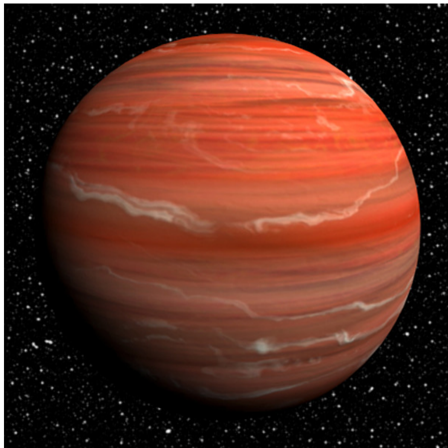


Challenges in Exoplanet Characterization

Ravit Helled

Institute for Computational Science

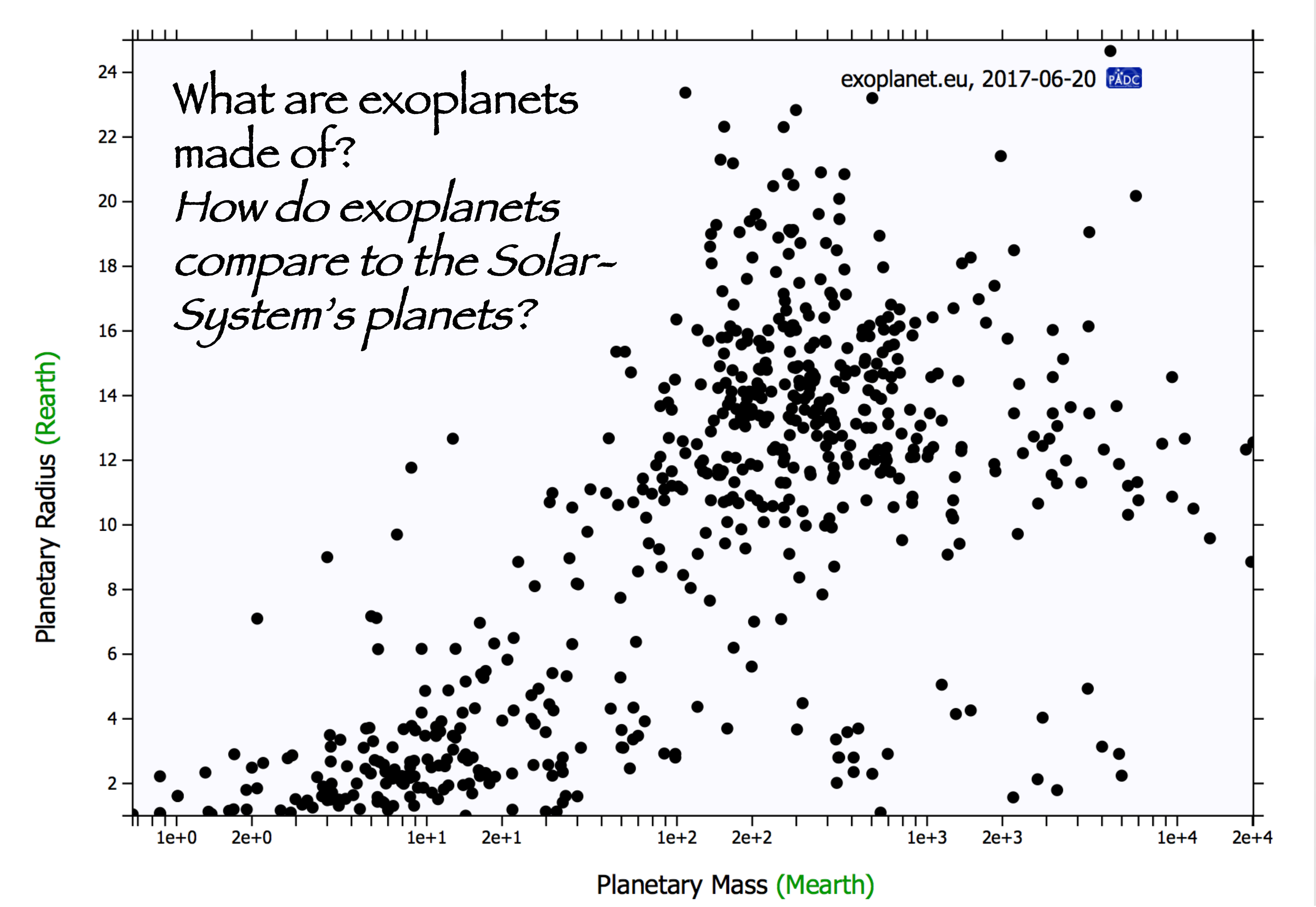
Center for Theoretical Astrophysics & Cosmology,

University of Zurich

EWASS - 2017

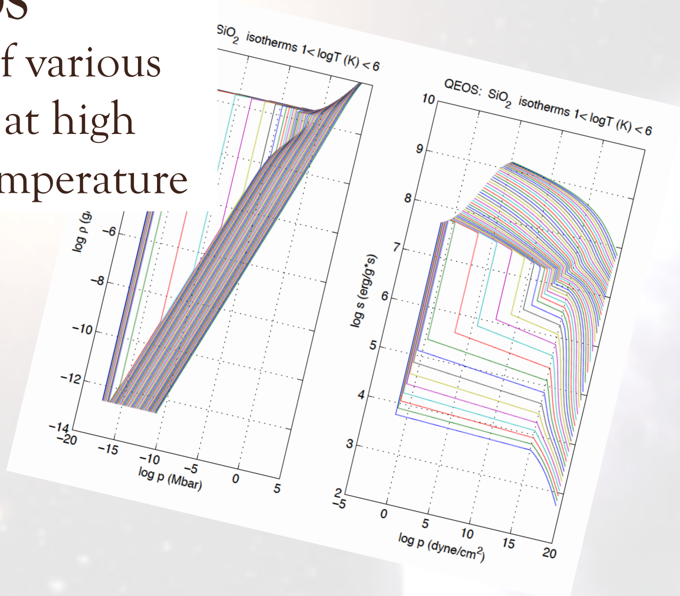
Exoplanets Discovery → Exoplanets Characterization

Planets are diverse: a large variety of masses and radii



Main sources of uncertainty/open issues

EOS
Behavior of various materials at high pressure/temperature



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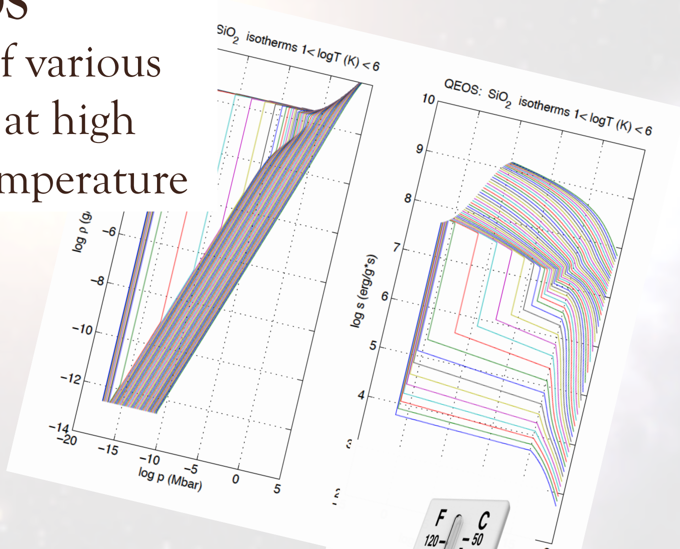
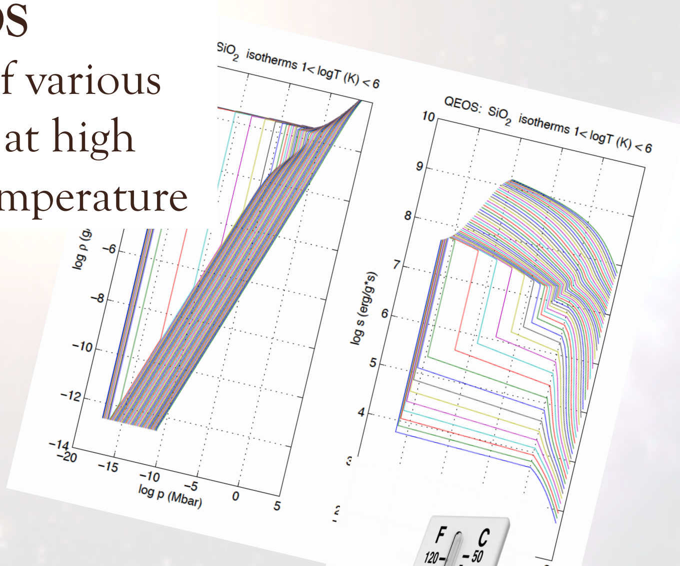
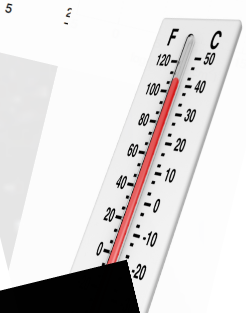


Temperature
(radial distance)
Different planetary type?

Main sources of uncertainty/open issues

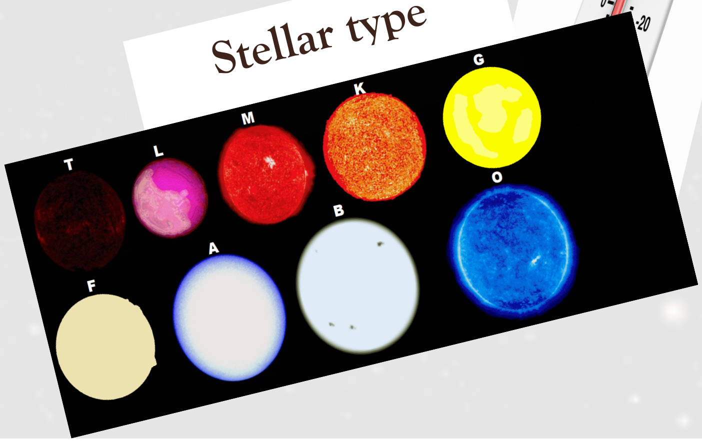
EOS
Behavior of various materials at high pressure/temperature





Temperature
(radial distance)
Different planetary type?

Stellar type



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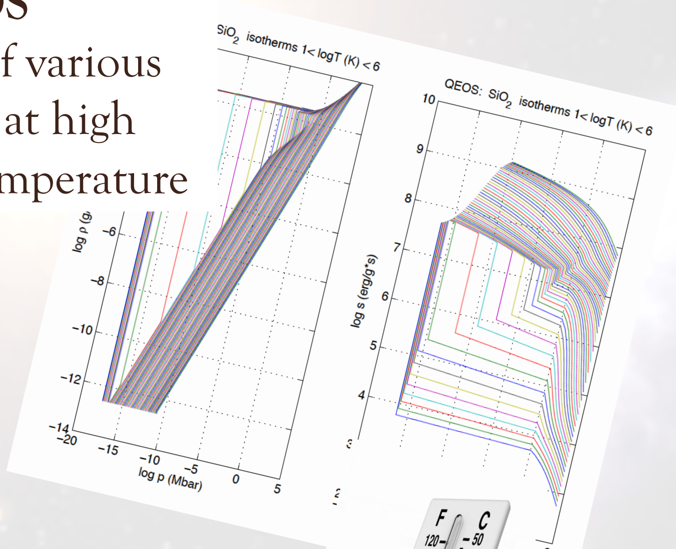
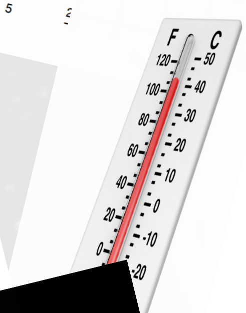
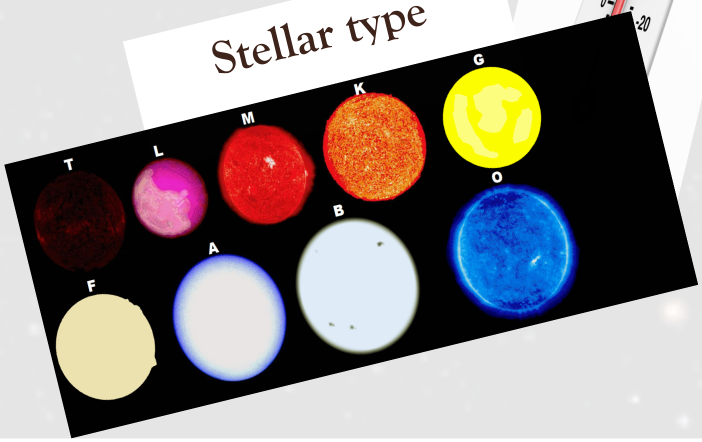
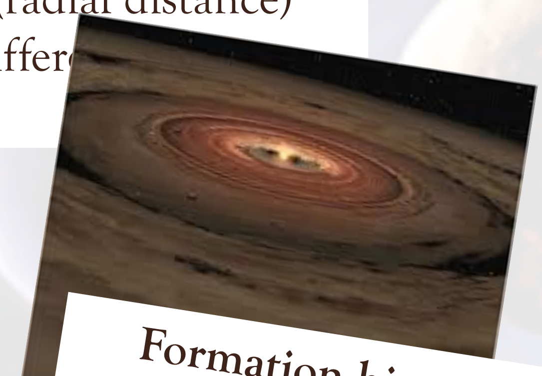




Temperature
(radial distance)
Differe

Stellar type

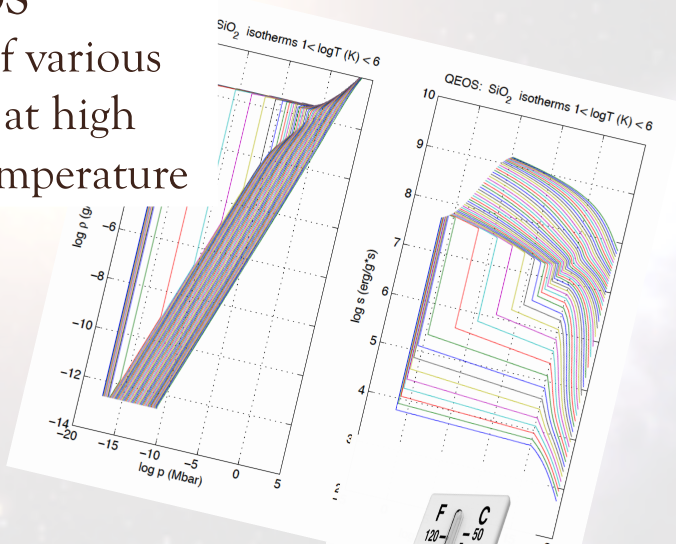




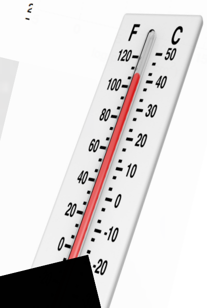
Formation history
How? Where? When?

Main sources of uncertainty/open issues

EOS
Behavior of various materials at high pressure/temperature

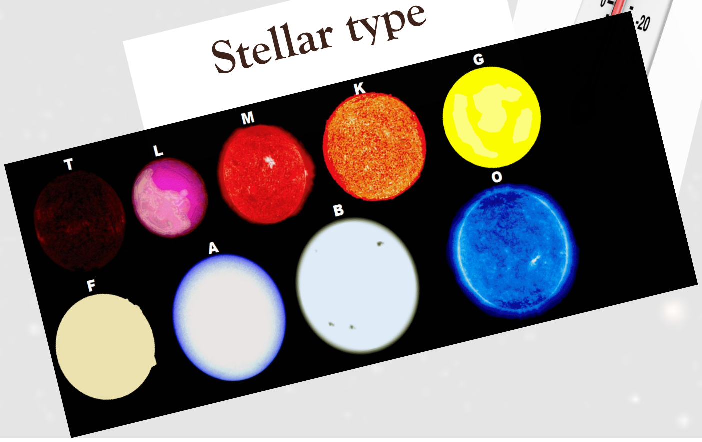


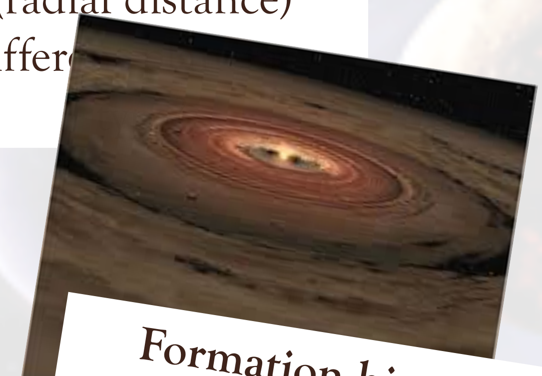
Time/Age
Evolution, time dependence



Temperature
(radial distance)
Differ

Stellar type





Formation history
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Main sources of uncertainty/open issues

EOS
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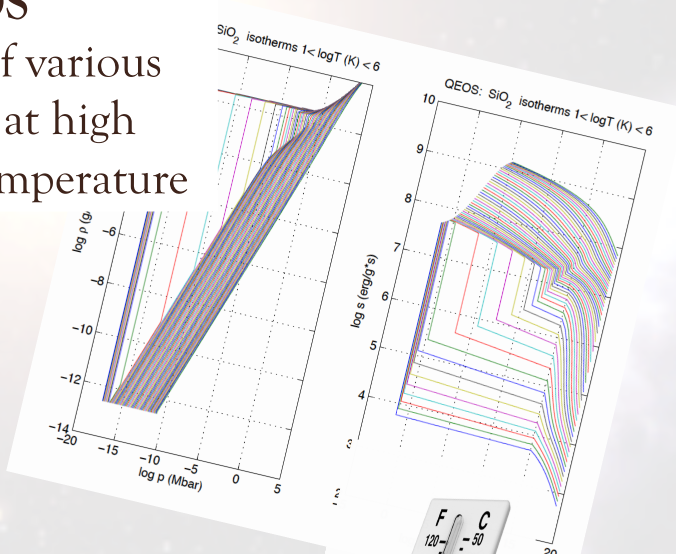
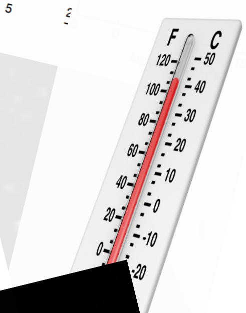
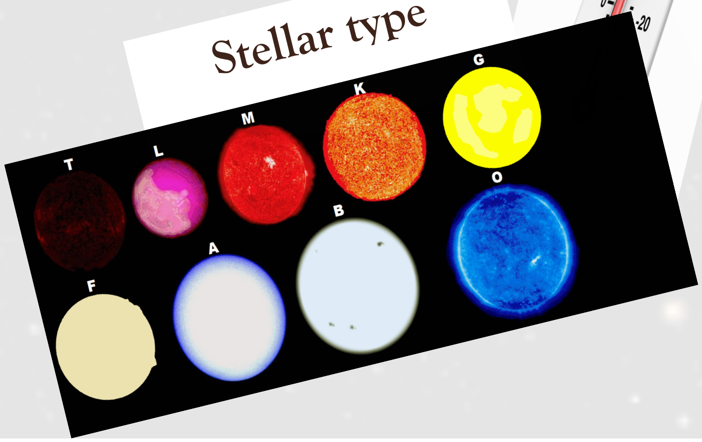


