降着円盤の振動現象

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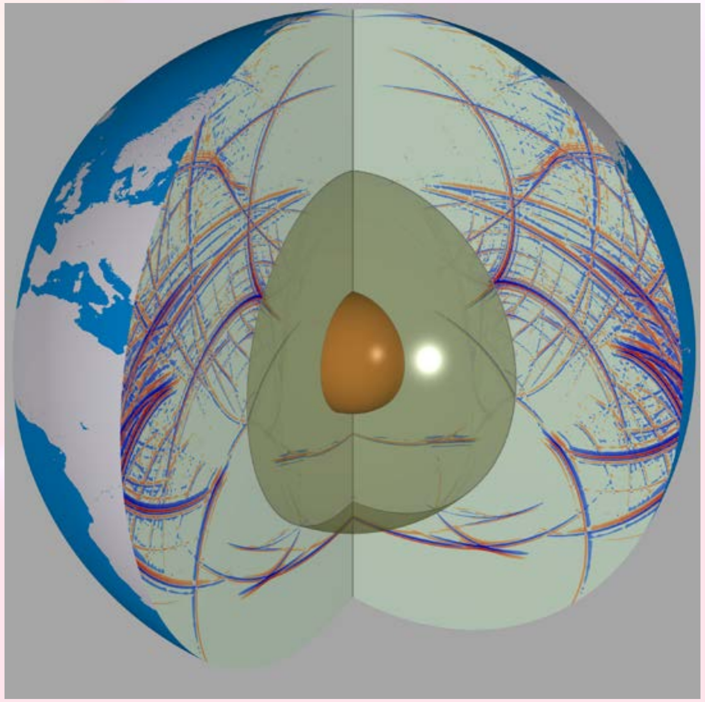
1. はじめに

振動現象を調べることの意味

振動現象は内部構造や環境との相互作用を理解するための優れた手がかり

地震学 (Seismology)

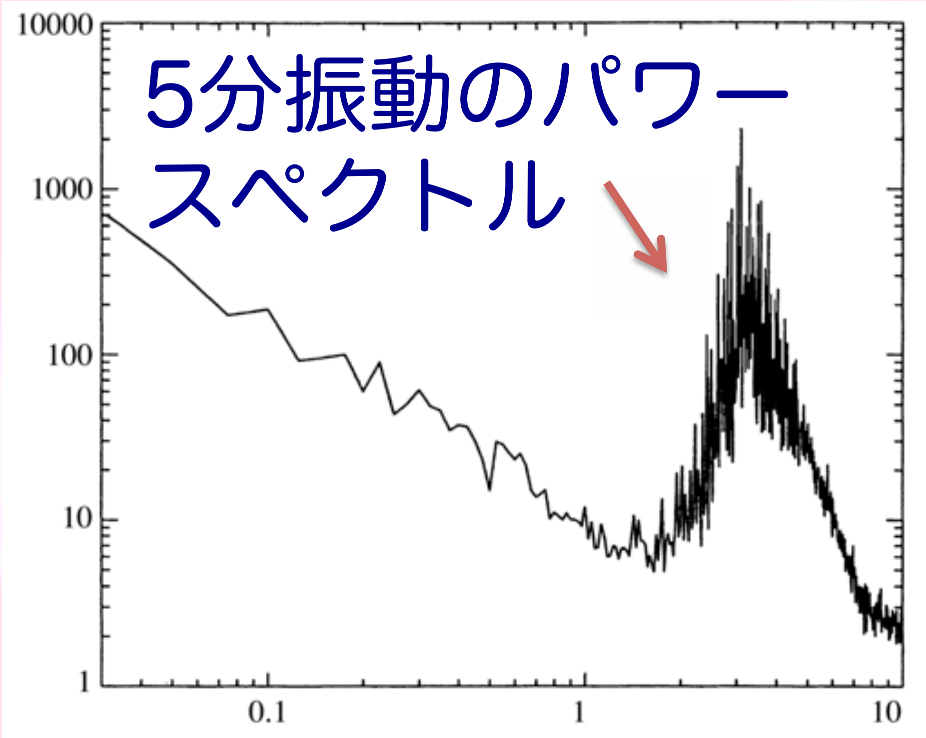
地震波の伝播を調べることで地球の内部構造が分かる



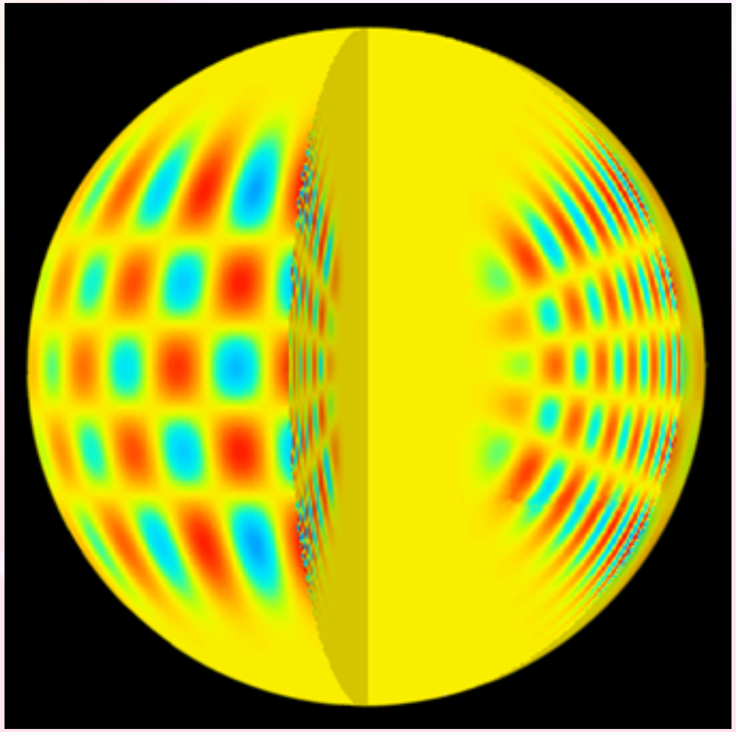
http://www.geophysik.uni-muenchen.de/research/seismology

日震学 (Helioseismology)

