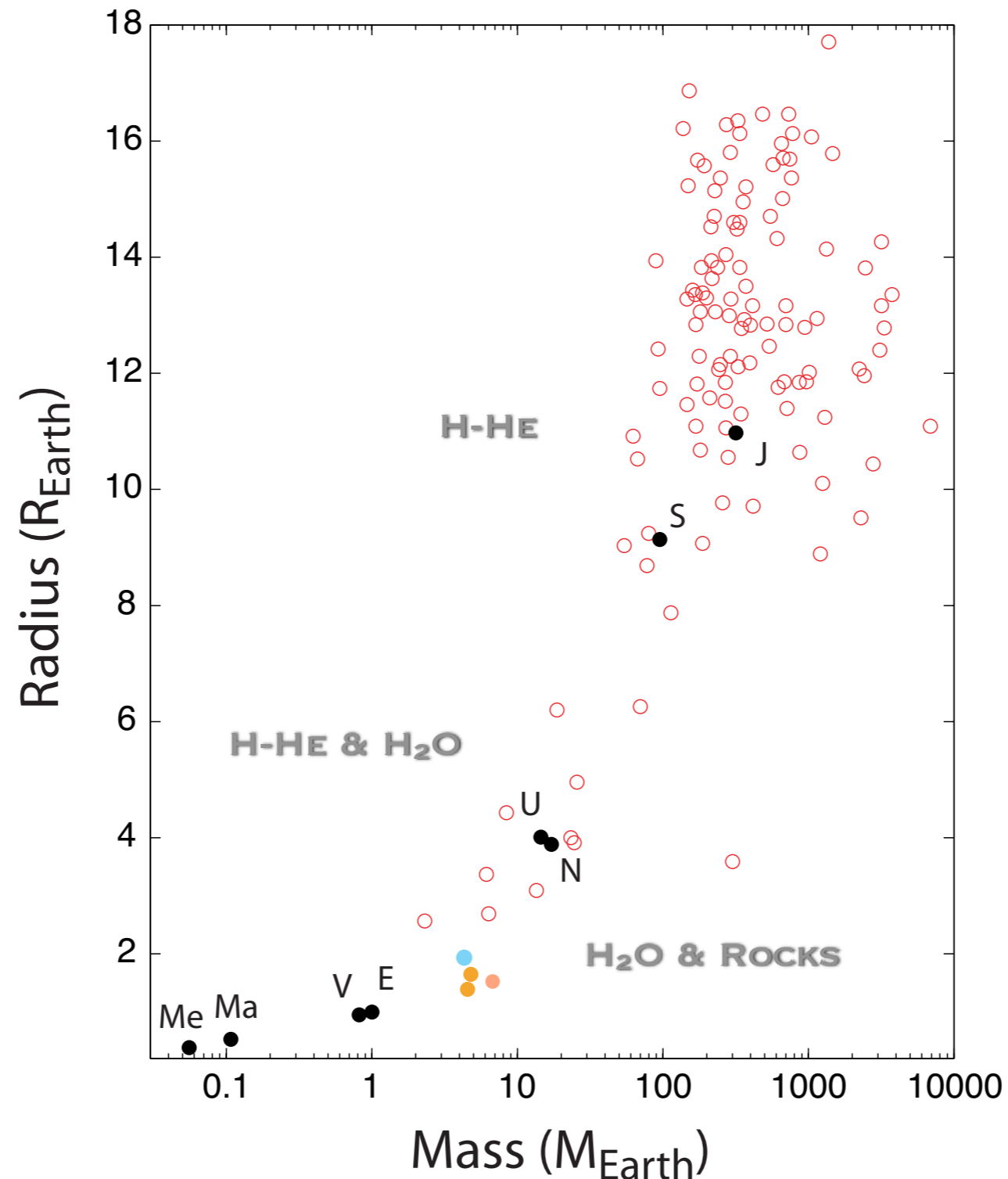


Composition and Interior Dynamics of Super-Earths

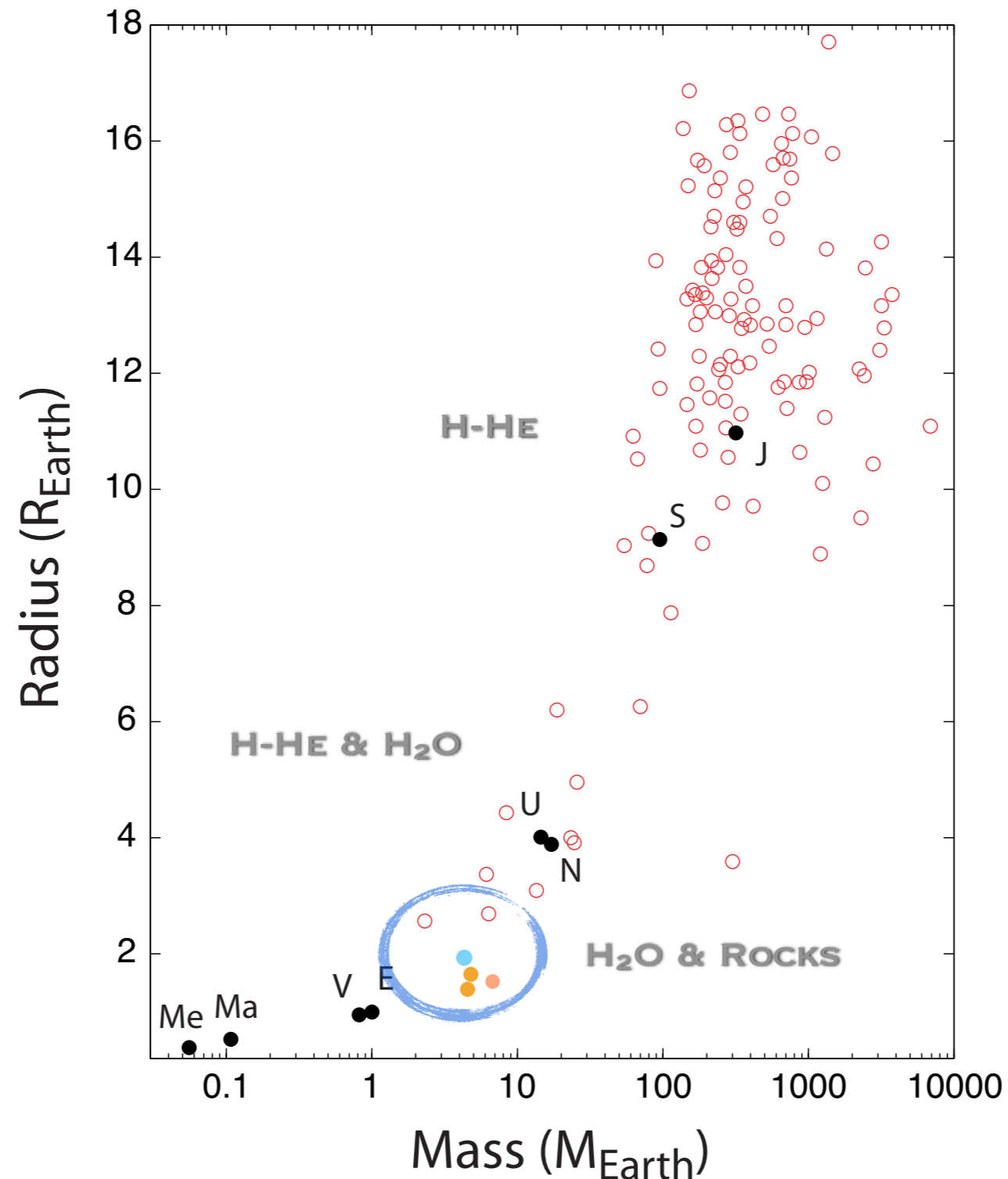
Diana Valencia
NASA Sagan Fellow
MIT

Ciera: The Future of Astronomy
Northwestern University, August 31st 2011

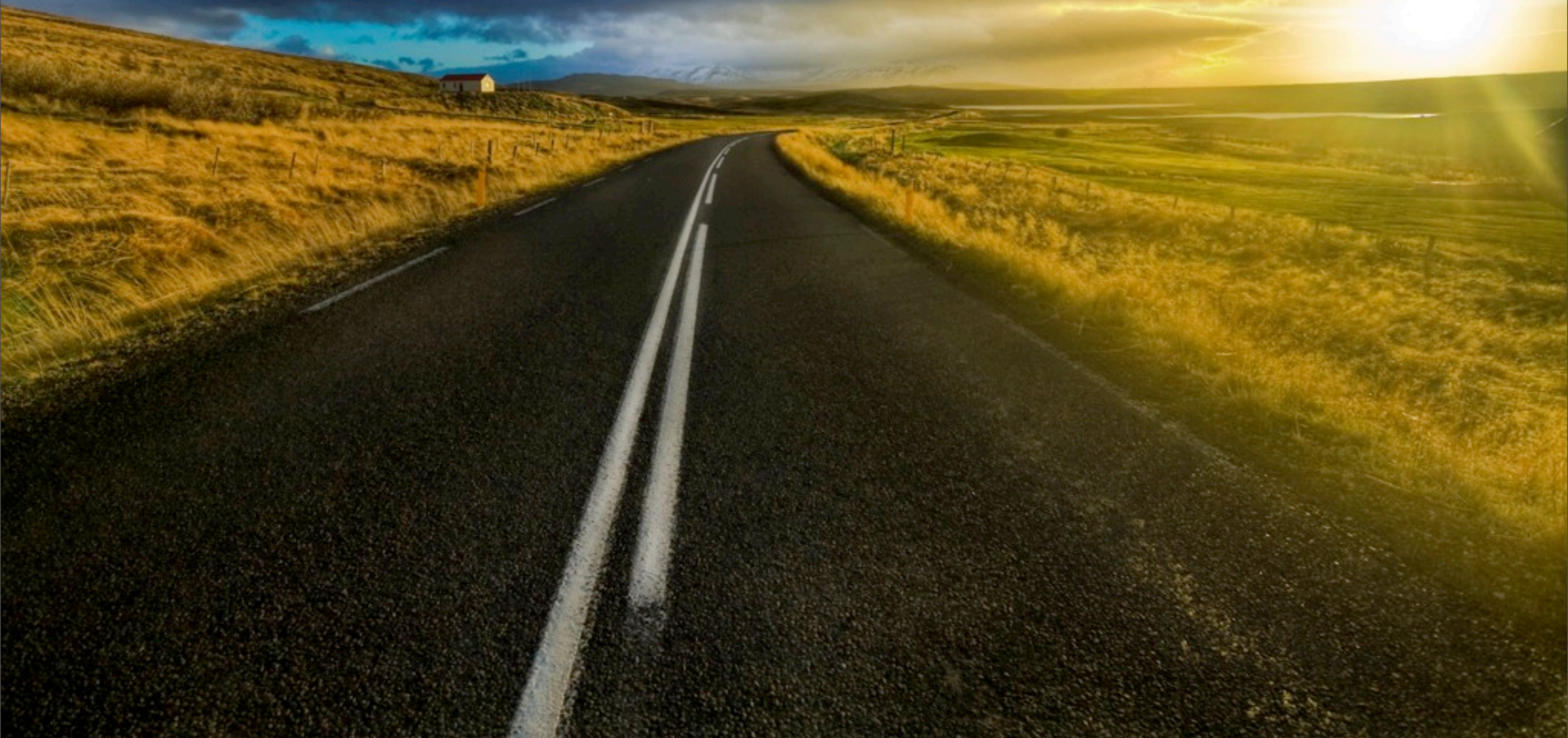
Super-Earths: the newest class of exoplanets



