3D ASPECTS OF DENSITY WAVES

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June 2013

COLLABORATORS

- General properties of 3D waves with low m (Ogilvie, Pringle)
- Buoyancy torques, 3D and high m (Zhu)

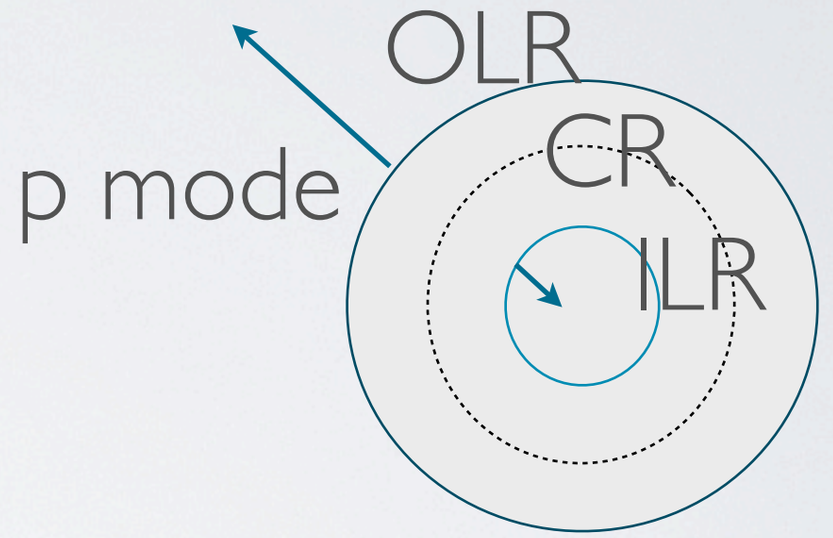
LIN & SHU (1964)

- 2D gas (star) dynamics
- Long Waves (self-gravity)
- Free waves
- Importance of resonances

FREE/DRIVEN WAVES

- Waves driven by external forcing Feldman & Lin (1973)
- Carry energy/angular momentum
- Change disk structure where waves damp
  - Bar - arms in ISM of galaxies
  - Star - truncate disks
  - Planet - open gaps, migration, wakes
  - Satellite - gaps, waves in planetary rings

2D WAVES NO SELF-GRAVITY



- Modified pressure waves: p modes propagate away from corotation

$$m^2(\Omega - \Omega_{\rm p})^2 = \kappa^2 + k^2 c^2$$

3D WAVES

- Various collective effects possible, in addition to self-gravity.
- f mode wave 3D (pressure, vertical buoyancy)
- p mode waves 3D (pressure forces)
- r mode waves 3D (rotation and inertial forces)
- g mode waves 3D (vertical buoyancy forces)

