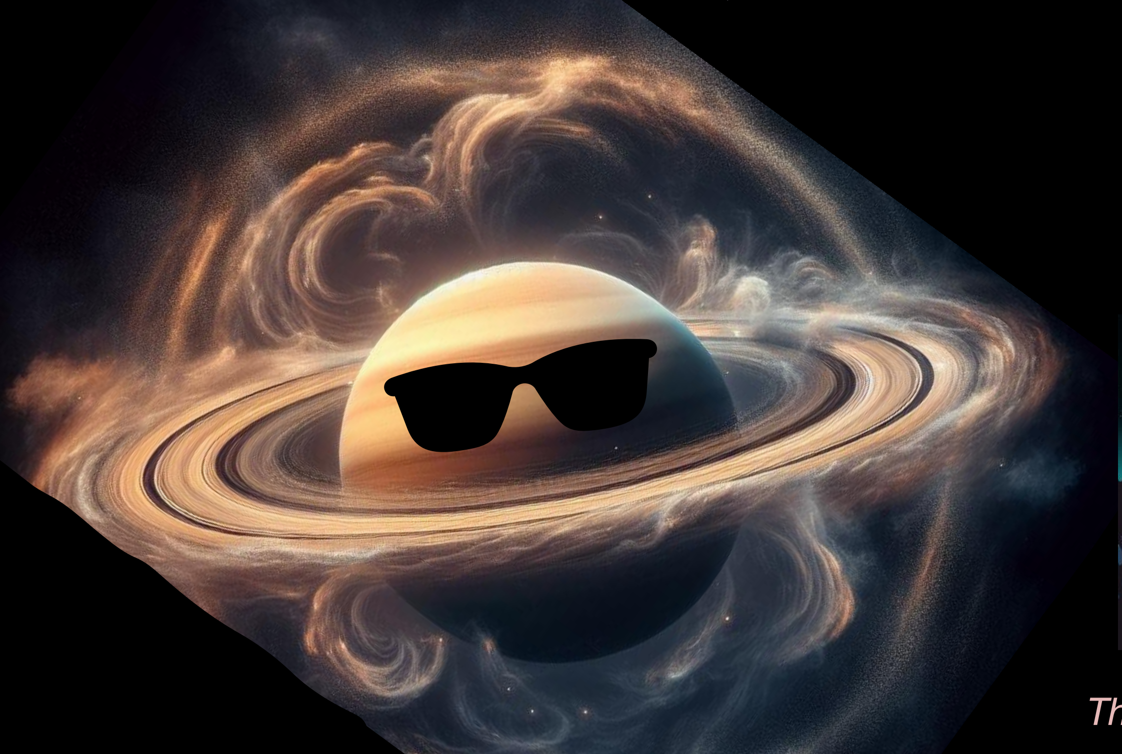
Formation, Evolution & Interiors



Ravit Helled

Dept. of Astrophysics

University of Zurich

Thanks to my students, postdocs & collaborators

Why cool giant planets?

Shape the architecture of planetary systems

- Large mass
- Fast formation: affect small bodies, volatile delivery

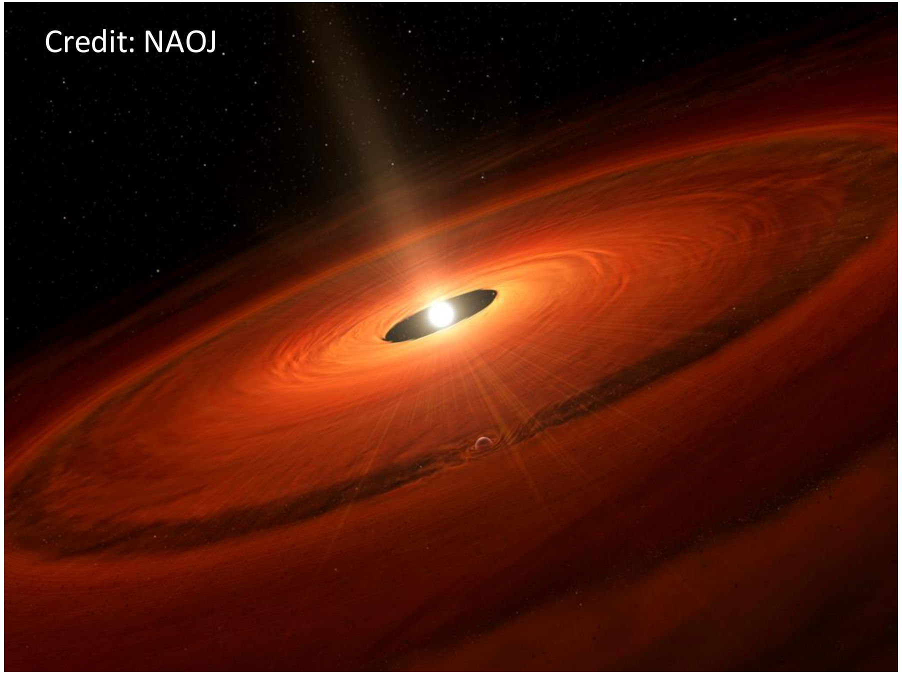
Composition

- Are not affected by an unknown inflation mechanism
- Provide information on the physical and chemical properties of proto-planetary disks

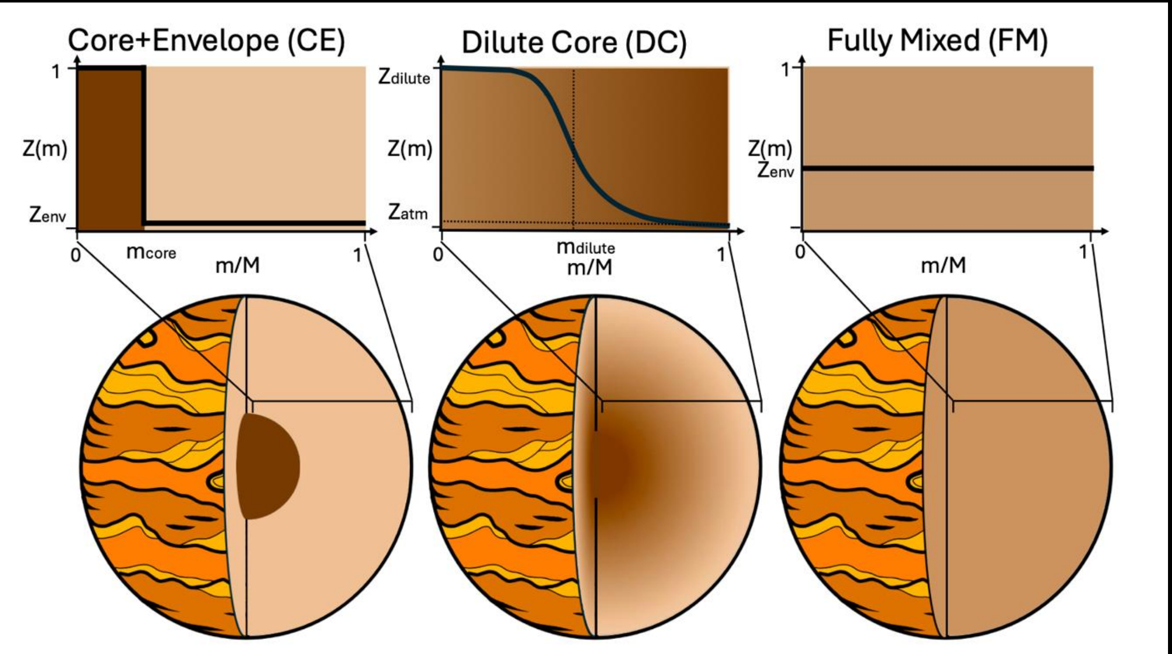
Natural laboratories

- Information on behavior of H, He and other elements at high P-T

Currently, still the ideal planets for detection and characterization



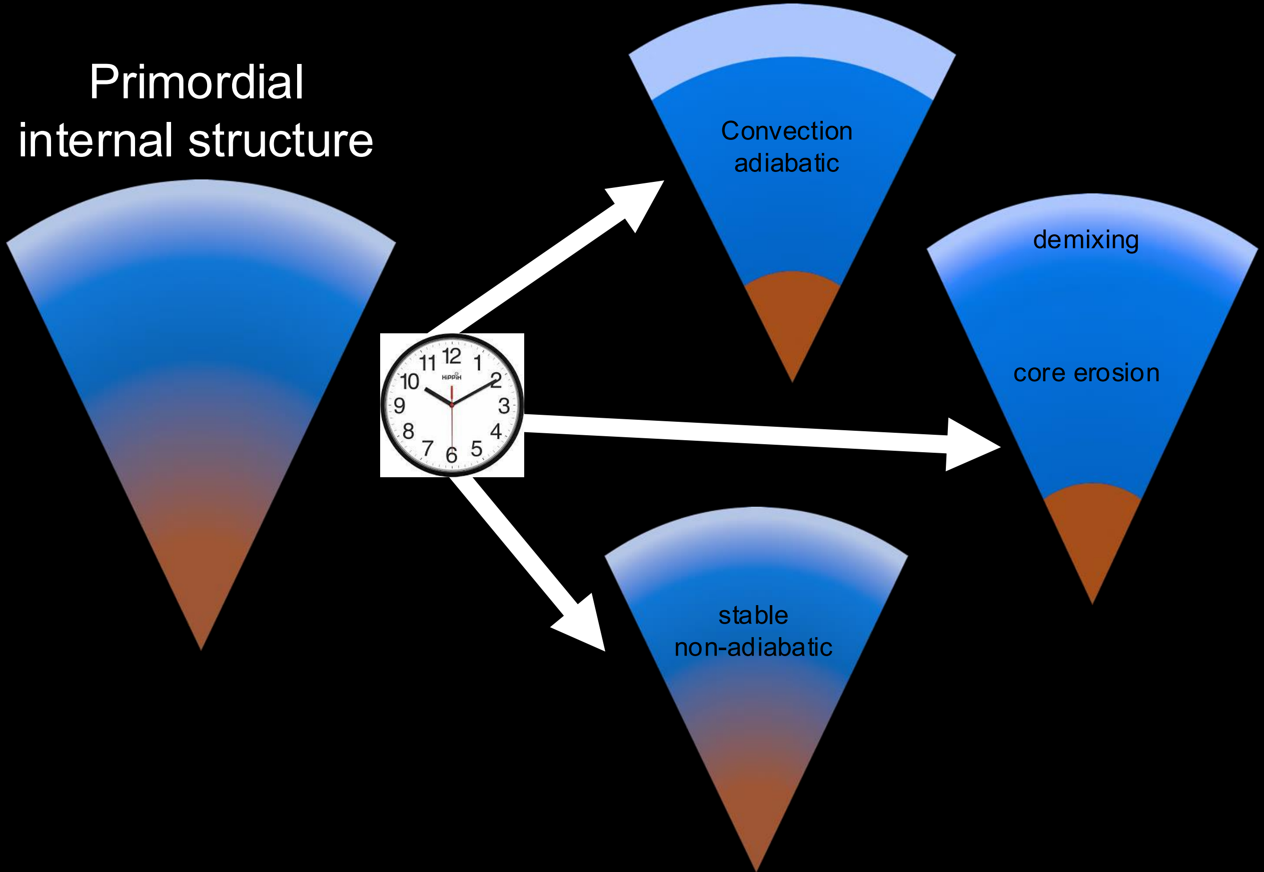
Why is the internal structure important?



Peerani et al. 2025

- Determines Mz
- Determines Mz_atm / Mz_interior
- More important for better data

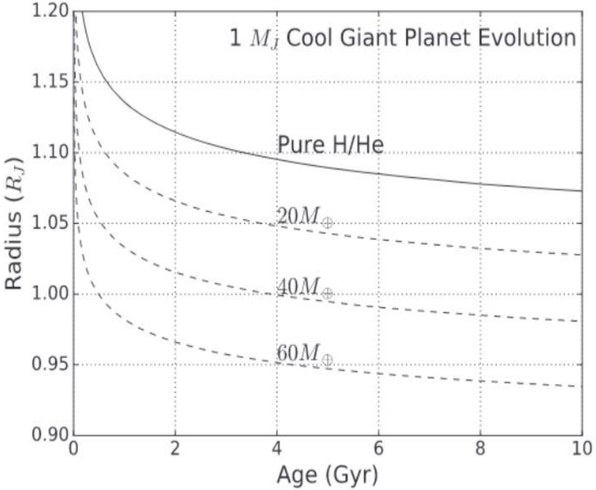
Why is the evolution important?



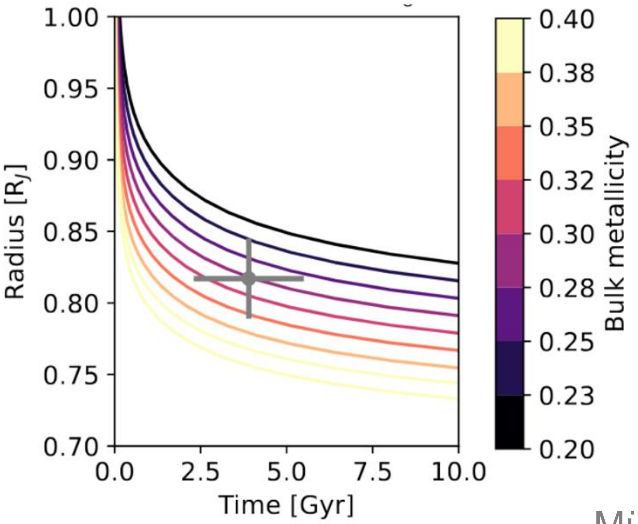
Internal structure changes with time

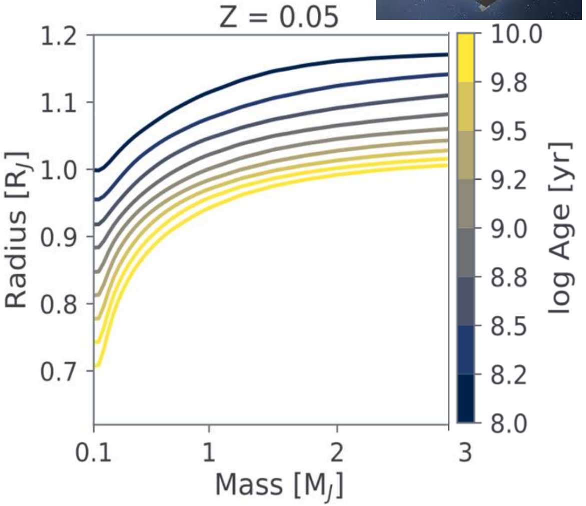
But also: internal structure determines the heat transport mechanism and therefore the cooling (R(t))

The planetary bulk metallicity is constrained given cooling tracks and radius, age and mass measurements:

