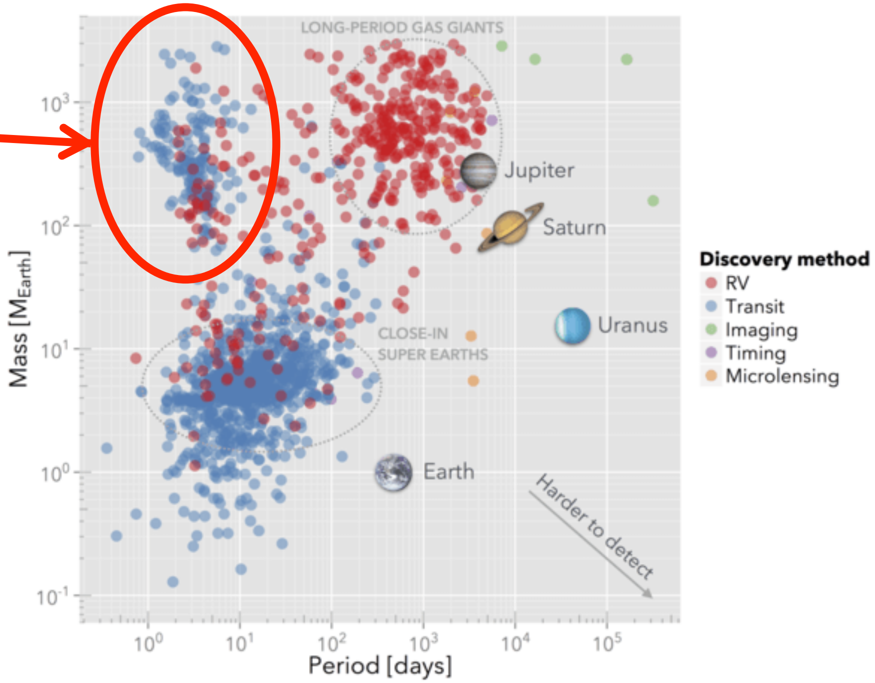
Shear-driven instabilities and shocks in the atmospheres of hot Jupiters

S. Fromang *(CEA Saclay, France)*
with
J. Leconte *(Obs. Bordeaux, France)* & ***K.Heng*** *(Bern Univ., Switzerland)*

Fromang, Leconte, Heng, 2016, A&A, 591, 144

Hot Jupiters: a class of exoplanets

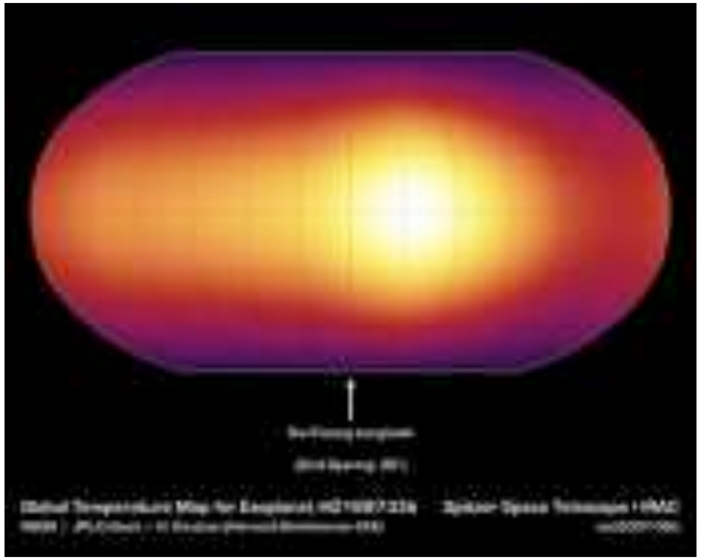
Hot Jupiters: Jupiter-mass planets orbiting very close to their star



- **~10% of known exoplanets**
- **Short orbital periods**
  T_{orb} ~ a few days
- **Strongly irradiated**
  Temperature up to 2000 K
- **Tidally locked**
  Constant day/night sides