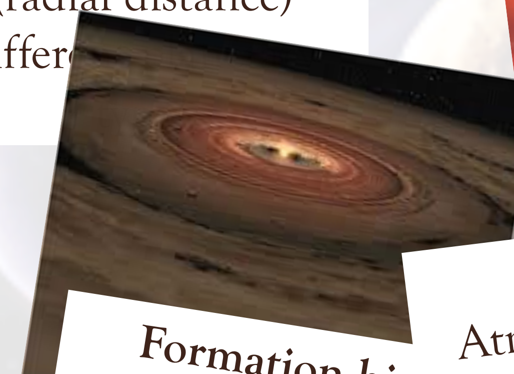
Time/Age
Evolution, time dependence



Temperature
(radial distance)
Differ

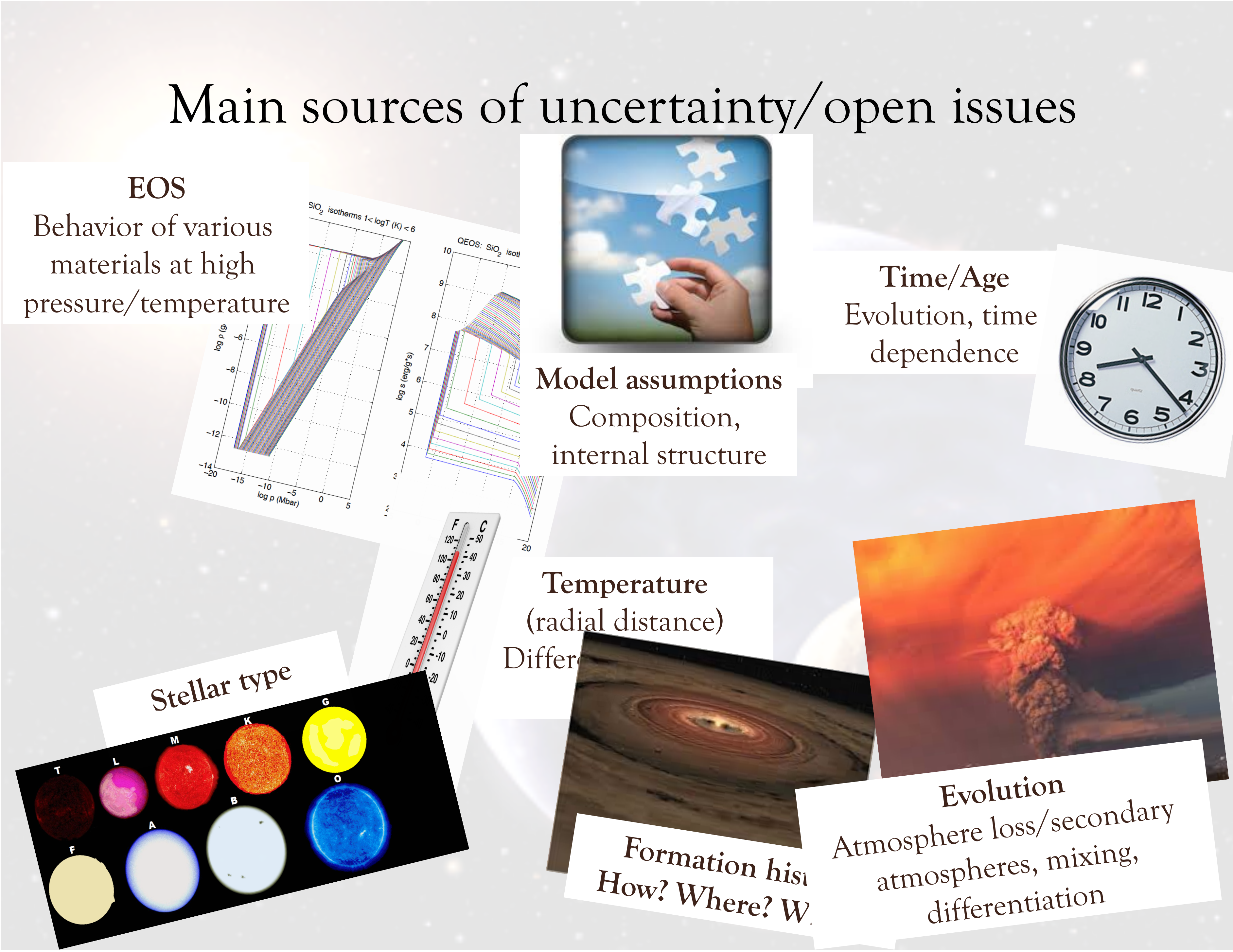
Stellar type





Formation hist
How? Where? W

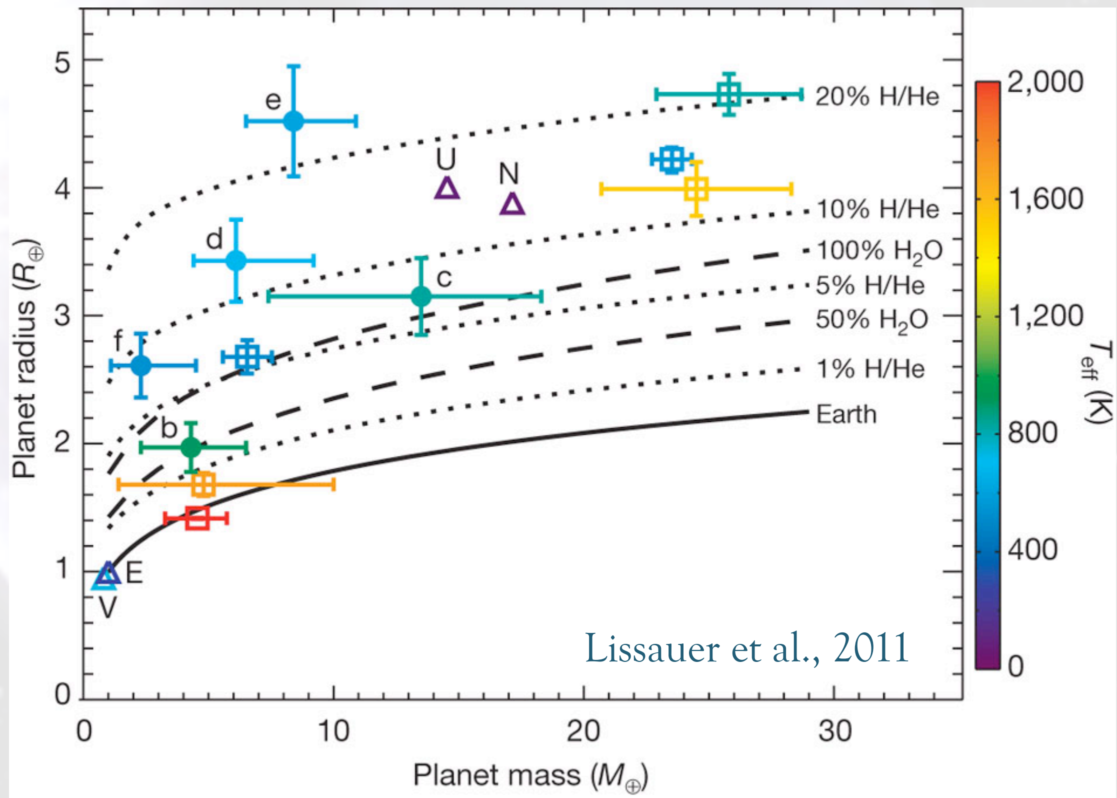
Evolution
Atmosphere loss/secondary atmospheres, mixing, differentiation


Main sources of uncertainty/open issues
EOS
Behavior of various materials at high pressure/temperature
SiO2 isotherms 1< logT (K) < 6
log p (Mbar)
QEOS: SiO2
log s (erg/g*s)
Model assumptions
Composition, internal structure
Time/Age
Evolution, time dependence
F
C
Temperature
(radial distance)
Differ
Stellar type
T
L
M
K
G
F
A
B
O
Formation hist
How? Where? W
Evolution
Atmosphere loss/secondary atmospheres, mixing, differentiation

How do we characterize exoplanets?

Measured mass & radius (M-R diagram) → mean density → composition.
How can we use the M-R relation to derive composition & internal structure?

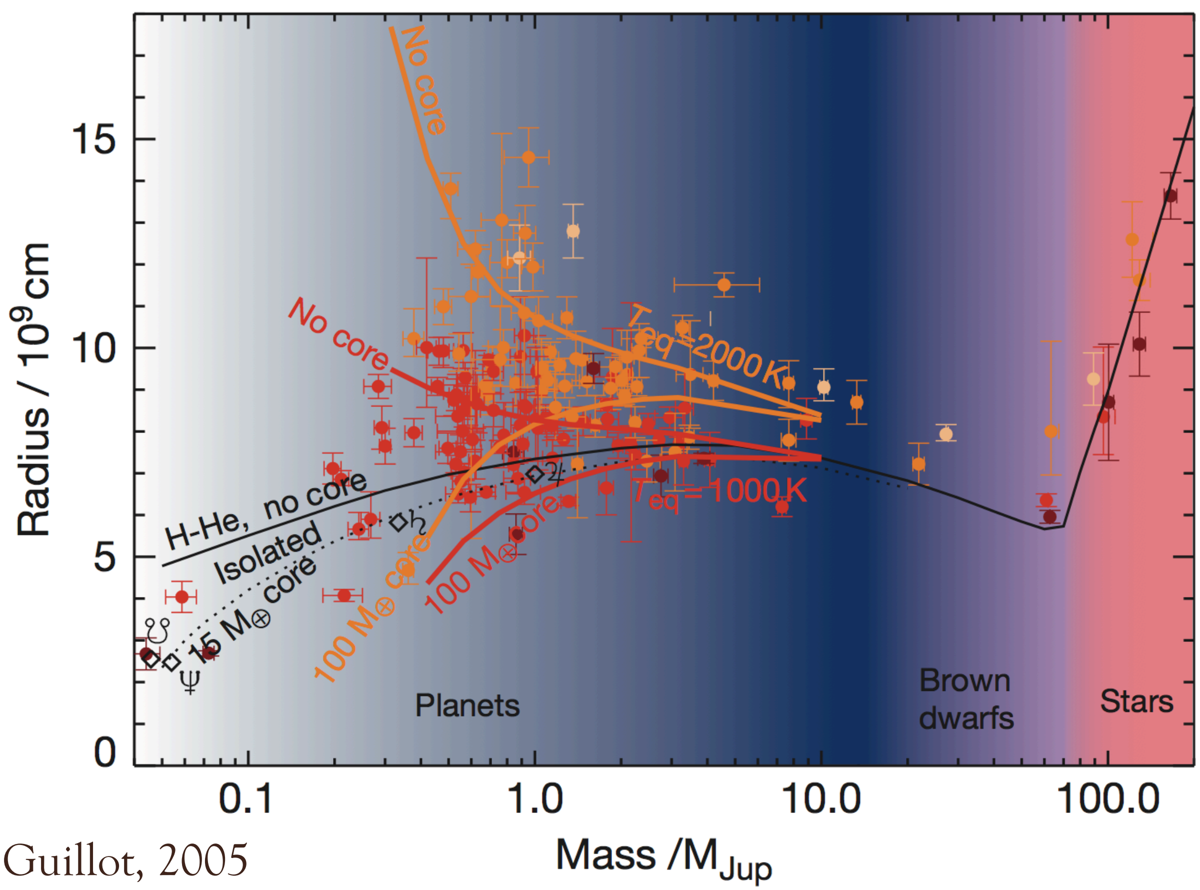
Mean density does NOT give us the distribution of the materials
A very large range of compositions will provide the *same* mean density



Lissauer et al., 2011

How do we know that there are heavy elements in giant planets?

The mass-radius relation is a relationship between the radius, R, of an astrophysical object and its mass, M.



Guillot, 2005

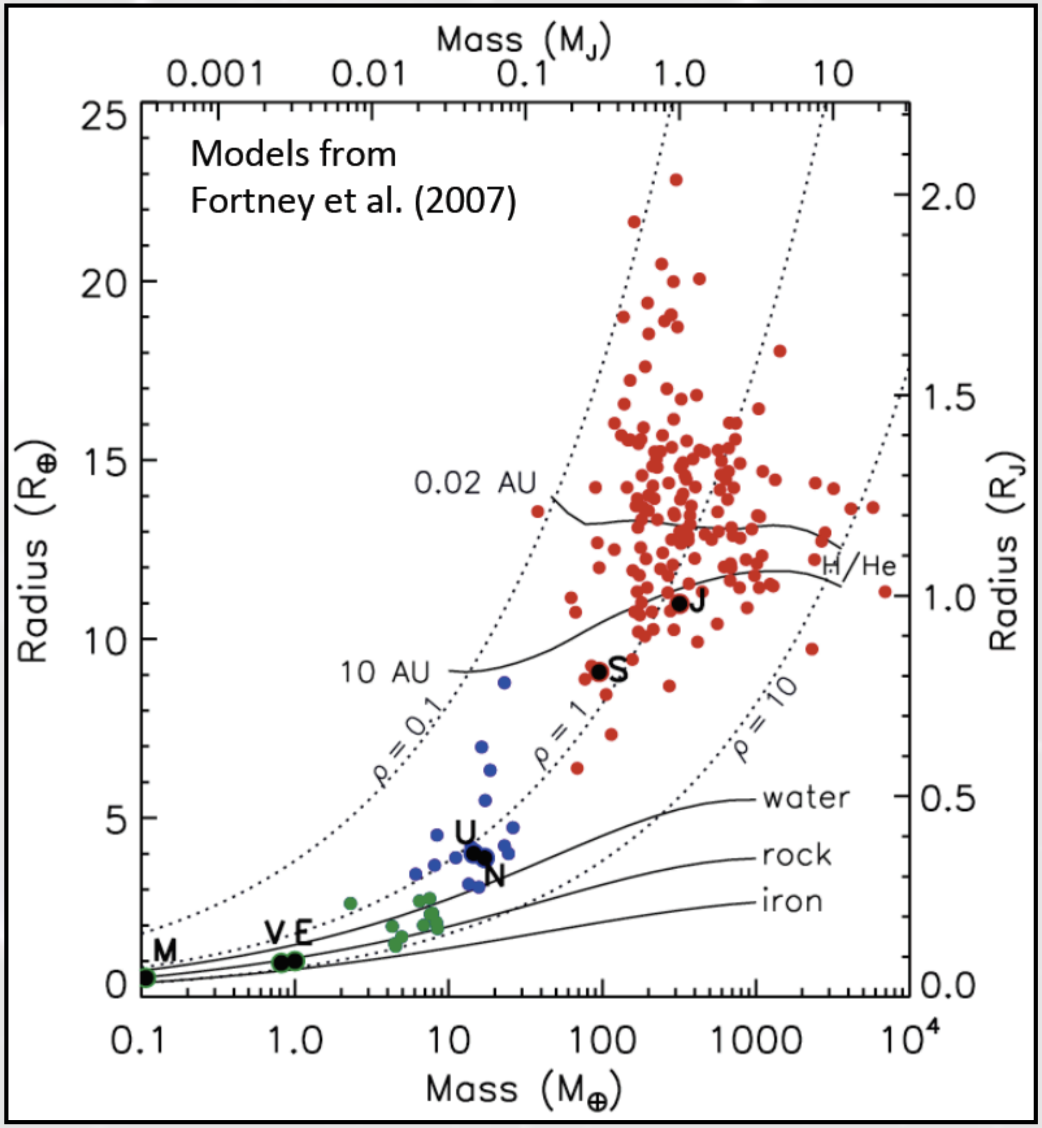
For stars:
$R \propto M$

Degenerate pressure:
$R \propto M^{-1/3}$

Coulomb pressure (small objects):
$R \propto M^{1/3}$

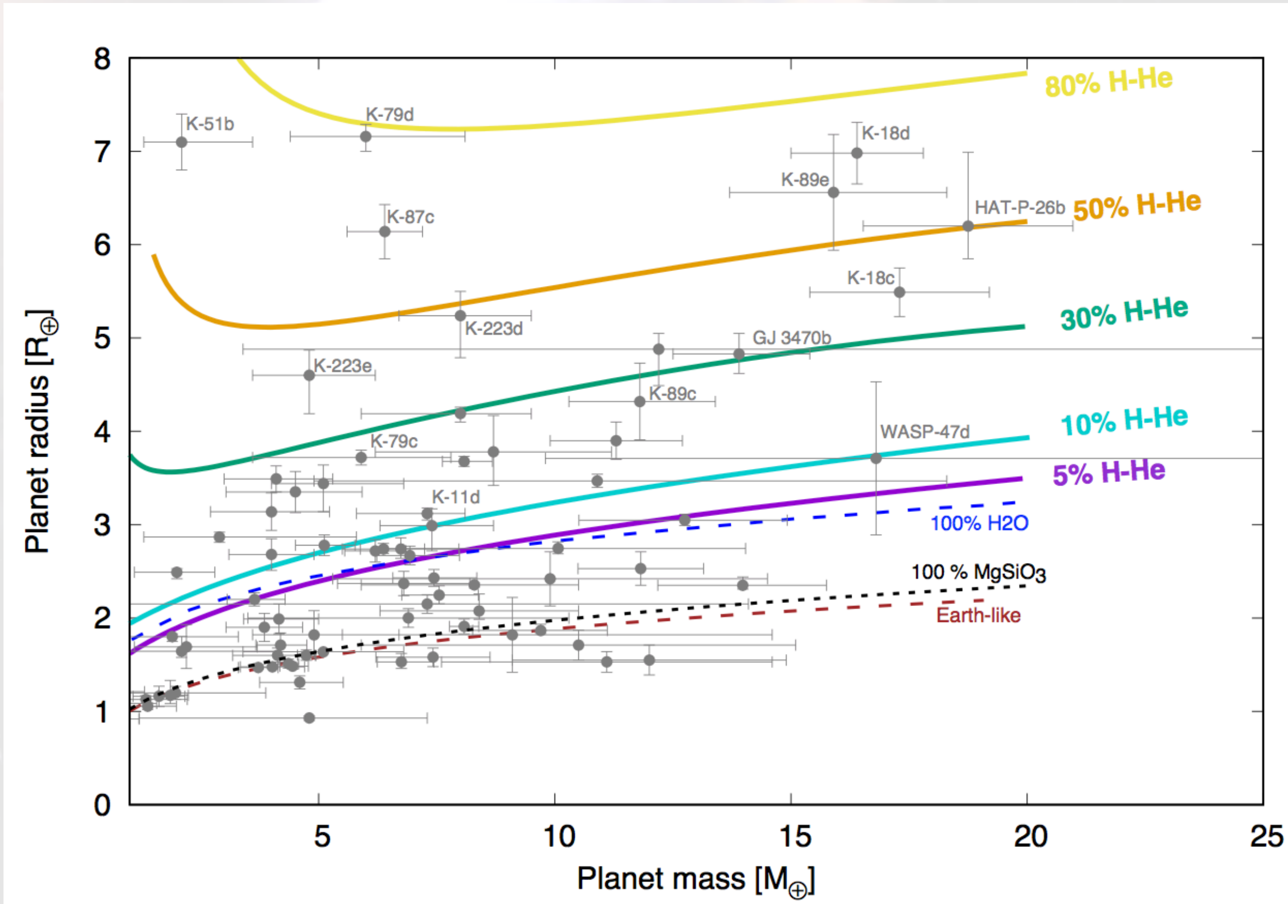
Masses and radii of exoplanets
gas giants

