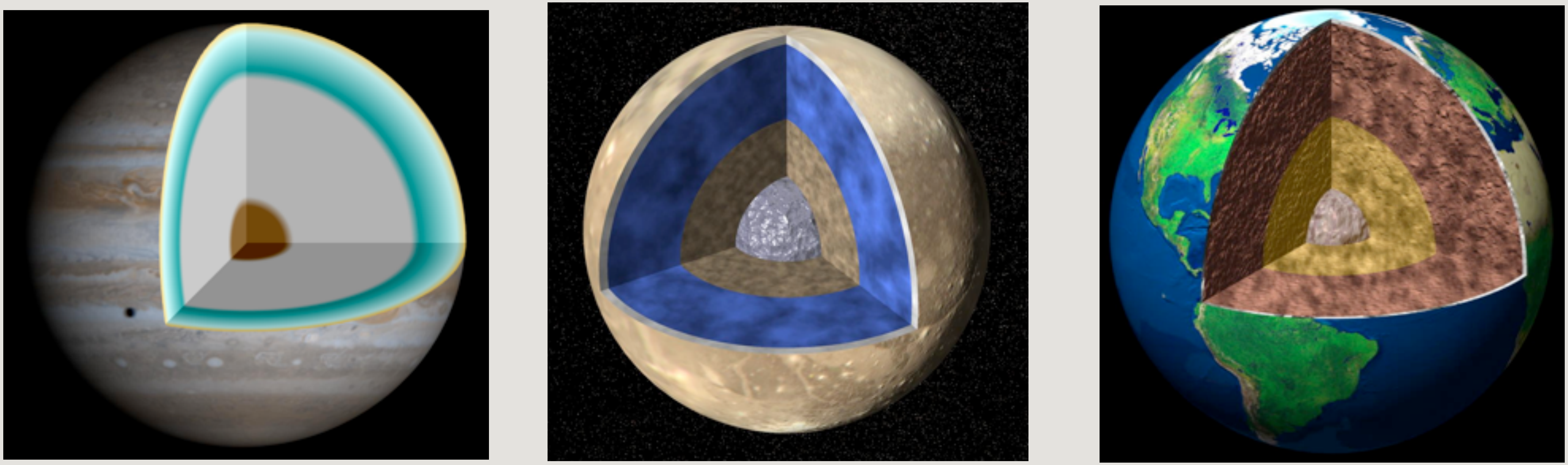
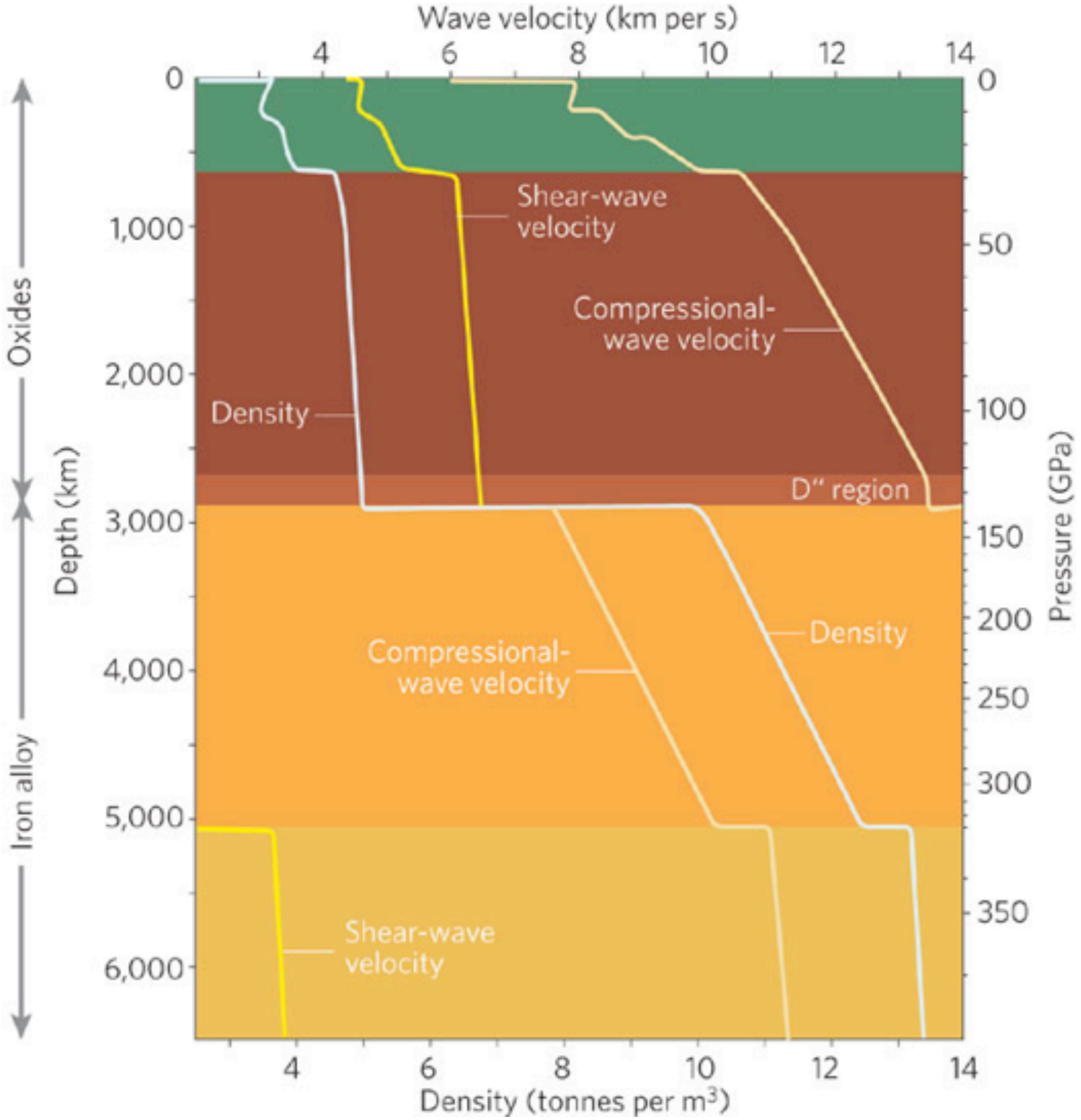
Observatoire de la CÔTE d'AZUR

Terrestrial Exoplanet Radii, Structure and Tectonics

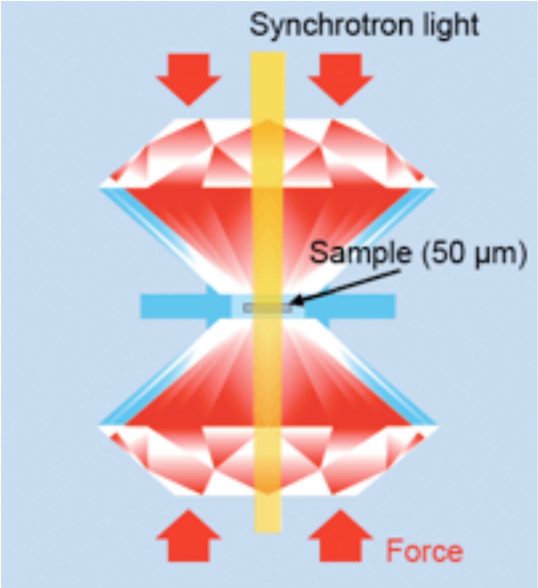
Diana Valencia (OCA), KITP, 31 March 2010

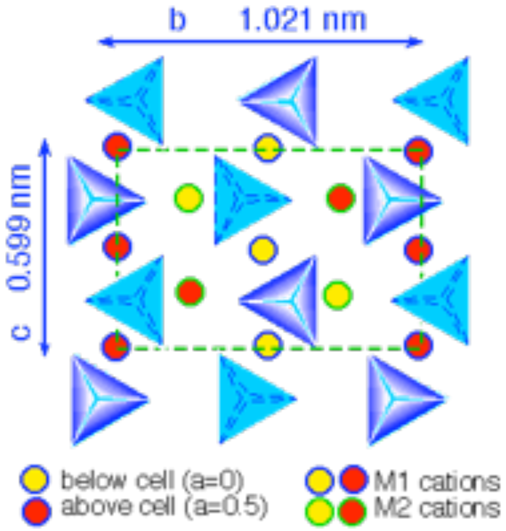


Earth's Structure



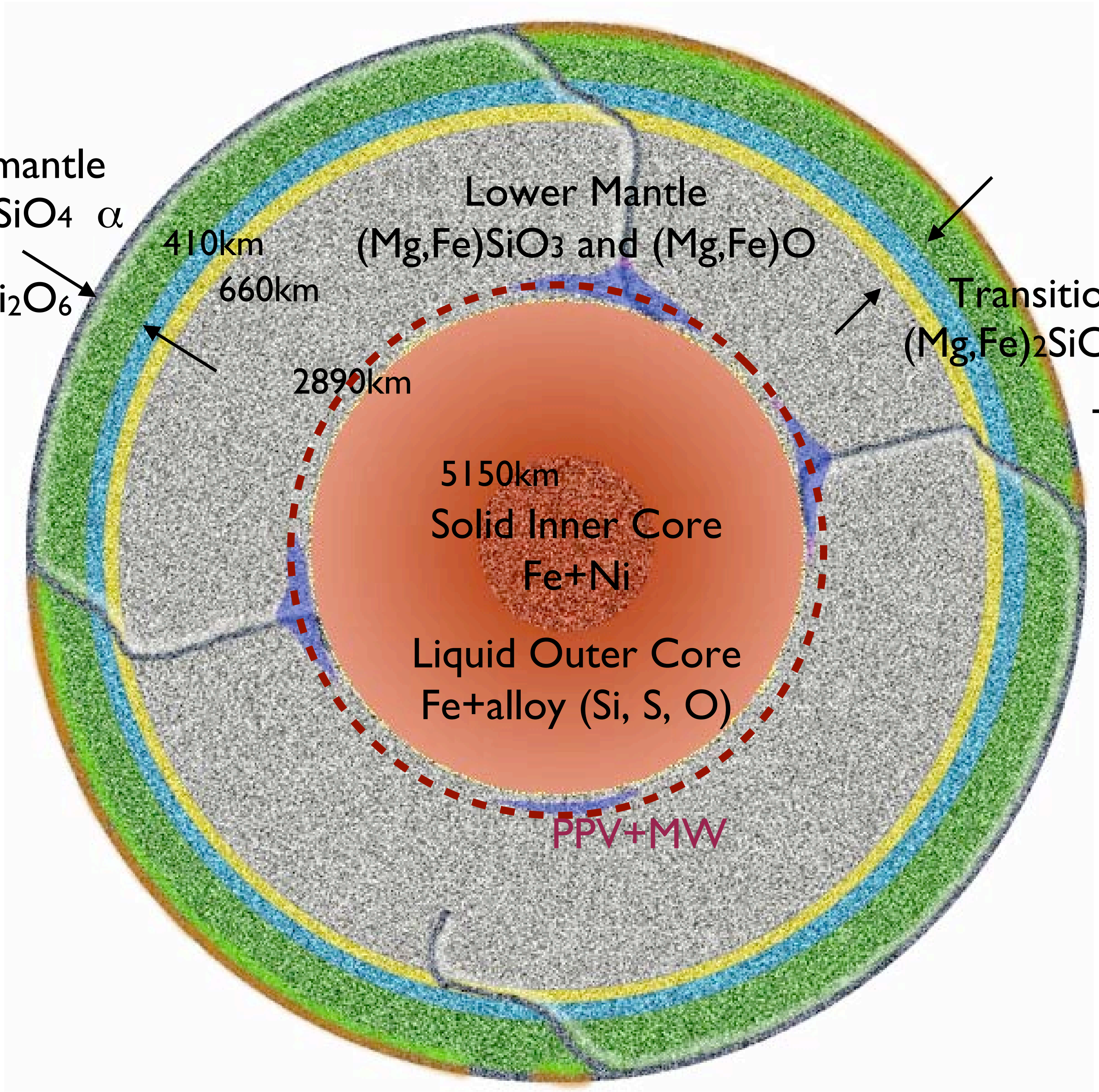
Romanowicz, 2008





Olivine Structure

Earth's Structure



Upper mantle

$(Mg,Fe)_2SiO_4$ α

$+(Mg,Fe)_2Si_2O_6$

410km

660km

Lower Mantle

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

Transition Zone

$(Mg,Fe)_2SiO_4$ β and γ

$+(Mg,Fe)_2Si_2O_6$

2890km

5150km

Solid Inner Core

Fe+Ni

Liquid Outer Core

Fe+alloy (Si, S, O)

PPV+MW

Internal Structure Model

Planets made of Mg, Si, O, Fe, H_2O, H/He

Input: M, P_{surf}, T_{surf}, guess R, g_{surf}, χ

$$\frac{d\rho}{dr} = -\frac{\rho(r)g(r)}{\phi(r)} \qquad \frac{dP}{dr} = -\rho(r)g(r)$$

$$\frac{dg}{dr} = 4\pi G\rho(r) - 2G\frac{m(r)}{r^3} \qquad \frac{dT}{dr} = -\frac{q}{k} \quad \text{and} \quad \frac{dT}{dr} = -\frac{g(r)\gamma(r)}{\phi(r)}T$$

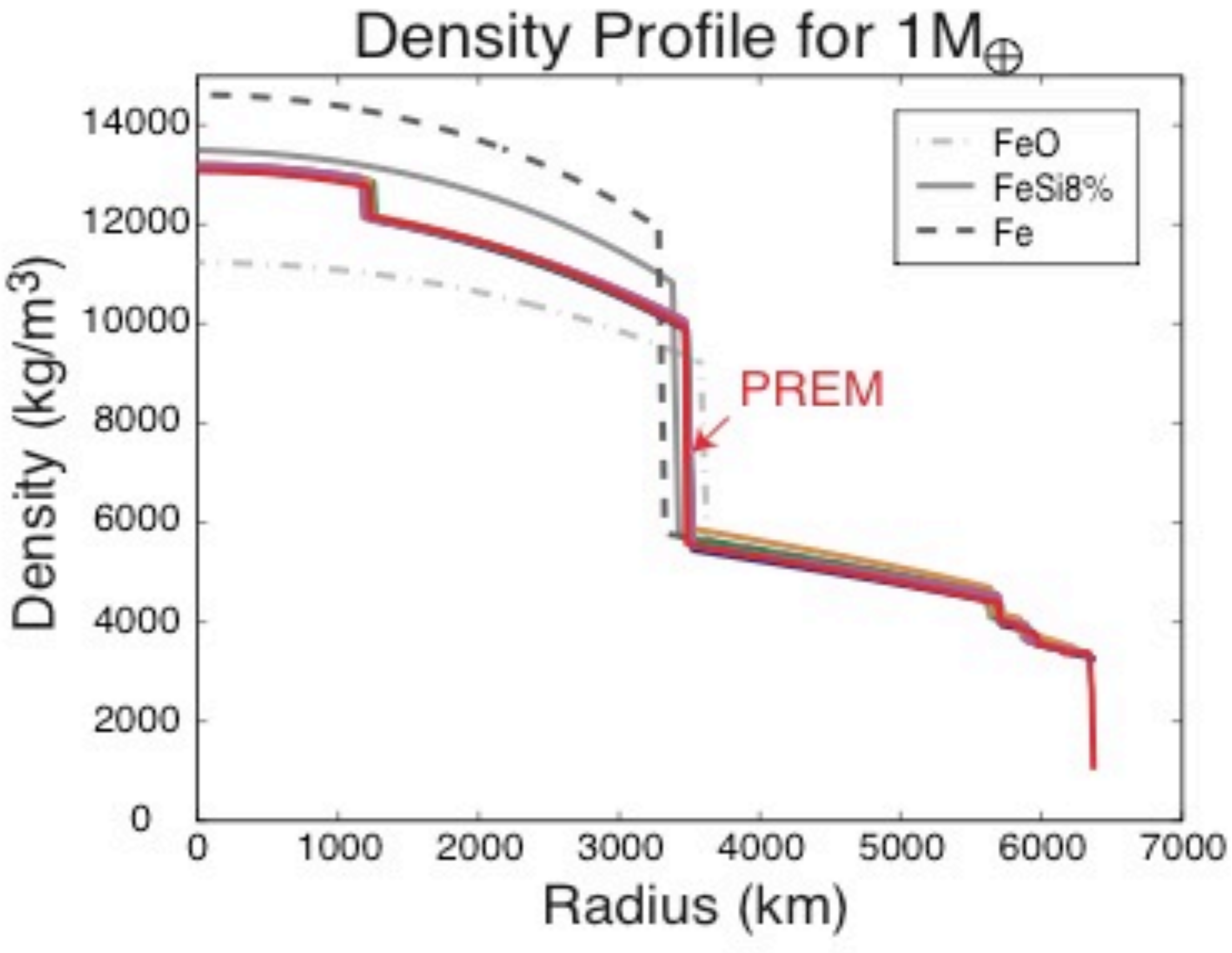
$$\frac{dm}{dr} = 4\pi r^2\rho(r)$$

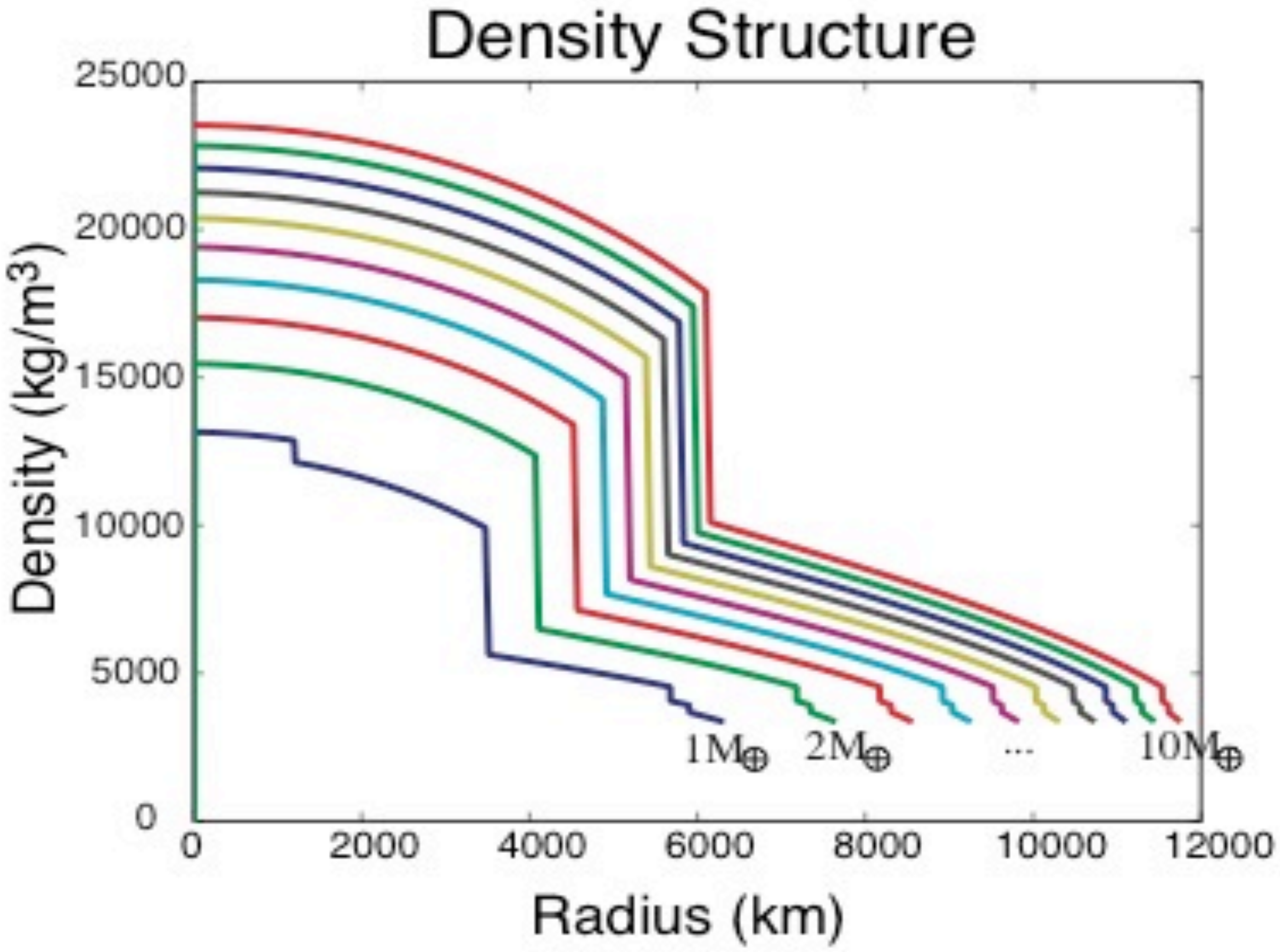
+ EOS(χ)

Output: R(M, χ);

ρ (r), P(r), g(r), m(r), I/MR^2, D, ...

