Are terrestrial exoplanets really tidally synchronized?

...and why does it matter?

Jérémy Leconte

F. Forget, K. Menou, N. Murray, H. Wu

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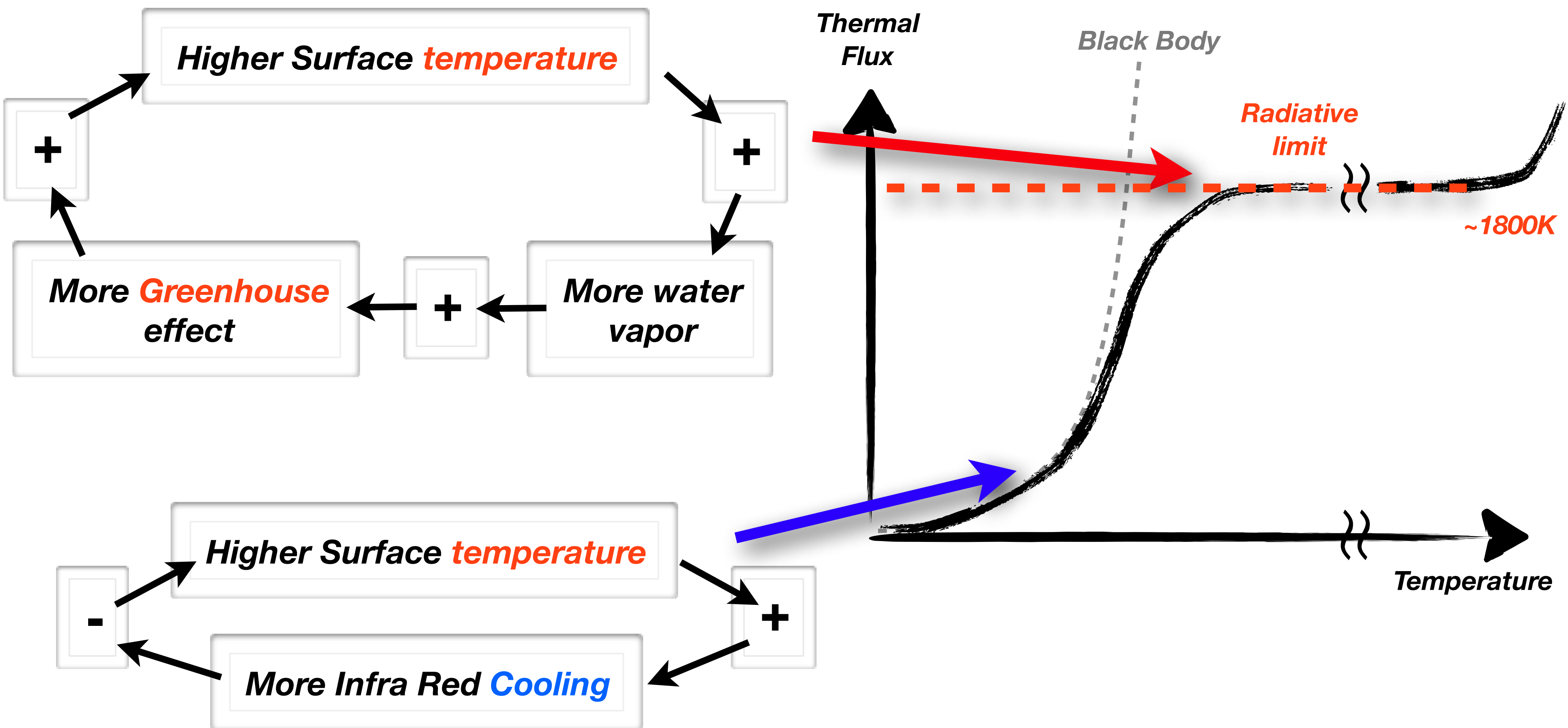
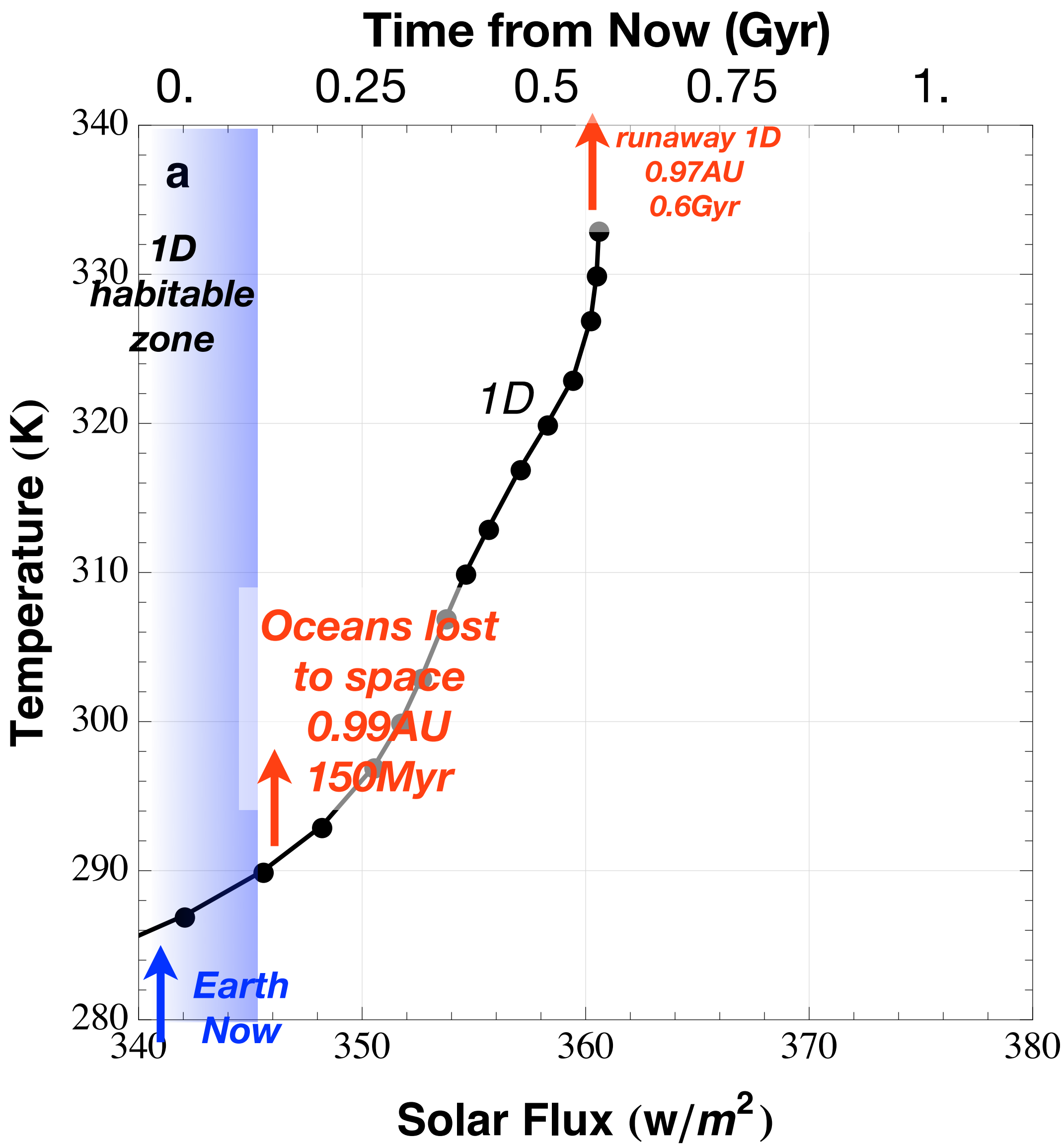
When will oceans boil?

The runaway greenhouse instability



Kasting (Icarus, 1988)

