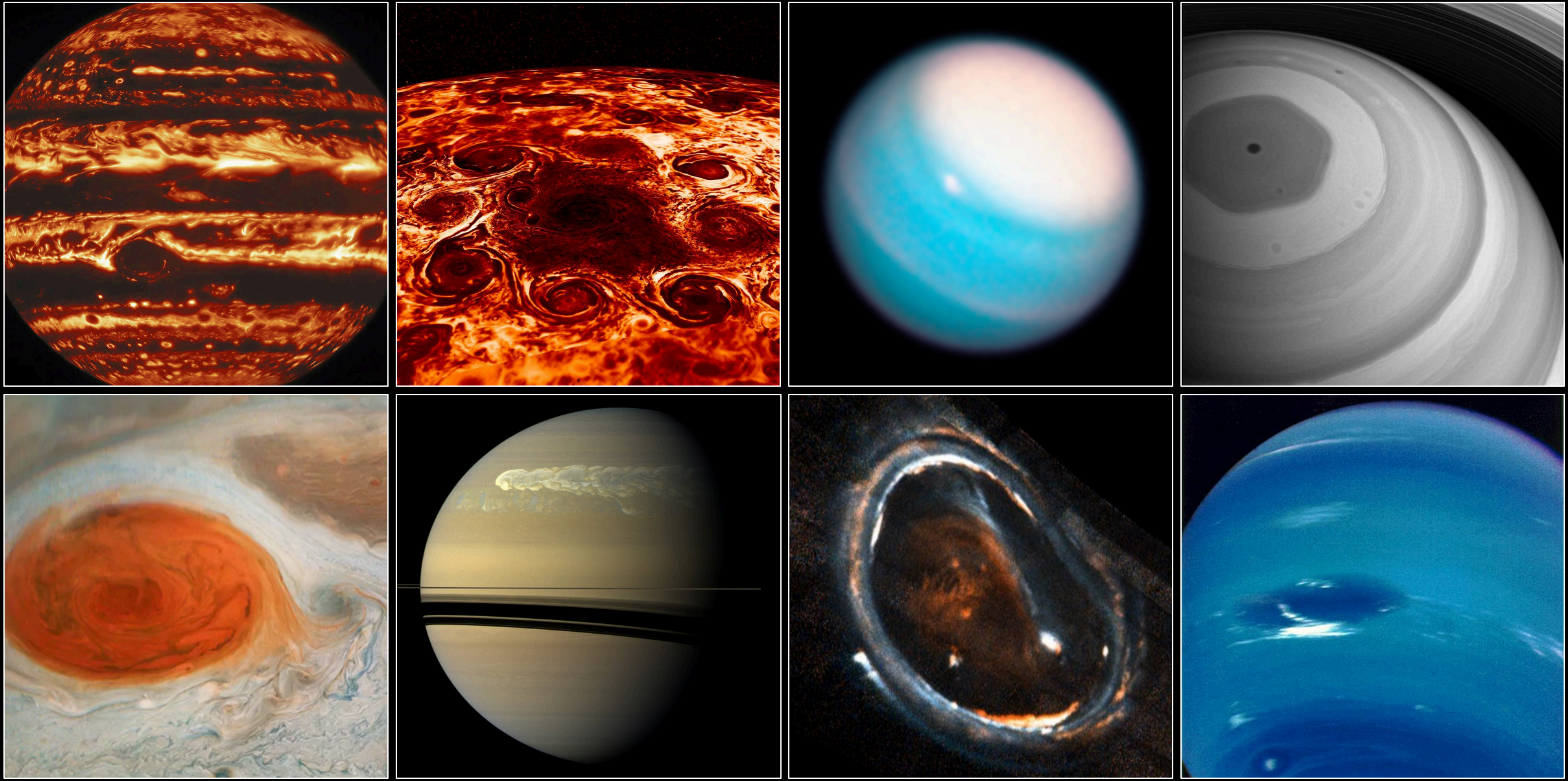
Linking atmospheres & interiors
Lessons from Juno

Tristan Guillot

Observatoire de la Côte d’Azur

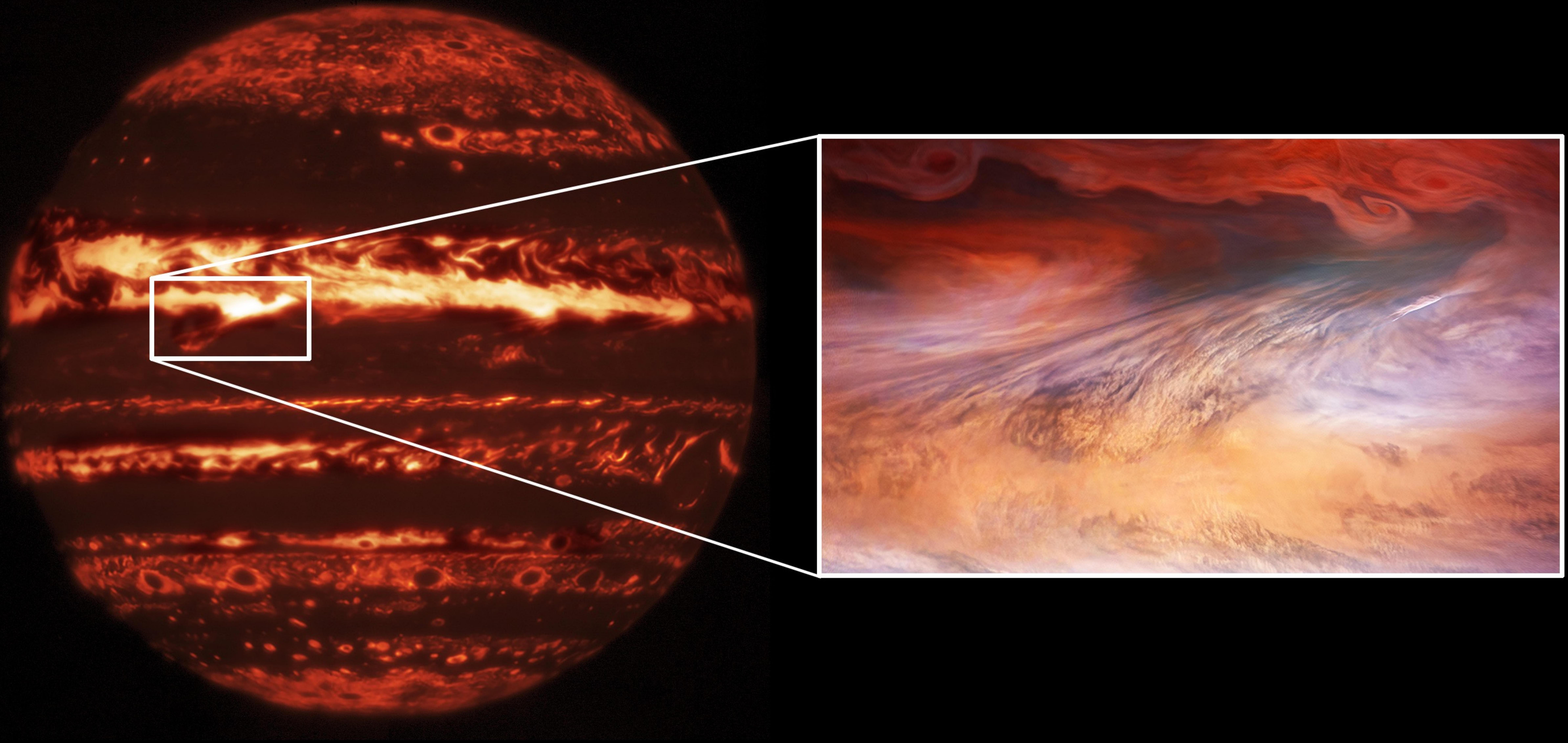
Les Houches, *Exoatmospheres*, 20 September 2022



Giant Planets from the Inside Out

Guillot, Fletcher, Helled, Ikoma, Line & Parmentier, *Protostars & Planets VII* (arXiv 2022)

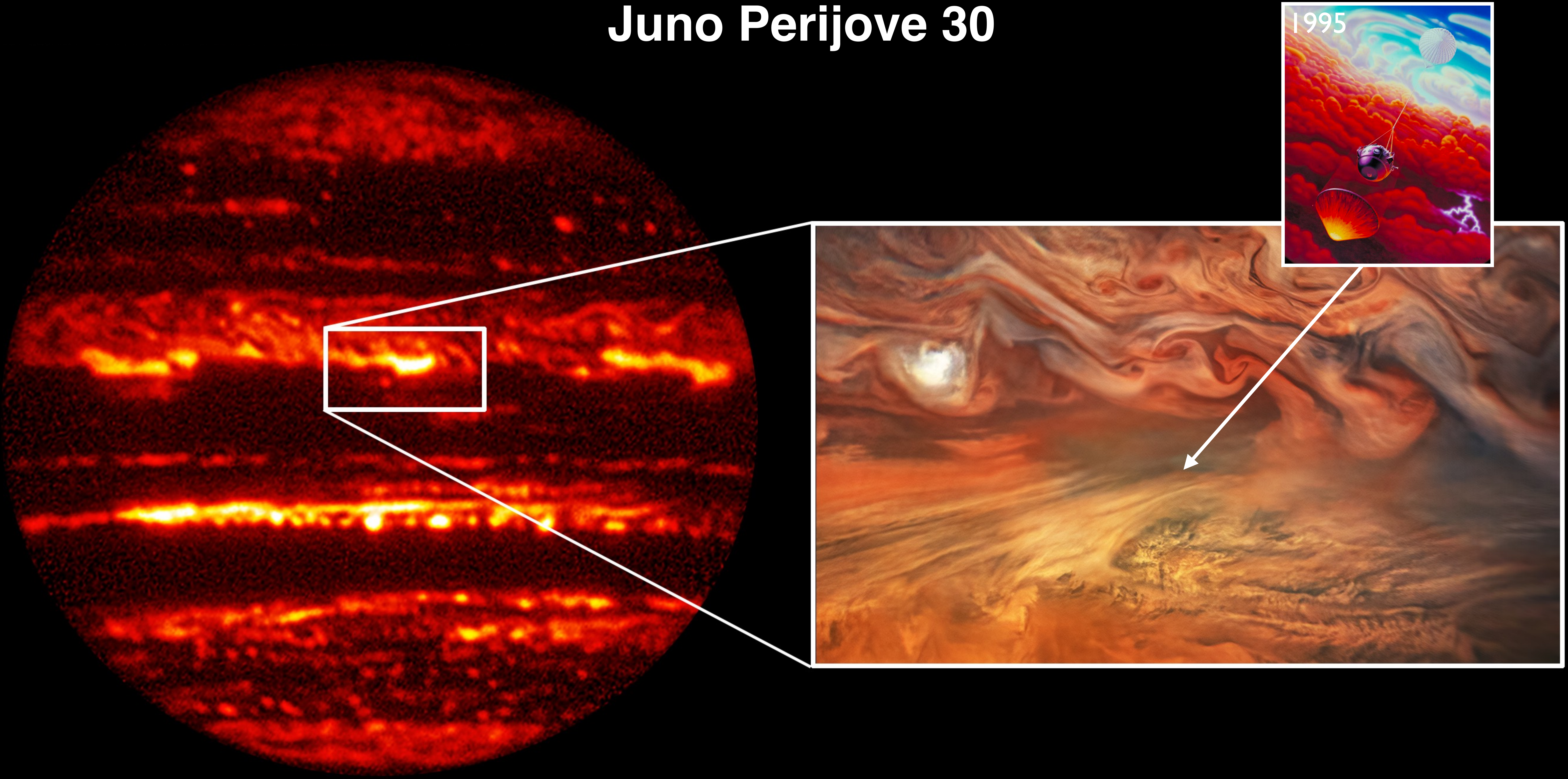
Juno Perijove 29



Gemini / NIRI 5 μm

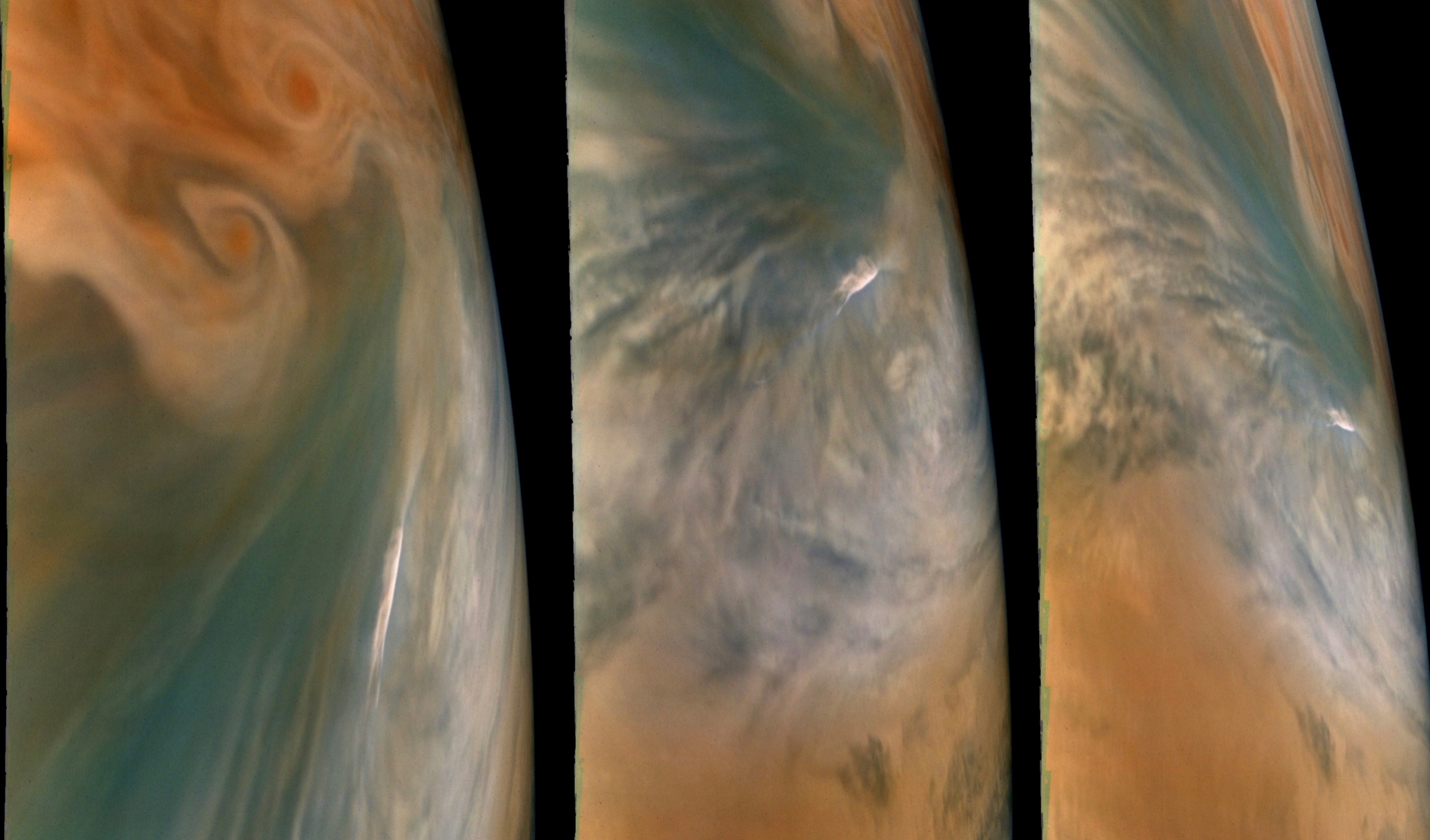
JunoCam

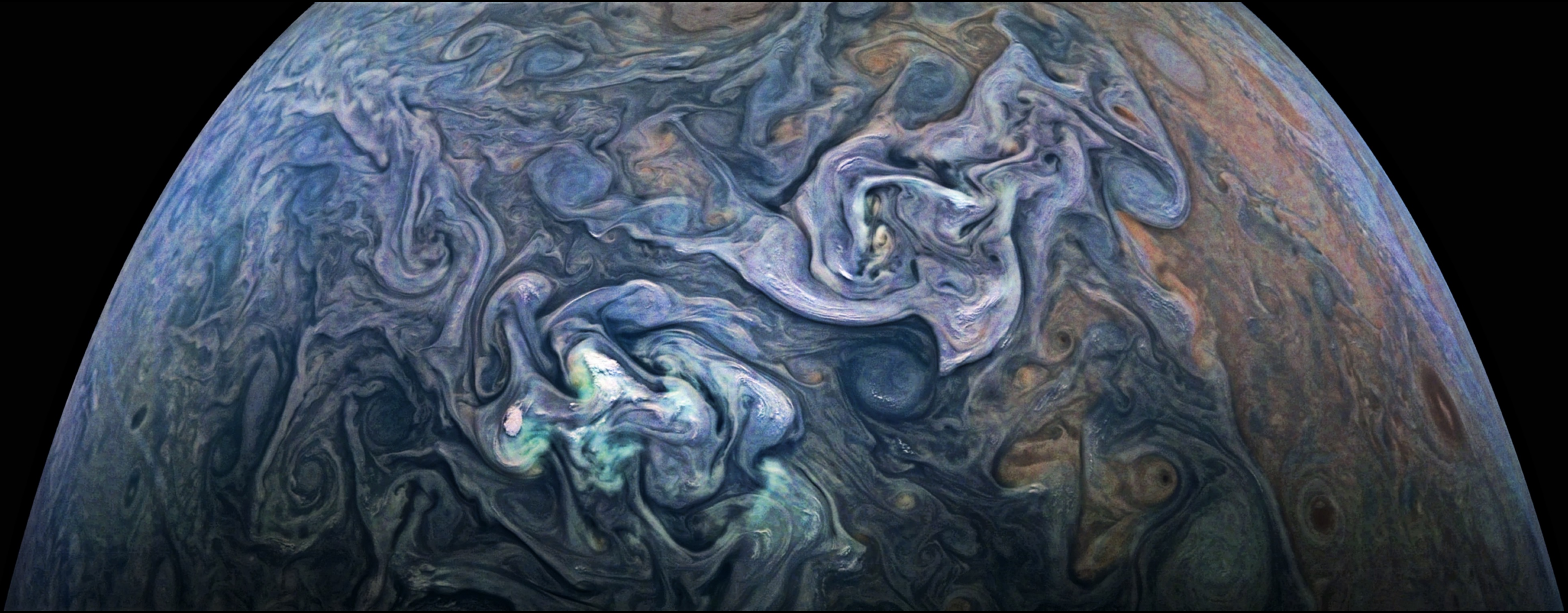
Juno Perijove 30



NASA / IRTF 5 μm

JunoCam





NASA / JPL-Caltech / SwRI / MSSS / Gerald Eichstädt

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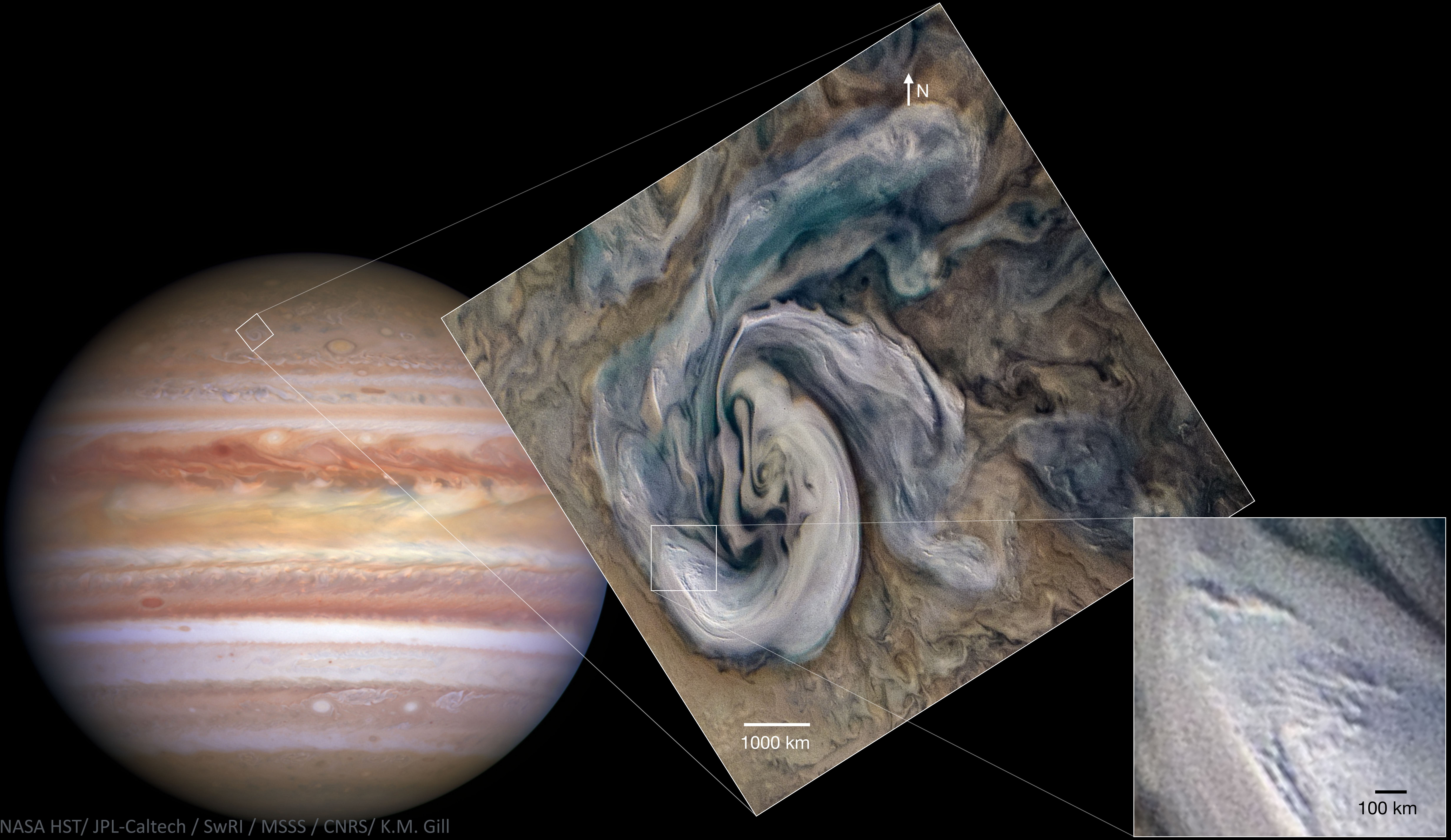

NASA HST/ JPL-Caltech / SwRI / MSSS / CNRS/ K.M. Gill

NASA / JPL-Caltech / SwRI / MSSS / Gerald Eichstädt

Outline

- Why studying giant planets?
- The formation of giant planets: basics
- Mission Juno
- Modeling the interiors of giant planets
- Jupiter's interior structure
  - How were heavy elements delivered?
- Jupiter's zonal flows
- Jupiter's inhomogeneous deep atmosphere
- Consequences for Exoplanets
- Why we need a mission to Uranus or Neptune

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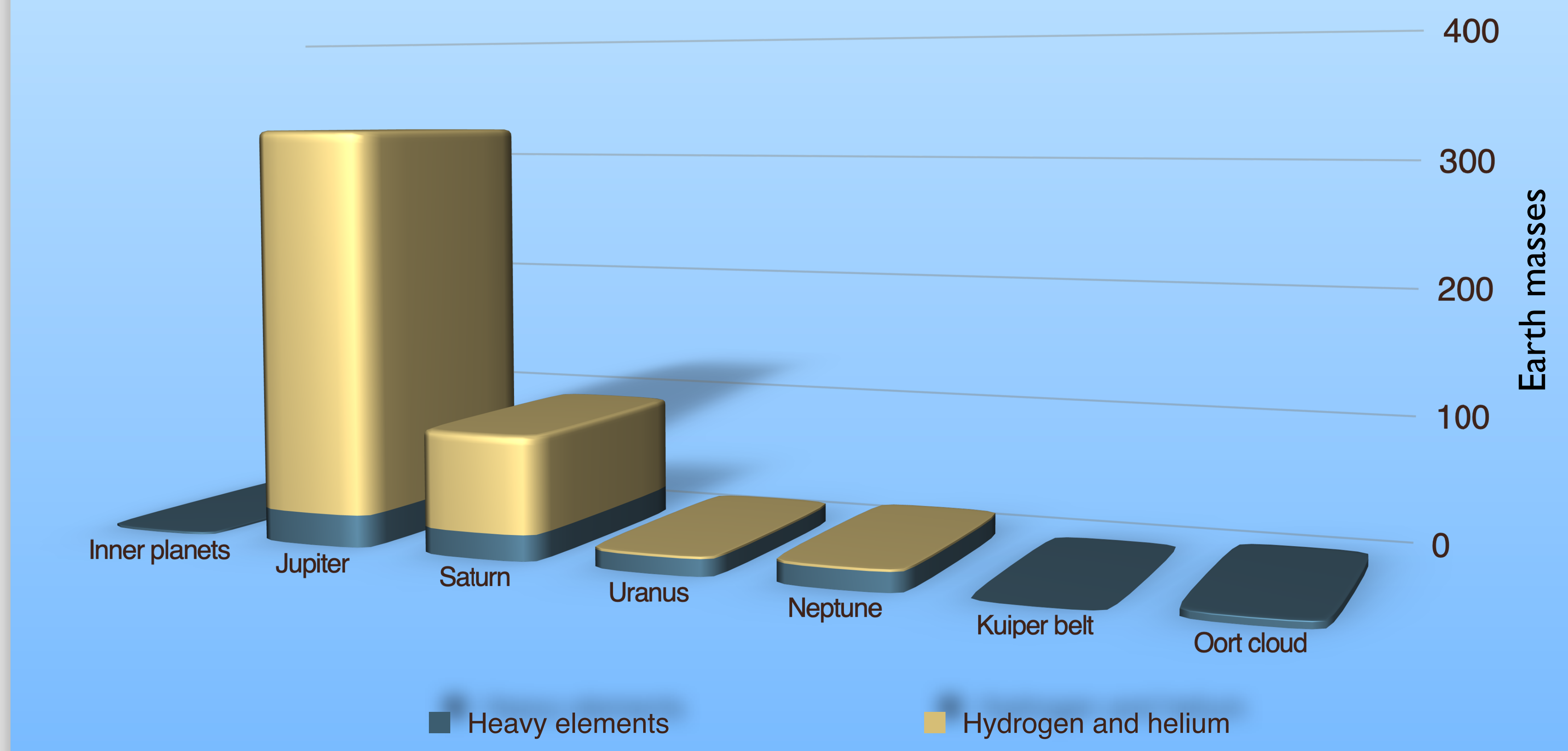
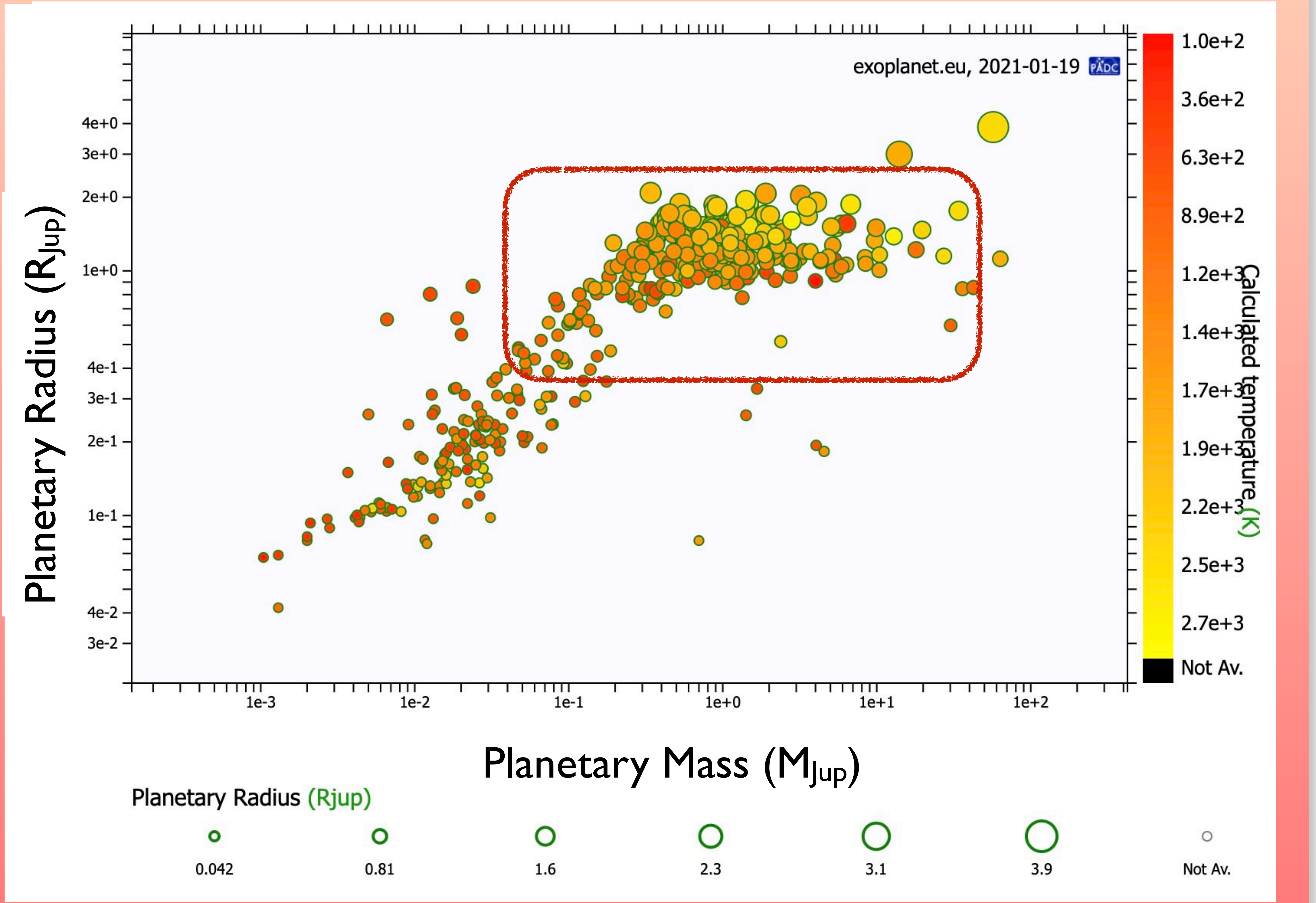
Completing the inventory

In our Solar System



Giant planets possess 99.5% of all the mass in the Solar System except the Sun

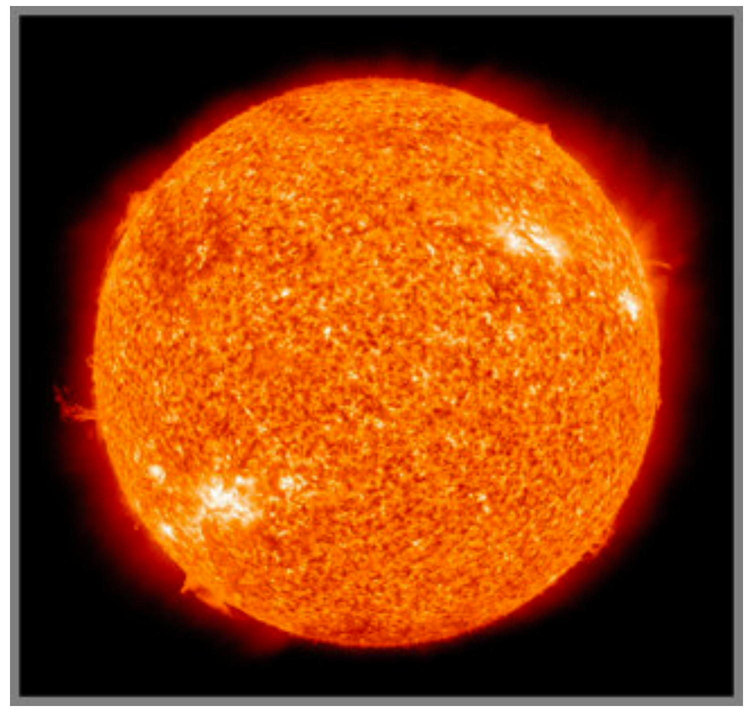
In the Galaxy



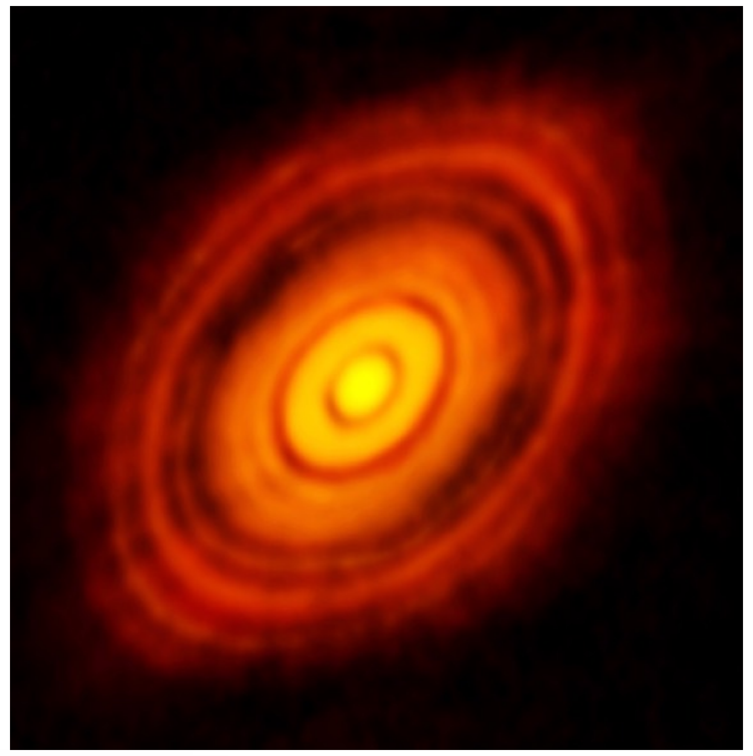
Giant planets represent a rich source of information (composition, history…)

detailed information ⟺ statistics

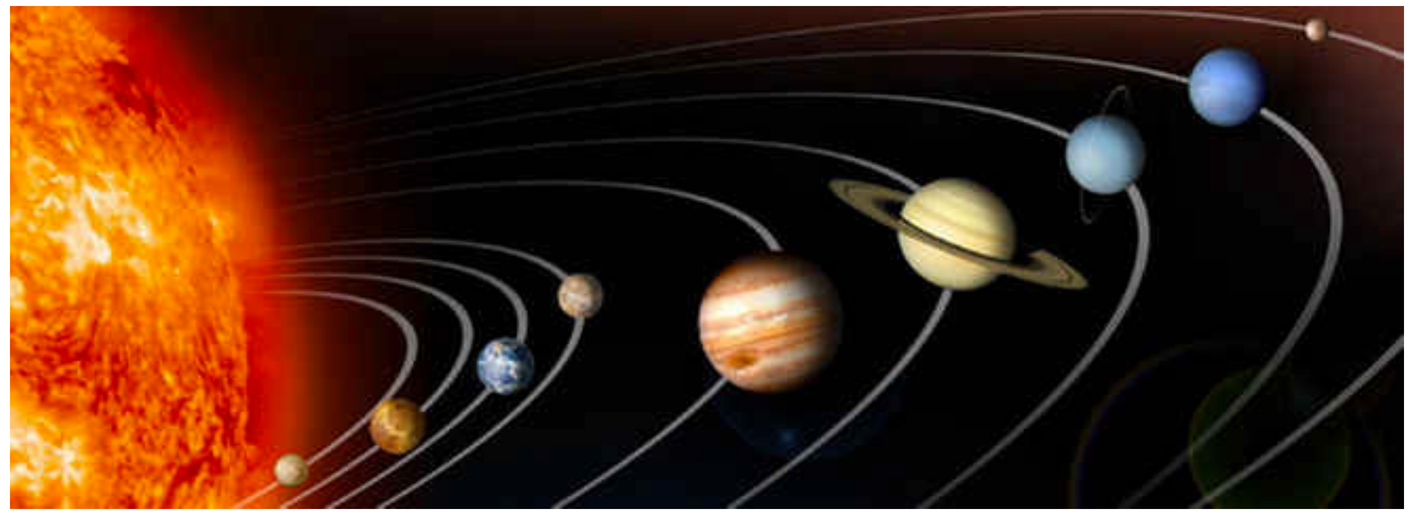
Completing the inventory: Z elements



5000 $M_\oplus$



500 $M_\oplus$?



~100 $M_\oplus$

+ejected

~100-200 $M_\oplus$

Assuming solids started forming planetesimals no earlier than when the disk was 0.1 M_{sun},
20-30% of solids must have formed planets

Kunitomo et al. (2018)
see also Manara et al. (2018)

Completing the inventory: atmospheric Z/Z⊙

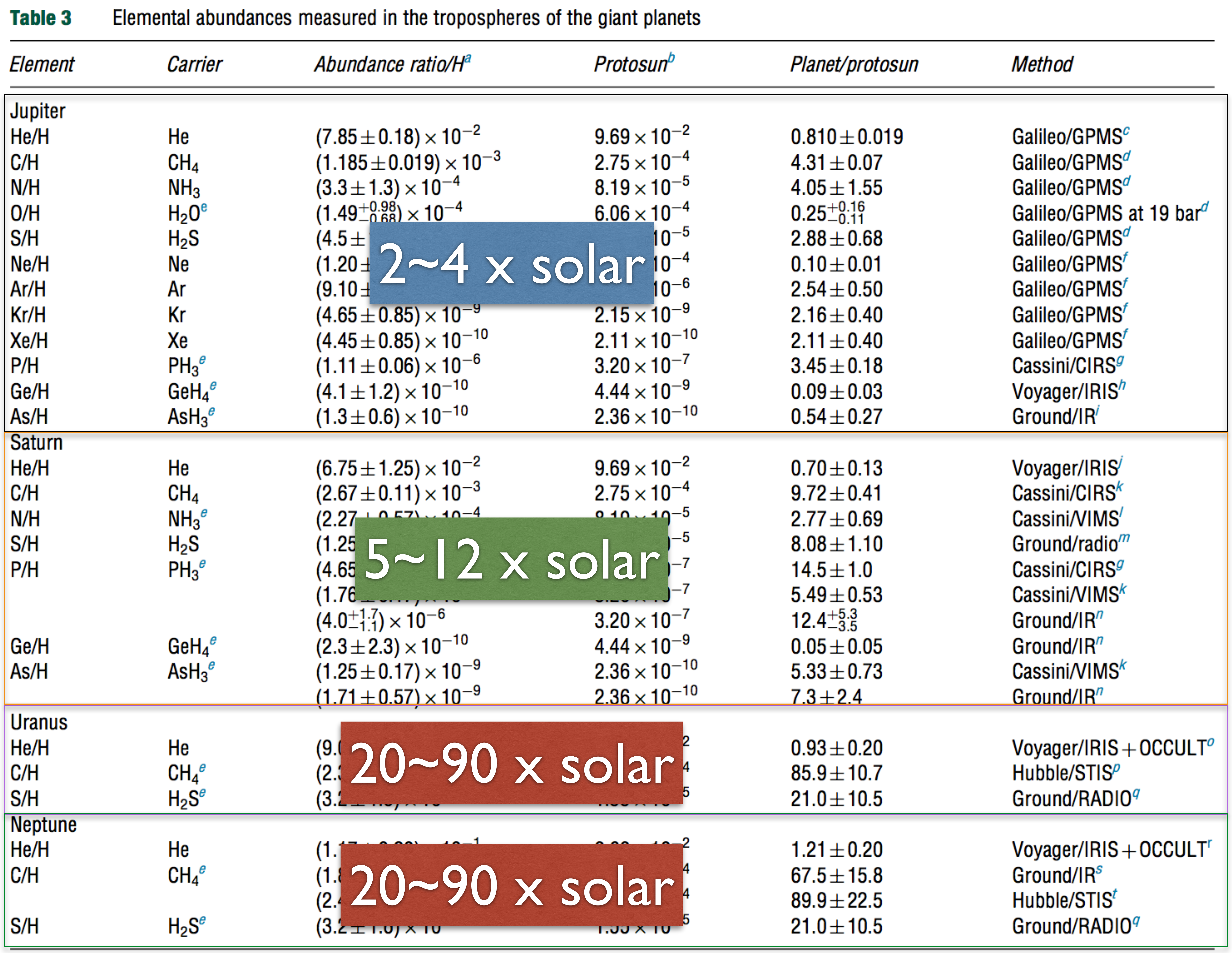


Table 3 Elemental abundances measured in the tropospheres of the giant planets

Element	*Carrier*	*Abundance ratio/H*[a]	*Protosun*[b]	*Planet/protosun*	*Method*
Jupiter					
He/H	He	$(7.85 \pm 0.18) \times 10^{-2}$	9.69×10^{-2}	0.810 ± 0.019	Galileo/GPMS[c]
C/H	CH_4	$(1.185 \pm 0.019) \times 10^{-3}$	2.75×10^{-4}	4.31 ± 0.07	Galileo/GPMS[d]
N/H	NH_3	$(3.3 \pm 1.3) \times 10^{-4}$	8.19×10^{-5}	4.05 ± 1.55	Galileo/GPMS[d]
O/H	H_2O[e]	$(1.49^{+0.98}_{-0.68}) \times 10^{-4}$	6.06×10^{-4}	$0.25^{+0.16}_{-0.11}$	Galileo/GPMS at 19 bar[d]
S/H	H_2S	$(4.5 \pm$	10^{-5}	2.88 ± 0.68	Galileo/GPMS[d]
Ne/H	Ne	$(1.20 \pm$	10^{-4}	0.10 ± 0.01	Galileo/GPMS[f]
Ar/H	Ar	$(9.10 \pm$	10^{-6}	2.54 ± 0.50	Galileo/GPMS[f]
Kr/H	Kr	$(4.65 \pm 0.85) \times 10^{-9}$	2.15×10^{-9}	2.16 ± 0.40	Galileo/GPMS[f]
Xe/H	Xe	$(4.45 \pm 0.85) \times 10^{-10}$	2.11×10^{-10}	2.11 ± 0.40	Galileo/GPMS[f]
P/H	PH_3[e]	$(1.11 \pm 0.06) \times 10^{-6}$	3.20×10^{-7}	3.45 ± 0.18	Cassini/CIRS[g]
Ge/H	GeH_4[e]	$(4.1 \pm 1.2) \times 10^{-10}$	4.44×10^{-9}	0.09 ± 0.03	Voyager/IRIS[h]
As/H	AsH_3[e]	$(1.3 \pm 0.6) \times 10^{-10}$	2.36×10^{-10}	0.54 ± 0.27	Ground/IR[i]
Saturn					
He/H	He	$(6.75 \pm 1.25) \times 10^{-2}$	9.69×10^{-2}	0.70 ± 0.13	Voyager/IRIS[j]
C/H	CH_4	$(2.67 \pm 0.11) \times 10^{-3}$	2.75×10^{-4}	9.72 ± 0.41	Cassini/CIRS[k]
N/H	NH_3[e]	$(2.27 \pm 0.57) \times 10^{-4}$	8.19×10^{-5}	2.77 ± 0.69	Cassini/VIMS[l]
S/H	H_2S	$(1.25$	$^{-5}$	8.08 ± 1.10	Ground/radio[m]
P/H	PH_3[e]	$(4.65$	$^{-7}$	14.5 ± 1.0	Cassini/CIRS[g]
		$(1.76$	$^{-7}$	5.49 ± 0.53	Cassini/VIMS[k]
		$(4.0^{+1.7}_{-1.1}) \times 10^{-6}$	3.20×10^{-7}	$12.4^{+5.3}_{-3.5}$	Ground/IR[n]
Ge/H	GeH_4[e]	$(2.3 \pm 2.3) \times 10^{-10}$	4.44×10^{-9}	0.05 ± 0.05	Ground/IR[n]
As/H	AsH_3[e]	$(1.25 \pm 0.17) \times 10^{-9}$	2.36×10^{-10}	5.33 ± 0.73	Cassini/VIMS[k]
		$(1.71 \pm 0.57) \times 10^{-9}$	2.36×10^{-10}	7.3 ± 2.4	Ground/IR[n]
Uranus					
He/H	He	$(9.$	^{2}	0.93 ± 0.20	Voyager/IRIS + OCCULT[o]
C/H	CH_4[e]	$(2.$	^{4}	85.9 ± 10.7	Hubble/STIS[p]
S/H	H_2S[e]	$(3.2$	^{5}	21.0 ± 10.5	Ground/RADIO[q]
Neptune					
He/H	He	$(1.$	^{2}	1.21 ± 0.20	Voyager/IRIS + OCCULT[r]
C/H	CH_4[e]	$(1.$	^{4}	67.5 ± 15.8	Ground/IR[s]
		$(2.$	^{4}	89.9 ± 22.5	Hubble/STIS[t]
S/H	H_2S[e]	$(3.2$	^{5}	21.0 ± 10.5	Ground/RADIO[q]

Jupiter

2~4 x solar

Saturn

5~12 x solar

Uranus

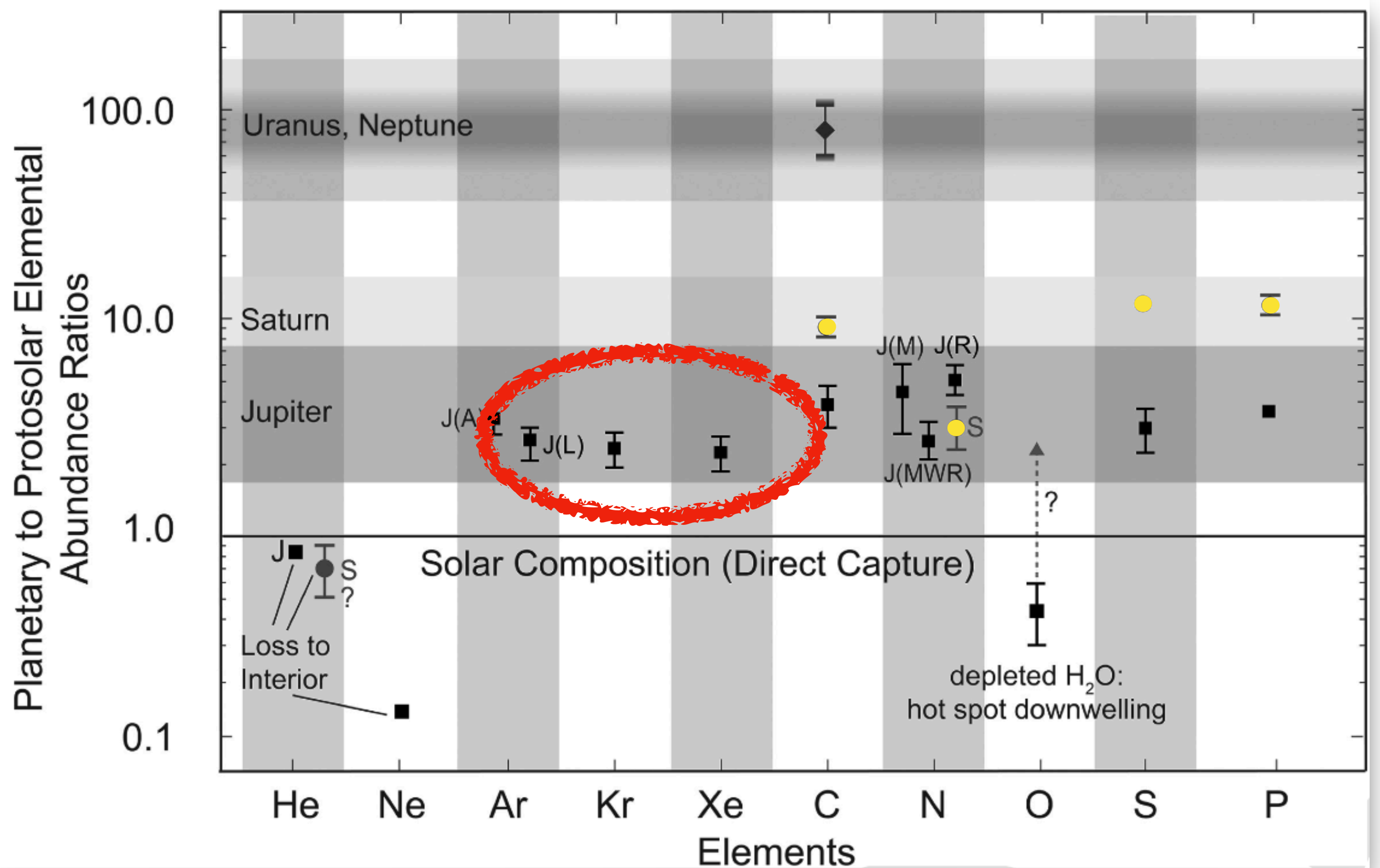
20~90 x solar

Neptune

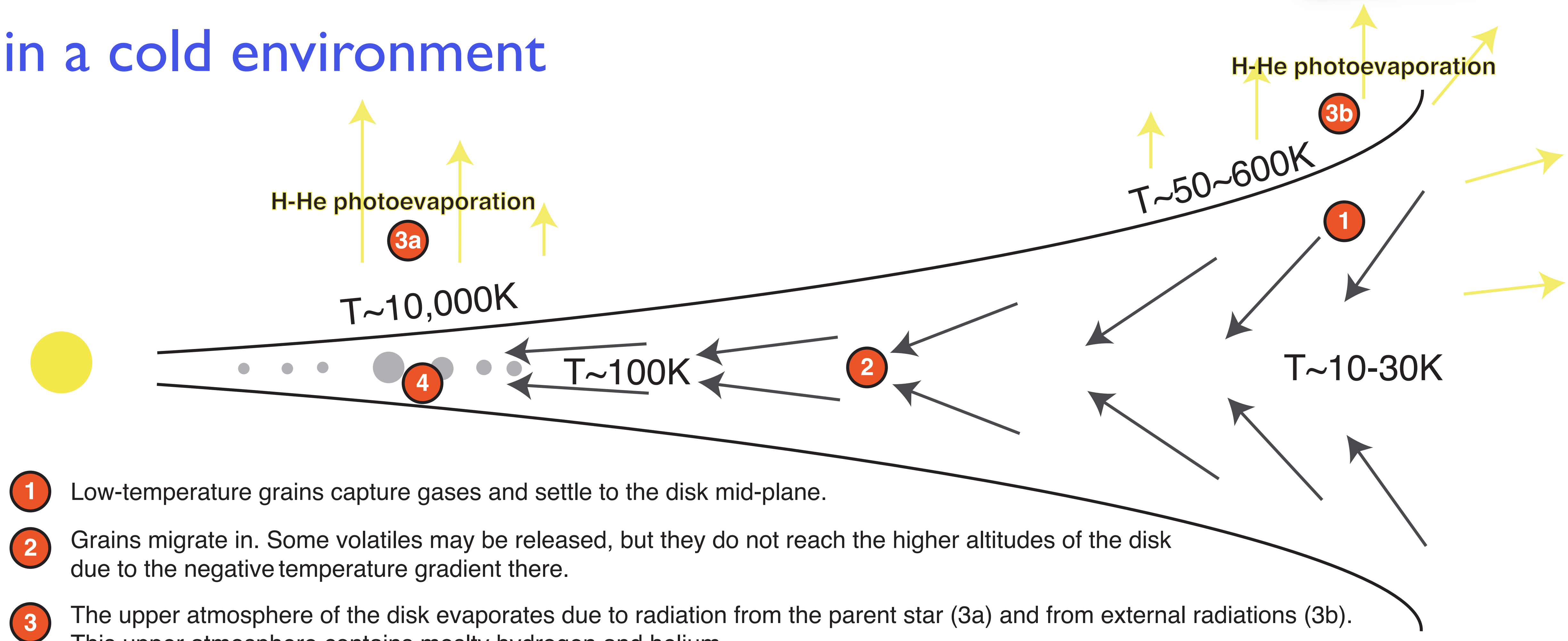
20~90 x solar

from Guillot & Gautier (2015)

Jupiter’s noble gases and disk photo evaporation



- Enriched in Jupiter
  - 2-3x solar
  - even though they are very difficult to trap in solids!
- How were they delivered?
  - formation of Jupiter in a cold environment
  - clathration
  - photoevaporation



① Low-temperature grains capture gases and settle to the disk mid-plane.

