Rocky and Vapor Worlds: Composition and Structure

Diana Valencia, 7 June 2011
NASA Sagan Fellow, MIT

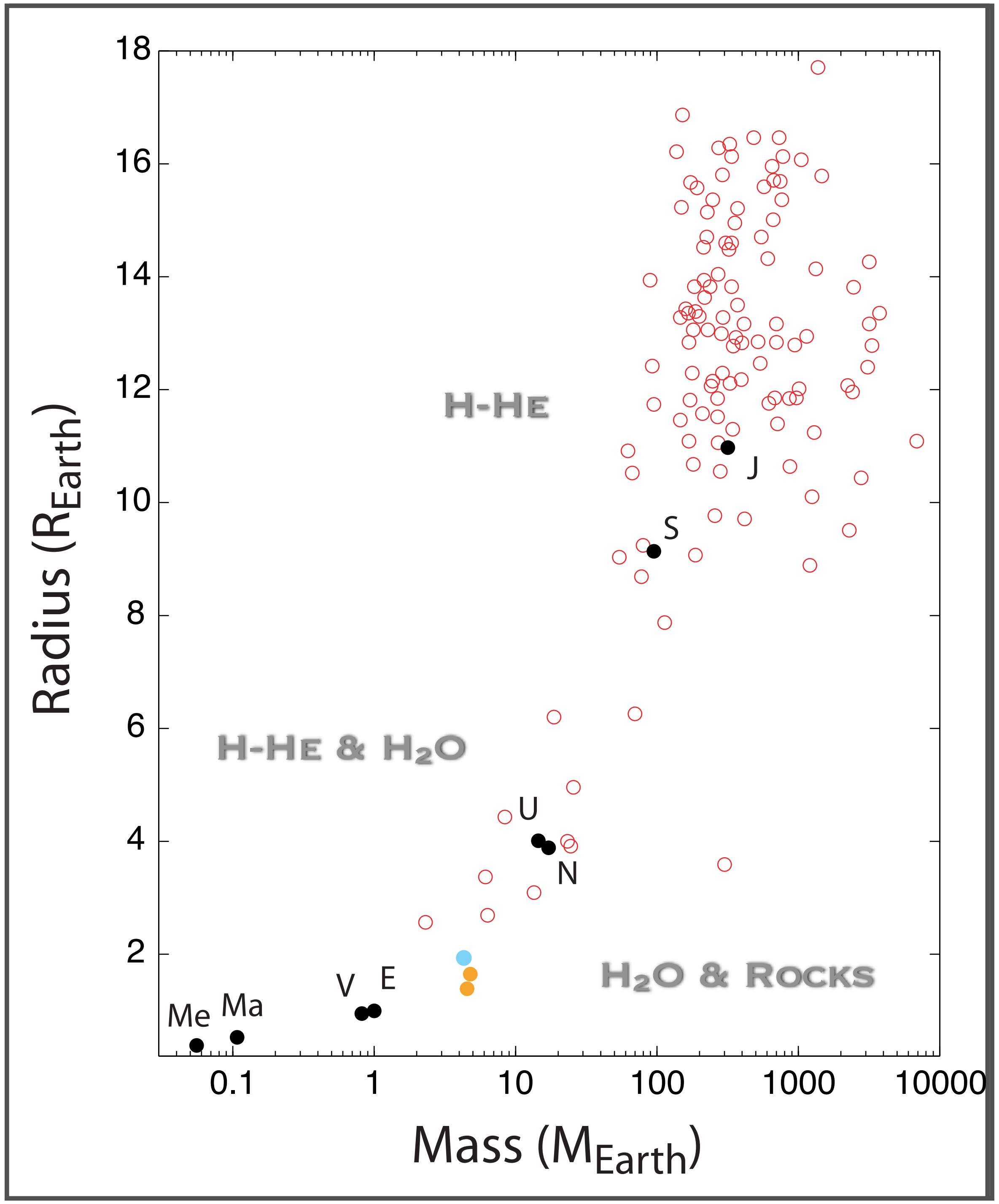
Extrasolar Planets: Towards Comparative Planetology beyond the Solar System

Super-Earths in the context of exoplanets

Super-Earths complete the inventory of planets for formation models

Intermediate objects that allow for comparative planetology

May be habitable

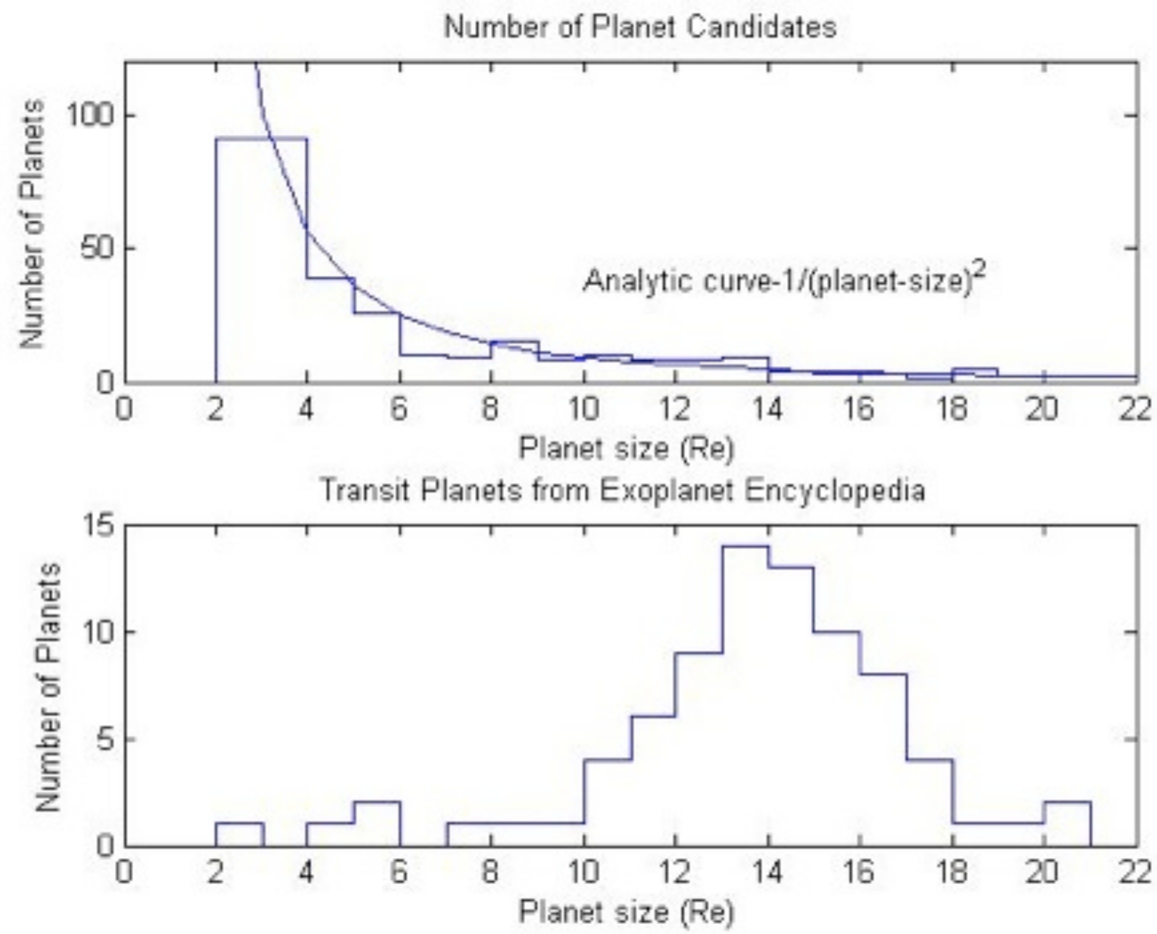


Super-Earths

Measured masses and radii of Super-Earths

About 15% of stars have SE planets (perhaps up to 40%)

Spectroscopy of super-Earths



Borucki, '10

Data & Challenges

Period & estimates of T_{eff}, Age

Minimum Mass -- RV surveys

Radius Only -- Kepler Candidates

M & R

Coarse Spectroscopy

Phase Curves

Complexity in Composition

Complex Dynamic Interiors

Complex Atmospheres

Few data points in the Solar System

Characterizing super-Earths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Are they habitable?


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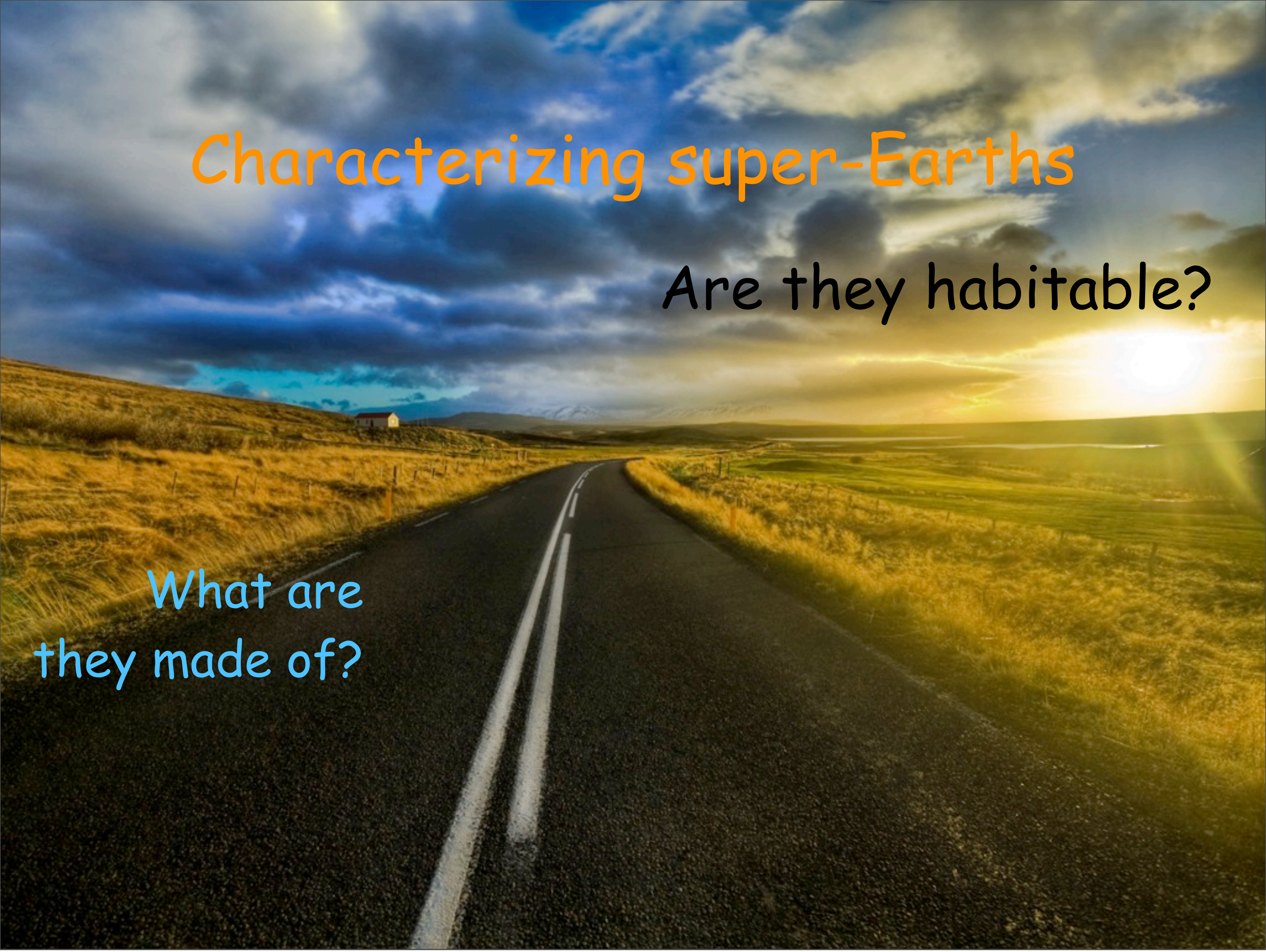
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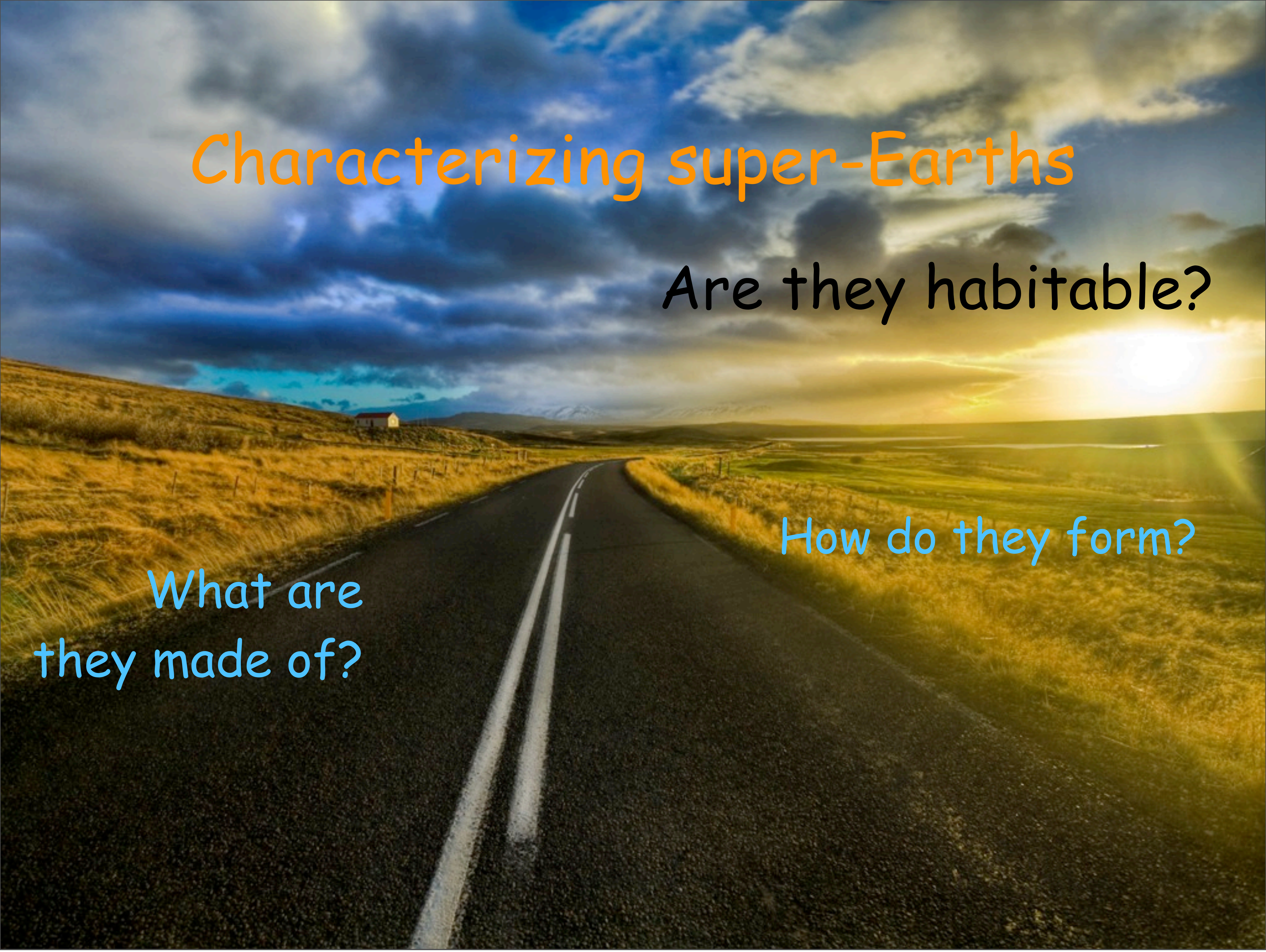
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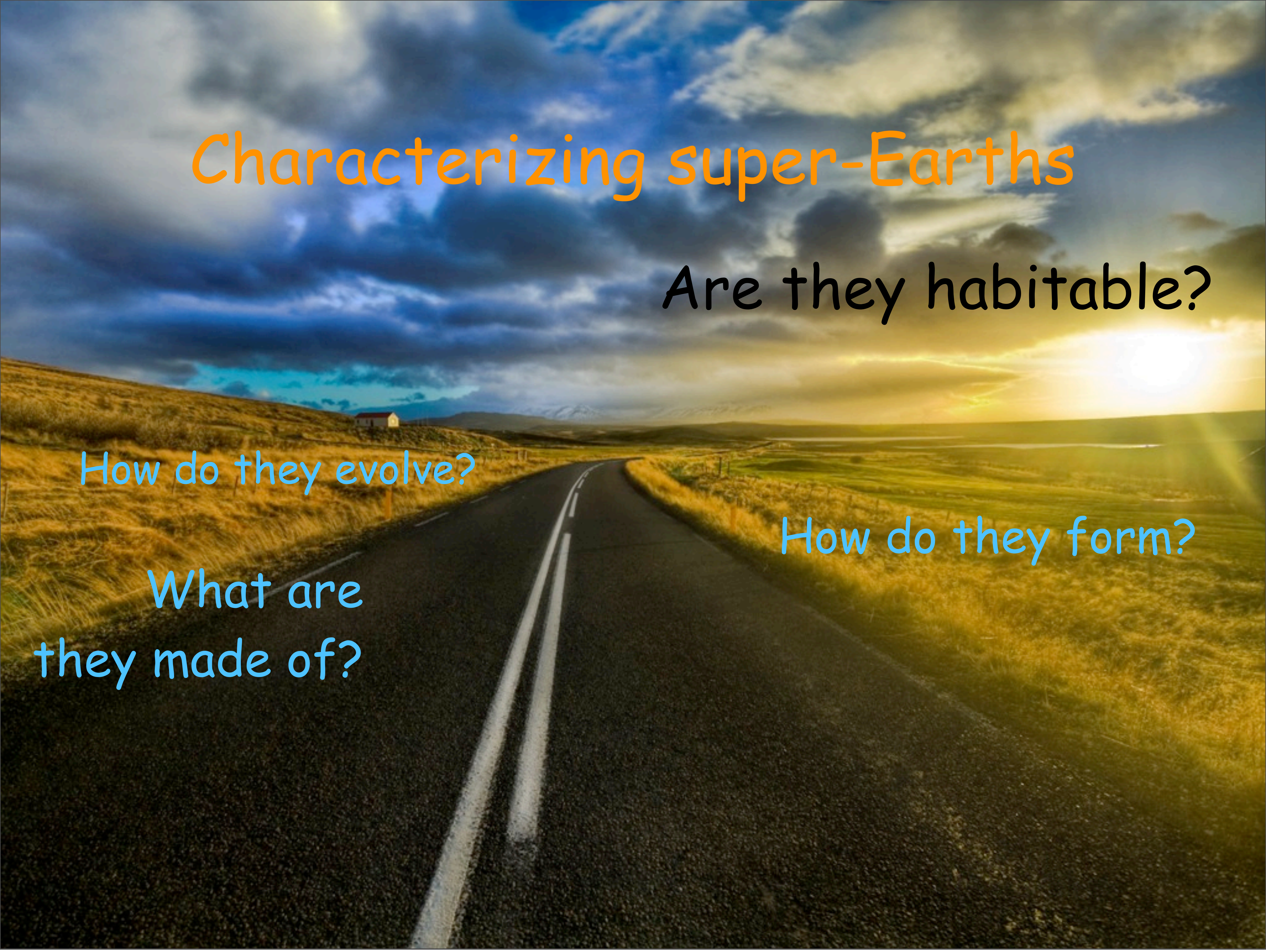
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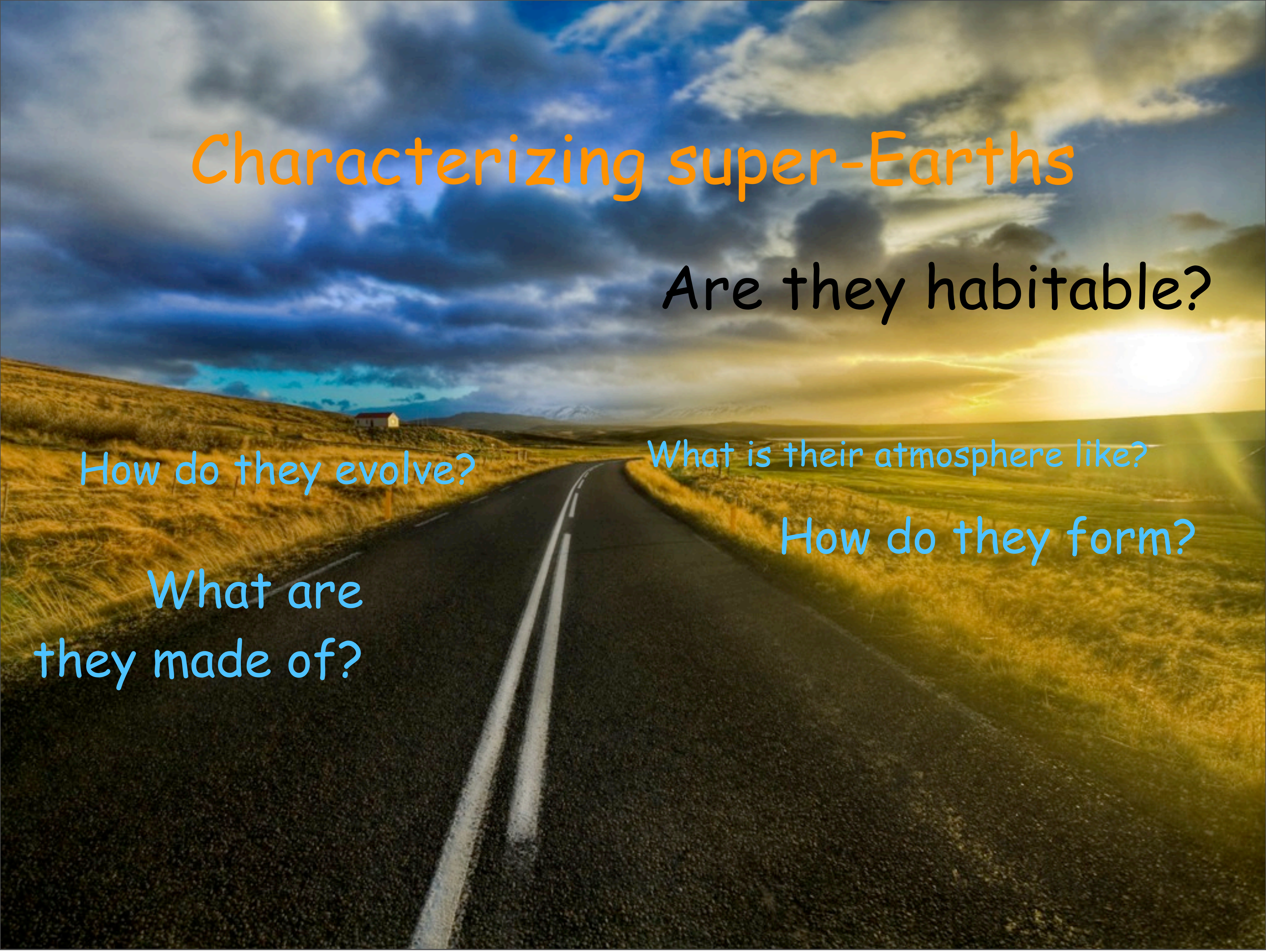
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Single Planets
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Now we have M & R + P, T_{eff}, Age

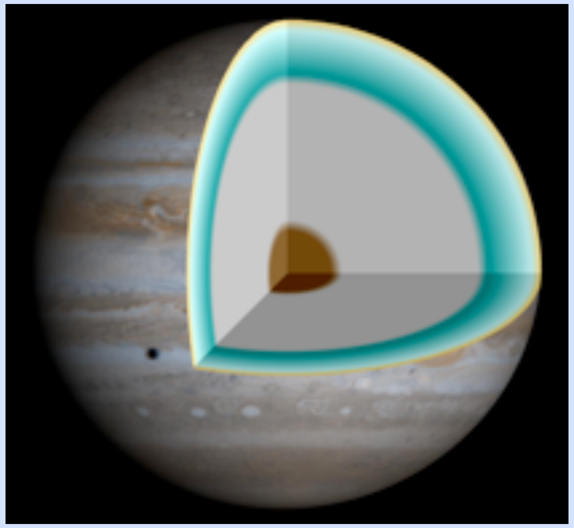
The First Transiting super-Earths

	CoRoT-7b	Kepler-10b	55Cnc-e	GJ 1214b
Radius (R_E)	1.58 ± 0.1	$1.416^{+0.033}_{-0.036}$	1.63 ± 0.16 $2.13^{+0.13}_{-0.14}$	2.678 ± 0.13 2.27 ± 0.08
Mass(M_E)	4.8 ± 0.8, 6.9 ± 1.5 8.0±1.2 , 5.7 ± 2.5, 2.3 ± 1.8 **7.26 ± 1.36**	$4.56^{+1.17}_{-1.26}$	8.57 ± 0.64 8.0 ± 0.7	6.55 ± 0.98
Period (J)	0.854	0.837	0.74	1.58
Age (Gy)	1.2 - 2.3	11.9 (± 4.5)	~ 5	3-10
Temp (K)	1800	1800	2000	393-555
Ref.	Leger et al '09, Queloz et al '09, Pont et al 10', Hatzes et al '10 & '11, Boise et al '10, Ferraz-Mello et al '10	Batalha et al 2010	Winn et al 2011 Demory et al 2011	Charbonneau et al 2009, Carter et al 2011

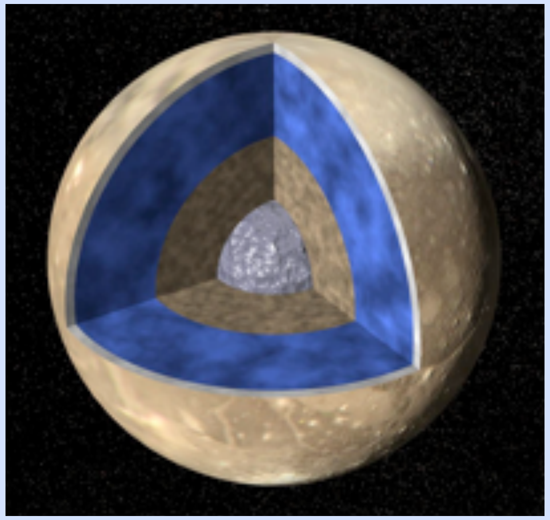
Recipe: Internal Structure Model

☑ Assume a composition

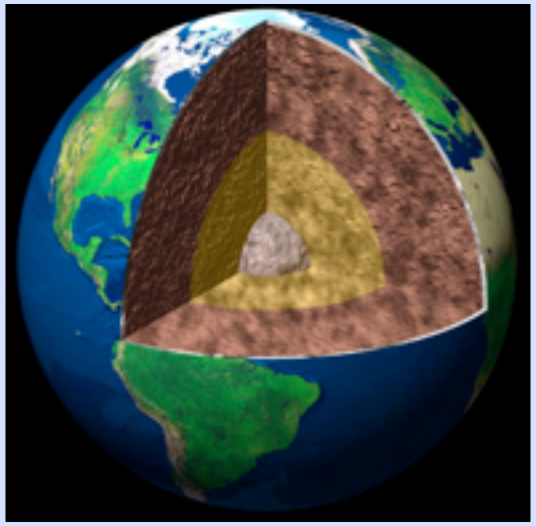
H-He



H_2O, CH_4,..



