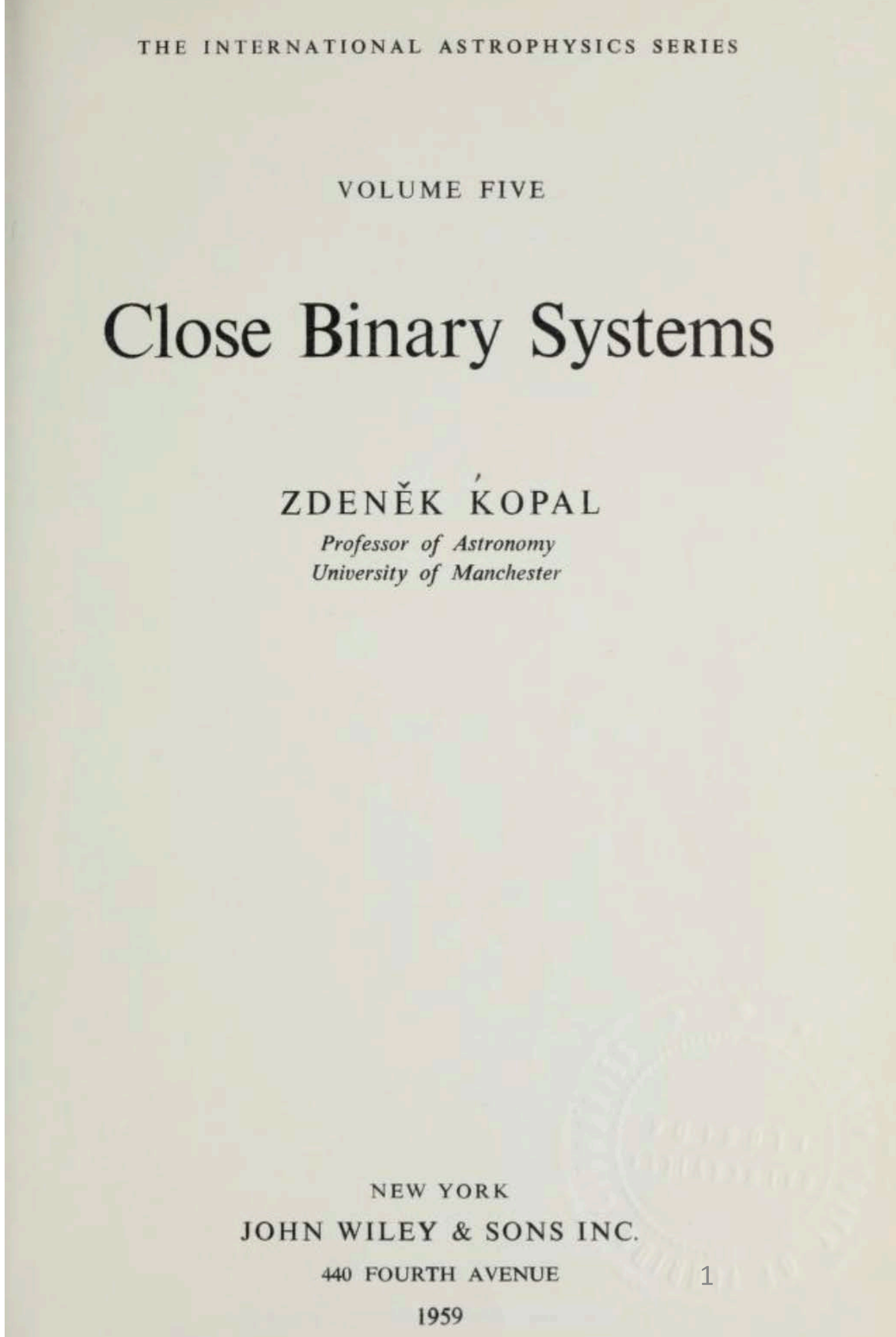


THE INTERNATIONAL ASTROPHYSICS SERIES

VOLUME FIVE

Close Binary Systems

ZDENĚK KOPAL

Professor of Astronomy
University of Manchester

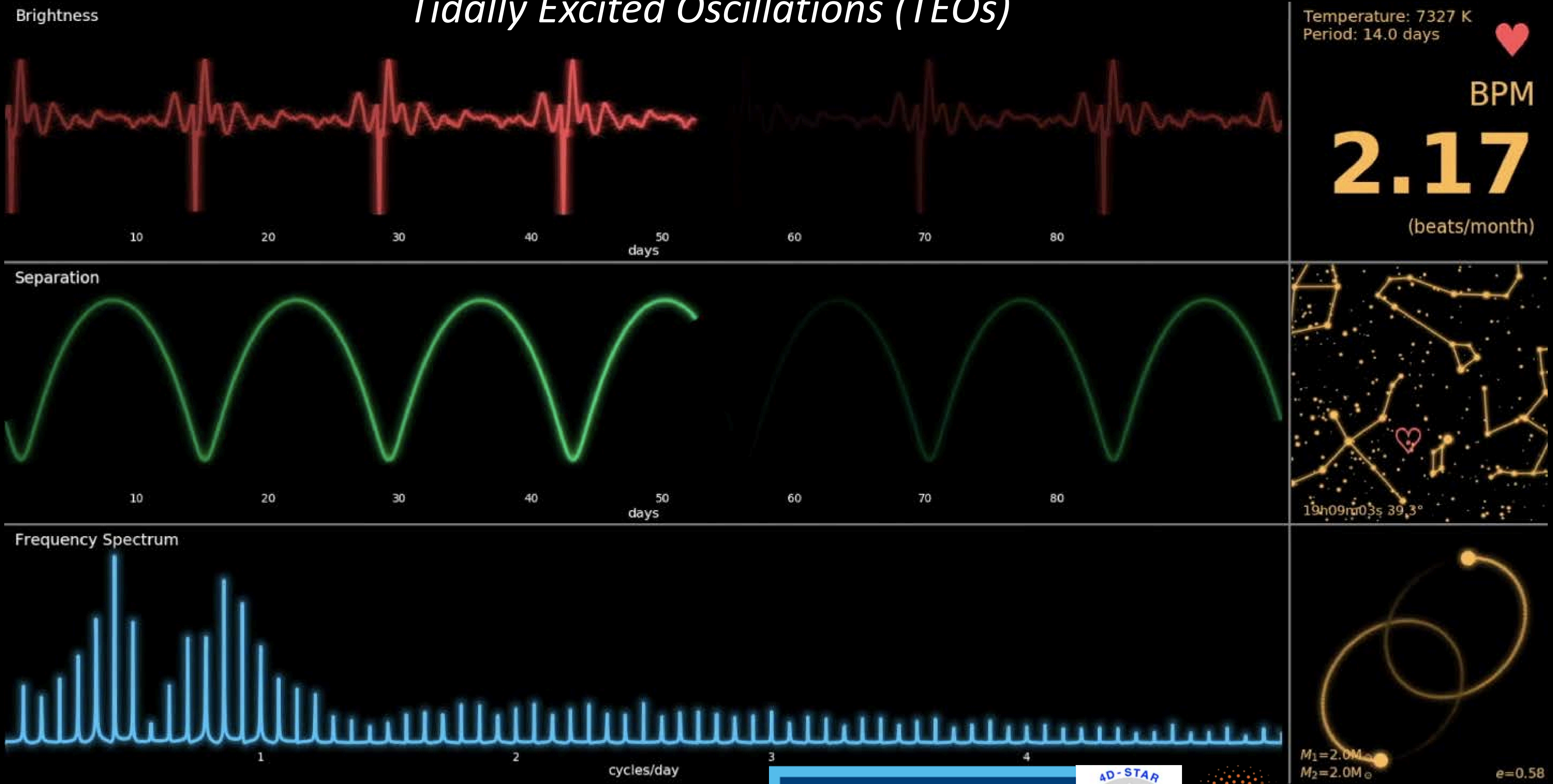
NEW YORK

JOHN WILEY & SONS INC.

440 FOURTH AVENUE

1959

Heartbeat Binary Stars (HBs):
Tidally Excited Oscillations (TEOs)



https://www.system-sounds.com/heartbeat-stars/

Zhao Guo

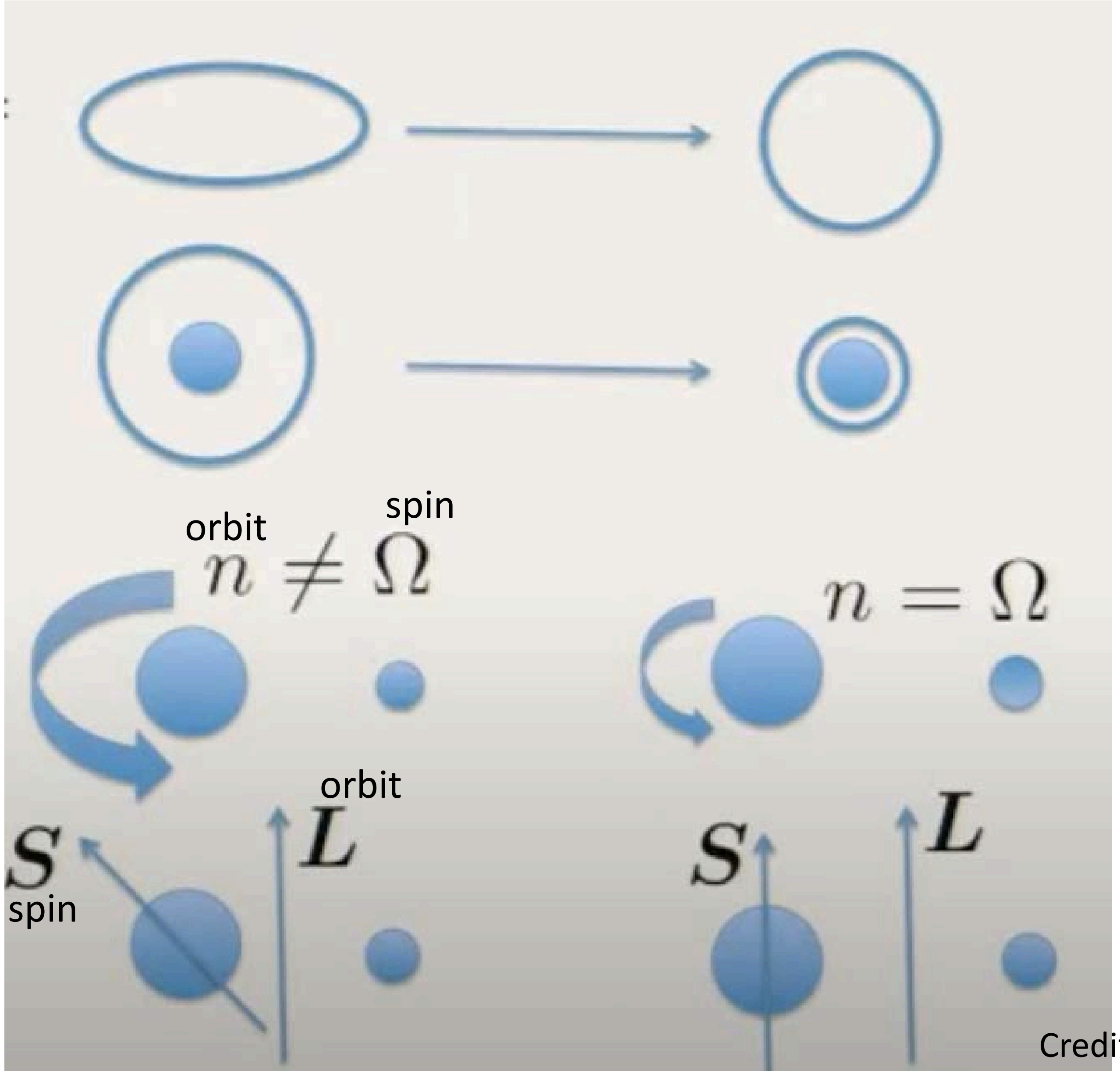
Tidal Evolution Effects

Circularization

Orbital Decay

Synchronization

Spin-Orbit alignment

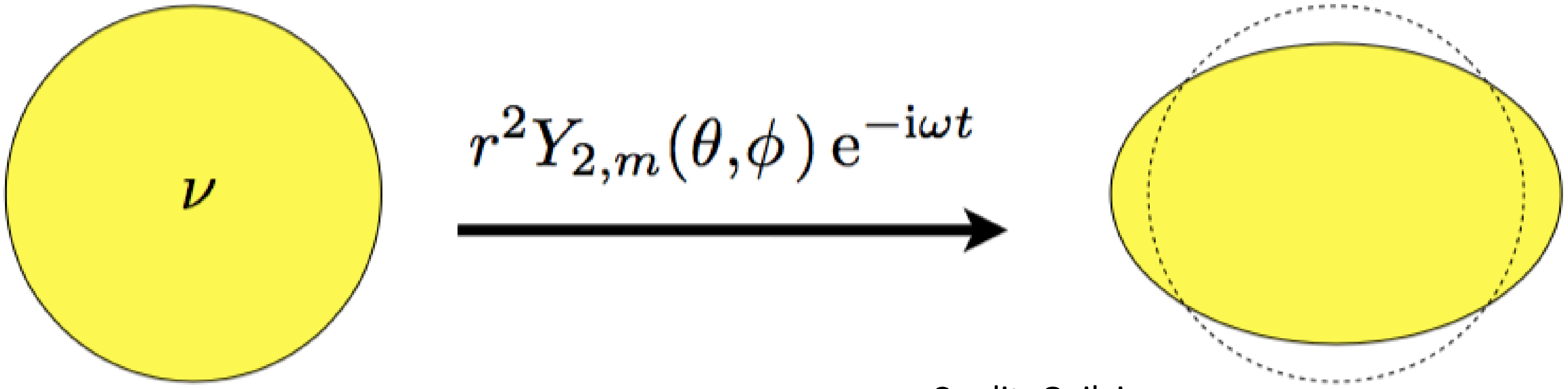


Credit: Phil Arras

J-P Zahn’s categorization :

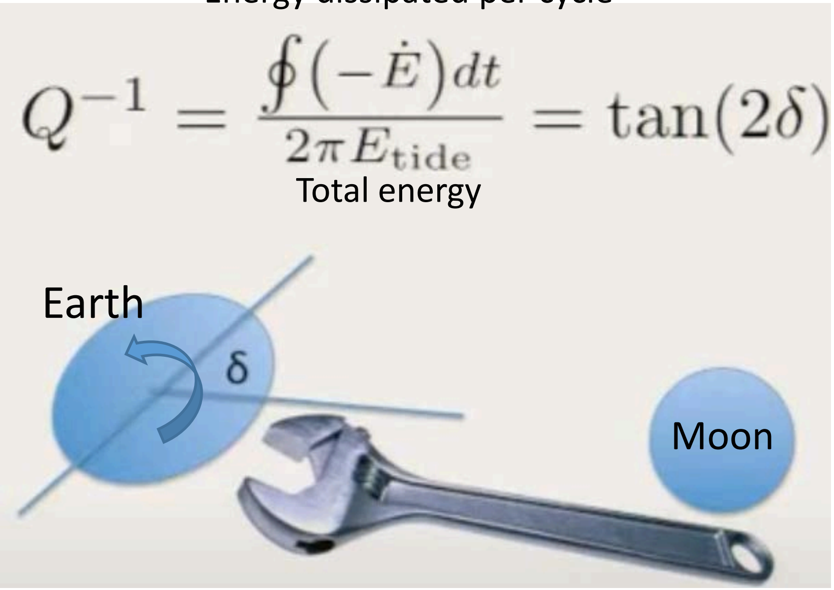
- **“Equilibrium tide”** (ν: Turbulent viscosity in convection zone)

Dissipation associated with large-scale tidal bulge (non-wave like)



Credit: Ogilvie

Energy dissipated per cycle



Total energy

credit: Arras

- **“Dynamical tide”**

Dissipation associated with low-frequency waves

Convection zone: Inertial Wave

(N=0)

Radiative region: (Inertia-) Gravity Wave
(stably stratified)

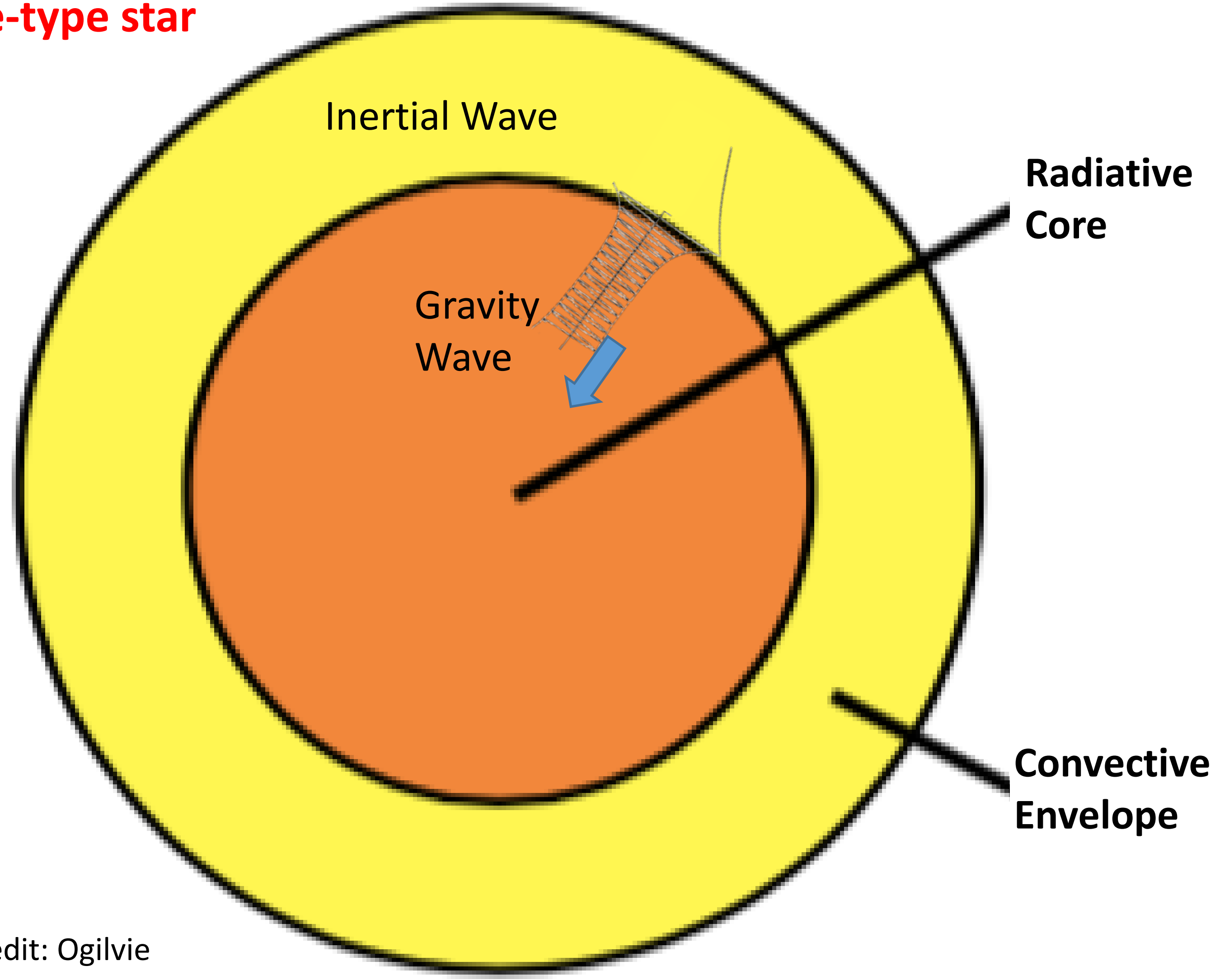
Tidal quality factor Q:

Earth ~ 10
Sun ~ 10^6
Jupiter ~ 10^5 -10^6

• "Dynamical tide"

Dissipation associated with low-frequency waves

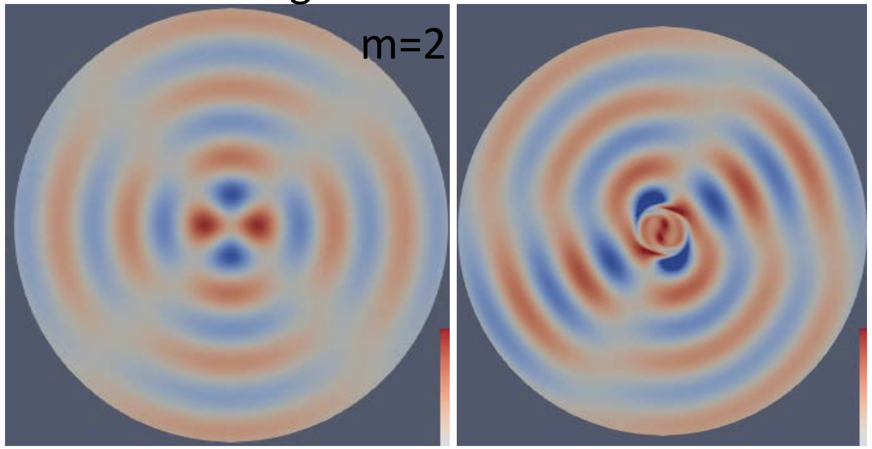
Late-type star



Credit: Ogilvie

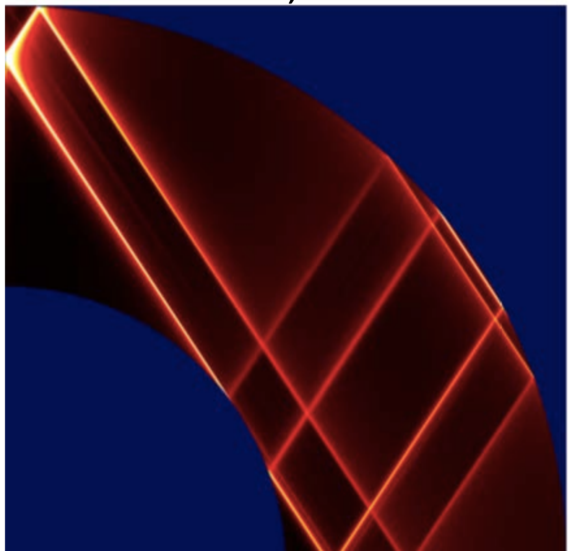
Gravity waves may

1 Form standing waves 2 Break near the center



Barker&Ogilvie2010
Guo+2023

Inertial wave in the convective shell
~ Narrow beams, not normal modes

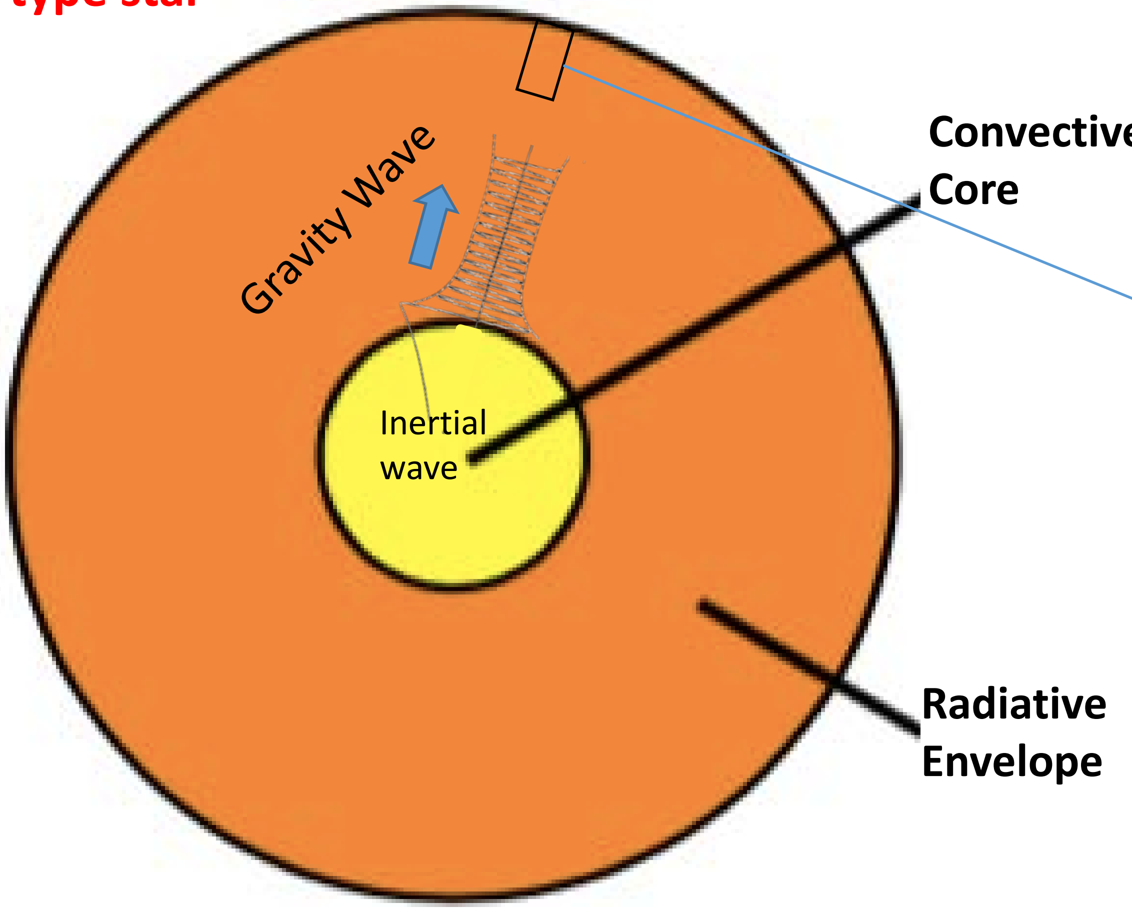


Ogilvie2004, 2007

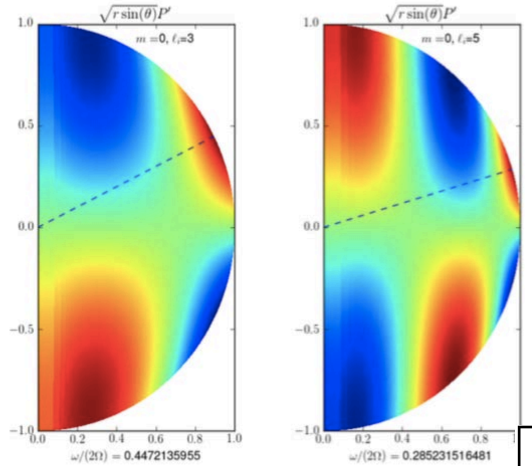
• “Dynamical tide”

