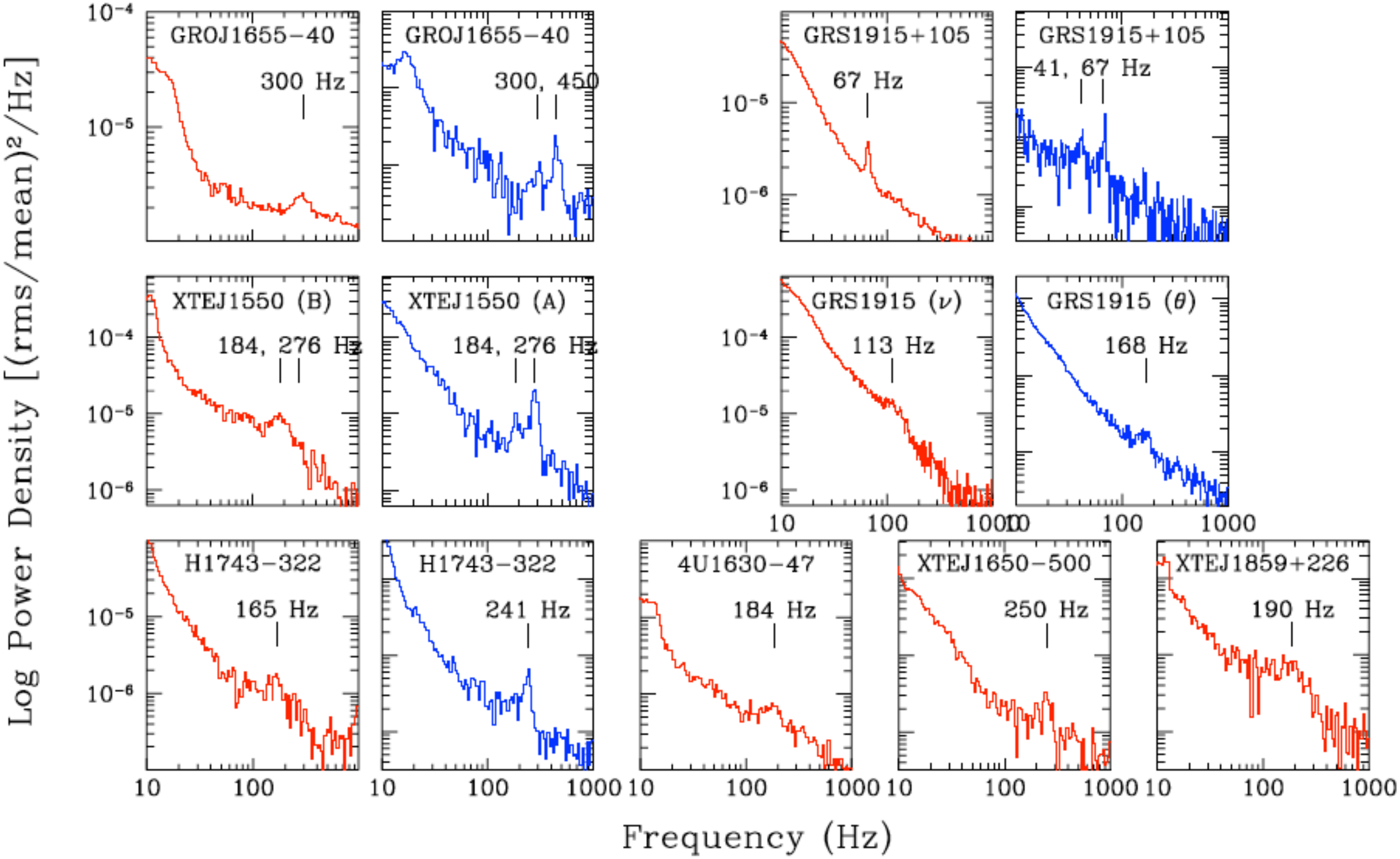
Global Oscillations of BH Accretion Flows and High-Frequency QPOs

Dong Lai
Cornell University

Prague Synergy 2013, “Relativistic Compact Objects”, 2013.11.26

High-Frequency QPOs in BH X-Ray Binaries



Remillard & McClintock 2006; also Belloni et al.2012

Basic Facts about HFQPOs

- 40-450 Hz: ~ orbital frequency at r_{isco}
- Frequency stable (<10% change when Mdot doubles)
- Some systems: ~2:3 ratio
- Only occur in "Transitional state" (="very high state") (Episodic jet)
- Weak QPOs: ~1% flux variation (in hard X-rays), Q~2-10

Reviews: Remillard & McClintock 2006; Belloni, Sanna, Mendez 2012

Phenomenology will be improved by future missions (e.g. LOFT…)

Theories/Models of HFQPOs

HFQPOs are related to (and thus probe) strong gravity…

HOW ?

Many Ideas/Models of HFQPOs (?)

Ideas/Models of HFQPOs

- Orbiting blobs (hot spots) in disks (Stella et al '99; Schnittman & Bertschinger '04)

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Astronomy & Astrophysics

Weak nonlinear coupling between epicyclic modes in slender tori

J. Horák

$$\kappa^{(p)}_{ABC} = \frac{1}{2}\int_V p\left\{(\gamma-1)^2\eta_A\eta_B\eta_C + 3(\gamma-1)\eta_{(A}\eta_{BC)} + 2\eta_{(ABC)}\right\}\mathrm{d}V, \quad (12)$$

$$\kappa^{(g)}_{ABC} = -\frac{1}{2}\int_V \rho\,\xi^i_A\xi^j_B\xi^k_C\nabla_i\nabla_j\nabla_k\Phi\,\mathrm{d}V, \quad (13)$$

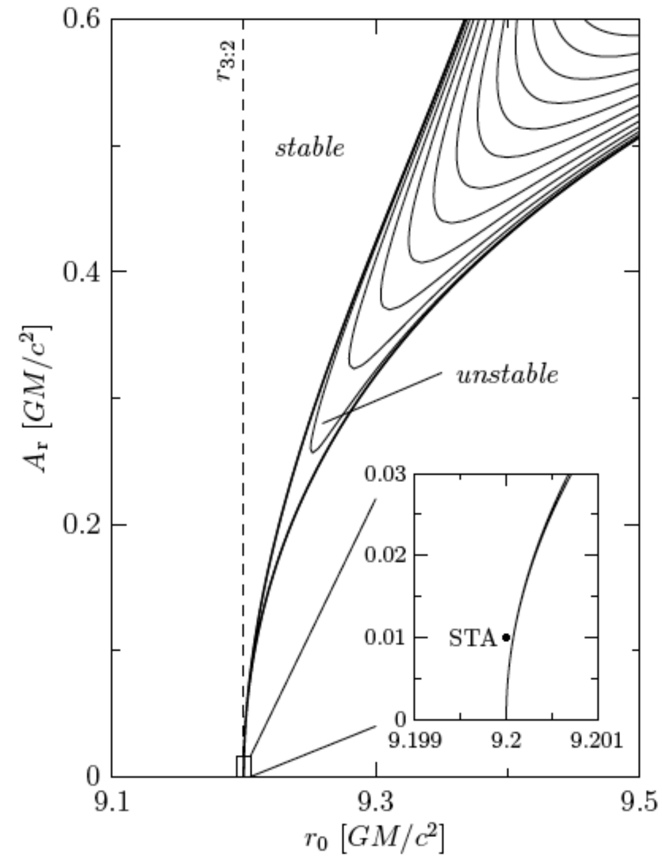
$$\kappa^{(p)}_{ABCD} = -\frac{1}{3!}\int_V \gamma p\left\{(3-3\gamma+\gamma^2)\,\eta_A\eta_B\eta_C\eta_D + 8\,\eta_{(A}\eta_{BCD)} + 6(\gamma-2)\,\eta_{(A}\eta_B\eta_{CD)} + 3\eta_{(AB}\eta_{CD)}\right\}\mathrm{d}V \quad (14)$$