Unidimensional results



Development of a «generic» global climate model

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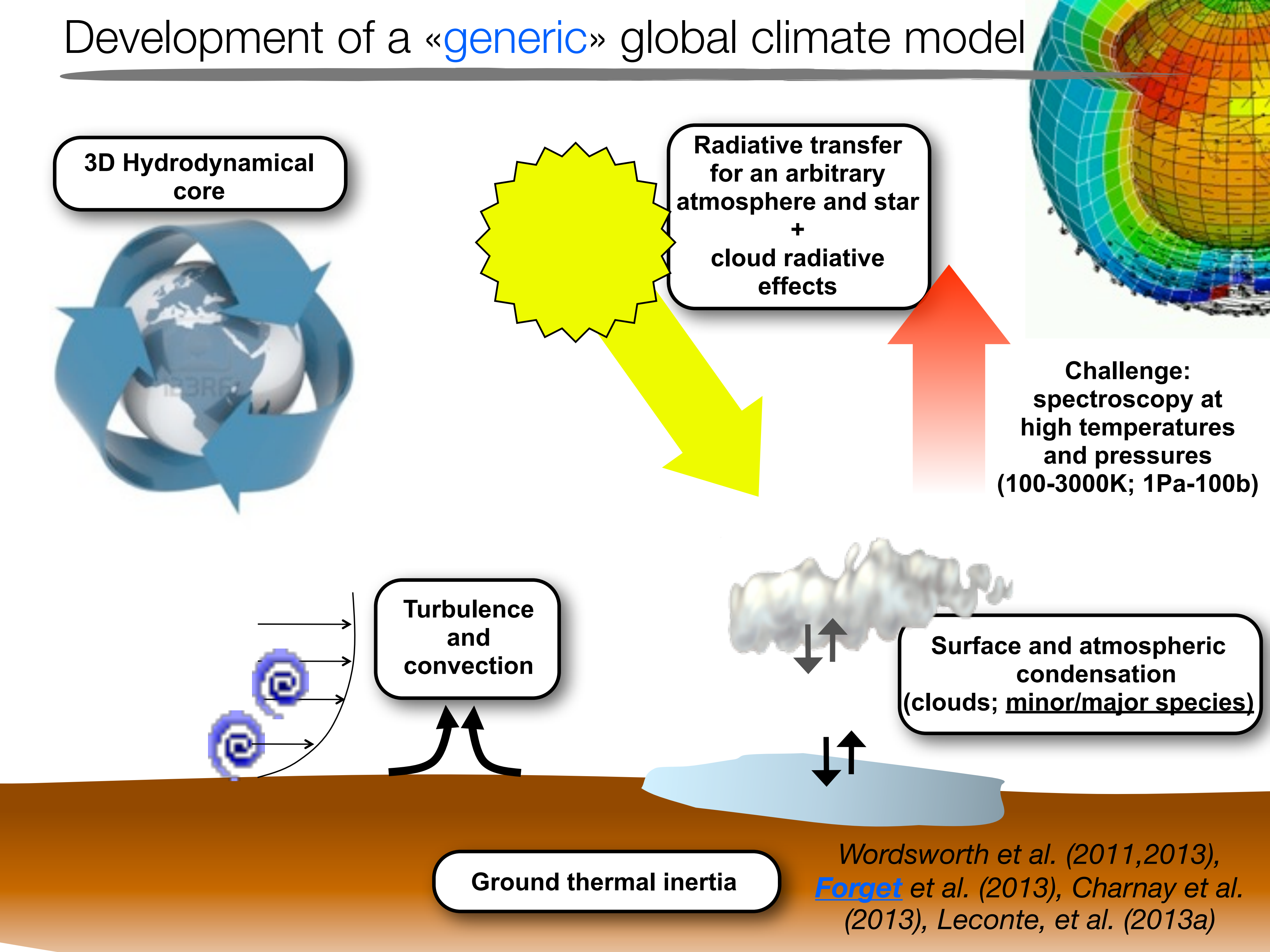
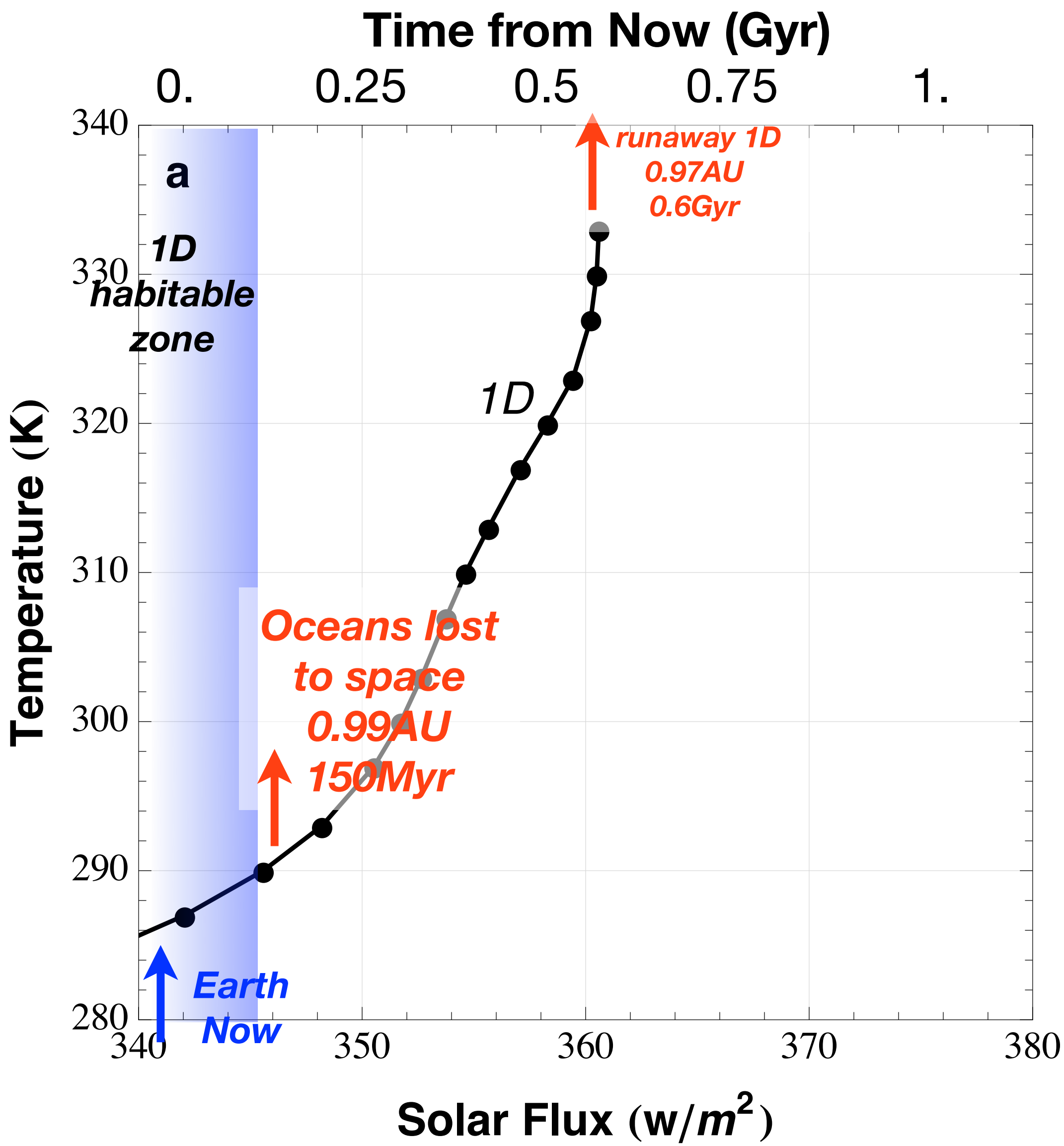
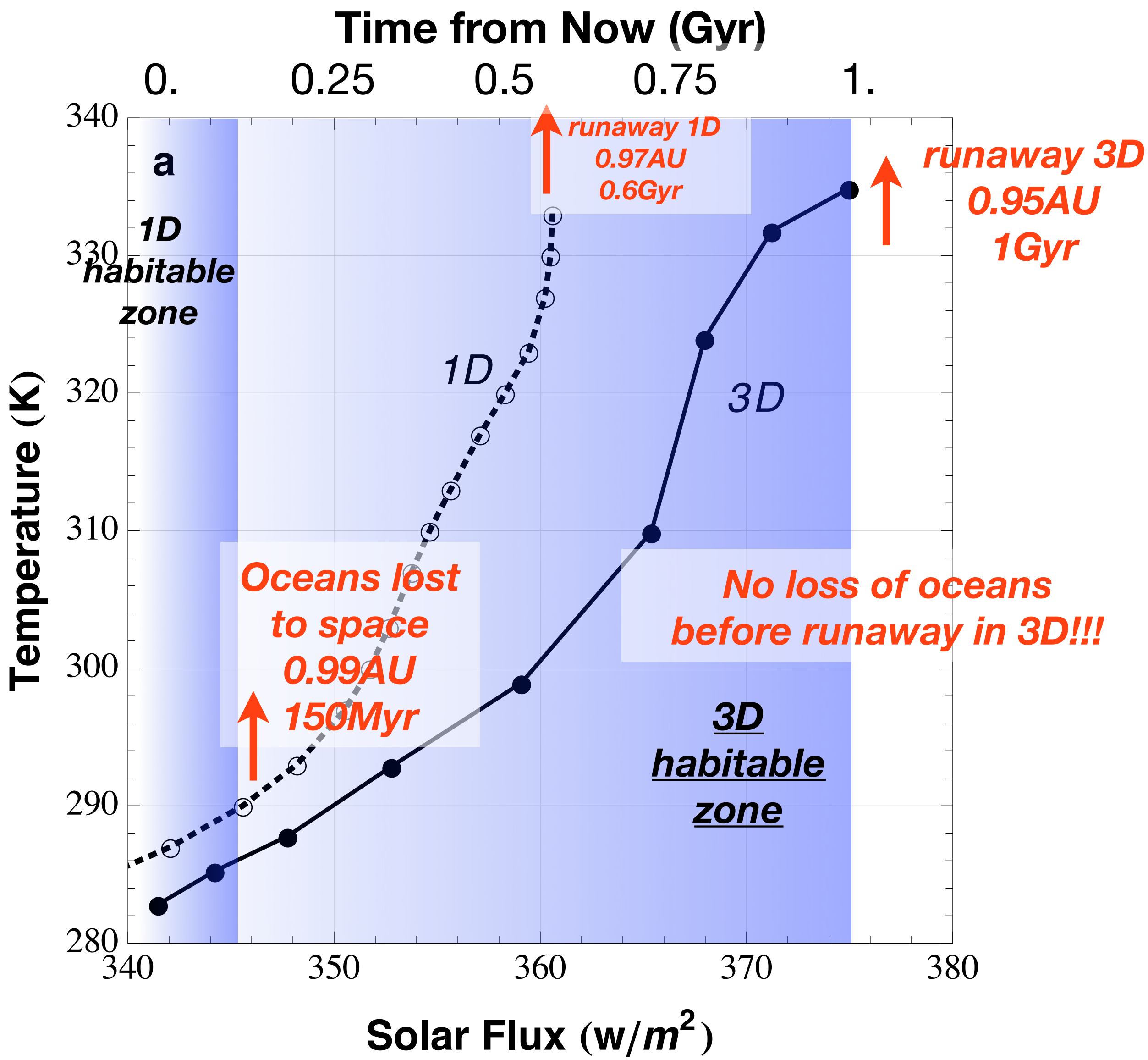