Super-Earths: the newest class of exoplanets



Characterizing super-Earths



Characterizing super-Earths

Are they habitable?

Characterizing super-Earths

Are they habitable?



Characterizing super-Earths

Are they habitable?

What are
they made of?

Characterizing super-Earths

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What are
they made of?

How do they form?

Characterizing super-Earths

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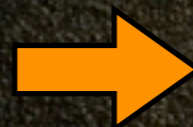
How do they evolve?

What is their atmosphere like?

How do they form?

What are they made of?

Single Planets



Population

Characterizing super-Earths

Are they habitable?

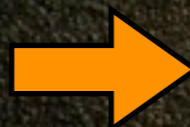
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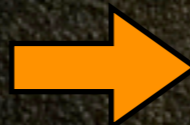
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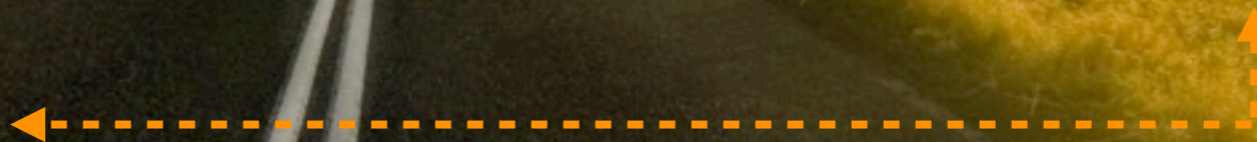
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Single Planets



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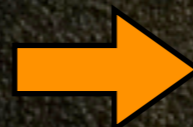
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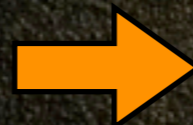
How do they evolve?

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How do they form?

What are they made of?

Single Planets



Population

The First Transiting super-Earths

	CoRoT-7B	KEPLER-10B	55CNC-E	GJ 1214B
RADIUS (R_E)	1.58 ± 0.1	$1.416^{+0.033}_{-0.036}$	$2.08^{+0.16}_{-0.17}$ 2.00 ± 0.614	2.678 ± 0.13 2.27 ± 0.08
MASS (M_E)	$4.8 \pm 0.8, 6.9 \pm 1.5,$ $8.0 \pm 1.2, 5.7 \pm 2.5,$ $2.3 \pm 1.8,$ 7.26 ± 1.36	$4.56^{+1.17}_{-1.26}$	7.87 ± 0.65 8.63 ± 0.35	6.55 ± 0.98
ORBITAL PERIOD (D)	0.854	0.837	0.74	1.58
AGE (GY)	1.2 - 2.3	> 9	~ 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	DEMORY ET AL 2011 WINN ET AL 2011	CHARBONNEAU ET AL 2009, CARTER ET AL 2011



Recipe: Internal Structure Model

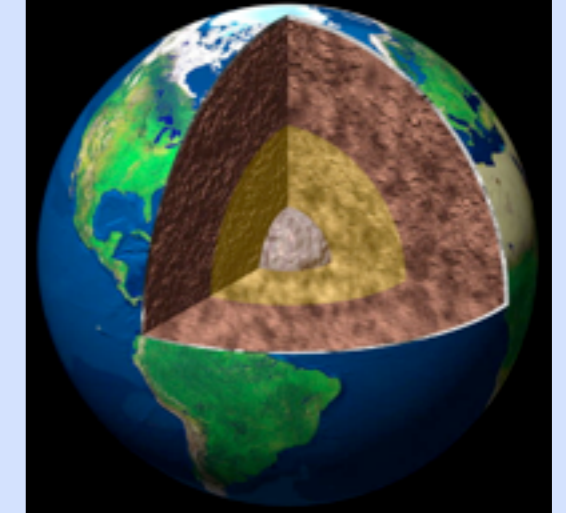
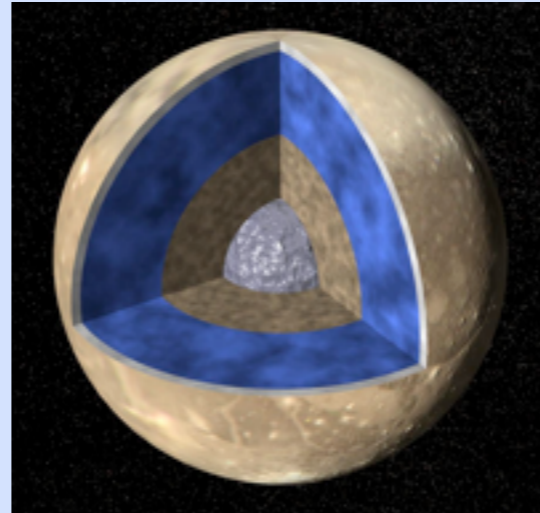
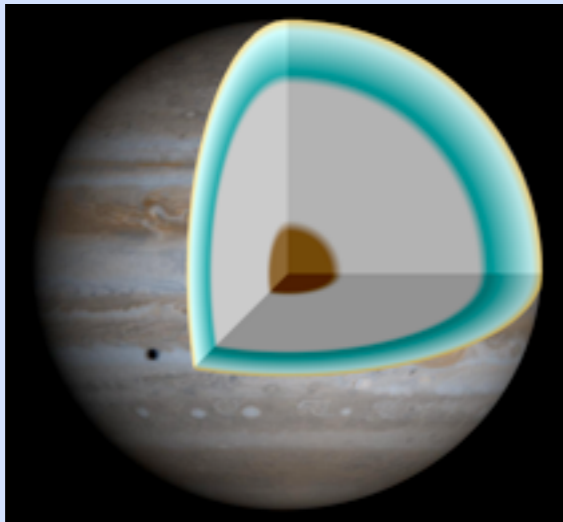


Assume a composition

H-He

H_2O, CH_4, \dots

Si, O, Mg, Fe



Solve structure equations

(M, ρ, P, g, T, S)



Need an **EQUATION OF STATE**

Valencia et al '06, Fortney et al '07, Sotin et al '07, Seager et al '07,
Grasset et al '09, Valencia et al '10, Rogers and Seager '10, Nettleman &
Fortney '10, Wagner et al 2011



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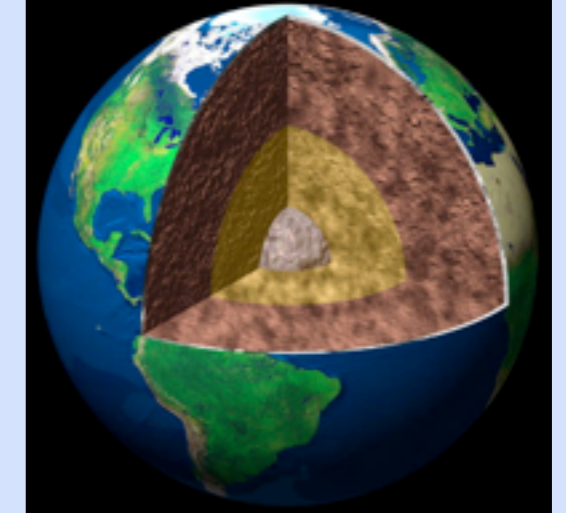
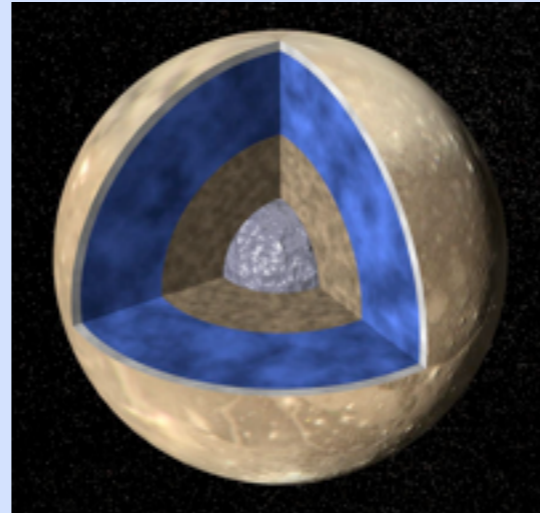
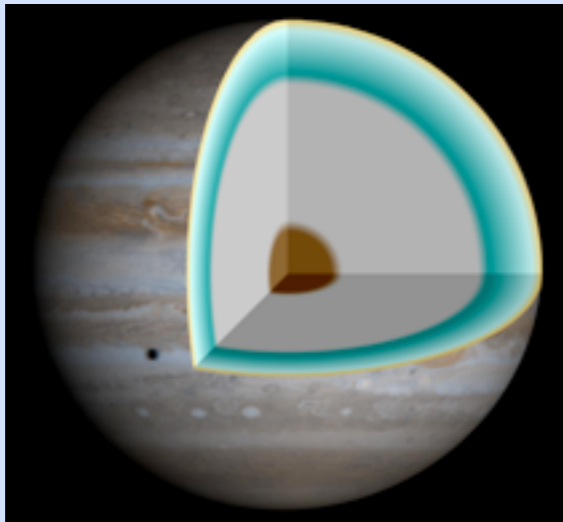


Assume a composition

H-He

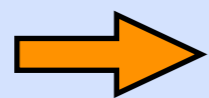
H₂O, CH₄,...