Si, O, Mg, Fe



☑ Solve structure equations
(M, ρ , P, g, T, S)

☑ Need an EQUATION OF STATE

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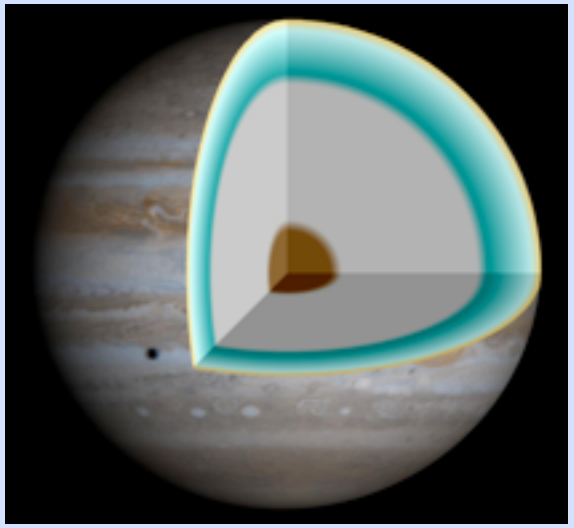

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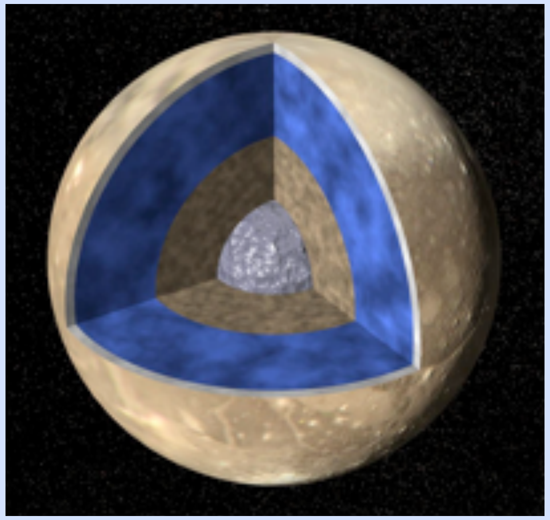

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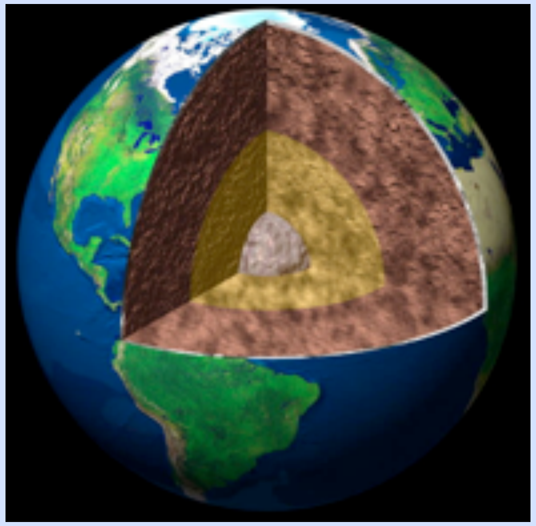

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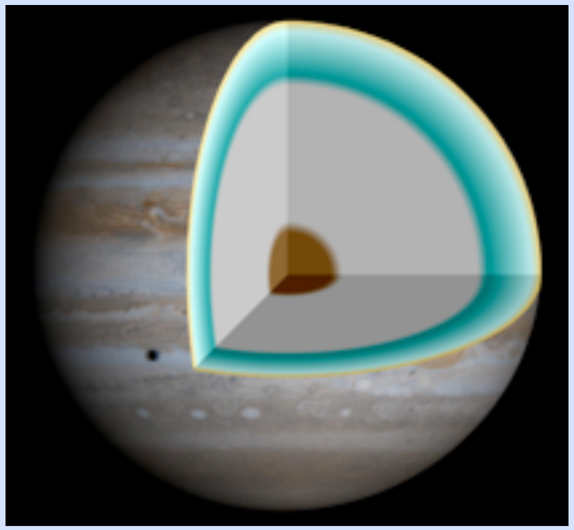

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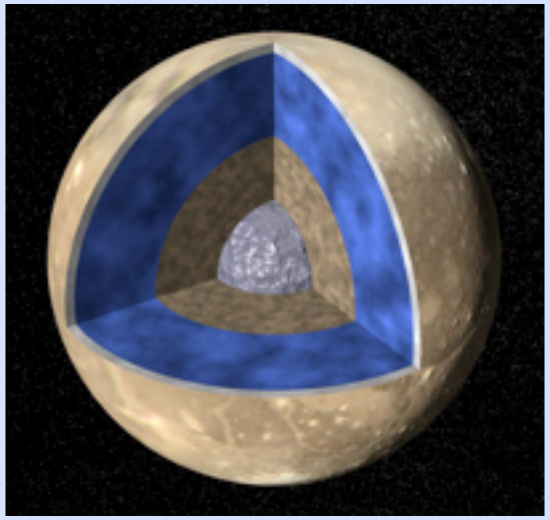

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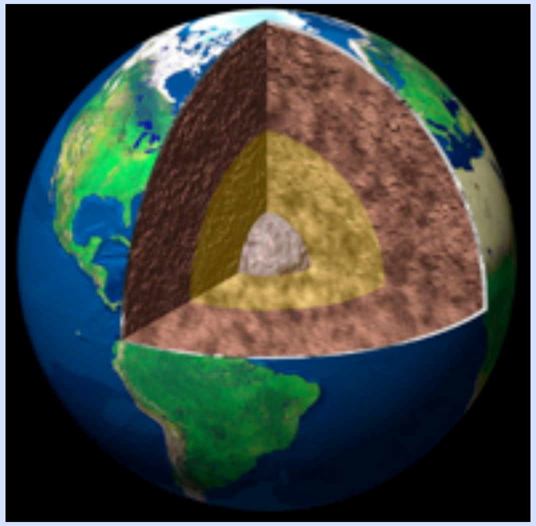

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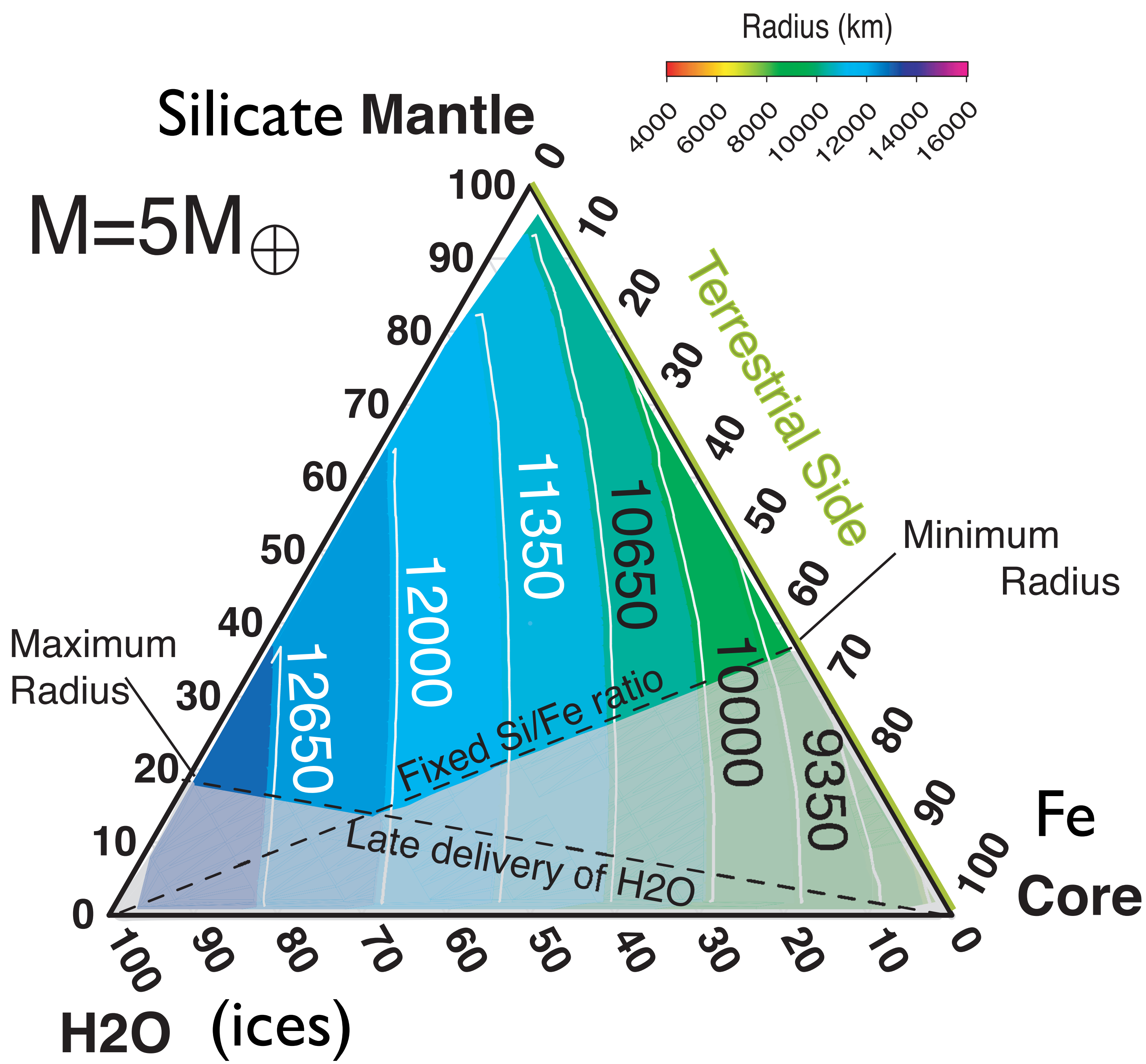
→ Obtain: $R(M; \chi)$

Valencia et al '06, Fortney et al '07, Grasset et al '07, Seager et al '07, Valencia et al '10, Rogers and Seager '10, Nettlemann & Fortney '10, Wagner et al 2011

Super-Earth Composition



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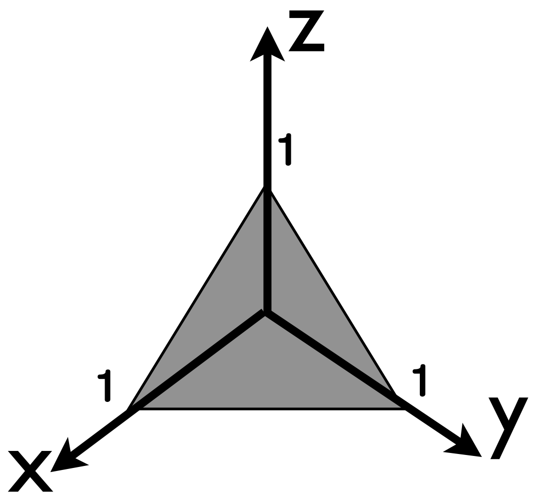

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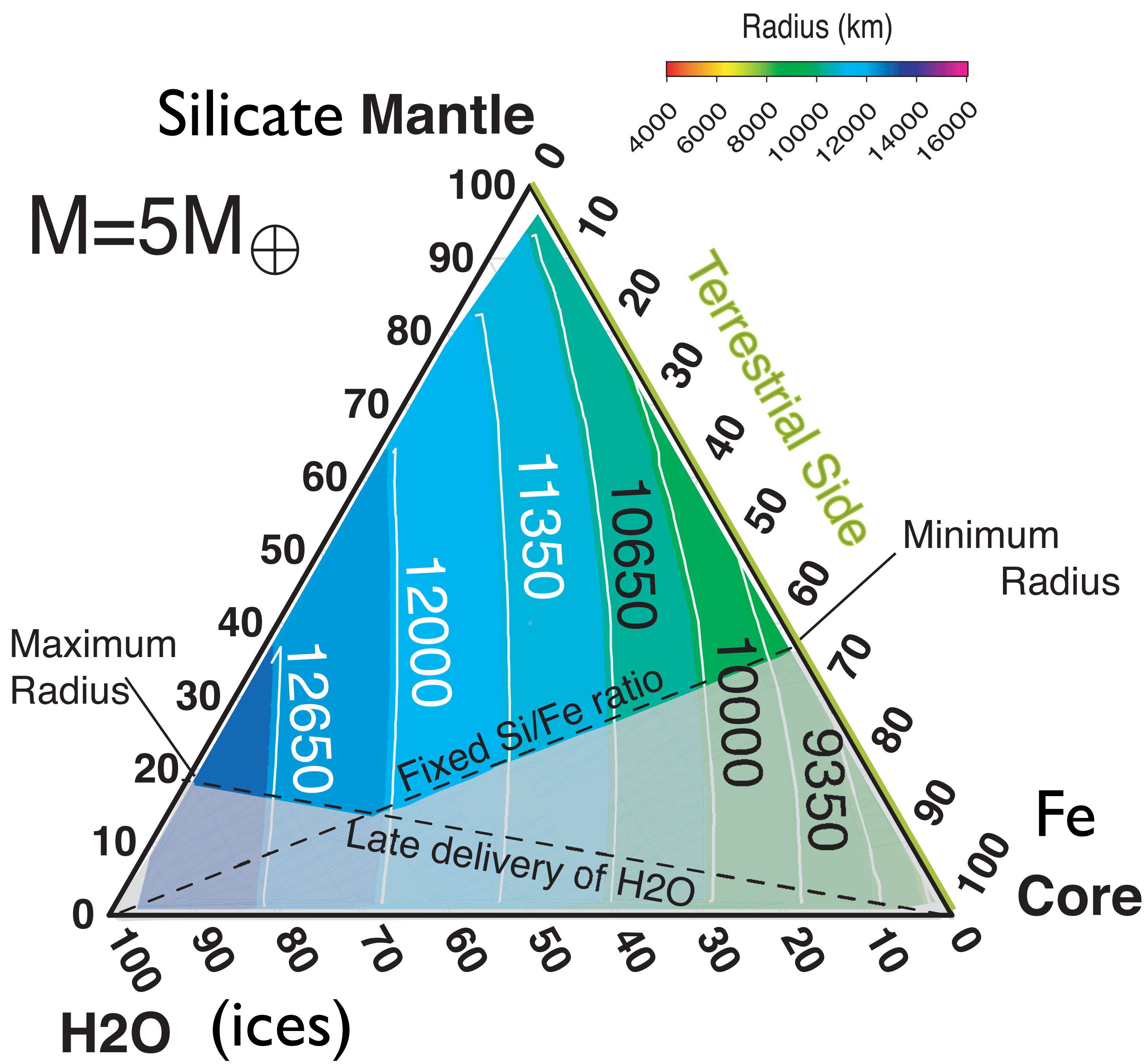

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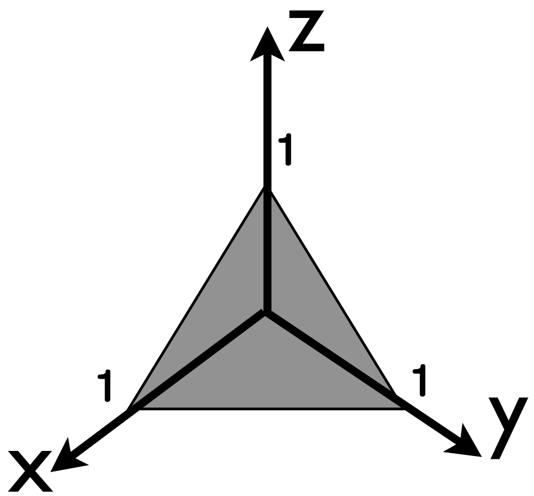
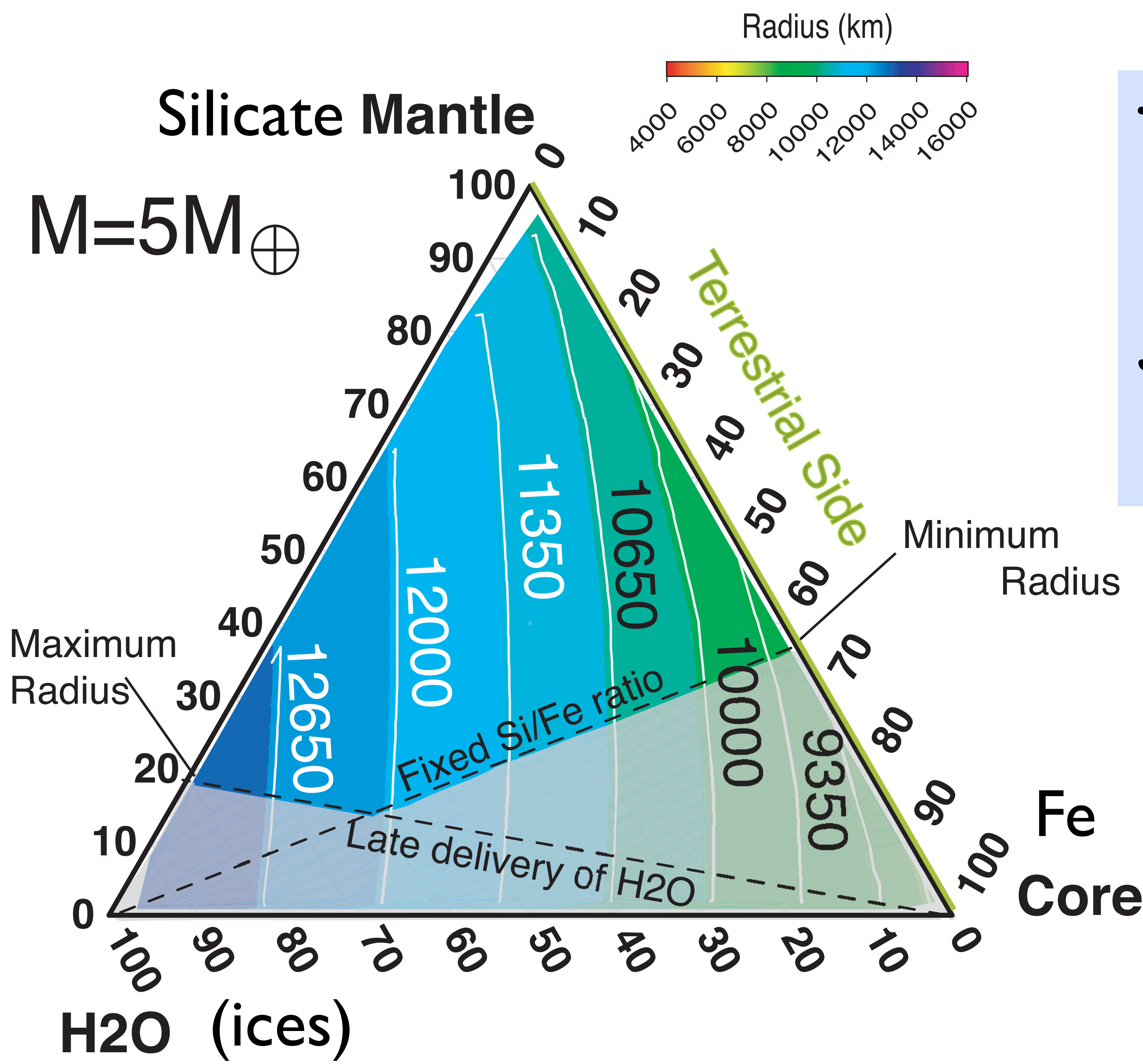




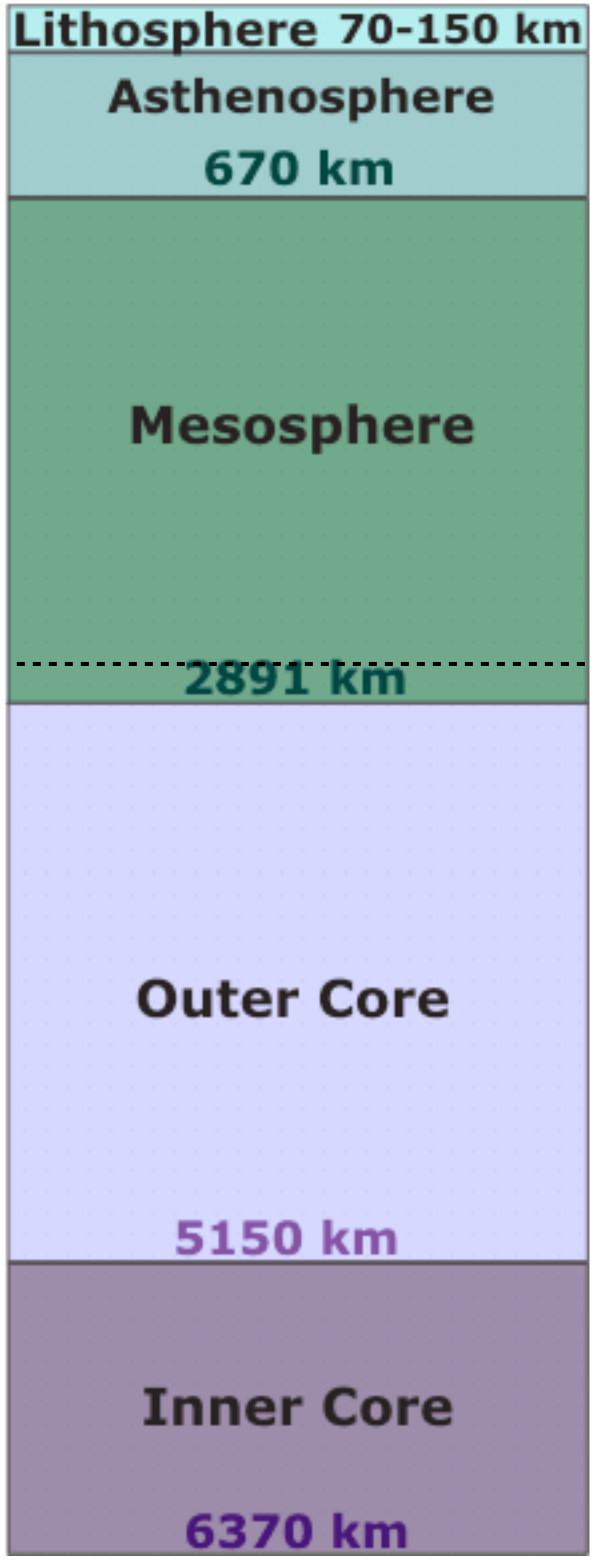
There is degeneracy in composition.
Some compositions are improbable.

