Reevaluation of the possibility and impact of layered convection: application to the radius anomaly of hot Jupiters

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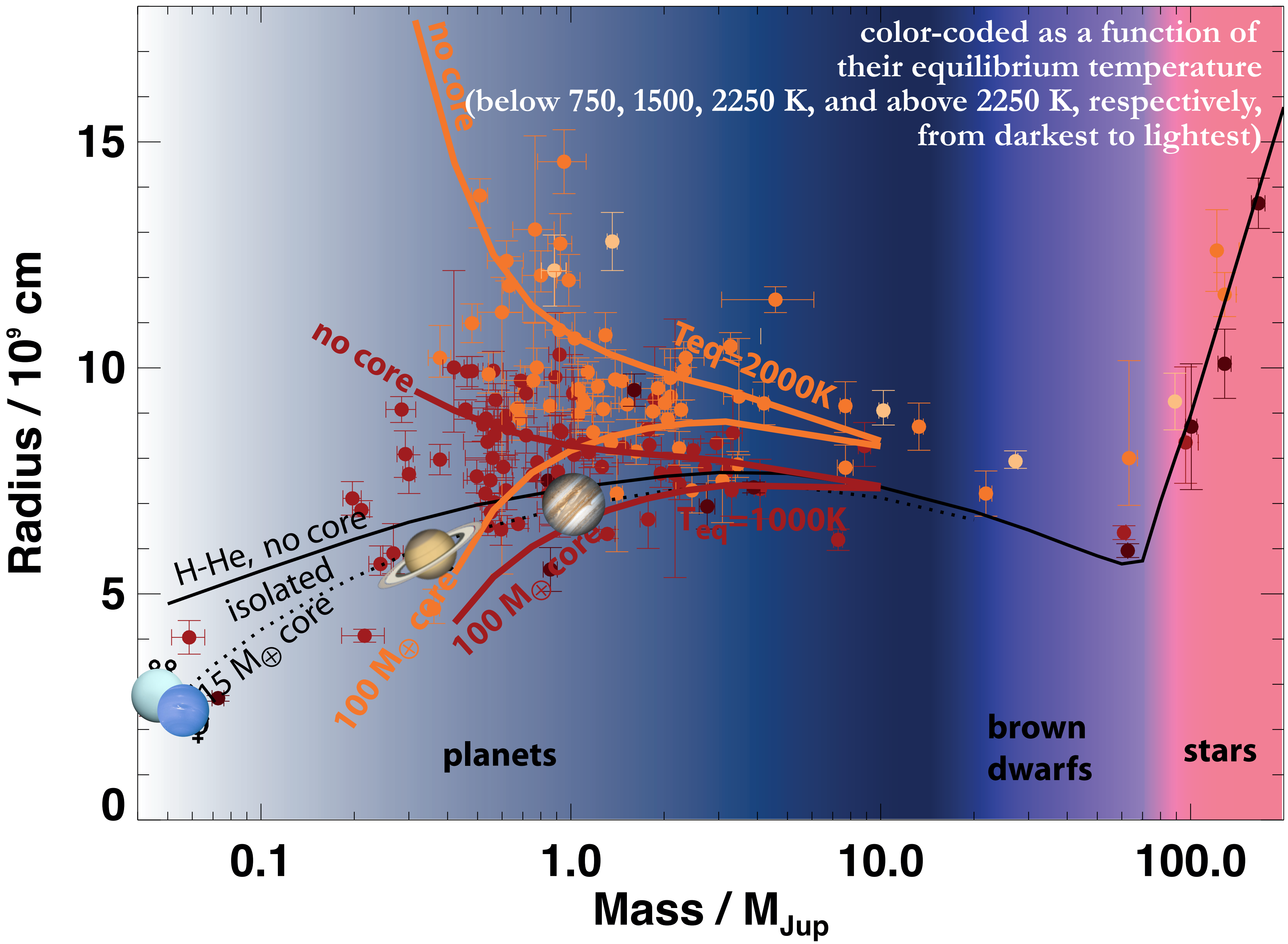
Inflated hot Jupiters

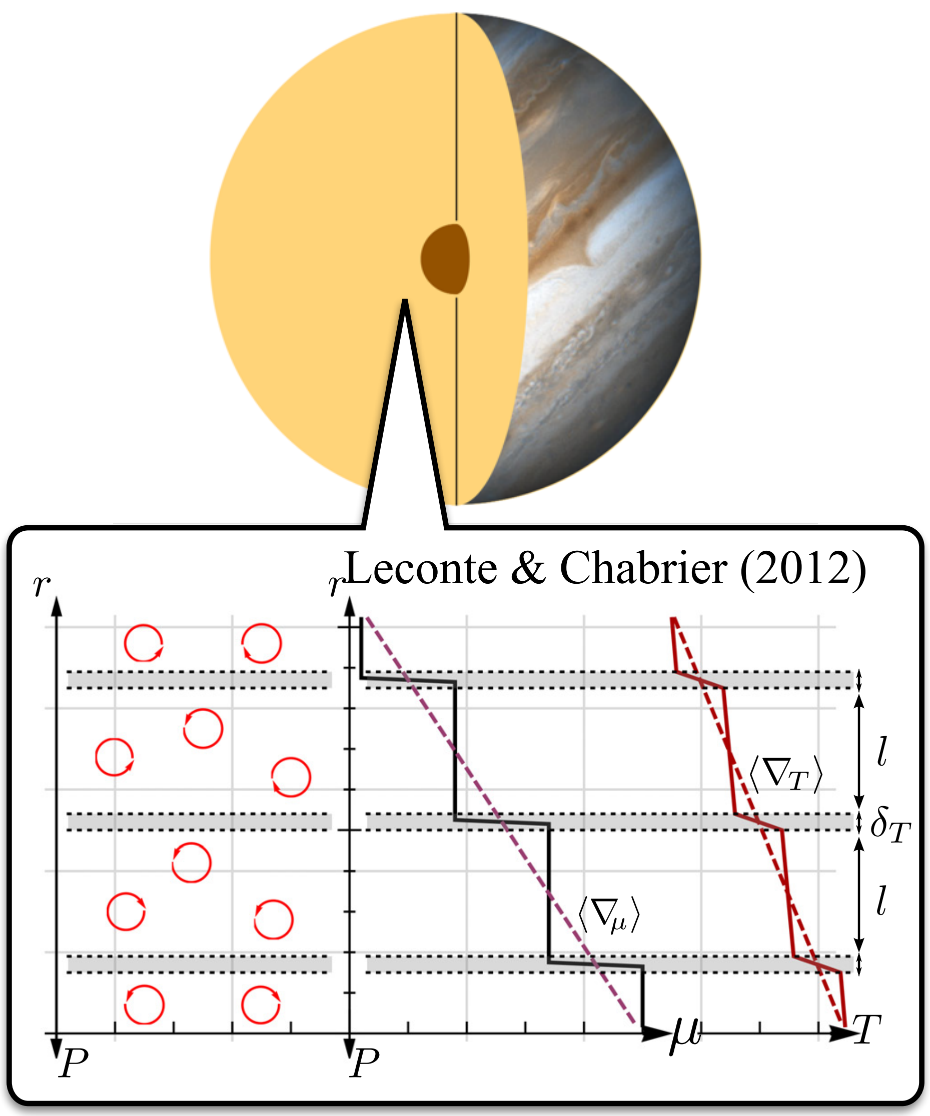
Theoretical and observed mass-radius relations (Guillot & Gautier, 2014)

