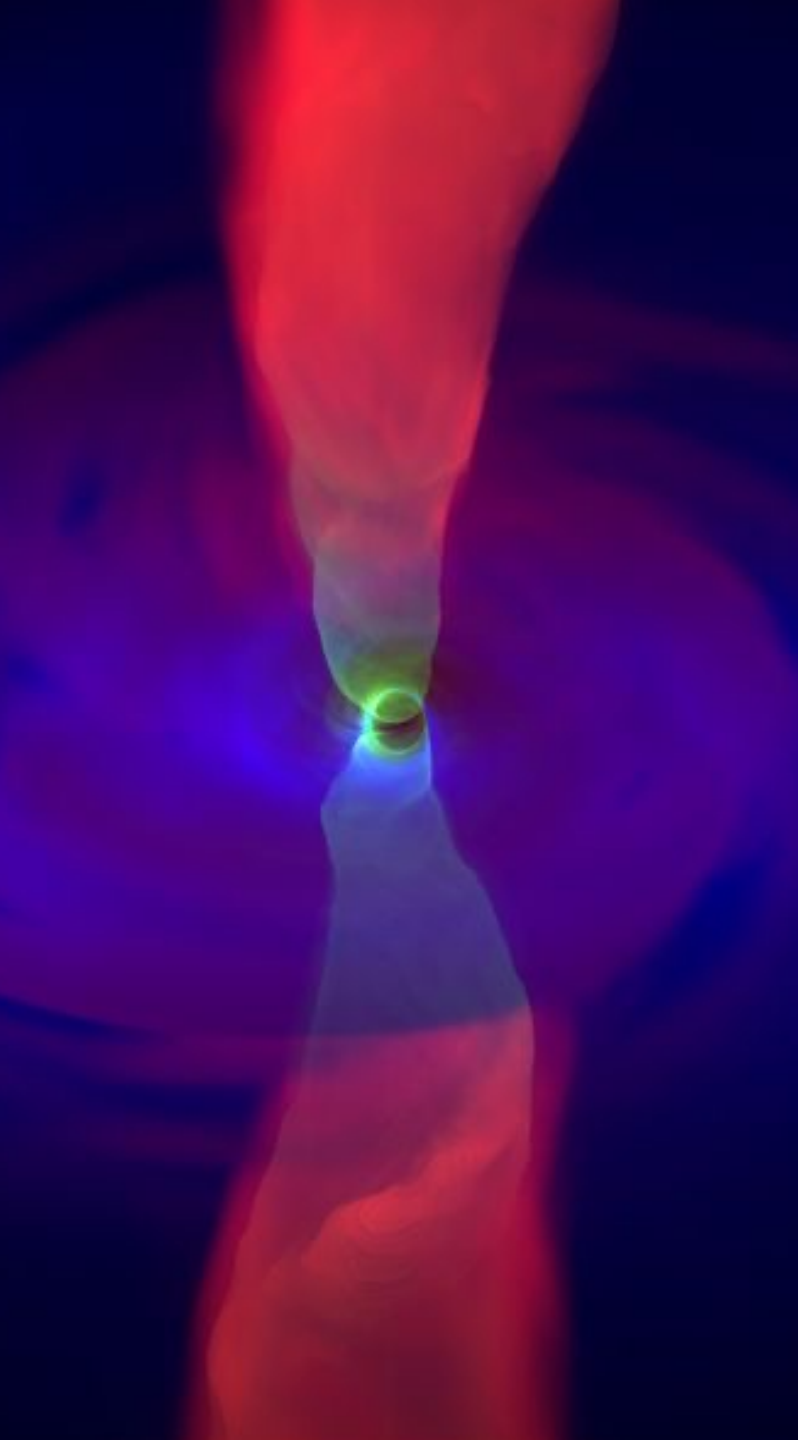


# Physically Motivated Electron Thermodynamics in GRRT Modelling of Sgr A\*

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- EHT Parametric Model
- Formulation
- Results and Discussions

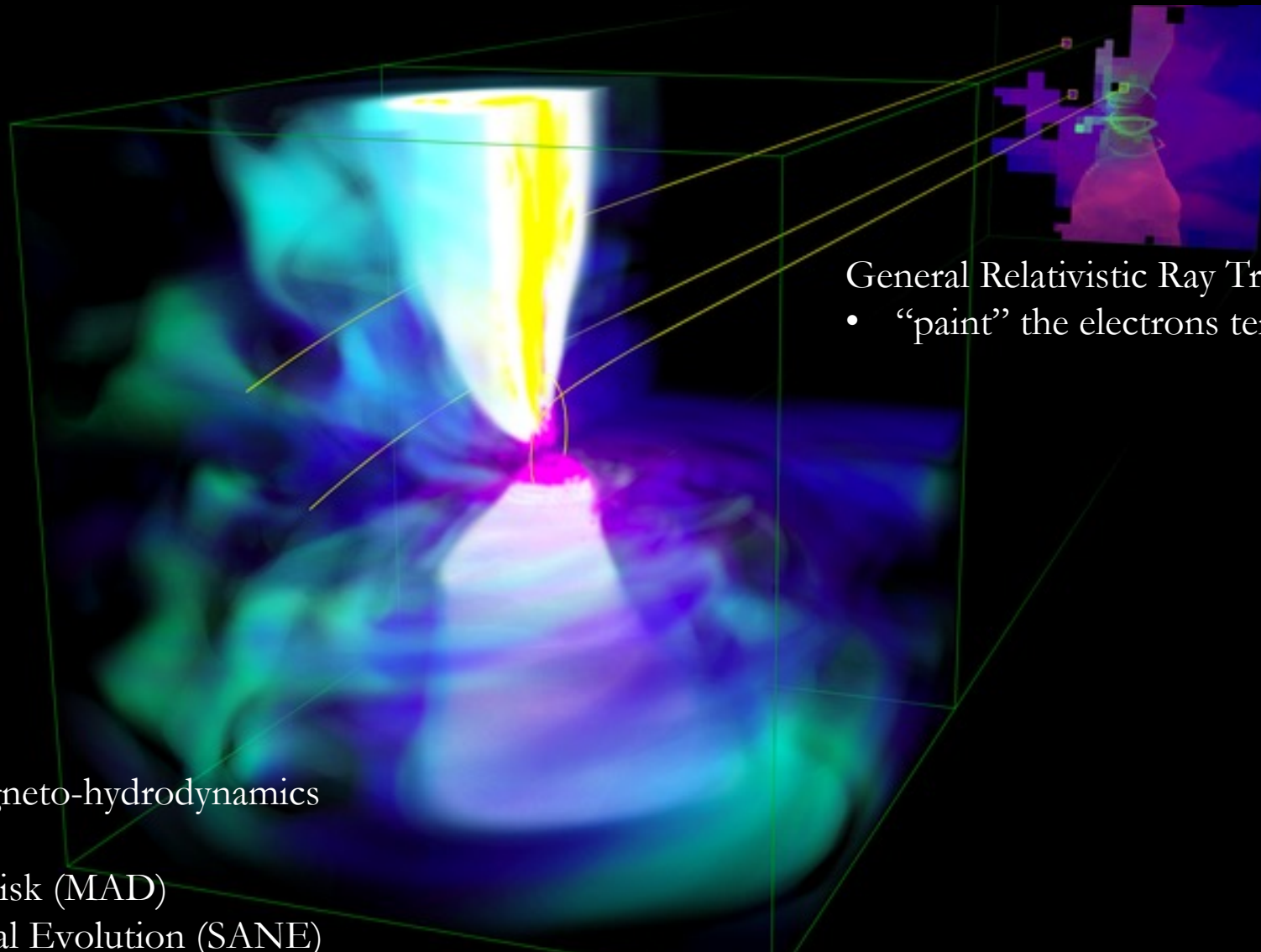
# Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes



