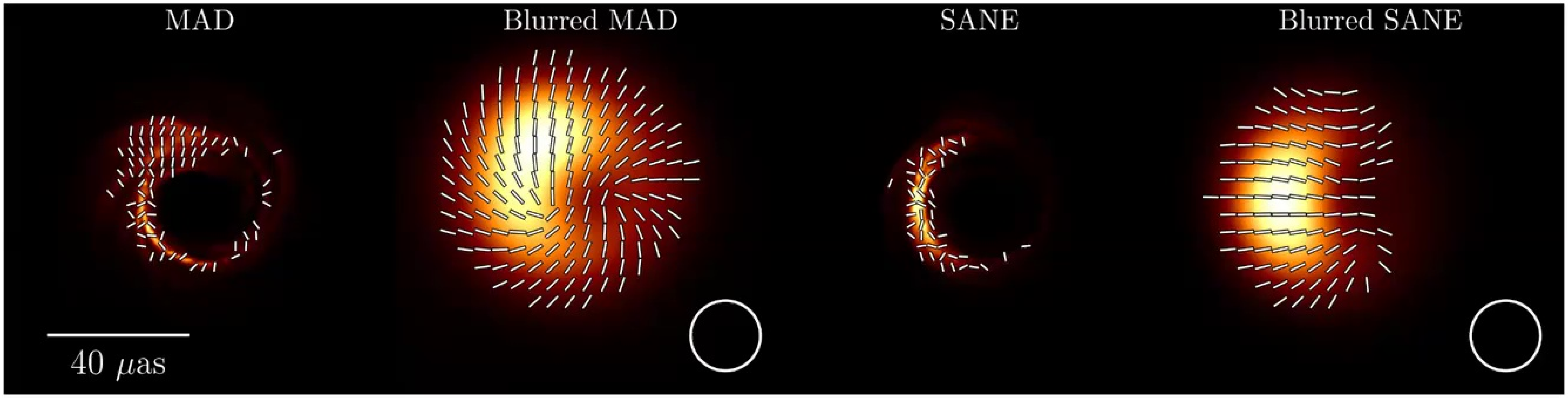


Rybicki+Lightman 1979

The EHT Library: 72,000 images of GRMHD simulations

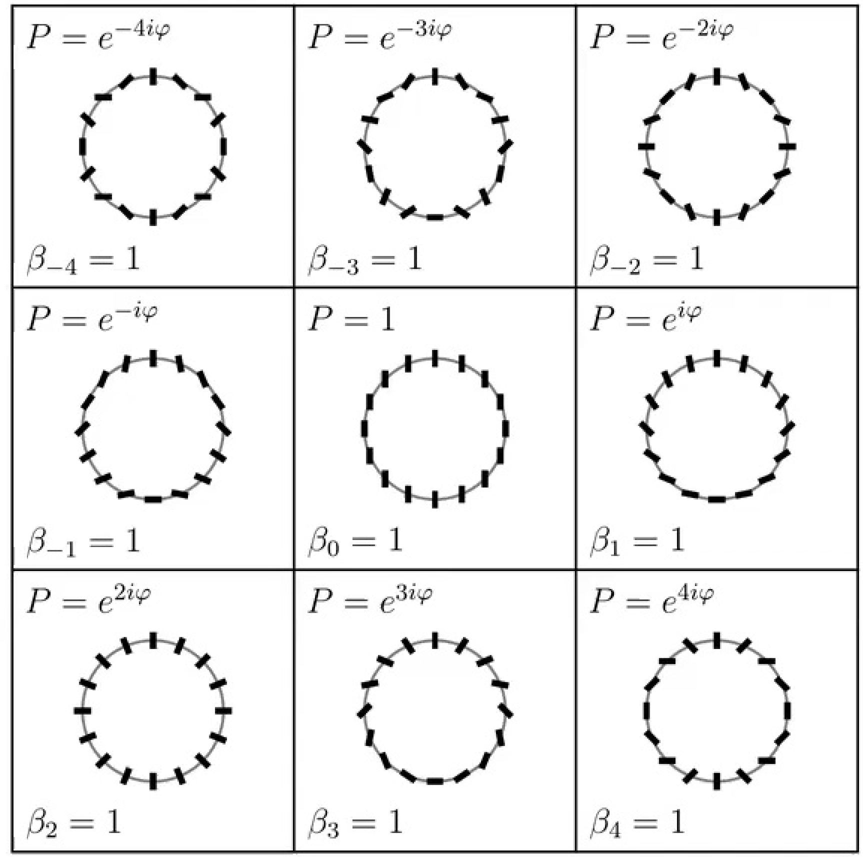


Decomposing polarization into an averaged polar basis

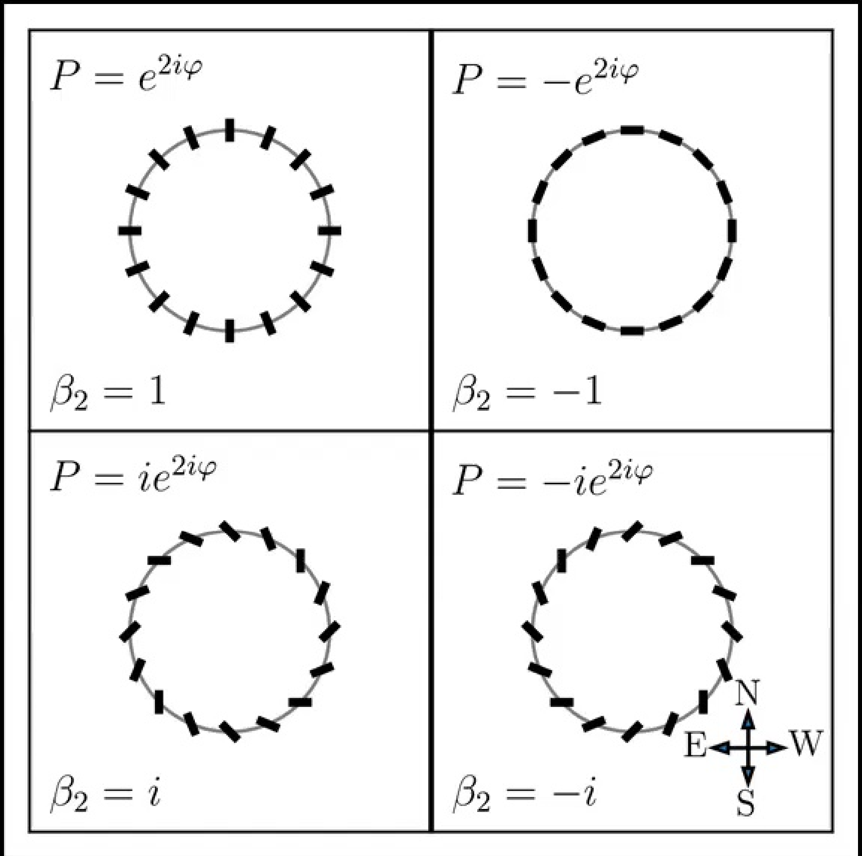
$$P(\rho,\varphi) = Q(\rho,\varphi) + iU(\rho,\varphi)$$

$$\beta_m = \frac{1}{I_{\text{ann}}} \int_{\rho_{\min}}^{\rho_{\max}} \int_0^{2\pi} P(\rho,\varphi) P_m^*(\varphi)\, \rho\, \mathrm{d}\varphi\, \mathrm{d}\rho$$

