Tidal Asteroseismology: KOI-54

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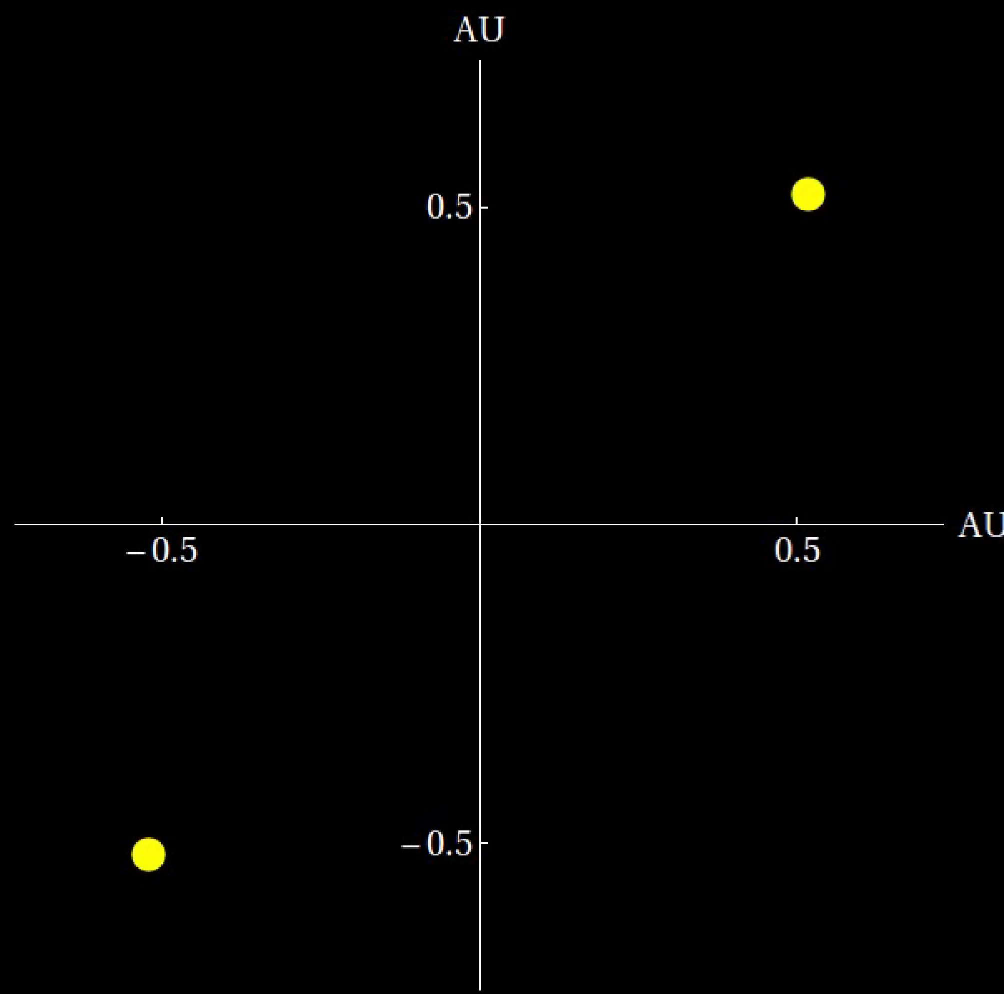

