Evaluating the imprints of planet formation on the compositions of stars

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References:
Kunitomo et al. (2017), A&A
Kunitomo et al., to be submitted

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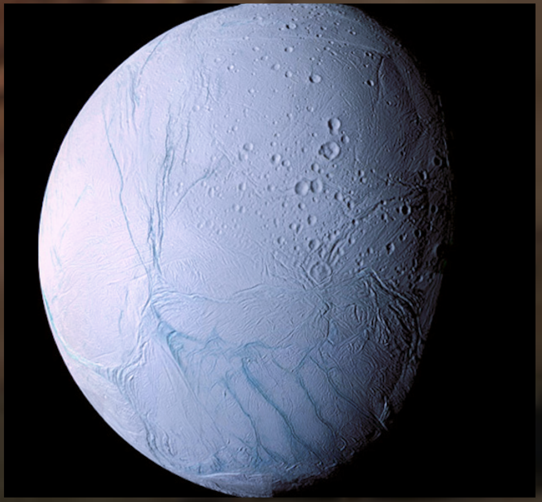
Composition of protoplanetary disks

- <u>Primordial composition of disks:</u>
  - mainly H_2 and He gas
  - ***volatile*** elements (~0.9wt%; C, N, O)
  - ***refractory*** elements (~0.4wt%)
    ("<u>rock-forming elements</u>"; Fe, Mg, Si, etc.)

Asplund+09

Icy objects



Rocky objects

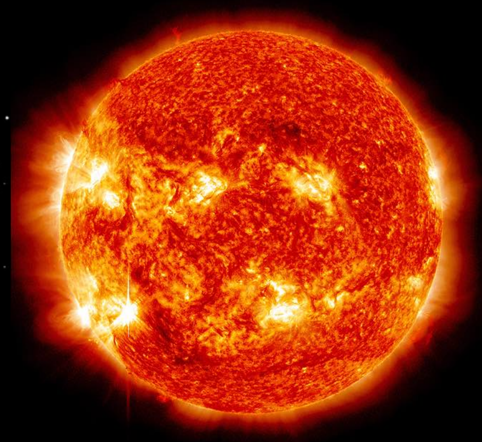
- Planets selectively retain metals
  → The disk composition is changed
- Disk gas eventually accretes onto stars

Does planet formation alter stellar surface composition?

(c) NASA

Solar composition anomaly

Sun



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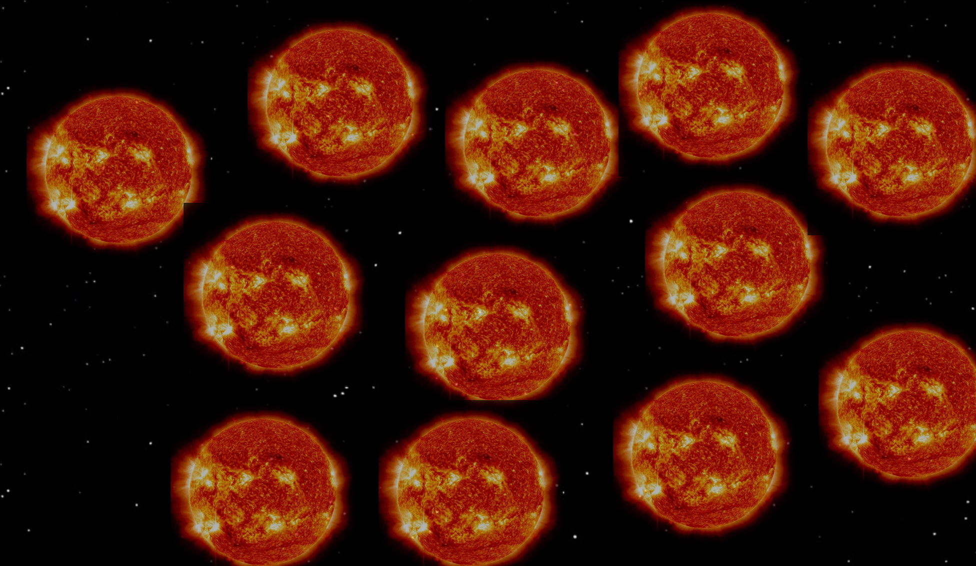
Solar twins



