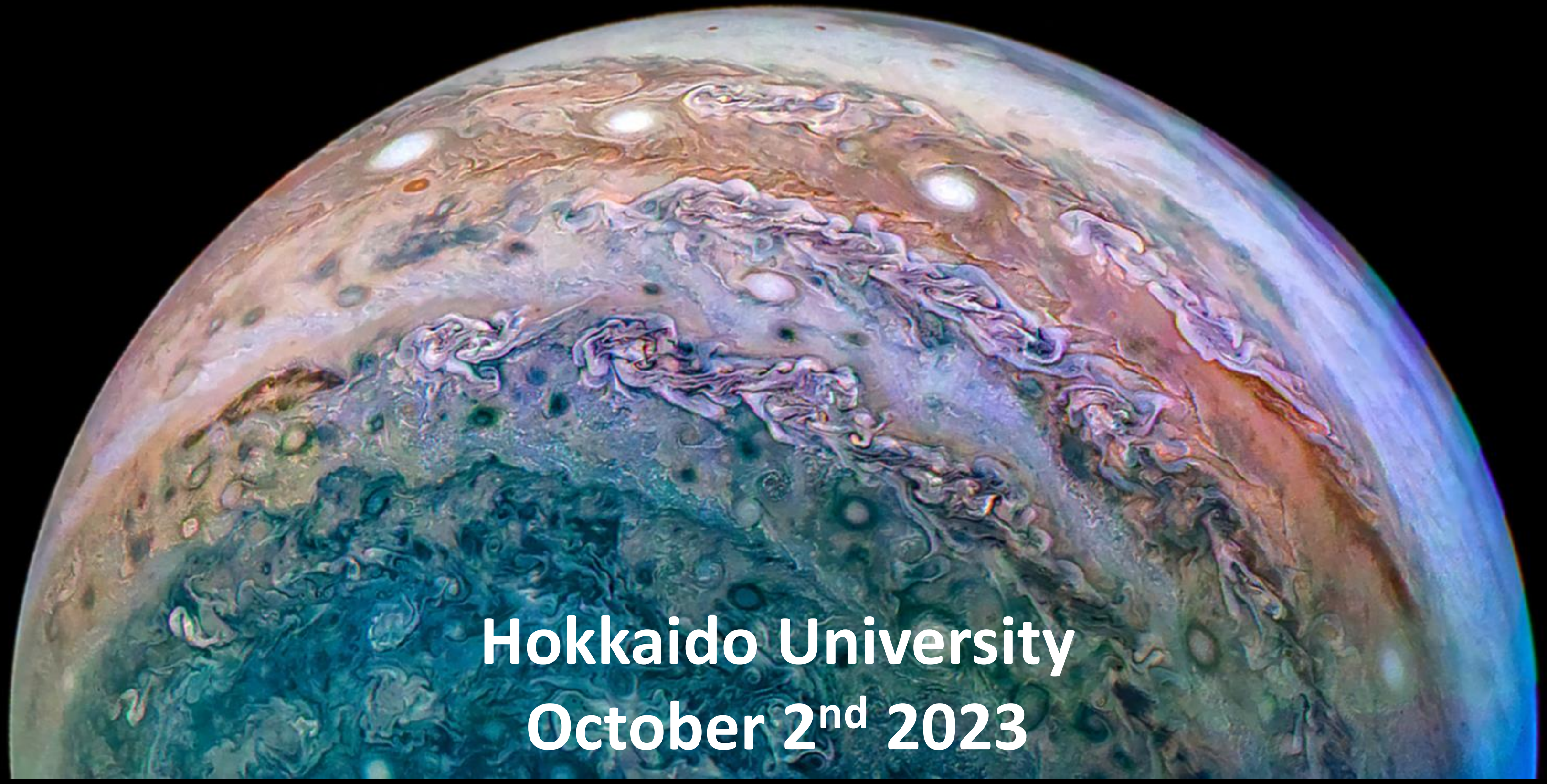
Atmospheric dynamics of giant planets: New insights from the Juno mission

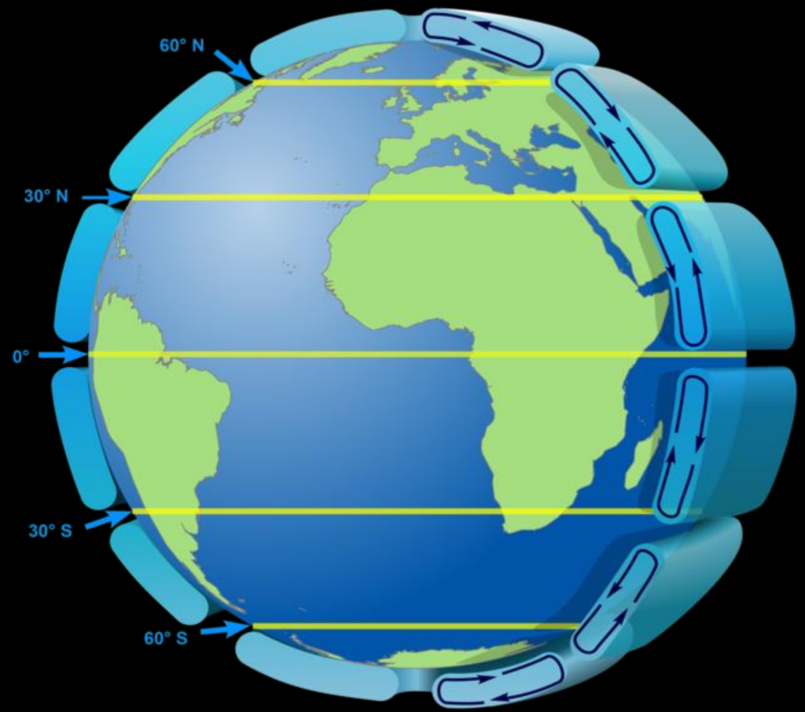
Yohai Kaspi

Weizmann Institute of Science

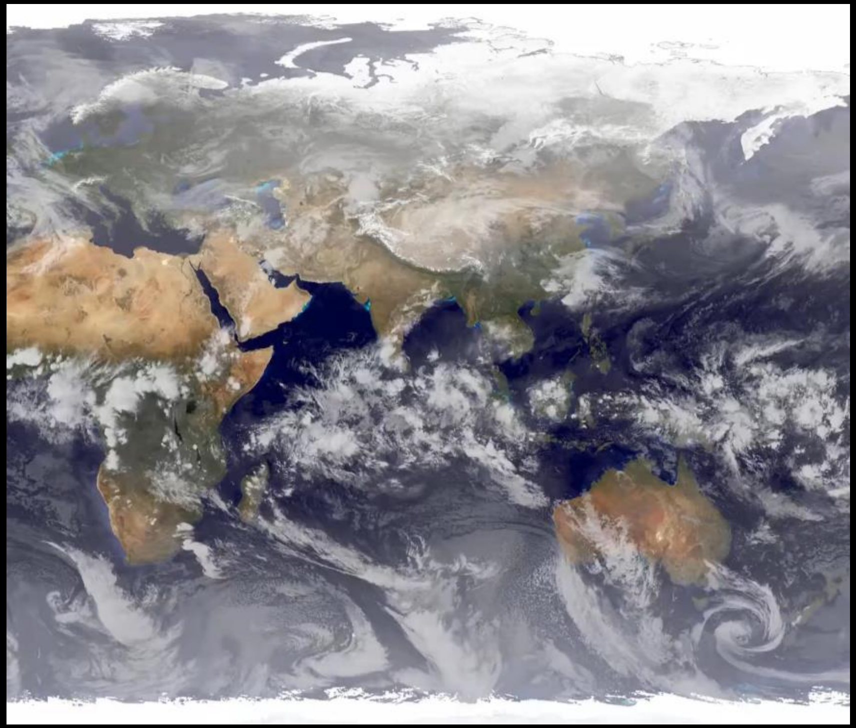


Hokkaido University

October 2nd 2023

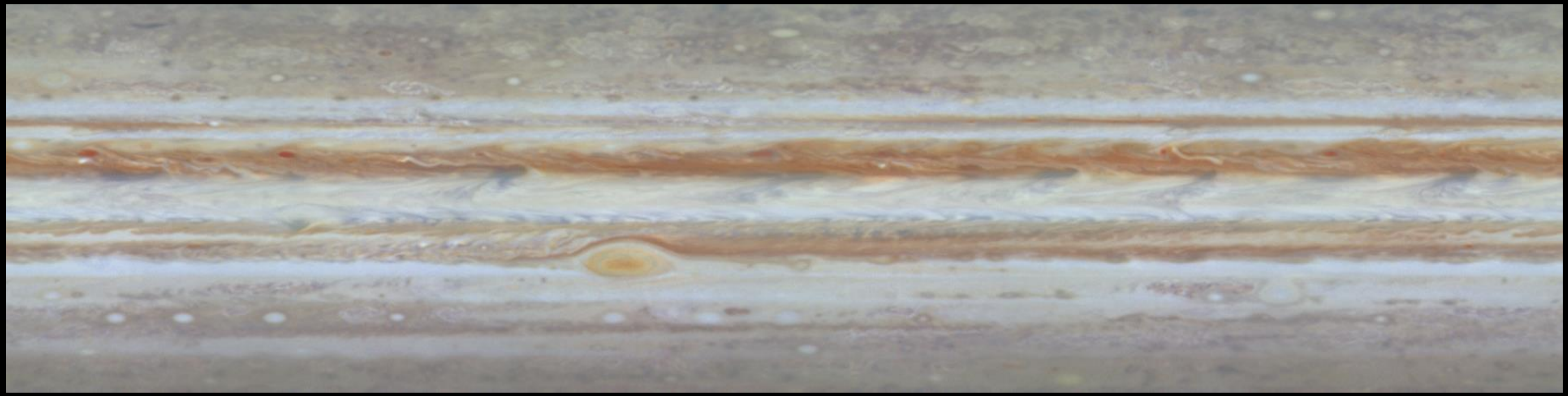


Earth



1000 km

Jupiter

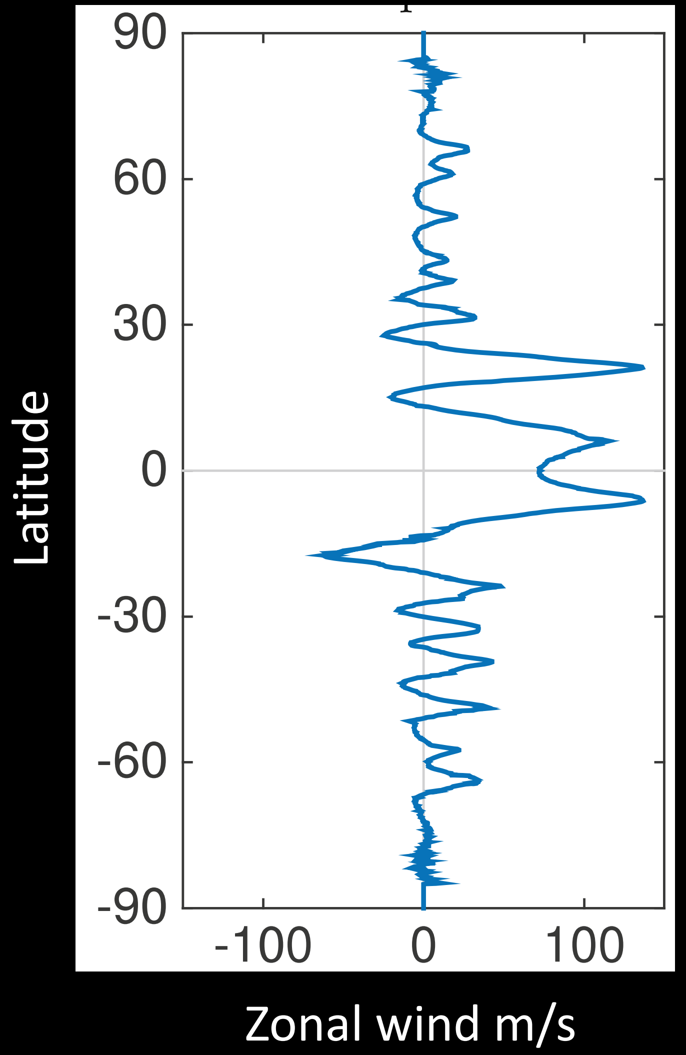


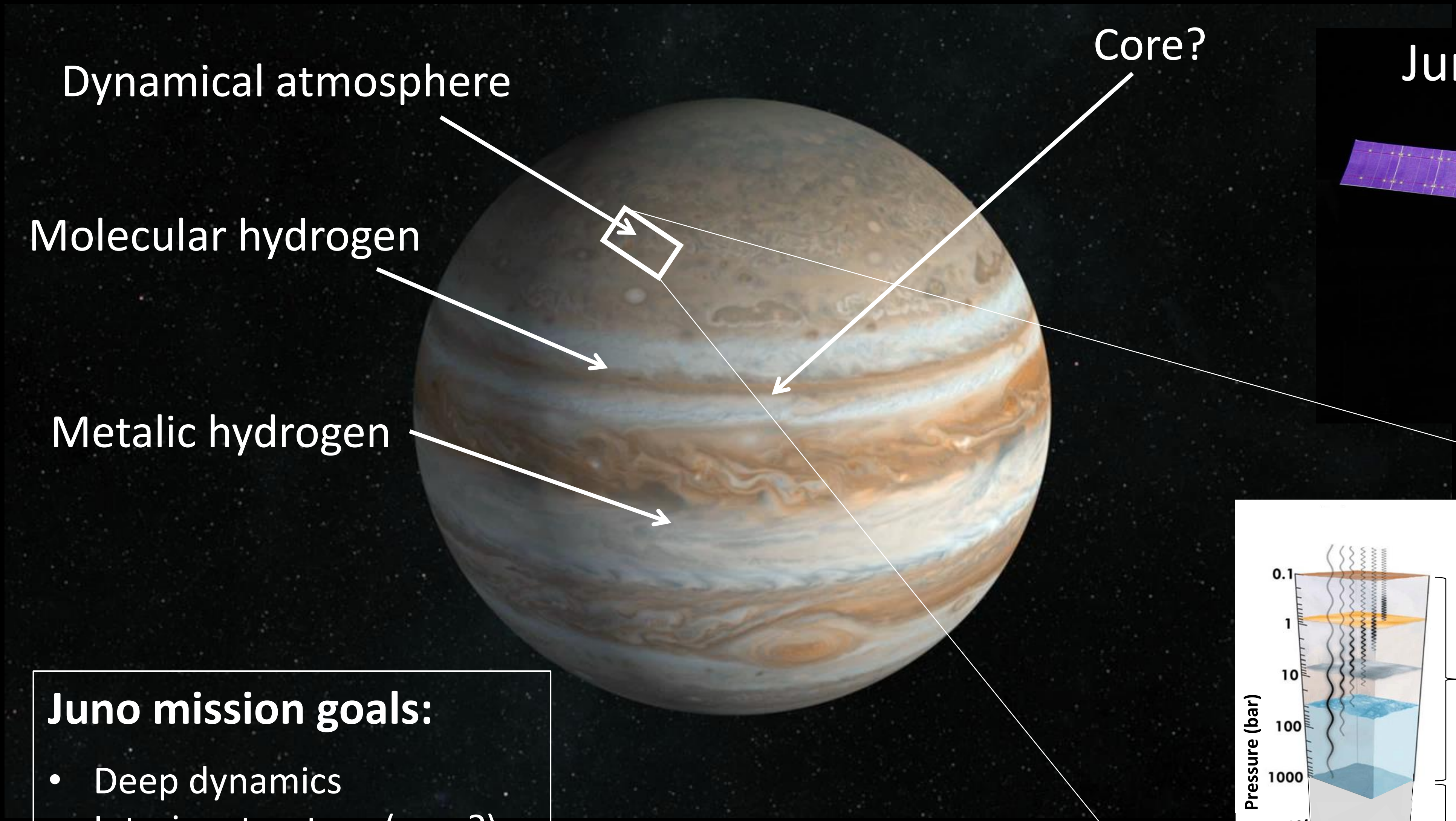
10000 km

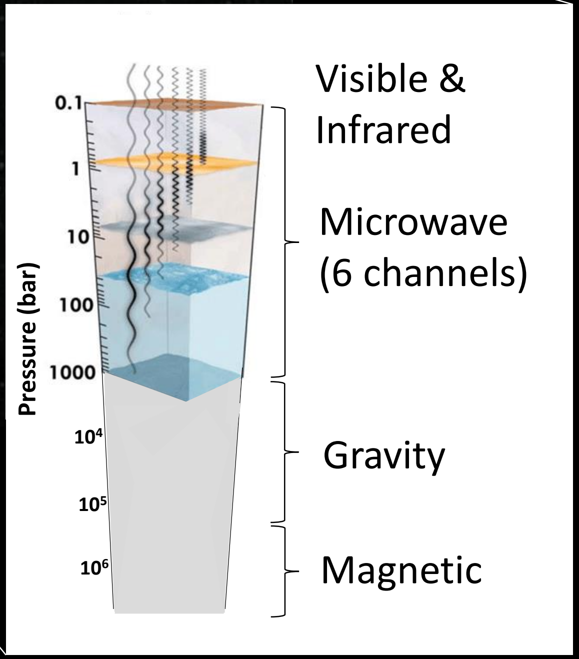
Jupiter

- 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

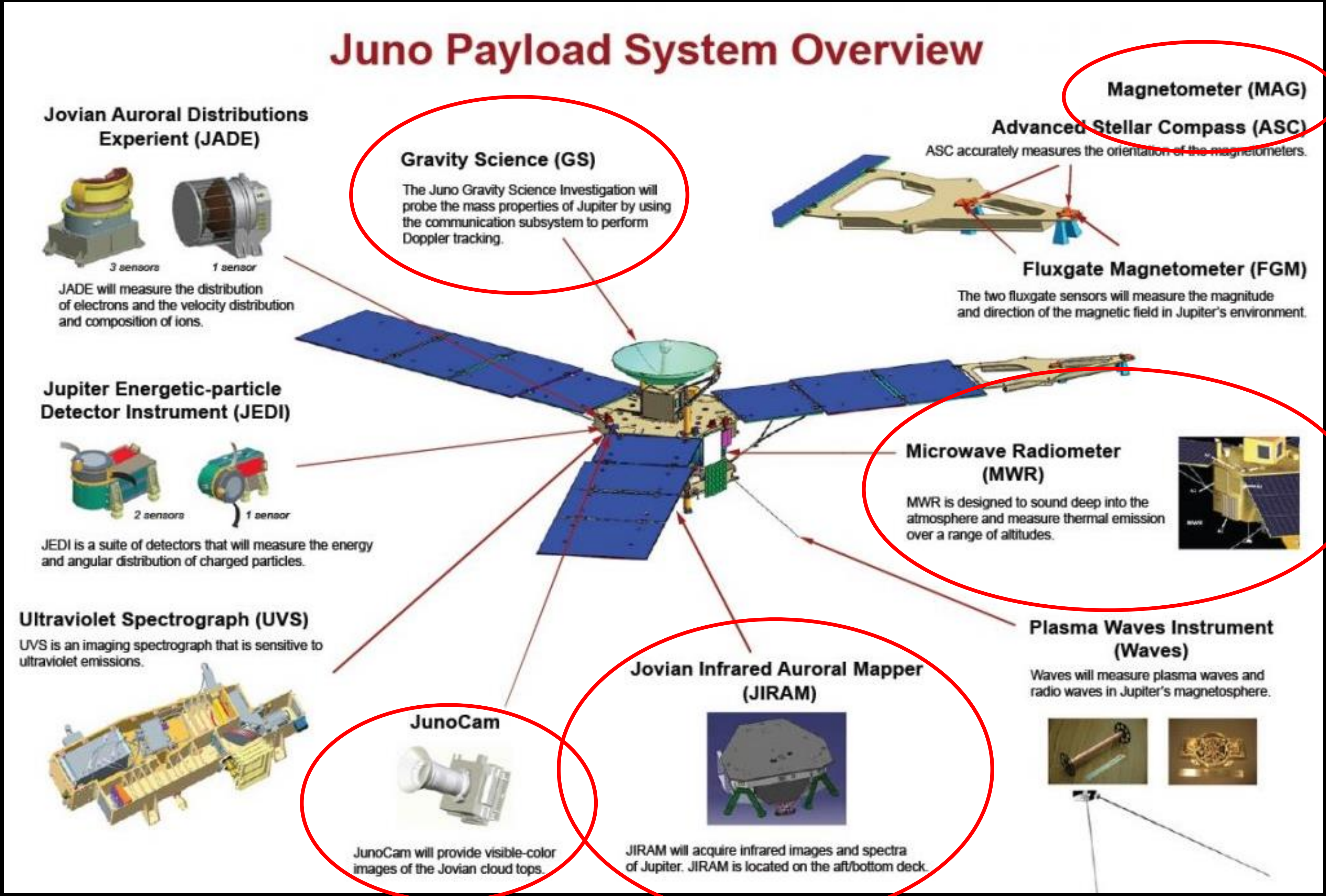






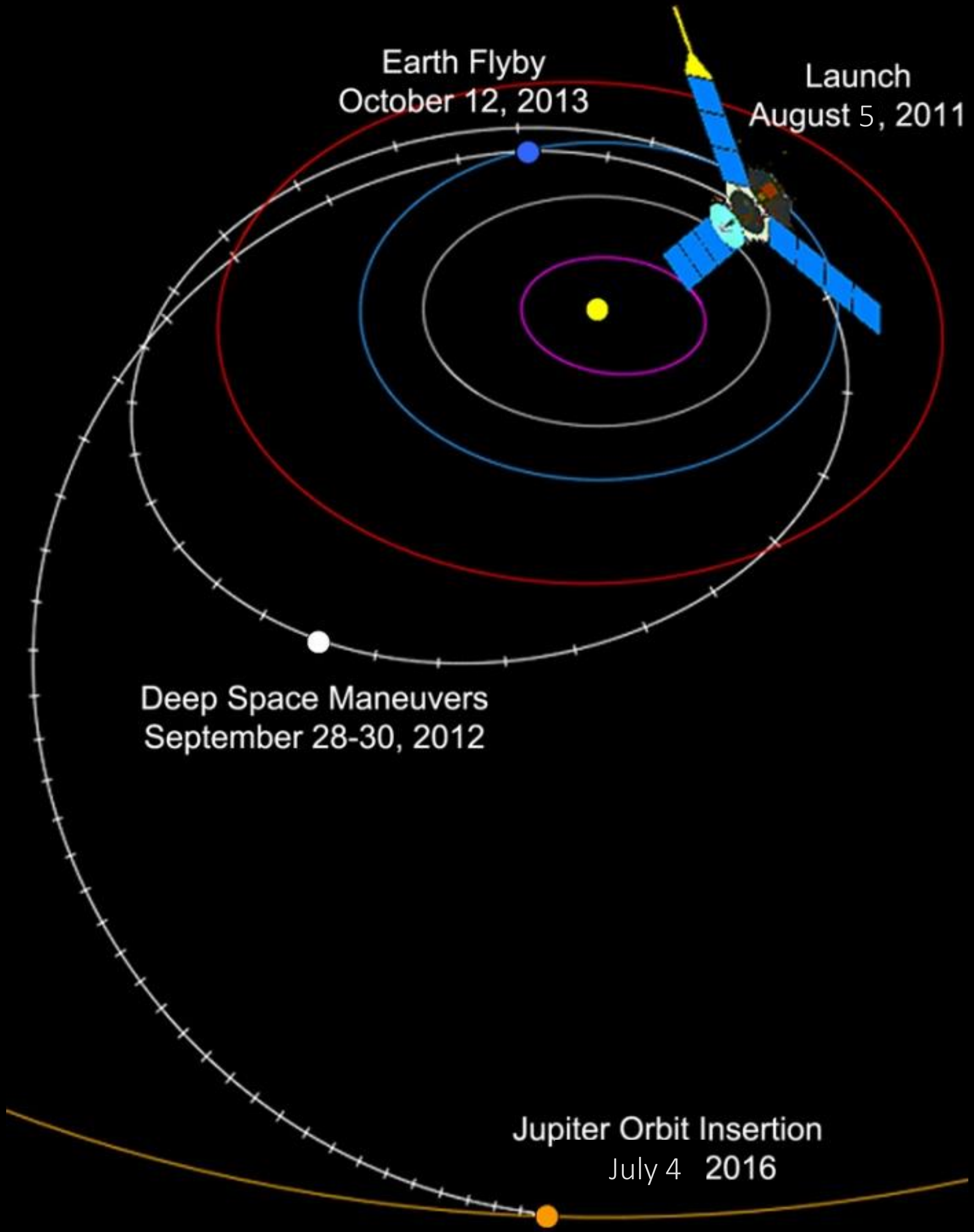
Juno mission goals:

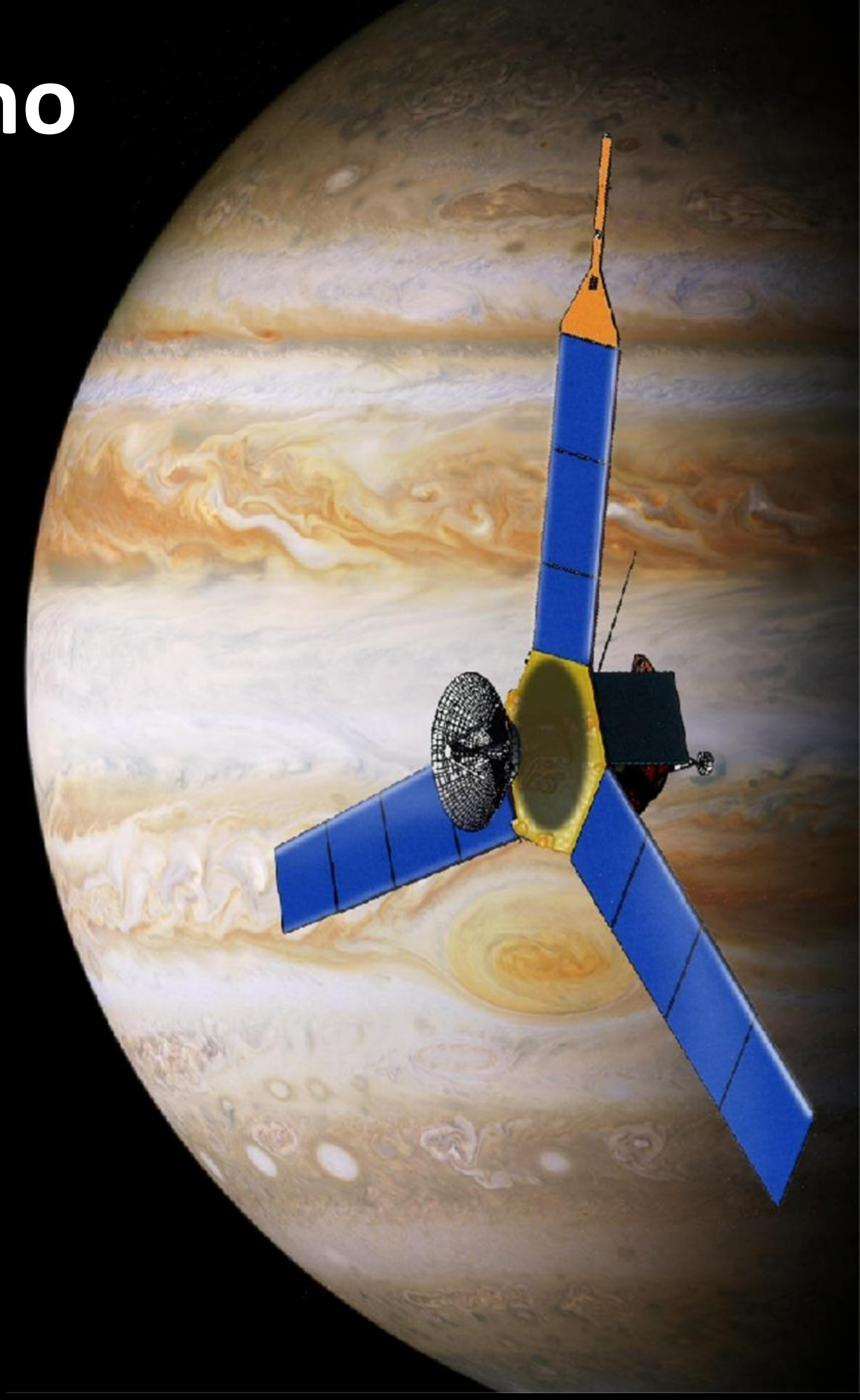
- Deep dynamics
- Interior structure (core?)
- Formation and evolution
- Magnetic field
- Magnetosphere



Juno Payload System Overview
Magnetometer (MAG)
Advanced Stellar Compass (ASC)
ASC accurately measures the orientation of the magnetometers.
Jovian Auroral Distributions Experient (JADE)
3 sensors
1 sensor
JADE will measure the distribution of electrons and the velocity distribution and composition of ions.
Gravity Science (GS)
The Juno Gravity Science Investigation will probe the mass properties of Jupiter by using the communication subsystem to perform Doppler tracking.
Fluxgate Magnetometer (FGM)
The two fluxgate sensors will measure the magnitude and direction of the magnetic field in Jupiter's environment.
Jupiter Energetic-particle Detector Instrument (JEDI)
2 sensors
1 sensor
JEDI is a suite of detectors that will measure the energy and angular distribution of charged particles.
Microwave Radiometer (MWR)
MWR is designed to sound deep into the atmosphere and measure thermal emission over a range of altitudes.
Ultraviolet Spectrograph (UVS)
UVS is an imaging spectrograph that is sensitive to ultraviolet emissions.
Plasma Waves Instrument (Waves)
Waves will measure plasma waves and radio waves in Jupiter's magnetosphere.
JunoCam
JunoCam will provide visible-color images of the Jovian cloud tops.
Jovian Infrared Auroral Mapper (JIRAM)
JIRAM will acquire infrared images and spectra of Jupiter. JIRAM is located on the aft/bottom deck.

