An imprint of **planet formation** in the deep interior of the **Sun**

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Take-home message

Planet formation

does **not** affect the **solar abundance problem,**

but **does** affect the **solar central metallicity**

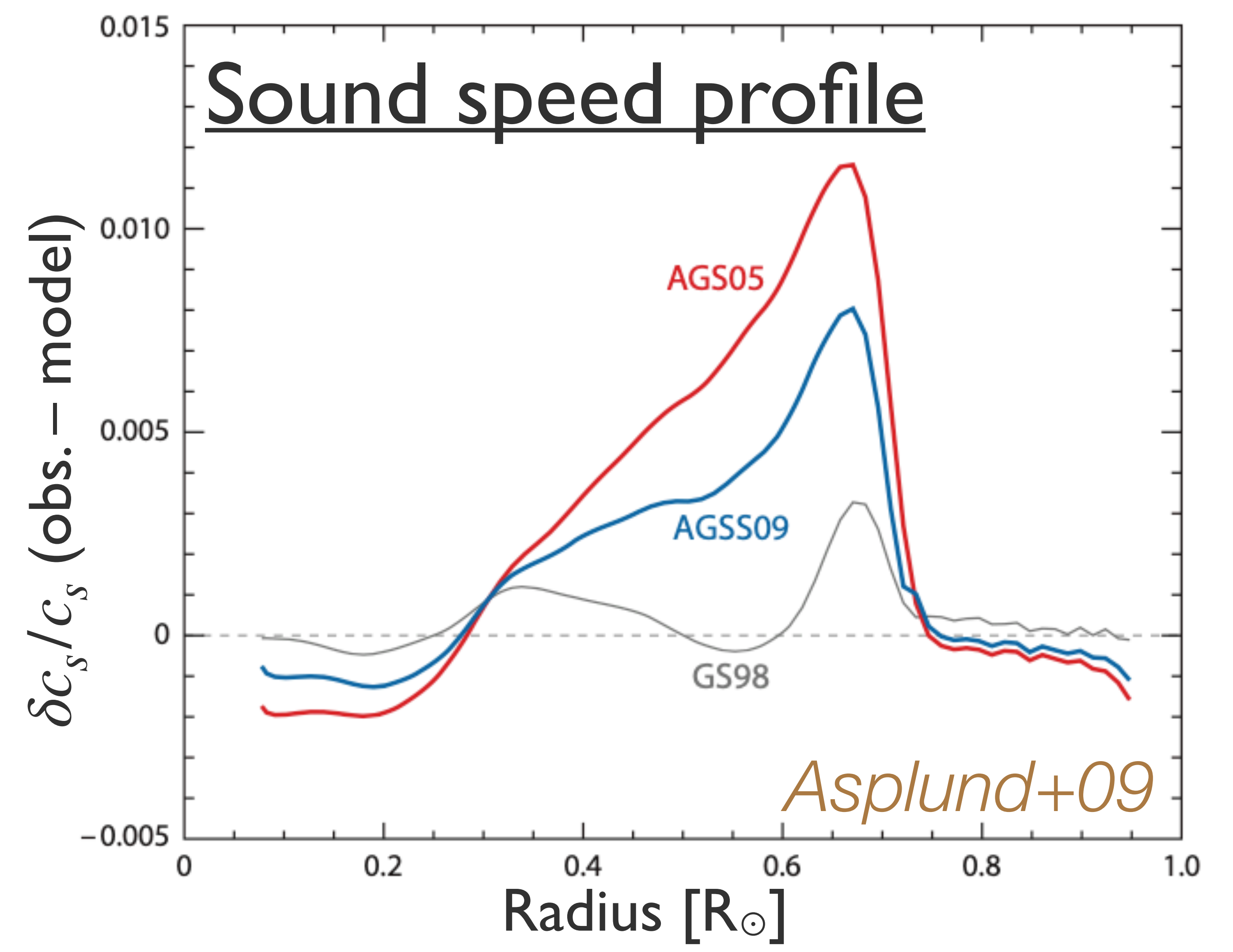
Kunitomo & Guillot, in prep.

