# *Equatorial dynamics of hot Jupiters and warm Neptunes*

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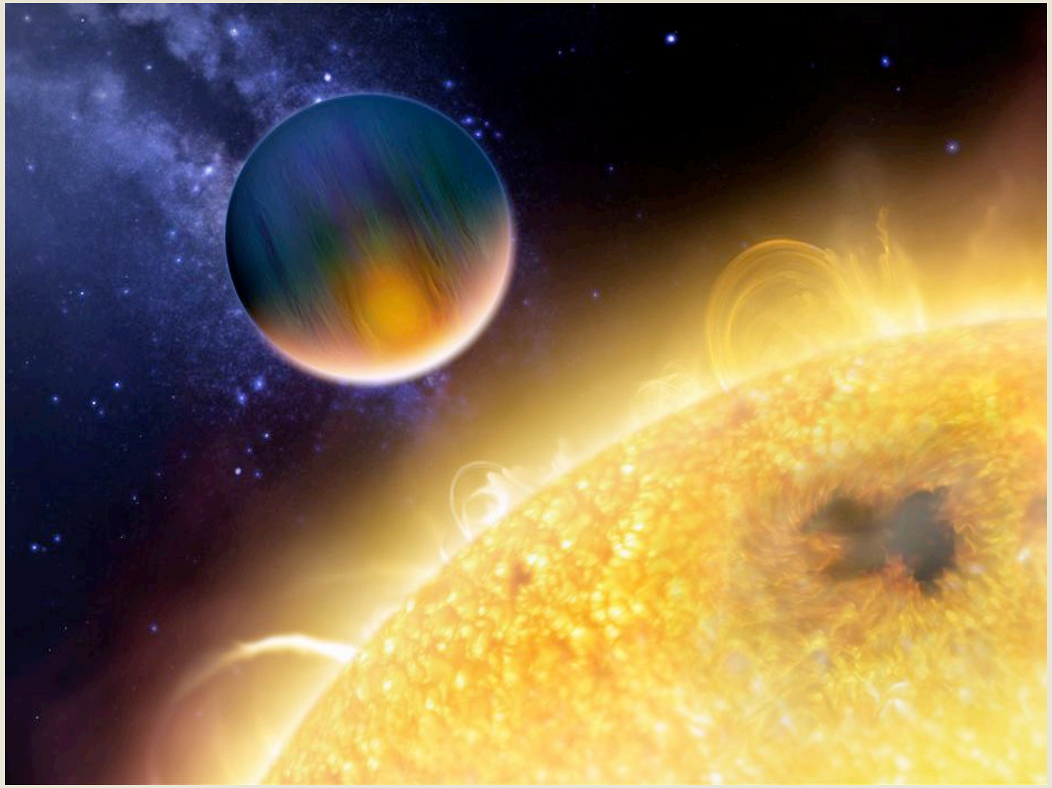
# Overview



I. *Observations and simulations*

II. *Warm Neptunes: breaking of the primitive equations*

III. *Hot Jupiters: spin-up of superrotation*

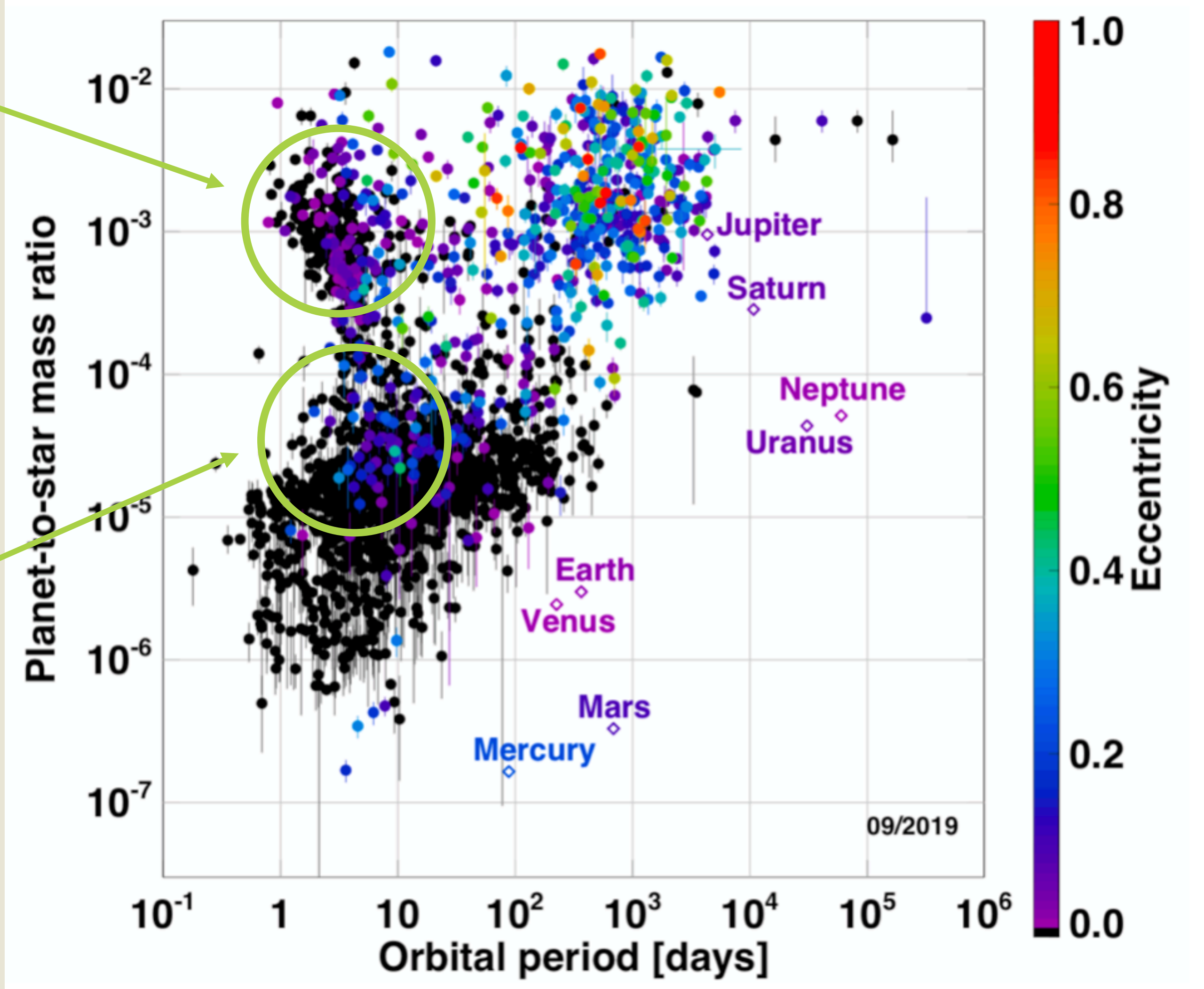


# I. Observations and simulations

Hot Jupiters

> 3500 confirmed exoplanets

Warm Neptunes



# I. Observations and simulations



Hot Jupiters

First discovery:
51 Peg b, Mayor & Queloz 1995

Jupiter mass and radius

**HD 209458b**

| Mass | Radius | Orbital period | Semi major axis |
|---|---|---|---|
| 0.7 $M_J$ = 222 $M_T$ | 95000 km = 1.36 $R_J$ | 3.5 days | 0.04 AU |

Short orbits: tidally locked

Day side – night side temperature difference: ~1000K

# I. Observations and simulations



## Warm Neptunes

First characterized:
Corot 7b, Leger et al. 2009

**GJ 1214b**

| Mass | Radius | Orbital period | Semi major axis |
|---|---|---|---|
| 6.5 $M_T$ | 2.7 $M_T$ | 1.5 days | 0.015 AU |

Warm Neptunes or super Earths ?

First atmospheric studies: GJ 1214b. Low density: extended atmosphere

# I. Observations and simulations



Detection

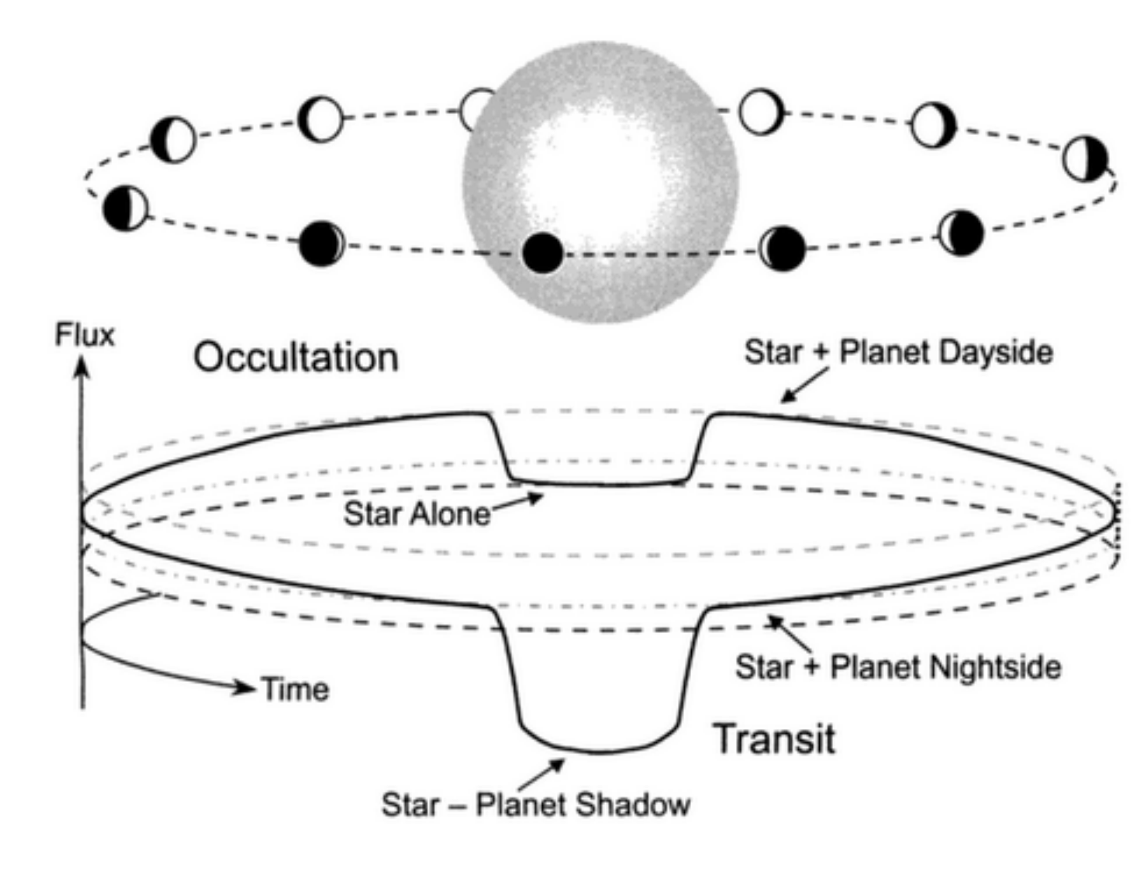
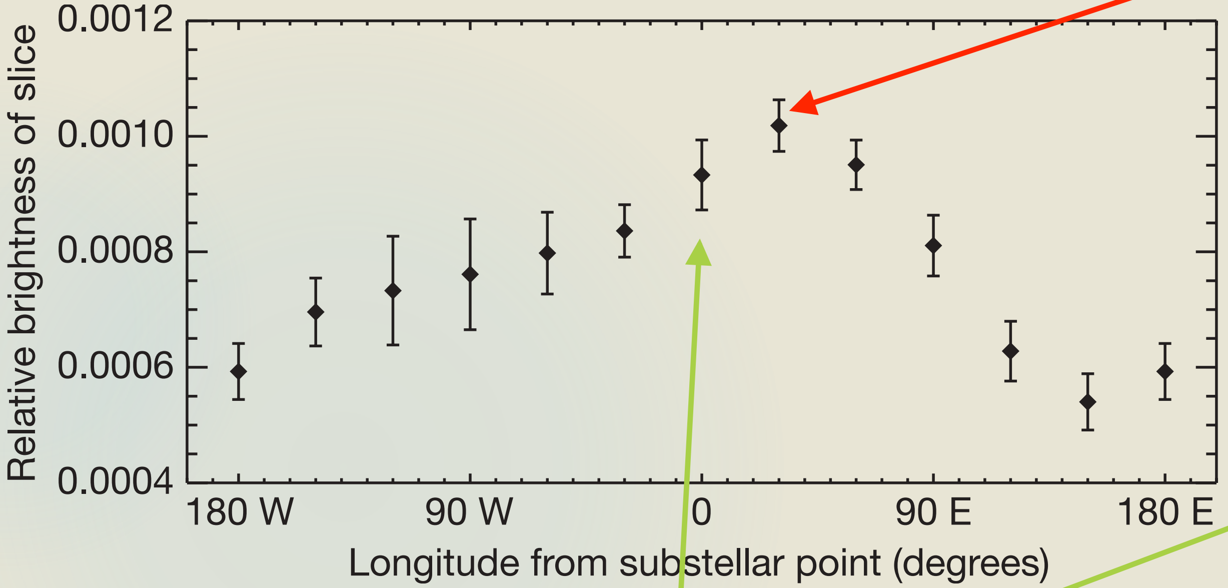


