Observations & Predictions

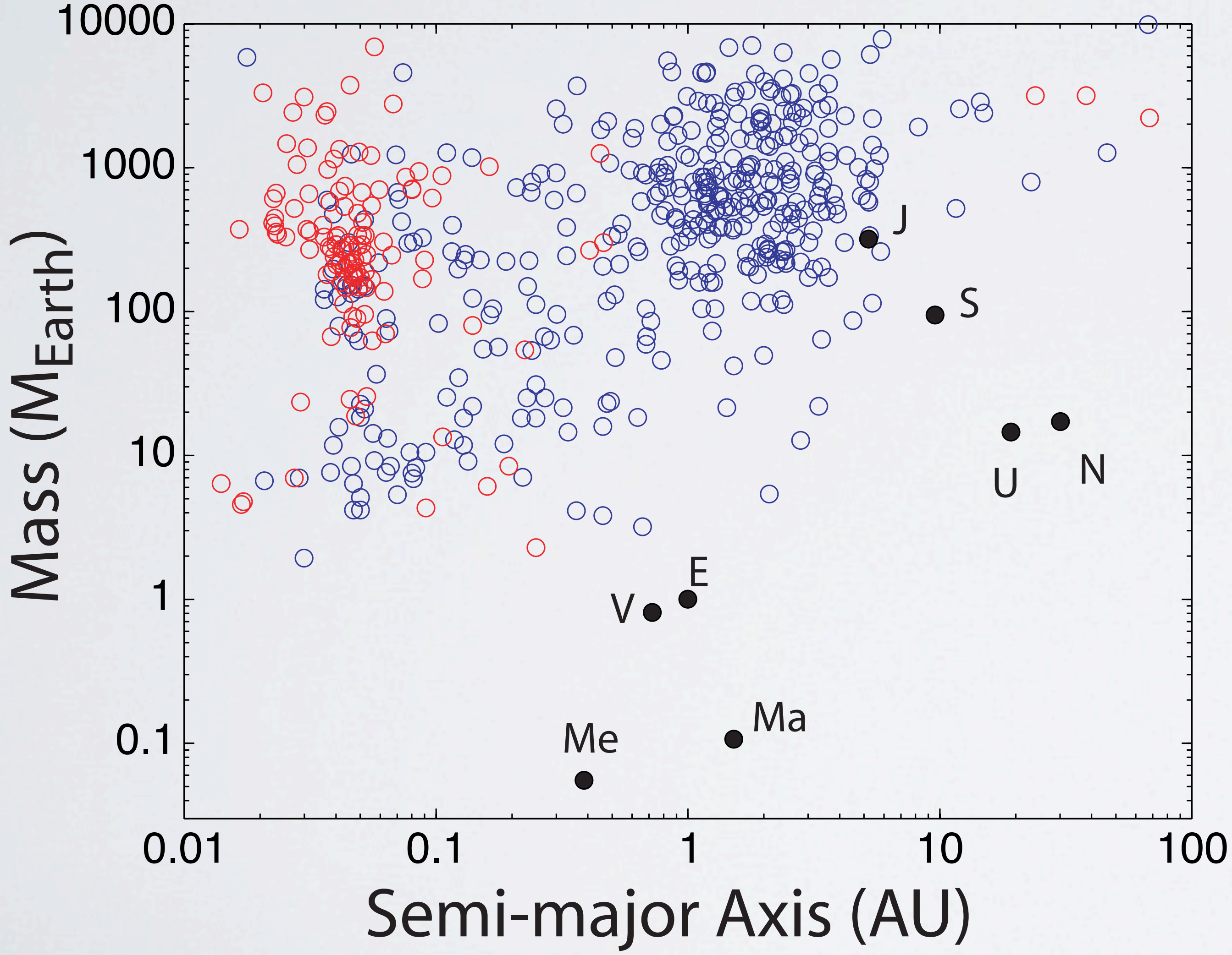
Credit: Ron Miller

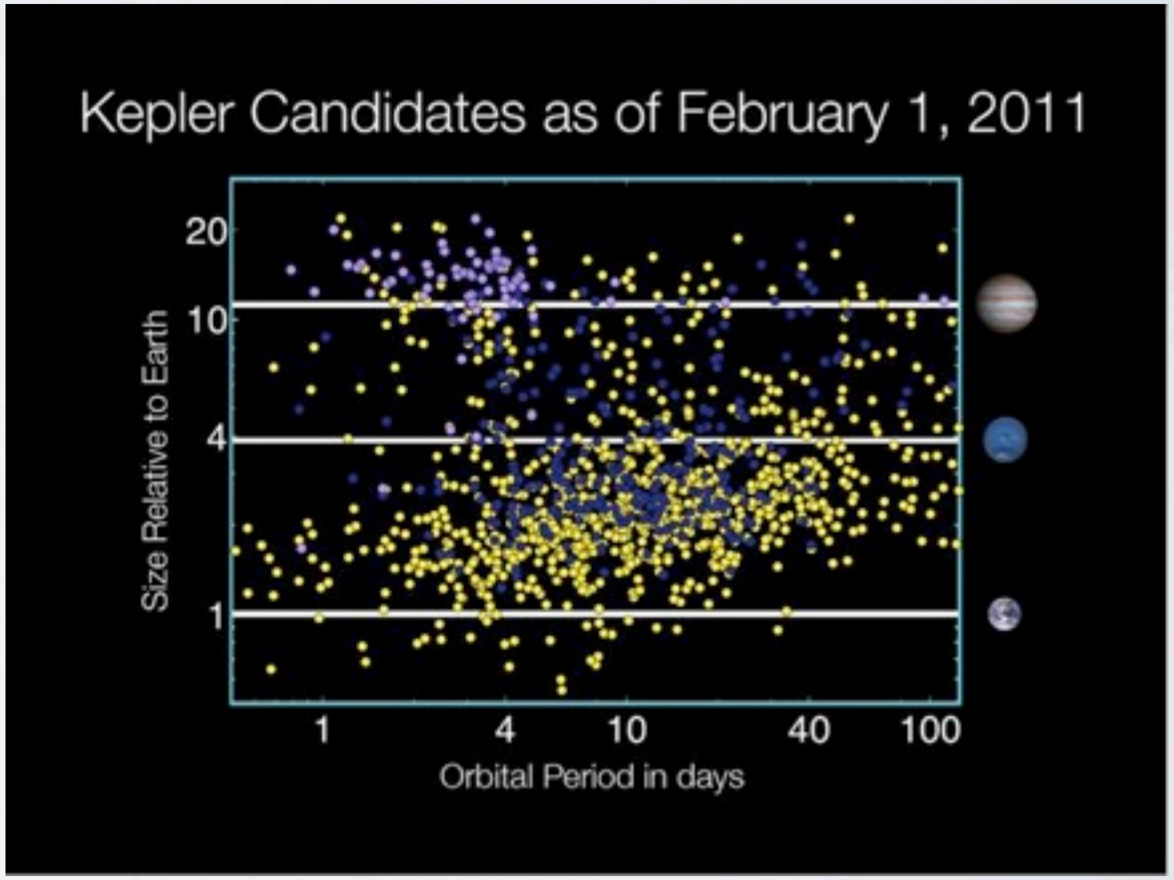
Diana Valencia
MIT

Outline
1. Overview of Observations
2. Internal Structure
3. Interior Dynamics

EXOPLANET OVERVIEW

> 750 Exoplanets and more than 2000 planet candidates!





METHODS FOR DETECTION

- Pulsar timing
- Radial velocity method
- Transit method
- Microlensing method
- Astrometry

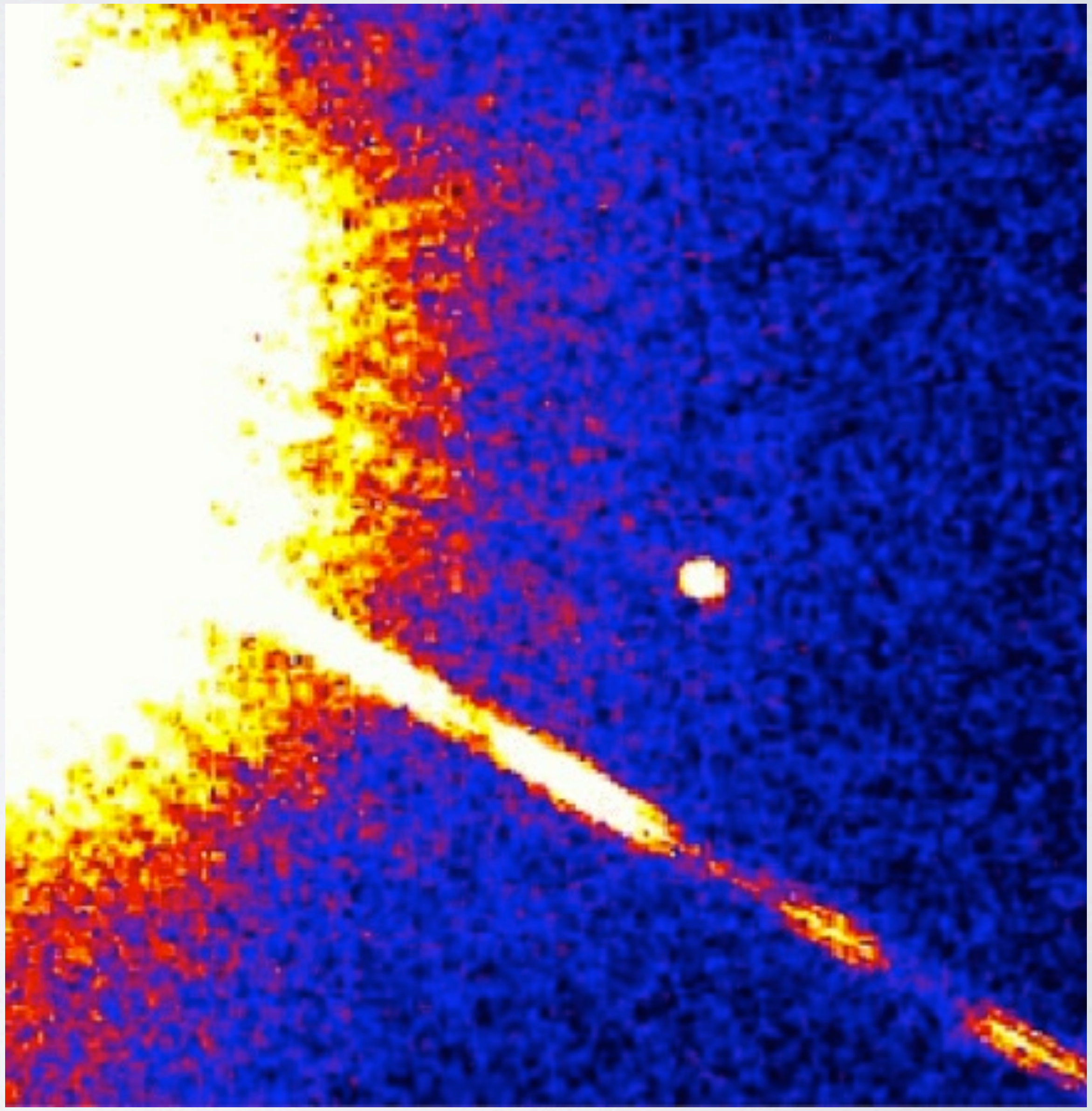
- Direct Imaging

Nearby star with faint companion "sub-star"

Earth would be:

* 50 times closer in

* 1 000 000 times fainter

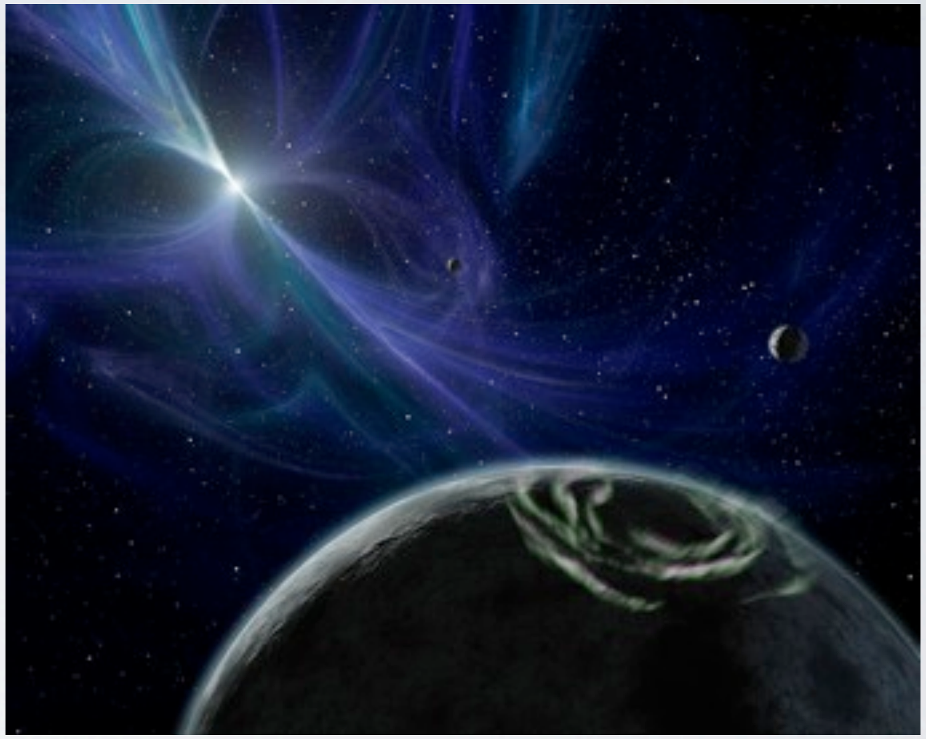


Gliese 229 and 229b - Hubble Space Telescope

PULSAR TIMING

- Timing of pulsar stars are extremely regular. However, if the star has a planet, it will perturb the motion of the star (and pulse arrival times) in a periodic manner.

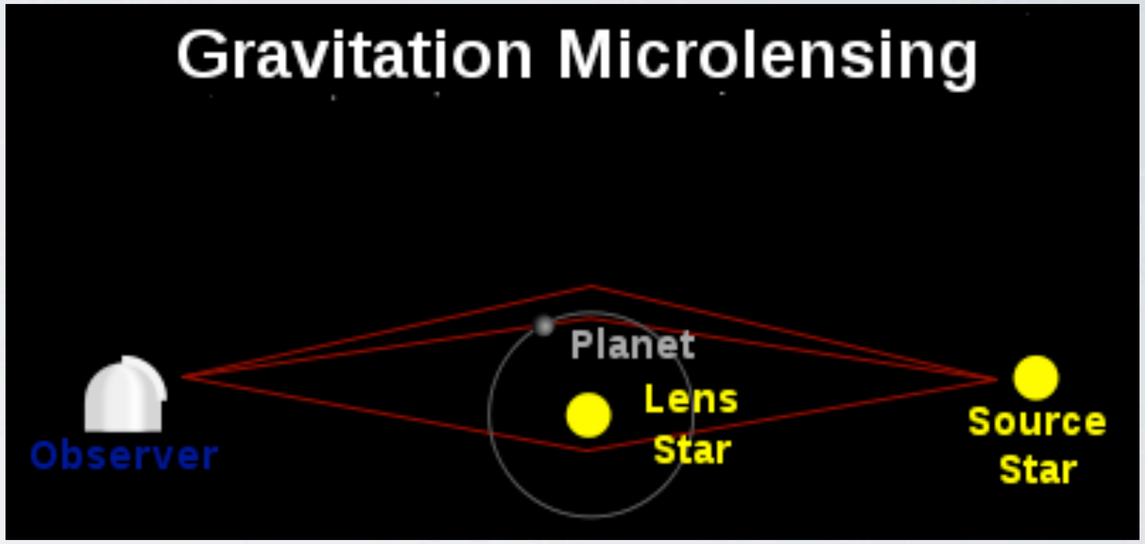
- Pulsar stars have undergone a supernova, thus it remains to be shown if the planets survived the explosion, or where formed from a secondary disk.

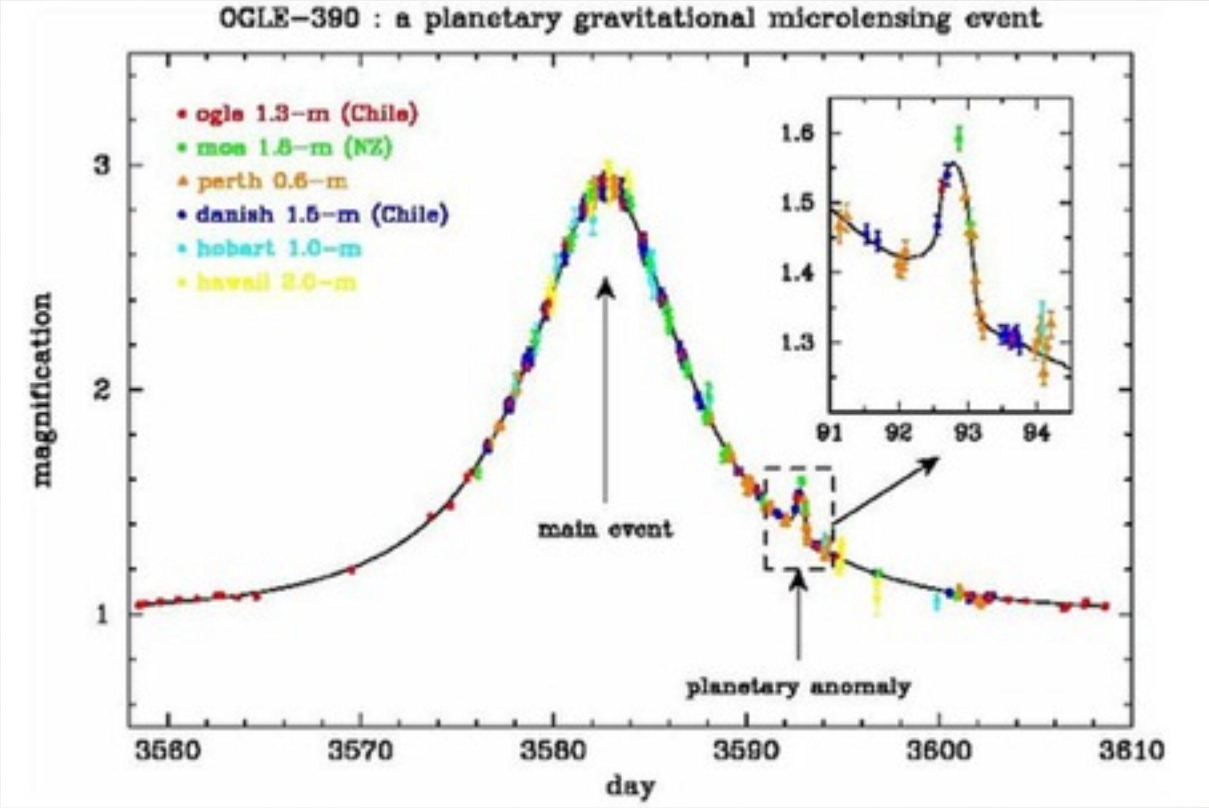


MICROLENSING METHOD

- A star that temporarily aligns with a background star will act as a lens and cause its light to 'bend' magnifying its luminosity temporarily
- If the foreground star has a planet, there will be an additional magnifying effect
- This magnification has a complicated dependency on the mass, the distance and velocity of the lens

- Pros: Can detect long-period and small planets
- Cons: Often no follow-up, only mass of the planet, and orbital distance can be deduced

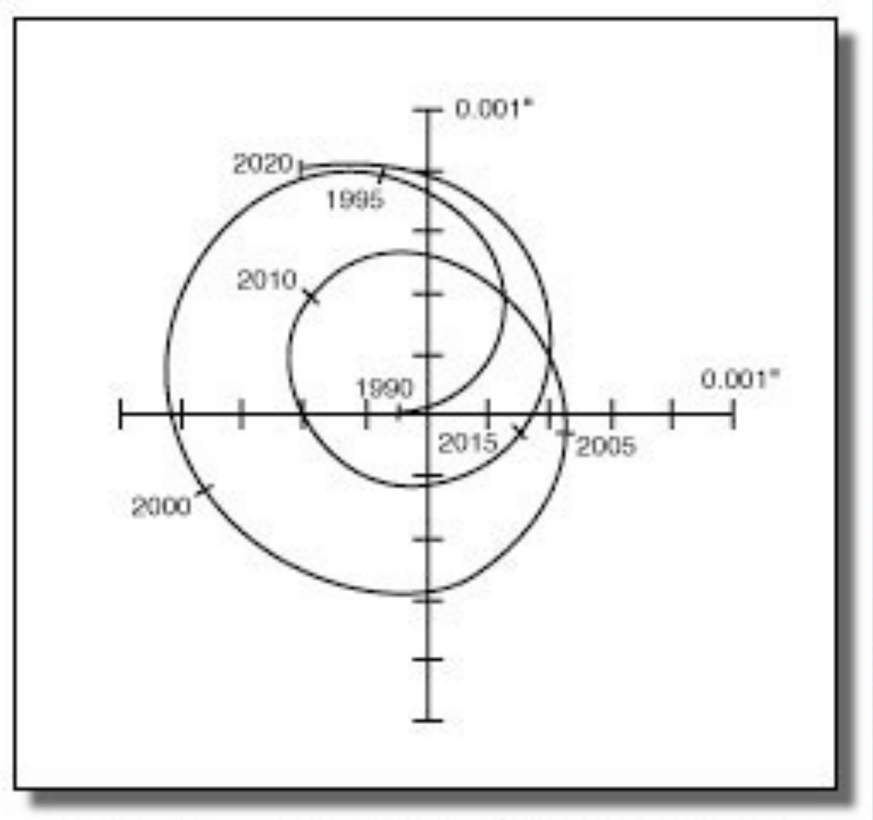




Beaulieu et al 2006

ASTROMETRY

- The gravitational effect of a planet on the host star will change its position on the sky
- No planets have been detected this way yet

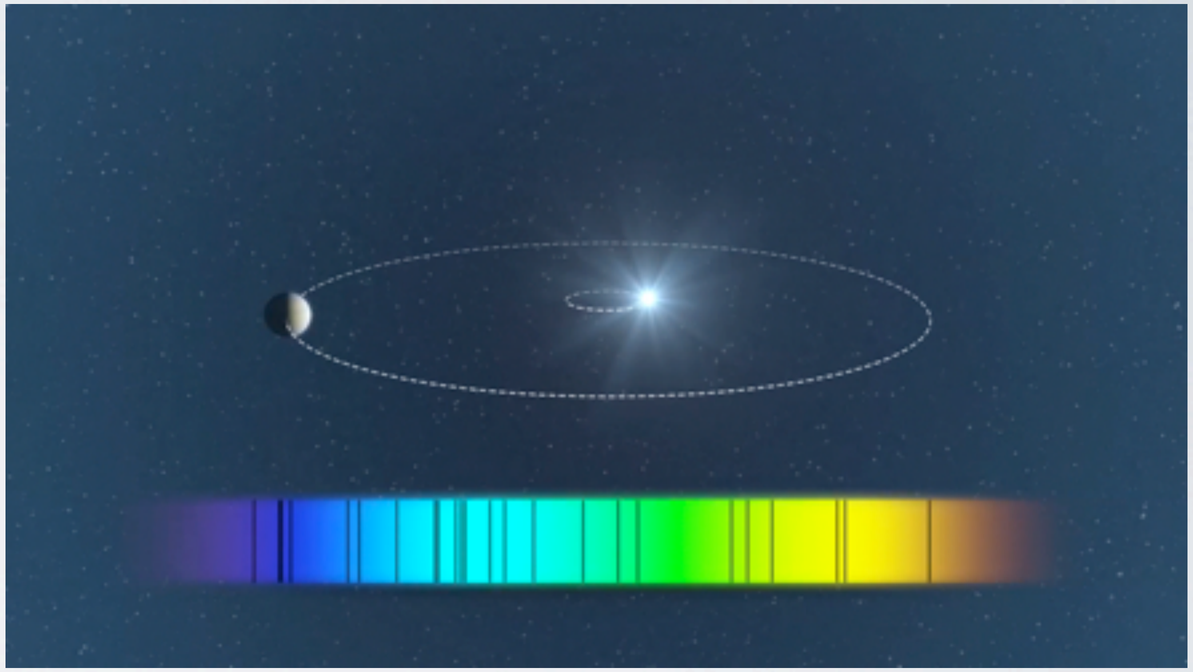


The motion of the sun due to Jupiter as seen from 10pc away

From http://sim.jpl.nasa.gov/science/planet.html

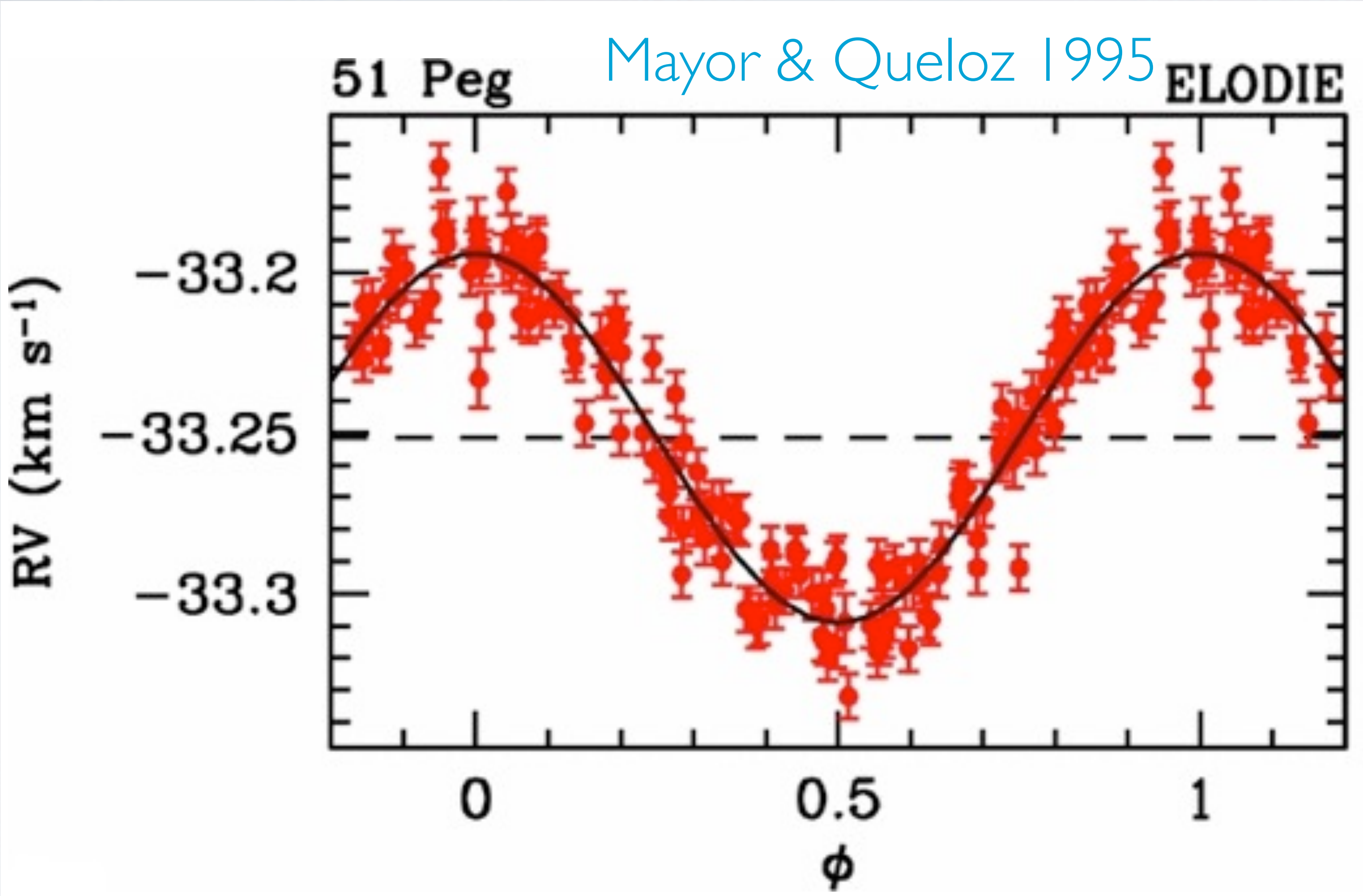
RADIAL VELOCITY

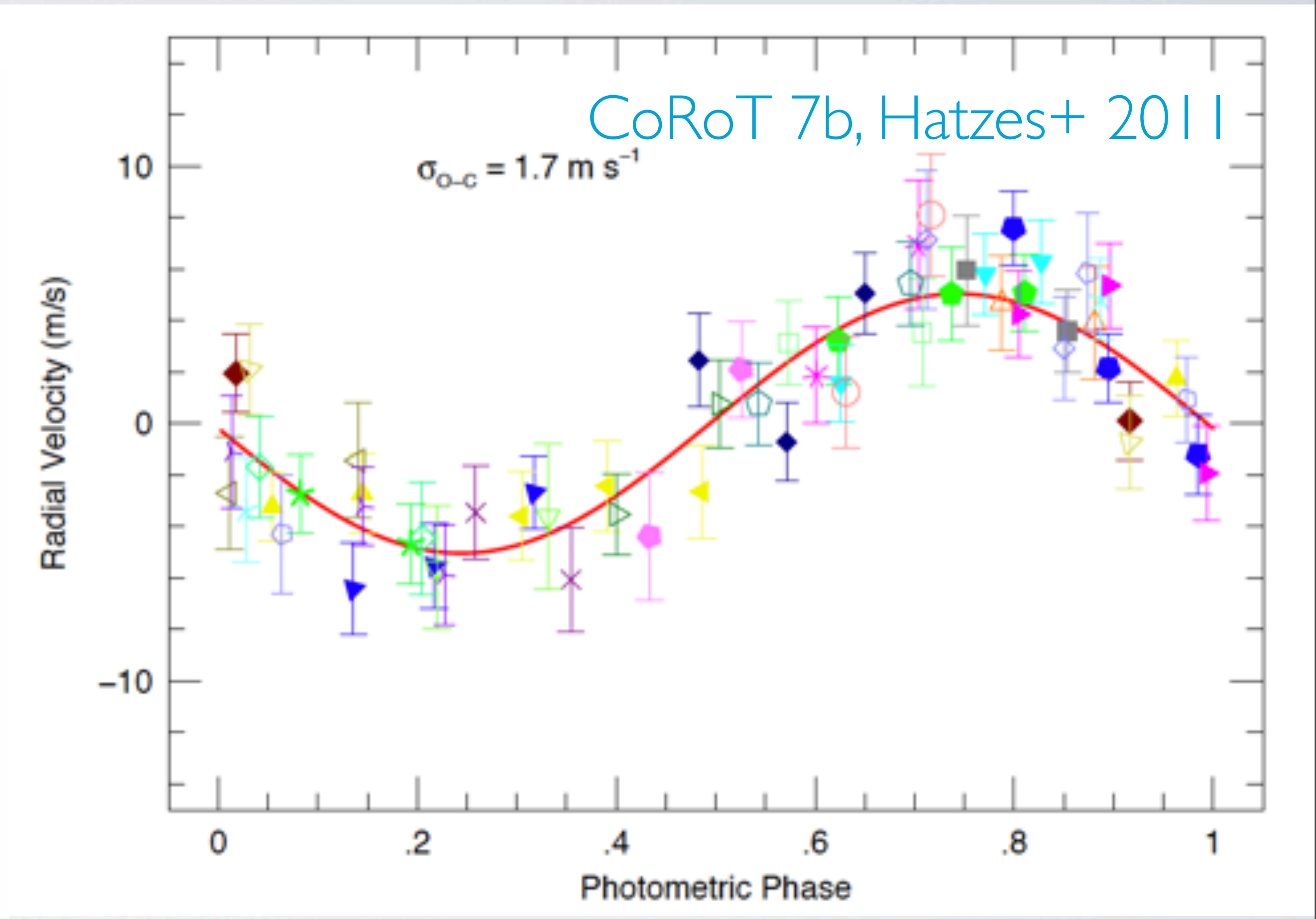
- A multi-body system will orbit around the center of mass. A star with a planet will have a periodic motion (or 'wobble') with respect to an observer
- The more massive and closer the planet is to the star, the stronger the signal
- The current detection limit is at 1m/s
- Pros: Repeatable, no need to go to space, yields no false positives
- Cons: Measures minimum mass



$$K_1 = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

RADIAL VELOCITY

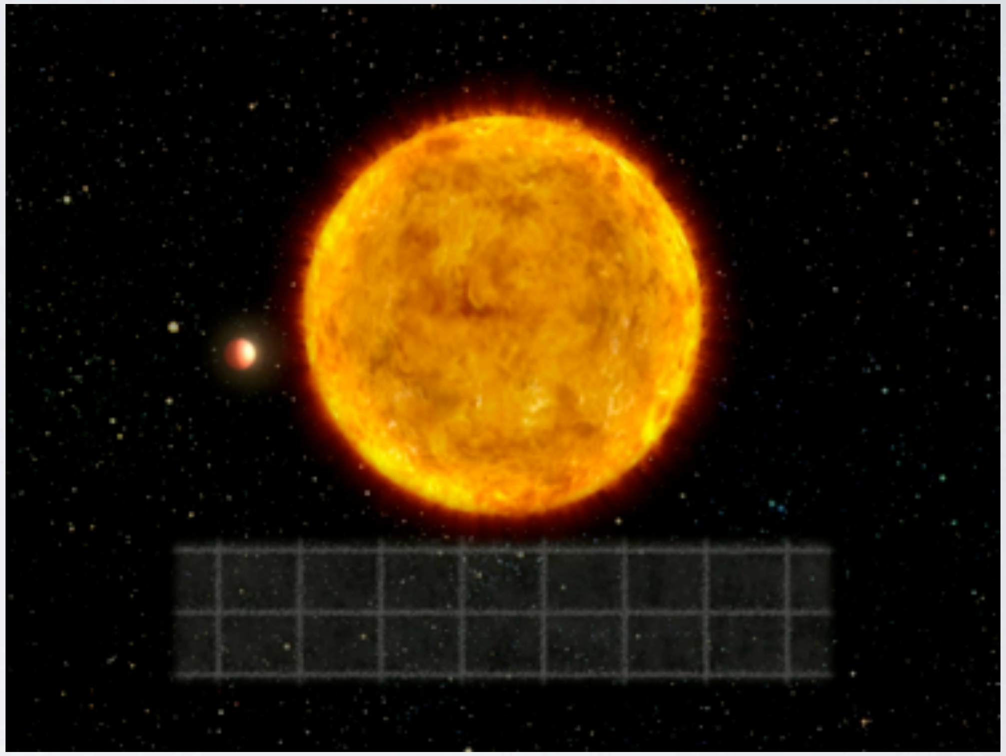

Mayor & Queloz 1995


CoRoT 7b, Hatzes+ 2011

Jupiter @ 0.1 AU : 30 m/s
Jupiter @ 1 AU : 13 m/s
Neptune @ 0.1 AU : 5 m/s
Neptune @ 1 AU : 1.5 m/s
Super-Earth (5 M_E) @ 0.1 AU : 1.4 m/s
Super-Earth (5 M_E) @ 1 AU : 45 cm/s
Earth : 10 cm/s

TRANSIT METHOD

- A transiting planet will periodically block part of the luminosity of the host star. This drop in luminosity is proportional to the ratio of planet to star radii.
- Larger, short-period planets will produce a bigger effect

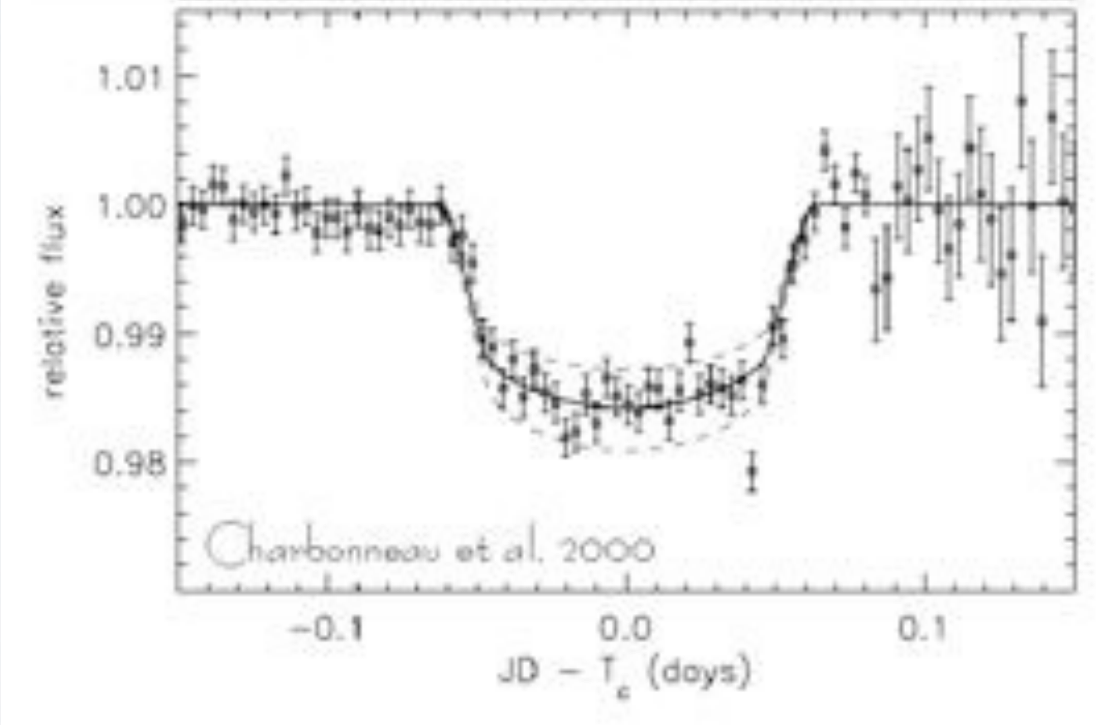


- Pros: Repeatable, yields actual size and configuration of the system (sin i), can yield also mass if there are TTVs caused by other planets
- Cons: has several false positives, need to go to space to detect small planets, information on the radius of the star is critical

