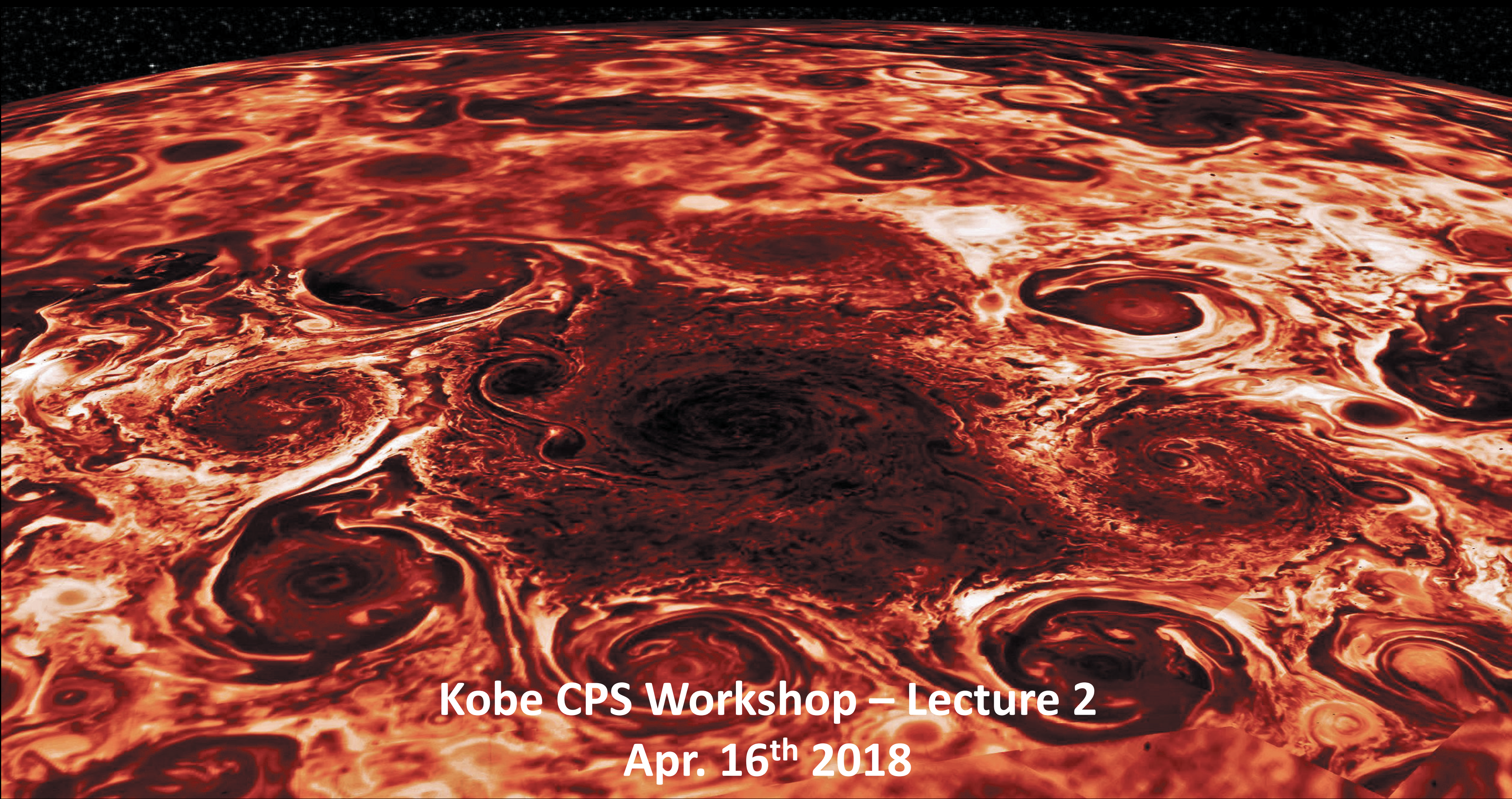
Juno at Jupiter: the first 18 months

Yohai Kaspi

Weizmann Institute of Science, Israel



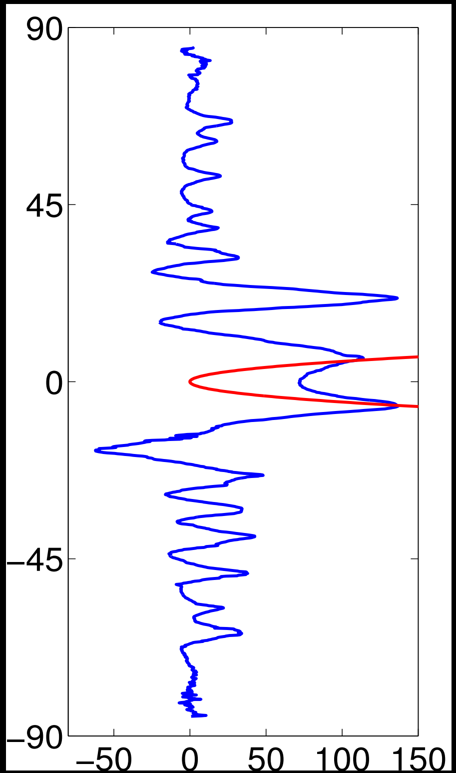
Kobe CPS Workshop – Lecture 2

Apr. 16th 2018

Jupiter

- Orbit: 5.4 AU
- Equatorial radius: 71,000 km
- Rotation period :9.92 hours
- Oblateness:1/16 (Earth = 1/298)
- Mass: 318 Earth masses

Jupiter

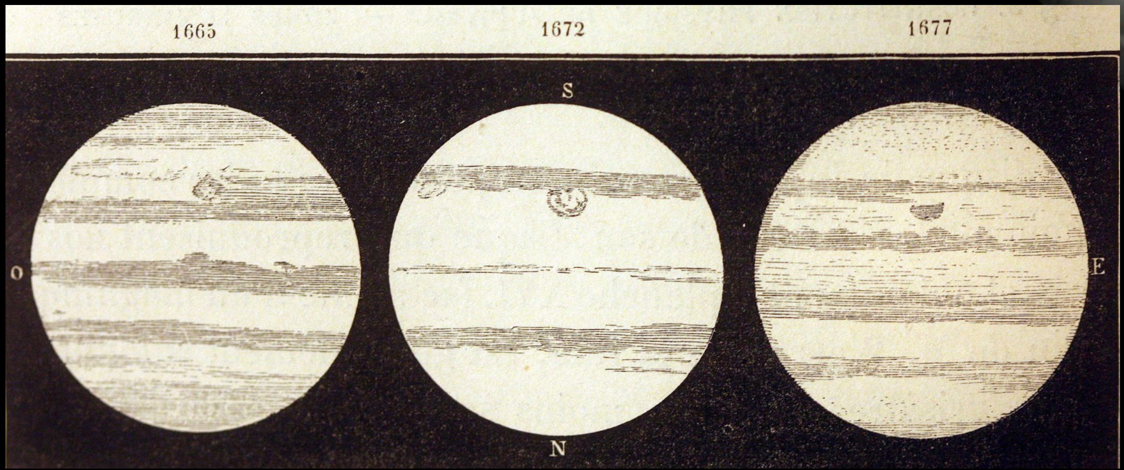


Zonal wind m/s

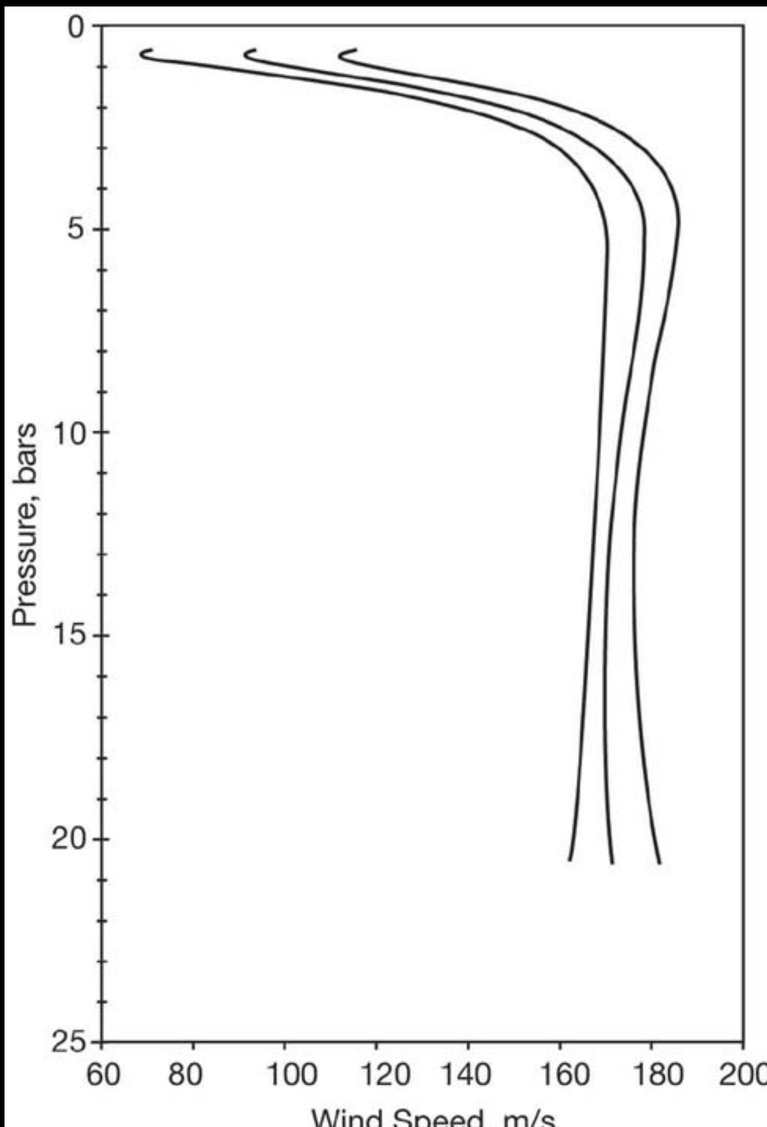
Jupiter

- Orbit: 5.4 AU
- Equatorial radius: 71,000 km
- Rotation period :9.92 hours
- Oblateness:1/16 (Earth = 1/298)
- Mass: 318 Earth masses

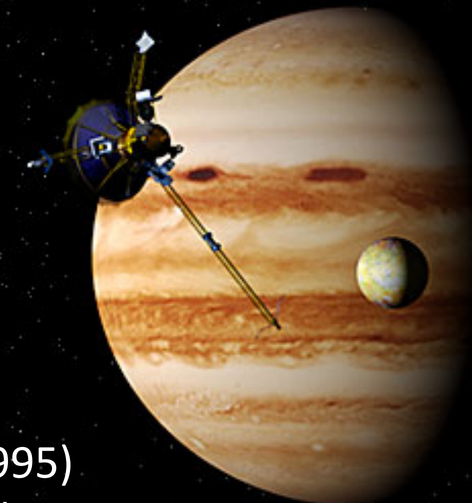
Giovanni Cassini, 1665



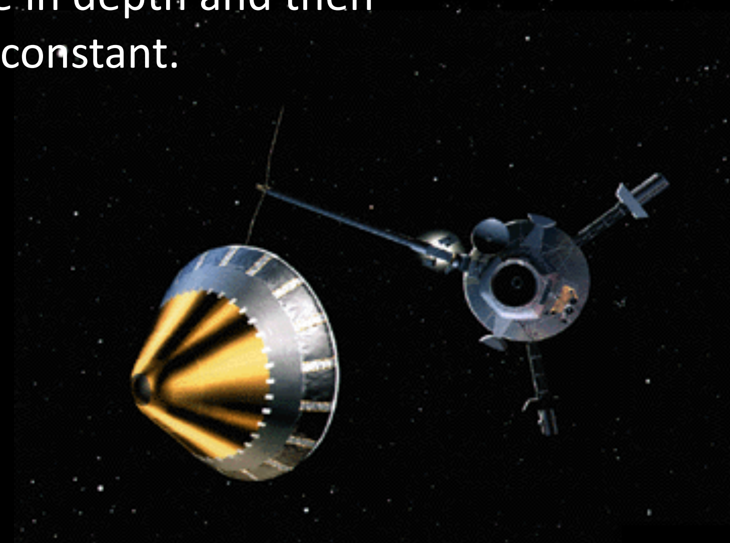
How deep are the zonal winds?

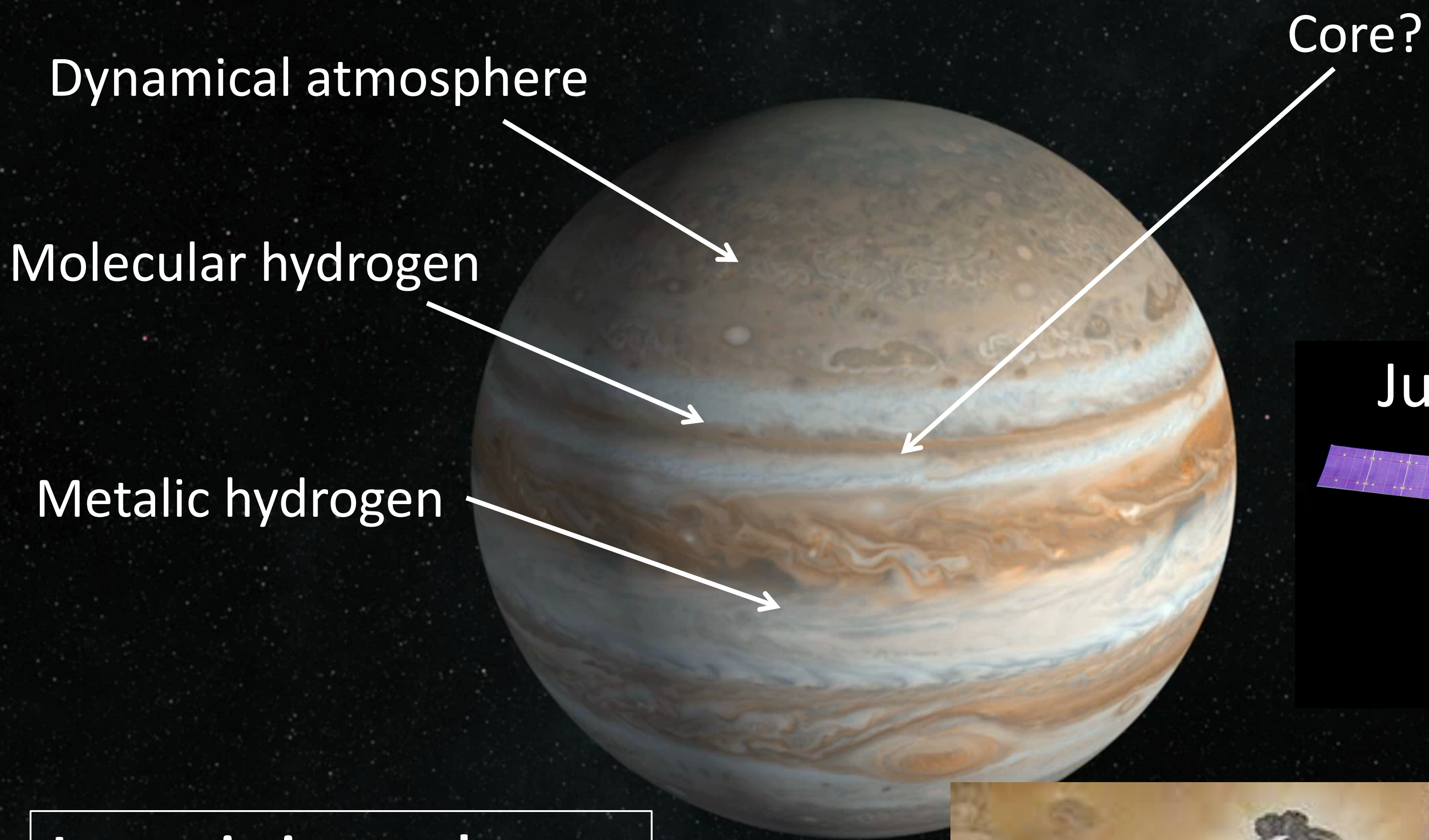


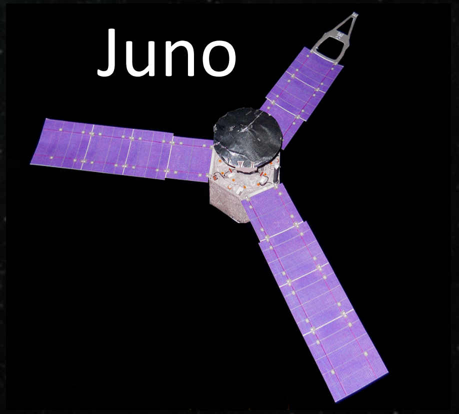
Atkinson et al., 1998



Galileo entry probe (1995) detected zonal winds that increase in depth and then remain constant.

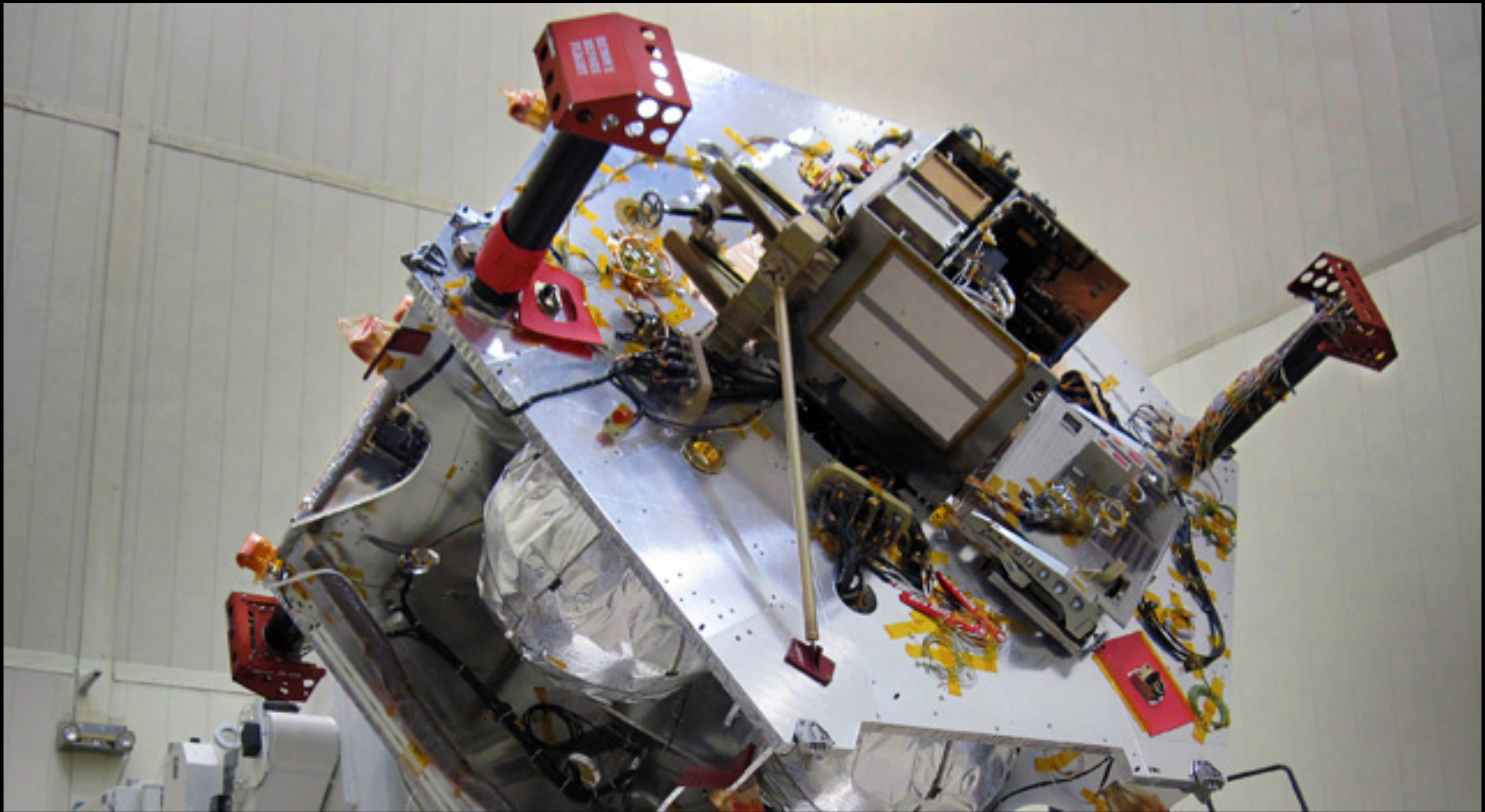






Juno mission goals:

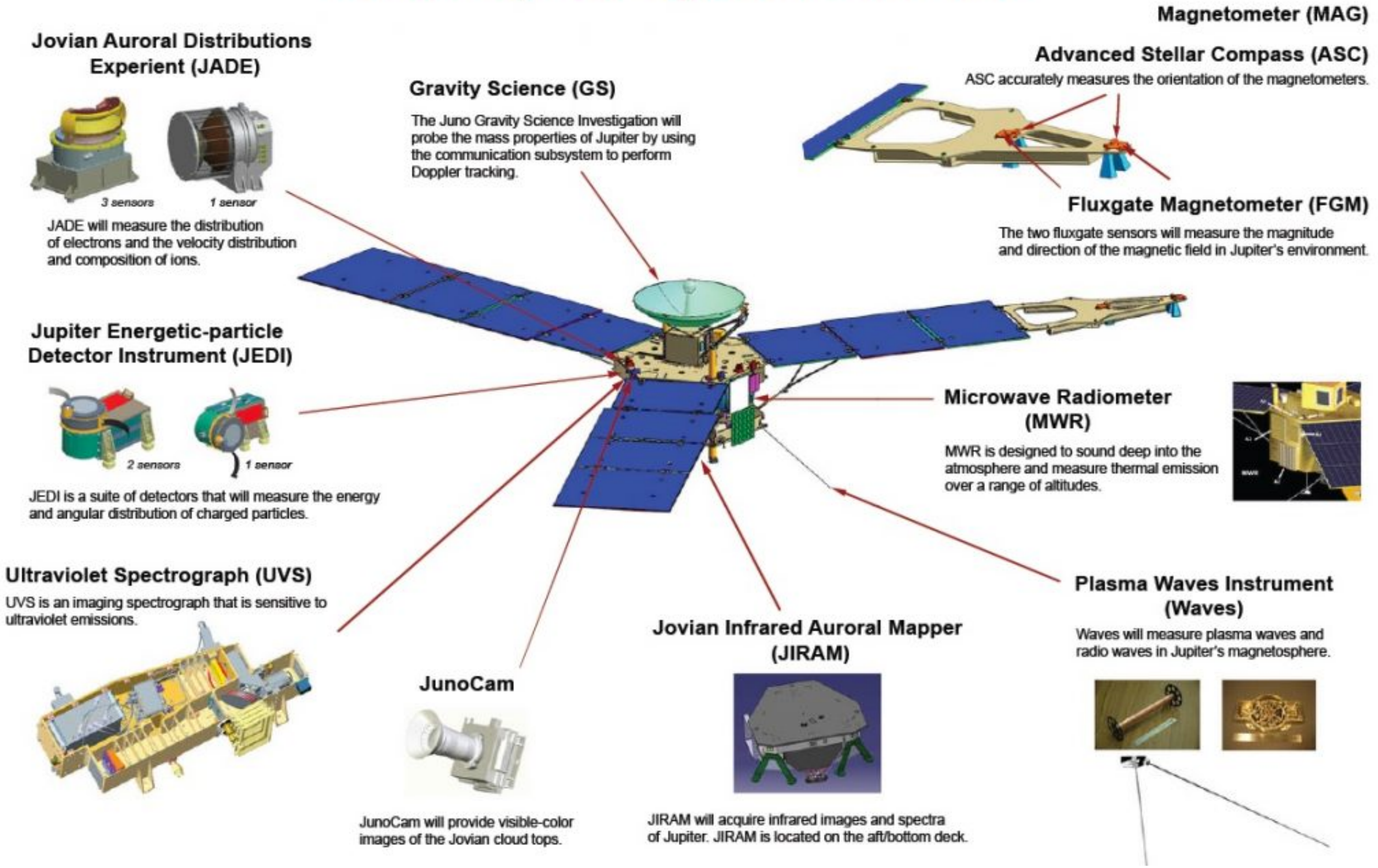
- Deep dynamics
- Interior structure (core?)
- Atmospheric composition
- Magnetosphere



