Exploring the Growth History of Massive Black Holes by Measuring the Spin of the Massive Black Hole Sagittarius A*

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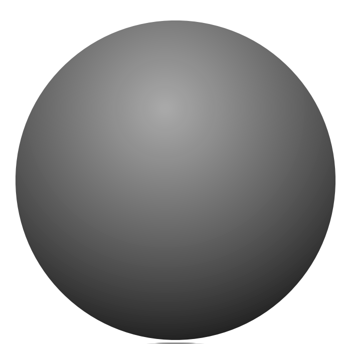
- Modeling black hole accretion flows
- Examining the models for radiative properties
  - Multi-wavelength spectra and images
- Determine the properties of black hole
  - Mass
  - Spin



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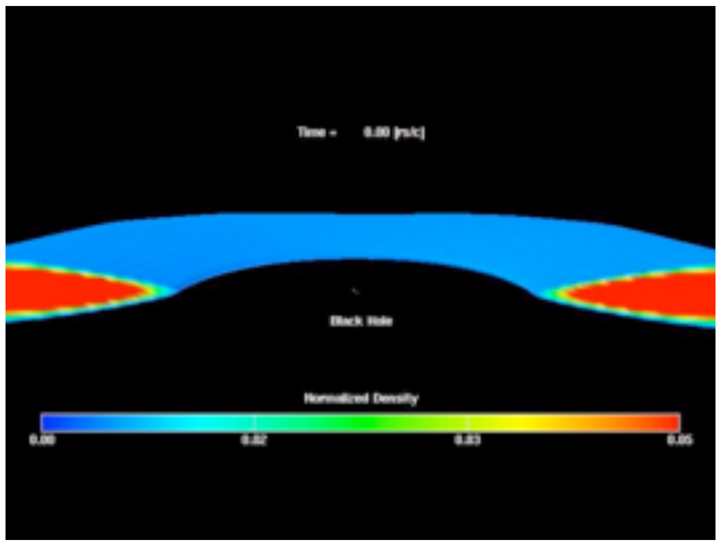
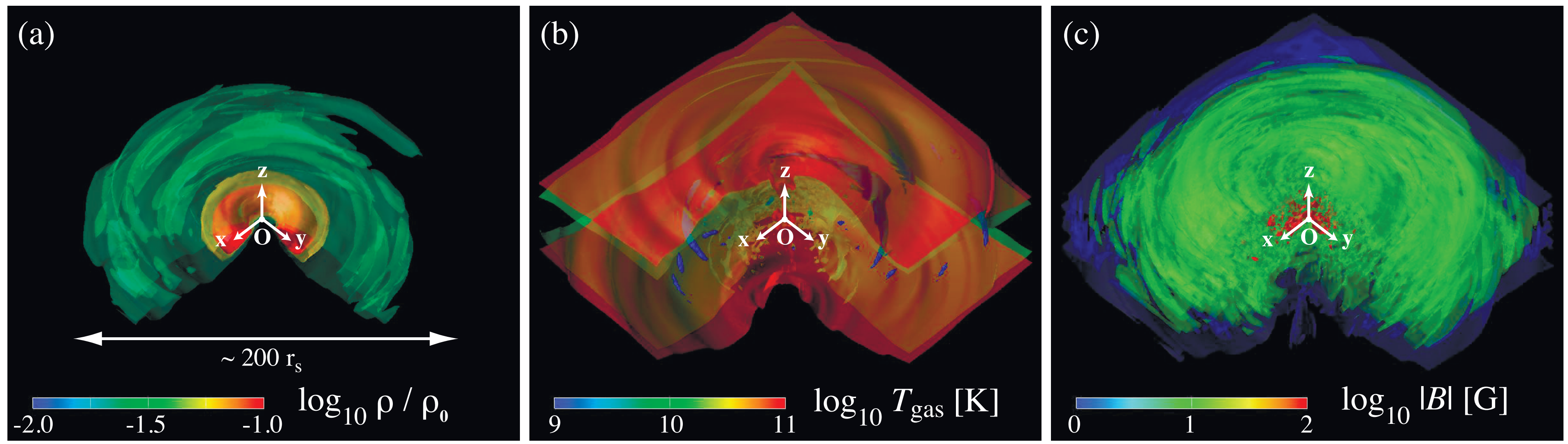
MHD Models of BH Accretion Flows

YK, Umemura, Ohsuga (2009)





$$\frac{1}{c}\frac{\partial \boldsymbol{I}_\nu}{\partial t} + \boldsymbol{n}\cdot\nabla \boldsymbol{I}_\nu = \chi_\nu(\boldsymbol{S}_\nu - \boldsymbol{I}_\nu) \longrightarrow \boldsymbol{n}\cdot\nabla \boldsymbol{I}_\nu = \chi_\nu(\boldsymbol{S}_\nu - \boldsymbol{I}_\nu)$$

$\boldsymbol{I}_\nu(\boldsymbol{r}, \boldsymbol{n}; t)$: specific intensity

$\chi_\nu(\boldsymbol{r}, \boldsymbol{n}; t) = \kappa_\nu + \sigma_\nu$: extinction coefficient

$$\boldsymbol{S}_\nu = \frac{\varepsilon_\nu}{4\pi\chi_\nu} + \alpha_\nu \oint \phi(\boldsymbol{n}; \boldsymbol{n}')\boldsymbol{I}_\nu(\boldsymbol{n}')d\boldsymbol{\Omega}'$$

$\varepsilon_\nu(\boldsymbol{r}, \boldsymbol{n}; t)$: emissivity

$\alpha_\nu = \frac{\sigma_\nu}{\chi_\nu}$: scattering albedo $\quad \phi(\boldsymbol{n}; \boldsymbol{n}')$: phase function

Free Parameters

$$\dot{M}_{\mathrm{accretion}} \leftrightarrow (\rho,\ M_{\mathrm{BH}})$$

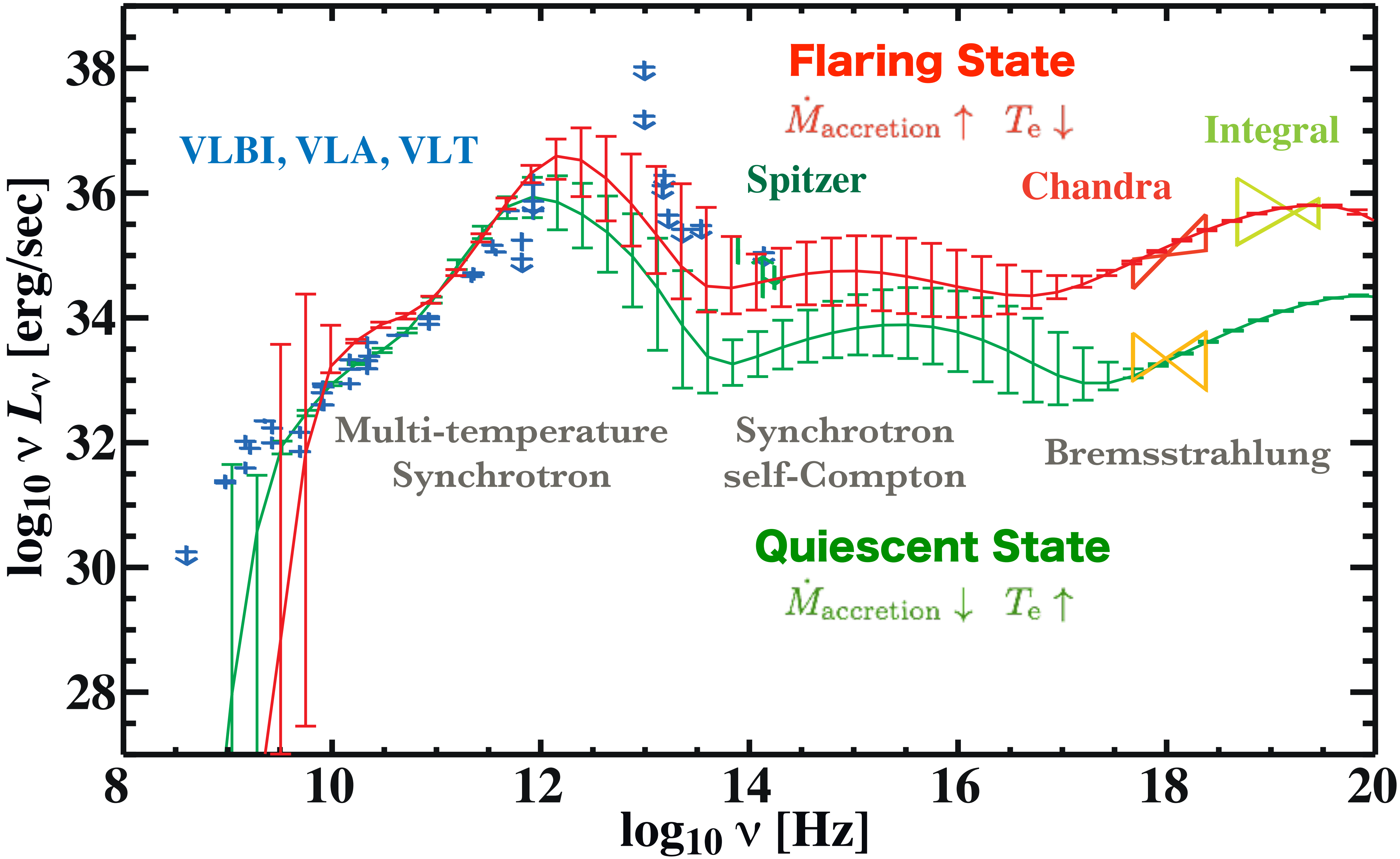
$$f_{\mathrm{ep}} = T_{\mathrm{e}}/T_{\mathrm{p}}$$