Si, O, Mg, Fe



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

Need an **EQUATION OF STATE**



Obtain: $R(M; \chi)$

Valencia et al '06, Fortney et al '07, Sotin et al '07, Seager et al '07,
Grasset et al '09, Valencia et al '10, Rogers and Seager '10, Nettelmann &
Fortney '10, Wagner et al 2011

Variety in Rocky Compositions

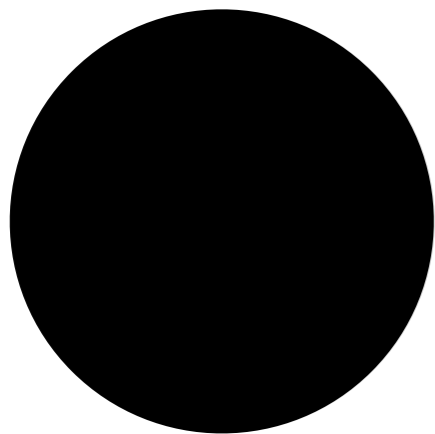
Fe, Mg, Si, O, Ca, Al, Ti

Different compositional budgets (Si/Fe, Mg/Fe ...)

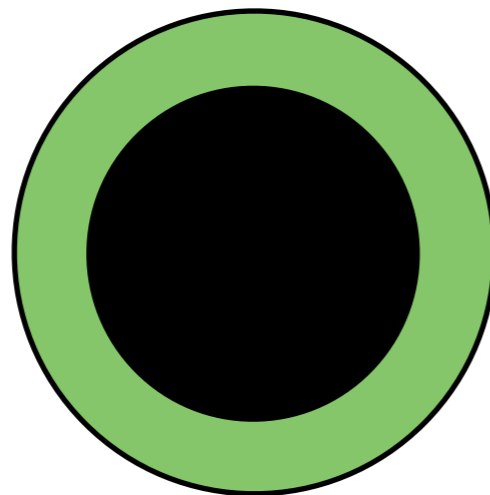
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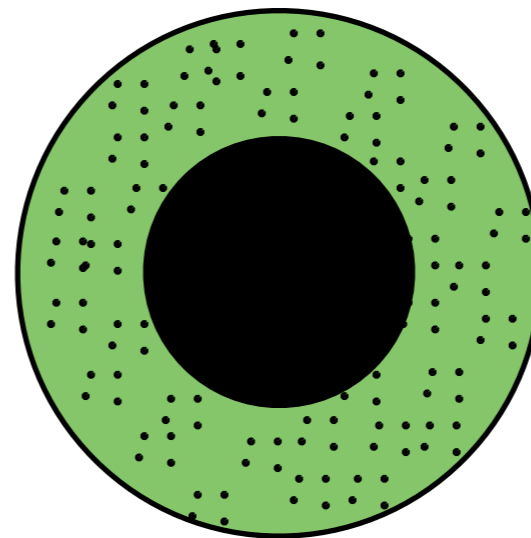


Iron



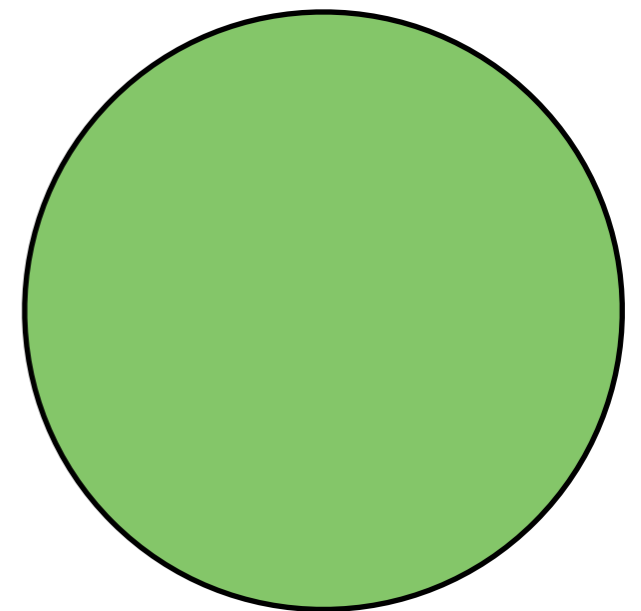
Iron-rich

(63% iron core
37% silicate mantle, no iron)