3D WAVEGUIDE MODEL

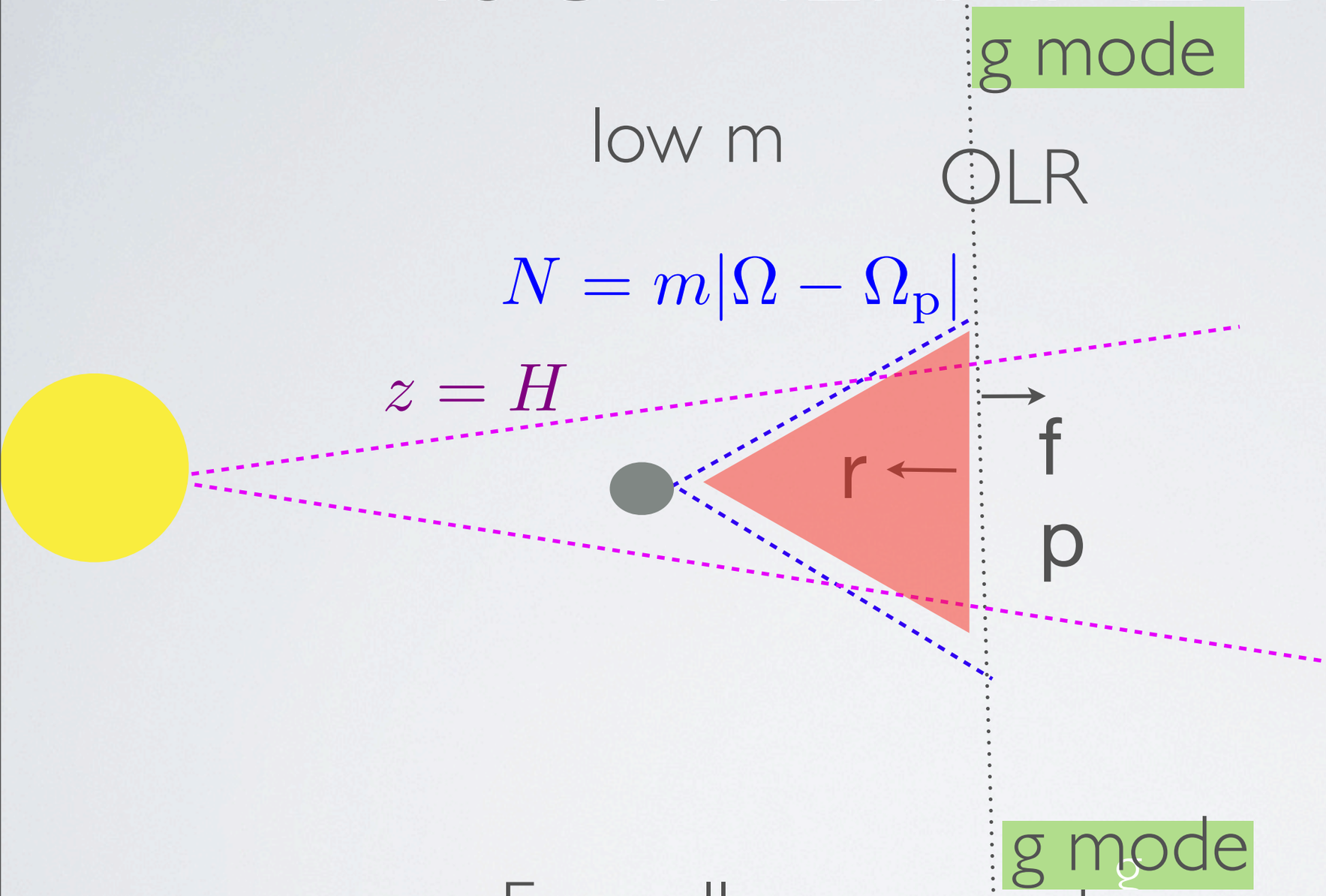
- Consider 3D waves of the form with m and Ω_{p} given

$$f(r,z)\exp\left[i(k_r(r)r + m(\phi - \Omega_{\mathrm{p}}t))\right]$$

- Solve for $k_r(r)$ and $f(r,z)$ locally in r as a function of z, subject to boundary conditions in z