Some observational constraints

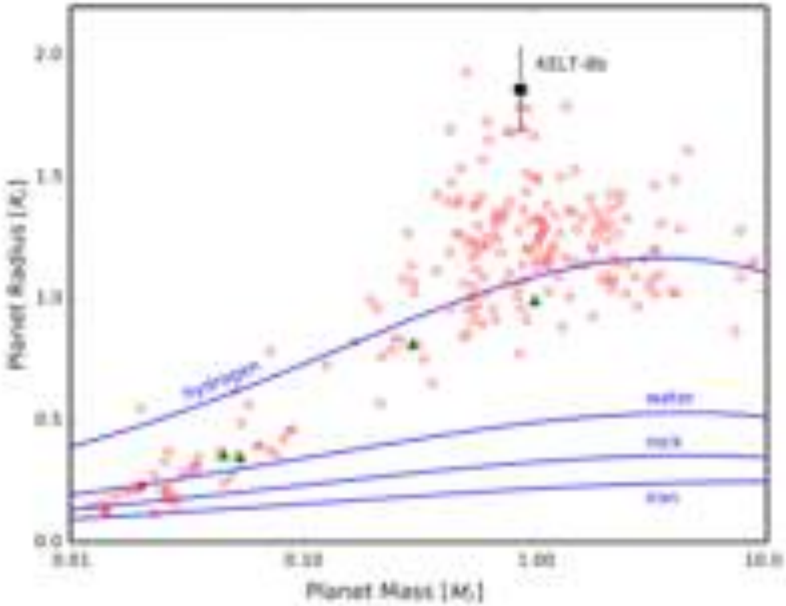
Temperature maps



(Knutson et al. 2007)

Hot spot shifted eastward compared to the substellar point!

Inflated radii



Fulton et al. (2015)

Hot Jupiter are larger than expected from standard internal structure models!

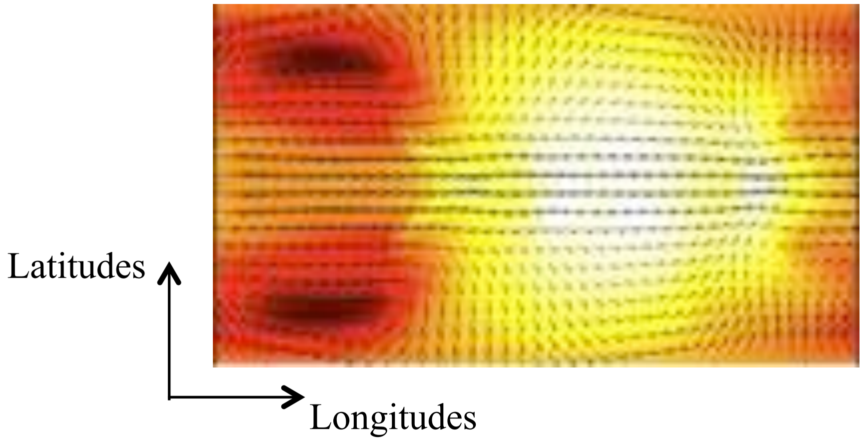
See talk by Pascal Tremblin…

+ *tentative wind detection, temperature-pressure profiles, composition, clouds…*

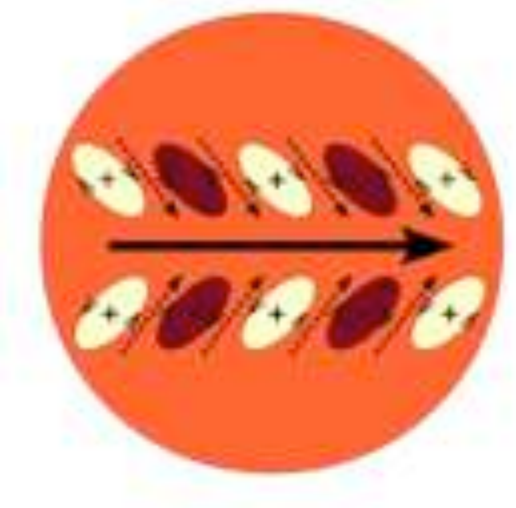
Global circulation models (GCM) results

Standard GCM robustly predict a fast eastward equatorial jet of a few km/s (Mach number ~2-3)

Excitation of a standing wave around the equator



Showman et al. (2009), Rauscher & Menou (2012), Heng et al. (2011)



Matsuno (1966), Gill (1980), Showman & Polvani (2010, 2011)

=> Interpreted as the origin of the hot spot eastward displacement

Caveat: rather limited resolution (typically one degree) and ad-hoc dissipation coefficients w/o much physical justification
=> uncertainties in jet velocity and drag origin