- First black hole photo
- Virtually Earth-sized telescope

# To compare observational images to theoretical simulation...



General Relativistic Ray Tracing (GRRT)

- “paint” the electrons temperature

General Relativistic Magneto-hydrodynamics (GRMHD) Simulation

- Magnetic Arrested Disk (MAD)
- Standard And Normal Evolution (SANE)

# Parametric Model in GRRT

Arbitrary Parameter, usually  $\beta_{crit} = 1$

$$R(\beta) = R_{high} \frac{(\beta/\beta_{crit})^2}{1 + (\beta/\beta_{crit})^2} + R_{low} \frac{1}{1 + (\beta/\beta_{crit})^2}$$

Highest attainable temperature ratio

Lowest attainable temperature ratio

- $\beta$ : plasma beta ( $P_g/P_B$ )
- Parameter to be modified:  $R_{high}$ ,  $R_{low}$ ,  $\beta_{crit}$
- $R$ : temperature ratio ( $T_i/T_e$ )
- Electron temperature is calculated by considering internal energy  $U$  in GRMHD



MAD

$$R_{\text{high}} = 160$$

$$a = +0.94$$

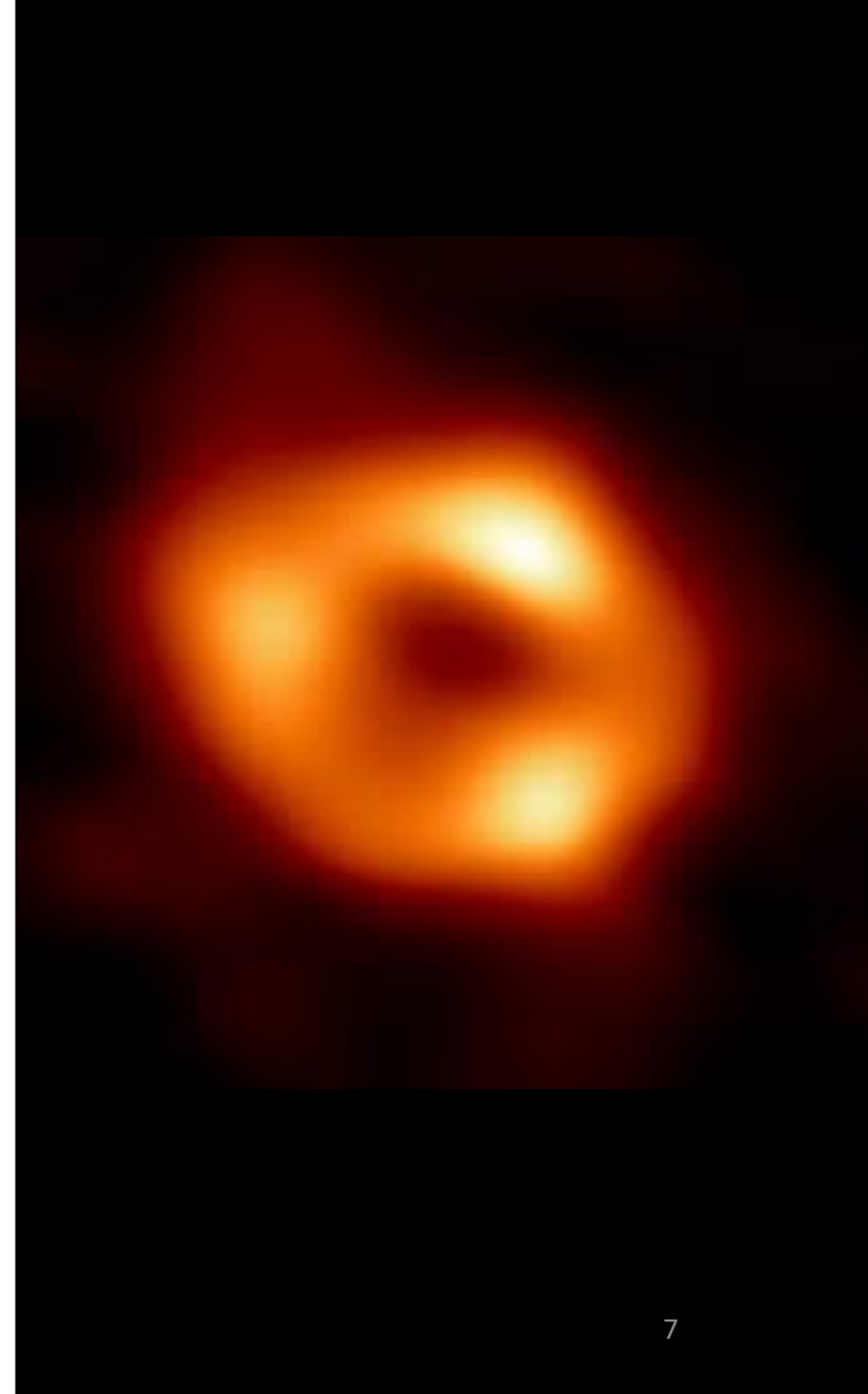
$$i = 90$$

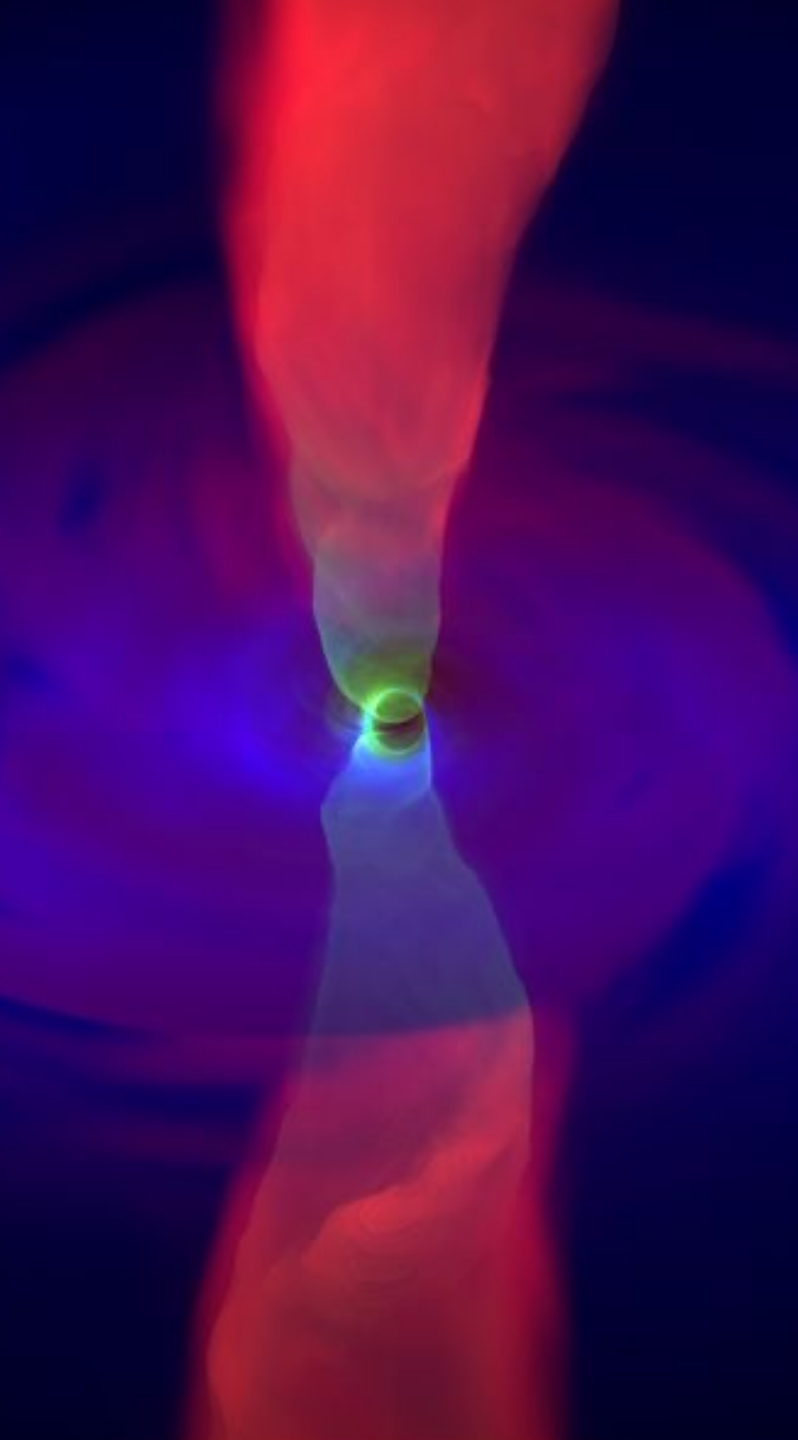
# Motivations and Objectives

Try to use a physically motivated electron model to...

- Reduce **computational expense**
- Bridge **microphysics** to observational image
- Explain the **symmetric** nature of Sgr A\*