April 2010

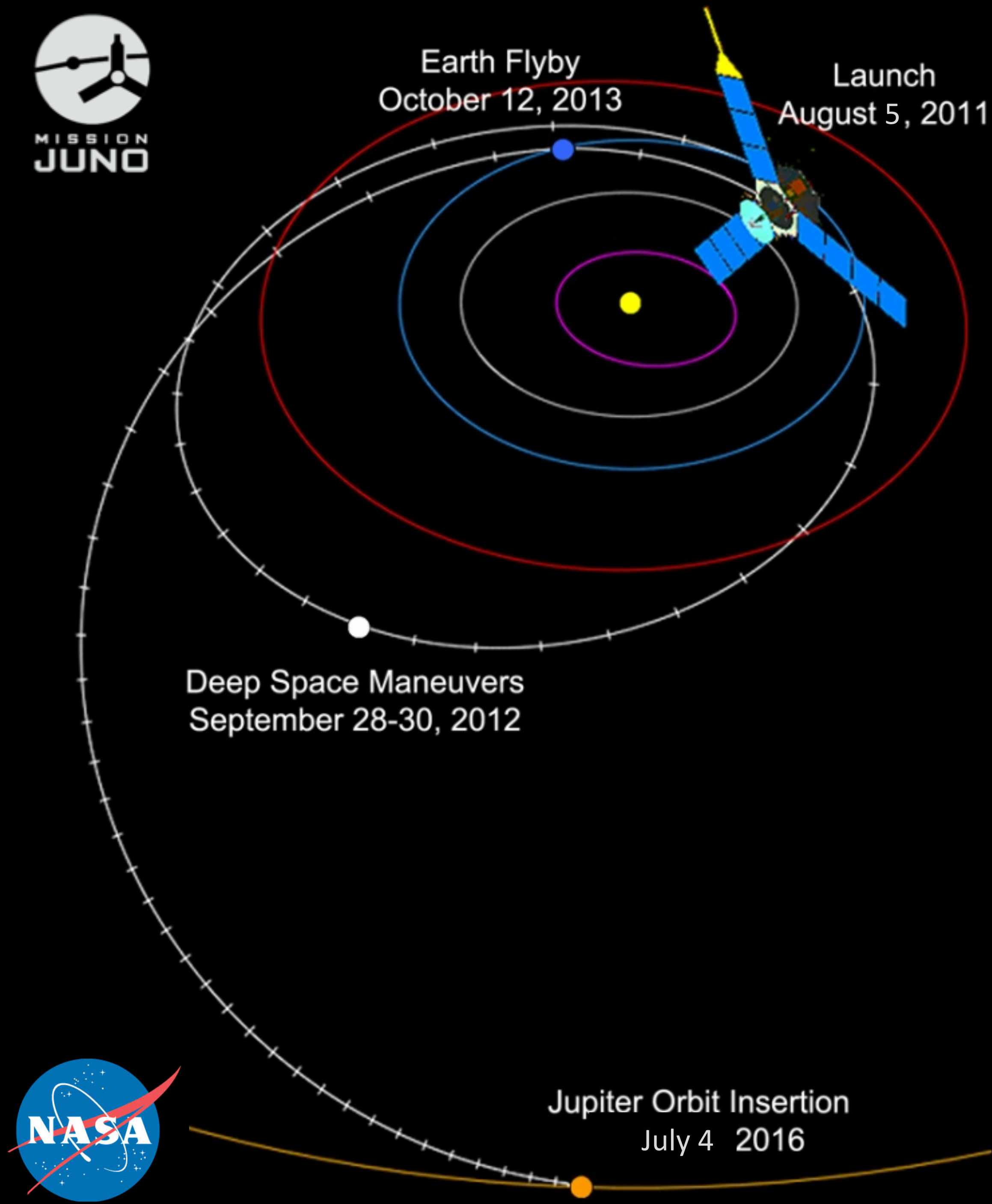
June, 2011

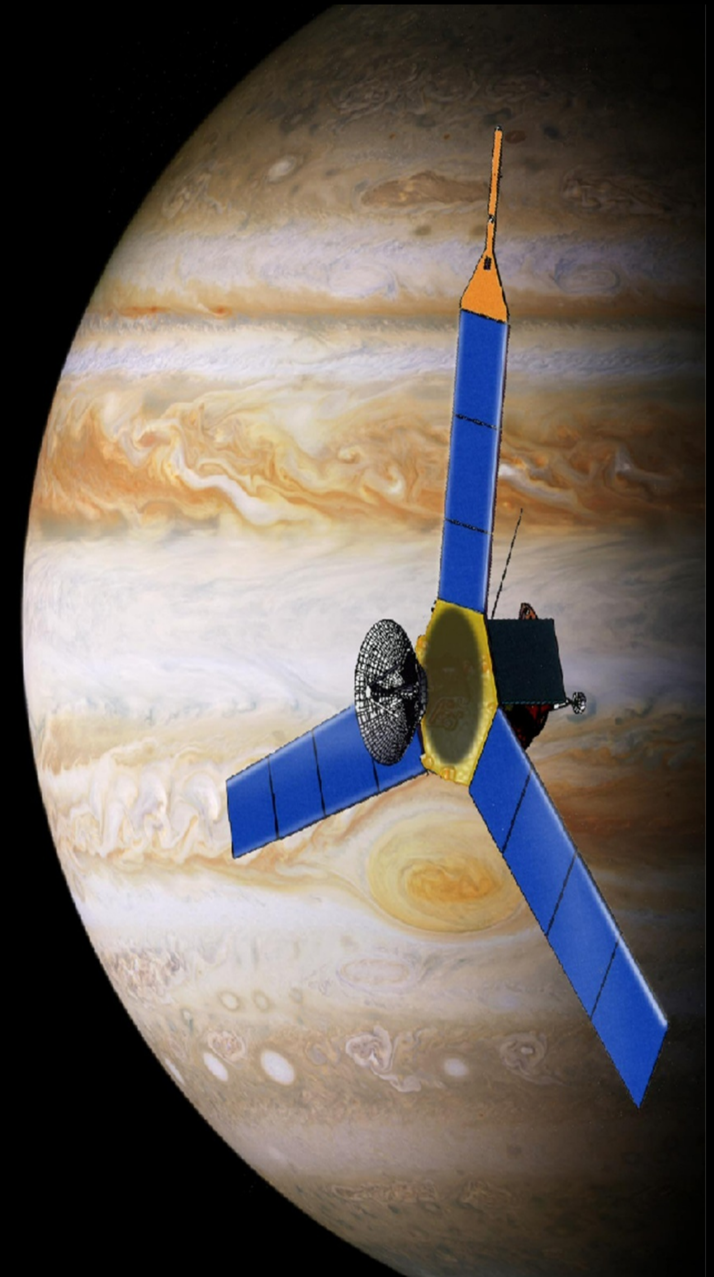
Juno Payload System Overview



Aug. 4th 2011

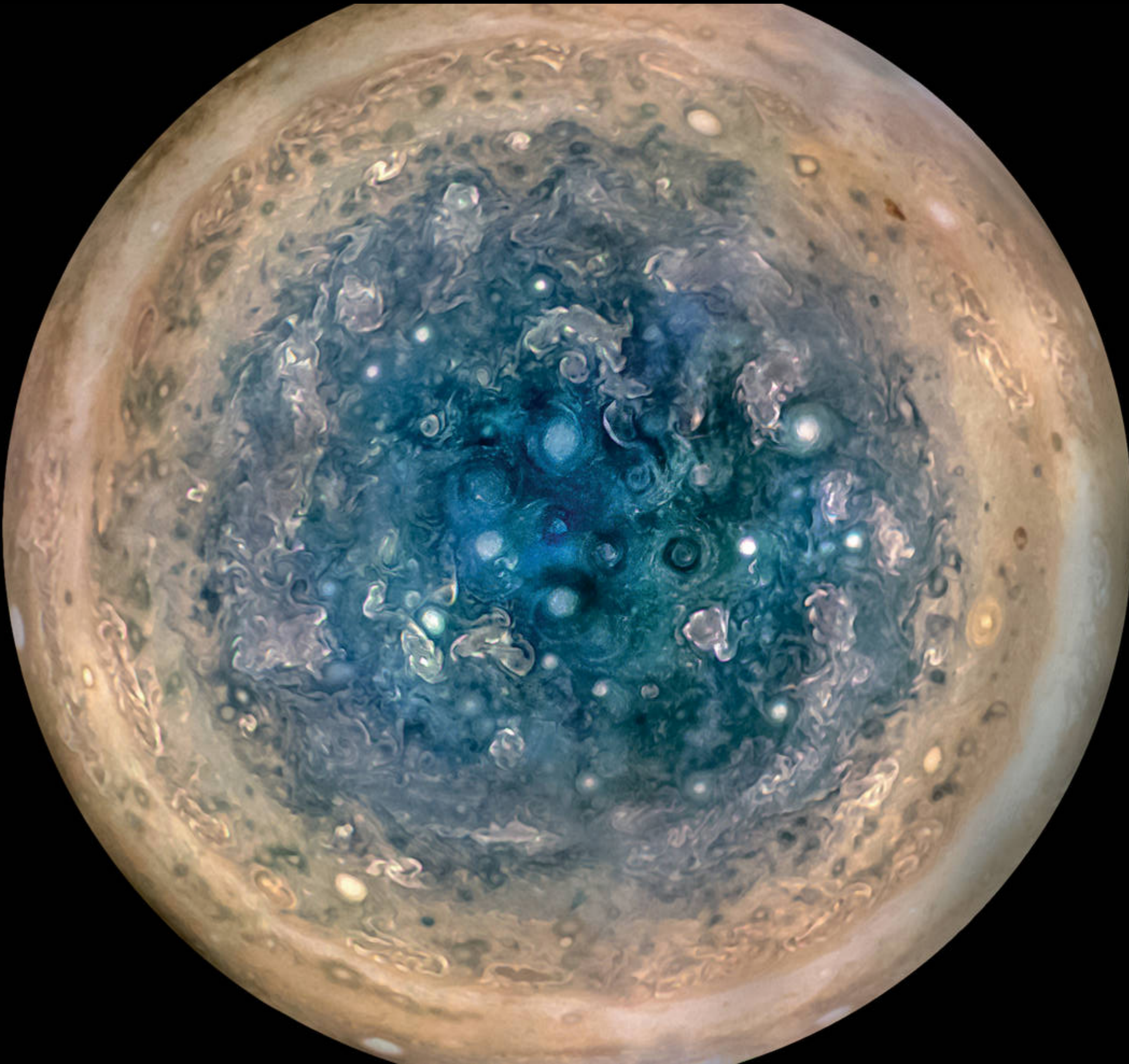
Juno

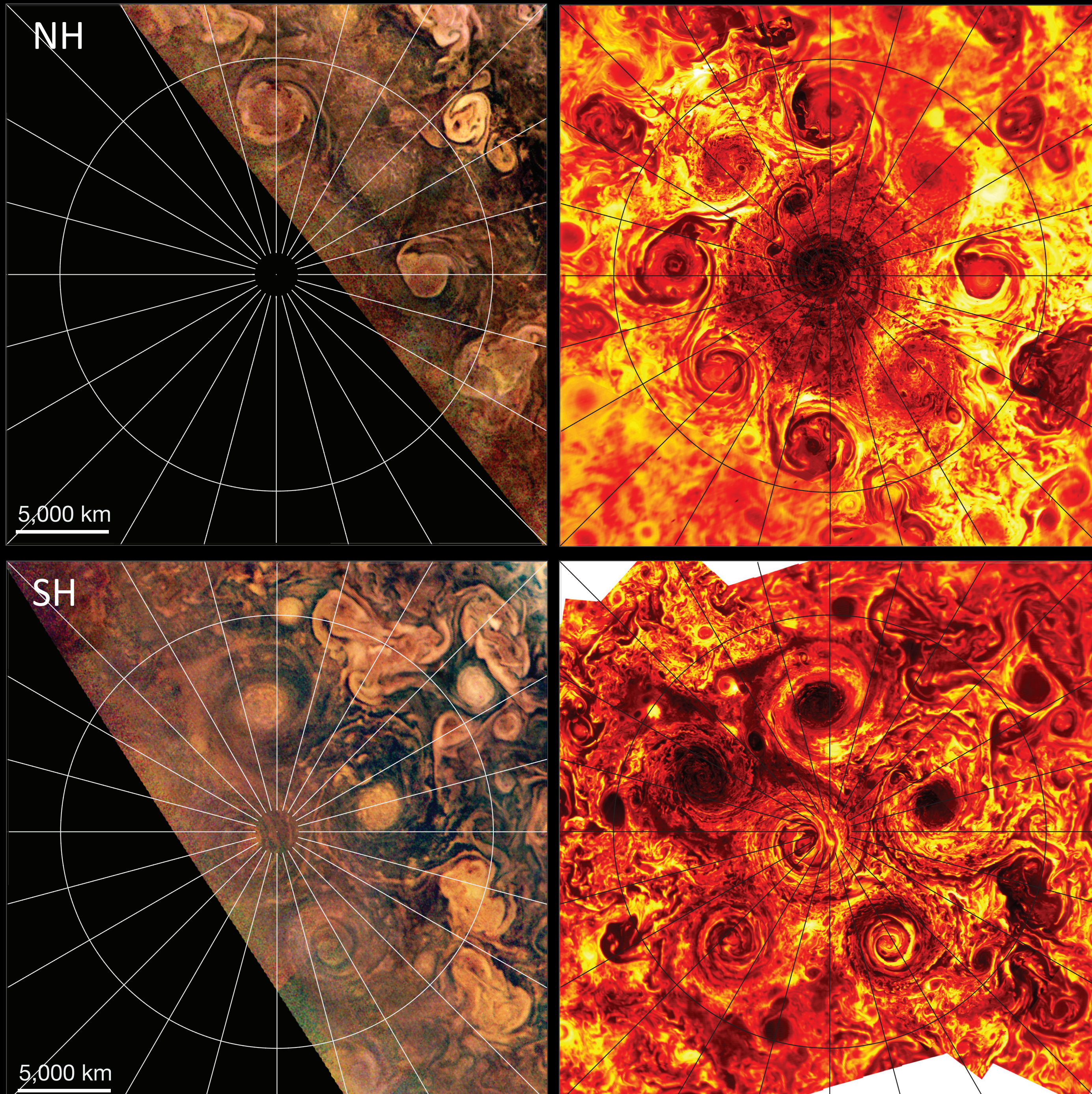

MISSION
JUNO
Earth Flyby
October 12, 2013
Launch
August 5, 2011
Deep Space Maneuvers
September 28-30, 2012
Jupiter Orbit Insertion
July 4 2016
NASA



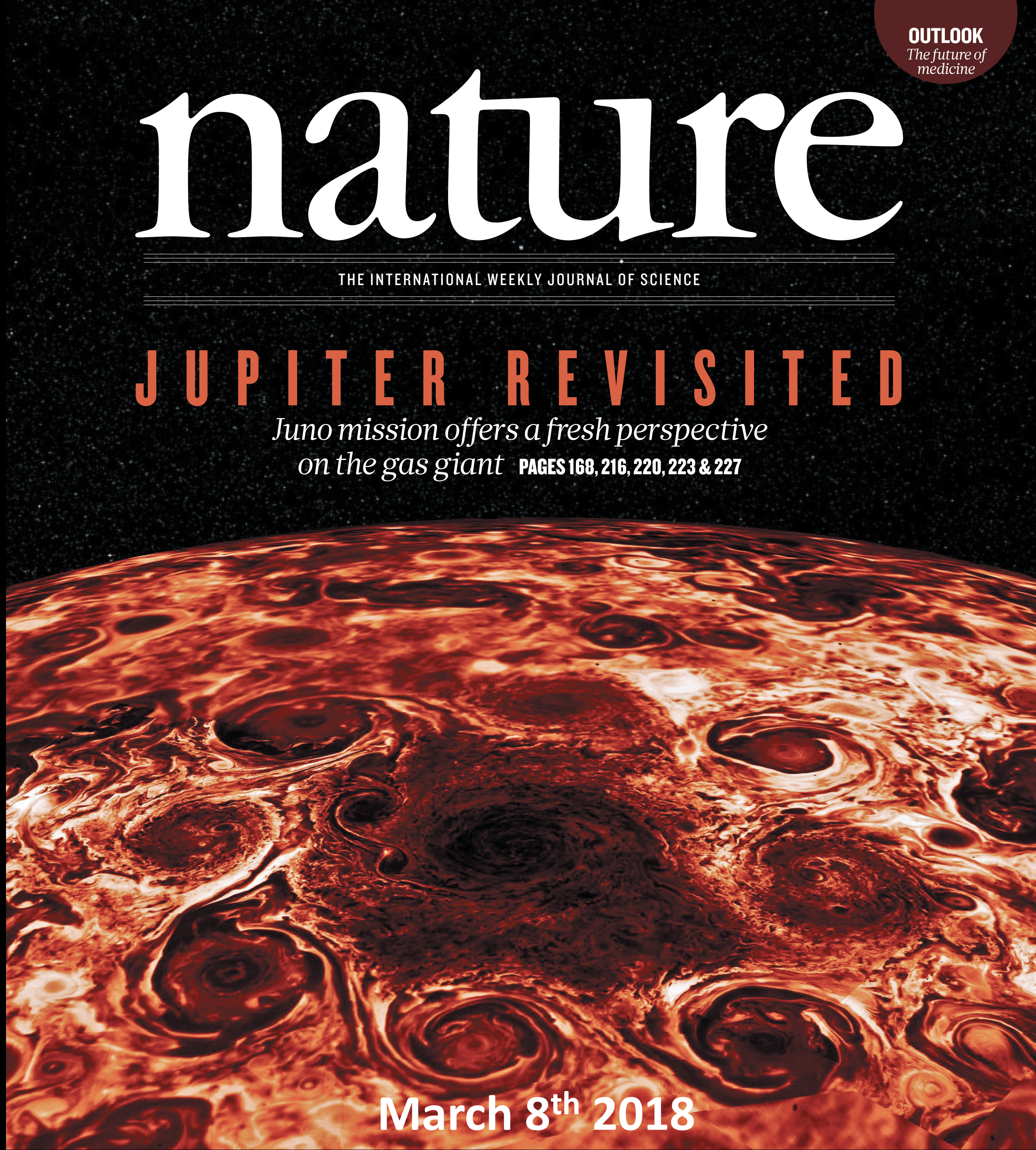
First images from Juno during approach - June 2016

- Juno is orbiting Jupiter every 53 days since July 2016
- Polar orbit with perijove drift of 1 degree northward
- Perijove distance is ~4000 km

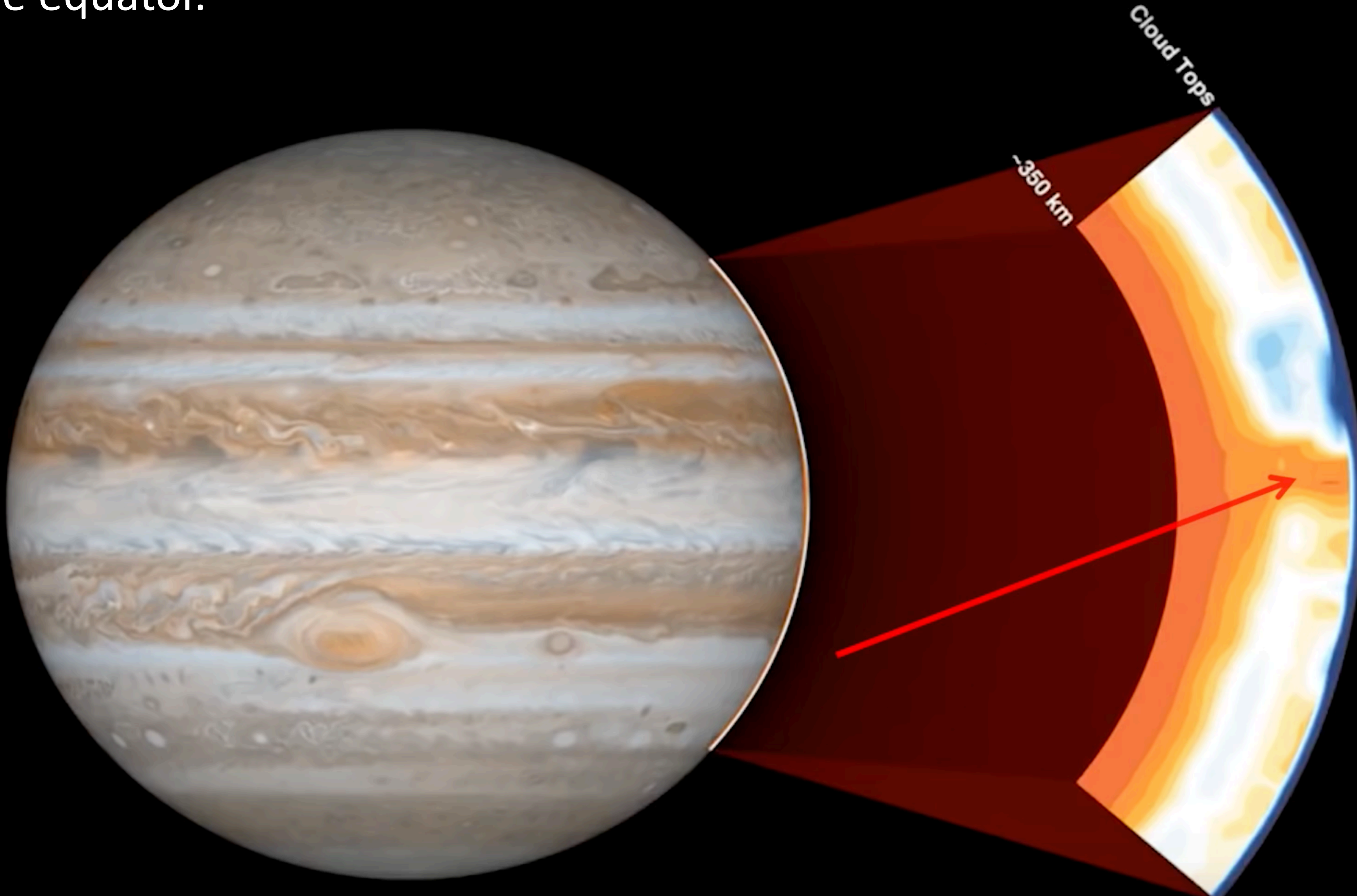




Adriani et al., 2018, *Nature*

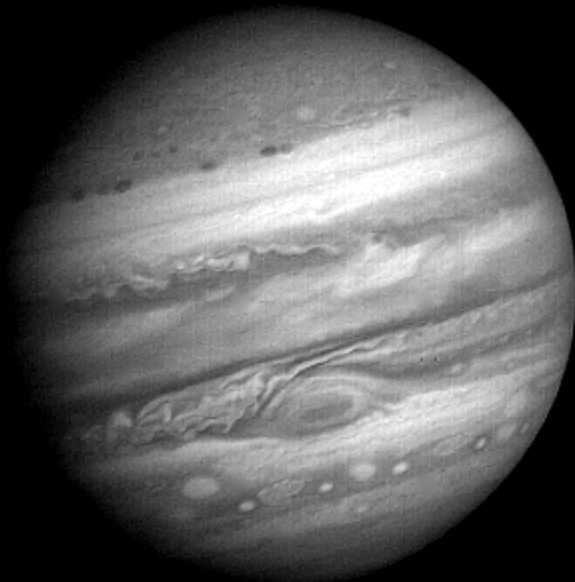

OUTLOOK
The future of medicine
nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
JUPITER REVISITED
Juno mission offers a fresh perspective on the gas giant
PAGES 168, 216, 220, 223 & 227
March 8th 2018

Juno's microwave measurements reveal an ammonia plume near the equator.



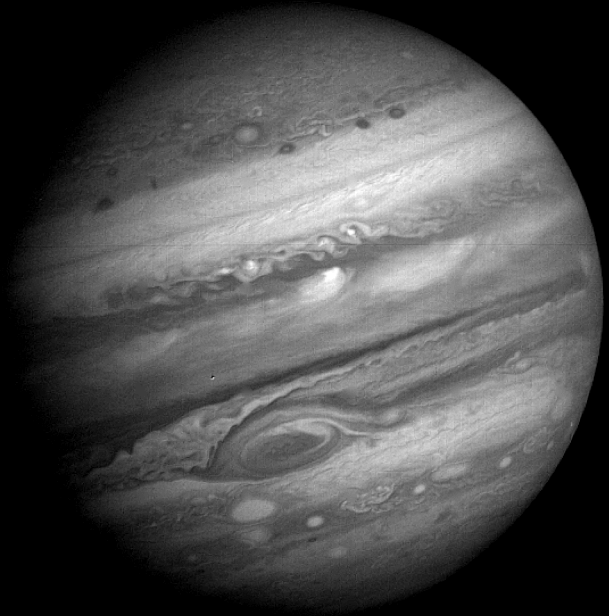
Bolton et al., 2017, *Science*

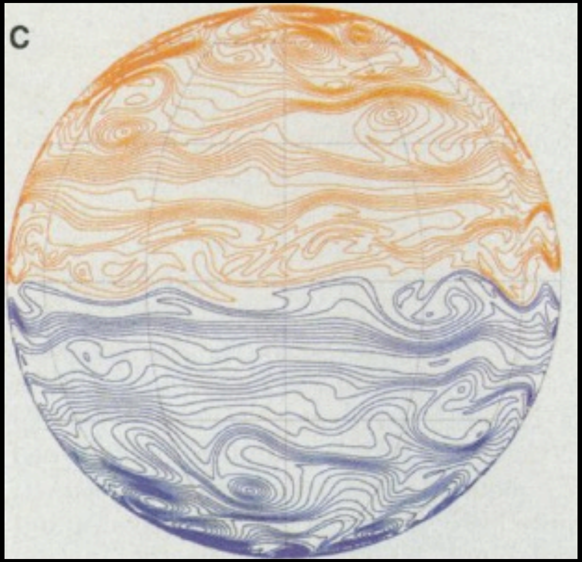
How deep are Jupiter's zonal jets?



Voyager 2: 1979

How deep are Jupiter's zonal jets?





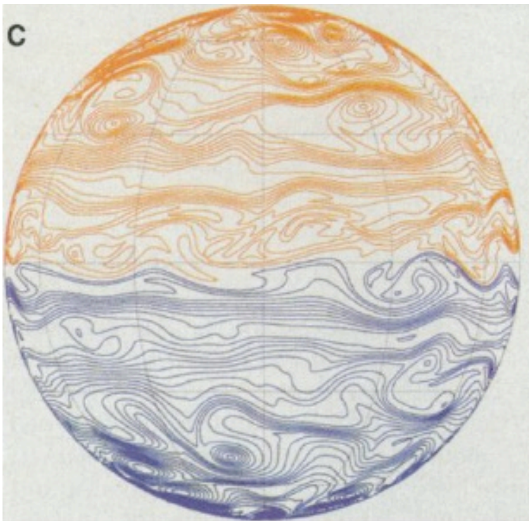
Shallow or deep?

Shallow geostrophic turbulence
(Rhines, 1975, Cho & Polvani 1996)

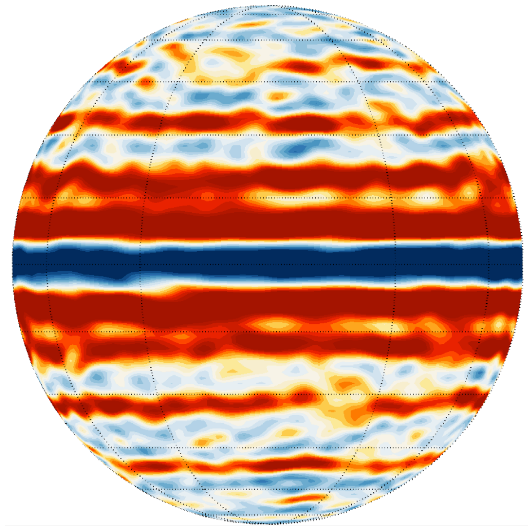
Deep internal convection
(Busse, 1976, Heimpel et al, 2005
Fig. from Ingersoll, 1990)

Shallow atmospheric models

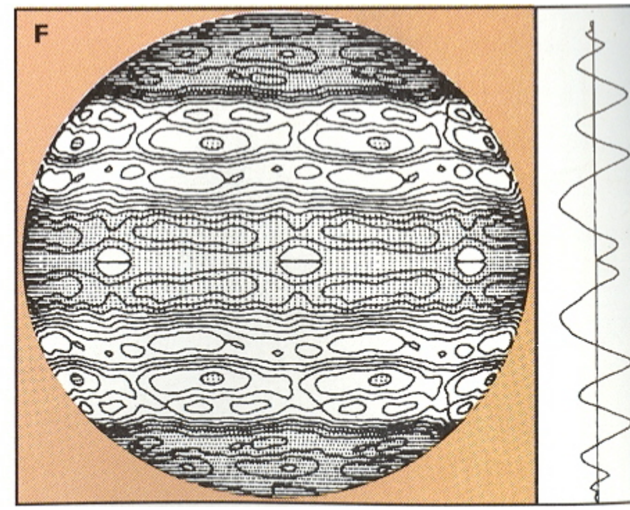
For a planet with Jupiter radius and rotation rate gostrophic turbulence leads to multiple jets:



Cho & Polvani, 1996



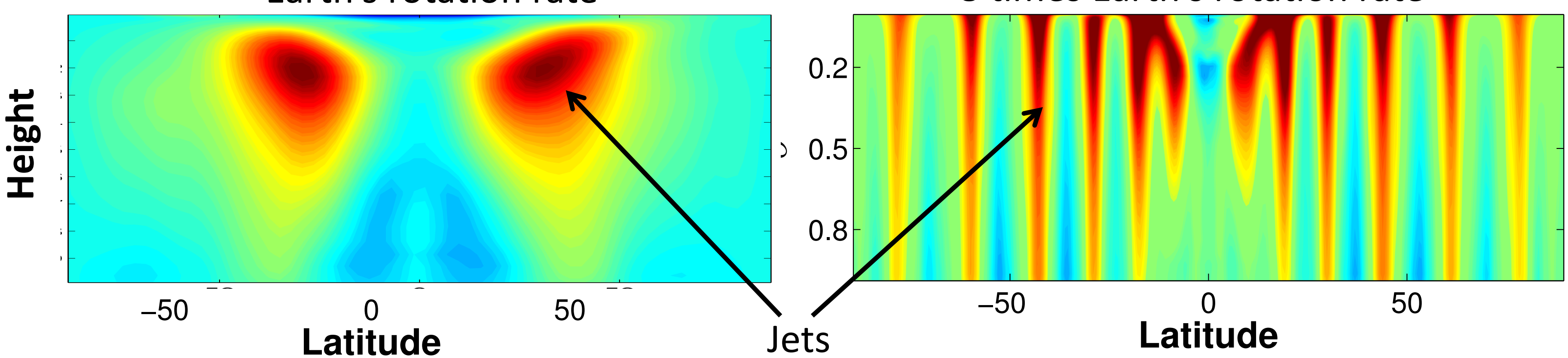
Chemke & Kaspi, 2015



Williams, 1978

Earth's rotation rate

8 times Earth's rotation rate



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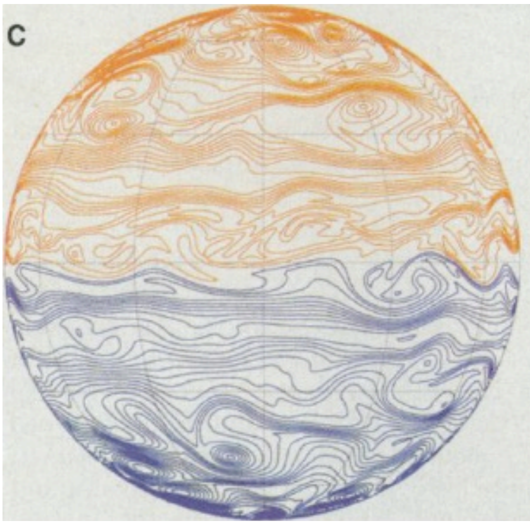
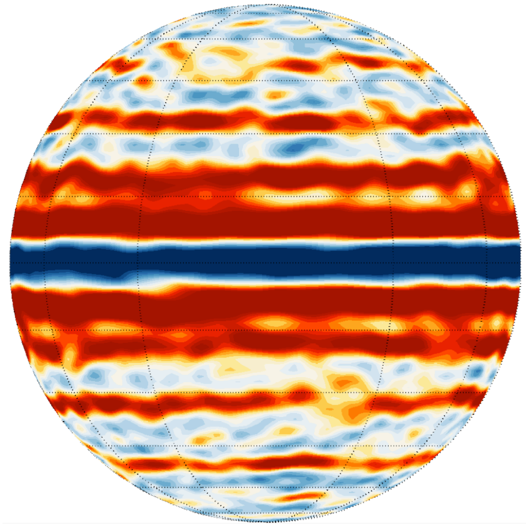
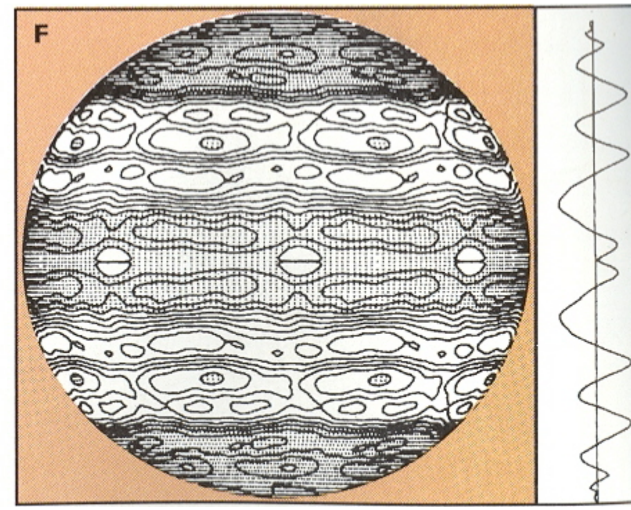