Motivations

Open questions:

- Supersonic flow

  => *Compressibility effects (shocks)?*

- Jet velocity ⬄ Source of drag

  => *Jet stability? Variability?*

- Heat distribution & transport

  => *origin of the inflated radii?*

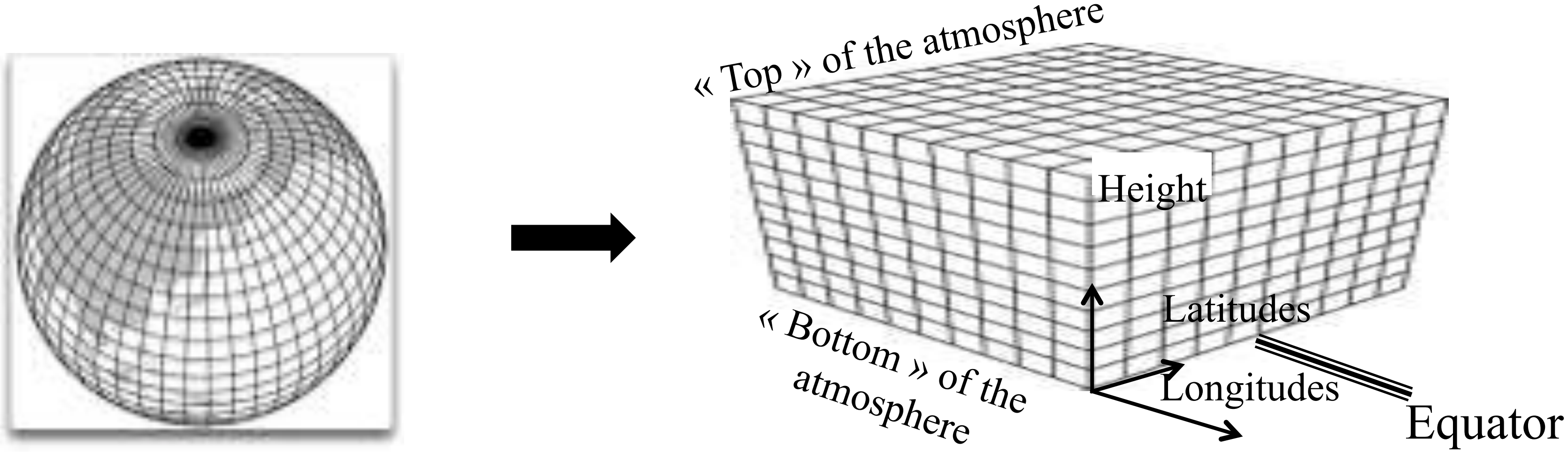
Numerical approach: an idealized model

Solve **compressible** hydrodynamic equations (code RAMSES)

No explicit dissipation, Total energy is conserved

I. Use **cartesian coordinates and the equatorial β–plane model**

x=longitudes, y=latitudes, neglect curvature terms



II. Use **simple cooling/heating function**

(Newtonian cooling – No radiative transfer)