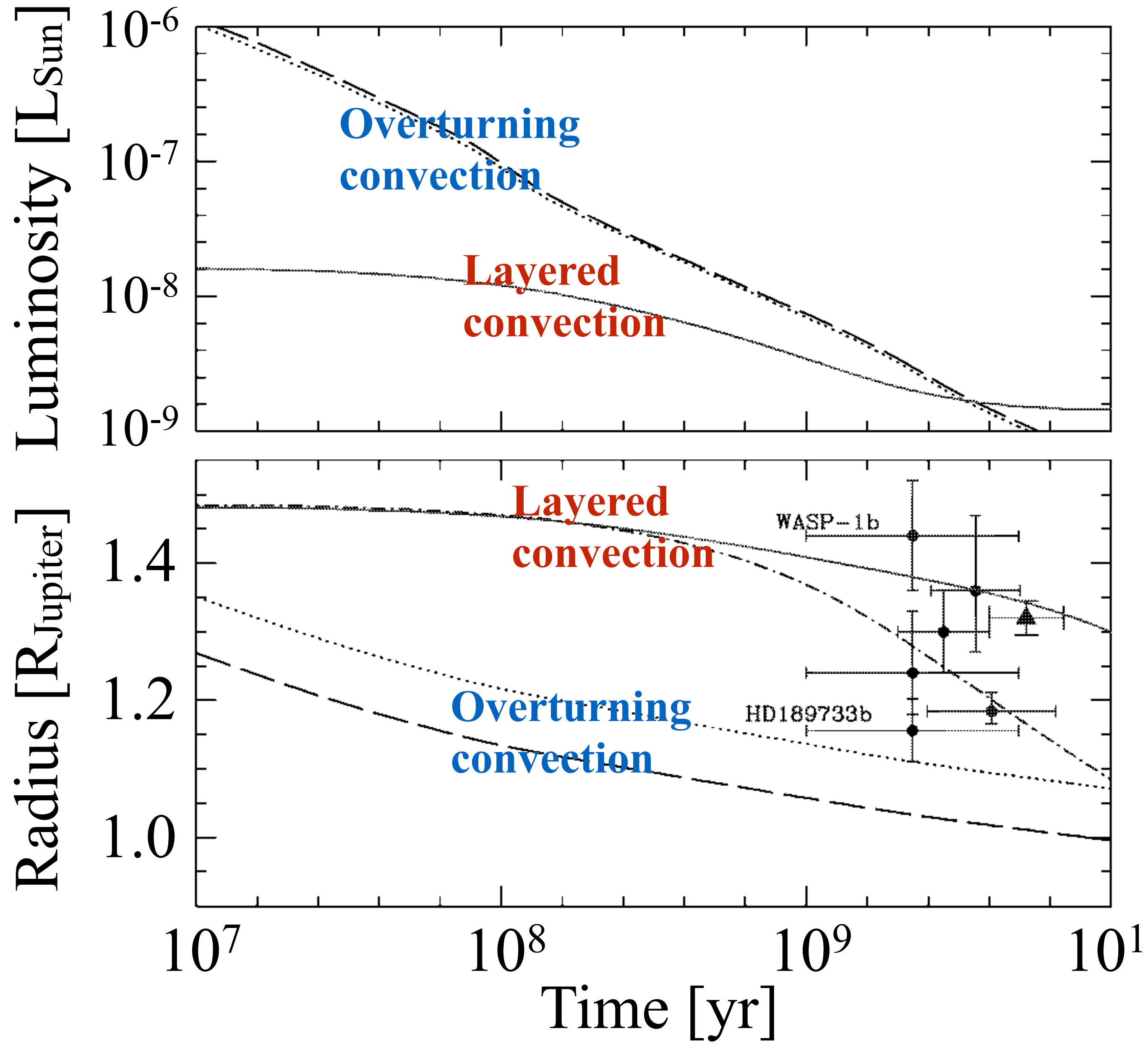


- Hot Jupiters have anomalously large radii
- It is crucial to understand the mechanism of the radius anomaly to constrain compositions and origins of exoplanets

Layered convection

Evolution of luminosity and radius of hot Jupiter (Chabrier & Baraffe, 2007)