And compare the images produced by this new physically motivated model to the **EHT best-fit SANE model**.

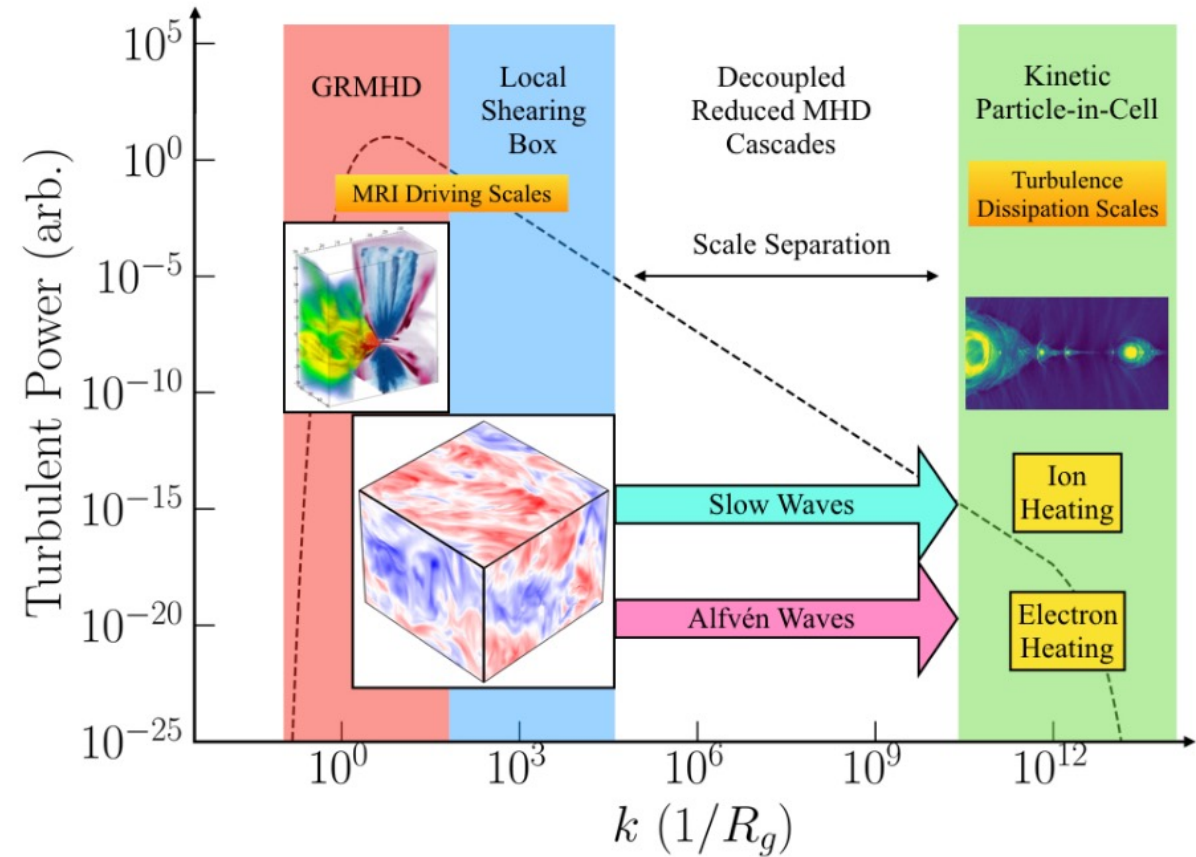




- EHT Parametric Model
- Formulation
- Results and Discussions

# SPÖ Model

- Derived by Satapathy, Psaltis, Özel (2023, 2024)
- covariant semi-analytic model
- incorporates **plasma microphysics** (e.g. Landau damping) and **turbulence physics** (e.g. MRI)



# SPÖ Model and Parametric Model

## Parametric Model

- Arbitrary  $R_{high}$

$$R(\beta) = R_{high} \frac{(\beta/\beta_{crit})^2}{1 + (\beta/\beta_{crit})^2} + R_{low} \frac{1}{1 + (\beta/\beta_{crit})^2}$$

## SPÖ Model

- Variables obtained in

GRMHD

➤ **Parameter Free**

Model

$$\frac{T_i}{T_e} = \frac{\gamma_i^{\text{eff}} - 1}{\gamma_e^{\text{eff}} - 1} \frac{1 - (\gamma_e^{\text{eff}} - 1)(2 - n_R)}{1 - (\gamma_i^{\text{eff}} - 1)(2 - n_R)(1 + \frac{2\zeta}{\beta})} \left( \frac{Q_i}{Q_e} \right)$$

# SPÖ Model

$$\frac{T_i}{T_e} = \frac{\gamma_i^{\text{eff}} - 1}{\gamma_e^{\text{eff}} - 1} \frac{1 - (\gamma_e^{\text{eff}} - 1)(2 - n_R)}{1 - (\gamma_i^{\text{eff}} - 1)(2 - n_R)(1 + \frac{2\zeta}{\beta})} \left( \frac{Q_i}{Q_e} \right)$$