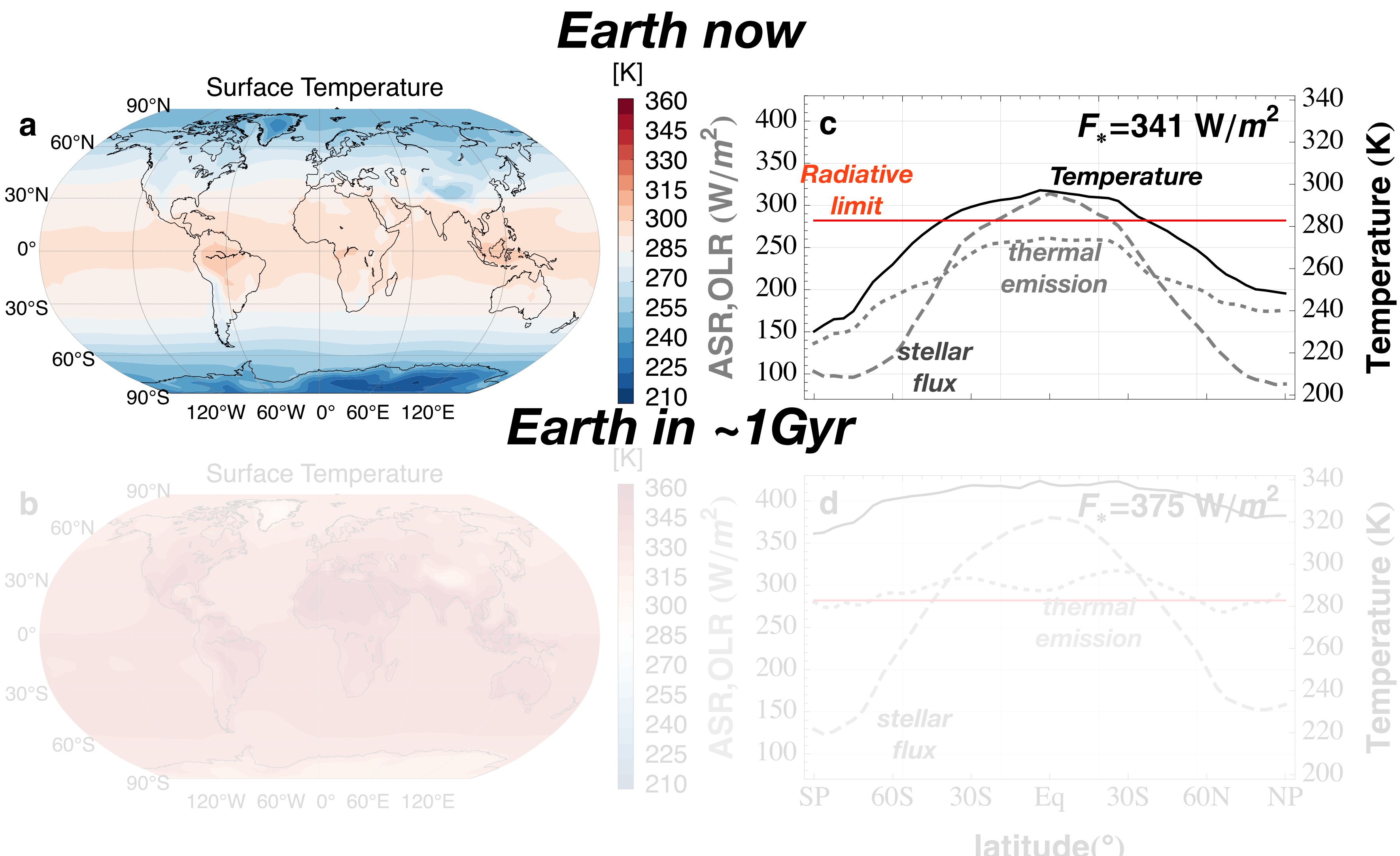
Unidimensional results



1D vs 3D: systematic biases

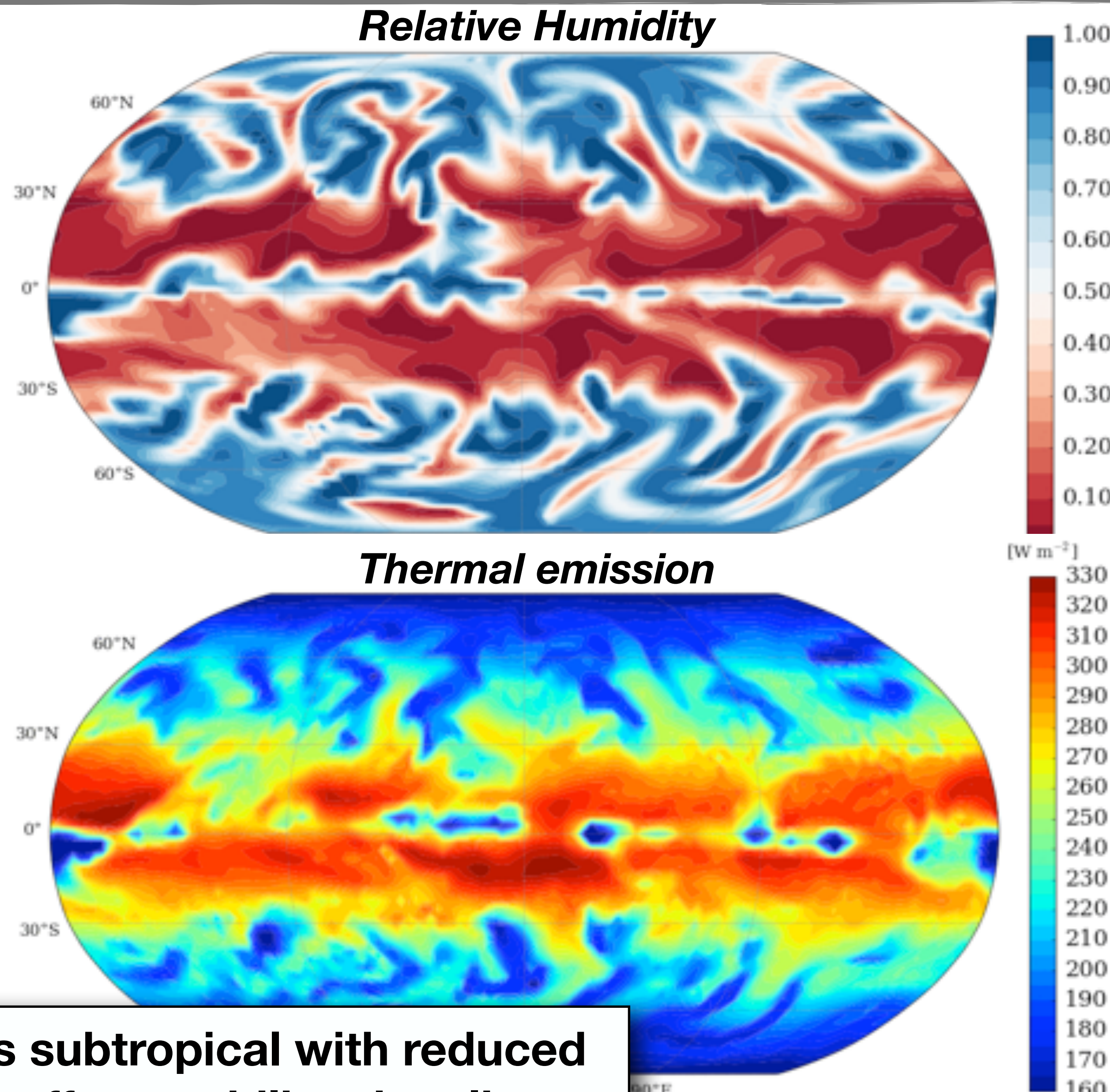


Heating the Earth!



Leconte et al. (Nature; 2013)

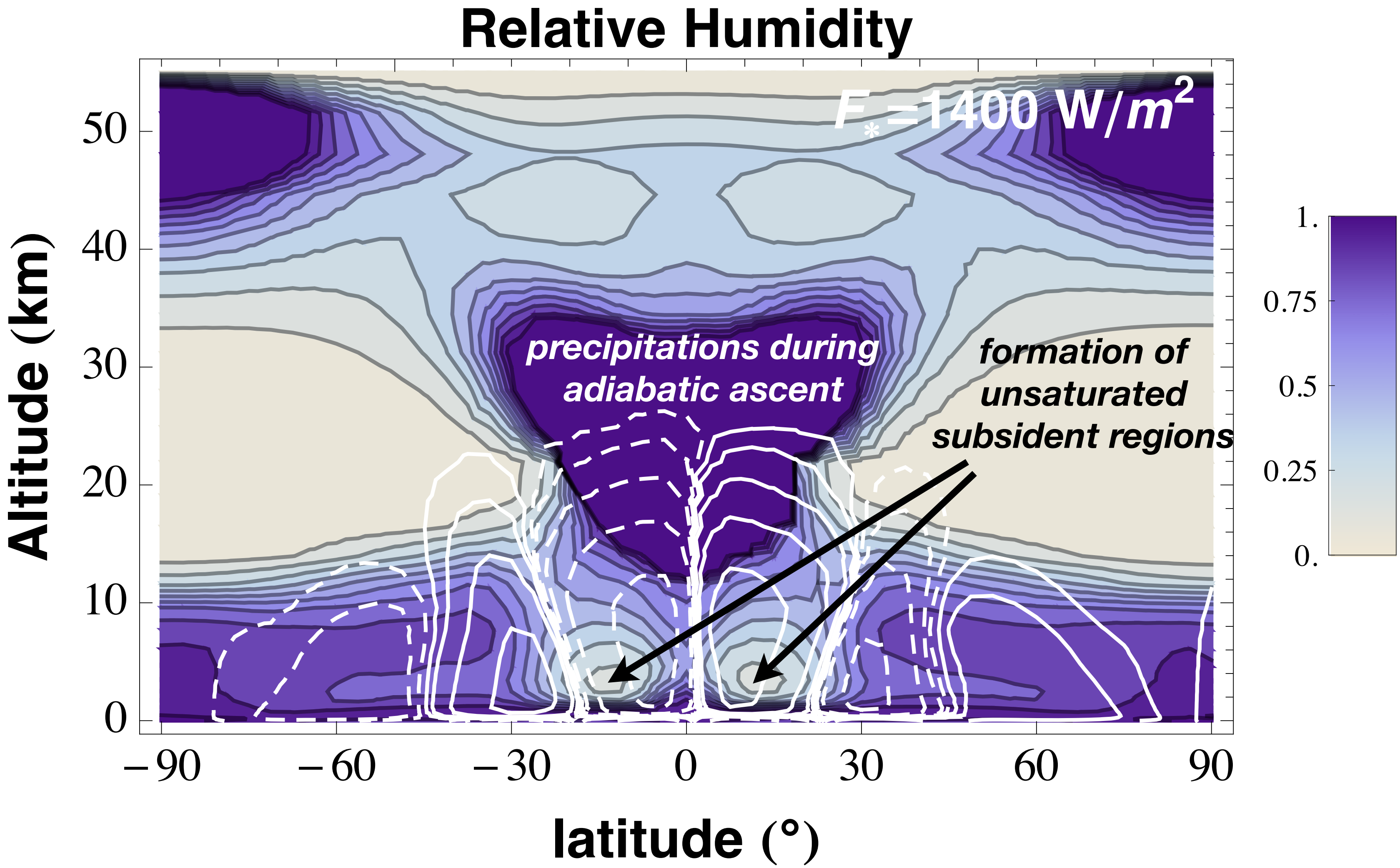
Unsaturated subtropical regions: radiative fins



Dry regions subtropical with reduced greenhouse effect stabilize the climate

…bert (JAS; 1995), Leconte et al. (Nature; 2013)