Monte-Carlo 3-D Full Radiative Transfer

→ Spectra & Imaging (& Polarization)

The SED of MHD Models and Sgr A*

YK, Umemura, Ohsuga (2009)

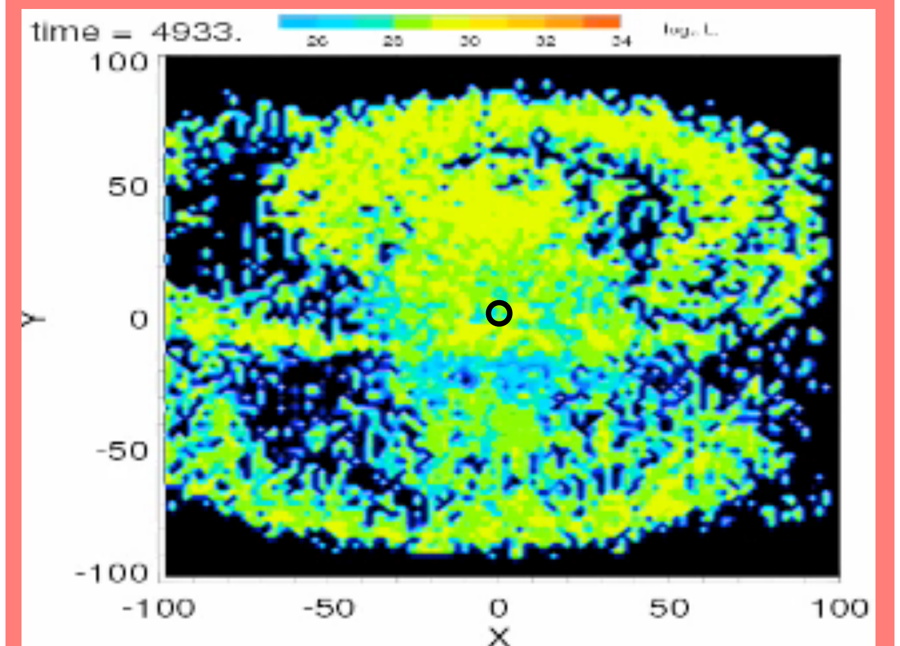


Emission Maps of MHD Models

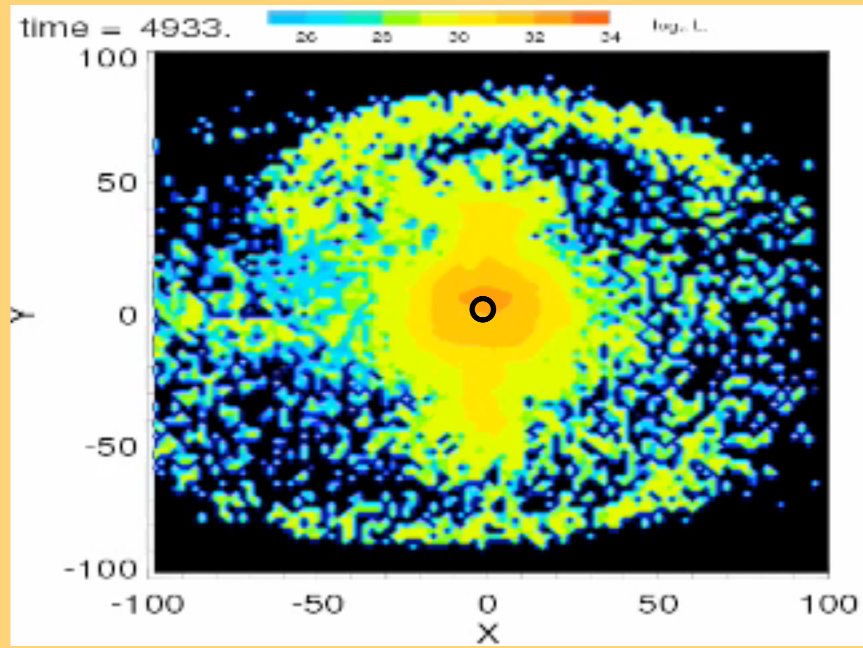
YK, Umemura, Ohsuga (2009)

