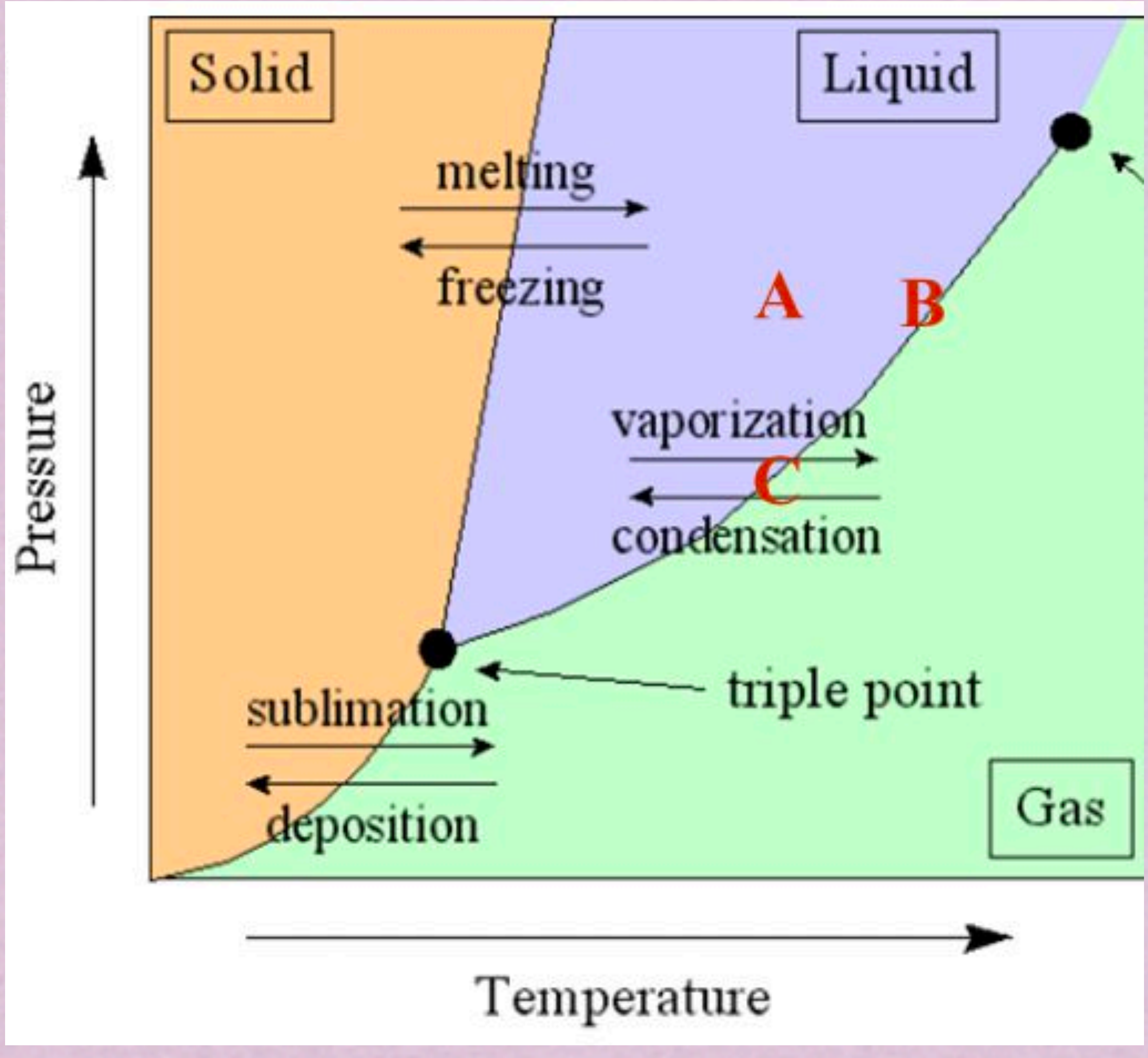
News and Reminders

Homework 3 is due now

Mid-semester proposal due dates:

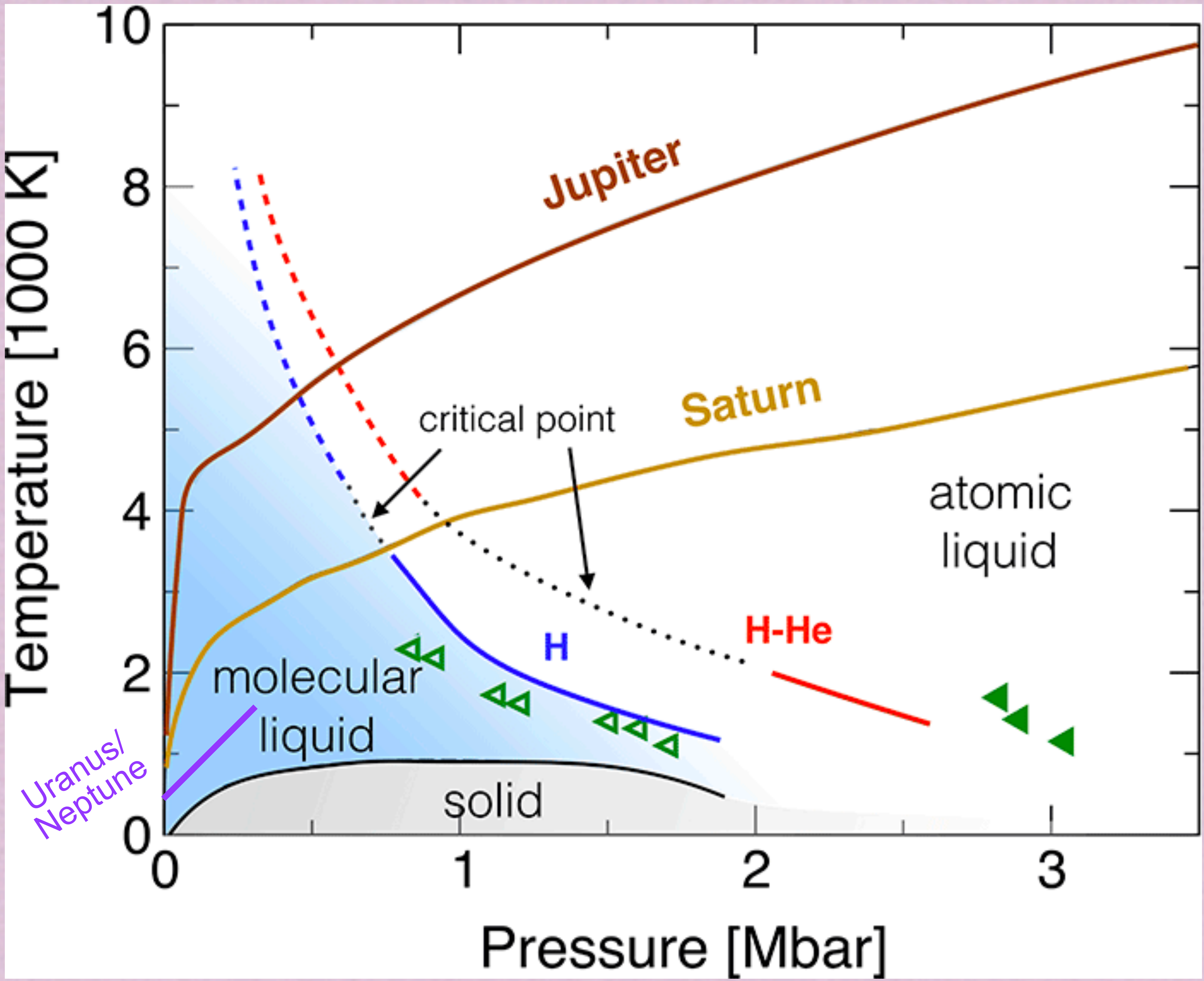
- Proposal due: Monday, October 28
- Proposal review: Wednesday, Oct. 30

Constituent Relations



At the high pressures and temperatures in planet interiors, hard to predict the state of the materials.