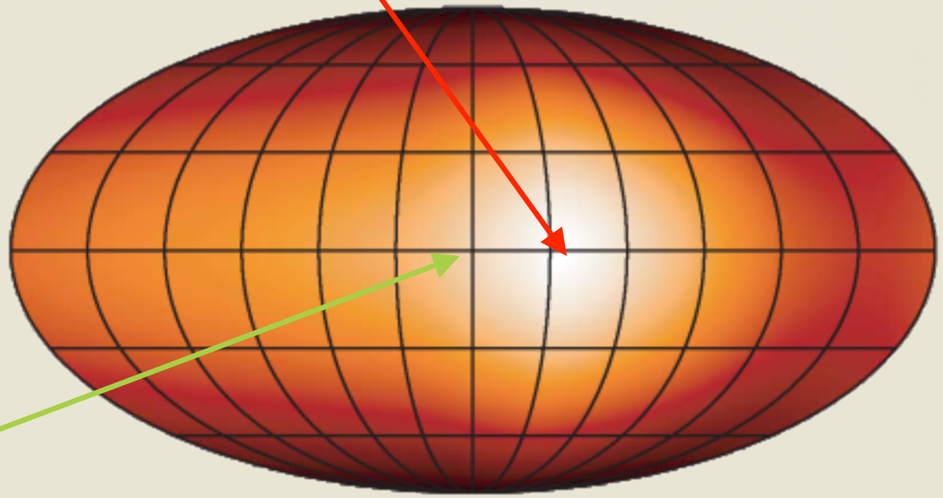

Image credit : Josh Winn

# I. Observations and simulations

Observations




Maximum temperature

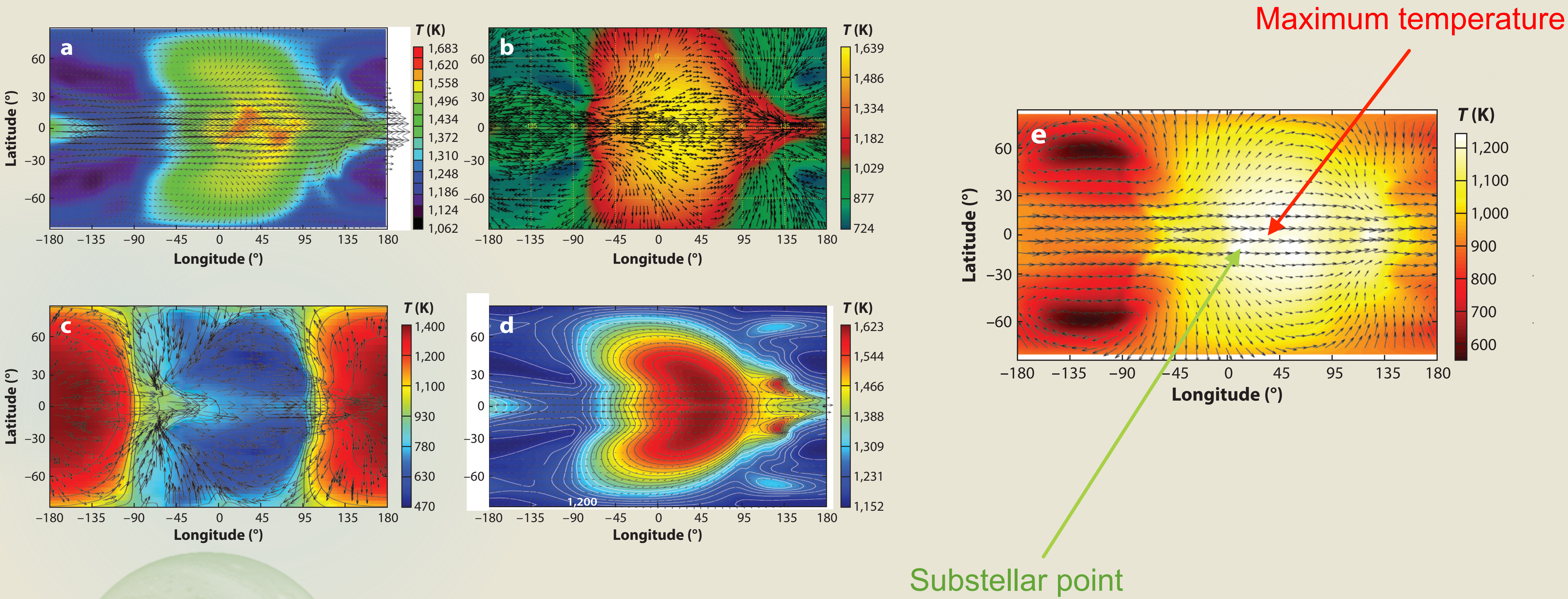


Substellar point

Knutson et al. 2007

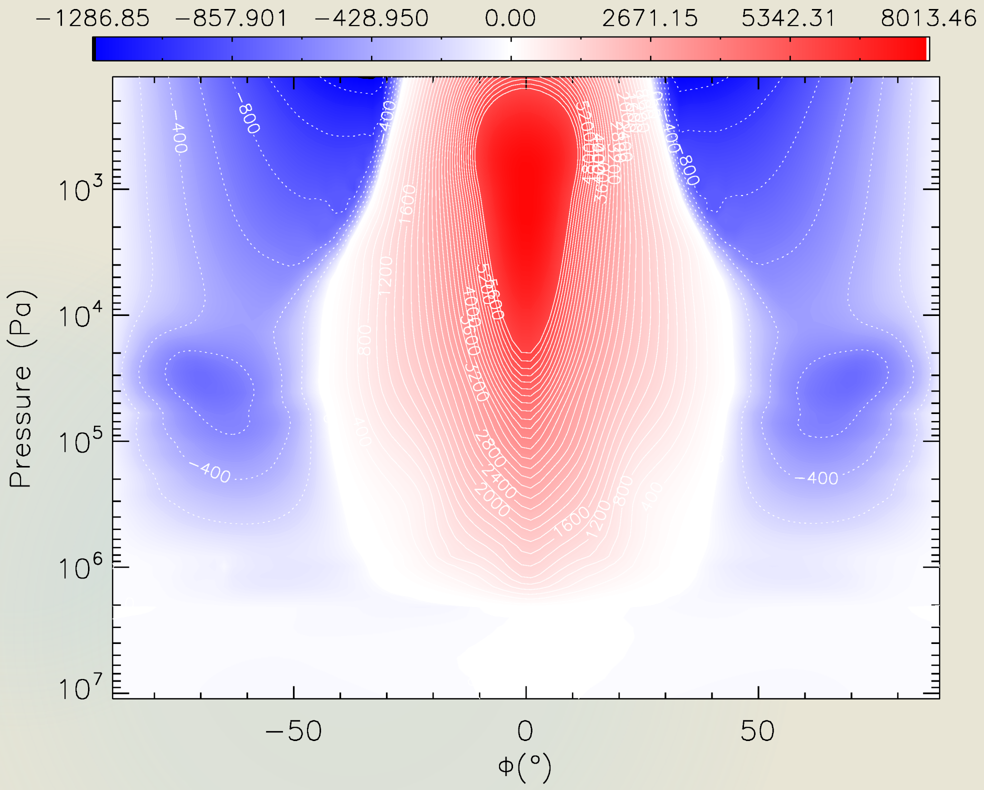
# I. Observations and simulations

Simulations

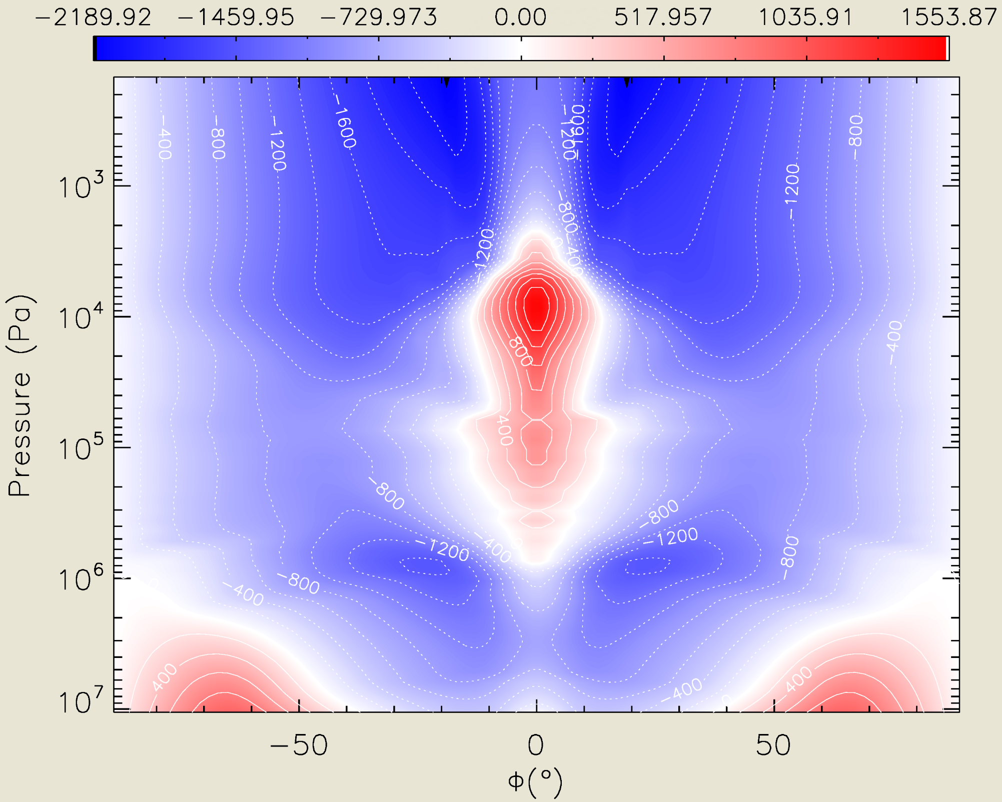


# I. Observations and simulations

## Robustness of superrotation




Mayne, Debras et al. 2017

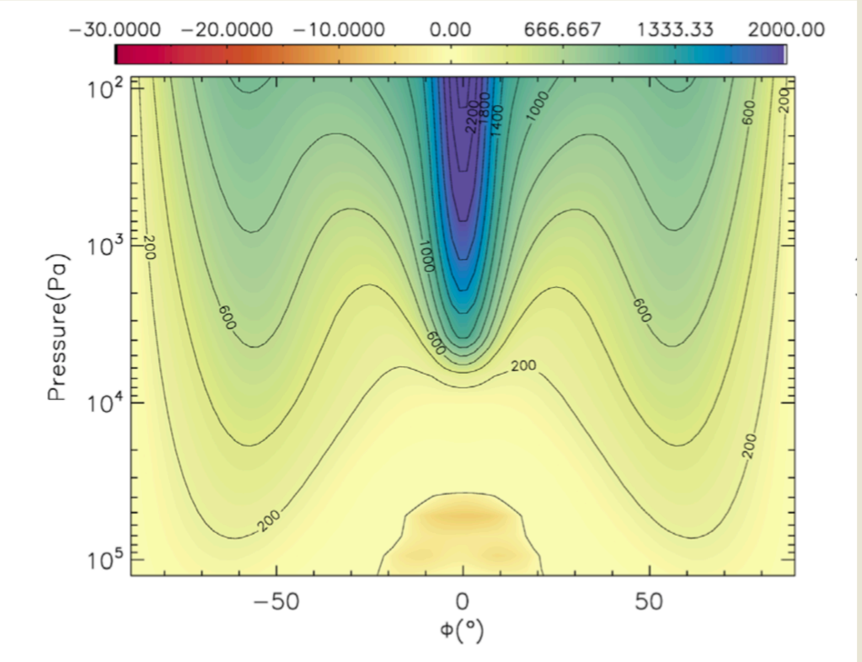


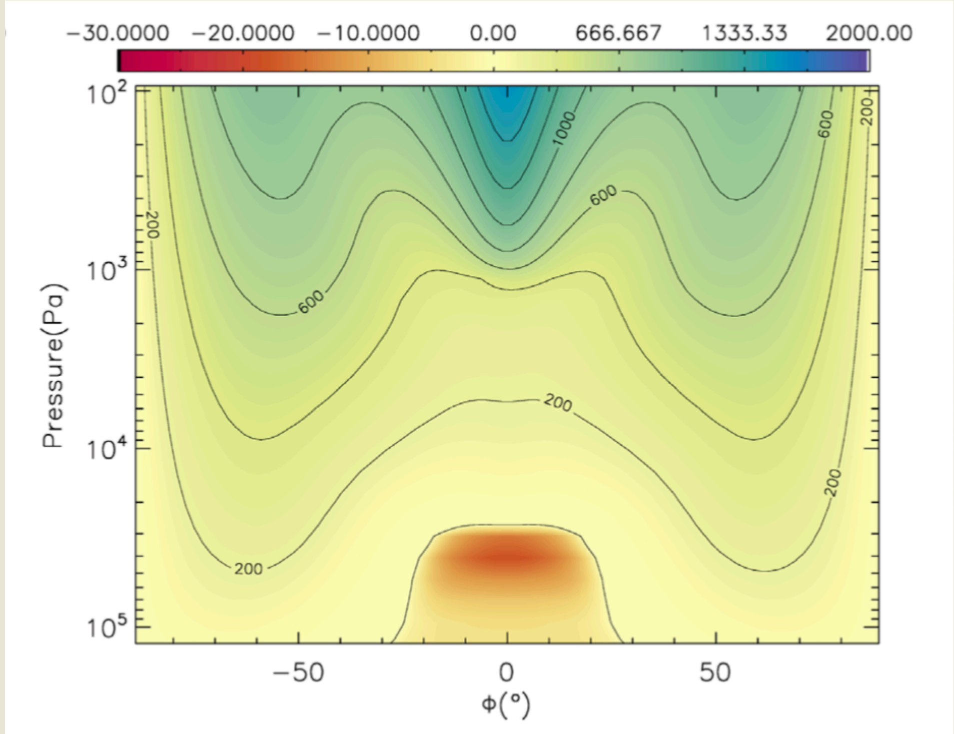

**What is the physical origin of superrotation on hot Jupiters ?**

# I. Observations and simulations

Primitive equations ?

Mayne et al 2014: primitive equations hot Jupiters




Mayne et al. 2019: what about warm Neptunes ?

**Can we model warm Neptunes/super Earths with the primitive equations ?**

# II. Warm Neptunes



## Primitive equations

Much faster computationnally than full equations.

Four approximations, based on the Earth's shallow atmosphere/oceans:

1) Hydrostatic balance. Never a problem in our simulations.
2) Shallow fluid approximation: $r \approx R$, $\partial/\partial r \approx \partial/\partial z$
3) Traditional approximation: buyoancy dominates Coriolis. No latitudinal component of rotation
4) Gravity is constant with height.

# II. Warm Neptunes

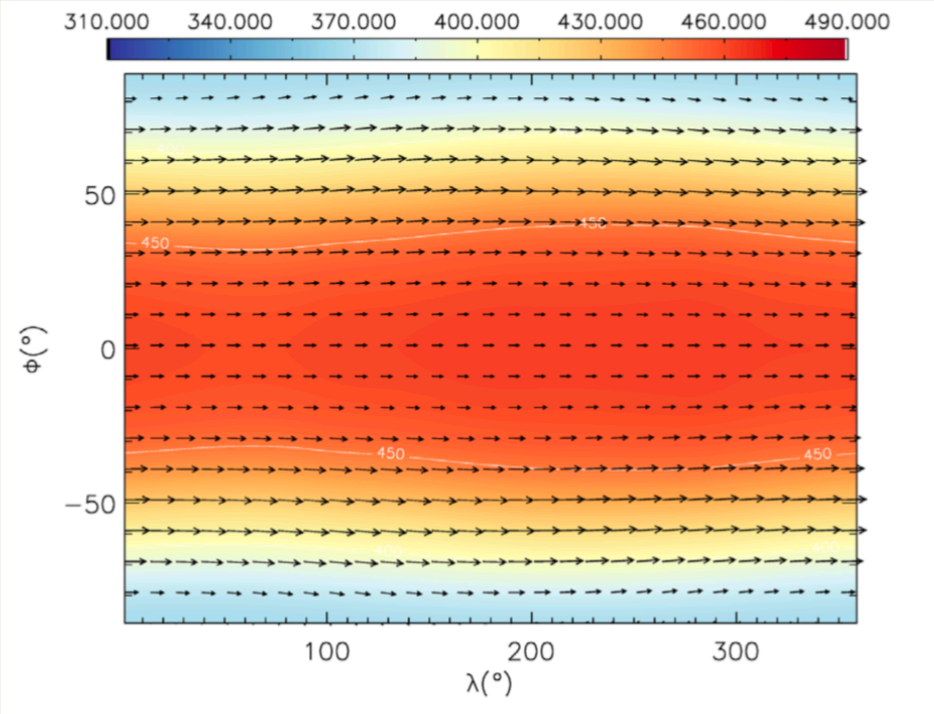


## Assumptions

Goal: estimate the validity of $w \ll v \tan(\varphi)$

Analytical estimates based on four assumptions:

1) The atmosphere is globally superrotating
2) $\Delta T \ll \Delta T_{forcing}$
3) V is only due to Coriolis
4) Incompressible hydrostatic atmosphere




0.3 bars

# II. Warm Neptunes

## Results

$U \sim \sqrt{\frac{3}{2\pi} R_p \mathcal{R} \Delta T_{forcing} / \tau_{rad}} \sim 1400\ m.s^{-1}$

$W \sim \frac{H}{L} \sqrt{\frac{3}{2\pi} R_p \mathcal{R} \Delta T_{forcing} / \tau_{rad}}$

$V \tan(\varphi) \sim \frac{\pi}{2} R_p \Omega \sin^2(\varphi)/\cos(\varphi)$

Increases with: radius, forcing
Decreases with; molecular weight

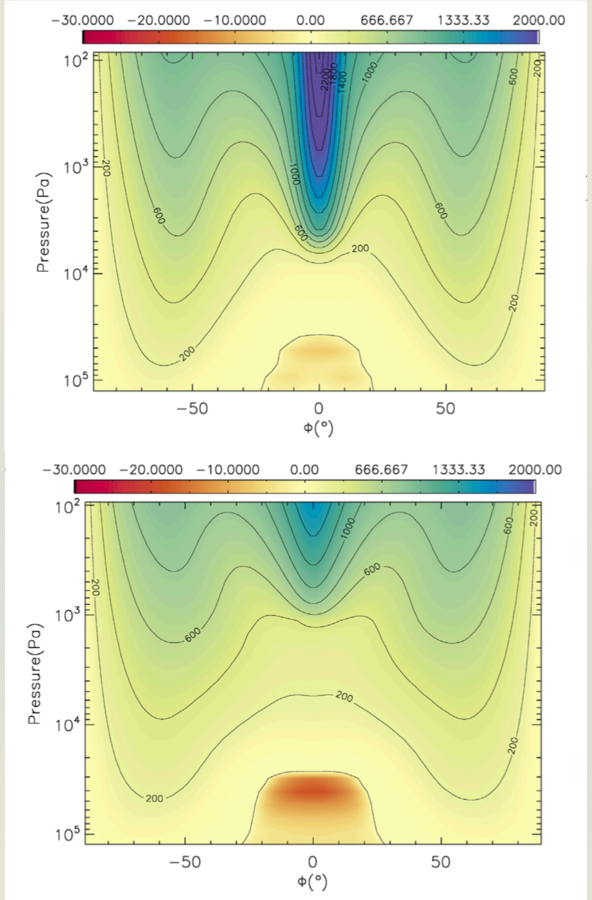
Increases with: radius, rotation rate

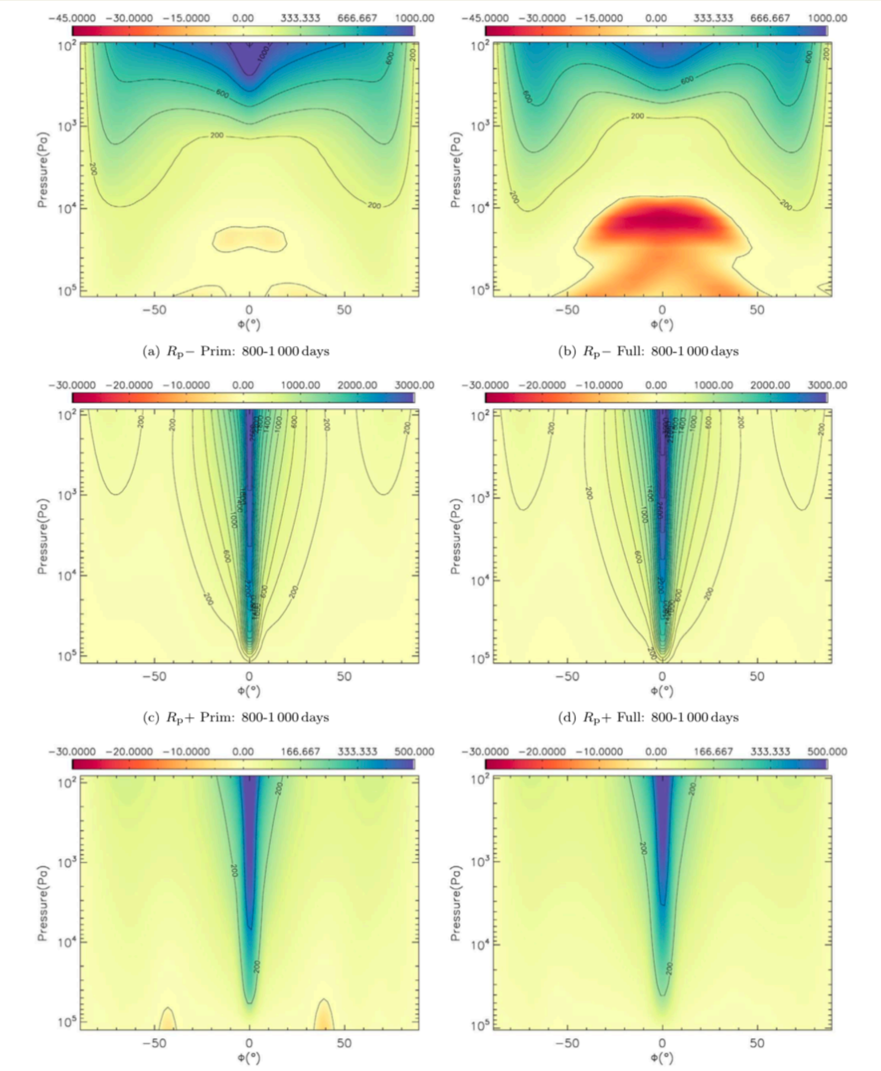
No dependence on gravity

# II. Warm Neptunes



## Verification





(a) $R_p-$ Prim: 800-1 000 days

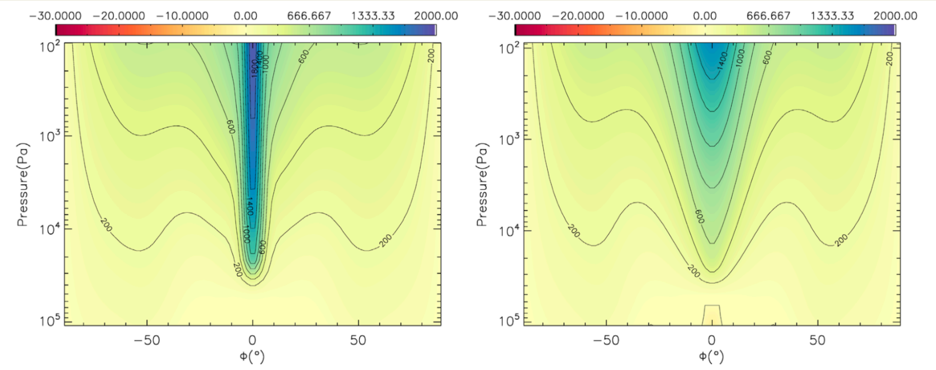
(b) $R_p-$ Full: 800-1 000 days

(c) $R_p+$ Prim: 800-1 000 days

(d) $R_p+$ Full: 800-1 000 days

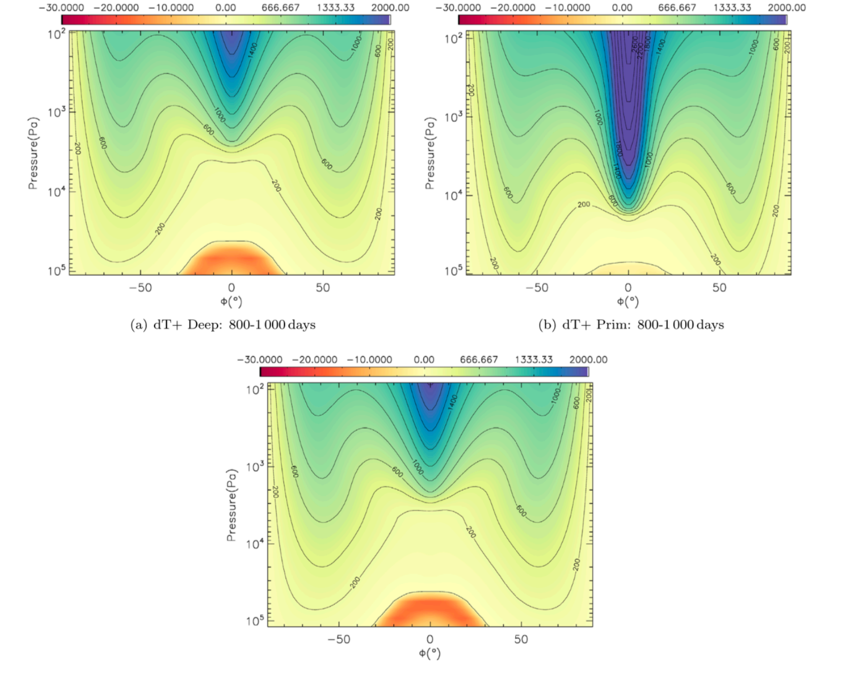
(e) $CO_2$ Prim: 800-1 000 days

(f) $CO_2$ Full: 800-1 000 days



(a) $\Omega+$ Prim: 800-1 000 days

(b) $\Omega+$ Full: 800-1 000 days



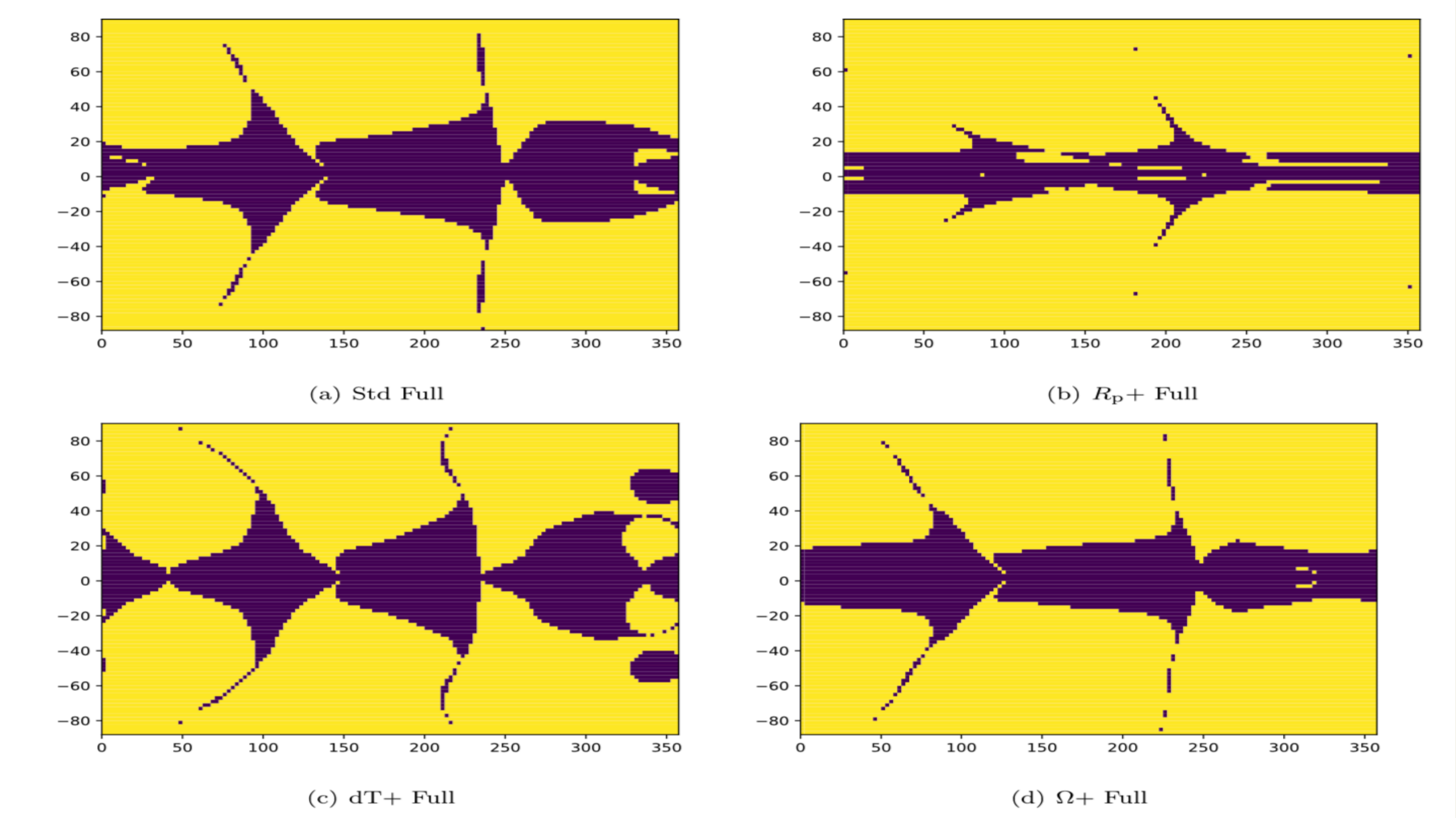
(a) dT+ Deep: 800-1 000 days

(b) dT+ Prim: 800-1 000 days

(c) dT+ Full: 800-1 000 days

# II. Warm Neptunes

## Verification




(a) Std Full

(b) $R_{\mathrm{p}}+$ Full

(c) dT+ Full

(d) $\Omega+$ Full

# II. Warm Neptunes

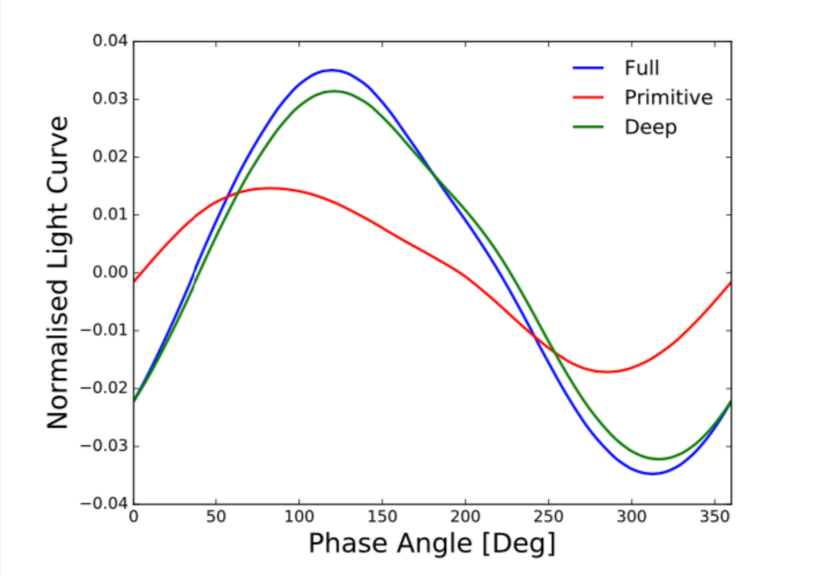
## Conclusions

Primitive equations: large planet moderately forced with heavy molecular weight

Counter intuitive: large rotation rate.

In the limit of global superrotation.

Impact: phase curves.