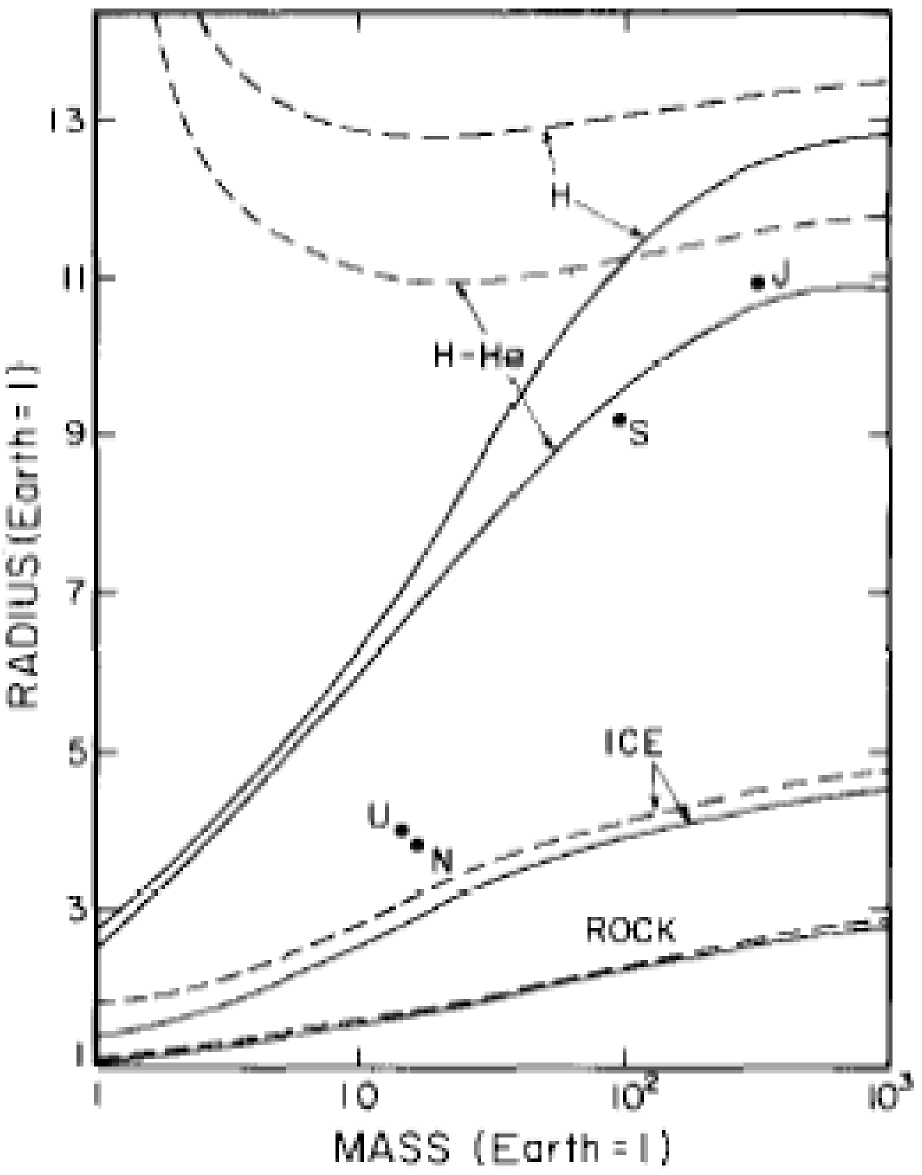
Earth and rocky super-Earths



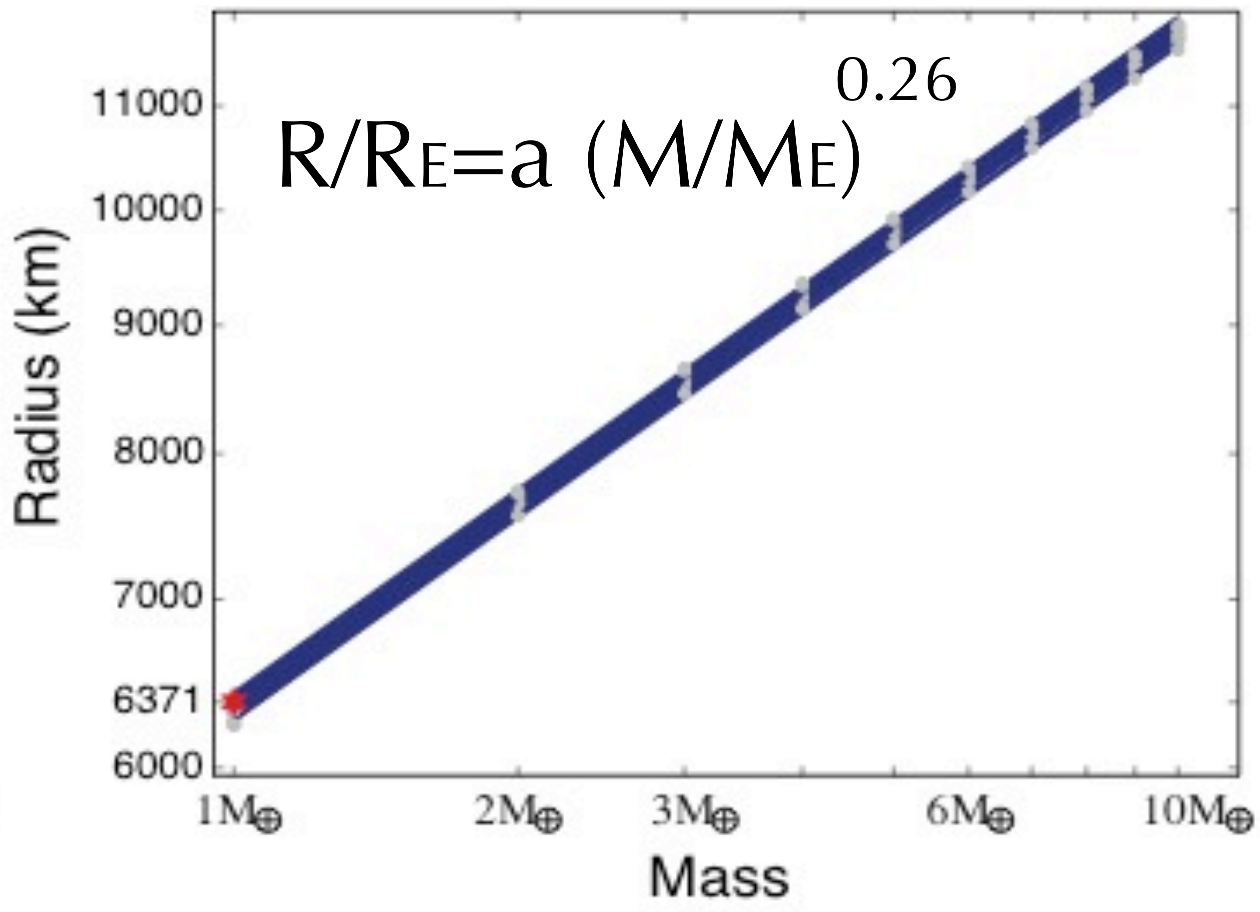


Valencia et. al, 2006

Mass-Radius Relationships



Salpeter & Zapolsky 1967
Stevenson 1982



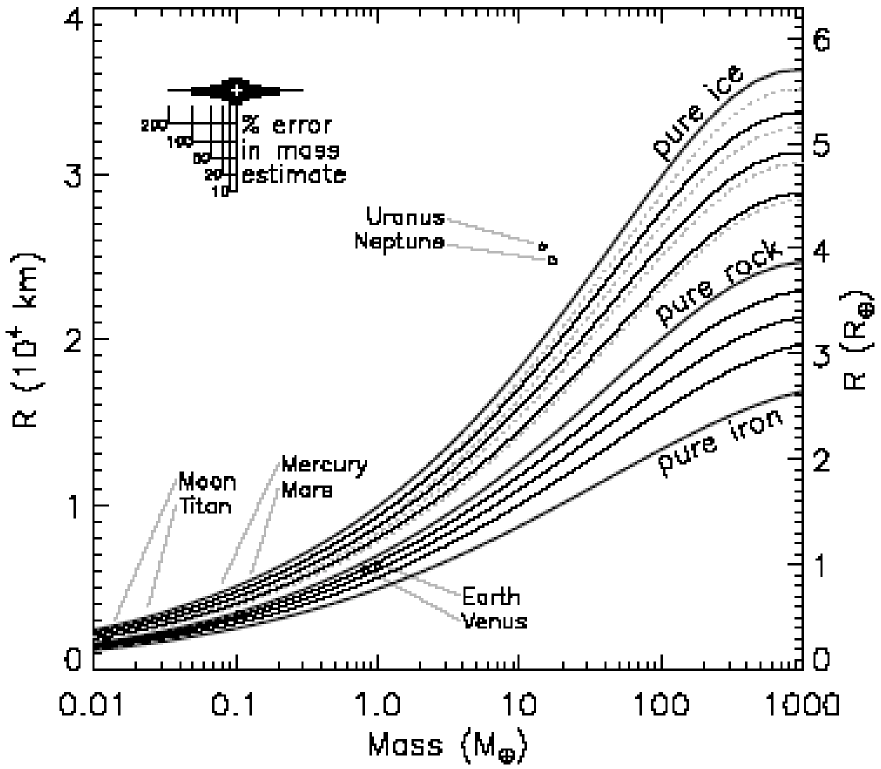
$R/R_E = a\ (M/M_E)^{0.26}$

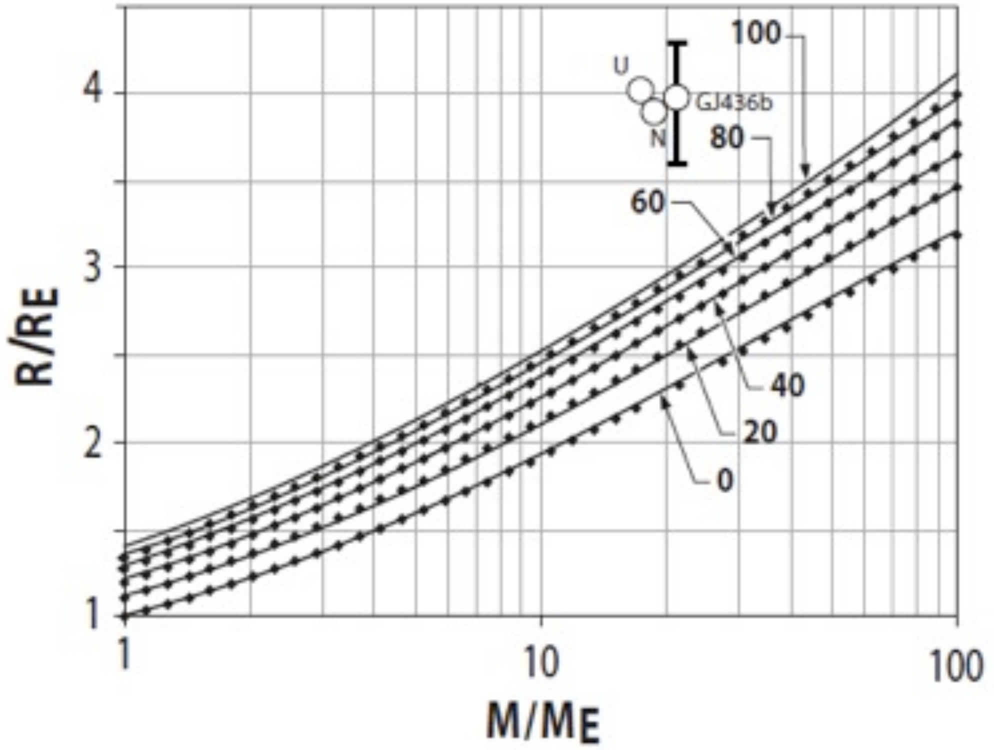
Valencia et. al, 2006

Exponent robust to EOS, Temperature Structure and CMF

Mass-Radius Relationships

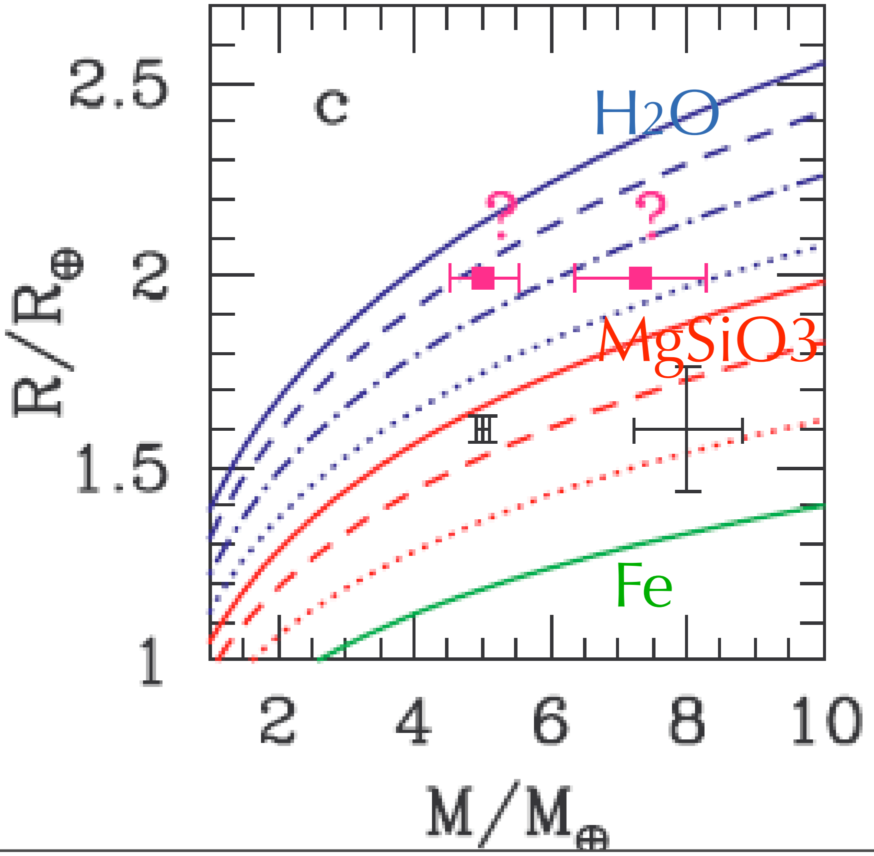
Fortney et al 2007



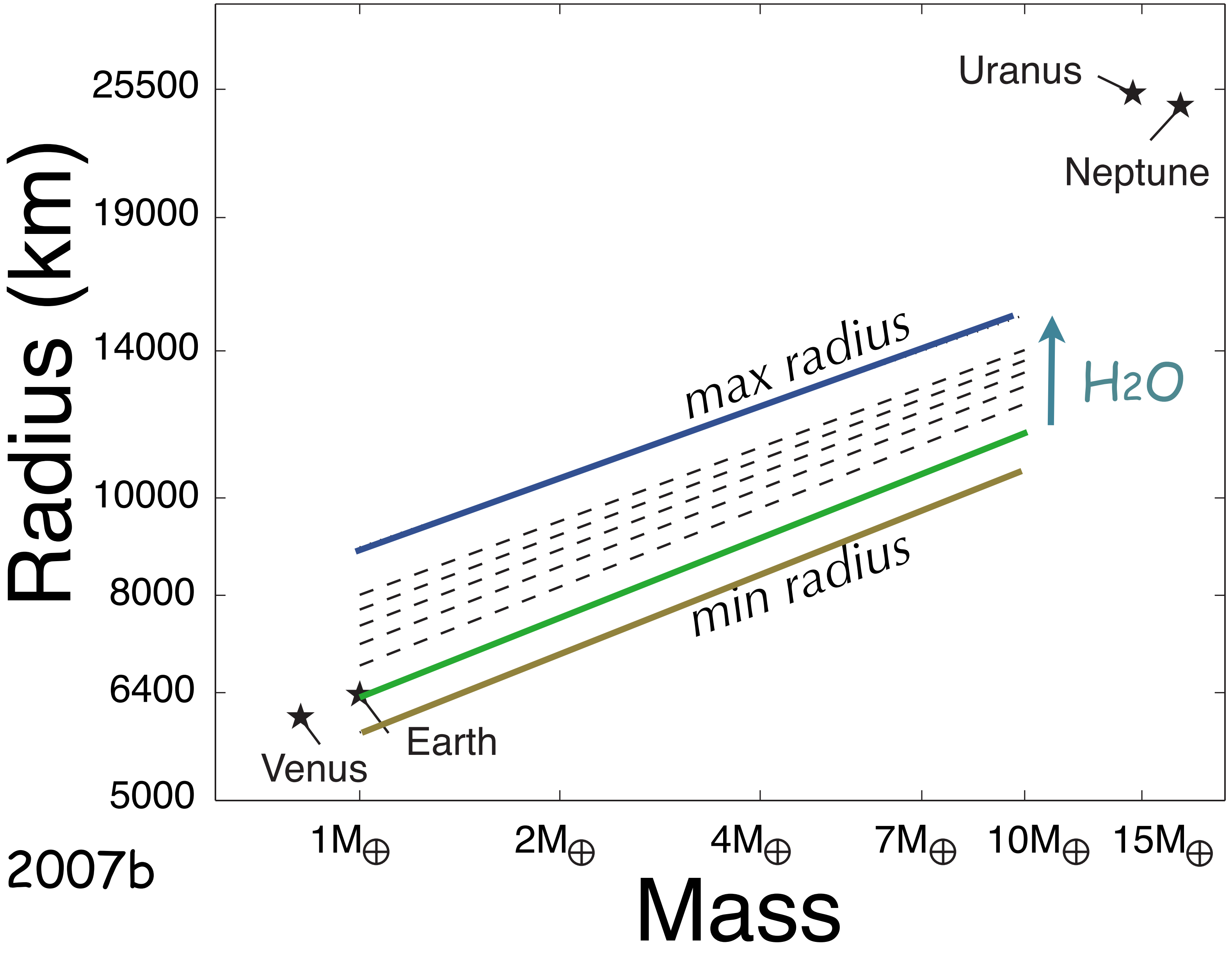


Sotin et al 2007,
Grasset et al 2009

Seager et al 2007



Generalized M-R relationship



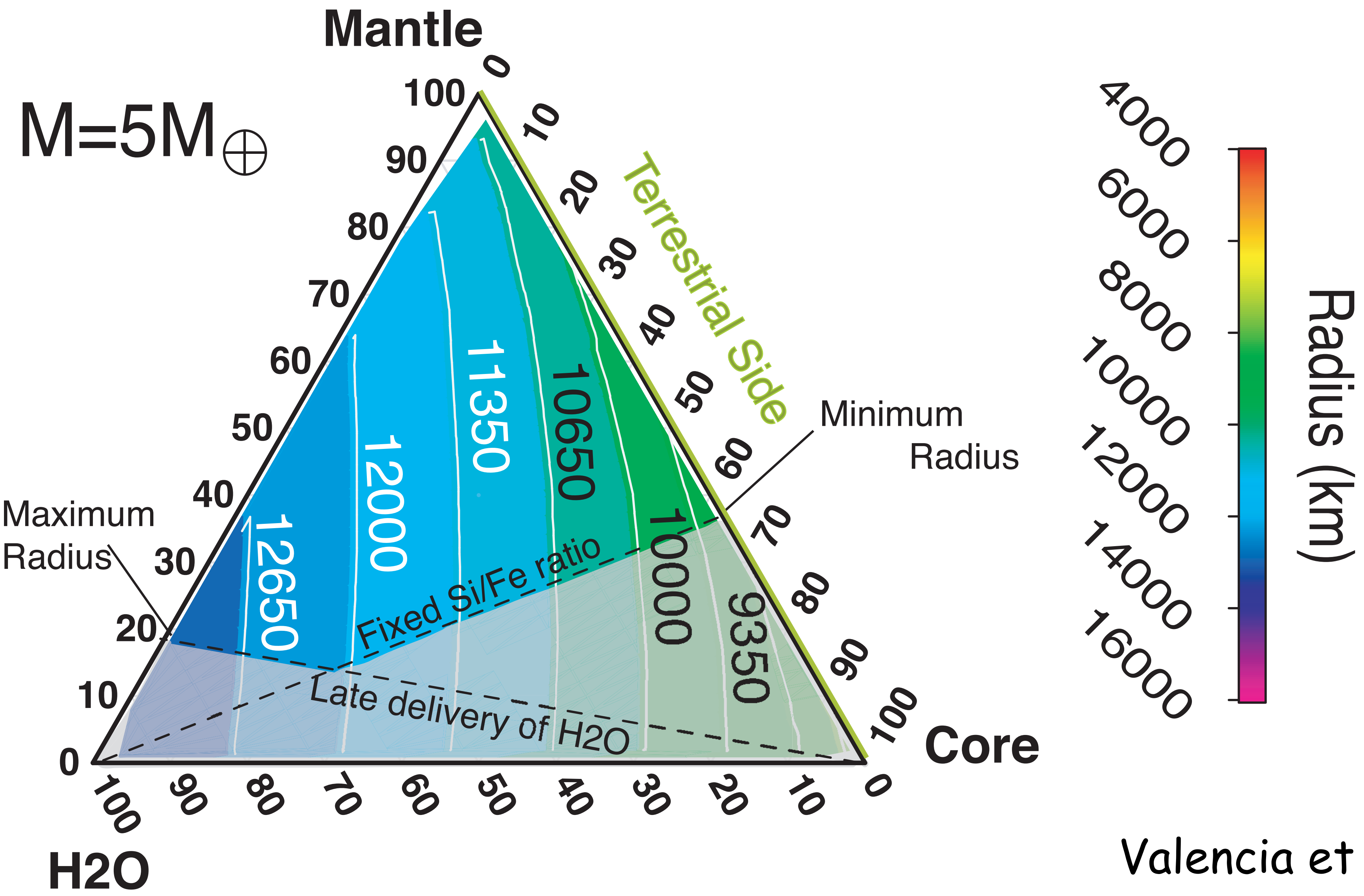
(Earth-like:
Fe/Si)

IMF: ice-mass
fraction

Valencia et al. 2007b

$$R/R_{Earth} = (1+0.56\ IMF)\ (M/M_{Earth})^{0.262(1-0.138\ IMF)}$$

Super-Earth Composition

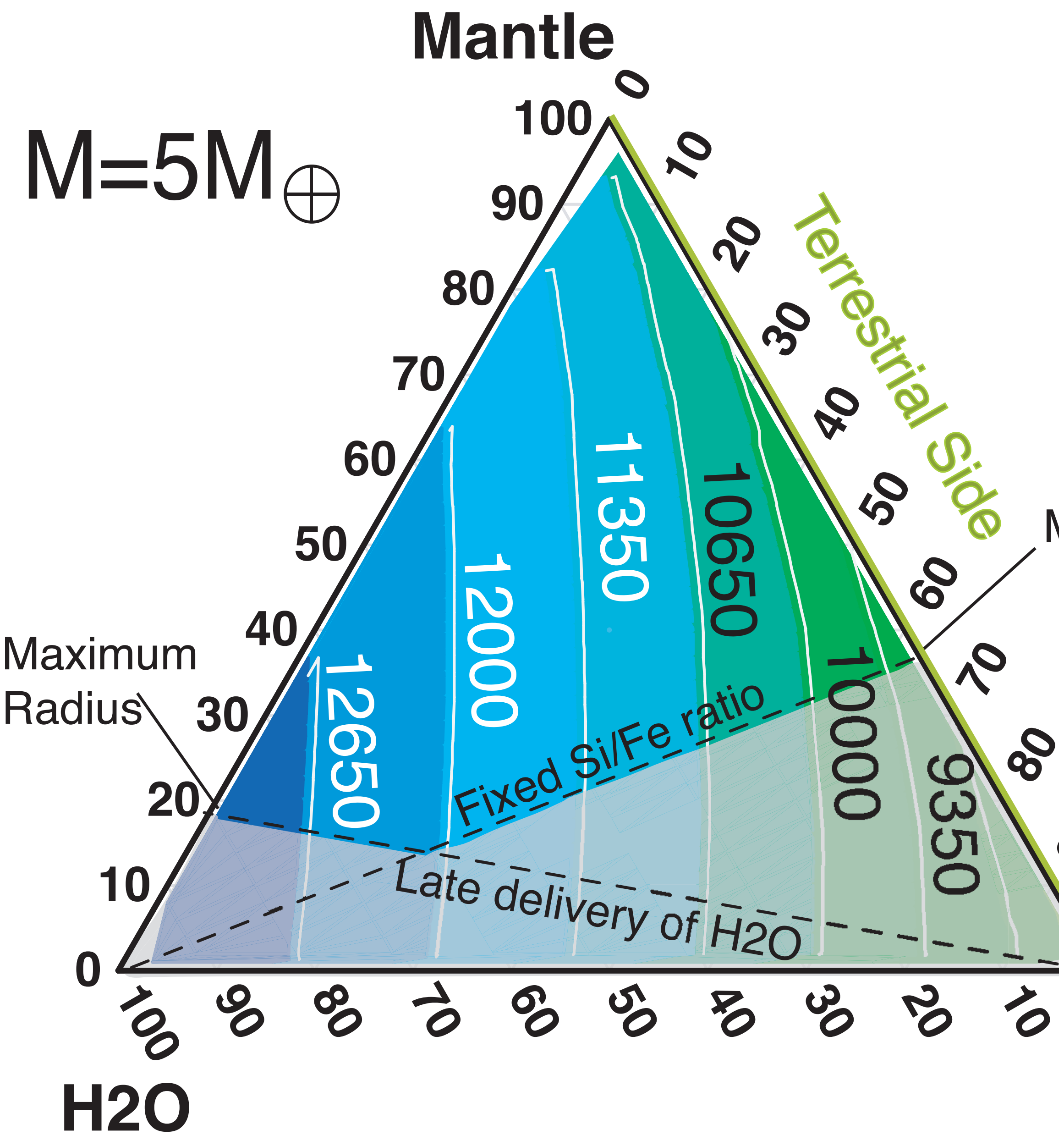


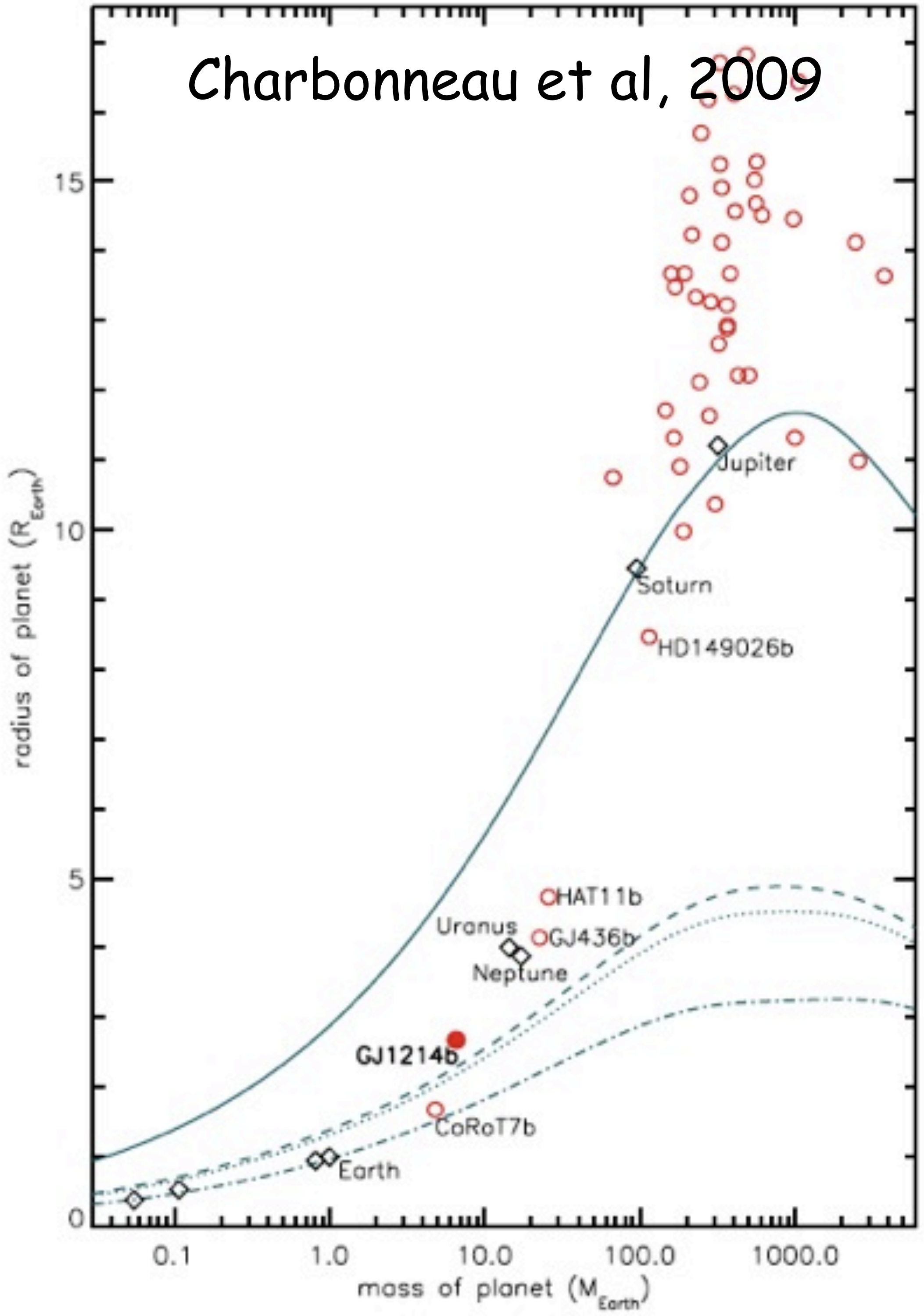
Valencia et al. 2007b

There is degeneracy in composition.

Some compositions are improbable.