Phase diagram of H_2



Atmospheric composition of the giant planets

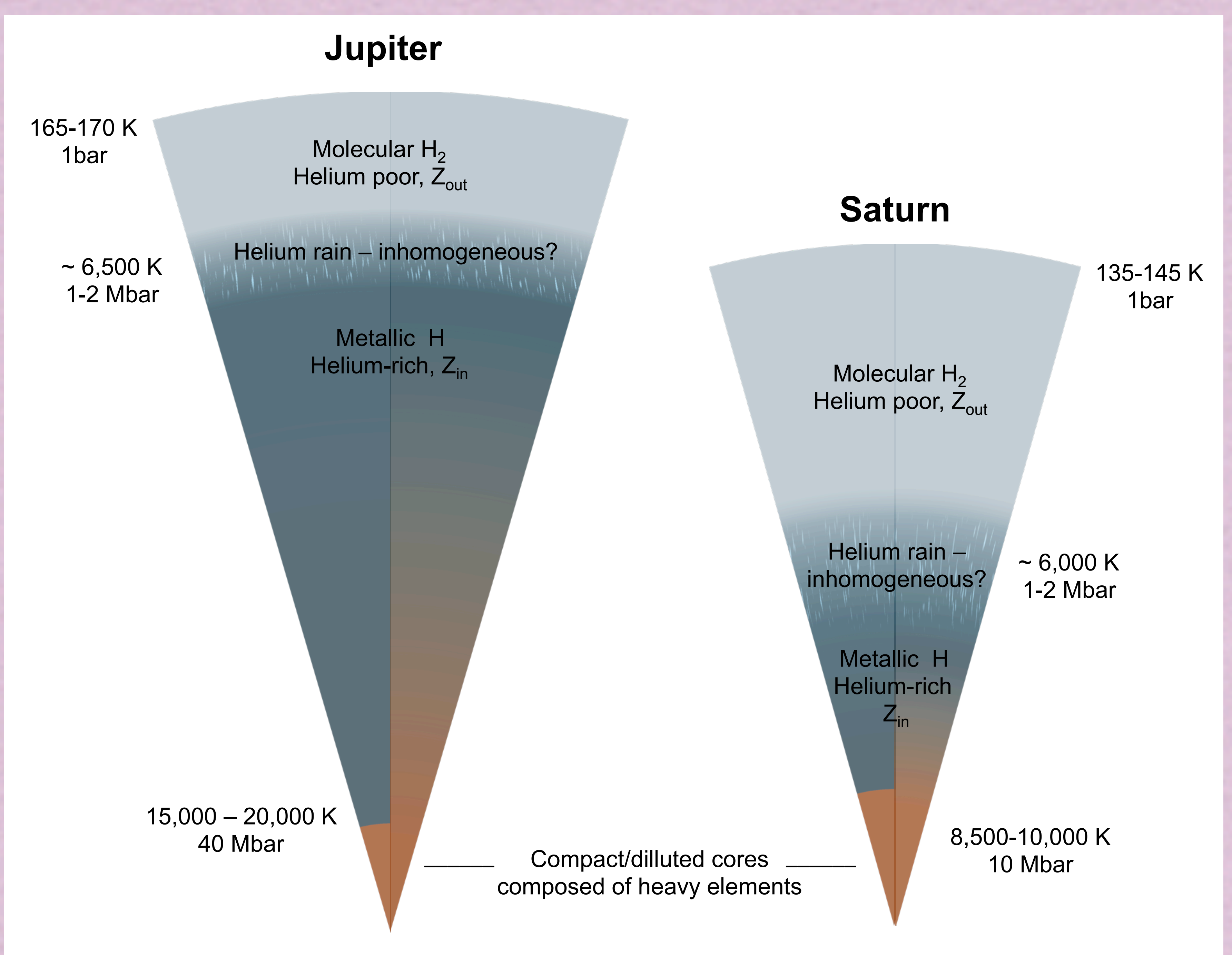
80 - 90% Hydrogen (by volume)

10 - 15% Helium (by volume)

	Protosolar	Jupiter	Saturn	Uranus	Neptune
H	**83.5%**	89.8%	96.3%	83%	82%
He	**16.2%**	10.2%	3.2%	15%	15%

But would expect 84% H and 16% He, like the protosolar nebula (unless some of their cores mixed into the atmospheres, or ingested planetesimals after forming).

Atmospheric composition of the giant planets



He/H = 13.7 % in Jupiter

vs

He/H = 16 % in Saturn

Gravity Field:

The gravitational potential of a body is:

for an axisymmetric body (e.g. a planet):

$$\Phi_g(r,\theta,\phi) = \frac{-GM}{r}\left(1-\sum_{n=2}^{\infty} J_n P_n(\cos\theta)\left(\frac{R}{r}\right)^n\right)$$

$P_n(\cos\theta)$: Legendre polynomials (solve $\nabla^2\Phi_g = 0$)

describe the non-uniform distribution of mass in a solid body: J_n: gravitational moments, determined by the body's mass distribution

For rotational symmetry about the equator (e.g. oblate planet):

odd n : $J_n = 0$
even n : $J_n \neq 0$

} generally a good approximation for the Solar System gas giants

However, at least for Jupiter, J_n for odd n are not 0.

Why? Asymmetric winds and zonal flows

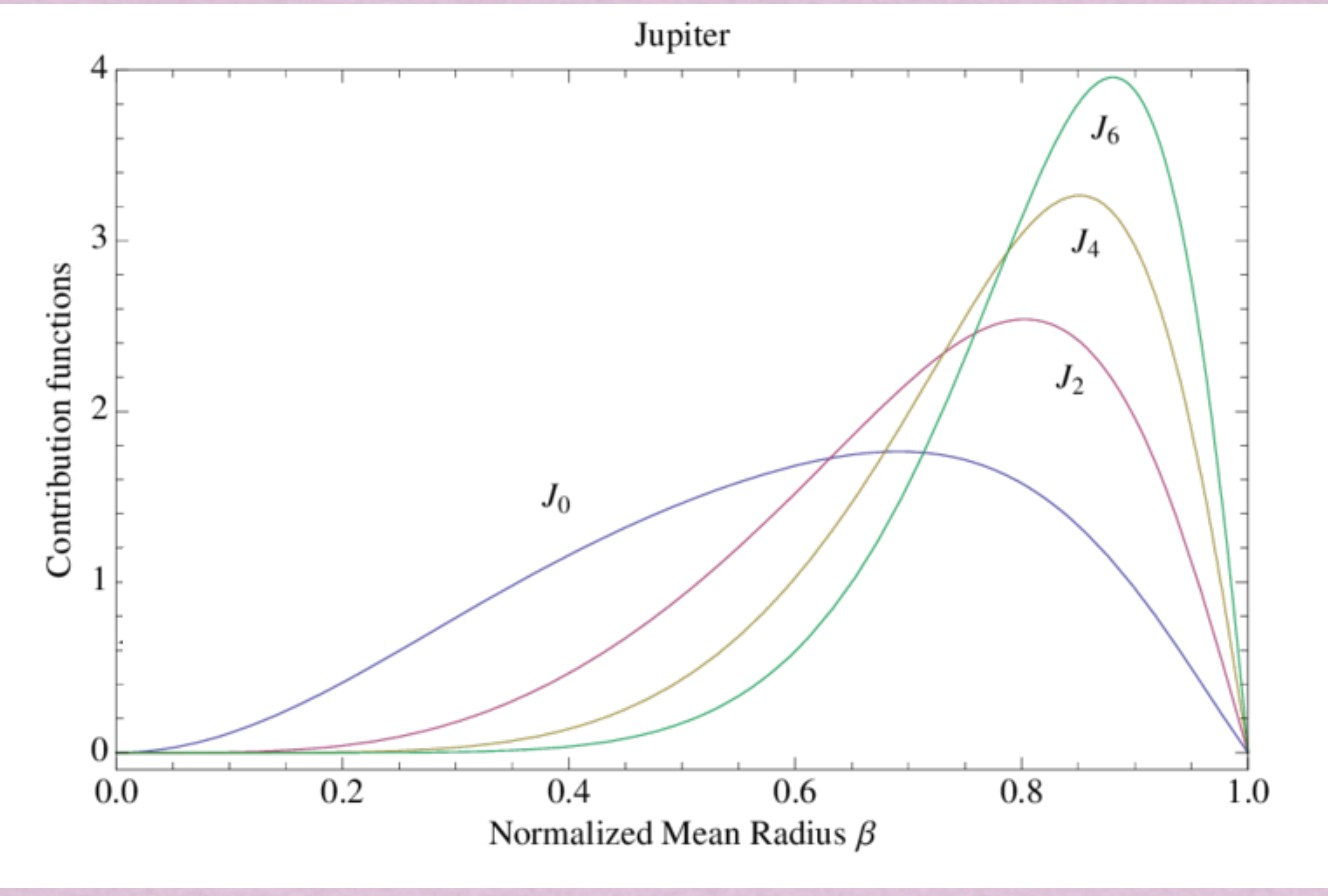
The 2nd harmonic, $J_2 = \frac{1}{3} K_T q_r$, is related to the difference between axial and equatorial moments of inertia

ratio of centrifugal to grav. force at body's surface: $q_r \equiv \frac{\omega_{rot}^2 R^3}{GM}$

