Disk-jet symbiosis in M87: Polarization of light and Faraday rotation in GRMHD simulations

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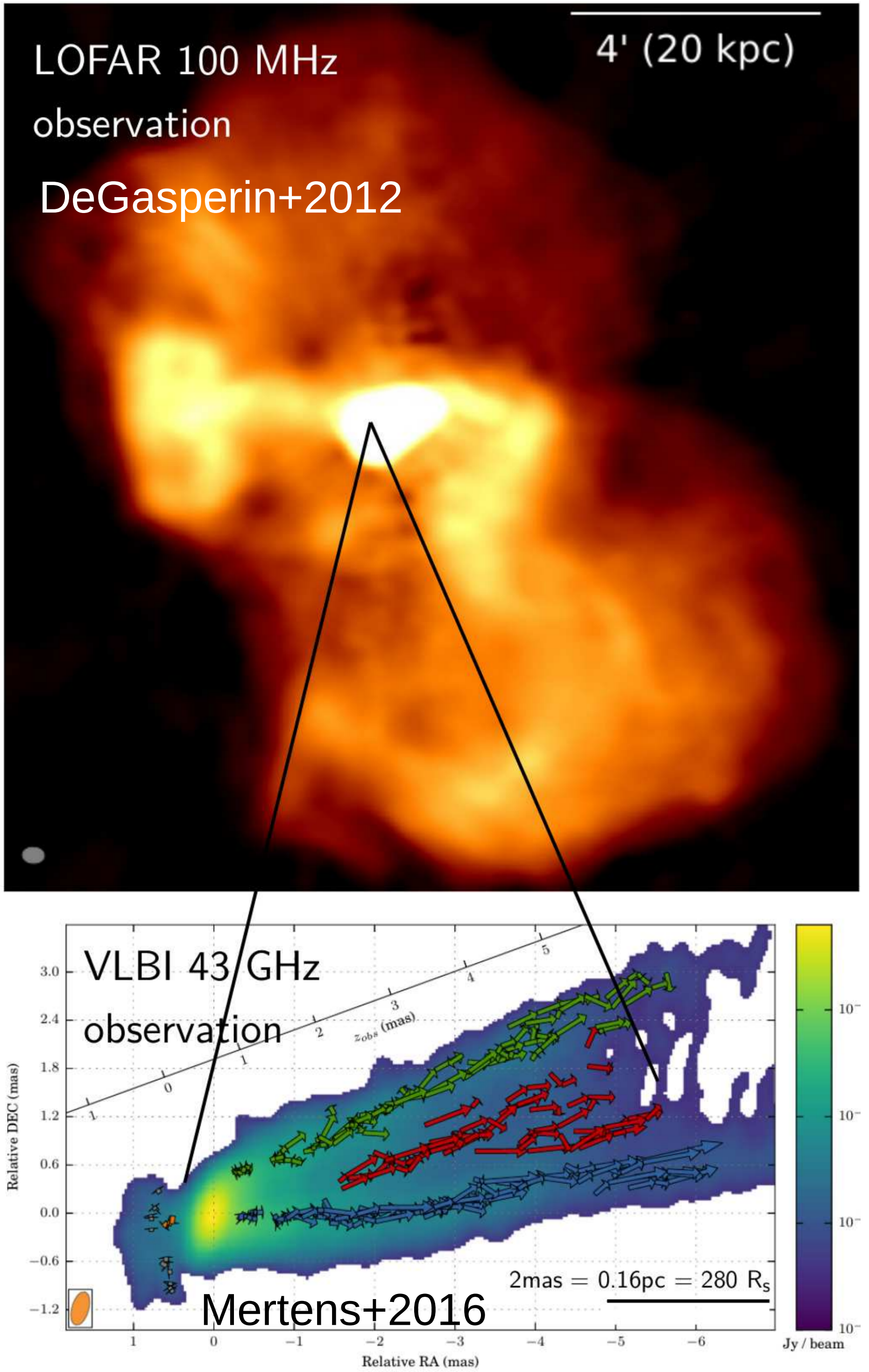
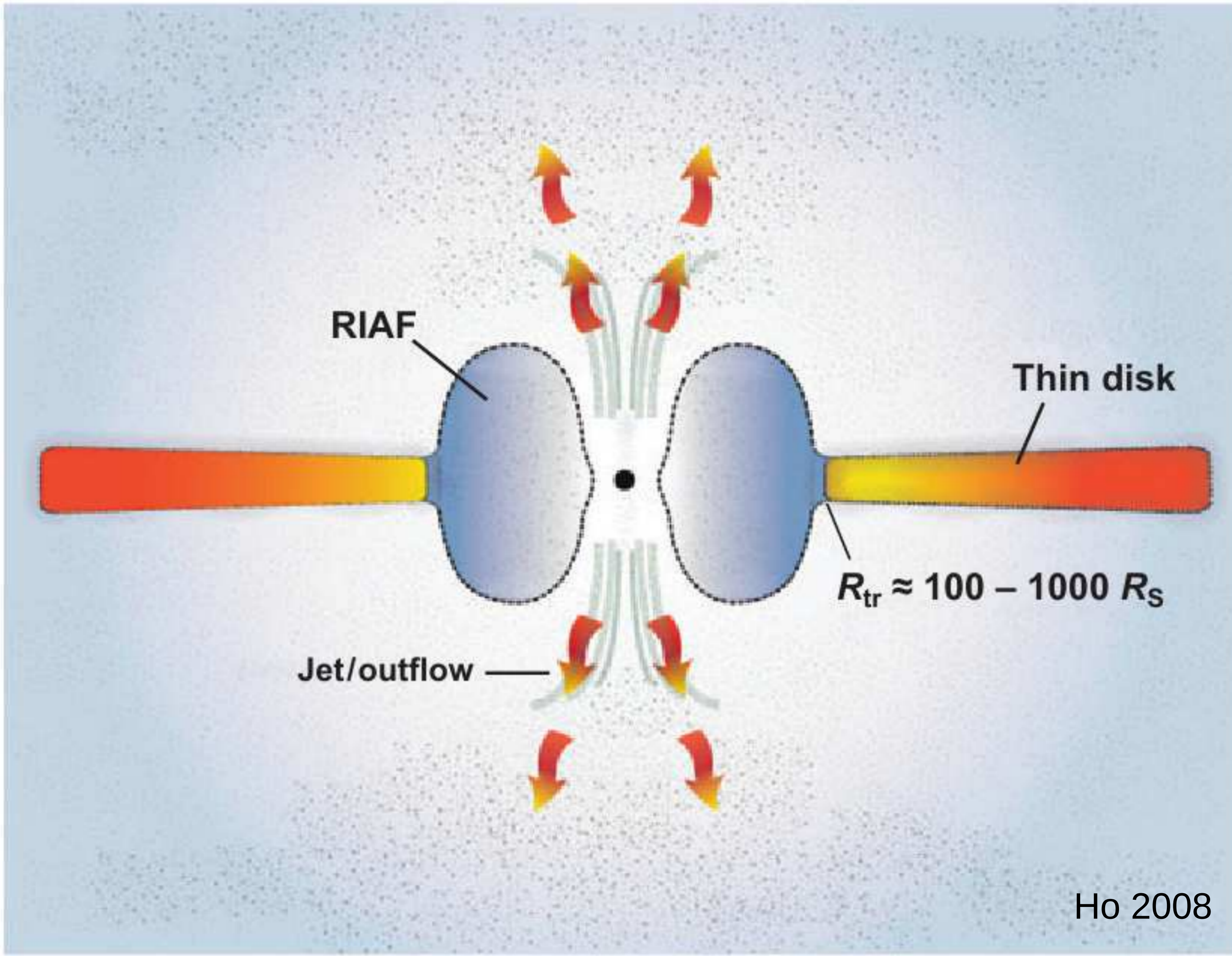
KITP - 10 February 2017