A simple M-R analysis suggests that something occurs in “hot Jupiters”



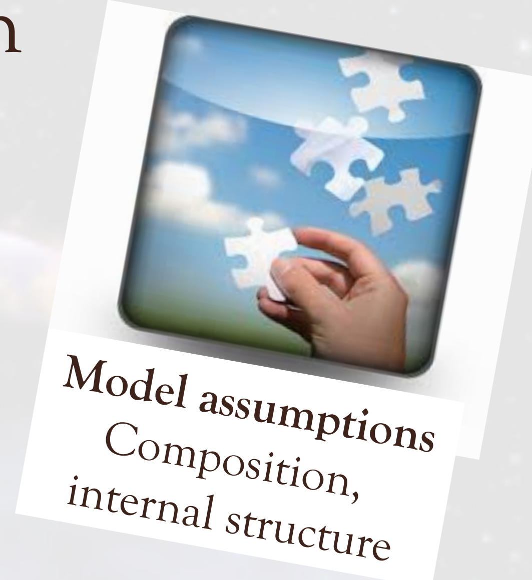
Masses and radii of exoplanets
small/intermediate masss

For small planets we can try to identify the composition and the existence of an atmosphere



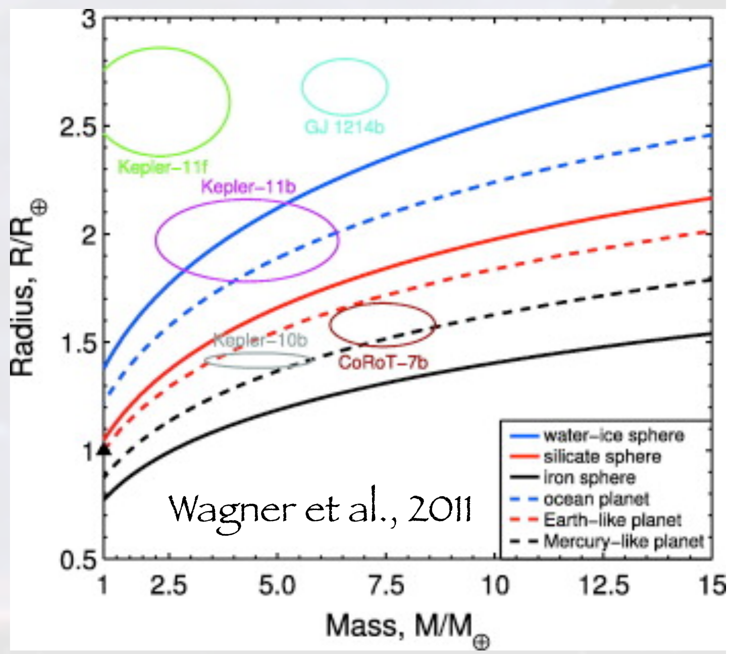
Venturini & Helled, 2017 (submitted)

Exoplanet characterization

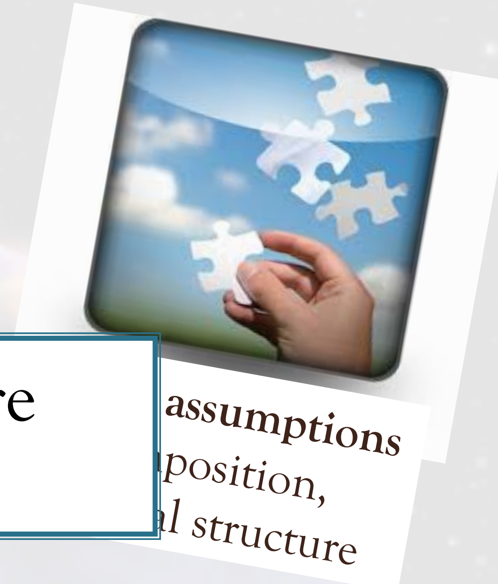


<u>The challenges for theory:</u>

- A degenerate problem: many unknowns and only a few constraints.
- Linking M-R relation and age of the system with planetary evolution.
- Model assumptions:
  - **What materials to use?**
  - **How many layers to assume?**
  - **Are the materials well-mixed or differentiated?**
  - **Is the planet fully adiabatic?**
  - **How to include interior-atmosphere interactions?**



Exoplanet characterization

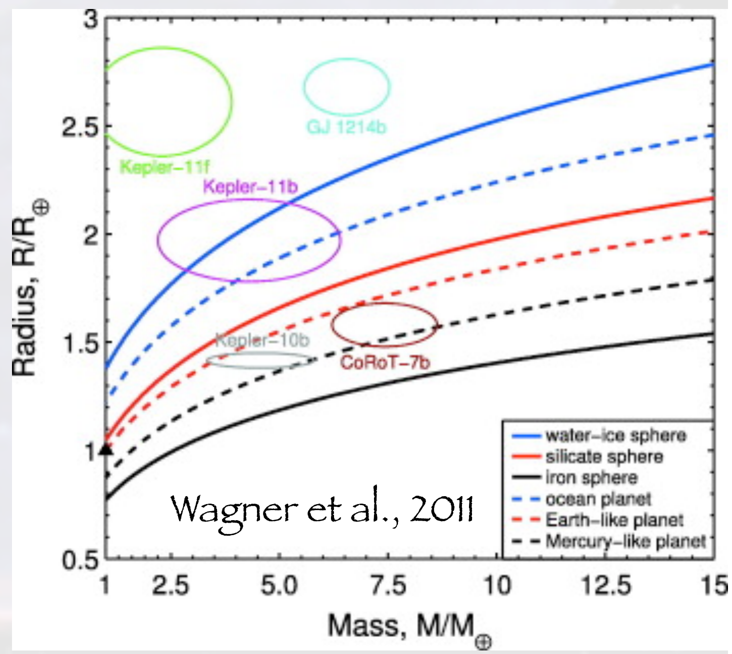


The challenges for theory:

- A degenerate problem: many unknow
- Linking
  system

Are there compositions which are impossible? more likely?

- Model assumptions:
  - What materials to use?
  - How many layers to assume?
  - Are the materials well-mixed or differentiated?
  - Is the planet fully adiabatic?
  - How to include interior-atmosphere interactions?



The Mass-Radius (M-R) relation

Gaseous planets:

- Hydrogen and helium, heavy elements
- Inflated hot-Jupiters (e.g., Guillot et al., 1996; Burrows et al., 2007)
- Cold Jupiters (e.g., Miller & Fortney, 2011)

Sensitive to temperature, internal structure, heavy element mass, EOS, age

Terrestrial planets:

- Super-Earths; mini-Neptunes (e.g.,Valencia et al., 2007; Seager et al., 2007)
- Earth-like composition, M-R relation of pure refractory materials

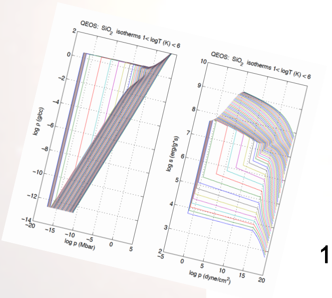
Sensitive to composition, EOS

What about a mixture?

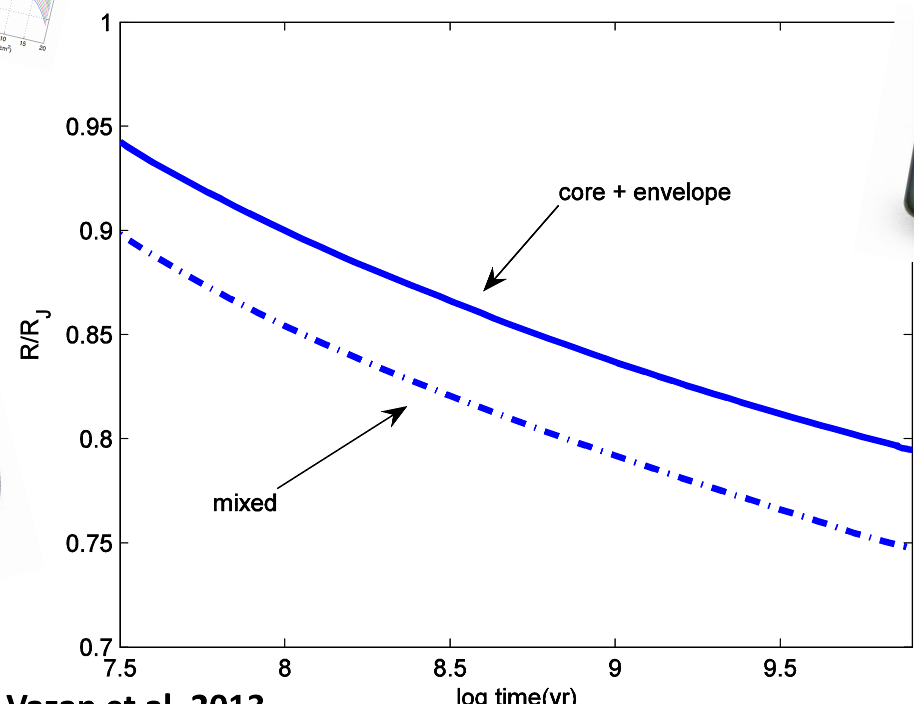
- Exoplanets are diverse – many intermediate mass with volatiles.
- The challenge: temperature, age, and internal structure (Baraffe et al., 2008; Vazan et al., 2013).

A few examples...

The importance of the distribution of heavy elements (and EOS)



Gaseous (massive) planets:



Vazan et al. 2013

1 M_J planet
Z=0.5

Distribution

Δ structure ~ 7%

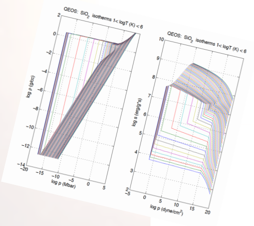
EOS

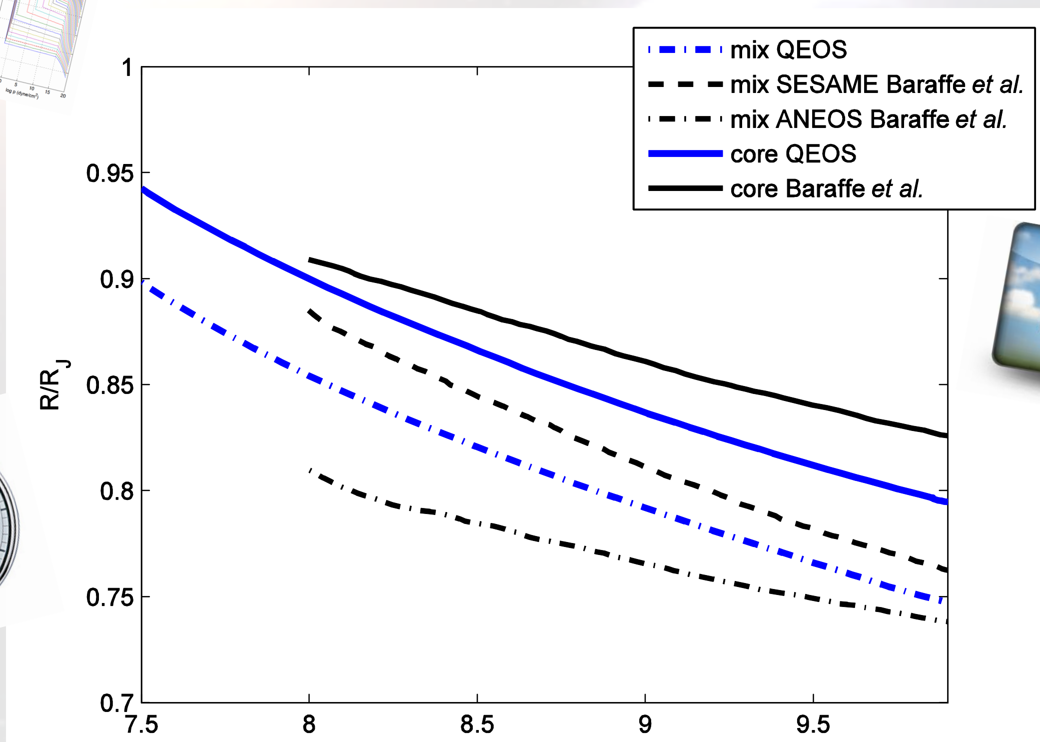
ΔEOS = 10%
(Baraffe et al. 2008)

M-R(t) is affected by the heavy-element distribution in metal-rich giant planets.

The importance of the distribution of heavy elements (and EOS)

Gaseous (massive) planets:





Vazan et al. 2013

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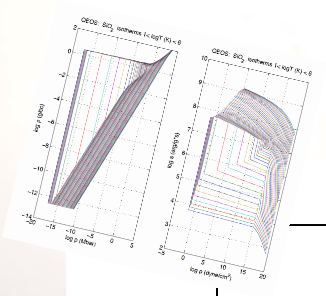
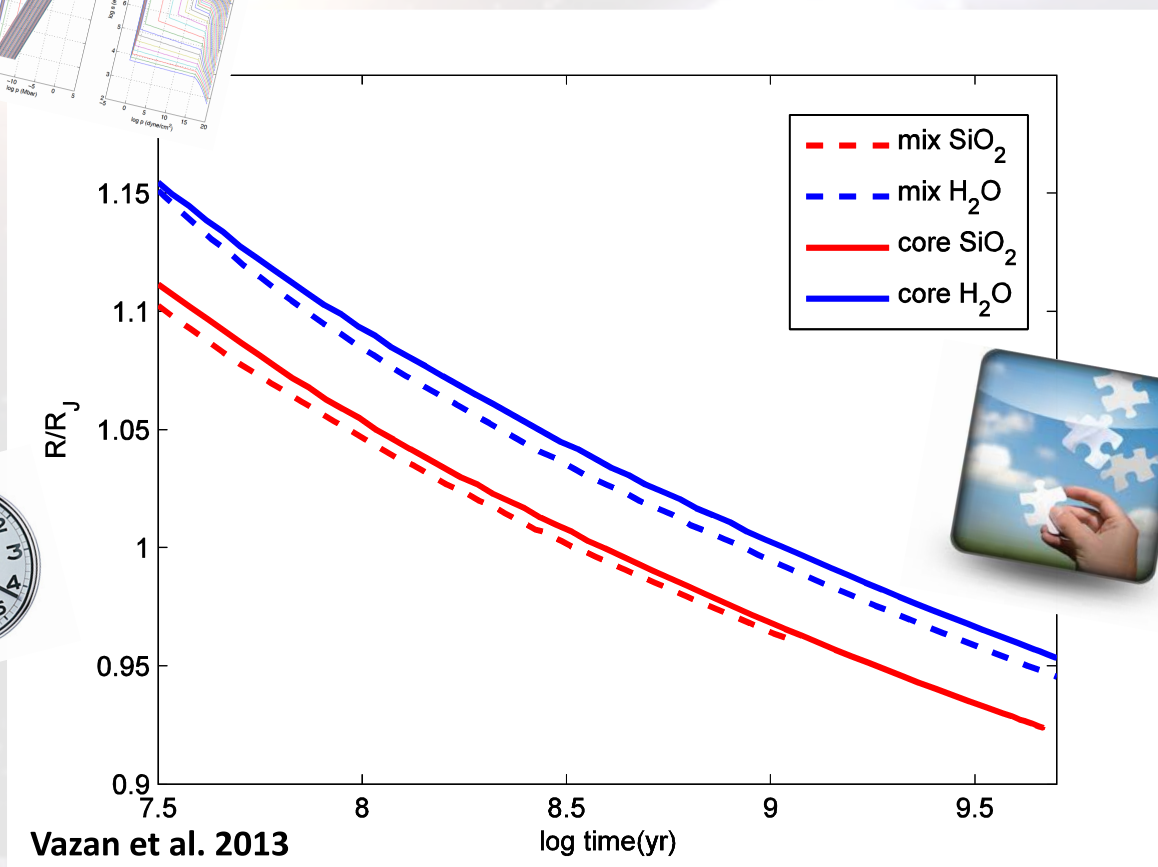


Gaseous (massive) planets:



1 M_J planet

Z=0.2

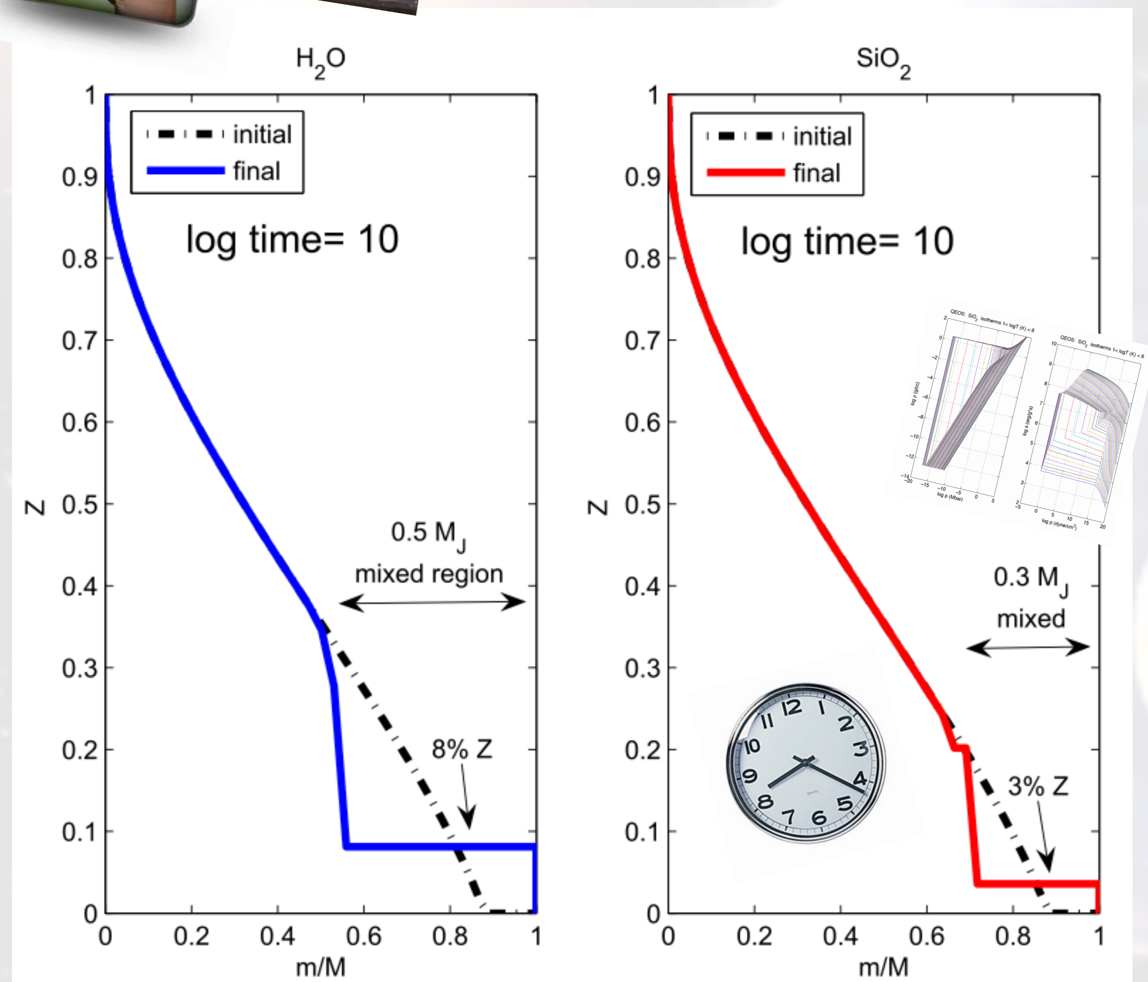
Composition

Δ rock-ice ~ 5-15%

For Z ≤ 0.2 the M-R relation is less sensitive to the assumed distribution.

