Internal structure and composition of giant planets

Nadine Nettelmann (1) and Ravit Helled (2)

(1)

Institute of Planetary Research
German Aerospace Center (DLR) Berlin

(2)

Institute for Computational Science
University of Zurich

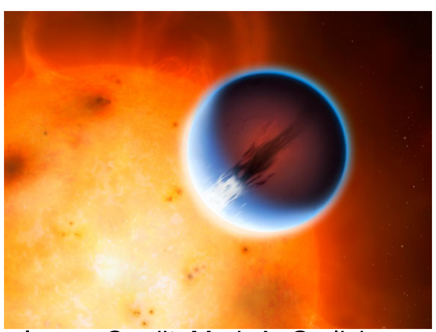
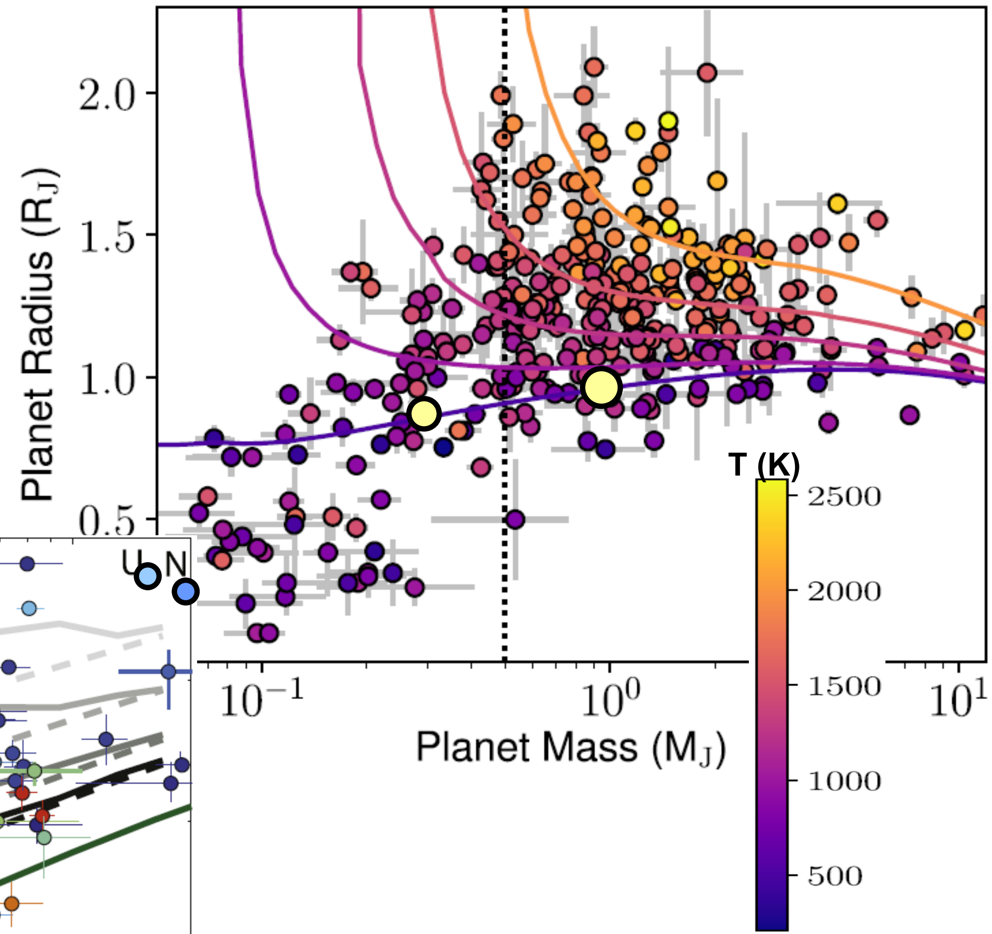


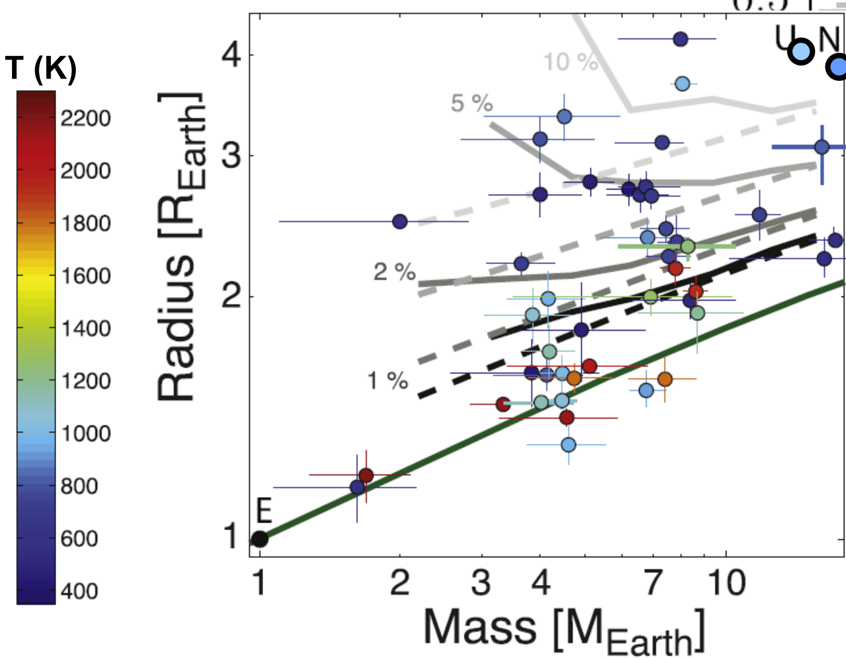
Image Credit: Mark A. Garlick

- Exoplanet composition
- Jupiter & Juno
- Love number k_2 of exoplanets and of Neptune