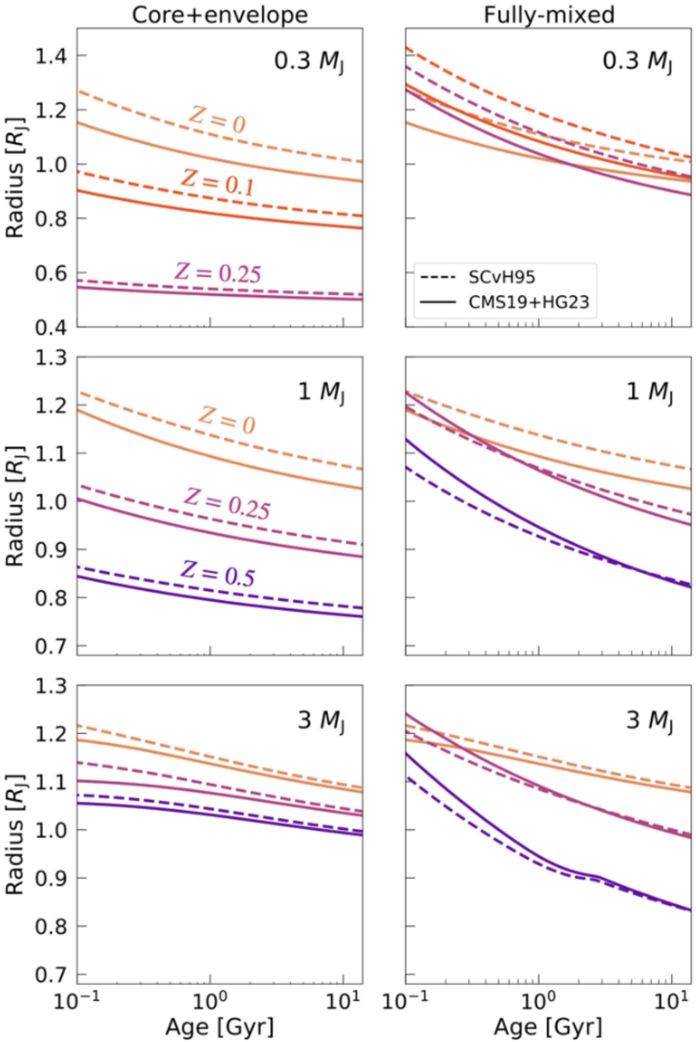


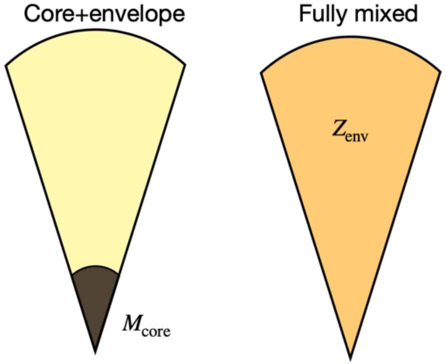
Thorngren et al. 2016





Müller et al. 2023





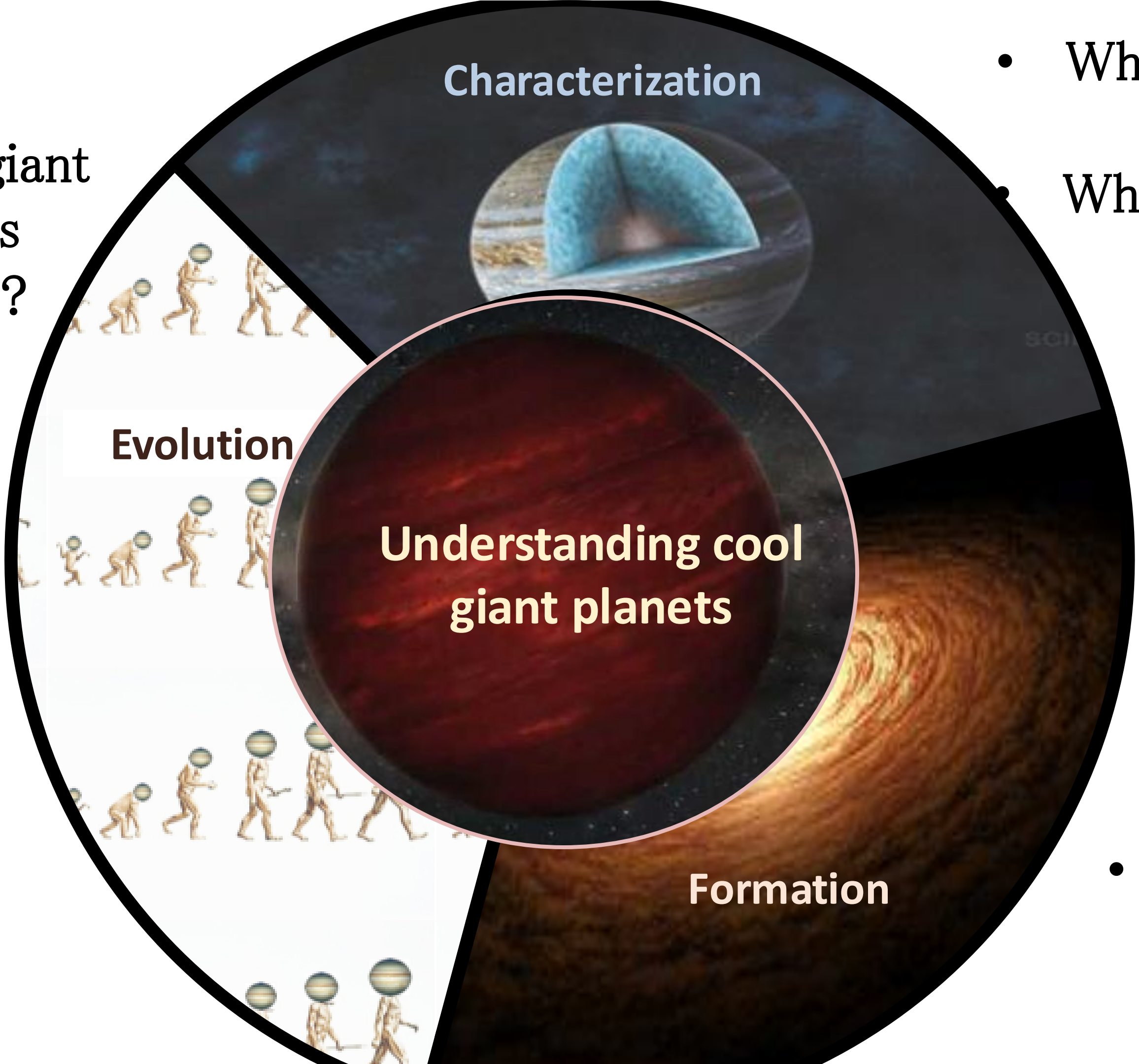
Bulk metallicity: $Z_p = M_Z / M_p$

$Z_p = M_{core} / M_p$ for core+envelope
$Z_p = Z_{env}$ for mixed

(critical for characterization & interpretation of atmospheric measurements)

Howard et al. 2024

How do giant planets evolve?



- What are giant planets made of?
- What are their internal structures?

- How do giant planets form?

Making an interior models

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho$$

$$\frac{\partial P}{\partial r} = -\rho g$$

$$\frac{\partial T}{\partial r} = \frac{\partial P}{\partial r}\frac{T}{P}\nabla_T$$

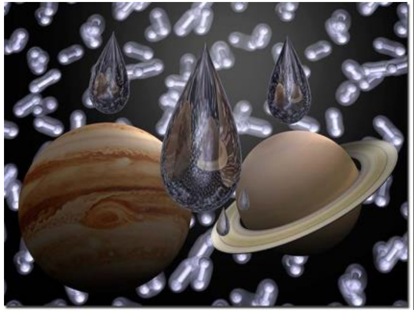
$$\frac{\partial L}{\partial r} = 4\pi r^2 \rho \left(\dot{\epsilon} - T\frac{\partial S}{\partial t}\right)$$

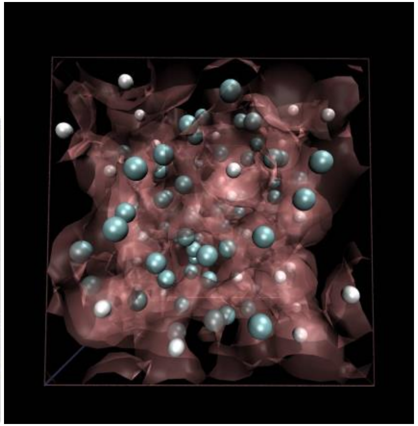
EOS is needed to solve this set of equations (knowledge of the behavior of multi-component systems at high pressure)

EOS: (P,T)→ ρ, S, etc.

Need to know how heat is transported to estimate ∇_T

∇_T: convection, radiation, conduction





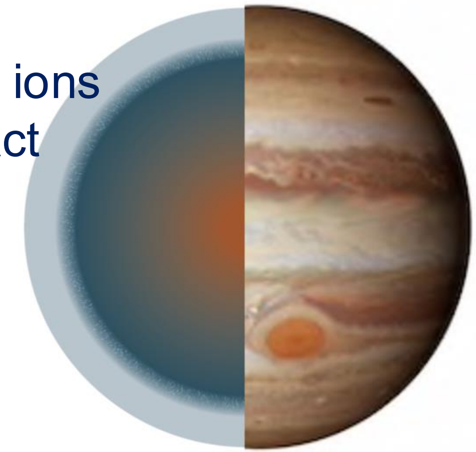
What composition to choose?

hydrogen, helium and heavy elements

easy ☺ proto-solar ratio
hard☹ EOS is complicated

easy ☺ we can choose anything
hard☹ EOS is not well known, mixtures?

molecules, atoms, ions
coexist & interact

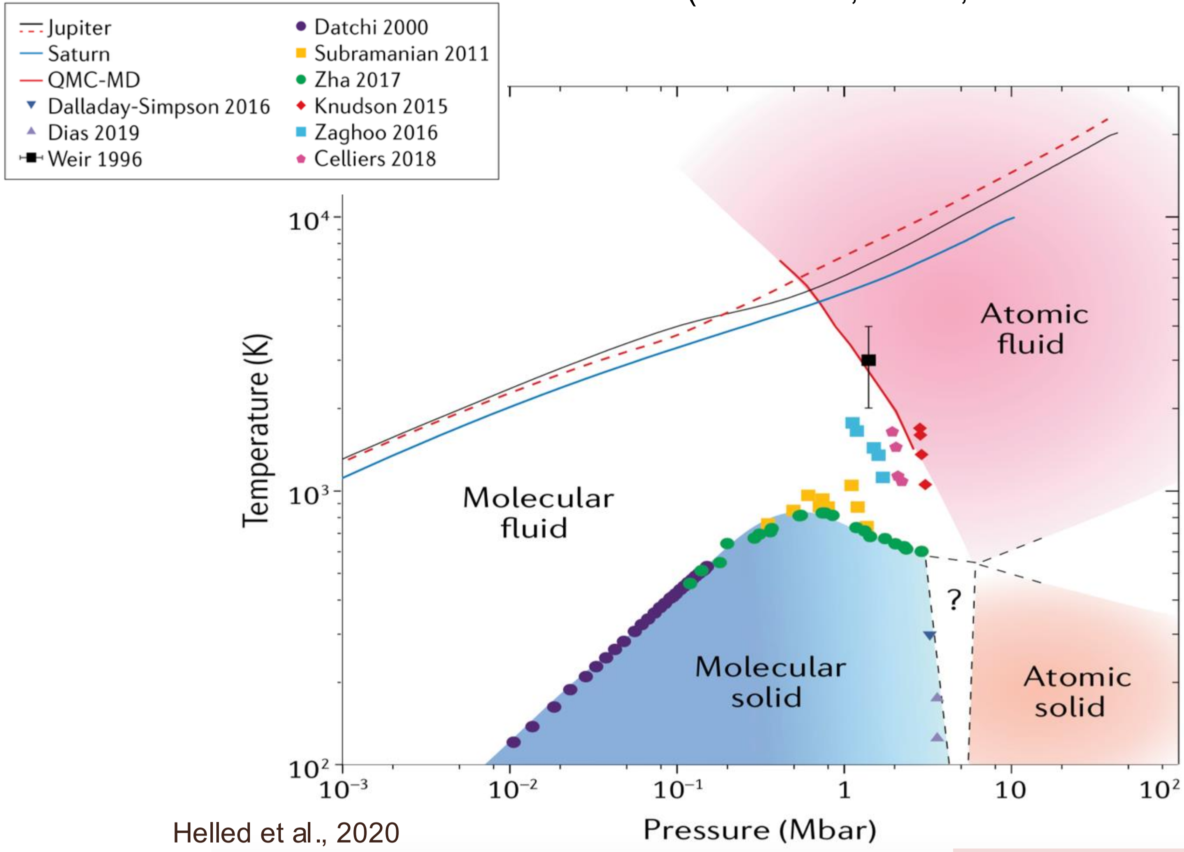


$$\frac{1}{\rho(P,T)} = \frac{X}{\rho_{\mathrm{H}}(P,T)} + \frac{Y}{\rho_{\mathrm{He}}(P,T)} + \frac{Z}{\rho_{\mathrm{Z}}(P,T)},$$

$$S(P,T) = XS_{\mathrm{H}}(P,T) + YS_{\mathrm{He}}(P,T) + ZS_{\mathrm{Z}}(P,T),$$

hydrogen

Giant planet interiors: high pressures & temperatures.
Equation of state (EOS) is difficult to calculate
(molecules, atoms, ions coexist and interact).



Helled et al., 2020

A strong connection to high-pressure physics

Giant planets are fluid

hydrogen

Giant planet interiors: high pressures & temperatures.
Equation of state (EOS) is difficult to calculate
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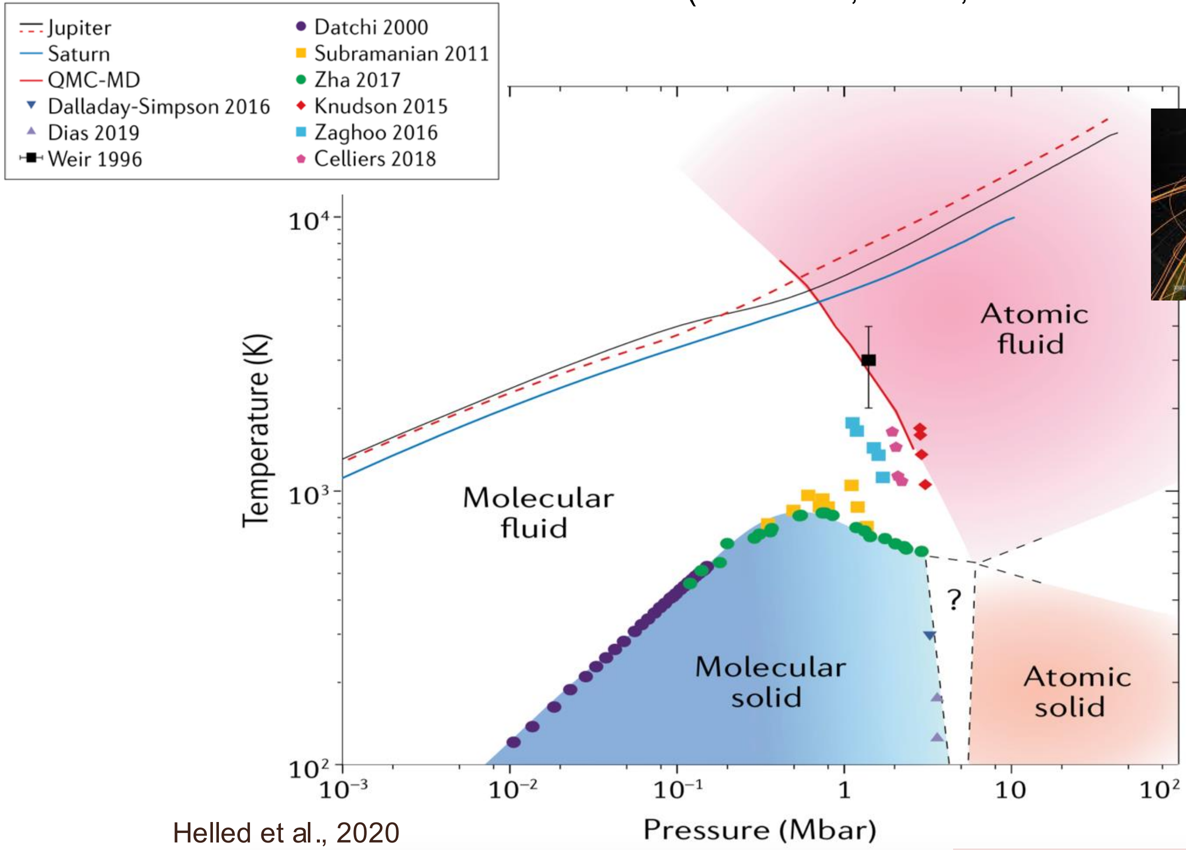
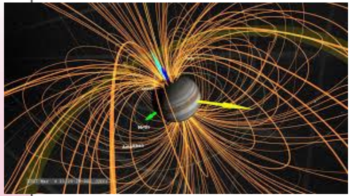