Super-Earth Composition



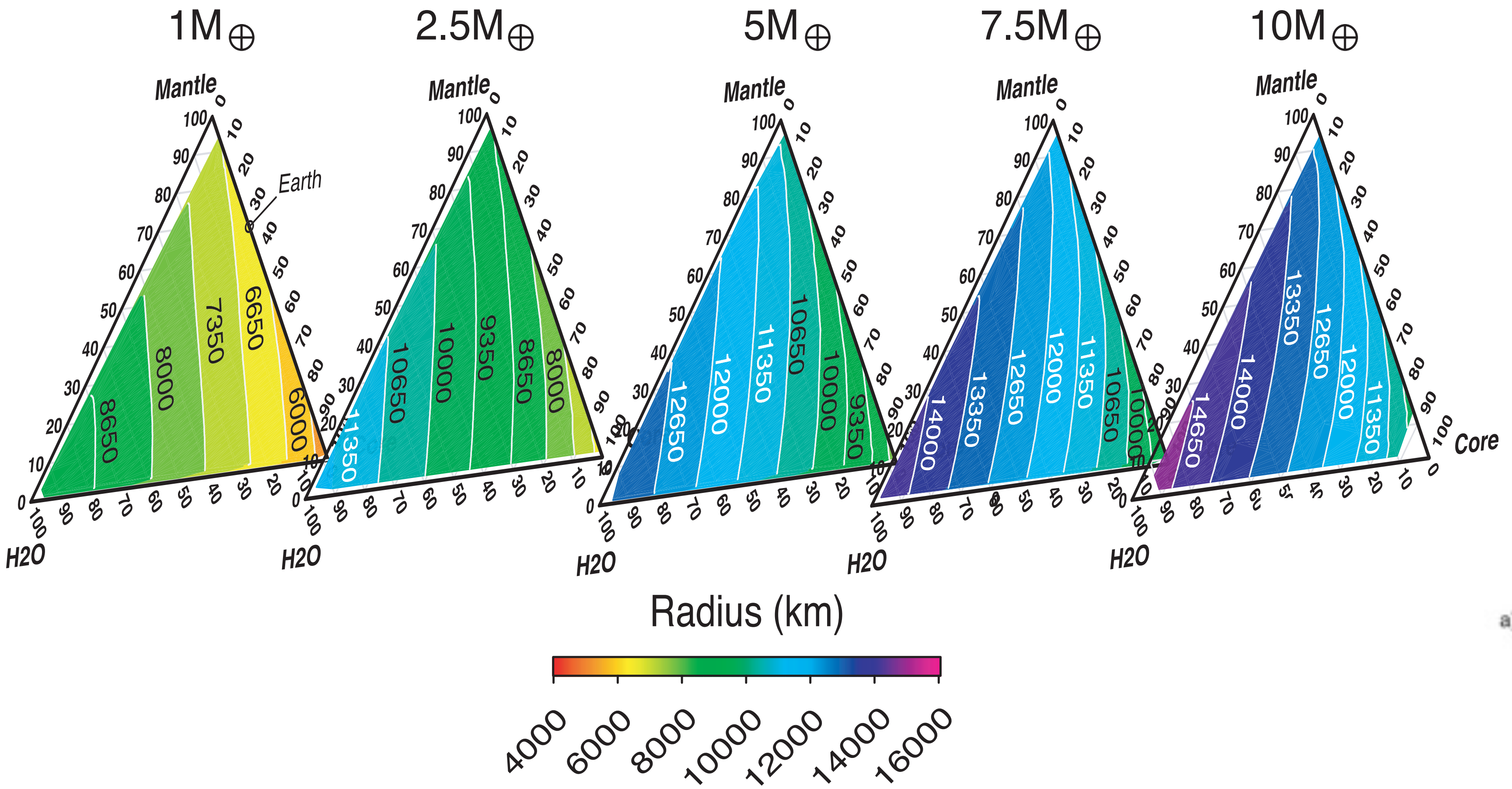


Charbonneau et al, 2009

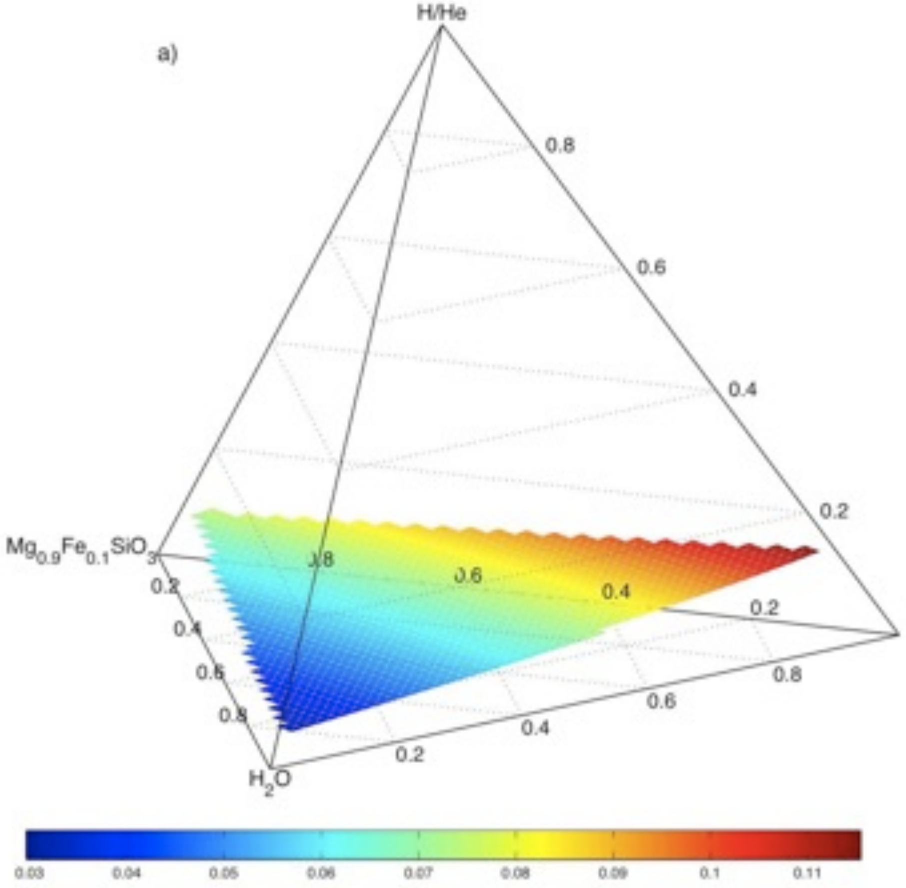
There is degeneracy ir

Some compositions are improbable.

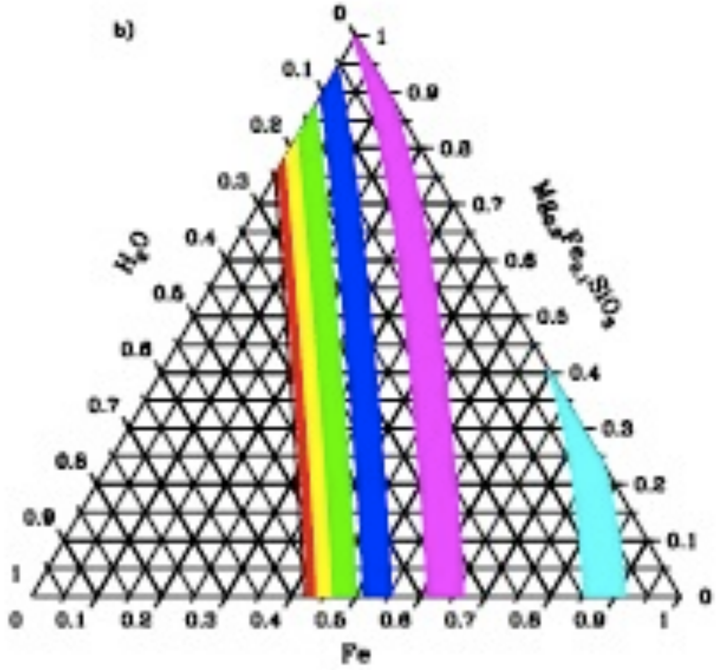
‘Toblerone’ Diagram



Valencia et al. 2007b



Rogers & Seager, 2010



CoRoT-7b: the first transiting super-Earth

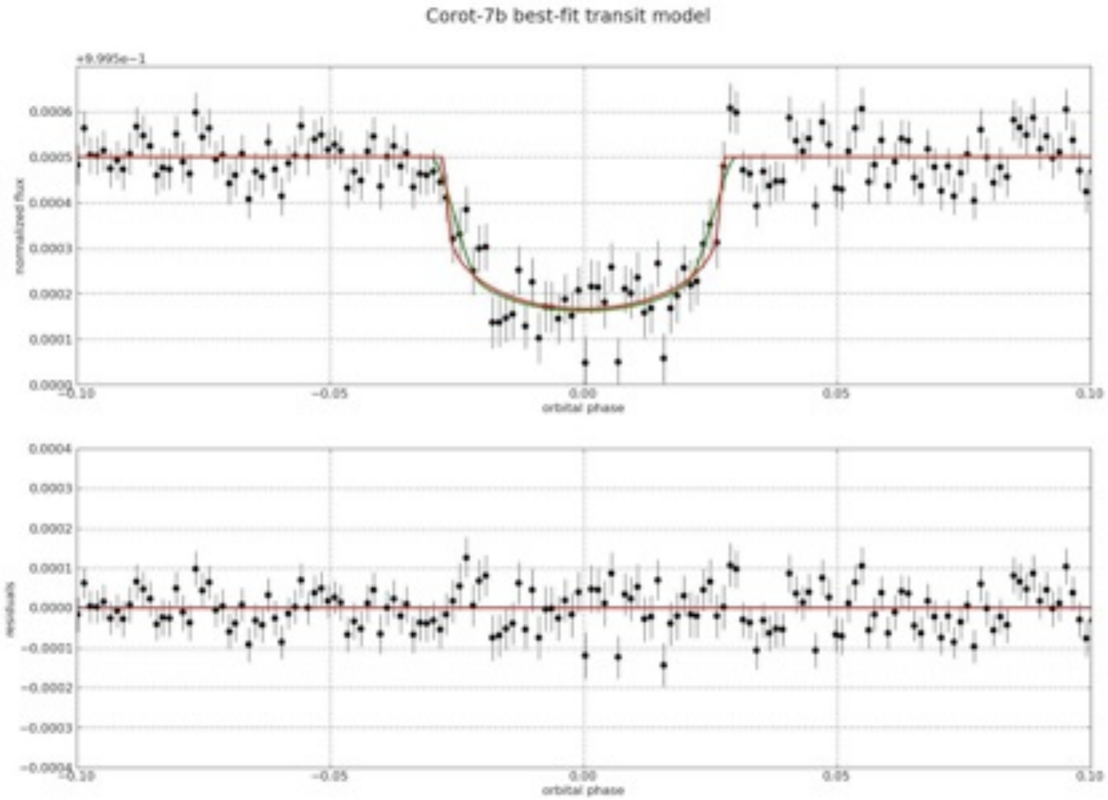
Radius = 1.68 ± 0.09 R_E

Period = 0.854 days

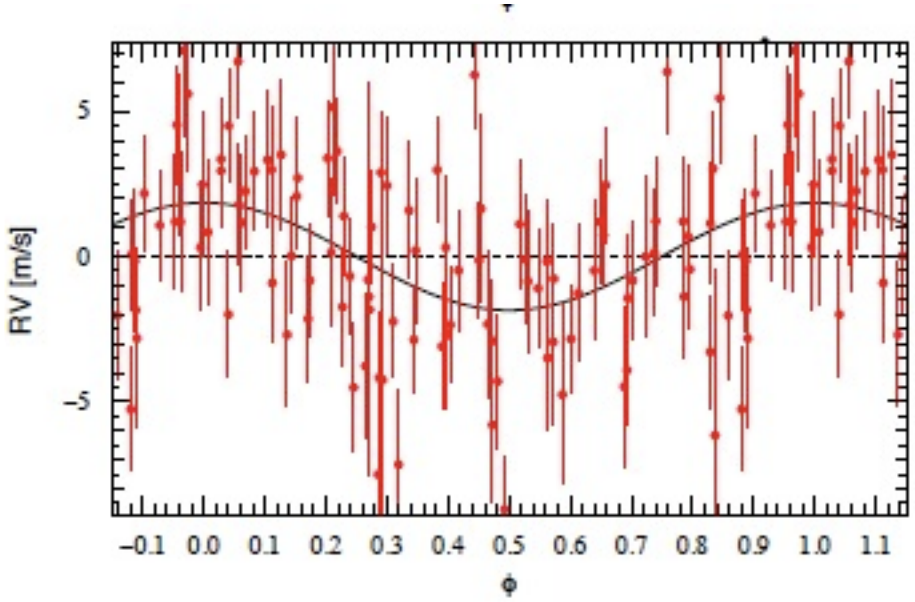
Age = 1.2-2.3 Gy

Mass = 4.8 ± 0.8 M_E

Leger et al, 2009



Queloz et al, 2009



Can it retain an atmosphere?

No, unless it is constantly resupplied

Energy limited calculation based on UV flux

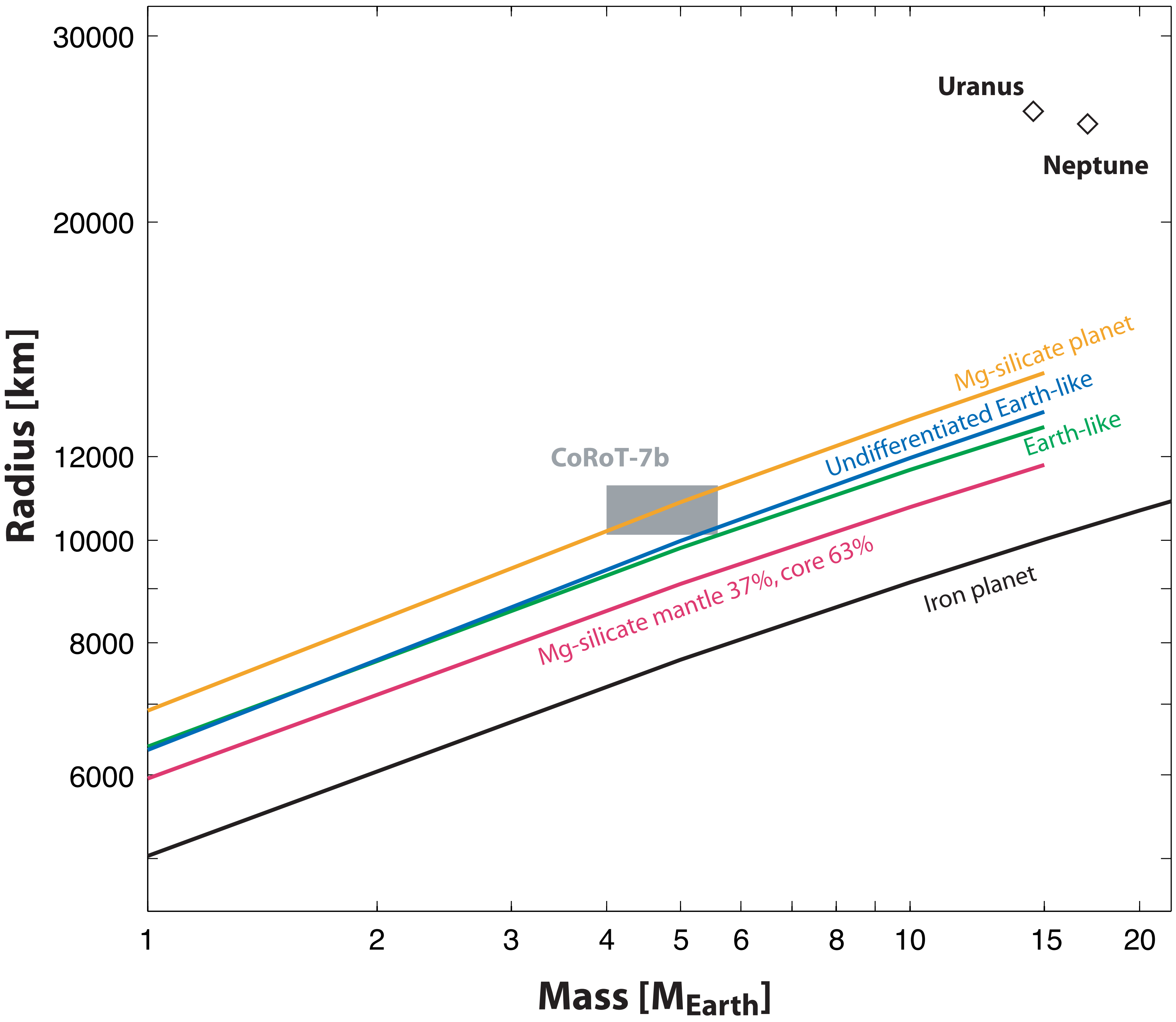
$$\frac{dM}{dt} = \frac{3\,\varepsilon\,F_{EUV}}{4\,G\,\rho\,K_{tide}} = 10^{11}\ \mathrm{g/s}$$

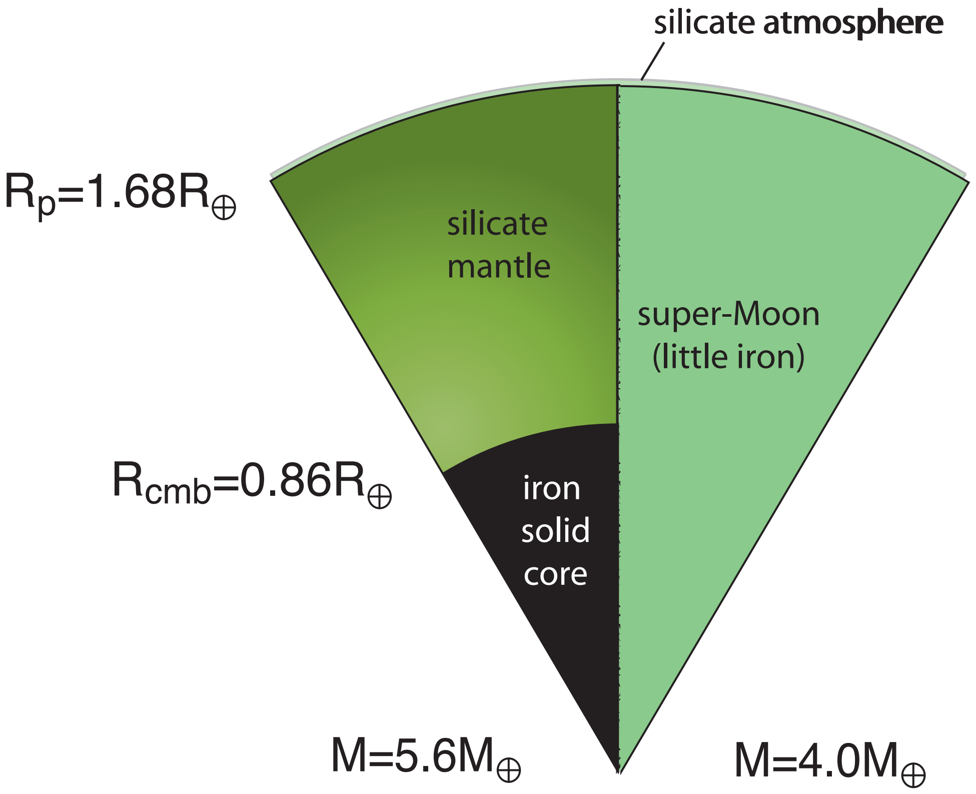
For more details on ε
see Lammer et al 09