Valencia et al. 2007b, see also Rogers and Seager 2010

Earth's Structure: Fe, Mg, Si, O, Ca, Al, Ti

MANTLE

CORE



Olivine + Pyroxene

$(Mg,Fe)_2SiO_4 + (Mg,Fe)_2Si_2O_6$

Perovskite + Magnesiowustite

$(Mg,Fe)SiO_3 + (Mg,Fe)O$

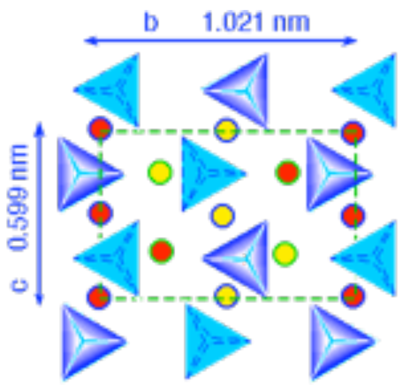
Post - Perovskite + Magnesiowustite

$(Mg,Fe)SiO_3 + (Mg,Fe)O$

Iron + alloy

Fe + (S, Si, O, H, C)

Iron-Nickel



Variety in Rocky Compositions

Fe, Mg, Si, O, Ca, Al, Ti

1. The planet has an Fe/Si, Fe/Mg ... budget which depends on its formation inventory and subsequent early evolution (giant impacts + atmospheric erosion)

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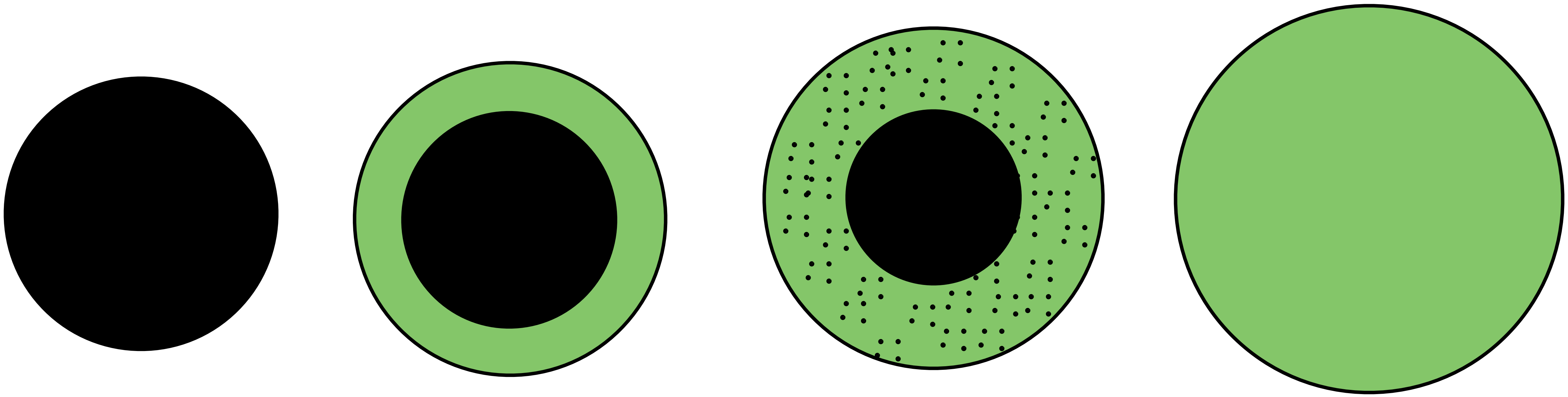


Iron

Iron-rich

(65% iron core
37 silicate mantle, no iron)

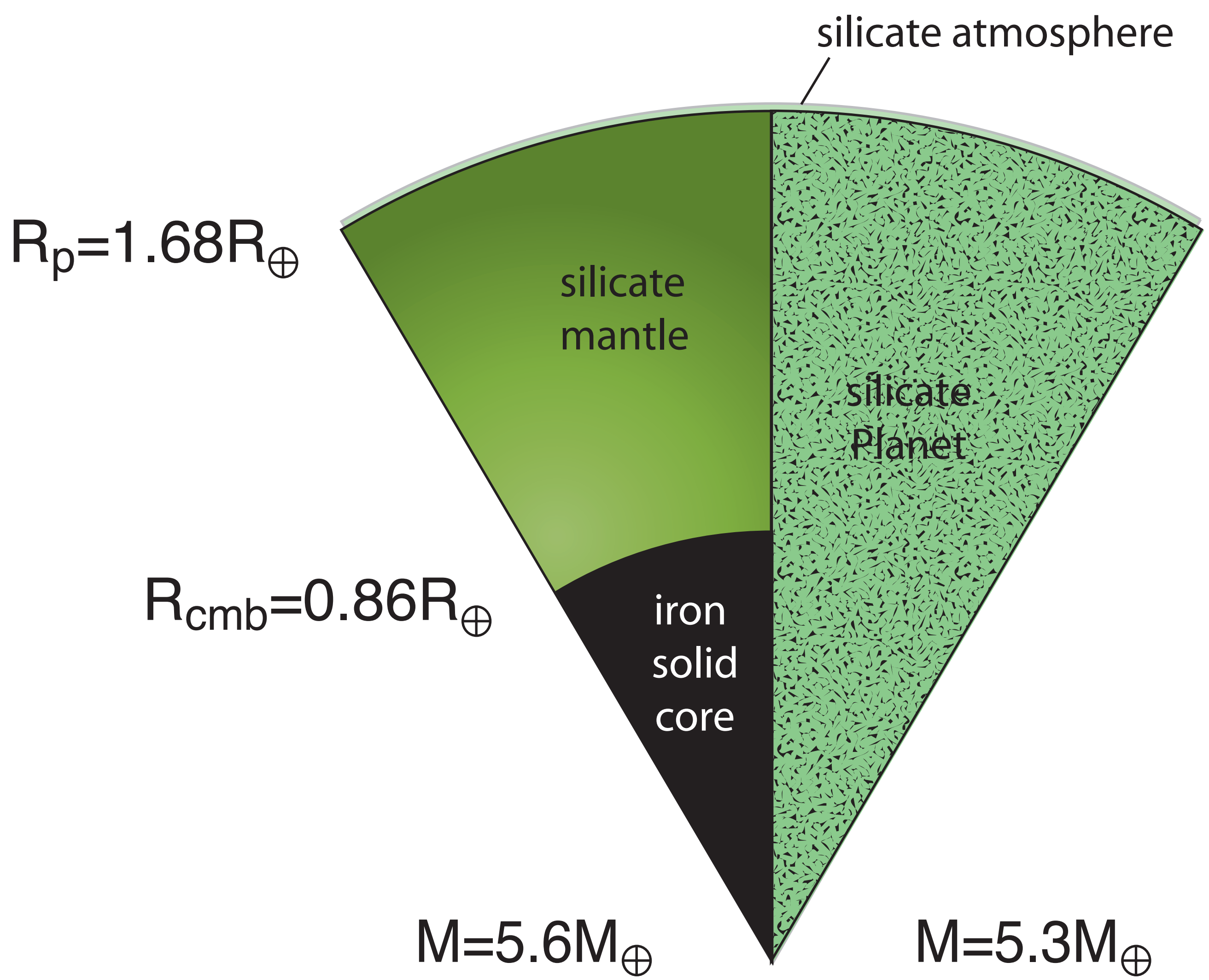
Earth-like

(33% iron core
67 silicate mantle,
10% iron by mol)

no-iron
(pure Mg-silicate)

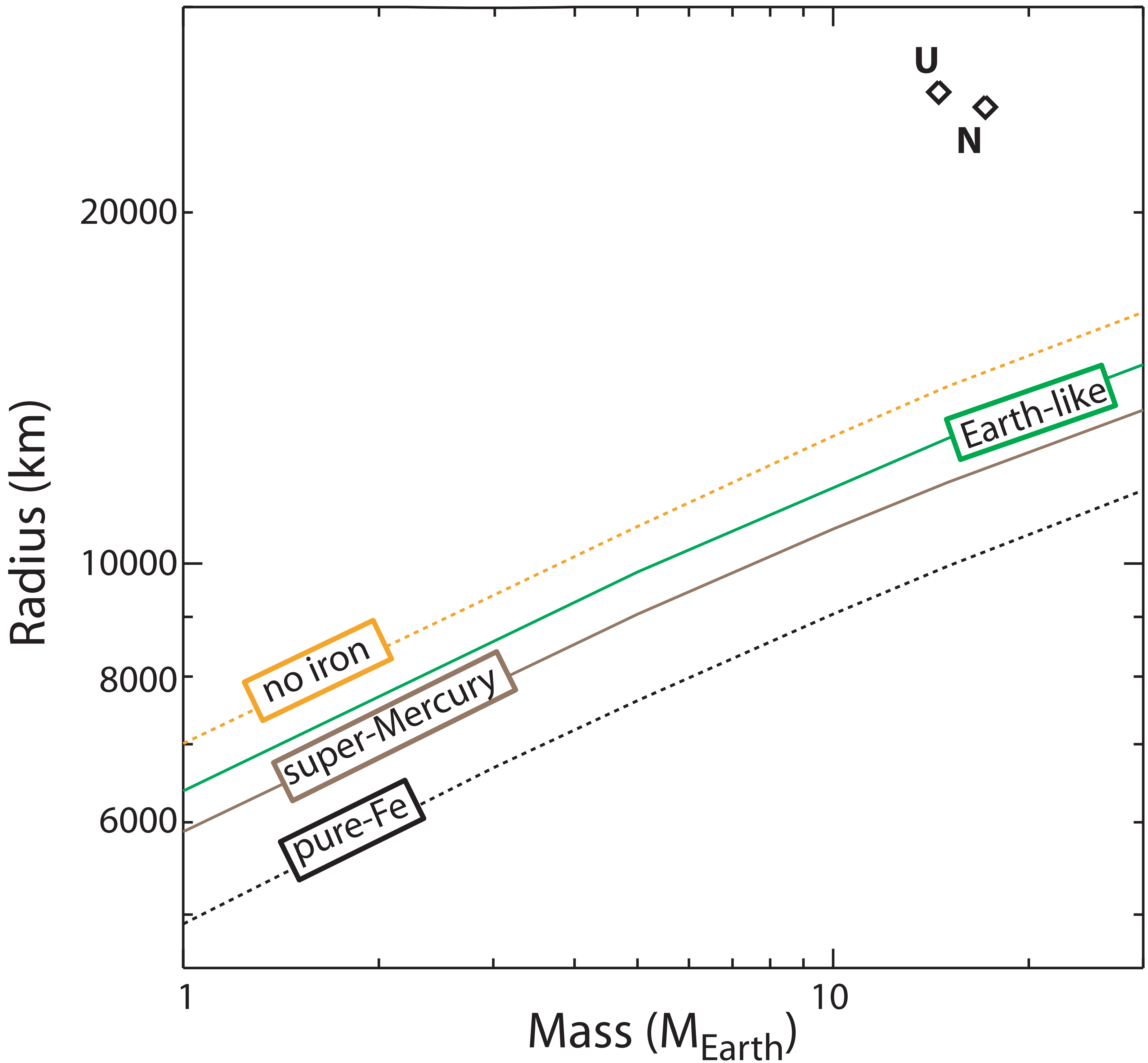
Variety in Rocky Compositions

2. Differentiated vs Undifferentiated planet



For CoRoT-7b first reported mass value Valencia et al, 2010; see also Tanton-Elkins and Seager 2009 for a mechanism for a coreless planet

Rocky Compositions



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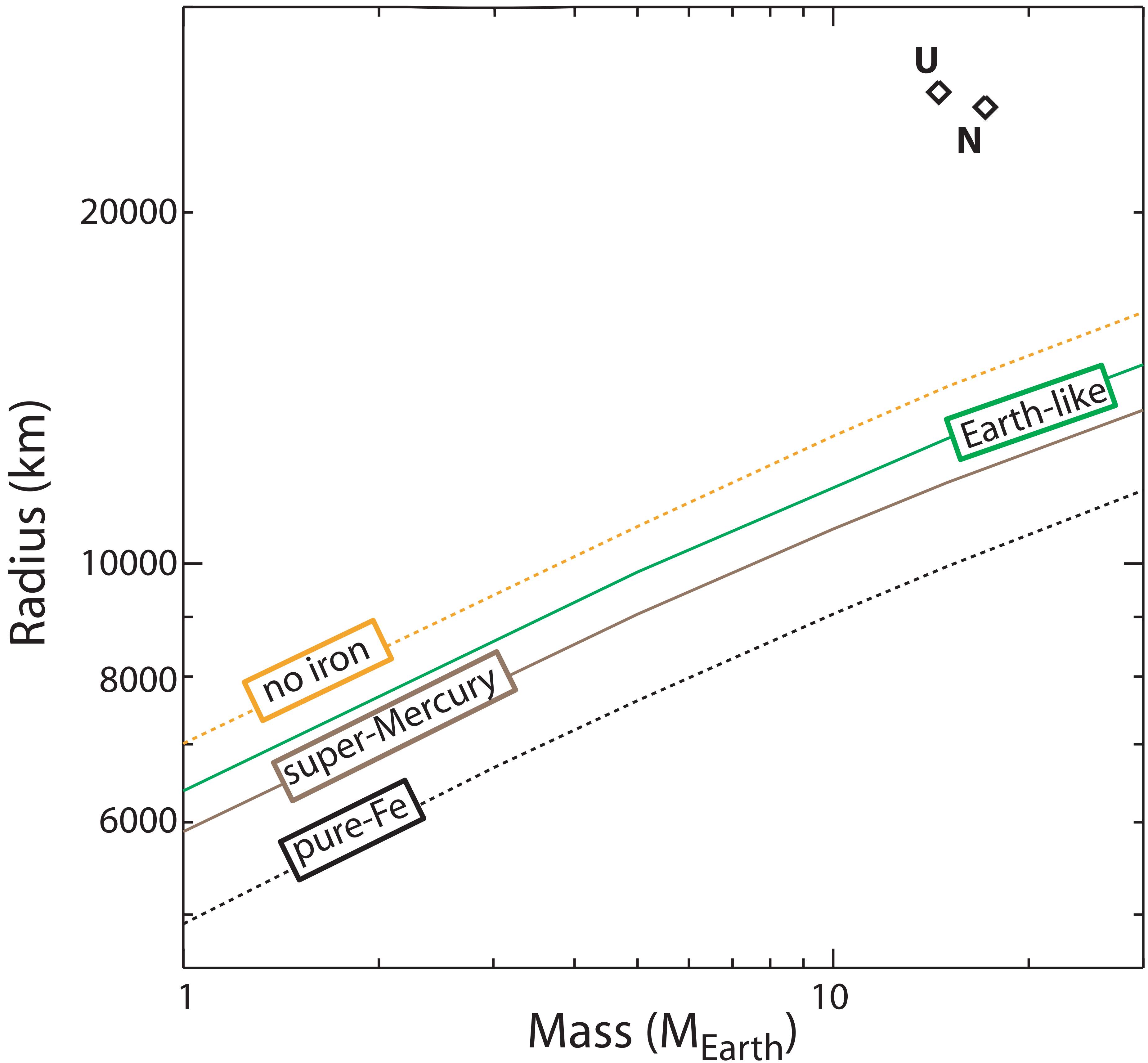
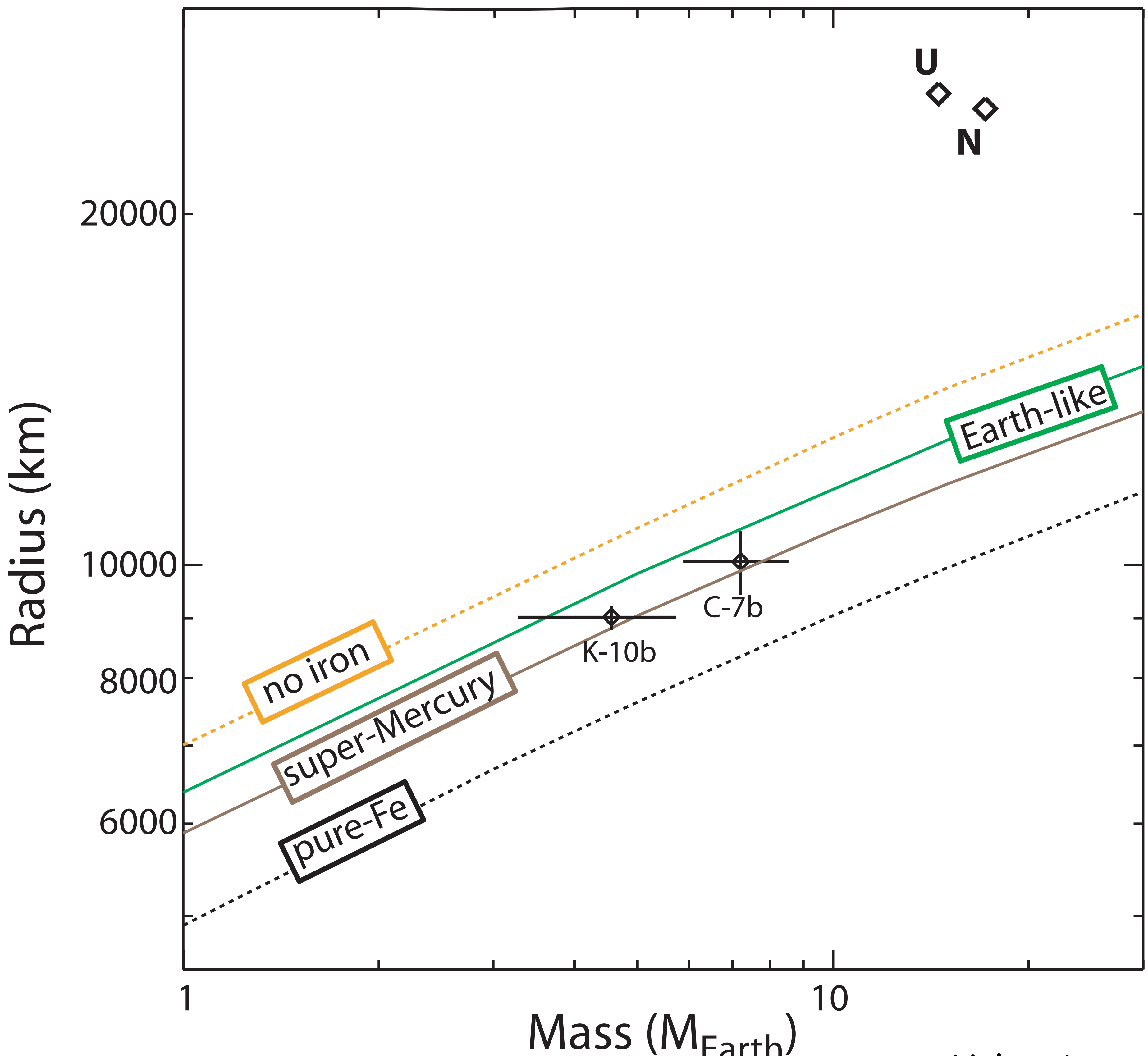


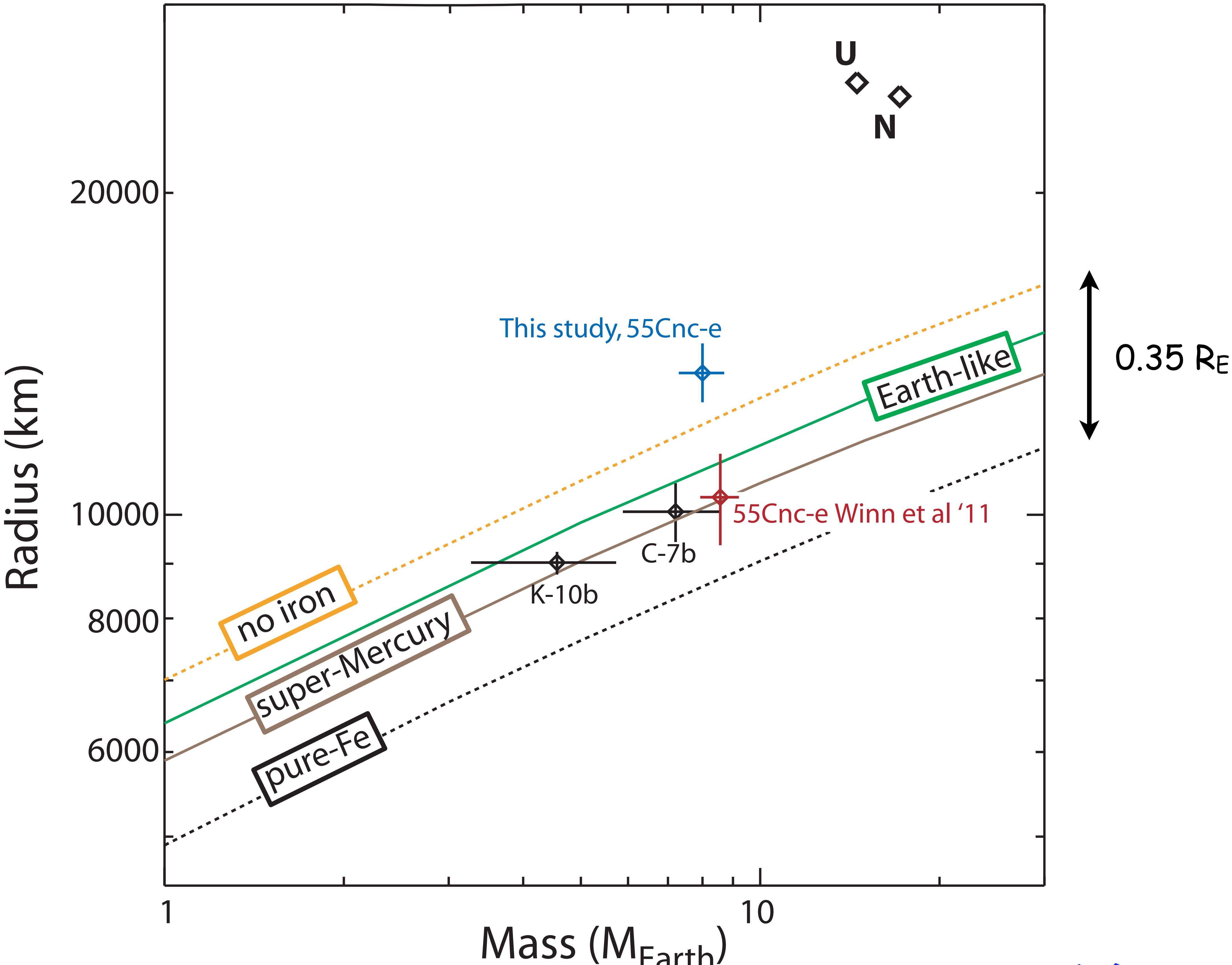
For a probable upper limit to the Fe/Si lower ratio see Marcus et al '10

Rocky Compositions



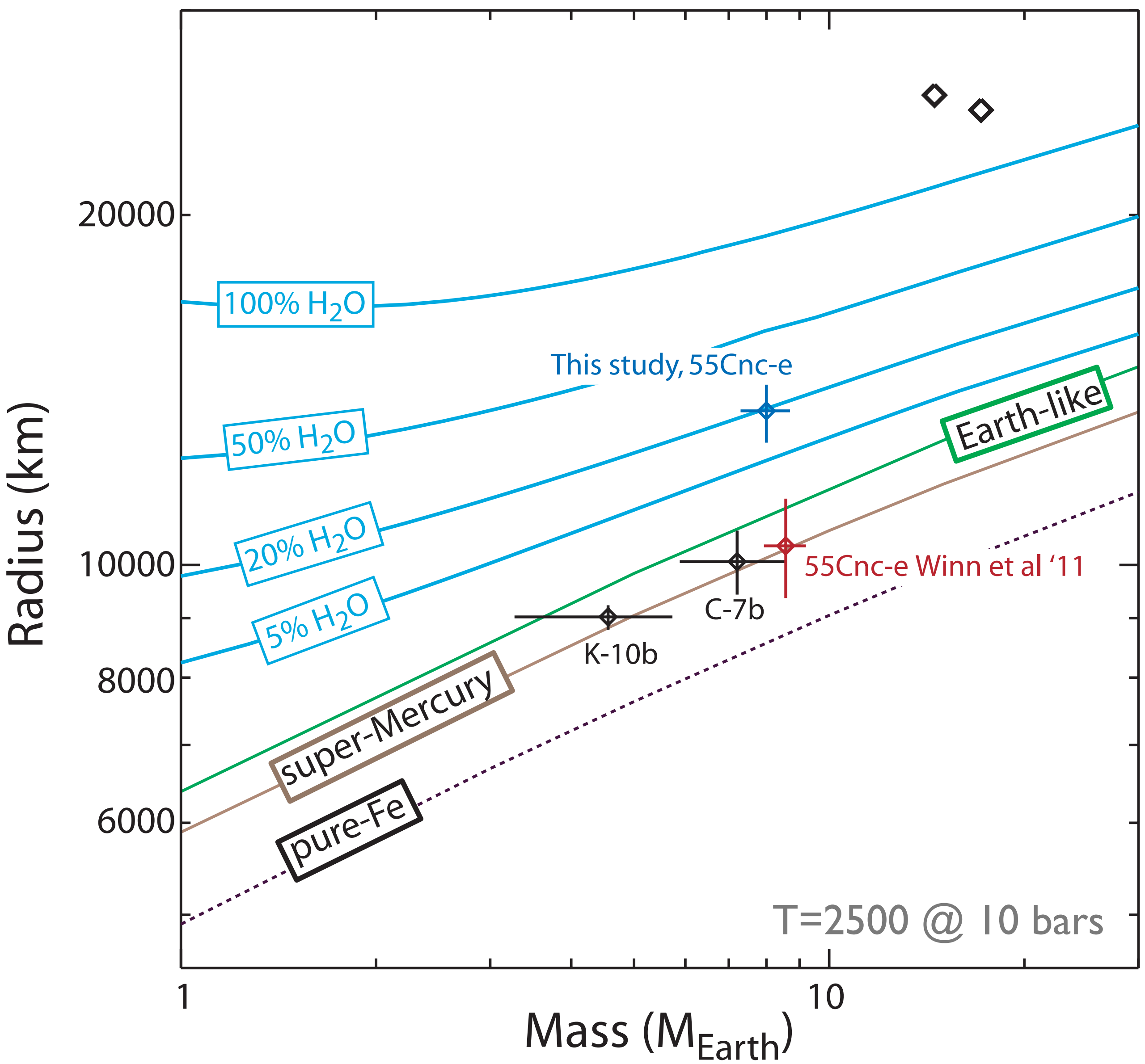
Valencia et al 2010, Valencia 2011

Rocky Compositions



in Demory et al 2011

What about their envelopes ?



Vapor Atmosphere

Valencia et al, 2010, Valencia 2011, Demory et al 2011

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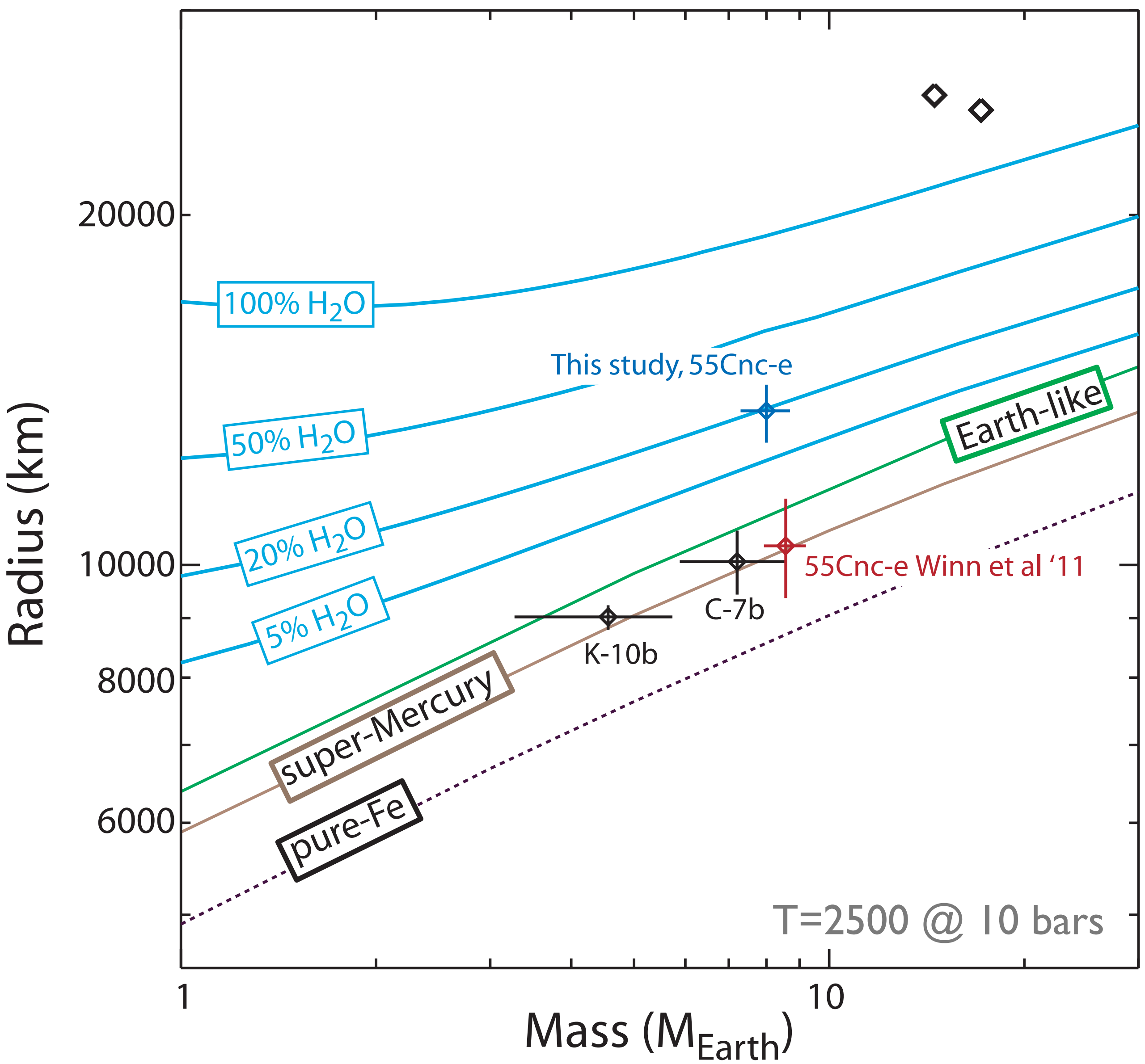

