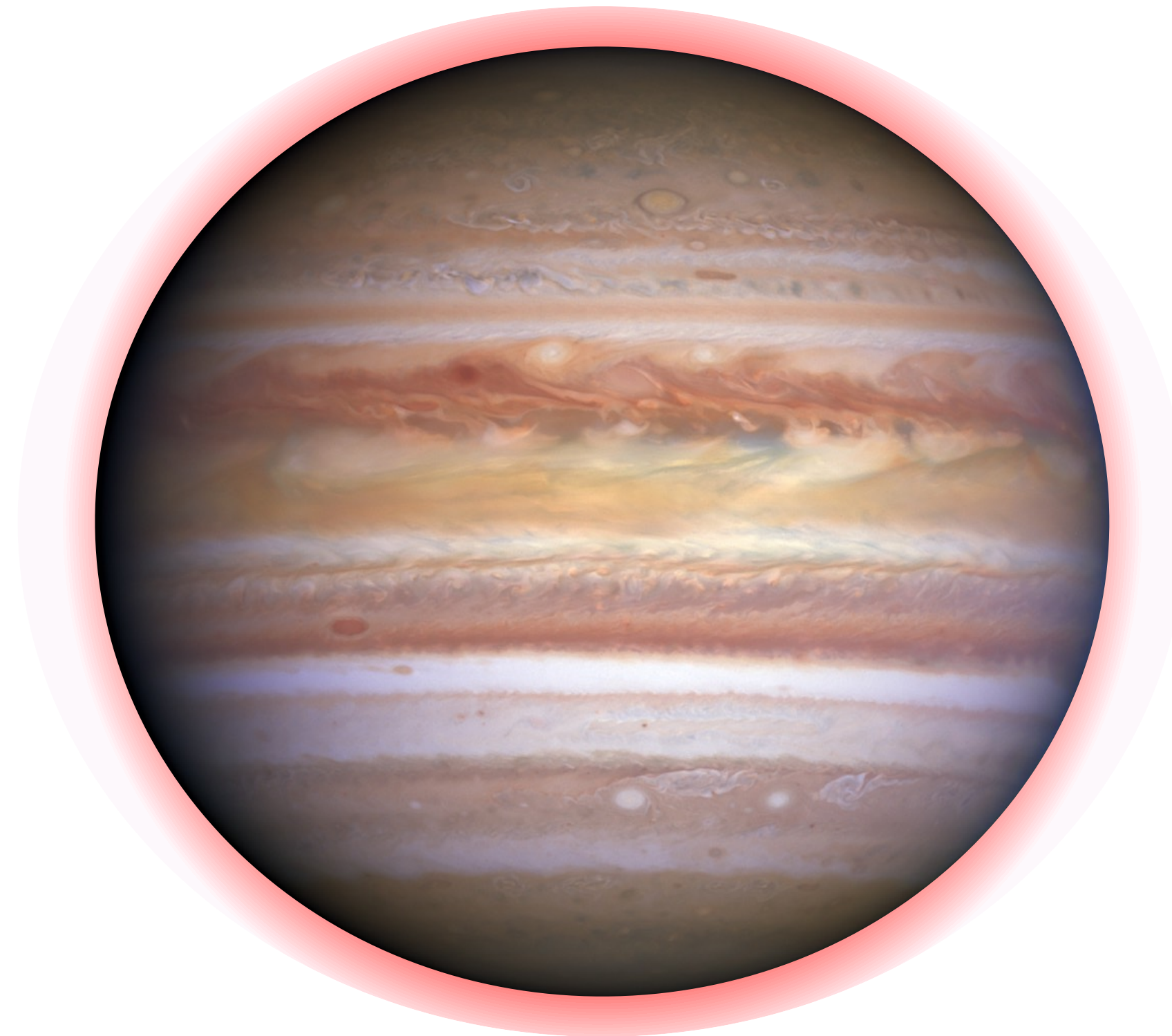


Modeling the internal structure and evolution of giant planets from Juno to Plato: Lessons and Challenges



Tristan Guillot,
Observatoire de la Côte d'Azur

National Aeronautics and Space Administration



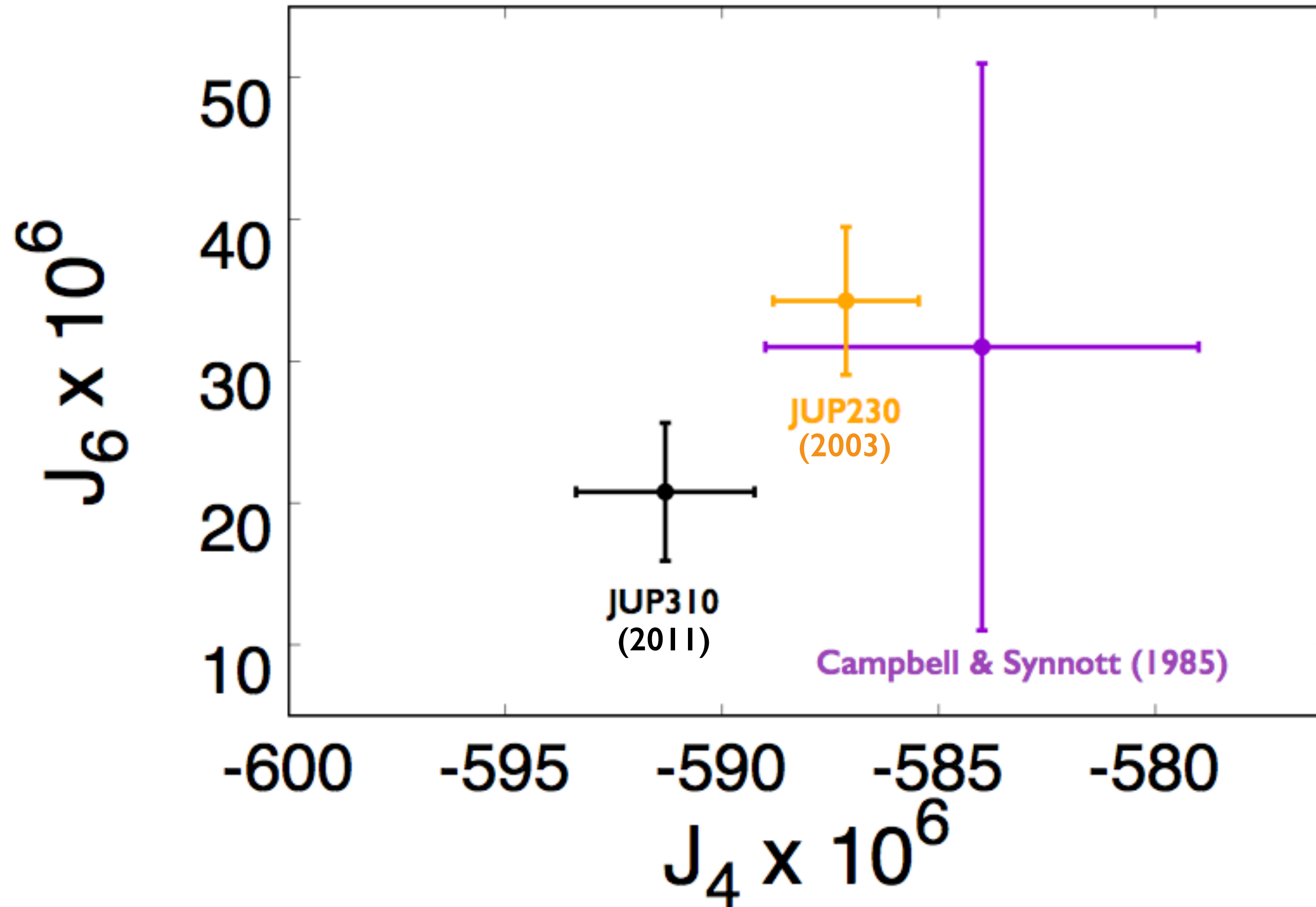
Juno

Mission to Jupiter

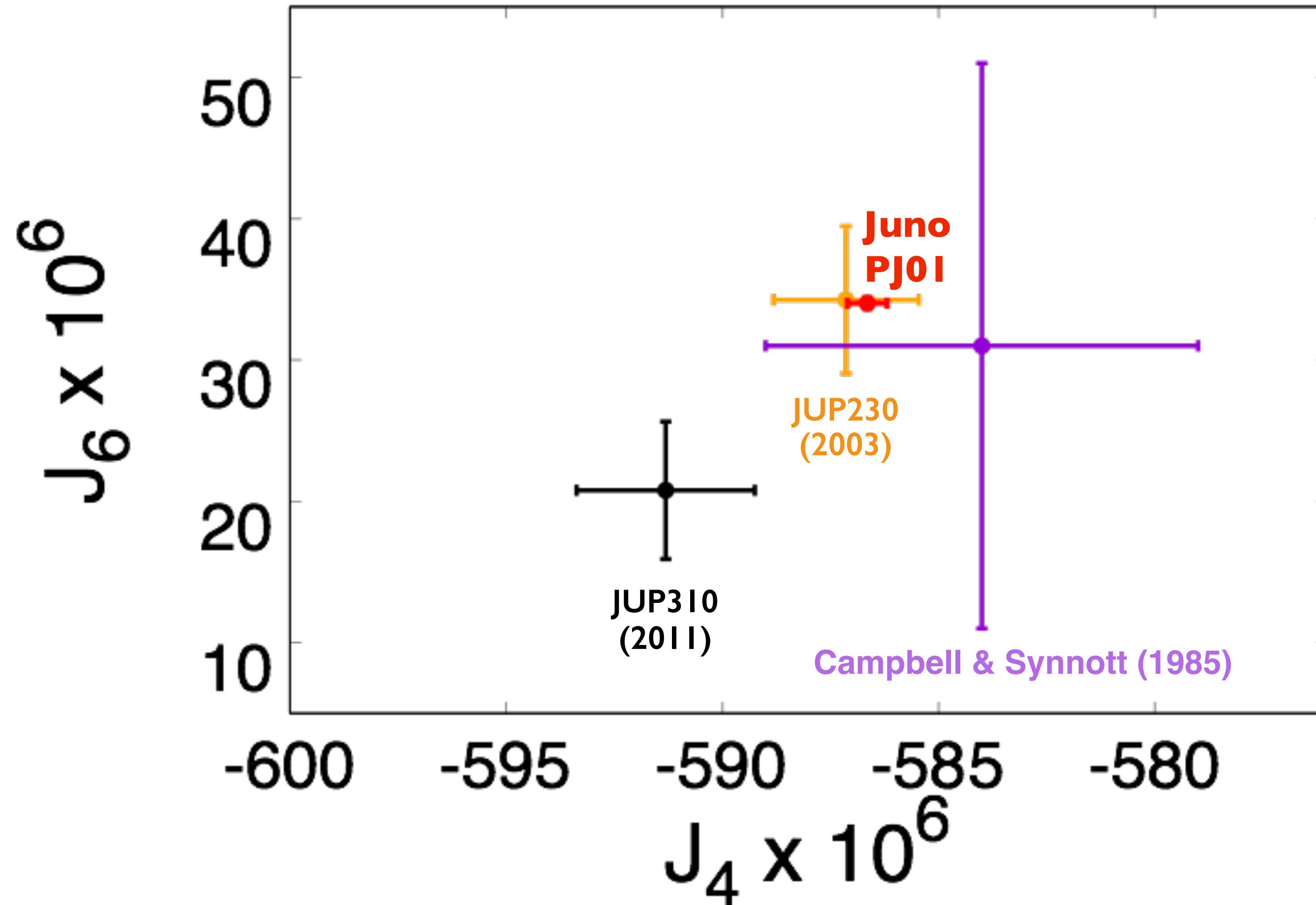


www.nasa.gov

J₆ vs J₄: pre-Juno gravity data

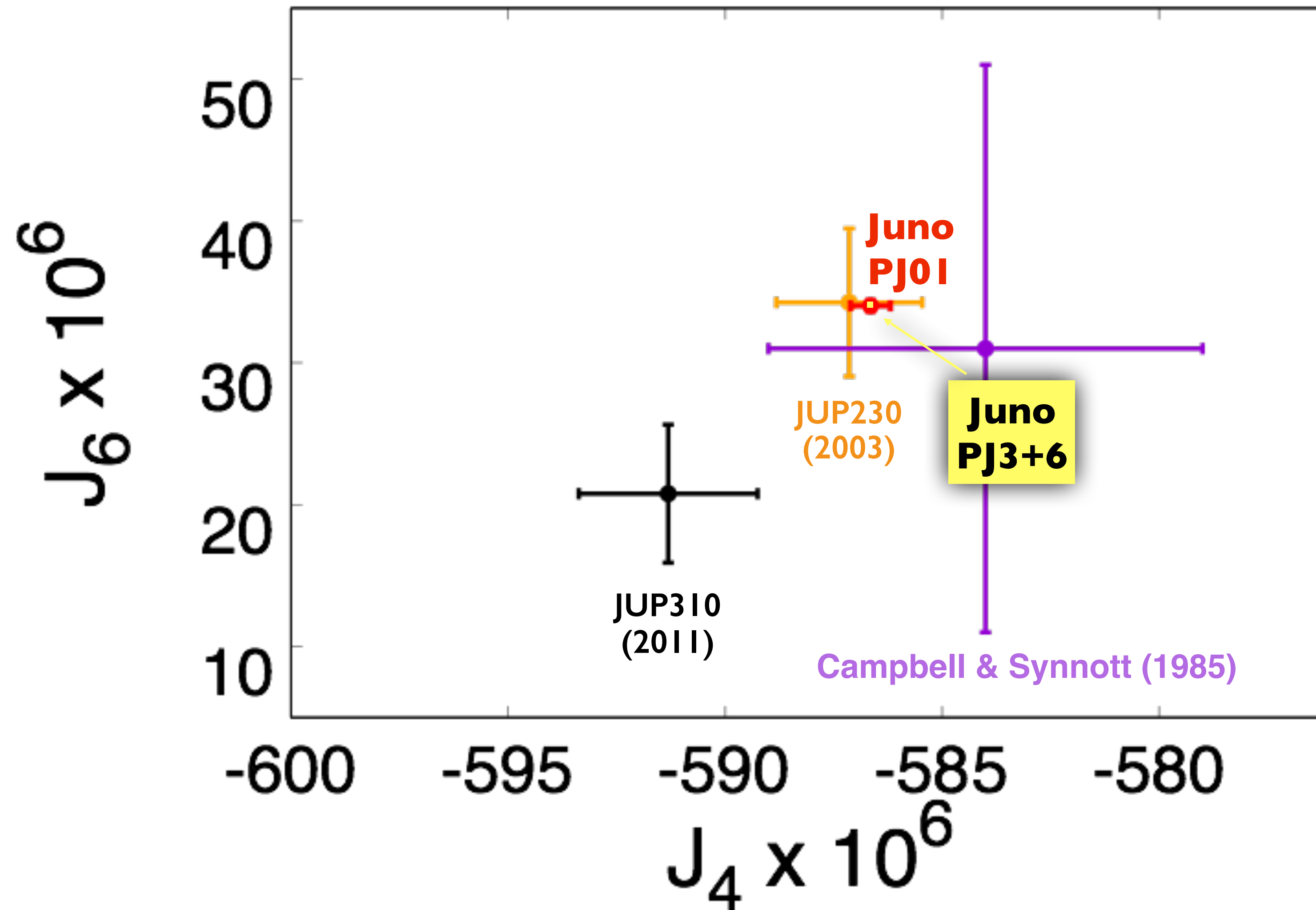


J₆ vs J₄: first flyby

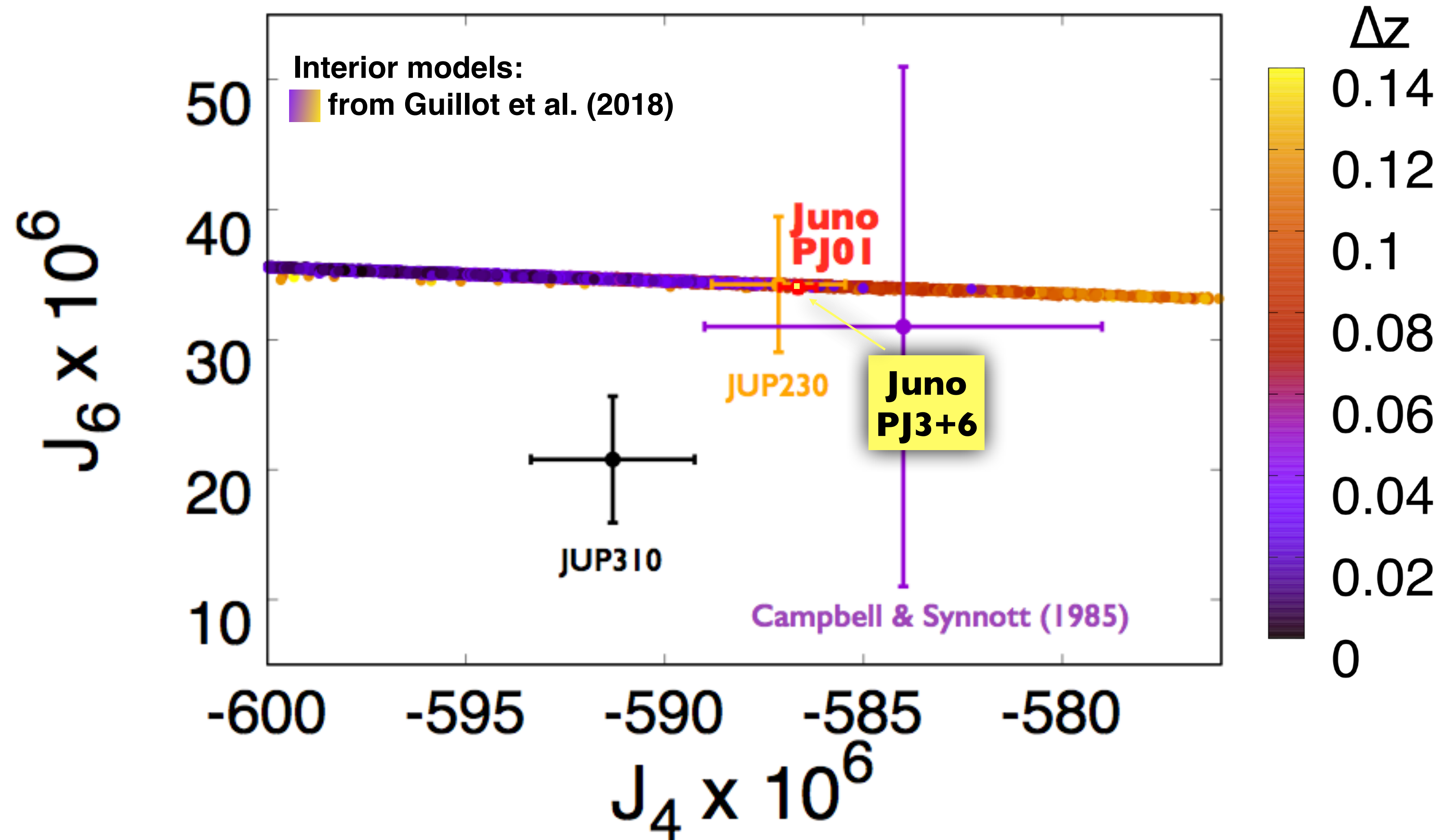


Bolton et al. (Science 2017)
Folkner et al. (GRL 2017)