(f) dT+ Prim/Full: 3 000 Pa

# III. Hot Jupiters

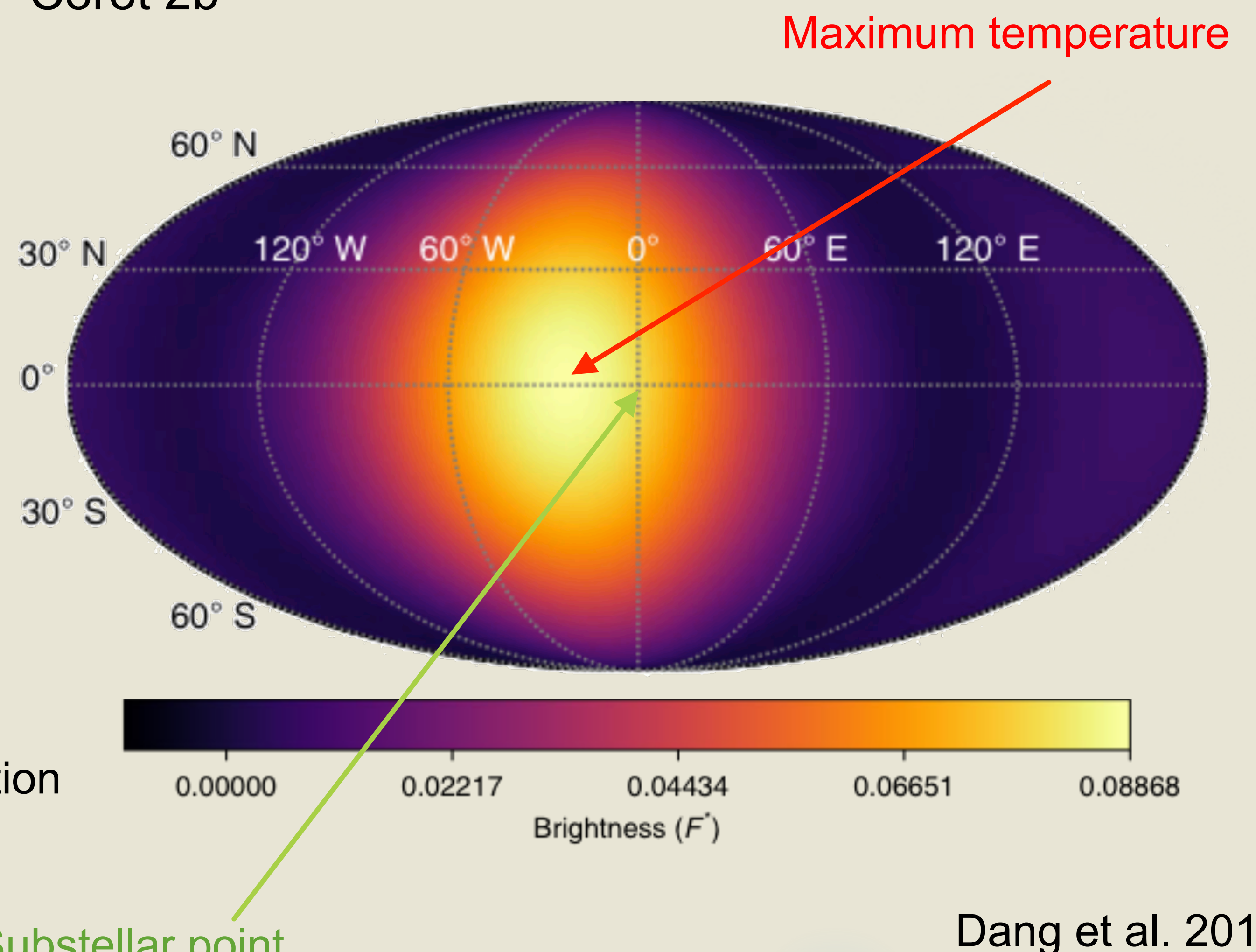


Corot 2b

Superrotation is ubiquitous in numerical simulations and detected indirectly.

BUT: Corot 2b

Need to understand physically superrotation




Dang et al. 2018

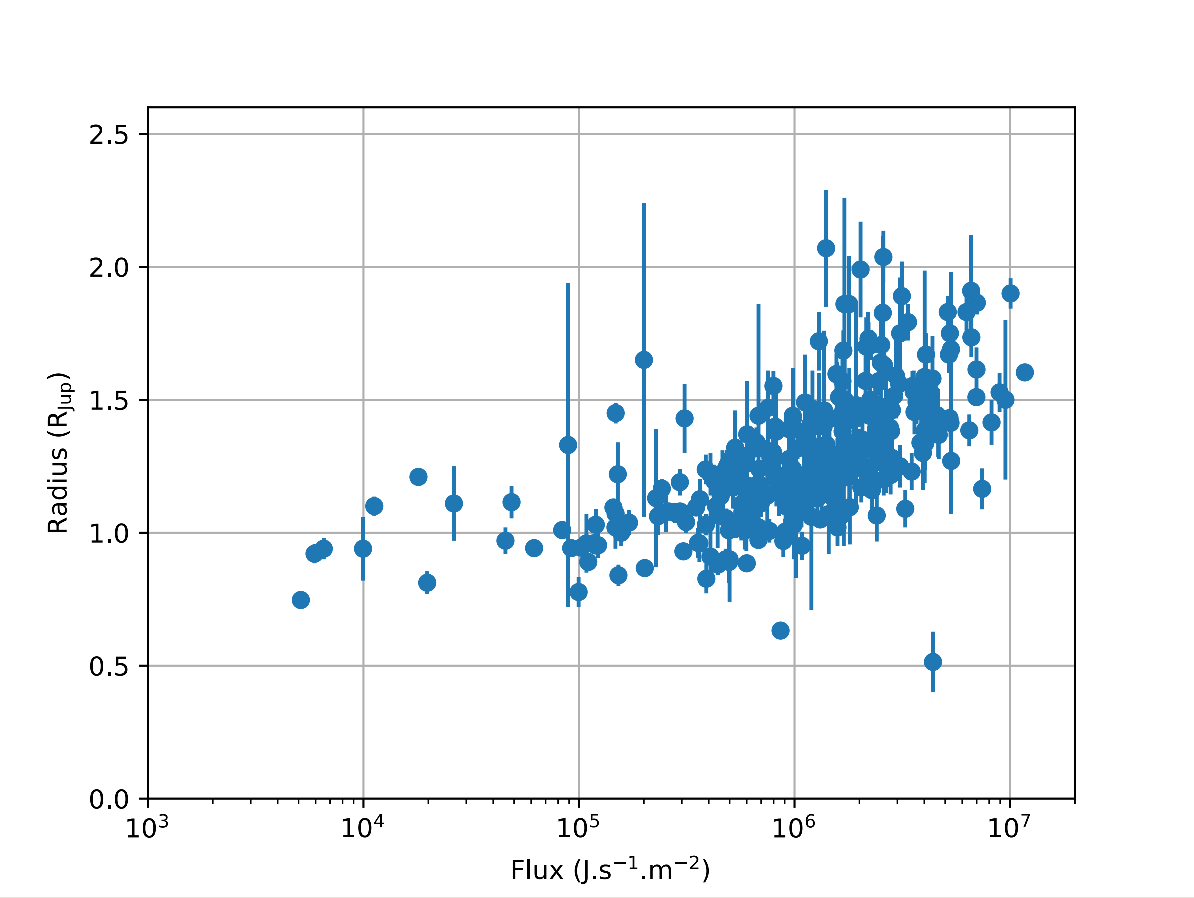
# III. Hot Jupiters



## The inflated radius

Simple evolution models (Guillot et al 1996 + Goukenleuque et al 2000):
HD209458b bigger than expected

Since then:

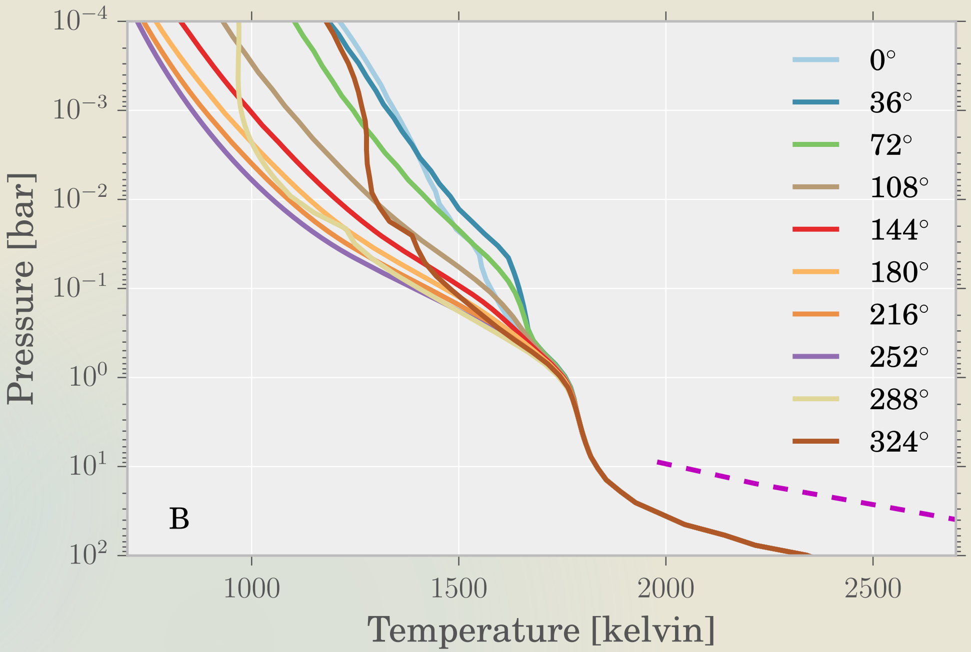


# III. Hot Jupiters

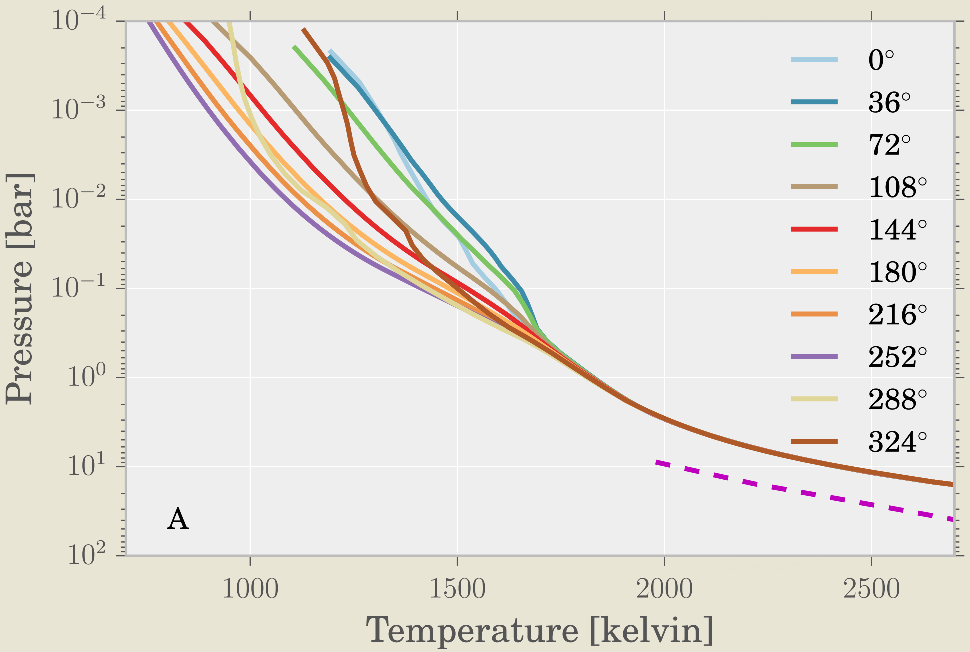


## Deep thermodynamic profiles

Tremblin et al. 2017




1D, no winds




2D, vertical winds

Internal temperature profile hotter:
hot interior because of **equatorial superrotation**

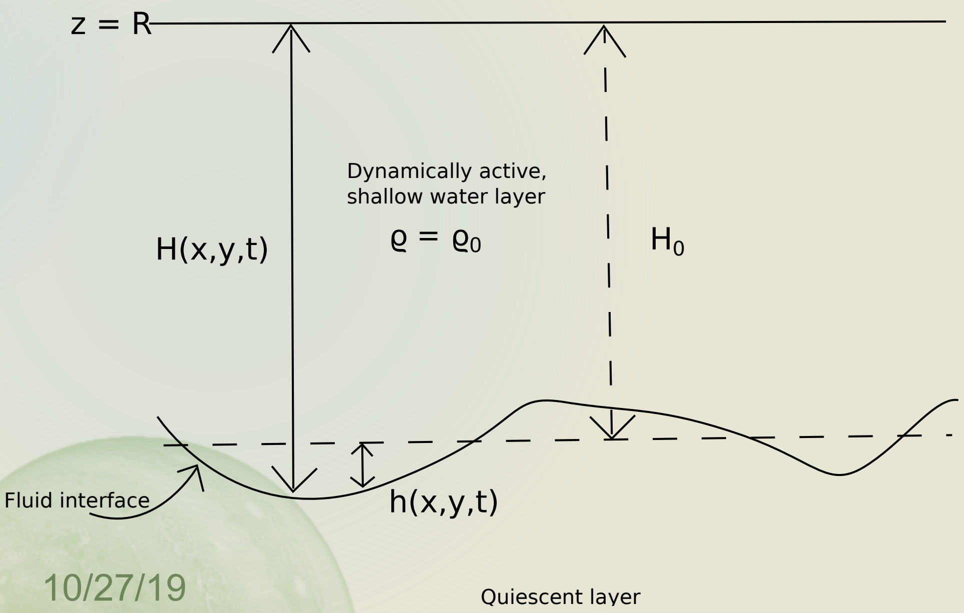
# III. Hot Jupiters

Showman Polvani 2011

Solar system: superrotation sometimes associated with propagation and dissipation of Rossby waves

Hot Jupiters: Rossby deformation radius ~ planet size

Beta plane shallow water




$$\partial u/\partial t - yv + \partial h/\partial x + u/\tau_{drag} = 0,$$

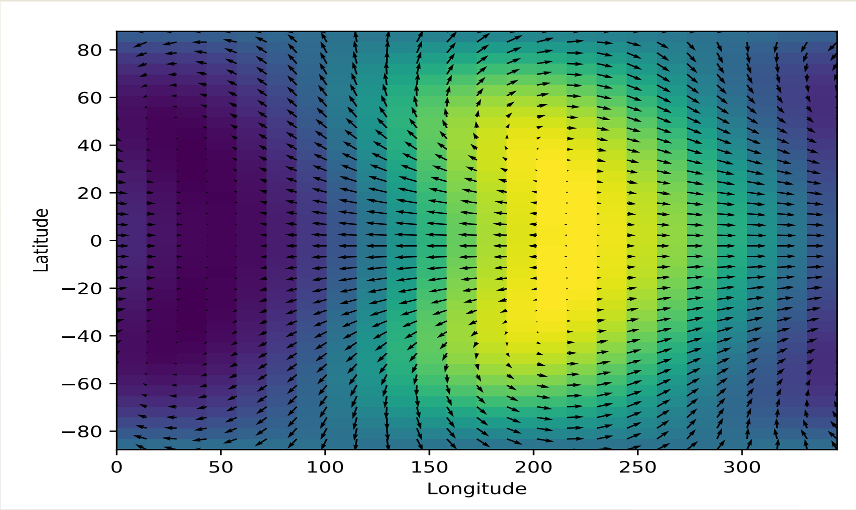
$$\partial v/\partial t + yu + \partial h/\partial y + v/\tau_{drag} = 0,$$