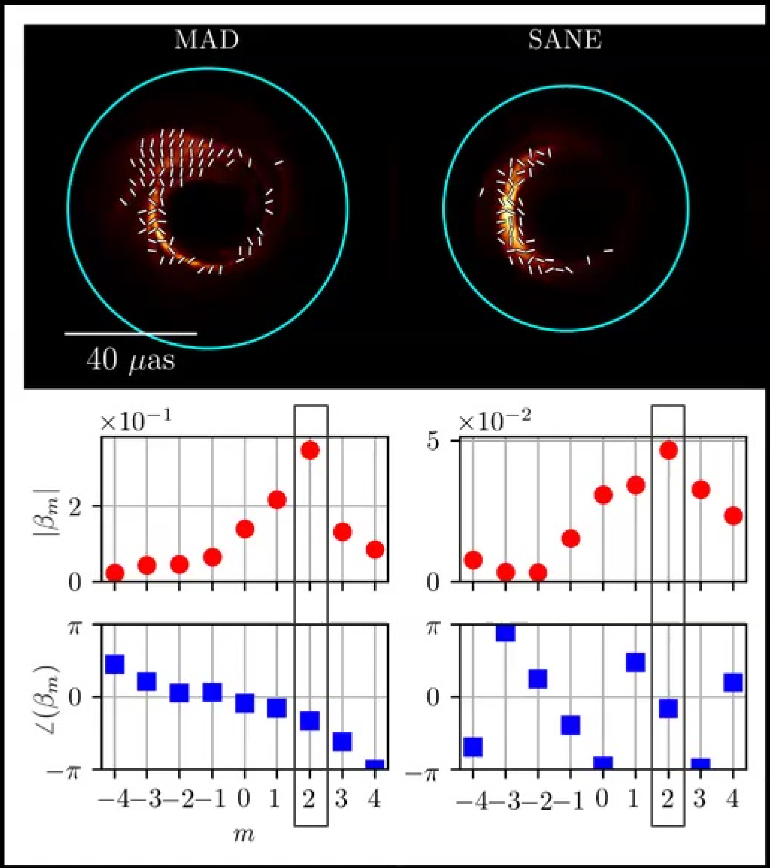
$$= \frac{1}{I_{\text{ann}}} \int_{\rho_{\min}}^{\rho_{\max}} \int_0^{2\pi} P(\rho,\varphi)\, e^{-im\varphi}\, \rho\, \mathrm{d}\varphi\, \mathrm{d}\rho,$$



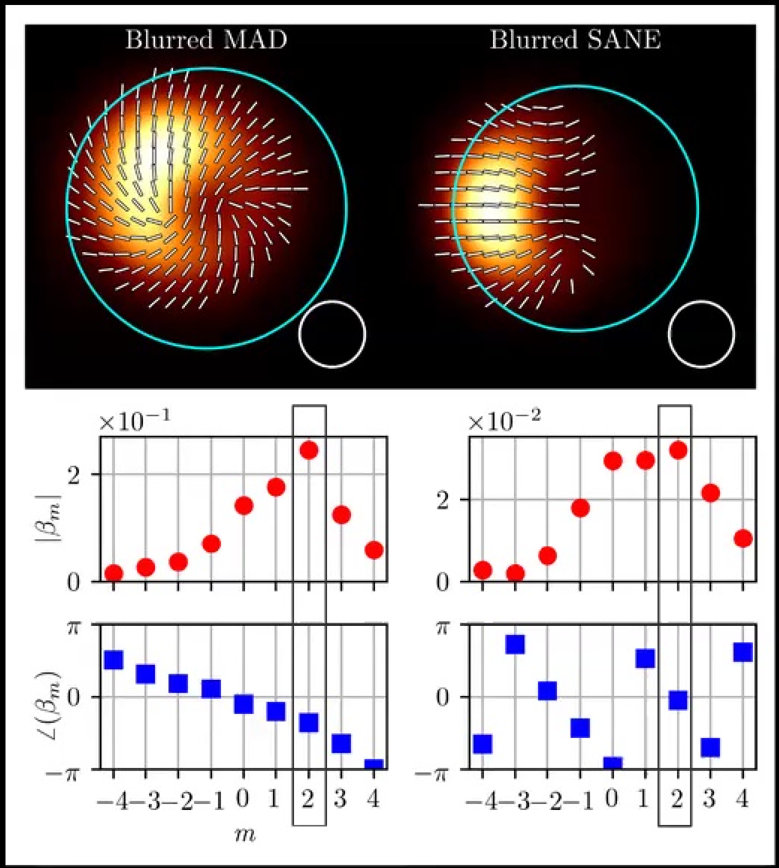
Pick out m=2 to measure rotational symmetry in EVPA