Core of M87

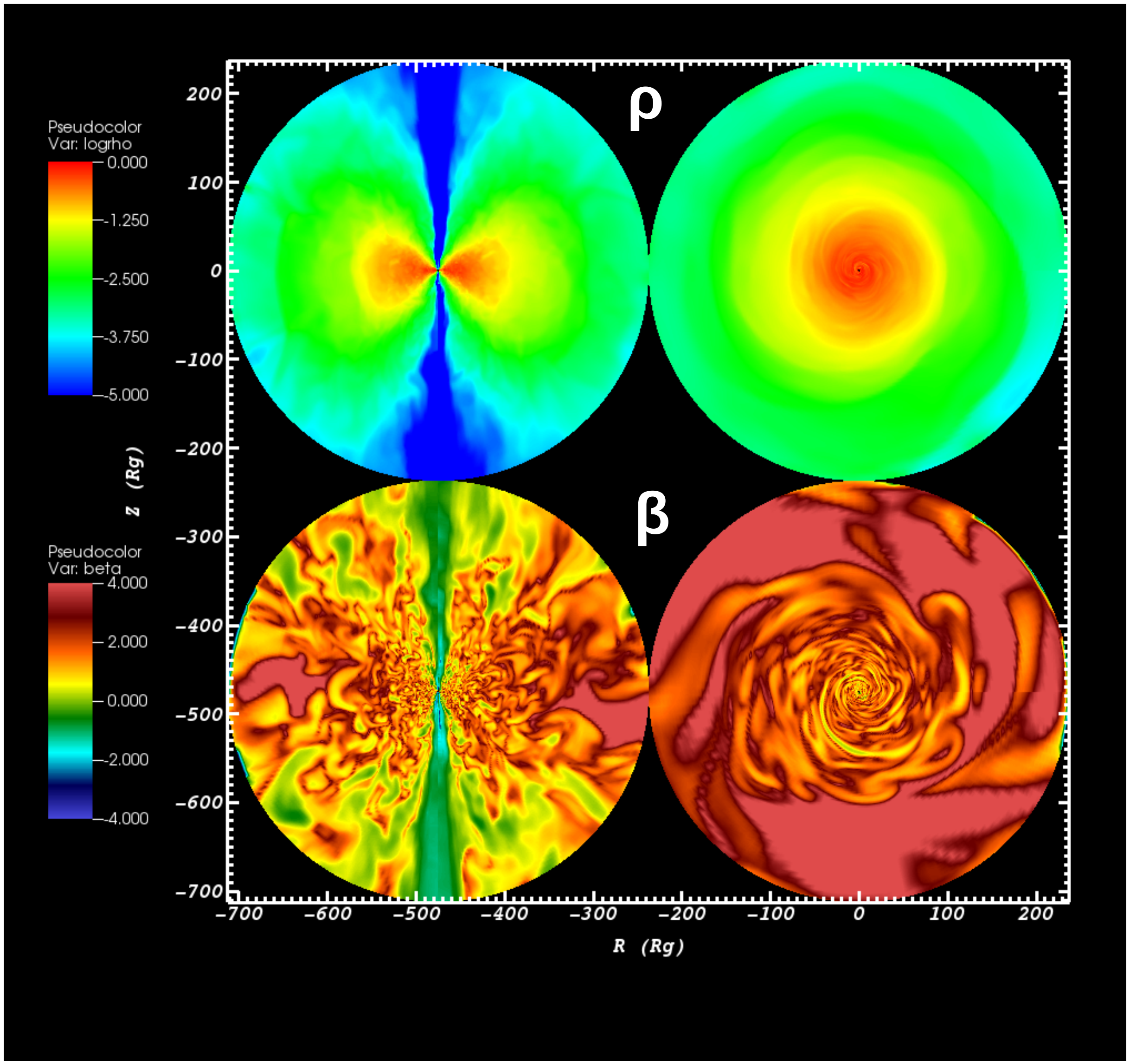
- M87: Virgo A, 16.7 Mpc, MBH=6×10^{9}Msun
- M87 core - prototype radio loud LLAGN ($L\sim10^{-6}\,L_{edd}$), FR-I jet (10^{45} ergs/s), i=20deg
- Source at freq $>$ 43 GHz not well resolved yet, model predictions
- Near future mm-VLBI observations w/ Event Horizon Telescope resolve 30 microarcsec $<$ BH_{shadow} = 38 microarcsec
- Unique source test MHD theory of accretion and jets symbiosis on the event horizon scales



Radiatively inefficient accretion flow in the center of LLAGN



General relativistic MHD simulations of RIAF



- Ideal-MHD in 3D
- Standard and normal evolution
- Disk: MRI turbulence
- Magnetized outflows, jets
- Collisionless, two-temperature plasma

$$\frac{T_{\rm p}}{T_{\rm e}} = R_{\rm high}\frac{\beta^2}{(1+\beta^2)} + R_{\rm low}\frac{1}{(1+\beta^2)}$$

