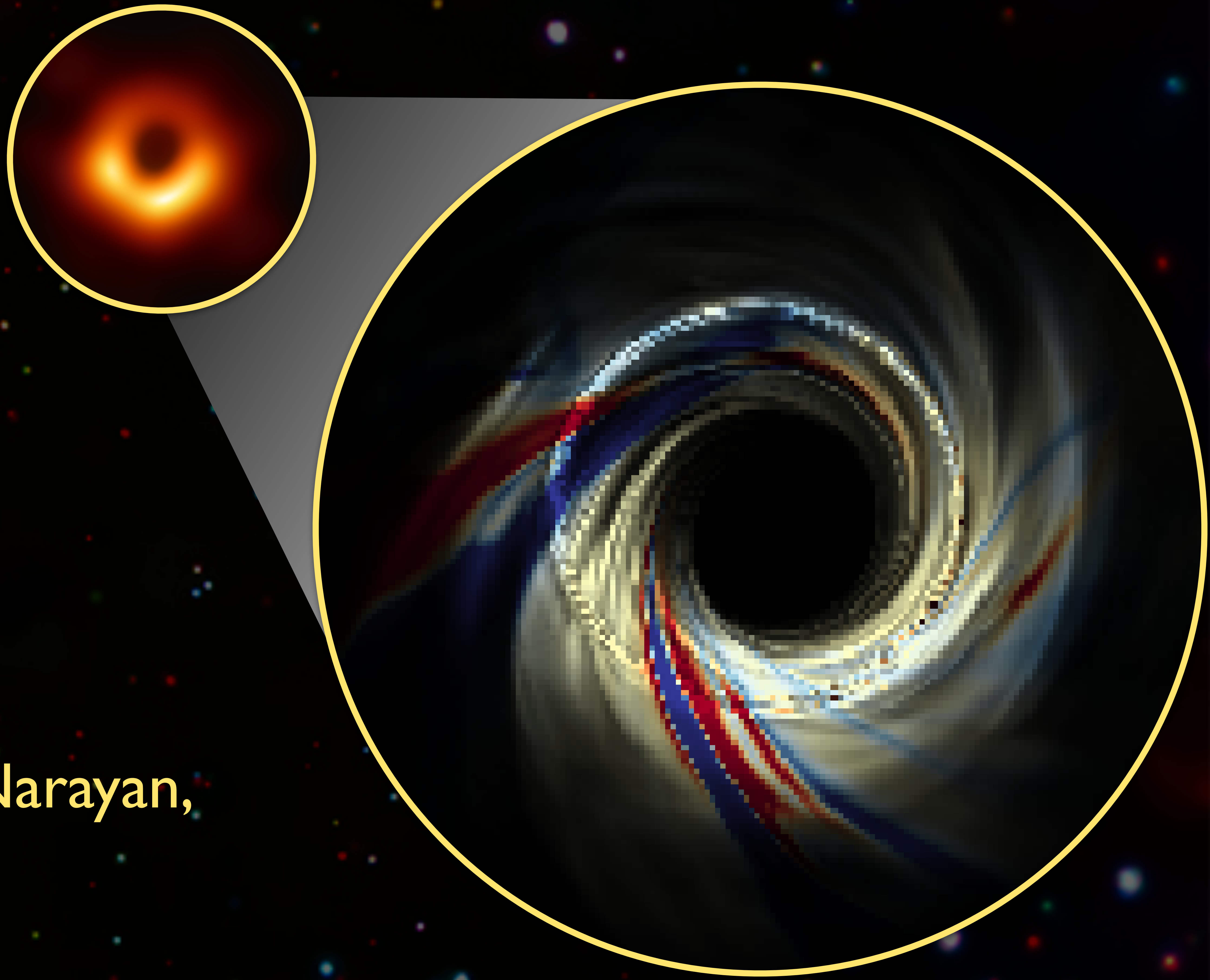
The Internal Faraday Rotation of BH Accretion Flows



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with Ben Prather, George Wong, Ramesh Narayan, Charles Gammie, and Michael Johnson

The Frontiers of Event Horizon Scale Accretion Oct 8th, 2020

Event Horizon Telescope

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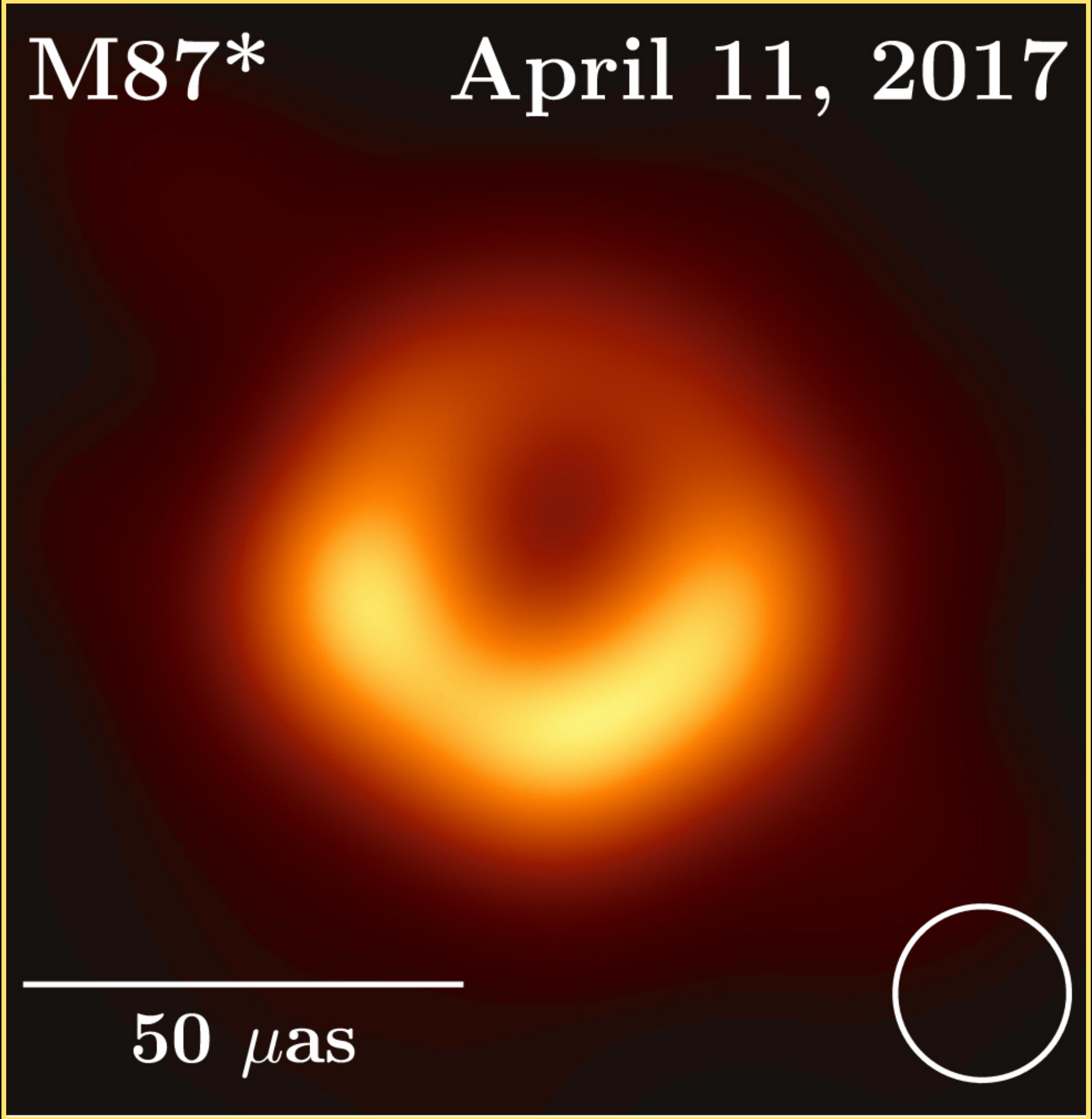
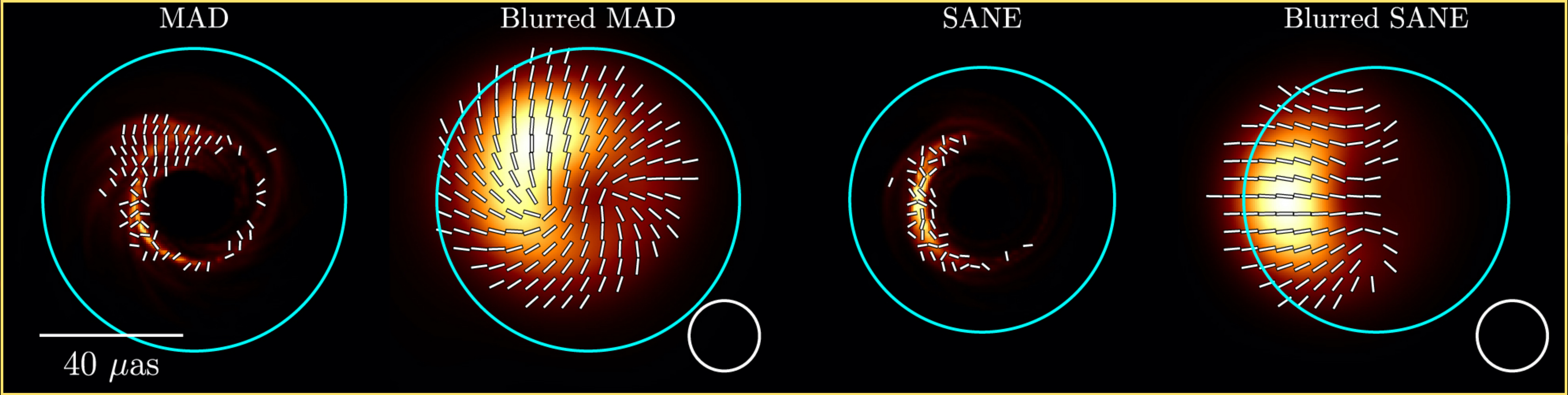
EHT Imaging Constrains The Accretion Flow



Event Horizon Telescope Collaboration (2019a-e)

- The Event Horizon Telescope Collaboration created a library of GRMHD models and their resultant ray traced images spanning three main parameters:
  - Magnetic Field Configuration: MAD or SANE?
  - BH spin: $a \in (-1,1)$
  - Electron temperature, parameterized with R_{high}.
- With combined multi-wavelength constraints, this has already ruled out all non-spinning BH models.
- This is only based on total intensity so far, when in fact polarized measurements were taken!