$$\kappa^{(g)}_{ABCD} = -\frac{1}{3!}\int_V \rho\,\xi^i_A\xi^j_B\xi^k_C\xi^l_D\nabla_i\nabla_j\nabla_k\nabla_l\Phi\,\mathrm{d}V \quad (15)$$

and

$$\kappa^{(p)}_{ABCDE} = \frac{1}{4!}\int_V \gamma p\left\{(1+6\gamma-4\gamma^2+3\gamma^3)\eta_A\eta_B\eta_C\eta_D\eta_E + 10\gamma(\gamma-3)\eta_{(A}\eta_B\eta_C\eta_{DE)} + 20\gamma\eta_{(A}\eta_B\eta_{CDE)} + 15(\gamma-1)\eta_{(A}\eta_{BC}\eta_{DE)} + 20\eta_{(AB}\eta_{CDE)}\right\}\mathrm{d}V, \quad (16)$$

$$\kappa^{(g)}_{ABCDE} = -\frac{1}{4!}\int_V \rho\,\xi^i_A\xi^k_B\xi^l_C\xi^m_D\xi^n_E\nabla_i\nabla_k\nabla_l\nabla_m\nabla_n\Phi\,\mathrm{d}V, \quad (17)$$



➔ Resonance is very weak

Ideas/Models of HFQPOs

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- Disk/Magnetosphere Boundary Layer Oscillations (Li & Narayan ‘04; Tsang & DL ’09; Fu & DL’12; see simulations by Mckinney et al 2012)

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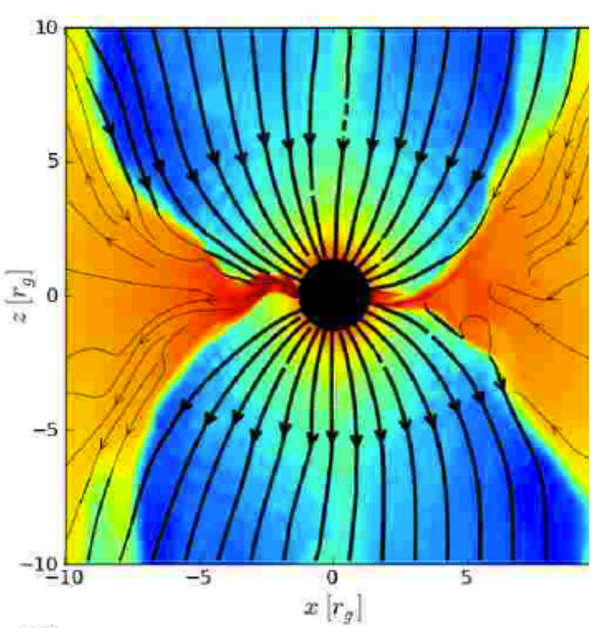
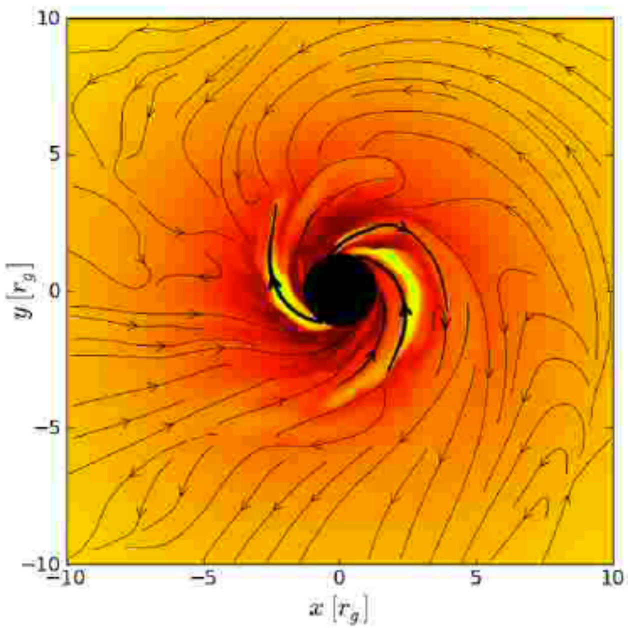
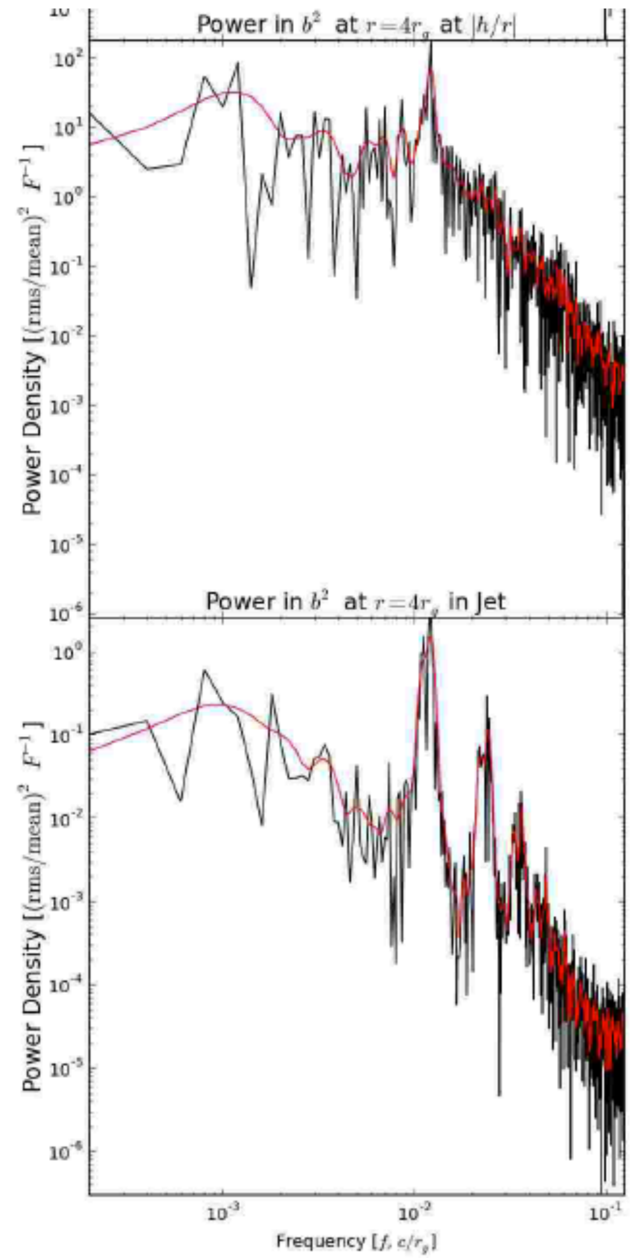
- Oscillation modes in relativistic disks (Kato, Wagoner etc, Varniere, Tagger)

GRMHD Simulations







Henisey et al. 2009; O'Neill et al. 2011;
Dolence et al. 2012; McKinney et al. 2012;
Shcherbakov & McKinney 2013

Future theoretical progress on QPOs

Requires

-- Full GRMHD simulations

-- Semi-analytic works (+Controlled studies)

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- **Oscillation modes in relativistic disks** (Kato, Wagoner etc)

Key issue: Excitation of the modes??