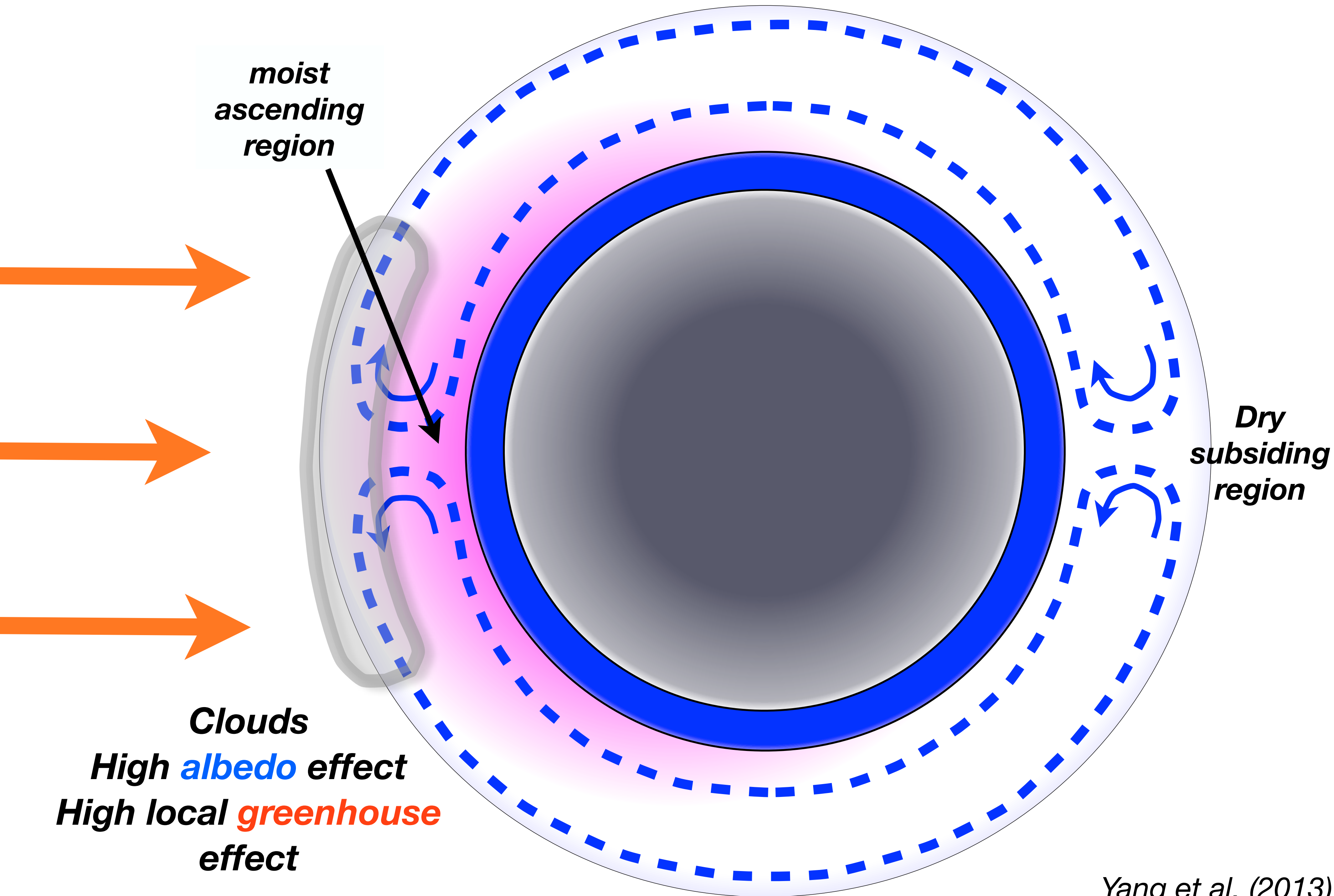
The impact of the Hadley cell



Pierrehumbert (JAS; 1995)

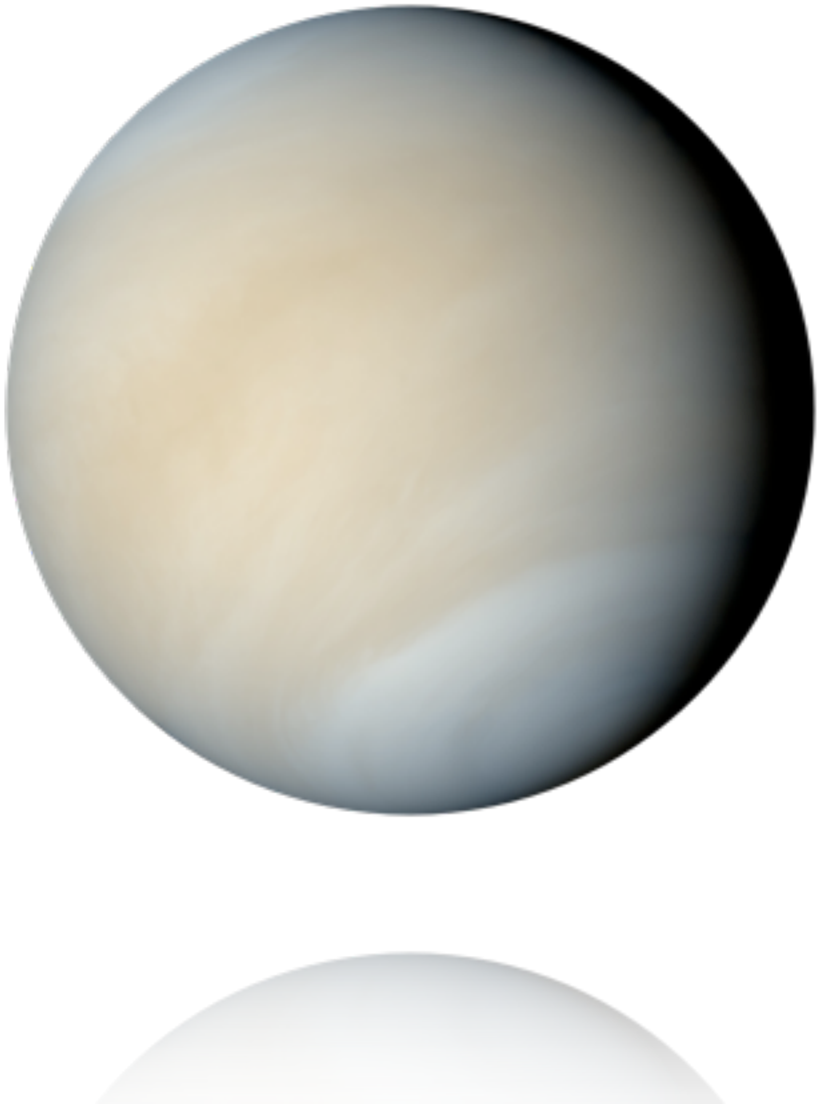
Leconte et al. (Nature; 2013)

Large scale cloud pattern on tidally locked planets



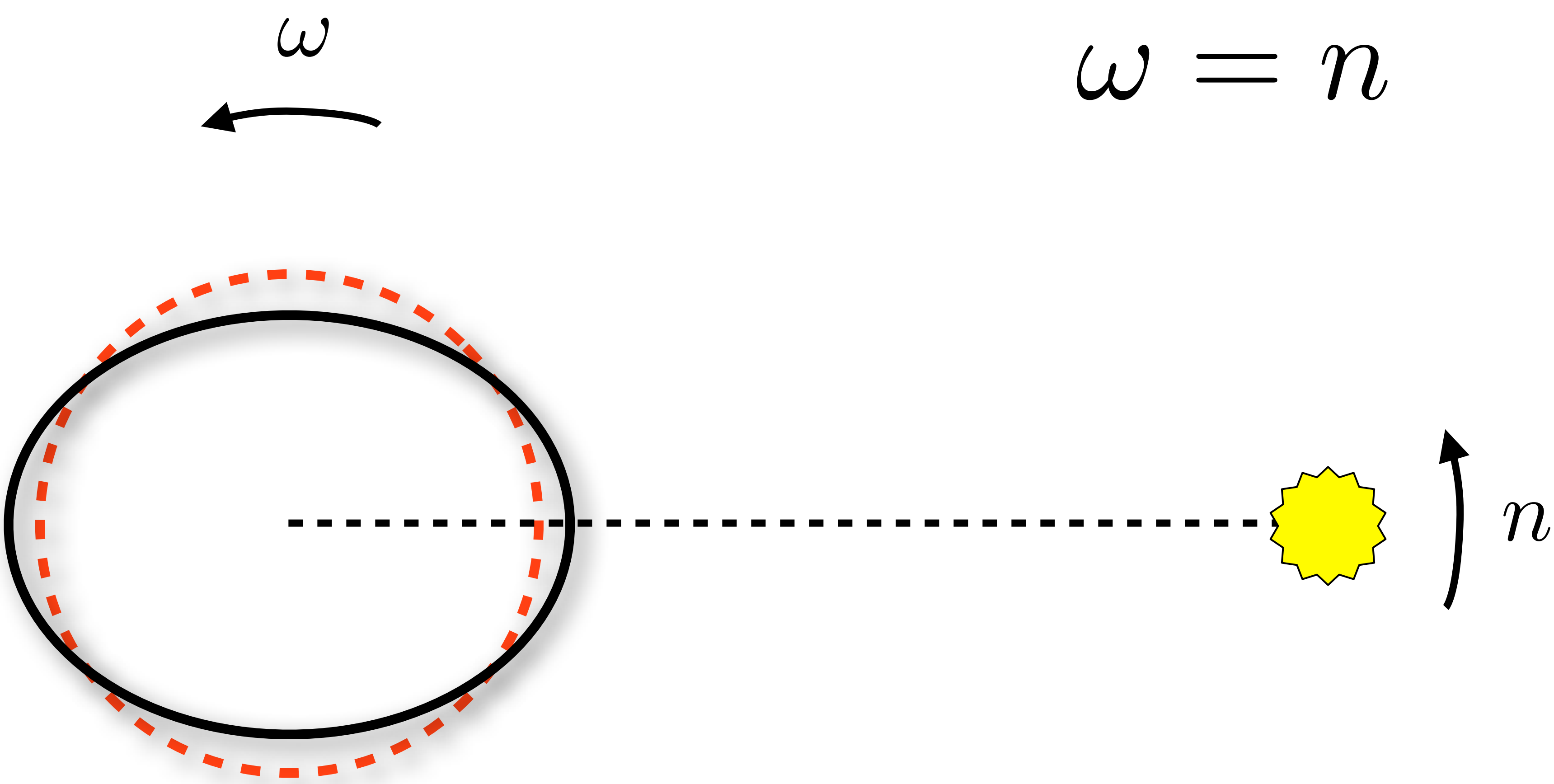
Are exoplanets really synchronized?

Venus is not!



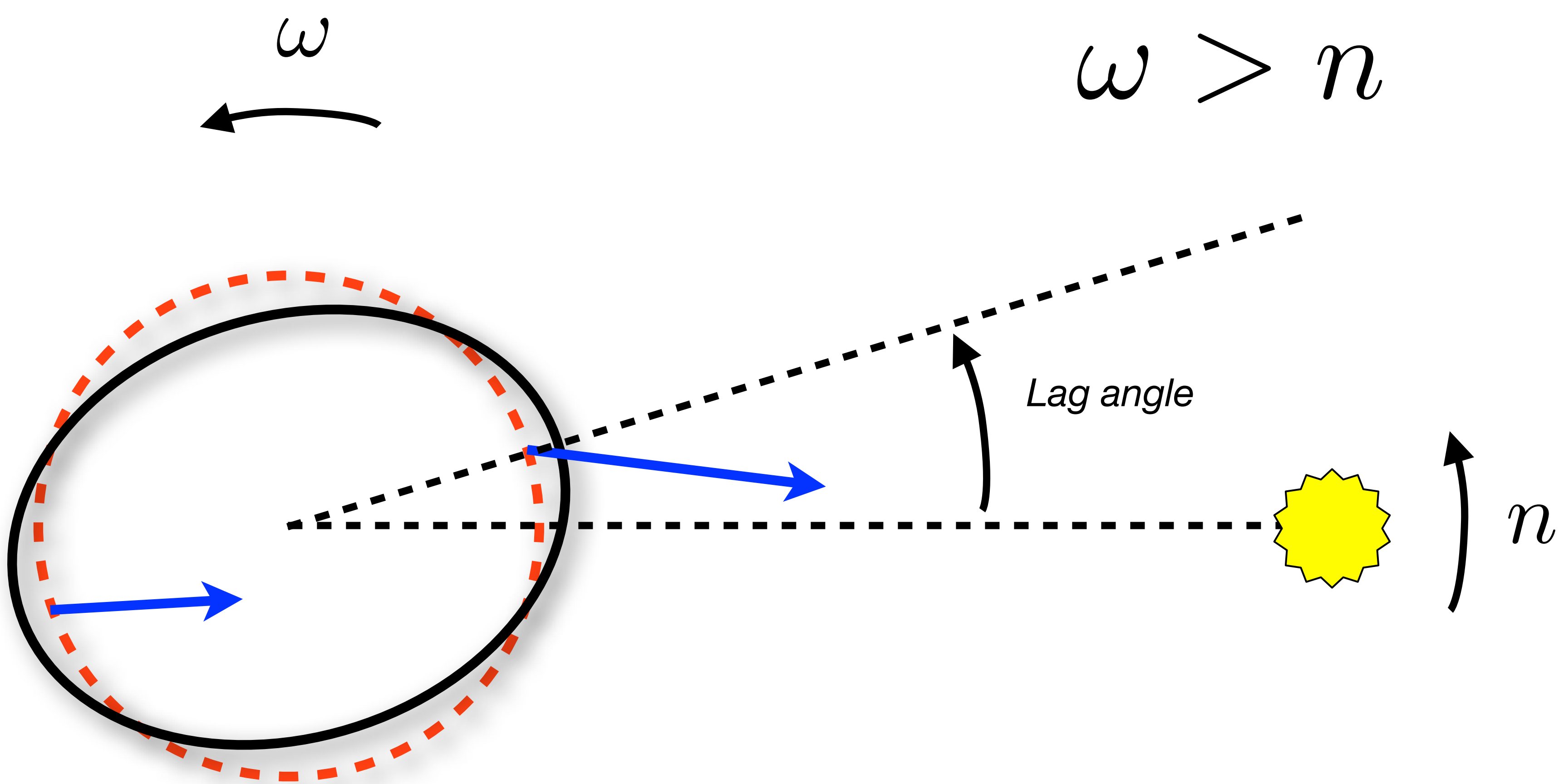
Are exoplanets really synchronized?