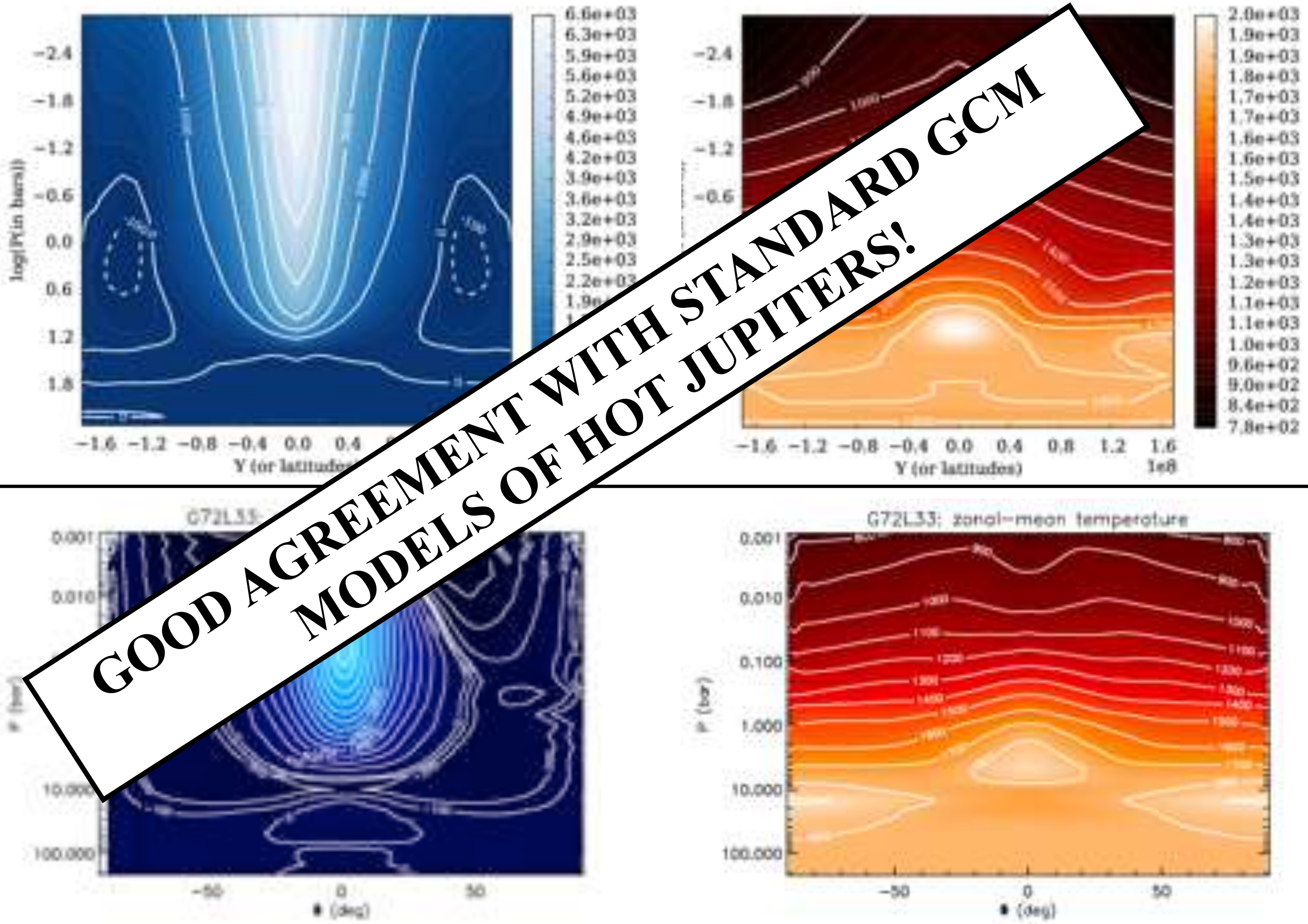
Low resolution model: $(N_x,N_y,N_z)=(64,33,48)$

Zonal wind (y-pressure plane)

Temperature (y-pressure plane)

Idealized model (equatorial β-plane)

Heng et al. (2011) (standard GCM)