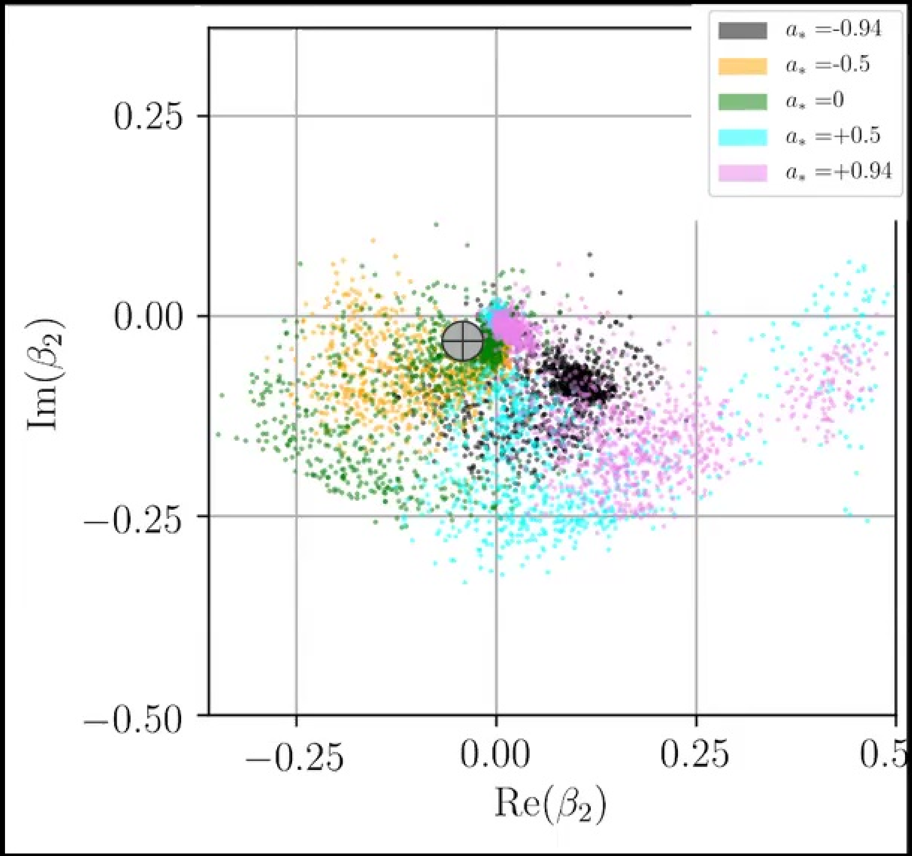
m=2 mode is dominant in amplitude

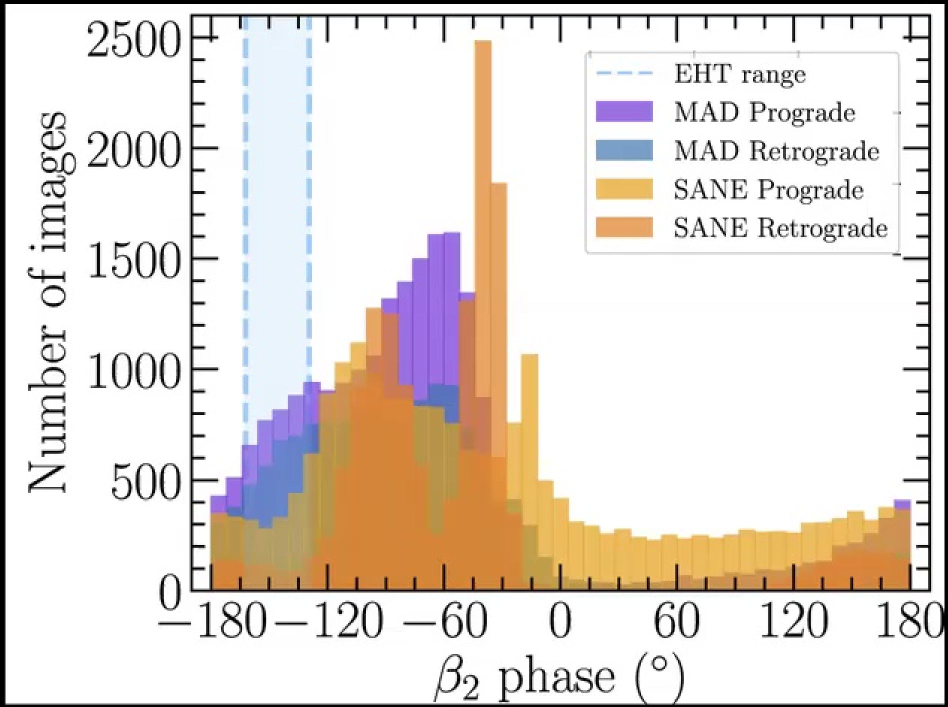


Blurring depolarizes but doesn't affect phase (at EHT res.)



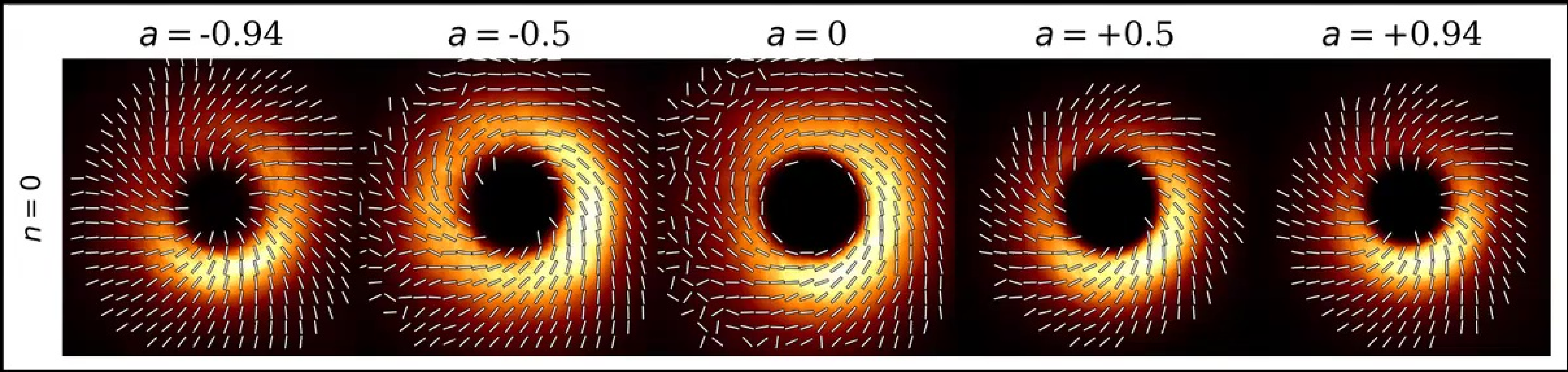
EHTC Paper VIII: PWP Phase Disfavors -a* SANEs