Effective ion adiabatic index under effects of turbulence

Power-law coefficient of radial velocity in accretion disk

Effective electron adiabatic index due to trans-relativistic behaviour

Fraction of thermal pressure that is contributed by turbulence

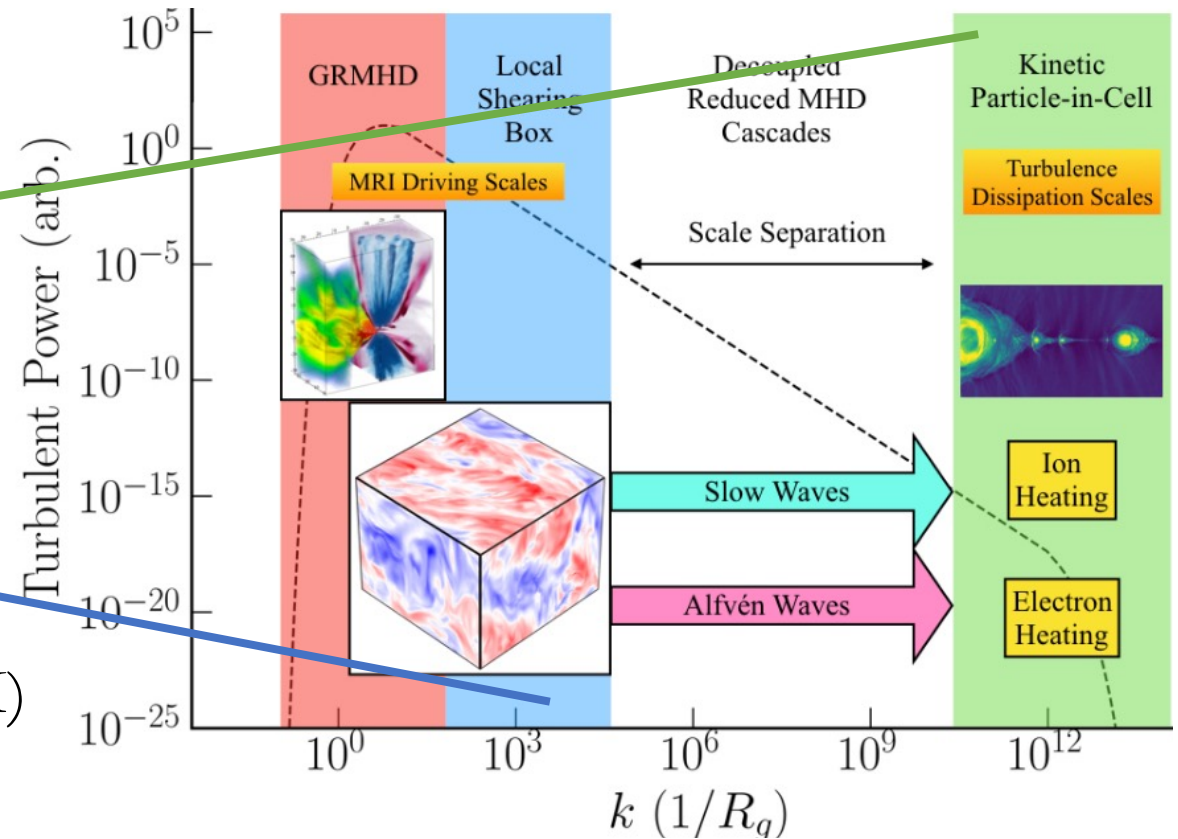
Ratio of energy dissipation between ions and electron

# SPÖ Model

Fitting Formula from  
hydro-gyrokinetic simulation  
(Kawazura, 2020)

$$\frac{Q_i}{Q_e} = \frac{35}{1 + (\beta/15)^{-1.4}} + \frac{P_{\text{comp}}}{P_A}$$

Includes the effects of turbulence (MRI) through shearing box simulation



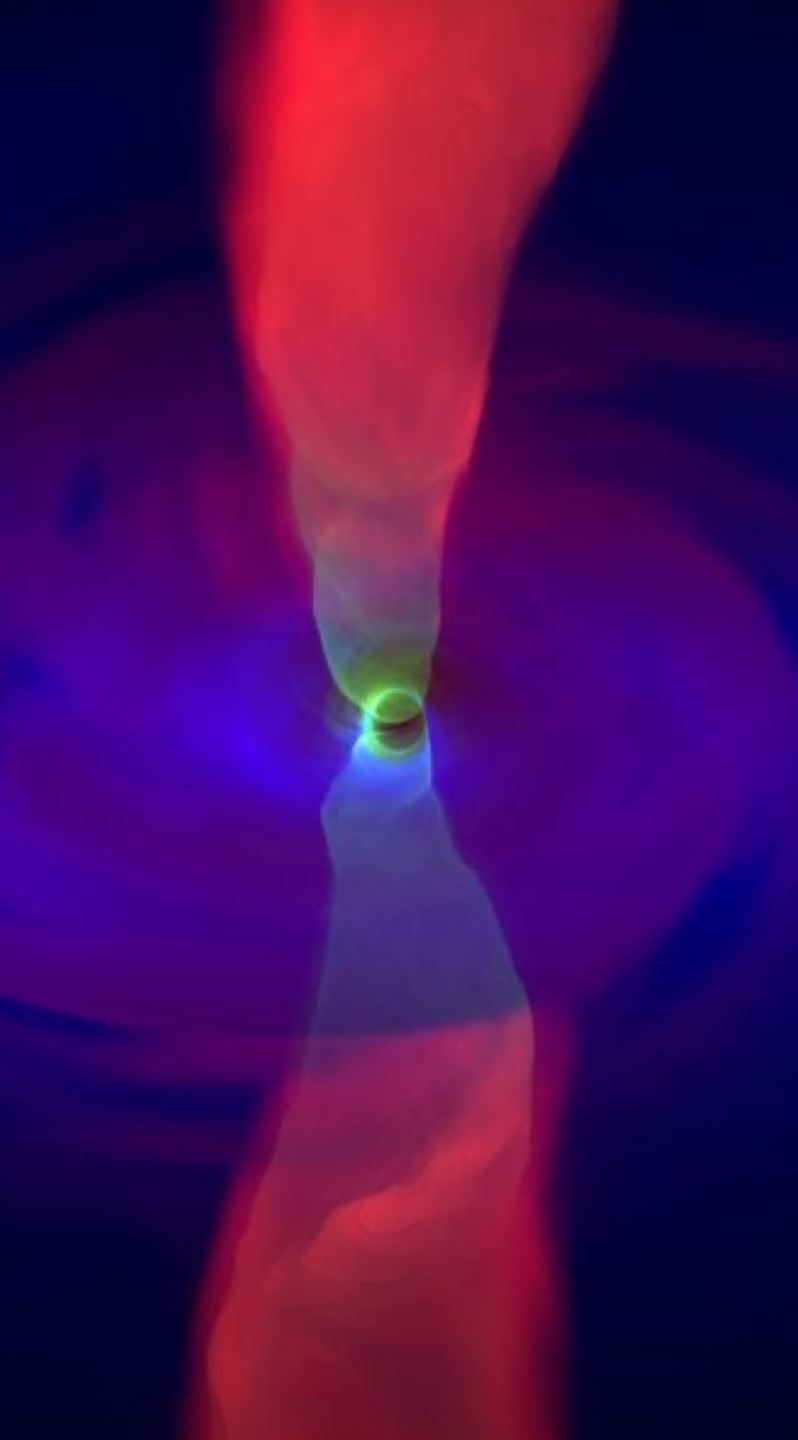
# SPÖ Model

$$\frac{Q_i}{Q_e} = \frac{35}{1 + (\beta/15)^{-1.4}} + \frac{P_{\text{comp}}}{P_A}$$

- Dominated by **Landau damping**  
in high-beta region

- Dominated by **compressive waves and Alfvénic wave**

$$\left. \frac{P_S}{P_A} \right|_{\text{linear MRI, } \vec{B}_0 \approx B_0 \hat{y}} = \frac{q \left( \left. \frac{M_{xy}}{R_{xy}} \right|_{\text{linear MRI}} + 1 \right)^{-2}}{2} = 1$$