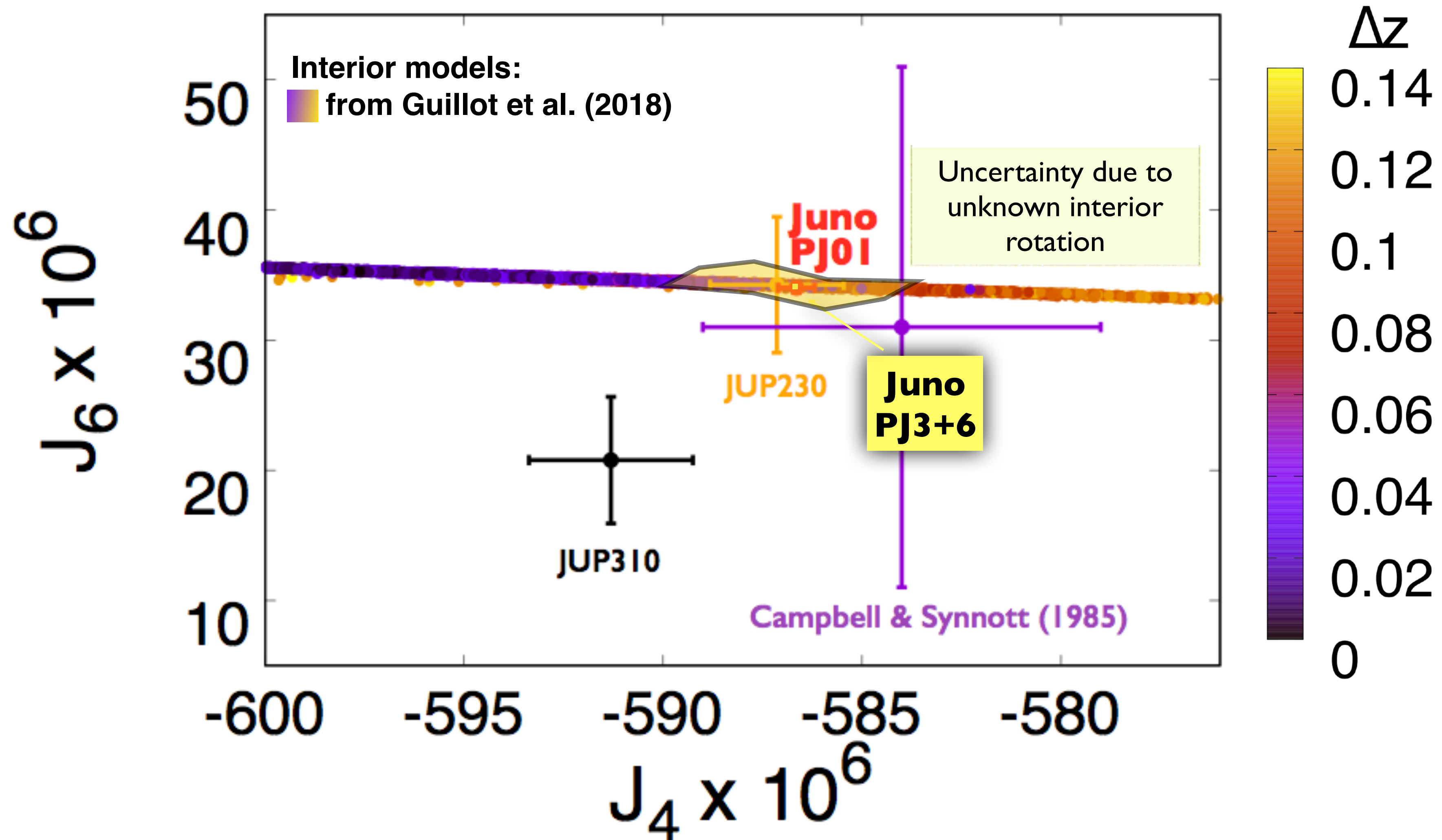
J₆ vs J₄: best Juno measurements so far



J_6 vs J_4 : a Z-inhomogeneous envelope

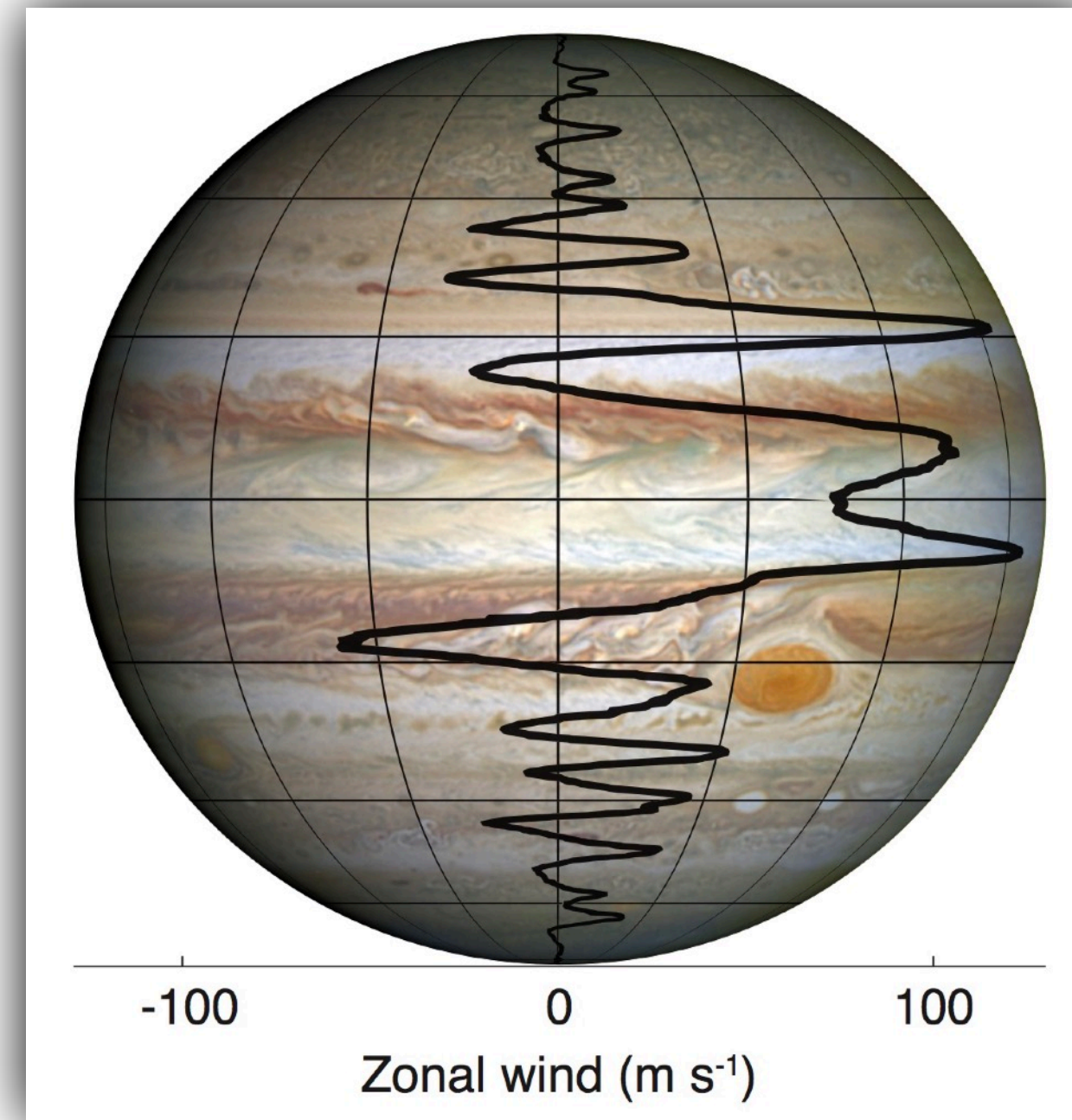
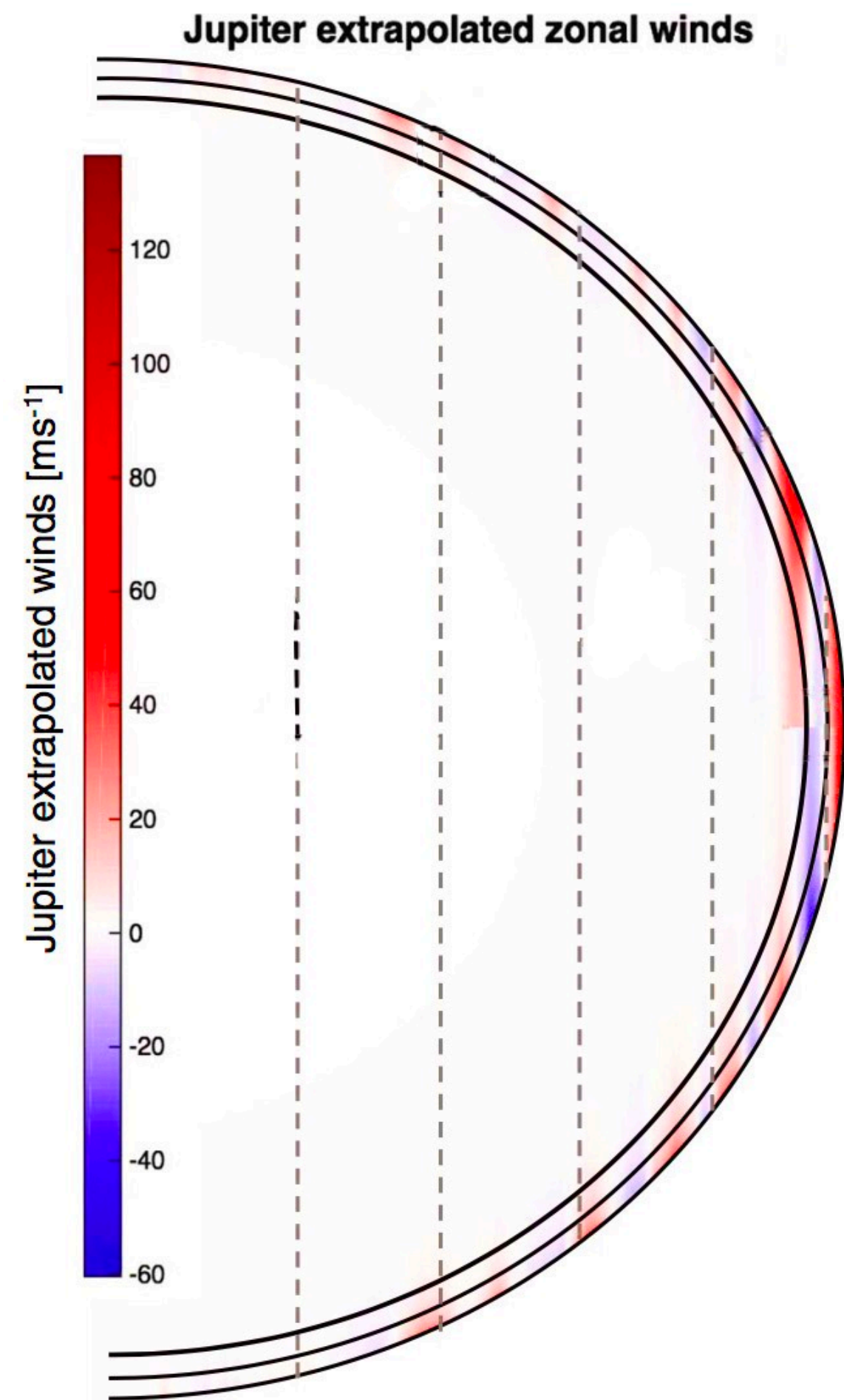


J₆ vs J₄: a Z-inhomogeneous envelope



from Guillot et al. (2018)

Extent of zonal flows

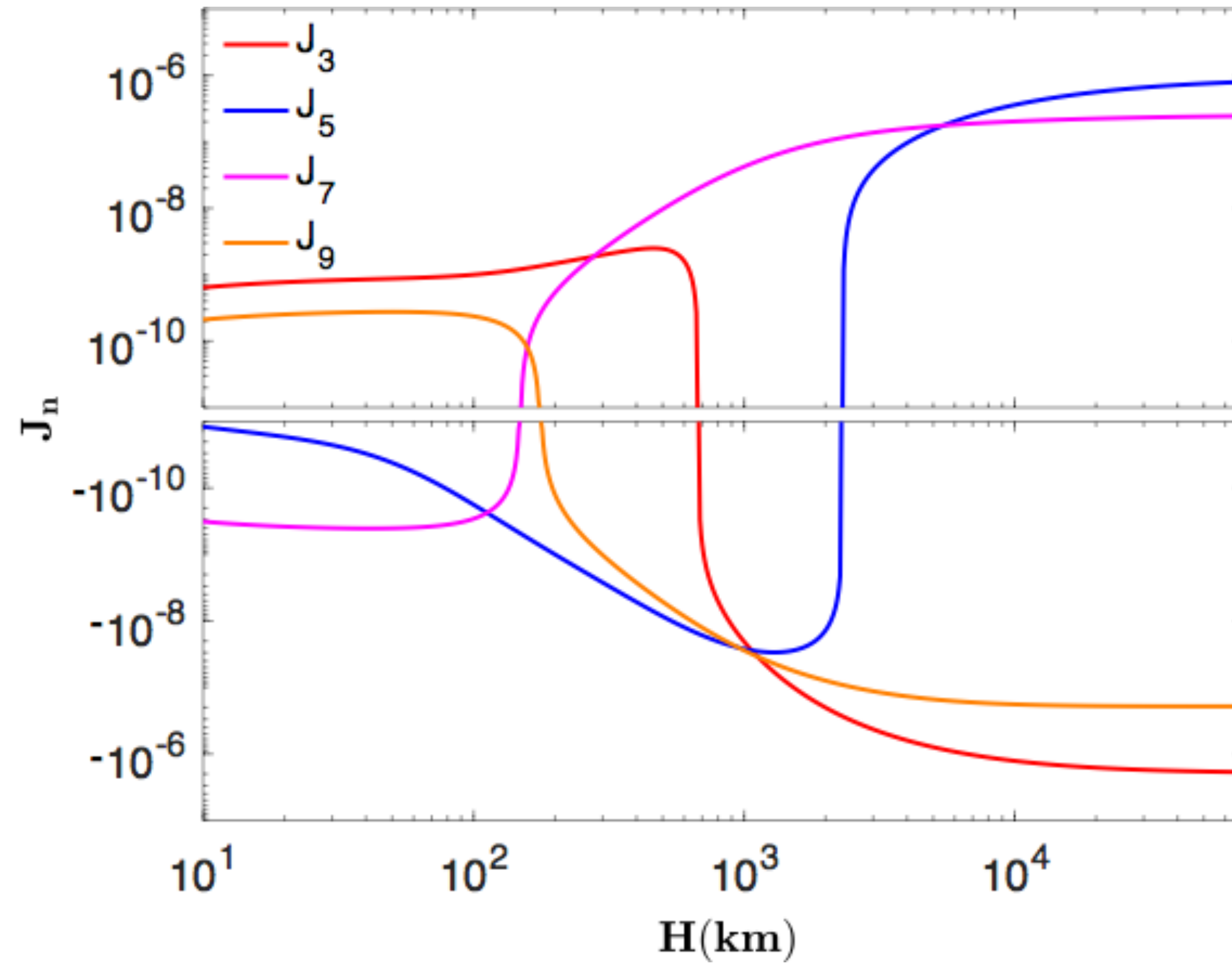
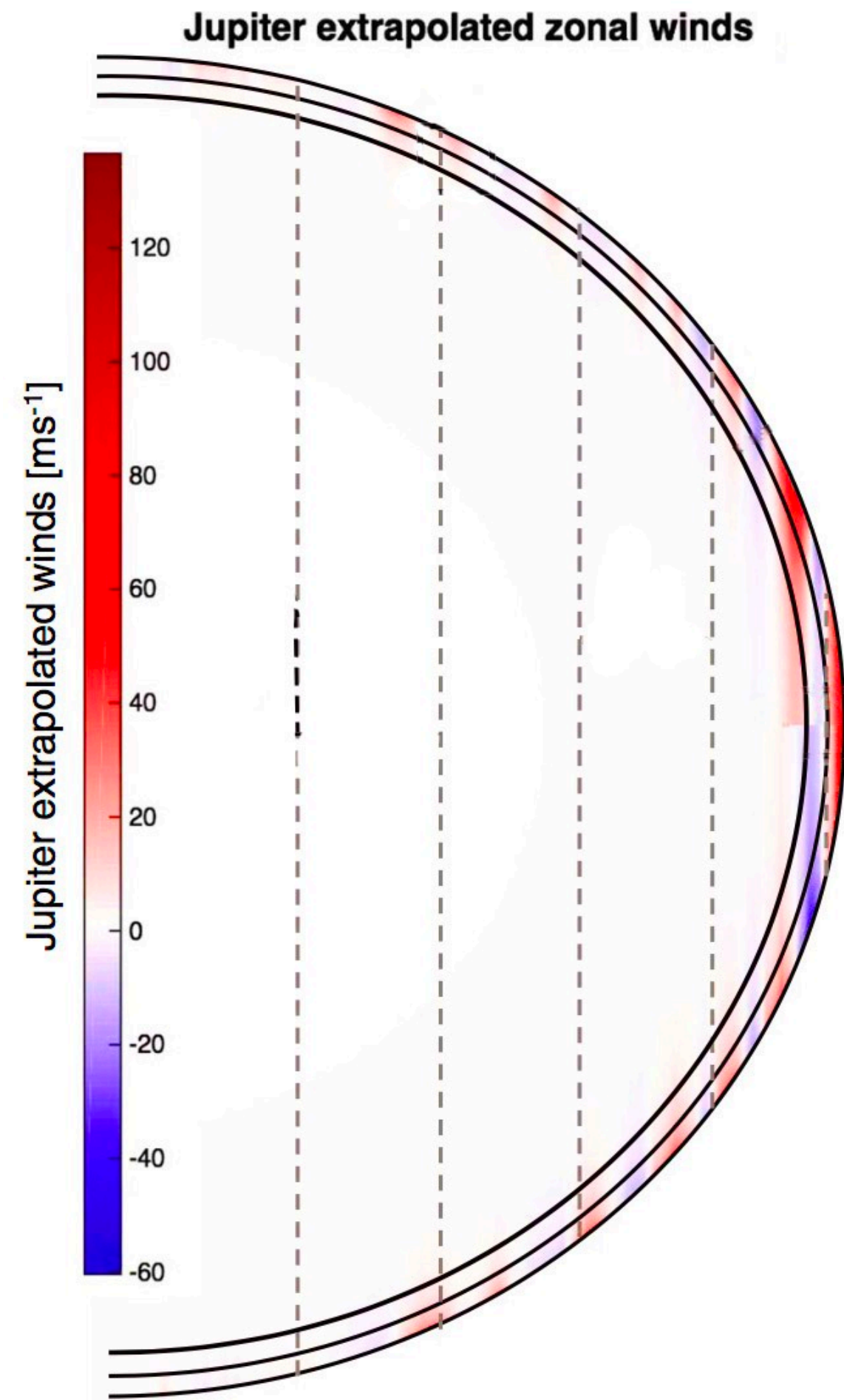


