Tidal Dissipation in Binaries

From Merging White Dwarfs to Exoplanetary Systems

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Tidal Dissipation in Binaries

I. Merging White Dwarf Binaries

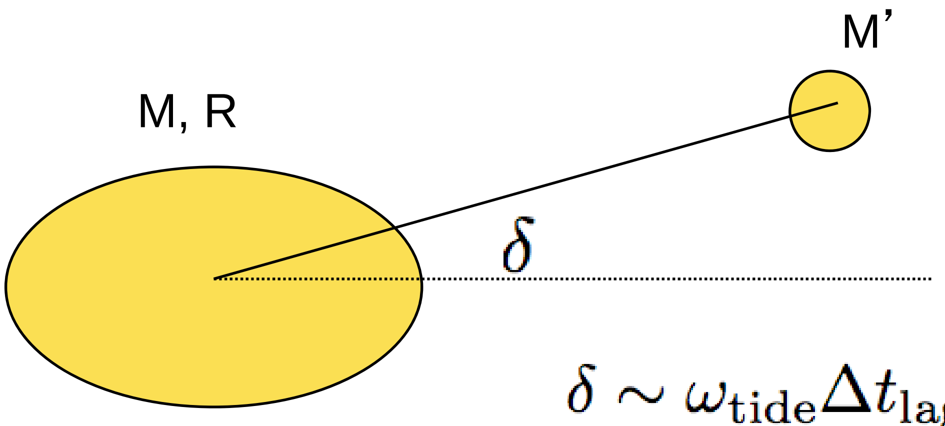
II. Kepler Heartbeat Stars (KOI-54)

III. Exoplanetary Systems

(a) Hot Jupiters

(b) Host Stars

Equilibrium Tide



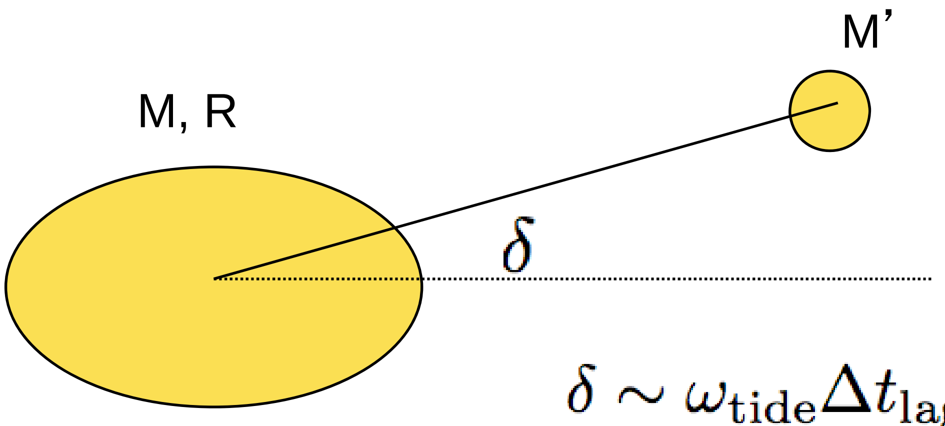
$$\delta \sim \omega_{\rm tide} \Delta t_{\rm lag} \sim 1/Q$$

$$\omega_{\rm tide} = 2(\Omega_{\rm orb} - \Omega_s)$$

$$\mathrm{Torque} \sim G \left(\frac{M'}{a^3} \right)^2 R^5 \, \frac{k_2}{Q}$$

$$k_2 = \mathrm{Love\ Number}$$

Equilibrium Tide



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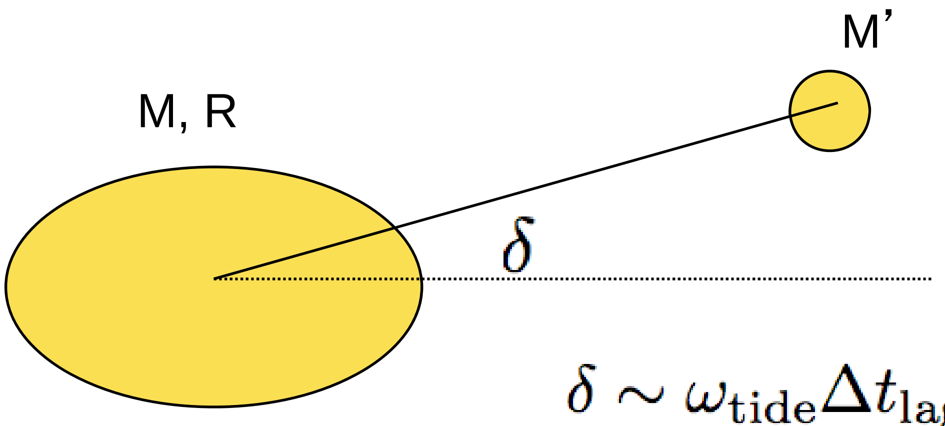
Weak friction theory: $\Delta t_{\rm lag} \sim (\omega_{\rm dyn}^2 t_{\rm visc})^{-1} = \text{const}$

Equilibrium Tide



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Problems:

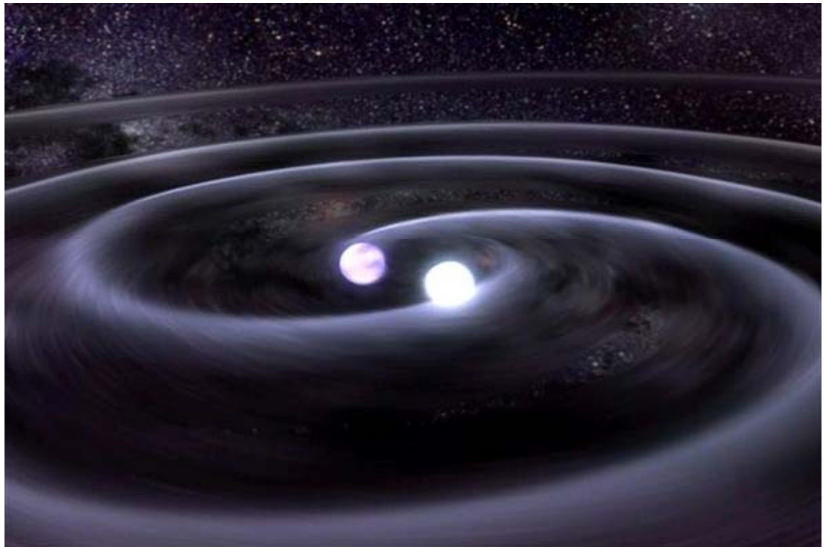
-- Parameterized theory

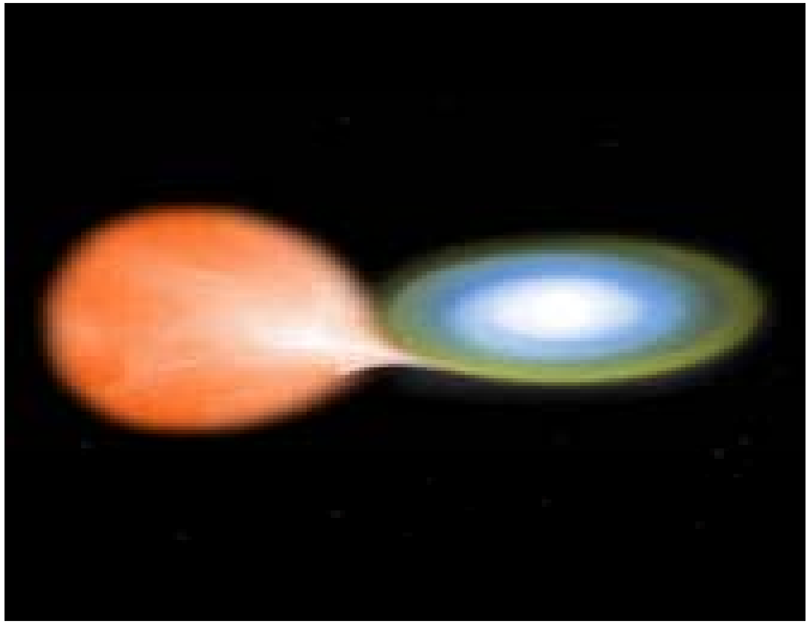
-- The physics of tidal dissipation is more complex:

Excitation/damping of internal waves/modes (Dynamical Tides)

-- For some applications, the parameterization is misleading

Compact White Dwarf Binaries (mins - hour)





-- Dominant sources of gravitational waves (10^{-4}-0.1 Hz)

Space interferometer (eLISA-NGO??)

