

# EHT image of Sgr A\*

Chen Zhihao, Diao Kangning, Meng Jiacheng

2022.05.20@student seminar

# Content

- Introduction to Sgr A\* and EHT VLBI observation (Diao Kangning)
- How to get the Horizon-scale Images from the visibilities (Chen Zhihao)
- Test astrophysical models and GR with Sgr A\* (Meng Jiacheng)

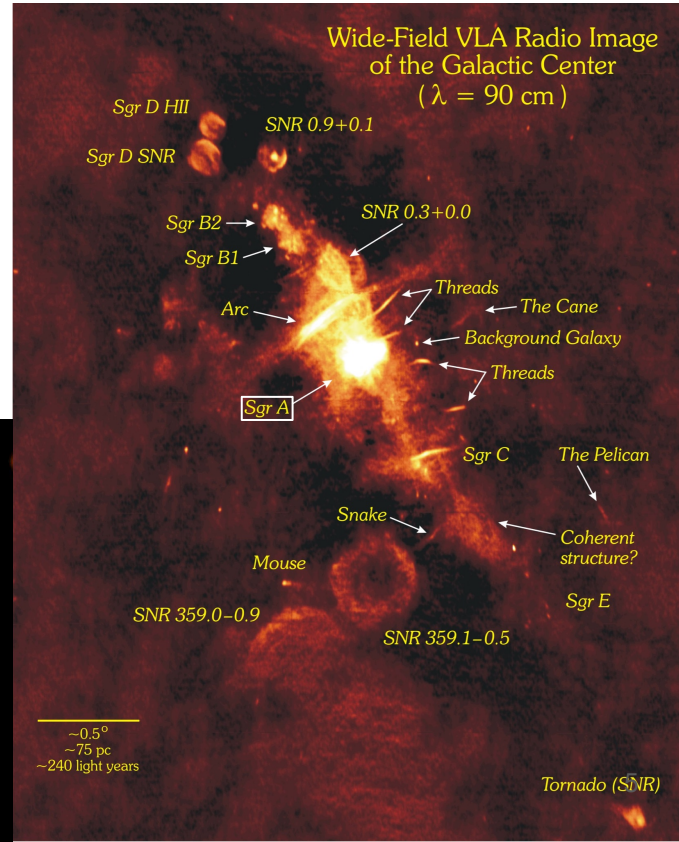
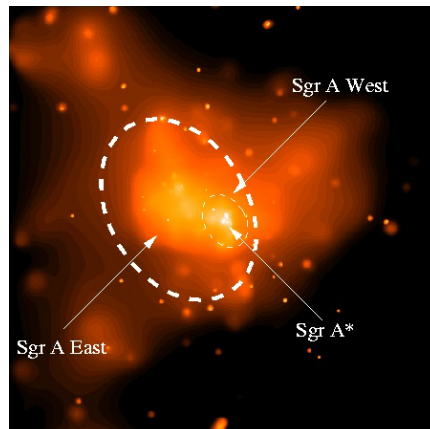
# **Introduction to Sgr A\* and EHT VLBI observation**

# Outline

- Introduction to Sgr A\*
- Introduction to Very Long Baseline Interferometry and EHT observations
- What does EHT raw data tell us

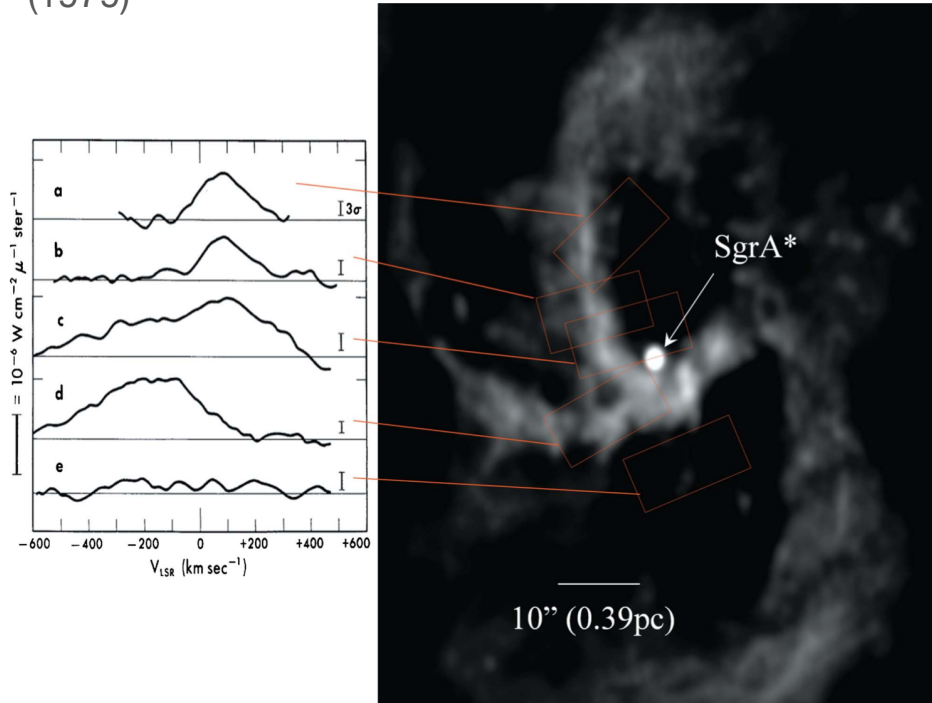
# Sgr A\*: a compact radio source

- Sgr A: A bright radio source in the Galactic center (Jansky 1933)
- Sgr A\*: A bright and compact ( $<0.1$  arcsec) radio source in the Galactic center (Balick & Brown 1974)
- \* means it's excited



# Is Sgr A\* a black hole?

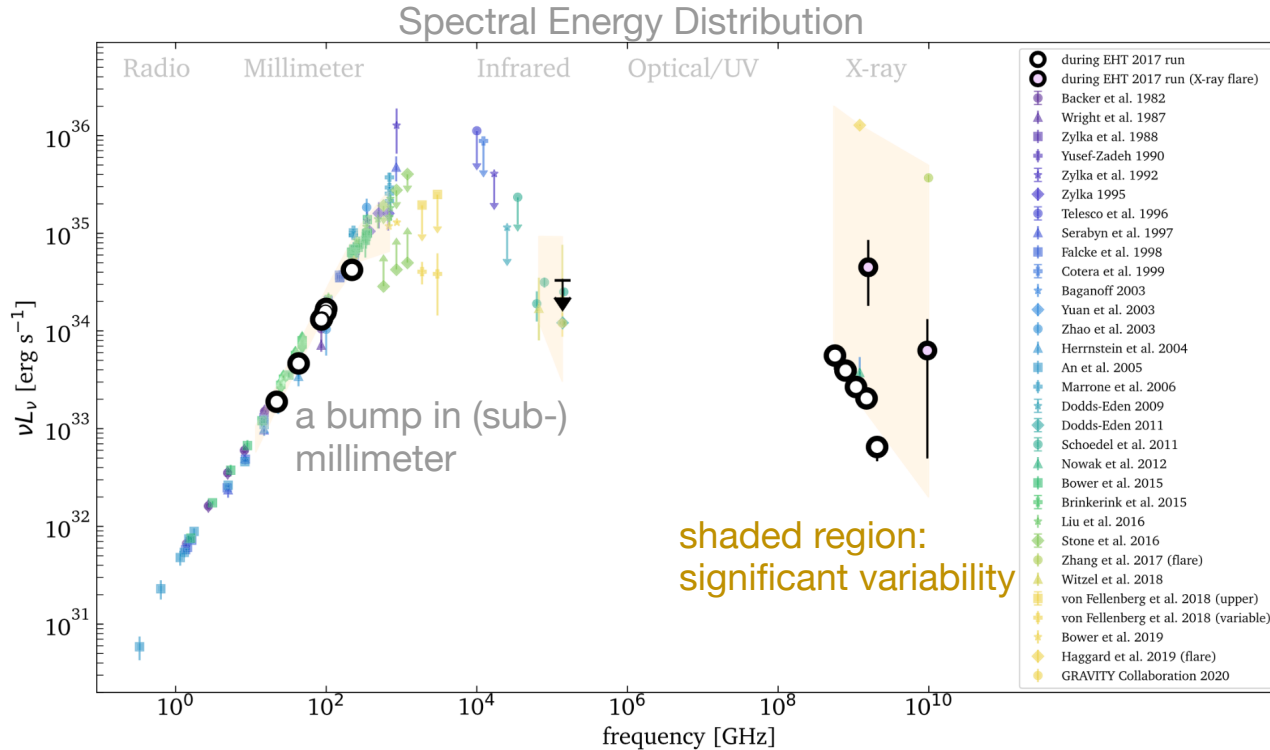
First Evidence from gas motion: Mass  $> 10^6 M_{\odot}$   
(1979)



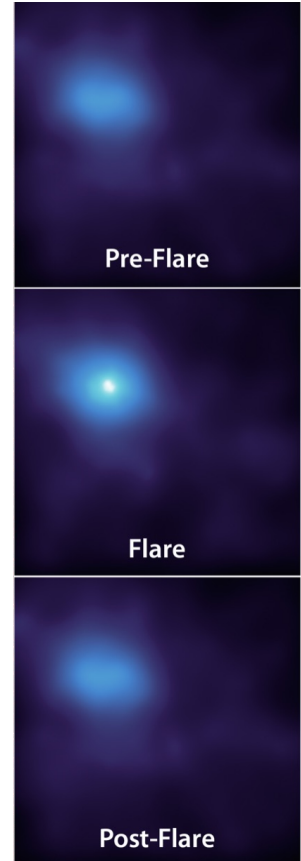
2021 result from stellar orbit:  
Mass =  $(4.297 \pm 0.013) \times 10^6 M_{\odot}$



# Multi-band observations of Sgr A\*

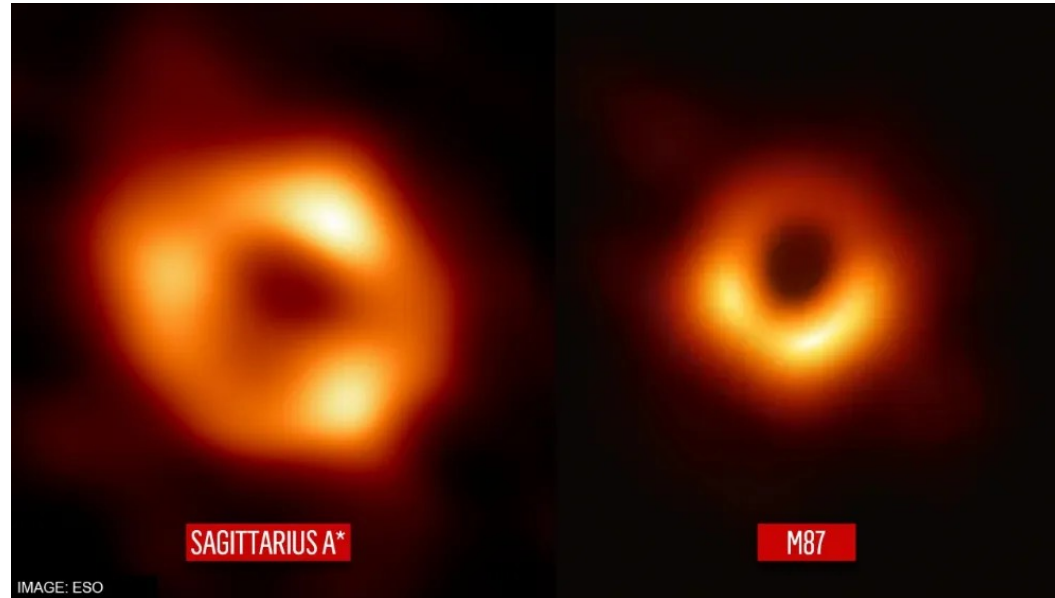


flares in minutes



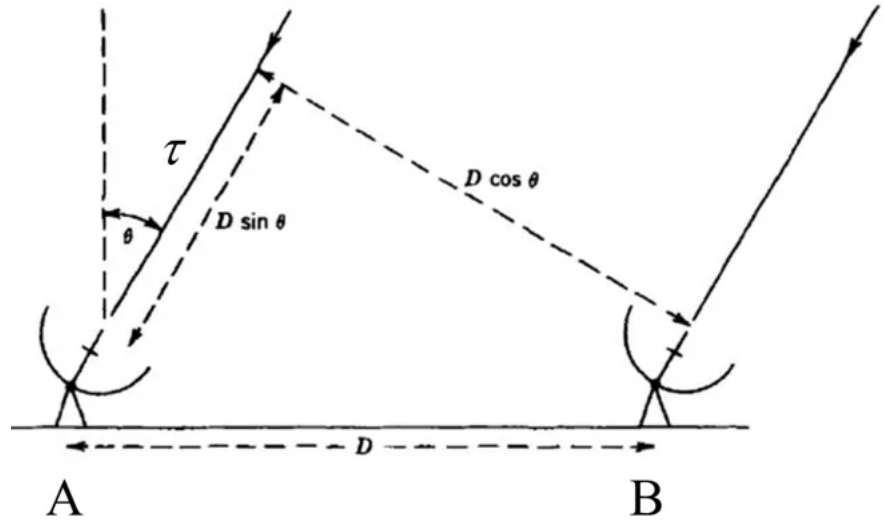
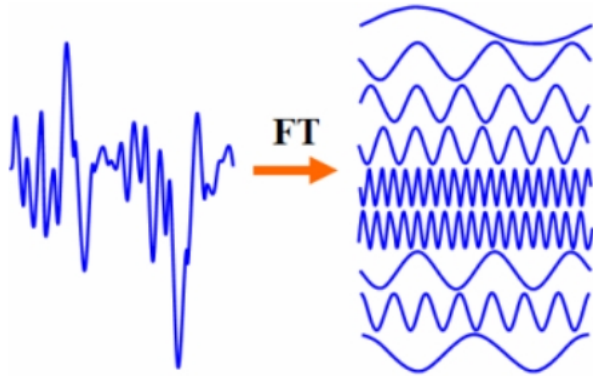
# Comparison to M87\*

- Less massive ( $\sim 1/1500$ ) and smaller
- Quick variations
- Less active  
( $\dot{M}_{\text{SgrA}^*} < 1/100 \dot{M}_{\text{M87}^*}$ )



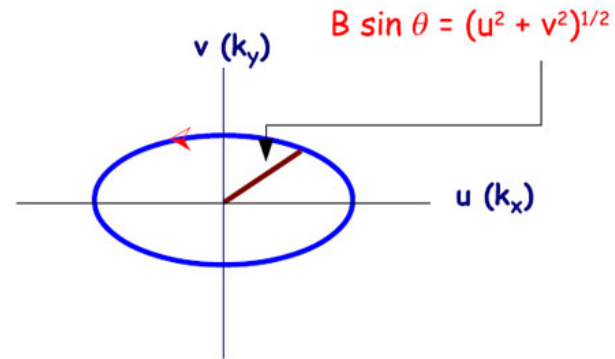
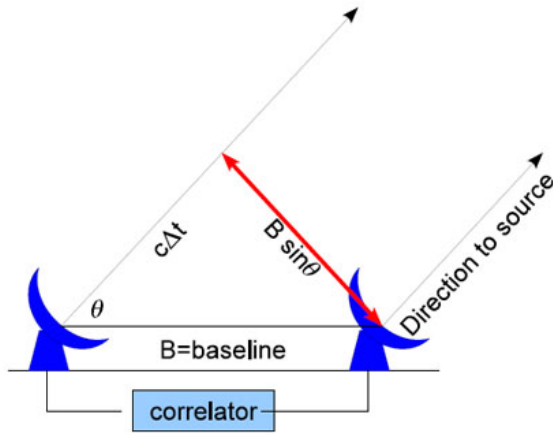
# EHT Motivation