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Phil Arras
Nevin Weinberg

Kepler Object of Interest 54

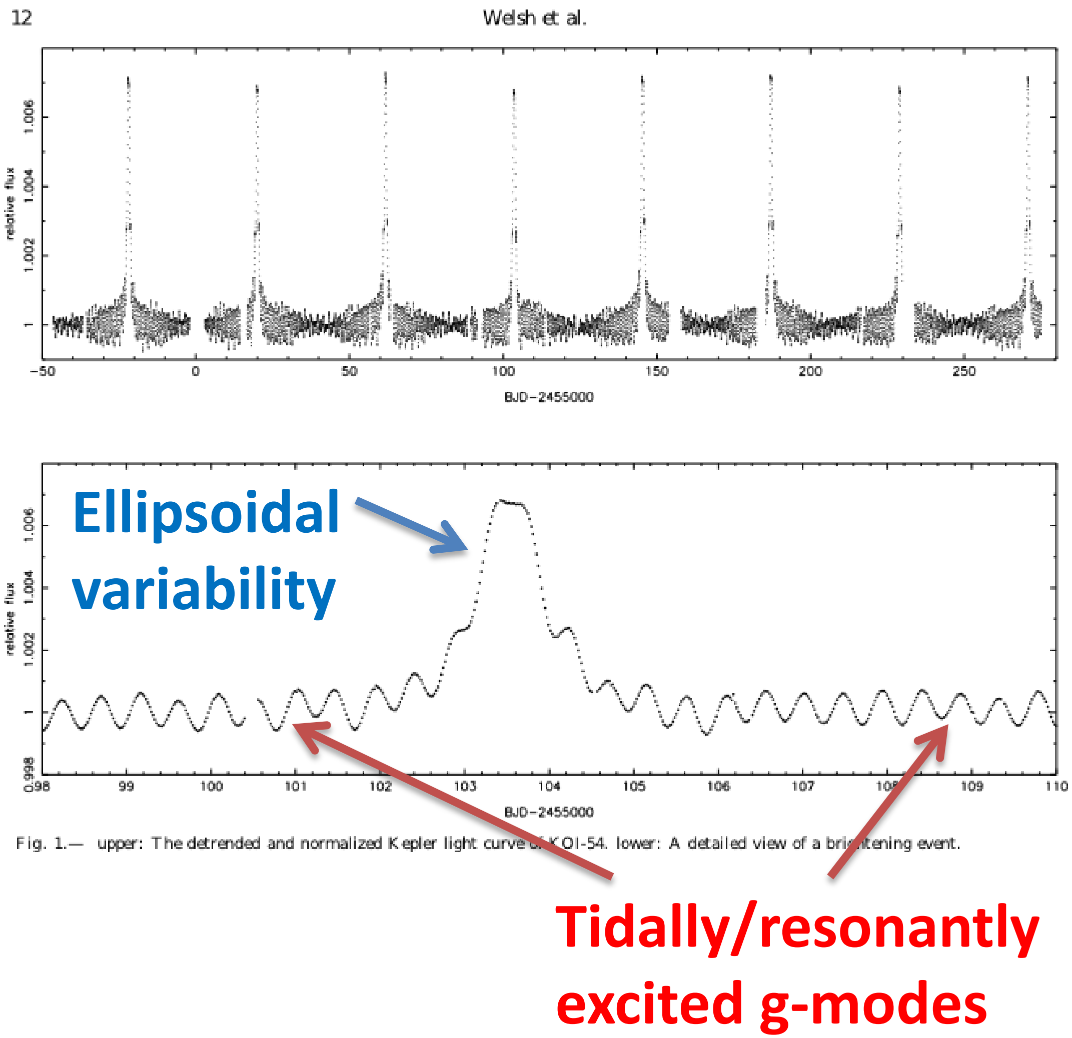


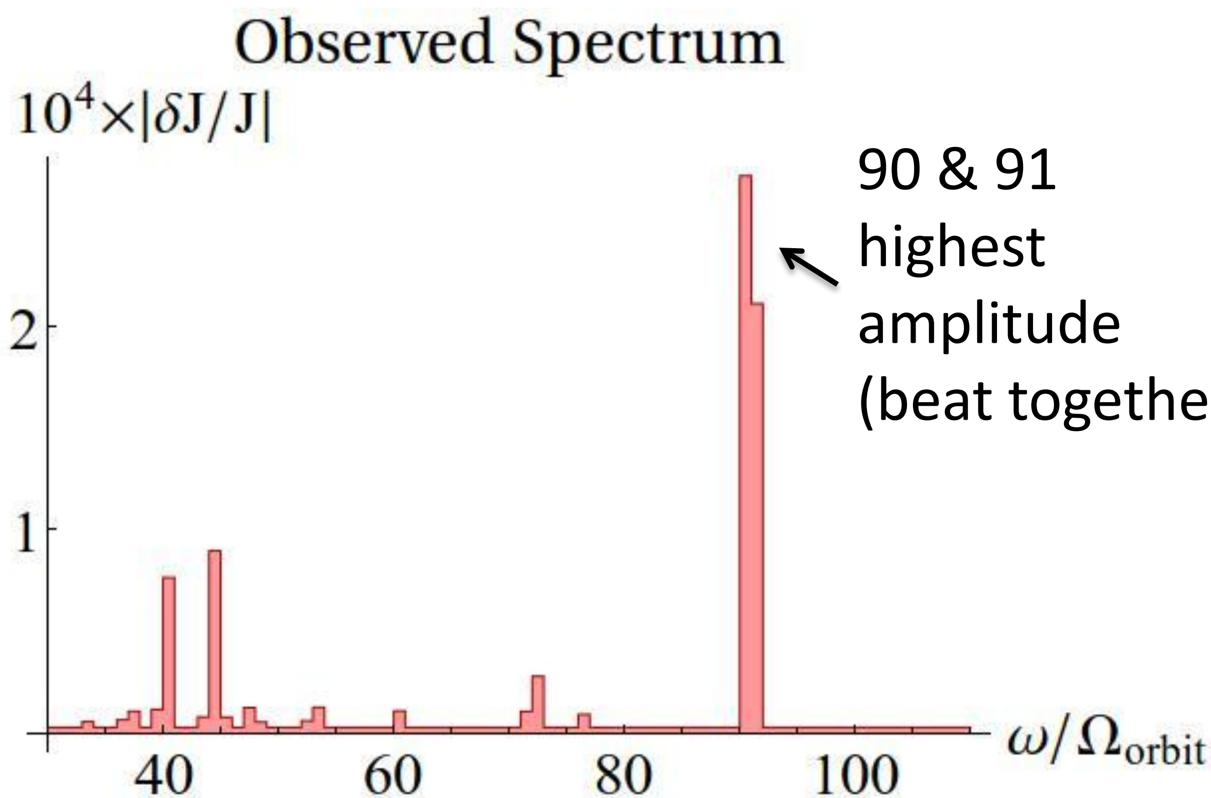
Fig. 1.— upper: The detrended and normalized Kepler light curve of KOI-54. lower: A detailed view of a brightening event.

- Eccentric stellar binary
  - $e = 0.83$
  - $P_{\text{orb}} = 42$ days
  - Two A stars
  - $M_{1,2} = 2.3\ M_{\text{Sun}}$

Welsh et al. (2011)

Dynamical Tide

- ~30 pulsations reported (many more observable)
- ~20 are perfect harmonics of the orbital frequency



90 & 91 highest amplitude (beat together)

Traditional Asteroseismology

Stellar parameters

↓

Theoretical stellar model

↓

Eigenmodes

↕

Observed frequencies

Modes excited by internal stellar processes

Modes ring at their natural frequencies

Tidal Asteroseismology

Stellar parameters

↓

Theoretical stellar model

↓

Eigenmodes

$\times 2$

↕

Observed

amplitudes + phases

Amplitudes set by tidal potential → Window into stars inaccessible by traditional asteroseismology