What do we expect from polarimetry?



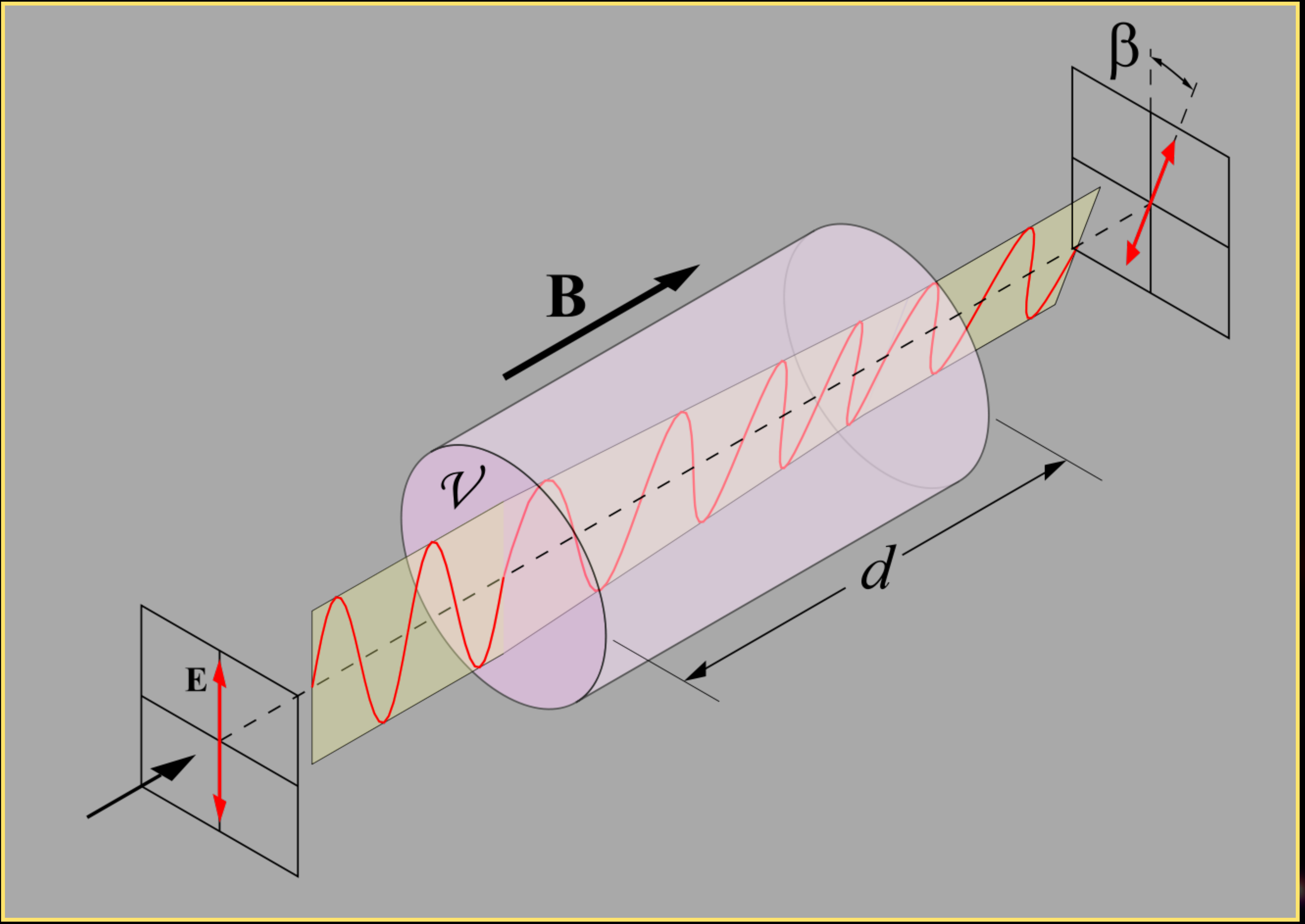
- In the mm, we observe synchrotron emission, which has an intrinsic linear polarization fraction $\gtrsim 70\,\%$ (e.g., Rybicki & Lightman 1986, Pandya+ 2016).
- The magnetic field geometry is imprinted on linear polarization ticks.
- Palumbo, Wong, and Prather (2020) show that MADs may have more "twisty" linear polarization patterns than SANEs.

Faraday Rotation

- As linear polarization travels through a magnetized plasma, it is transformed by effects sensitive to the density, temperature, and magnetic field.

- Faraday rotation changes the orientation of the polarization plane as a function of wavelength.

- The orientation of the polarization plane is called the Electric Vector Position Angle (EVPA). Here, the EVPA is Faraday rotated by an angle β.



Rotation Measure (RM)

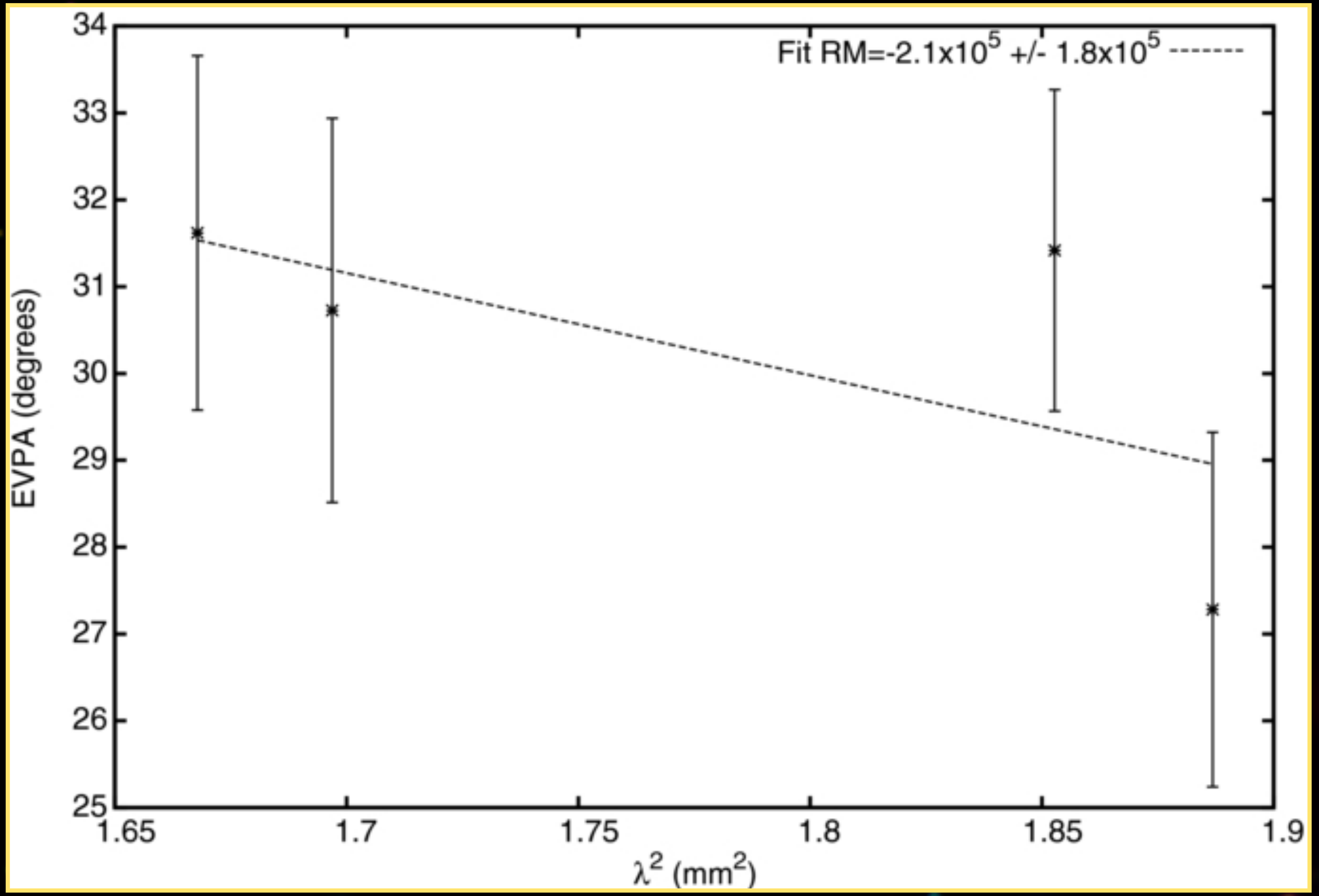
Observers define the rotation measure,

$$\mathrm{RM} \equiv \frac{\mathrm{EVPA}_1 - \mathrm{EVPA}_2}{\lambda_1^2 - \lambda_2^2} .$$

RMs of $\sim 10^{5-6}$ rad m^{-2} have been measured in the mm for Sgr A* and a handful of other low-luminosity AGN.†

The RM can be related to the plasma via

$$\mathrm{RM} = 0.81 \ \mathrm{rad\ m^{-2}} \int f_{\mathrm{rel}}(T_e) \frac{n_e}{1\ \mathrm{cm^{-3}}} \frac{B_{||}}{\mu G} \frac{ds}{\mathrm{pc}} .$$



For EHT target M87*, $|\mathrm{RM}| < 7.5 \times 10^5$ rad m^{-2}.