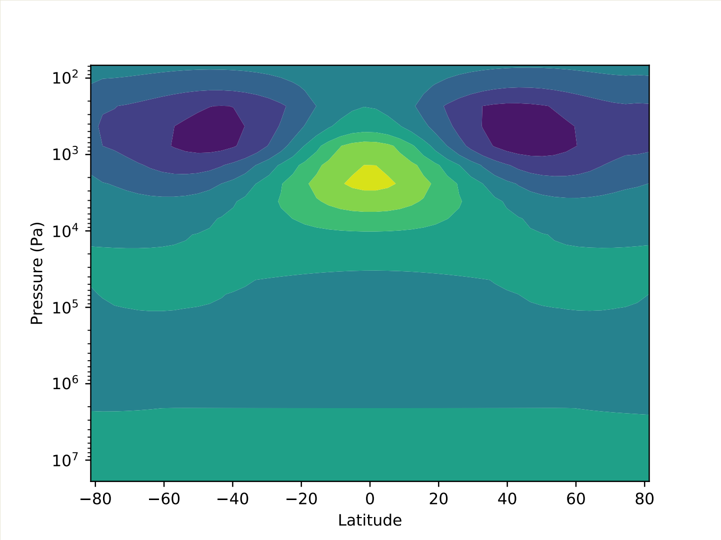
$$\partial h/\partial t + \partial u/\partial x + \partial v/\partial y + h/\tau_{rad} = Q.$$

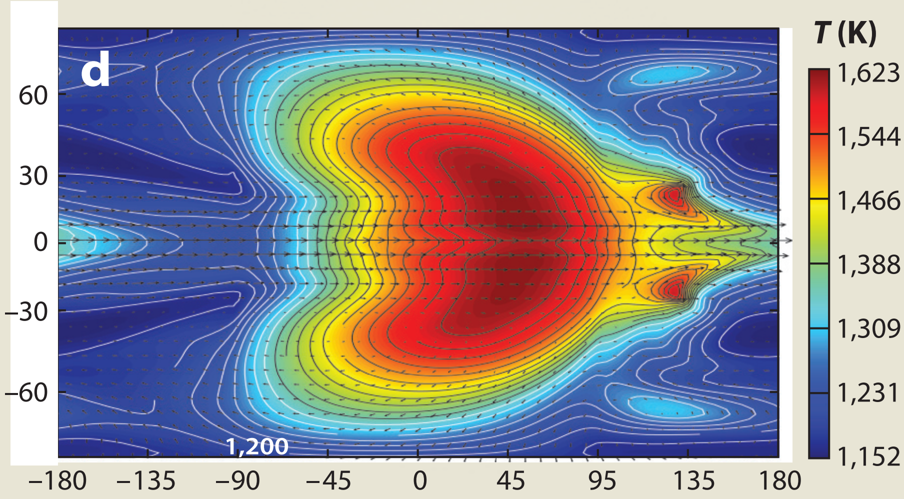
# III. Hot Jupiters



Timeline from SP11




"Switching on the star"

Linear steady state

Superrotation

Time

Linear wave propagation and dissipation

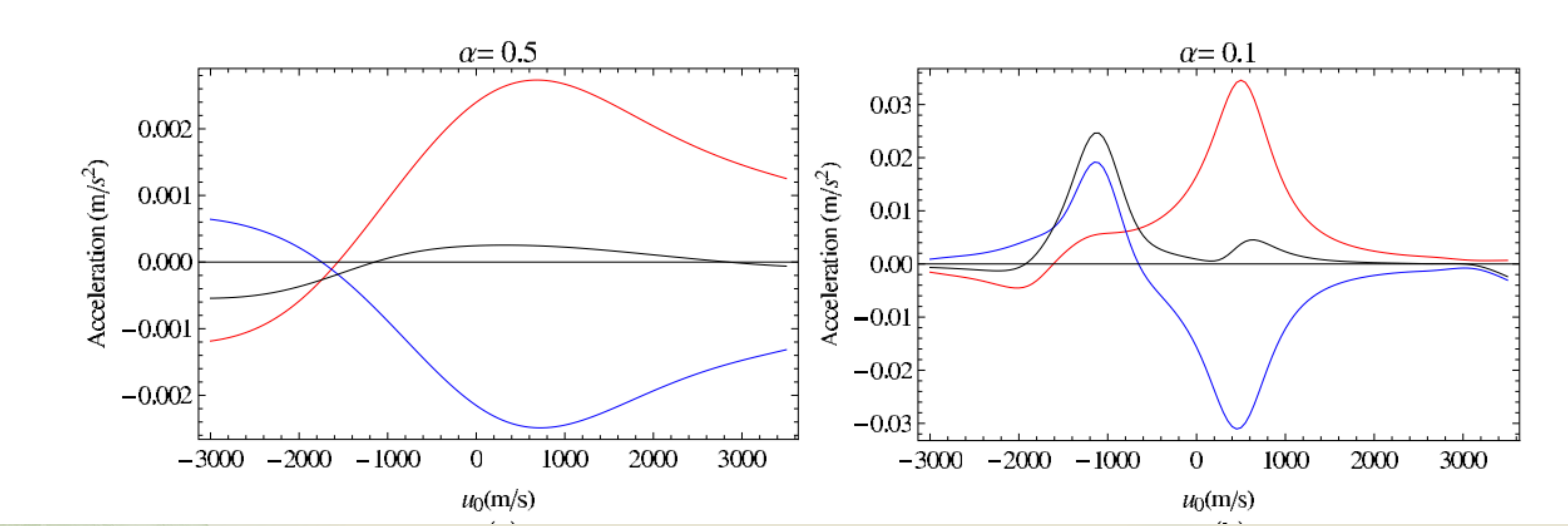
Non linear acceleration

# III. Hot Jupiters



Superrotation in hot Jupiters

Equilibration of the jet: sequence of linear steady states, Tsai et al. 2014. Vertical tilt of the wave



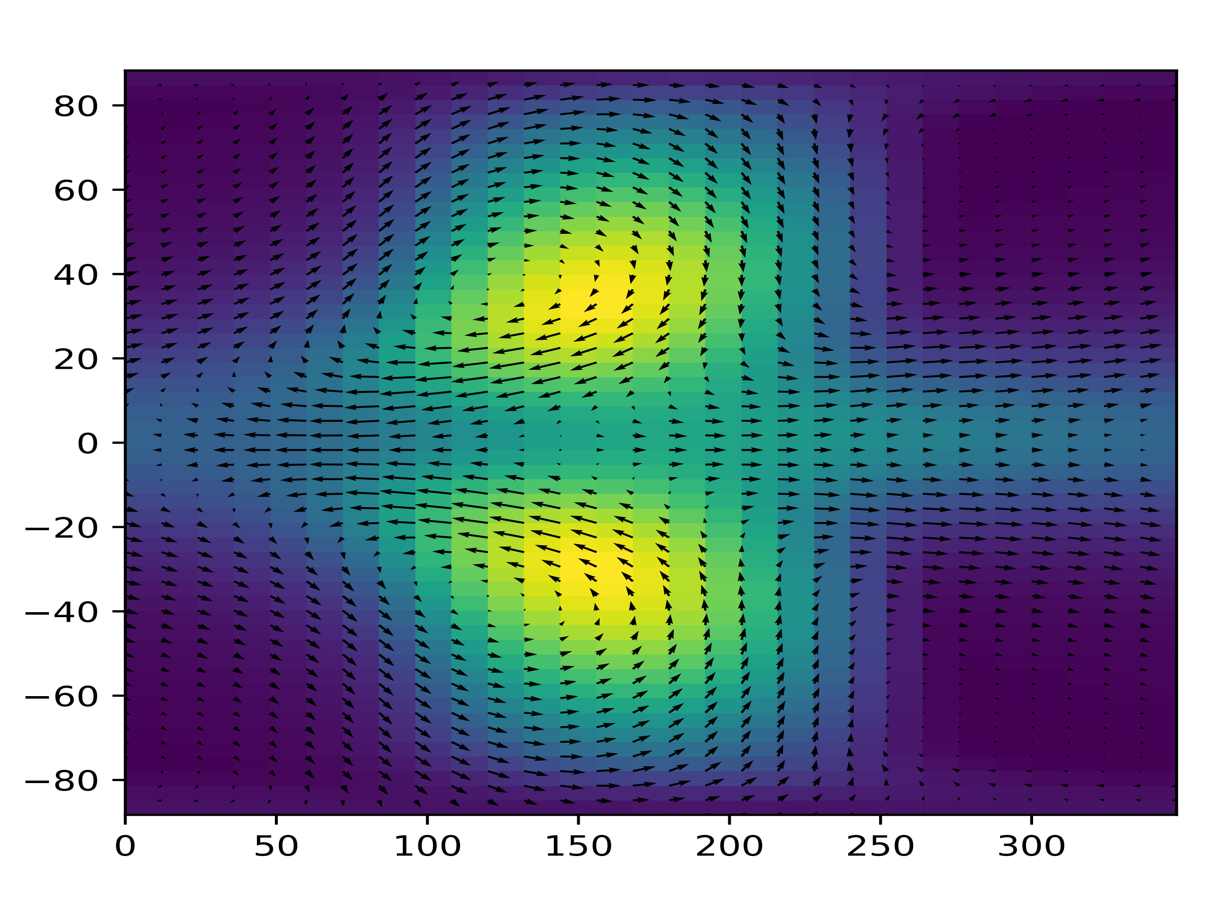
# III. Hot Jupiters



## Limits of SP11 and Tsai et al. 2014

Tsai: Need for an initial superrotation followed by slow evolution. Given by SP11 ?

Linear steady state of SP11 with appropriate $\tau_{drag}$ and $\tau_{rad}$ :
(komacek & showman 2016)




Linear steady state never reached

Need for time dependent considerations

# III. Hot Jupiters

Debras et al.2019, accepted

Linear time dependent solution:

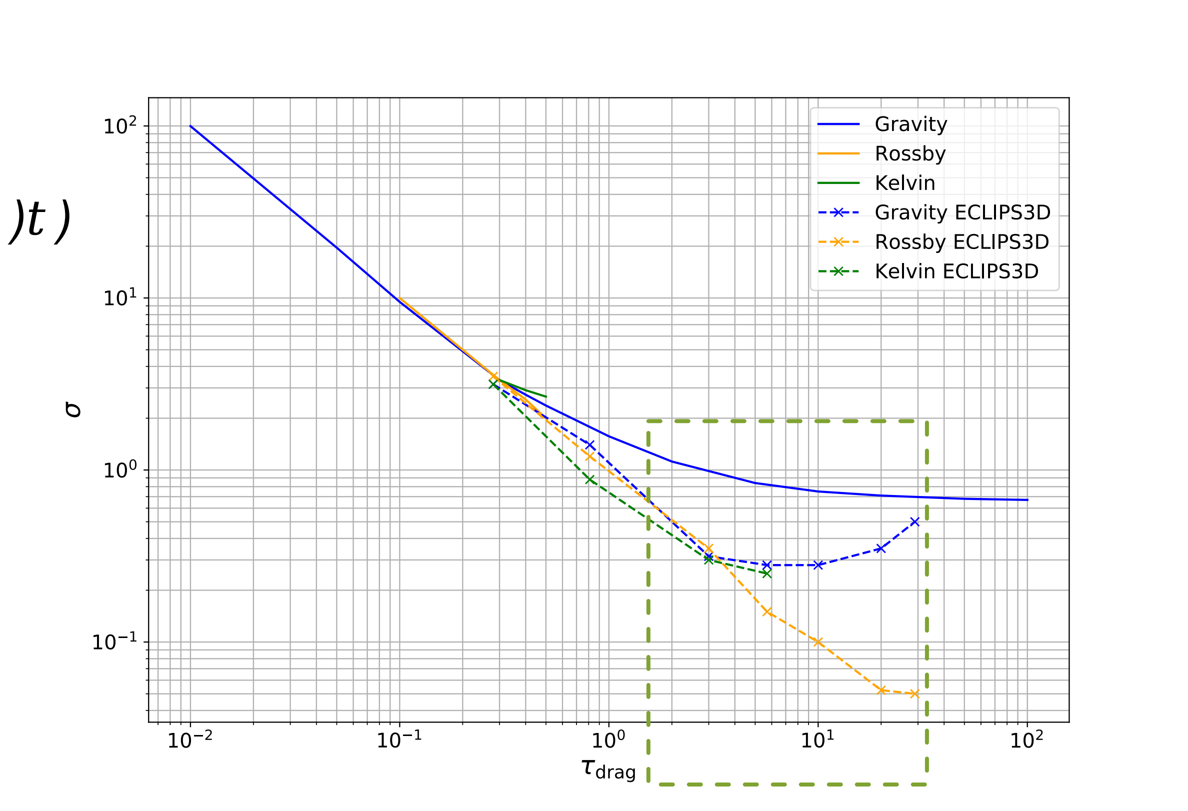
$$X_F = \sum_n \frac{q_n X_n}{\sigma_n - i\omega_n}\left(1 - e^{(i\omega_n - \sigma_n)t}\right)$$