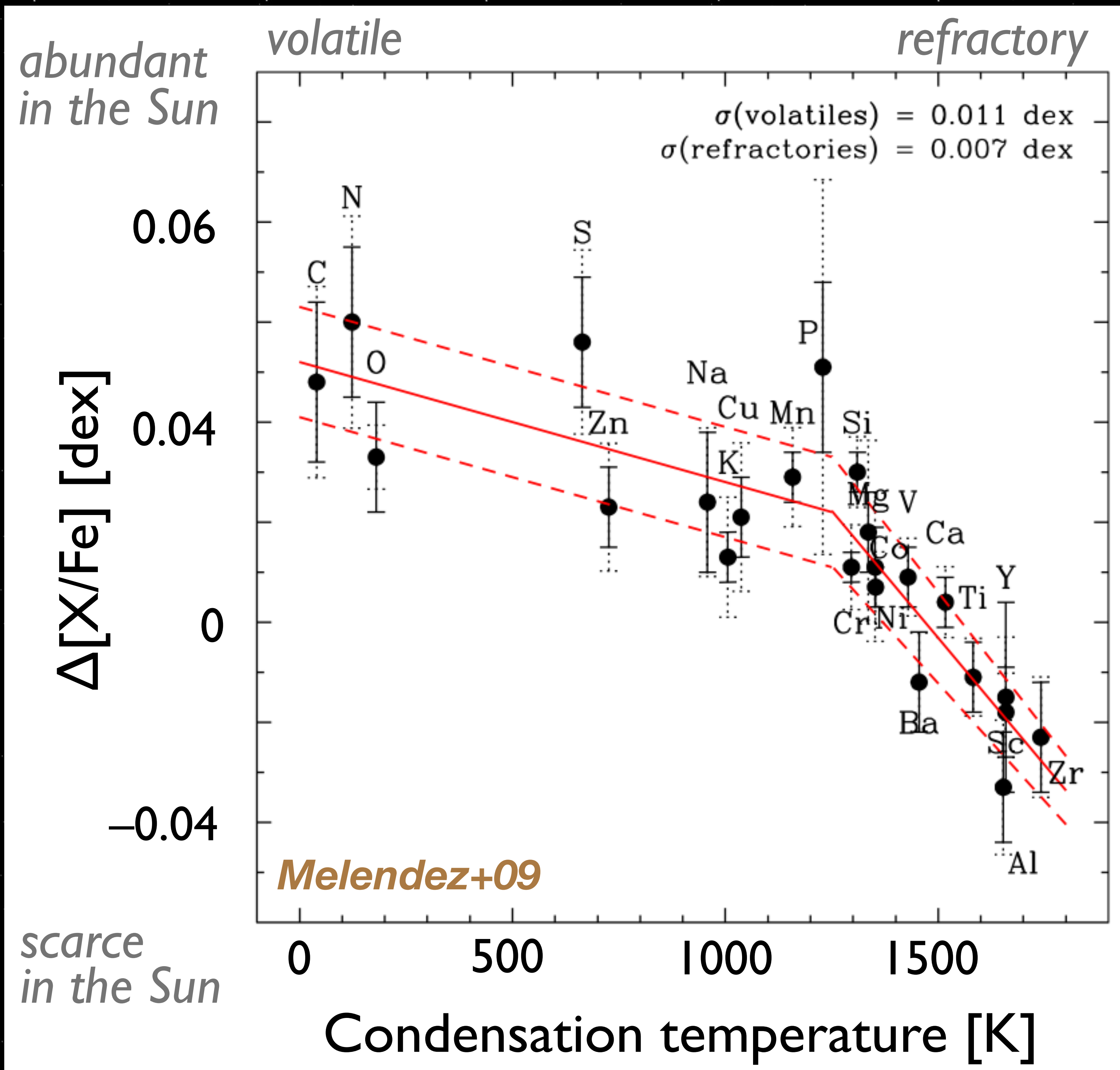
Stars with similar metallicity, mass, age, and temp. to the Sun