Dissipation associated with low-frequency waves

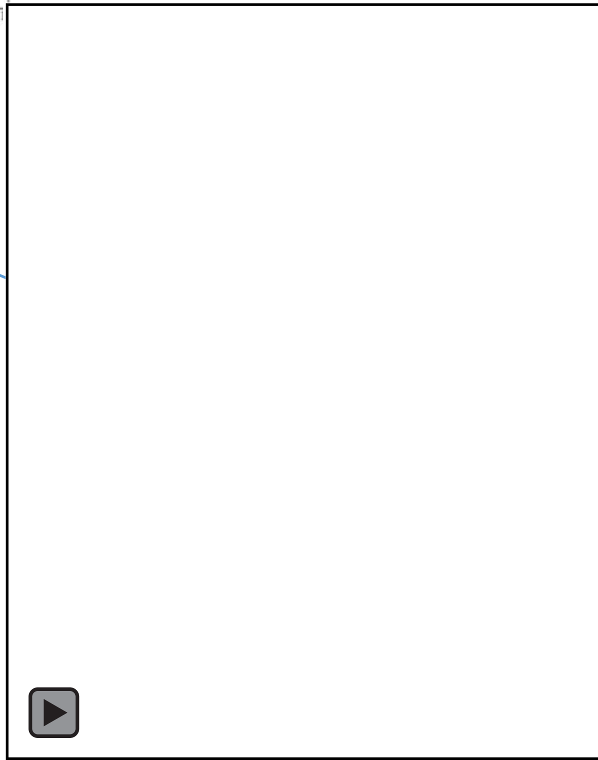
Early-type star



Inertial wave in the core
~ can form normal modes



Dips in ΔP -P
Saio, Ouazzani, Aerts



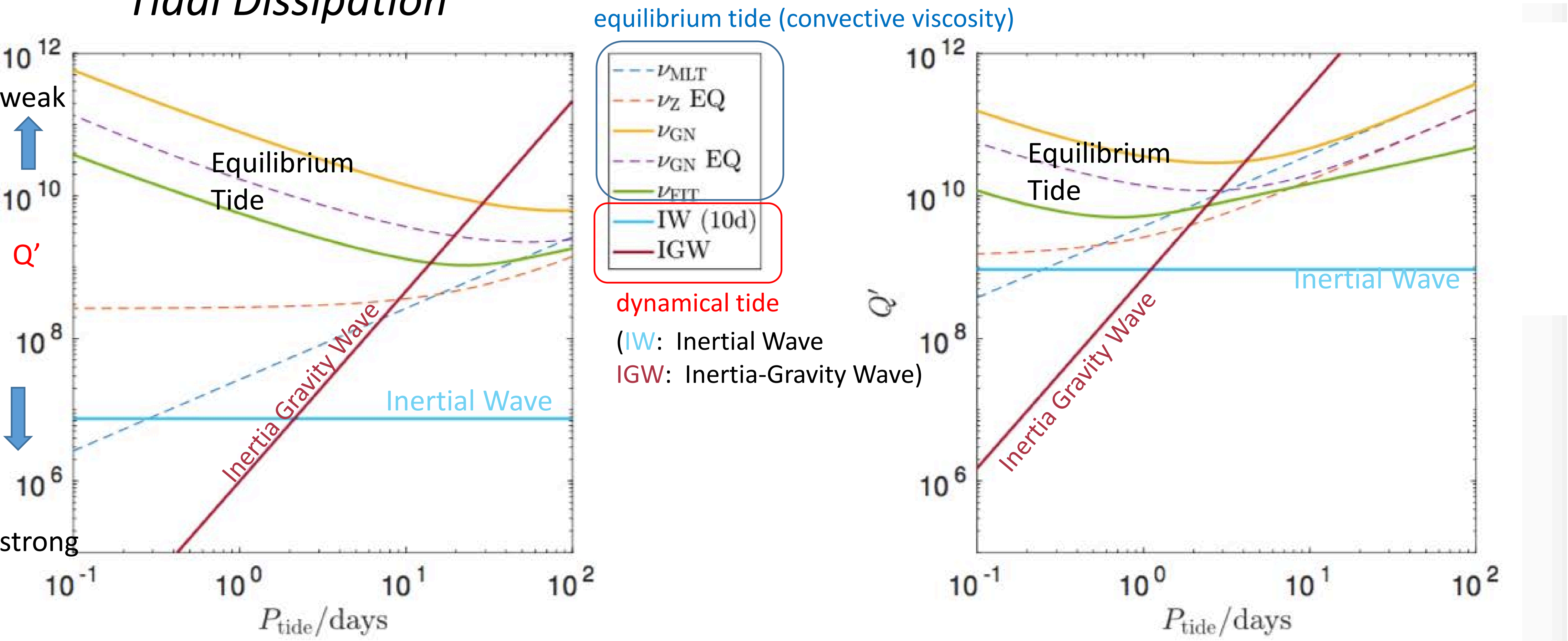
Gravity waves may
1 Form standing waves
-> g-mode seismology

2 Break near the surface
->form critical layer

Credit: Ogilvie

Su+20

Tidal Dissipation

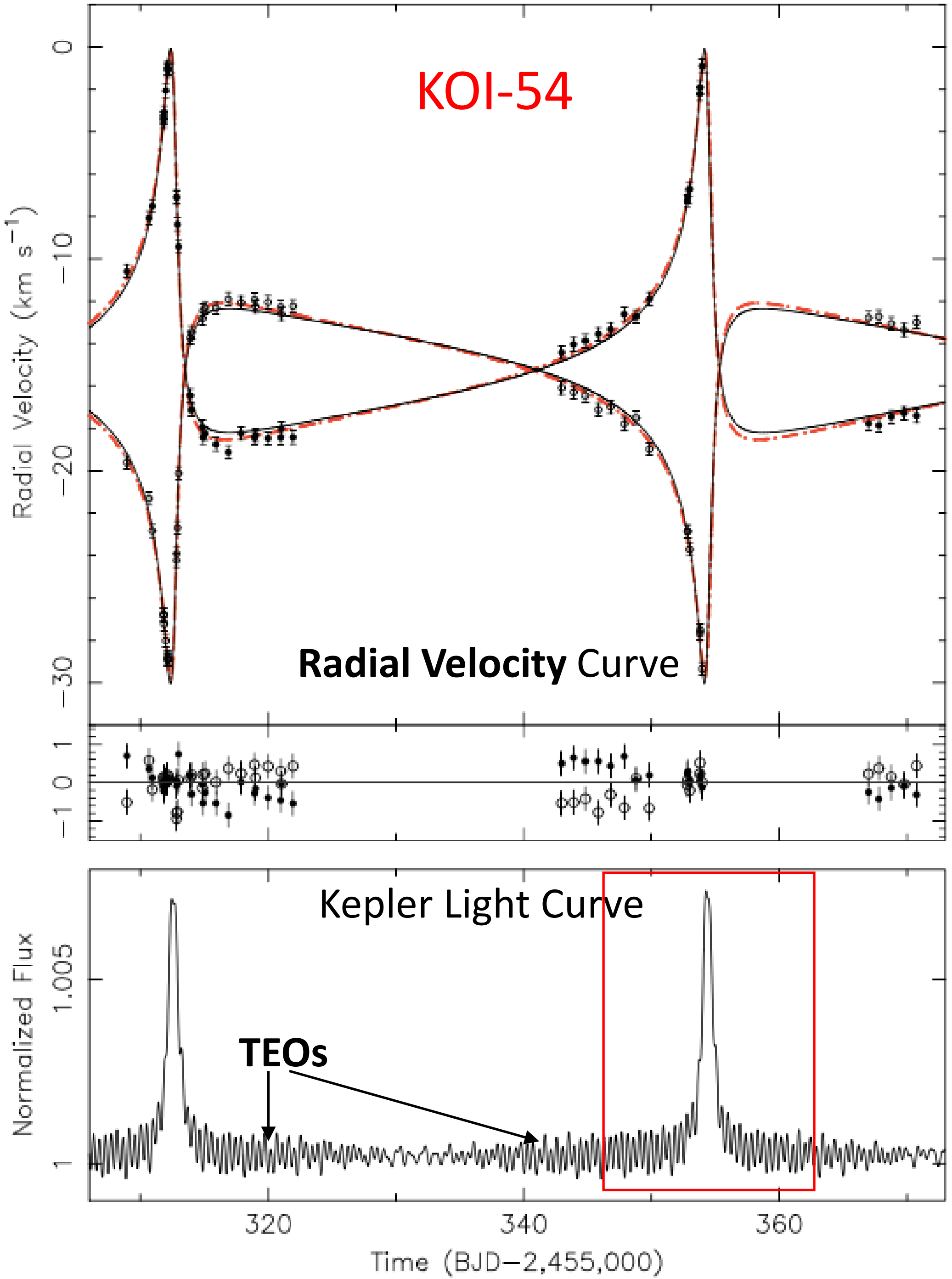


(c) $M/M_\odot = 1$, age/yr $= 4.70 \times 10^9$

(d) $M/M_\odot = 1.4$, age/yr $= 1.29 \times 10^9$

(Assuming IGW breaks)

Barker2020

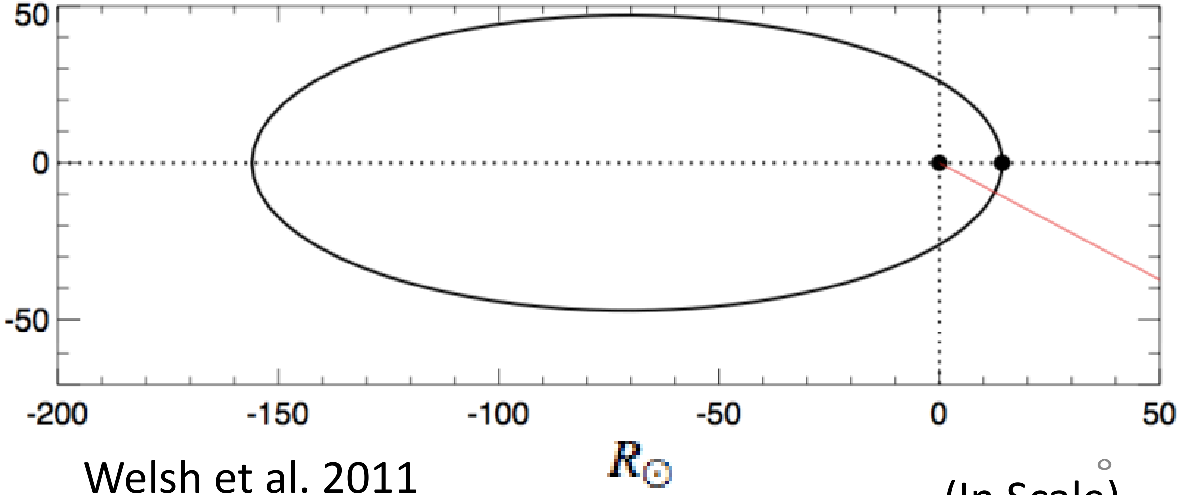


The Prototype of Heartbeat Stars

Two A stars (T_{eff} ~8500K)
M_1~2.33, M_2 ~2.39 (R_1=2.20, R_2=2.33)
e=0.83, ω=39.5deg, P= 41.8 days,

Face-on: inclination=5.5 deg

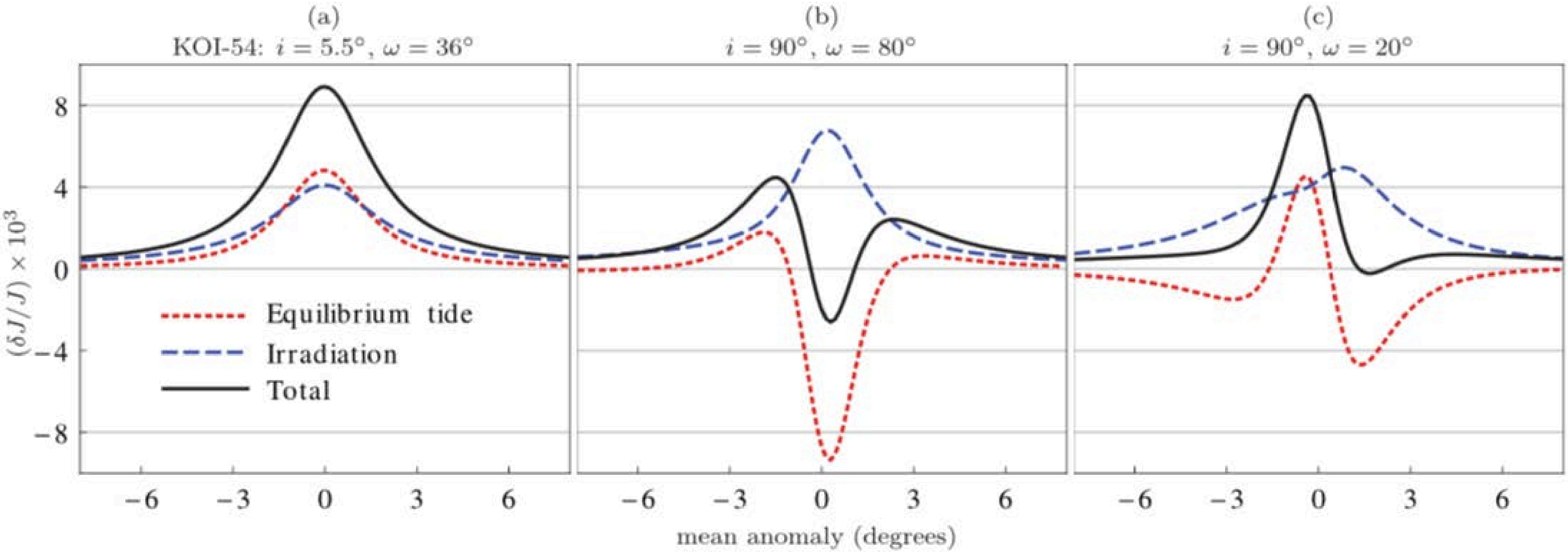
Tidally excited oscillation (TEOs) at exactly
90 and 91 times of orbital frequency



Welsh et al. 2011

(In Scale)

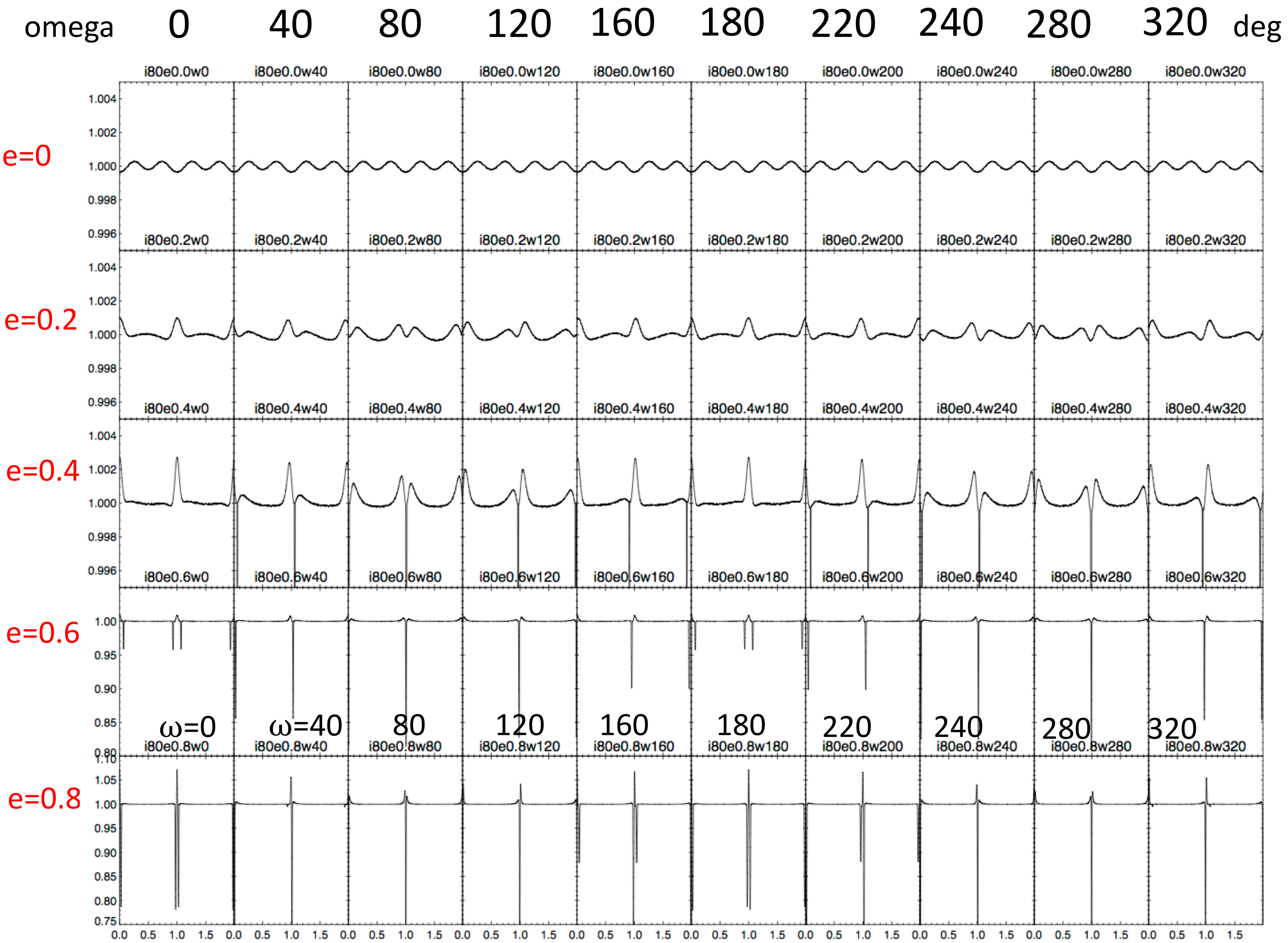
Light Curve of KOI-54 at different i, ω



ellipsoidal variation from equilibrium tide
+ mutual irradiation

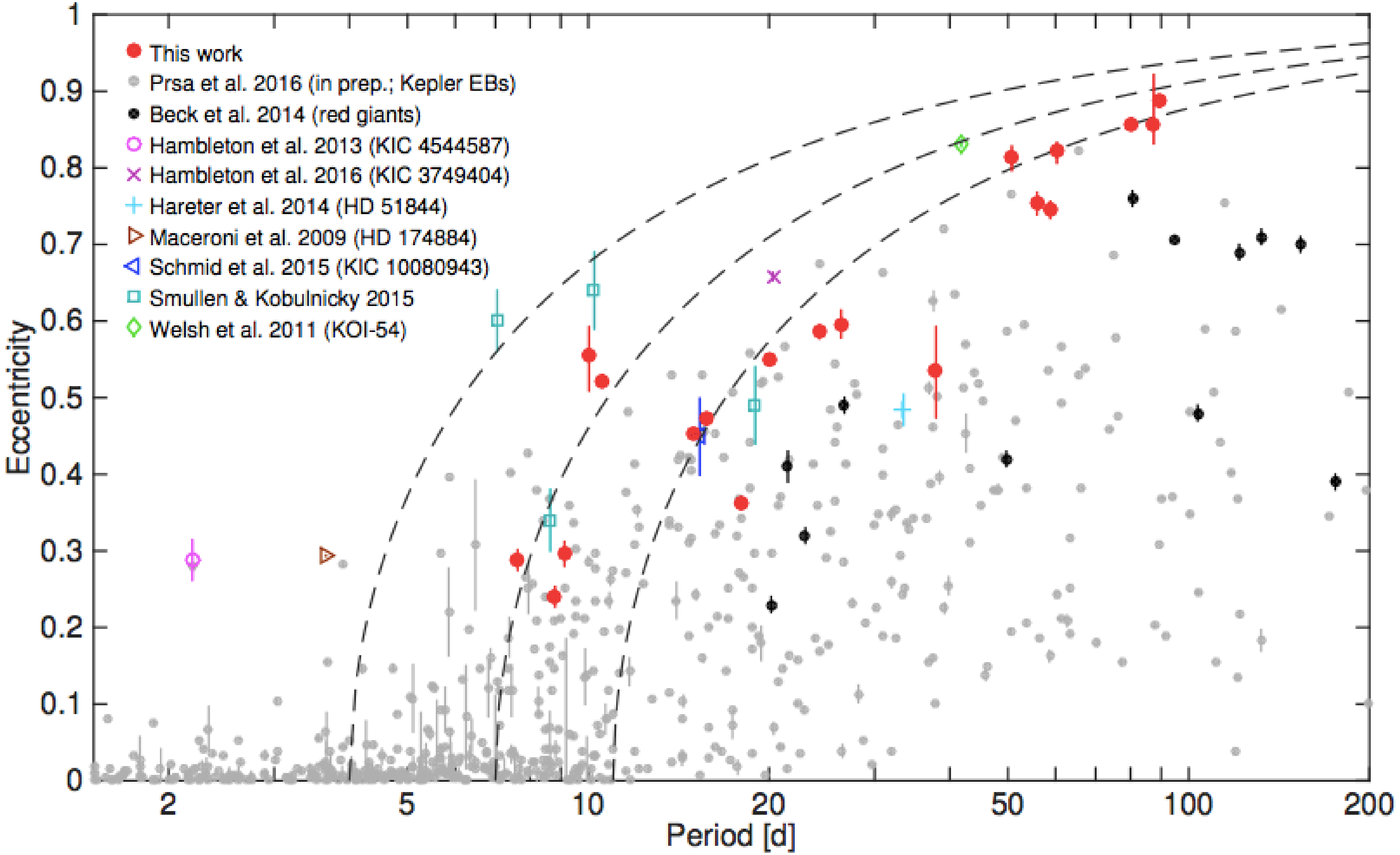
(e, i, ω)