$\omega = k\Omega_{\mathrm{orb}}$,

$k \in$ Integers

Orbital parameters

↙

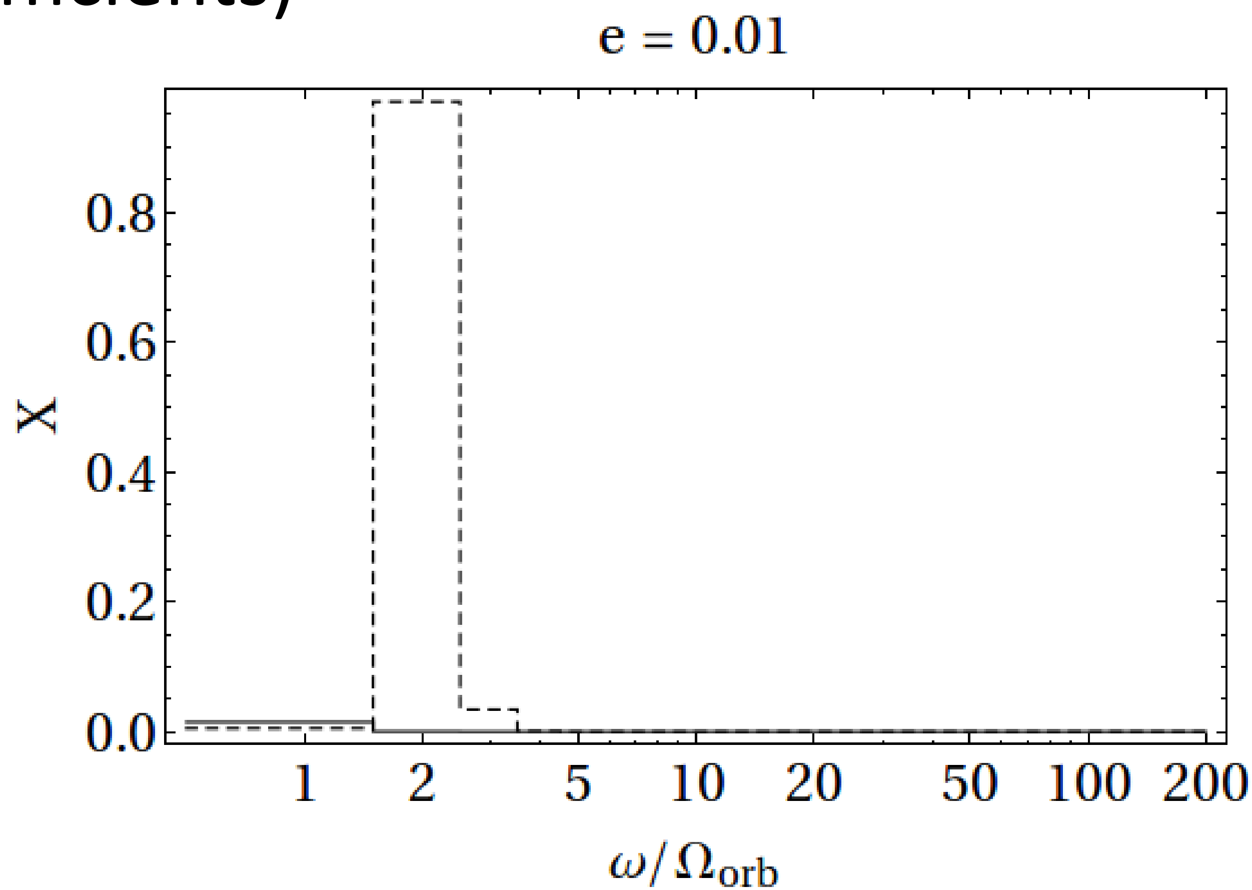
Tidal physics

Mode Excitation

- Excited by periodic tidal potential
  - Tidal strength $\sim \left(\frac{M_2}{M_1}\right)\left(\frac{R_1}{a(1-e)}\right)^{l+1}$
- Mode identification
  - Quadrupolar: $l = 2$
  - $|m| = 0, 2$
    - Pulsation phases strongly influenced by m
      - $\Delta J/J \propto \cos[\omega(t - t_p) - \delta], \quad \delta \sim \pm m\phi_o$
    - Visibility dependent on inclination
      - KOI-54 is face on $\rightarrow$ mostly $m = 0$
  - Mostly g-modes

What Frequencies are Excited?

- Distribution of driving frequencies (Hansen coefficients)