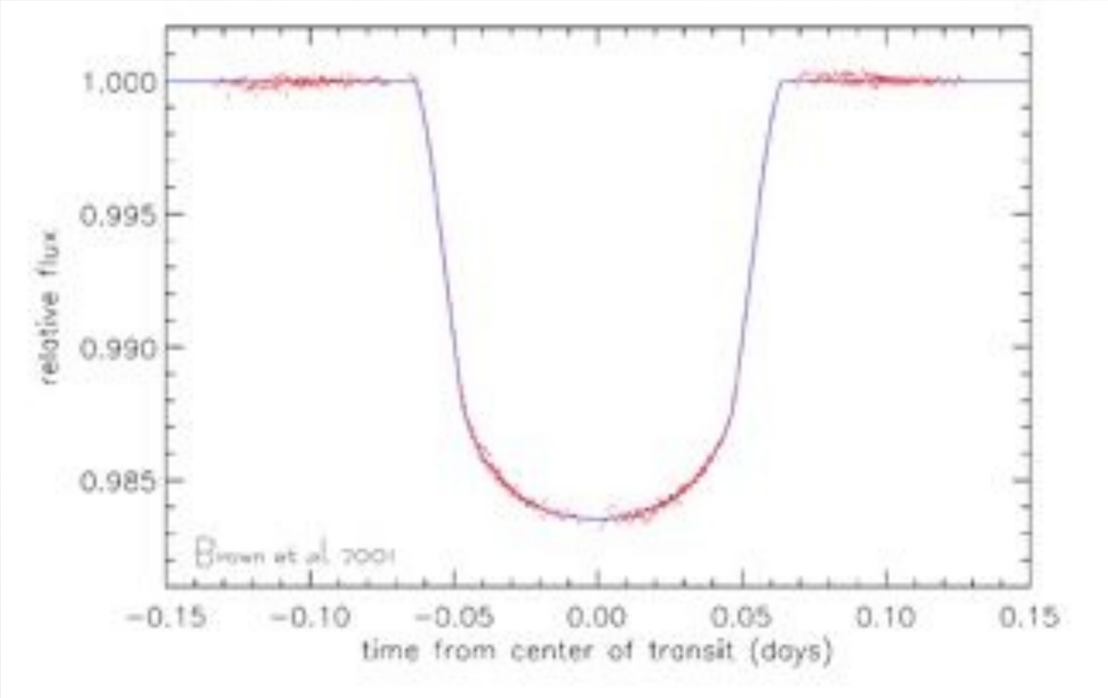
TRANSIT METHOD

HD209458b: exojupiter

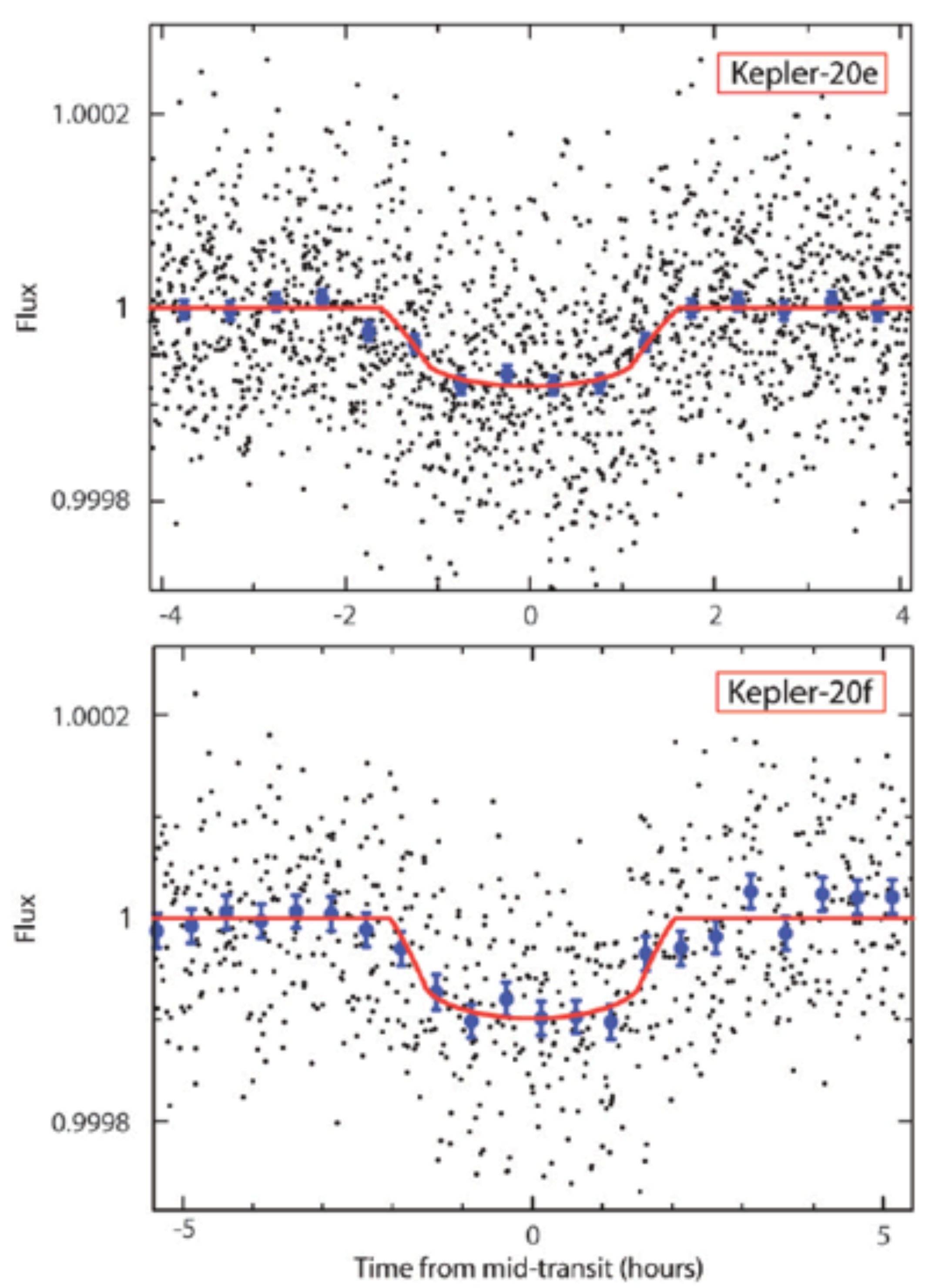
Charbonneau et al 2000



with HST



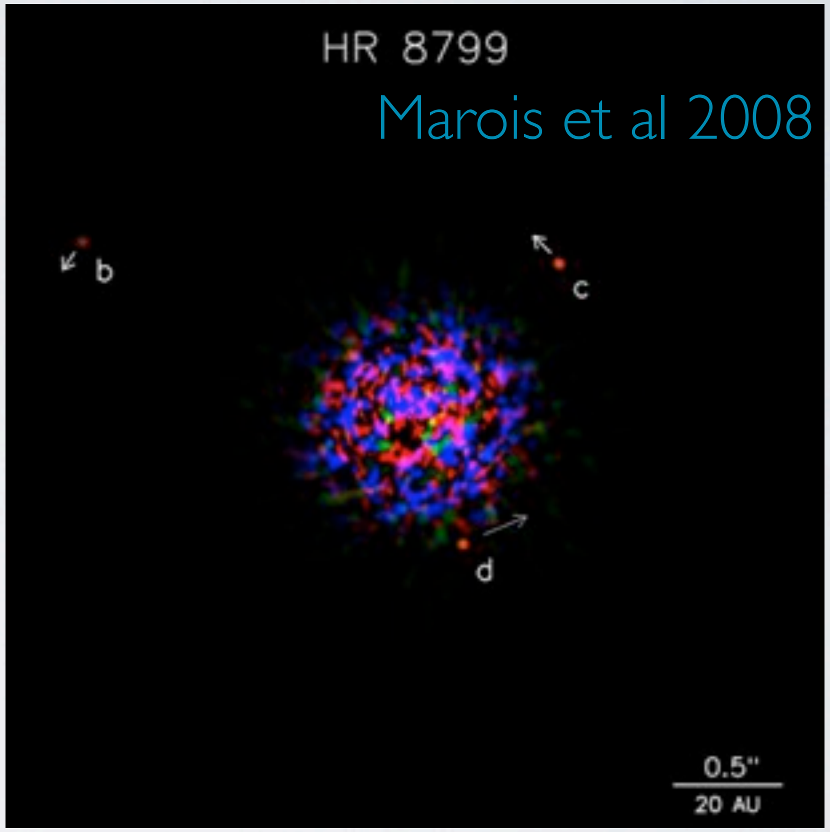
Kepler 20e & f: sub-earth sized



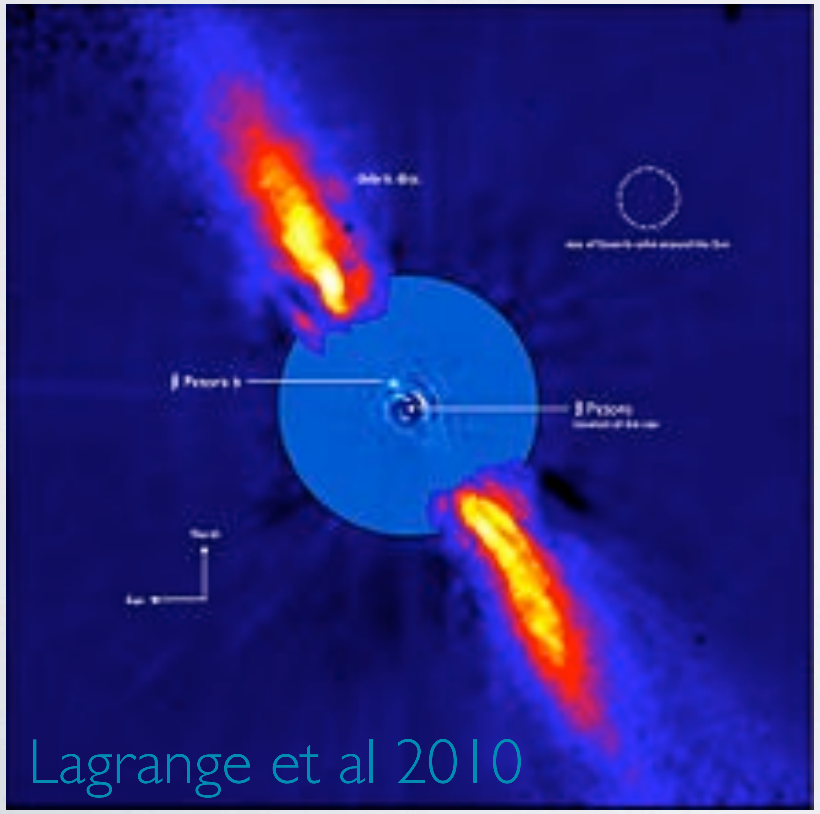
Fressin et al 2011

DIRECT DETECTION

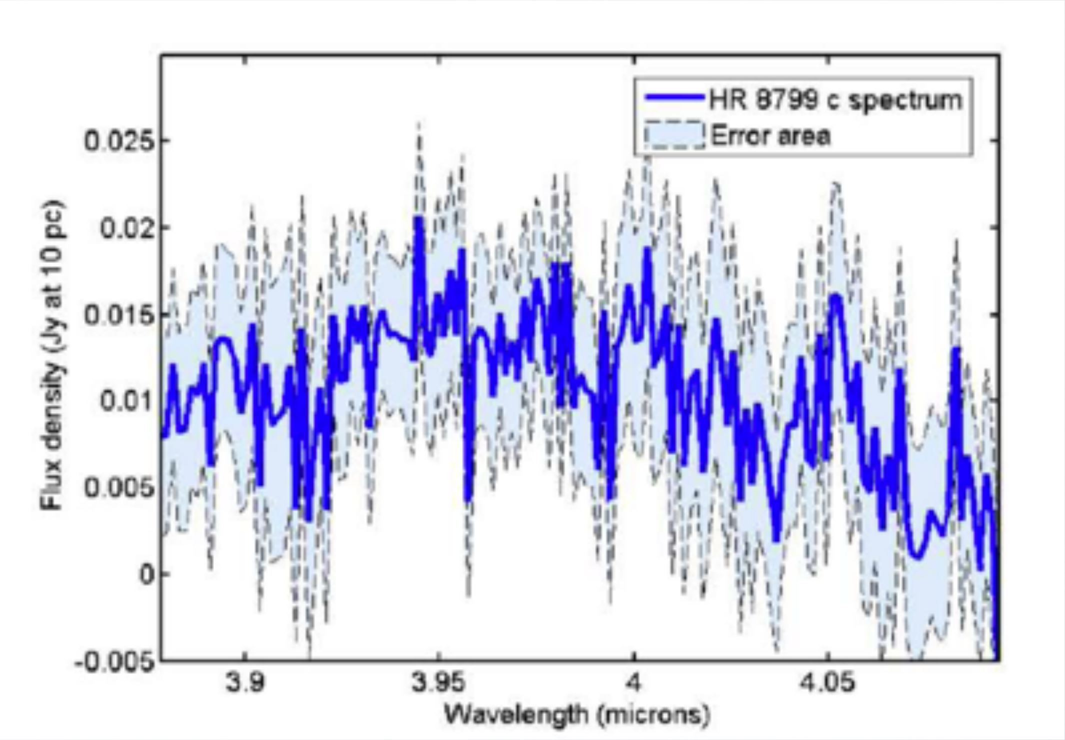
- The challenges posed by this method is that planets are too dim and difficult to spatially resolve from the host star
- The best candidates are bright (young) planets that are far away from the star
- New observational techniques have yielded ~a few planetary systems



Marois et al 2008

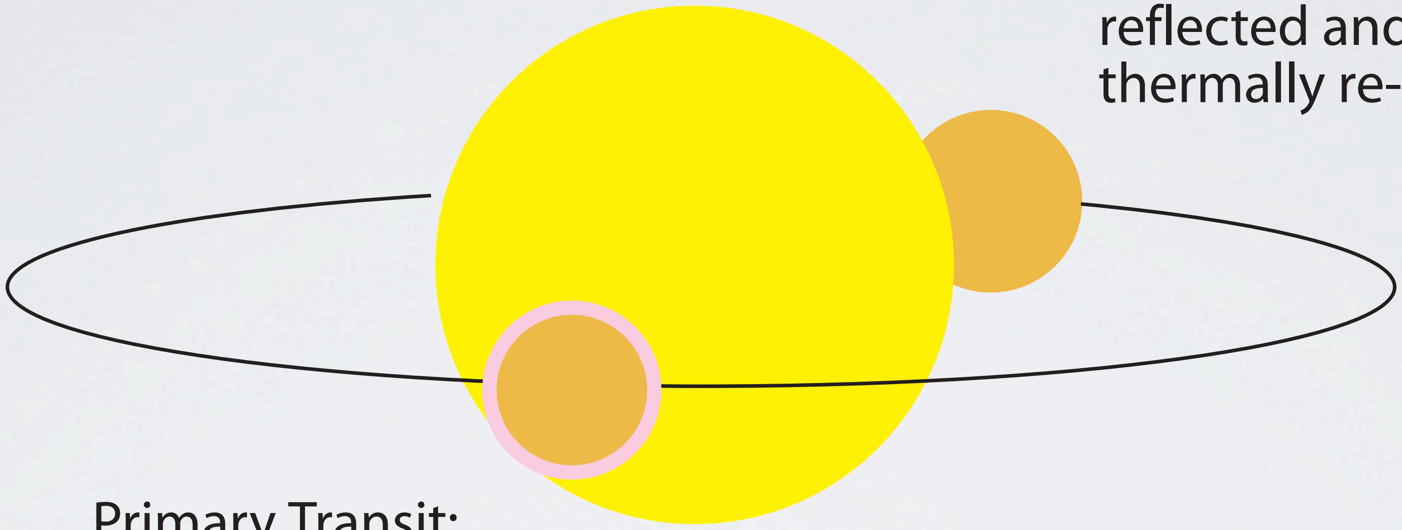


Lagrange et al 2010



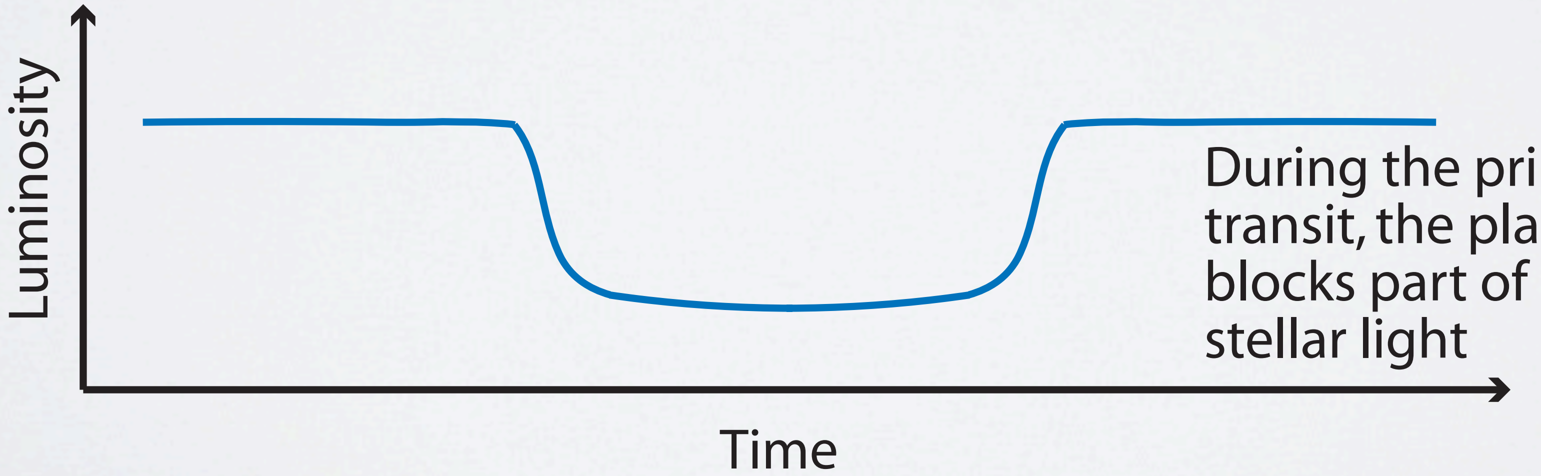
Janson et al 2010

TRANSIT METHOD OPPORTUNITY



Secondary Transit:
starlight is partly
reflected and partly
thermally re-emitted

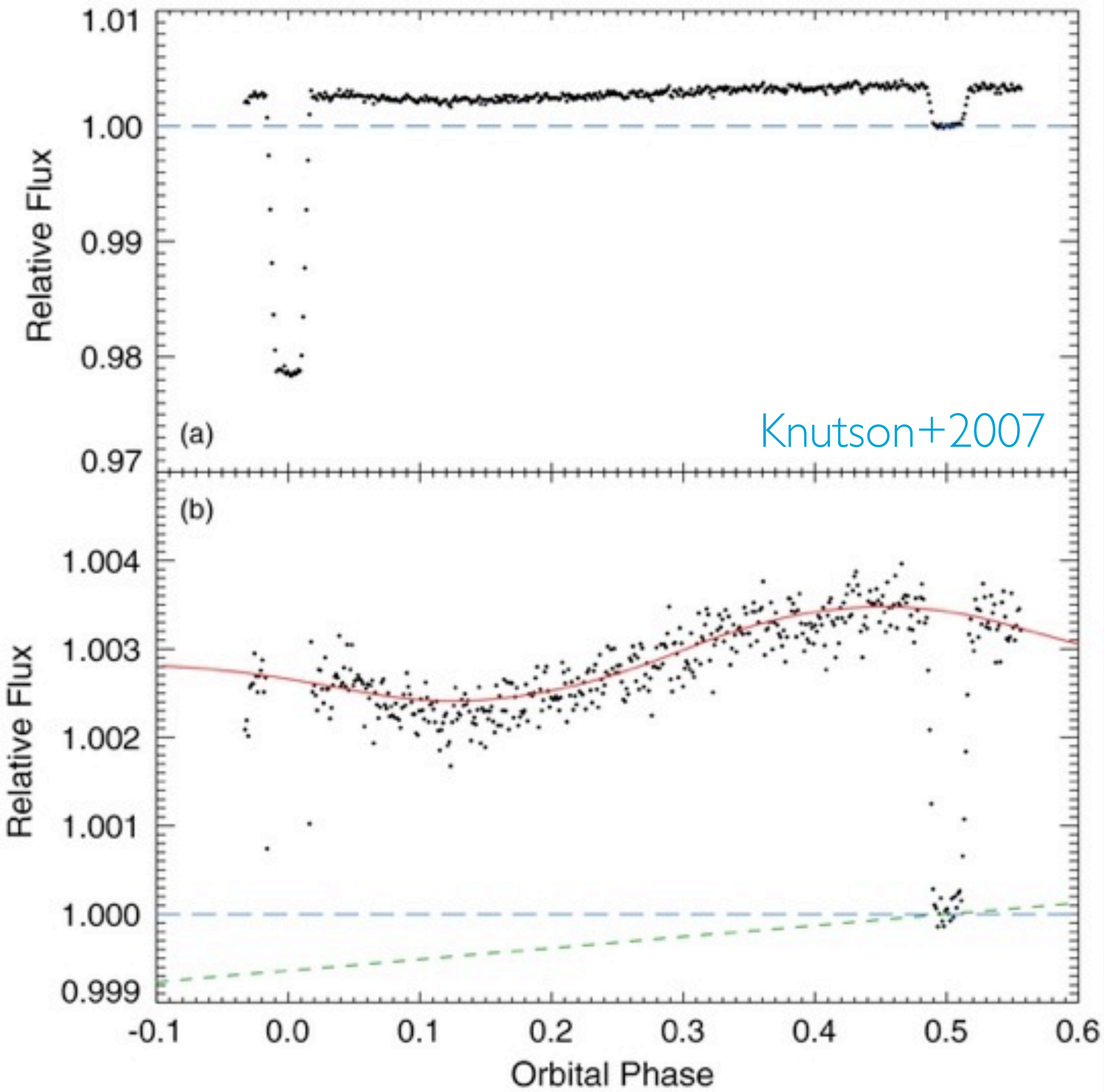
Primary Transit:
starlight passes through
the planet's atmosphere
(transmission spectrum)

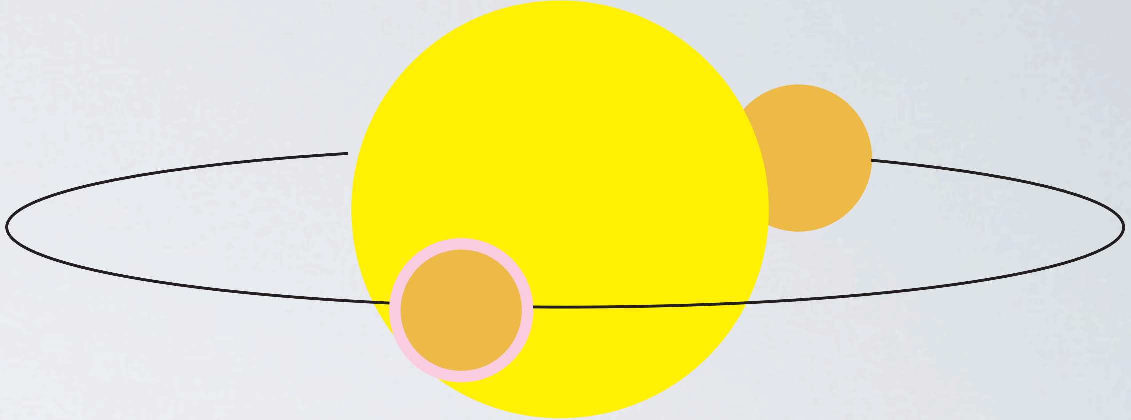


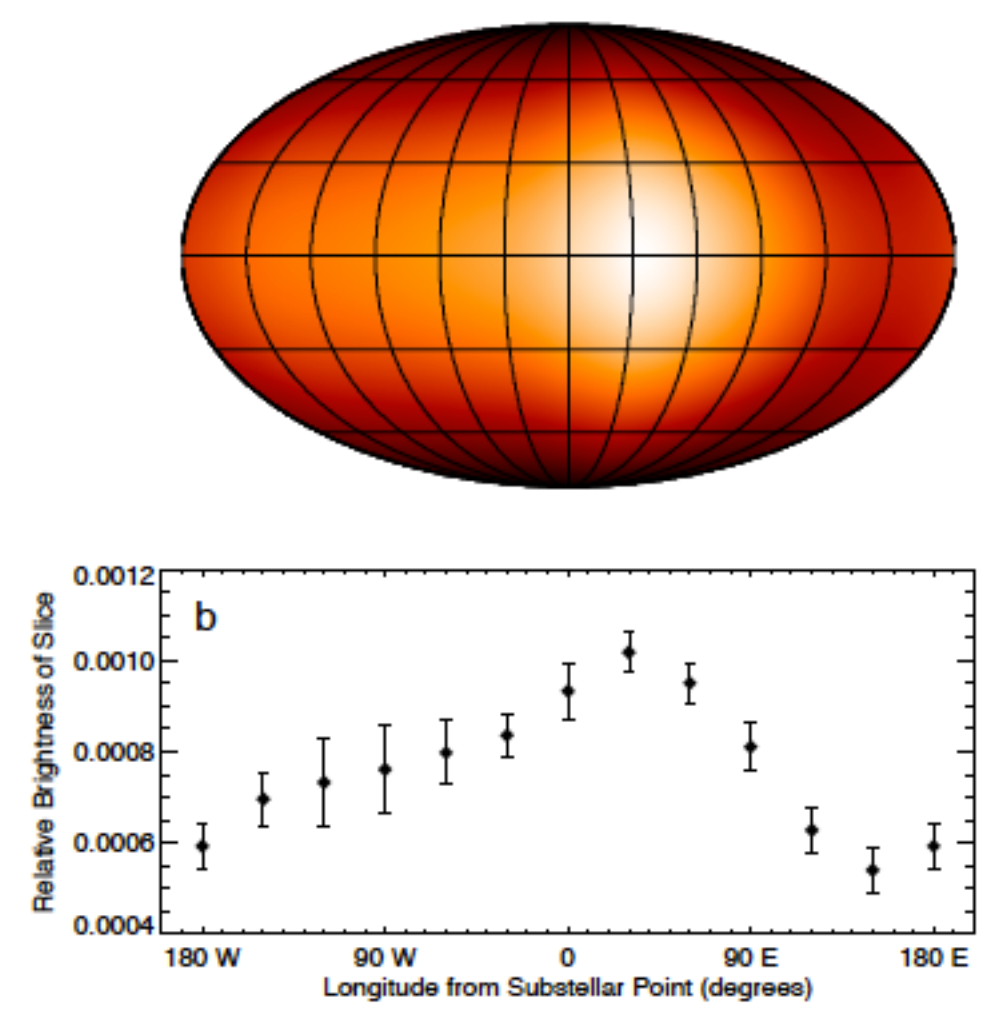
During the primary
transit, the planet
blocks part of the
stellar light

PHASE CURVES

HD 189733b

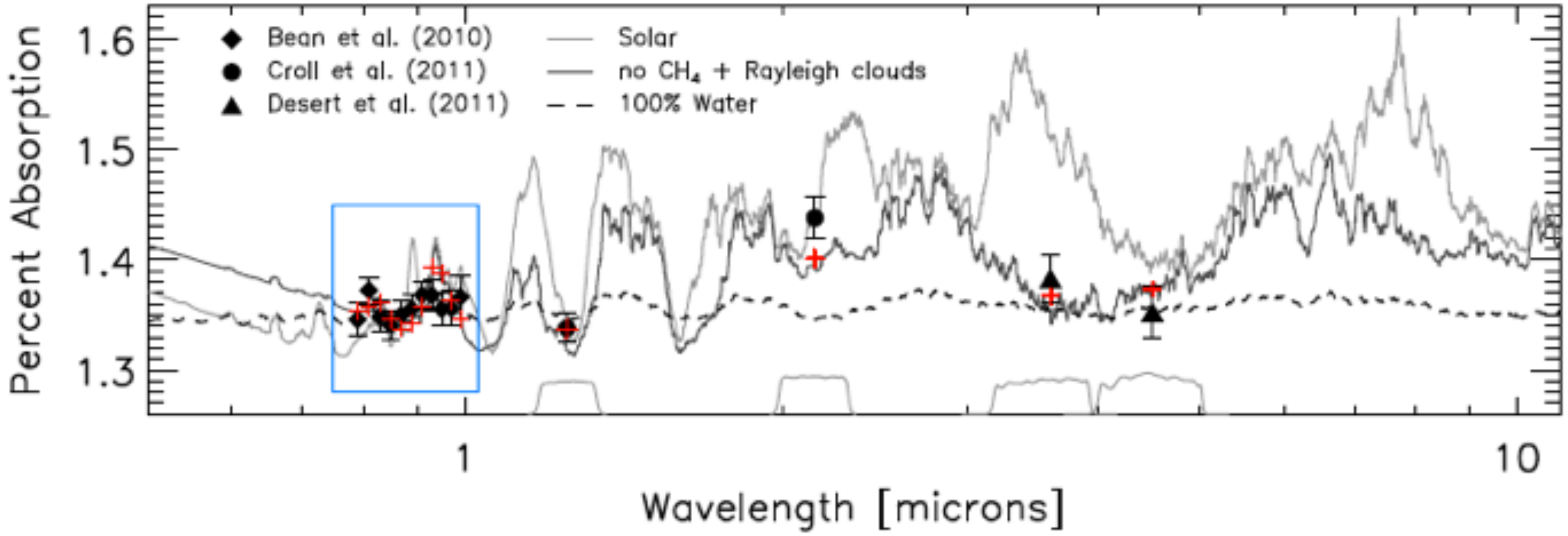

Knutson+2007





PROBING EXOPLANET ATMOSPHERES

GJ 1214b: a 2.7 R_{Earth} planet @ 0.01 AU



Bean et al. 2011, Croll et al. 2011, Dessert et al. 2011, Crossfield et al. 2011, Mooij et al. 2011, Berta et al 2011

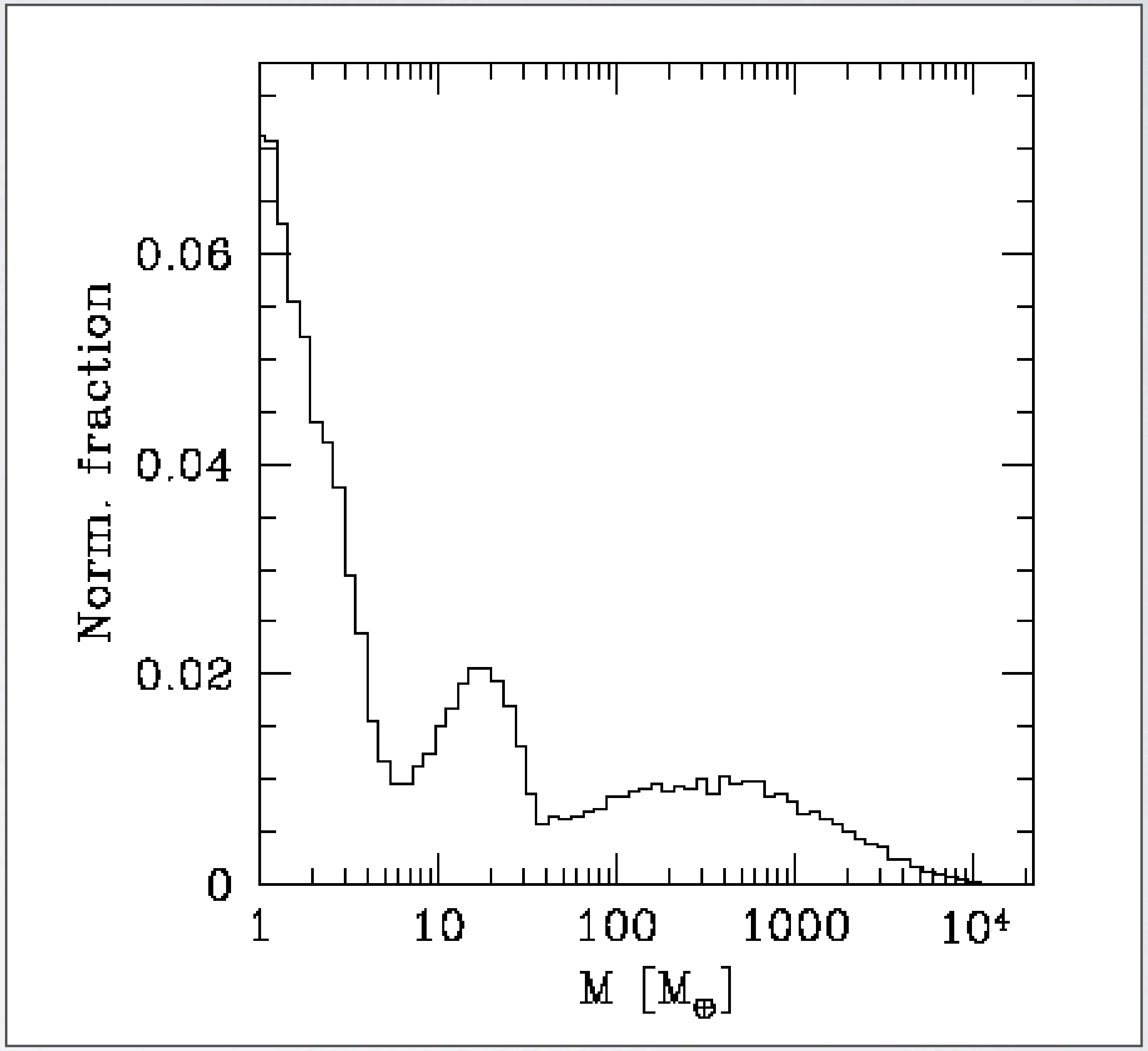
A promising future with ELTs and proposed space missions (Echo, Finesse)

MORE EXOTIC OBSERVATIONS

- Exo-moons (Kipping, 2009)
- Specular reflection from an ocean (Williams and Gaidos, 2008)
- Regional spectroscopy (Palle et al. 2008)
- ......

SMALL PLANETS ARE ABUNDANT

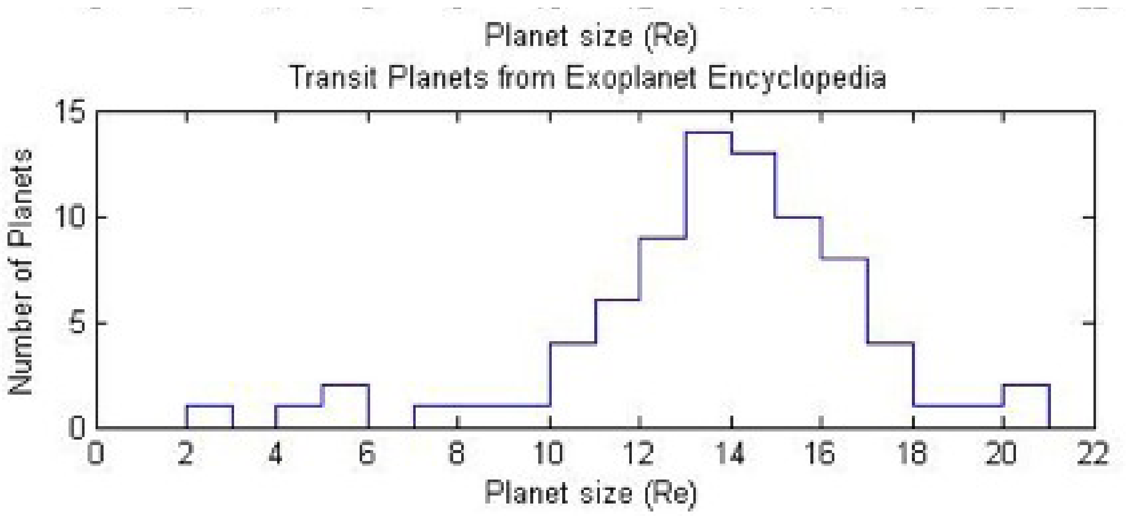
- Planet formation models have predicted a larger number of low-mass planets relative to more massive ones



Mordasini et al. 2009, also models by Ida & Lin

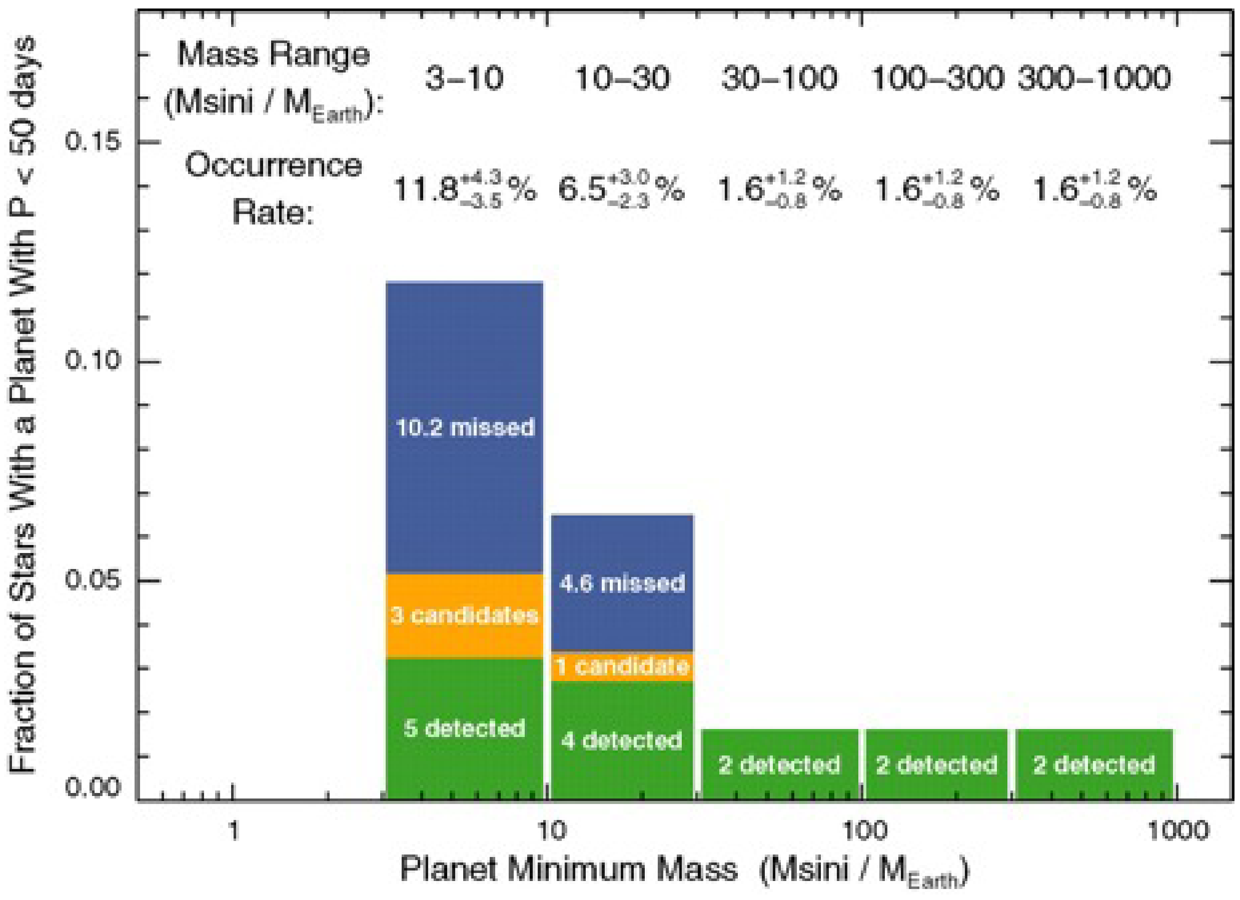
SMALL PLANETS ARE ABUNDANT

Transit Method



Borucki et al. 2010

RV Method



Howard et al. 2010

Observations are consistent with low-mass, small-sized planets being more numerous

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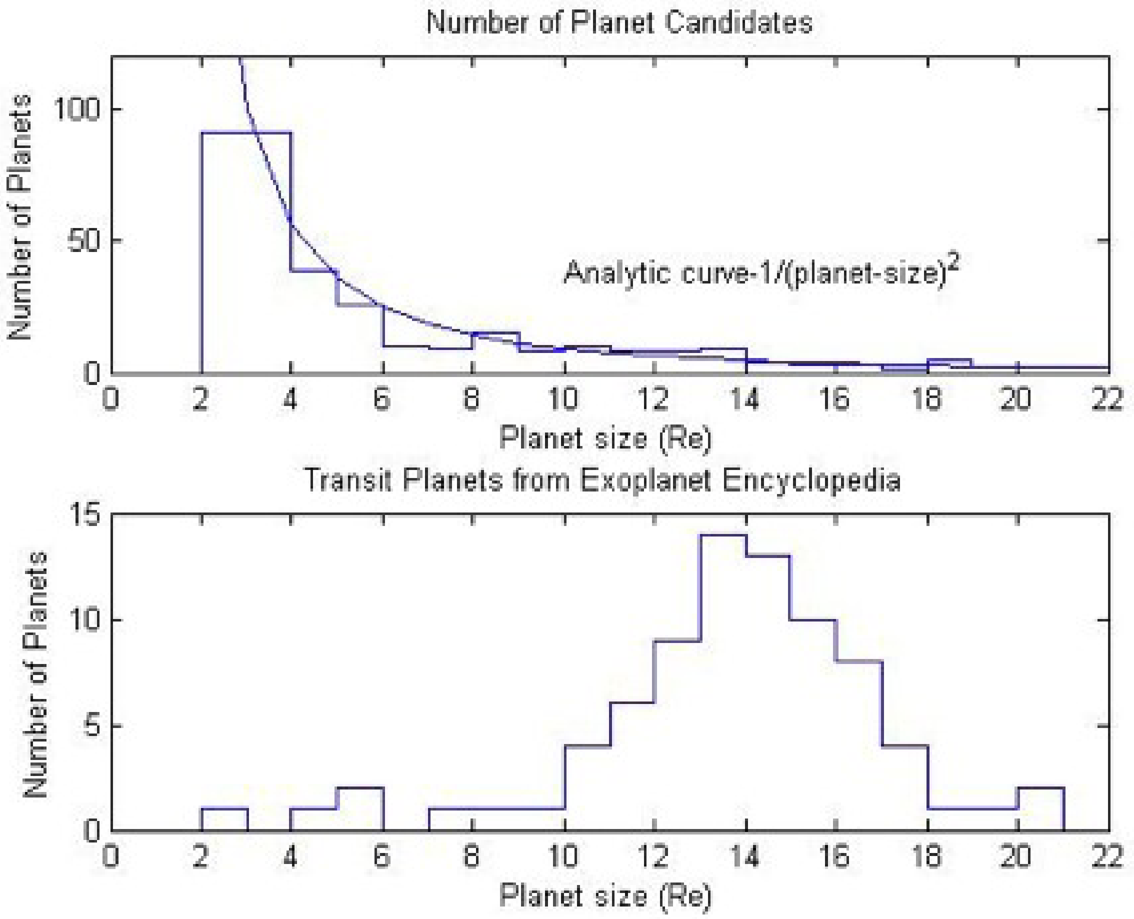