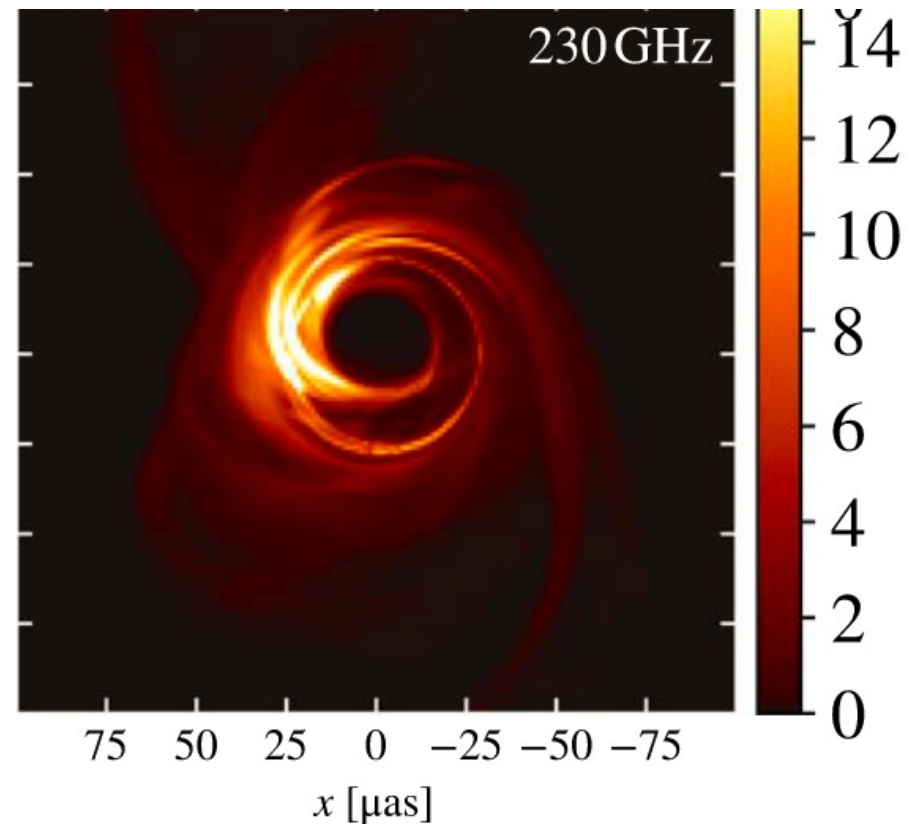


- EHT Parametric Model
- Formulation
- Results and Discussions

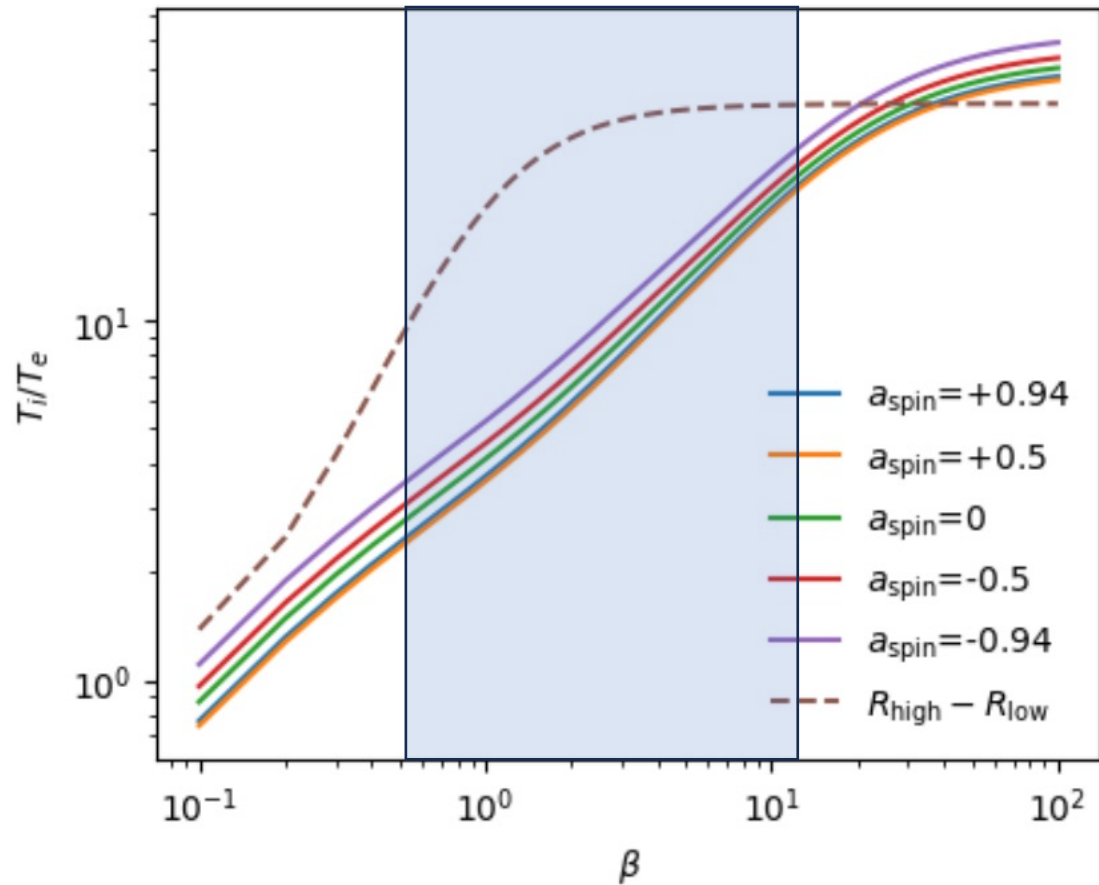
# Comparison with EHT Best-fit SANE Model

$$R(\beta) = R_{\text{high}} \frac{(\beta/\beta_{\text{crit}})^2}{1 + (\beta/\beta_{\text{crit}})^2} + R_{\text{low}} \frac{1}{1 + (\beta/\beta_{\text{crit}})^2}$$

- $R_{\text{low}}$ : **1**;  $R_{\text{high}}$ : 1, 10, **40**, 160;  $\beta_{\text{crit}}$ : **1**
- Uses SANE due to derivation in SPÖ model
  - EHT suggests that Sgr A\* is **MAD**
  - Test if the new model improves **SANE's agreement** with the observations.



# Comparison between two models



- Increases electron heating in **mid- $\beta$  region**
- Plateaus at the  $\sim$ EHT best-fit SANE model value in the **high- $\beta$  region**