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

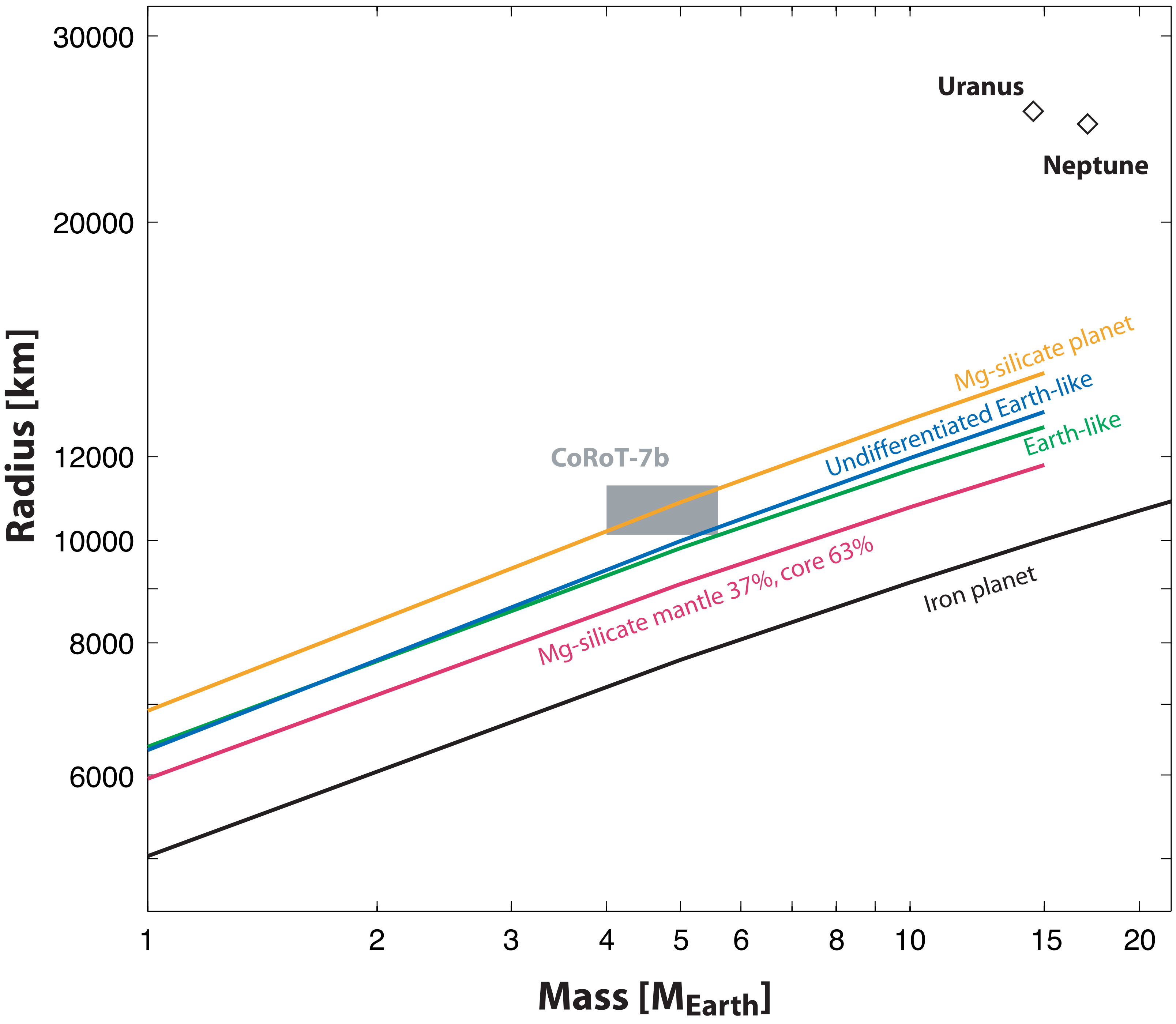
Rocky CoRoT-7b

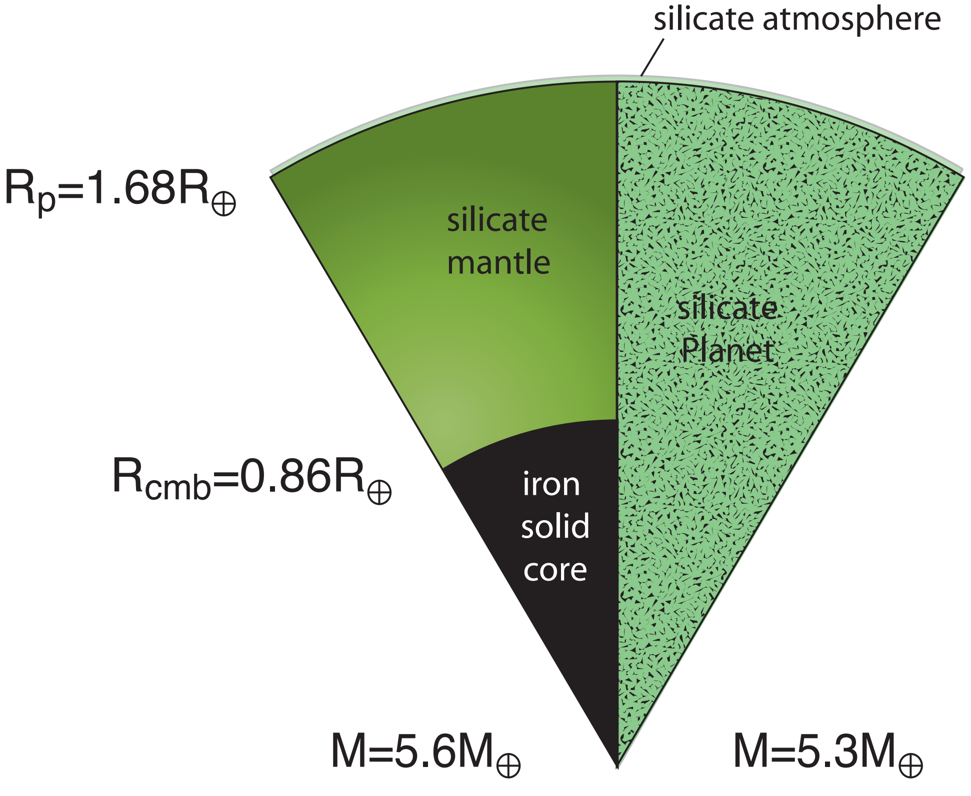




Valencia et al, 2010

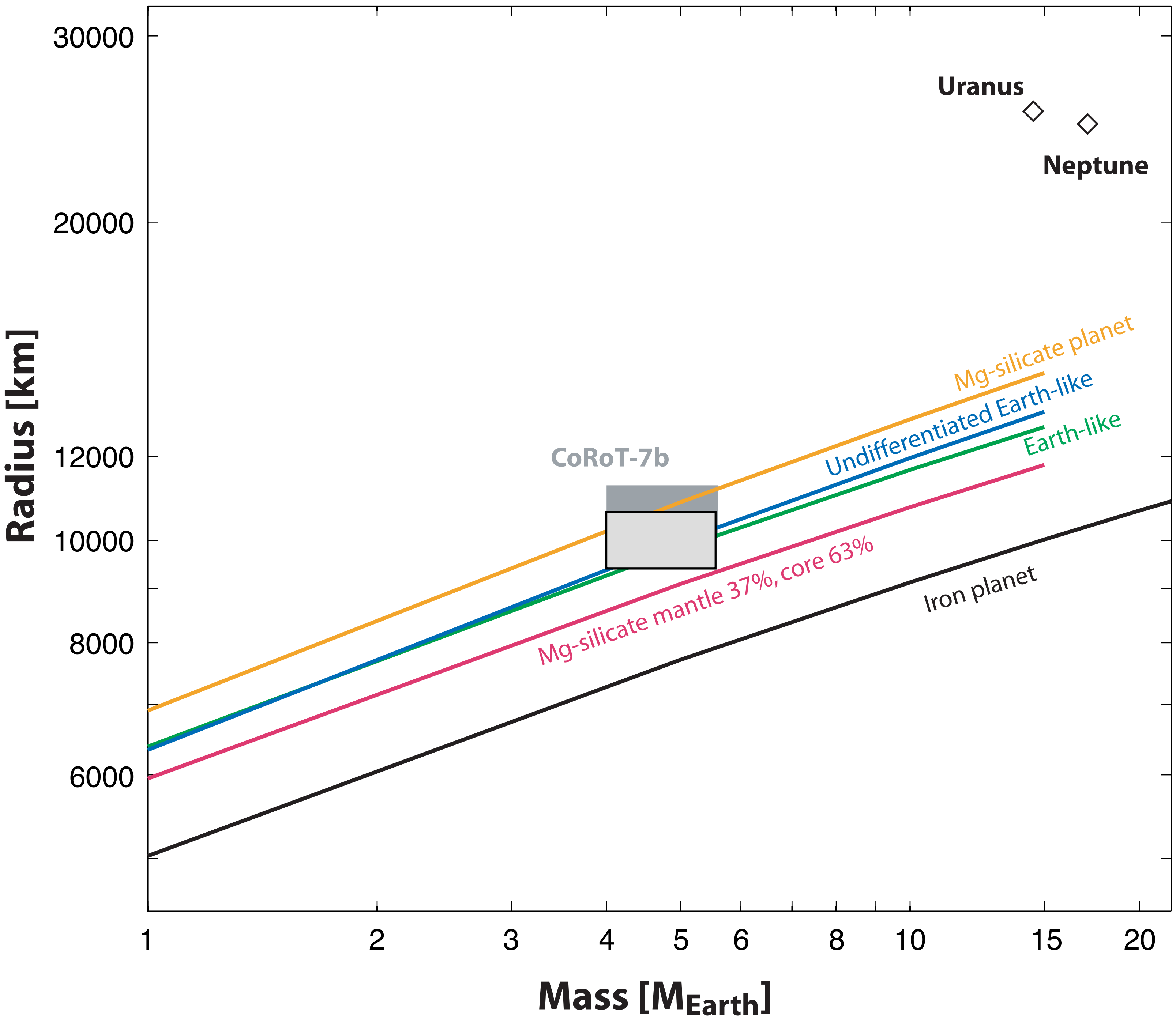
Rocky CoRoT-7b

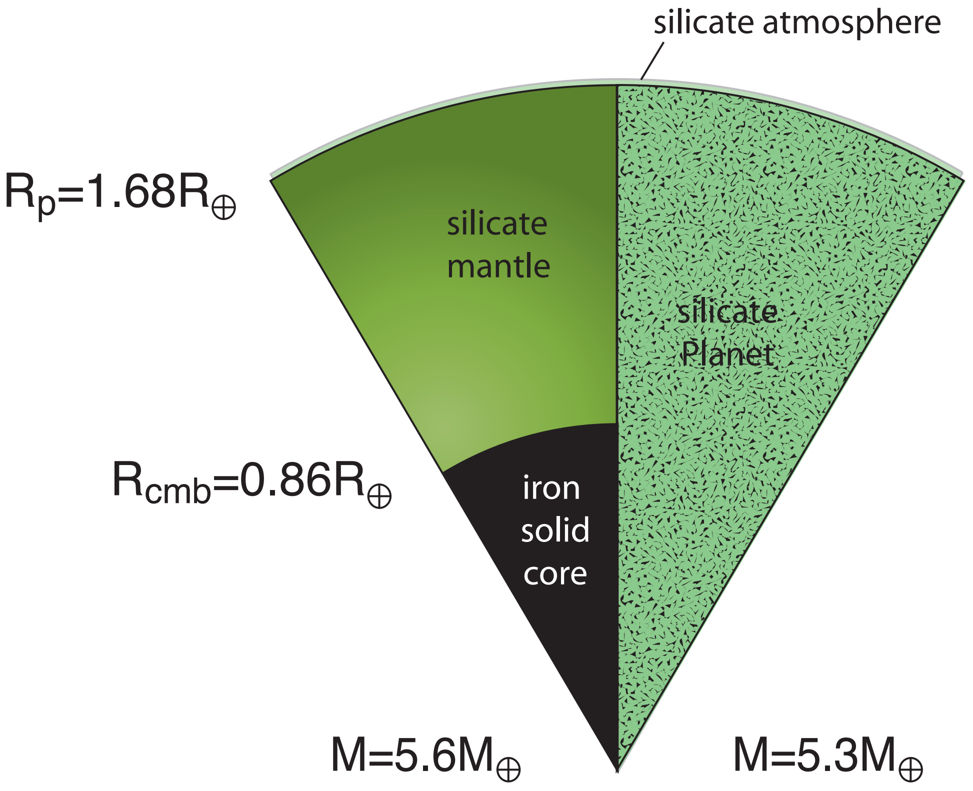




Valencia et al, 2010

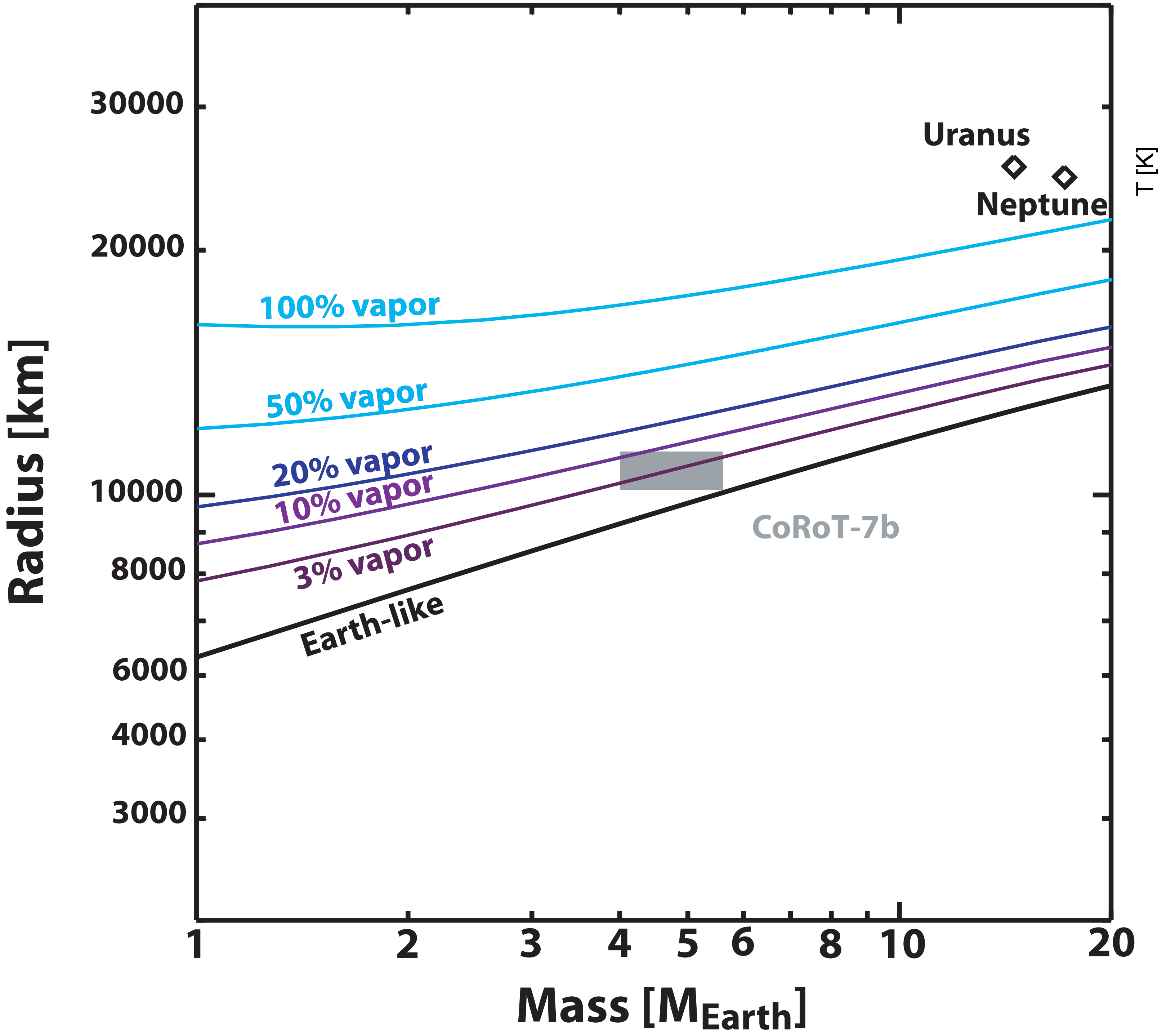
Rocky CoRoT-7b

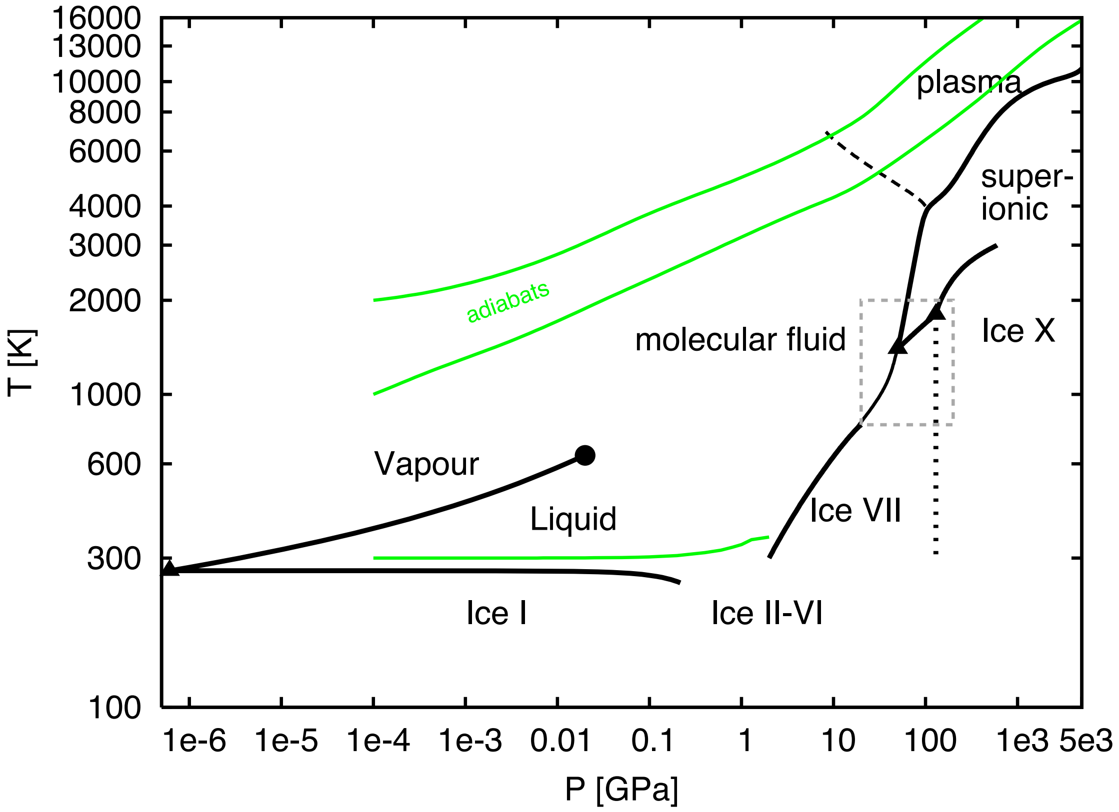




Valencia et al, 2010

H2O Vapor CoRoT-7b



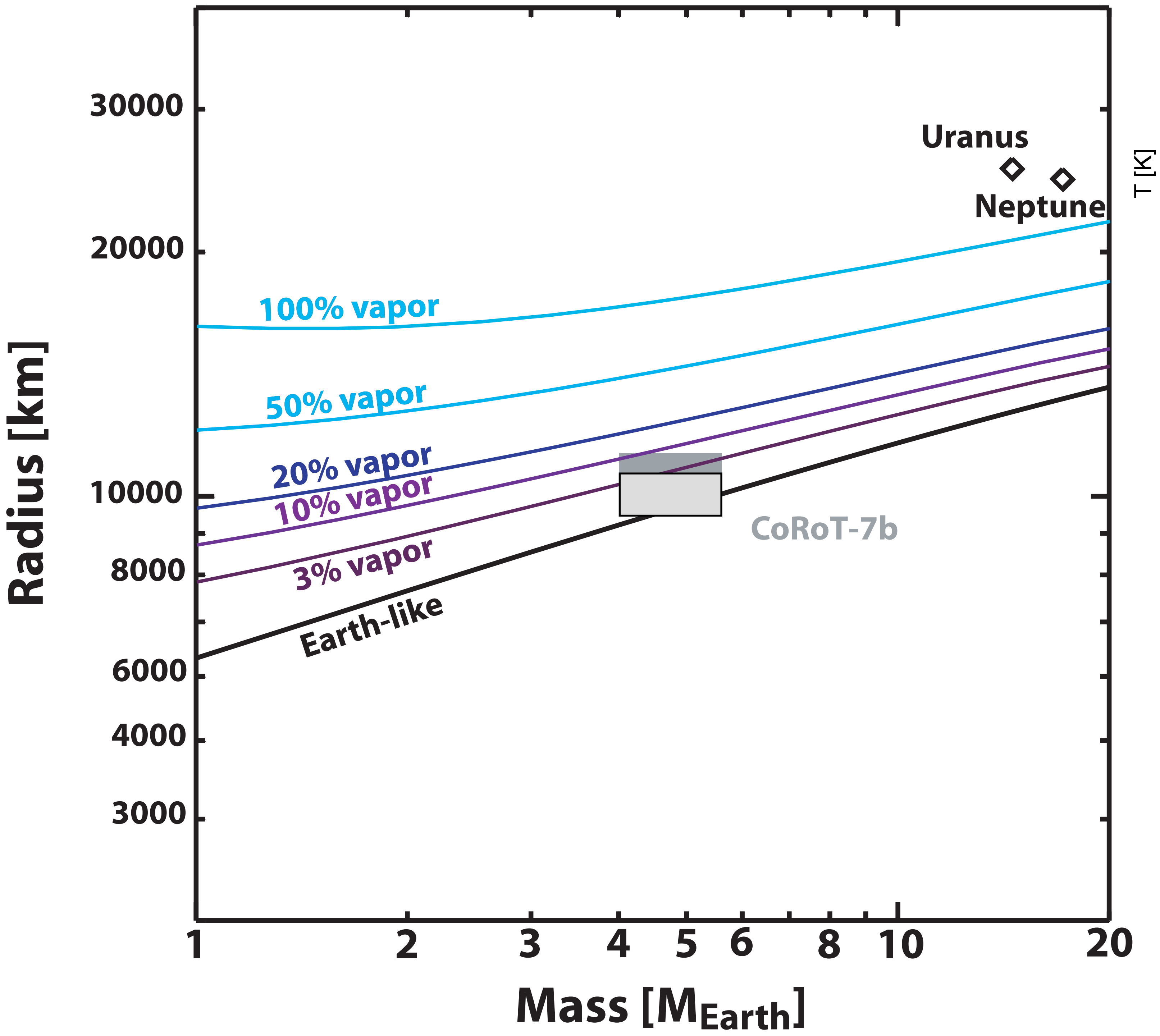


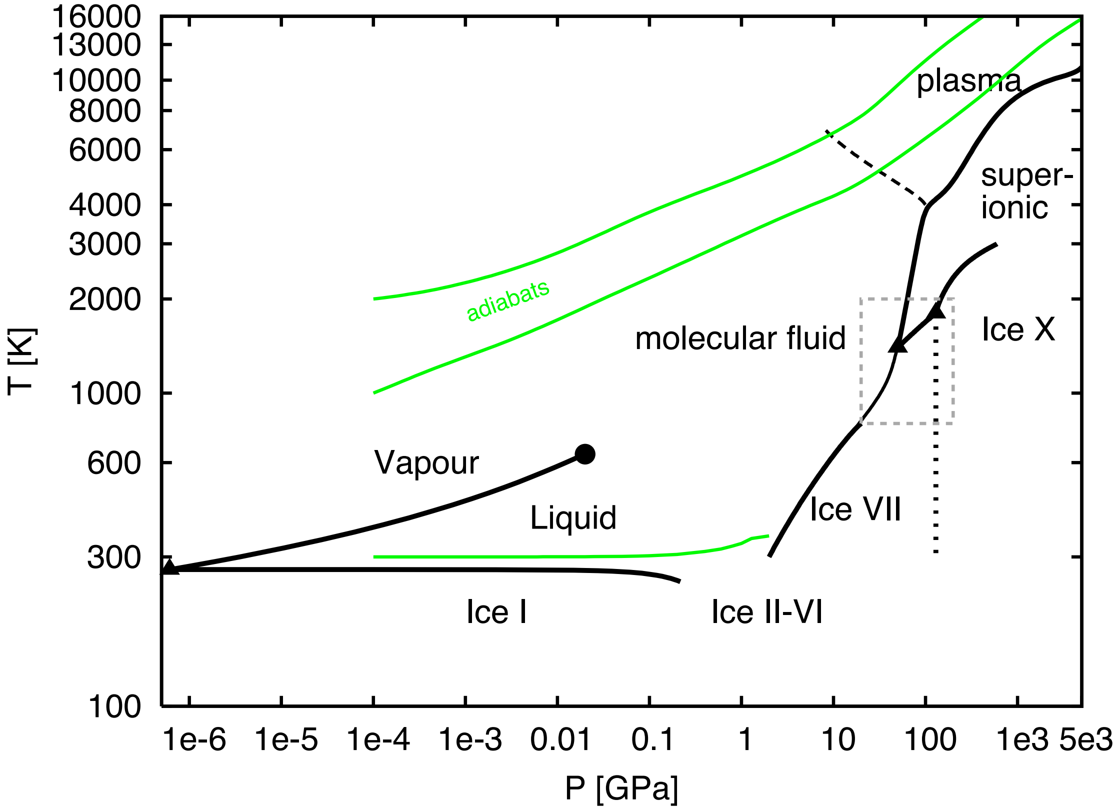
Evaporation

Timescale ~ 1 Gy

Valencia et al, 2010

H2O Vapor CoRoT-7b



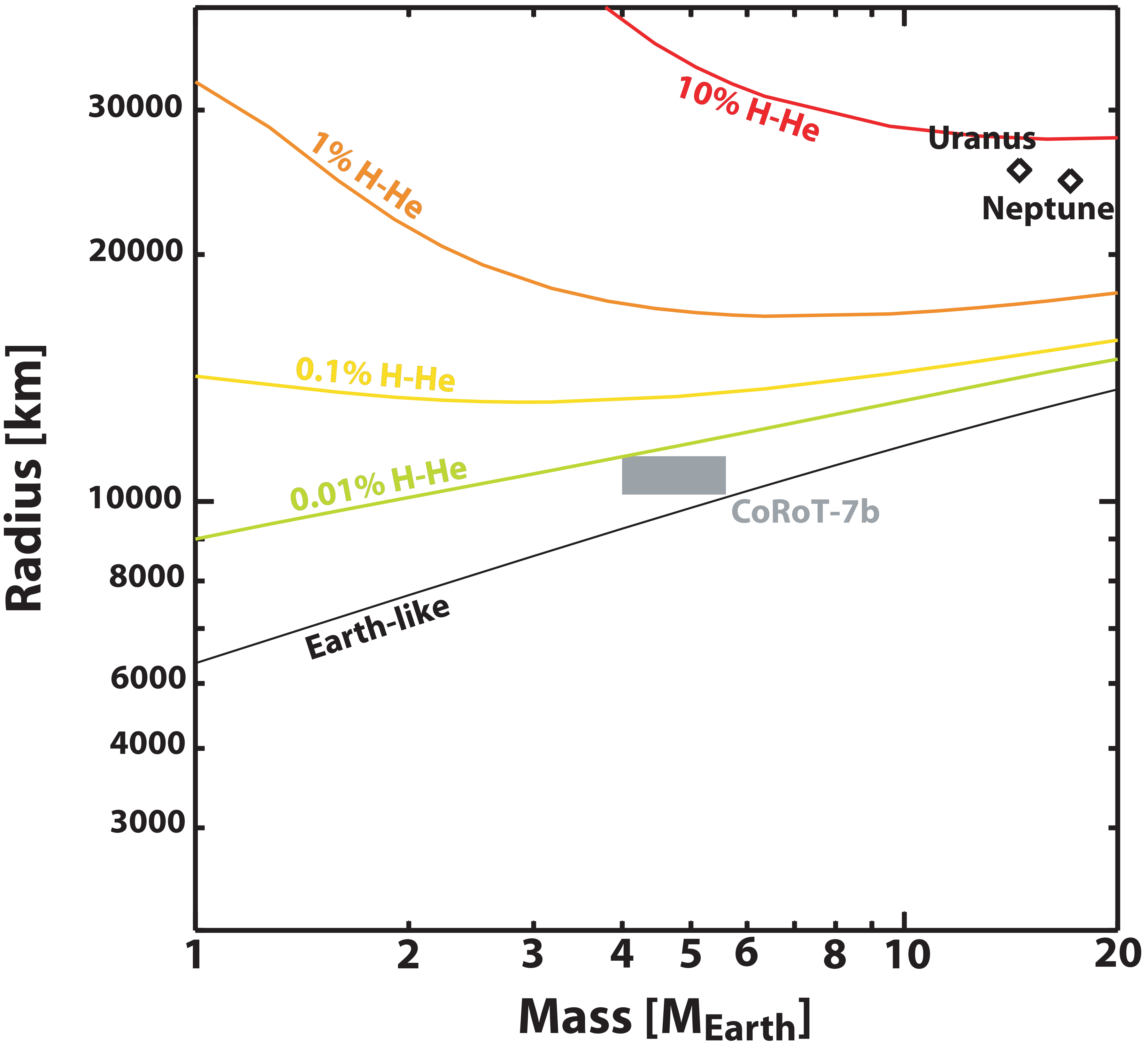


Evaporation

Timescale ~ 1 Gy

Valencia et al, 2010

Hydrogen or Helium?



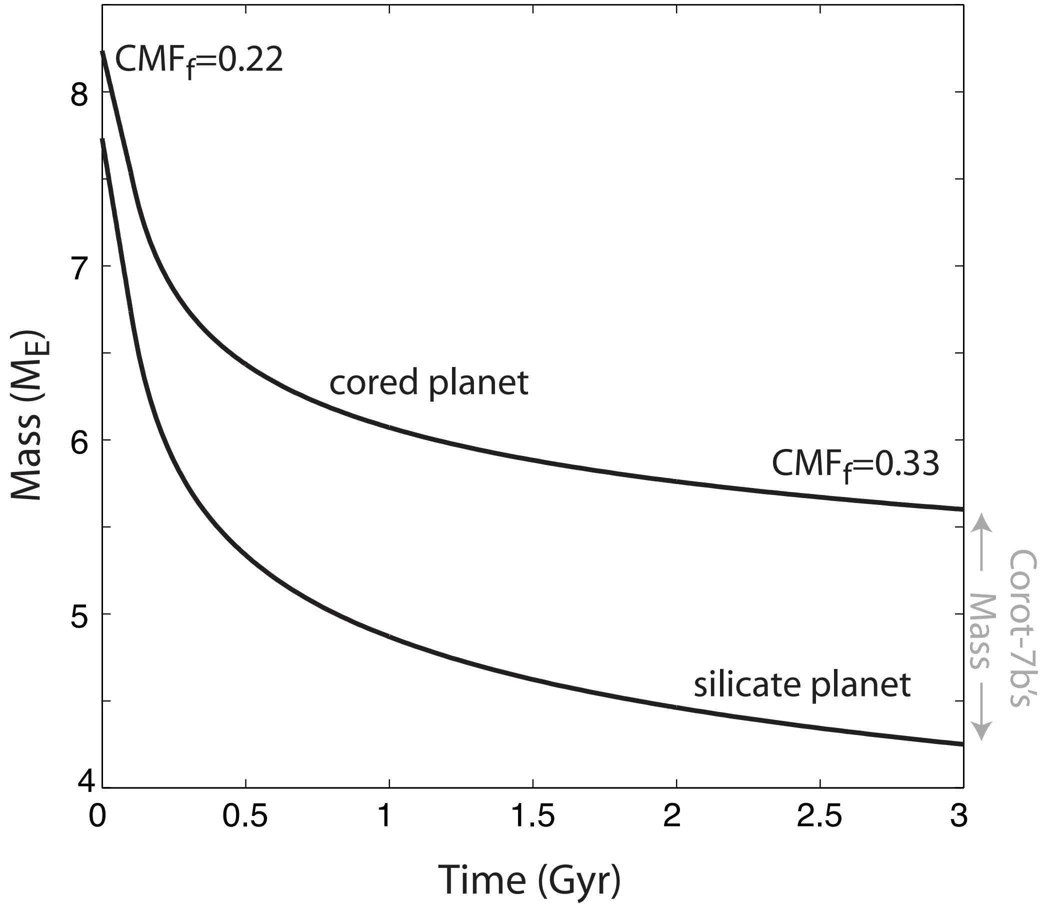
Evaporation Timescale ~ 1 My!

Valencia et al. 2010

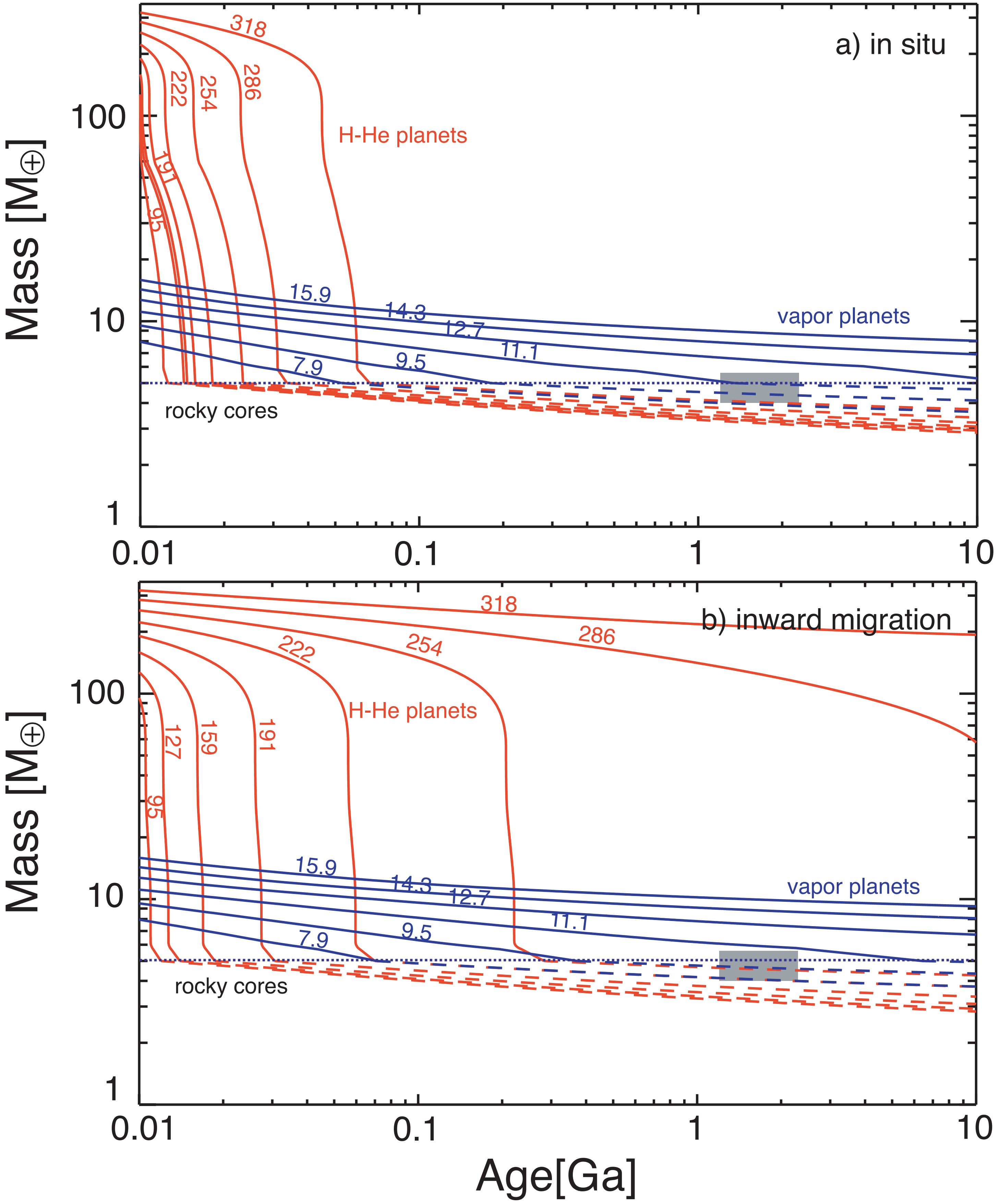
CoRoT-7b's origin?