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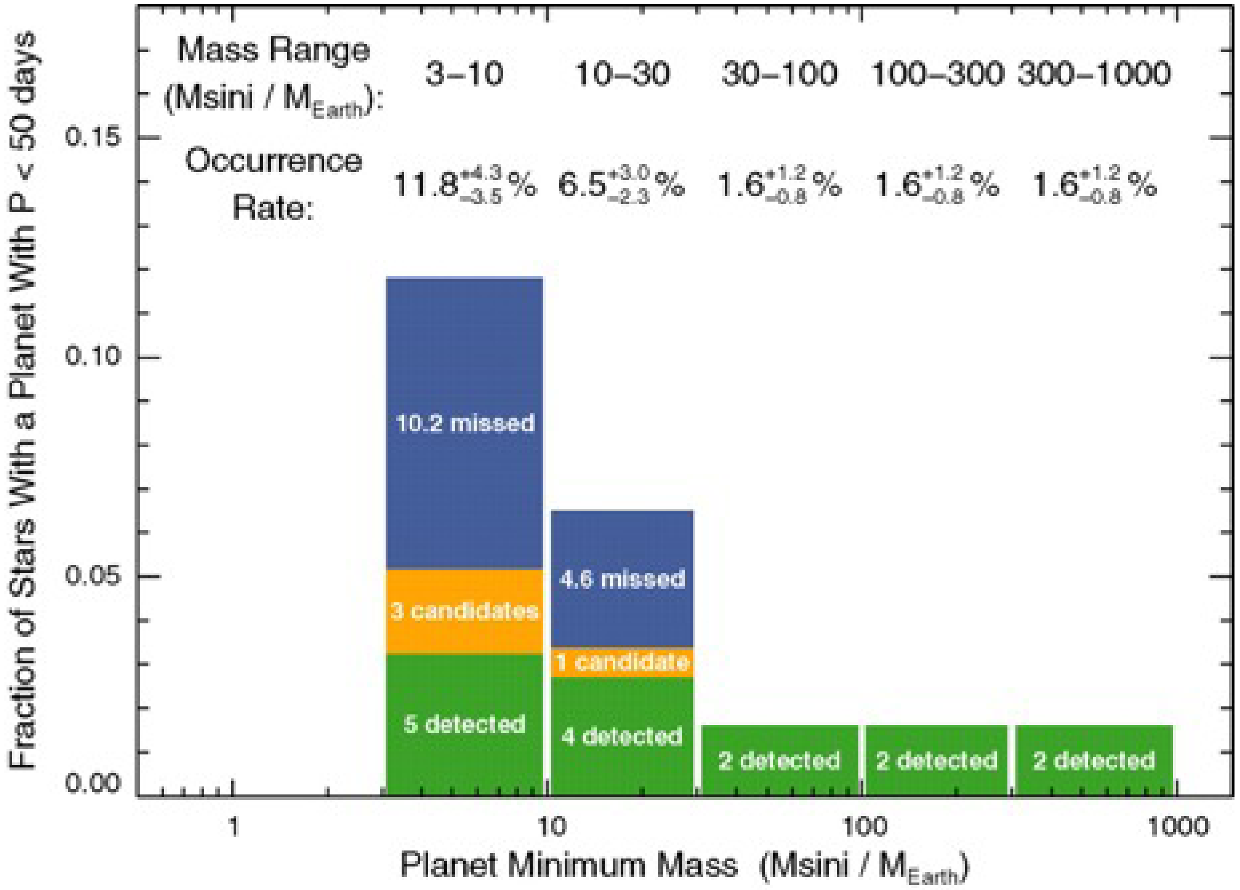

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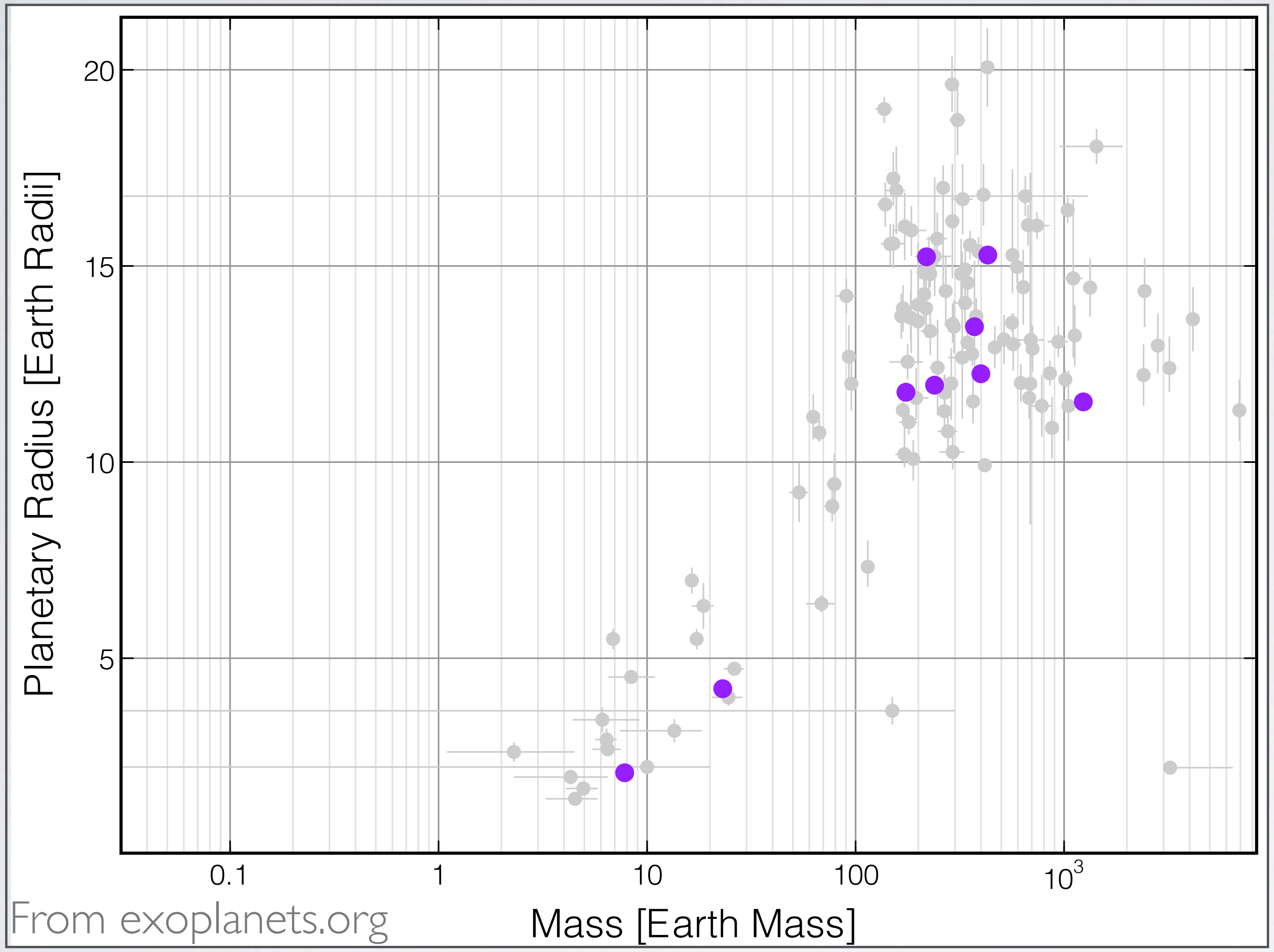
EXOPLANETS IN 2004

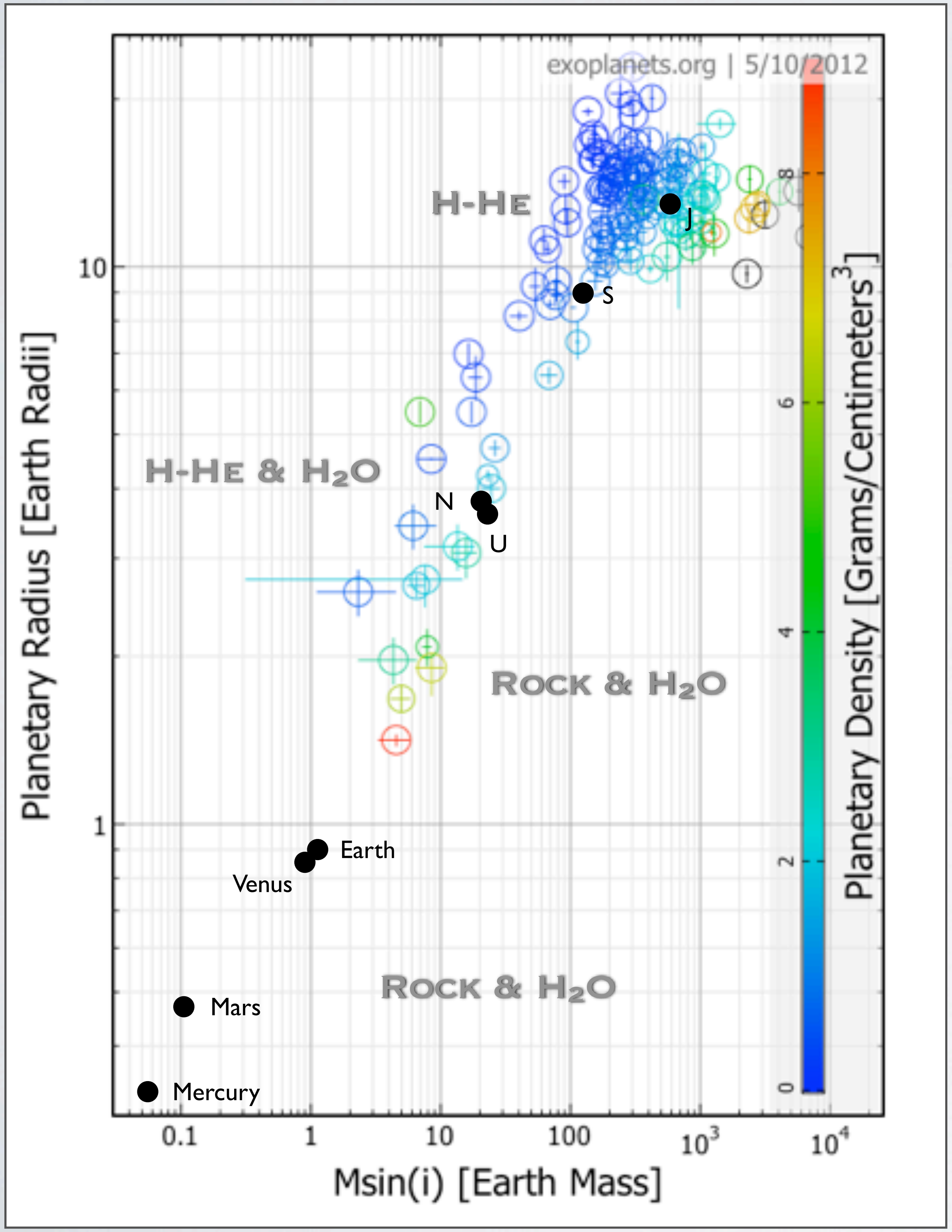


From exoplanets.org

- Only ExoJupiters and Neptunes-like planets
- Mass and Radius of a handful of planets
- Hot Jupiters & Inflated planets
- First few atmospheric compound detections (e.g. Na in HD209458b)

EXOPLANETS TODAY

THE SUPER-EARTH ERA



- Are these planets scaled up versions of Earth, or down-sized versions of Neptune?
- or something else altogether?

EXOPLANETS TODAY

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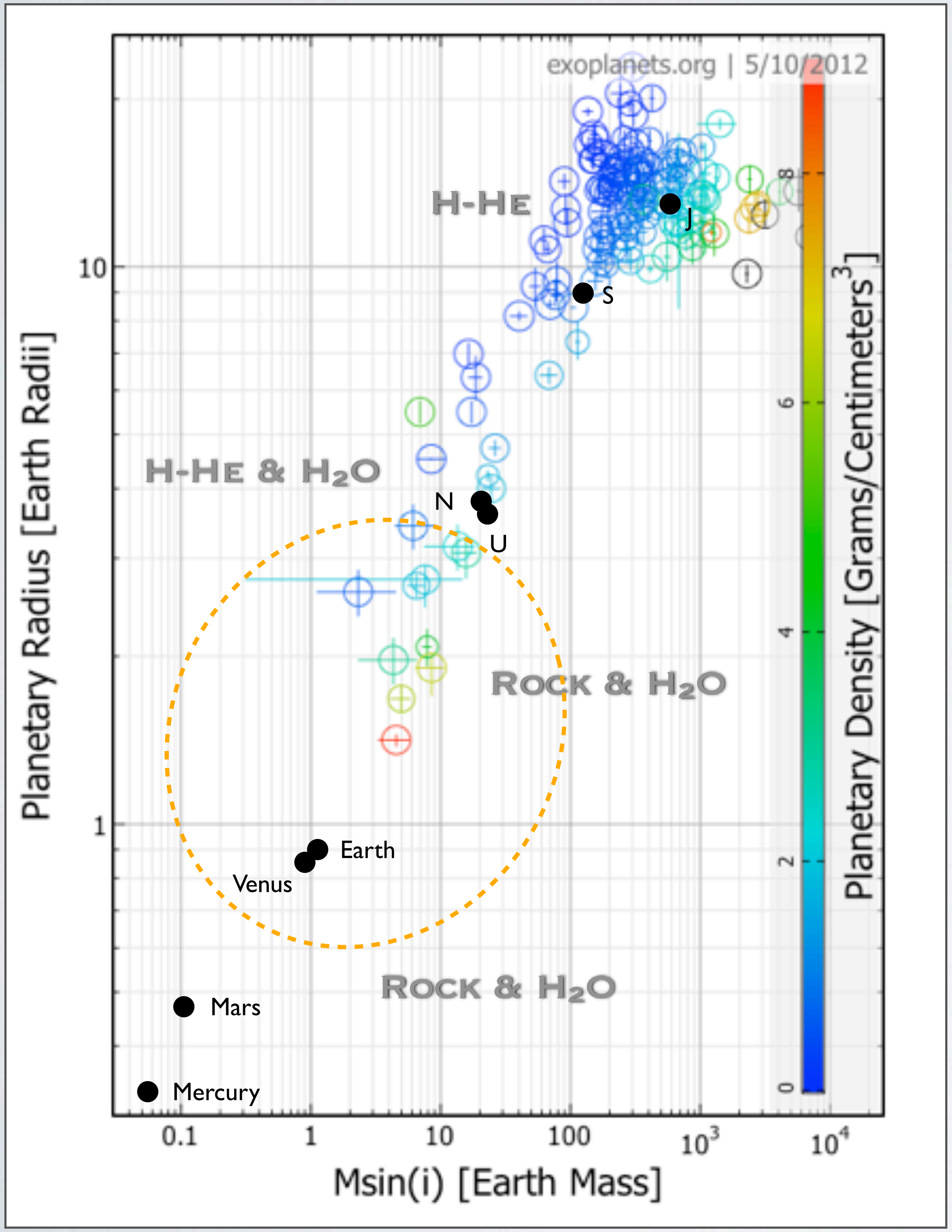

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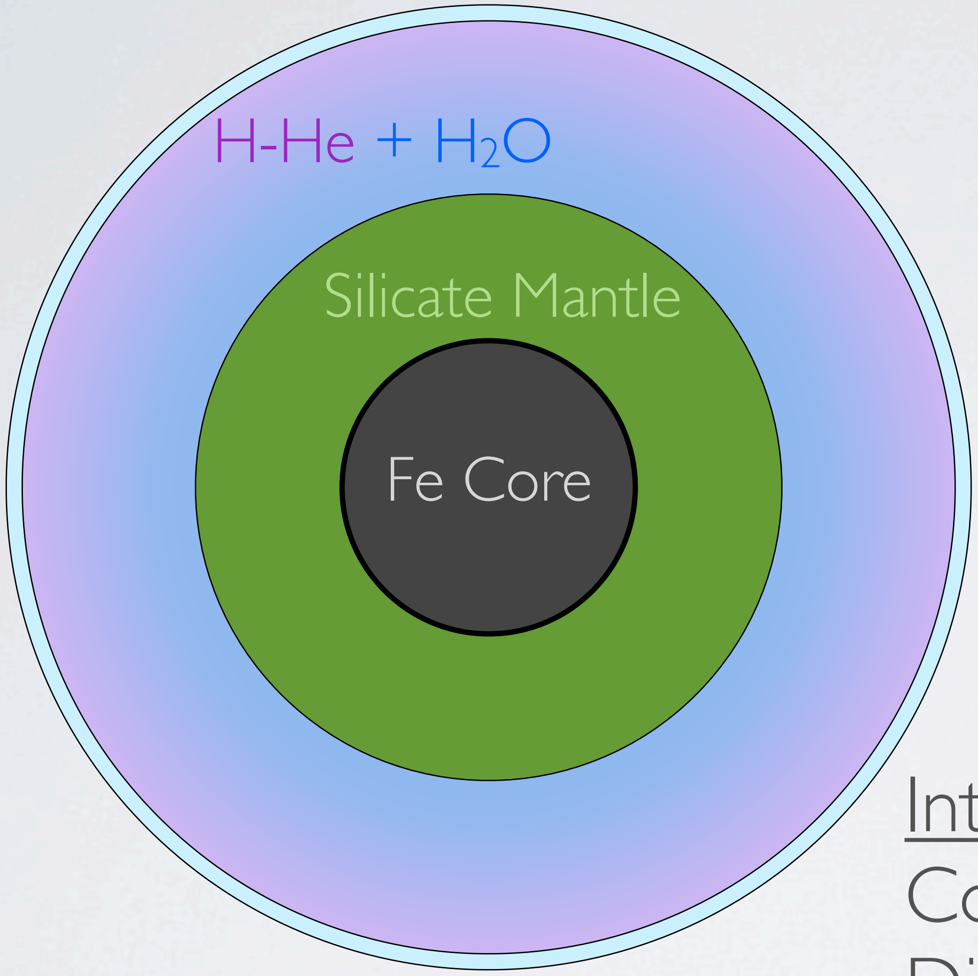
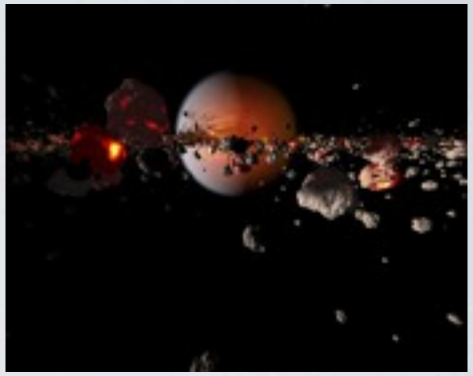
THEORY OF LOW-MASS PLANETS



Orbit
Mass
Radius
T_{eq}

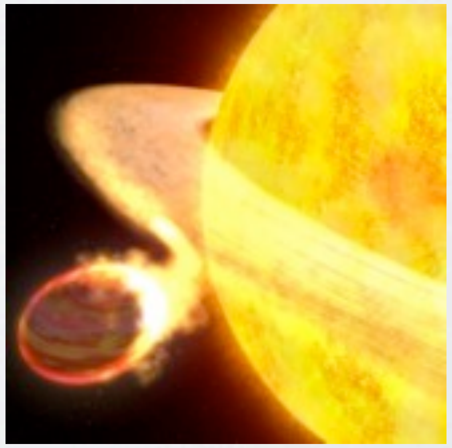
Coarse
Spectrum



Formation:
Mechanism
Migration
Existence of envelope

Interior:
Composition
Differentiation
Evolution

Atmosphere/Envelope:
acquisition (timing, disk properties)
evaporation

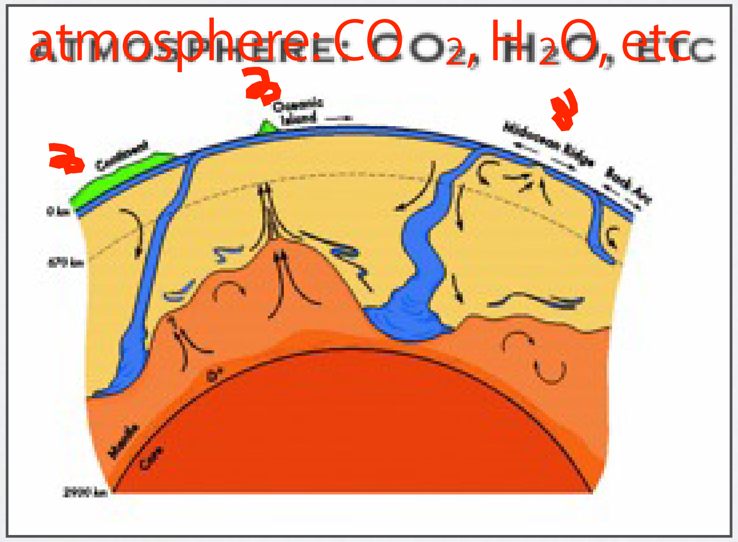


THEORY OF SOLID PLANETS

Orbit
Mass
Radius
T_{eq}

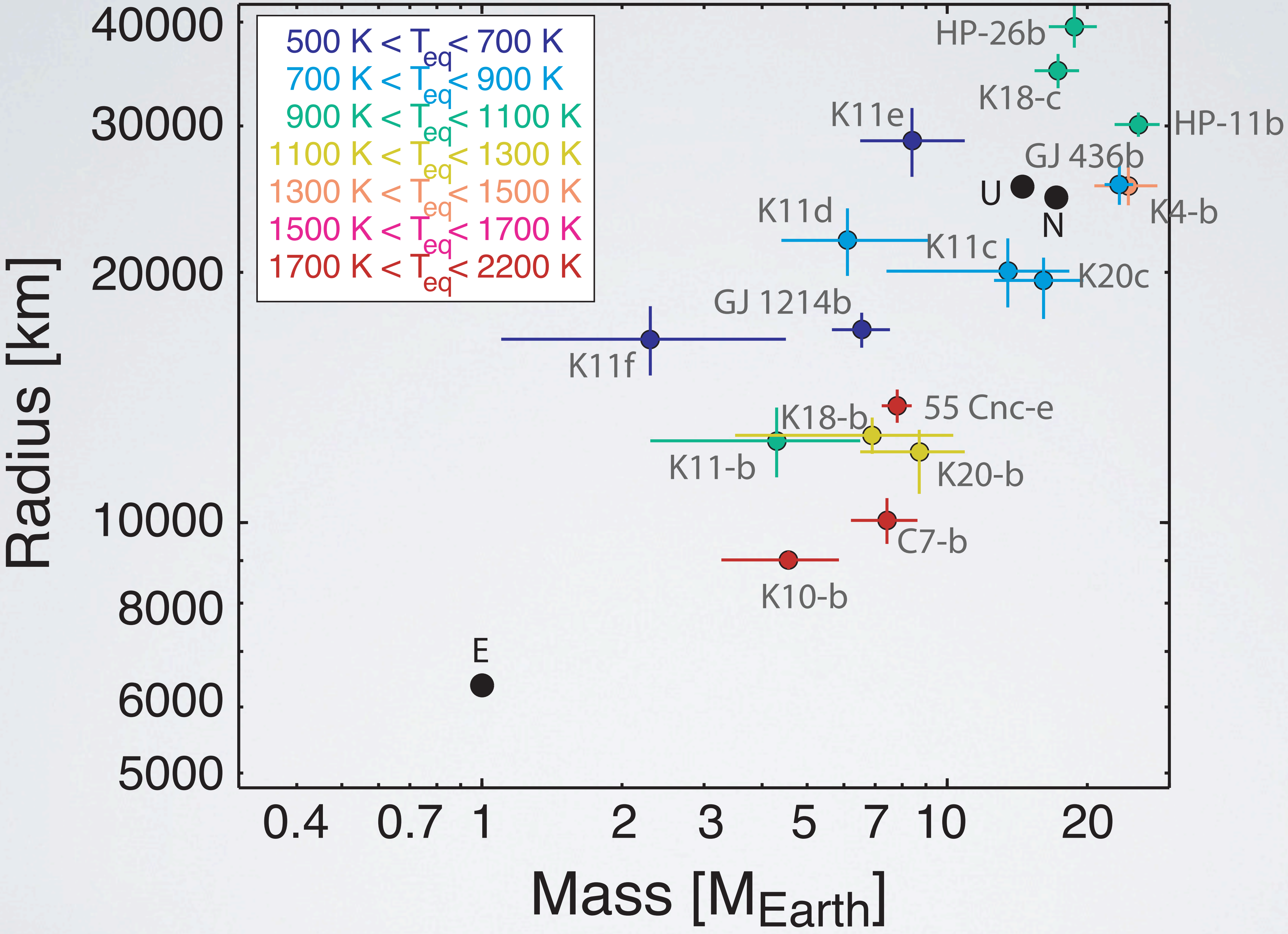
Coarse
Spectrum

Differentiation
Mantle stripping/erosio
Water Delivery
Thermal Evolution
Atmospheric Composition
Habitability



kelogg et al. 1999

TRANSITING SUPER-EARTHS



INTERNAL STRUCTURE MODEL

$$\partial_r \rho = -\rho^2 g/Ks$$

$$\partial_r g = 4\pi G\rho - 2Gm/r^3$$

$$\partial_r m = 4\pi r^2\rho$$

$$\partial_r P = -\rho g$$

$$\partial_r T = \partial_r P\, T/P \quad \nabla_T \left\{\begin{array}{c}\text{cond}\\ \text{conv}\\ \text{rad}\end{array}\right.$$

$$\partial_r L = 4\pi r^2\rho\,(\dot{\varepsilon} - T\dot{S})$$

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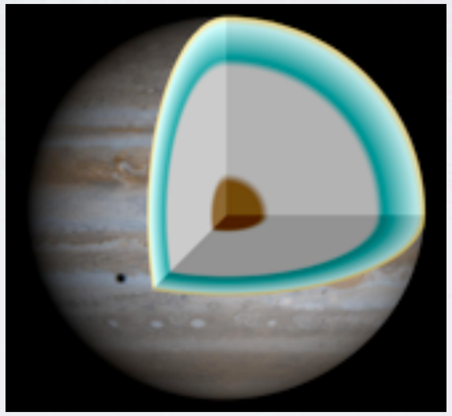
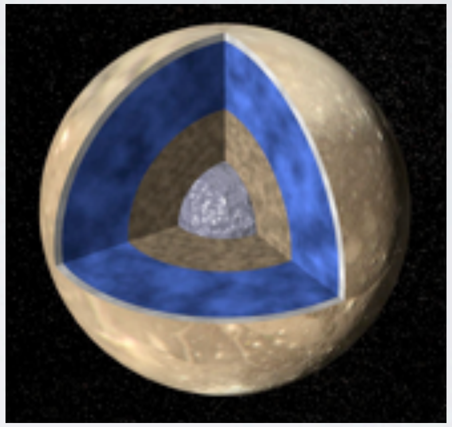
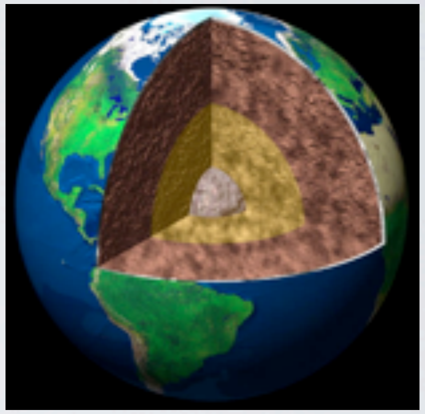


H/He



H_2O, CH_4, NH_3



$(Mg,Fe)O + SiO_2$

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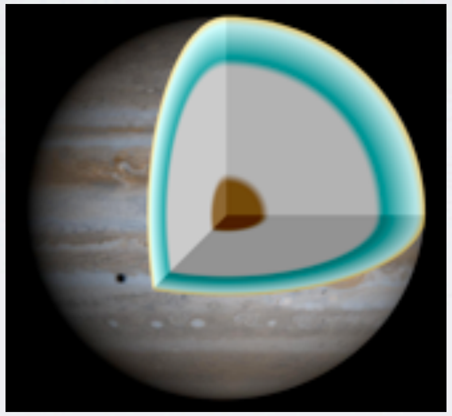
- Need an EOS



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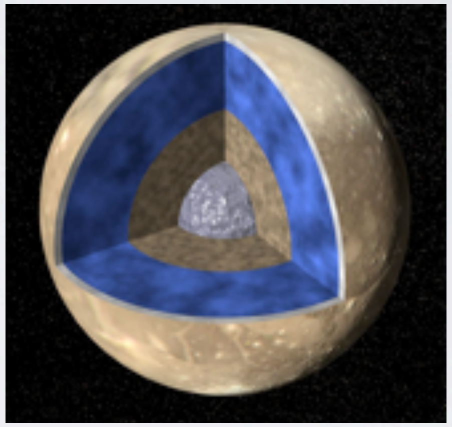

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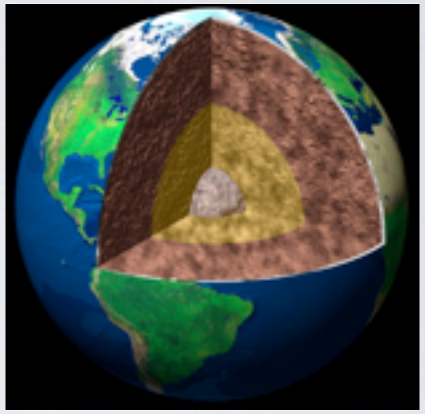

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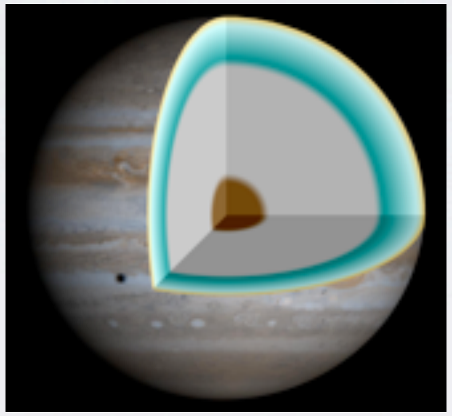

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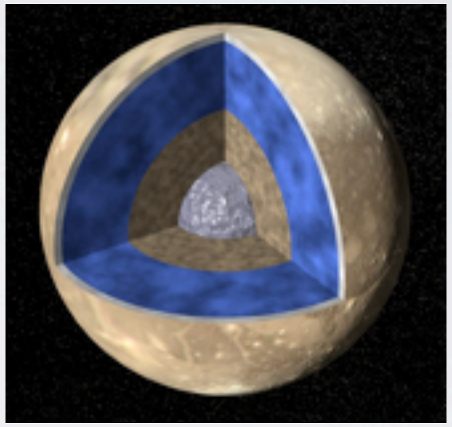

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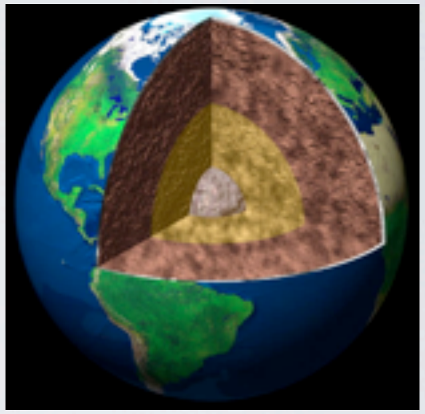

$(Mg,Fe)O + SiO_2$

- Need an EOS

- $R = R\,(M, \chi\,)$

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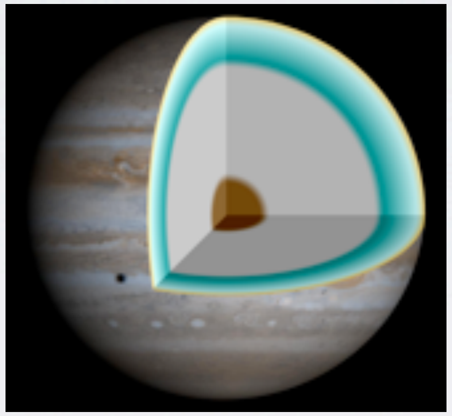

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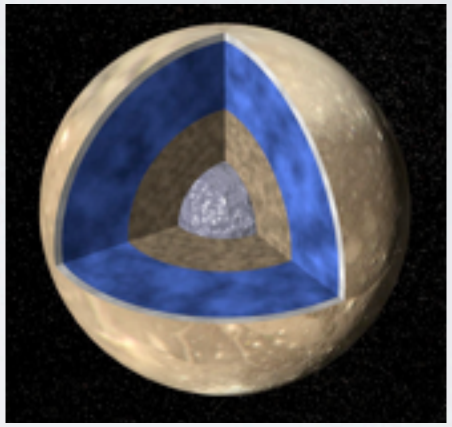

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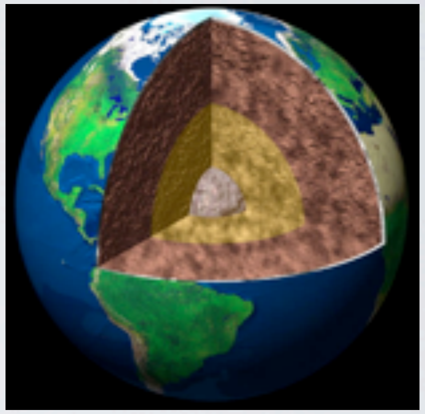


(Mg,Fe)O + SiO_2

- Need an EOS

- Temperature has little effect on the density of rocks, but not the case for gaseous constituents

- $R = R(M, \chi)$

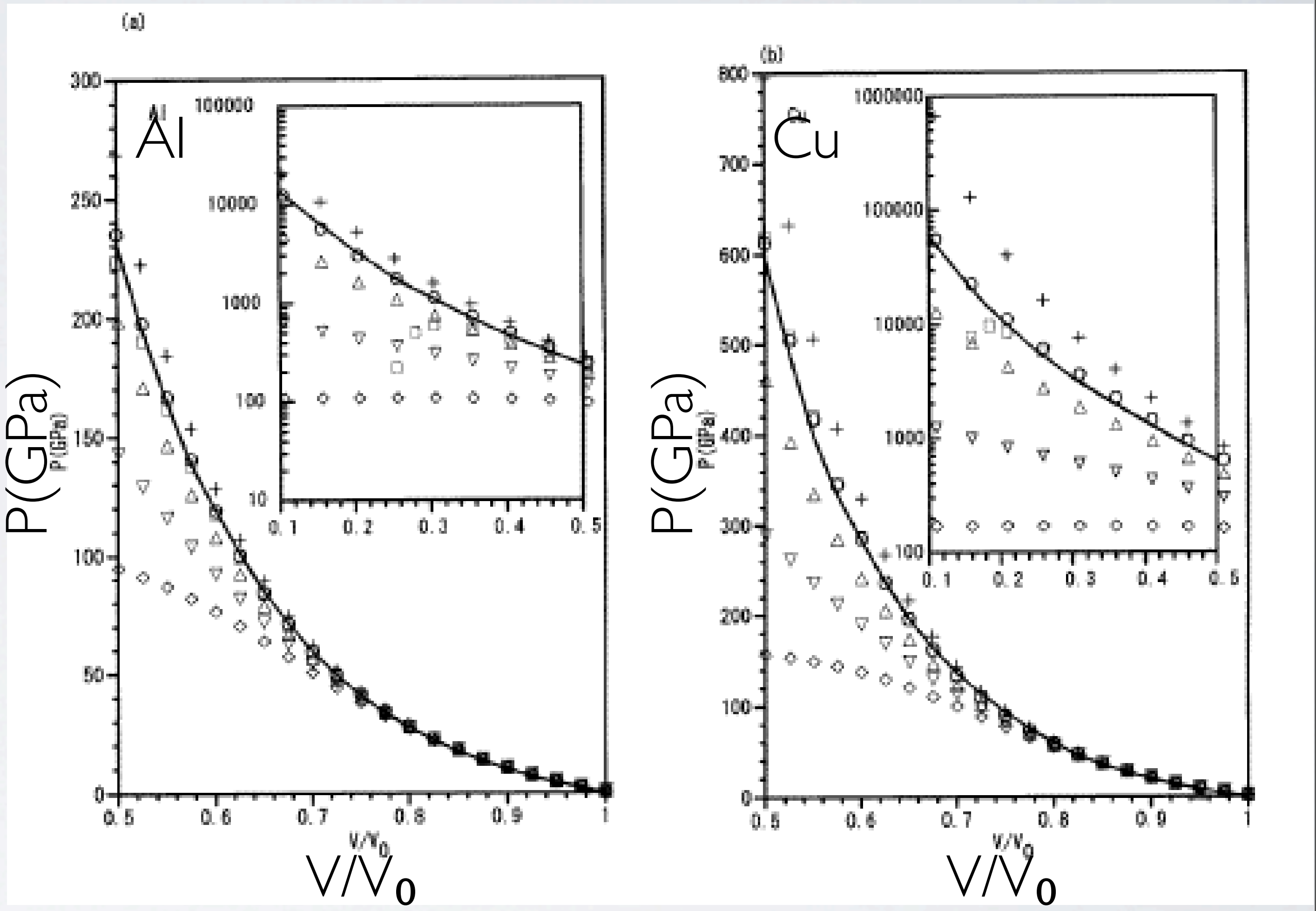
A FEW WORDS ABOUT EOS

Geophysics approach:

- Birch Murnaghan EOS
- Vinet EOS

Astrophysical approach:

- Sesame
- Aneos



Hama & Suito 1996

- squares: Vinet
- diamond: BM3

At high enough pressures the EOS should appropriately describe the behaviour of matter (the Fermi limit)

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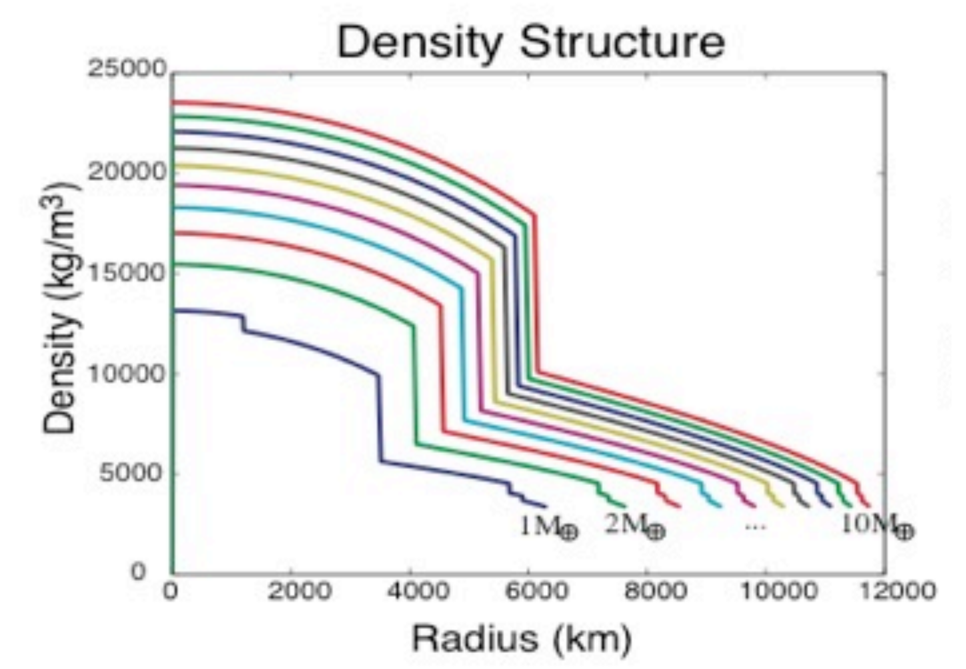
$$\partial_r P = -\rho g$$

$$\partial_r T = \partial_r P\, T/P \quad \nabla_T \left\{\begin{array}{c}\text{cond}\\ \text{conv}\\ \text{rad}\end{array}\right.$$