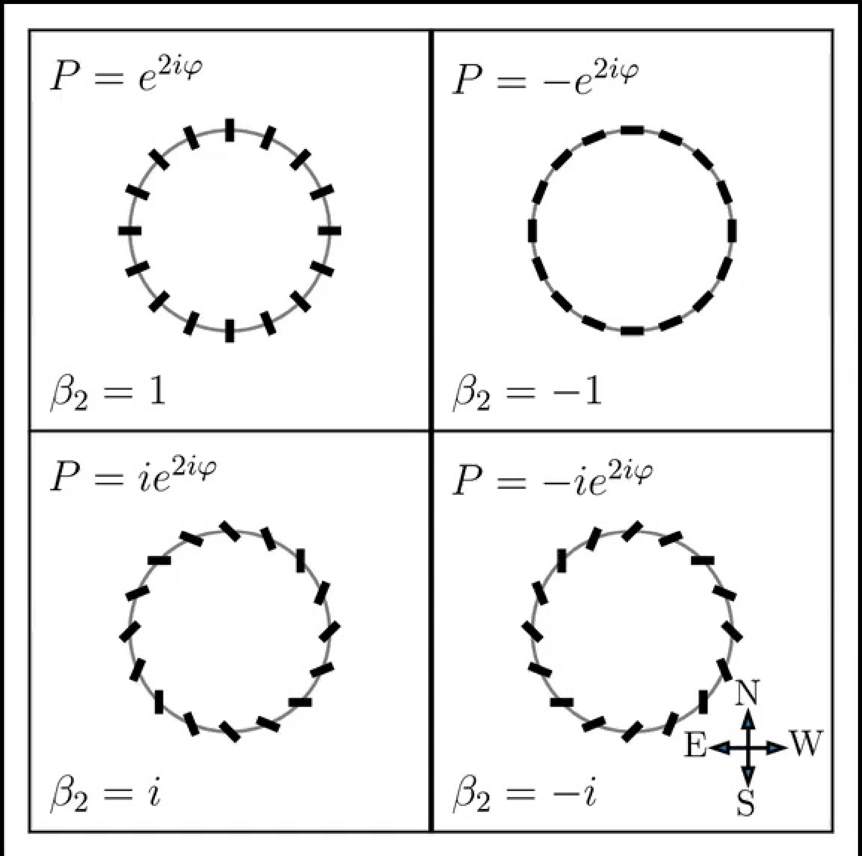


EHTC VIII, Figure 9

Spin reveals itself in polarization

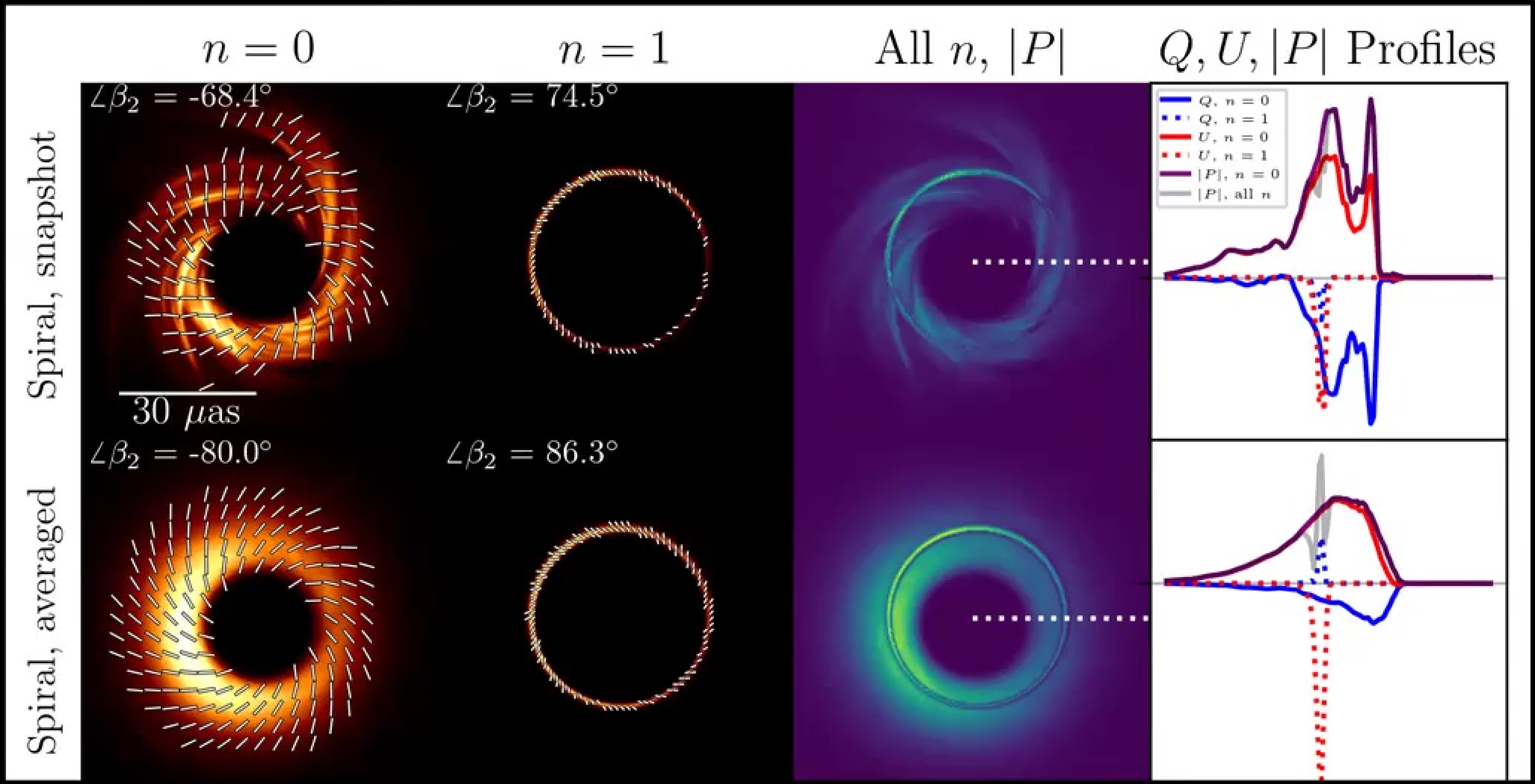


A return to photon rings for a mental exercise



"Spiral" images with ~imaginary $\beta 2$ partially depolarize!

- MAD, Spin 0.5, Rhigh 10



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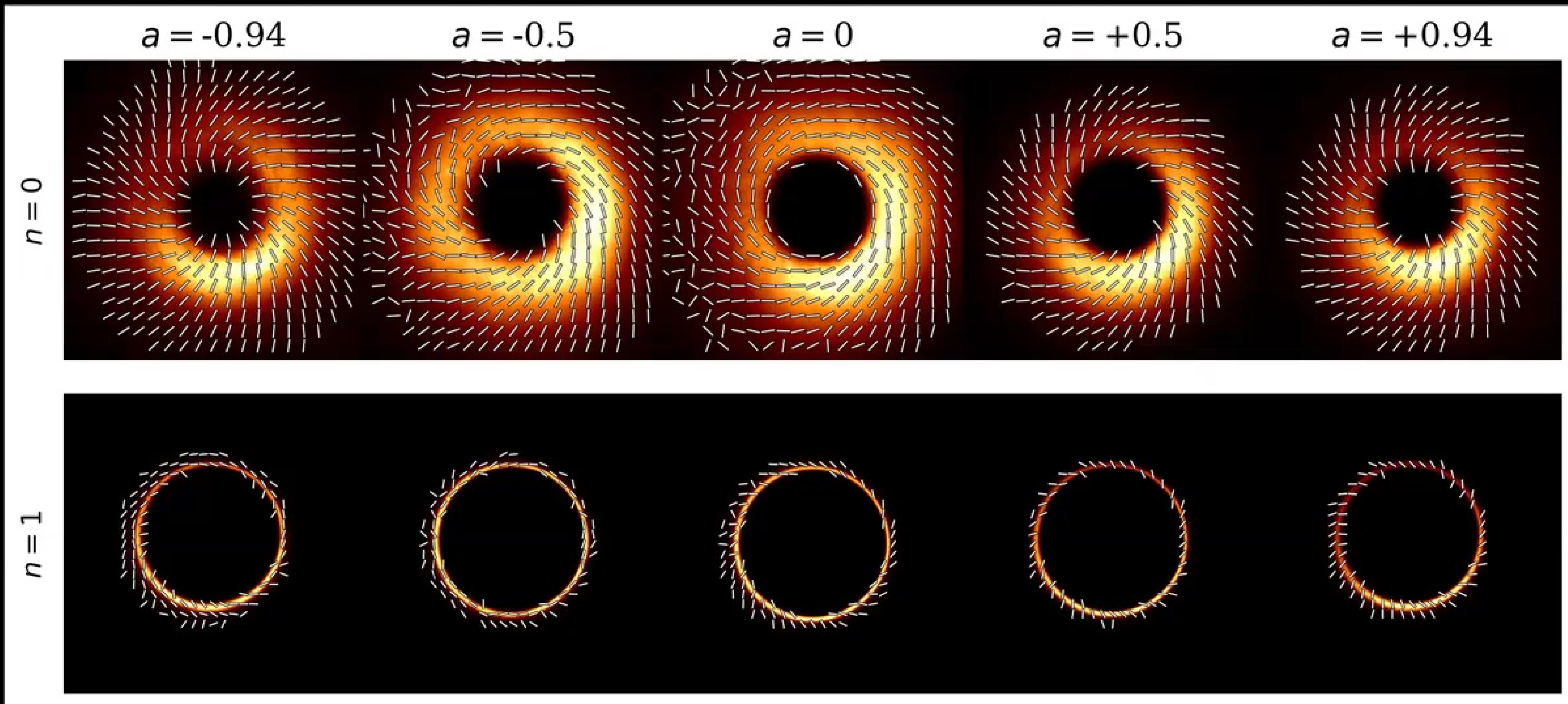
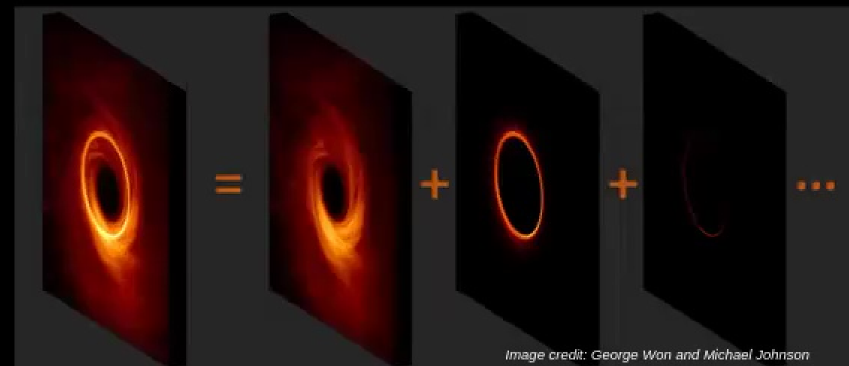
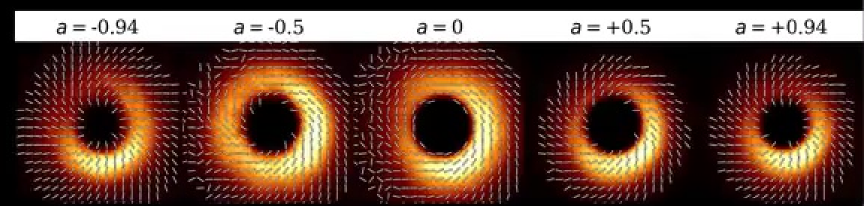