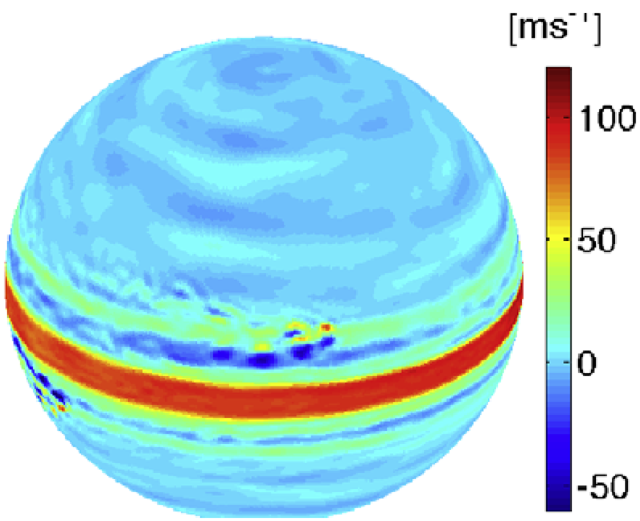
Cho & Polvani, 1996



Chemke & Kaspi, 2015

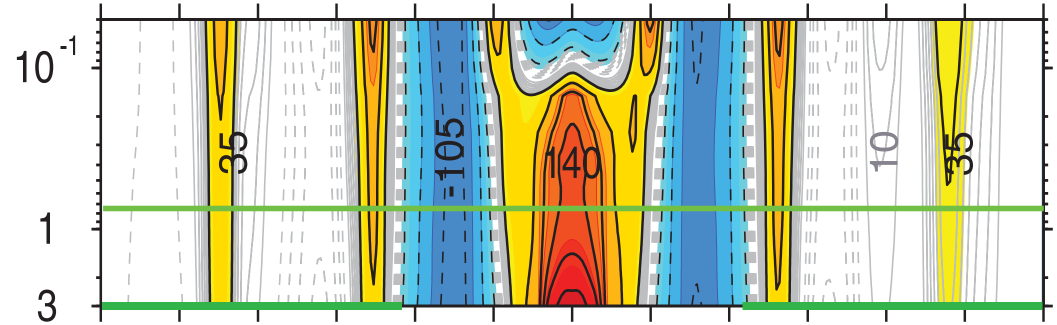


Williams, 1978



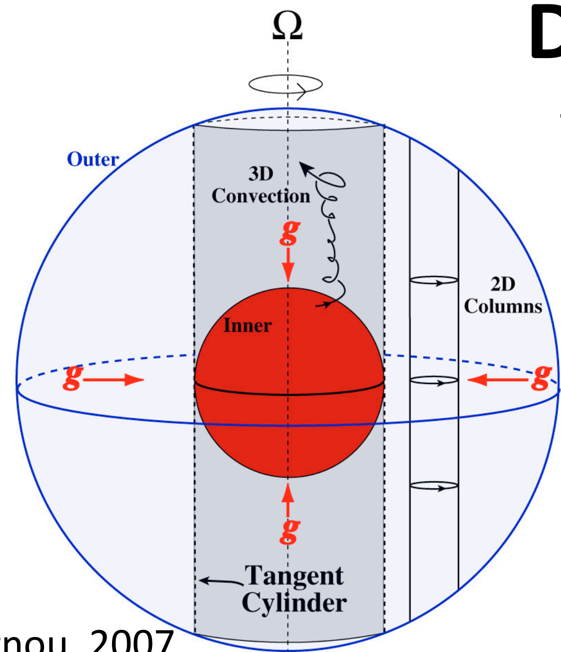
Lian & Showman 2010

For superrotation a source of equatorial eddy momentum flux convergence is needed.

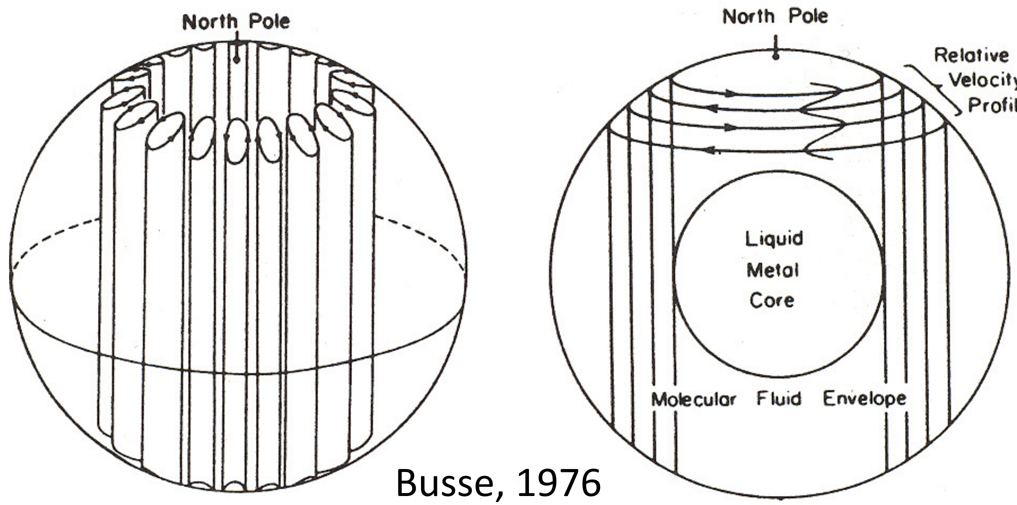


Liu & Schneider 2010

Deep convection models

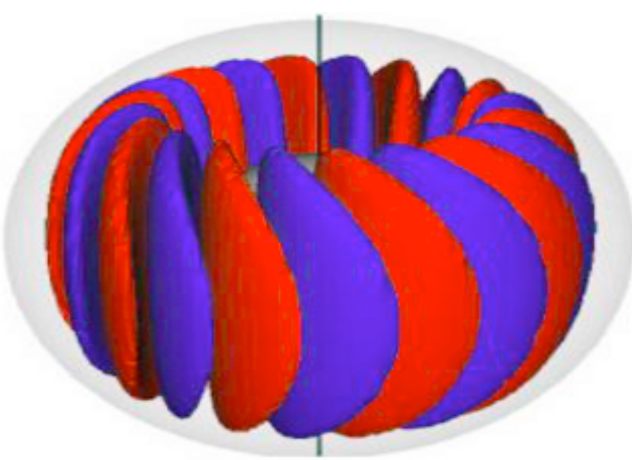


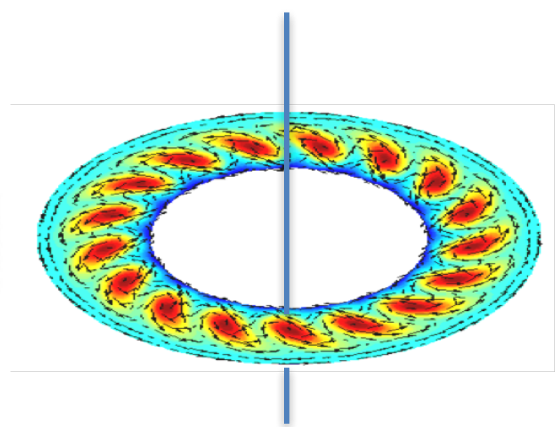
Aurnou, 2007



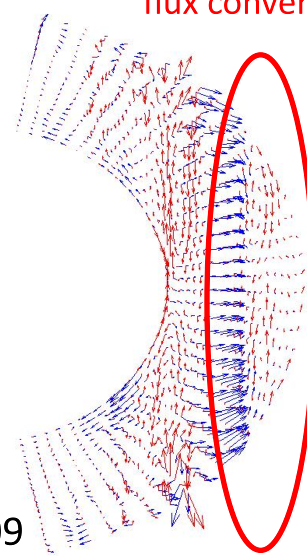
Busse, 1976

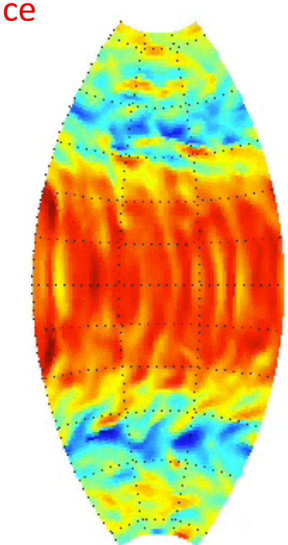
Superrotation due to angular momentum eddy flux
in the direction perpendicular to the spin axis.





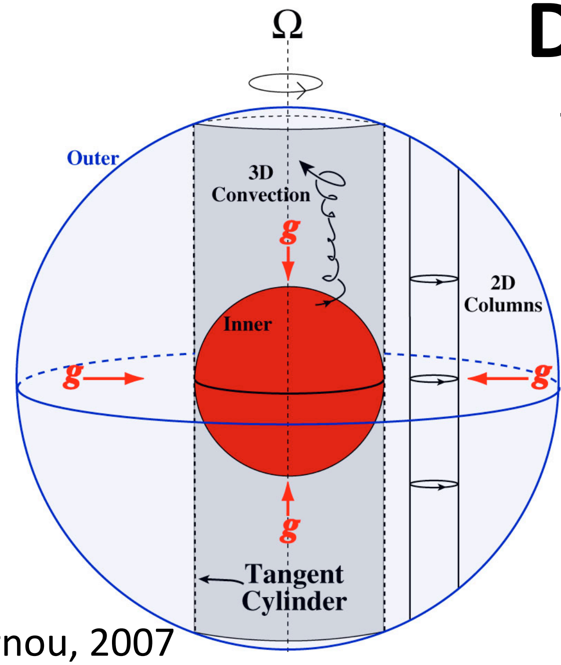
Angular momentum
flux convergence



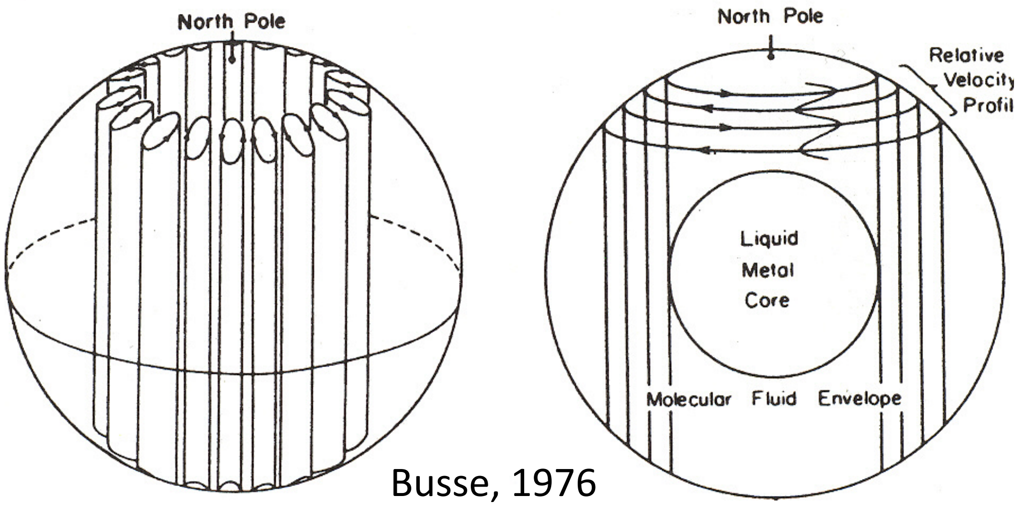


Kaspi et al., 2009

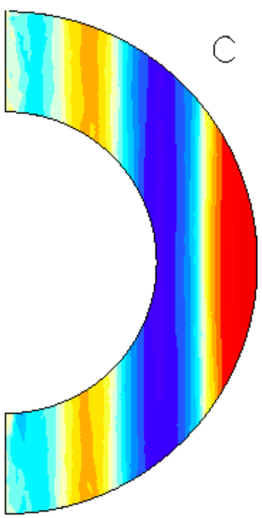
Deep convection models



Aurnou, 2007

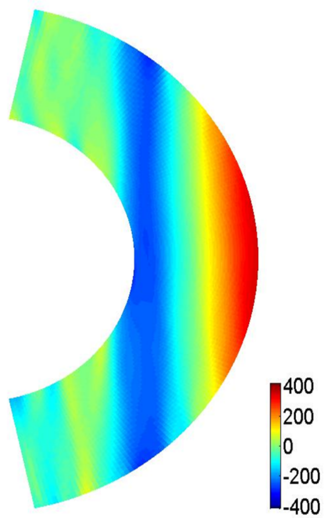


Busse, 1976

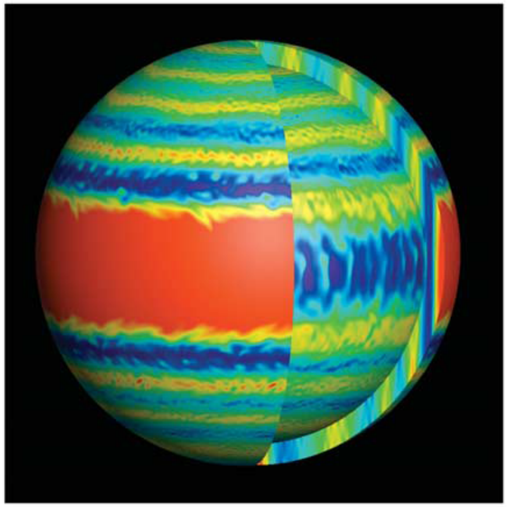


Christensen, 2002

Heimpel & Gomez-Perez, 2011



Kaspi et al., 2009



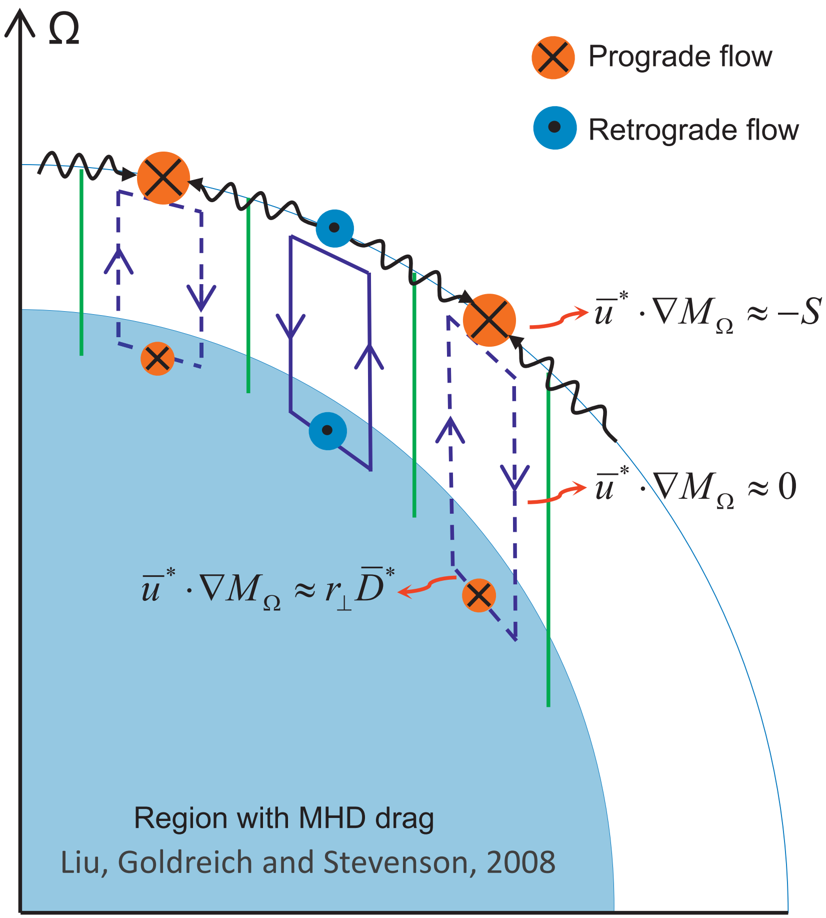
Heimpel et al., 2005

Angular momentum balance:

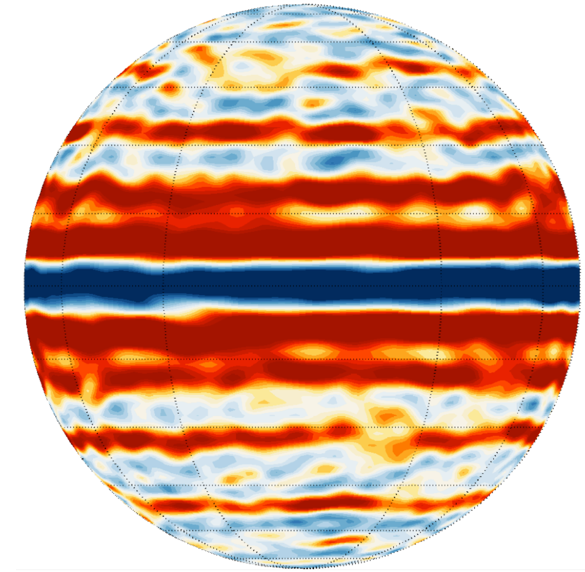
$$M = \Omega r^2 \cos^2\theta + ur\cos\theta$$

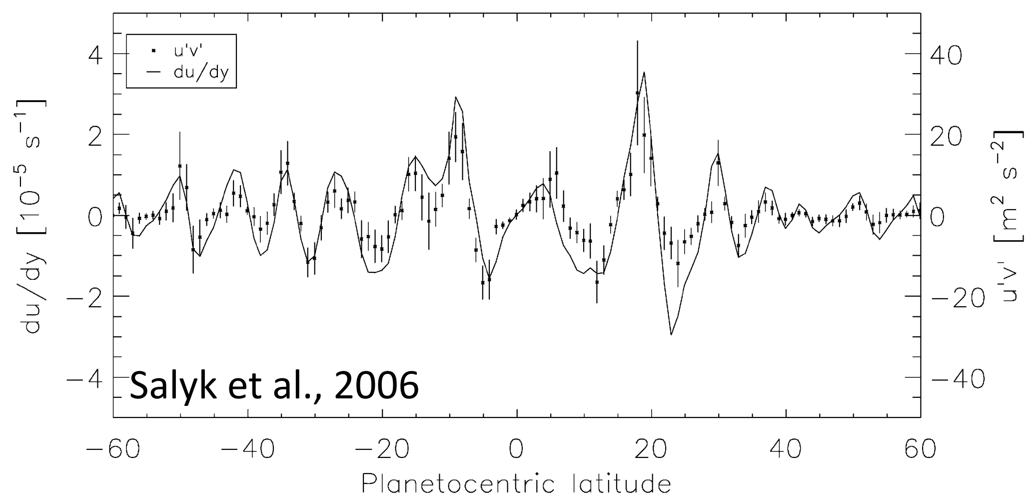
$$\mathbf{u}\cdot\nabla M = D - \frac{1}{\rho}\nabla\cdot\left(\rho\overline{\mathbf{u}'M'}\right)$$

Mean circulation	Lorentz Drag	AM Reynolds stress



Liu and Schneider, 2010





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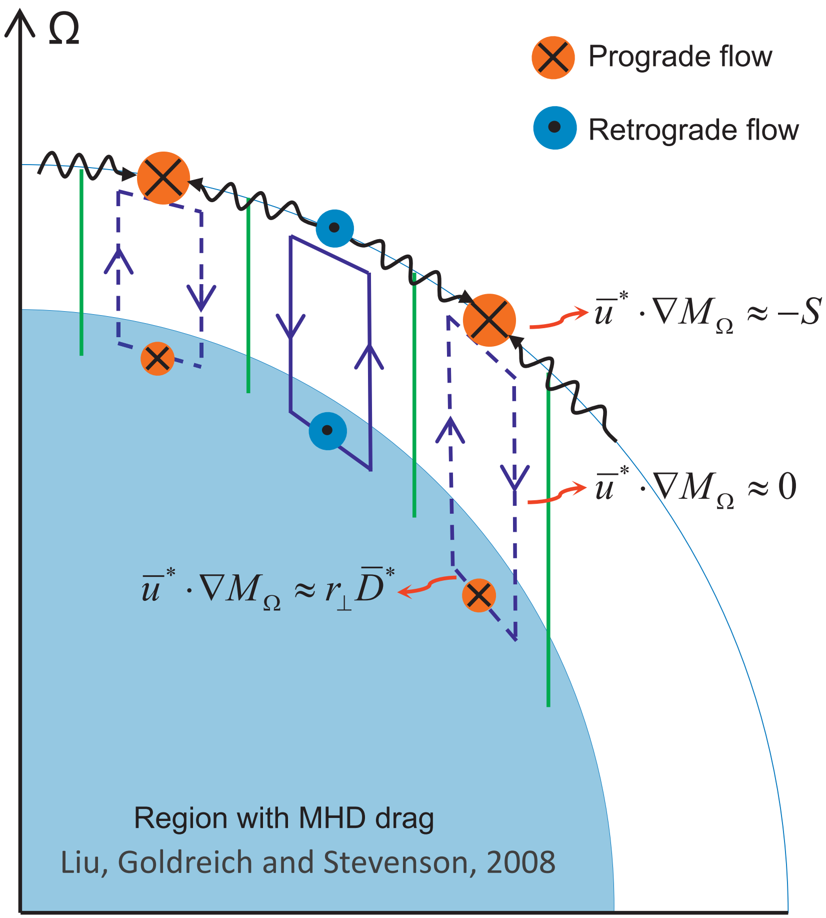
Mean circulation | Lorentz Drag | AM Reynolds stress



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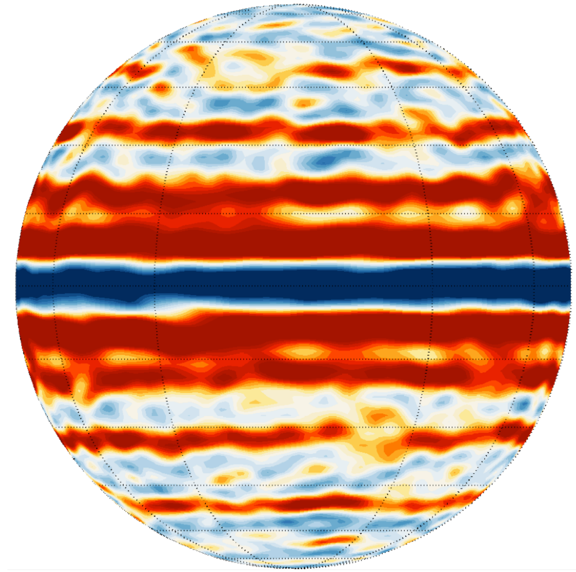
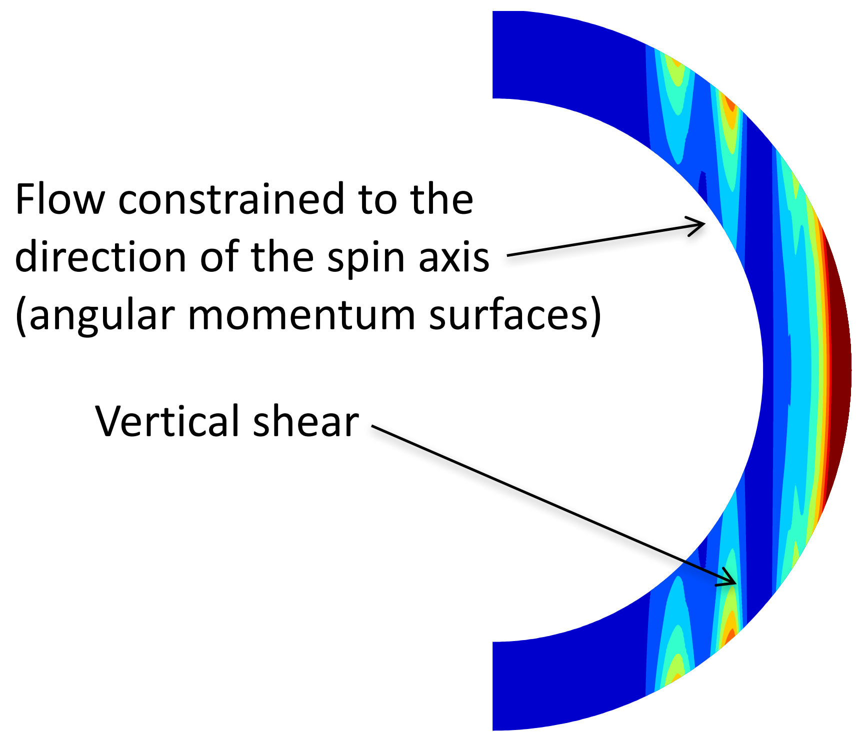
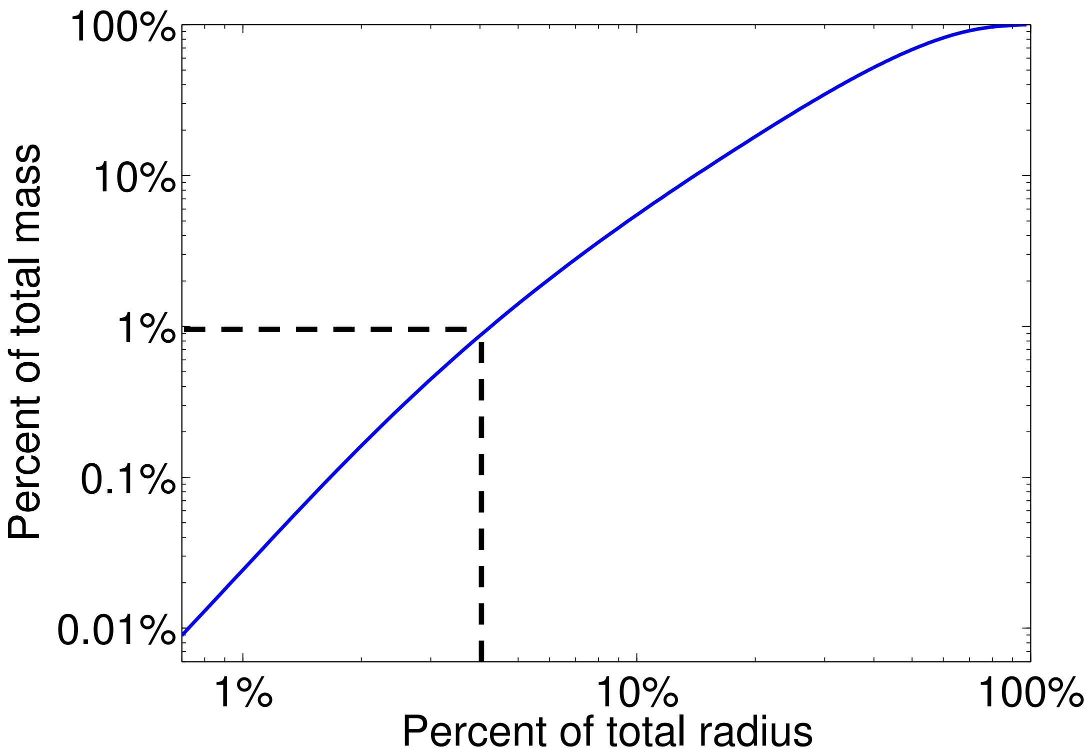
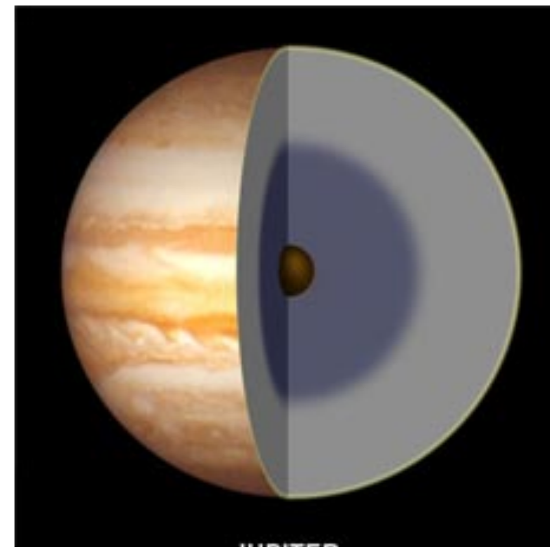




Perturbations to the gravity field due to internal dynamics

Since the planet has no solid surface, if the flow is deep enough it may contain a significant fraction of the mass.