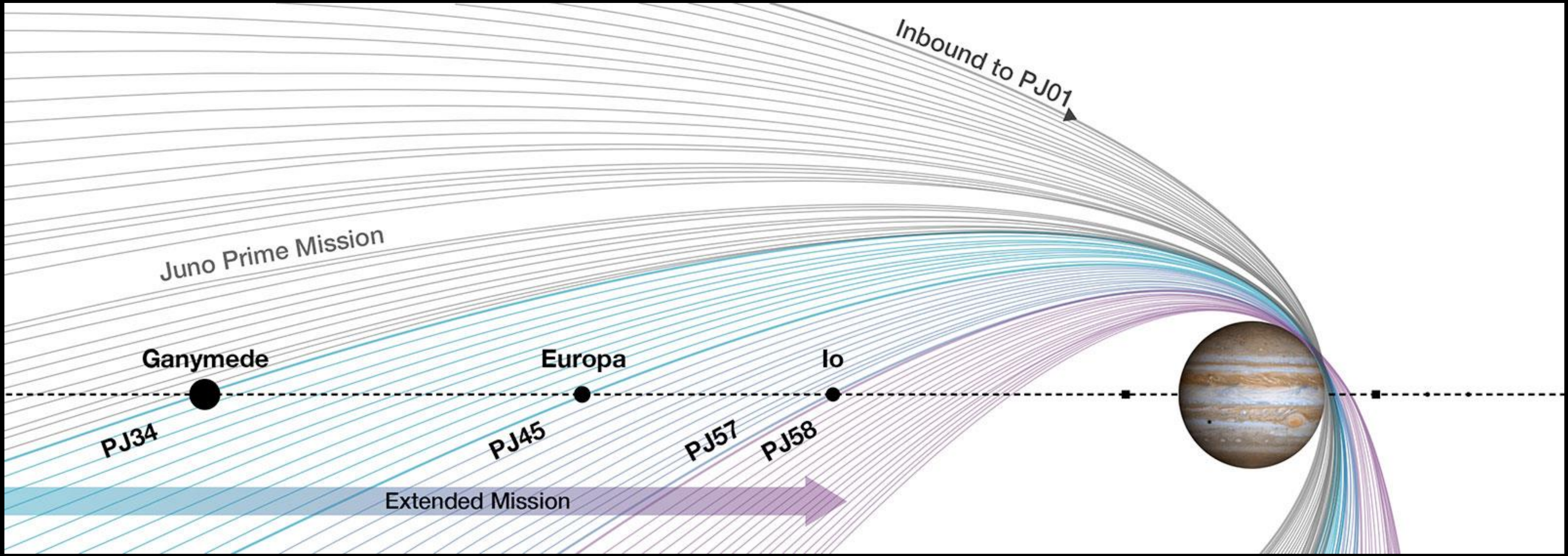
Juno


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



- During the prime mission Juno orbited Jupiter every 53 days (34 orbits: July 2016 - June 2021)
- Juno is now in a 34 day orbit (since Europa flyby in September 2022)
- Polar orbit with perijove drift of 1 degree northward
- Perijove distance is ~4000 km

Juno extended mission (since July 2021)



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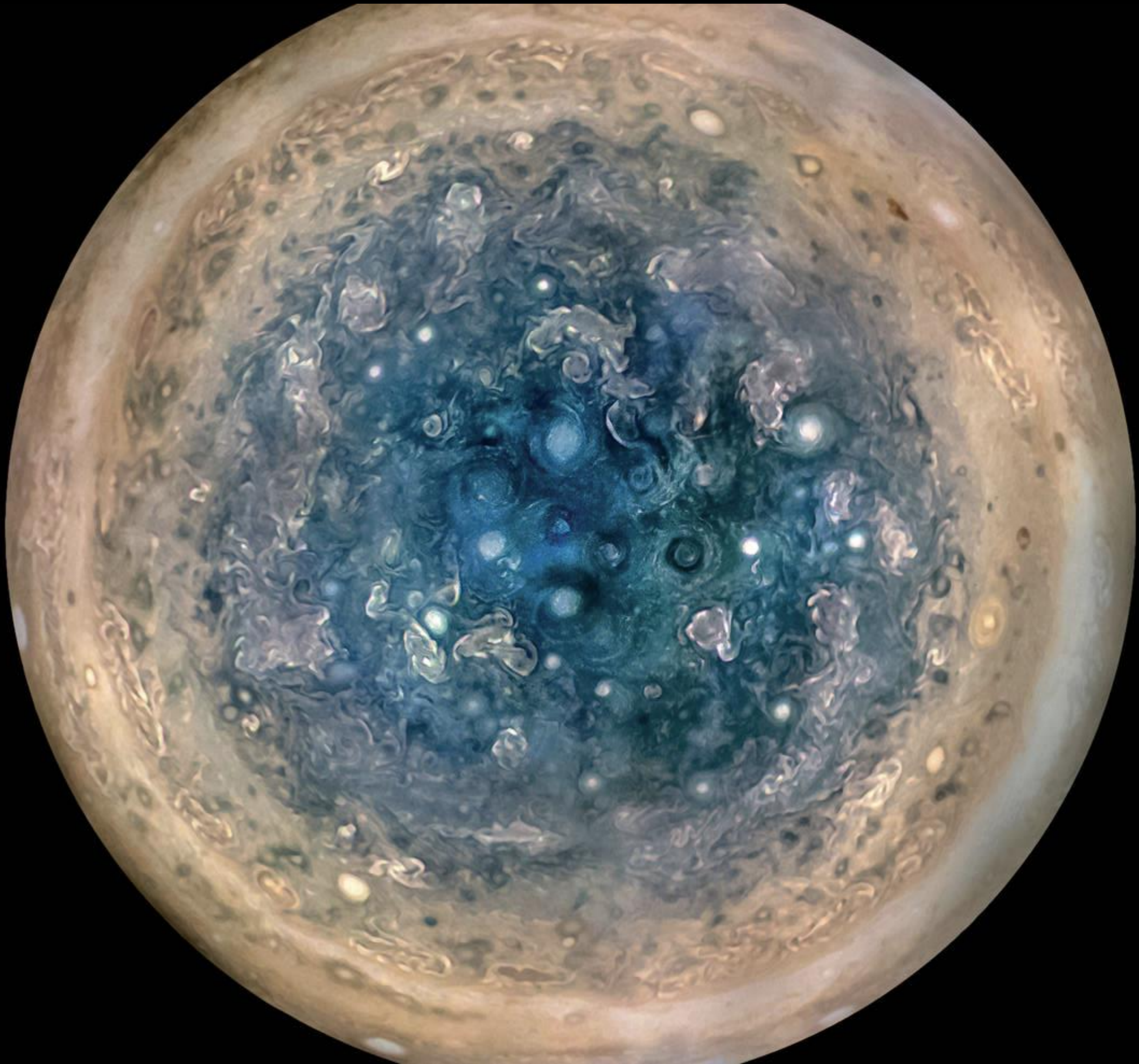
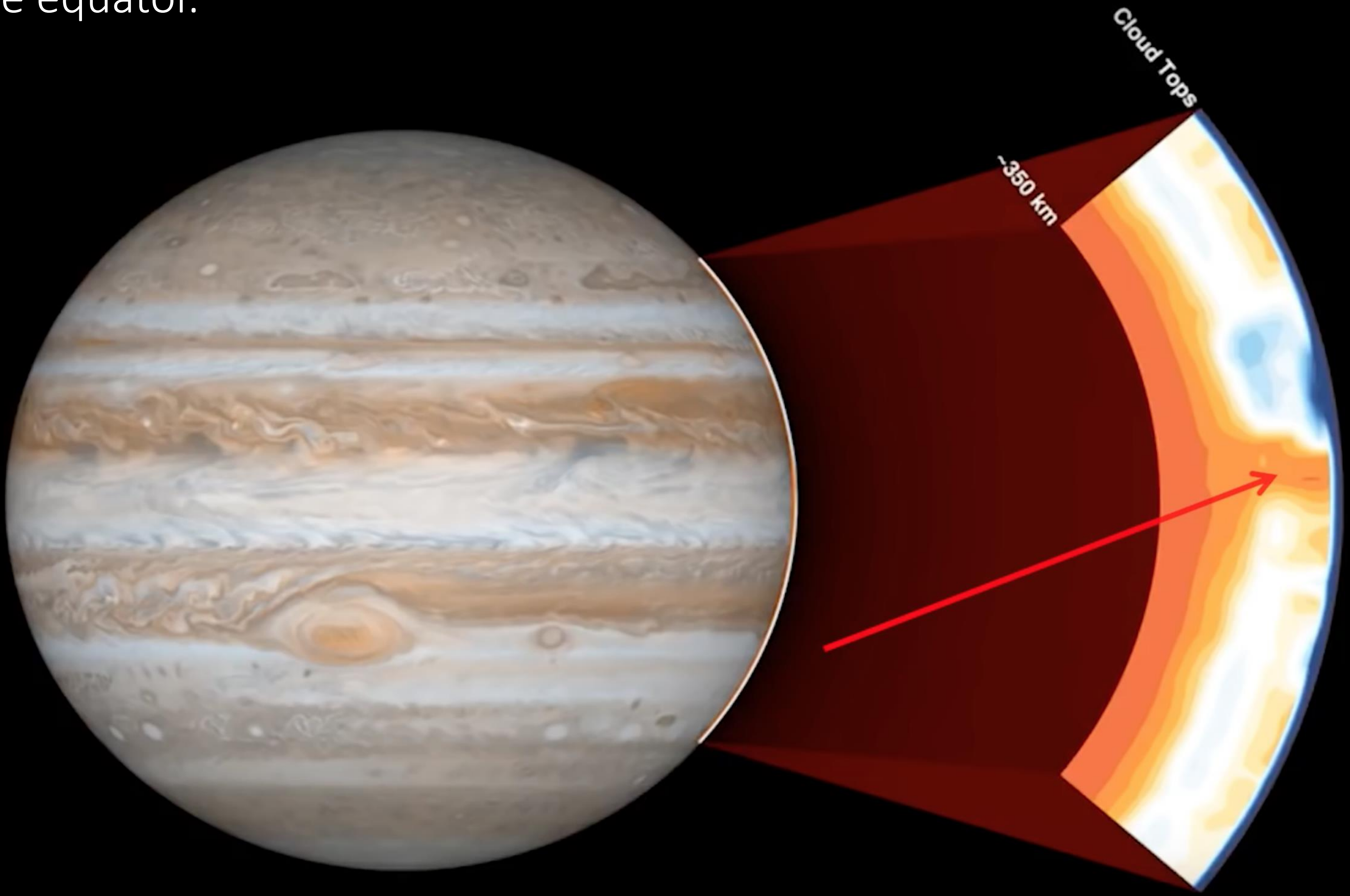
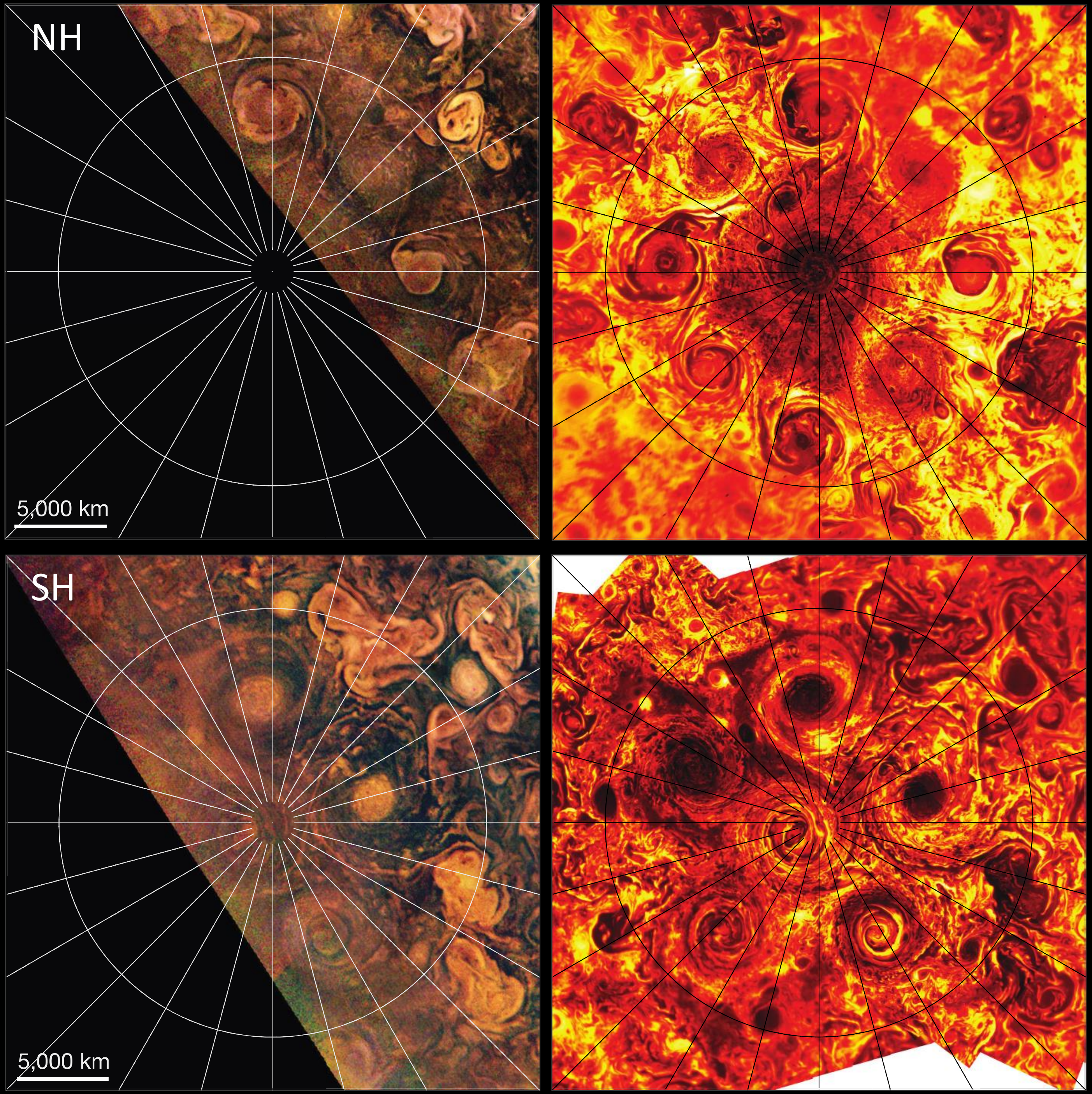


Juno's microwave measurements reveal an ammonia plume near the equator.

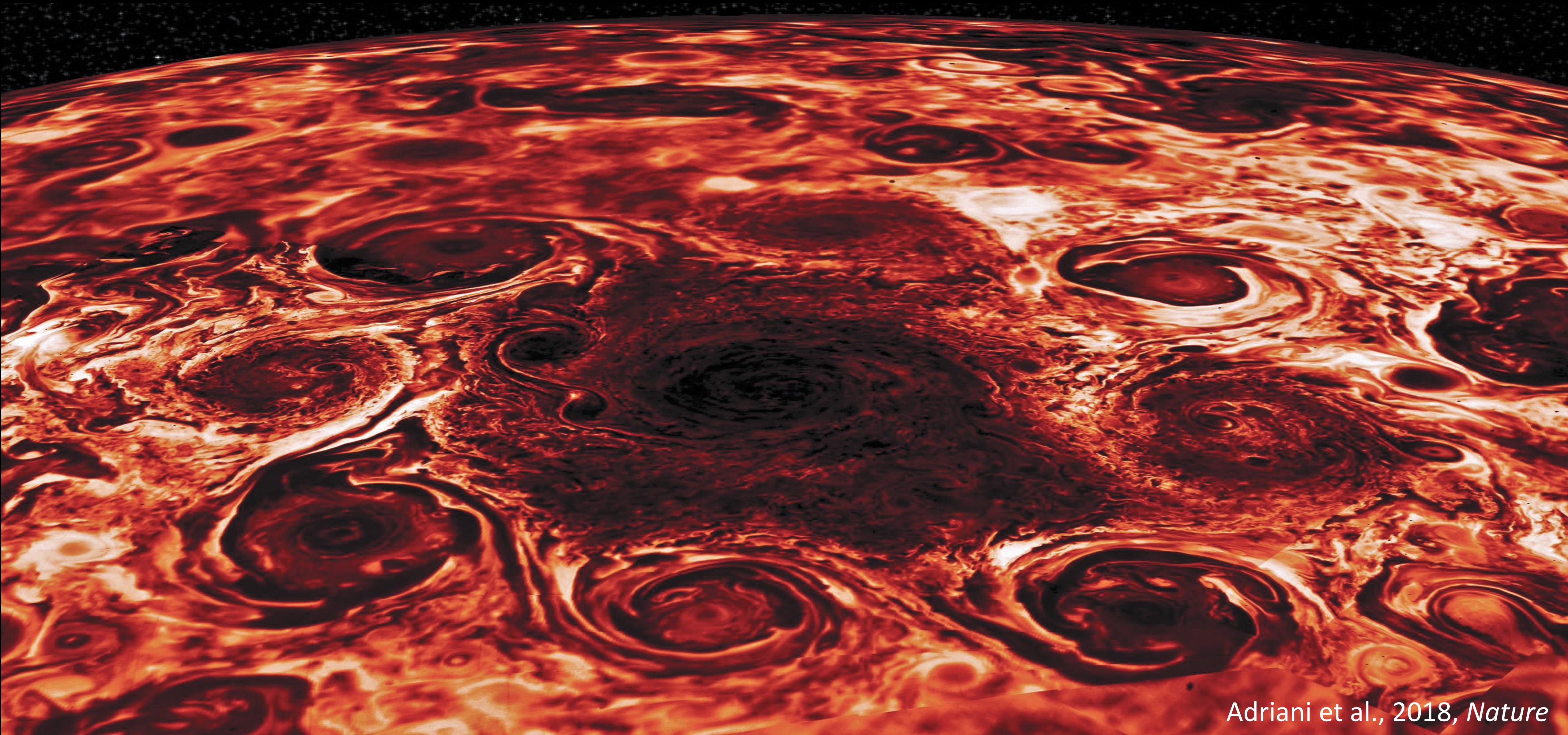


Bolton et al., 2017, *Science*



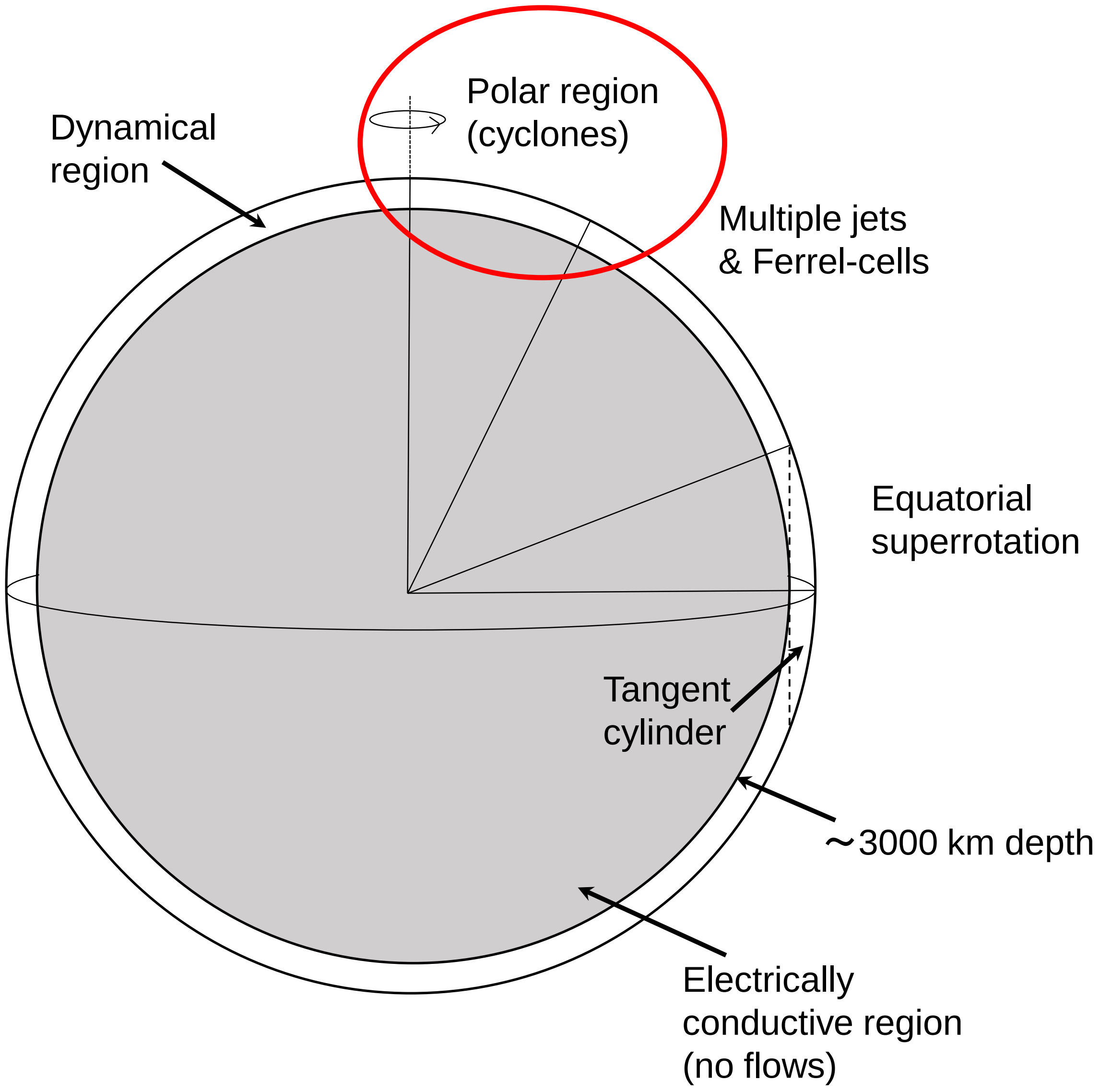
Adriani et al., 2018, *Nature*

Side view of the north pole



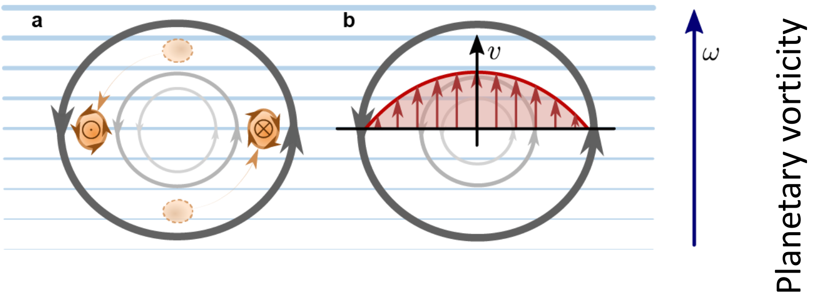
Adriani et al., 2018, *Nature*

Jupiter’s dynamical regimes



What sets the stability and location of the circumpolar cyclones?

beta-drift:

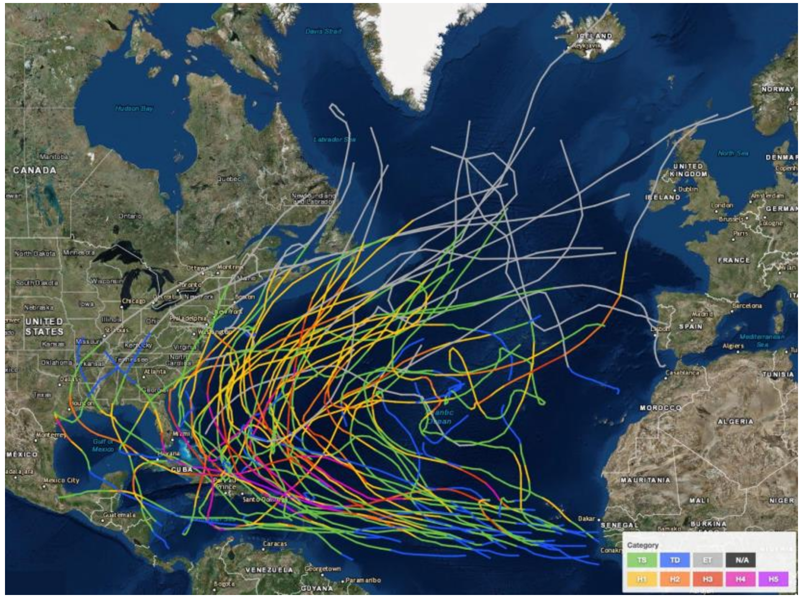


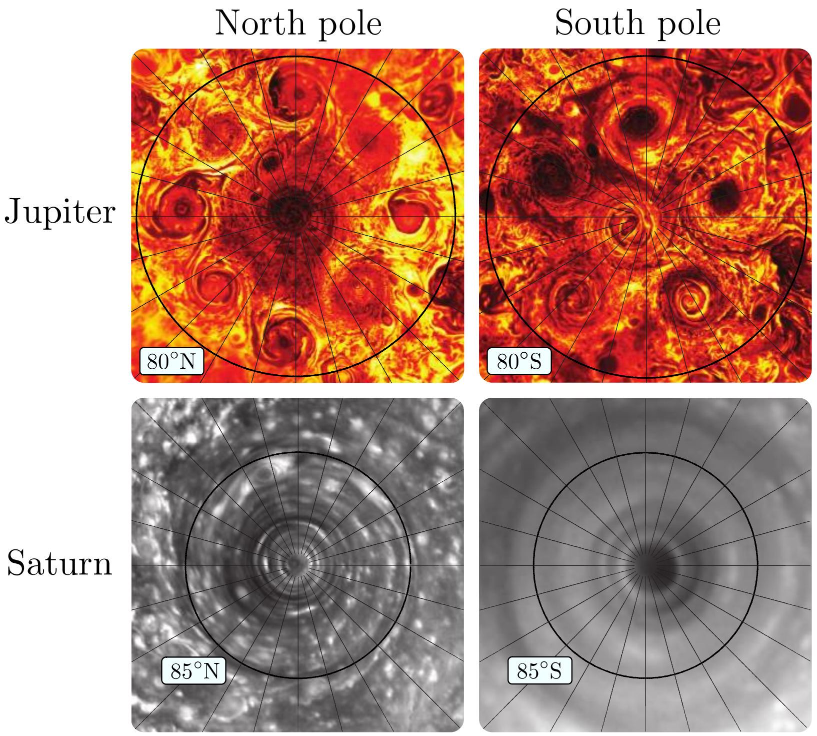
Conservation of barotropic potential vorticity:

$$\frac{D}{Dt}\left(\zeta + 2\Omega \sin\theta\right) = 0$$

Relative vorticity

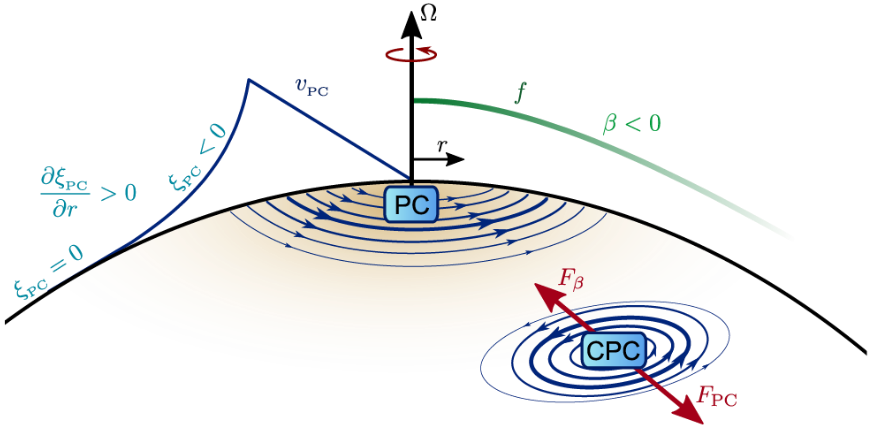
Planetary vorticity

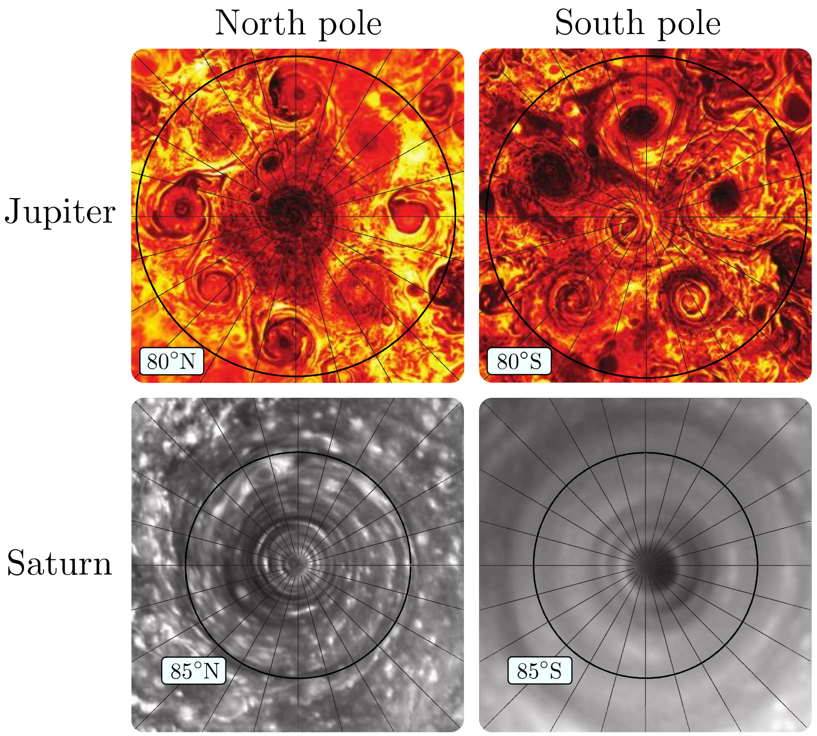




Gavriel and Kaspi, 2021, *Nat. geo*

What sets the stability and location of the circumpolar cyclones?

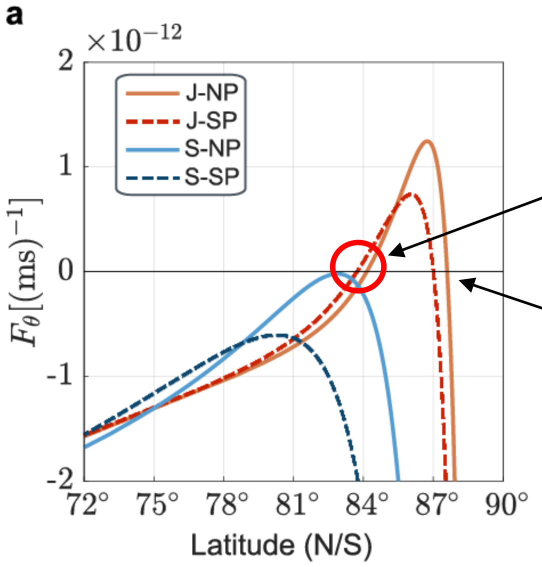




$$F_\theta \equiv \frac{\partial \xi_{PC}}{\partial r} + \beta$$

Polar cyclone vorticity gradient

beta-drift



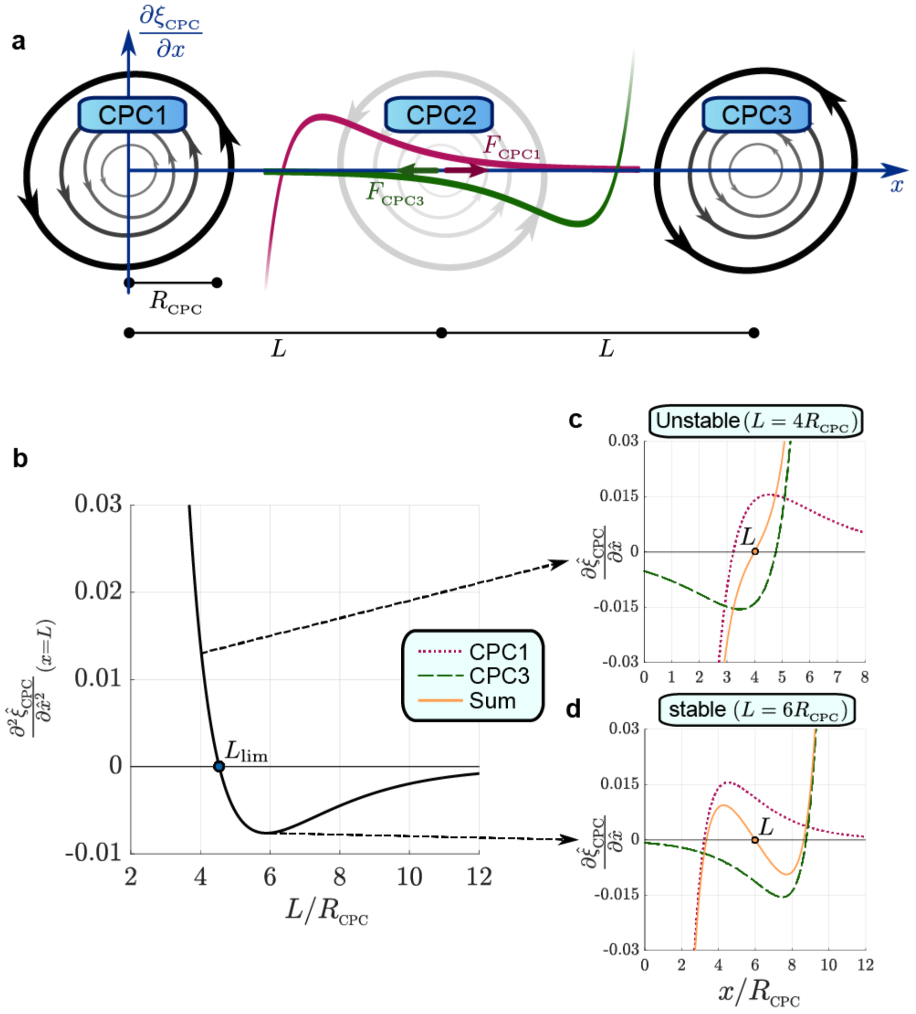
stable equilibrium

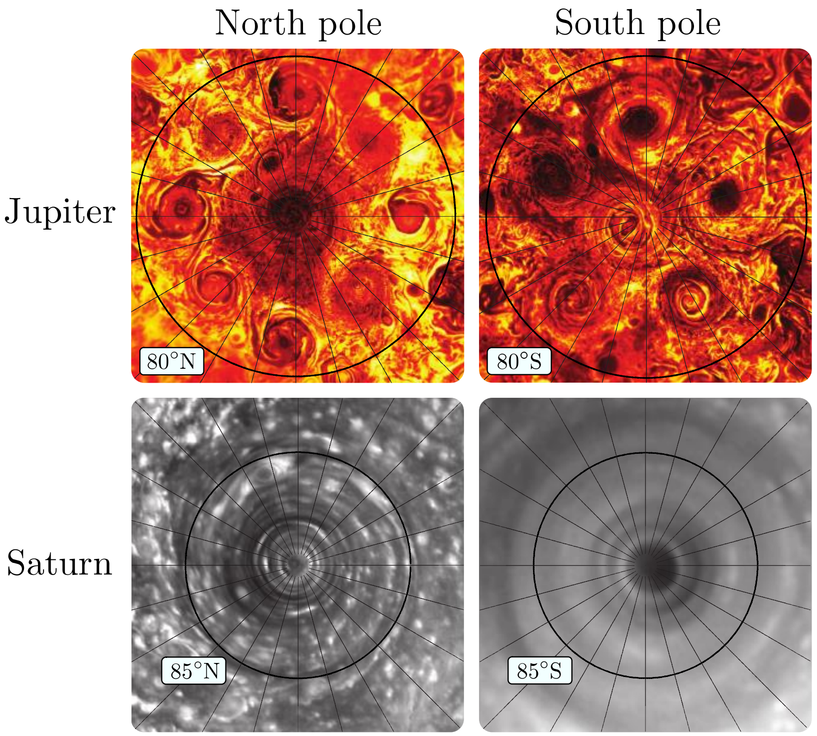
unstable equilibrium

- Saturn has no equilibrium points and thus no circumpolar cyclones
- Jupiter has a stable equilibrium point at 84° N/S setting the location of the circumpolar cyclones

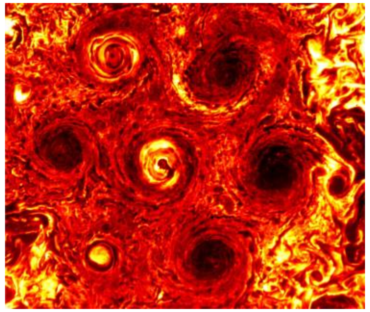
Gavriel and Kaspi, 2021, *Nat. geo*

What sets the stability and location of the circumpolar cyclones?