- Want to see clearer picture!
- Interferometry: a common way to higher resolution



# EHT Motivation

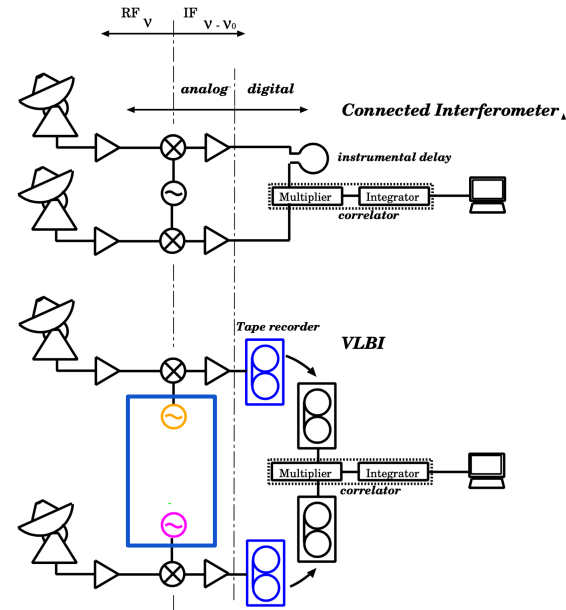
- Want to see clearer picture!
- Interferometry: a common way to higher resolution



# Very long baseline interferometry

- From interferometry to VLBI: 3 major requirements

1. Reliable frequency reference
2. Reliable clock



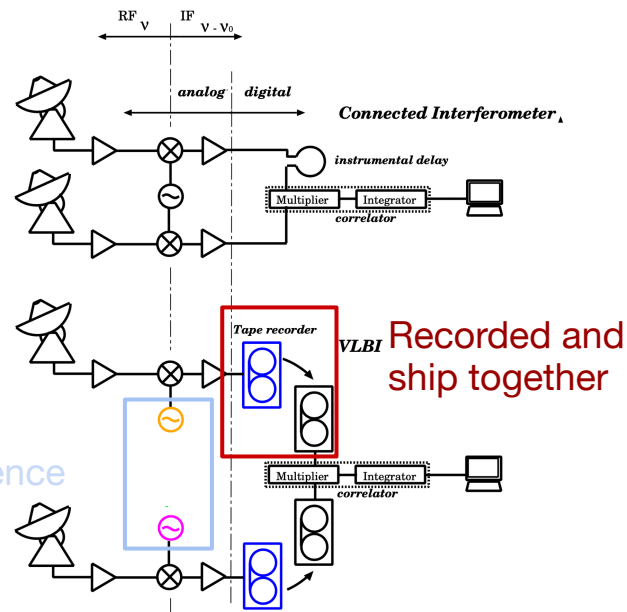
Different frequency reference

# Very long baseline interferometry

- From interferometry to VLBI: 3 major requirements

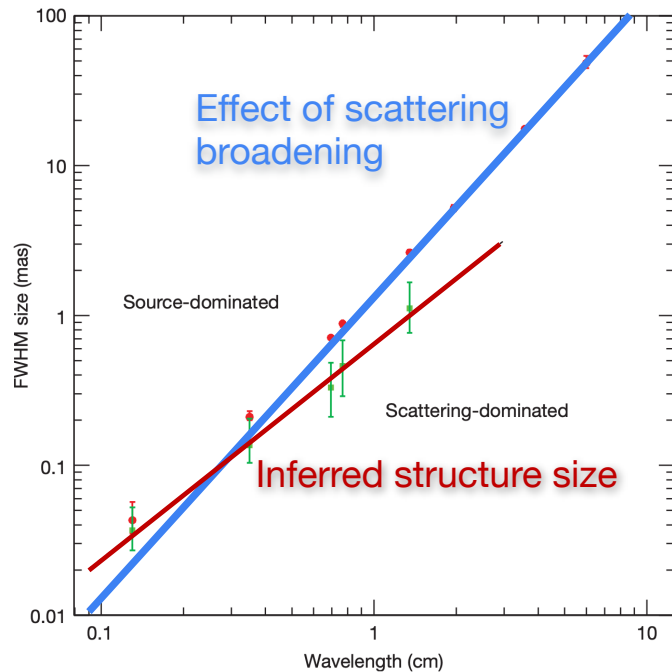
1. Reliable frequency reference
2. Reliable clock
3. Fast data recorder

Different frequency reference



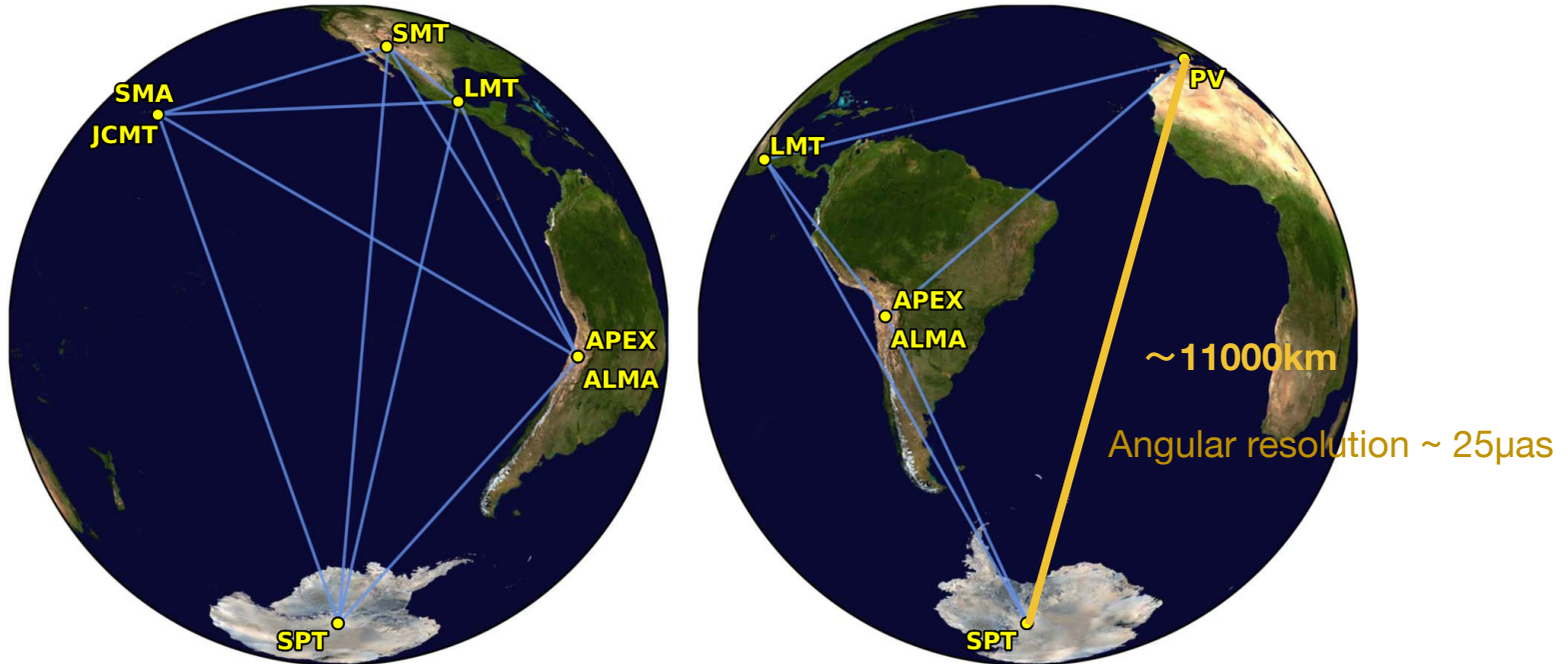
# History of Sgr A\* VLBI observations

- high frequency reveals the intrinsic structure!
- But higher frequency VLBI are harder
- 1.3mm: the shortest successful wavelength



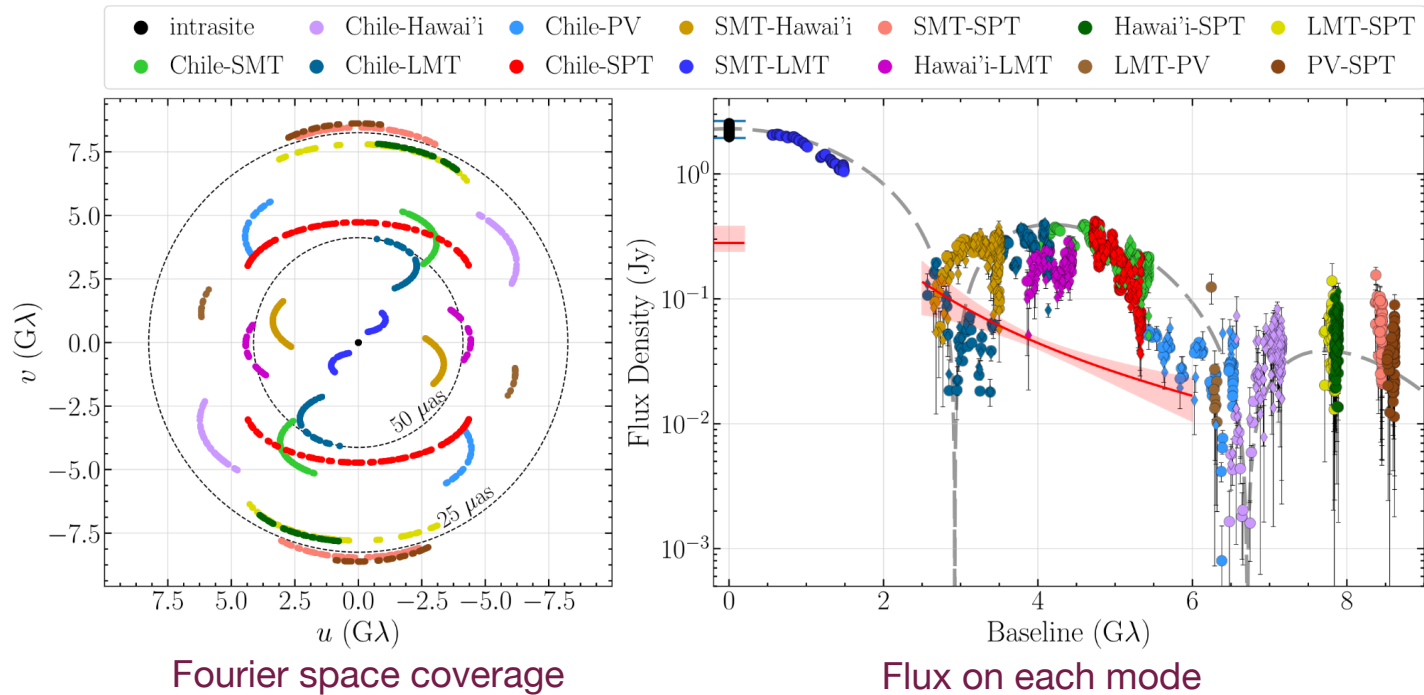
# EHT Facilities

- 8 telescopes in 6 locations, observe in 1.3mm (230GHz).



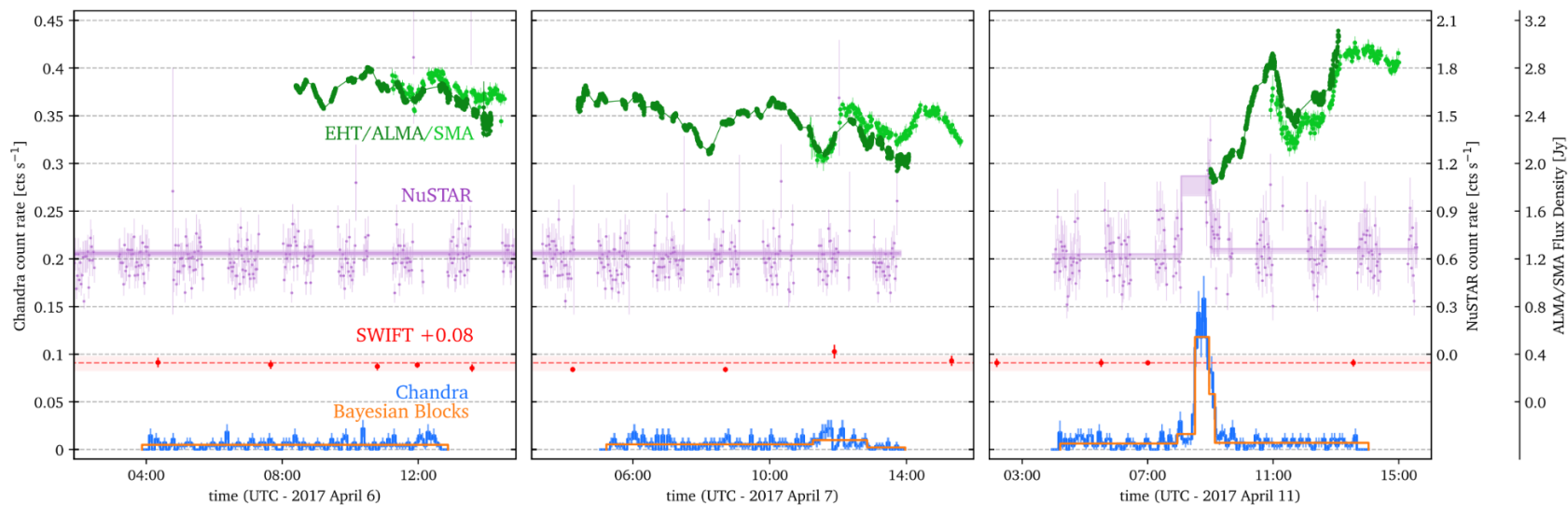
# EHT observation on Sgr A\*

- 5 nights, only 1-2 nights data are used.



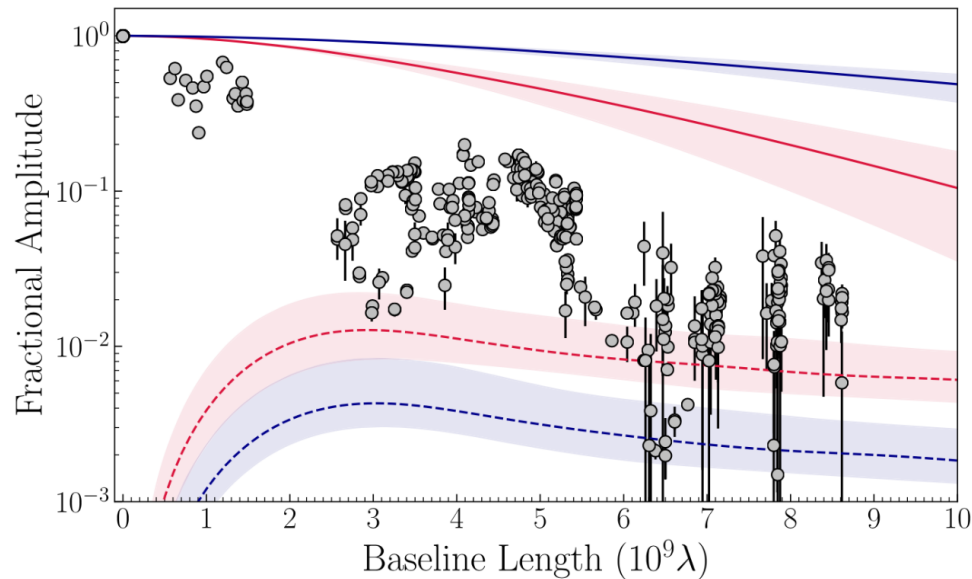
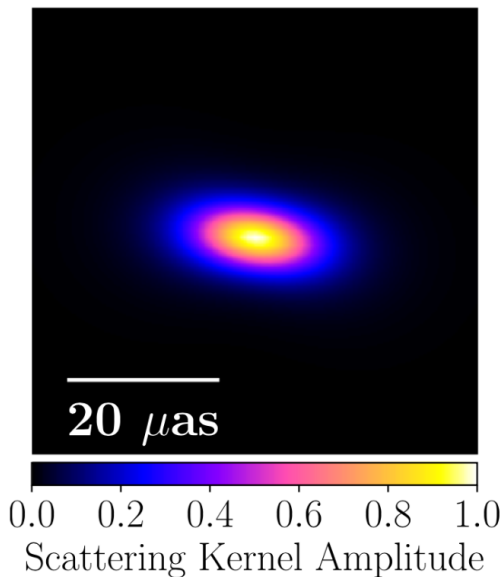
# Is Sgr A\* quiet?