Size of BH shadow

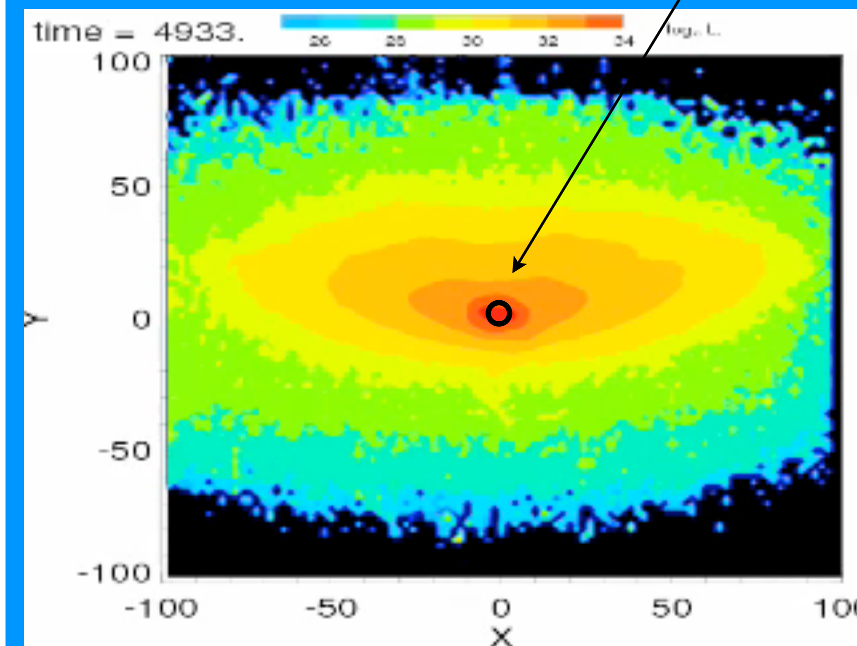
10 - 100 GHz



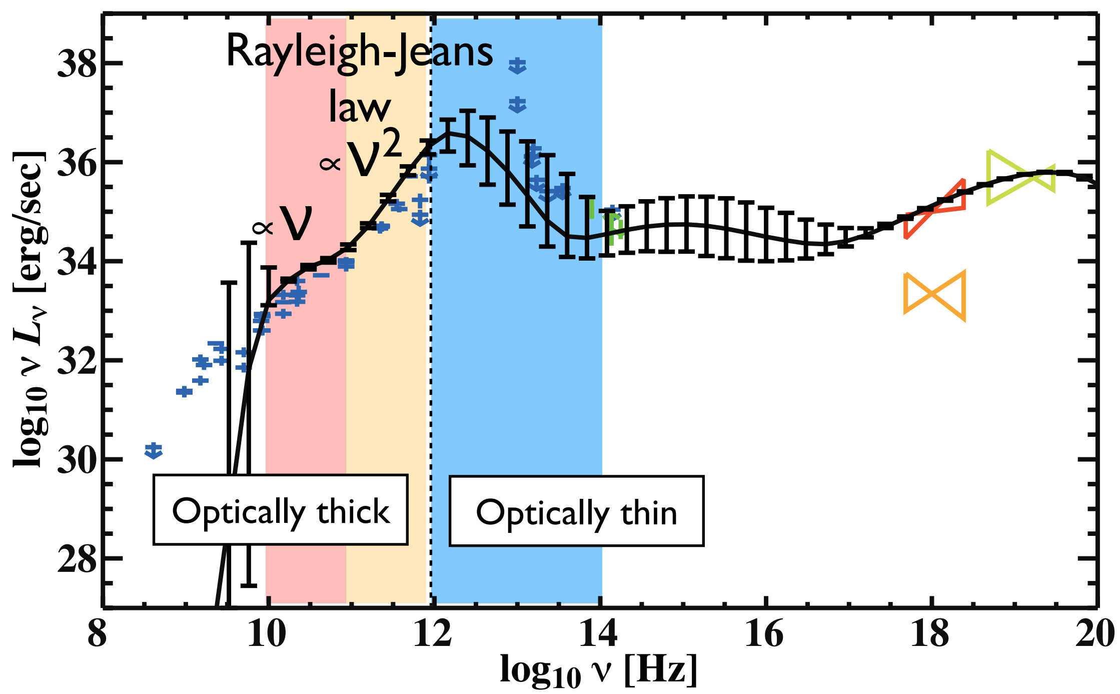
0.1 - 1 THz



1 - 100 THz



Diffused emission region
One/Two-armed structure



Disk like emission region
High variability

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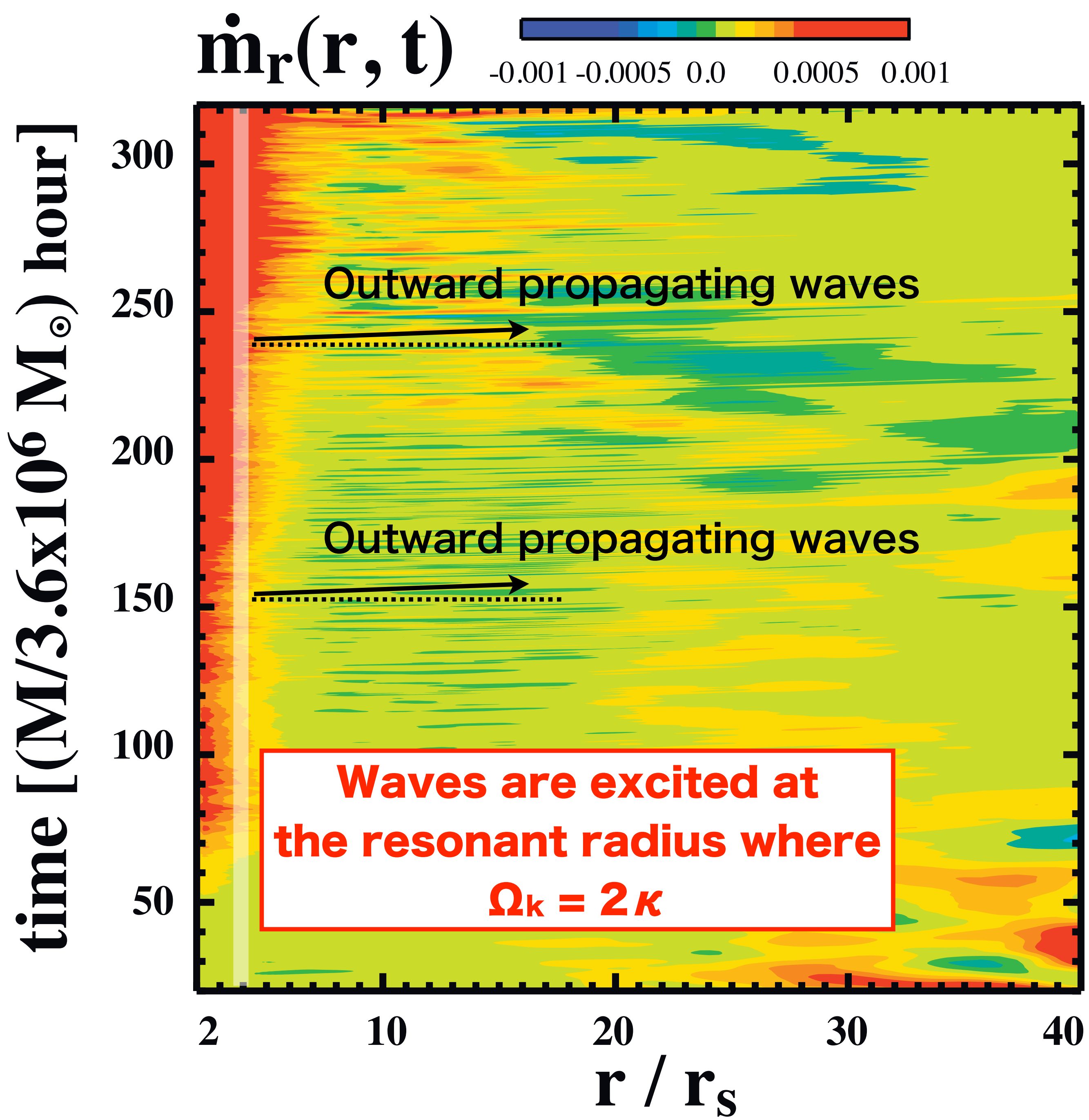
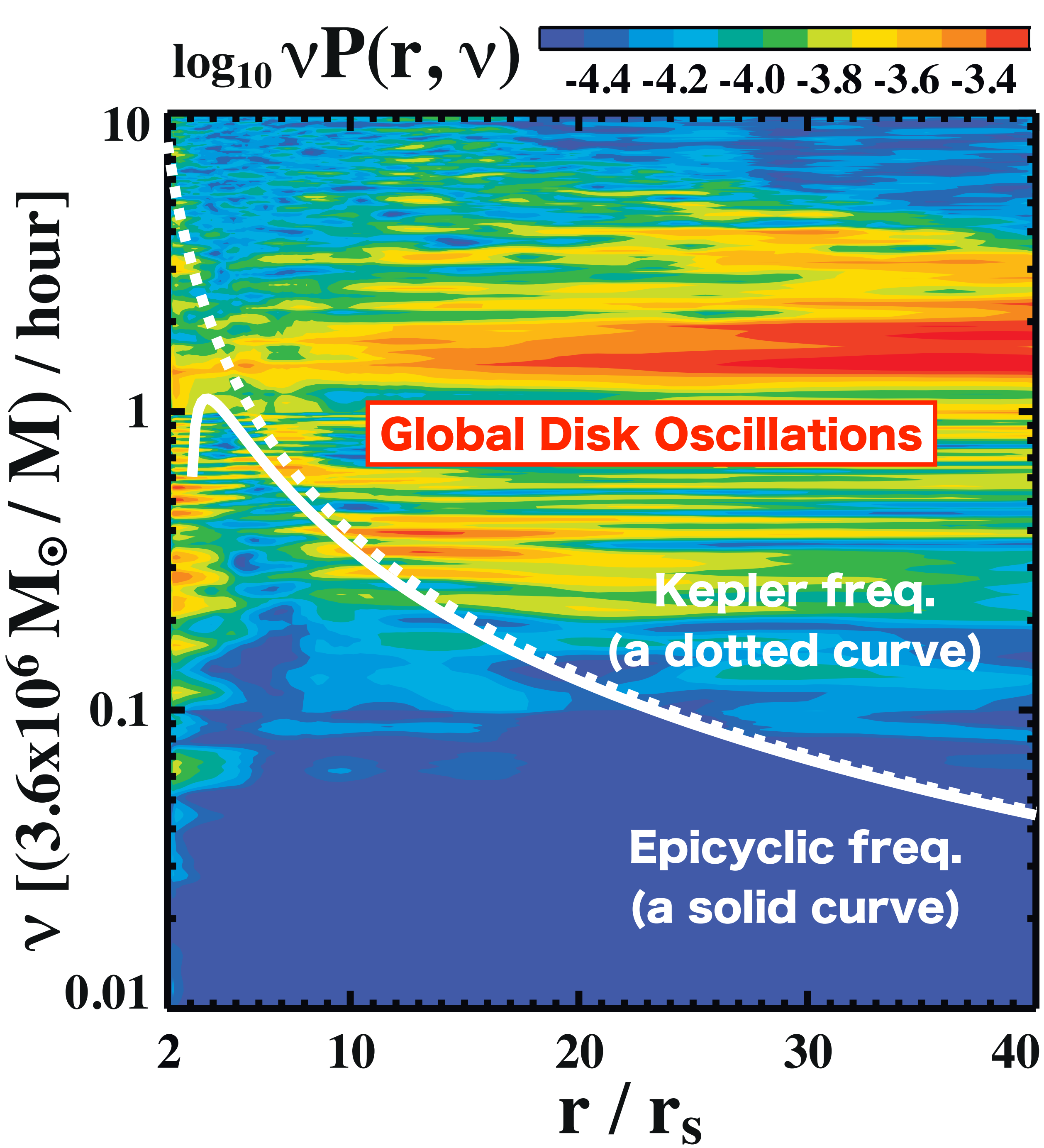
Excitation acoustic wave in the accretion disk