The importance of composition gradients
Effect of composition

Gaseous (massive) planets:



1 M_J with Z=0.35

Efficiency of mixing depends on the primordial internal structure and on the assumed composition

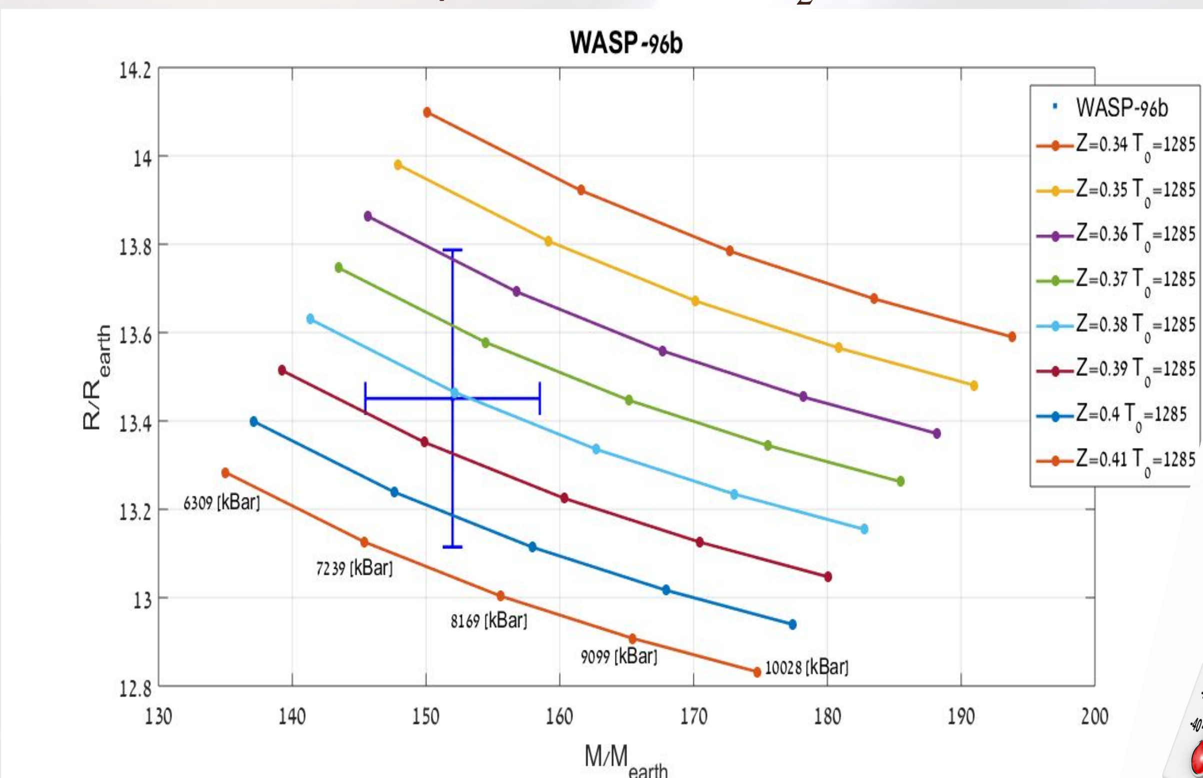
Vazan et al. 2015

Adiabatic models

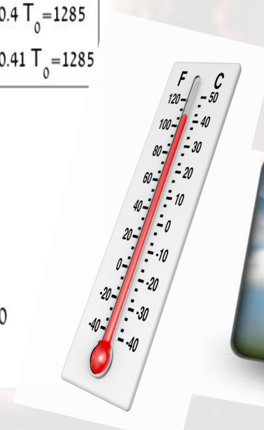
The example of WASP-96b

M_p=0.48±0.03M_J
Rp=1.2±0.06R_J
a = 0.0453±0.00128 AU
$M_\star$=1.06±0.09$M_\odot$

1 bar temperature: of 1285 K
Heavy elements – H_2O



Best fit composition:
Z=0.38
A highly enriched giant planet!



Lahav et al., in prep.

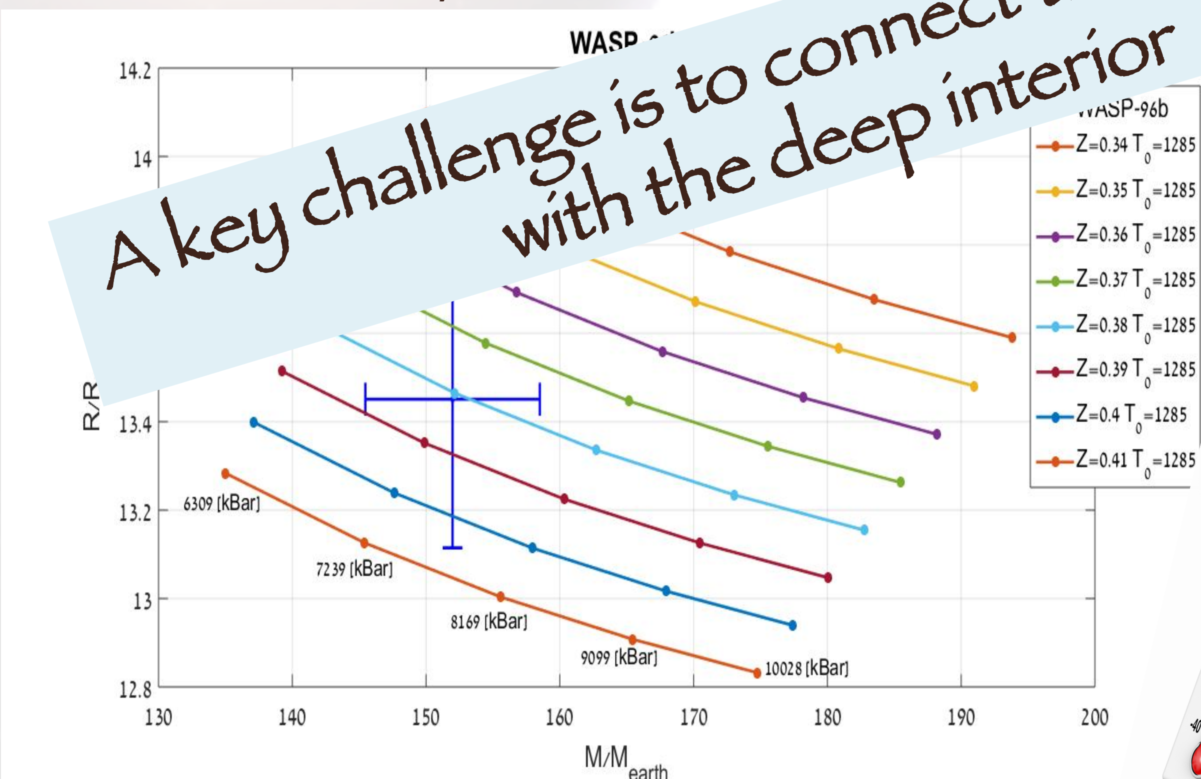
Adiabatic models

The example of WASP-96b

M_p=0.48±0.03M_J
Rp=1.2±0.06R_J
a = 0.045… …0128 AU
… 9$M_\odot$

1 bar temperature: of 1285 K
Heavy elements – H_2O

A key challenge is to connect the atmosphere with the deep interior



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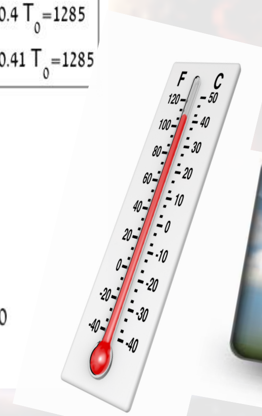
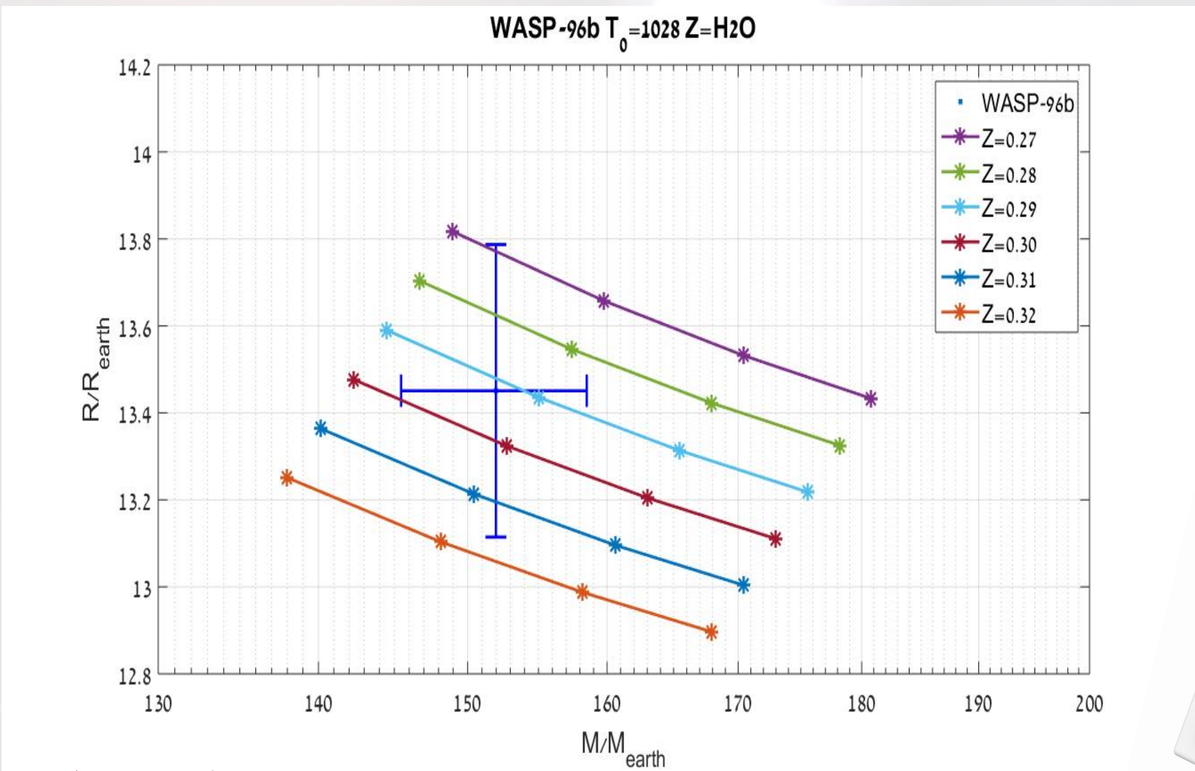


Adiabatic models

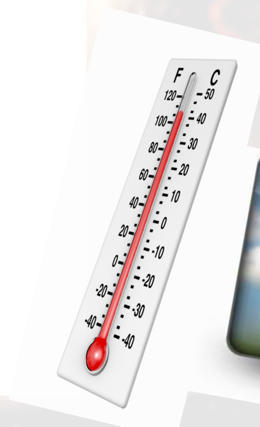
The example of WASP-96b

M_p=0.48±0.03M_J
Rp=1.2±0.06R_J
a = 0.0453±0.00128 AU
$M_\star$=1.06±0.09$M_\odot$

1 bar temperature is lowered by 20%
Heavy elements – H_2O



Best fit composition:
Z=0.29
Z decreases by ~35%!



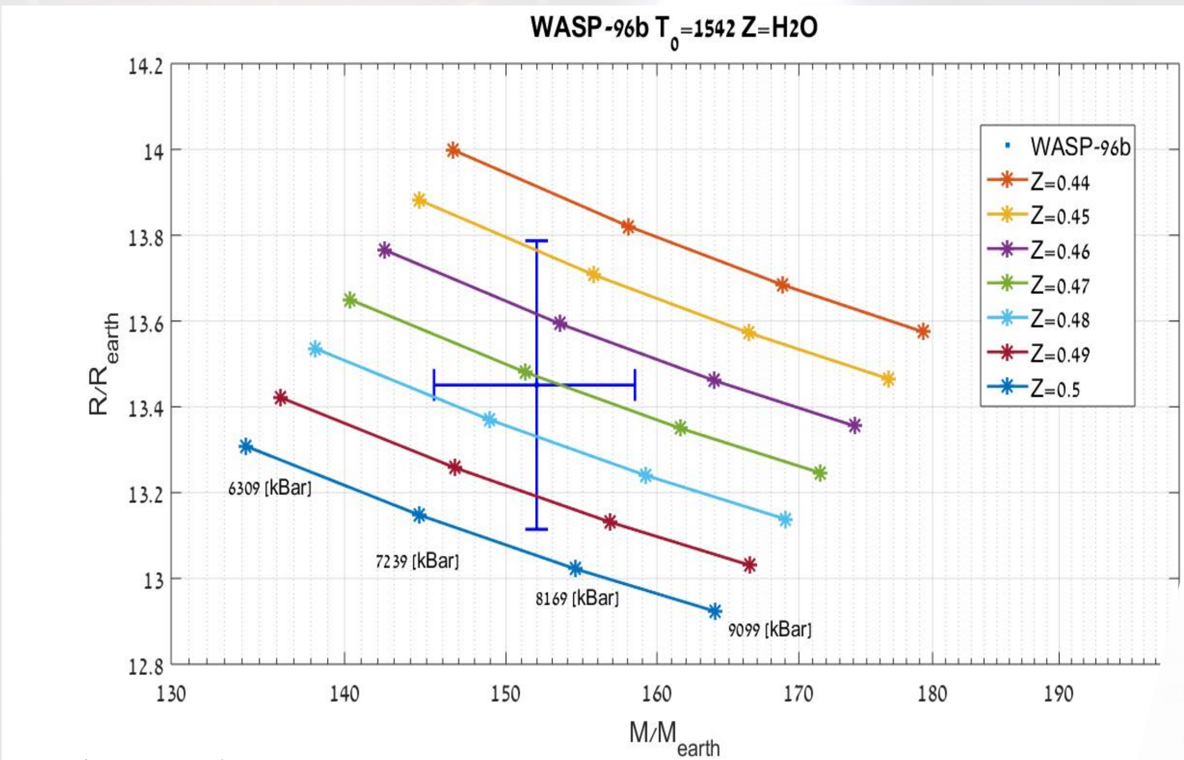
Lahav et al., in prep.

Adiabatic models

The example of WASP-96b

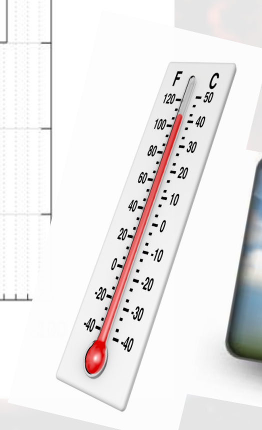
$M_p=0.48\pm0.03M_J$
$Rp=1.2\pm0.06R_J$
$a = 0.0453\pm0.00128$ AU
$M_\star=1.06\pm0.09M_\odot$

1 bar temperature is increased by 20%
Heavy elements – H_2O



Lahav et al., in prep.

Best fit composition:
Z=0.47
Z increases by ~20%!