Solar photospheric abundances are different from solar twins' ones

Melendez+09

Solar composition anomaly

Solar abundances
normalized by the average of solar twins' ones



- **the Sun has refractory-poor abundances** compared to most solar twins
- difference: **~10%**

  e.g., Melendez+09, Ramirez+09

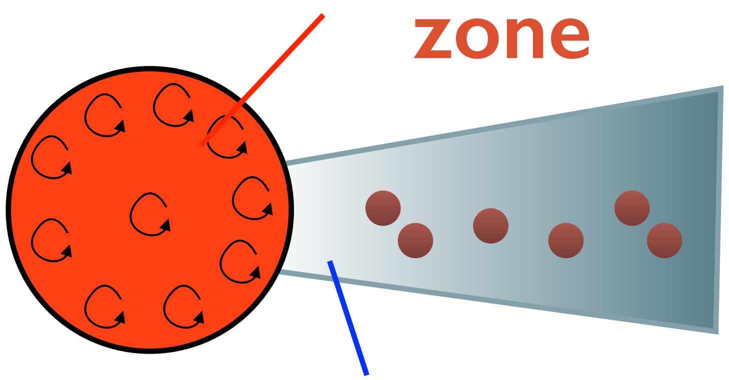
8 planets in the solar system

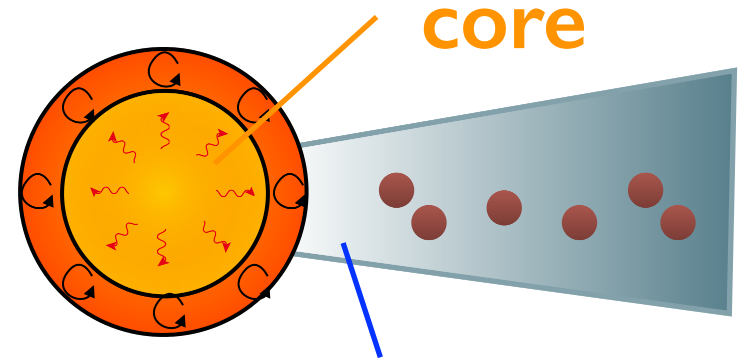
→ Chambers10 claimed **4M⊕ rock retention** can compensate for this

One caveat

stellar structure is important in this scenario

because accreting materials are distributed only in the surface conv. zone





Fully convective stars
→ Alternation is limited

even if planets are formed

Stars w/ a large radiative core
→ *Strong alteration*

Purpose of this study

- Chambers (2010) concluded that **formation of $4M_{\oplus}$ rocks induces the compositional difference between the Sun and solar-twins** with assuming the internal structure of main-sequence stars
  - cf. the present-day Sun has a radiative structure (conv. zone=$0.025M_{\odot}$)

- However, planets are formed and disks exist around pre-MS stars, which have in general much thicker convective zones

We revisit this scenario with up-to-date models of pre-MS evolutions

Basic equations and settings

- Stellar structure equations (1D) solved with a public code MESA

Paxton+11,13,15

1. **Continuity** $$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}$$ M_r: mass coordinate

2. **Momentum** $$\frac{\partial P}{\partial M_r} = -\frac{G M_r}{4\pi r^4}$$ (hydrostatic equilibrium)

3. **Energy** $$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$ *entropy injection by accretion*

4. **Temp. gradient** $$\frac{\partial T}{\partial M_r} = -\frac{G M_r T}{4\pi r^4 P}\nabla$$ (w/ MLT)

5. **Composition** $$\left(\frac{\partial X_i}{\partial t}\right)_{M_r} = \frac{m_i}{\rho}\left(\sum_j r'_{ji} - \sum_k r'_{ik}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial X_i}{\partial r}\right)$$

nuclear reaction — diffusion

- Settings: Accretion: **0.01M$_\odot$ → 1M$_\odot$ in 10Myr**

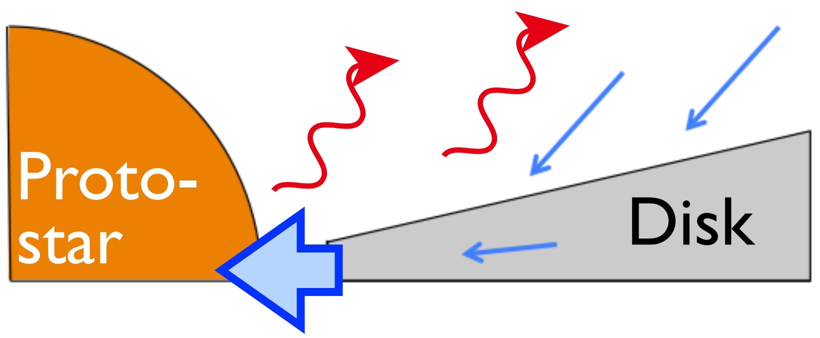
Composition: Z=0.02, Deuterium content = 28 ppm