Internal flows can have a measurable effect on the gravity field.

Perturbations to the gravity field of the planet can be expressed by zonal gravity harmonics:

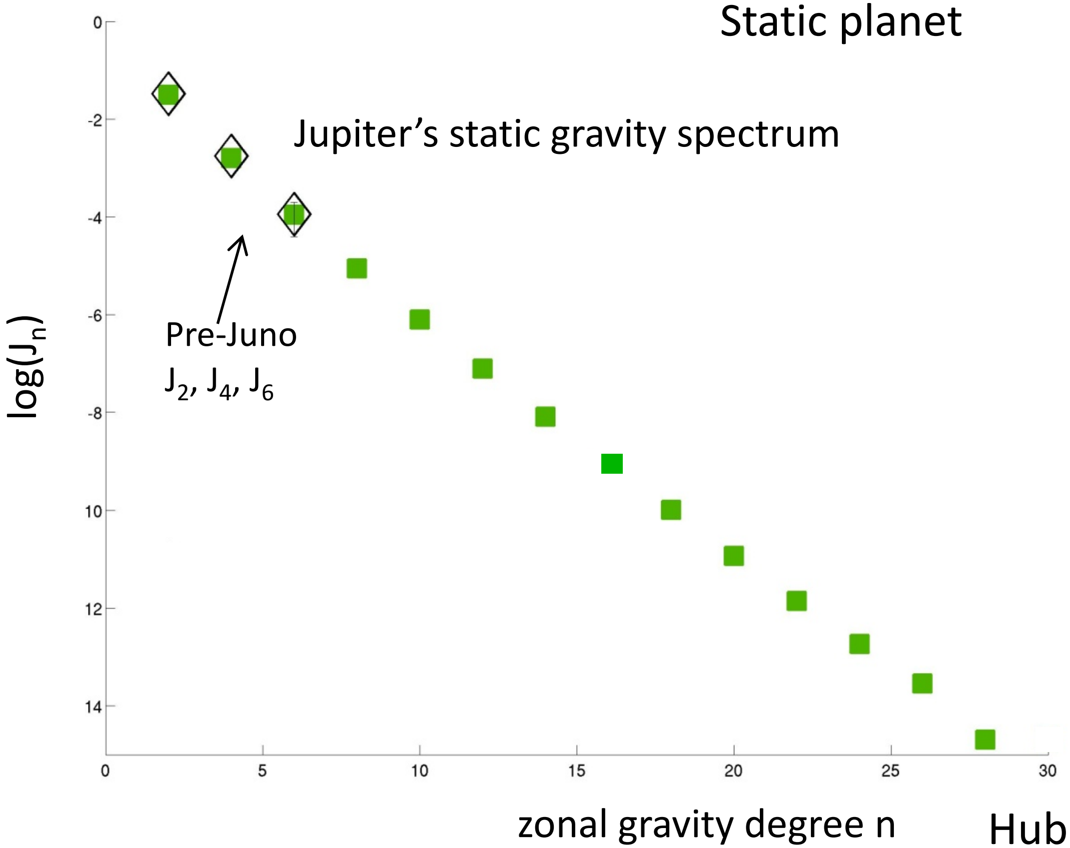
$$J_n = -\frac{1}{a^n M}\int r^n P_n(\theta)\rho(r,\theta)d^3r$$

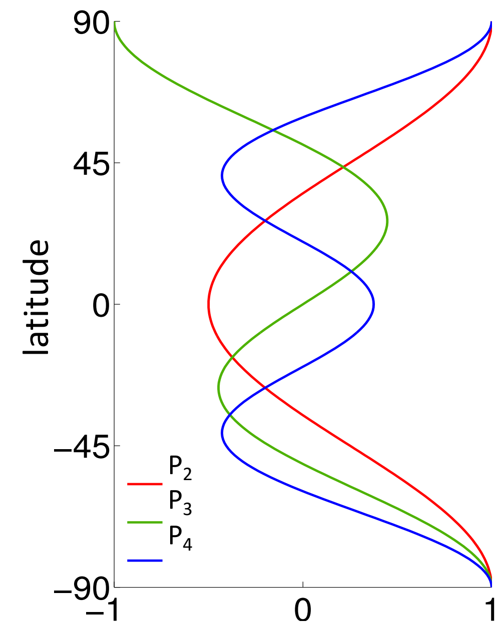
$$\rho = \bar{\rho}(r,\theta) + \rho'(r,\theta)$$

Static planet

variation due to dynamics

a = mean radius
M = total mass
P_n = Legendre polynomial





Hubbard, 1999

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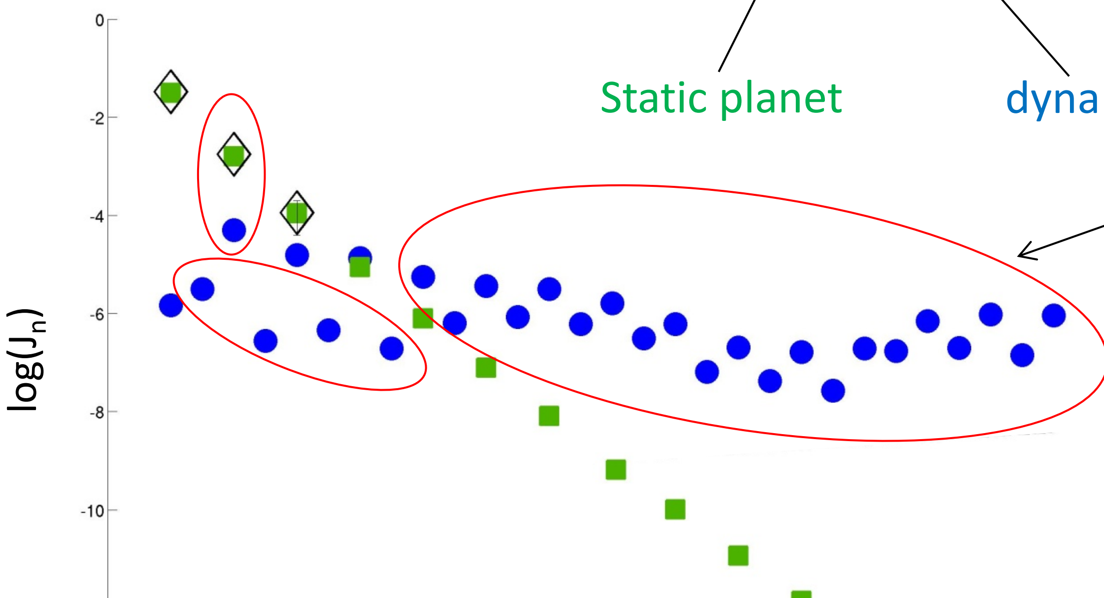
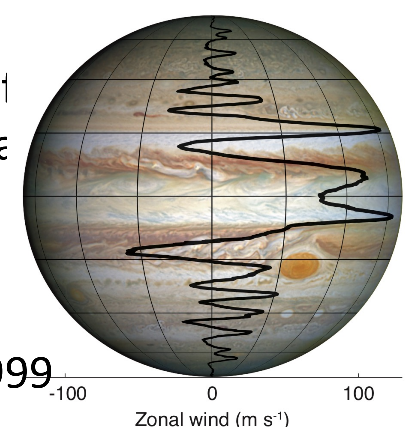
Static planet

dynamics

GCM simulations



- High order gravity harmonics
- Low order **odd** gravity harmonics
- Di served,
  sta es



Hubbard, 1999

We seek a model with which we can systematically vary the atmospheric and interior flow and calculate the resulting gravity field

Perturbations to the gravity field of the planet can be expressed by zonal gravity harmonics:

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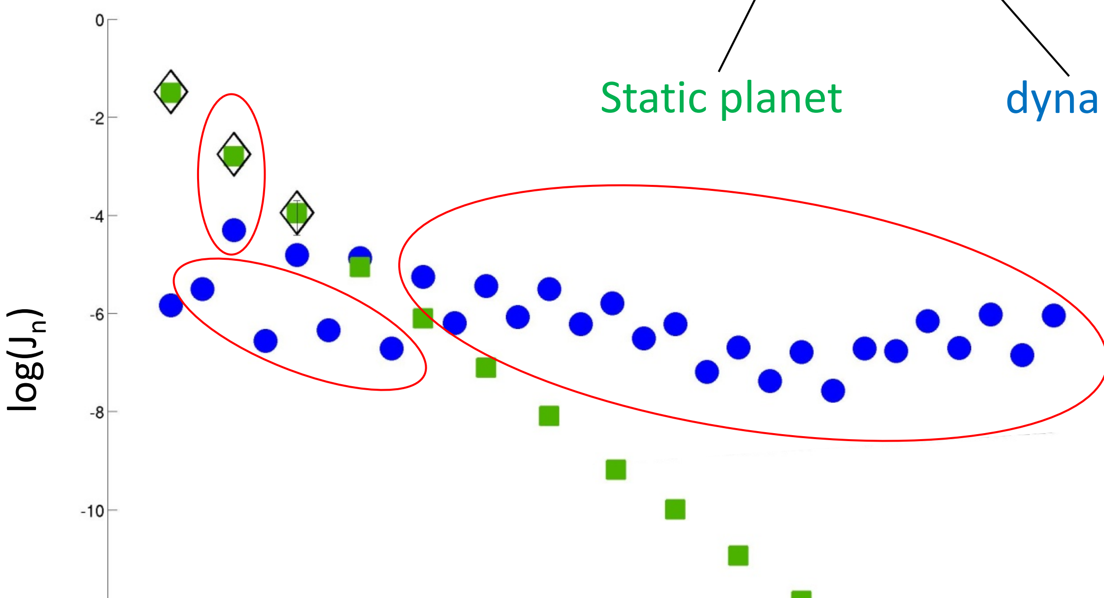
Static planet

dynamics



- High order gravity harmonics
- Low order **odd** gravity harmonics
- Difference between observed, static and dynamic values

Flow ⟷ Density ⟷ Gravity

Thermal wind balance: $2\Omega\cdot\nabla(\bar{\rho}u) = \nabla\rho'\times g$

Perturbations to the gravity field of the planet can be expressed by zonal gravity harmonics:

$$J_n = -\frac{1}{a^n M}\int r^n P_n(\theta)\,\rho(r,\theta)\,d^3r$$

$$\rho = \bar{\rho}(r,\theta) + \rho'(r,\theta)$$

a = mean radius
M = total mass
P_n = Legendre polynomial

Static planet

dynamics

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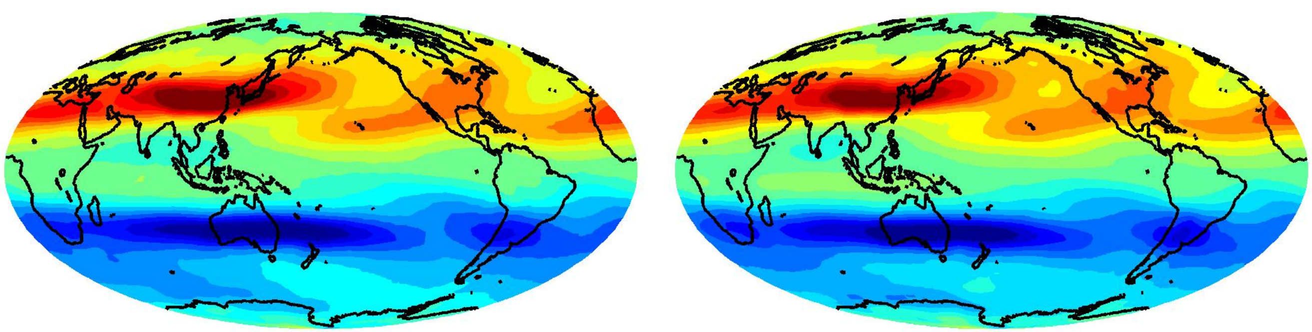
Thermal wind balance

$$2\Omega\frac{\partial u}{\partial z} \qquad -\frac{g}{Tr_0}\frac{\partial T}{\partial \theta}$$



General solution for relating the flow and density fields on an oblate spheroid

Momentum equation on an oblate spheroid

$$2\Omega \times \mathbf{u}\rho \quad = \quad -\nabla p - \rho \mathbf{g} - \rho \Omega \times \Omega \times \mathbf{r}$$

Denote the static solution as $\rho_{0,} p_{0,} \mathbf{g_0}$, and the dynamical solution as $\rho', p', \mathbf{g}'$ where

$$\rho = \rho_0(r,\theta) + \rho'(r,\theta)$$
$$p = p_0(r,\theta) + p'(r,\theta)$$
$$\mathbf{g} = \mathbf{g}_0(r,\theta) + \mathbf{g}'(r,\theta)$$

To leading order when: $\frac{U}{\Omega r} \ll 1$ $\quad 0 \quad = \quad -\nabla p_0 - \rho_0 \mathbf{g_0} - \rho_0 \Omega \times \Omega \times \mathbf{r}$

The next order gives the dynamical equation:

$$2\Omega \times \mathbf{u}\rho_0 \quad = \quad -\nabla p' - \rho_0 \mathbf{g}' - \rho' \mathbf{g_0} - \rho' \Omega \times \Omega \times \mathbf{r}$$

Taking the curl of this equation and looking at the azimuthal direction gives:

$$\underbrace{-2\Omega r \partial_z(\rho_0 u)}_{\text{flow}} \quad = \quad \underbrace{r g_0^{(\theta)} \frac{\partial \rho'}{\partial r} - g_0^{(r)} \frac{\partial \rho'}{\partial \theta} + r \frac{\partial \rho_0}{\partial r} g'^{(\theta)} - g'^{(r)} \frac{\partial \rho_0}{\partial \theta}}_{\text{gravity}} \underbrace{- \Omega^2 r \left[\frac{\partial \rho'}{\partial \theta} \cos^2\theta + \frac{\partial \rho'}{\partial r} r \cos\theta \sin\theta \right]}_{\text{centrifugal}}$$

$$\boxed{-2\Omega r\partial_z(\rho_0 u)} = rg_0^{(\theta)}\frac{\partial\rho'}{\partial r}\boxed{-g_0^{(r)}\frac{\partial\rho'}{\partial\theta}}+r\frac{\partial\rho_0}{\partial r}g'^{(\theta)}-g'^{(r)}\frac{\partial\rho_0}{\partial\theta}-\Omega^2 r\left[\frac{\partial\rho'}{\partial\theta}\cos^2\theta+\frac{\partial\rho'}{\partial r}r\cos\theta\sin\theta\right]$$

This is a difficult equation to solve!
Note that every term on the rhs involves $\rho'(r,\theta)$: $\mathbf{g}'(r,\theta) = -2\pi G\nabla\int\int\left(\frac{\rho'(r,\theta)}{|\mathbf{r}-\mathbf{r}'|}\right)d^2\mathbf{r}$

Simplest solution: Thermal wind $\rho = \rho_0(r)+\rho'(r,\theta)$

$$\mathbf{g} = \mathbf{g}_0(r)$$

In the spherical limit only two terms are retained: $2\Omega\frac{\partial}{\partial z}(\rho_0 u) = \frac{g_0^{(r)}}{r}\frac{\partial\rho'}{\partial\theta}$

Integration gives the density perturbation up to an arbitrary function of radius

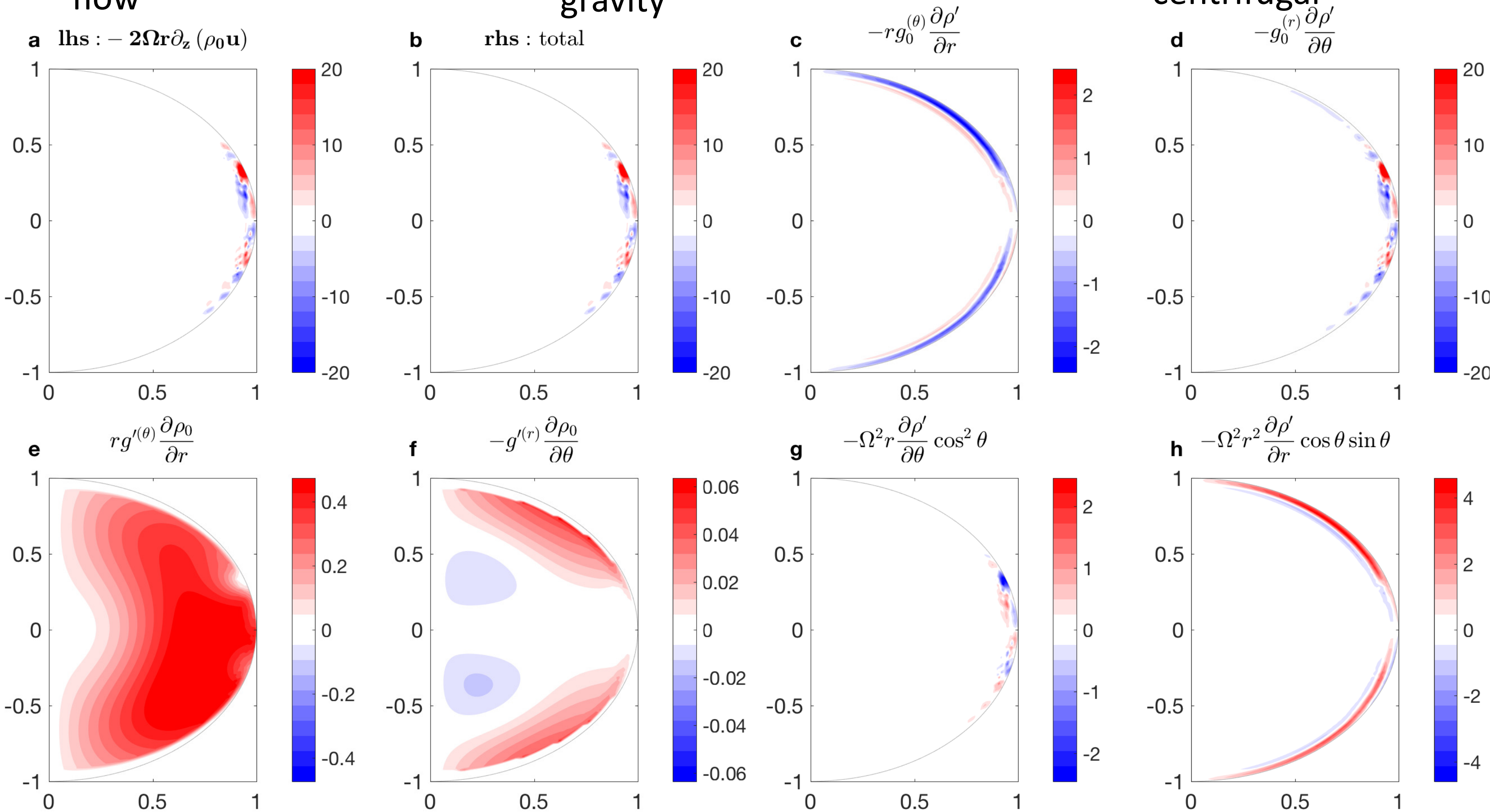
$$\rho'(r,\theta) = \int^{\theta}\frac{2\Omega r}{g}\frac{\partial}{\partial z}\left(\rho_0 u(r,\theta')\right)d\theta'+\rho_0'(r)$$

Dynamical gravity harmonics $\Delta J_n = -\frac{1}{Ma^n}\int_{-\pi/2}^{\pi/2}\cos\theta d\theta\int_0^R r^{n+2}P_n(\cos\theta)\rho'(r,\theta)dr.$

But still the gravity harmonics can be found uniquely: $\int_{-\pi/2}^{\pi/2}\cos\theta d\theta\int_0^R r^{n+2}P_n(\cos\theta)\rho_0'(r)dr = 0$

Full vorticity balance:

$$\underbrace{\boxed{-2\Omega r\partial_z\left(\rho_0 u\right)}}_{\text{flow}} = \underbrace{r g_0^{(\theta)}\frac{\partial\rho'}{\partial r}\boxed{-g_0^{(r)}\frac{\partial\rho'}{\partial\theta}}+r\frac{\partial\rho_0}{\partial r}g'^{(\theta)}-g'^{(r)}\frac{\partial\rho_0}{\partial\theta}}_{\text{gravity}}\underbrace{-\Omega^2 r\left[\frac{\partial\rho'}{\partial\theta}\cos^2\theta+\frac{\partial\rho'}{\partial r}r\cos\theta\sin\theta\right]}_{\text{centrifugal}}$$

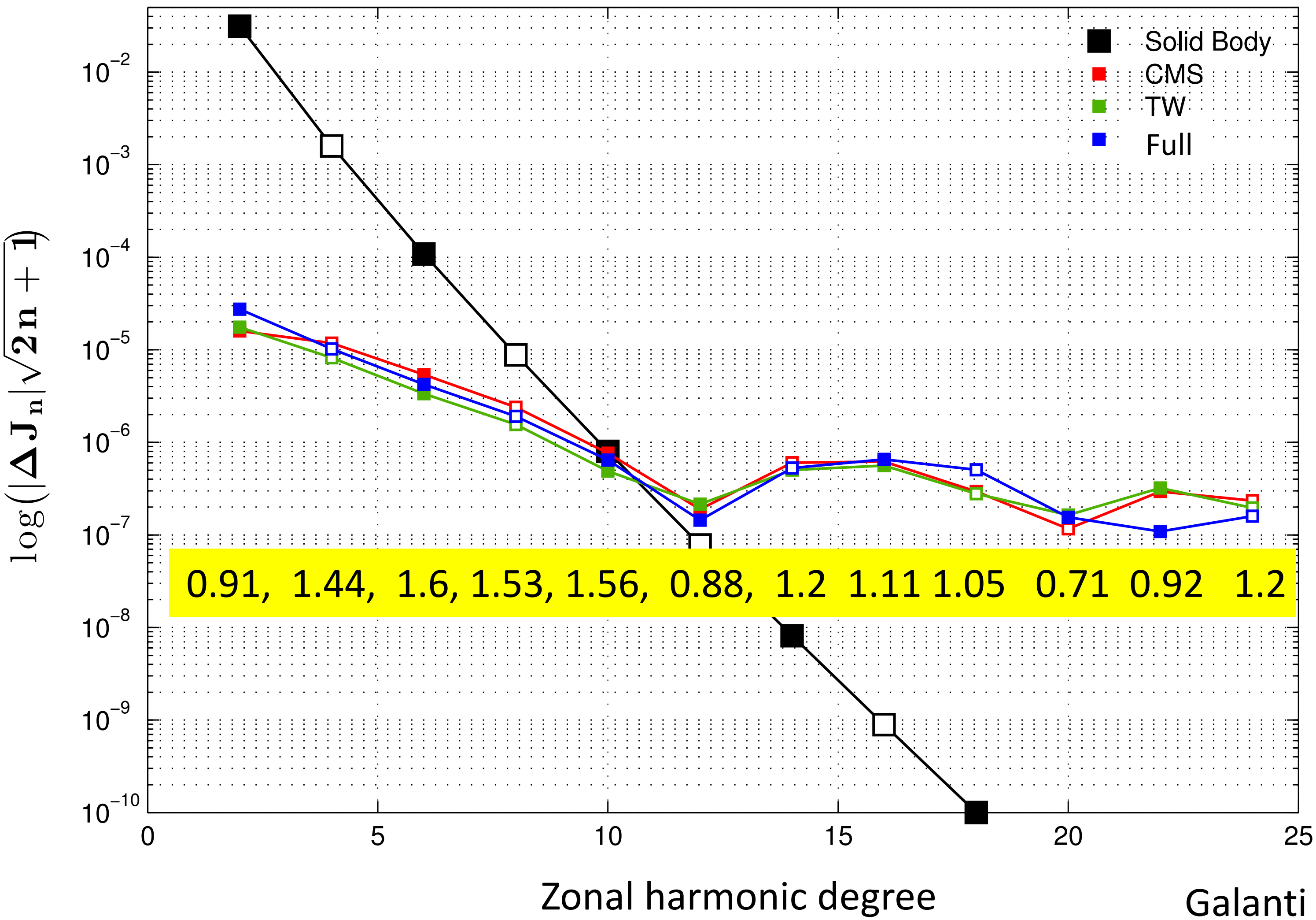


Galanti et al., *JFM*, 2017

$$\boxed{-2\Omega r\partial_z\left(\rho_0 u\right)} = r g_0^{(\theta)}\frac{\partial\rho'}{\partial r}\boxed{- g_0^{(r)}\frac{\partial\rho'}{\partial\theta}} + r\frac{\partial\rho_0}{\partial r}g'^{(\theta)} - g'^{(r)}\frac{\partial\rho_0}{\partial\theta} - \Omega^2 r\left[\frac{\partial\rho'}{\partial\theta}\cos^2\theta + \frac{\partial\rho'}{\partial r}r\cos\theta\sin\theta\right]$$

$$\rho = \rho_0(r) + \rho'(r,\theta)$$

$$\mathbf{g} = \mathbf{g}_0(r).$$

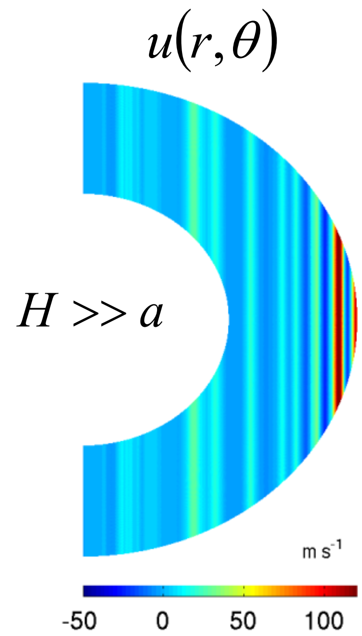


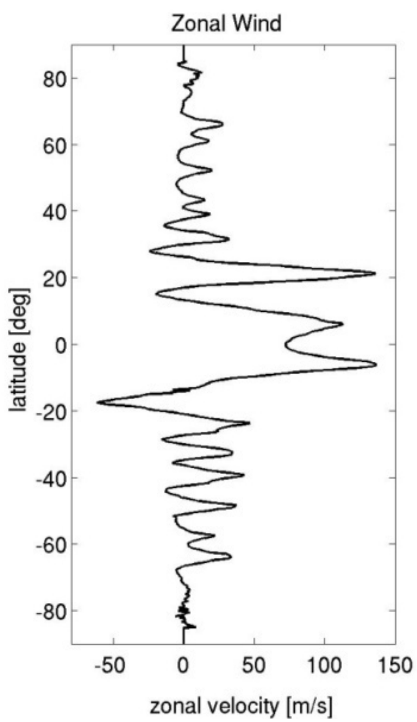
Galanti et al., *JFM*, 2017

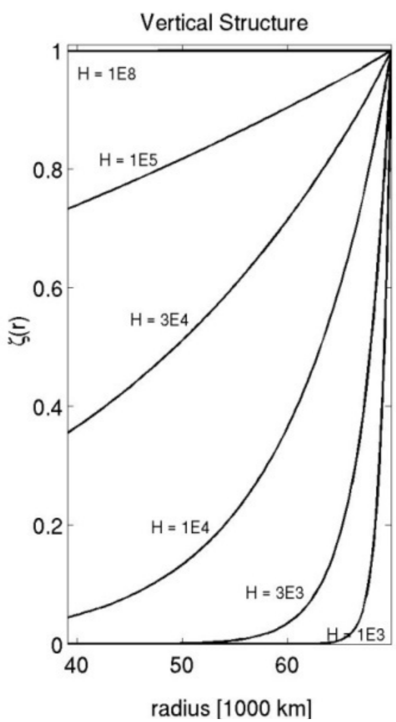
A simple model for estimating the dynamical gravity signature