(SMA; Kuo et al. 2014)

† Sgr A* (Bower+2003, Marrone+2007, Bower+2018), 3C 84 (Plambeck+2014, Kim+2019), 3C 273 (Hovatta+2019)

Magnetic field parallel to photon wave-vector

Electron number density

$$\mathrm{RM} = 0.81\ \mathrm{rad\ m^{-2}} \int f_{\mathrm{rel}}(T_e) \frac{n_e}{1\ \mathrm{cm}^{-3}} \frac{B_{||}}{\mu G} \frac{ds}{\mathrm{pc}}.$$

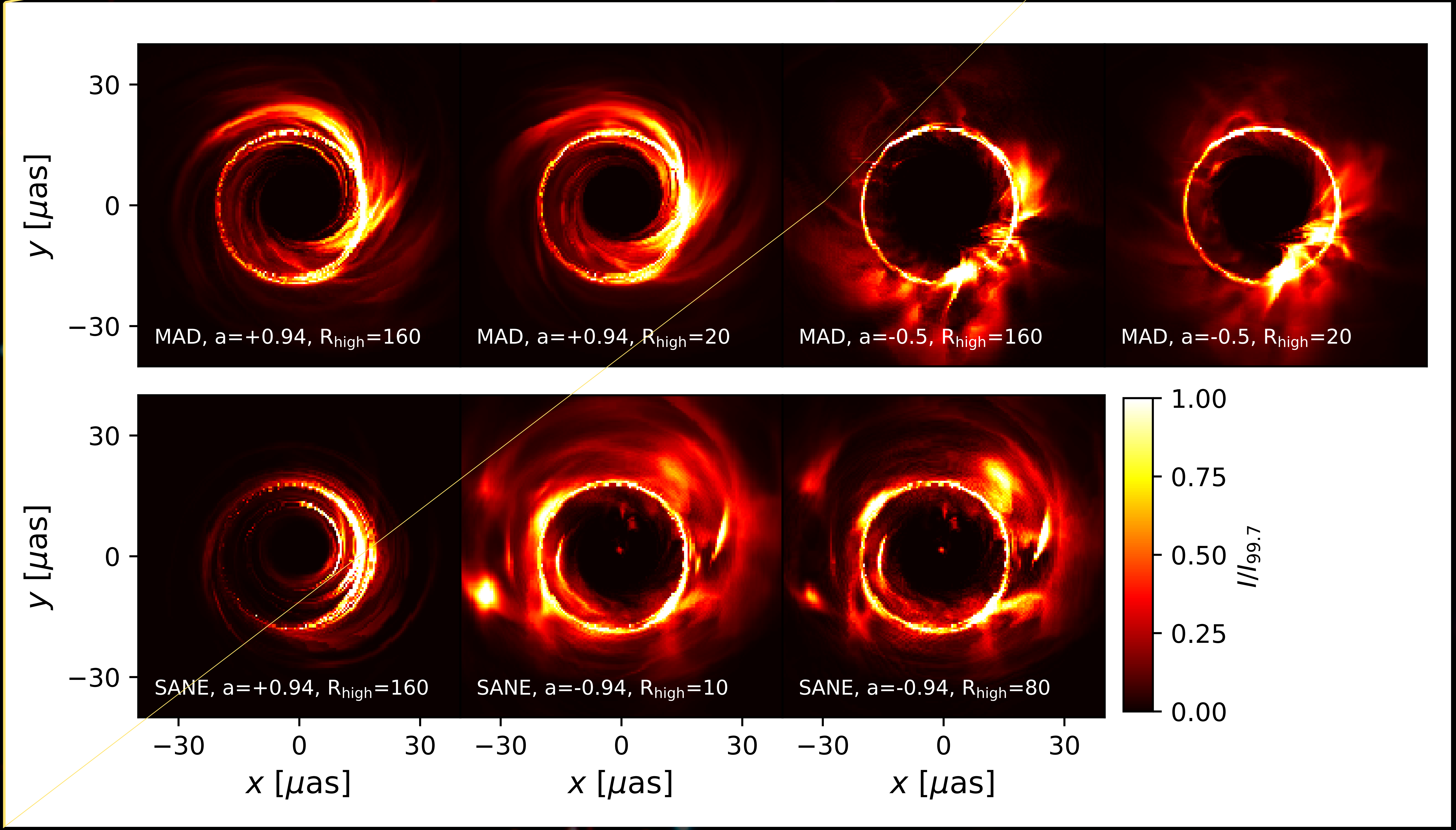
Suppression factor for relativistic temperatures

Caveat: Assumes that the emission is a point source entirely behind the Faraday rotator!

Using 7 passing models from the EHTC...

Polarized ray tracing with IPOLE (Moscibrodzka & Gammie 2018), 11 snapshots, 5 inclinations

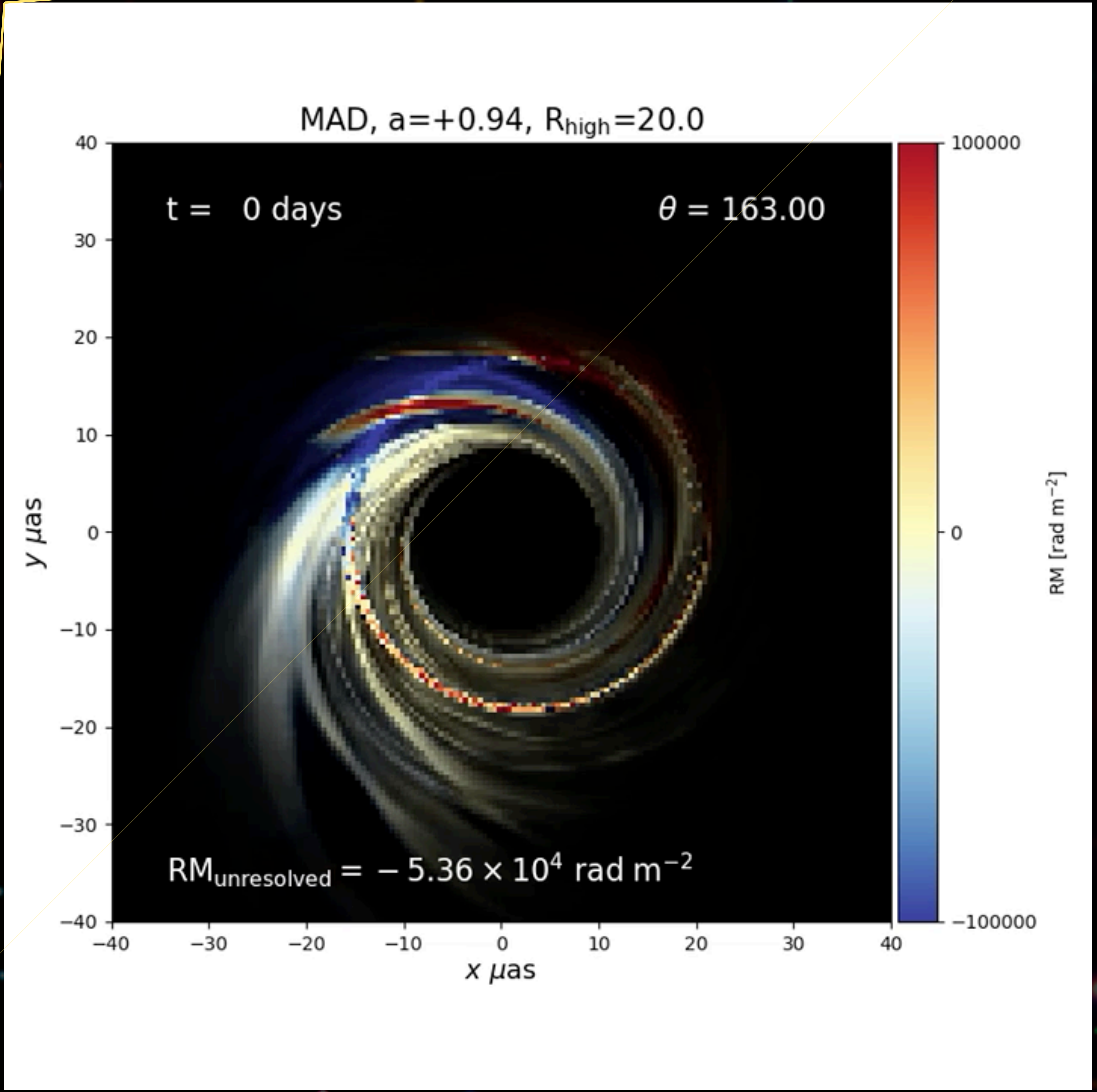
B-field	Spin	R_{high}
MAD	0.94	160
MAD	0.94	20
MAD	-0.5	160
MAD	-0.5	20
SANE	0.94	160
SANE	-0.94	10
SANE	-0.94	80