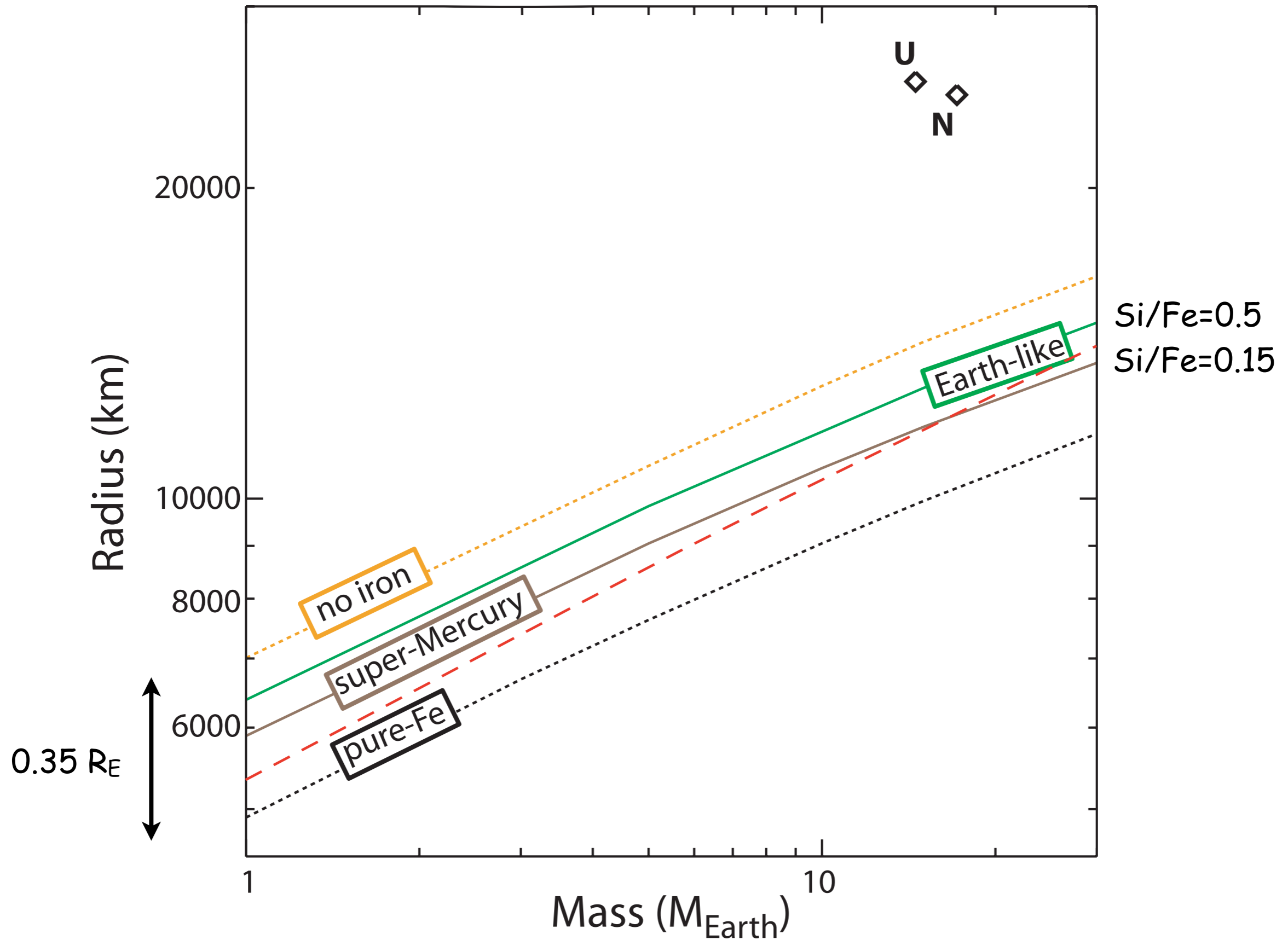
Earth-like

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

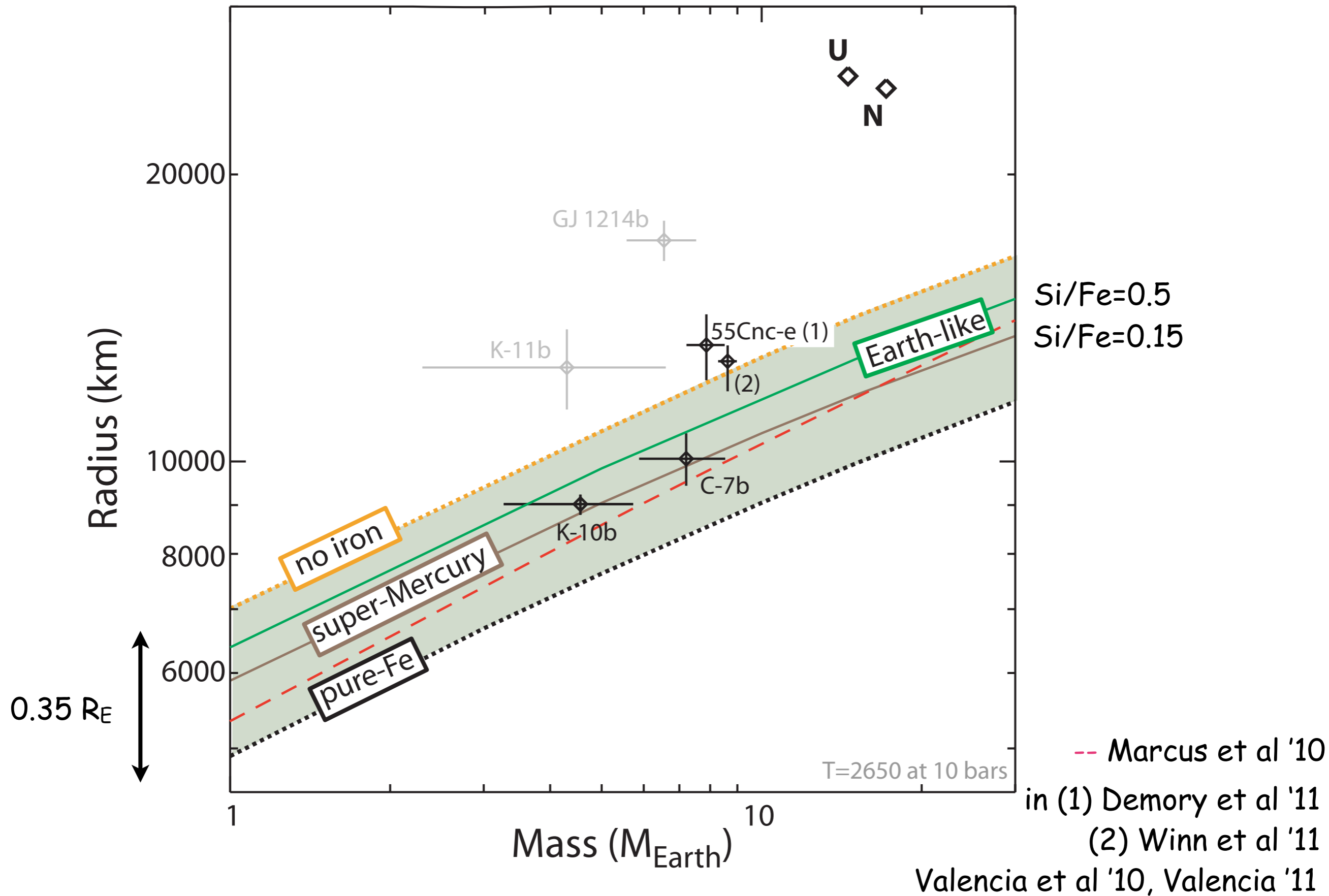


no-iron
(pure Mg-
silicate)

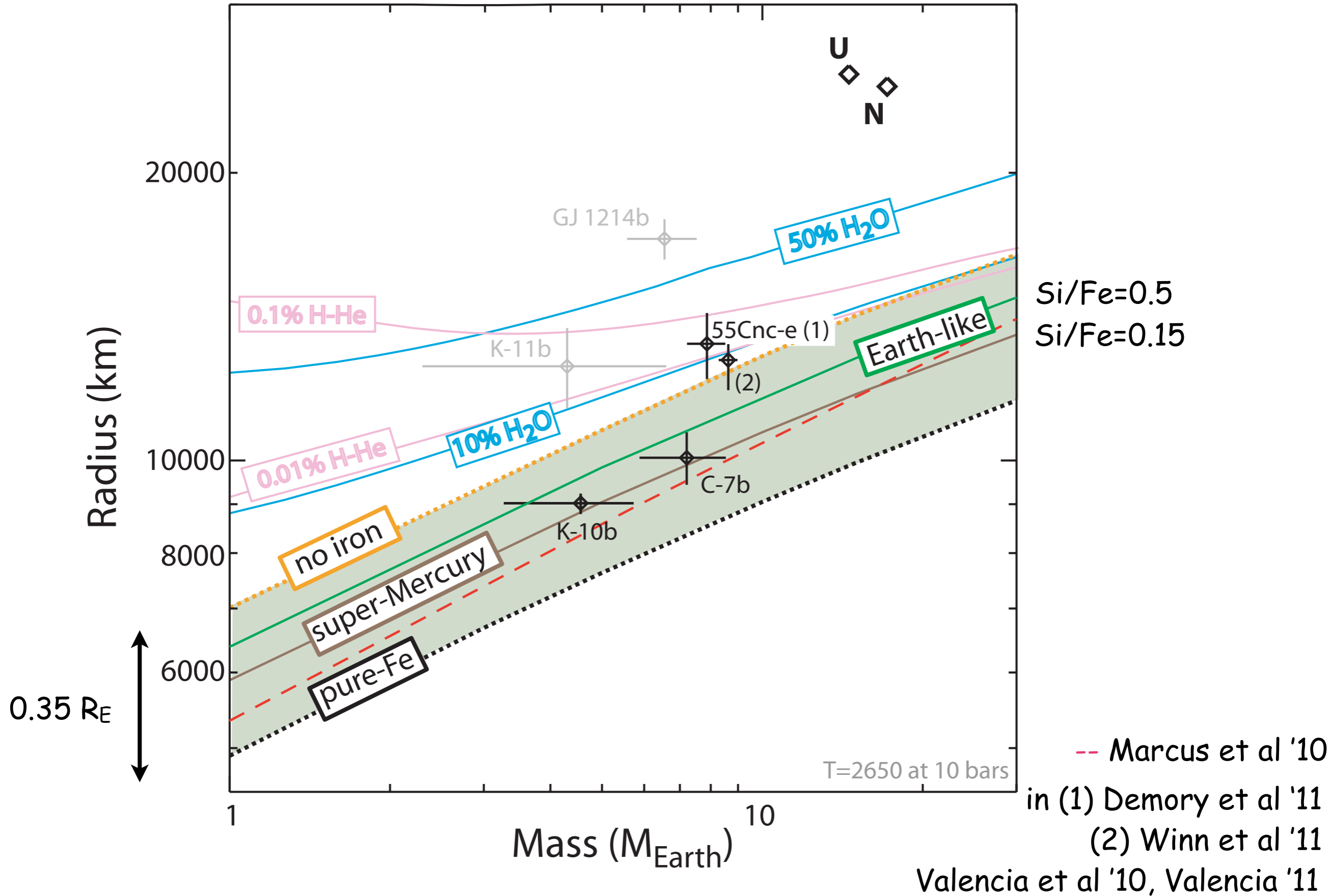
Rocky Compositions



Rocky Compositions

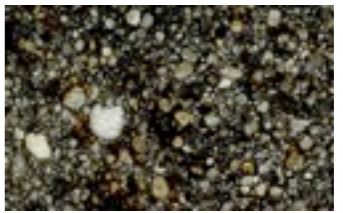


Rocky Compositions



From dust to planets

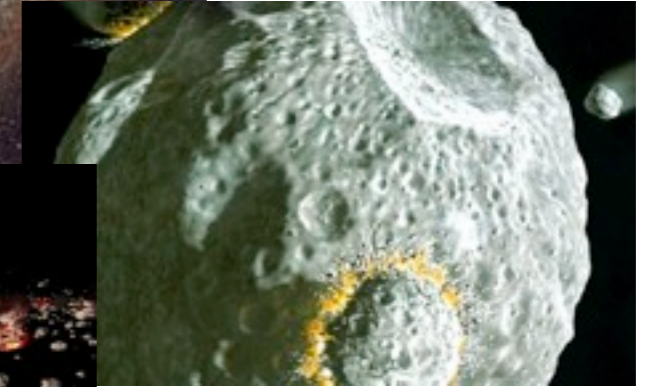
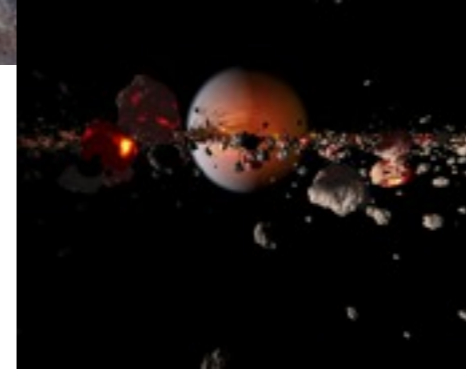
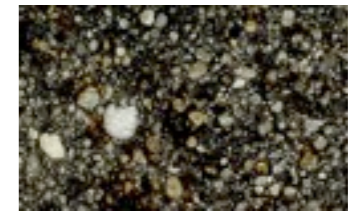
Solar Nebula Composition



From dust to planets

Solar Nebula Composition

From dust to oligarchs

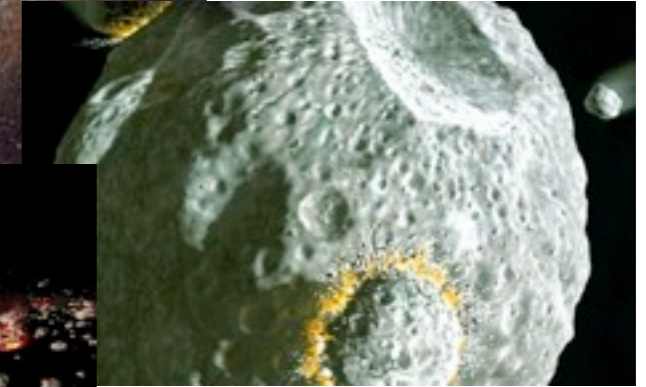
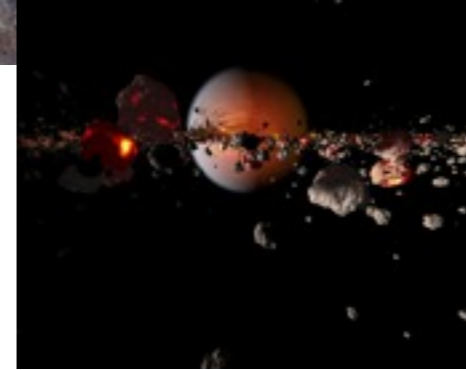
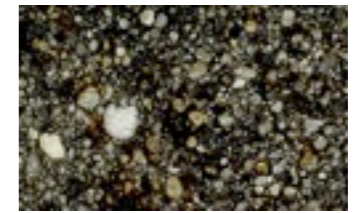