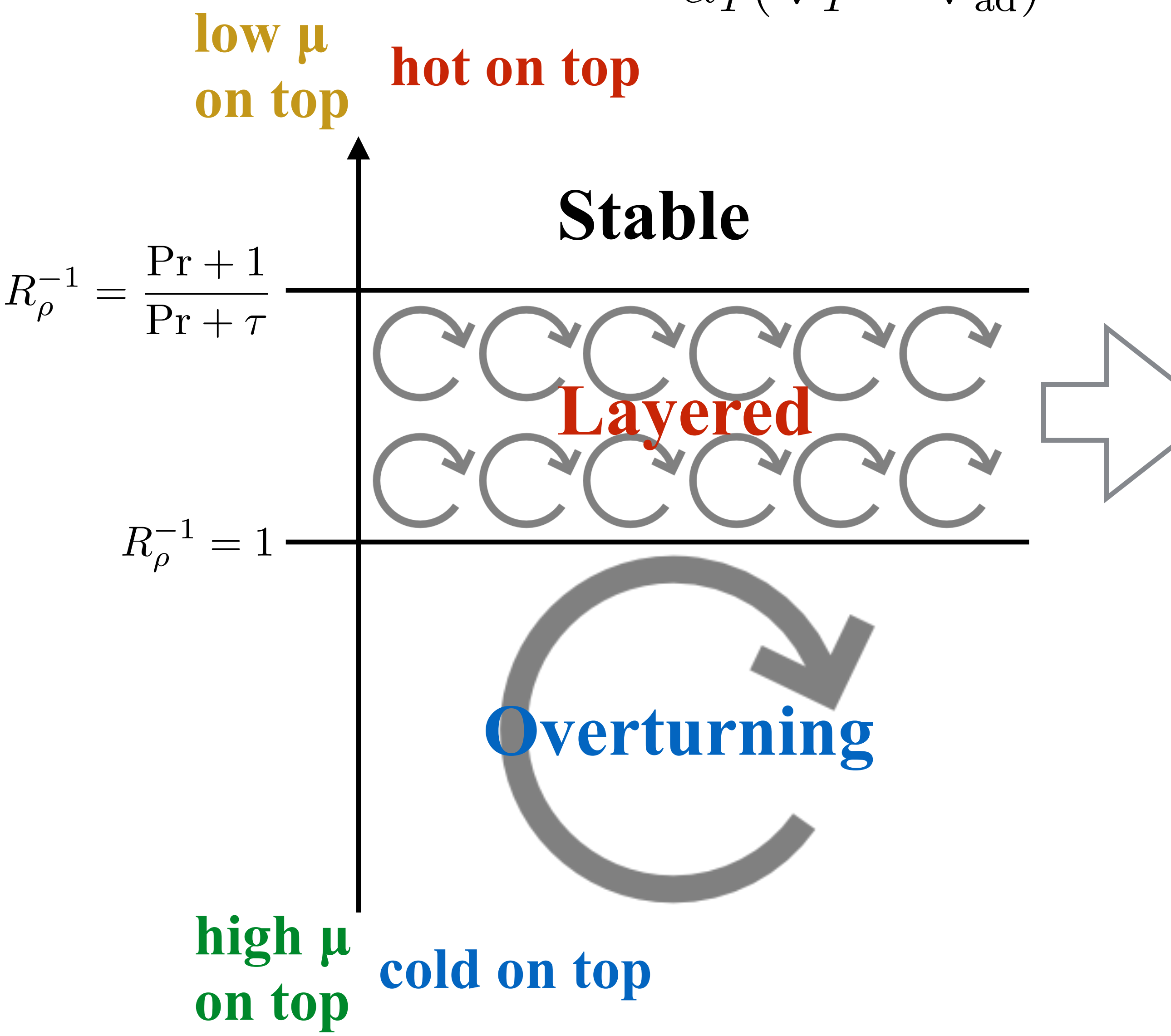
- Layered convection leads to much less heat transport and inflated radii (CB2007)
- Solar-system gas giants may also have layered-convective interiors (Leconte & Chabrier, 2012; 2013)

Evaluating the possibility of the layered convection is necessary to understand both exoplanets and solar-system gas giants