- Quiet at April 6 and 7



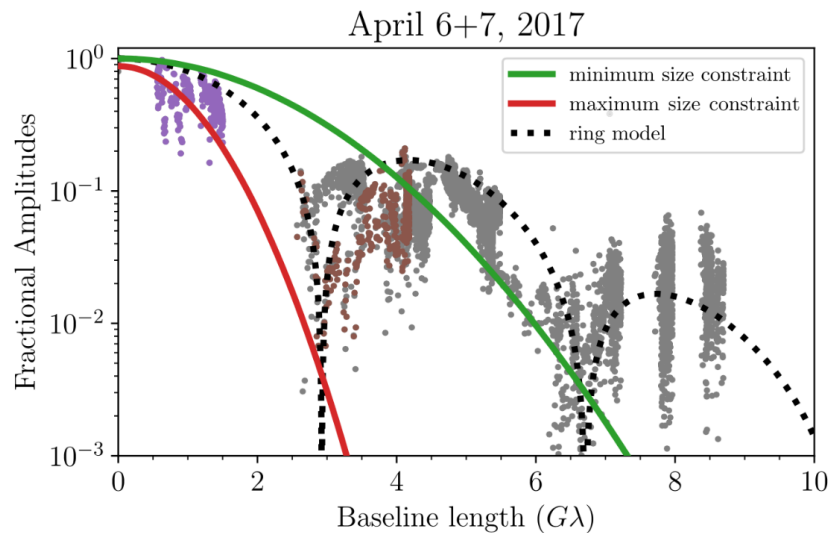
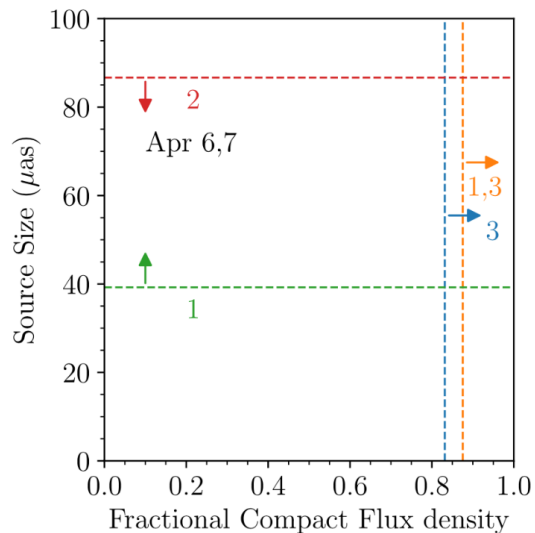
# Is scattering really not dominating?

- Compare with scattering effects.



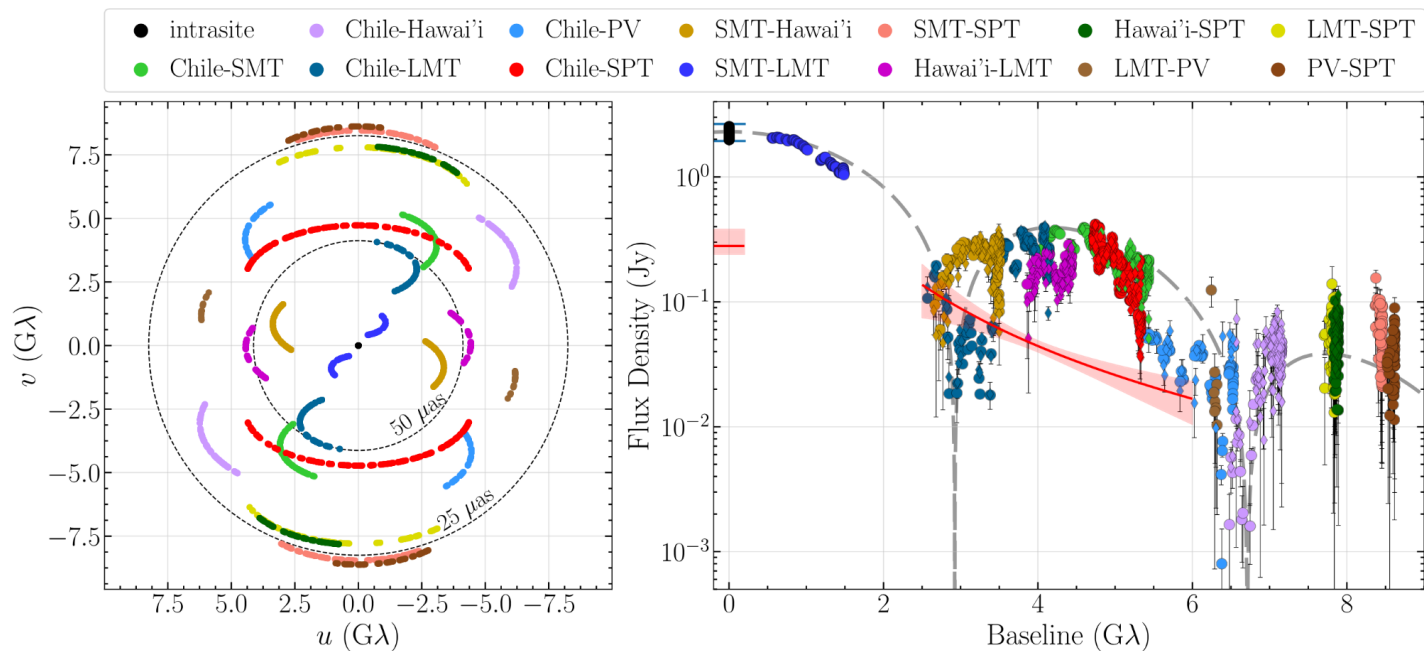
# Size constraints

- Very good fit of a ring model



# Size constraints

- Beyond ring model: anisotropy in Fourier space



# Summary

- Sgr A\* is a SMBH at the center of our galaxy
- EHT is a VLBI network aiming for Sgr A\* imaging
- EHT raw data shows an anisotropic ring model

# **How to get the Horizon-scale Images from the observed visibilities**

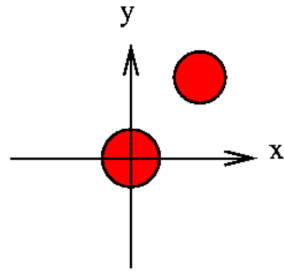
Zhihao Chen  
2022.5.20

# Outline

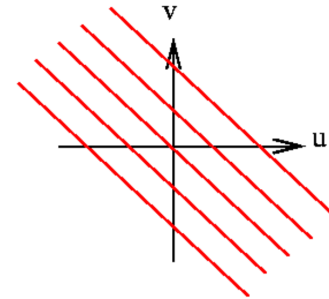
- A brief introduction
- Challenges on Sgr A\*
- Imaging Methods
- Basic properties of the Images

# Basic theory of interferometry

Sky  
Brightness  
Distribution

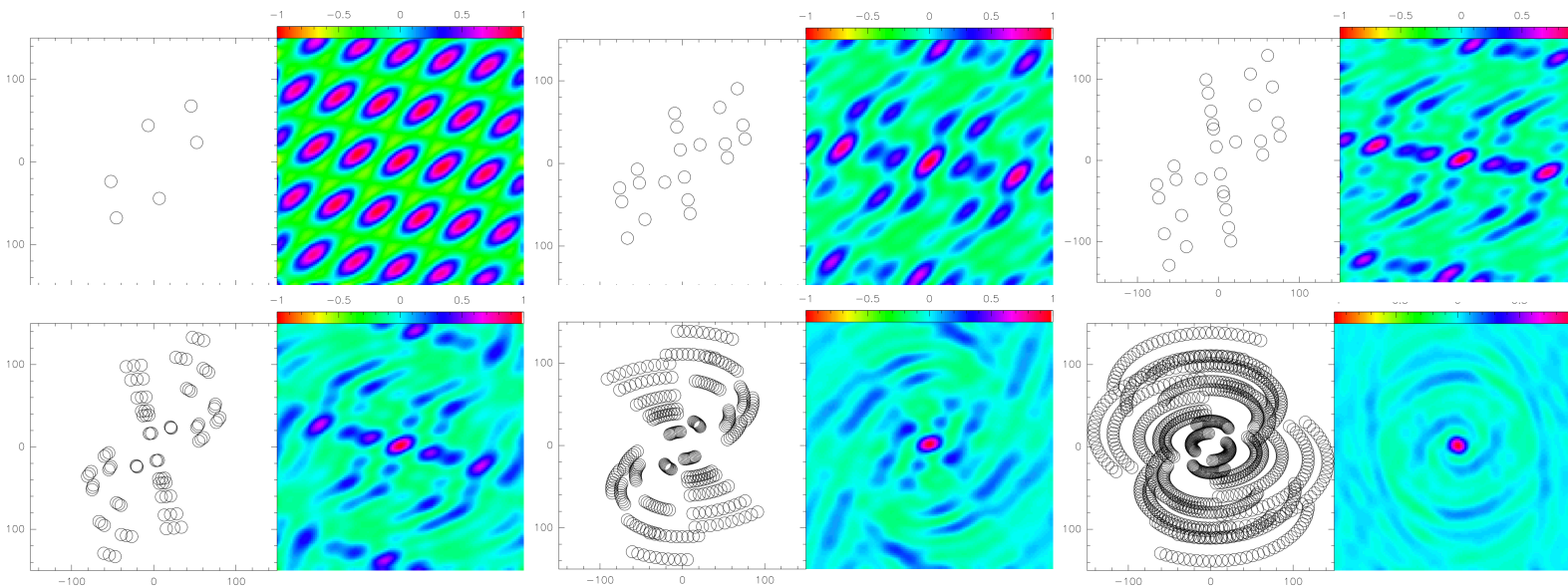


Fourier  
Transform



Interference  
Fringe  
Visibility

The better coverage => The better quality

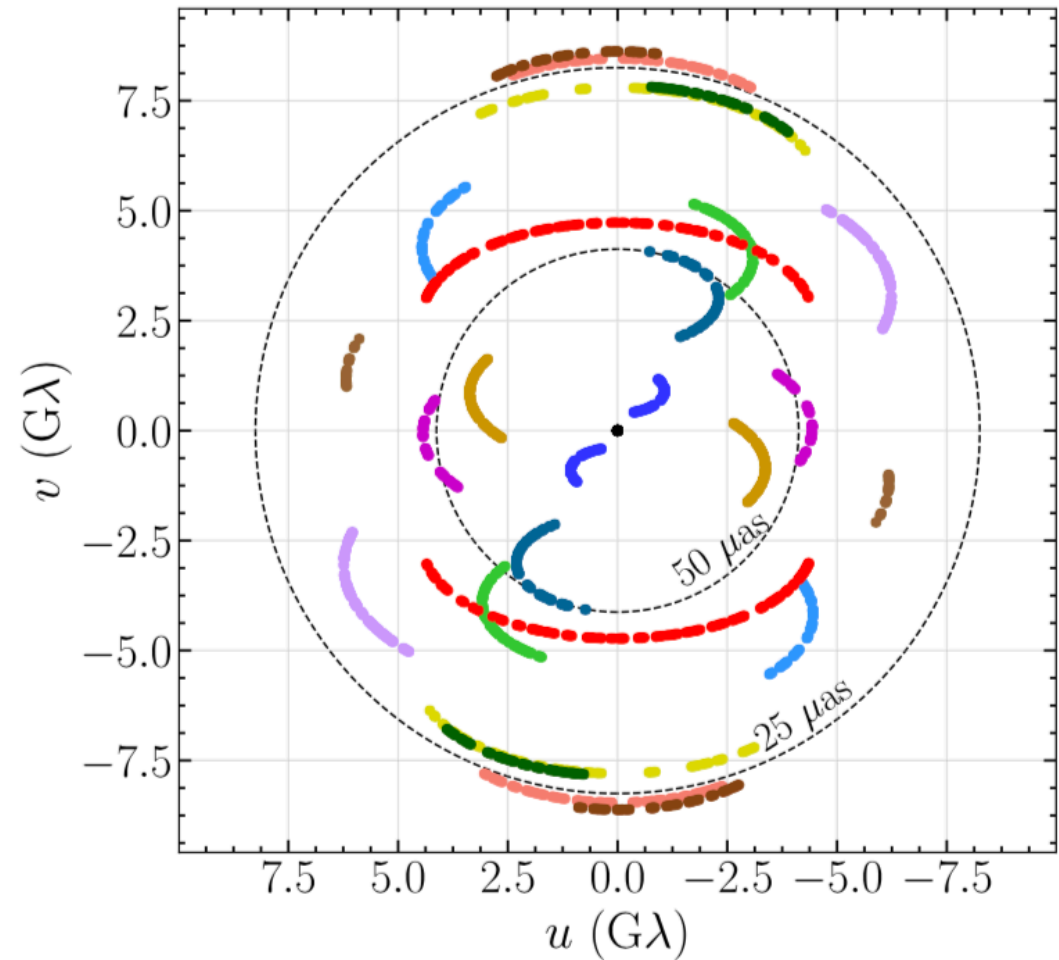


Adding telescopes

Earth rotating

# Challenges on Sgr A\*

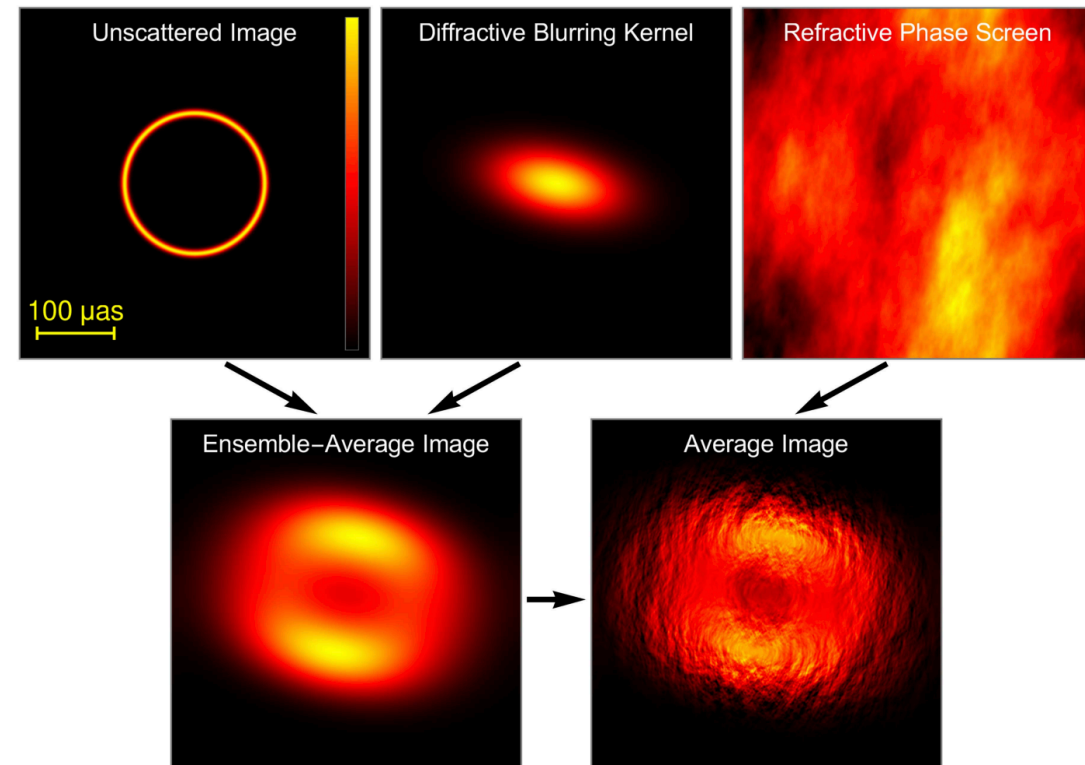
- Incompletely sampled
- Structured noise
- **Interstellar scattering**
- **Short-timescale variability**



# Effects of Interstellar Scattering

- Diffraction:

An **invertible** angular broadening.