YK (2004)

The radial mass flux

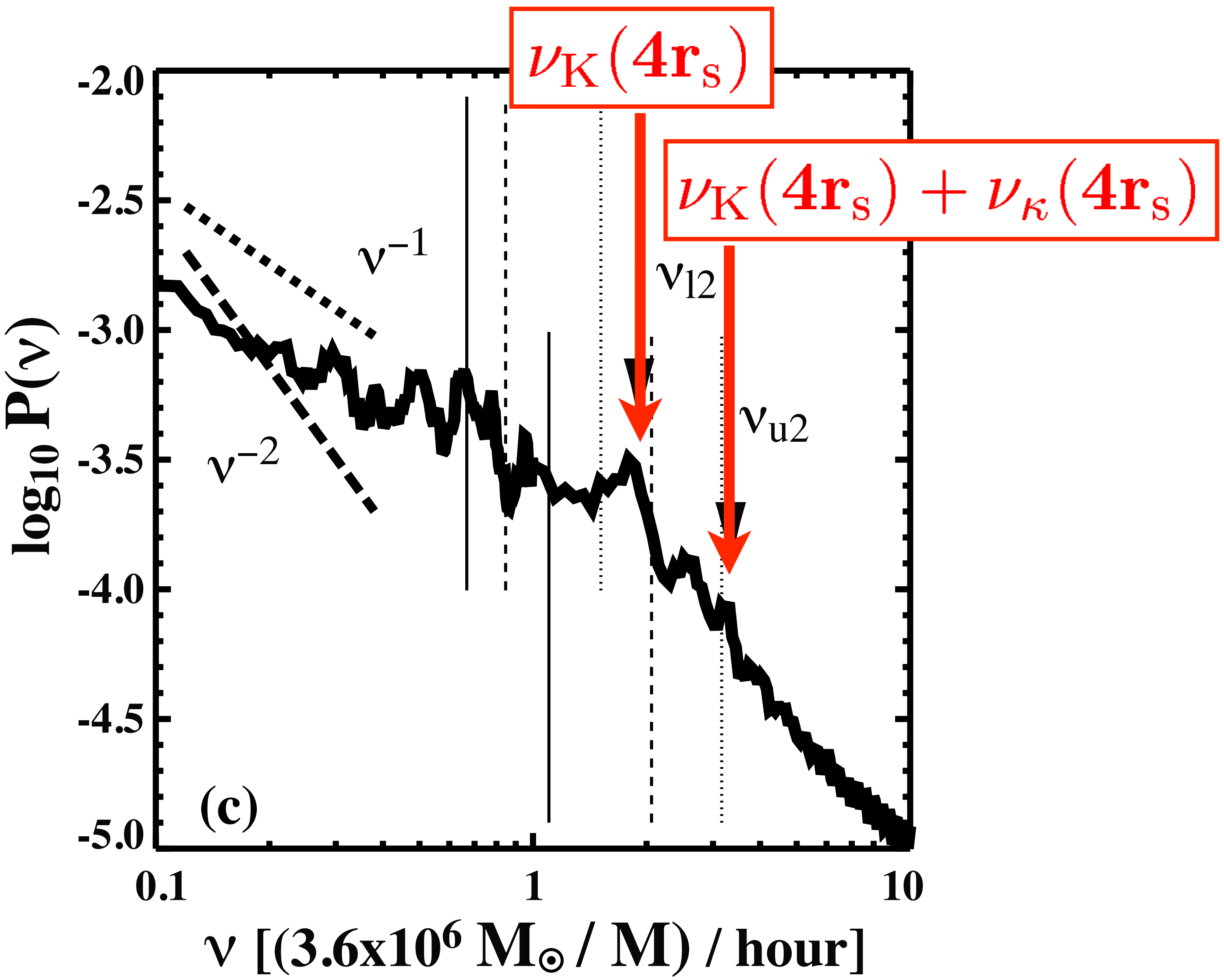


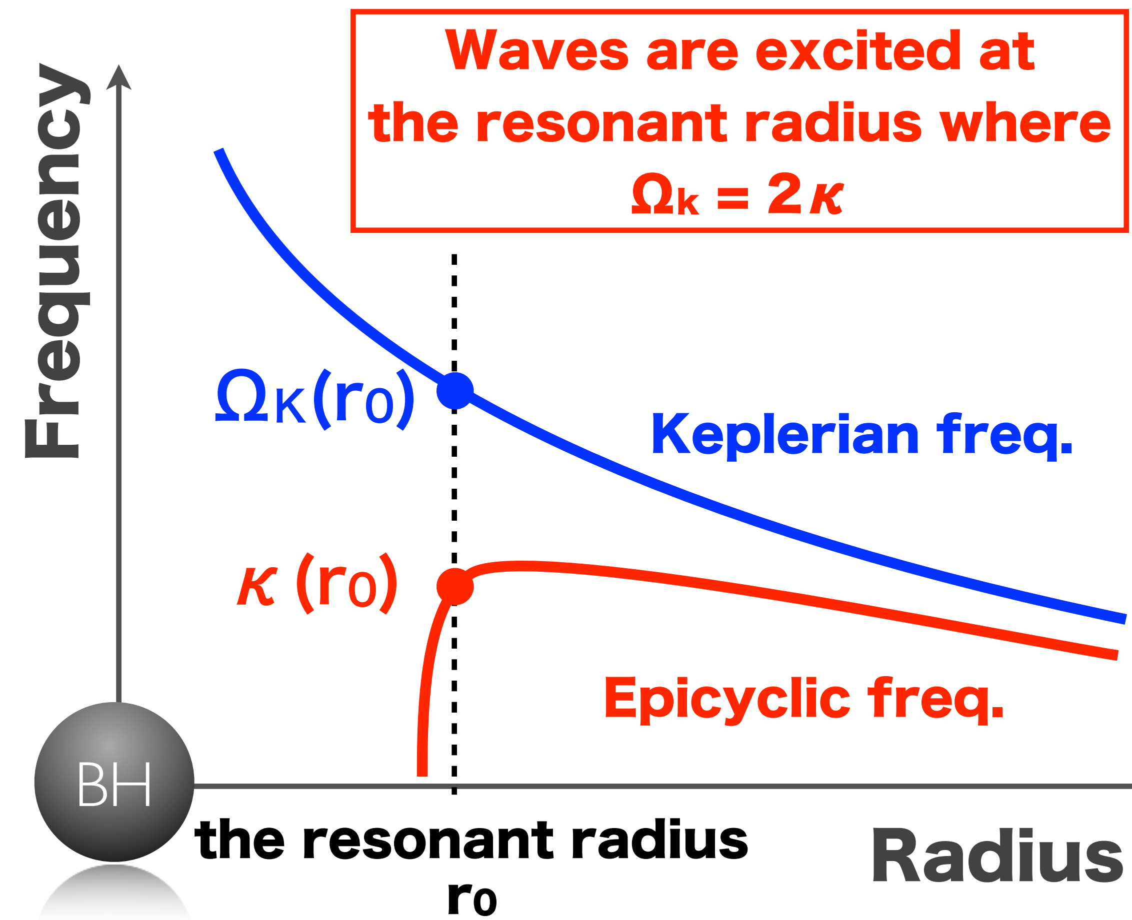
PSD of the radial mass flux



Power Spectrum of Variable Mass Accretion Flows

YK (2004)