Helled et al., 2020

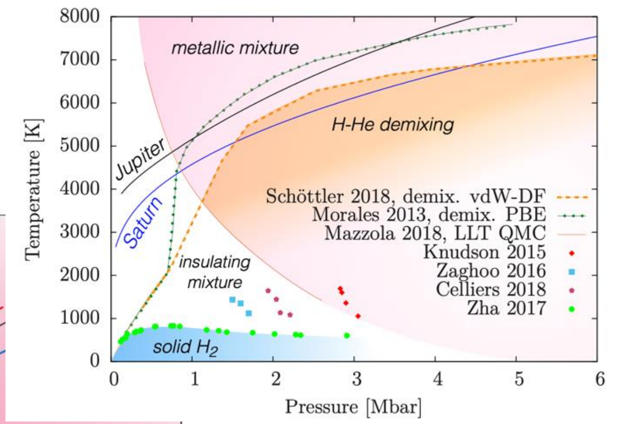
magnetic field

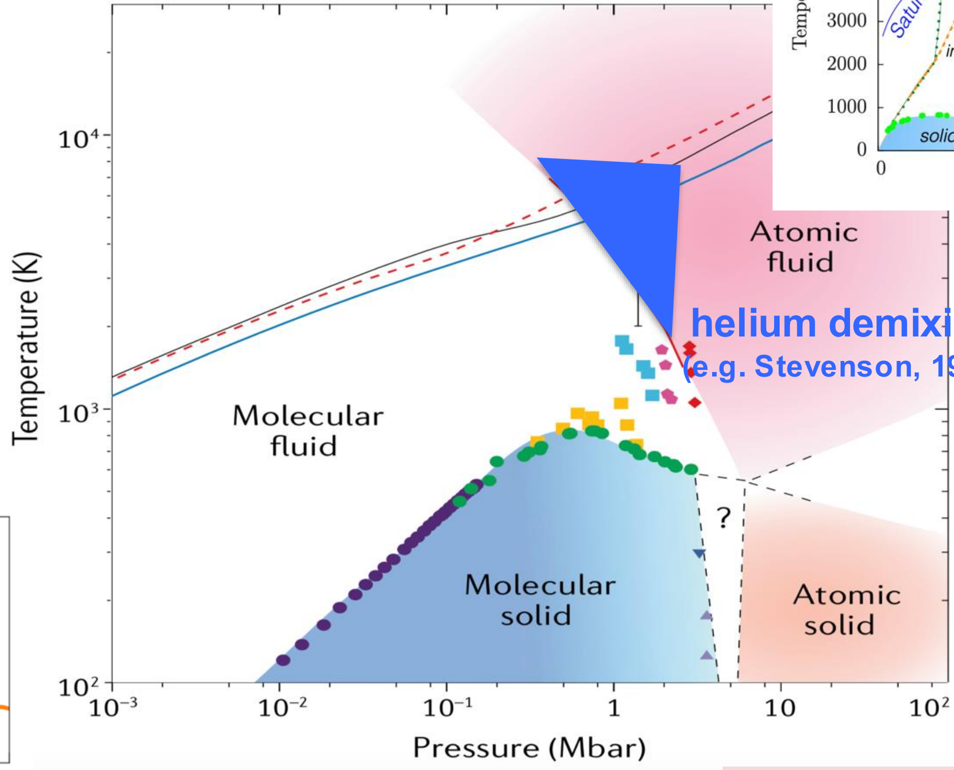


A strong connection to high-pressure physics

Giant planets are fluid

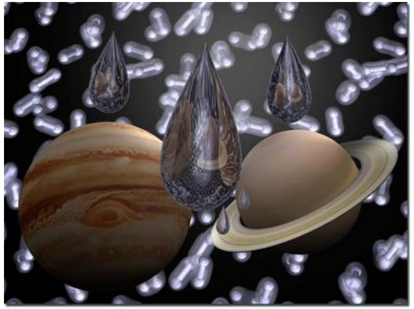
Hydrogen-helium

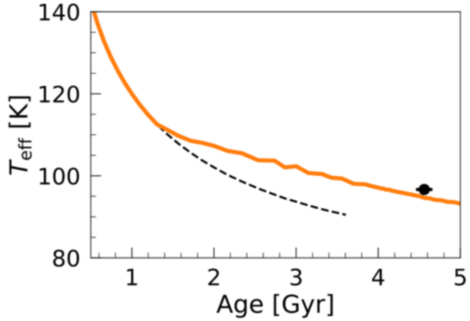




helium demixing
(e.g. Stevenson, 1982)

helium rain

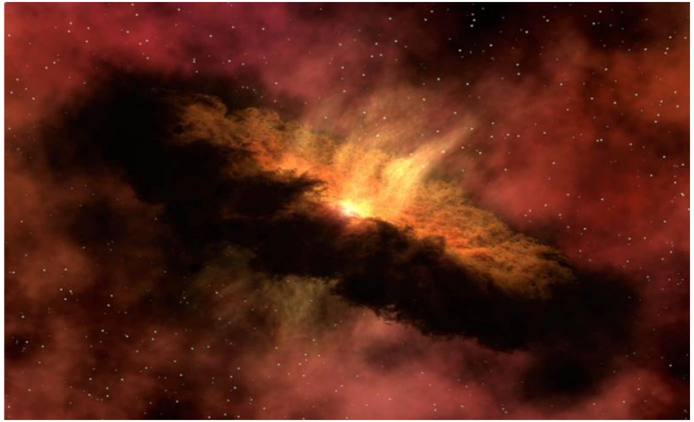




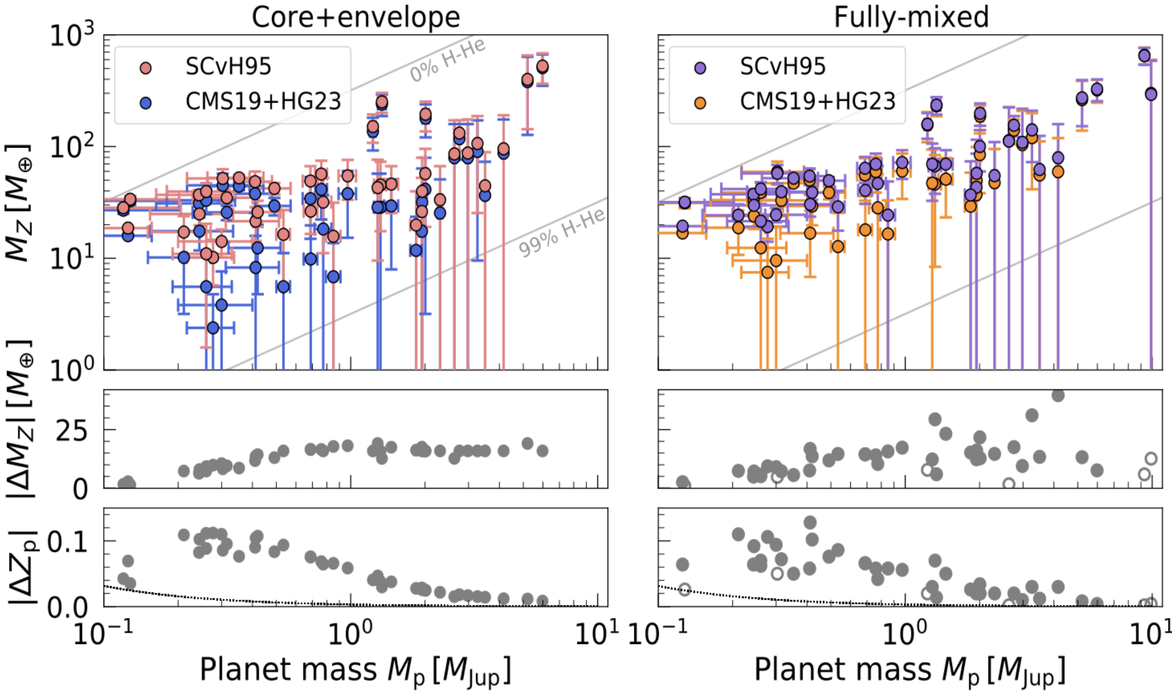
Giant planets are fluid

M_Z vs. M_p
(Z_p/Z_*)

Can help to understand planet formation



The structure & H-He EOS matter

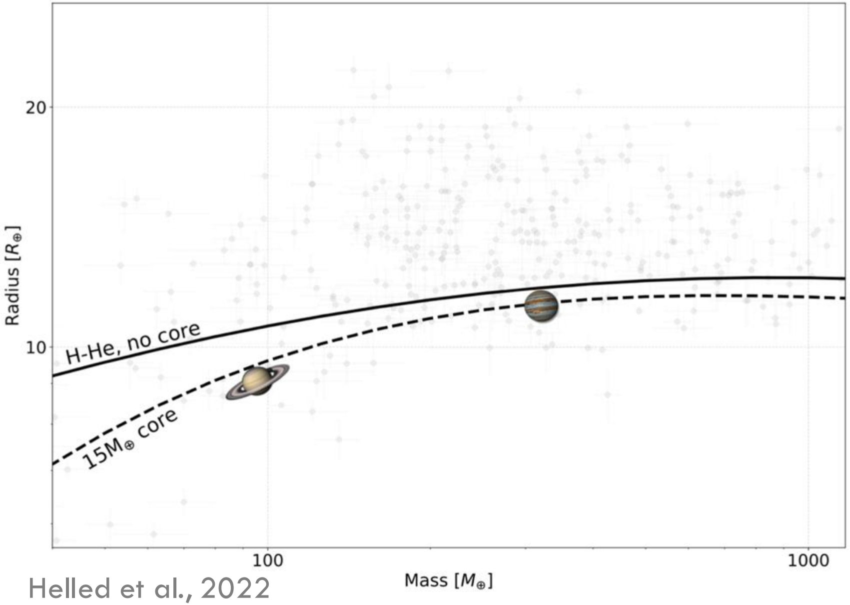


Howard et al. 2025 (see also Thorngren et al., 2016, Müller & Helled, 2024, Chachan et al., 2025, Peerani et al. 2025 *and references therein..)*

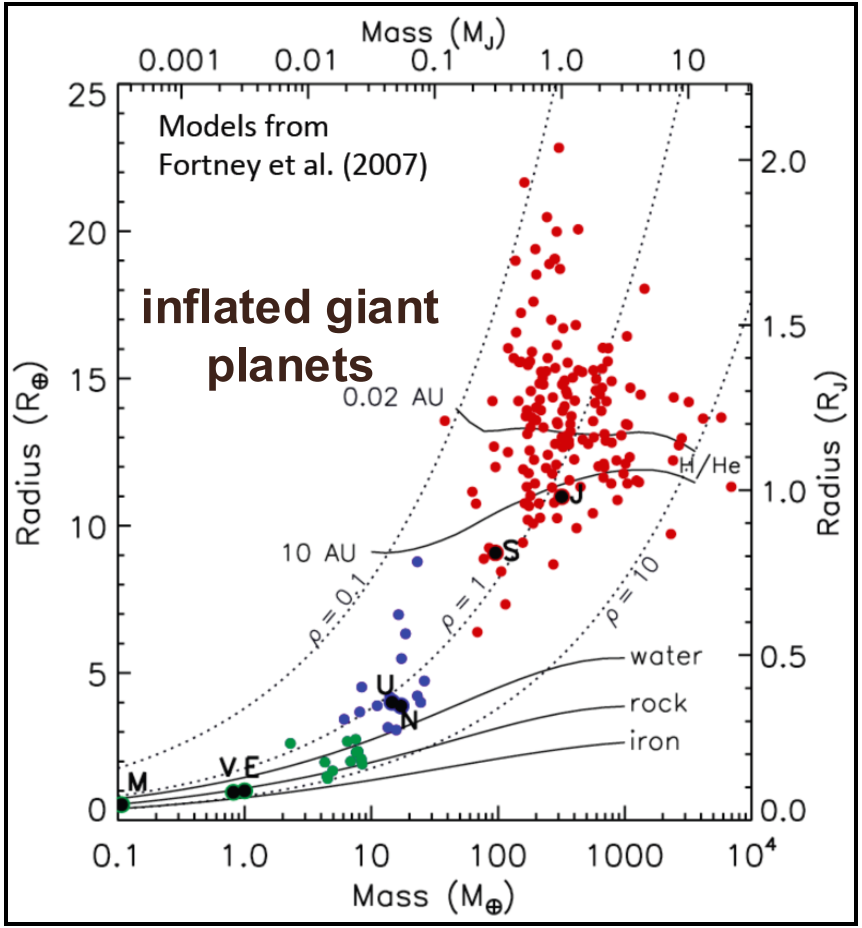
(helium rain, phase separation, demixing are not included…)