From dust to planets

Solar Nebula Composition

From dust to oligarchs

Giant Impacts



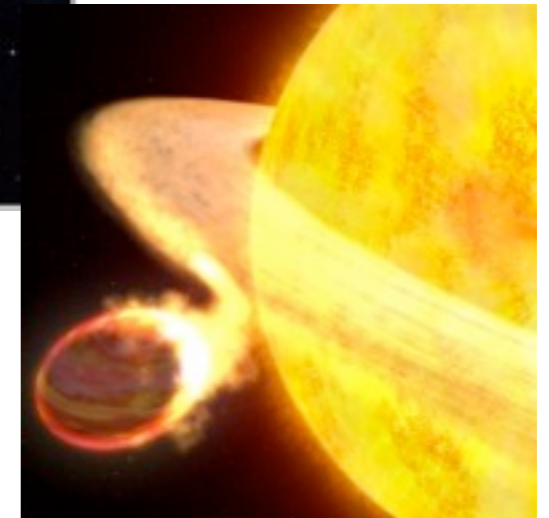
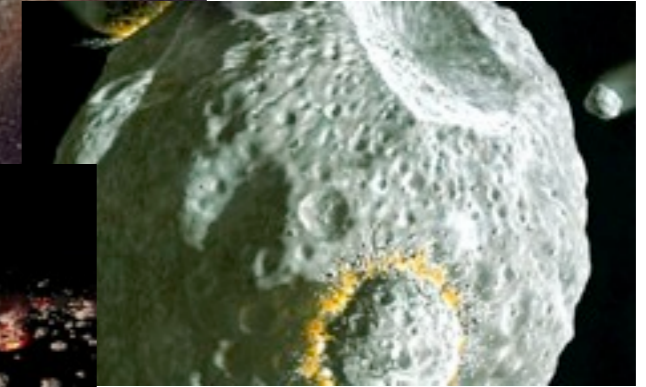
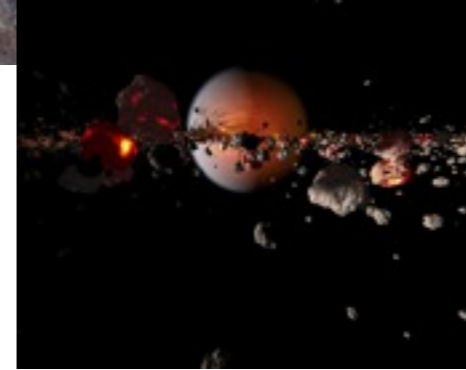
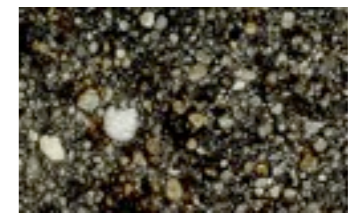
From dust to planets

Solar Nebula Composition

From dust to oligarchs

Giant Impacts

Atmospheric Evaporation



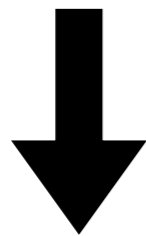
From dust to planets

Solar Nebula Composition

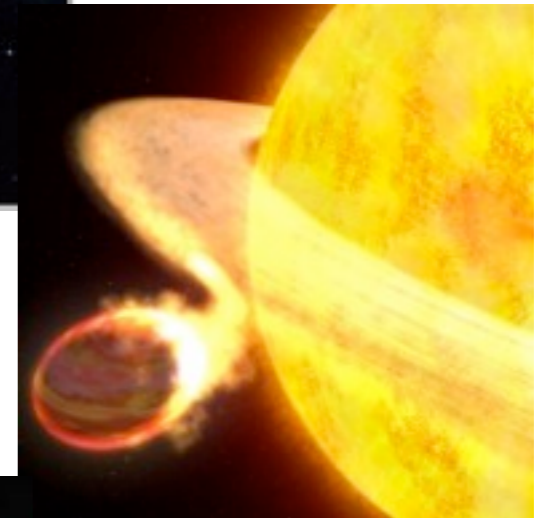
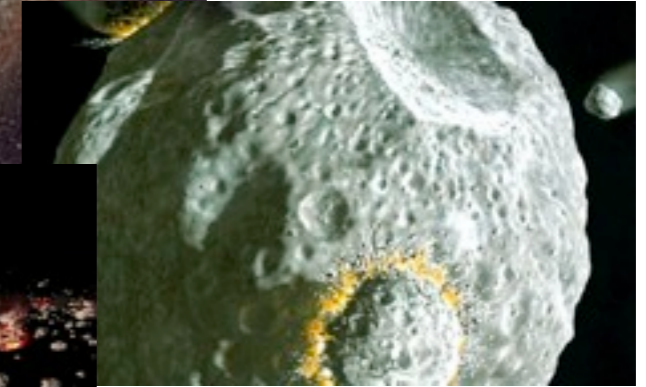
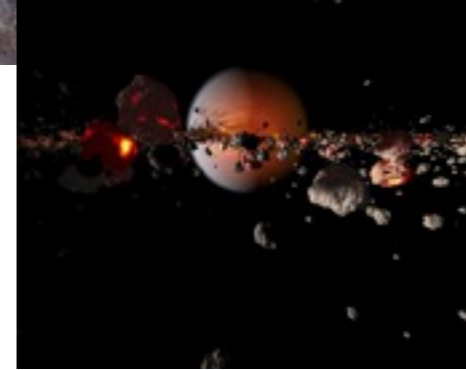
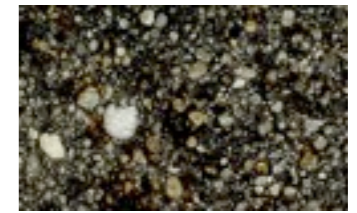
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Composition of Planets



From dust to planets

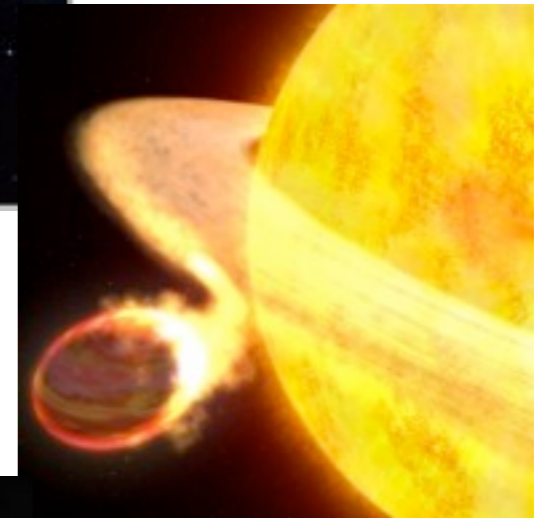
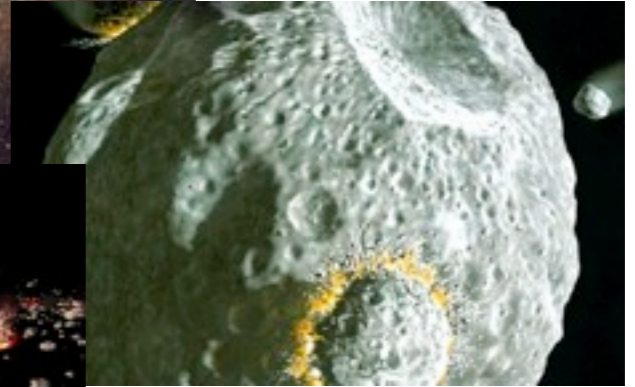
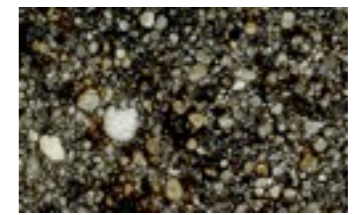
Solar Nebula Composition

From dust to oligarchs

Giant Impacts

Atmospheric Evaporation

Composition of Planets



From dust to planets

Characterizing super-Earths

Are they habitable?

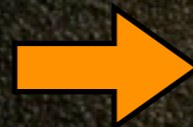
How do they evolve?

What is their atmosphere like?

How do they form?

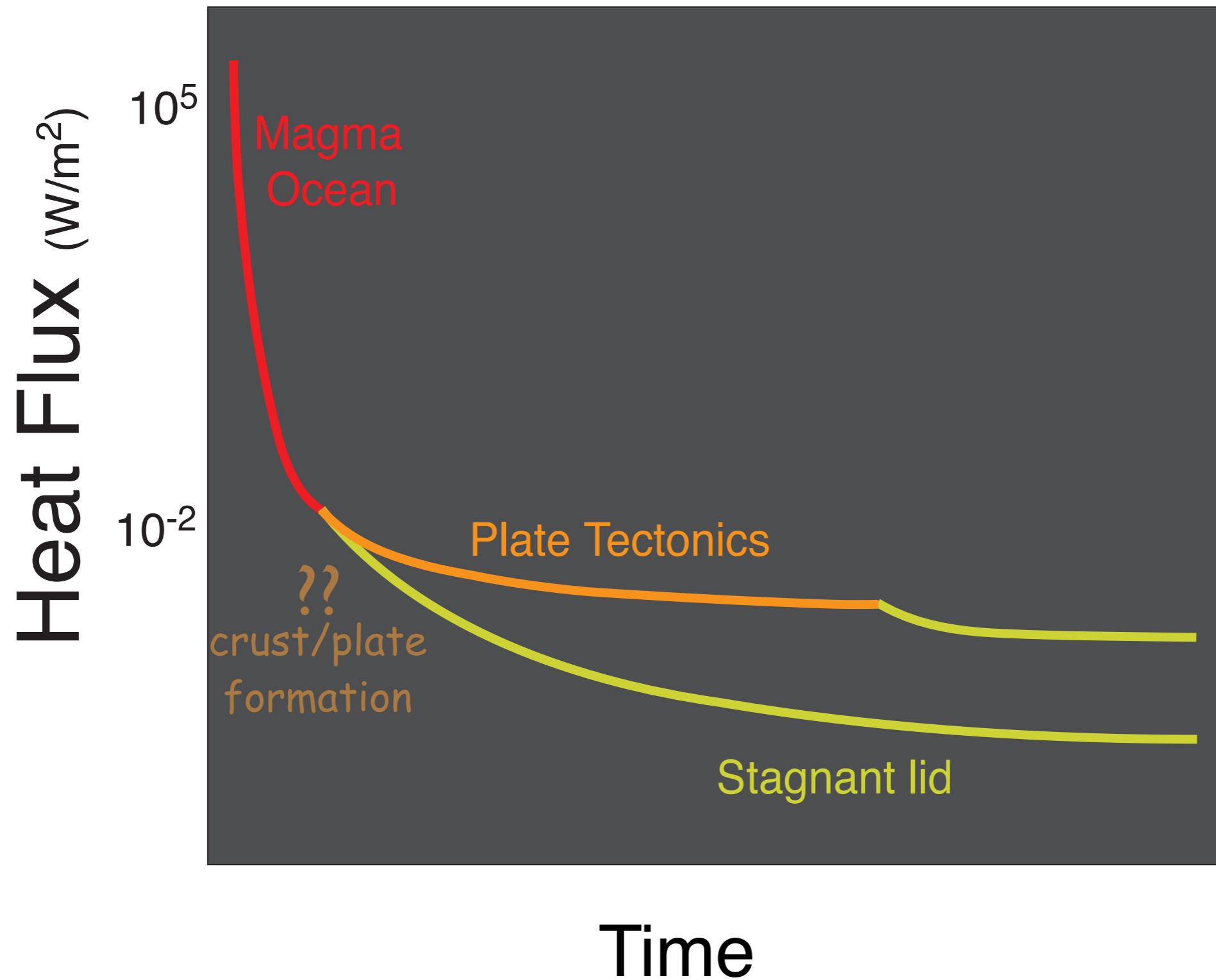
What are they made of?