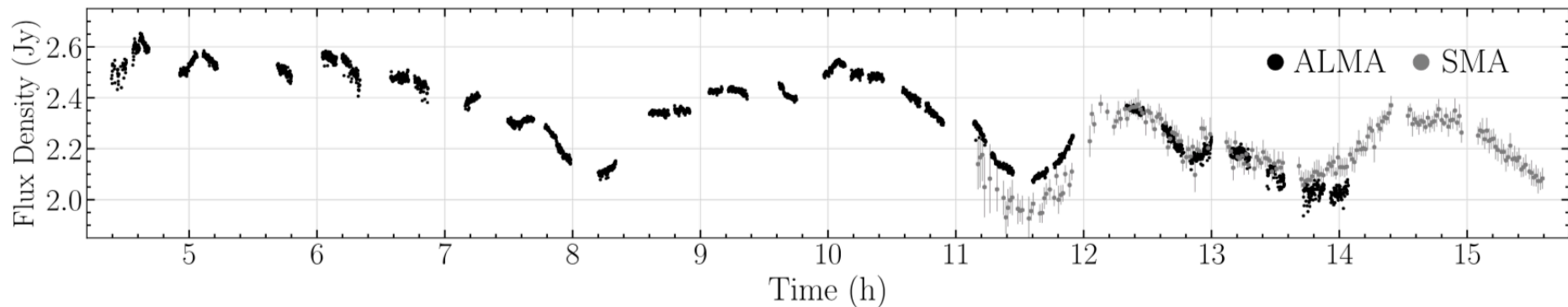
- Refraction:

A stochastic noise.

Expand the noise budgets

# Effects of Time Variability

- Timescale:  $\leq$  a few mins
- Light curves vary at  $\sim 10\%$  over  $\sim$ hours, 4%–13% per night.
- An order of magnitude **stronger** than Interstellar Scattering.
- Dynamic images or Time averaged images with larger error

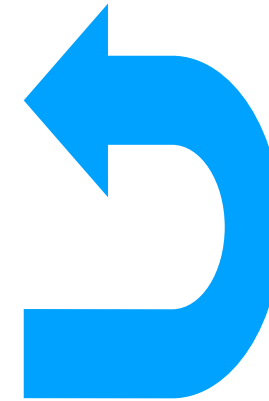


# Imaging Methods

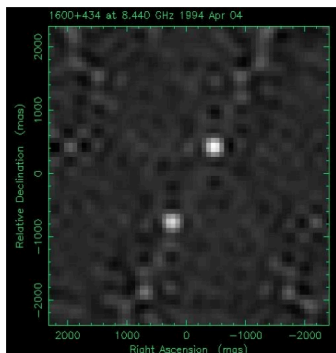
- CLEAN algorithm
- Regularized maximum likelihood (RML)
- A Bayesian posterior sampling method

# CLEAN algorithm

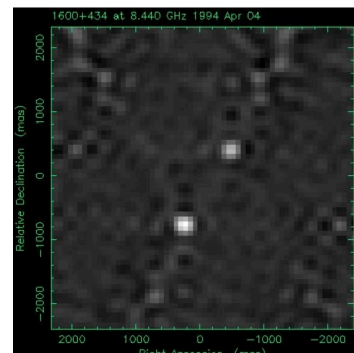
- [1] locating the brightness peak in the dirty image (inverse Fourier transform of the visibilities).
- [2] generating a point source at this location.
- [3] subtracting the influence of the point source.



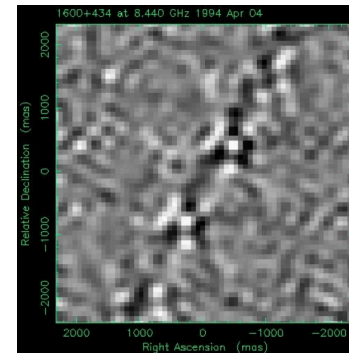
Large iterations



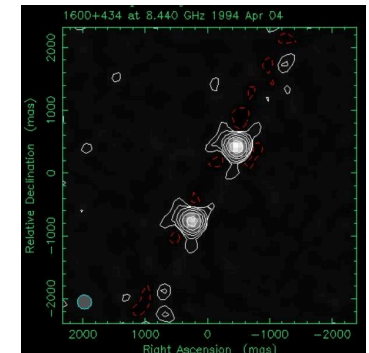
Dirty image



1 iteration



100 iterations



Clean image

# RML and Bayesian posterior sampling

- Find an image  $I$  by minimizing a specified objective function:

$$J(I) = \sum_{\text{data terms}} \alpha_D \chi_D^2(I, V) - \sum_{\text{regularizers}} \beta_R S_R(I).$$

hyper-parameters

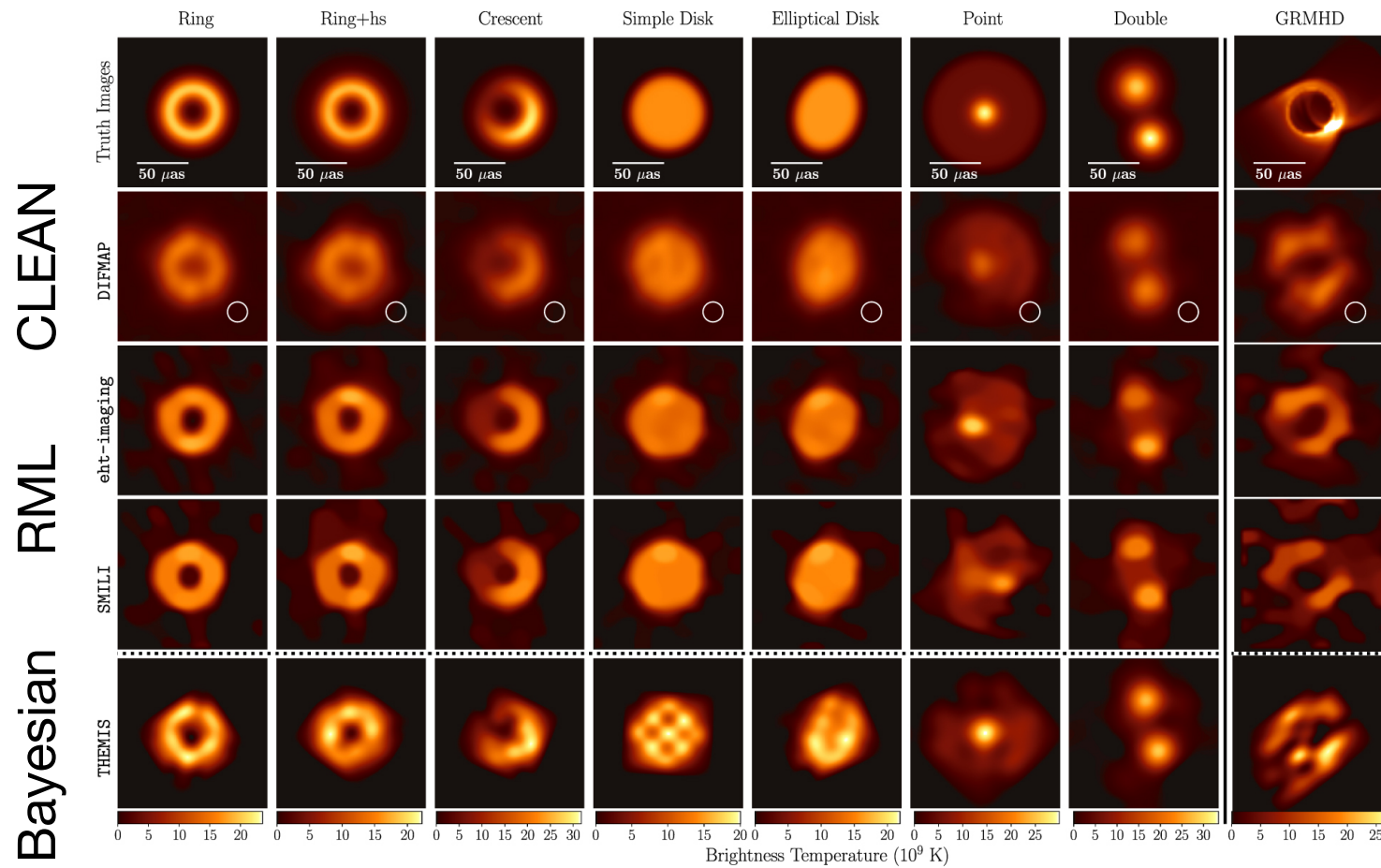
regularization terms  
e.g. related with Entropy

- Bayesian posterior sampling: a natural extension of RML
- Output a group of images => the typical image reconstruction + uncertainty

# Tests on these methods

Geometric Models

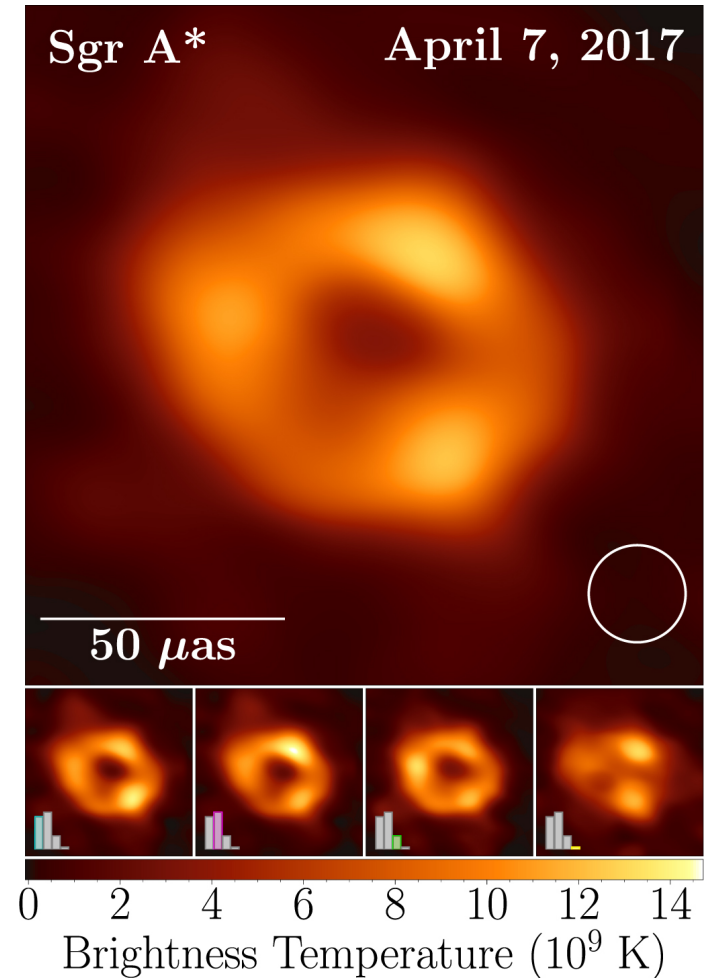
Simulation



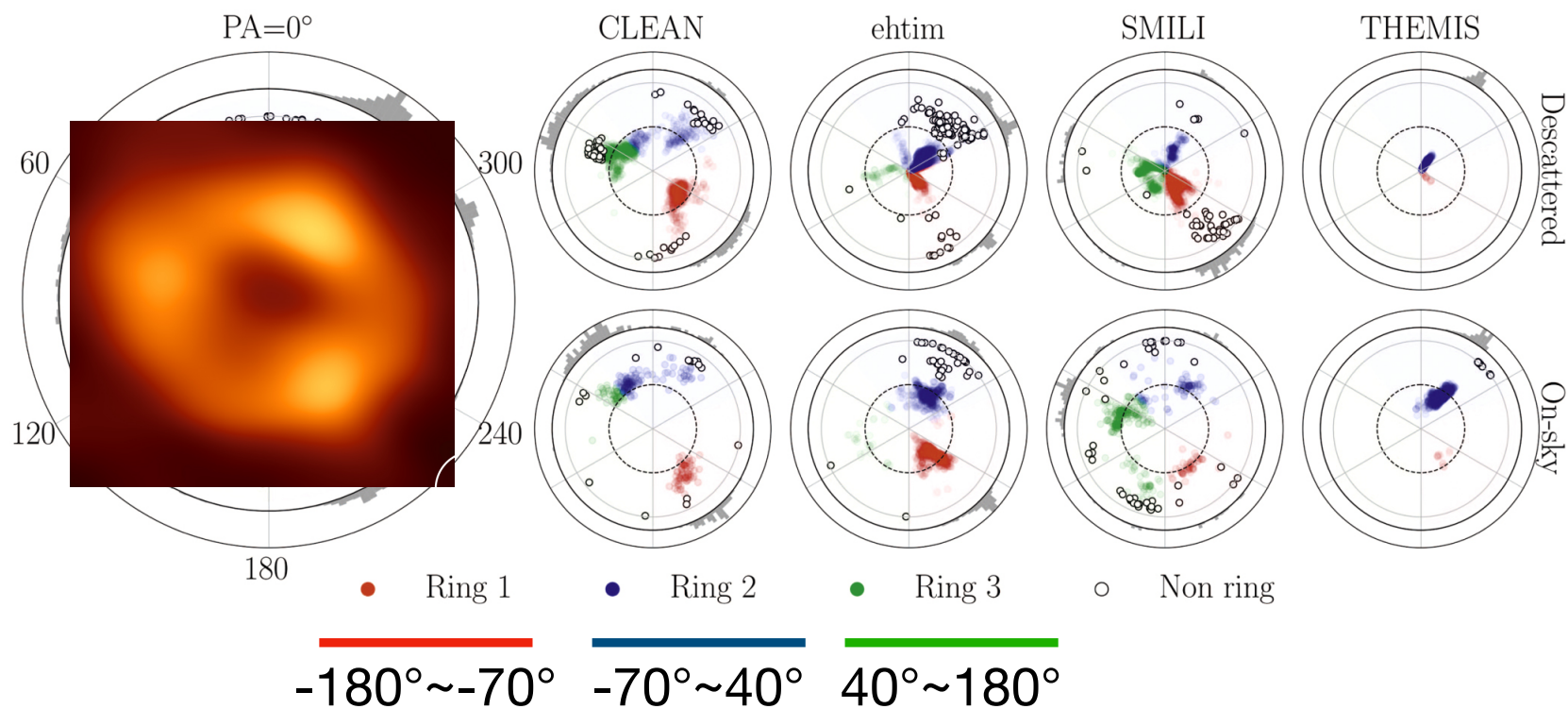
# Horizon-scale Images of Sgr A\*

- Based on the data from April 7.
- The average image of a Top Set images.
- Top Set: all acceptable images for data
  
- Three clusters with varying position angles
  
- A small fraction (<5%) of nonring images

**Sgr A\* is a ring!**



# Three knots?



Very large uncertainty in position angle!