Composition of giant exoplanets: mostly M, R, age

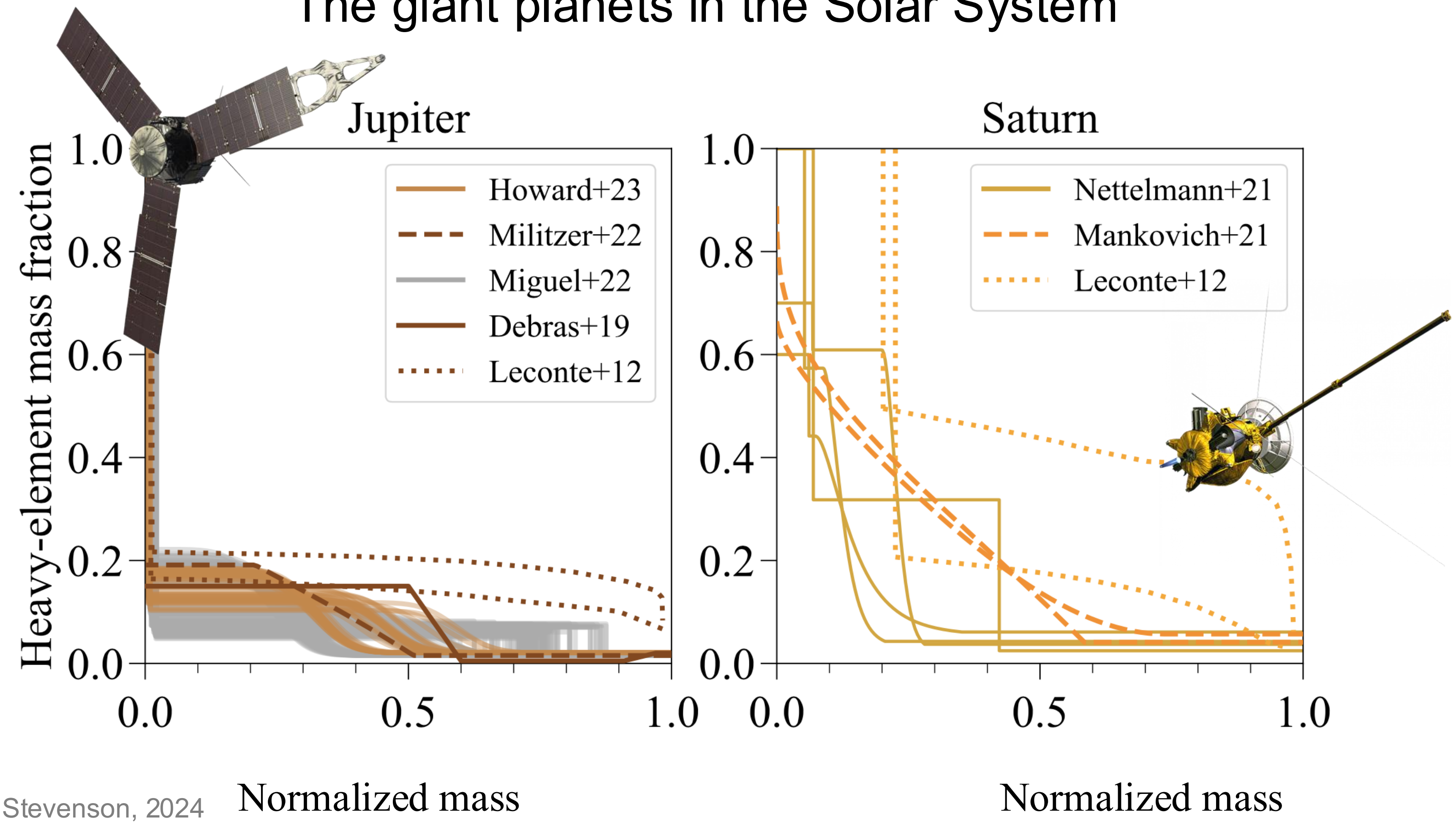
(but sometimes also atmospheric composition)



Helled et al., 2022

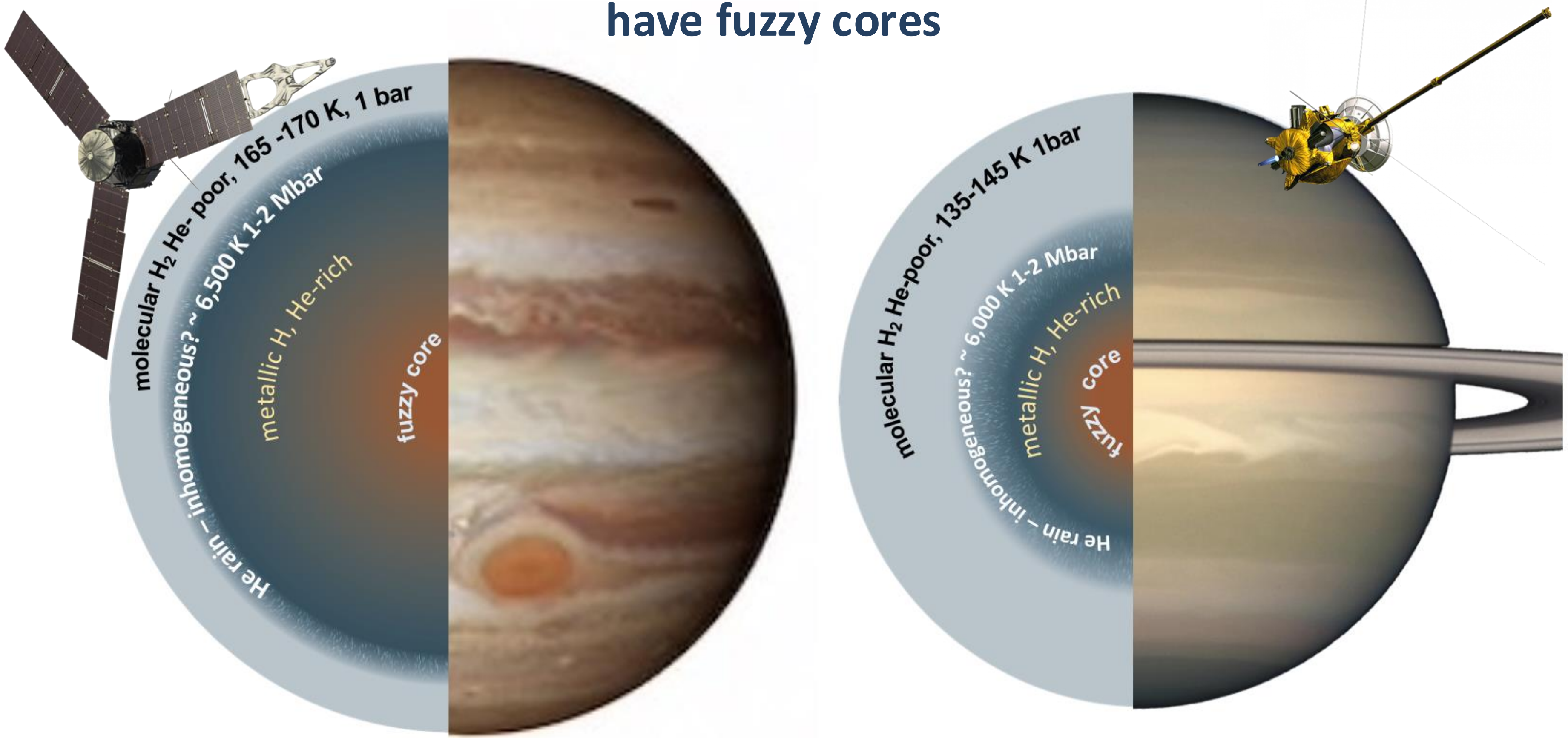


The giant planets in the Solar System



Helled & Stevenson, 2024
Helled & Howard, 2024

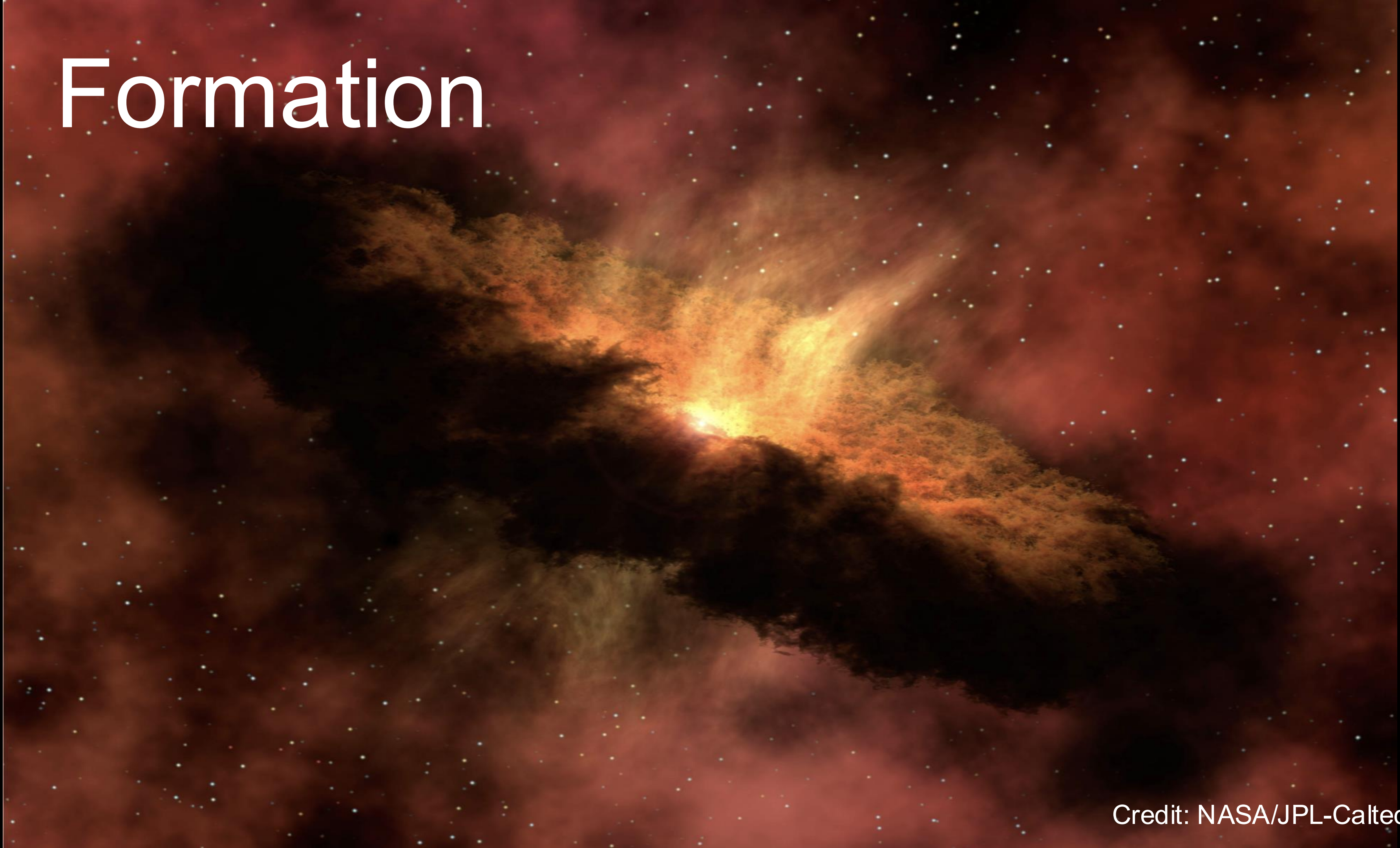
Giant planets are non-homogenous, not fully convective and have fuzzy cores



Need to modify exoplanets models

e.g., Helled et al. 2022

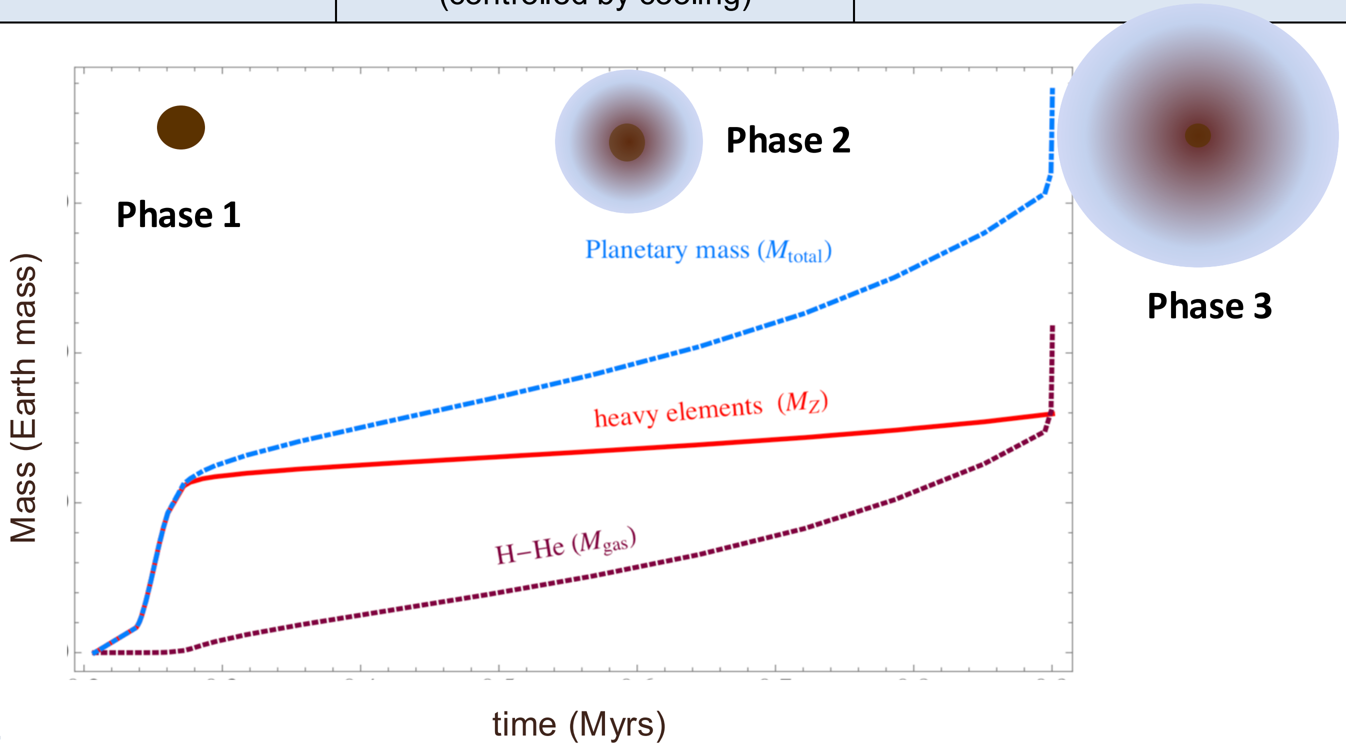
Formation



Credit: NASA/JPL-Caltech

(Giant) Planet Formation

Terrestrial planets	Neptunes, mini-Neptunes	Gas giants
Formation of a heavy-element core via planetesimal/pebble accretion	The core is massive enough to accrete and retain gas (H-He) (controlled by cooling)	The gas accretion rate exceeds the solid accretion rate → runaway growth



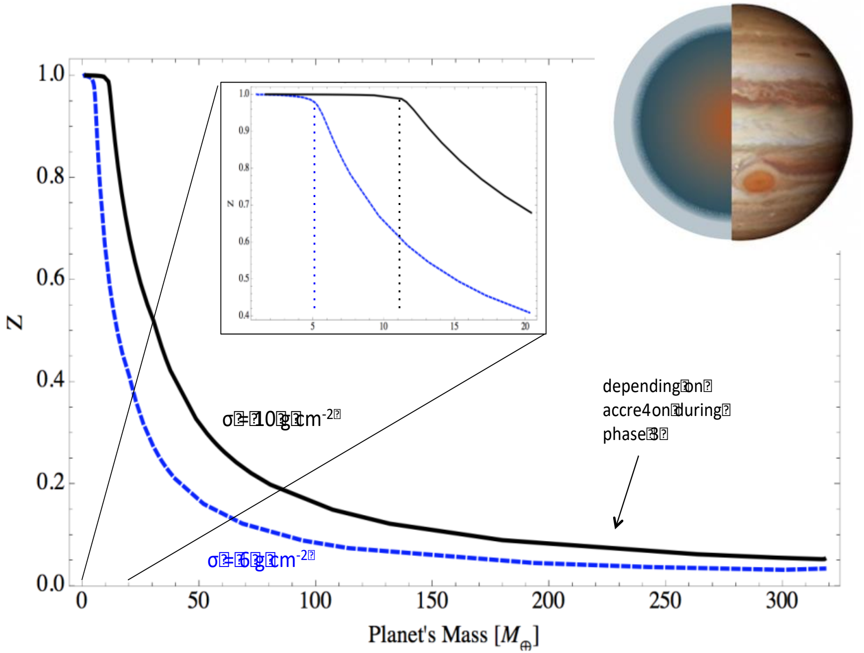
[*]see e.g., Helled et al. 2014, 2022, Helled & Morbidelli, 2021

Updated formation models predict fuzzy cores & composition gradients

Historically: $M_Z = M_{core}$.
Reality: once M_{core}~a few $M_{\oplus}$, most of the heavy elements remain in the envelope.