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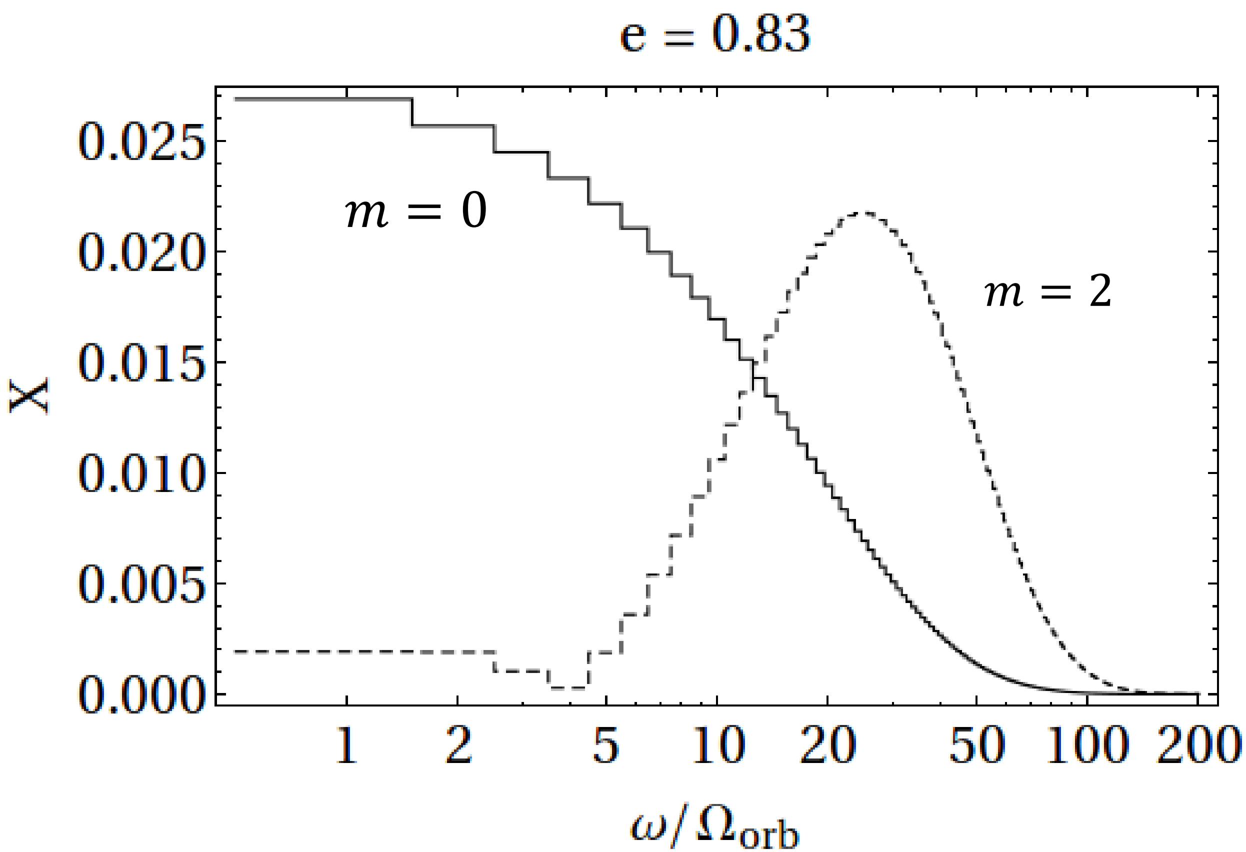
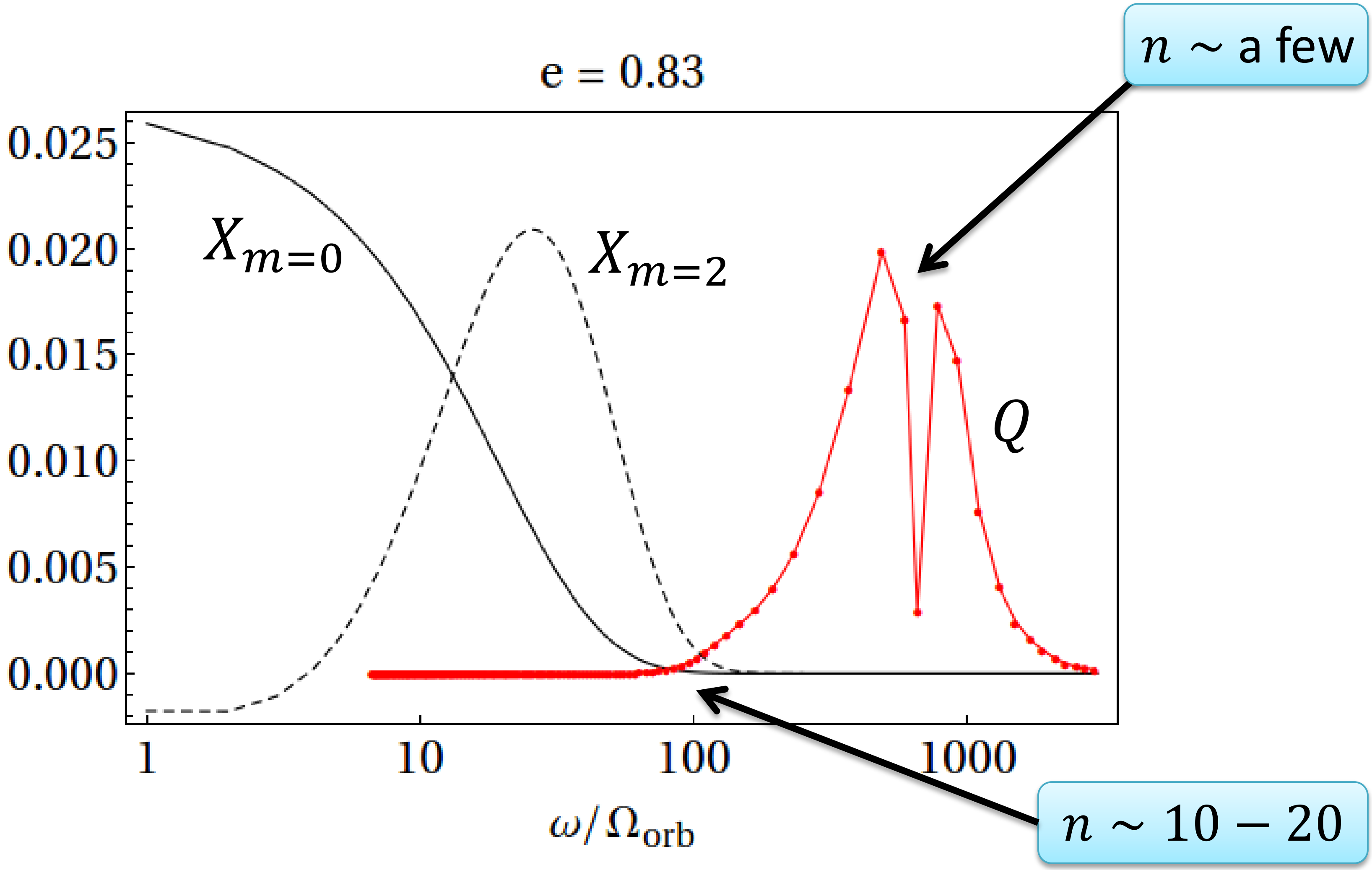