Total intensity images, final snapshot

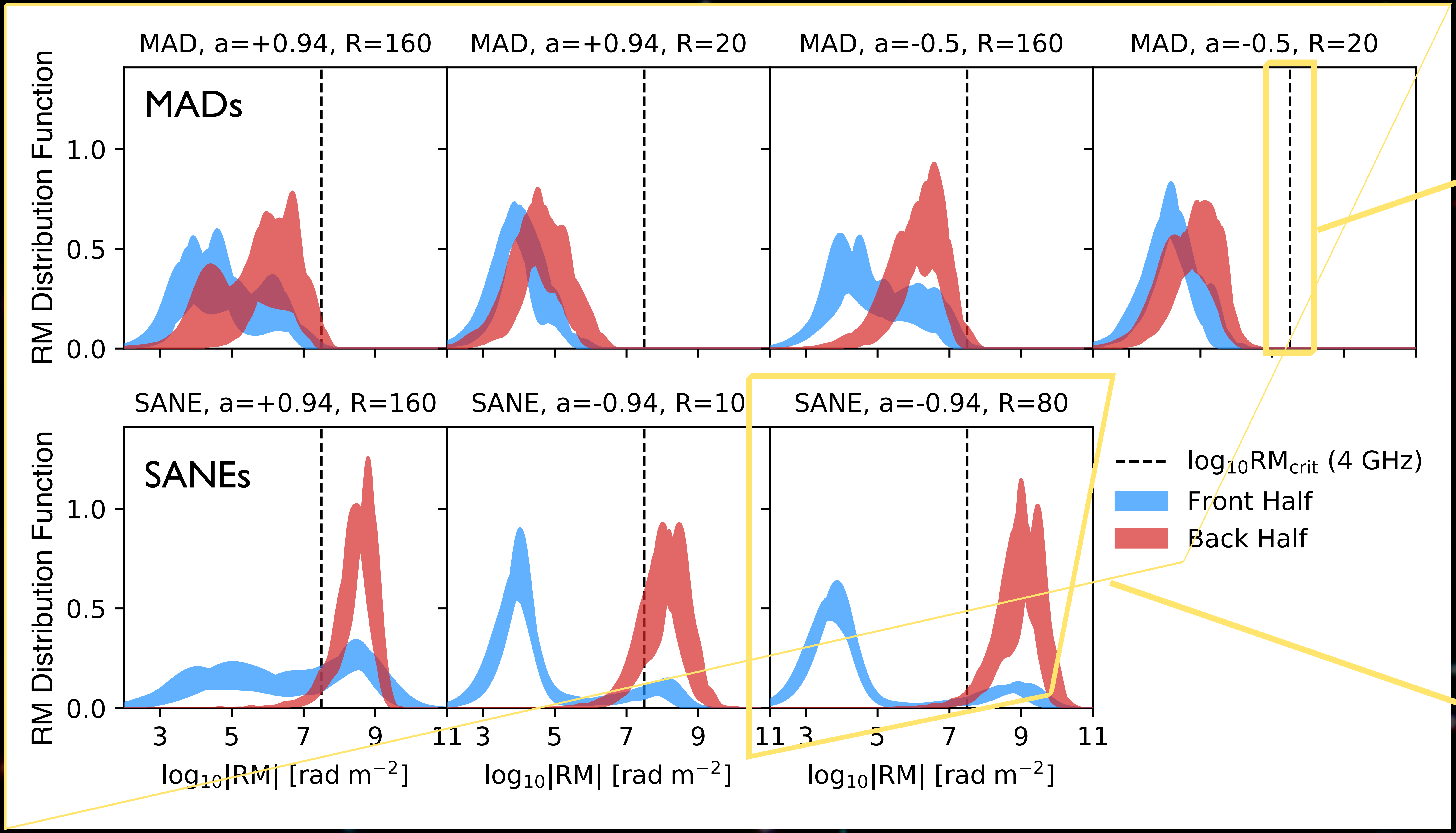
One Example Model

- Emission is not a point source, and the Faraday rotator is spatially complex. We need to interpret RM carefully.
- Unresolved RM varies rapidly by orders of magnitude and can flip sign.



Photon RM Distribution Functions

What is the intensity-weighted distribution of RM among pixels in the image?

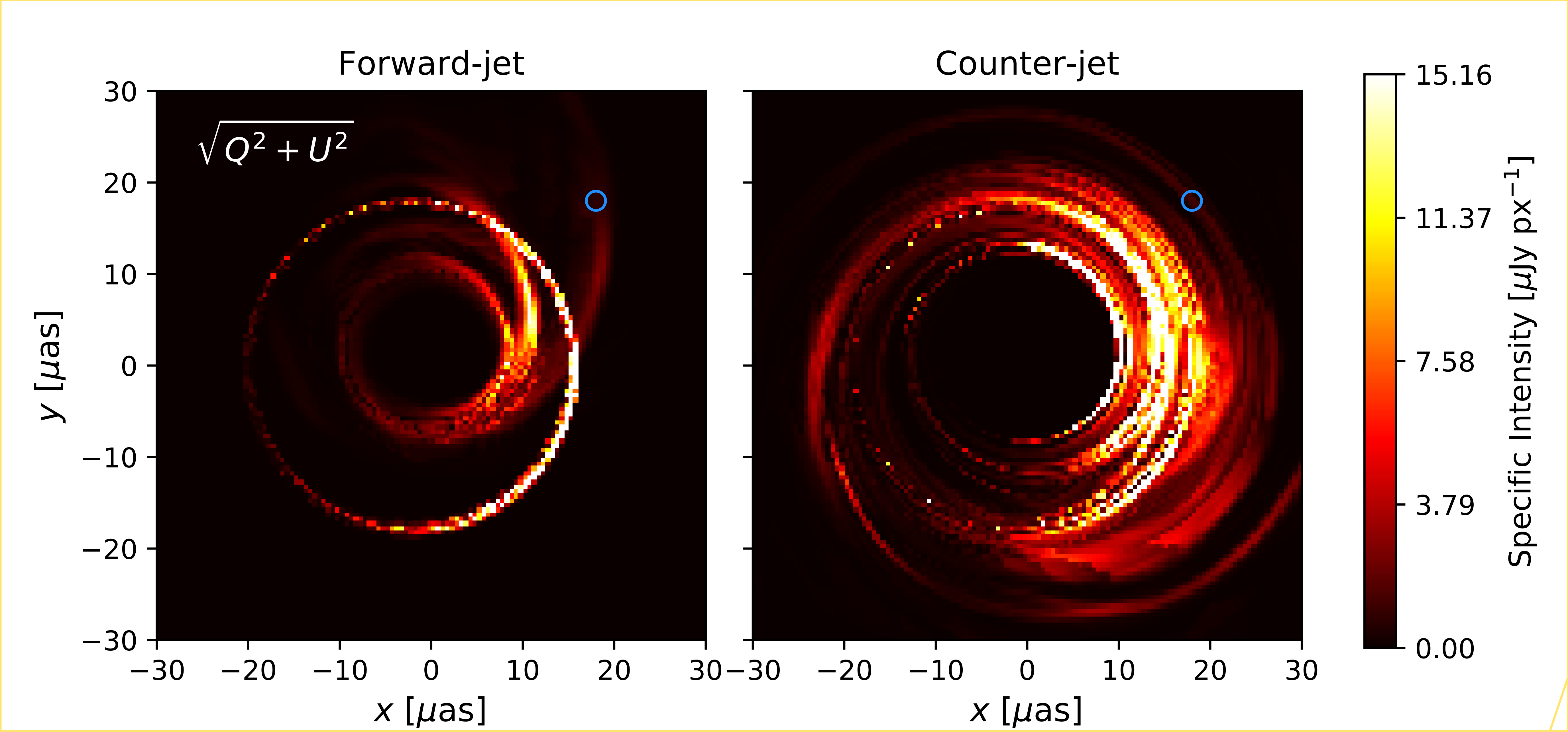


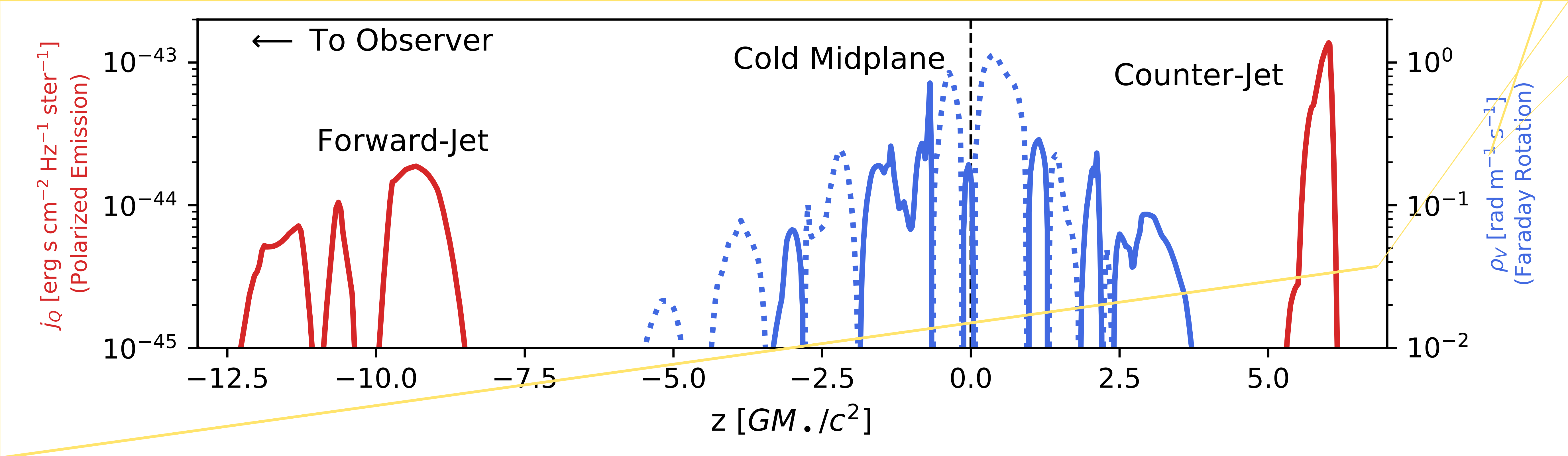
To the right of this line, bandwidth depolarization suppresses polarization by >50%.