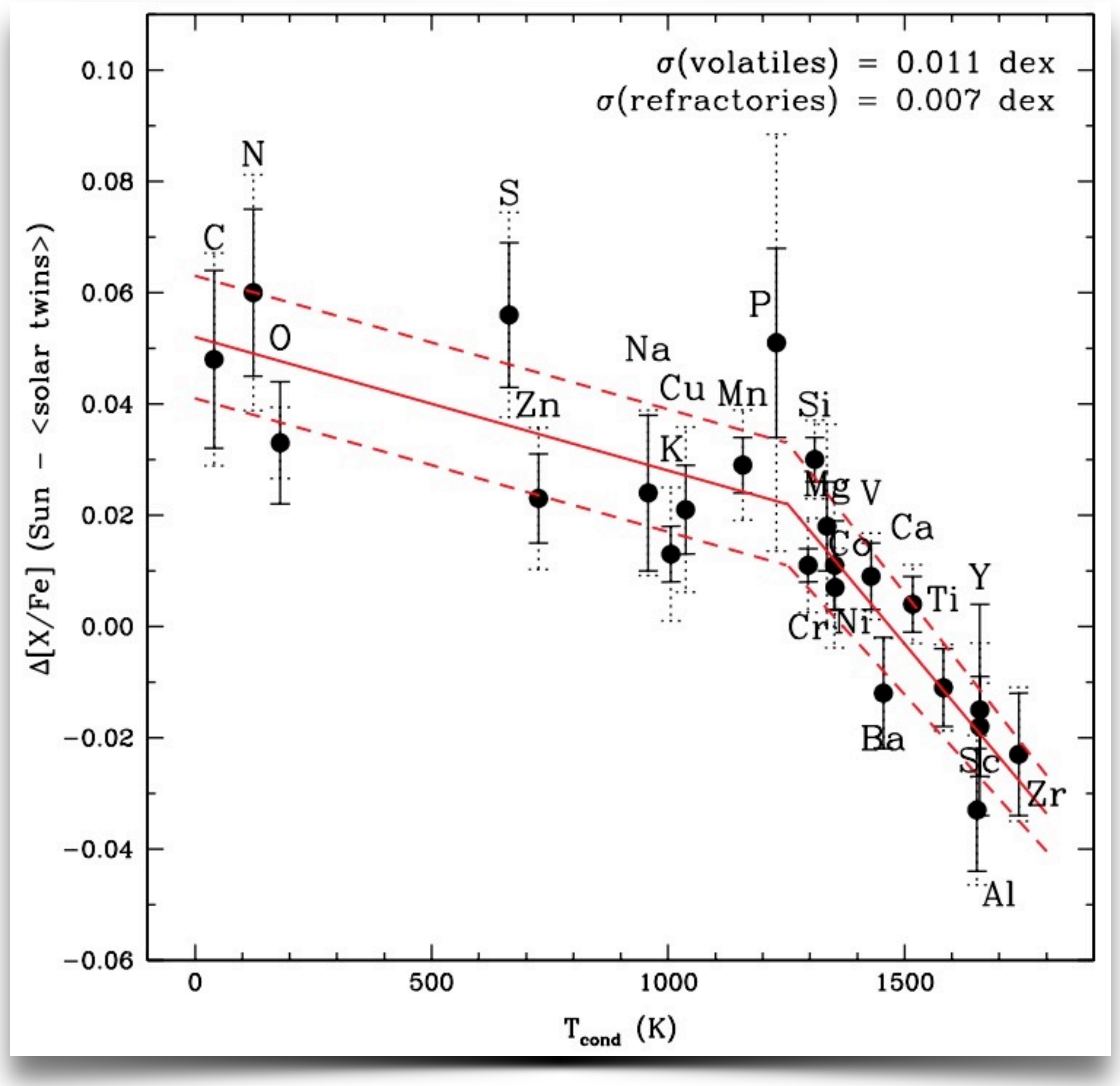
② Grains migrate in. Some volatiles may be released, but they do not reach the higher altitudes of the disk due to the negative temperature gradient there.

③ The upper atmosphere of the disk evaporates due to radiation from the parent star (3a) and from external radiations (3b). This upper atmosphere contains moslty hydrogen and helium.

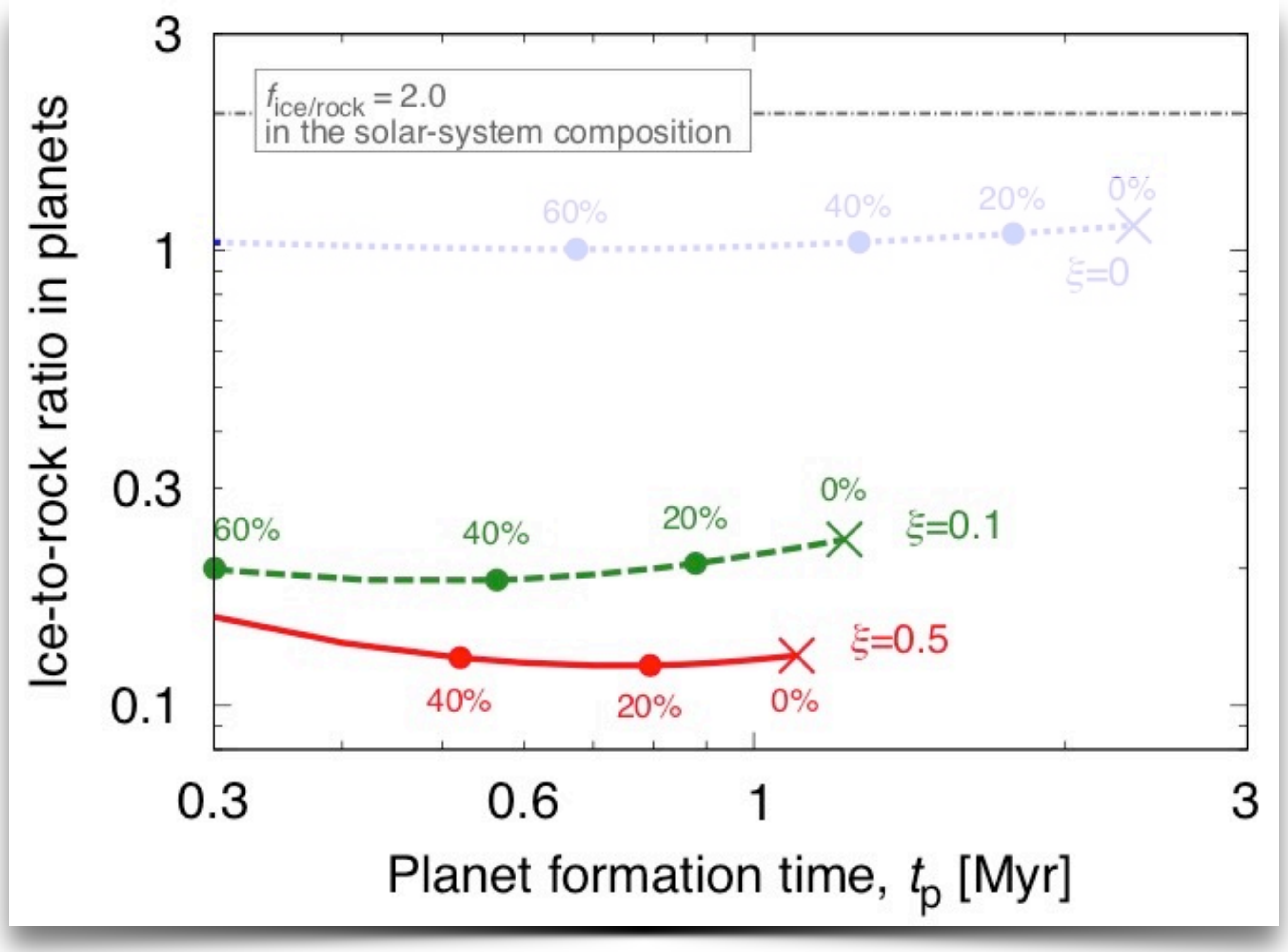
④ Giant protoplanets gradually capture a disk gas which is enriched in non-hydrogen-helium species.

Guillot & Hueso (MNRAS, 2006)
Atreya et al., Saturn book (2018)
see also Monga & Desch (2015)

The Sun’s composition and the I/R ratio in giant planets



Melendez et al. (2009)



Kunitomo et al. (2018)

The lack of refractory
elements in the Sun
compared to solar twins

…may be explained by…

planet formation
if the ice-to-rock ratio in **giant** planets
is very low (~0.2)

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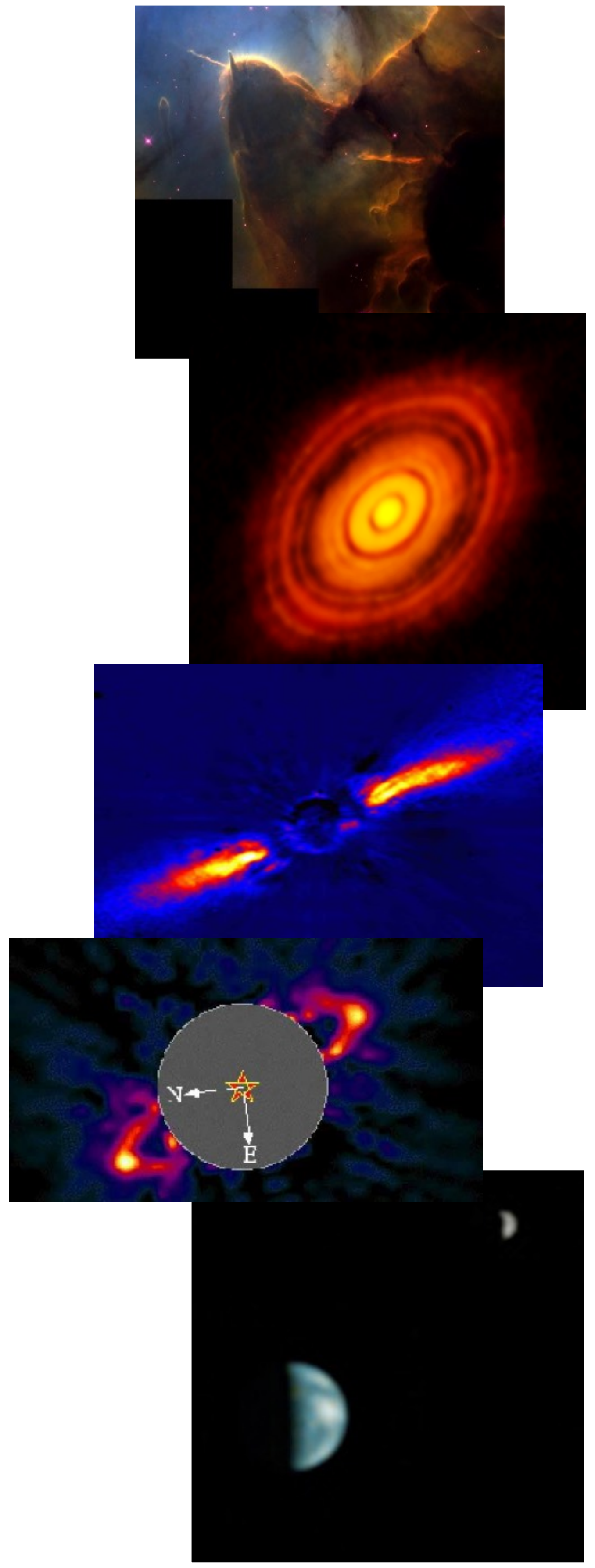
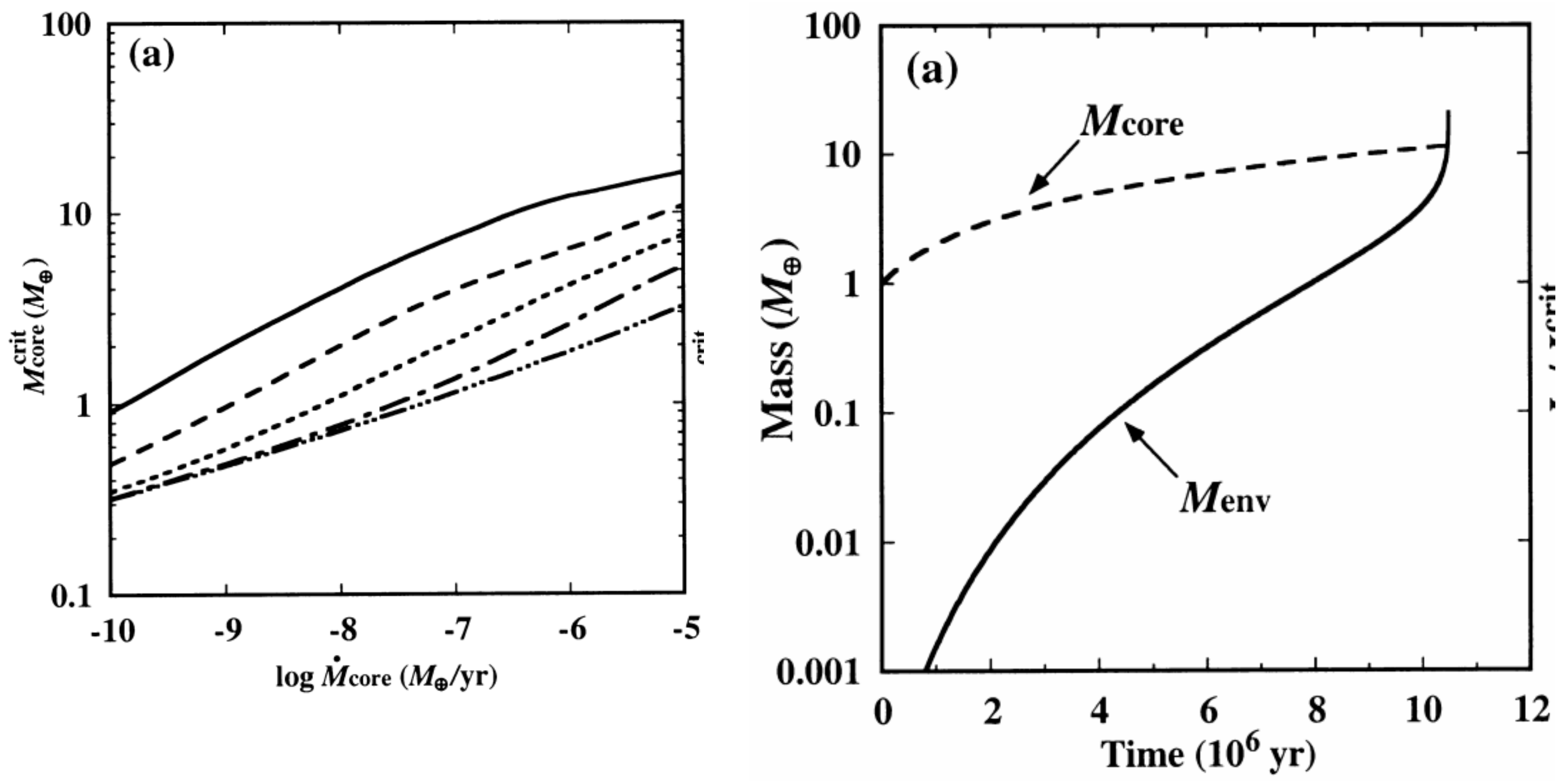
The steps towards giant planet formation



- A circumstellar disk form from the collapse of a molecular cloud core and spreads viscously (e.g., Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974, Shu 1977)
  - The collapse of the cloud takes $\sim 10^5$ yrs, disk spreading takes 10^6 to 10^8 yrs.
- Planetesimals (1-10km) form rapidly (e.g., Weidenschilling 1980)
  - Settling to the mid-plane + gravitational instabilities lead to a formation of planetesimals in 10^4 to 10^5 yrs.
- Runaway growth: (Greenberg et al. 1978; Wetherill & Steward 1989; Ida & Makino 1992)
  - Gravitational focusing means that large embryos grow at the expense of small ones
  - This phase ends when relative velocities become too large, i.e., for masses around a Ceres mass, and in $\sim 10^5$ yrs
- Oligarchic growth (Kokubo & Ida 1998, Thommes et al. 2003)
  - Slower growth of oligarchs by accretion of smaller embryos.
  - This phase ends when the mass in small planetesimals has become too small to damp the eccentricities of large embryos. This occurs for masses between moon mass at 1 au and up to 10 M_{Earth} at 10 au, on timescales of $\sim 10^5$ yrs to several 10^6 yrs.

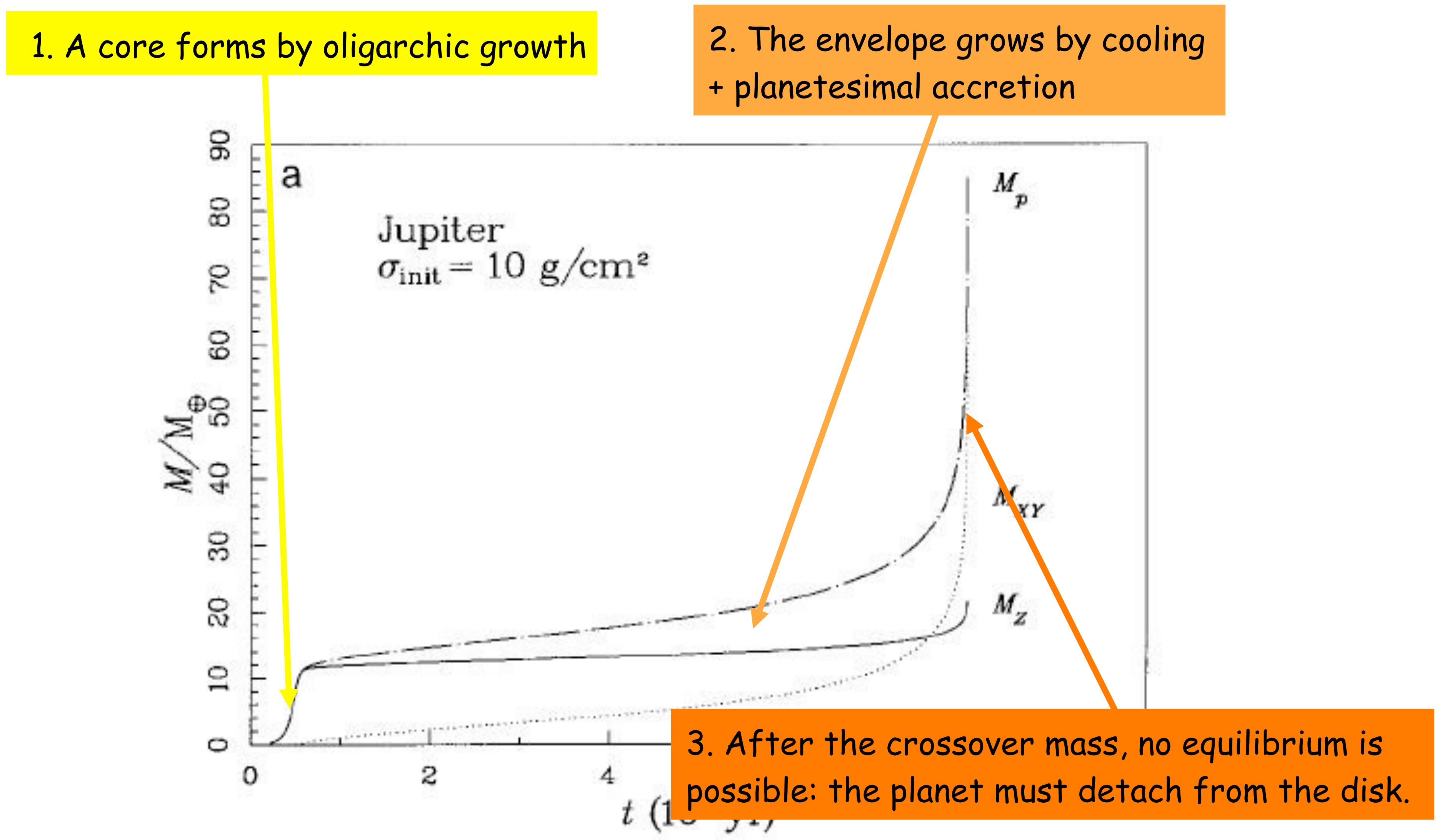
The steps towards giant planet formation

- Past a certain mass, a growing protoplanetary core cannot be in hydrostatic equilibrium with the circumstellar disk: it must accrete hydrogen and helium (Mizuno 1980, Stevenson 1981)



Ikoma et al. (2000)

- Giant planets grow by the accretion of a solid core, the cooling of the surrounding envelope, followed by runaway growth (Pollack et al. 1996)
  - Phase I is generally 1Myr or less, Phase II is a few Myr, Phase III may be extremely quick (<0.1 Myr) but may slowed if the gas supply is limited.



1. A core forms by oligarchic growth

2. The envelope grows by cooling + planetesimal accretion

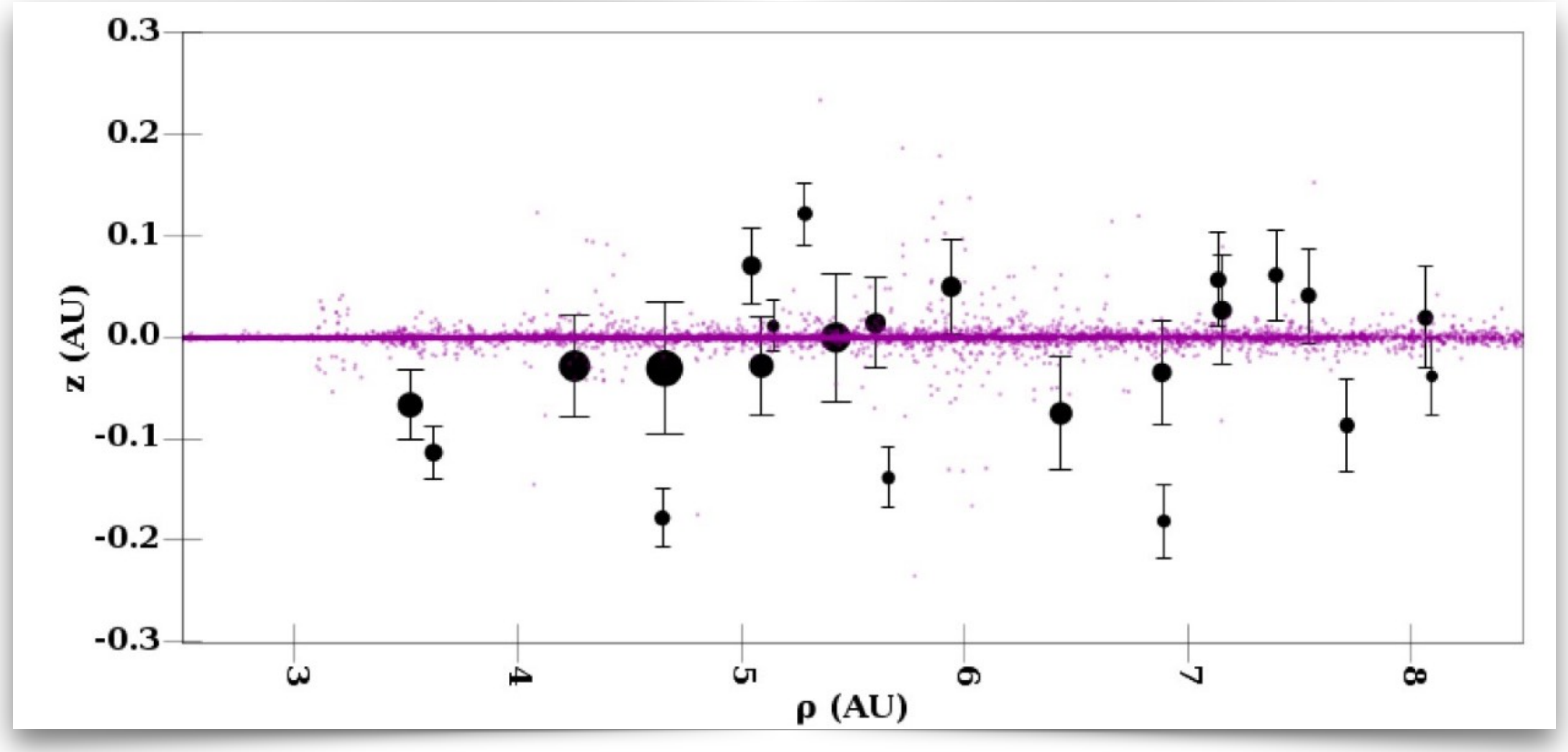
3. After the crossover mass, no equilibrium is possible: the planet must detach from the disk.

Pollack et al. (1996)

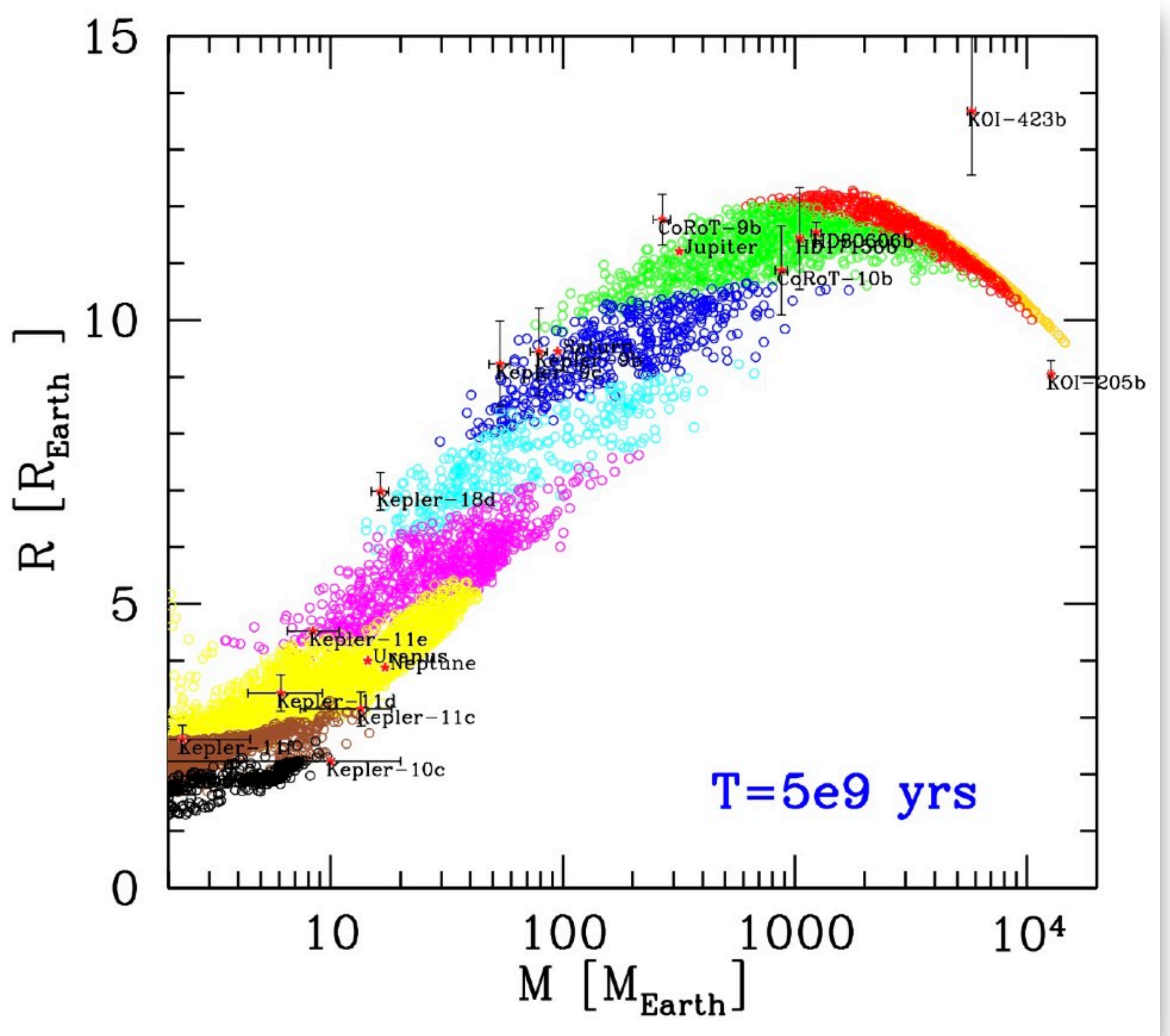
The steps towards giant planet formation

- Modern models of planet formation must include several complications
  - An evolving protoplanetary disk
  - Planet migration (i.e. the fact that planets can move in the protoplanetary disk and access new reservoirs of material)
  - A population of solids including different sources: micron-sized dust, pebbles, planetesimals
  - Photoevaporation
  - Tidal downsizing
  - Ice lines…

- Planet synthesis models can make predictions that can be usefully compared to exoplanet observations (see e.g., Ida & Lin 2004, 2013, Mordasini et al. 2012a,b, Alibert et al. 2018…etc, etc)

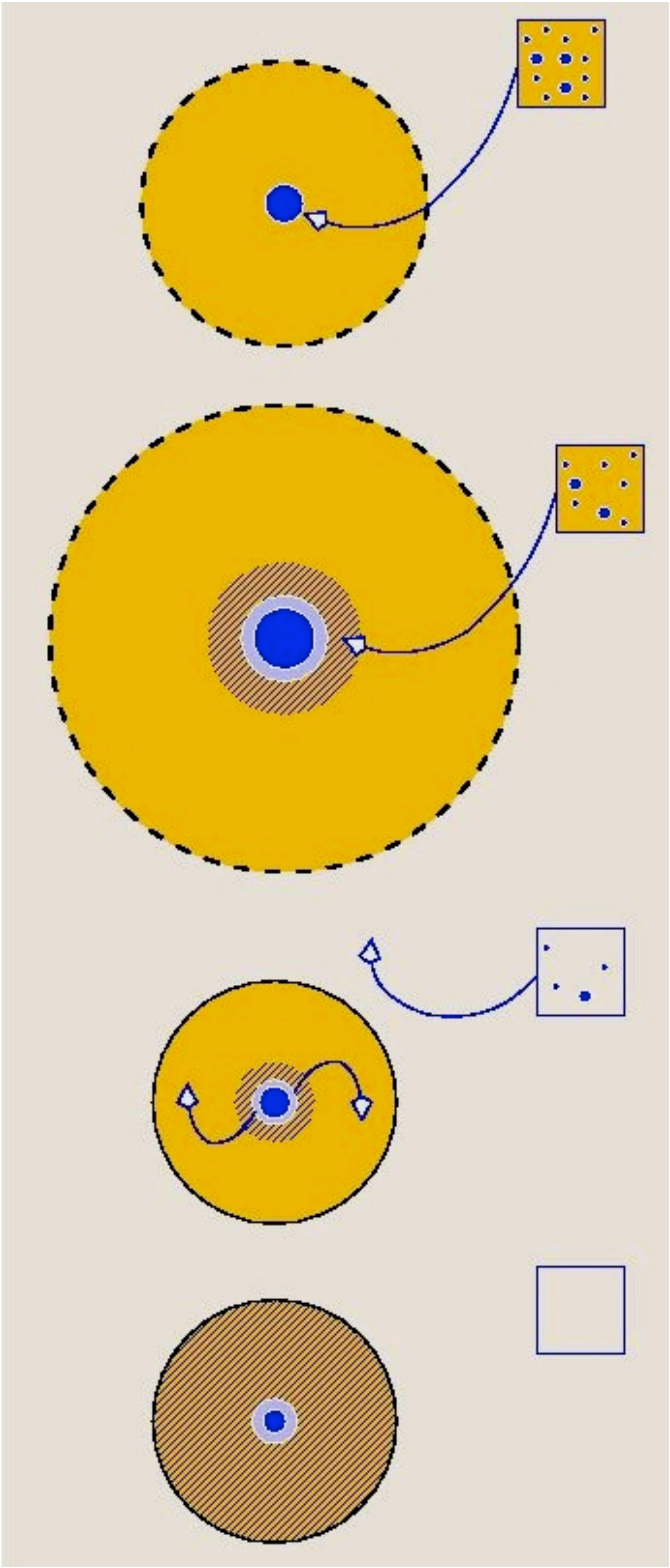


Levison et al. (2015)



Mordasini et al. (2012)

How to enrich giant planet atmospheres?



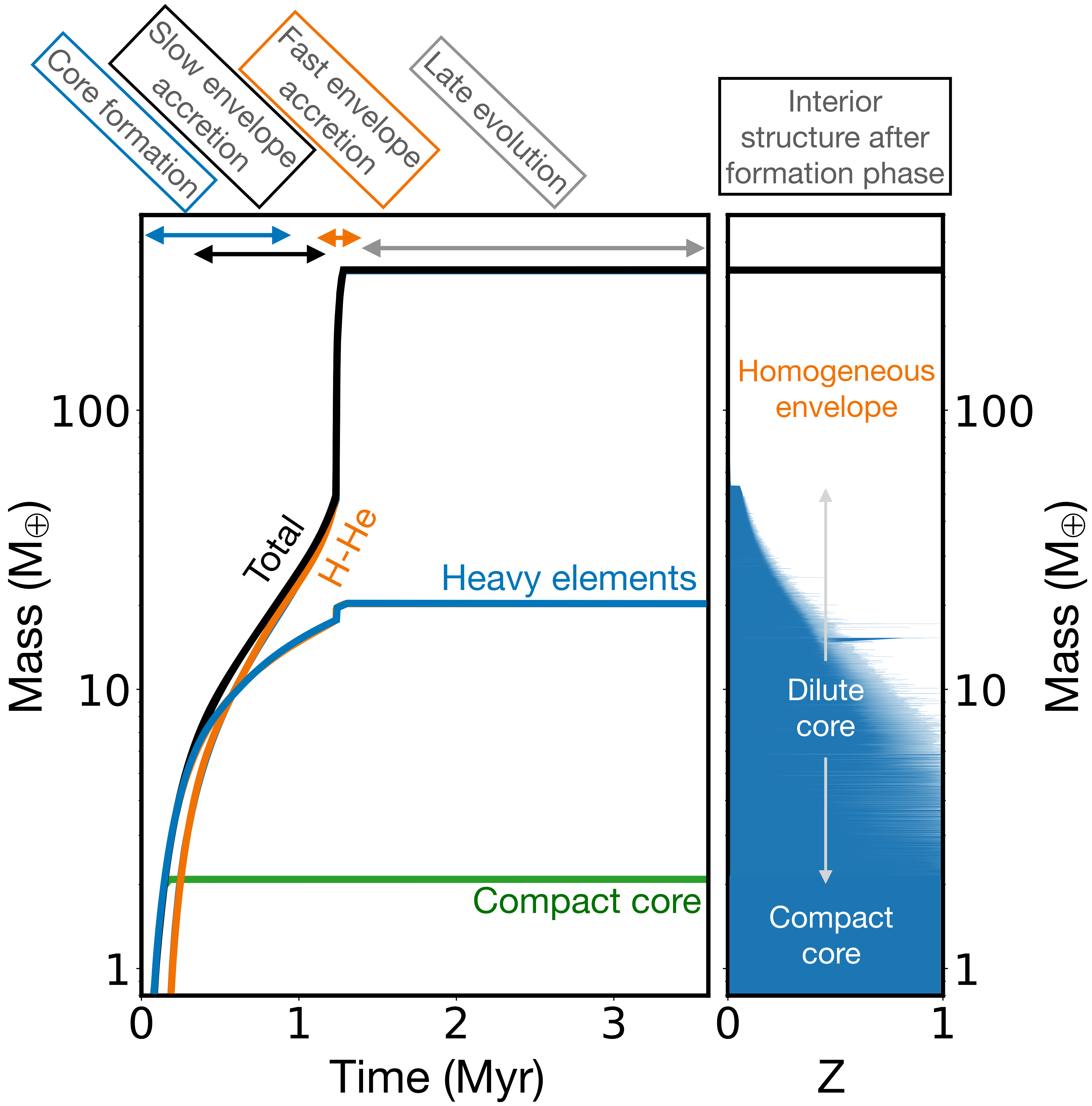
- Core accretion: planetesimals are delivered onto the central core.
- Core accretion: planetesimals cannot reach the core intact. (Podolak et al. 1988; Pollack et al. 1996)
- Envelope capture: accretion efficiency drops (Guillot & Gladman 2000): core erosion (see Guillot et al. 2004; Moll et al. 2017)?
- Present: enriched atmosphere.

or

- Heavies are accreted with the envelope because the feeding zone expands (e.g., Alibert et al. 2005; Lissauer et al. 2009; Lozovsky et al. 2017)

How to enrich giant planet atmospheres?

- During the slow envelope-accretion phase, solids and gas are accreted together
  - Up to tens of Earth masses may be accreted, although the precise value is very uncertain
  - Lozovsky et al. (2017), Helled & Stevenson (2017), Ormel et al. (2021)



Guillot et al., Protostars & Planets VII (arXiv 2022)

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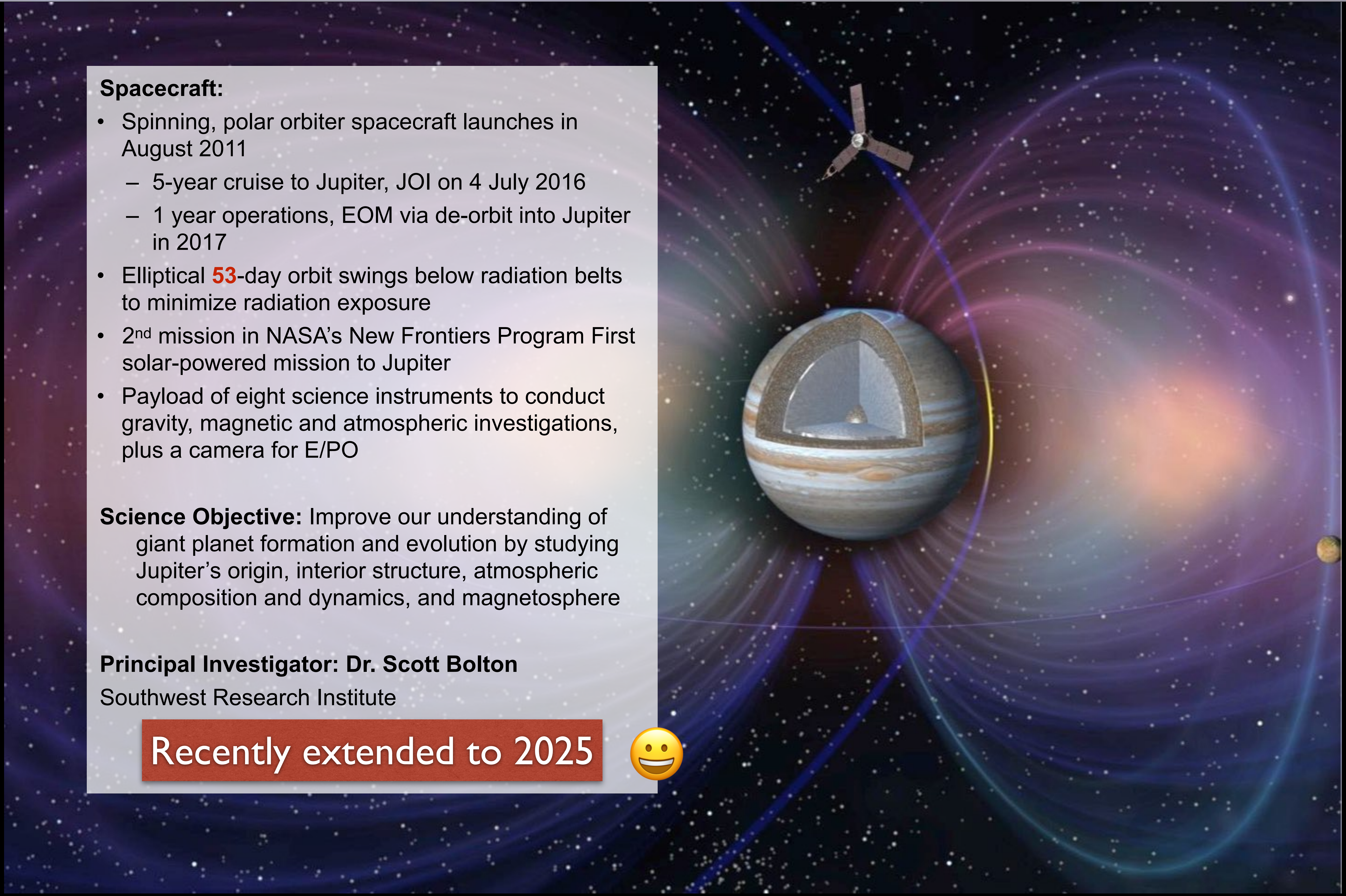
Jupiter Orbit Insertion: 4 July 2016

Juno in a few numbers



Spacecraft:

- Spinning, polar orbiter spacecraft launches in August 2011
  - 5-year cruise to Jupiter, JOI on 4 July 2016
  - 1 year operations, EOM via de-orbit into Jupiter in 2017
- Elliptical 53-day orbit swings below radiation belts to minimize radiation exposure
- 2nd mission in NASA's New Frontiers Program First solar-powered mission to Jupiter
- Payload of eight science instruments to conduct gravity, magnetic and atmospheric investigations, plus a camera for E/PO

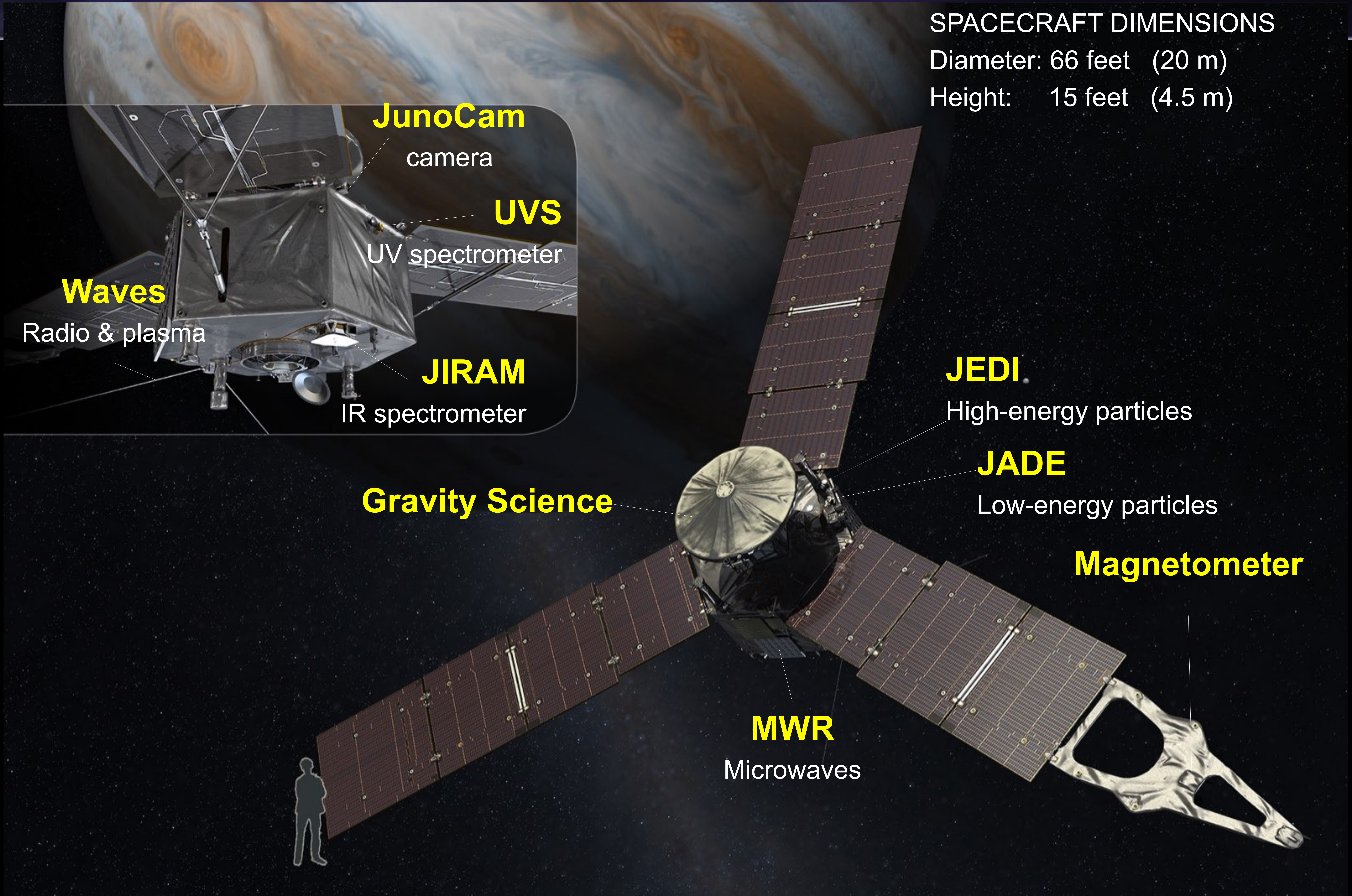
Science Objective: Improve our understanding of giant planet formation and evolution by studying Jupiter's origin, interior structure, atmospheric composition and dynamics, and magnetosphere