South pole in PJ22

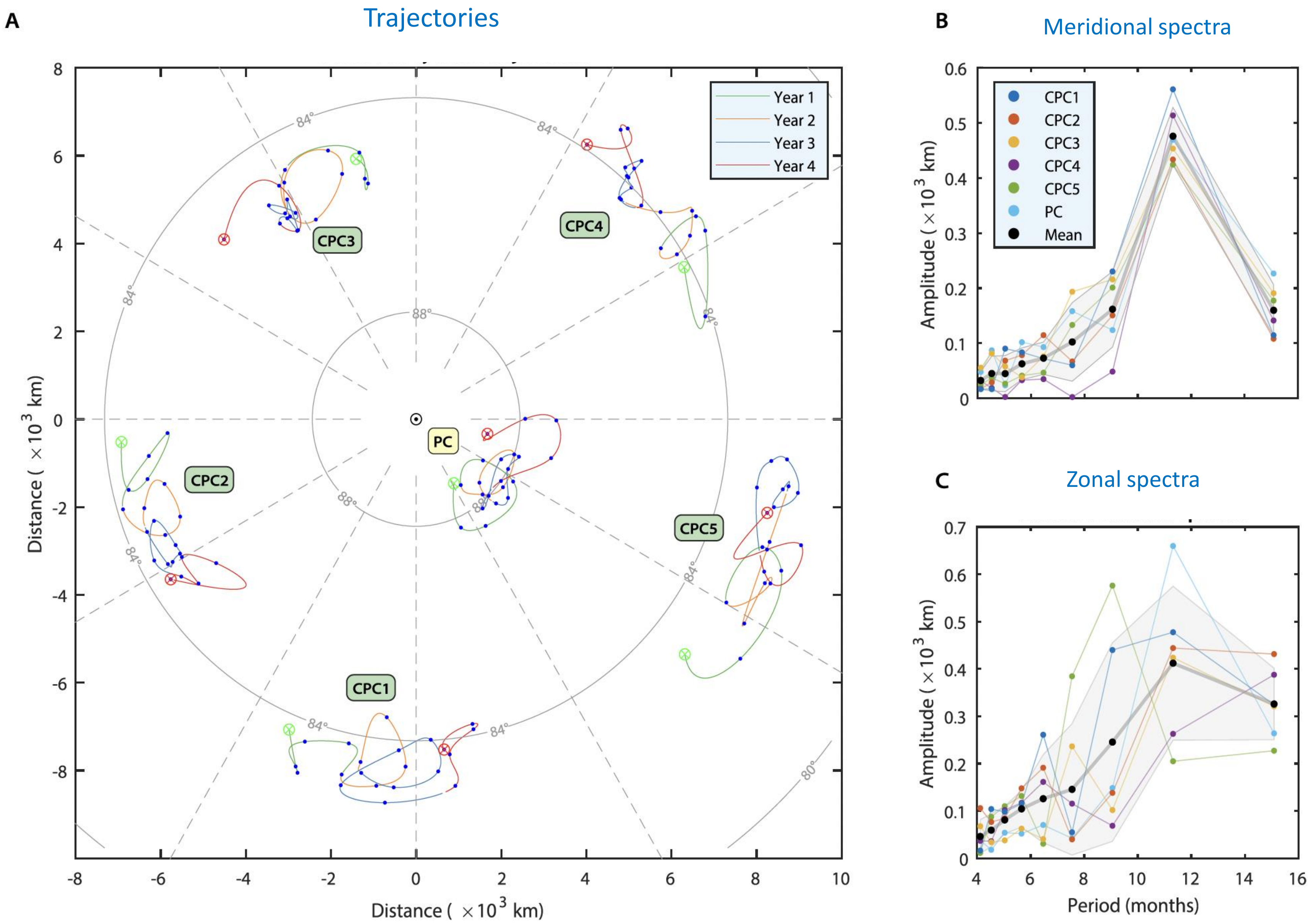


- Saturn has no equilibrium points and thus no circumpolar cyclones
- Jupiter has a stable equilibrium point at 84° N/S setting the location of the circumpolar cyclones

Stability analysis of a ring of cyclones reveals a maximum of 8 vortices in the north pole and 5-6 in the south pole.

Gavriel and Kaspi, 2021, *Nat. geo*

The circumpolar cyclones' temporal oscillations



Gavriel and Kaspi, 2022, *GRL*

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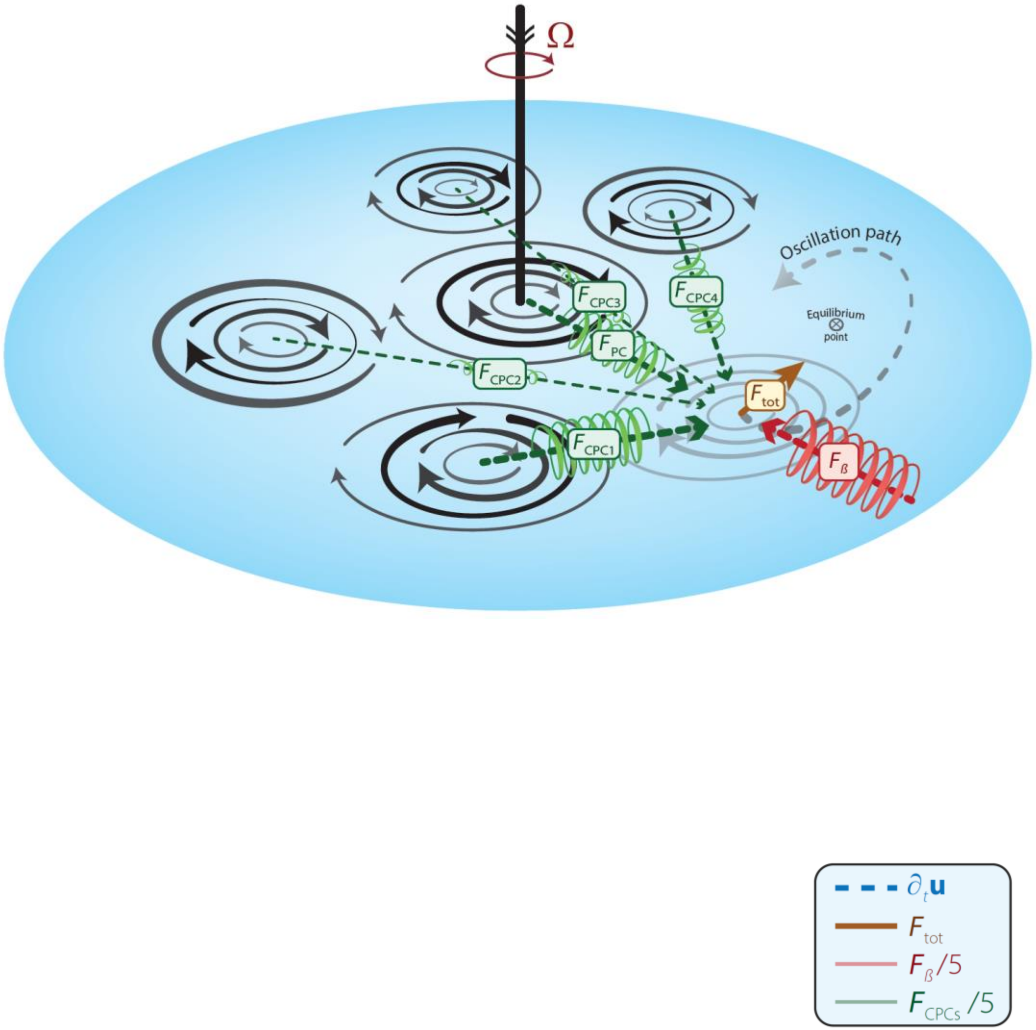
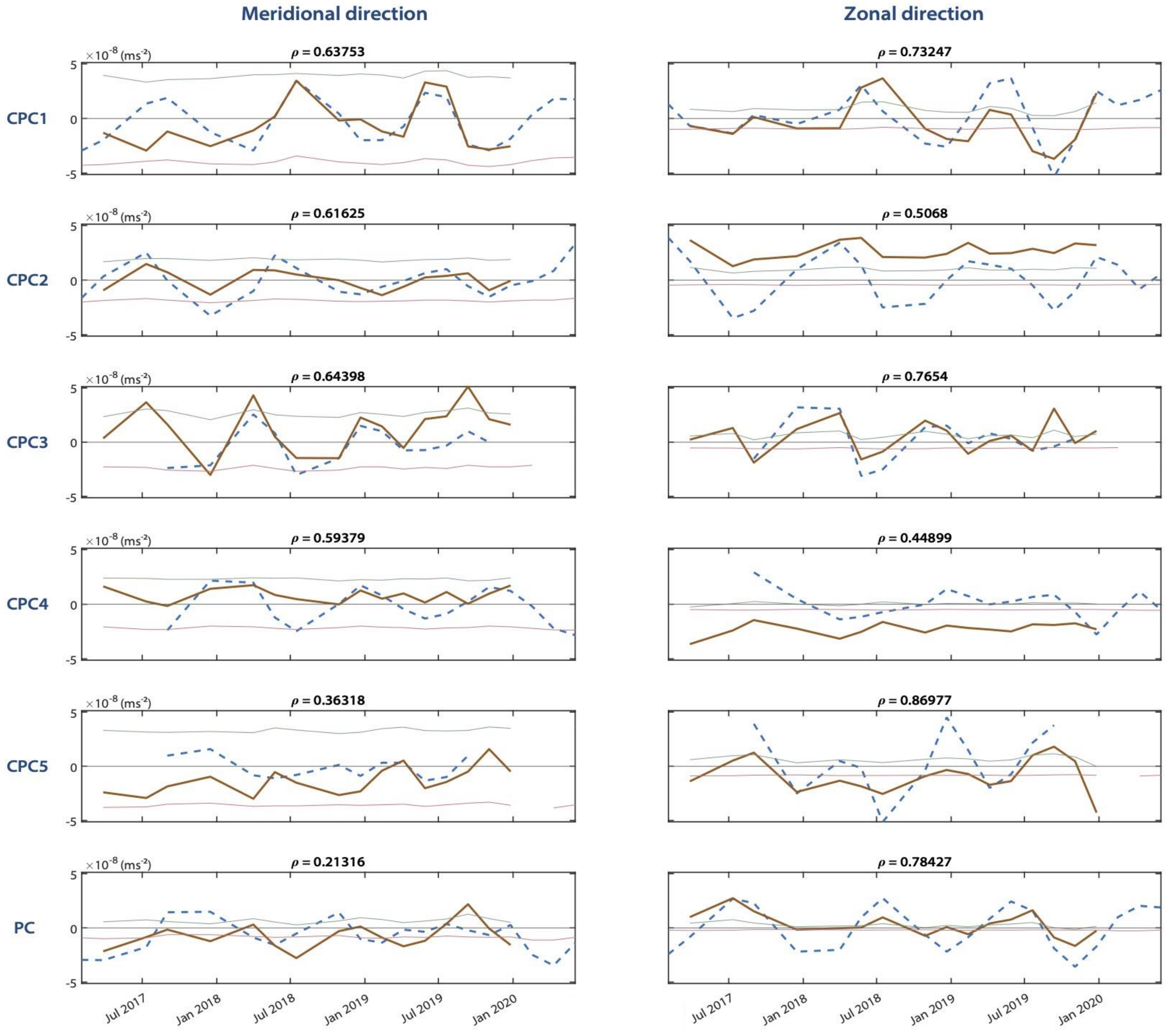
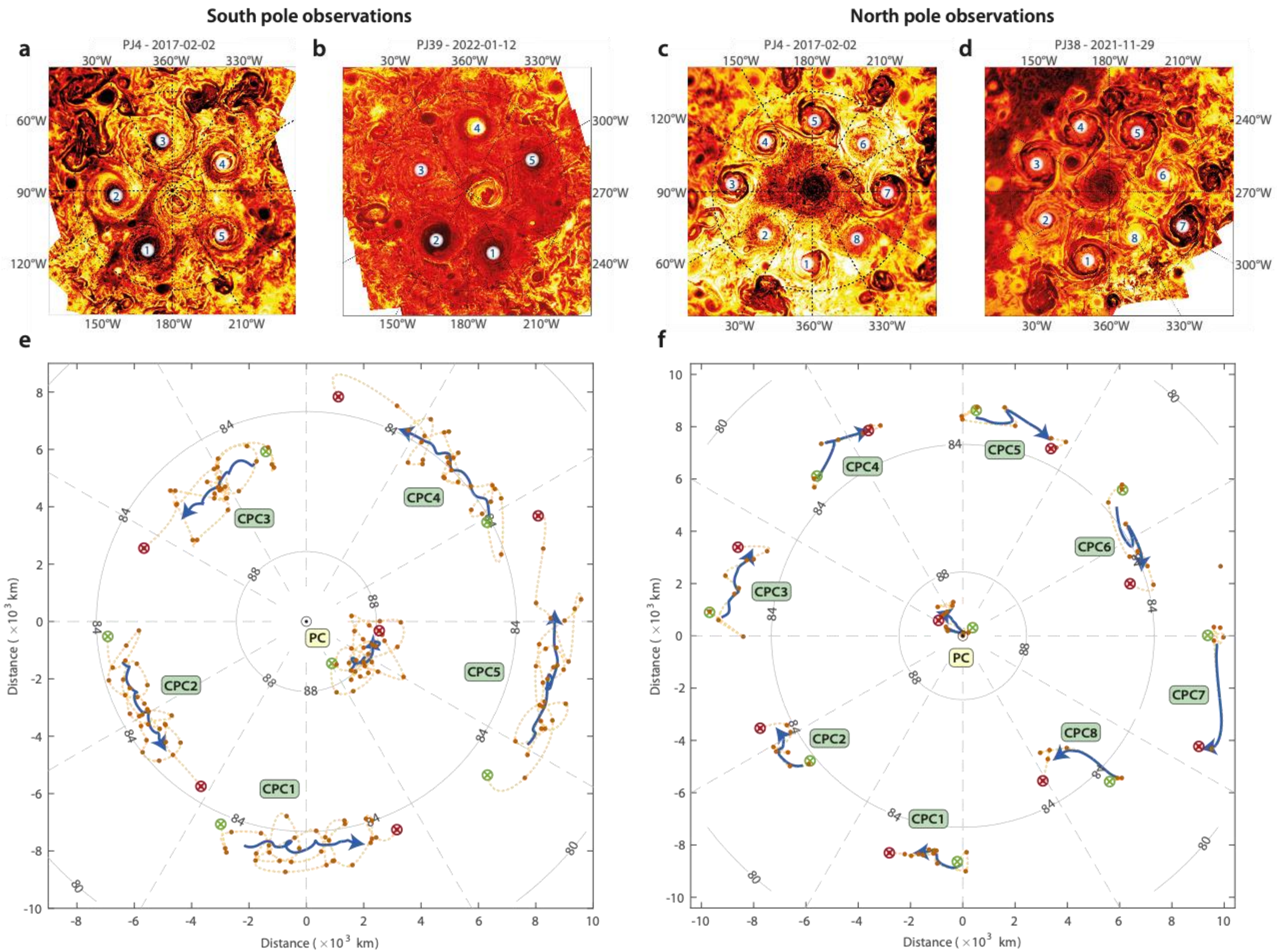


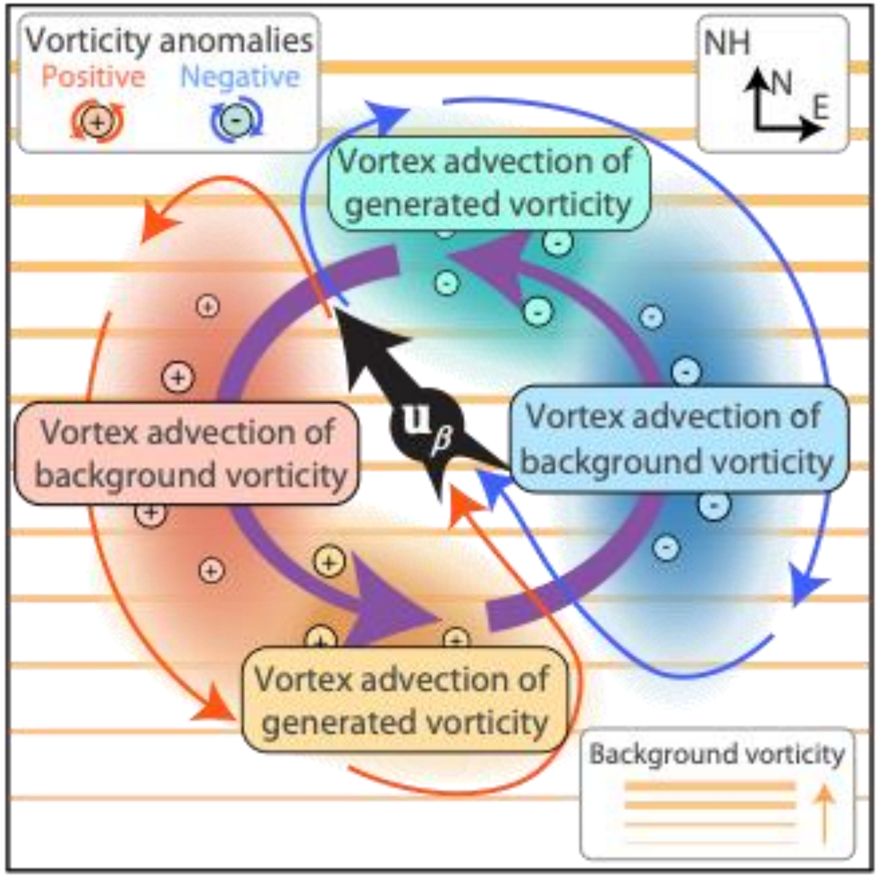


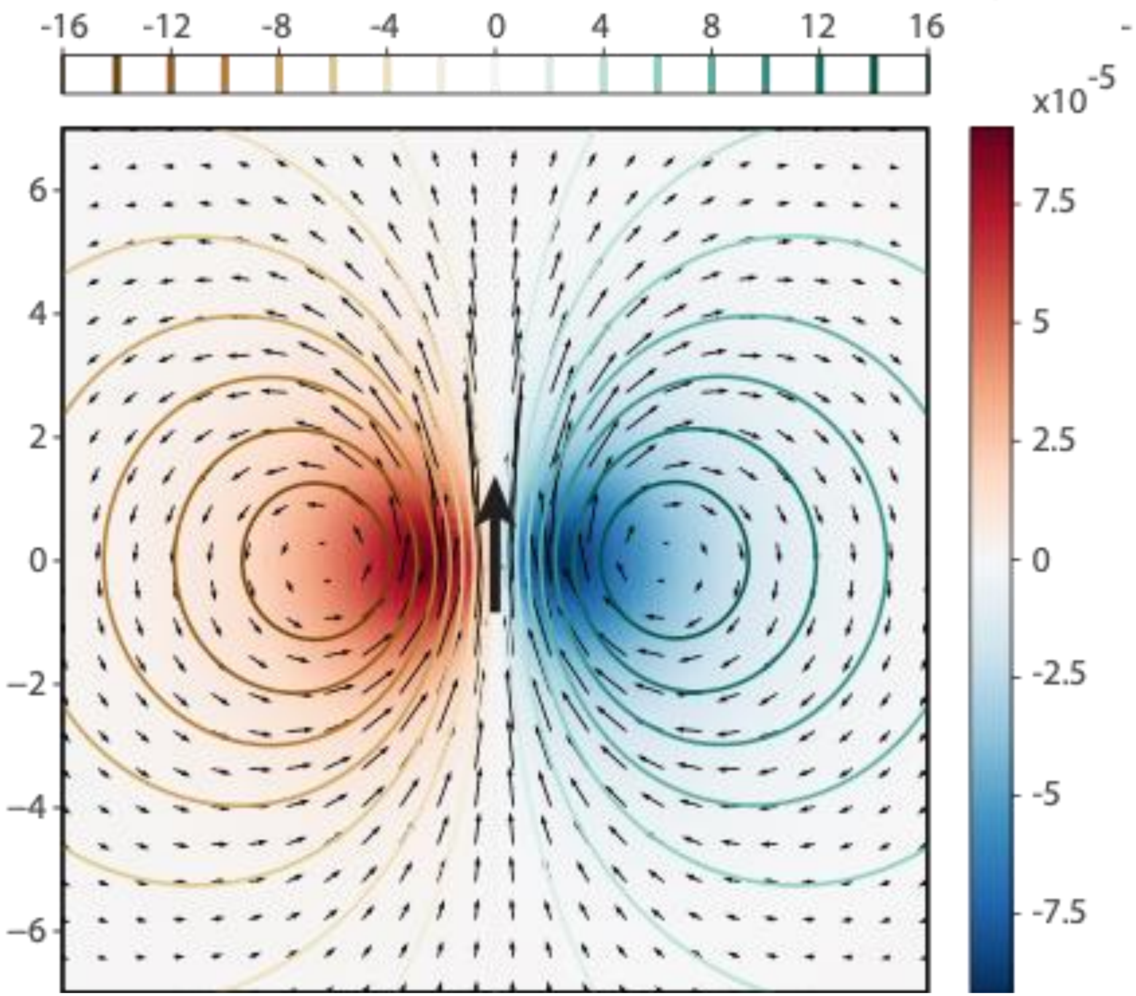
Gavriel and Kaspi, 2022, *GRL*

The circumpolar cyclones' westward drift



The beta-drift secondary circulation





Gavriel and Kaspi, *GRL, 2023*

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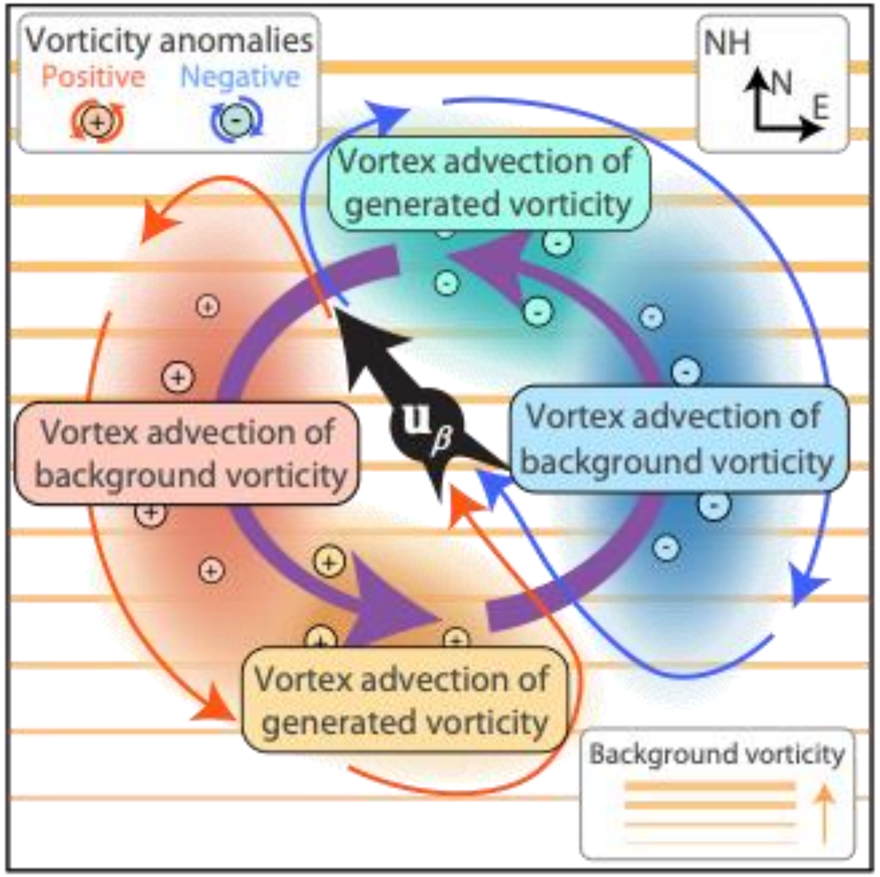
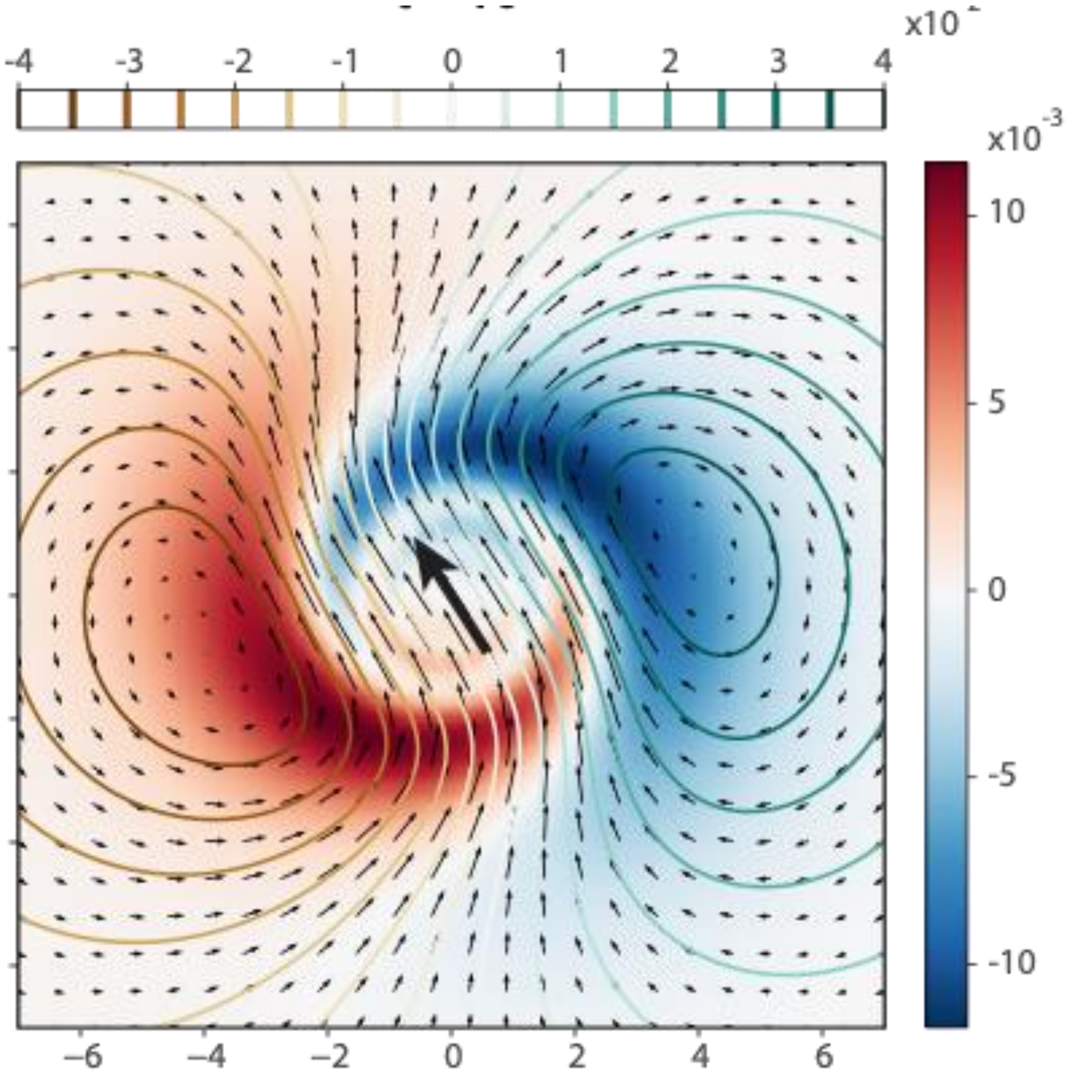
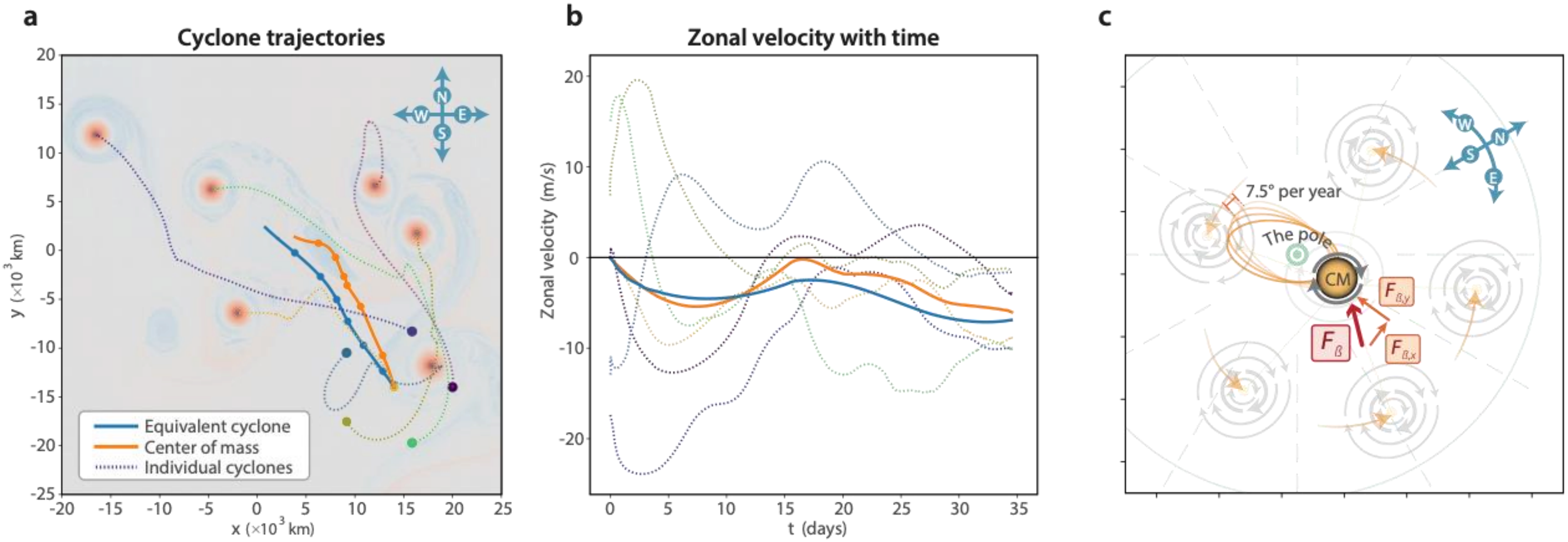