Ω_{K0}	:	$\Omega_{K0} + \kappa_0$	:	$2\Omega_{K0}$
2	:	2 + 1	:	2×2
2	:	3	:	4

BH mass and spin can be measured by detecting the resonant disk oscillations whose ratio are 2 : 3 : 4

Concept for measuring the spin of BH

by using the resonant disk oscillations

- Properties of BHs (Mass and Spin)

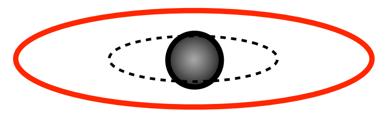
Geodesic frequencies
Keplerian freq. : Ω_k
Epicyclic freq. : κ

- Properties of Accretion Disks

Resonant disk oscillations
$\Omega_k : \Omega_k + \kappa : 2\Omega_k = 2 : 3 : 4$

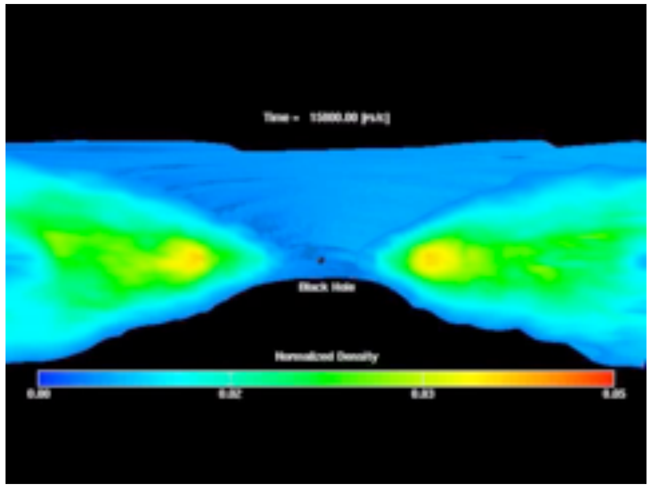
- Properties of Radiation

Resonant disk oscillation =
Variable emissions

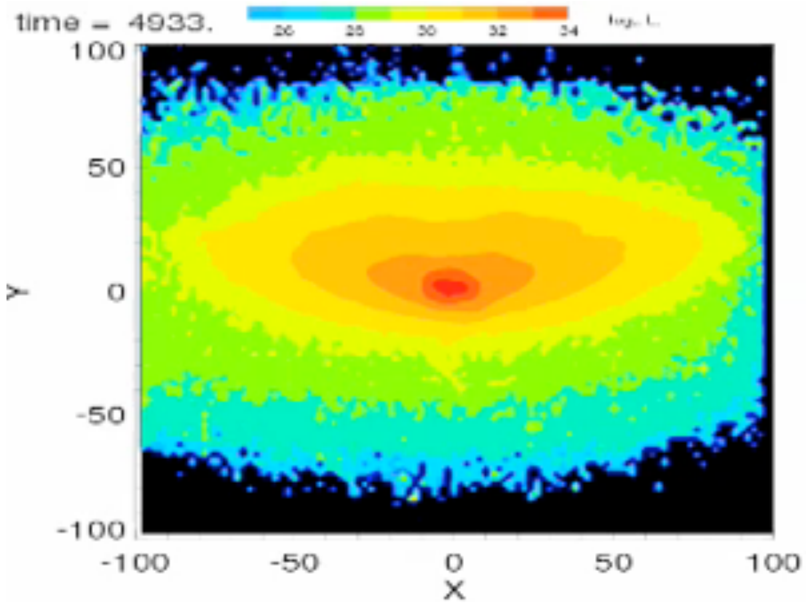


ISCO

Resonant radius where $\Omega_k = 2\kappa$



Resonant disk oscillations
in 3-D MHD model



Variable emissions
in 3-D MHD model

Find a correspondence between variabilities and resonant disk oscillations

Variable Emissions from BHs

Stellar-mass BHs

Freq. ratio

3 : 2

= 450 : 300 = 276 : 184 ≈ 168 : 113

Objects	Freq. of X-ray variabilities (Hz)	Mass of BHs
XTE J1859+226	190	7.6 - 12.0
GRO 1655-40	300, 450	6.0 - 6.6
XTE 1550-564	(92), 184, 276	8.4 - 10.8
GRS 1915+105	(41), (67), 113, 168	10.0 - 18.0
XTE J1650-500	250	4.0 - 7.3

Massive BH Sgr A*

16.8 : 22.2 : 33

1 : 2

2 : 3

3 : 4 : 6

Freq. ratio

1/3 : 1/4 : 1/6 = 4 : 3 : 2

Obs. Date (UT)	Observed bands	Periods (min)
2003.06.15 - 16	IR : K-band	16.8±2, 17.1
2004.09	IR : 1.60, 1.87, 1.90 (μm)	33±2
2002.10, 2004.08	X-ray : 2 - 10 (keV)	22.2
2007.04.04	IR : L-band	22.6
2007.07.22	IR : L-band	45.4
2004.03.08 09:30 - 16.30	Radio : 43 (GHz)	16.8±1.4, 22.2±1.4, 32.2±1.5, 56.35±6