Burkart+12



Inclination= 80 deg

Heartbeats on the Period - e diagram



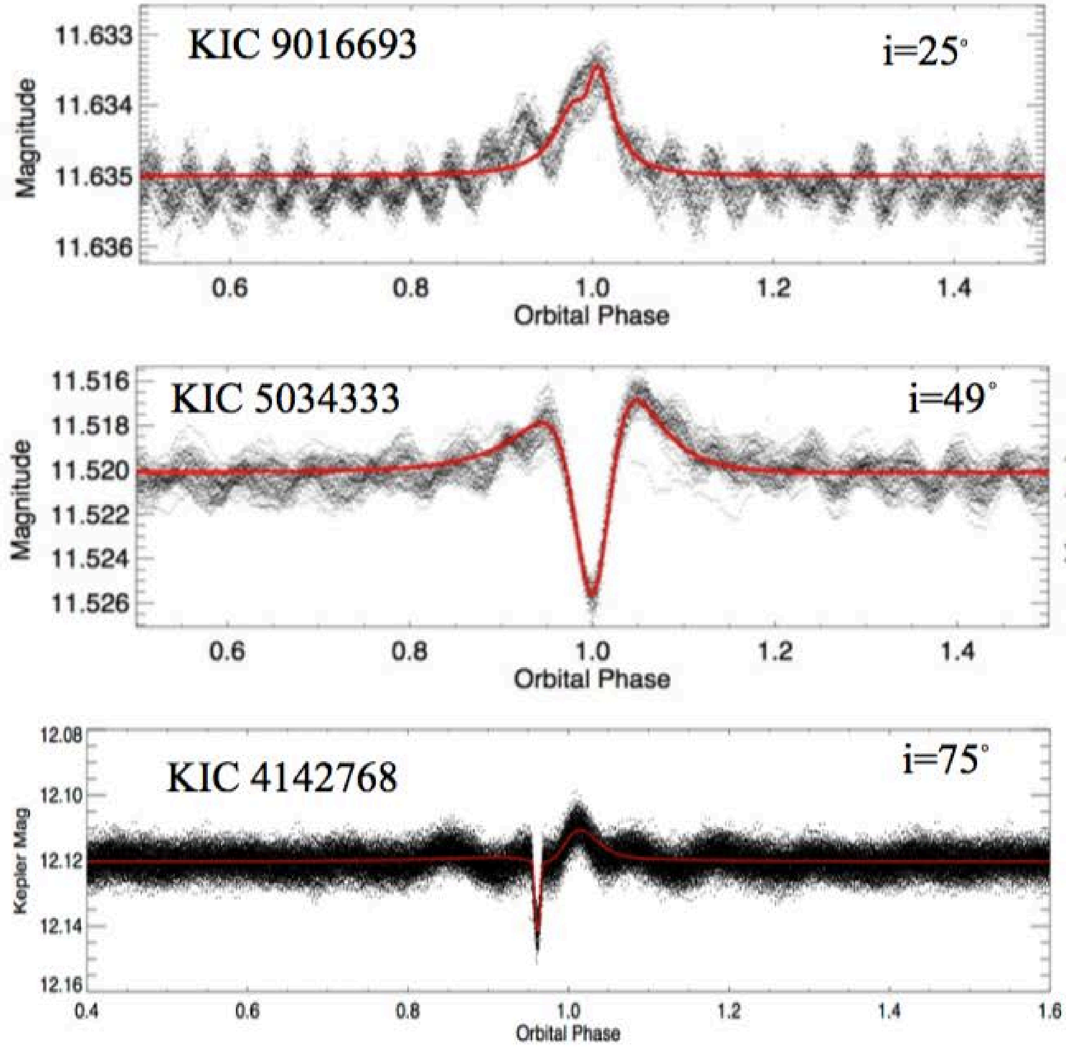
Shporer+16

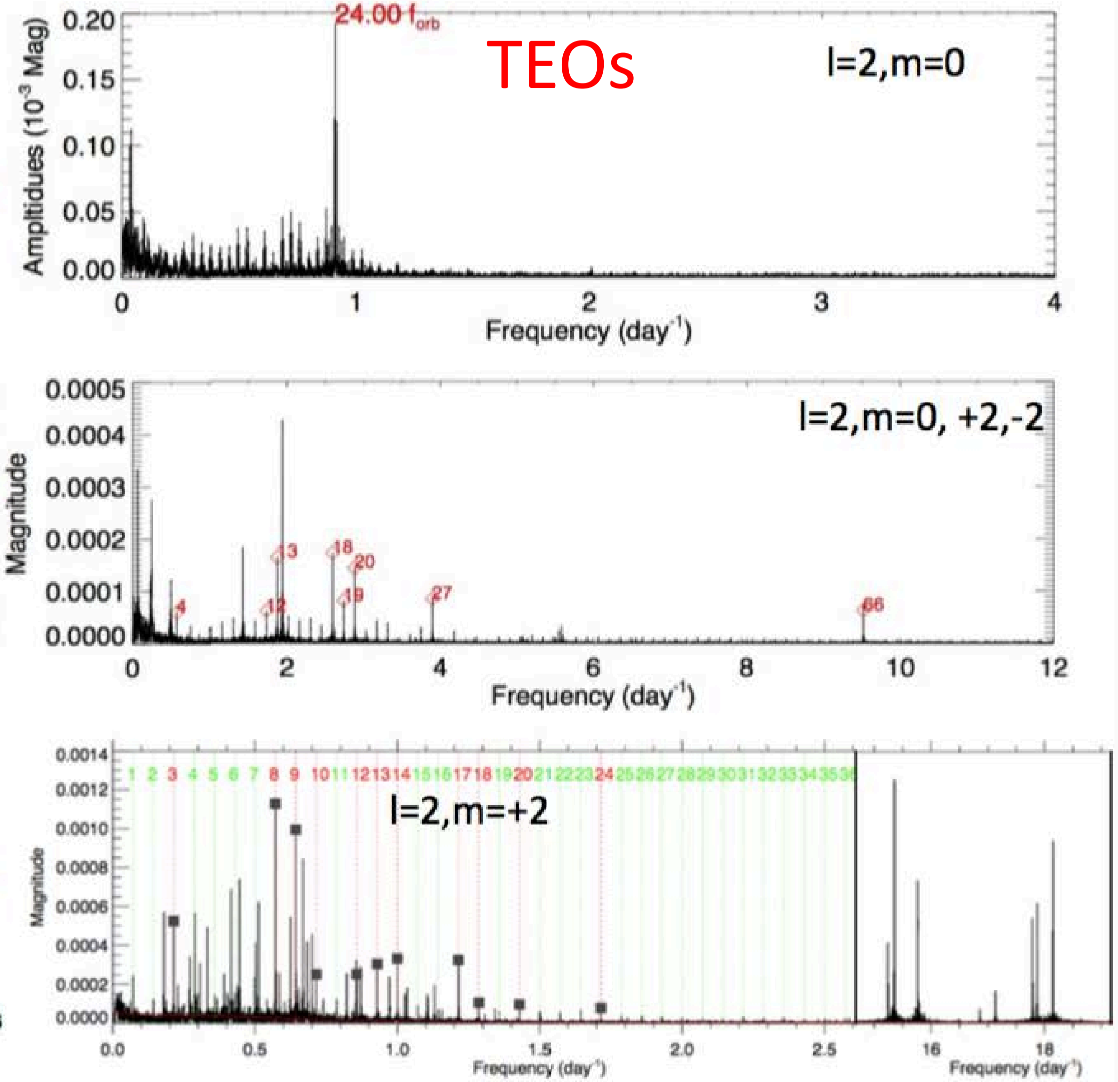
-> Heartbeat stars have e > ~0.2

-> Heartbeat stars depict the upper envelope of the Period-ecc. diagram

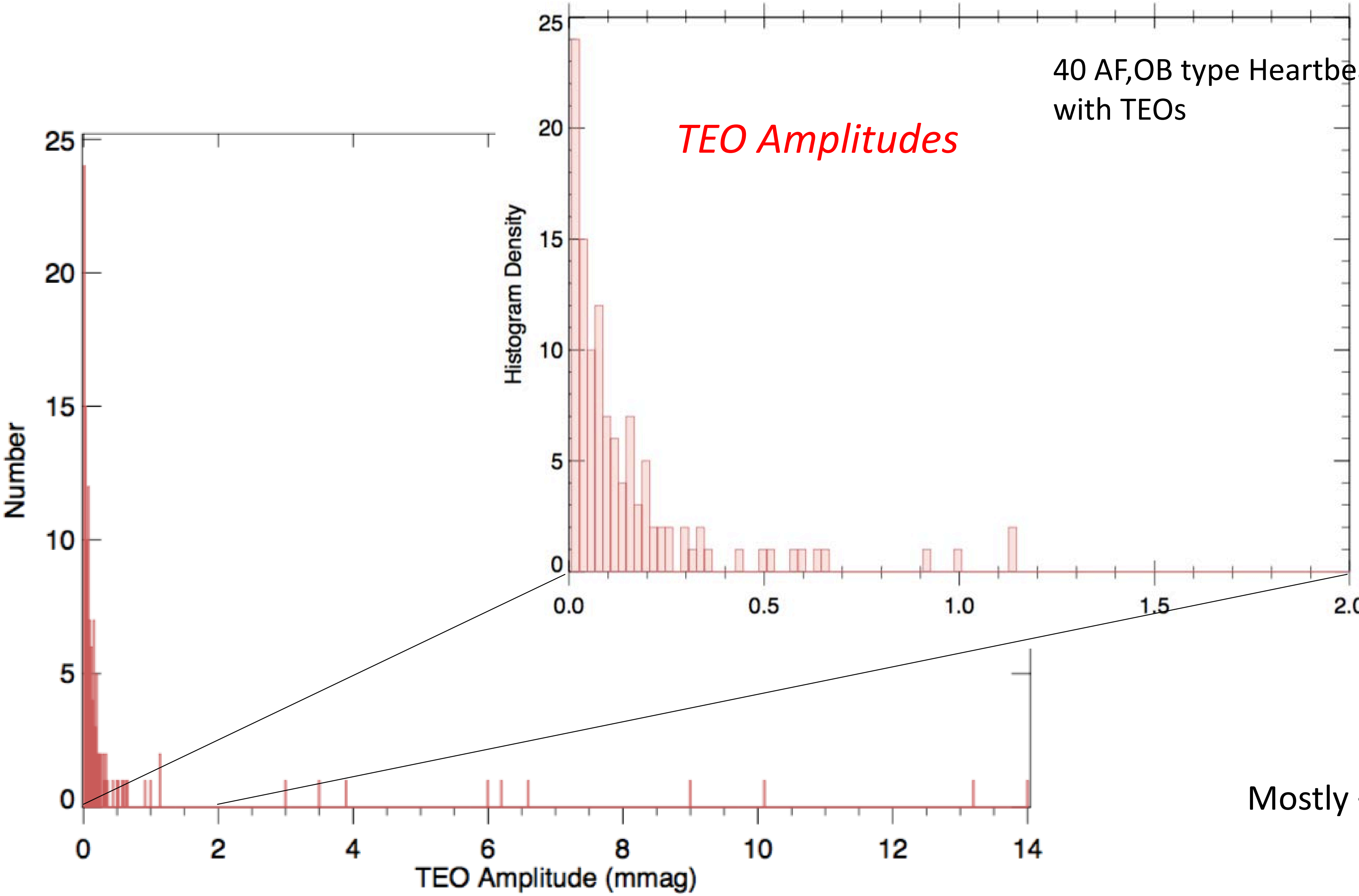
Fourier spectra -> Tidally Excited Oscillations

Binary Light curve fitting



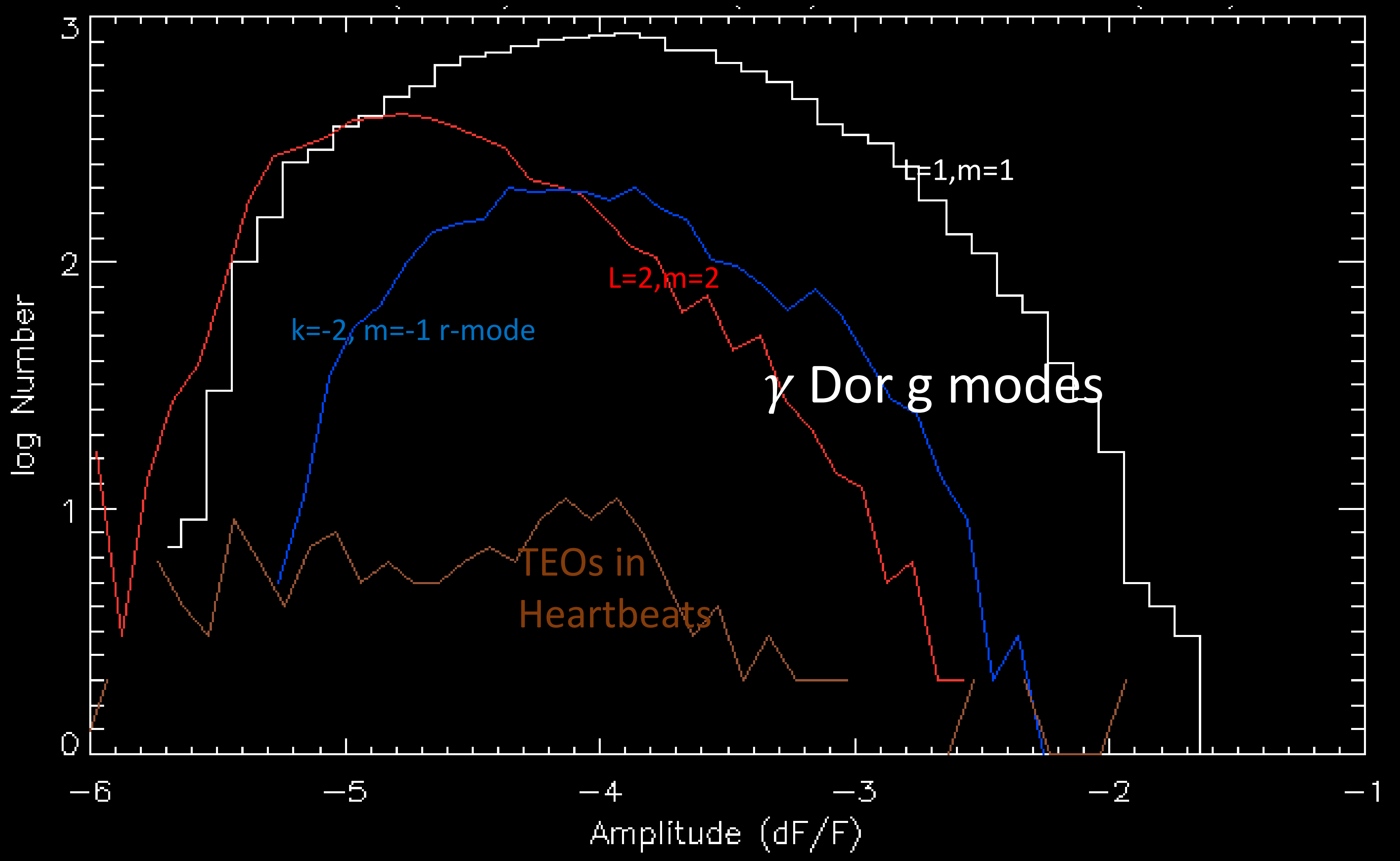


Guo 2020



40 AF,OB type Heartbeat binaries with TEOs

Mostly < 1 mmag

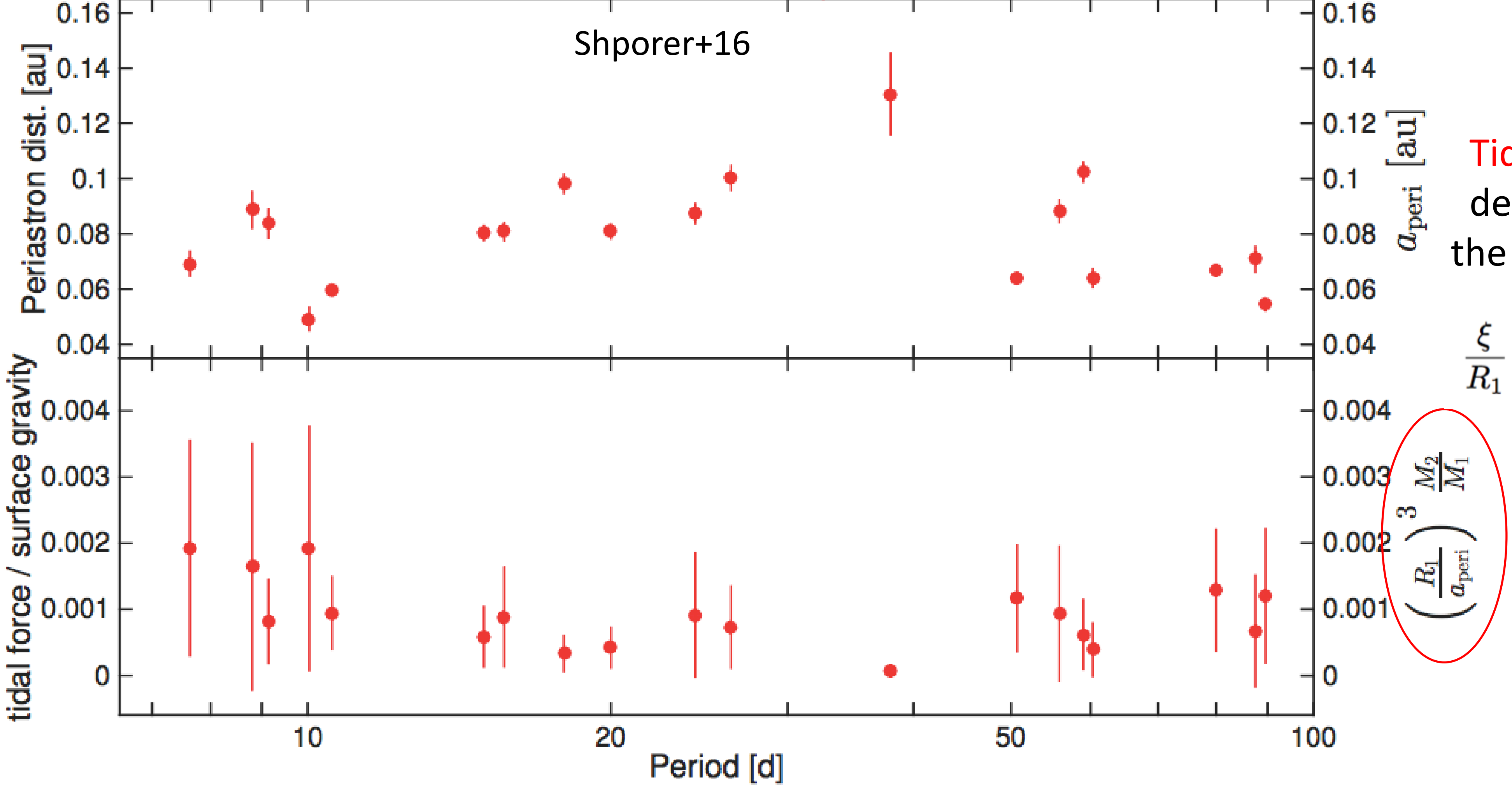


γ Dor gmode amplitude histogram

vs.

Tidal g mode amplitude histogram

TEO Amplitudes



Tidal Parameter determines the amplitude of tidal strength

$$\frac{\xi}{R_1} \sim \varepsilon_l = \left(\frac{M_2}{M_1}\right)\left(\frac{R_1}{D_{\rm peri}}\right)^{l+1}$$

$$D_{\rm peri} = a(1-e)$$

Observation:

HBs have tidal parameter ~ 10^-3 , and D_peri ~ 0.05 - 0.1 AU

In the Solar System:
2×10^{-7} (Jupiter, due to Io)
3×10^{-8} (Saturn, due to Titan)
8×10^{-8} (Neptune, due to Triton)

TEO Amplitudes -MD

a) Tidally Excited Oscillation (linear)   (~ forced harmonic oscillator)

$$\partial^2 \boldsymbol{\xi}/\partial t^2 + \boldsymbol{L}(\boldsymbol{\xi}) = \boldsymbol{f}$$

-> Mode Decomposition (MD)

Tidal response -> Sum of eigenfunctions of free oscillations $\sum_\alpha C(t)\boldsymbol{\xi}_\alpha(\boldsymbol{x})$
Use orthogonality condition to obtain eqn. for C(t)

Tidal potential from companion

M' Companion mass
D distance
Ωs spin frequency
Ω: orbital frequency

$$\dot{c}_\alpha + (\mathrm{i}\omega_\alpha + \gamma_\alpha)c_\alpha = \frac{\mathrm{i}}{2\varepsilon_\alpha}\langle \boldsymbol{\xi}_\alpha(\boldsymbol{r}), -\nabla U\rangle$$

$$= \frac{\mathrm{i}GM'W_{lm}Q_\alpha}{2\varepsilon_\alpha D^{l+1}}\mathrm{e}^{\mathrm{i}m\Omega_{\mathrm{s}}t - \mathrm{i}m\Phi} = \frac{\mathrm{i}GM'W_{lm}Q_\alpha}{2\varepsilon_\alpha a^{l+1}}\sum_{N=-\infty}^{\infty} F_{Nm}\mathrm{e}^{\mathrm{i}(m\Omega_{\mathrm{s}} - N\Omega)t}$$

Non-homog. Solution: $c_\alpha(t) = \frac{GM'W_{lm}Q_\alpha}{2\varepsilon_\alpha a^{l+1}}\sum_{N=-\infty}^{\infty}\frac{F_{Nm}\mathrm{e}^{-\mathrm{i}(N\Omega - m\Omega_{\mathrm{s}})t}}{(\sigma_\alpha - N\Omega) - \mathrm{i}\gamma_\alpha}$

Observationally, tidal excited oscillations -> frequency of forcing = orbital frequency harmonics

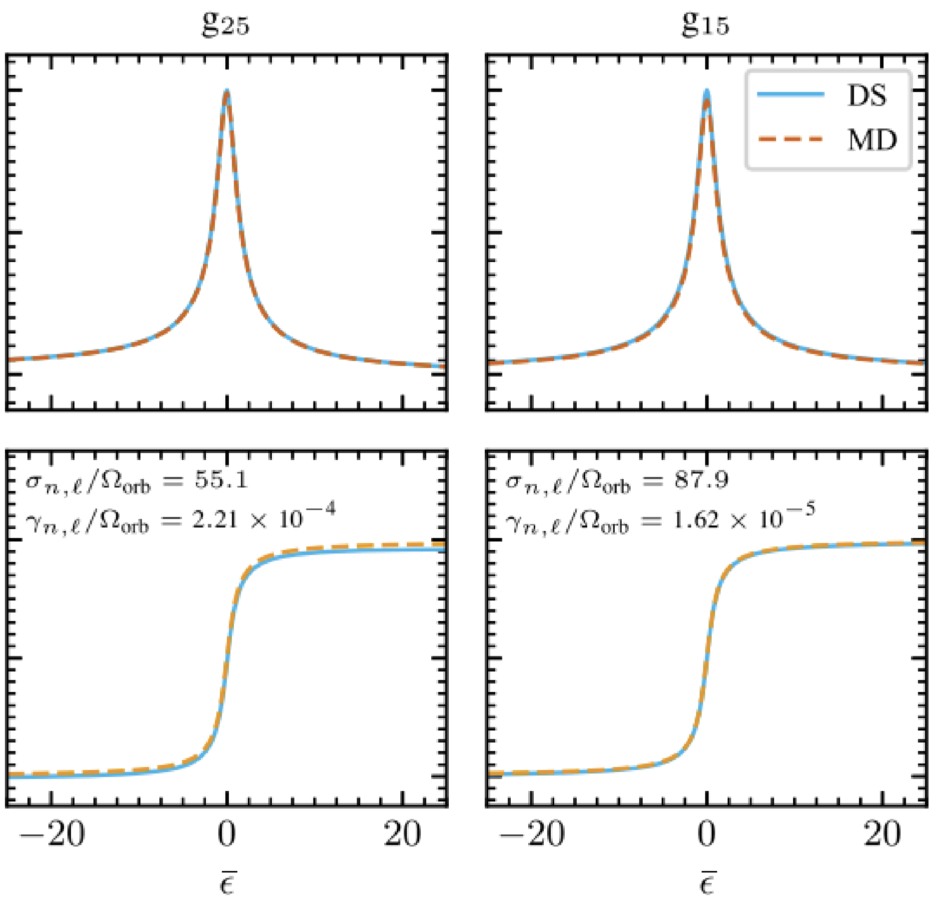
Kumar95; Fuller&Lai 12, 17; Burkart+12; Fuller17; Schenk01

GYRE-TIDE

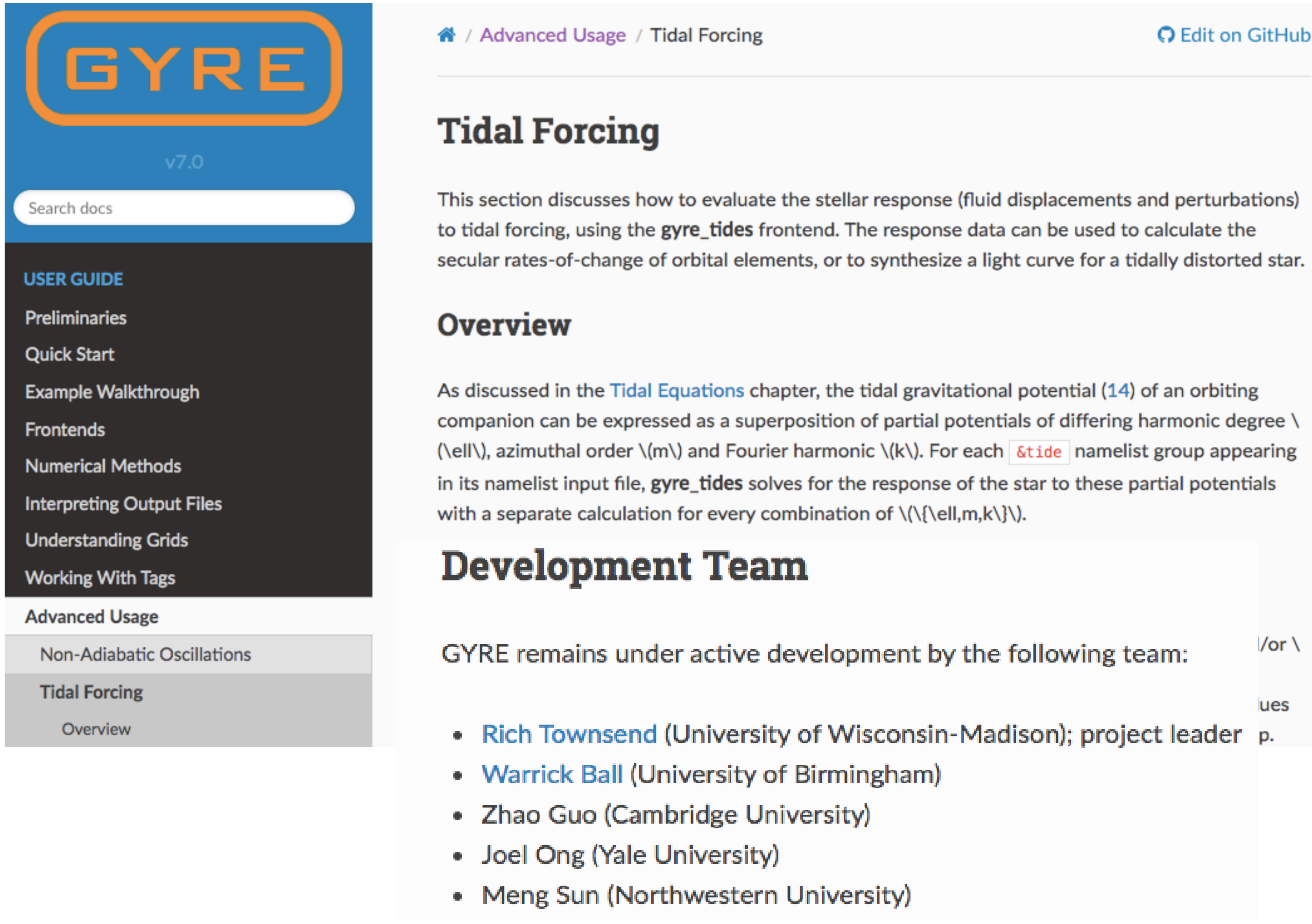
1 Direct Solving (DS)
2 Mode Decomposition (MD)

(Rotation NOT Included)

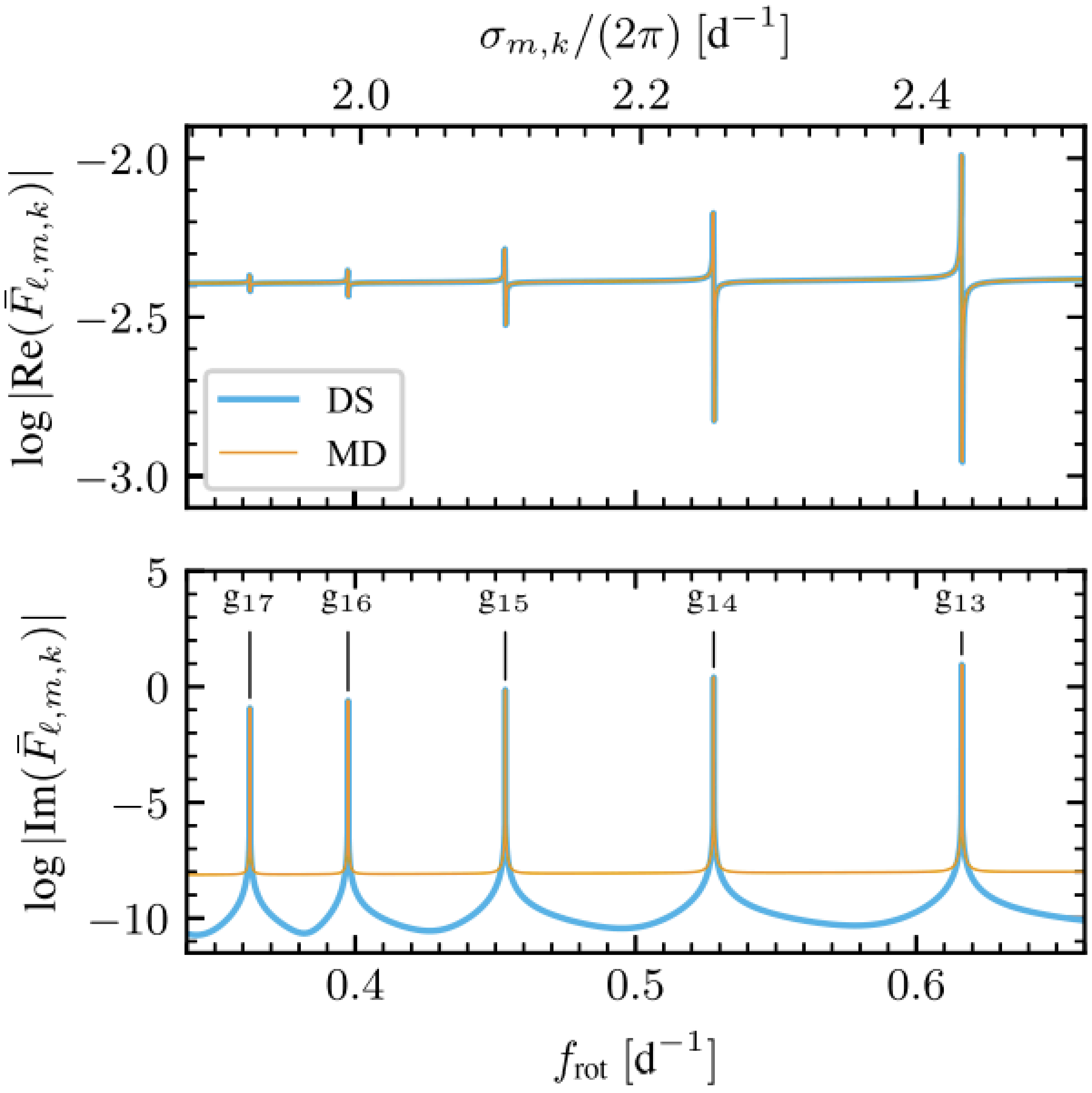
Non-adiabatic



Forcing frequency offset from resonance



(Sun, Townsend & Guo 2023)



igure 2. Normalized response function $\bar{F}_{\ell,m,k}$ plotted against stellar rotation equency f_{rot} for the $\{\ell, m, k\} = \{2, -2, 50\}$ partial tide of the KOI-54 primary odel. The real (imaginary) part of the function is shown in the upper (lower) anel, and separate curves are plotted for the DS and MD approaches. Peaks