Principal Investigator: Dr. Scott Bolton

Southwest Research Institute

Recently extended to 2025 😀

Spacecraft & Payload



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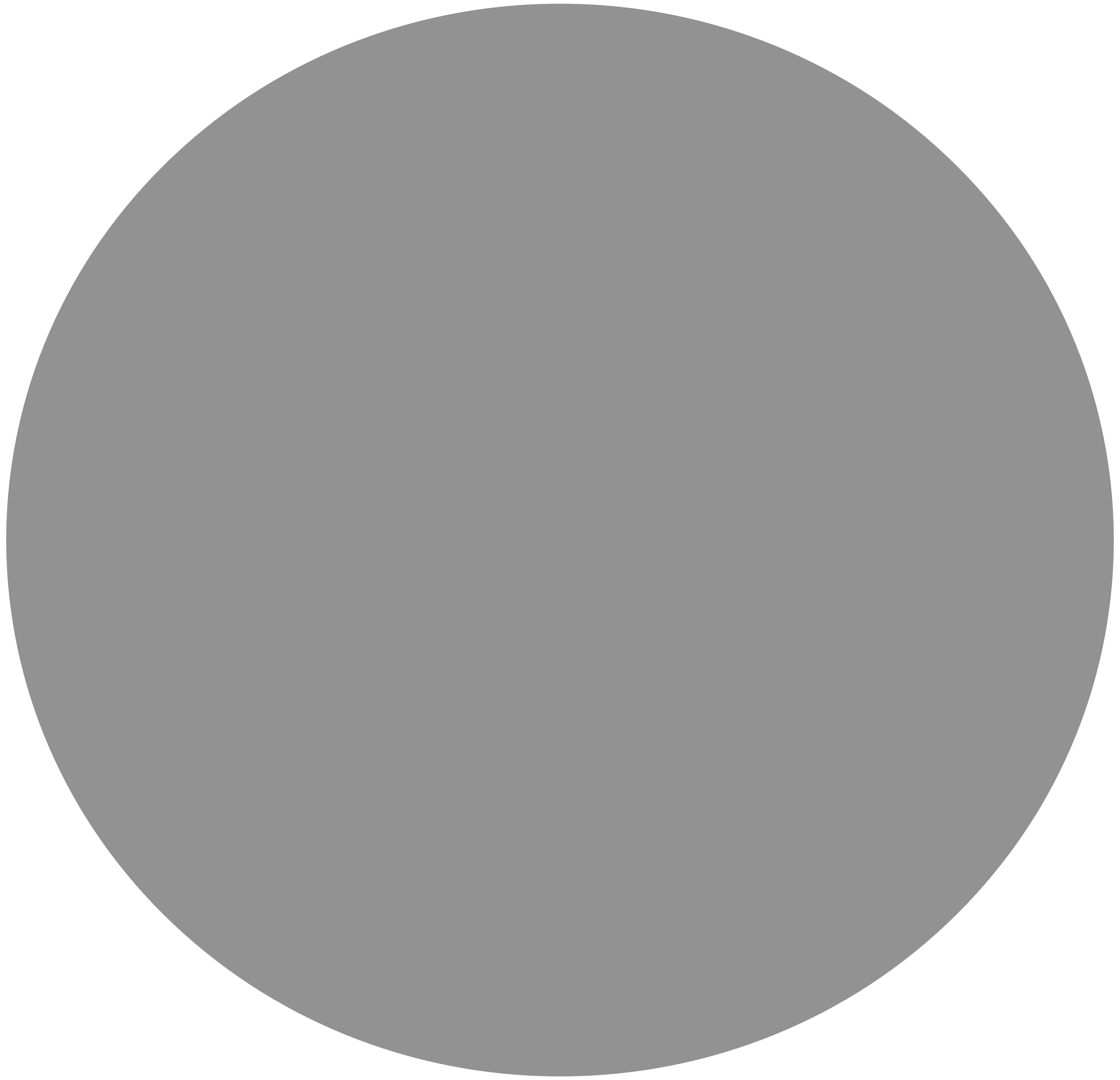
Interior models: principle



Mass

Radius

Luminosity

Atmospheric T-P profile

Atmospheric composition

Rotation rate, gravity field

Interior models: hydrostatic structure

$$
\begin{aligned}
\frac{\partial P}{\partial r} &= -\rho g \\
\frac{\partial T}{\partial r} &= \frac{\partial P}{\partial r}\frac{T}{P}\nabla_T. \\
\frac{\partial m}{\partial r} &= 4\pi r^2 \rho. \\
\frac{\partial L}{\partial r} &= 4\pi r^2 \rho \left(\dot{\epsilon} - T\frac{\partial S}{\partial t}\right)
\end{aligned}
\qquad
\left\{
\begin{aligned}
\frac{\partial P}{\partial m} &= -\frac{Gm}{4\pi r^4} \\
\frac{\partial T}{\partial m} &= \left(\frac{\partial P}{\partial m}\right)\frac{T}{P}\nabla_T, \\
\frac{\partial r}{\partial m} &= \frac{1}{4\pi r^2 \rho}, \\
\frac{\partial L}{\partial m} &= \dot{\epsilon} - T\frac{\partial S}{\partial t},
\end{aligned}
\right.
$$

$$
\rho = \rho(P, T, \{X_i\}); \qquad S = S(P, T, \{X_i\})
$$

Interior models: boundary conditions

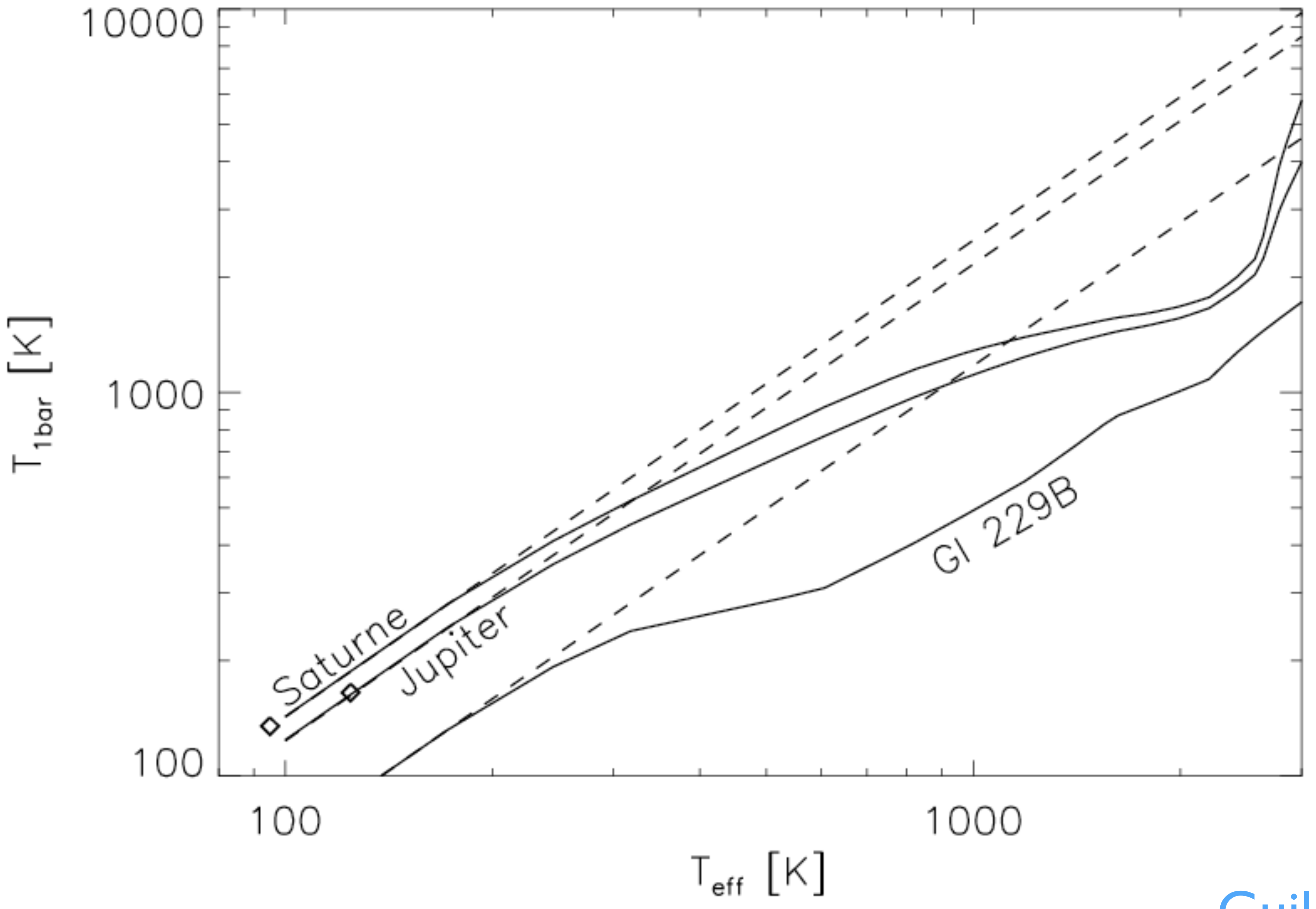
$$m = 0 \longrightarrow r = L = 0$$

$$m = M \longrightarrow P = P_{\text{phot}}(g, L)$$
$$T = T_{\text{phot}}(g, L)$$

Example: Eddington approximation

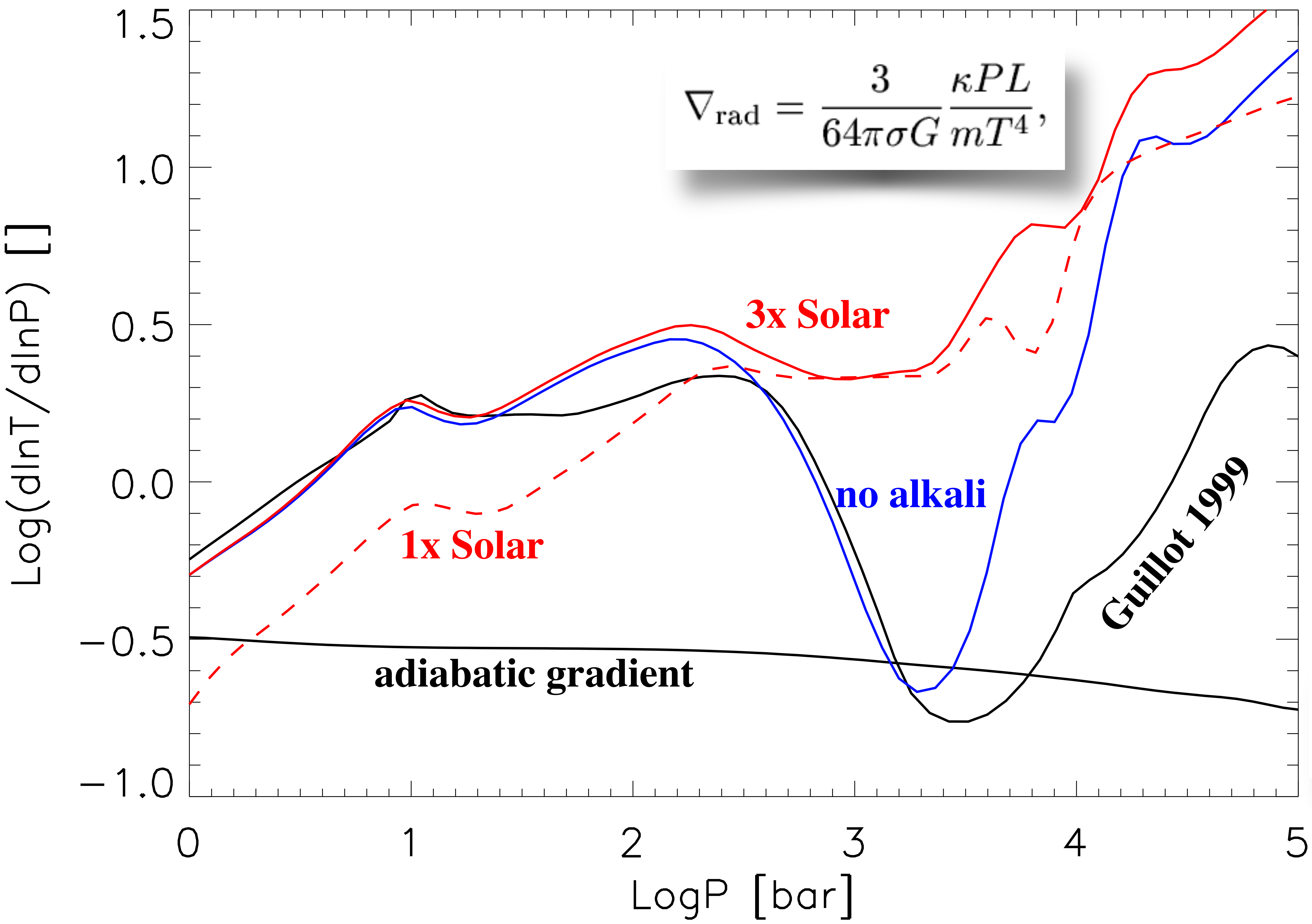
$$T = T_{\text{eff}}$$
$$P = \frac{2}{3}\frac{g}{\kappa}$$

Atmospheric model:



Guillot (Saas-Fee 2000)

Interior models: Energy transport



$$\nabla_{\rm rad} = \frac{3}{64\pi\sigma G}\frac{\kappa P L}{m T^4},$$

$$\nabla_{\rm ad} \equiv \left(\frac{\partial \ln T}{\partial \ln P}\right)_S$$

Guillot et al., «Jupiter book» (2004)

Interior models: Energy transport

- Jupiter & Saturn are fluid & largely convective (Hubbard 1968)
- The intrinsic heat can be transported with negligibly small superadiabaticity

$$\nabla_T - \nabla_{\rm ad} \sim \left[\frac{4\sqrt{2}}{\alpha^2\delta^{1/2}}\frac{F_{\rm conv}}{c_P T(\rho P)^{1/2}}\right]^{2/3},$$

$$v \sim \left[\frac{\alpha\delta}{4}\frac{P}{\rho c_P T}\frac{F_{\rm conv}}{\rho}\right]^{1/3},$$

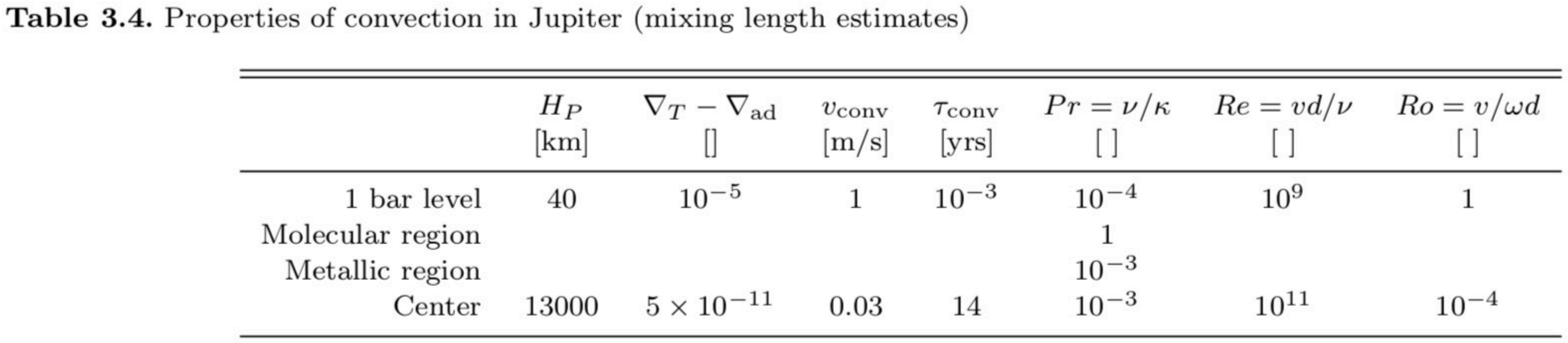
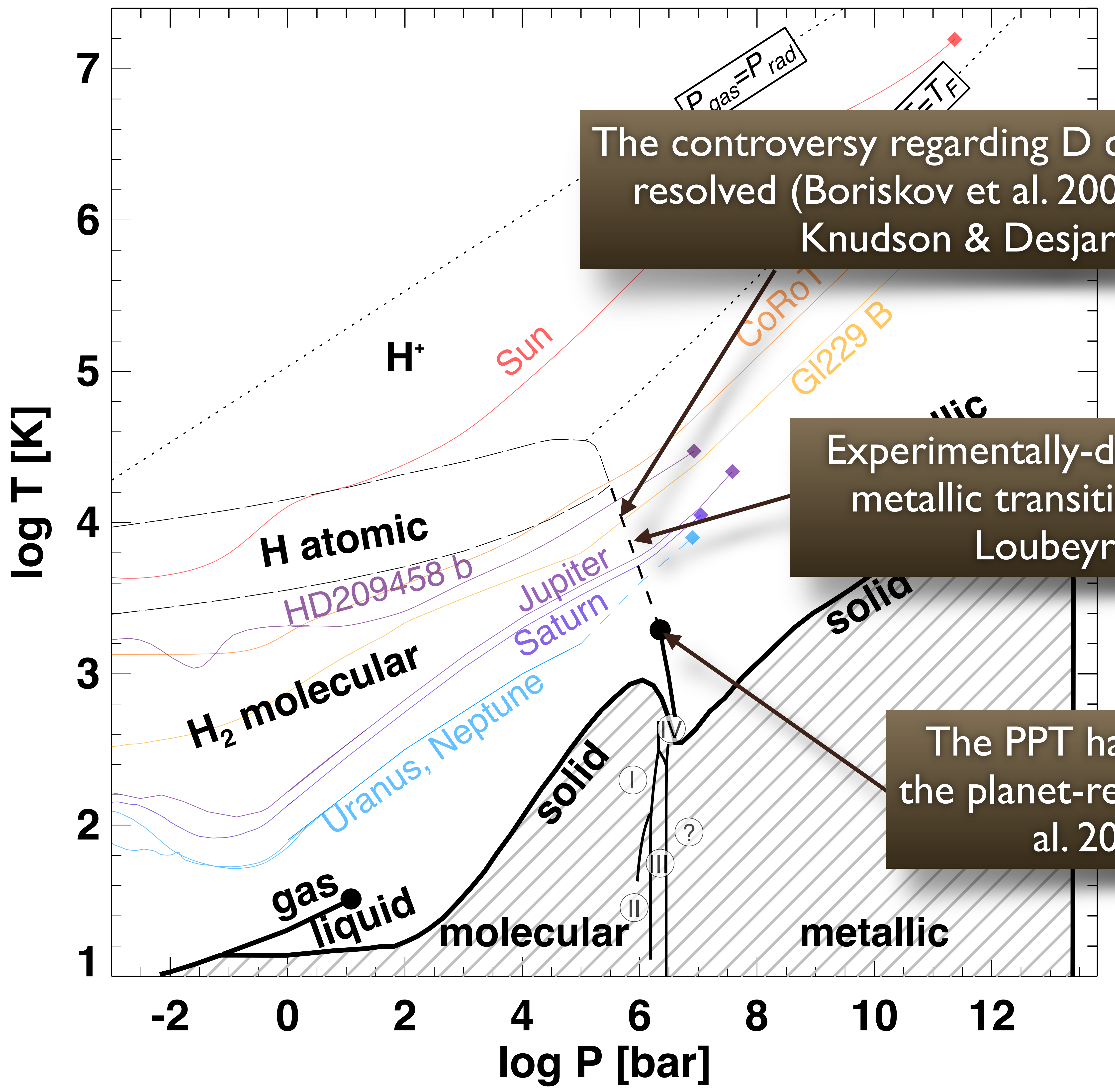


Table 3.4. Properties of convection in Jupiter (mixing length estimates)

	H_P [km]	$\nabla_T - \nabla_{\rm ad}$ []	$v_{\rm conv}$ [m/s]	$\tau_{\rm conv}$ [yrs]	$Pr = \nu/\kappa$ [ ]	$Re = vd/\nu$ [ ]	$Ro = v/\omega d$ [ ]
1 bar level	40	10^{-5}	1	10^{-3}	10^{-4}	10^{9}	1
Molecular region					1		
Metallic region					10^{-3}		
Center	13000	5×10^{-11}	0.03	14	10^{-3}	10^{11}	10^{-4}

Guillot et al., «Jupiter book» (2004)

Interior models: Phase diagram of hydrogen



The controversy regarding D compression is mostly resolved (Boriskov et al. 2005, Hicks et al. 2009, Knudson & Desjarlais 2009)

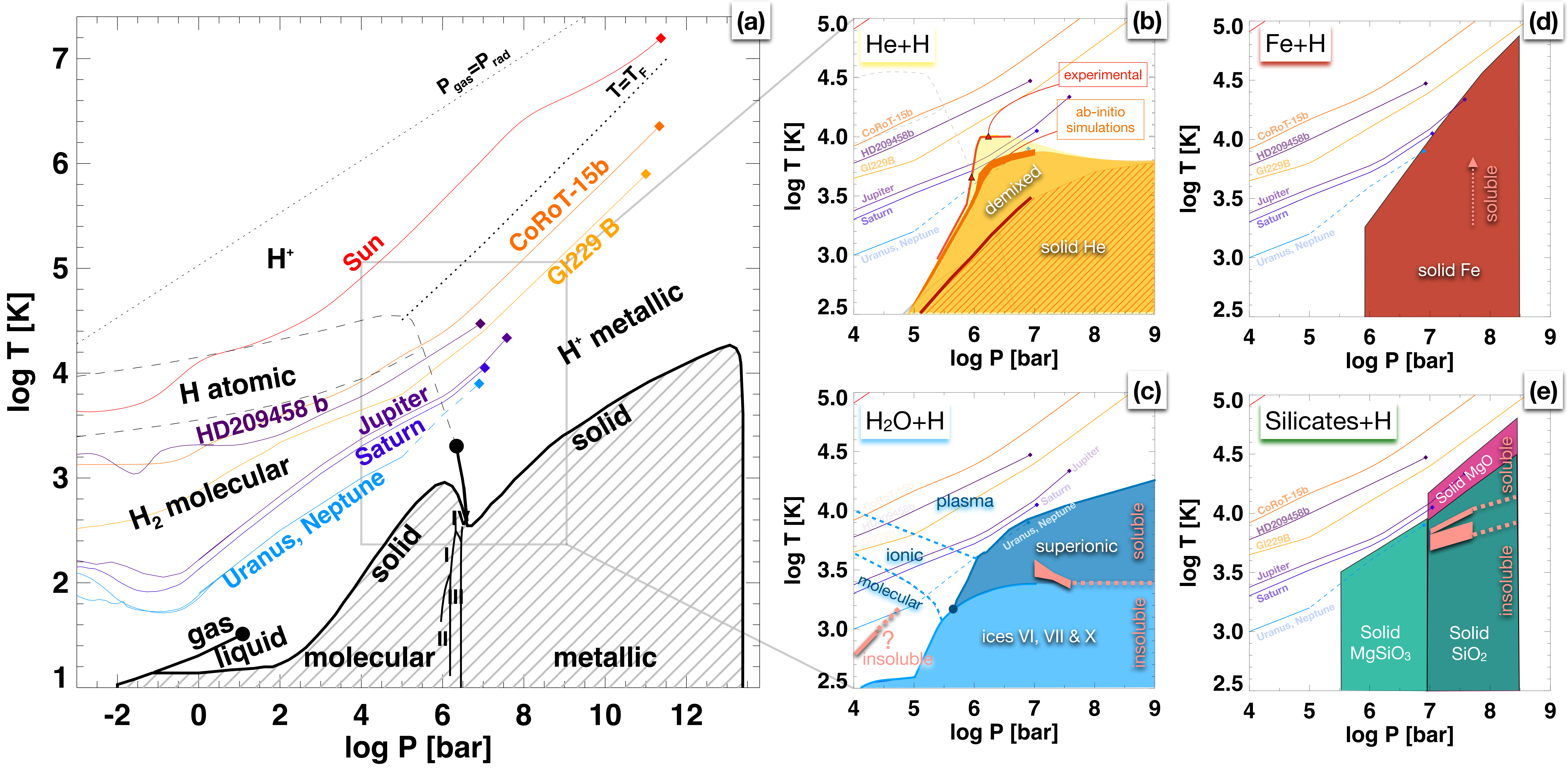
Experimentally-determined molecular-metallic transition (Sano et al. 2011, Loubeyre et al. 2012)

The PPT has moved out of the planet-regime (Morales et al. 2010, 2013)

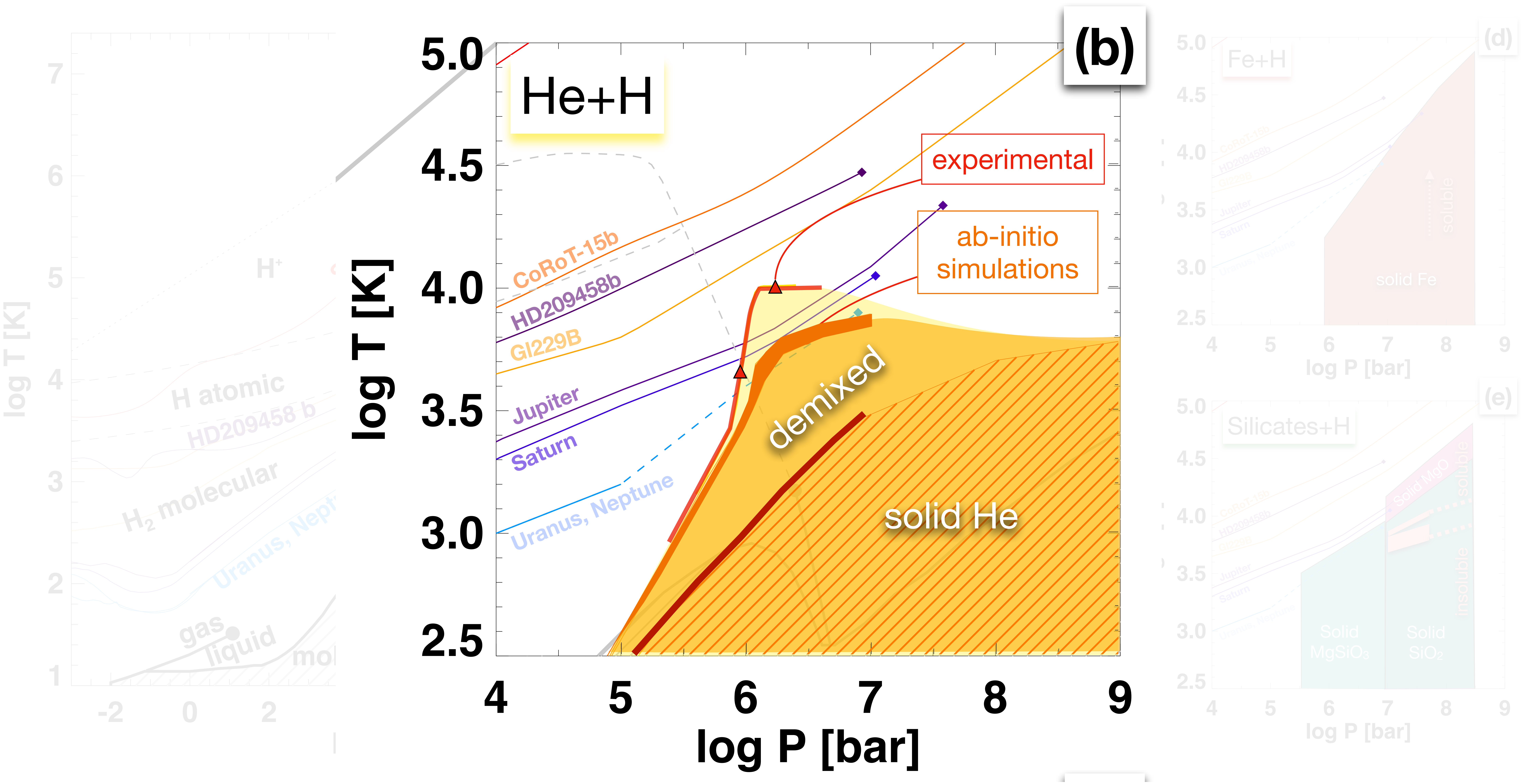
Guillot & Gautier (2015)

see also McMahon et al. (2012)

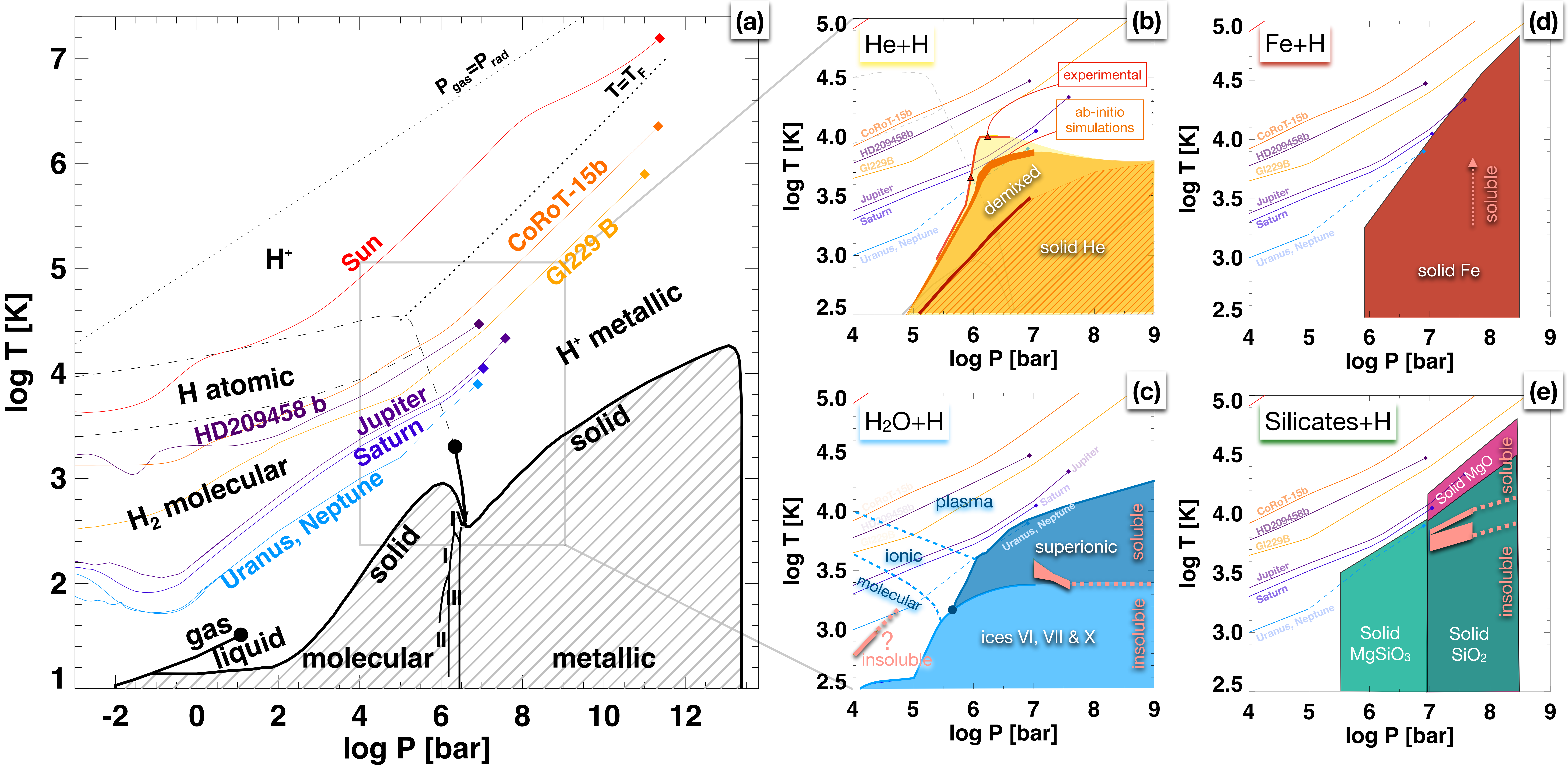
Interior models: Phase diagrams



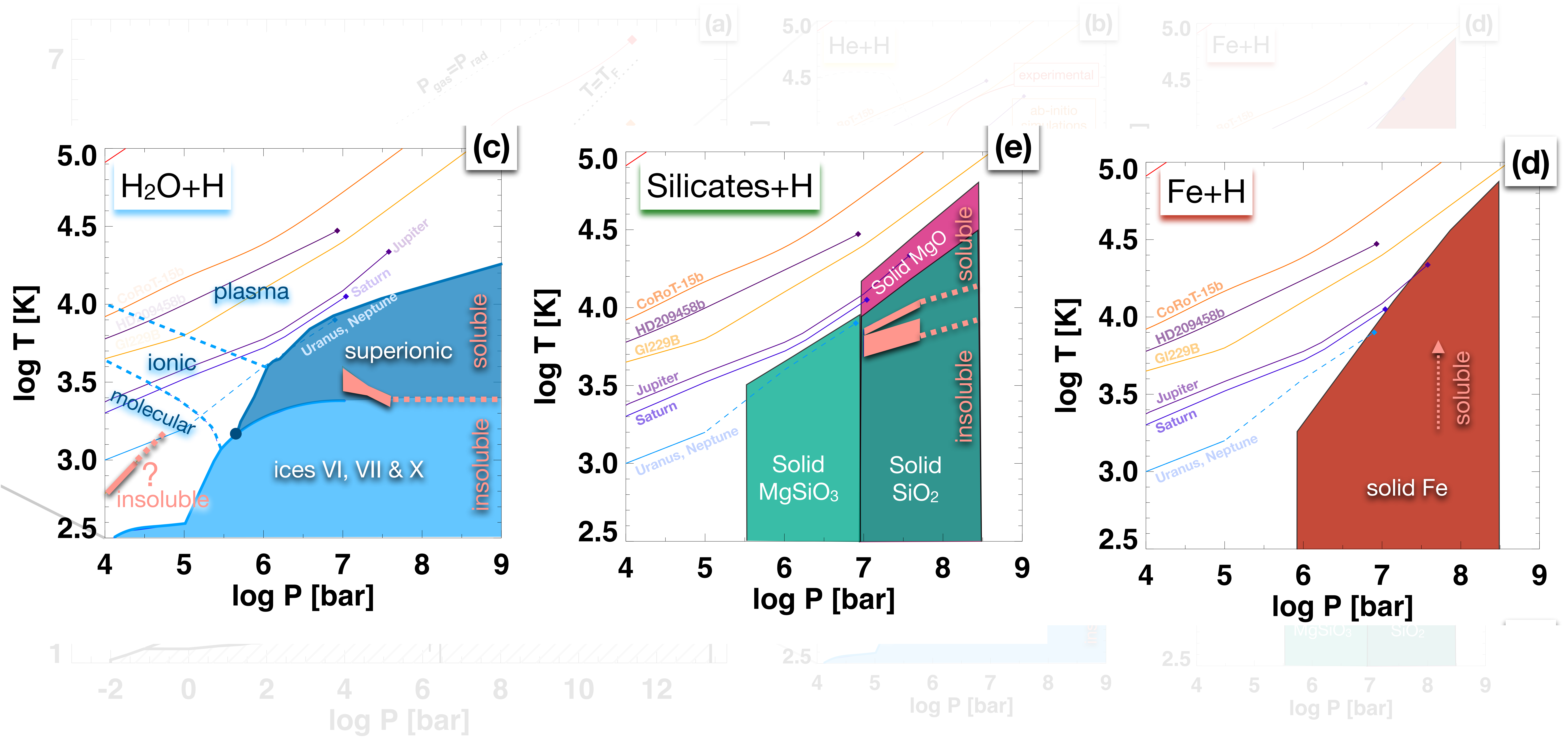
Interior models: Phase diagrams



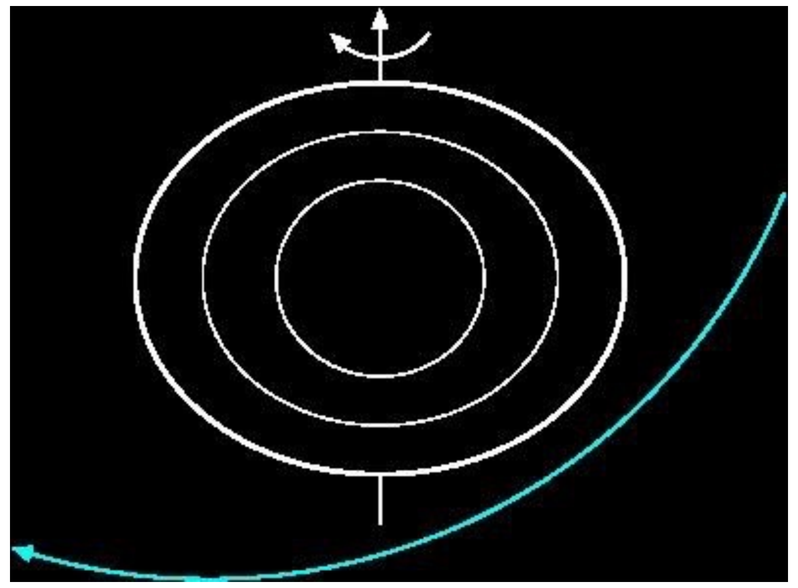
Interior models: Phase diagrams



Interior models: Phase diagrams



Interior models: Constraints from rotation

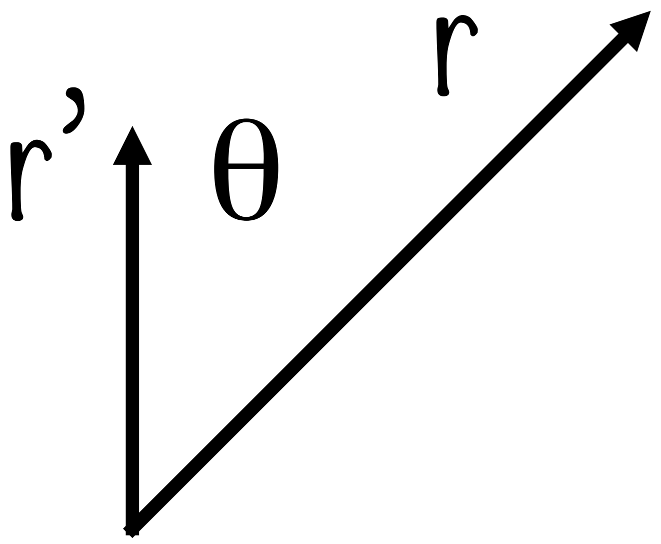


Measured: external gravity potential

$$V_{ext} = \frac{GM}{r}\left[1 - \sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{2n} J_{2n}P_{2n}(\cos\theta)\right]$$

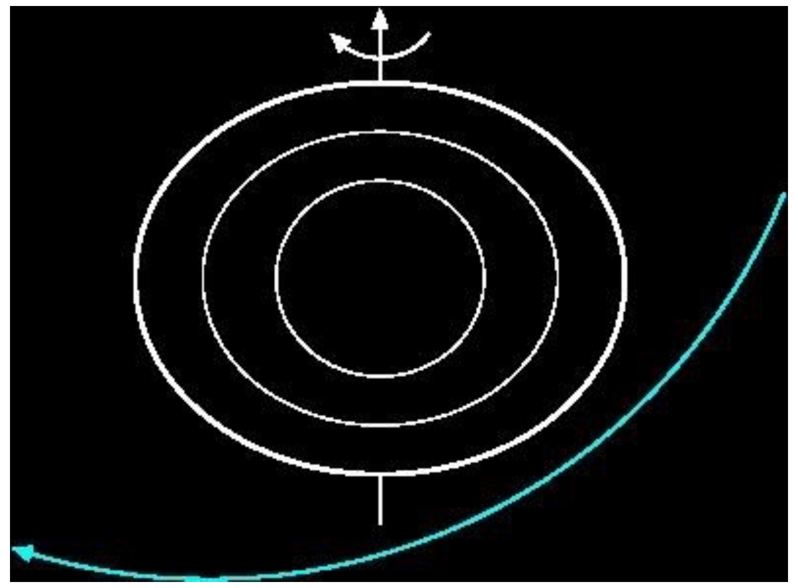
$$\frac{\nabla P}{\rho} = \nabla V - \Omega\times(\Omega\times\mathrm{r})$$

$$V = G\int\frac{\rho(\mathrm{r}')}{|\mathrm{r}-\mathrm{r}'|}d^3\mathrm{r}'$$



$$\frac{1}{|\mathrm{r}-\mathrm{r}'|} = \begin{cases} \frac{1}{r}\sum\left(\frac{r'}{r}\right)^{n} P_n(\cos\theta) & \text{if } r > r' \\ \frac{1}{r}\sum\left(\frac{r'}{r}\right)^{-n-1} P_n(\cos\theta) & \text{if } r < r' \end{cases}$$

Interior models: Constraints from rotation



Measured: external gravity potential

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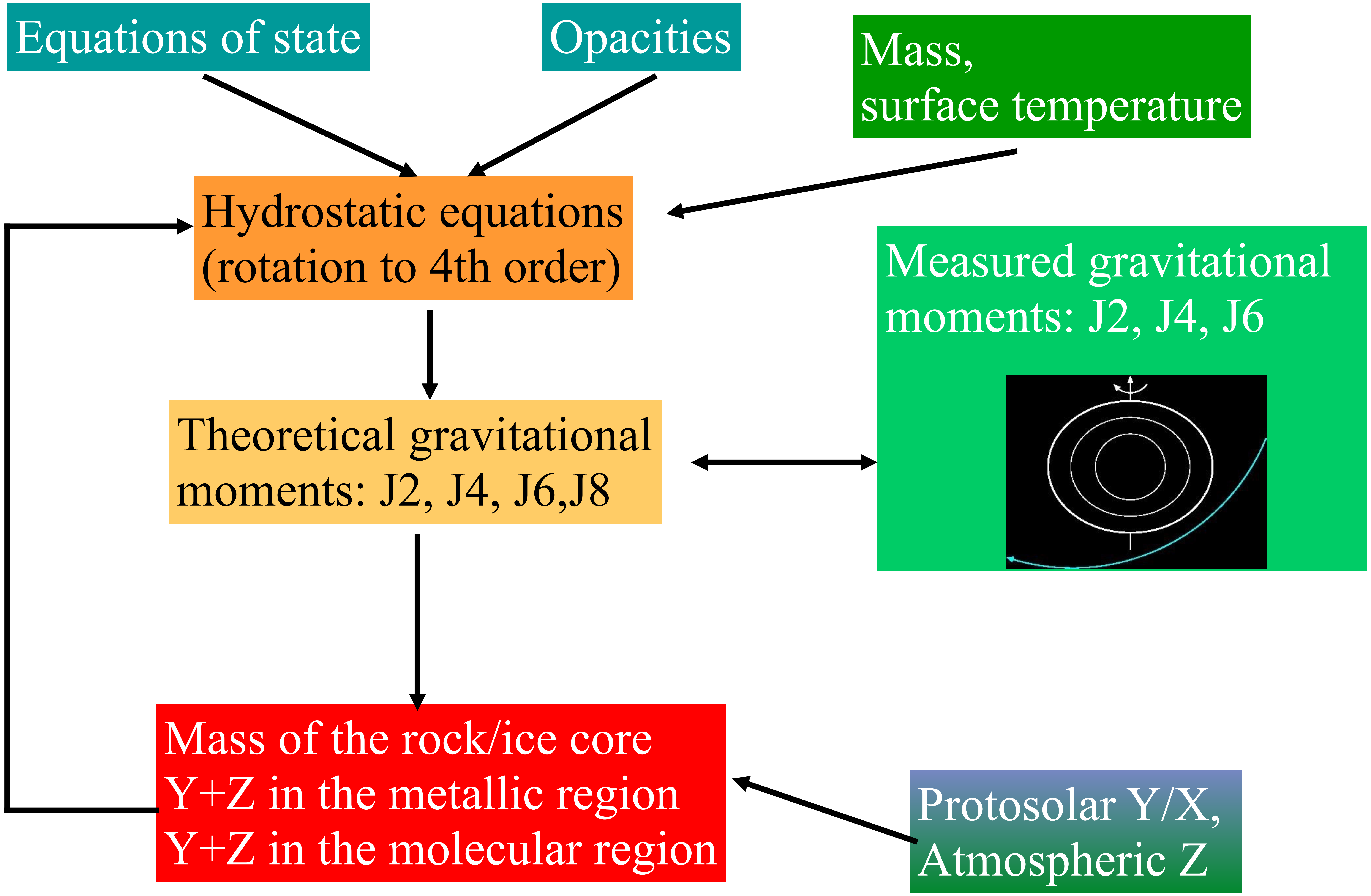
$$V_{\text{ext}} = \frac{G}{r}\sum r^{-2n}\int \rho r'^{2n} P_{2n}(\cos\theta) d^3r'$$

$$J_{2\text{n}} = -\frac{1}{Ma^{2n}}\int \rho r'^{2n} P_{2n}(\cos\theta) d^3r'$$

Interior models: Optimization



Equations of state

Opacities

Mass,
surface temperature

Hydrostatic equations
(rotation to 4th order)

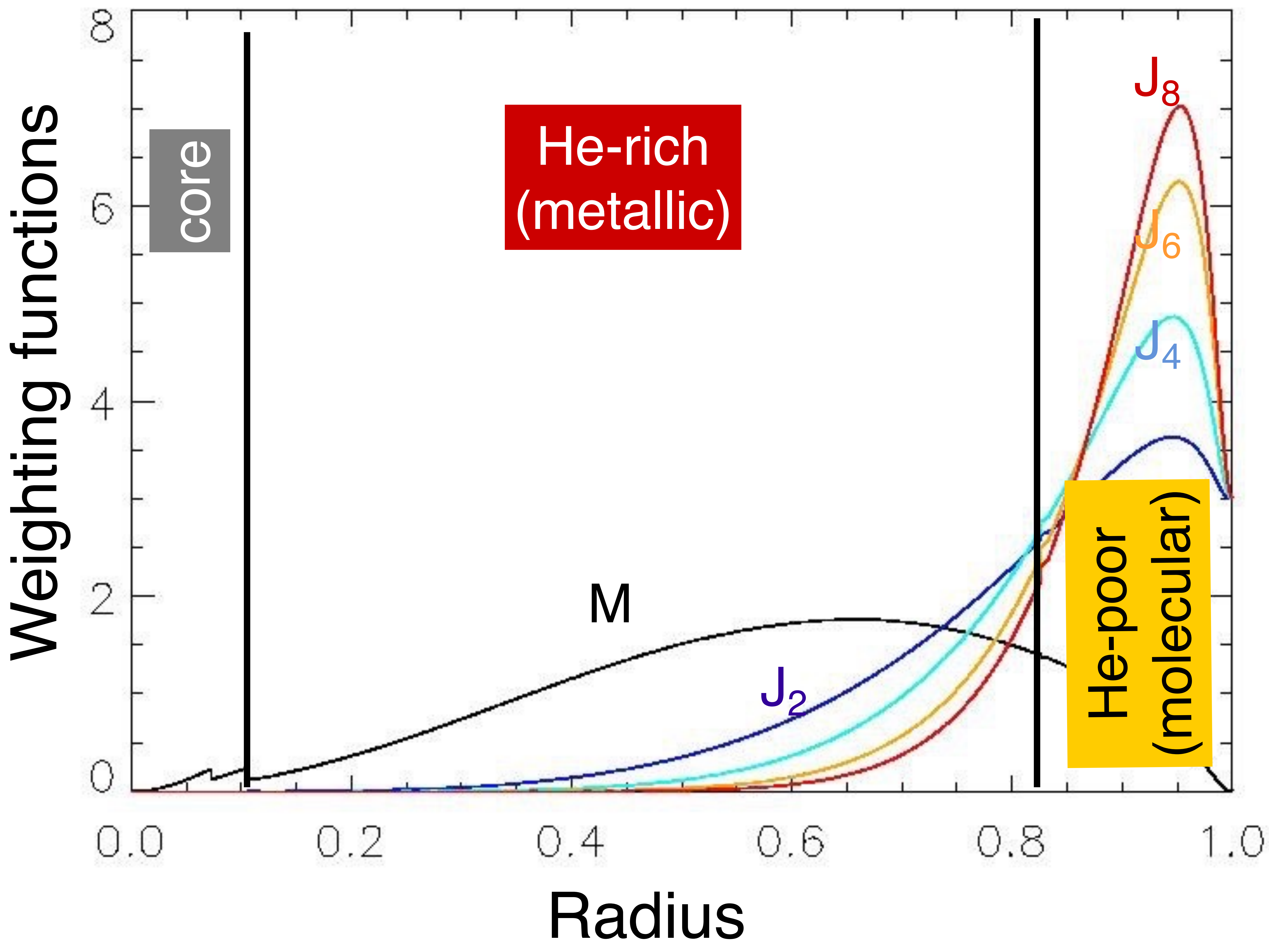
Measured gravitational
moments: J2, J4, J6

Theoretical gravitational
moments: J2, J4, J6,J8

Mass of the rock/ice core
Y+Z in the metallic region
Y+Z in the molecular region

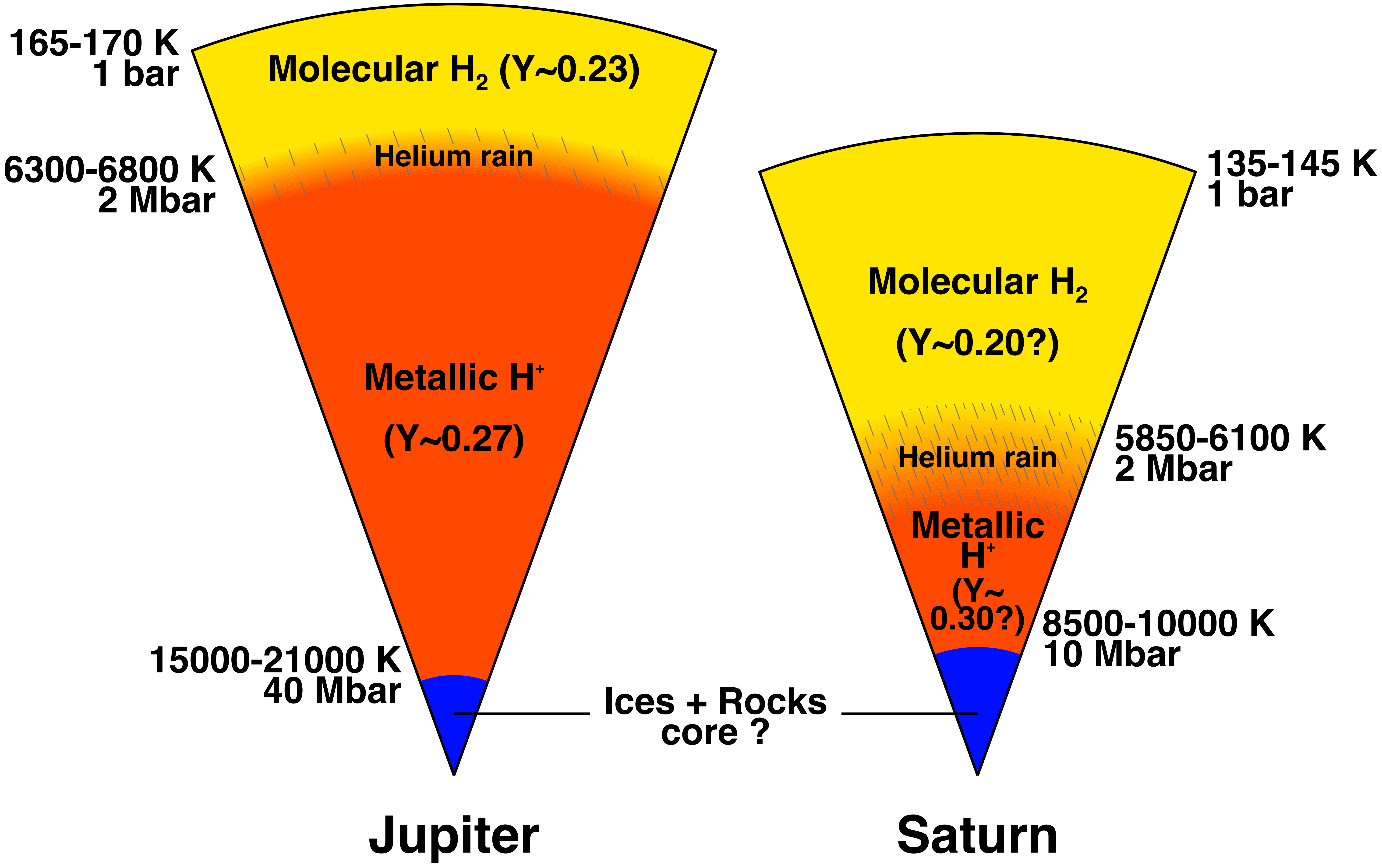
Protosolar Y/X,
Atmospheric Z

Interior models: Contribution functions



Guillot (Ann. Rev. Earth Plan. Sci. 2005)

Interior models



165-170 K
1 bar

Molecular H_2 (Y~0.23)

6300-6800 K
2 Mbar

Helium rain

Metallic H^+

(Y~0.27)

15000-21000 K
40 Mbar

Ices + Rocks
core ?