The ratio is what we expected from the resonant disk oscillation

Measuring the spin of BH

by using the resonant disk oscillations

YK, Miyoshi, Takahashi, Negoro, Matsumoto (2010) MNRAS Letter

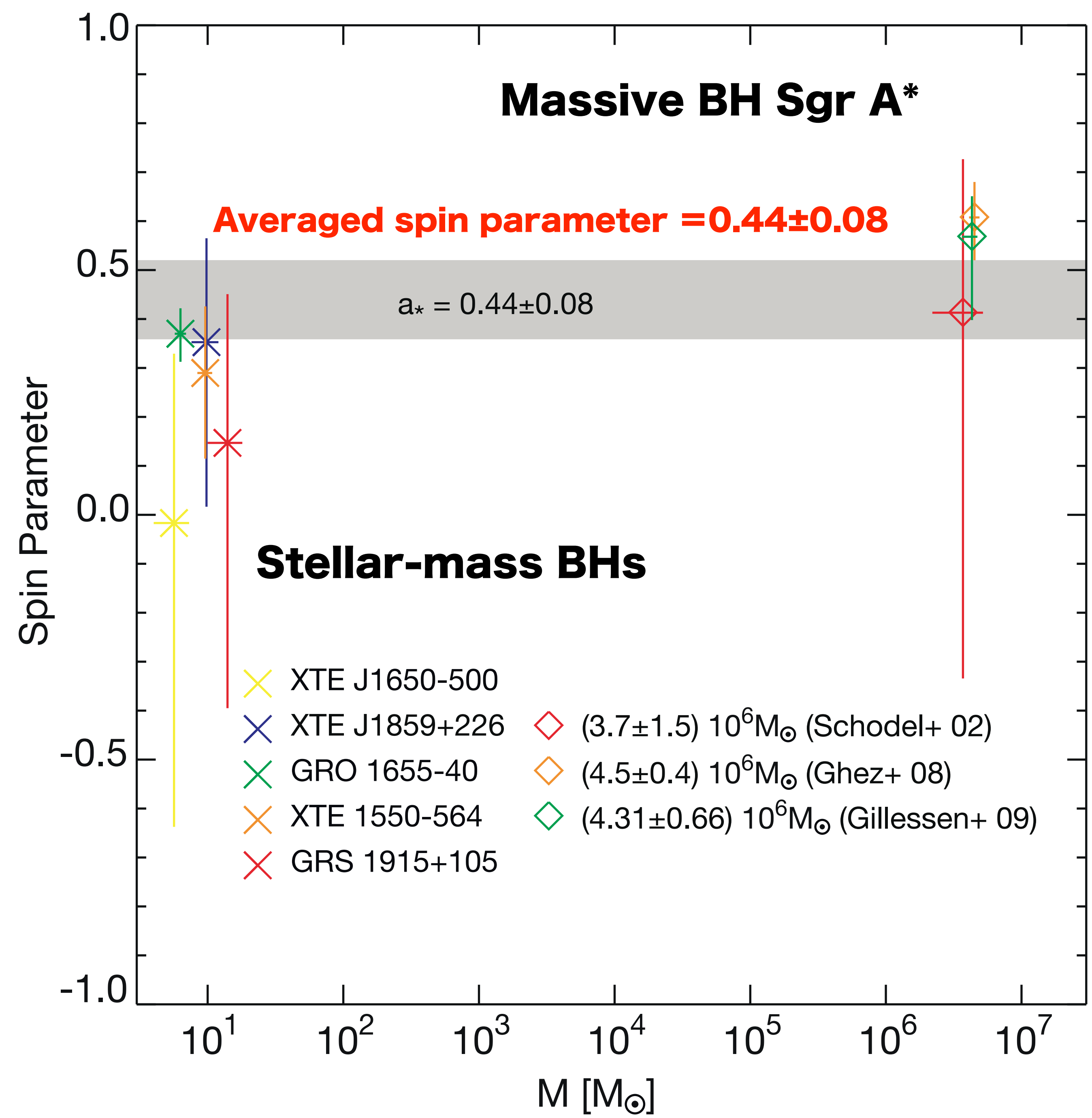
Input parameters

Freq. of variabilites : ν

Estimated BH mass : M

$$a_* = c^3 \left[\frac{1}{2\pi\nu GM} - \left(\frac{R}{GM} \right)^{3/2} \right]$$

$$\nu = \Omega_{\rm K}(R) = 2\kappa(R)$$



Blandford-Znajek mechanism

Blandford & Znajek (1977)

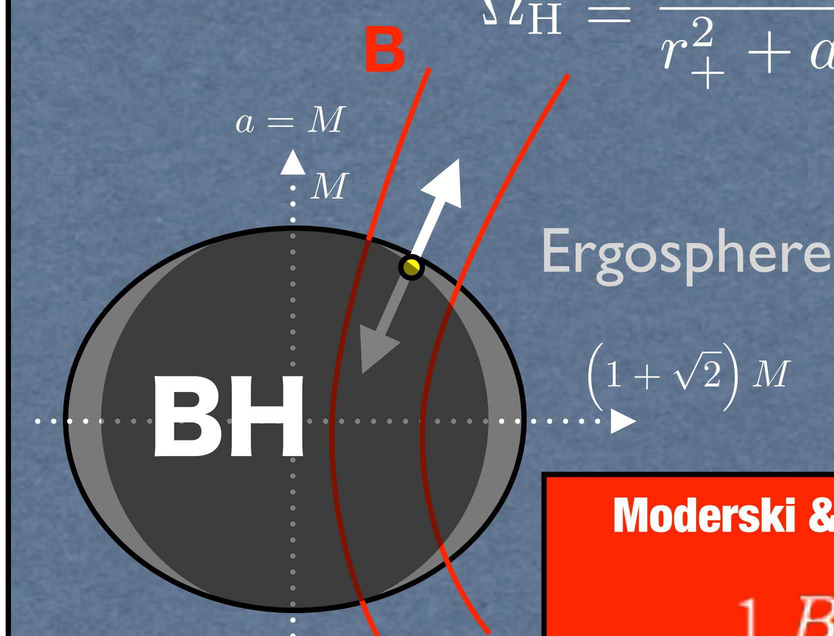
$T^{\mu\nu}_{;\nu} = 0$ the total energy-momentum tensor

ω : the electromagntic angular velocity

$$\varepsilon^r = T^r_0$$

$$= \omega\left(\Omega_{\rm H} - \omega\right)\left(\frac{A_{\phi,\theta}}{r_+^2 + a^2\cos^2\theta}\right)^2\left(r_+^2 + a^2\right)\epsilon_0$$

$$\Omega_{\rm H} \equiv \frac{a}{r_+^2 + a^2}$$

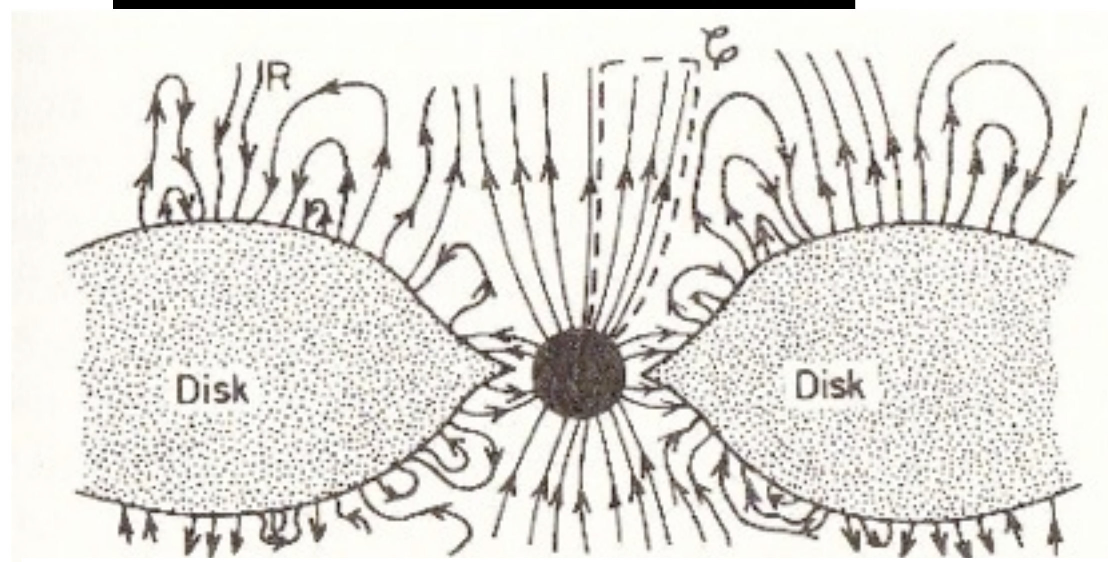


Moderski & Sikora 1996; Camenzind 2007

$$\mathcal{P} \simeq \frac{1}{8}\frac{B_\perp^2\,\tilde{r}_{\rm BH}^4}{c}\Omega_{\rm F}\left(\Omega_{\rm BH} - \Omega_{\rm F}\right)$$

Formation of Magnetic-Tower

[redacted]



Thorne, Price, and Macdonald 1986

[redacted]

YK, Mineshige, Shibata 2004

Modeling growth history of BHs by accretion disks

- **Mass accretion**
- **Angular momentum transport**
  - ➡ Gain of angular momentum via accretion
  - ➡ Loss of angular momentum via BZ

$$\frac{d\ln M_{\rm BH}}{dt} = \dot{M}e_{\rm in} - \frac{\mathcal{P}}{M_{\rm BH}c^2} \qquad \frac{dJ_{\rm BH}}{dt} = \dot{M}l_{\rm in} - \frac{\mathcal{P}}{\Omega_{\rm F}}$$