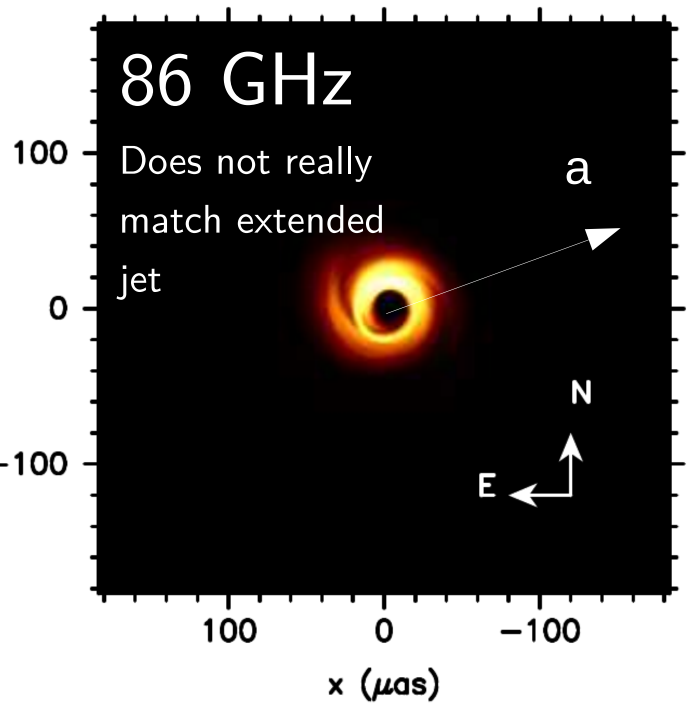
Modeling emission from GRMHD models of RIAF

- We model millimeter emission (EHT: 230 GHz and GMVA: 86 GHz)
  - synchrotron emission dominant cooling process (relativistically hot, magnetized plasma)
  - near horizon emission – Doppler boosts, gravitational lensing

- The goal is to constrain the model free parameters
  - Proton/electron coupling ratios
  - Mass accretion rate onto the BH
  - Spin of the BH
  - Geometry of magnetic fields near BH event horizon

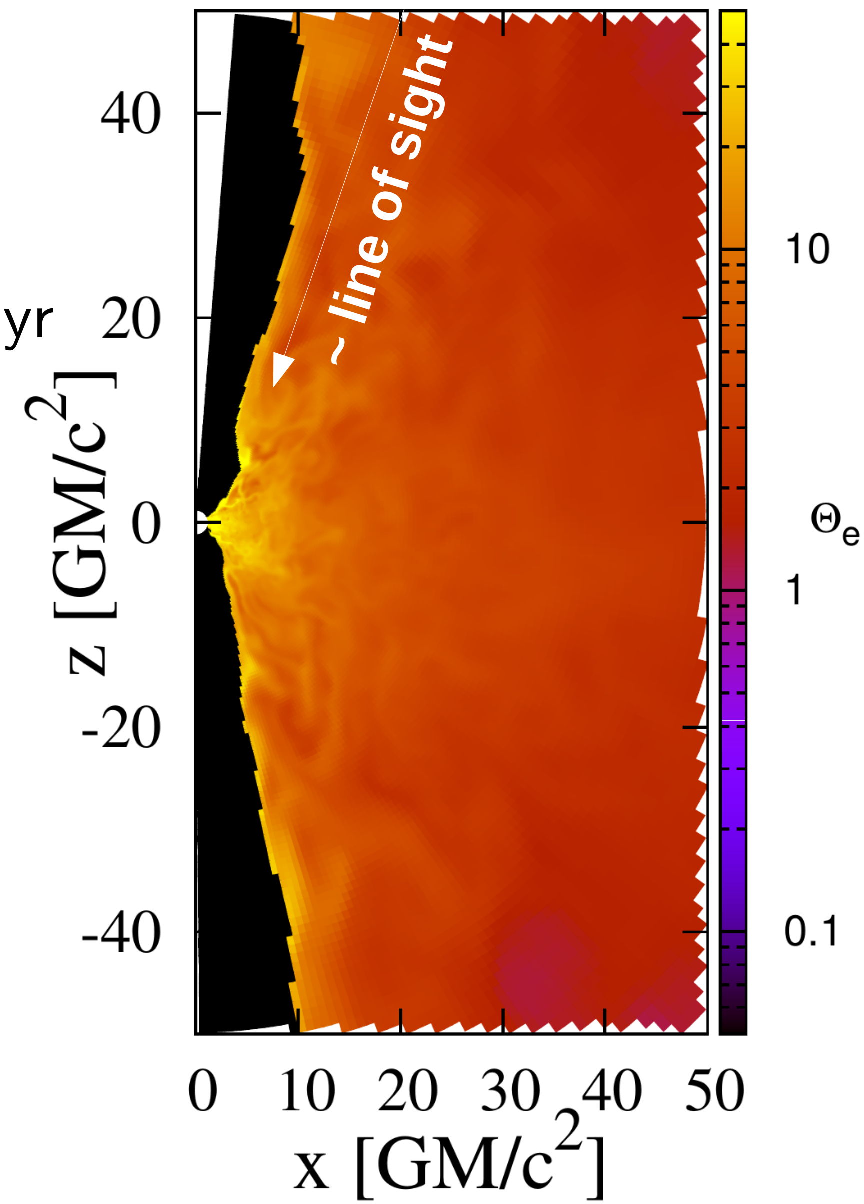
1) GRMHD model + radiative transfer model = radio image

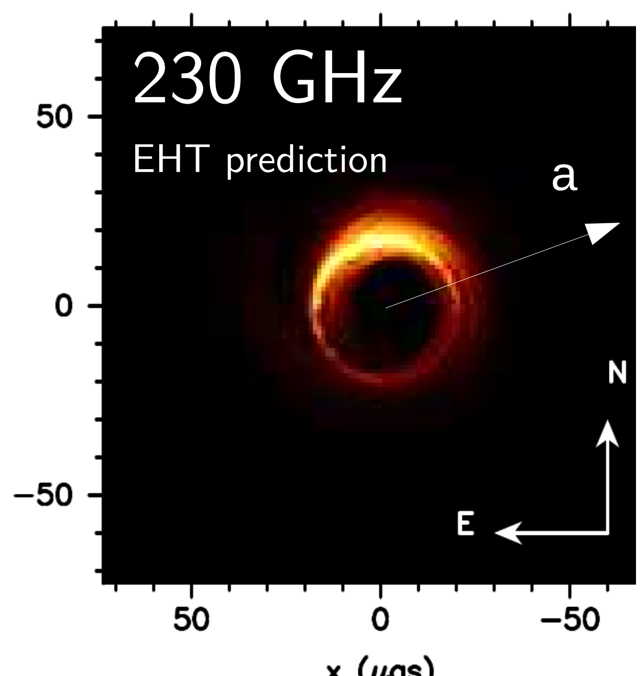
$$\frac{T_{\rm p}}{T_{\rm e}} = R_{\rm high}\frac{\beta^2}{(1+\beta^2)} + R_{\rm low}\frac{1}{(1+\beta^2)}$$