135-145 K
1 bar

Molecular H_2

(Y~0.20?)

5850-6100 K
2 Mbar

Helium rain

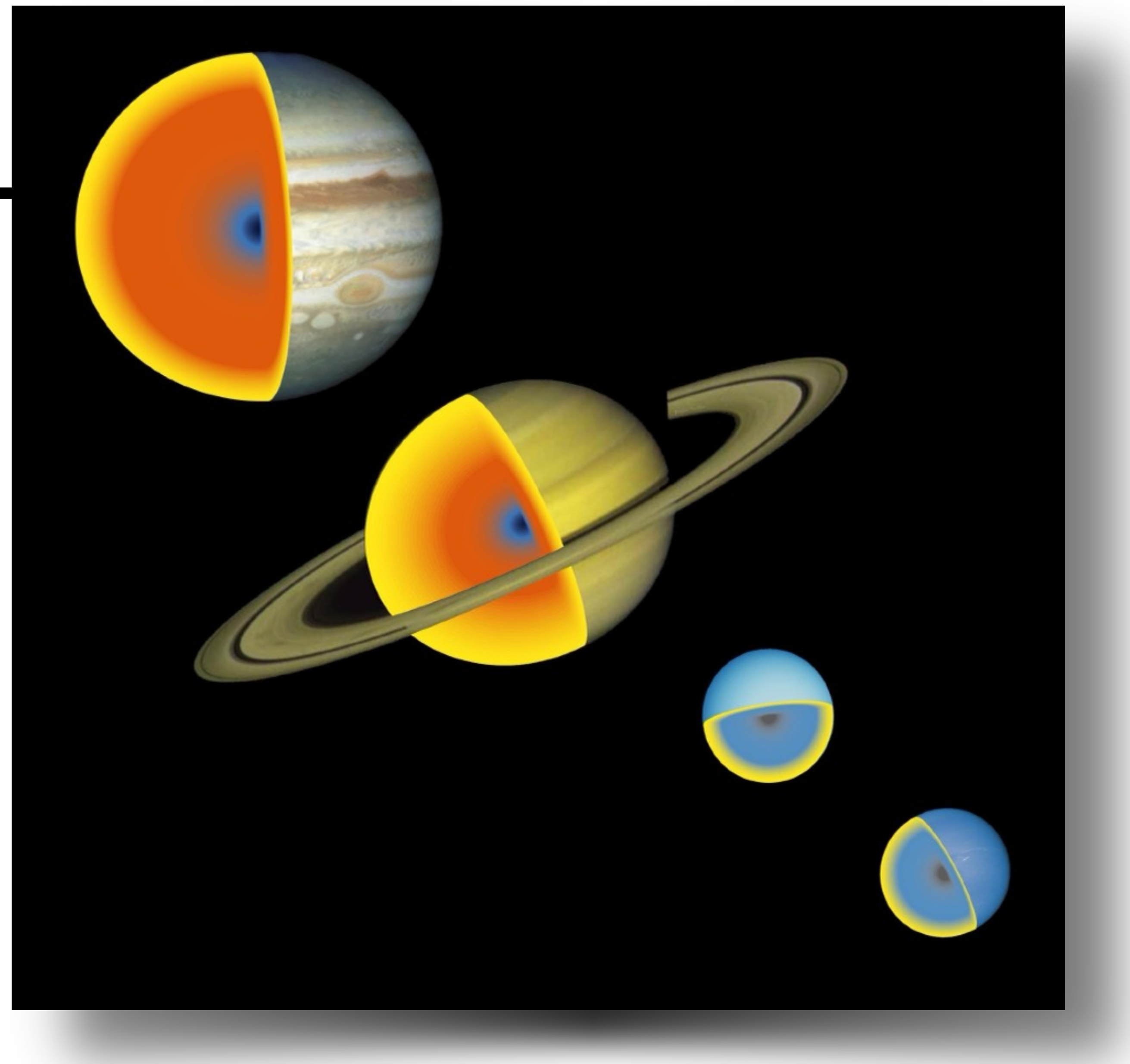
Metallic H^+

(Y~0.30?)

8500-10000 K
10 Mbar

Jupiter

Saturn



Guillot (Ann. Rev. Earth Plan. Sci. 2005)

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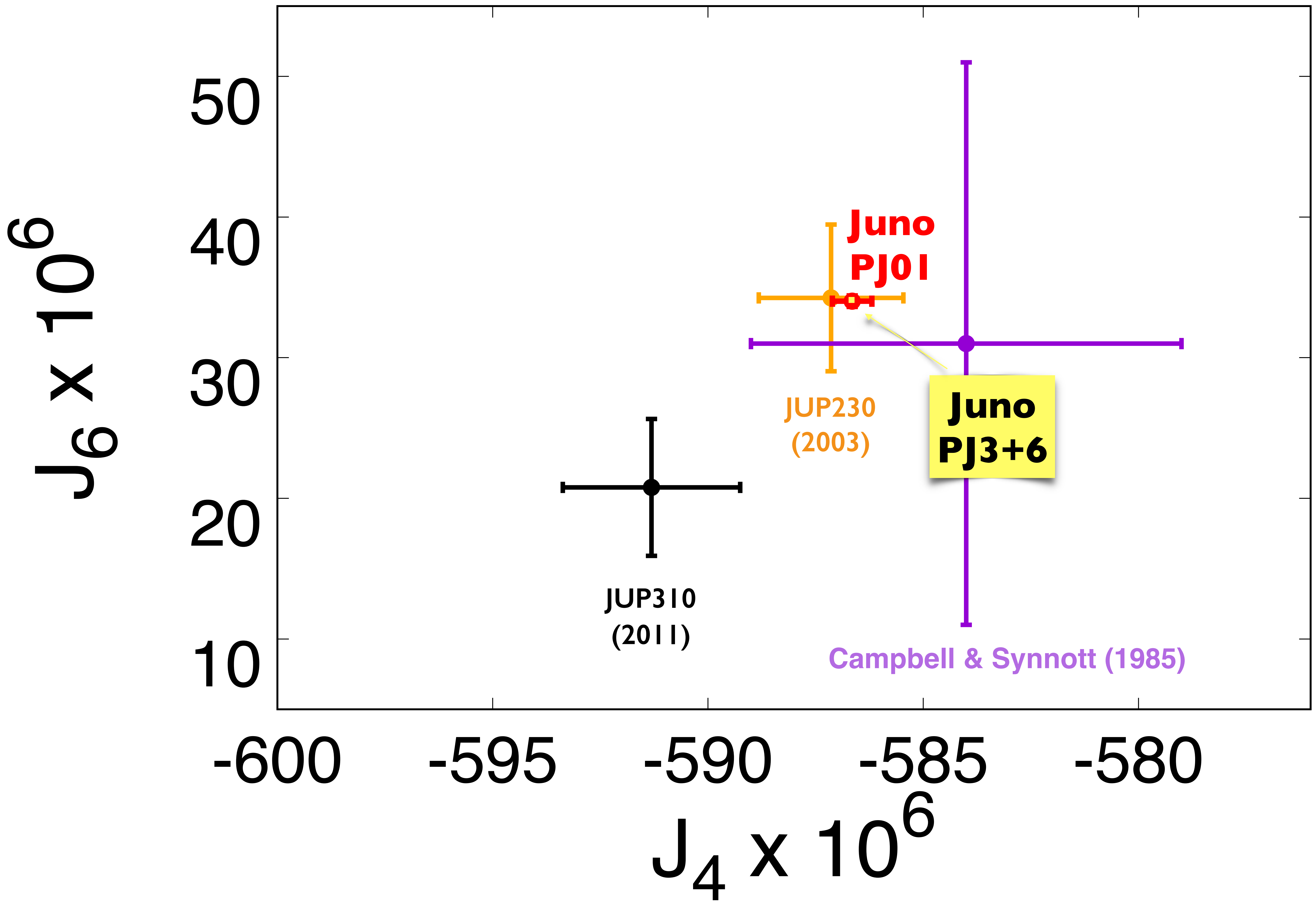
J_6 vs J_4: constraining interior models



Iess et al. (Nature 2018)

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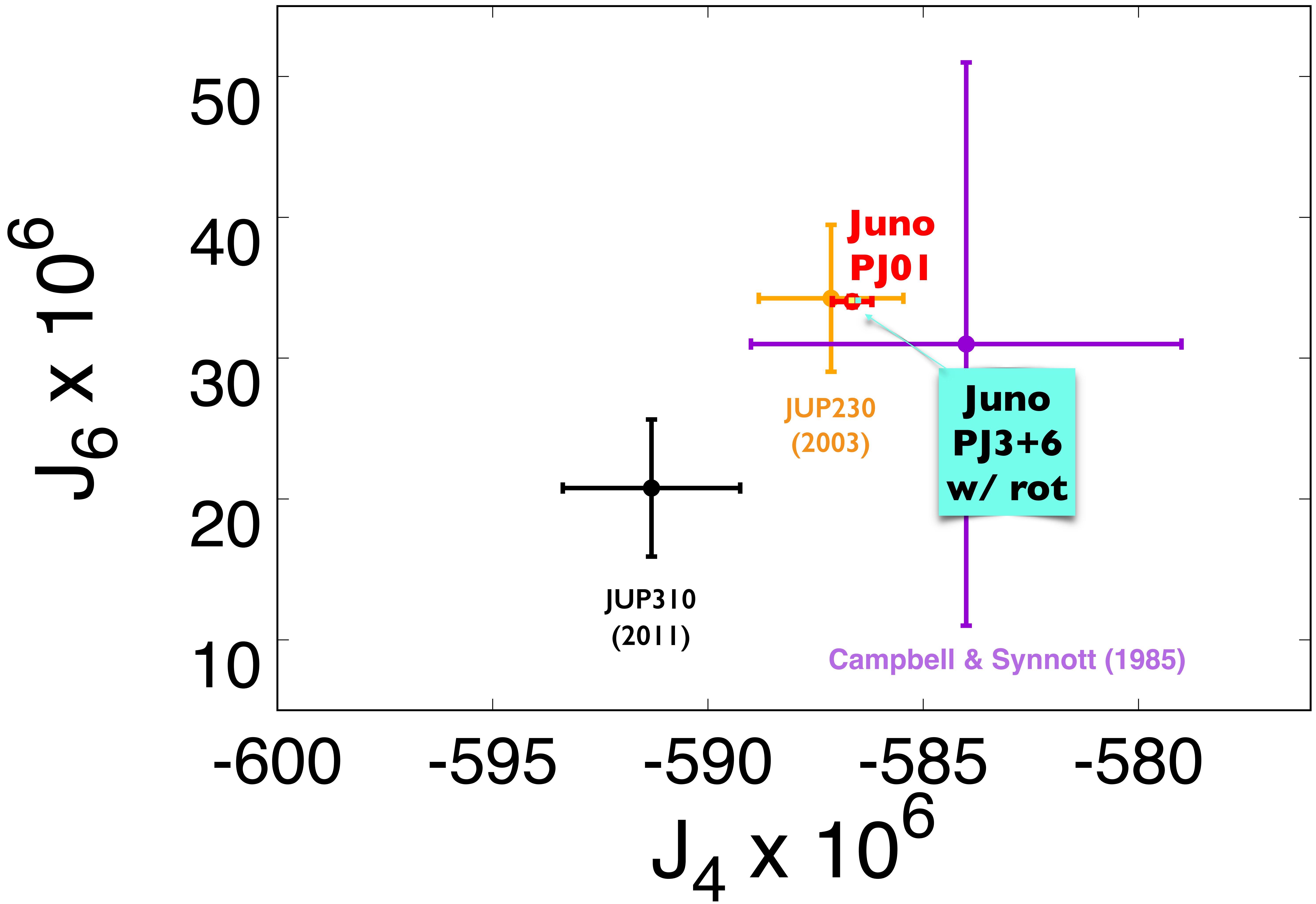
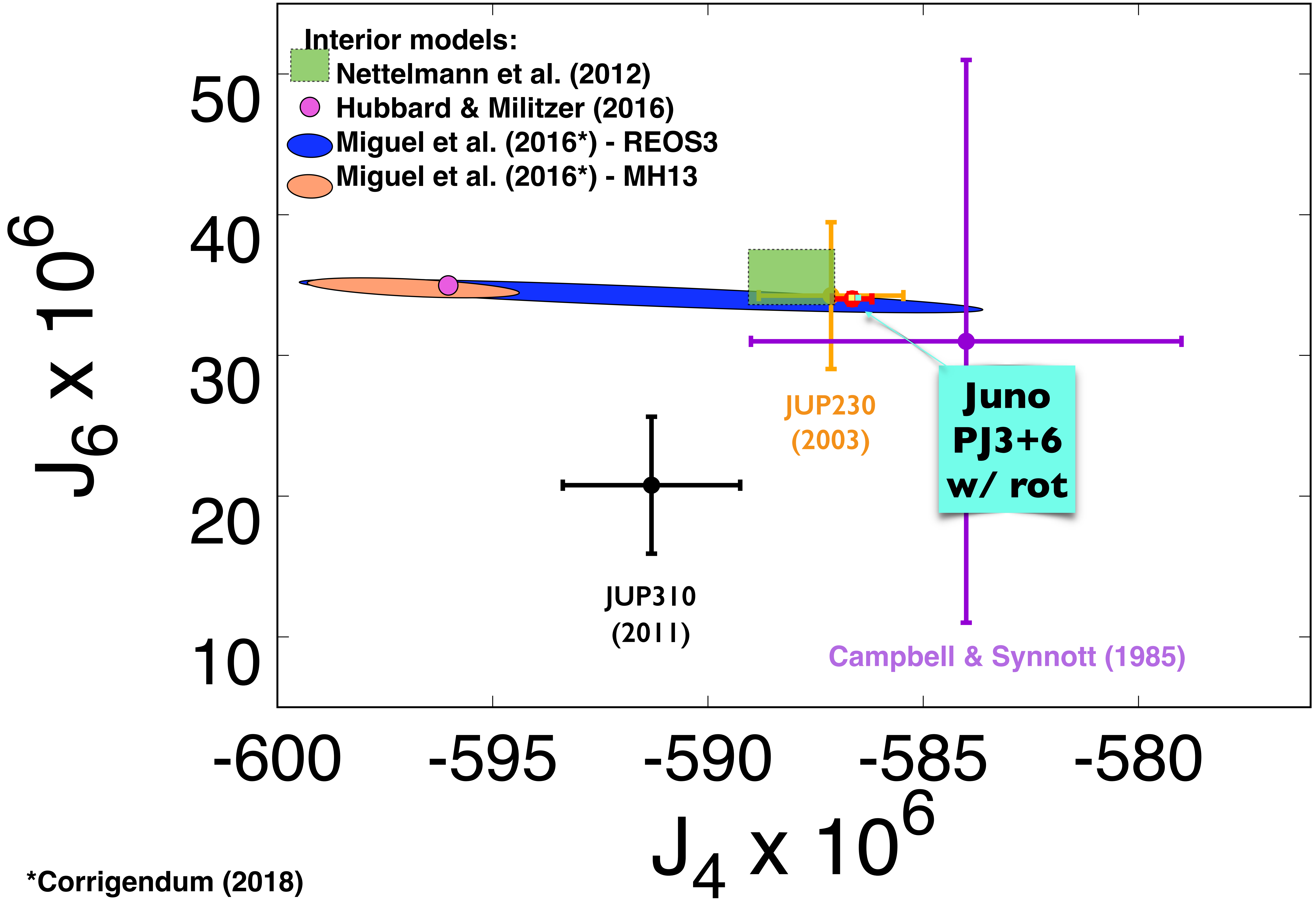


Kaspi et al., Guillot et al. (Nature 2018)

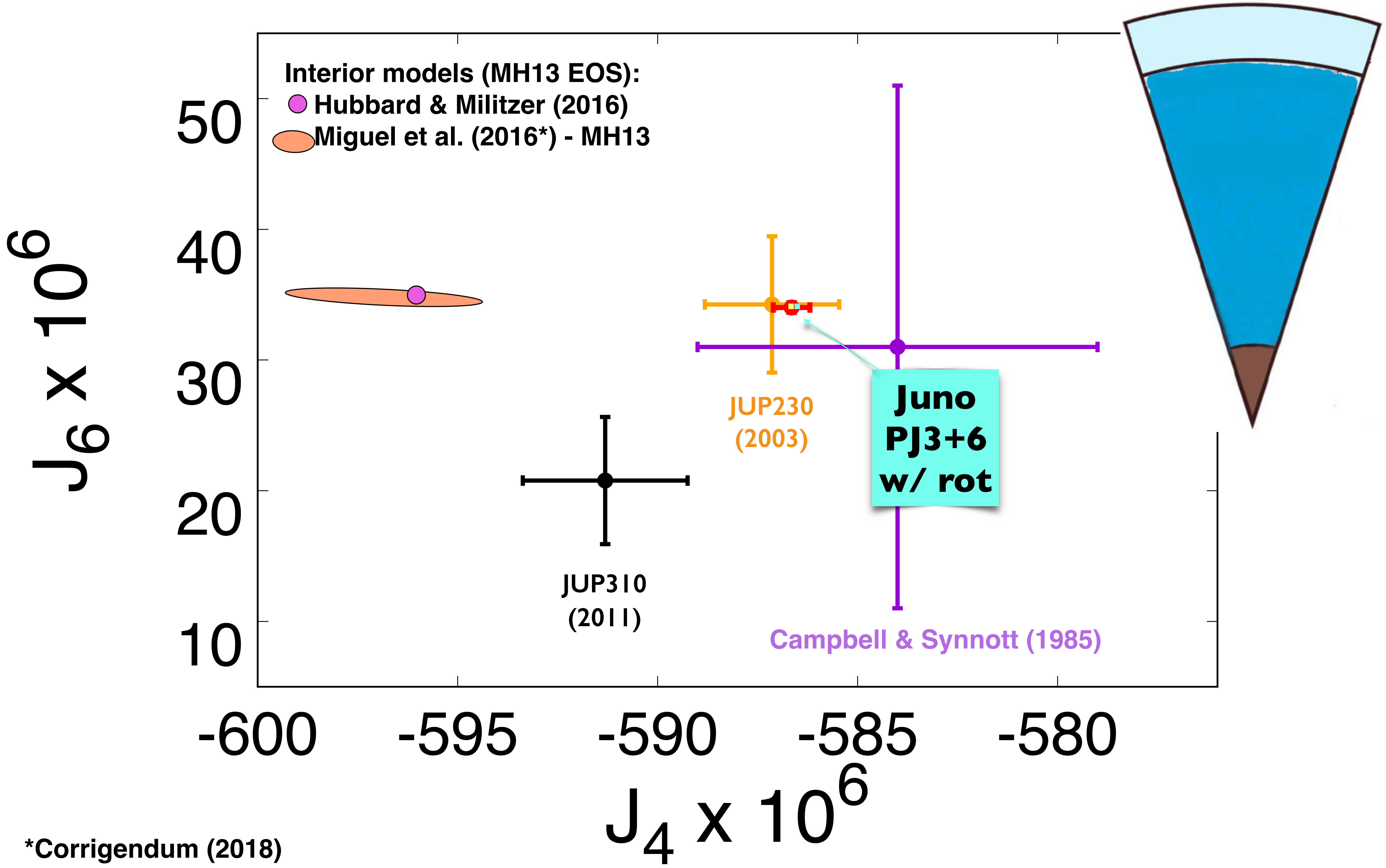
J_6 vs J_4: constraining interior models



*Corrigendum (2018)

Miguel et al. (2016*)

J_6 vs J_4: constraining interior models



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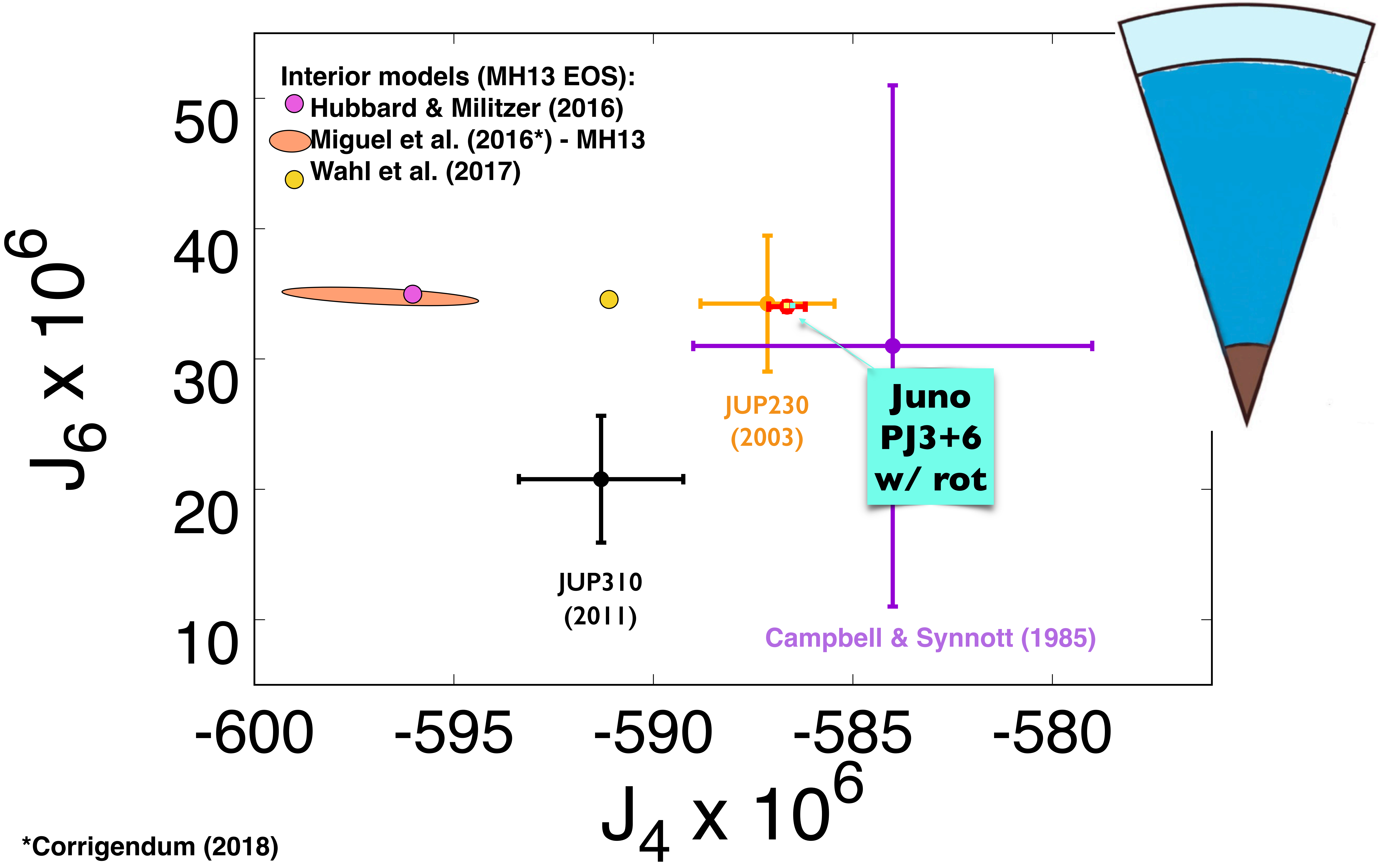

*Corrigendum (2018)

Wahl et al. (2017)

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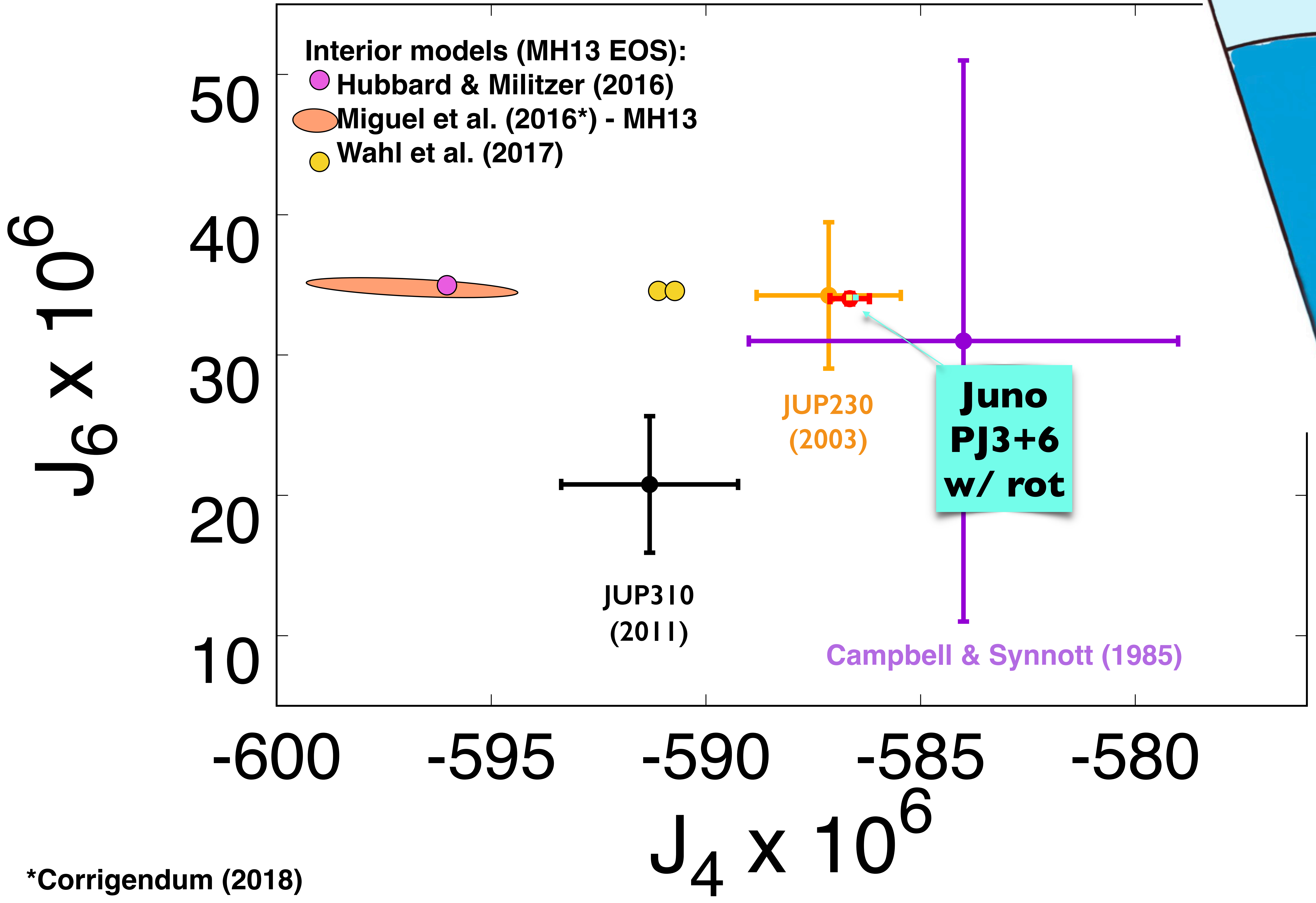

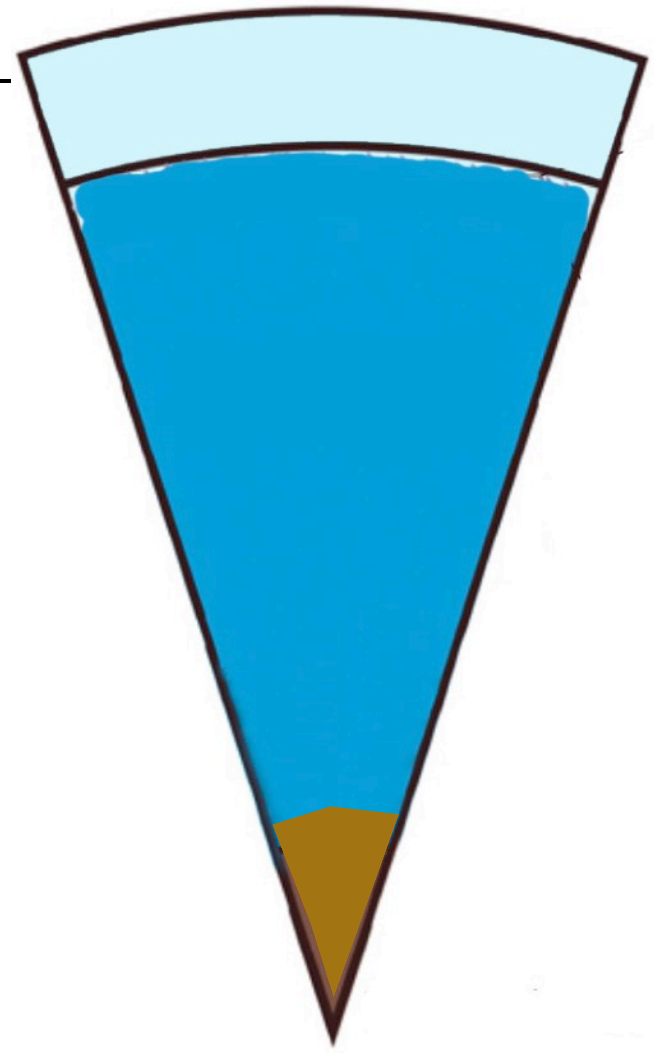

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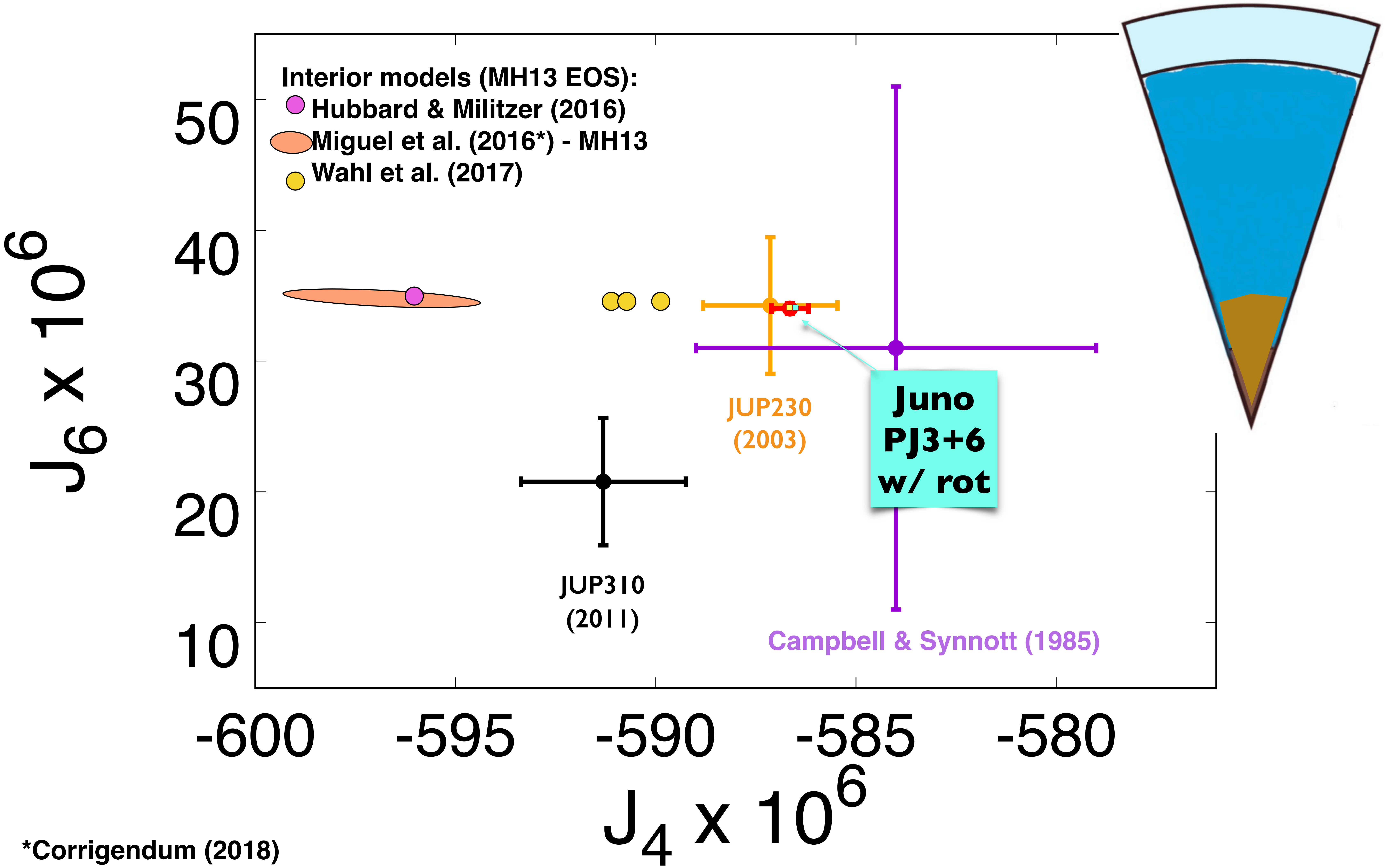

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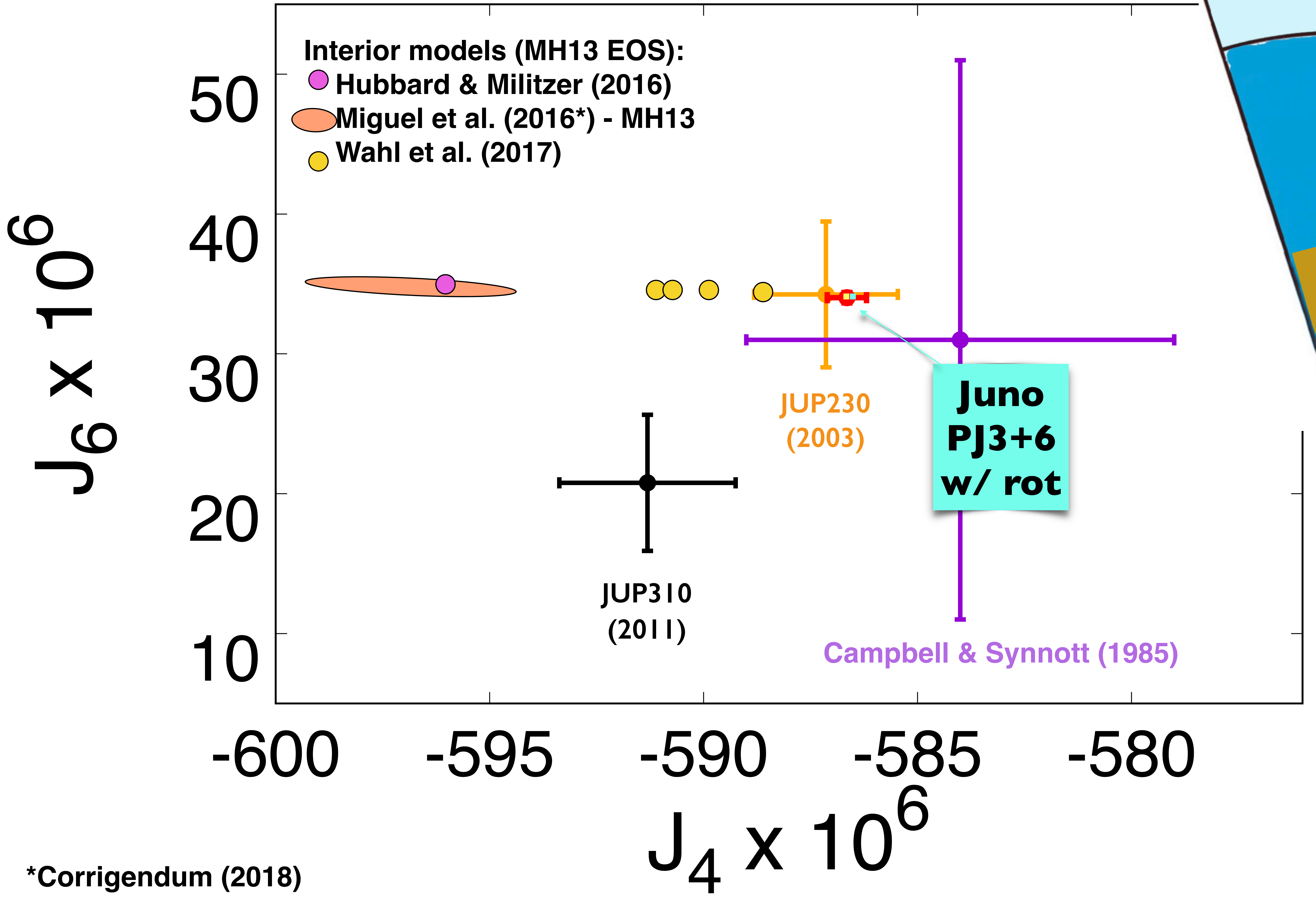

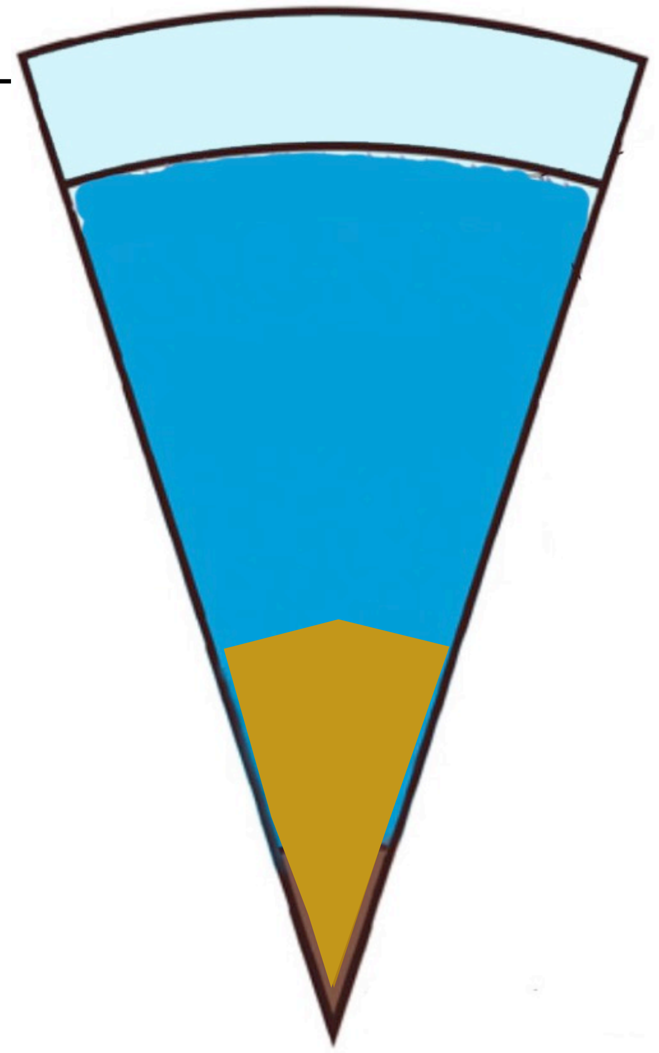

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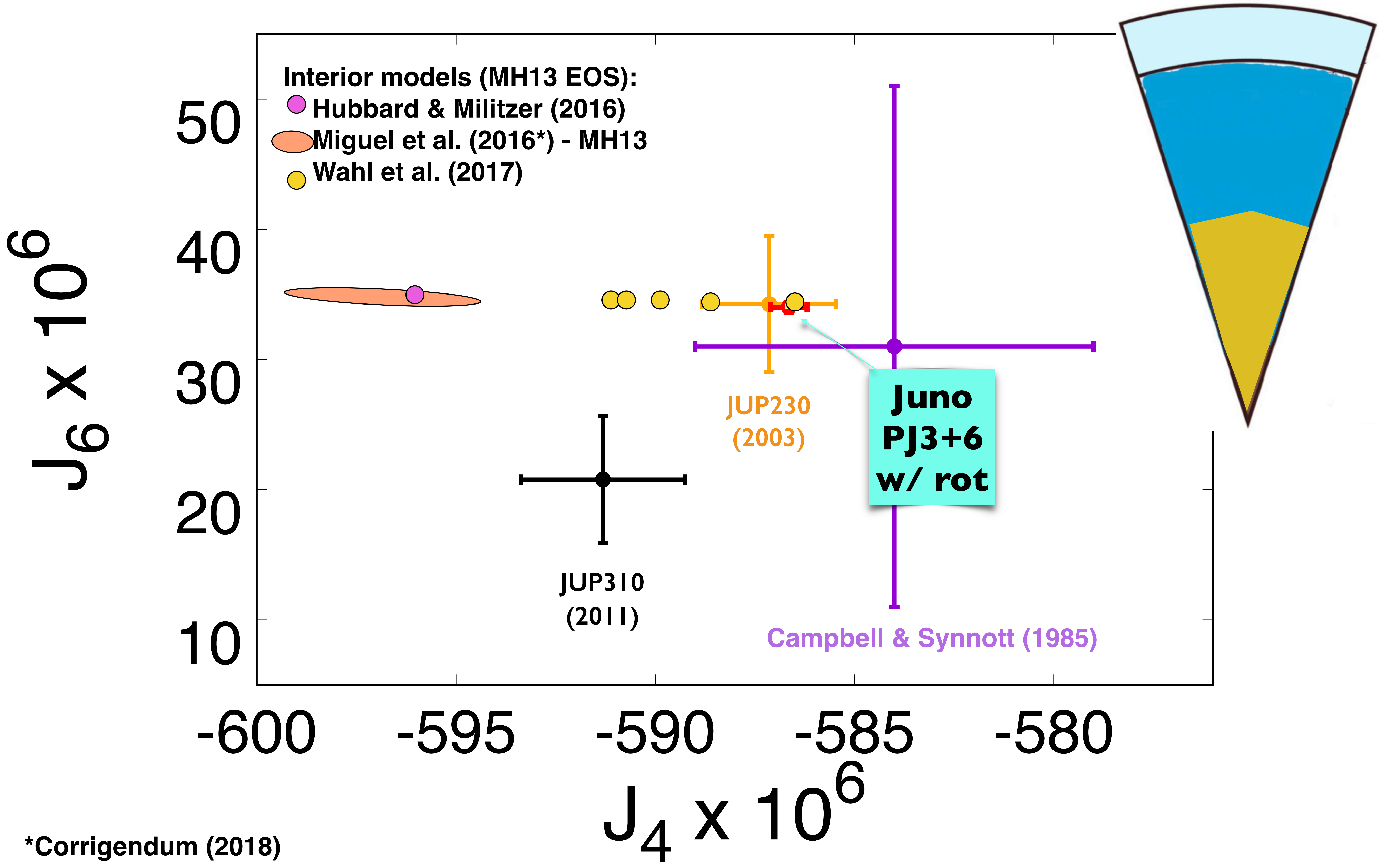

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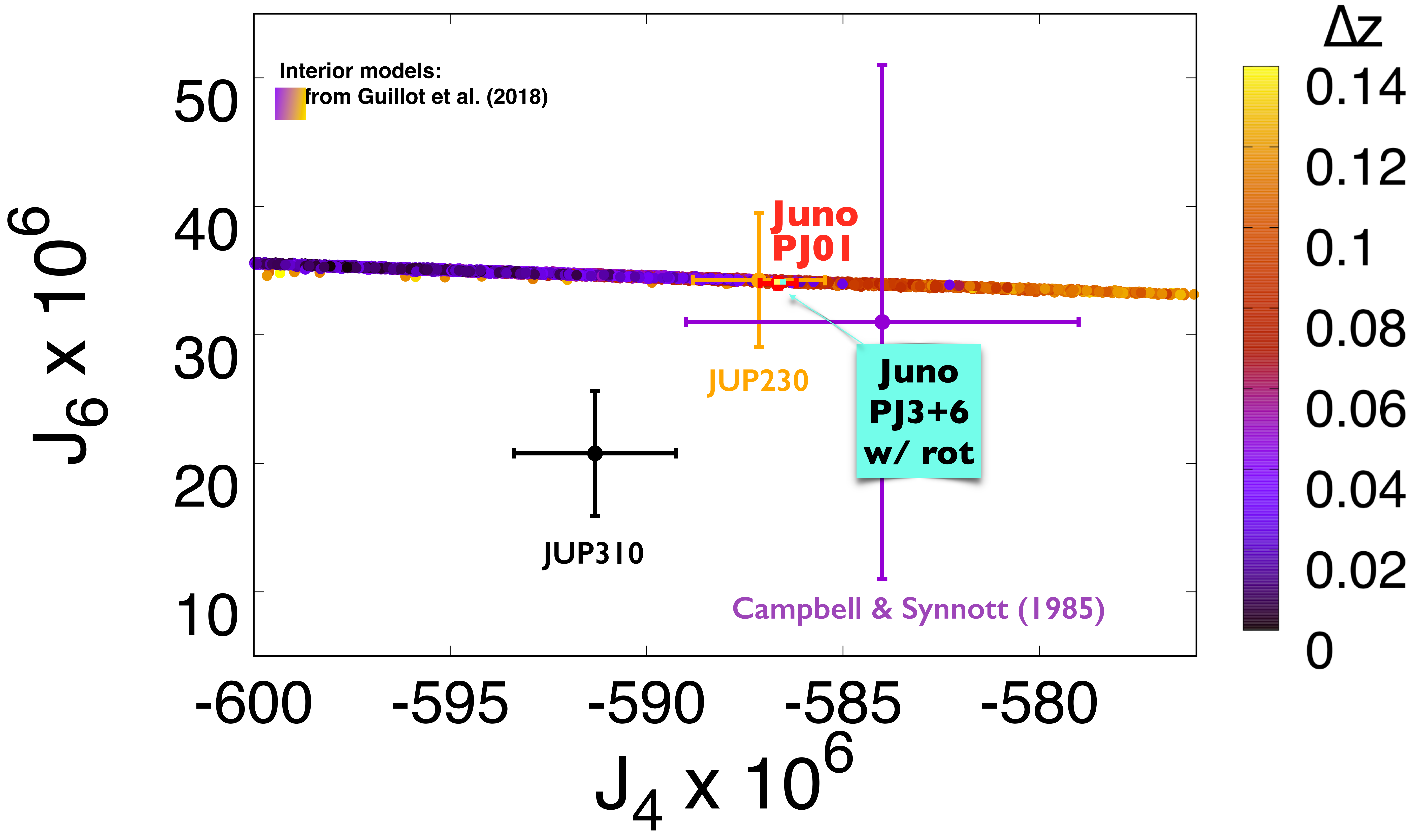

