Tidal dissipation in stars and the orbital decay of hot Jupiters

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The Leverhulme Trust

Tides in stars: orbital decay of hot Jupiters

- First tentative evidence for tidally-driven orbital decay for WASP-12 b (Maciejewski et al. 2016; Patra et al. 2017)

$$\dot{P} = -29 \pm 3\mathrm{msyr}^{-1} \Rightarrow P/\dot{P} = 3.2\mathrm{Myr}$$

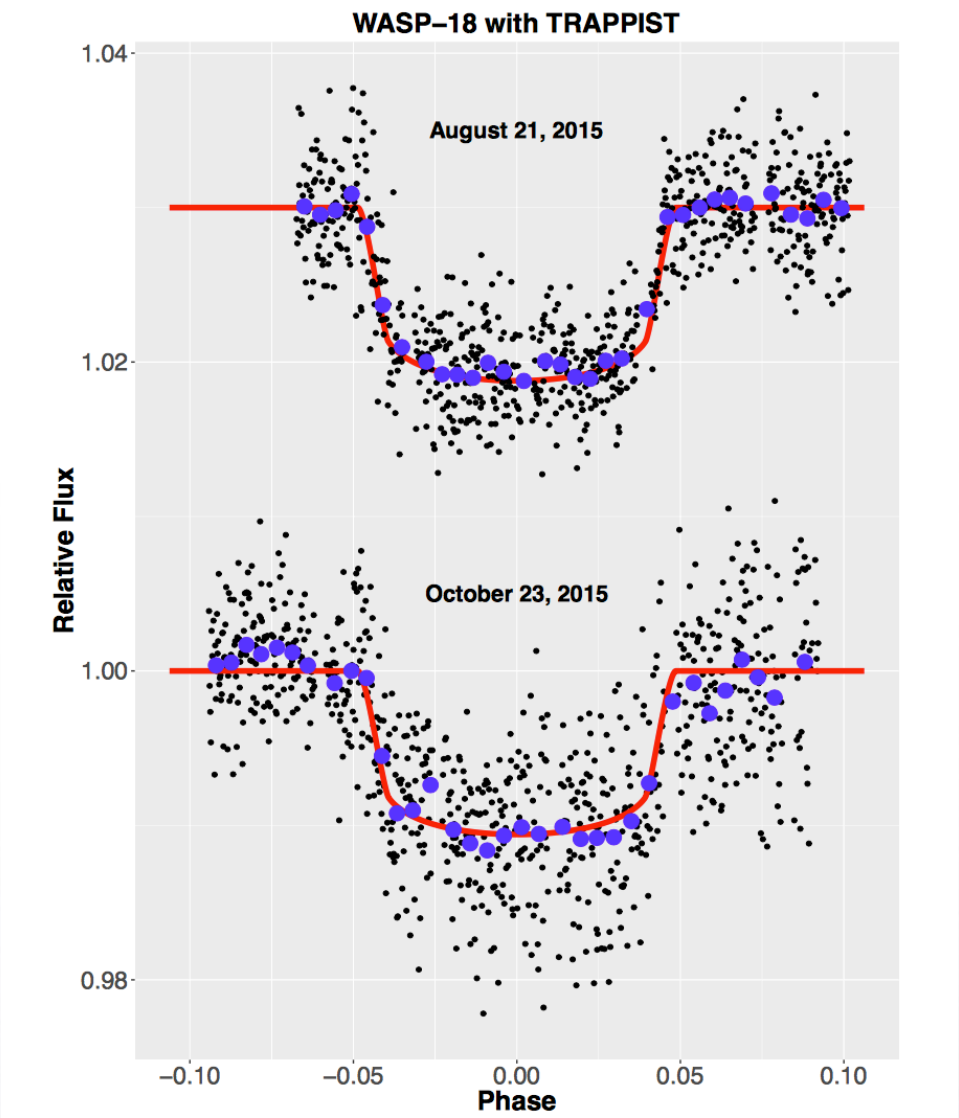
(see also WASP-4 b; Bouma et al. 2019)

- Evidence against rapid orbital decay for WASP-18 b (Wilkins et al. 2017)

- Further detections possible with TESS & PLATO…

- Tidally-driven orbital decay of hot Jupiters due to dissipation in the star => *what mechanisms are responsible?*

Wilkins, Delrez, Barker et al. (2017)



$$T_{shift} = -\left(\frac{27}{8}\right)\left(\frac{M_p}{M_*}\right)\left(\frac{R_*}{a}\right)^5\left(\frac{2\pi}{P}\right)\left(\frac{1}{Q_*'}\right)T^2$$

Dimensionless measure of the efficiency of tidal dissipation

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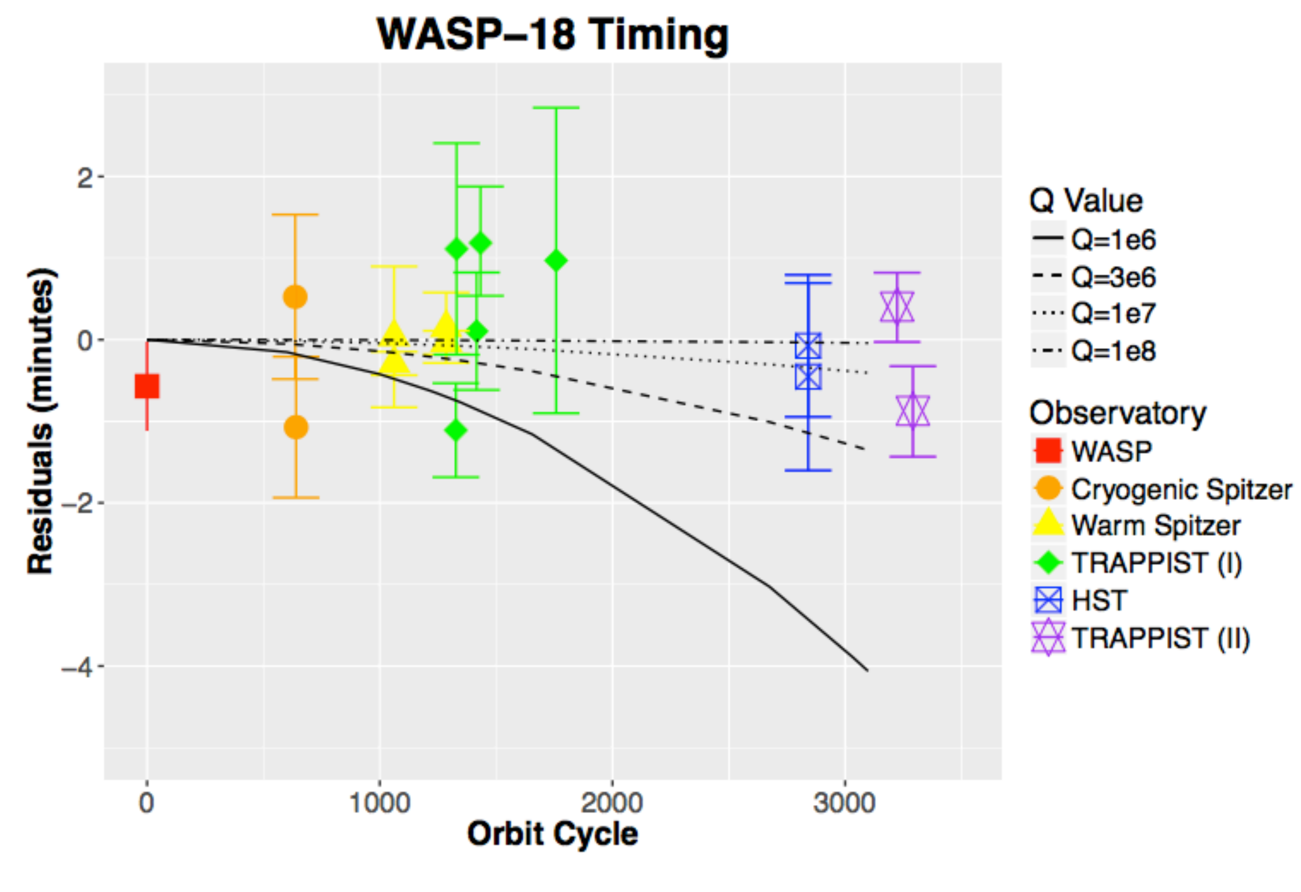