Extending the observed flows to a depth H by assuming thermal wind balance

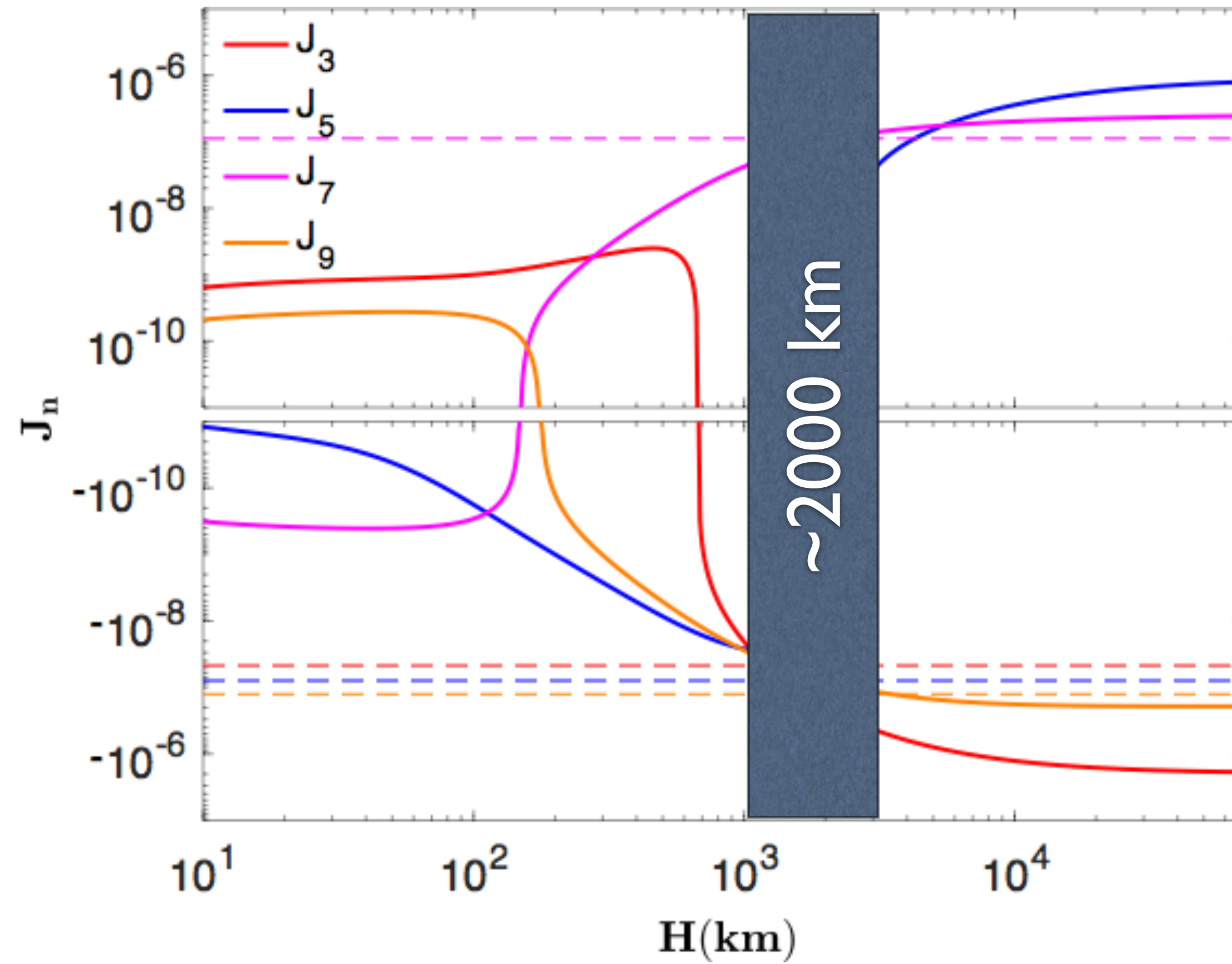
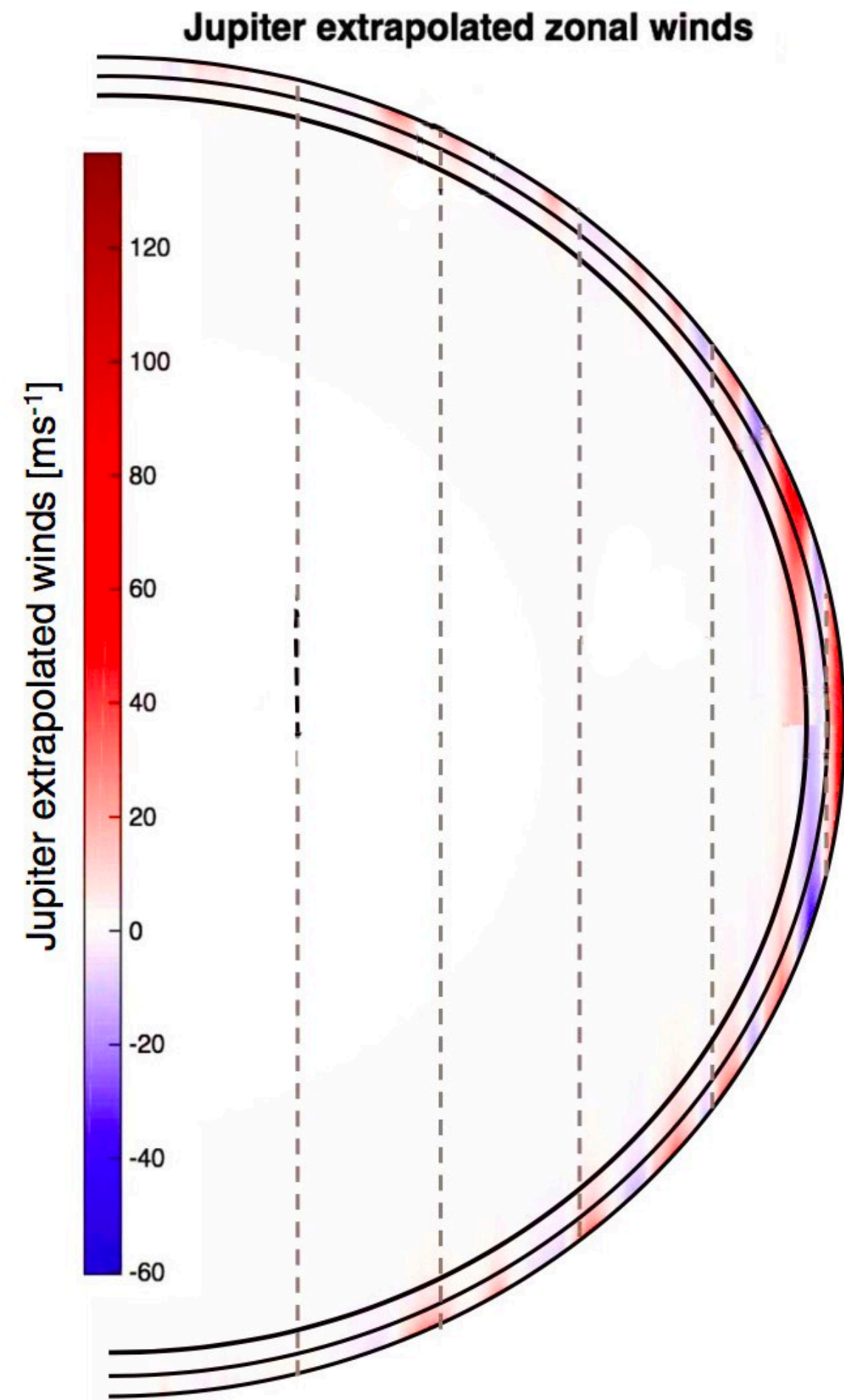
$$2\Omega \cdot \nabla (\rho_s \mathbf{u}) = \nabla \rho' \times \mathbf{g},$$

$$\delta J_i(H)$$

Extent of zonal flows and odd Js

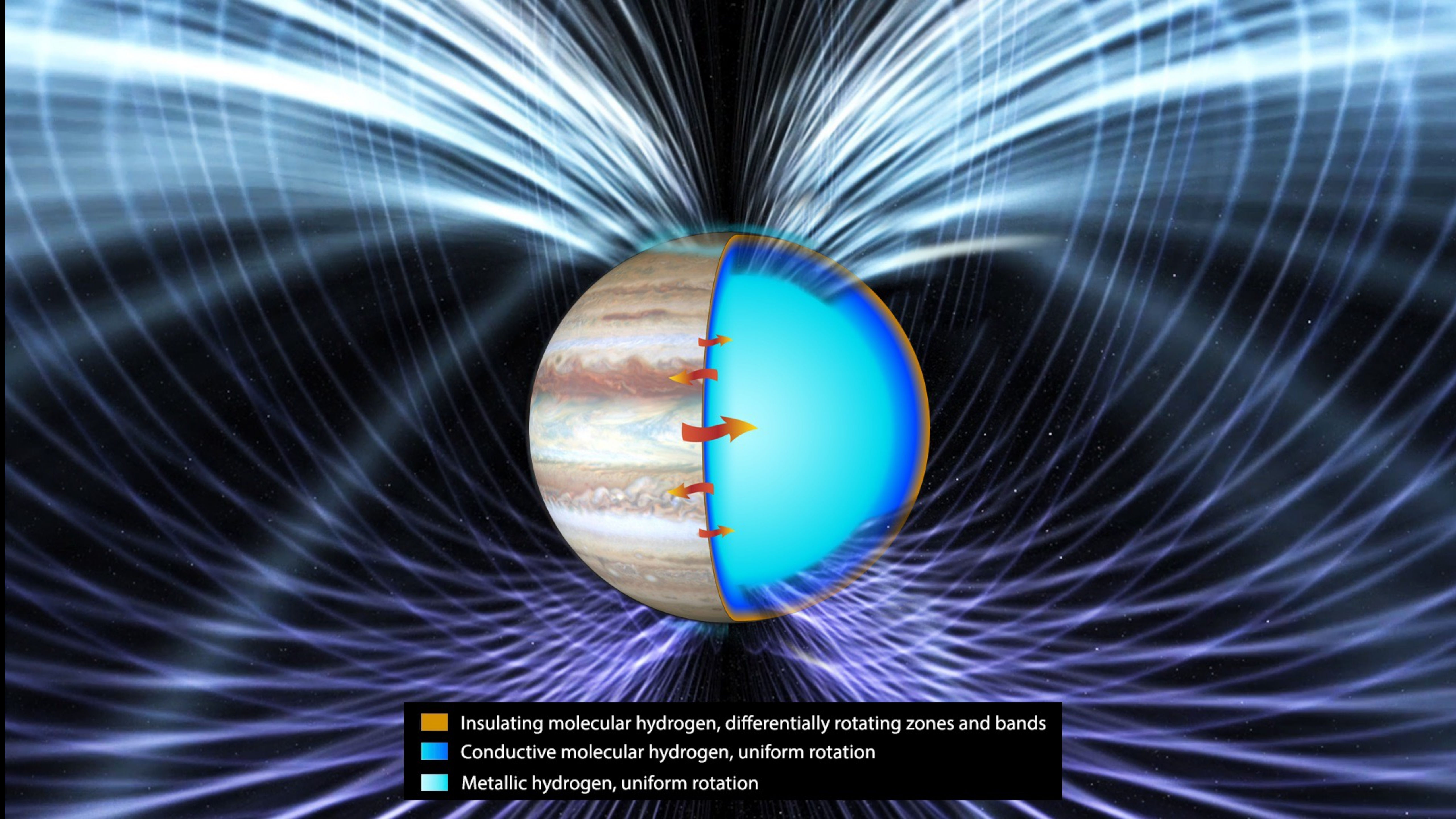


Extent of zonal flows and odd Js



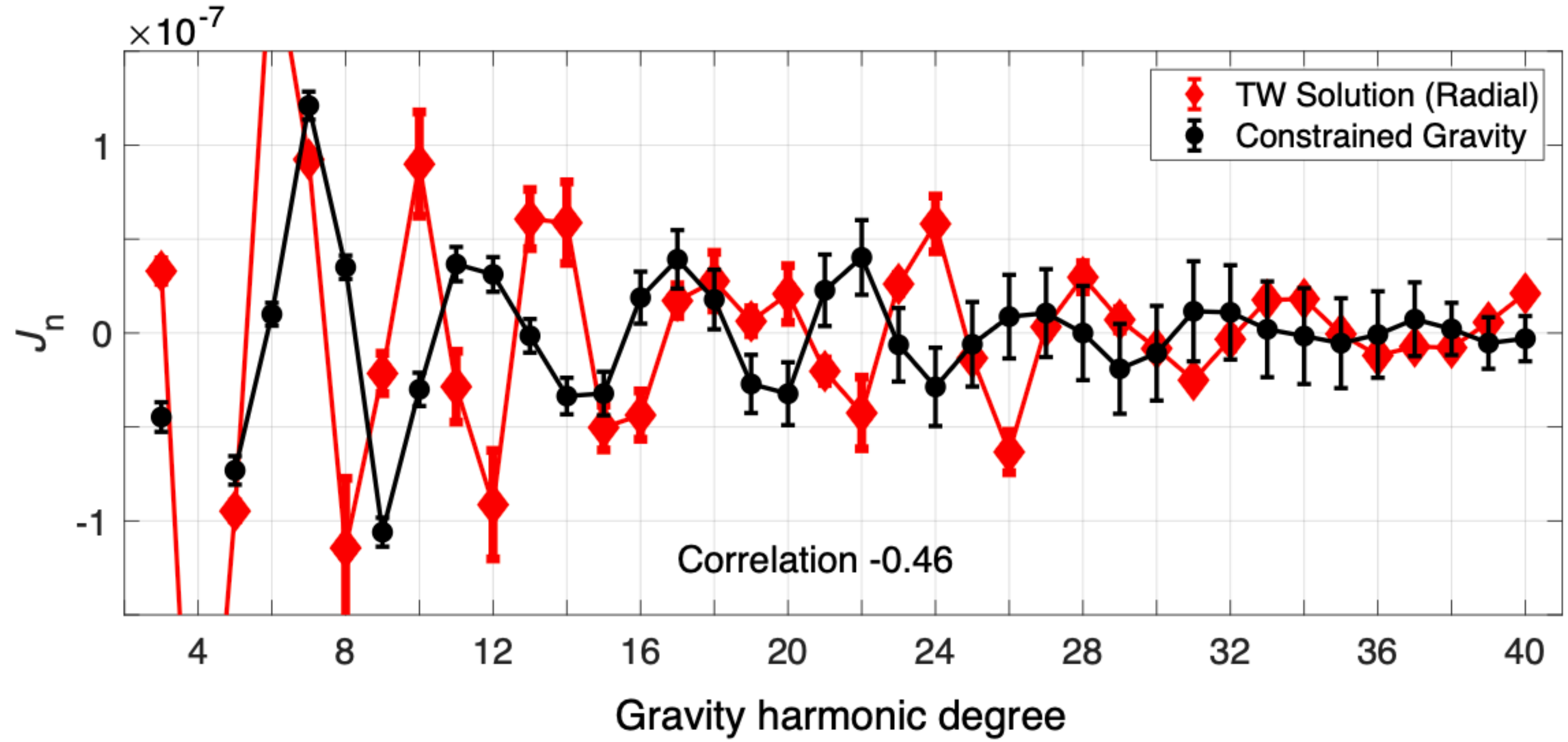
Kaspi et al. (2018)

See Eli Galanti, [EGU2018-5885](#)

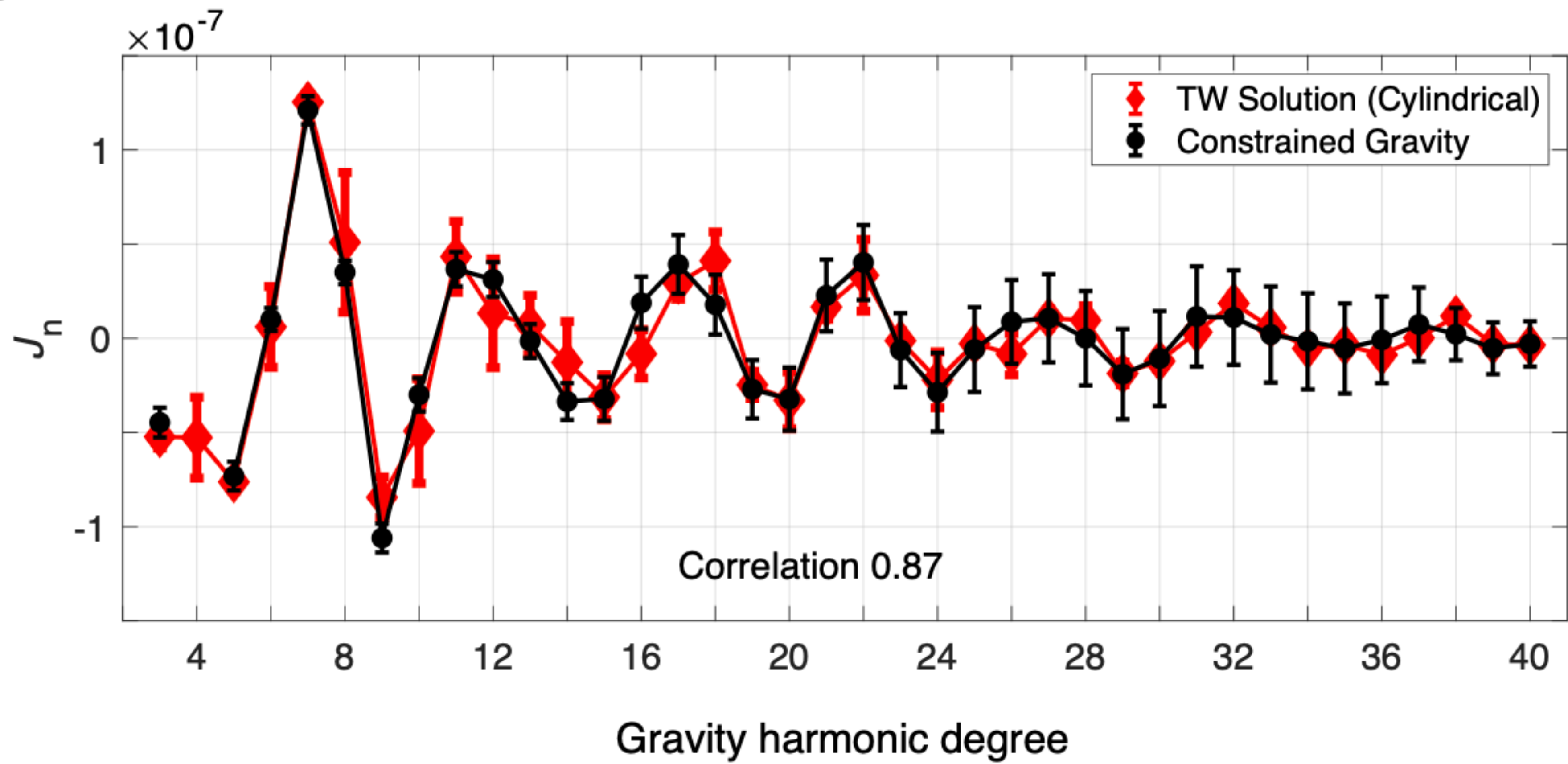


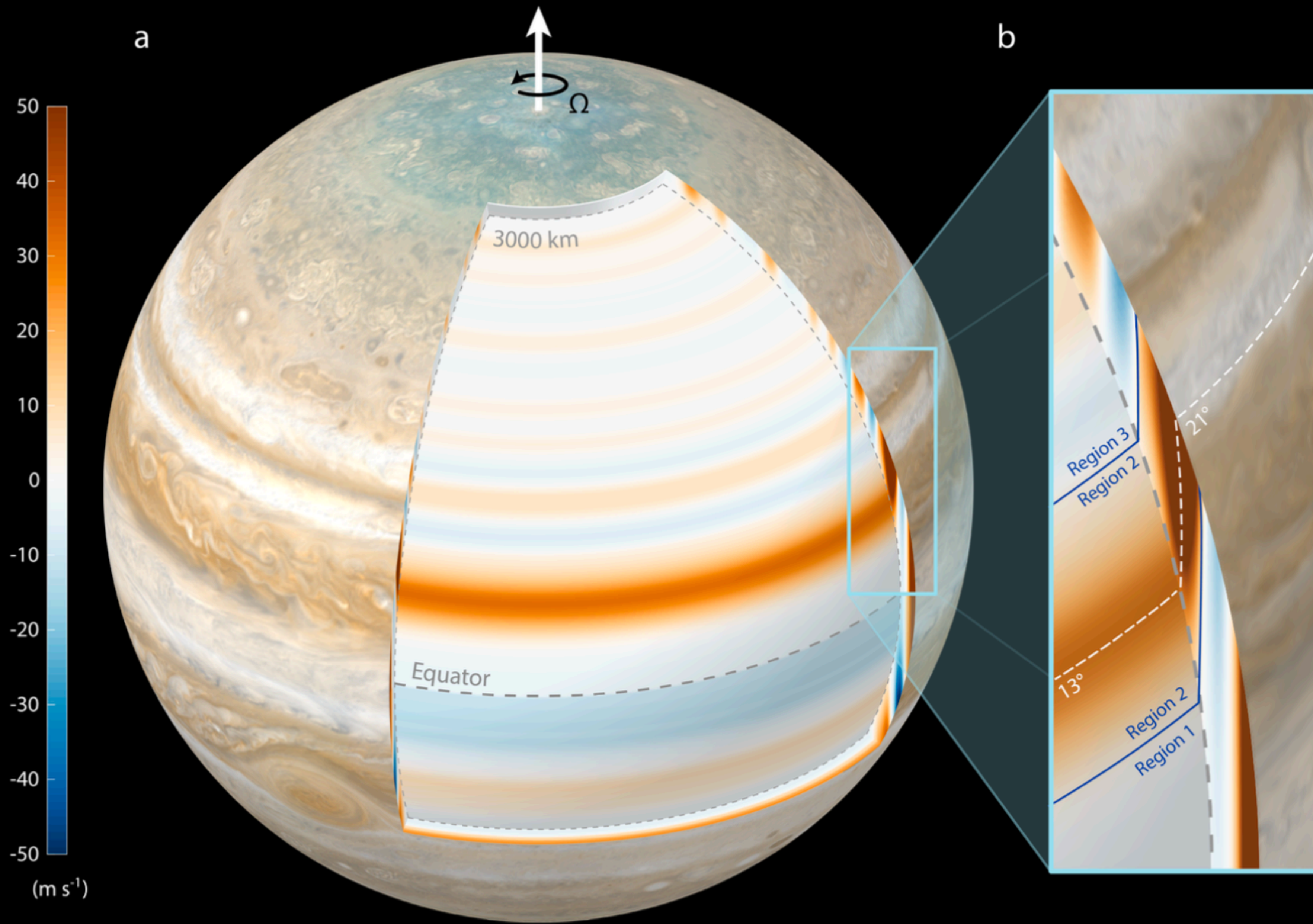
- Insulating molecular hydrogen, differentially rotating zones and bands
- Conductive molecular hydrogen, uniform rotation
- Metallic hydrogen, uniform rotation