Asplund+09

Method: Heat injection by accretion

Energy Eq. $$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$

Radiative cooling



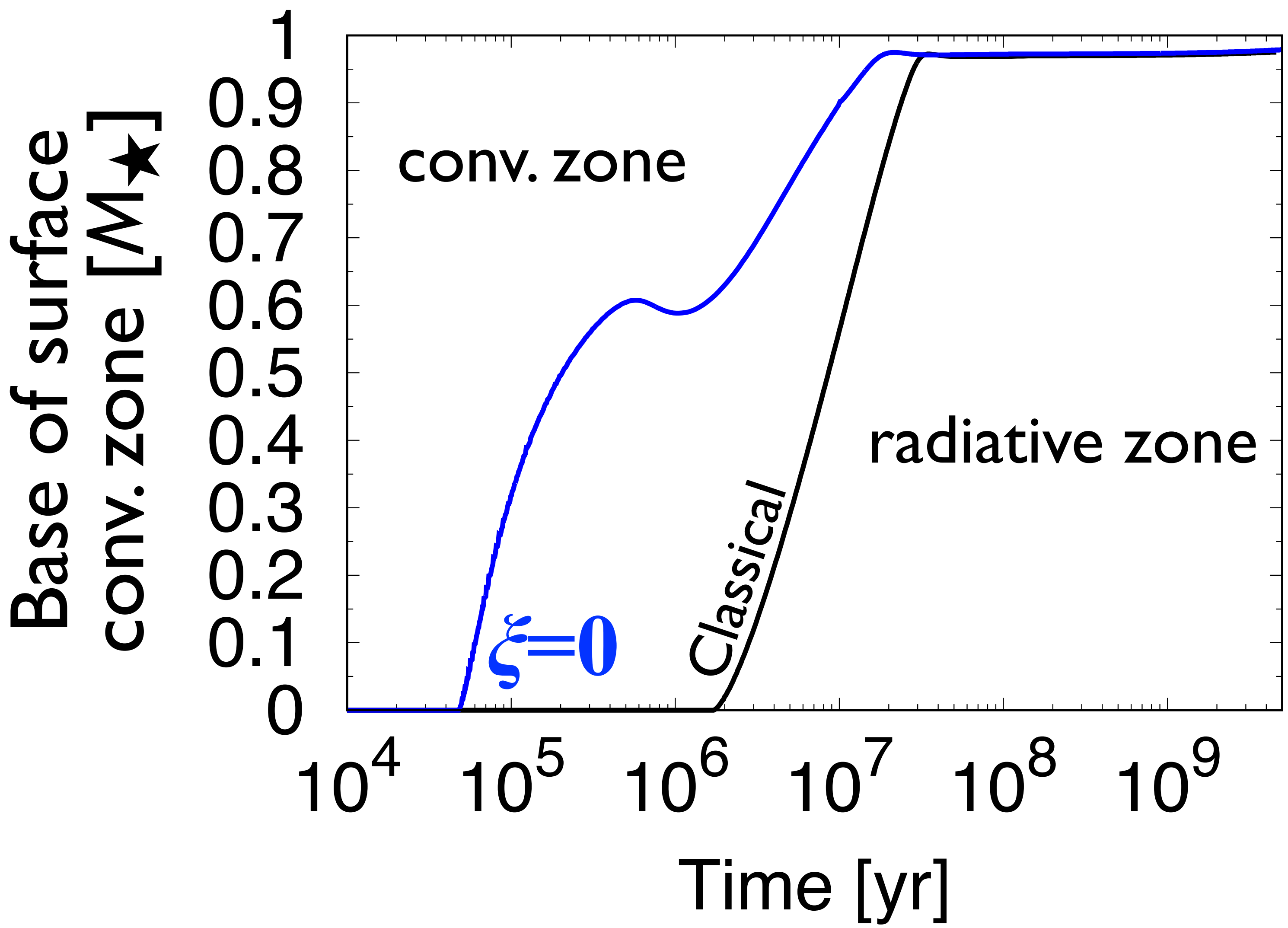
$$\varepsilon_{\rm add} = \xi\, L_{\rm acc}/M_\star$$