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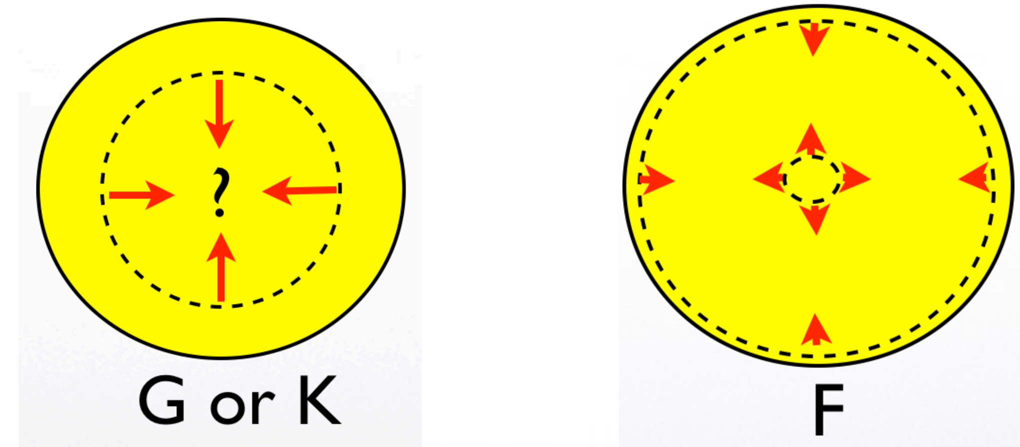
Dimensionless measure of the efficiency of tidal dissipation

Tides in stars: mechanisms

- Hot Jupiters typically orbit much faster than the host star rotates => tidal dissipation inside the star leads to planetary inspiral

- Mechanisms of tidal dissipation in HJ host stars:

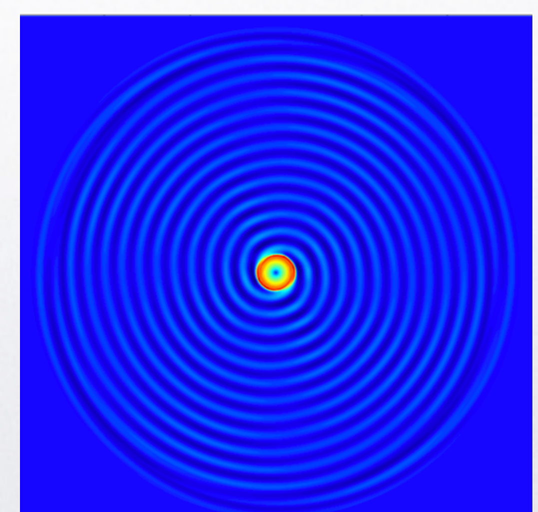


1. Internal gravity waves in radiative regions
   (e.g. Zahn 1977; Goodman & Dickson 1998; Barker & Ogilvie 2010; Barker 2011; Fuller & Lai 2012; Weinberg et al. 2017; Chernov et al. 2017)

→ Probably the most important for solar-type hosts currently. If WASP-12 b has a radiative core, this mechanism could neatly explain the observed $\dot{P}$. The absence of this mechanism may explain WASP-18 b.

2. Inertial waves in convective regions
   (e.g. Wu 2005; Ogilvie & Lin 2007; Goodman & Lackner 2009; Ogilvie 2013; Favier, Barker et al. 2014; Barker 2016; Bolmont & Mathis 2016)

3. Interaction between tides & convection
   (e.g. Zahn 1966/1989; Goldreich & Nicholson 1977; Penev et al. 2008/9; Ogilvie & Lesur 2012)



Barker & Ogilvie 2010

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2. Inertial waves in convective regions
   (e.g. Wu 2005; Ogilvie & Lin 2007; Goodman & Lackner 2009; Ogilvie 2013; Favier, Barker et al. 2014; Barker 2016; Bolmont & Mathis 2016) → Probably important in the past, but most HJ hosts rotate too slowly for this to operate *at the present day*.

3. Interaction between tides & convection
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3. <u>Interaction between tides & convection</u> →
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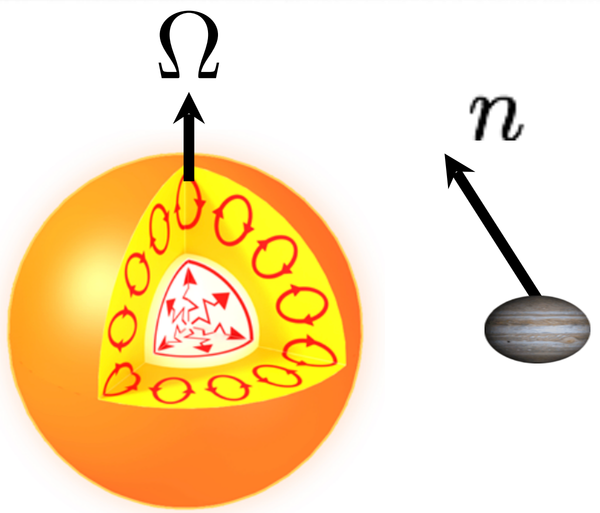
> To summarize, the main weaknesses of the tidal theory, when applied to stars with a convective envelope, reside in our limited knowledge of the dynamics of the convective motions and of their interaction with the tidal flow. (Zahn 1989)

Focus of this talk. Theoretically uncertain. Potentially important for MKG stars, probably less so for F stars (and not for A stars)

Interaction between tides & convection



- Turbulent convection is thought to act as an effective viscosity (ν_E) in damping large-scale tidal flows, but there is a long-standing controversy over the efficiency of this process for large ratios of tidal ($\omega = 2(n - \Omega)$) to convective (ω_c) frequencies

- Phenomenological arguments:
  Zahn (1966): $\nu_E \propto \frac{ul}{3}\min\left[1, \frac{\omega_c}{\omega}\right]$ → $\nu_E \propto \omega^{-1}$ (For $\omega \gg \omega_c$)

  Goldreich & Nicholson (1977): $\nu_E \propto \frac{ul}{3}\min\left[1, \left(\frac{\omega_c}{\omega}\right)^2\right]$ → $\nu_E \propto \omega^{-2}$

- Asymptotic linear analysis for high frequencies (applied to simple flows) predicts: $\nu_E \propto \omega^{-2}$ (Ogilvie & Lesur 2012)