Outline - spin as the centerpiece of future EHT science

- The black hole photon ring



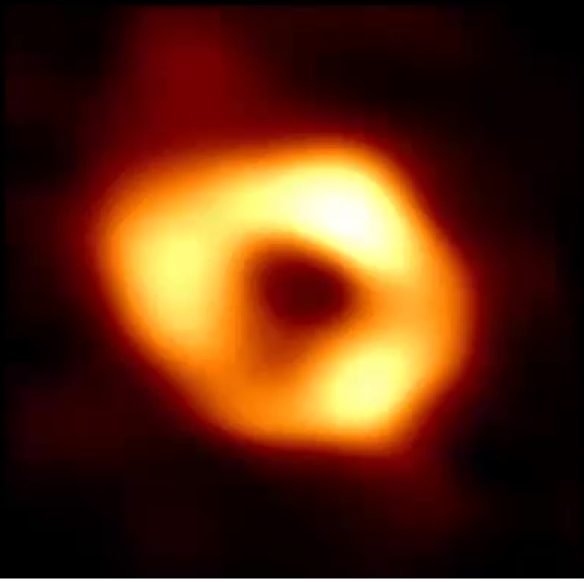
- Polarization spirals



- **Rapid semi-analytic model fitting of the accretion flow**

Just fit the black hole accretion system!

- We want to fit geometric models for the emission, rather than the intensity image on the sky
- Fitting accretion flow parameters alongside BH parameters enables conservative constraints on mass, spin, etc. with uncertainties set by underlying degeneracies



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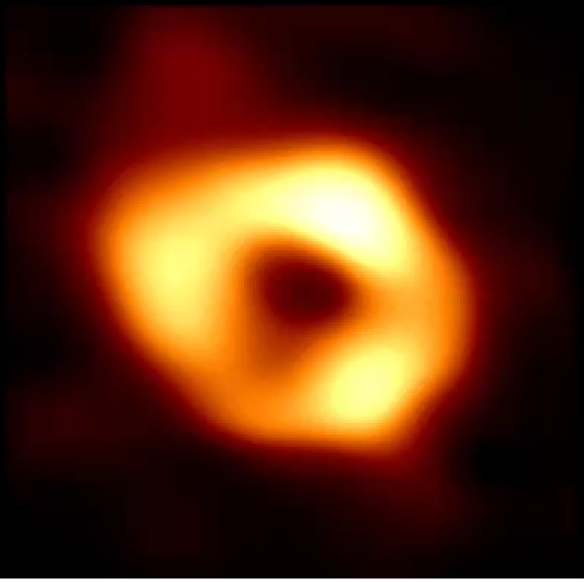
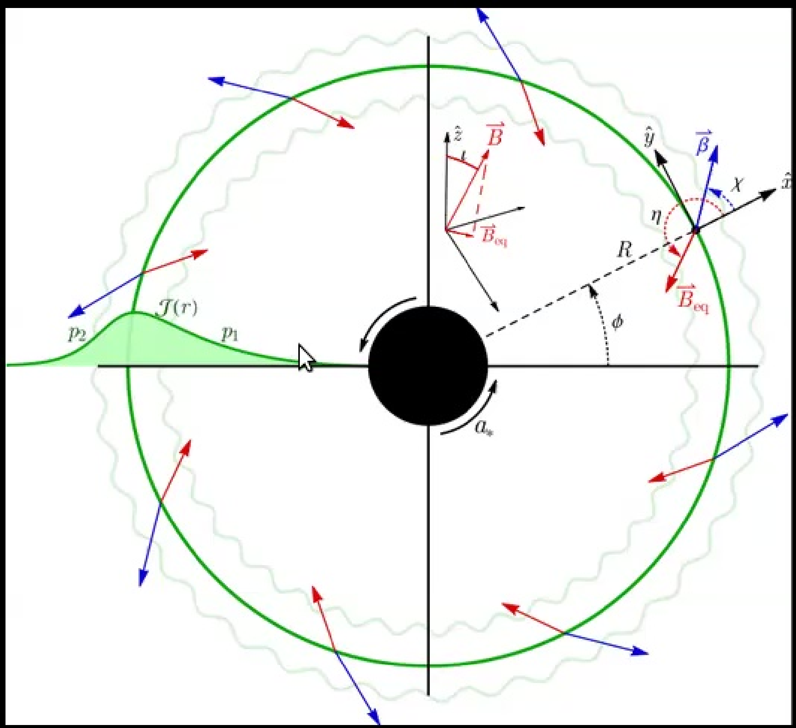
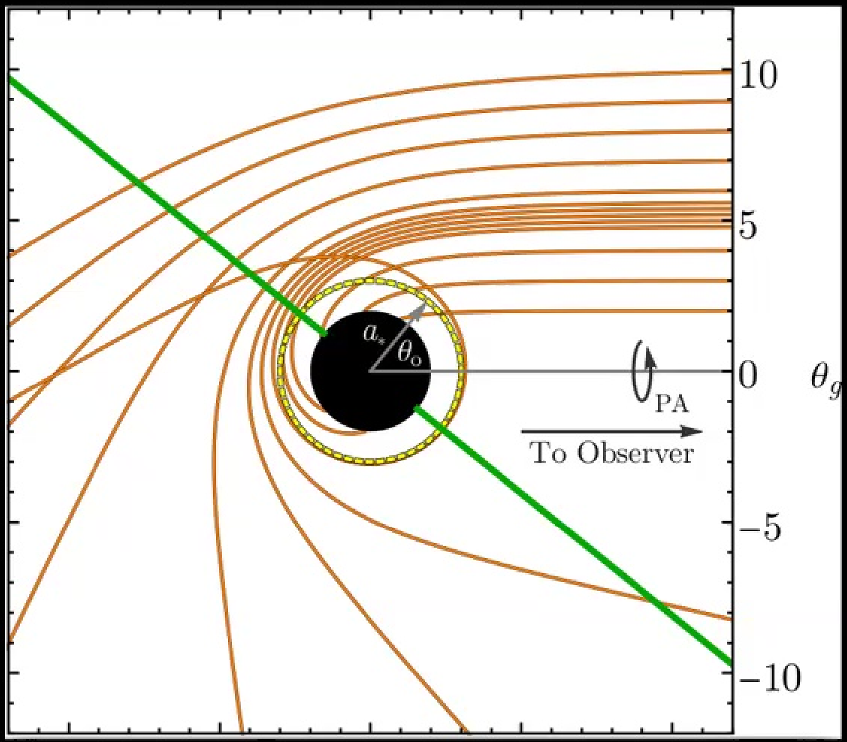