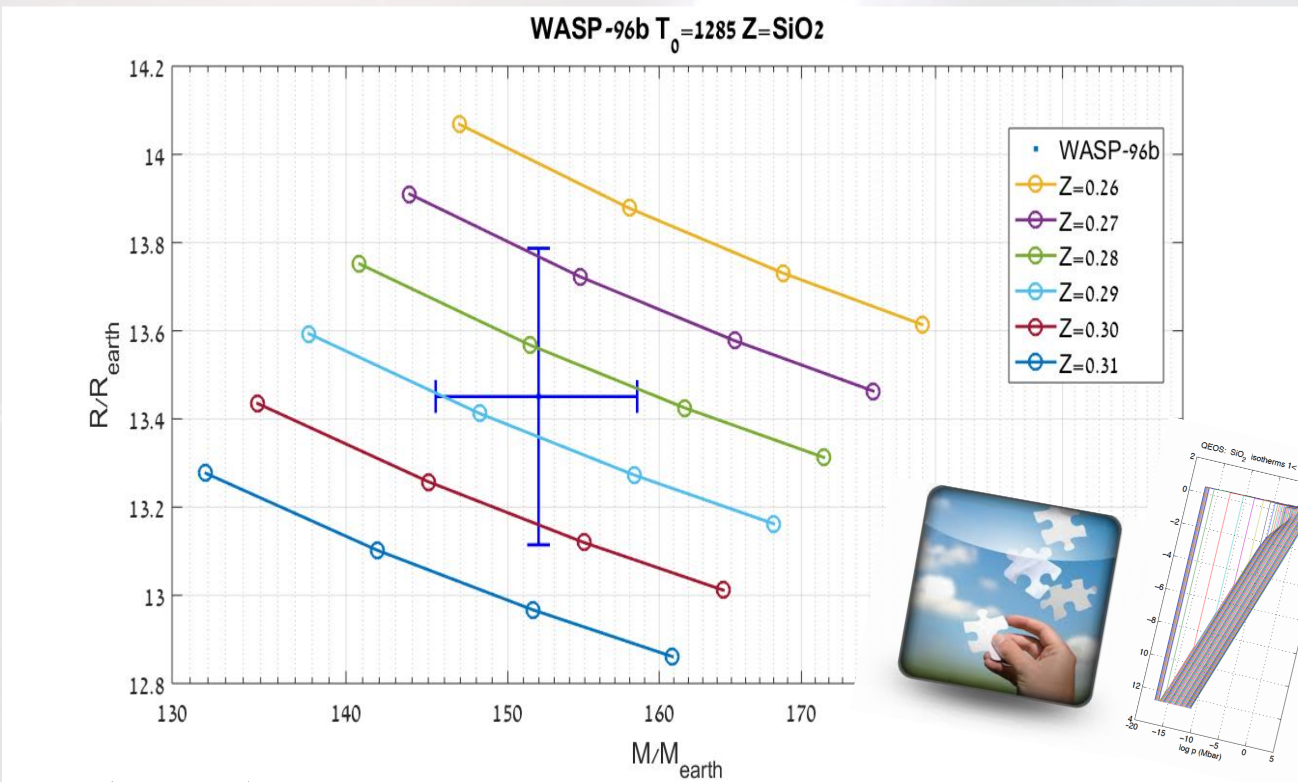


Adiabatic models

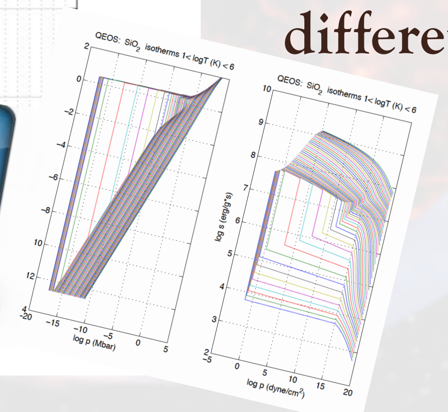
The example of WASP-96b

M_p=0.48±0.03M_J
Rp=1.2±0.06R_J
a = 0.0453±0.00128 AU
$M_\star$=1.06±0.09$M_\odot$

1 bar temperature: of 1285 K
Heavy elements – SiO_2



Best fit composition:
Z=0.295
More than 20% difference due to different EOS.



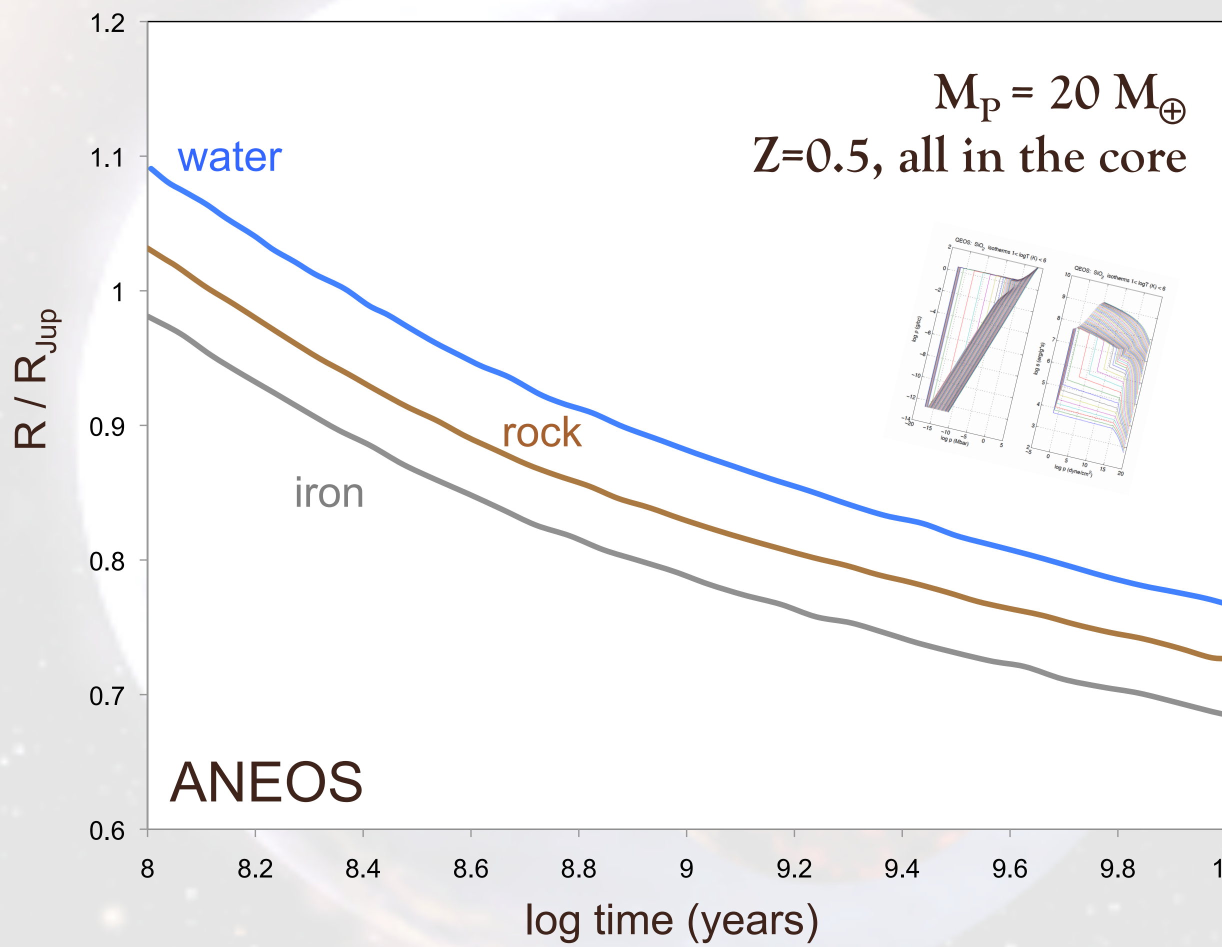
Lahav et al., in prep.

The importance of the assumed composition (high-Z)

Intermediate-mass planets:

$M_P = 20\ M_\oplus$
$M_Z = 10\ M_\oplus$

$\Delta \sim 10\%$
uncertainty in R
at a given age



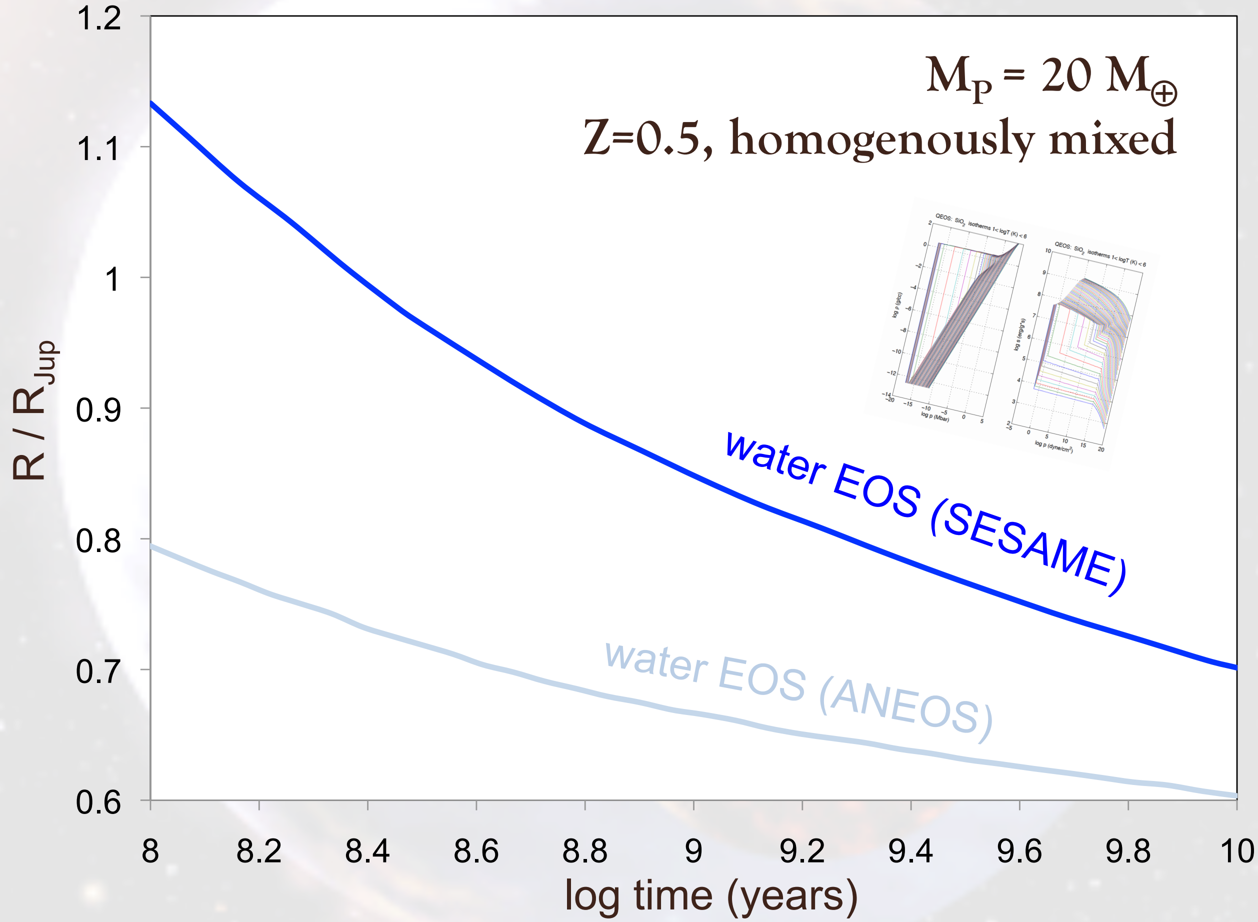
see Baraffe et al.,2008 for details

The importance of the EOS (mixed model)

Intermediate-mass planets:

$M_P = 20\ M_\oplus$
$M_Z = 10\ M_\oplus$

Δ ~10-20% uncertainty in R at a given age homogenous interior



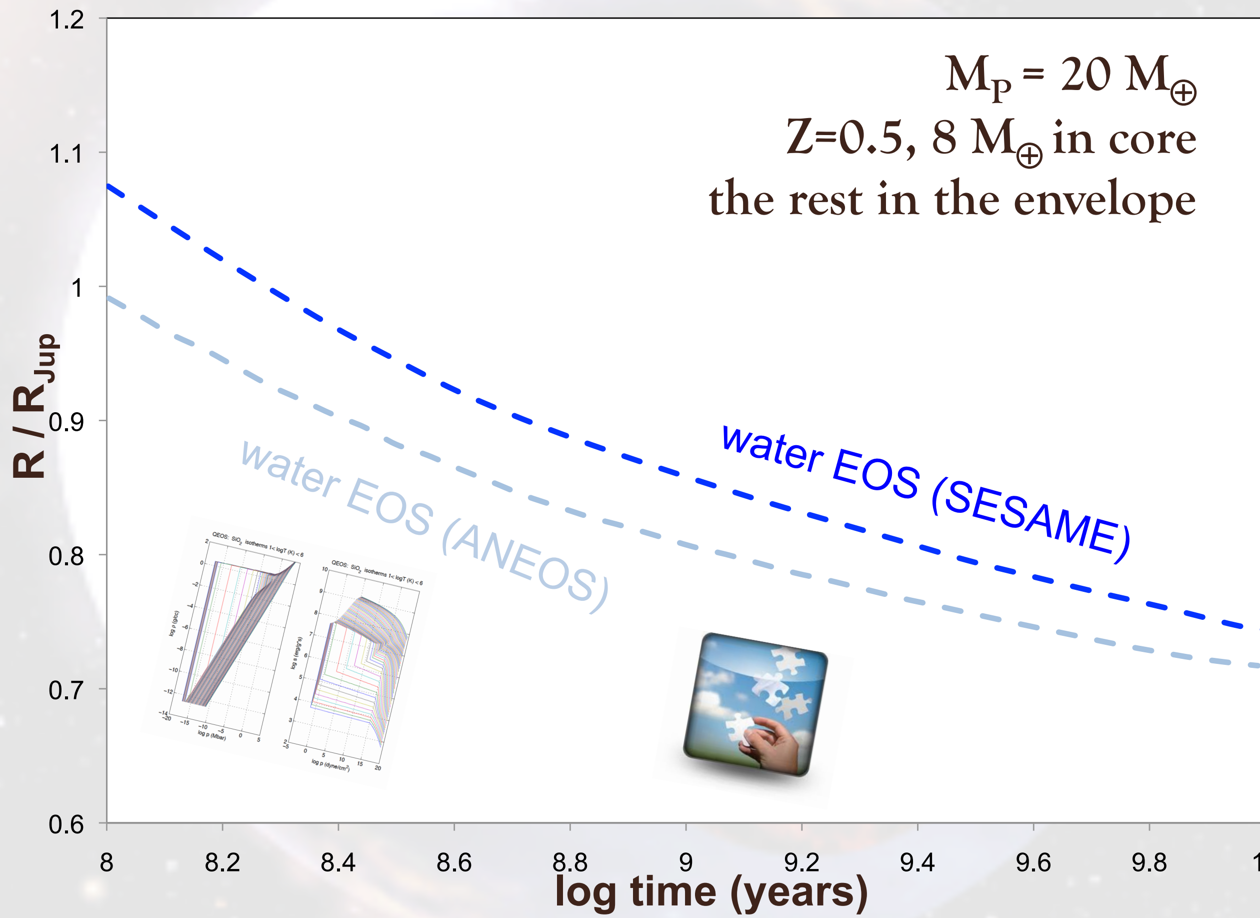
see Baraffe et al.,2008 for details

The importance of the EOS (core+envelope)

Intermediate-mass planets:

$M_P = 20\ M_\oplus$
$M_Z = 10\ M_\oplus$

$\Delta < \sim 10\%$
uncertainty in R at
a given age
core + envelope



see Baraffe et al.,2008 for details

The importance of the EOS (core+envelope)

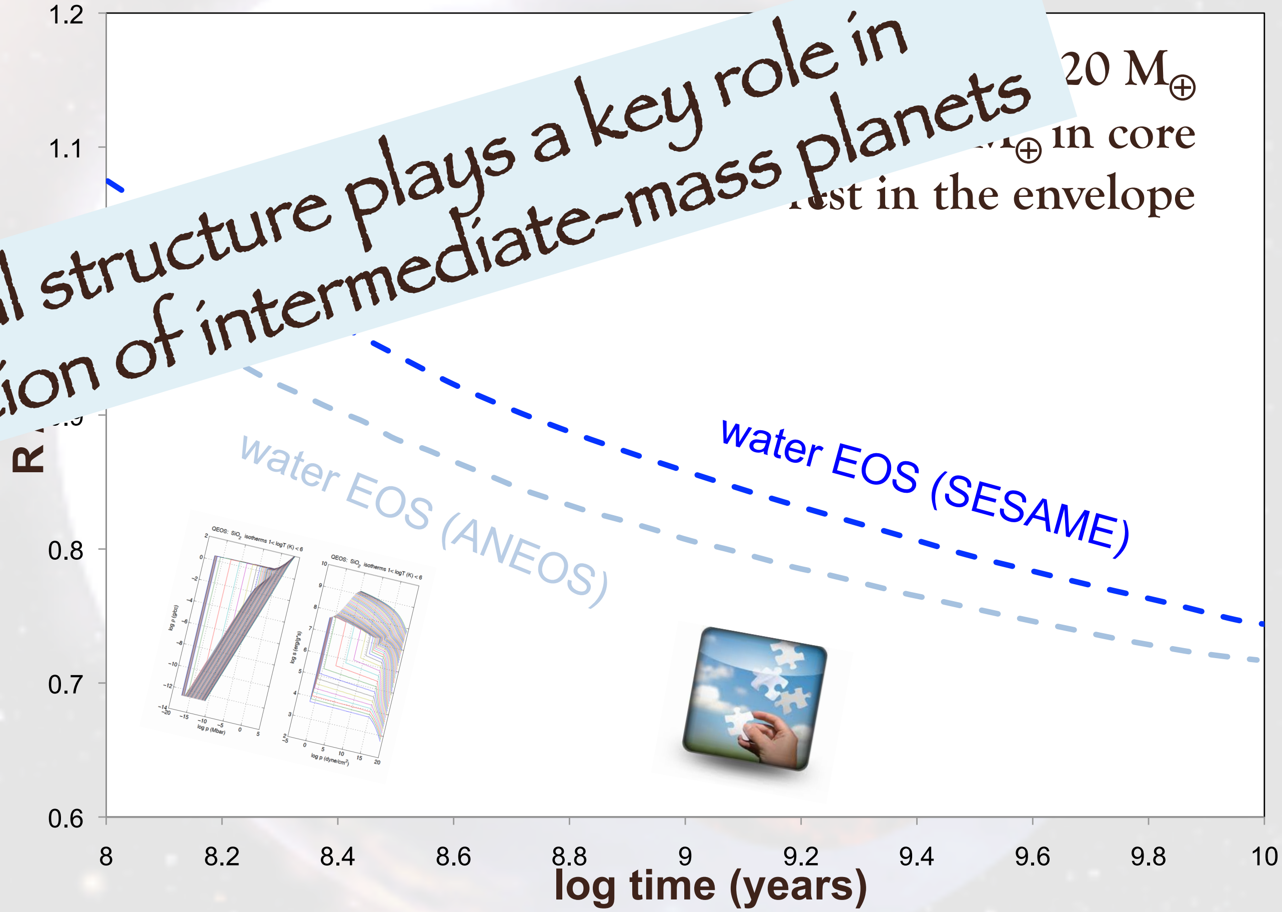
Intermediate-mass planets:

$M_P = 20\ M_\oplus$

$M_Z = 10\ M_\oplus$

The internal structure plays a key role in characterization of intermediate-mass planets

[illegible] < ~10%
uncertainty in R at a given age
core + envelope

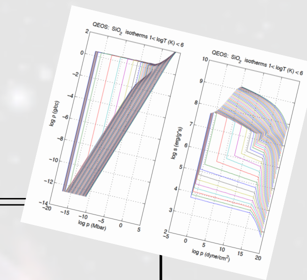


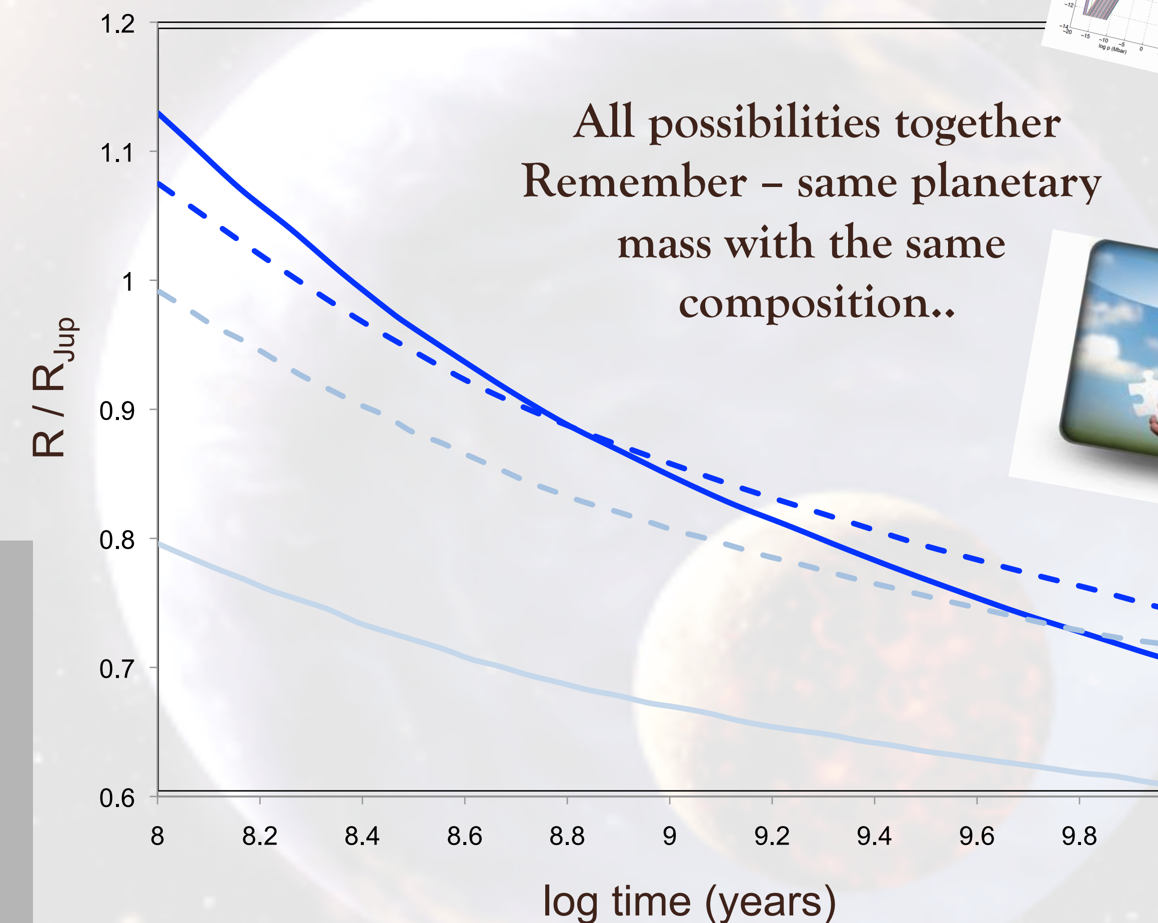
see Baraffe et al.,2008 for details

The importance of assumed composition, distribution, EOS

Intermediate-mass planets:

$M_P = 20\ M_\oplus$
$M_Z = 10\ M_\oplus$





All possibilities together
Remember – same planetary mass with the same composition..

Δ > ~20% uncertainty in radius at a given age
this is large

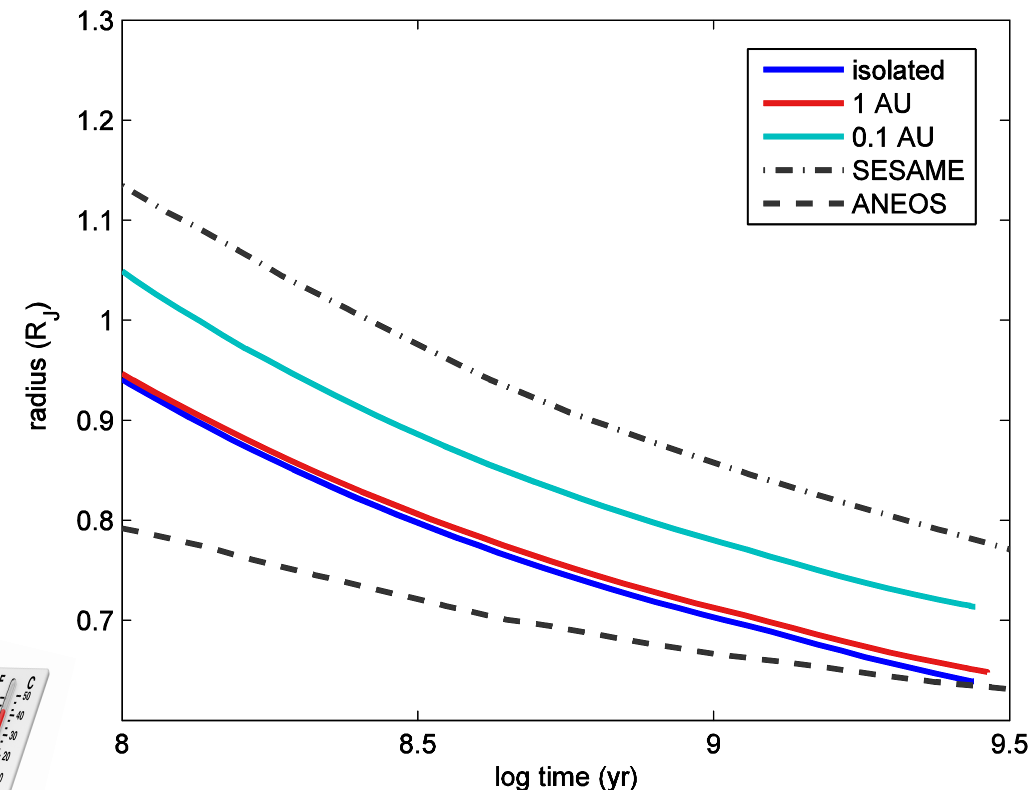
The importance of radial distance

Intermediate-mass planets:

$M_P = 20\ M_\oplus$
Z=0.5 (mixed)

EOS is very important for Neptune-mass (Z > 0.2), especially for homogenous interiors

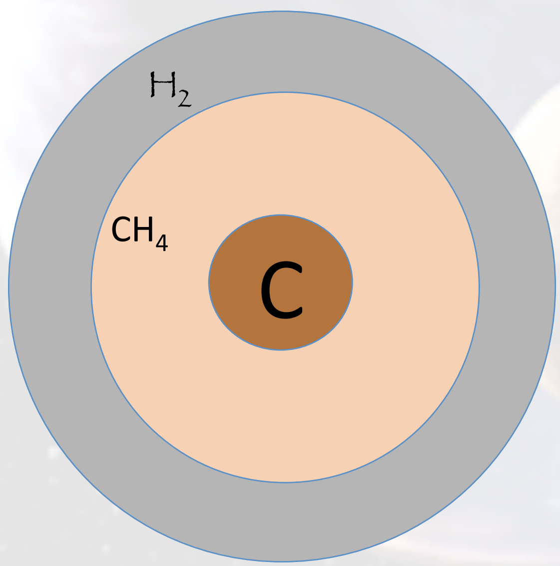
Vazan et al. 2013

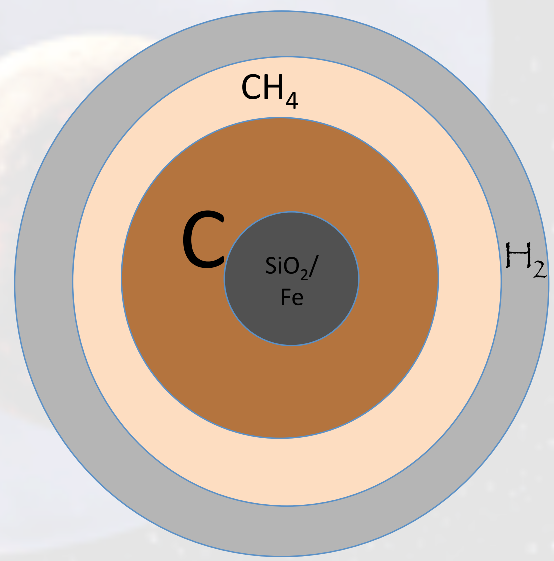


A non-monotonic behavior of M-R due to dissociation (the example of CH_4 planets)

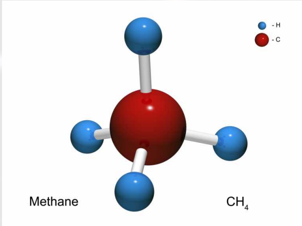
- **Pure CH_4 planets:**
  If $P_c > P_{diss}$ carbon EOS (core). Dissociation of CH_4 produces $1/3 M_C$ of H which is assumed to form H_2-atmosphere. The remaining mass is in a CH_4 shell.
- **CH_4 planets + SiO_2/Fe core:**
  Innermost region is SiO_2/Fe above the core, if $P > P_{diss}$ carbon EOS, otherwise CH_4. Mass of H-atmosphere is 1/3 the mass of the carbon shell.

To be explored in detail: other materials; temperature profiles; photo-evaporation; differentiation, chemical interactions

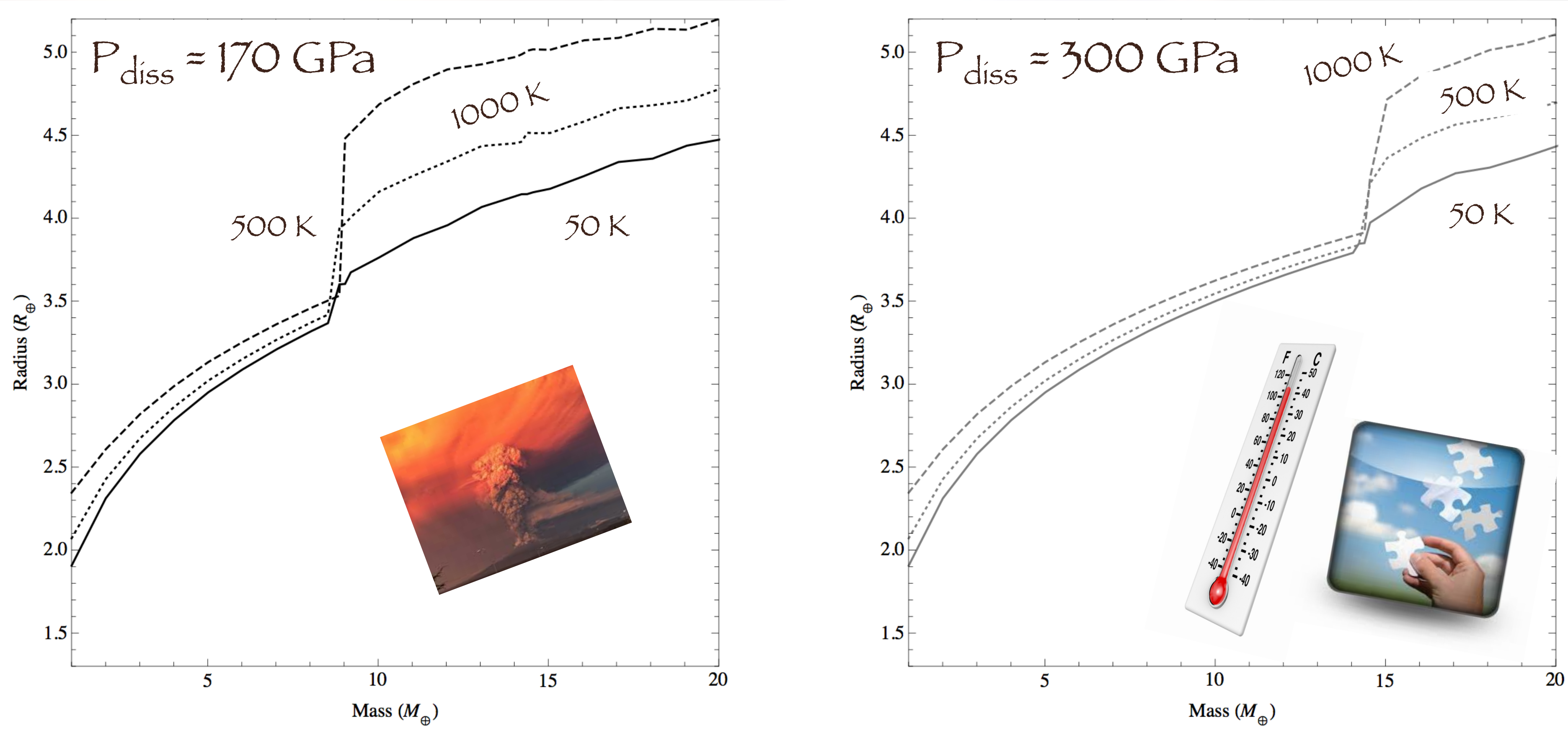




M-R relation: CH_4 planets

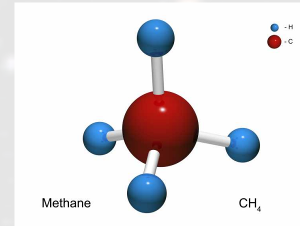


Helled et al., 2015

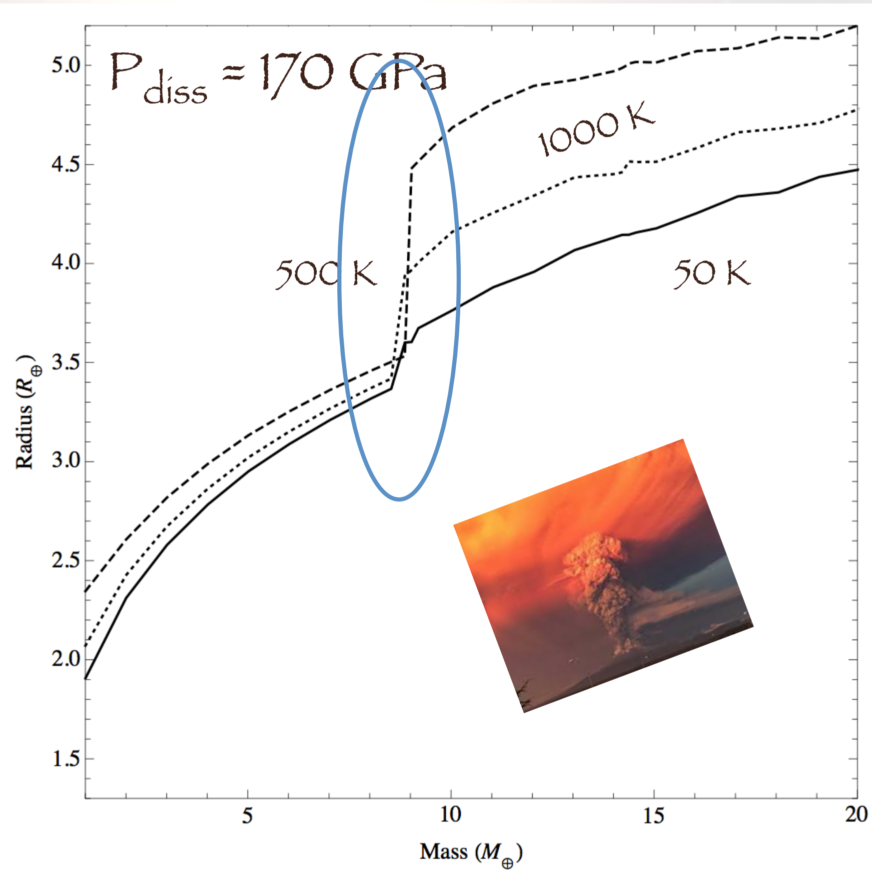


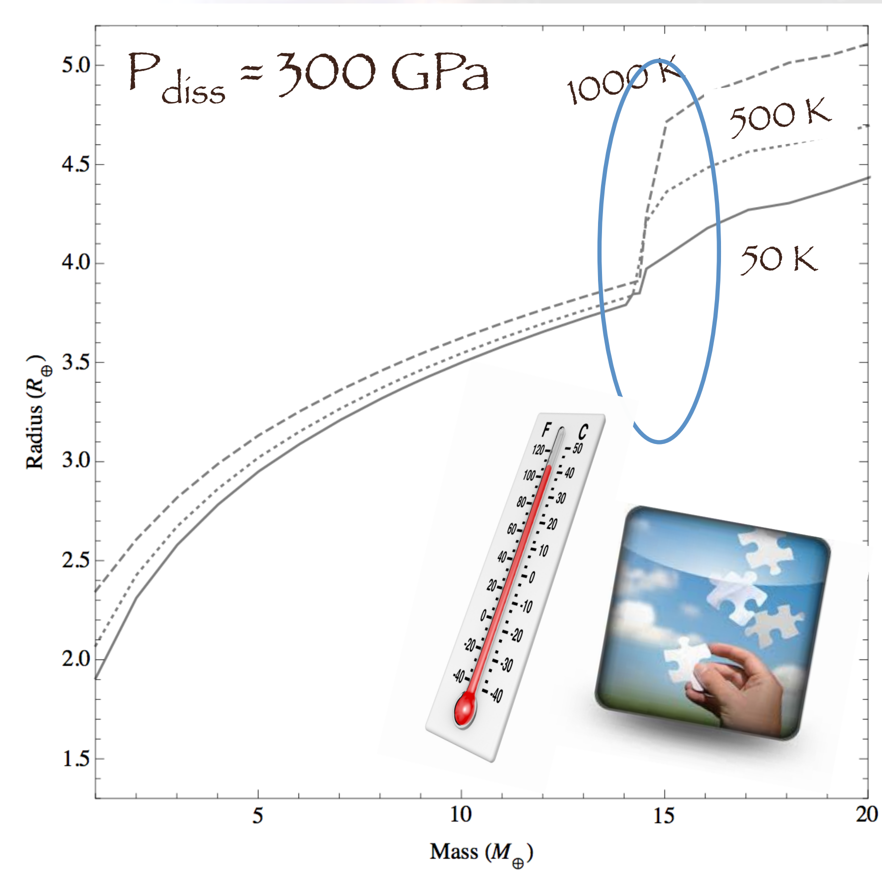
At high enough mass (depending on P_{diss}) CH_4 dissociates → a jump in M-R relation