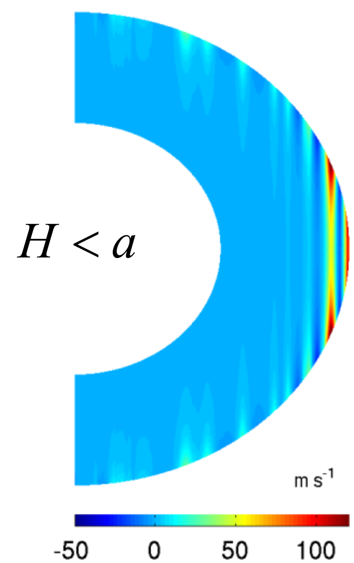
Thermal wind balance model:
Uses the observed winds on Jupiter and assumes an idealized interior vertical structure with a decay length *H.*

$$u = u_{cyl} e^{-\left(\frac{a-r}{H}\right)}$$







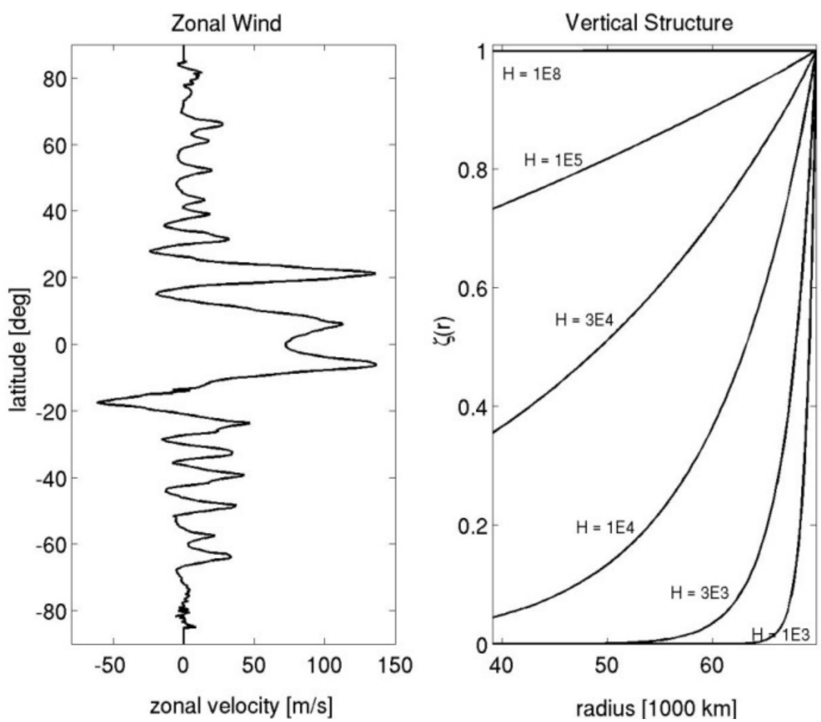


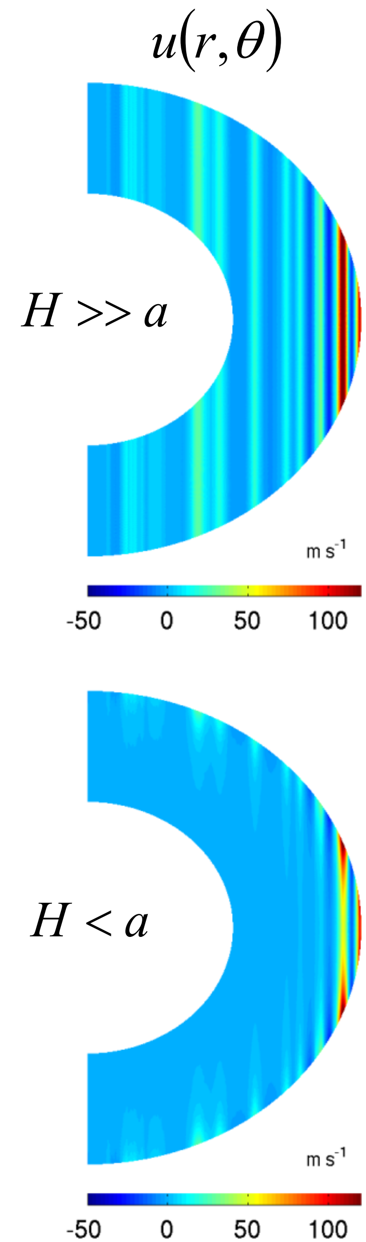
Kaspi at al., *GRL*, 2010

A simple model for estimating the dynamical gravity signature

Thermal wind balance model:
Uses the observed winds on Jupiter and assumes an idealized interior vertical structure with a decay length *H.*

$$\boxed{2\Omega\cdot\nabla\left(\bar{\rho}\vec{u}\right) = \nabla\rho'\times\vec{g}_0}$$

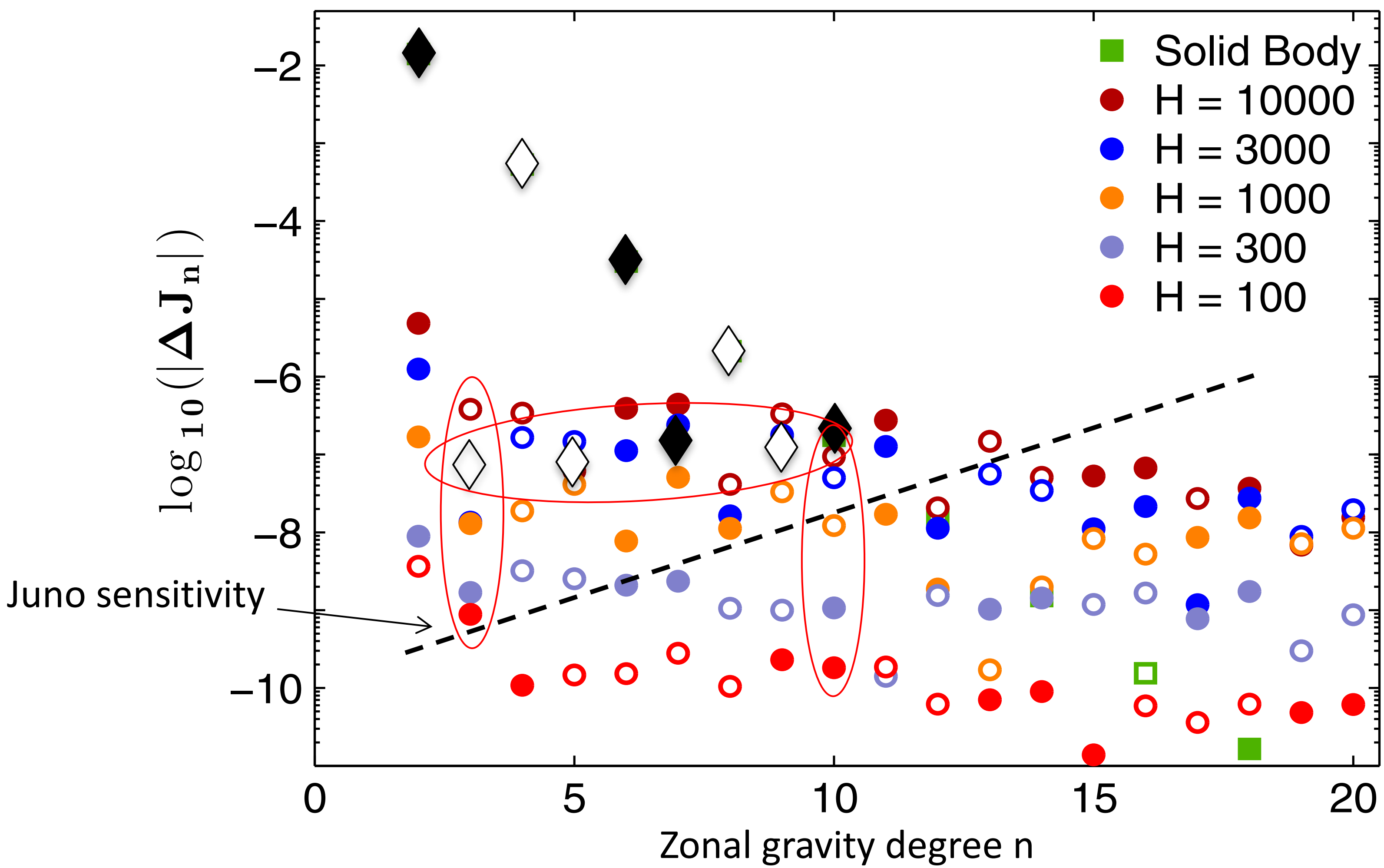




Kaspi at al., *GRL*, 2010

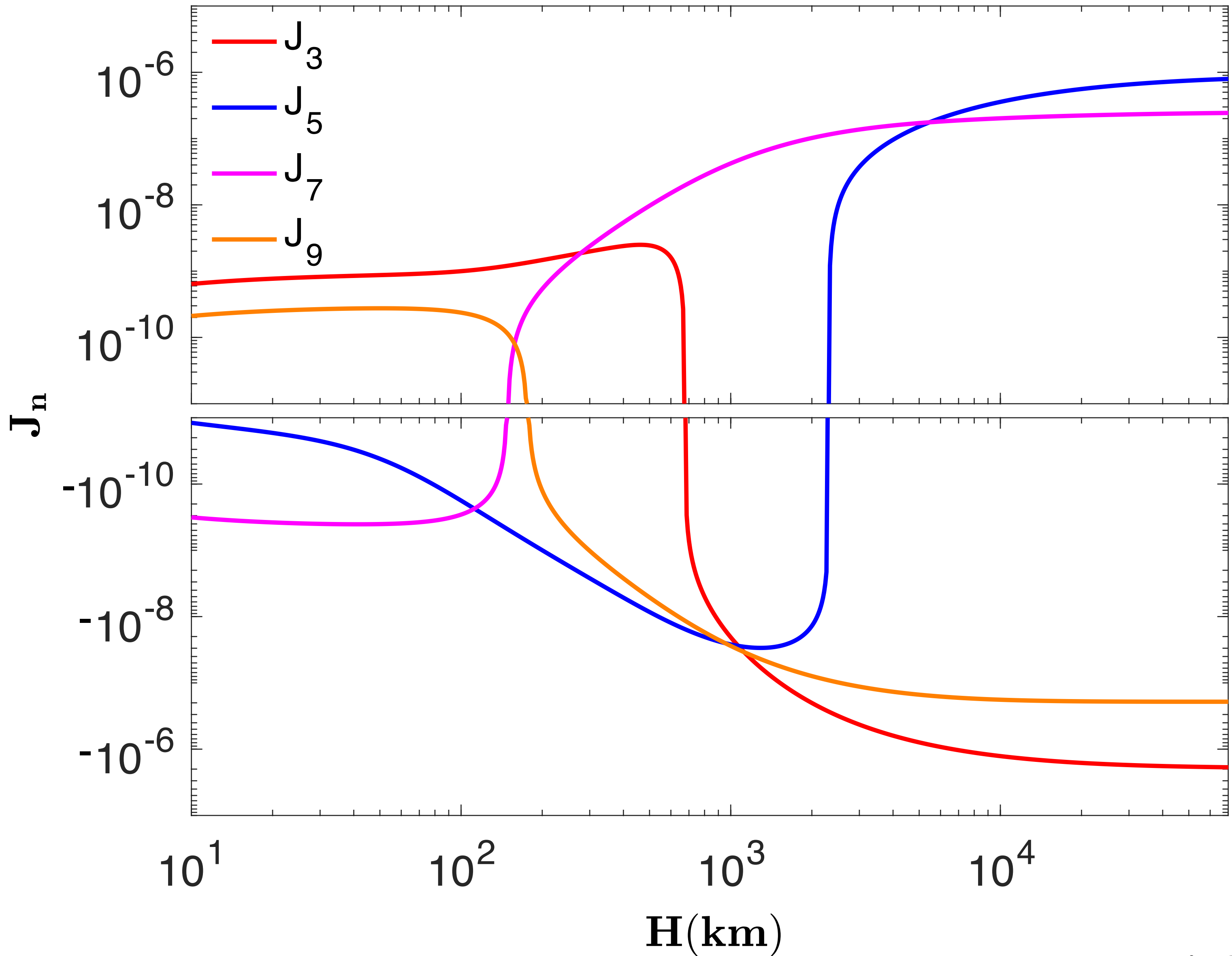
Gravity spectrum as function of e-folding decay depth of the cloud-level wind (H):

Juno measurements (2017)



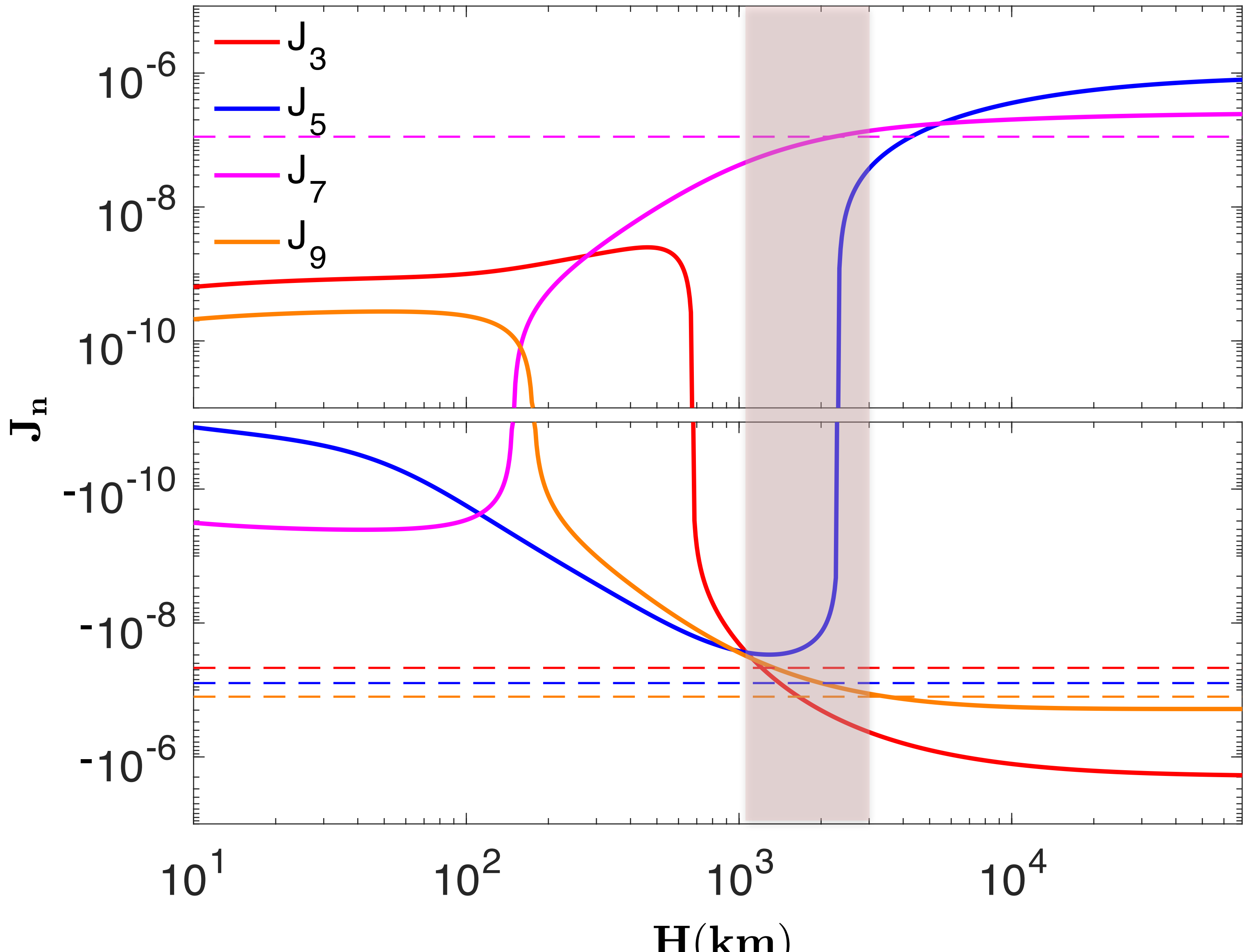
Kaspi, *GRL*, 2013

J_{2n+1} for simple exponential decay model



Kaspi, *GRL*, 2013

J_{2n+1} for simple exponential decay model



Kaspi, *GRL*, 2013

Gravity Inversion model

Cost function

$$L = \sum_n W_n \left(\Delta J_n^m - \Delta J_n^0 \right)^2$$

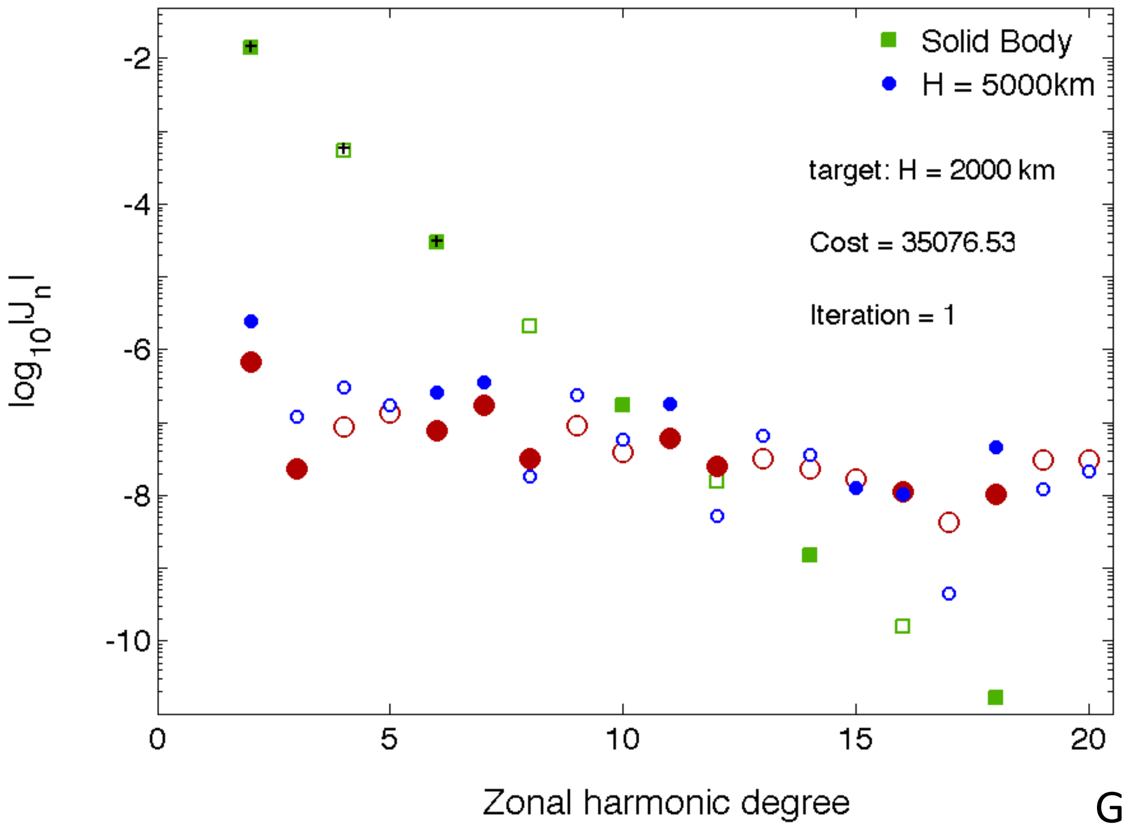
Weights

Model solutions

observations

Minimize the cost function by calculating the sensitivity to the decay parameter:

$$\lambda = \frac{\partial L\left(\Delta J_n^m\right)}{\partial H}$$



Galanti and Kaspi, 2016

Gravity Inversion model

Cost function

$$L = \sum_n W_n \left(\Delta J_n^m - \Delta J_n^0 \right)^2$$

Weights

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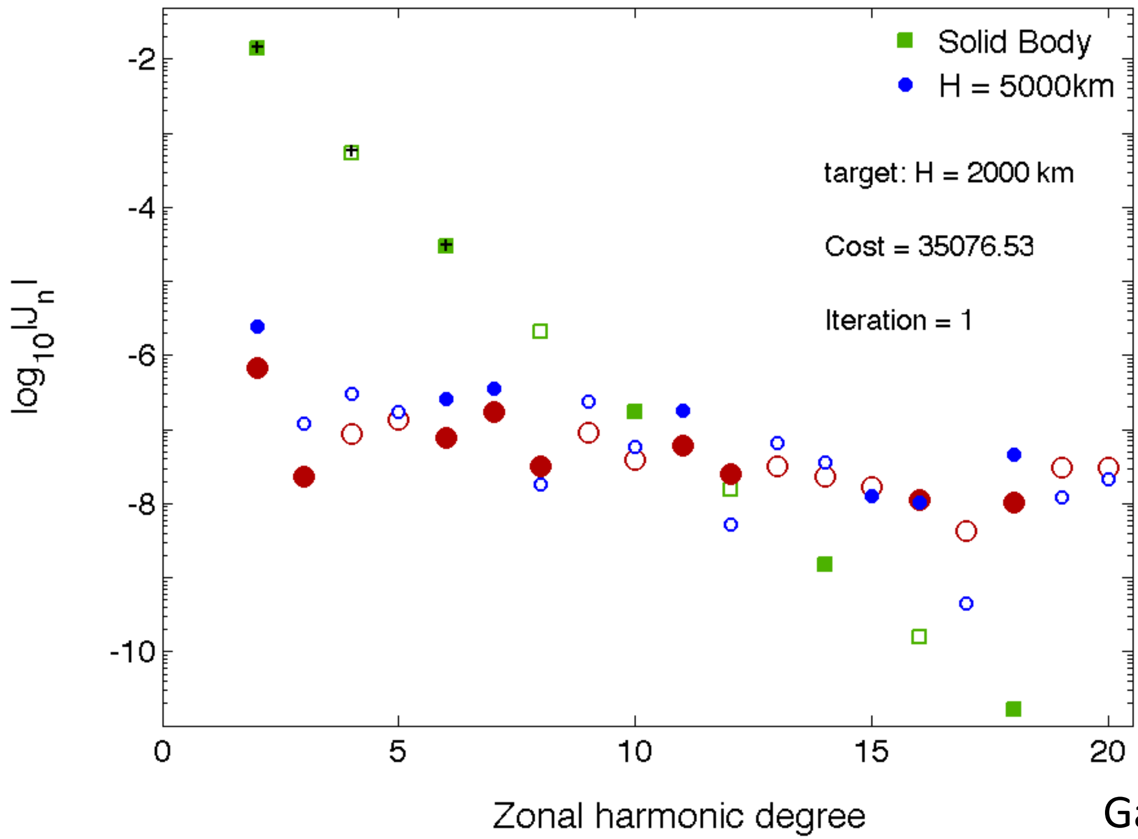
Minimize the cost function by calculating the sensitivity to the decay parameter: $\lambda = \frac{\partial L\left(\Delta J_n^m\right)}{\partial H}$



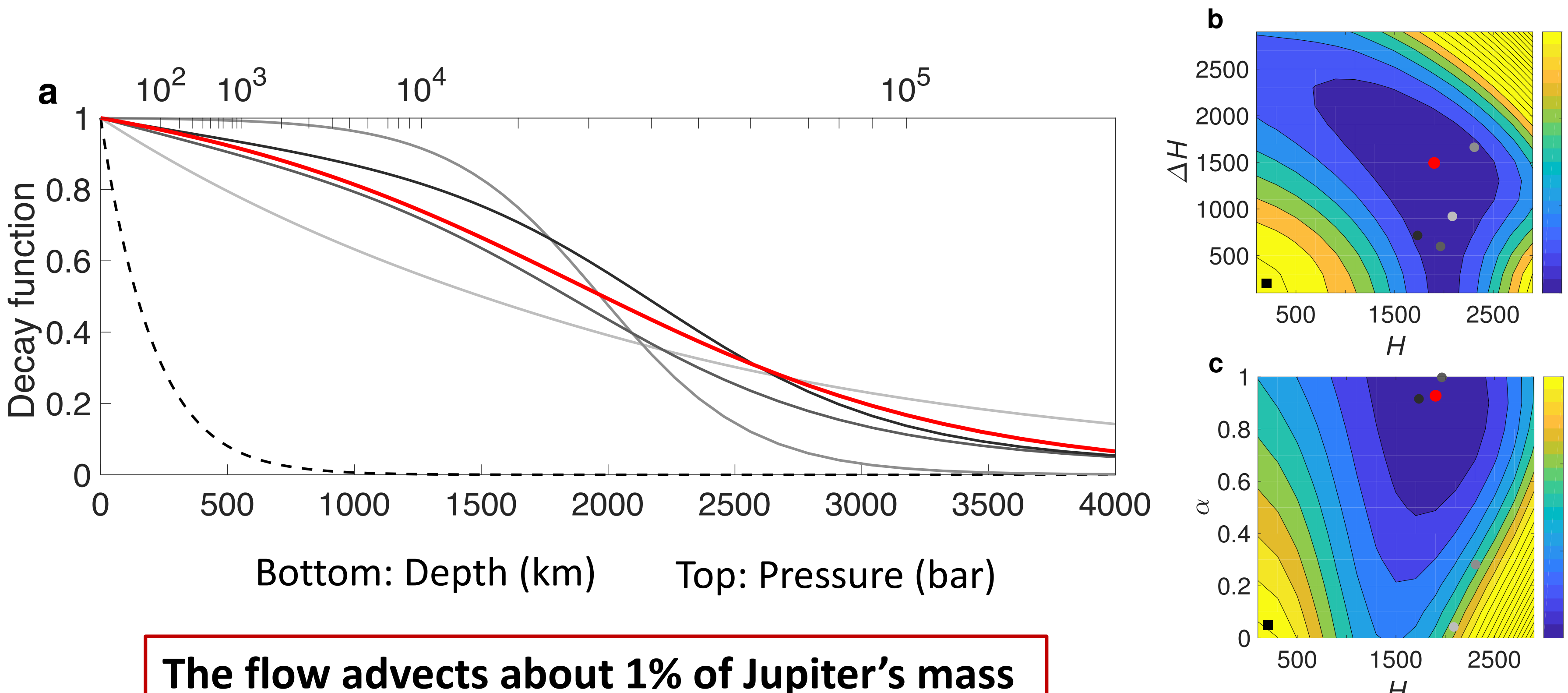
Galanti and Kaspi, 2016

The vertical structure of the flow on Jupiter

More physically based vertical structure:

1. The 1995 Galileo probe measured constant wind between 4 and 22 bars (Atkinson et al., 1998)
2. MHD arguments suggest a rapid decay at depths ~3000km (Liu et al, 2008, Cao & Stevenson, 2017)

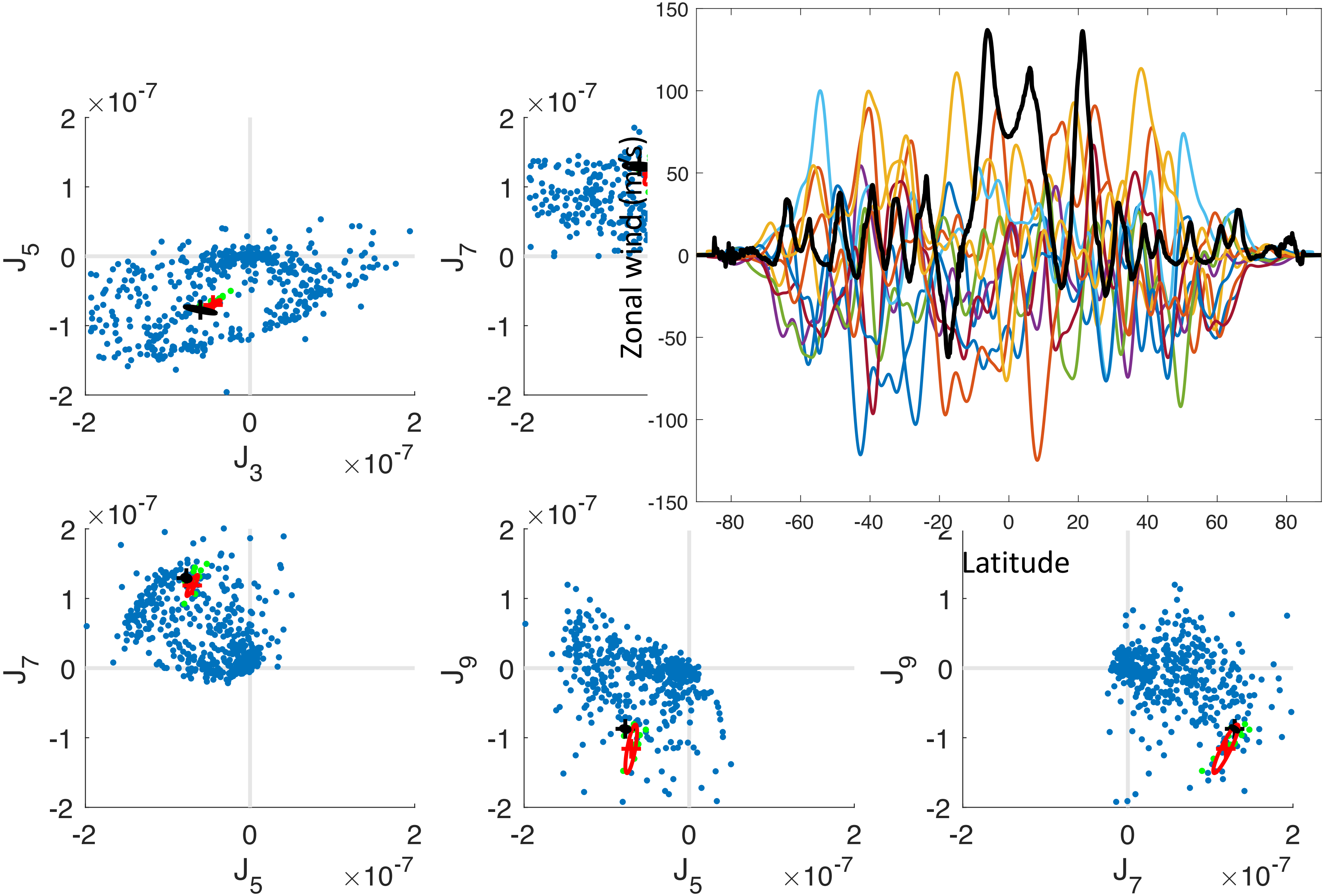
Optimization based on inversion of the gravity field using an adjoint model