Planet mass and radius

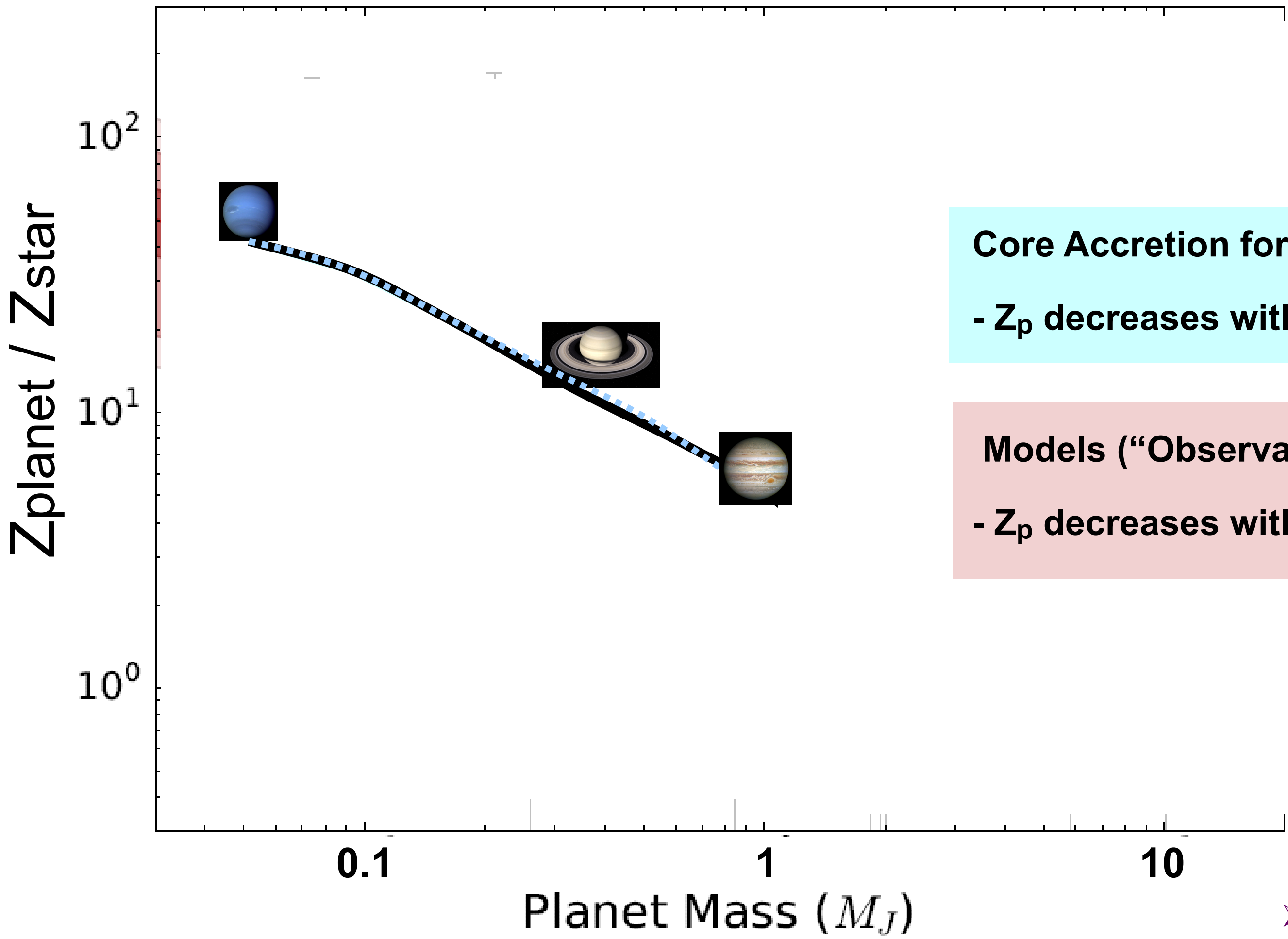
	ΔMp	Δ Rp
Jup	**0.02%**	**6 km (0.009 %)** *Voyager*
Sat	**0.02%**	**6 km (0.01 %)** *Voyager*
Ura	**0.02%**	**10 km (0.04 %)** *Voyager*
Nep	**0.02%**	**20 km (0.08 %)** *Voyager*





- ➢ Thorngren & Fortney 2018, AJ
- ➢ Pu & Valencia 2017, ApJ
- ➢ Guillot & Gautier 2014, Treat. Geophys.

Giant planets: inferred metal enrichment



Core Accretion formation:

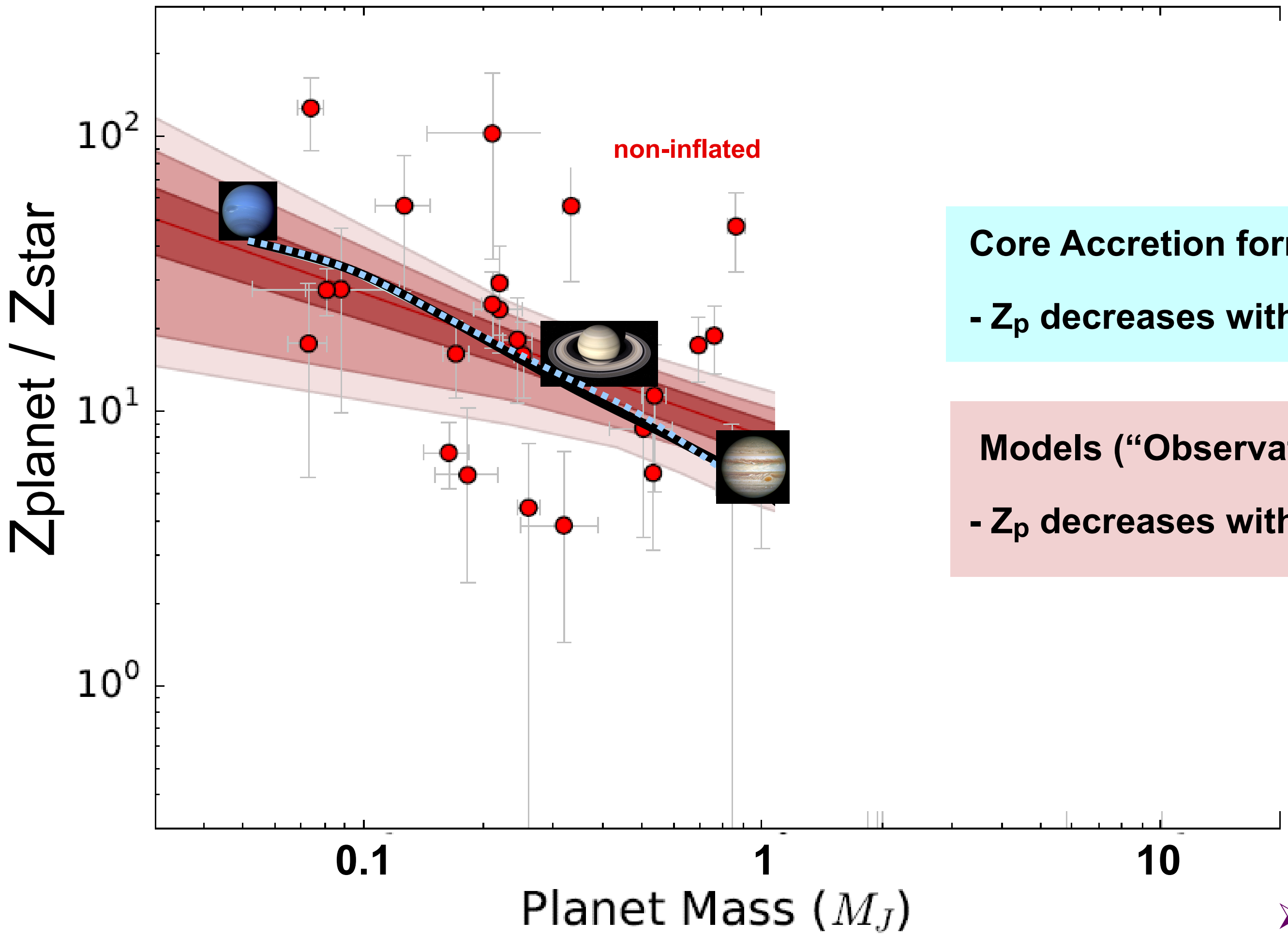
- Z_p decreases with M_p

Models ("Observation"):