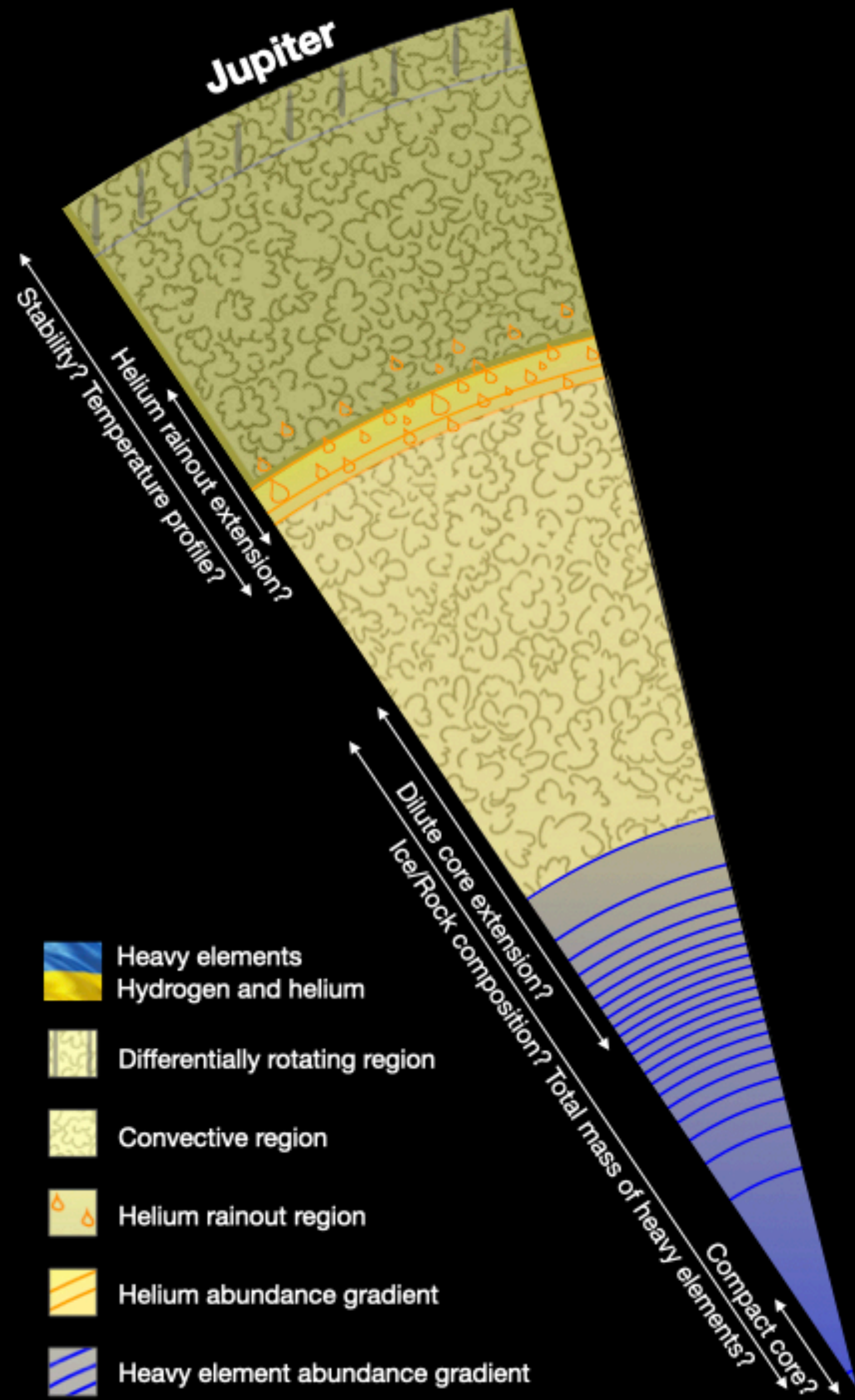
b





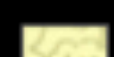




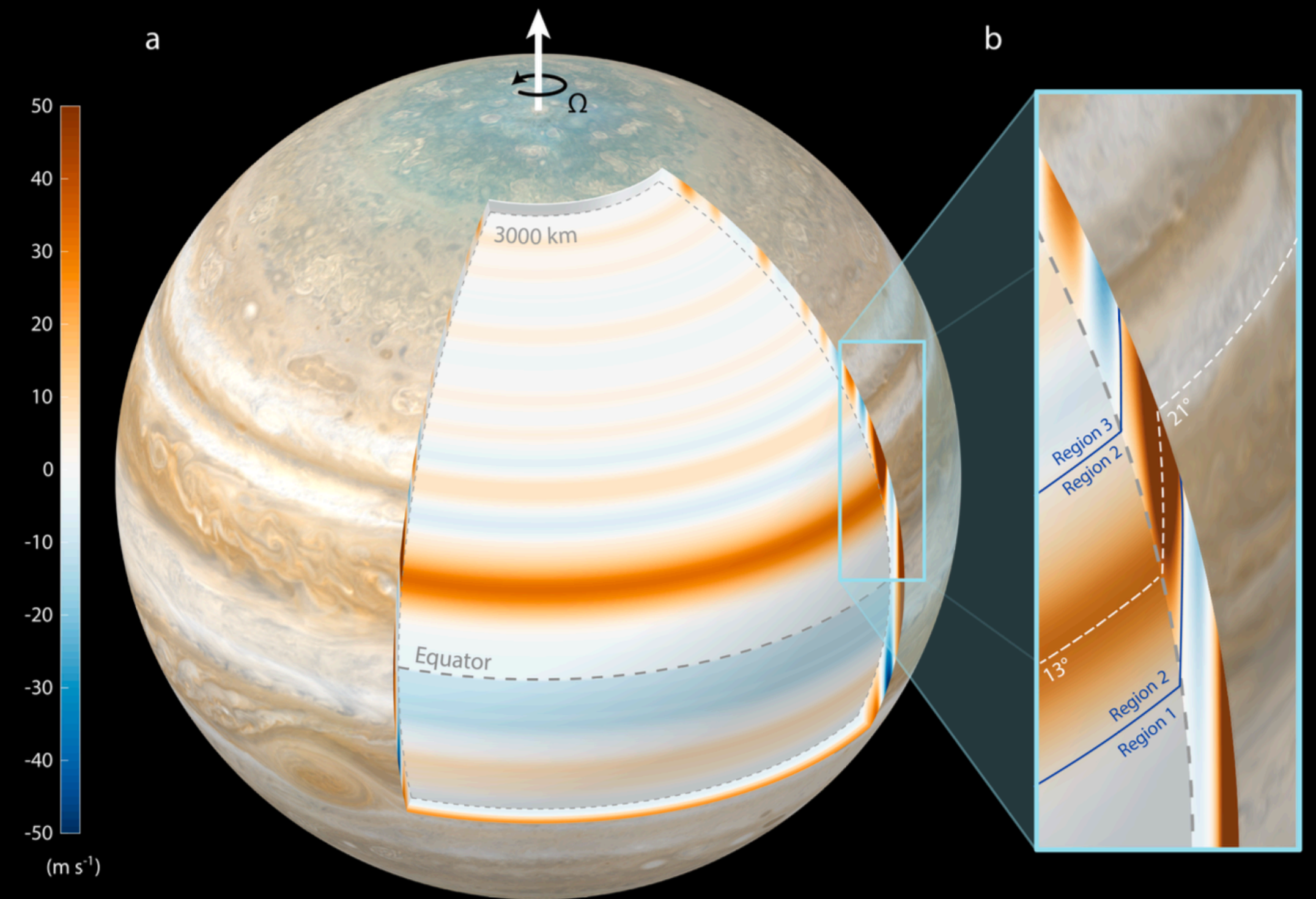
a

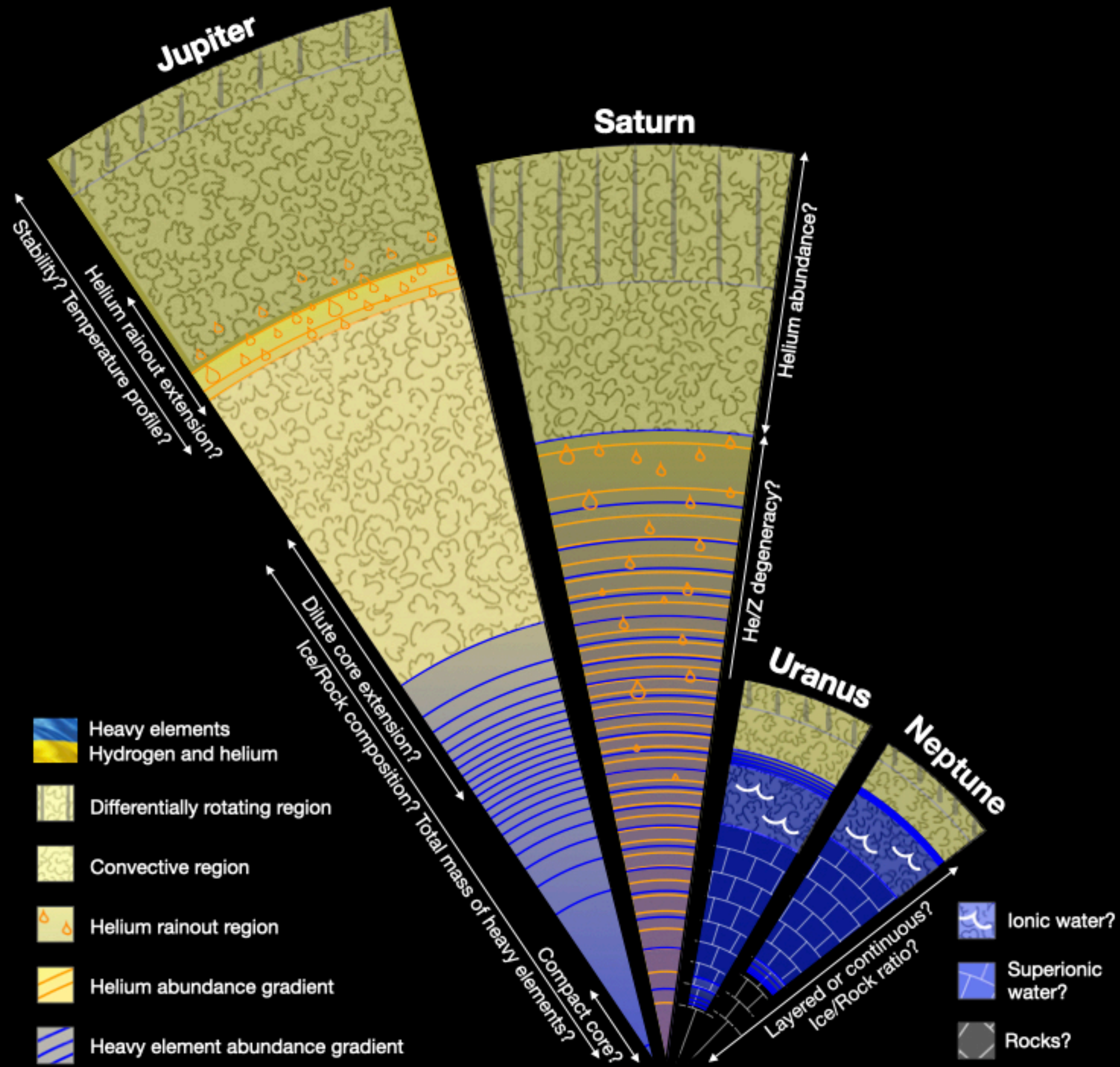


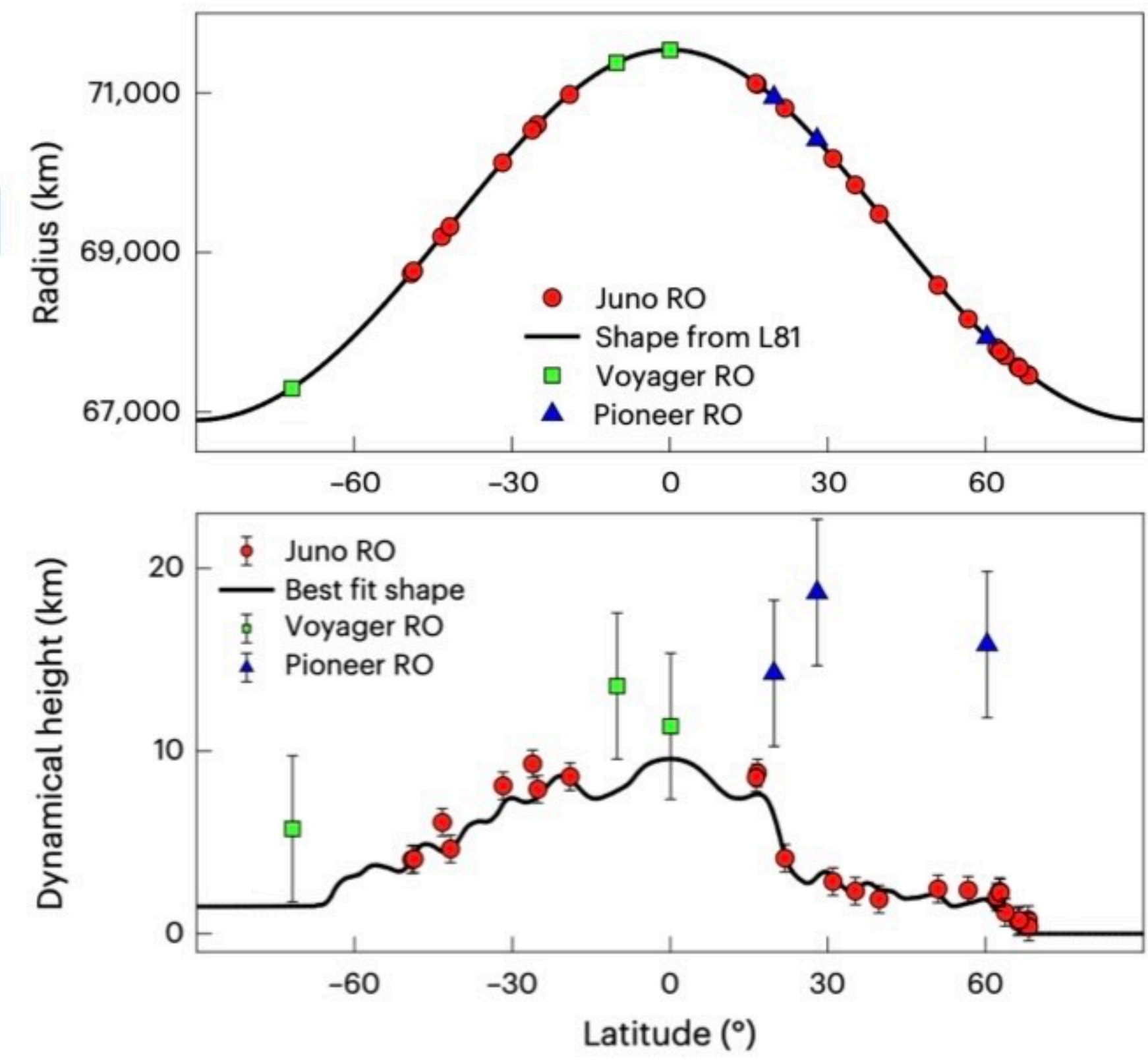
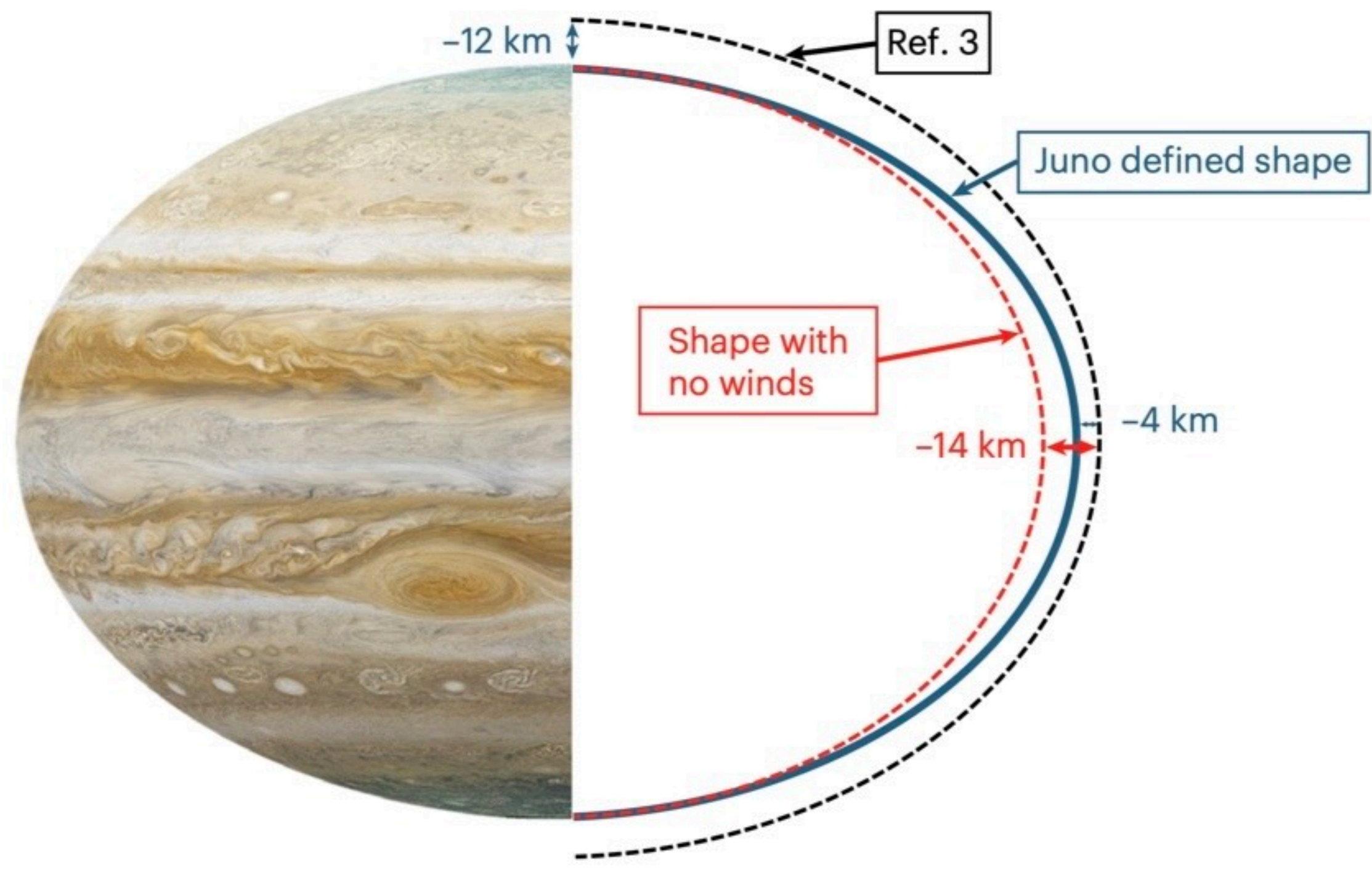




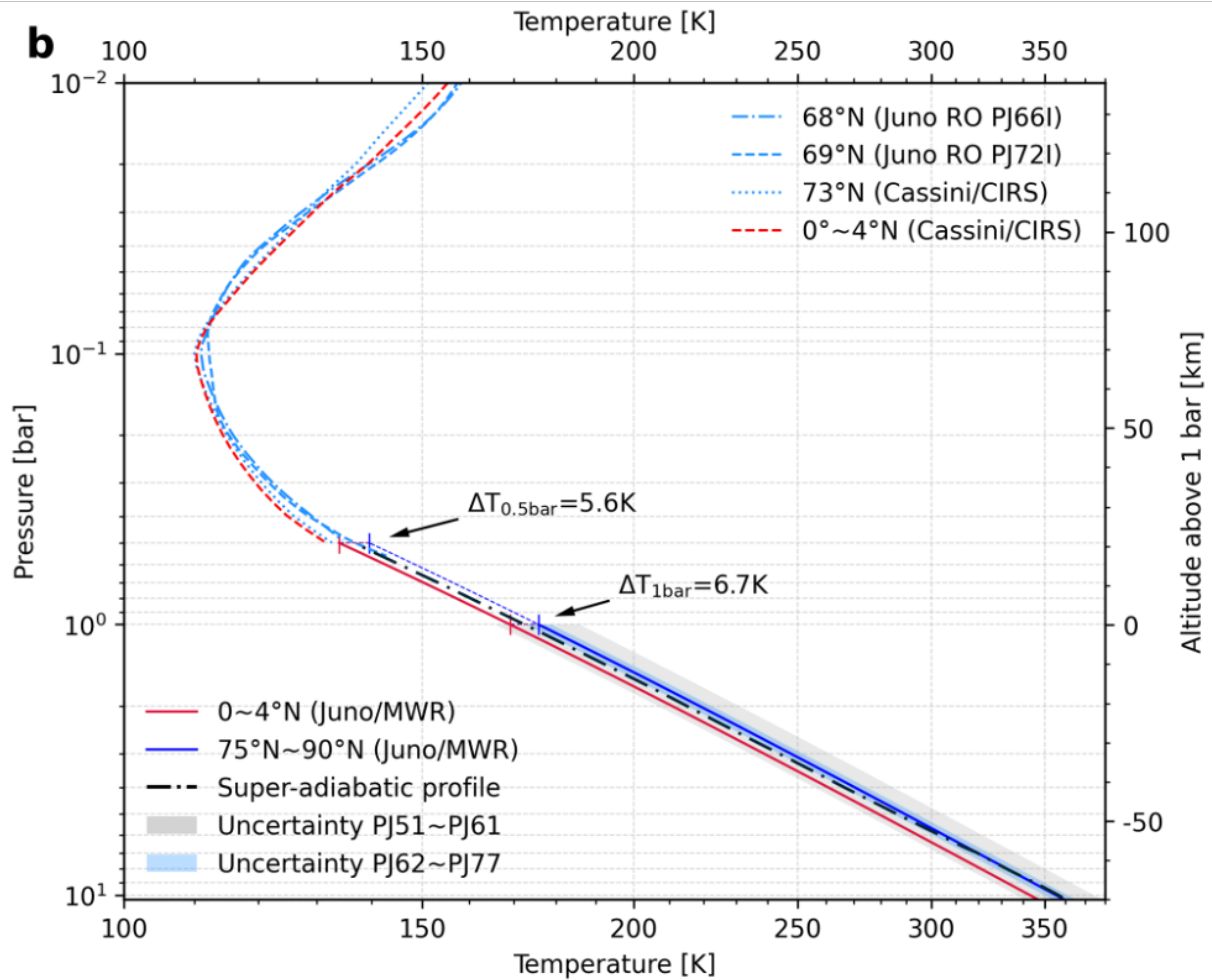
-  Heavy elements
-  Hydrogen and helium
-  Differentially rotating region
-  Convective region
-  Helium rainout region
-  Helium abundance gradient
-  Heavy element abundance gradient