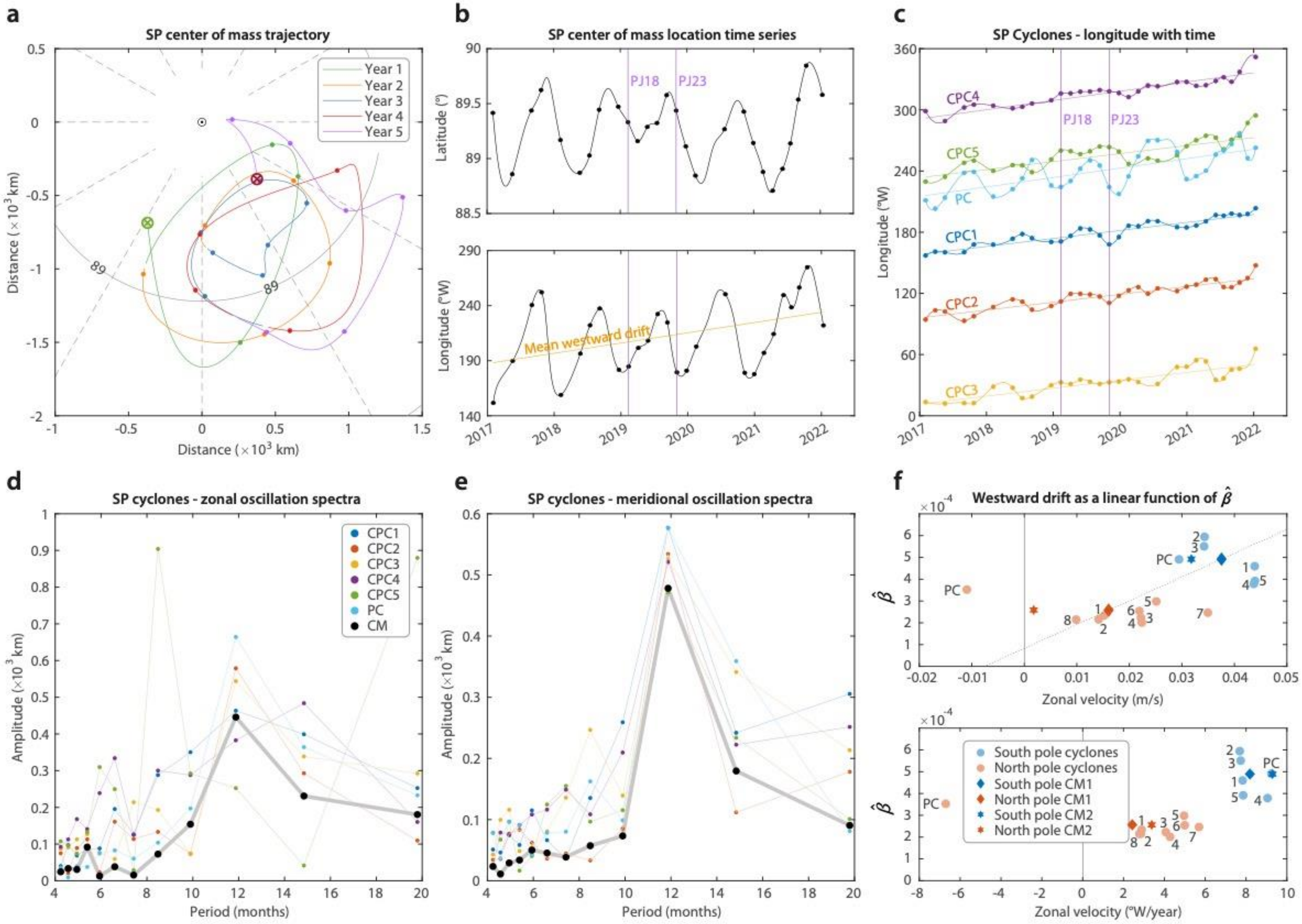
Gavriel and Kaspi, *GRL, 2023*

Center of mass approach



Beta-plane simulation demosntreating the westward drift

Gavriel and Kaspi, *GRL, 2023*



Gavriel and Kaspi, *GRL, 2023*

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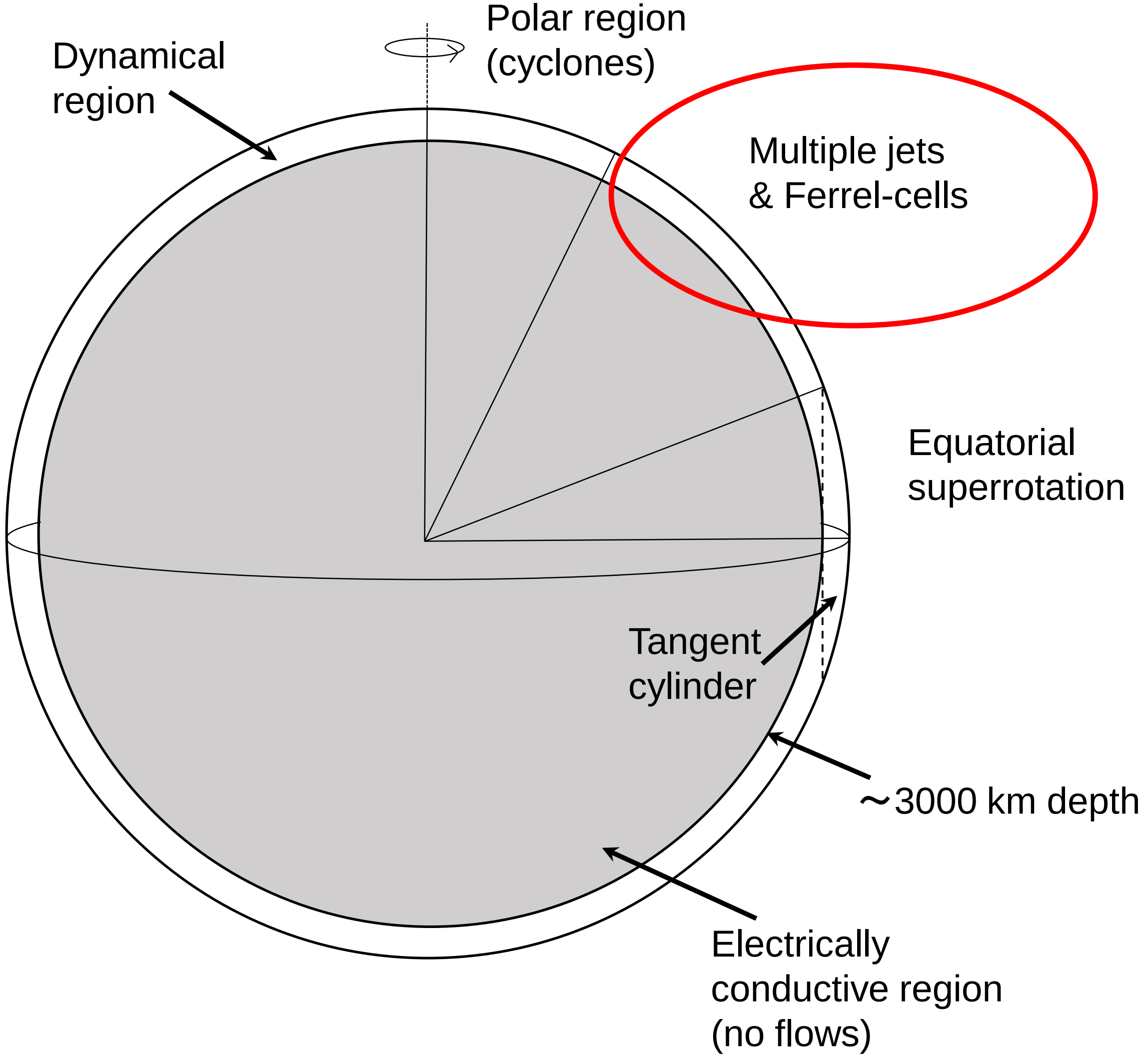
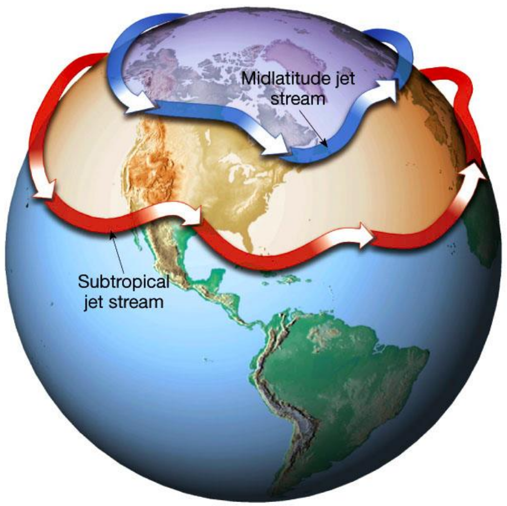
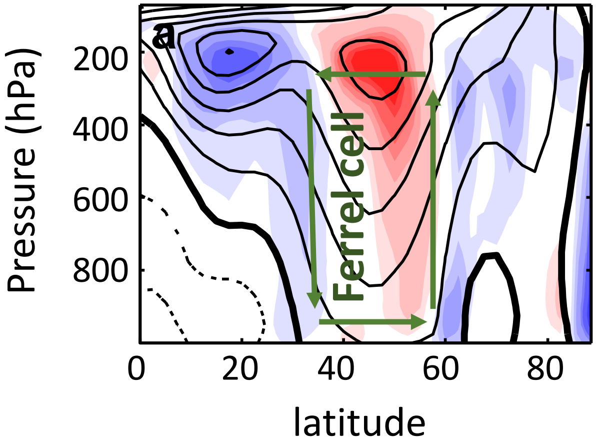


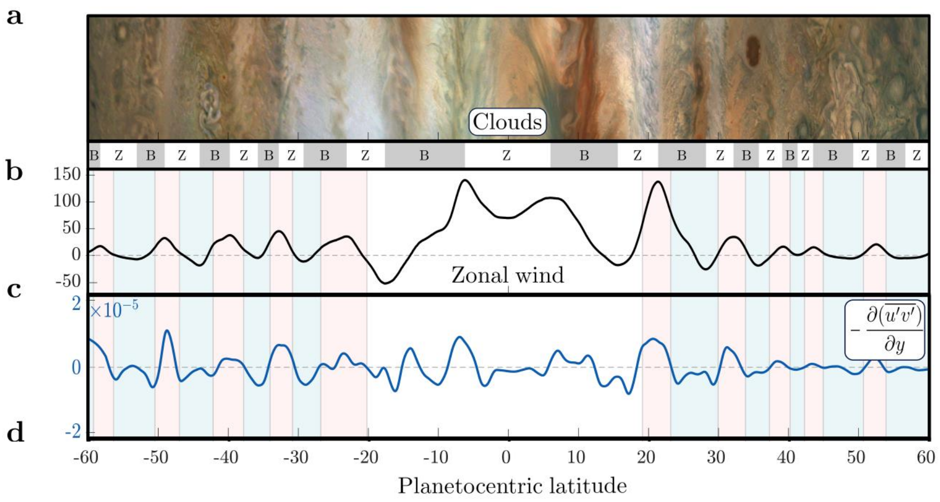
The midlatitude jet-streams

- Eastward jets are driven by a momentum flux convergence
- Westward jets are driven by a momentum flux divergence





Earth's Northern Hemisphere zonal wind (contour) and momentum flux convergence (color).



after Salyk et al., 2006

$$-f\bar{v} = -\frac{\partial\left(\overline{u'v'}\right)}{\partial y}$$

Coriolis parameter

Meridional velocity

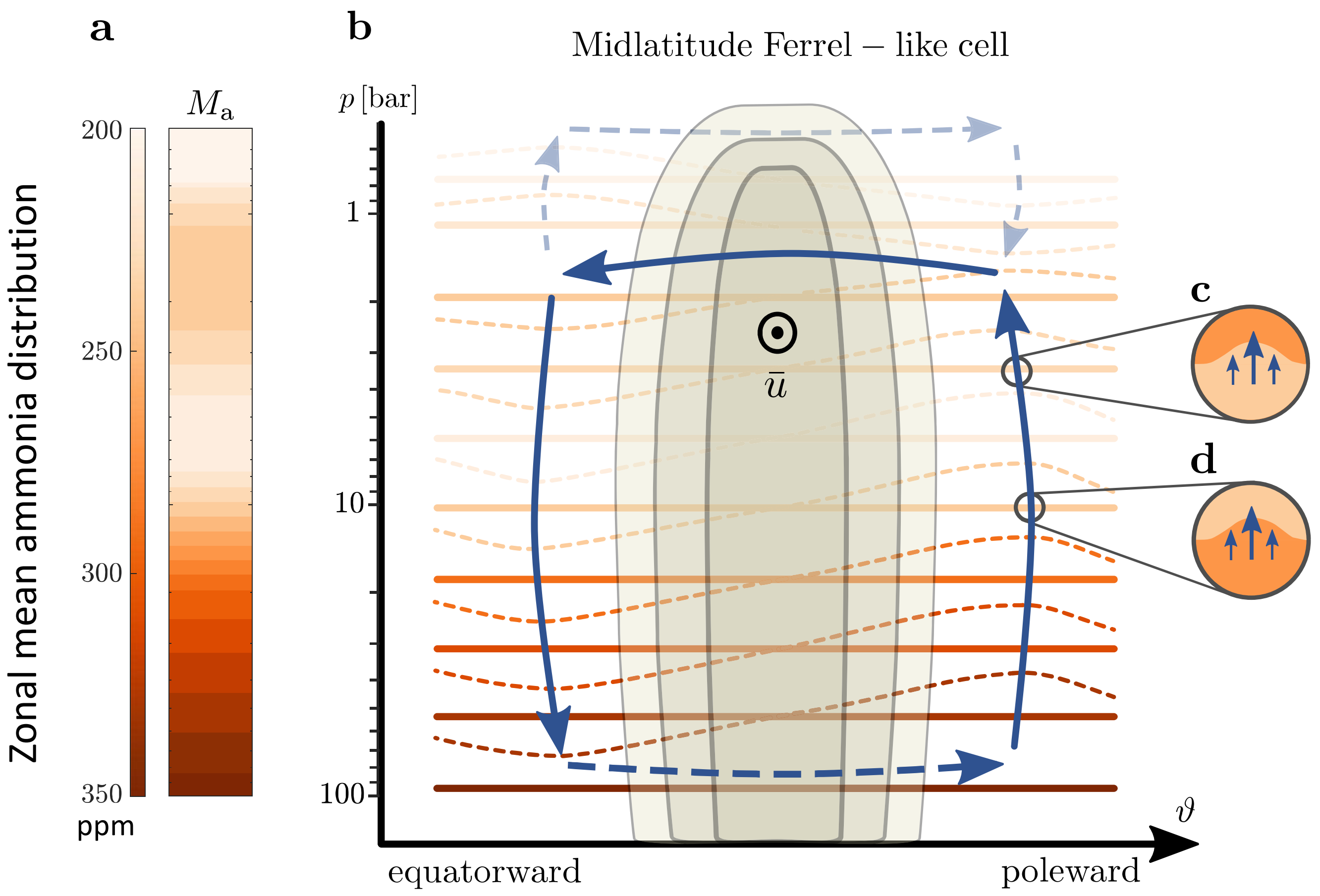
Momentum flux convergence

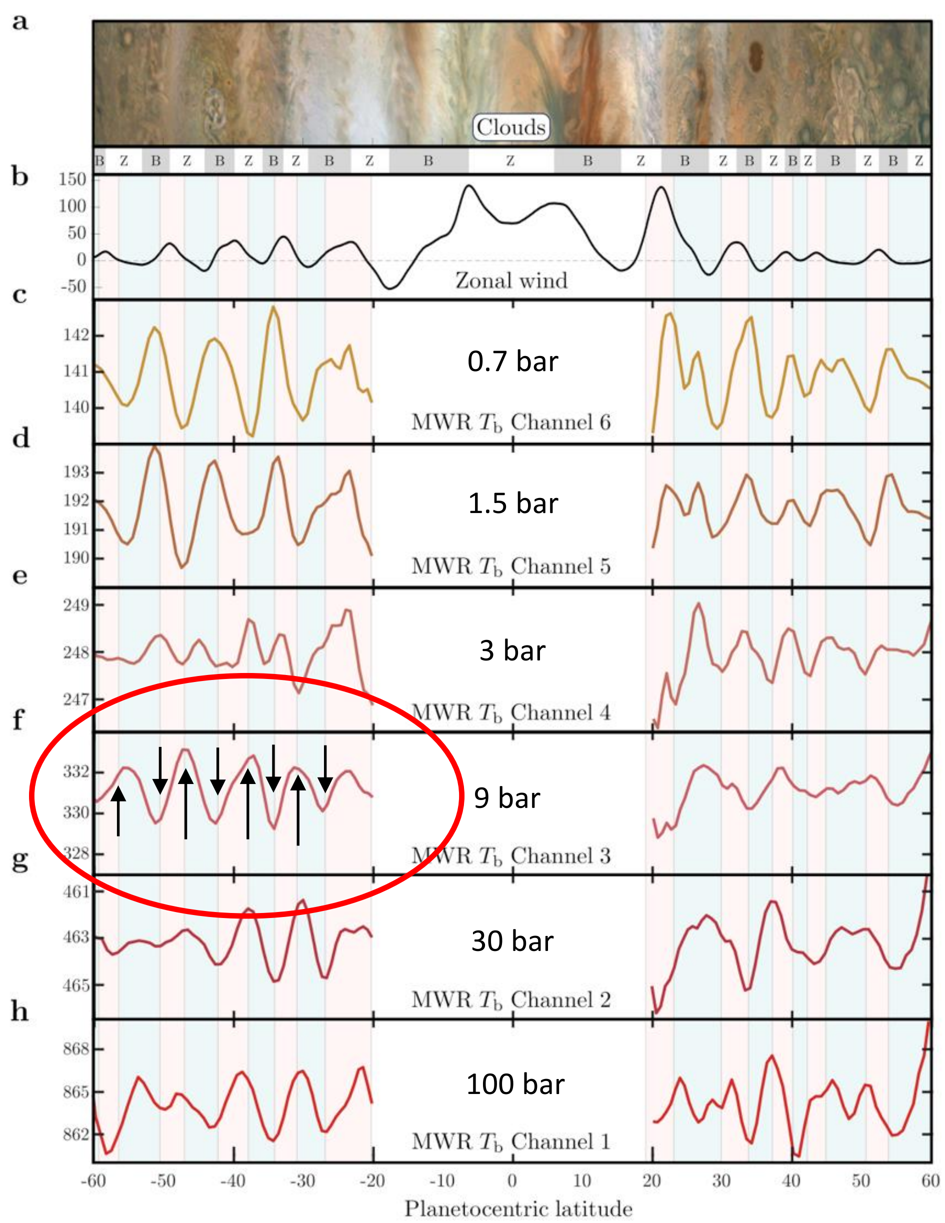
Earth has one Ferrel cell in each hemisphere, containing one (eddy driven) jet.

Can we identify such Ferrel cells on Jupiter?

The midlatitude jet-streams

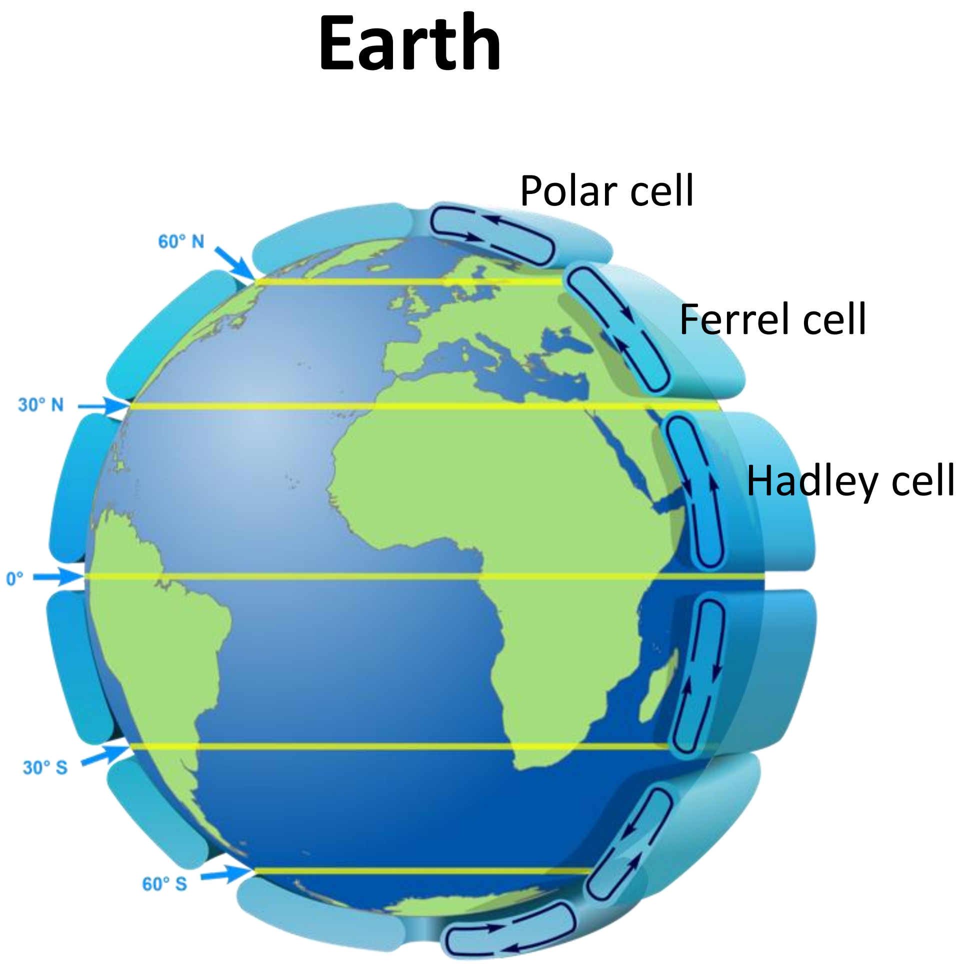
- Eastward jets are driven by a momentum flux convergence
- Westward jets are driven by a momentum flux divergence

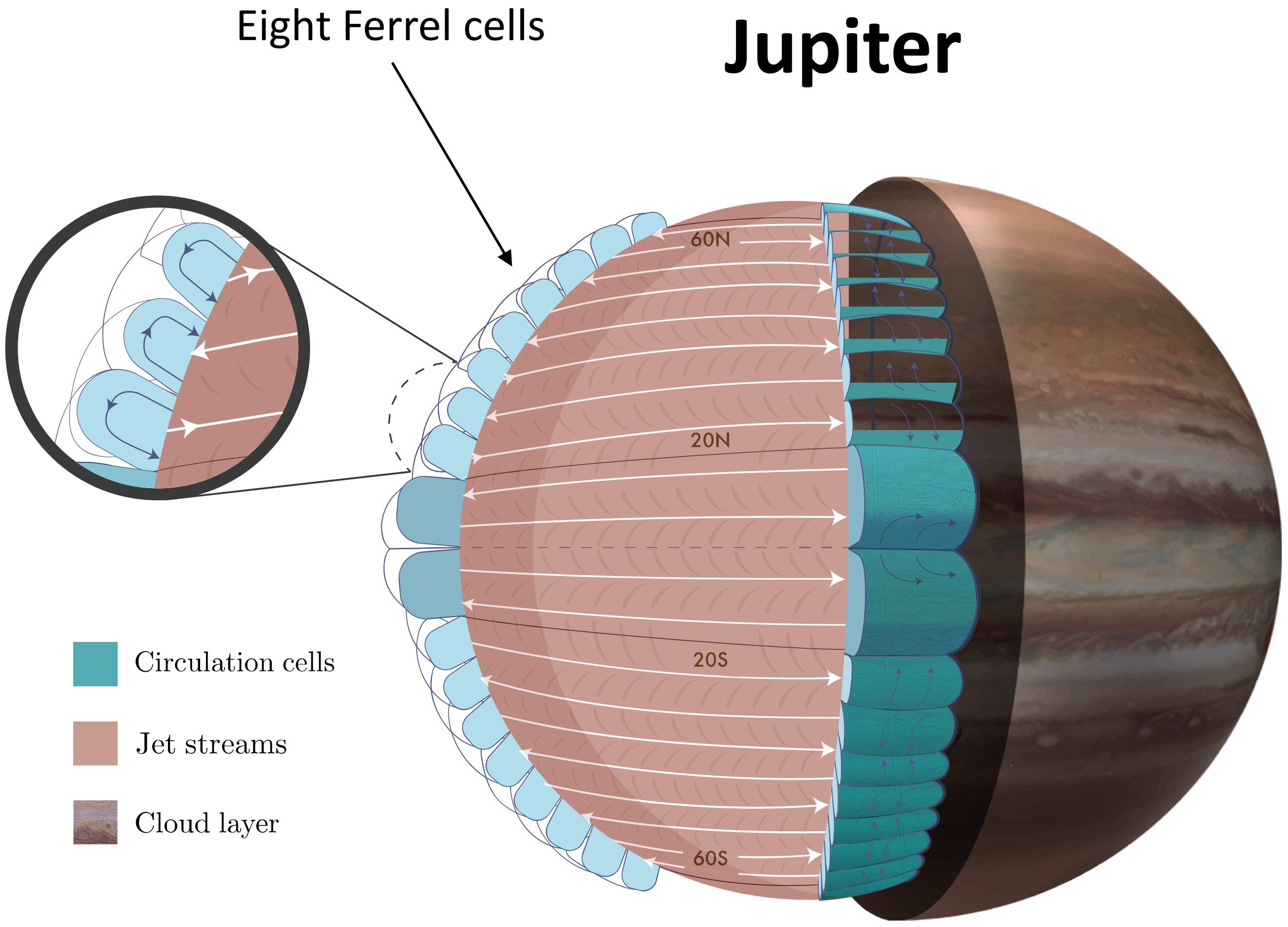


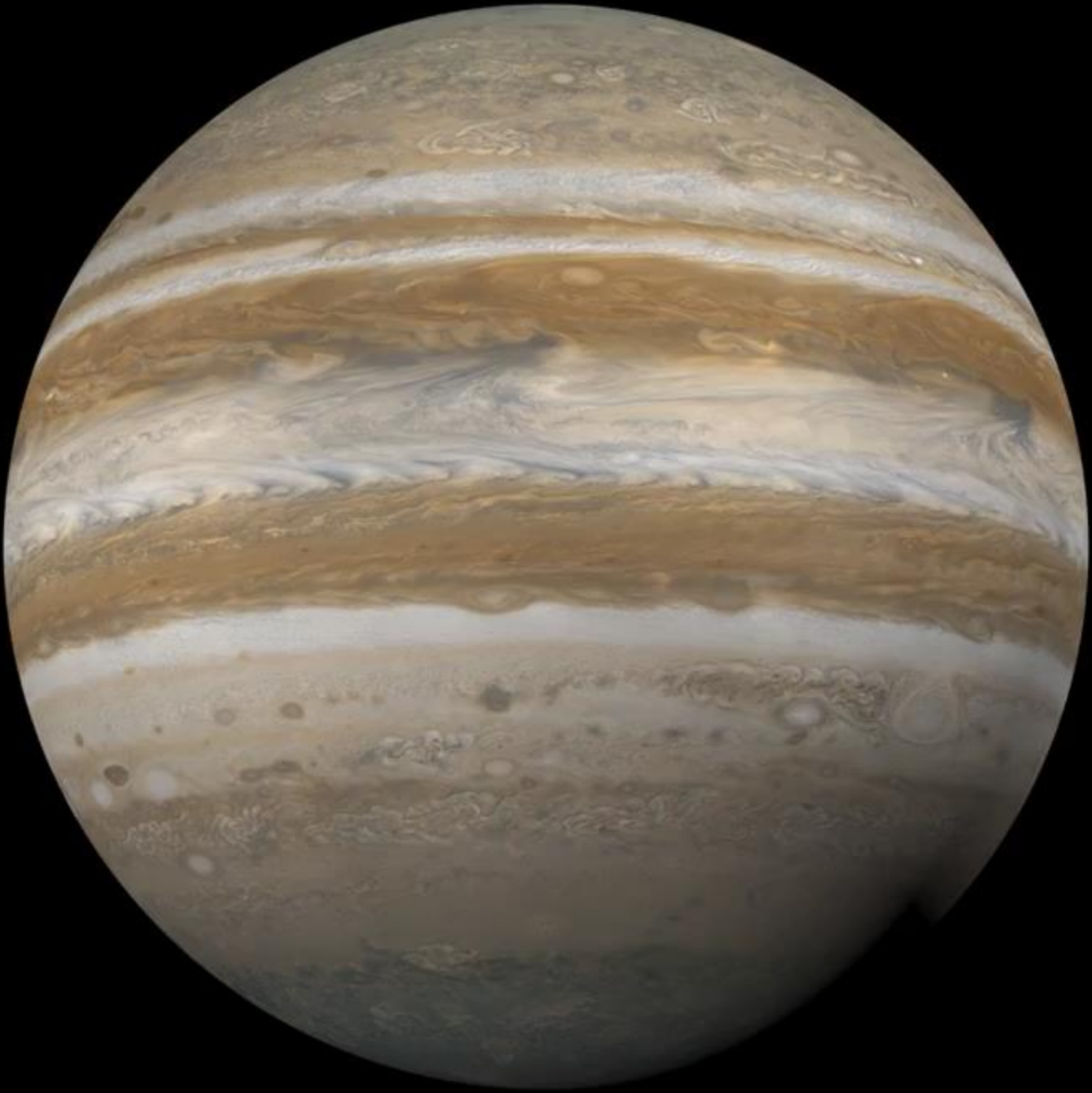


Duer, Gavriel et al., 2021, GRL

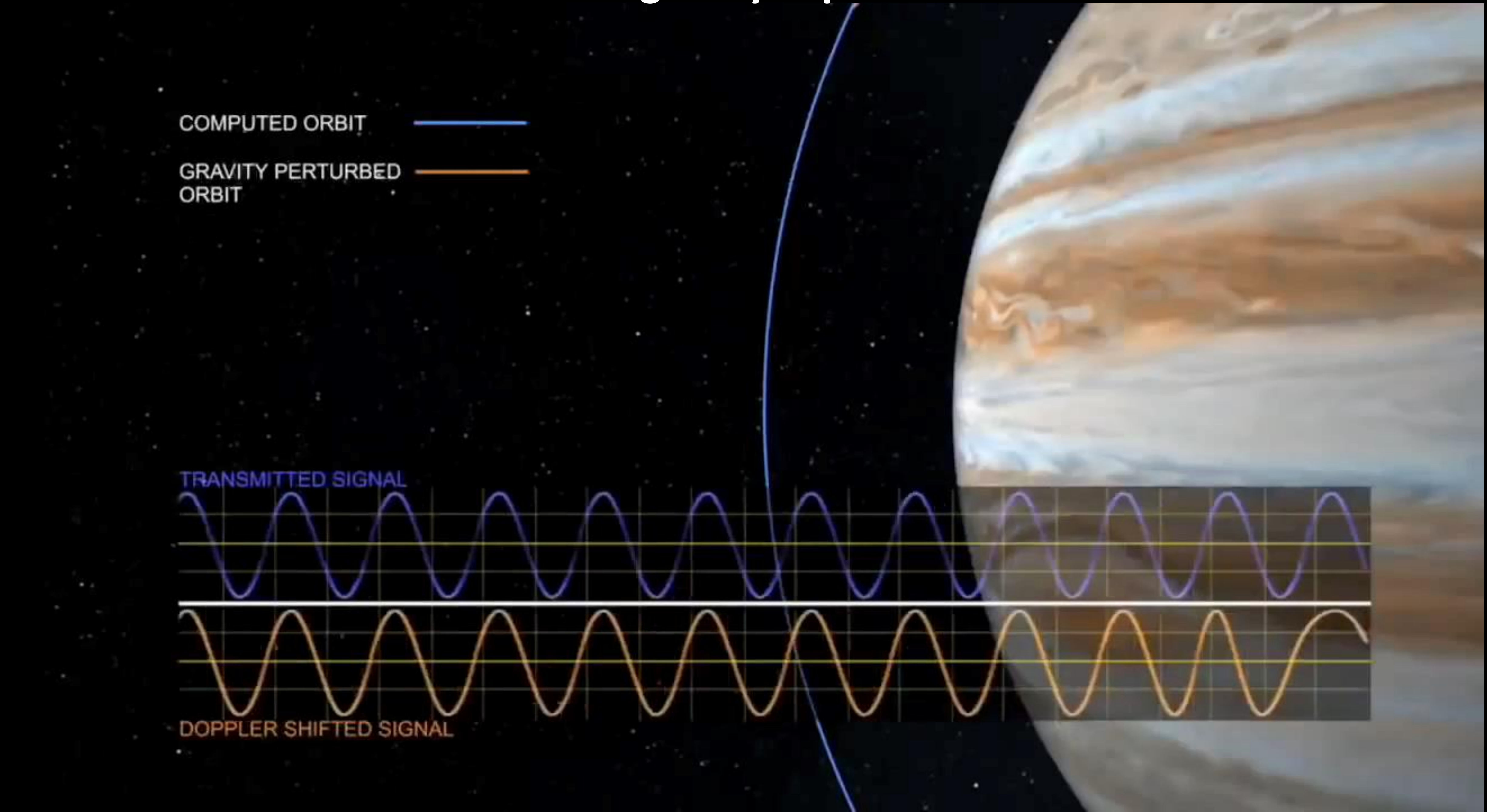
Multiple Ferrel cells on Jupiter







The Juno gravity experiment



The measured gravity field

Zonal gravity harmonics:

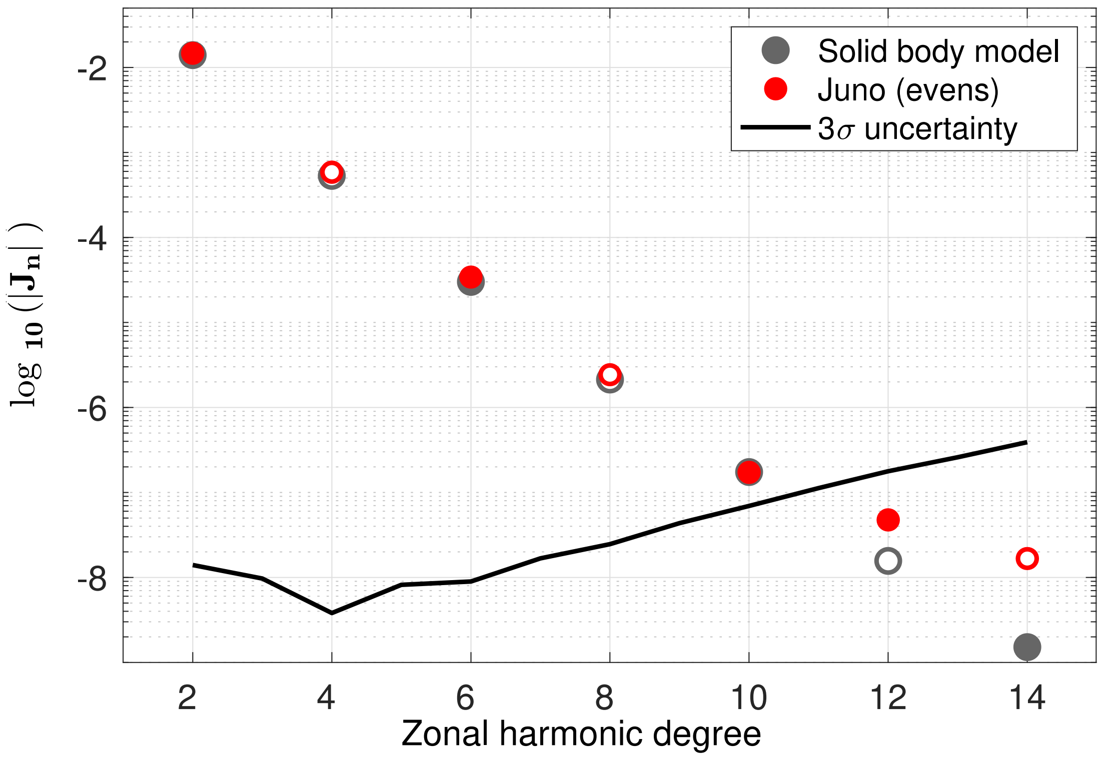
$$J_n = -\frac{1}{a^n M} \int r^n P_n(\theta)\, \rho(r,\theta)\, d^3 r$$

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

Density has 2 components:

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

Rigid body   Dynamics



- Even gravity harmonics are close to the rigid body prediction.