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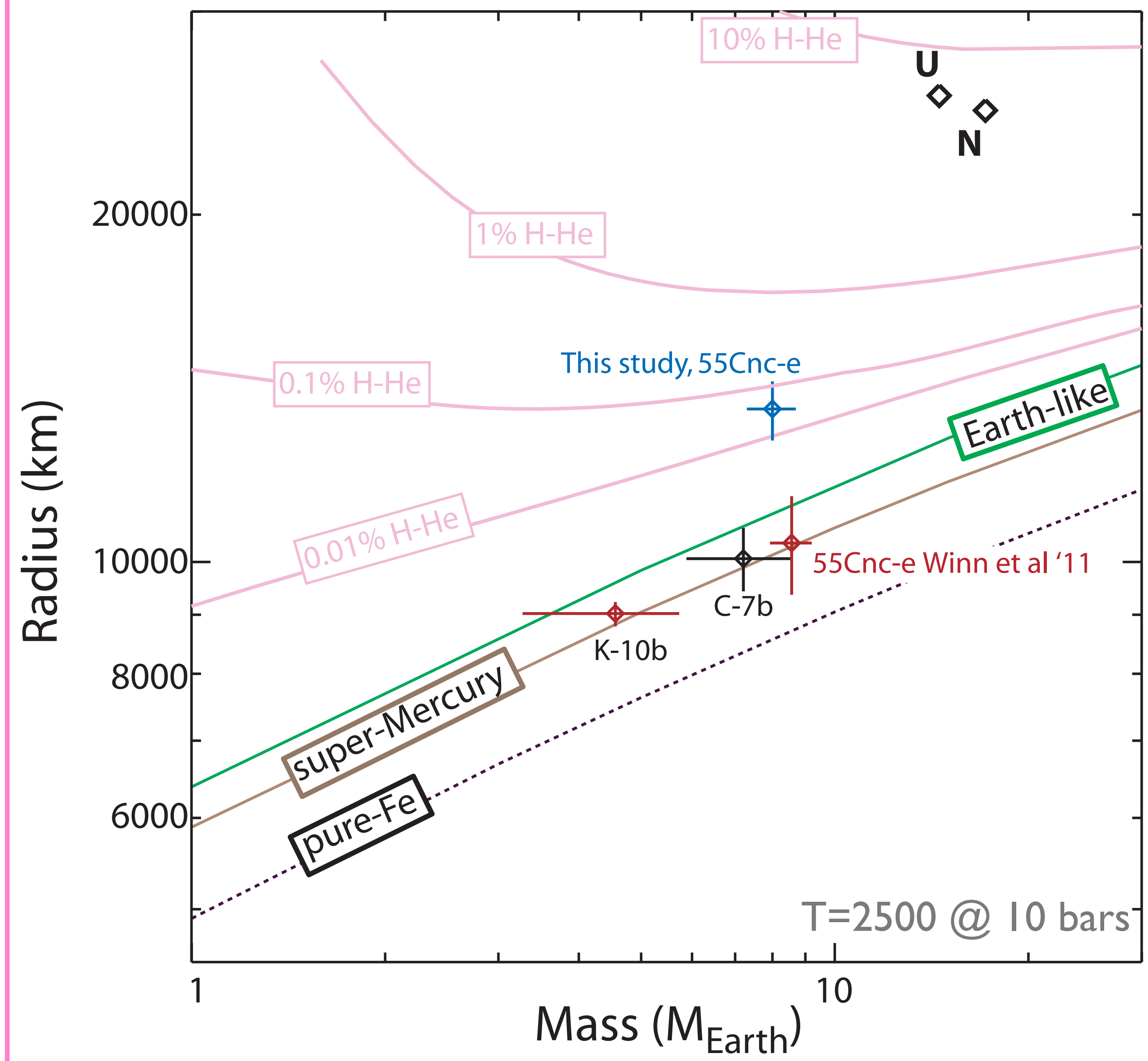

H-He Atmosphere

Valencia et al, 2010, Valencia 2011, Demory et al 2011

Atmospheric Erosion

Energy limited calculation based on UV flux

$$\frac{dM}{dt} = \frac{3\,\varepsilon\,F_{EUV}}{4\,G\,\rho\,K_{tide}} = 10^{11}\ \text{g/s}$$

For more details on ε see Lammer et al 09

within an order of magnitude of the escape rate of HD 209458b

Even if it has a silicate atmosphere, it is thick enough for UV absorption

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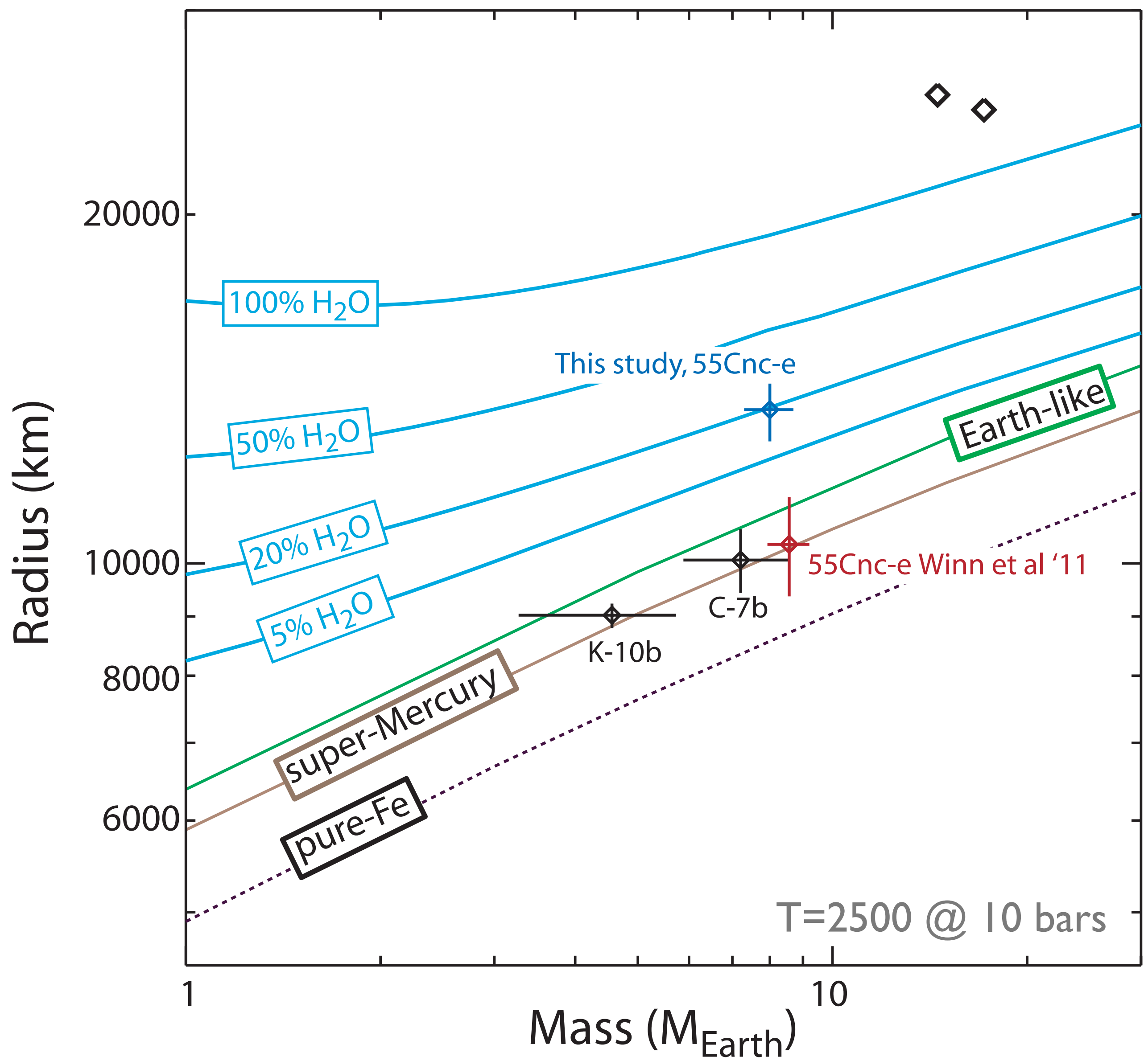

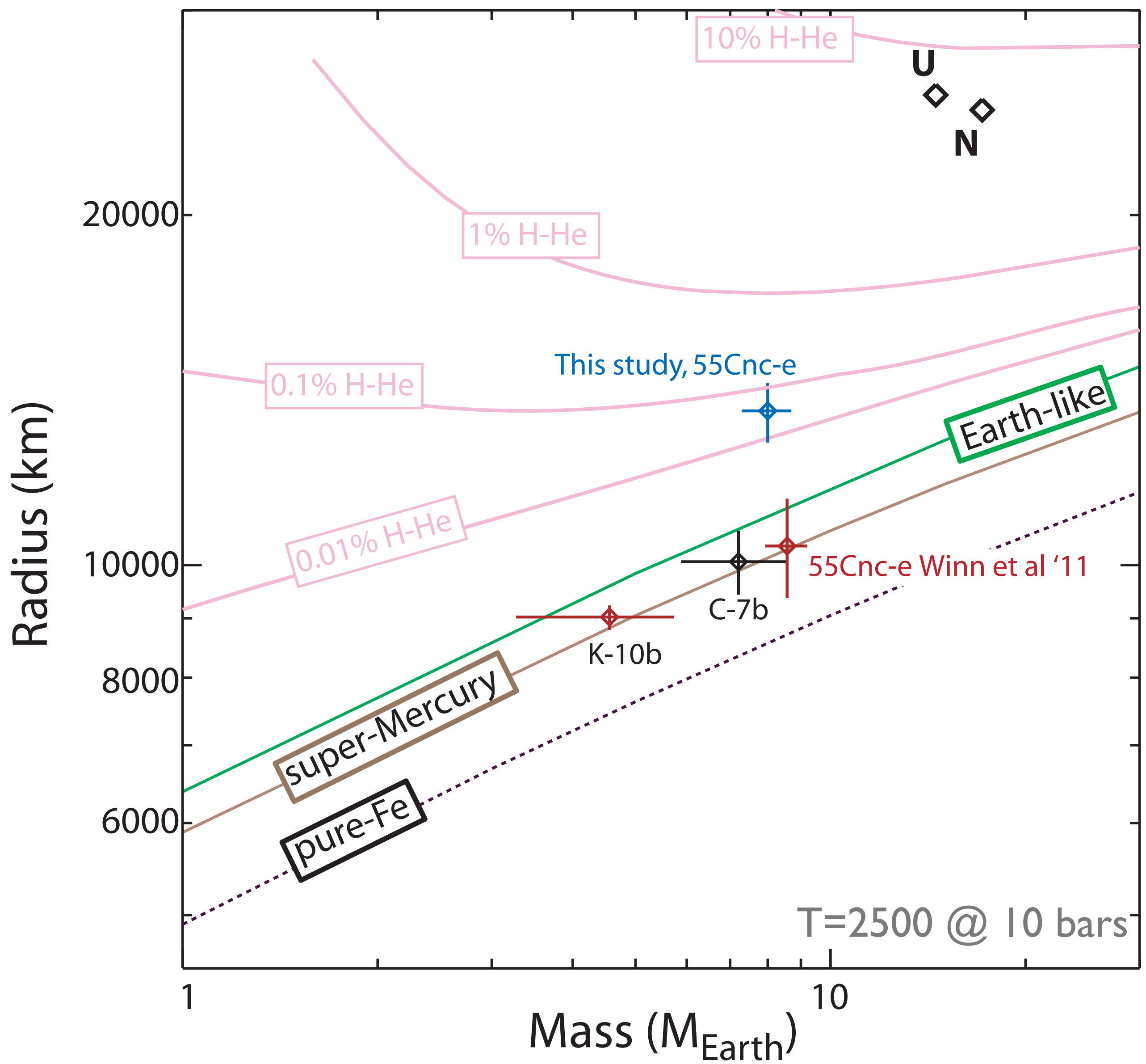

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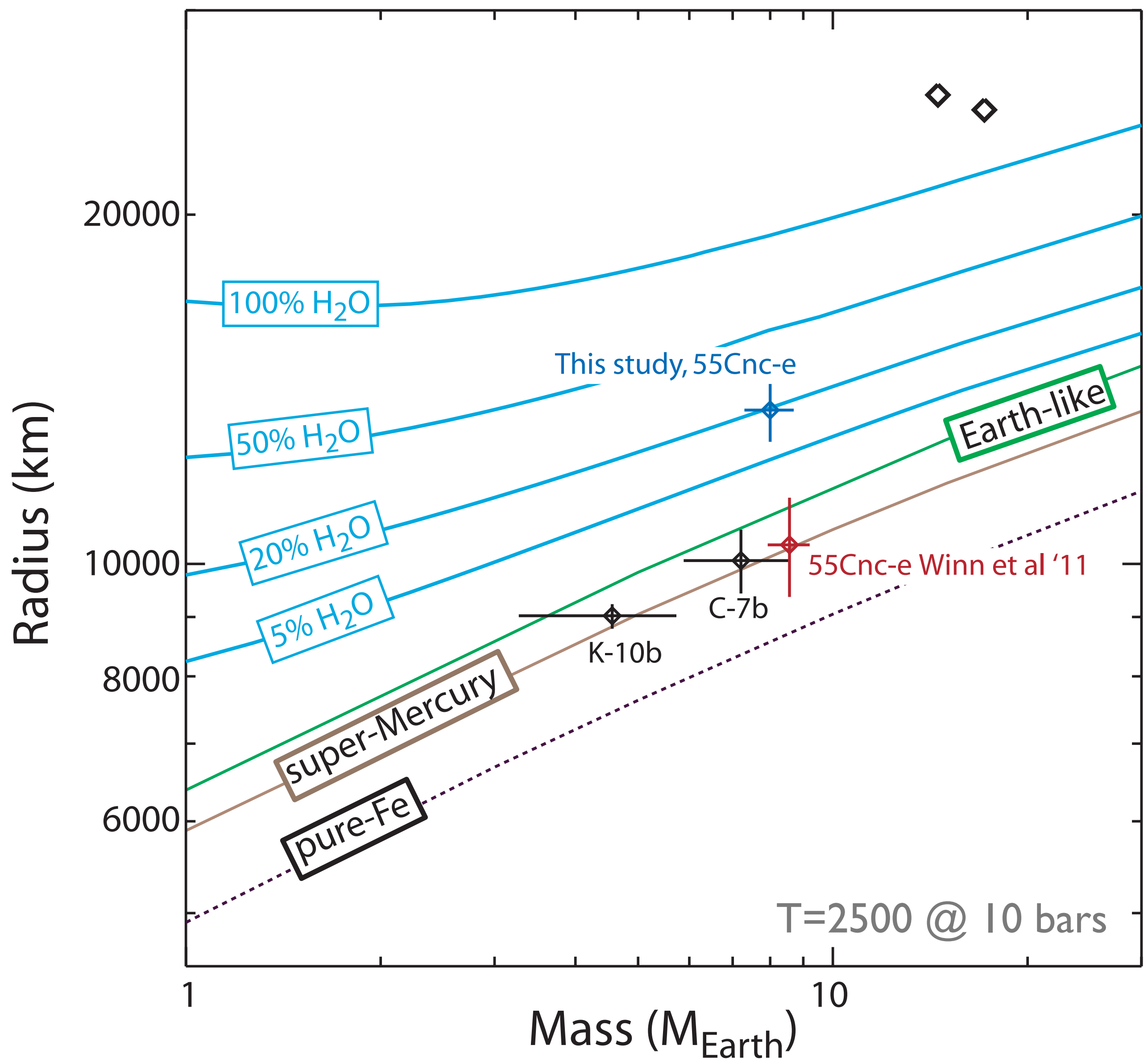
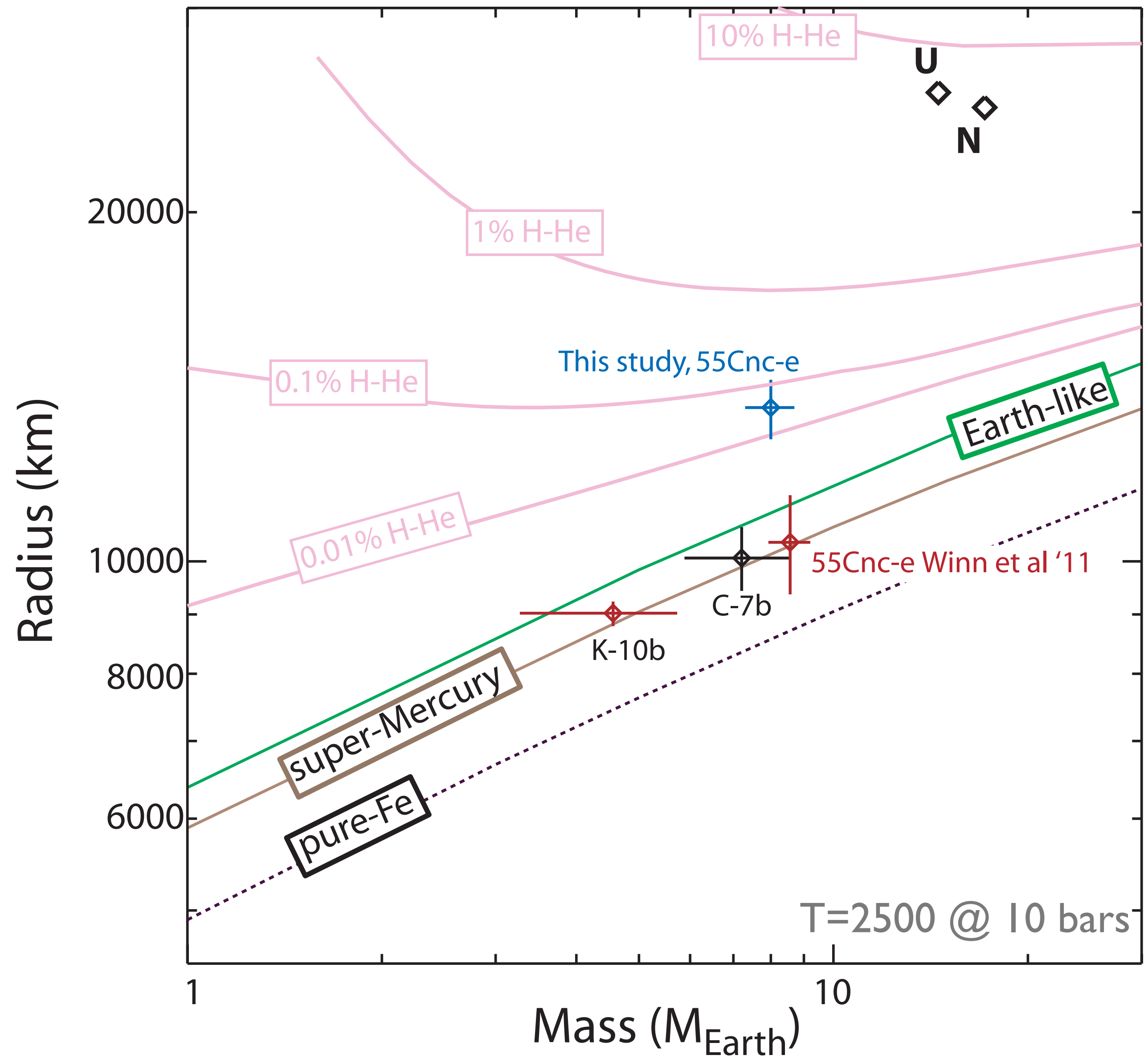
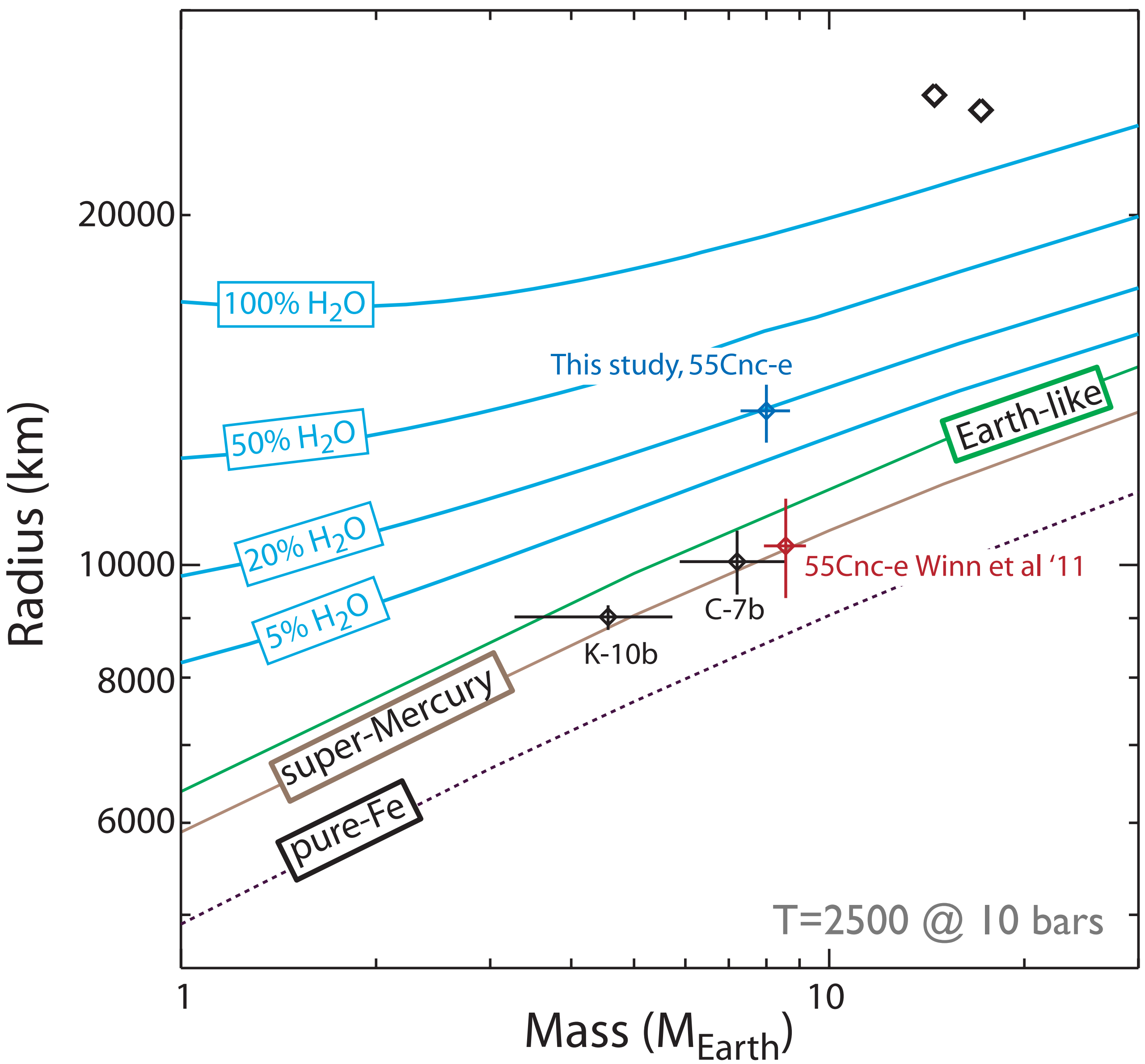




Evaporation Timescale ~ 1 Gy

What about their envelopes ?