entropy injection by accretion

- $L_{\rm acc}$: the gravitational energy of accreting materials ($=GM_\star\dot{M}/R_\star$)
- **A fraction (ξ) of $L_{\rm acc}$ is injected into the star**
- $\xi L_{\rm acc}$ is uniformly redistributed in the entire star ➔ $M_\star^{-1}$

We change ξ **from 0 to 0.5**

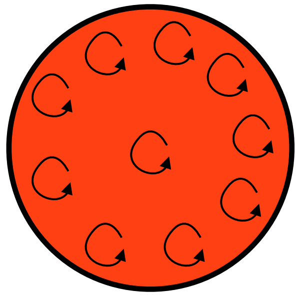
Internal structure evolutions

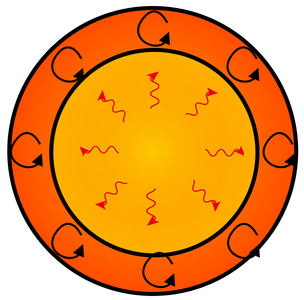


- In the classical evolution case (w/o accretion), the surface conv. zone shrinks at ~30Myr

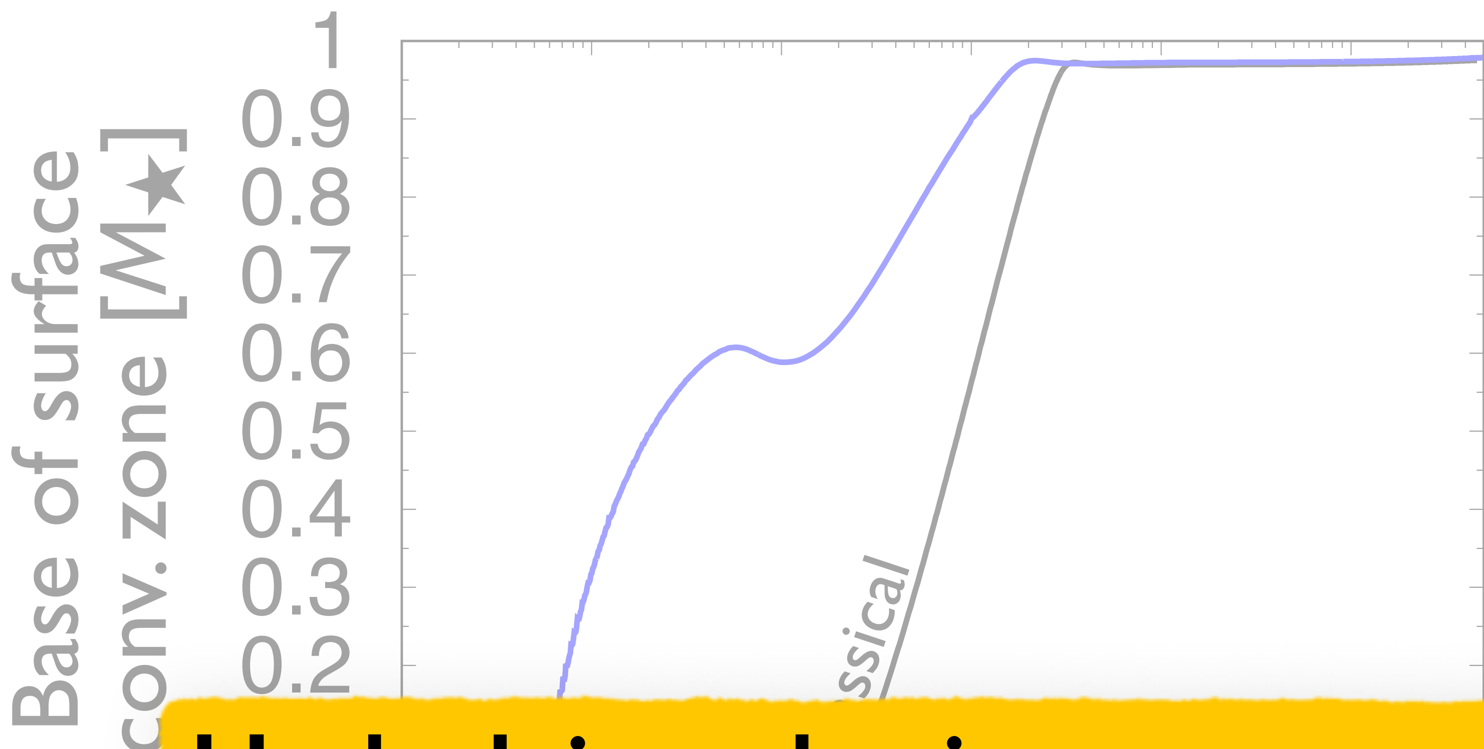
- With ξ=0, it shrinks more rapidly

(see also Baraffe+Chabrier10)





Internal structure evolutions



- In the classical evolution case (w/o accretion), the surface conv. zone shrinks at ~30Myr
- With ξ=0, it shrinks more rapidly

er10)

<u>Underlying physics</u>

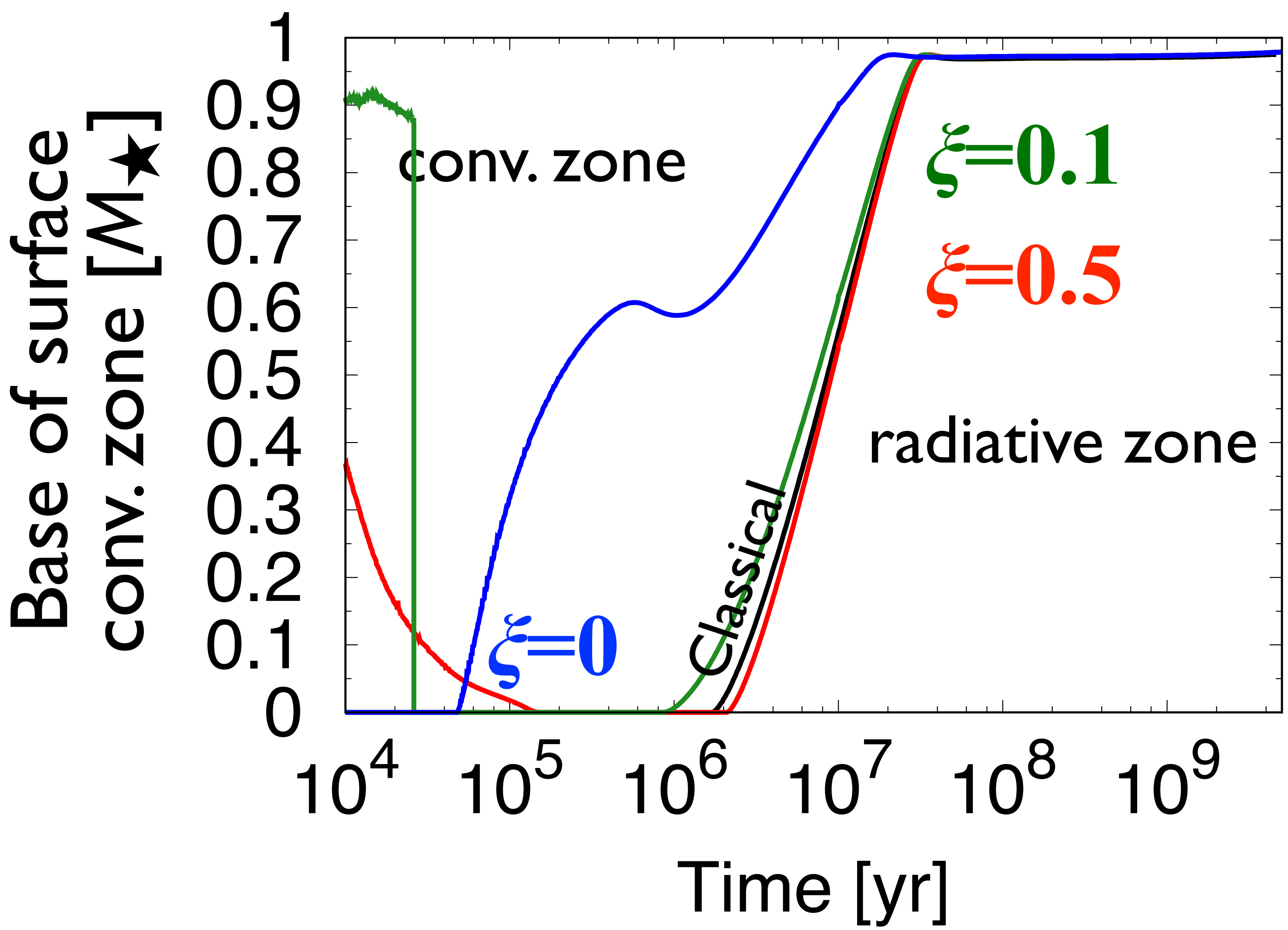
Stars have the negative specific heat (cf. Virial theorem)