Moderski & Sikora 1996; Camenzind 2007

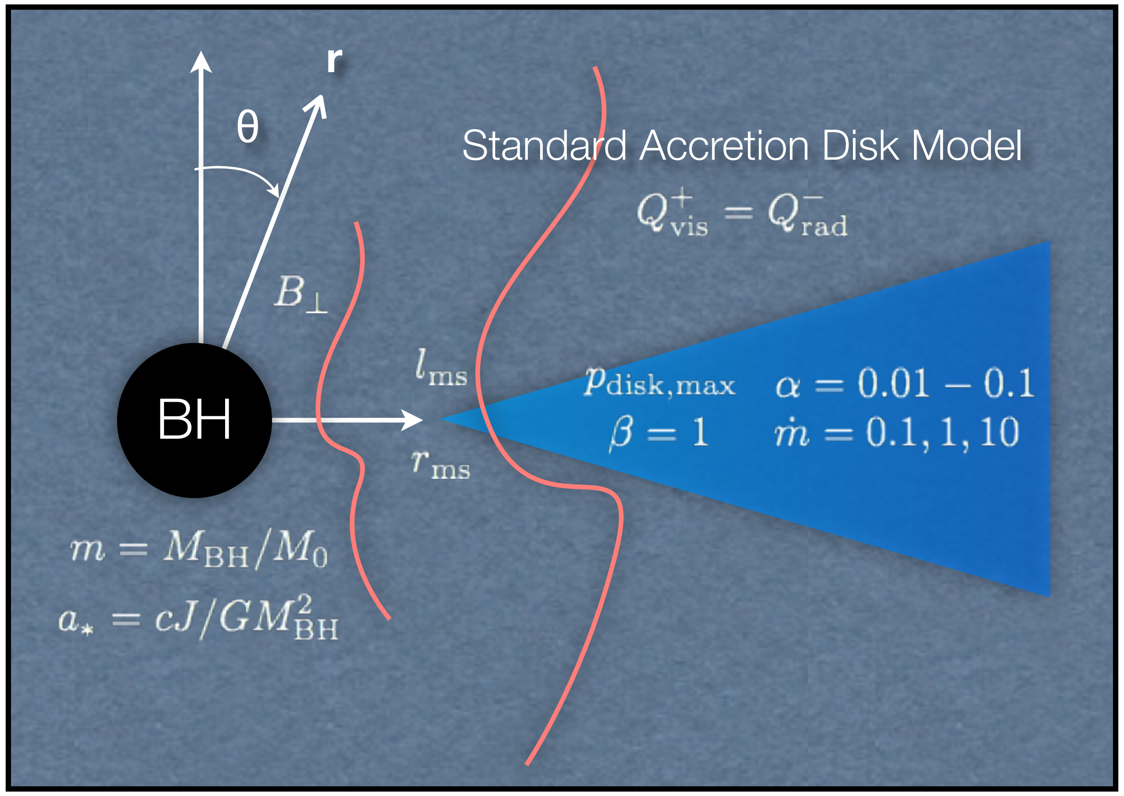
$$\mathcal{P} \simeq \frac{1}{8}\frac{B_\perp^2 \tilde{r}_{\rm BH}^4}{c}\Omega_{\rm F}\left(\Omega_{\rm BH} - \Omega_{\rm F}\right) \qquad B_\perp^2 = 8\pi p_{\rm disk,max}/\beta$$

$$\eta_{\rm BZ} \equiv \frac{\mathcal{P}}{\dot{M}_{\rm Edd}c^2} \qquad \tau_{\rm Edd} \equiv \frac{M}{\dot{M}_{\rm Edd}}$$

$$e_{\rm in} = e_{\rm ms} \qquad l_{\rm in} = l_{\rm ms}$$

$$\tilde{r}_{\rm BH} = c^2 r_{\rm BH}/GM_{\rm BH} = 1 + \left(1 - a_*^2\right)^{1/2} \qquad k = \Omega_{\rm F}/\Omega_{\rm BH}$$

Schematics of BH and accretion disk



Eqn. of BH evolution

$$\frac{d\ln m}{dt} = \frac{1}{\tau_{\rm Edd}}\left(e_{\rm ms} - \eta_{\rm BZ}\right)$$

$$\frac{da_*}{dt} = \frac{1}{\tau_{\rm Edd}}\left[\left(l_{\rm ms} - 2a_*e_{\rm ms}\right) - 2\eta_{\rm BZ}\left(\frac{\tilde{r}_{\rm BH}}{ka_*} - a_*\right)\right]$$