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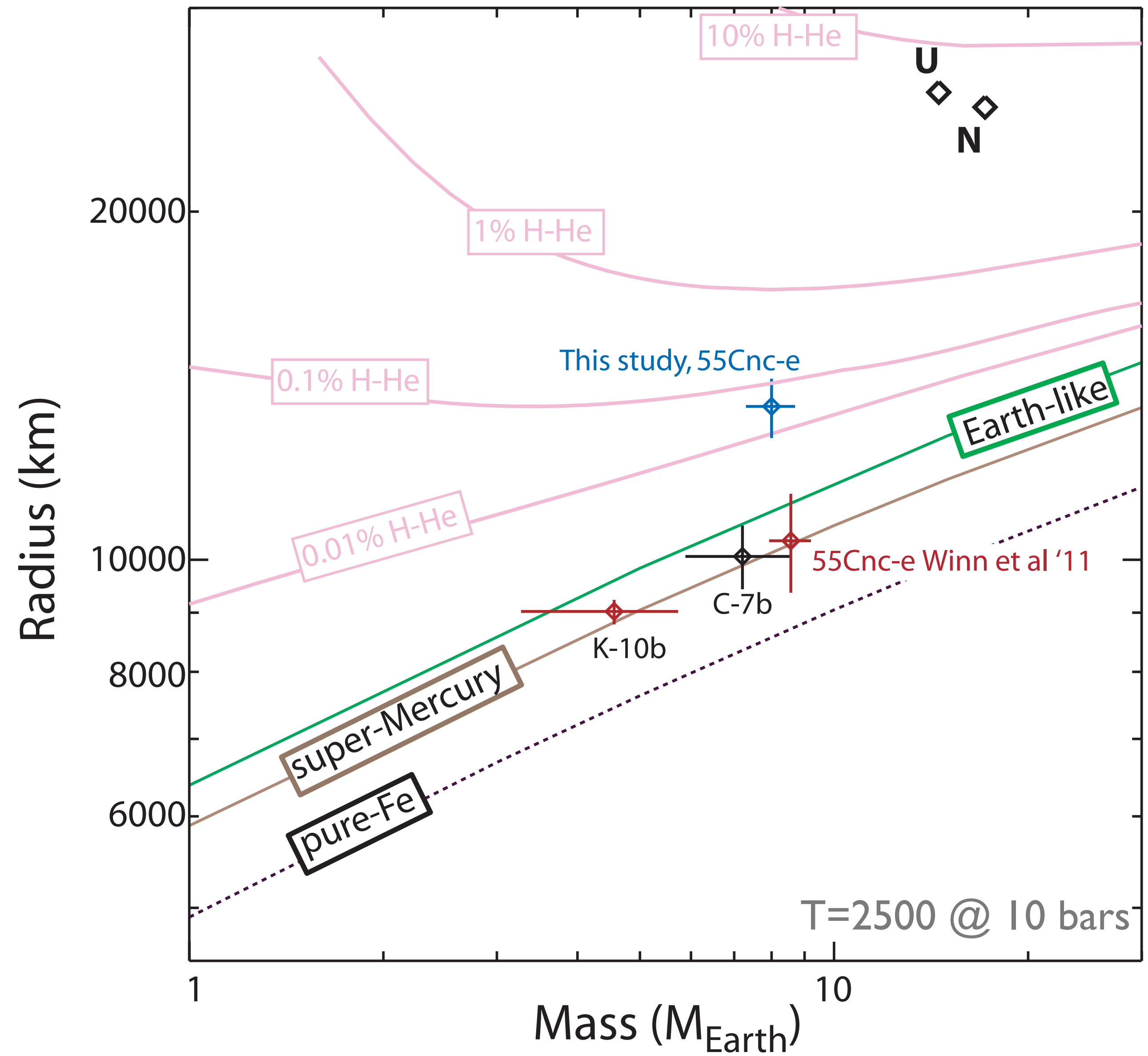
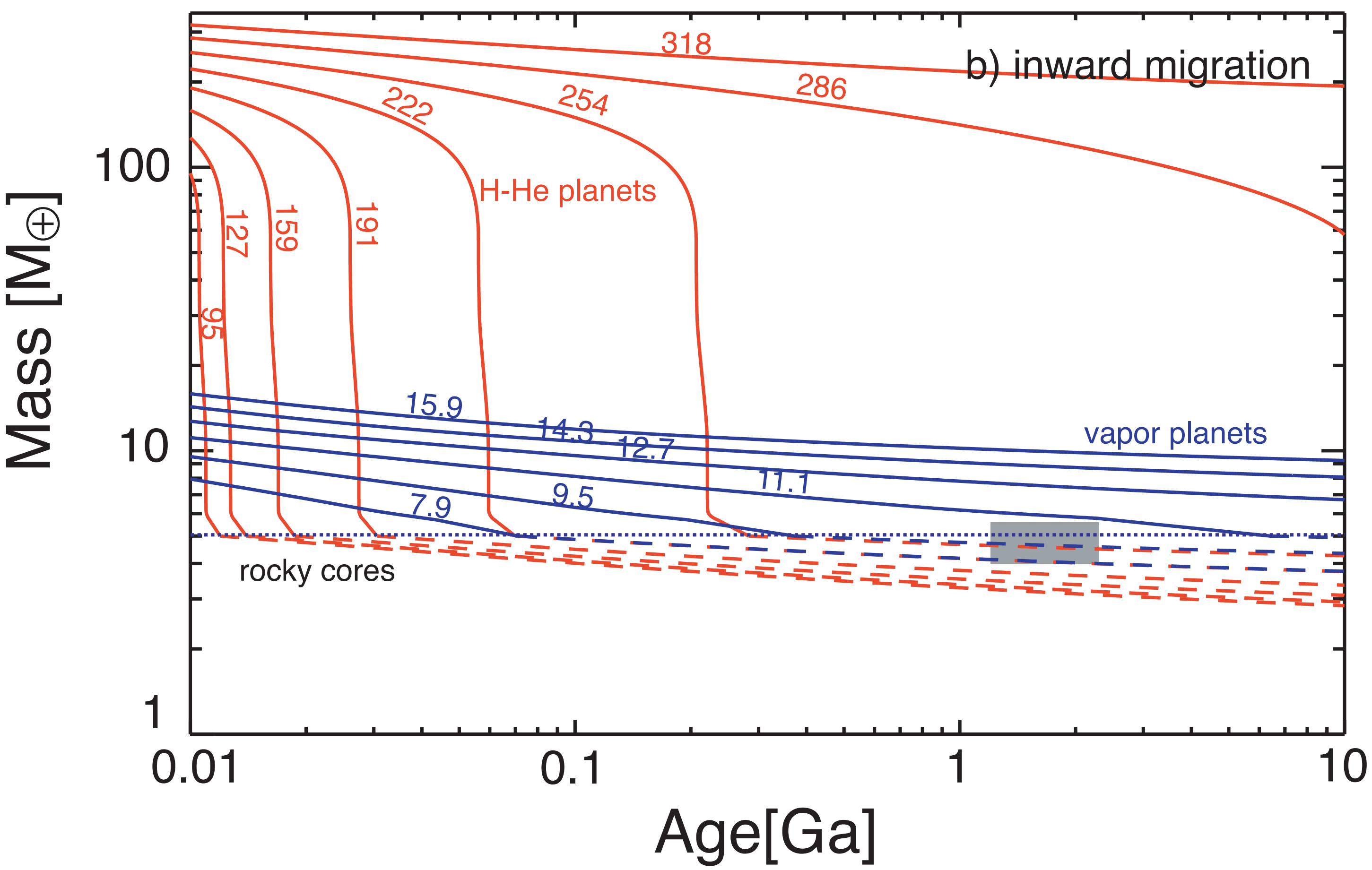


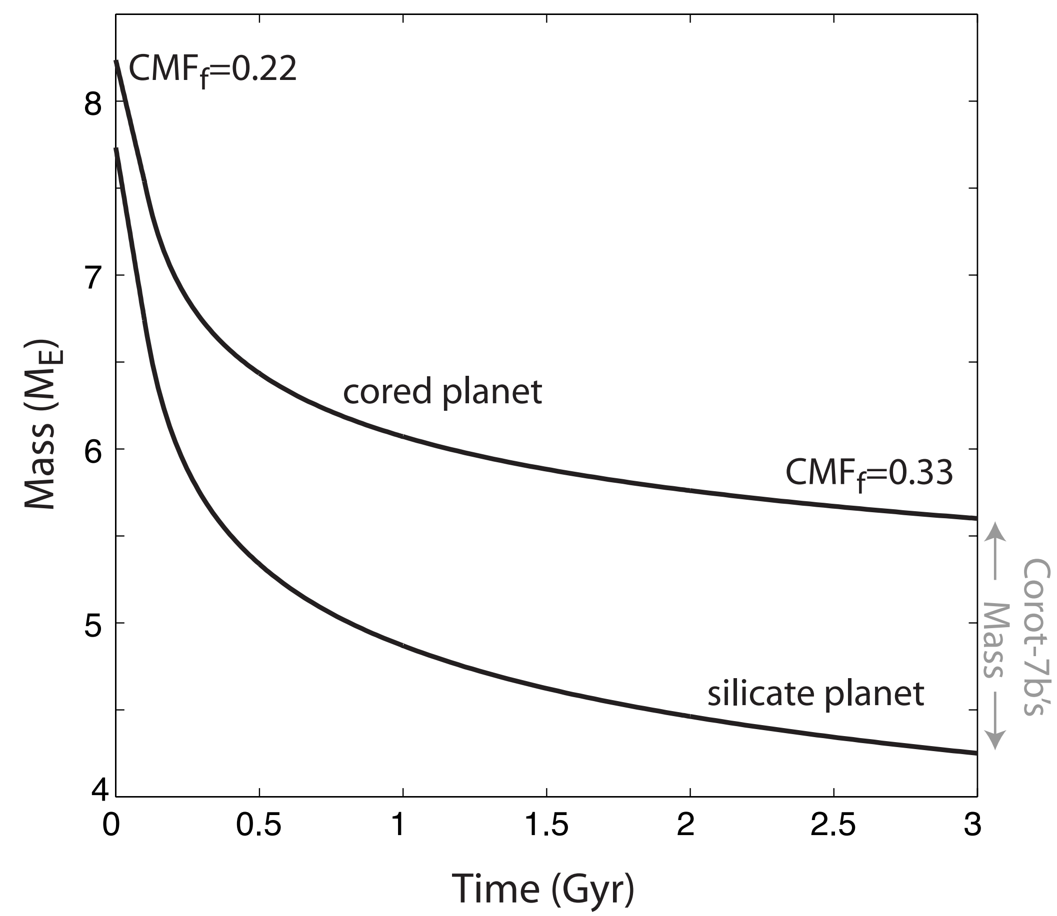
Evaporation Timescale ~ 1 My!

CoRoT-7b's origin?

Volatile Origin



Rocky Origin

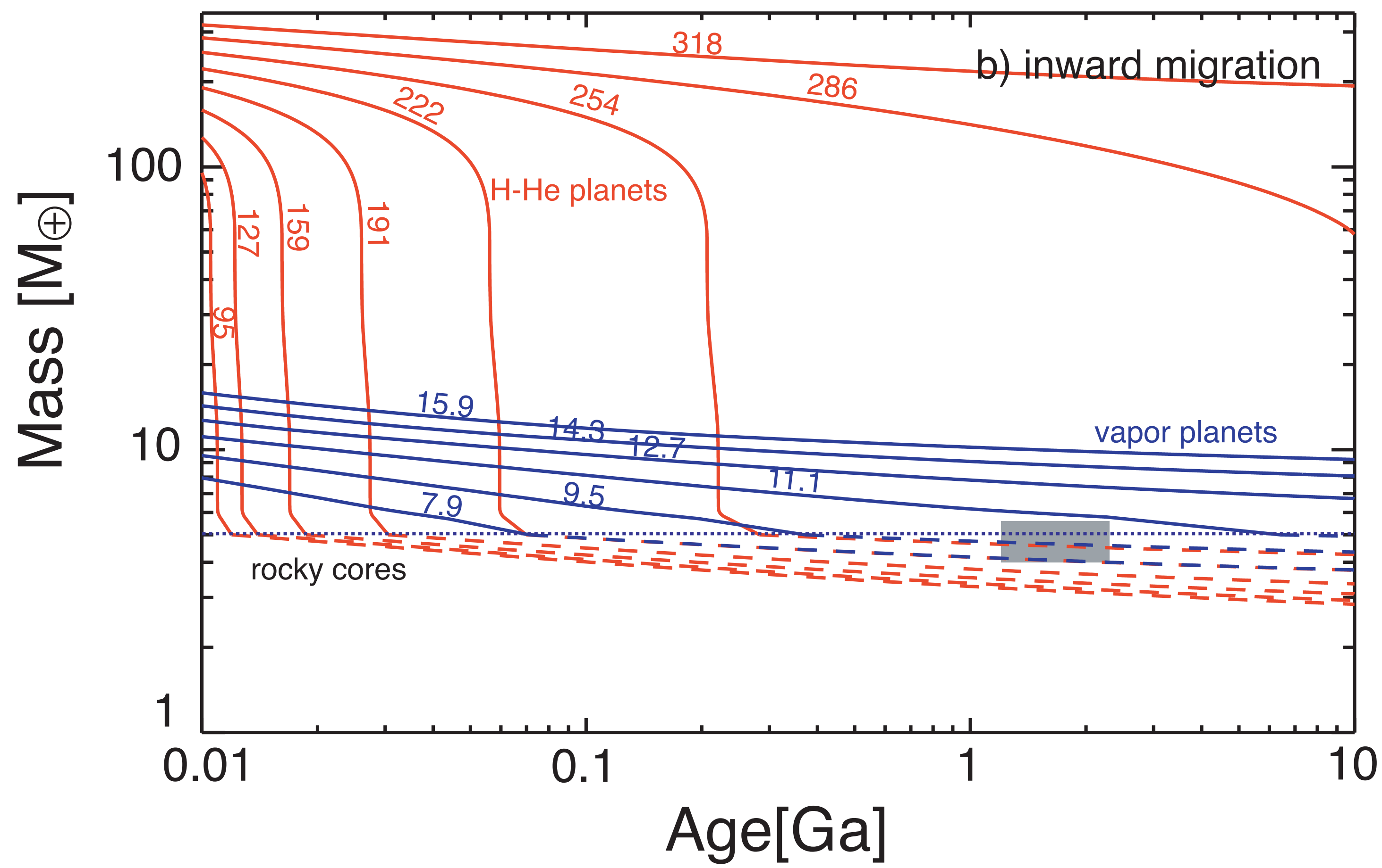


Valencia et al. 2010, see also Jackson et al 2010

CoRoT-7b's origin?

Unconstrained

Volatile Origin



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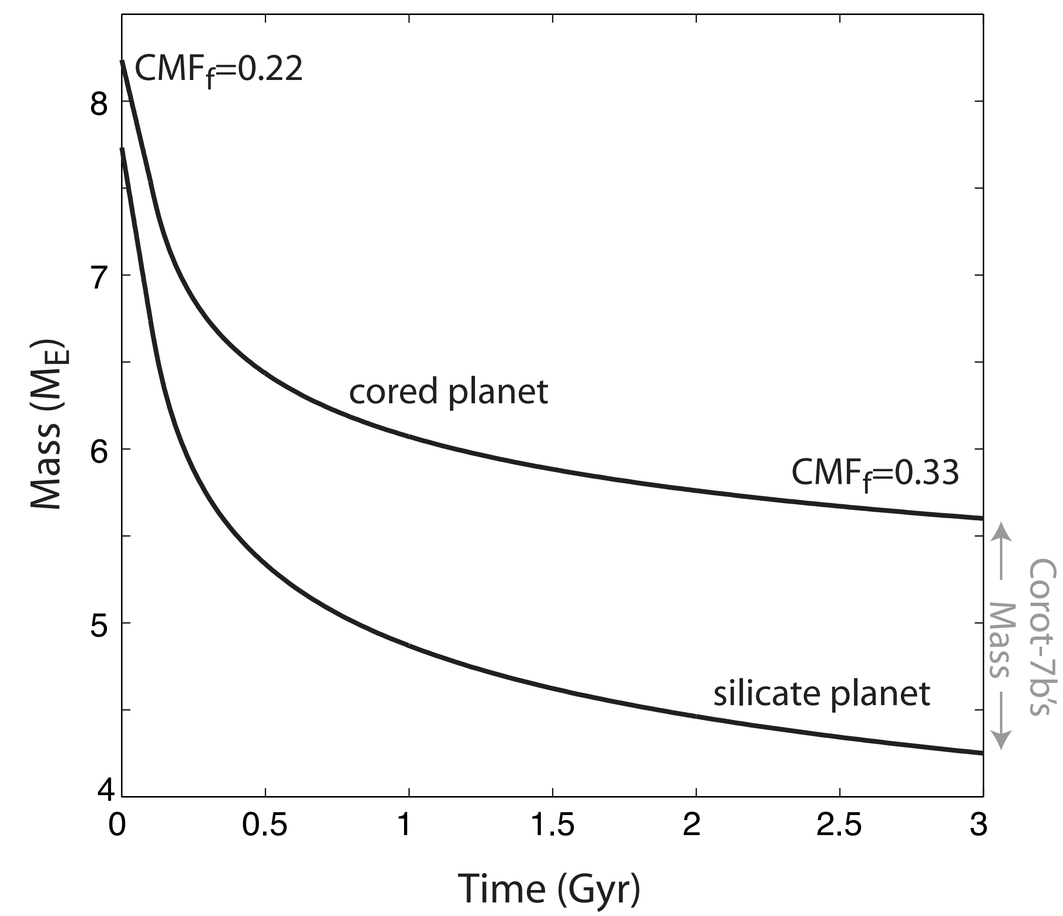

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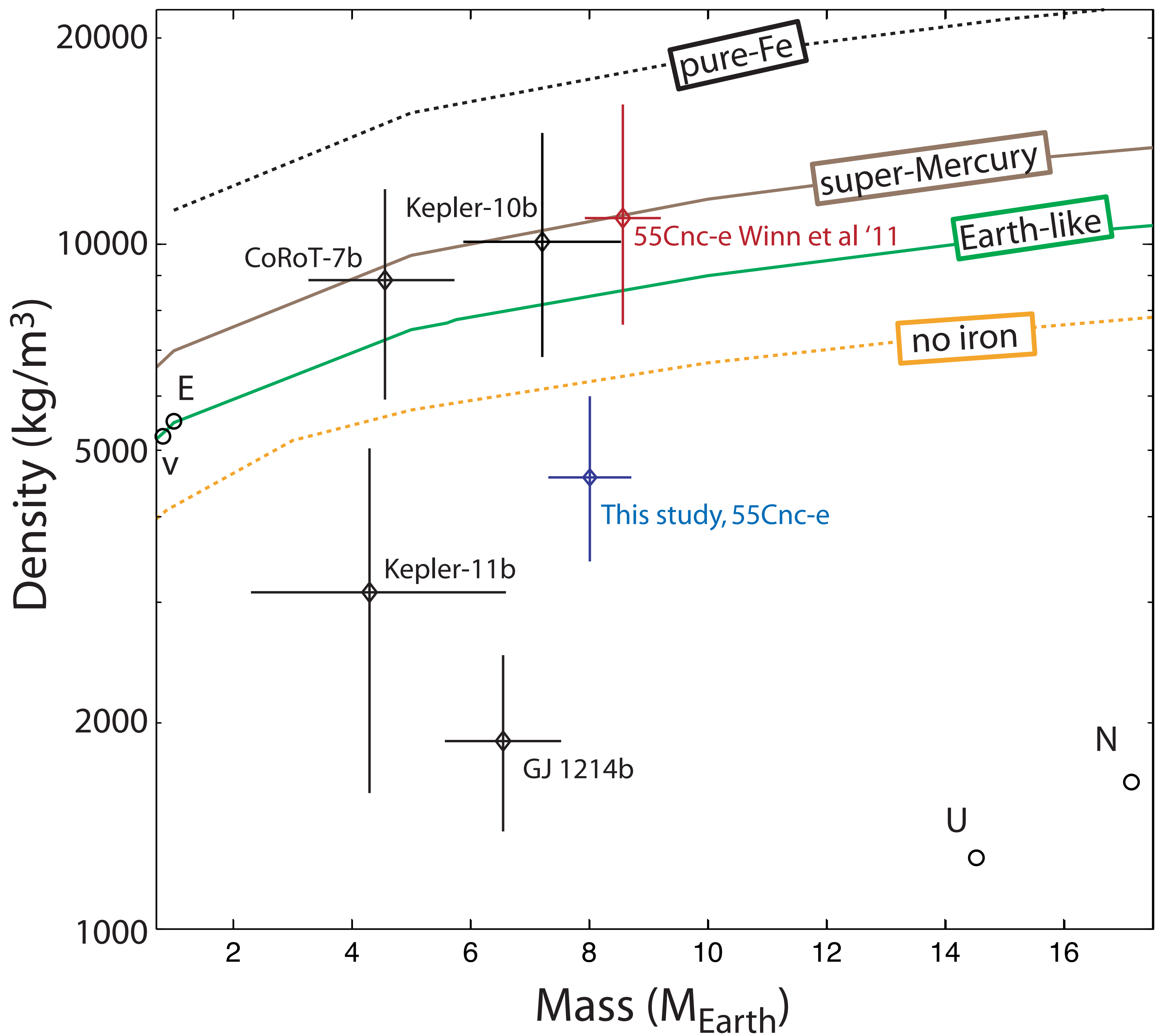

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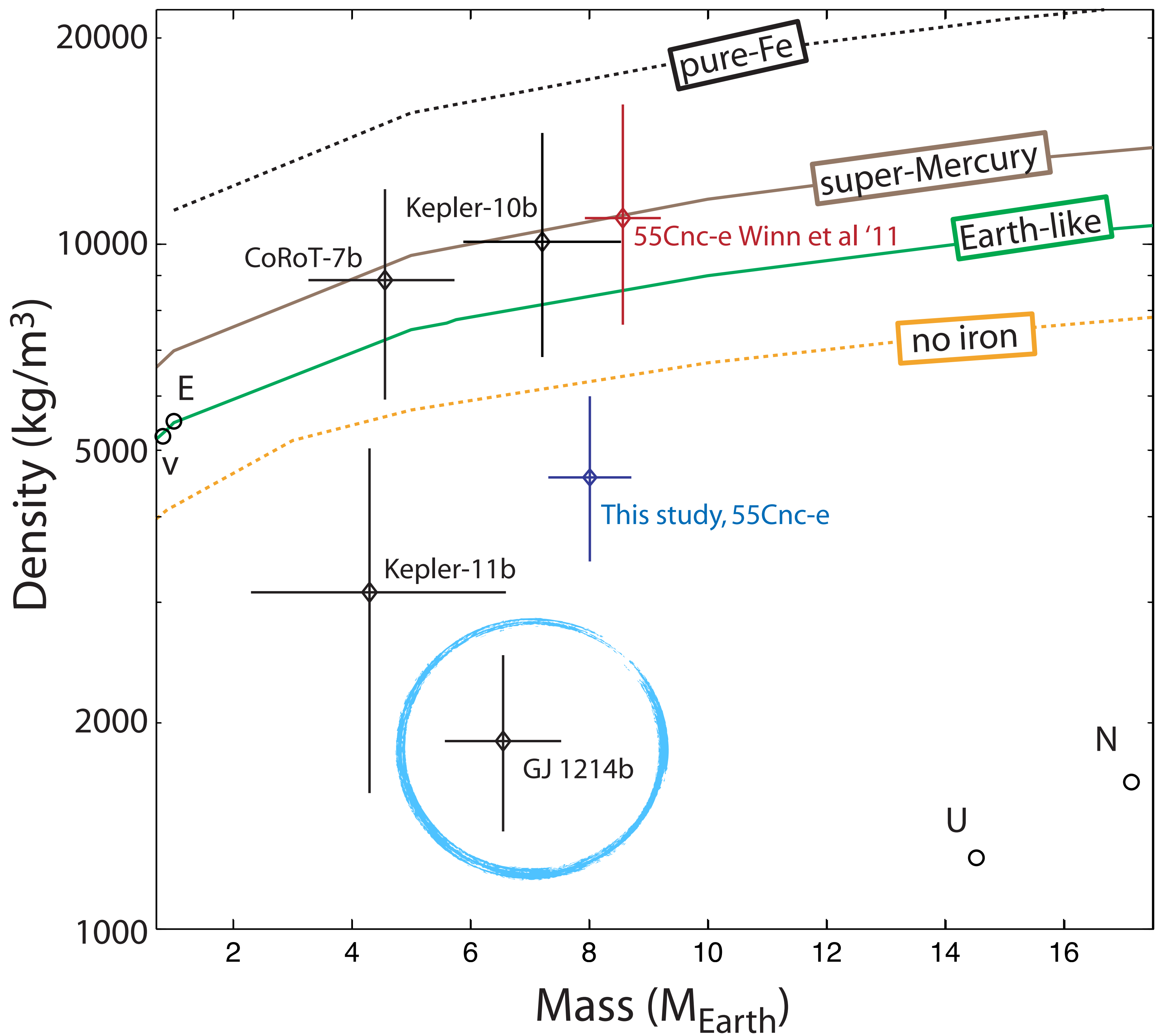


in Demory et al 2011

GJ 1214b

Radius = 2.678 ± 0.13 R_{Earth}

Mass = 6.55 ± 0.98 M_{Earth}

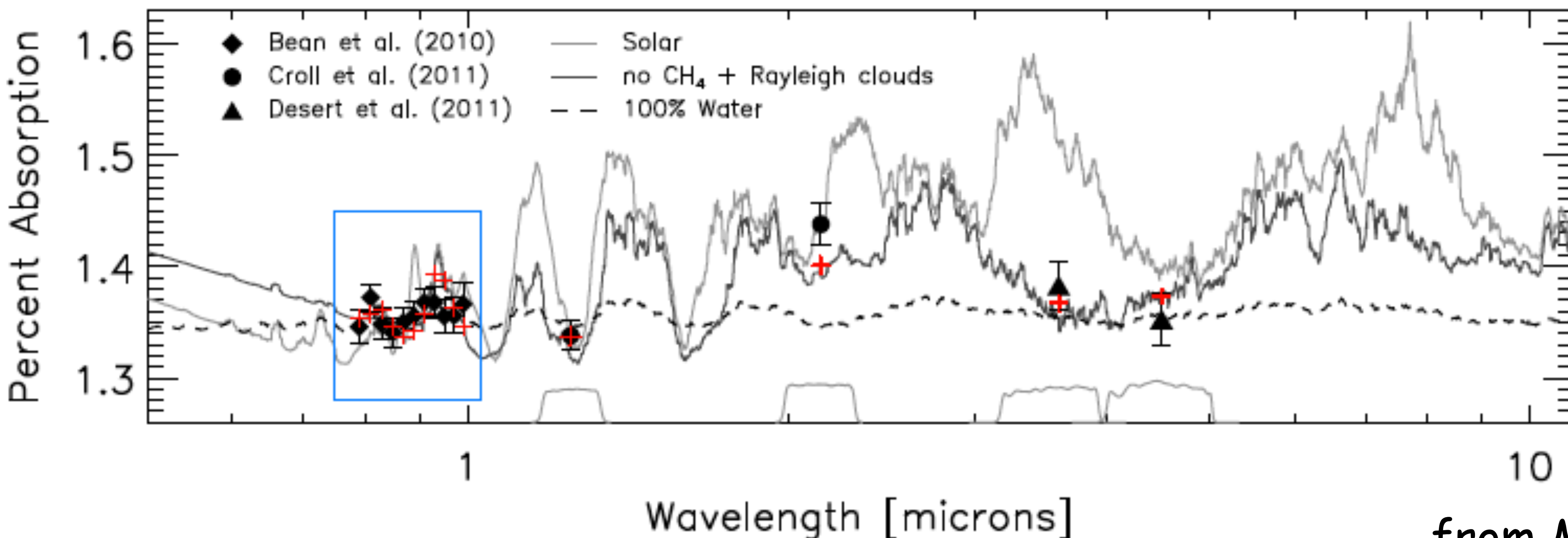
Period = 1.58 days

Age = 3-10 Gy

T = 393-555 K

Charbonneau et al 2009

GJ 1214b's atmosphere



from Miller-Ricci-Kempton et al '11

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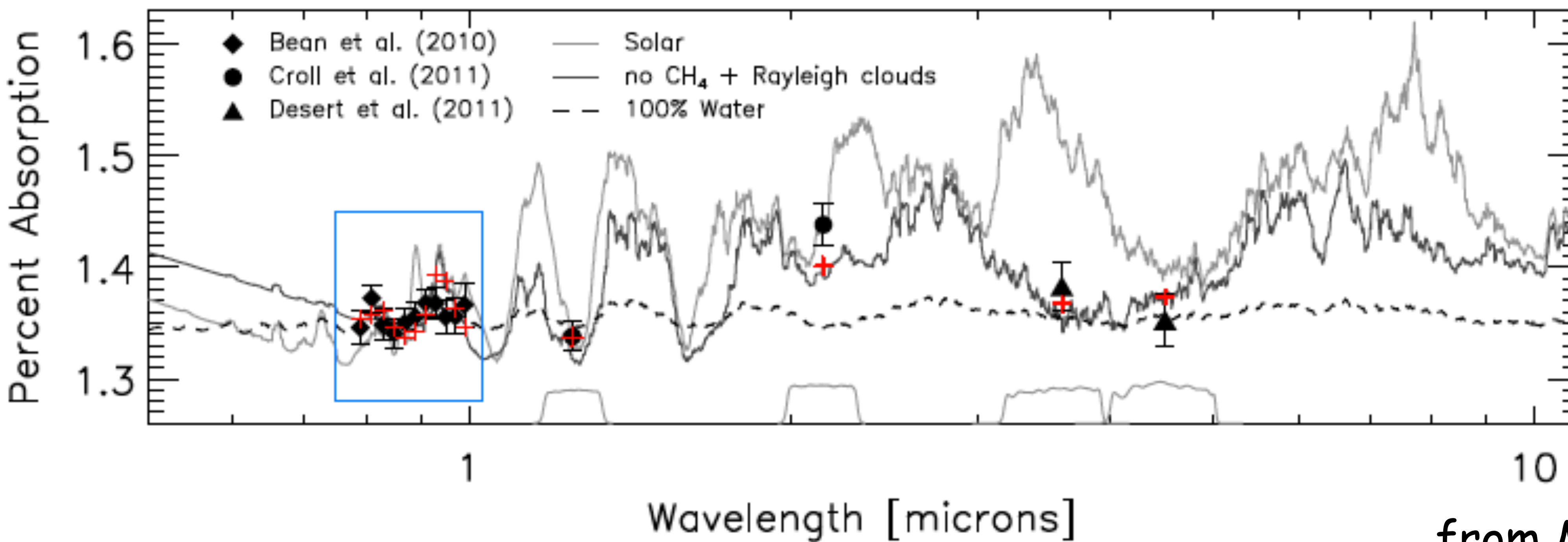