The flow advects about 1% of Jupiter's mass

Kaspi et al., 2018, *Nature*

Statistical significance test using other meridional wind profiles:

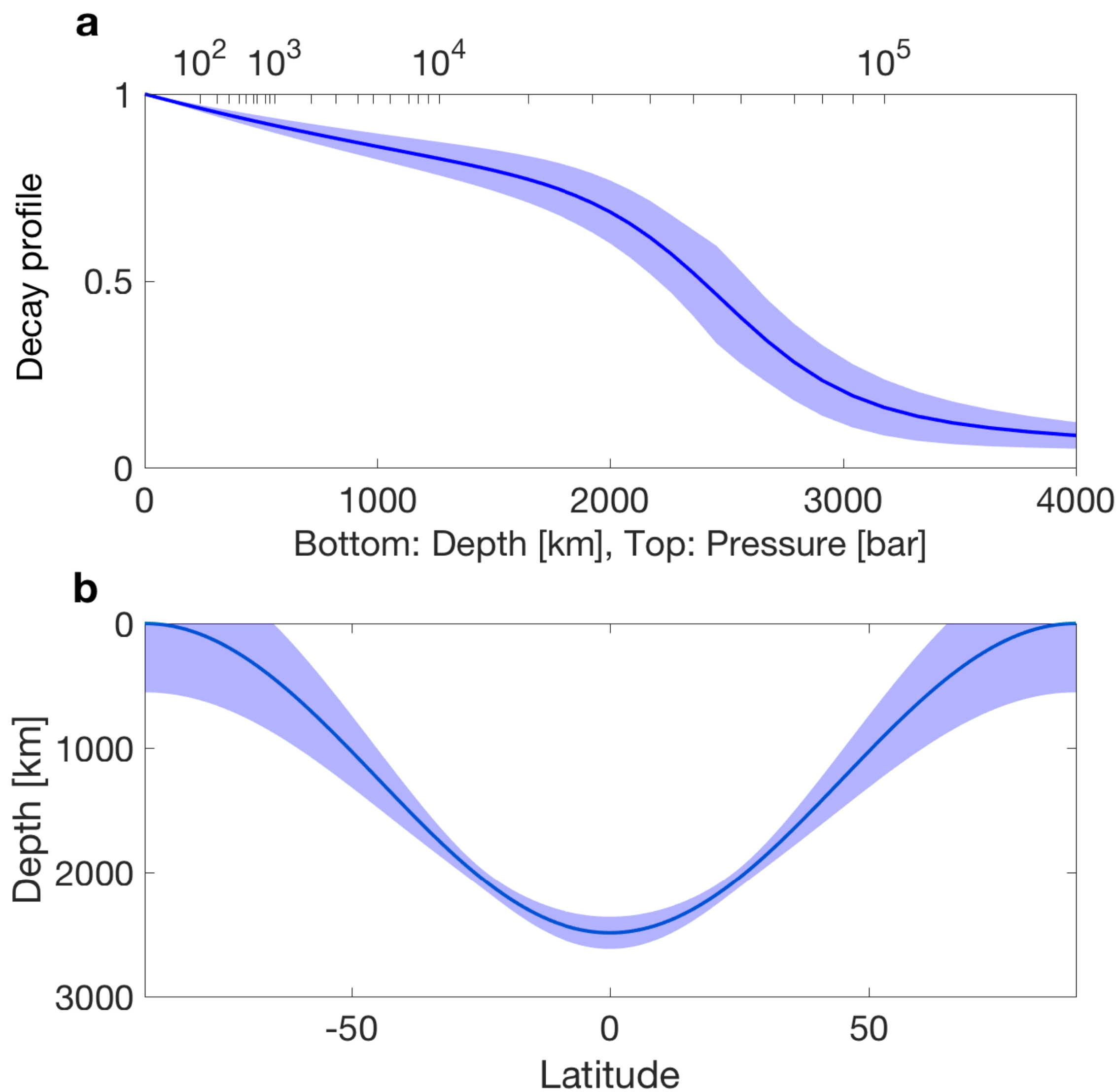


The vertical and meridional structure of the flow

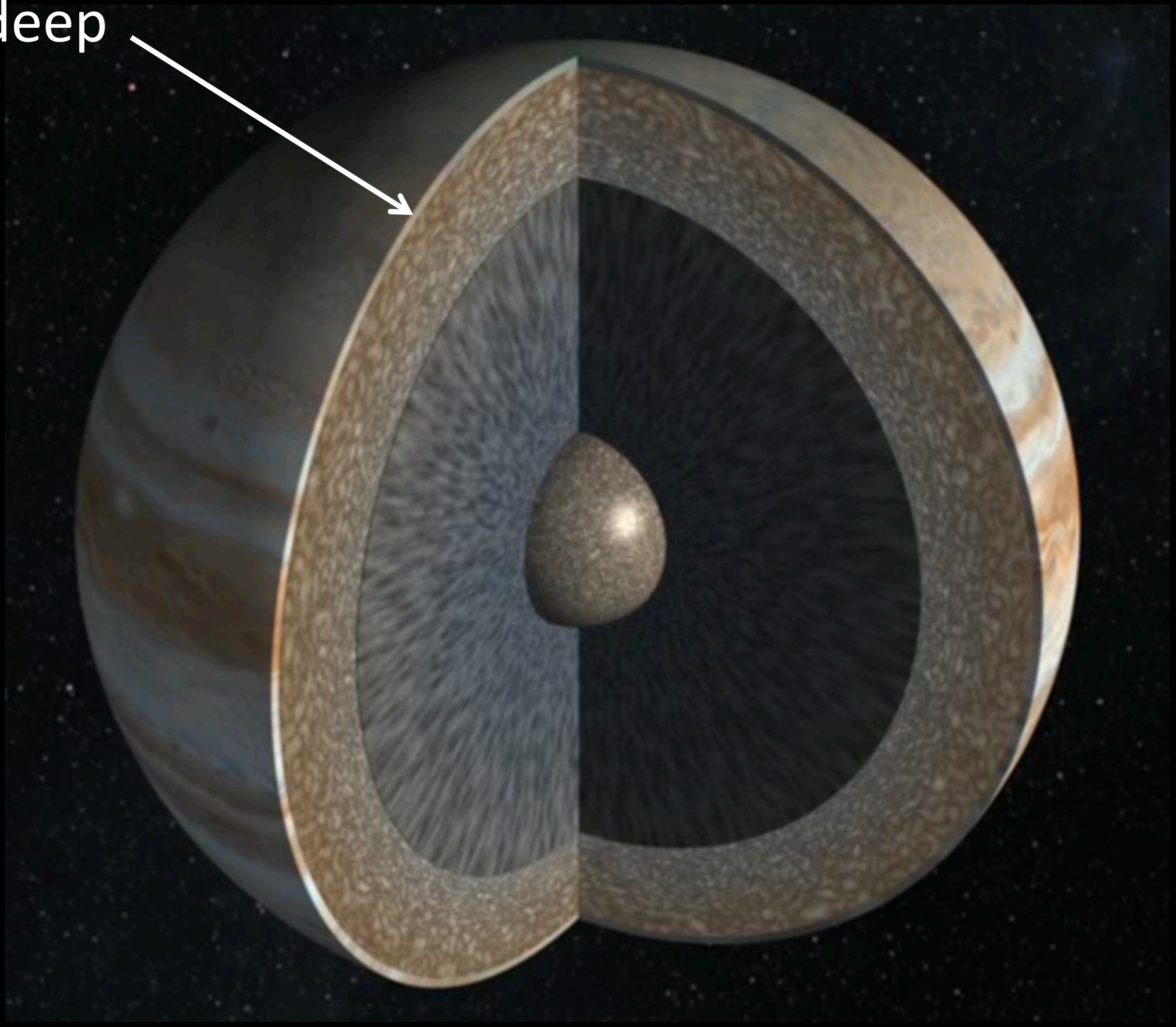
Allowing also the depth of the flow to vary with depth:

Vertical profile at the equator

Latitudinal profile of the mid point depth

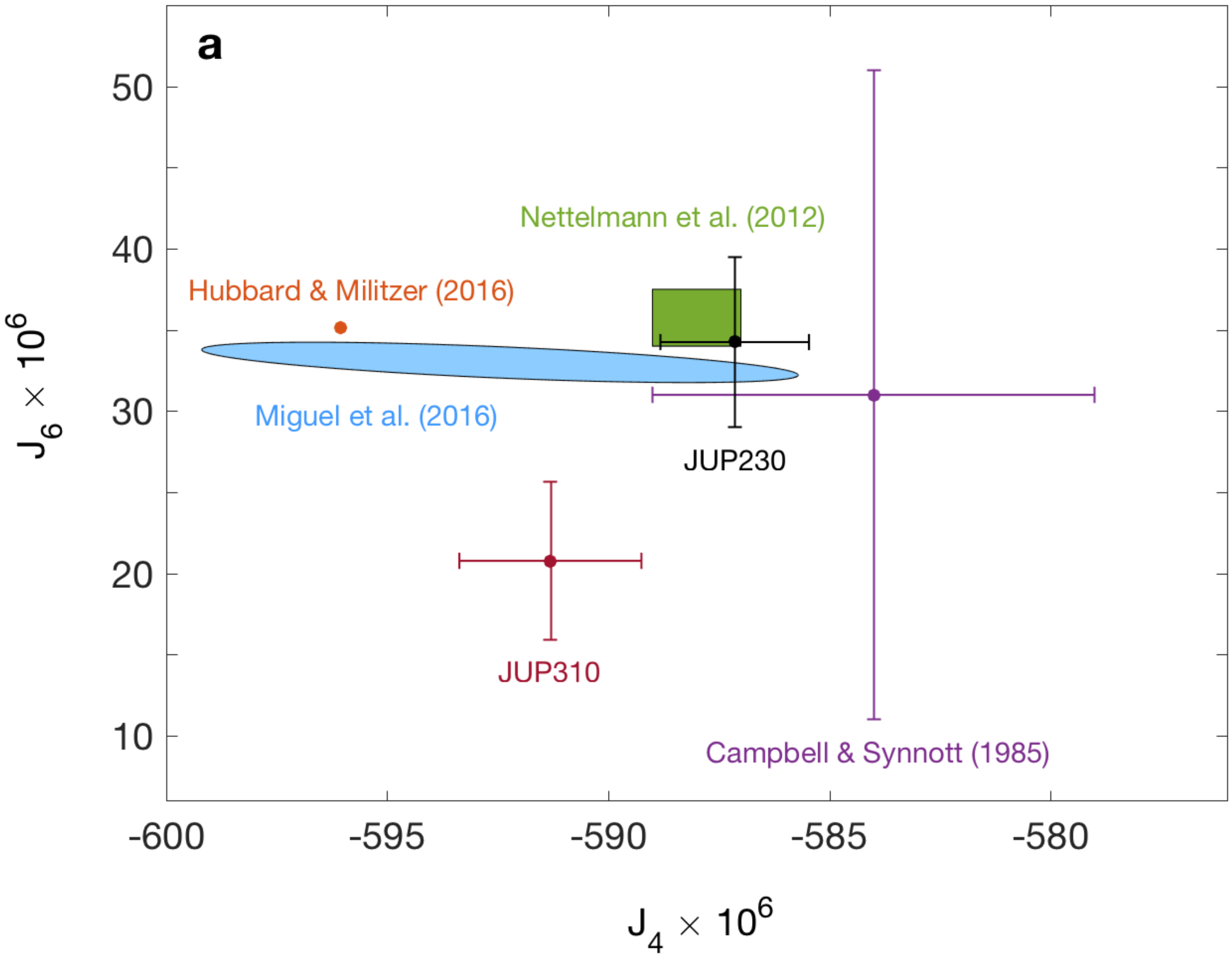


Kaspi et al., 2018, *Nature*

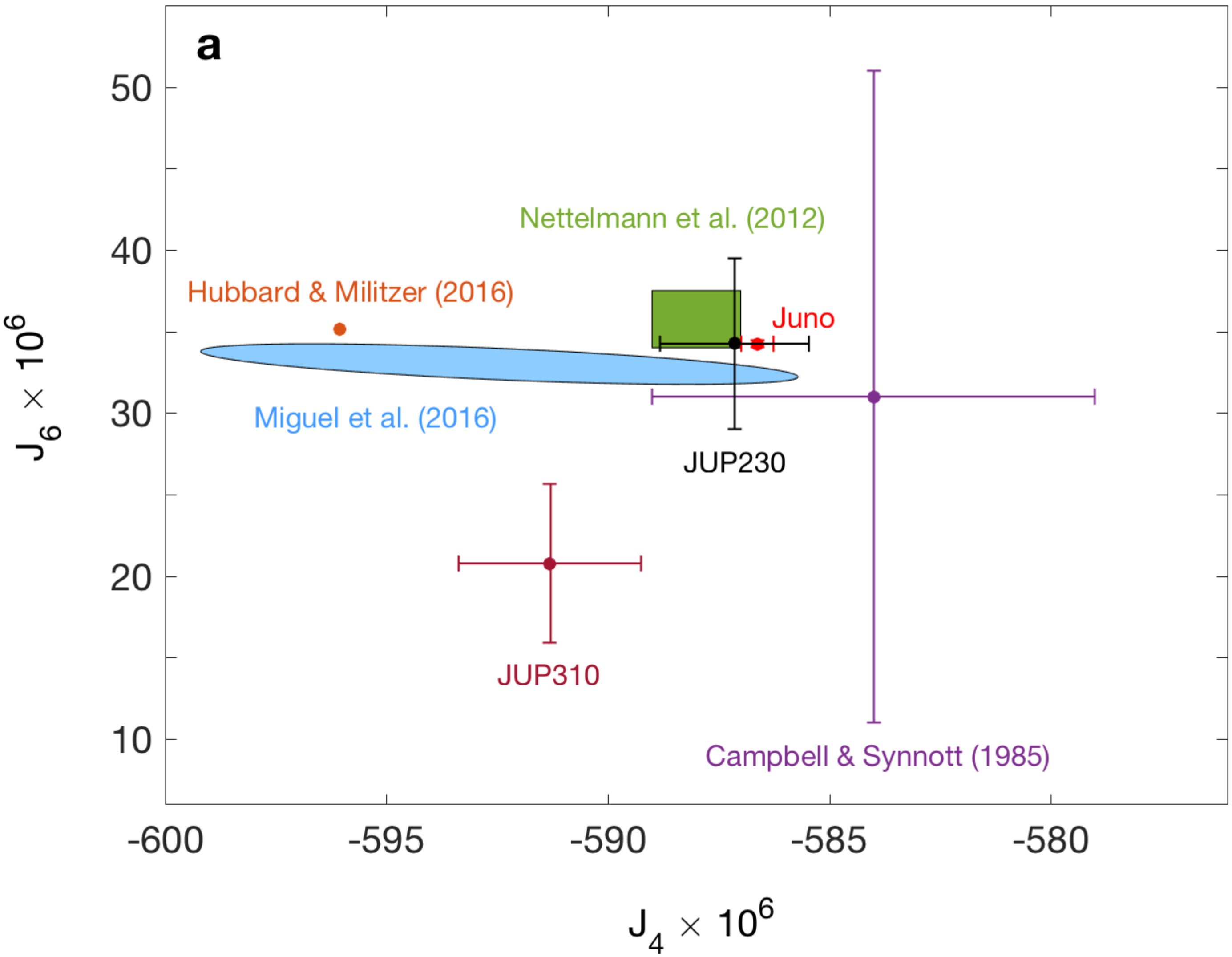


What can gravity tell us about the interior? Internal flows?

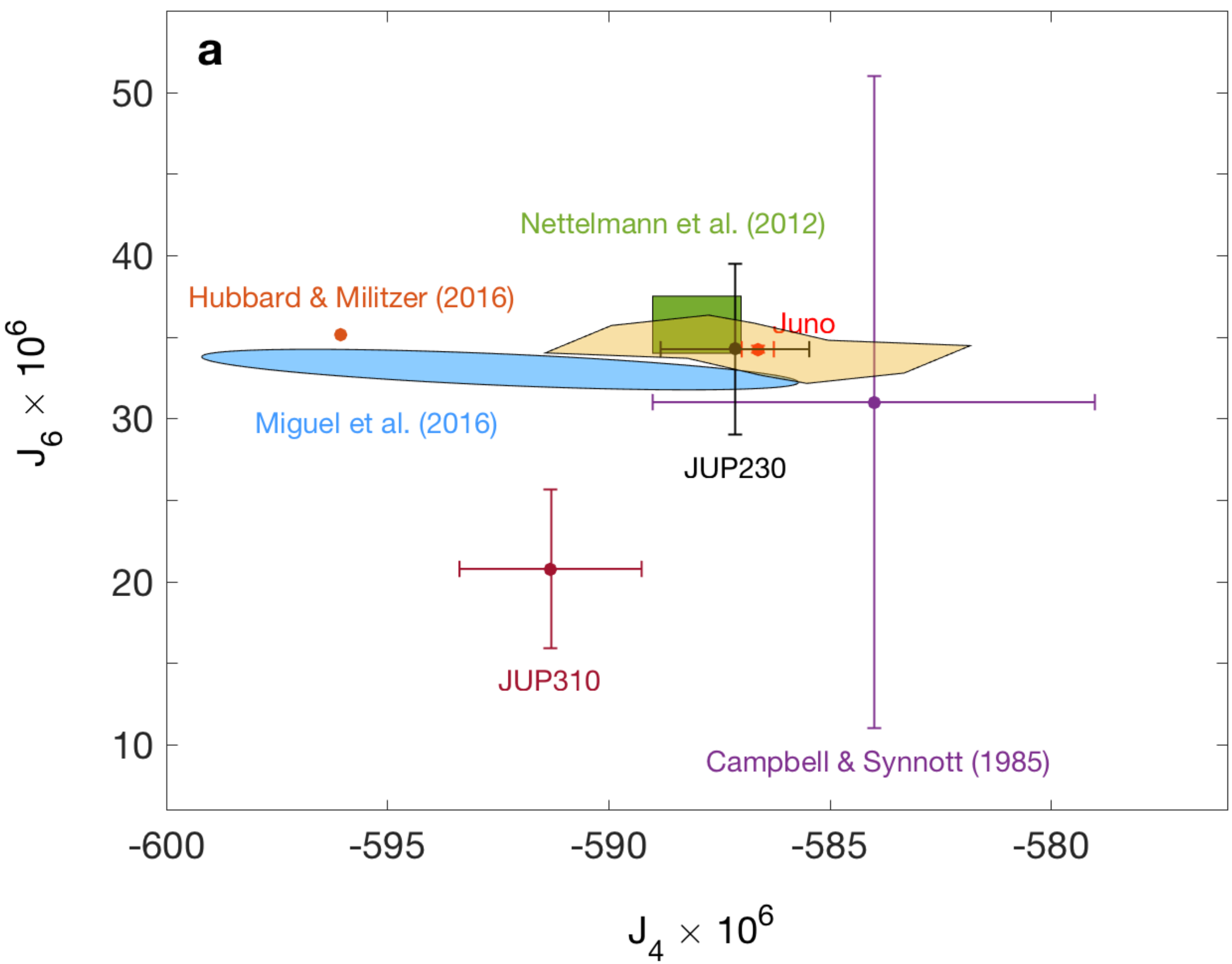
Interior structure



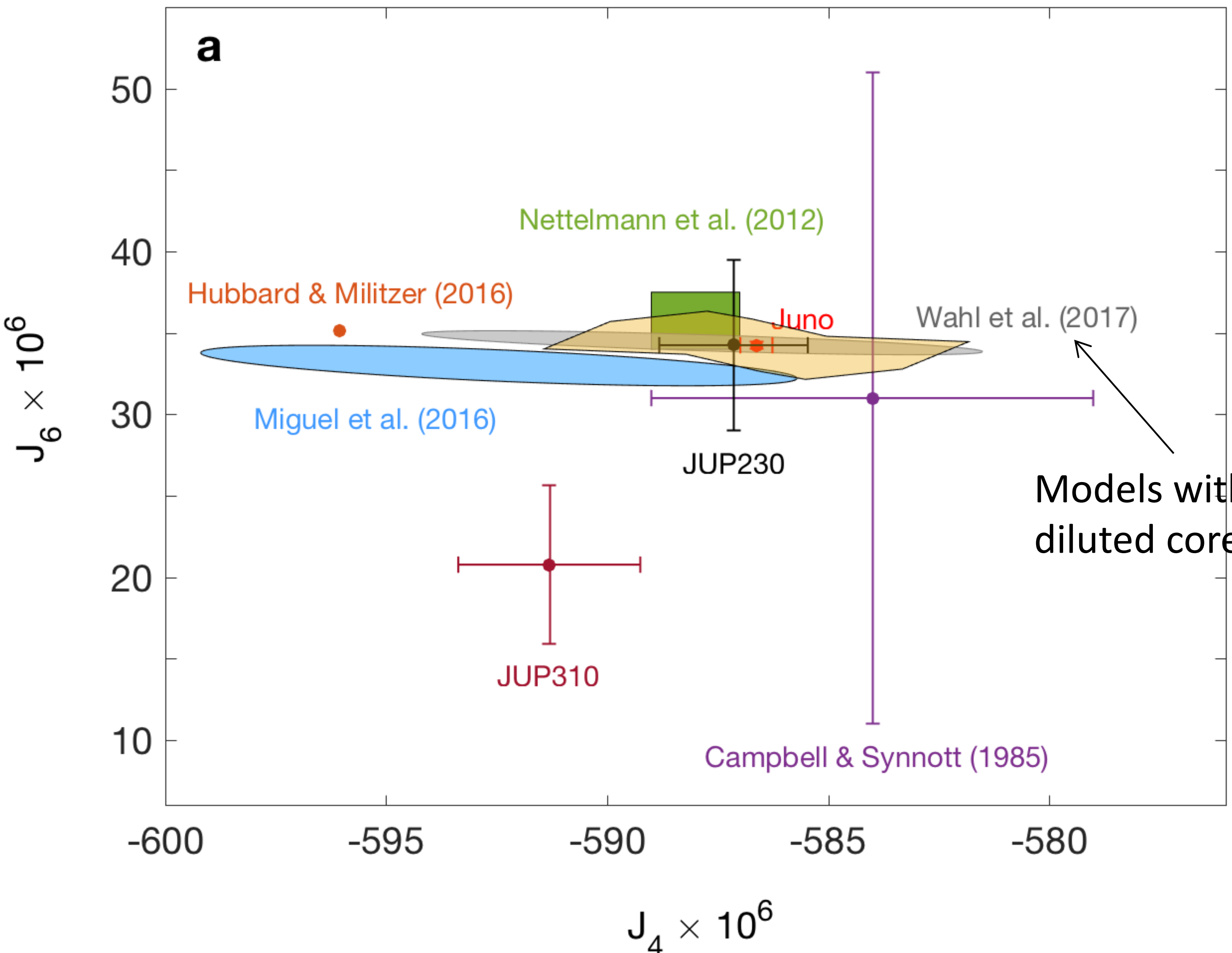
Interior structure



Interior structure

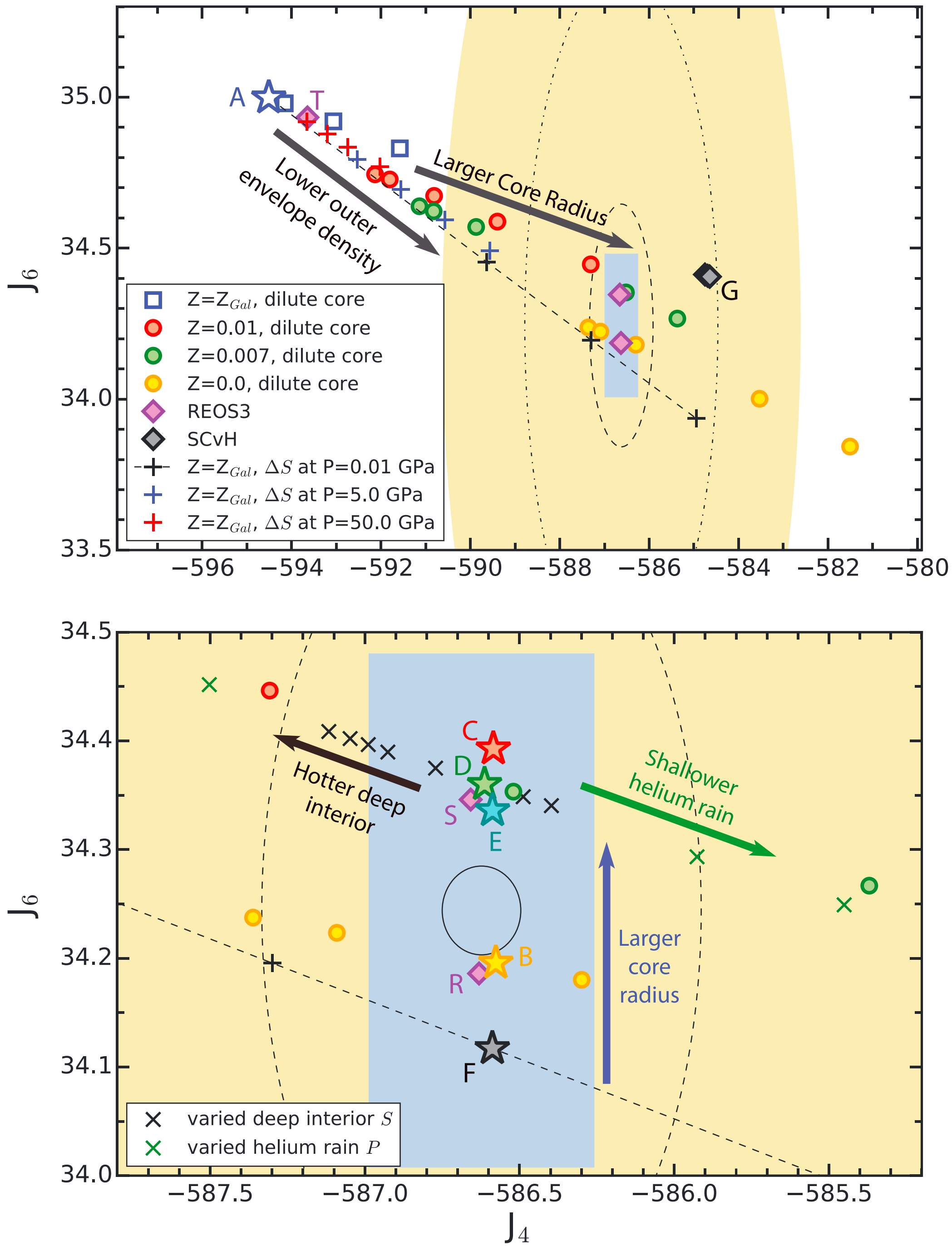


Interior structure



Models with larger, diluted cores

Kaspi et al., *GRL,* 2017



Whal et al., *GRL*, 2017

Perturbations to the gravity field of the planet can be expressed by zonal gravity harmonics:

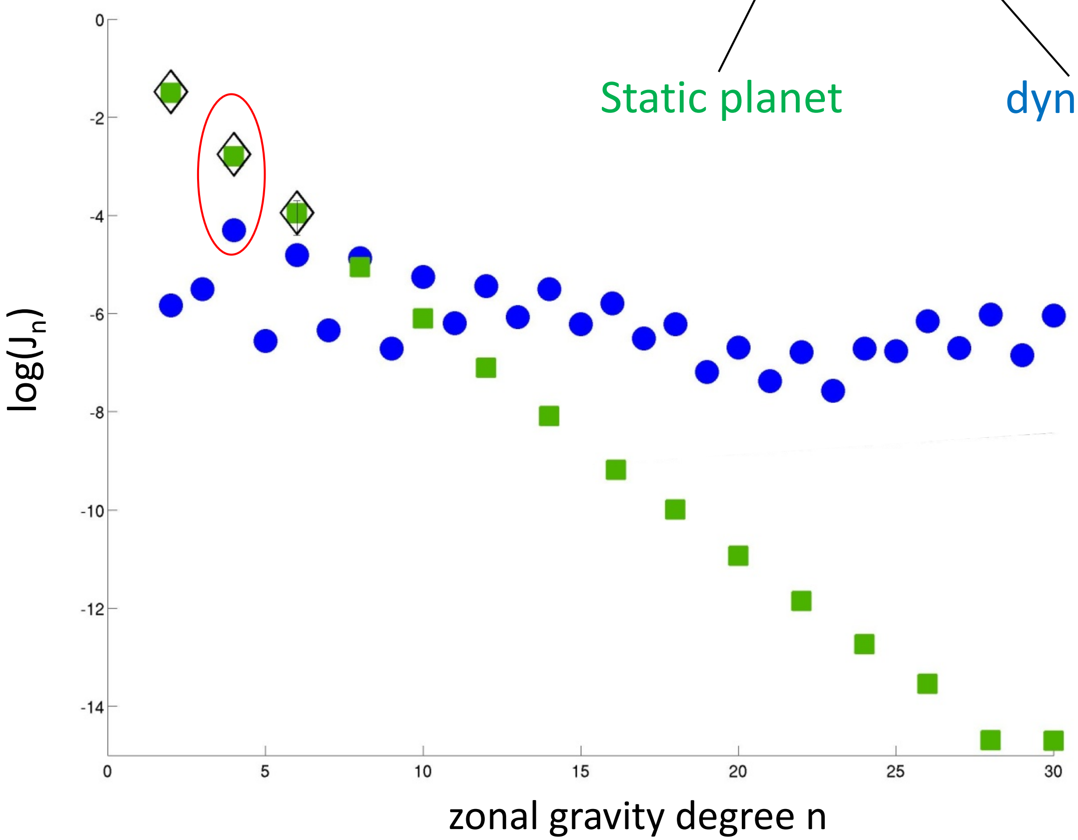
$$J_n = -\frac{1}{a^n M}\int r^n P_n(\theta)\rho(r,\theta)d^3r$$

$$\rho = \overline{\rho}(r,\theta) + \rho'(r,\theta)$$

a = mean radius
M = total mass
P_n = Legendre polynomial

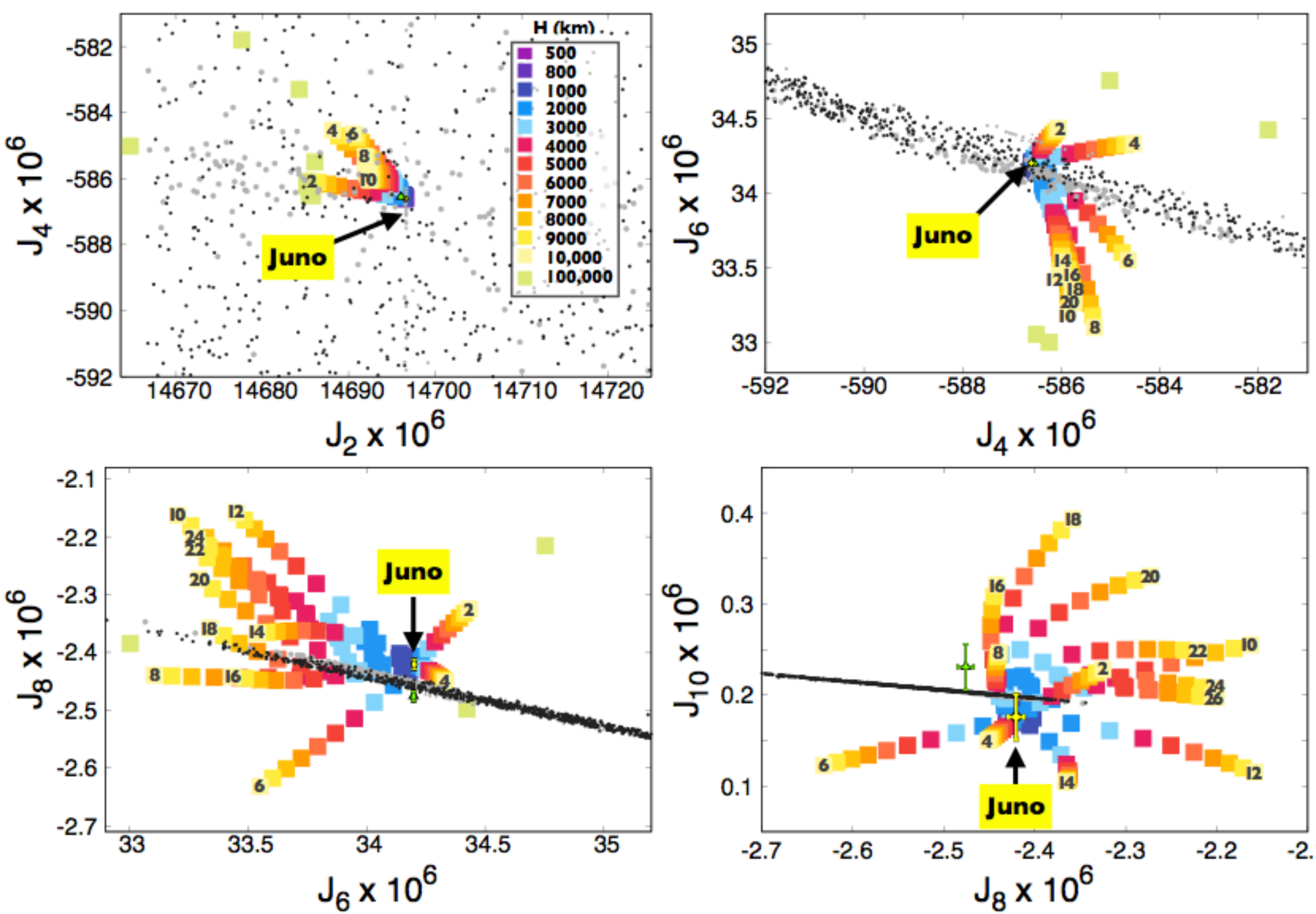
Static planet

dynamics



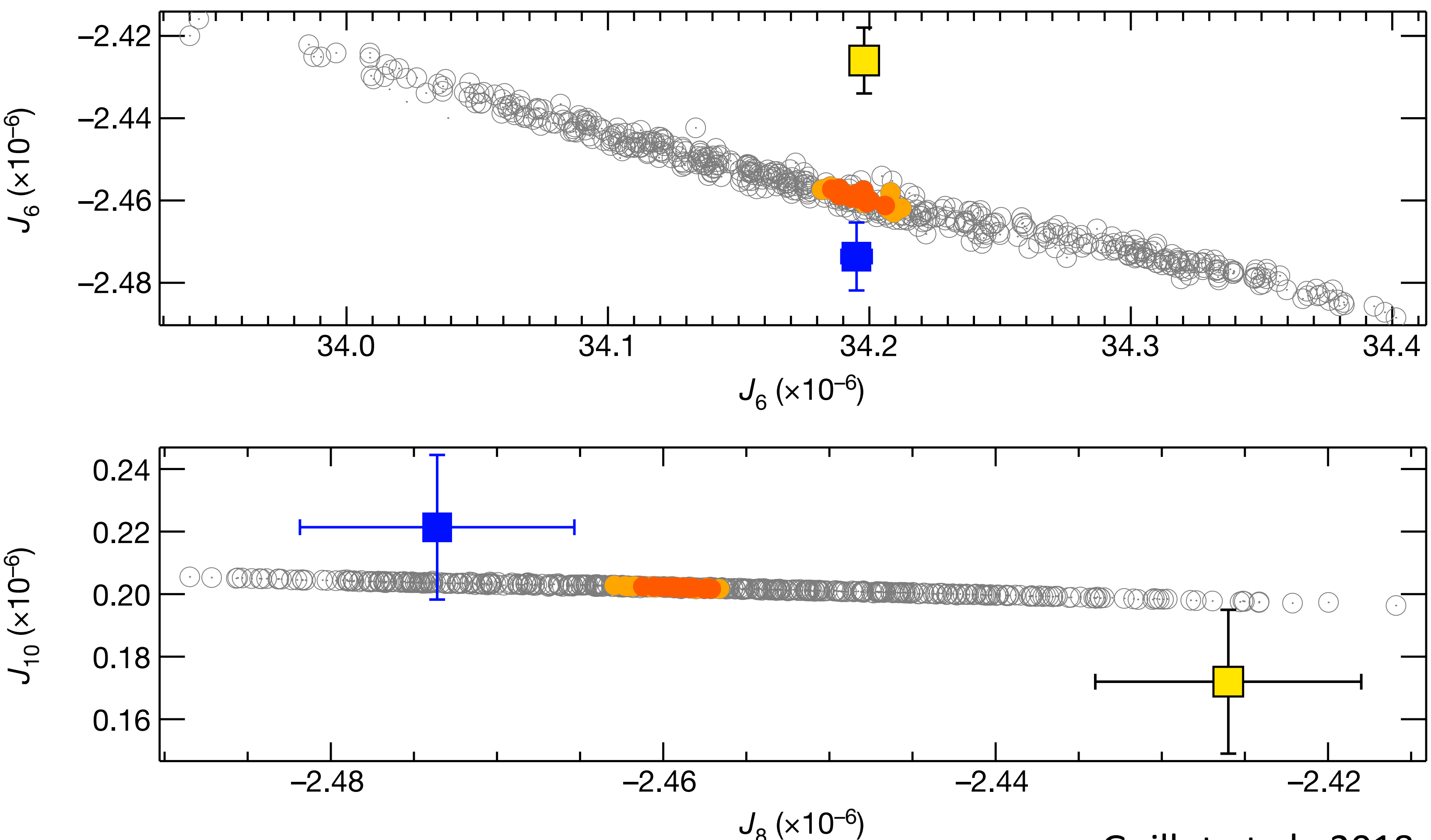
- High order gravity harmonics
- Low order **odd** gravity harmonics
- Difference between observed, static and dynamic values

Deep zonal flows beneath the atmospheric layer



Guillot et al., 2018, *Nature*

High order even moments (J_6-J_{10})



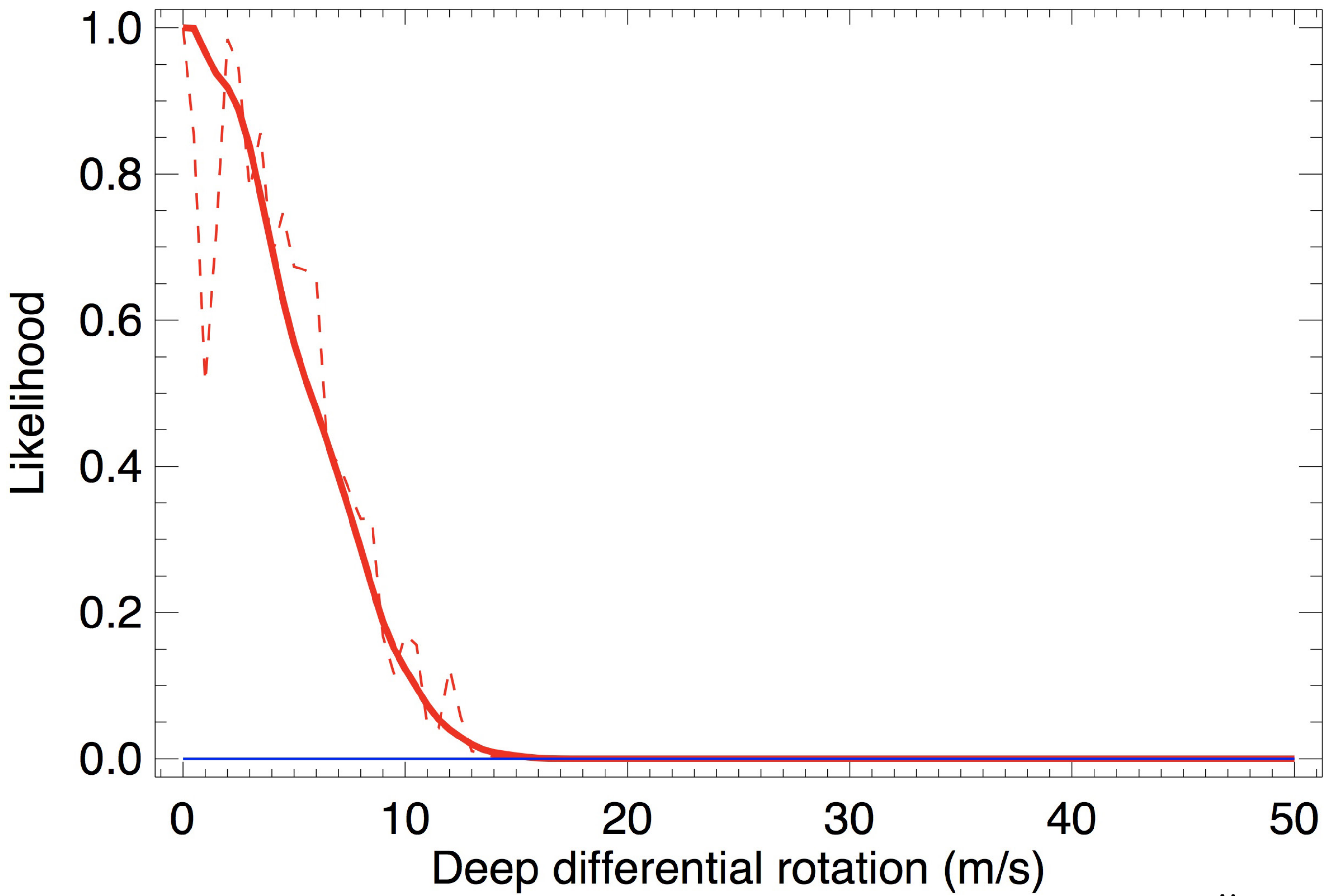
Guillot et al., 2018, *Nature*

Juno measurements

Best fit model from odd harmonics only

Interior models that match J_2-J_{10} measurements within 3 sigma

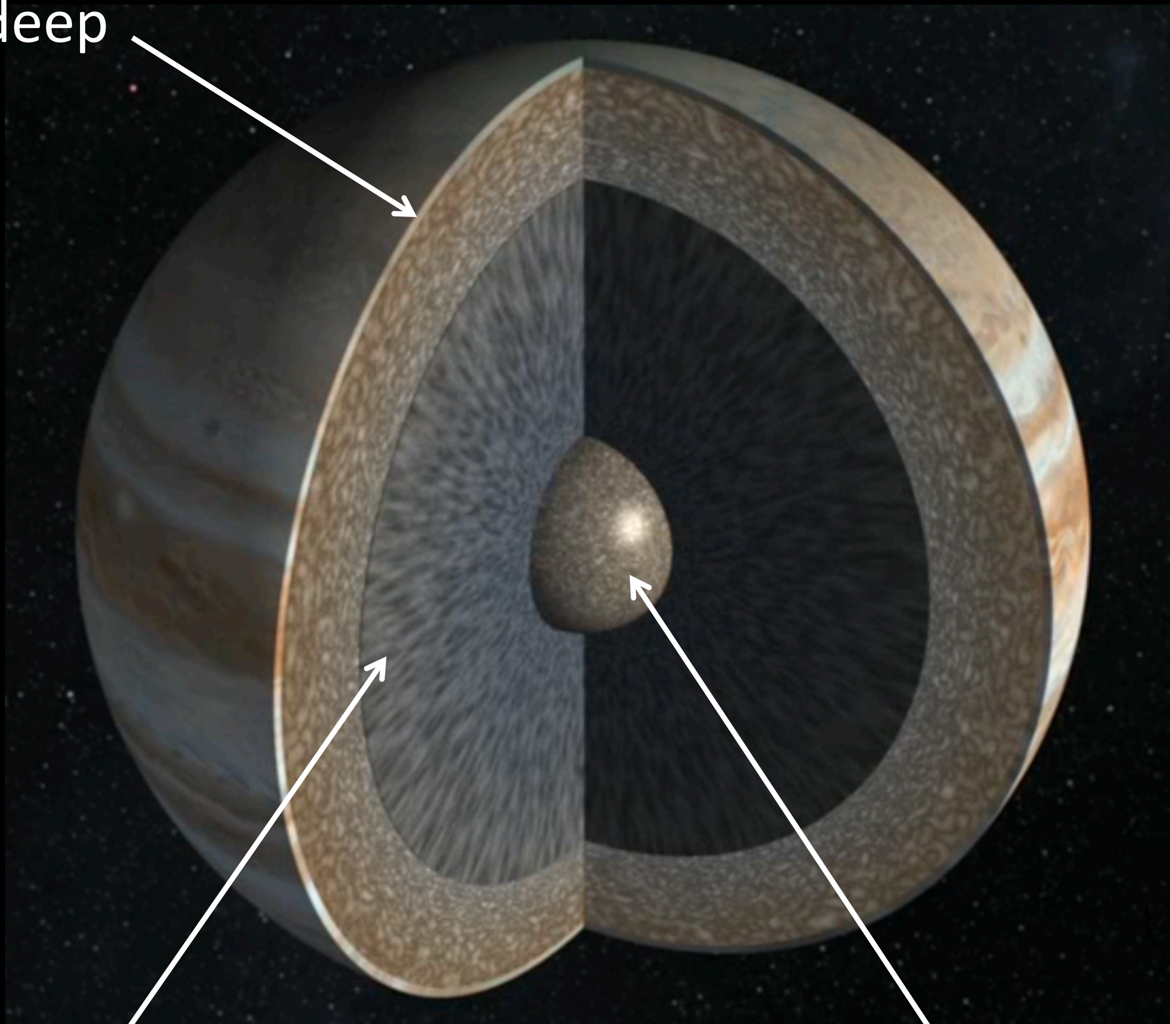
Statistical analysis of likelihood of interior velocity



Guillot et al., 2018, *Nature*

Flow in the interior must be less than 10m/s and likely much weaker

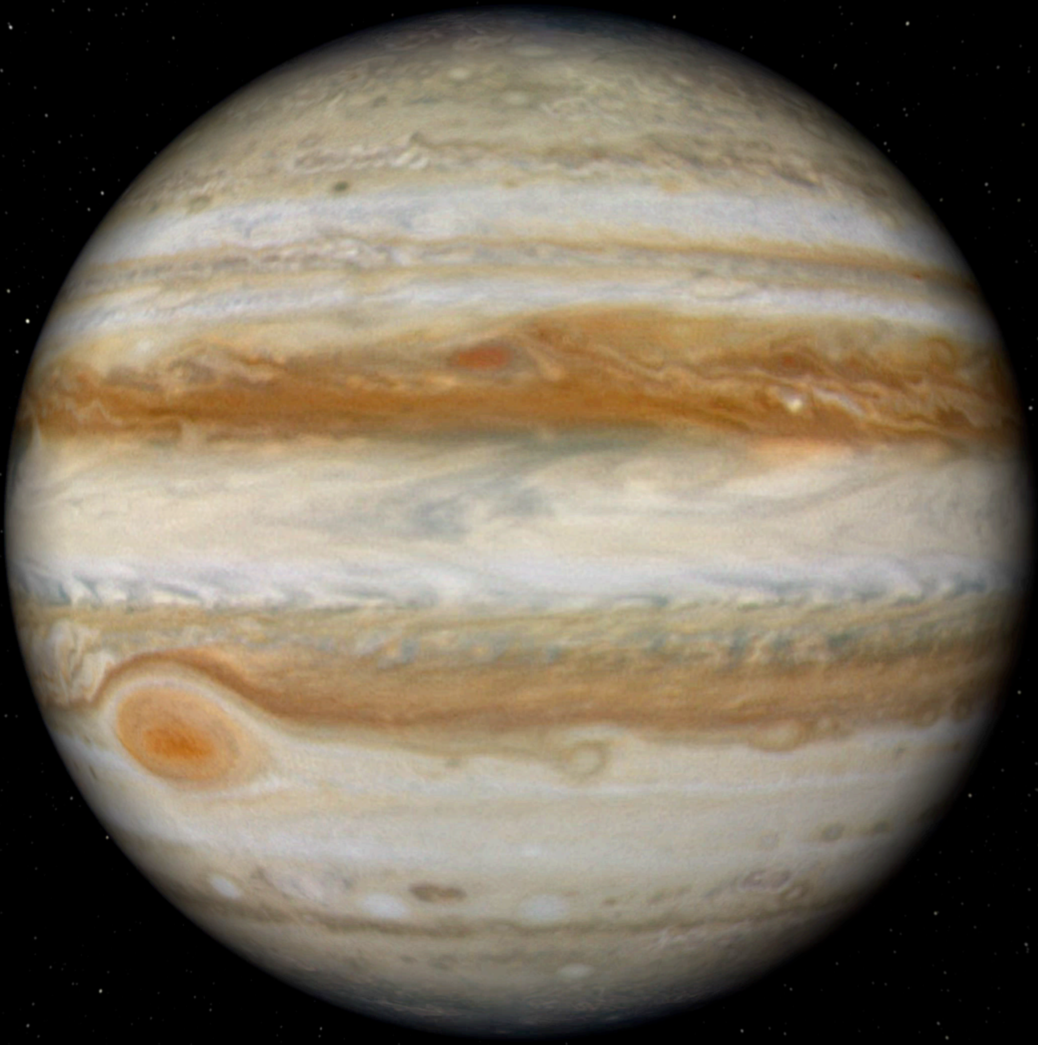
3000 km deep



No deep internal flows

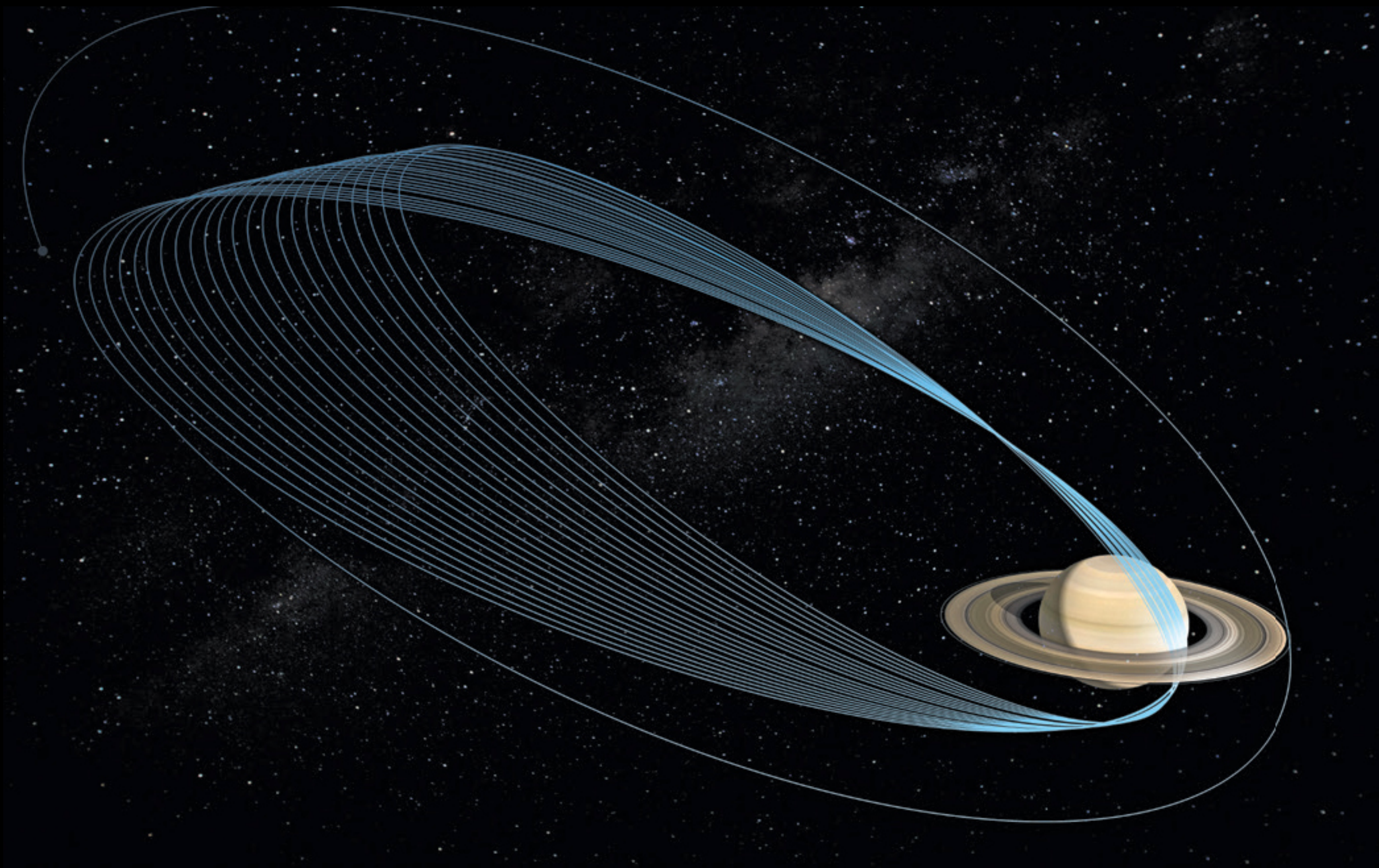
”Fuzzy core”???

Summary animation

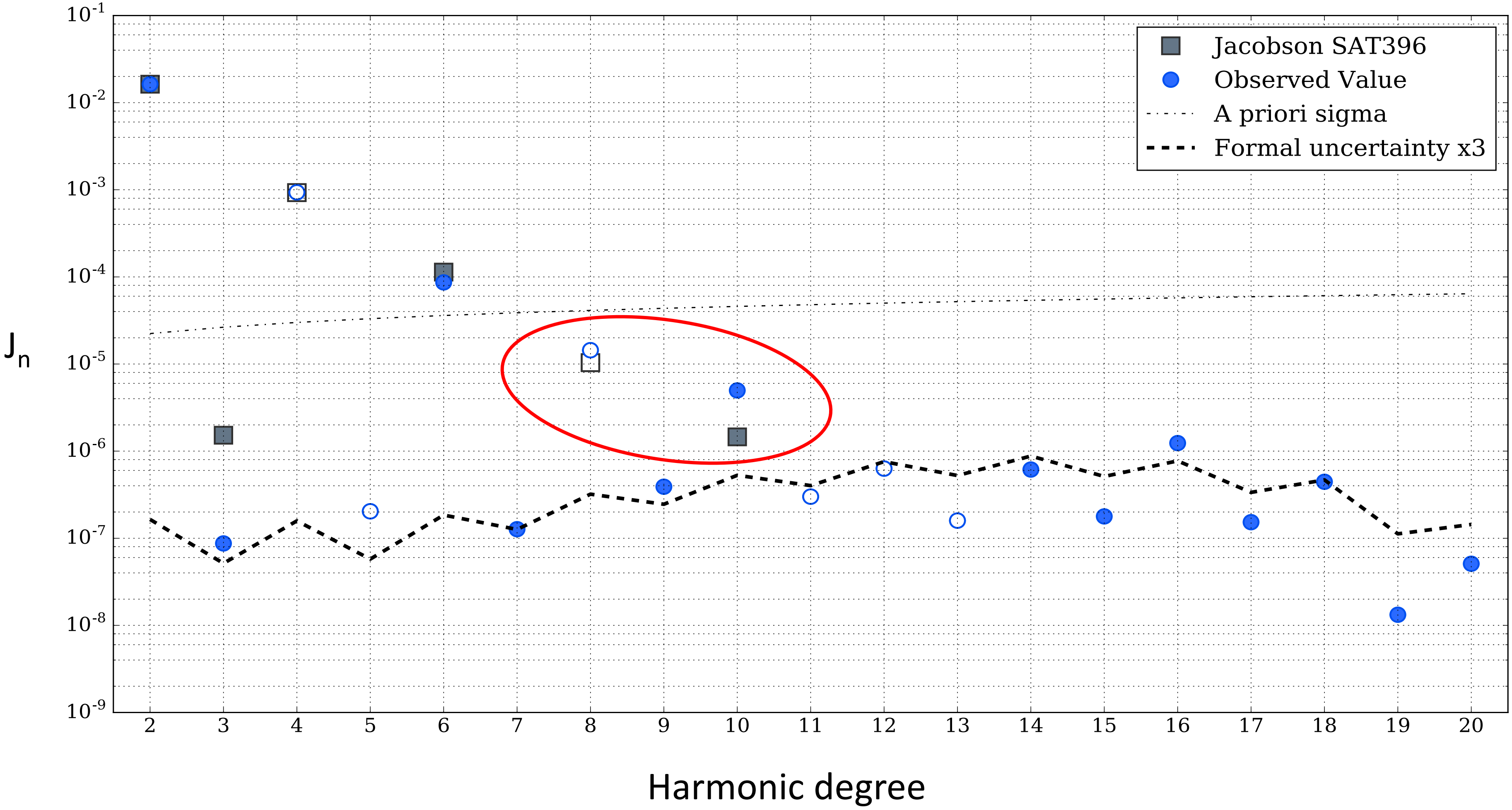


What about Saturn?