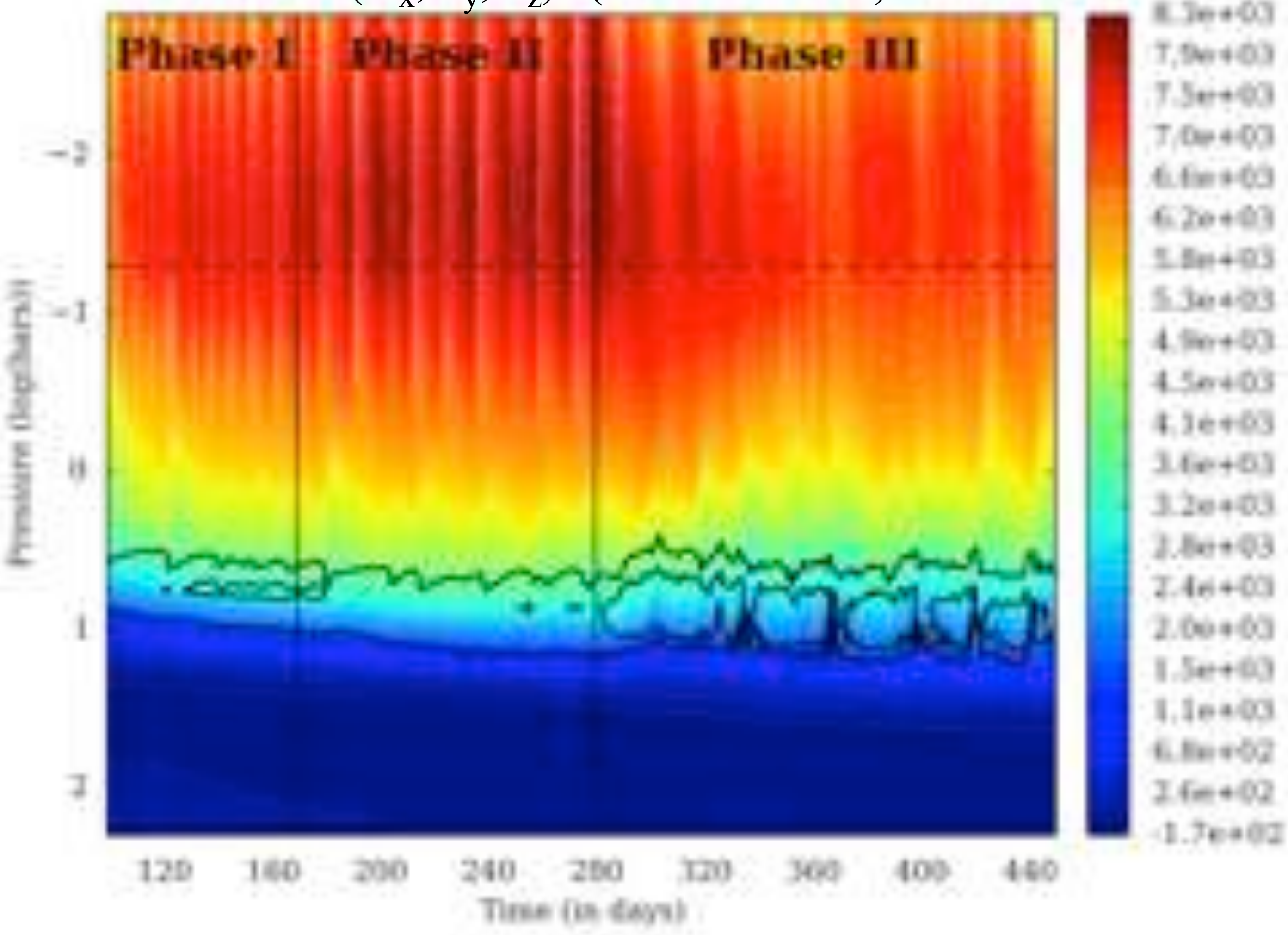


GOOD AGREEMENT WITH STANDARD GCM MODELS OF HOT JUPITERS!