Cores of giant planets are “fuzzy”:

- The core is not distinct from the envelope
- The “core” can include H-He
- This affects the long-term evolution, implications to giant planet characterization..



Helled & Stevenson, 2017, Lozovsky et al., 2017, Valletta & Helled, 2020, 2022…

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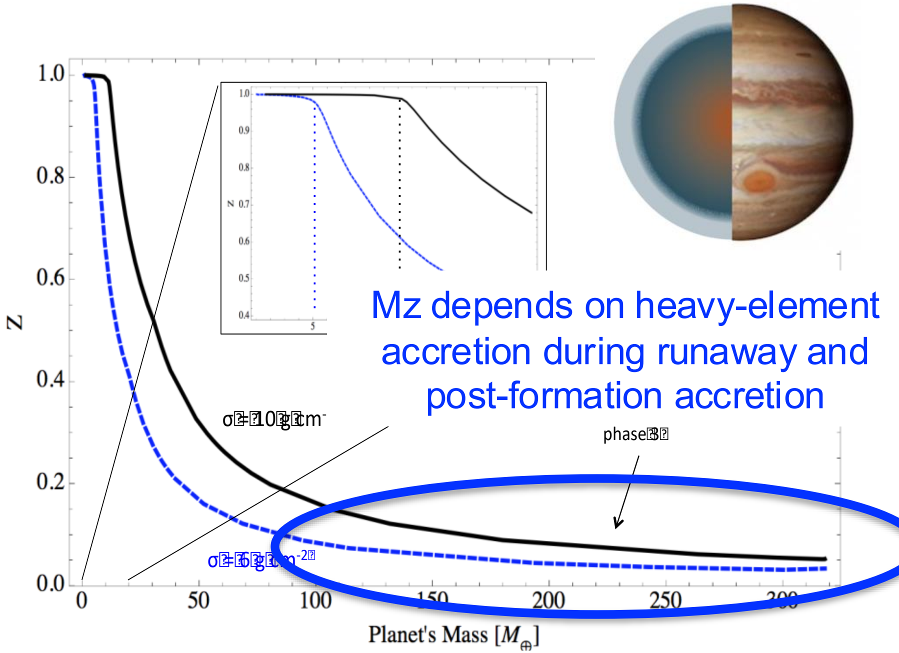
The composition and primordial internal structure of giant planets depends on their growth history:
The ratio of heavy elements accretion to gas accretion.

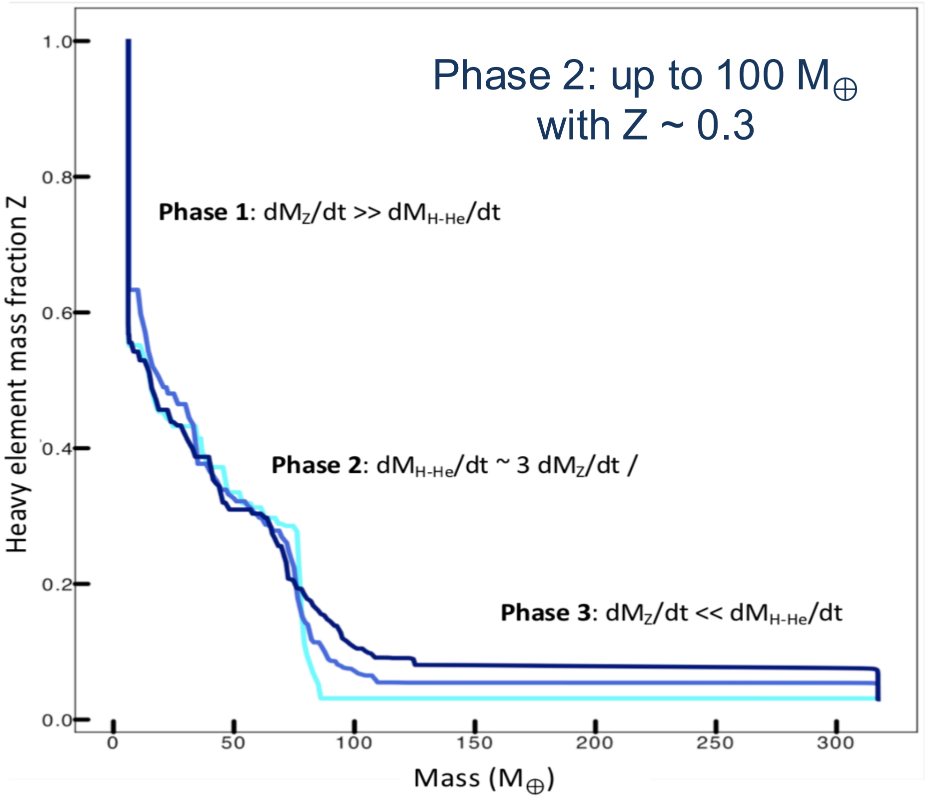


Mz depends on heavy-element accretion during runaway and post-formation accretion

Helled & Stevenson, 2017, Lozovsky et al., 2017, Valletta & Helled, 2020, 2022…

Predicting composition gradients and extended fuzzy cores:

gas accretion occurs only after a few Myr at M_p~100 $M_\oplus$



Alibert et al., 2018, Venturini & Helled, 2019, Helled et al. 2022, Helled, 2023..

Predicting composition gradients and extended fuzzy cores:

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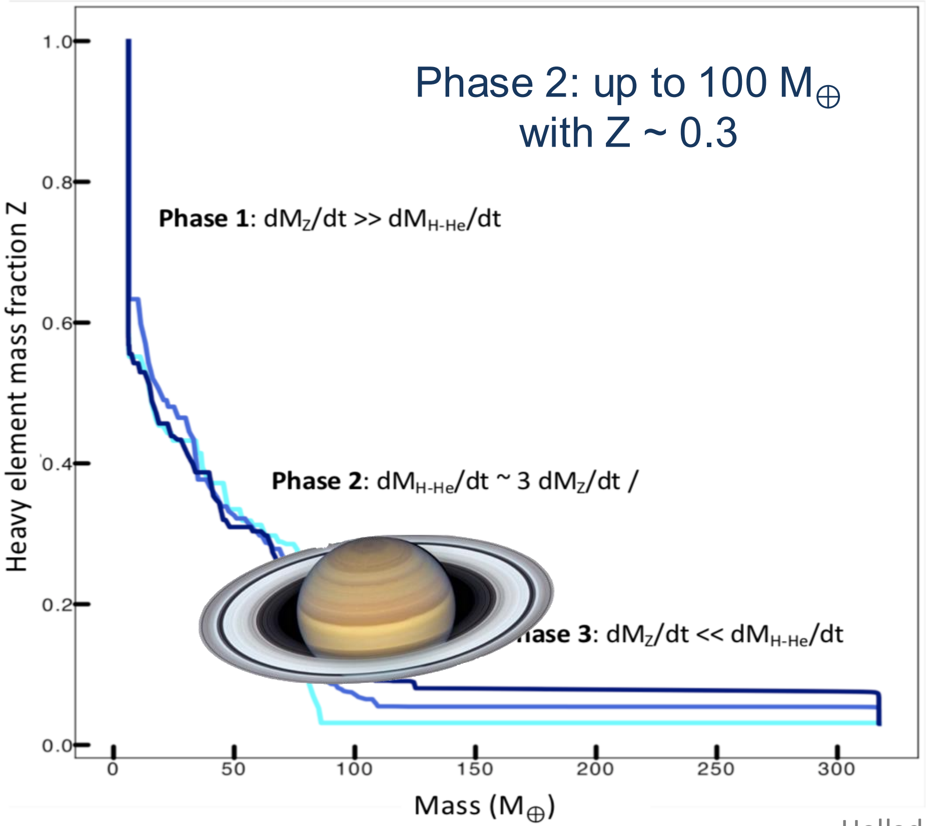


Saturn may have 'failed' as a gas giant

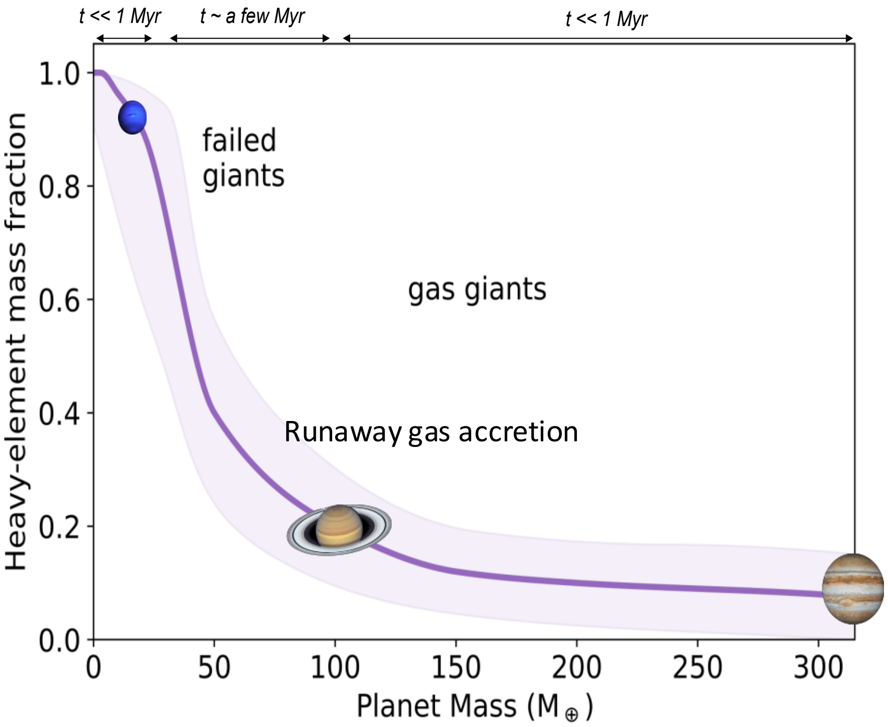
News By Paul Sutter published July 27, 2023

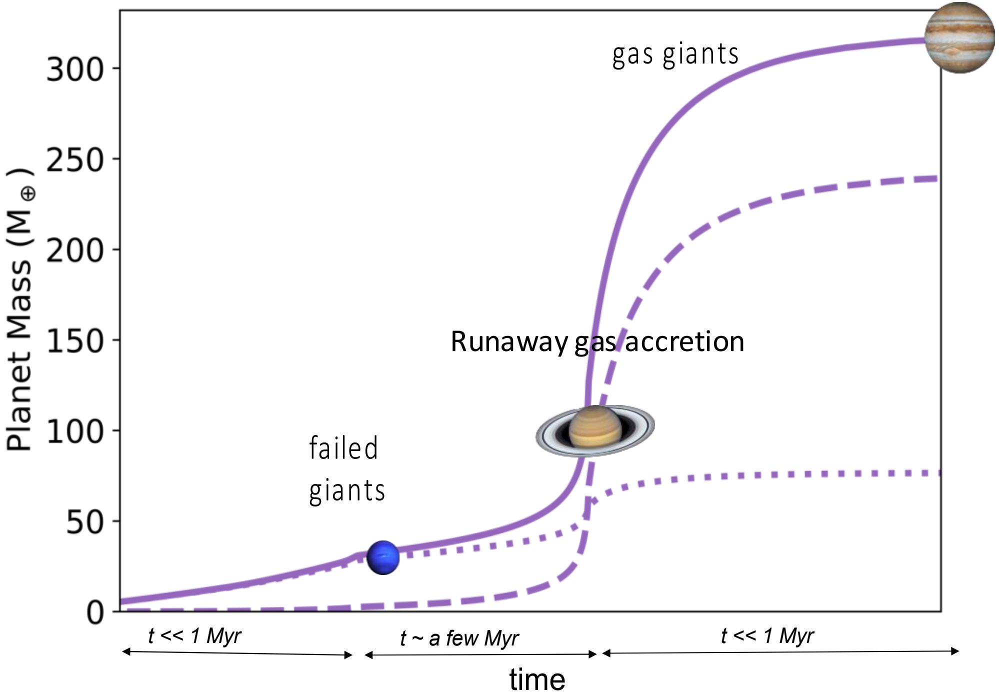
The ringed planet is definitely gaseous, but is it really 'giant?'

Comments (8)

Helled et al. 2022

Can this scenario explain all the four giant planets?