Non-adiabatic Calculations

Problem with the Mode Decomposition method

Tidal response $\sum_{nlmk} A_{nlmk} (\Delta L/L)_{nlm}$

Mode amplitude

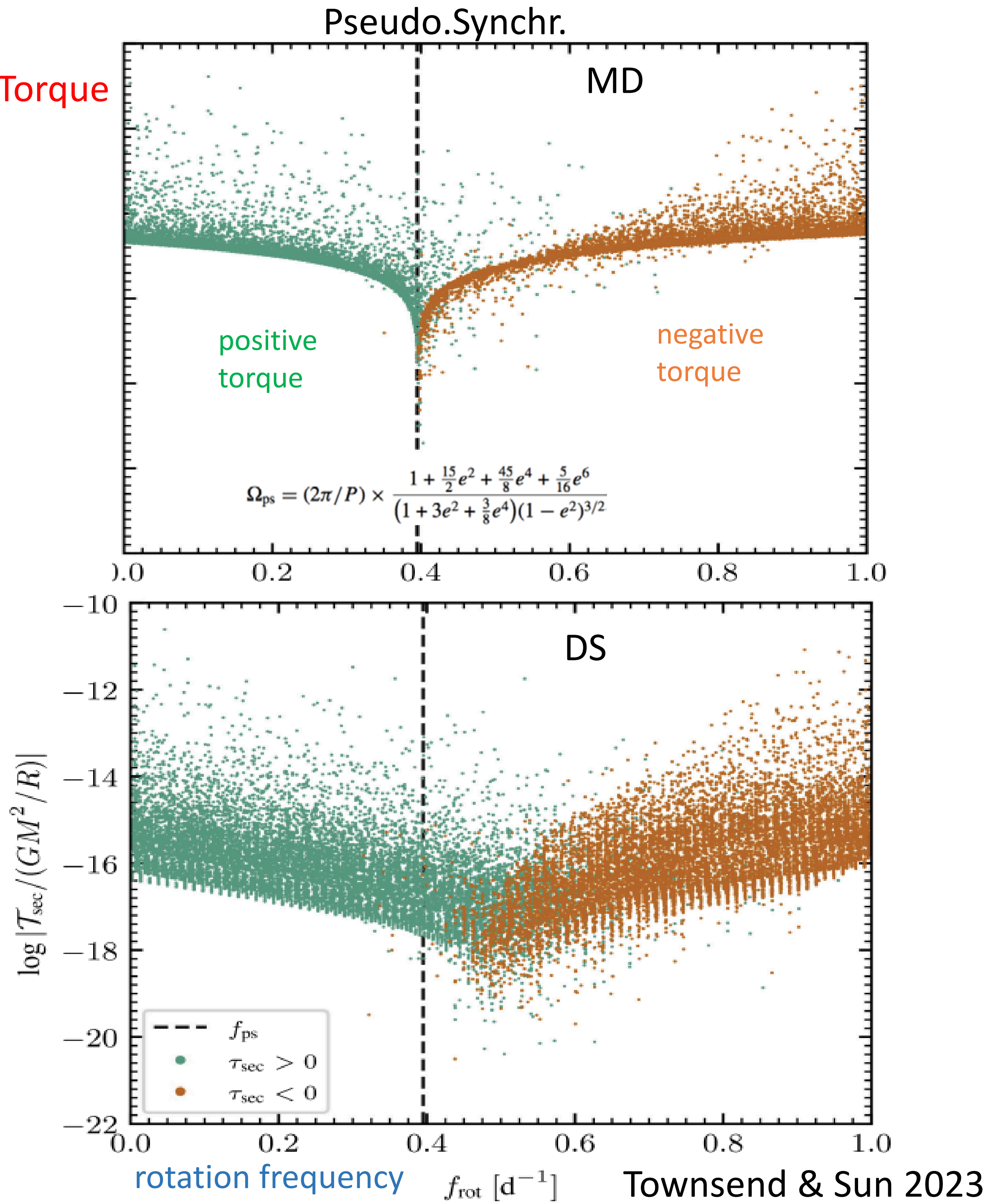
$$A_{n,\ell,m,k} = \frac{2\varepsilon_{\mathrm{T}}\, Q_{n,\ell}\, \bar{c}_{\ell,m,k}\, \Delta_{n,\ell,m,k}}{E_{n,\ell}}.$$

Lorentzian

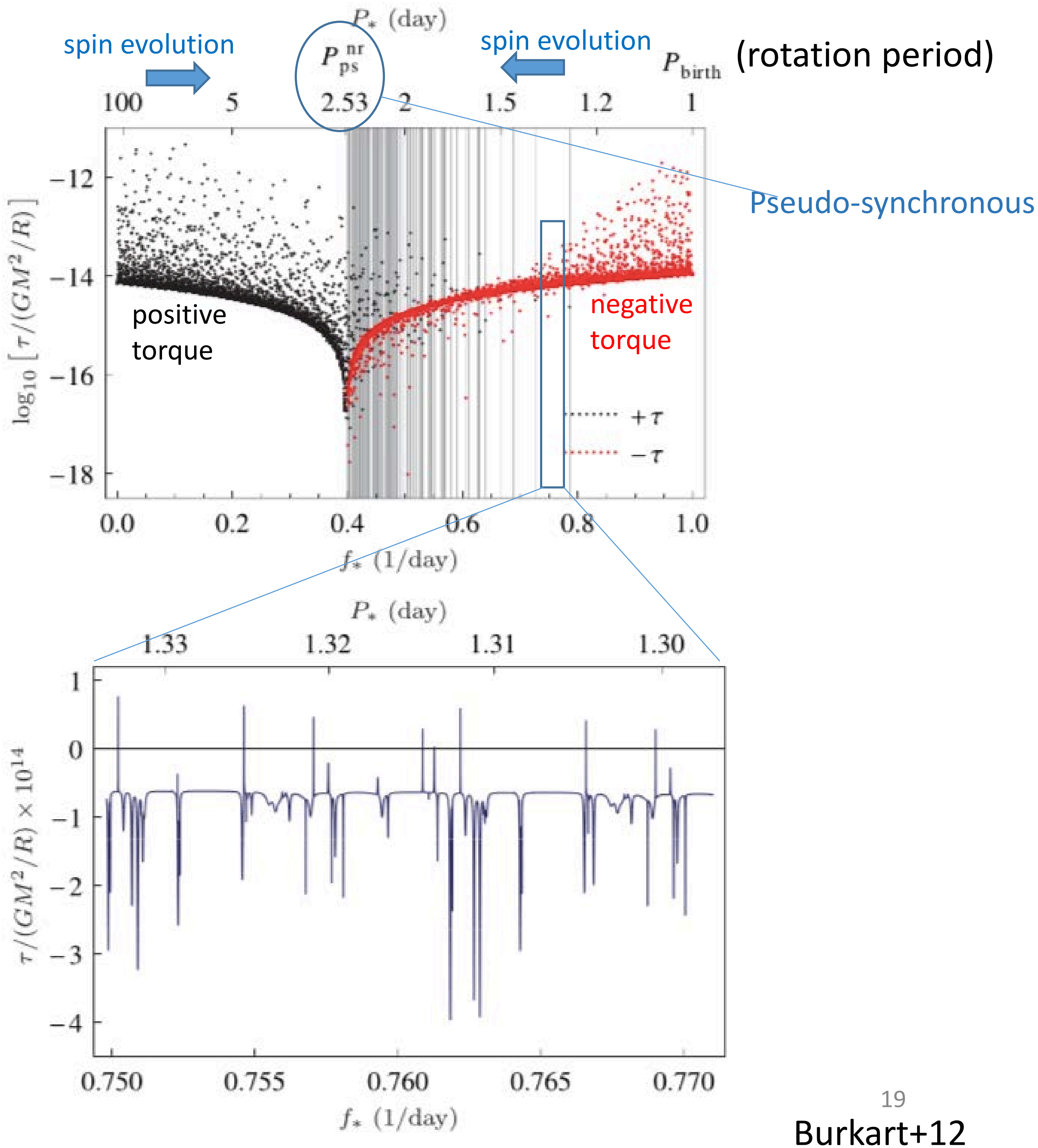
$$\Delta_{n,\ell,m,k} \equiv \frac{\sigma_{m,k}^2}{(\hat{\sigma}_{n,\ell}^2 - \sigma_{m,k}^2) - 2i\hat{\gamma}_{n,\ell}\sigma_{m,k}}$$

Damping rate

Townsend & Sun 2023; Dewberry& Wu 24



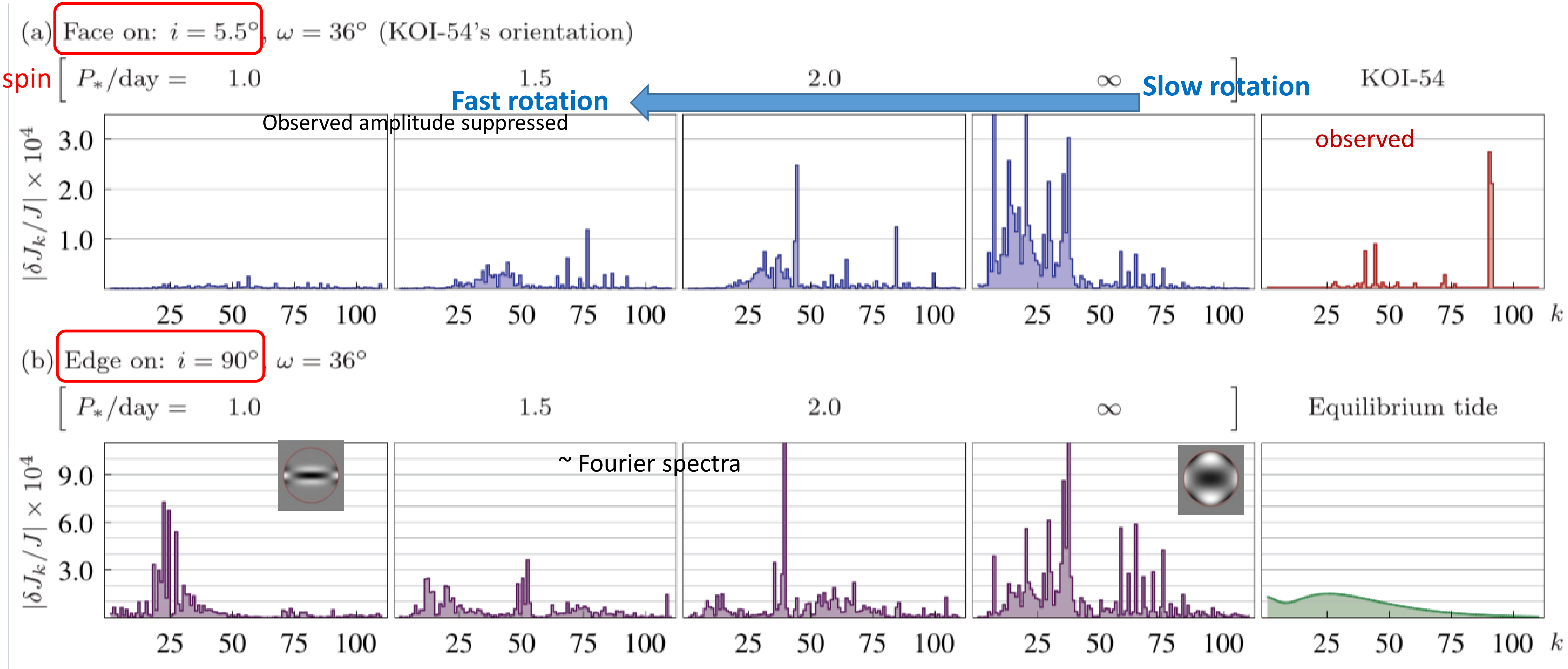
Townsend & Sun 2023



Burkart+12

TEO amplitude: The Effect of rotation

Direct Solving + Traditional approximation

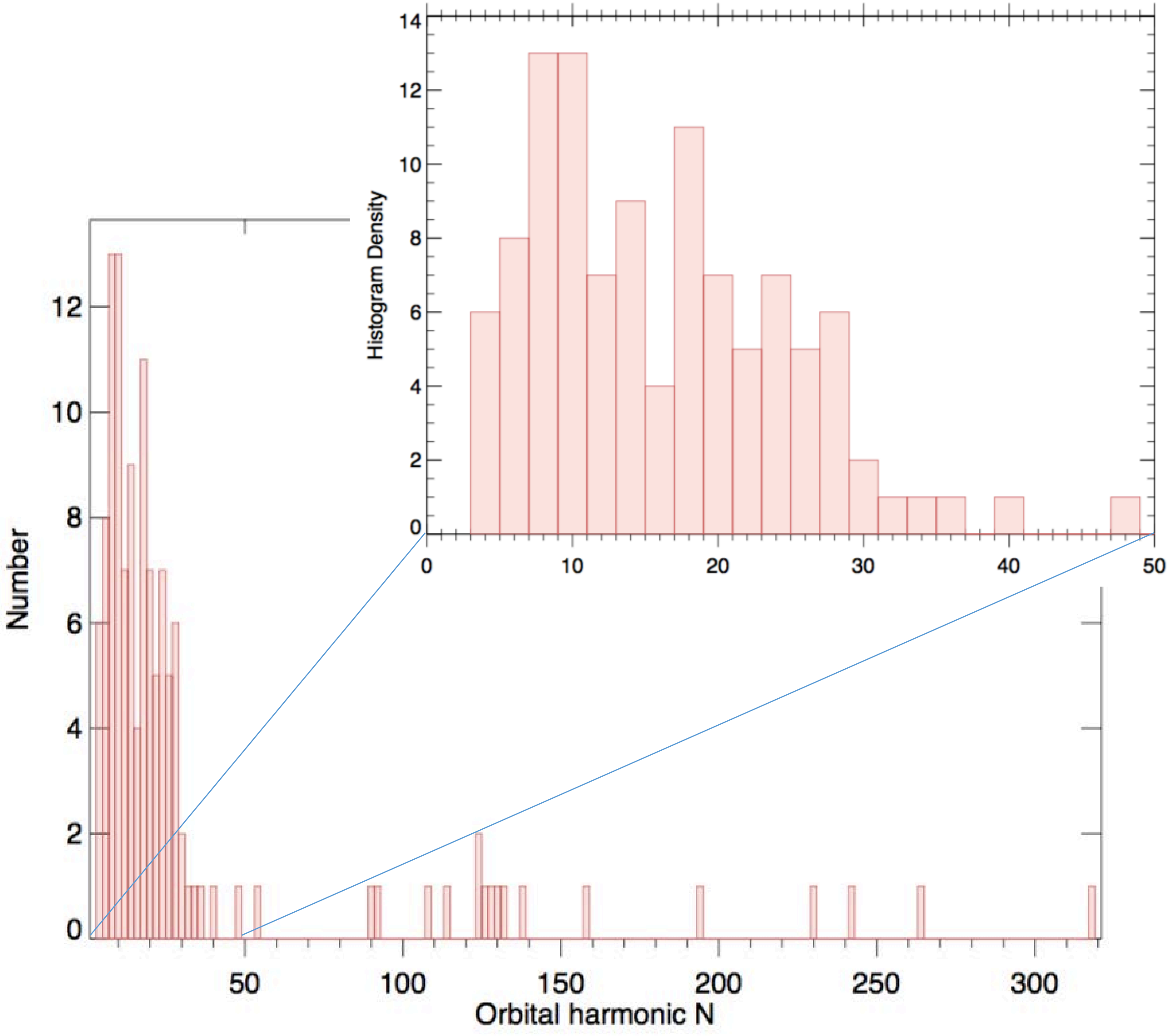


Burkart+12

Face on: Observed TEO amplitude suppressed for faster rotation

Edge on: Suppression not so strong

Which orbital harmonics N do we expect?

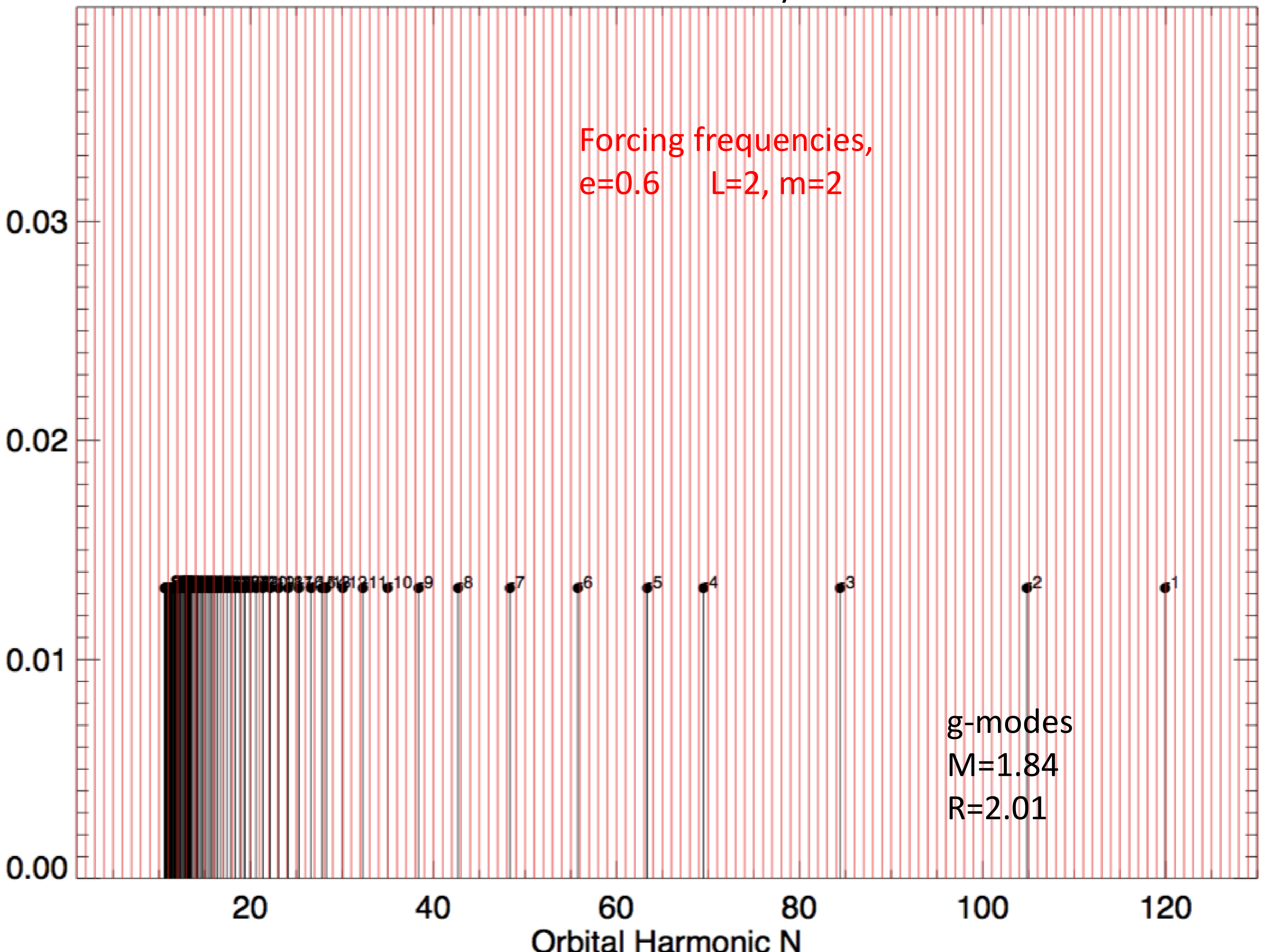


TEO orbital-harmonic number

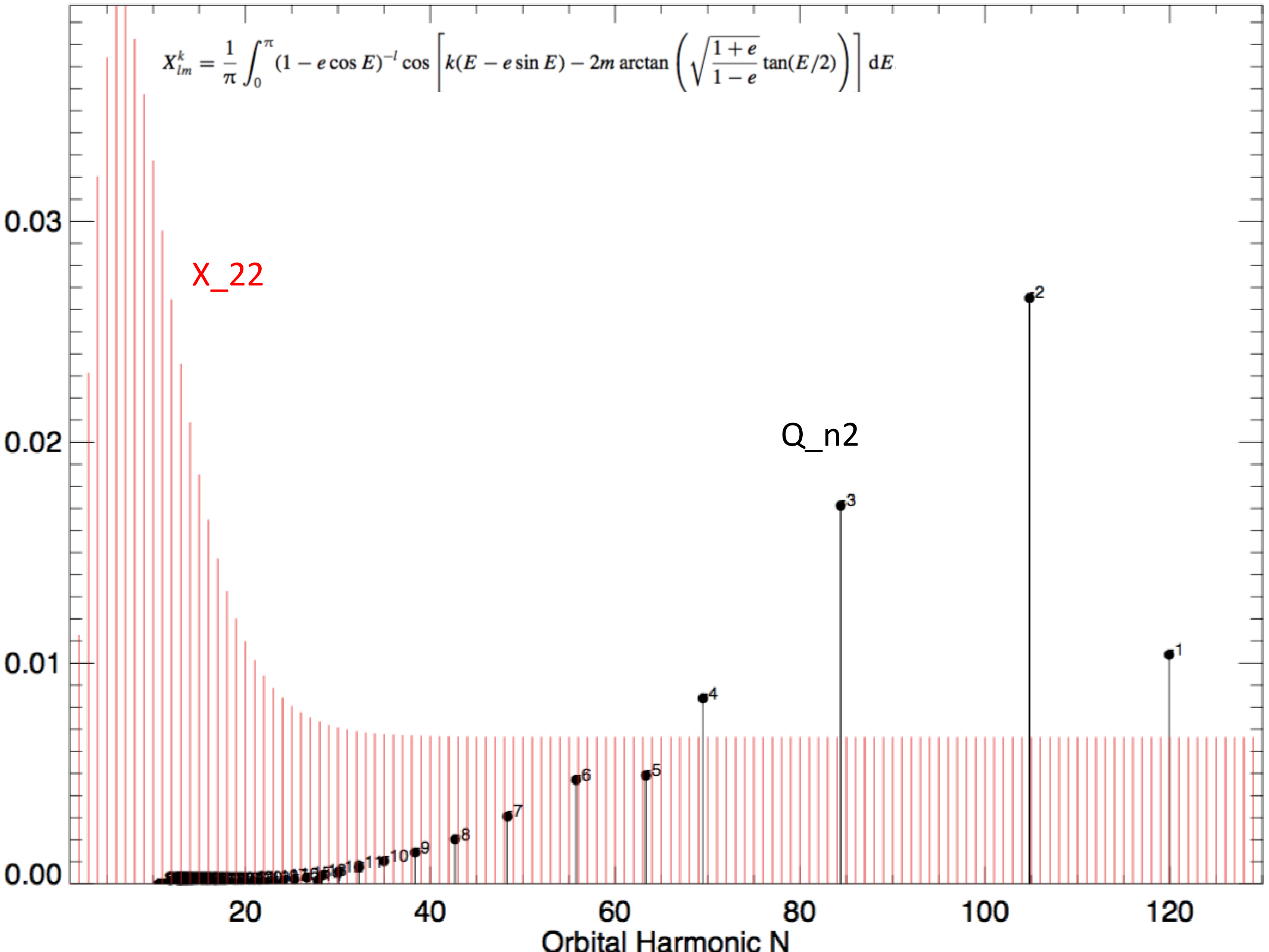
N can reach ->300 (KIC8164262)

Mostly from 4 to 40

Which orbital harmonics N are tidally excited?