Valencia et al. 2010

Rocky Origin



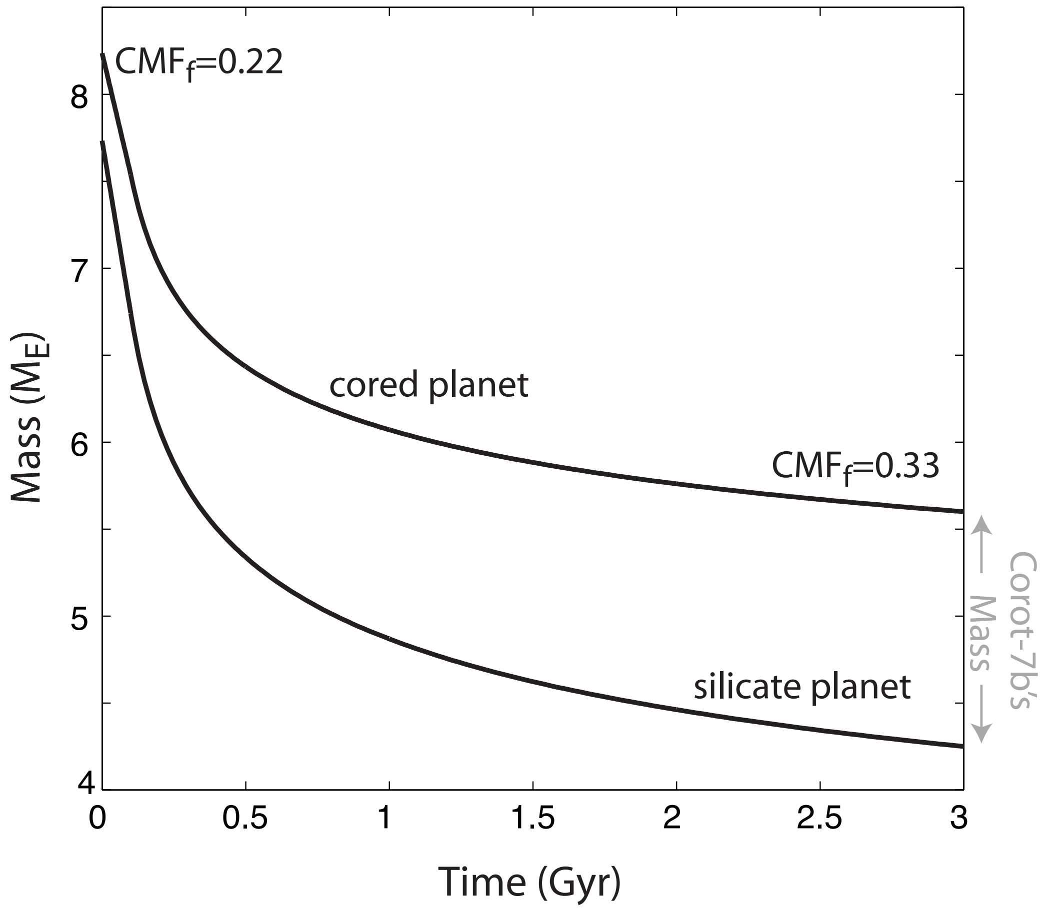
Volatile Origin



CoRoT-7b's origin?

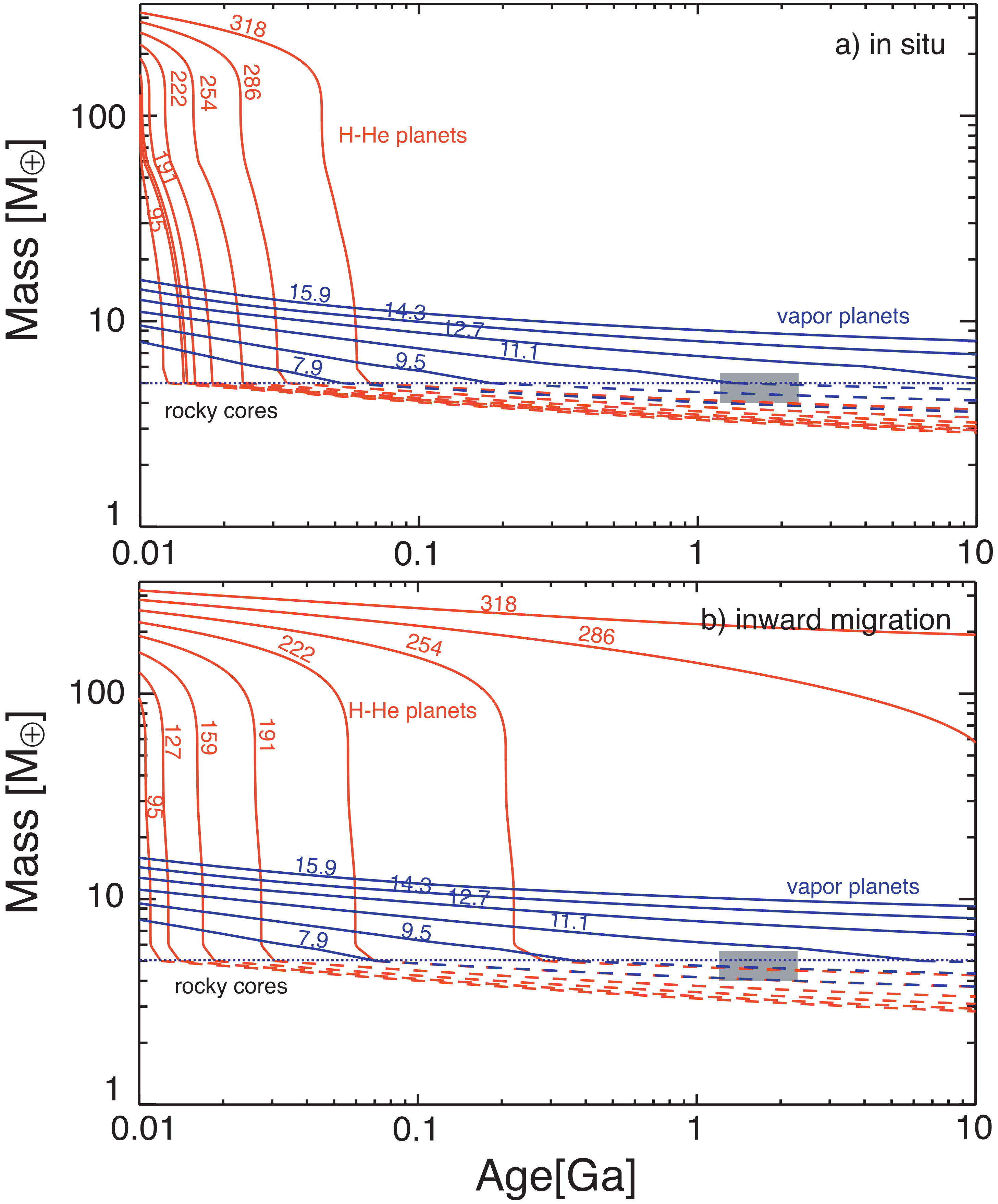
Unconstrained

Rocky Origin

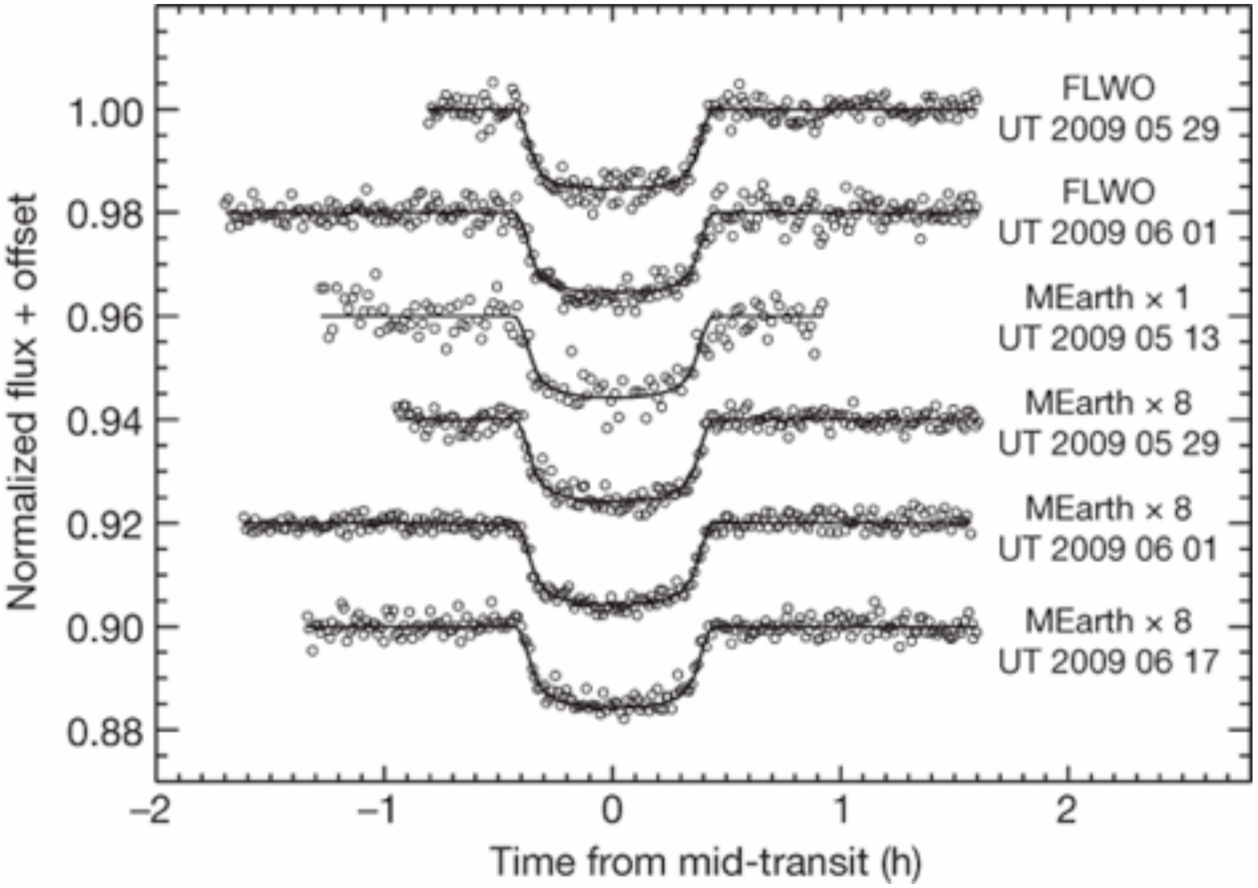


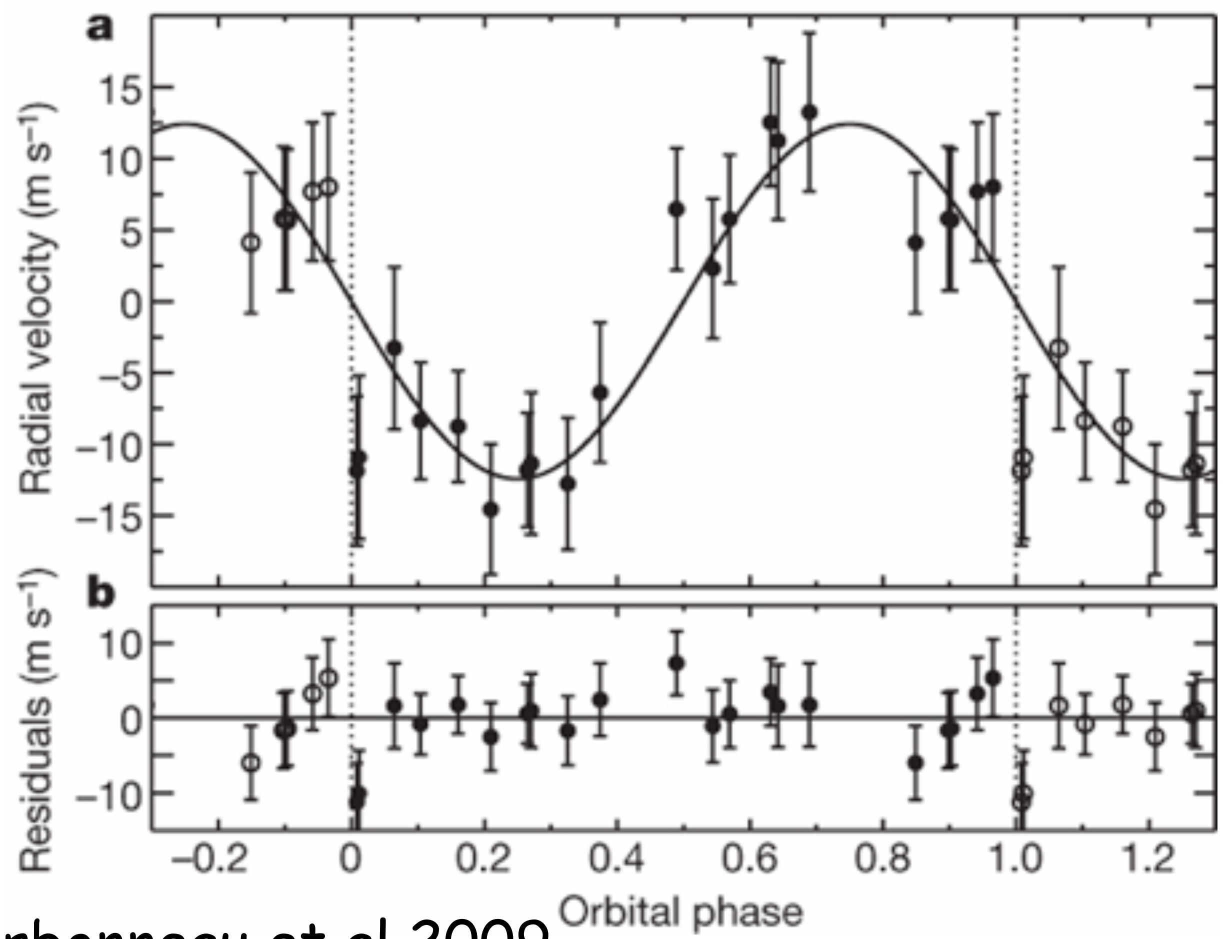
Valencia et al. 2010

Volatile Origin



GJ 1214b





Charbonneau et al 2009

Radius = 2.678 ± 0.13 R_E

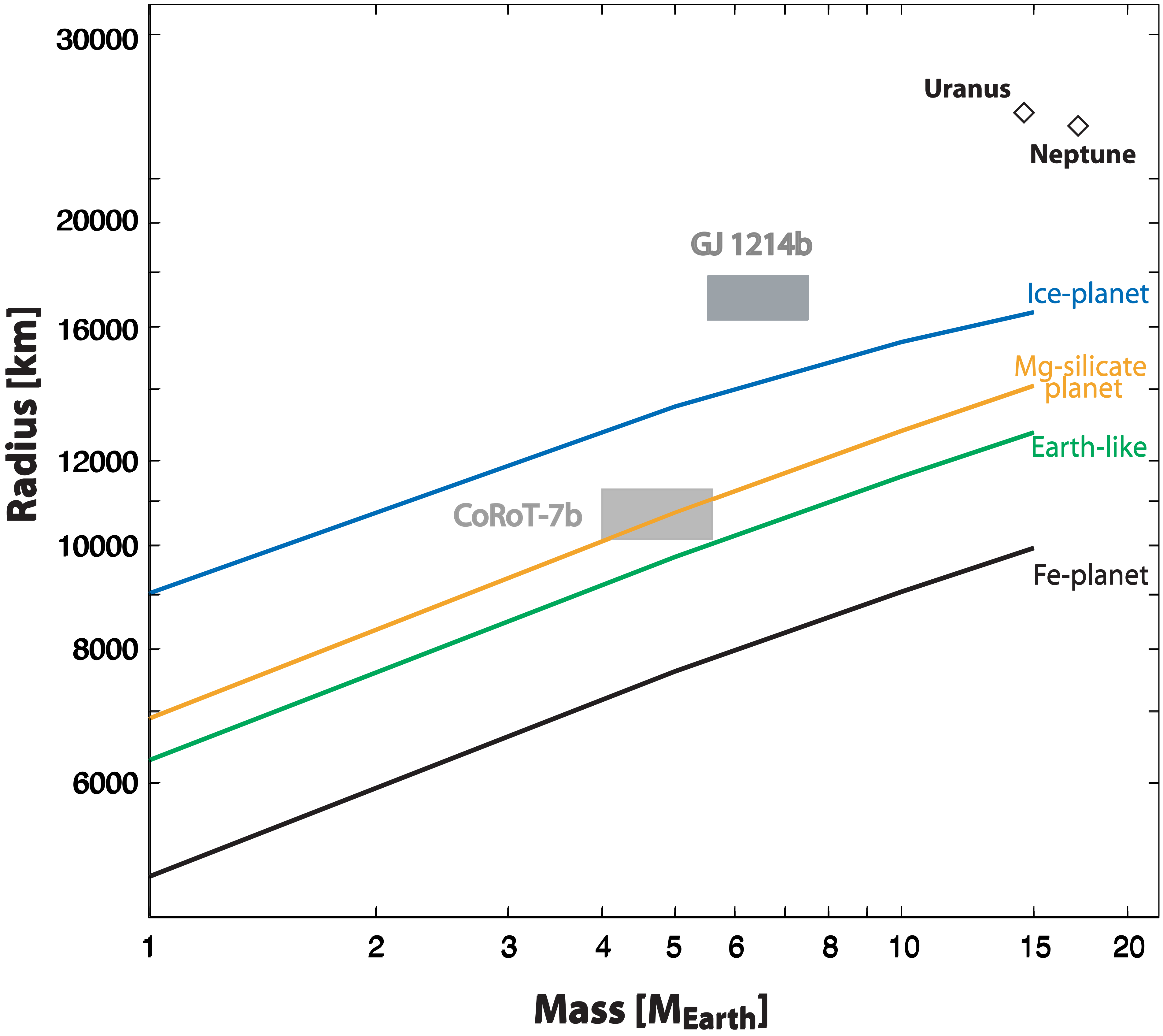
Mass = 6.55 ± 0.98 M_E

Period = 1.58 days

Temp = 393-555 K

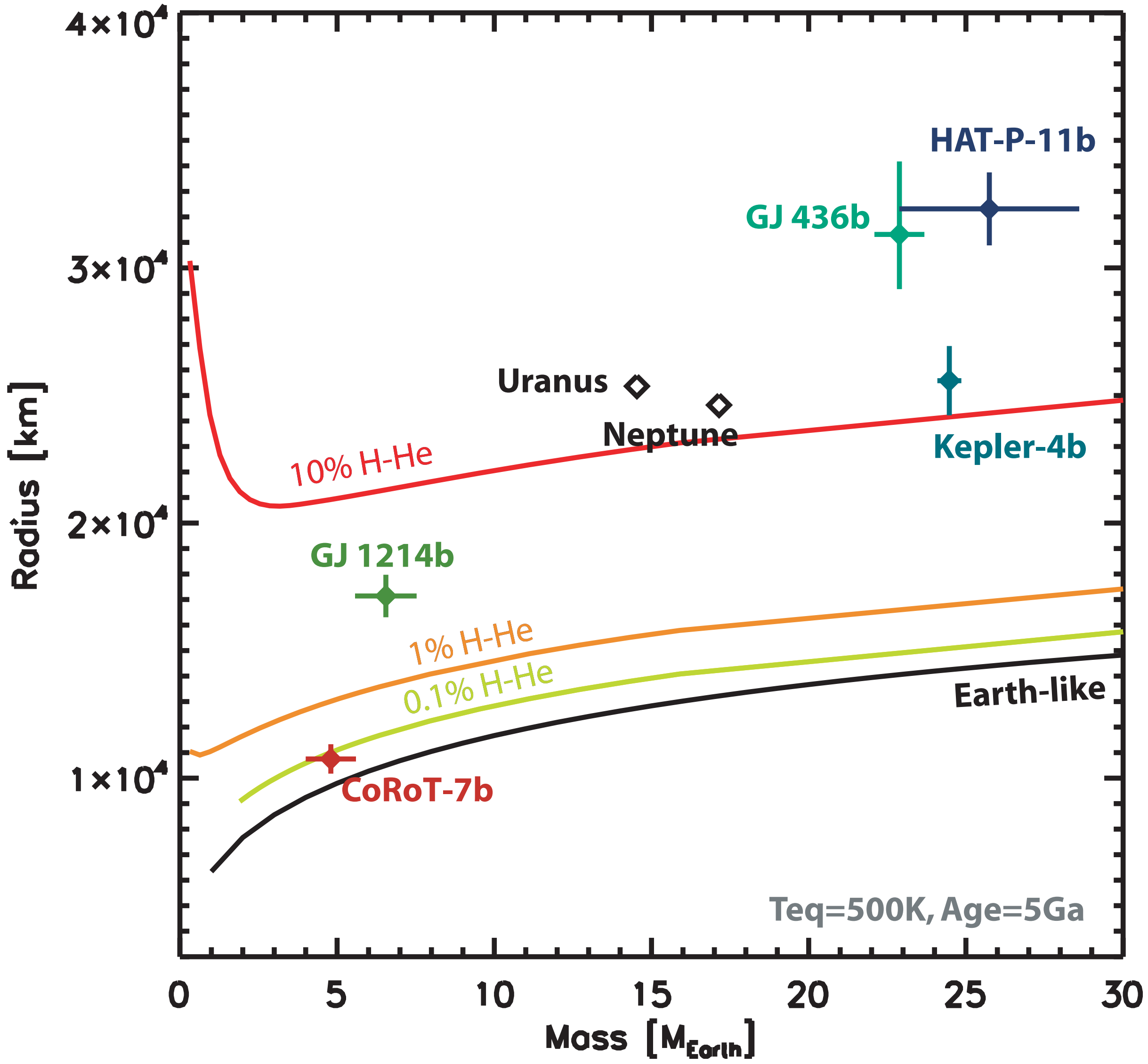
See also: Rogers & Seager, 2010
Miller-Ricci & Fortney 2010

Solid GJ 1214b ?

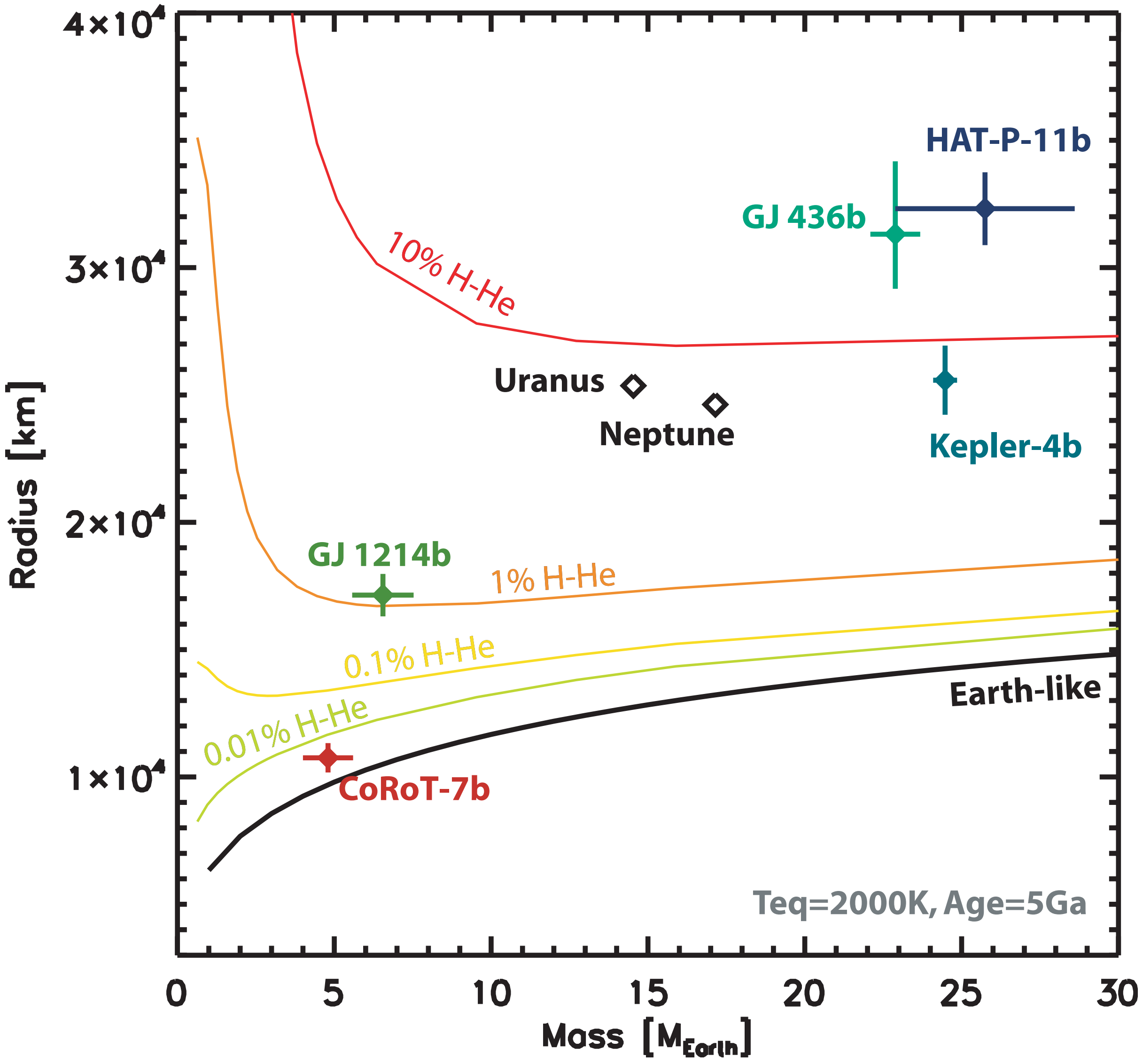


H/He in GJ 1214b ?