-- Lead to various outcomes:

R CrB stars, AM CVn binaries, transients

If total mass ~ $1.4M_{sun}$: AIC => NS or SN Ia

Dynamical Tides in Compact WD Binaries

with Jim Fuller
(Ph.D. 2013 → Caltech)

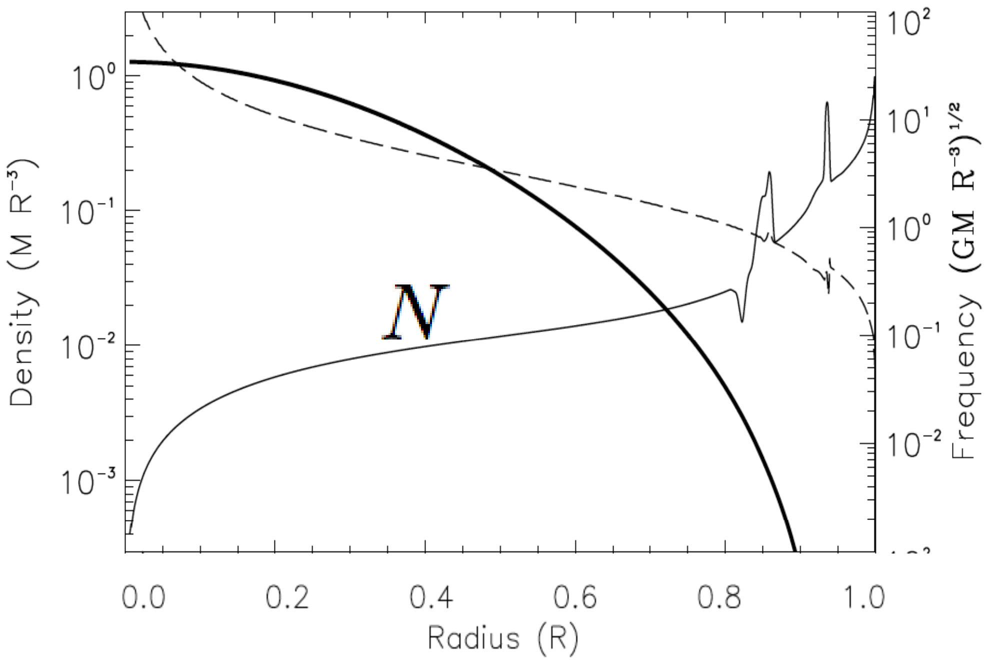
Issues:

-- Spin-orbit synchronization?

-- Tidal dissipation and heating?

-- Effect on orbital decay rate? (e.g. eLISA-NGO)

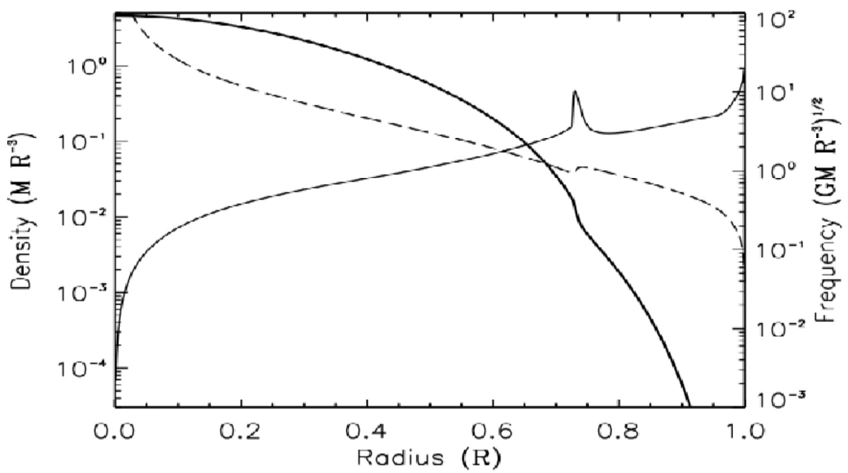
White Dwarf Propagation Diagram



N = Local Buoyancy Freq

CO WD

$0.6 M_{\odot},\ 8720\,\mathrm{K}$



He-core WD

$0.3 M_{\odot},\ 12000\,\mathrm{K}$

“Continuous” Excitation of Gravity Waves

Waves are excited in the interior/envelope, propagate outwards
and dissipate near surface

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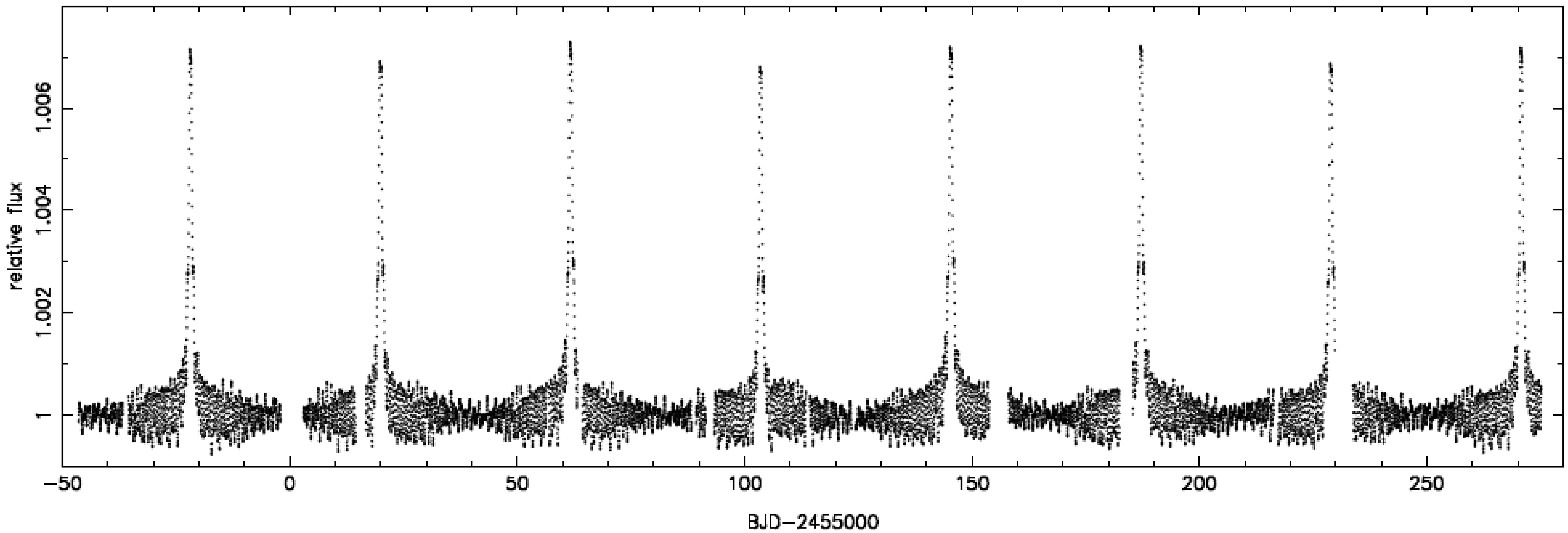
“Heartbeat Stars”

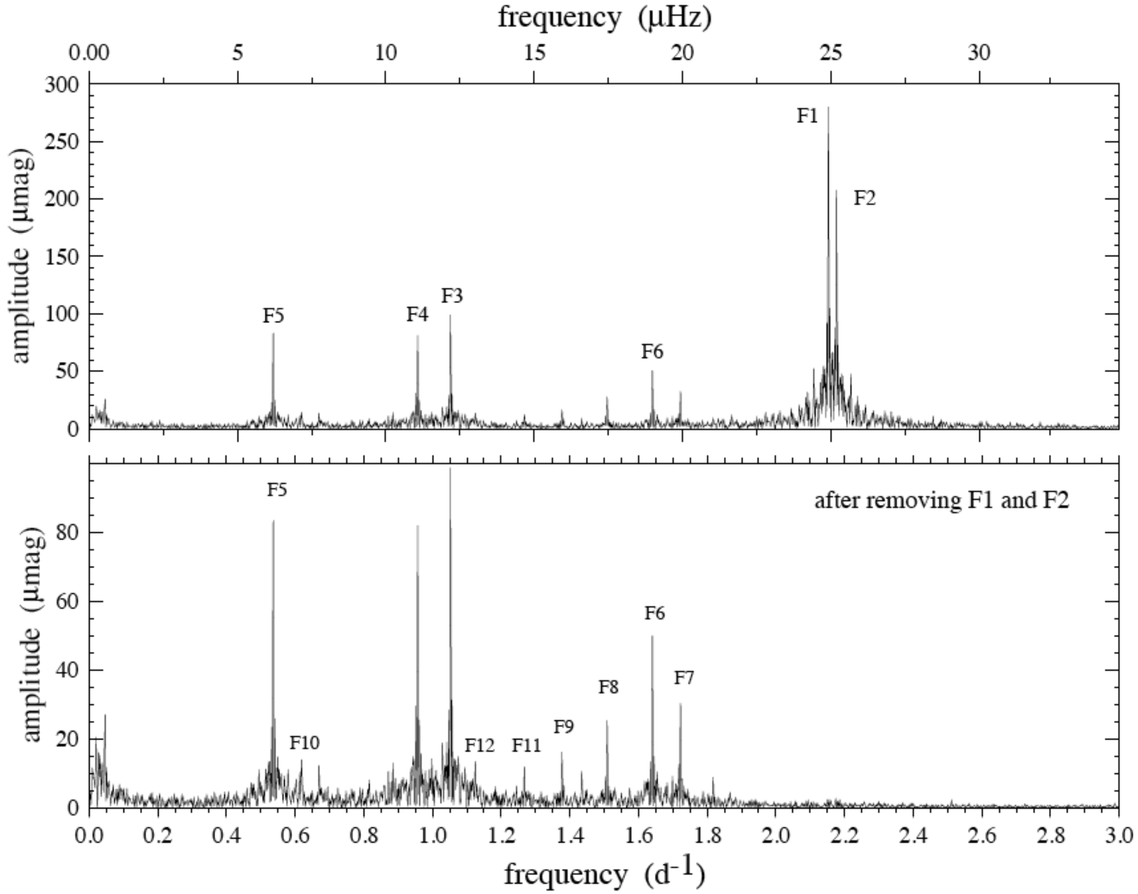
Tidally Excited Oscillations in Eccentric Binaries