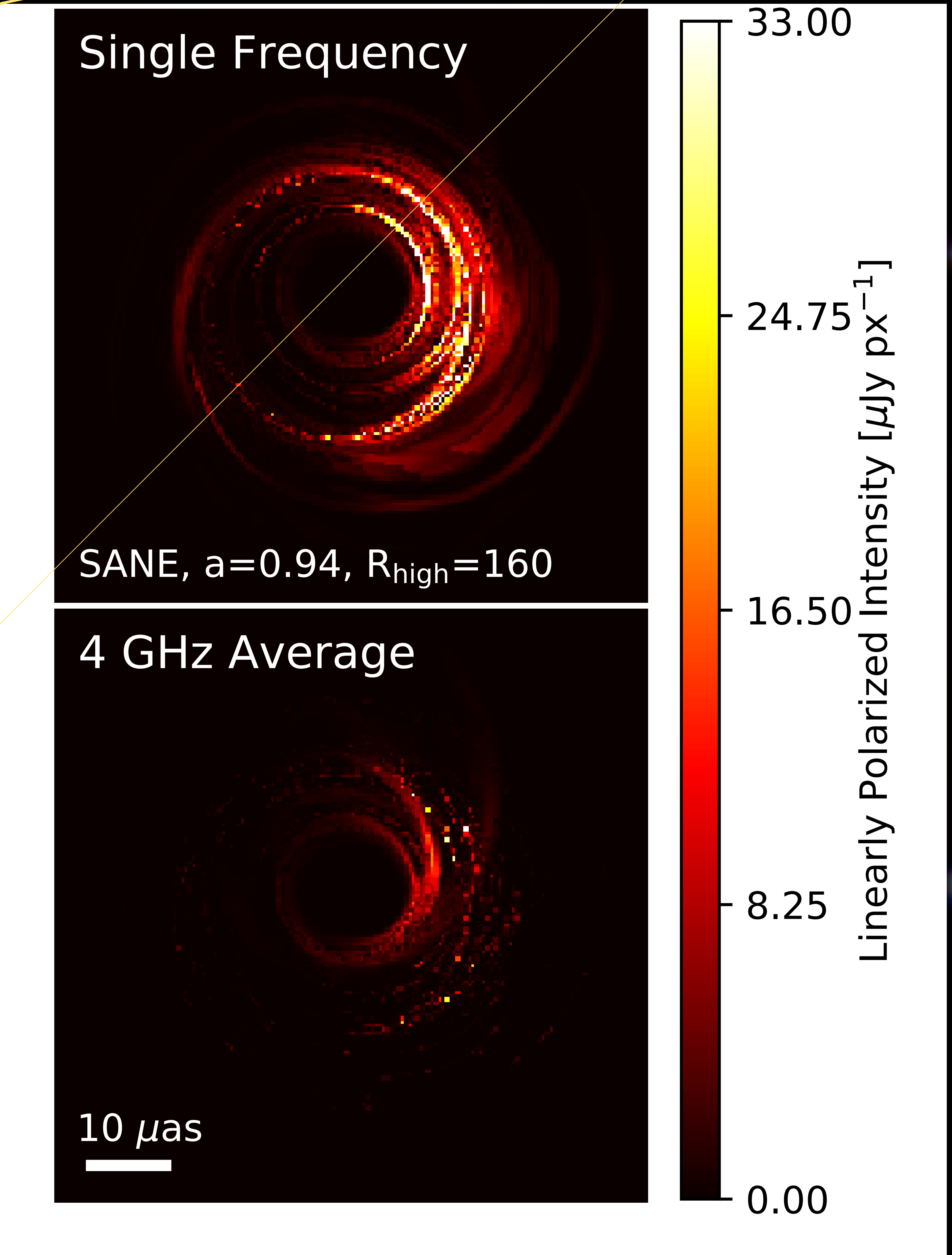
I split emission depending on its original location.

In this extreme example, the counter-jet has so much Faraday rotation that it is mostly depolarized, while the forward-jet hardly exhibits any RM at all!

Large R_{high} SANEs Have "Cold" Mid-planes



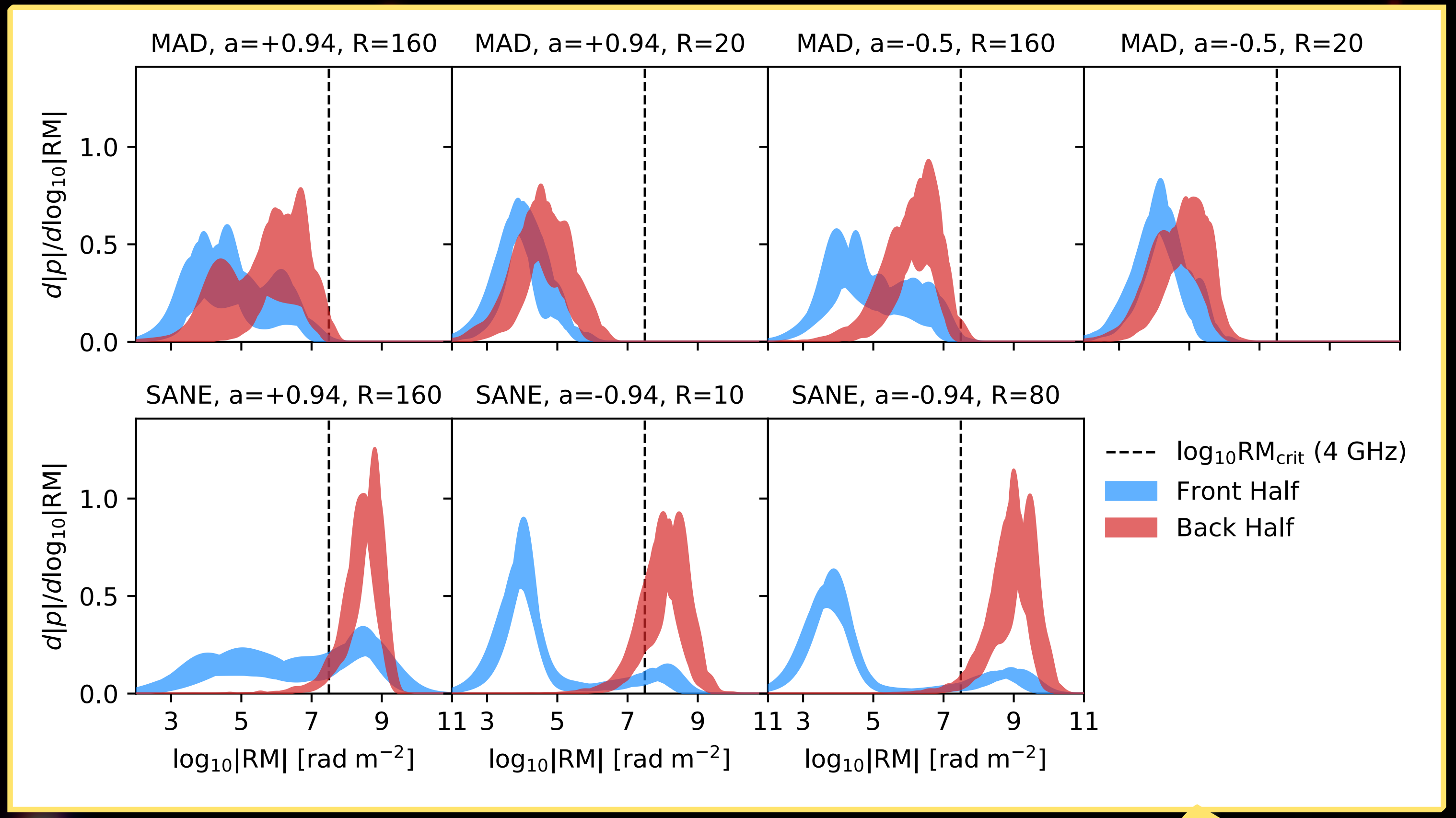




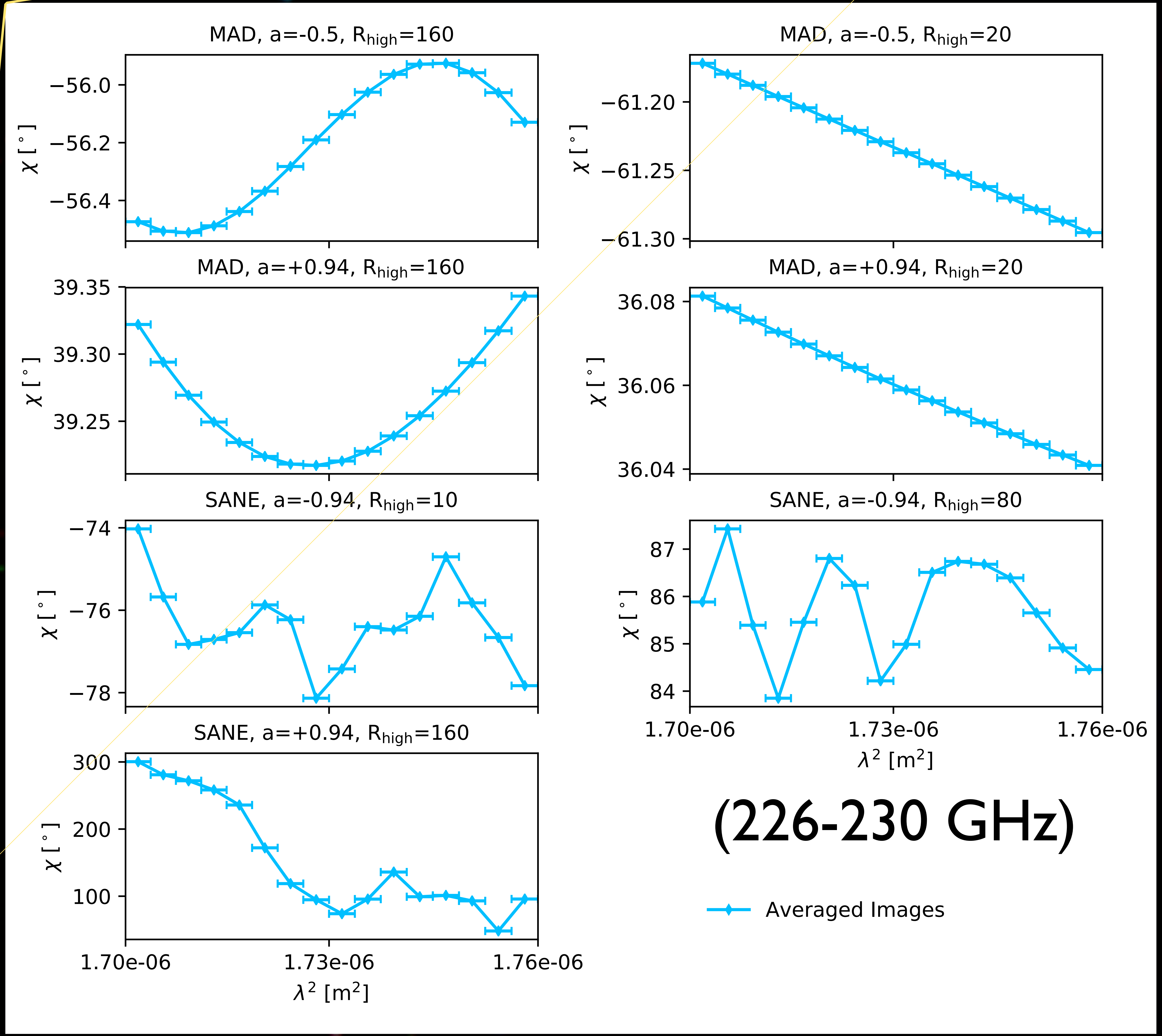
See also Moscibrodzka, Dexter, Davelaar, and Falcke (2017)