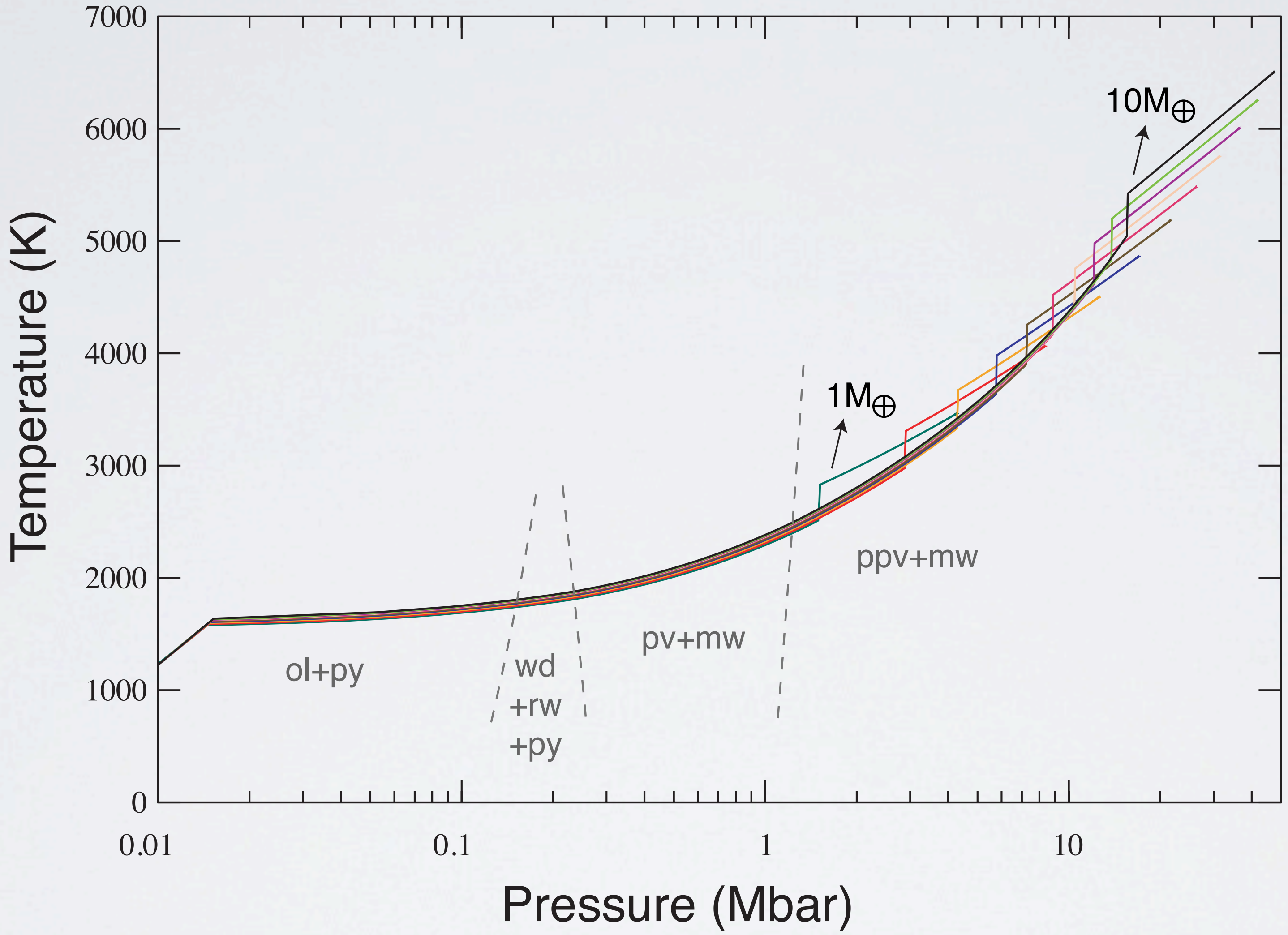
$$\partial_r L = 4\pi r^2\rho\,(\dot{\varepsilon} - T\dot{S})$$



Valencia et al. 2006

See also:
Sotin et al, 2007, Grasset et al. 2009, Seager et al. 2007, Swift et al. 2001, Wagner et al. 2011

INTERNAL STRUCTURE



Valencia et al. 2009

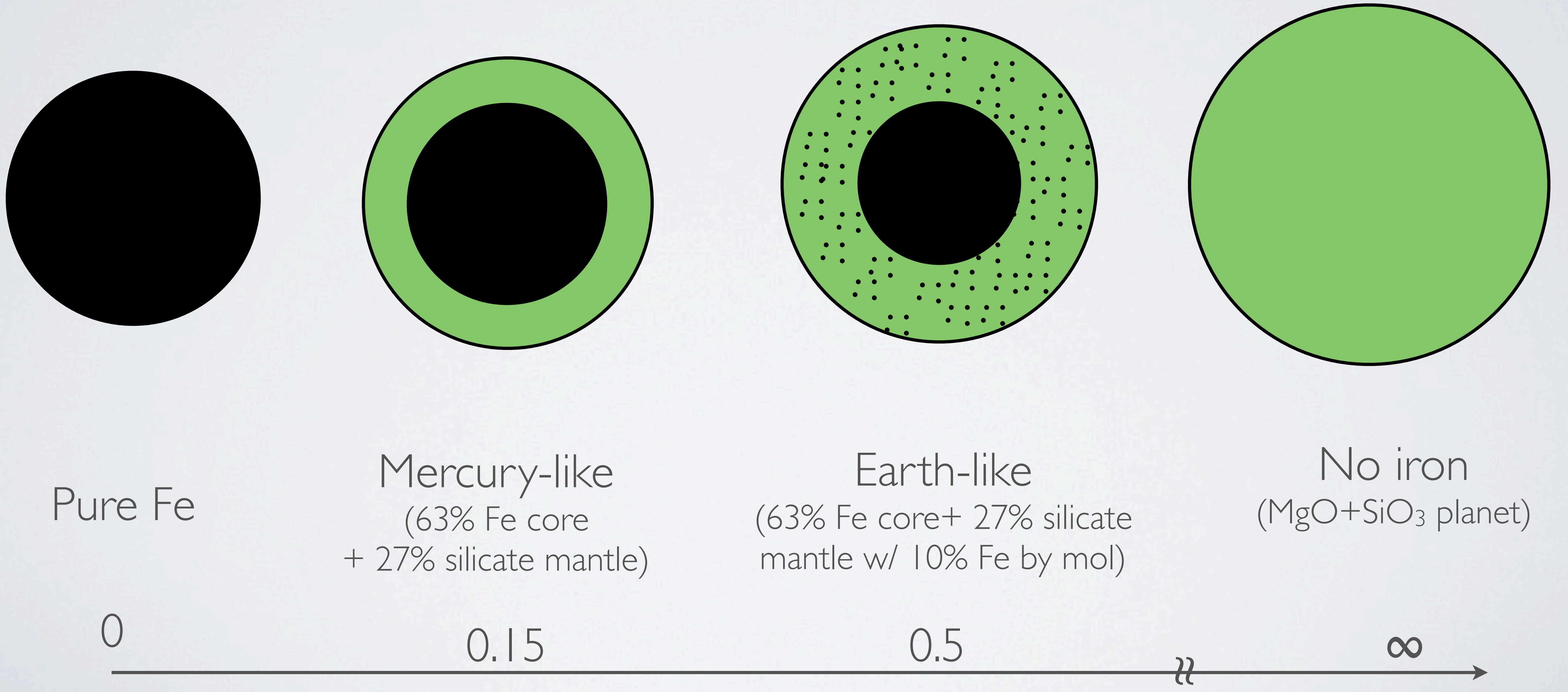
$R \sim M^{1/4}$

Pressure scales ~linearly with mass

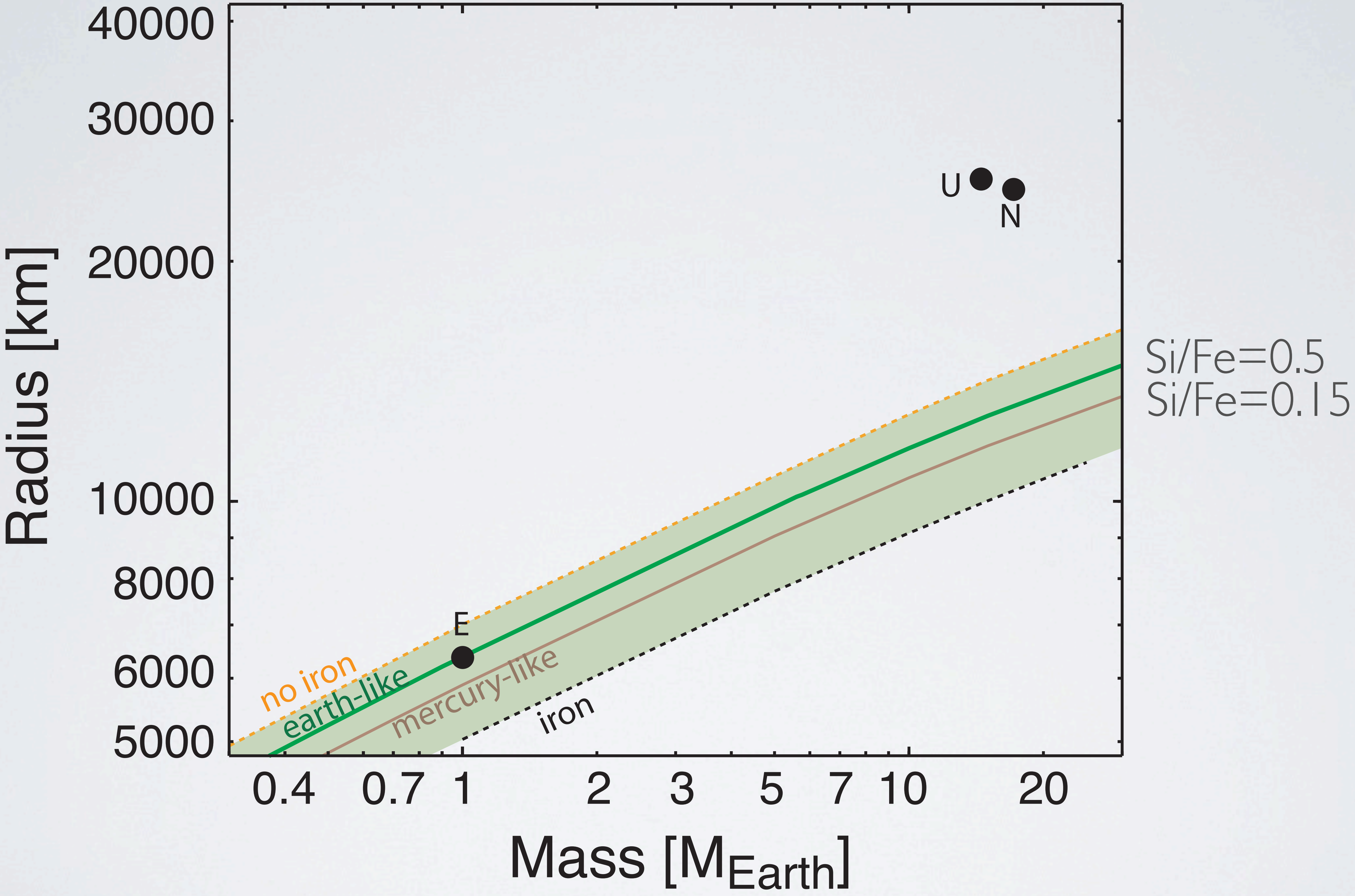
VARIETY IN ROCKY COMPOSITIONS

Refractory material: **Fe**, Mg, Si, O, Al, Ti, Ca

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



ROCKY COMPOSITIONS



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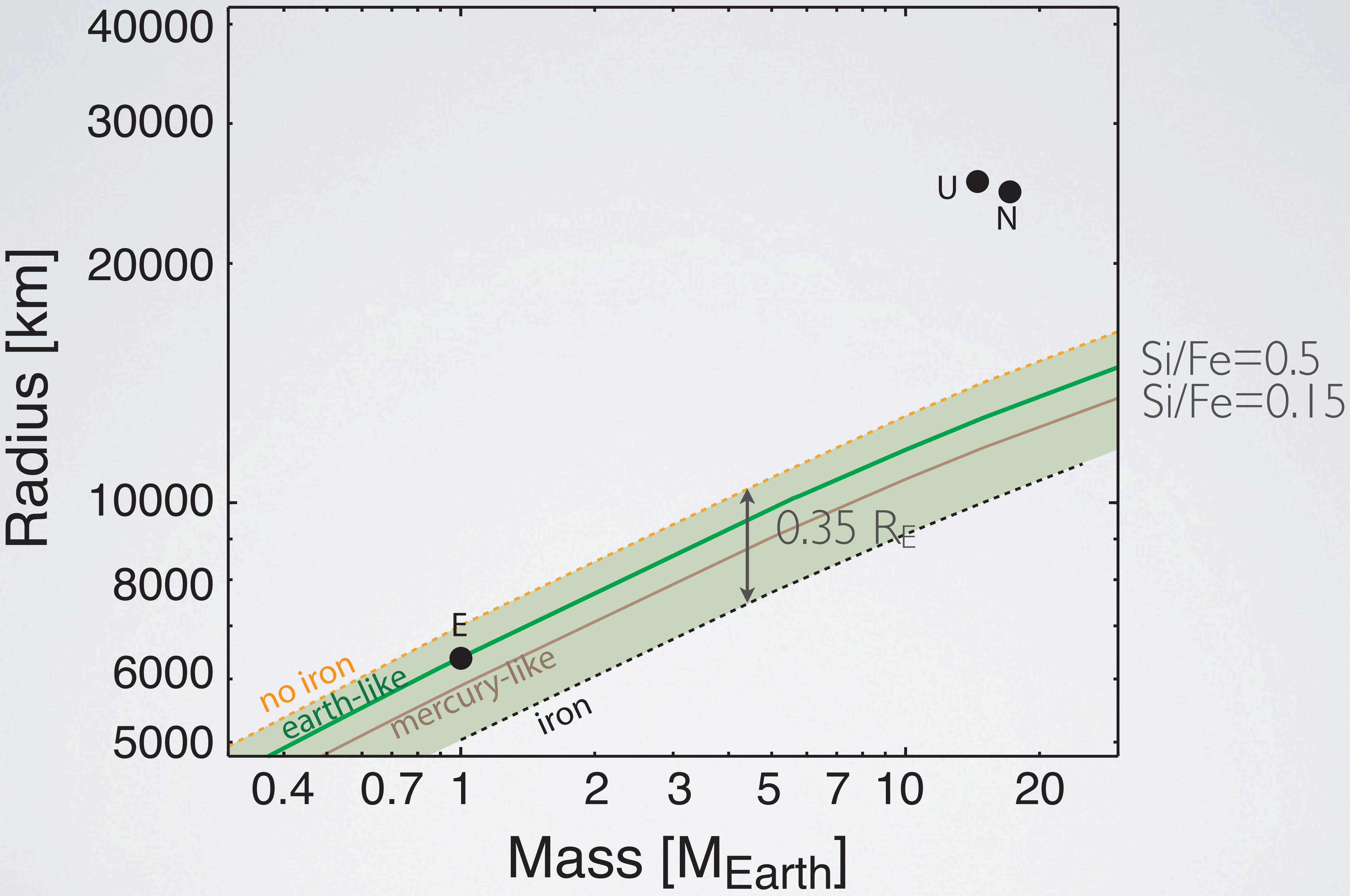

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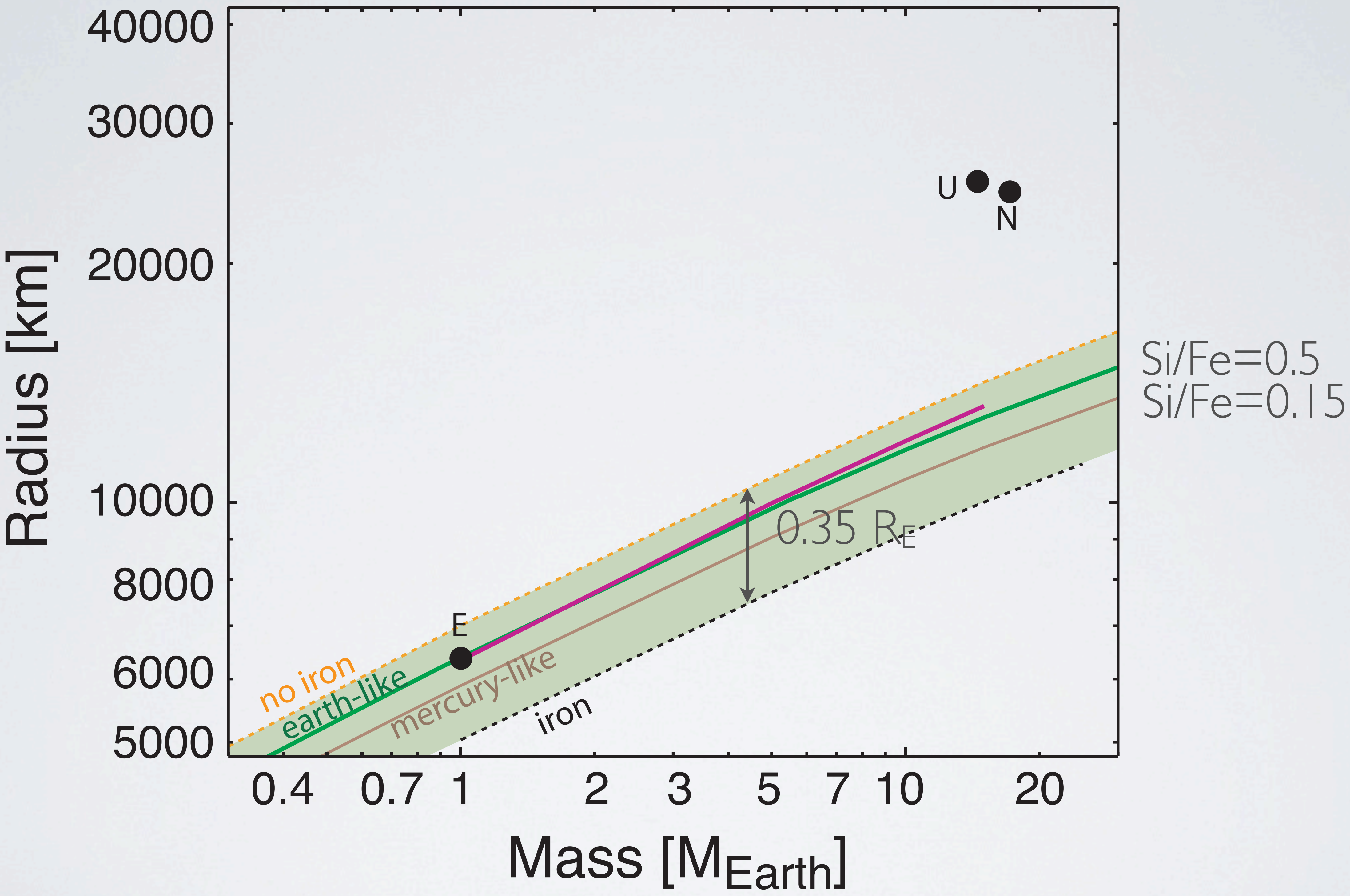

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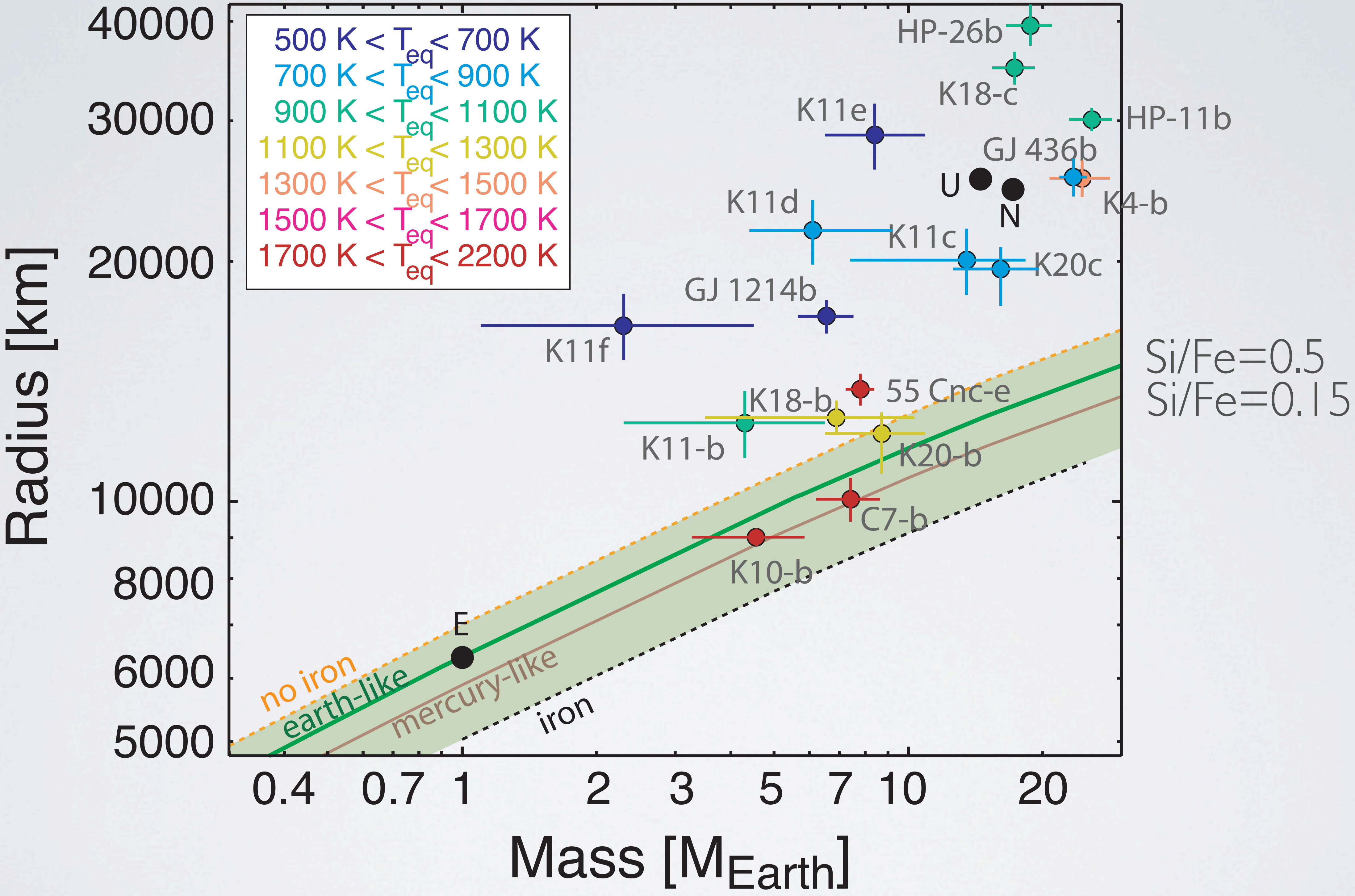
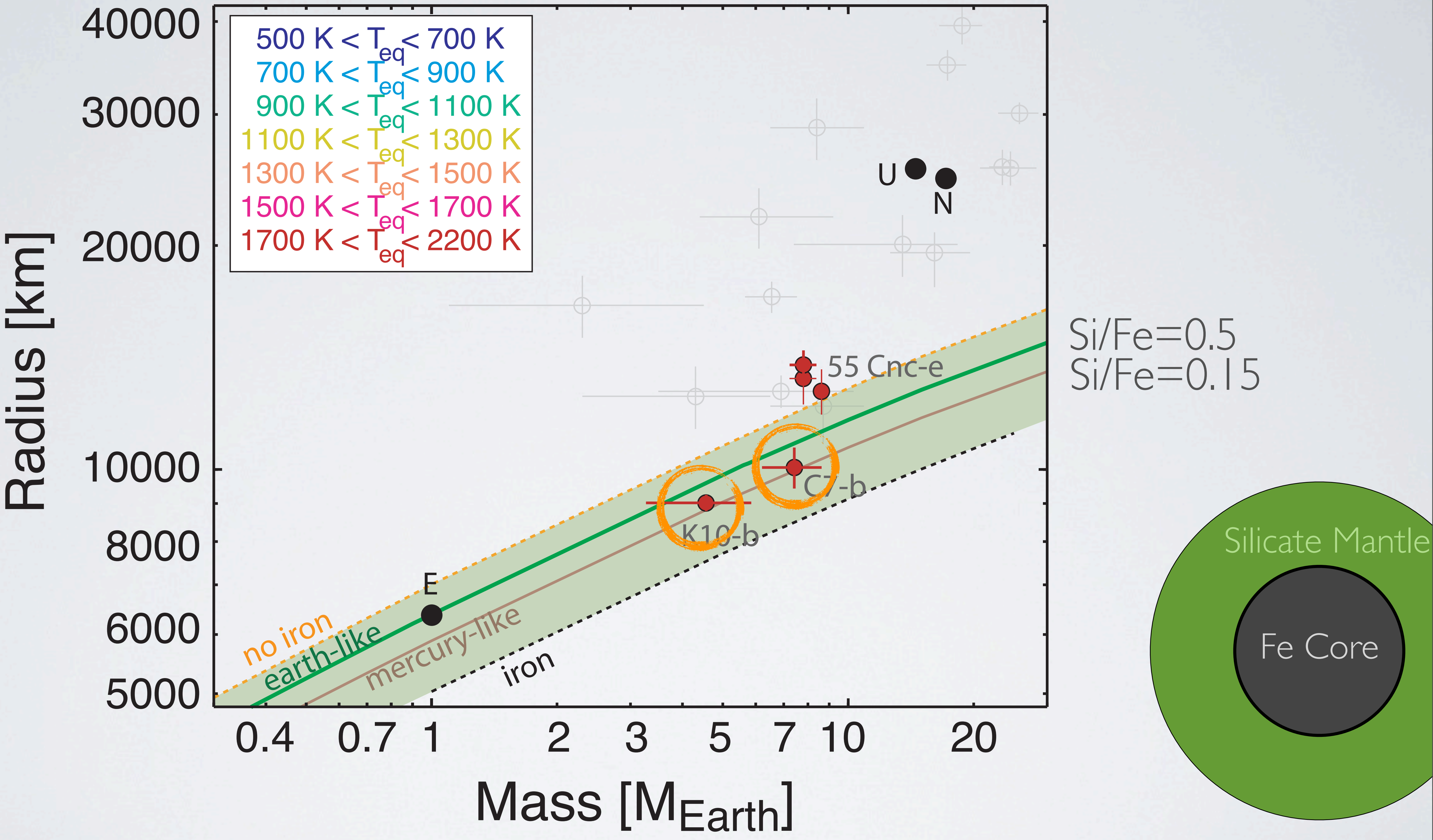


ROCKY COMPOSITIONS



CoRoT-7b & Kepler-10 b are enriched in iron by a factor of ~6 with respect to Earth

HIGH-DENSITY SUPER-EARTHS

1. Primordial composition
2. Collisional stripping
3. Mantle Erosion

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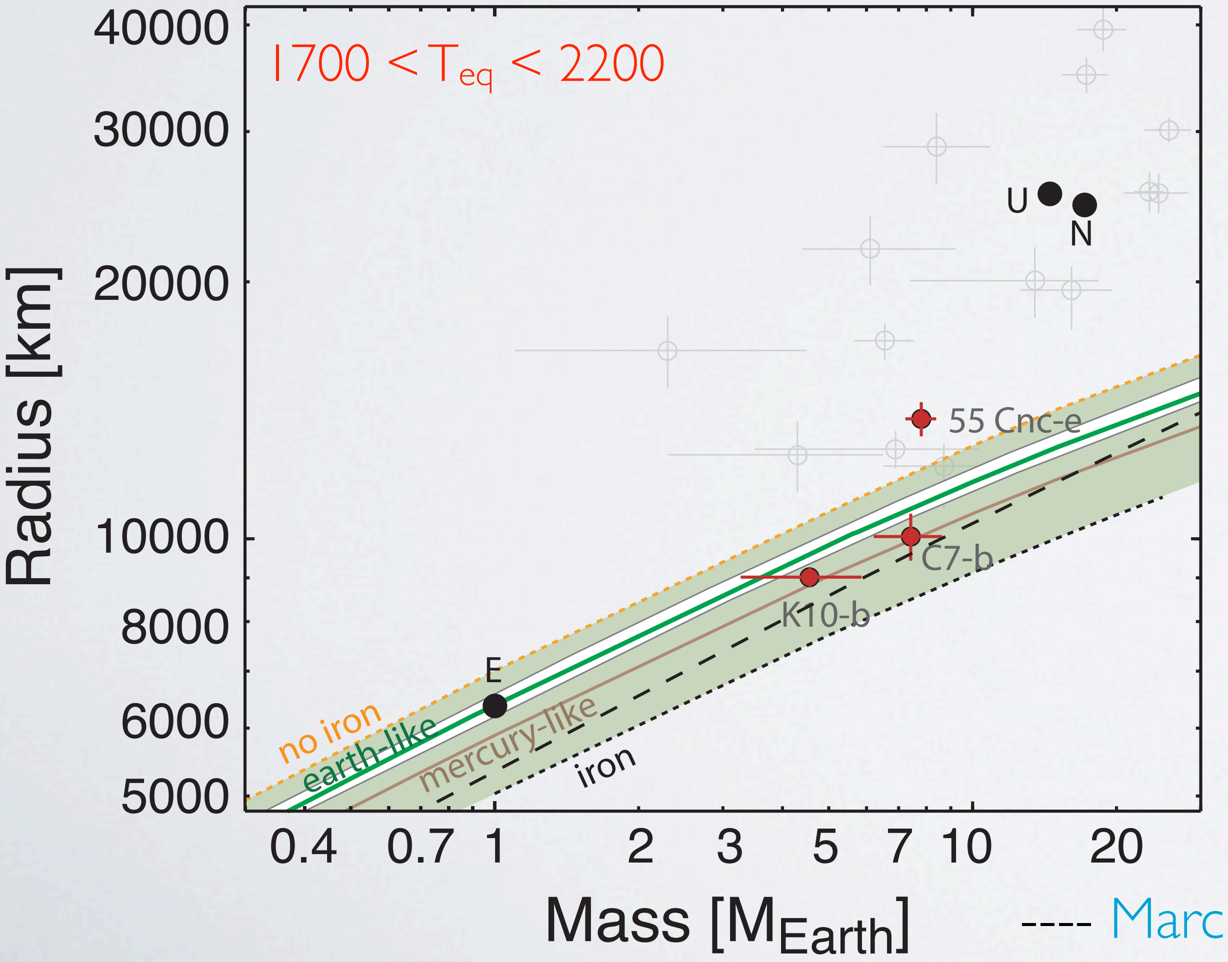

1.78x $(\mathrm{Si/Fe})_\oplus$
0.8x $(\mathrm{Si/Fe})_\oplus$

---- Marcus et al '10

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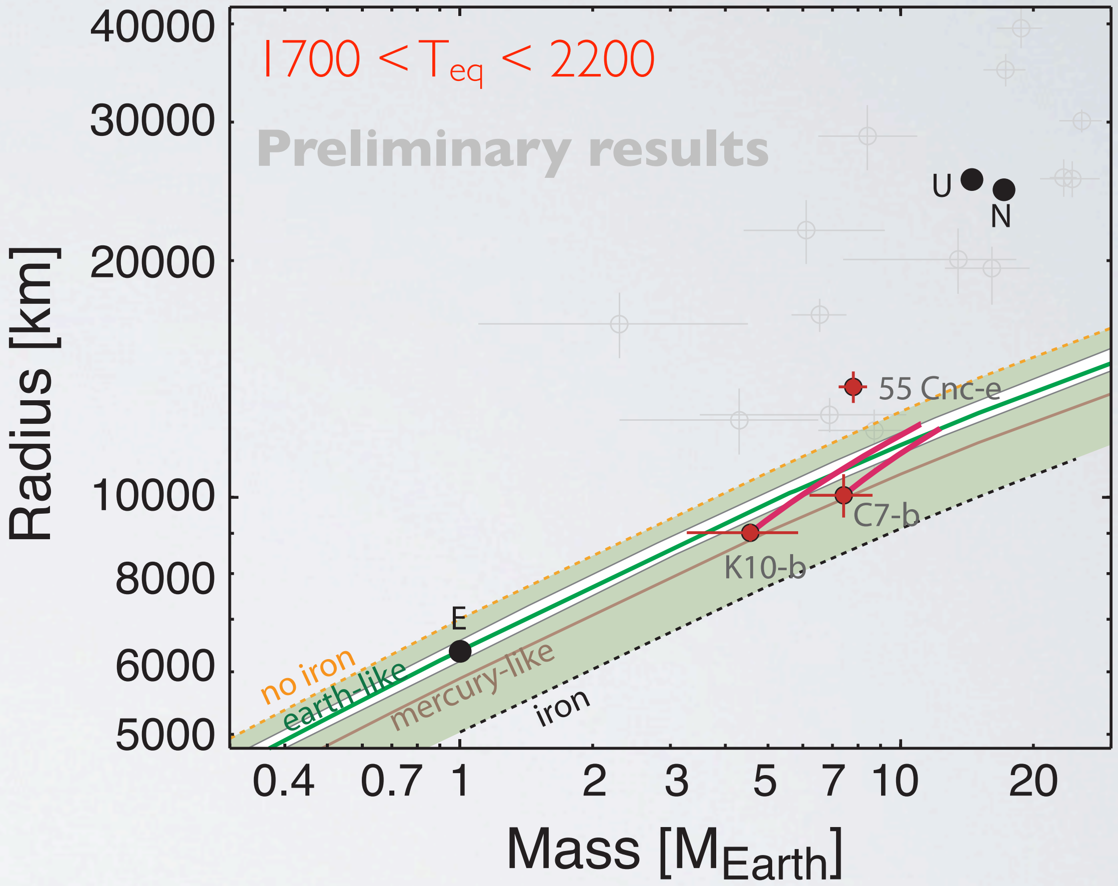

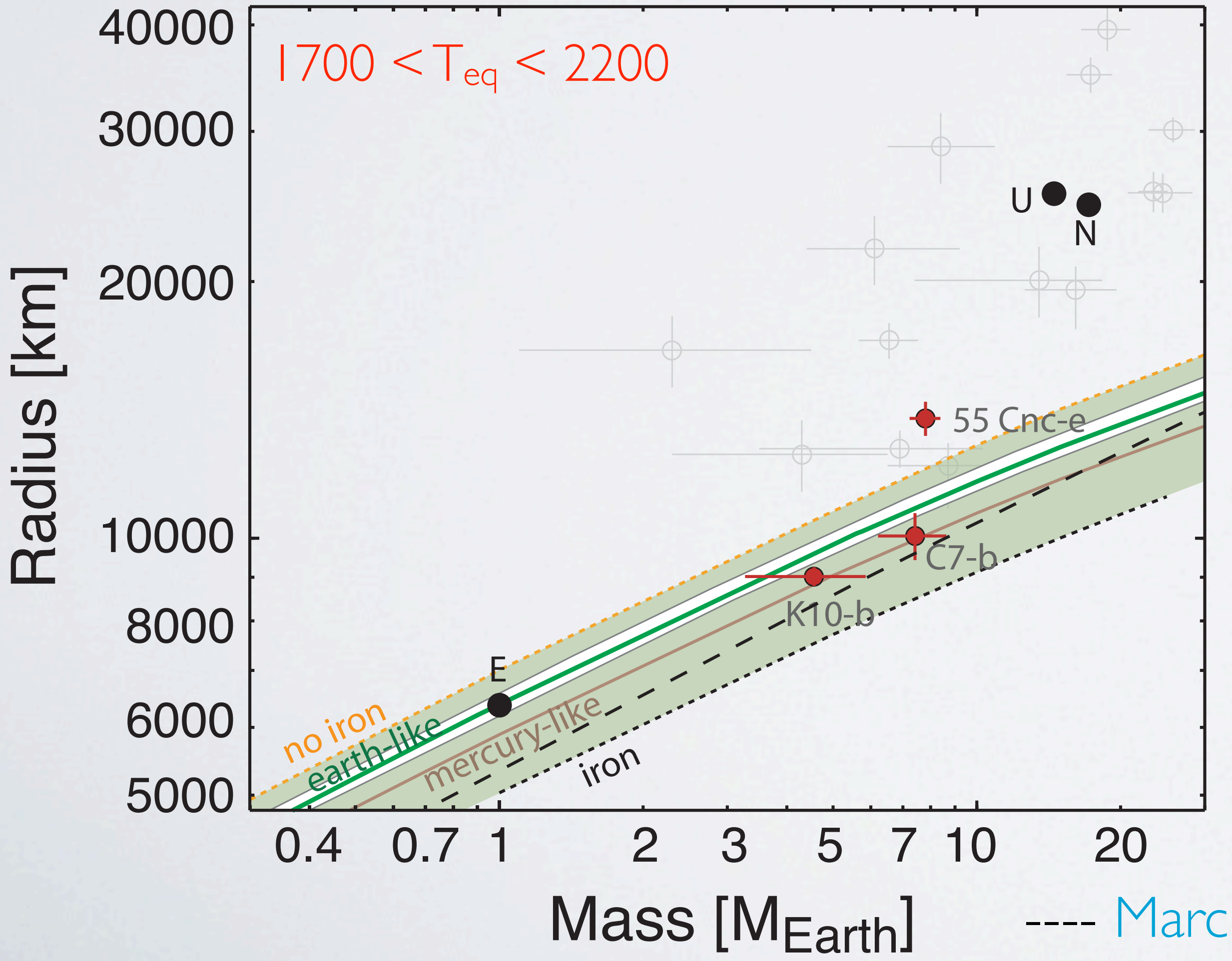

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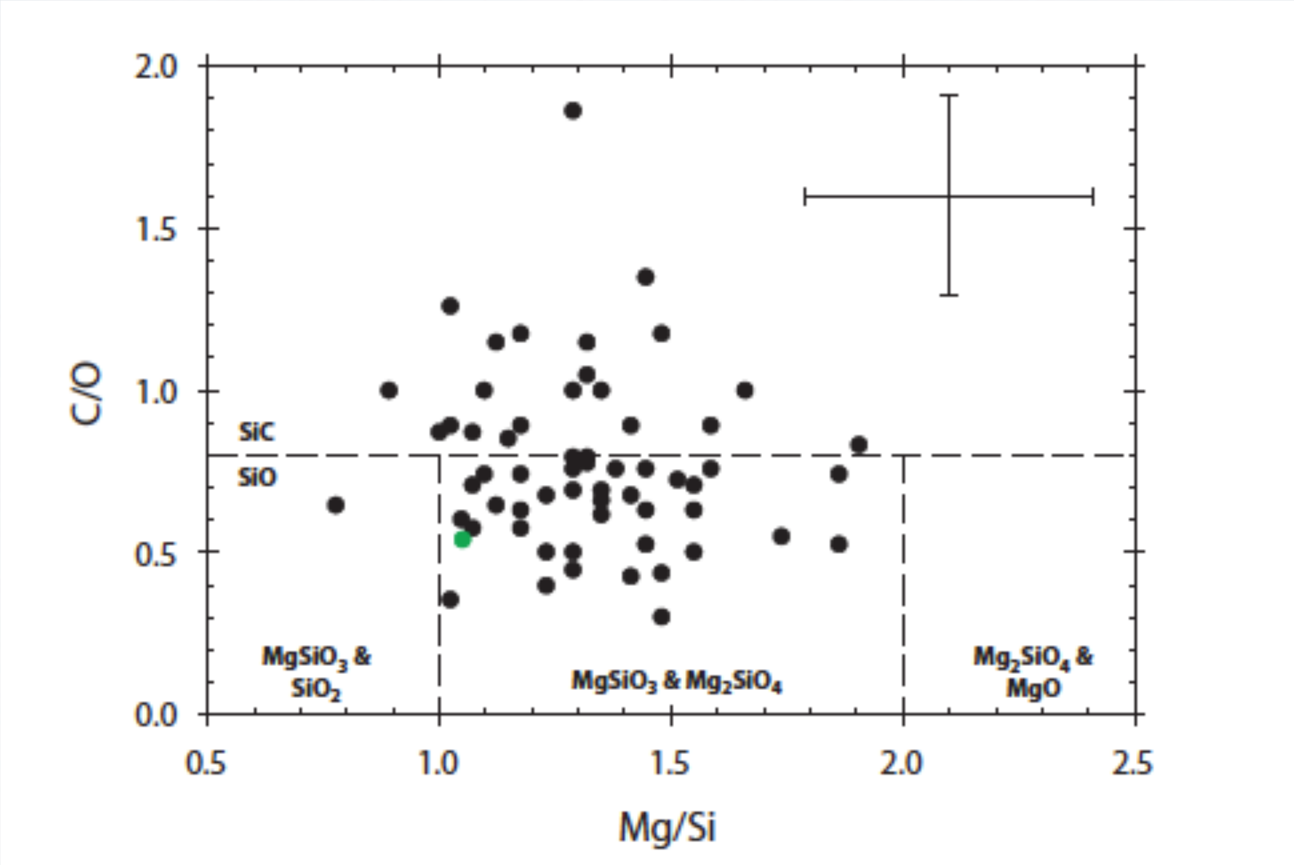
OTHER SOLID COMPOSITIONS



Bond et al, 2010

If C/O > 0.8: C will bind to Si to form carbides

The Mg/Si ratio has an implication on the proportion of pyroxene to olivine formed