Steady state dominated by **Rossby** waves

BUT

Limit of short timescales: **Rossby** and **Kelvin** waves with comparable amplitudes

$$X_F \approx \sum_n q_n X_n t$$

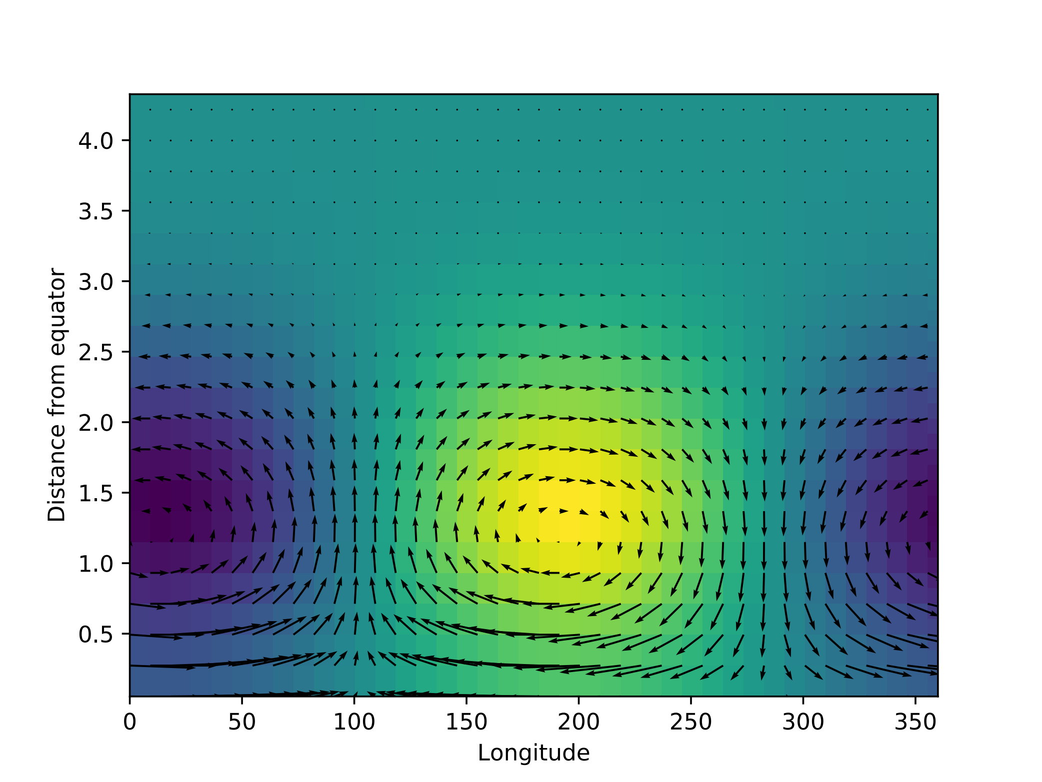


# III. Hot Jupiters

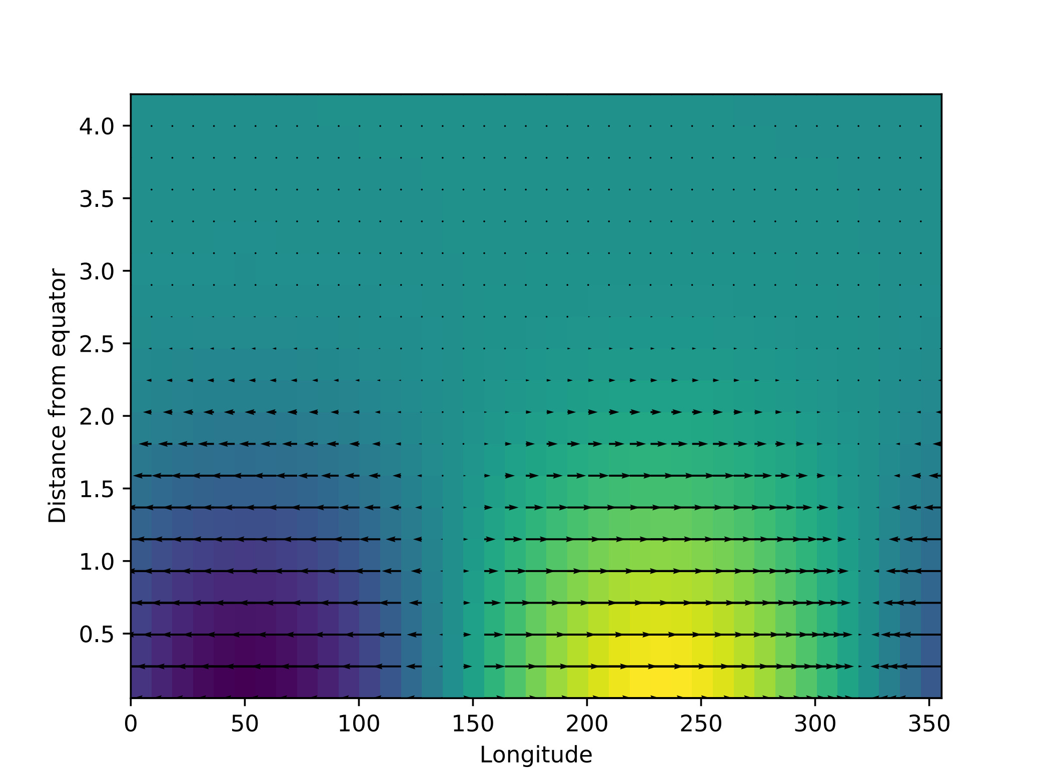


## Rossby and Kelvin waves

**Rossby**: ~ zero pressure at the equator, rotating winds




**Kelvin**: no meridional winds, maximum pressure at the equator

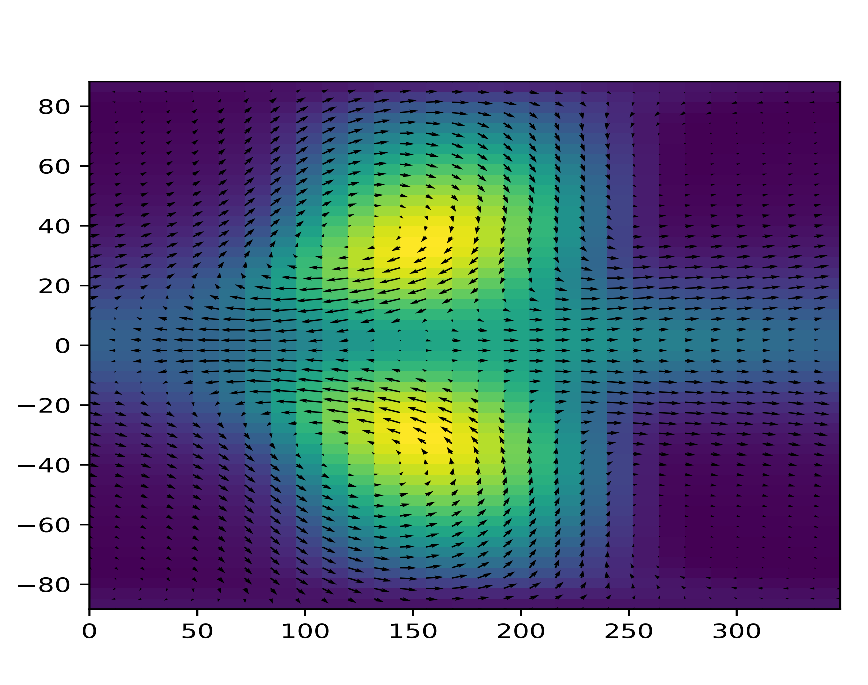


# III. Hot Jupiters

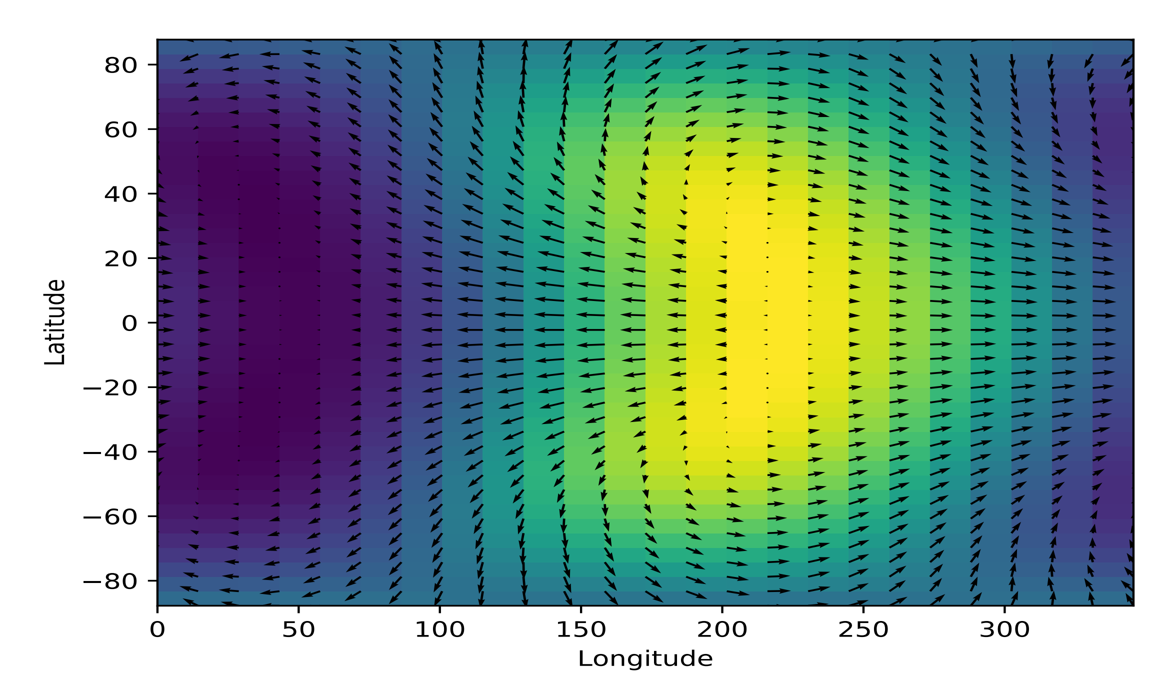


## Intermediate and steady linear state

Steady: **Rossby** dominated



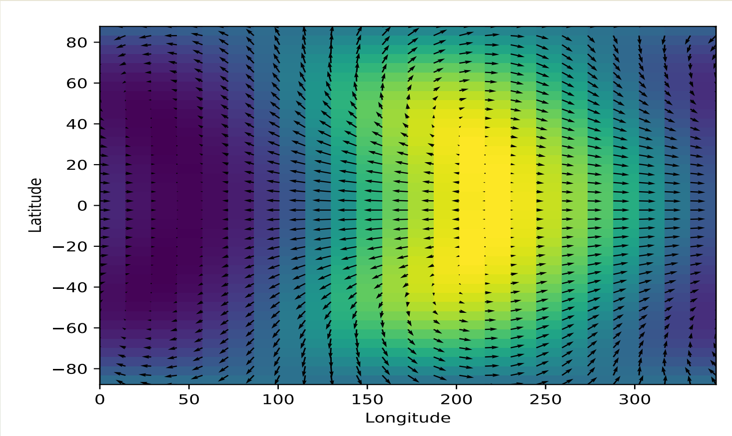

Short timescales state: mix **R**-**K**,
Similar to SP11 steady state

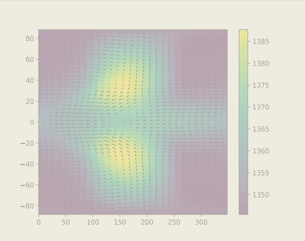


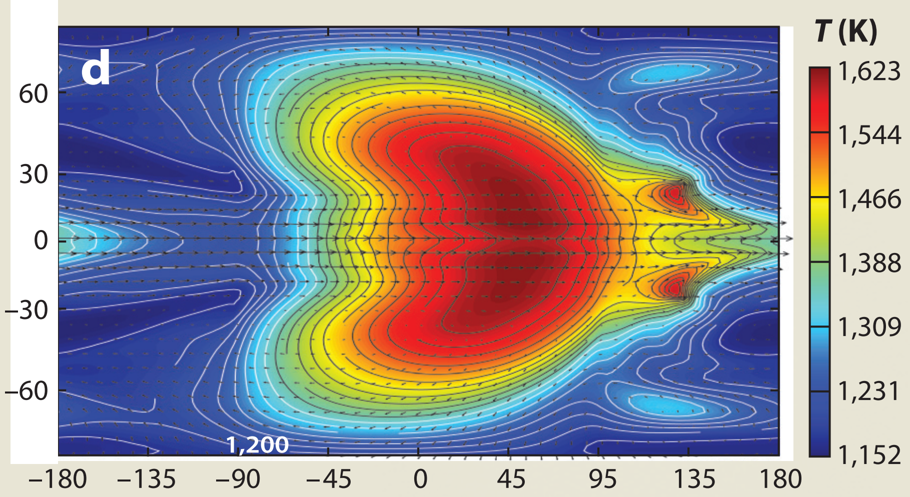
# III. Hot Jupiters



More accurate timeline






"Switching on the star"

$U>U_{max}$

Linear steady state

Superrotation

Time

Linear wave propagation and dissipation

Non linear acceleration

# III. Hot Jupiters

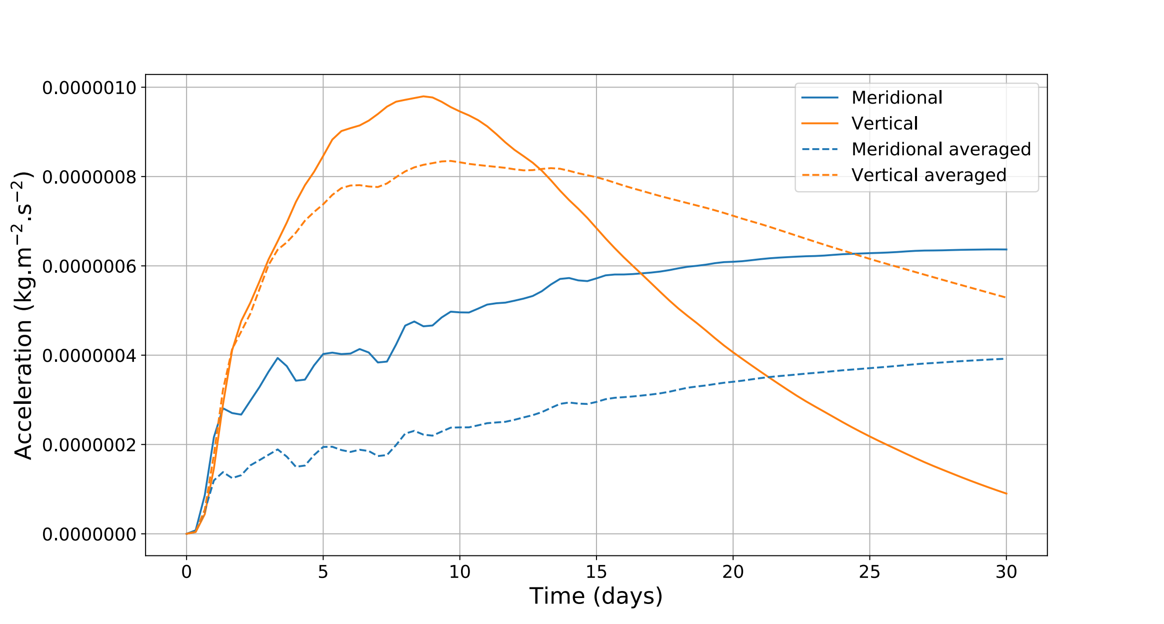


## Quasi-linear studies and accelerations

Separation of linear and non linear considerations too simple

Quasi linear/statistical studies ? Srinivasan & Young 2012, Bouchet et al. 2013, Bakas et al. 2015

Vertical accelerations:



# Summary



**Can we model warm Neptunes/super Earths with the primitive equations ?**

Range of planets where traditional approximation breaks

Analytical priors verified numerically

Strong impact on the comparison with observations

**What is the physical origin of equatorial superrotation on hot Jupiters ?**

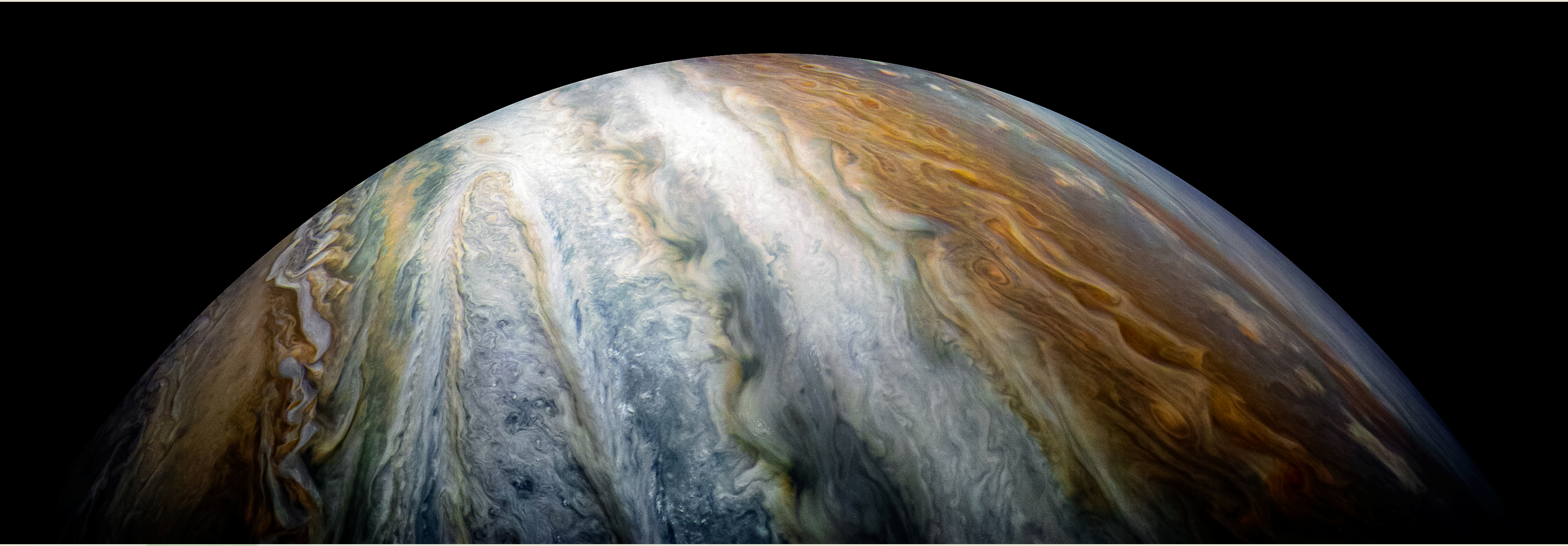
Initial phases of  simulated superrotation not perfectly understood

Time dependent linear processes needed to be taken into account

Crucial link between superrotation and interior profiles

# Thank you !





# Perspectives



Models compatible with Saturn ?