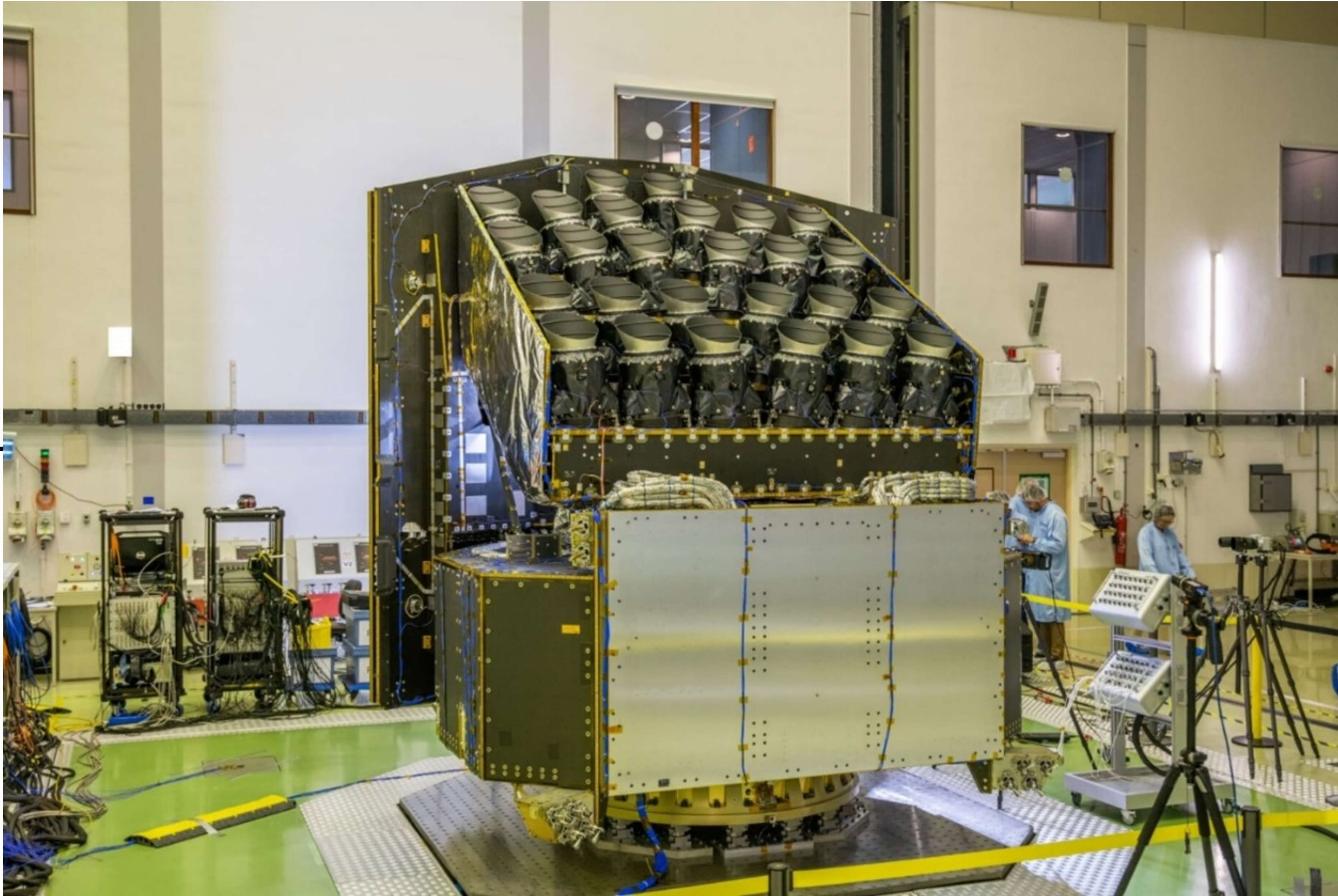






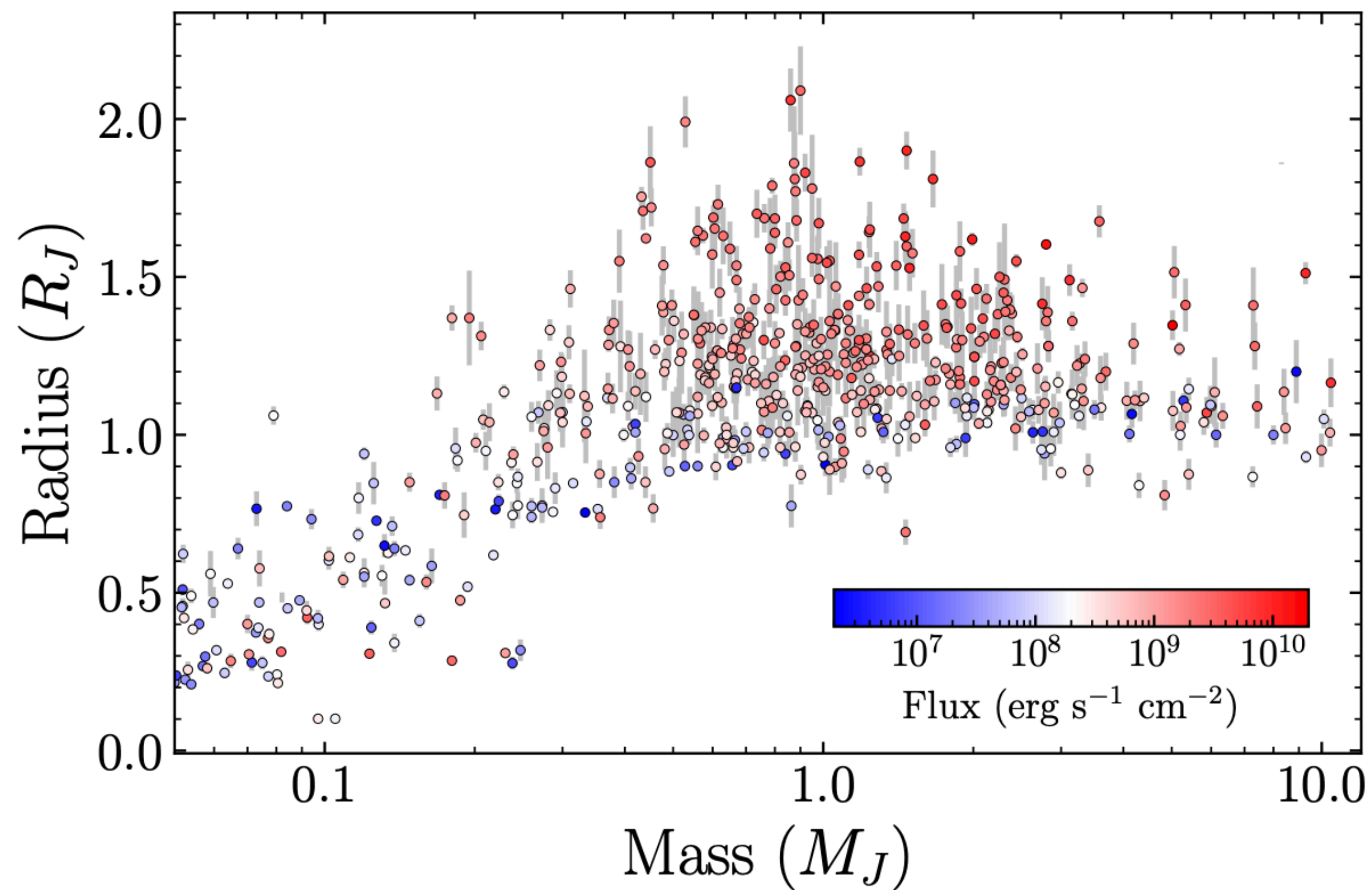
Galanti et al. (2026)



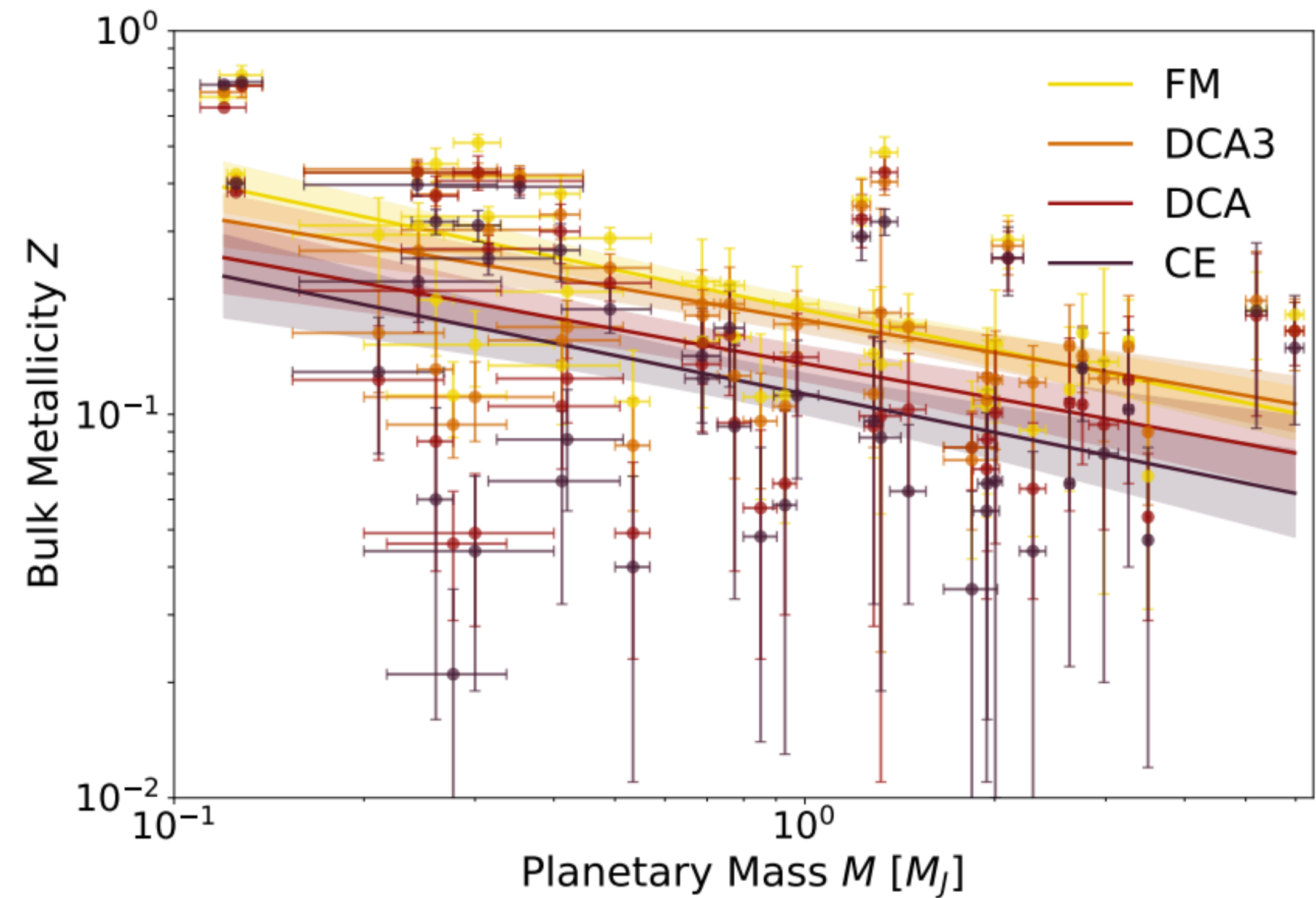


PLATO

Measuring compositions from mass and radius

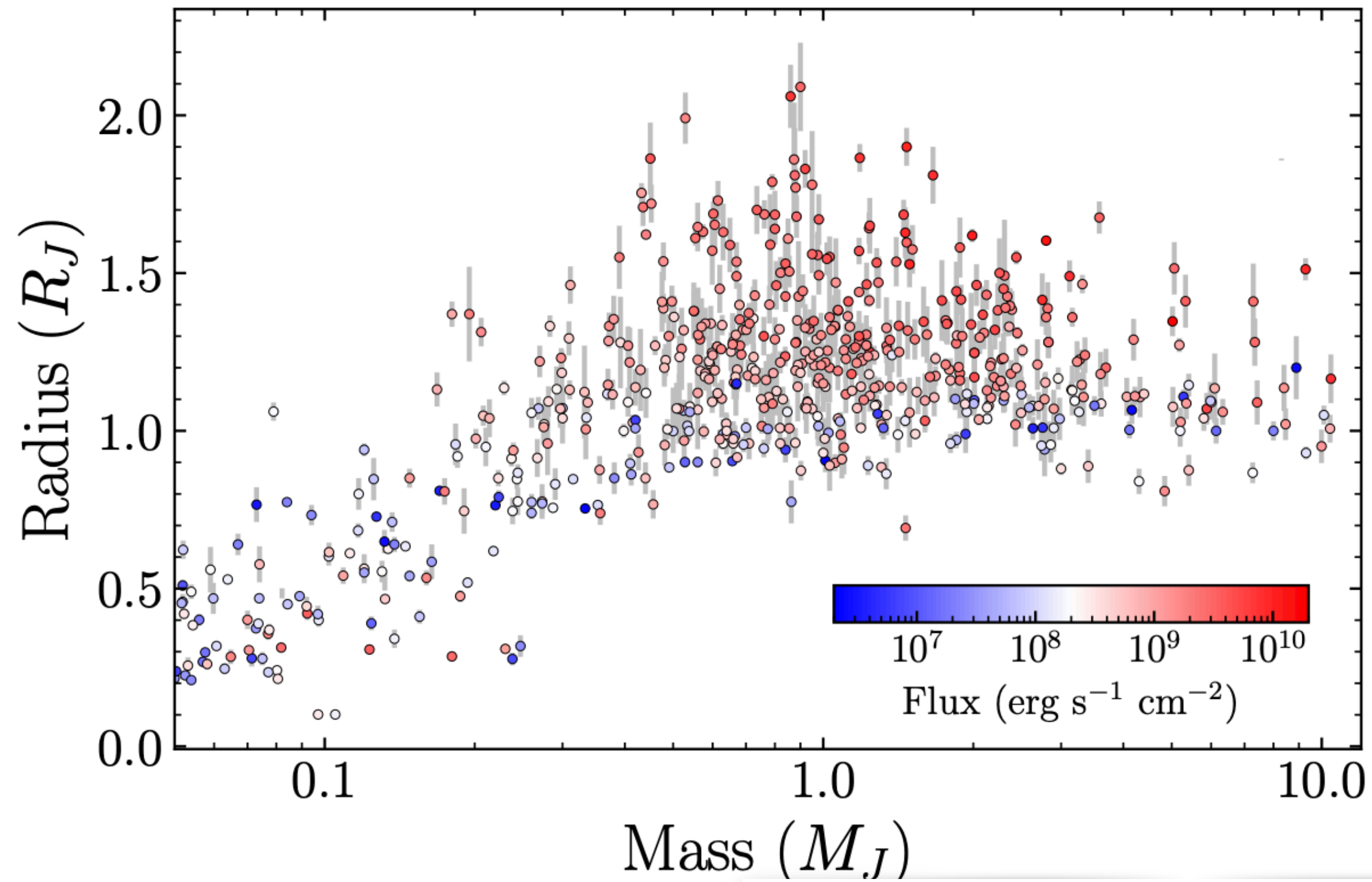


Thorngren (2025)

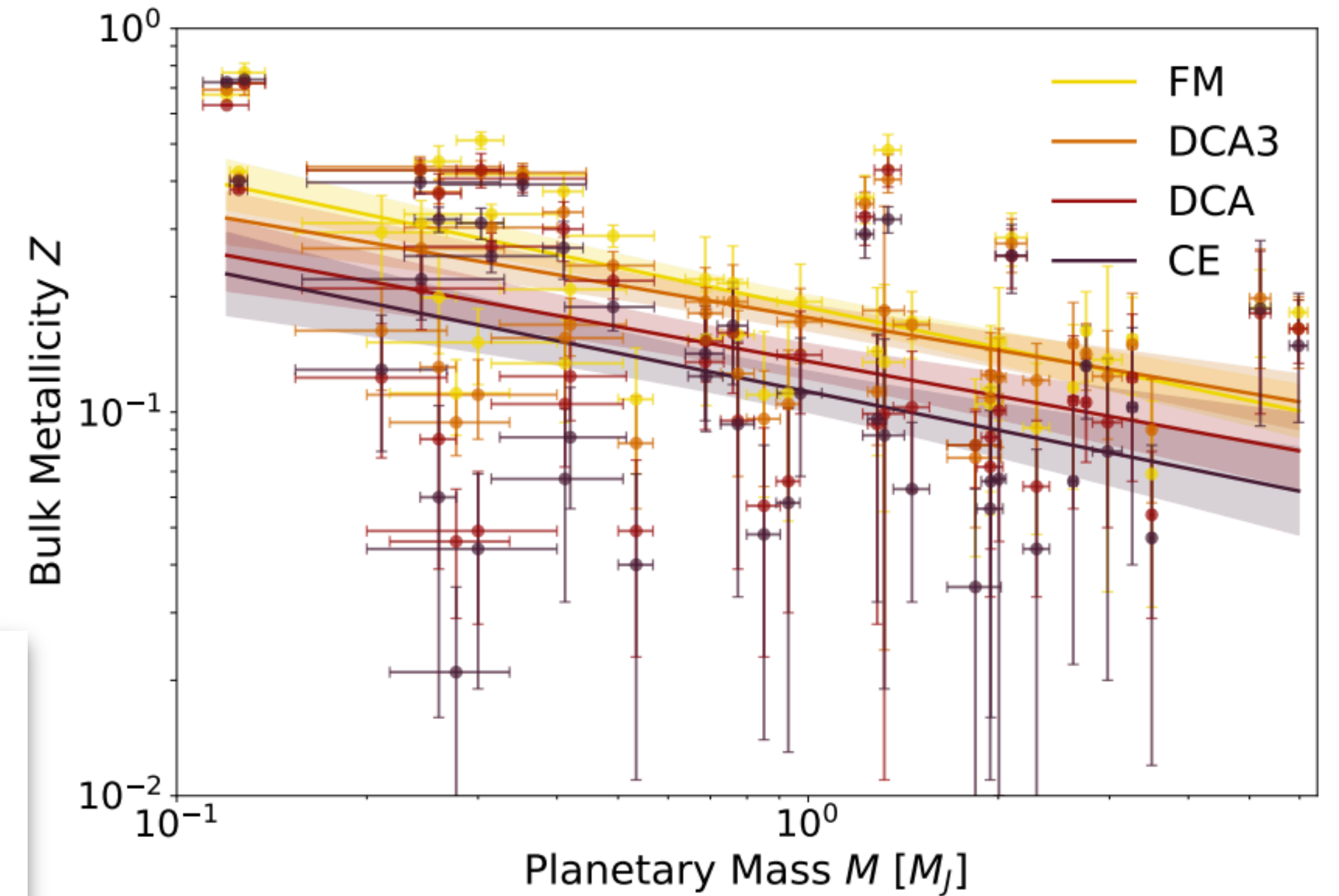


Peerani et al. (2026)

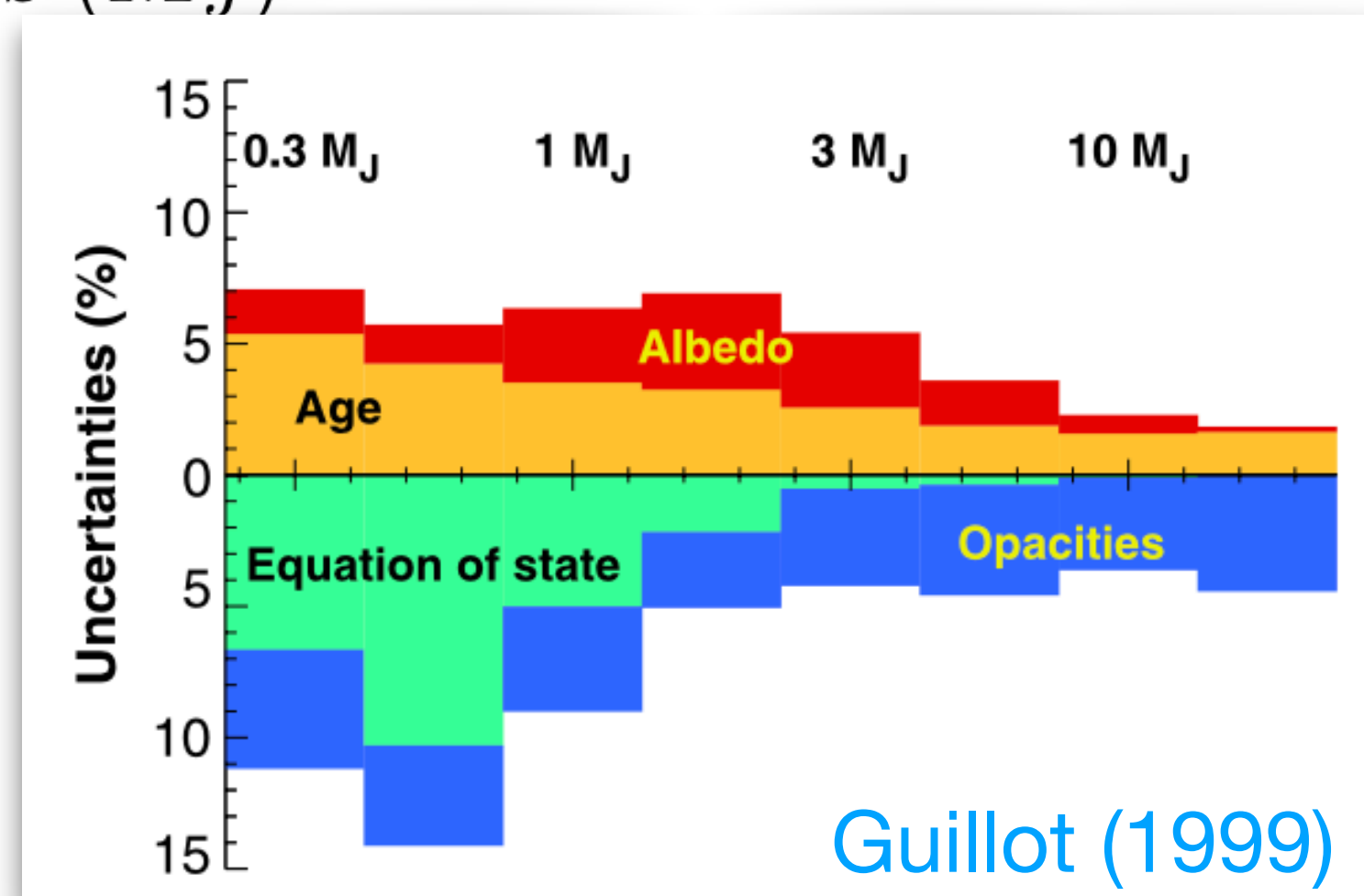
Measuring compositions from mass and radius