-- m=0 inertial modes excited by global disk deformation (e.g. warps)
(Kato ' 08; Ferreira & Ogilvie '08; Henisey et al.10; Kato 2012, 2013)

-- Our effort: Mode growth due to corotation resonance, nonlinear effect, magnetic field, turbulence, etc.

(DL & Tsang '09; Tsang & DL '08,' 09a,b; Fu & DL '09,' 11,12;
Horak & DL' 13; Miranda et al.'13; Yu & DL '13)

Global Oscillations & Their Excitations in BH Accretion Disks

with David Tsang (Cornell→Caltech/McGill)
Wen Fu (Cornell→Rice)
Jiri Horak (Prague)
Cong Yu (YNAO/CAS)
Ryan Miranda (Cornell)

Main points of our works:

P-modes ("inertial-acoustic modes", "spiral density modes")

-- Trapped (partially) in the innermost region of disk

-- Frequencies can be calculated: robust, agree largely with observations

-- Can grow due to corotation resonance ("corotational instability")

GR plays an important role

-- Large-scale B field may enhance the mode growth

(=> "transitional state", connection with jets)

-- Turbulent viscosity may reduce or enhance mode growth
Also excite quasi-nomal modes of disk

References: DL & Tsang 09; Tsang & DL 08, 09; Fu & DL 09,11,12
Horak & DL 13; Yu & DL (in prep); Miranda, Horak & DL (in prep)

Waves in 2D disks (Spiral density waves):

$$\delta v, \delta\Sigma \propto \exp(im\varphi - i\omega t)$$

Can propagate only in the region:

$$r < r_{\rm ILR} \qquad \text{or} \qquad r > r_{\rm OLR}$$

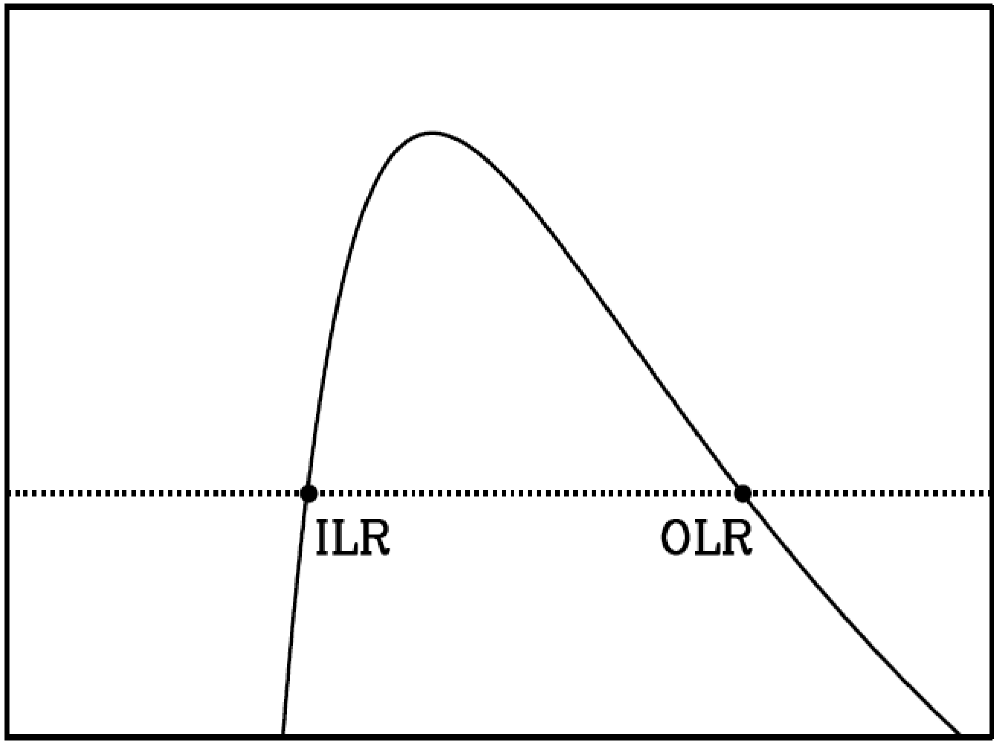
Lindblad Resonances: $\omega - m\Omega(r) = \pm\kappa(r)$

where $\Omega(r) = \text{disk rotation rate}$

$\kappa(r) = \text{radial epicyclic frequency}$

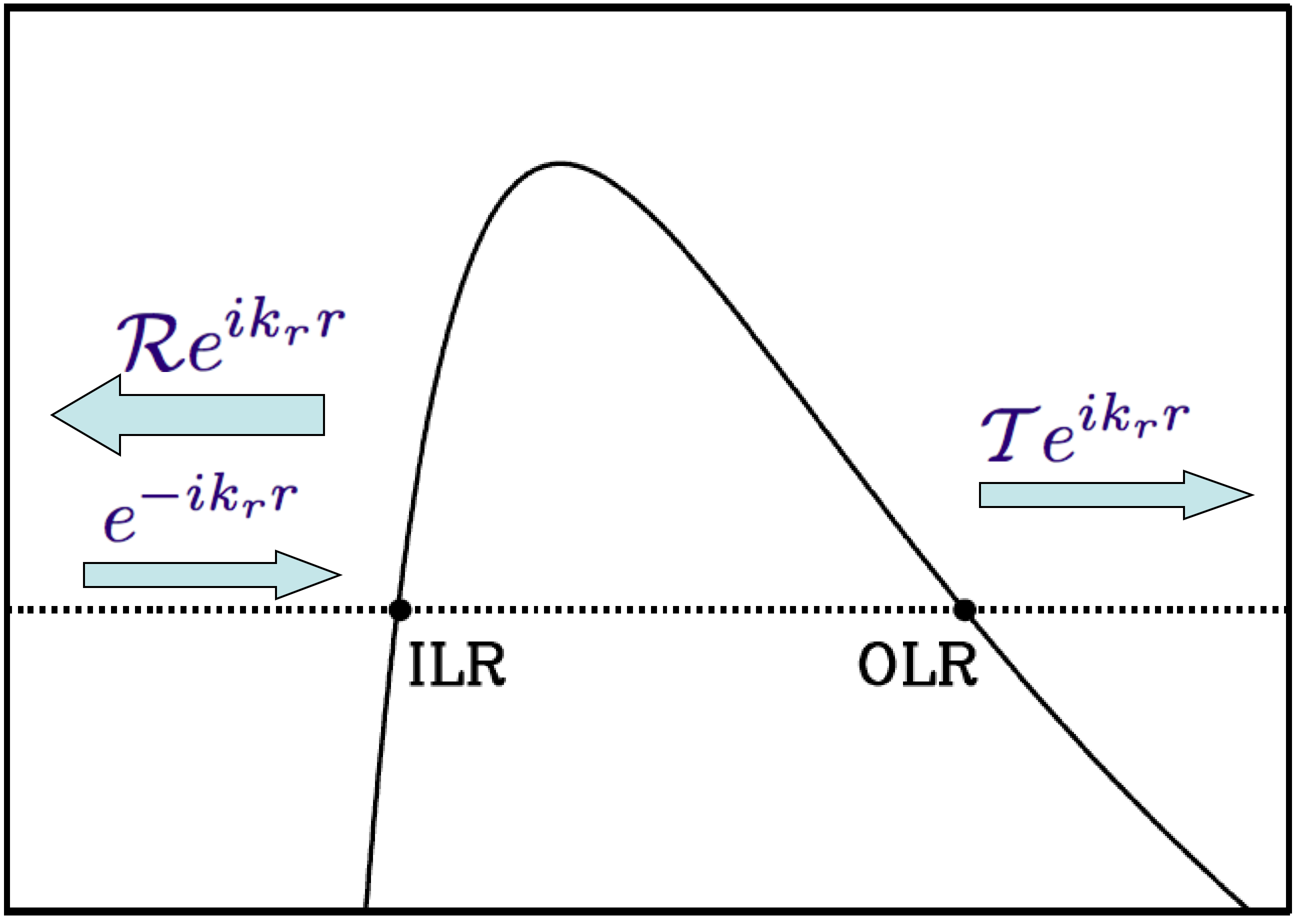
$$\kappa^2 = \frac{2\Omega}{r}\frac{d}{dr}(r^2\Omega)$$