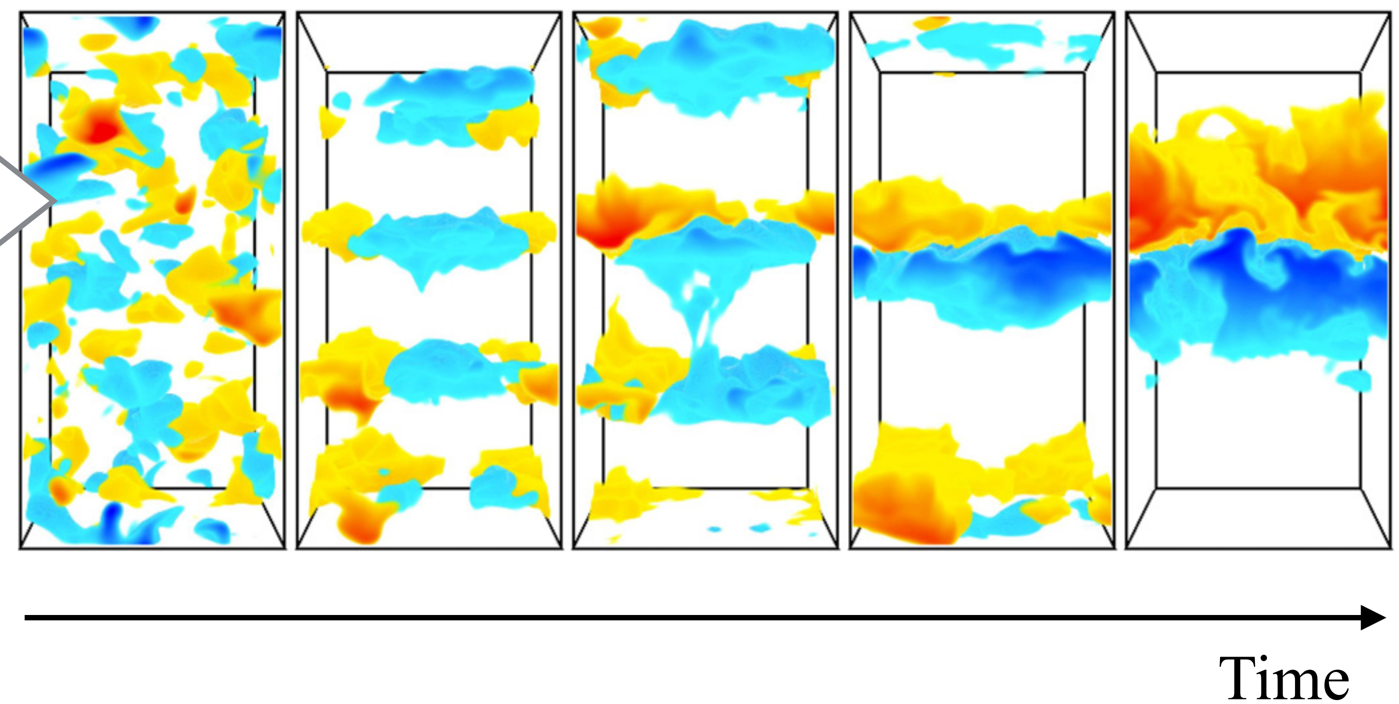
Condition to form layered convection

<u>Layered convection forms in limited parameter range</u>

Density ratio: $R_\rho^{-1} \equiv \dfrac{\alpha_\mu \nabla_\mu}{\alpha_T(\nabla_T - \nabla_{\rm ad})}$



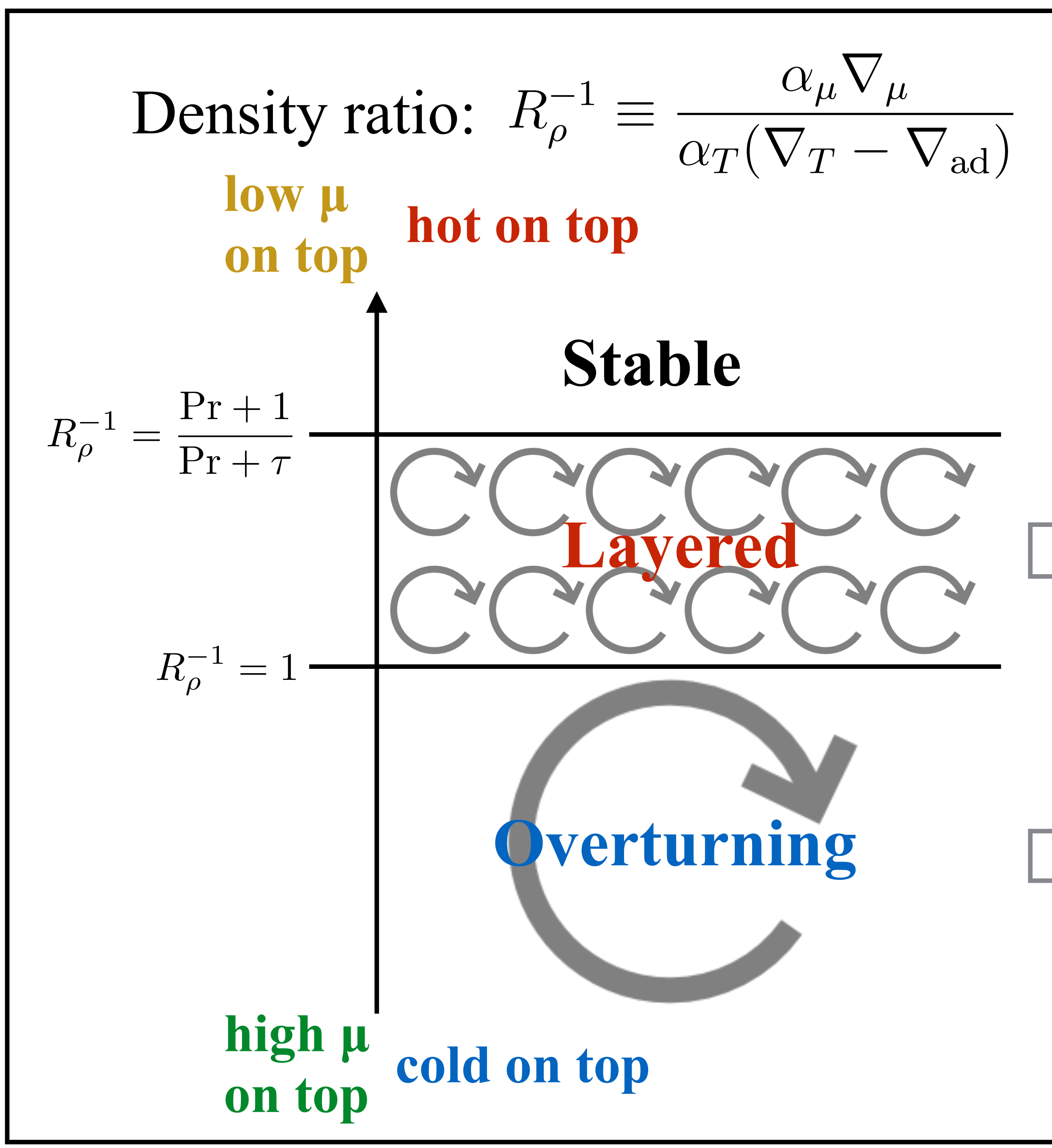
Formation of layered convection
in numerical experiment
(Rosenblum et al., 2011)