Thorngren (2025)



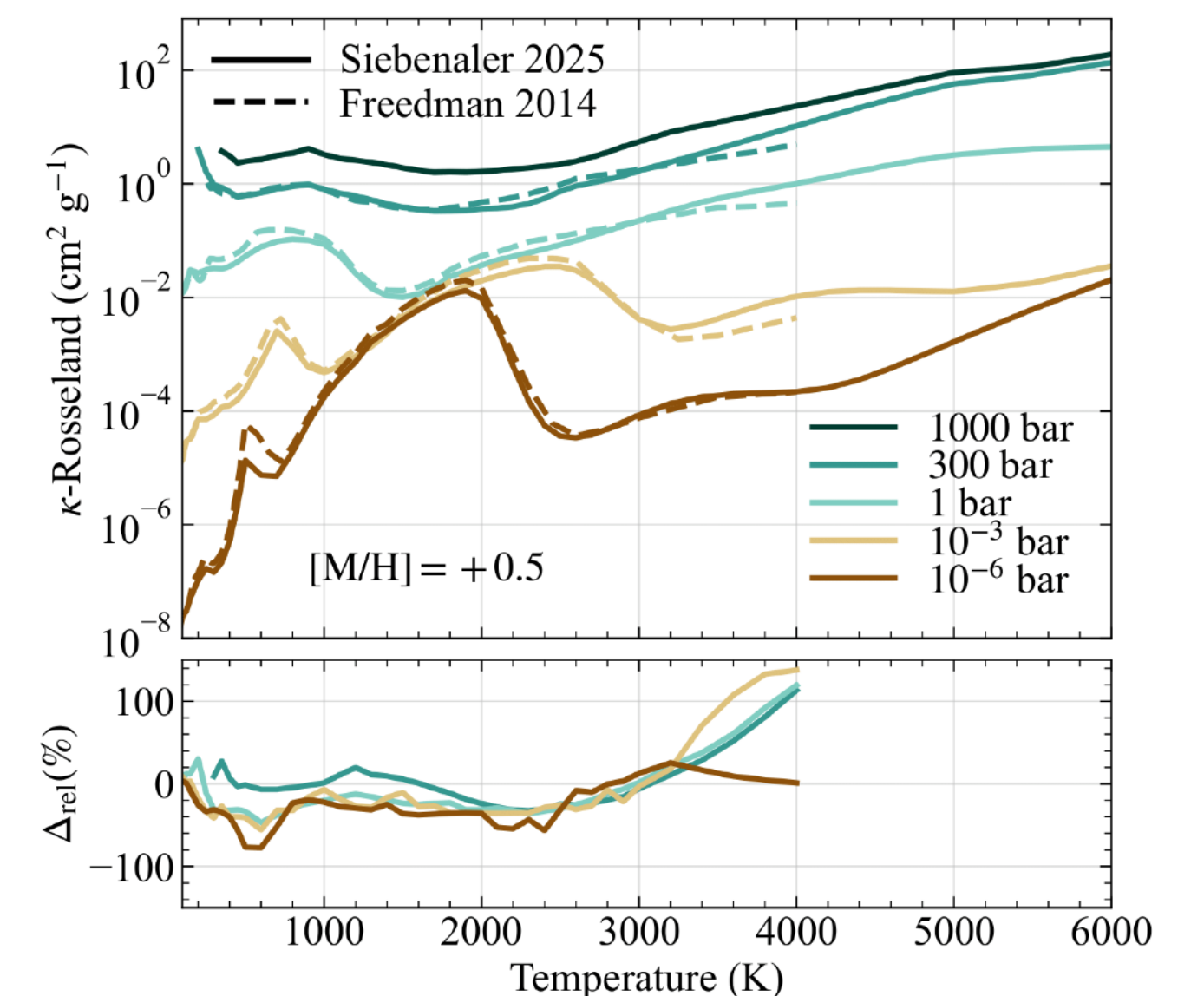
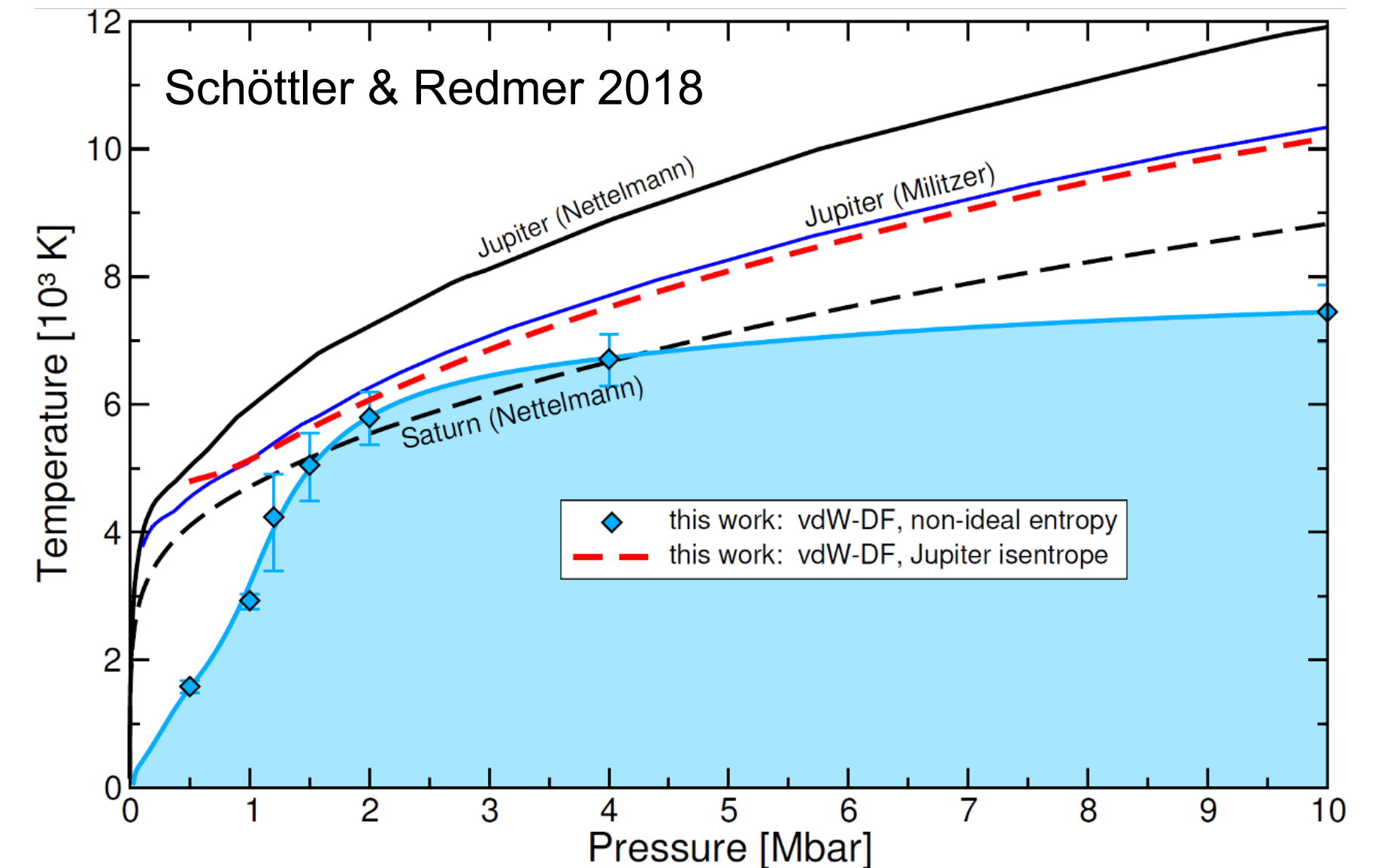
Peerani et al. (2026)

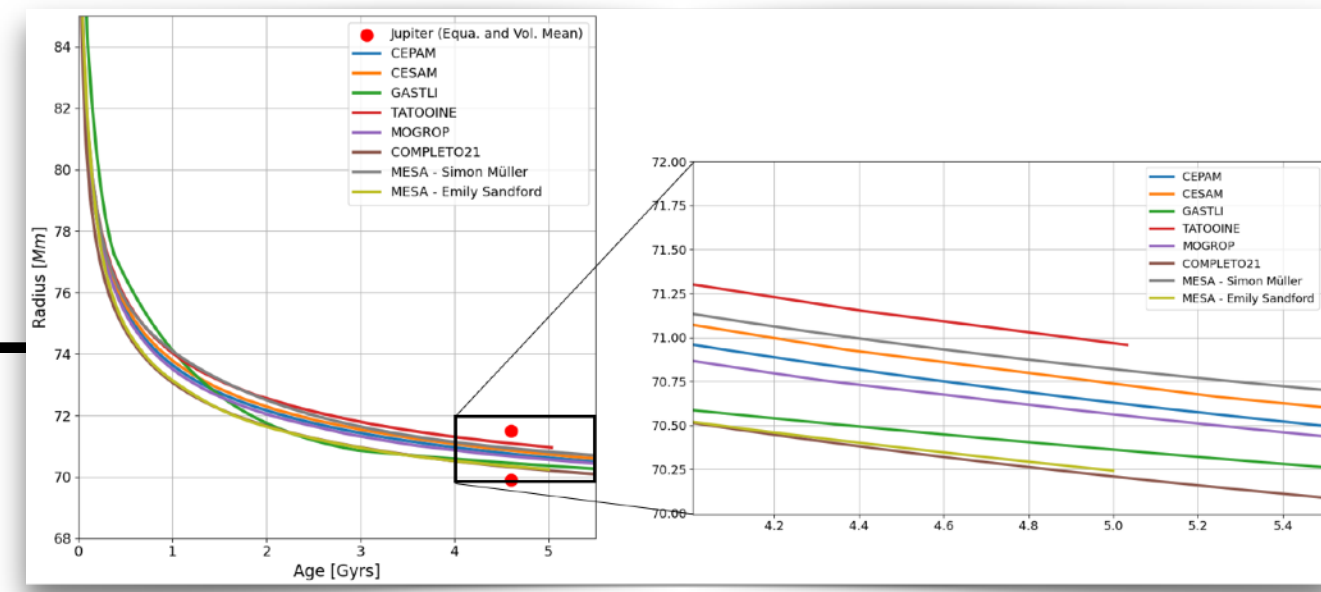


Guillot (1999)

The building blocks of interior & evolution models

- Interior model (quasi-hydrostatic)
- Atmospheric boundary conditions
 - radiative-convective boundary determination
 - opacities: grains, clouds, ...
- Equation(s) of state
 - Including possible phase separations
- Interior opacities
 - Radiative, conductive (Siebenaler and Miguel 2025)
- Additional physics
 - Heat dissipation (Ohmic, tidal...), evaporation, mixing...
- Initial conditions (a.k.a. formation model)





Benchmarking

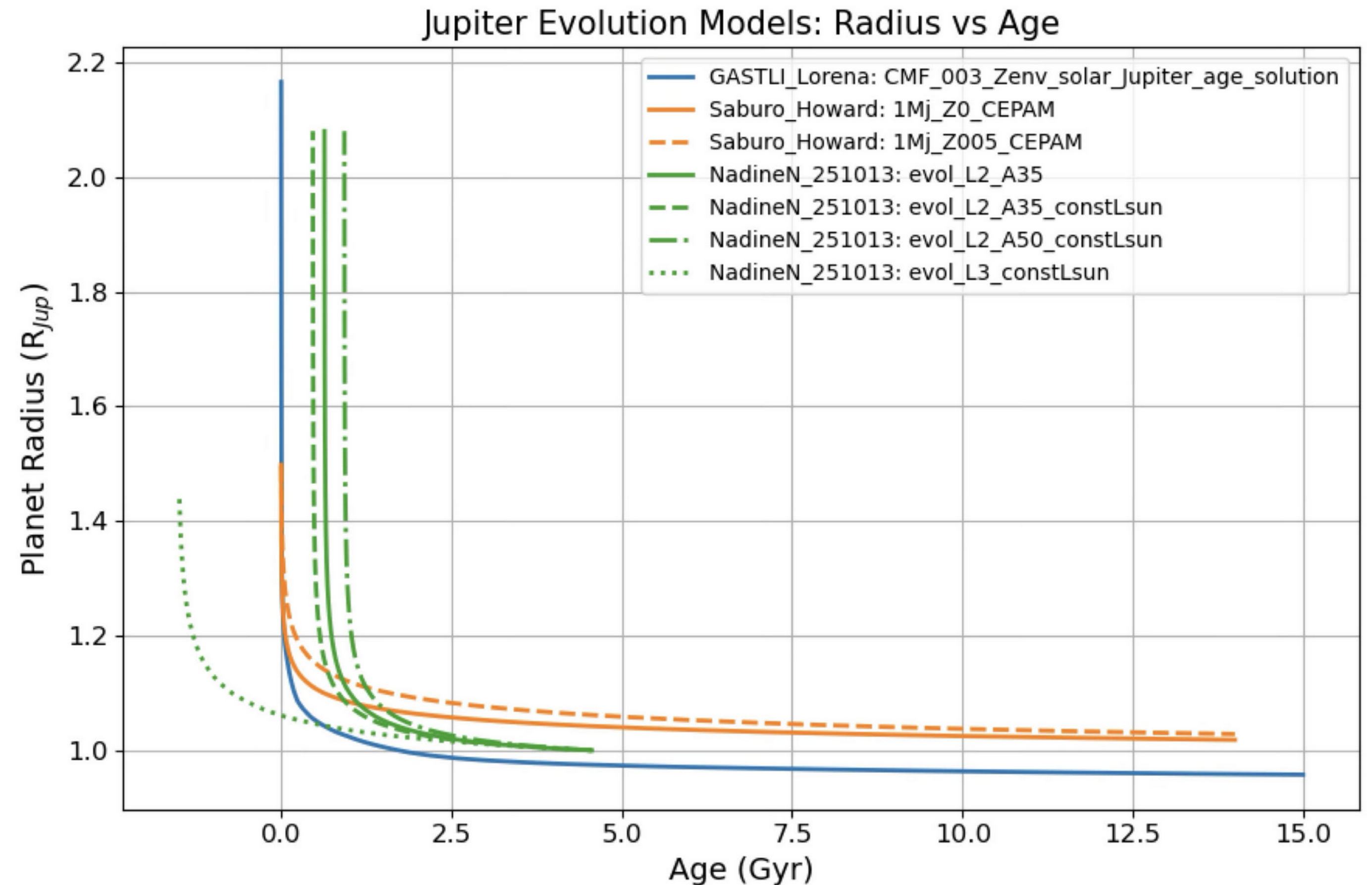
Interior and evolution models

Code	CEPAM	CESAM2k20	<u>COMPLETO21</u>	GASTLI	MESA	<u>MOGROP</u>	TATOOINE
Based on stellar evolution code	✓	✓			✓		
Mass range (Mj)	0.1-50	0.2-10000	0.01-50	0.05-5	-10 ⁵	0.01-10	0.01-10
Teq range (K)	0-2500	0-200	0-2500	100-1000	0-4000	0-4000	0-3000
Rad/conv zones?	✓	✓	✓	✓	✓	✓	✓
Interior mixing?		✓	✓		✓		
Phase sep?	✓				✓	✓	✓
Link w/ formation?			✓		✓		
Infer composition from R, M	✓		✓	✓	✓	✓	✓
<u>Reference</u>	Guillot & Morel 1995	Manchon et al. 2025	Mordasini et al. 2012	Acuña+ 2024	Paxton+	Nettelman n+2012	Baumeister+ 2020

Benchmarking: Initial step

A simple evolution model:

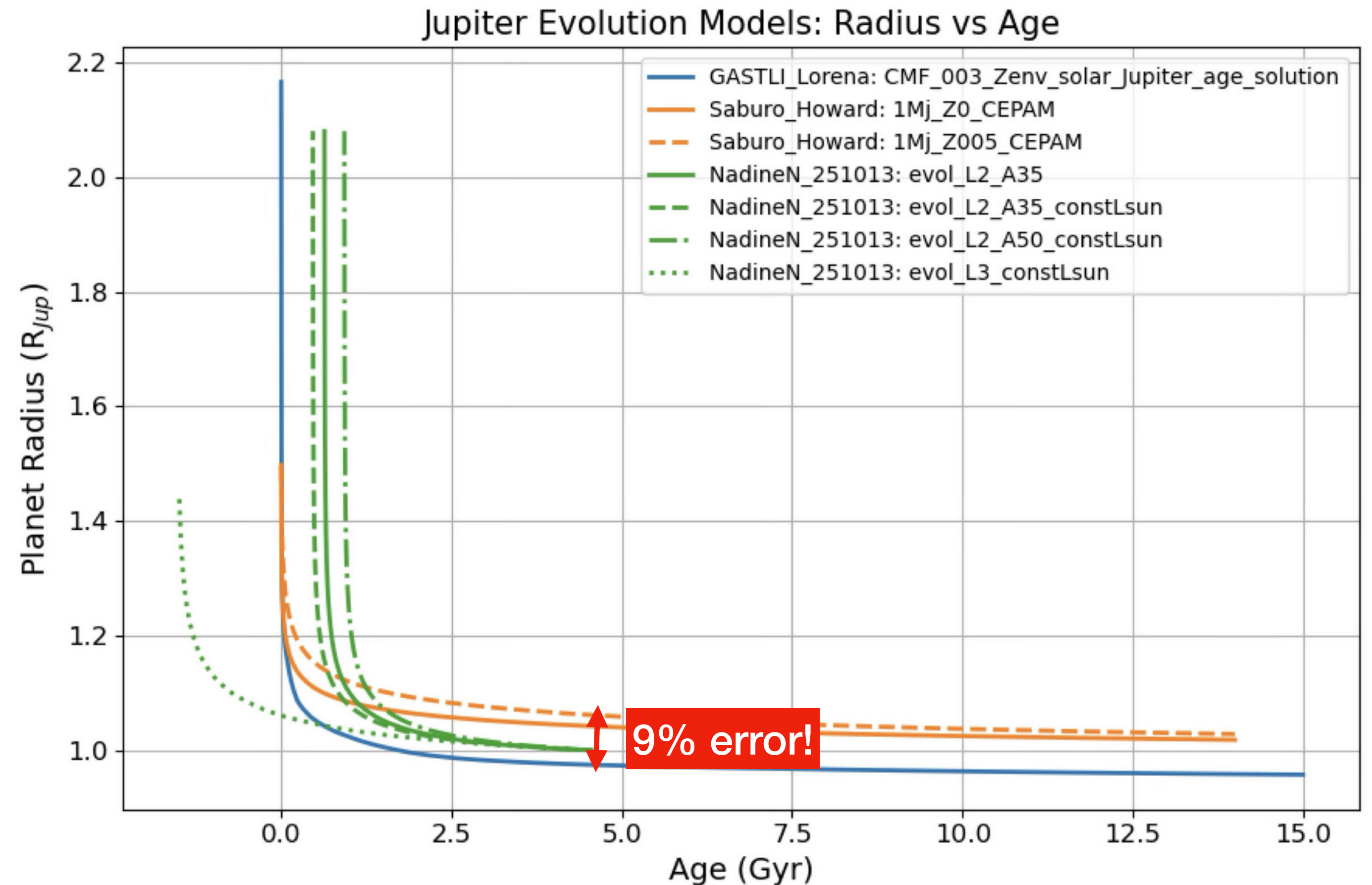
- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)



Benchmarking: Initial step

A simple evolution model:

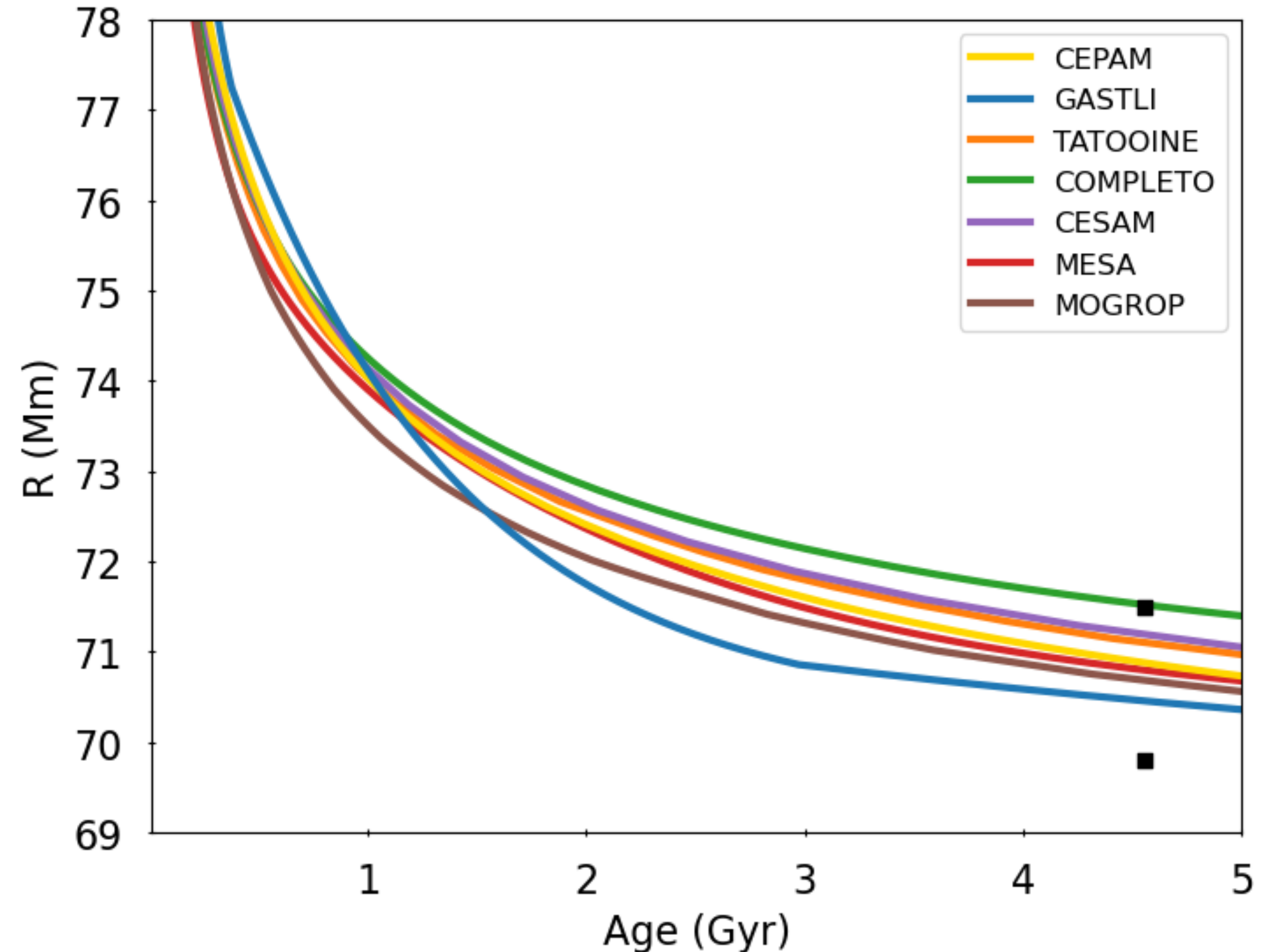
- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)



Benchmarking: January 2026

A simple evolution model:

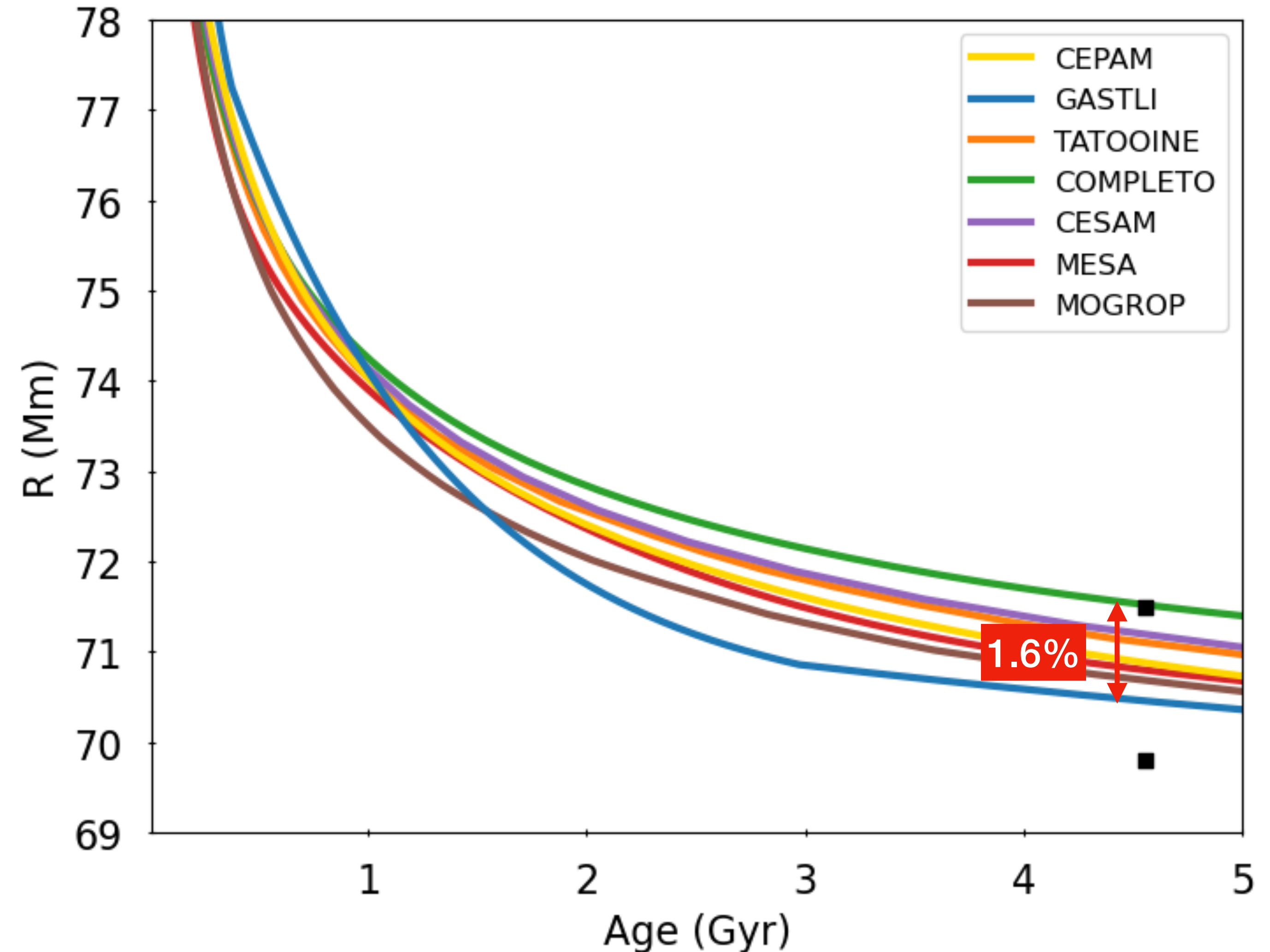
- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)



Benchmarking: January 2026

A simple evolution model:

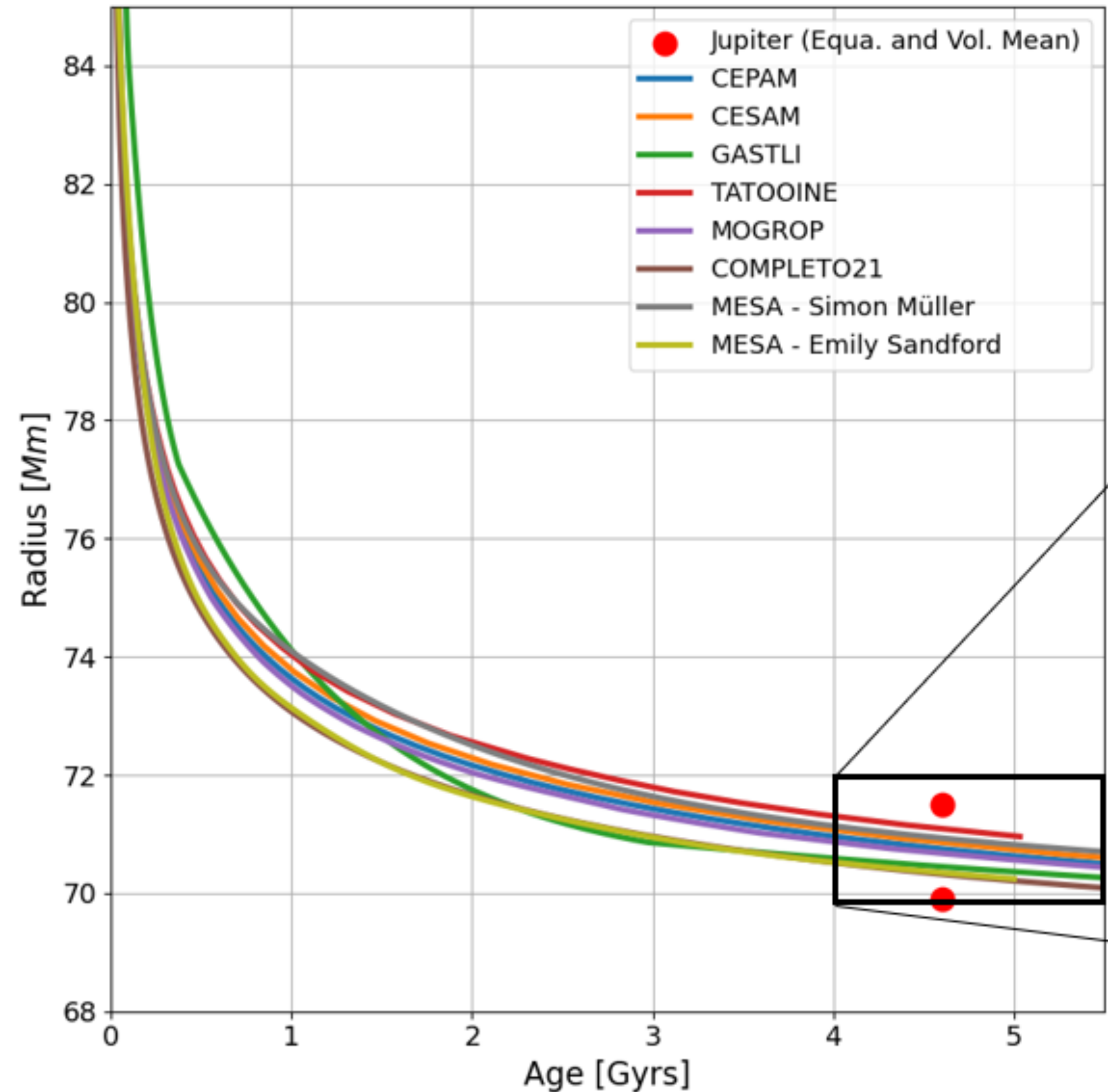
- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)



Benchmarking: Latest models

A simple evolution model:

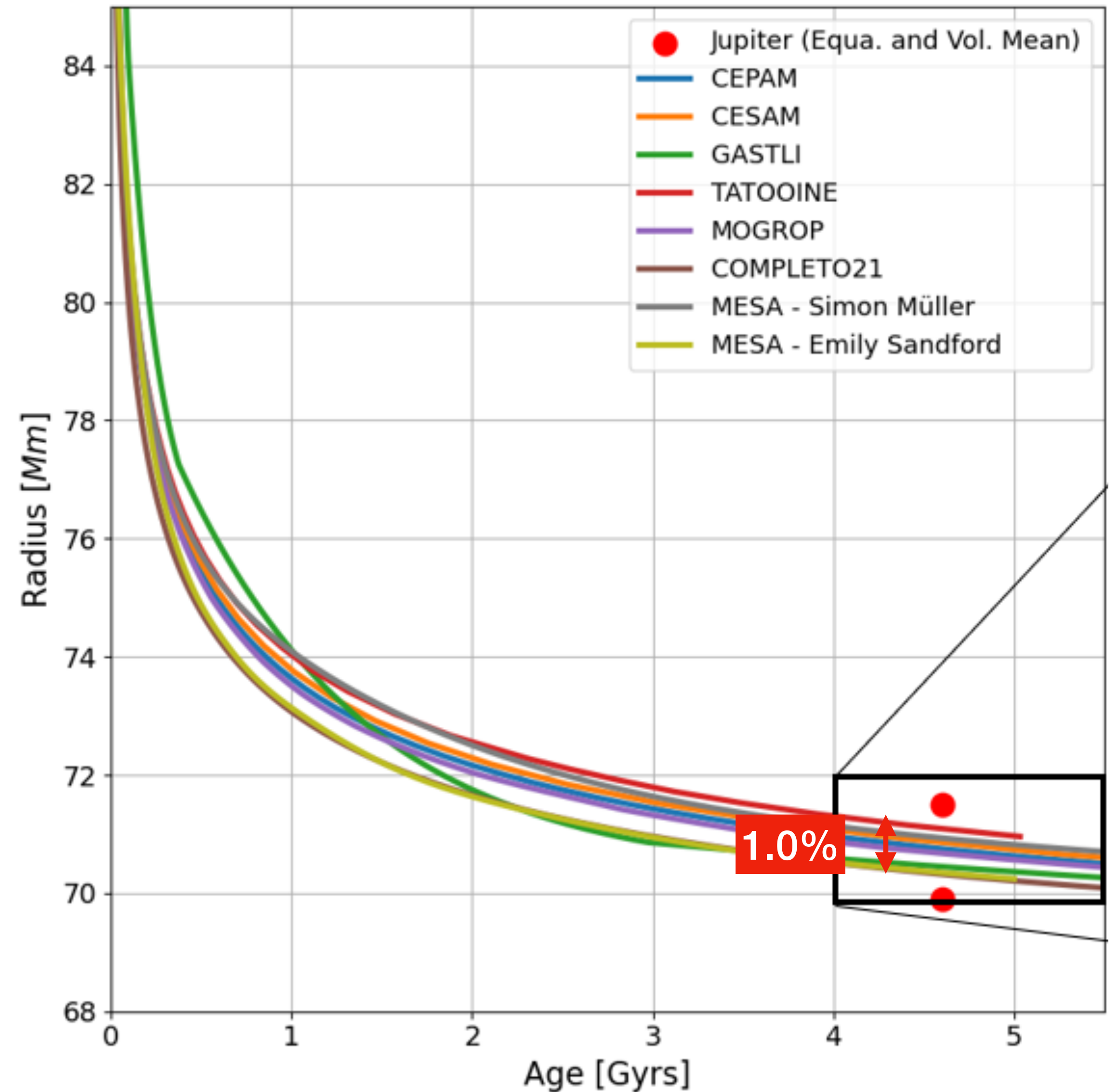
- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)



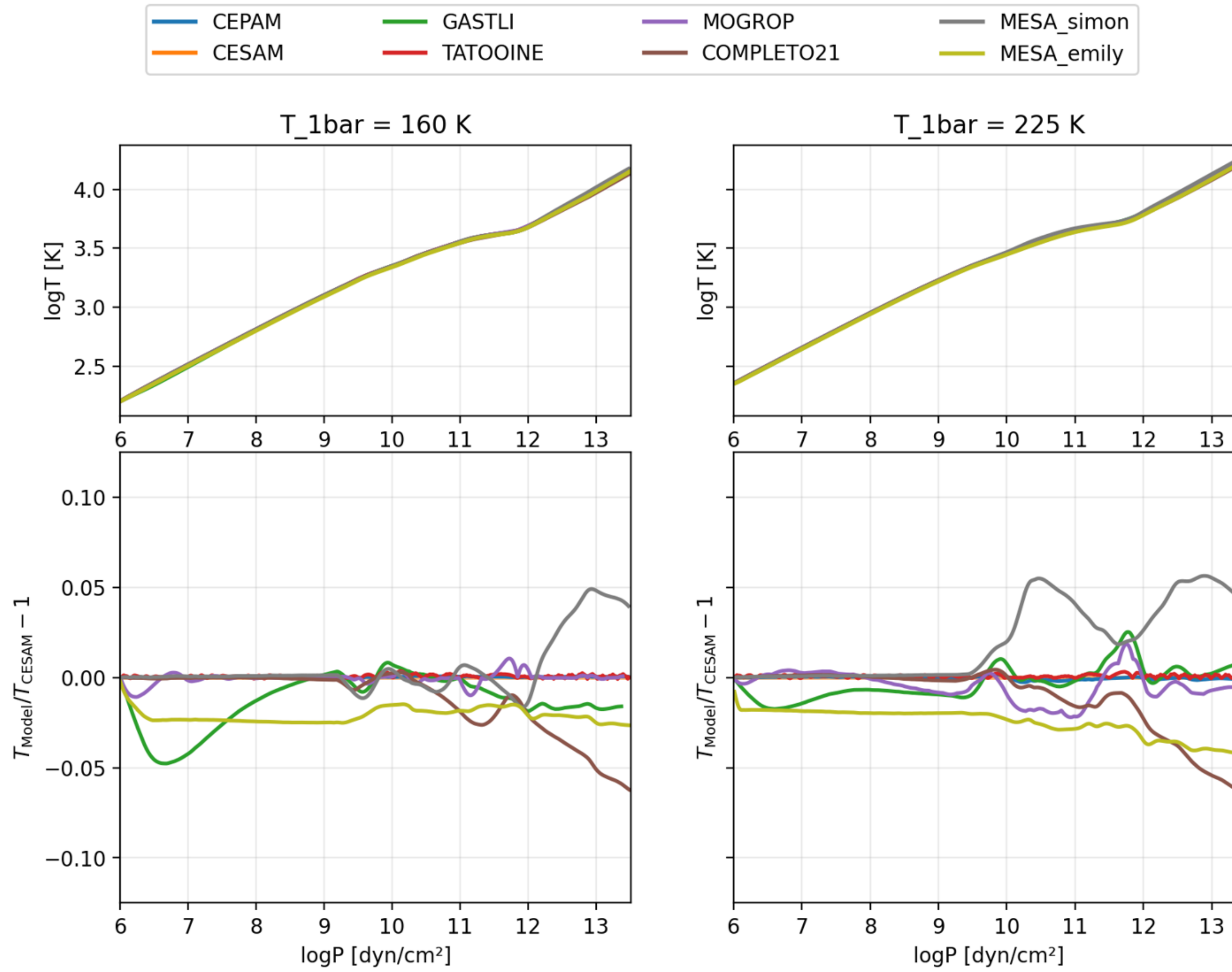
Benchmarking: Latest models

A simple evolution model:

- 1 Mj
- $Y=0.275$
- H-He EOS (Chabrier & Debras 2021)
- NO core
- NO heavy elements
- Adiabatic interior
- Simplified boundary condition from Guillot+2010 ($T^4 = 5T_{\text{int}}^4 + T_{\text{eq}}^4$)