太陽表面の振動現象を調べると内部構造や回転分布がわかる

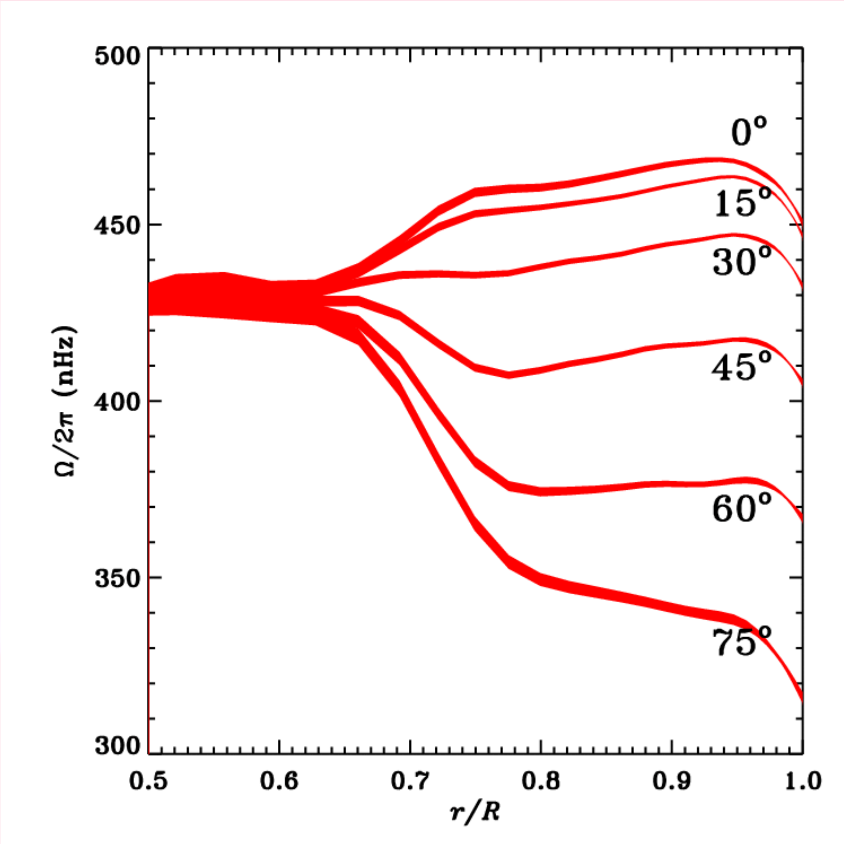


5分振動の構造

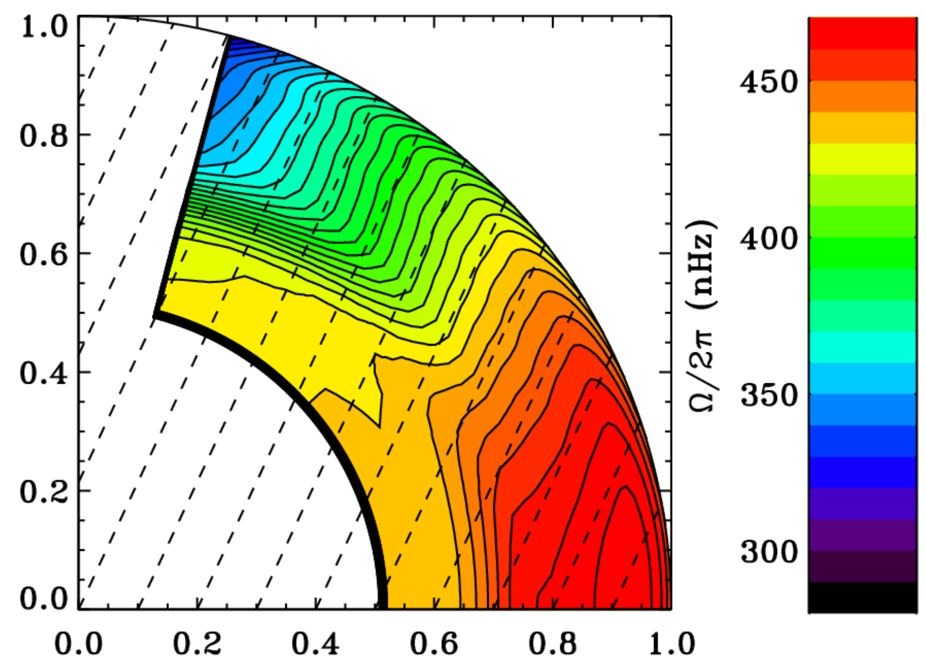


太陽内部の回転分布

r方向



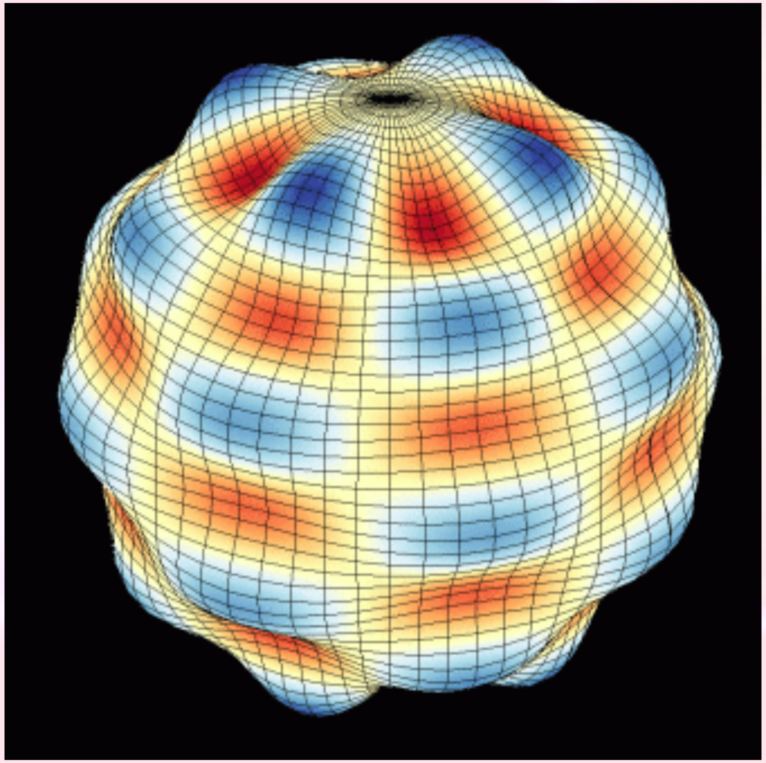
(r, z)面



星震学 (Asteroseismology)

変光、スペクトル変動

➡ 星の内部構造、回転分布



<u>振動の励起機構</u>

- ε mechanism (核エネルギー発生率の変動)
- κ mechanism (放射の吸収の変動)

円盤振動学 (Diskoseismology)

"..., we focus on the spectrum of normal modes of oscillation, which must exist at some level (determined by the driving and damping processes in the disk). In the same spirit with which helioseismology probes the interior of the Sun, this probe of the Kerr metric (and its accretion disk) has been dubbed (relativistic) diskoseismology." (Wagoner 1998)

2. Diskoseismology

(Kato 2001; Kato, Fukue, & Mineshige 2008)

Restoring forces in geometrically thin disks w/o B-fields

Horizontal oscillations

- rotation $\sim \Omega^2 r$
- pressure gradient force in horizontal plane (if short wavelengths) $\sim c_\mathrm{s}^2/\lambda$

Vertical oscillations

- vertical gravity $\sim \Omega_\perp^2 z$
- pressure gradient force in vertical direction (for overtones) $\sim c_\mathrm{s}^2/H$

Local analysis of oscillations in Keplerian Disks

Eq. of continuity, eq. of motion, energy eq.