- Infinitely many modes with different number of nodes in z

PROPAGATION IN ADIABATIC ISOTHERMAL DISK

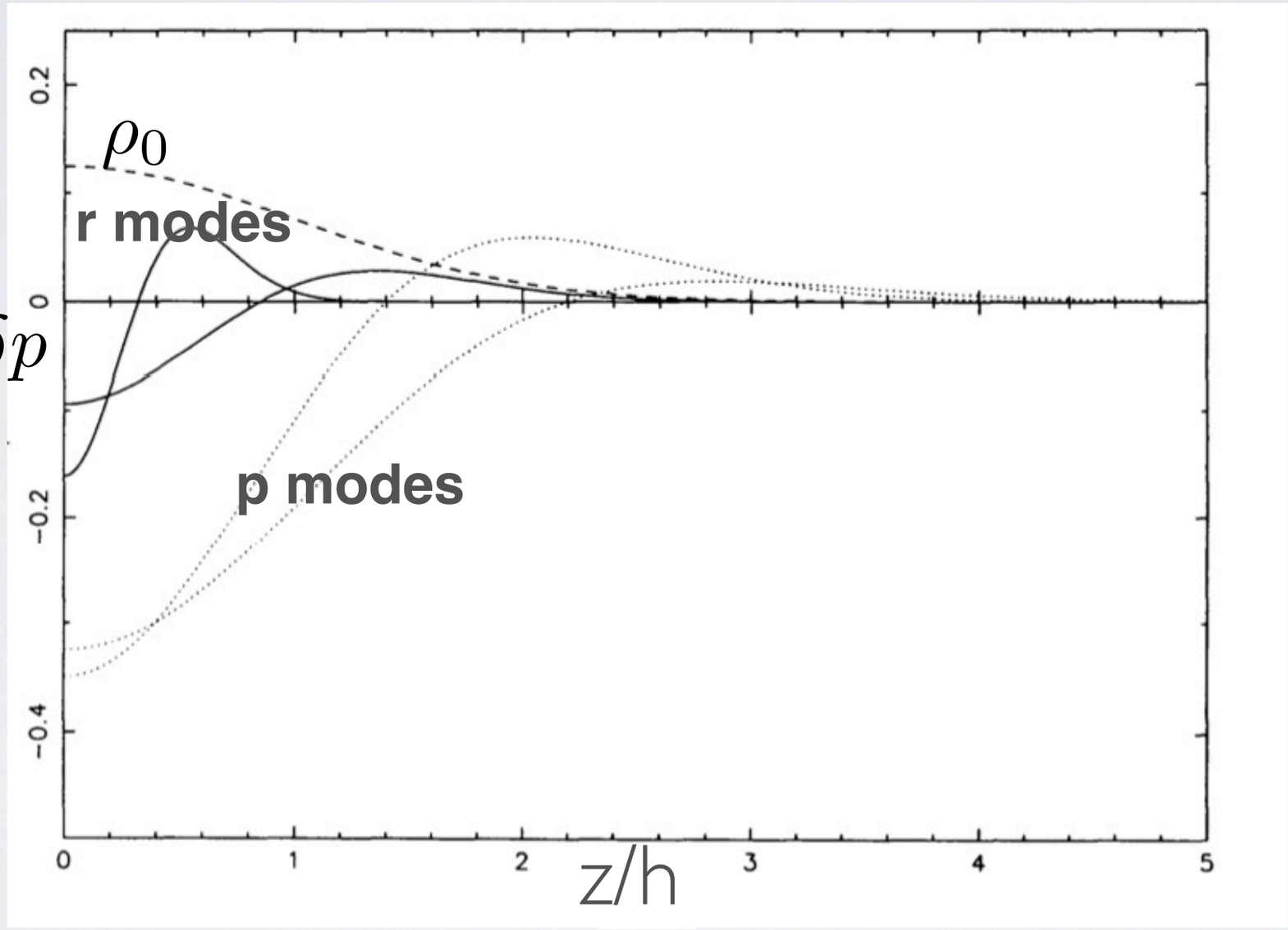


Formally, no g modes.