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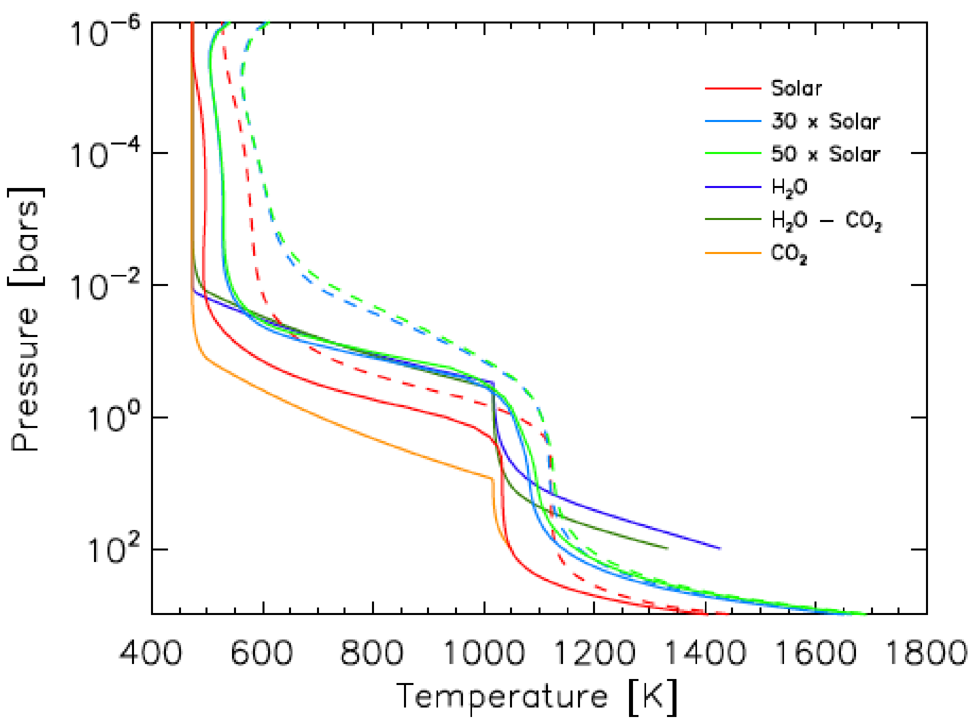
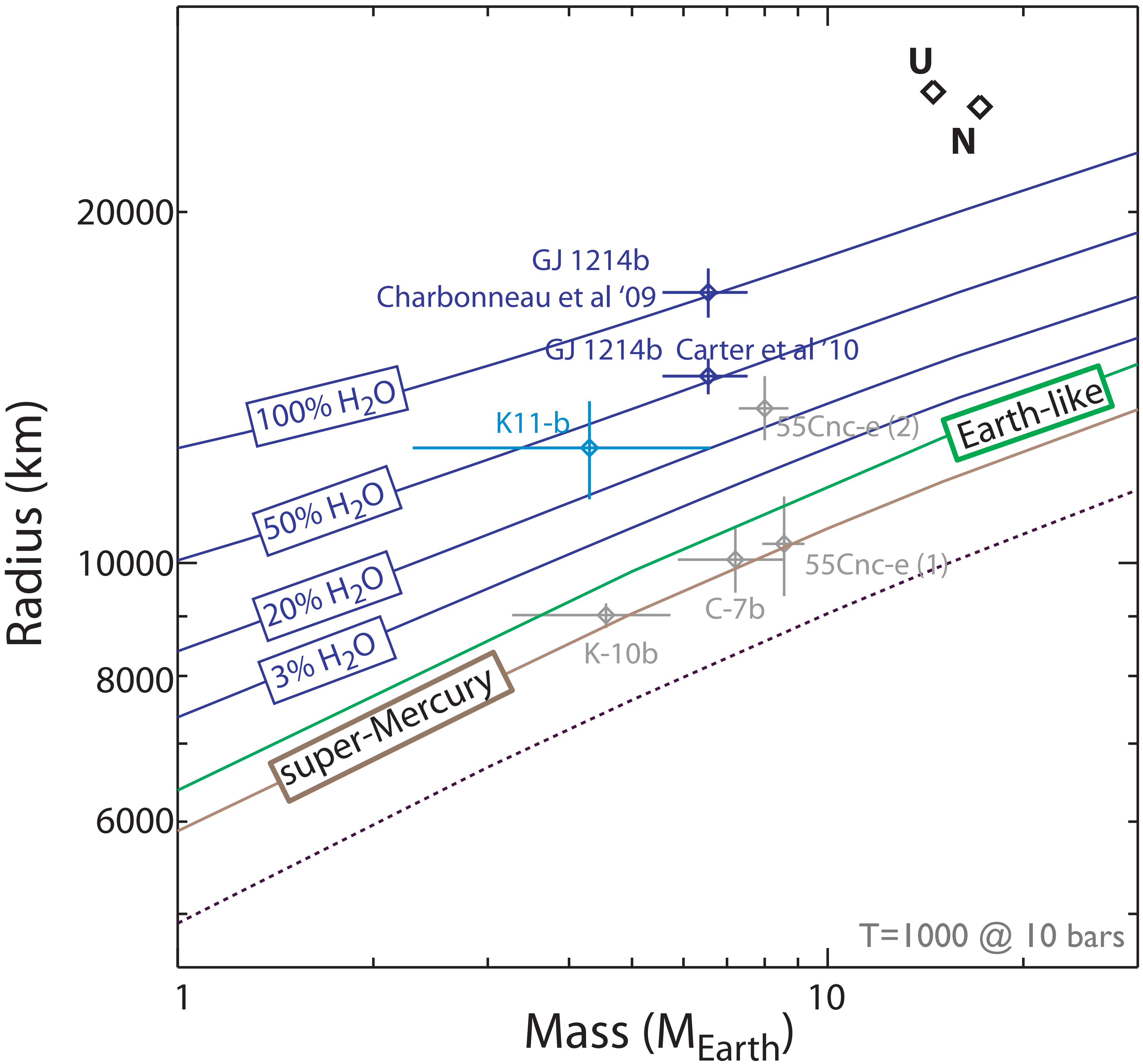


Miller-Ricci & Fortney 2010

GJ 1214b Composition



see also Rogers and Seager 2010
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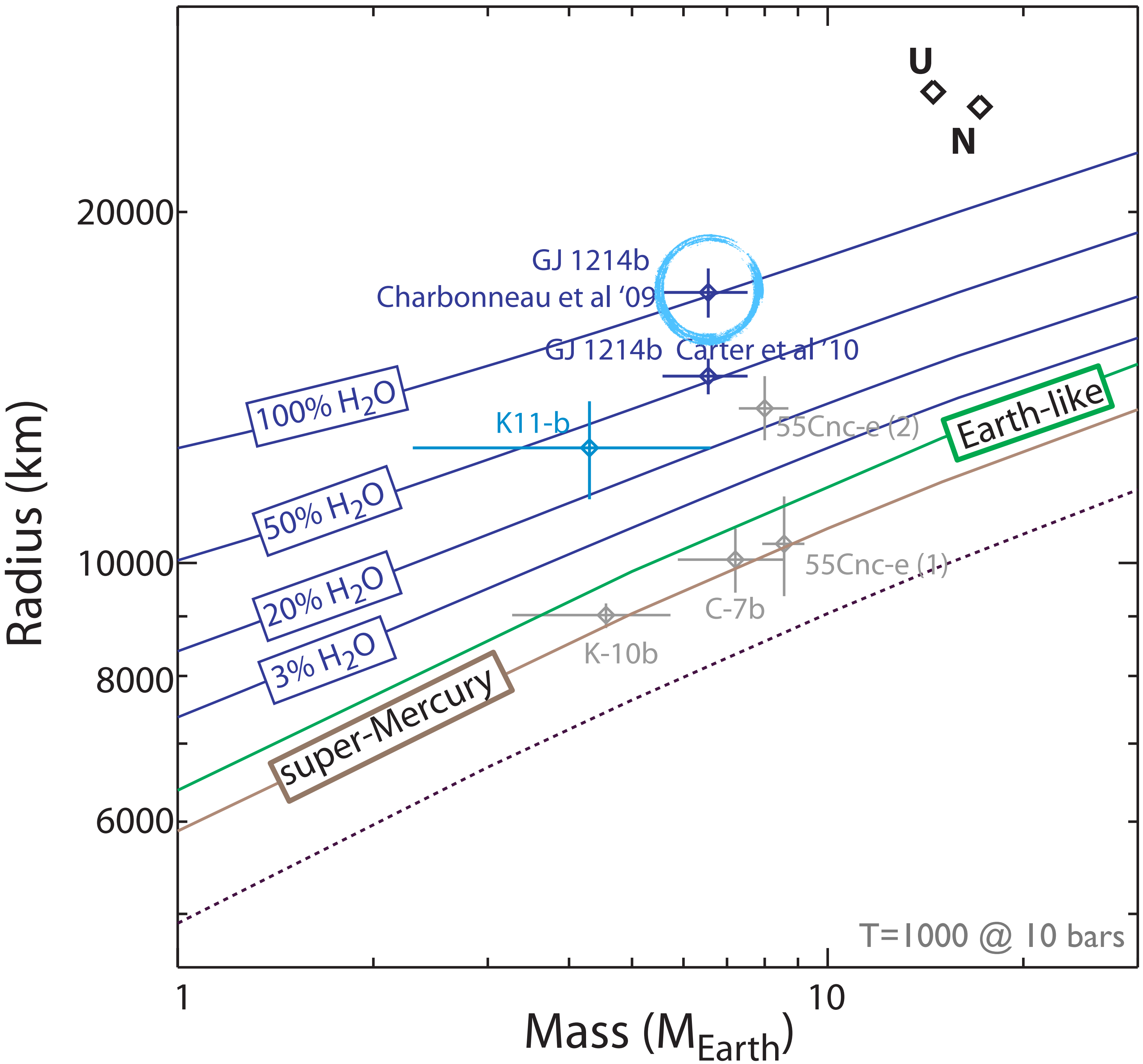

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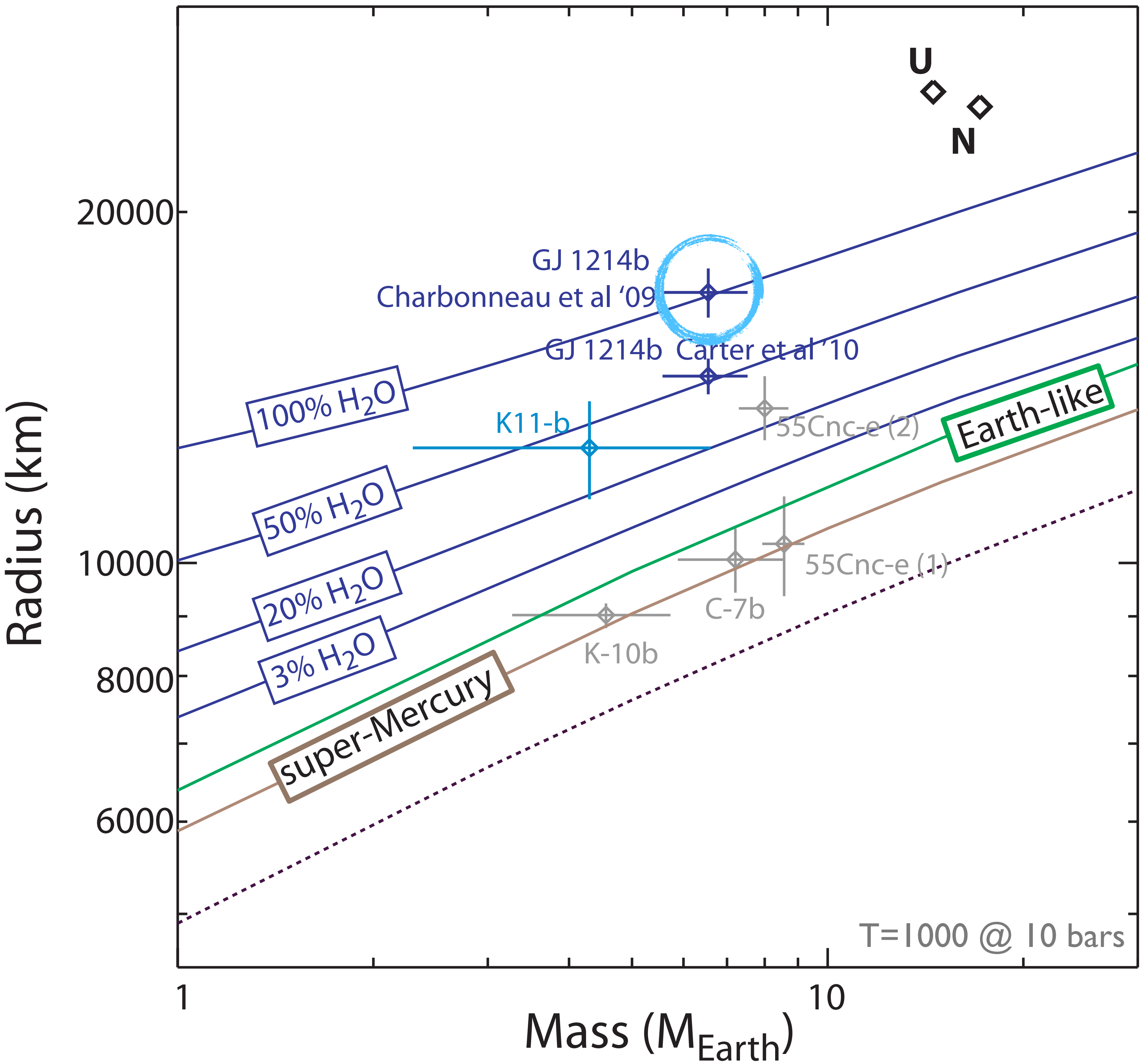

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see also Rogers and Seager 2010
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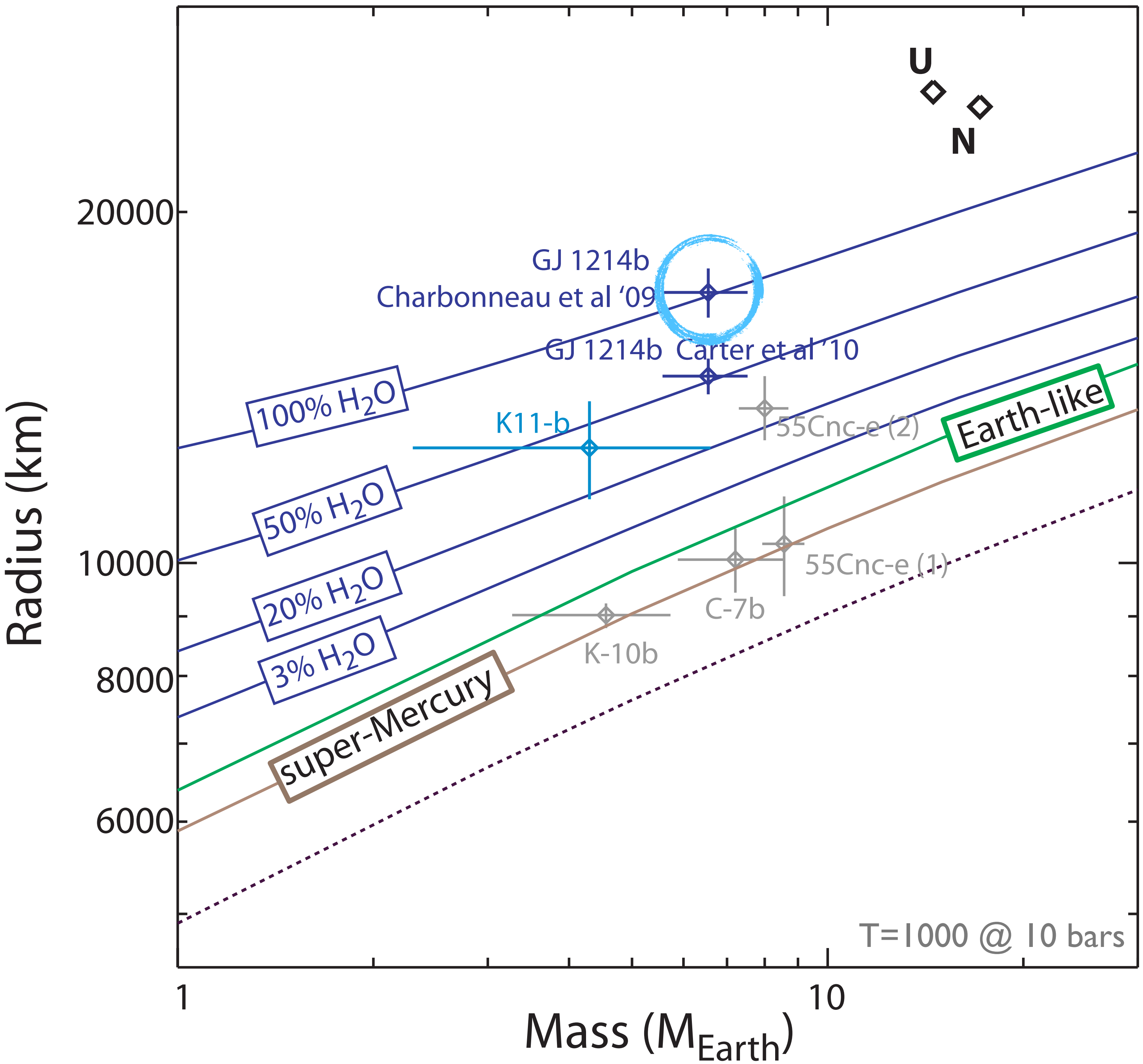

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We calculate that H-He is present in amounts less than ~8%

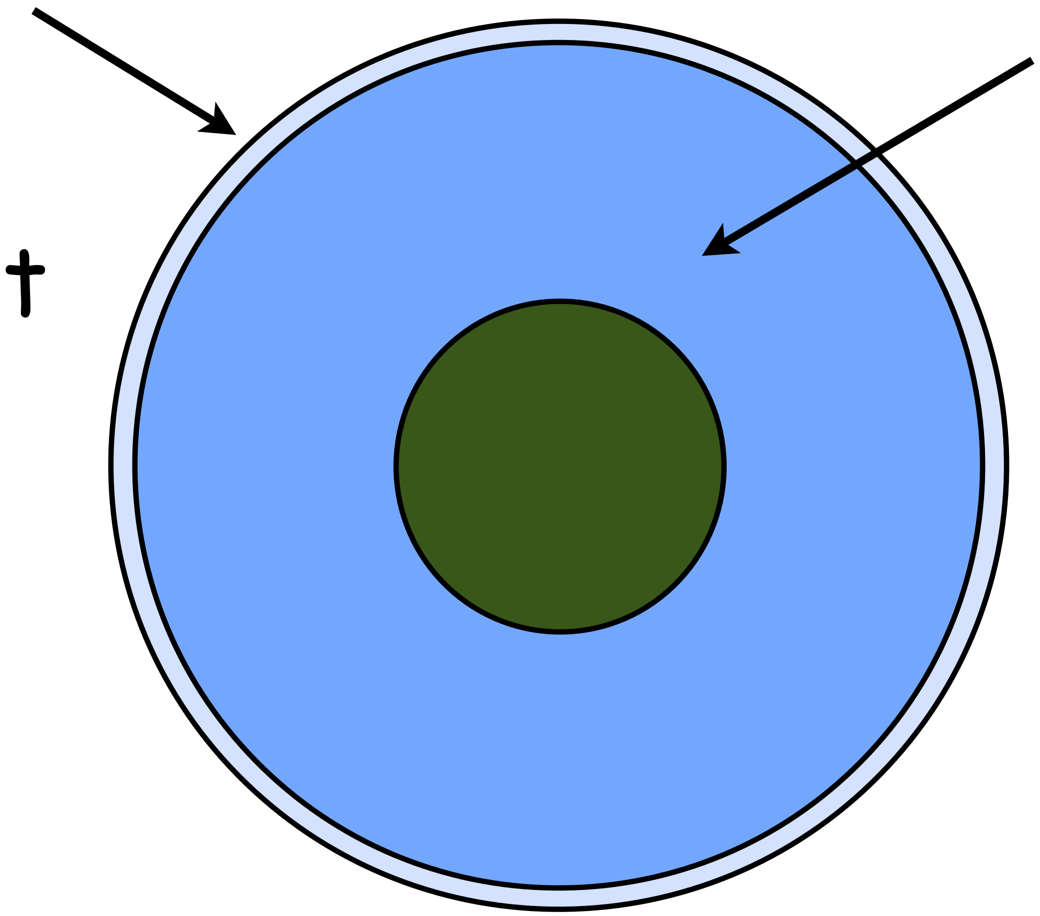
see also Rogers and Seager 2010
Nettlemann & Fortney 2010

GJ1214b: Unfolding picture

Observations at the ~ millibar level

Interior models start ~ bar level

low or high molecular weight atmosphere?



From discovery paper: Atmosphere probably has H-He

What is the composition of the nucleus?

With small R (from Carter et al '11), very little room for H-He

Summary I

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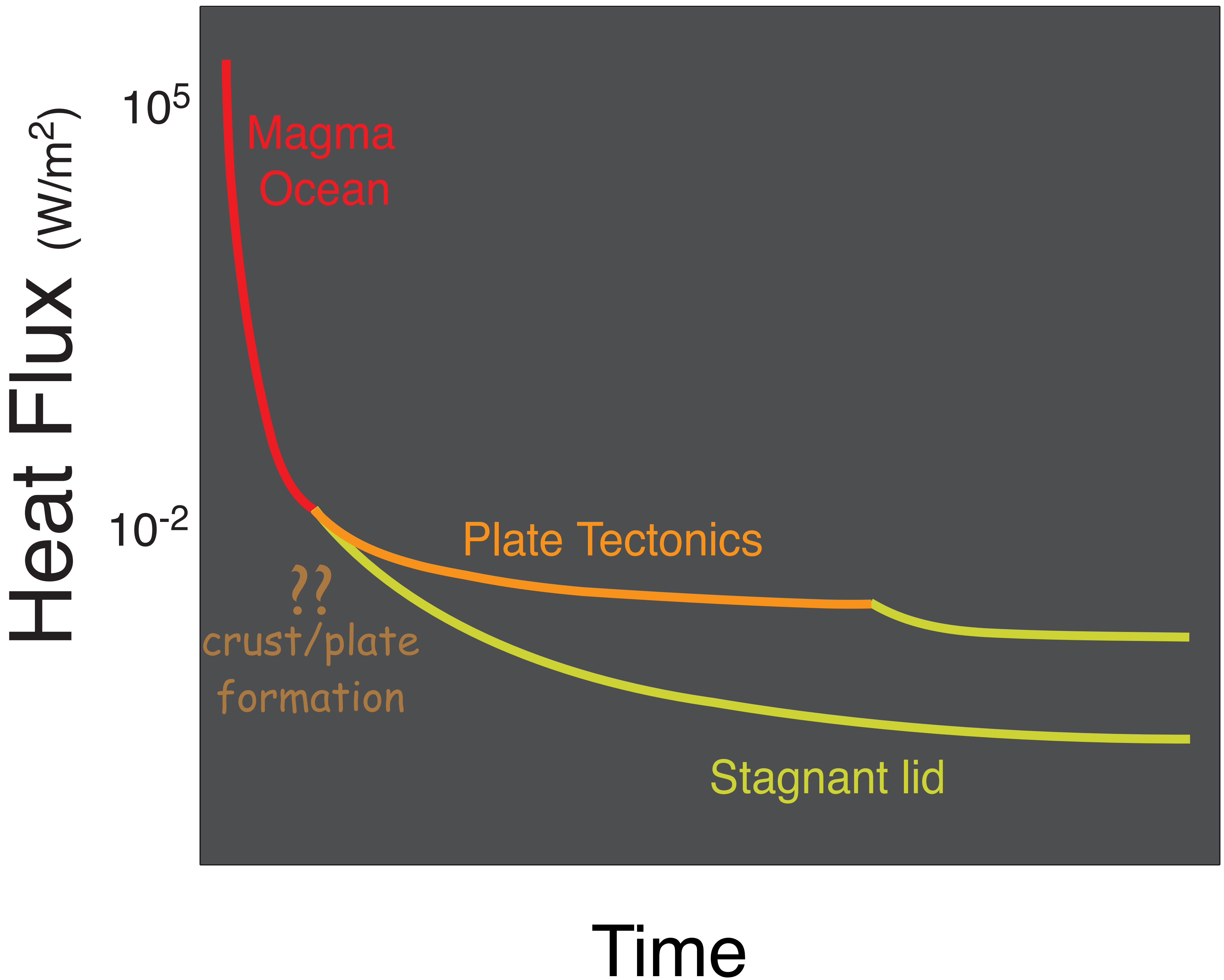
- The composition of CoRoT-7b and Kepler-10b is very similar: iron-enriched (by ~3x compared to Earth)
- 55Cnc-e is a vapor planet with an H2O-rich envelope of ~20% by mass
- GJ1214b undoubtedly has a volatile envelope. The observations of the atmosphere seem to be (somewhat) conflicting about its composition. Interior models predict at most ~10% of H-He by planetary mass.