Time variability of the jet velocity

High resolution

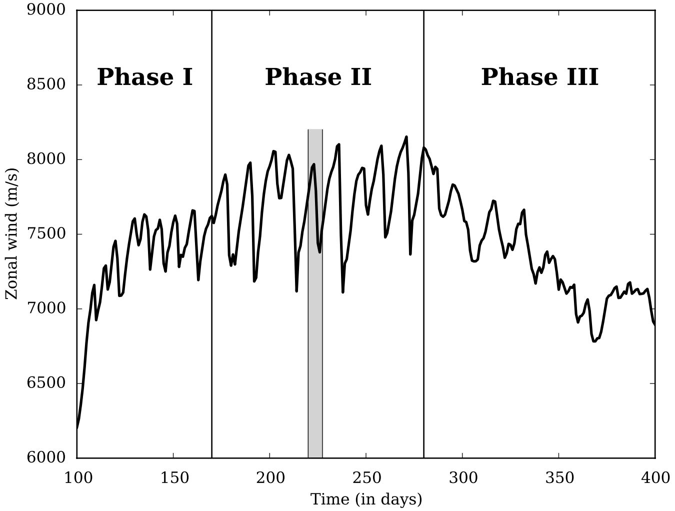
$(N_x,N_y,N_z)=(1024x195x48)$

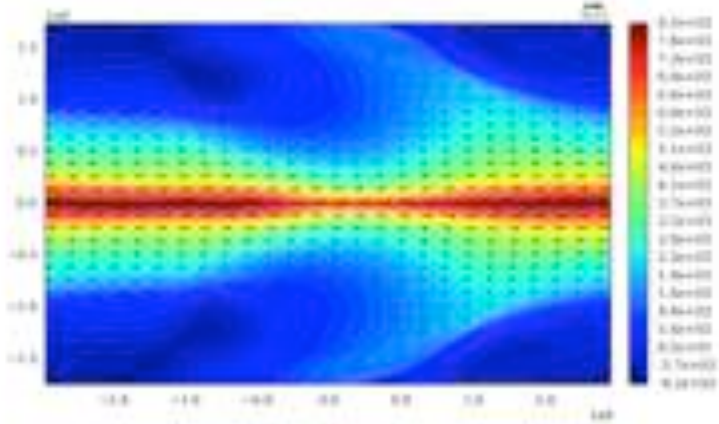


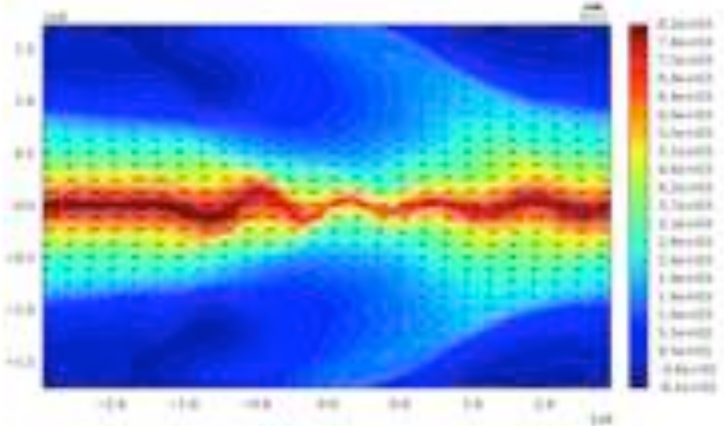
Spacetime diagram of the zonal wind at the equator

Phase II: regular oscillations

- Variations of the mean zonal wind of the jet: ~1 km/s
- Typical timescale: ~7 planet days

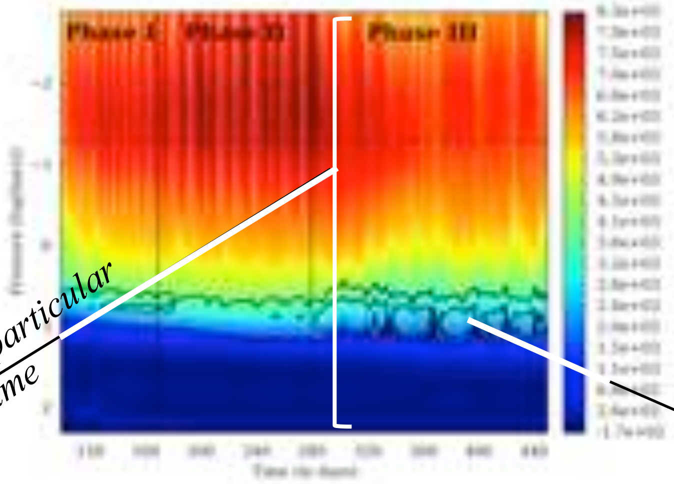



Zonal jet


Meandering jet

=> Further analysis suggest the flow is unstable to a horizontal Kelvin-Helmholtz instability!

Phase III: A vertical shear instability

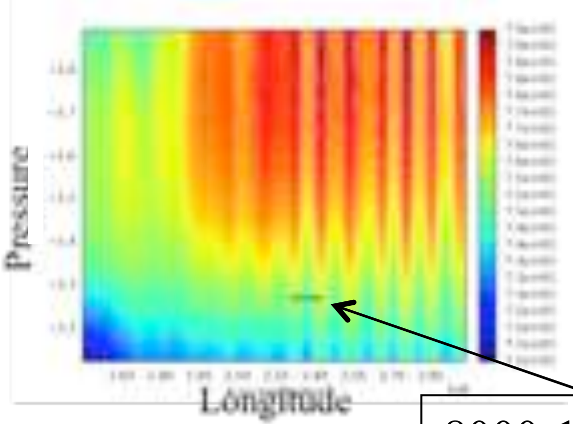


Select one particular time

Ri contours: 0.1, 0.25

Jet velocity at the equator

Richardson number contours



8000-10000 km

$$Ri = \frac{N^2}{(\partial U/\partial z)^2},$$

Instability for Ri<~0.25

(Showman & Guillot 2002, Li & Goodman 2010)