- Z_p decreases with M_p

➢ Venturini, Alibert, +2016. A&A

Giant planets: inferred metal enrichment



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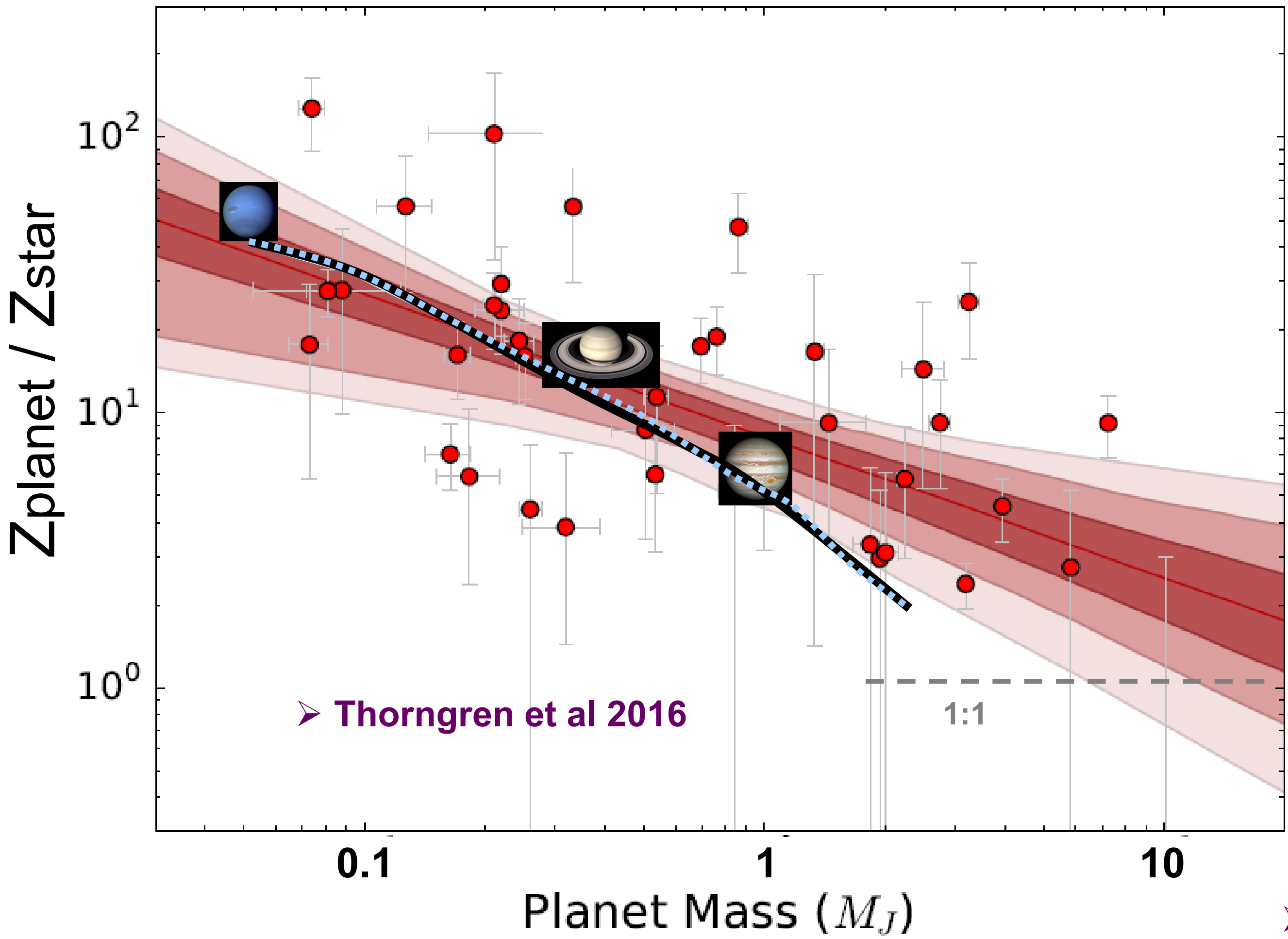
Exoplanet composition: statistics



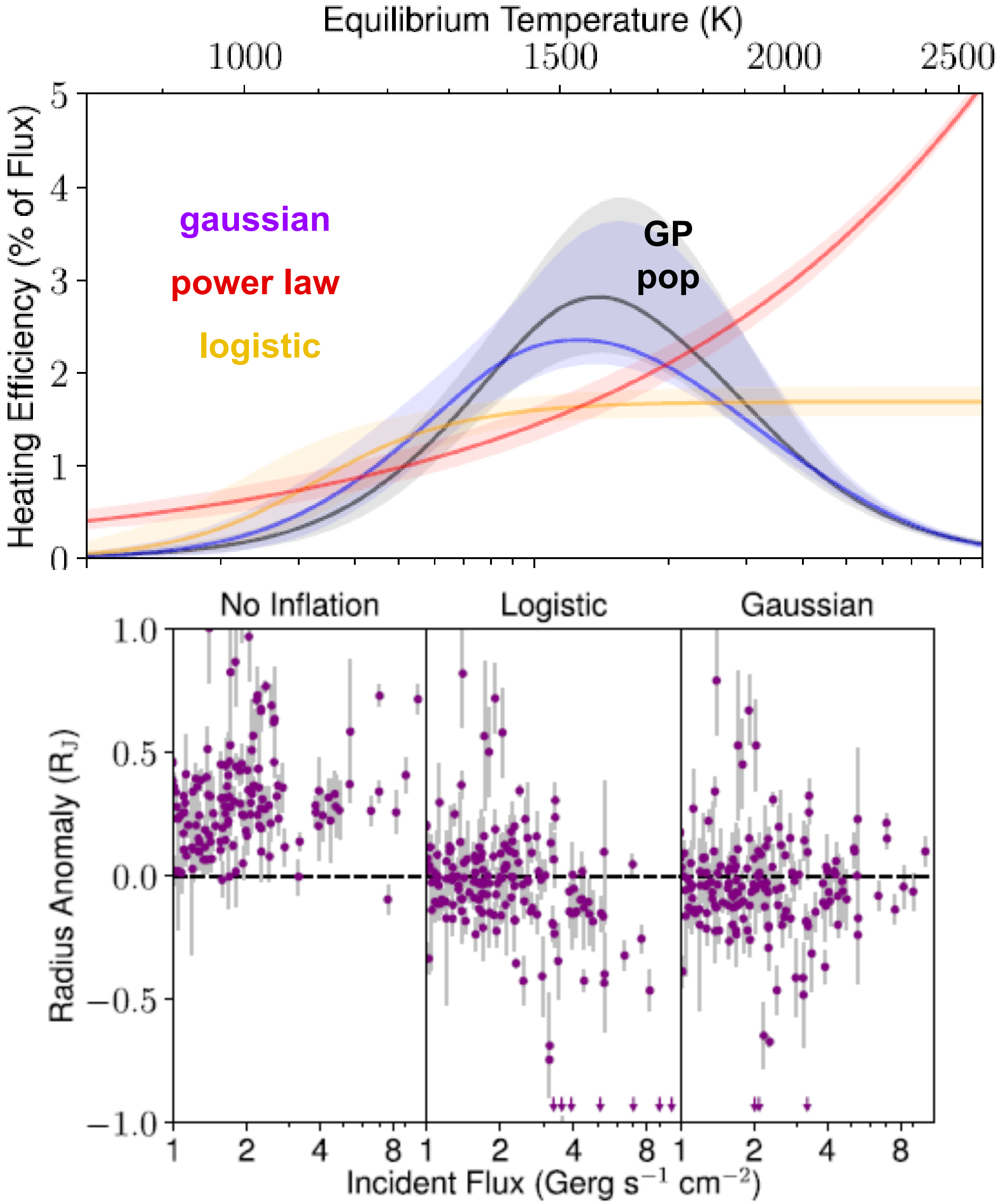
CA formation:

- Z_p decreases with M_p

- $M_p \gg 1\ M_J$: $Z_p \rightarrow Z_{star}$

"Observation": different slope

- Venturini, Alibert, +2016, A&A
- Thorngren & Fortney 2016



Exoplanet extra heating:

Statistical analysis suggests Gaussian behavior in agreement with predictions from Ohmic heating.