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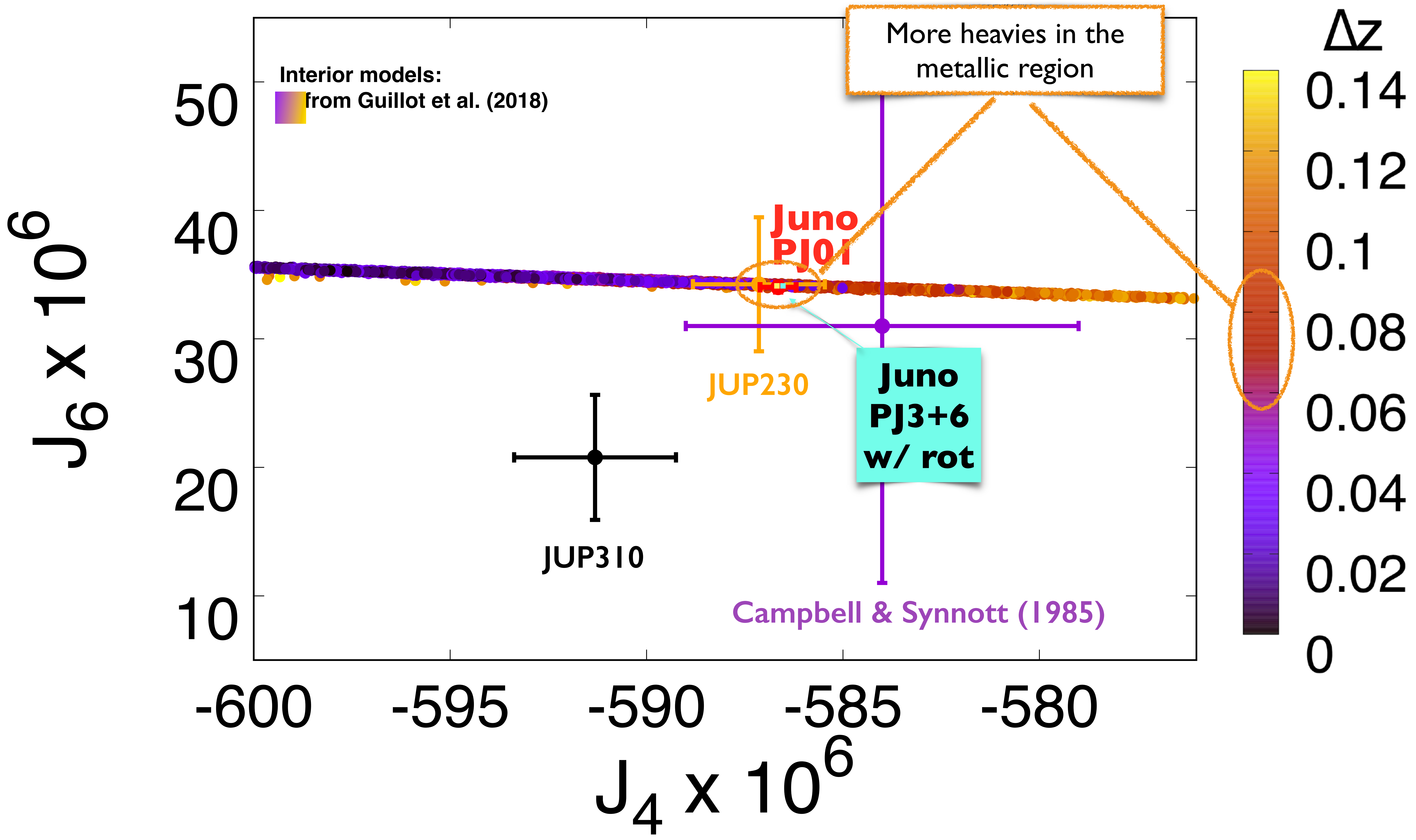
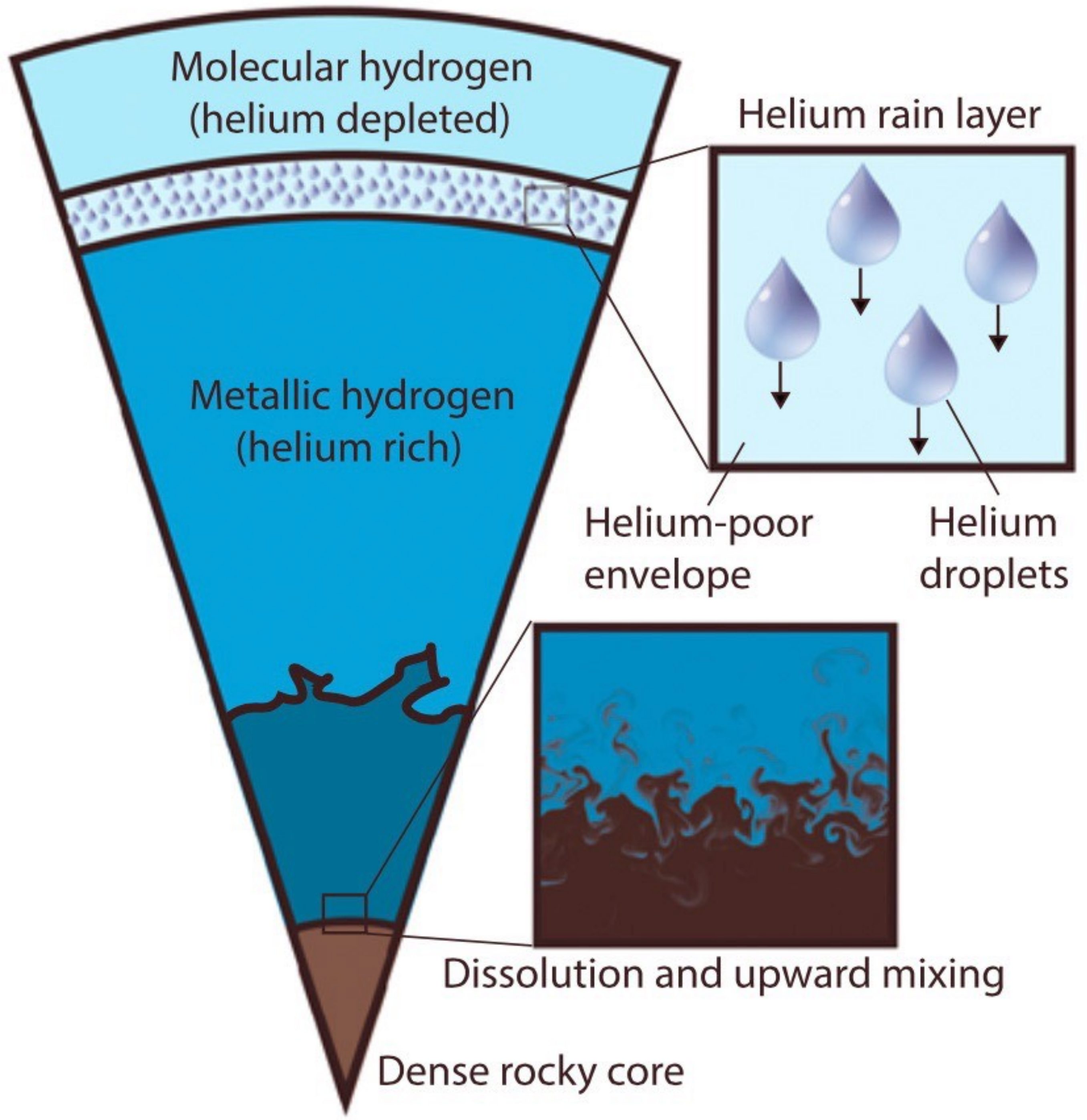
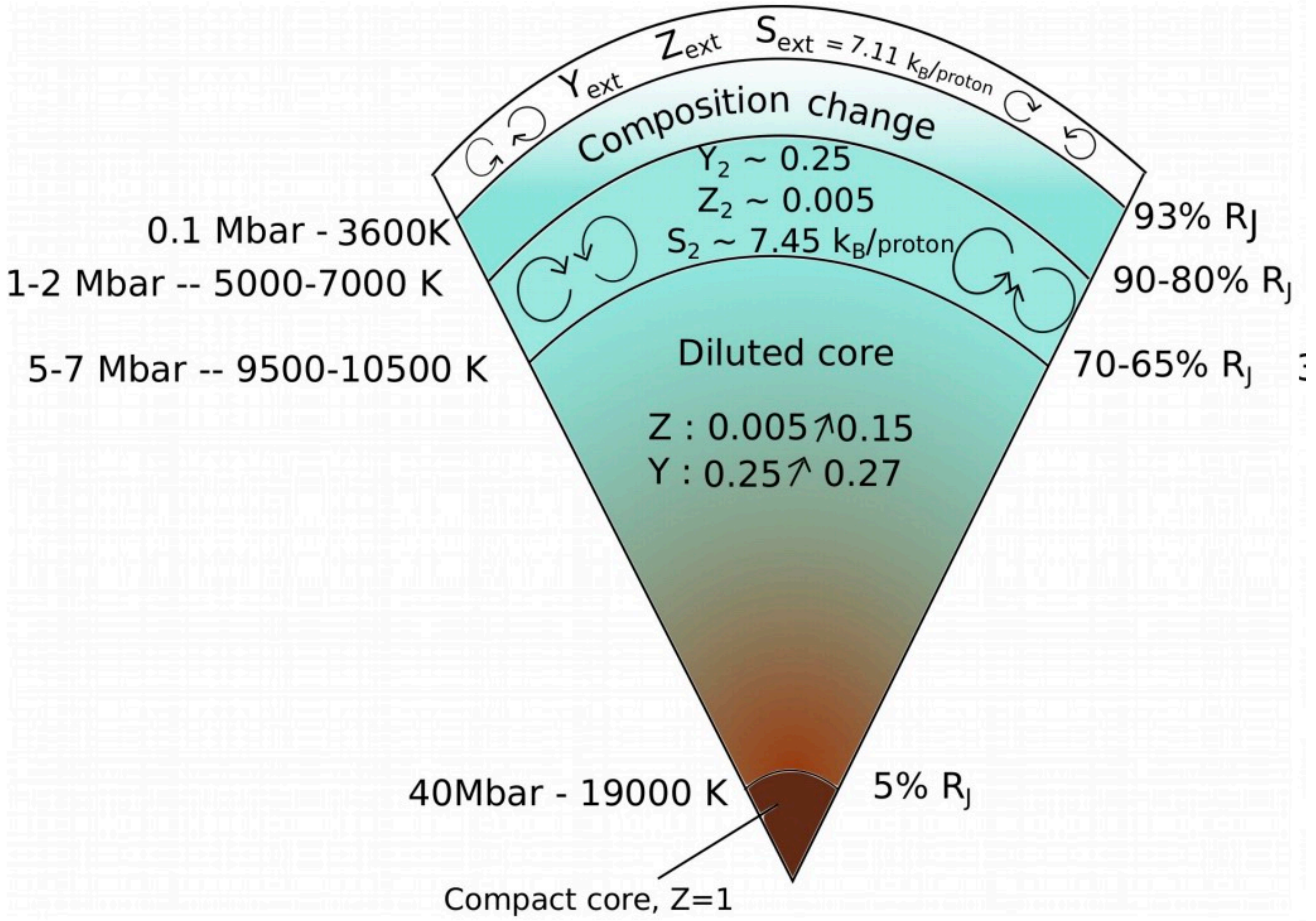


Jupiter's interior structure

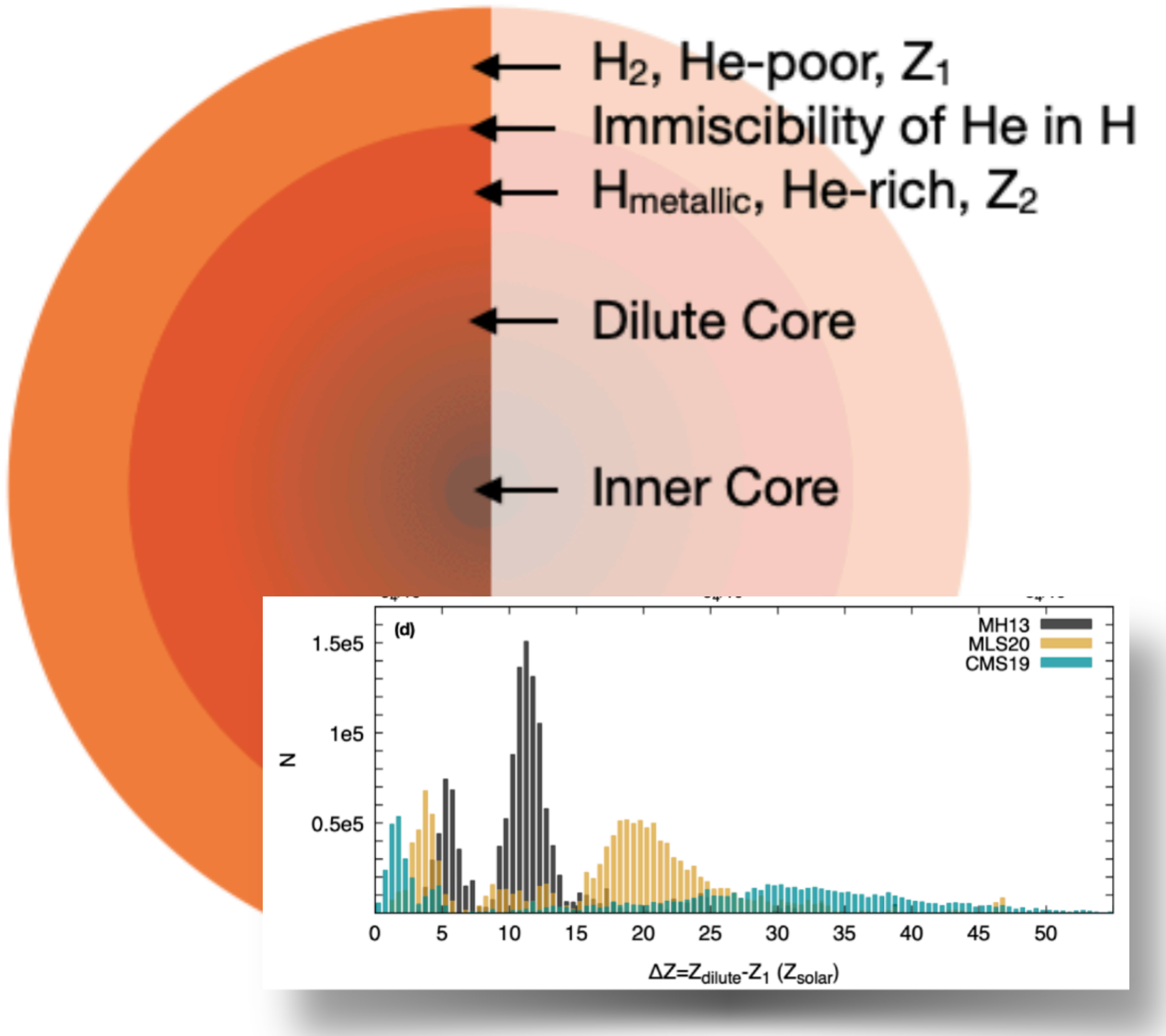
… from precise Juno gravity field measurements



Wahl et al. (2017)



Debras & Chabrier (2019)



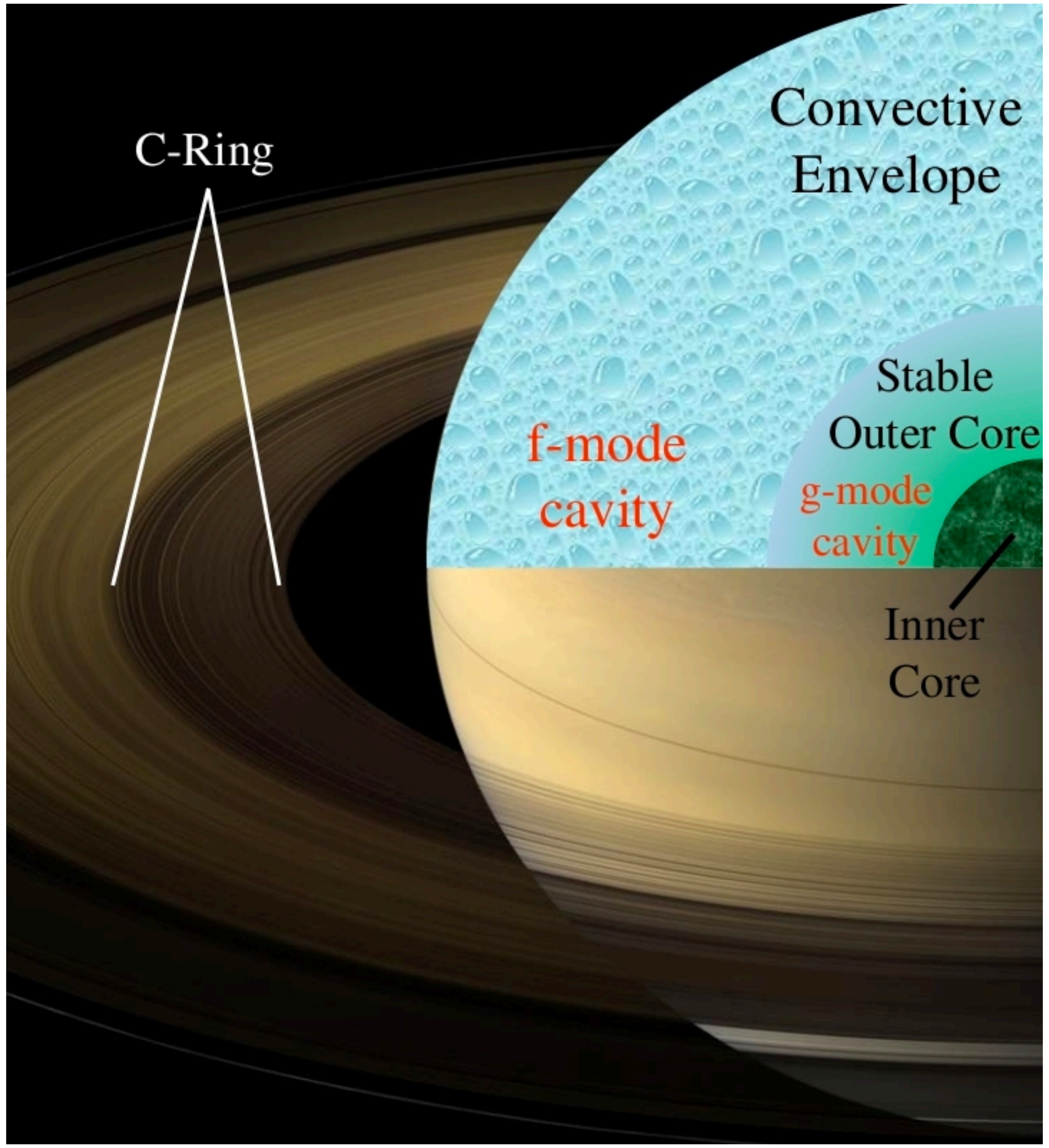
Miguel et al. (2022)
see also Militzer et al. (2022)

Jupiter's envelope is not homogeneous

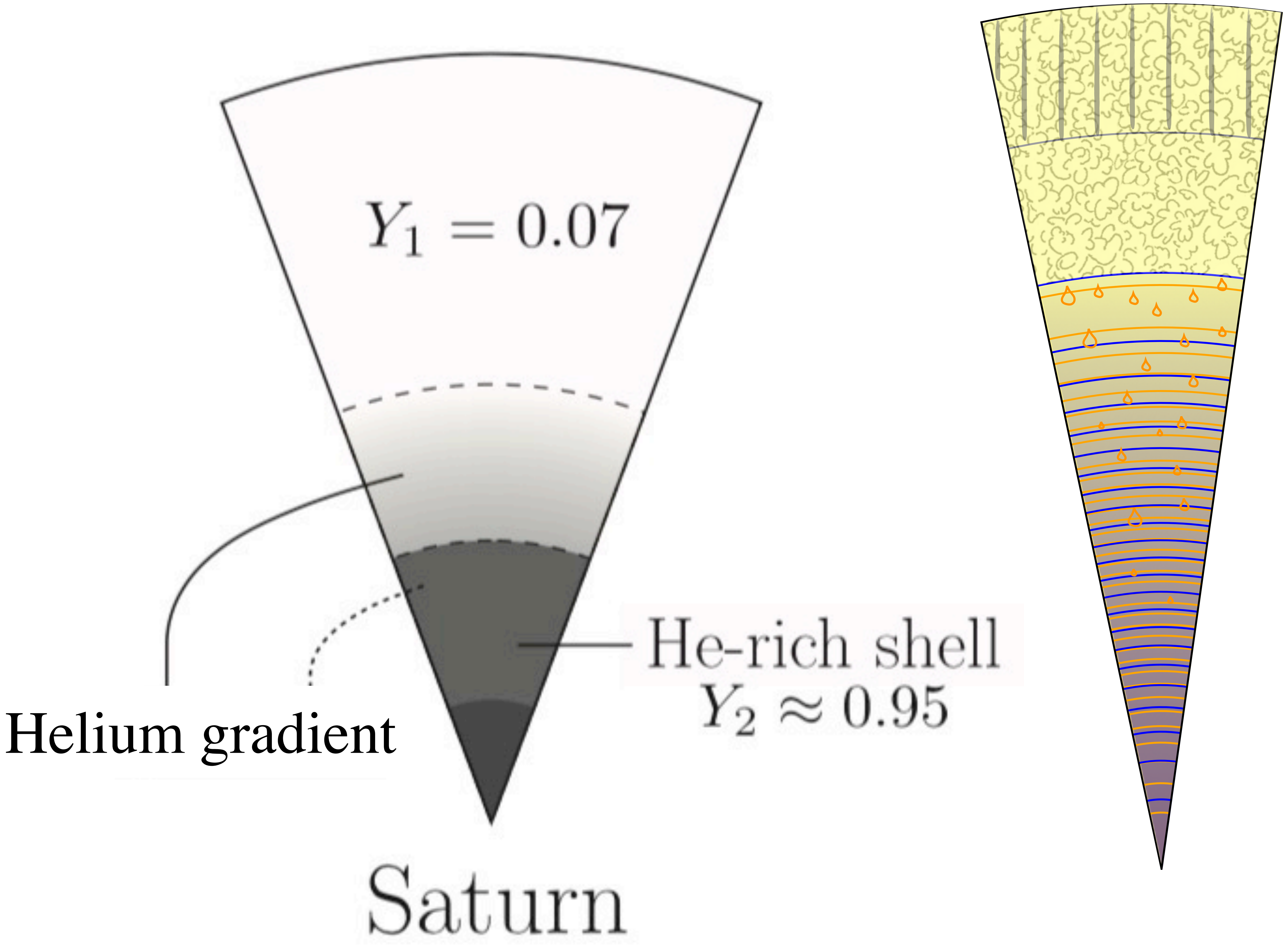
(This is in line with some formation models, e.g., Liu et al. 2015
Lozovsky et al. 2017, Helled & Stevenson 2017)

Saturn’s interior structure

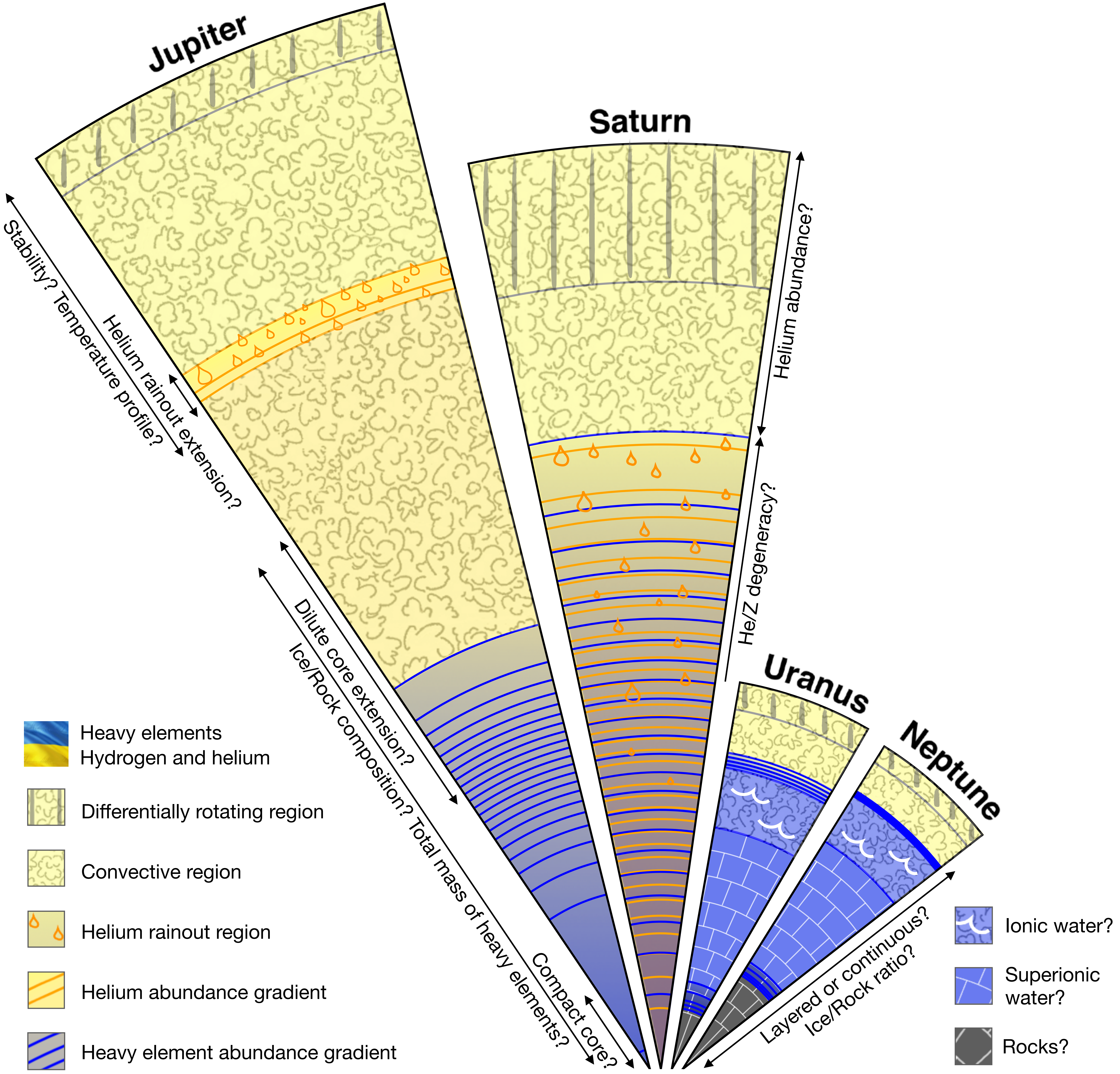
from Cassini seismology & gravimetry



Fuller (2014)



Mankovich & Fortney (2020)
see also Mankovich & Fuller (2021)



Guillot et al., Protostars & Planets VII (arXiv 2022)

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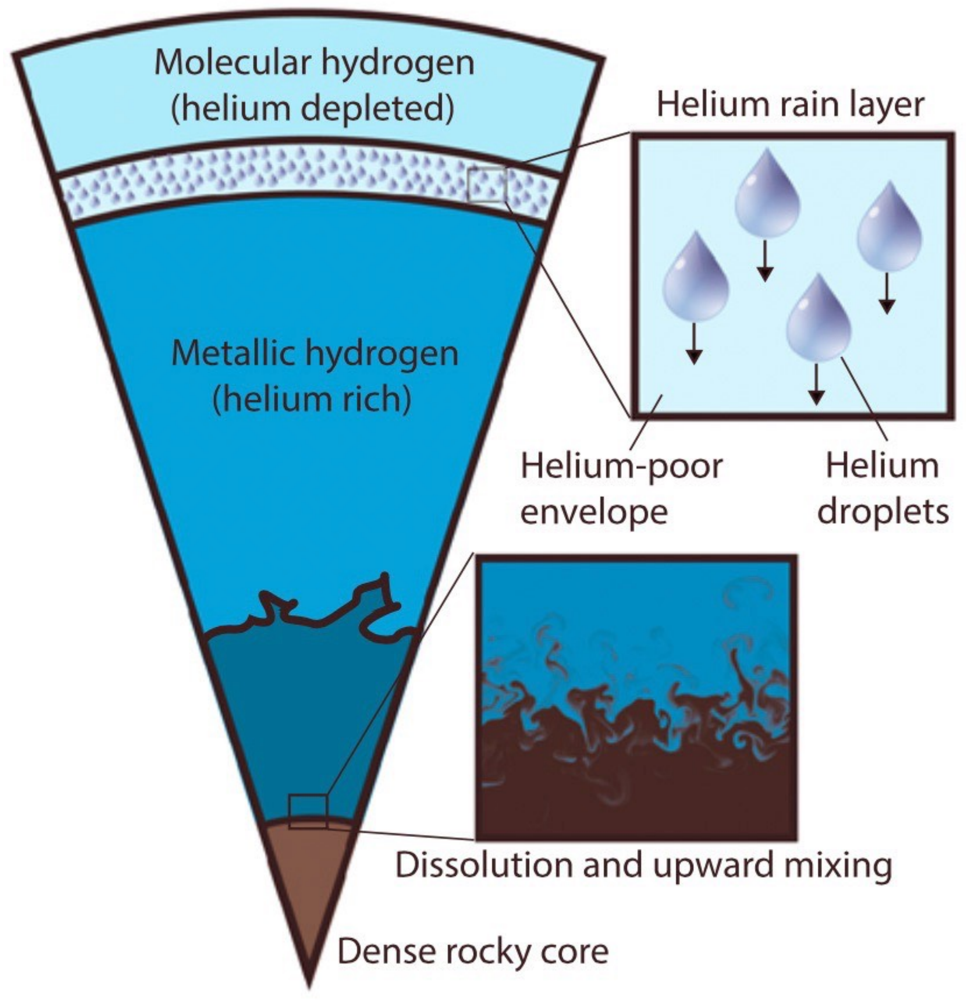
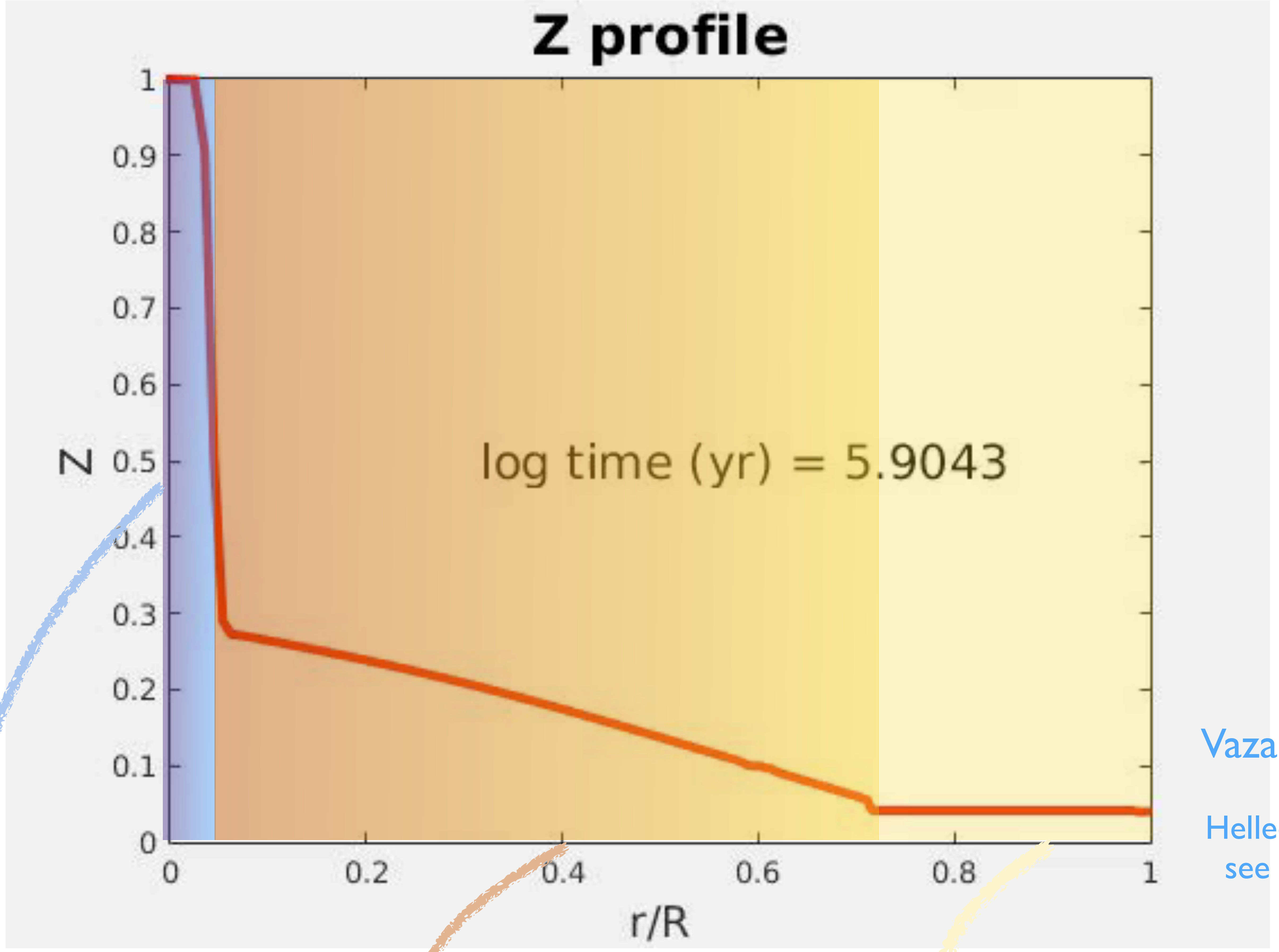
How & when were heavy elements delivered?



Wahl et al. (2017)



Vazan, Helled & Guillot (A&A, 2018)

see also: Lozovsky et al. (ApJ, 2017)

Helled & Guillot (Exoplanet handbook 2017)

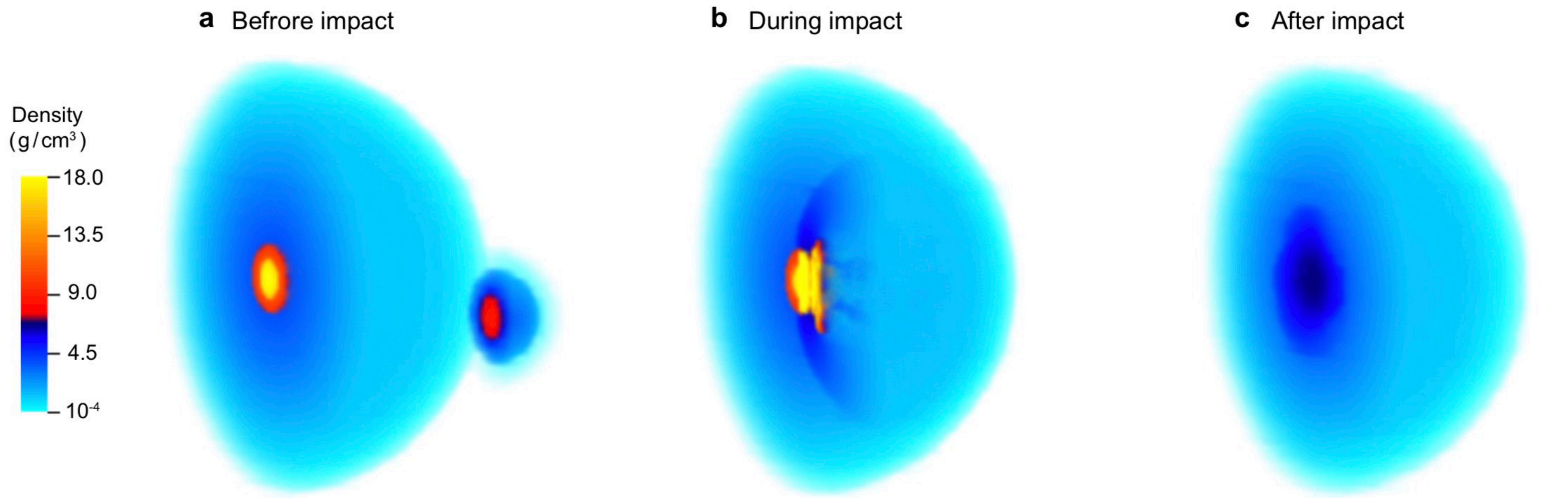
see also Liu, Agnor, Lin & Li (MNRAS, 2015)

Inner ~3-10 $M_\oplus$
Dense core Z~100%

Middle ~10-200 $M_\oplus$
Dilute core Z~5-30%

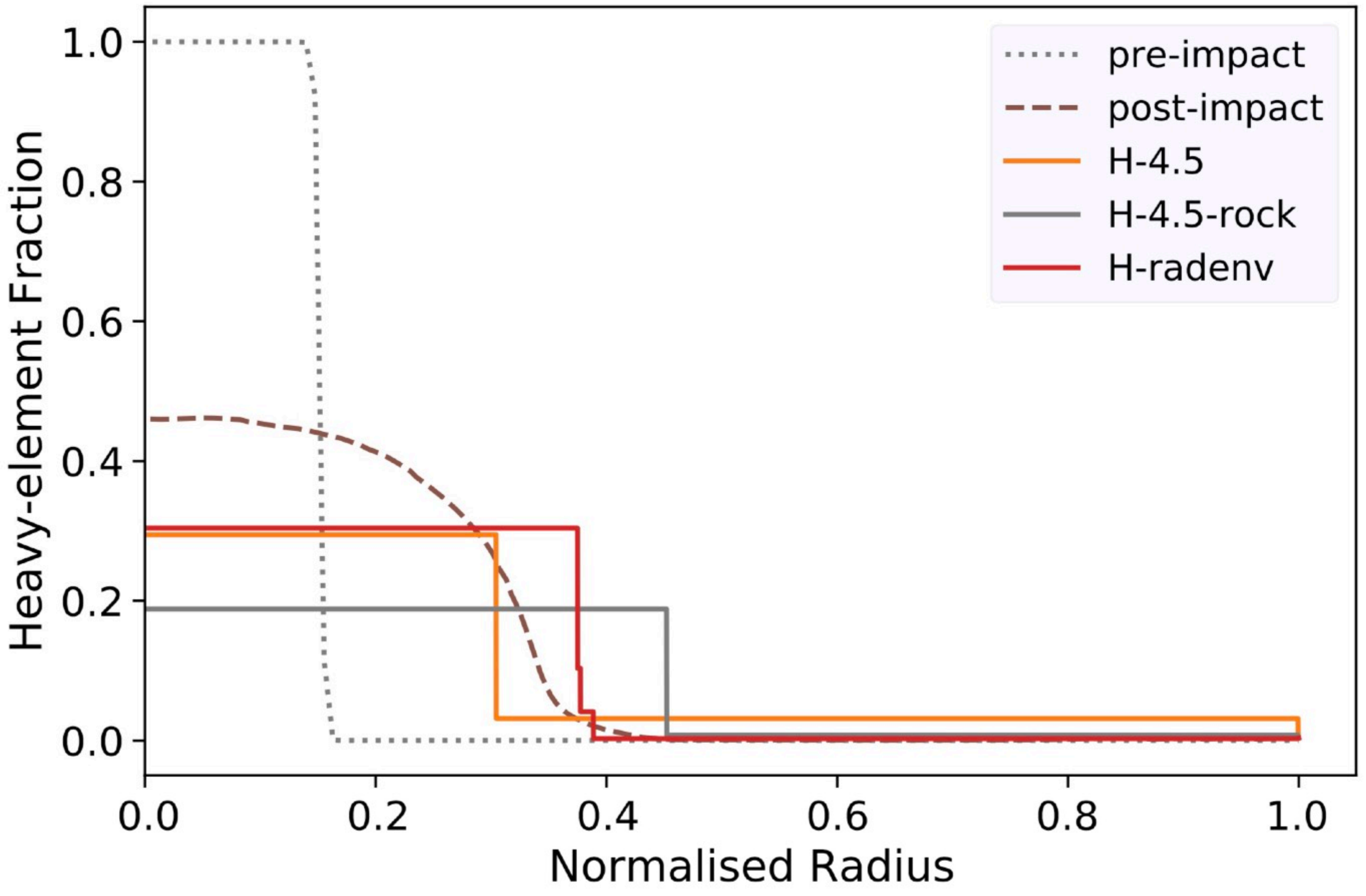
Outer ~200-320 $M_\oplus$
Mainly H+He
+Noble gases?

The giant impact scenario

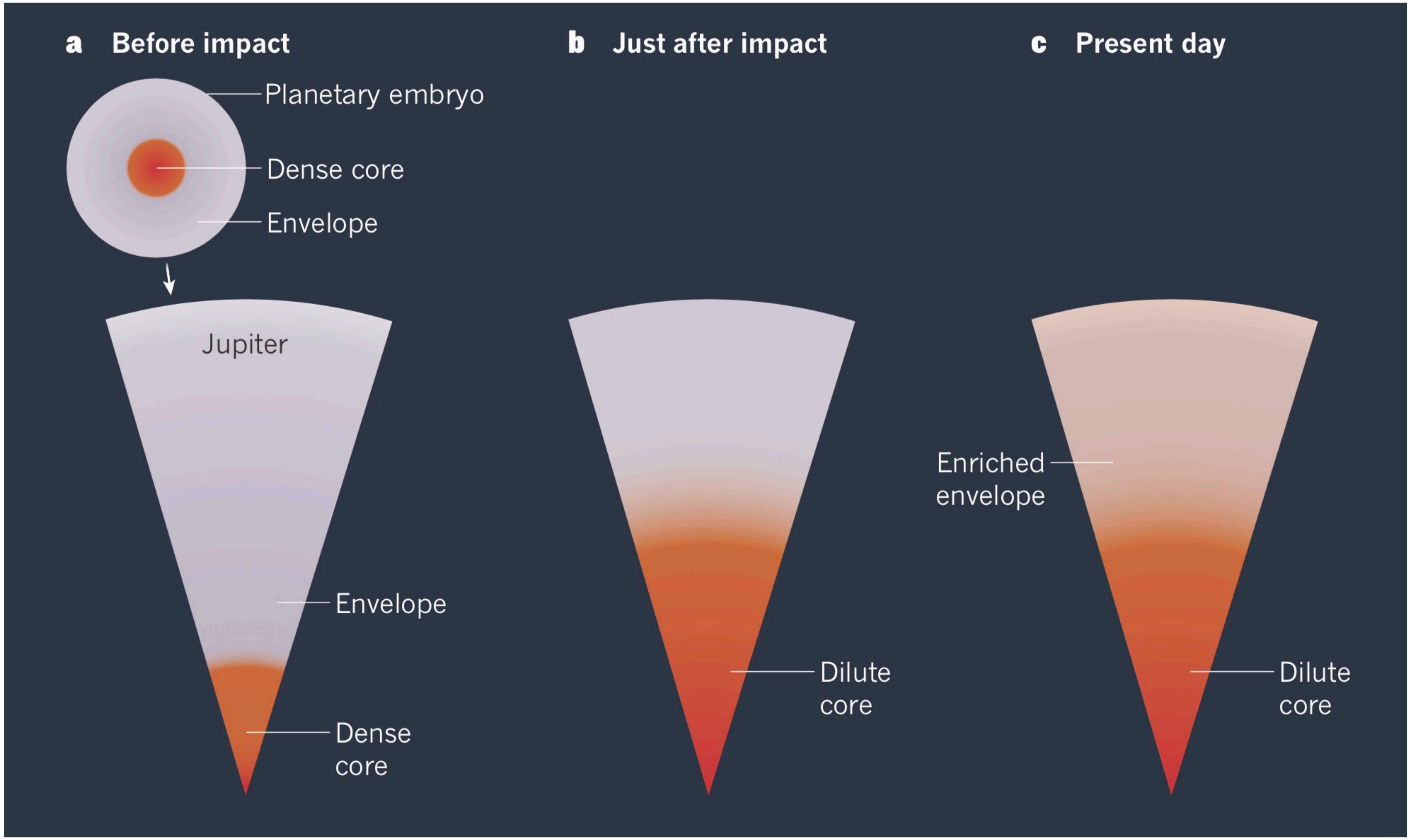


A head-on impact with a $10M_\oplus$ embryo can shatter the primordial core and partially mix it with the envelope. Subsequent mixing is only partial.