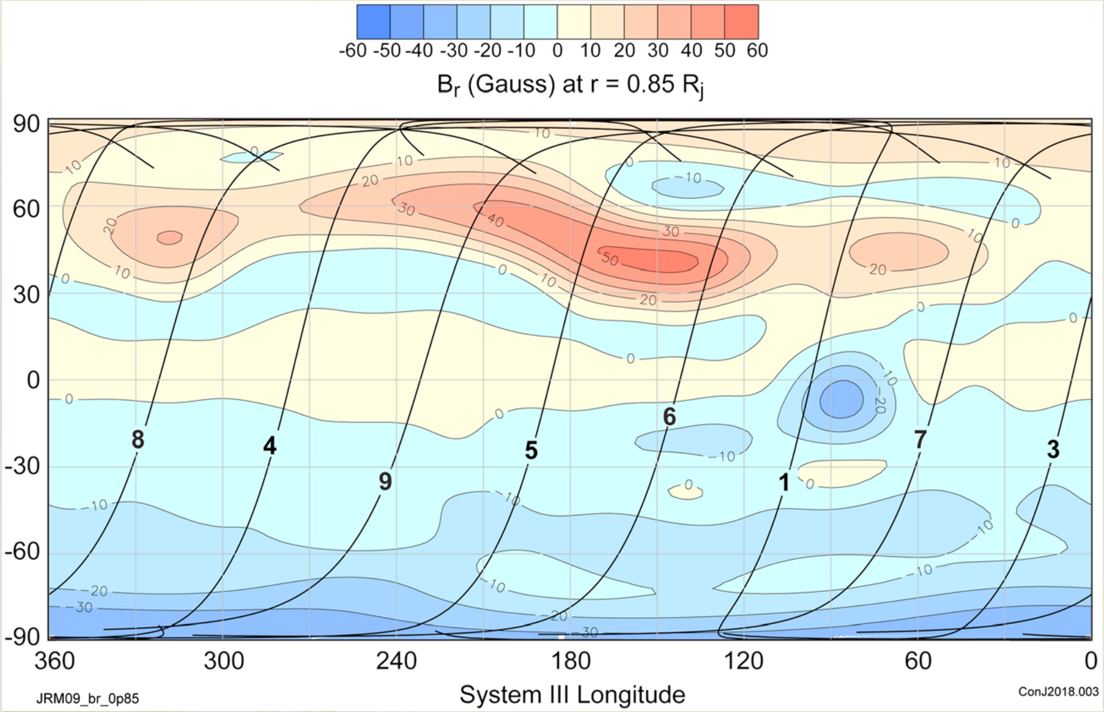
Love numbers with CMS method

Interior of hot Jupiters: flatter temperature gradient, favorable for semi convection

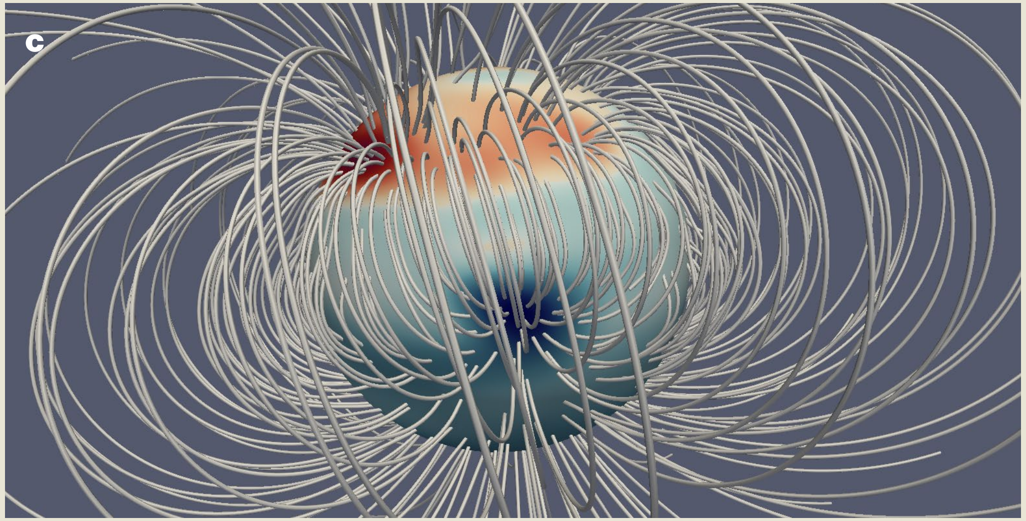
Radius re-inflation for a non convective planet ?

# Perspectives

Magnetic field: Moore et al. 2018, sign of two dynamo regions ?



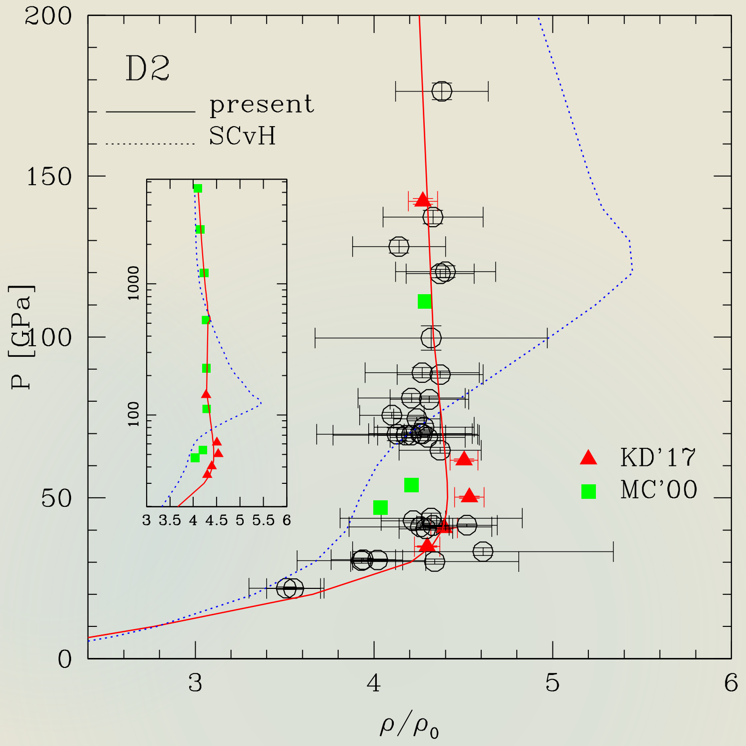

Connerney et al. 2018

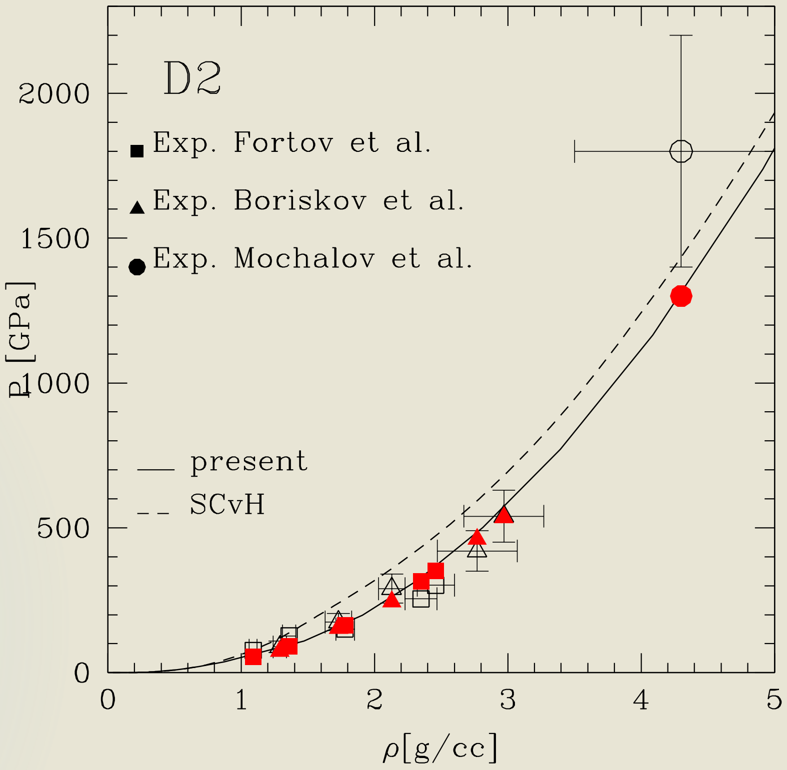


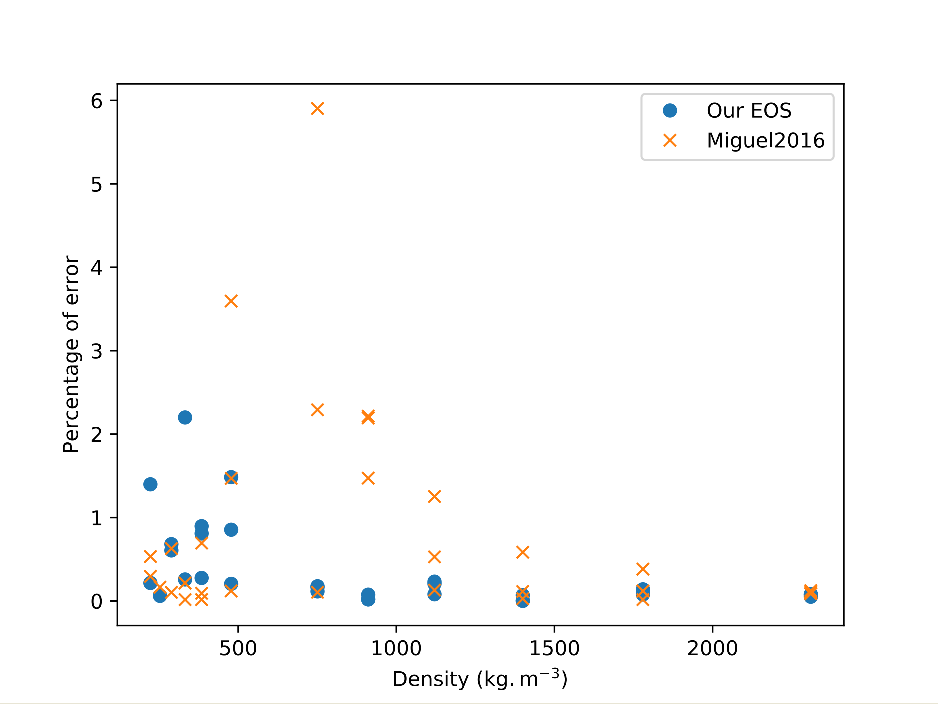

Moore et al. 2018

Post doctoral position in Toulouse

# EOS


D2
present
SCvH
KD'17
MC'00
P [GPa]
ρ/ρ0

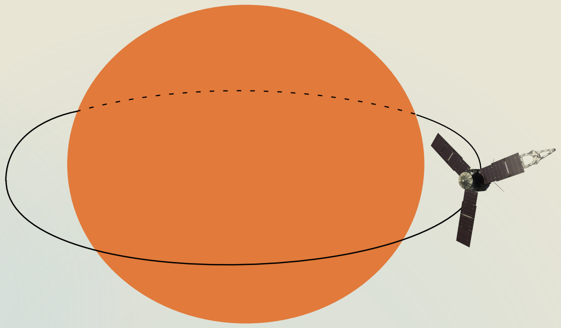

D2
Exp. Fortov et al.
Exp. Boriskov et al.
Exp. Mochalov et al.
present
SCvH
P [GPa]
ρ[g/cc]

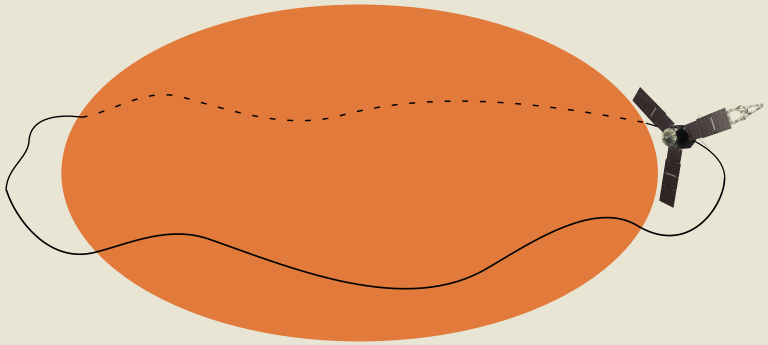

Our EOS
Miguel2016
Percentage of error
Density (kg. m−3)

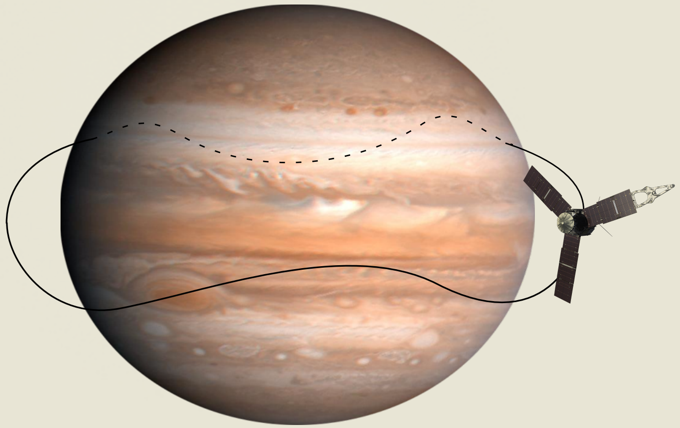
# I. Global picture of Jupiter



Why is gravity interesting ?