Bandwidth depolarization suppresses the counter-jet.

Some models should produce complex EVPA(λ^2)



implies

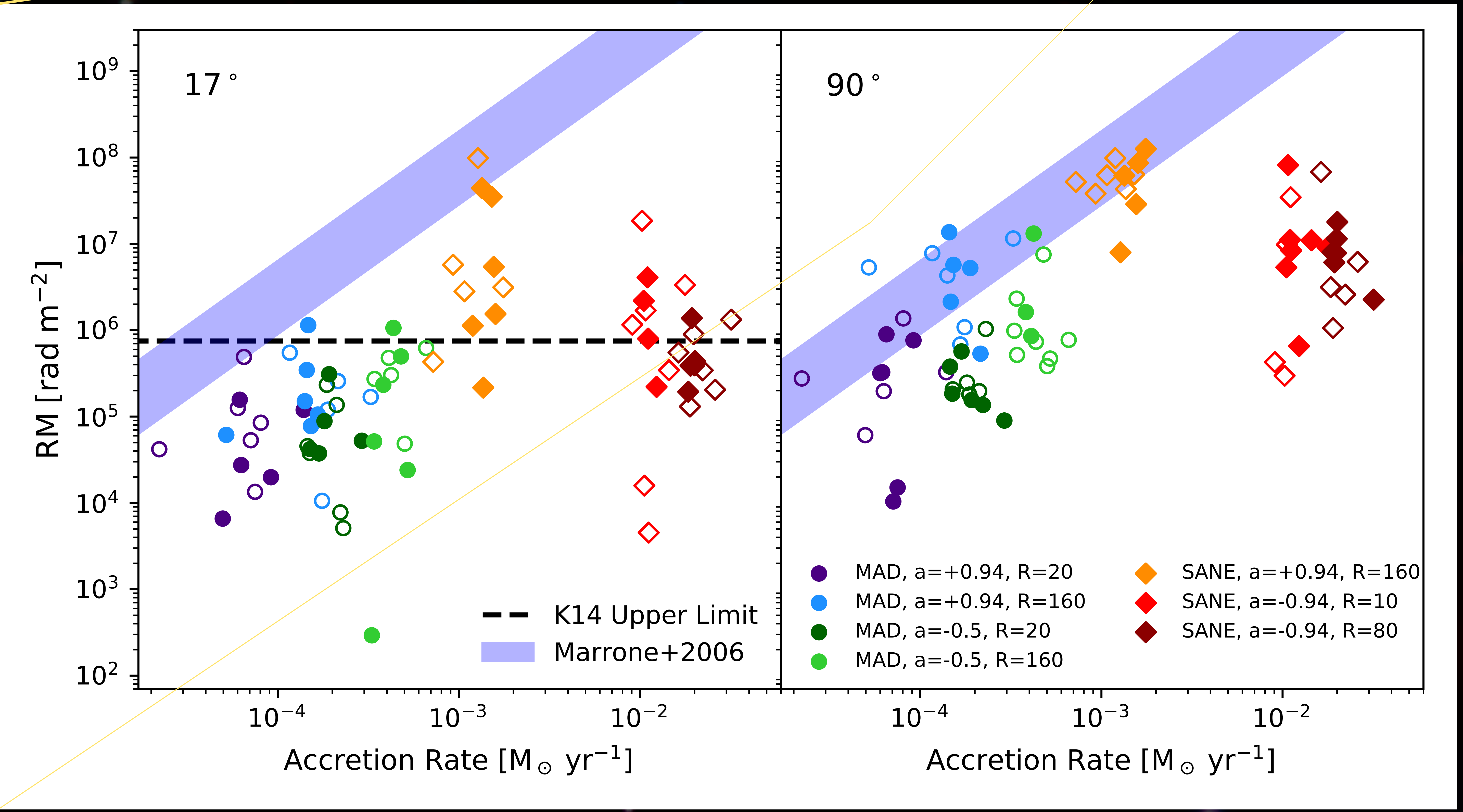


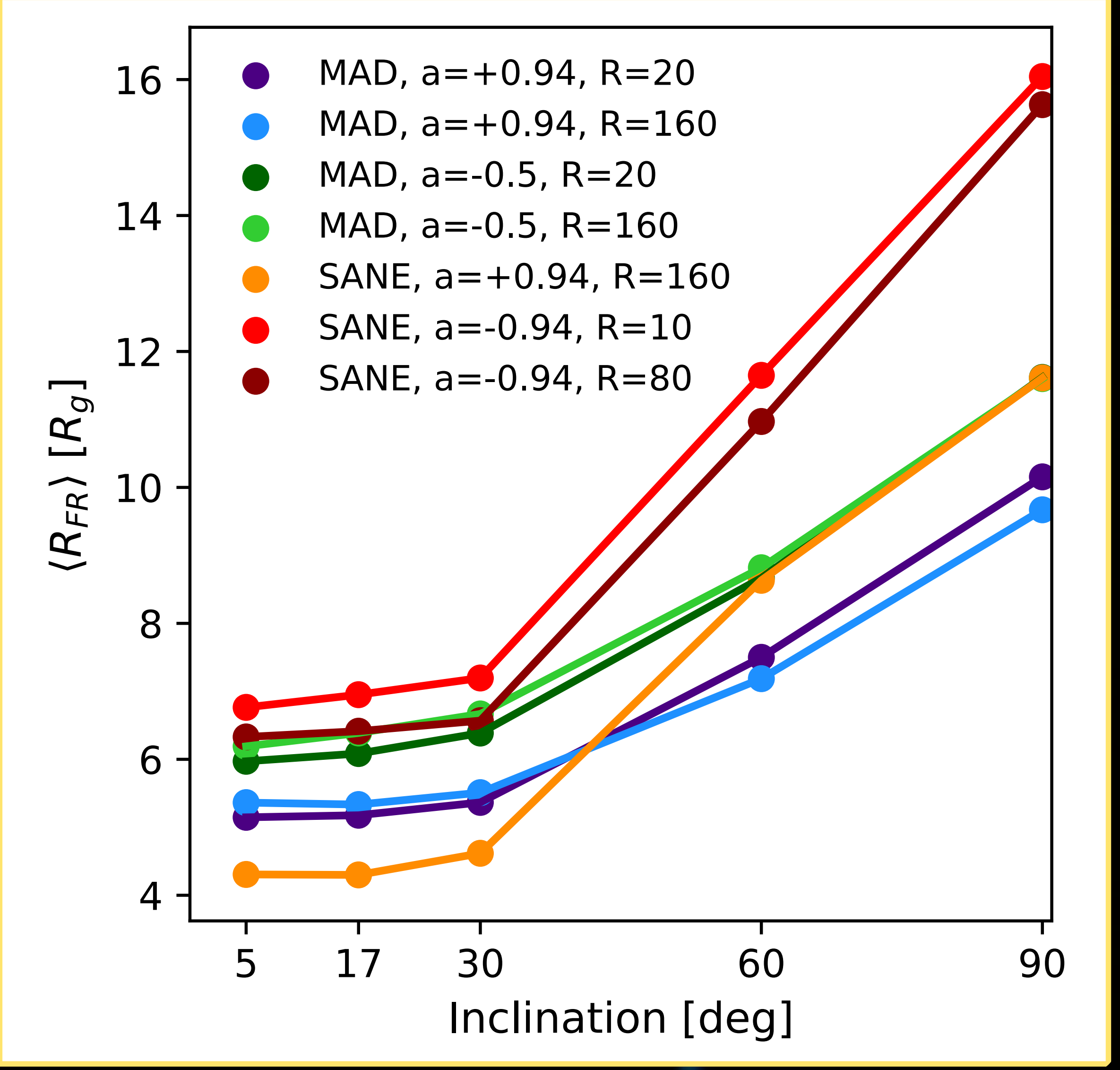
Some models are linear, others are not.

If we can measure this, the degree of non-linearity in $\chi(\lambda^2)$ can constrain models.