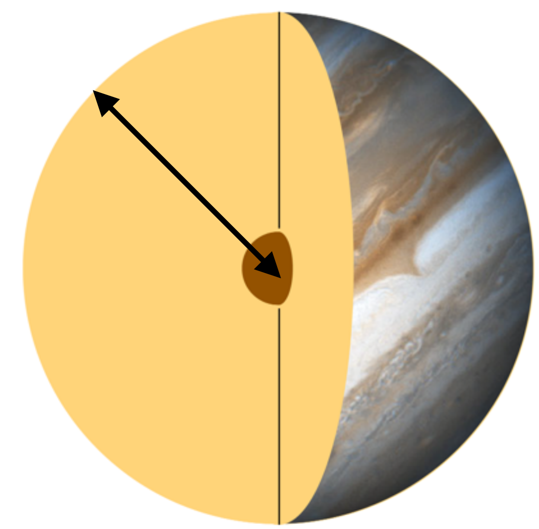


We reevaluate the possibility and impact of the layered convection based on self-consistent treatment of convection regimes

Model

- 1D thermal evolution calculation
  (Henyey method, modified from Kurokawa & Kaltenegger, 2013; Kurokawa & Nakamoto, 2014)
- Parameterized convection models of overturning and layered convection
- Evolution of compositional profile is not considered for simplicity





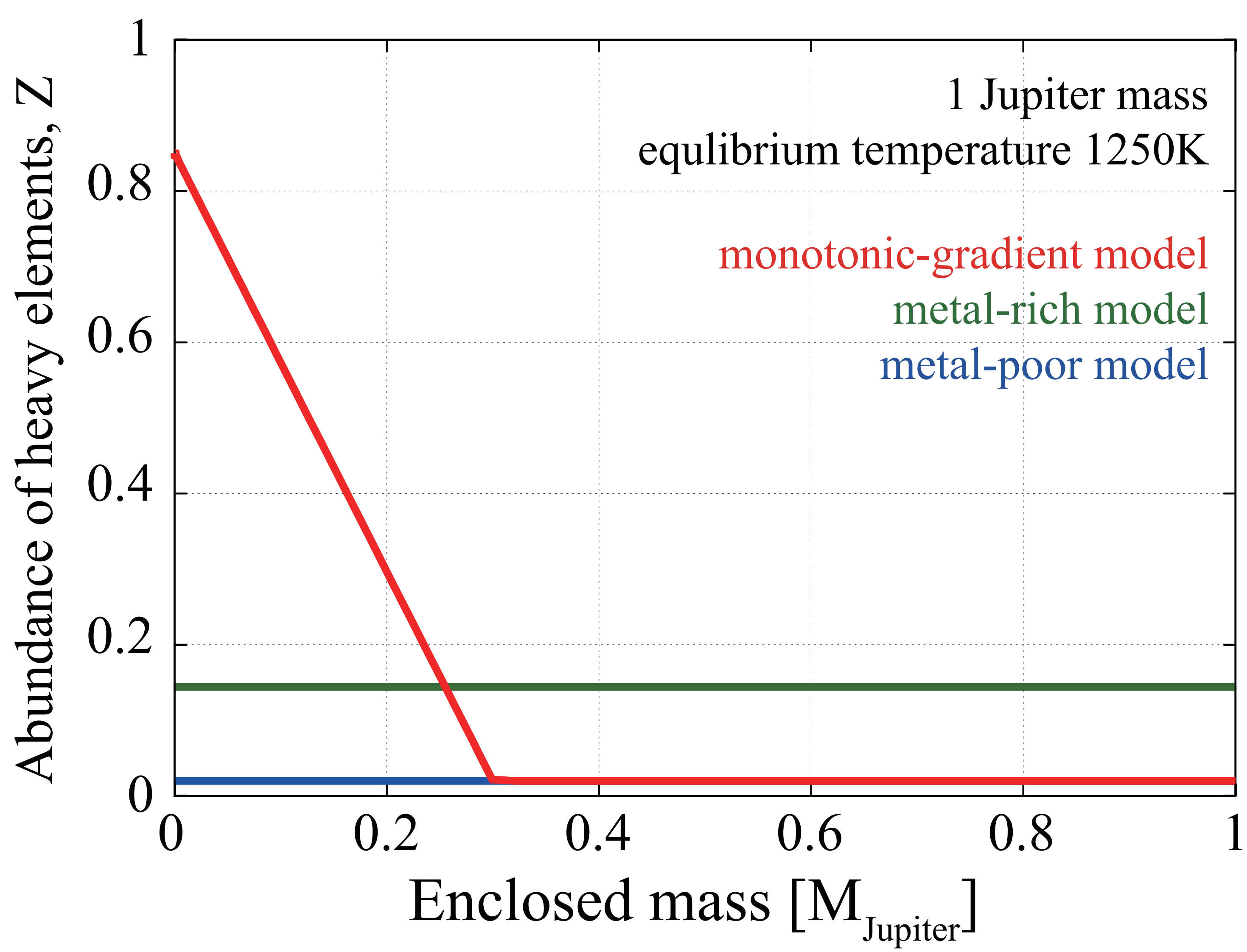
Coarse graining model
(Leconte & Chabrier, 2012)
***l/H*$_P$ = 10^{-7} is adapted**

Mixing length theory with compositional gradient
(similar with Stevenson & Salpeter, 1977; Umezu & Nakakita, 1988)