Data properties (e.g., sparsity or low-S/N data)

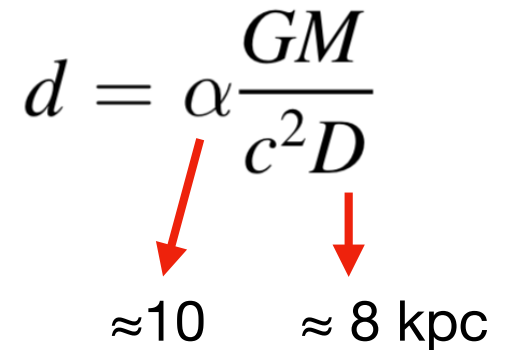
Intrinsic structure of Sgr A\*

# Basic Properties from Morphology

- Ring Size  $d$ :  $51.8 \pm 2.3 \mu\text{as}$
- Ring Thickness: 30~50% of  $d$
- Position Angle and Asymmetry: Not well confined
- Mass  $M$ :  $4.0_{-0.6}^{+1.1} \times 10^6 M_{\odot}$

$$d = \alpha \frac{GM}{c^2 D}$$

$\approx 10$        $\approx 8 \text{ kpc}$



# Short-timescale Dynamic Properties

- 60s snapshots during the 100-minute selected region.
- On April 6, most reconstructed images recover a stable position angle.
- But on April 7, the position angle evolution highly depends on position, prior assumption.

**May exhibit interesting and measurable dynamics**

**But cannot conclusively determine its evolution**

# summary

- Two challenges : Interstellar scattering & Short-timescale variability
- 95% ring images + 5% nonring images
- Ring Size:  $d \sim 50 \mu\text{as}$
- Mass:  $M \sim 4 \times 10^6 M_{\odot}$

# **Test Astrophysical Models and GR with Sgr A\***

Jiacheng Meng

2022.5.20

# Outline

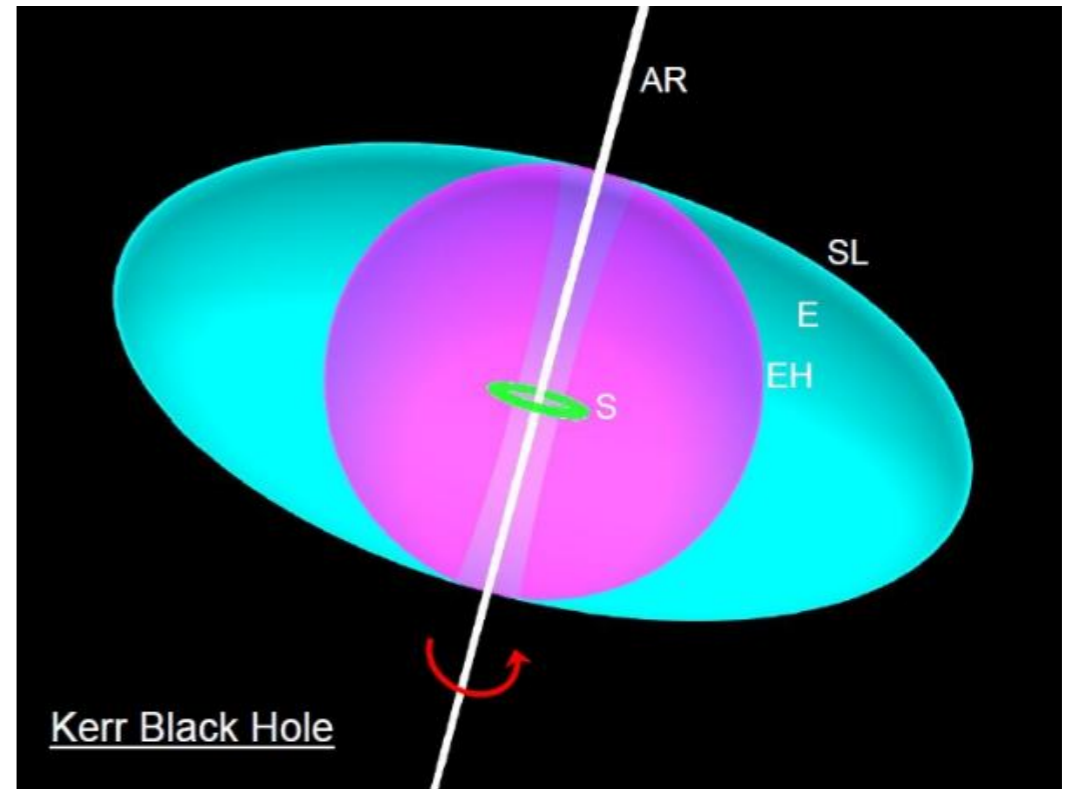
- The physical picture of Sgr A<sup>\*</sup>
- Test on astrophysical models of Sgr A<sup>\*</sup>
- Test on GR with Sgr A<sup>\*</sup>

# Kerr Black Hole

1

**No-hair theorem:** black holes are determined by mass, electric charge, and angular momentum.

**Kerr black hole:** possesses only mass and angular momentum.



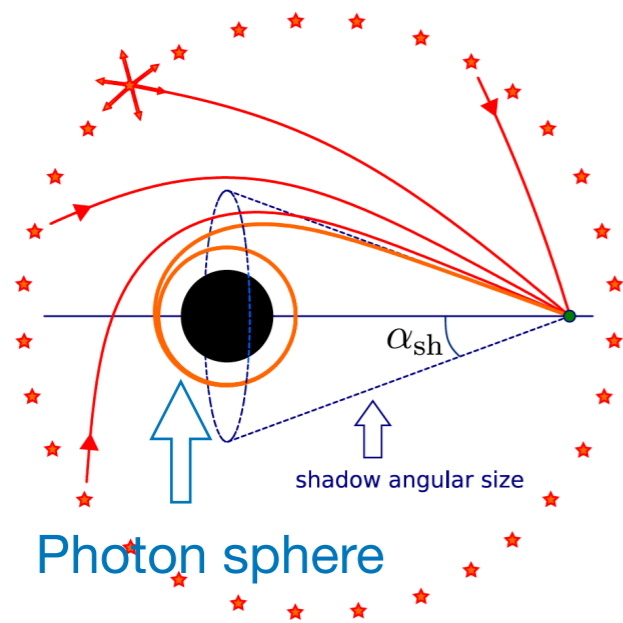
$$\text{Dimensionless spin: } \alpha_* \equiv \frac{Jc}{GM^2} \quad -1 < \alpha_* < 1$$

$$\text{Event horizon: } r_e = (1 + \sqrt{1 - a_*^2}) \frac{GM}{c^2}$$

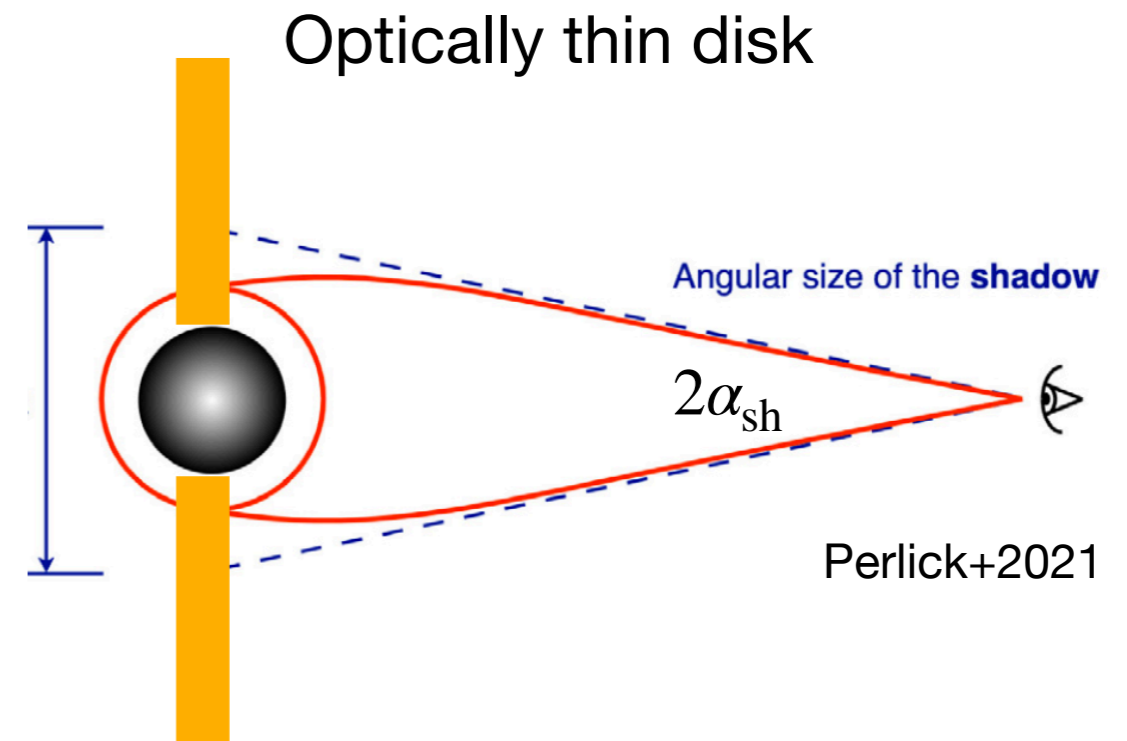
$$\text{Define: } r_g = \frac{GM}{c^2} \quad \text{If } \alpha_* = 0, r_e = 2r_g \text{ (Schwarzschild black hole).}$$

# Black Hole Shadow and Bright Ring

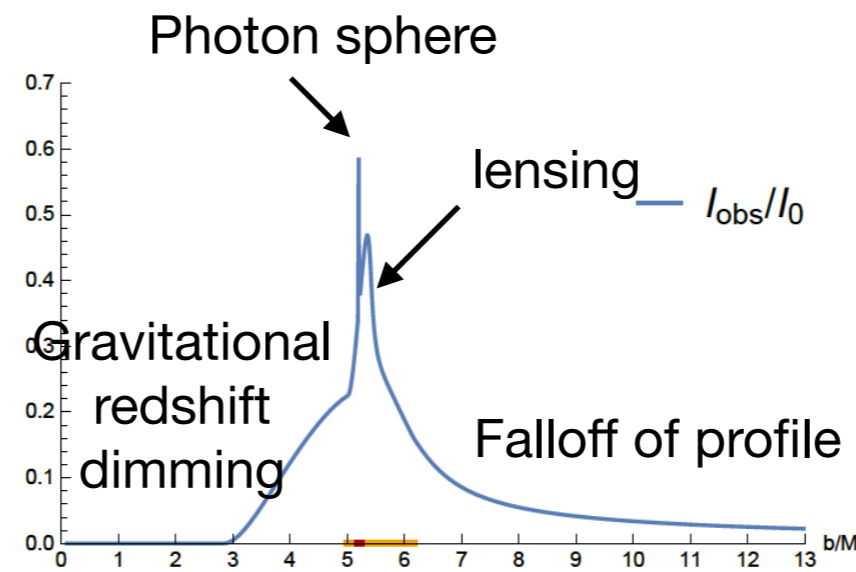
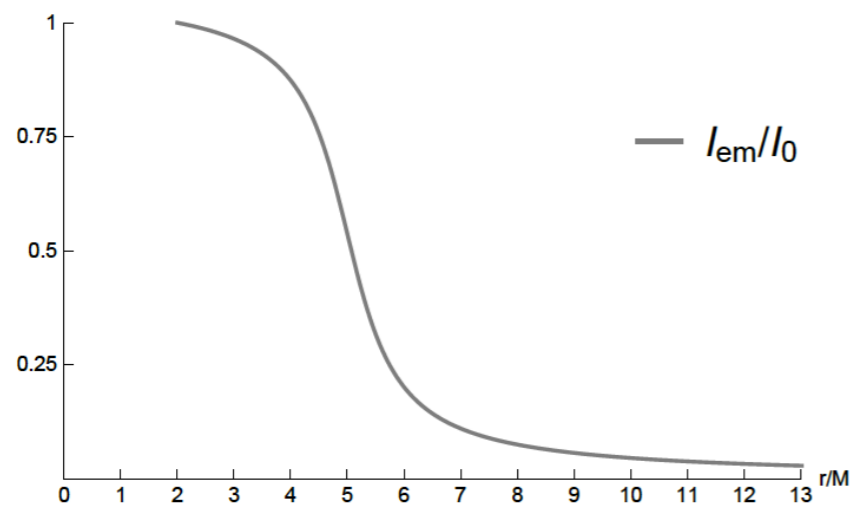
Schwarzschild black hole  $r_{ph} = 3r_g$



$$2r_{sh} = 2 \times 3\sqrt{3}r_g$$



Perlick+2021



Gralla+2019

Similar to the situation of Kerr black hole.