- Now possible to directly test with simulations: pioneering work by Penev et al. 2008/09 and Ogilvie & Lesur (2012), Braviner (PhD 2015)

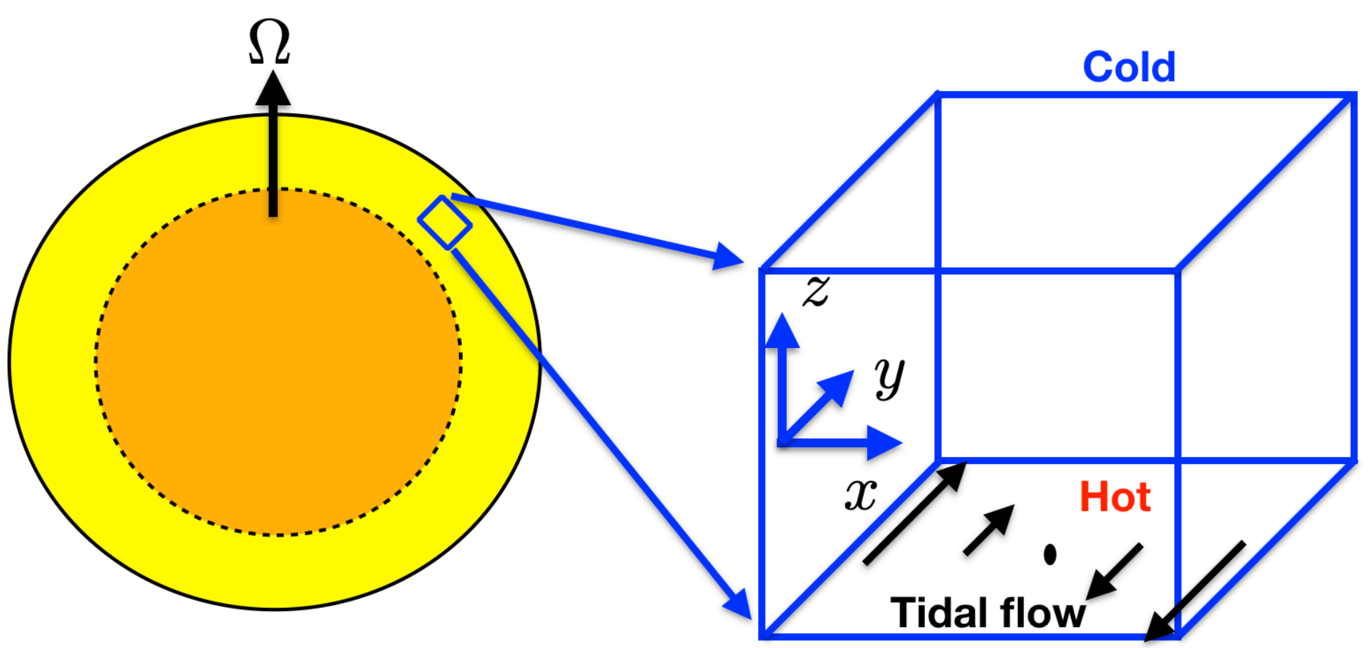
- Why does it matter? Crude estimate for inspiral time of HJ on 1d orbit $\omega/\omega_c \sim 40$
  ~10-100 Myr (ν_E const)
  ~1Gyr ($\nu_E \propto \omega^{-1}$)
  >>10Gyr ($\nu_E \propto \omega^{-2}$)
  => essential to resolve this to predict/explain orbital decay of HJs

Local model to study tides & convection

- Small-patch of convection zone of star
- Rayleigh-Bénard (Boussinesq) non-rotating convection subjected to an imposed oscillatory tidal (shear) flow

$$\boldsymbol{U}_0 = A\omega x \cos\omega t \boldsymbol{e}_y$$

- => probe interaction between this flow and convective flow by analysing Reynolds stresses
- Similar setup to Ogilvie & Lesur (2012) & Braviner (2015), but we drive convection differently



- Cartesian spectral code Snoopy (G. Lesur), using a basis of shearing waves (i.e. shearing-periodic boundary conditions in x)
- BCs: impenetrable, stress-free and fixed temperature in z. Periodic in y.

$$\mathrm{Ra} = \frac{-N^2 L_z^4}{\nu\kappa} \qquad R = \frac{\mathrm{Ra}}{\mathrm{Ra}_c} \qquad \mathrm{Pr} = \frac{\nu}{\kappa} = 1$$

Local model to study tides & convection

- We *define* the effective viscosity by equating the volume-averaged rate at which the tidal shear does work on the convective flow with the viscous dissipation rate of the tidal flow, i.e.

$$-(A\omega)\cos\omega t\langle u_x u_y\rangle = \nu_E\langle|\nabla\times\boldsymbol{U}_0|^2\rangle$$

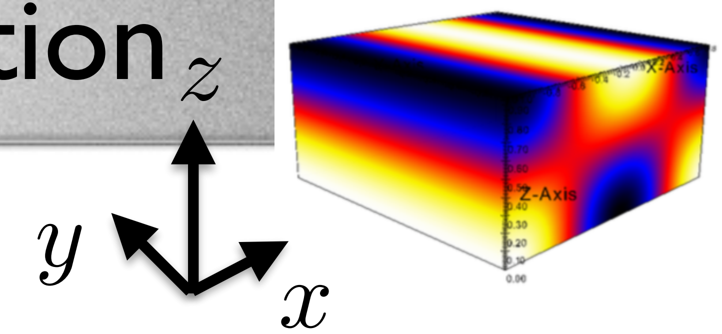
- Time-averaging gives the *effective viscosity* at this frequency:

$$\nu_E(\omega) = \frac{-2}{A\omega T}\int_{T_0}^{T_0+T}\langle u_x u_y\rangle\cos\omega t\mathrm{d}t \qquad \propto \frac{\dot{P}}{P}$$

For HJ orbital decay

- Positive values indicate that the tidal flow is being damped by its interaction with the convection i.e. the classical picture.
- But it need not be positive! Negative values indicate tidal anti-dissipation: the convective flow transfers energy into the tidal flow.