$$\omega = n$$



Gravitational Tides

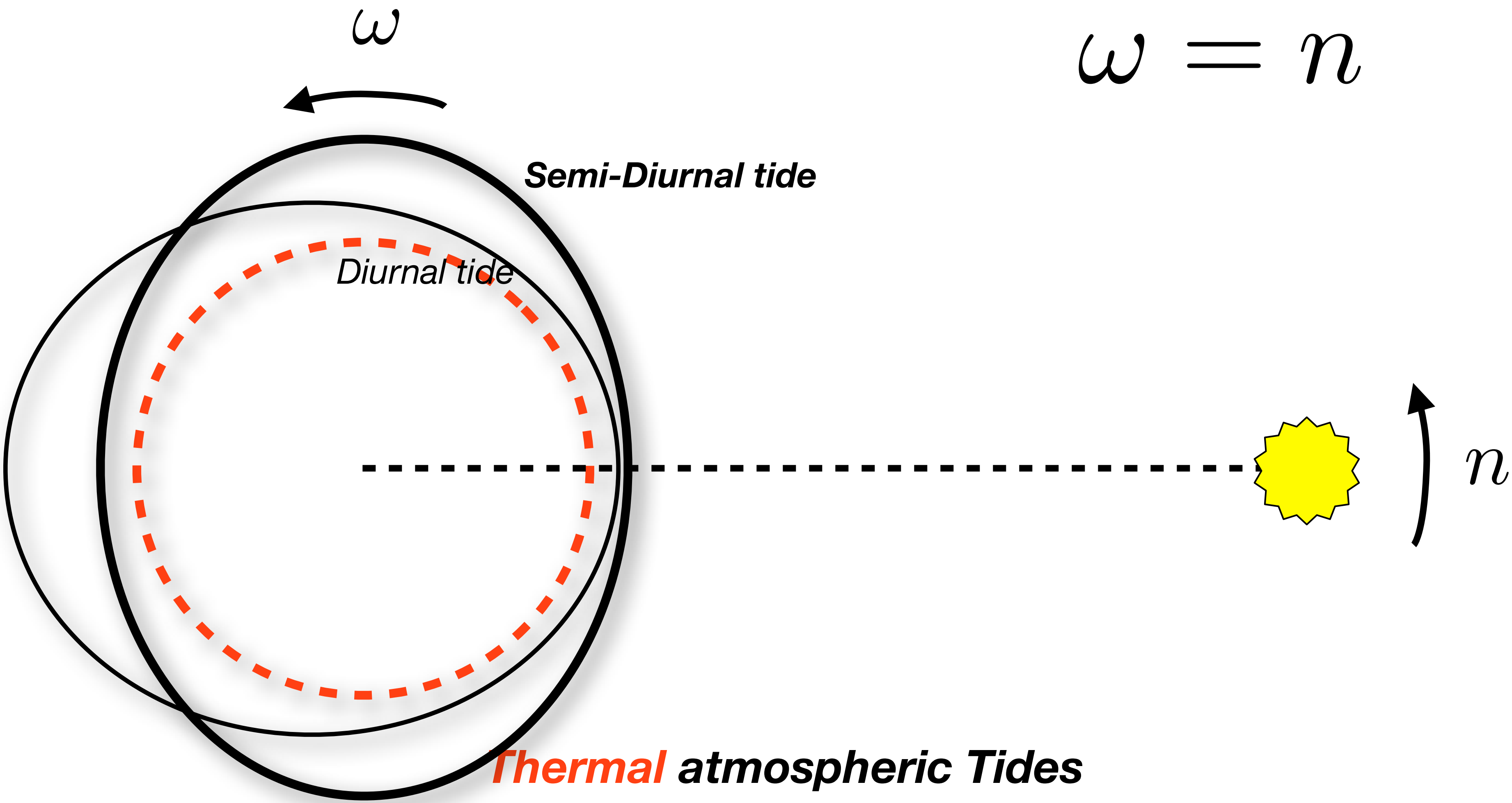
Are exoplanets really synchronized?



Gravitational Tides

Negative torque => Spins down and synchronizes

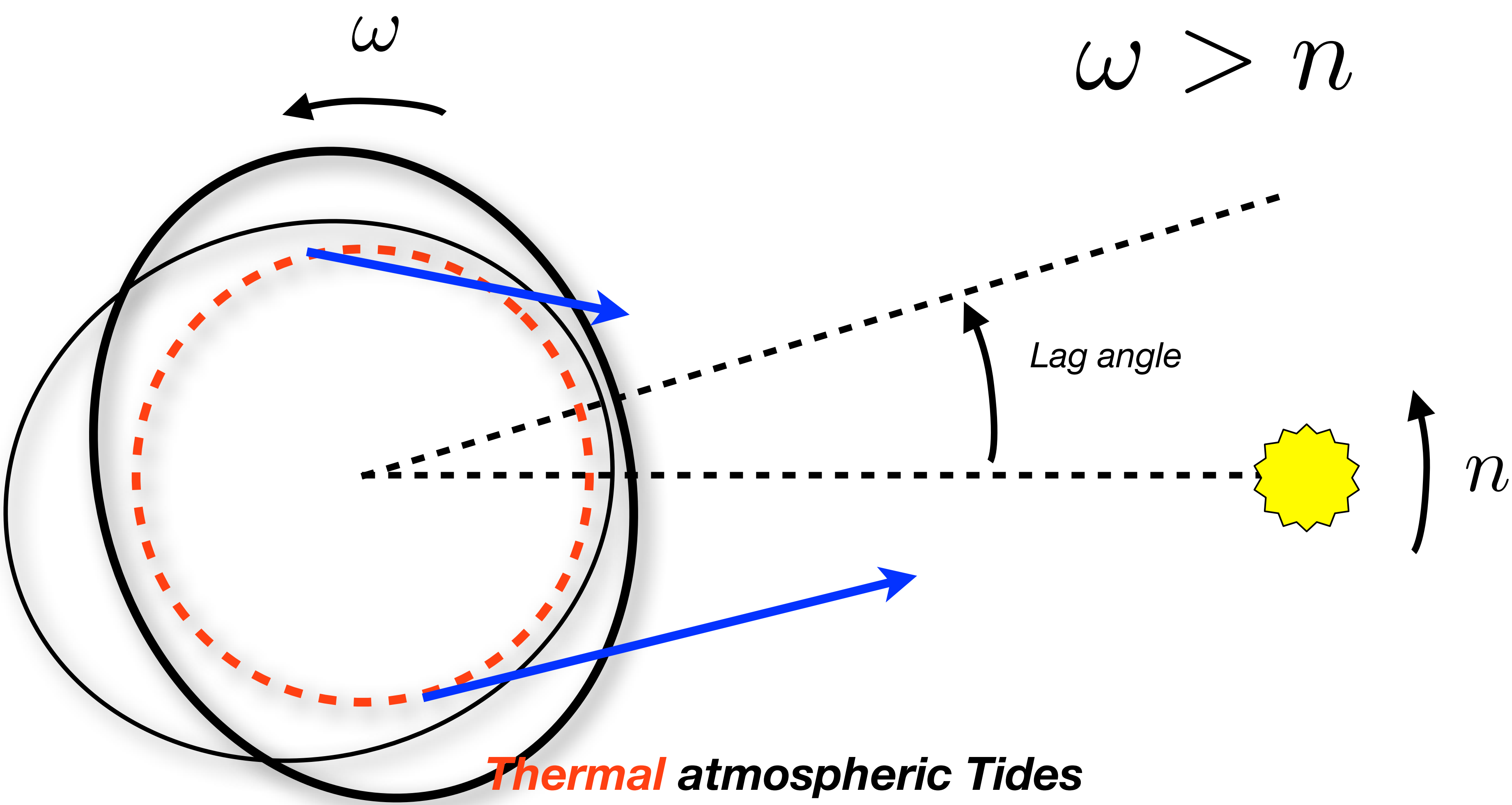
Are exoplanets really synchronized?



***Thermal* atmospheric Tides**

Gold and Soter (ApJ, 1969), Ingersoll & Dobrovolskis (Nature, 1978), Correia & Laskar (Nature, 2001; JGR, 2003; Icarus, 2003)

Are exoplanets really synchronized?