Helled, 2023

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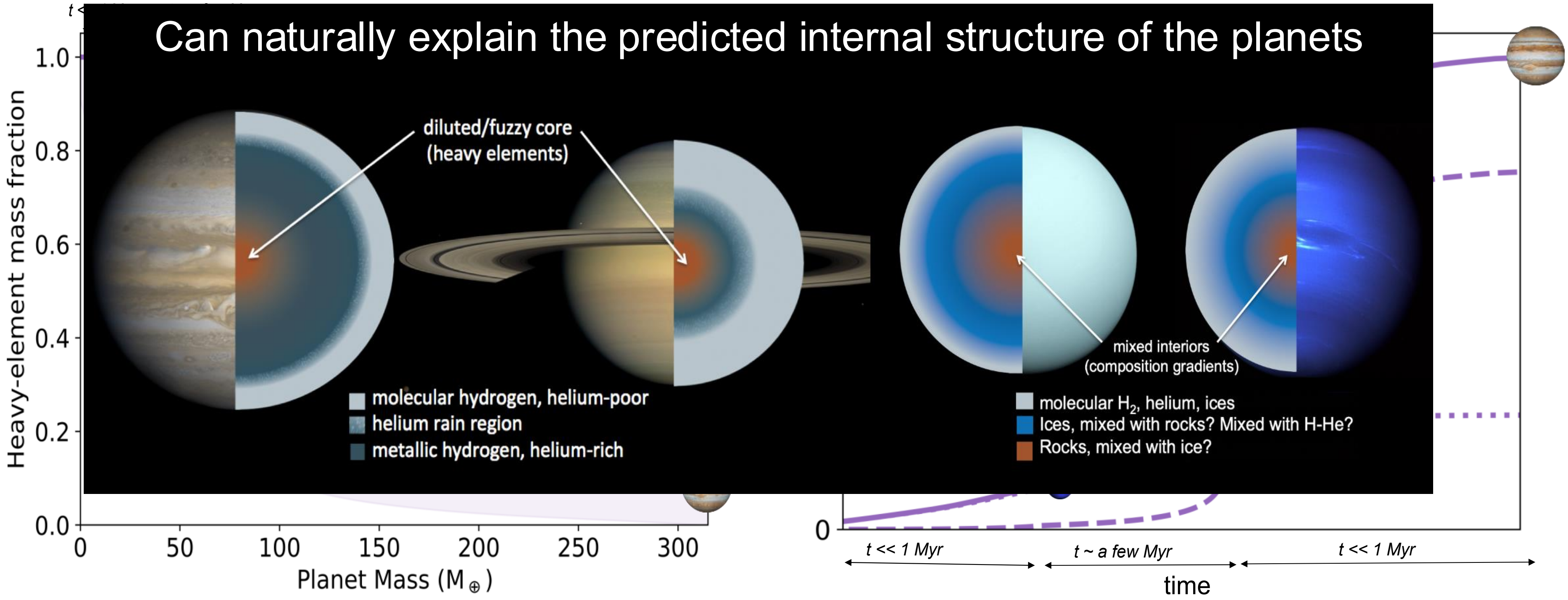
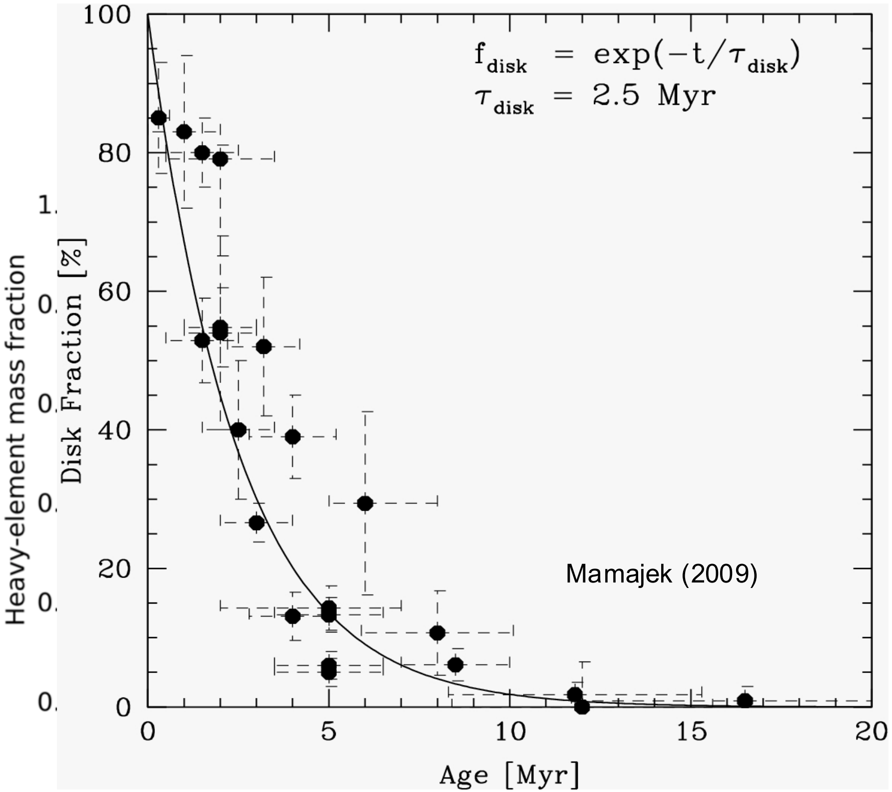
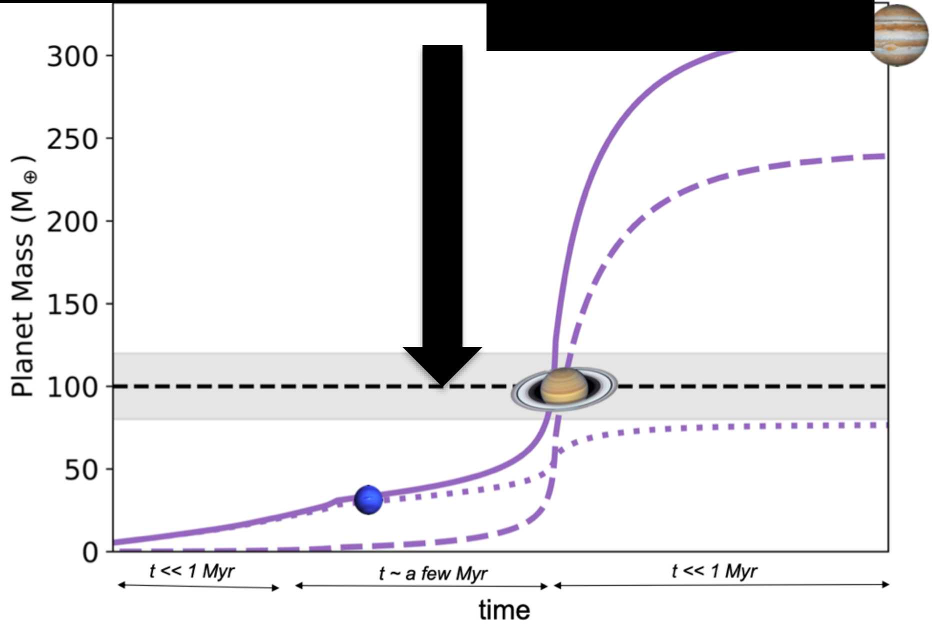


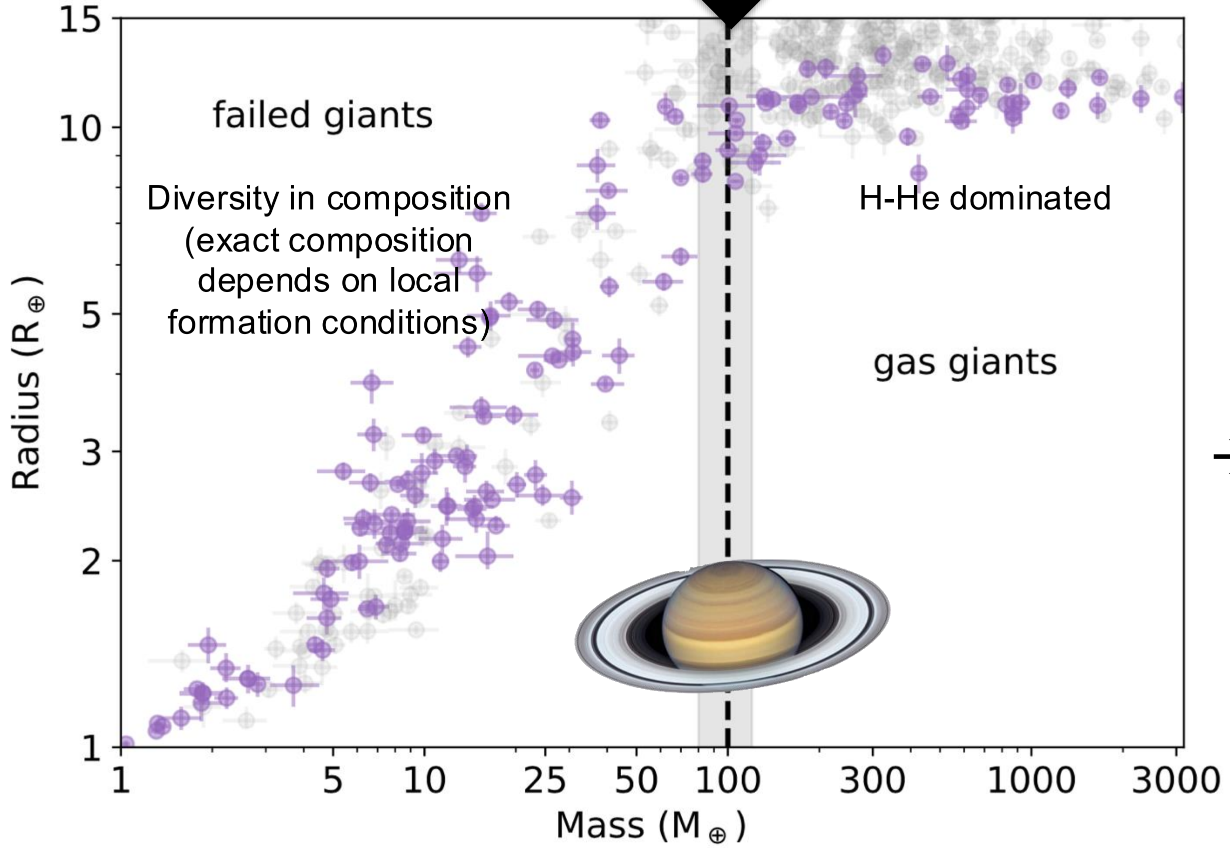
*****A link between planetary structure & origin*****

If runaway gas accretion occurs only after a few Myr, it can explain why giant planets are less common in the galaxy…



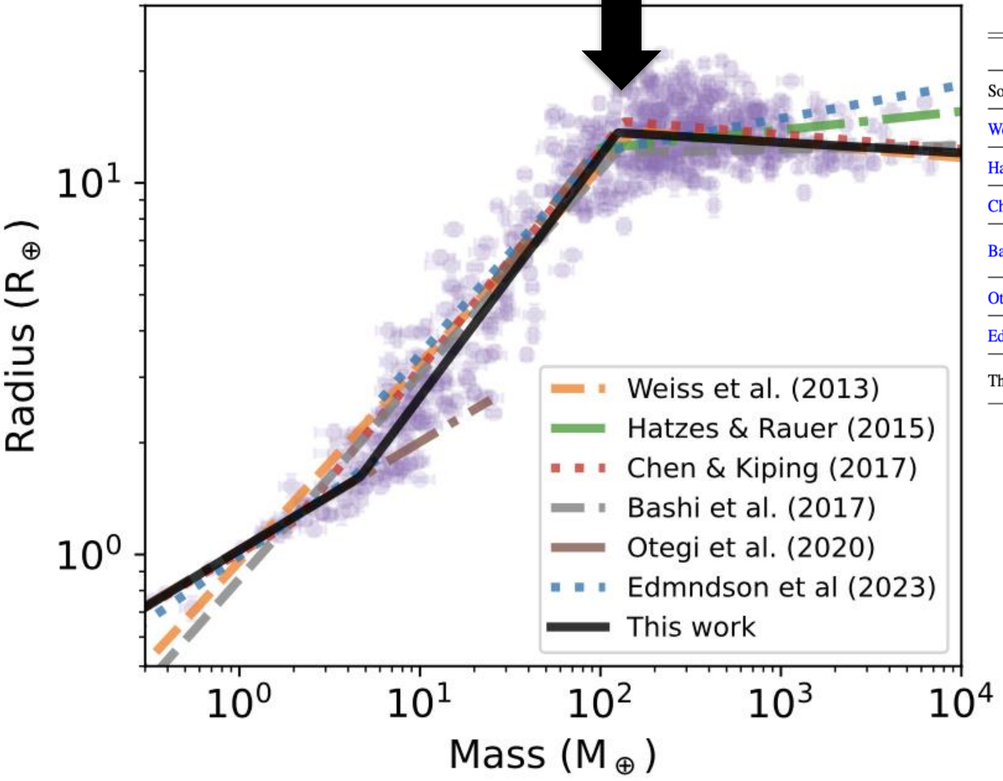


The transition to gas giant planets



M-R relation transitions at ~Saturn's mass
→ the transition to gas giant planets (H-He dominated)

The transition to gas giant planets

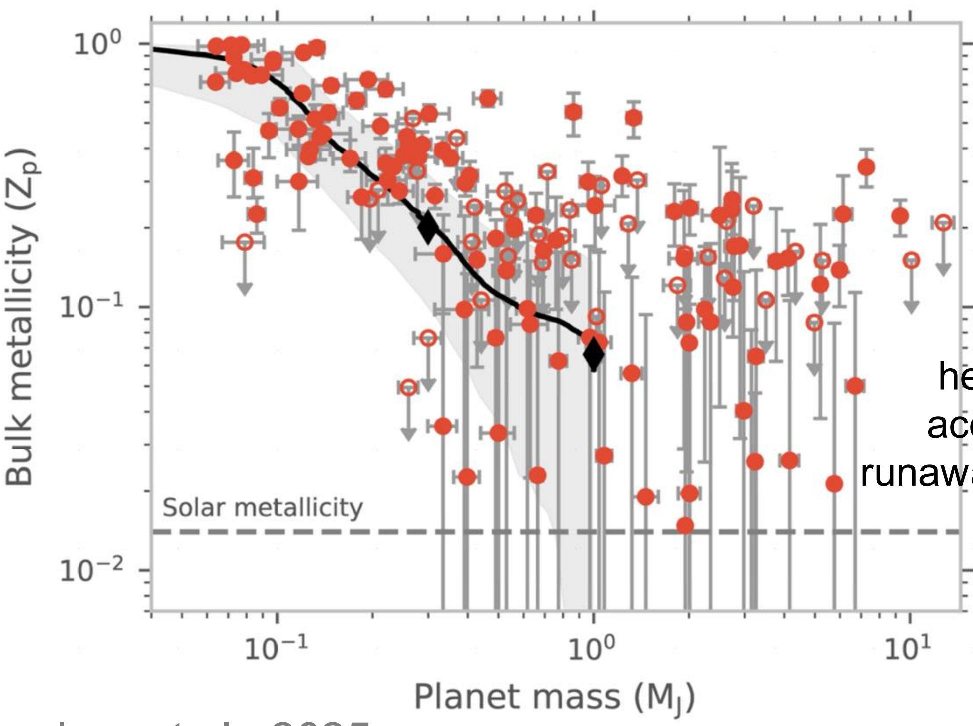


	Small planets	Intermediate planets		Giant planets	
Source	Mass–radius: $R(M)$	Transition	Mass–radius: $R(M)$	Transition	Mass–radius: $R(M)$
Weiss et al. (2013)	–	–	$0.96^{+0.08}_{-0.07} M^{0.53\pm0.05}$	$M = 150^{(\dagger)}$	$16.9^{+4.5}_{-3.6} M^{-0.04\pm0.01}$
Hatzes & Rauer (2015)	–	–	–	$M = 95.3^{(\dagger)}$	$.83^{+0.34}_{-0.35} M^{0.05\pm0.01}$
Chen & Kipping (2017)	$1.01 \pm 0.05 M^{0.28\pm0.01}$	$M = 2.04^{+0.66}_{-0.59}$	$0.81 \pm 0.05 M^{0.59}$	$M = 132^{+18}_{-21}$	$7.8^{+9.7}_{-5.9} M^{-0.04\pm0.02}$
Bashi et al. (2017)	–	–	$0.86^{+0.08}_{-0.07} M^{0.55\pm0.02}$	$M = 124 \pm 7$ $R = 12.1 \pm 0.5$	$.5 \pm 0.6 M^{0.01\pm0.02}$
Otegi et al. (2020)	$1.03 \pm 0.02 M^{0.29\pm0.01}$	Water line	$0.70 \pm 0.11 M^{0.63}$	–	–
Edmondson et al. (2023)	$0.99 \pm 0.02 M^{0.34\pm0.01}$	Pure-ice EOS	$0.97 \pm 0.07 M^{0.55}$	$M = 115 \pm 19$	$01 \pm 0.48 M^{0.09\pm0.001}$
This work	$1.02 \pm 0.03 M^{0.27\pm0.04}$	$M = 4.37 \pm 0.72$ $R = 1.64 \pm 0.05$	$0.56 \pm 0.03 M^{0.67\pm0.05}$	$M = 127 \pm 7$	$18.6 \pm 6.7 M^{-0.06\pm0.07}$

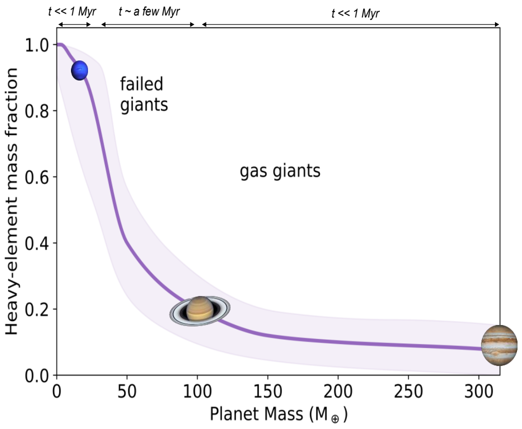
All M-R studies find a transition at ~Saturn mass!