Iess et al., 2018, *Nature*

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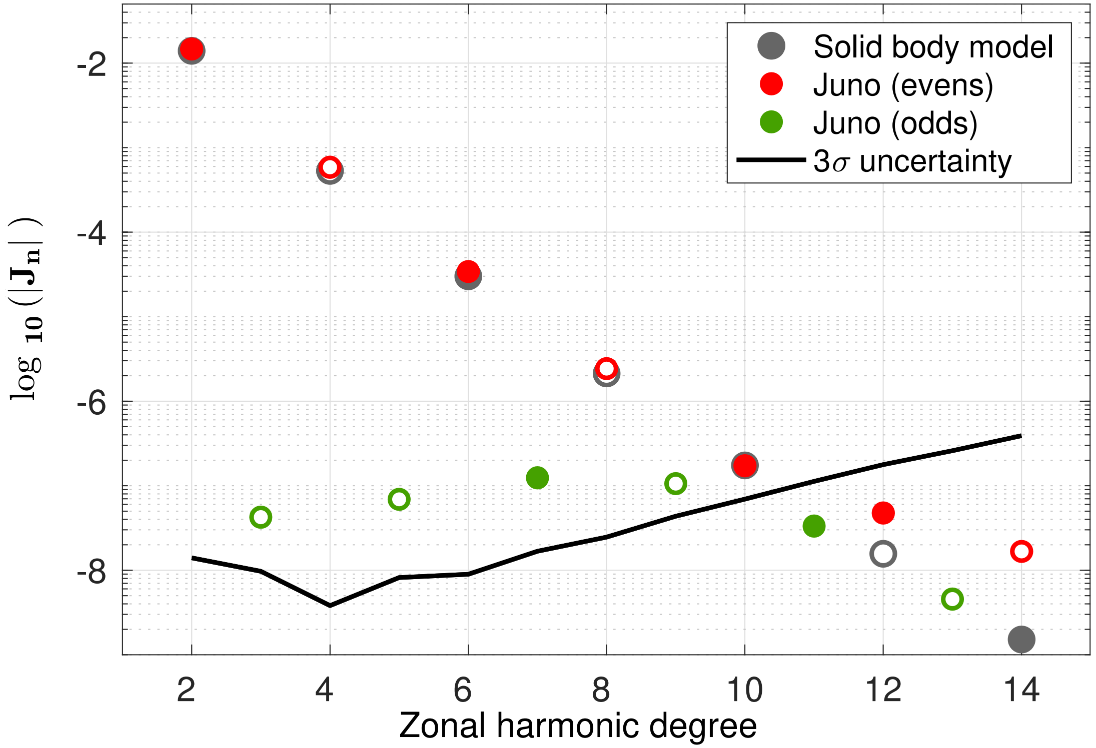
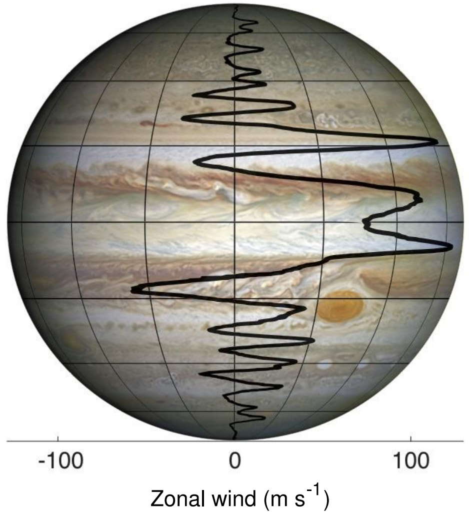
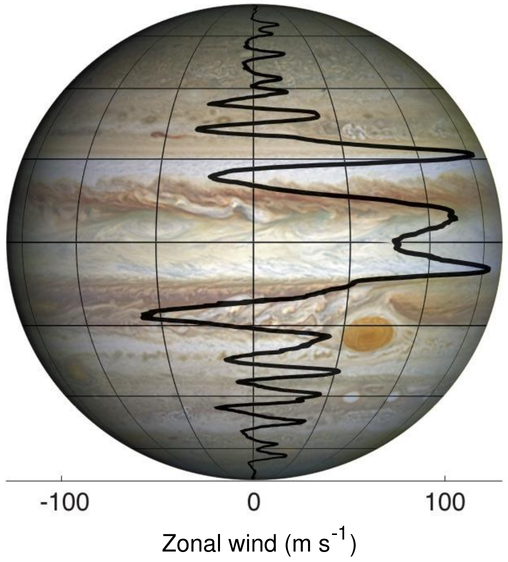




- Even gravity harmonics are close to the rigid body prediction.
- Odd harmonics are large and must be a pure signature of dynamics.

Iess et al., 2018, *Nature*

The dynamical gravity signature

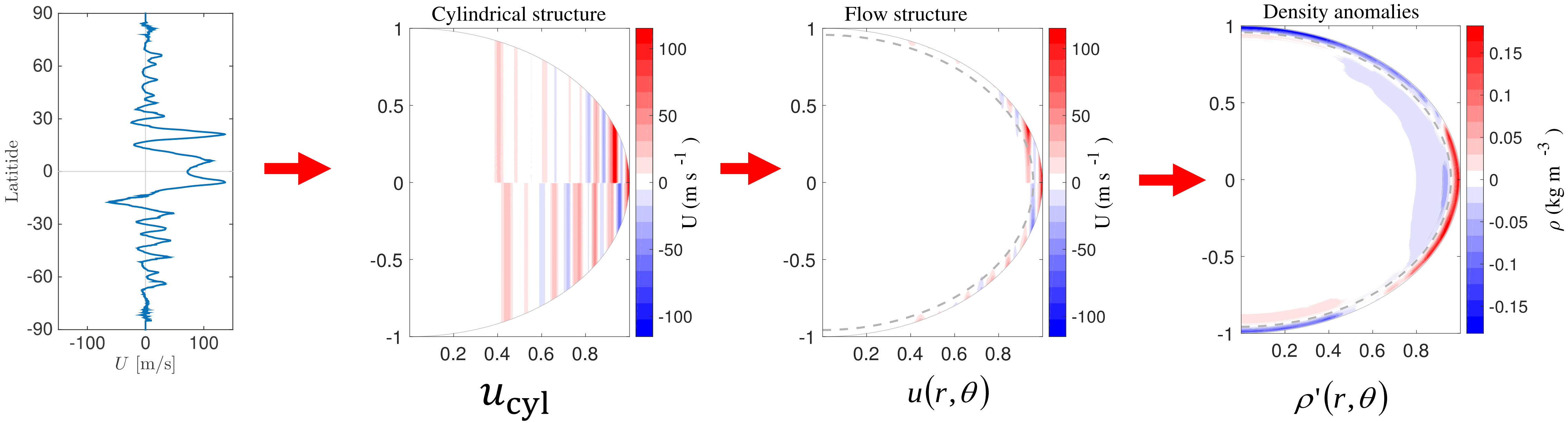


- Use the observed winds at the cloud level and extend them inward on cylinders.

- Use thermal wind balance to relate between the flow and the density anomalies (gravity signal): $2\Omega \cdot \nabla(\bar{\rho}\vec{u}) = \nabla\rho' \times \vec{g}_0$

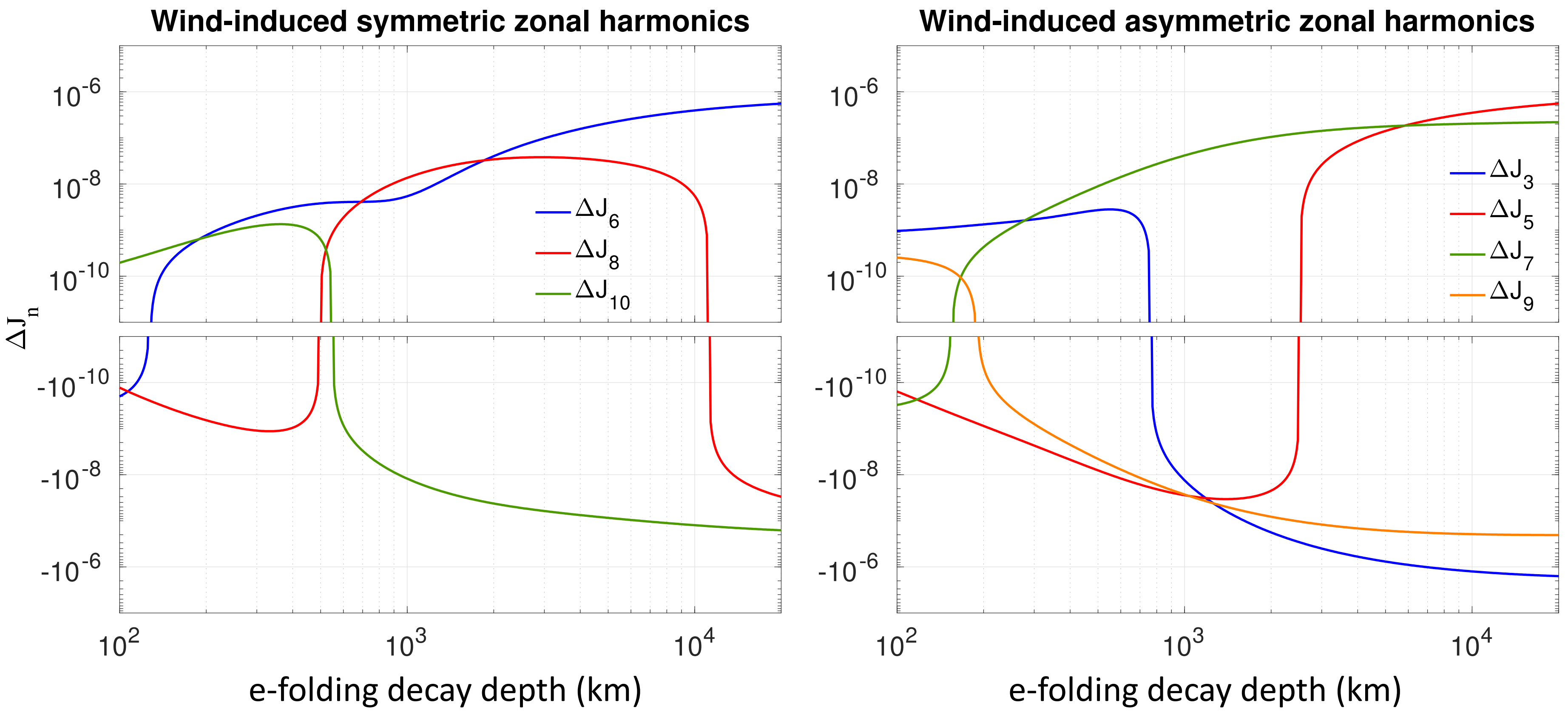
$$u = u_{\mathrm{cyl}} e^{-\left(\frac{a-r}{H}\right)}$$

Thermal wind balance



Gravity harmonics resulting from extension inward of the cloud-level winds

- Assuming an e-folding depth for the cloud level winds
- Relating the wind profile to the density anomaly through thermal wind balance
- Using the dynamical density to calculate the gravity harmonics $J_n = -\frac{1}{a^n M}\int r^n P_n(\theta)\,\rho(r,\theta)\,d^3r$



Kaspi, 2013, *GRL*

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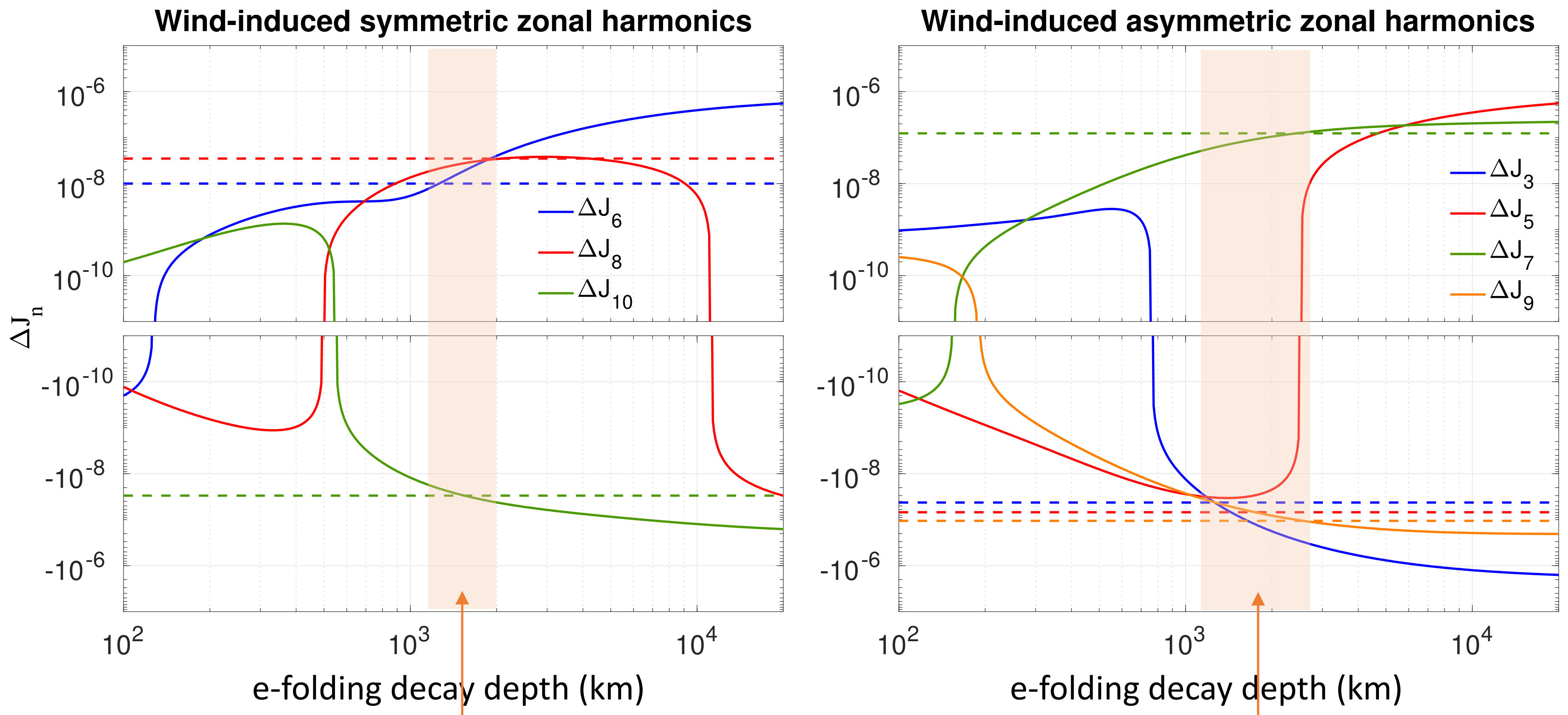


Even with a simple model, a specific depth range of 1,000-3,000 km is identified.

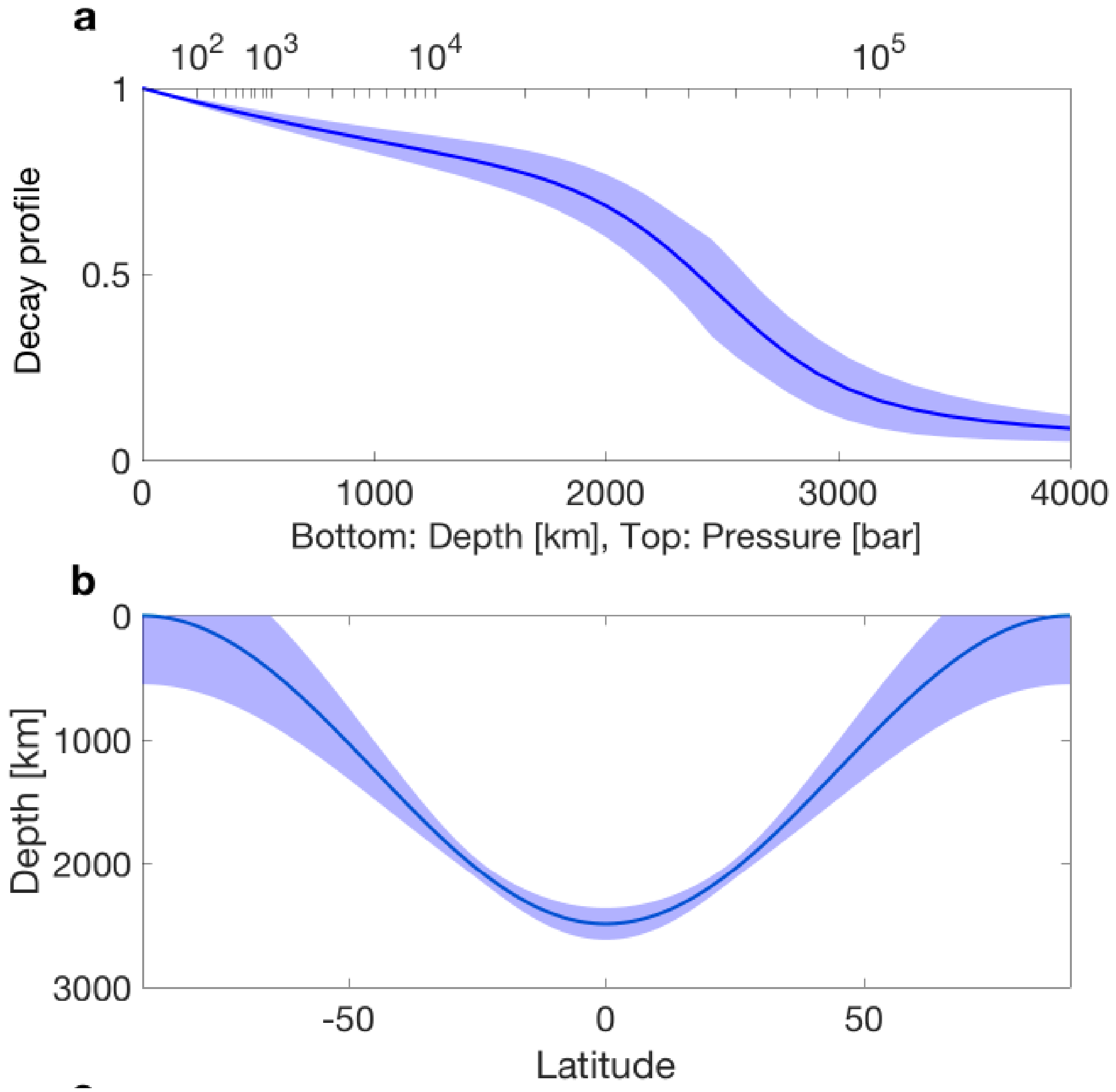
Kaspi et al., 2018, *Nature*

The vertical and meridional structure of the flow

Allowing also the depth of the flow to vary with depth, and optimizing for the vertical profile:

Vertical profile at the equator

Latitudinal profile of the mid point depth



Kaspi et al., 2018
Galanti and Kaspi, 2021

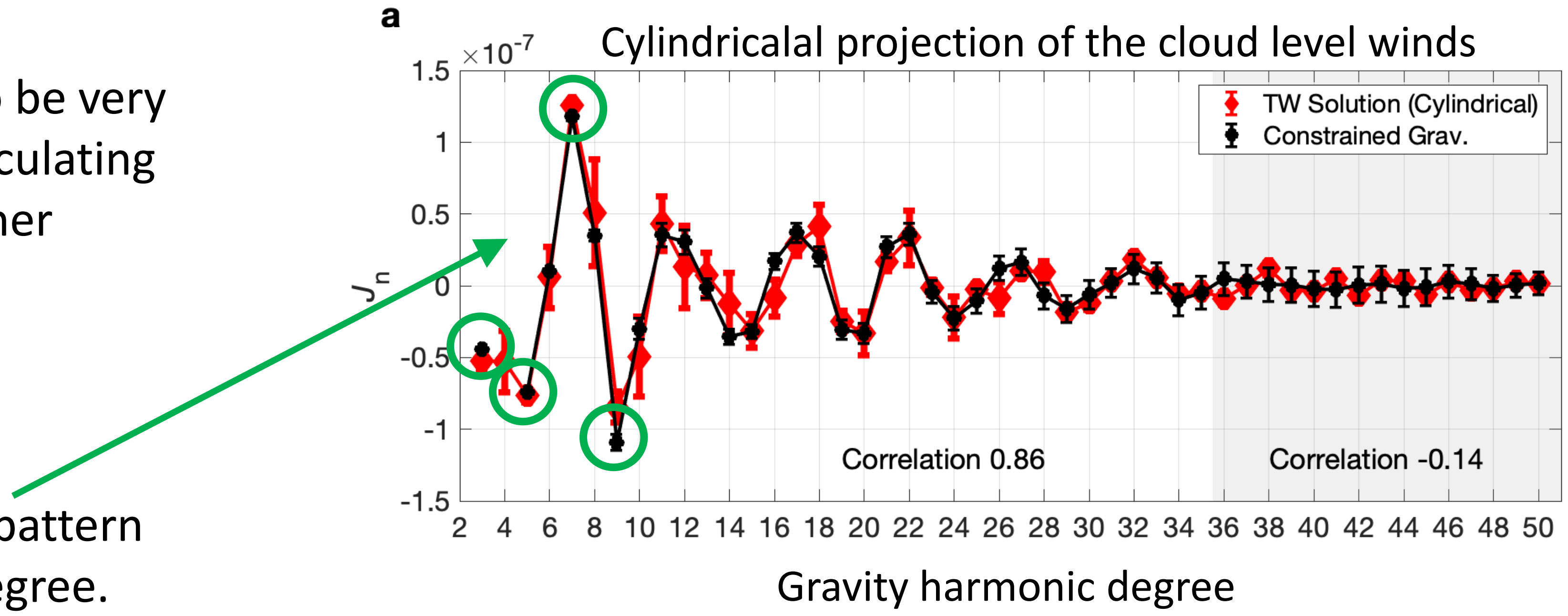
The high-degree gravity harmonics

- Constraining the gravity solution to be very small towards the poles, allows calculating the gravity harmonics to much higher degree.

- High correlation all the way to J35.

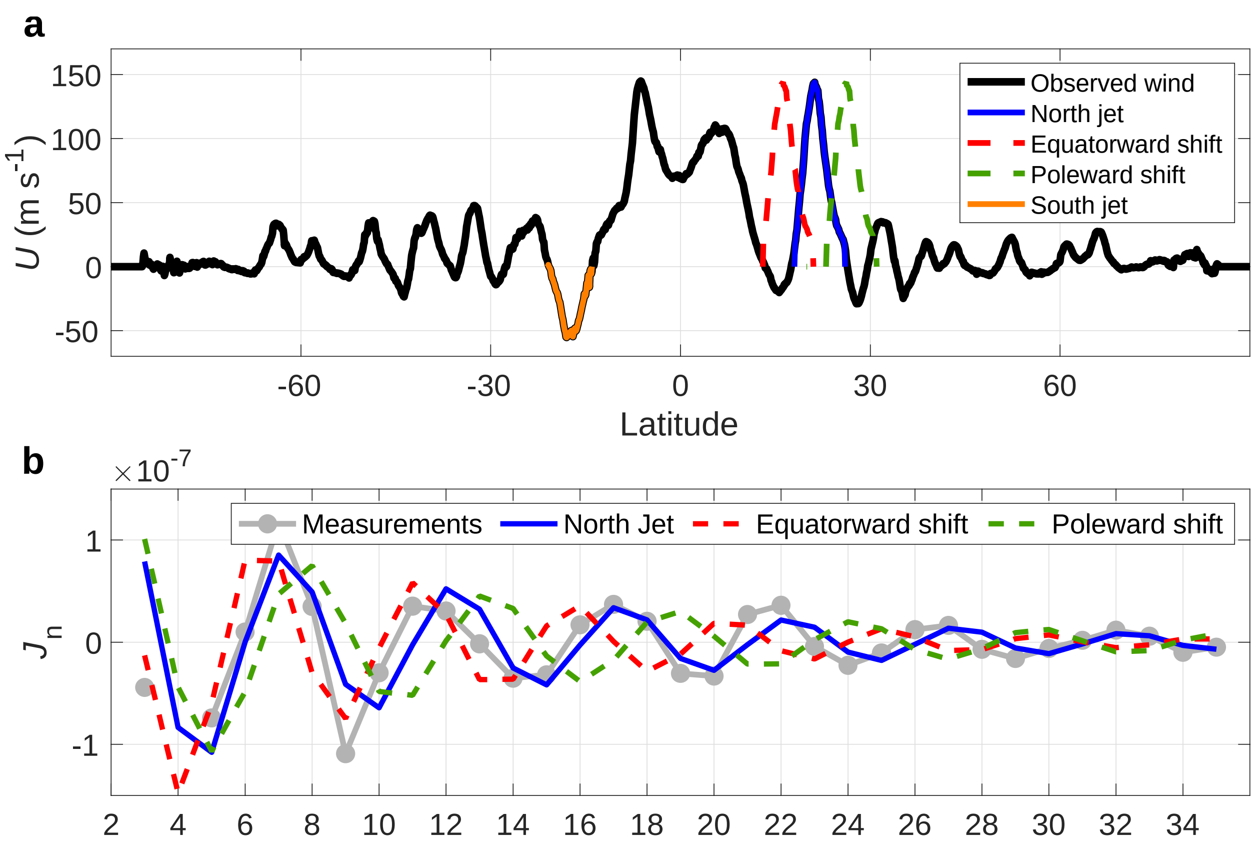
- J3, J5, J7 and J9 are part of a wavy pattern which continues to much higher degree.

- Projecting the winds inward radially does not match the measurements.



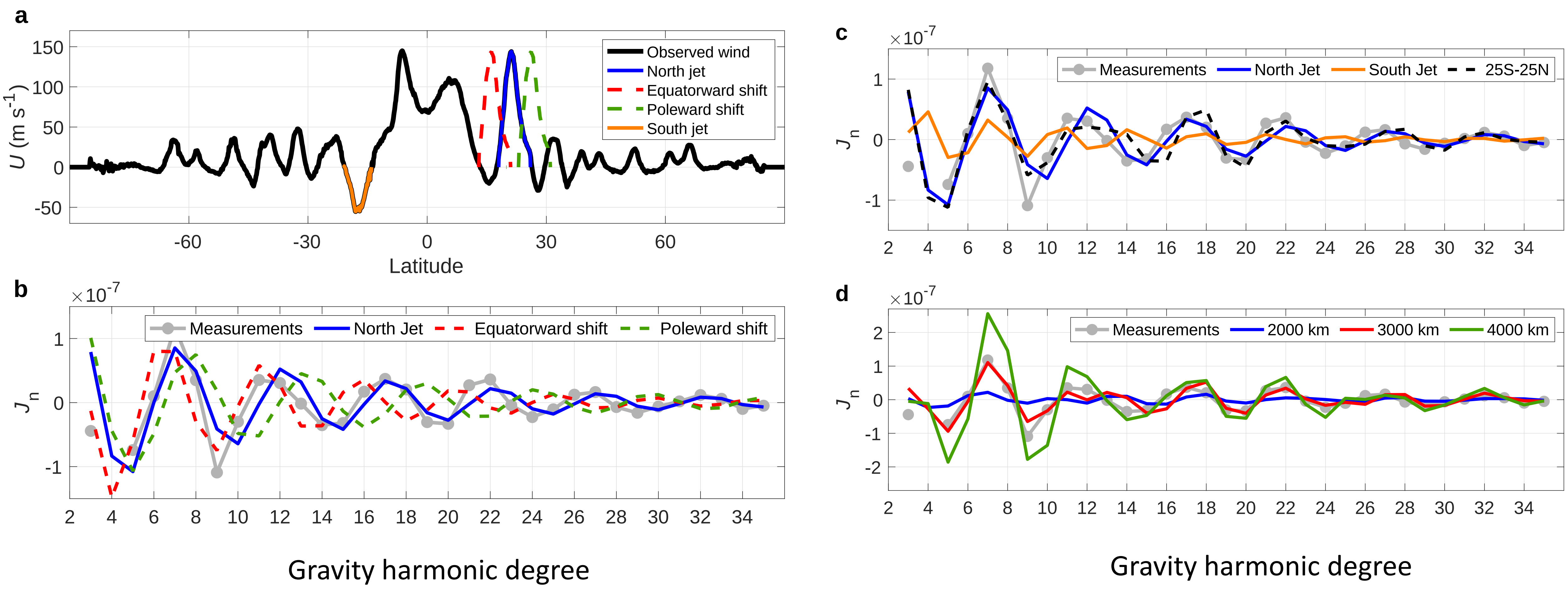
Where does the wavy pattern come from?