↓ $\rho = \rho_0 + \rho_1, \ p = p_0 + p_1, \ \vec{v} = \vec{v}_0 + \vec{v}_1$

Linearized perturbation equations

↓ Normal mode analysis

$$\rho_1, \ p_1, \ \vec{v}_1 \propto e^{i(\omega t - k_r r - m\phi)} H_n(z/H)$$

+ WKBJ approximation: $|k_r r| \gg 1$

$$(\tilde{\omega}^2 - \kappa^2)(\tilde{\omega}^2 - n\Omega_\perp^2) = \tilde{\omega}^2 k_r^2 c_s^2,$$

where $\tilde{\omega} = \omega - m\Omega$

Wave propagation region ($k_r^2>0$)

- waves with no vertical node $(n=0)$ (inertial-acoustic modes)

$$\tilde{\omega}^2 > \kappa^2 \quad \Rightarrow \quad \begin{cases} \omega > m\Omega + \kappa \\ \text{or} \\ \omega < m\Omega - \kappa \end{cases}$$

- waves with vertical nodes $(n \geq 1)$

$$\tilde{\omega}^2 < \kappa^2 \quad \Rightarrow \quad m\Omega - \kappa < \omega < m\Omega + \kappa$$

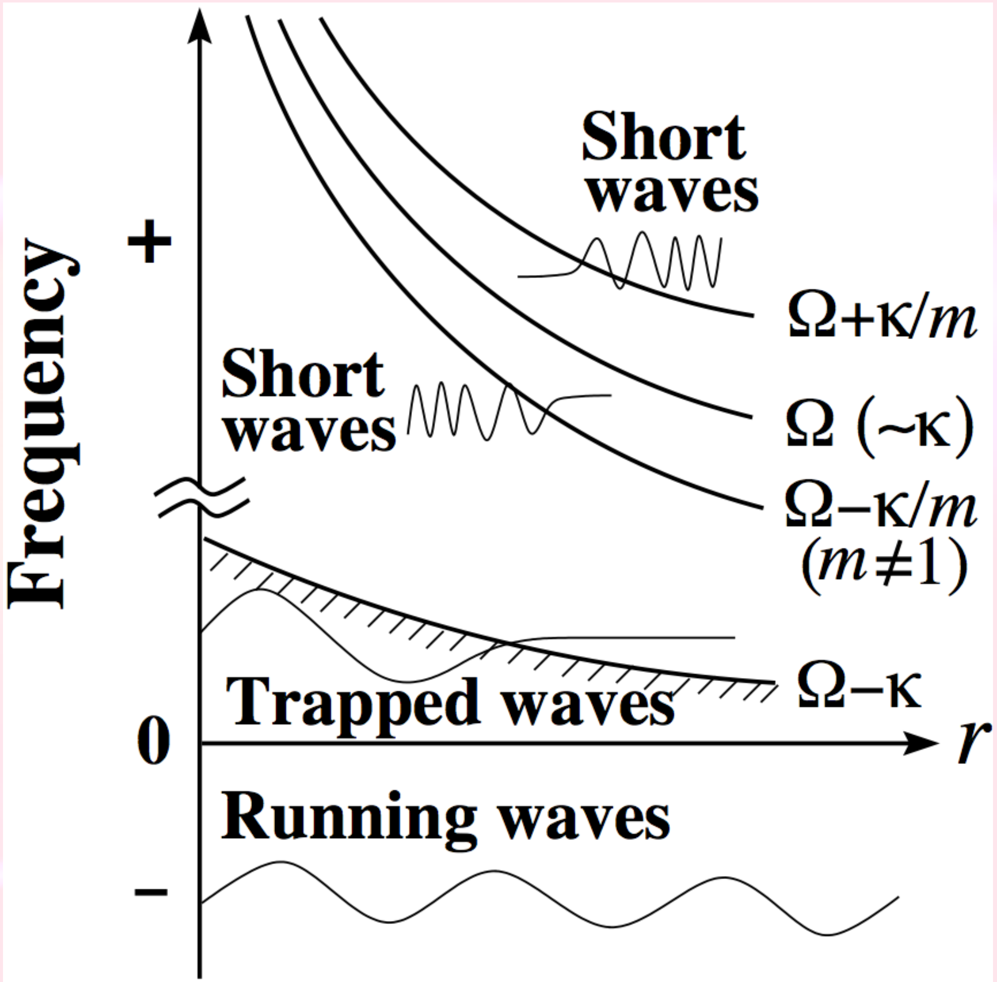
or

$$\tilde{\omega}^2 > n\Omega_\perp^2 \quad \Rightarrow \quad \begin{array}{l} \omega > m\Omega + \sqrt{n}\Omega_\perp \quad \text{or} \\ \omega < m\Omega - \sqrt{n}\Omega_\perp \end{array}$$

Global inertial-acoustic modes in non-relativistic disks ($\Omega=\Omega_{\perp}=\kappa$)

Only prograde m=1 modes are confined in disks

(Kato 1983)



(Okazaki 2000)