KOI-54a,b Binary

Welsh et al 2012

A-type stars: 2.32, 2.38 M_{sun}
P=42 days, e=0.834, face-on (5.5 deg)
--> At periastron: $a_p = 6.5R, \quad f_p = 20 f_{\rm orb}$





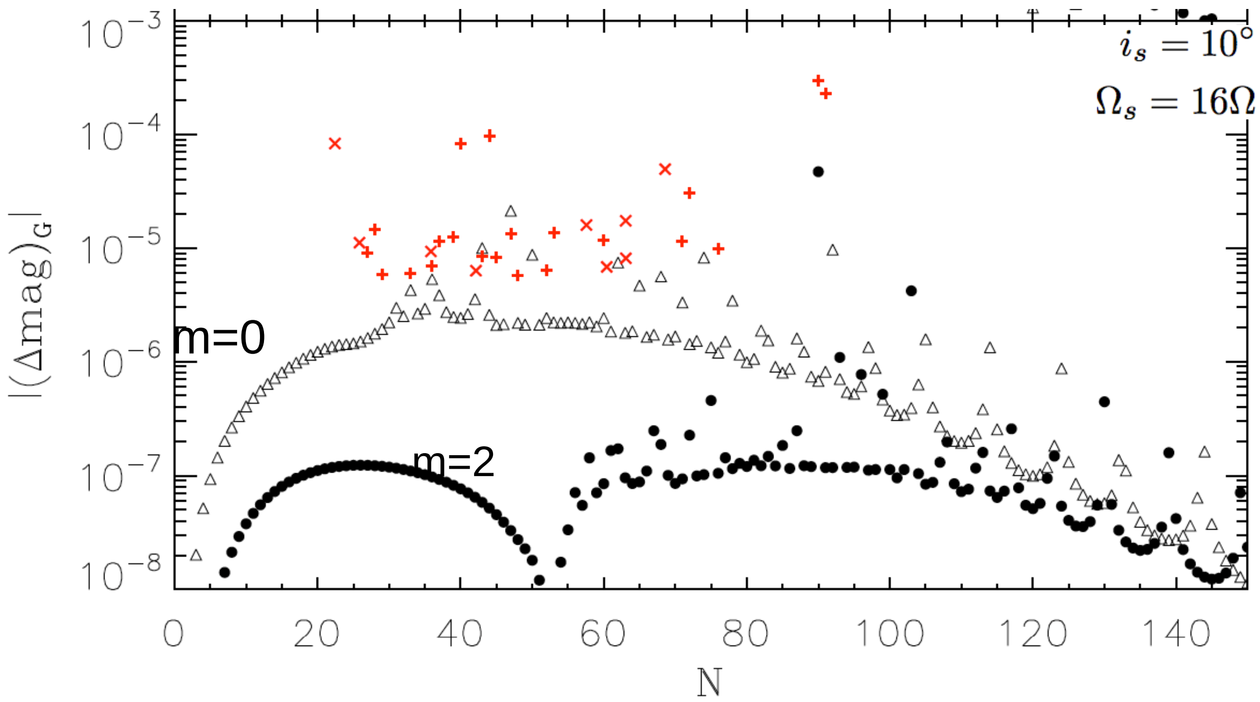
30 pulsations (21 are integer $\times f_{\rm orb}$)

$22.42 f_{\rm orb} \rightarrow 91 f_{\rm orb}$

Welsh et al 2012

amplitude (μmag)	f/f_{orbit}
297.7	90.00
229.4	91.00
97.2	44.00
82.9	40.00
82.9	22.42
49.3	68.58
30.2	72.00
17.3	63.07
15.9	57.58
14.6	28.00
13.6	53.00
13.4	46.99
12.5	39.00
11.6	59.99
11.5	37.00
11.4	71.00
11.1	25.85
9.8	75.99
9.3	35.84
9.1	27.00
8.4	42.99
8.3	45.01
8.1	63.09
6.9	35.99
6.8	60.42
6.4	52.00
6.3	42.13
5.9	33.00
5.8	29.00
5.7	48.00

Tidally Forced Oscillations: Flux Variations



Fuller & DL 2012

Most of the observed flux variations are explained by m=0 modes (more visible for near face-on orientation)

Variations at 90,91 harmonics require very close resonances $(N\Omega = \omega_\alpha)$

Non-Linear Mode Coupling

- 9 oscillations detected at non-integer multiples of orbital frequencies

- Could be produced by nonlinear coupling to daughter modes

$$\omega_p = \omega_{d1} + \omega_{d2}$$

- In KOI-54,

$$\frac{\omega_2}{\Omega} = 91.00 \qquad \frac{\omega_5}{\Omega} = 22.42 \qquad \frac{\omega_6}{\Omega} = 68.58$$

- Other non-integer modes likely due to nonlinear coupling in which one of the daughter modes is invisible

Recent work: O'Leary & Burkart 2013

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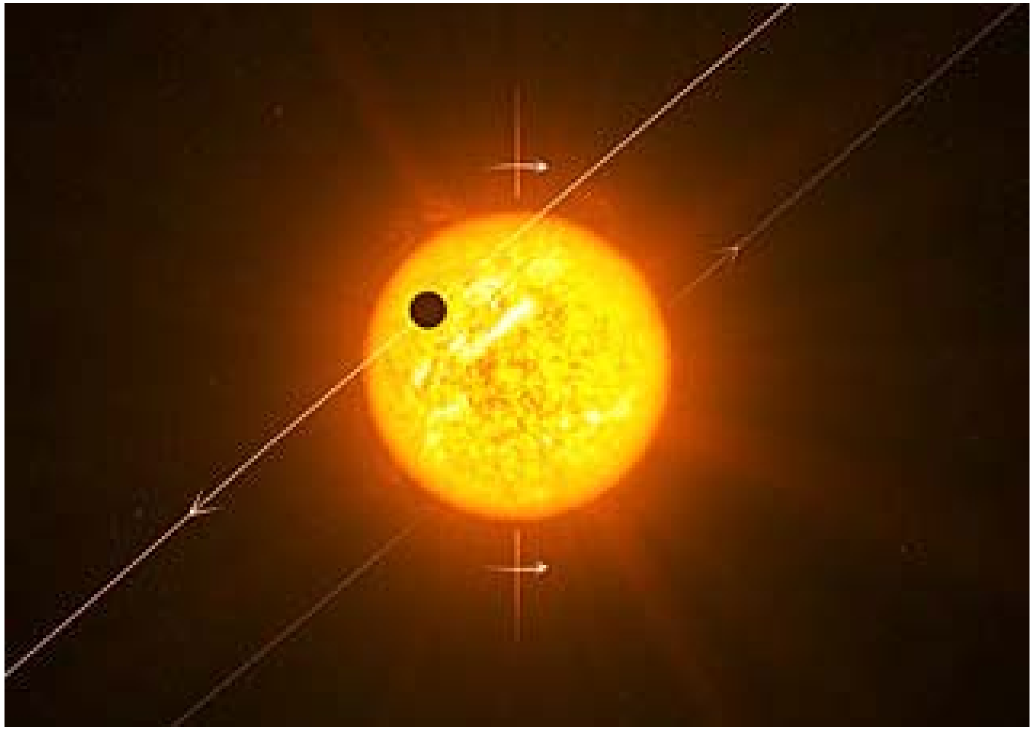
Tides in Exoplanetary Systems