K_T: tidal Love number (quantifies polar flattening)

oblateness: $\epsilon = \frac{R_e - R_p}{R_e} \approx \frac{3}{2} J_2 + \frac{q_r}{2}$

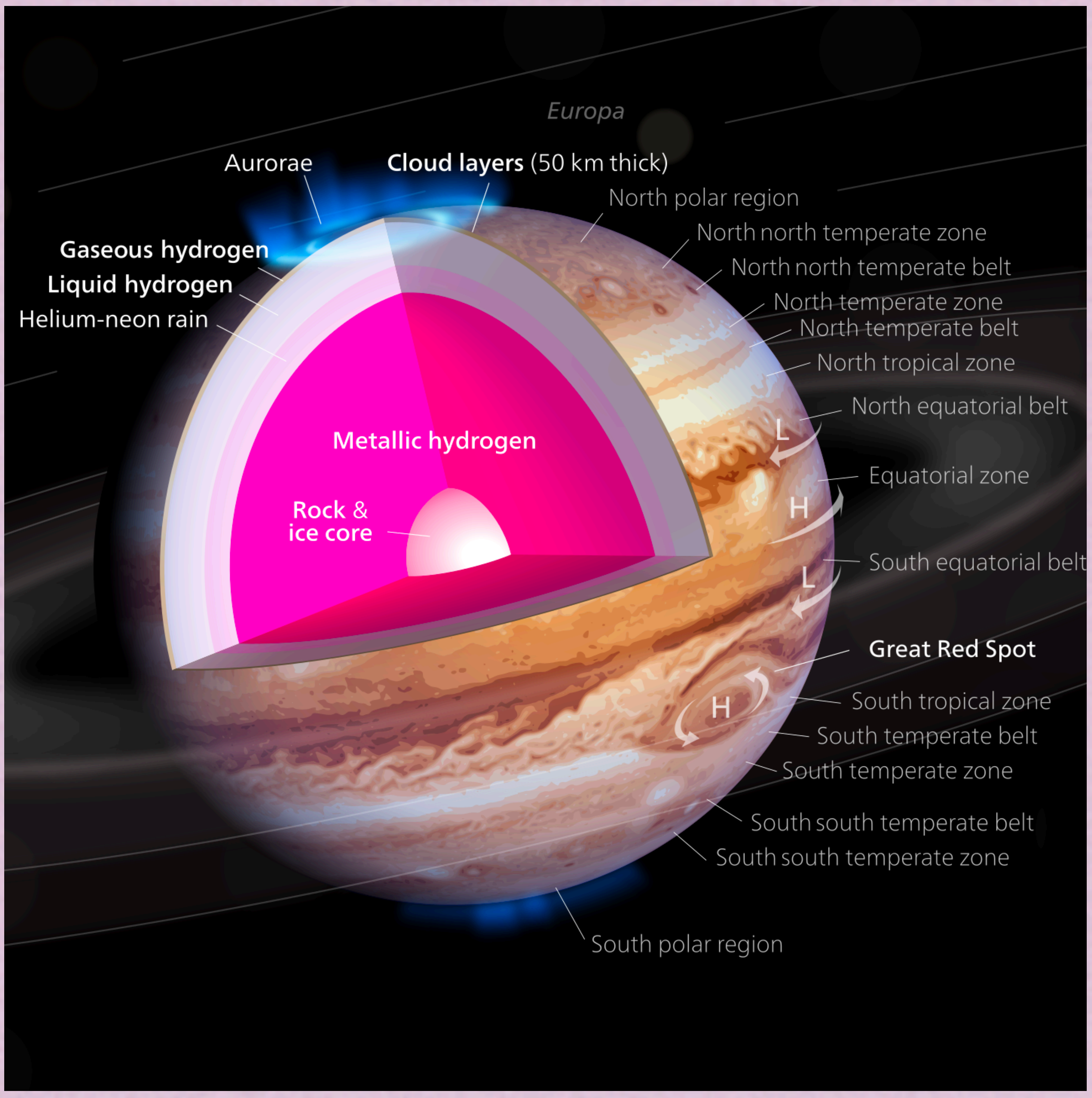
Gravity Moments



Interior of Jupiter

Models predict a wide range of core masses (0 - 30 M_{Earth})

But is this still the picture today?