# Hot Accretion Flows Around Black Holes

- Sgr A\* has low luminosity

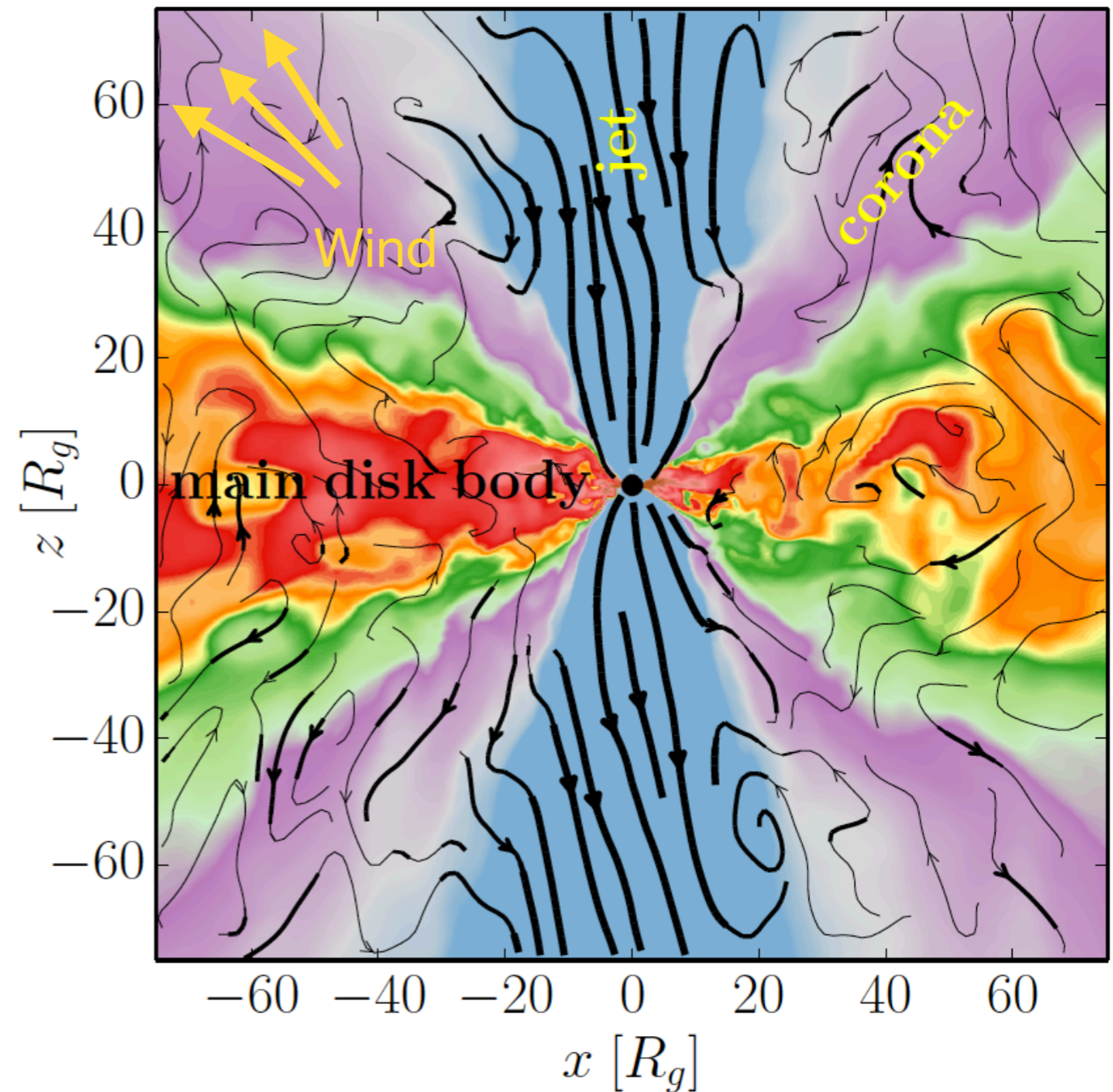
$$\frac{L_{\text{bol}}}{L_{\text{Edd}}} \sim 1.9 \times 10^{-10}$$

- Advection-dominated accretion flow (ADAF)

$$\beta = \frac{P_{\text{gas}}}{P_{\text{mag}}}$$

1. Disk:  $\beta \sim 10 - 100$ , equatorial inflow
2. Corona:  $\beta \sim 1$ , wind

3. Funnel:  $\sigma = \frac{B^2}{4\pi\rho c^2} \gg 1$ , jet



# Two Modes of ADAF

Magnetic flux through the horizon  $\phi$

Standard and normal evolution (SANE)

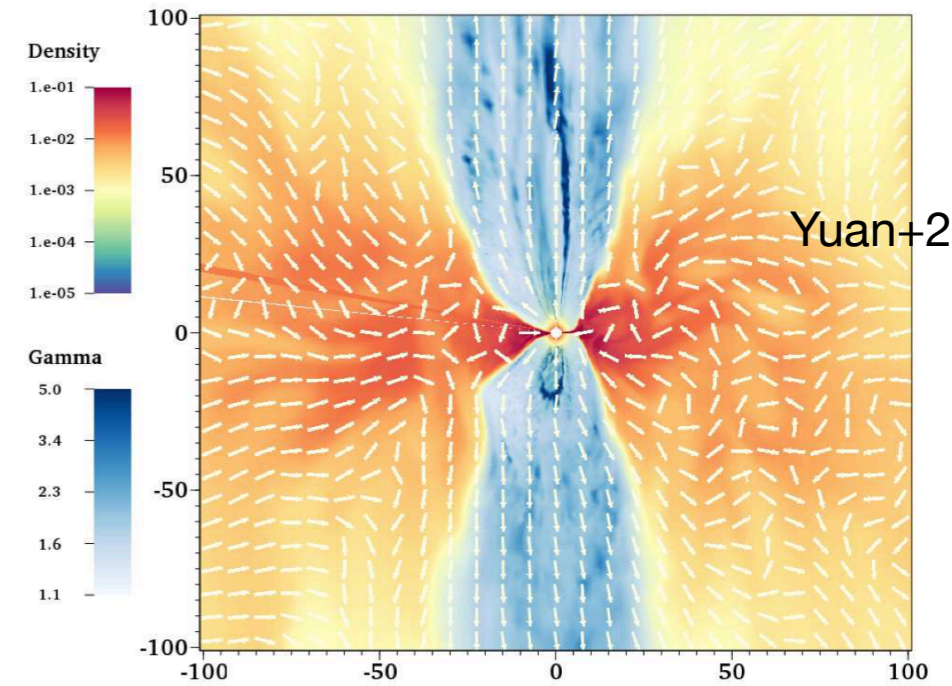
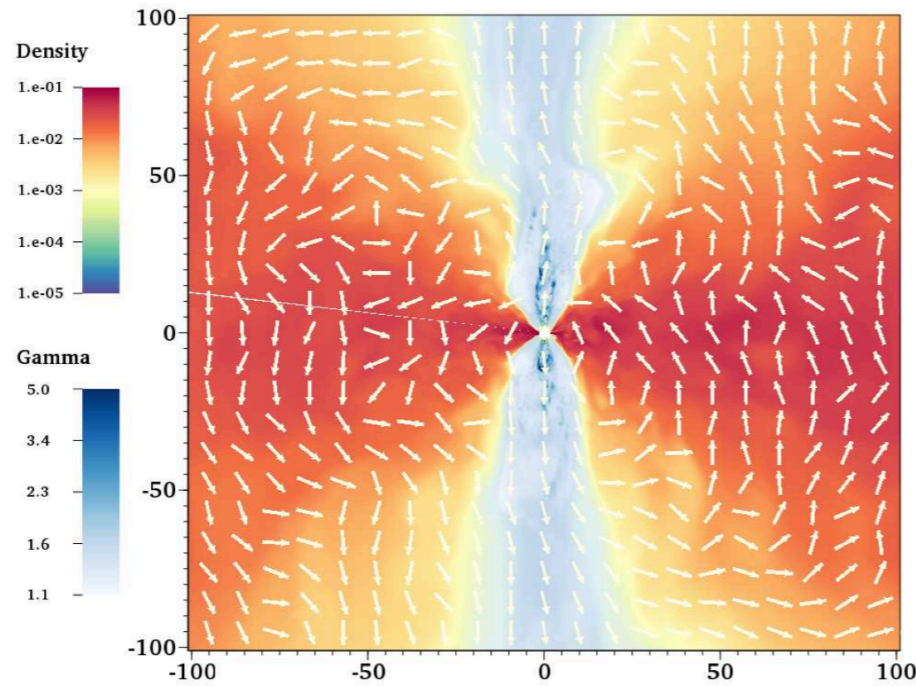
$$\phi \sim 1$$

Magnetically arrested disk (MAD)

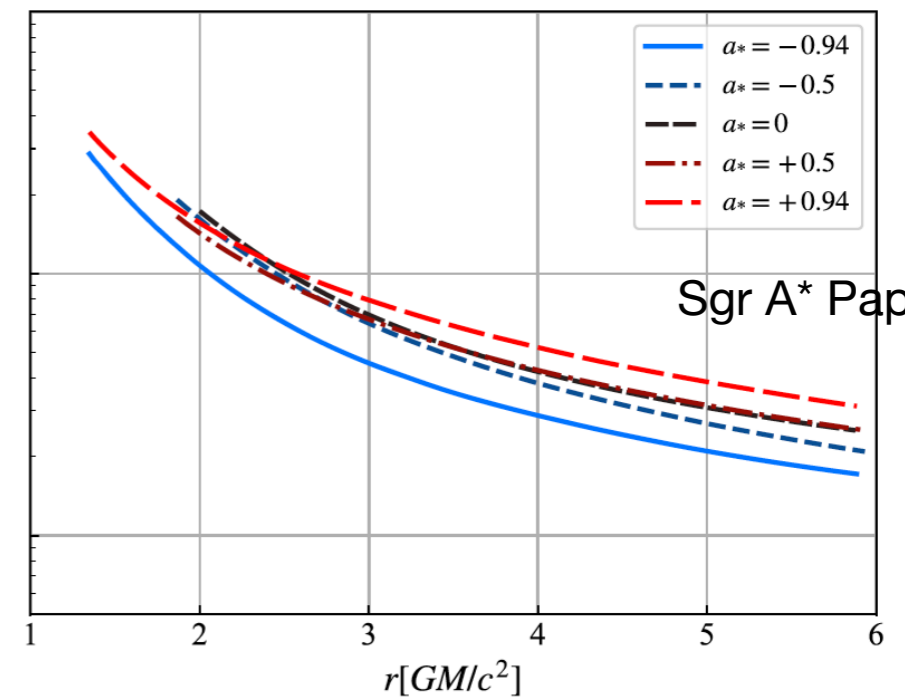
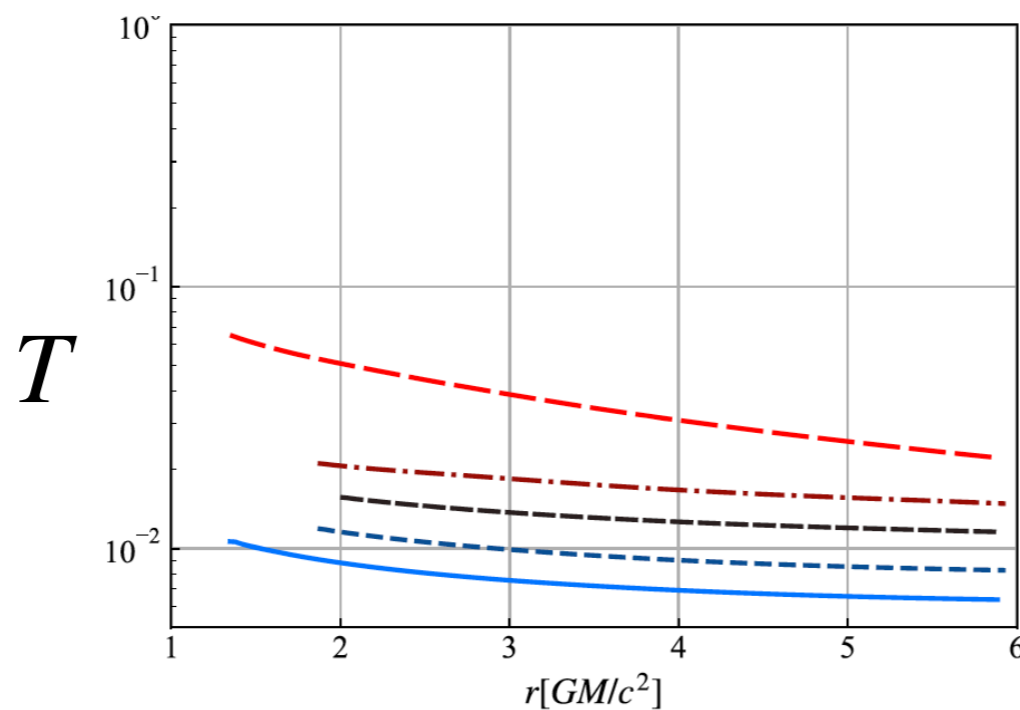
$$\phi \sim 60$$