Wave propagation diagram (effective potential)



wave at $r > r_{\mathrm{OLR}}$: $\omega/m > \Omega \;\Rightarrow\;$ positive energy

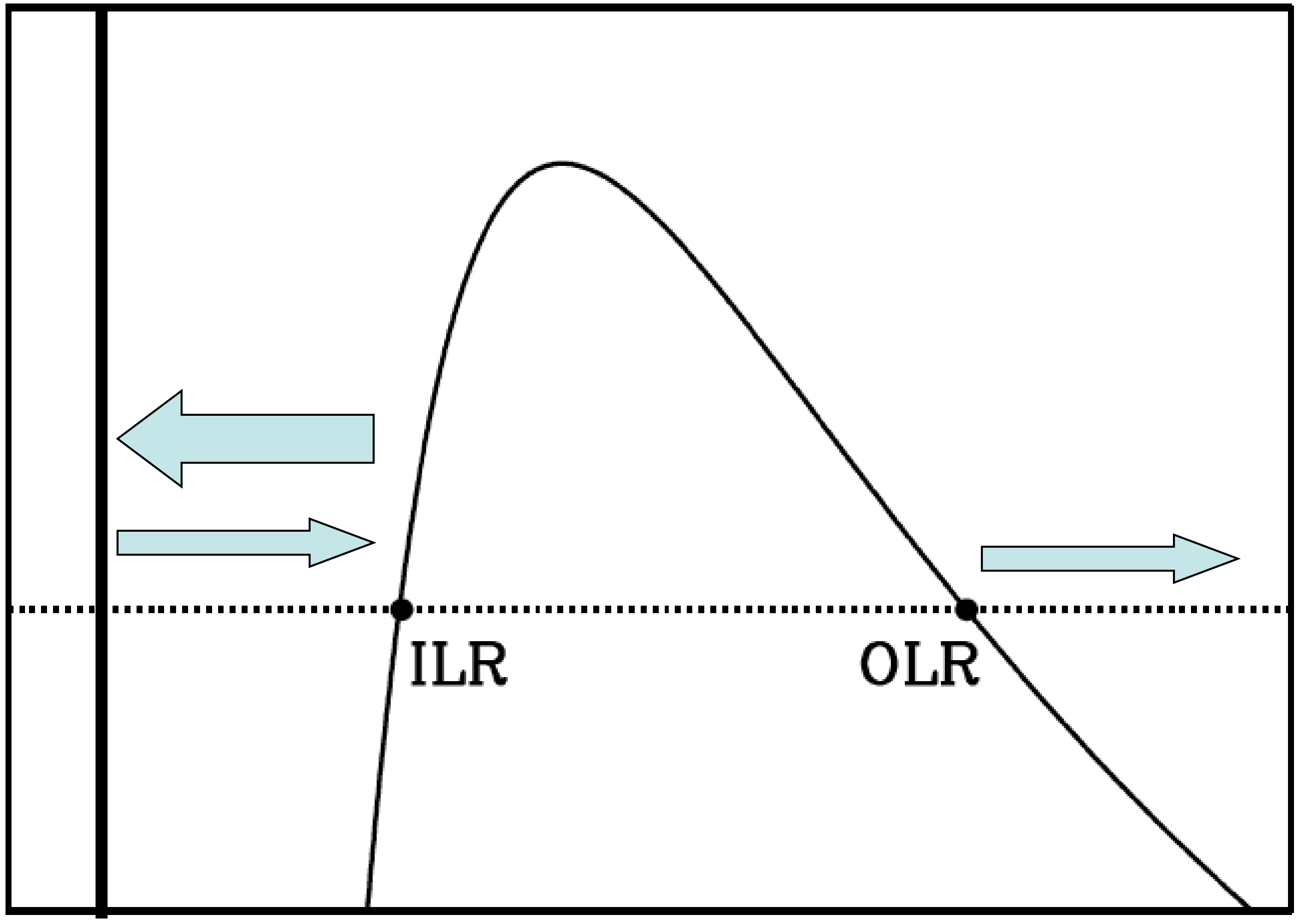
wave at $r < r_{\mathrm{ILR}}$: $\omega/m < \Omega \;\Rightarrow\;$ negative energy