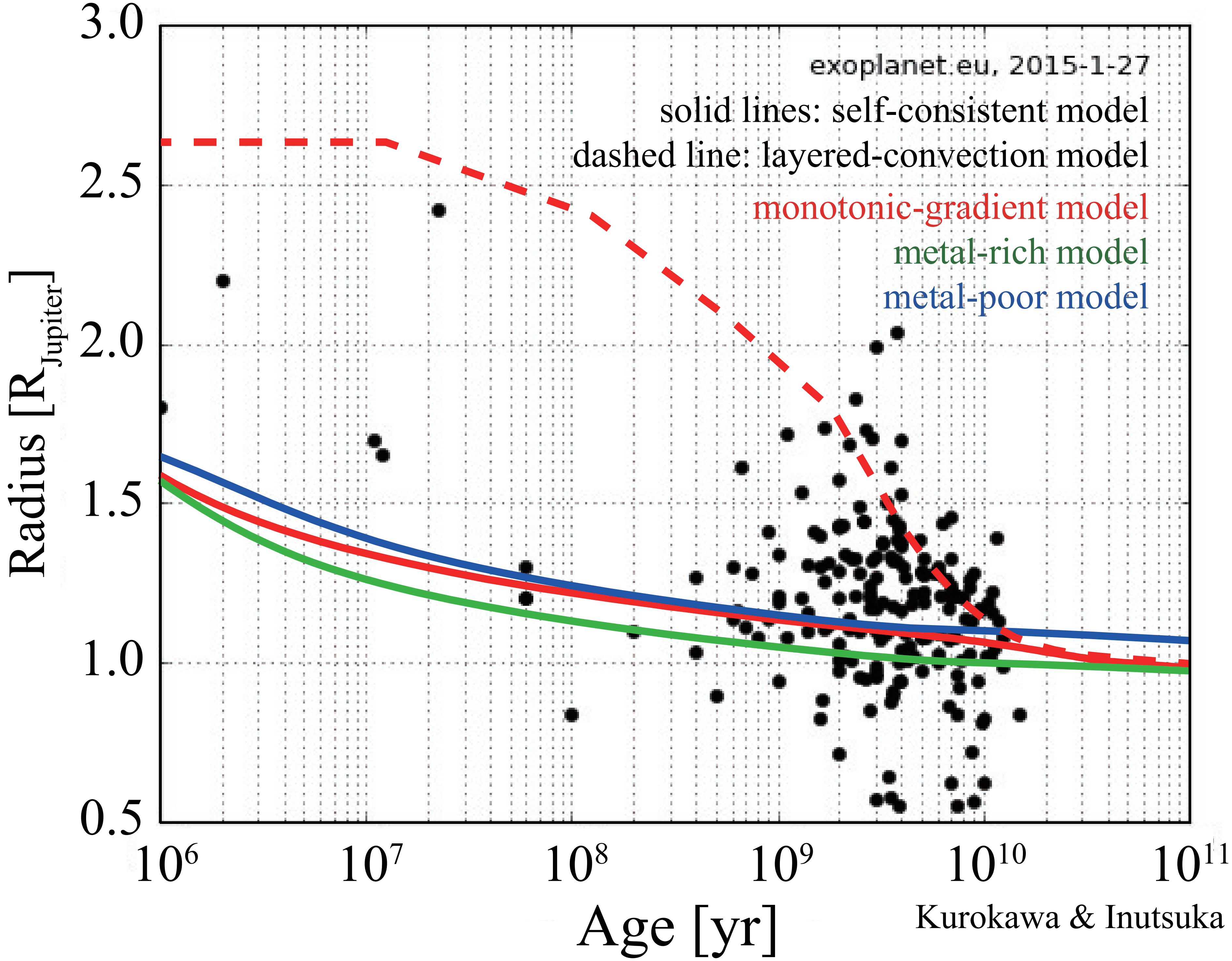
Settings

Following CB2007,

- $M_{planet} = 1\ M_{Jupiter}$
- T_{eq} = 1250K (~0.045 AU from the Sun)
- monotonic gradient model: CB2007-like, but monotonic profile
  metal-rich model: the same mass of heavy-elements, but homogeneous profile
  metal-poor model: solar composition, homogeneous
- start from a high-entropy state expected from formation theory (Marley et al., 2007)