Density

Velocity



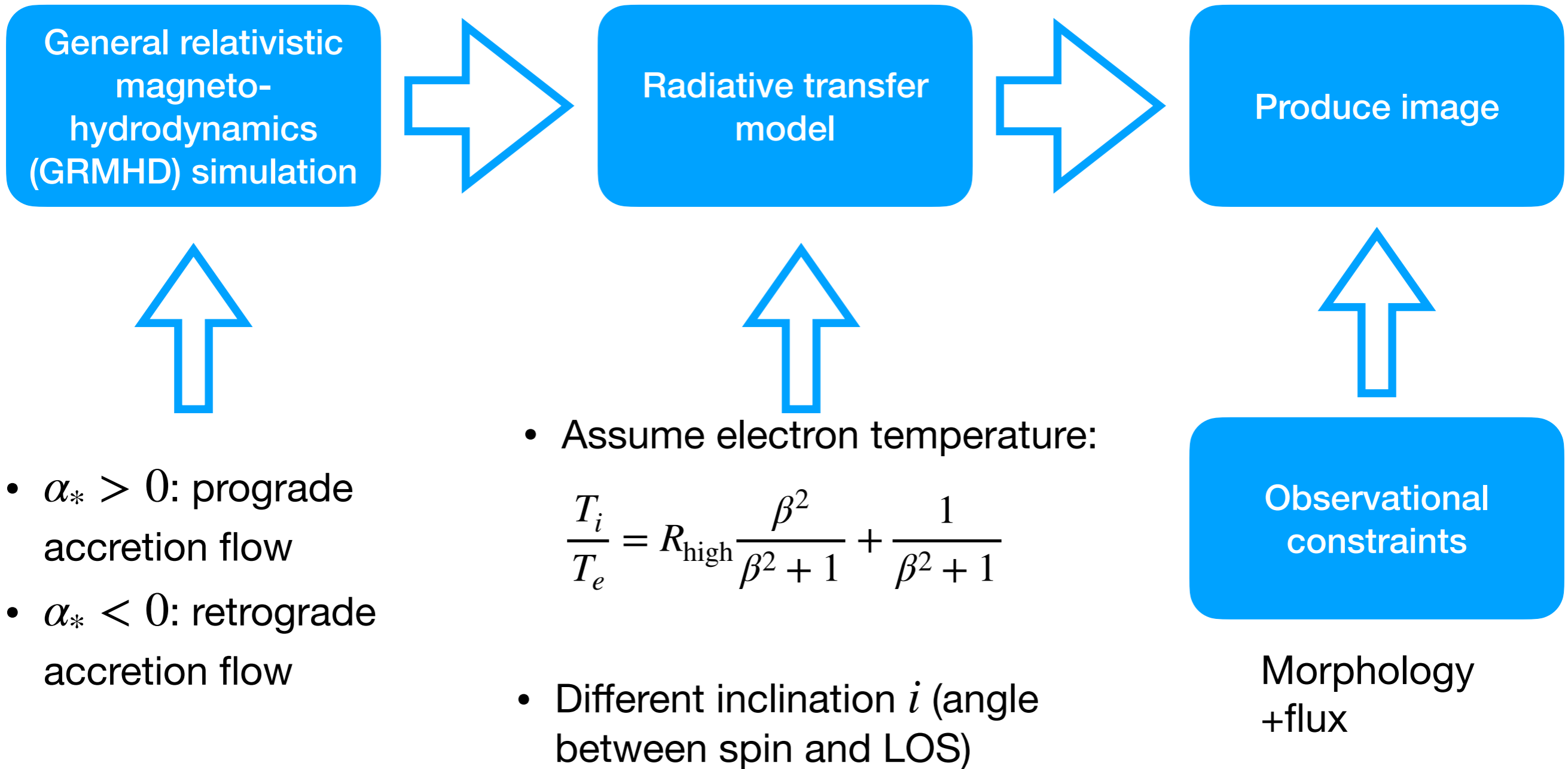
Yuan+2014



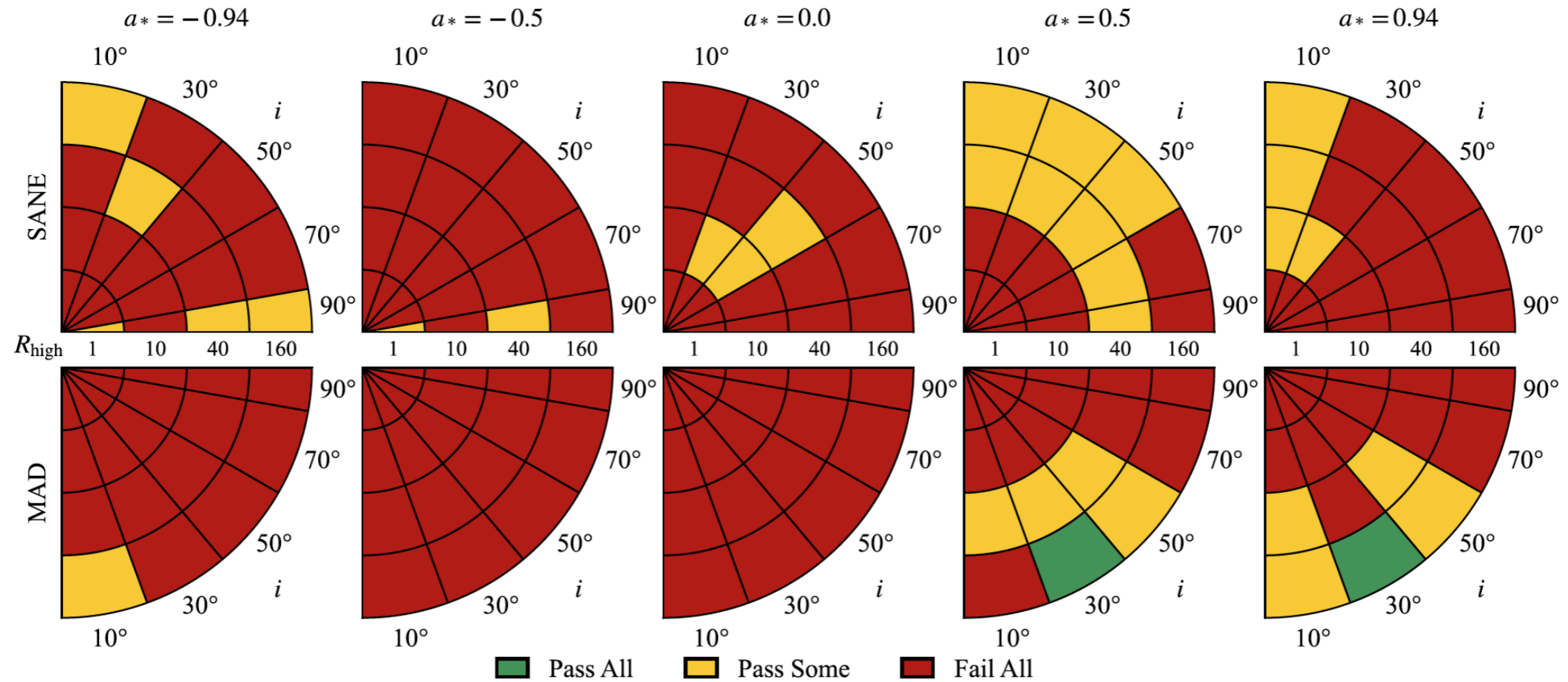
Sgr A\* Paper V

- $a_* = -0.94$
- - -  $a_* = -0.5$
- - -  $a_* = 0$
- . - .  $a_* = +0.5$
- - -  $a_* = +0.94$

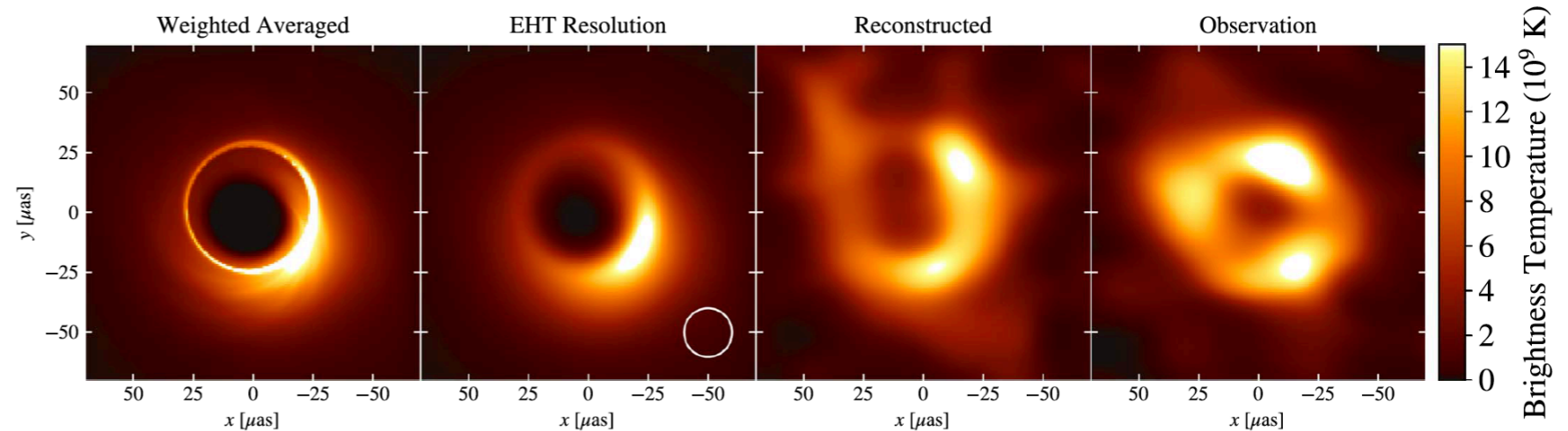
# Test on Astrophysical Models of Sgr A\*



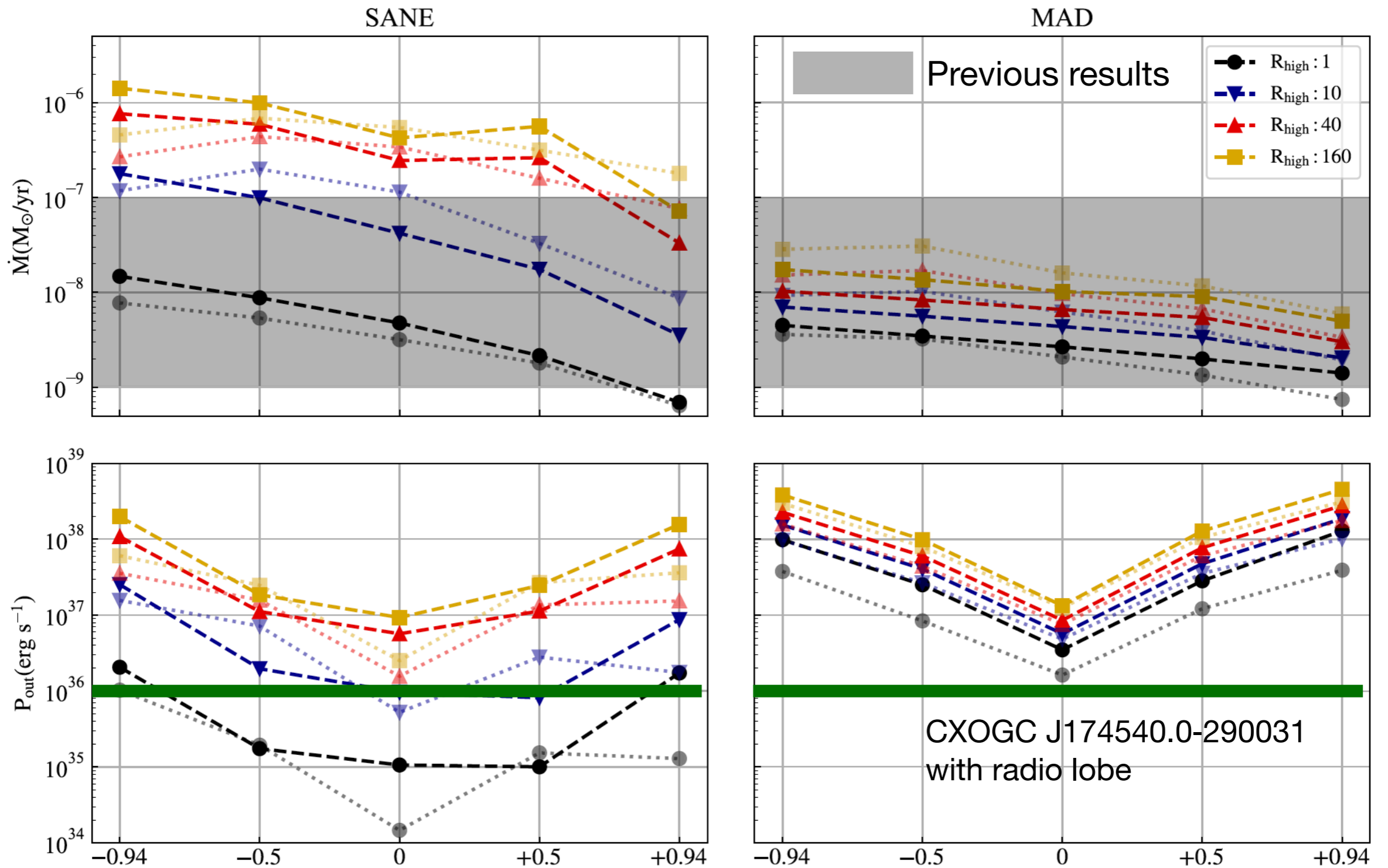
# Model Comparison



- Disfavor: (1) high inclination ( $i > 50^\circ$ ); (2) non-spinning black holes; (3) retrograde accretion disks.

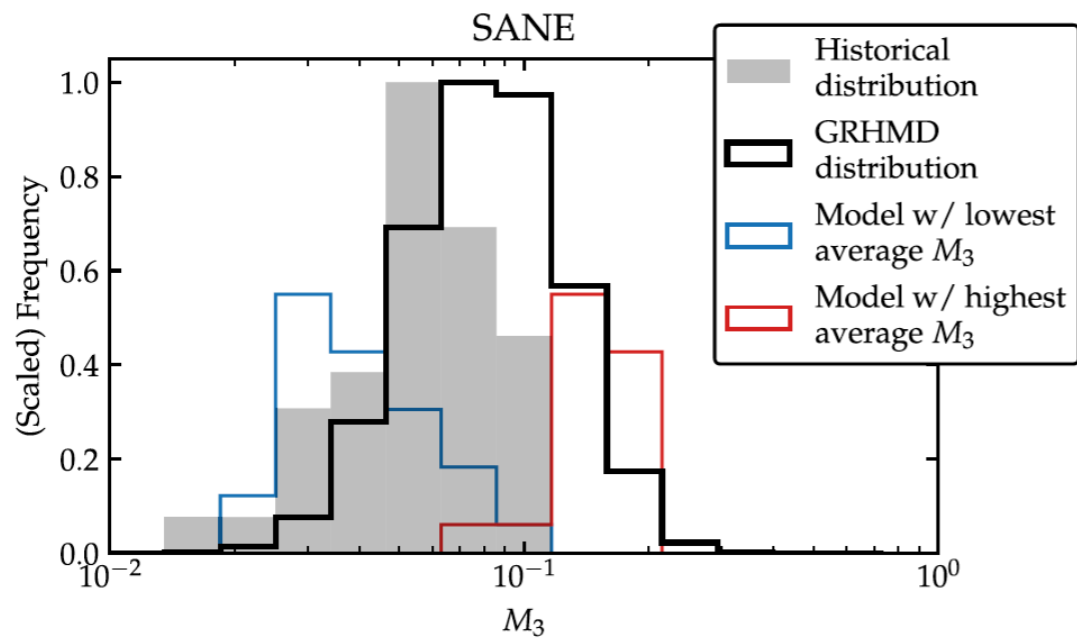
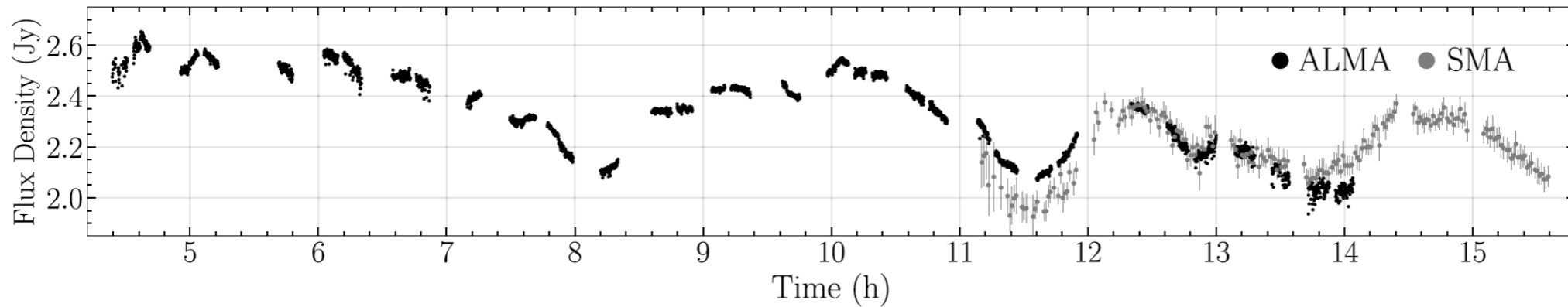