Mode Excitation

- Competition sets range of frequencies



Mode Excitation

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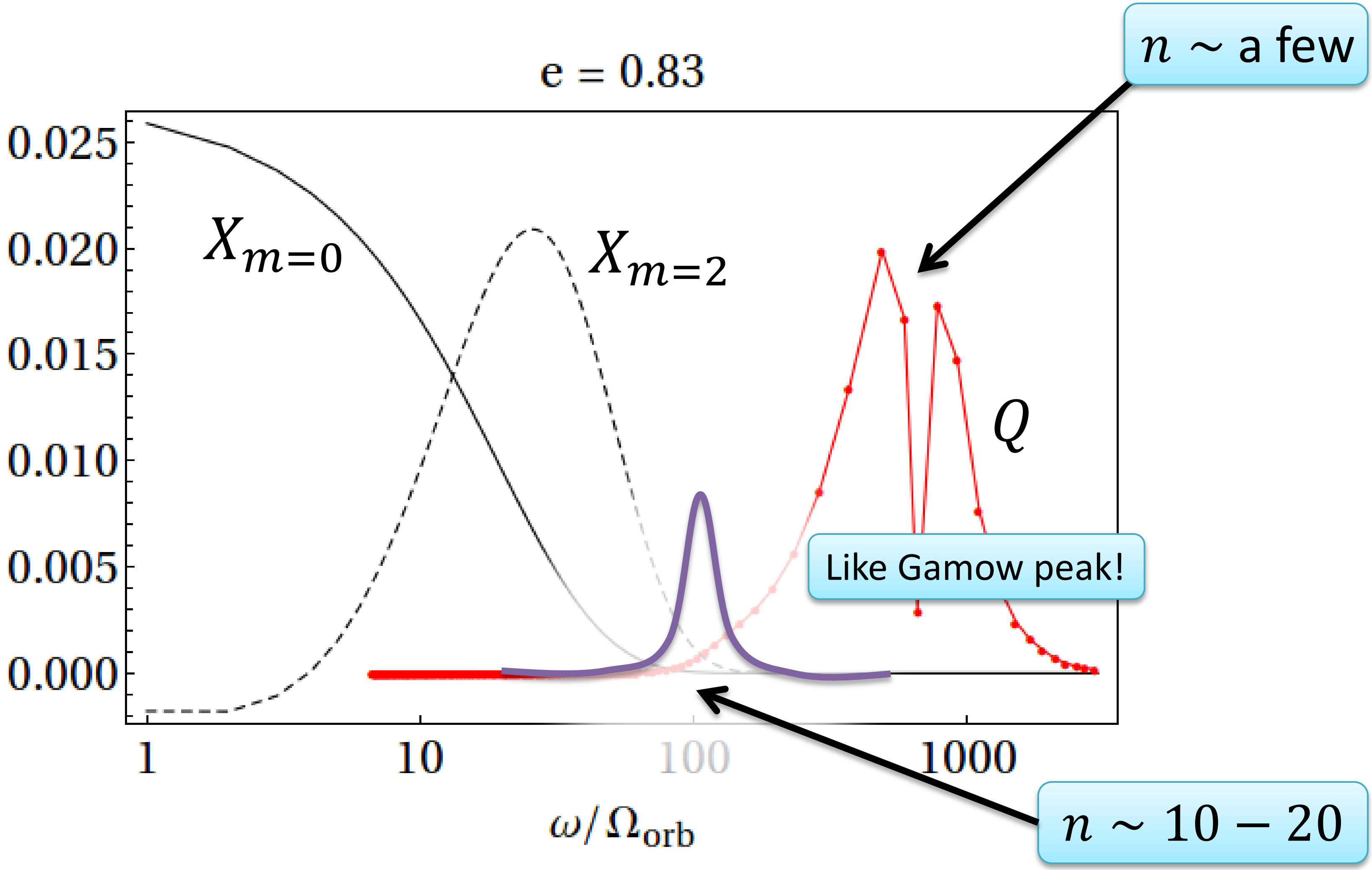
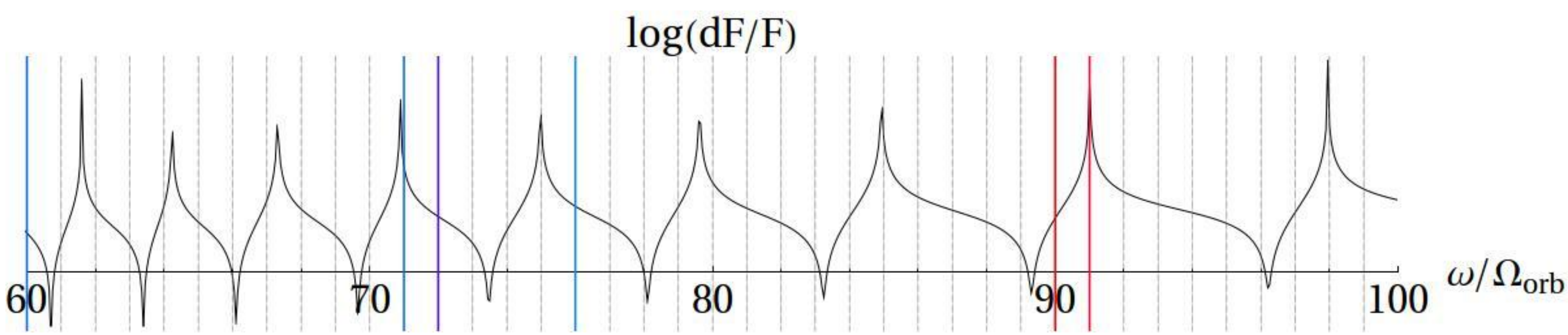


Resonances

- Driving frequencies (corotating frame): $\sigma_{km} = k\Omega_{\mathrm{orb}} - m\Omega_{\mathrm{rot}}, k \in \mathrm{Integers}$
  - If mode frequency $\omega_n = \sigma_{km}$, large resonance
- Modes ring in the inertial frame at harmonics of orbital frequency: $k\Omega_{\mathrm{orb}}$ (no Doppler shift)