Characterizing super-Earths
Are they habitable?
How do they evolve?
What is their atmosphere like?
How do they form?
What are they made of?
Single Planets
Population

Terrestrial Evolution



Terrestrial Evolution

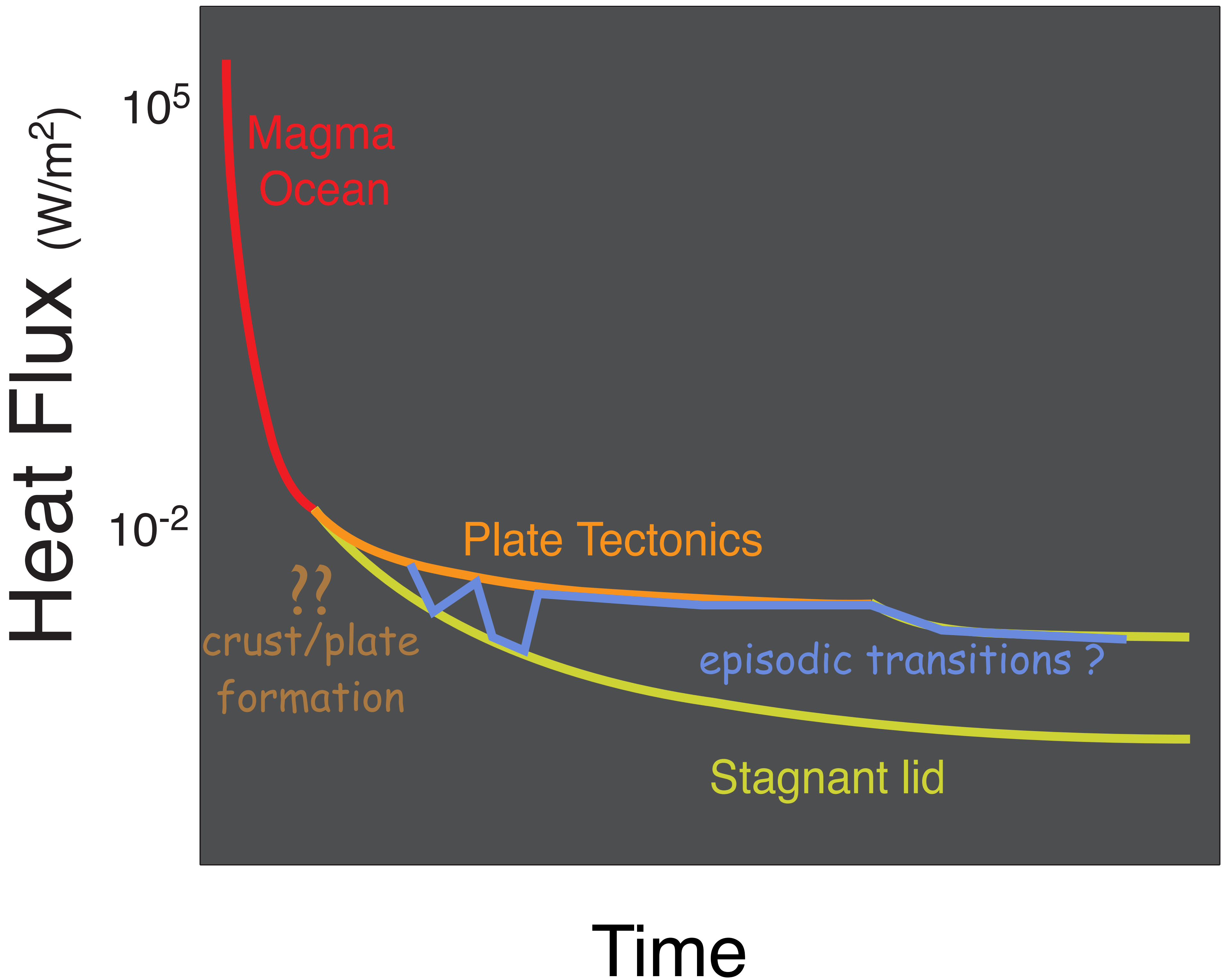
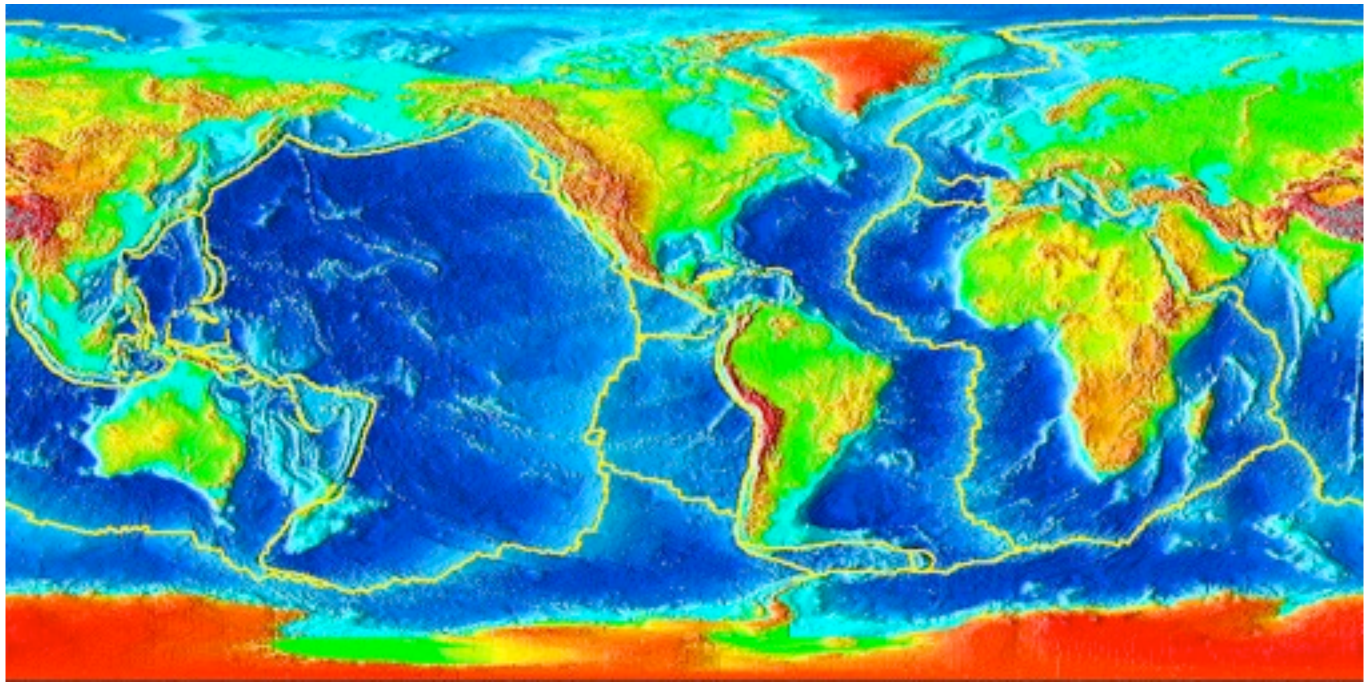
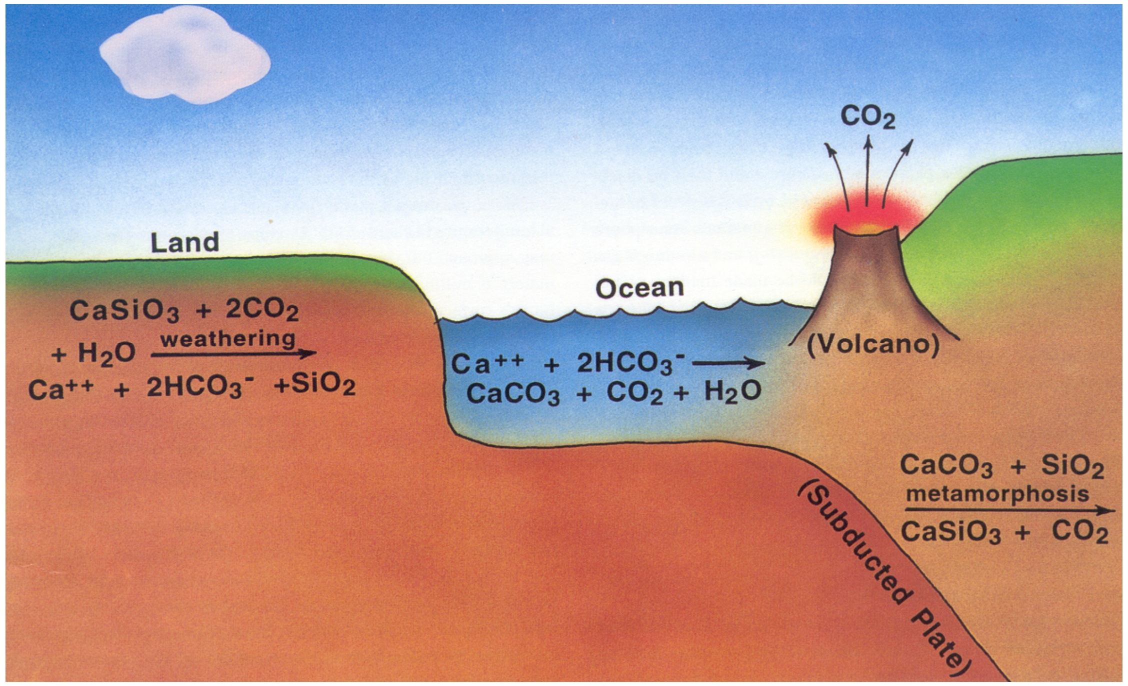


Plate Tectonics





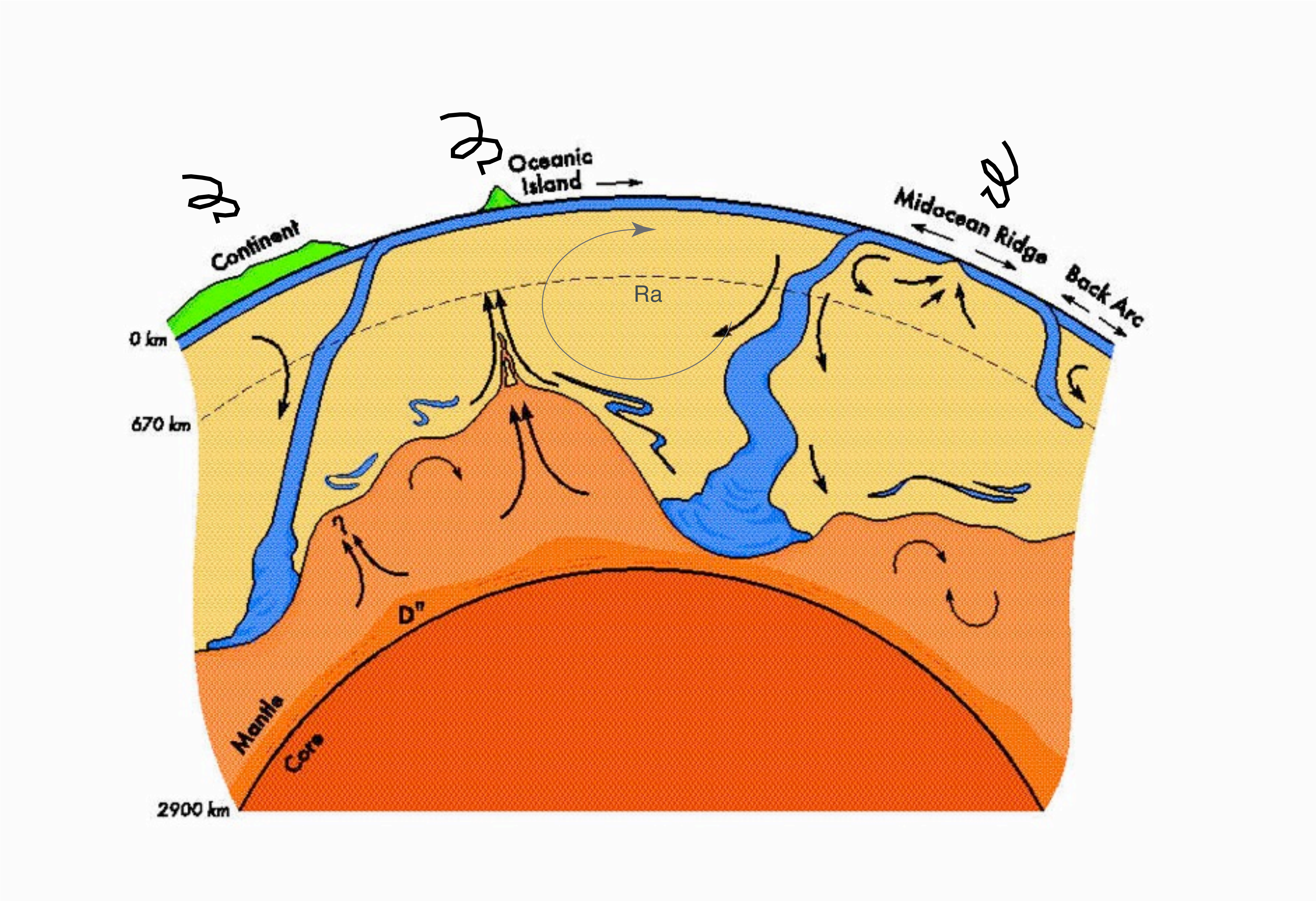
Walker 1981, Kasting 1996

Strong, coherent plate; deformation on boundaries

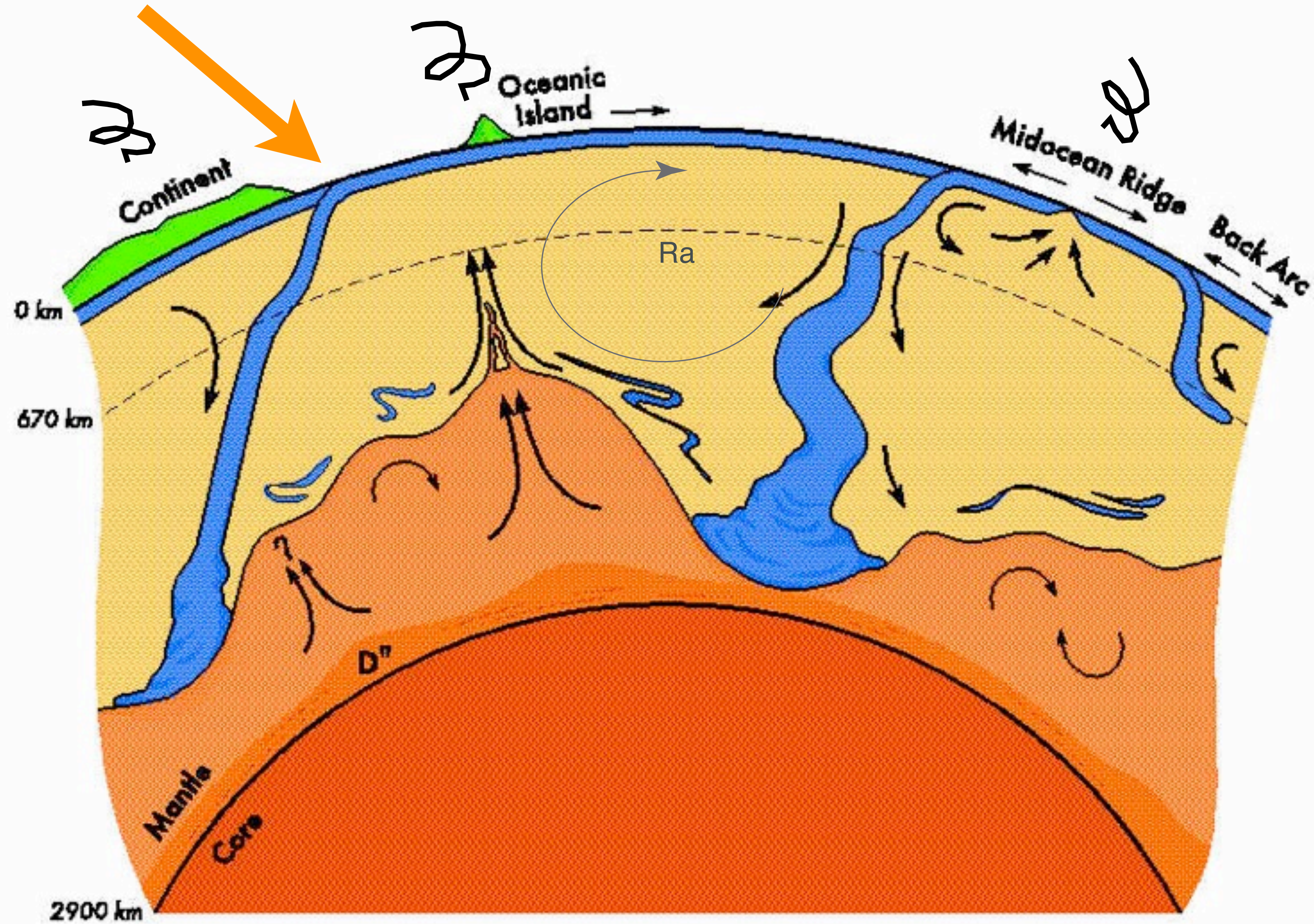
PT is the surface expression of mantle convection

PT has enabled the C-Si cycle to operate (which acts as a thermostat) on Earth over geological timescales

Interior dynamics and the atmosphere

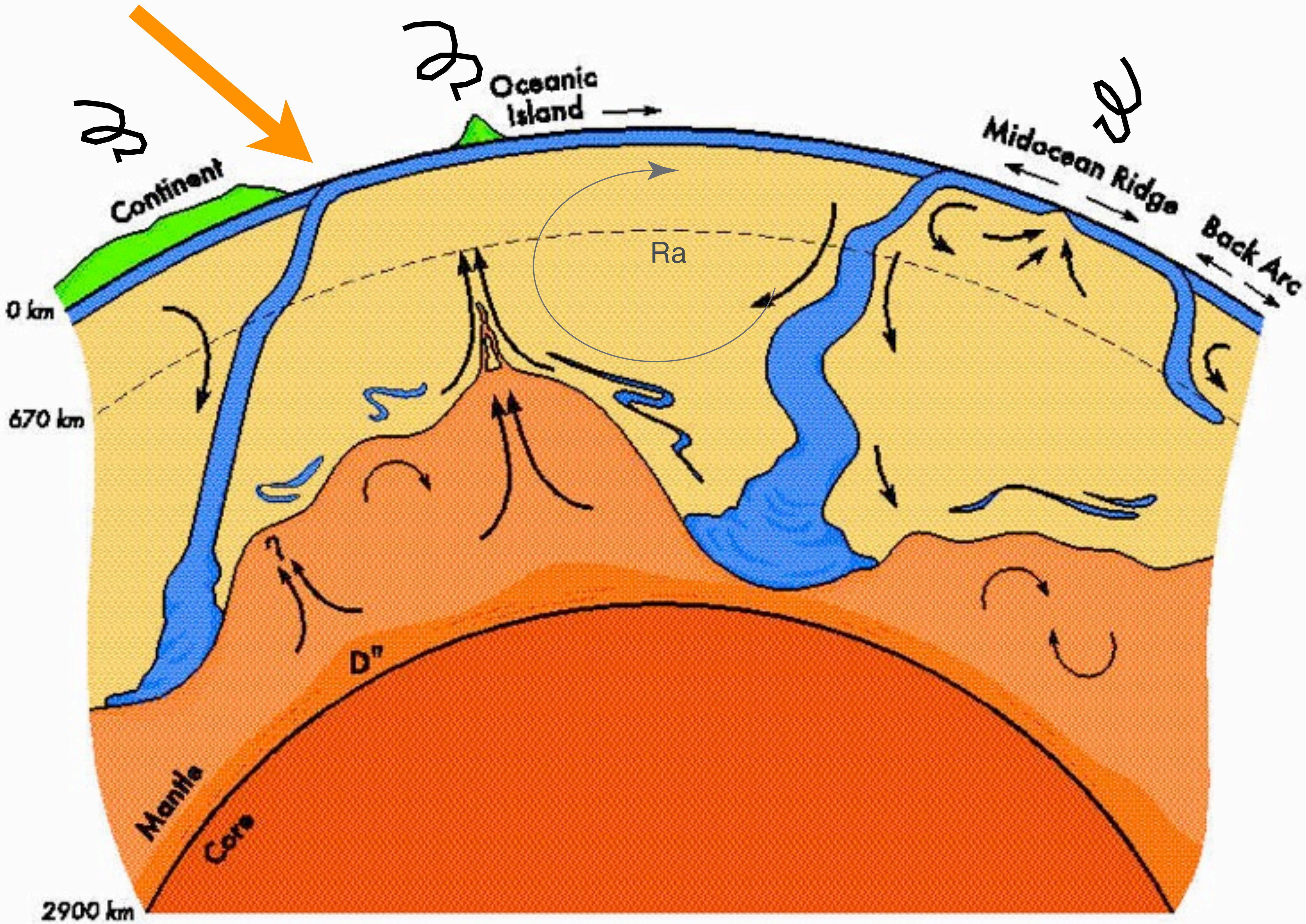


Interior dynamics and the atmosphere

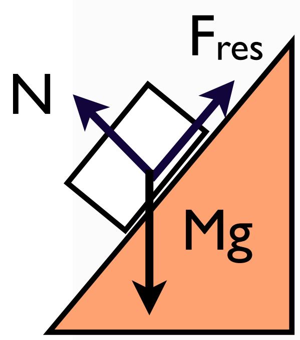


Interior dynamics and the atmosphere

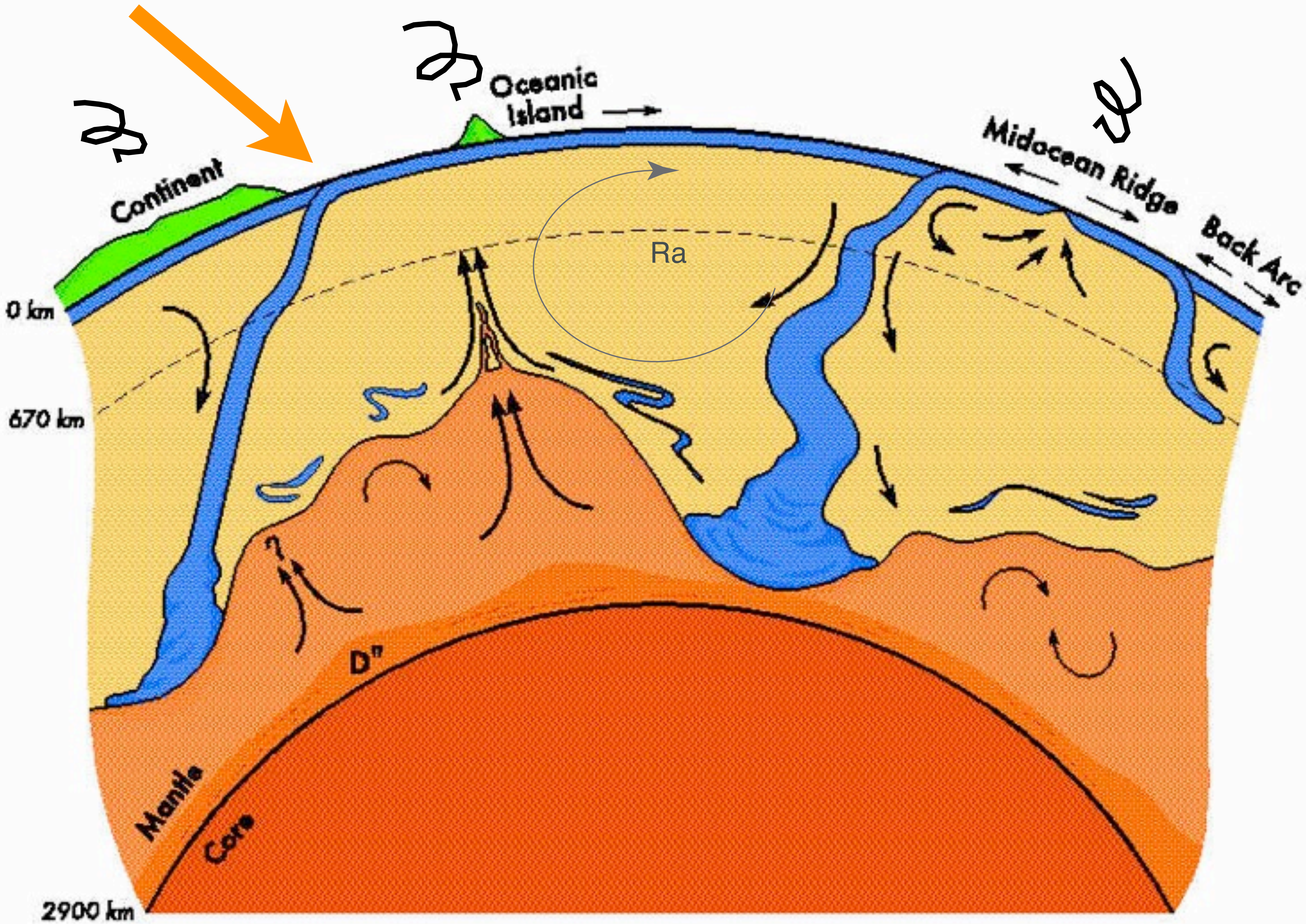
Coulomb failure criterion for plate deformation



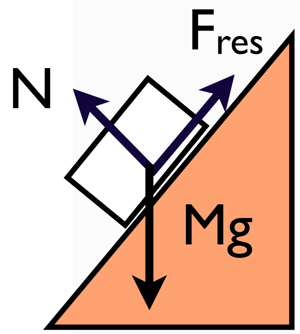
Interior dynamics and the atmosphere



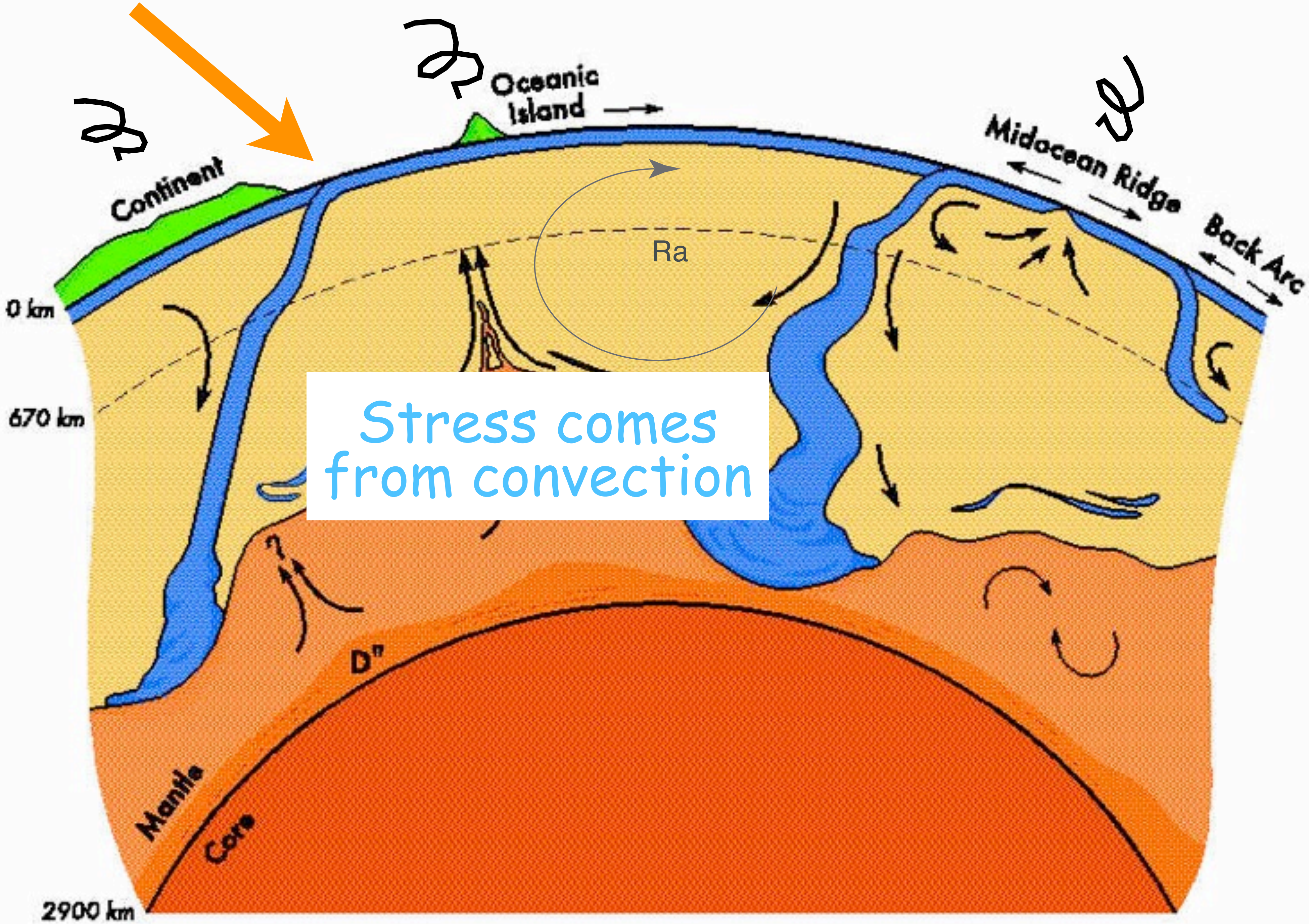
Coulomb failure criterion for plate deformation