Typical scale of perturbations consistent with linear stability analysis

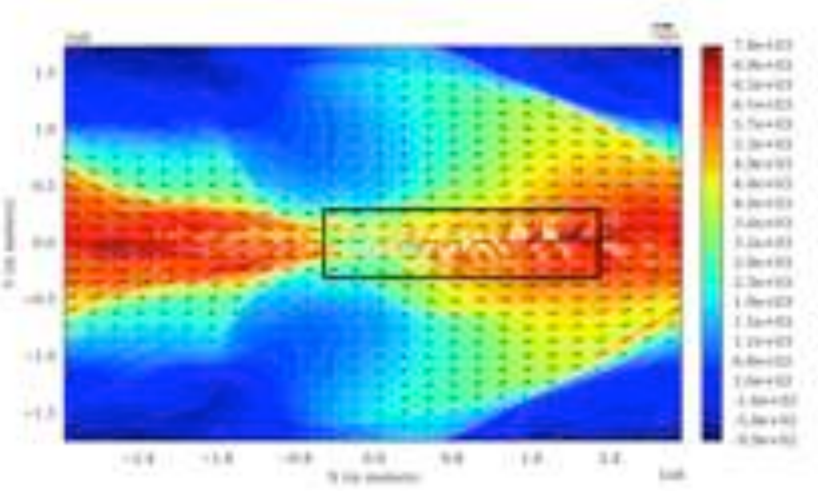
Li & Goodman (2010)

$k_x H$ ~0.5 => ~11 000 km

Consequences

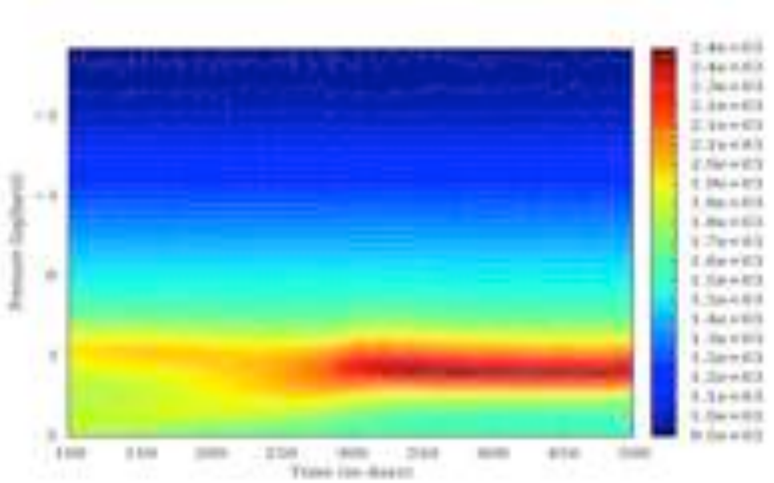
Two consequences → sharp velocity variations in the upper layers

Two consequences → heating deep in the atmosphere



Can be shown to be weak shocks (M~1.5).

Dynamical origin still unclear…



Kinetic energy transfered into heat.

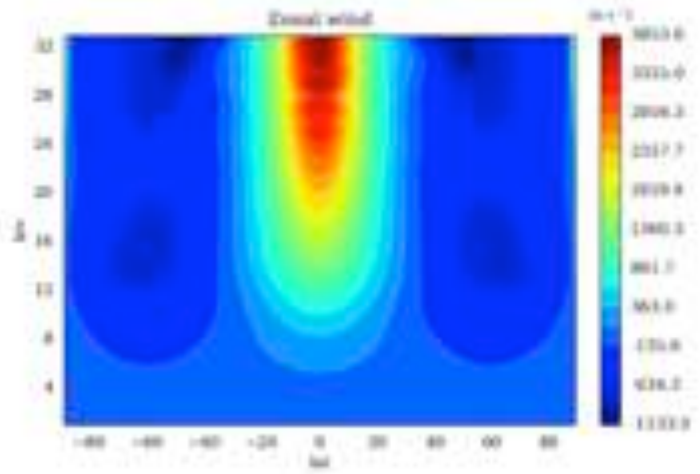
Robustness & importance for the inflated radii problem still unclear…