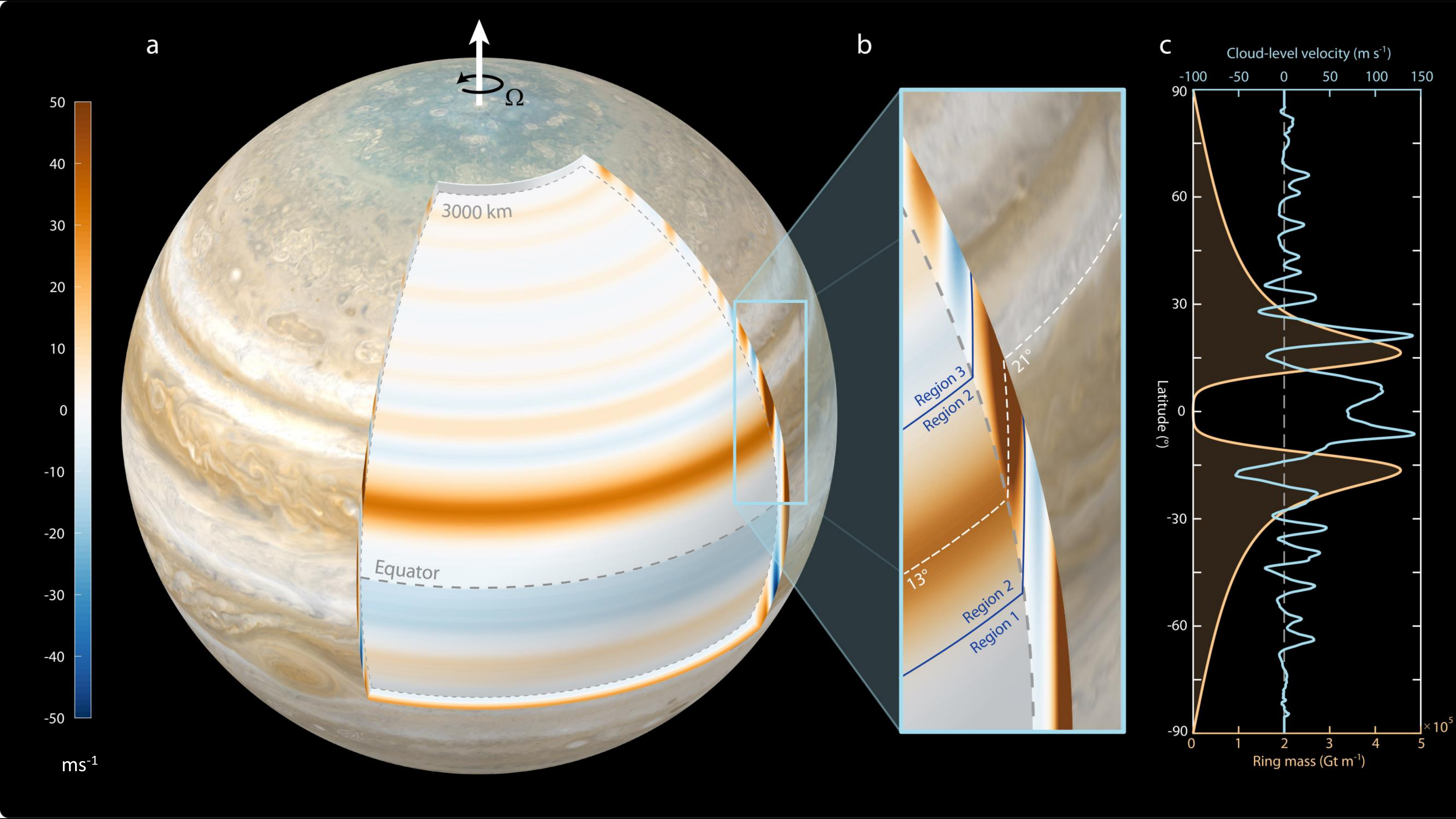
The source of the gravity signal



Gravity harmonic degree

The source of the gravity signal

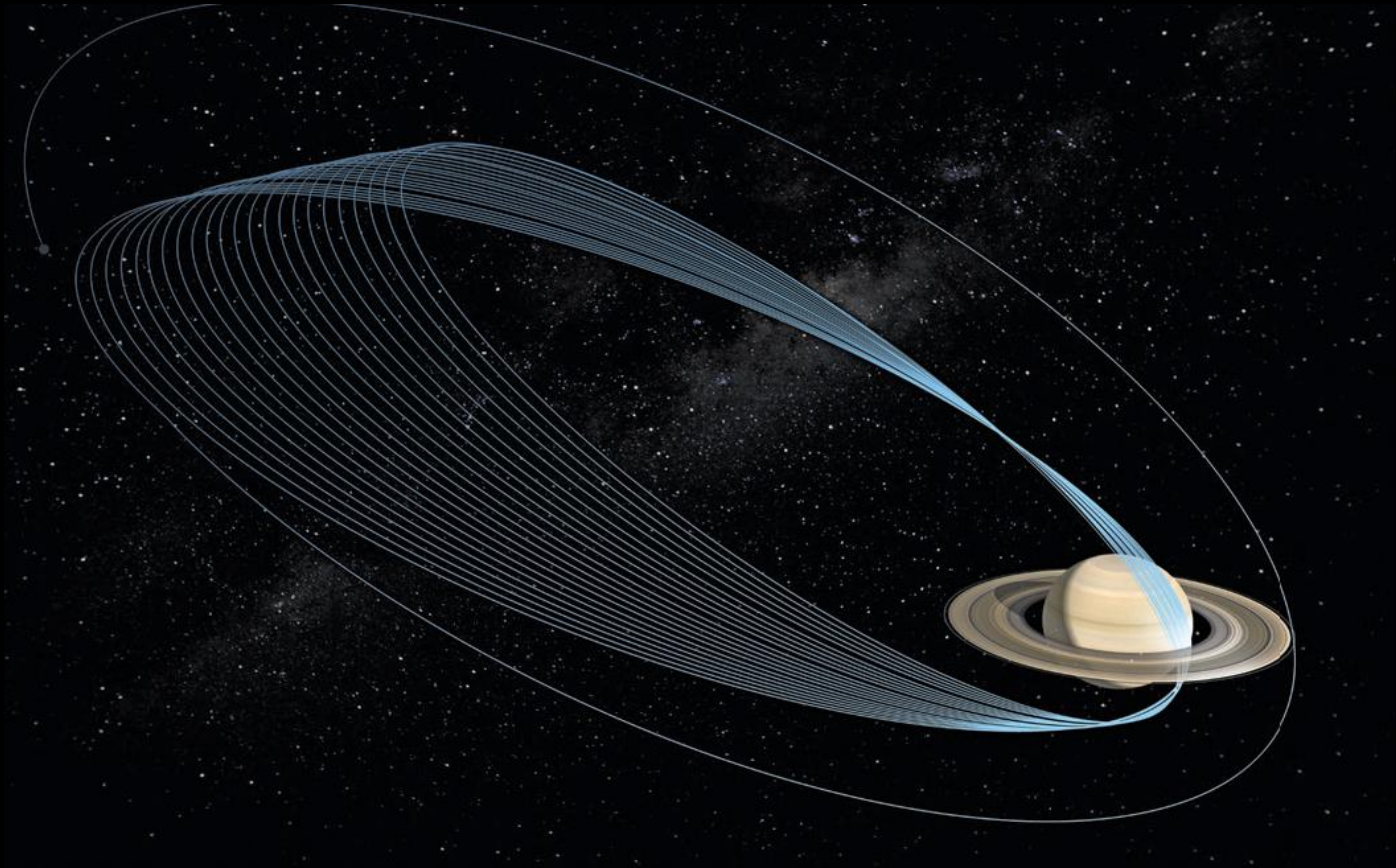




a
b
c
50
40
30
20
10
0
-10
-20
-30
-40
-50
ms-1
Ω
3000 km
Equator
Region 3
Region 2
21°
13°
Region 2
Region 1
Cloud-level velocity (m s-1)
-100
-50
0
50
100
150
90
60
30
0
-30
-60
-90
Latitude (°)
0
1
2
3
4
5
×10^5
Ring mass (Gt m-1)

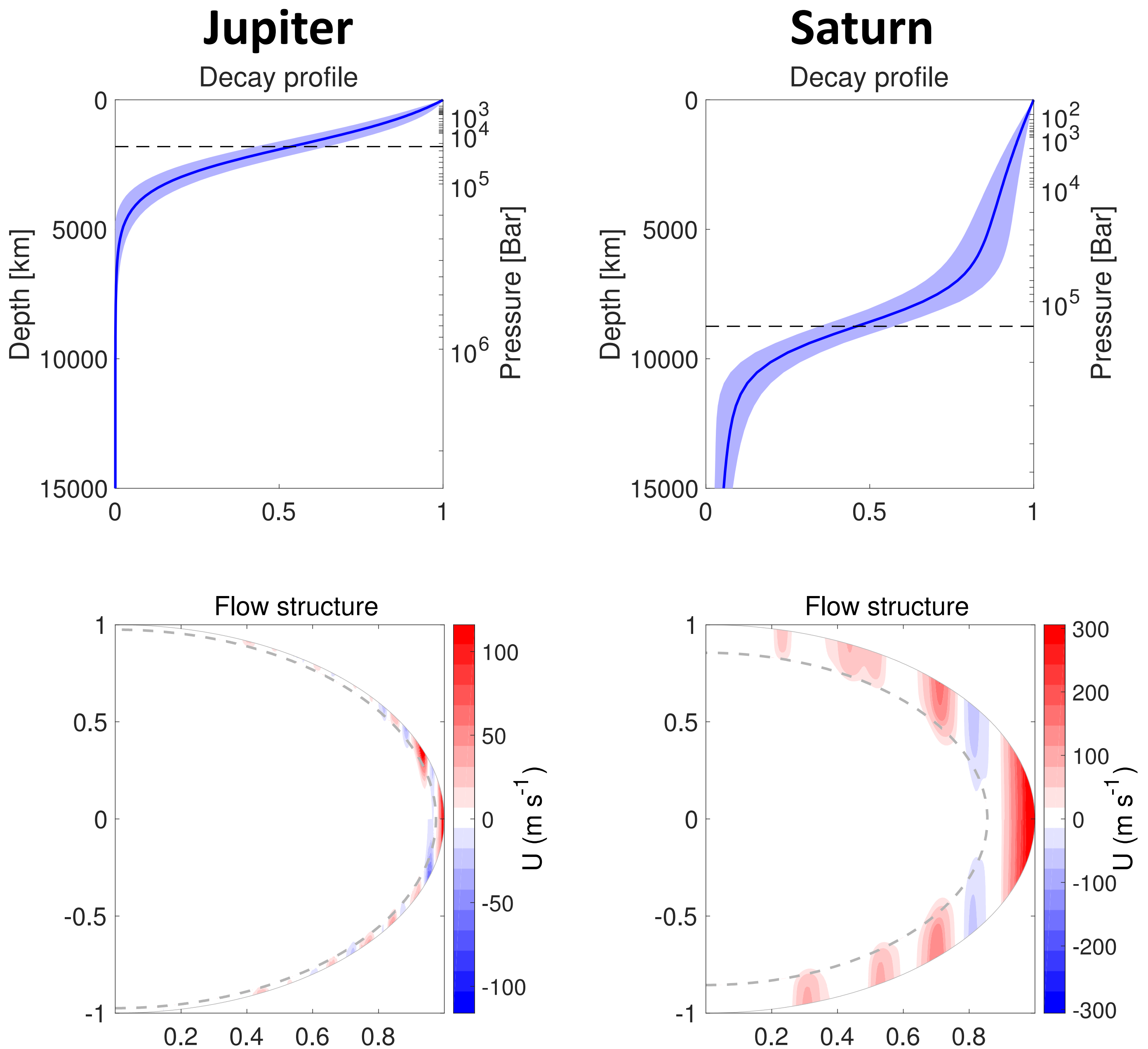
Similar gravity measurements of Cassini at Saturn

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



The deep flow structure inferred from gravity

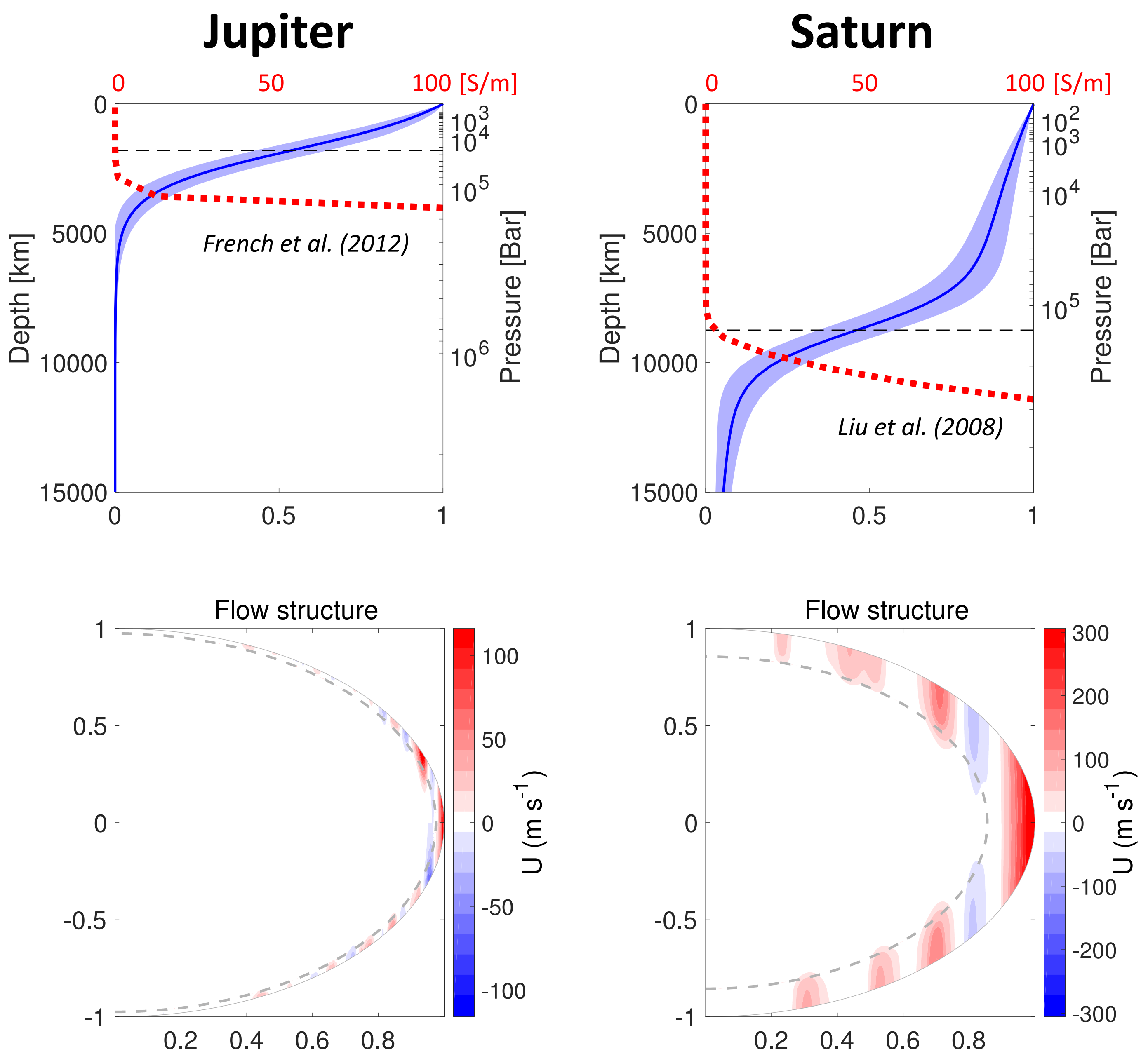
- In blue: Optimal decay profile matching the gravity measurements.
- Winds on Jupiter extend to depth of ~3000km
- On Saturn the winds reach depth of ~9,000km.



Kaspi et al., 2020, *Space Sci. Rev.*

The deep flow structure inferred from gravity

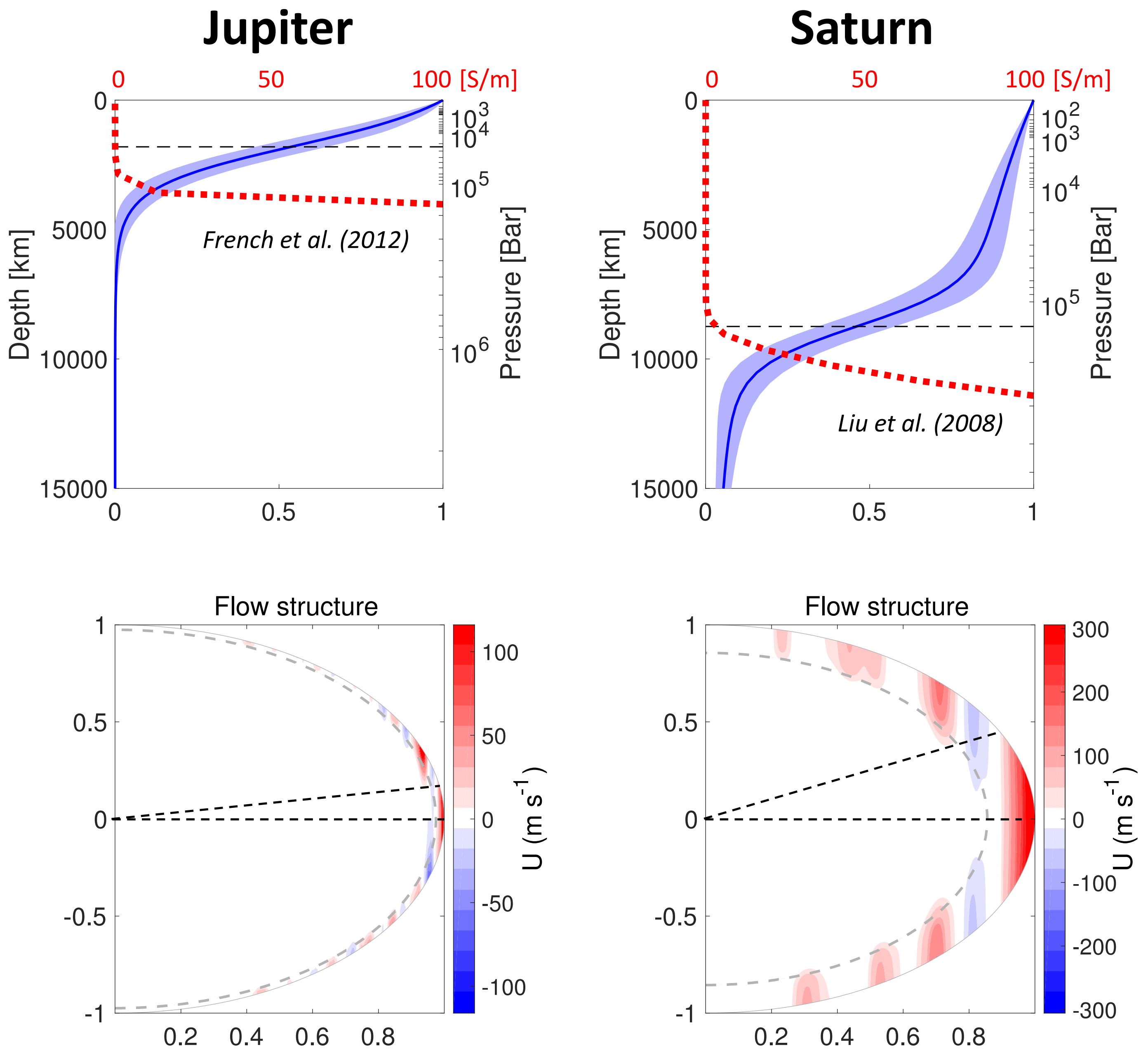
- Electrical conductivity is expected to affect the flow in the semi-conducting region via Ohmic dissipation (Liu et al., 2008, Cao & Stevenson, 2017).
- In both planets, conductivity increases where the flow decays.



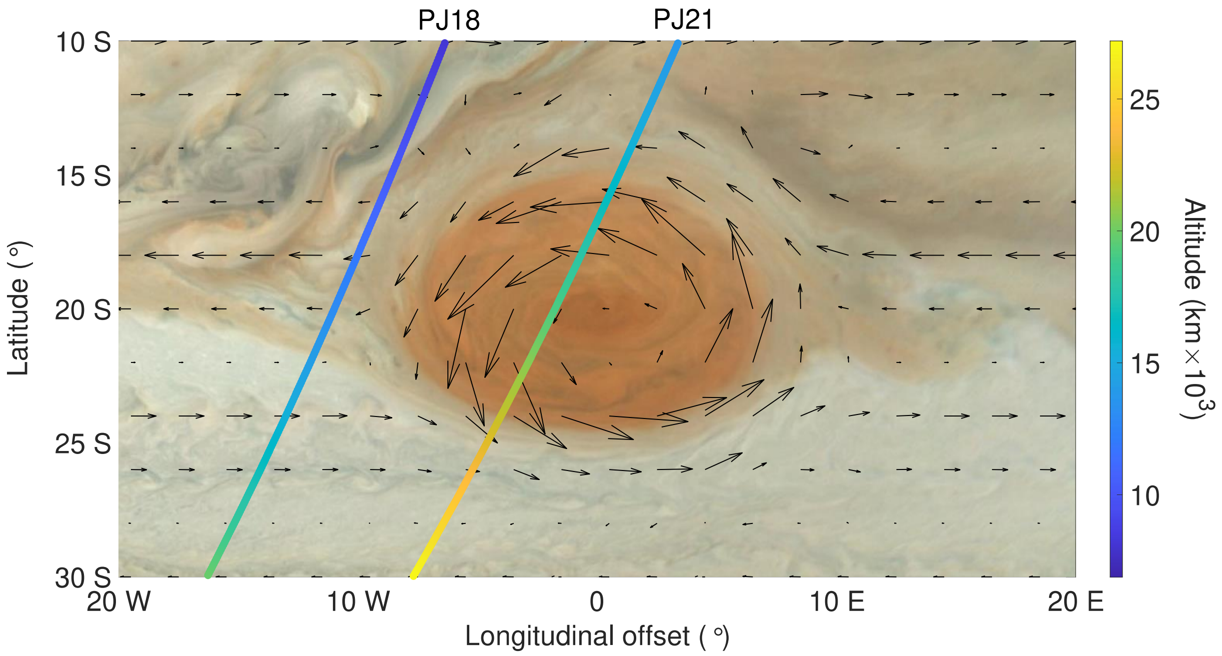
Kaspi et al., 2020, *Space Sci. Rev.*

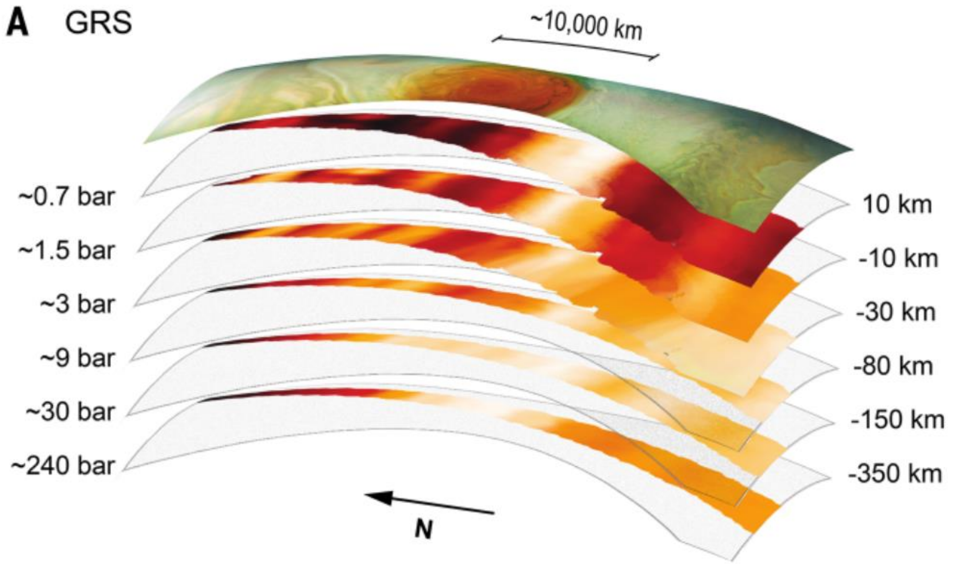
The deep flow structure inferred from gravity

- Electrical conductivity is expected to affect the flow in the semi-conducting region via Ohmic dissipation (Liu et al., 2008, Cao & Stevenson, 2017).
- In both planets, conductivity increases where the flow decays.
- The depth inferred from gravity alone defines a tangent cylinder, out of which there is prograde flow.

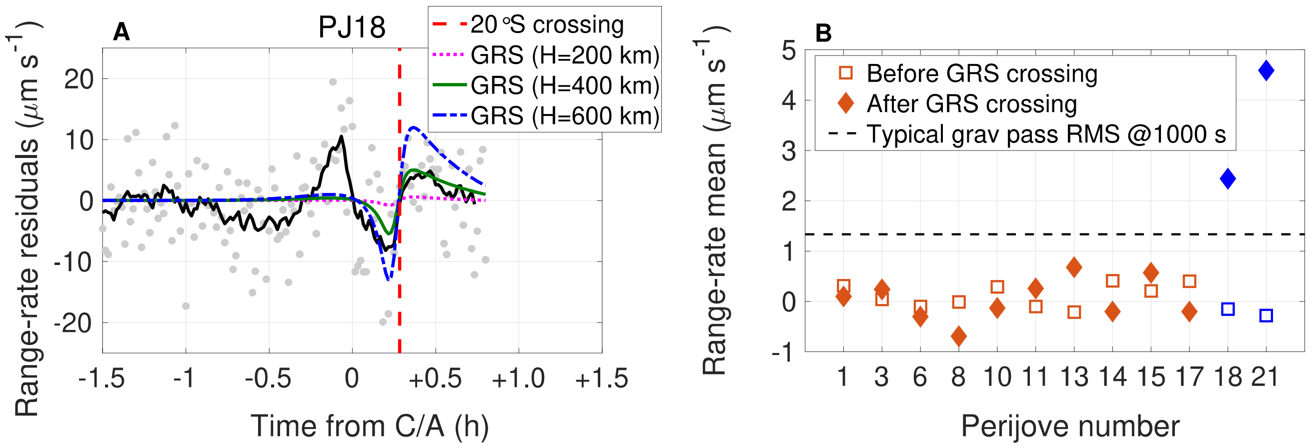


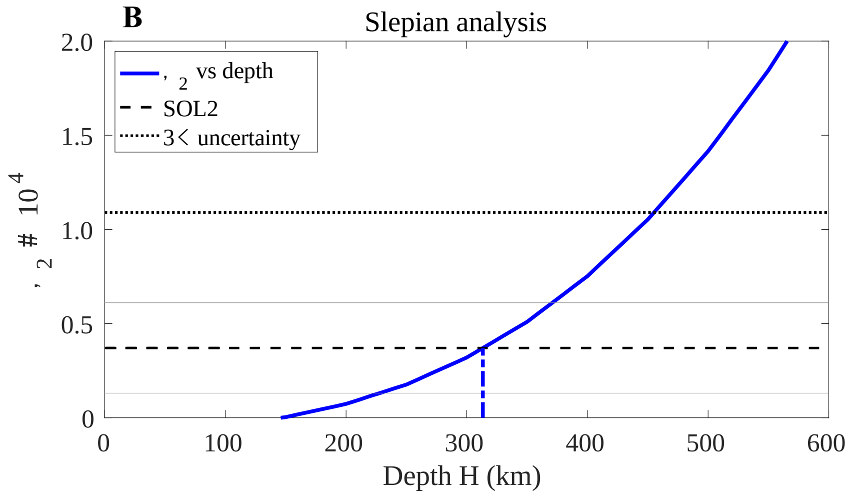
How deep is the Great Red Spot?