Effective viscosity for laminar convection



Positive values for y-aligned convective rolls

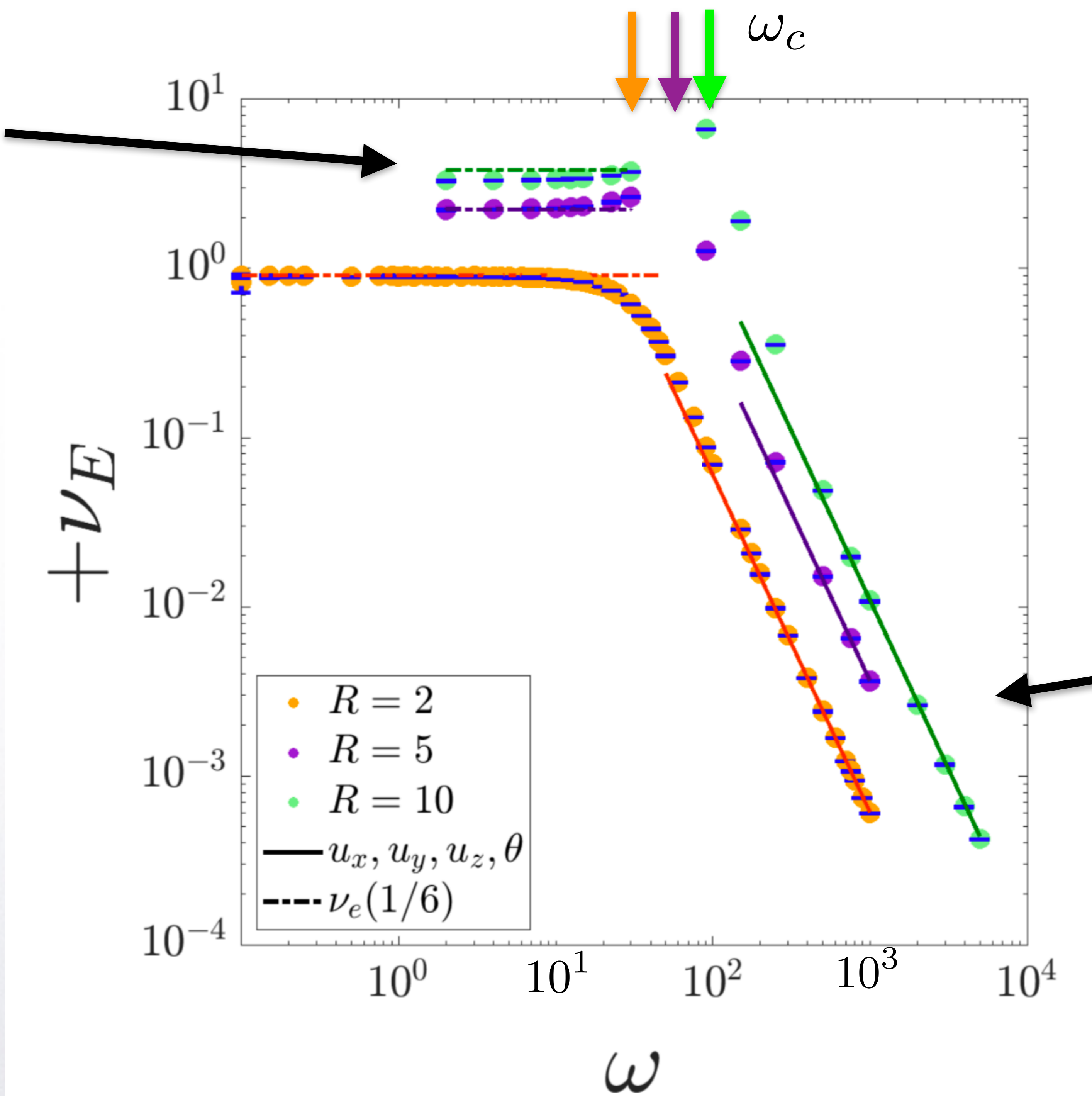
MLT scaling

$\nu_E \sim u\ell$

(proportionality constant is 1/6)

$\omega \lesssim \omega_c$

[~ constant tidal lag-time (e.g. Darwin 1879; Alexander 1973; Mignard 1979; Hut 1981)]



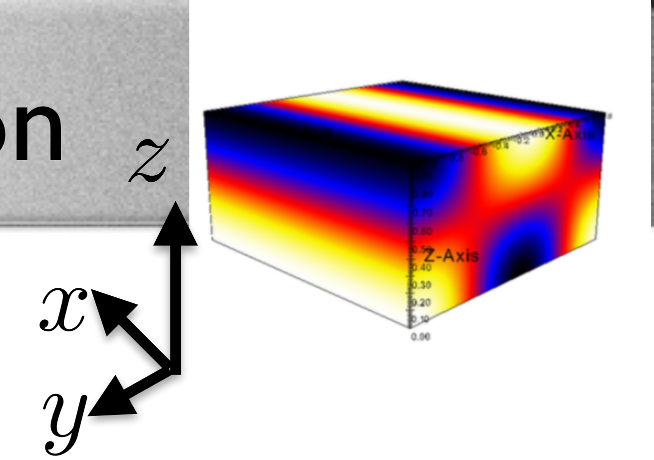
$\nu_E \propto \omega^{-2}$

Analytical asymptotic theory prediction

$\omega \gg \omega_c$

[Neither constant lag-time nor constant Q' is appropriate]

Effective viscosity for laminar convection



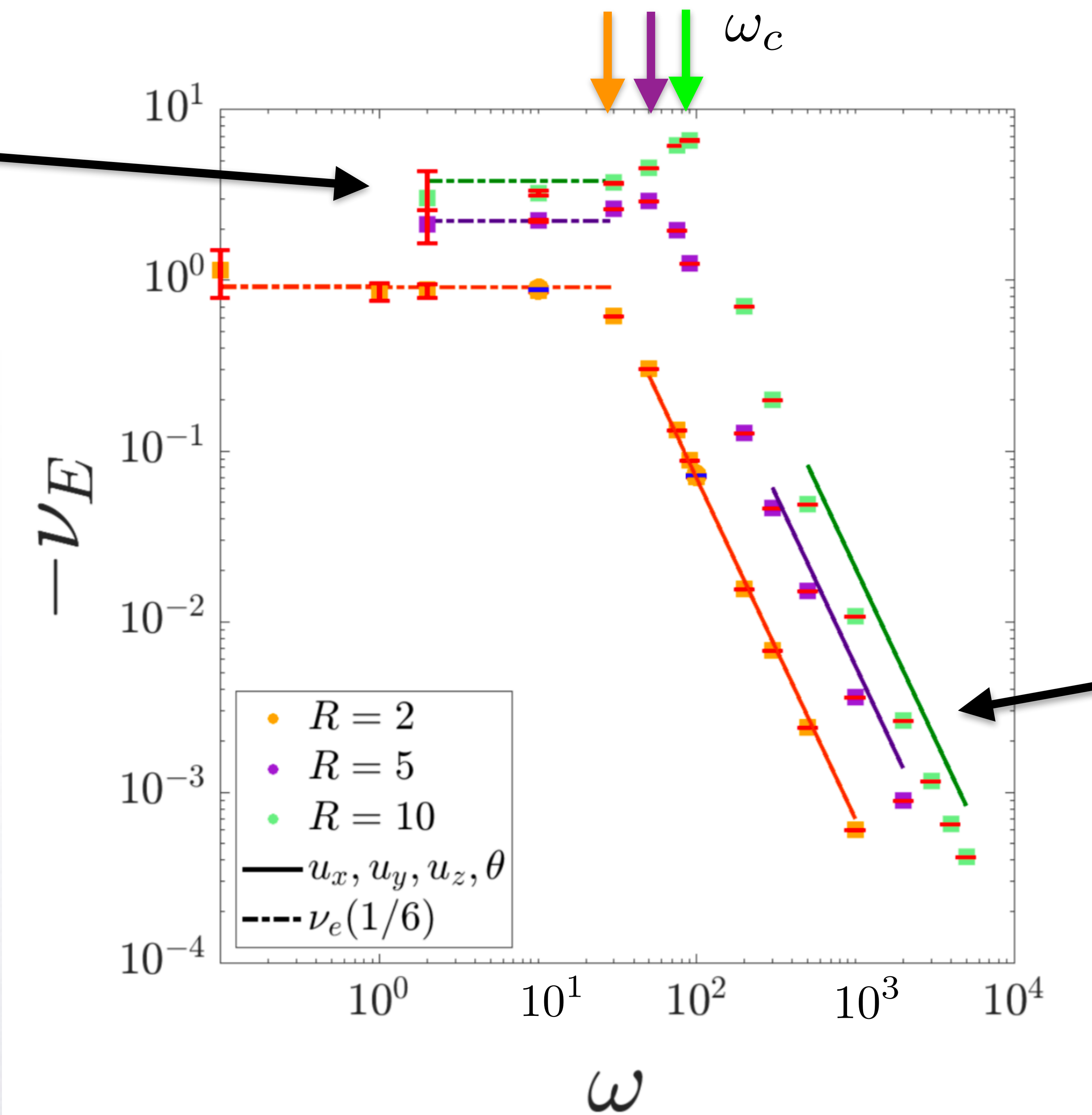
Negative values for x-aligned convective rolls!