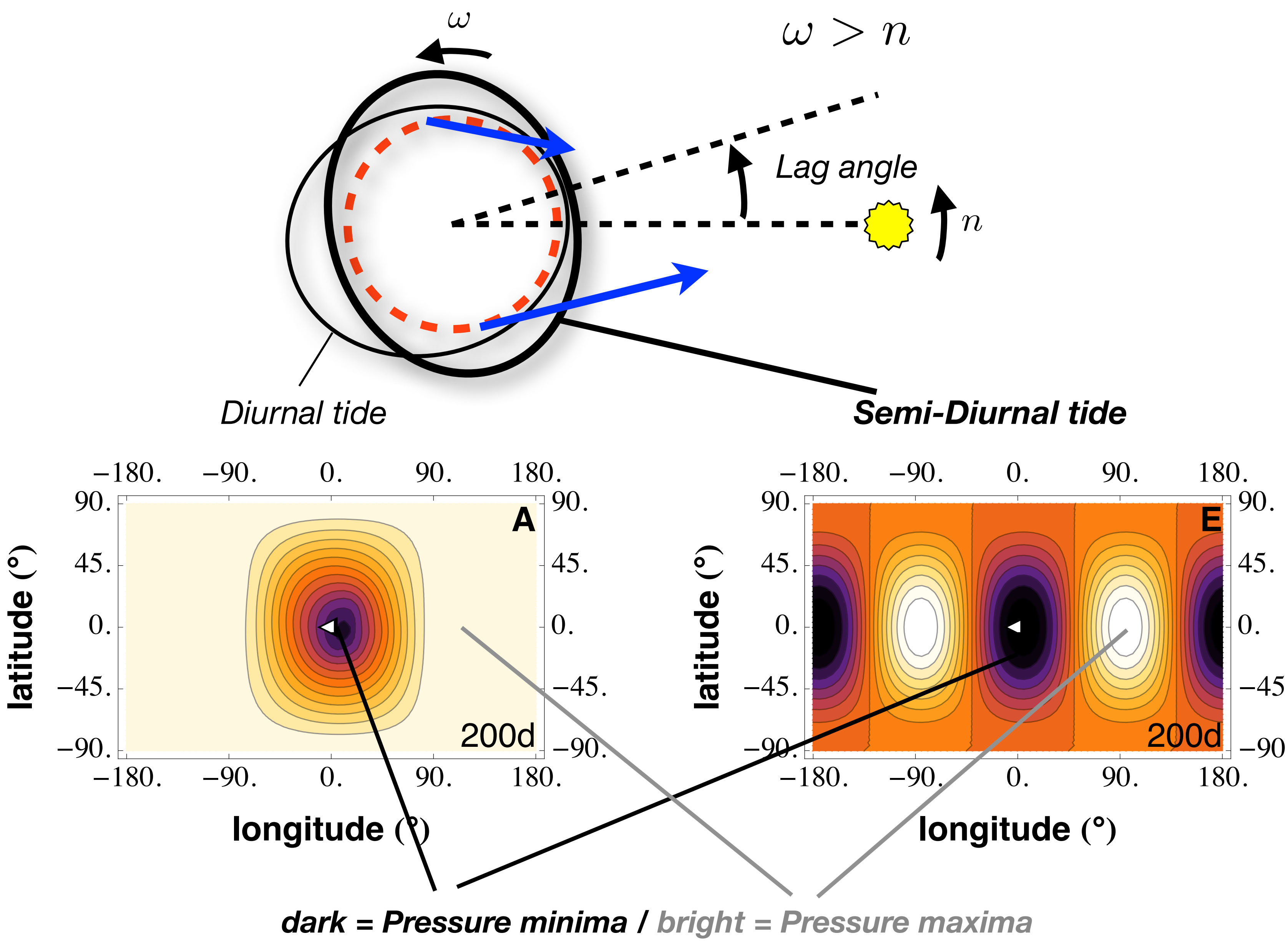


***Thermal* atmospheric Tides**

Positive torque => drives away from synchronization

Gold and Soter (ApJ, 1969), Ingersoll & Dobrovolskis (Nature, 1978), Correia & Laskar (Nature, 2001; JGR, 2003; Icarus, 2003)

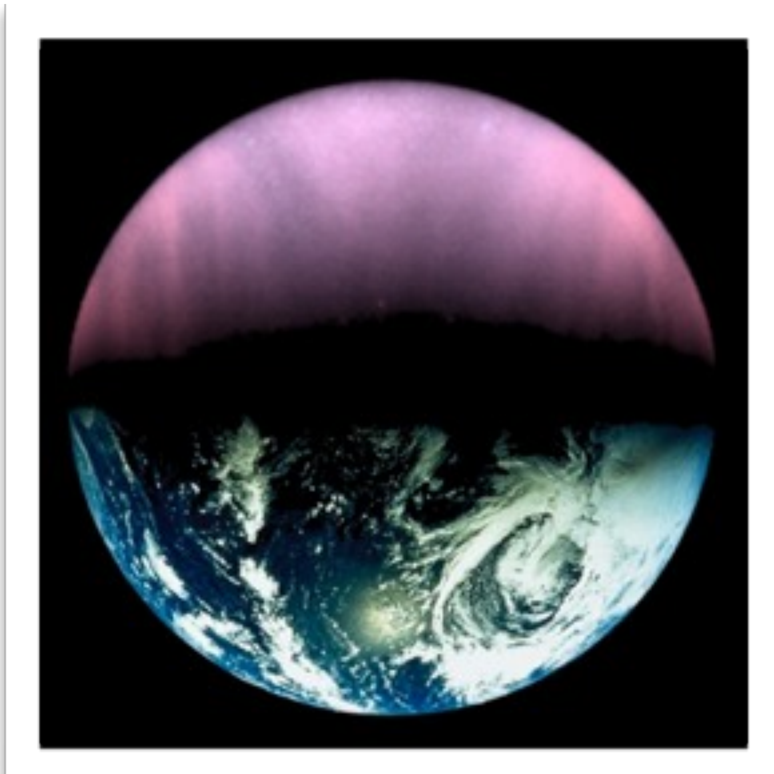
Are exoplanets really synchronized?



Can it work for exoplanets?

in principle ***yes*** *(Correia et al., A&A, 2008),* ***but...***

$$T_{\rm a} \propto \frac{p_{\rm s}}{H_{\rm p}}$$



Venus

CO_2, 92bars, 700K

Terre

N_2, 1bar, 300K

Tides 50 times weaker

(For the same forcing frequency)

Simulations of the surface pressure field: Numerical model

★ *Goal: quantify the torque*

➡ *need mass redistribution*

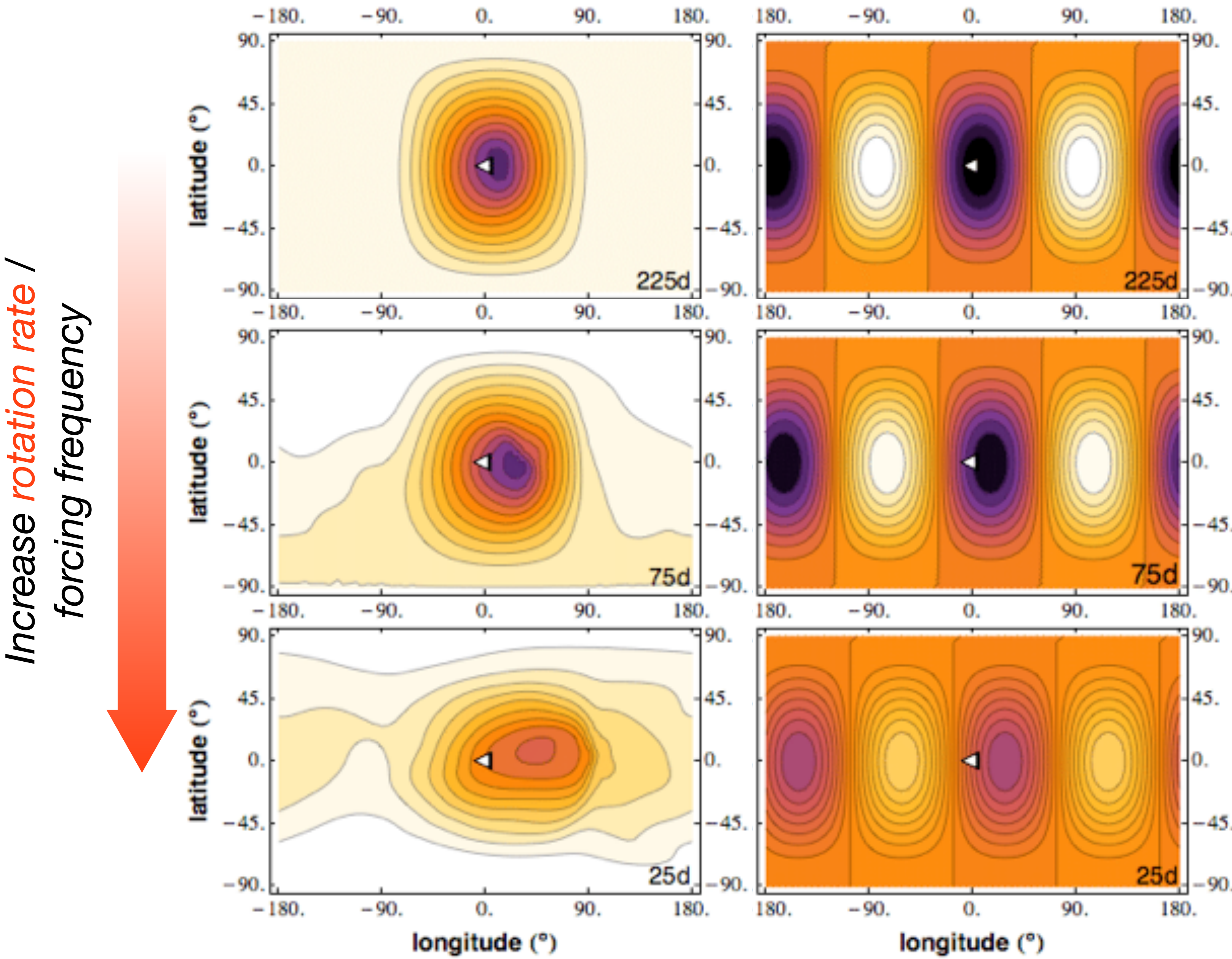
- ➡ *need surface pressure =>* $m_{\mathrm{atm}} = p_{\mathrm{s}}/g$