Hot Jupiters with DYNAMICO: first attempt

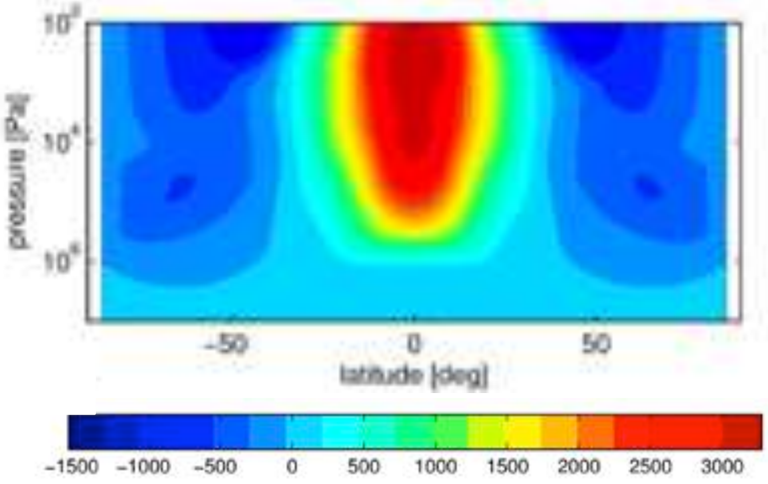
Motivation

Can these results (supersonic equatorial jet, horizonal KH instability) be reproduced with dynamico?

Setup: modification of the Held-Suarez configuration: Newtonian cooling - no additional physics, bottom layer at 220 bar, coarse resolution (nbp=20) – 33 levels with constant spacing in log(pressure) – dt=120 sec.



Zonally and time averaged (over 500 days) zonal wind in latitude-pressure coordinates



Good agreement with Liu & Showman (2010)!

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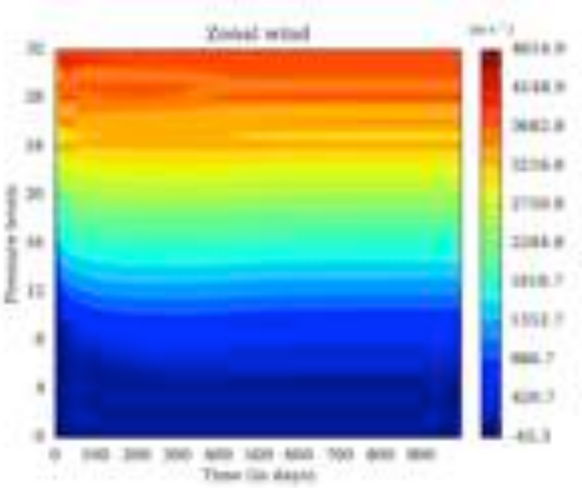
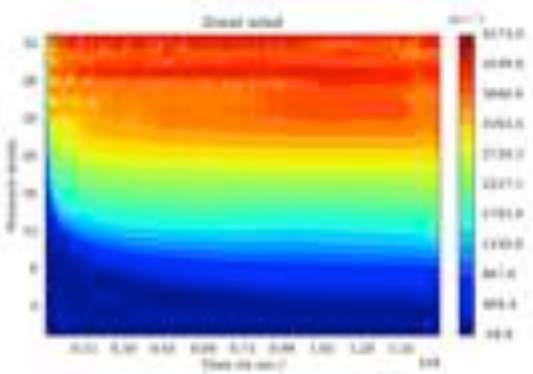
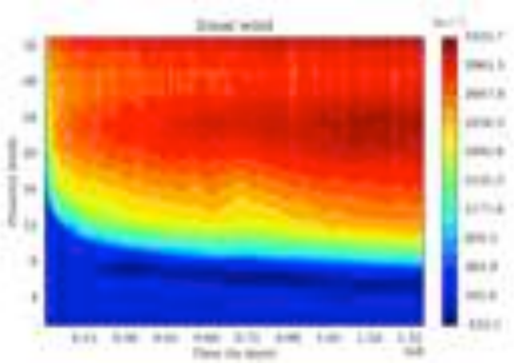
But: large dissipation needed to filter out small scale oscillations and reach steady state



Tdissip=100 sec.



Tdissip=300 sec.



Tdissip=5000 sec.

More work needed….

Conclusions

- **« Simple » cartesien, compressible model in agreement with standard GCM**
- **Jet unstable to KH instabilities**
  - => Variability and shocks in atmosphere upper layers
  - => Heating of deep atmospheric layers (~10 bars)
- **First results with dynamico are encouraging – but sensitivity to dissipation…**
  - => drag & KH instability in the upper atmosphere
  - => Vertical shear instability: non hydrostatic configuration