➢ Thorngren & Fortney 2018, AJ

Part 2/3, Jupiter & Juno

1973/74	Pioneer 10, 11 flybys	gravity field, thermal emission, radiation belt
1979	Voyager 1, 2 flybys	gravity field to 1 : 10^5, magnetic field
1995—2003	Galileo orbiter	entry probe: atmospheric He, Ne, Ar, Kr, Xe, C, N, O

2016—2022 Juno Orbiter

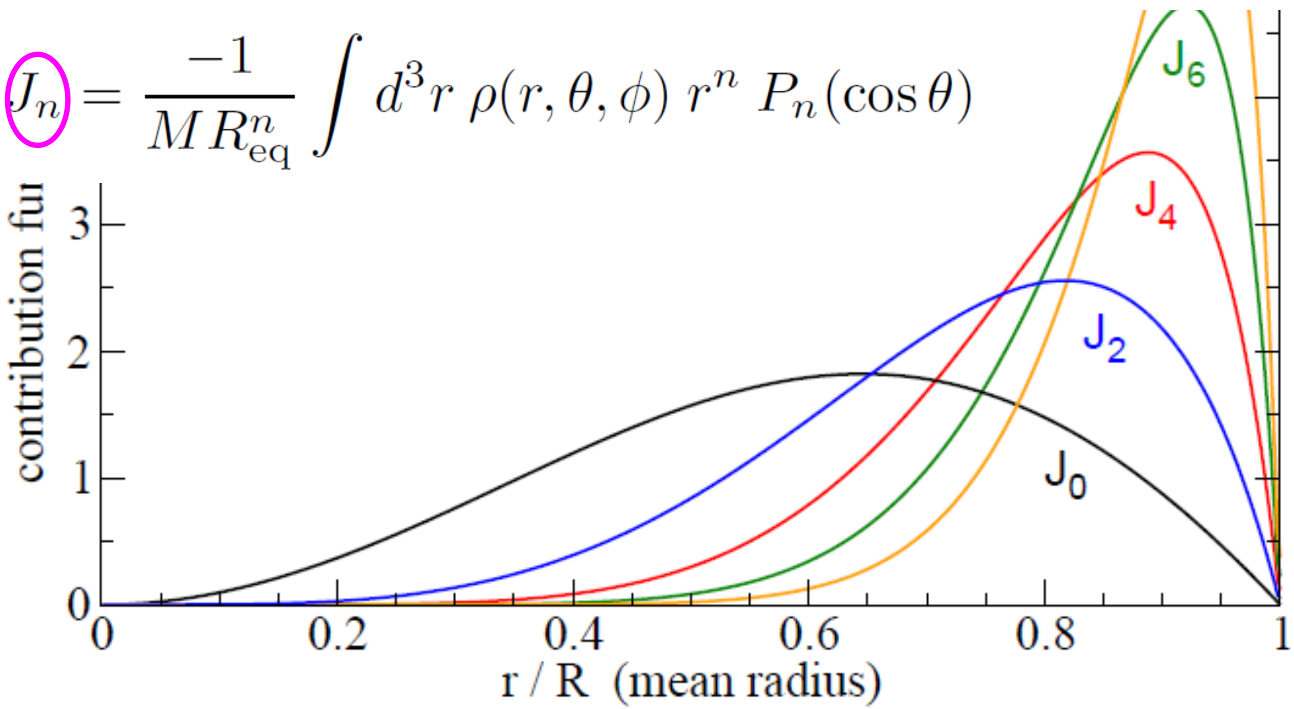
- gravity field to 1 : 10^9 — ongoing
- magnetic field — global, next: variability
- global atmospheric O/H — difficult due to N

gravity field (J_{2n}) probes internal density distribution

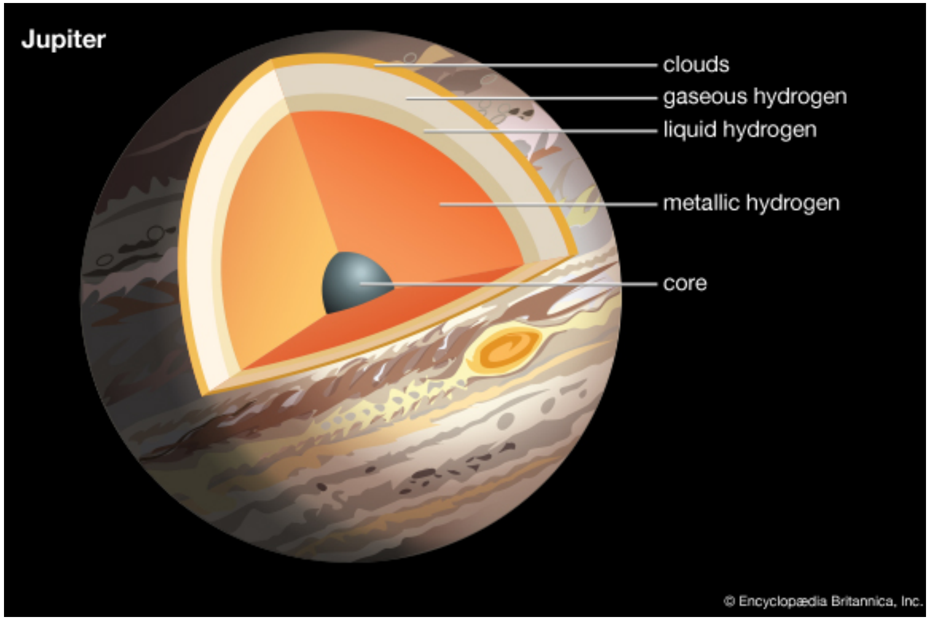
$$V(r,\lambda,\phi) = \frac{GM}{r}\left[1 - \sum_{n=2}^{\infty}\left(\frac{R}{r}\right)^n J_n P_{n,0}(\sin\phi) + \sum_{n=2}^{\infty}\sum_{m=1}^{n}\left(\frac{R}{r}\right)^n P_{n,m}(\sin\phi)\left[C_{n,m}\cos(m\lambda) + S_{n,m}\sin(m\lambda)\right]\right],$$

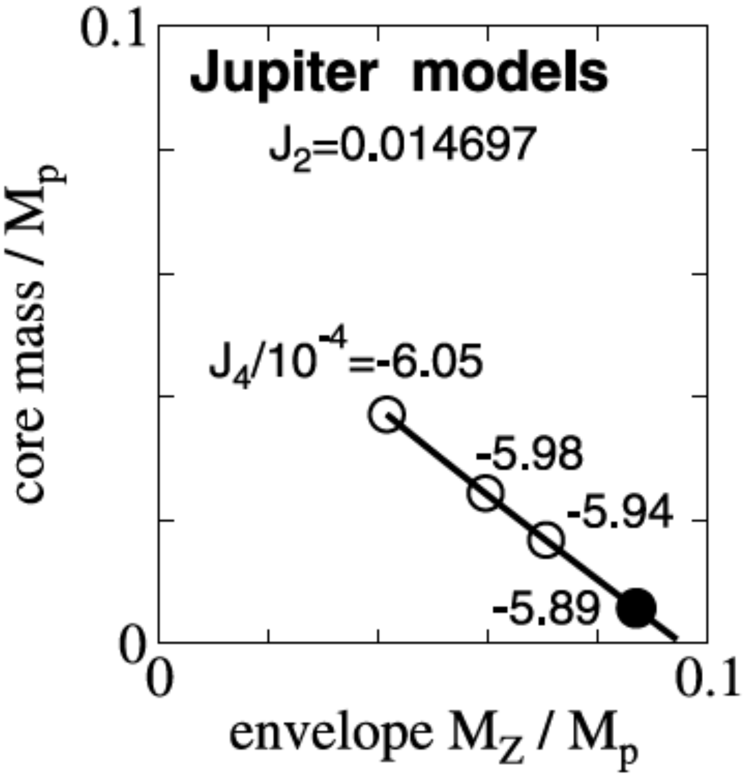
Love numbers

$$J_n = \frac{-1}{M R_{\rm eq}^n}\int d^3r\,\rho(r,\theta,\phi)\,r^n\,P_n(\cos\theta)$$



At least 3 layers are needed to explain pre-Juno gravity data.





