Chandra Fellows Symposium

Instability in Accretion Disks and Quasi-Periodic Oscillations in X-Ray Binaries

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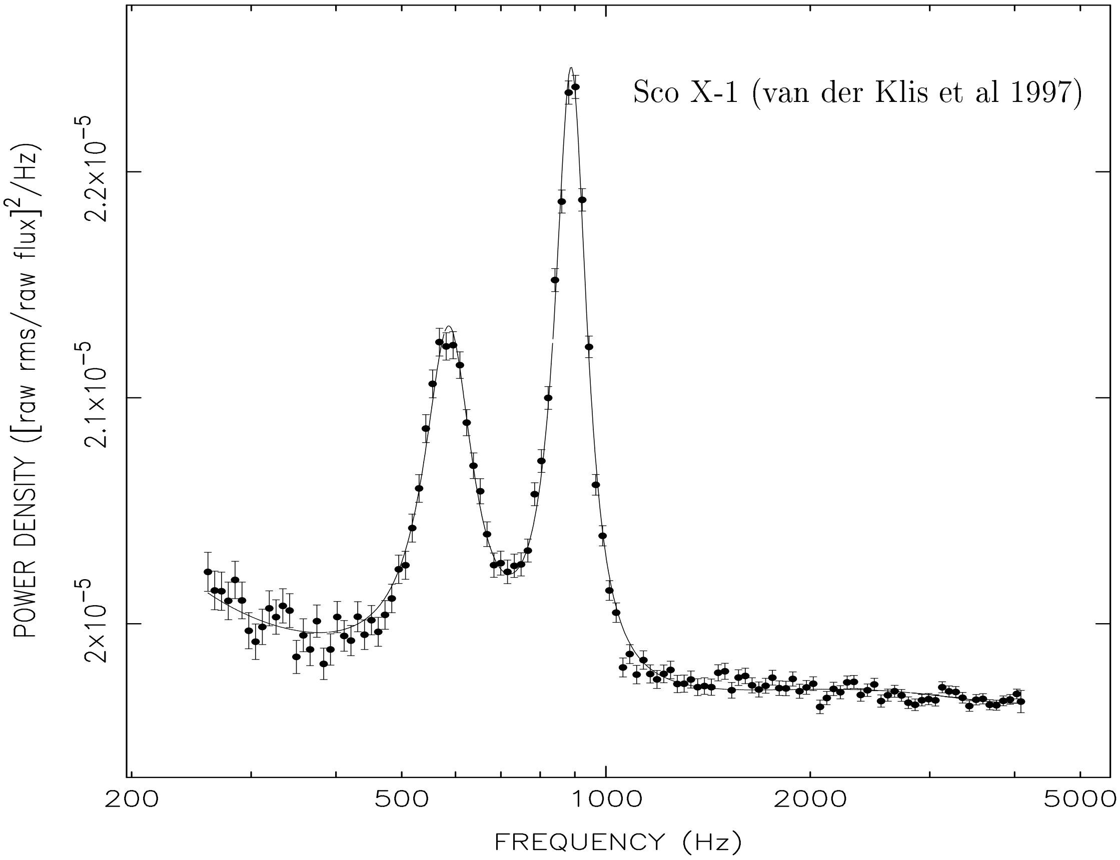
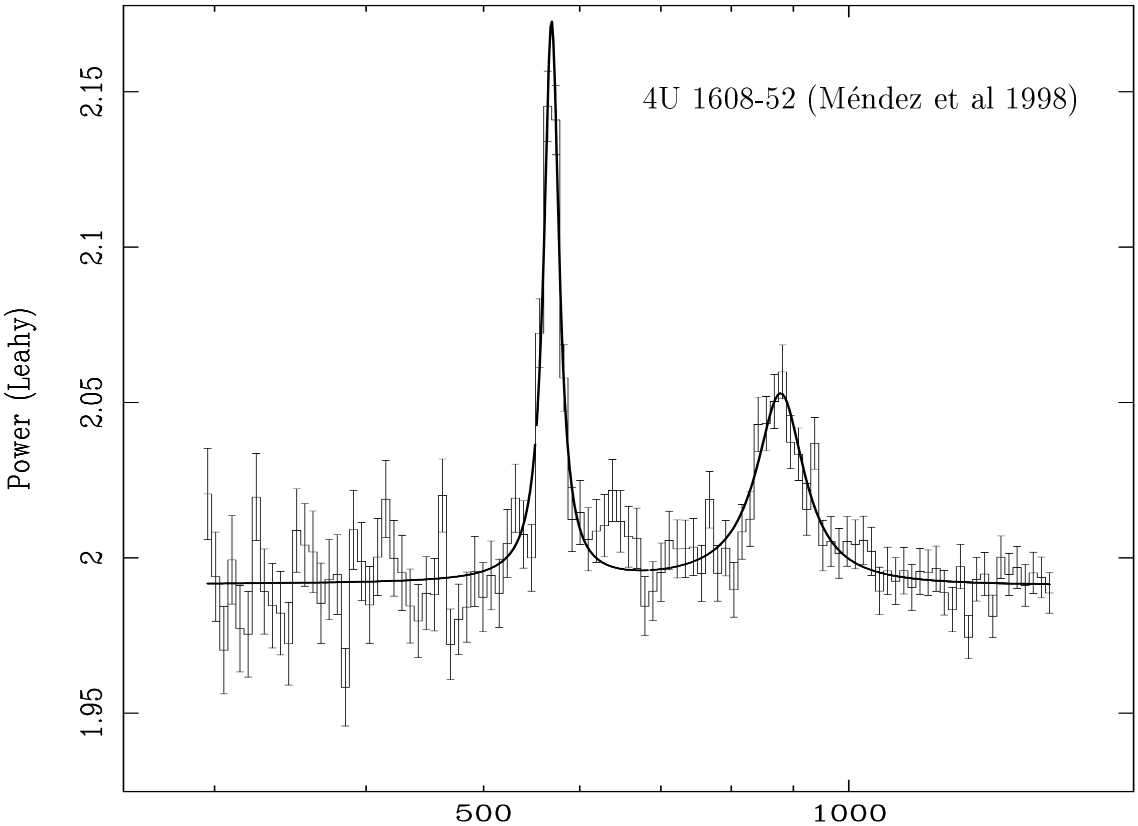
- Introduction
- Outline of the Model
- Results
- Summary and Future Prospect