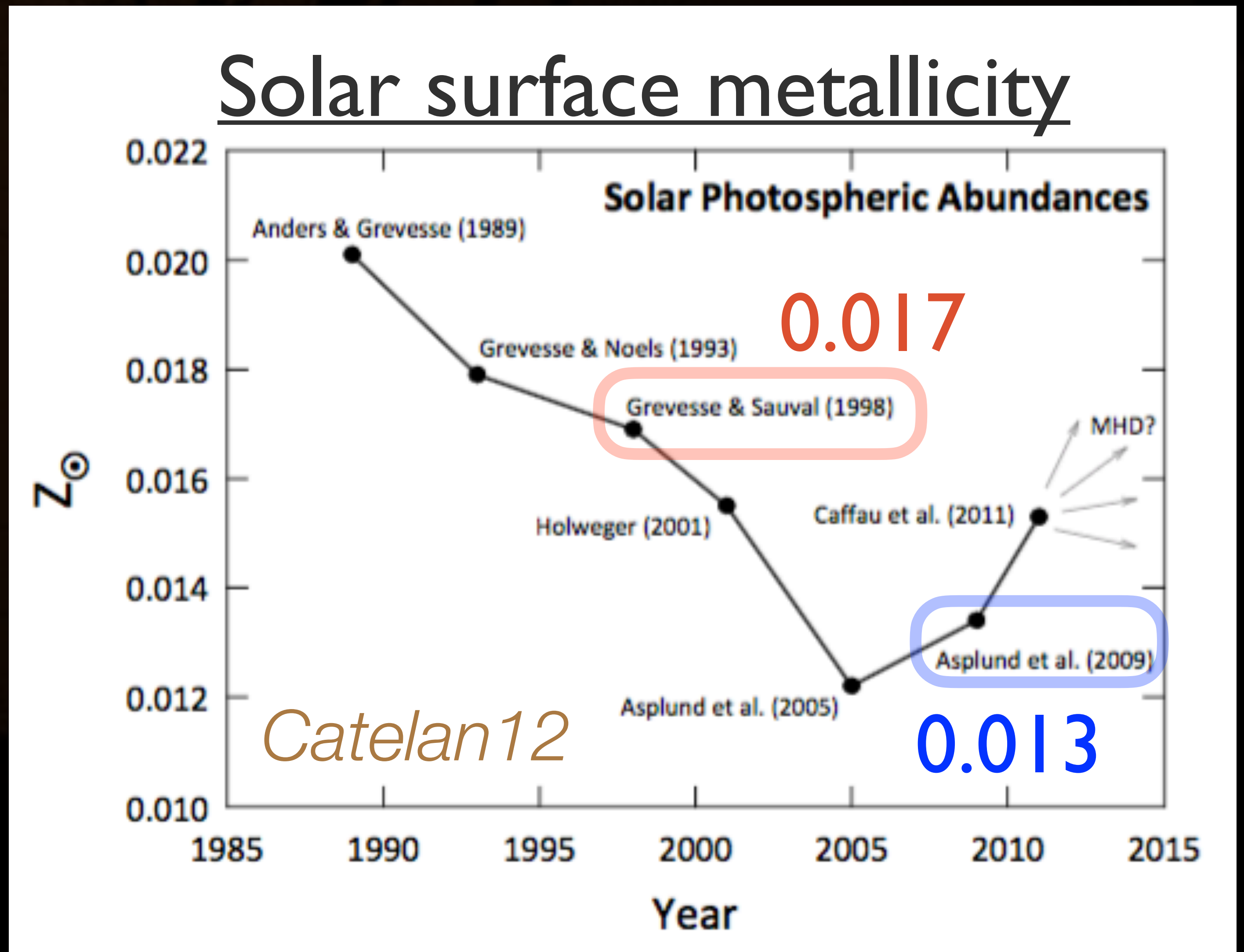
see also Kunitomo+18, A&A and Kunitomo+17, A&A

Solar abundance problem

e.g., Asplund+09, Serenelli+09

- Solar models from stellar evolution simulations disagree with helioseismic constraints
  - In 2000s, the solar surface abundances were revised ➔ the problem became prominent





Proposed scenarios

- Uncertainties in opacity
- **Composition gradient due to accretion**
- Extra mixing (overshooting, rotation, etc.)