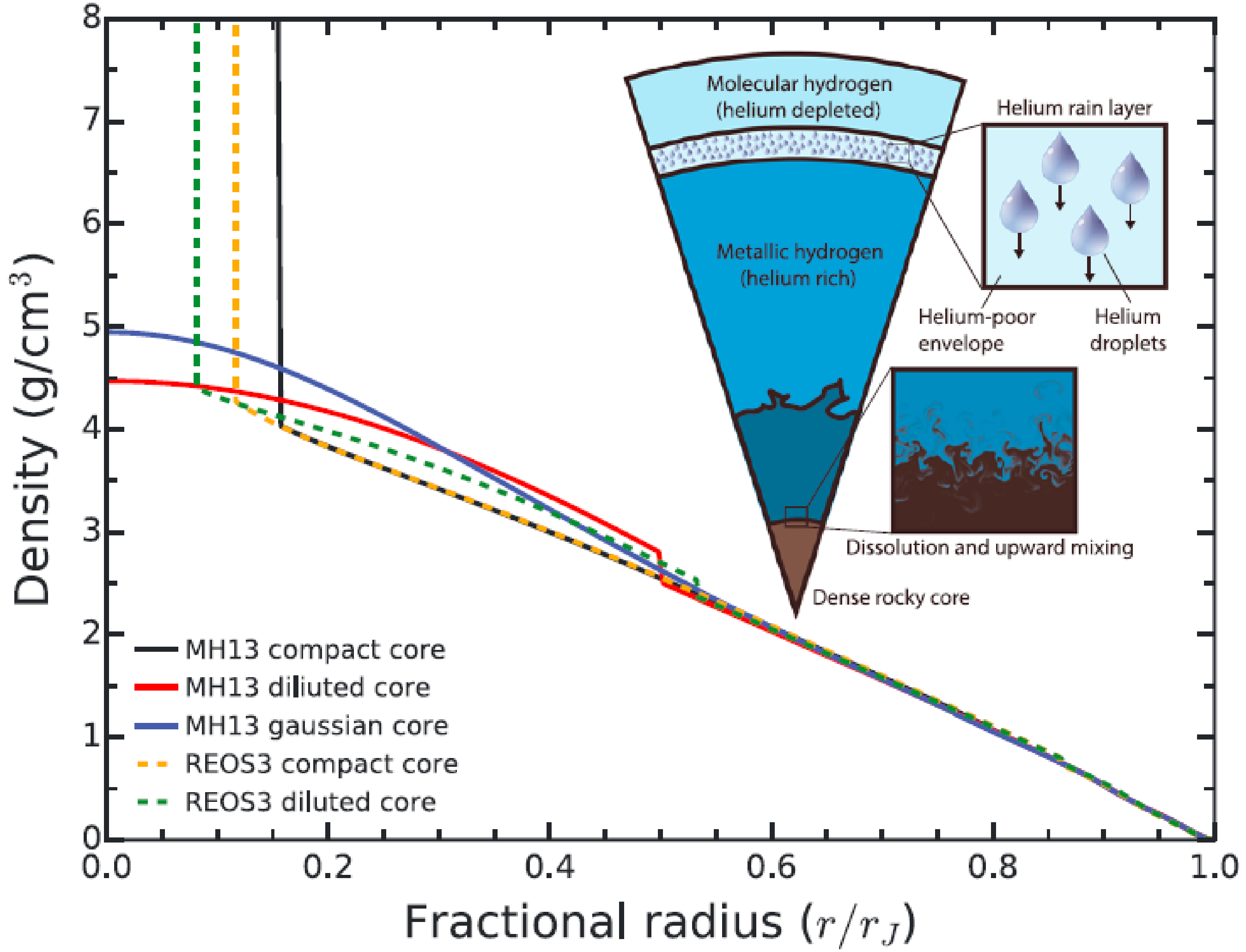
pre-Juno: $-J4/10^6$ = 579—589

Juno: $-J4/10^6$ = 586.610 (4)

- Iess, Folkner, ..., Helled, +2018, Nature

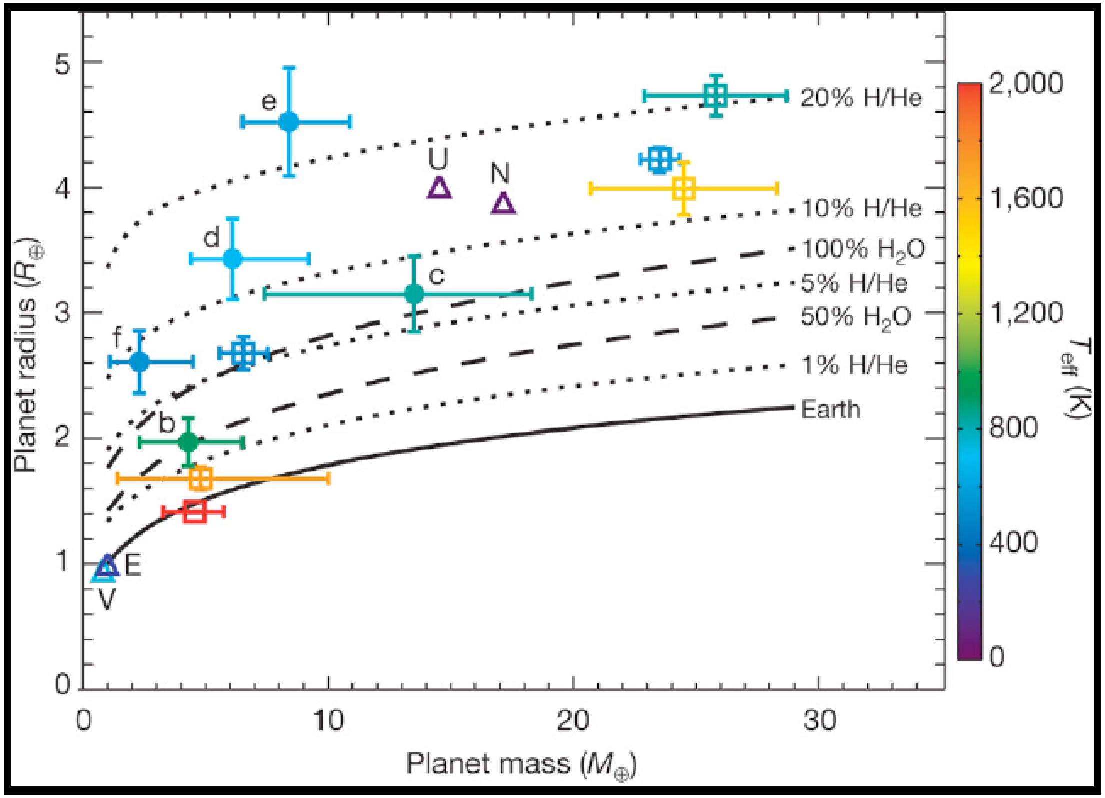
- Nettelmann 2011, ASS
- Militzer, Hubbard, +2008, +2016, ApJ
- Nettelmann, +2008, +2012, ApJ