# Effective Temperature Profile

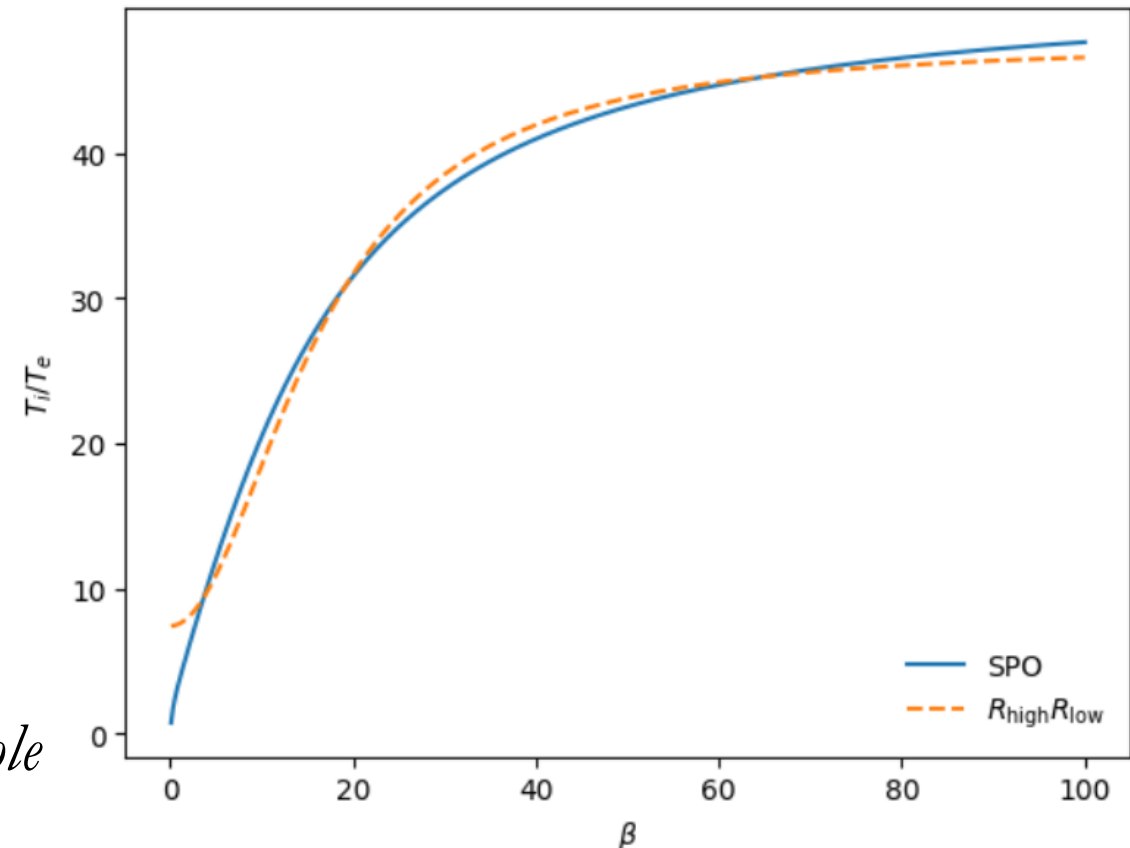
Fitting SPÖ model to the parametric model

- $R_{low}$ : 7.43
- $R_{high}$ : 47.6
- $\beta_{crit}$ : 16.22

EHT Best-fit SANE Model

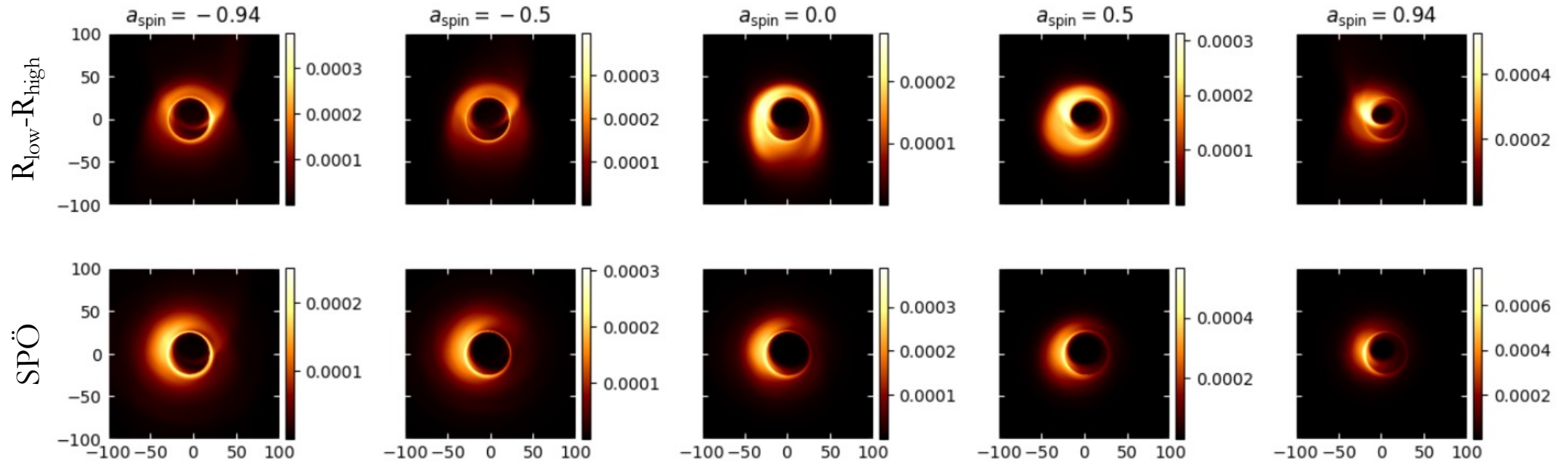
- $R_{low}$ : 1
- $R_{high}$ : 40
- $\beta_{crit}$ : 1

- Implement SPÖ model into GRRT code *ipole* to compare the performance of two models

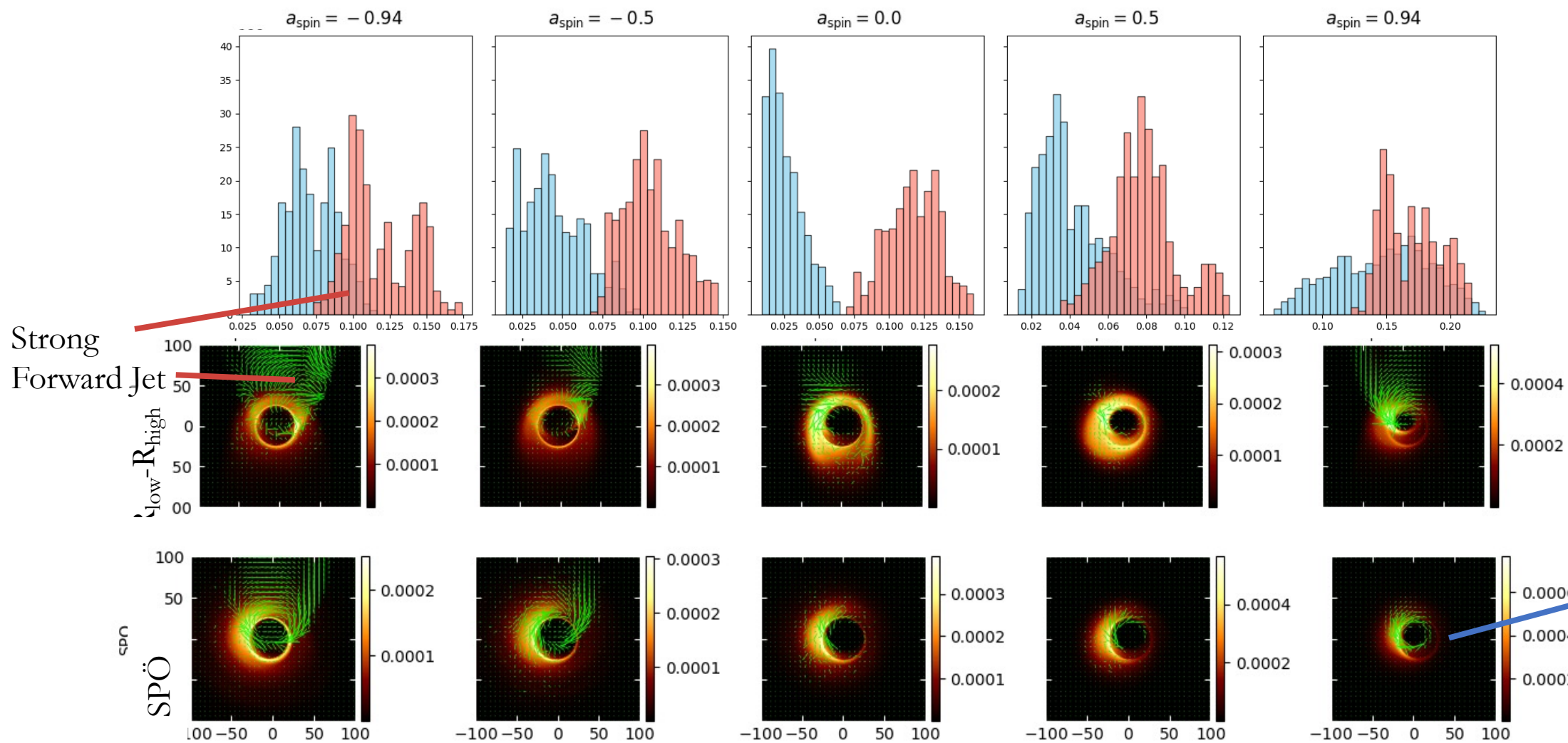
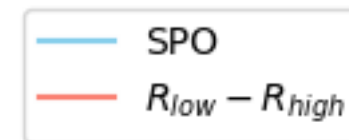