Forcing frequencies
=
Orbital harmonic N*f_{orb}

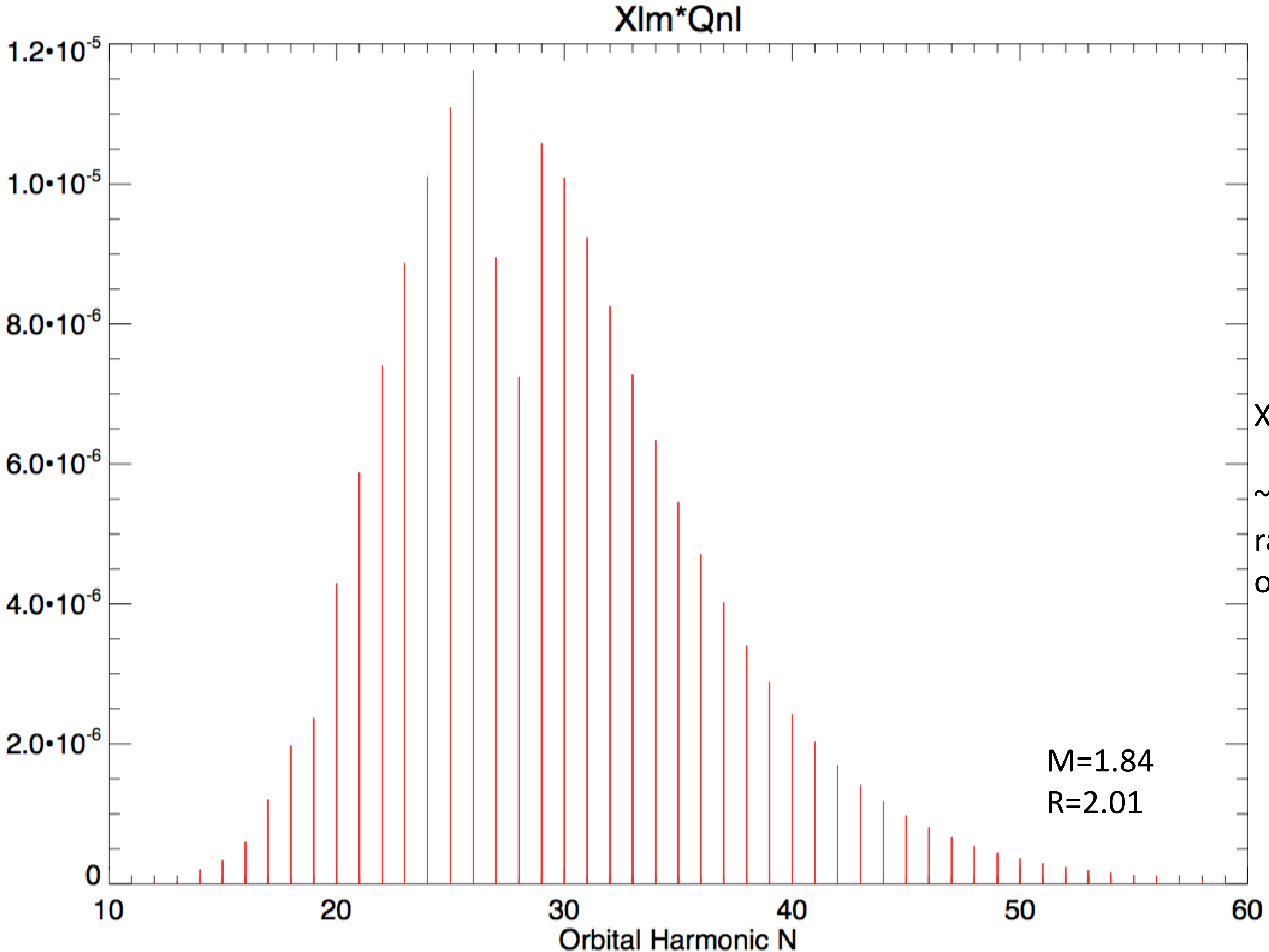


G-mode do not couple with the tidal potential equally

weights:

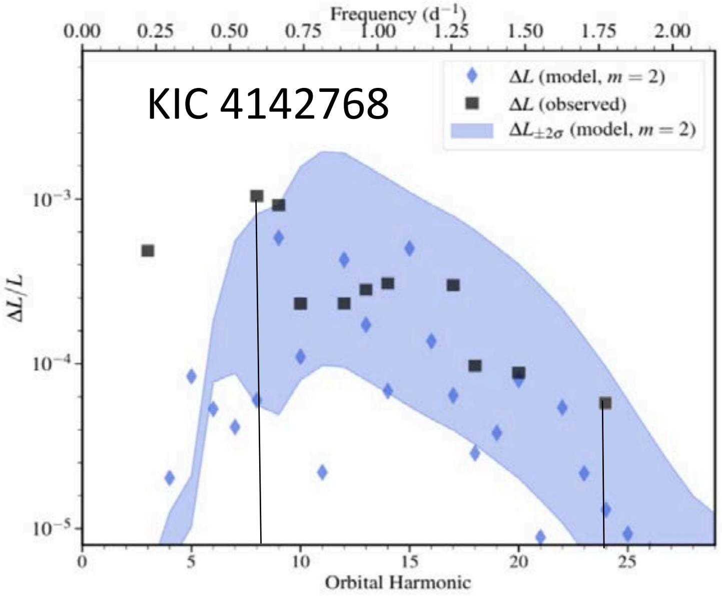
Tidal overlap integral Q_n2

$$= \frac{1}{MR^{\ell}}\int d^3x\rho\xi_a^* \cdot \nabla(r^{\ell}Y_{\ell m})$$

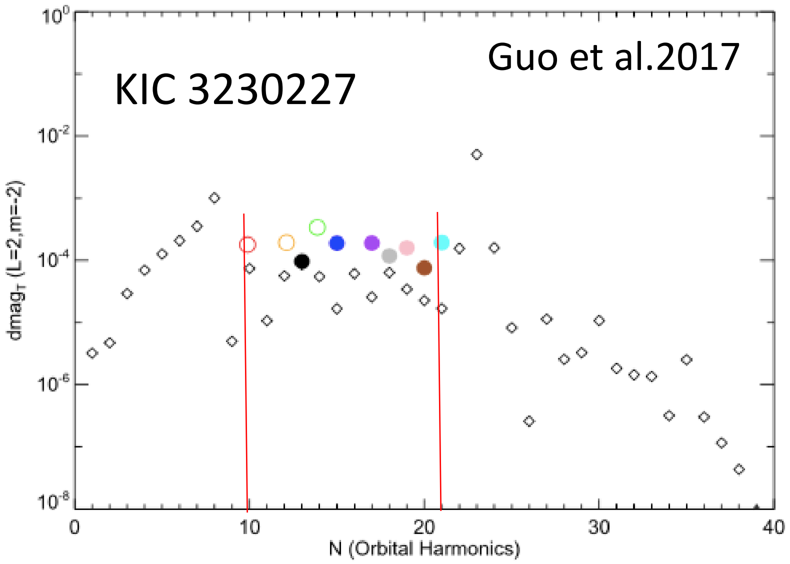


X_lm *Q_nl

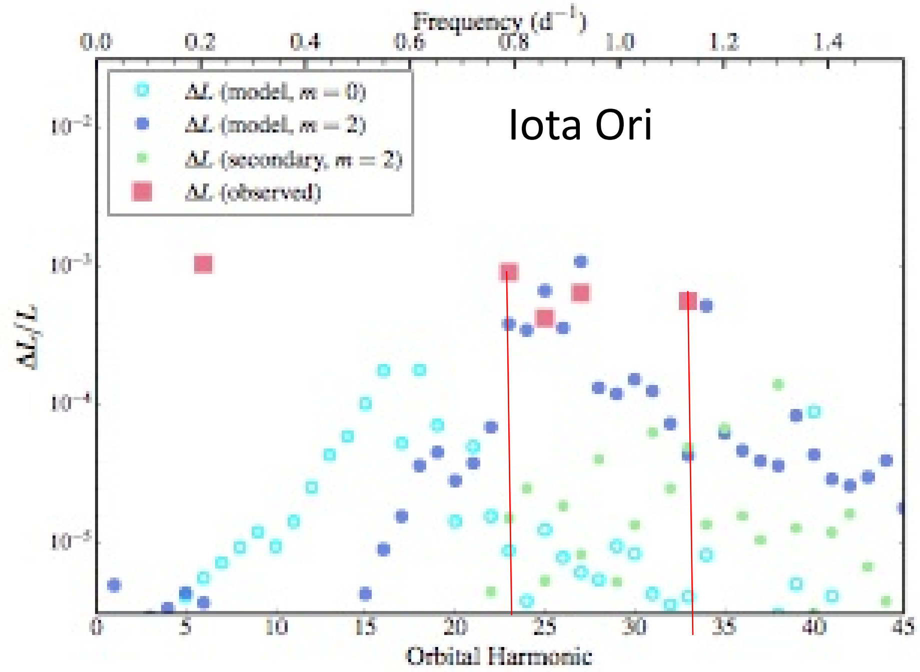
~ roughly determines the range of the excited orbital harmonics N



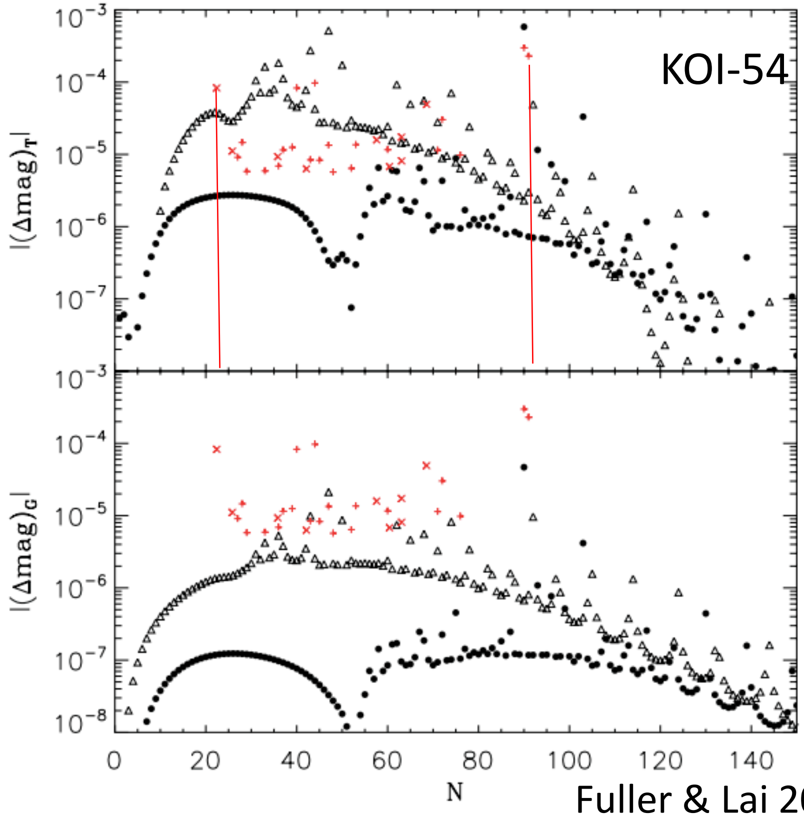
Guo et al.2019



TEO Amplitude Modeling



Pablo et al. 2017

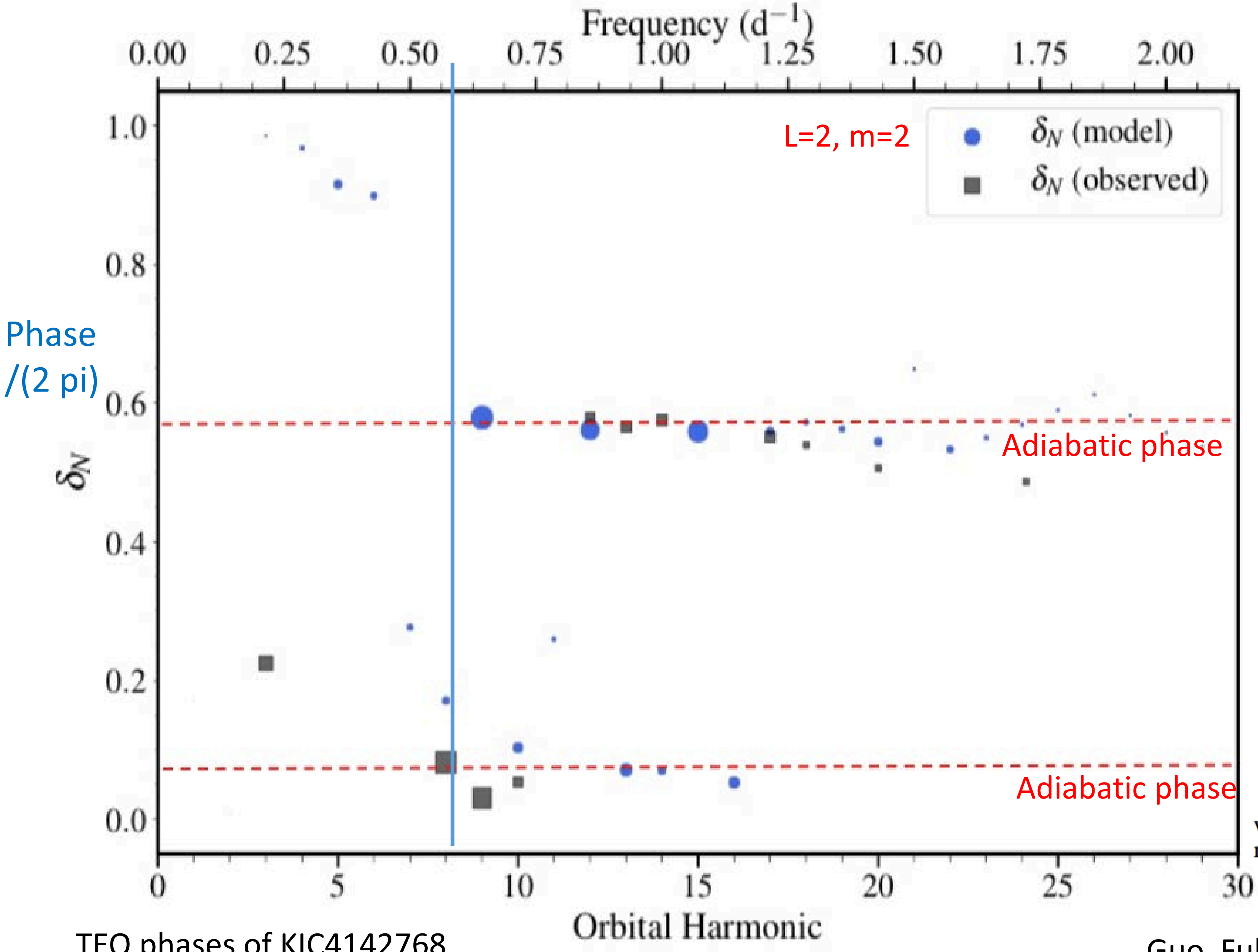


Fuller & Lai 2012

$$A_{nlmk} = \frac{2\,\varepsilon_l\, Q_{nl}\, \widetilde{X}^k_{lm}\, W_{lm}\, \Delta_{nlmk}}{E_{nl}}$$

TEO Phases

TEO phases



TEO phases of KIC4142768

-> observer's coordinates

-> ω (argument Of periastron)

N < 8 f_orb

Strong non-ad. Effect

Most observed TEO phases agree with adiabatic phases,

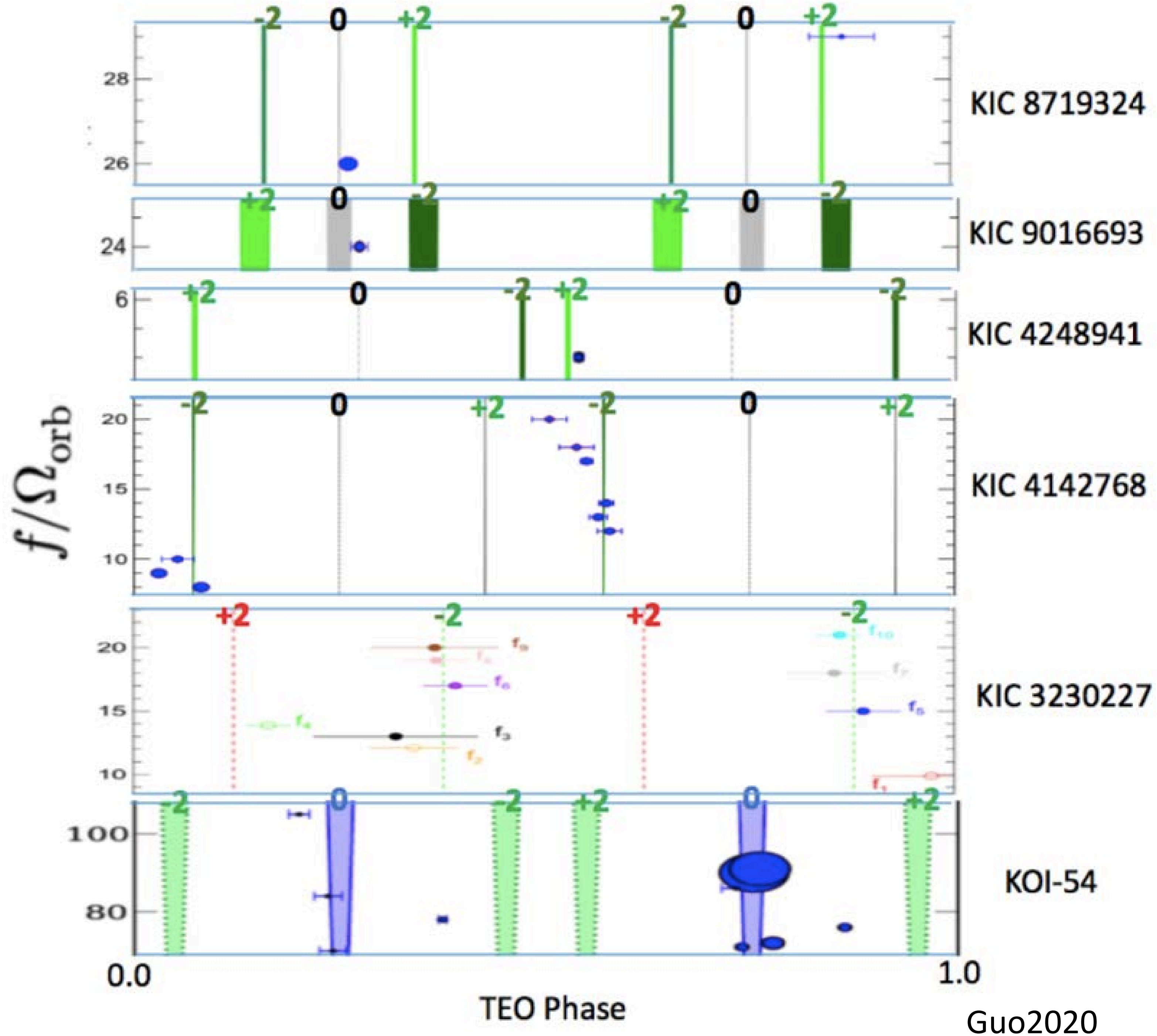
~ Scatter around the adiabatic predictions

$$\phi_{l=2,m} = \begin{cases} 0.25 + m\phi_0 & \text{if } m = 2 \text{ or } -2 \\ 0.25 & \text{if } m = 0 \end{cases} \tag{3}$$

where $\phi_0 = 0.25 - \omega_p/(2\pi)$ and m is the mode azimuthal number.

Guo, Fuller et al. 2019

TEO phases



Guo2020

Observed TEO phases agree with adiabatic phases,
Scatter around the adiabatic predictions

TEO phases:

Burkart12; Oleary & Burkart14
Jayasinghe20;
Guo+20; Li+24

-> Can be used to identify spin-orbit misalignment

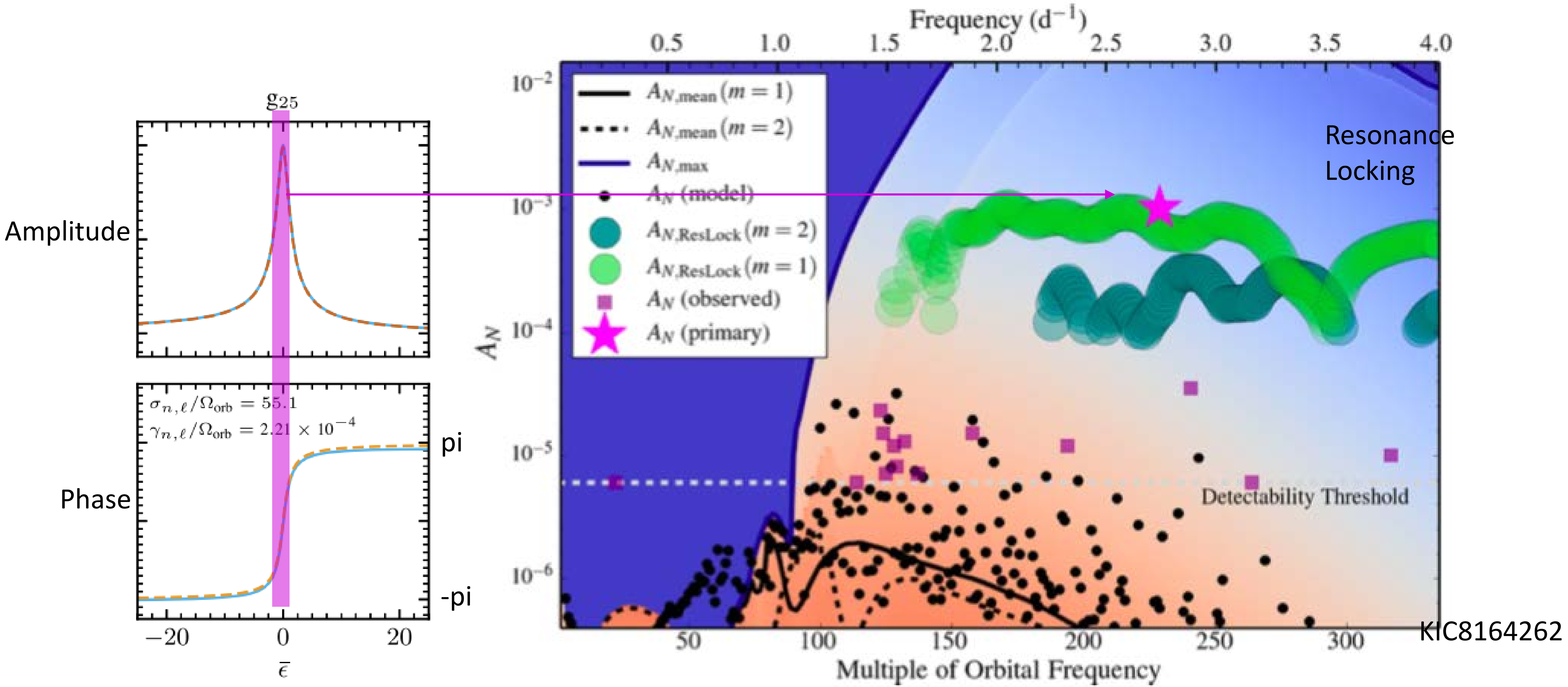
TEOs in Resonance Locking

mode freq.= forcing freq.

If the mode is locked in resonance, then this condition does not change with time, i.e.

$$\dot{\sigma}_\alpha \simeq \dot{\sigma}_N = N\dot{\Omega},$$

TEOs in Resonance Locking



Fuller 17

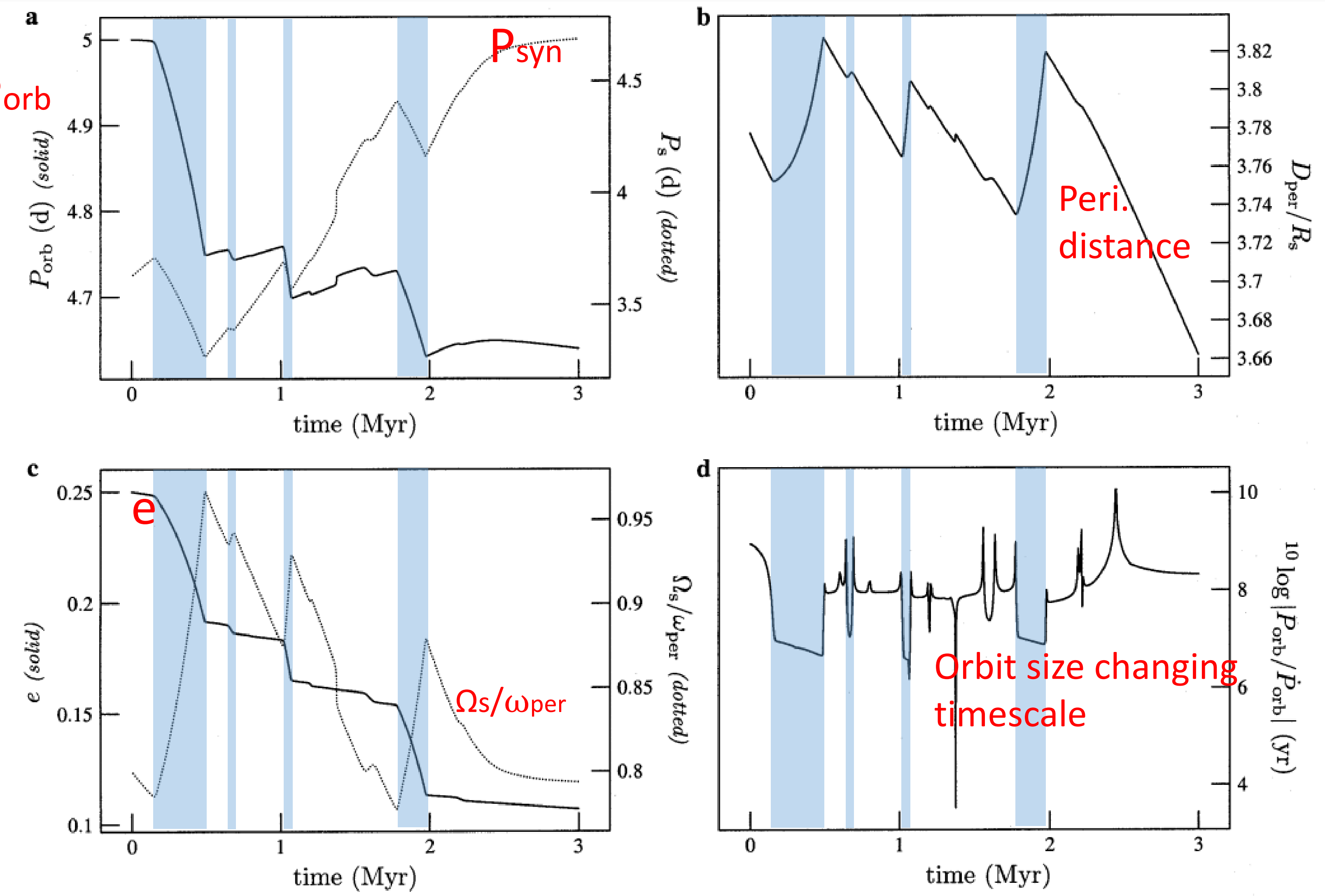
TEOs in Resonance Locking show larger amplitudes and more random phases, limited range of N

10M + 1.4M binary

e =0.25

Porb =5days

Fast evolution of P, e during Resonance Locking



Resonance Locking

Fig. 3a–f. Orbital evolution of a system with initial period $P_{orb} = 5$ days and eccentricity $e = 0.25$. Initially the star rotates sub-synchronously ($\Omega_s/\omega_{per} = 0.8$), but resonance locking of the $n = 7$ harmonic of the tidal forcing quickly forces the star to spin near (pseudo) corotation. During the subsequent tidal evolution of the system, a few more cases of resonance locking (now with the $n = 6$ harmonic) occur, recognizable by the more or less square shape of the dips in panel **d**, which shows the timescale for the orbital decay. **a** Orbital and stellar rotation period, **b** ratio of periastron distance to stellar radius, **c** eccentricity and ratio of stellar rotation frequency to orbital frequency at periastron, **d** timescale for the change of the size of the orbit, **e** and **f** schematic representation of the frequency distribution of forcing harmonics and stellar resonance frequencies at $t = 0$ (panel **e**) and $t = t_{max}$ (panel **f**).