# Accretion Rate and Outflow Power



$\alpha_*$

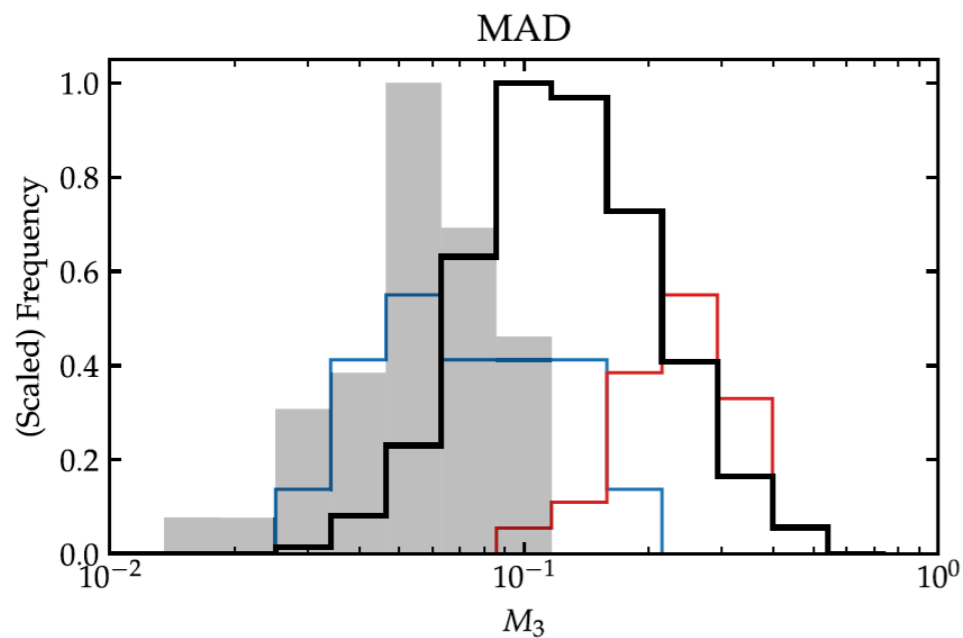
# Failure on Flux Variability



$$\text{Modulation index: } M_3 = \frac{\sigma_{3\text{hr}}}{\mu_{3\text{hr}}}$$

## Reason:

1. Some flux from extended structure that is slowly varying.
2. Missing physics in models.



# Test on GR with Sgr A\*

**Bright ring diameter:**  $\hat{d}_m = \alpha_c d_{\text{sh}} = \alpha_c (1 + \delta) 6\sqrt{3} \theta_g$

$\alpha_c$ : calibration factor, from simulation

$d_{\text{sh}}$ : shadow diameter

$$\theta_g = \frac{GM}{Dc^2}$$

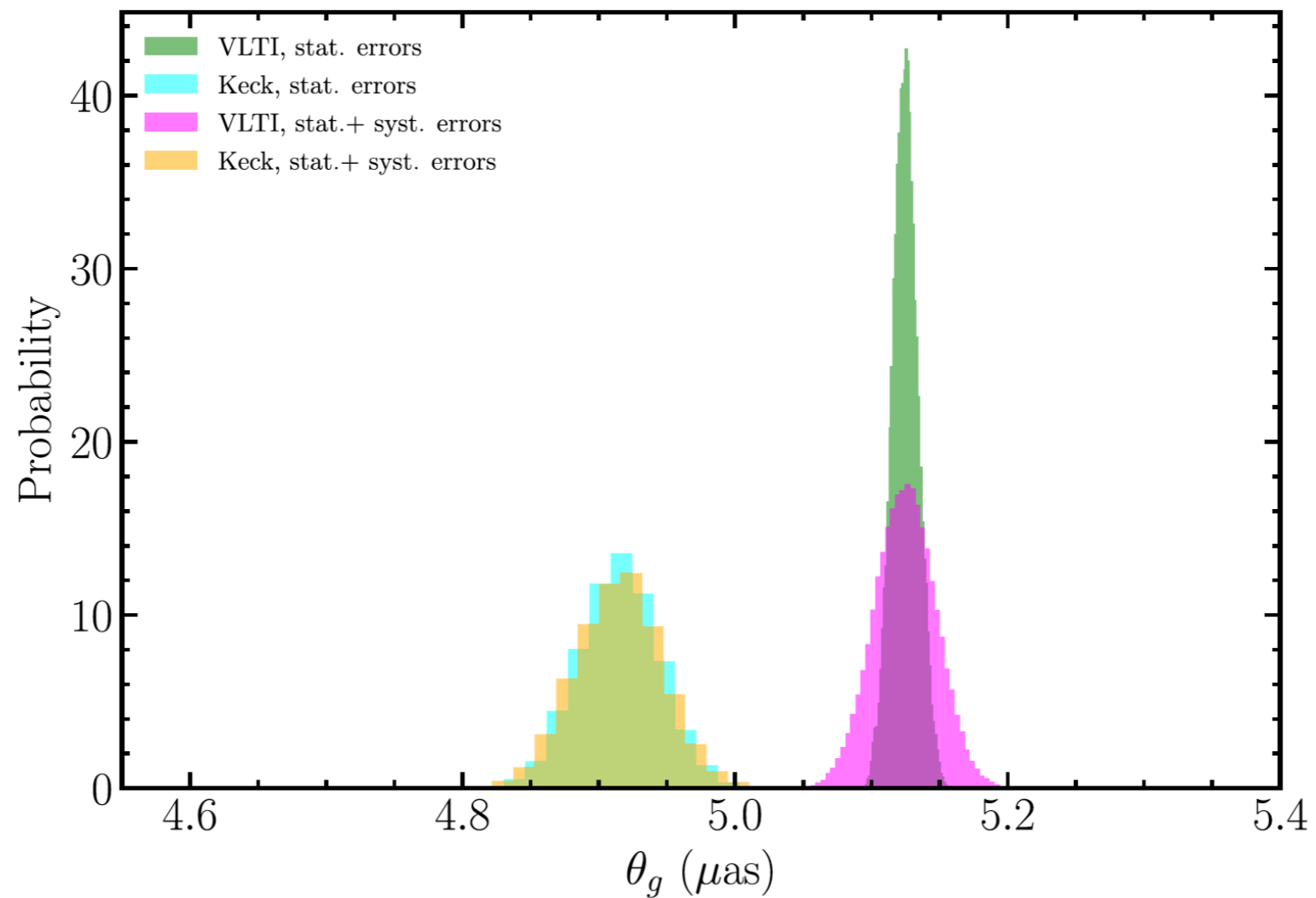
$\delta$ : deviation from Schwarzschild black hole

**Kerr prediction:**  $\delta \in [-7.5\%, 0]$

# Prior on $\theta_g$

$$\theta_g = \frac{GM}{Dc^2}$$

Mass and distance can be measured from the dynamics of stars around Sgr A\*.

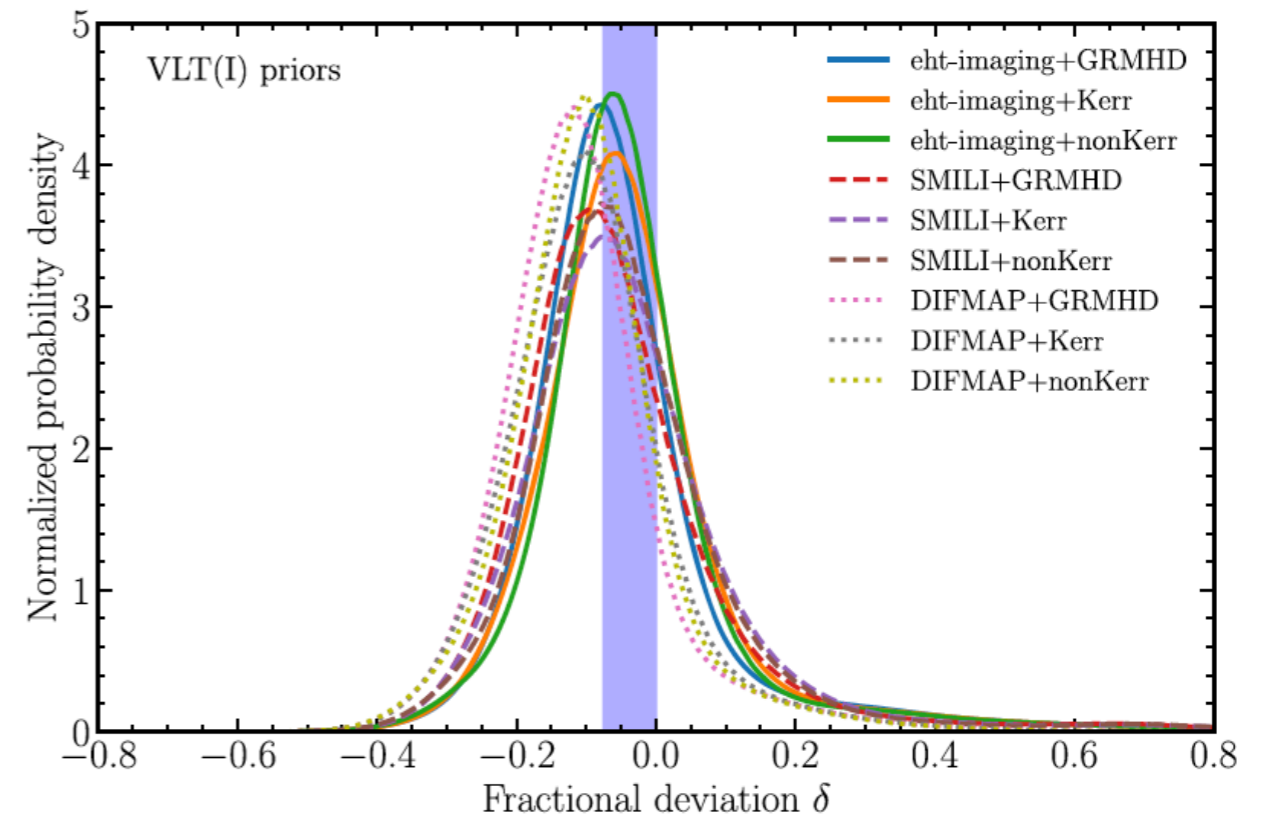
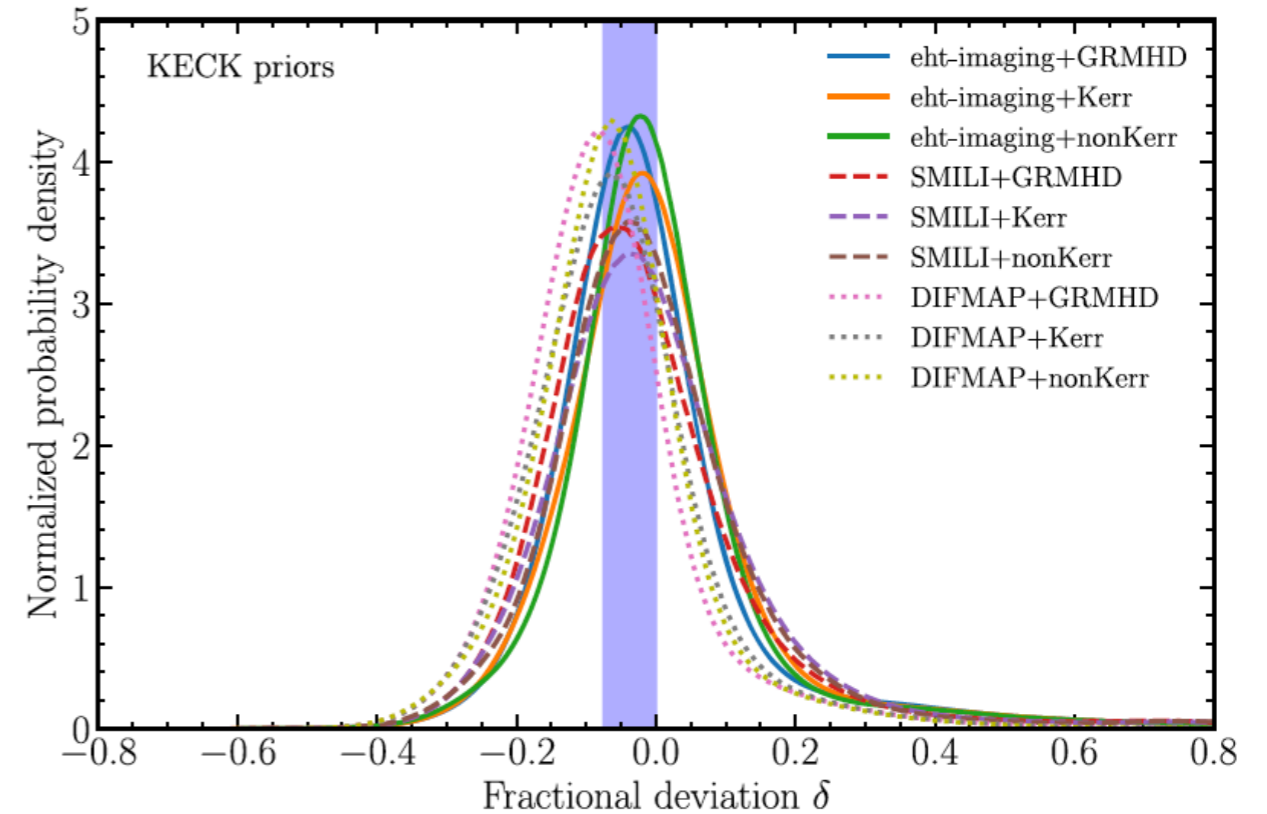


# Bayesian inference on $\delta$

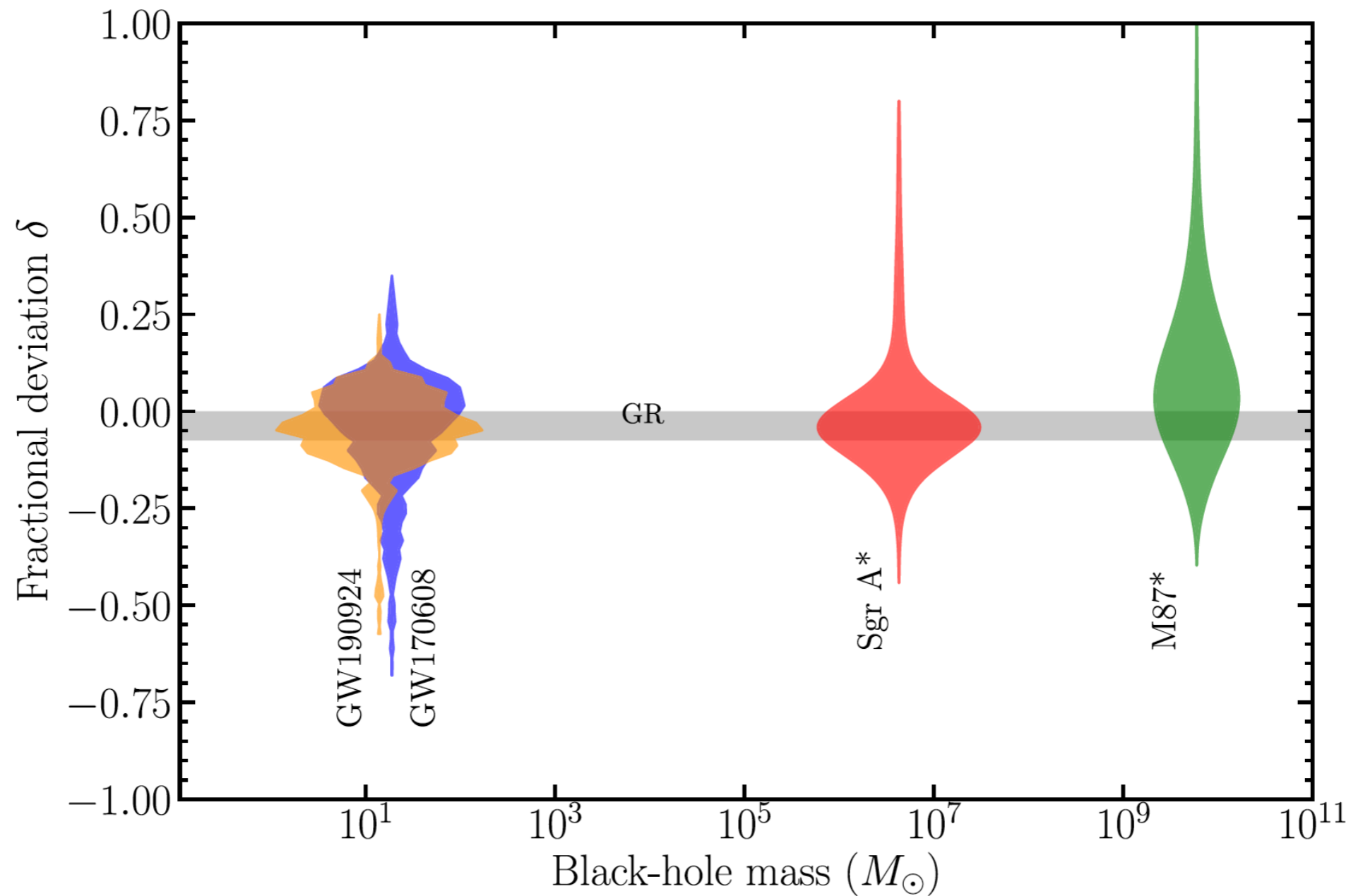
- For measured bright ring diameter  $\hat{d}$ , the posterior distribution is

$$P(\delta | \hat{d}) \sim \underbrace{\mathcal{L}(\hat{d} | \delta, \theta_g, \alpha_c)}_{\text{Likelihood function}} \times \underbrace{P(\delta)P(\theta_g)P(\alpha_c)}_{\text{Prior}}$$

- Results are consistent with GR.



# Comparison to other tests



Sgr A\* Paper VI

- Results are consistent with GR across 8 orders of magnitude.

# Summary

- Sgr A\* is a Kerr black hole and there are advection-dominated accretion flow (ADAF) around it.
- Simulation models can explain the morphology and flux from the EHT observation, but have variability excess.
- Combined with GW and EHT results of M87\*, the results are consistent with GR across 8 orders of magnitude.