S^*-L_p misalignment in Exoplanetary Systems
➔ The Importance of few-body interactions

"High-Eccentricty Migration"

-- Planet forms at a few AUs

-- Interaction with another body pumps it into high-e/inclined orbit

-- Tidal dissipation on planet circularizes the orbit

-- "Chaos" in spin evolution ! (Storch, Anderson & DL 2014)

High-e Migration requires
tidal dissipation in giant planets

Tidal Q of Solar System Planets

Measured/constrained by orbital evolution of their satellites
(Goldreich & Soter 1966, Peale …)

Jupiter:

$$6 \times 10^4 \lesssim Q \lesssim 2 \times 10^6$$

$$Q \simeq 4 \times 10^4$$ (Lainey et al. 2009) $$P_{\rm tide} = 6.5 \text{ hr}$$

Saturn:

$$2 \times 10^4 \lesssim Q \lesssim 10^5$$

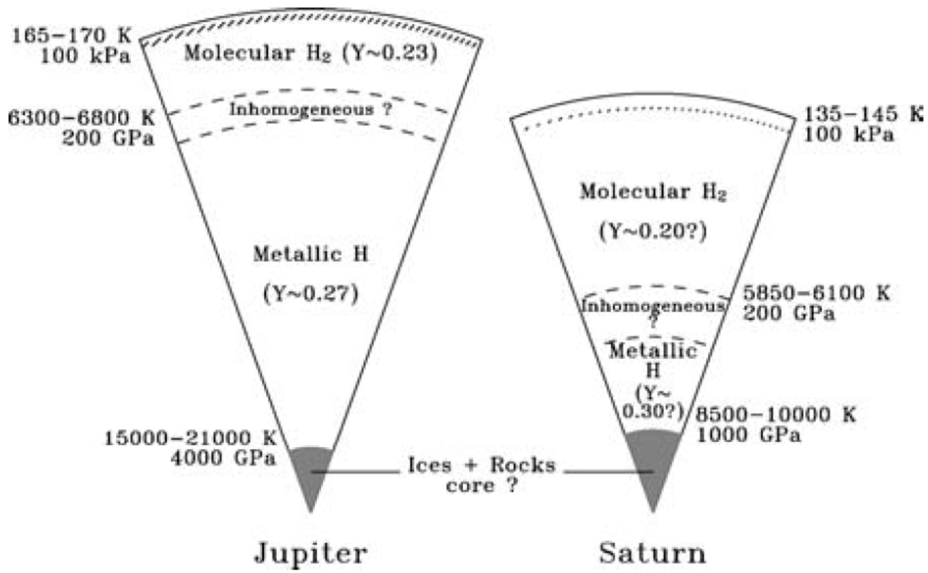
$$Q = (1-2) \times 10^3$$ (Lainey et al. 2012) $$P_{\rm tide} \simeq 5.8 - 7.8 \,\text{hrs}$$

Theory of Tidal Q of Giant Planets

-- Viscous (turbulent) dissipation of equilibrium tide in convective envelope ➔ $Q>10^{13}$
(Goldreich & Nicholson'77)

-- Gravity waves in outer radiative layer ➔ $Q>10^{10}$
(Lubow et al. 1997)

-- **Inertial waves**
(Ogilvie & Lin 2004,07; Ogilvie 2009,13; Goodman & Lackner 2009)



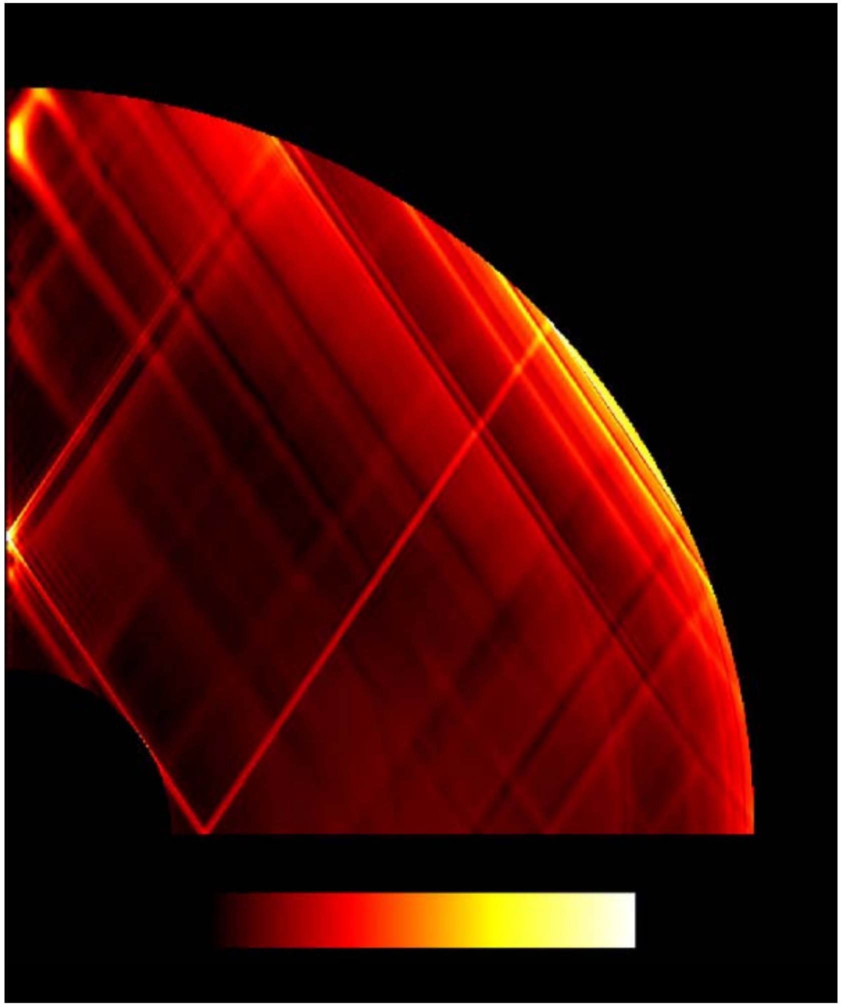
Inertial Waves in Rotating Fluid

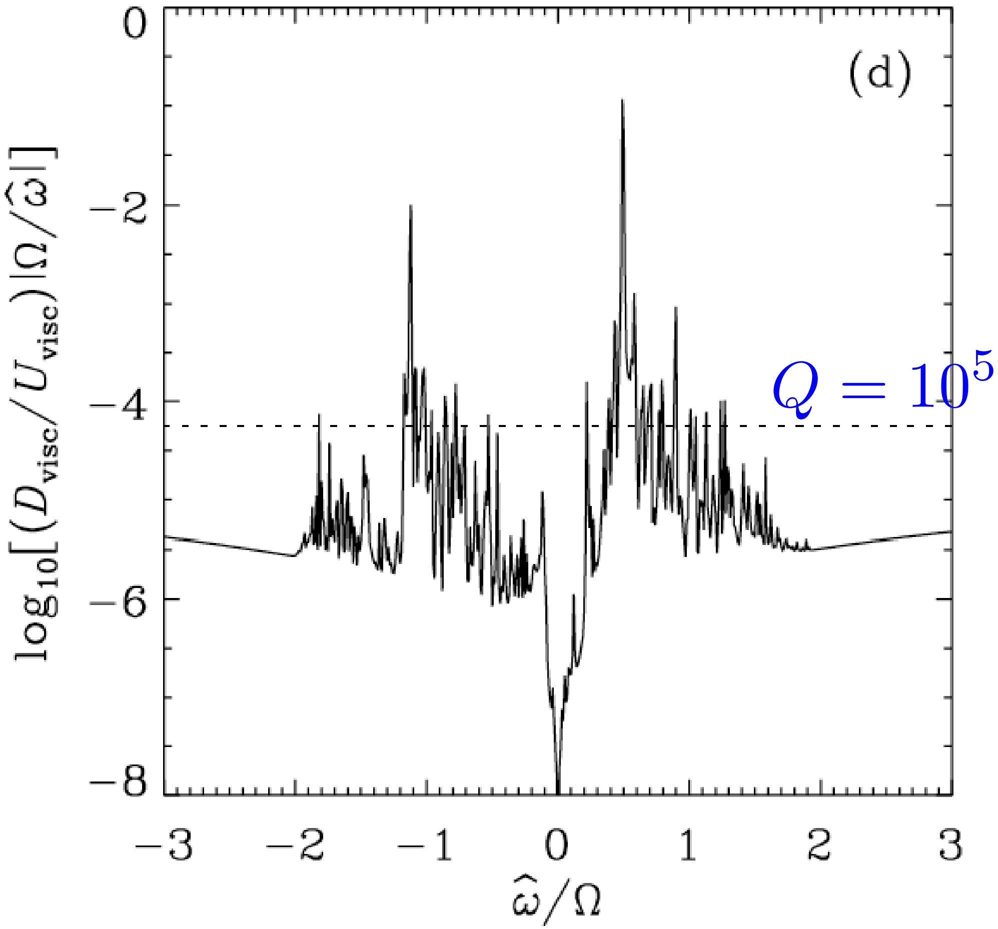
Dispersion relation (in rotating frame)