Teq=500K



Teq=2000K



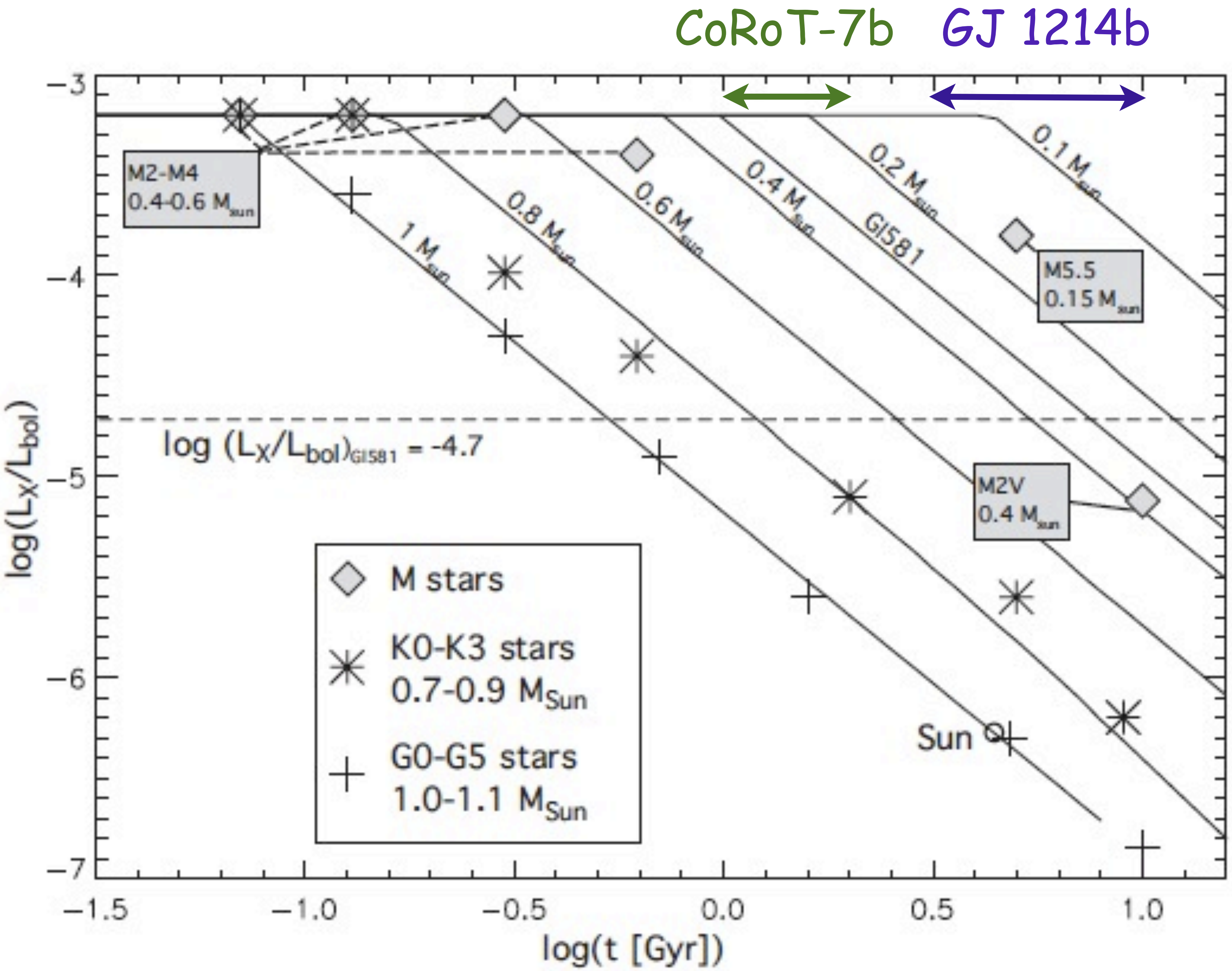
In preparation

GJ 1214b: escape rate

$\rho = 0.34\ \rho_E$

Age = 3-10 Gy

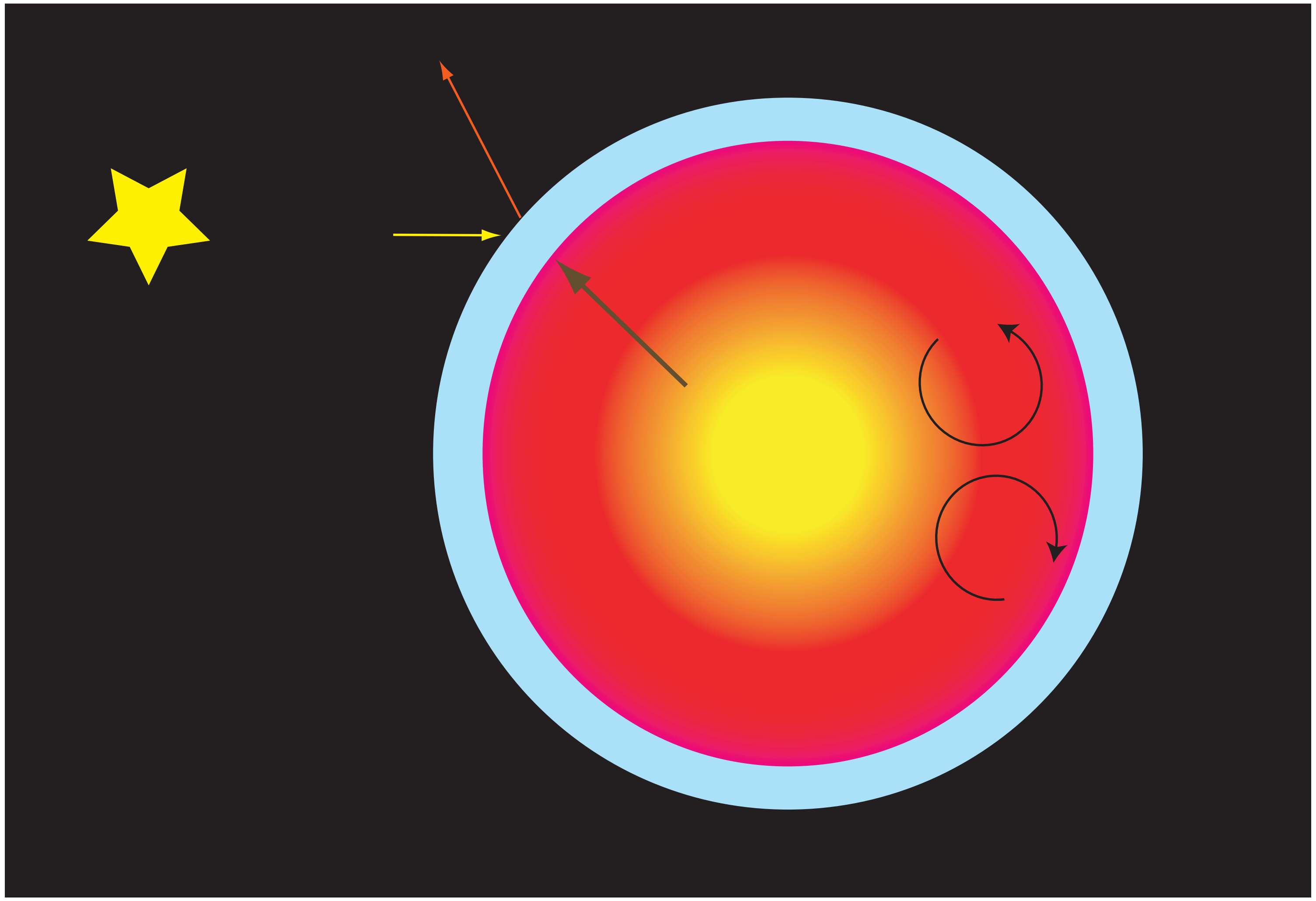
$$\frac{dM}{dt} = \frac{3\ \varepsilon\ F_{EUV}}{4\ G\ \rho\ K_{tide}}$$



Selsis et al, 2007

Habitability from a Planetary Perspective: Follow the water ...

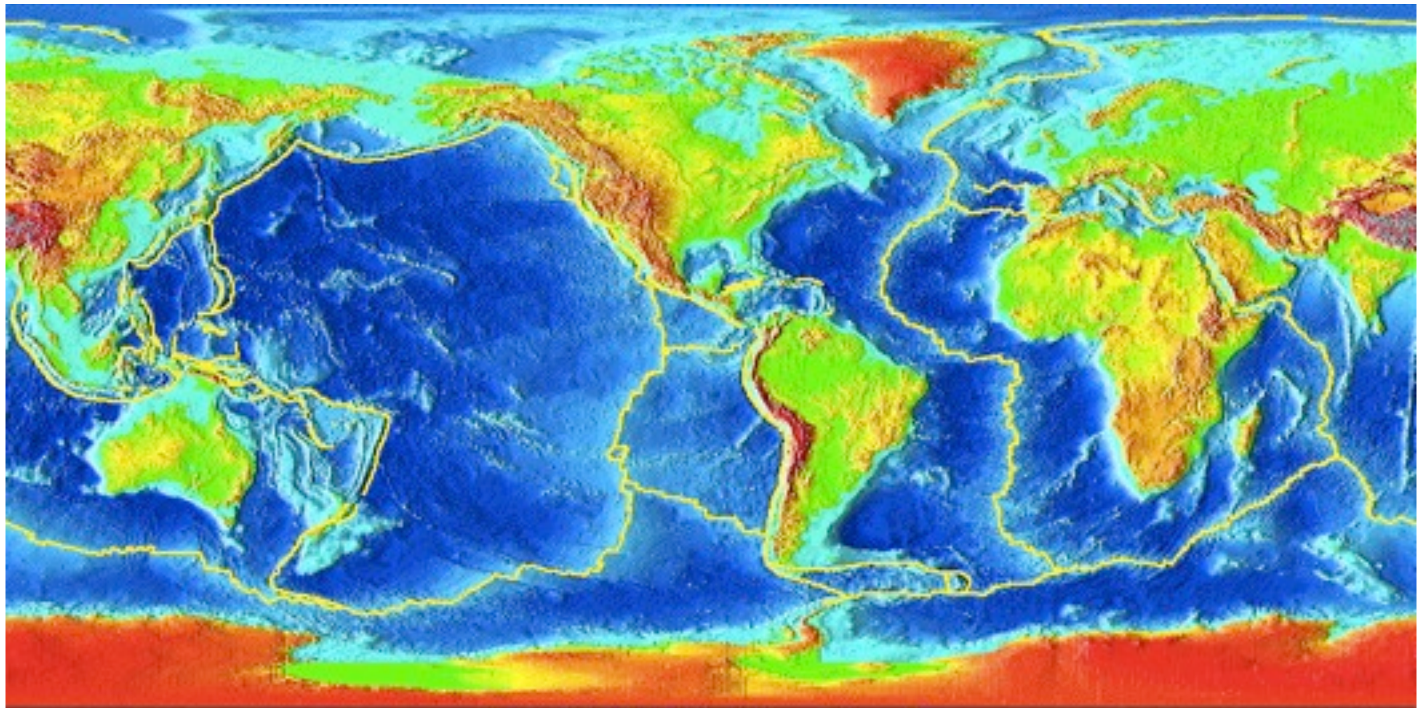
Surface temperature depends on insolation, interior heat flux and atmospheric response

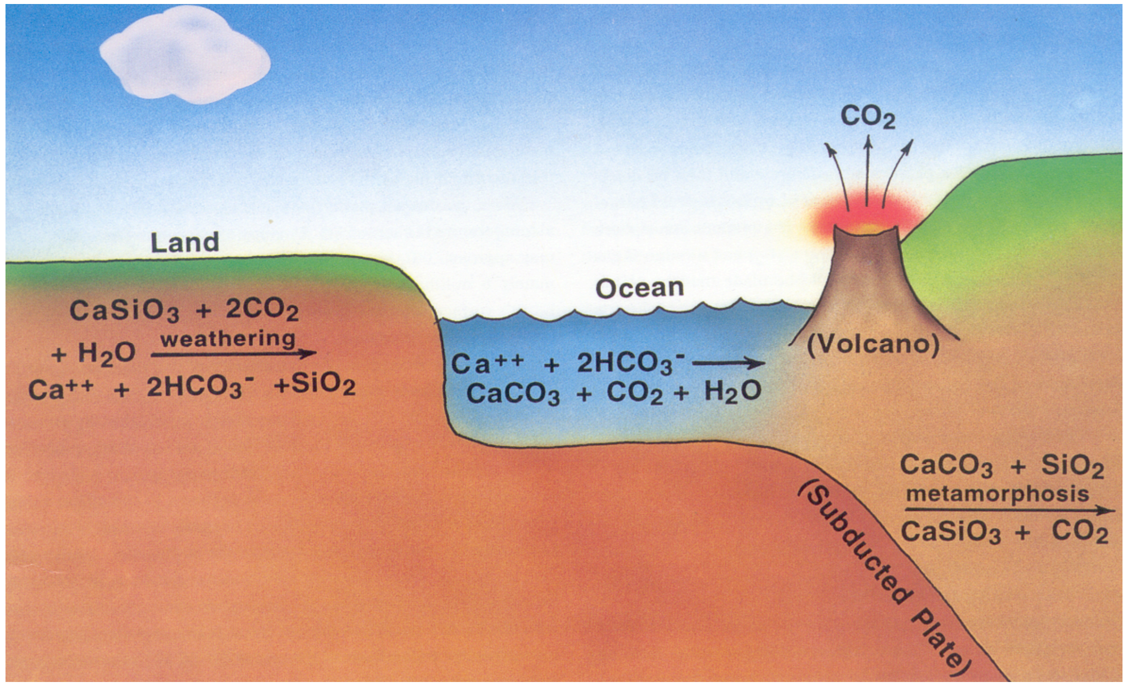


atmospheric composition

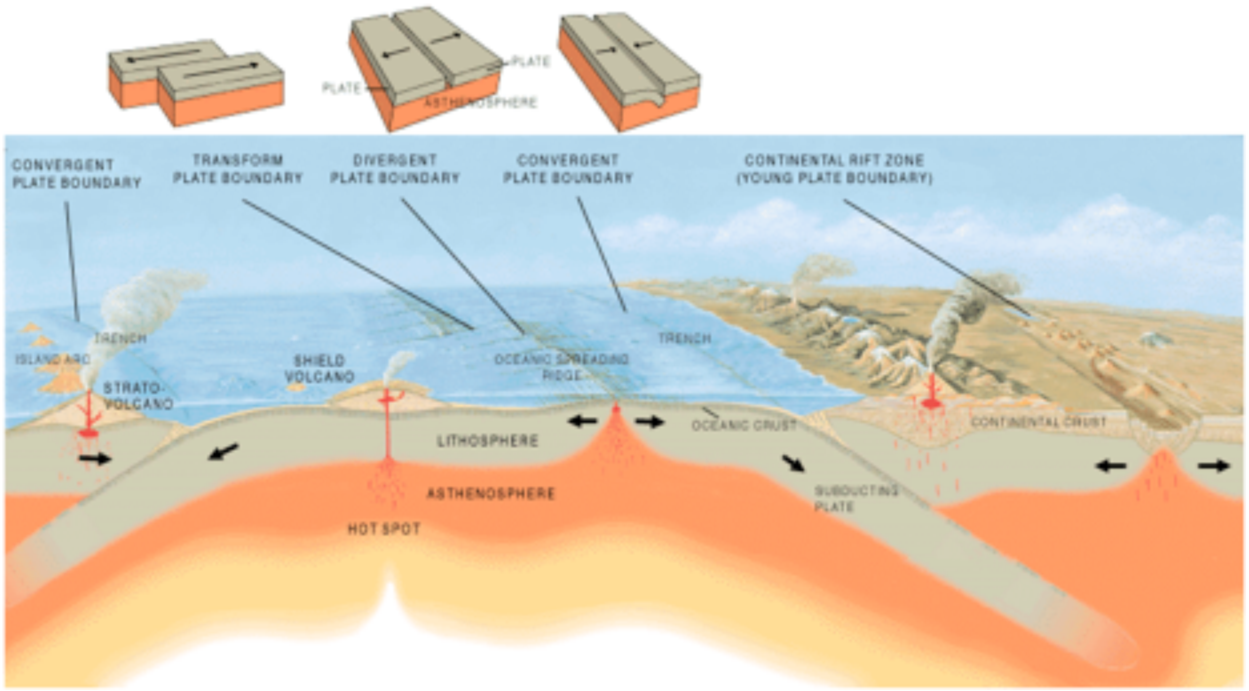
Interior processes: tectonics, volcanism, magnetic field

Can a massive rocky planet have plate tectonics?





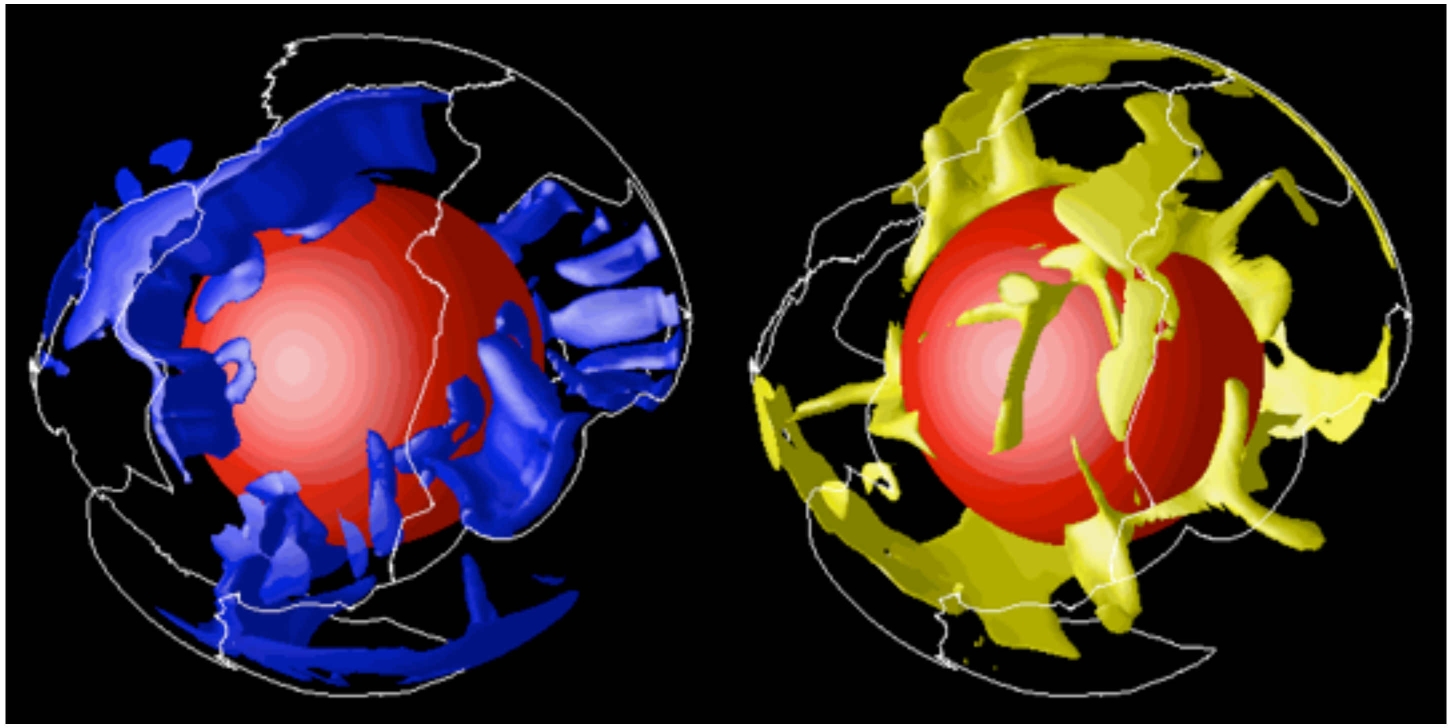
Walker 1981, Kasting 1996



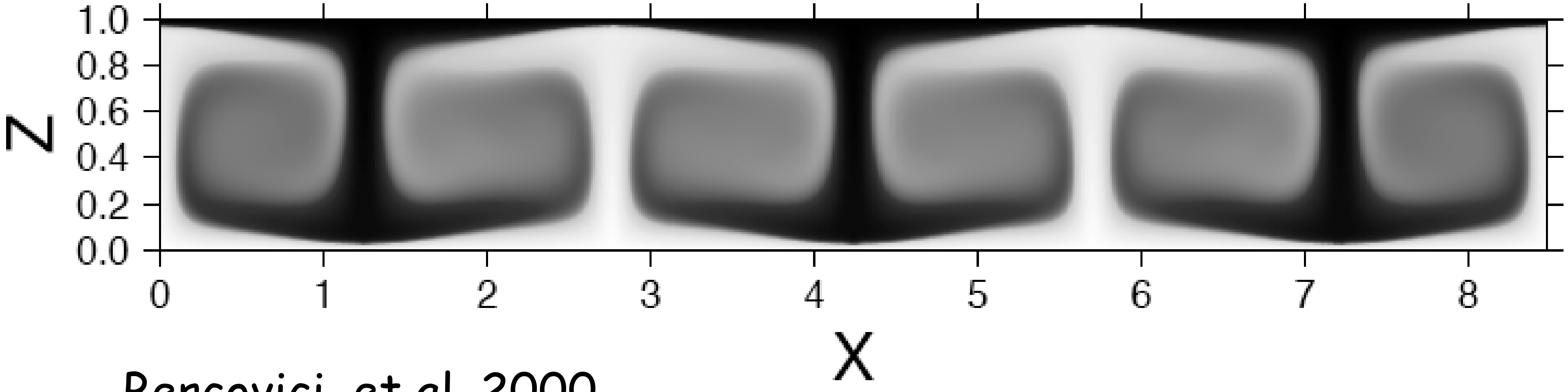
Strong, coherent plate;
deformation on boundaries;
PT is the surface expression
of mantle convection

Plate Tectonics and Mantle Convection

- Navier Stokes equations
- Classical Boundary layer theory
- Numerical modeling
- Laboratory Experiments



Bernard Convection



Bercovici, et al. 2000

Conditions for PT

1. Deformation of the plate

Valencia et al, 2007, 2009
O'Neill & Lenardic 2007
Van Heken & Tackley, 2009
Sotin & Jackson, 2009

2. Negative buoyancy

Valencia, 2009
Kite et al 2009

3. Energy dissipation at subduction zones is not enough to halt PT

Valencia et al, 2009

Can terrestrial super-Earths have plate tectonics?

Can terrestrial super-Earths have plate tectonics?

under debate

Can terrestrial super-Earths have plate tectonics?

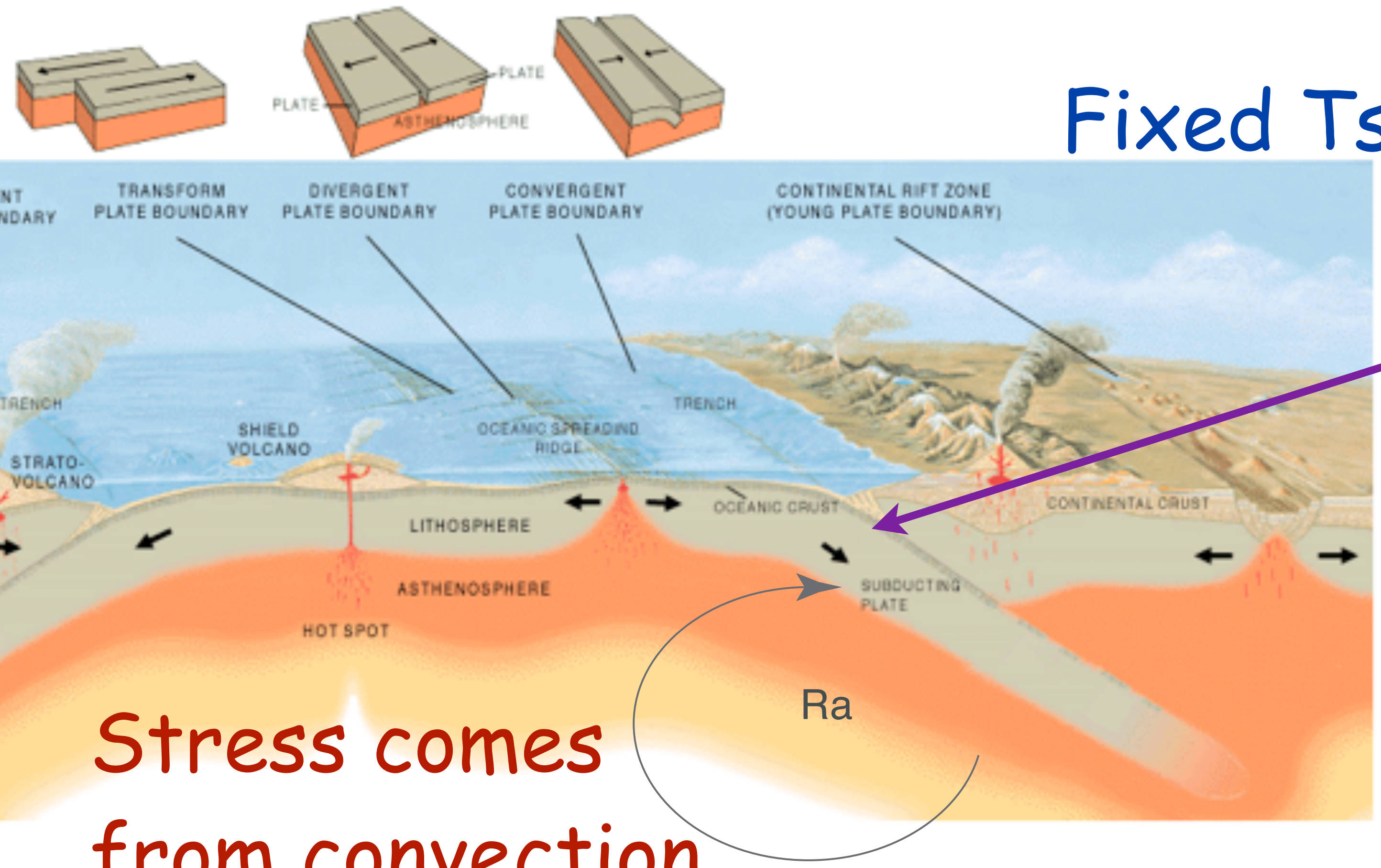
under debate

Valencia et al 2007: "... as mass increases, the process of subduction, and hence plate tectonics, becomes easier. Therefore, massive super-Earths will very likely exhibit plate tectonics"

O'Neill and Lenardic 2007: "...these results suggest super-Earths may in fact be in an episodic or stagnant-lid regime, rather than a mobile lid regime similar to Earth's plate tectonics."