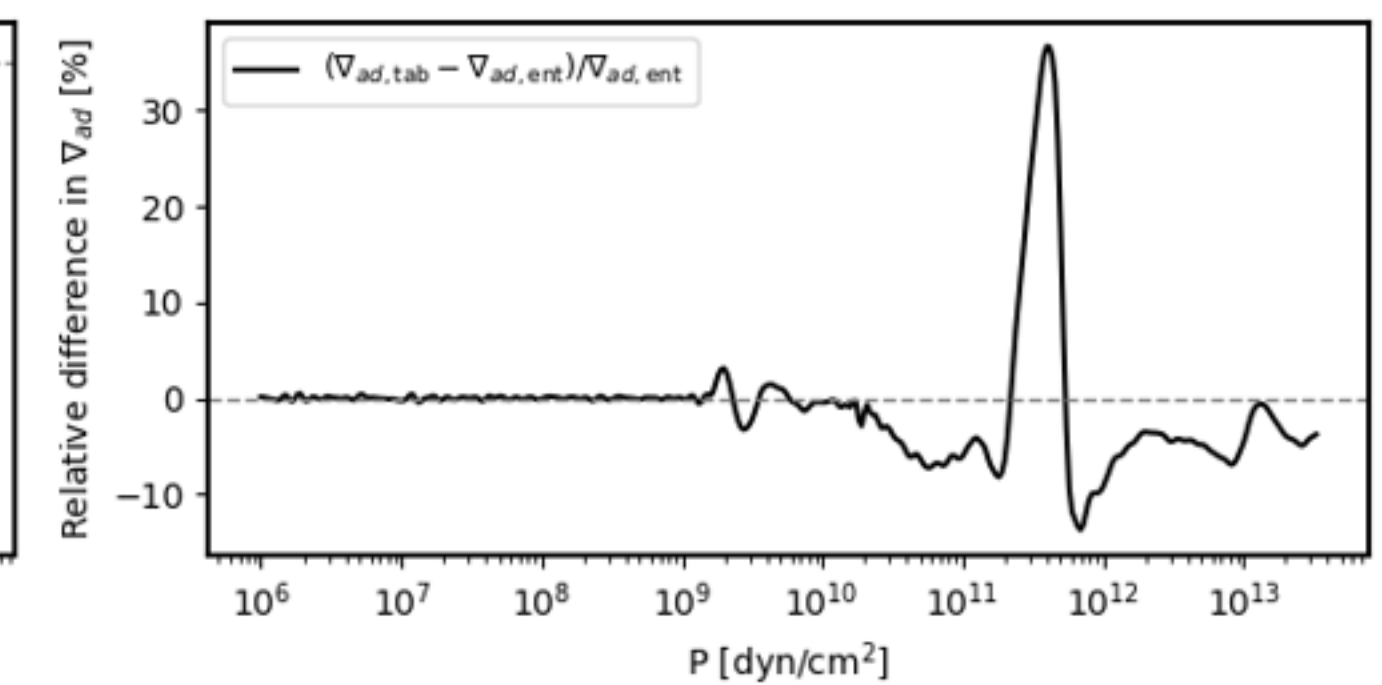
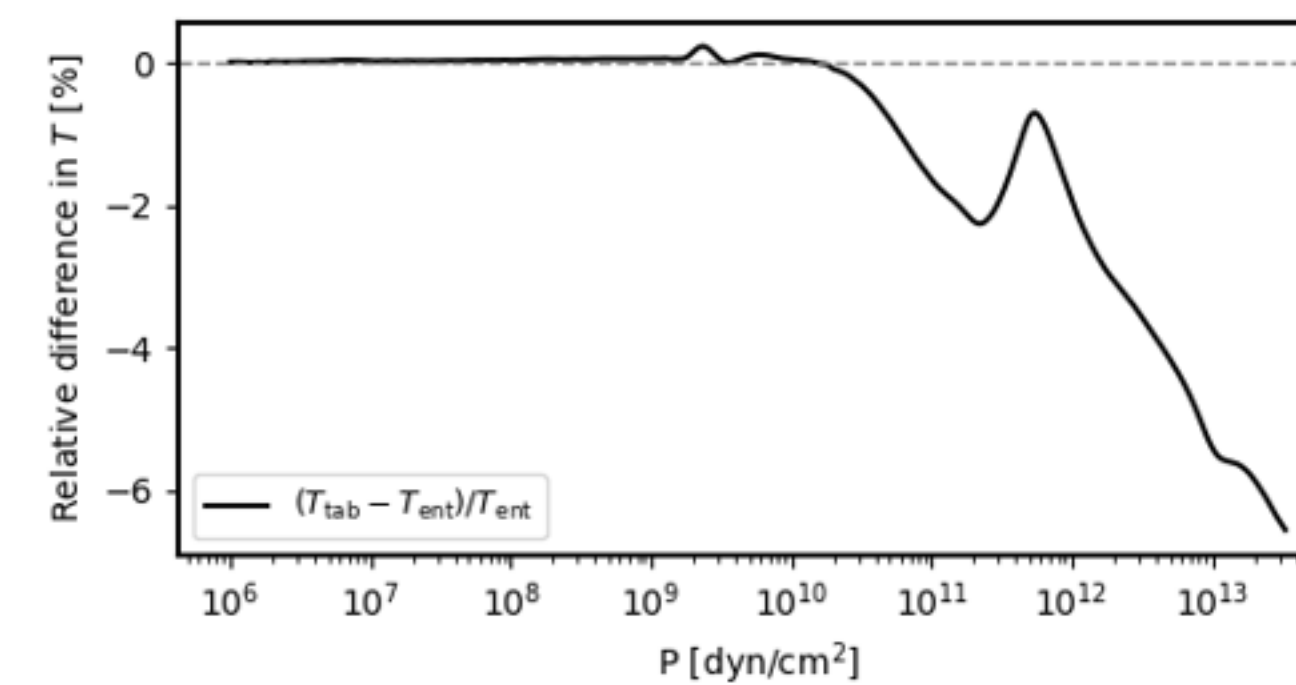
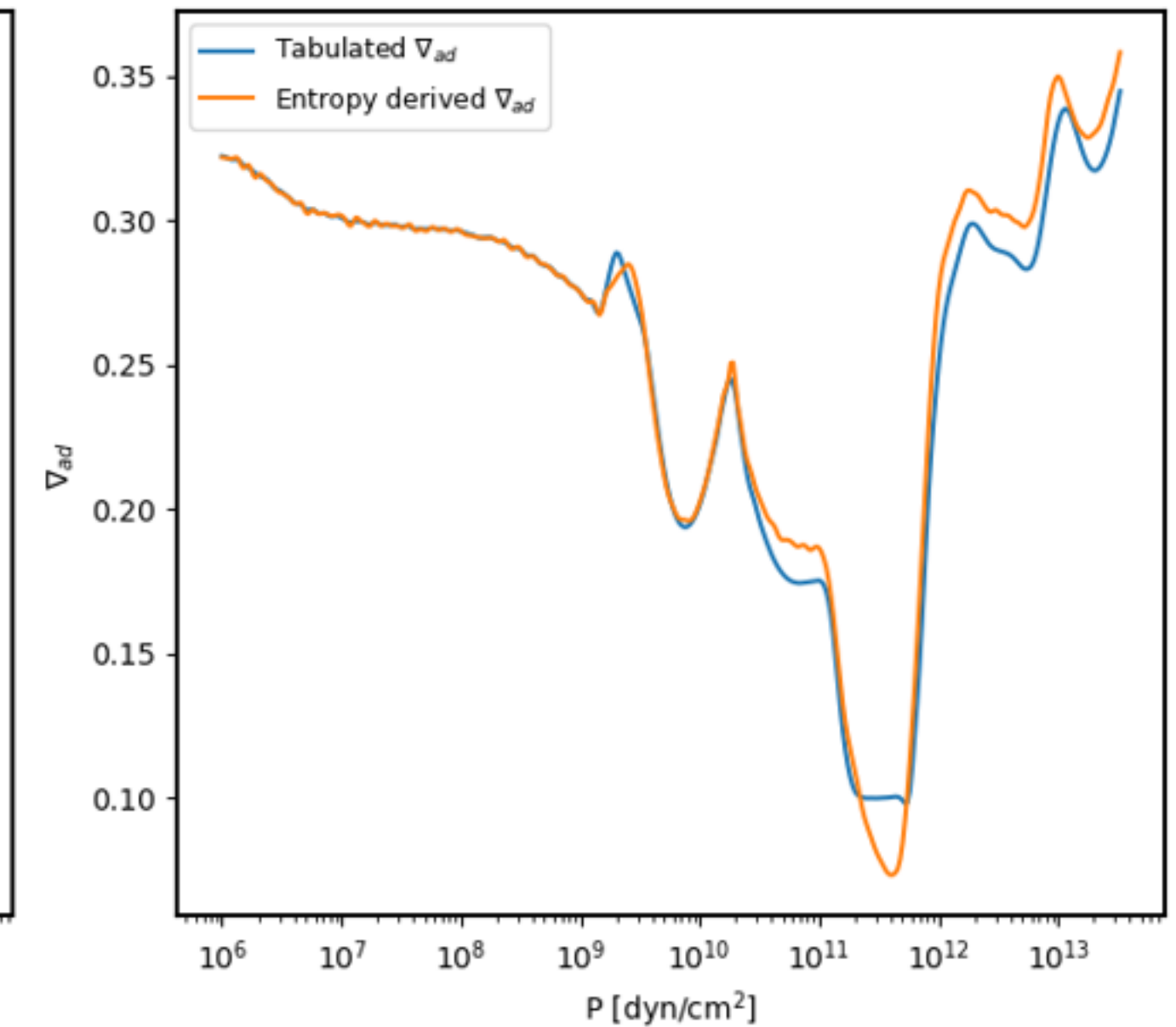
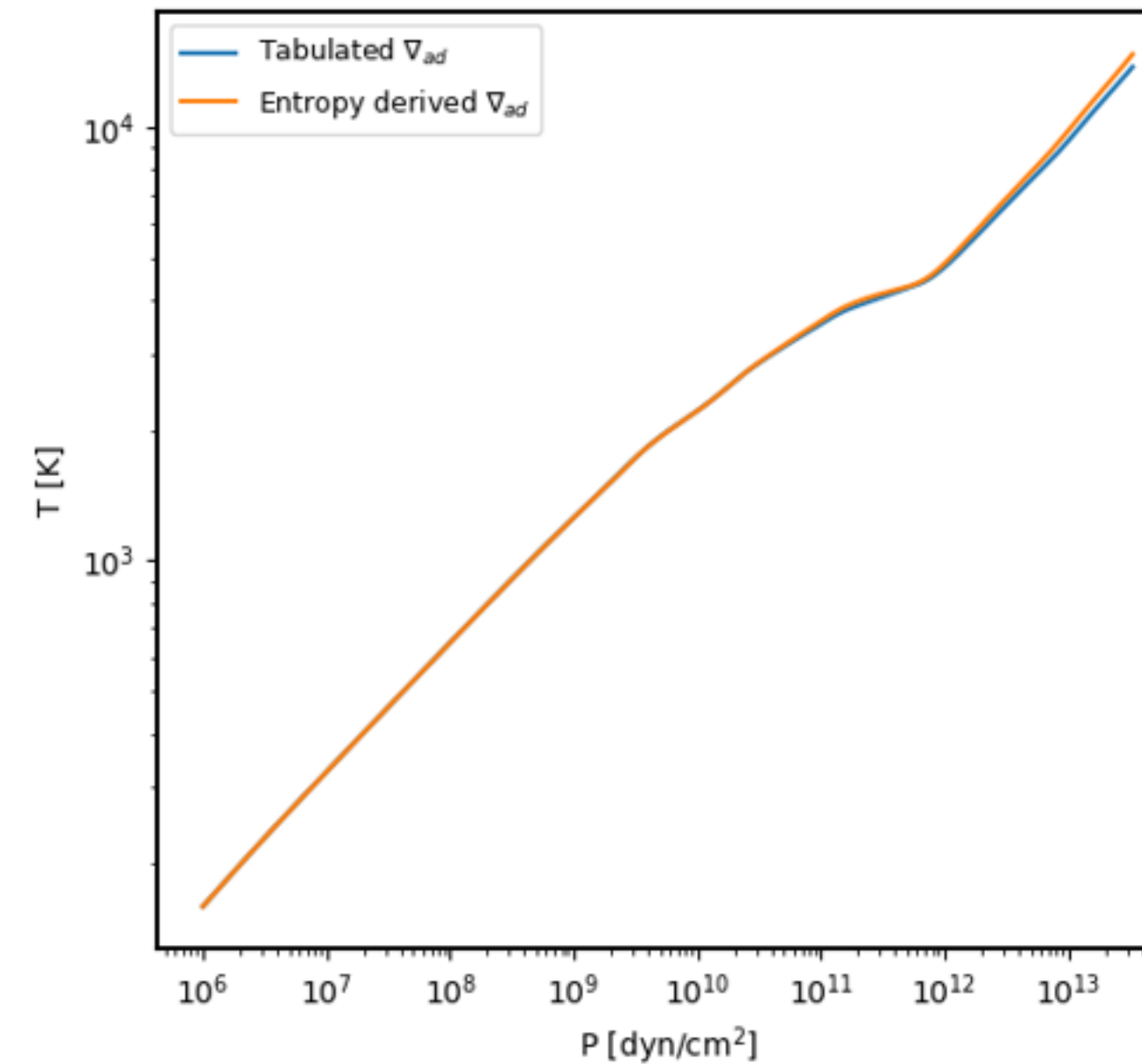


Comparison of interior profiles



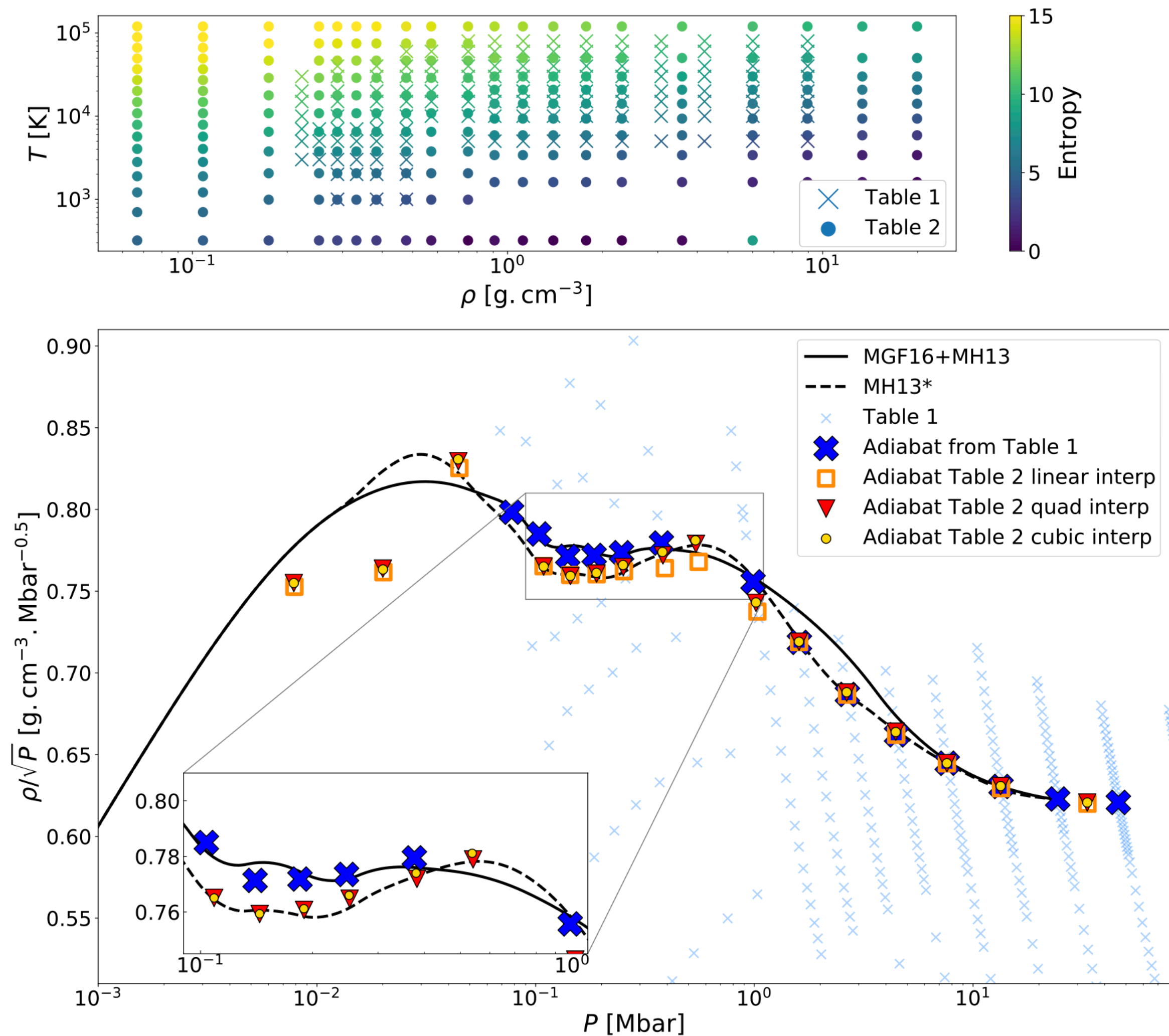
EOS problems

- In CMS19/CD21, using the tabulated vs calculated adiabatic gradient leads to a 6% temperature offset!
 - (Nadine Nettelmann, Luke Gauvrit)
- Issues with how tables are joined
 - talk by Luke Gauvrit
- Issues with thermodynamic consistency
 - talk by Emily Sandford



EOS problems

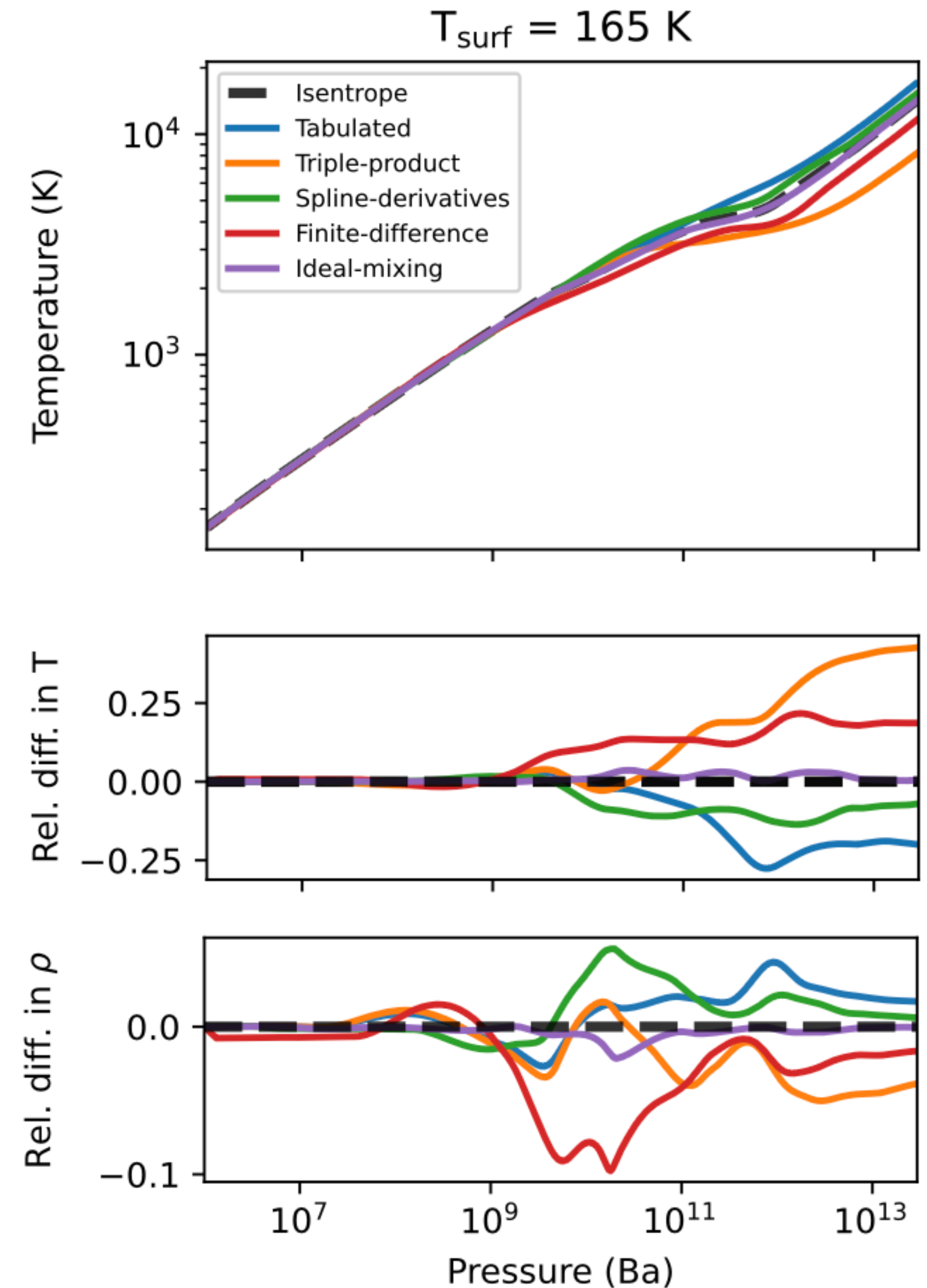
- In CMS19/CD21, using the tabulated vs calculated adiabatic gradient leads to a 6% temperature offset!
- (Nadine Nettelmann, Luke Gauvrit)
- Issues with how tables are joined
- talk by Luke Gauvrit
- Issues with thermodynamic consistency
- talk by Emily Sandford
- Issues with numerical derivatives!



Howard et al. (2023)
based on Militzer & Hubbard (2013)

EOS problems

- In CMS19/CD21, using the tabulated vs calculated adiabatic gradient leads to a 6% temperature offset!
- (Nadine Nettelmann, Luke Gauvrit)
- Issues with how tables are joined
 - talk by Luke Gauvrit
- Issues with thermodynamic consistency
 - talk by Emily Sandford
- Issues with numerical derivatives!
 - Müller & Helled (submitted)



Müller & Helled (submitted)

Next steps

- Adding hot Jupiter models
 - With radiative zone
 - Analytical atmospheric boundary condition vs. from a radiative transfer grid
- Comparing inferred masses of heavy elements
 - For known planets in the LOPS2 field (still TBD)

Summary

- Juno provides a view of Jupiter's complexity
 - Depth of zonal flows
 - Dilute core
 - Shape
 - A new equatorial radius, 71488 km
 - A ~5K warmer pole than equator at depth ?
- PLATO will provide accurate parameters of 100s of ice and gas giants
 - Benchmarking is essential
 - Absolute vs. Relative differences
- We're entering an era of comparative planetology