$$\omega = \pm 2\,\mathbf{\Omega}_s \cdot \hat{\mathbf{k}}$$

Can be excited if tidal forcing frequency satisfies

$$|\omega| < 2\Omega_s$$





Ogilvie & Lin 2004

Tidal Dissipation in High-e Migration: Phenomenological Approach

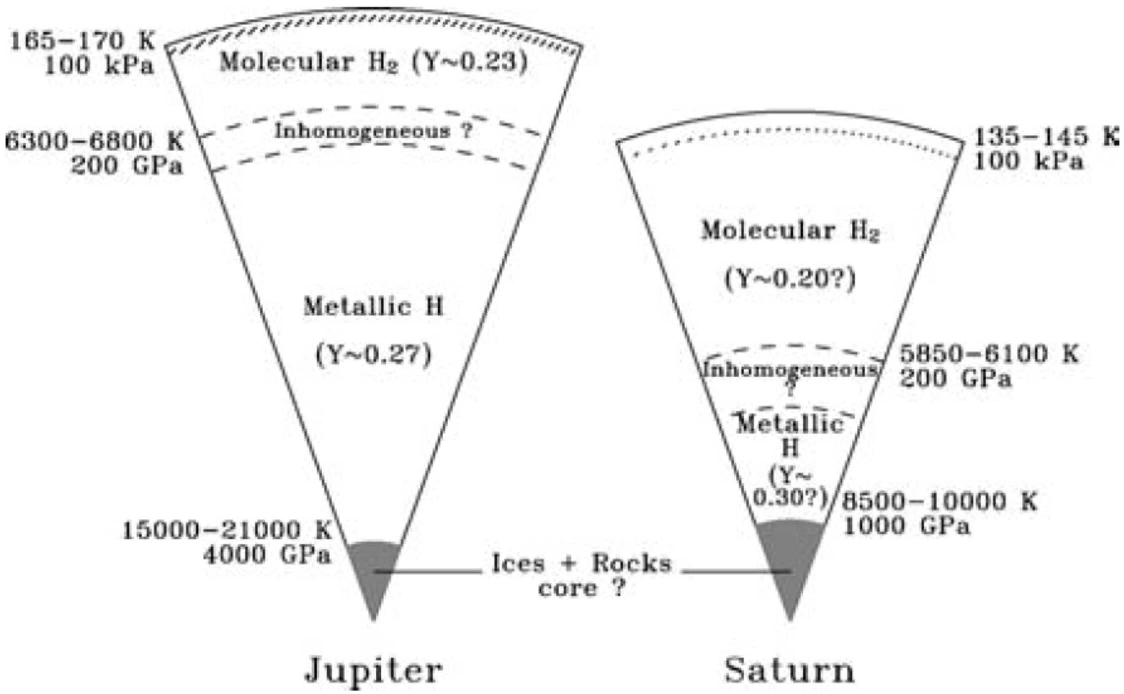
Using measured Q for Jupiter (6.5 hr), extrapolate to high-e (~5 days) using weak friction theory: (many papers…)

$$\delta \sim \omega_{\rm tide}\Delta t_{\rm lag} \sim 1/Q \qquad \text{with} \quad \Delta t_{\rm lag} = \mathrm{const}$$

➔ Hot Jupiters need to be >10 times more dissipative than our Jupiter (e.g., Socrates et al 2013)

Tidal Dissipation in Solid Core of Giant Planets

with Natalia Storch



Rocky/icy core: highly uncertain …

Can be important if $R_{\rm core} \gtrsim 0.1 R_p$

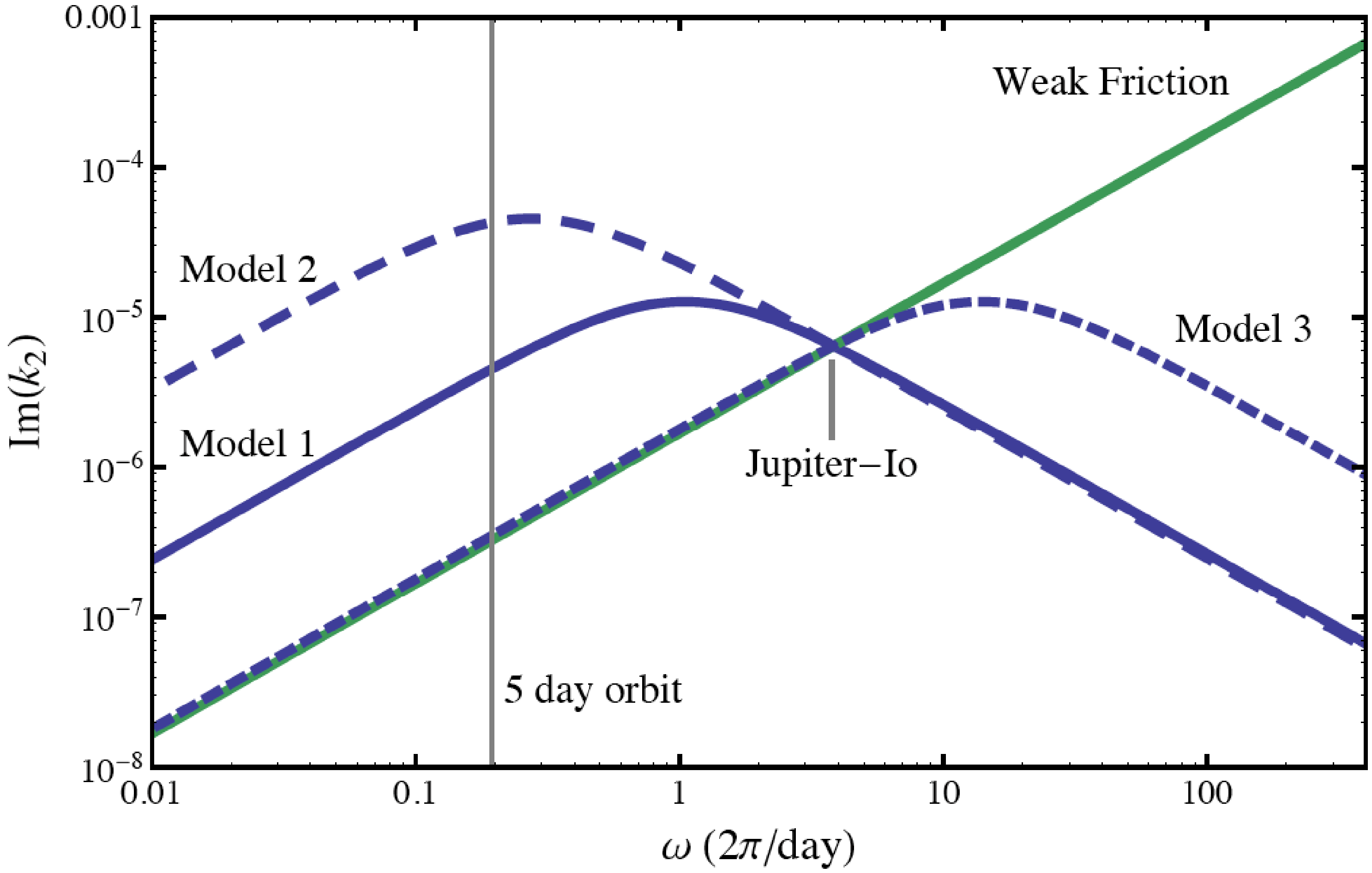
Fun Facts about rocks for non-geophysicists:

-- Rock is more dissipative than fluid:
stress → thermally activated creep/diffusion