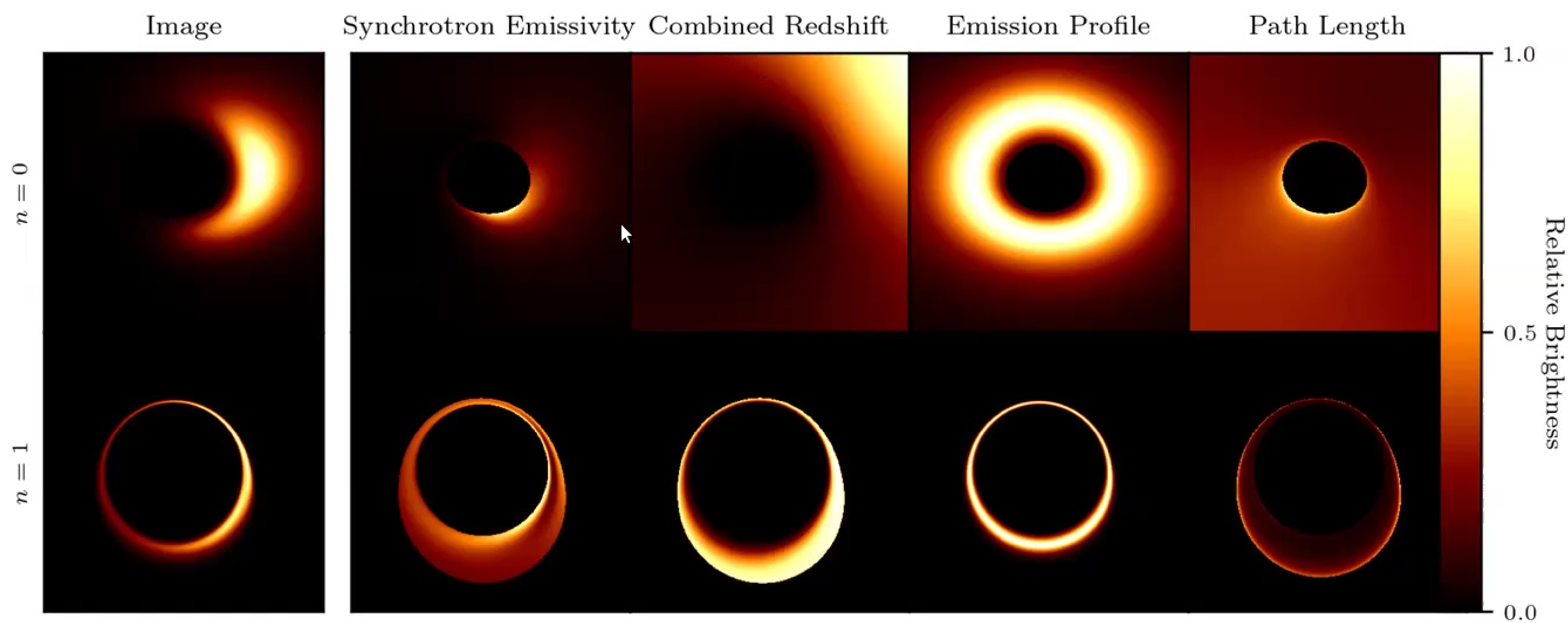
- My answer: **Kerr B**ayesian **A**ccretion **M**odeling
  - KerrBAM!