Müller at al., A&A, 2024

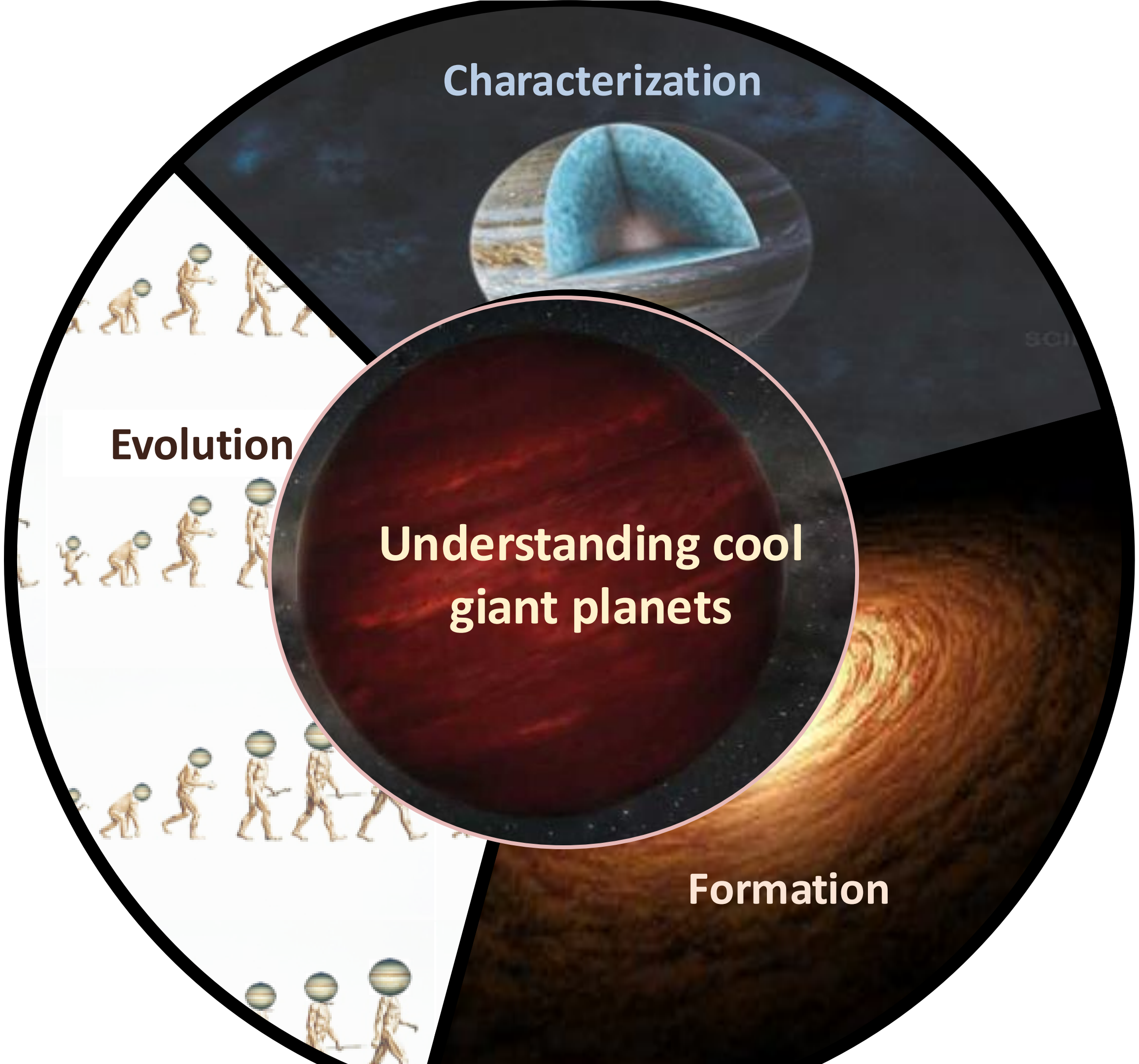
Connecting composition to formation



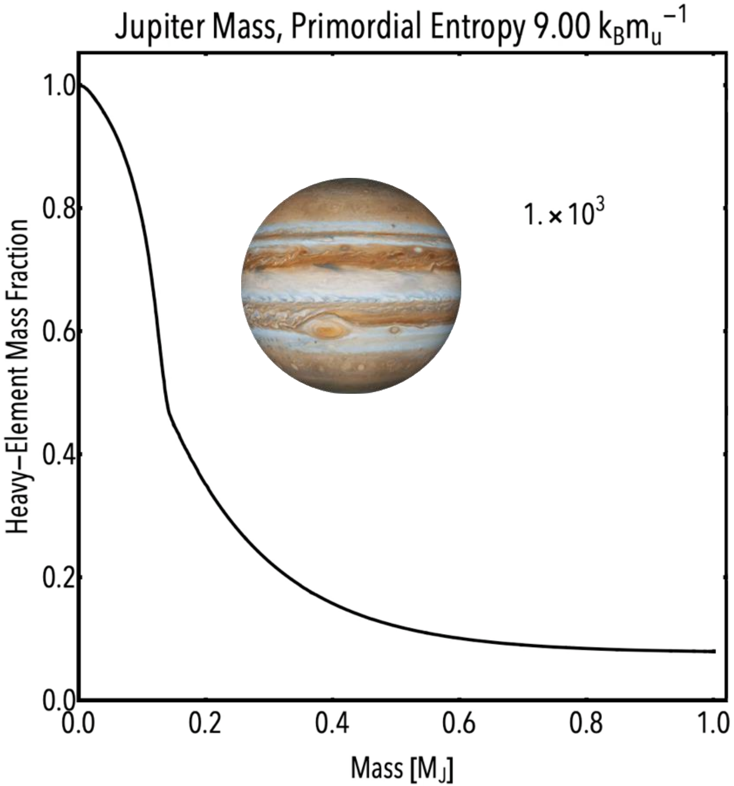
Chachan et al., 2025

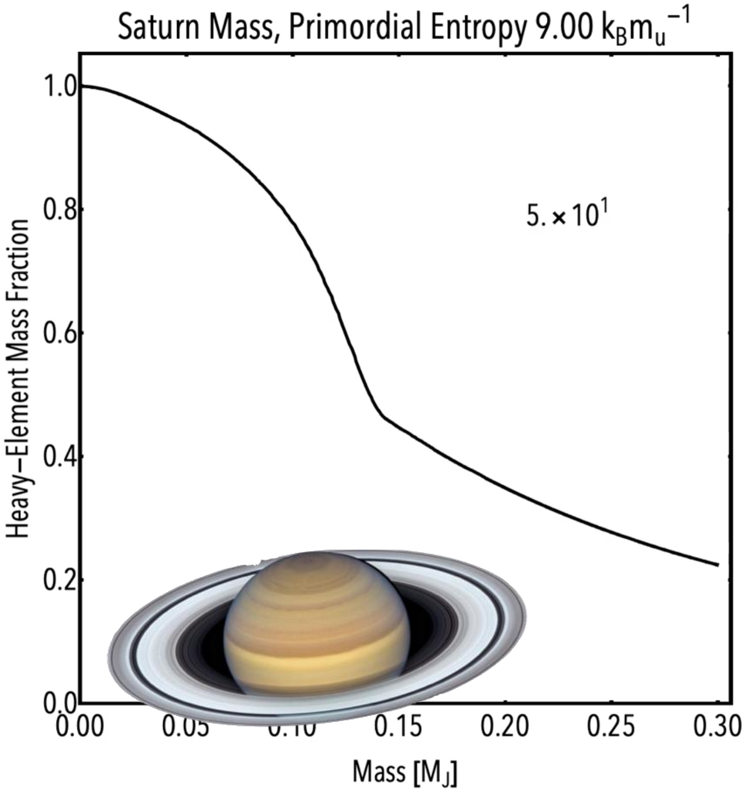


heavy-element
accretion during
runaway/post-formation


Characterization
Evolution
Understanding cool giant planets
Formation

Convective mixing can change the internal structure

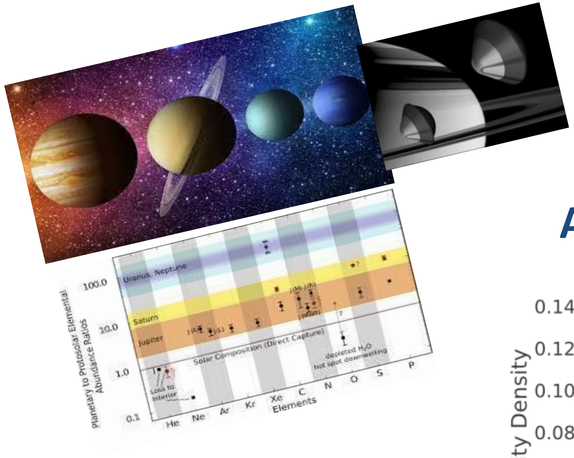




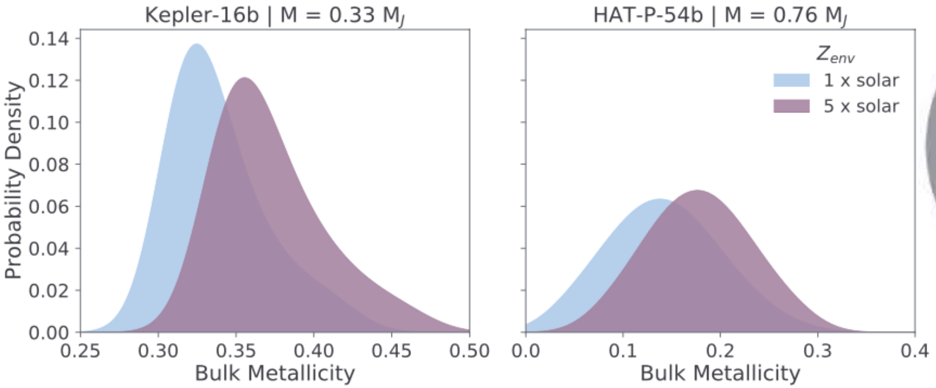
Knierim & Helled, 2024, more from Henrik

Atmosphere-bulk composition

- If giant planets are not fully mixed, how do we interpret atmospheric measurements?
- A better understanding of interior-atmosphere connection



Atmospheric metallicity – bulk composition



Upcoming talks…

What's next?

<u>Theory</u>

- ✓ A unified theoretical framework for formation-evolution-structure
- ✓ Reflect our understanding of SS planets on exoplanets and vice versa
- ✓ A better understanding of the theoretical vs. observational uncertainties
- ✓ ….

<u>Observations:</u>

✓Mass-metallicity relation (various distances)

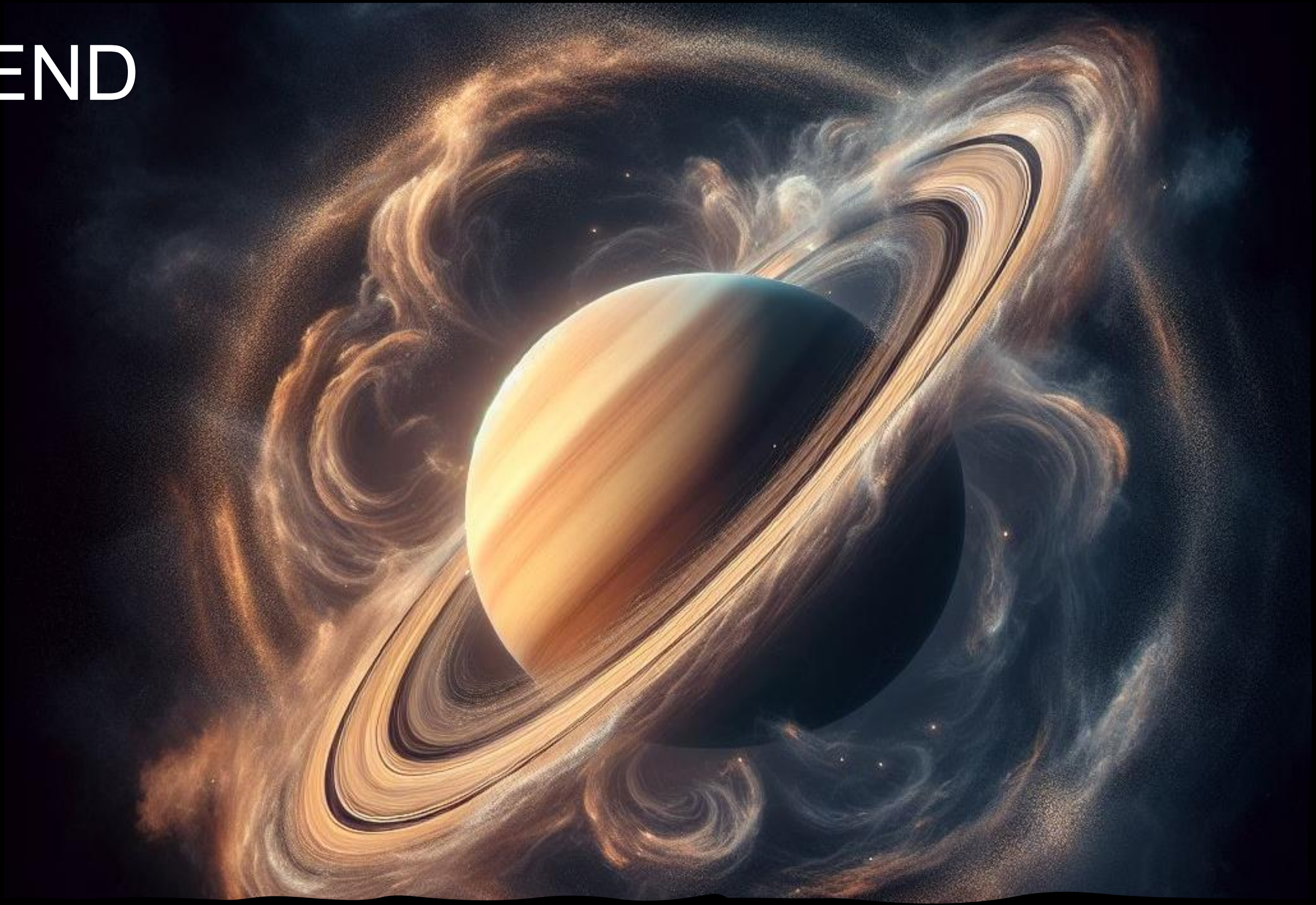
✓Atmospheric composition – bulk composition relation