Witte & Savonije 1999

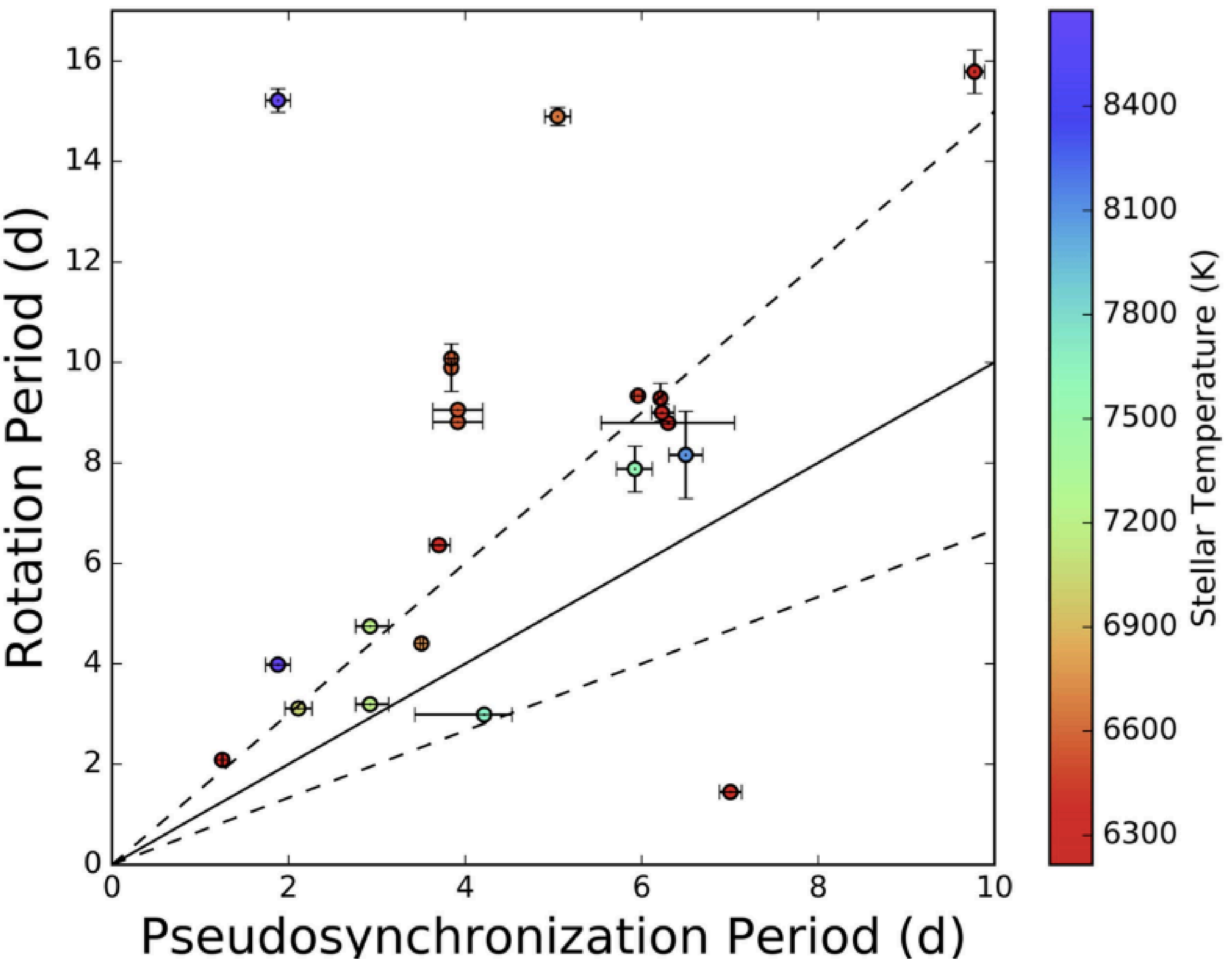
$\Omega_s/\omega_{per}=1$: Pseudo-syn. rotation

$\Omega_s/\omega_{per}<1$: sub-Pseudo-syn. rotation

Stellar Spins in HBs

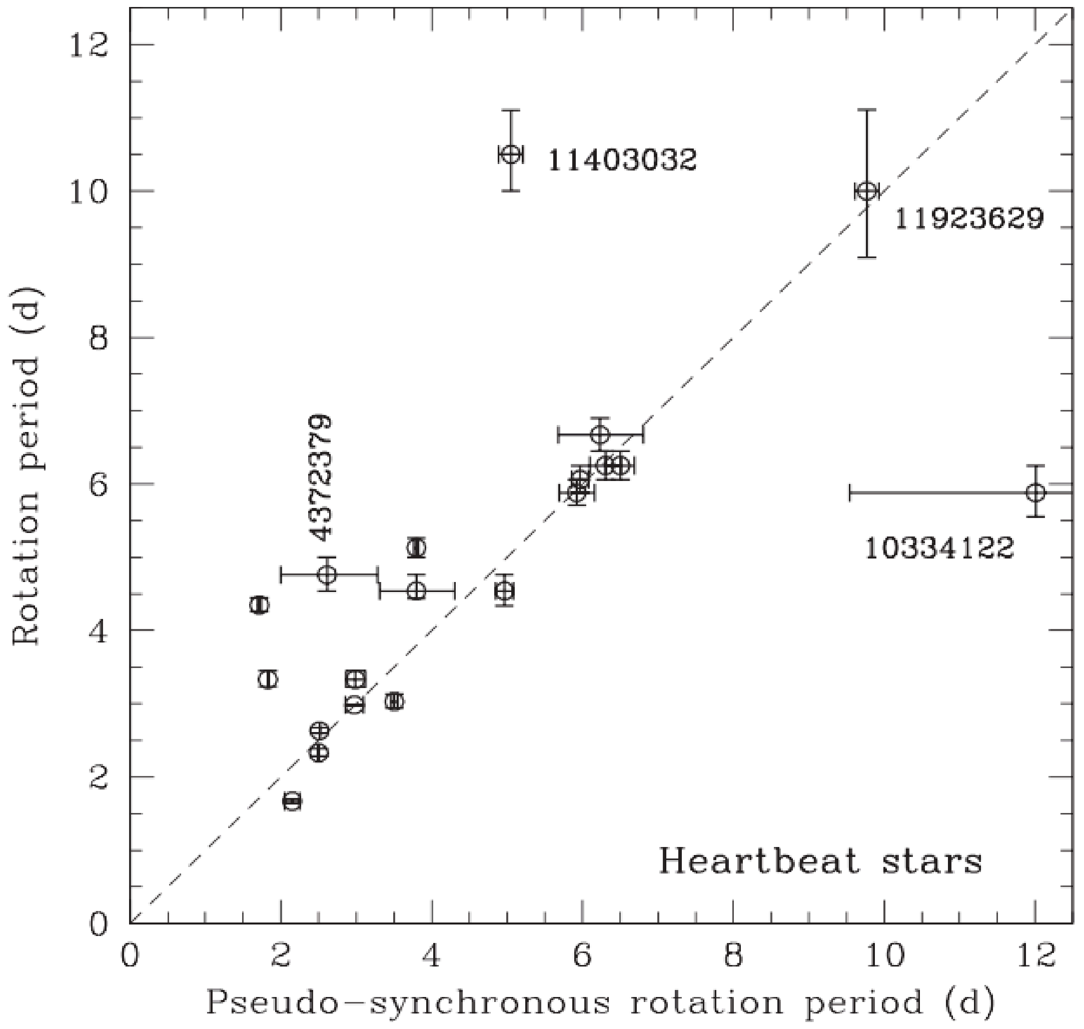
Stellar Spin in Heartbeat Binaries: 2:3 or 1:1?

Zimmerman+17

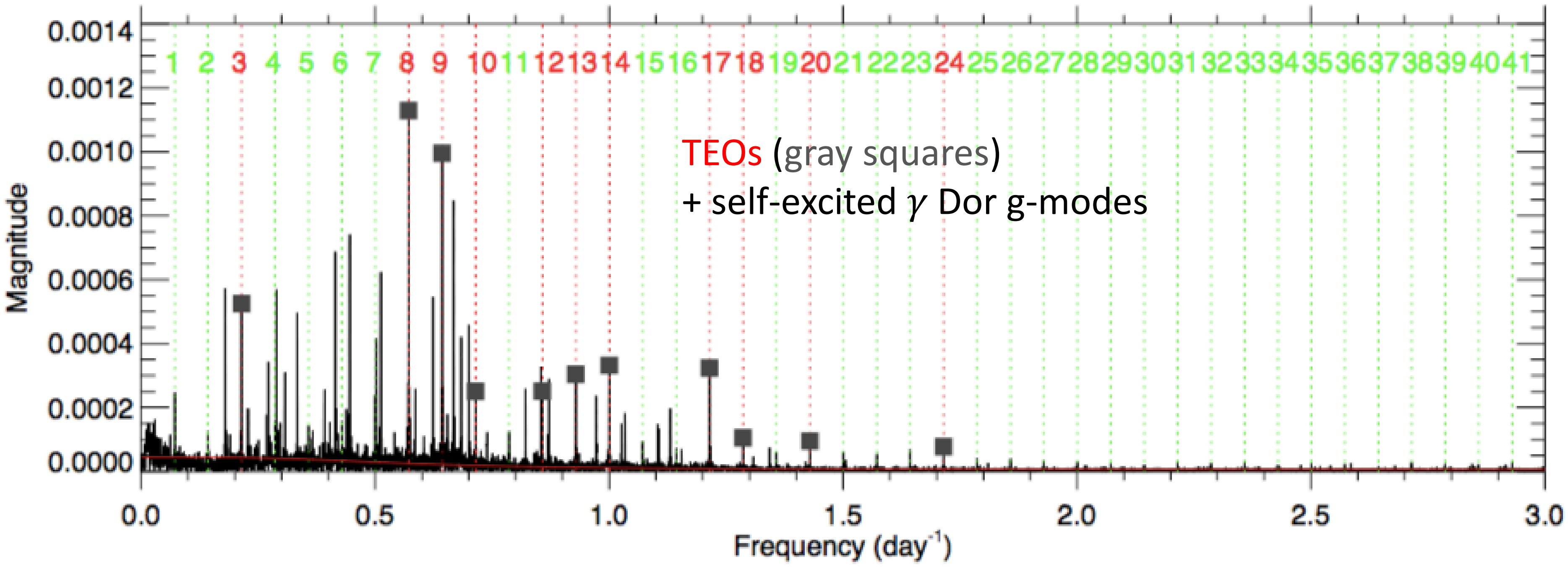


P_rot ~ 2/3 P_pseudosyn

Saio & Kurtz 2022 (r-mode fitting)



P_rot ~ P_pseudosyn



KIC 4142768
two A-star
~ M=2.05

P=14, e=0.6

TEOs

+ γ Dor oscillations

+ δ Sct oscillations

Very slow rotation
In KIC 4142768

P_core ~ 1000 +/-300 days !!

vsini=7km/s

1) Fuller 2021 : “Inverse tide”

->Energy can be transferred from the self-excited γ Dor g-modes to the orbit

-> a negative tidal Q

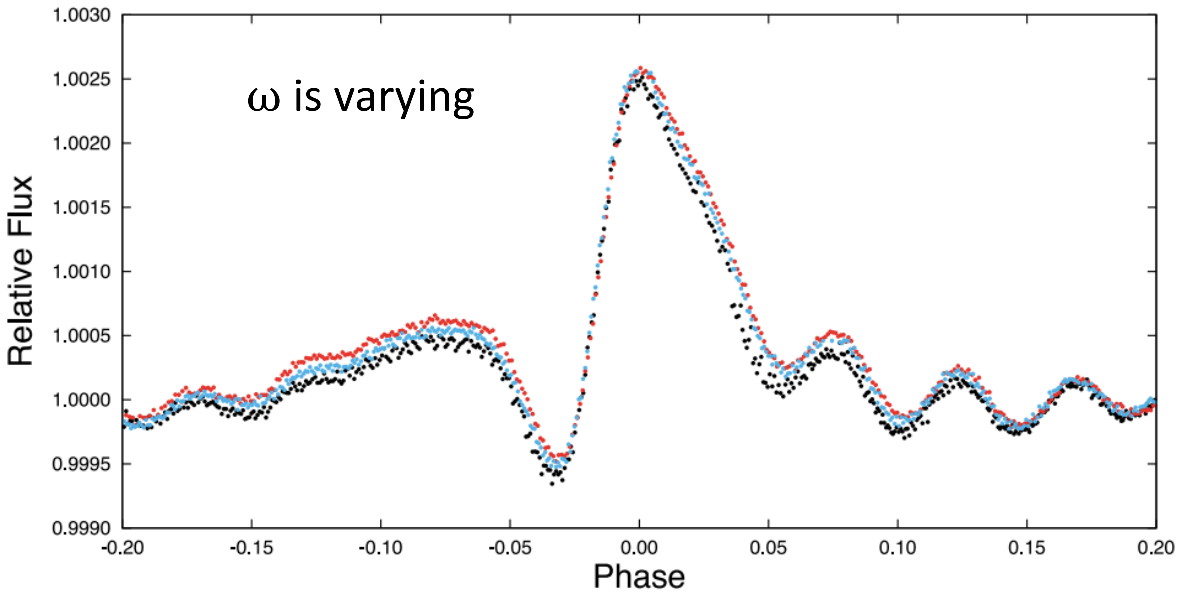
2) Triples

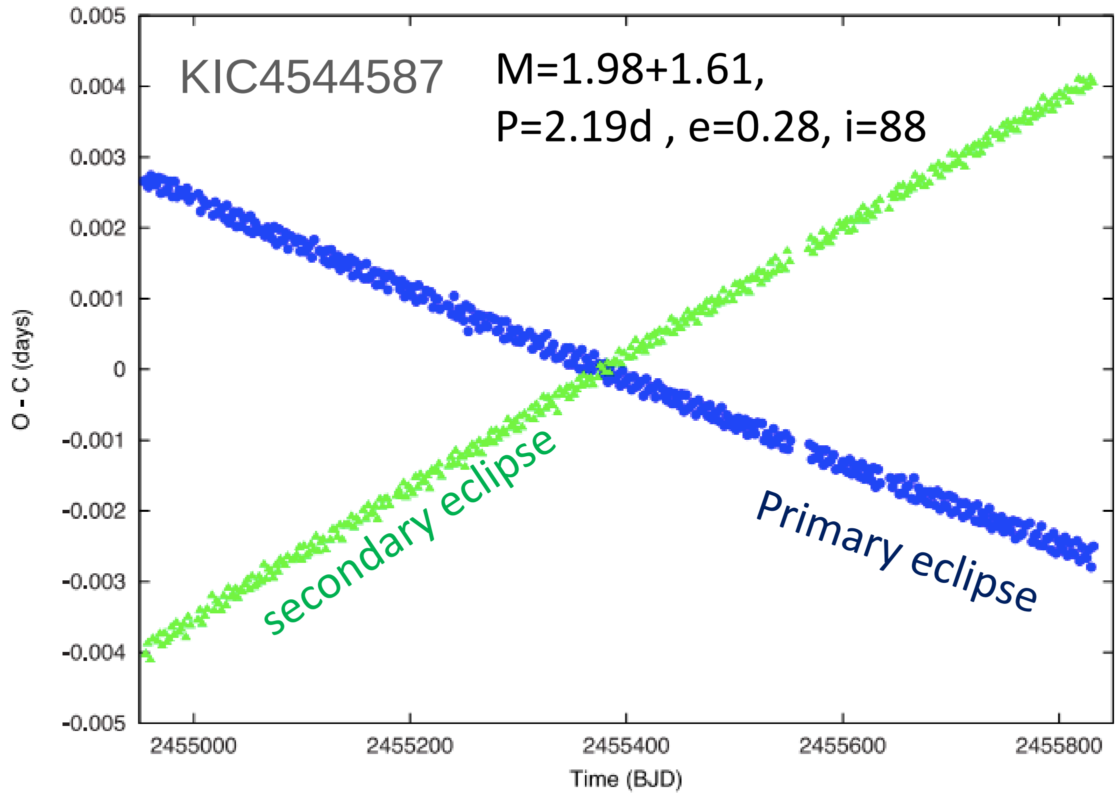
A new equilibrium state:
Cassini State 2

Guo et al. 2019

Spin-Orbit Misalignment & Apsidal Motion in HBs

HBs: Apsidal motion





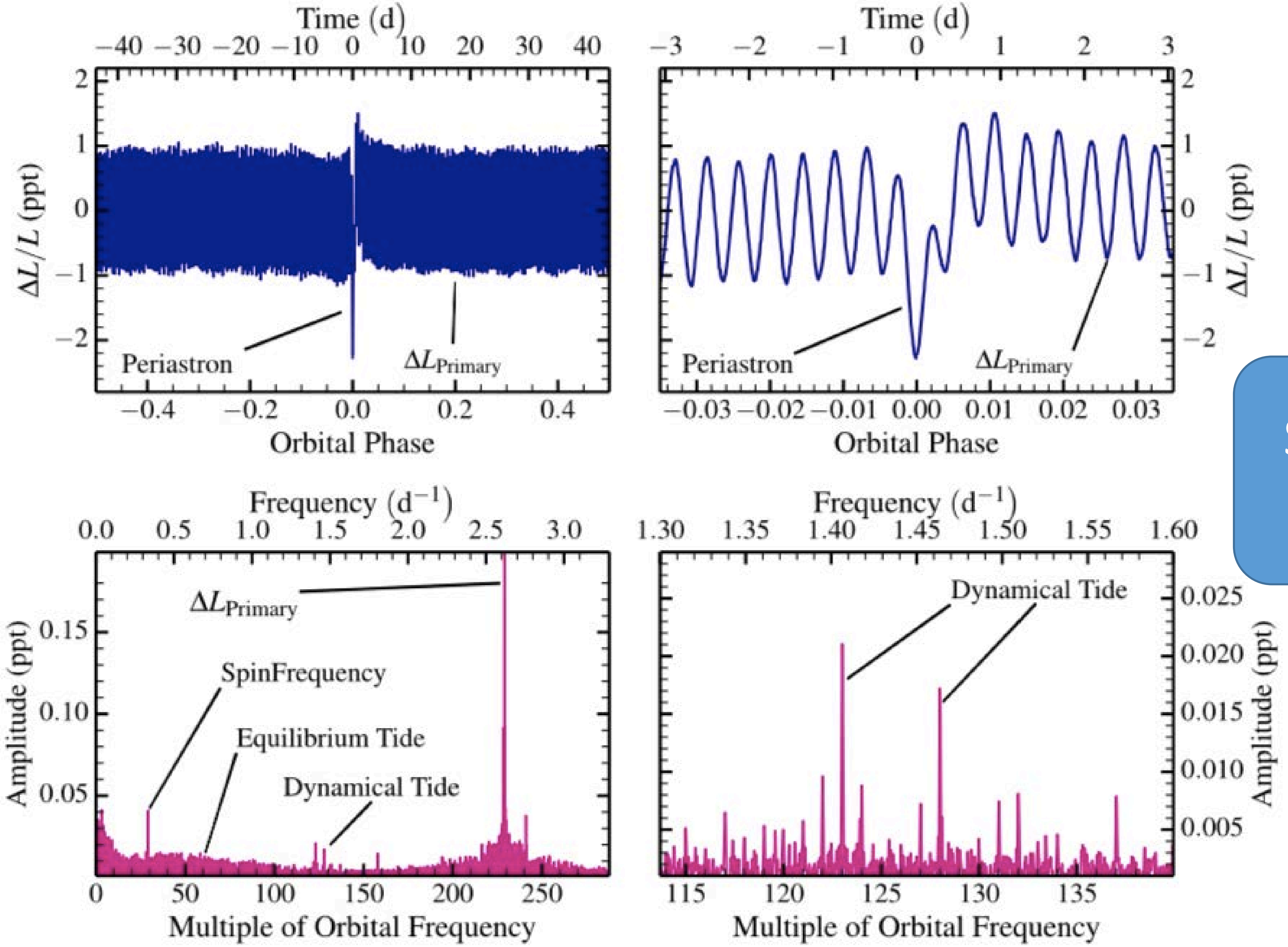
Hambleton+13; Ou+21,

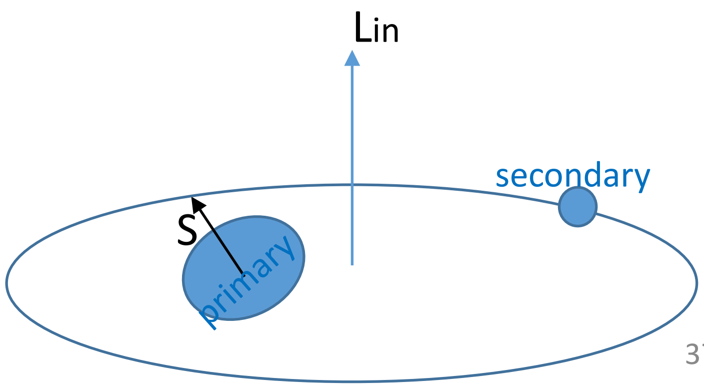
Hambleton+ 2016
KIC3749404, 3rd star

The opposing direction
-> classical apsidal motion signature, P_ap ~ 182 yr
-> Newtonian + GR + Dynamical tide

-> 3rd star

Spin-orbit misalignment in KIC 8164262





Masses: 1.70 + 0.36
e=0.89, P= 87.45d,

Hambleton+18
Fuller17

Orbital inclination ~ 65deg, Spin incl.=35deg
-> Misaligned!

Very slow stellar rotation/high obliquity
in Heartbeat Binaries

Slow Stellar Spin in Cassini State 2

Explanation: triples

Stars in triple systems can become caught in a Cassini State (CS2)
(a high spin–orbit obliquity and slow rotation of one or both stars).

For main-sequence stars, an inner binary period of Pin ~1–10 d with tertiary periods of Pout ~10–10^5 d.

Such systems would stand out as having very long rotation periods Ps ~ 10–10^3 d

in contrast to the expectation of tidal synchronization at short orbital periods

Spin Evolution in a triple system

We follow Su & Lai (2021), and assume that the spin AM, S, is much smaller than the orbital AM, L. The spin-orbit evolution equations are given by

$$\frac{\mathrm{d}\hat{s}}{\mathrm{d}t} = \alpha \cos\theta\, \hat{s} \times \hat{L}_{\rm in} + \frac{1}{t_{\rm al}} \hat{s} \times (\hat{L}_{\rm in} \times \hat{s}), \tag{1}$$

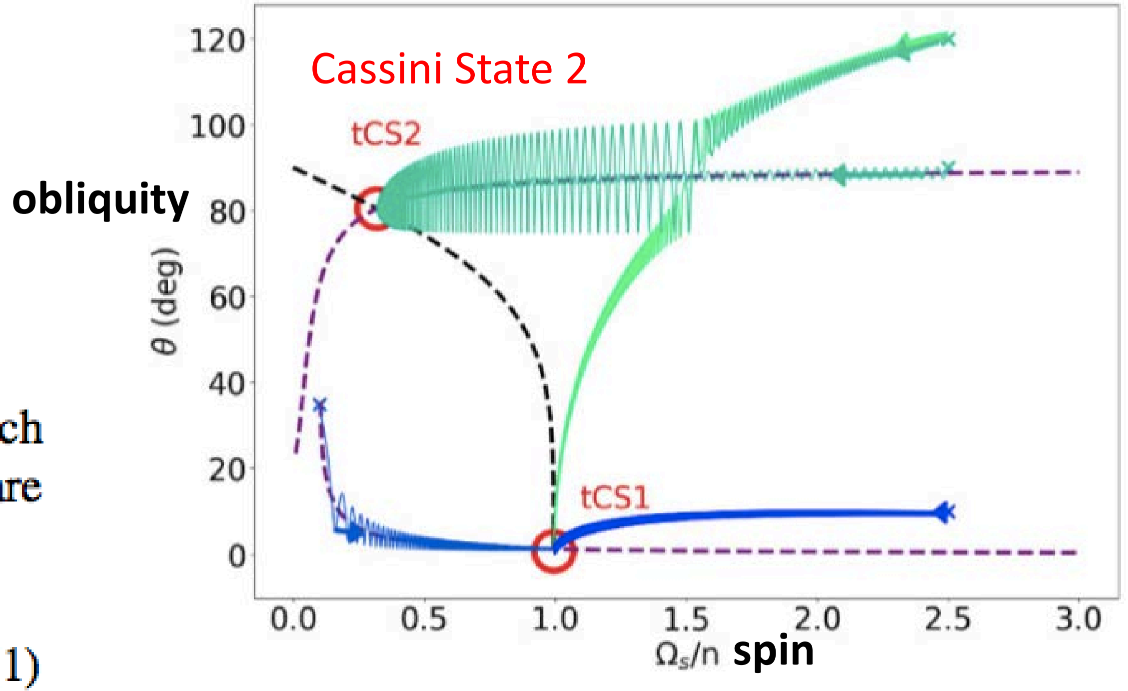
$$\frac{\mathrm{d}\hat{L}_{\rm in}}{\mathrm{d}t} = \omega_{\rm lp} \cos I\, \hat{L}_{\rm in} \times \hat{L}_{\rm out} = -g \hat{L}_{\rm in} \times \hat{L}_{\rm out}, \tag{2}$$

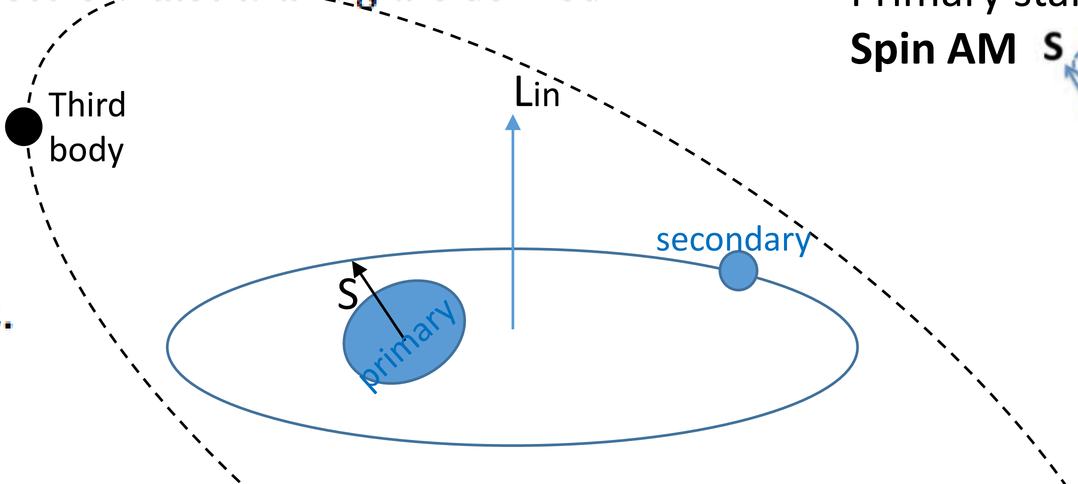
where θ is the obliquity, and the precession rates α and g are defined via