M-R relation: CH_4 planets



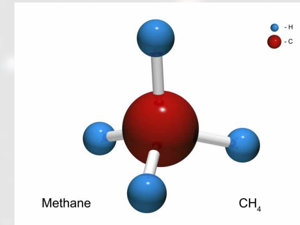
Helled et al., 2015

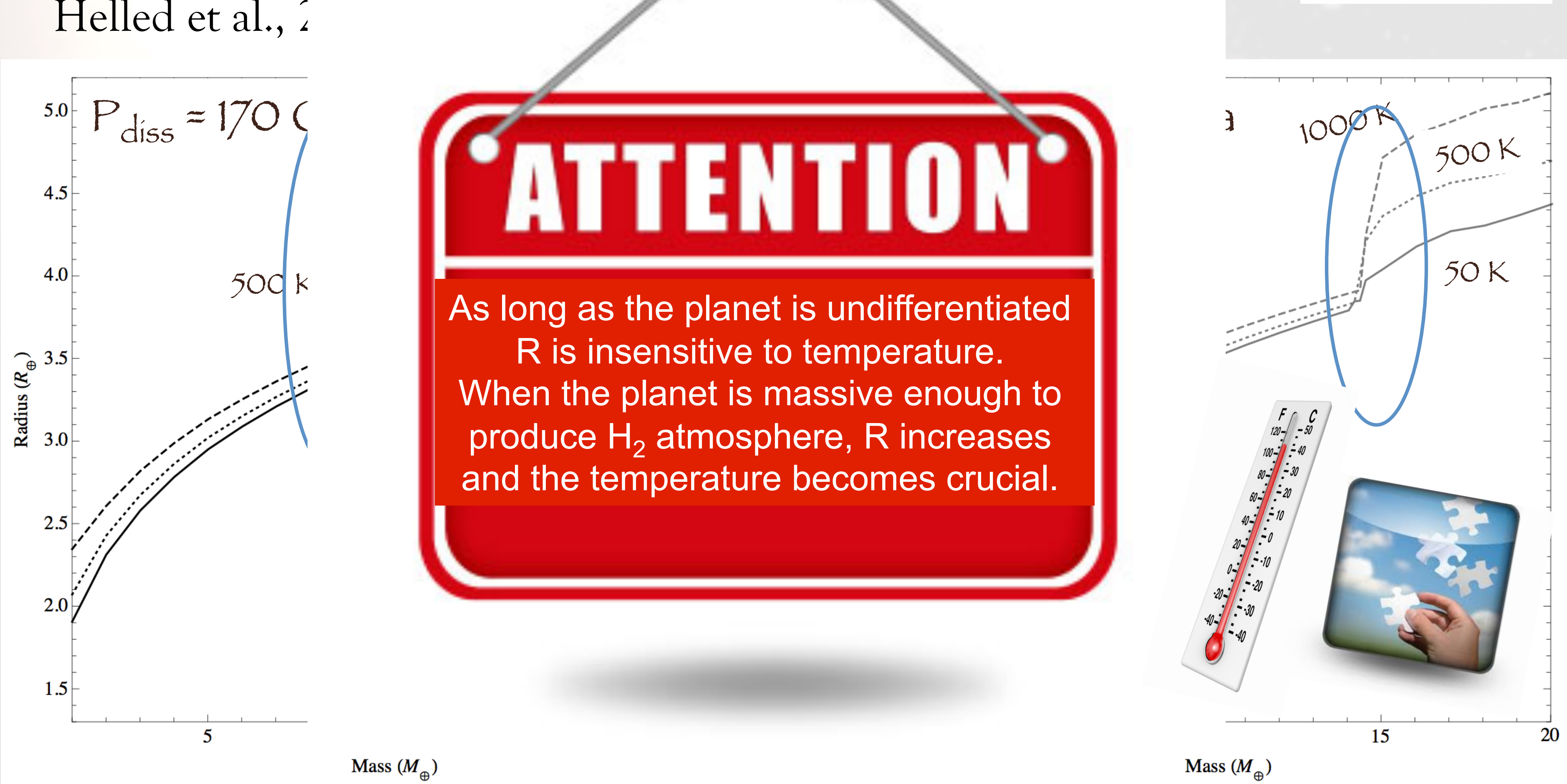




At high enough mass (depending on P_{diss}) CH_4 dissociates → a jump in M-R relation

Helled et al., 2





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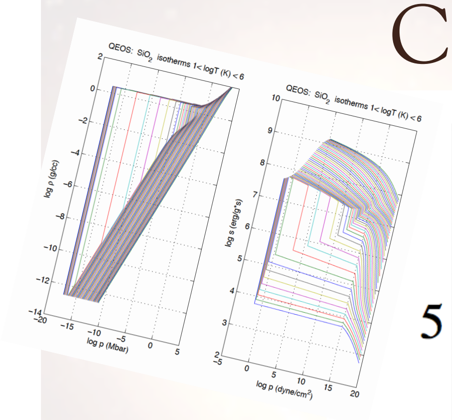
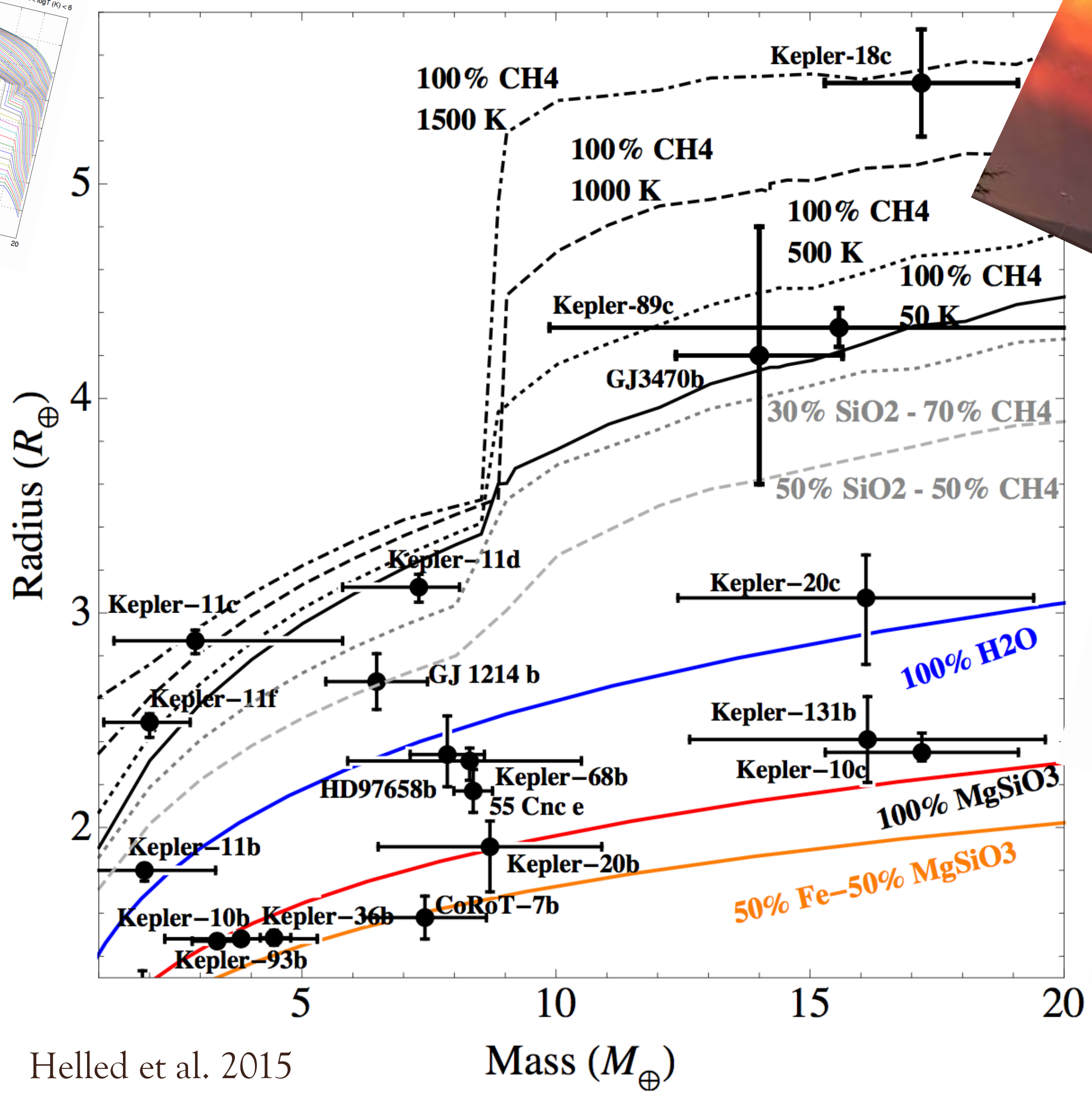
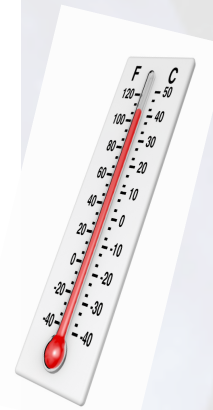
CH_4 planets & detected exoplanets

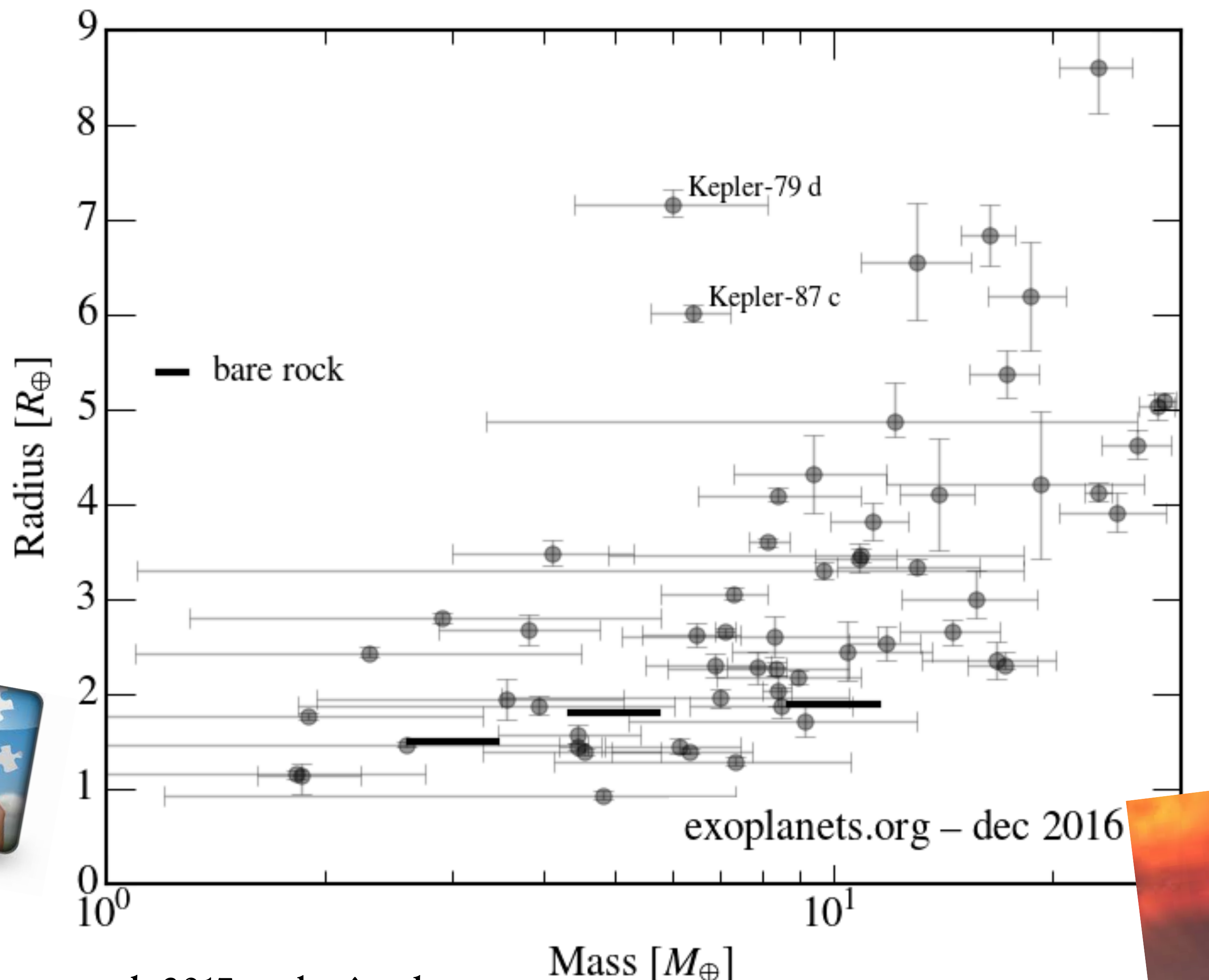






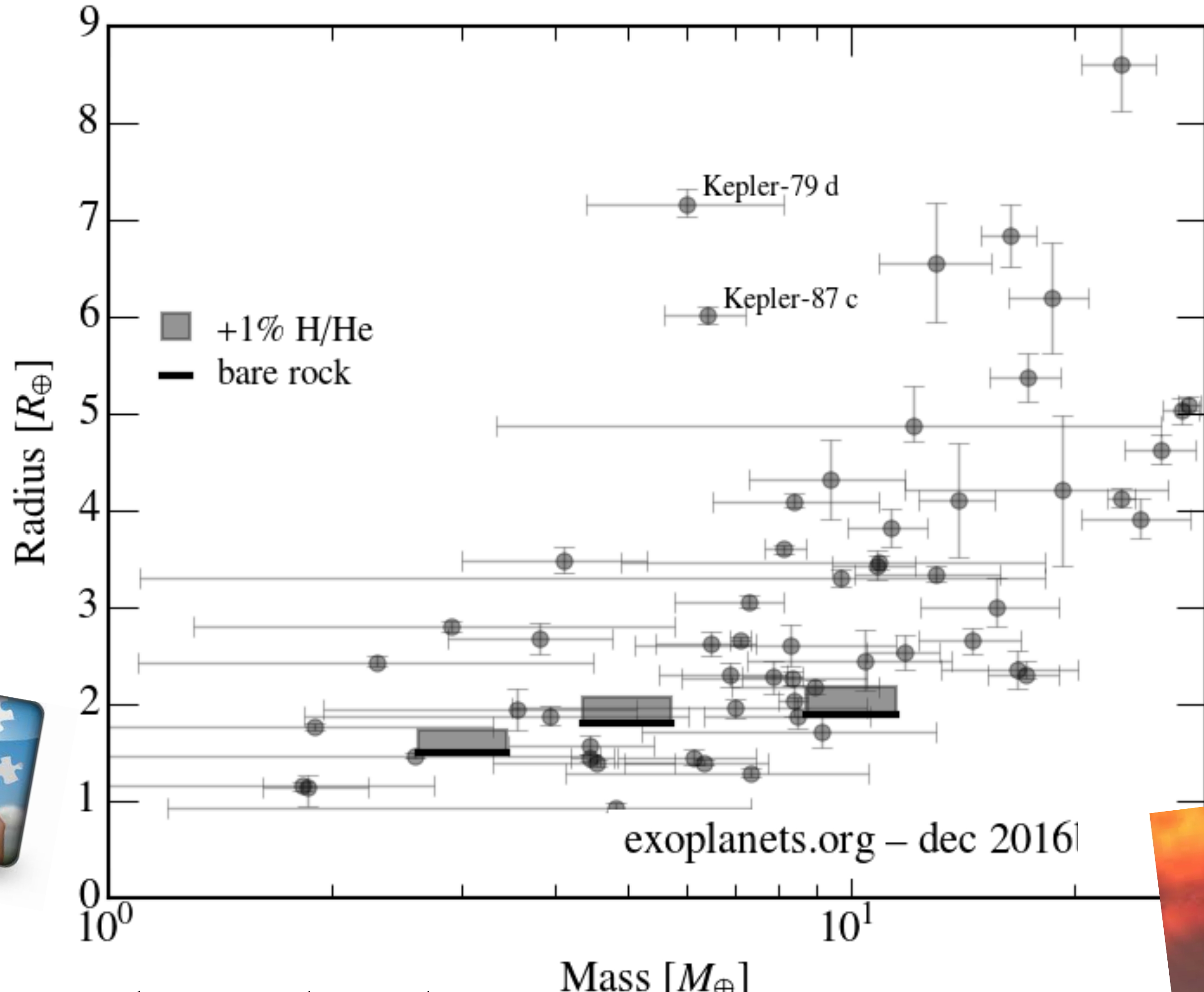
Helled et al. 2015

The importance of thermal effects & existence of an atmosphere on the M-R relation