Schematic diagram showing m=1 modes can be global in non-relativistic disks

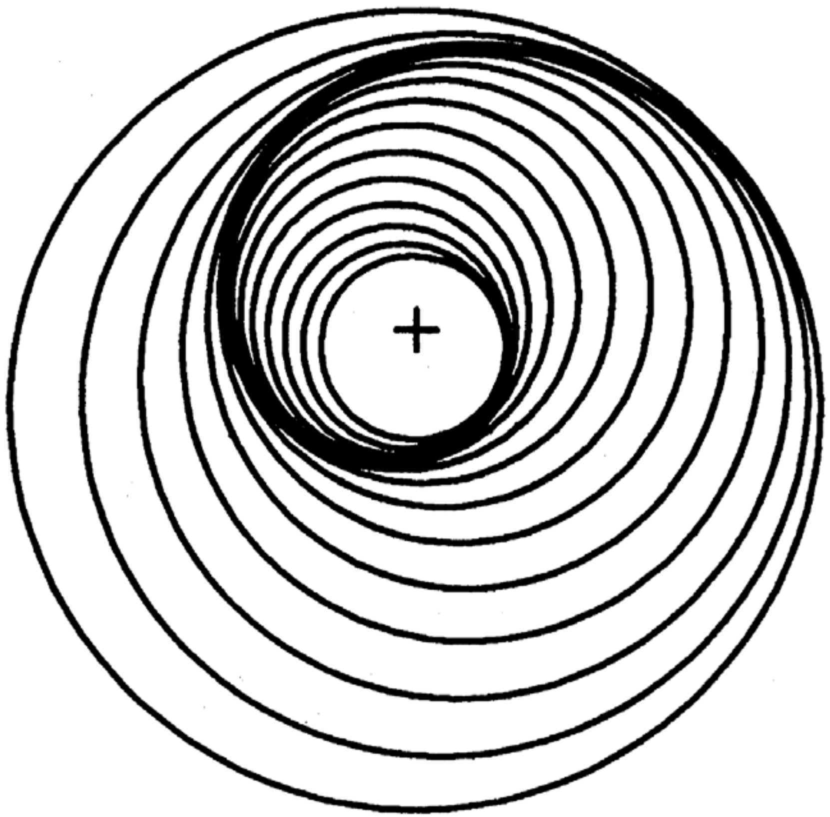


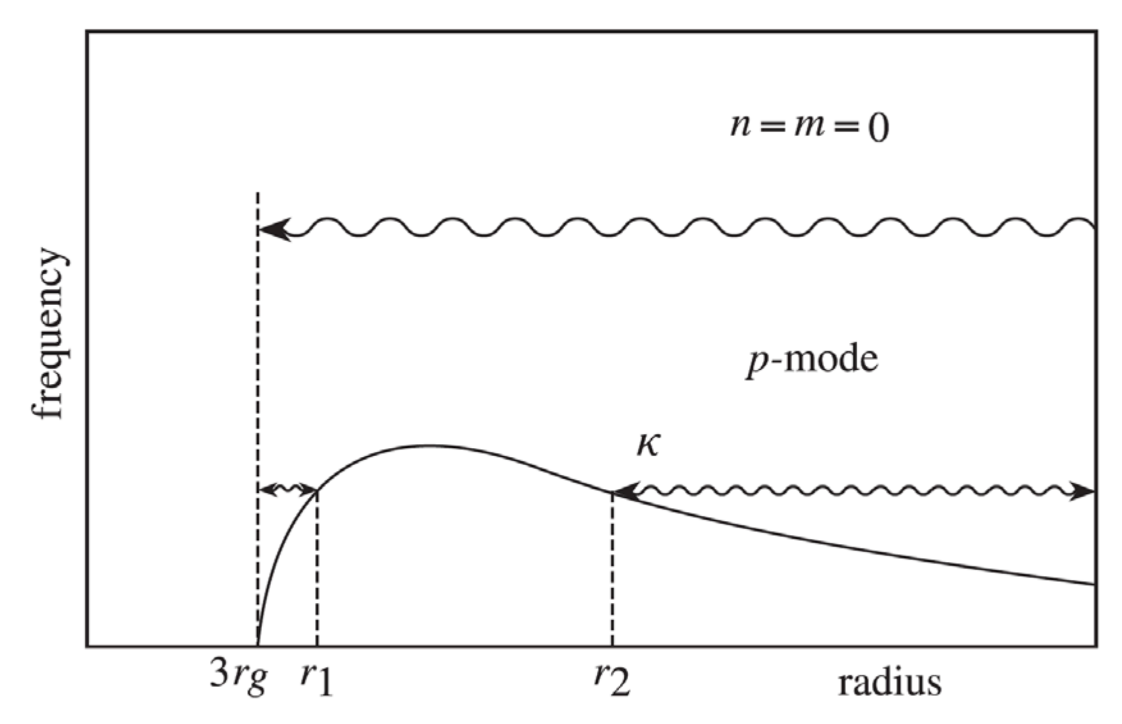
FIG. 2.—Schematic diagram of $m = 1$ elliptical streamlines oriented to produce a one-armed spiral. Cross denotes the position of the star.

(Adams+ 1989)

Inertial-acoustic modes in relativistic disks ($\Omega>\Omega_{\perp}>\kappa$)

Only m=0 modes with $\omega<\kappa_{max}$ are confined in innermost part of disk

(Kato, Fukue 1980)

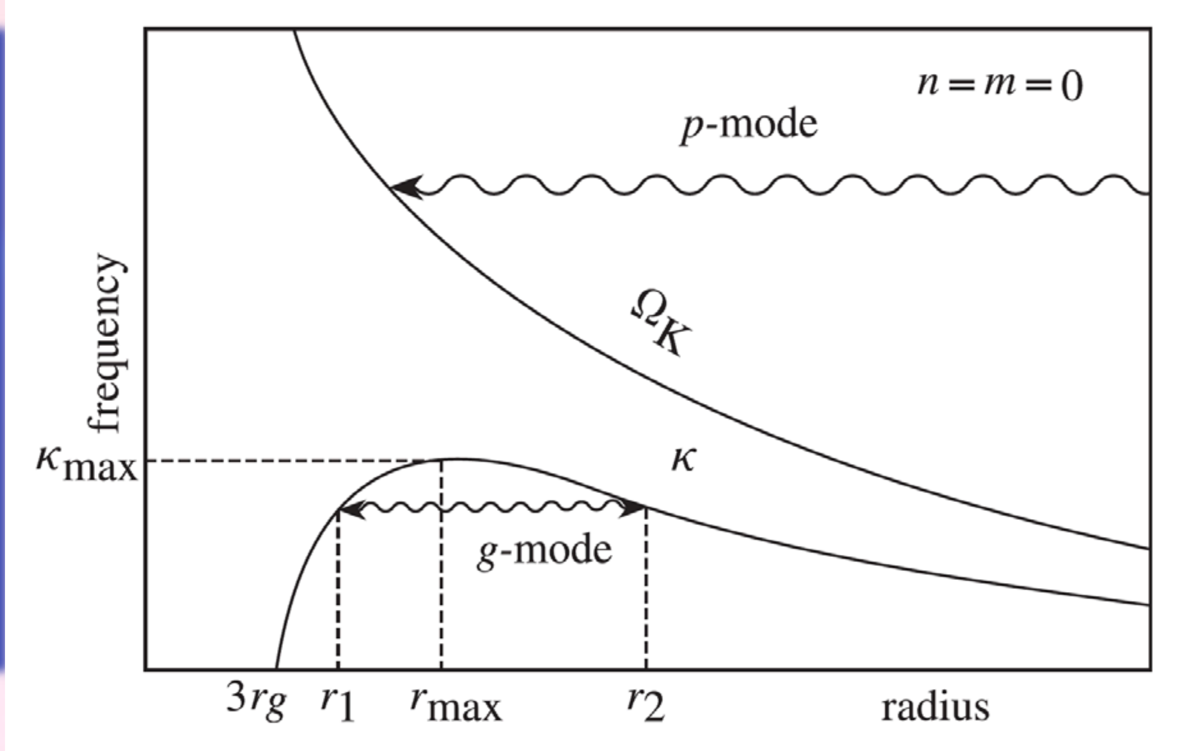


(Kato 2001)

Global g-modes in relativistic disks ($\Omega > \Omega_\perp > \kappa$)

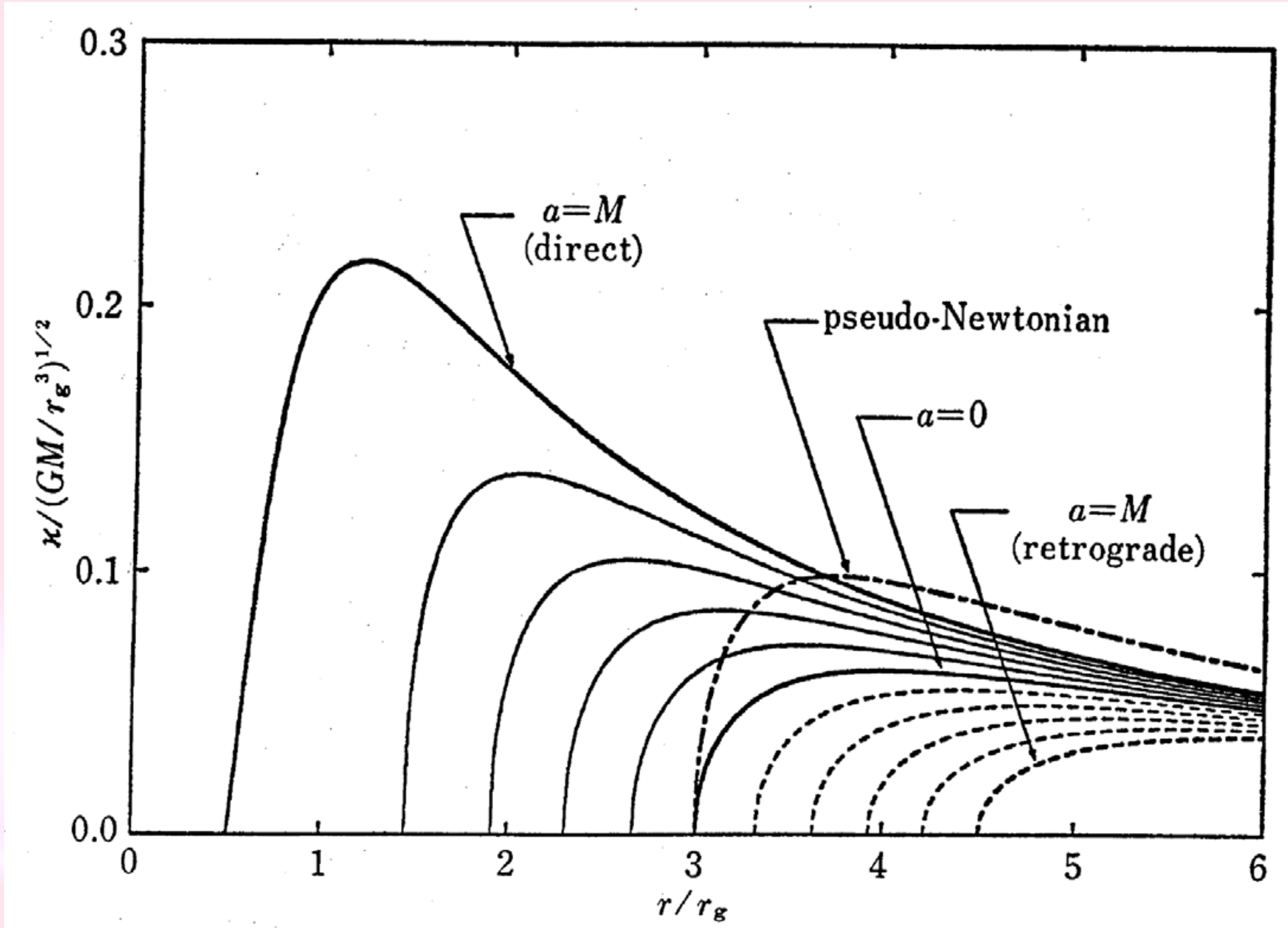
Axisymmetric (m=0) g-modes are confined in region near κ_{max}