Single Planets

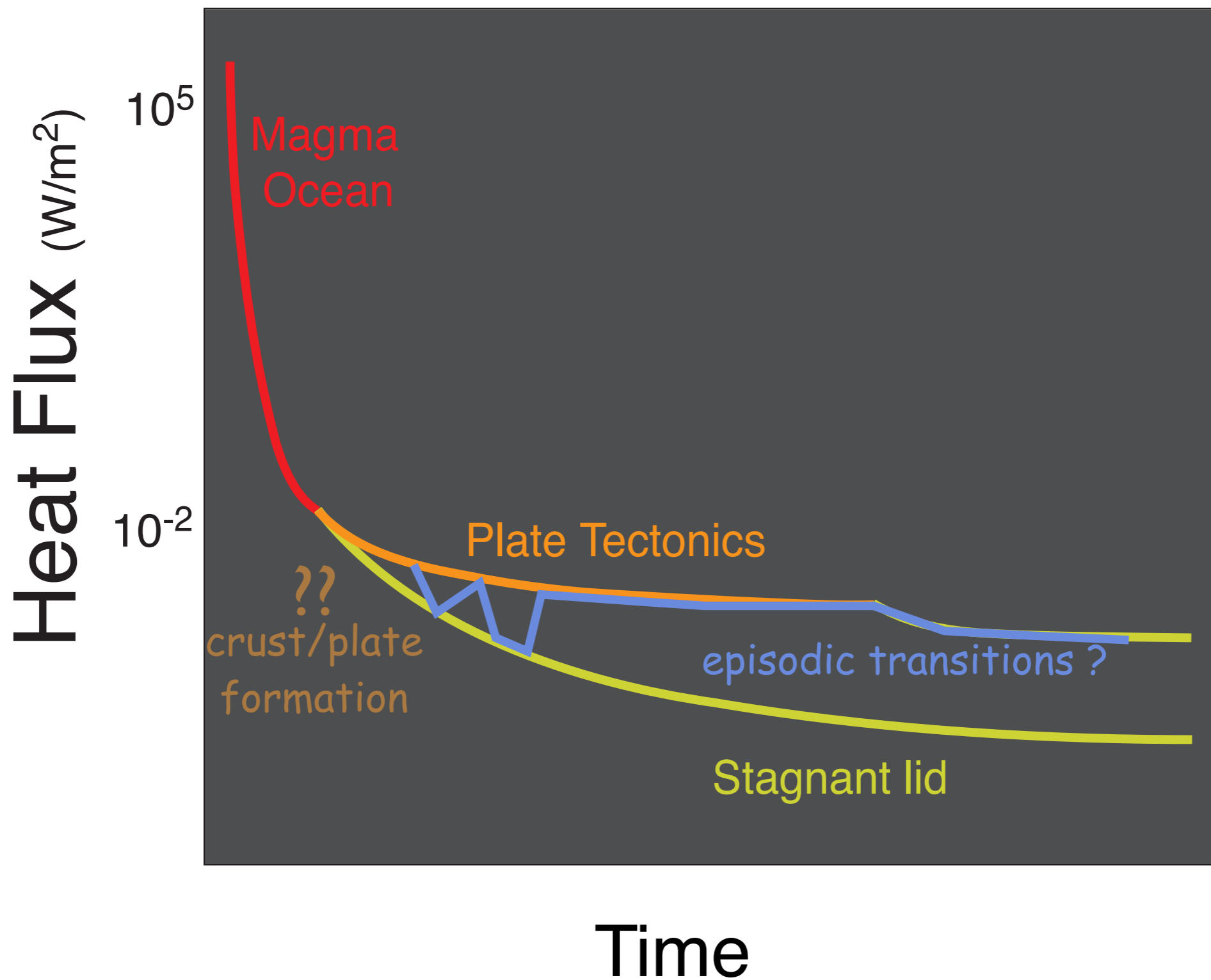


Population

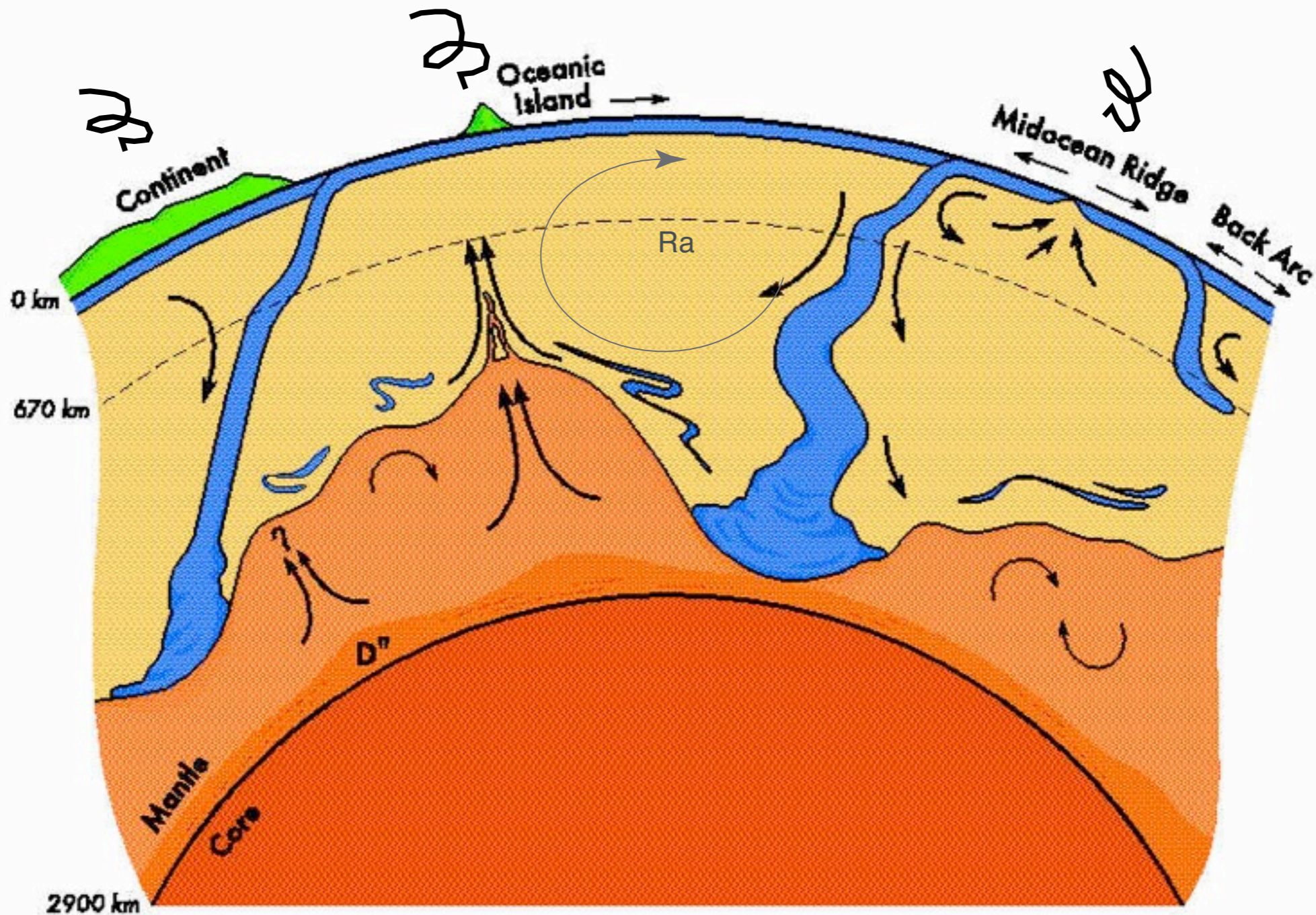
Terrestrial Evolution



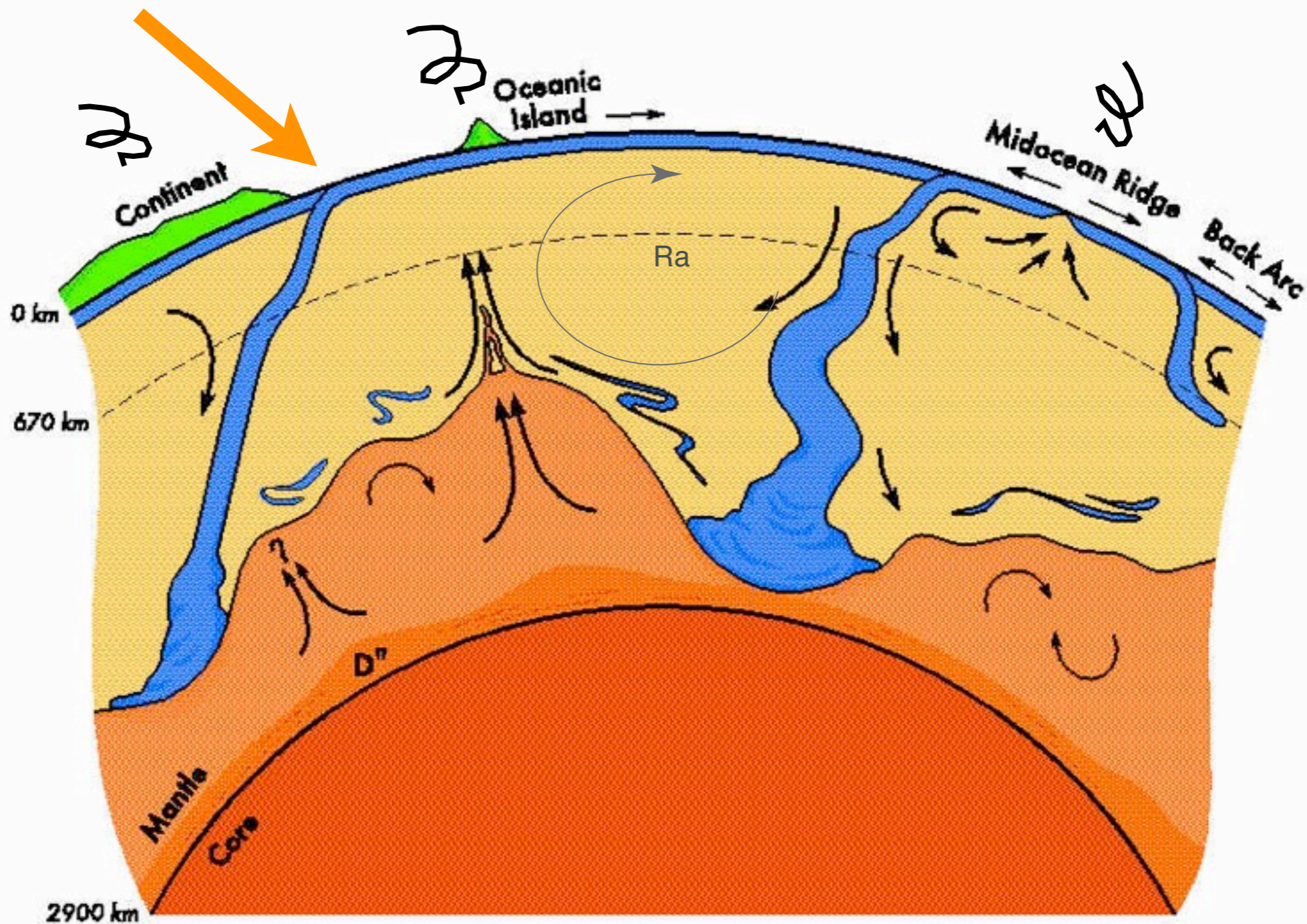
Terrestrial Evolution



Interior dynamics & the atmosphere