-- Rock is both viscous fluid and elastic solid

Tidal response of Jupiter with visco-elastic core

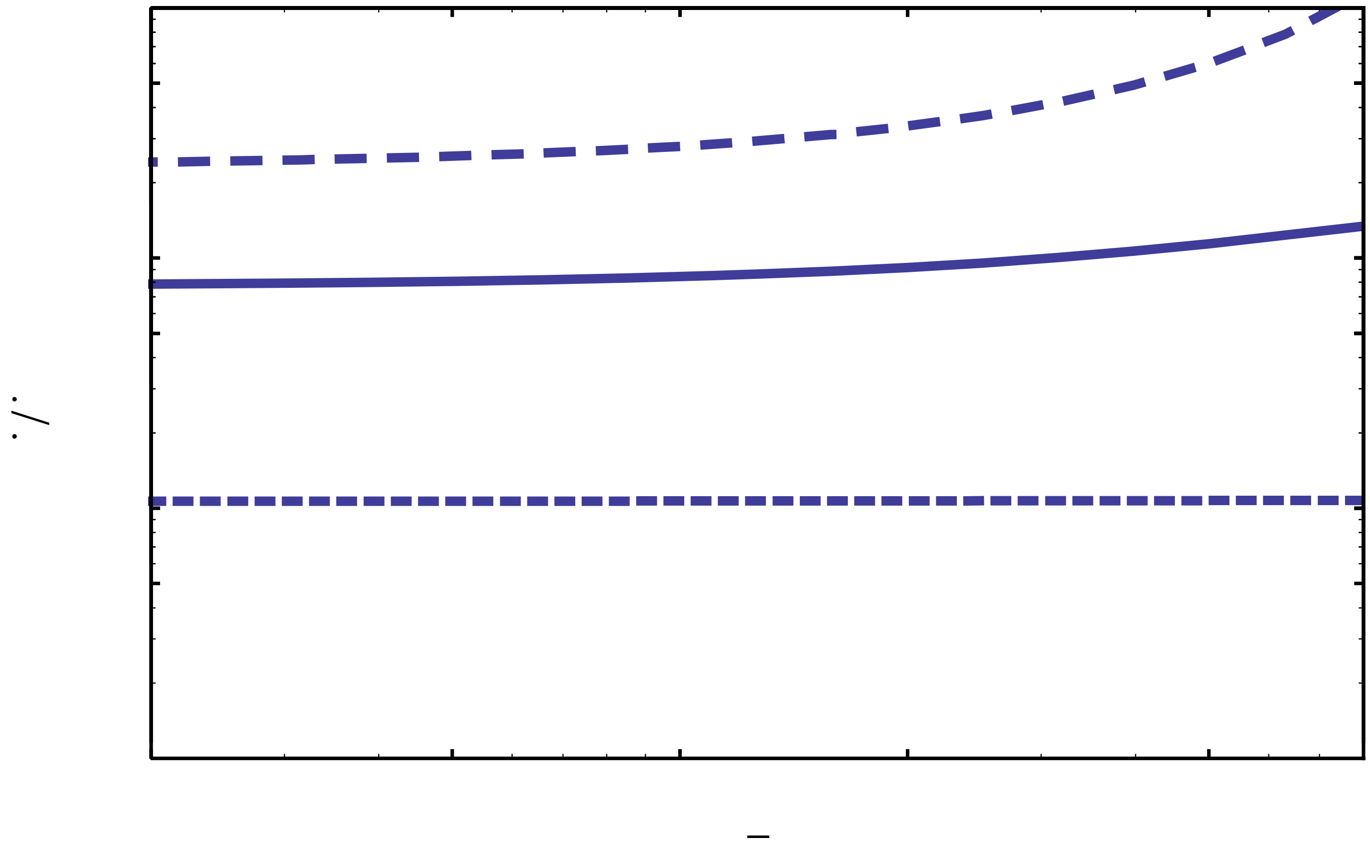
$$\frac{k_2}{Q}$$



Storch & DL 2013

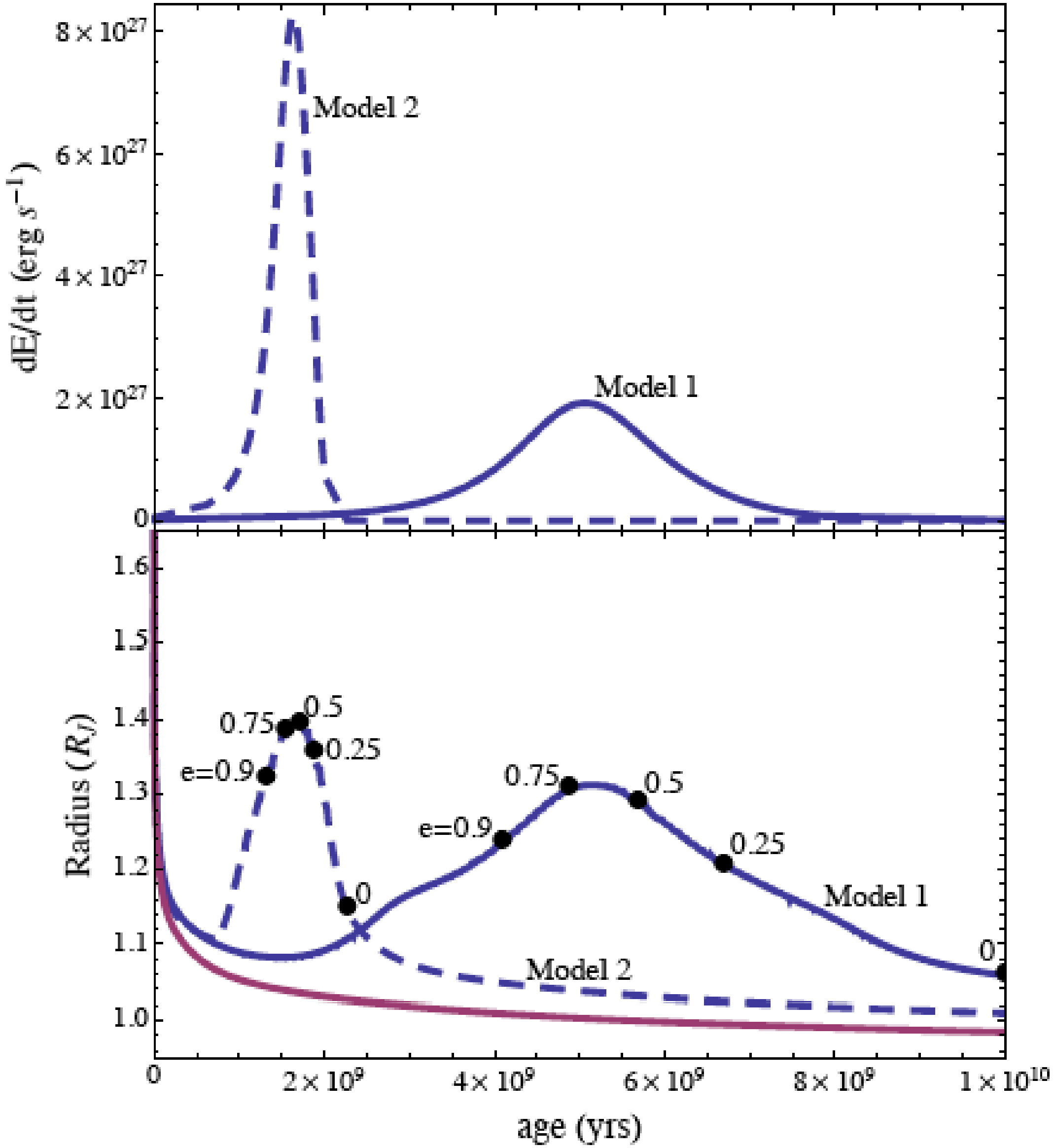
Orbital decay/circularization of proto hot Jupiters

(visco-elastic core vs weak friction)