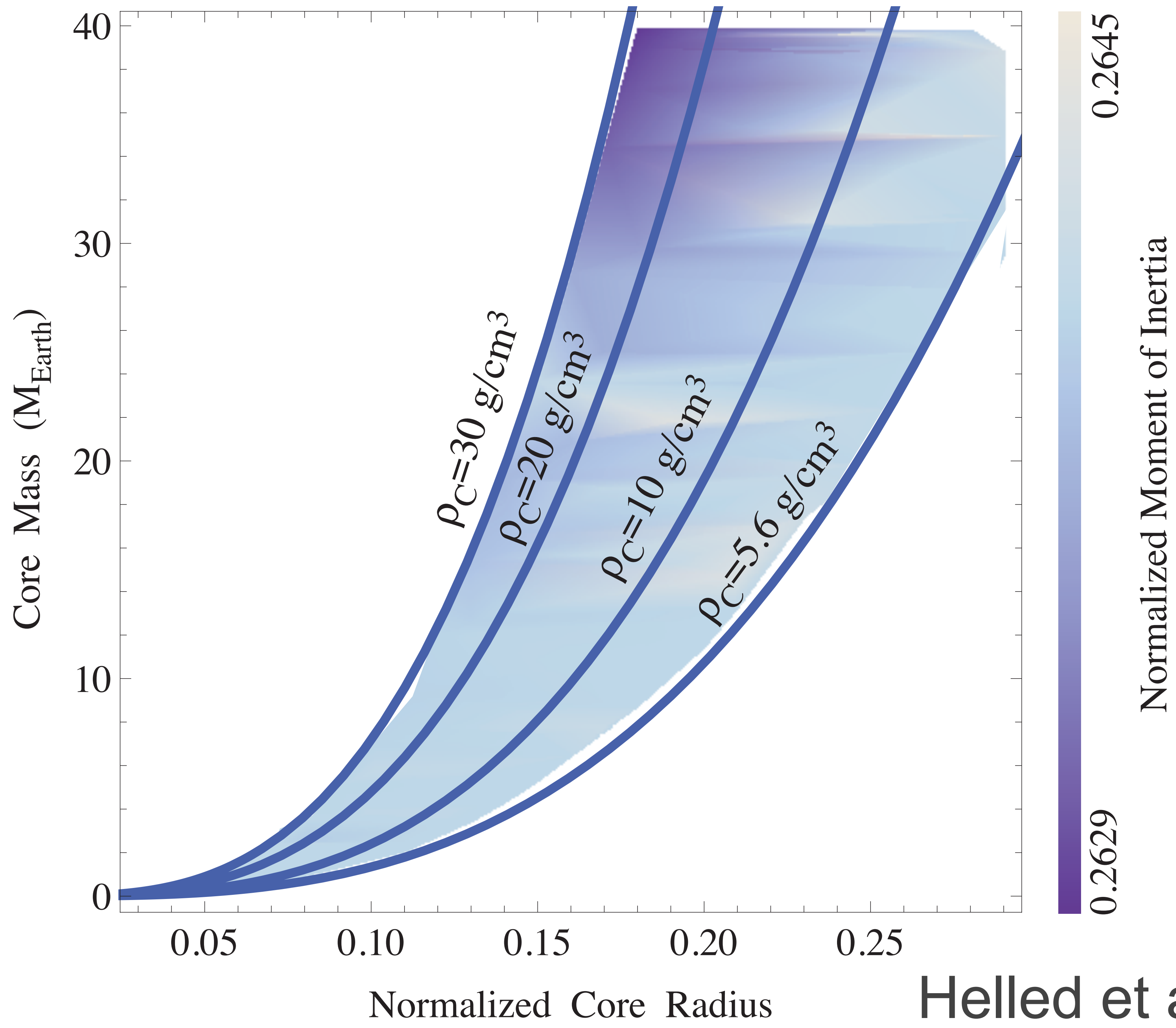
Interior of Jupiter

Parameter	Value
G^a (global parameter)	$6.672598 \times 10^{-11} \pm 2 \times 10^{-17}$ m^{3}kg^{-1}s^{-2}
$G \times M_J{}^b$	$(126686533 \pm 2) \times 10^9$m^{3}s^{-2}
M_J	1.89861×10^{27} kg
$R_{eq}{}^c$	71492 ± 4 km
$R_{polar}{}^c$	66854 ± 10 km
ω^d	$1.7585324 \times 10^{-4} \pm 6 \times 10^{-10}$ s^{-1}
$\bar{\rho}$	1326.5 kg m^{-3}
$m = 3\omega^2/4\pi G\bar{\rho}$	0.083408
$q = \omega^2 R_{eq}^3/GM_J$	0.0891954
$J_2 \times 10^{6\,e}$	14696.572 ± 0.014
$-J_4 \times 10^{6\,e}$	586.609 ± 0.004
$J_6 \times 10^{6\,e}$	34.198 ± 0.009
$-J_8 \times 10^{6\,e}$	2.426 ± 0.025
$J_{10} \times 10^{6\,e}$	0.172 ± 0.069

and I/(MR^2) = 0.276

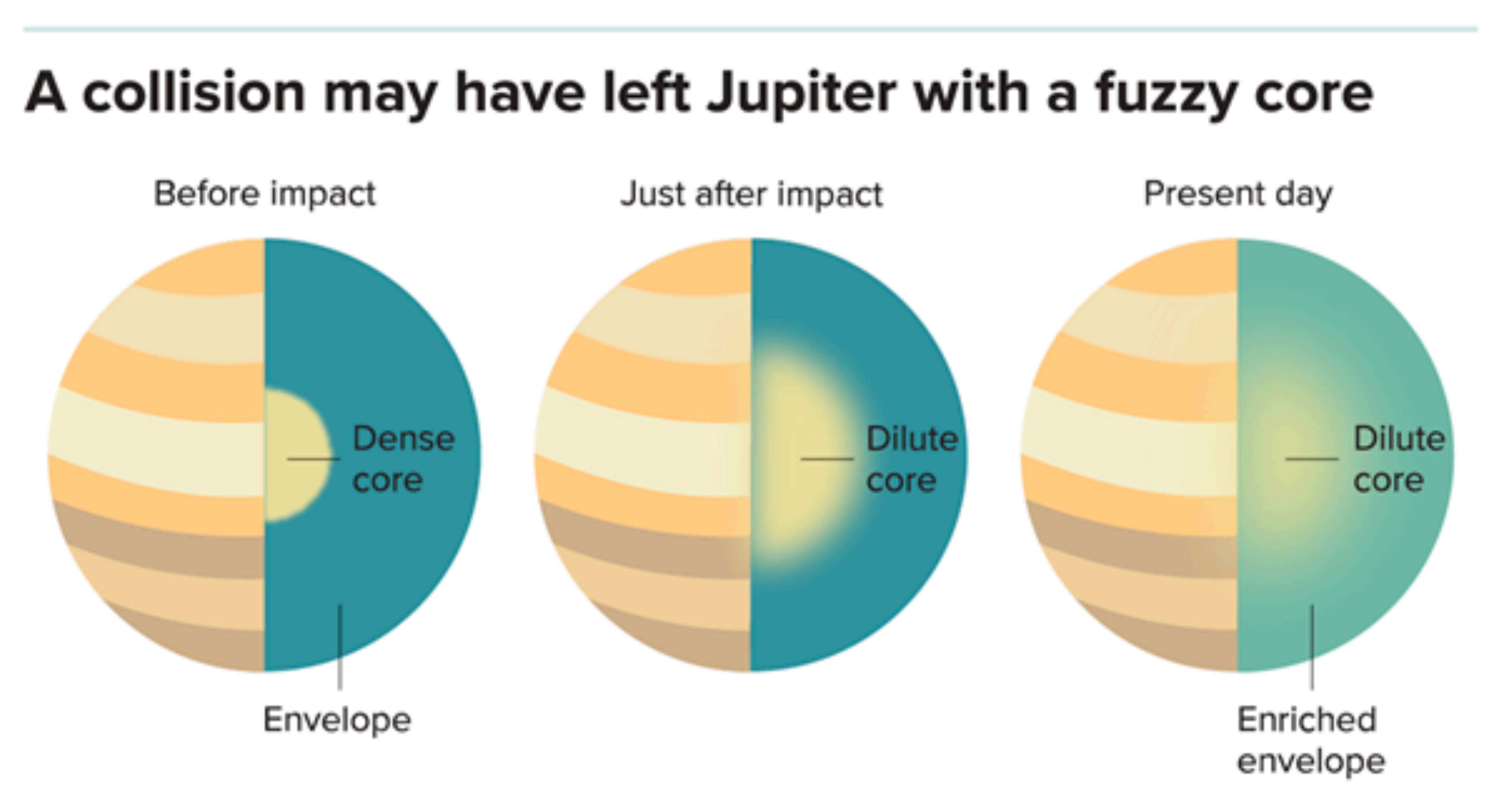
Interior of Jupiter

pre-Juno predictions:



Helled et al. 2011

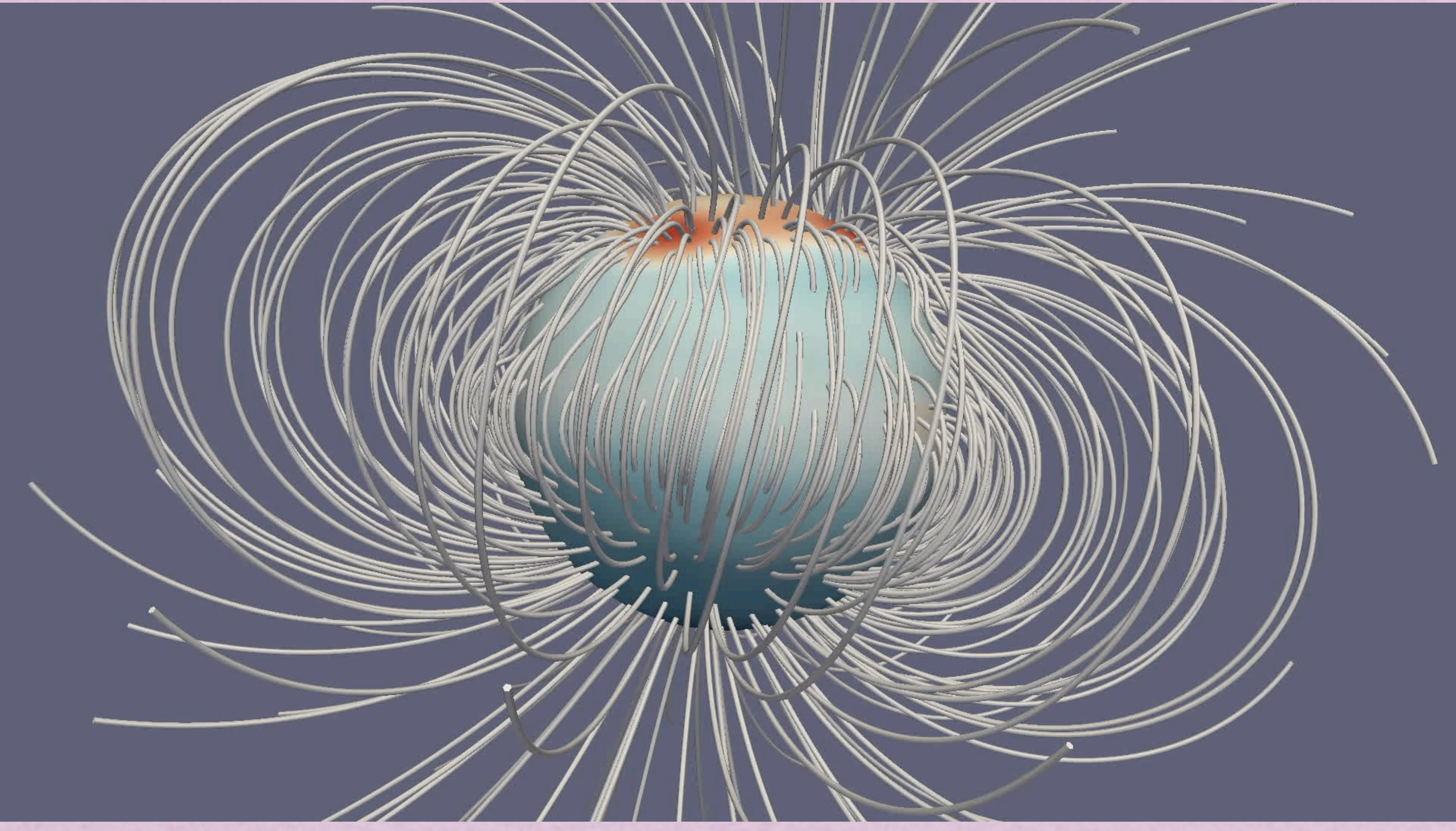
Interior of Jupiter



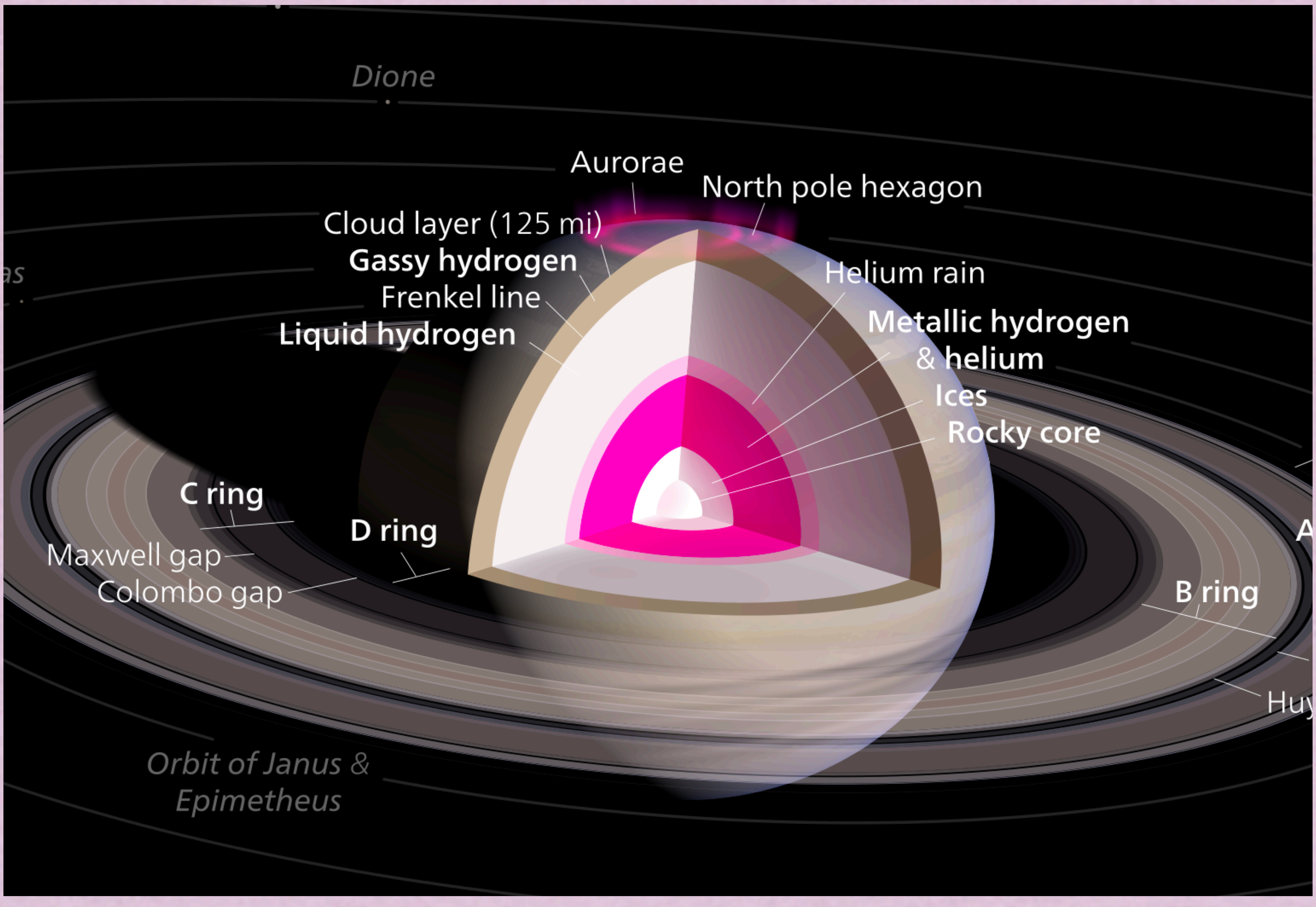
Liu et al. (2020)