RM Does Not Trace Accretion Rate Very Well…

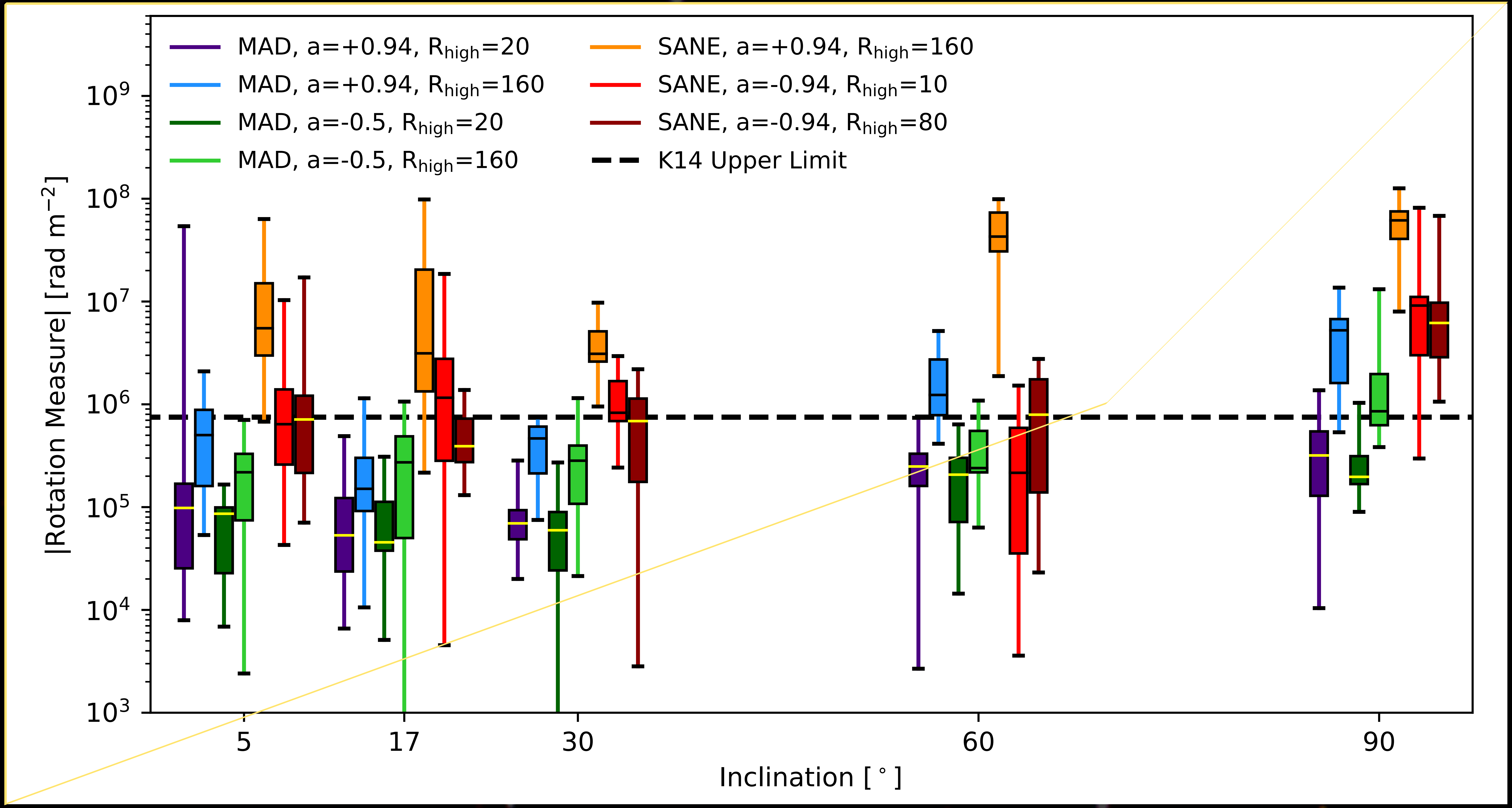
- By assuming a simple ADAF model, RM has been used to set limits on BH accretion rates (Marrone+2006, Kuo+2014). Instead, we expect overwhelming scatter.
- In addition, these models often assume Faraday rotation occurs far from the horizon, but this is **not** the case.





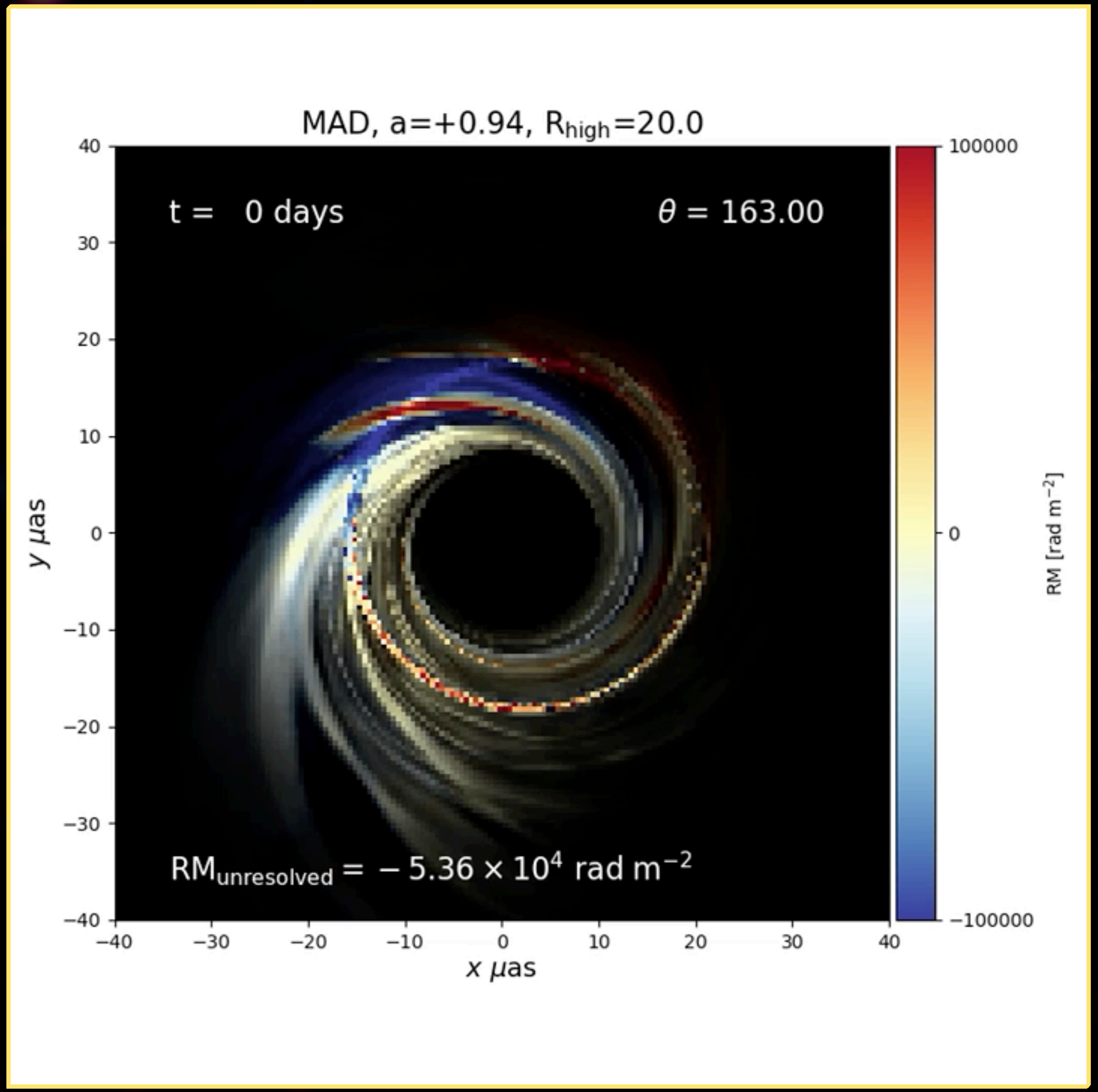
Each point of the same color is a different snapshot.
Filled circles symbols are positive RM, while open circles are negative RM.

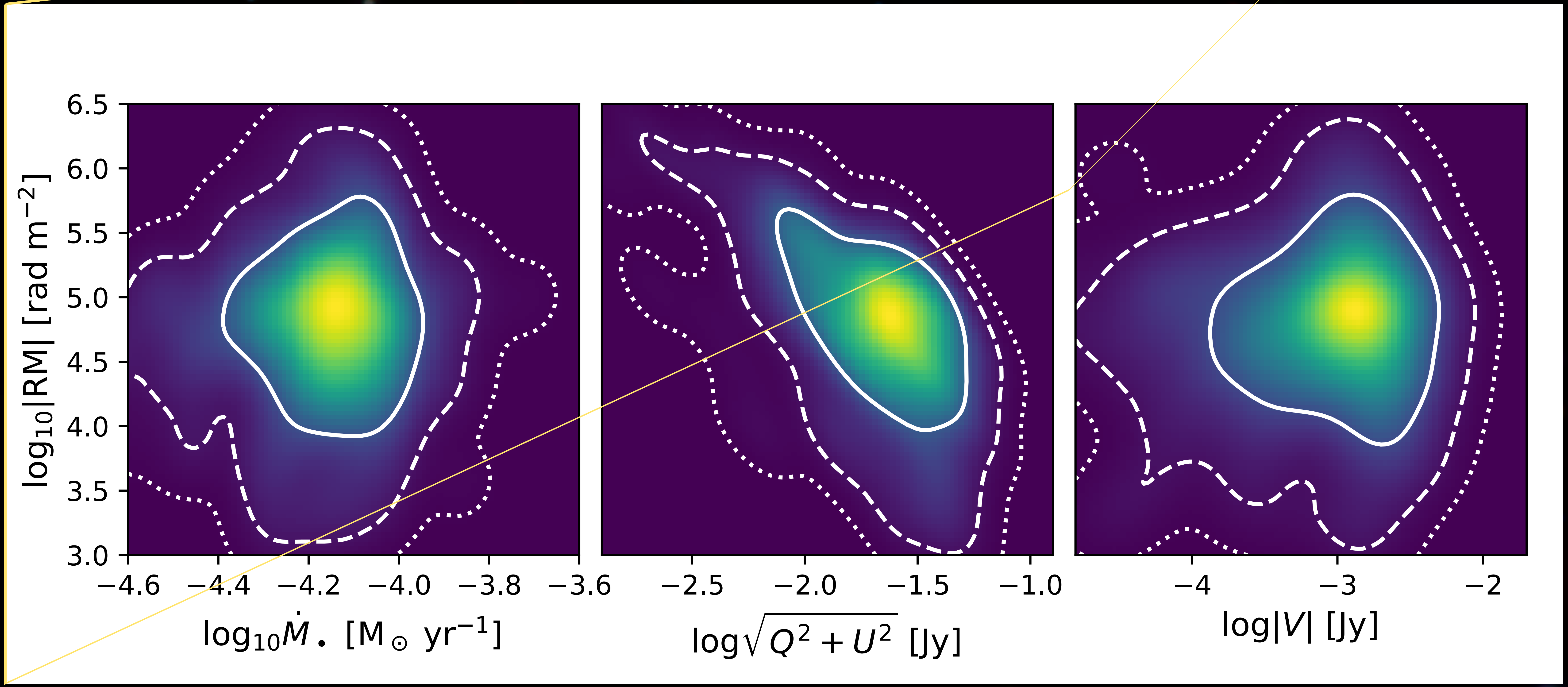
More RM at High Inclination, but Scatter is Large