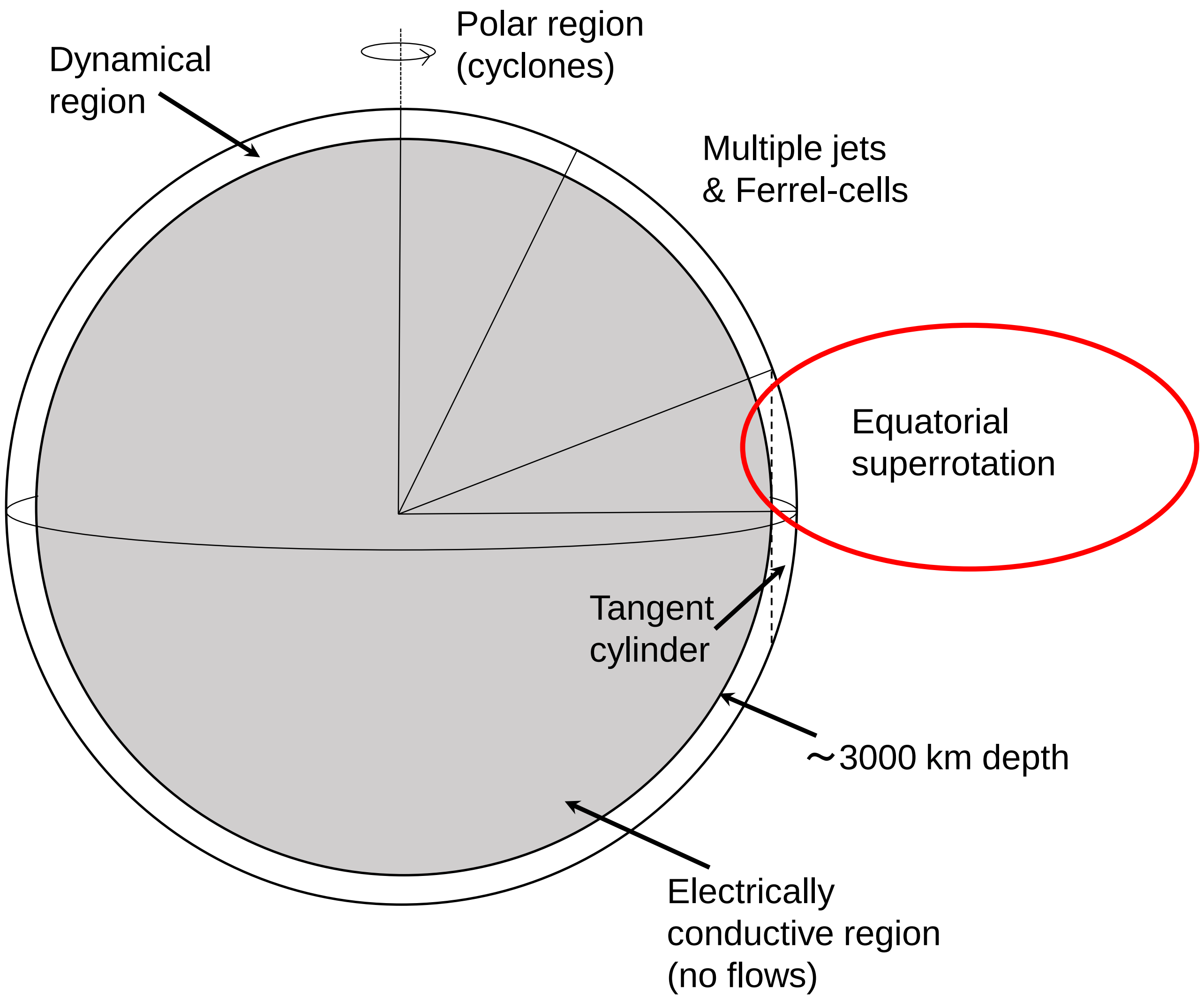
Bolton et al. 2021, *Science*



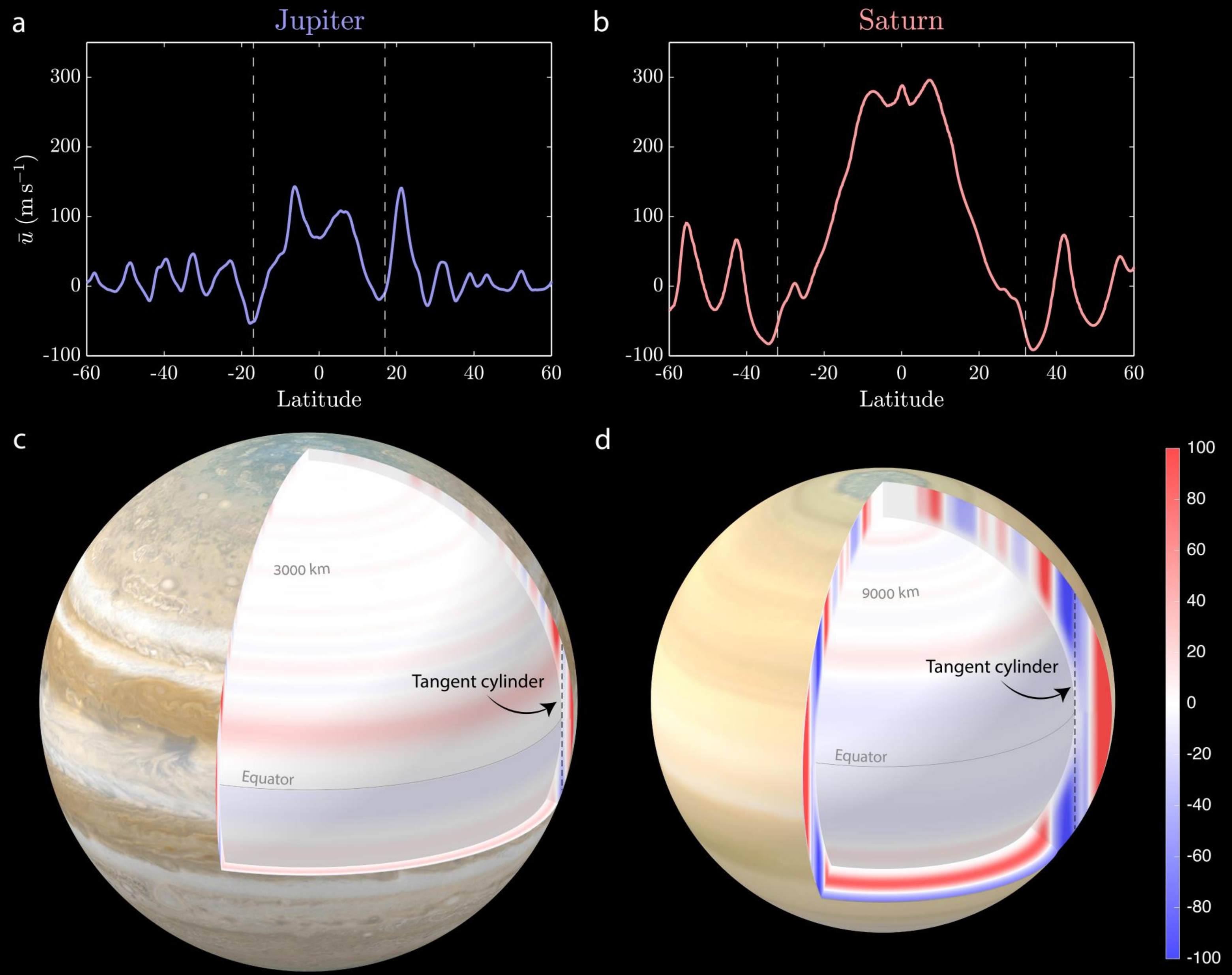


Parisi et al. 2021, *Science*

Summary: Jupiter's dynamical regimes

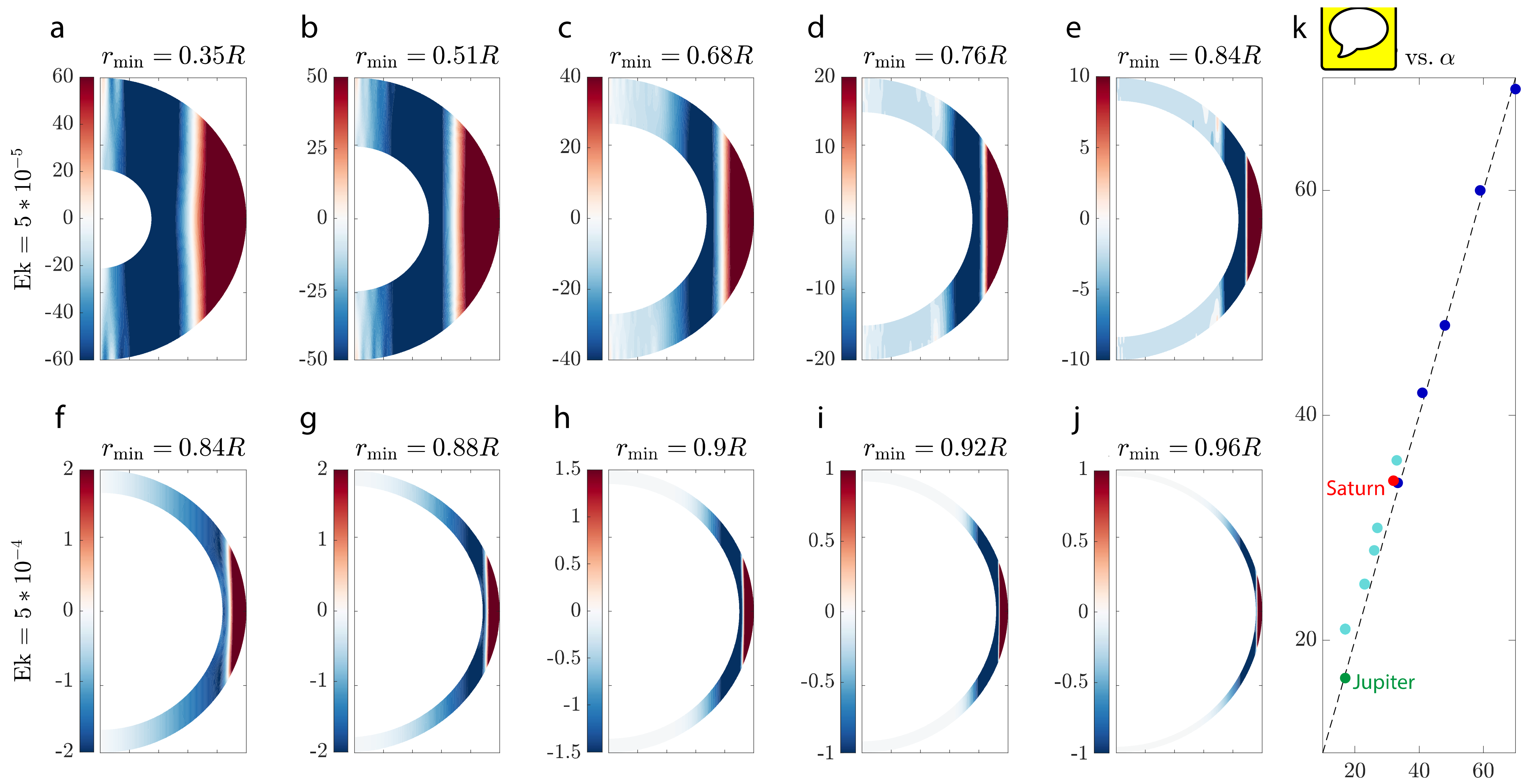


The equatorial region

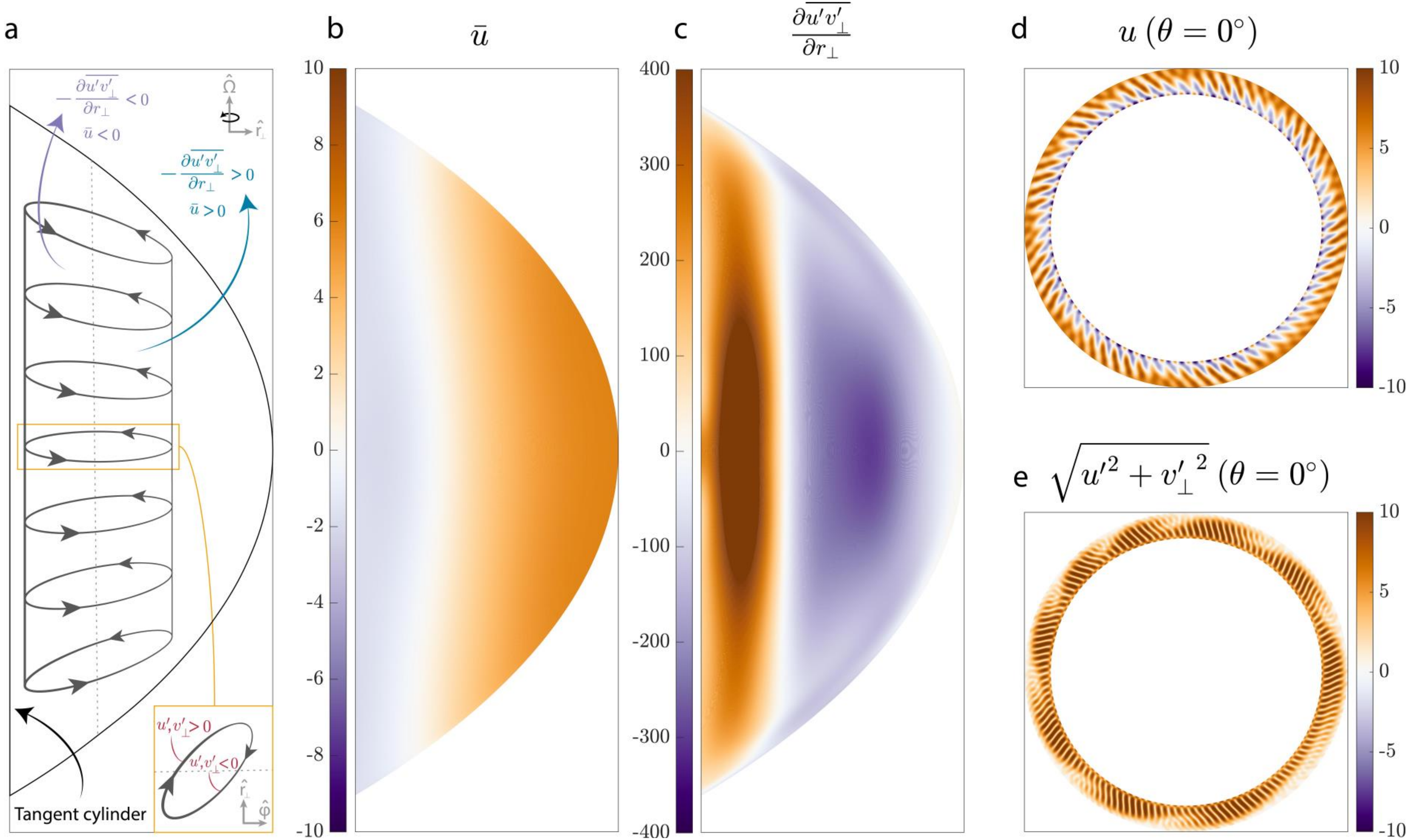


Duer et al., submitted

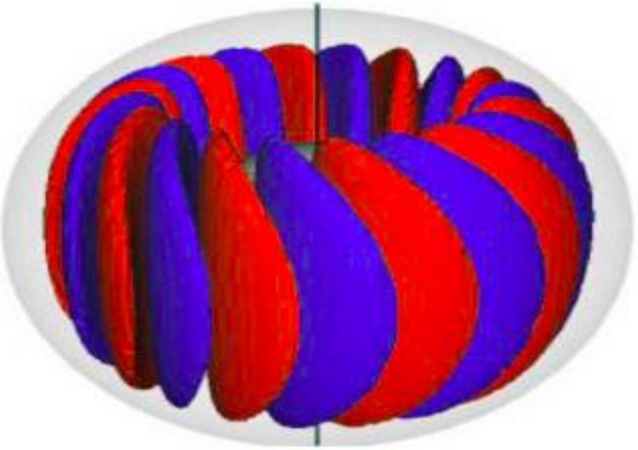
The relation between the domain depth and equatorial flow extent



The mechanism for equatorial superrotation

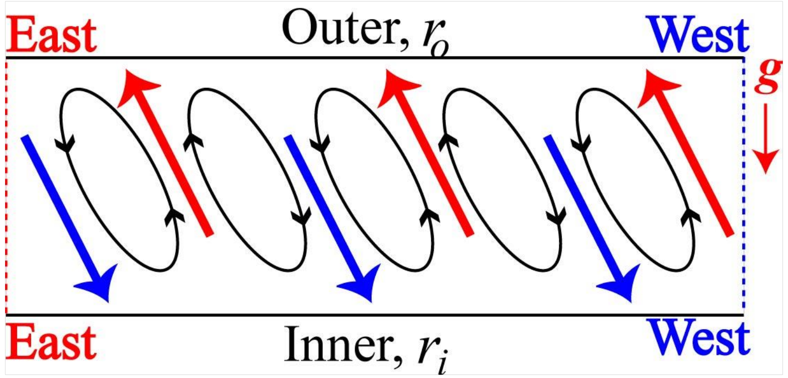


Mechanism for equatorial superrotation (weakly supercritical example)



Analytic solutions of linear convection in a rotating sphere. (Zhang and Schubert, 1997; Simitev, 2012)

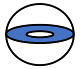
Outward momentum flux

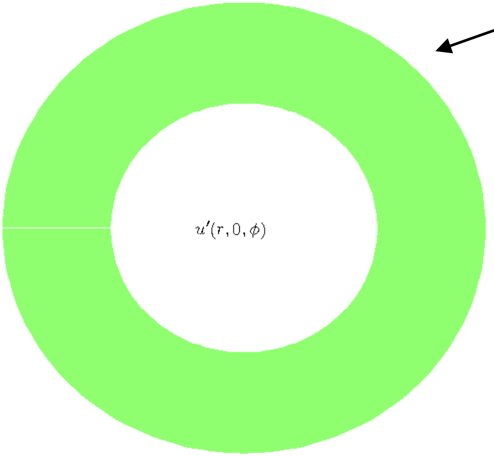


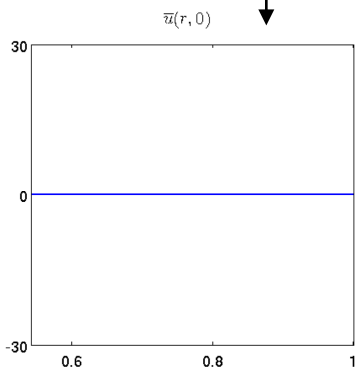
Busse, 2002; Aurnou, 2007

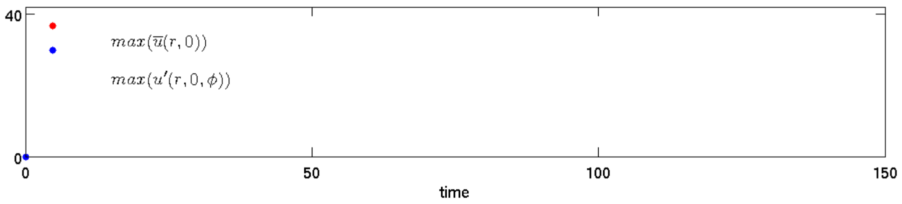
3D deep GCM simulation (weakly supercritical)

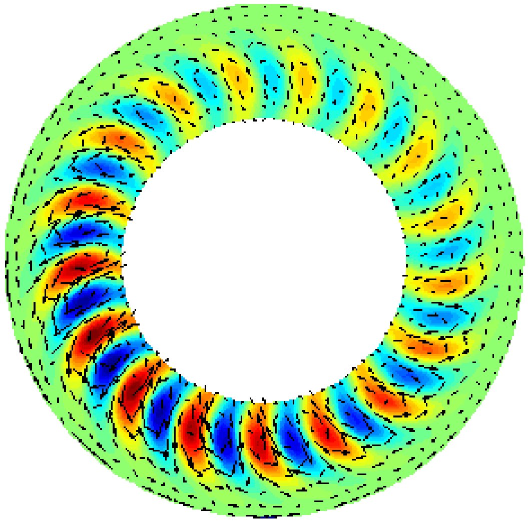
zonal velocity: $u(r,0,\phi) = u'(r,\phi) + \bar{u}(r)$

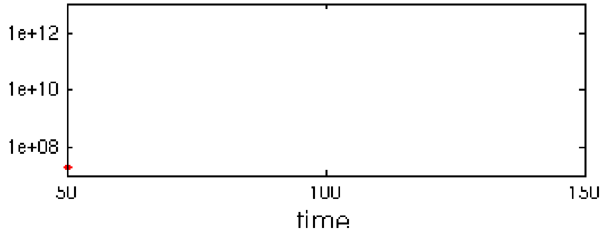






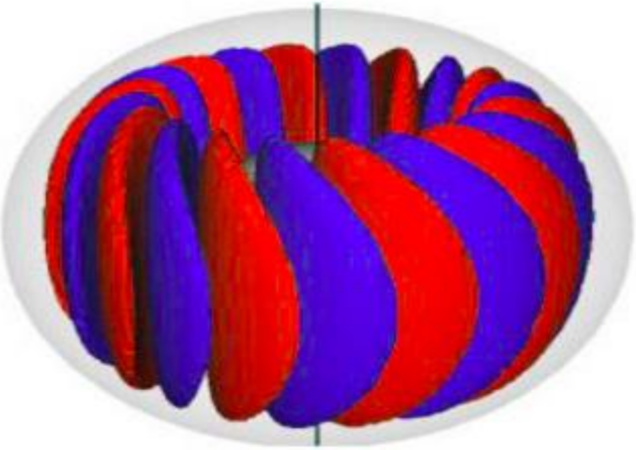


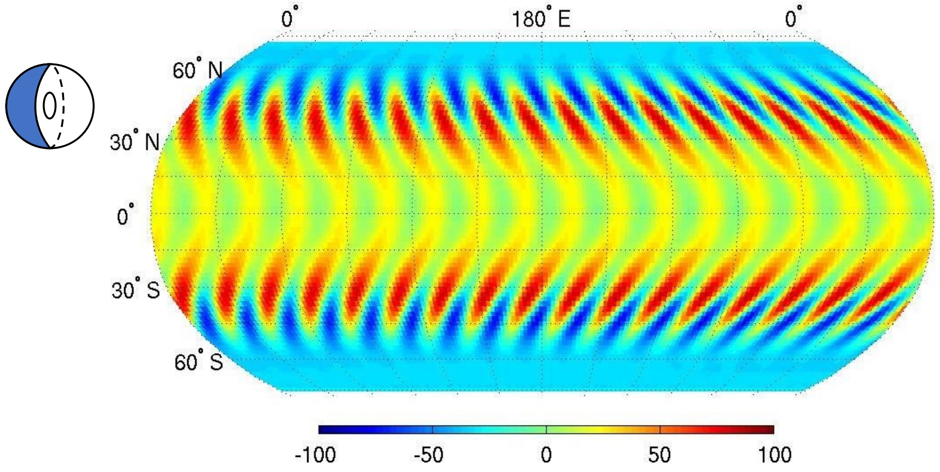




Kaspi, 2008

Mechanism for equatorial superrotation (weakly supercritical example)





Kaspi, 2008

3D deep GCM simulation (weakly supercritical)

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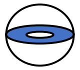
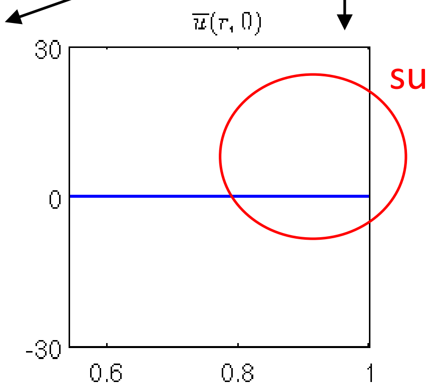
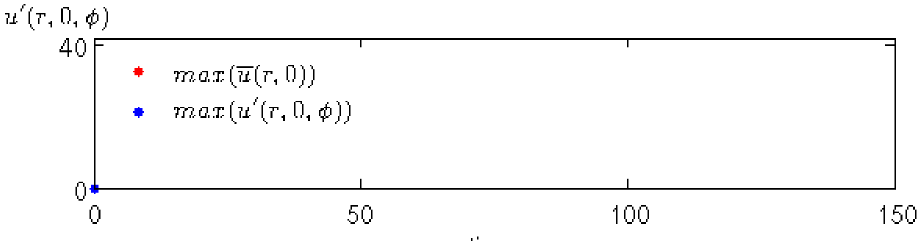




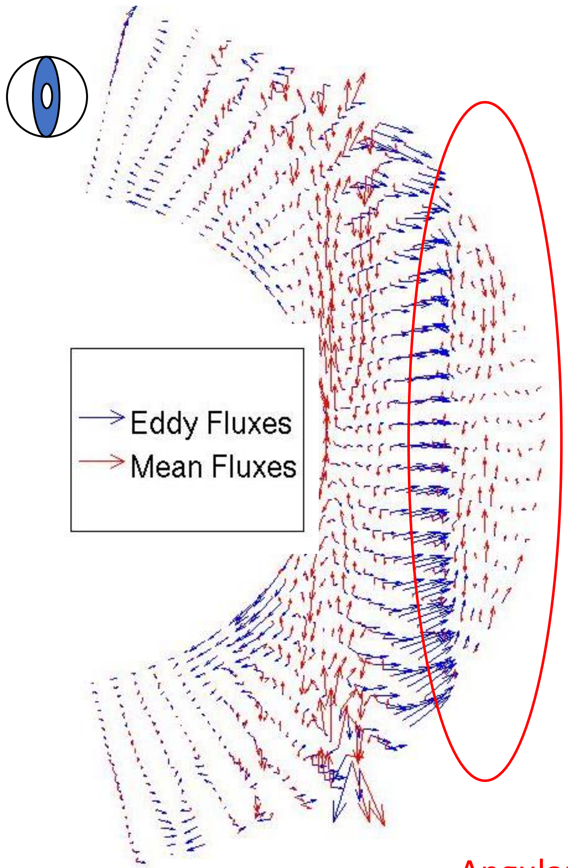
superrotation



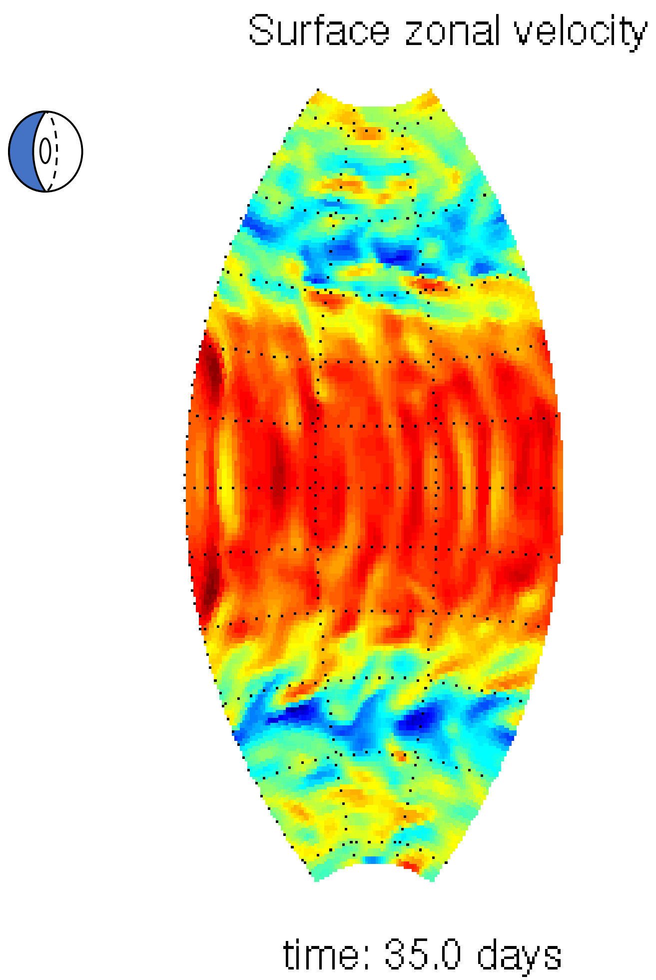
Acceleration due to an eddy momentum flux convergence

$$\frac{\partial u}{\partial t} = -\vec{\nabla}\left(\rho \vec{u}' u'\right) + \nu \vec{\nabla}^2 u$$

Equatorial superrotation in deep models



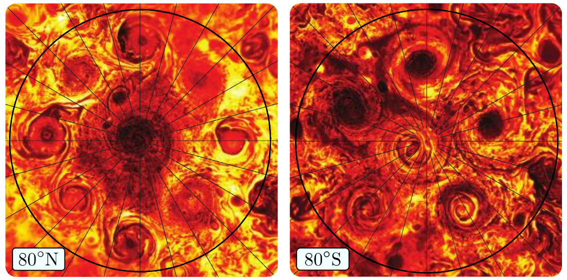
Angular momentur
flux convergence



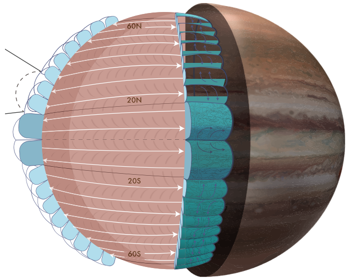
Tilted convection columns lead to eddy angular momentum flux perpendicular to the direction of the spin axis.

Summary

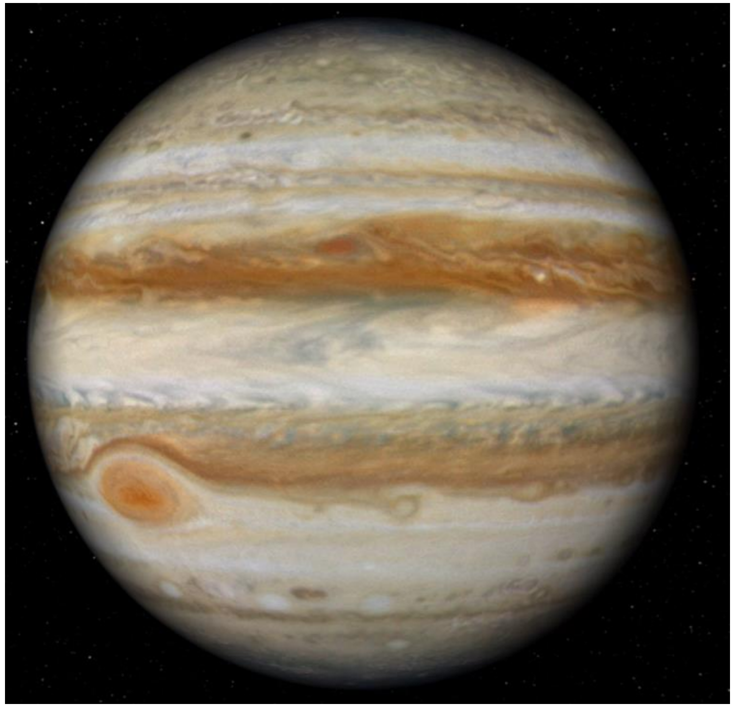
- Juno enabled better understating of the dynamical regimes of Jupiter’s atmosphere



- Jupiter’s north (south) pole has 8 (5) circumpolar cyclones, which are held stable due to a balance between the beta-drift and the vorticity gradient of the cyclones.



- Jupiter’s midlatitudes feature 8 Ferrel cells in each hemisphere around the eddy-driven jets.

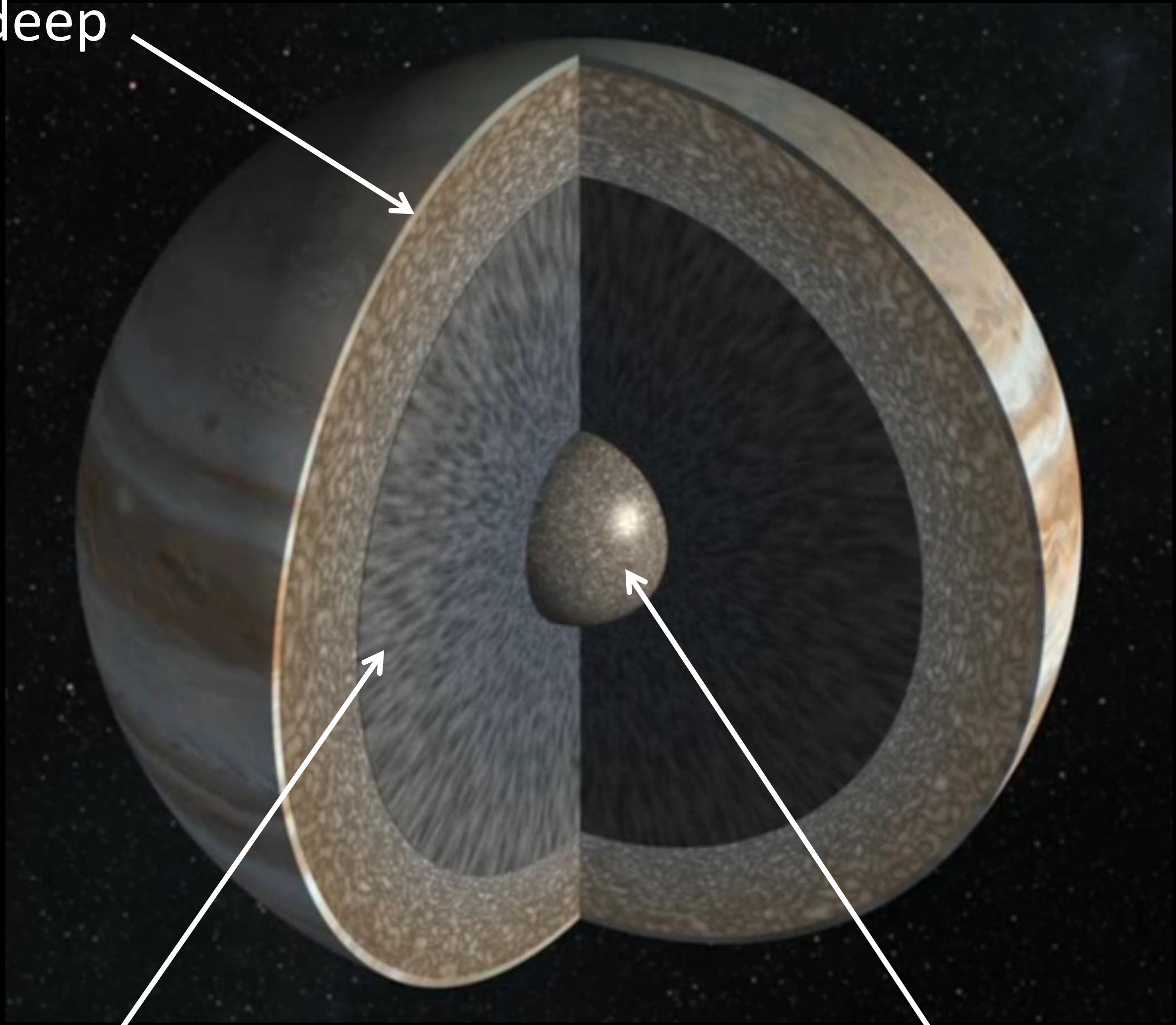


- Jupiter’s gravity field is hemispherically (north-south) asymmetric: a pure signal of deep dynamics.

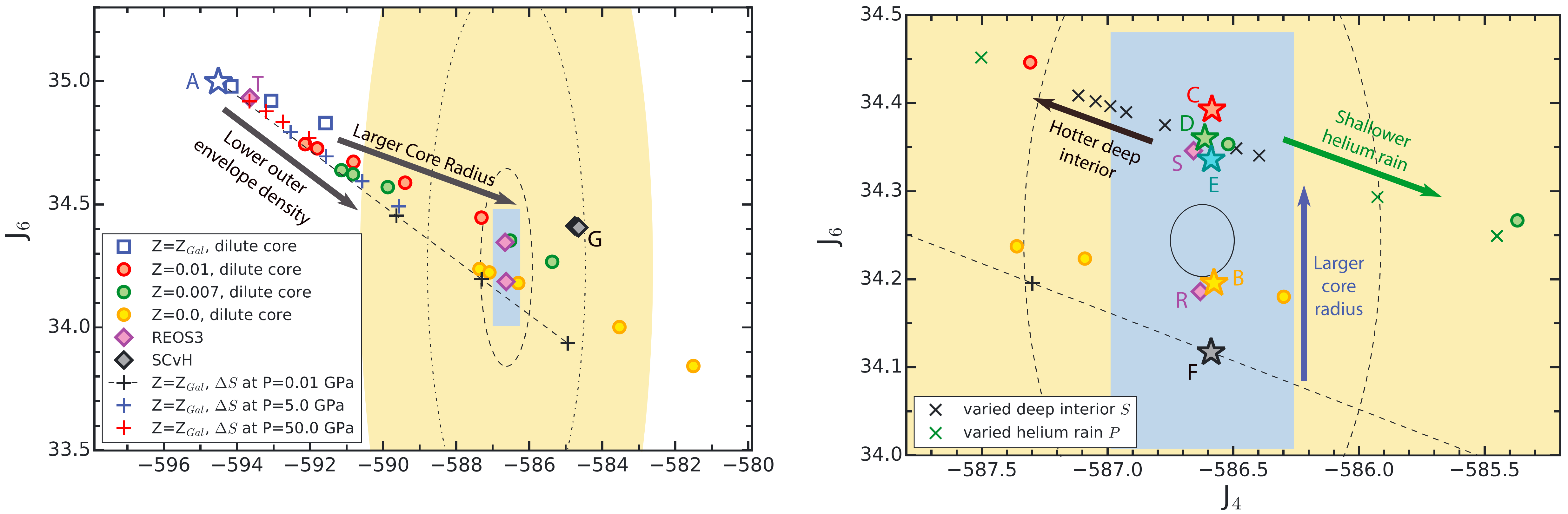
- This allowed determining that the depth of the cloud-level flows reach approximately 3000 km beneath the cloud level, which is the level of magnetic dissipation.

- Cassini results for Saturn indicate flows extending down to 9000 km, consistent in pressure with the depth on Jupiter and with MHD theory.

- GRS overflight gravity measurements indicate the GRS depth is <500 km.