$R_{high}=\mathbf{1}$ $R_{low}=1$

$M_{acc}= \mathbf{10^{-4}}$ M_{sun}/yr



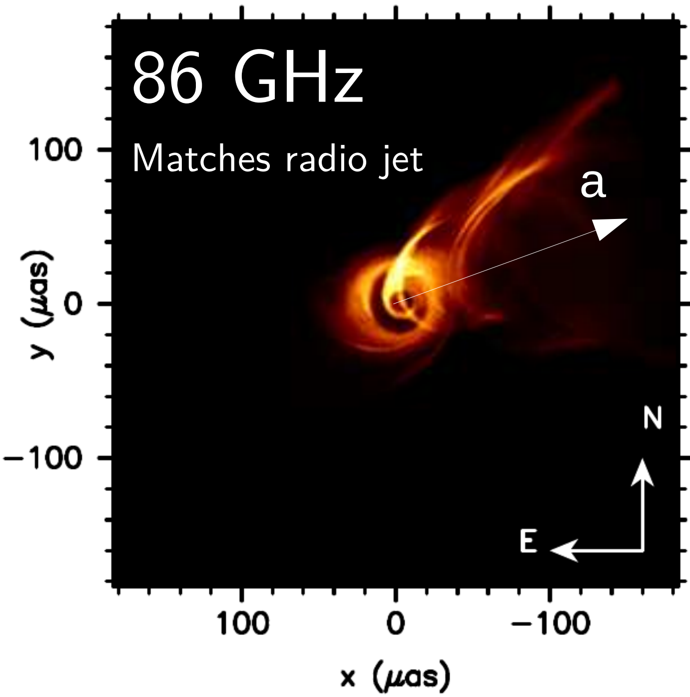


Disk emission dominated images

Moscibrodzka et al. 2016

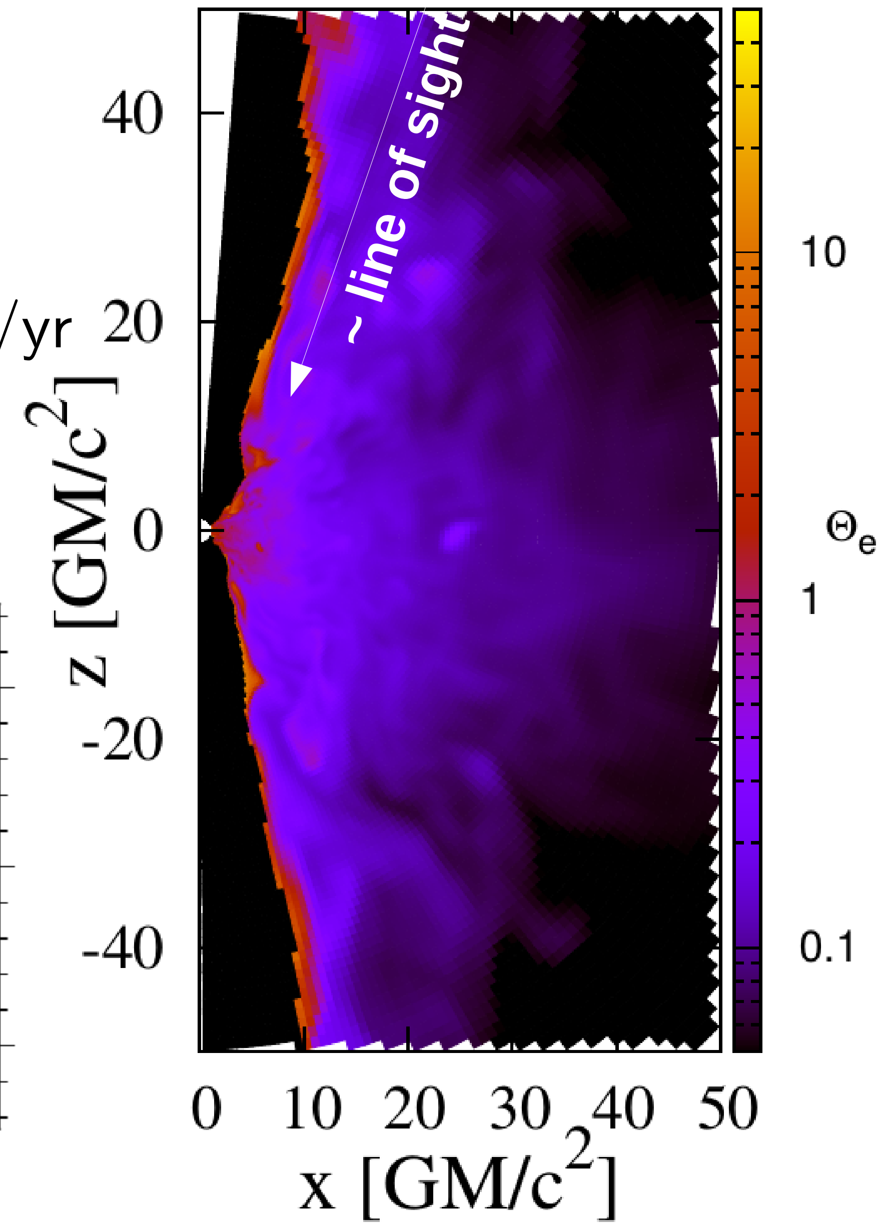
2) GRMHD model + radiative transfer model = radio image

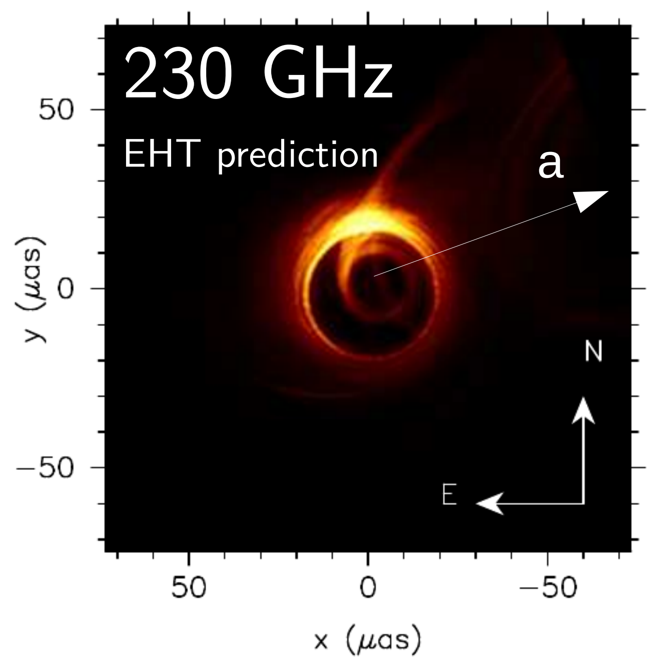
$$\frac{T_{\rm p}}{T_{\rm e}} = R_{\rm high}\frac{\beta^2}{(1+\beta^2)} + R_{\rm low}\frac{1}{(1+\beta^2)}$$