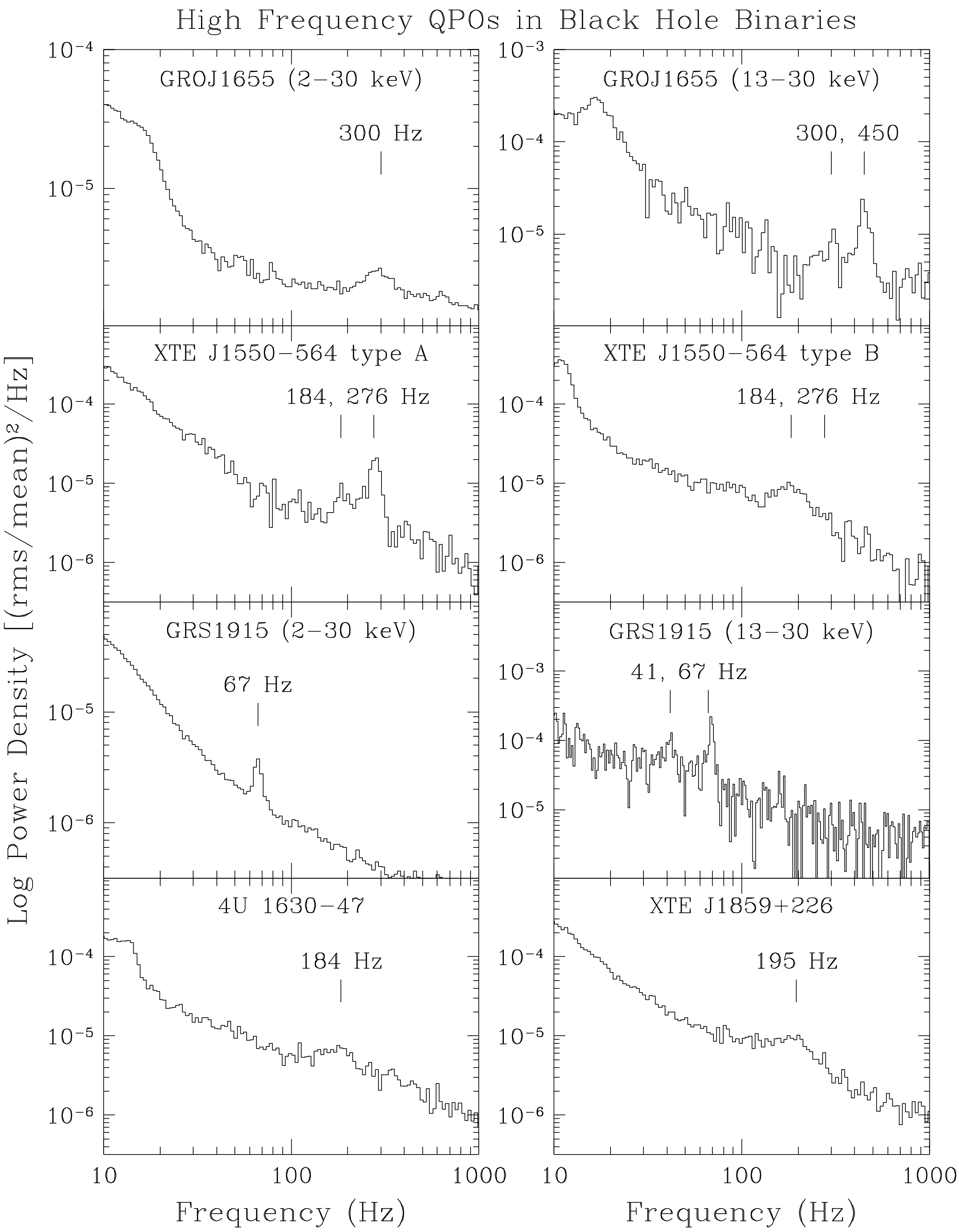
I. Introduction

- *Quasi-periodic oscillations (QPOs) in X-ray binary systems*: They appear in both neutron-star and black-hole systems.
- *Kilohertz QPOs*: frequency $\sim 10^2 - 10^3$Hz. They are believed to be produced by processes in the accretion flow near the accreting object.
- *Some important features in kHz QPOs*:
  – Occur at a similar frequency in NS sources that differ in X-ray luminosity by more than two orders of magnitude;
  – Often appear in pairs with separation anti-correlated to the QPO frequencies;
  – Separation in QPO frequencies is correlated to the spin of the central neutron star;
  – In several sources the twin QPO frequencies seem to occur in the ratio of simple integers.

- *Models for kHz QPOs*:
  - The beak-frequency model
    (Lamb et al; Strohmayer);
  - Disk seismology
    (Kato; Wagoner et al).


Sco X-1 (van der Klis et al 1997)
POWER DENSITY ([raw rms/raw flux]^2/Hz)
2.2×10^{-5}
2.1×10^{-5}
2×10^{-5}
200
500
1000
2000
5000
FREQUENCY (Hz)


4U 1608-52 (Méndez et al 1998)
Power (Leahy)
2.15
2.1
2.05
2
1.95
500
1000
Frequency (Hz)



(Remillard et al 2002)

II. Outline of the Model

- *Model*: A cylindrical disk threaded by a vertical magnetic field. In the equilibrium state, the mass density has a jump at $r = r_m$, being larger on the outside and smaller on the inside. There may be also a jump in the angular velocity $\Omega \propto r^{-q}$.