(Okazaki, Kato, Fukue 1987)



(Kato 2001)

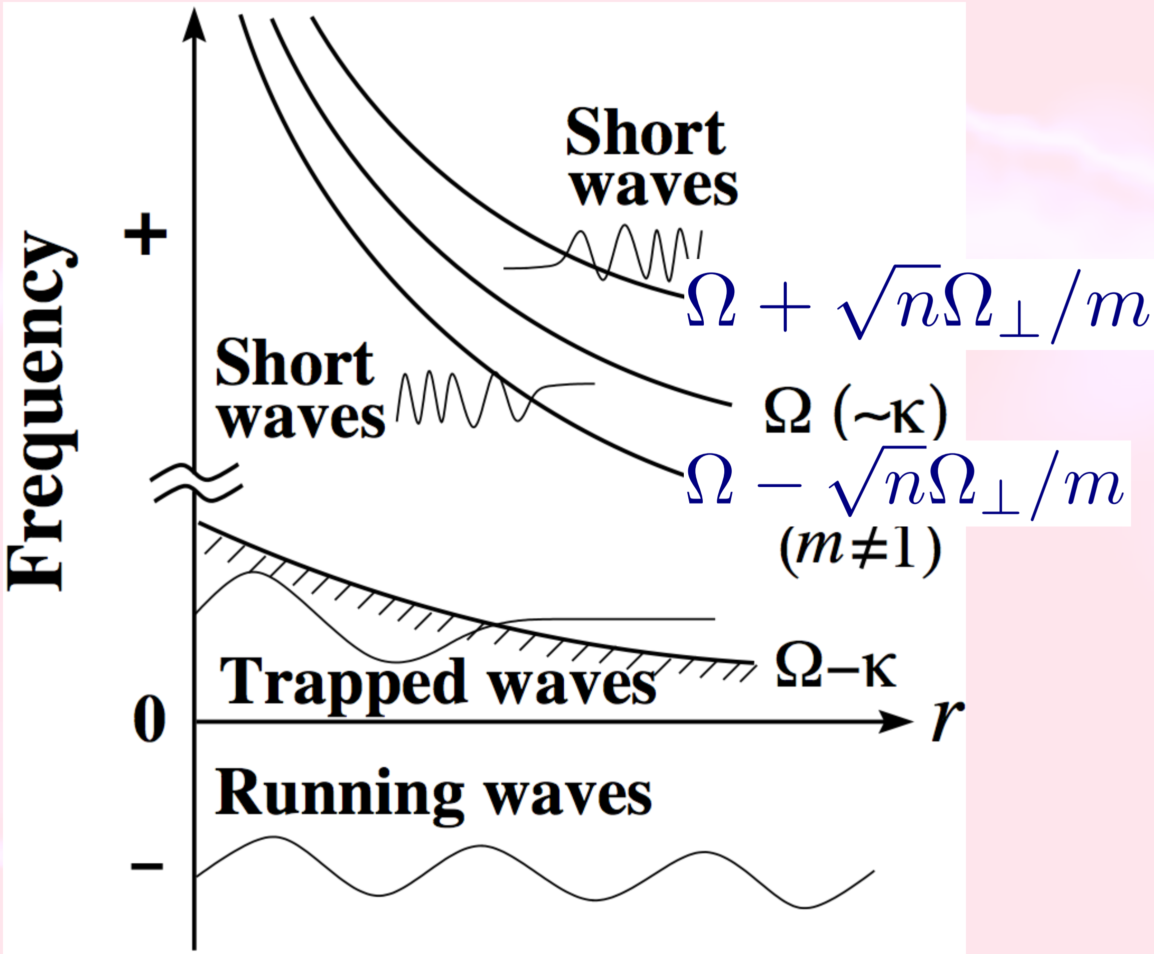
Epicyclic frequencyのBH spin依存性



(Okazaki, Kato, Fukue 1987)

Global corrugation (= warping) modes (m=1, n=1)

They are global in both non-relativistic and relativistic disks.



Possible excitation mechanisms of disk oscillations (1/2)

- Turbulent viscosity

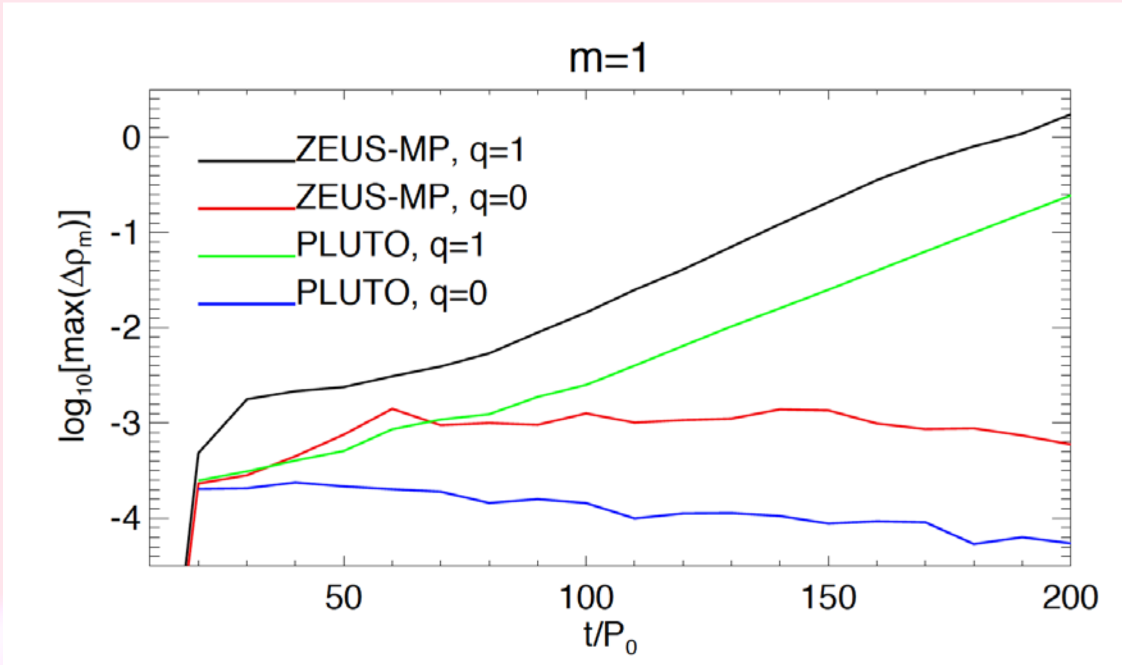
  Inertial-acoustic modes are overstable to effects of viscosity (Kato 1978).