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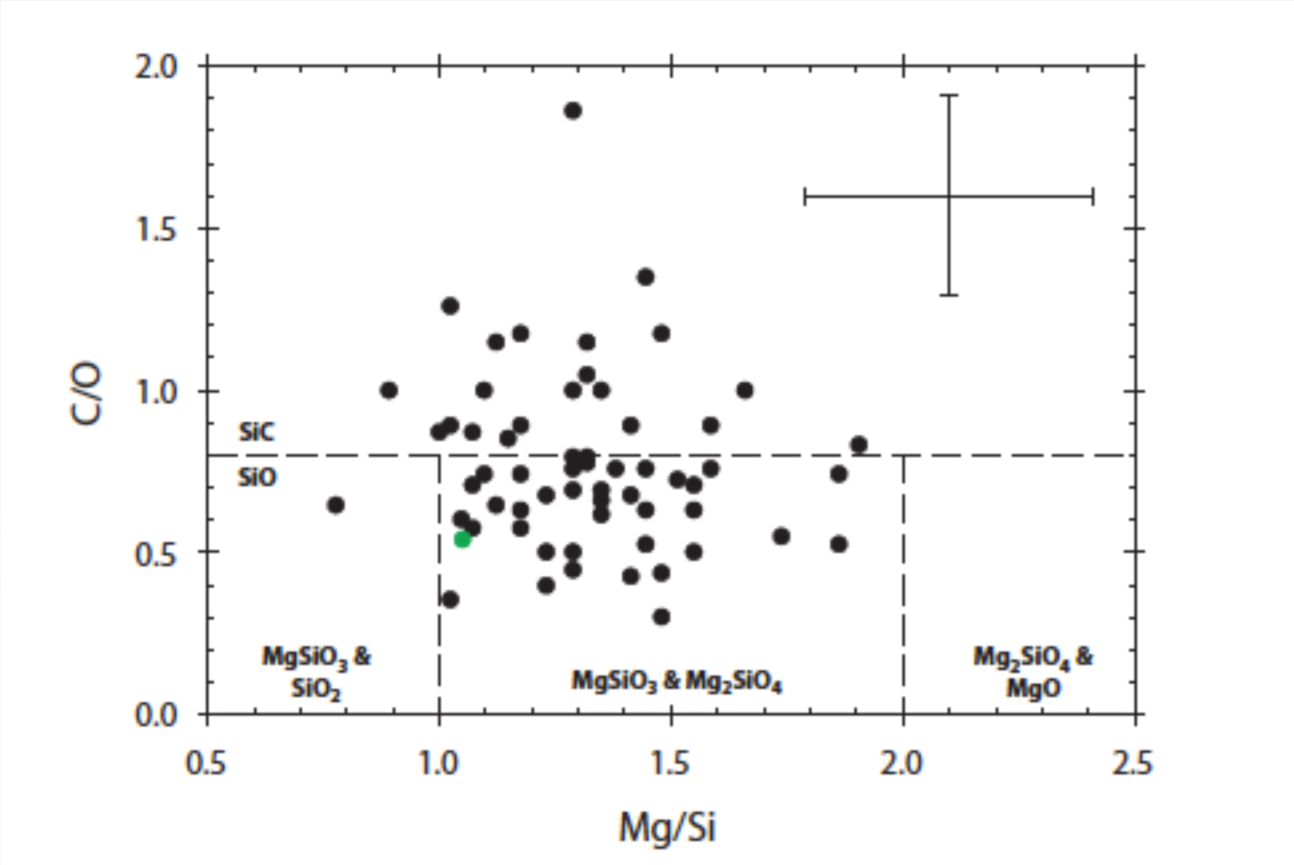
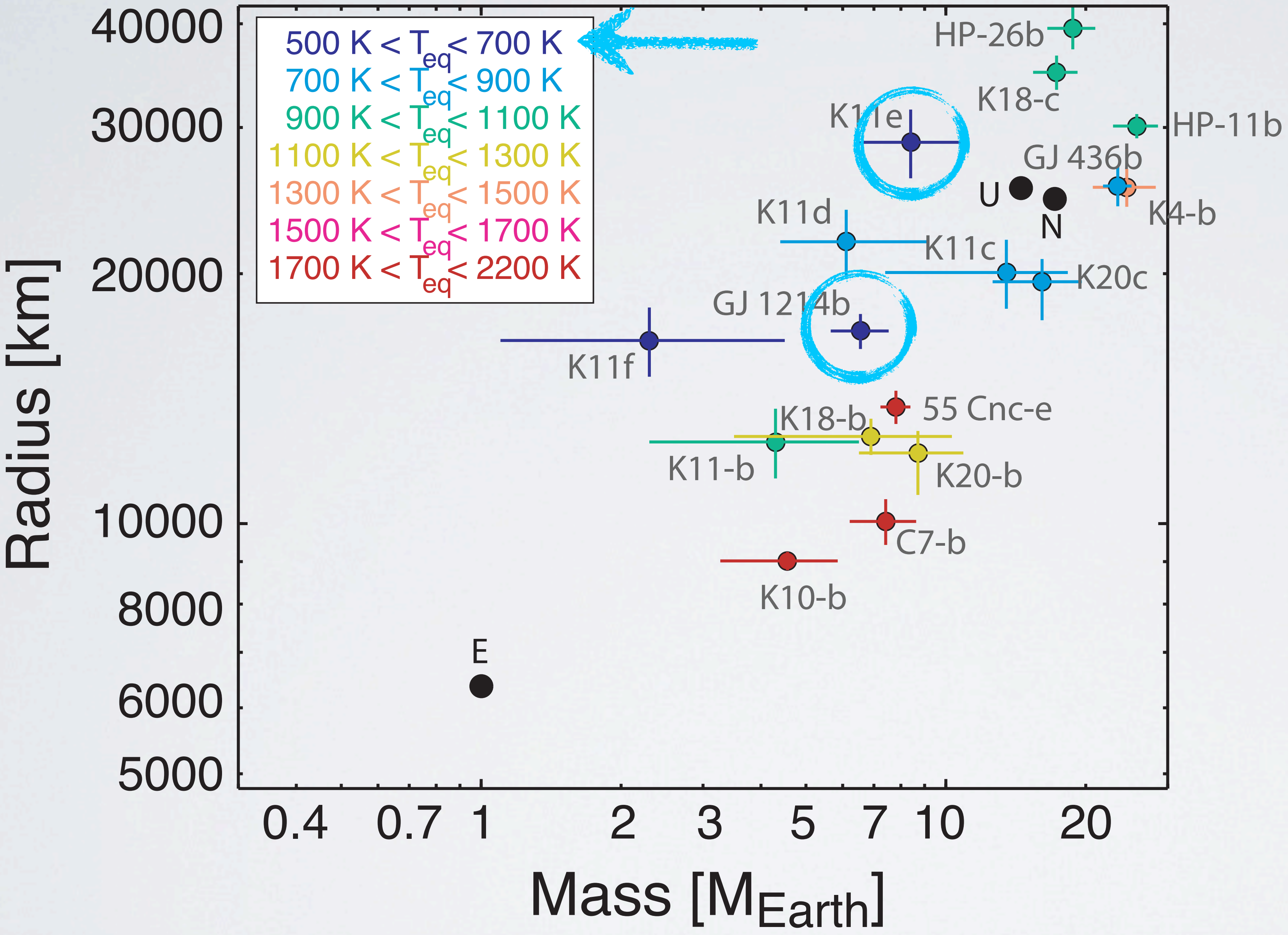


Bond et al, 2010

If C/O > 0.8: C will bind to Si to form carbides
The Mg/Si ratio has an implication on the proportion of pyroxene to olivine formed

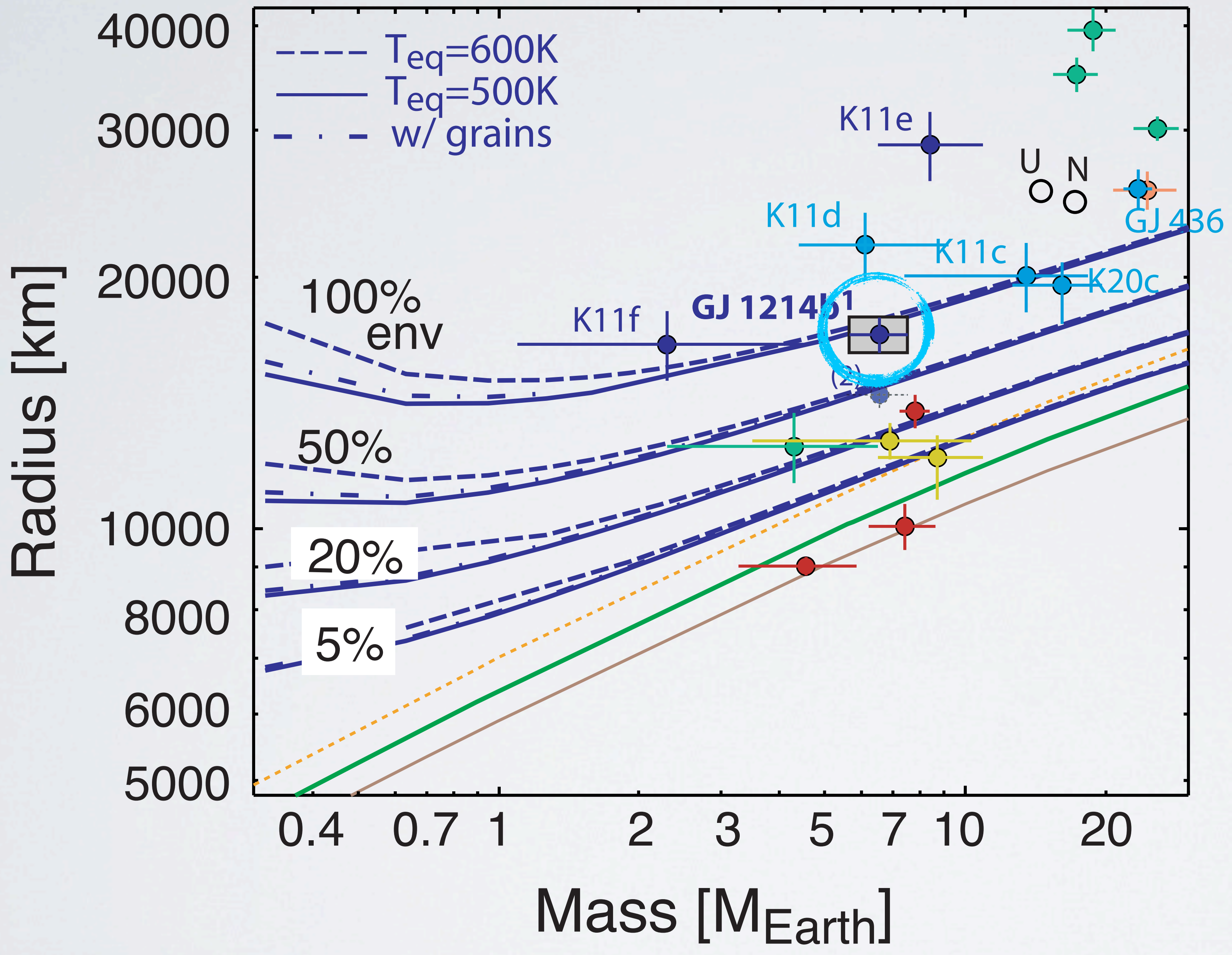
WARNING: the measurement of C and O in stars is challenging due to the few spectral lines, at this point a high C/O ratio is controversial

WARM MINI-NEPTUNES

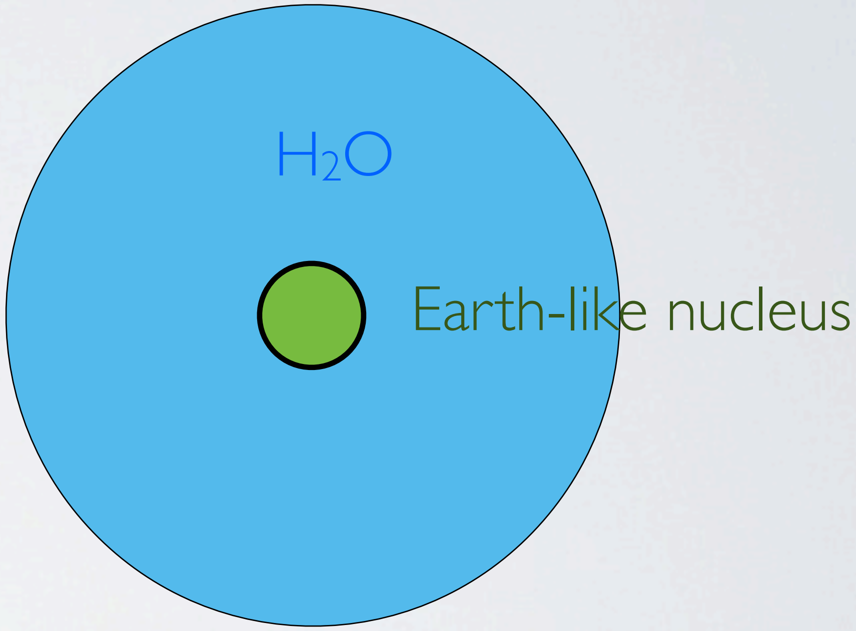


WARM MINI-NEPTUNES

Envelope composition: 100% H_2O + ices



500 K < T_{eq} < 700 K
700 K < T_{eq} < 900 K
900 K < T_{eq} < 1100 K
1100 K < T_{eq} < 1300 K
1300 K < T_{eq} < 1500 K
1500 K < T_{eq} < 1700 K
1700 K < T_{eq} < 2200 K



Valencia & Guillot, in prep

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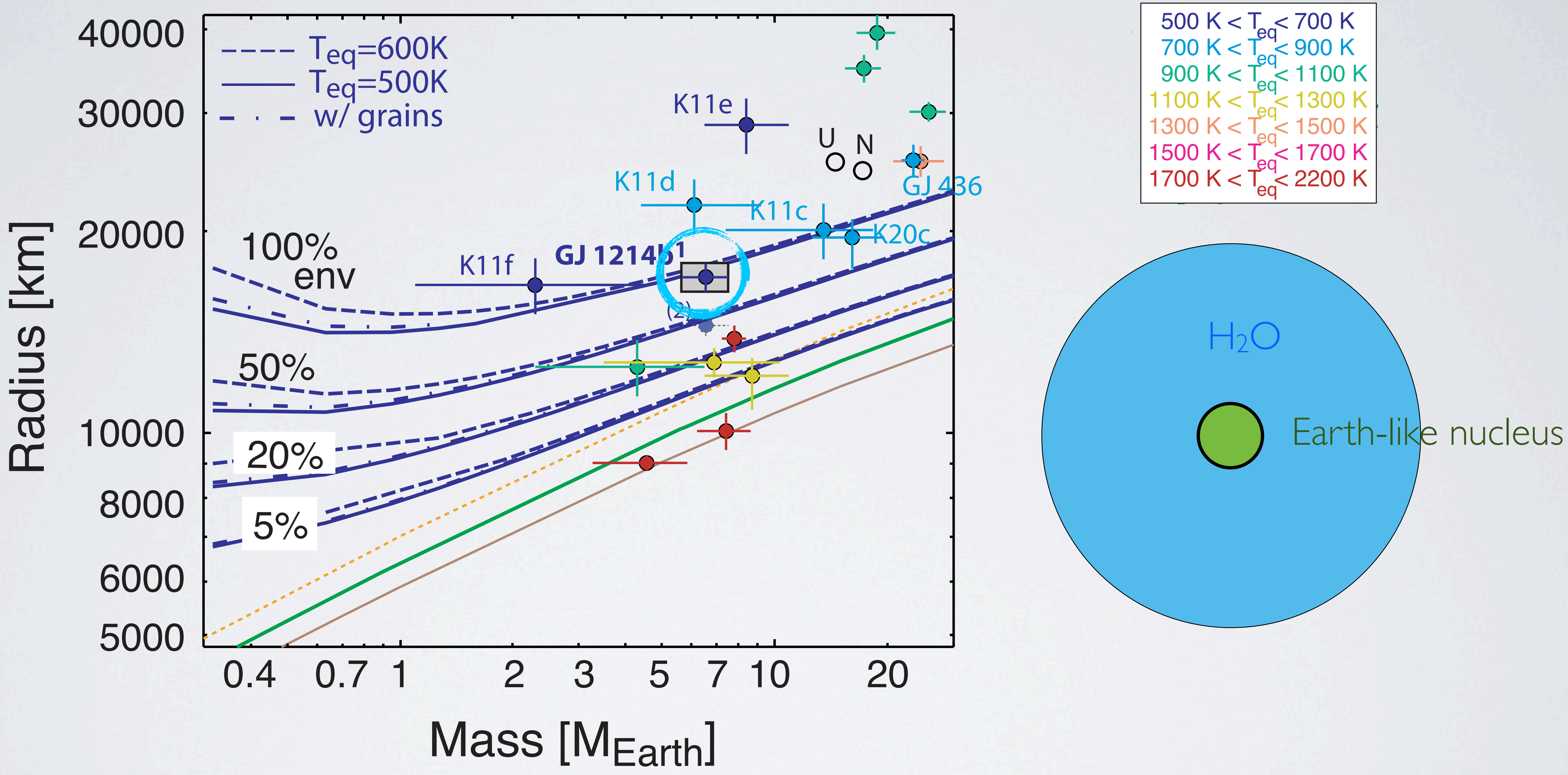

- GJ 1214b must have H-He

Valencia & Guillot, in prep

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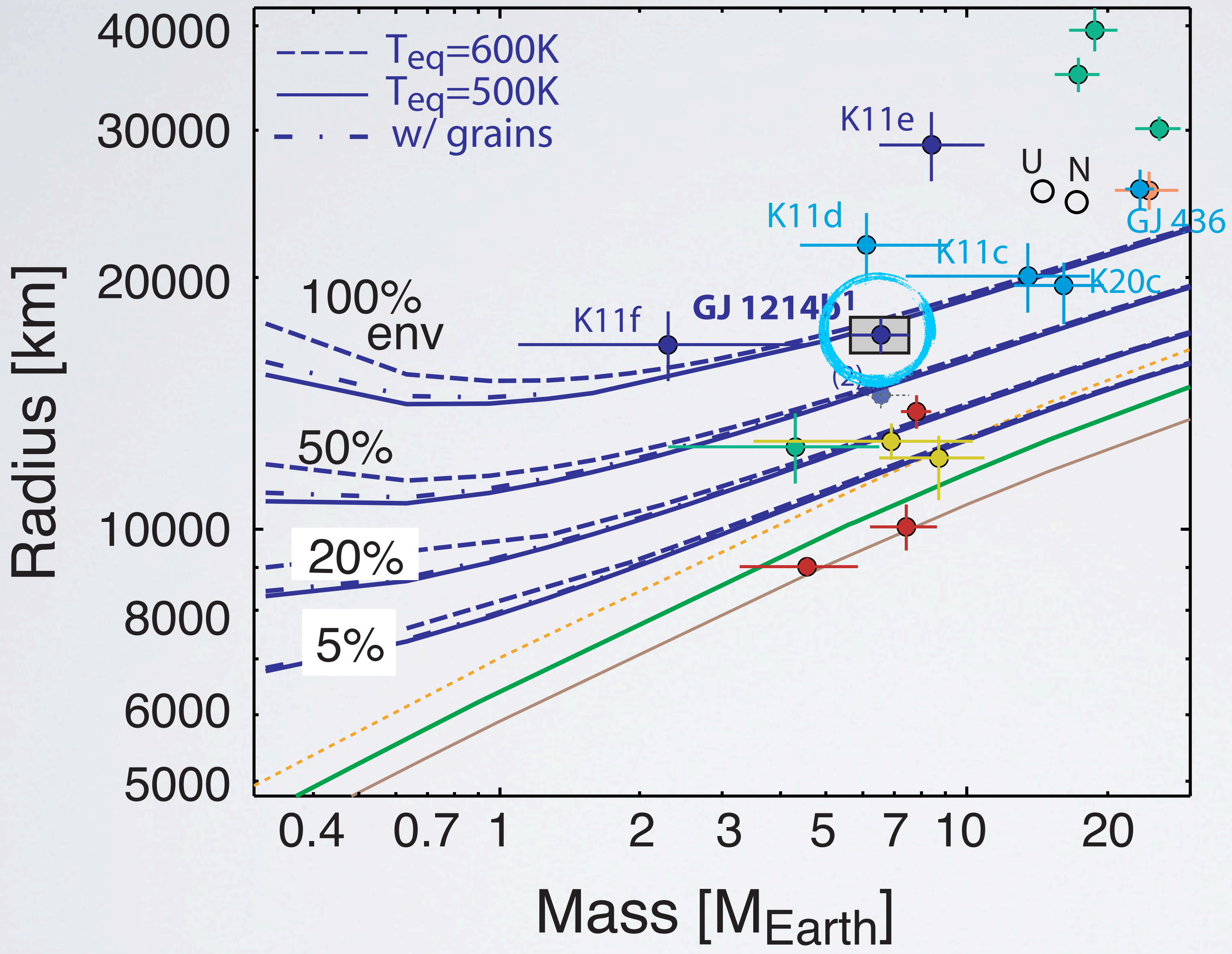

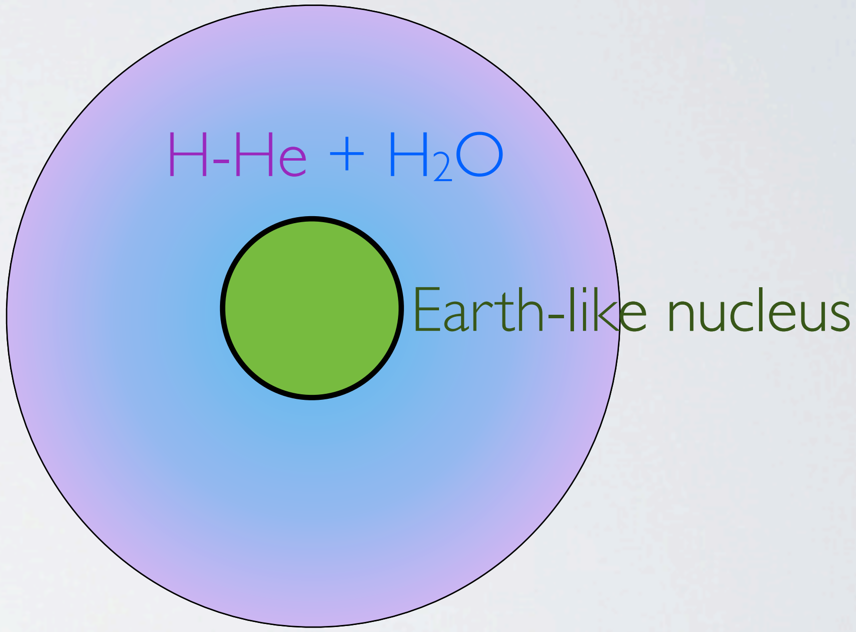

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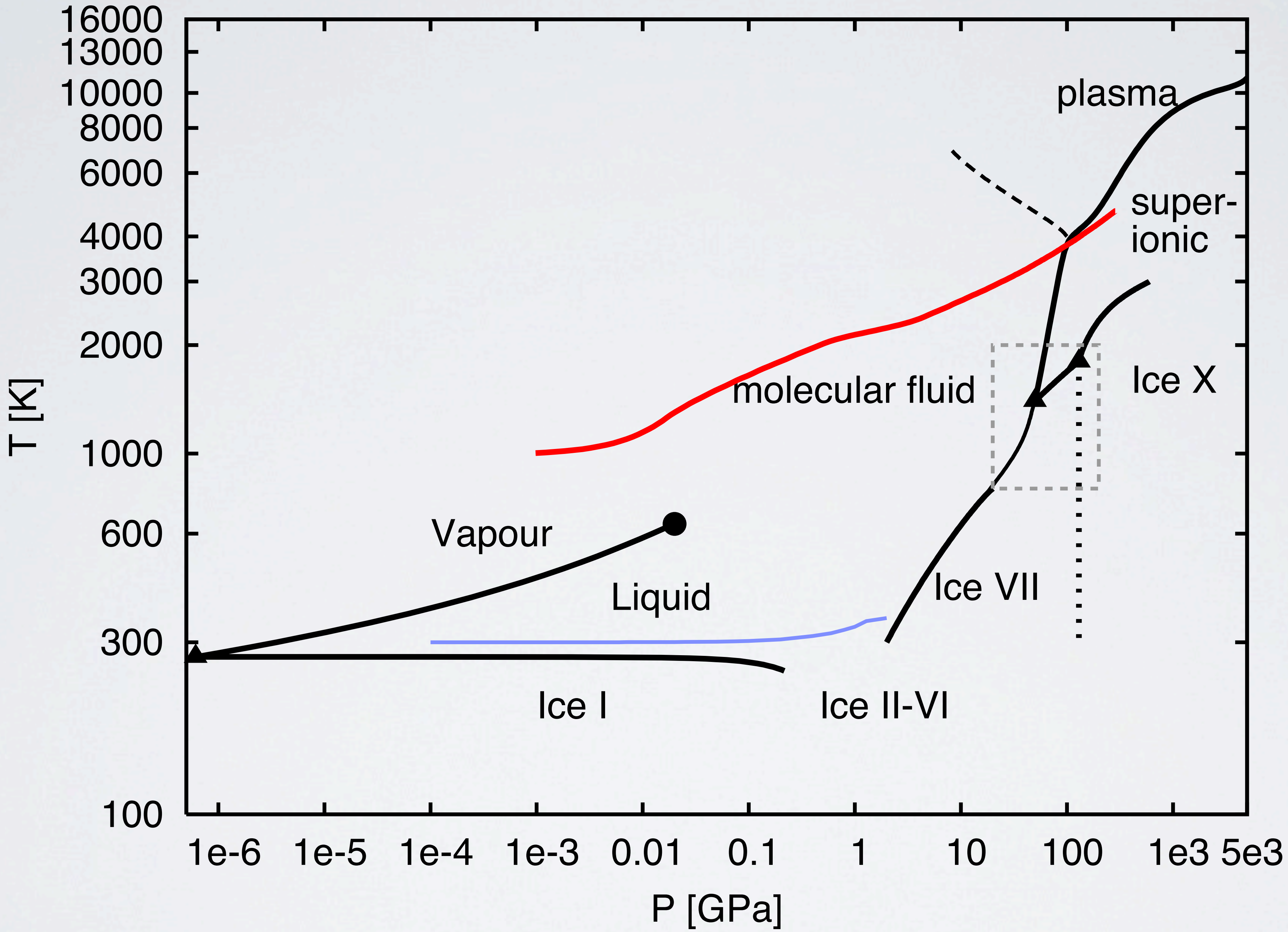
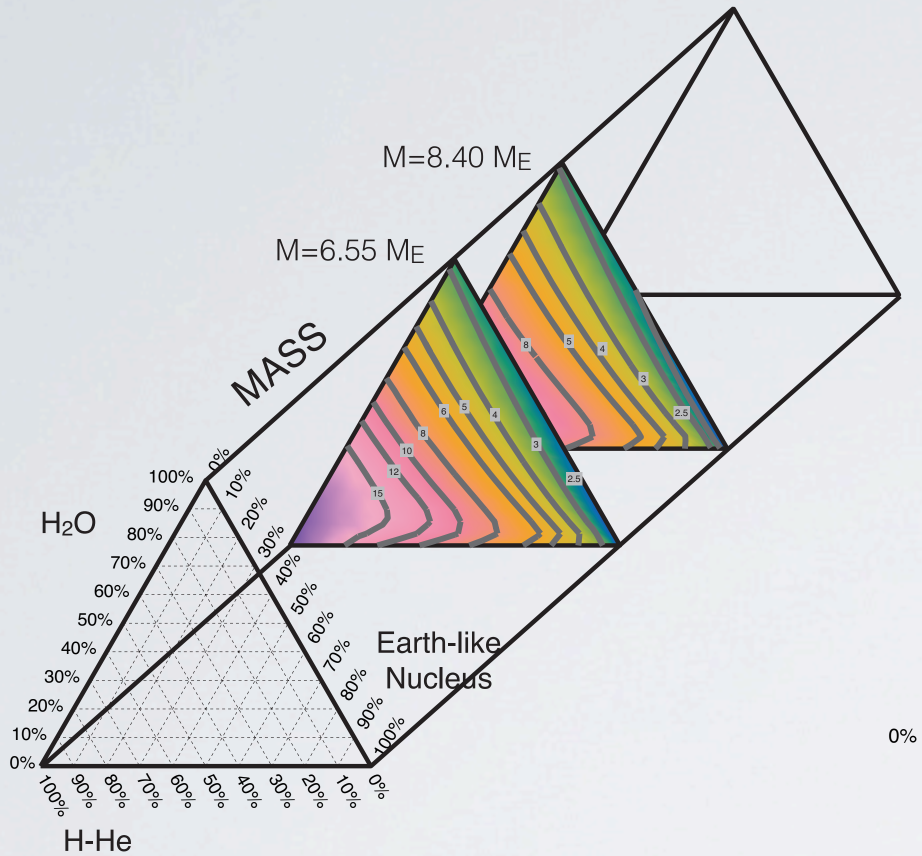
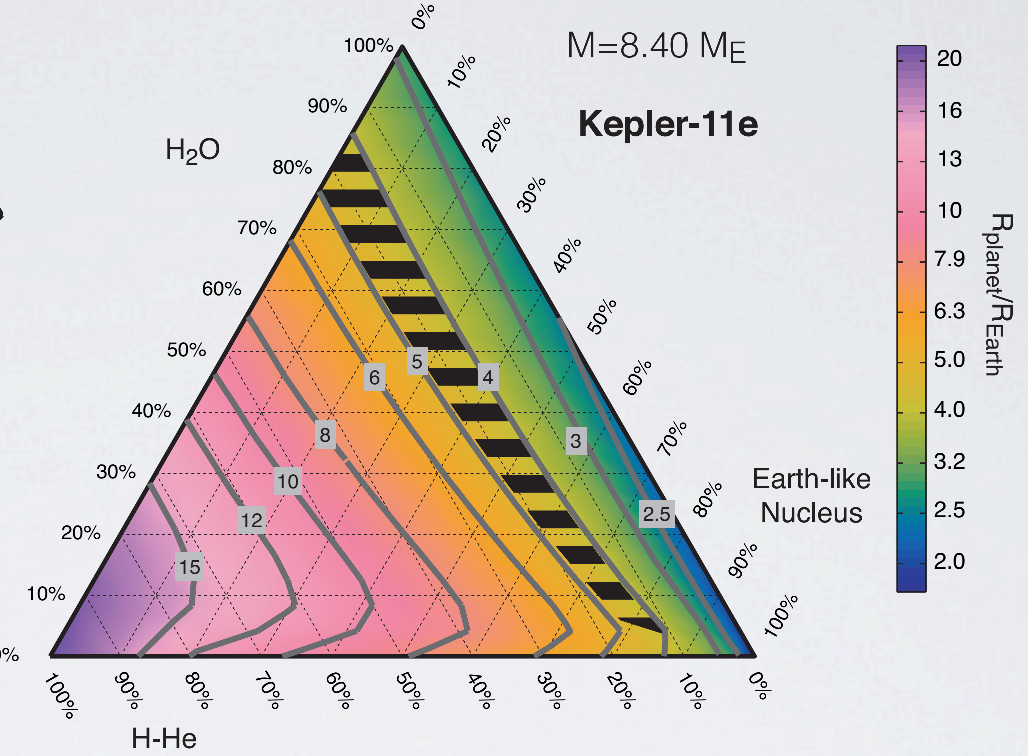
Valencia & Guillot, in prep

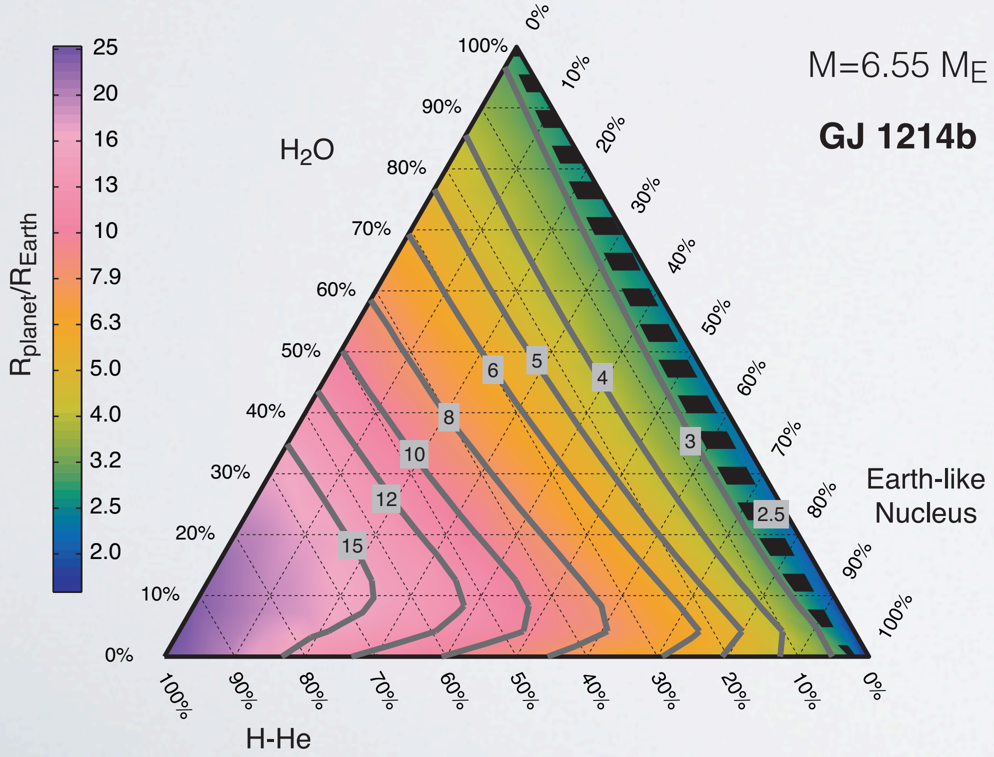
STRUCTURE OF A WATER GJ1214B



NATURE OF ENVELOPES







Valencia & Guillot, in prep

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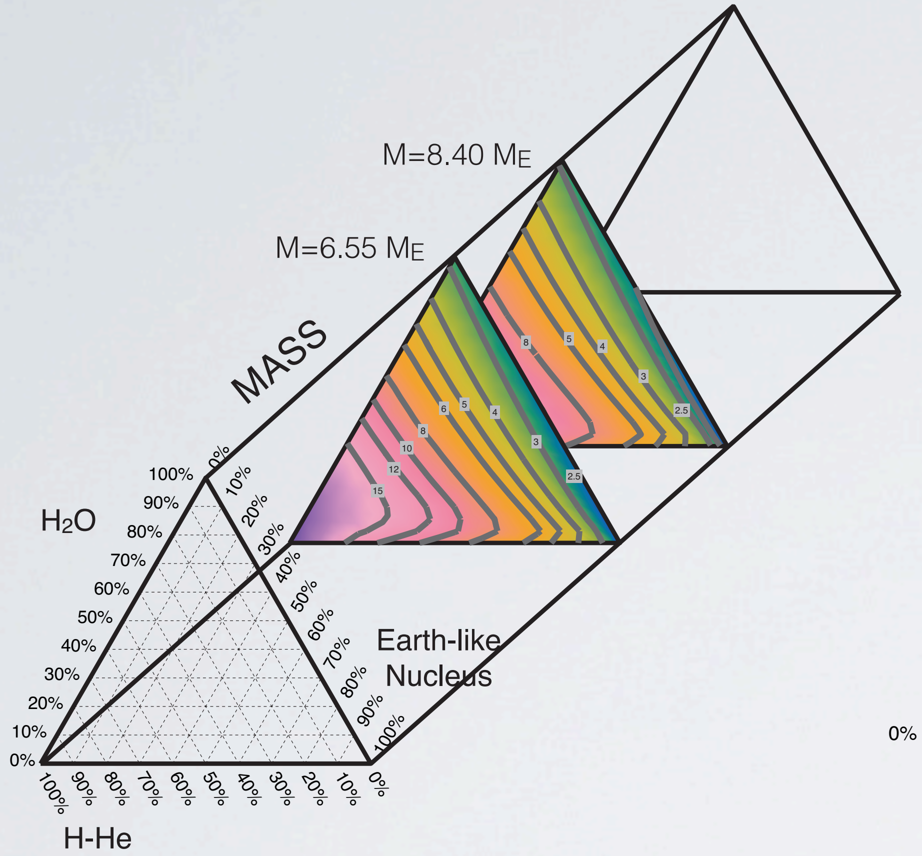
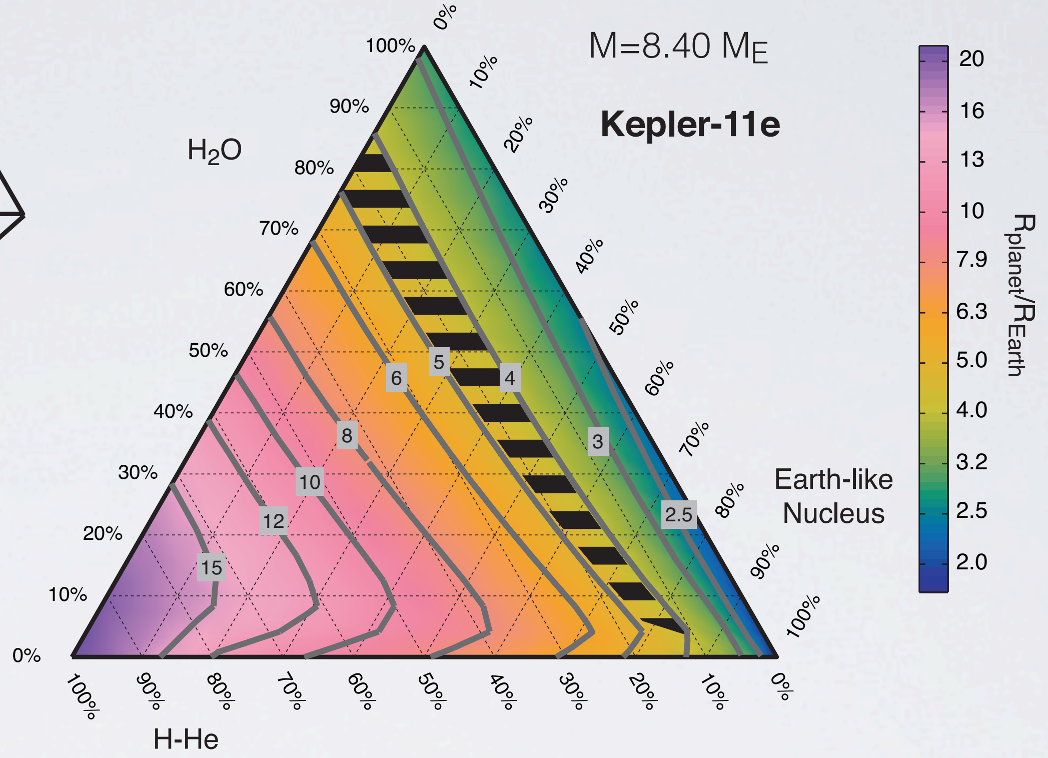
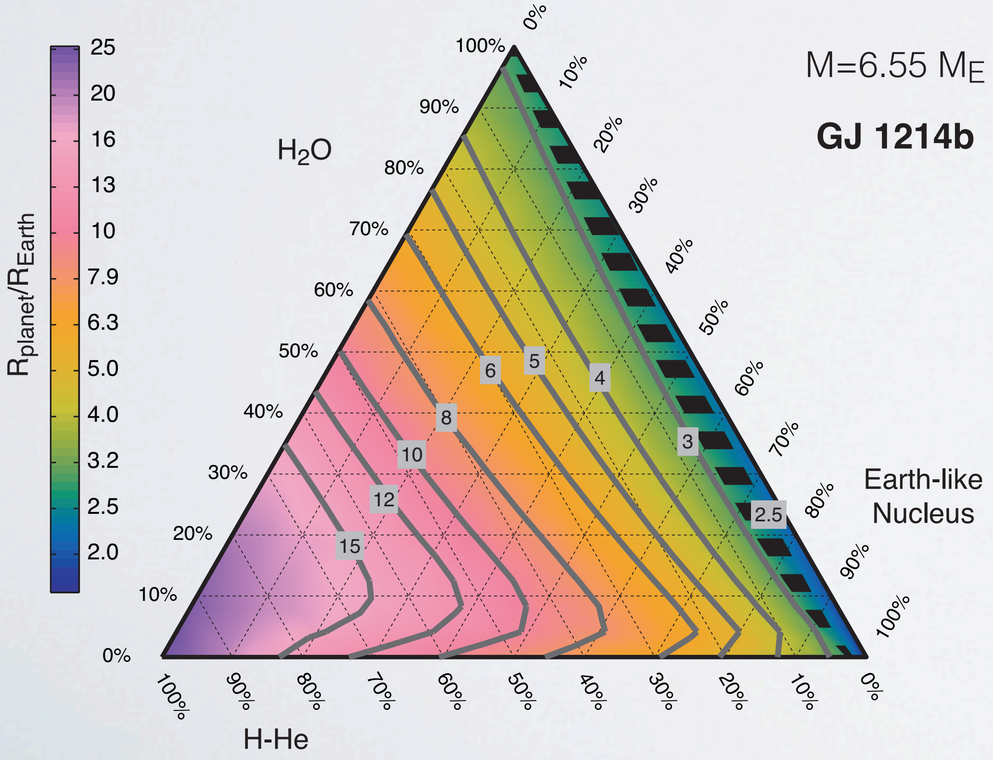






- The content of H-He largely sets the radius of warm mini-Neptunes

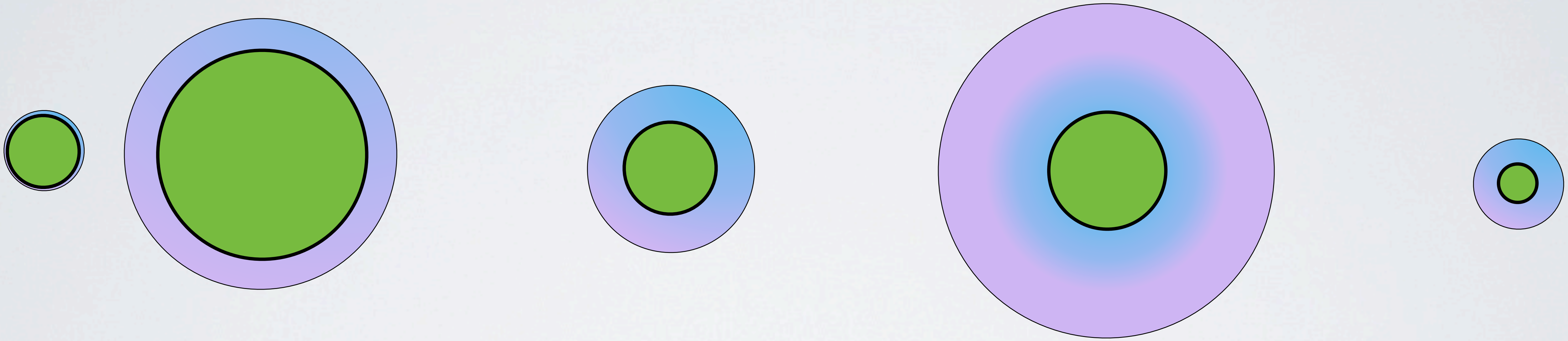
- All low-mass planets ($< 10M_E$) detected so far have less than 10% H-He, except for Kepler-11e which has 10-25% H-He

Valencia & Guillot, in prep

FORMATION & COMPOSITION

FORMATION & COMPOSITION

Kepler 11 system:



b	c	d	e	f
$4M_E$	$13M_E$	$6M_E$	$8M_E$	$2M_E$
	<10% H-He	<10% H-He	10-25% H-He	<10% H-He

FORMATION & COMPOSITION

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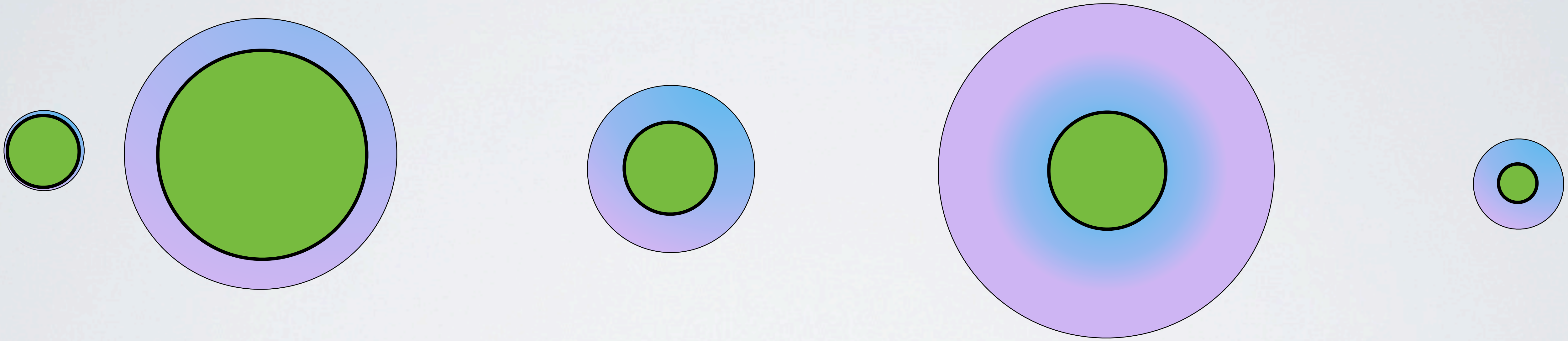

b

c

d

e

f

$4M_E$

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<10% H-He

How do you make this system?