Mass of the diffuse core is between 10 and 24 M_{Earth}

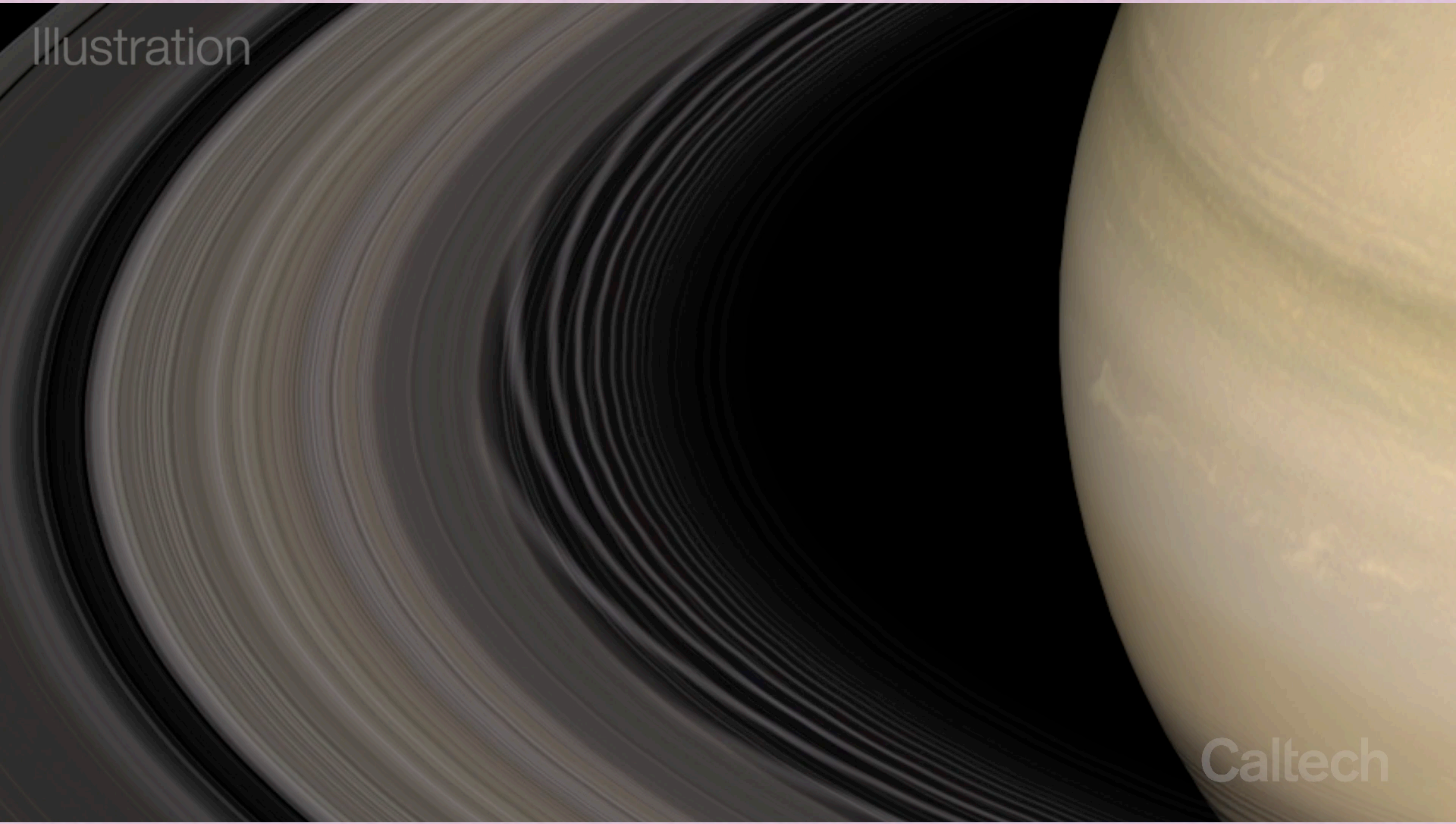
Magnetic Field of Jupiter



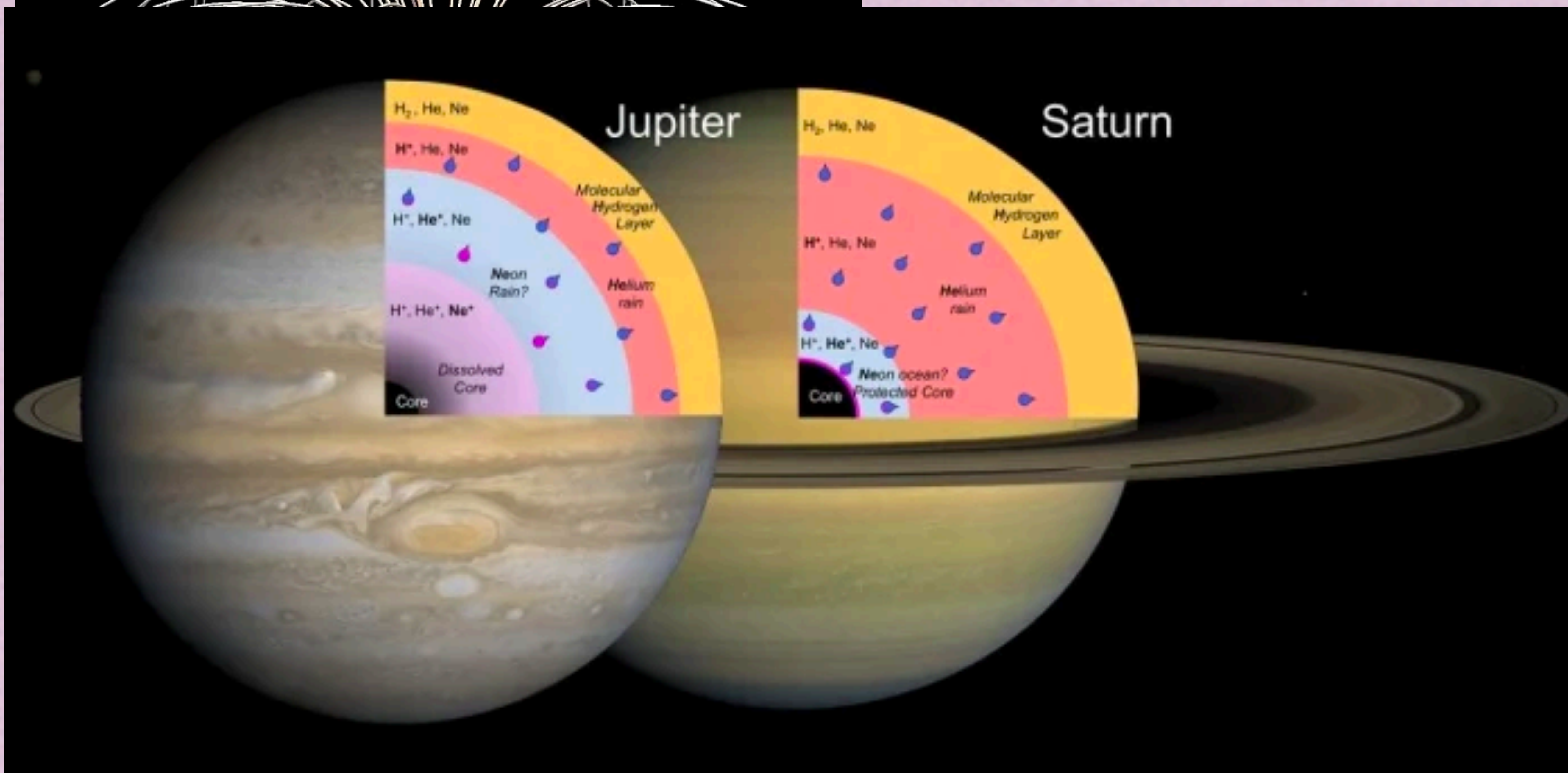
Interior of Saturn



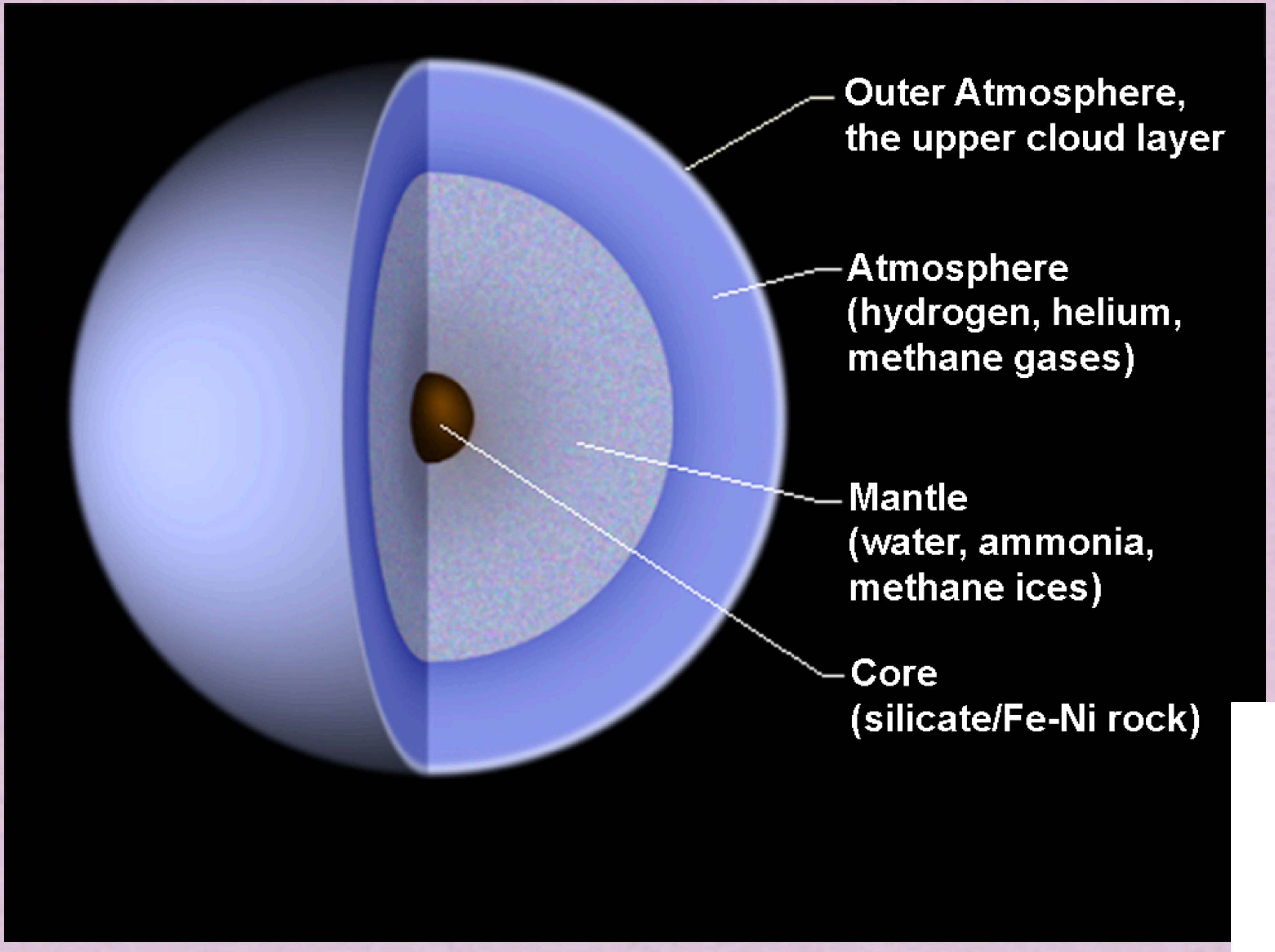
Interior of Saturn

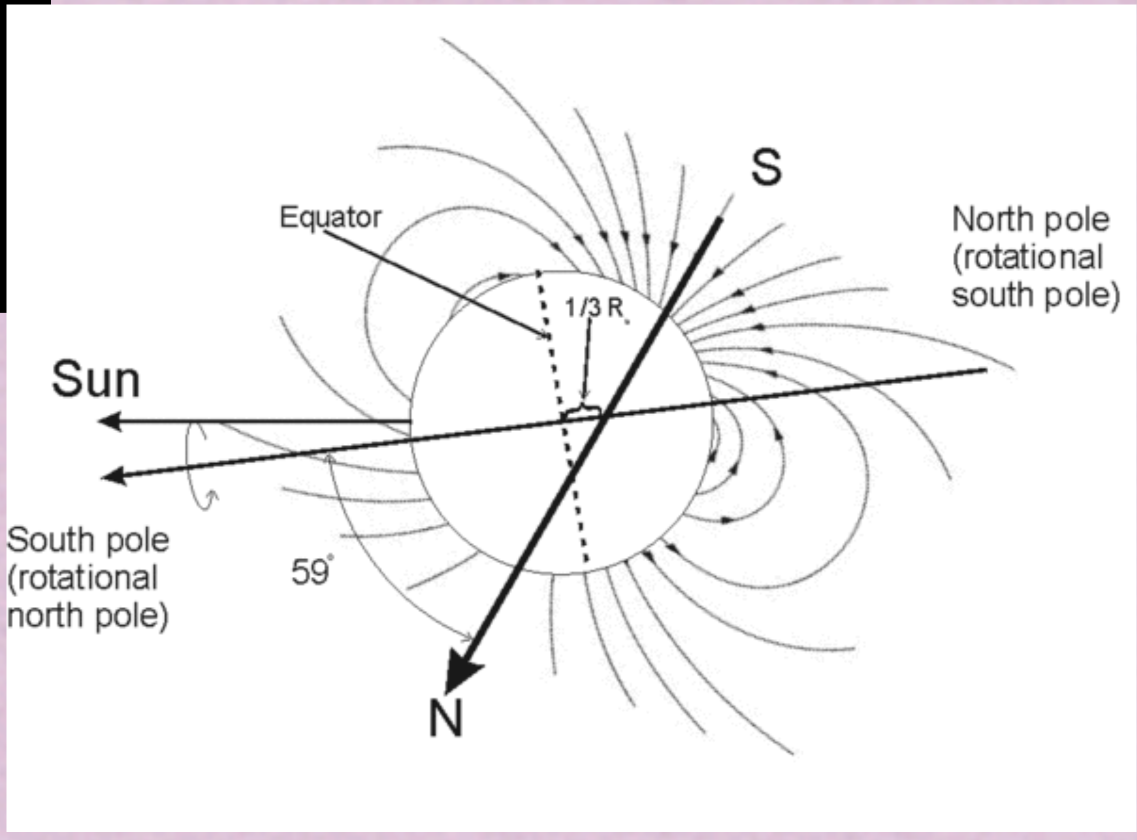


Magnetic Field of Saturn

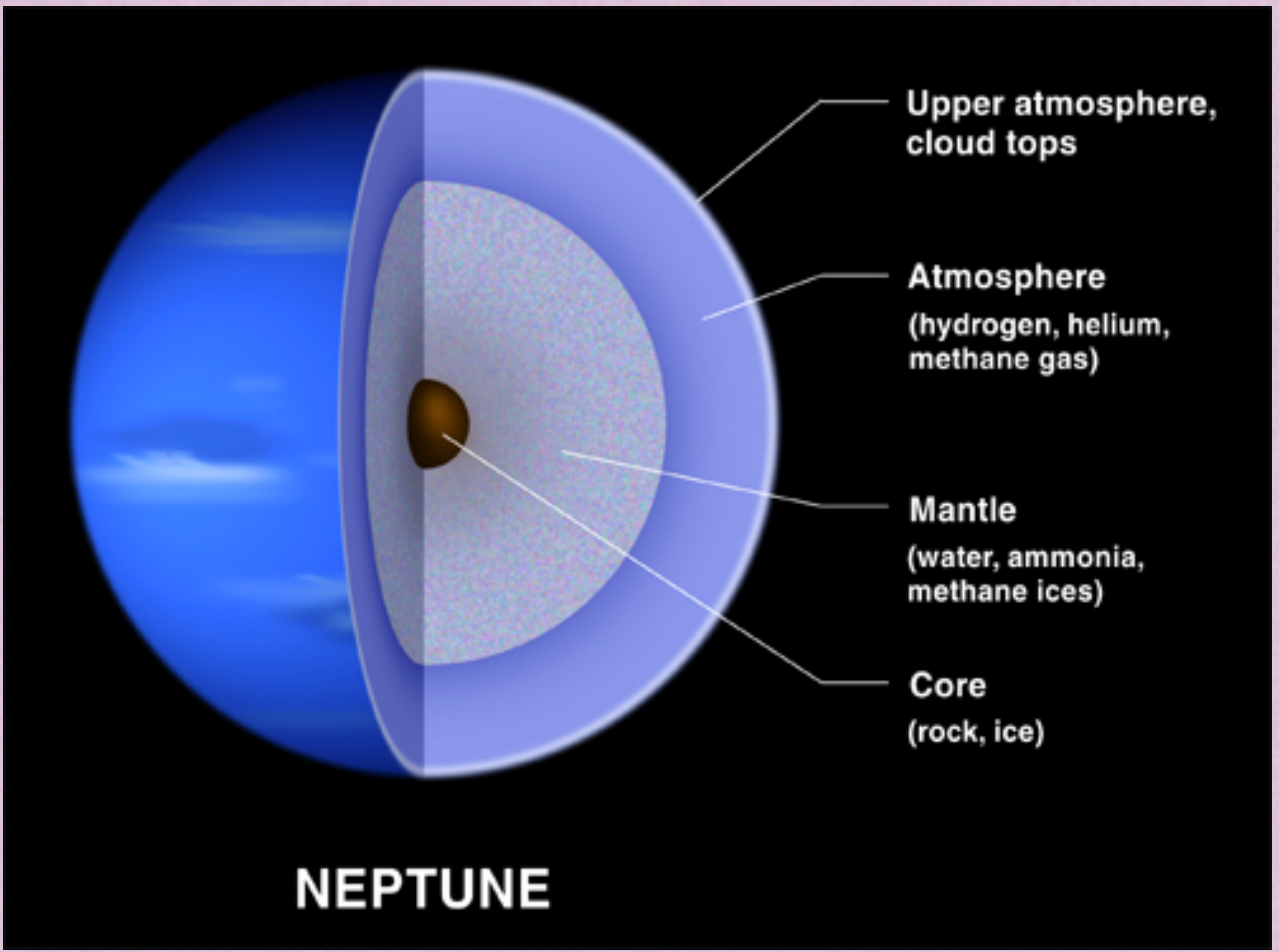


Interior and Magnetic Field of Uranus



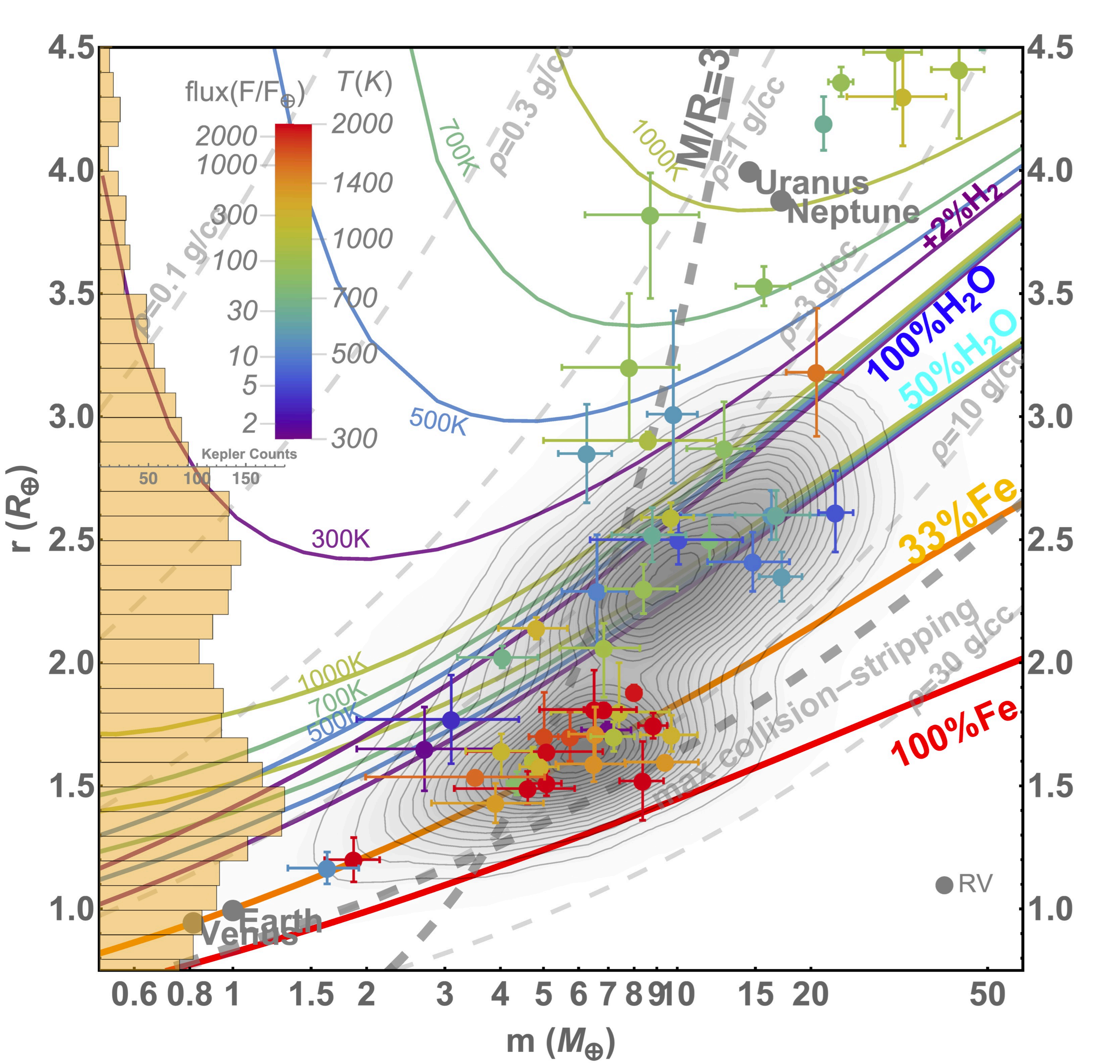


Interior and Magnetic Field of Neptune



Gravitational Moments

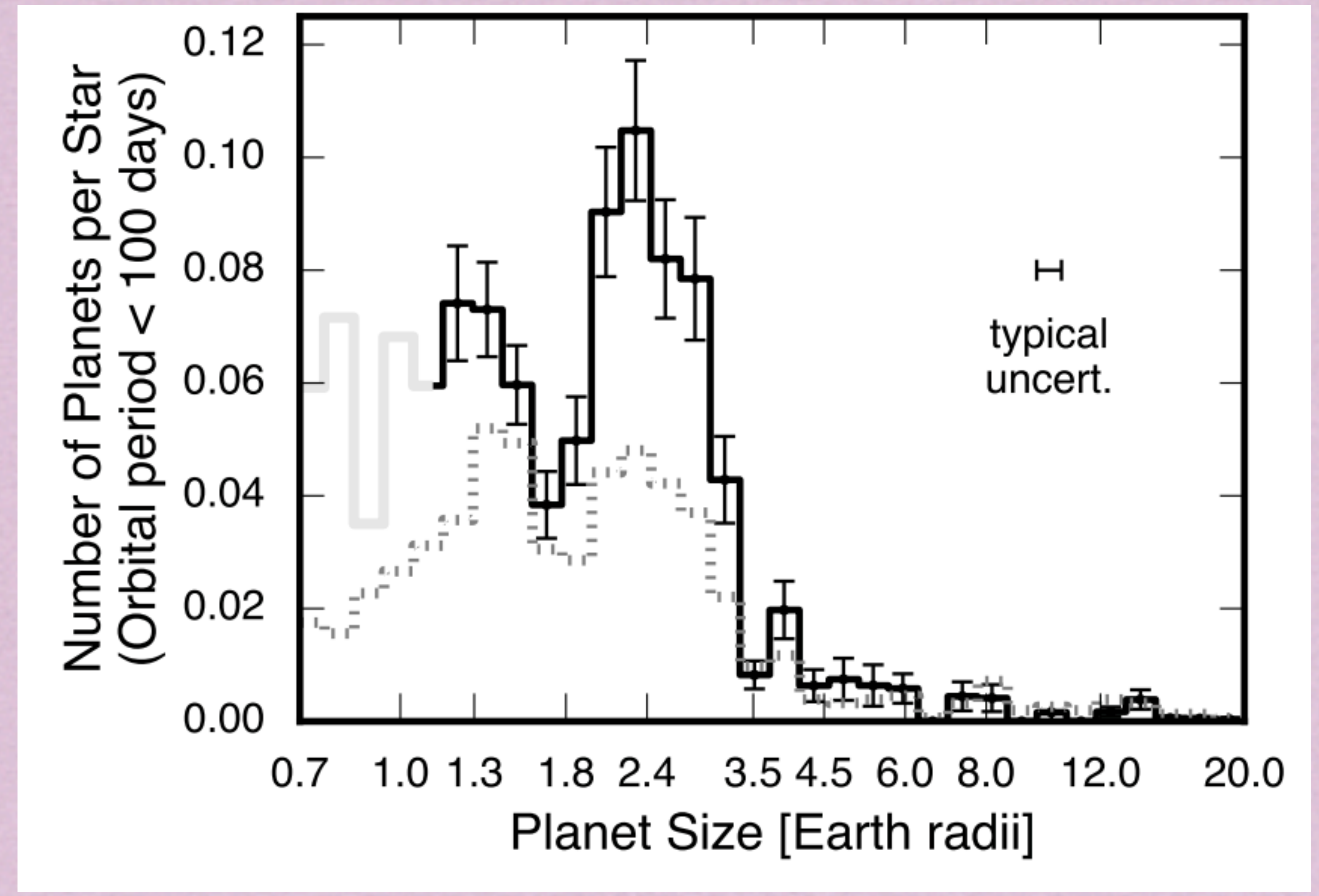