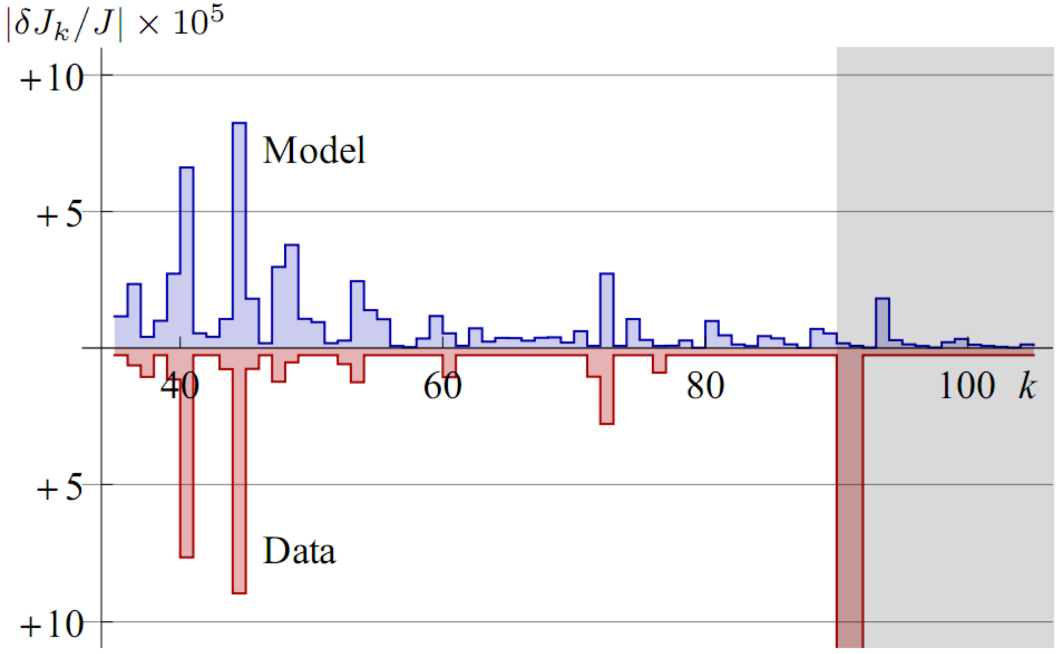


Our Oscillation Code

- Tidally forced (inhomogeneous)
- Essential physics:
  - Nonadiabaticity
    - Adiabatic assumption ok for global eigenfrequencies, not for surface behavior of eigenmodes
  - Rotation
    - Linear perturbation theory insufficient
      - Coriolis parameter: $\frac{2\Omega_{\mathrm{rot}}}{\omega} \sim 1$
    - Traditional approximation

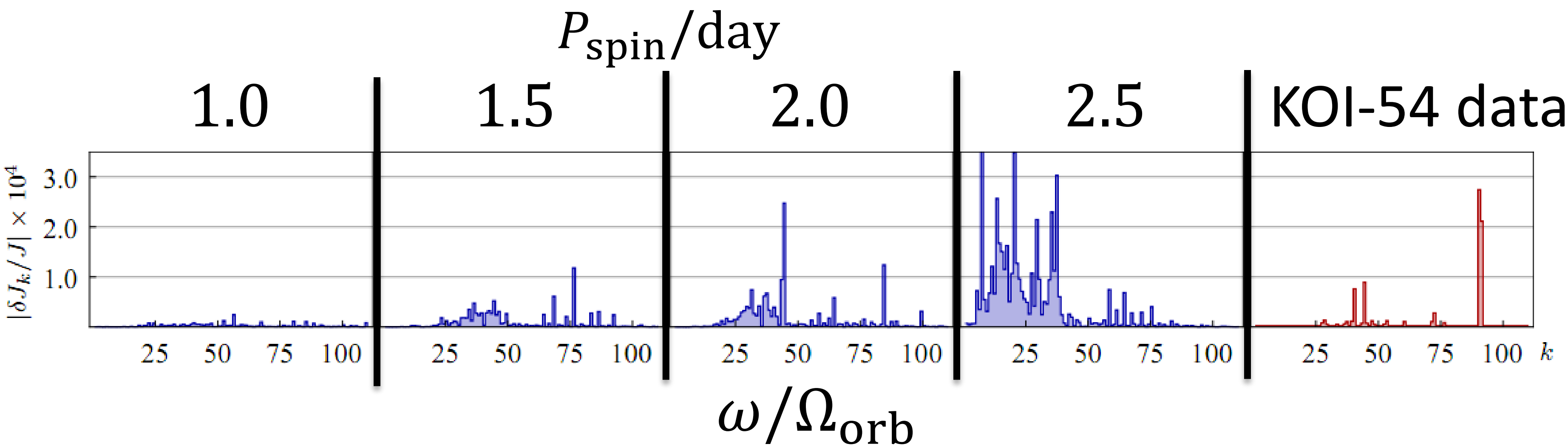
Modeling Results

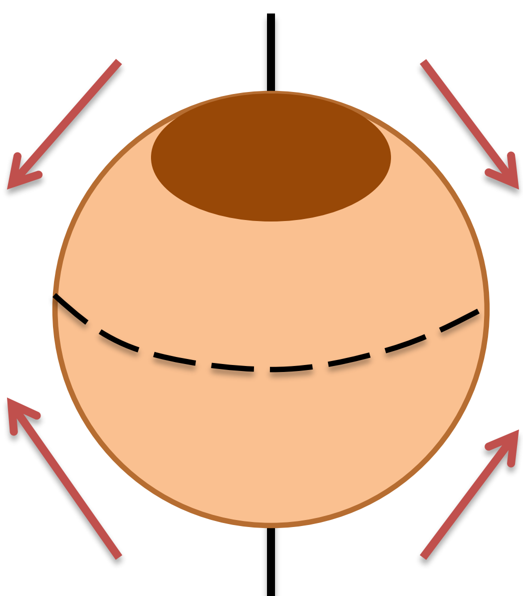
- Preliminary optimization over two grids of MESA models