★ *Approach:*

➡ *Define an atmosphere (p_s, Flux, n, ...)*

➡ *Simulate atmospheric circulation for various rotation rates (synodic period)*

Simulations of the surface pressure field: Numerical model



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★ *Approach:*

➡ *Define an atmosphere (p_s, Flux, n, ...)*

➡ *Simulate atmospheric circulation for various rotation rates (synodic period)*

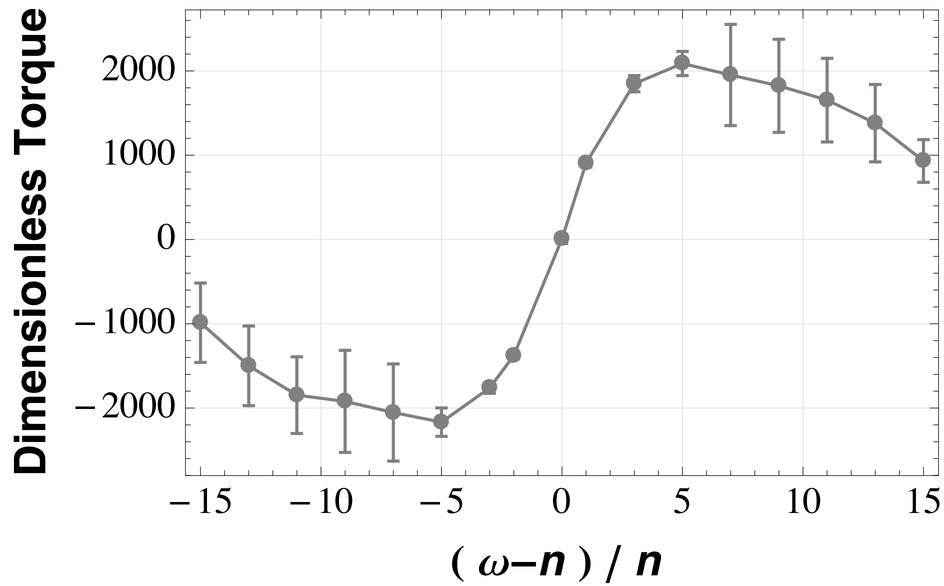
➡ *Quantify the torque*

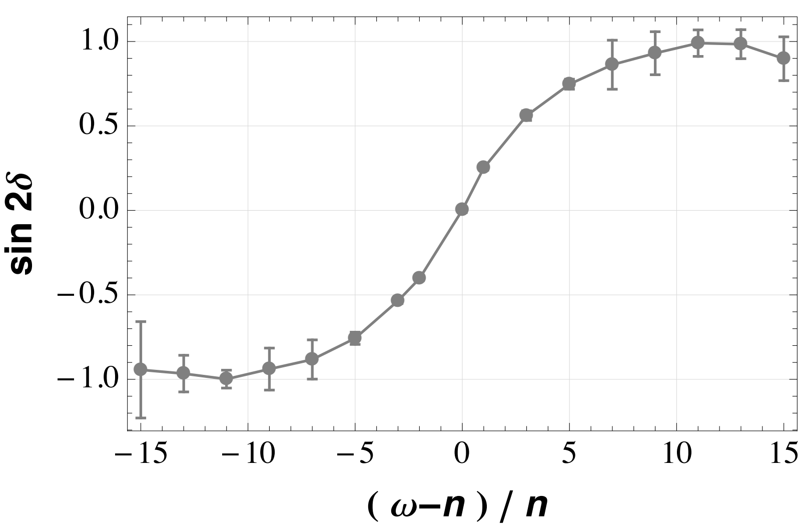
$$T_{\rm a} = -\frac{G M_\star R_{\rm p}}{g} \sum_{l=2}^{\infty} \frac{4\pi}{2l+1} \left(\frac{R_{\rm p}}{r}\right)^{l+1} \sum_{m=-l}^{l} i\, m\, p_l^m\, Y_l^m(\theta_\star = \frac{\pi}{2}, \phi_\star),$$

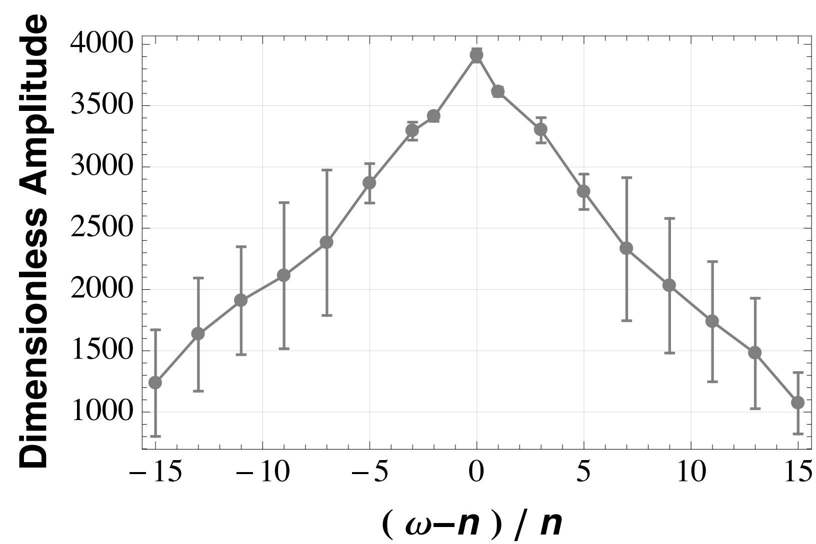
$$T_{\rm a} = K_{\rm a}\, \mathbb{I}{\rm m}(p_2^2)$$

$$p_l^m \equiv \int Y_l^{m*}\, p_{\rm s}\, {\rm d}\Omega$$

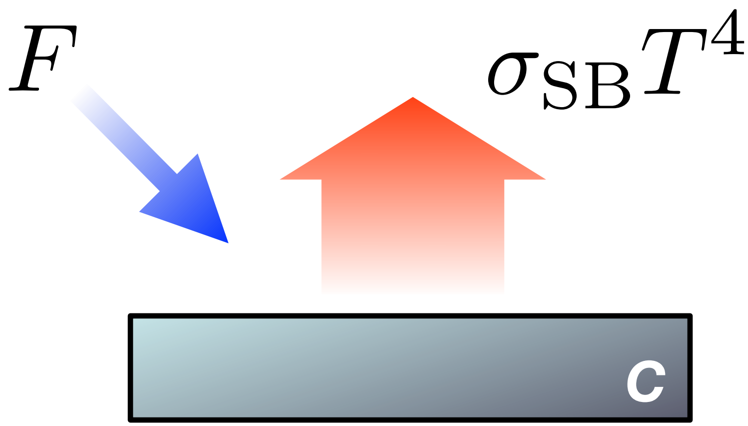
Pressure moment







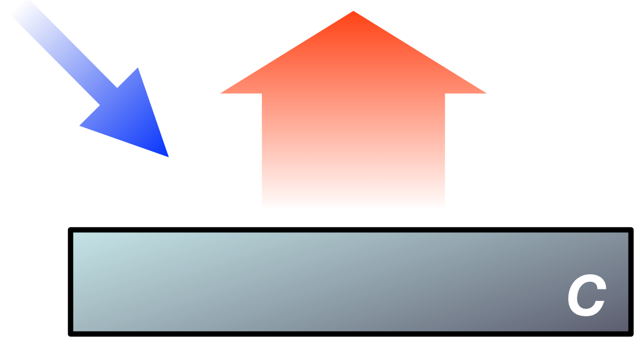
A simple analytical model: periodically heated slab



$$C\frac{\mathrm{d}T}{\mathrm{d}t} = F - \sigma T^4$$

A simple analytical model: periodically heated slab

$$F_0 + \delta F e^{i\sigma t} \qquad \sigma_{\mathrm{SB}} T_0^4 + 4\,\sigma_{\mathrm{SB}} T_0^3\,\delta T\,e^{i\sigma t}$$



$$C\frac{\mathrm{d}}{\mathrm{d}t}\delta T = F_0 - \sigma T_0^4 + \delta F - 4\sigma T_0^3 \delta T.$$

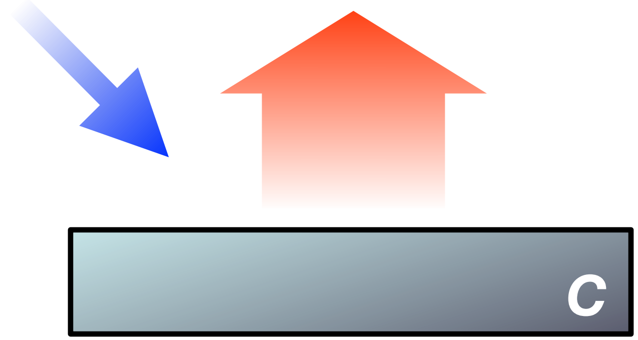
$$\delta T = \frac{\delta F}{2\,\omega_0\,C}\frac{1}{1 + i\sigma/(2\omega_0)}$$

$$\delta p = \frac{q_0}{1 + i\sigma/(2\omega_0)}$$

A simple analytical model: periodically heated slab

$$F_0 + \delta F e^{i\sigma t}$$

$$\sigma_{\rm SB} T_0^4 + 4\, \sigma_{\rm SB} T_0^3\, \delta T\, e^{i\sigma t}$$

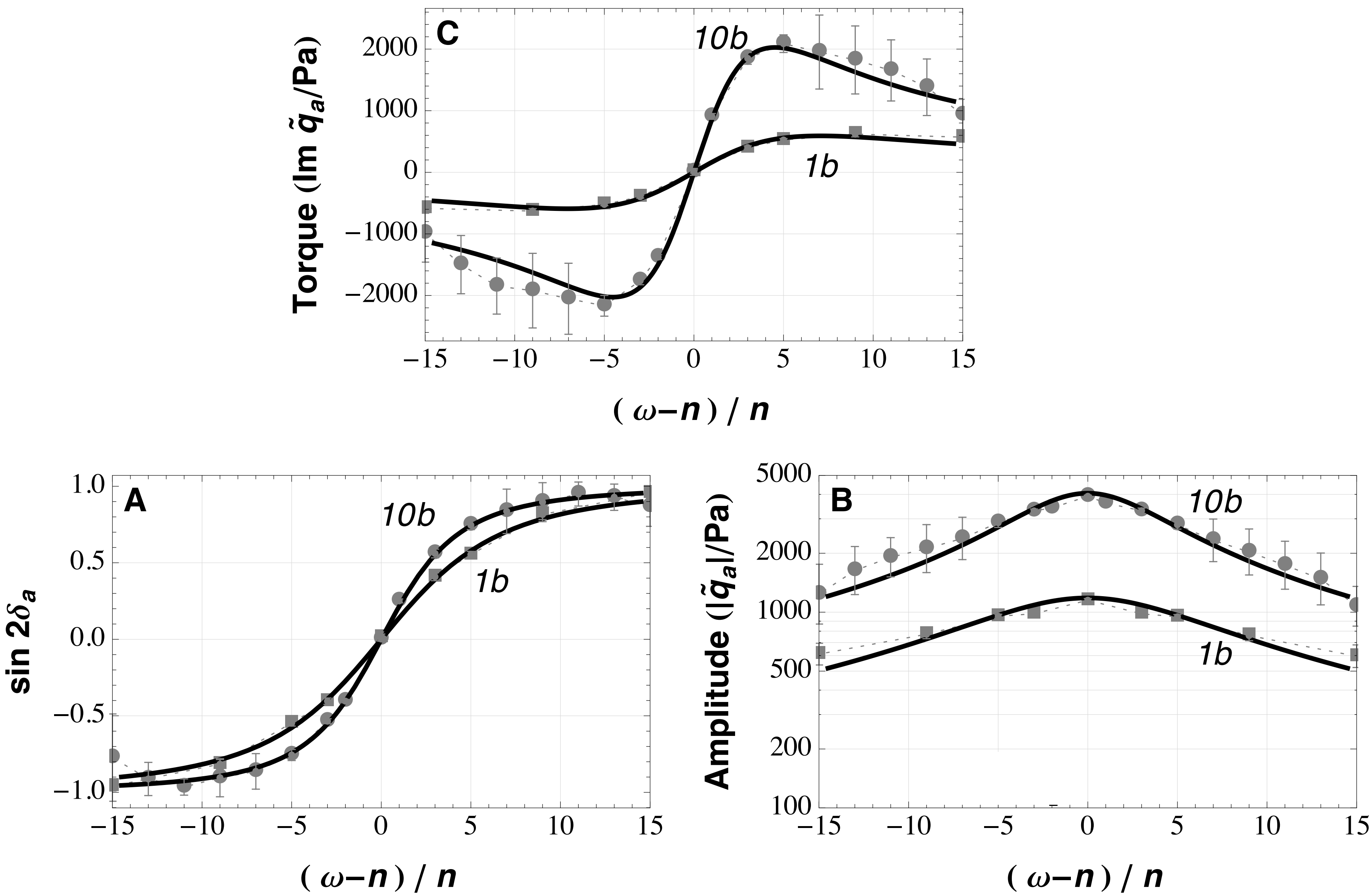


$$C \frac{\mathrm{d}}{\mathrm{d}t} \delta T = F_0 - \sigma T_0^4 + \delta F - 4\sigma T_0^3 \delta T.$$