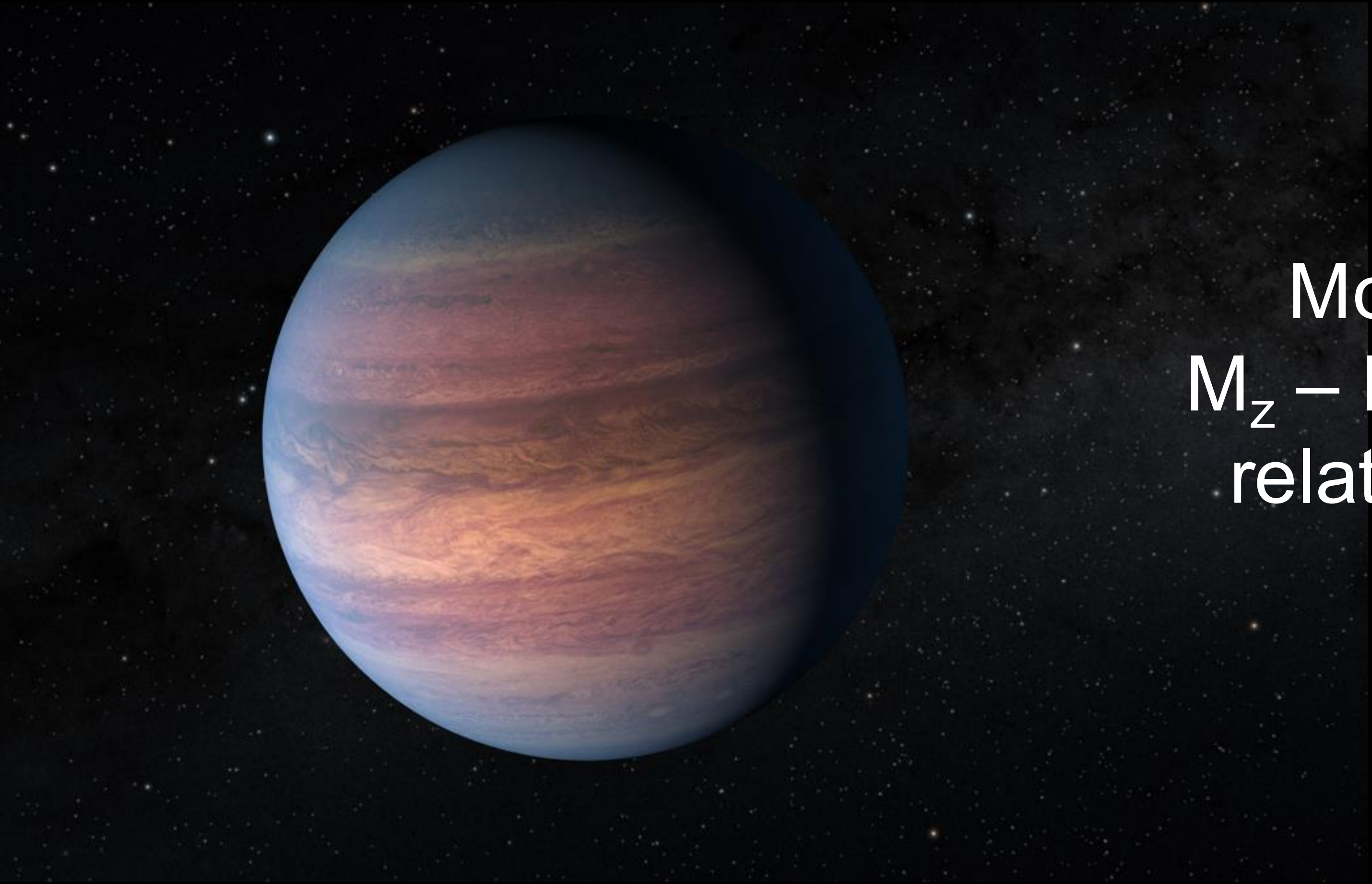
✓Atmospheric refractory-to-volatile ratio (various masses, staller properties, distances…)

✓Luminosities – various ages, masses (+atmospheric composition)

✓….

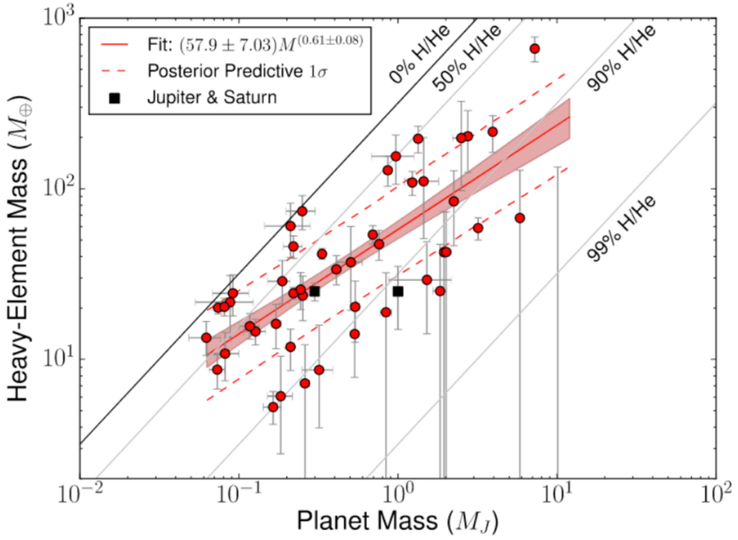
The END

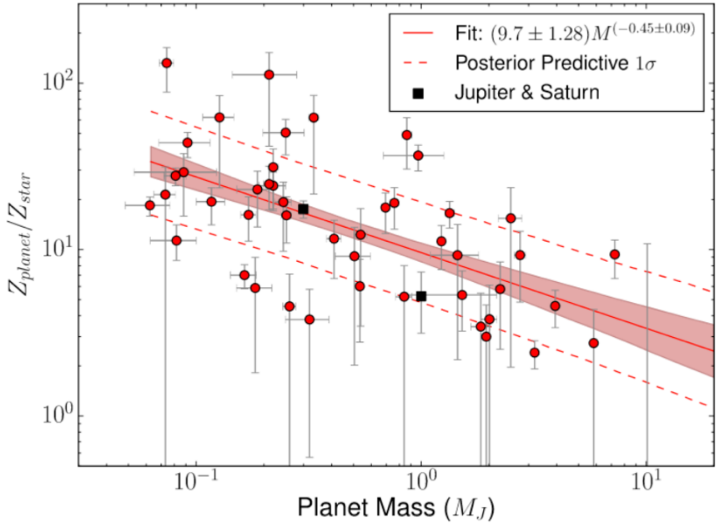




More M_z – M_{planet} relations

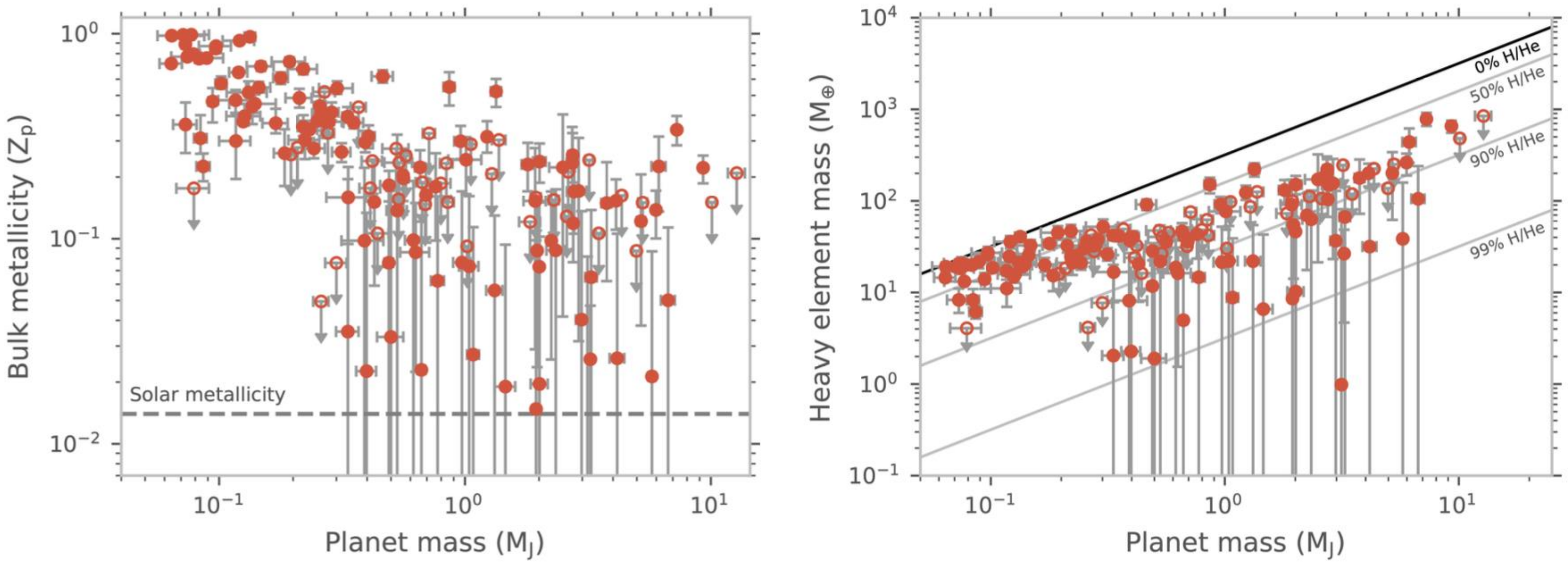
Mass-Metallicity relation for cool giant planets





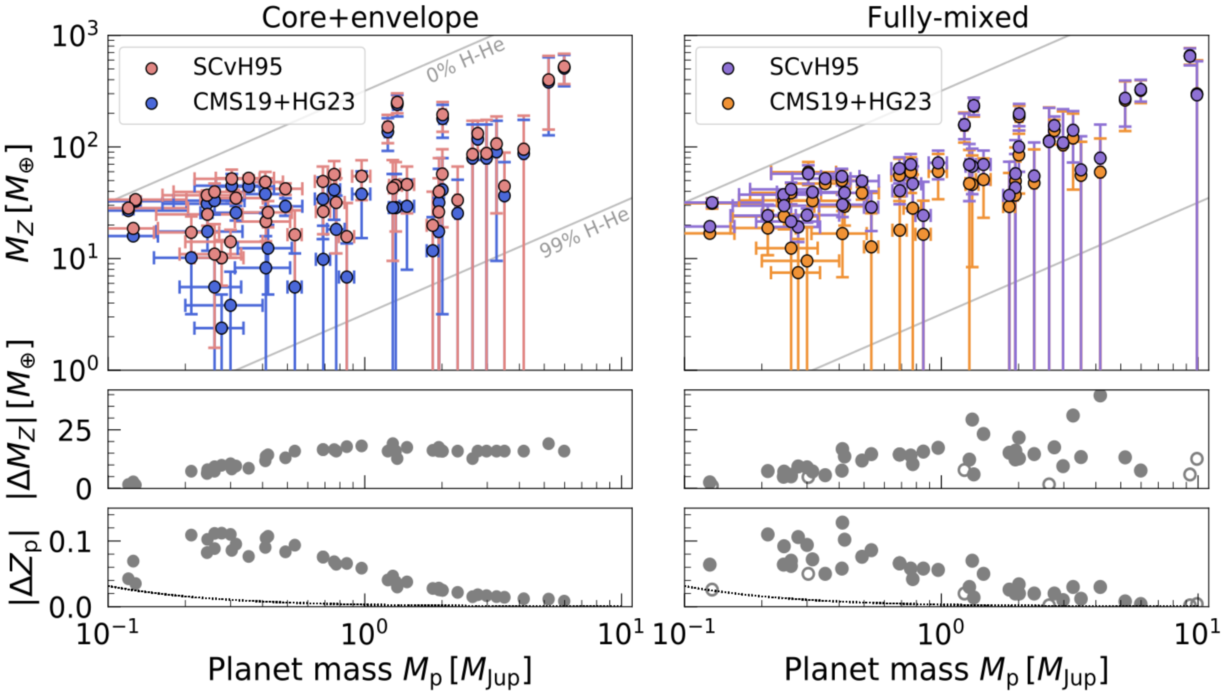
Thorngren et al., 2016

Mass-Metallicity relation for cool giant planets



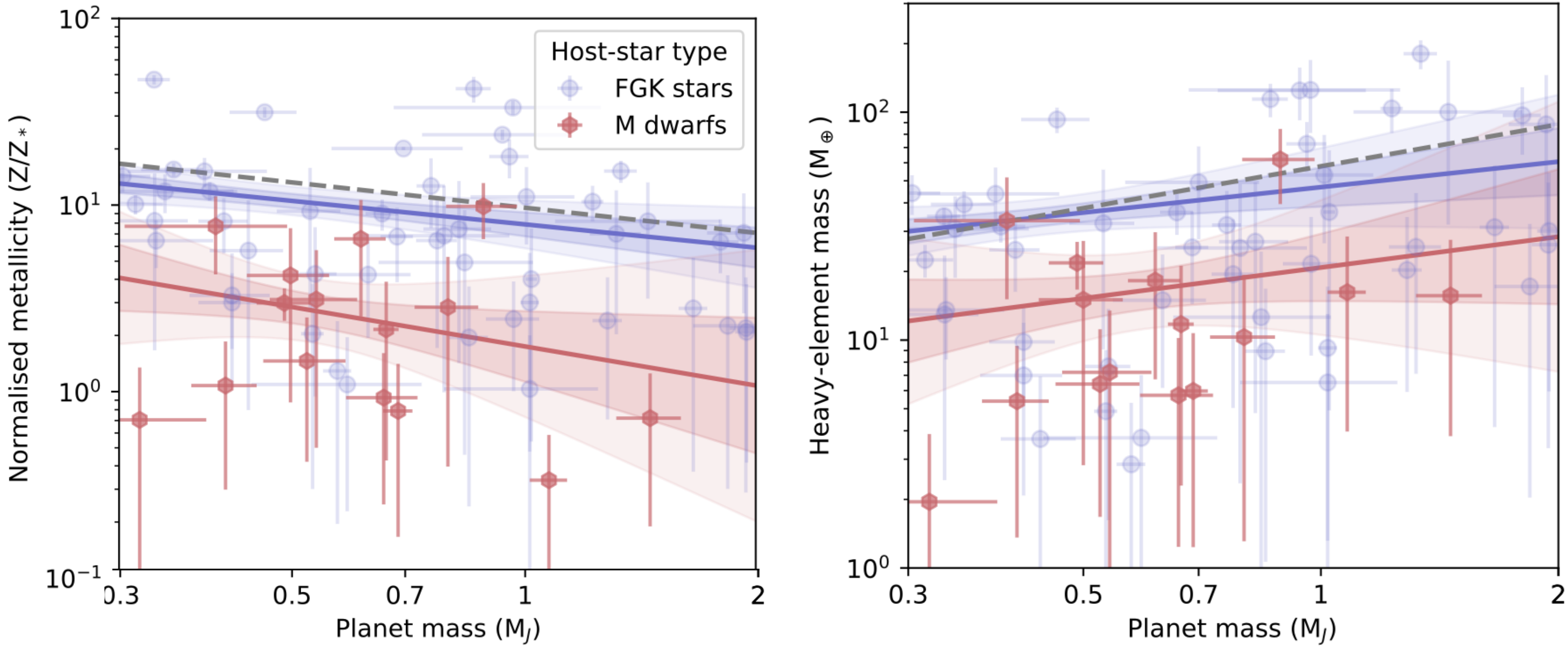
Chachan et al., 2025

Mass-Metallicity relation for cool giant planets



Howard et al., 2025

Is the trend the same across different stellar types?



Müller & Helled, 2024