- No unique best fit – many comparably good models

Influence of Rotation





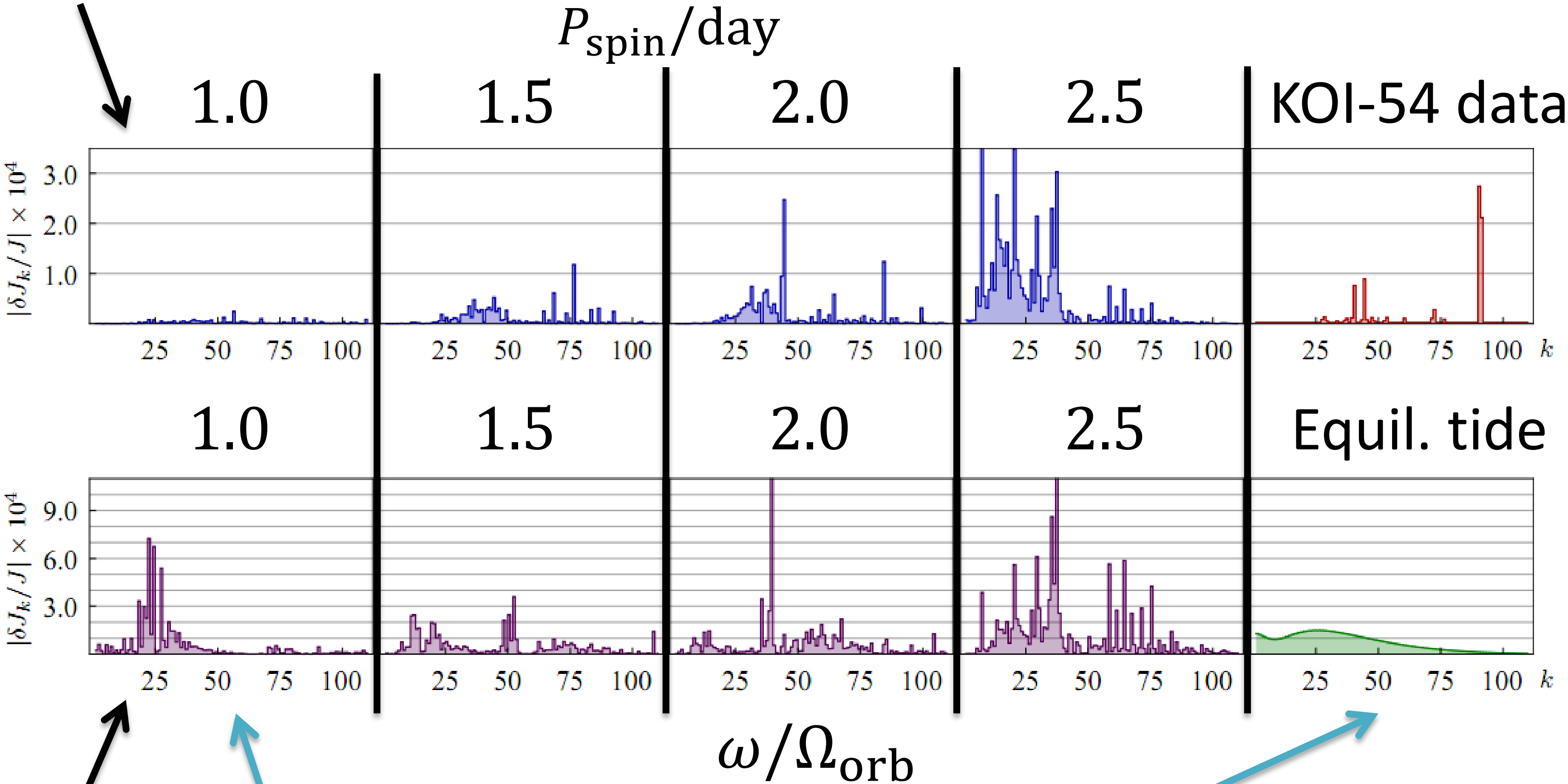
Equatorial mode confinement

$$\Omega_{\rm spin}\uparrow,\quad l\uparrow,\quad n\uparrow,\quad k_r\uparrow,\quad \gamma\uparrow$$