- *Assumptions*:
  - The disk fluid is incompressible;
  - The disk fluid is perfectly conducting;
  - Every quantity does not depend on z.
- *Goal*: Looking for unstable modes and their relations to QPOs.

III. Results

- *Basic equations*:

$$\nabla \cdot \mathbf{v} = 0 \ , \qquad \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = 0$$

$$\begin{aligned} \rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} \ &= \ -\rho \nabla \Phi - \nabla \left(p + \frac{B^2}{8\pi} \right) \\ &+ \frac{1}{4\pi} \mathbf{B} \cdot \nabla \mathbf{B} \end{aligned}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \ , \qquad \nabla \cdot \mathbf{B} = 0$$

- *Solutions for the equilibrium state*:

$$g_{\rm eff} = -\frac{1}{\rho_0} \frac{dp_{t0}}{dr}$$

where

$$g_{\rm eff} \equiv \Omega_{\rm eff}^2 r = \frac{d\Phi}{dr} - \Omega^2 r \ , \qquad p_t \equiv p + \frac{B^2}{8\pi}$$

- *Linear perturbation*: Consider $Q \propto \exp[i(-\omega t + m\phi)]$. A wave equation is derived

$$\frac{1}{r\rho_0}\frac{d}{dr}\left(r\rho_0\frac{dW}{dr}\right) - \frac{m^2}{r^2}\left[\frac{\Omega_{\rm eff}^2}{\sigma^2}\frac{d\ln\rho_0}{d\ln r} - \frac{2\zeta}{m\sigma}\frac{d\ln(\rho_0\zeta)}{d\ln r} + 1\right]W = 0$$

where $W \equiv ru$, $\sigma \equiv \omega - m\Omega$, $\zeta \equiv r^{-1}d(r^2\Omega)/dr$.