$$(-1) = (-1)|\mathcal{R}|^2 + |\mathcal{T}|^2$$

$$\Rightarrow \; |\mathcal{R}|^2 = 1 + |\mathcal{T}|^2 > 1$$

Super-reflection

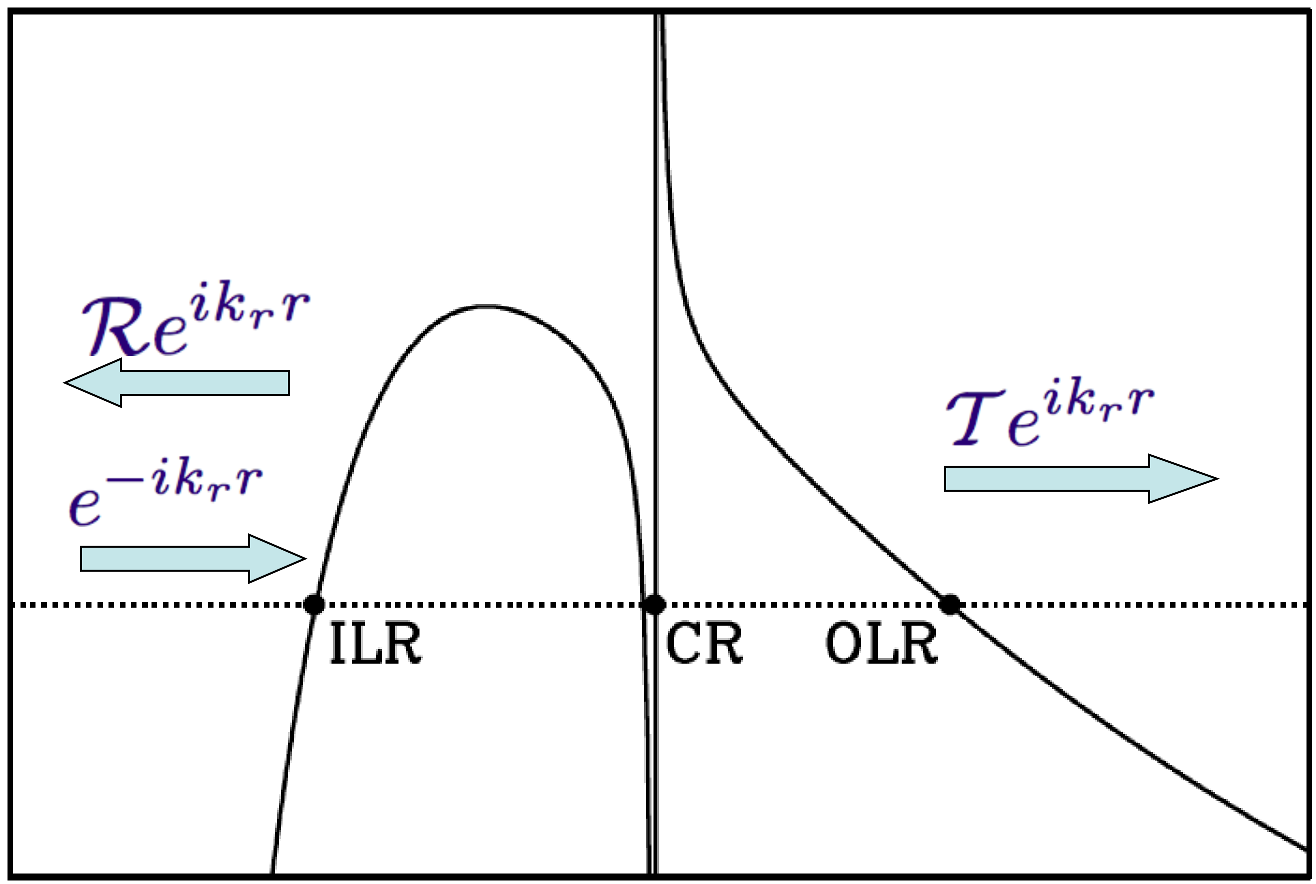


Trapped mode between r_{in} and r_{ILR} : overstable

Even more important/interesting…

Corotation resonance, where

$$\omega/m = \Omega$$



$$(-1) = (-1)|\mathcal{R}|^2 + |\mathcal{T}|^2 + \mathcal{D}_c$$

$$\Rightarrow |\mathcal{R}|^2 = 1 + |\mathcal{T}|^2 + \mathcal{D}_c$$

Wave absorption at corotation

Can have both signs !

Reflectivity at ILR: $|\mathcal{R}|^2 = 1 + |\mathcal{T}|^2 + \mathcal{D}_c \simeq 1 + \mathcal{D}_c$

Sign depends on sign of $d\zeta/dr$

$$\zeta = \frac{\kappa^2}{2\Omega\Sigma}$$ (vortensity)

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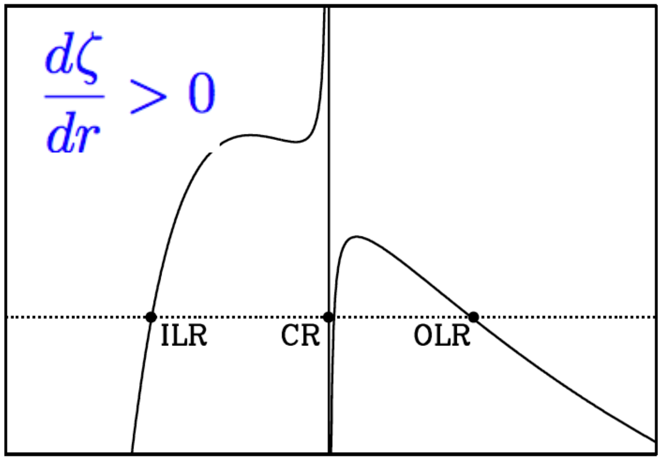

$$\frac{d\zeta}{dr} > 0$$

$$\Rightarrow \mathcal{D}_c > 0$$

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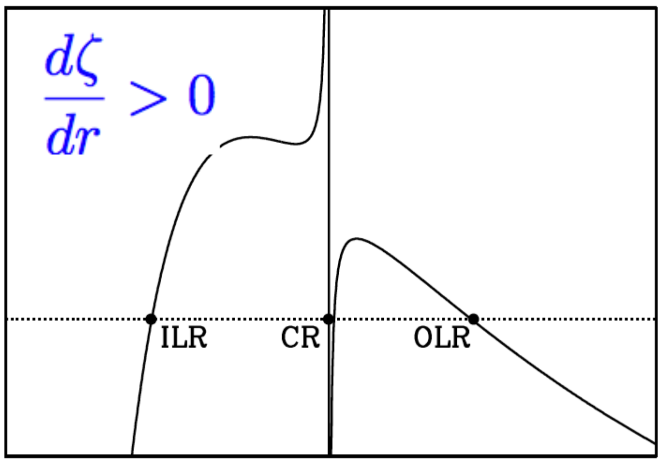
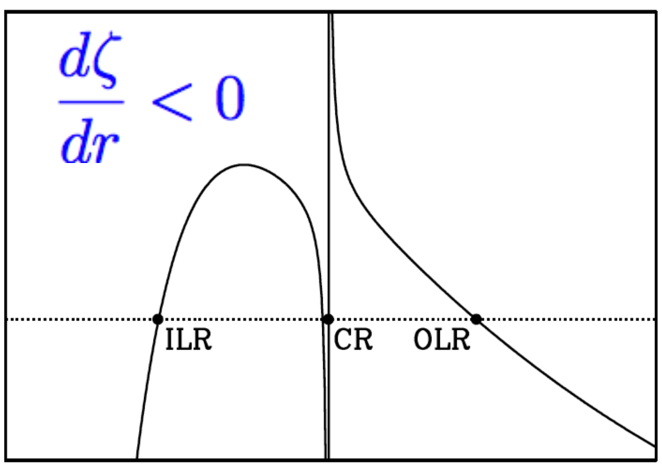


$\Rightarrow \mathcal{D}_c > 0$



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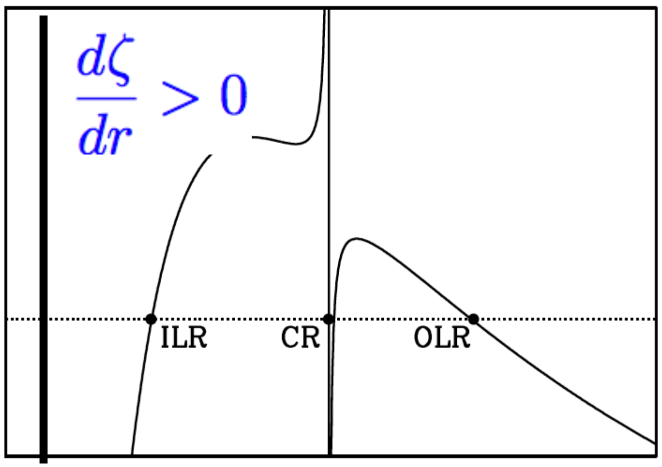
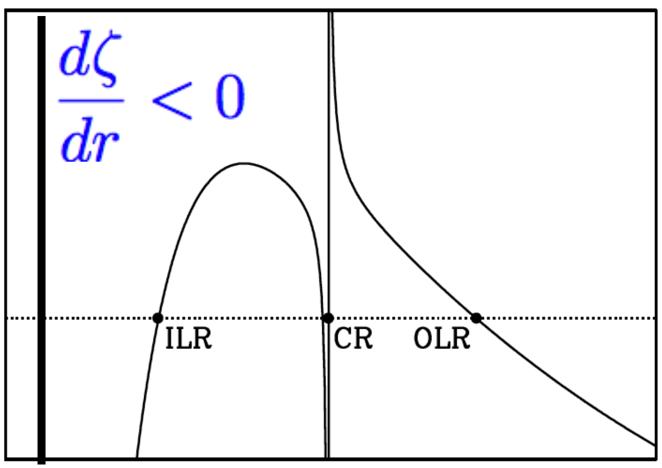