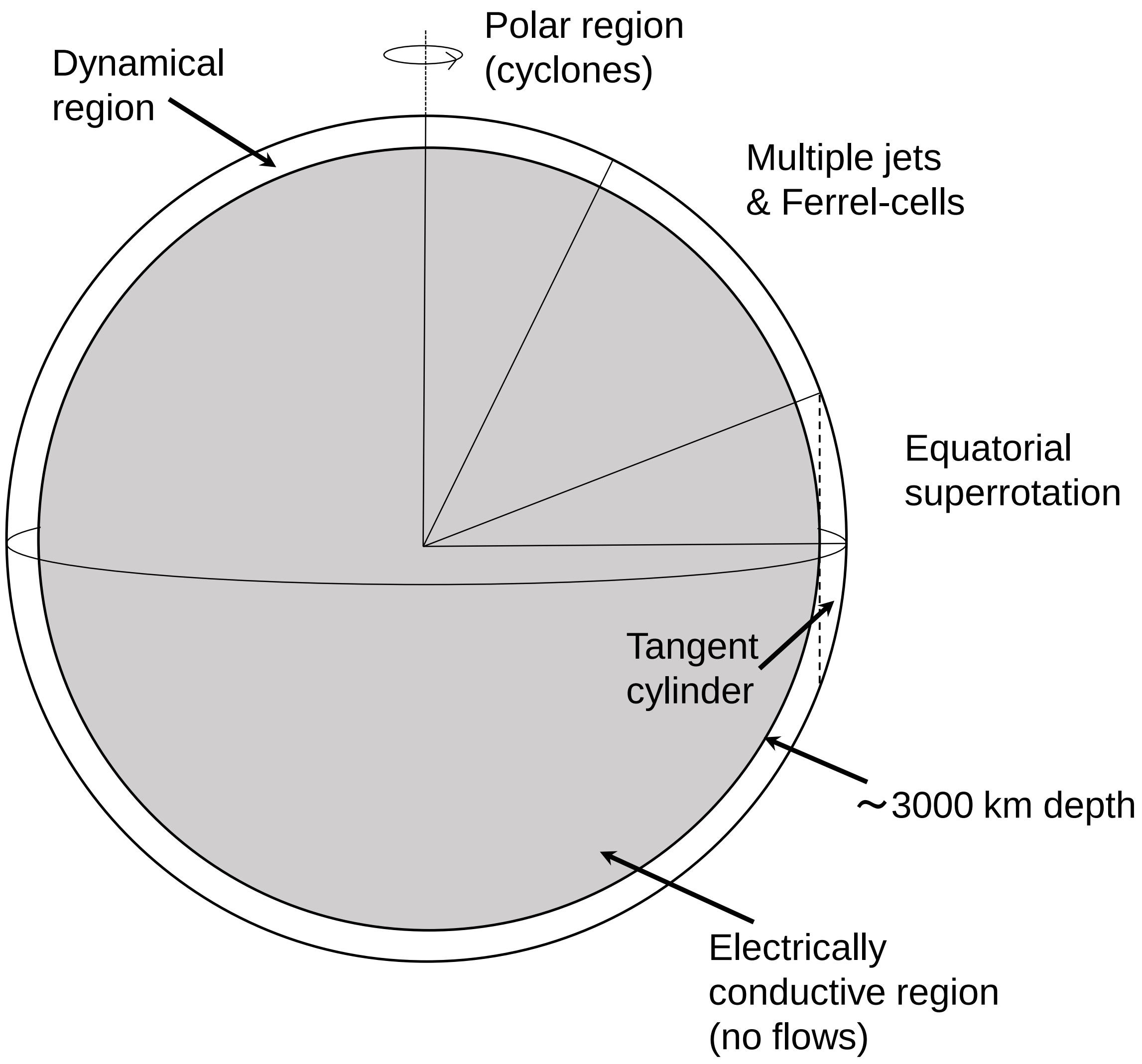

3000 km deep
No deep internal flows
”Fuzzy core”???

Interior structure properties and core

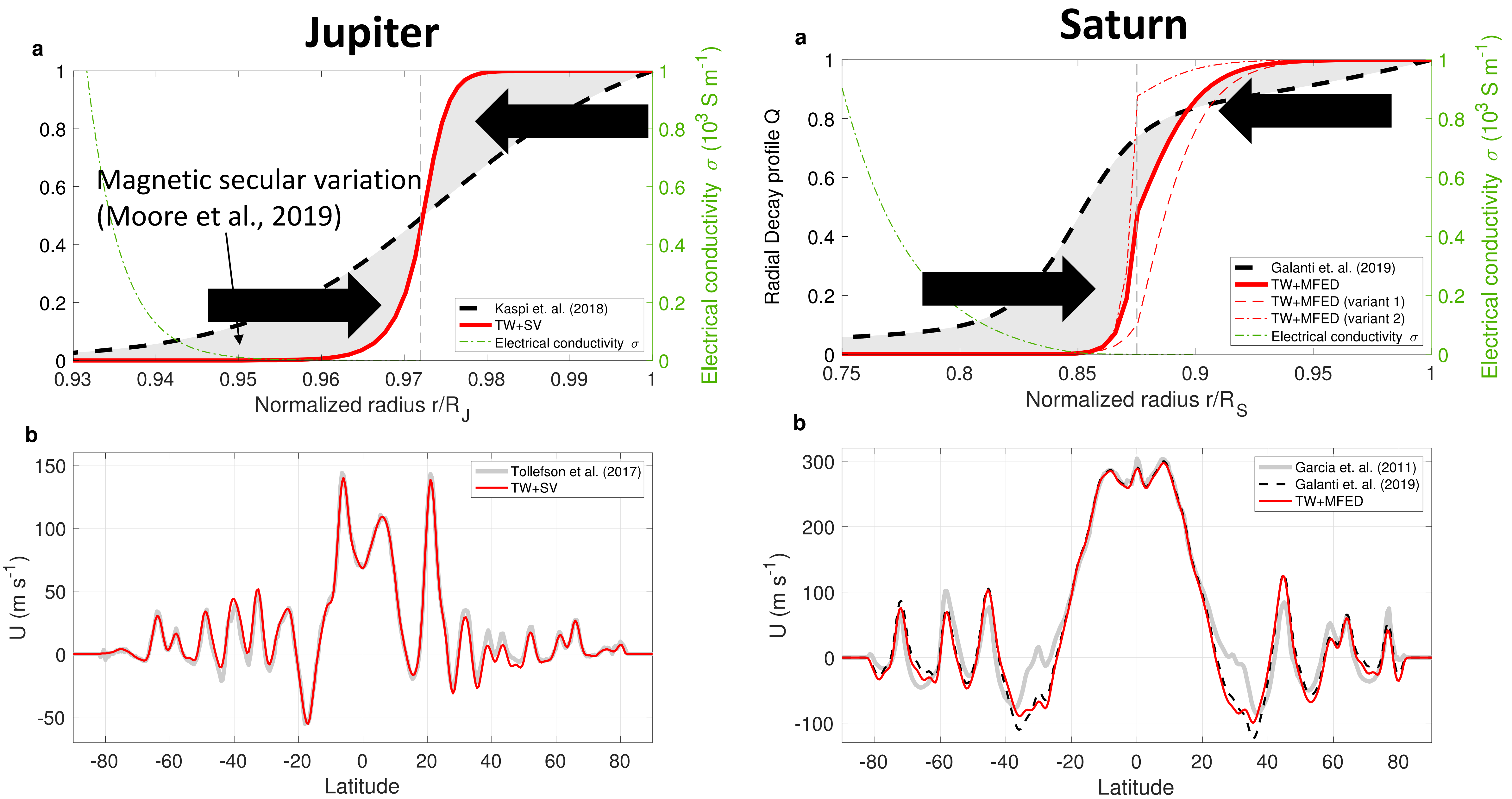


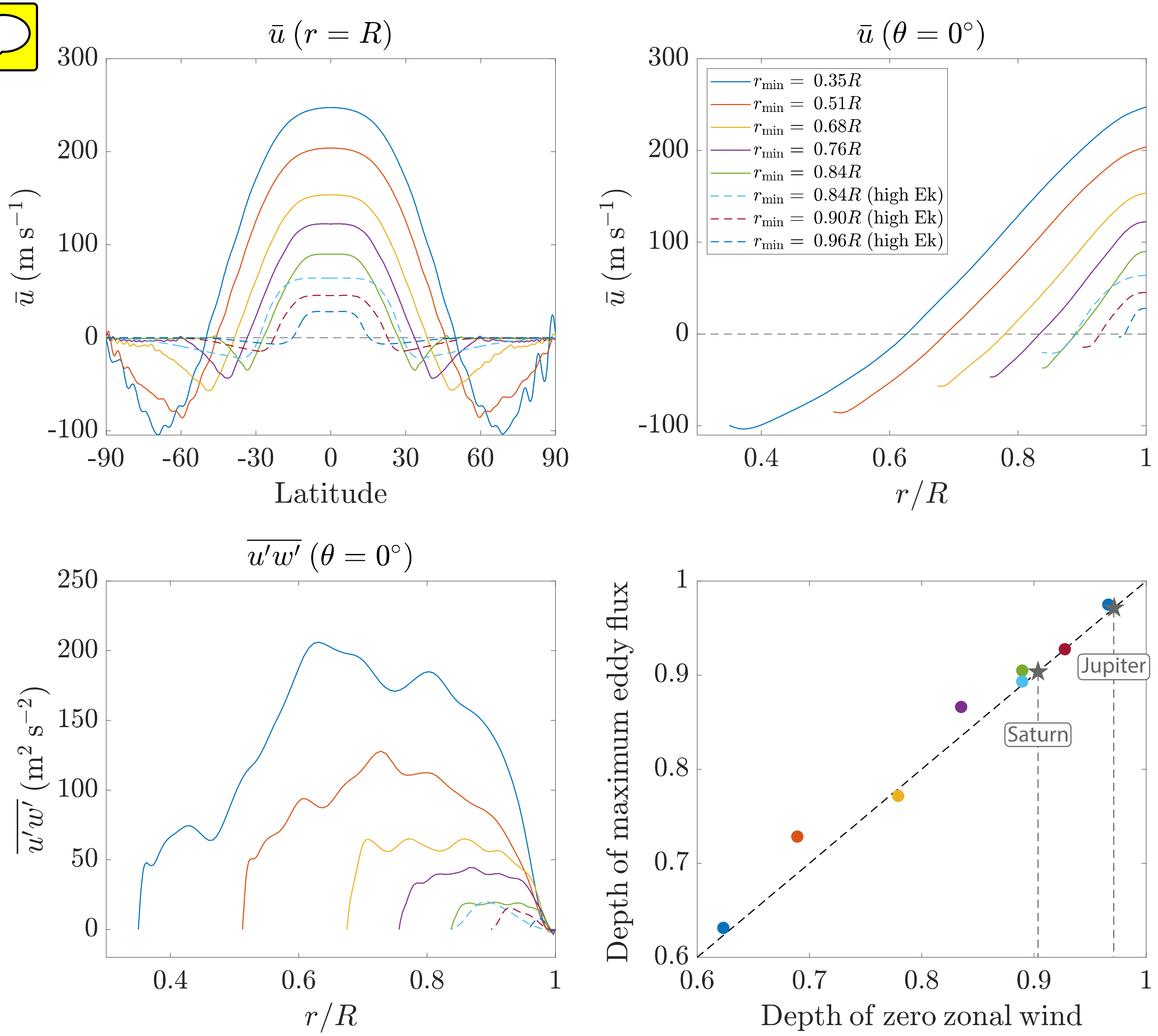
Whal et al., *GRL,* 2017

Summary: Jupiter’s dynamical regimes

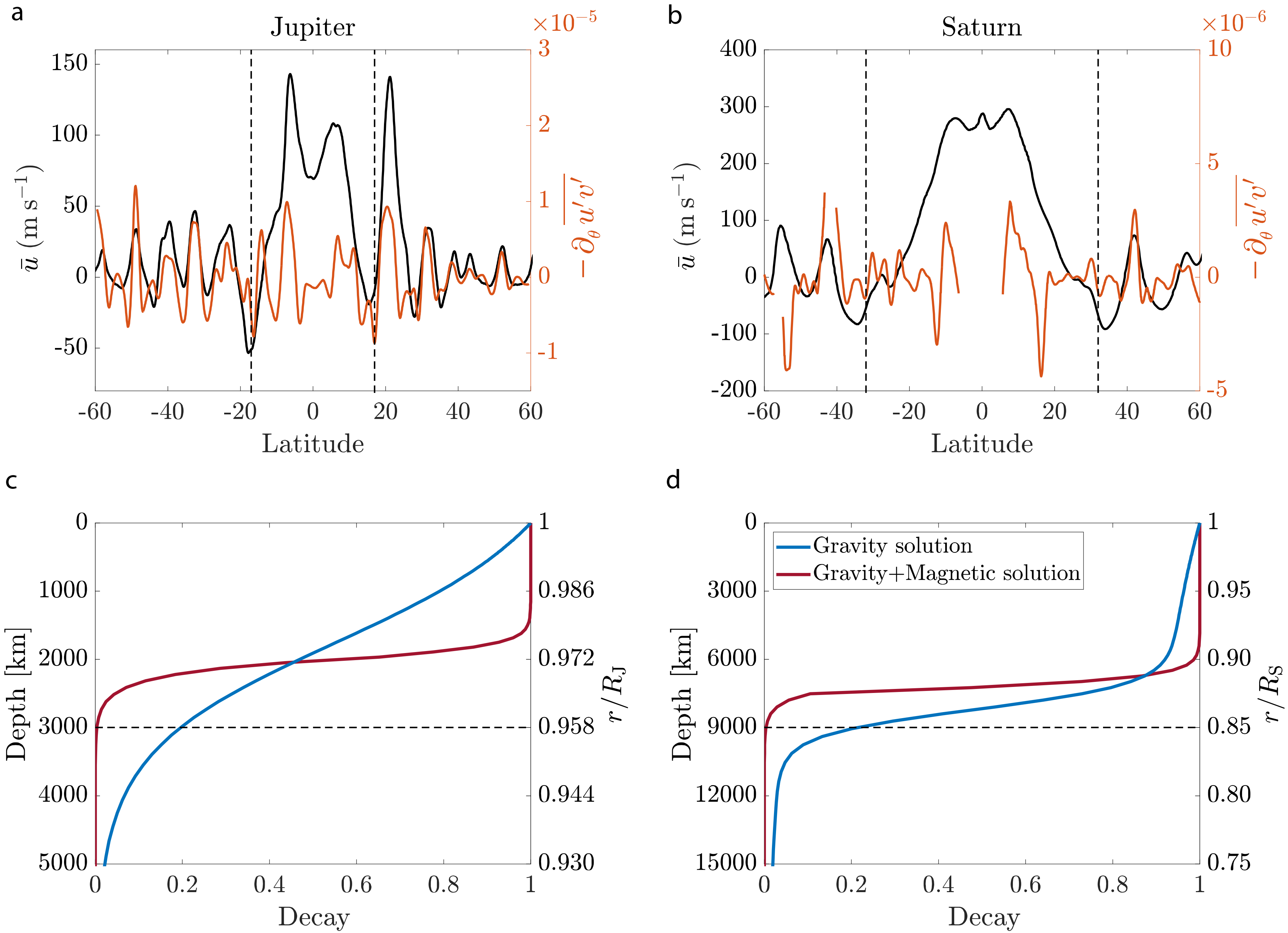


Vertical flow profile combining gravity and magnetic field measurements

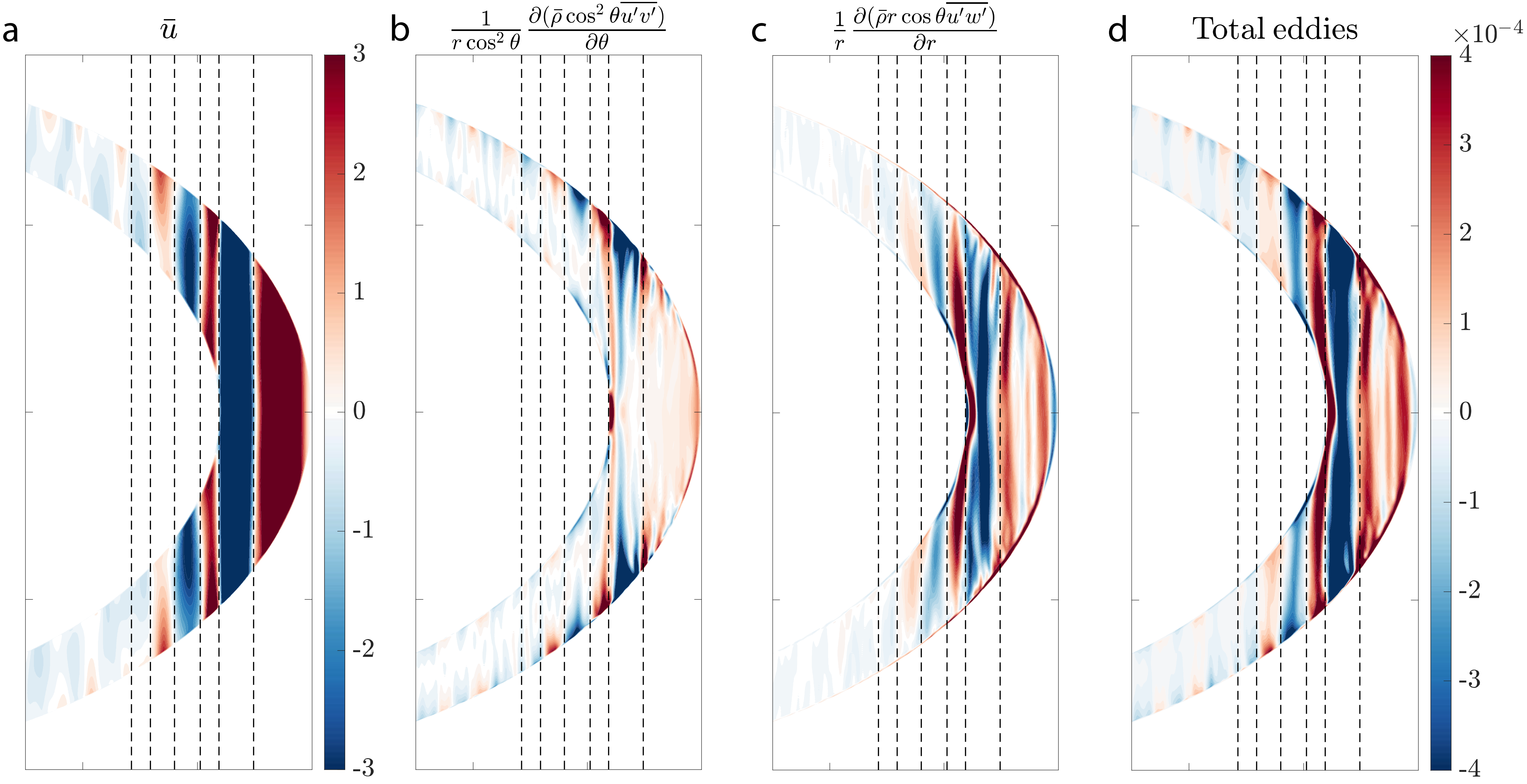




$\bar{u}$ $(r = R)$
$\bar{u}$ (m s^{-1})
Latitude
$\bar{u}$ $(\theta = 0°)$
$r_{\min} = 0.35R$
$r_{\min} = 0.51R$
$r_{\min} = 0.68R$
$r_{\min} = 0.76R$
$r_{\min} = 0.84R$
$r_{\min} = 0.84R$ (high Ek)
$r_{\min} = 0.90R$ (high Ek)
$r_{\min} = 0.96R$ (high Ek)
r/R
$\overline{u'w'}$ $(\theta = 0°)$
$\overline{u'w'}$ (m^2 s^{-2})
r/R
Depth of maximum eddy flux
Depth of zero zonal wind
Jupiter
Saturn

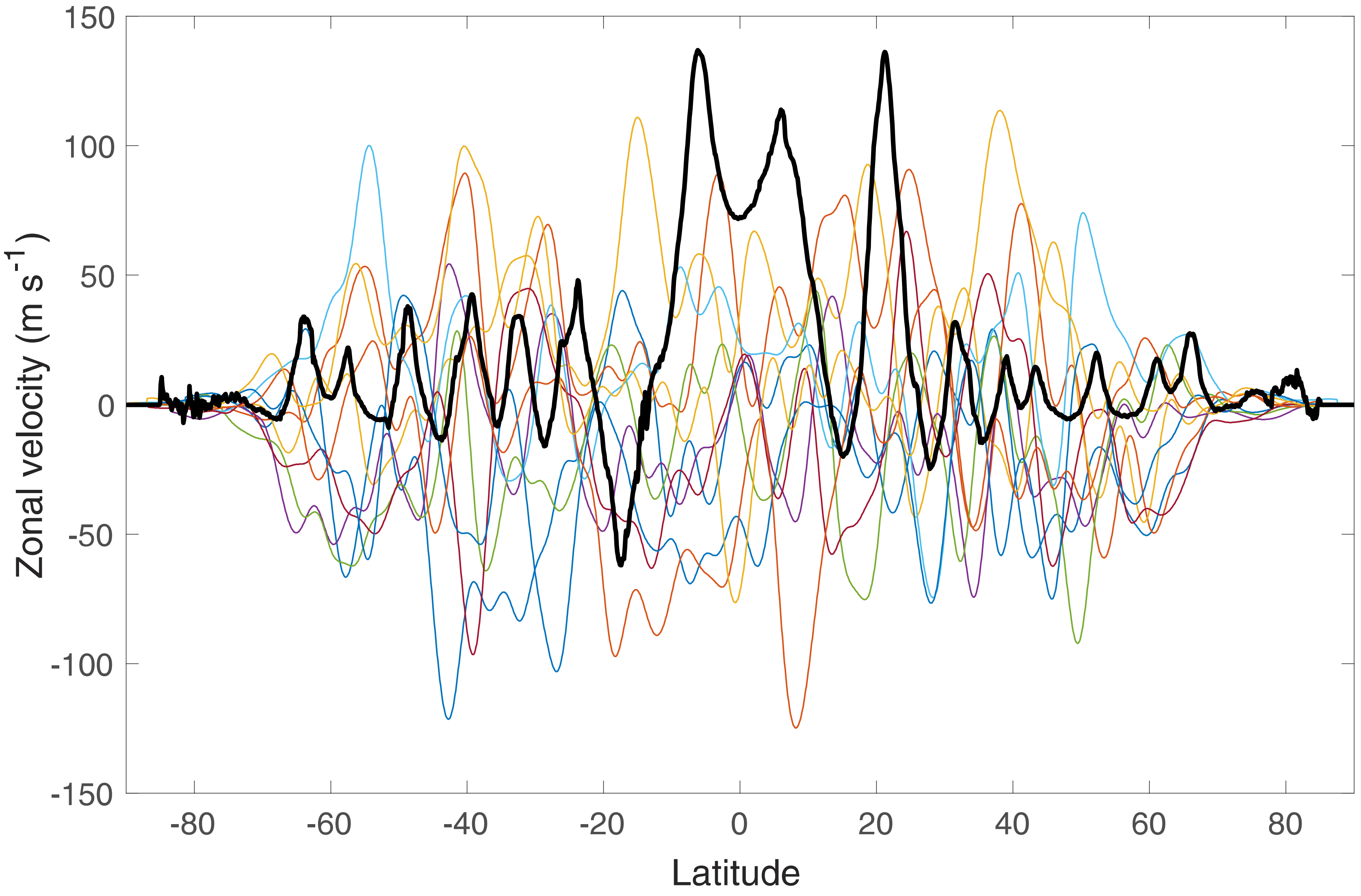


a
Jupiter
b
Saturn
$\bar{u}\ (\mathrm{m\,s^{-1}})$
$-\partial_\theta \overline{u'v'}$
$\times 10^{-5}$
$\times 10^{-6}$
Latitude
c
d
Gravity solution
Gravity+Magnetic solution
Depth [km]
r/R_J
r/R_S
Decay

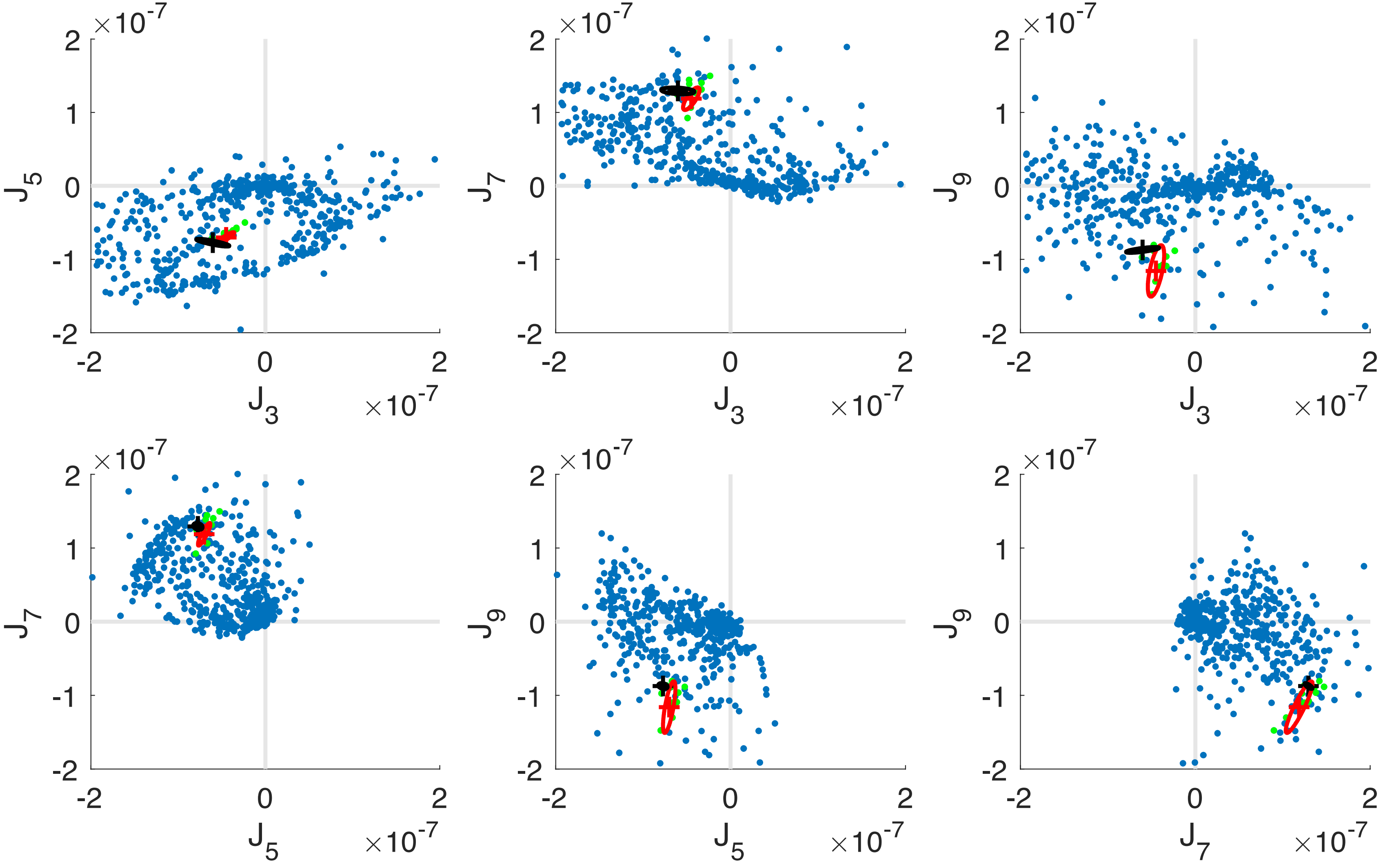


a
$\bar{u}$
b
$\frac{1}{r\cos^2\theta}\frac{\partial(\bar{\rho}\cos^2\theta\overline{u'v'})}{\partial\theta}$
c
$\frac{1}{r}\frac{\partial(\bar{\rho}r\cos\theta\overline{u'w'})}{\partial r}$
d
Total eddies
3
2
1
0
-1
-2
-3
$\times10^{-4}$
4
3
2
1
0
-1
-2
-3
-4

Statistical significance test for other wind profiles



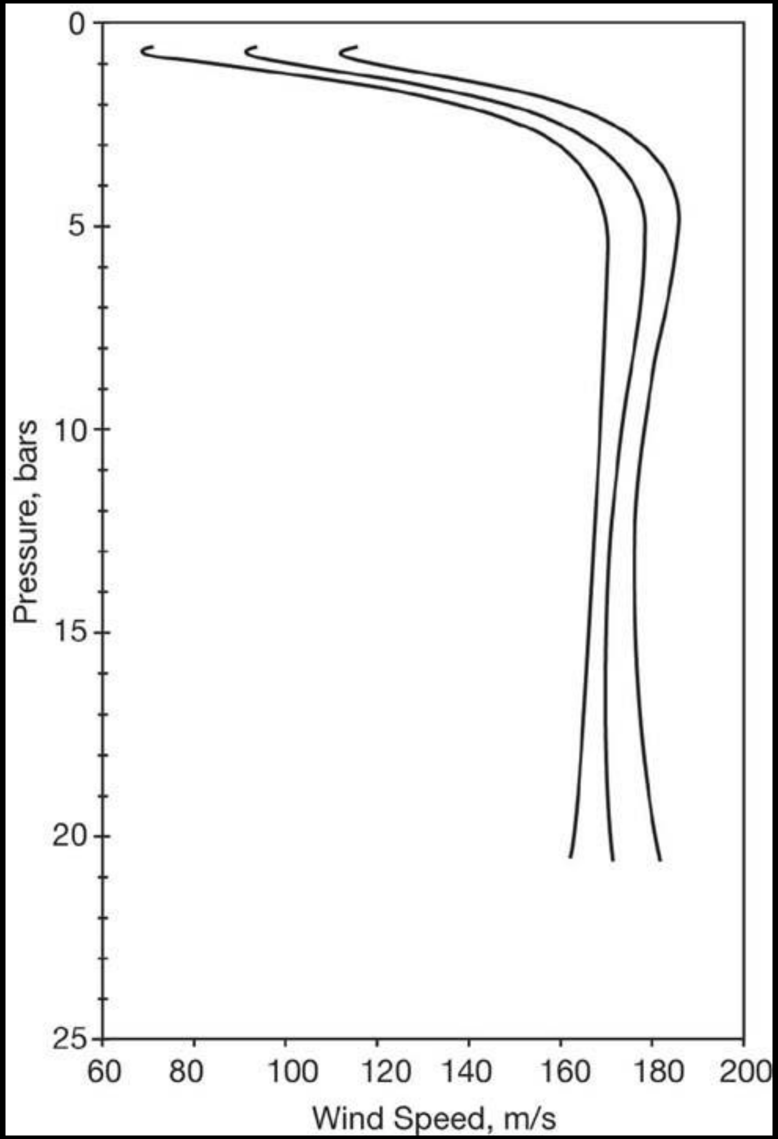
Statistical significance test for other wind profiles



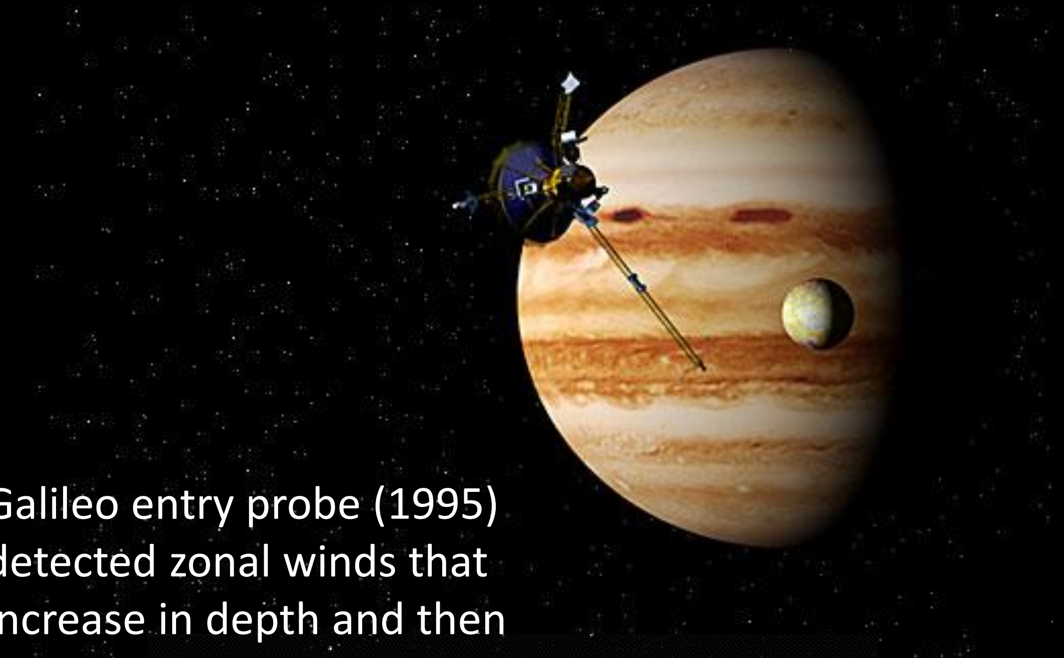
With high likelihood the meridional profile of the flow at depth does not vary from that at the cloud-level (mainly at low-latitudes)

Kaspi et al., 2018
Duer et al., 2020

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.