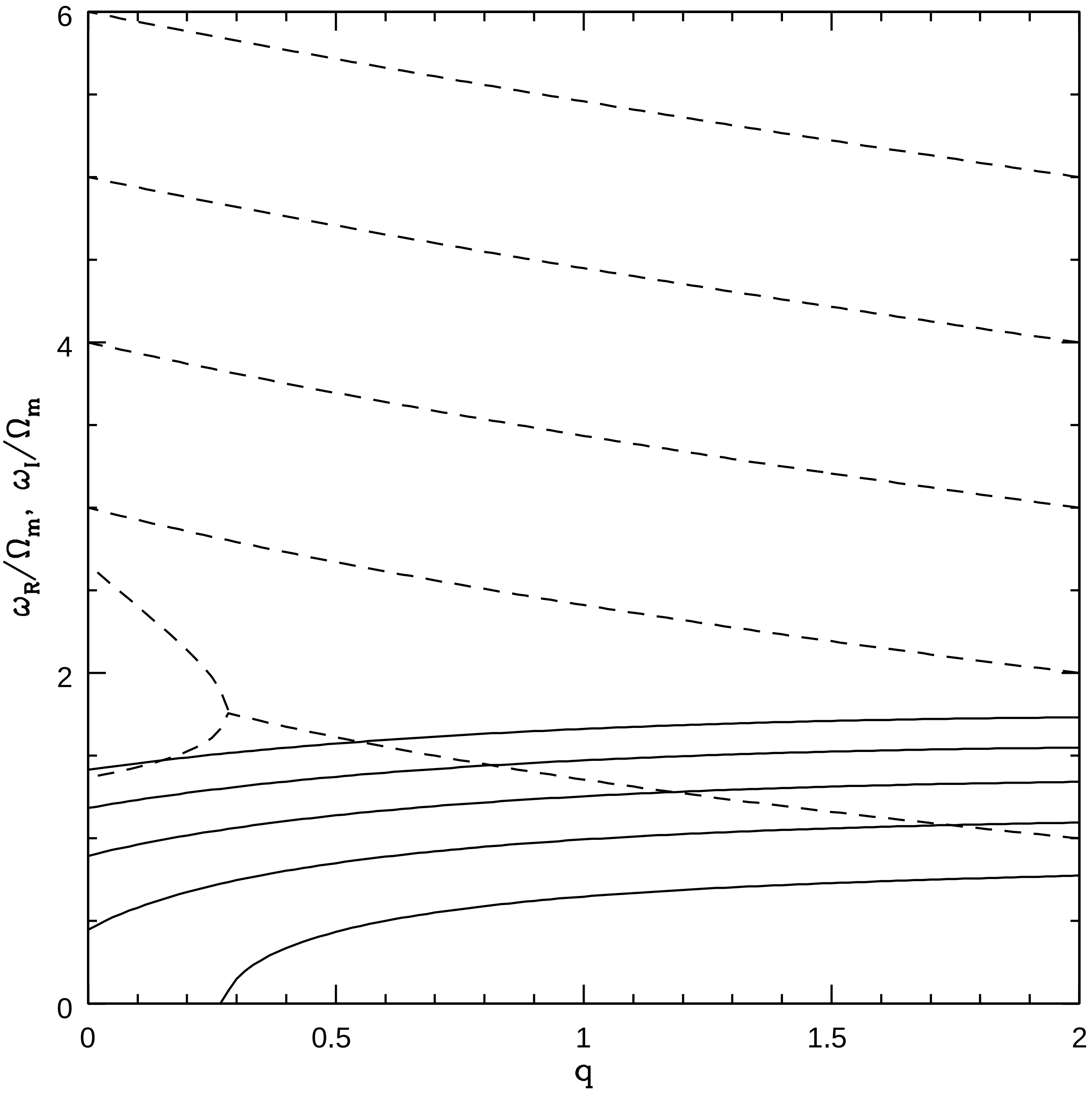
- *Junction conditions at $r = r_m$*:

$$\Delta_m\left(\frac{W}{\sigma}\right) = 0$$

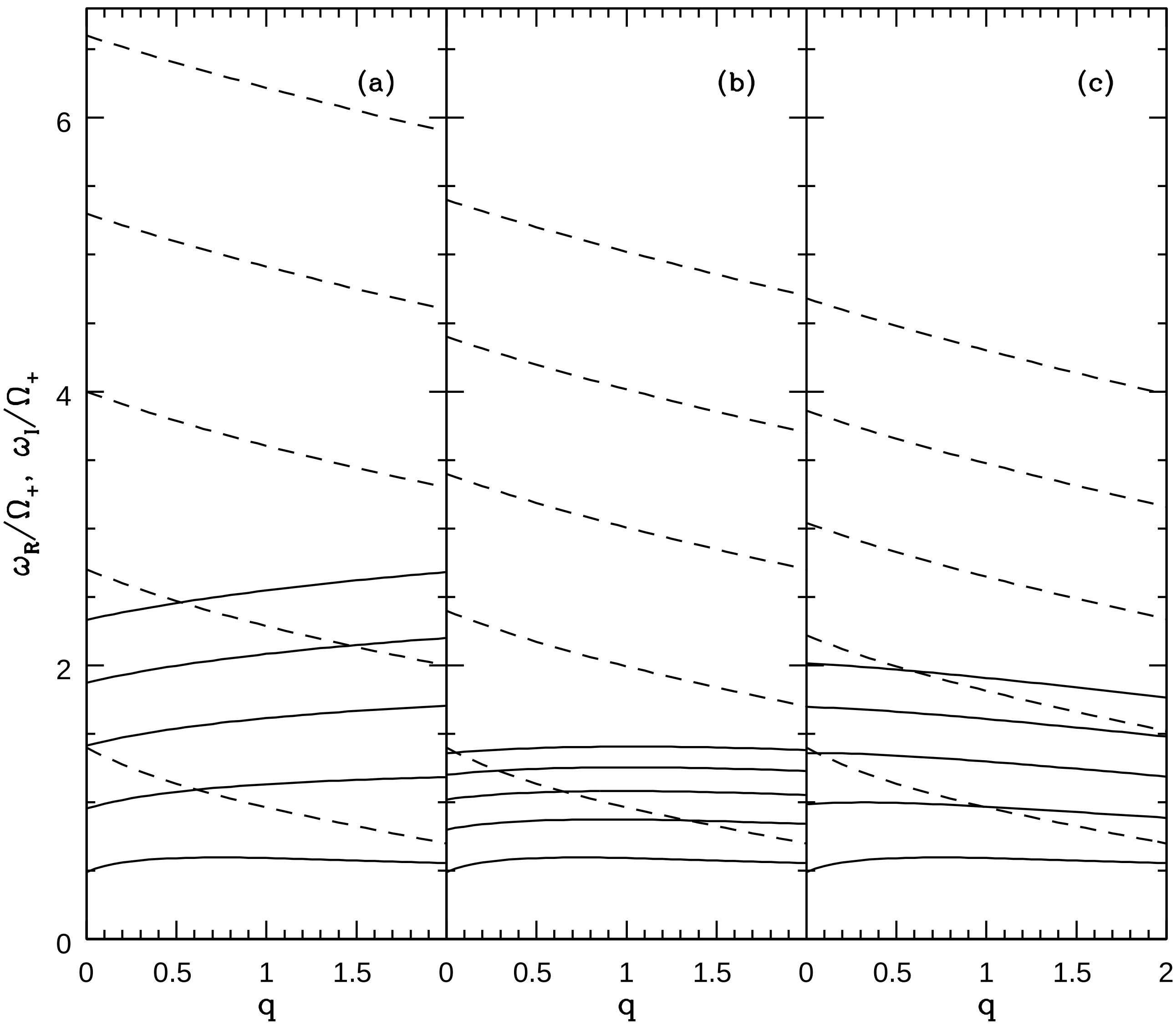
$$\Delta_m\left[\sigma\rho_0\frac{dW}{dr} - \frac{m}{r}\left(\frac{m\Omega_{\rm eff}^2}{\sigma} - 2\zeta\right)\rho_0 W\right] = 0$$

- *Solutions*: $\omega = \omega_{\rm R} + i\omega_{\rm I}$

  For $q = 0$ and 2 exact solutions can be found. For other q the wave equation has to be solved numerically.



Black-hole case (Ω is continuous): $m = 1, 2, 3, 4, 5$ (bottom to top).



Neutron-star case (Ω is discontinuous): $m = 1, 2, 3, 4, 5$ (bottom to top). (a) $\Omega_- = 2\Omega_+$; (b) $\Omega_- = \Omega_+$ (c) $\Omega_- = 0.4\Omega_+$.

IV. Summary

- The solutions show that the gas at $r = r_m$ is unstable to Rayleigh-Taylor and Kelvin-Helmholtz instabilities.
- The growth rate $\omega_{\rm I} \sim \Omega$; the oscillation frequency $\omega_{\rm R} \sim m\Omega$.
- *Future work*: toward explanation of the correlation between QPO frequencies and the neutron-star spin frequency.

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The paper version of this talk:

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