R_{high}=**100** R_{low}=1

M_{acc}= **9x10^-3** M_{sun}/yr





Jet(wall) emission dominated images

Moscibrodzka et al. 2016

Polarized Transport through turbulent plasma around Kerr BH

(**grtrans,** Dexter 2016)

Synchrotron emissivities

Synchrotron Absorptivity, rather optically thin plasma

$$\frac{d}{ds}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & \rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & -\rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

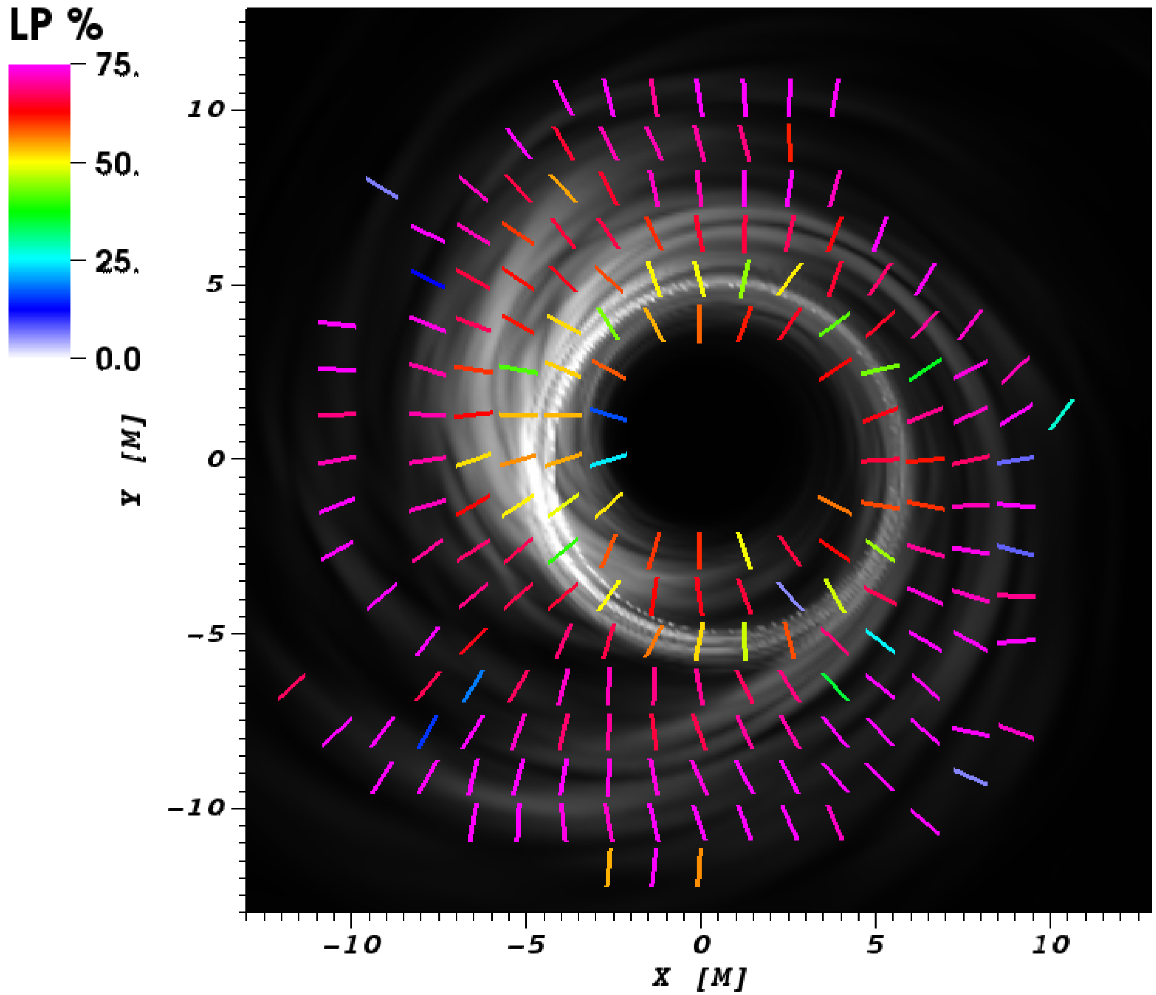
Faraday conversion- Conversion of linear to circular polarization

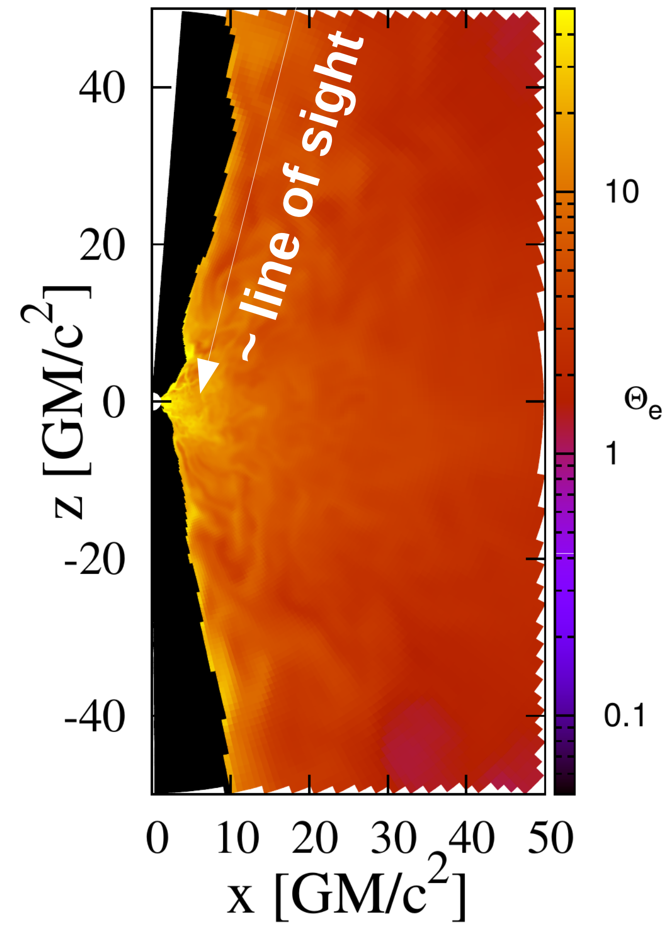
Faraday rotation – rotates plane of linear polarization (polarization ticks)