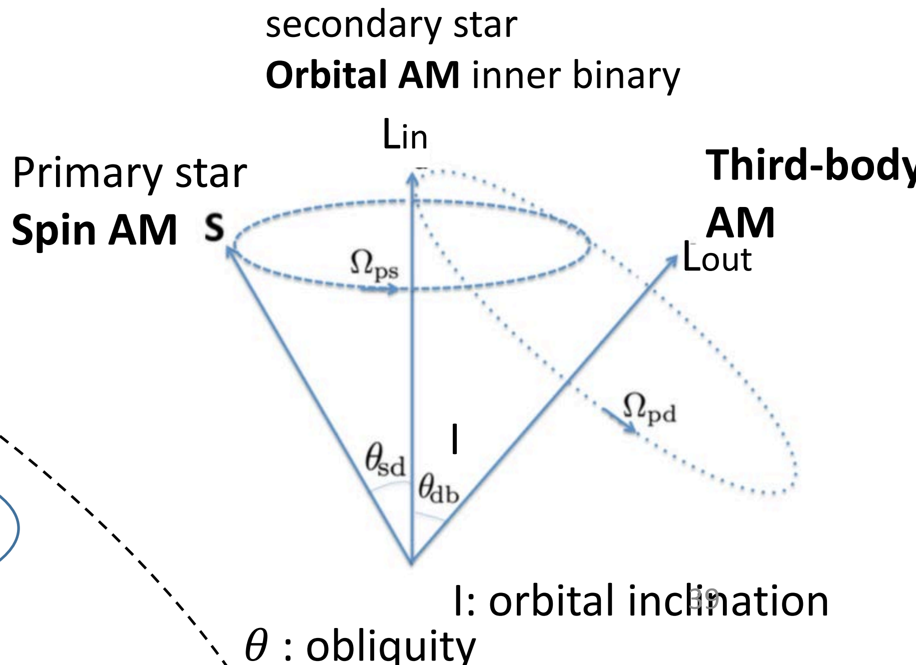
$$\alpha = \frac{k_2}{2k} \frac{M_2}{M_1} \left(\frac{R}{a_{\rm in}}\right)^3 \Omega_{\rm s},$$

$$g = -\frac{3M_{\rm out}}{4(M_1 + M_2)} \left(\frac{a_{\rm in}}{a_{\rm out}}\right)^3 \cos I\ n.$$

Felce & Fuller 23







Constraints on the orbit of the third Star

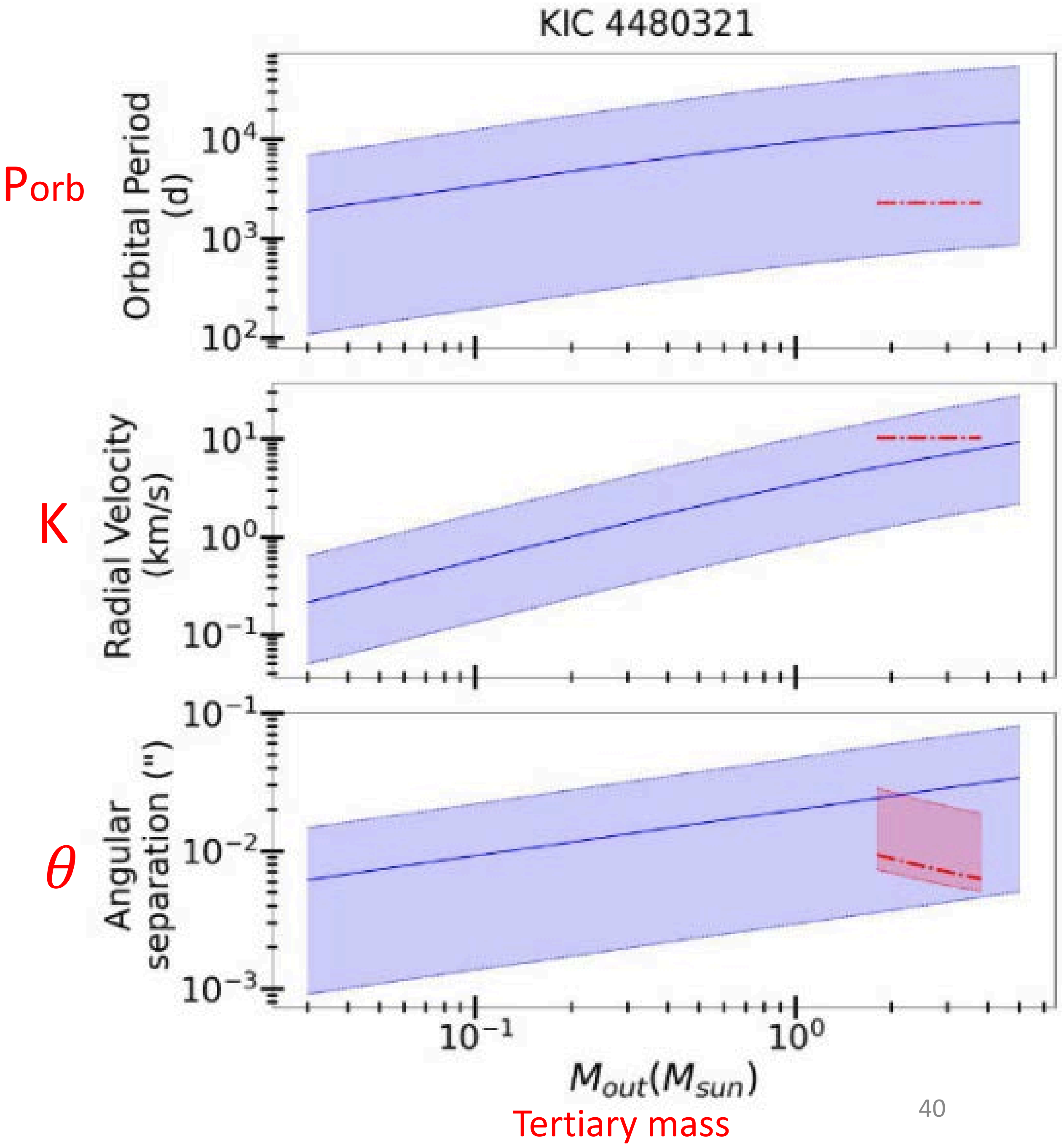
Assuming Cassini State 2:

$$a_{\rm out} = \left(\frac{3k}{2k_2} \frac{M_{\rm out} M_1}{M_2(M_1+M_2)} \frac{a^6}{R^3} \frac{\cos I}{\eta_{sync}} \right)^{1/3}. \quad (46)$$

The projected radial velocity of the inner binary about the tertiary system's centre of mass is

$$K_{12} = m_{\rm out} \sin i \sqrt{\frac{G}{a_{\rm out}(m_{\rm out}+M_1+M_2)}}. \quad (47)$$

Felce & Fuller 2023



(Weakly) Nonlinear TEOs

damping linear tide non-linear tide ~ cancel with equil. tide

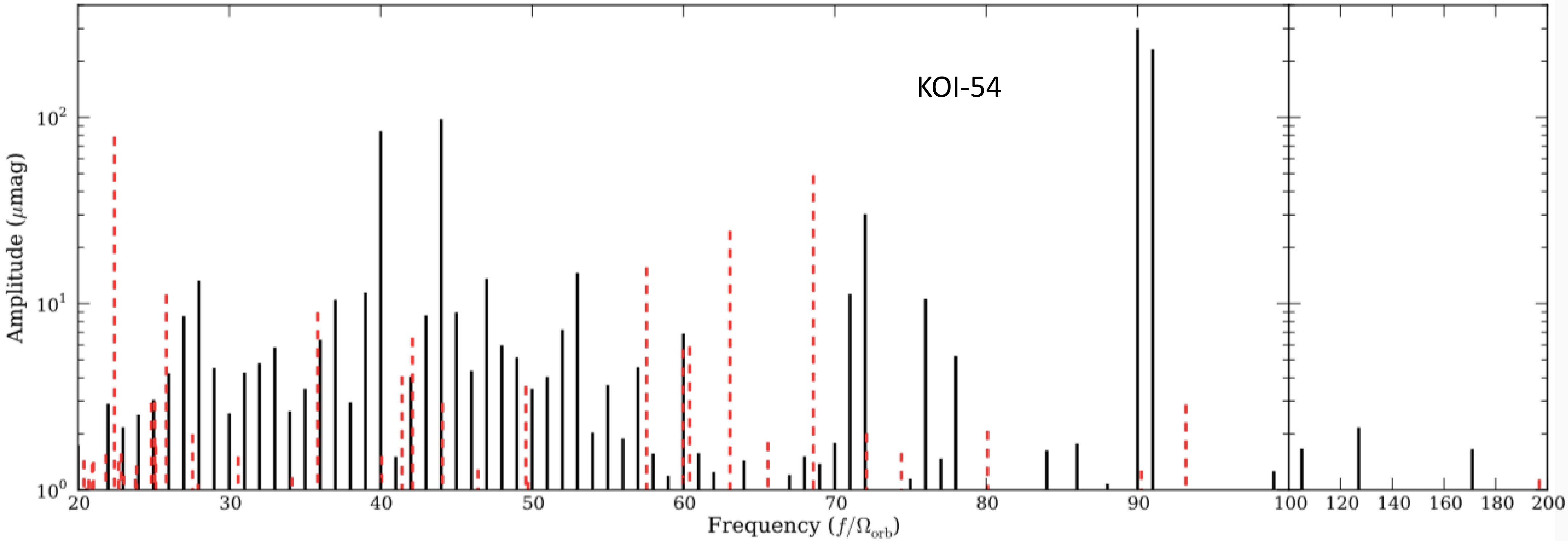
$$\dot{q}_a + i\omega_a q_a = -\gamma_a q_a + i\omega_a U_a(t) + i\omega_a \sum_b U^*_{ab}(t) q^*_b$$

$$+ i\omega_a \sum_{bc} \kappa^*_{abc} q^*_b q^*_c .$$

+ High Order Terms … …

three-mode coupling

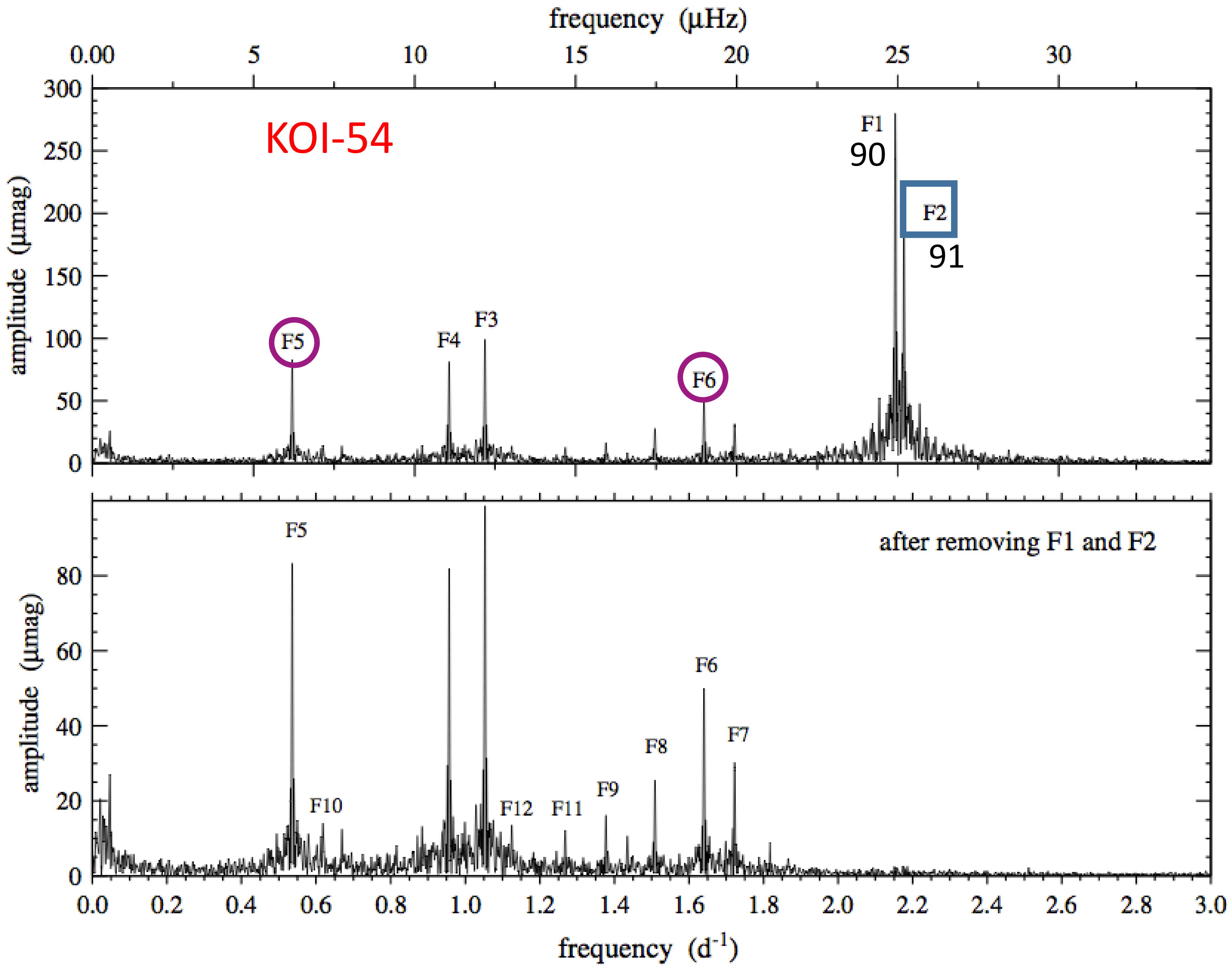
Weinberg+12



Oleary & Burkart 14

Black: orbital harmonic TEOs (excited by linear dynamical tide)

Red: non-orbital harmonic TEOs (non-linear mode coupling)

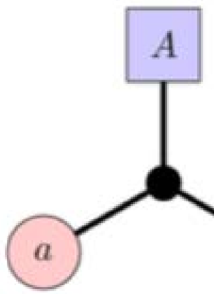


Parent mode = 91 orbital harmonic

linearly driven by tide, it has

Four pairs of daughter modes:

fA = fa + fb   resonance condition



=91*forb

... ...

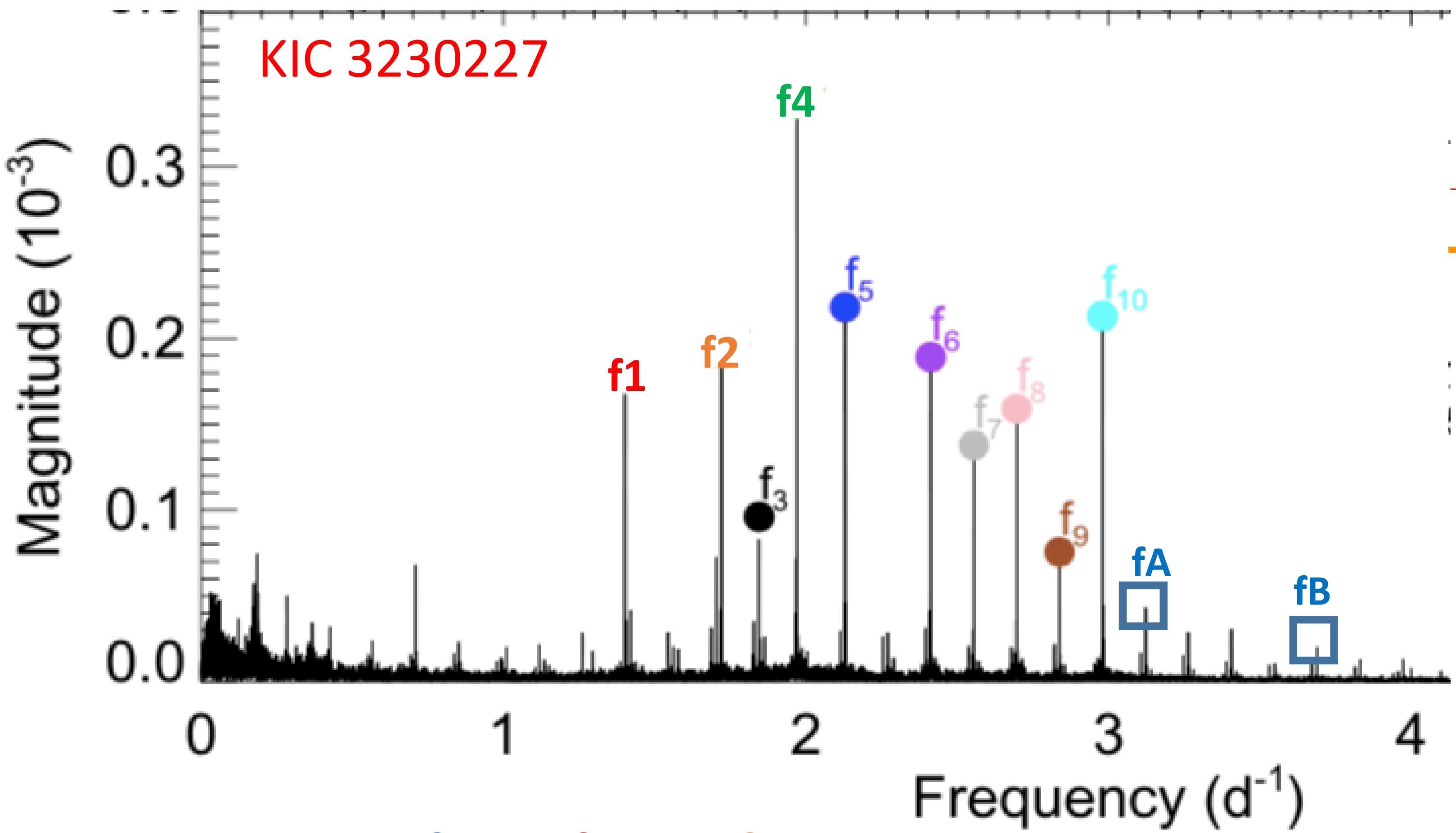
F2 (=91*forb)
= F5 + F6
= F8 + F100
= F25 + F76
= F39 + F42

fA has larger amplitude, than daughter modes (fa, fb) =(F5, F6)

F5 22.419 **F25** 60.419 **F39** 41.417
F6 68.582 **F76** 30.587 **F42** 49.589

F8 63.076
F100 27.929

O'Leary &Burkart 2014



		Frequency	N forb
fa	f_1	1.40214 ± 0.00002	$9.88 f_{orb}$
fb	f_2	1.71988 ± 0.00002	$12.12 f_{orb}$
	f_3	1.84482 ± 0.00002	$13 f_{orb}$
fd	f_4	1.969765 ± 0.000008	$13.88 f_{orb}$
	f_5	2.12855 ± 0.00001	$15 f_{orb}$
	f_6	2.41235 ± 0.00001	$17 f_{orb}$
	f_7	2.55425 ± 0.00002	$18 f_{orb}$
	f_8	2.69615 ± 0.00002	$19 f_{orb}$
	f_9	2.83805 ± 0.00002	$20 f_{orb}$
	f_{10}	2.979948 ± 0.000008	$21 f_{orb}$

fA = 22 forb

fB = 26 forb

Selection Rules:

fA = f1 + f2

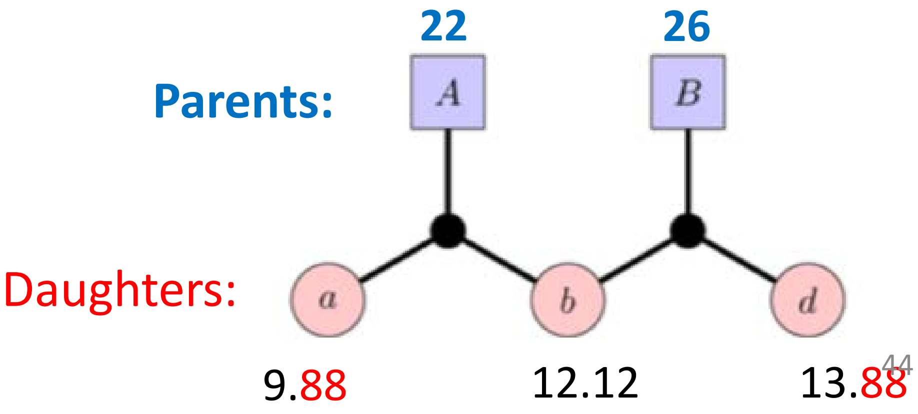
fB = f4 + f2

$$m_A = m_a + m_b,$$

$$\mathrm{mod}(l_A + l_a + l_b, 2) = 0,$$

and

$$|l_a - l_b| \le l_A < l_a + l_b.$$

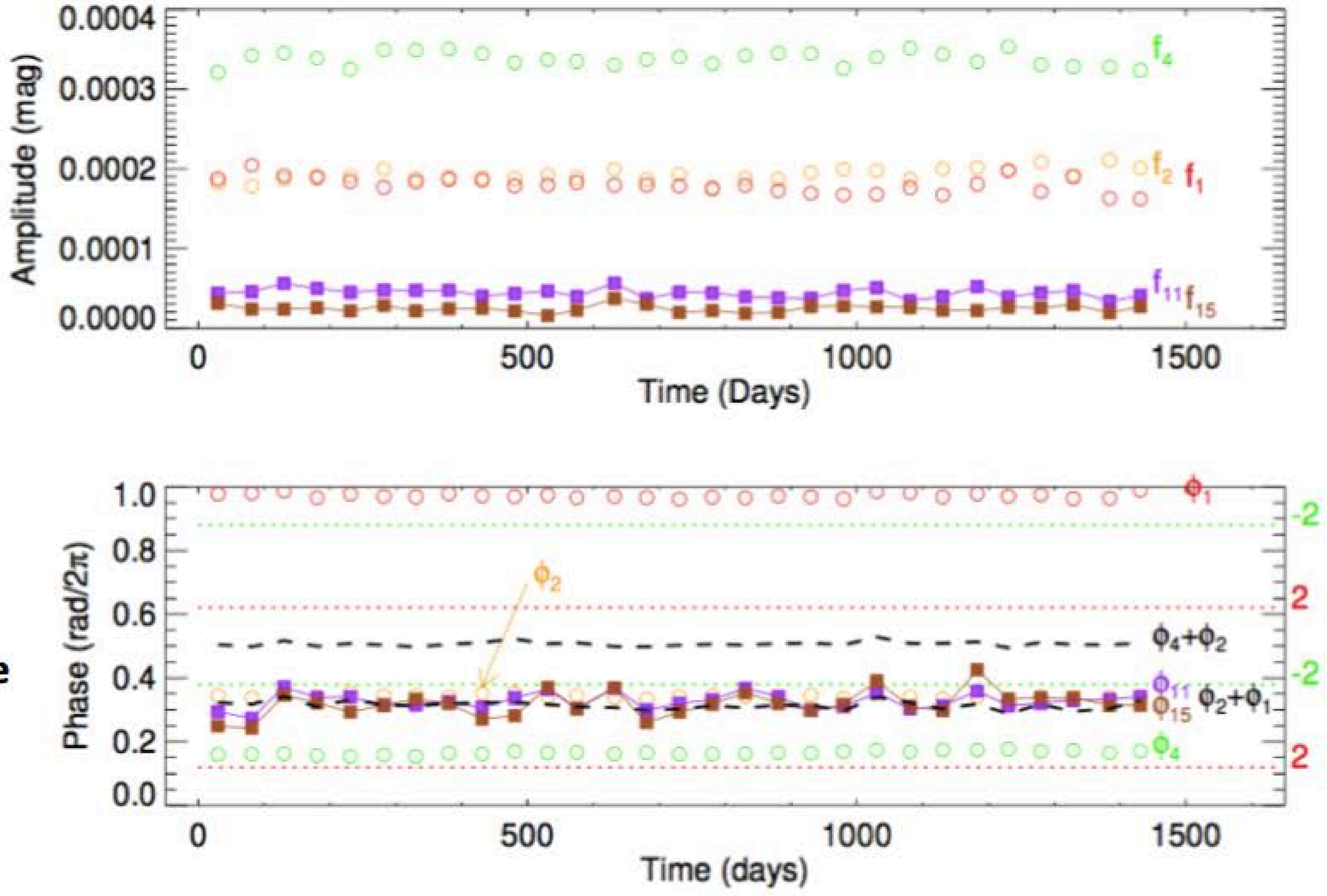


Guo+17,20

Amplitude

Temporal variations (4yr Kepler+ 1yr TESS)

Phase



Mode coupling in ***a steady state*** or *limit cycle* ?