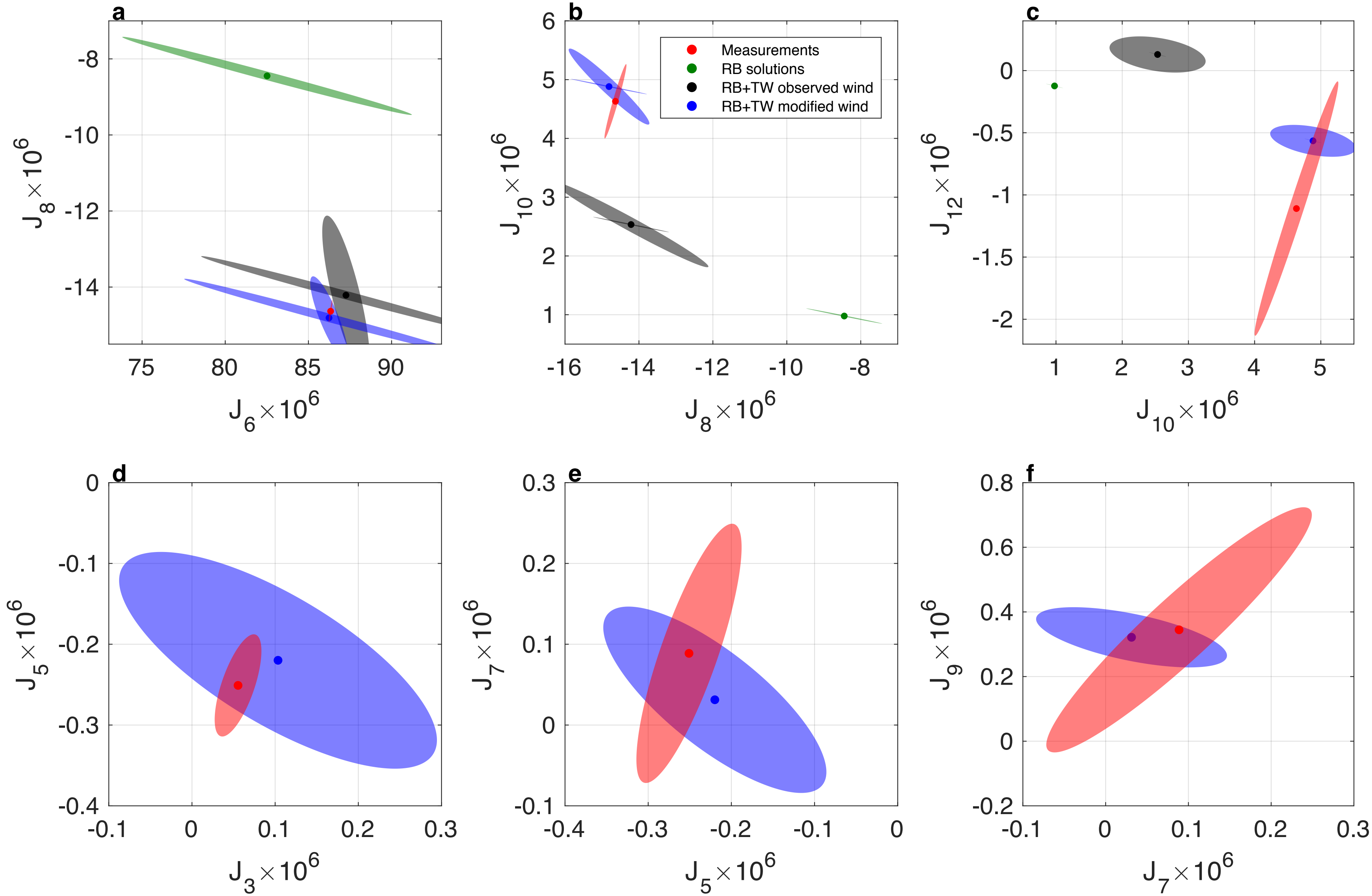
The Cassini Grand finale (May-Aug 2017) made 6 gravity measurements, improving significantly the known gravity spectrum of Saturn



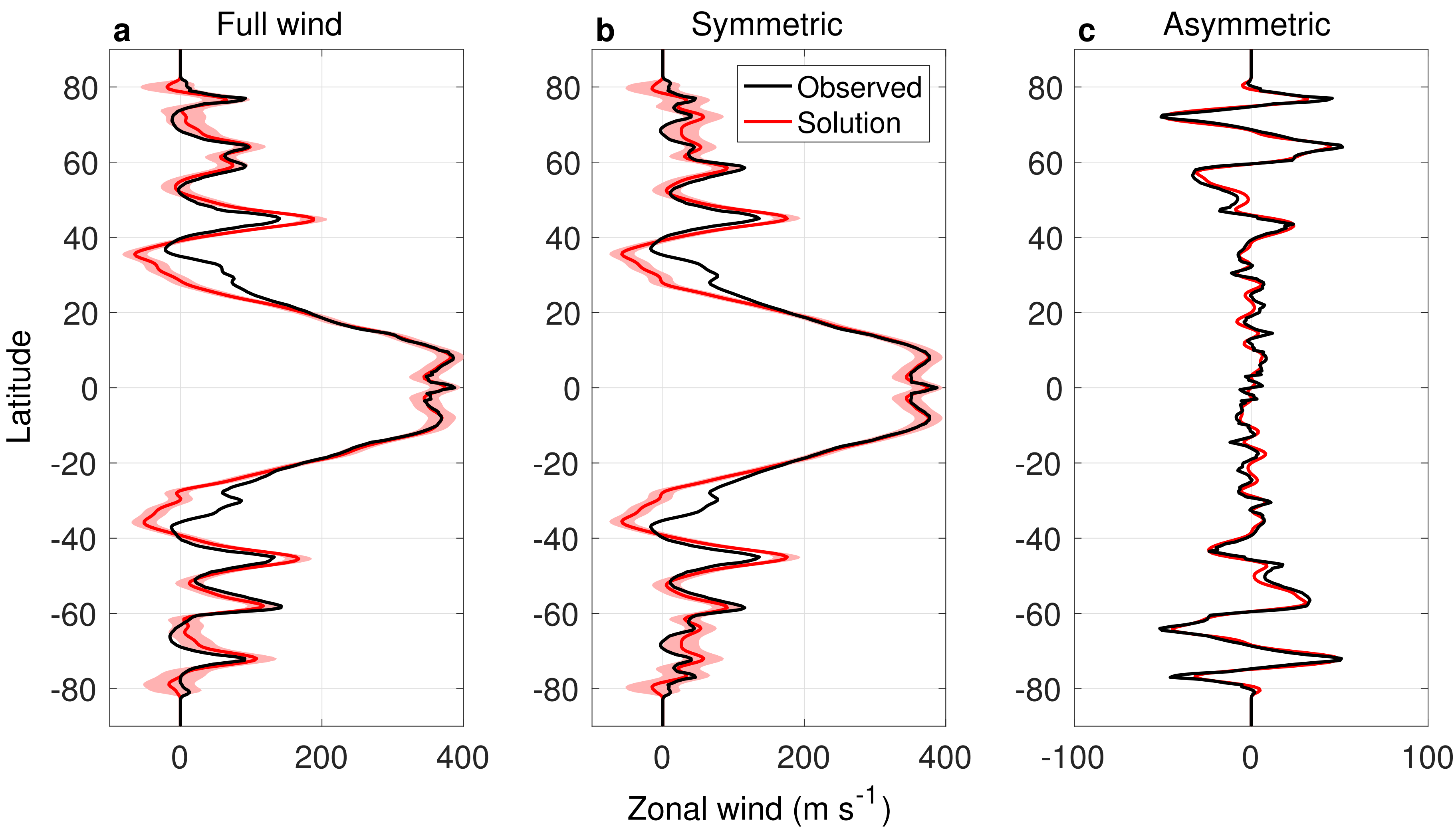
Saturn Cassini measured gravity spectrum



Saturn Cassini measured gravity spectrum

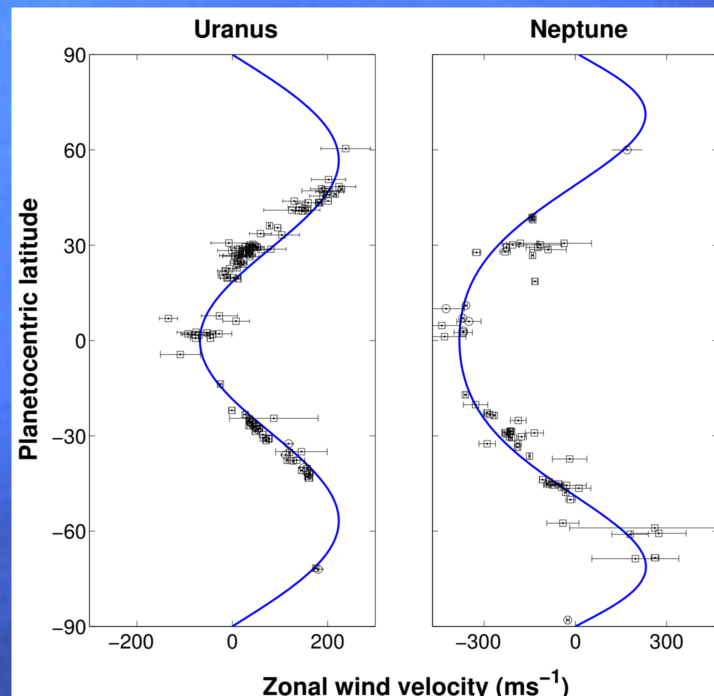


Flow field that best matches the measurements



Vertical extent is about 9000 km (three times as deep as Jupiter).

Atmospheric Confinement of jet-streams on Uranus and Neptune



In collaboration with Adam Showman, William Hubbard, Oded Aharonson & Ravit Helled

Kaspi et al., 2013

Uranus and Neptune

Signature of dynamics appears at the measured J_4

1. Planets are less massive with relatively strong winds
2. Broad jets have a signature at lower harmonics

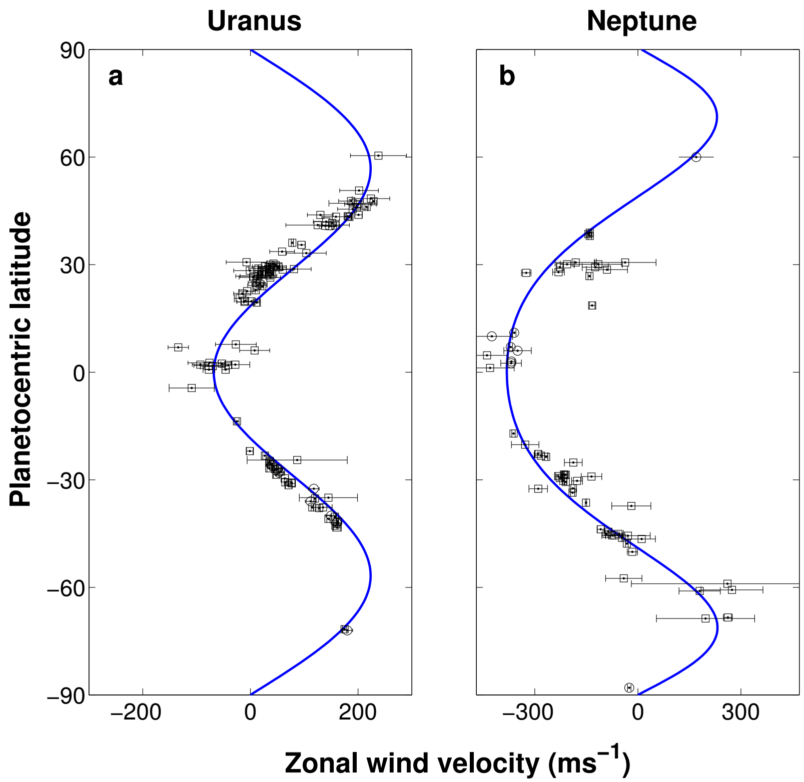
$$J_n^{dyn} = \frac{1}{a^n M} \int r^n P_n(\theta) \rho'(r,\theta,\phi) d^3 r$$

$$J_4^{observed} = J_4^{static} + J_4^{dyn}$$

Measured ± error (Voyager and HST)

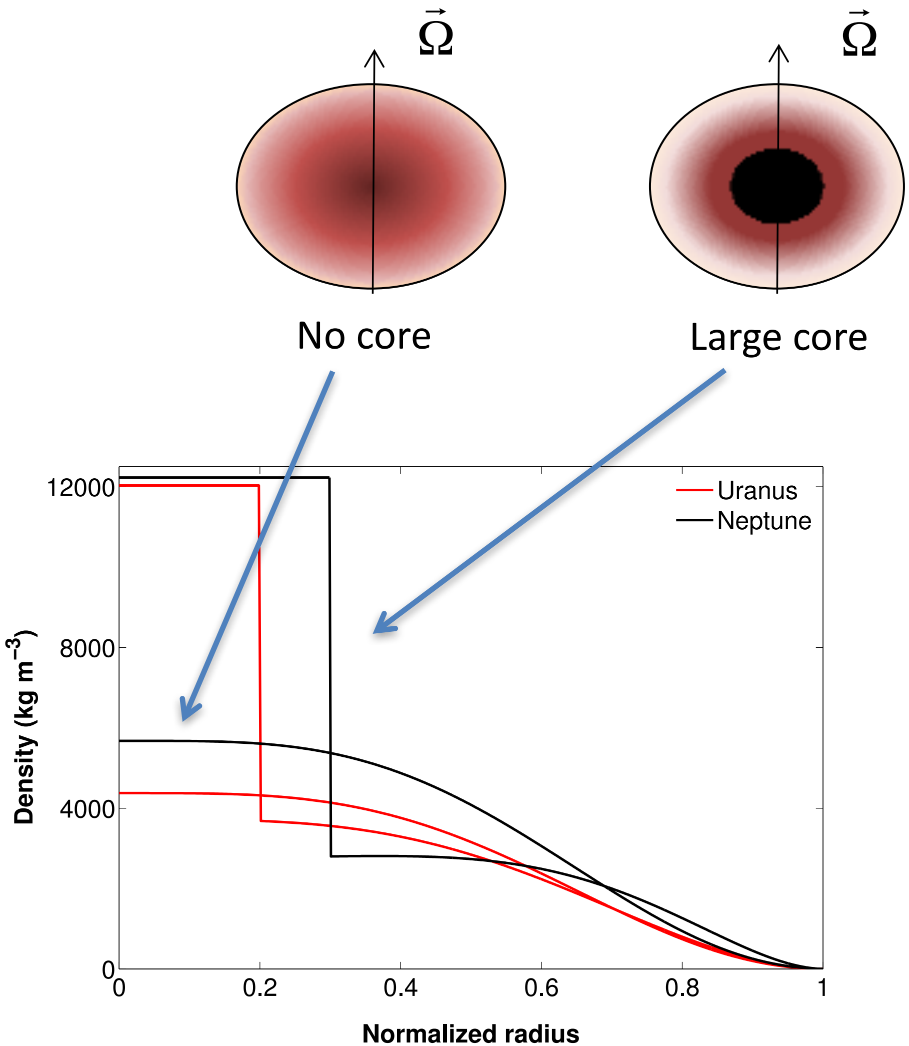
Interior structure models

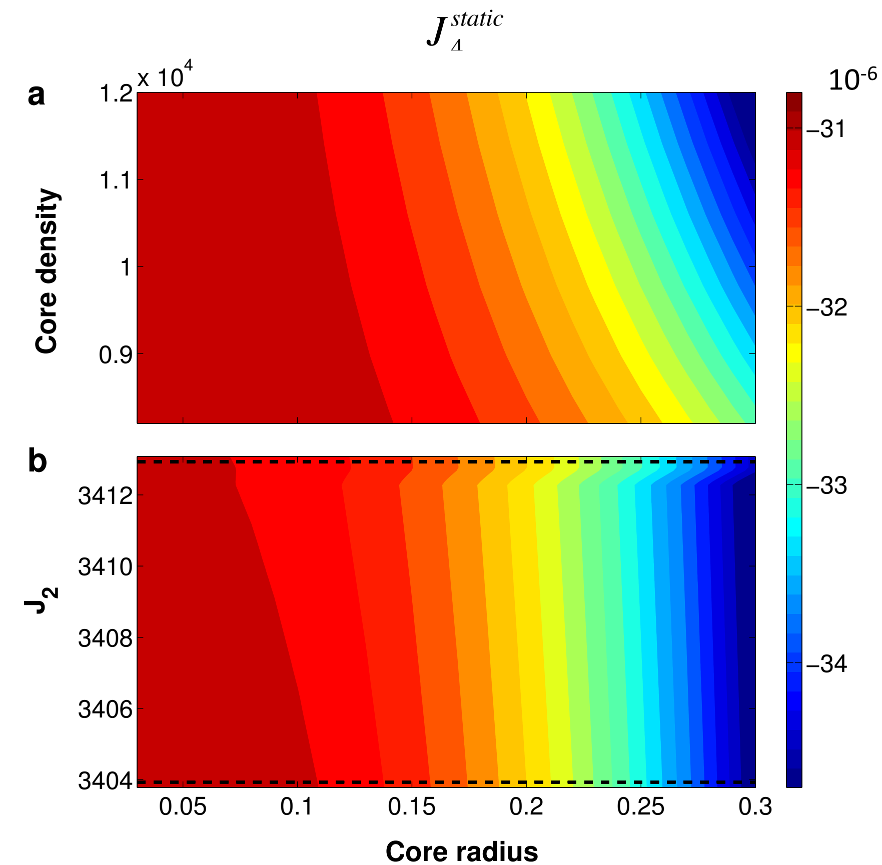
The **maximum possible** difference between $J_4^{observed}$ and J_4^{static} (taking into account the measurements error and the largest possible range of interior models) will give the **maximum possible** contribution that dynamics can make to J_4.



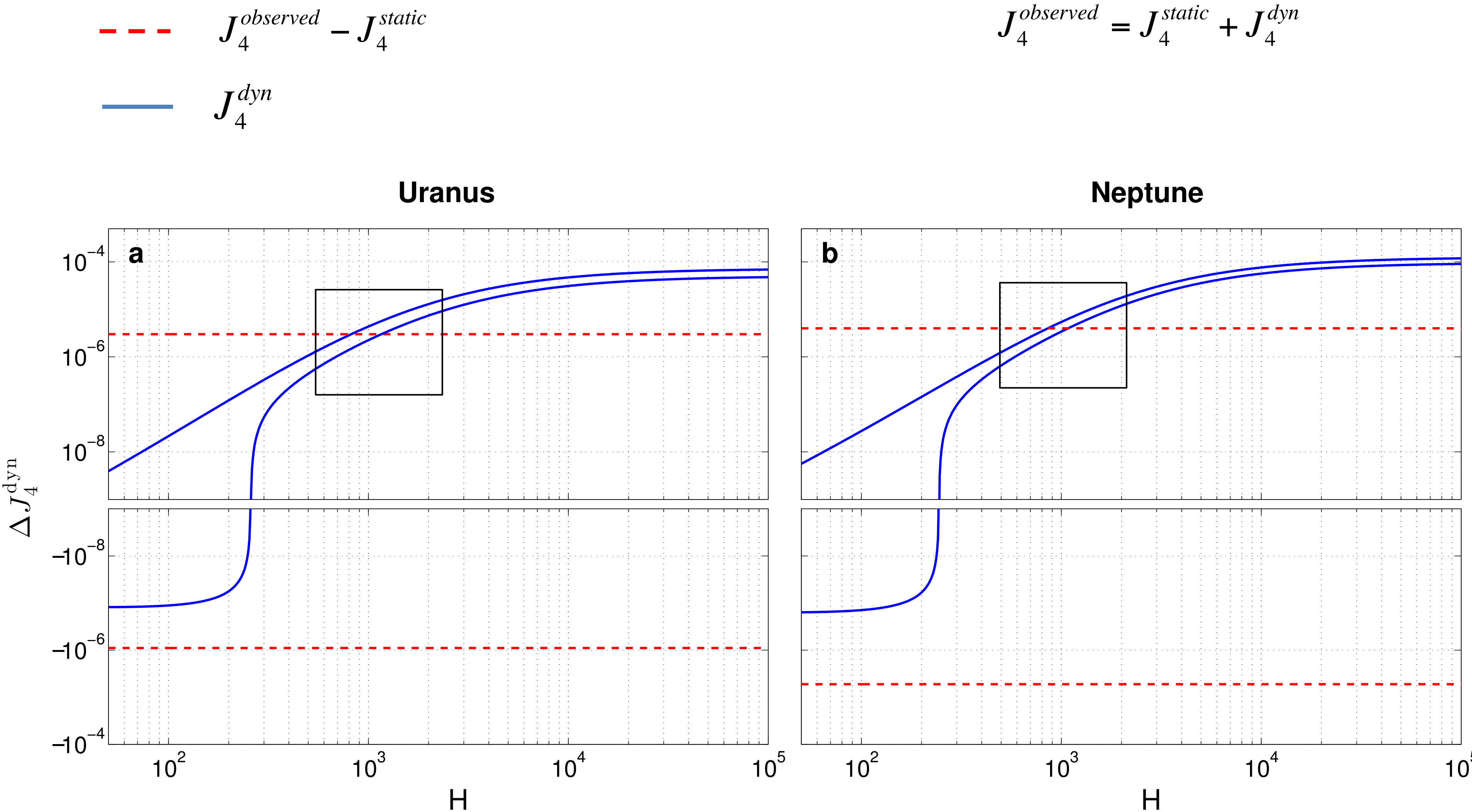
Uranus and Neptune

Taking the widest possible range of interior models:





gives an **upper limit** to $J_4^{observed} - J_4^{static}$



Dynamics must be constrained to the upper ~1000 km

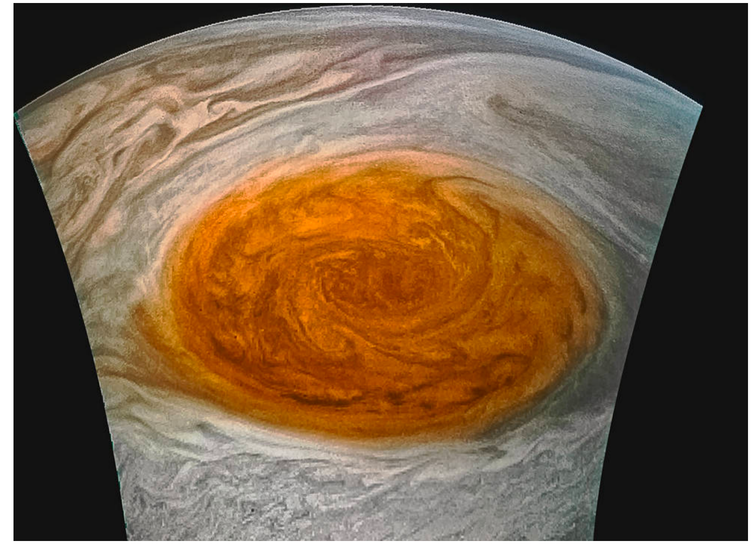
Uranus: (0.15% of the mass, ~2000 bars)

Neptune: (0.2% of the mass, ~4000 bars)

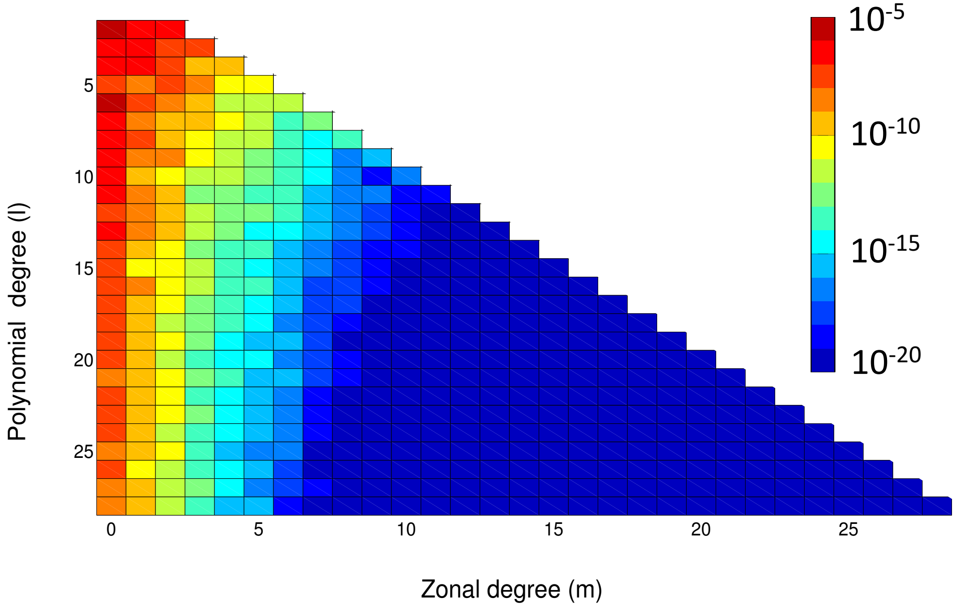
Next :How deep is the Great Red Spot?

Juno flew over the GRS in orbit 7 and will repeat this in orbits 12 and 21.

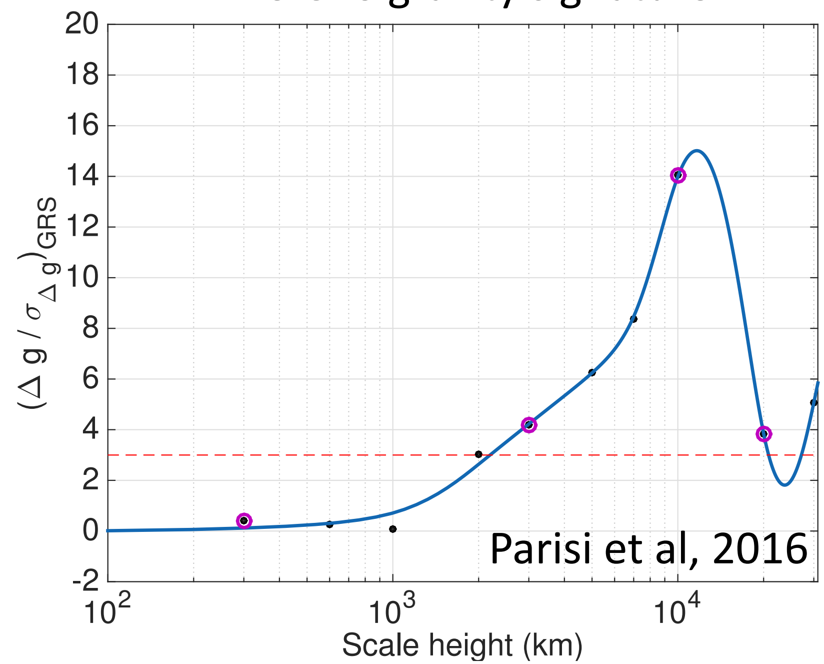
Can we detect the gravity signal of the GRS?



Tesseral gravity harmonics



The GRS gravity signature



Summary

- Juno is orbiting Jupiter every 53 days, and successfully operating with all instruments.
- The poles of Jupiter are dominated by large vortices, and very different from most latitudes which are dominated by jets.
- Jupiter's gravity field was found to be hemispherically (north-south) asymmetric – a pure signal of deep dynamics.
- This allowed determining that the depth of the cloud-level flows, reach approximately 3000 km beneath the cloud level, which is the level of magnetic dissipation.
- The even gravity harmonics indicate no significant flows in the interior
- Preliminary Cassini results for Saturn indicate flows extending down to 9000 km.
- A very deep O(2000 km) GRS will produce a detectable gravity signal.