An equatorial, axisymmetric magnetized fluid



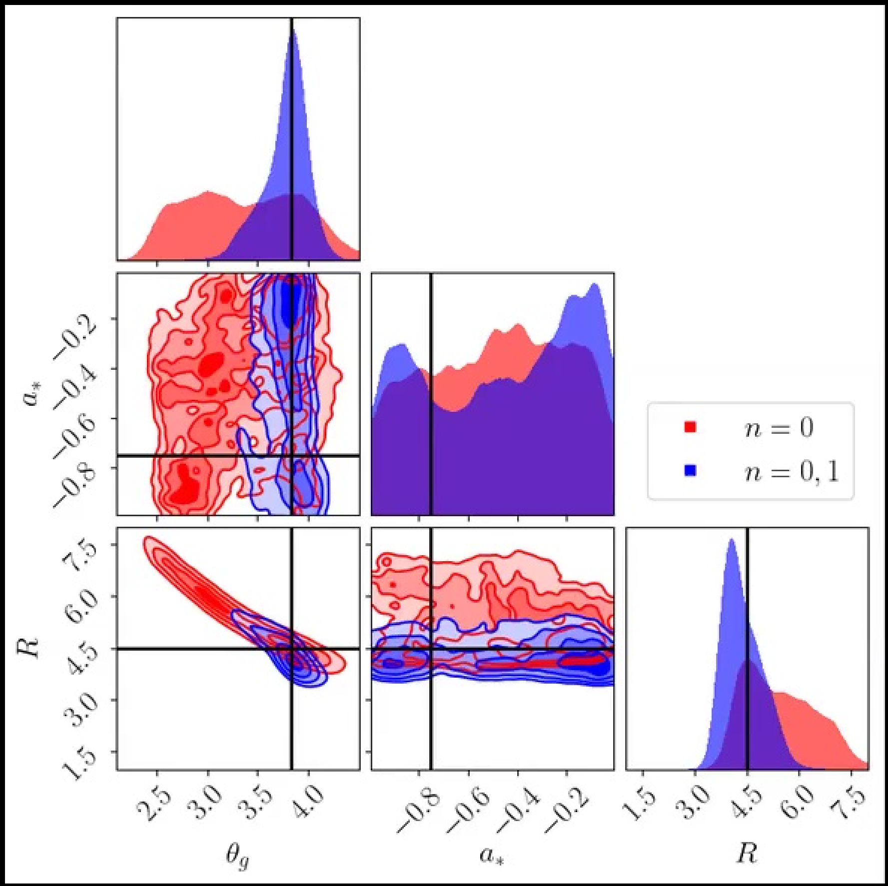


Decomposing the model



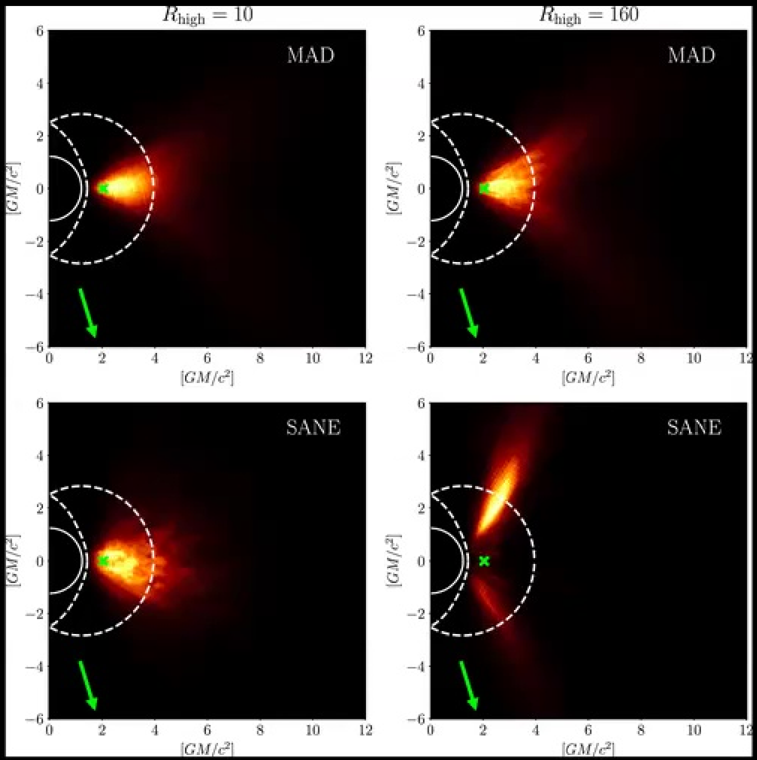
A subset of a self-fit - n=1 cleaves degeneracies!

- n=0 alone has completely degenerate M/D and emission radius
- Adding n=1 helps with M/D sensitivity, but spin is still unconstrained by the 2017 EHT data



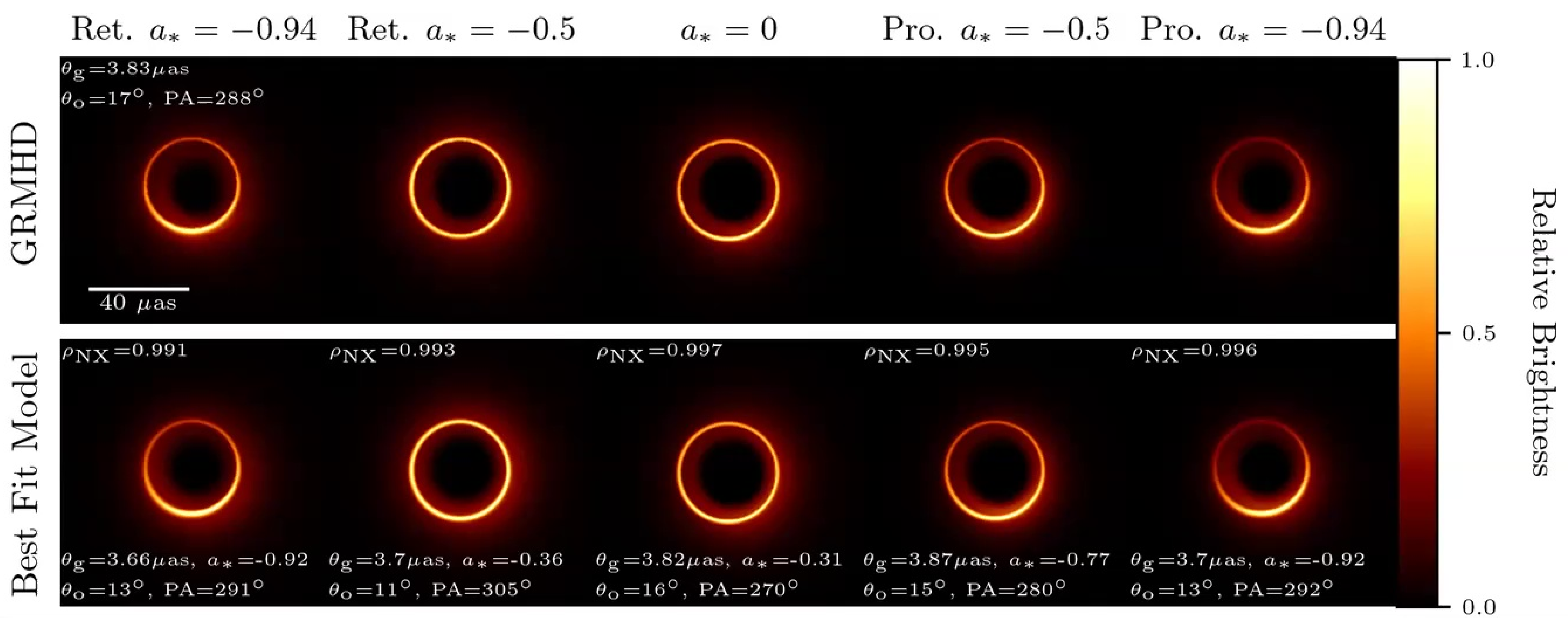
First GRMHD tests: image domain only, NXCorr

- We know the model is misspecified
  - GRMHD are not equatorial, though MADs are more so than SANEs at high Rhigh
- Before fitting VLBI data, want to characterize capabilities and biases of the ring model with “perfect” data
- Maximize normalized cross correlation as a proxy for the “perfect data MAP”