However, we only integrate within a radius of 20 M. There may be more Faraday rotation outside this volume, especially for more edge-on inclinations.

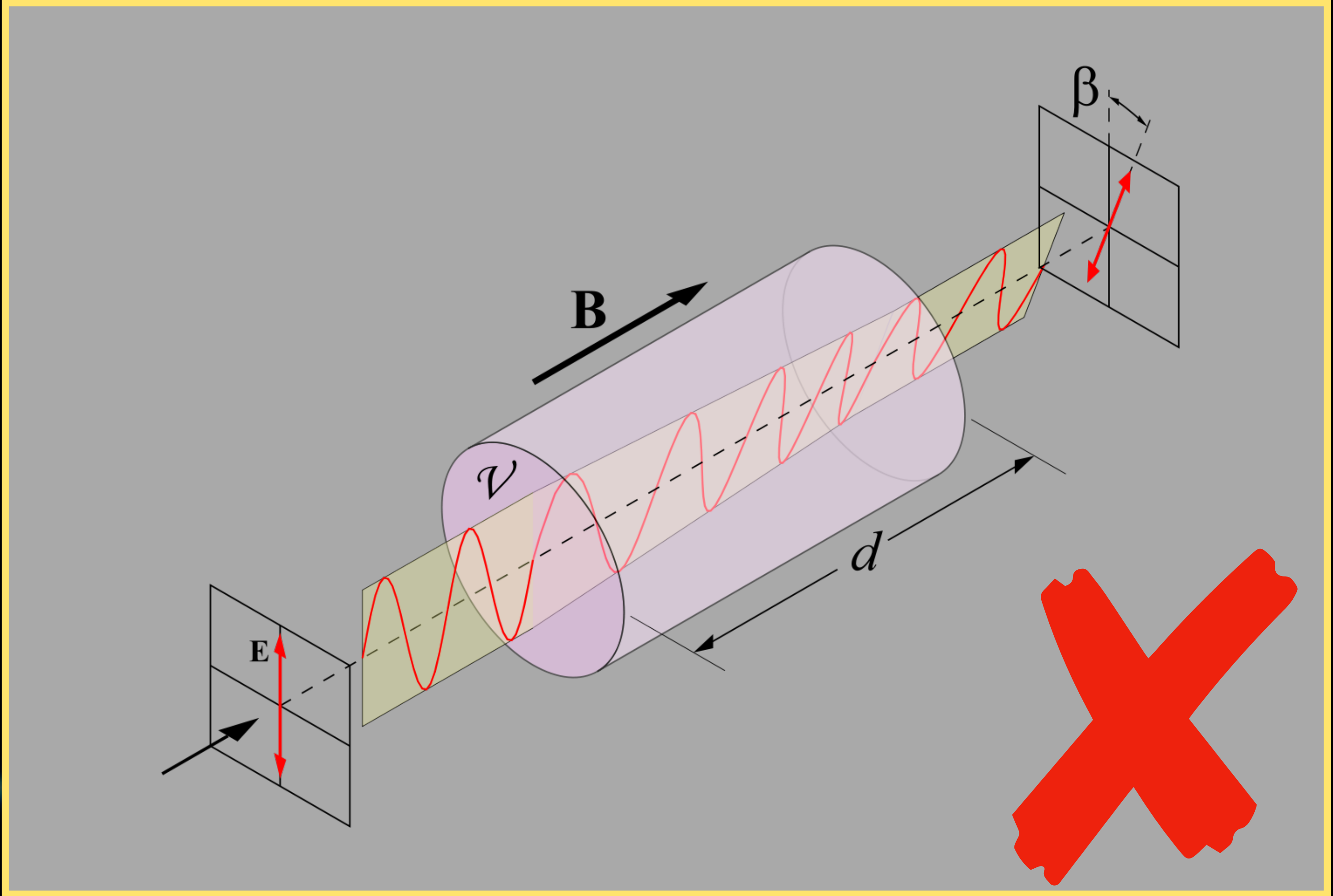
More on Time Variability

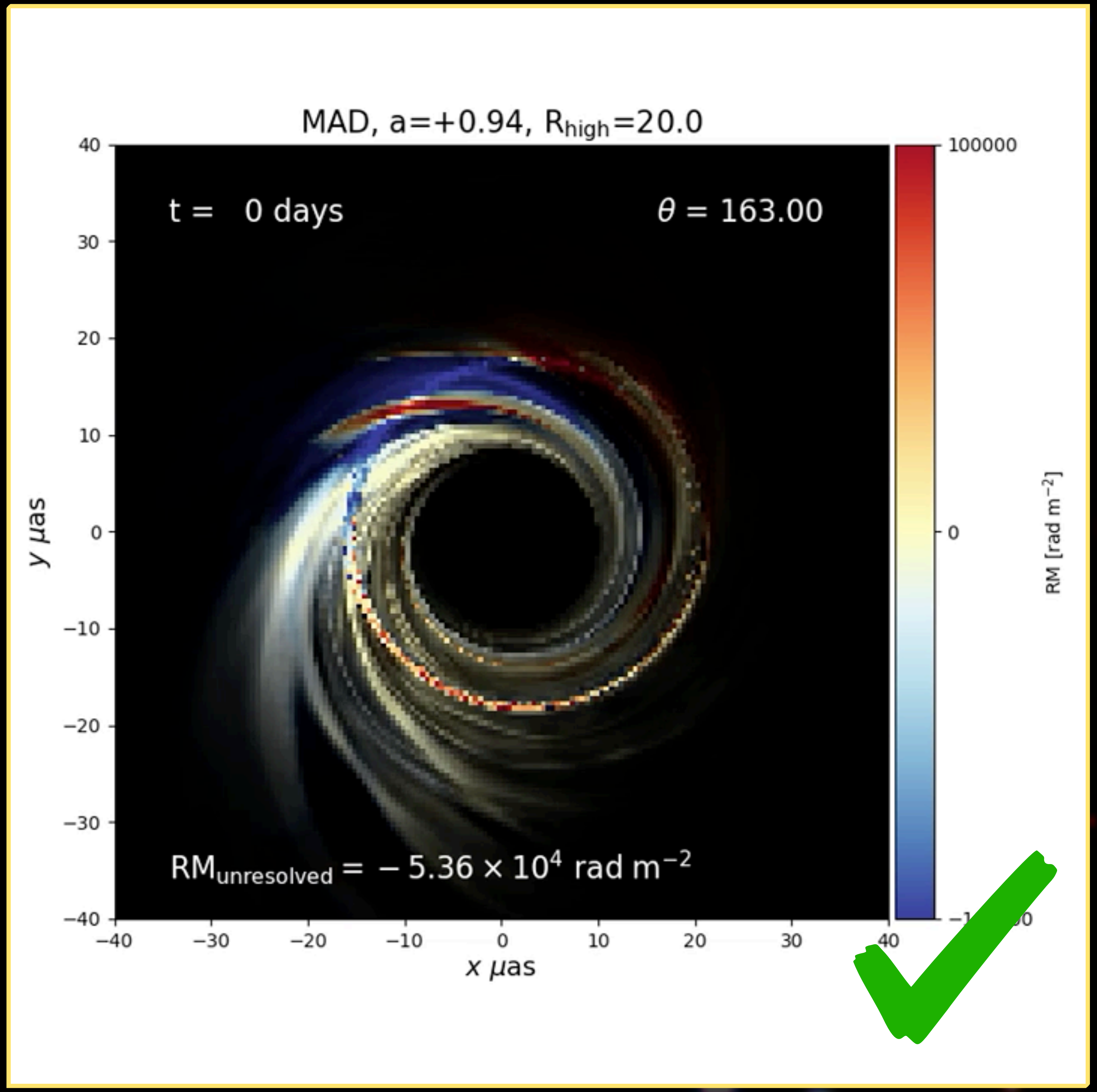




- The RM of M87* can vary significantly across one week.
- Puzzlingly, Sgr A* has actually exhibited a relatively stable RM for decades (Bower+2018). Maybe that means the dominant source of Faraday rotation is outside the simulation domain.
- RM and the linear polarization are anti-correlated. More scrambling implies less polarization.

Conclusions





- Faraday rotation is co-spatial with the emission and highly non-uniform. There can be interesting signatures in…
  - **Time**: we expect significant variability and even sign flips. Repeated observations can verify this.
  - **Frequency**: Some models should produce wiggles in the EVPA as a function of frequency even for small bandwidths. Is this observable?
  - **Space**: RM should be non-uniform in a resolved image.