# Temporally Averaged Optical Images

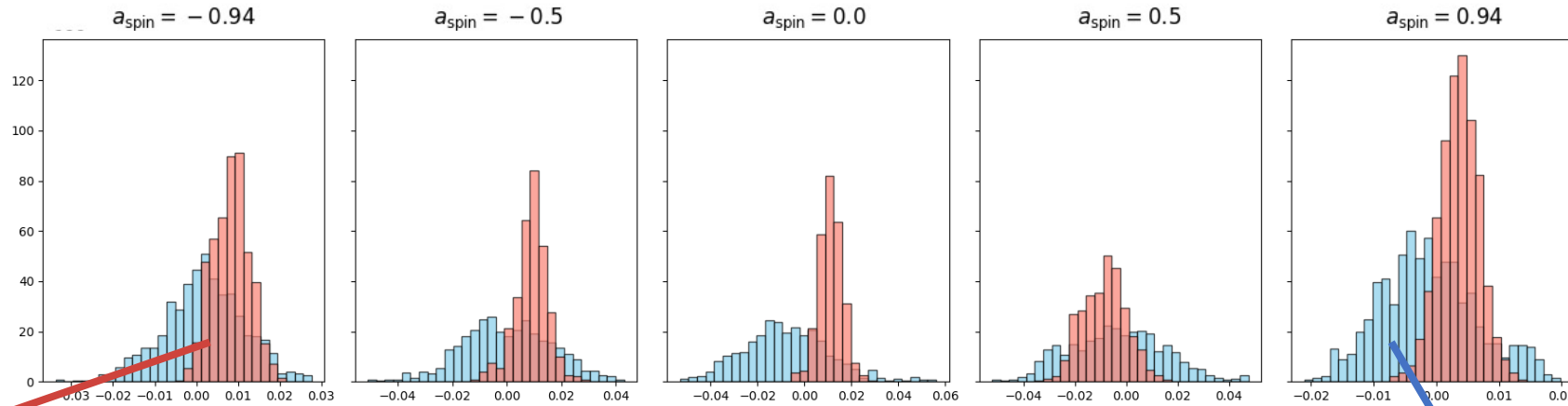
- Optically thinner
- Asymmetric accretion disk
- More prominent photon ring



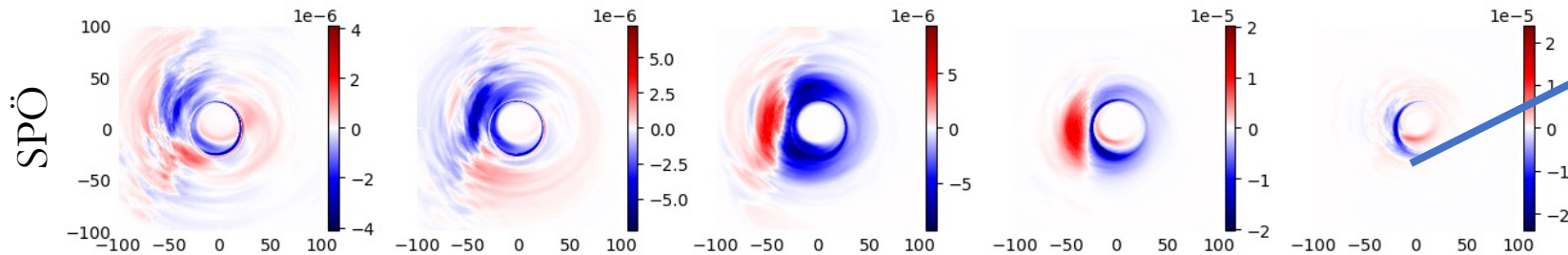
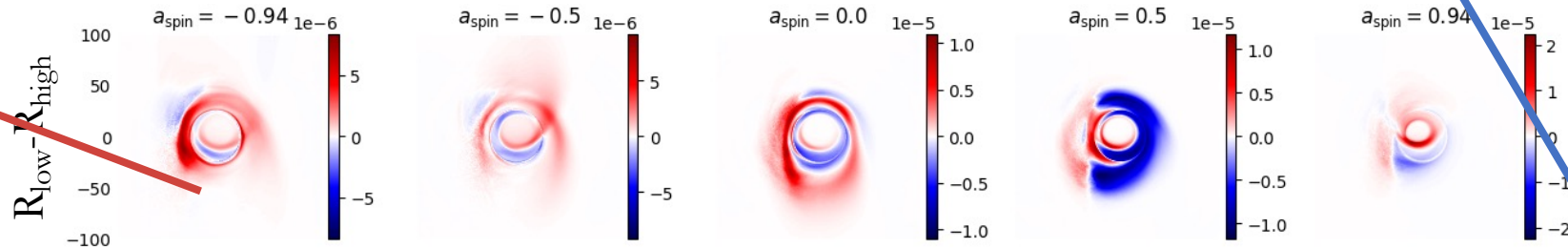
# Linear Polarization ( $m_{avg}$ )



# Circular Polarization ( $v_{avg}$ )



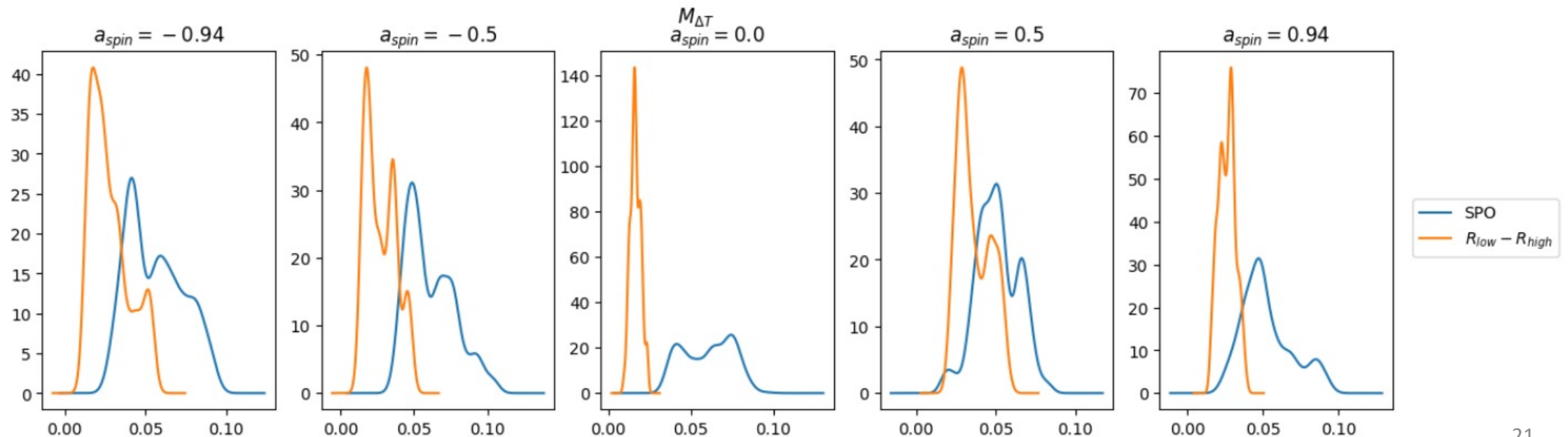
Strong  
Forward Jet



Mainly from  
Photon ring and  
Inner accretion disk

# Variability

- 3-hour Modulation Index:  $M_{\Delta T} = \frac{\sigma_{\Delta T}}{\mu_{\Delta T}}$
- SPÖ produces more **variable SANE**