Two parent modes: **F15**, **F11**

3 Daughter modes: **f1**, **f2**, **f4**

Amplitude/Phase Stable over 4 yrs

Guo2020

Three-mode Coupling: (a, b, c) = (f11, f2, f1)

Parent mode self-excited

Parent mode driven by tide

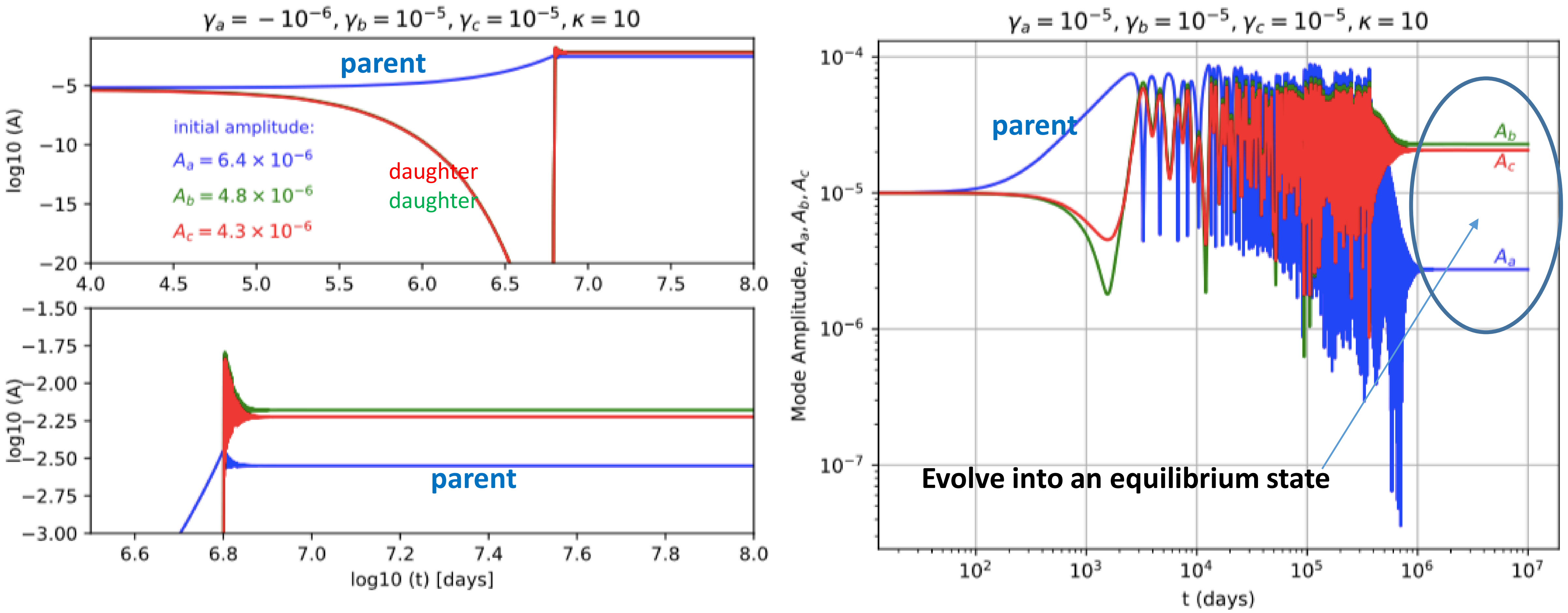
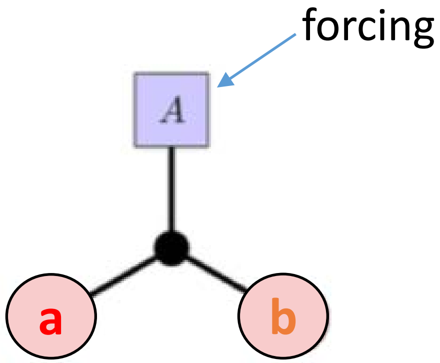
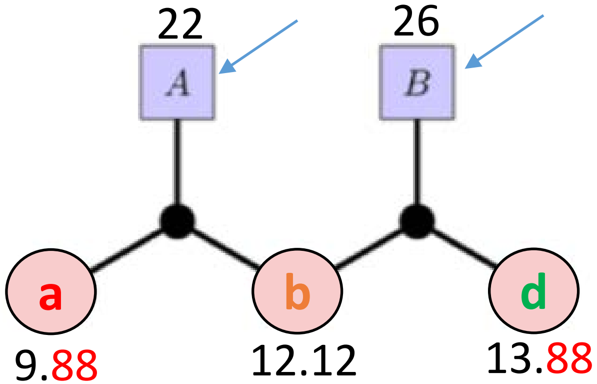


Figure 3. Mode amplitude evolution of a three-mode system representing the observed g-mode triplet in KIC 3230227: $(f_a, f_b, f_c) = (f_{11}, f_2, f_1)$. Left: Parent mode is self-excited, with $\gamma_a < 0$; Right: Parent mode is stable ($\gamma_a > 0$), but driven by a tidal term $U_a e^{-i\omega t}$, with ω being an orbital harmonic ($=22 f_{\rm orb}$). In both cases, the three-mode system settles into an equilibrium state.

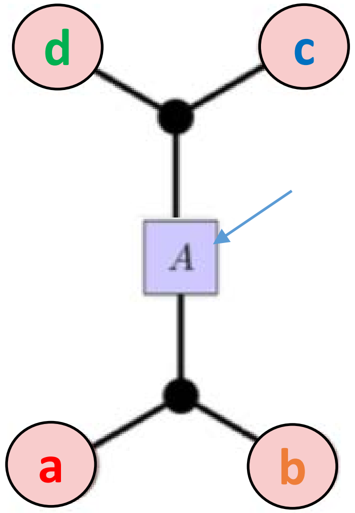
Guo2020



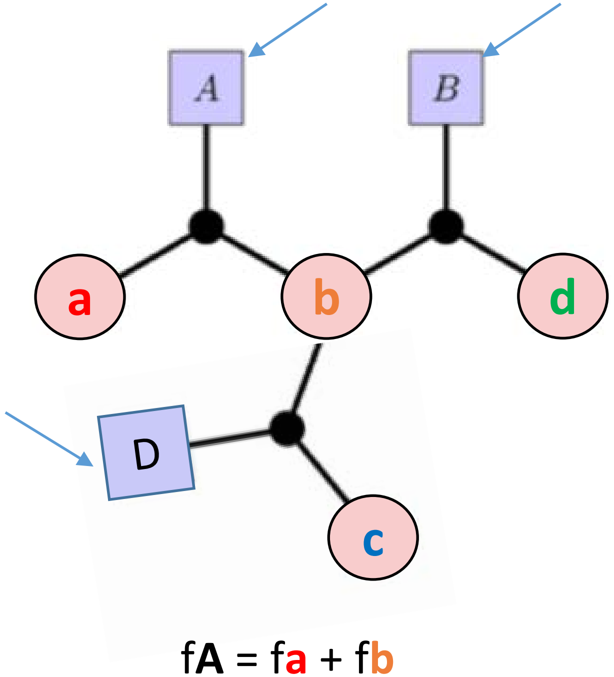
fA = fa + fb



fA = fa + fb
fB = fd + fb



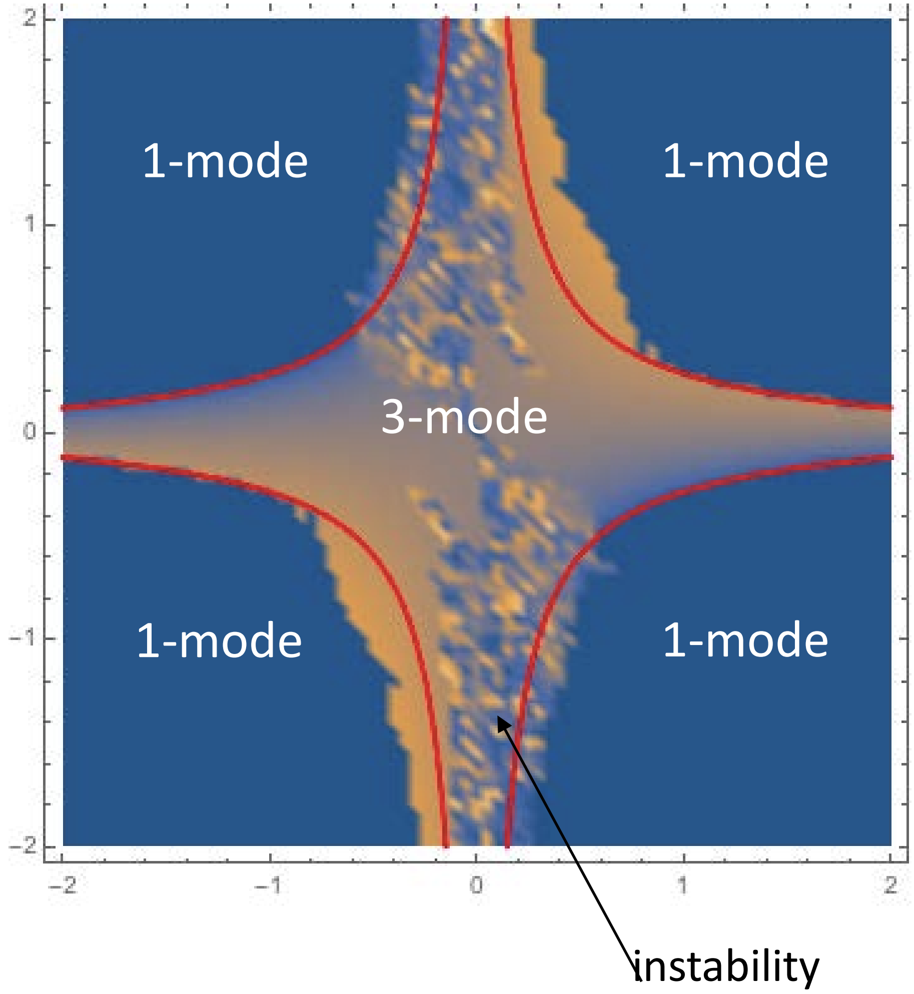
fA = fa + fb
fA = fc + fd



fA = fa + fb
fB = fd + fb
fD = fc + fb

2nd-order coupling

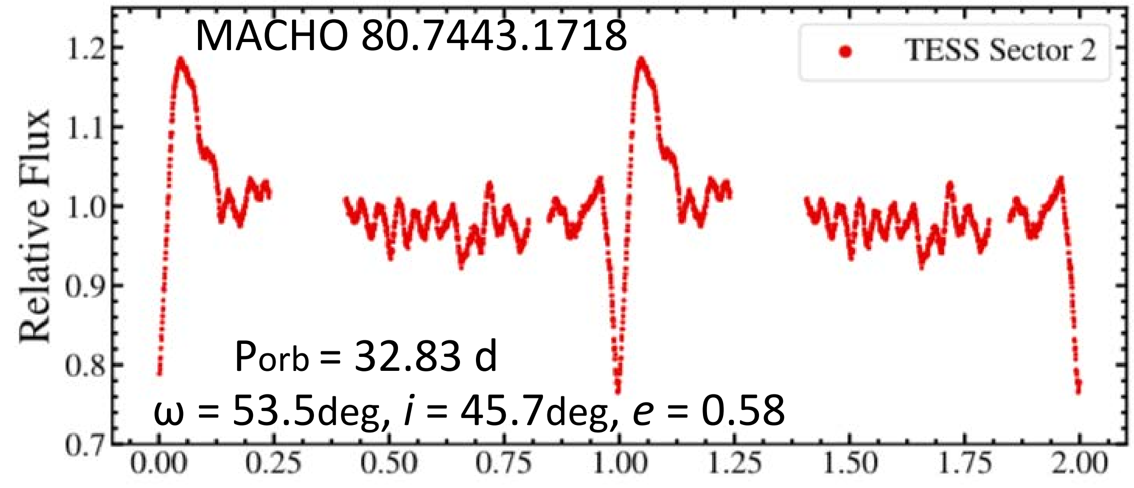
Forced 3-mode coupling system

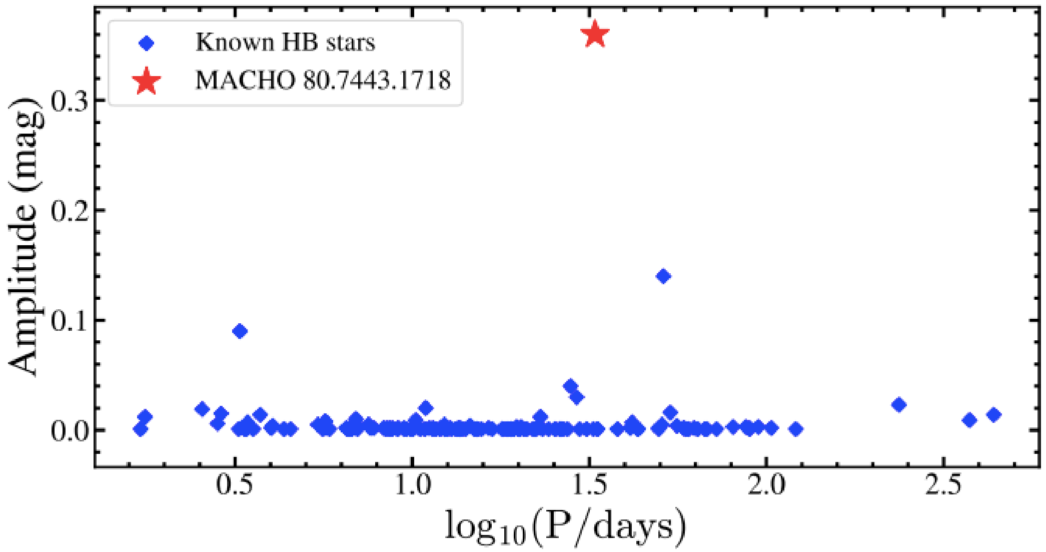


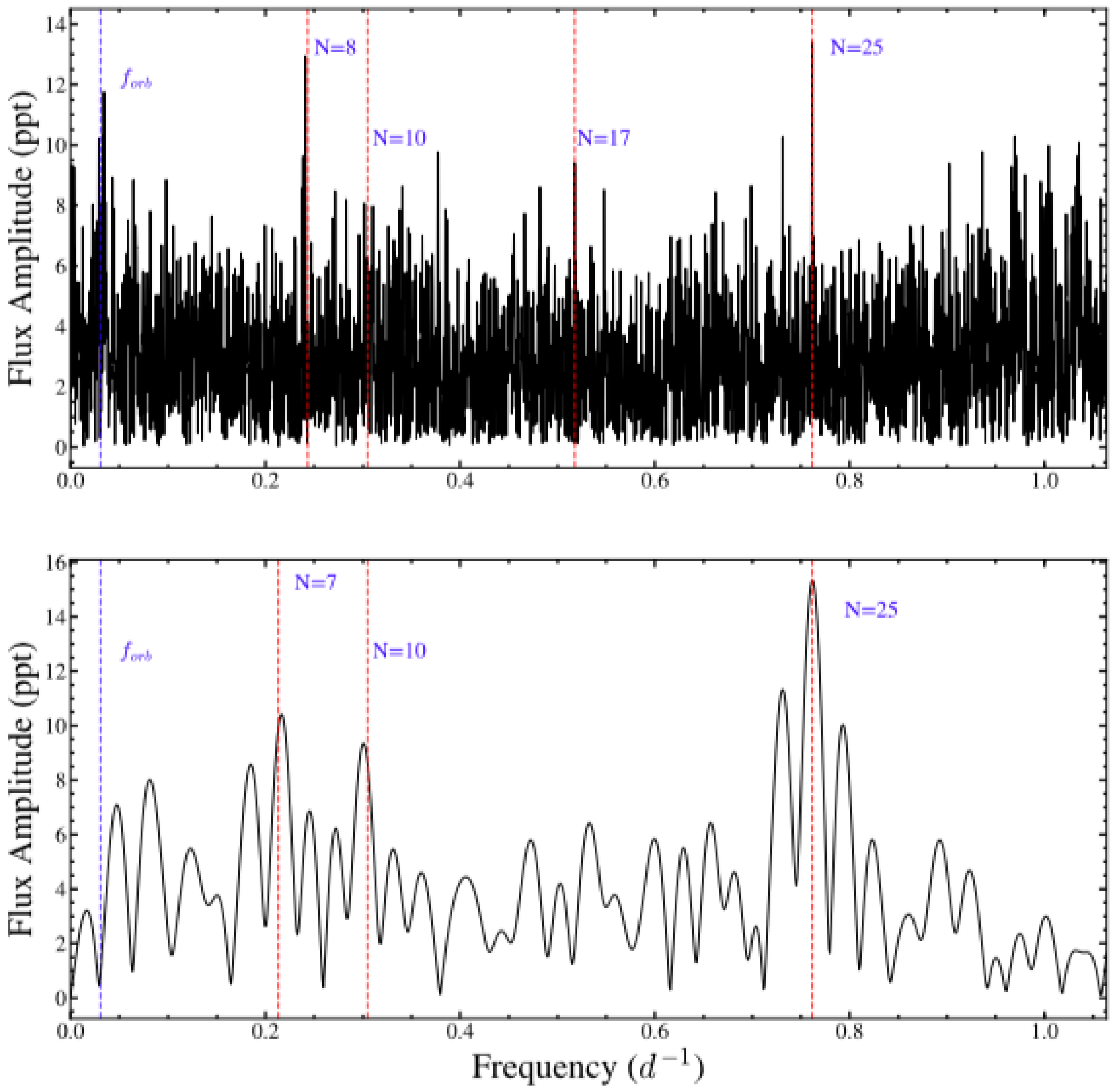
Limit cycle, Period doubling, chaotic;
Hysterisis

Notable HB systems

Heartbeat Star with the largest TEO amplitude



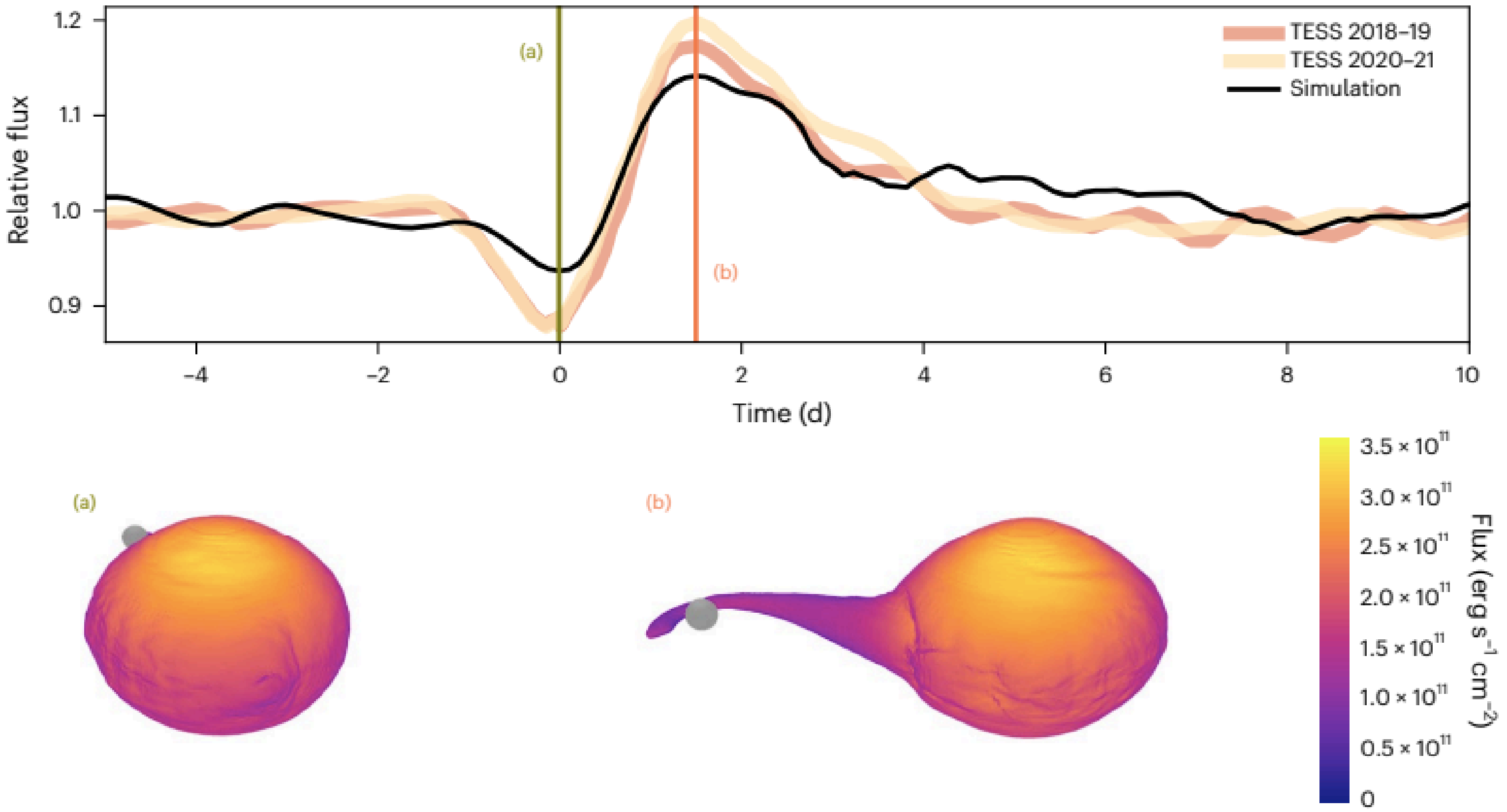


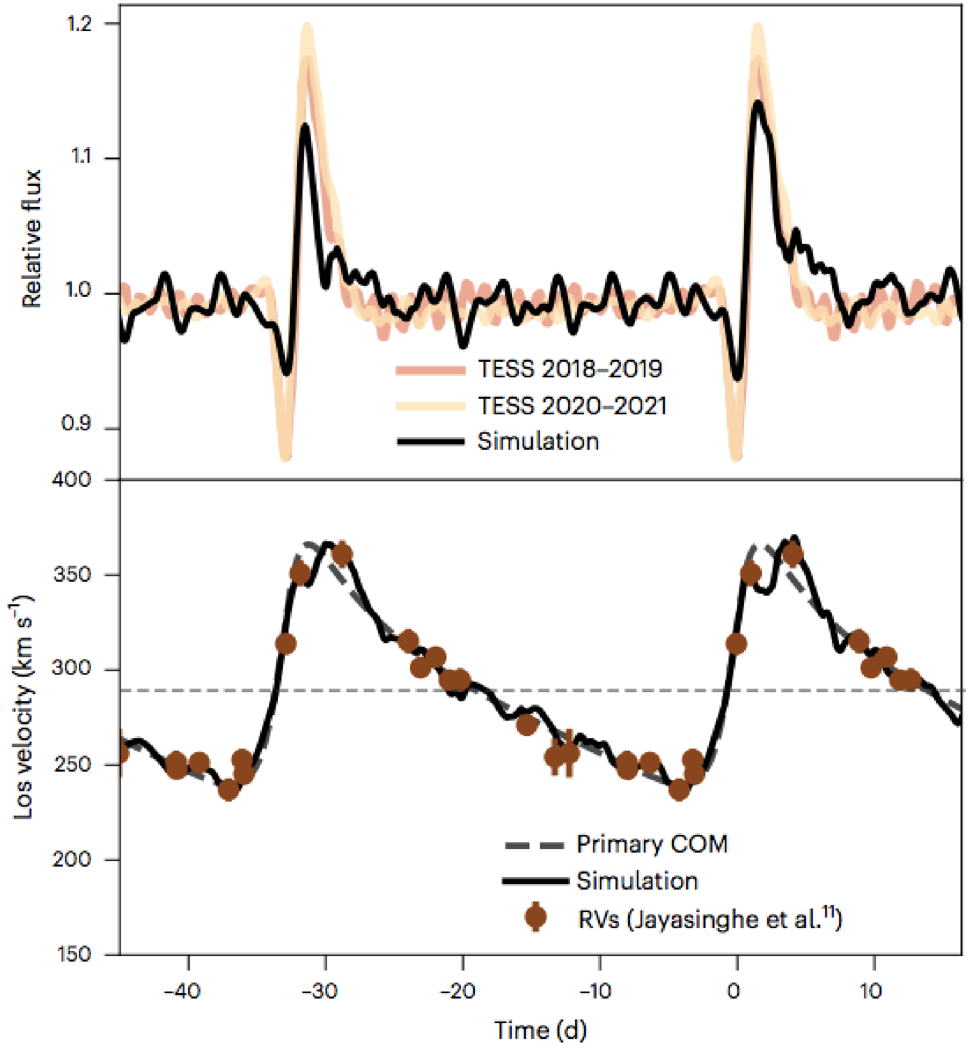


Jayasinghe+ 2019

M~ 35, R~24 (solar)

From Heartbeat to Heartbreak?





Macleod & Loeb 23

Jayasinghe +19,21; Kolaczek-Szymanski+22,24; Macleod 23;

M1~ 35, R1~24 (solar units)

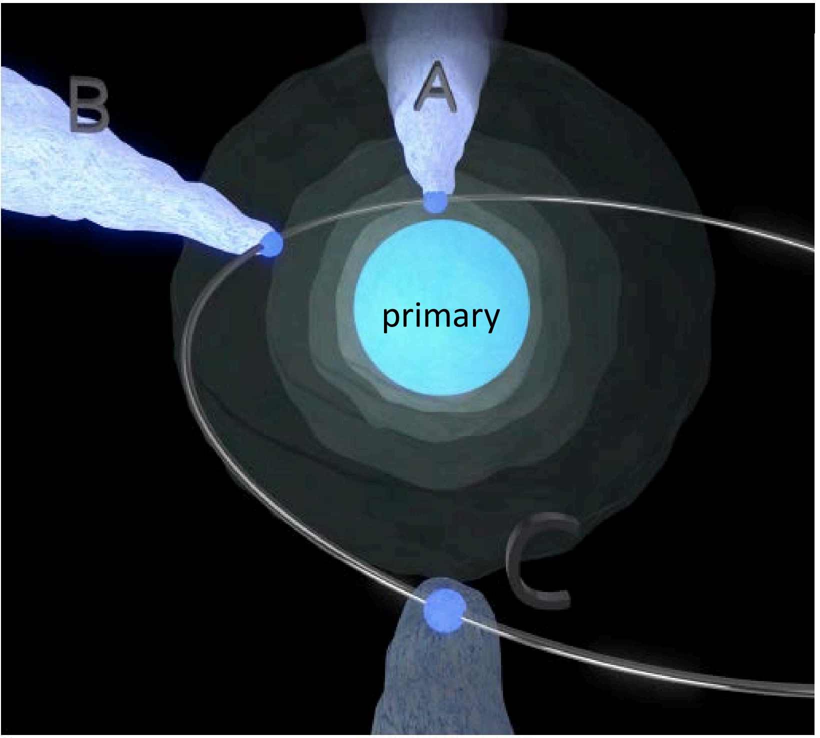


Fig. 12. Artistic representation of the orbit (silver ellipse) of the secondary component of ExtEV (dark blue circle) around the primary component (light blue circle near the center). The size of the orbit and both components are to scale. The orientation of the orbit corresponds to the view of the ExtEV in the sky (i.e., as seen by the observer on Earth). The primary component is the source of a slow but dense stellar wind (semi-transparent spheres, concentric with the primary component), which, after colliding with the surface of the wind of the secondary component, forms a WWC cone, a turbulent structure, with its apex located near the secondary component. Three orbital phases are labeled, corresponding to: the superior conjunction (A), periastron passage (B), and inferior conjunction (C). More details can be found in the main text.

Kolaczek-Szymanski+ 23

No wave breaking!

large amplitude explained by
Wind-Wind Collision cone (WWC)

Summary

Tidal Dissipation: Equilibrium tide vs. Dynamical Tide
(turbulent viscosity) (Inertial Wave, Internal Gravity Wave)
IGW -> Normal modes -> TEOs

TEO Amplitude, Phases, Orbital-harmonic Number
mode-decomposition vs direct solving
The effect of rotation
Resonance locking
Non-adiabaticity: GYRE-tide (pseudo-syn. blurring)

Stellar spins in HBs
very slow rotators/misaligned systems -> Triple -> Cassini State 2
HB apsidal motion/orbital decay ->Triple

Nonlinear TEOs
seismology with daughter modes only
coupling networks

Thank you very much for your attention!

Notable HB Systems (WWC cone ~ resemble heartbeat feature)