M87 Paper V, figure 4

Despite 3d structure, the model mimics GRMHD - MADs



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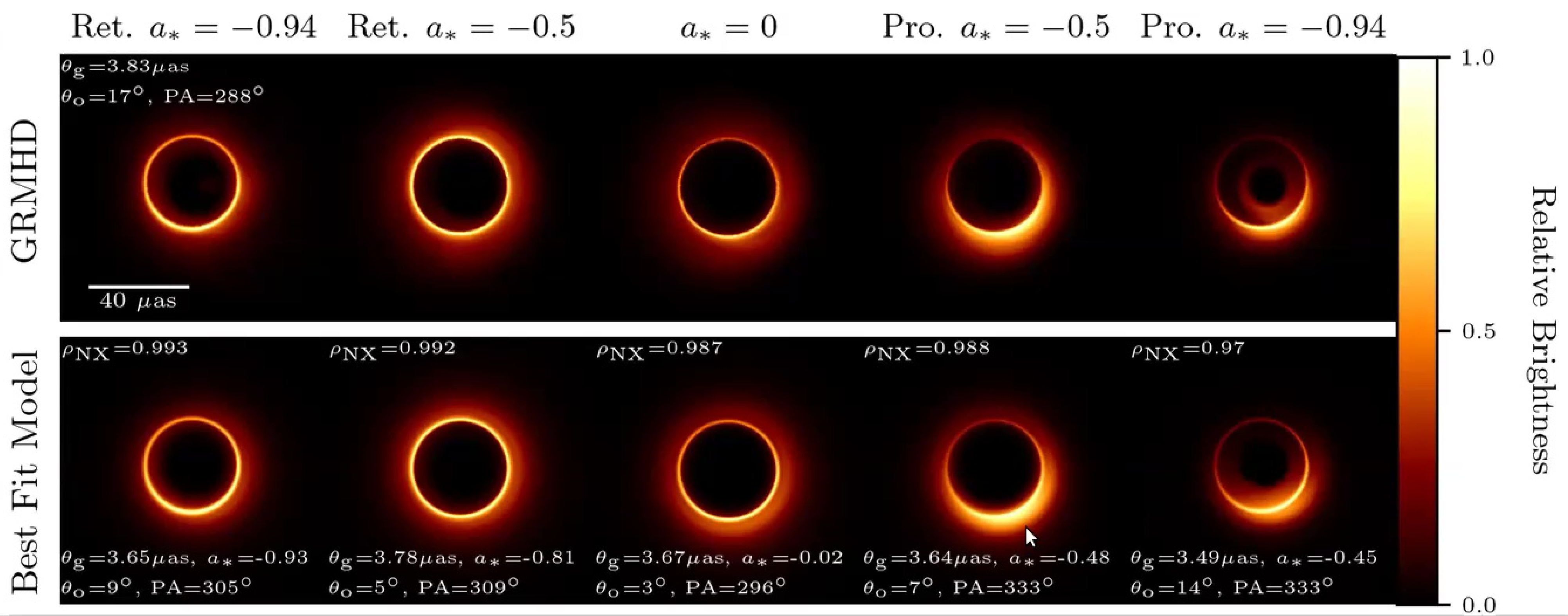
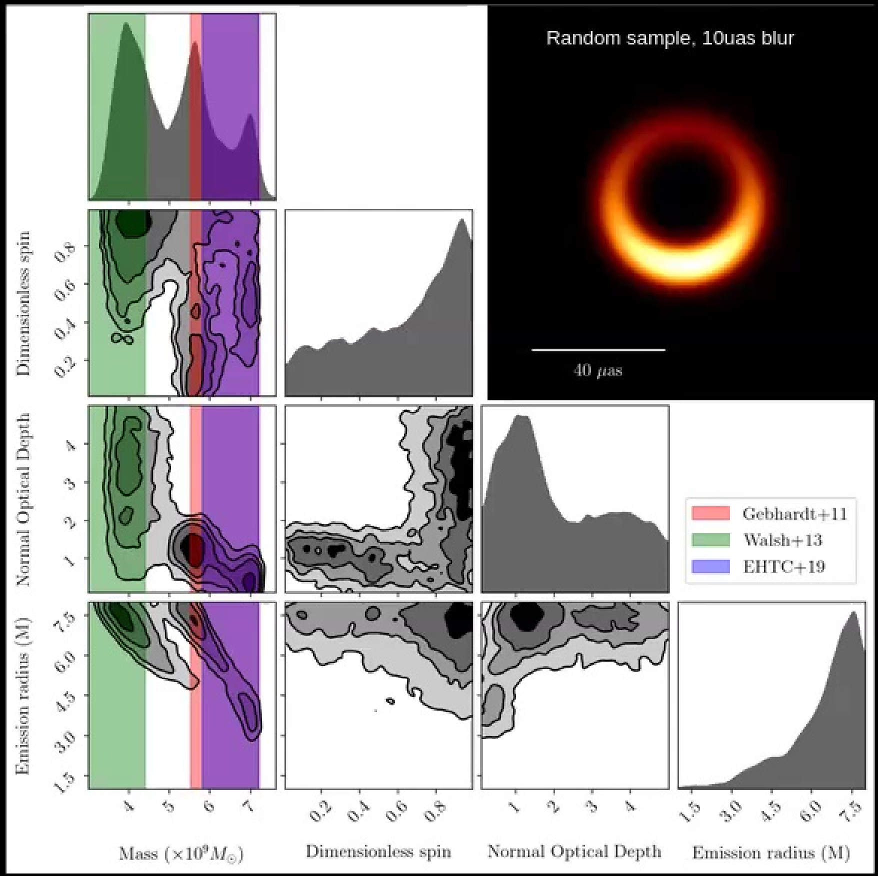


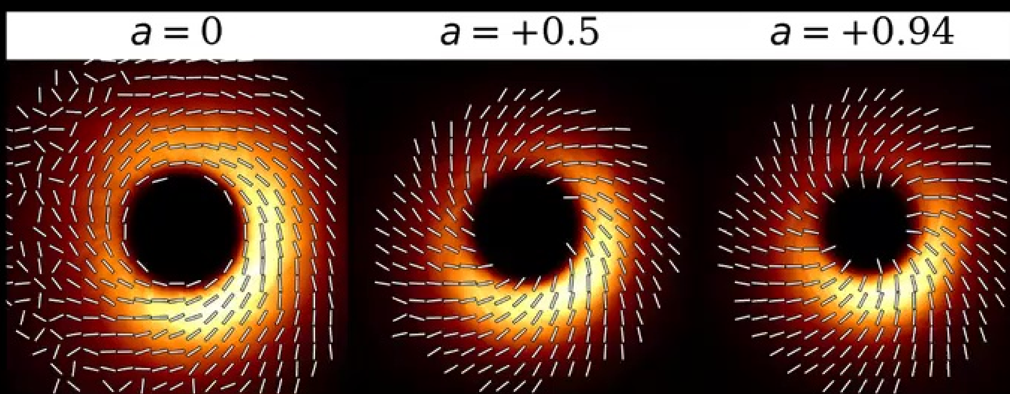
(Very) preliminary fits to M 87*

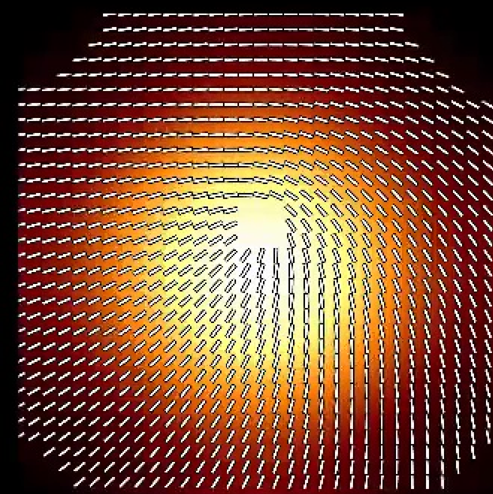
- Parametrize the normal midplane-crossing optical depth
- In M 87* fits, find distinct modes depending on optical depth



So what's next?

- More general classes of emissivity models are on the horizon
- Meanwhile, ongoing fits of KerrBAM on M 87* and Sgr A*
  - Both are leaning MAD, just need to approximate quiescence
- Spin demographics





See *Pesce, Palumbo et al 2021 and 2022*

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- Conclusion: the future of EHT data analysis lies in informative priors

Decomposing the model