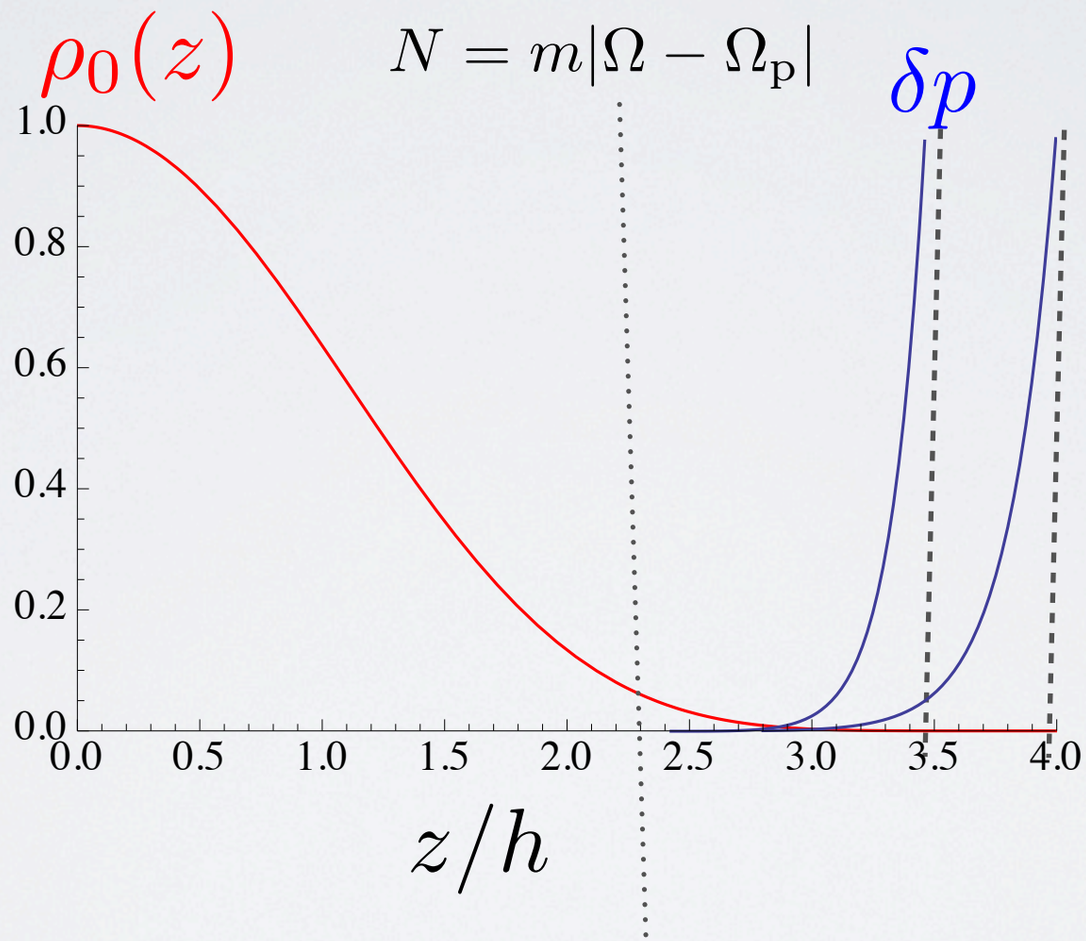
g modes can occur at upper/lower boundaries or in nonisothermal disk

EXAMPLE

m=0 waves, low order in z



GRAVITY MODES



edges

g modes concentrated near z edge, if present

RESONANCES

- Waves launched where wavelength is long
- So potential can interact with wave
- Occurs at resonances
- Resonance width determined by collective effects: pressure, self-gravity
- Case of planet: high m LRs set away from planet ~ H
- Torque decreases with m > r/H

WAVES EXCITED AT 3D LINDBLAD RESONANCES

- Isothermal nonadiabatic disk, $\gamma = 1$,
  wavefronts perpendicular to orbital plane.
  One mode only
  No vertical motion. Same as 2D case

- Isothermal adiabatic, $\gamma > 1$
  3D motions: p, g, and r modes excited
  2D motions: f mode

SUMMARY OF 3D WAVES/ RESONANCES

- Torques associated with propagating waves
- Waves launched at resonances: turning points of free waves
- Waveguide model locally sin/cos in r, ϕ, and t. Determine structure in z and radial wavenumber.
- Resonance width controlled by collective effects such as pressure (including corotation)