Similarities

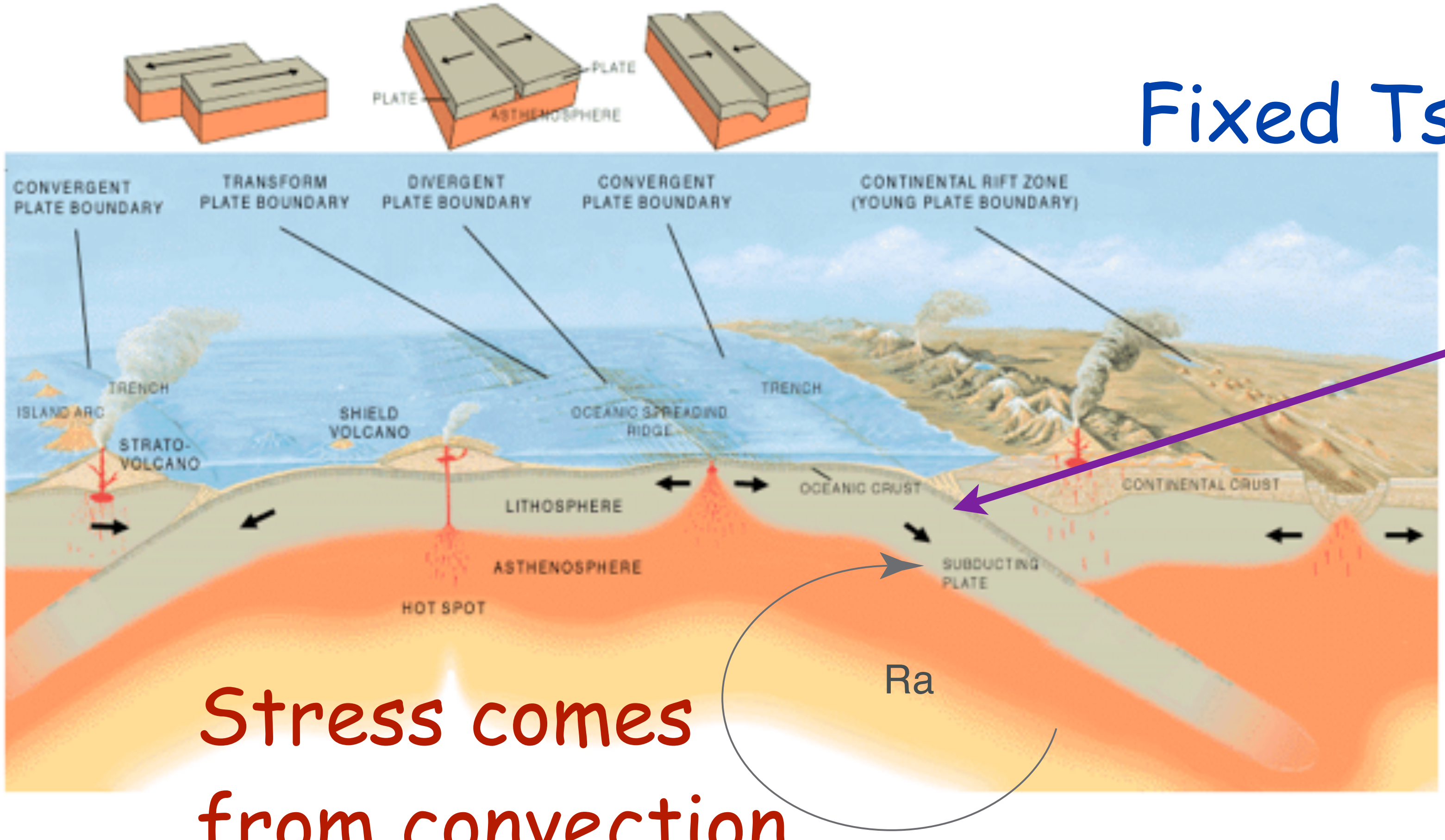
Fixed Tsurf



Coulomb failure criterion for plate deformation

Stress comes from convection

Similarities



Fixed Tsurf

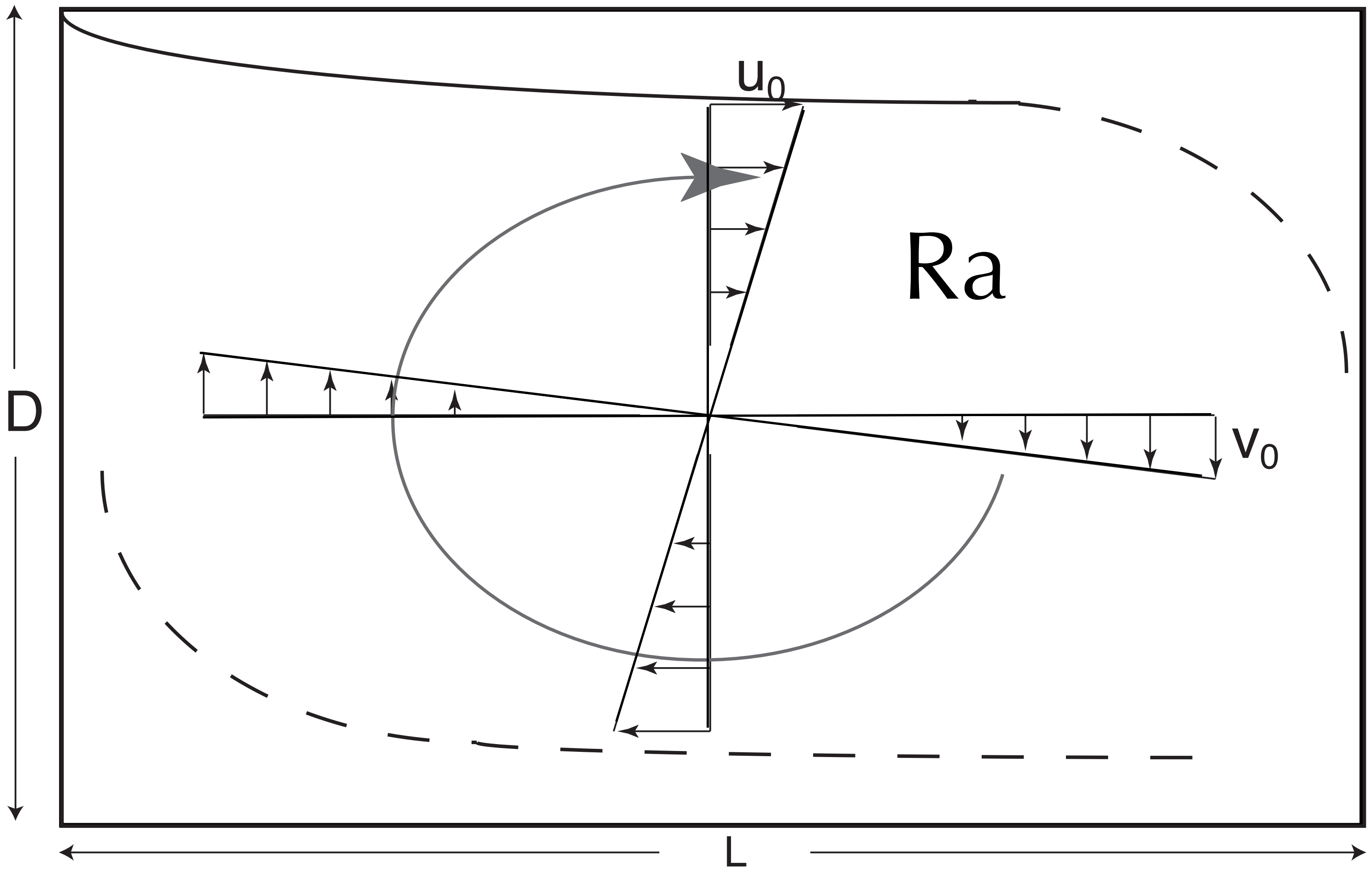
Coulomb failure criterion for plate deformation

Stress comes from convection

Differences

Valencia et al:	OL 2007
Classical Boundary Layer Structure model to scale parameters	Scaled a numerical model (Moresi and Solomatov, 1998) Constant density scaling
Dominated by radioactive heating	Mixed heating

Classical Boundary Layer Theory



velocity u

stress $\Delta\ \tau_{xy}$

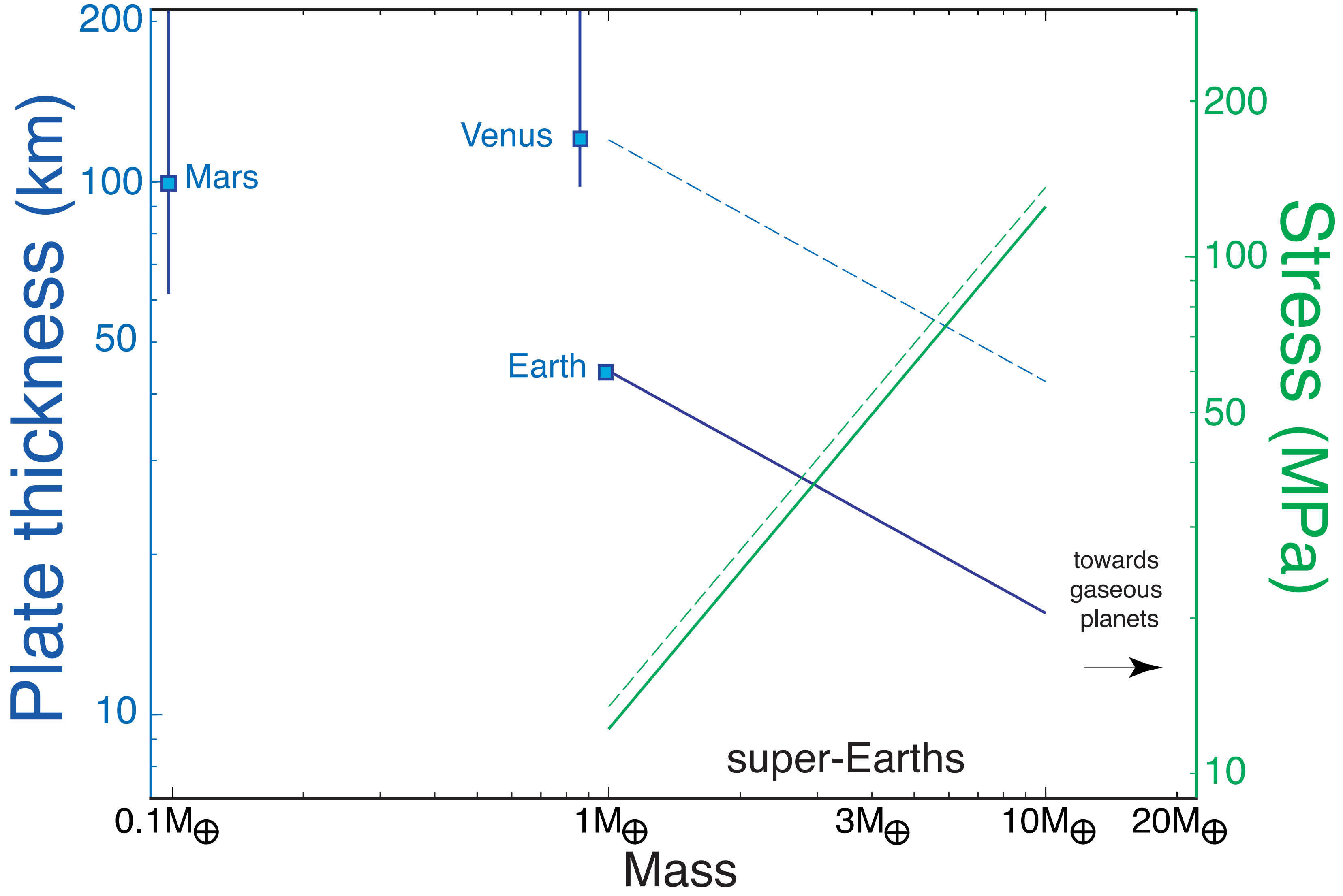
plate length L

timescale

Turcotte & Schubert, 2002

Internally heated: $Ra = \rho g \alpha D^4 q / \kappa \eta(T) k$ $\qquad D/2\delta \sim Ra^{1/4}$

Convective Parameters on super-Earths



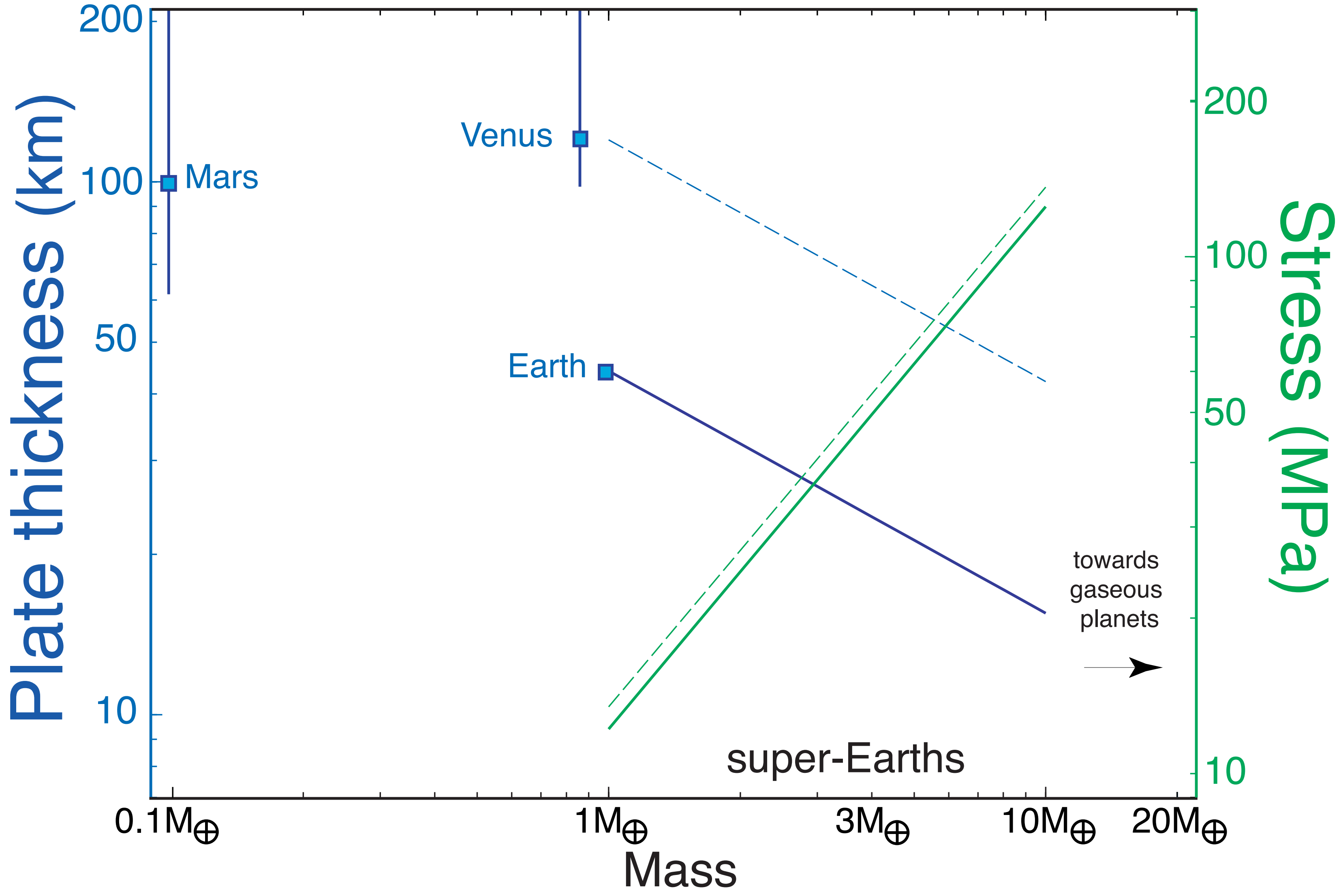
$$u \sim \kappa / D \; Ra^{1/2}$$

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

Valencia et al., 2007c

Convective Parameters on super-Earths

Plate P-T structure is nearly invariant with mass



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Convective Parameters on super-Earths

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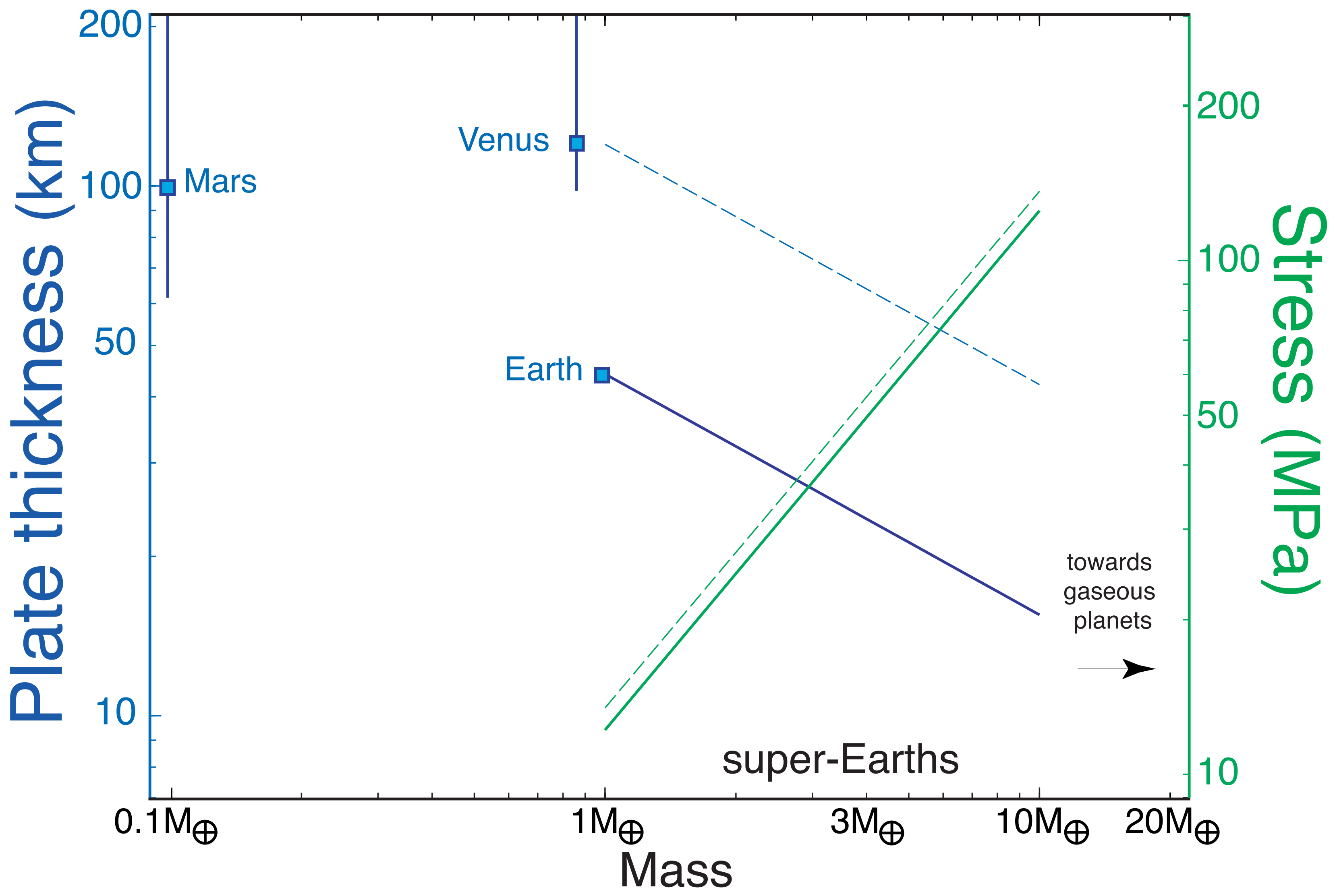


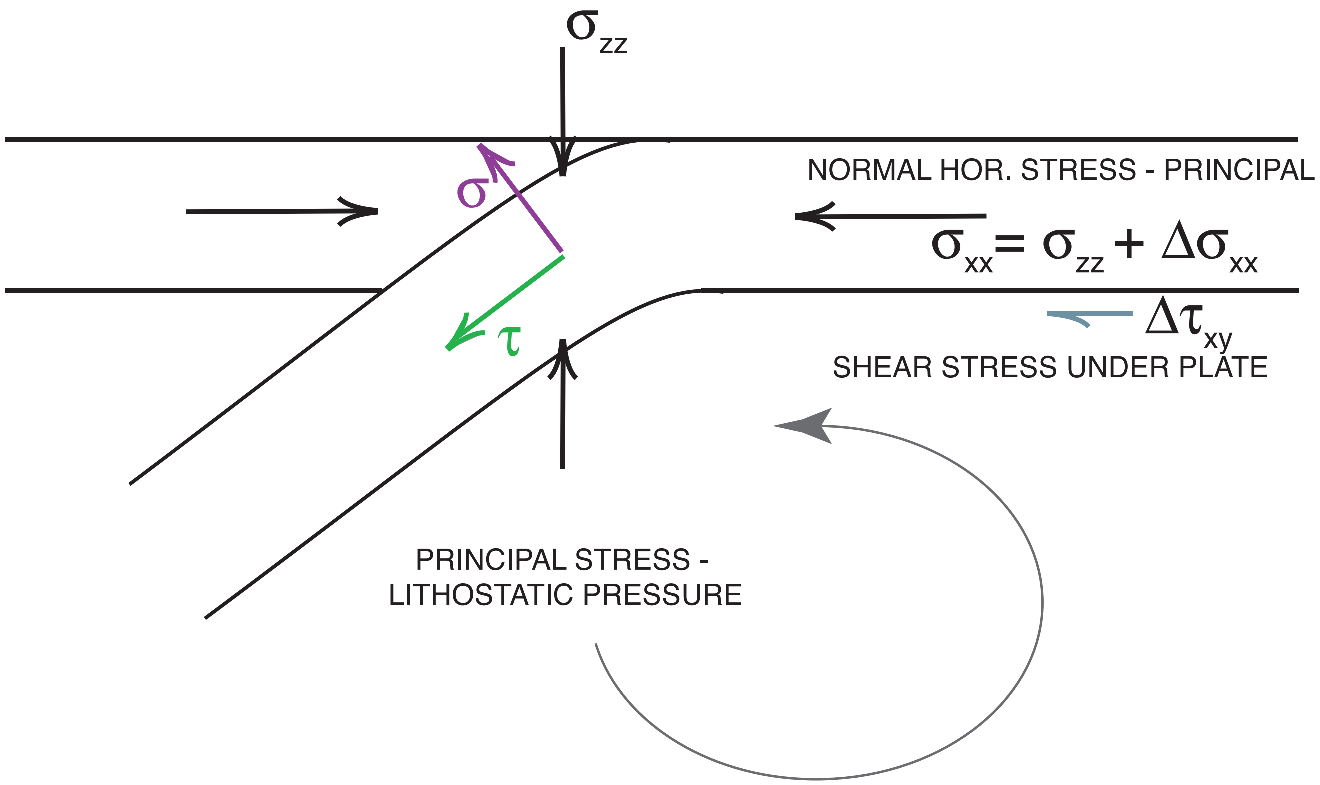
$$u \sim \kappa / D \, Ra^{1/2}$$

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

Valencia et al., 2007c

Super-Earth's: thinner plates and larger driving forces

Plate deformation:
Coulomb Failure Criterion



For deformation:

$$\frac{\tau}{\text{yield stress}} > 1$$

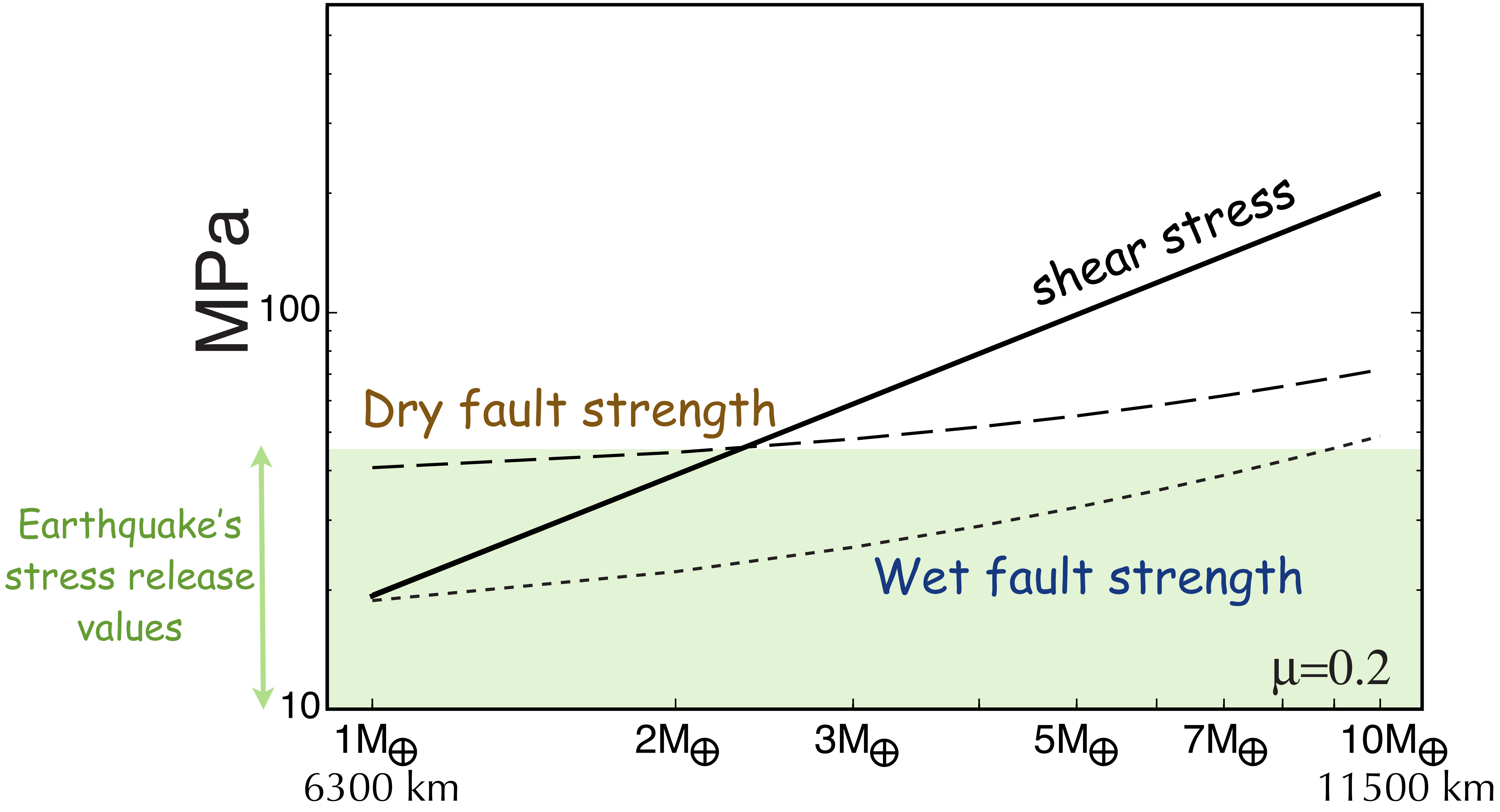
$$\tau = 0.5\,\Delta\sigma_{xx}\sin 2\theta$$

$$\sigma = \sigma_{zz} + 0.5\,\Delta\sigma_{xx}\,(1+\cos 2\theta)$$

Water reduces strength

$$\text{yield stress} = S_0 + \mu(\sigma - \lambda\sigma_{zz})$$

Stress vs. Strength on Faults

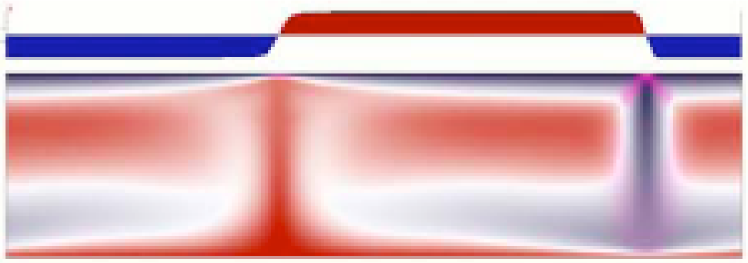


Water could
matter for Earth

but not
for super-Earths

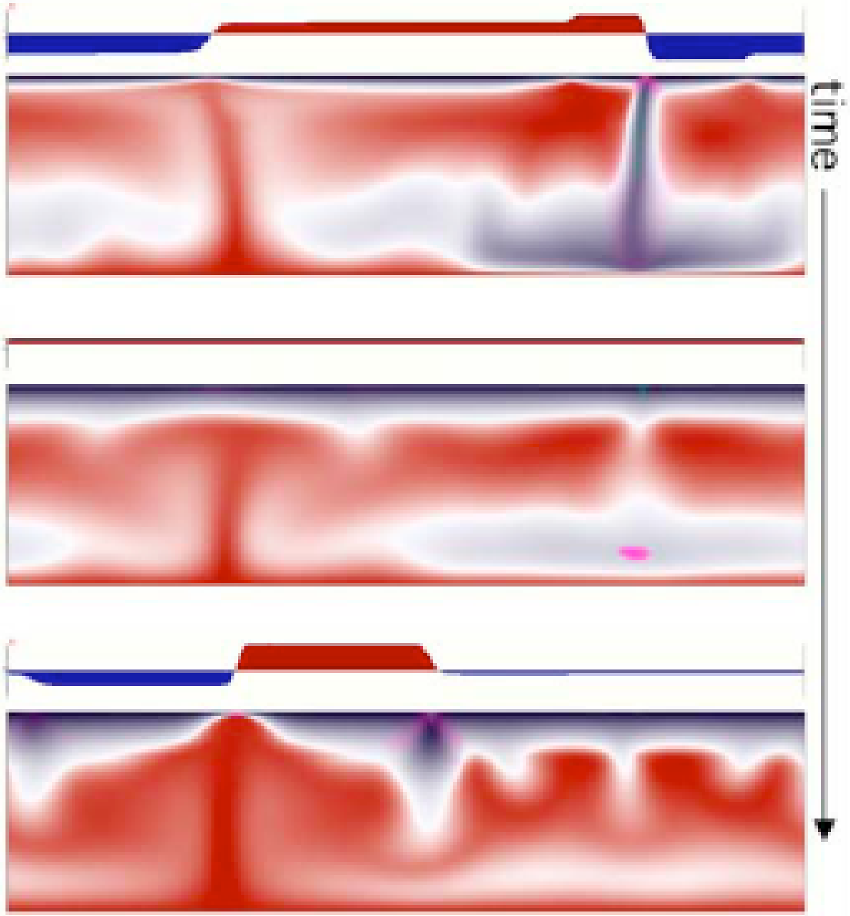
Valencia et al., 2009b

PT on super-Earths ?