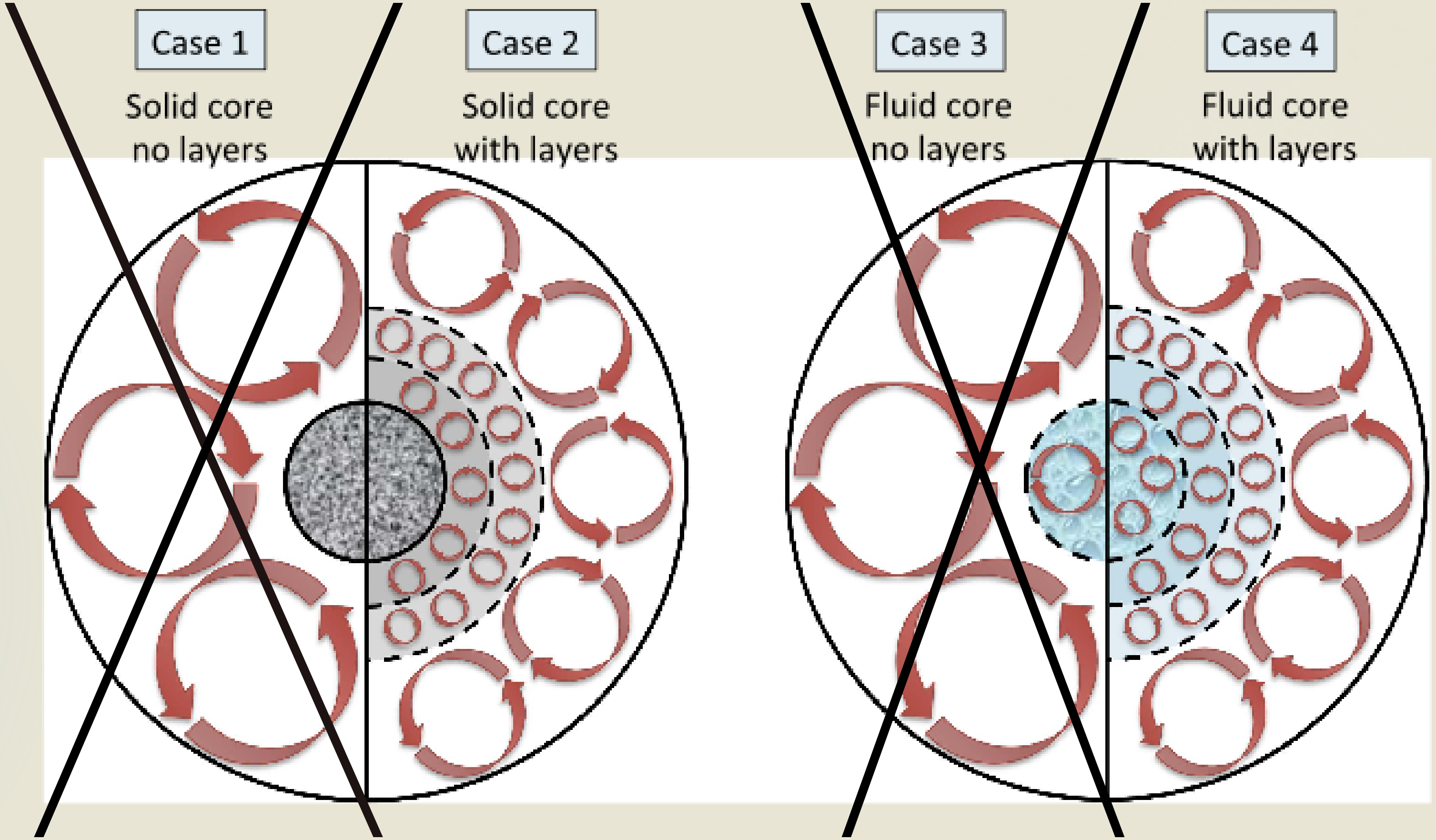
$$J_{2k} = -\frac{4\pi}{MR^{2k}} \int_0^R \int_0^1 \rho(\vec{r'}) r'^{2k+2} P_{2k}(\mu') d\mu' dr'$$

Pioneer 10-11: 1973-1974
Voyager 1-2: 1978-1979
**Galileo: 1995**

# Diluted Core



Moll et al. 2017



# III. New models of the interior of Jupiter

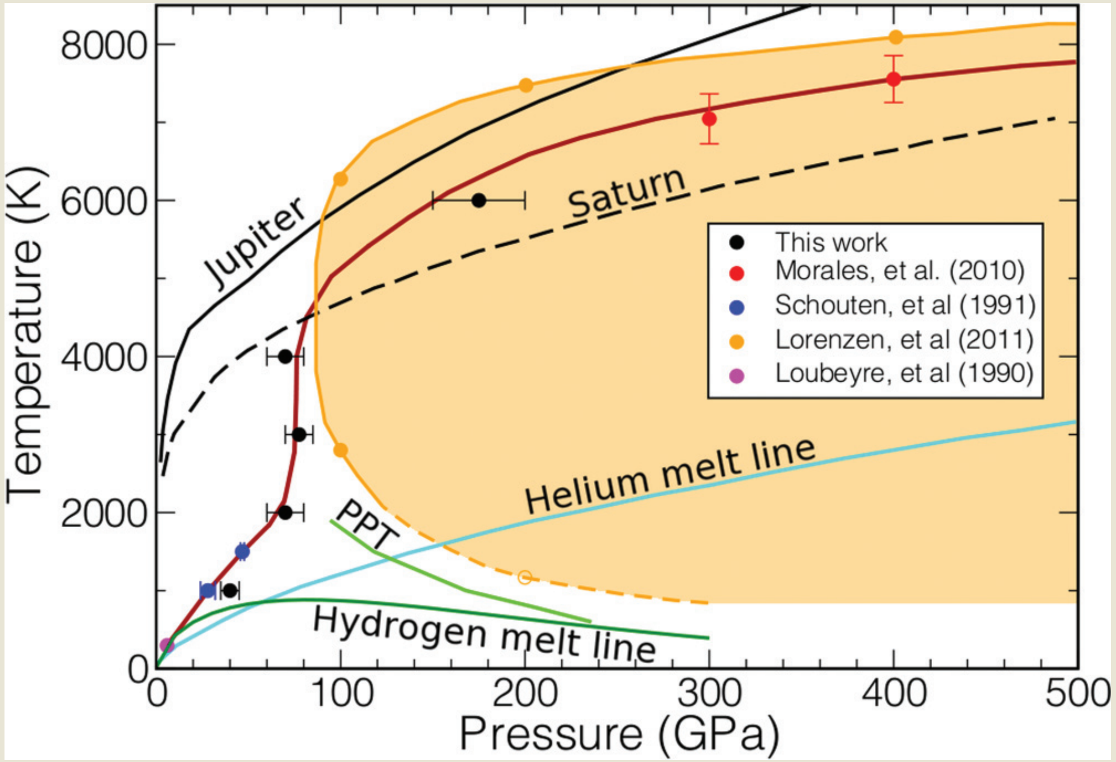


Immiscibility

Metallic H/He immiscibility possible

Helium rain: heating up the planet
Stevenson Salpeter 1977

Decrease in Z < 10%



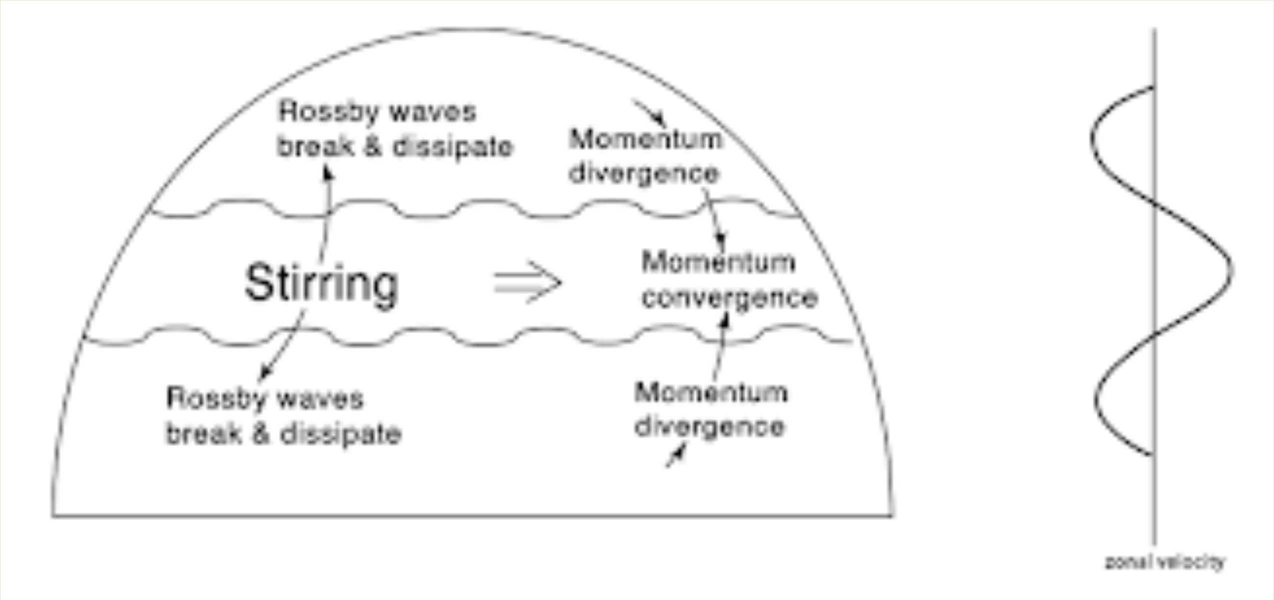
# II. Superrotation



Solar system

Mid latitudes jet (Jupiter, Saturn, Earth) : Rossby waves

Global superrotation (Venus) : Meridional momentum diffusion



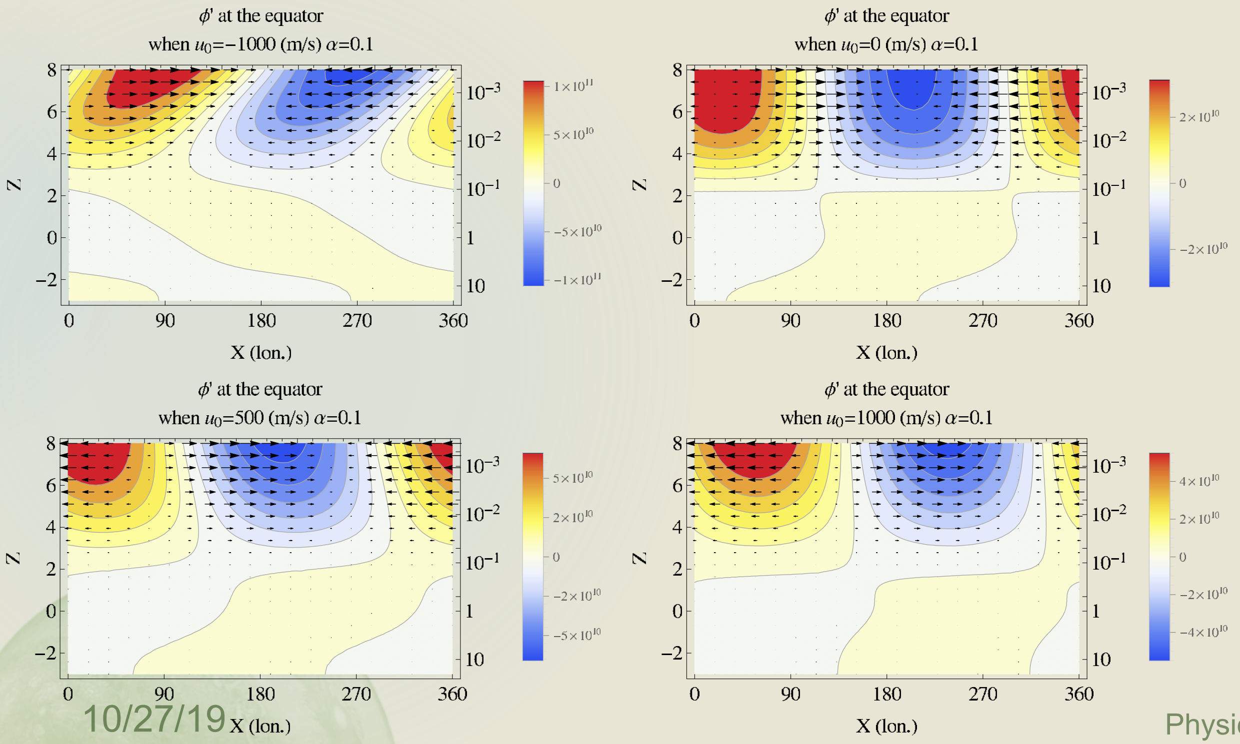

Equatorial jet : Rossby waves from magnetic field of heat fluxes

# II. Spin-up of superrotation



Tsai et al. 2014

3D = infinite sum of 2D with different equivalent depths (wu et al. 2000) : projection of the heating function in the vertical




Equilibration of the jet from the vertical structure

# II. Spin-up of superrotation



My contribution : time dependent solution

$$\frac{\partial u}{\partial t} - yv + \frac{\partial h}{\partial x} + \frac{u}{\tau_{\mathrm{drag}}} = 0,$$
$$\frac{\partial v}{\partial t} + yu + \frac{\partial h}{\partial y} + \frac{v}{\tau_{\mathrm{drag}}} = 0,$$
$$\frac{\partial h}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{h}{\tau_{\mathrm{rad}}} = Q,$$

$$(\mathrm{i}\omega + \frac{1}{\tau_{\mathrm{drag}}})u - yv + \mathrm{i}kh = 0,$$
$$(\mathrm{i}\omega + \frac{1}{\tau_{\mathrm{drag}}})v + yu + \frac{\partial h}{\partial y} = 0,$$
$$(\mathrm{i}\omega + \frac{1}{\tau_{\mathrm{rad}}})h + \mathrm{i}ku + \frac{\partial v}{\partial y} = 0\ .$$

Homogeneous solution : $$X_{\mathrm{H}} = \sum_{n,l} \alpha_{n,l} X_{n,l},$$ With $$X_{n,l} = \tilde{X}_{n,l}(x,y)e^{(\mathrm{i}\omega_{n,l} - \sigma_{n,l})t}$$

Forced solution : $$X_{\mathrm{F}} = \sum_{n,l} \frac{q_{n,l}\tilde{X}_{n,l}}{\sigma_{n,l} - i\omega_{n,l}} \left(1 - e^{(i\omega_{n,l} - \sigma_{n,l})(t)}\right)$$

# II. Spin-up of superrotation



Non linear considerations

$$u_{\mathrm{max}} \sim \frac{L}{\tau_{\mathrm{drag}}}$$

For real forcing, umax >> usteady :
linear steady state never reached

Timescale analysis : limit of short times,
Kelvin and Rossby waves have same amplitude
different from limit of long times
(Rossby dominate)