$\Rightarrow \mathcal{D}_c > 0$

Overstable mode

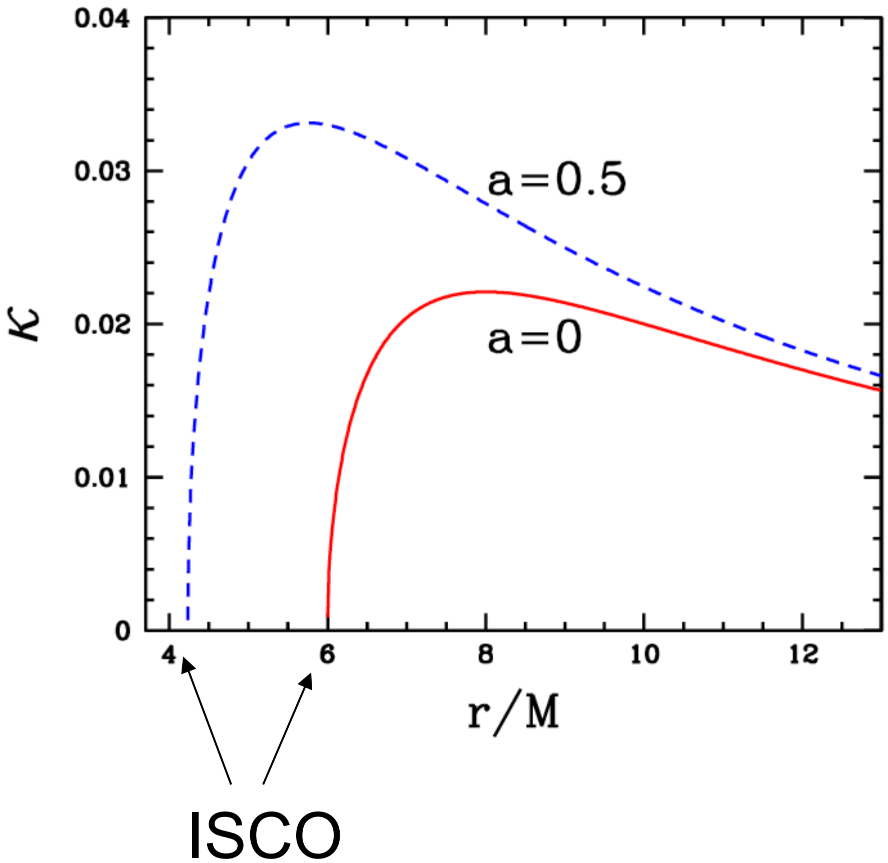


$\Rightarrow \mathcal{D}_c < 0$

Damped mode

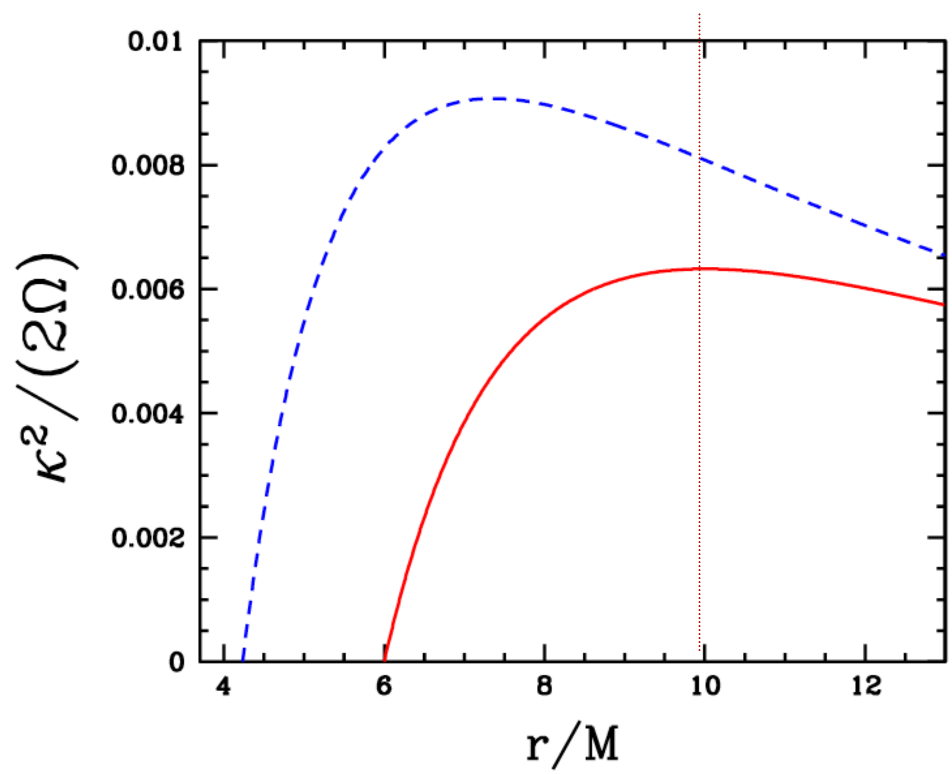
General Relativity Effect

See Horak's talk

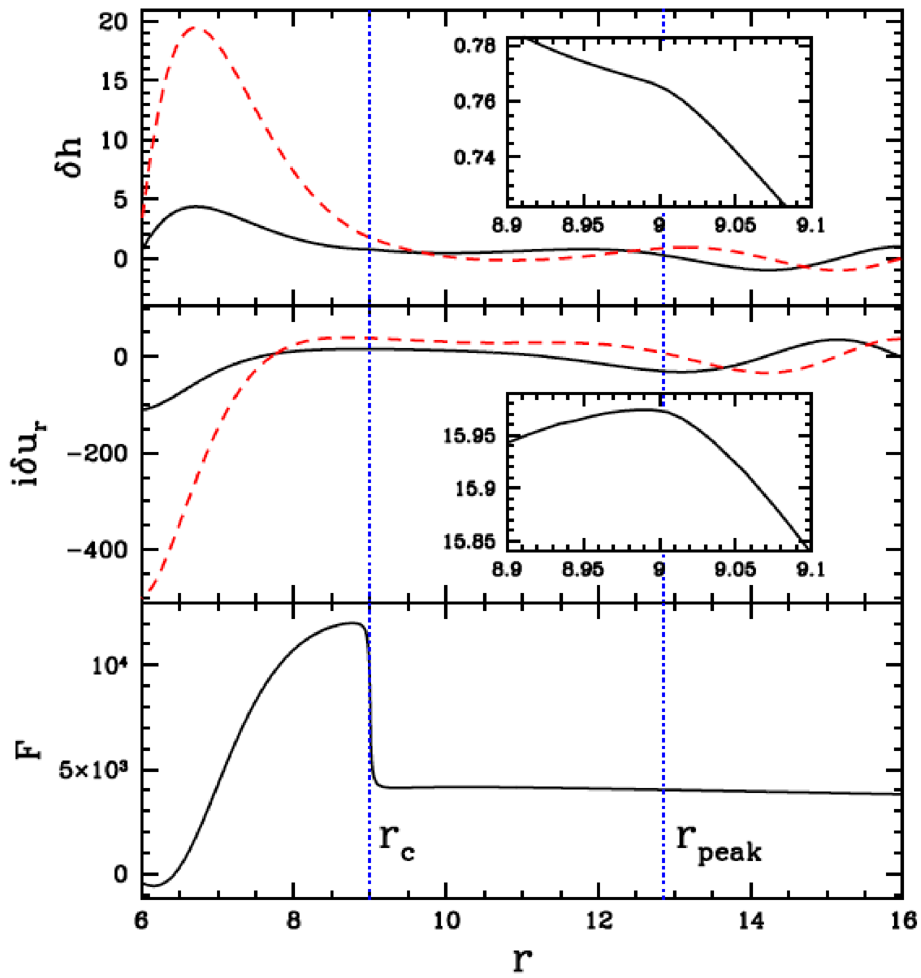


Vortensity $\zeta = \frac{\kappa^2}{2\Omega\Sigma}$

GR makes $d\zeta/dr > 0$
in the Inner-most disk region
==> makes the mode grow !

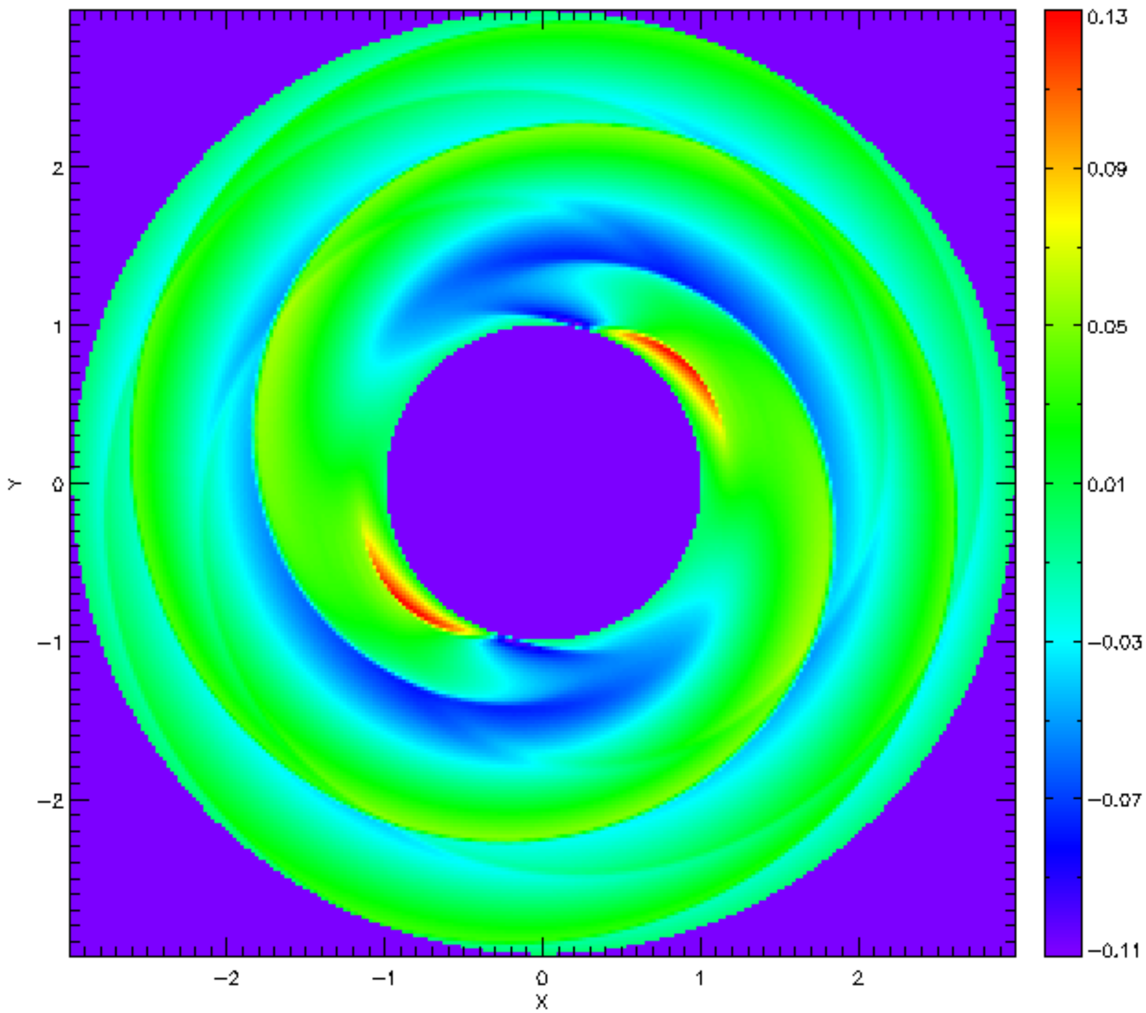


Linear Mode Calculation (Mode freq. and growth rate)



DL & Tsang 2009,2010

Nonlinear Simulation (2D) of Growing Modes



Wen Fu & DL, 2012

Results: Overstable Disk P-Modes

Mode Frequencies:

- (Largly) consistent with known BH mass (and spin)
- varies (~10%) as Mdot changes (~3)
- Frequency ratio approximately: 1:2:3:4… (not exactly)

Mode growth due to corotation resonance

(GR plays an important role)

A possible candidate for HFQPOs

Complications:

Mode damping due to radial infall

For standard thin (SS) disks, radial velocity incresases rapidly near $r_{ISCO.}$

==> Tends to damp the p-modes;
(but not completely, due to sharp density gradient around r_{in})

Competition: mode growth (due to corotation) and damping (due to infall)

==> **Net result:**

In standard thin disk, p-modes are likely damped
==> No HFQPOs in thermal state

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Real disks (in “intermediate state”) are more complicated…

Magnetic fields…

Effects of Magnetic Fields on P-Modes

-- Mode frequencies are slightly/modestly affected: Robust…

-- Mode growth rates can be significantly affected:

1. Magnetic fields may accumulate inside r_{isco}

(e.g. Lovelace et al 2009; simulations by Hawley, Krolik etc)

==> The inner disk edge may be more reflective than standard SS disk (Tsang & DL 2009b; Fu & DL 2012)