FORMATION & COMPOSITION

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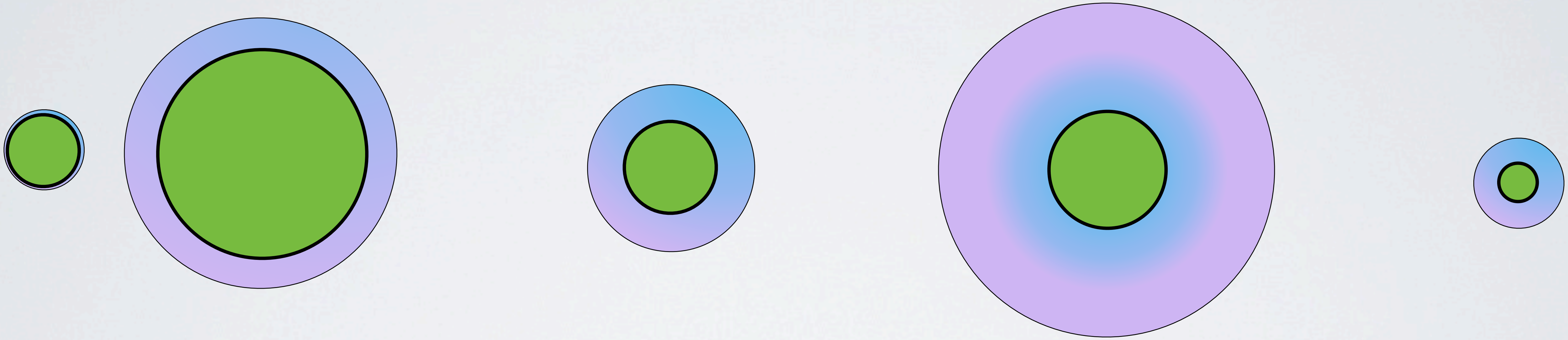

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How do you make this system?

see Ikoma & Hori, 2012

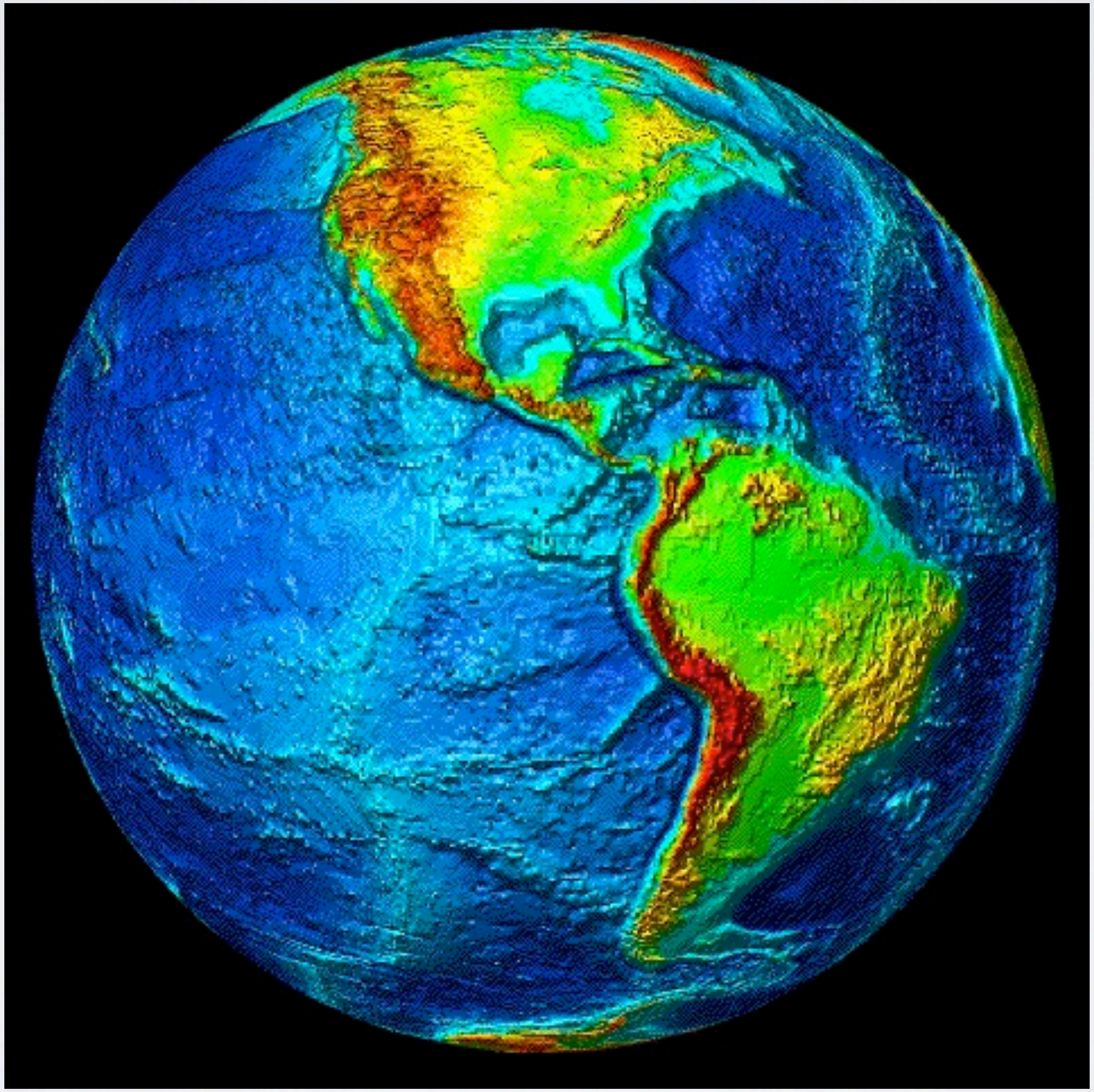
SUMMARY

The data for exoplanets mostly constitutes mass, radius, orbital parameters, and coarse spectra

Smaller planets are abundant

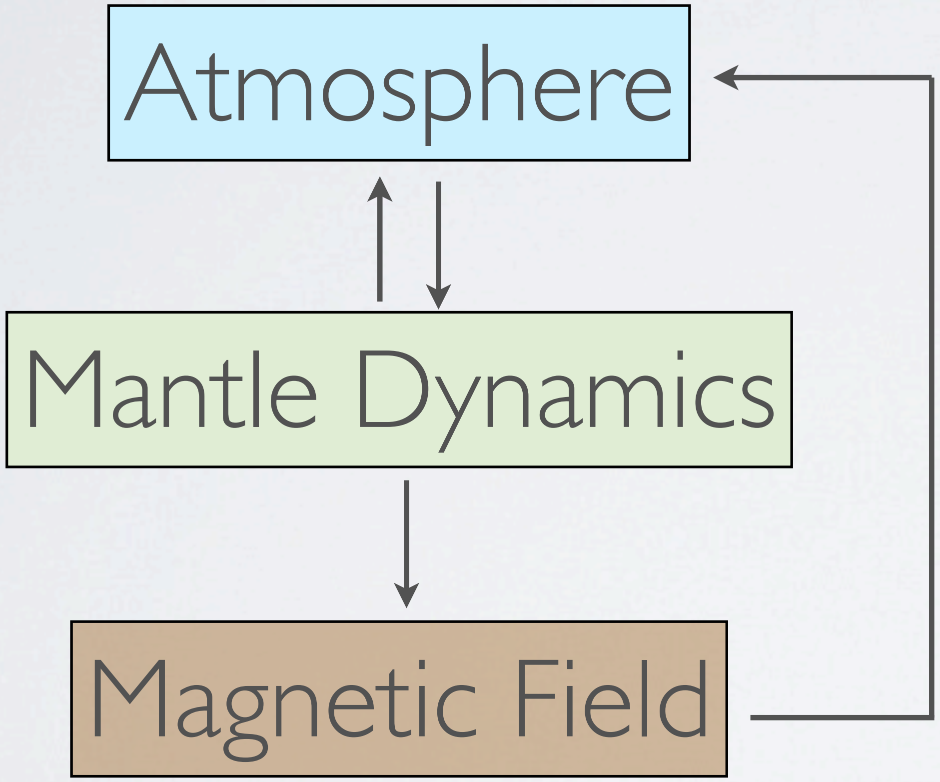
Within a small mass range (2-10 M_E) there is a variety of properties in planets

INTERIOR DYNAMICS



INTERIOR DYNAMICS

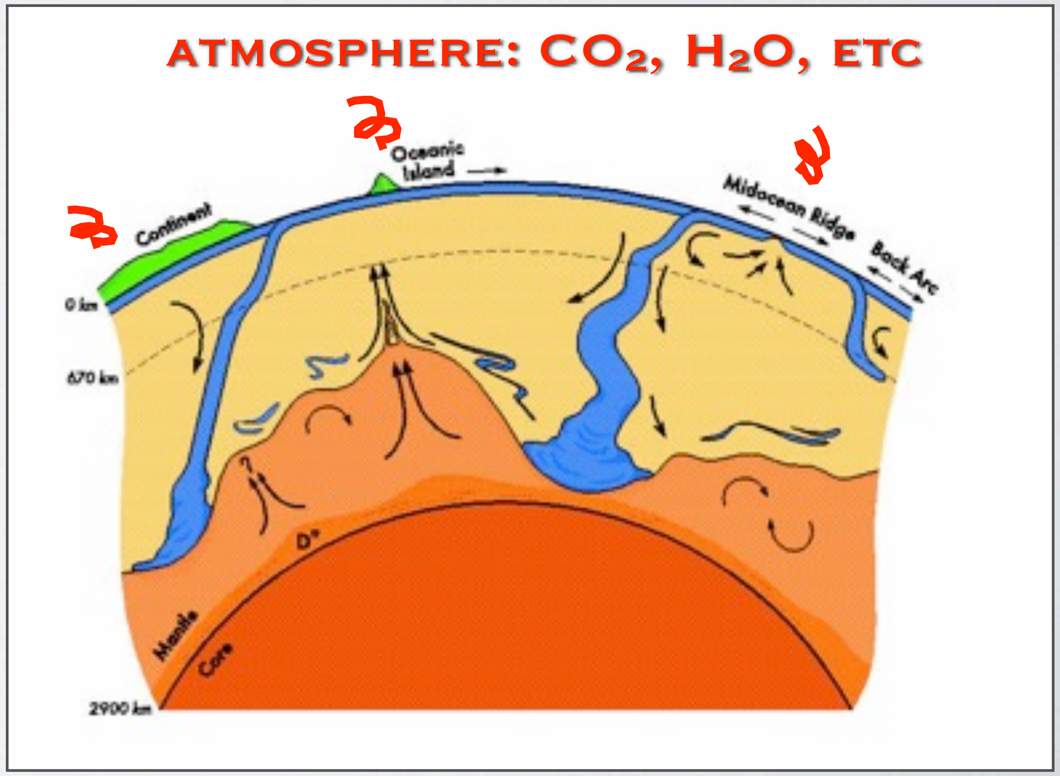
- A planet evolves habitable conditions
- Composition of atmosphere gets set by degassing and loss mechanisms
- Mantle dynamics affects the existence of a magnetic field



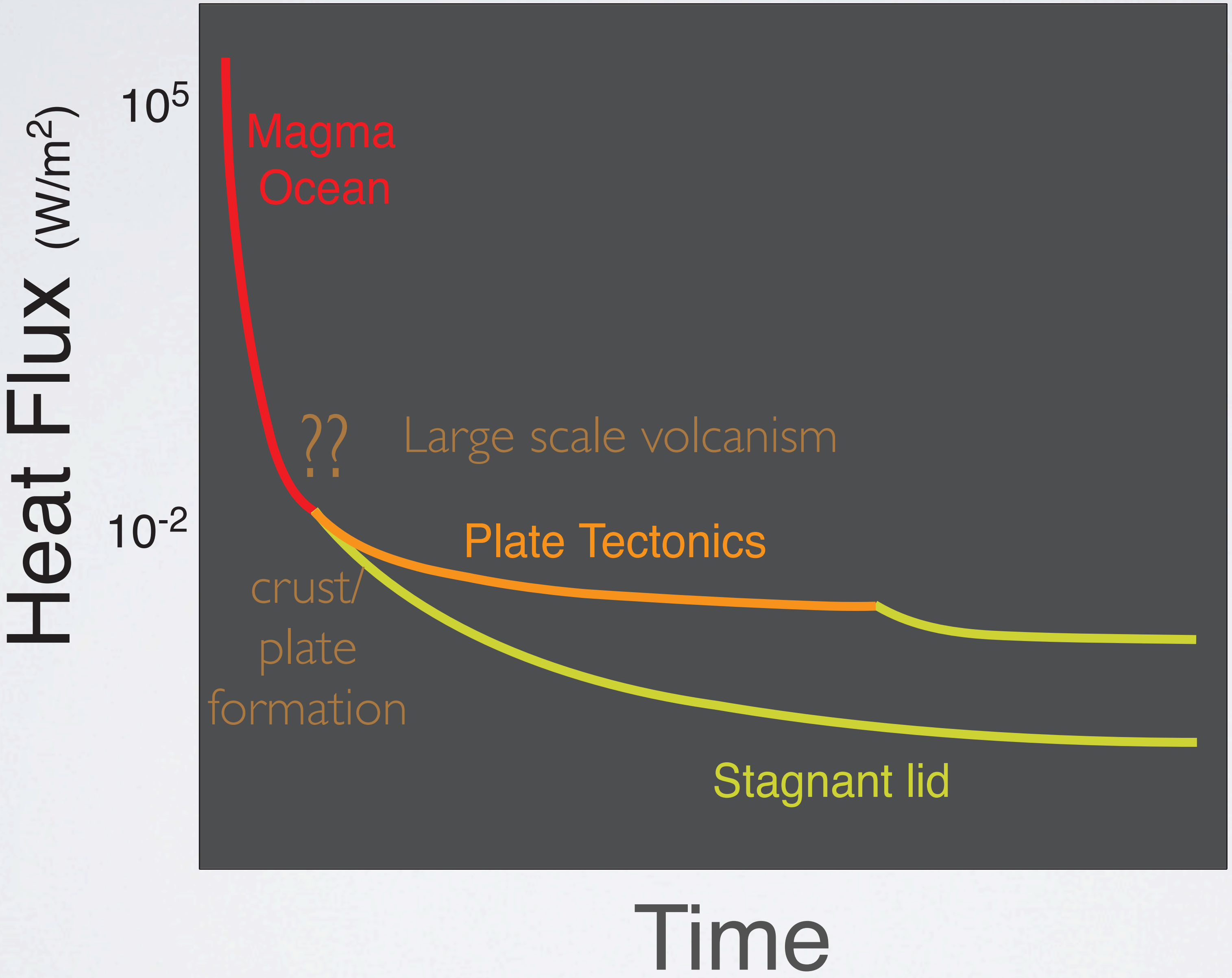
Atmosphere

Mantle Dynamics

Magnetic Field



QUALITATIVE TERRESTRIAL EVOLUTION



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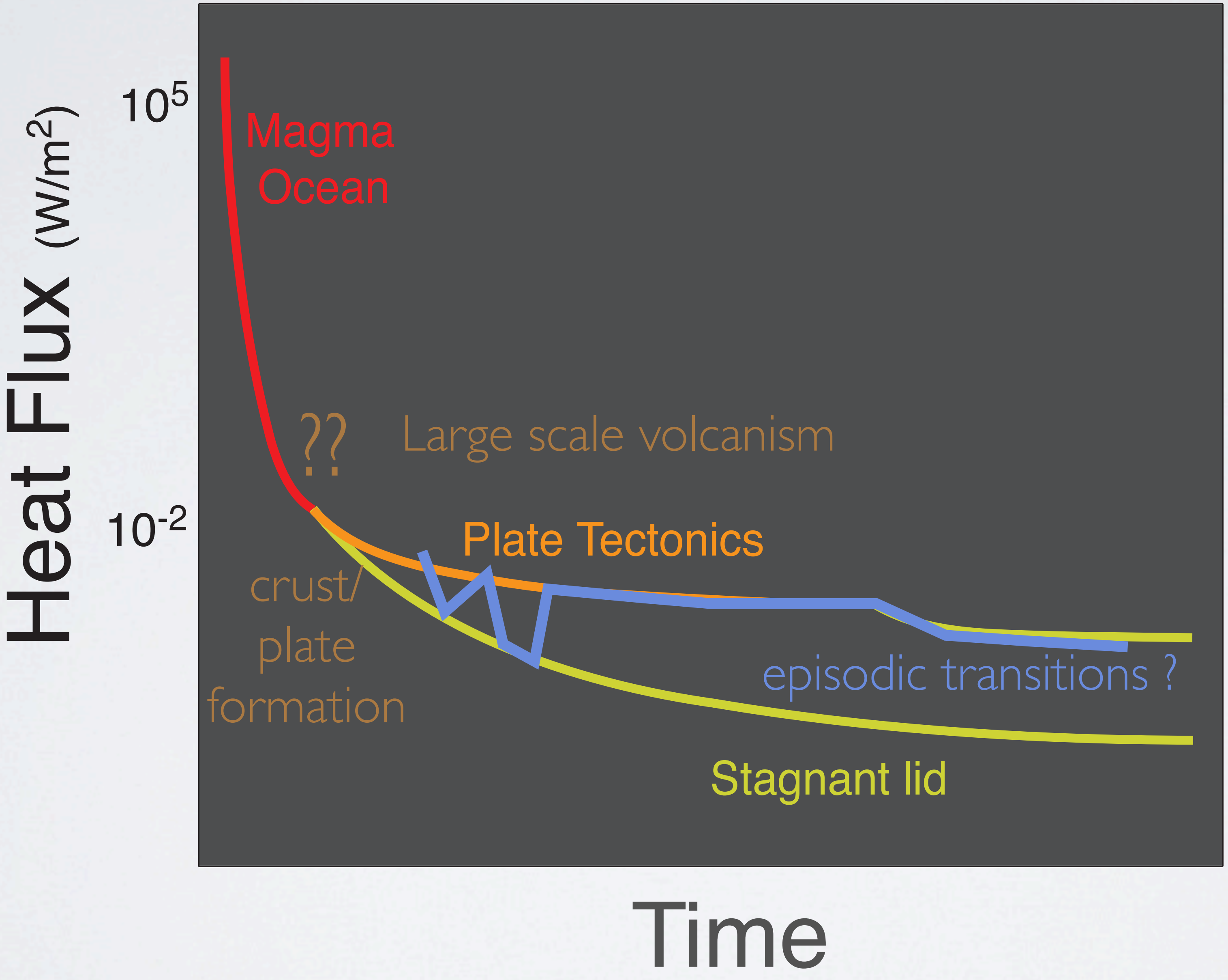
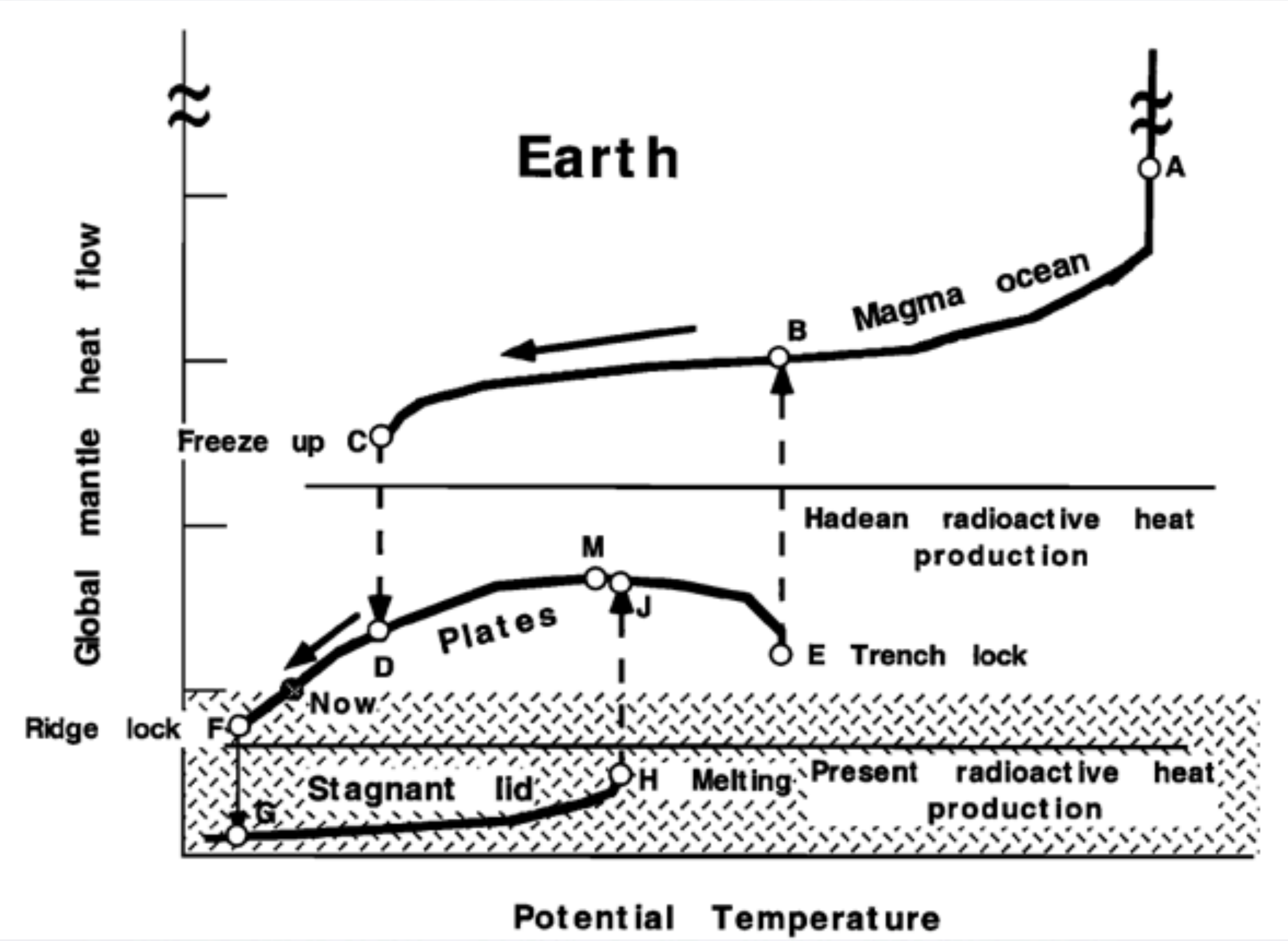
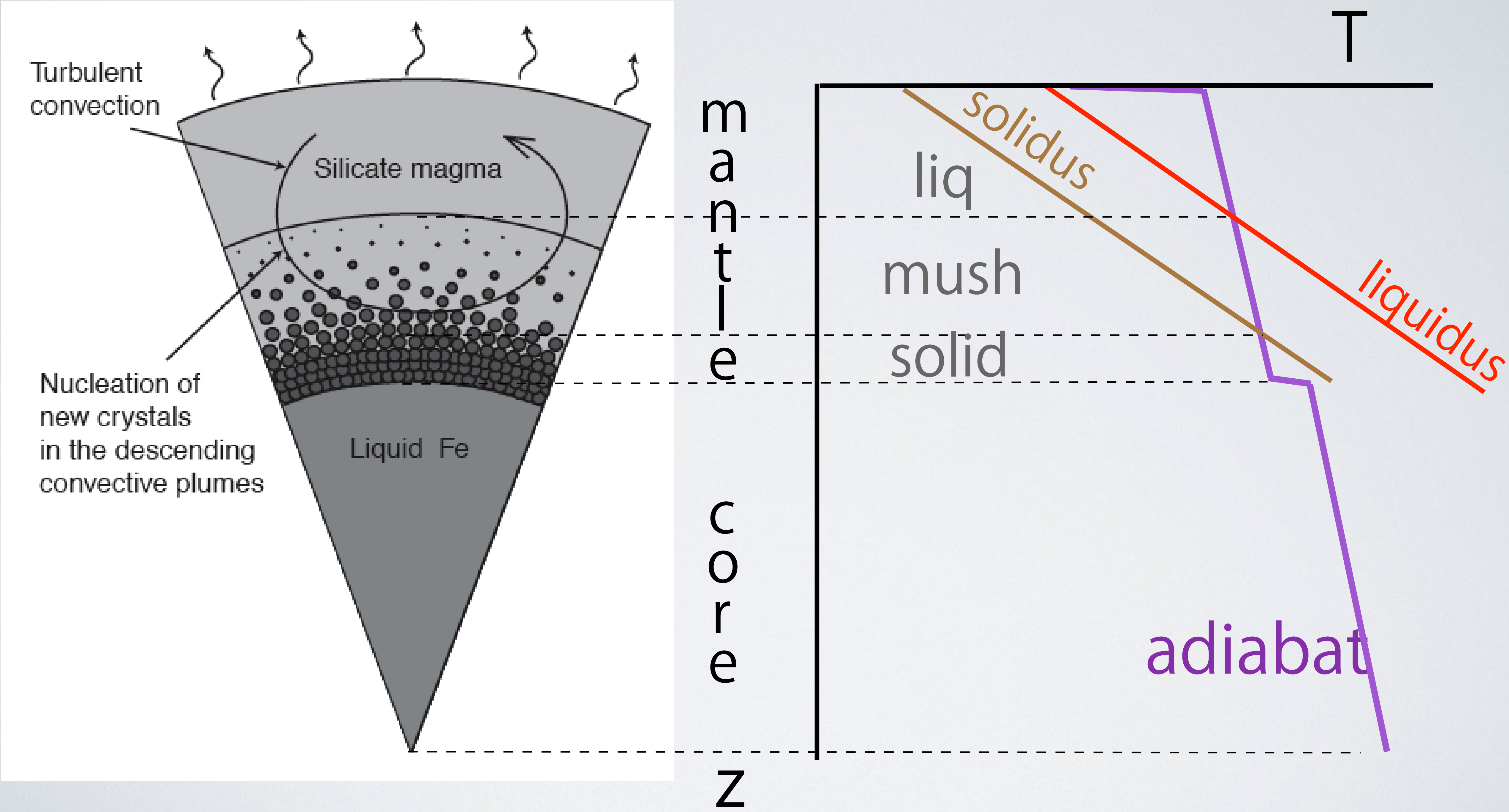


EPISODIC EVOLUTION



Sleep, 2000

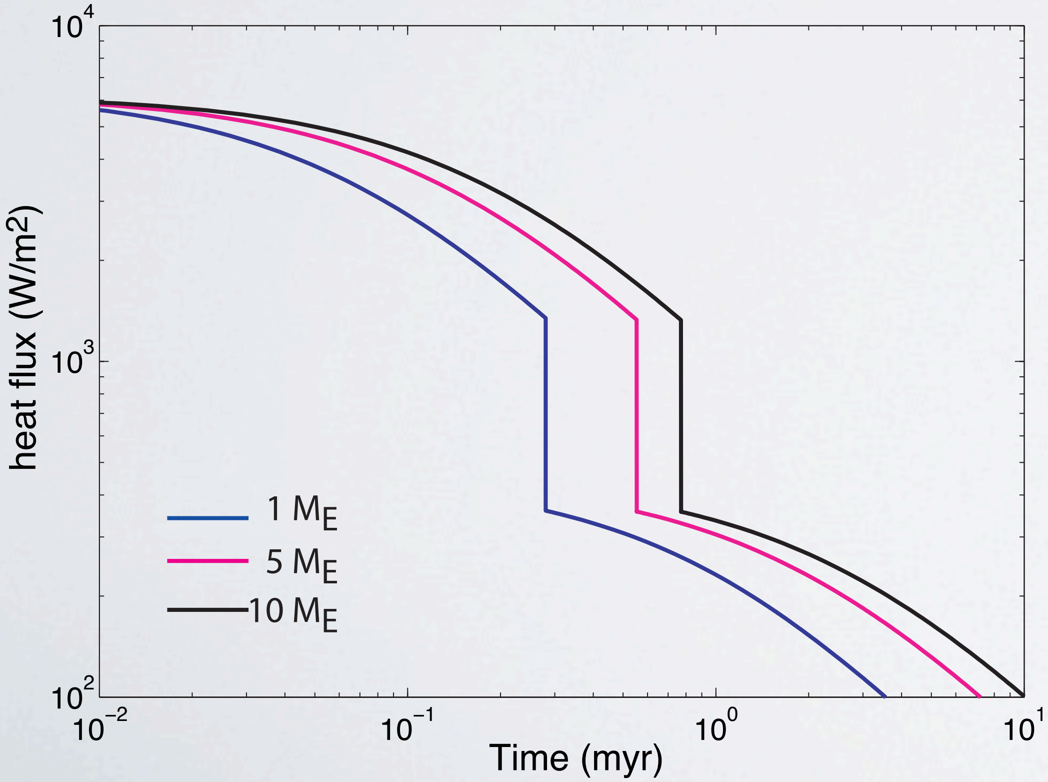
MAGMA OCEANS



Solomatov 2000

MAGMA OCEANS

- The brightest epoch of the lifetime of a terrestrial planet
- Perhaps amenable to direct detection
- There is a trade-off between brightness and lifetime. There might be a sweet-spot for observations



Valencia & Pierrehumbert, in prep

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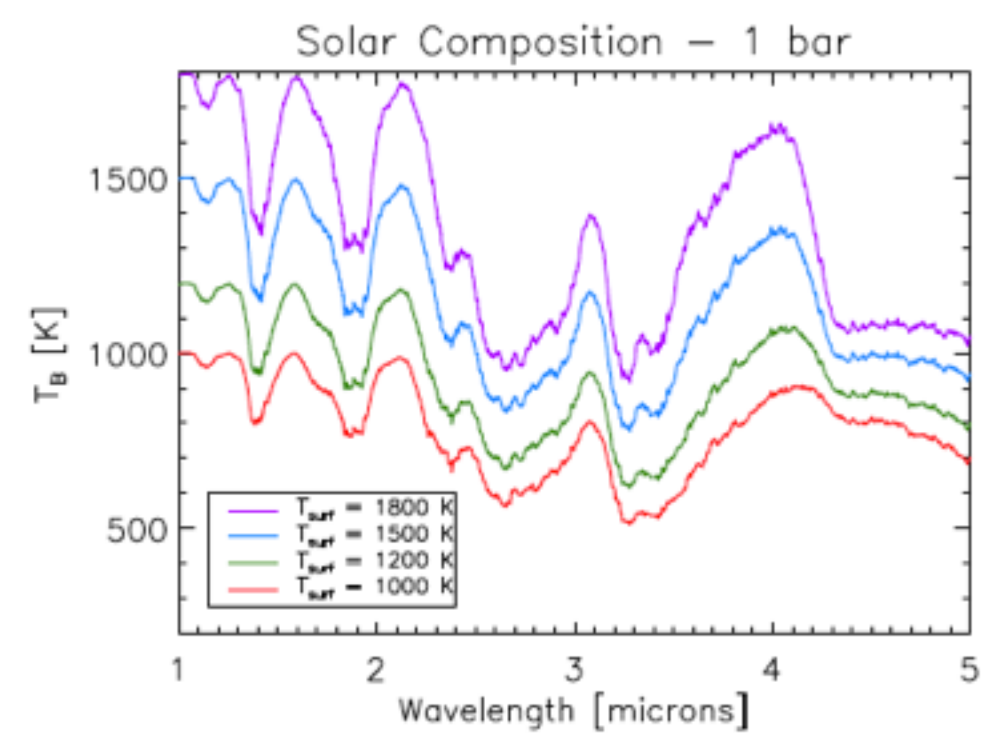
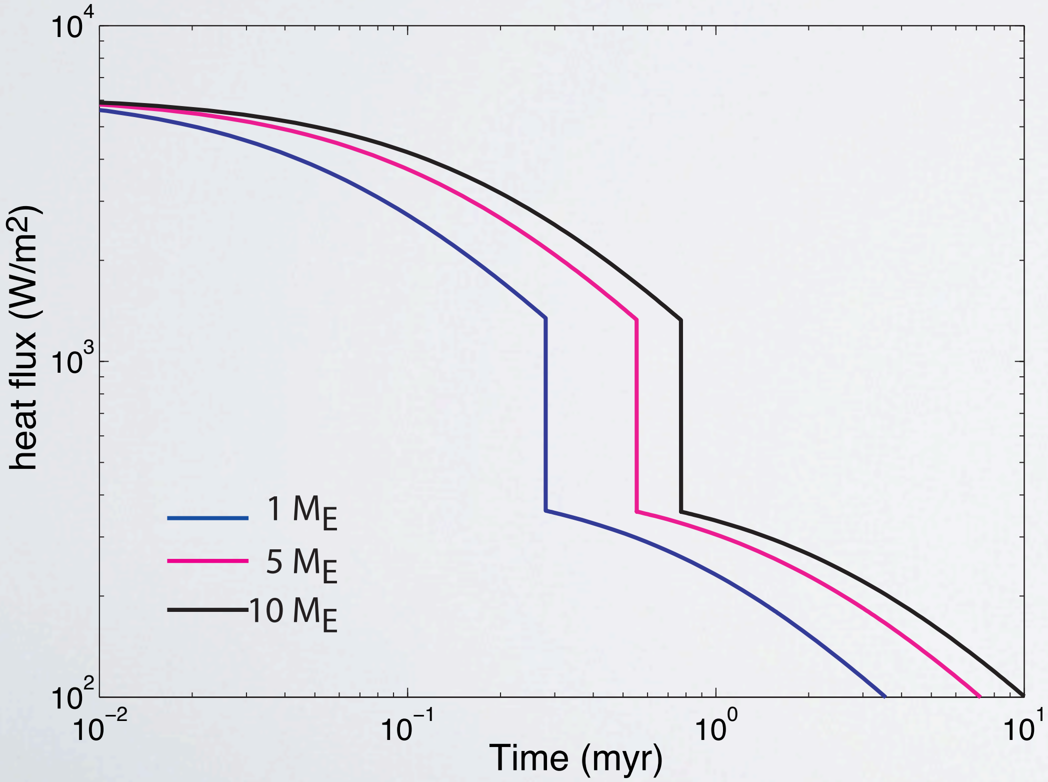
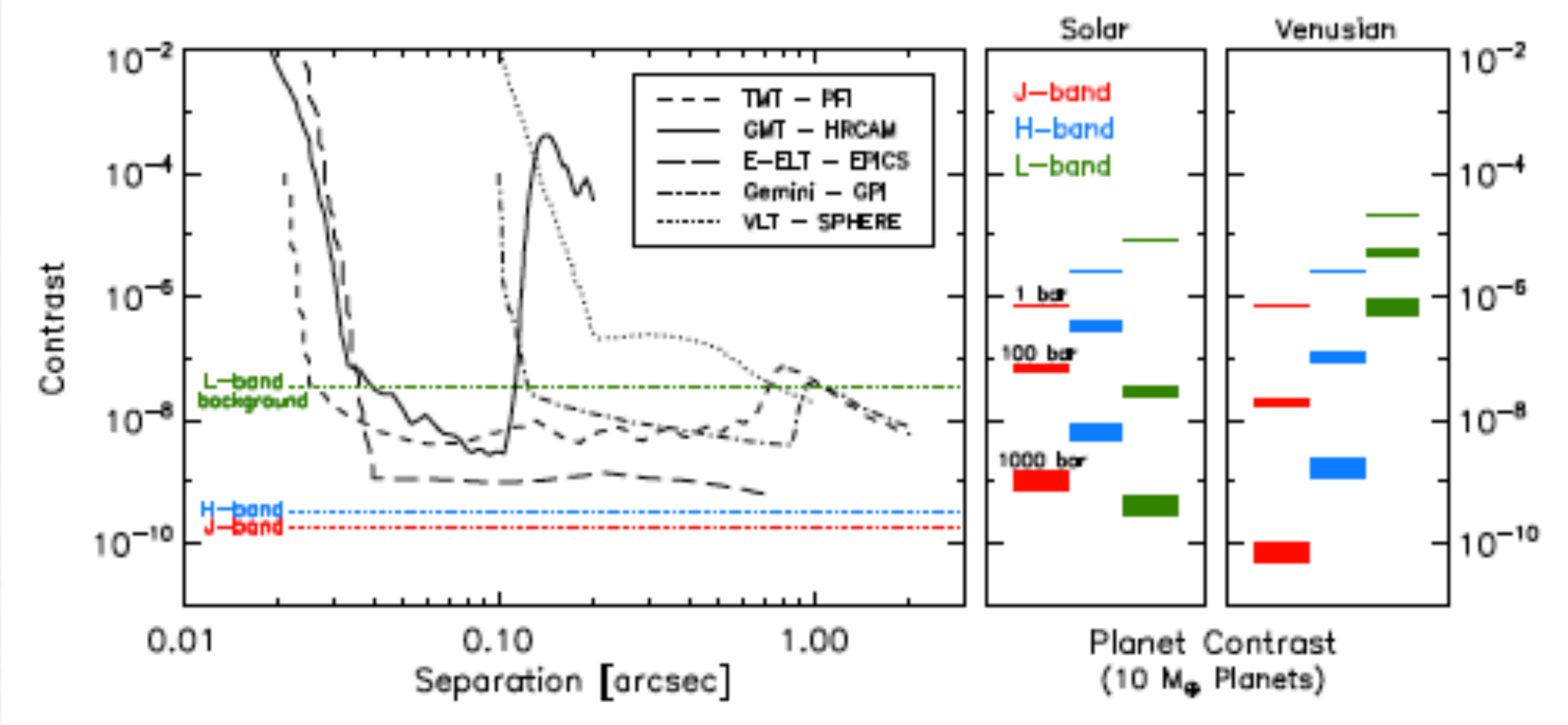