Faraday optical thickness >> 1 ~ 10^6 (equations can be stiff)

1) Polarization structure of **disk emission** dominated models

Moscibrodzka et al. 2017





- EVPA organized, strong linear polarization
- in non-VLBI beam depolarized down to LP ∼ 5% (inconsistent with existing obs., Kuo+2014)

2) Polarization structure of **jet emission** dominated models

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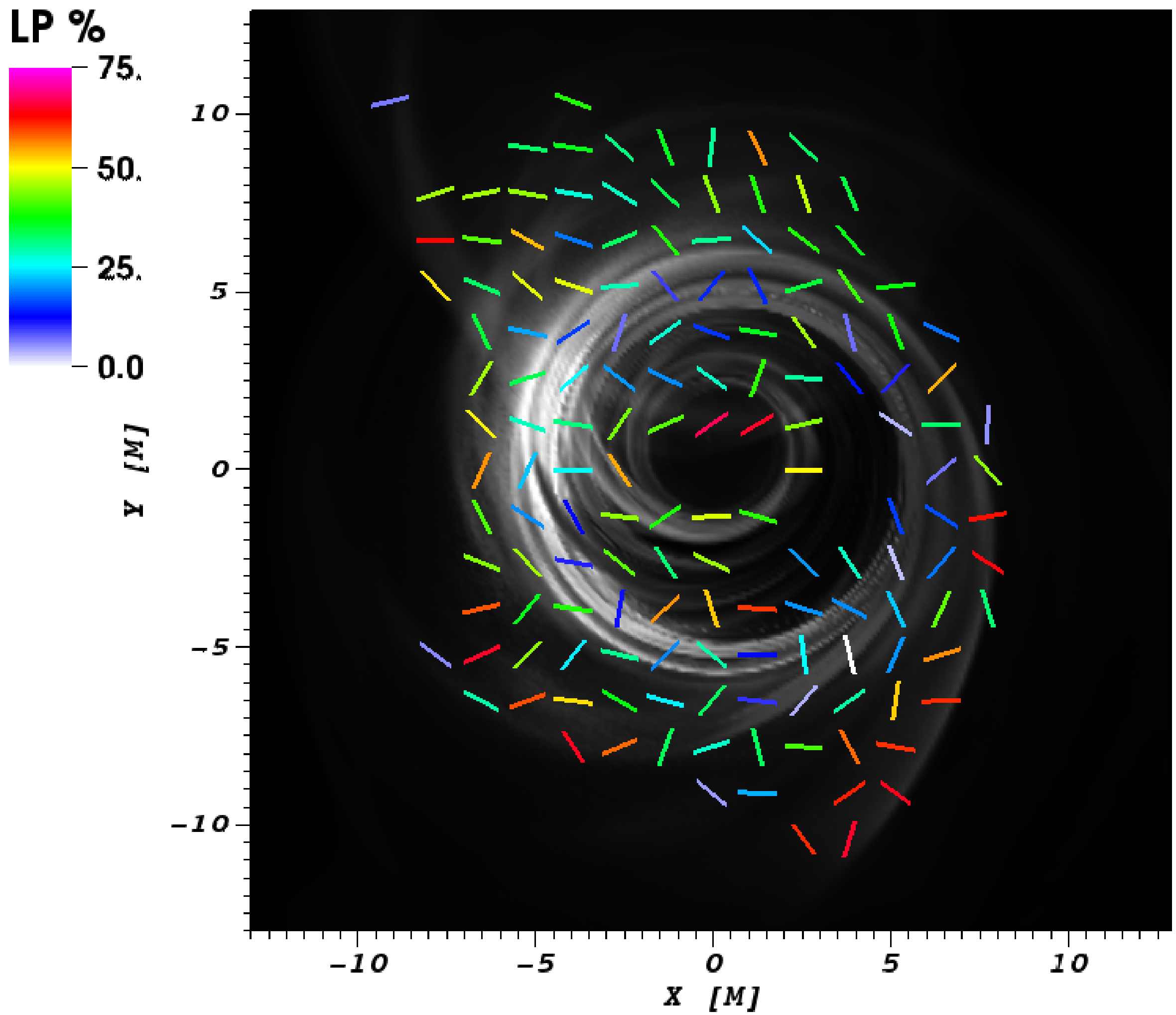

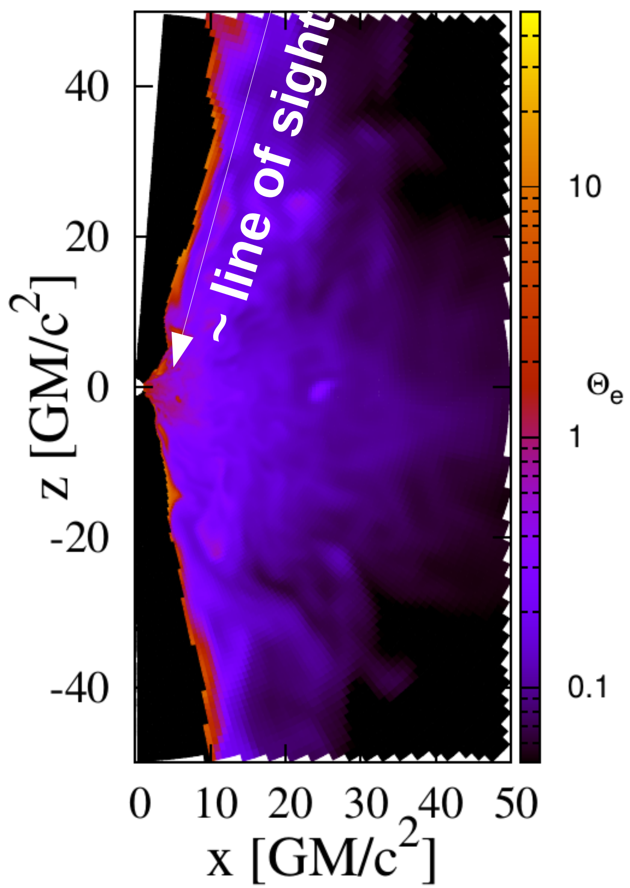

- overall lower LP but some strongly polarized patches offset from intensity peak
- in non-VLBI beam depolarized down to LP $\sim 1\%$ (consistent with obs.)
- No coherent polarization pattern