Liu S-F. et al. (Nature, 2019)



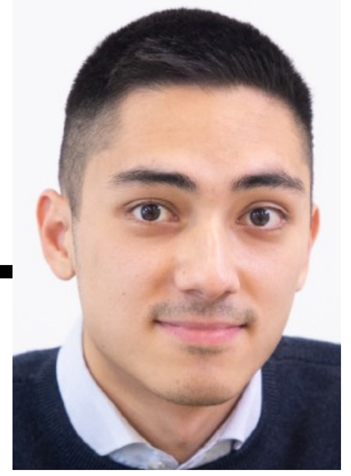
The giant impact scenario



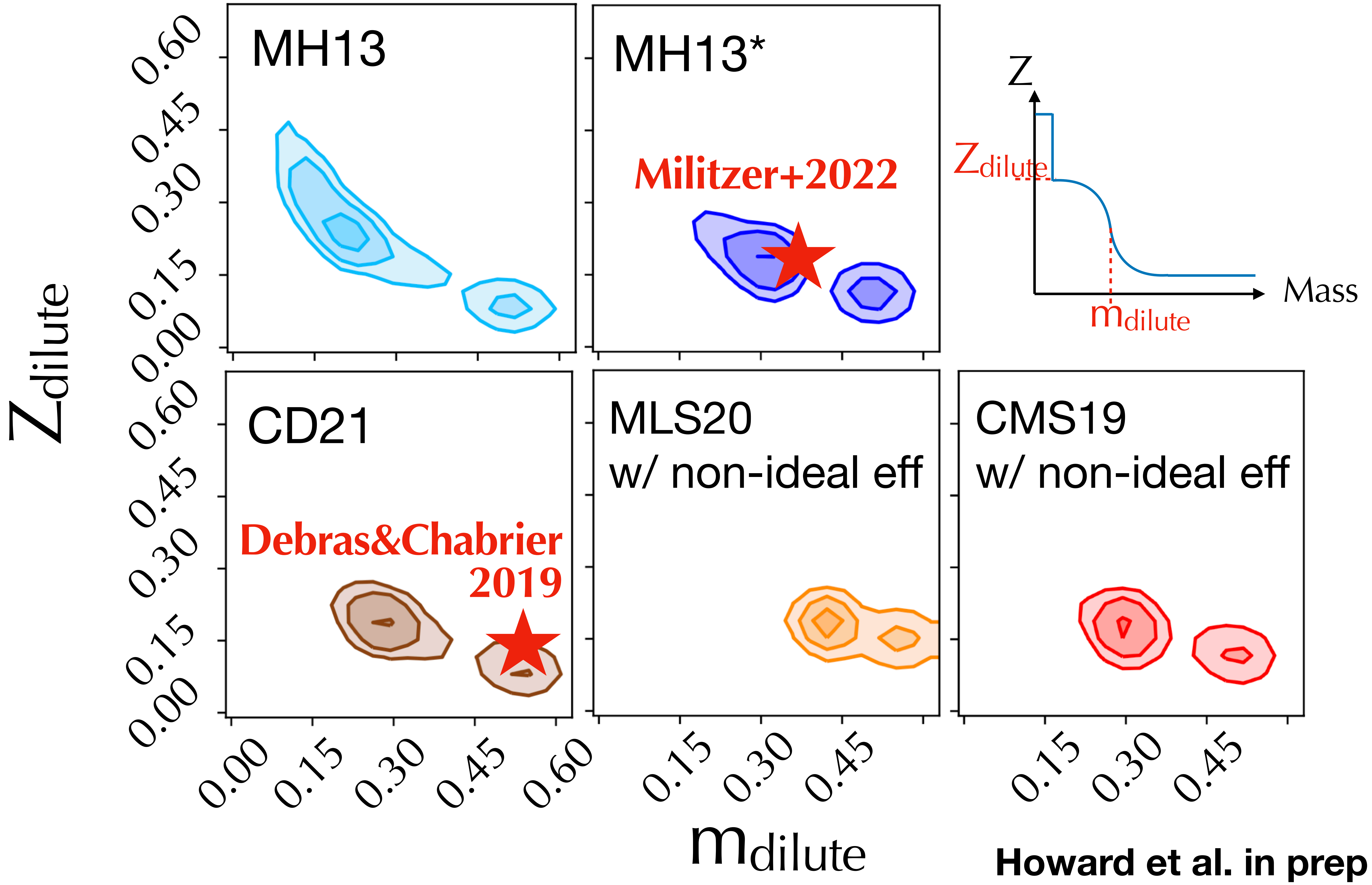
Liu S-F. et al. (Nature, 2019)
see also News & Views, Guillot (2019)

See however Müller, Helled & Cumming (2020)

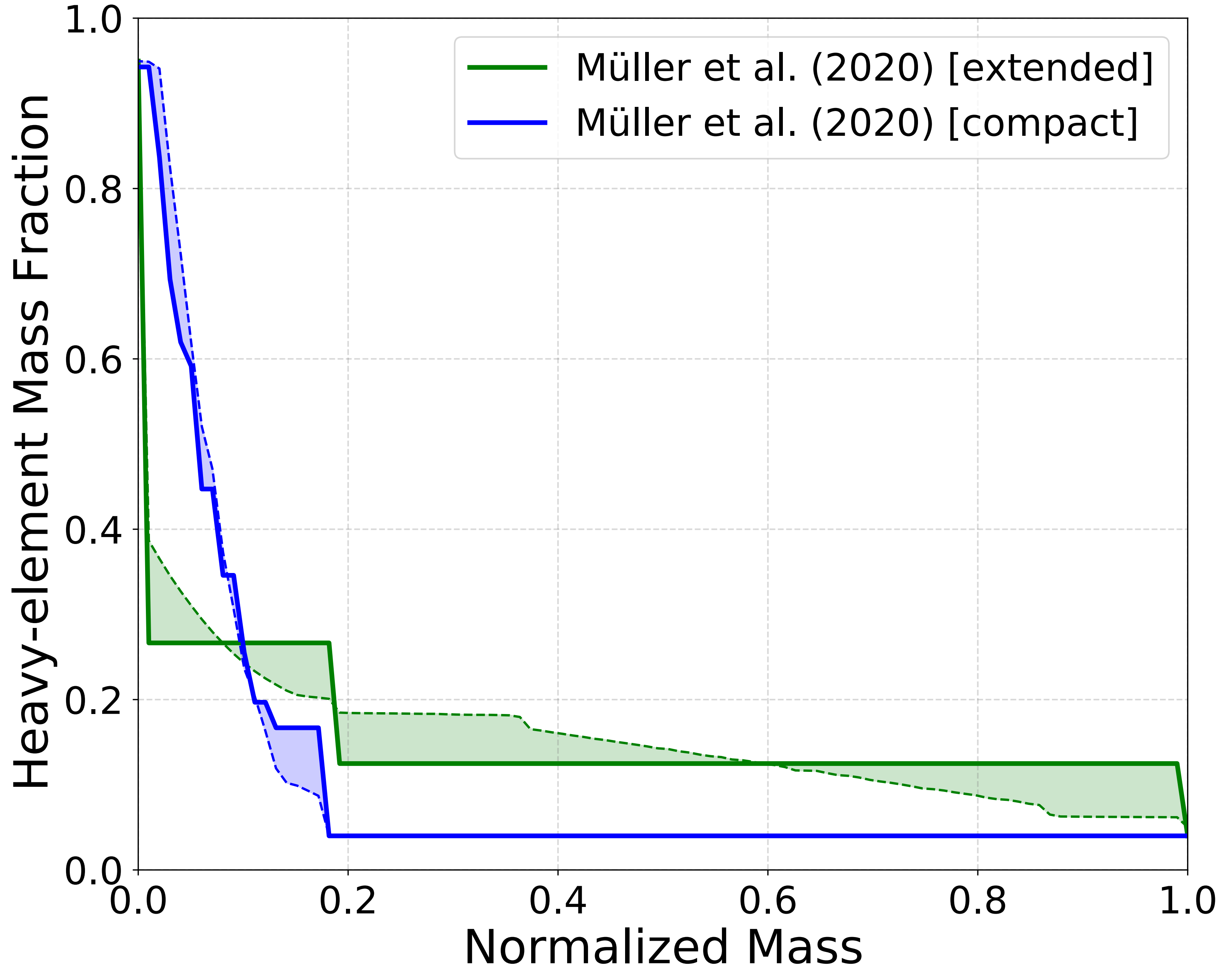
The extent of Jupiter's dilute core



Saburo
HOWARD



Howard et al. in prep



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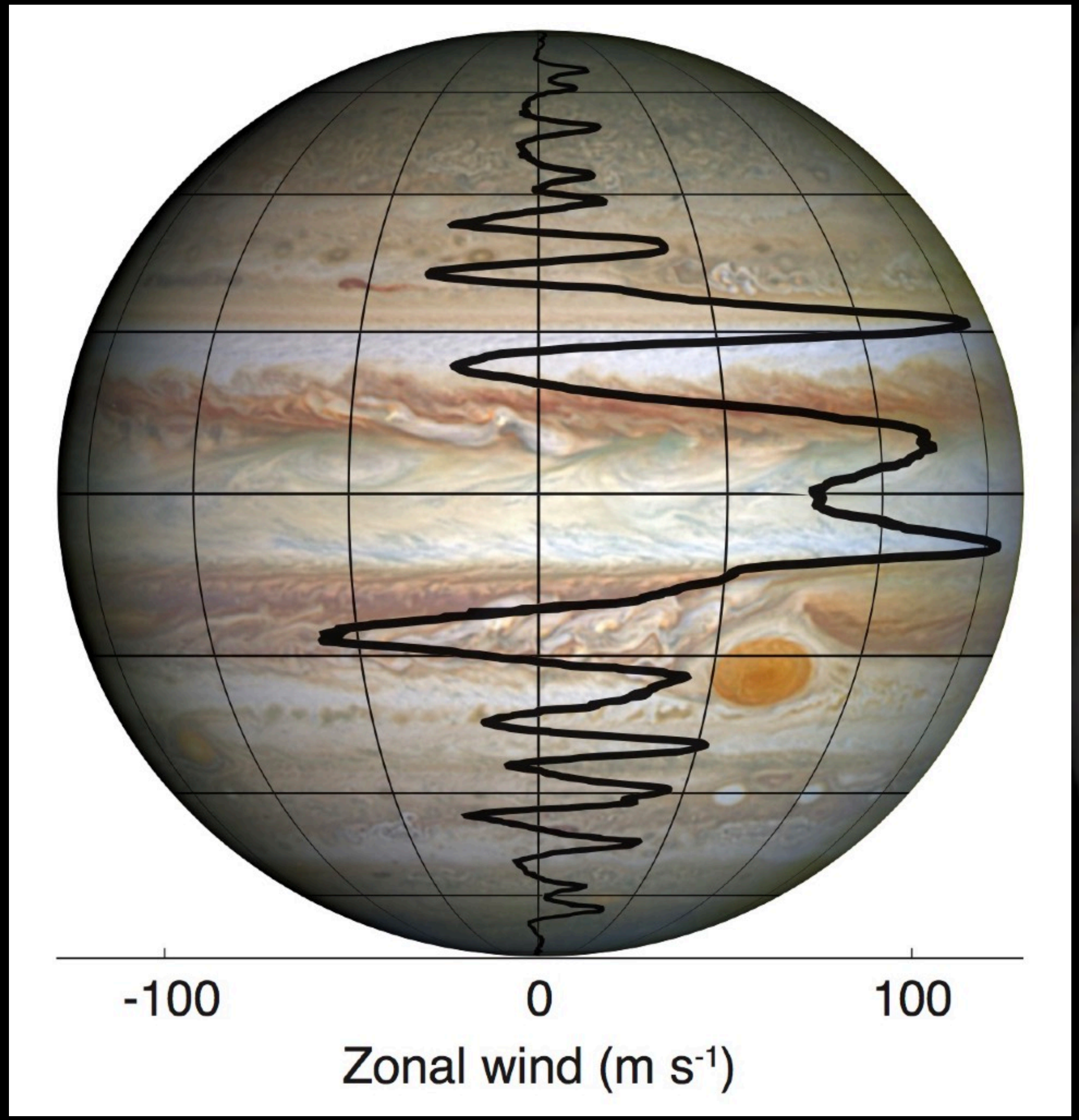
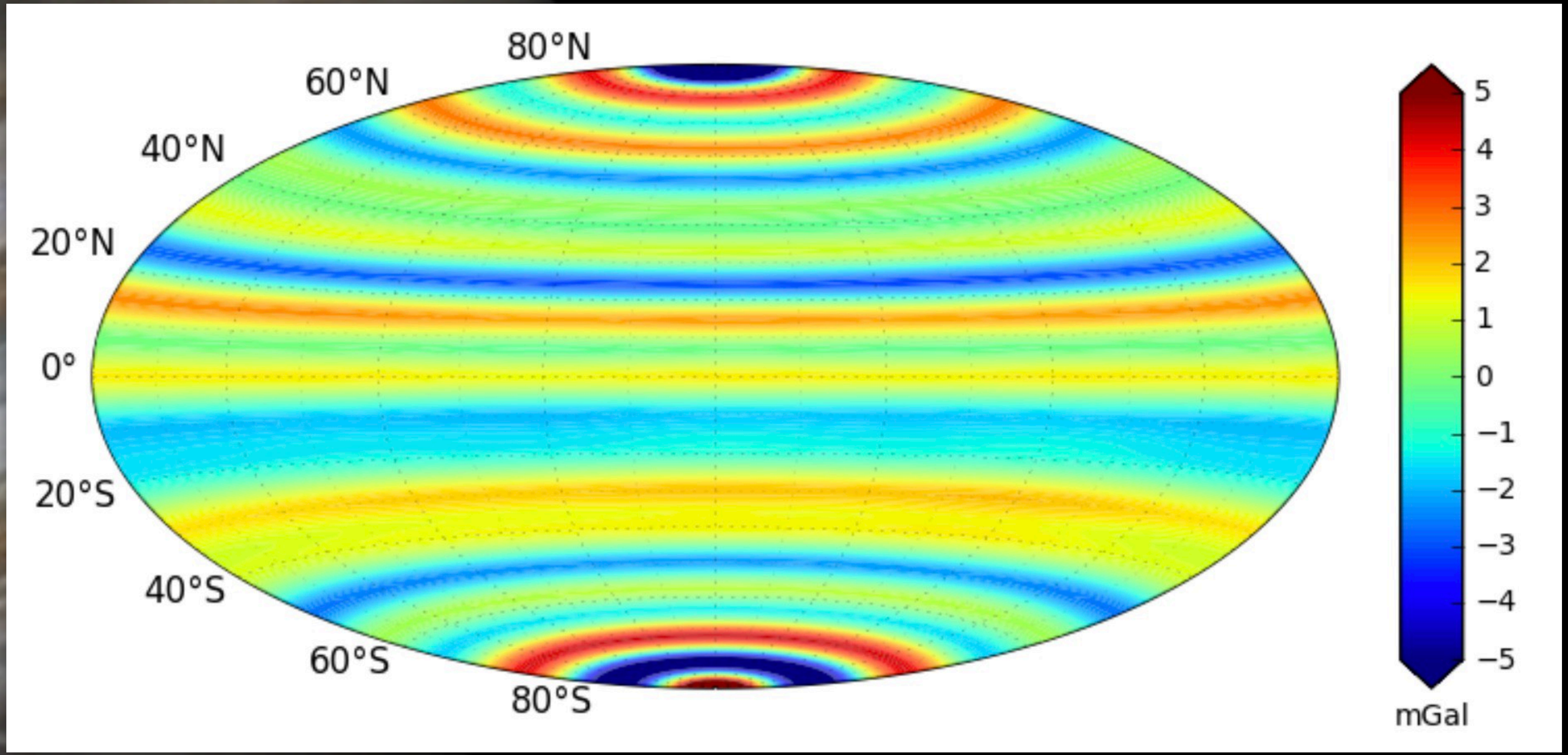
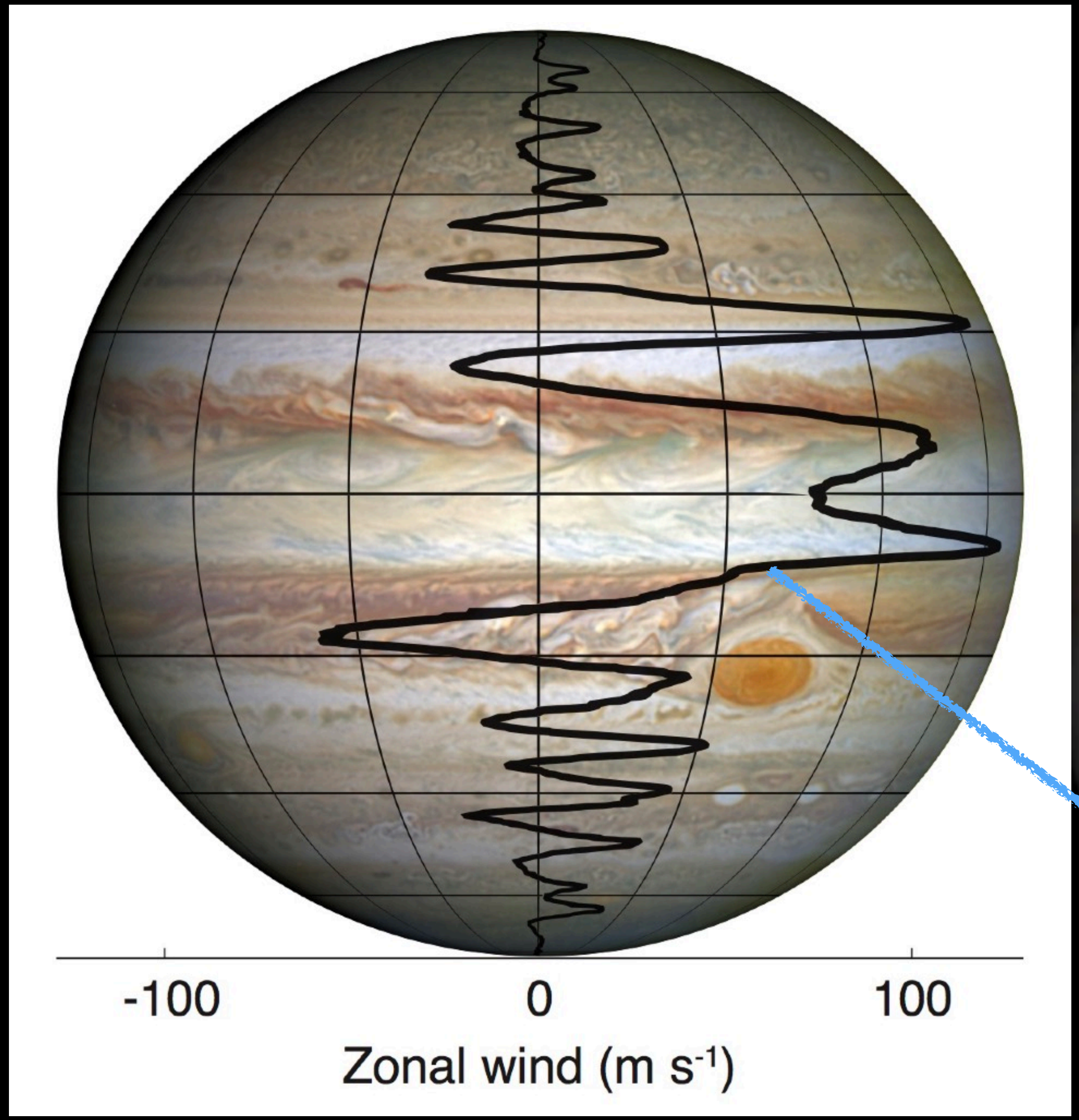
Zonal winds

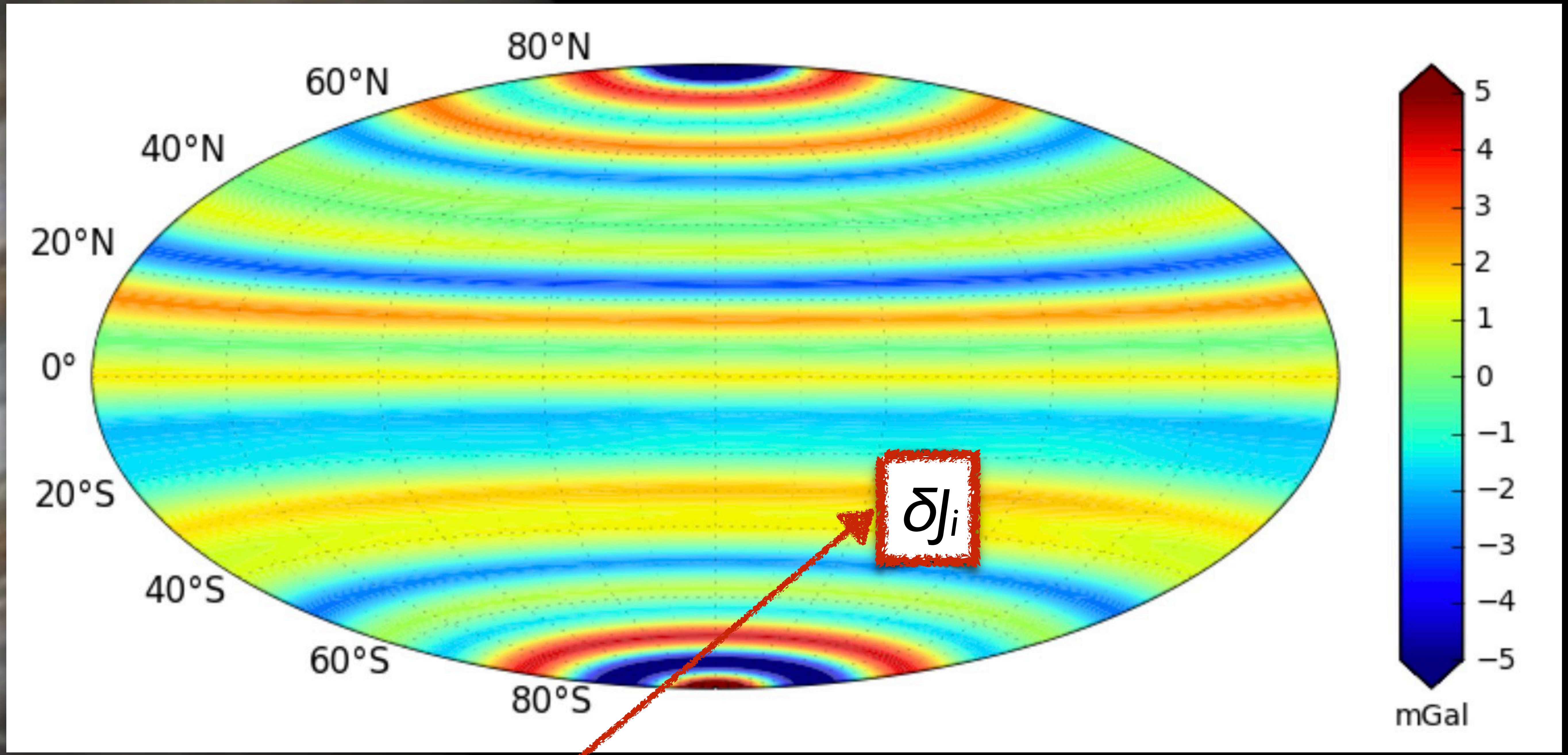


Map of gravity anomalies

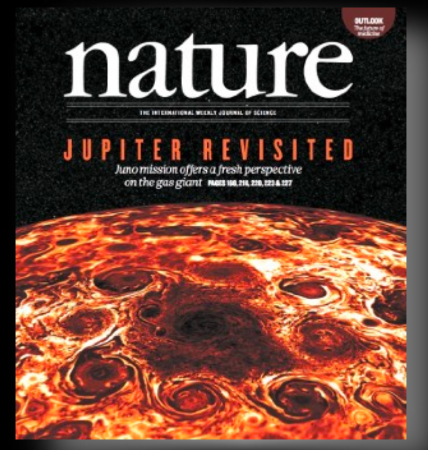


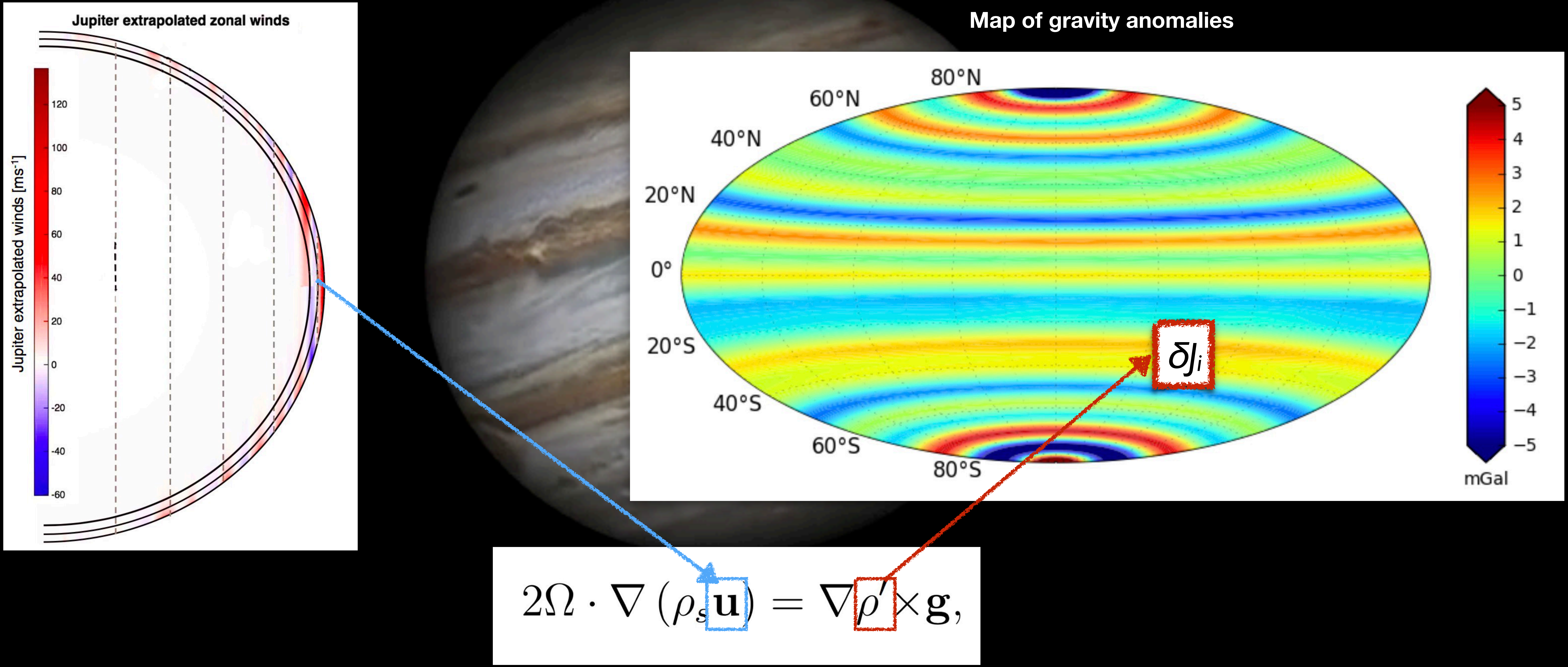
Iess et al. (2018)


Zonal winds


Map of gravity anomalies

$$2\Omega \cdot \nabla \left(\rho_s \boxed{\mathbf{u}}\right) = \nabla \boxed{\rho'} \times \mathbf{g},$$





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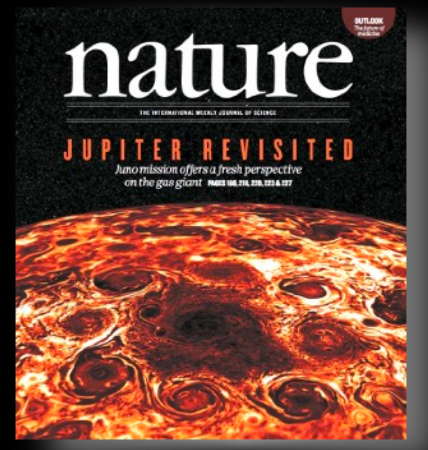

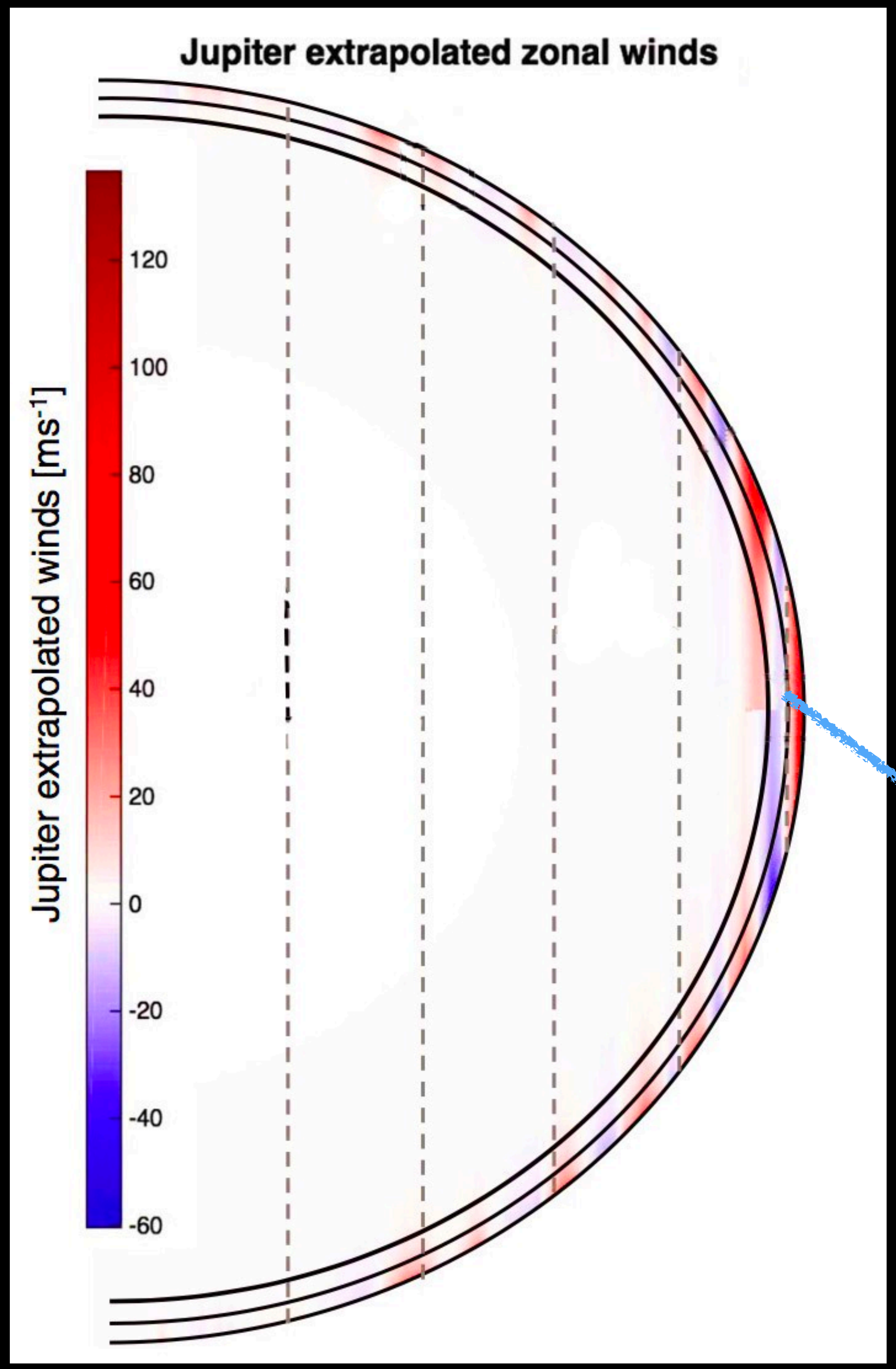

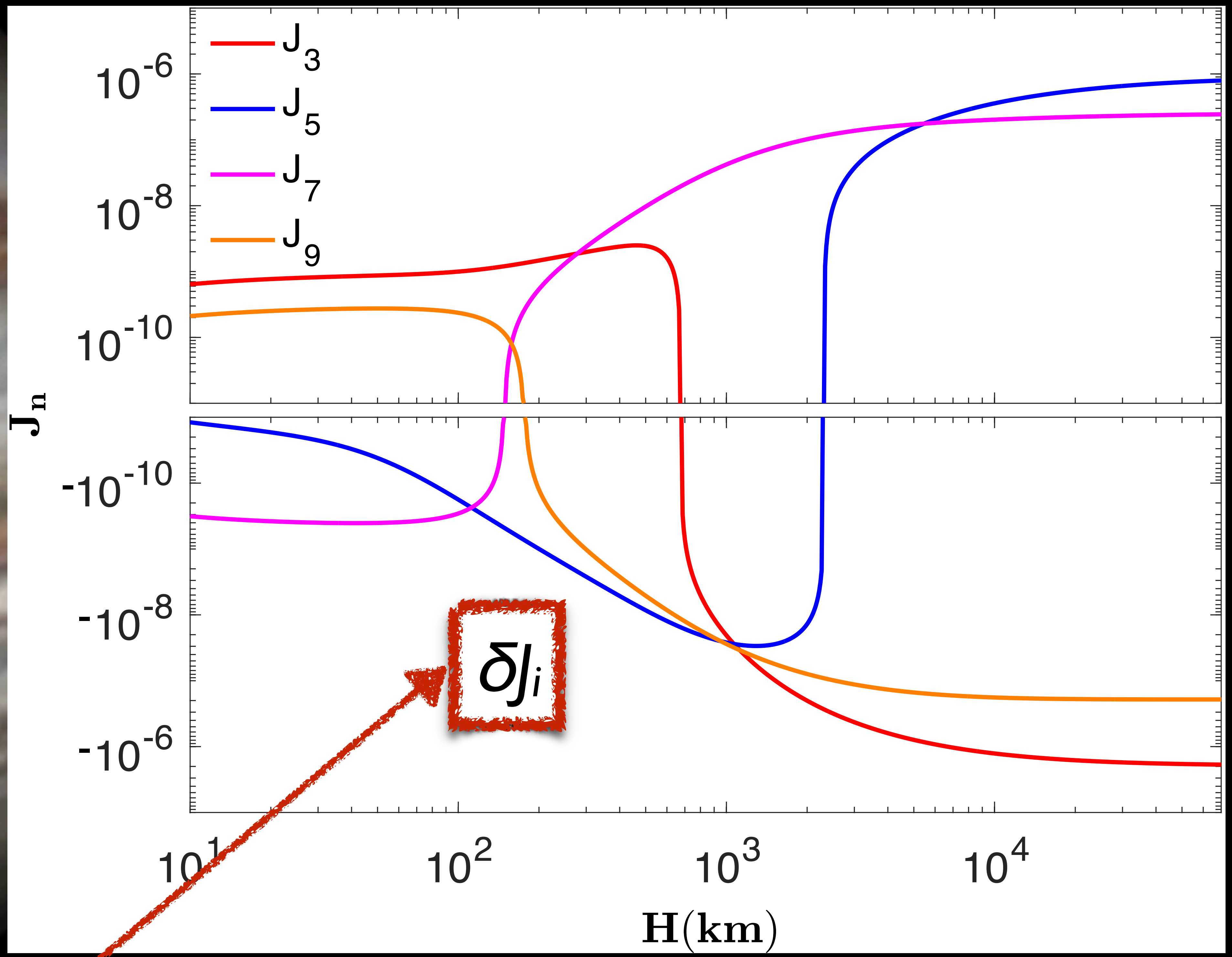

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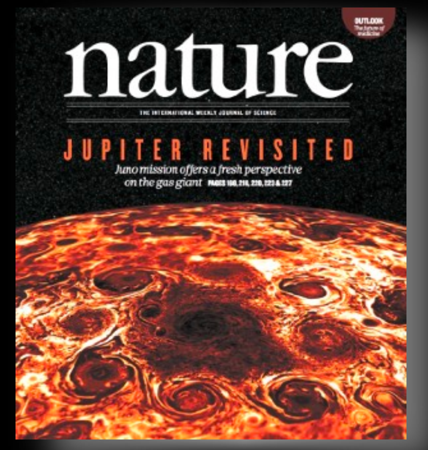

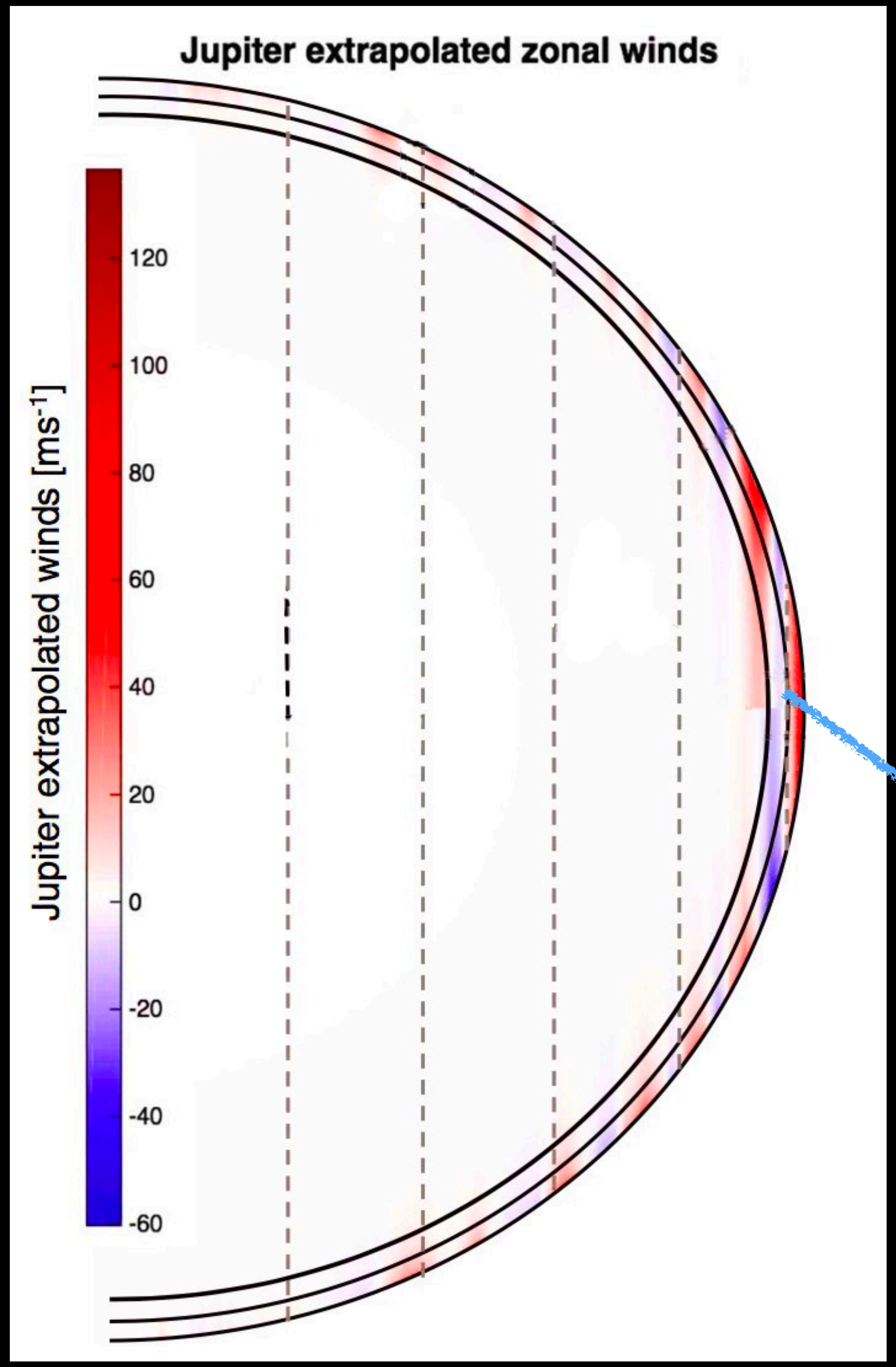

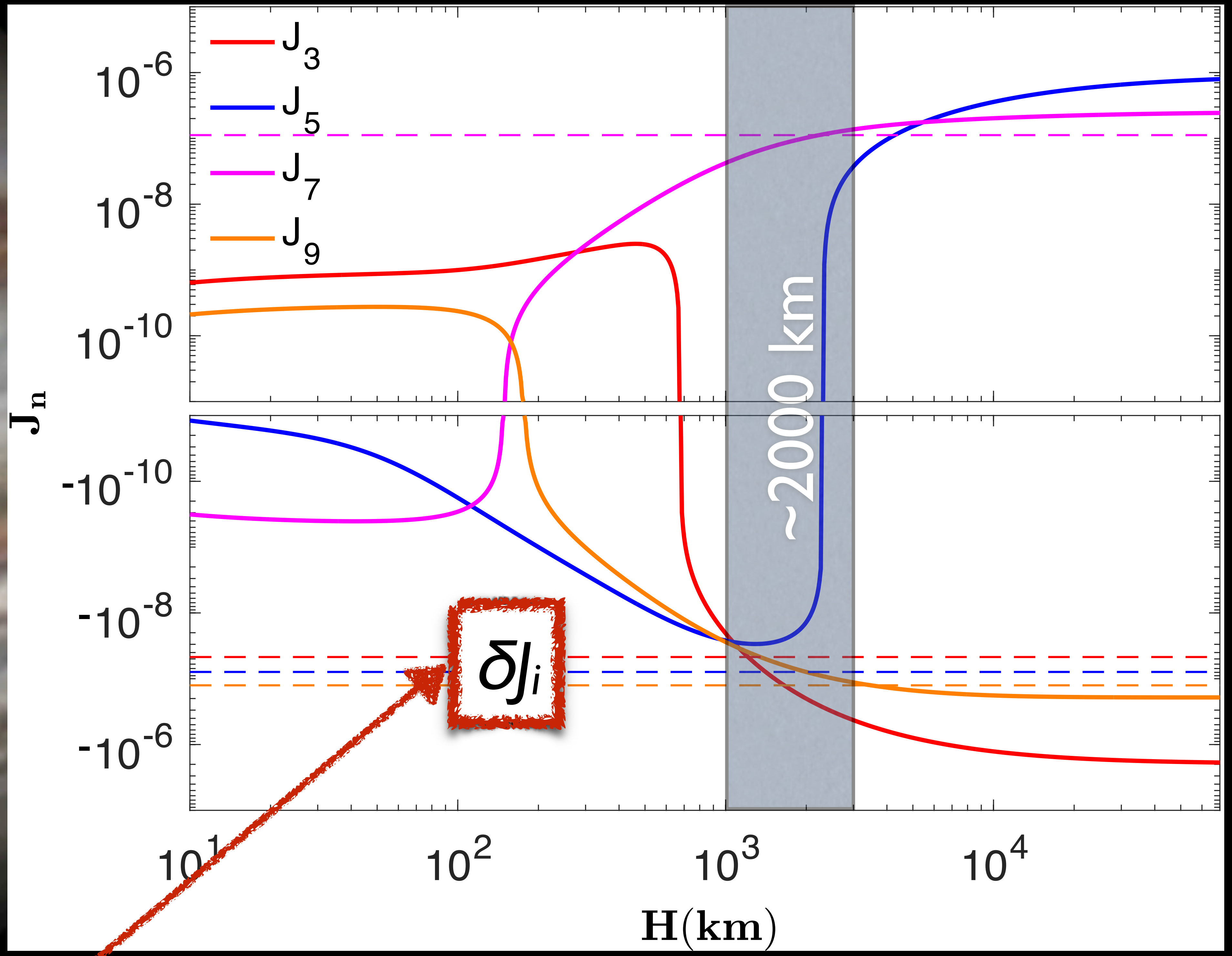

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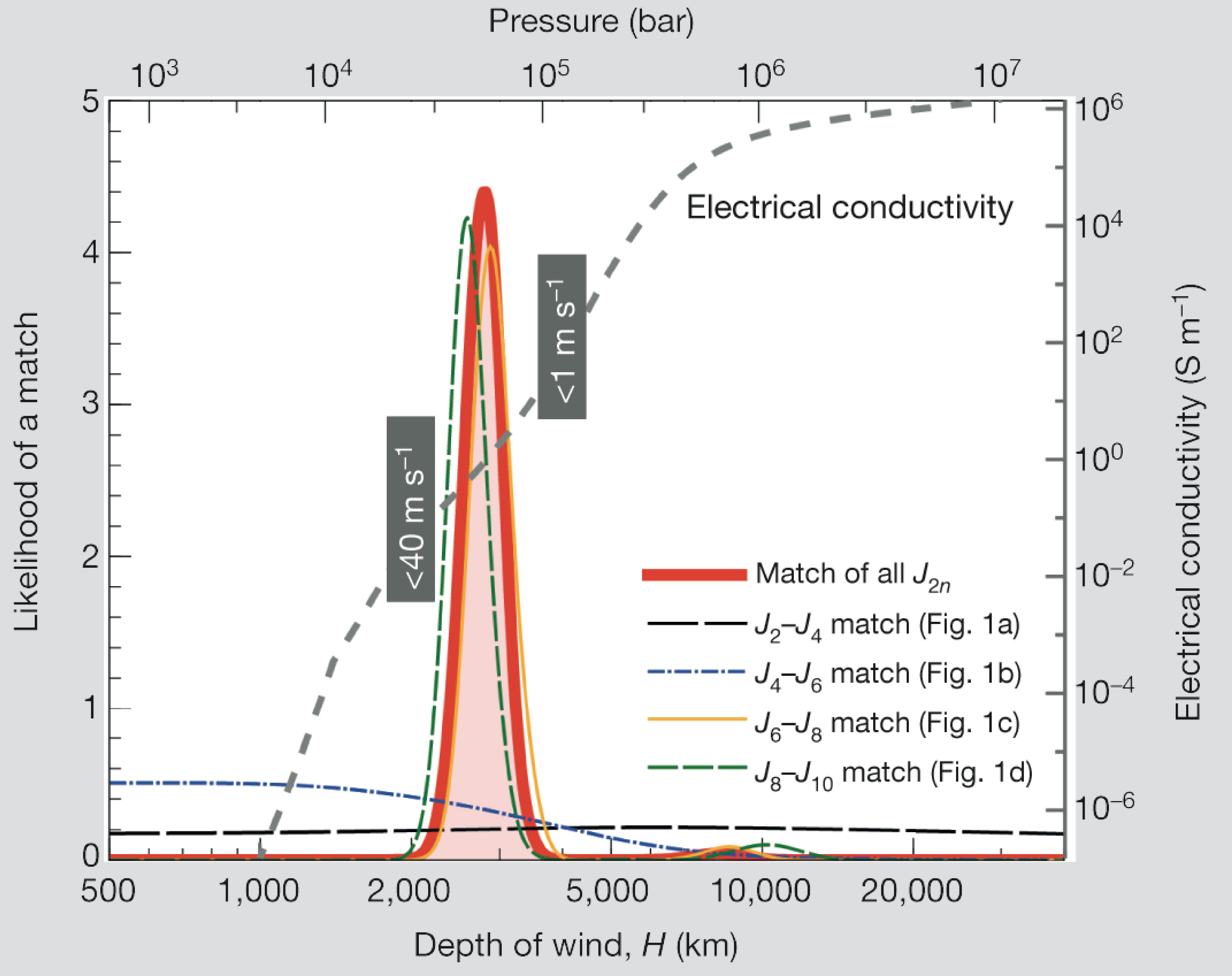
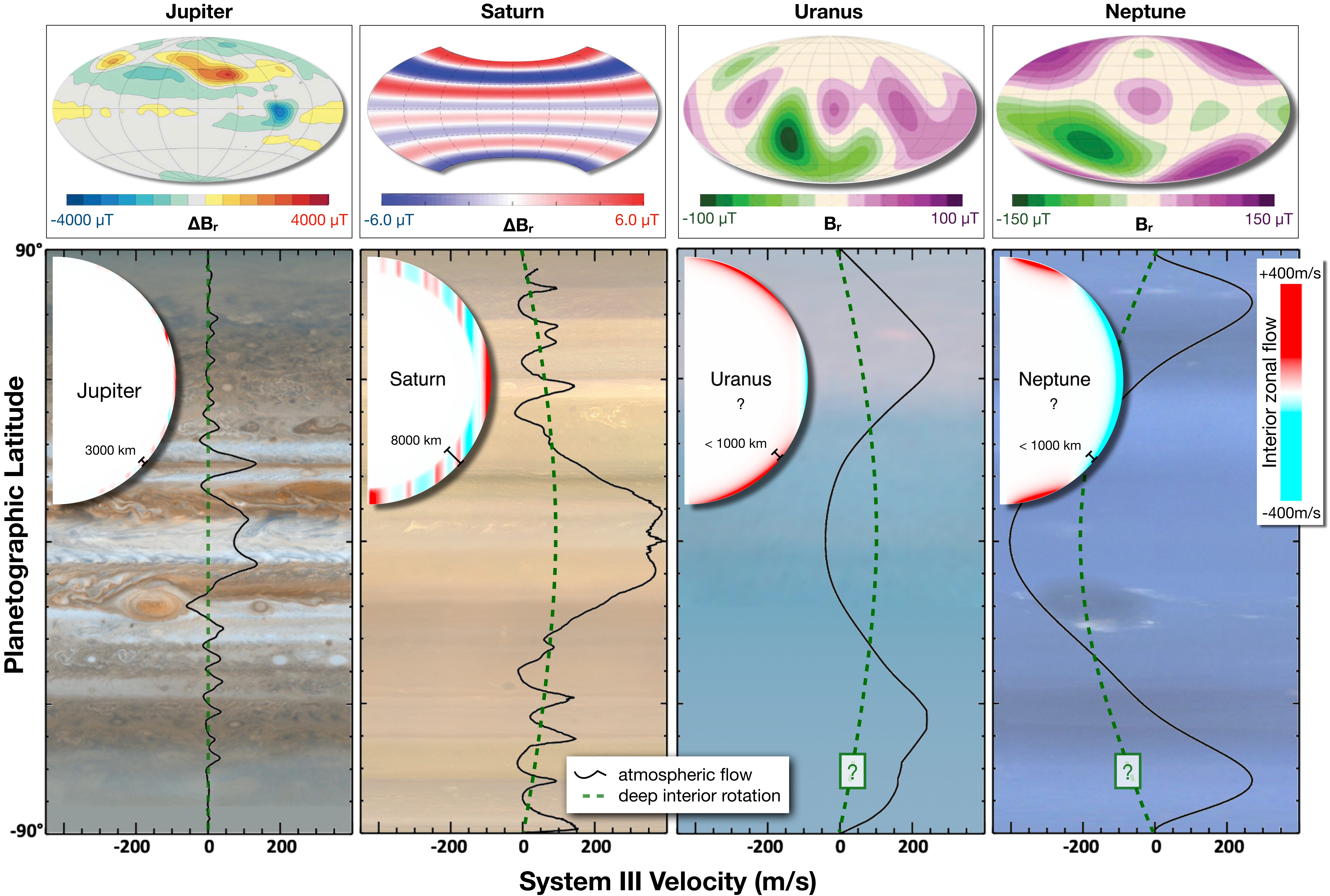


Guillot et al. (2018)

- 🟧 Insulating molecular hydrogen, differentially rotating zones and bands
- 🟦 Conductive molecular hydrogen, uniform rotation
- 🟦 Metallic hydrogen, uniform rotation

Guillot et al. (2018)



Guillot et al., Protostars & Planets VII (arXiv 2022)

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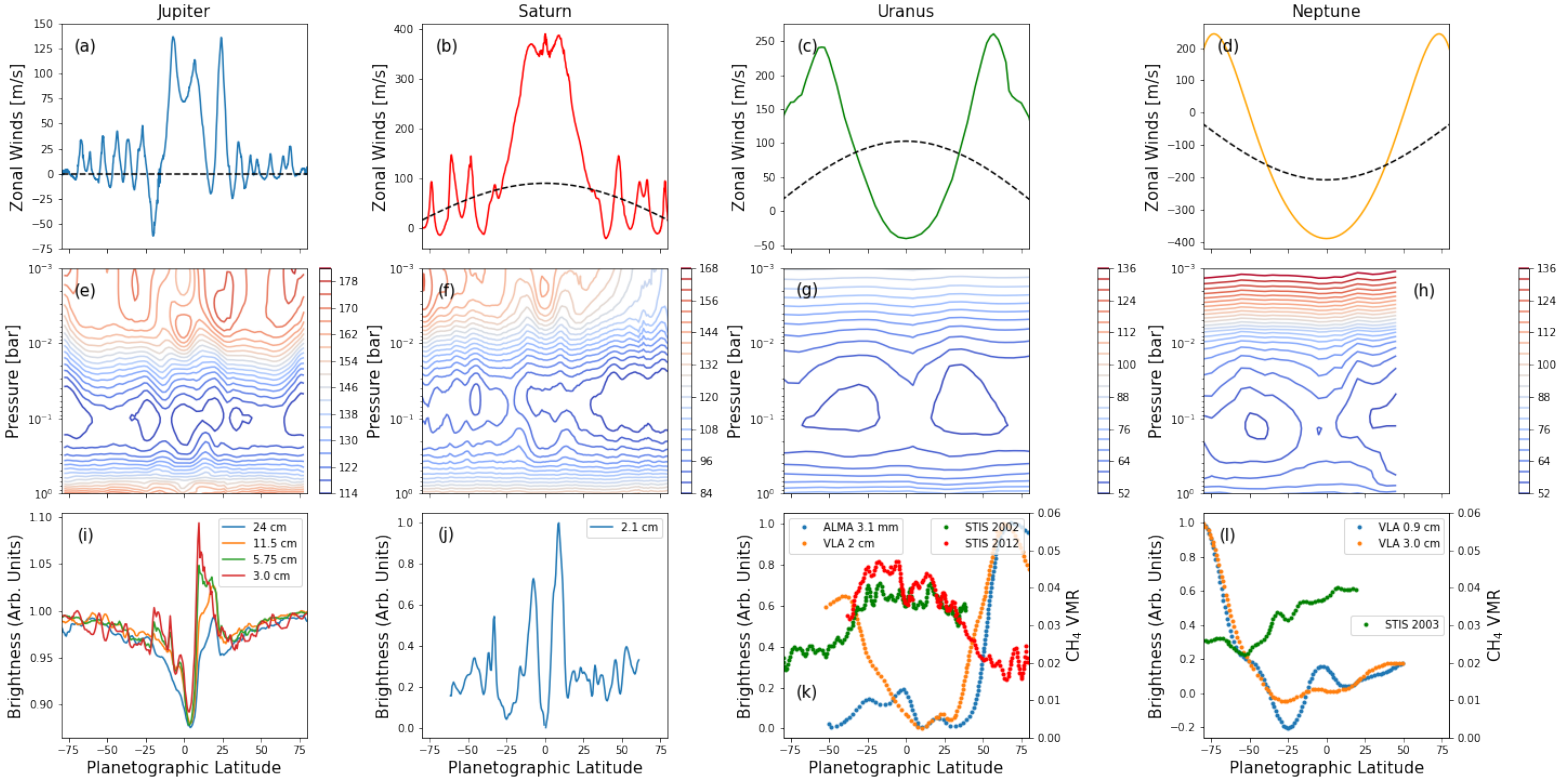
The atmospheric boundary condition