Body	J_2 ($\times 10^{-6}$)	J_3 ($\times 10^{-6}$)	J_4 ($\times 10^{-6}$)	J_6 ($\times 10^{-6}$)	q_r	Λ_2	I/MR^2	C_{22} ($\times 10^{-6}$)	Refs.
Mercury	60 ± 20				1.0×10^{-6}	60	0.33		1
Venus	4.46 ± 0.03	-1.93 ± 0.02	-2.38 ± 0.02		6.1×10^{-8}	73	0.33		1
Earth	1 082.627	-2.532 ± 0.002	-1.620 ± 0.003	-0.21	3.45×10^{-3}	0.314	0.331		1
Moon	203.43 ± 0.09				7.6×10^{-6}	26.8	0.393	22.395	1, 2
Mars	$1\,960.5 \pm 0.2$	31.5 ± 0.5	-15.5 ± 0.7		4.57×10^{-3}	0.429	0.365		1
Jupiter	$14\,696.4 \pm 0.2$		-587 ± 2	34 ± 5	0.089	0.165	0.254		1
Saturn	$16\,290.7 \pm 0.3$		-936 ± 3	86 ± 9	0.151	0.108	0.210		4
Uranus	$3\,343.5 \pm 0.1$		-28.9 ± 0.2		0.029	0.114	0.23		1
Neptune	$3\,410 \pm 9$		-35 ± 10		0.026	0.136	0.23		1
Io	$1\,860 \pm 3$				1.7×10^{-3}	1.08	0.378	558.8	3
Europa	436 ± 8				5.02×10^{-4}	0.87	0.346	131.5	3
Ganymede	128 ± 3				1.91×10^{-4}	0.67	0.312	38.3	3
Callisto	33 ± 1				3.67×10^{-5}	0.90	0.355	10.2	3



flux(F/F⊕)
T(K)
Kepler Counts
M/R=3
ρ=0.1 g/cc
ρ=0.3 g/cc
ρ=1 g/cc
ρ=3 g/cc
ρ=10 g/cc
ρ=30 g/cc
300K
500K
700K
1000K
Uranus
Neptune
+2%H2
100%H2O
50%H2O
33%Fe
100%Fe
max collision-stripping
Earth
Venus
RV
r (R⊕)
m (M⊕)

Size Distribution

Small Planets Are Common



Fulton & Petigura (2018)