Juno data suggest “diluted“ core, but H/He EOS dependent



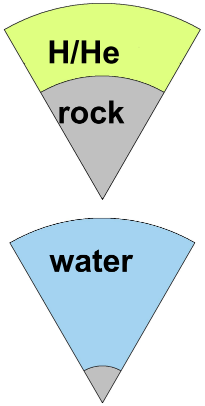
➢ Wahl, Hubbard, Militzer, et al 2017, JGR

Part 3/3, Composition of (sub-)Neptune sized planets

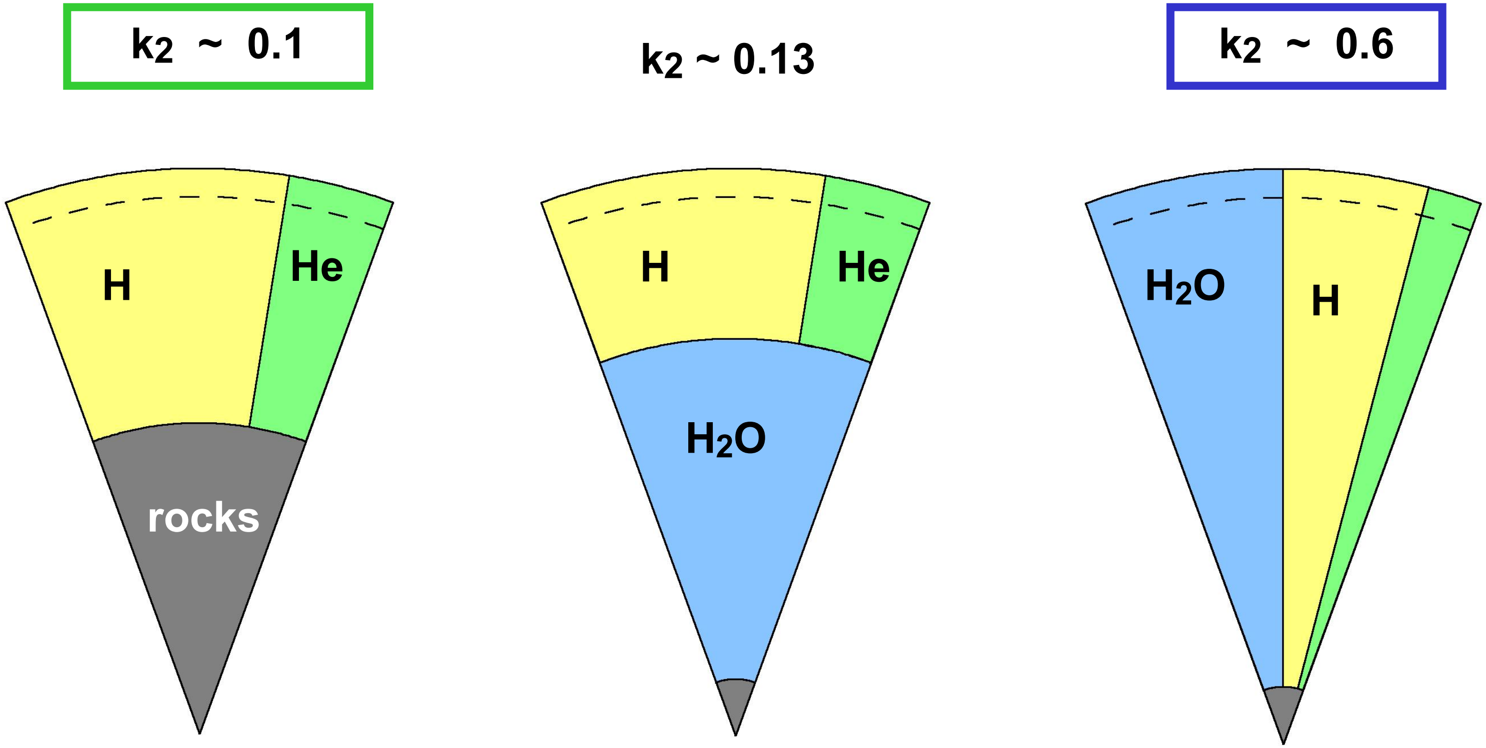


Lissauer et al., 2011

Degeneracy problem: different compositions can yield same M_p—R_p



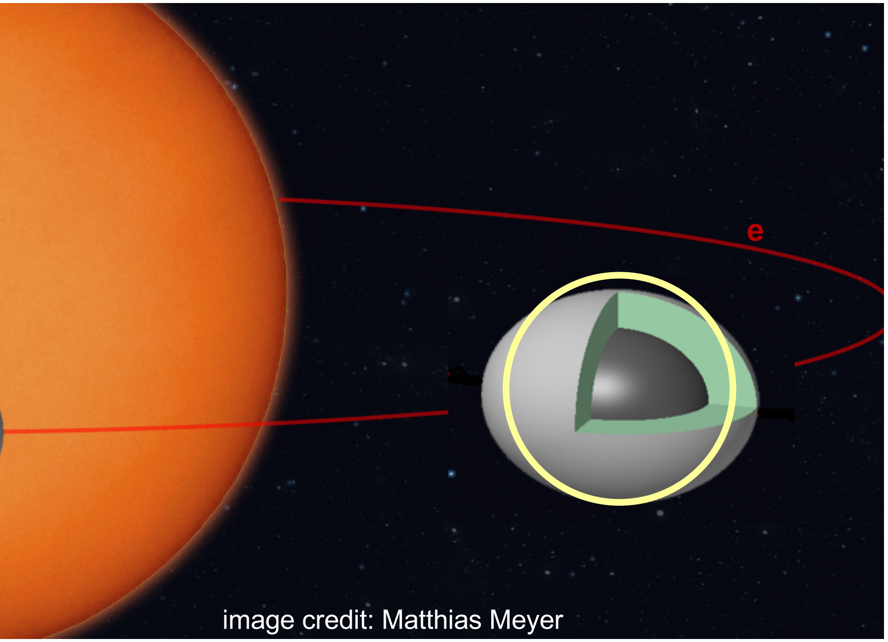
Measured Love number k_2 could break the degeneracy



HATP-7b like: 40 M_E, 6 R_E, a=0.04 AU, T_* = 4000 K, M_* = R_* = 0.65 MR_{sun}

➢ Sir A.E.H. Love 2011

Measuring the tidal Love number k_2 of exoplanets



Measurement:

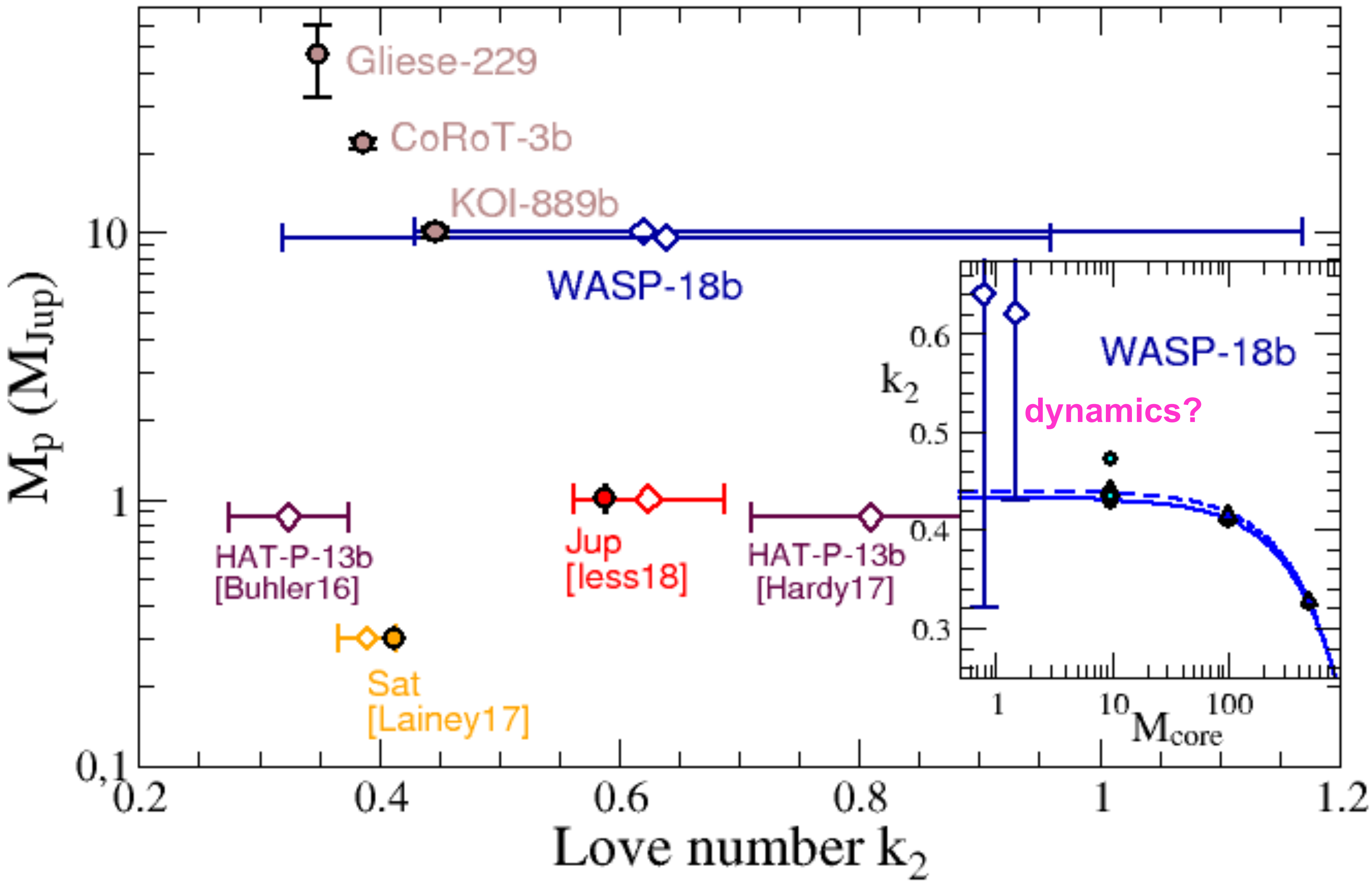
- shape deformation from Transit Light curve

< 100 ppm

- Transit Timing Variation (orbital precession)

- Radial Velocity Variations (orbital precession)

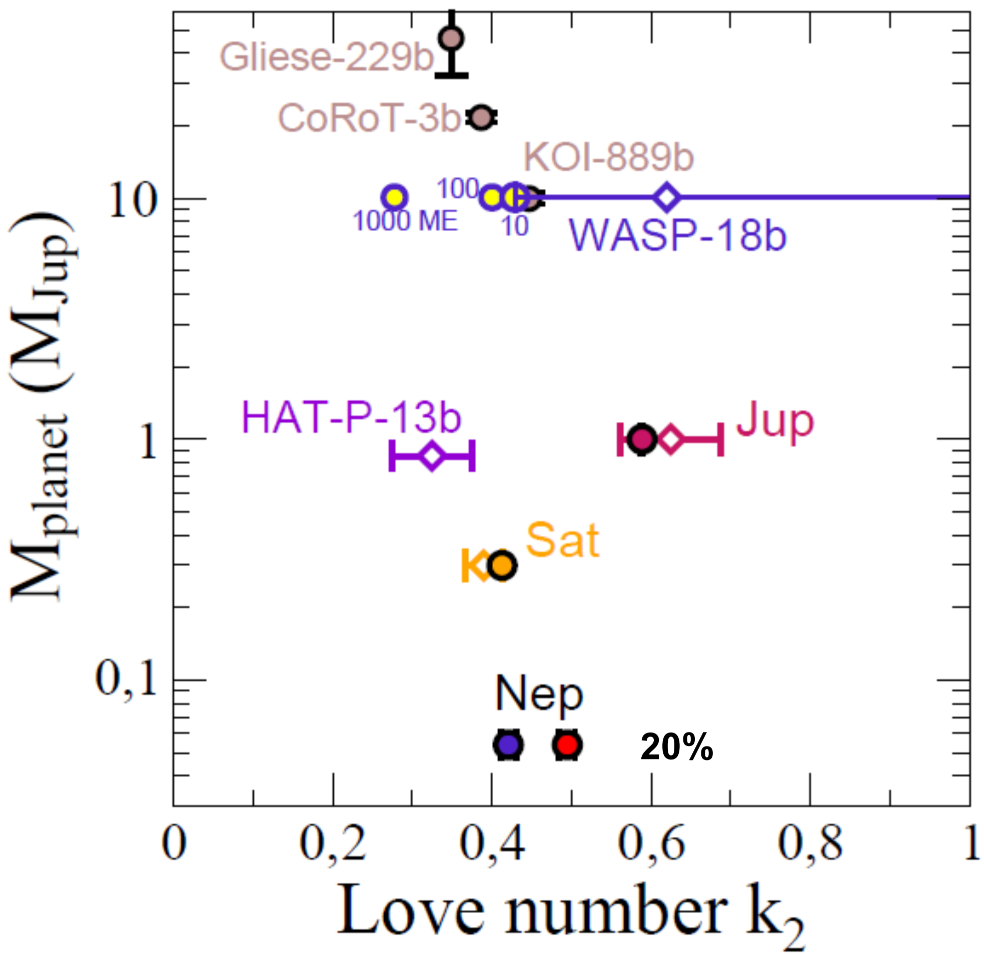
Love number k_2 measurements: new direction in (exo)planetary science



- Csizmadia, Hellard +2018, A&A
- Nettelmann, Csizmadia et al, submitted

Rotation rate and (static) k_2 value of Neptune

- **16h 06m** *Voyager 2* **, from magnetic field**
- **17h 27m minimization of wind energy**
  - Helled, Anderson, Schubert 2010, Icarus
  - Helled, Schubert, Anderson 2009, PSS
- **same J2, J4, different k2**
- **Juno: $\Delta k_2 \sim 0.1\%$ (Iess et al 2019)**
- **measurement requires Orbiter ~ 2040ies?**



Summary

Statistical analysis of giant exoplanets with measured mass and radius (age, period, star) provides constraints on bulk composition (metal content) and thus on planet formation theories.

Gravity field perturbations due to rotation (J_2, J_4) or tides (k_2) constrain the interior distribution of heavy elements.

Jupiter‘s heavy element abundance increases toward the center.
Juno-data suggest smooth transition between core and envelope.

Love number k_2 measurements is an emerging new field for giant planets.

Static k_2 equivalent to J_2.

Neptune‘s k_2 could be used to infer its deep rotation rate; requires Orbiter.