$$\delta p = \frac{q_0}{1 + i\sigma/(2\omega_0)}$$

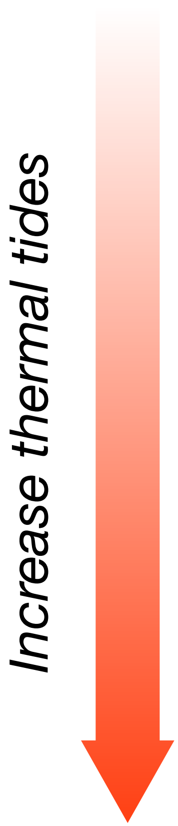
$$T_{\rm a} = \mathrm{Im}(\delta p) = K_{\rm a} \frac{(\omega - n)/\omega_0}{1 + ((\omega - n)/\omega_0)^2}$$

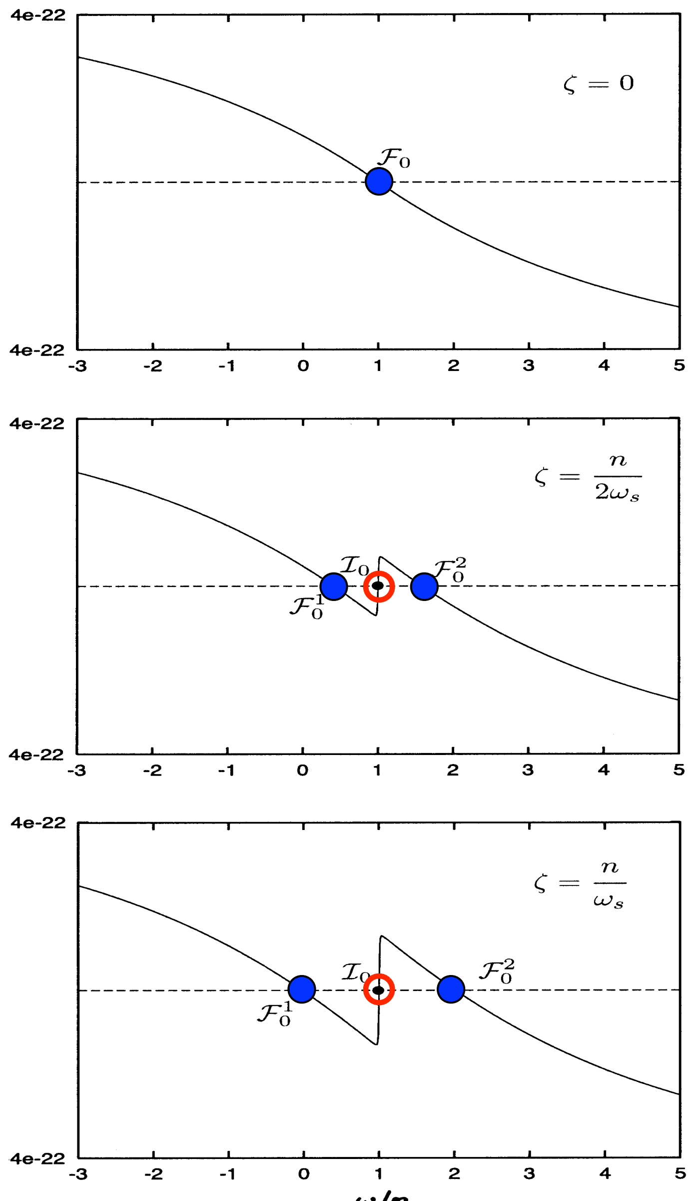
Model validation



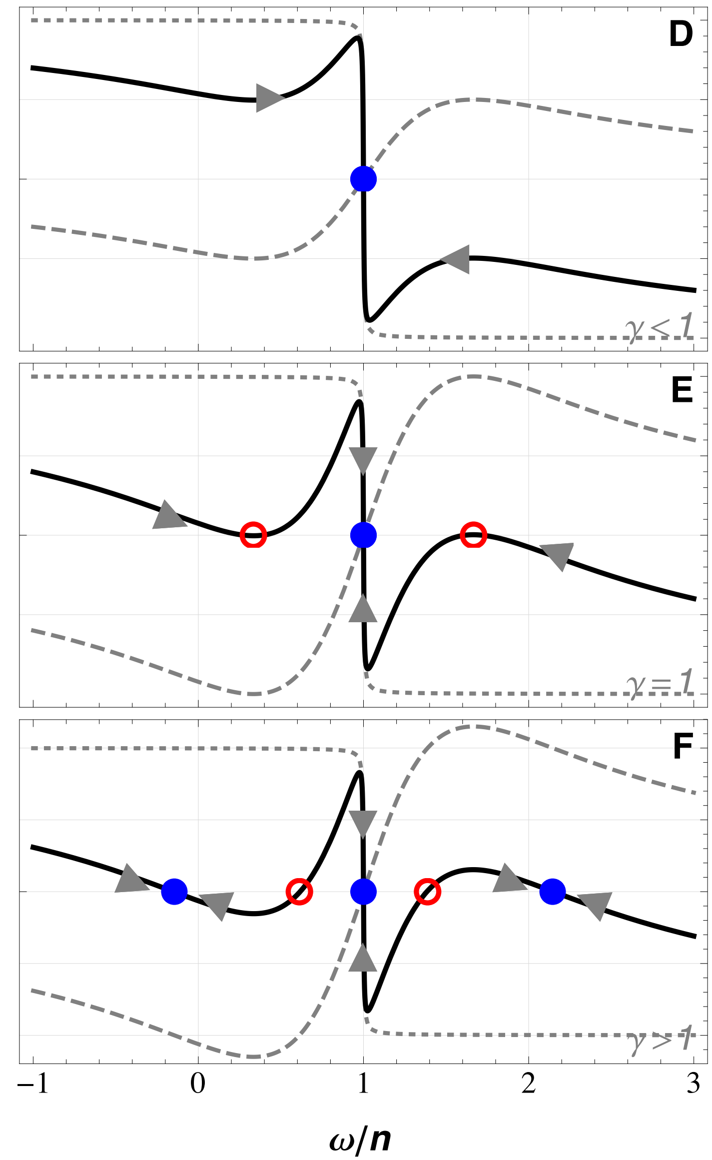
Leconte et al. (2015, Science)

Equilibrium spin states



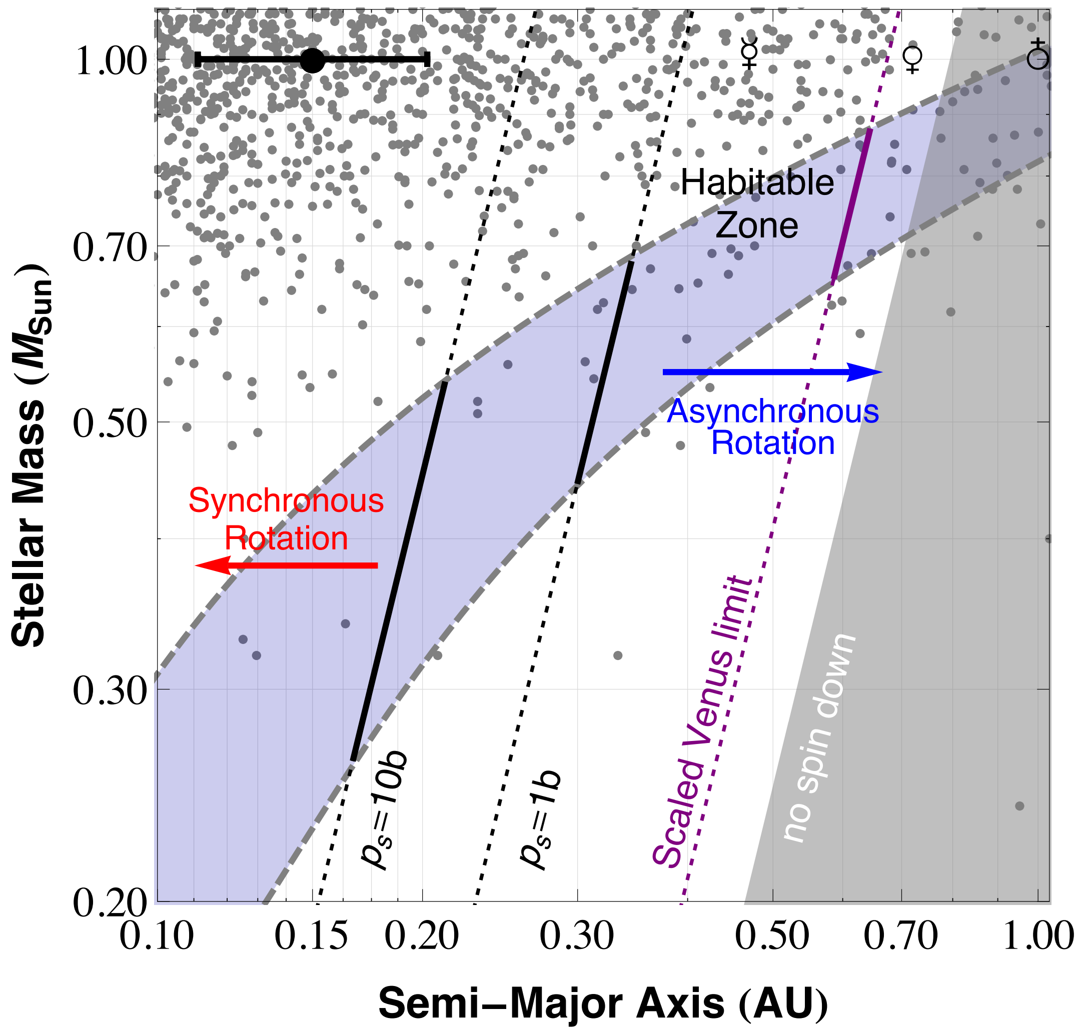


Correia, Laskar, Neron de Surgy (Icarus, 2003)



Leconte et al. (2015, Science)

Critical asynchronous distance



Leconte et al. (2015, Science)