MLT scaling

$\nu_E \sim u\ell$

(proportionality constant is 1/6)

$\omega \lesssim \omega_c$



$\nu_E \propto \omega^{-2}$

Analytical asymptotic theory prediction

$\omega \gg \omega_c$

Effective viscosity for “turbulent” convection (R=100)

Transition to negative values for high frequencies

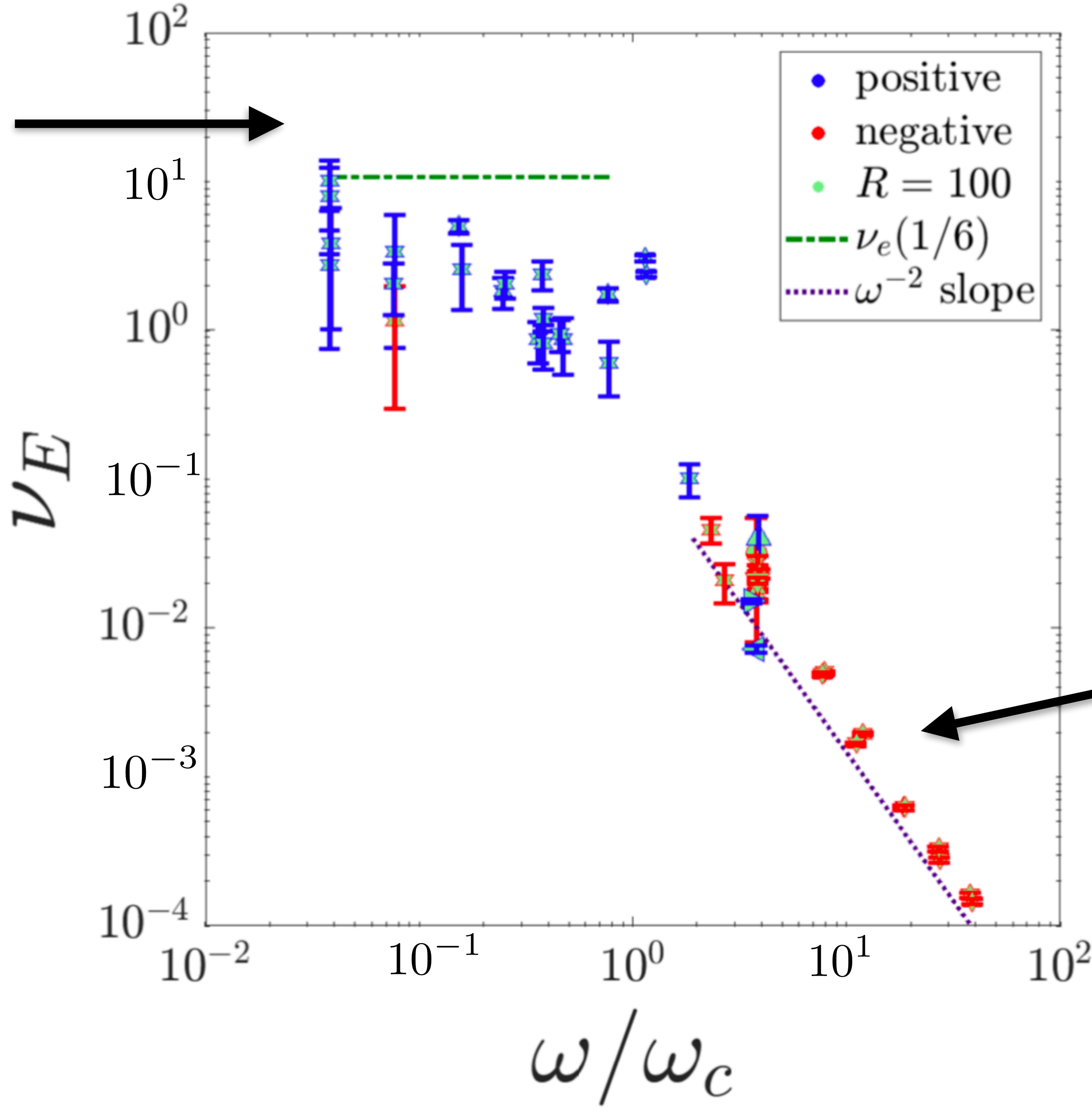
MLT scaling

$\nu_E \sim u\ell$

(proportionality constant < 1/6)

$\omega \lesssim \omega_c$

[~ constant tidal lag-time (e.g. Darwin 1879; Alexander 1973; Mignard 1979; Hut 1981)]



$\nu_E \propto \omega^{-2}$

$\omega \gg \omega_c$

[Neither constant lag-time nor constant Q’ is appropriate]

Effective viscosity for “turbulent” convection (R=1000)