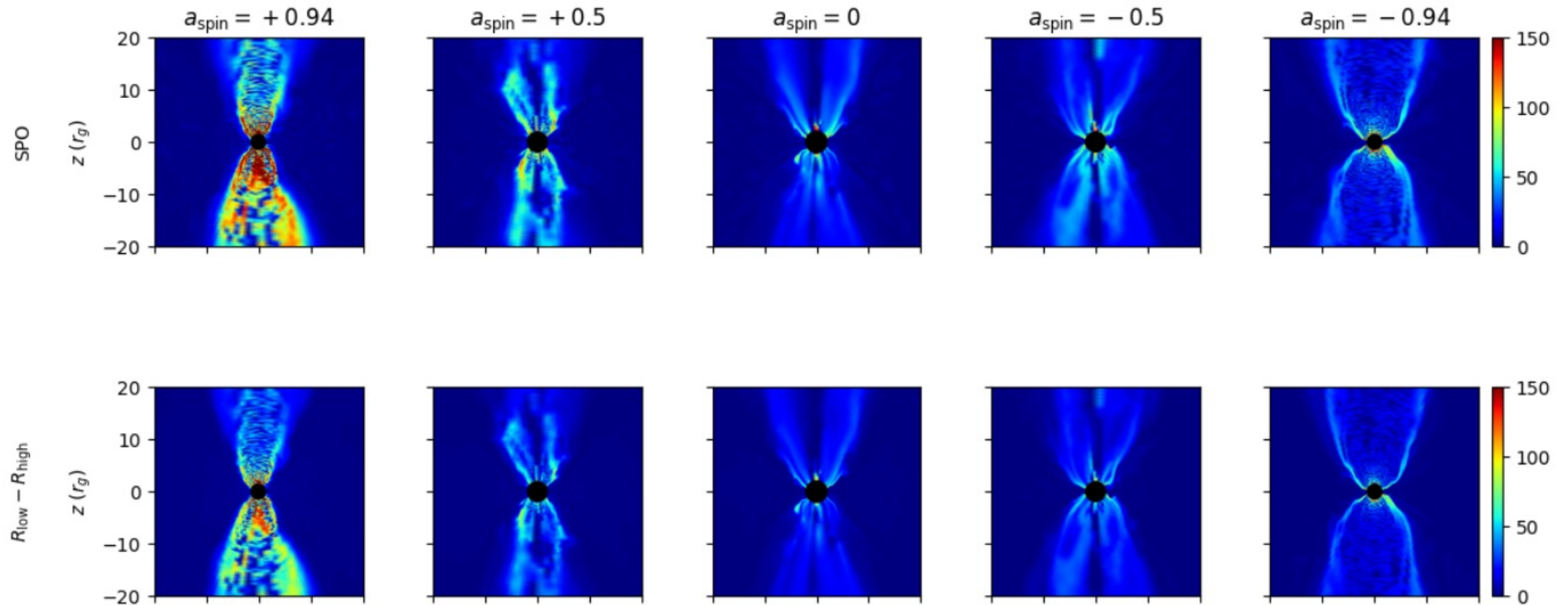
# Conclusion and Future Work

- The effects **unexplored parameter space**  $R_{low}$  and  $\beta_{crit}$  in the parametric model to the observational images
  - Modifying  $R_{low}$  and  $\beta_{crit}$  can modify the **image morphology, polarization, and variability**
- SPÖ model still suggests that **Sgr A\* is not a SANE**
  - Equal importance of electron model and MAD/SANE
- Extend SPÖ model into MAD

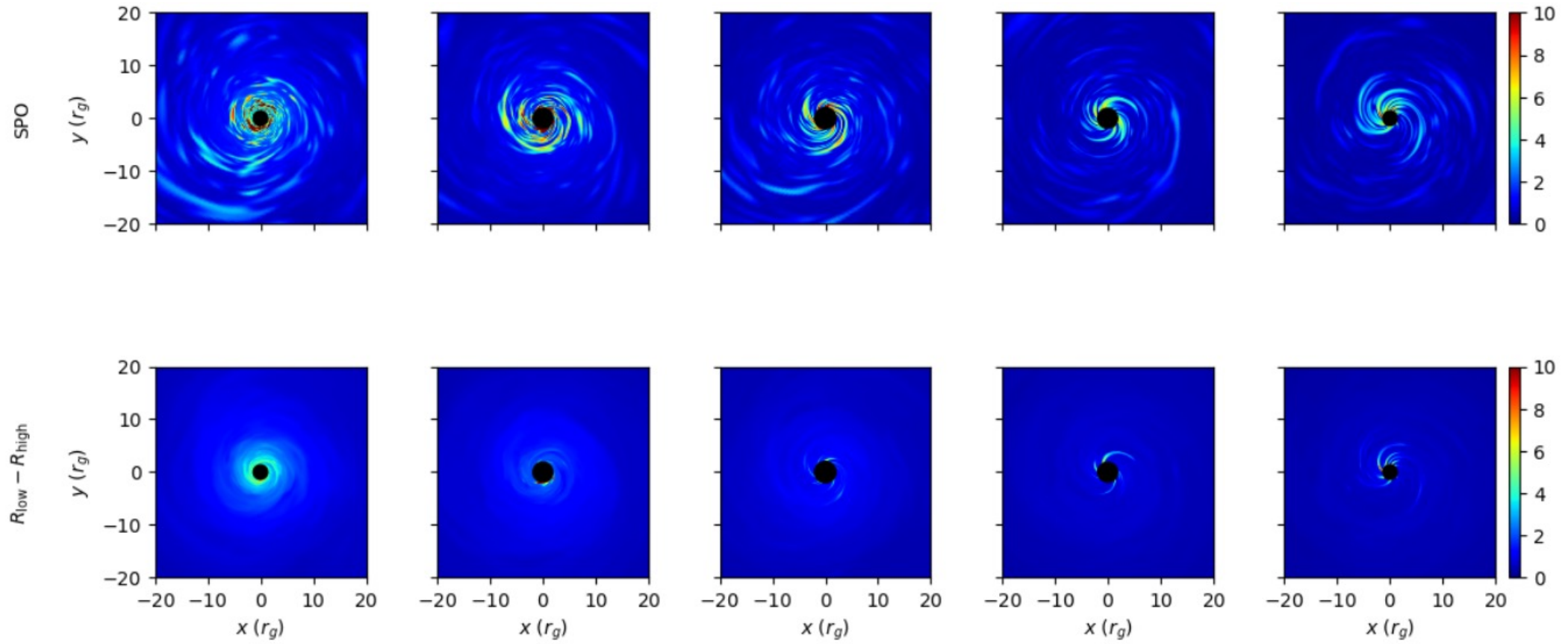
Thank You!

Q&A

# Electron Temperature Profile (xz-plane)



# Electron Temperature Profile ( $xy$ -plane)



# Fitting of $n_R$ and $q$