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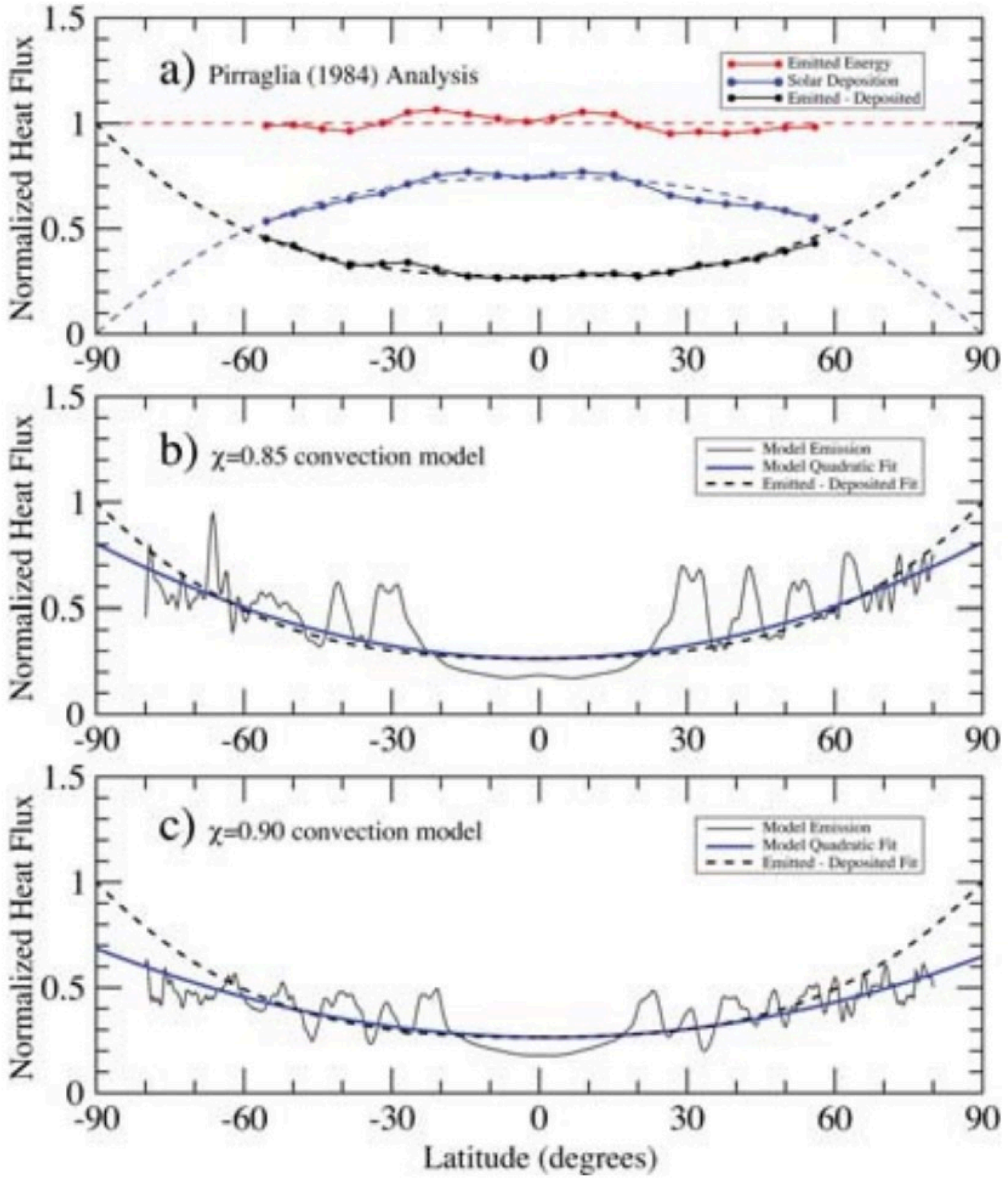

Heat flux is ~uniform because of:

- mixing in the atmosphere (Conrath & Gierasch 1984)
- thermal gradients at depth counterbalance latitudinal insolation gradients (Ingersoll & Porco 1978)
- deep convection generate heat flux that is stronger at the poles and weaker at the equator (Aurnou et al. 2008)

Aurnou et al. (2008)


1.2 Ghz Antenna

The promise of satellite monitoring for preserving biodiversity p. 926

Antiaging diets dissected p. 953

How a viral RNA hijacks host machinery p. 955

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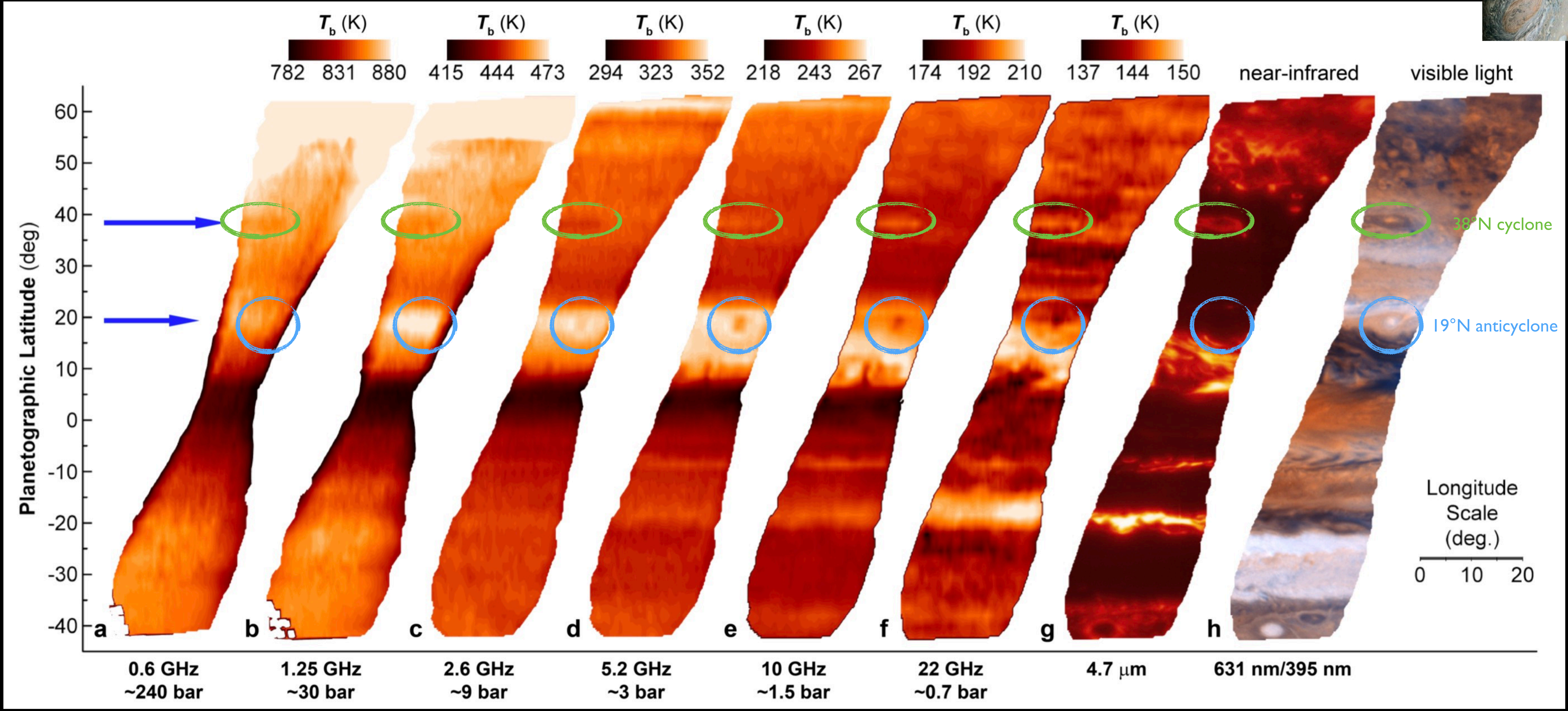
AAAS

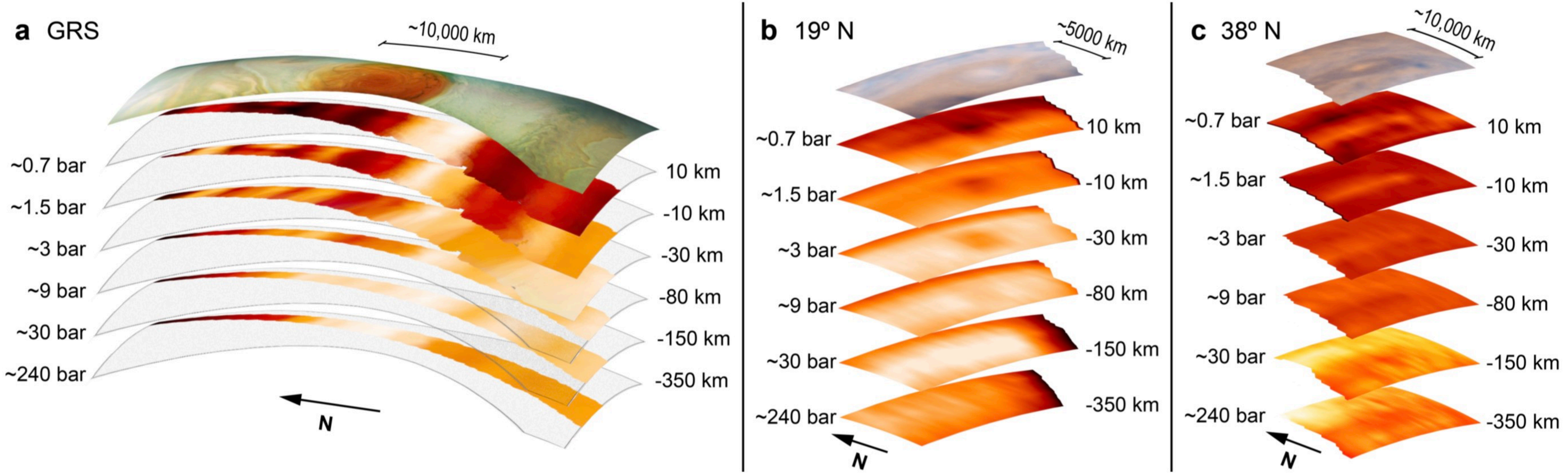
JUPITER'S STORMS

Juno peers into the atmosphere

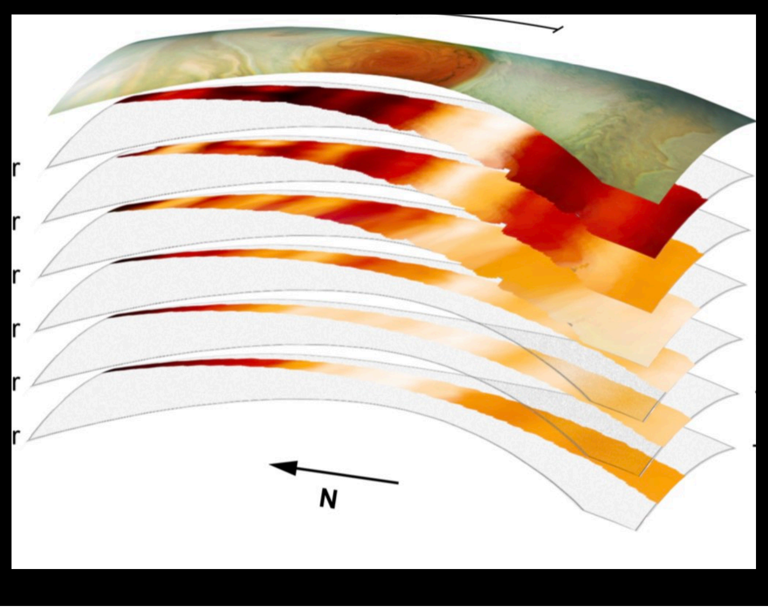
pp. 964 & 968

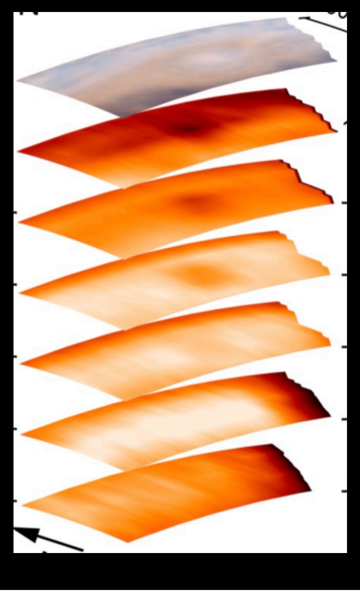


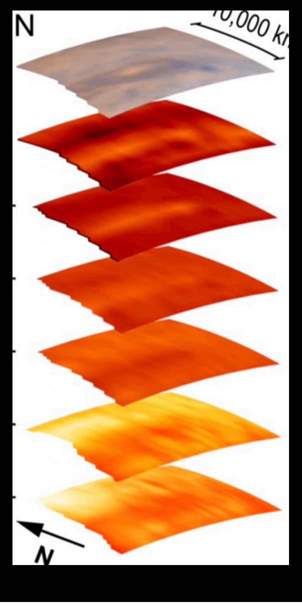
Bolton et al. (2021)



Bolton et al. (2021)



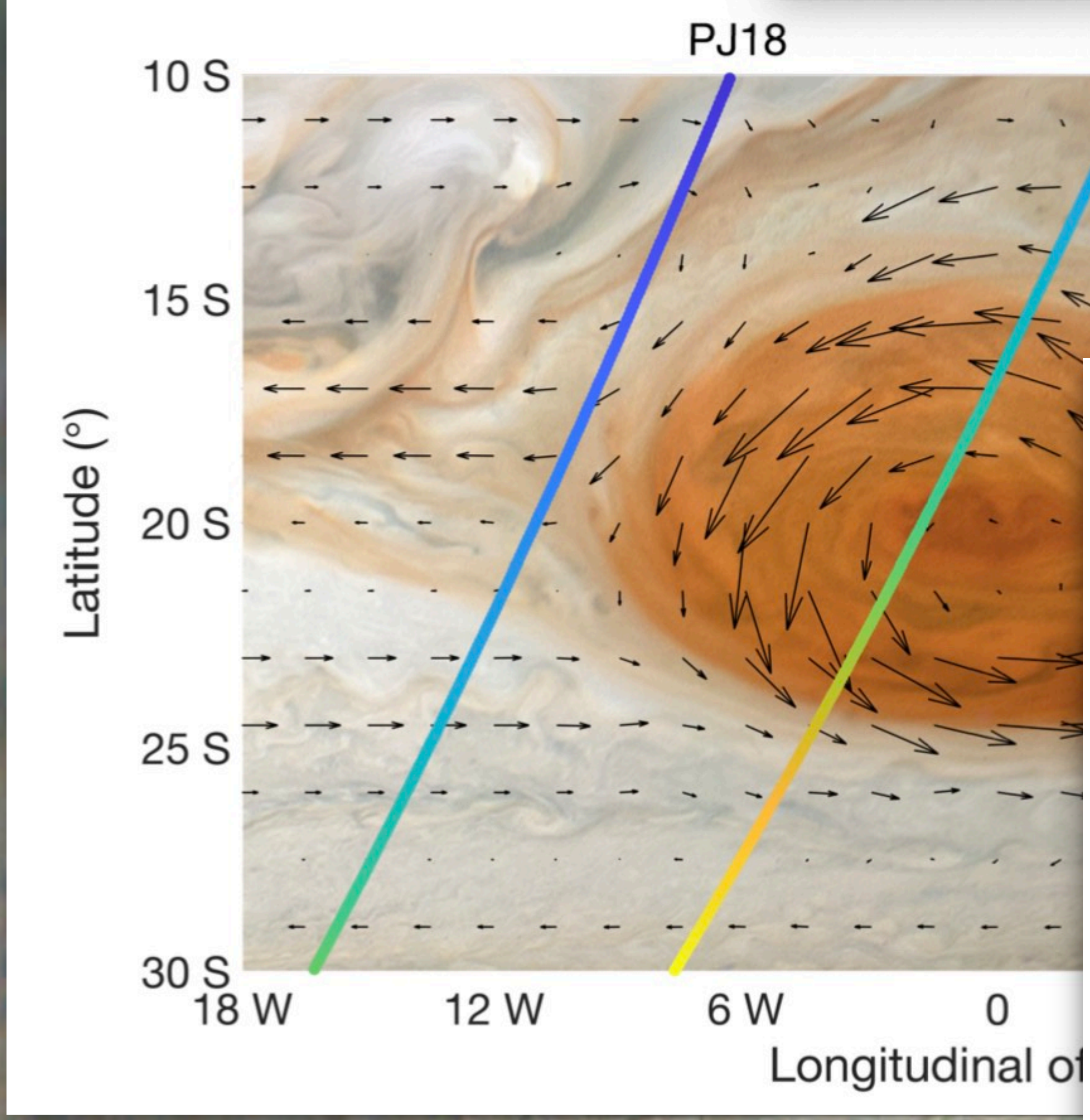


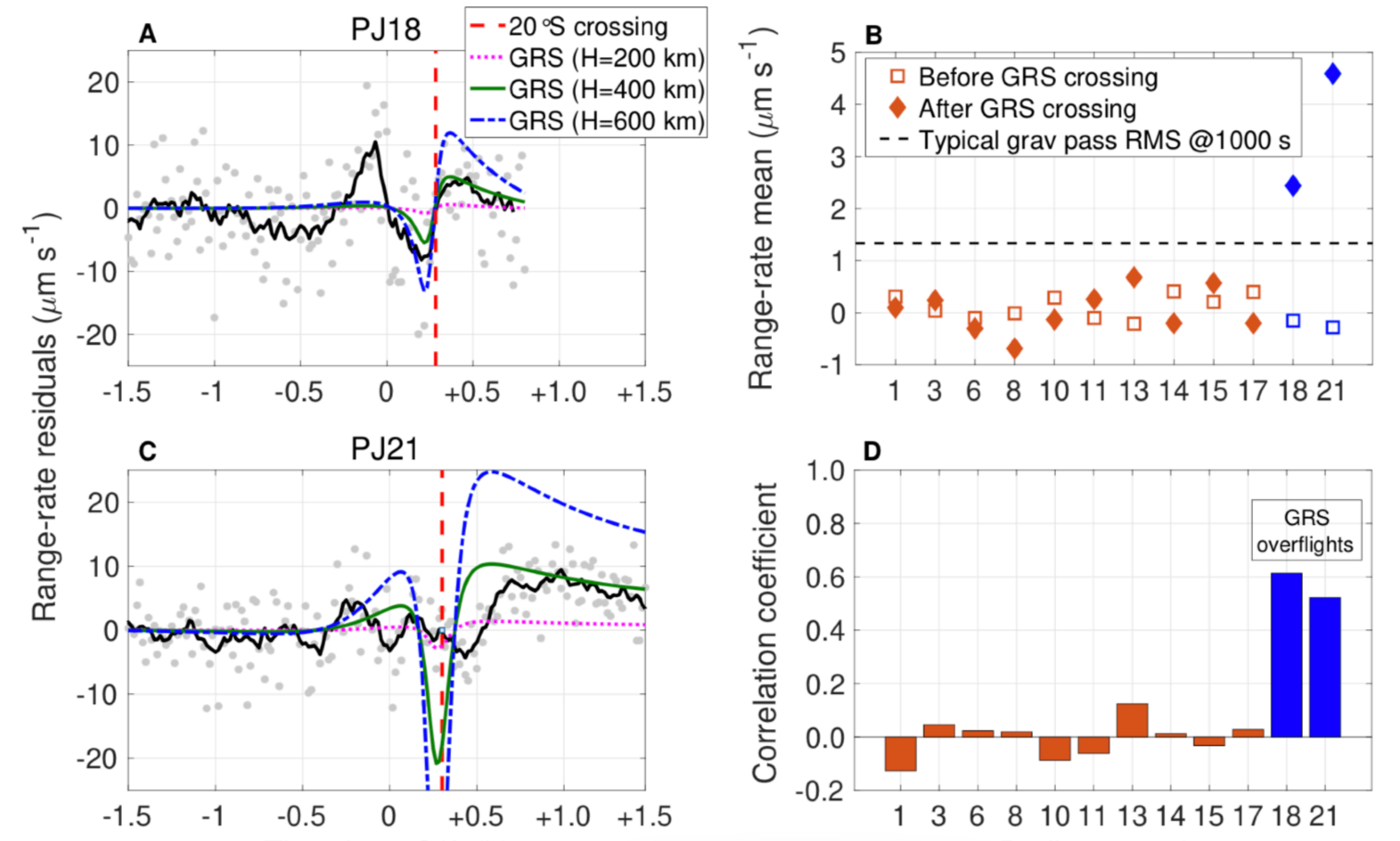


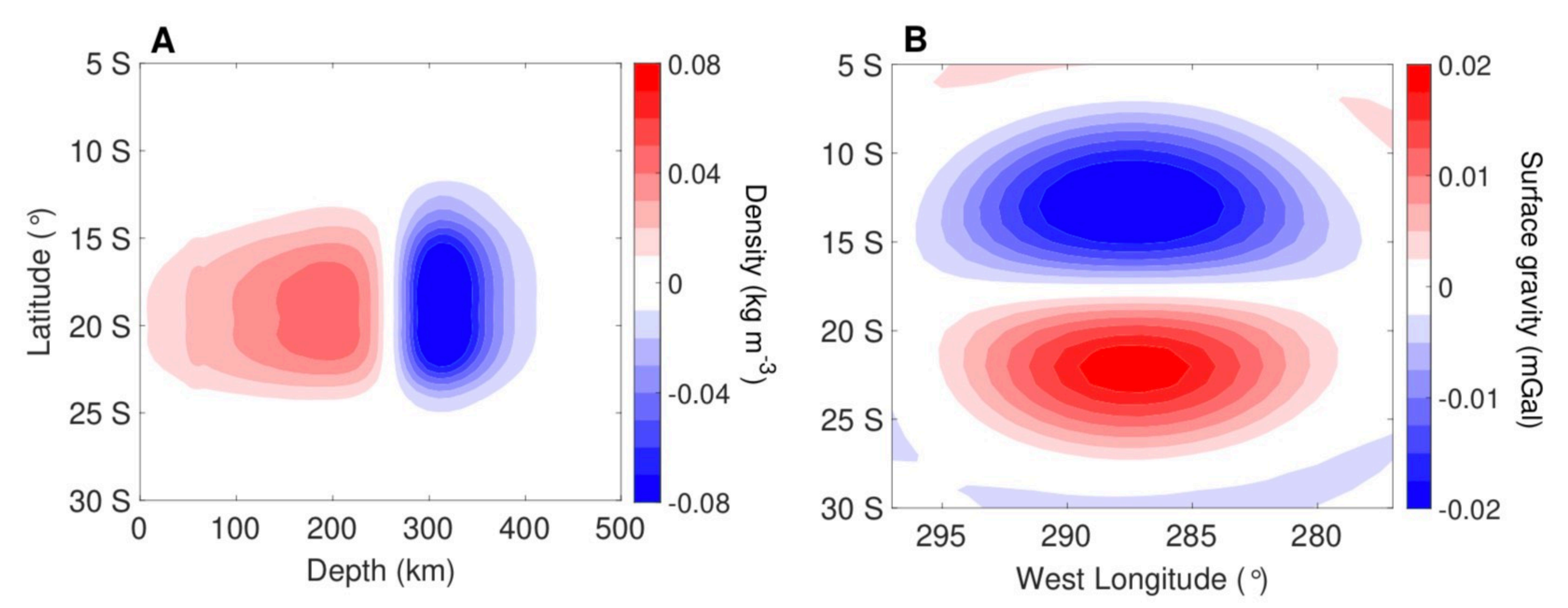
Bolton et al. (2021)

JunoCam

HST

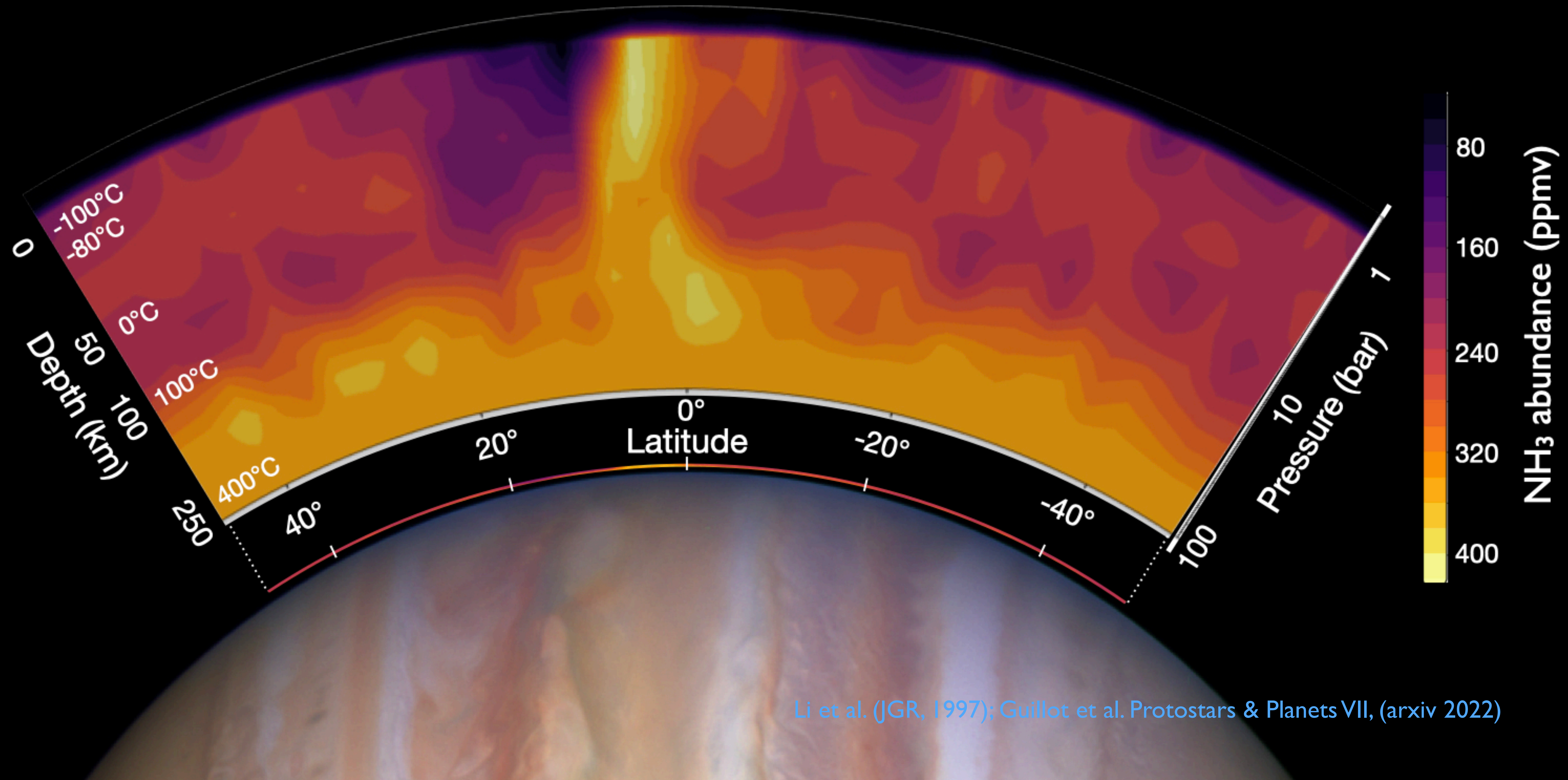




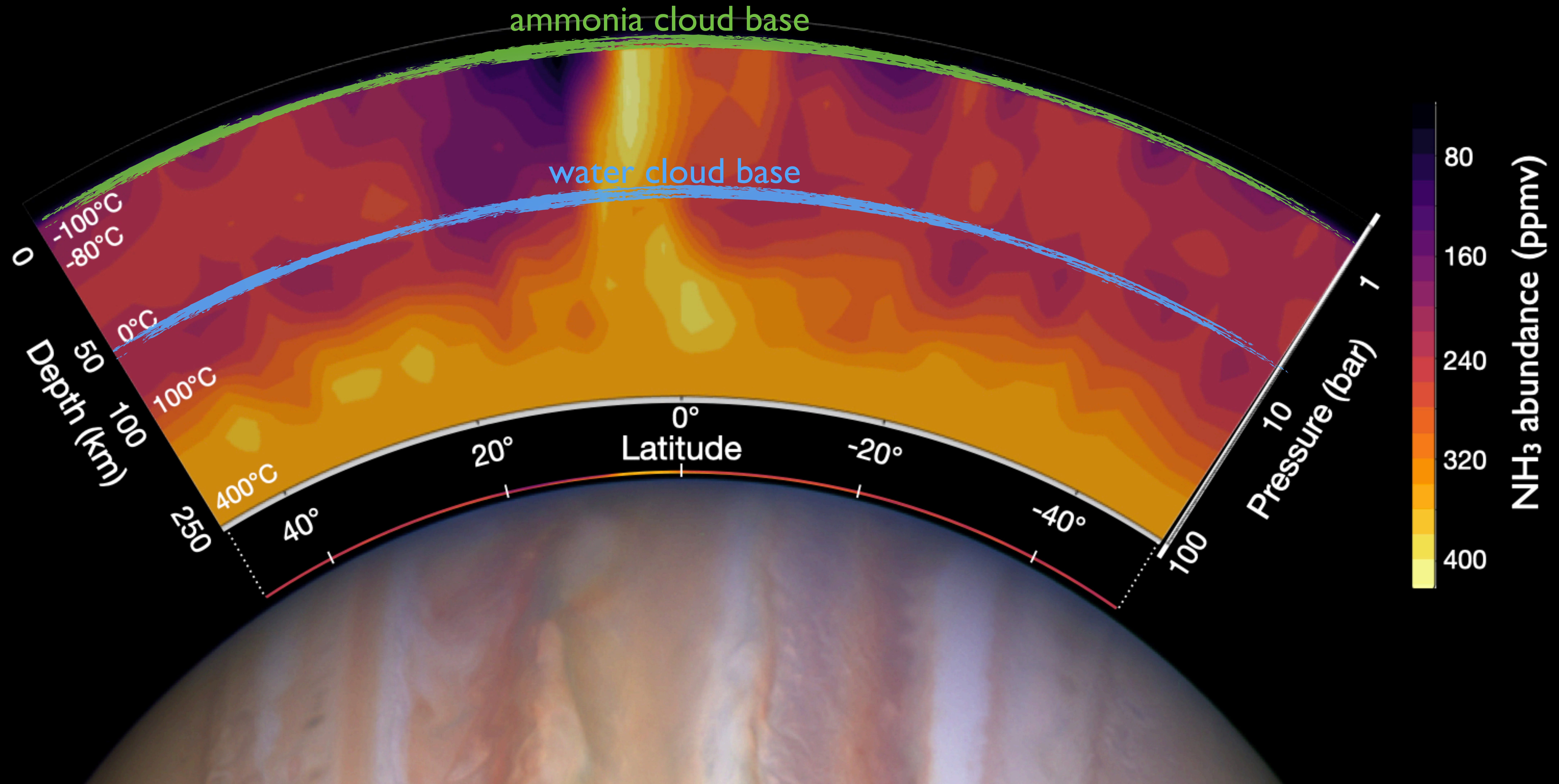


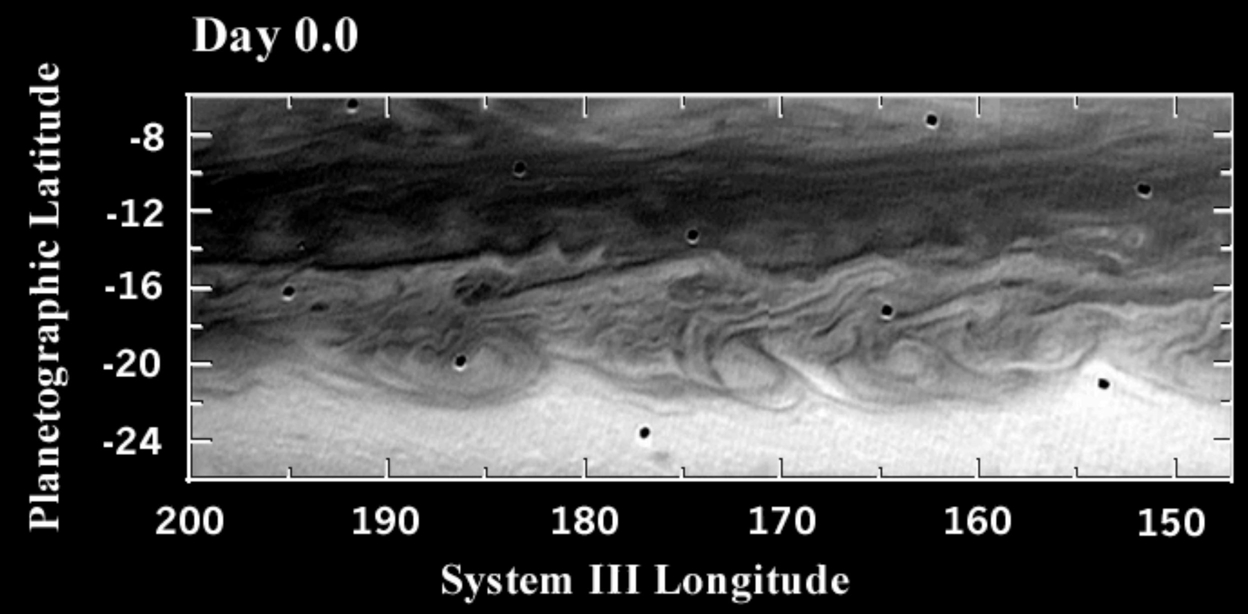
Parisi et al. (2021)

Parisi et al. (2021)

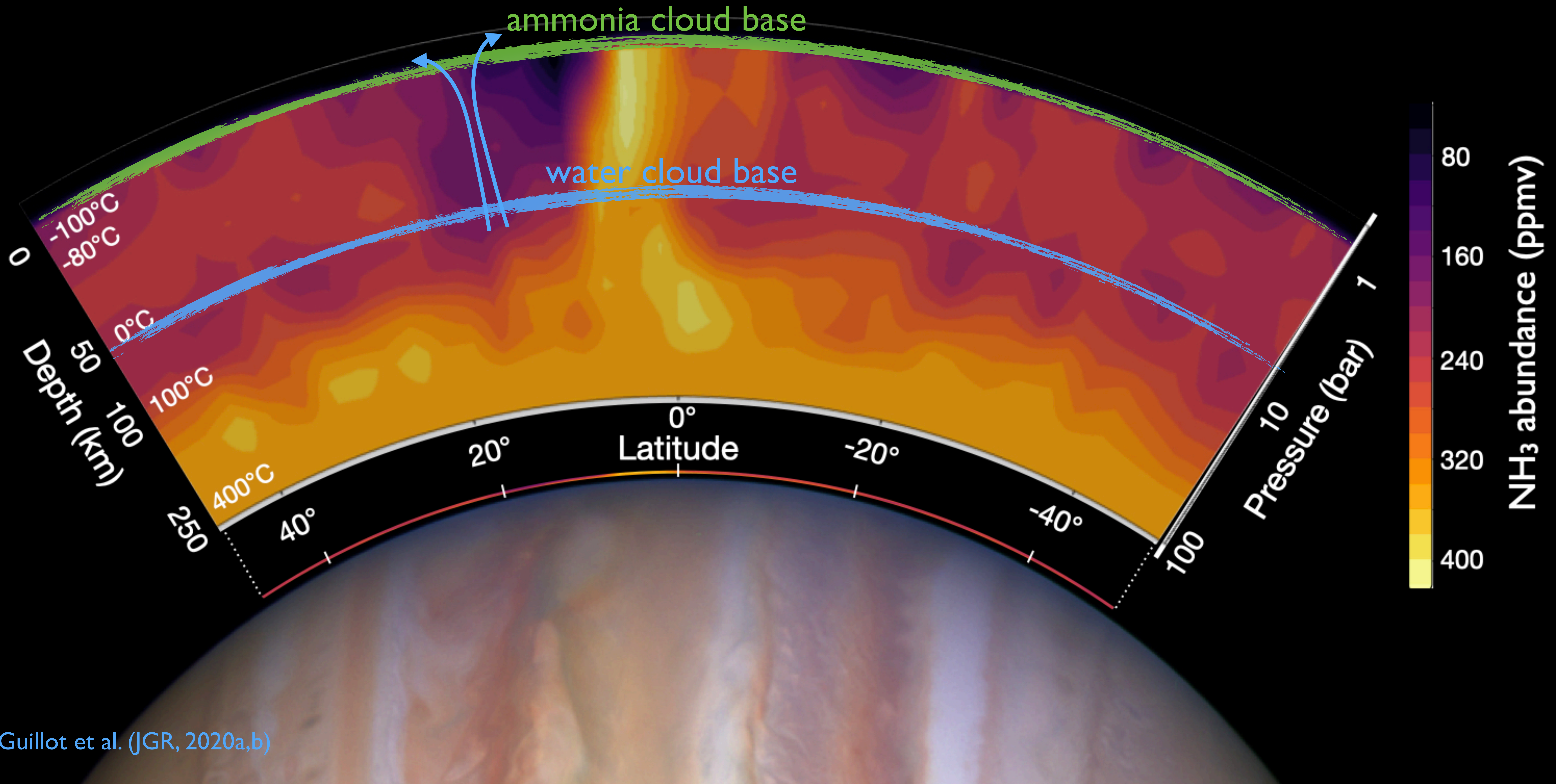


Li et al. (JGR, 1997); Guillot et al. Protostars & Planets VII, (arxiv 2022)


ammonia cloud base
water cloud base
-100°C
-80°C
0°C
100°C
400°C
0
50
100
250
Depth (km)
0°
20°
40°
-20°
-40°
Latitude
1
10
100
Pressure (bar)
80
160
240
320
400
NH_3 abundance (ppmv)

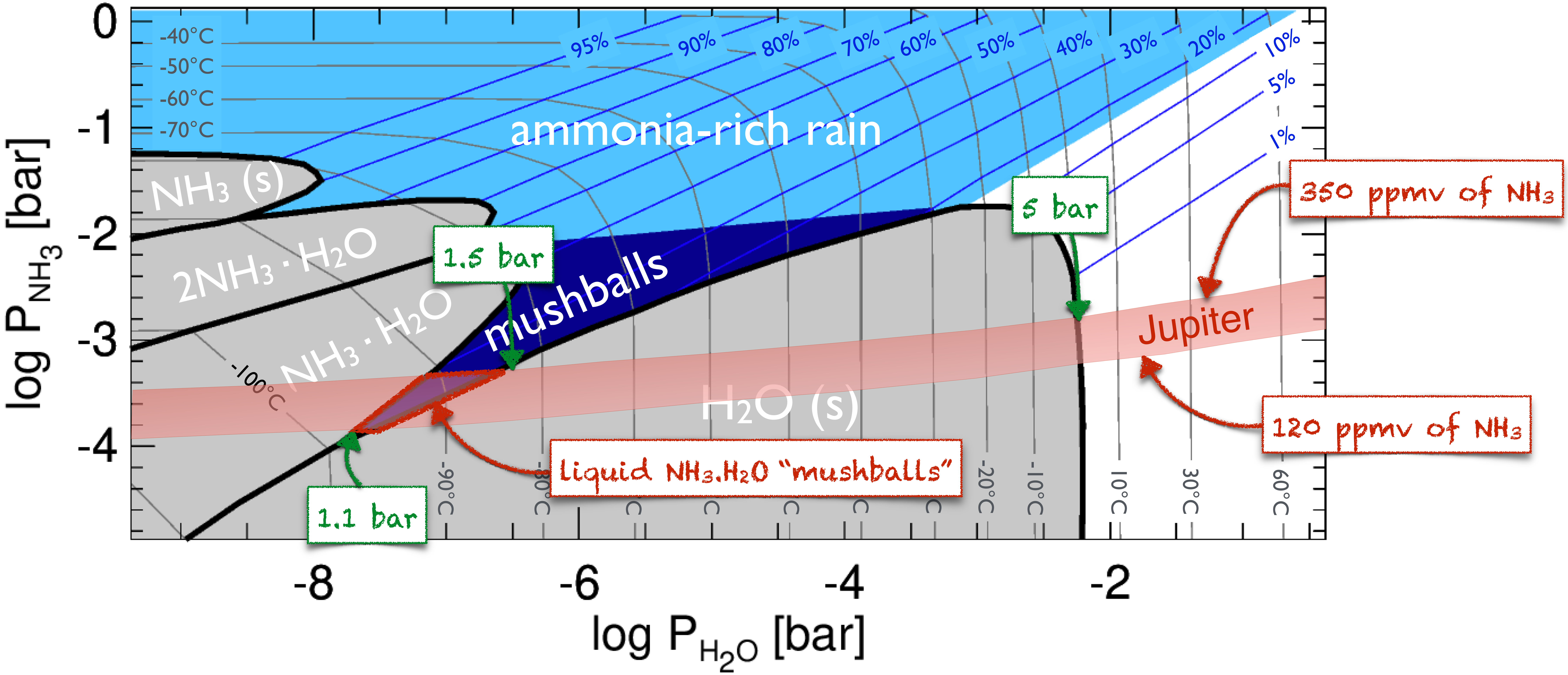


Hueso, Sanchez-Lavega & Guillot (2002)



Guillot et al. (JGR, 2020a,b)

H_2O-NH_3 phase diagram



1.5 bar

5 bar

1.1 bar

350 ppmv of NH_3

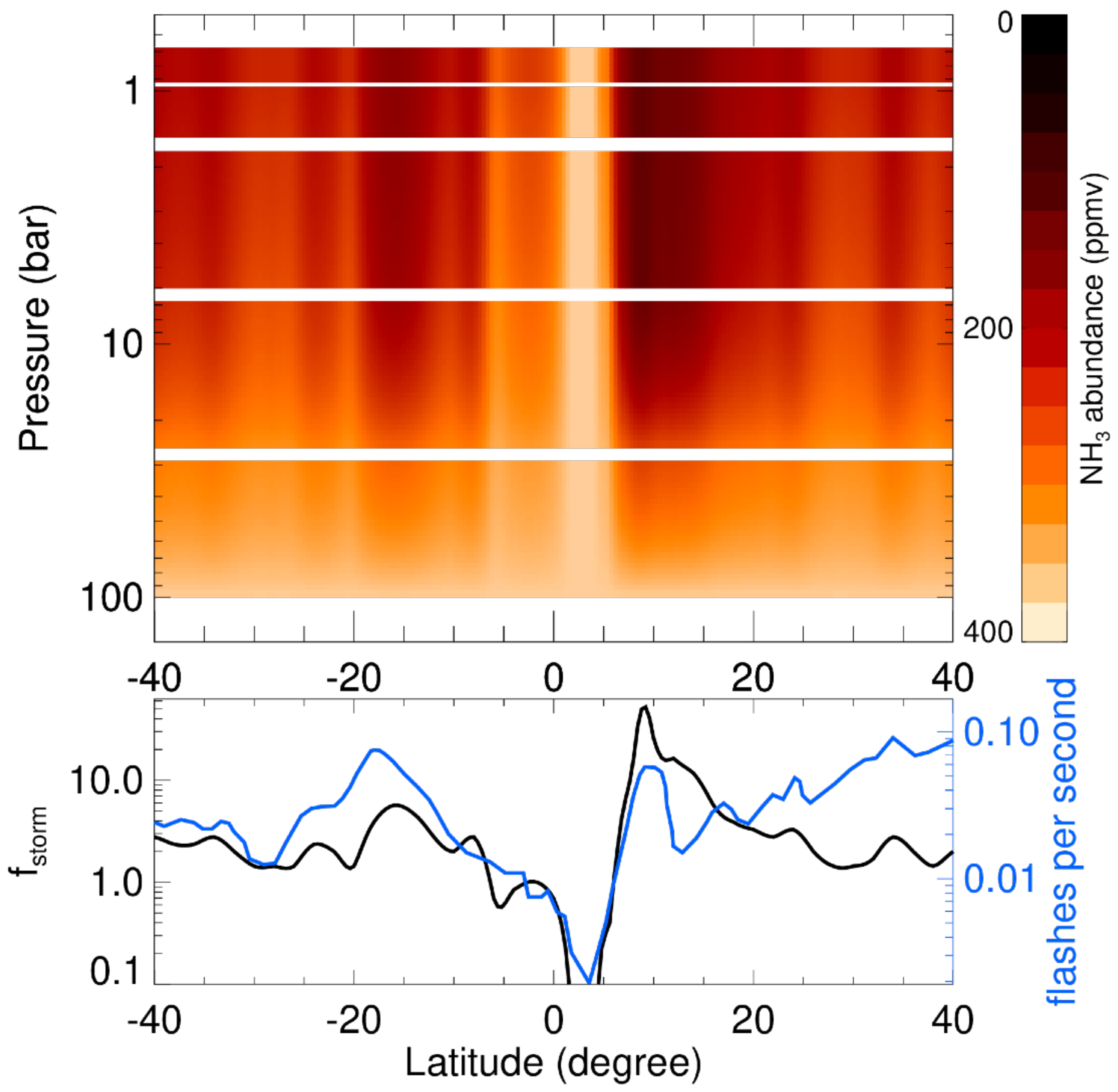
120 ppmv of NH_3

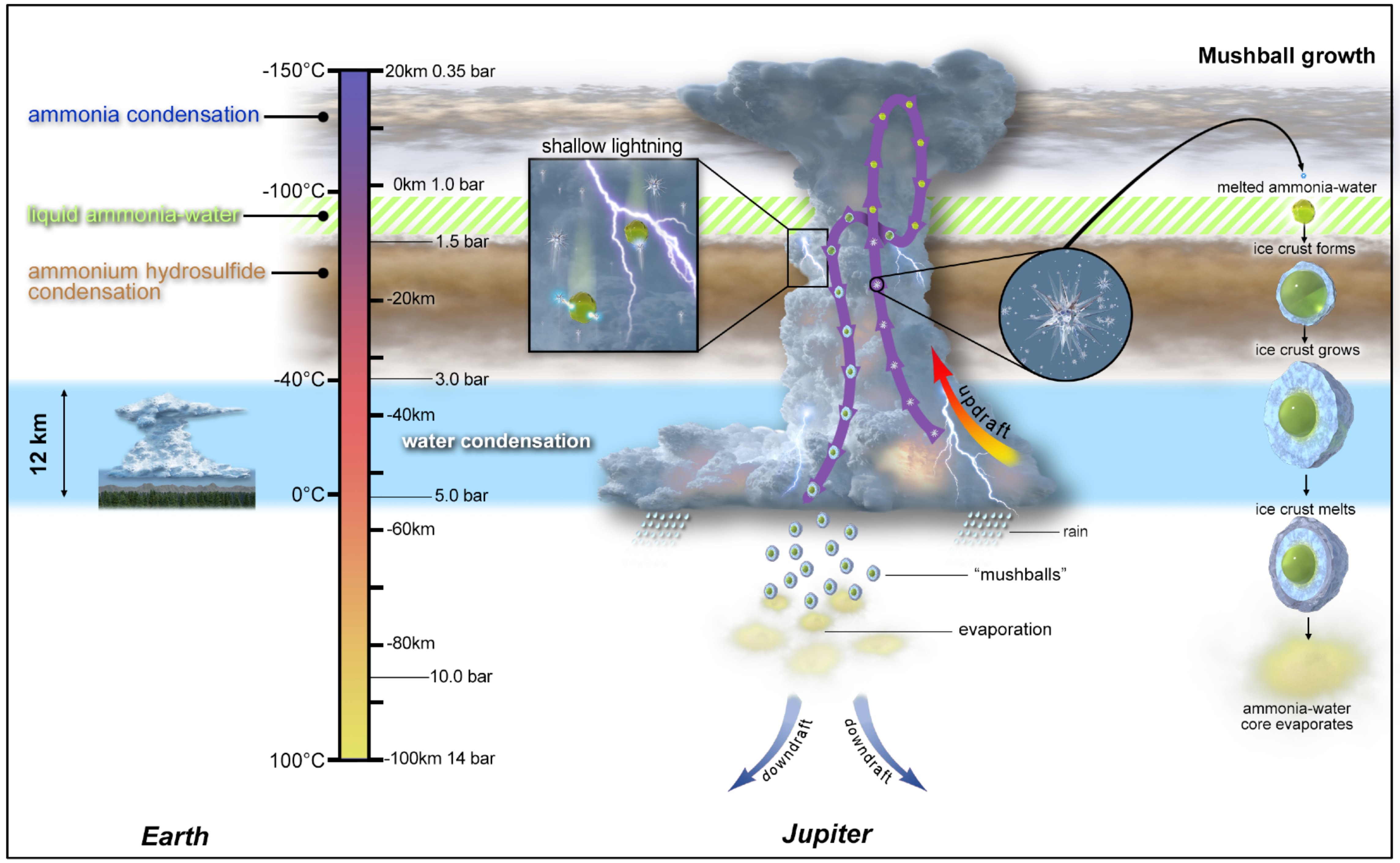
liquid $NH_3.H_2O$ "mushballs"