Transition to negative values for high frequencies

MLT scaling

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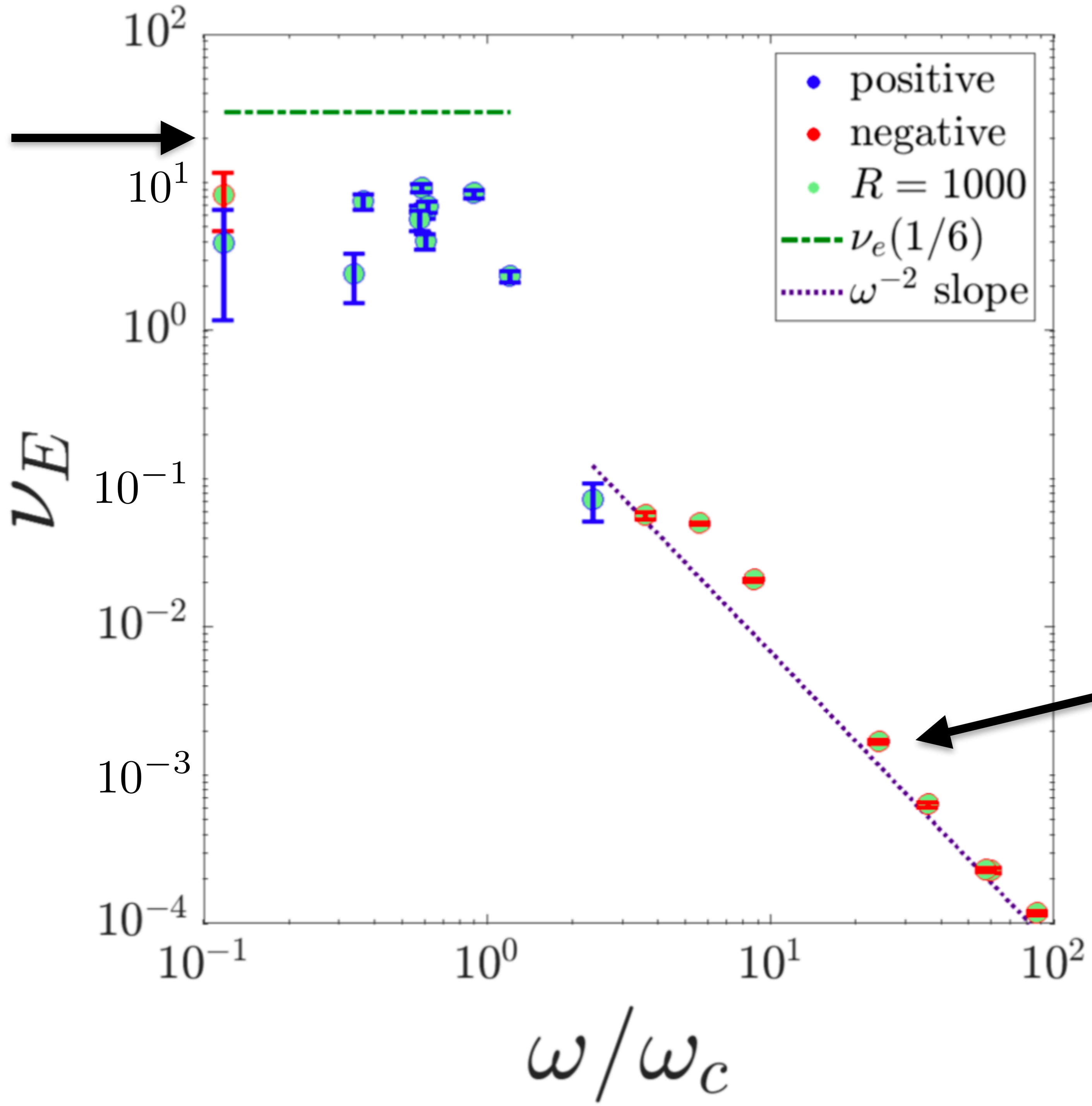


$\nu_E \propto \omega^{-2}$

$\omega \gg \omega_c$

[Neither constant lag-time nor constant Q’ is appropriate]

Duguid, Barker & Jones, in prep

University of Leeds

Global model to study tides & convection

- Idealised homogeneous ~spherical star with (Boussinesq) convection driven by internal heating

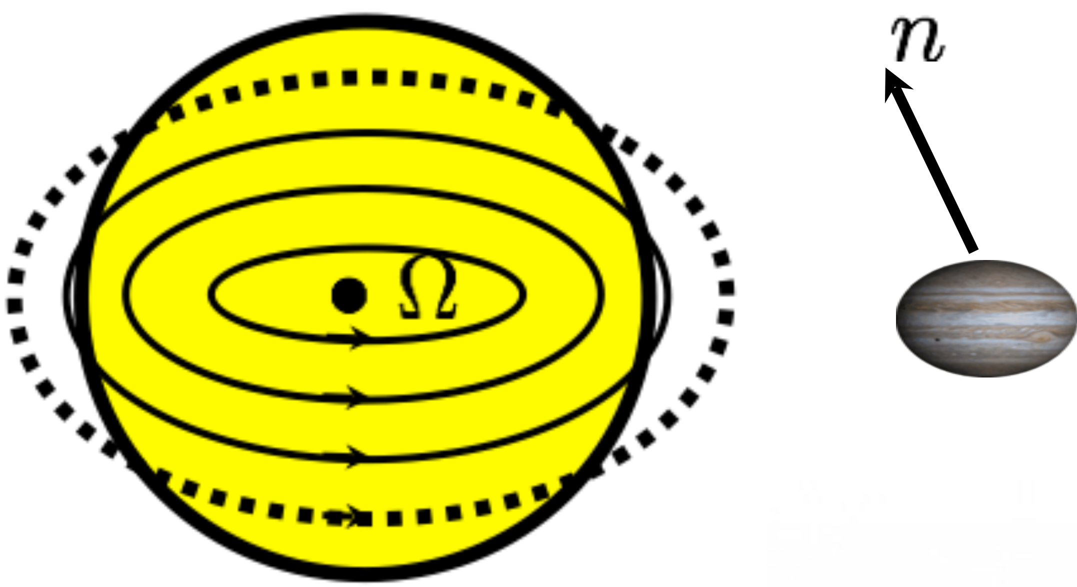
- Study non-wave-like tidal flow, in the fluid frame:

$$\boldsymbol{U}_0 = A\omega \begin{pmatrix} -\sin\omega t & \cos\omega t & 0 \\ \cos\omega t & \sin\omega t & 0 \\ 0 & 0 & 0 \end{pmatrix} \boldsymbol{x}$$

- Analyse Reynolds stresses and define the effective viscosity similarly

$$\nu_E = \frac{1}{4AT}\int_{T_0}^{T_0+T} \langle u_x^2 - u_y^2 \rangle \sin\omega t - 2\langle u_x u_y \rangle \cos\omega t \,\mathrm{d}t$$

- Spectral element code Nek5000, with no-slip impenetrable (spherical) boundaries for small tidal amplitudes (typically A=0.01 to 0.05)