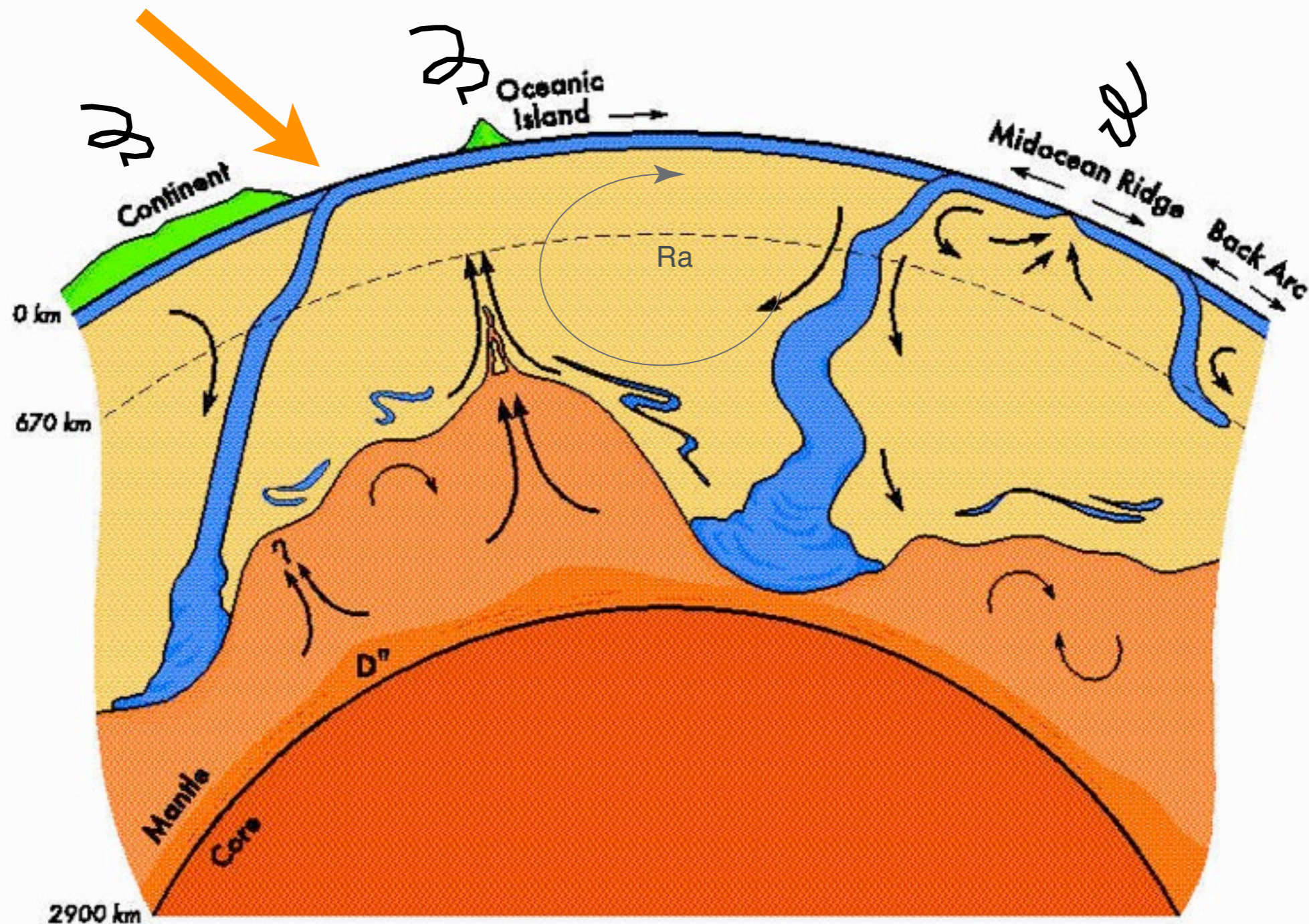


Interior dynamics & the atmosphere

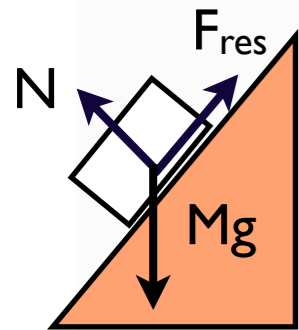


Interior dynamics & the atmosphere

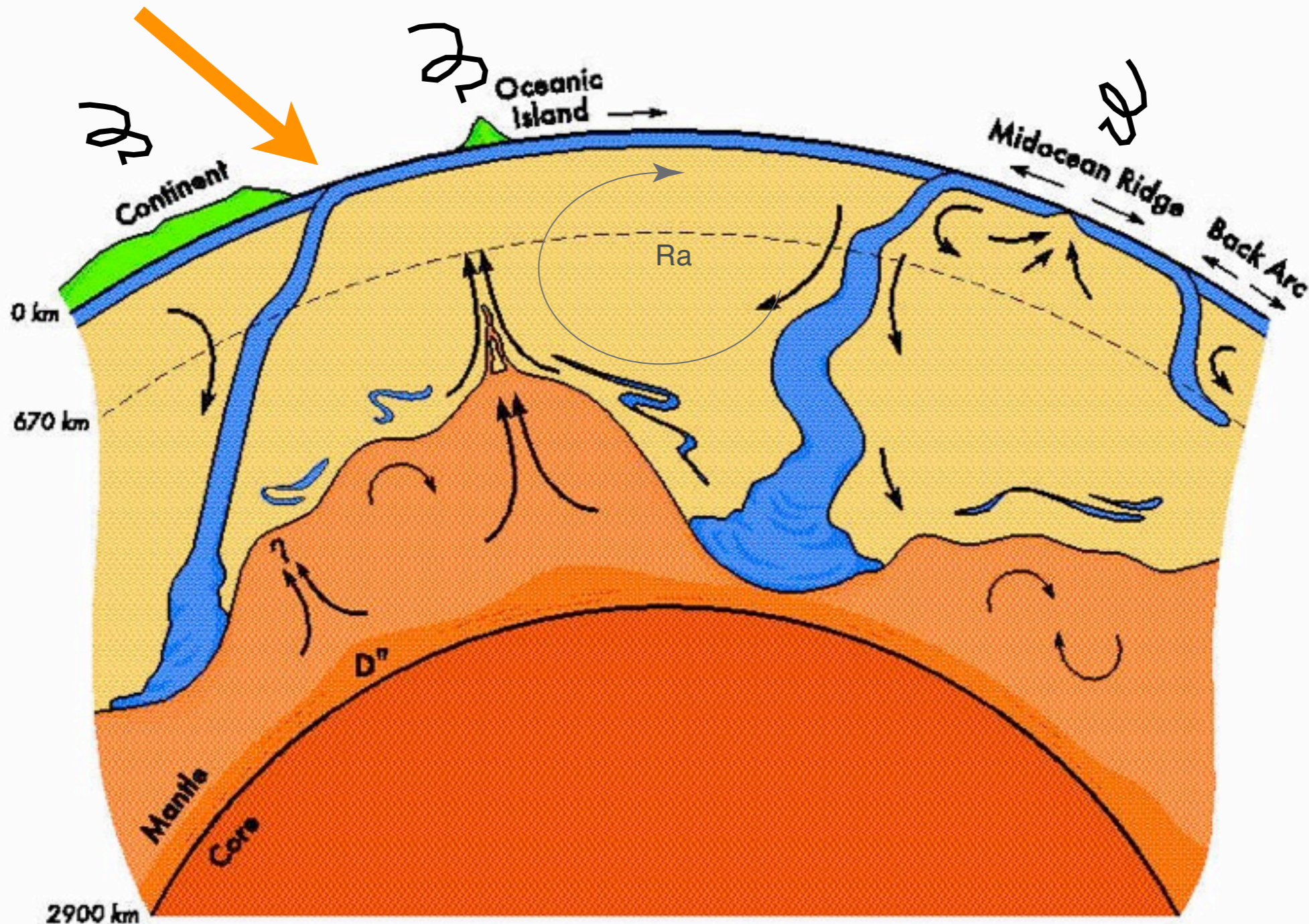
Coulomb failure criterion for plate deformation