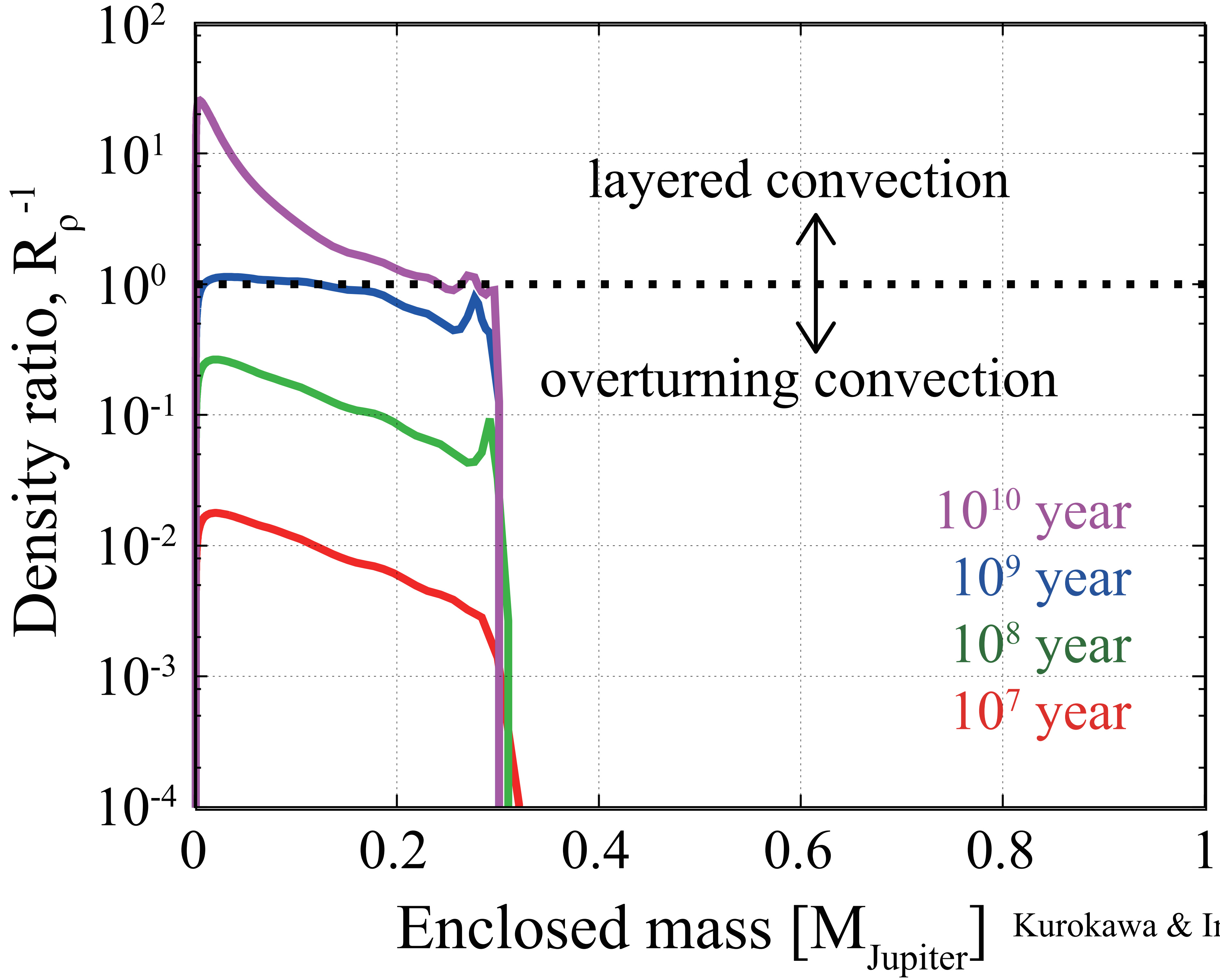
Evolution of radius



Kurokawa & Inutsuka (2015) *in prep.*

- **The impact of compositional inhomogeneity is limited in the case where the self-consistent treatment of convection regimes is adapted**
- The effect of increased heavy-elements compensates that of compositional inhomogeneity on the radius

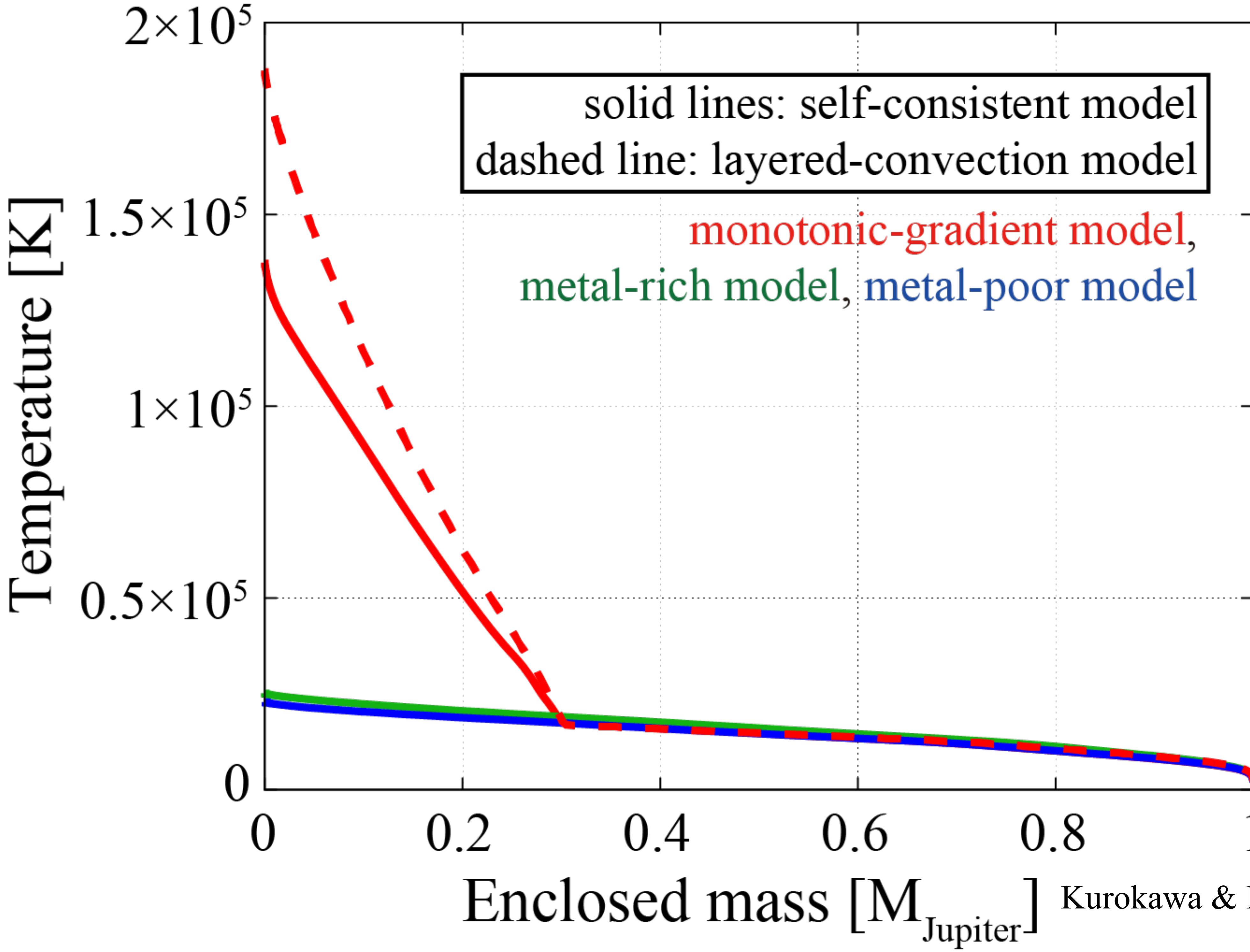
Evolution of convection regime



Kurokawa & Inutsuka (2015) *in prep.*

- **Convection regime is overturning convection for the first 1 Gyr**
  → Efficient mixing of compositional inhomogeneity?
- Layered convection forms after 1 Gyr passed, when the planet has already cooled

Temperature profile at 5 Gyr



Kurokawa & Inutsuka (2015) *in prep.*

The planet cools down more efficiently because of the overturning convection, which leads to the smaller radius

Discussion

- **Relation to Chabrier & Baraffe (2007)**

CB2007 assumed the presence of the layered convection.
We showed that layered convection does not spontaneously form from the monotonic compositional profile for the first 1 Gyr *in the evolution stage*.
The development *in planet formation stage* and the long-term stability is still unknown.