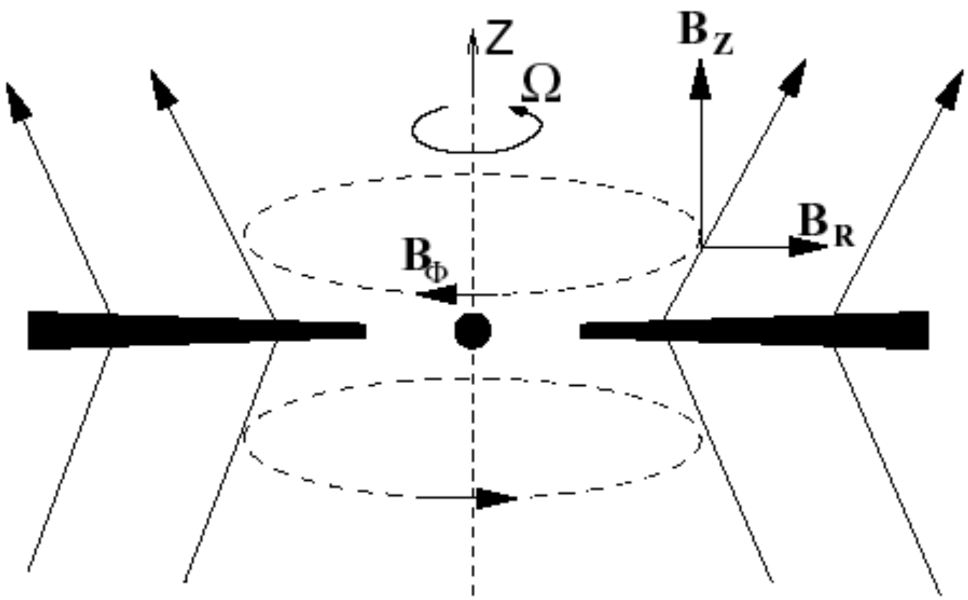
==> Enhance net growth of p-modes

2. Large-scale poloidal field can reduce mode frequency and enhance corotational instability

==> Enhance growth of p-modes

(Yu & DL, in prep)

Disks threaded by large-scale poloidal magnetic fields (embedded in a corona)



-- Increase the p-mode growth rate due to corotation resonance

Disk + Corona (coupled by B field) oscillate together,
the “clock” is mainly set by disk

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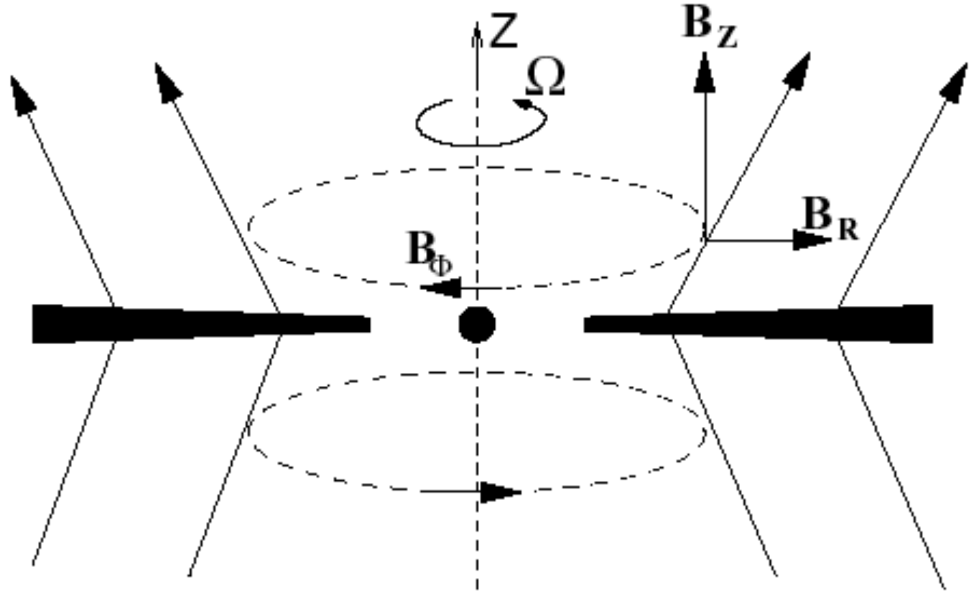

-- Increase the p-mode growth rate due to corotation resonance

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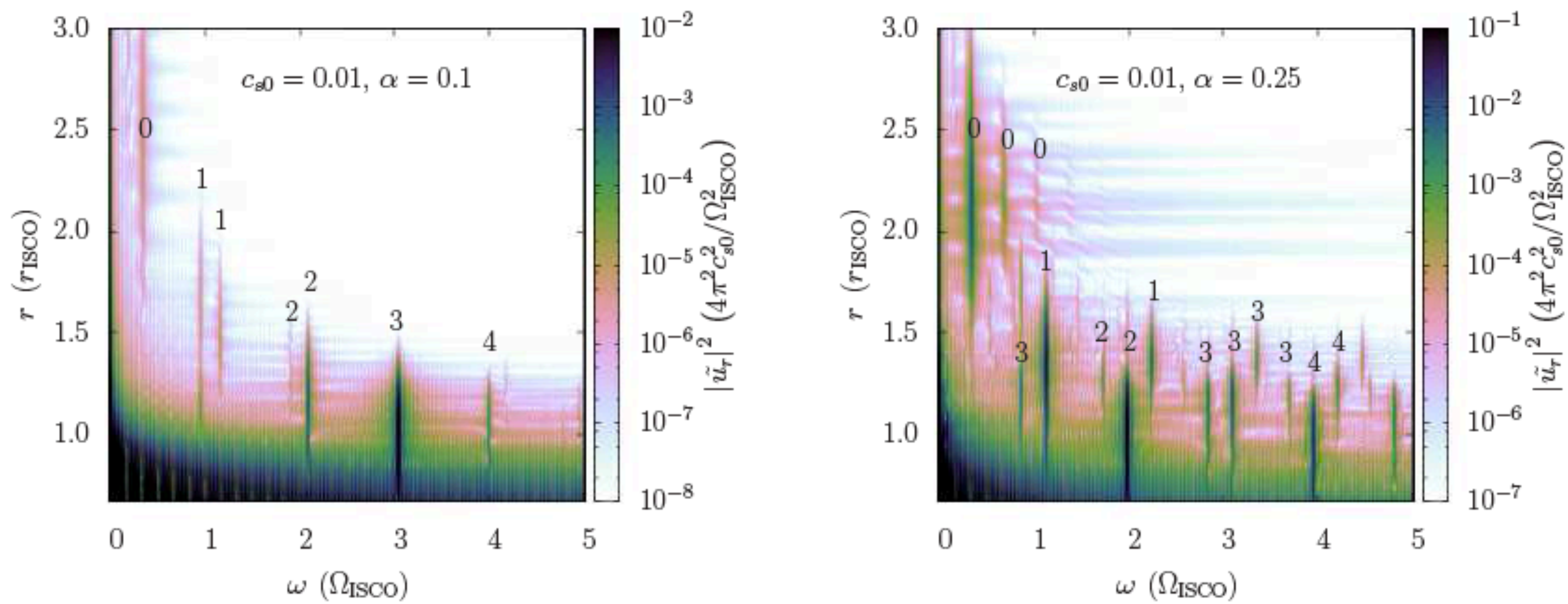
the "clock" is mainly set by disk

-- Such large-scale field is ideal for producing jets/outflows
("Intermediate state")

Quasi-normal Disk Oscillation Modes excited by turbulent viscosity



Ryan Miranda, Horak & DL 2014

Summary

- There are many concepts/ideas theoretical models for HFQPOs, but many have not been worked out… Theorists need to work hard

- P-modes (spiral density modes) partially trapped in the inner-most region of disks is possible candidate:

  -- Frequencies can be calculated from first principle

  robust, largely agree with observations (consistent mass, spin)

  -- Can grow naturally due to corotation resonance (GR important)

  -- In this theory, there are good reasons to expect that

  (i) They are not present in thermal state (mode damping due to infall)

  (ii) They are present in intermediate state (effect of large-scale B field)

* Turbulent excitations of quasi-normal oscillation modes

Thanks!