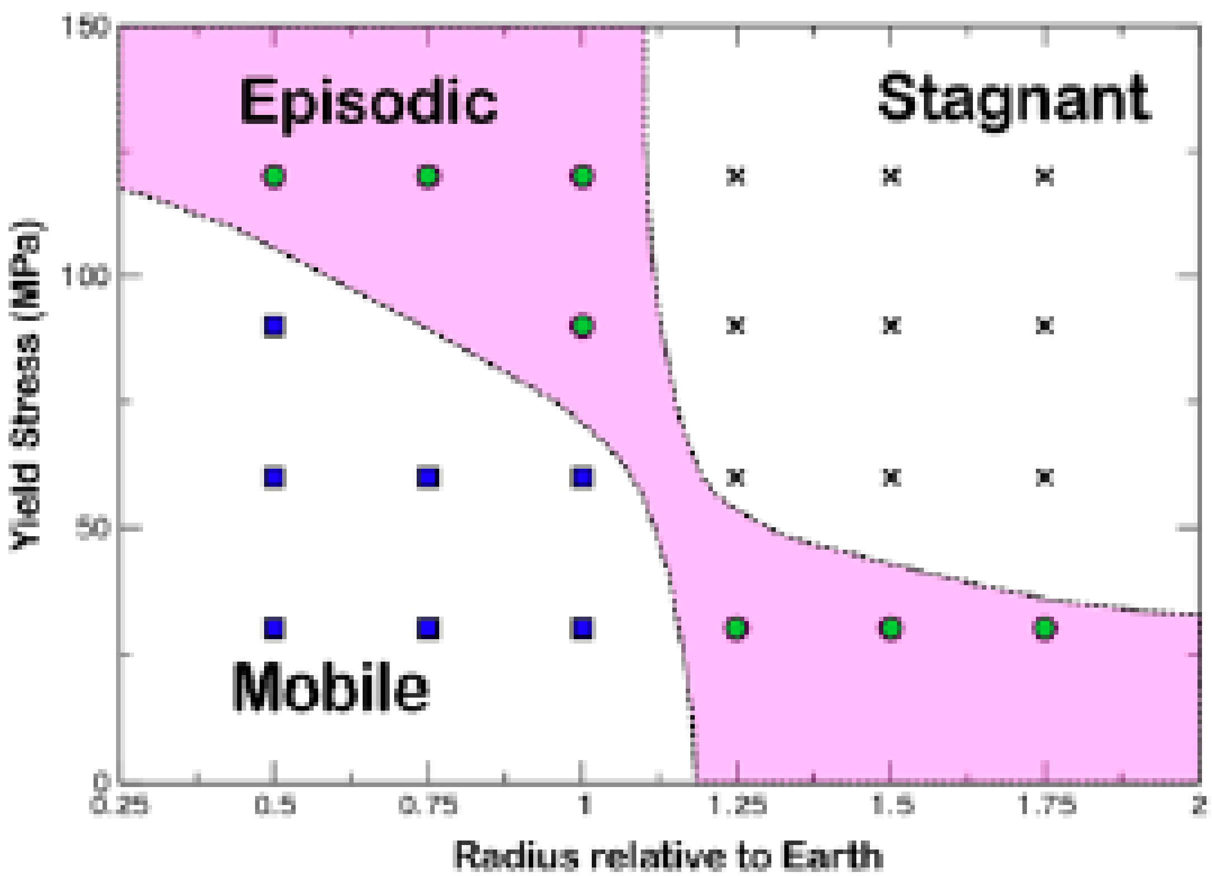
Interior dynamics and the atmosphere



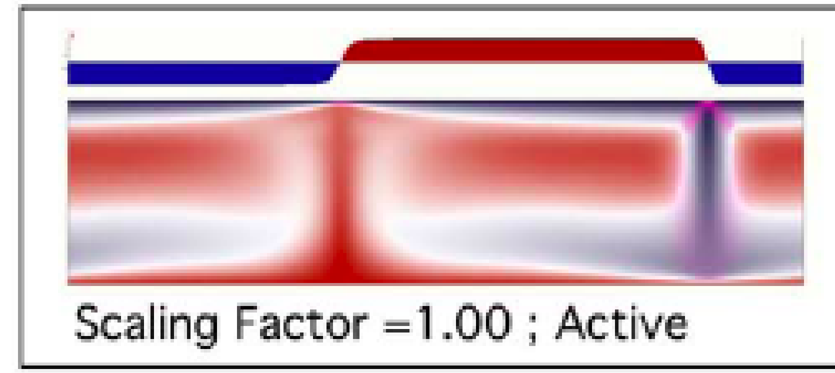
Coulomb failure criterion for plate deformation



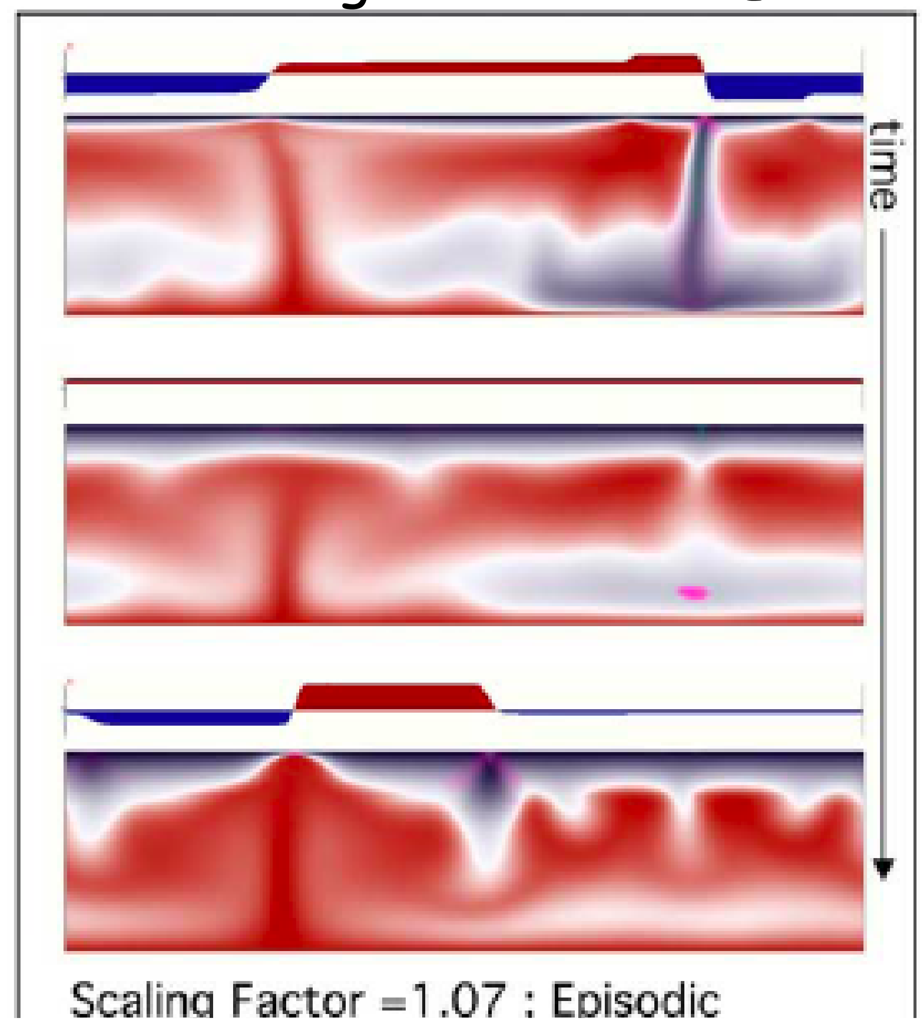
O'Neill & Lenardic '07: at most in an episodic regime
Argue that faults are too strong due to high g

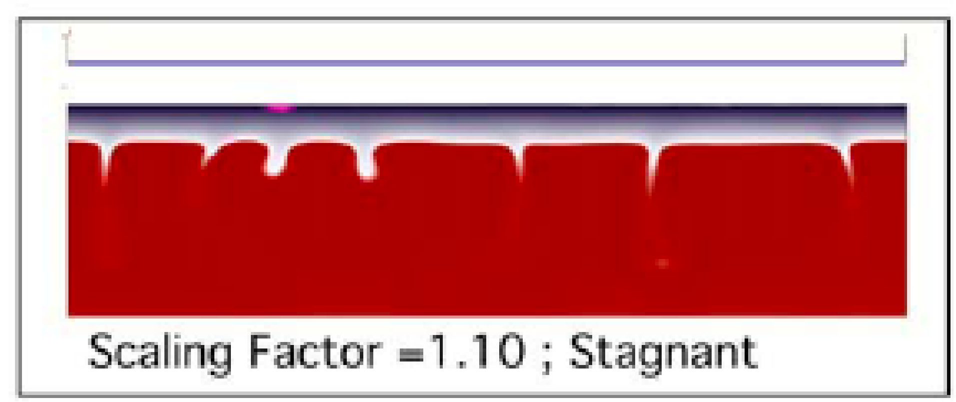


O'Neill & Lenardic, 2007

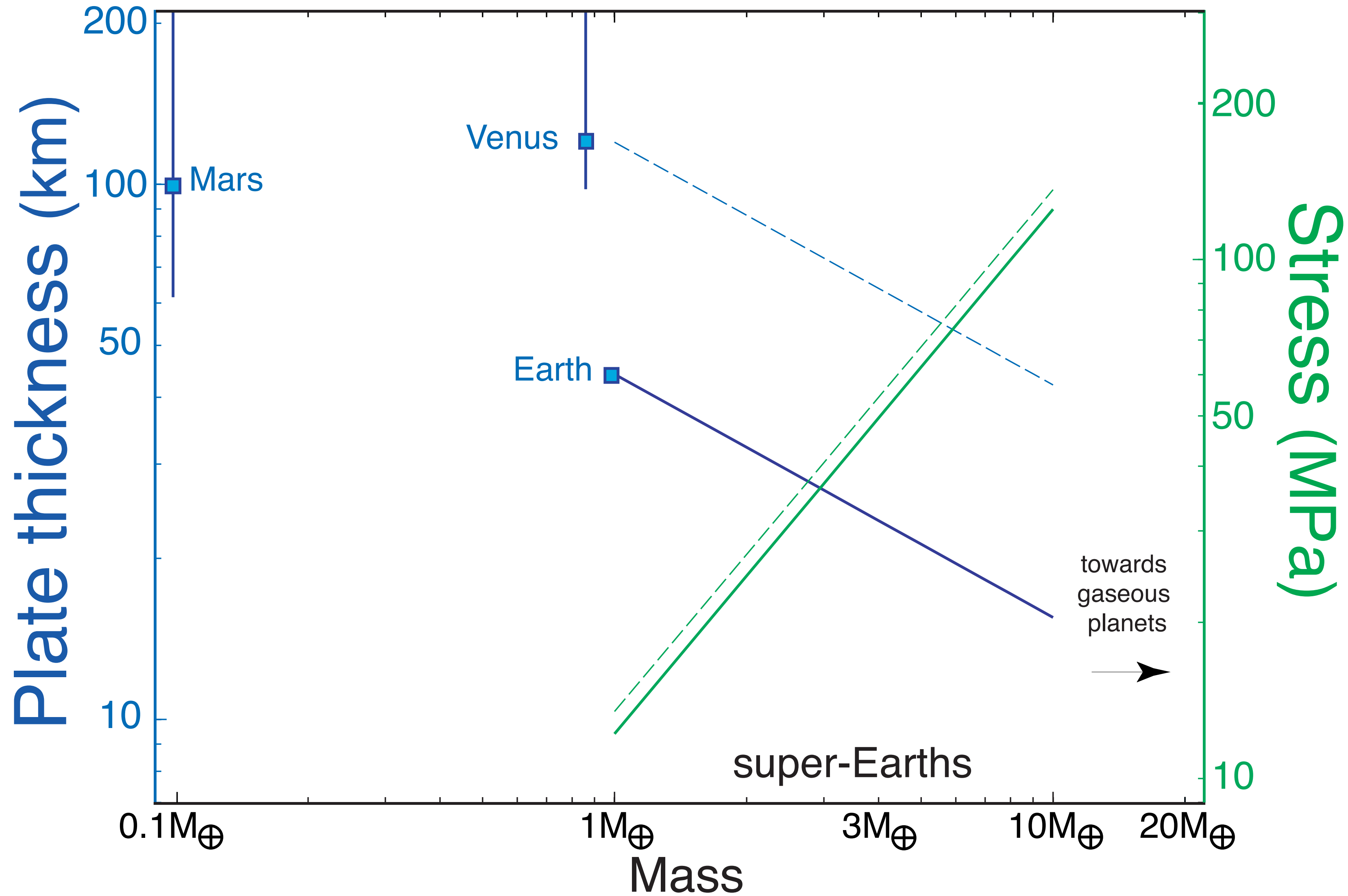


Scaling Factor = R/R_E





Valencia et al '07: more likely to have PT, based on thinner planets and larger convective stresses



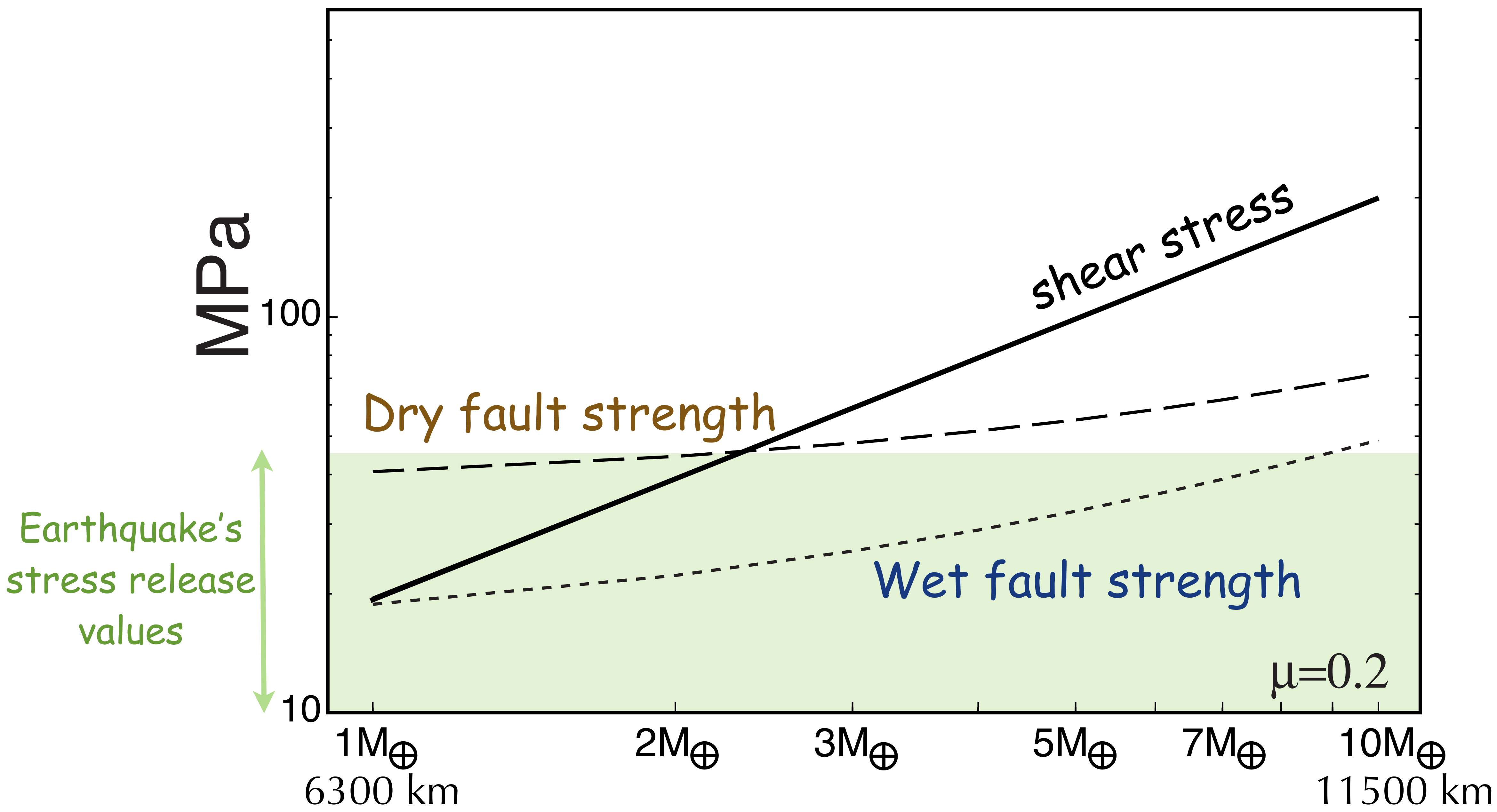
$$\delta \sim D/2\ (Ra/R_{ac})^{-1/4}$$

$$u \sim \kappa/D\ (Ra/R_{ac})^{1/2}$$

$$\Delta\ \tau_{xy} \sim \eta(T)\ u/D$$

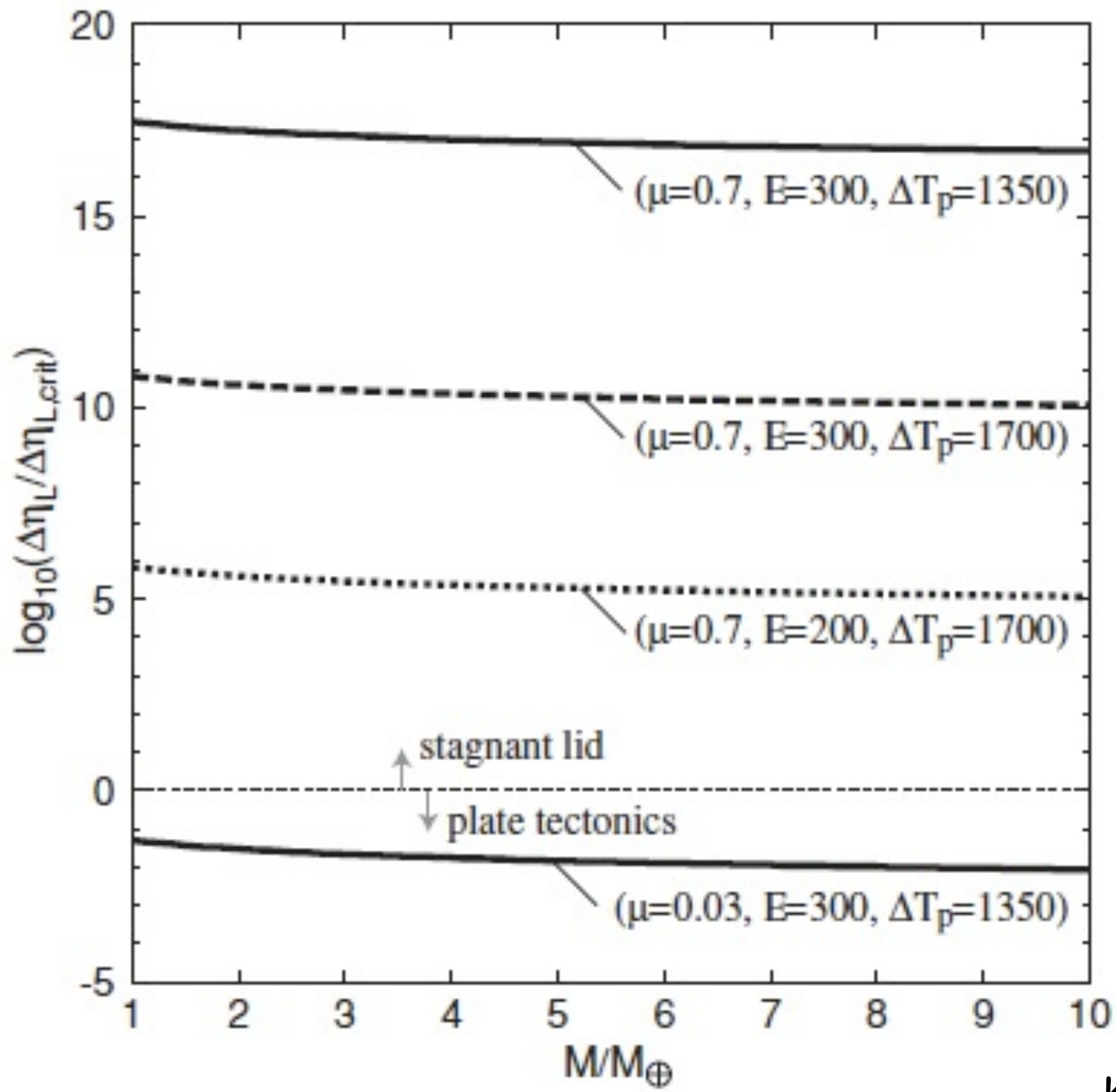
Valencia et al., 2007c

Valencia & O'Connell '09: faults do become stronger but driving stresses can overcome the plates resistance to deformation



Valencia et al., 2009b

Korenaga 2010: even though SE might have better conditions, the most important factor is to have a low coefficient of friction, which can be achieved with water



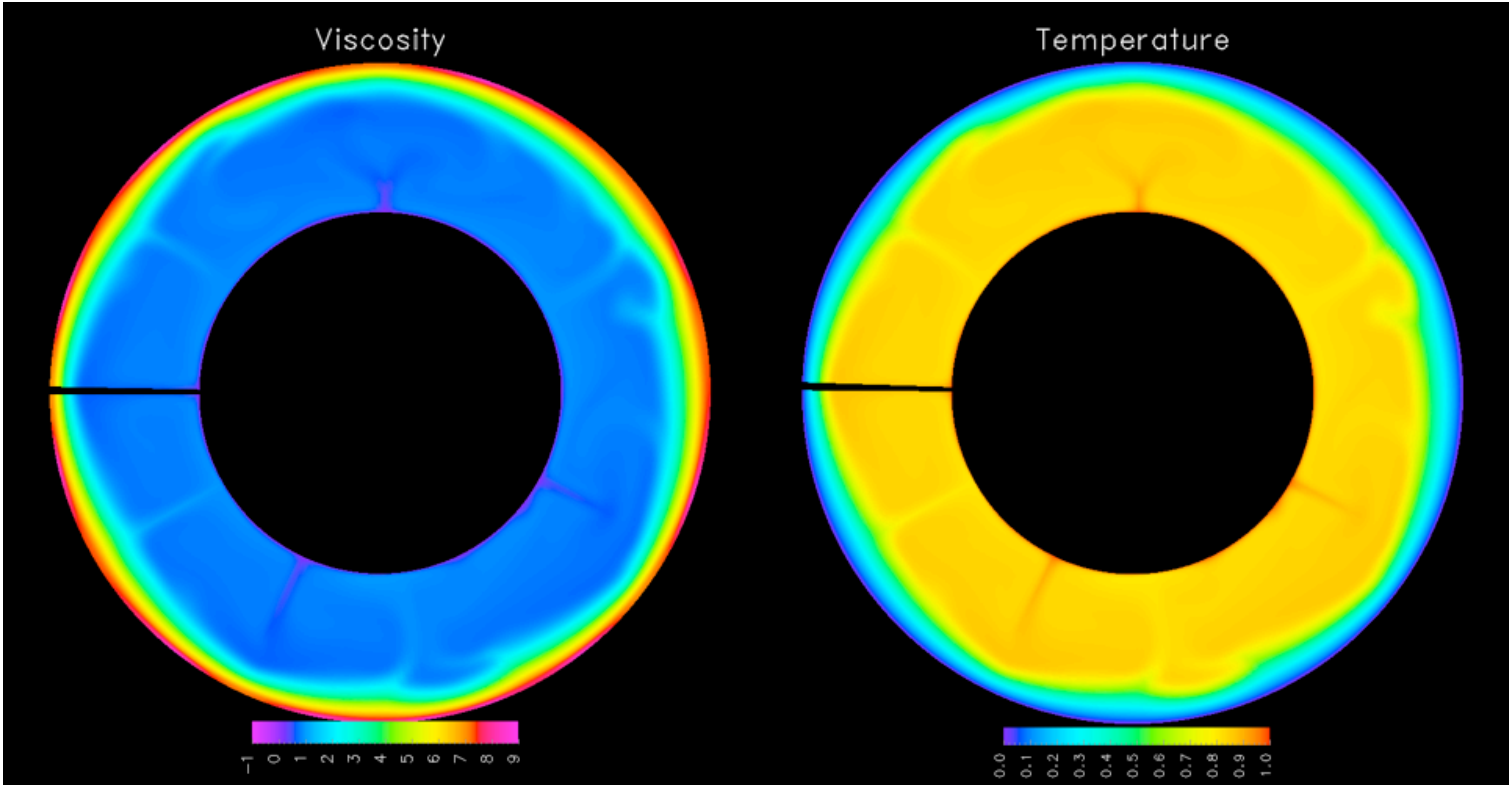
Korenaga 2010

Plate Tectonics on Exo-Earths?

$R/R_E=2$

Van Heck & Tackley, 2009

Plate Tectonics on Exo-Earths?



$R/R_E=2$

Van Heck & Tackley, 2009

Summary II

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- Low-mass planets evolve habitable conditions.

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- Their atmosphere is tied to interior dynamics, expect diversity!

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- Low-mass planets evolve habitable conditions.
- Their atmosphere is tied to interior dynamics, expect diversity!
- Plate Tectonics on SE is under debate: role of water, role of surface temperature, depth dependent rheology, etc...

Additional Slides