Scaling Factor =1.00 ; Active

Scaling Factor = R/R_E



Scaling Factor =1.07 ; Episodic

Numerical Model by:
Moresi and Solomatov (1998)

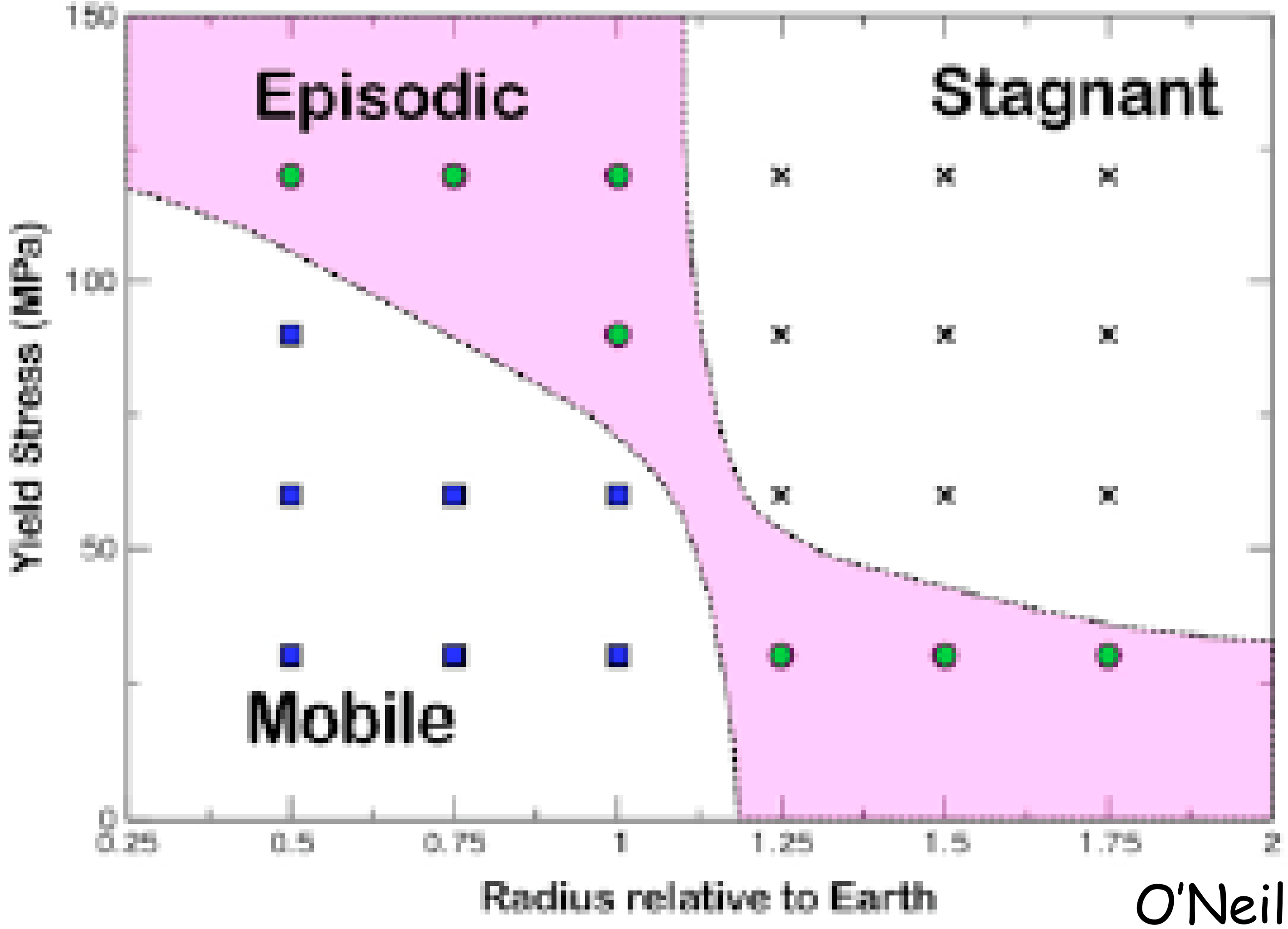
Coulomb Failure Criterion

Non-newtonian rhelogy (plateness, zones of weakness)

Scaling Factor =1.10 ; Stagnant

O'Neill & Lenardic, 2007

Plate Tectonics on super-Earths

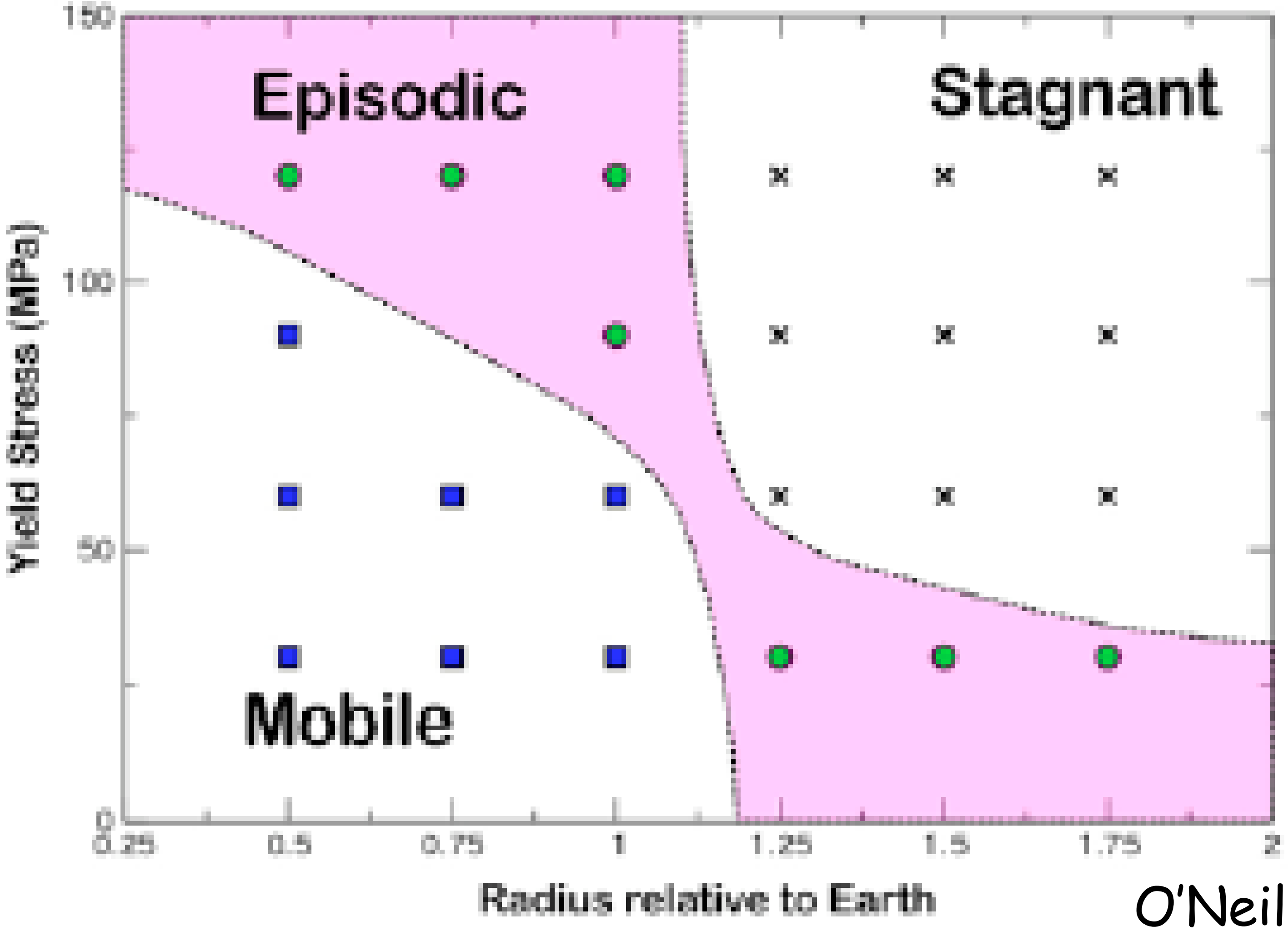


$$u \sim \kappa/D\ Ra^{1/2}$$

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

O'Neill & Lenardic, 2007

Plate Tectonics on super-Earths



O'Neill & Lenardic, 2007

$$u \sim \kappa/D \; Ra^{1/2}$$

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

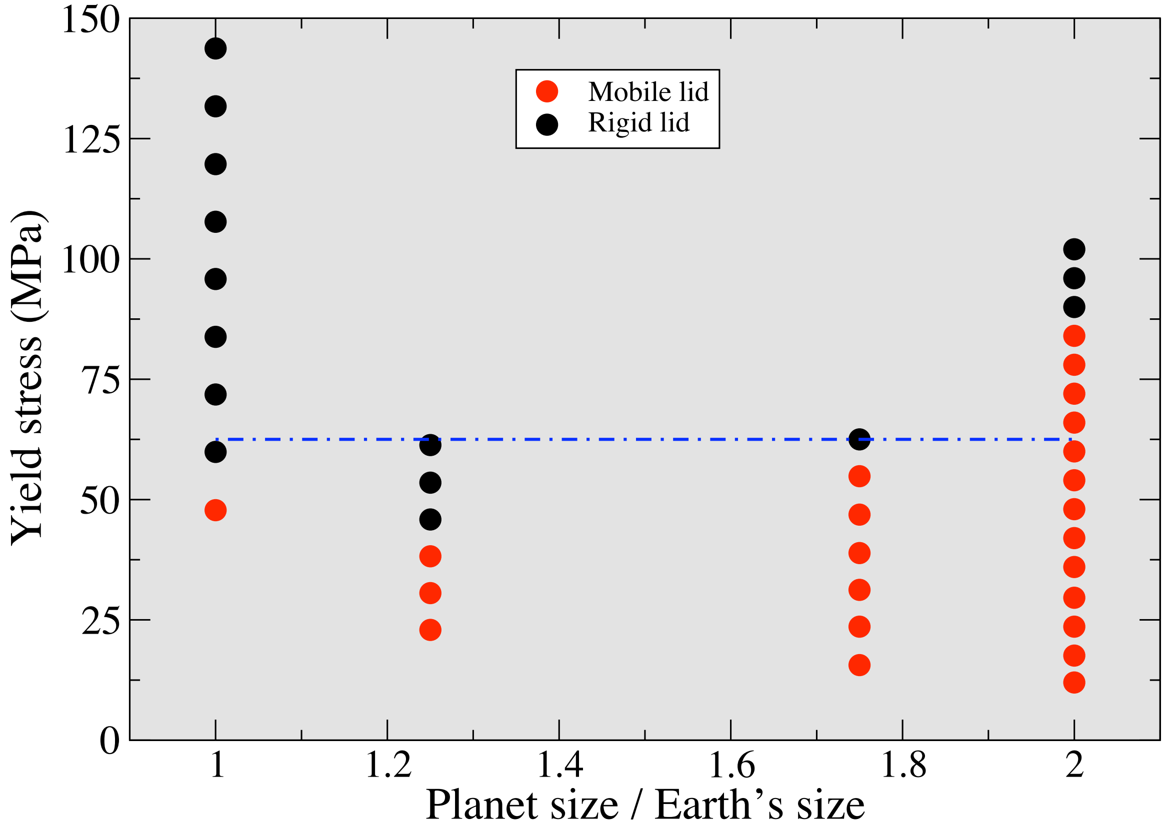
Small planets are cold and large planets are hot.

Convective stress is dominated by internal viscosity, so hotter means lower convective stress. If the yield of the lithosphere is constant, hot planets can not have plate tectonics

Other Studies

Sotin & Jackson 2009 predict a high stress/strength ratio for internally heated and mixed heated systems

Van Heck & Tackley 2009 show that for planets that are heated internally the stress/strength ratio is constant with mass, and for planets that are heated from below the ratio increases


Internally heated cases
2D spherical annulus

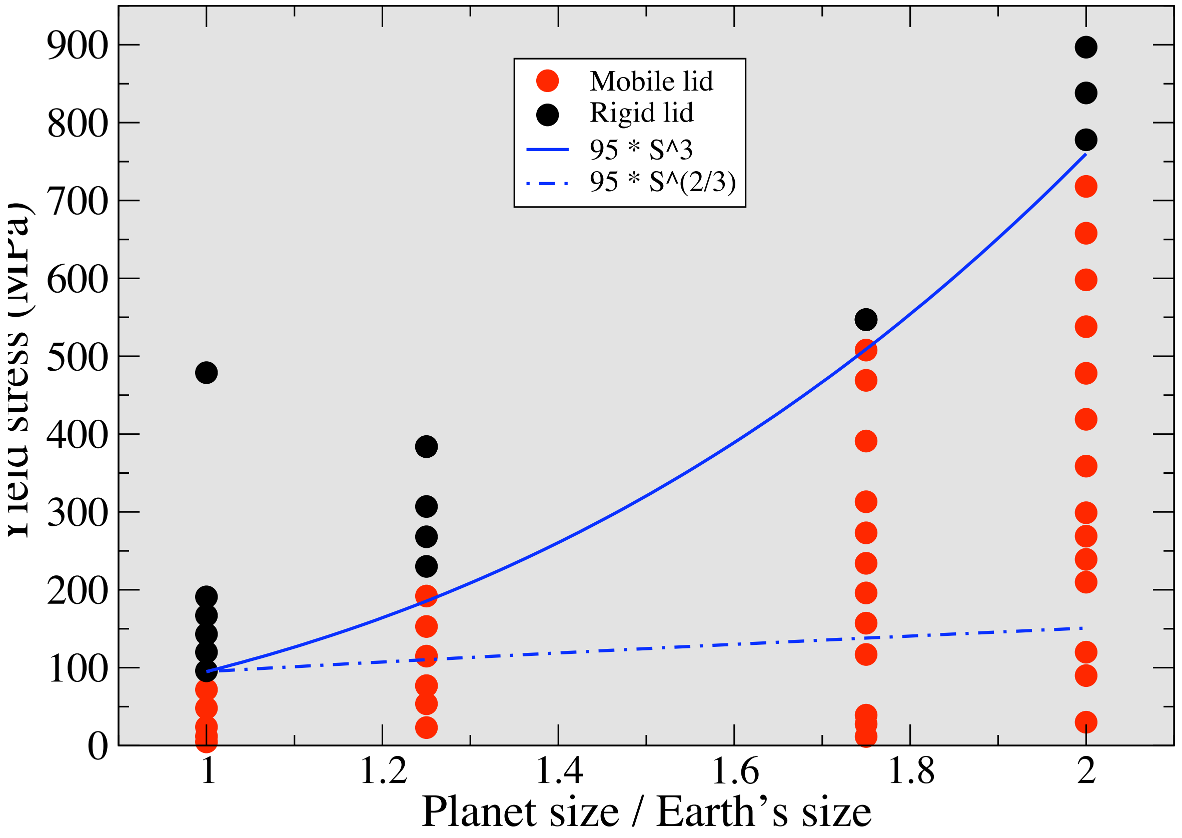
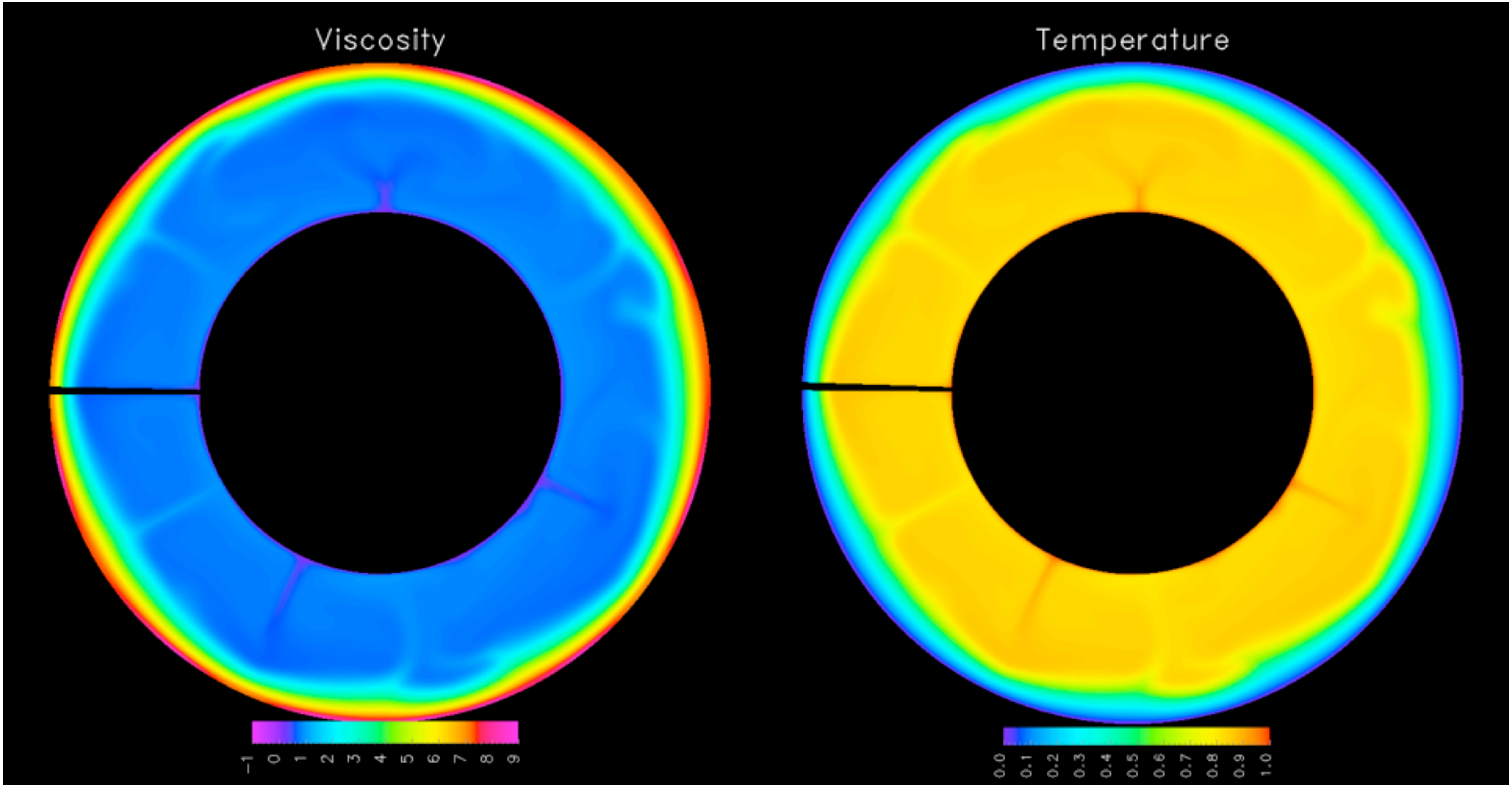

Bottom heated cases
2D spherical annulus

Plate Tectonics on Exo-Earths?

$R/R_E=2$

Van Heck & Tackley, 2009

Plate Tectonics on Exo-Earths?

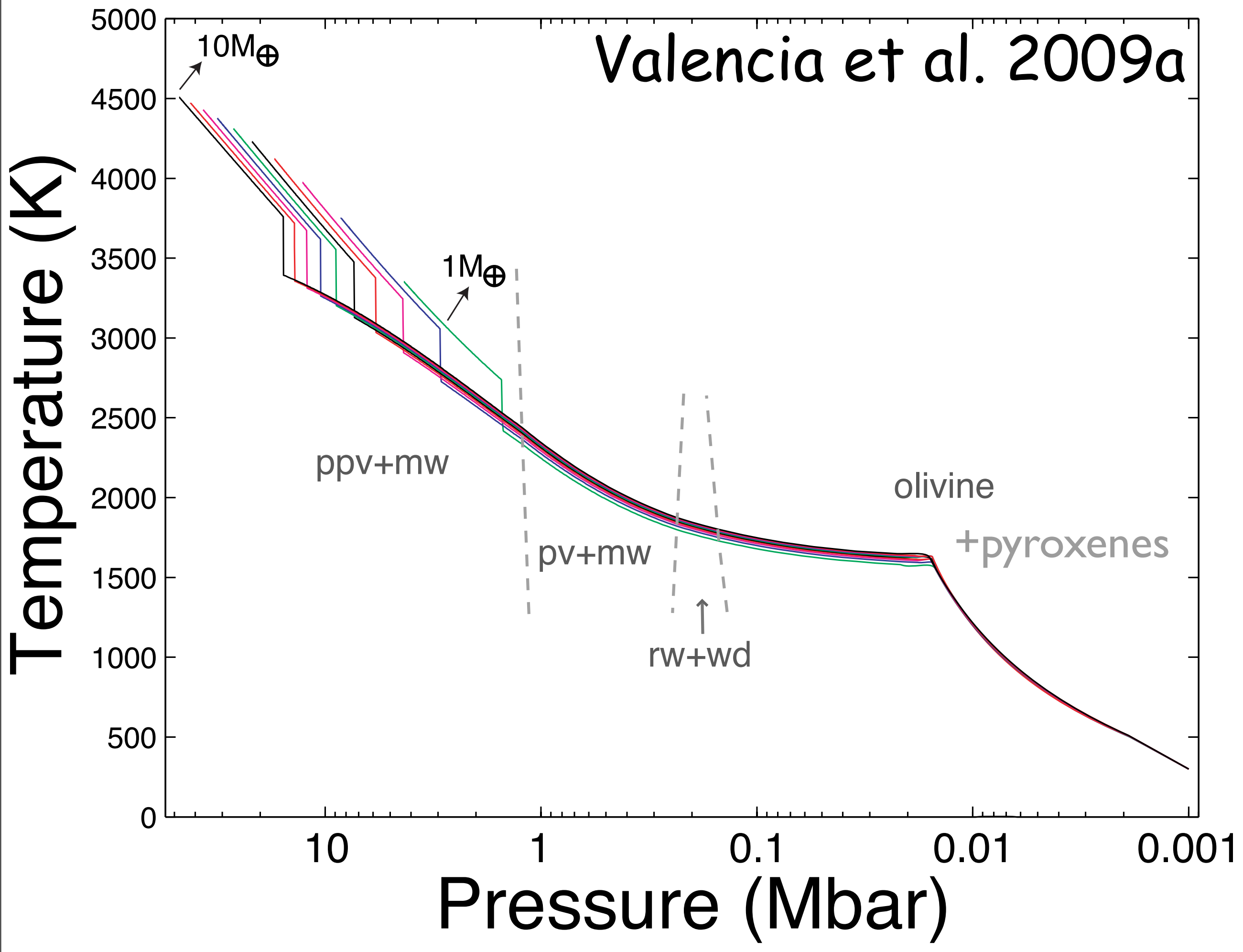


Van Heck & Tackley, 2009

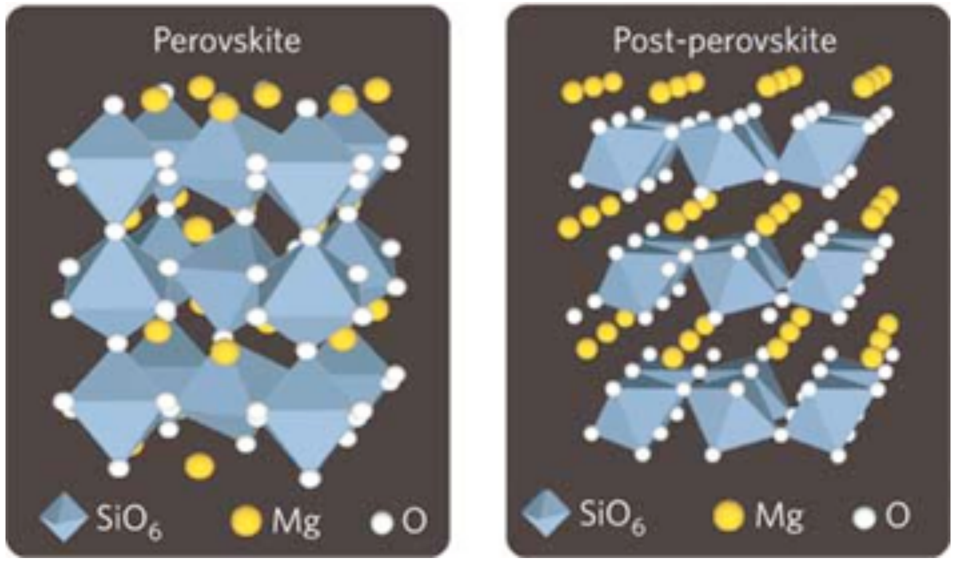
$R/R_E=2$

Additional slides

Uncertainties in the Interior



Valencia et al. 2009a



Murakami et al 2004

Super-Earths' mantles are mostly composed of PPV

What is PPV's stability region?
Are there any other phase transitions?

Virtually incompressible oxide:
$Gd_3Ga_5O_{12}$ (Mashimo et al '06)

Dissociation of silicates at high P?
MgSiO3 --> MgO + SiO2

(Umemoto et al '06)
(Grocholski et al '10 doesn't agree)