Guillot et al.,(JGR 2020a, 2020b)
from Weidenschilling & Lewis (Icarus, 1973)

Storms, Mushballs & Downdrafts

NH_3



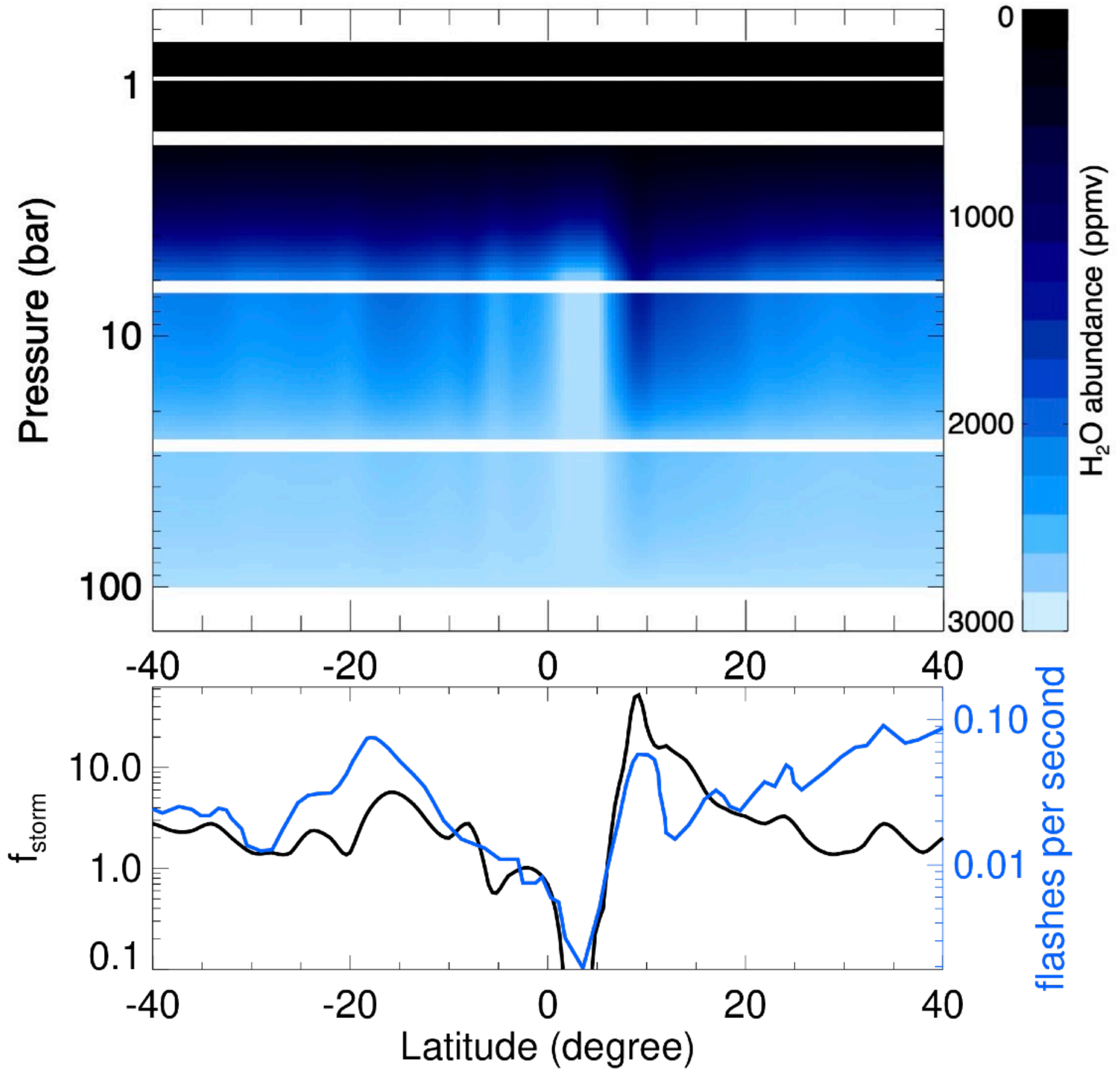


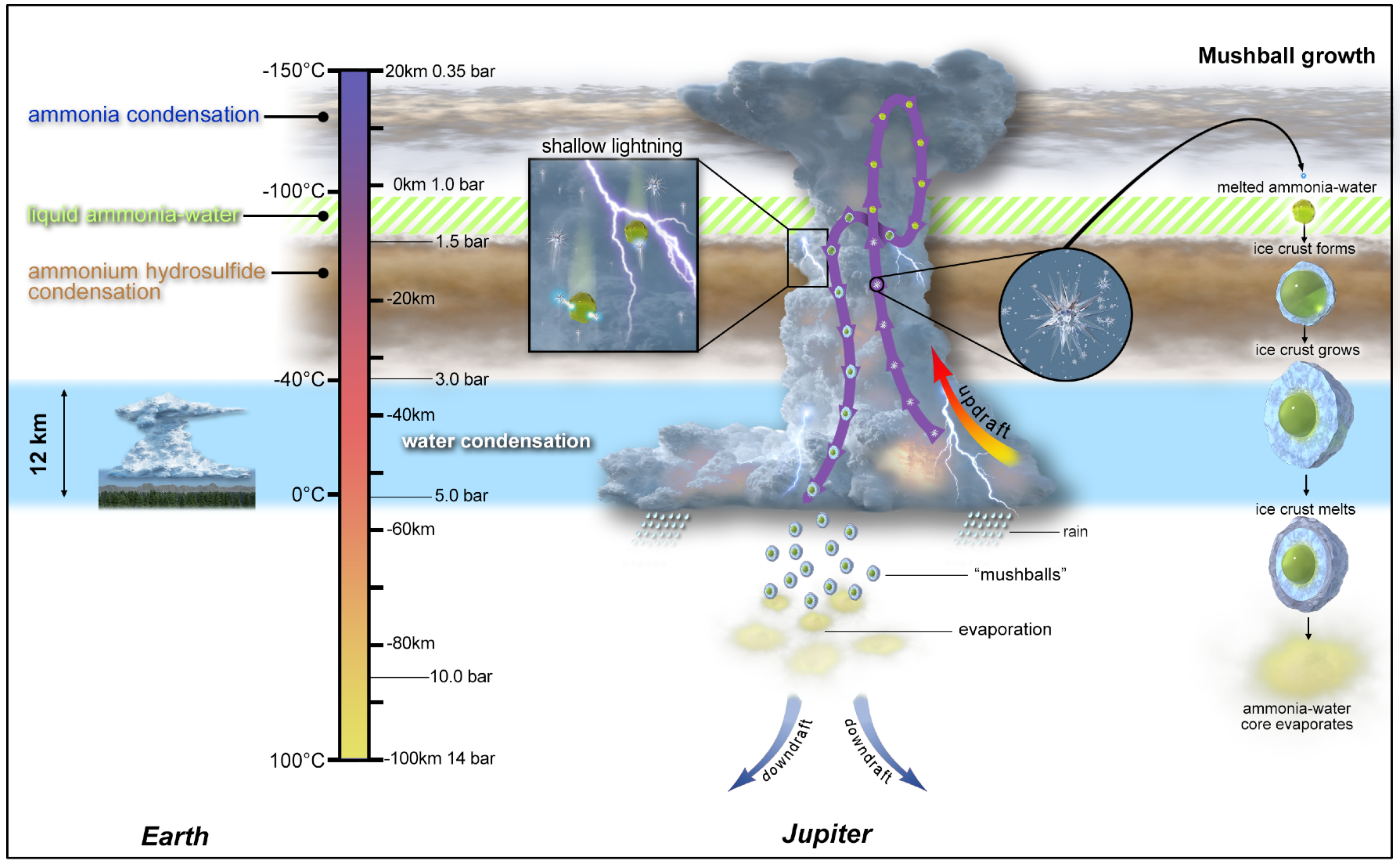
Guillot et al., JGR (2020a, 2020b)
Becker et al. Nature (2020)

- A model involving storms & ammonia-water hailstones (mushballs) reproduces the Juno/MWR observations
- In stormy regions, NH_3 is transported downwards to great depths

Storms, Mushballs & Downdrafts

H_2O

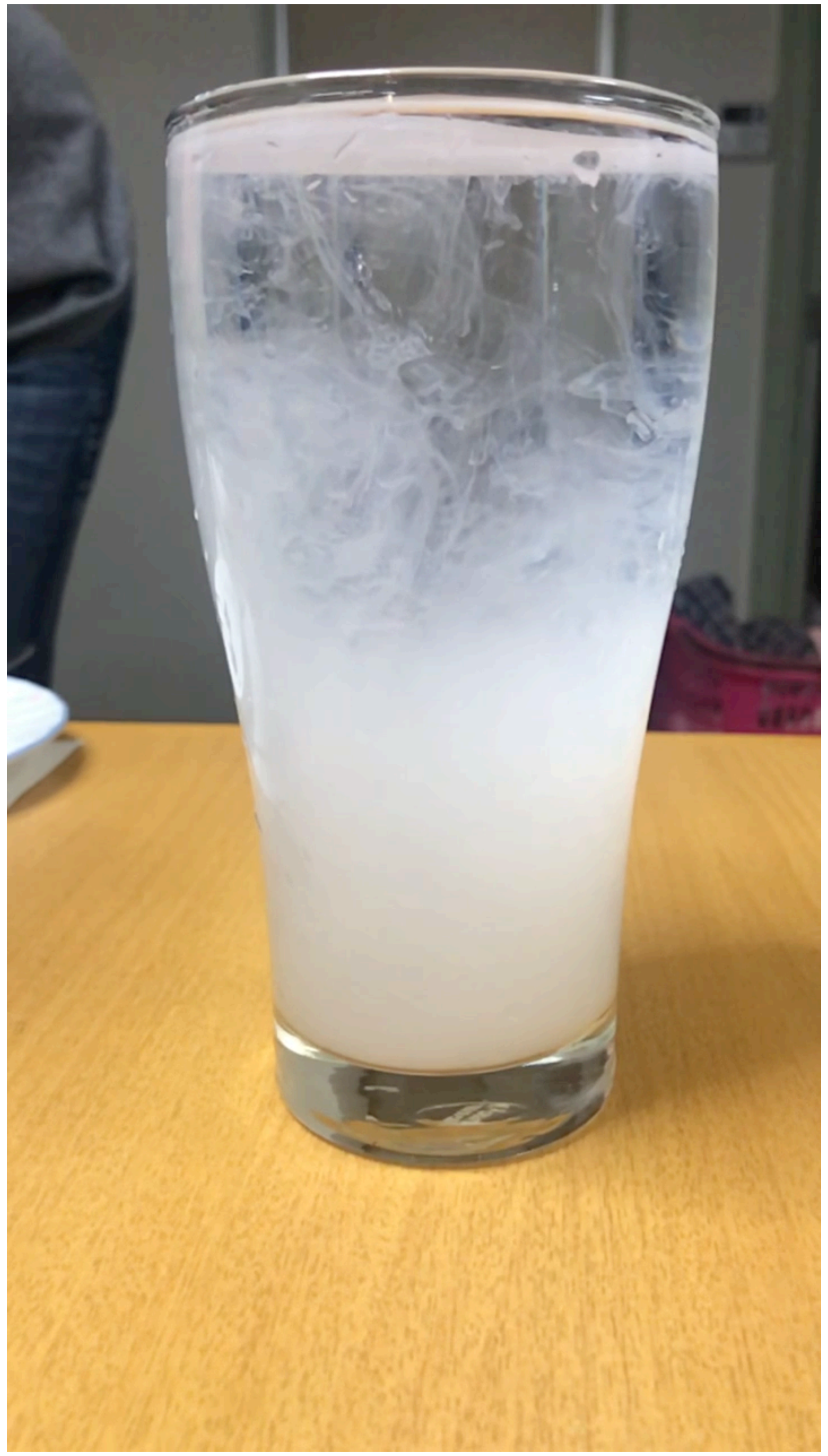




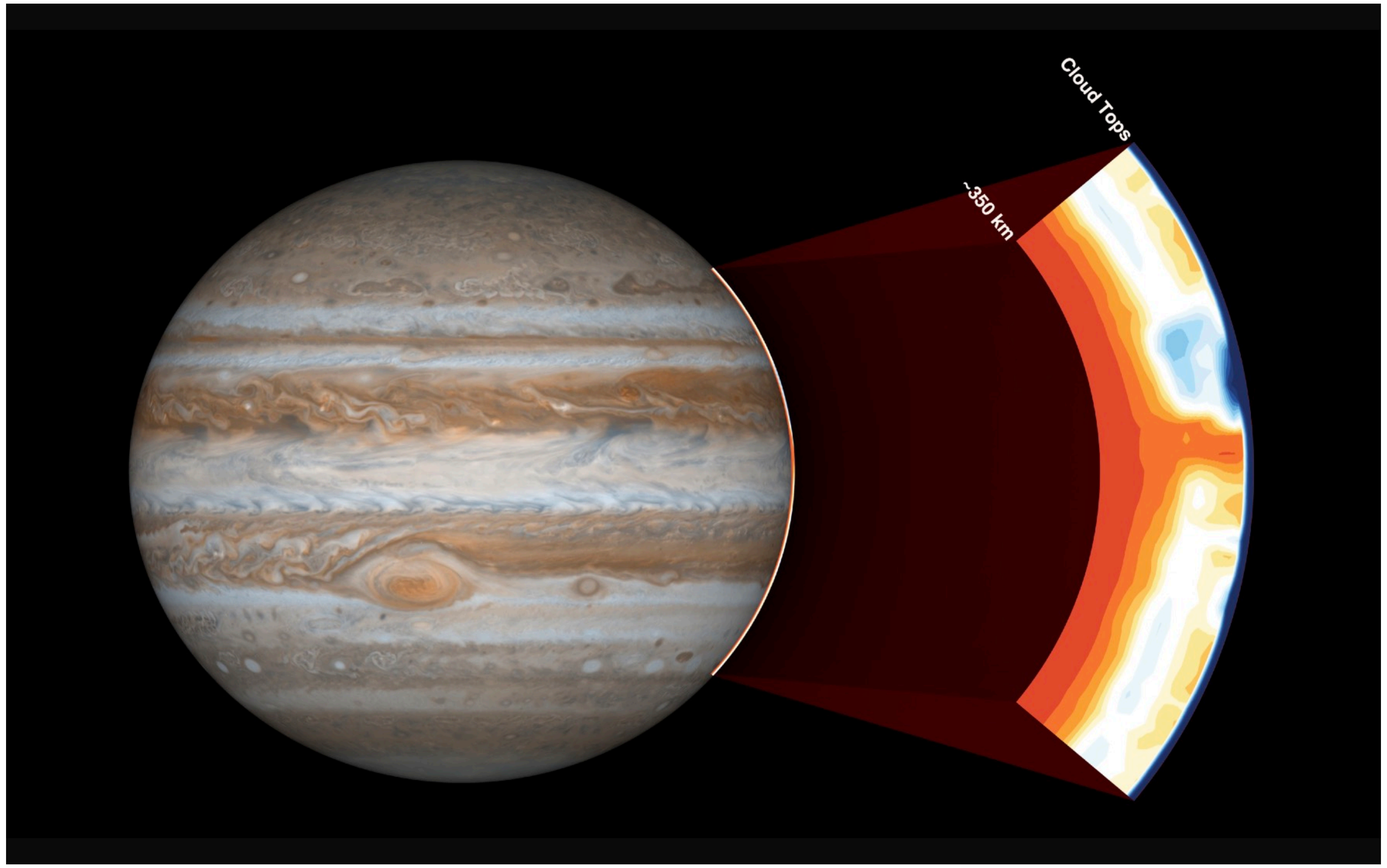
Guillot et al., JGR (2020a, 2020b)
Becker et al. Nature (2020)

- We predict that in stormy regions, H_2O is also transported downwards to great depths

Atmospheric complications

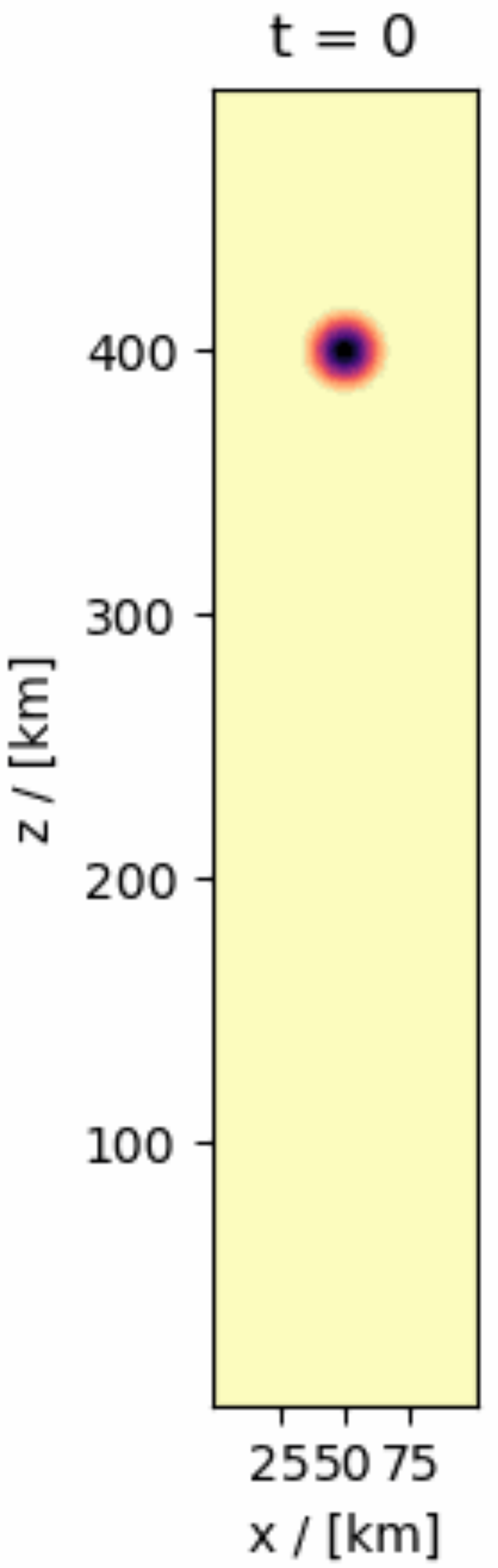


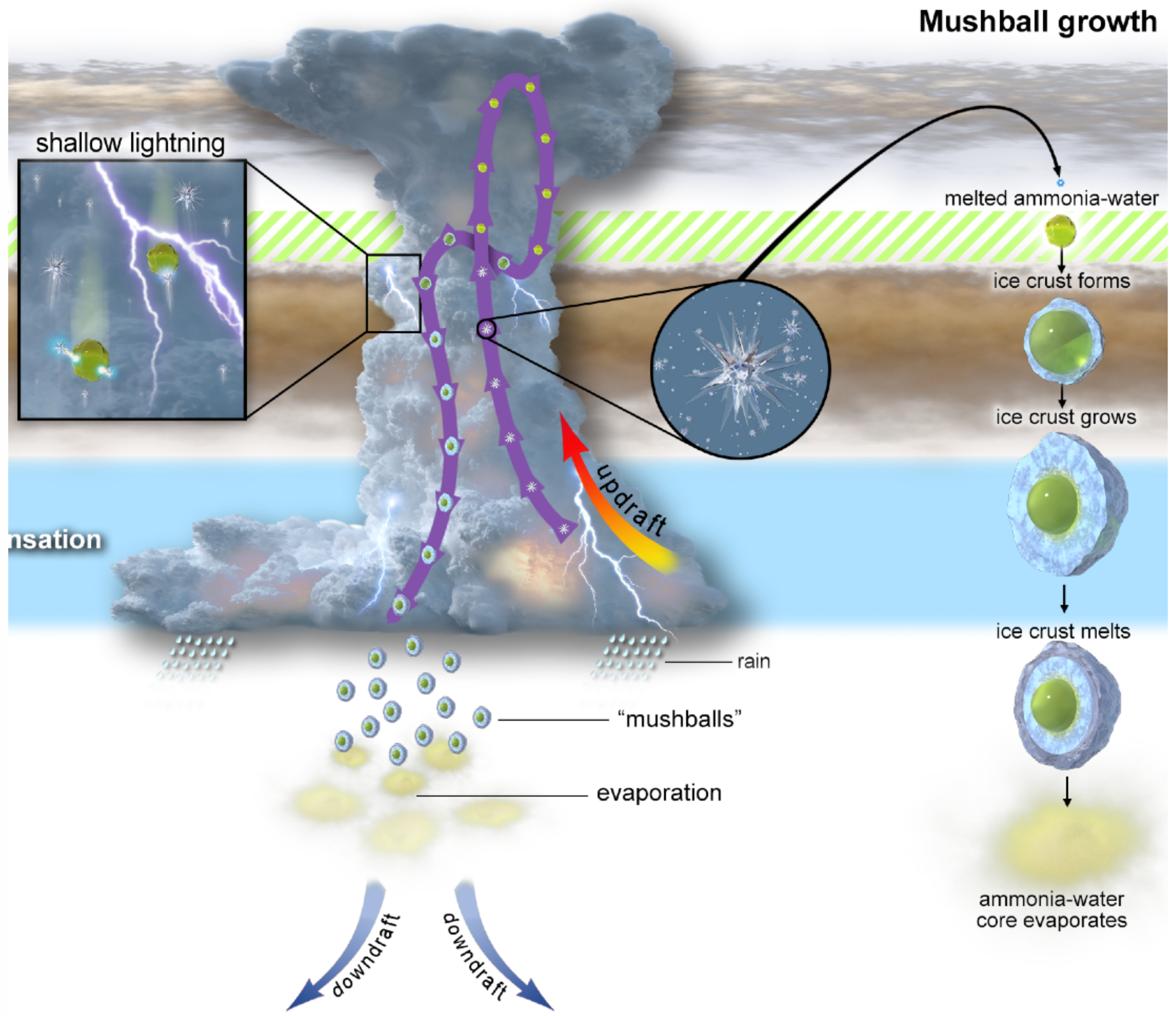
Atmospheric complications



Bolton et al. (2017), Li et al. (2017)

How deep do condensates fall to?
Is that latitude-dependent?





Calculation by Steve Markham
based on SNAP (Li & Chen 2019)

An inhibition of moist convection

- Criterion for convective instability with moist convection:

$$(1-\underset{\sim 1\text{ factor}}{\varpi}\,\underset{\beta=L/RT\sim 20}{\beta}\,\underset{\text{mass mixing ratio of condensing species}}{f})(\nabla_T-\nabla^{*}_{\text{ad}})>0$$

- Moist convection is suppressed if

$$f>f_0\equiv\frac{1}{\varpi\beta}$$

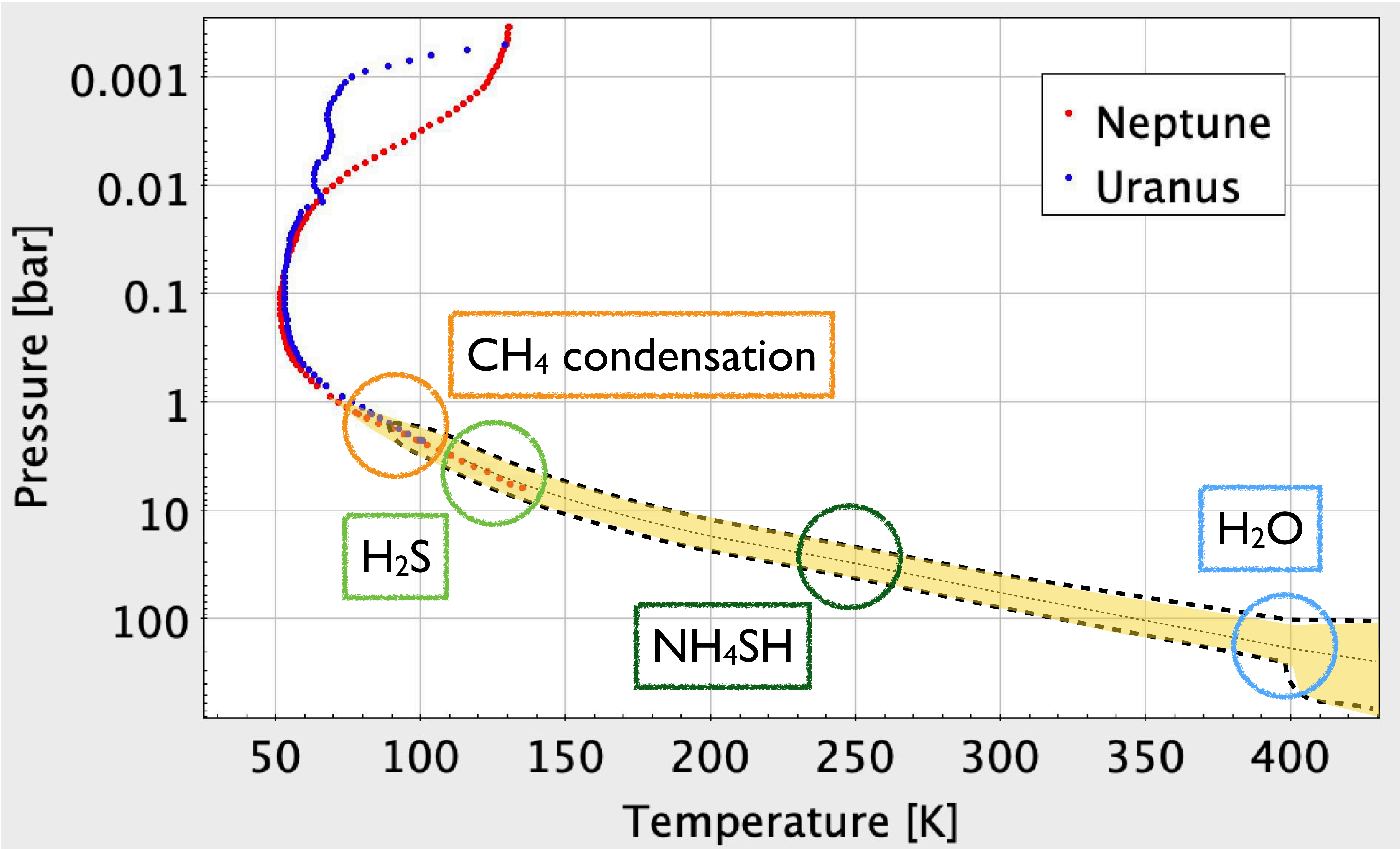
Guillot (Science 1995)

Enrichment over solar:

	CH_4	NH_3	H_2O	Fe
ϖ	0.85	0.86	0.87	0.96
$T_{\text{ref}}(K)$	80	150	300	3500
$M_{\text{v}}L/RT_{\text{ref}}$	12.	19.	16.	12.
Critical mixing ratio (q_{cri})	0.10	0.062	0.070	0.089
Enrichment over solar	40.	78.	9.9	74.

Leconte et al. (A&A 2017), Friedson & Gonzales (Icarus 2017)

Consequences for temperature structure?



Effect of condensates on temperature profile?

sub adiabatic?

super adiabatic?

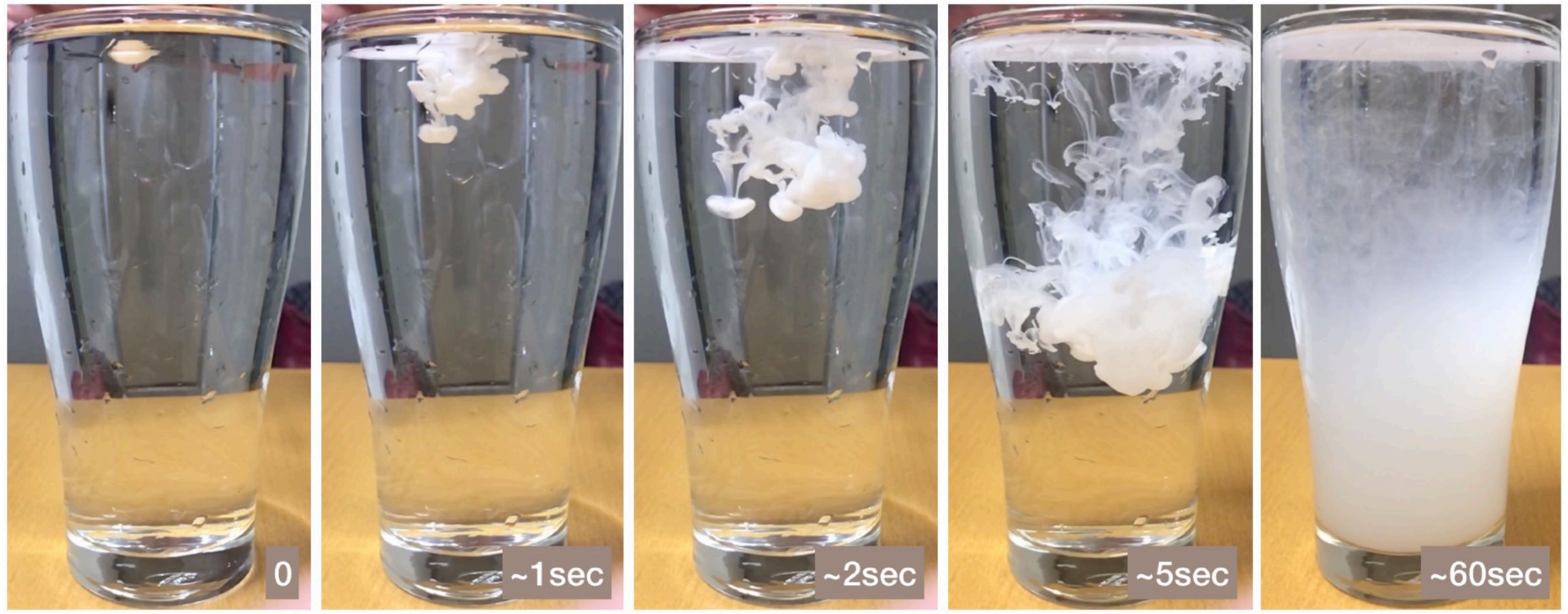
see Guillot (1995), Leconte et al. (2017), Friedson & Gonzales (2017)

time-dependent?

see Li & Ingersoll (2015)

Storms, Mushballs & Downdrafts

- In planets with hydrogen atmospheres, condensates are always heavier
  - When concentration mechanisms exists (storms & precipitation), they can potentially sink
  - Vertical composition gradients may be formed, leading to regions that are stable on average
    - see Guillot et al. (JGR, 2020b)
- For very high abundances of condensates (e.g.,~10 times solar O/H) moist convection is locally inhibited.
  - Resulting temperature, composition profile is unknown
    - see Guillot (Science 1995), Leconte et al. (A&A 2017), Friedson & Gonzales (Icarus 2017)
- How deep?
  - Depth of compositional gradients is unknown
    - The Galileo probe measured an abundance of water still increasing at 20 bar (Wong et al. 2004)
    - Juno/MWR measured variable ammonia down to tens of bars (Li et al. 2017)
  - A mission to Uranus or Neptune would tell
    - (Guillot ESA White Paper 2019, Guillot et al. NASA White Paper 2020)



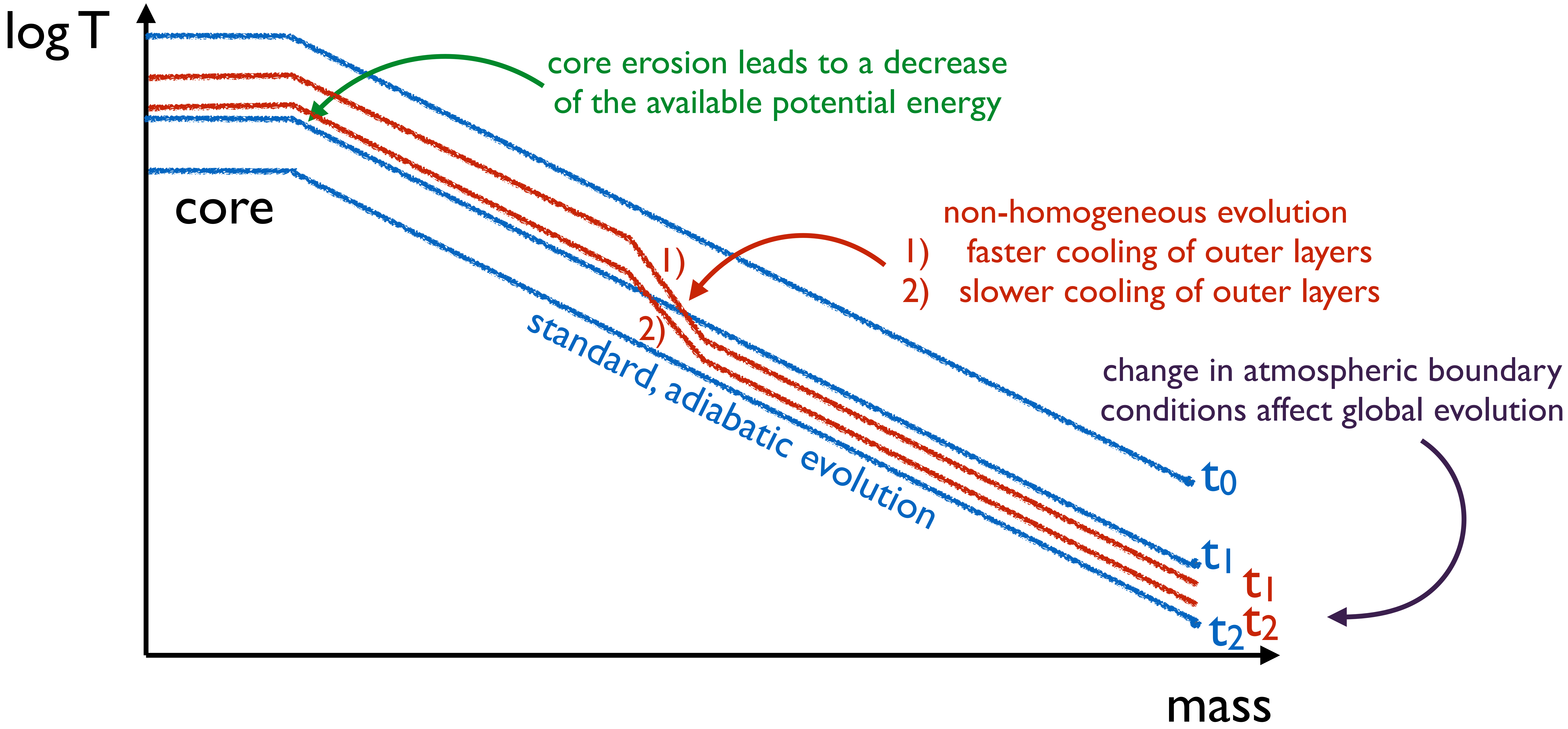
Outline

- Why studying giant planets?
- The formation of giant planets: basics
- Mission Juno
- Modeling the interiors of giant planets
- Jupiter's interior structure
  - How were heavy elements delivered?
- Jupiter's zonal flows
- Jupiter's inhomogeneous deep atmosphere
- Consequences for Exoplanets
- Why we need a mission to Uranus or Neptune

Consequences for exoplanets

- A more complex planetary evolution
  - Core mixing
    - Part of the internal heat is used to mix the core upward leading to a relative increase of the gravitational potential energy (see Guillot et al. 2004, Moll et al. 2017)
  - Deep compositional gradients
    - Lead to a possible suppression of heat transport, late release of internal energy
    - See Chabrier & Baraffe (2007), Leconte & Chabrier (2012)
  - Modified atmospheric properties
    - Link between measured atmospheric abundances and deep ones?
    - May affect the cooling properties of the atmosphere

Consequences for exoplanets



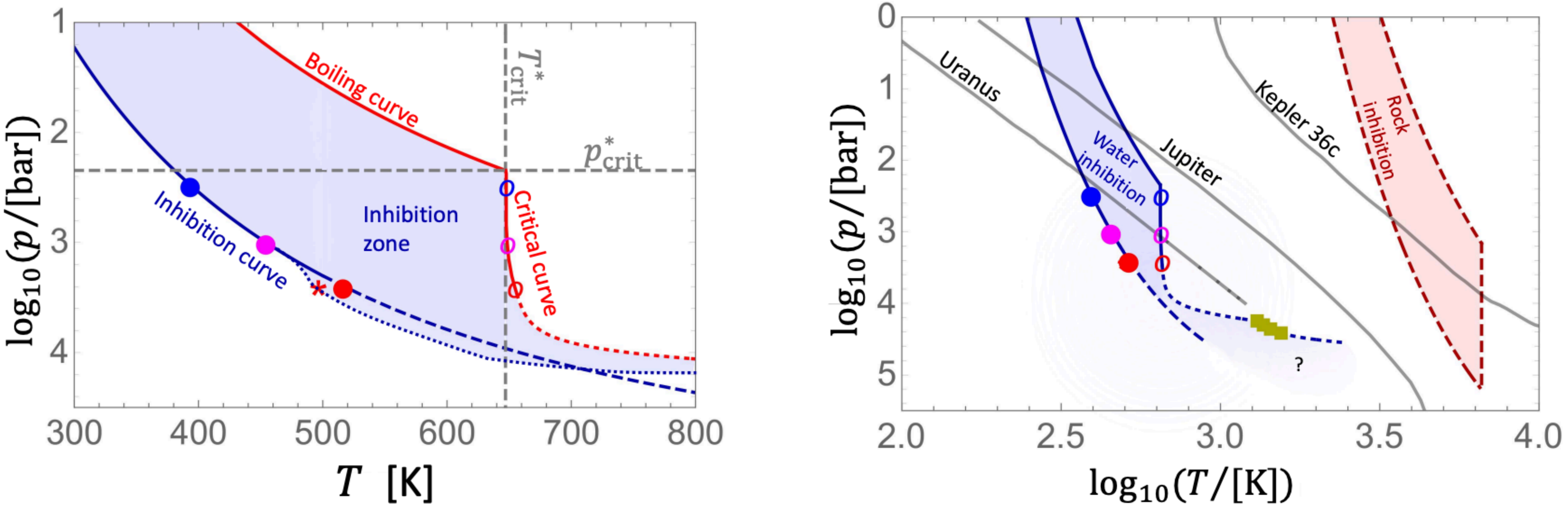
core erosion leads to a decrease of the available potential energy

non-homogeneous evolution
1) faster cooling of outer layers
2) slower cooling of outer layers

change in atmospheric boundary conditions affect global evolution

Consequences for exoplanets

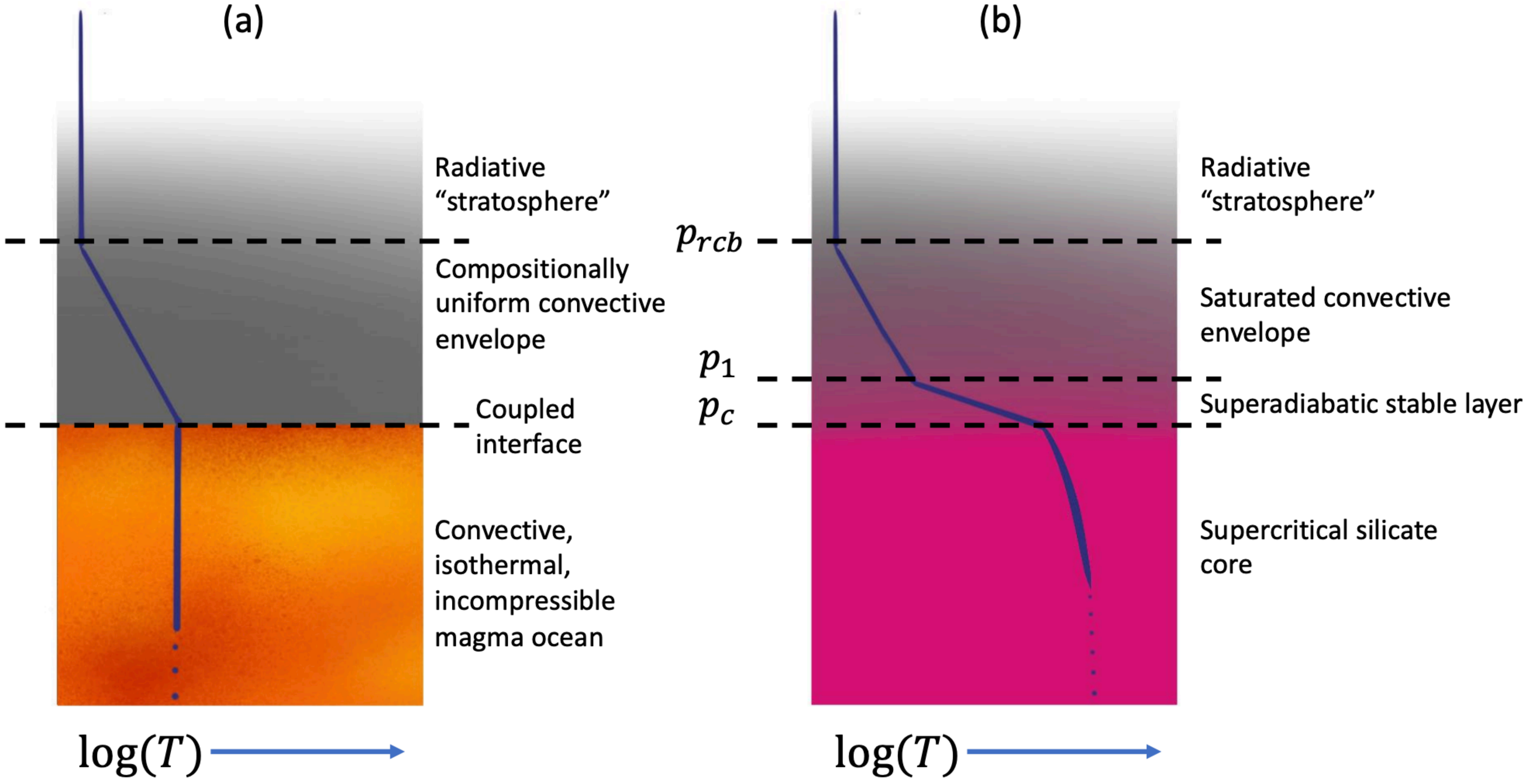
Convection inhibition will affect the evolution potentially drastically



Markham, Guillot & Stevenson (2022)

Consequences for exoplanets

Convection inhibition will affect the evolution potentially drastically



Super-Earths may be much warmer.

Markham, Guillot & Stevenson (2022)

Consequences for exoplanets

- Measuring accurate ages is key
  - to link planetary densities and bulk composition
  - to understand planetary cooling
    - requires a comparison between planets with different ages but similar characteristics

- Temperate giant planets should have more complex atmospheres
  - shaped by storms, with possibly strong compositional gradients
  - true both for gas giants, ice giants and super-Earths with hydrogen atmospheres!

Questions & opportunities

- Do giant planets have cores?
  - Juno, Cassini, k2 determination in exoplanets (PLATO, others)
- Are they enriched in heavies?
  - Juno, Cassini, JWST, PLATO, ARIEL
  - spectroscopy of exoplanets
- How are these distributed in the interior?
  - Juno, Cassini, JWST, TESS, CHEOPS, PLATO, ARIEL
  - Combining atmospheric & bulk measurements
- What is controlling atmospheric circulation in gas giants?
  - Juno, JWST, TESS, PLATO
  - Combining ultra-accurate visible & IR lightcurves+ spectroscopy
- How do planets form?
  - A combination of the above

Strategy

- Statistics!
  - Observe many gas & "ice" giant planets
  - Accurate lightcurves & stellar parameters
    - Crucial to constrain bulk composition
    - Precise ages, masses & radii are crucial
- Discover key targets
  - Bright:
    - Can be studied in more details by other instruments
    - Ultra-precise light curves
  - Rare: e.g. with possibility to measure k_2
    - ~1 day period, (slightly) eccentric to measure hot Jupiter precession
    - short period, tidal deformation measurement from light curve
    - fixed-point eccentricity multiple systems (needs eccentricity)
  - Temperate, long period exoplanets
    - stormy, with complex atmospheres
    - water clouds & storms!

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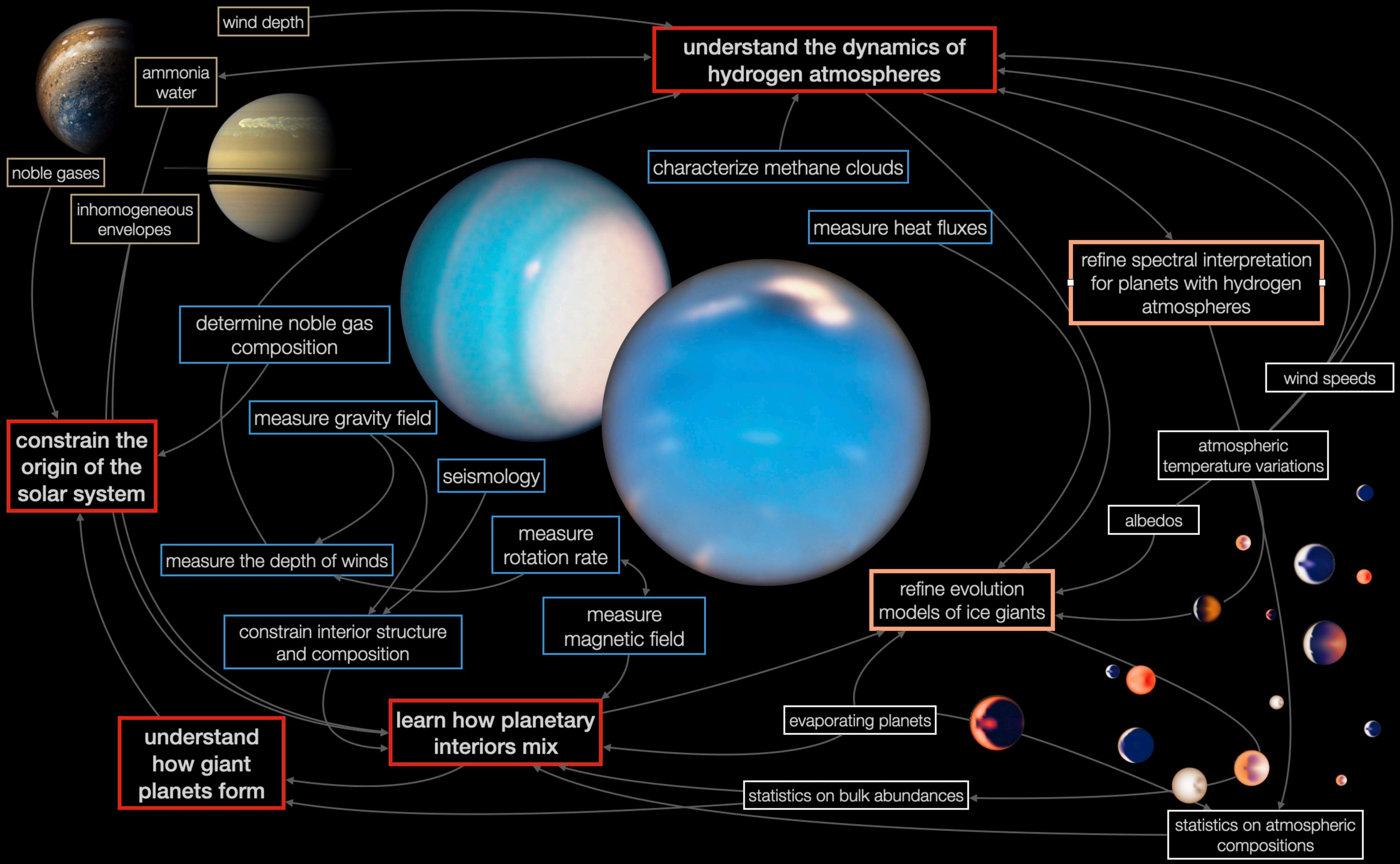
Uranus & Neptune: the missing link



wind depth

ammonia
water

noble gases

inhomogeneous
envelopes

understand the dynamics of hydrogen atmospheres

characterize methane clouds

measure heat fluxes

refine spectral interpretation for planets with hydrogen atmospheres

wind speeds

atmospheric
temperature variations

albedos

determine noble gas composition

measure gravity field

seismology

constrain the origin of the solar system

measure the depth of winds

measure rotation rate

measure magnetic field

constrain interior structure and composition

refine evolution models of ice giants

evaporating planets

learn how planetary interiors mix

understand how giant planets form

statistics on bulk abundances

statistics on atmospheric compositions

Guillot, Fortney et al.
(NASA White Paper 2020)