Polarization structure of **jet emission** dominated models

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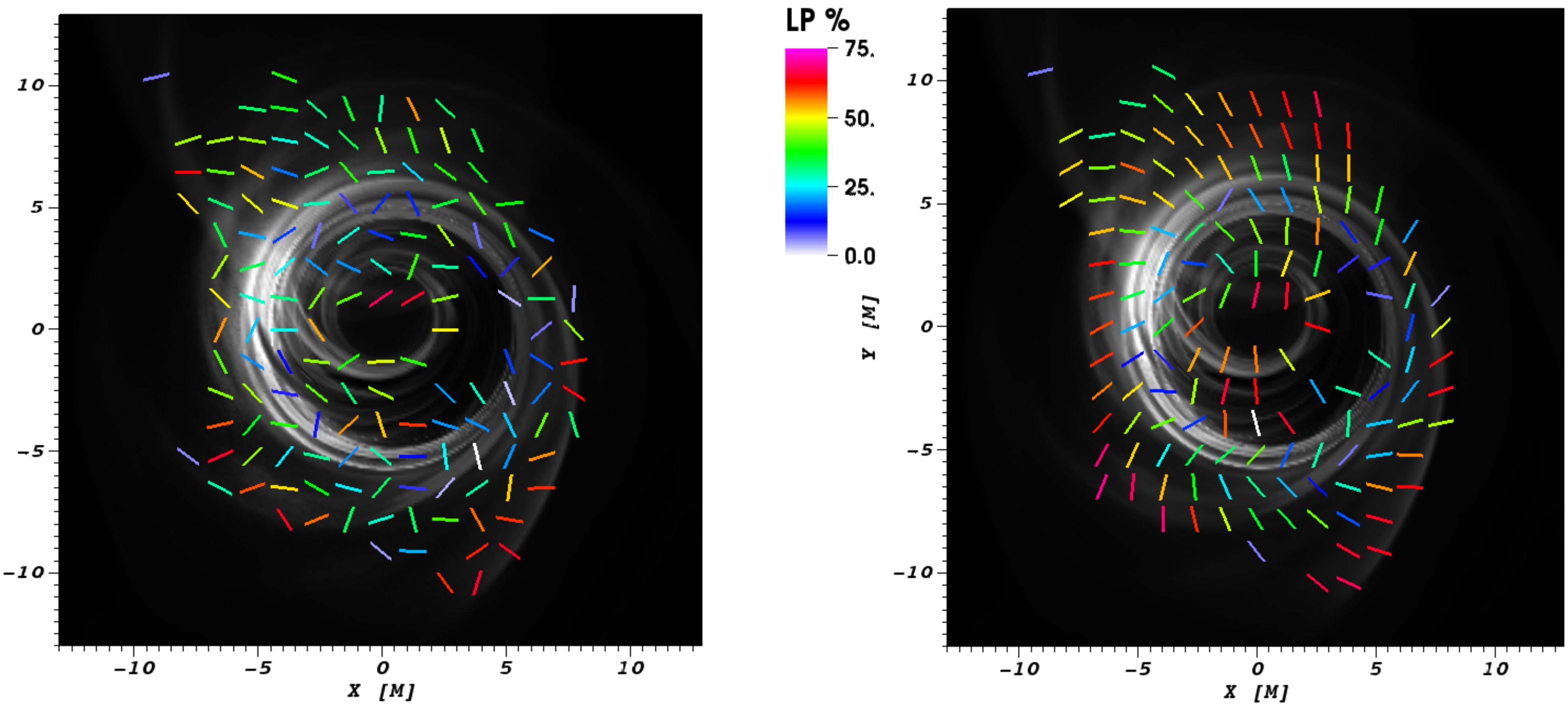

Full set of equations

Without Faraday effects

Faraday rotation measure in Sgr A* and M87

- Faraday rotation measure

$$RM = \frac{\chi(\lambda_1) - \chi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

Faraday rotation measure in Sgr A* and M87

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- RM in our black hole systems @ λ=1.3mm (230 GHz) with non-VLBI

Sgr A*: LP ~ 5 %, RM = - 5.6($\pm$0.7)x10^5 rad/m^2

(Marrone+2007 & ref. therein)

M87: LP ~ 1%, |RM| < 7.5x10^5 rad/m^2 (Kuo+2014)

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- Constraints on accretion rates using semi-analytical RIAF models:

$$RM = 10^4 \frac{e^3}{2\pi m_\mathrm{e}^2 c^4} \int f_\mathrm{rel} n_e B_{||} dl$$

  Sgr A*: M_{acc} = 5x10^{-9} – 2x10^{-7} M_{sun}/yr

  M87: M_{acc} < 9x10^{-4} M_{sun}/yr

Faraday rotation measure in Sgr A* and M87

Should we limit GRMHD free parameters with these accretion rate constraints?

- Semi-analytical RIAFs have: no B field geometry; no jets; no GR effects
- Assumption that polarized source is behind Faraday screen, $\chi(\lambda) \sim \lambda^2$ (shown in Sgr A* only, not in M87)
- M87 viewing angle $\sim$ 20deg $\rightarrow$ looking at source through outflowing matter (are we measuring M_{acc}?)