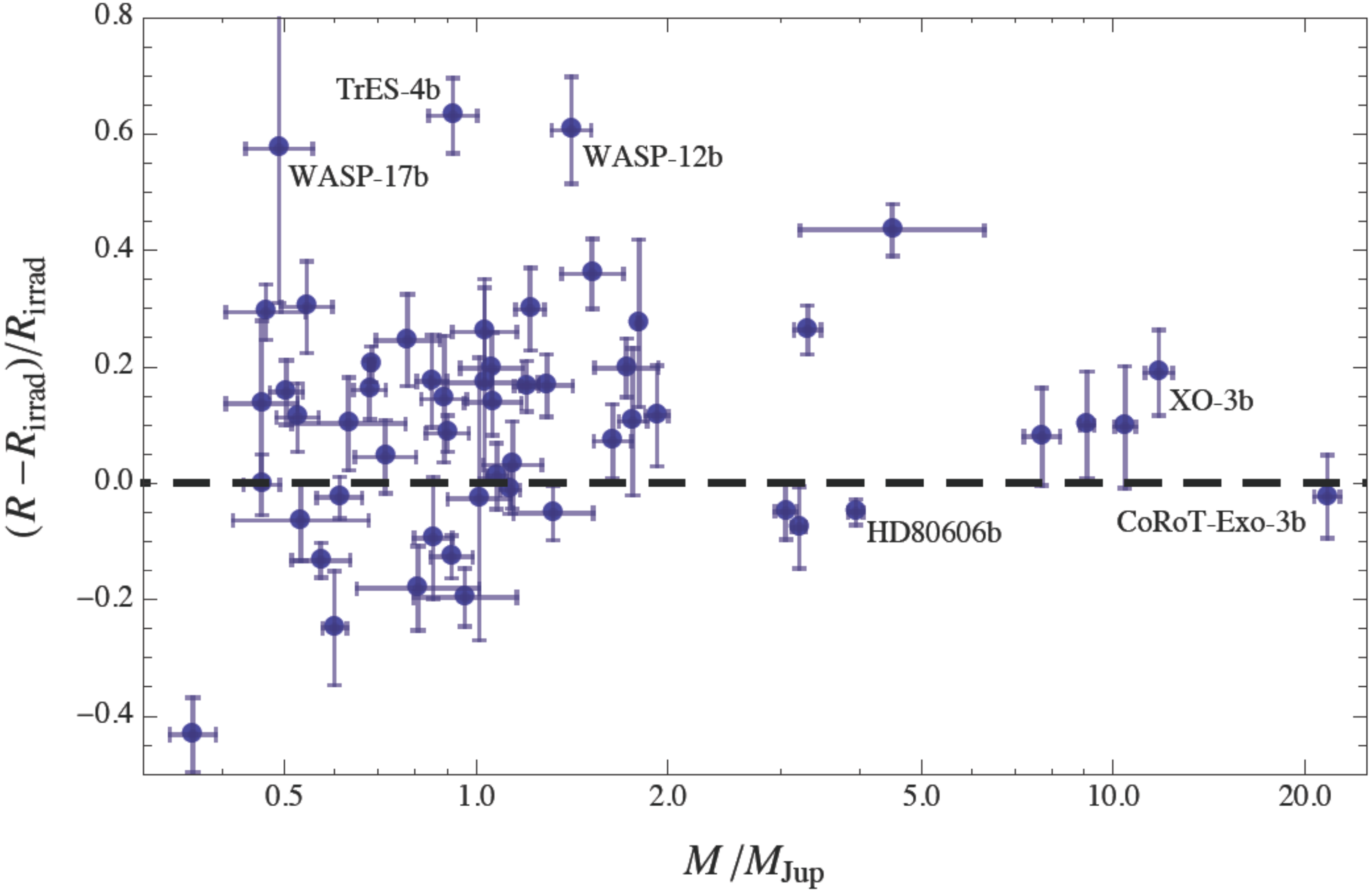
Storch & DL 2013

Tidal heating of rocky core



Storch & DL '13

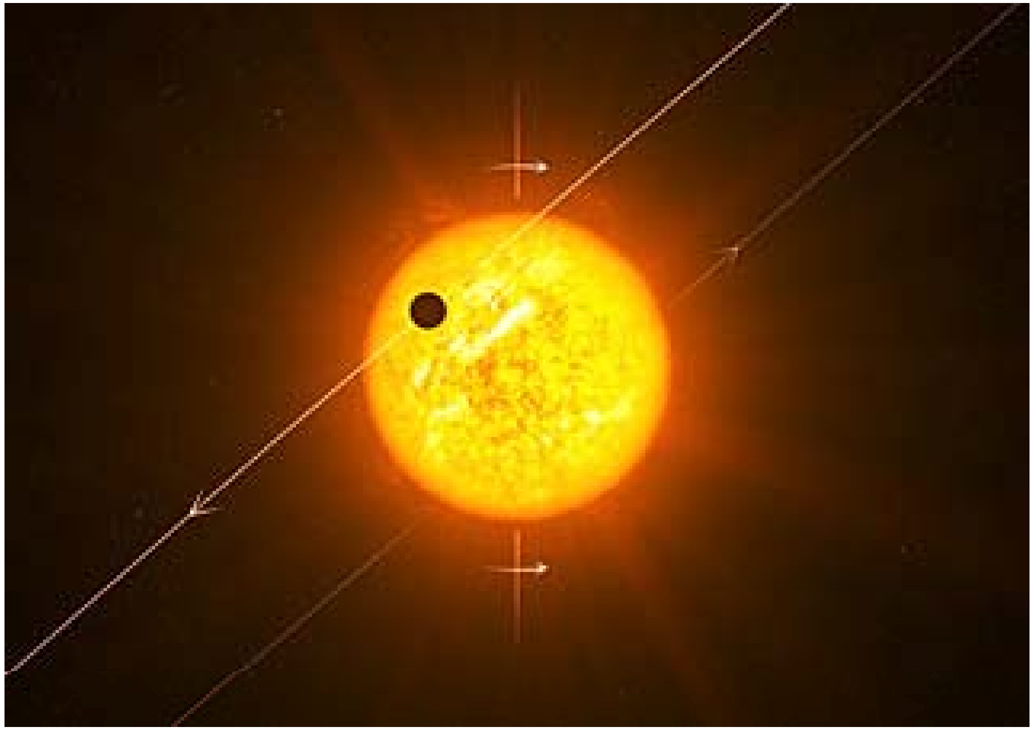
Hot Jupiter Radius Inflation



Leconte et al. 2010

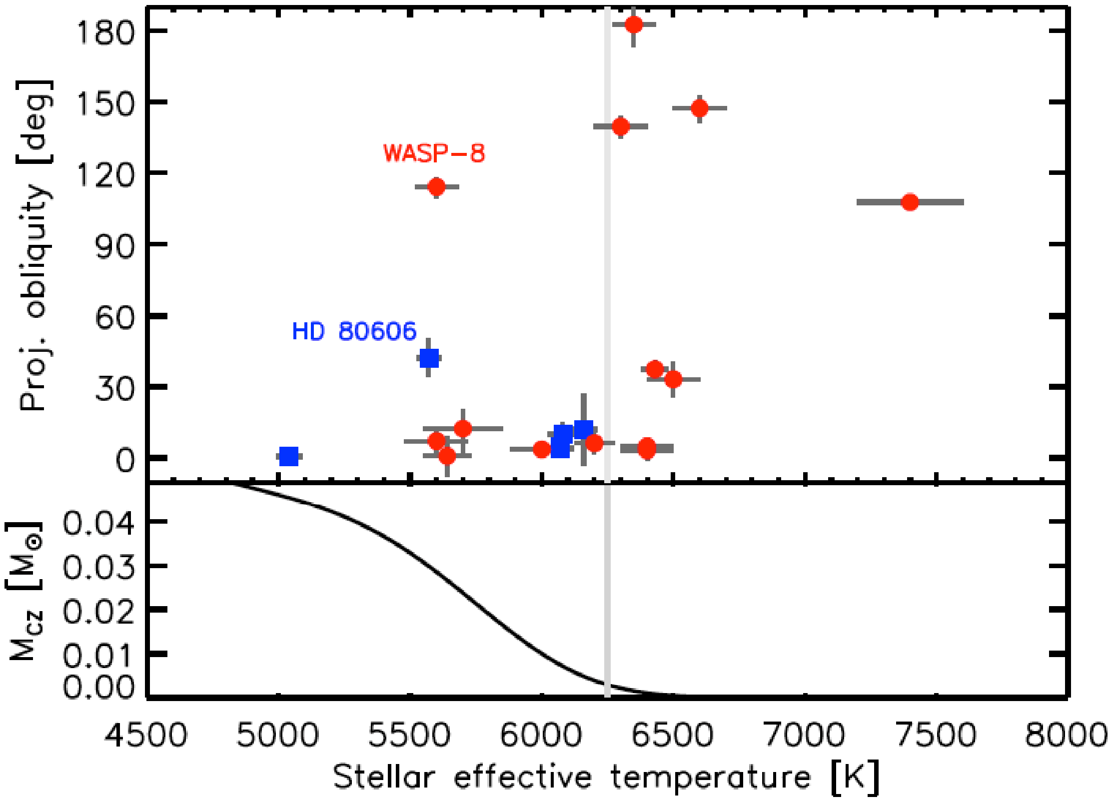
Tidal Dissipation in Planet Host Stars:

Misalignment Damping and Survival of Hot Jupiters



Correlation: Misalignment -- Stellar Temperature/Mass

Winn et al. 2010; Schlaufman 2010



Winn et al.2010

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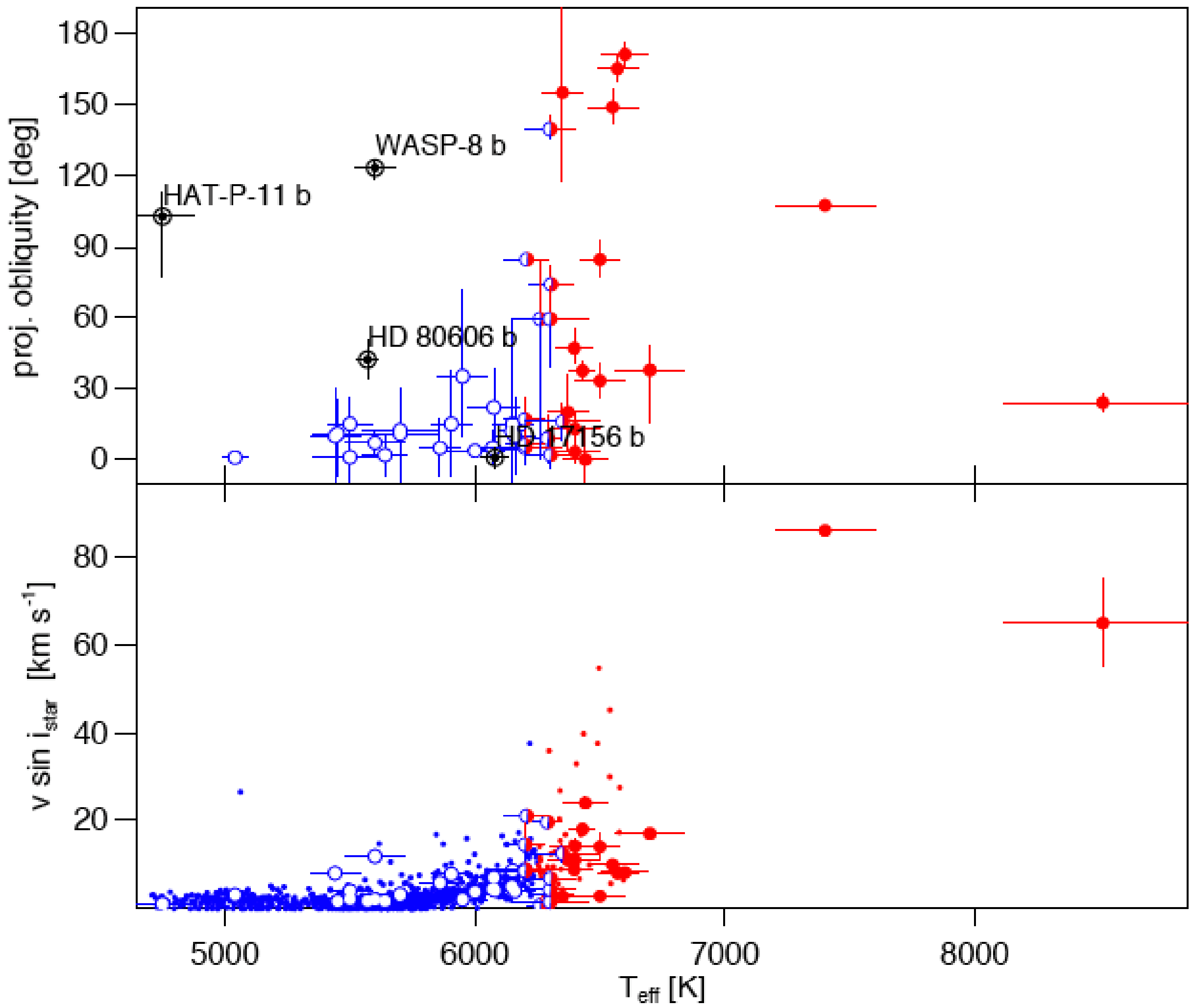

Albrecht, Winn, et al 2012

Correlation: Misalignment -- Stellar Age

Triaud 2011

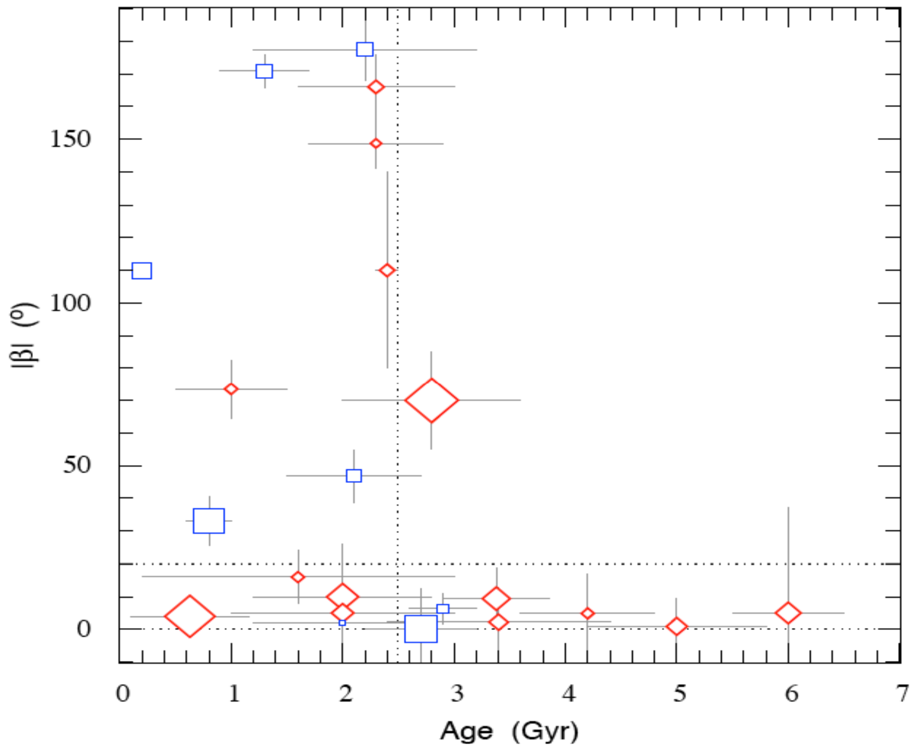

Fig. 2. Secure, absolute values of β against stellar age (in Gyr), for stars with $M_\star \geq 1.2\,M_\odot$. Size of the symbols scales with planet mass. In blue squares, stars with $M_\star \geq 1.3\,M_\odot$; in red diamonds $1.3 > M_\star \geq 1.2\,M_\odot$. Horizontal dotted line show where aligned systems are. Vertical dotted line shows the age at which where misaligned planets start to disappear.

Reasonable Hypothesis:

Many hot Jupiters are formed in misaligned orbits

Tidal damping of misalignment (especially for cooler stars)

Problem with Equilibrium Tide (with the parameterization…)

$$t_{\rm decay} \simeq 1.3 \left(\frac{Q'_\star}{10^7}\right) \left(\frac{M_\star}{10^3 M_p}\right) \left(\frac{P_{\rm orb}}{1\,{\rm d}}\right)^{13/3} {\rm Gyr}$$

$$\frac{t_{\rm align}}{t_{\rm decay}} \simeq \frac{2S_\star}{L} \simeq 2 \left(\frac{M_\star}{10^3 M_p}\right) \left(\frac{10\,{\rm d}}{P_s}\right) \left(\frac{1\,{\rm d}}{P_{\rm orb}}\right)^{1/3}$$

Possible Solution (?): DL 2012 (But see Rogers & Lin 2013)

Different Tidal Q's for Orbital Decay and Alignment ?

Tidal Forcing Frequency=?

For aligned system

$$\omega = 2(\Omega_{\rm orb} - \Omega_s)$$

For misaligned system

$$\omega = m'\Omega_{\rm orb} - m\Omega_s \qquad m, m' = 0, \pm 1, \pm 2$$

7 physically distinct components

==> Effective tidal evolution equations with 7 different Q's

Inertial Waves in Rotating Fluid

Dispersion relation (in rotating frame)

$$\omega = \pm 2\,\mathbf{\Omega}_s \cdot \hat{\mathbf{k}}$$

Can only be excited if tidal forcing frequency satisfies

$$|\omega| < 2\Omega_s$$

Stellar Tides in Hot Jupiter Systems

For aligned system:

$$\omega = 2(\Omega_{\rm orb} - \Omega_s) \gg \Omega_s$$

==> Cannot excite inertial waves

For misaligned system:

$$\omega = m'\Omega_{\rm orb} - m\Omega_s$$

The m'=0, m=1 component has $\omega = -\Omega_s$

This component leads to alignment, but not orbital decay

Summary: Tides in Hot Jupiter Systems

Tidal dissipation in giant planets:

-- Required for high-e migration
-- Inertial wave excitation?
-- Dissipation in solid core?

Tidal dissipation in host stars:

-- Spin-orbit misalignment may be damped faster than orbital decay
-- Different Q's for different processes (equilibrium tide parameterization misleading)
-- Ongoing/future works: A lot of unsolved issues/puzzles...

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Thanks !