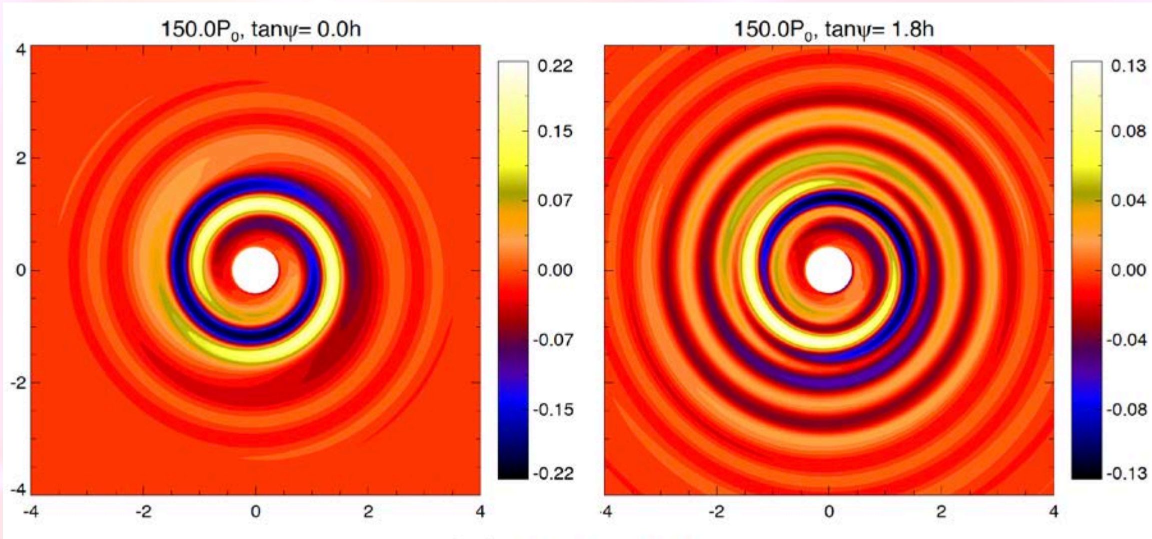
  Growth timescale
  ~ viscous timescale

Possible excitation mechanisms of disk oscillations (2/2)

- Baroclinic instability
  (Non-relativist case)
  One-armed spiral density waves are excited if disk is not barotropic (e.g., temperature is constant vertically, but not so radially) (Lin 2015)

Excitation of m=1 mode in a baroclinic disk





(a) ZEUS-MP

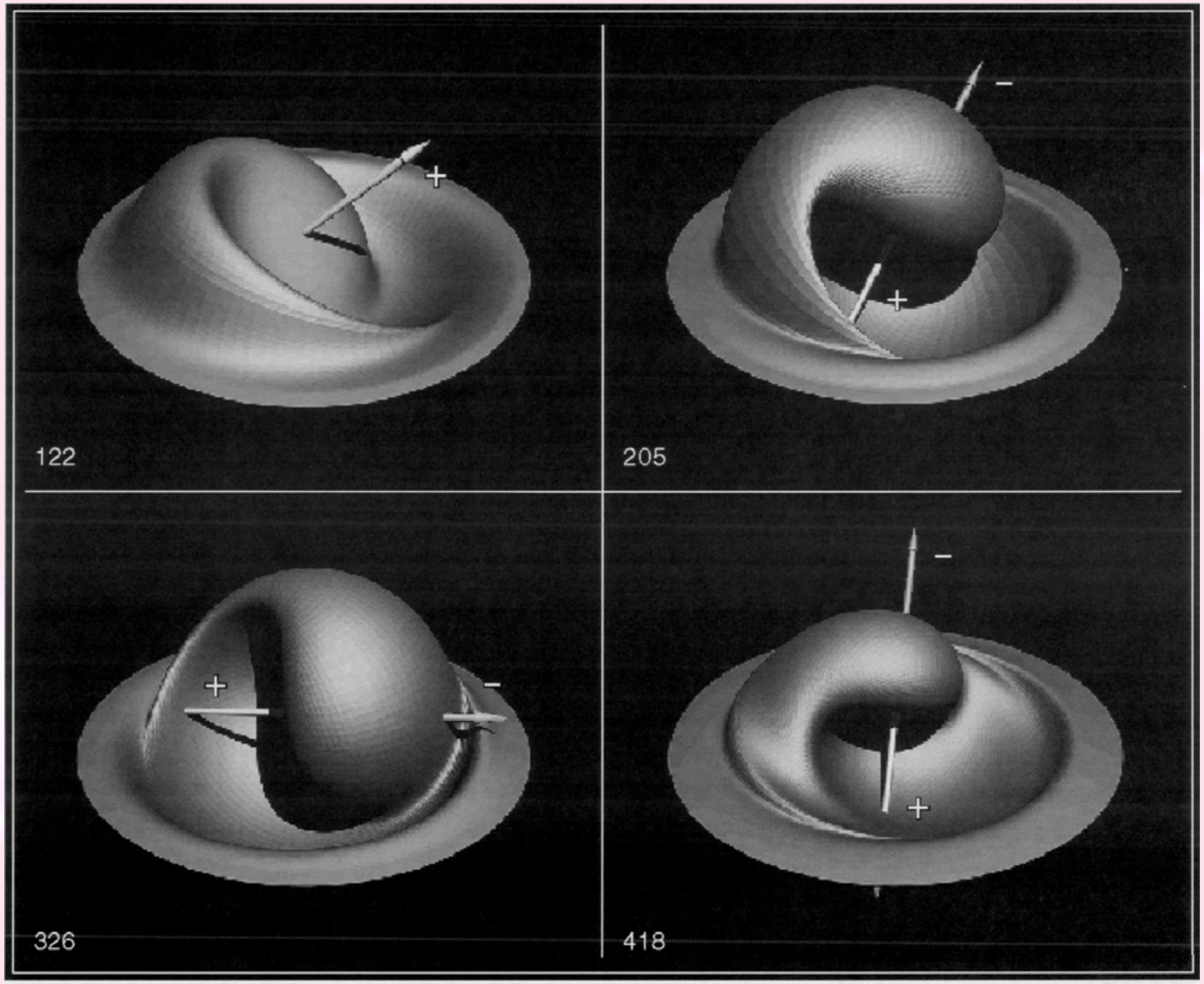
(Lin 2015)

3. Disk deformation/ oscillations excited by external forces

Radiation-driven warping

- The optically-thick part of an accretion disk with a central radiation source can be unstable to warping (Pringle 1996).
- Direction of the precession depends on the shape of the warp.