Equilibrium spin and Evolution of spin

YK, Miyoshi, Takahashi, Negoro, Matsumoto (2010) MNRAS Letter

Gas pressure dominated **Radiation pressure dominated**

Equilibrium spin

$$\frac{da_*}{dt} = 0$$

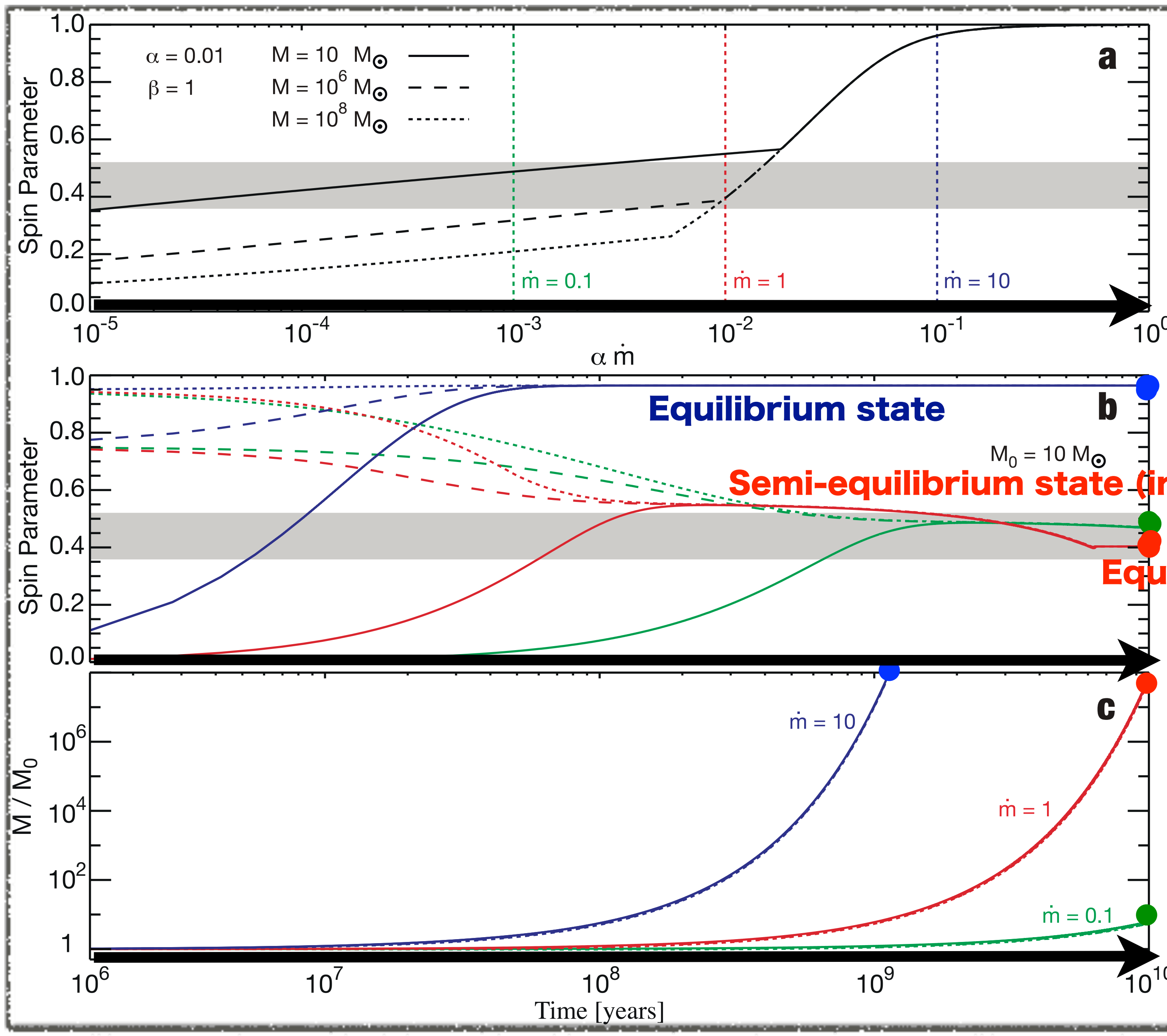
Time evolution of spin

High mass accretion

Eddington mass accretion

Low mass accretion

Time evolution of BH mass



Our result a_*=0.44±0.08

Mass accretion rate

Our result a_*=0.44±0.08

Elapsed time

Elapsed time

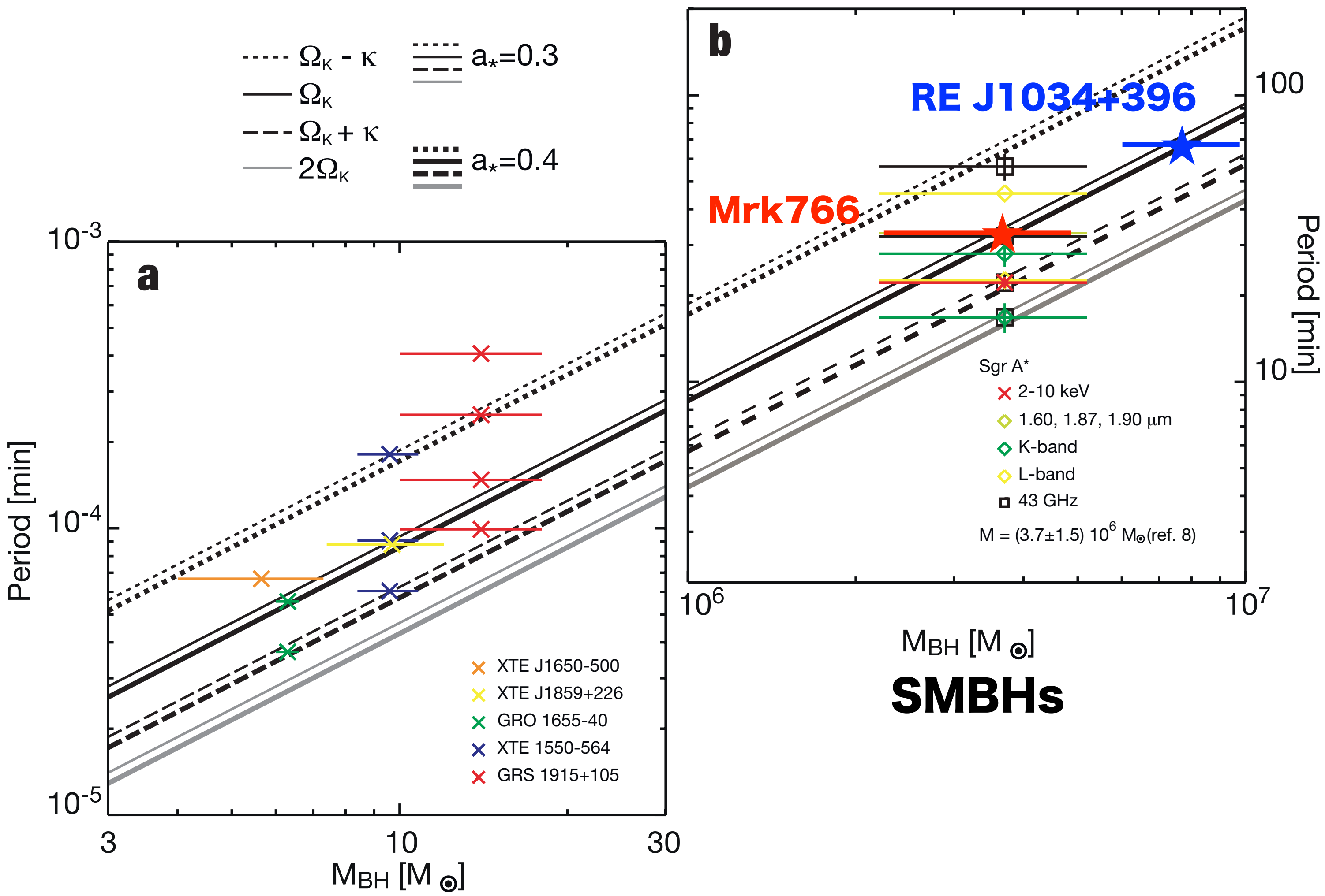
Summary & Conclusion

- Measure the spin of the massive BH Sgr A* by using resonant disk oscillations,
- Plot the relation between BH mass and spin,
- Discover the unique spin, $a_* = 0.44 \pm 0.08$, which correspond to the equilibrium value,
- Moderate spin parameter of the Massive BH Sgr A* is a result of the energy extraction via BZ mechanism.

The mass and spin of other SMBHs

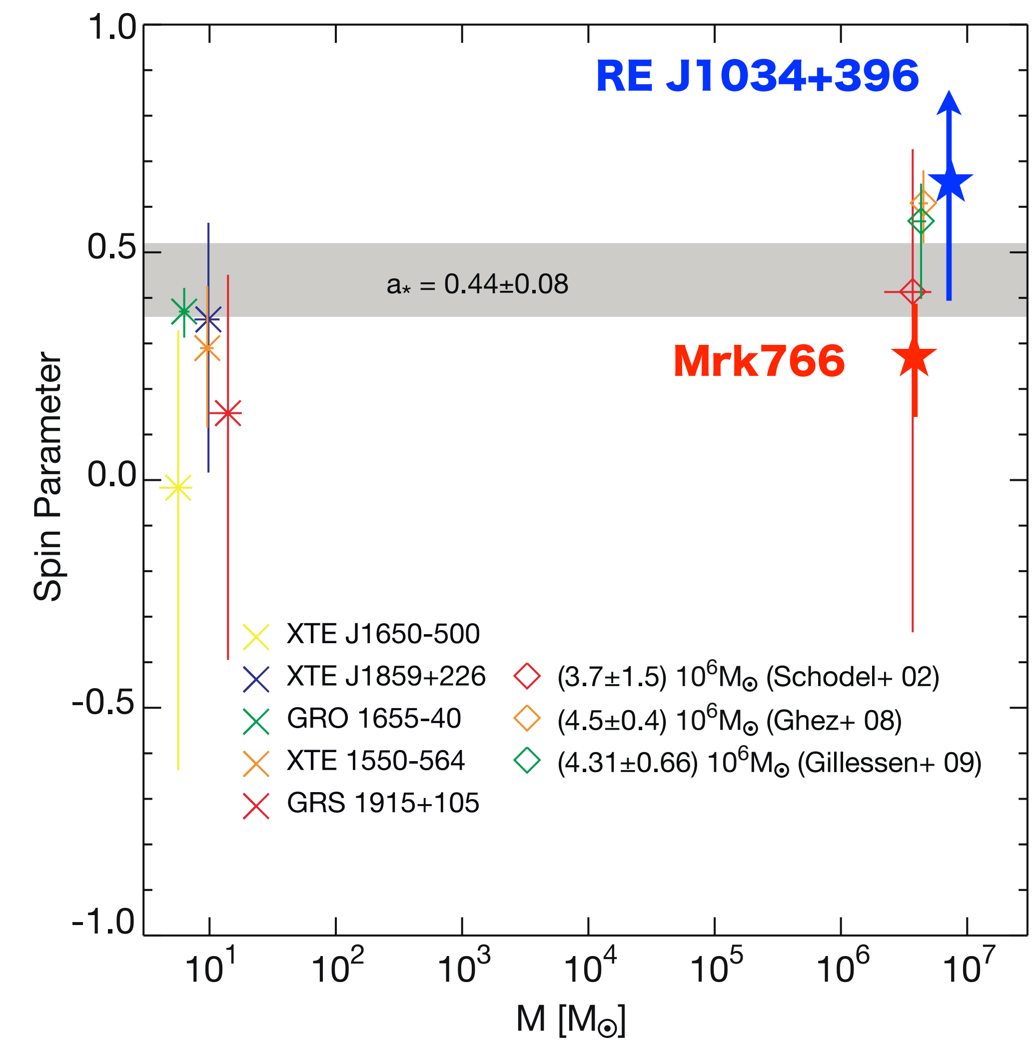
Markowitz et al. 2007; Gierlinski et al. 2008 Nature

Relation between variabilities and resonant disk oscillations



Stellar-mass BHs

Measurement of spins by using the resonant disk oscillations



BH mass