➔ Lower energy injection (i.e., lower ξ) = higher temp.

➔ Lower opacity (cf. Kramers law, $\kappa \propto T^{-3.5}$)

➔ Radiative cores develop more easily

Internal structure evolutions



- In the classical evolution case (w/o accretion), the surface conv. zone shrinks at ~30Myr

- With ξ=0, it shrinks more rapidly

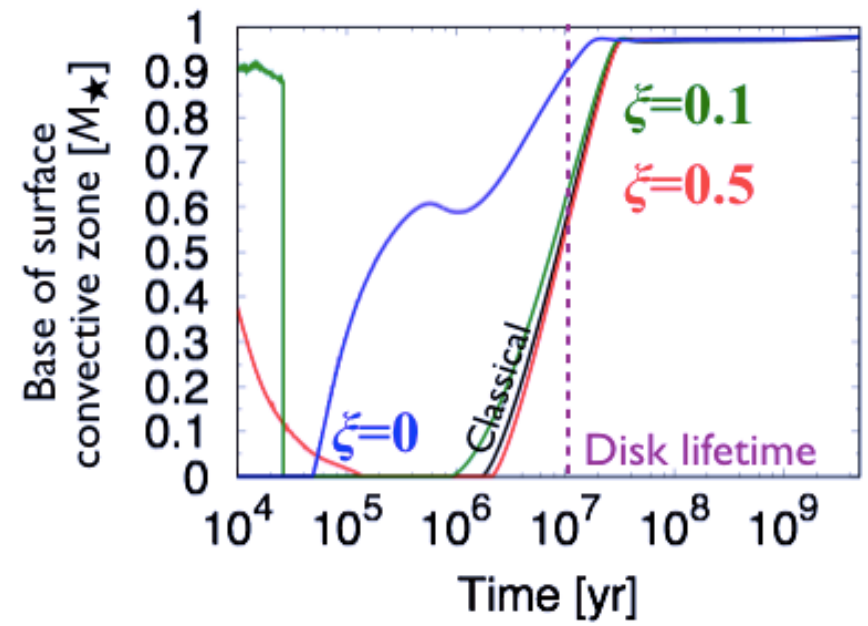
(see also Baraffe+Chabrier10)

- Internal structure evolutions of young stars are sensitive to the accretion heat (ξ)
- Even with ξ=0, the conv. zone is thicker (0.1$M_\odot$) than that of MS stars (0.025$M_\odot$) before ~10Myr

Required rock mass for the comp. anomaly

- Chambers (2010): With a $0.025M_\odot$ convective zone, $4M_\oplus$ rock retention can compensate for the compositional differences between the Sun and solar-twins

$$M_{\rm rock} = 4\,{\rm M}_\oplus \left(\frac{M_{\rm CZ,eff}}{0.025\,{\rm M}_\odot} \right)$$



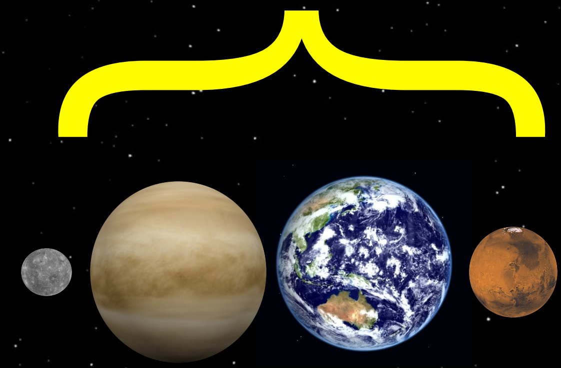
$M_{\rm CZ,eff}$: time-averaged convective-zone mass