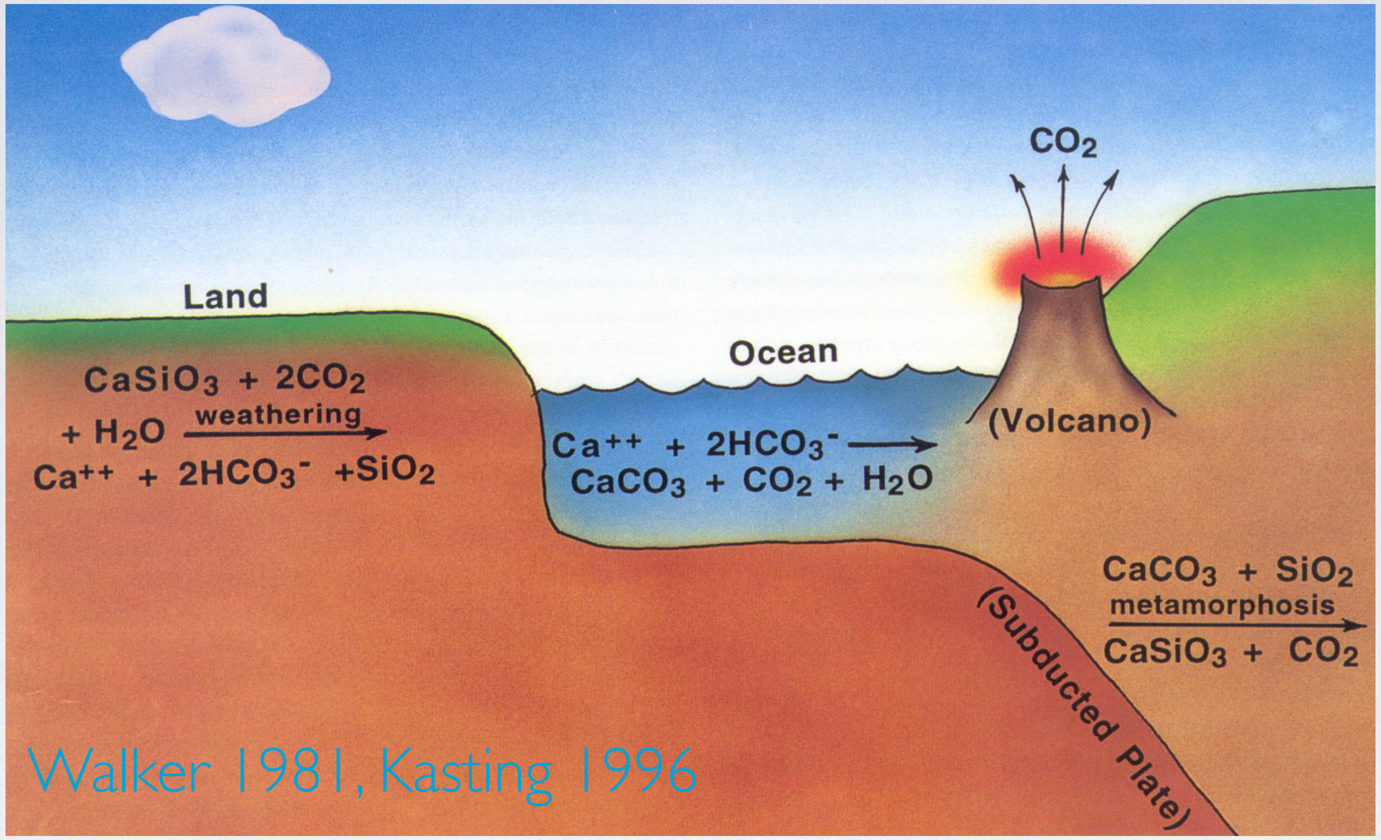




Valencia & Pierrehumbert, in prep

Miller-Ricci et al 2009

PLATE TECTONICS

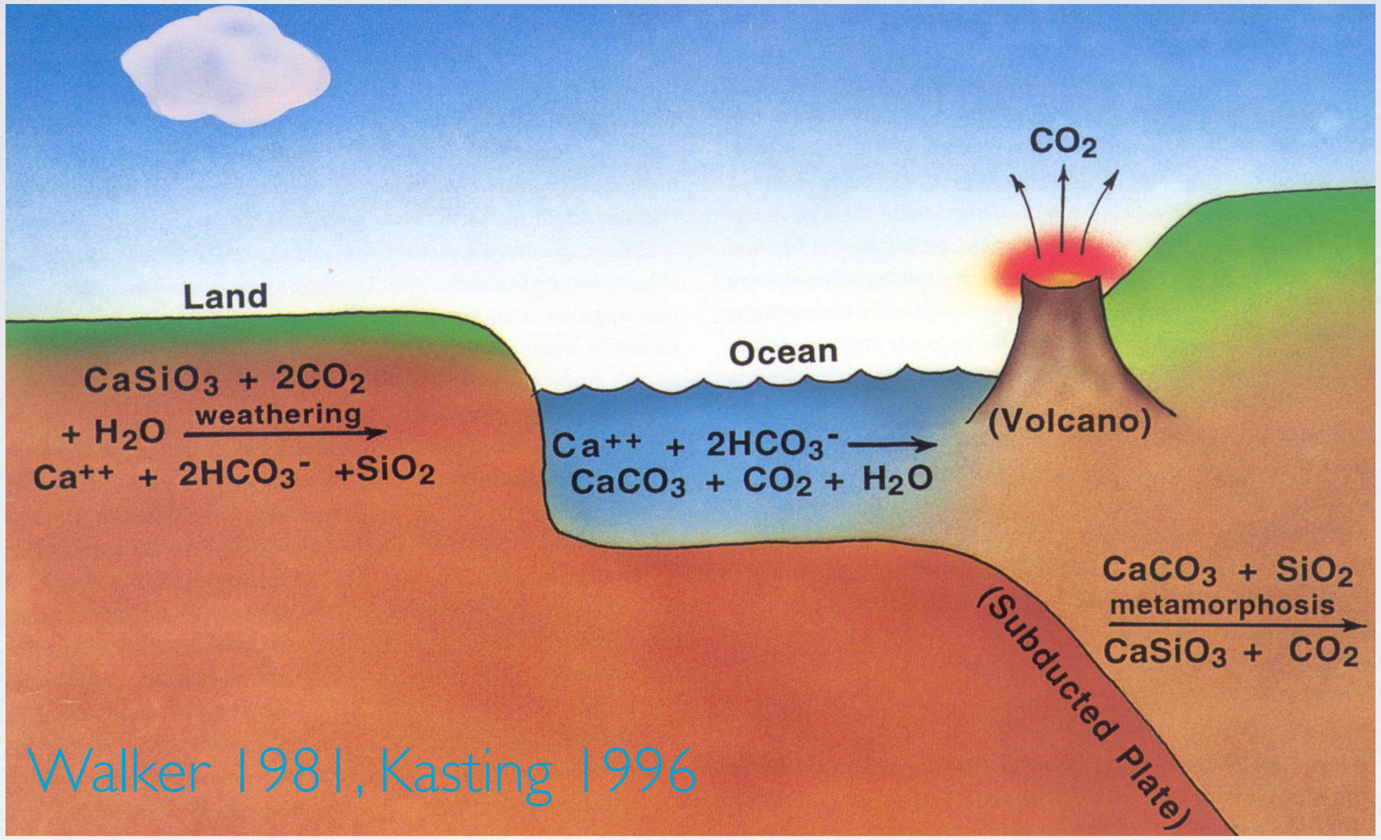


Walker 1981, Kasting 1996

Mode of convection is expected to have an influence on the degassing history of the planet

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

PLATE TECTONICS



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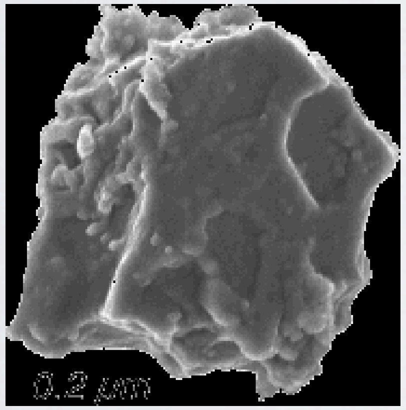
Is it the only mechanism to regulate climate?
How about episodic foundering like that in Io?

PLATE TECTONICS & MINERALS

Does the origin of life require some minimal degree of mineral evolution? -- Robert Hazen

To go from 12 minerals to more than 4300 at the Earths surface:
Water, Plate Tectonics, Oxidation



Pre-solar grains

CAIs, chondrites

Diversity of minerals

INTERIOR DYNAMICS: MODELING

Navier-Stokes eqns

$$\boldsymbol{\nabla} \cdot (\rho\, \mathbf{u}) = 0$$

$$\rho\, \mathrm{D}_t\, \mathbf{u} = \boldsymbol{\nabla} p + \boldsymbol{\nabla} \cdot (\,\eta\ \ \nabla\ \mathbf{u}) + \rho\, g\, \hat{r}$$

$$\rho C p\ \mathrm{D}_t\, T - \ \alpha\ T\, \mathrm{D}_t\, P = \boldsymbol{\nabla}\ \mathbf{u} : \boldsymbol{\sigma}\ + \boldsymbol{\nabla} \cdot (k \boldsymbol{\nabla} T) + \rho H$$

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- Computational Approach

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

$$\nabla \cdot \boldsymbol{\sigma} - \nabla p = Ra\, \hat{\mathbf{r}}\, \rho / \Delta\rho$$

$$\rho C p\ D_t\, T = -Di\ (\alpha\, \rho\, T\, v_r + Ra^{-1}\ \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}) + \nabla \cdot (k \nabla T) + \rho H$$

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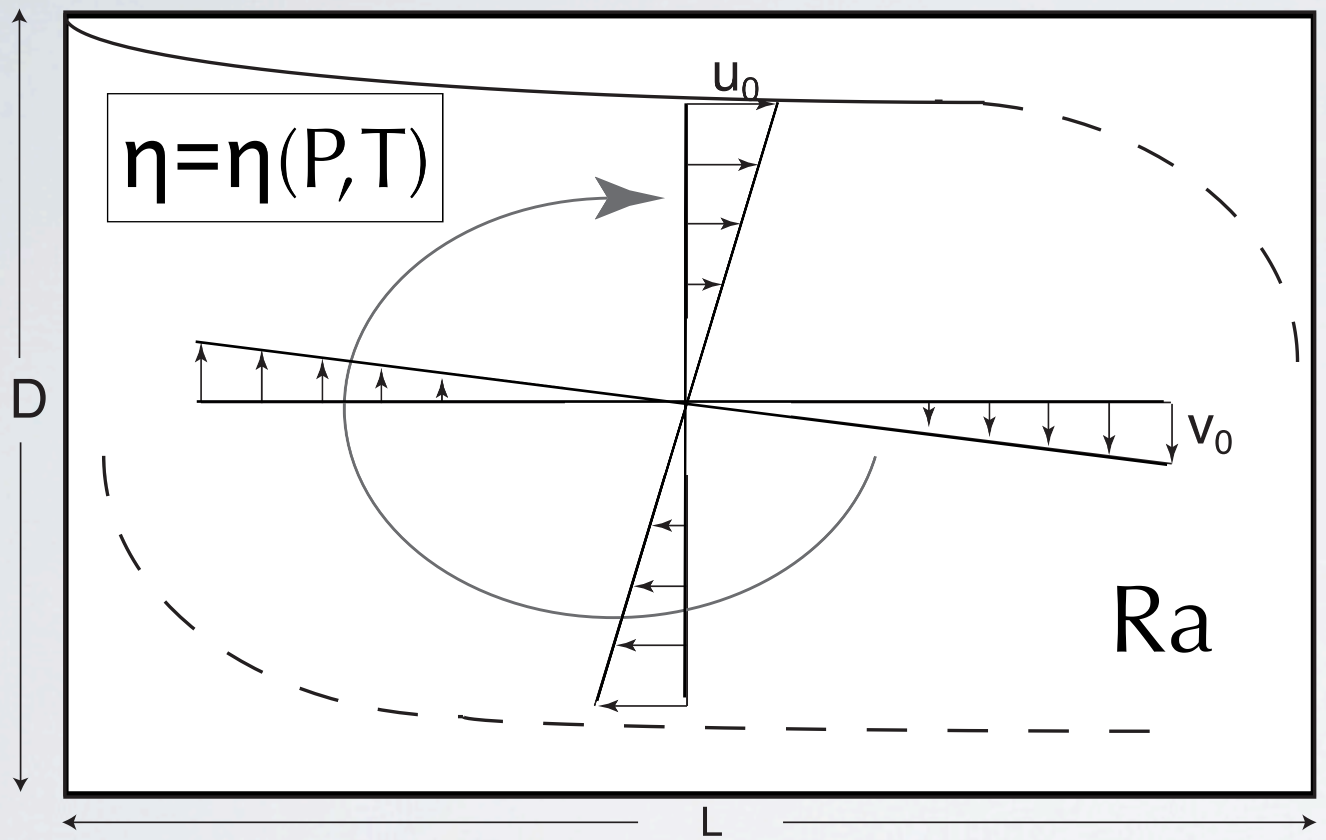


see Turcotte & Schubert (book)
Hager & O'Connell (1982)

Boundary conditions

- System heated from within
- System heated from below

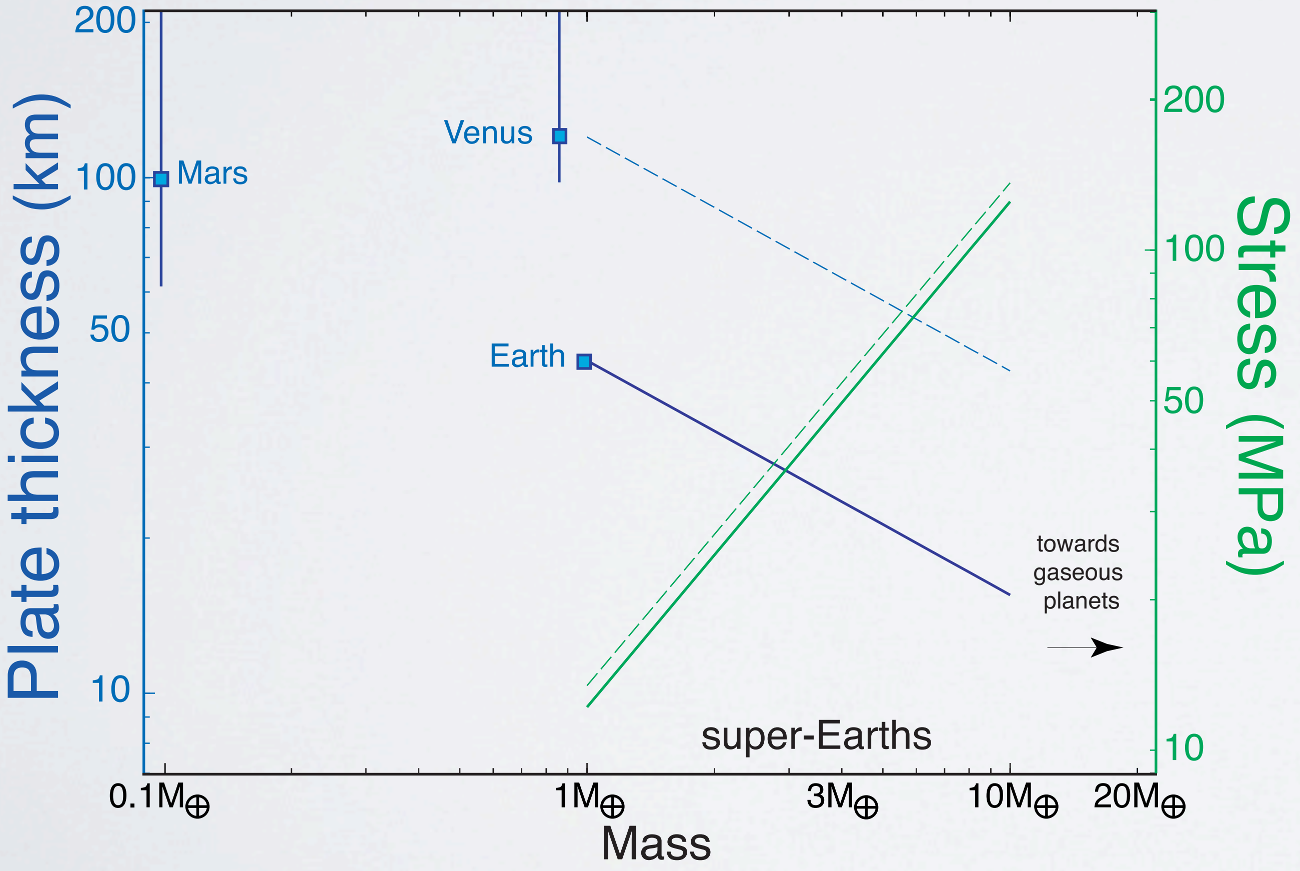
$$\boxed{Ra = \rho g \alpha D^4 q/(\kappa \eta k)}$$

$$D/2\delta \sim (Ra/Ra_c)^{1/4}$$

$$\Delta\tau_{xy} \sim \kappa(L/D)\eta/D^2(Ra/Ra_c)^{2/3}$$

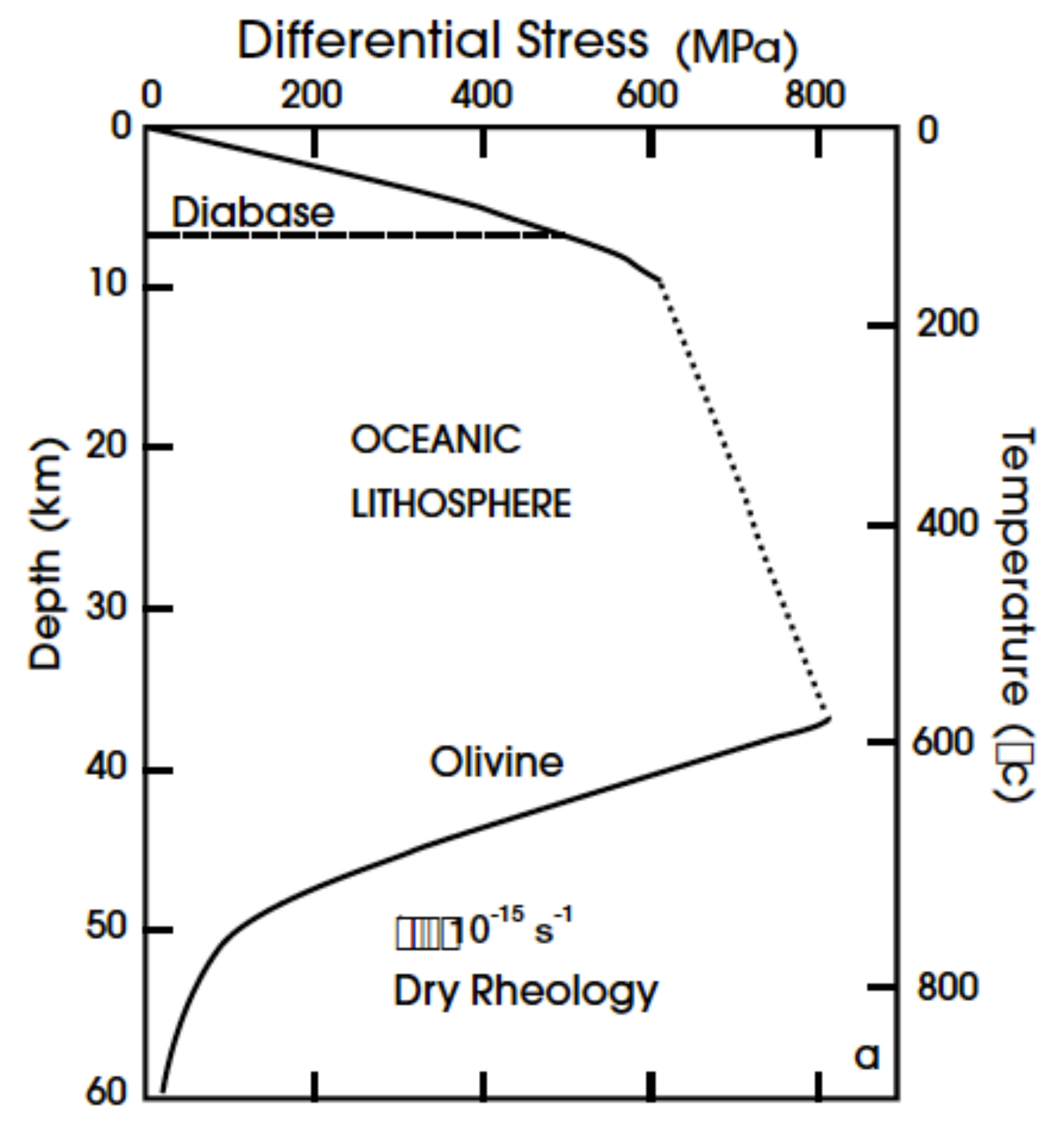
Valencia et al ’07:

- more likely to have PT, based on thinner planets and larger convective stresses
- pressure-temperature structure of plates are very similar (T increases only slightly)



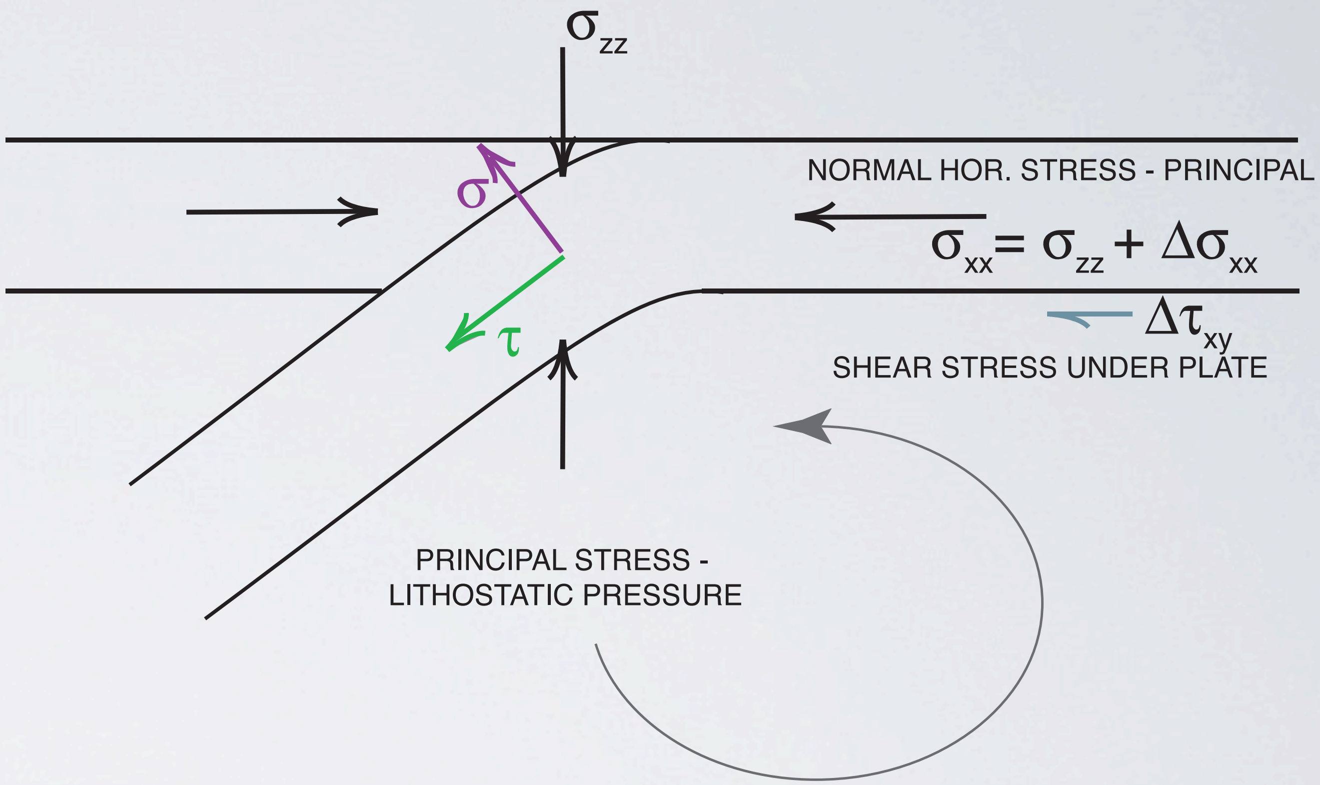
Valencia et al., 2007

PLATES NEED TO FAIL



Bercovicci, 2003

COULOMB FAILURE



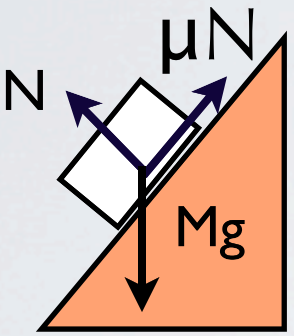
$\tau/\sigma_y > 1$ subduction, PT

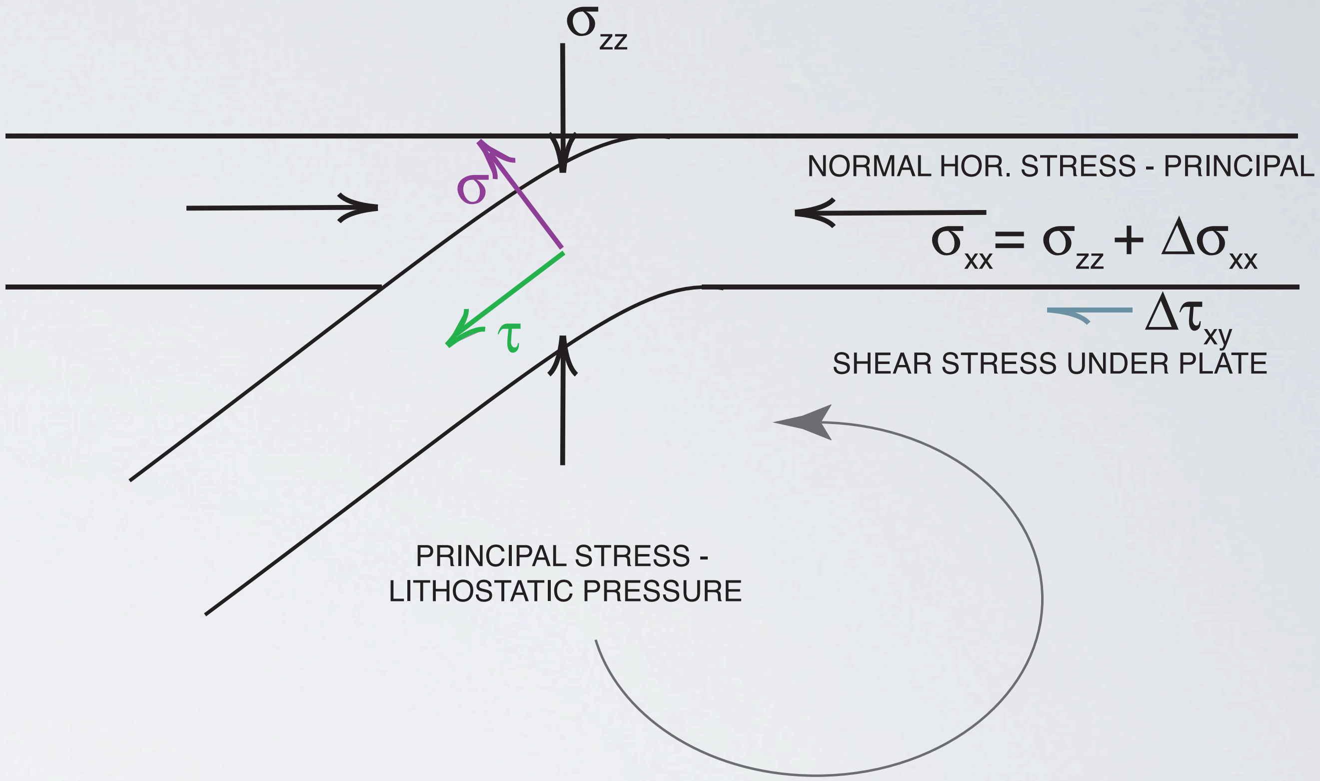
$\tau/\sigma_y < 1$ stagnant lid

COULOMB FAILURE

Coulomb failure criterion for plate deformation:

$$\sigma_y = S_0+\mu(\sigma-\lambda\sigma_{zz}) \sim \mu_{eff}\rho g\delta$$





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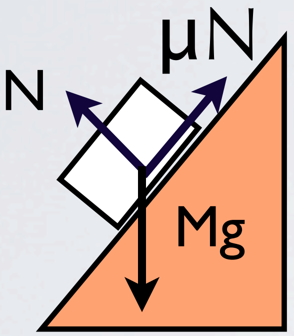

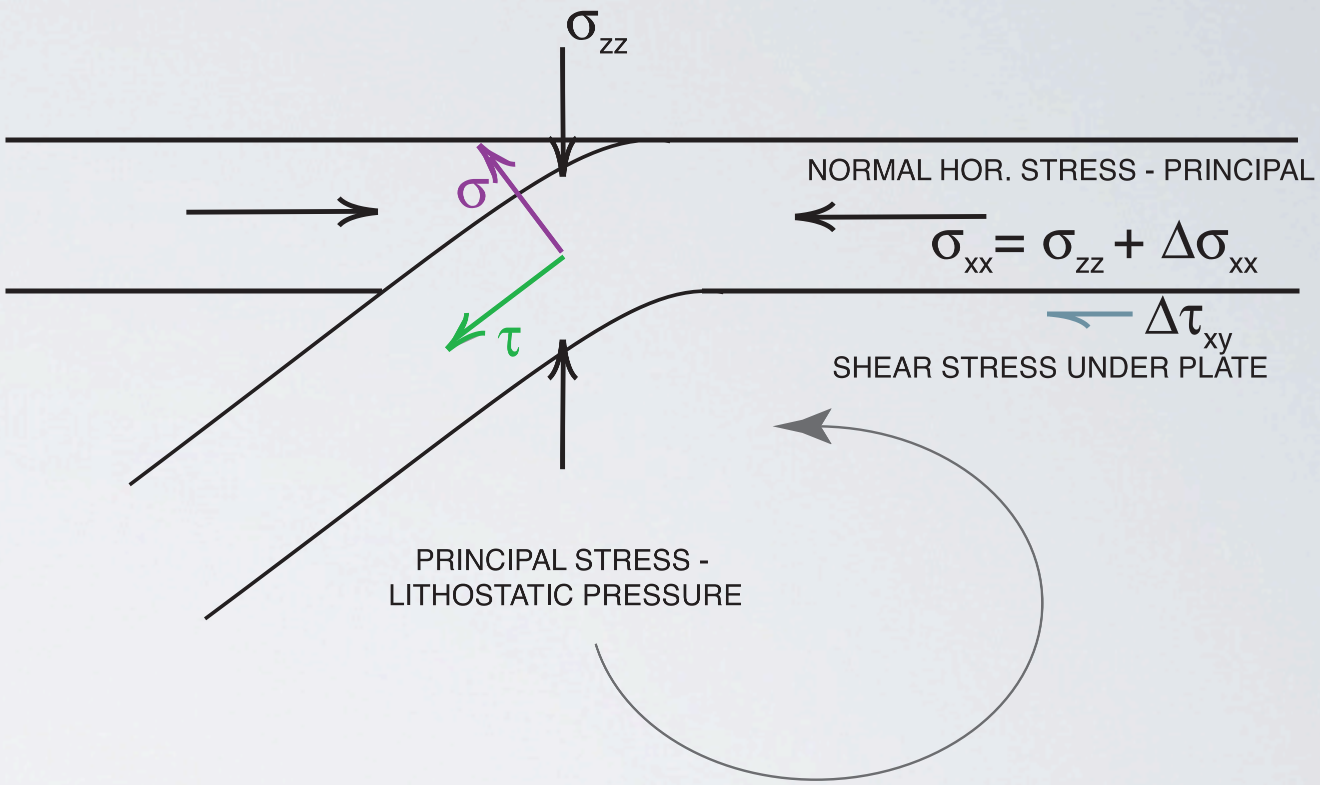

see Foley et al 2012 for a treatment based on damage

$\tau/\sigma_y > 1$ subduction, PT

$\tau/\sigma_y < 1$ stagnant lid

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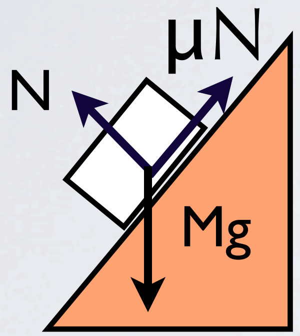

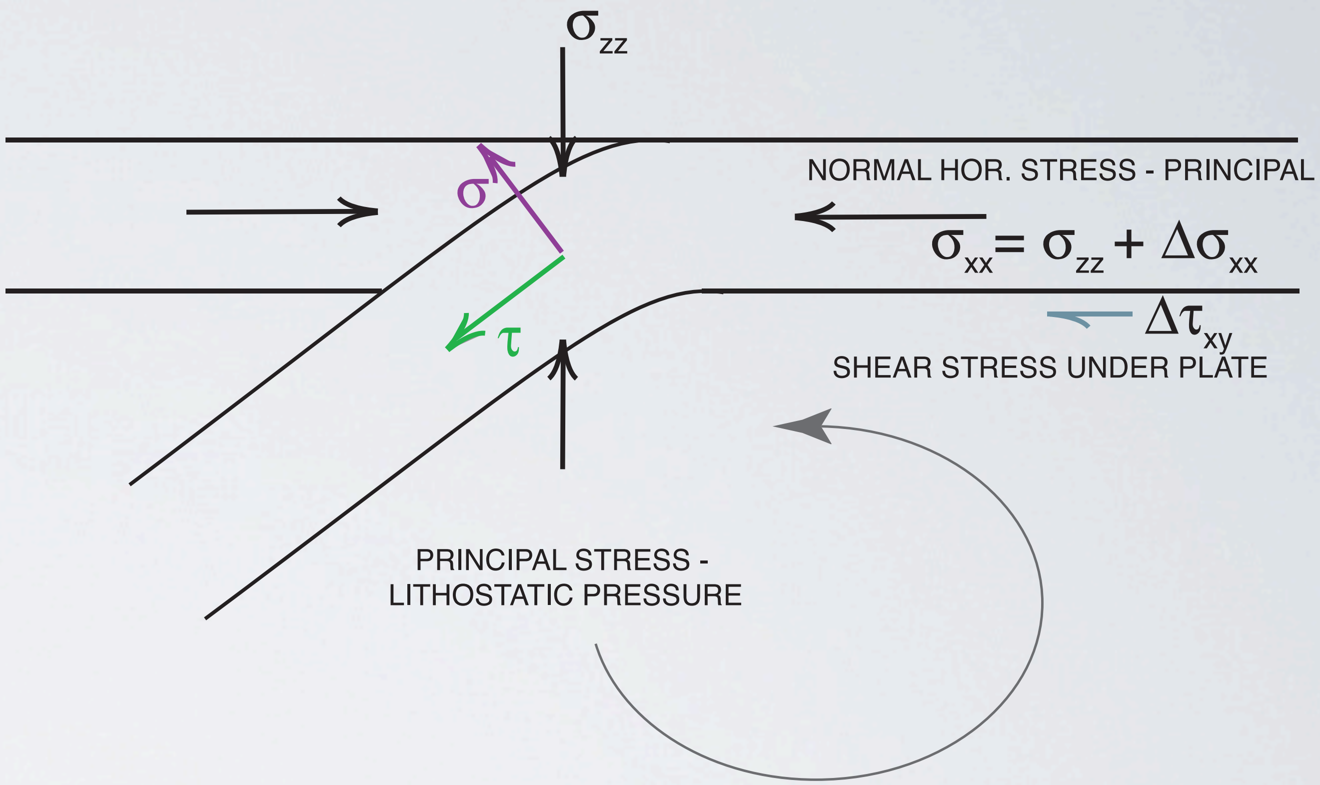

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Stress comes from convection:

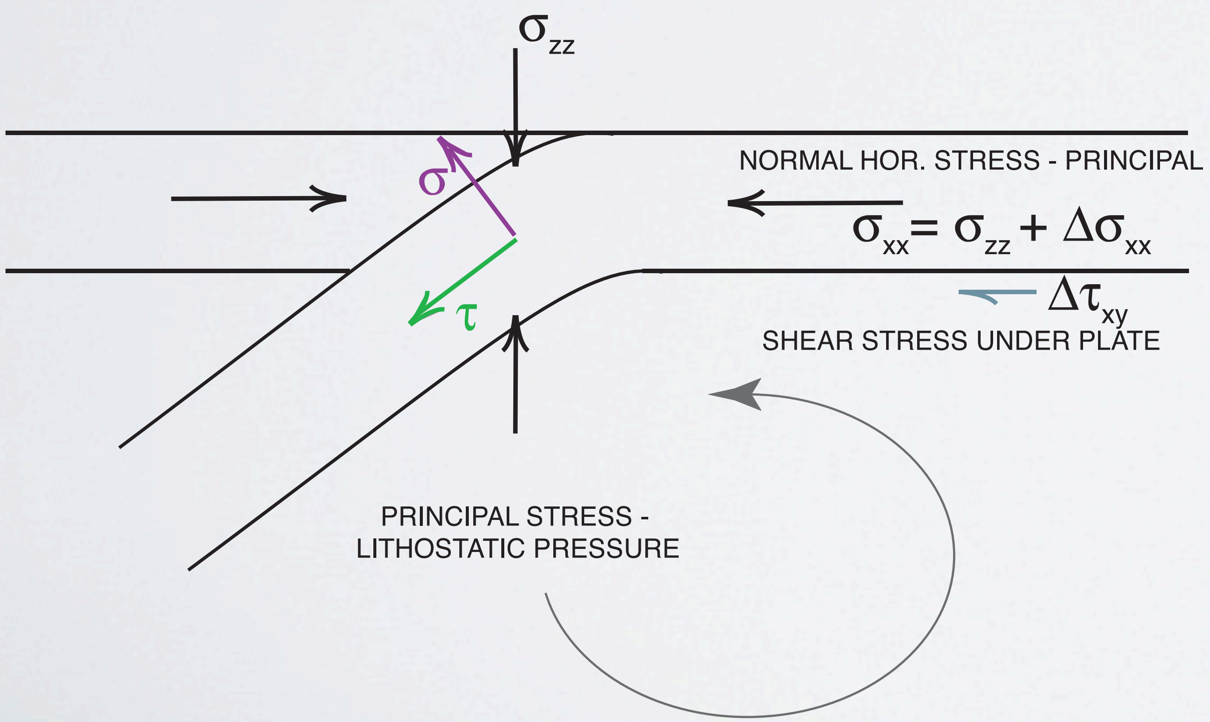
$$\Delta\tau_{xy}/\sigma_y = (L/D)\alpha\,\Delta T/ Ra_c$$

PLATE TECTONICS

$\tau \sim \Delta\sigma_{xx} \sim (L/\delta)\Delta\tau_{xy}$

$\boxed{\tau/\sigma_y \sim (L/\delta)}$

The convective shear stress gets amplified at the fault



- Scalings for rocky super-Earths:

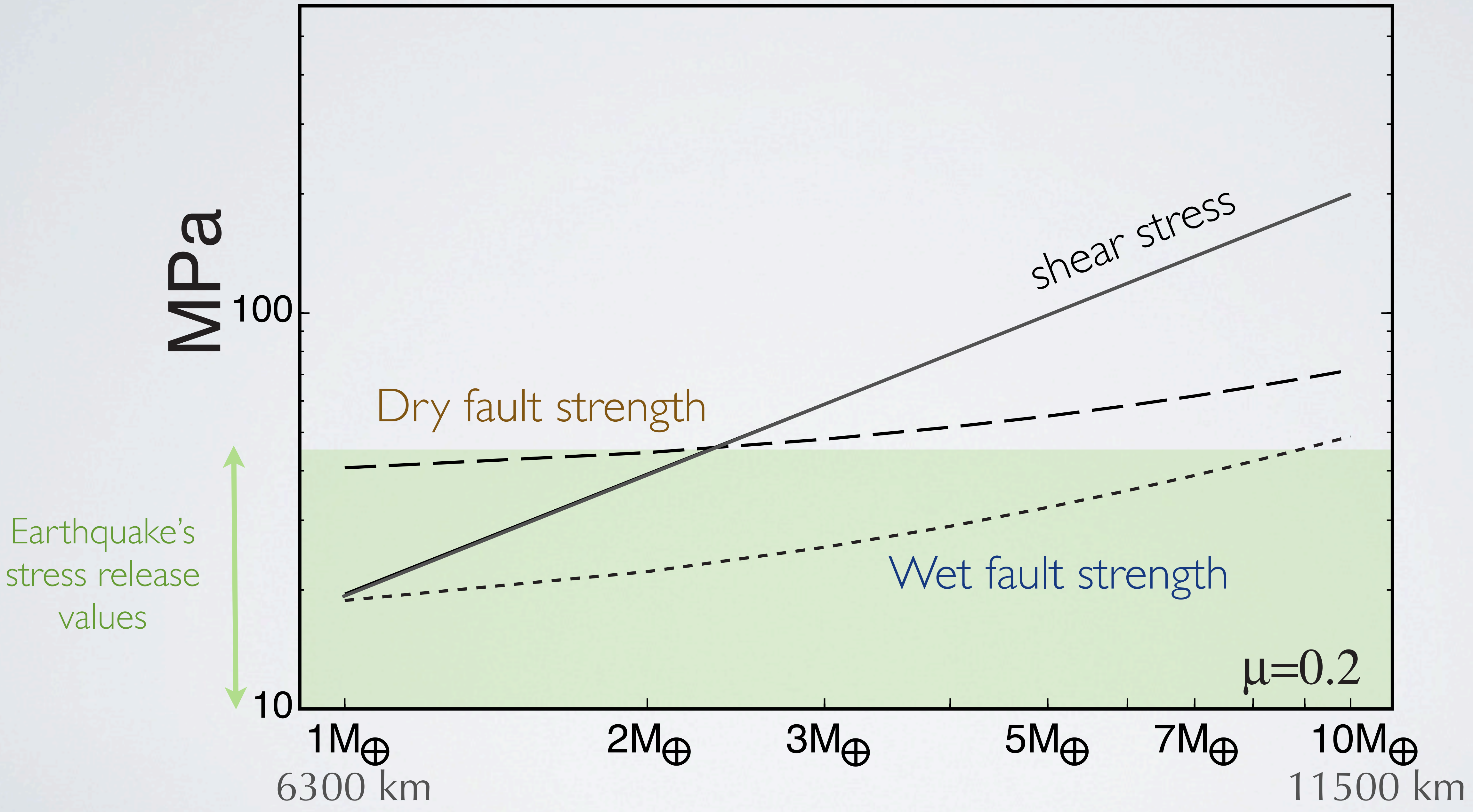
$\boxed{R \sim M^{1/4}}$

τ / σ_y	basal heating	internal heating
const ρ	$R^{4/3}$ $M^{4/9}$	R^2 $M^{1/4}$
$\rho(M)$	$R^{5/3}$ $M^{5/9}$	R^3 $M^{3/4}$

see also van Heck & Tackley 2011

Valencia & O'Connell '09:

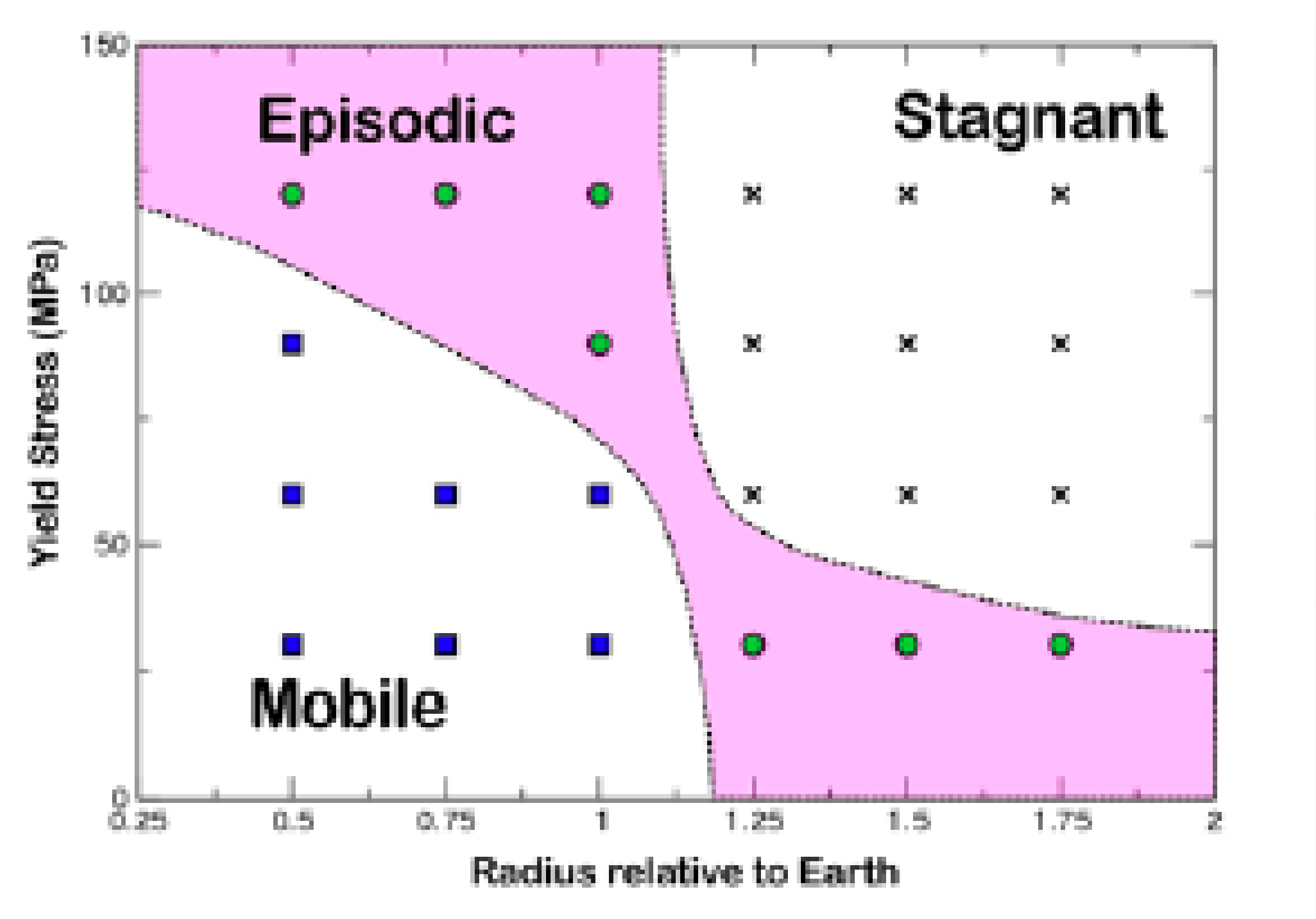
- faults do become stronger but driving stresses can overcome the plates resistance to deformation



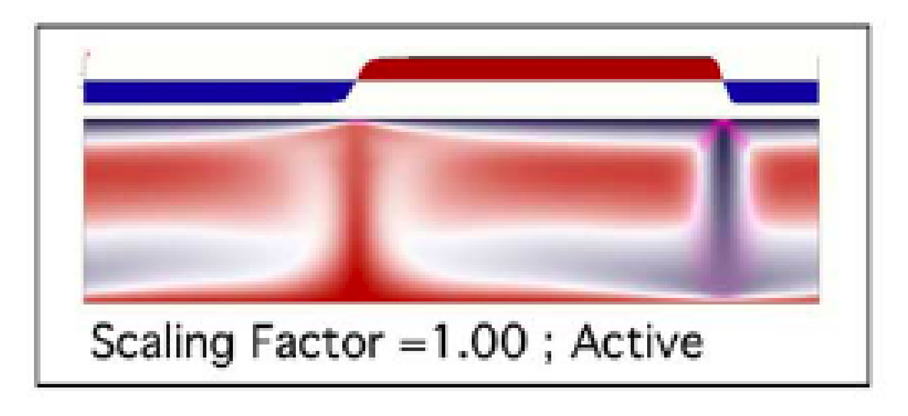
Valencia et al., 2009

O’Neill & Lenardic ‘07:

- at most in an episodic regime
- Argue that faults are too strong due to high g

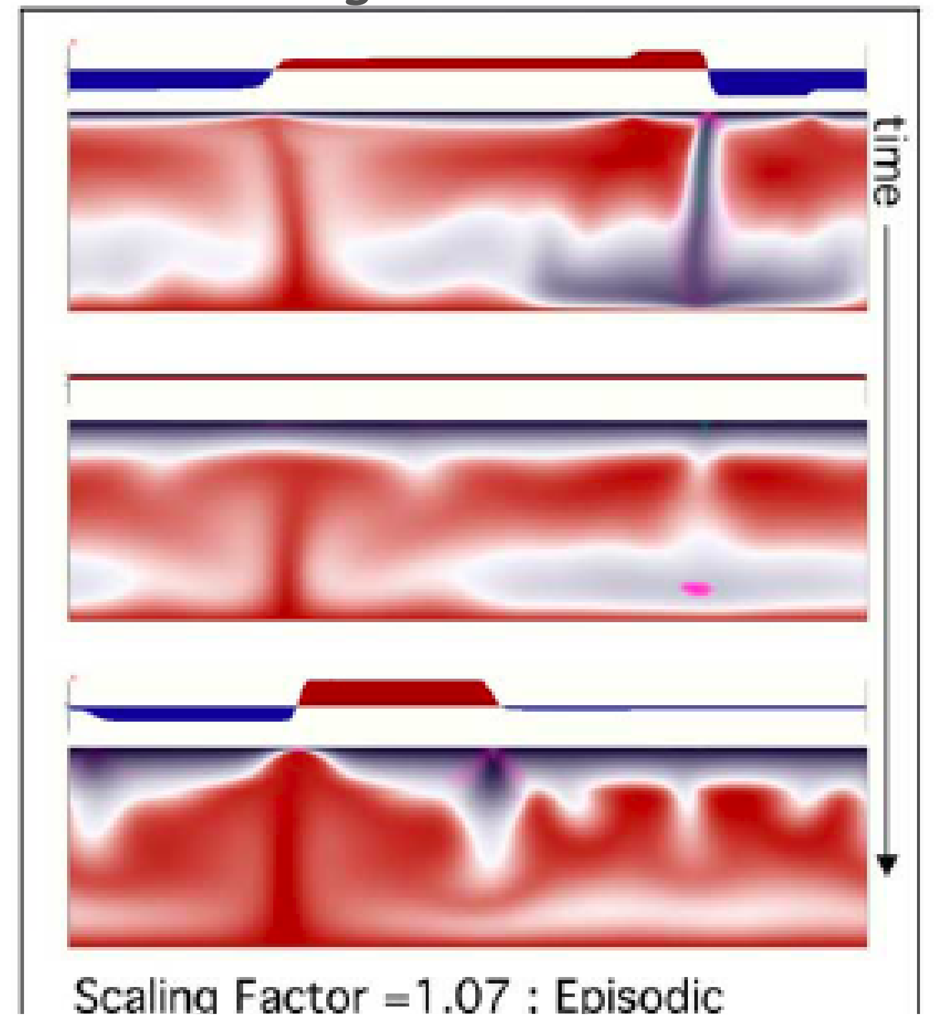


O’Neill & Lenardic, 2007

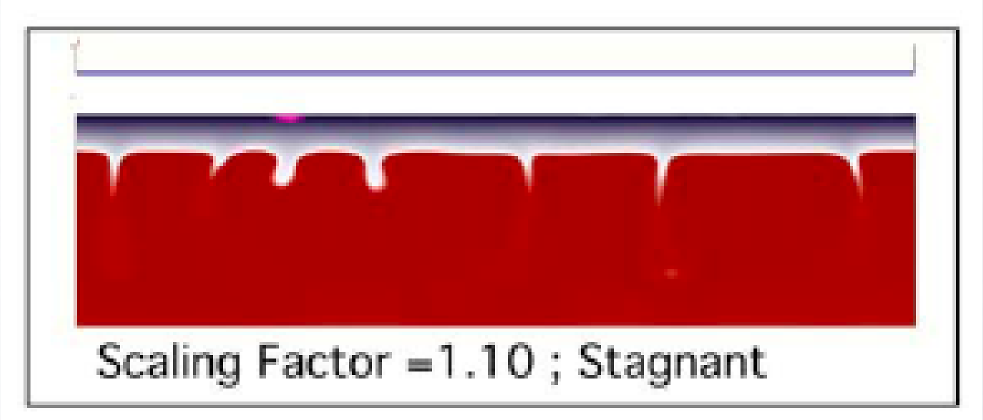


Scaling Factor =1.00 ; Active

Scaling Factor = R/R_E



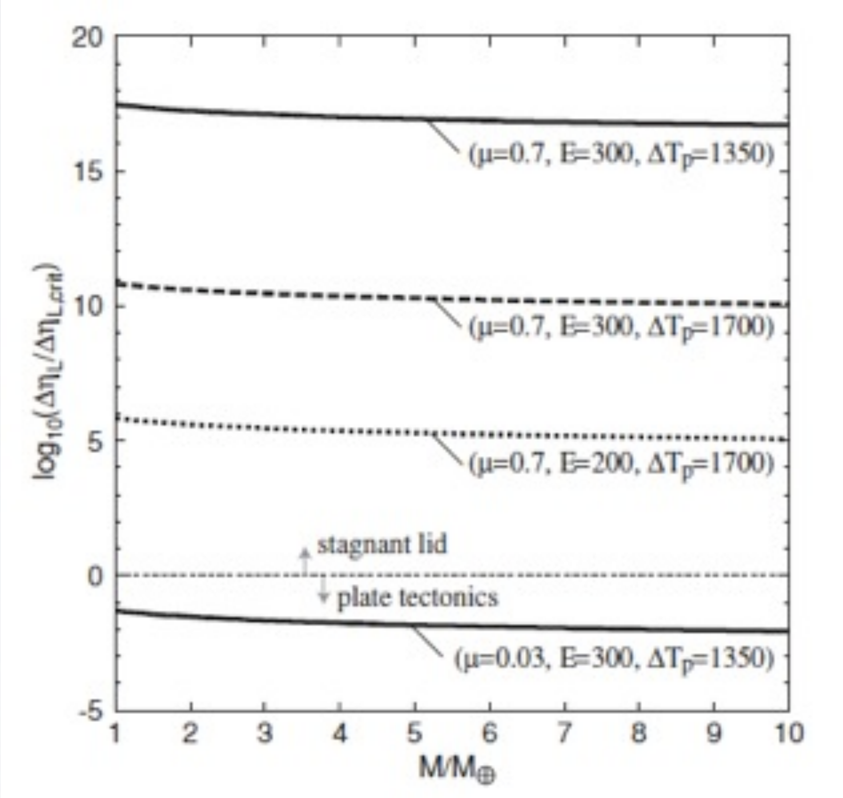
Scaling Factor =1.07 : Episodic



Scaling Factor =1.10 ; Stagnant

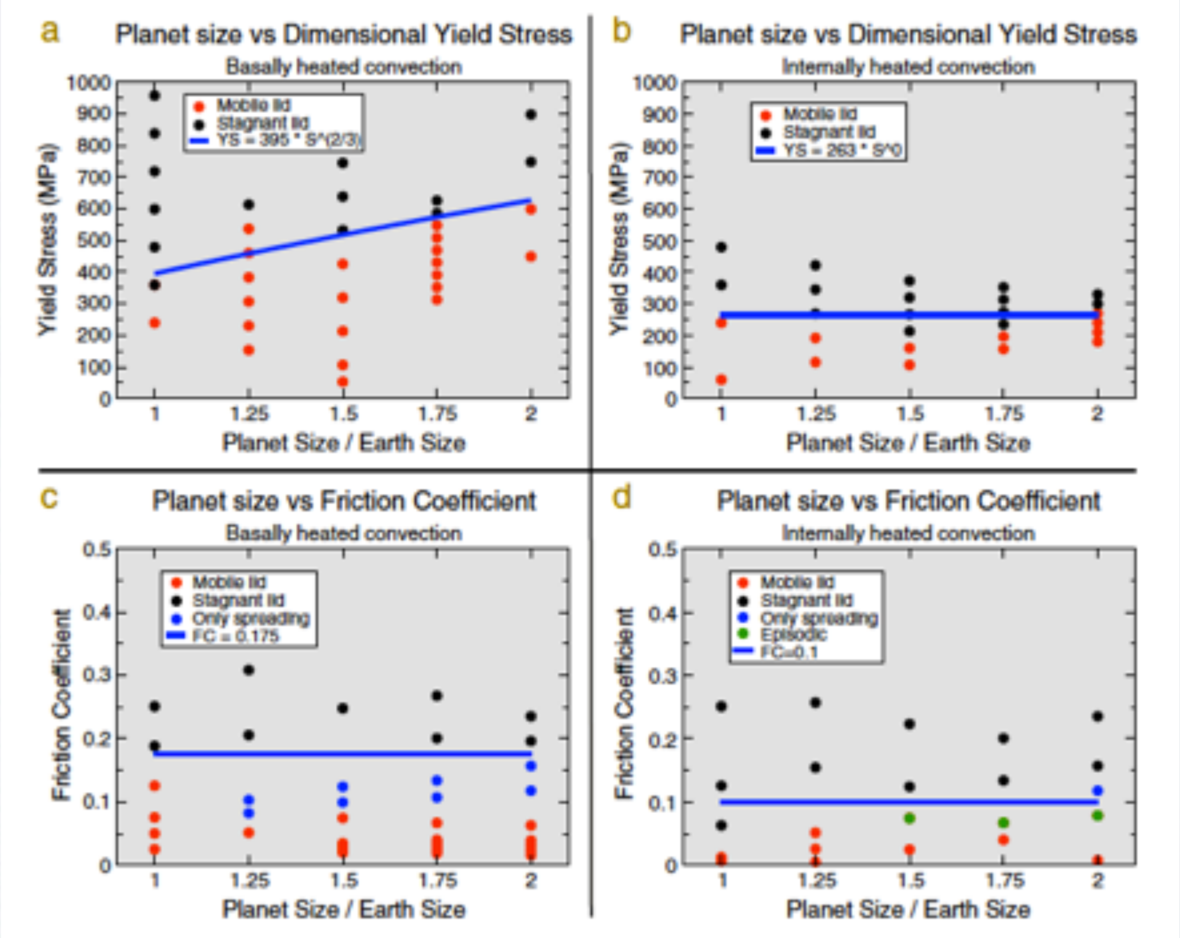
Korenaga 2010:

- 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



Van Heck & Tackley 2011:

- planets are equally likely to have PT, when the increase in density is taken into account, PT becomes more likely



Stamenkovic et al. 2012:

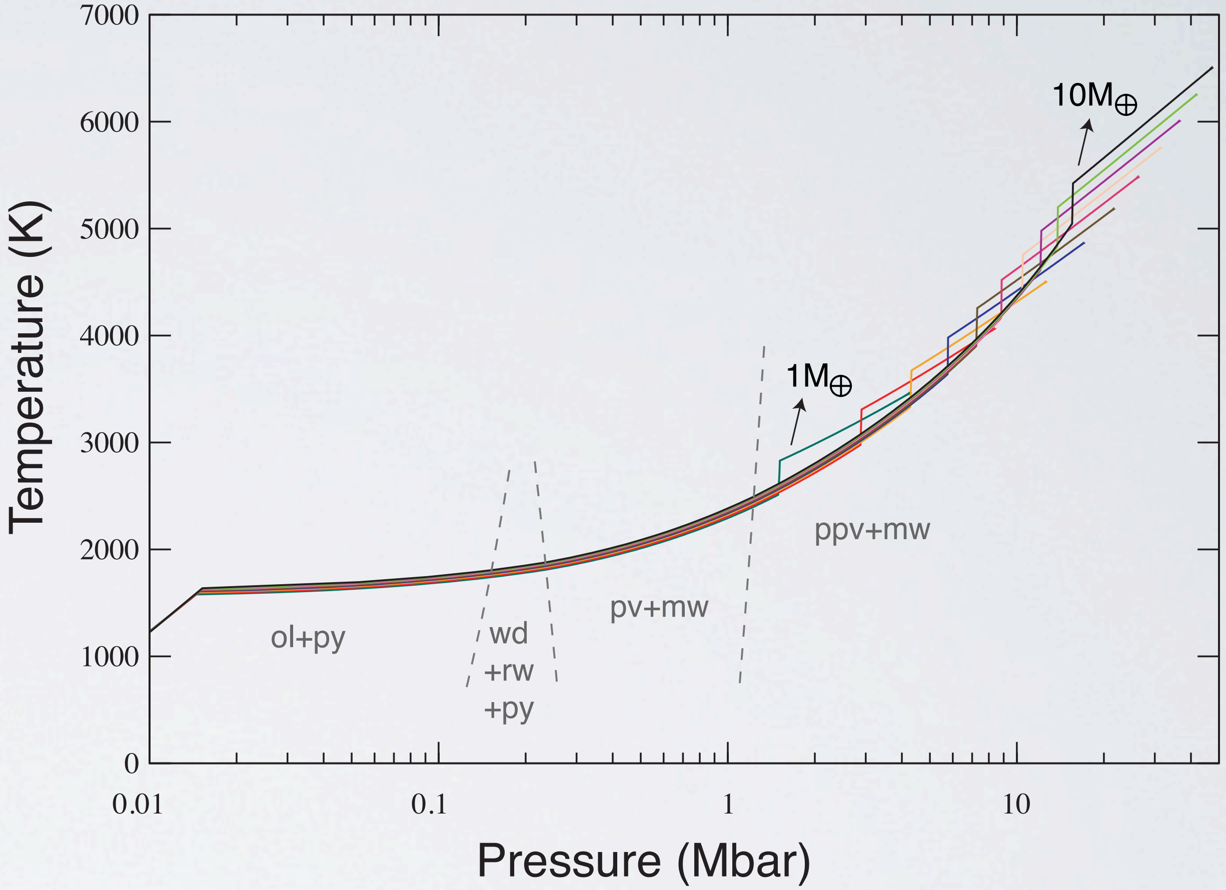
- the results depend on the activation volume. The viscosity of the lower mantle can be so large that would hinder flow.

VISCOSITY:

$$\eta = b \exp(H/ RT)$$

$$H = E + P V(P)$$

Valencia et al., 2007

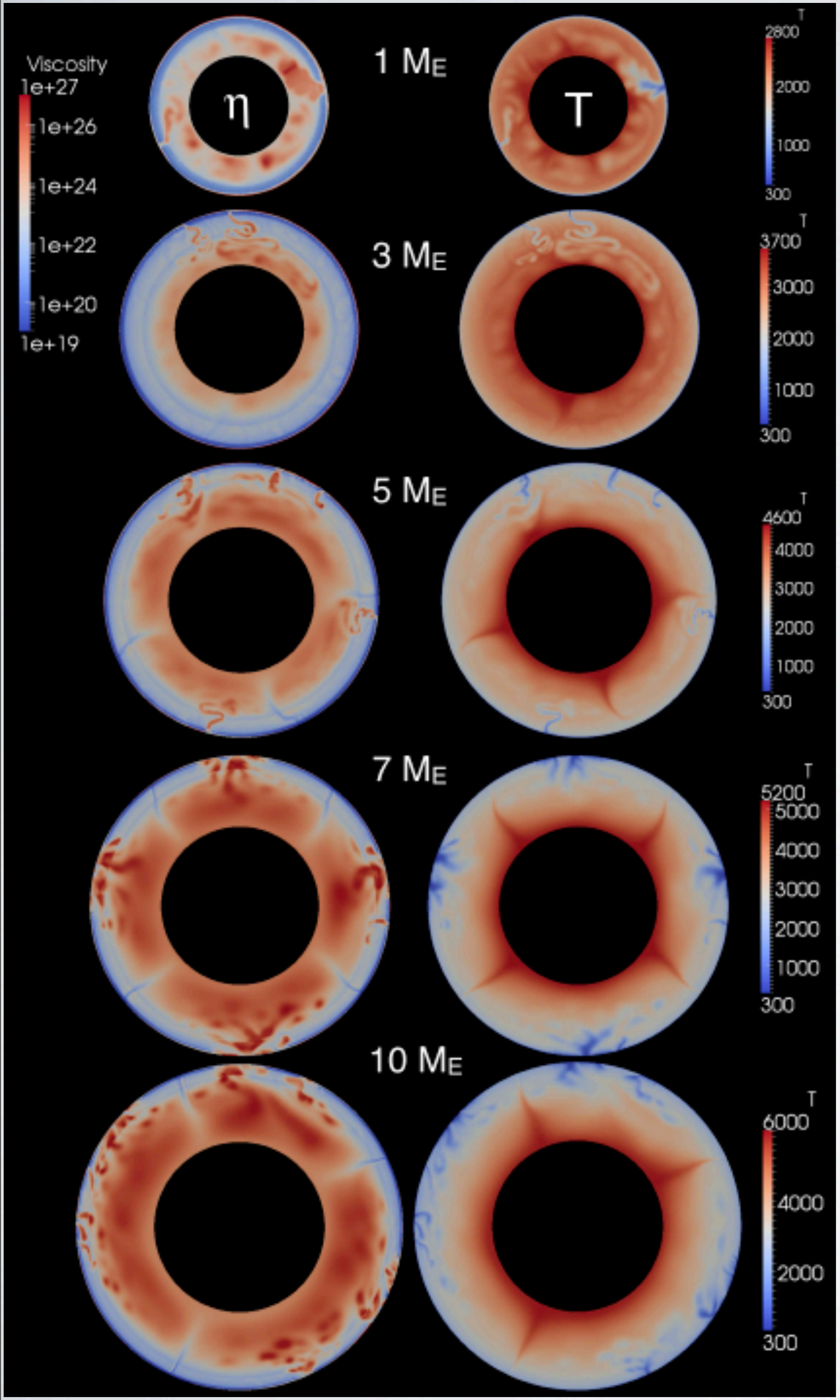


A simple exercise shows that at constant V, the viscosity at the deep mantle of rocky super-Earths can increase by 30 orders of magnitude!

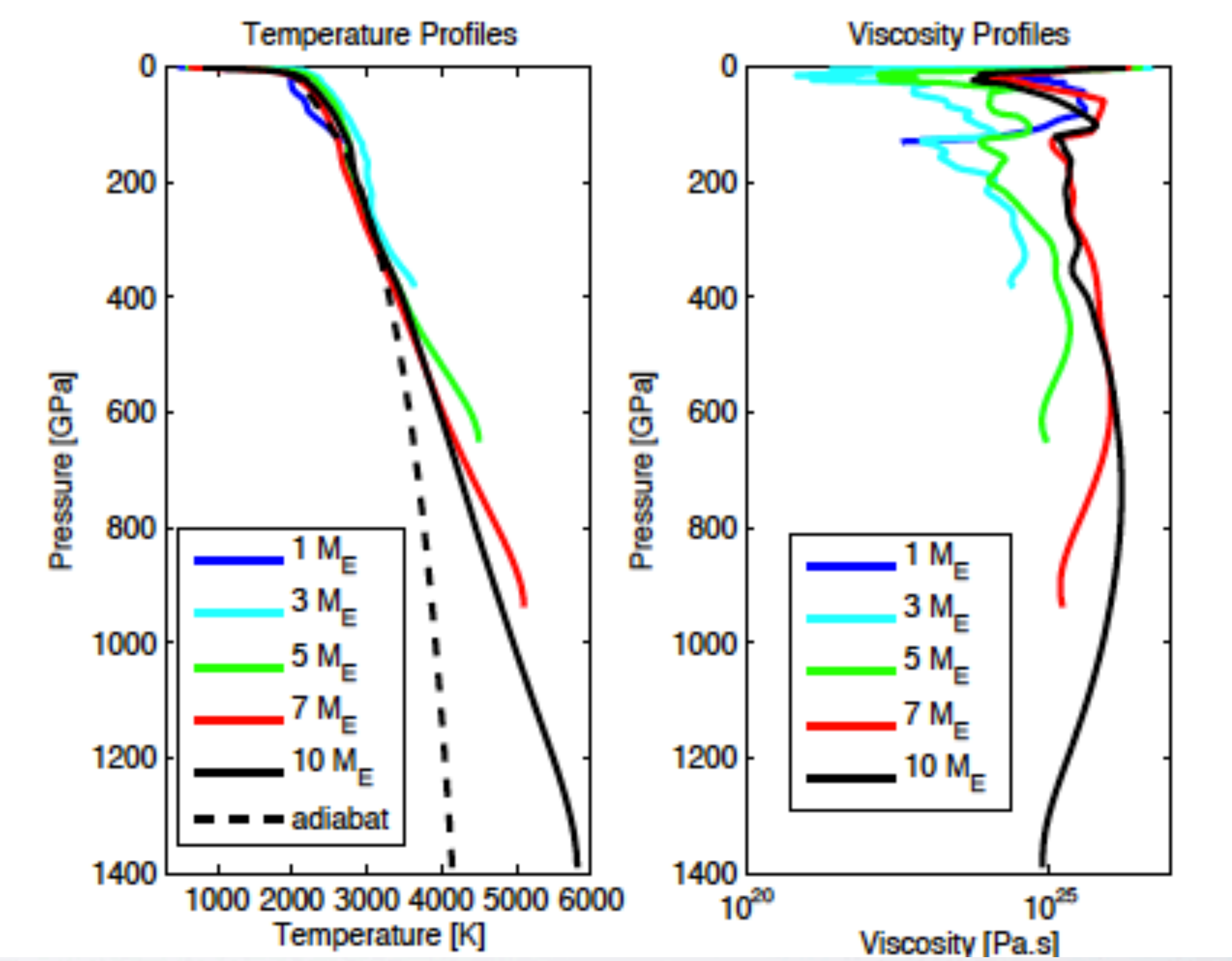
Ammann et al. 2010 suggests that V decays with pressure: $V=V_0 \exp(- p/p_{decay})$

Karato, 2011 disagrees

INTERIOR DYNAMICS



Tackley et al, in review

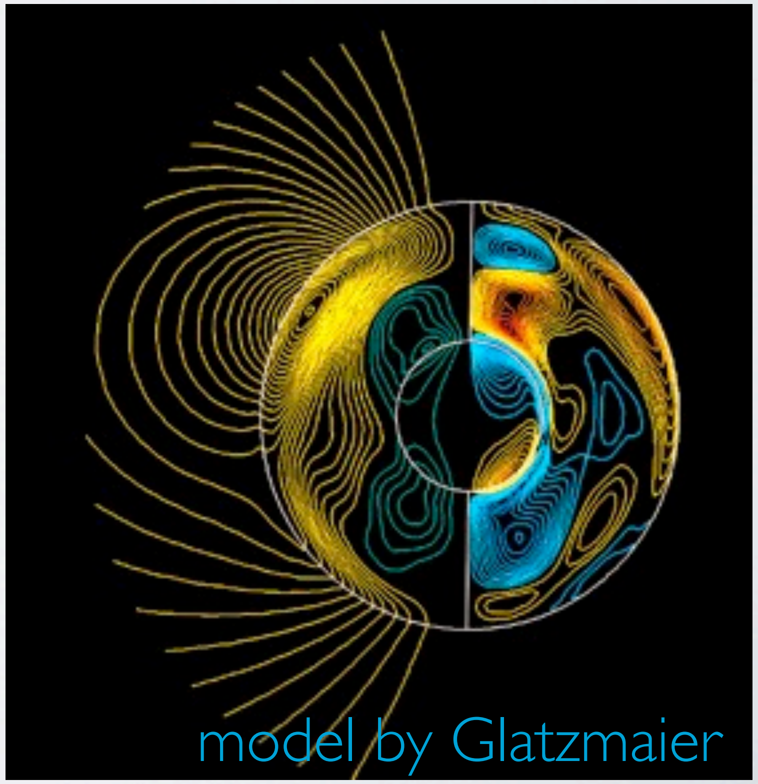


- The system is self-regulating through viscosity

MAGNETIC FIELDS

- Unclear if they are essential to support life, perhaps needed for complex life

- Conditions for a magnetic field in a terrestrial planet:
  - The core has to be at least partly molten (to allow for convection)
  - The rate of core cooling, which is controlled by the rate of mantle cooling, has to be large enough

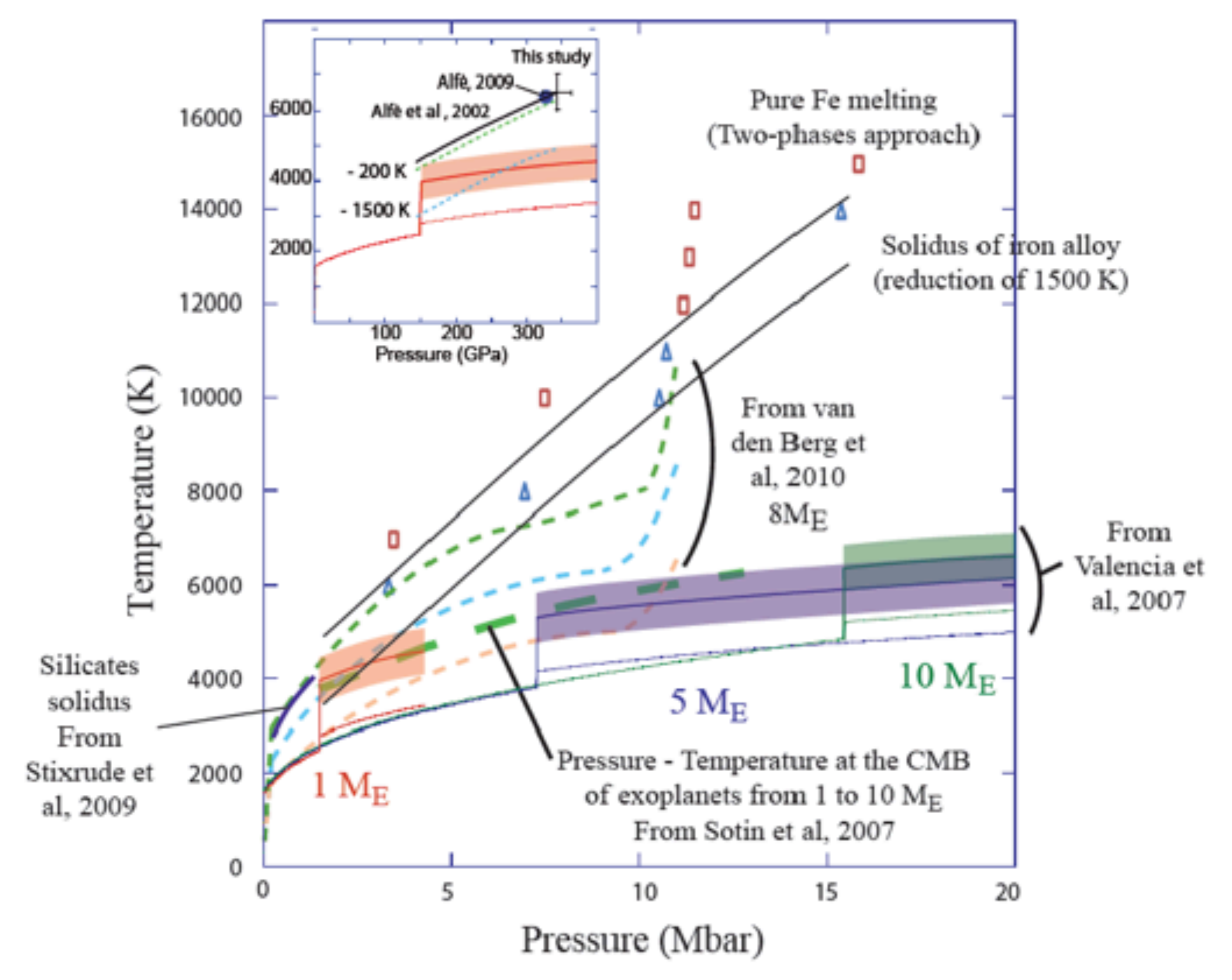


model by Glatzmaier

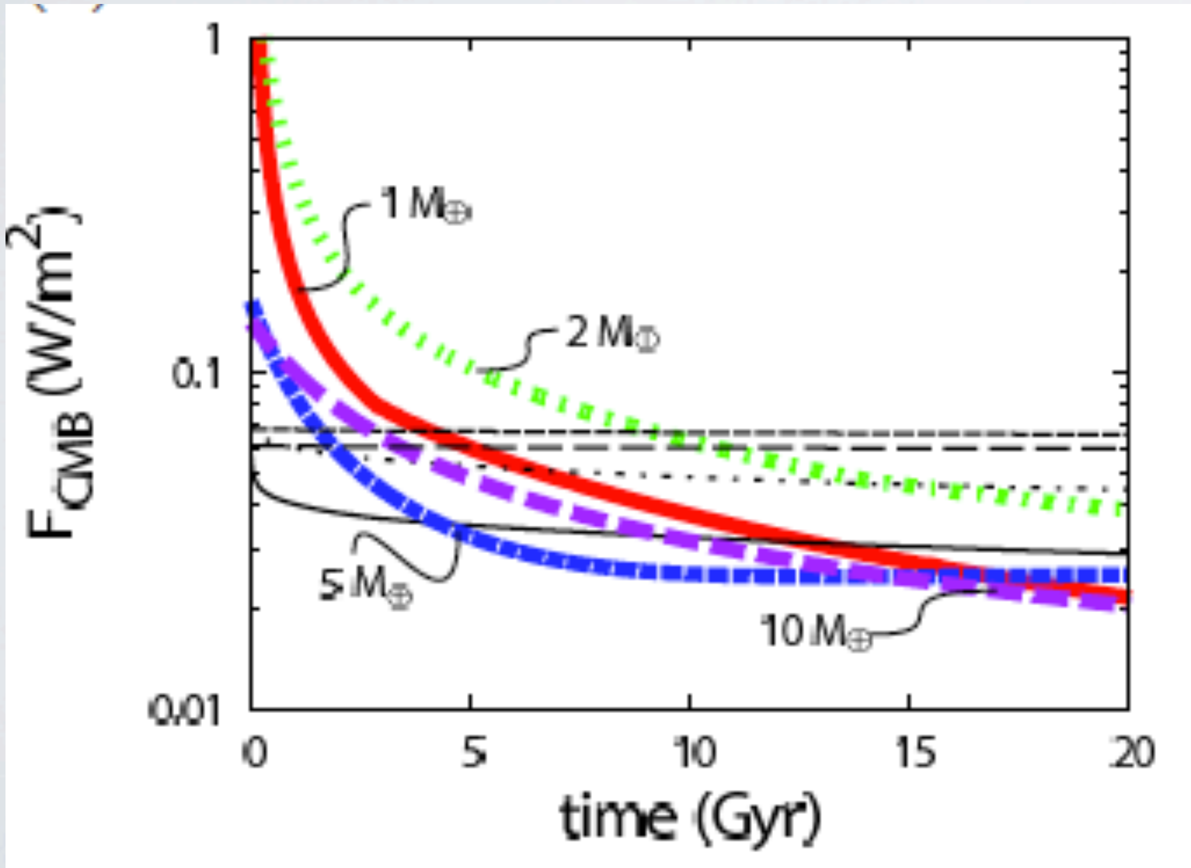
LIQUID OR SOLID CORE?

The melting curve of iron has a steep T-dependence

The answer is epoch-dependent



Morard et al. 2010



Planets with less than a few Earth masses might have a magnetic field (and it may be short lived)

Tachinami et al. 2011, see also Gaidos et al 2011

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SUMMARY

- Solid planets evolve habitable conditions. We need to understand their thermal evolution and interior dynamics
- Their atmosphere is tied to interior dynamics, expect diversity!
- Plate Tectonics on SE is under debate: the role of water, surface temperature, depth dependent rheology, etc ...
- Magnetic fields do not seem very likely to exist for long times in terrestrial super-Earths

SOLID (EXO)PLANETS QUESTIONS

- How does mantle convection happen in a tidally locked solid body?
- How does tides affect the mantle dynamics of solid planets?
- How does the atmosphere/mantle system evolve?
- What are the possible observables?
- What is the pathway(s) to habitability?

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