Faraday Rotation measure simulation

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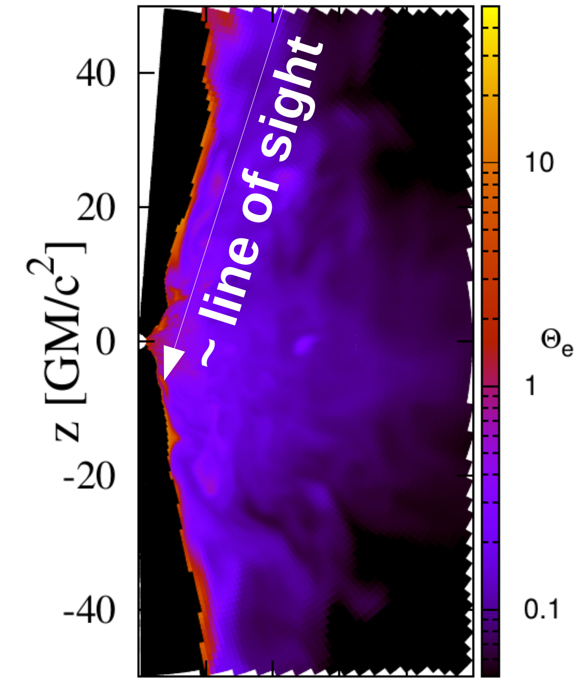
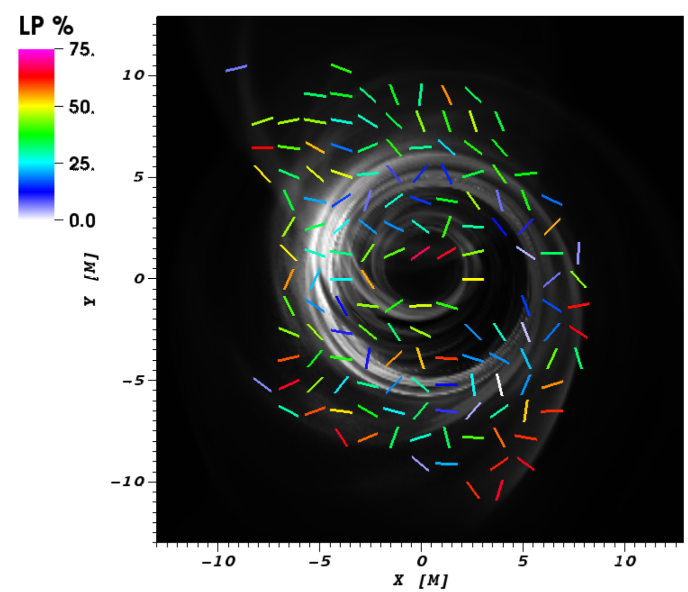
- $$\frac{d}{ds}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & \rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & -\rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$



$$\chi_{\rm tot} \equiv arg(Q_{\rm tot} + iU_{\rm tot})/2$$

$$RM_{observed} = \frac{\chi_{tot}(\lambda_1) - \chi_{tot}(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$



- $$RM = 10^4 \frac{e^3}{2\pi m_{\rm e}^2 c^4} \int f_{\rm rel} n_e B_{||} dl$$

Rotation measure from radiative transfer models (blue points, 230-240 GHz), from integral (red points)

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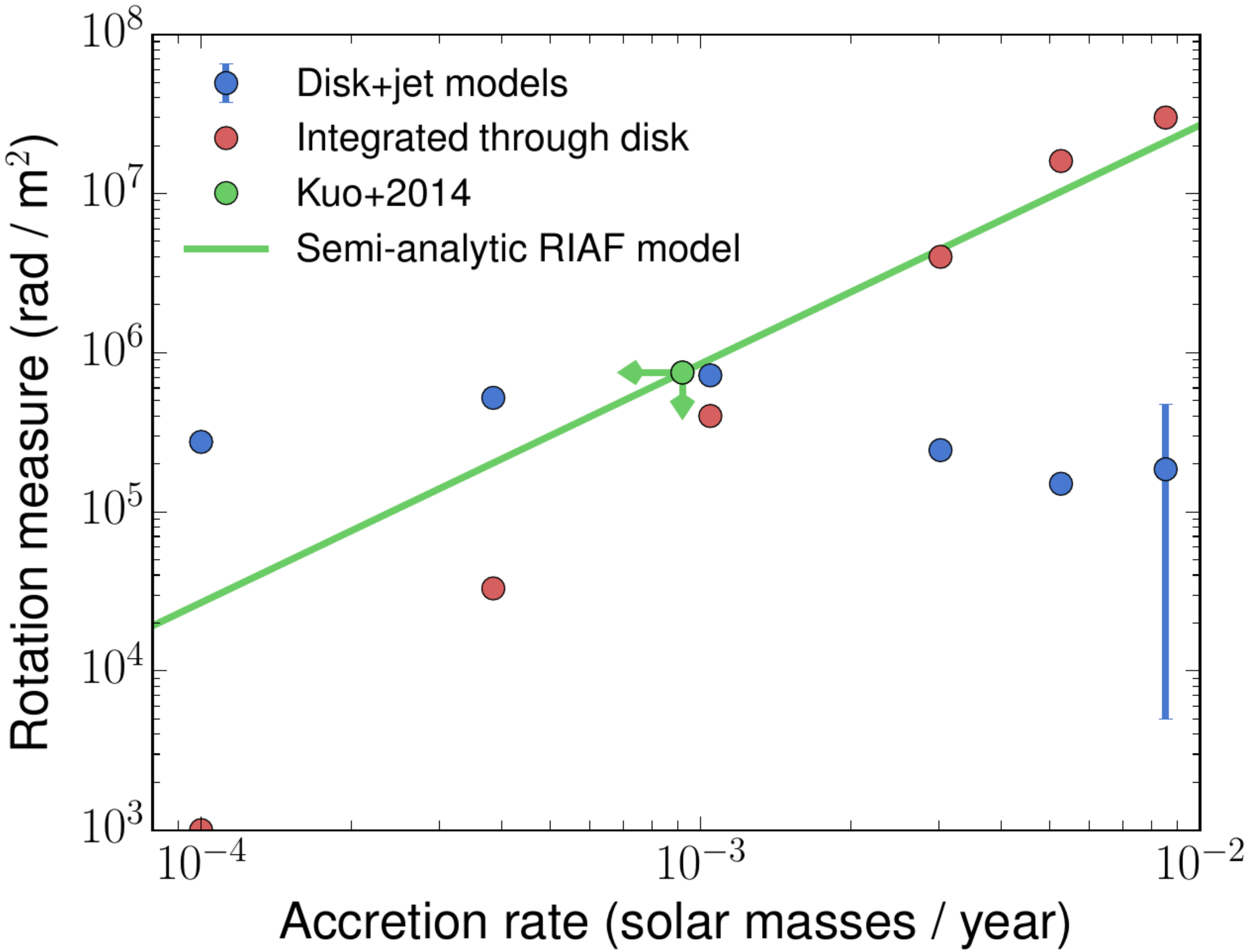

Summary

- We show first GRMHD-based polarized images of M87 jet-disk connection near event horizon
- Disk dominated models: lower accretion rates, organized EVPAs , higher LP
- Jet dominated models (that nicely connect to radio jet): 100xhigher accretion rates, strong EVPA scrambling, low polarization (image integrated 1%, observed 1%)
- Jet dominated models that require $M_{acc} >> 9 \times 10^{-4}$ M_{sun}/yr (limits from RM simple models) are actually consistent with RM when modeled correctly
- We can probably test models with mm-VLBI imaging, however
  - We see jets but no disks – maybe difficult to test accretion theory
  - A lot of polarization scrambling due to Faraday effects, can we constrain the magnetic fields in the disk and jets?