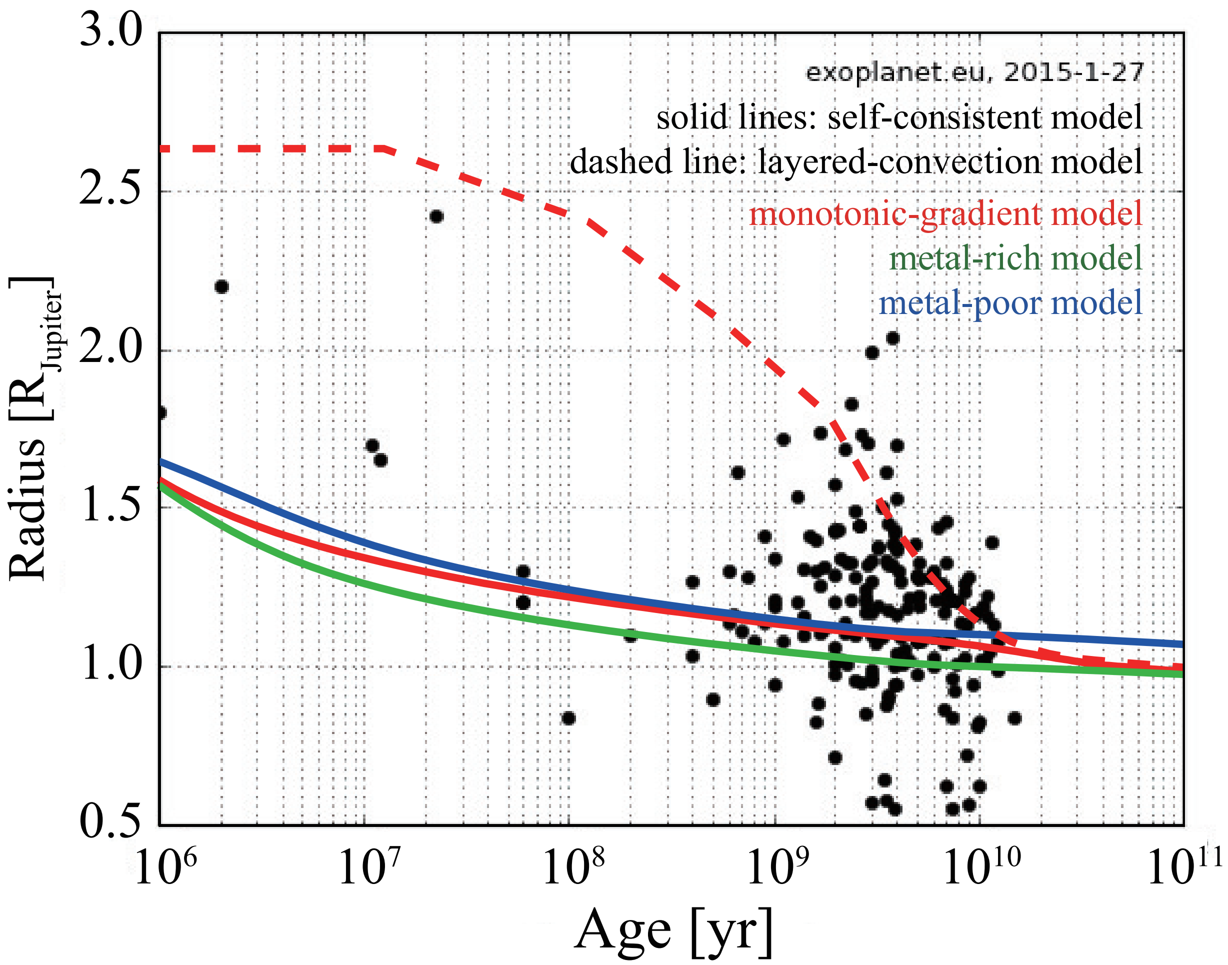
- **Later-formed layered convection**

Compositional inhomogeneity created in the formation stage may be smoothed out by the overturning convection in the early stage.
In this case, compositional inhomogeneity that emerges in the late phase may contributes to form the layered convection (e.g., core erosion, phase separation).
The later-formed layered convection may account for luminosity problems of our solar-system giant planets (Leconte & Chabrier, 2013), but it is hard to account for the inflated radii of hot Jupiters.

- **Evolution of compositional profile**

Vazan et al. (2015) found the formation of stair-like compositional profiles caused by the compositional transport of the overturning convection.
Compositional transport of the overturning convection may possibly create a sharp, stabilizing compositional gradient before it is smoothed out.

Summary



- Layered convection induced by compositional inhomogeneity has been proposed to account for the infrared radii of hot Jupiters.
- We developed an evolutional model with a self-consistent treatment of convection regimes and applied the model to the hot Jupiters that have the monotonic compositional gradients.
- **The layered convection was absent for the first 1 Gyr. As a result, the impact of compositional inhomogeneity on the radius was limited at least in the case of the monotonic compositional gradient.**
- Core erosion or phase separation may contribute the late formation of the compositional gradient and the layered convection, but it seems to be difficult to account for the inflated radii of hot Jupiters.
- **Further study is needed to understand the consequence of the compositional transport due to the overturning convection.**