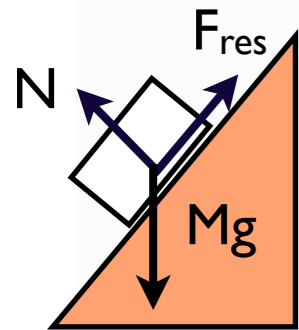
Interior dynamics & the atmosphere



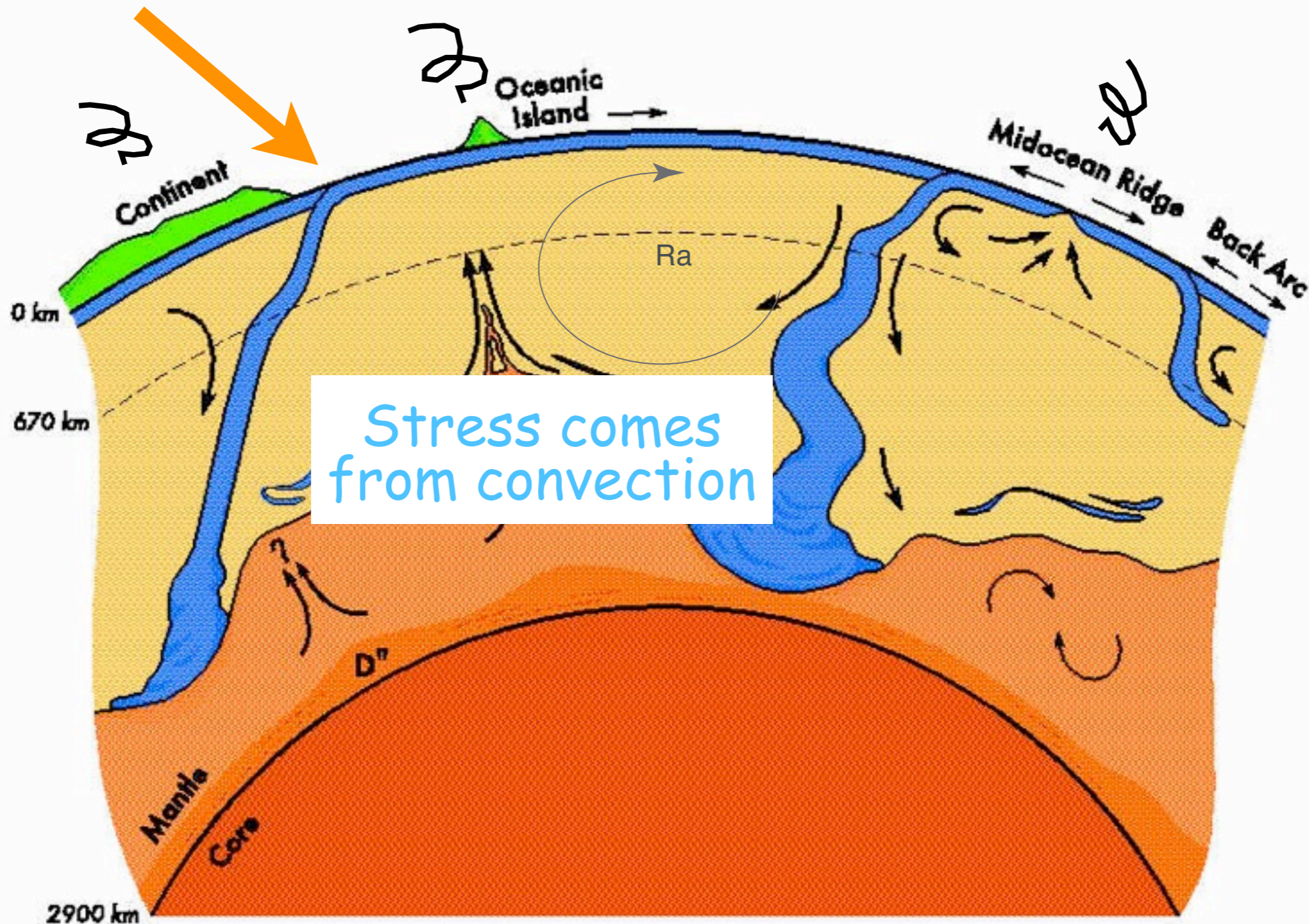
Coulomb failure criterion for plate deformation



Interior dynamics & the atmosphere



Coulomb failure criterion for plate deformation



Stress comes from convection

Plate Tectonics on Super-Earths

Valencia et al. '07 : more likely on SE, thinner plates, larger convective forces

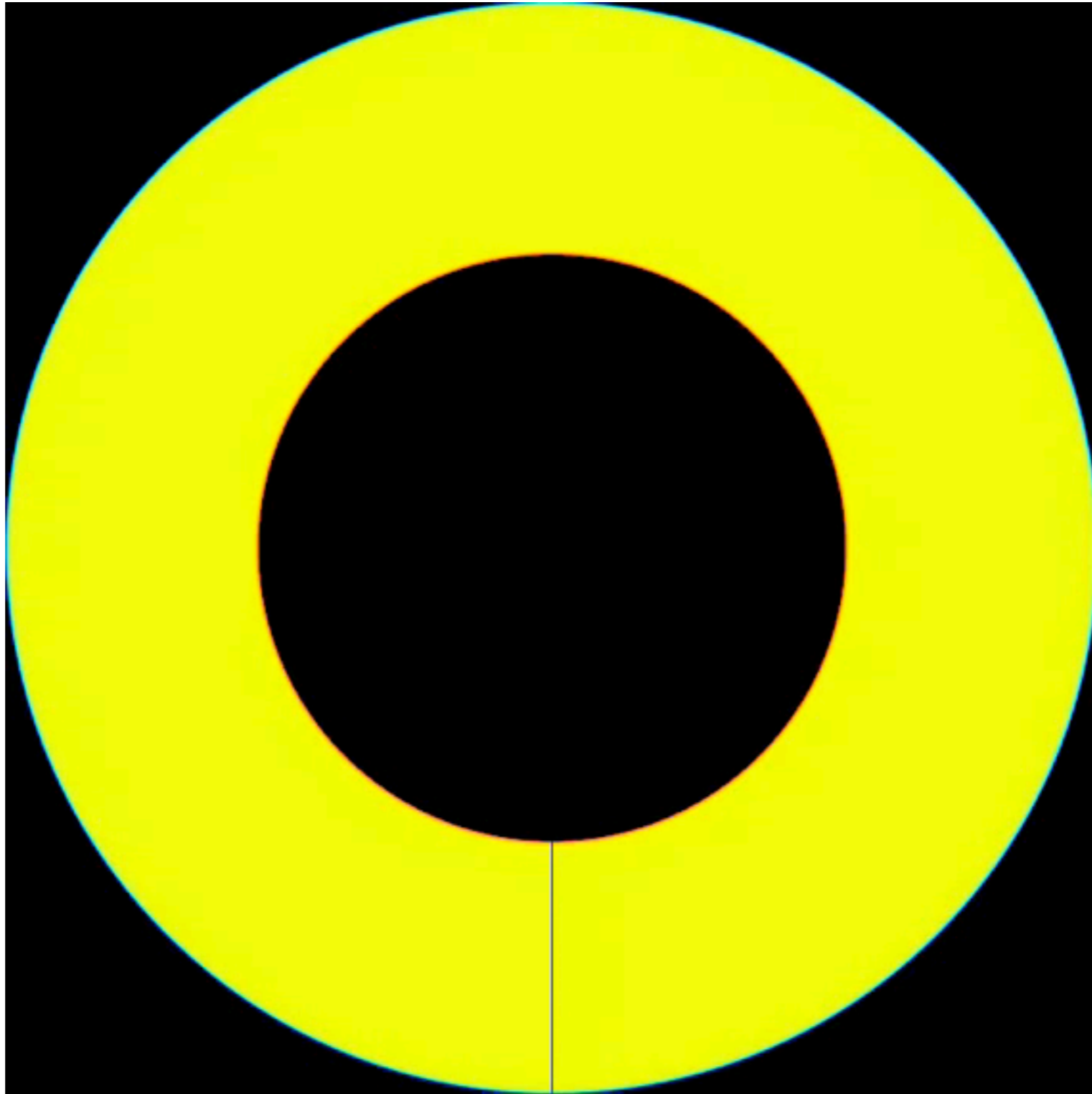
O'Neill & Lenardic '07 : at best, episodic

Valencia et al. '09 : smaller planets depend more on the presence of water

Korenaga '10 : slightly more likely, but most important is the presence of water

Tackley et al '11 : all planets achieve PT, slow convection on deep mantles

Convection on $3 M_E$ - Earth-like



Conclusions

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- The study of super-Earths is a frontier-field in astrophysics & planetary sciences

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- It is possible that 55 Cnc-e is a scaled-up version of the Moon
- There is a large variety in compositions within a small range of masses (2-9 M_E)
- Understanding the habitability of these planets requires understanding their interior dynamics