Disk shape at various times (Pringle 1997)



Tidal warping

(Lubow & Ogilvie 2000; Martin+ 2011)

Tidal torques have alignment effect on a tilted disk toward the orbital plane.

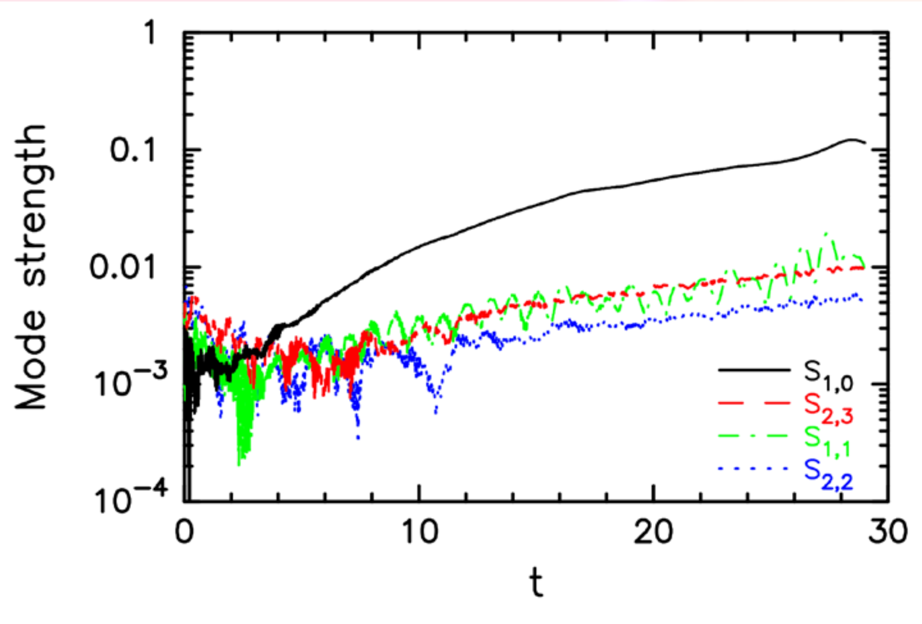
$$t_{\rm align} = \frac{\Sigma (GM_* r)^{1/2}}{T_{\rm tid}}$$

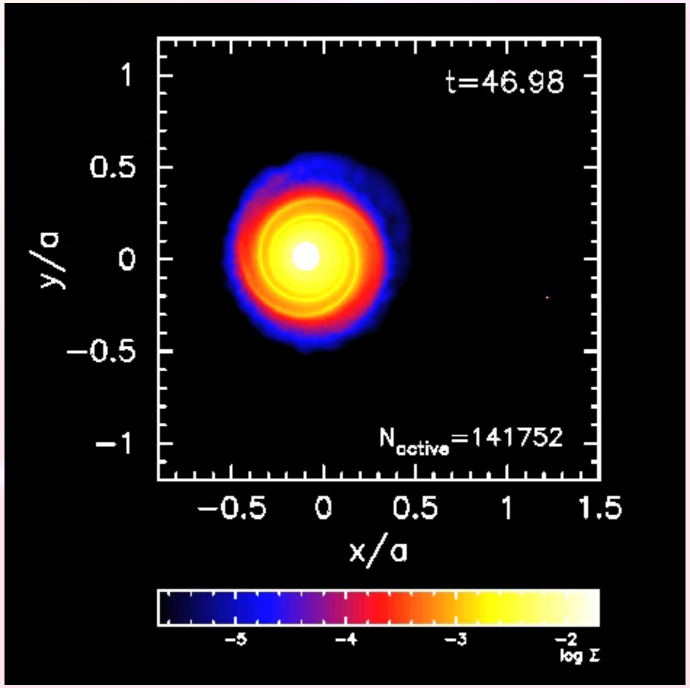
$t_{\rm align} \ll t_{\rm vis}$: Disk aligns with orbital plane

$t_{\rm align} \gg t_{\rm vis}$: Disk moves towards orbital plane even if it doesn't completely align

Excitation of m=1 modes in eccentric binaries

Due to m=1 Fourier component of tidal potential, m=1 (eccentric) mode grows linearly in time (Lubow & Artymowicz 2000)