$$\left(\text{g-modes: } \omega \sim \omega_0 \times \frac{l}{n}\right)$$

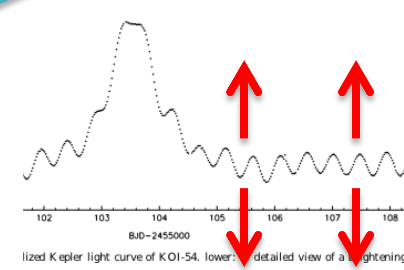
Influence of Rotation

Face on



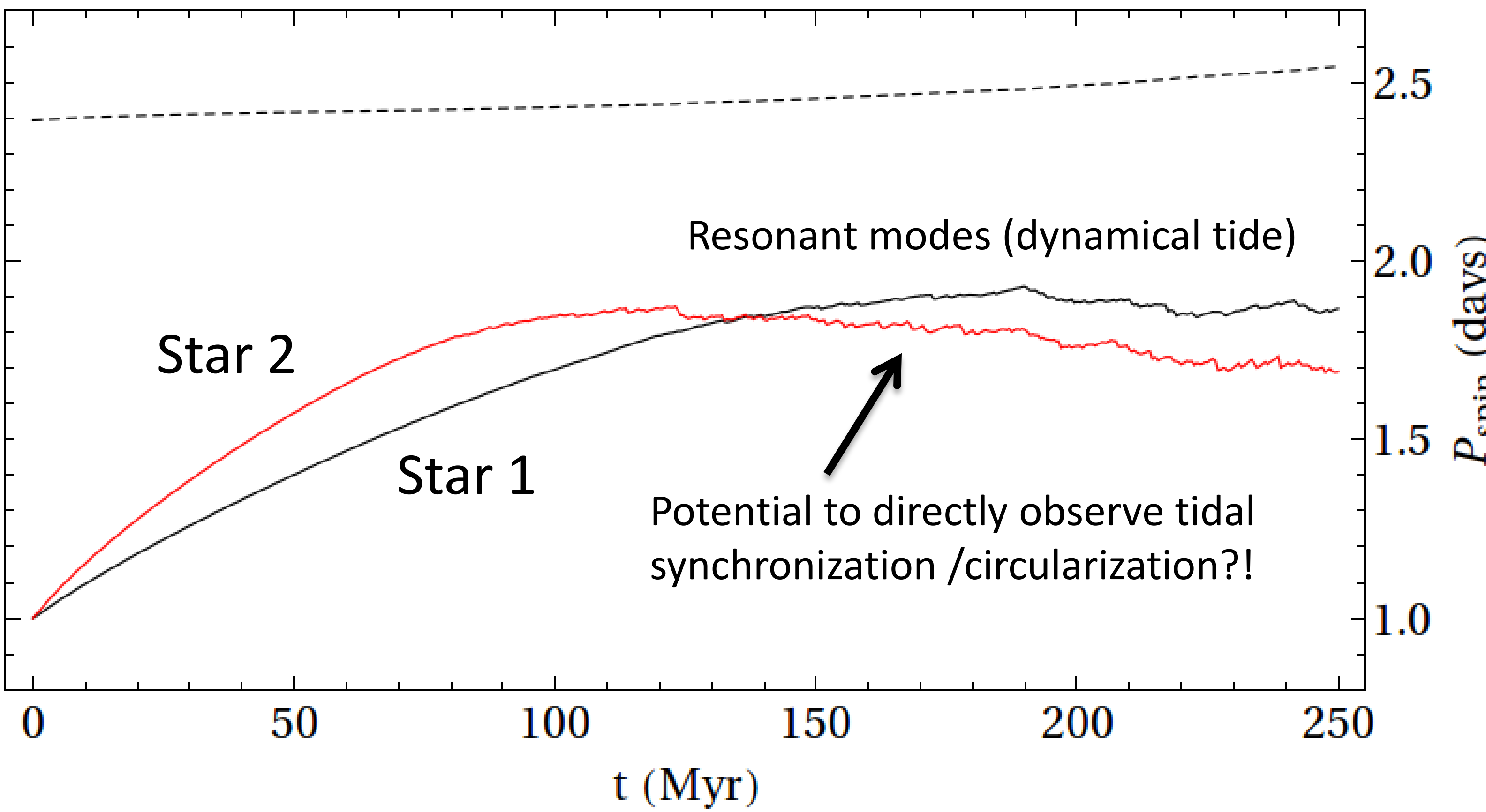
Edge on

Prediction: pulsations overwhelm ellipsoidal variation in edge-on systems?



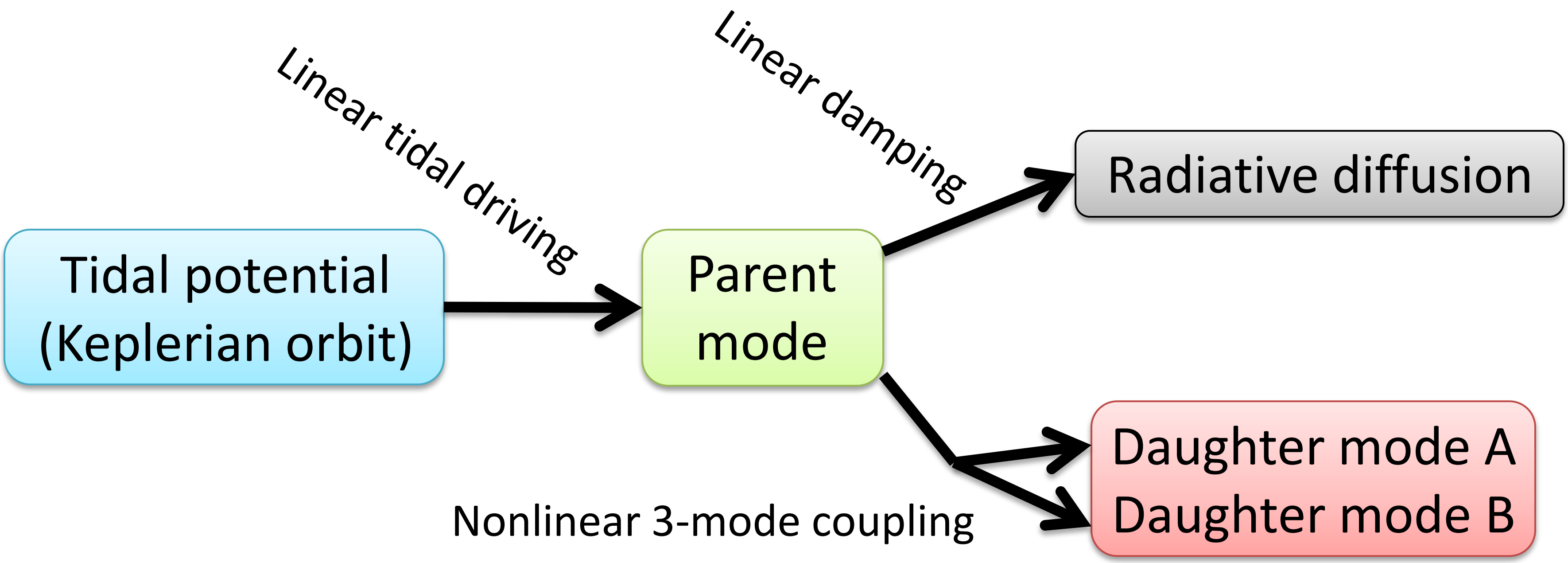
Rotational Pseudosynchronization

- Secular orbital evolution simulation
  - Predicts spin periods consistent with pulsation modeling



Nonharmonic Pulsations: Nonlinear Coupling

- $91.00 = 22.42 + 68.58$! (in units of Ω_{orb})
  - Nonlinear parametric resonance of linearly driven parent to daughter pair (e.g. Weinberg et al. 2011)



Nonharmonic Pulsations: Nonlinear Coupling

- > 10 other nonharmonic pulsations, but no other pairs with $\omega_{\mathrm{parent}} = \omega_{\mathrm{d1}} + \omega_{\mathrm{d2}}$?
  - OK: Pair members have different energies and/or m & l values → one much less observable
- Nonlinear stability analysis: parent amplitude $\sim 100 \times$ below instability threshold?
- Observationally tests theory of nonlinear mode coupling
  - Relevant for theory of tidal dissipation

Tidal Asteroseismology Summary

- Asteroseismology for eccentric binaries
  - Tidally driven oscillations rather than unstable modes
  - Model amplitudes/phases, not frequencies
  - Not just the instability strip
  - Mode identification advantages ($l = 2$, etc.)
- Essential stellar mode physics:
  - Nonadiabaticity (radiative diffusive damping)
  - Rotation > linear order
- Direct observation of nonlinear mode coupling
- Still forthcoming:
  - Observations + theory $\rightarrow$ detailed system constraints