White papers advocating a Neptune Orbiter:

---Ice giant systems (L. Fletcher) 2019. ESA‘s Voyage2050:
launch in 2041, arrival in 2057, k_2 in 2061?

---Neptune and Triton (A, Masters) 2013. ESA‘s Cosmic Vision

Bulk heavy element mass in Jupiter

convective, adiabatic models:

H/He-EOS	MZ (ME)	Ref.
SCvH:	20—40	Miguel, Guillot +2016, A&A
REOS.3	30—35	Nettelmann 2017, A&A

super-adiabatic He-rain layer

MH13	24—26	Wahl, Hubbard +2017, JGR

largely semi-convective interior:

SCvH	< 70	Leconte & Chabrier 2012, A&A

⟹ **25-40 M_{Earth} of heavy elements inside Jupiter**

various assumptions: rocky/diluted core, ice-rock ratio, entropy , ...

Exoplanet modeling

$$\bar{\rho} = \frac{M}{\frac{4}{3}\pi R^3}$$

Constraints

Mass, Radius -> **mean density**

Stellar XUV -> **mass loss**

Stellar age -> **internal temperatures**

Tstar, a -> **Teq**

high Teq -> **Ohmic heating**

orbit ecc -> **tidal heating**

H_2O abundance -> **composition distribution**

➢ Wakeford, Sing, +2018, AJ: WASP-39b

Love number k_2 -> **density distribution**

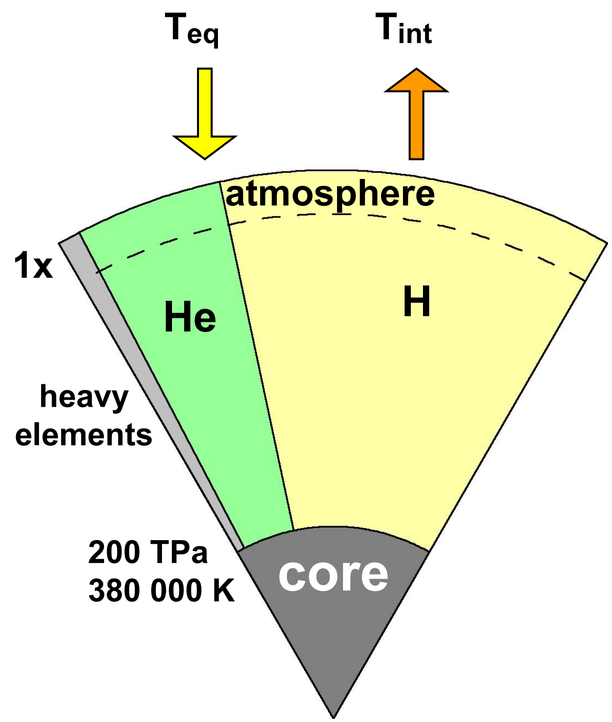
➢Csizmadia, Hellard +2019, A&A: WASP-18b

Assumptions

-- all metals in core, or homogeneous

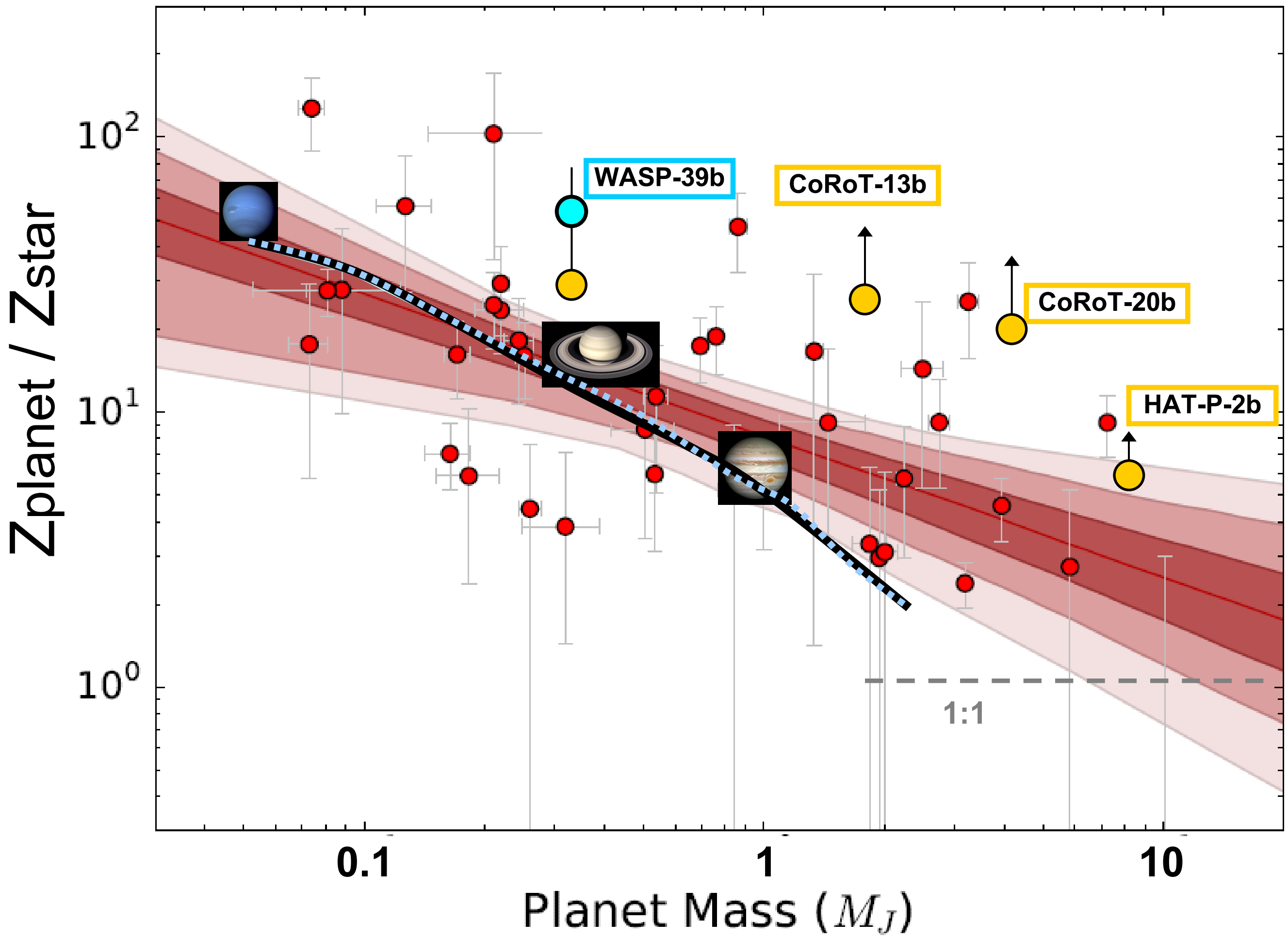
-- all metals are ices (H C N O) or rocks (Si Mg Fe)

-- adiabatic thermal structure (fits Jupiter's Teff)



➢ Linder, Mordasini, +2019, A&A

Exoplanet composition: statistics



CA formation:

- Z_p decreases with M_p
- for $M_p >> 1\ M_J$: Z_p -> Z_{star}

"Observation":
. different slope

- Cabrera, Bruntt, +2010, A&A
- Deleuil, Bonomo, +2011, A&A
- Leconte, Chabrier, +2009, A&A
- Wakeford, Sing, +2018, AJ
- Venturini, Alibert, +2016, A&A
- Thorngren & Fortney 2016, ApJ