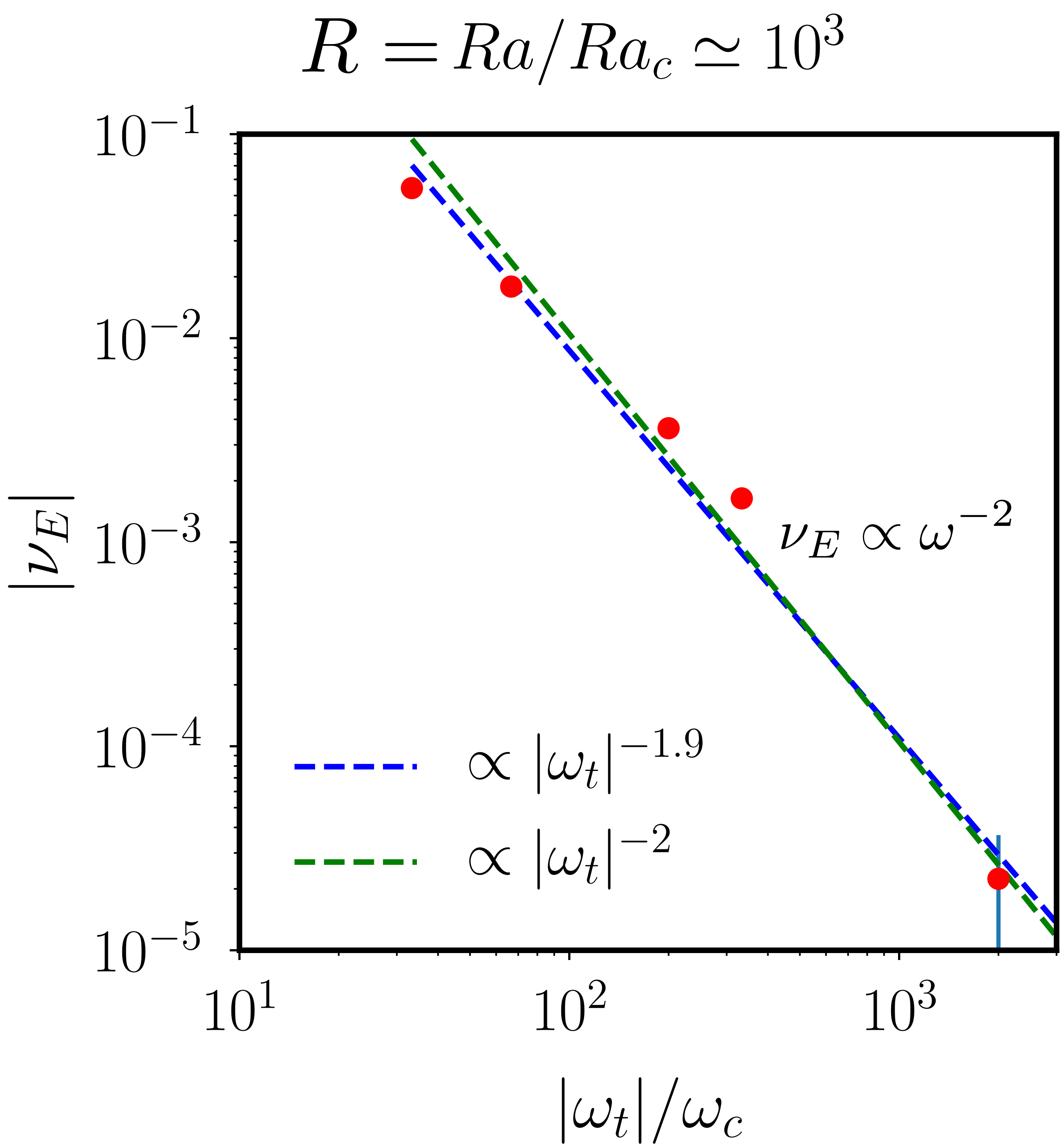


$$\omega = 2(n - \Omega)$$

$$\mathrm{Ra} = \frac{(Q/3)R^4}{\nu\kappa^2} \qquad R = \frac{\mathrm{Ra}}{\mathrm{Ra}_c} \qquad \mathrm{Pr} = \frac{\nu}{\kappa} = 1$$

Effective viscosity from global simulations

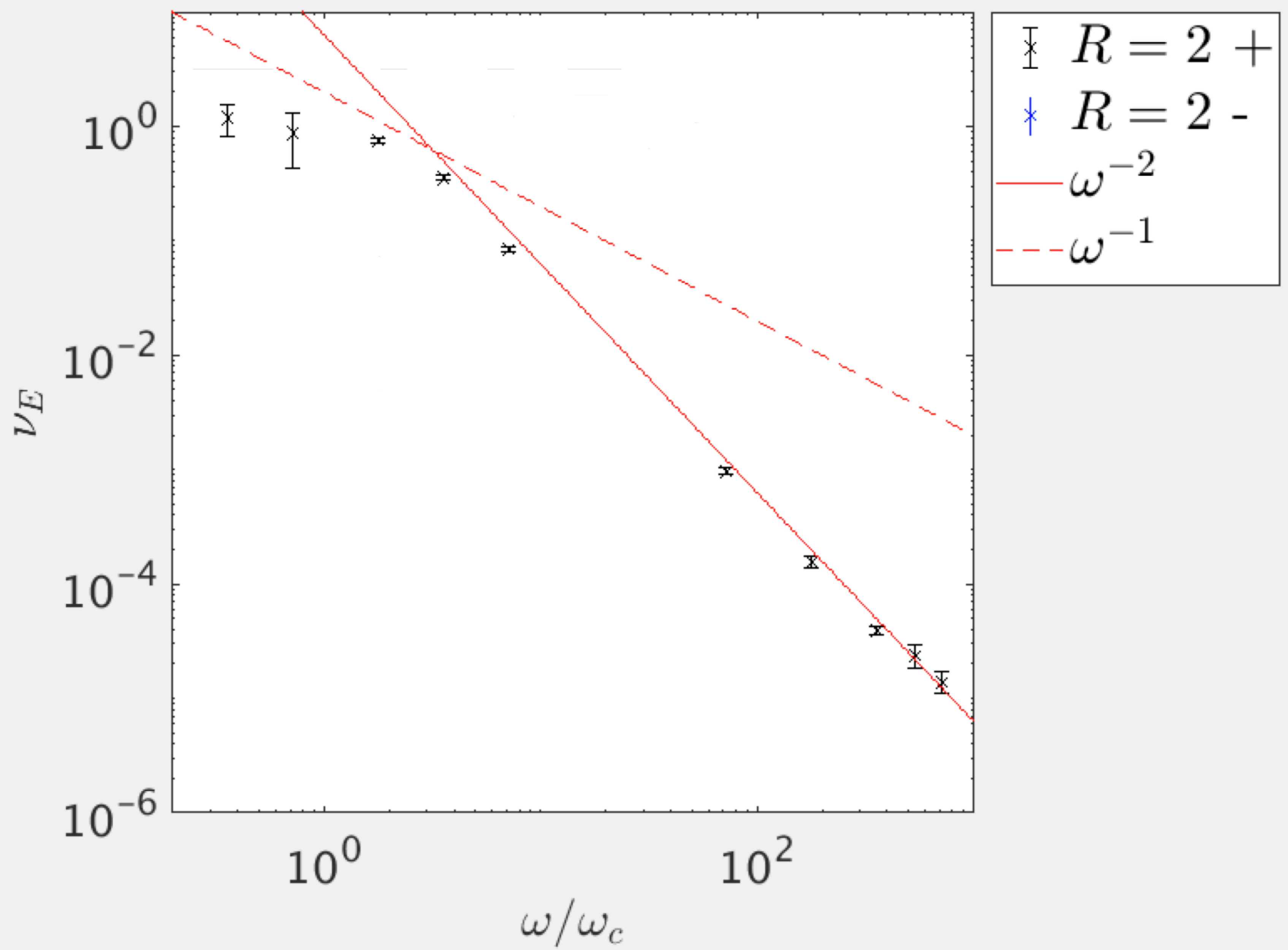
Preliminary results: negative values for high frequency tides



Effective viscosity from local simulations

Preliminary! Local model using the full non-wave-like flow: $\boldsymbol{U}_0 = A\omega \begin{pmatrix} -\sin\omega t & \cos\omega t & 0 \\ \cos\omega t & \sin\omega t & 0 \\ 0 & 0 & 0 \end{pmatrix} \boldsymbol{x}$

Laminar



[Similar to approach Barker & Lithwick 2013]