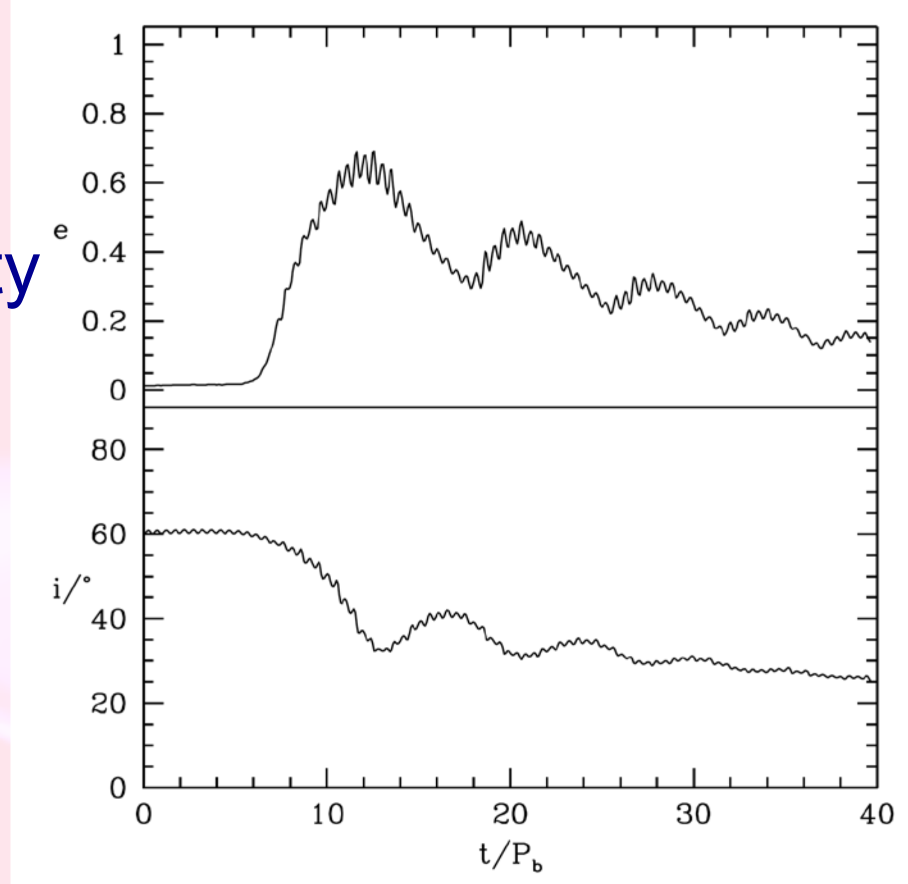


Kozai mechanism also works if disk is highly inclined

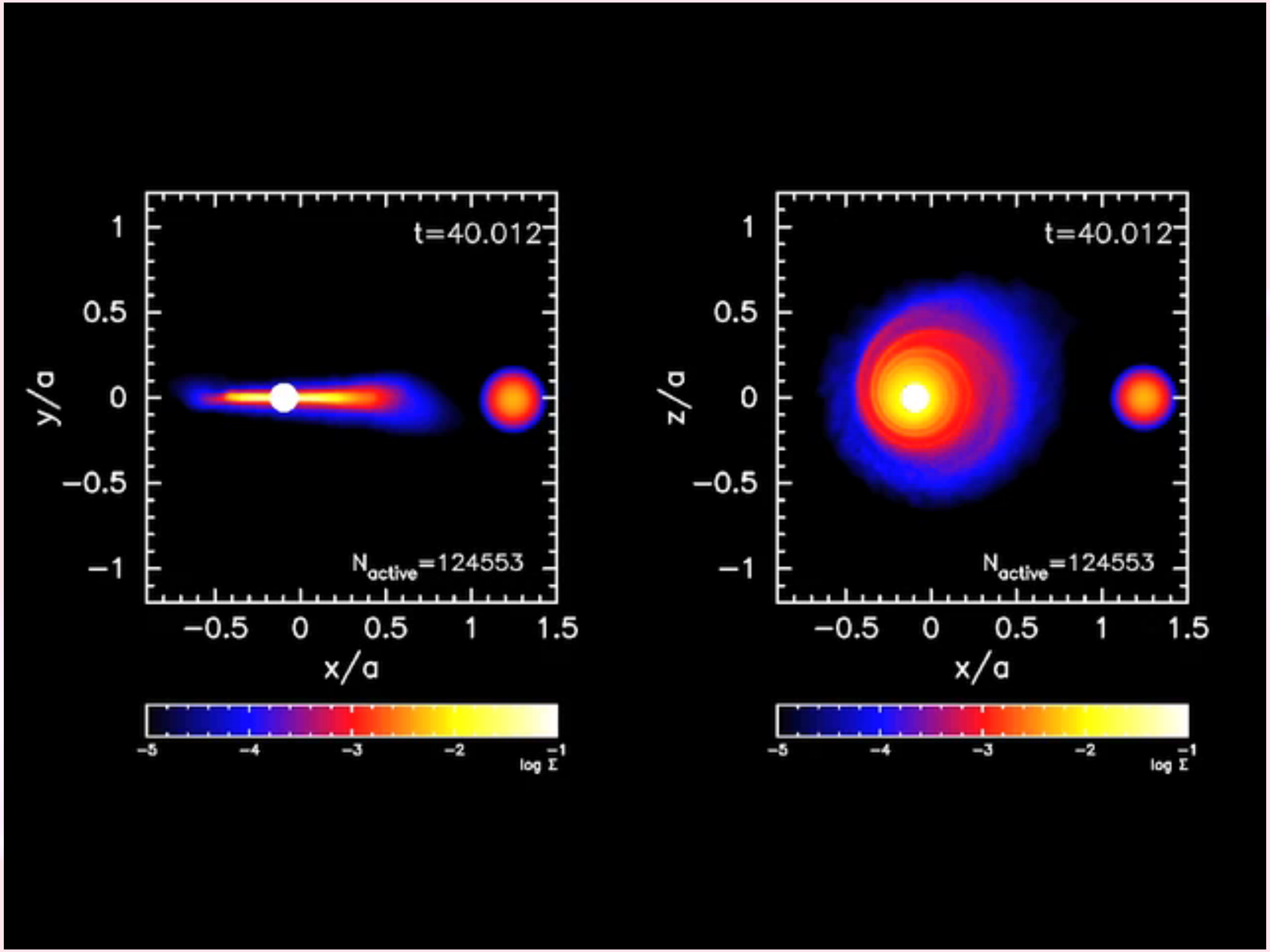
$$\sqrt{1-e^2}\cos i \sim \mathrm{const}$$

Disk eccentricity

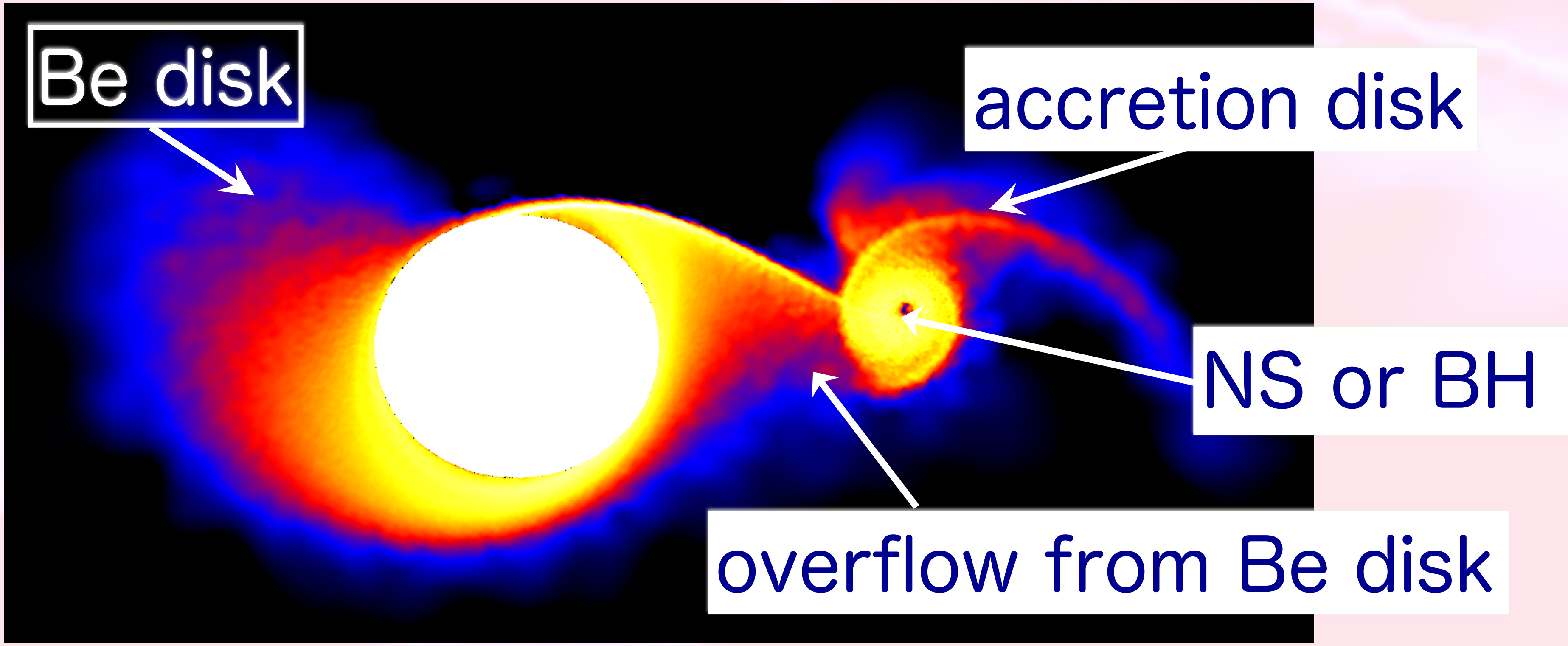
Disk inclination



(Martin+ 2014)


t=40.012
N_{active}=124553
y/a
z/a
x/a
log Σ

BeXRBs with large *e*



結論に替えて

「振動現象は内部構造や環境との相互作用を理解するための優れた手がかり」

⇒ 観測とどこまで比較できるかというと定量的な比較をするにはまだまだ。

- まだあまり調べられていない機構もある
- 非線形振動のシミュレーション必要
- MHDシミュレーションも必要
- などなど