Required rock mass with pre-MS structures

- ξ=0: ~$30M_\oplus$
- ξ=0.1: ~$100M_\oplus$
- ξ=0.5: ~$120M_\oplus$

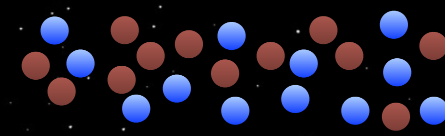
The rocky objects in the solar system are at most ~$4M_\oplus$
→ **Insufficient** for the requirements…

* not to scale

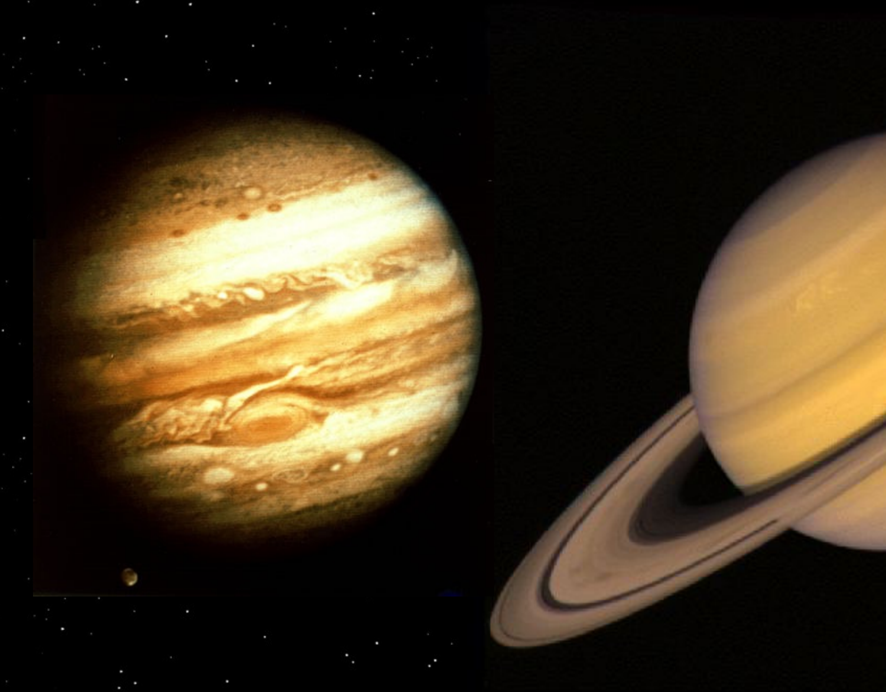


O'Brien+07

Primordial:
$\sim 2.0M_\oplus$



In total, pure rocks are
<u>at most $4M_\oplus$</u>



Outer planets
beyond snow line
retain much more solids
(<u>$\sim 150M_\oplus$</u> in total)

including cores of giant planets (Jupiter, …, Neptune), TNOs, ejected objects from the early solar system

Required rock mass for the comp. anomaly

Total solid mass in the solar-system planets

$\sim 150 M_\oplus$

Required rock mass with pre-MS structures to create the comp. anomaly

- $\xi=0$: $\sim 30 M_\oplus$
- $\xi=0.1$: $\sim 100 M_\oplus$
- $\xi=0.5$: $\sim 120 M_\oplus$

The rest: solar photospheric composition

ice-to-rock ratio $f_{ice/rock} = 2.0$

Lodders03

We obtained the constraints:
The solar composition anomaly can be originated from planet formation

If $f_{ice/rock} = 1.1, 0.2, 0.1$ in the solar-system planets
for $\xi = 0, 0.1, 0.5$

Summary

We revisited the solar compositional anomaly with up-to-date pre-MS evolution models and found

(1) Stellar structure evolutions are sensitive to accretion heat (ξ)

(2) Rocky planet formation alone cannot explain the anomaly

(3) If $f_{\mathrm{ice/rock}}$ **~ 0.1–1.1 (for ξ=0–0.5)** in the solar-system planets, the anomaly can be originated from the planet formation