Effective viscosity from local simulations

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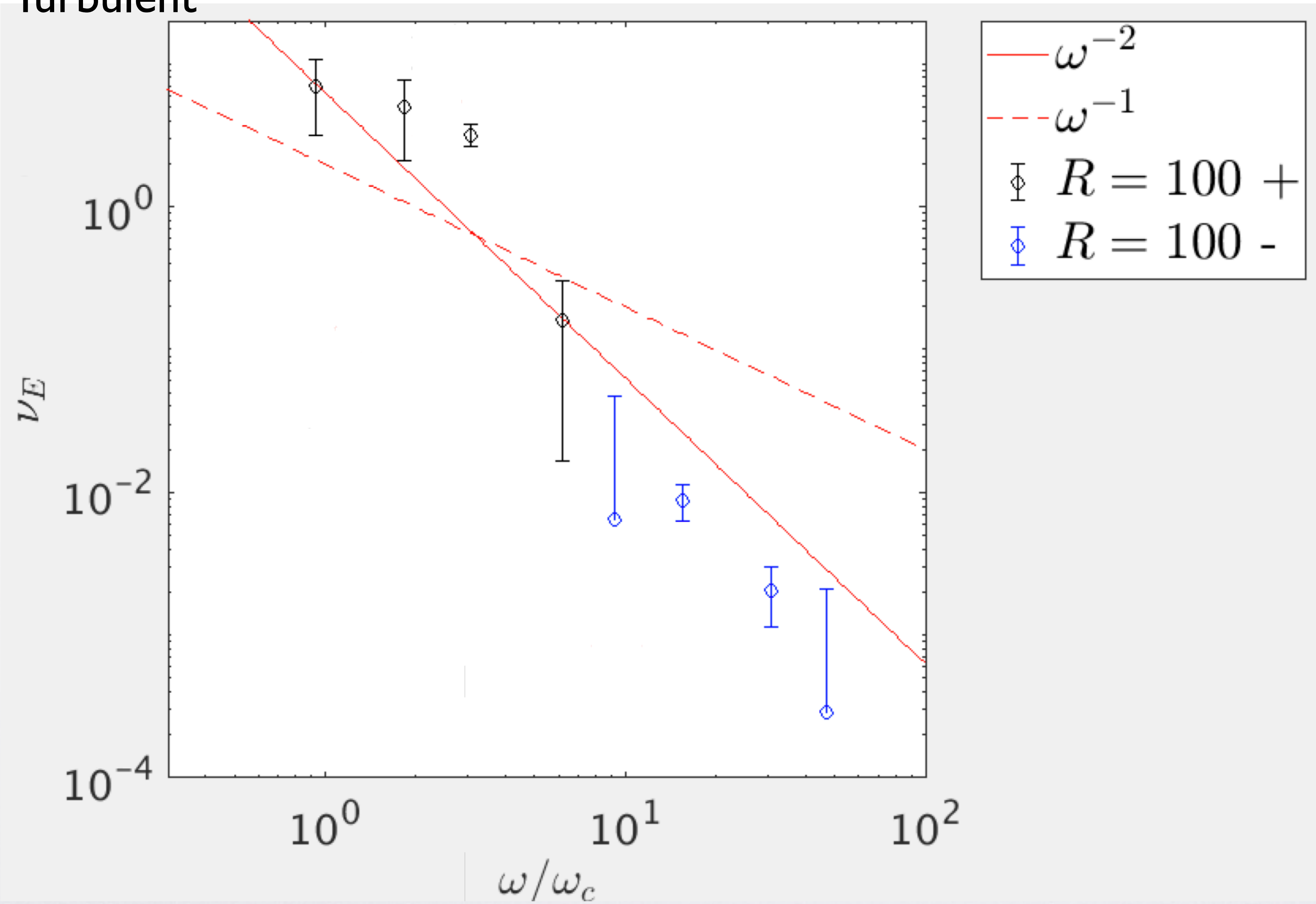
"Turbulent"

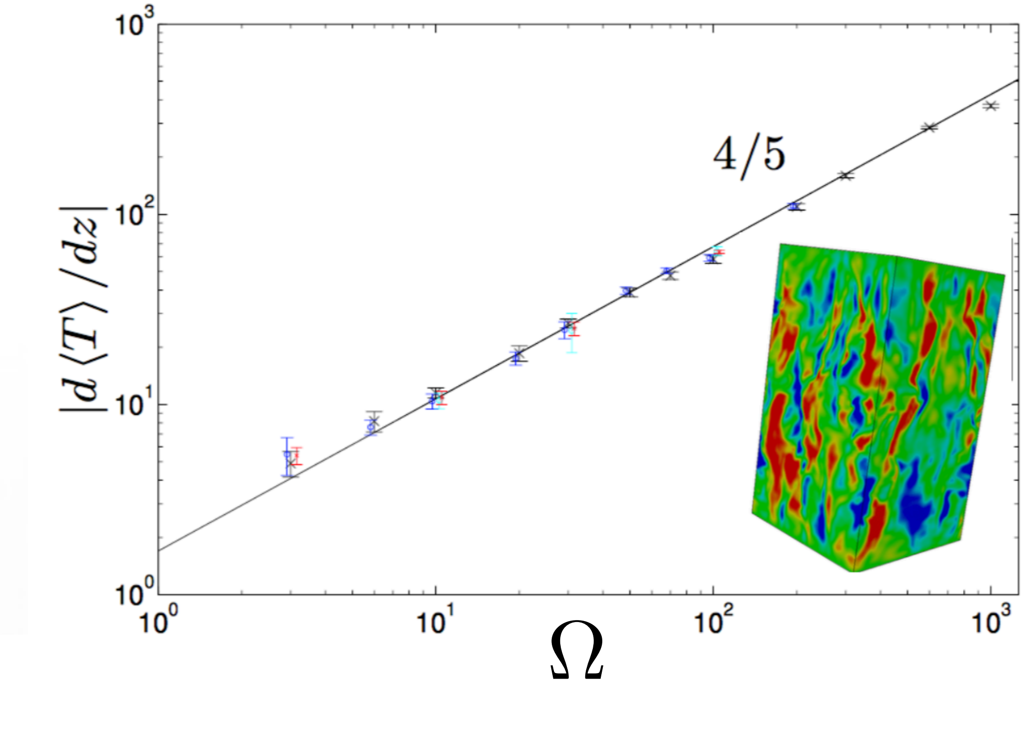


[Similar to approach Barker & Lithwick 2013]

Future work

- Much future work is needed to address:

1. Simulate "more turbulent" convection both locally and globally
2. Explore the effects of rotation on ν_E : does it behave as predicted by rotating mixing-length theory? (e.g. Stevenson 1979; Barker et al. 2014; Mathis et al. 2016; Currie, Barker, Lithwick & Browning, in prep)
3. Adopt more realistic density profiles and study density-stratified convection. Dependence on properties of convection zone?
4. How does convection interact with tidally-excited inertial waves?



Conclusions

- Tidal dissipation in stars produces orbital decay of hot Jupiters. Transit observations are now potentially able to test tidal theories
- I have presented idealised local and global simulations to study the interaction between tidal flows and convection in stars (or giant planets) from first principles:

1. For small tidal frequencies ($\omega \lesssim \omega_c$) we obtain a frequency-independent effective viscosity (~constant tidal lag-time)
2. For large tidal frequencies ($\omega \gg \omega_c$) we find strong evidence in favour of $\nu_E \propto \omega^{-2}$ (neither constant Q' nor constant lag-time)
3. Negative effective viscosities (suggesting tidal anti-dissipation) are possible
4. These results have been confirmed by an independent asymptotic linear analysis

- Quadratic reduction agrees with Ogilvie & Lesur (2012), Braviner (2015, PhD) & Goldreich & Nicholson (1977) but not with Zahn (1966, 1989)
- Much further work is required to study tidal flows in more realistic stellar/planetary models and to incorporate additional effects omitted here (e.g. rotation, density stratification)