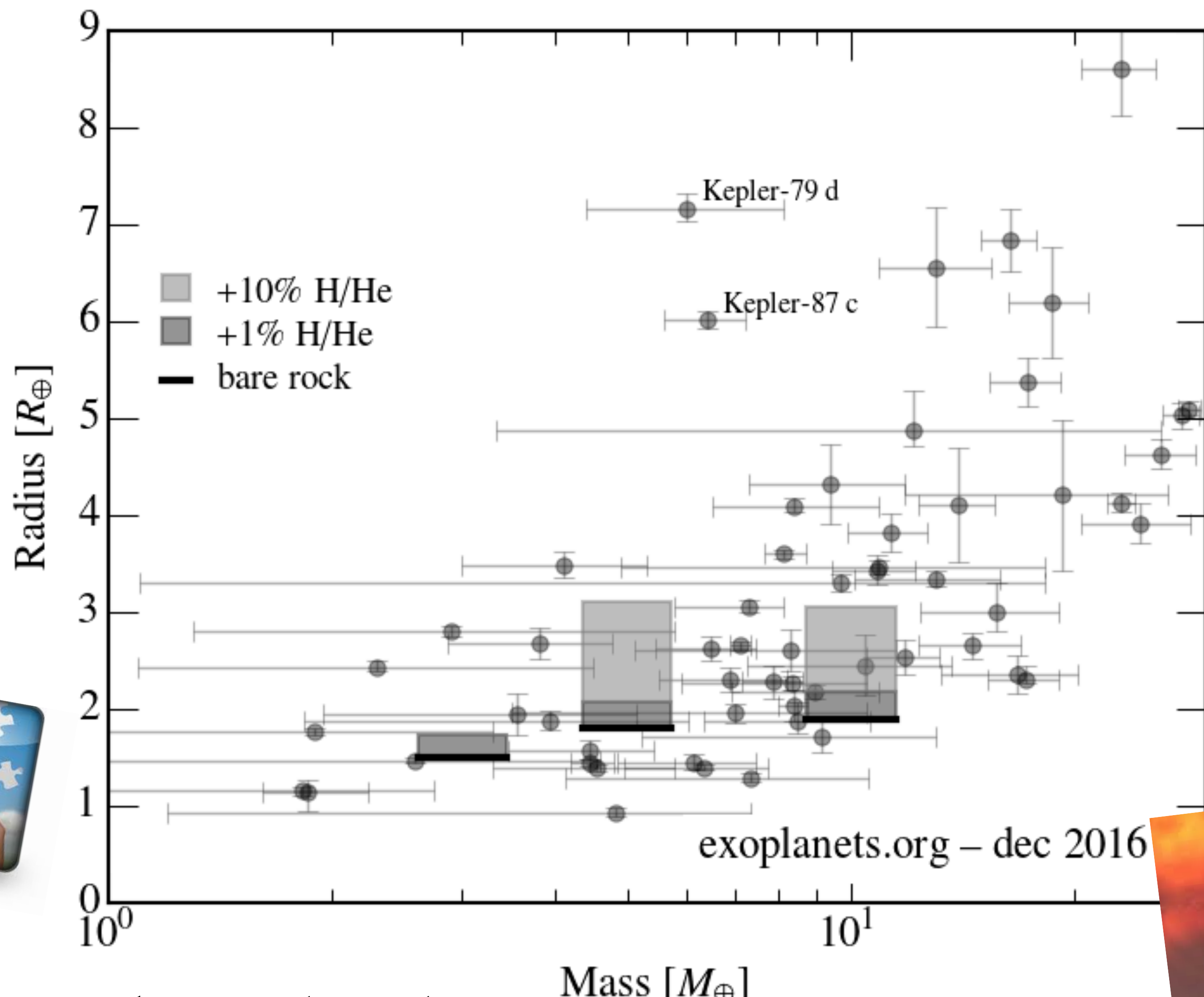
Vazan et al. 2017 - submitted

The importance of thermal effects & existence of an atmosphere on the M-R relation



Vazan et al. 2017 - submitted

The importance of thermal effects & existence of an atmosphere on the M-R relation



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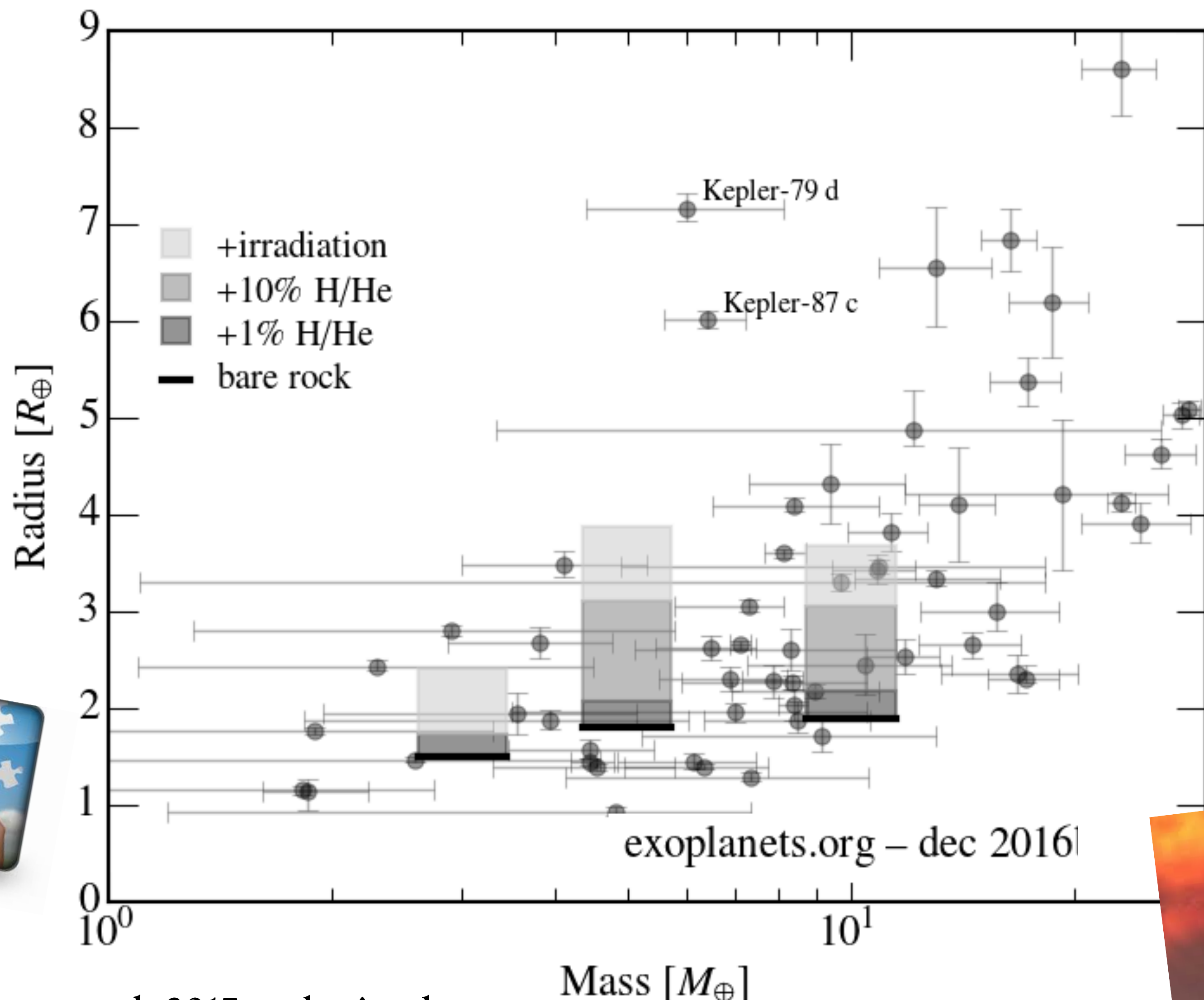

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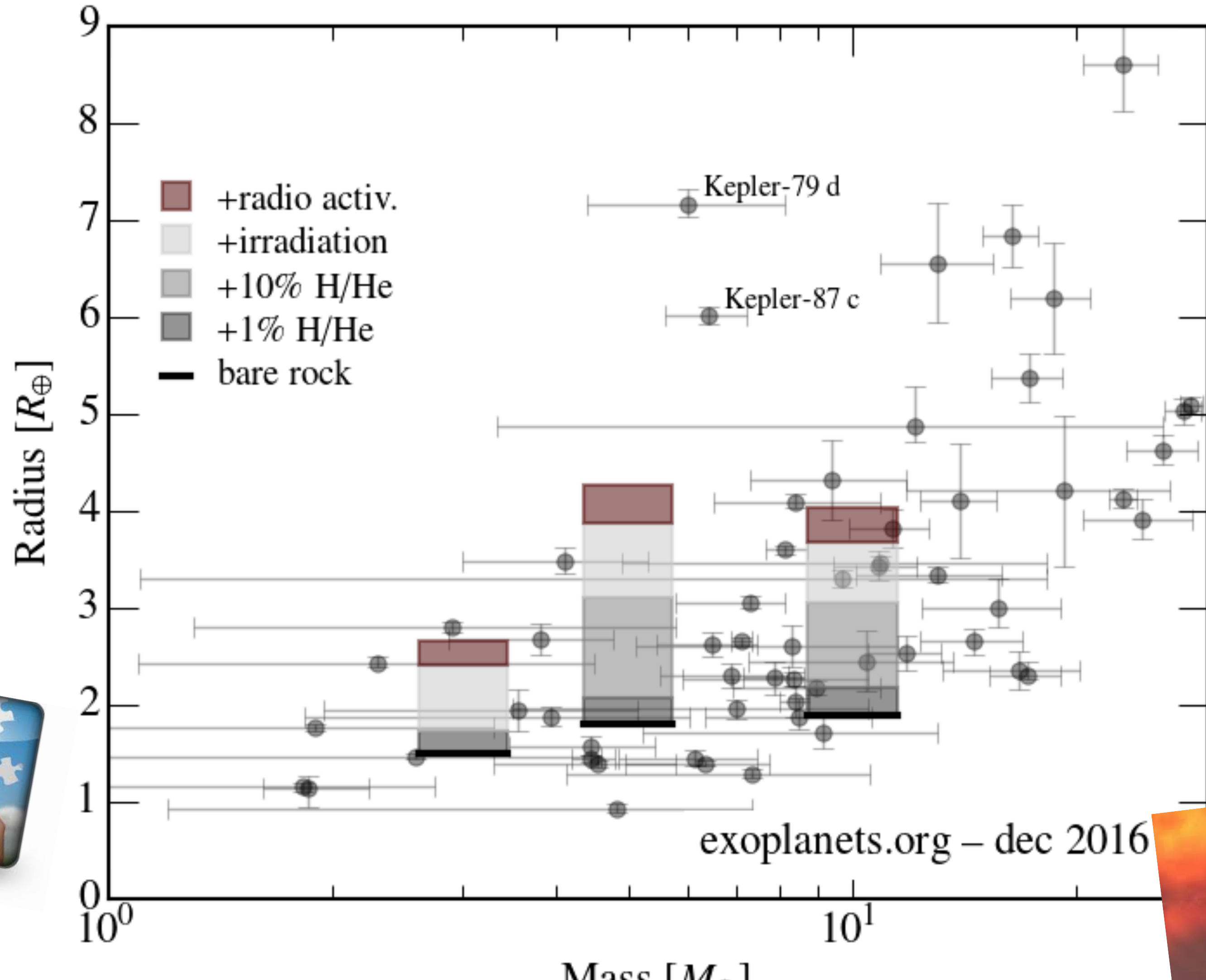

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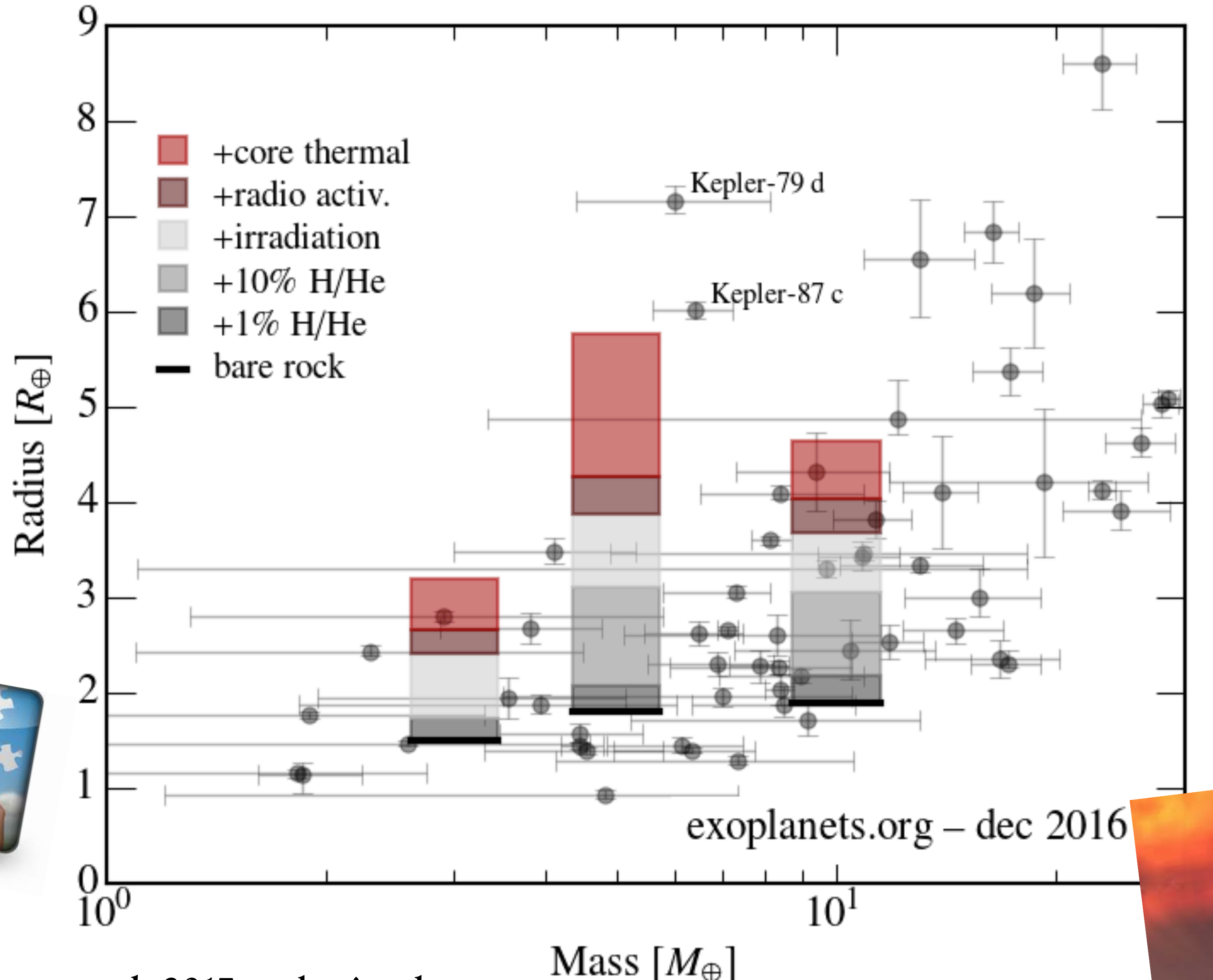

Vazan et al. 2017 - submitted

Conclusions & future work

- The M-R relation depends on assumed composition, EOS & distribution of heavy elements, age, temperature, opacity, irradiation.
- Intermediate-mass planets (with volatiles) are more sensitive to the EOS and the materials' distribution.
- The M-R relation can be complex including a non-monotonic behavior. Geophysical processes: mixing, outgassing, atmospheric loss, etc.

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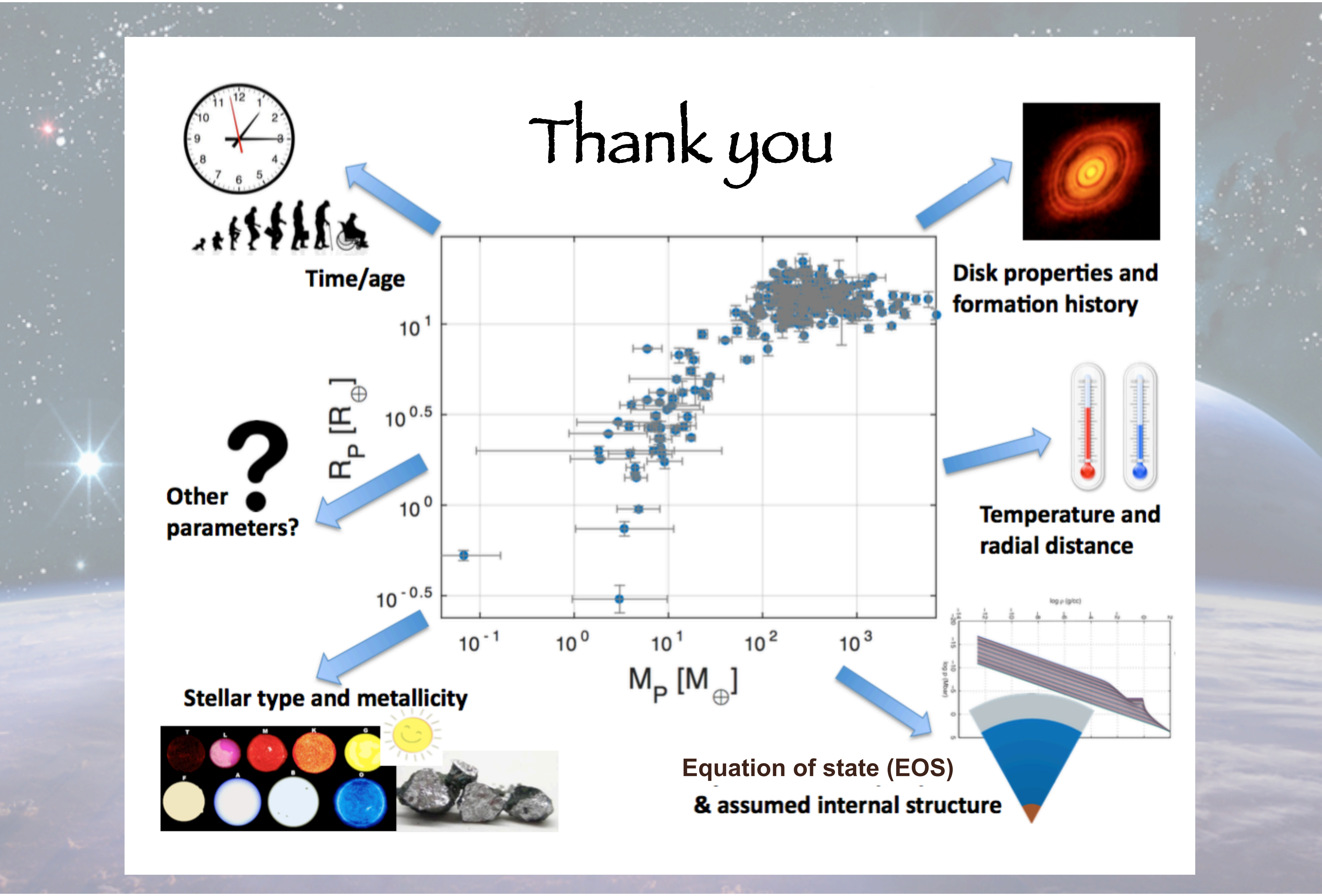
Future work:

- Identify theoretical uncertainty on M-R relation → a crucial piece for data interpretation (TESS, CHEOPS, PLATO 2.0).
- Connect atmospheric measurements with deep interior.


Thank you
Time/age
Disk properties and formation history
Temperature and radial distance
Other parameters?
Stellar type and metallicity
Equation of state (EOS)
& assumed internal structure
R_P [$R_\oplus$]
M_P [$M_\oplus$]
10^{1}
$10^{0.5}$
10^{0}
$10^{-0.5}$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}