Christensen-Dalsgaard+09, Bailey+15, Serenelli+11, Yang19

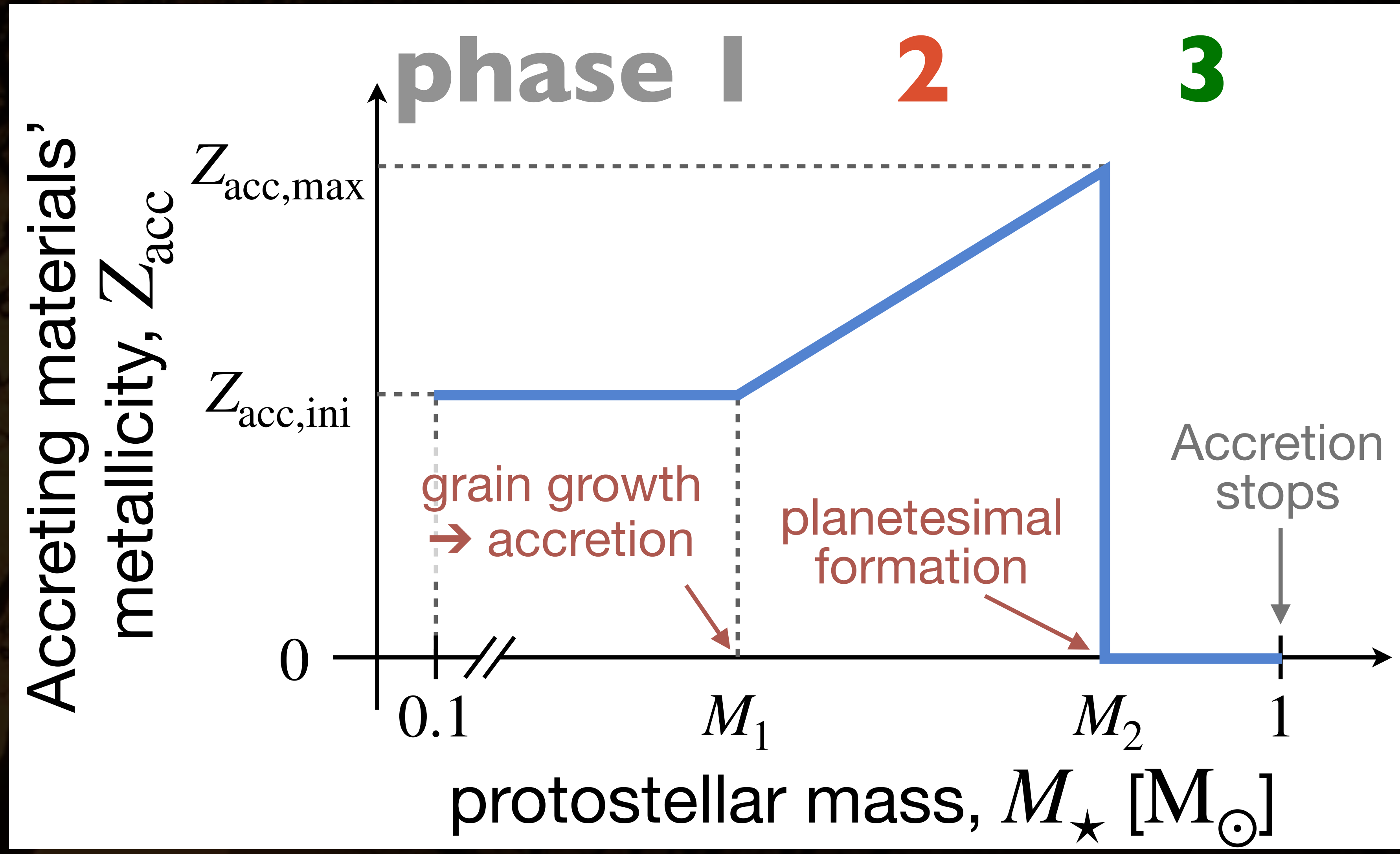
This study

We revisit the effect of accretion considering the recent progress in planet formation theory

- Even if the surface is metal-poor, the interior may be metal-rich
- Planet formation can induce metal-poor gas accretion

Composition of accreting materials

- Evolution of dust grains in disks is complicated:
  - phase 1: Small (≲ mm) dust grains couple to gas
  - phase 2: Once dust grains grow to ~cm size (pebbles), they are decoupled and grains migrate inward
    ➔ Accreting materials' metallicity, $Z_{\rm acc}$, increases
  - phase 3: Once planetesimals or protoplanets form, they efficiently filter grains ➔ $Z_{\rm acc}$ decreases



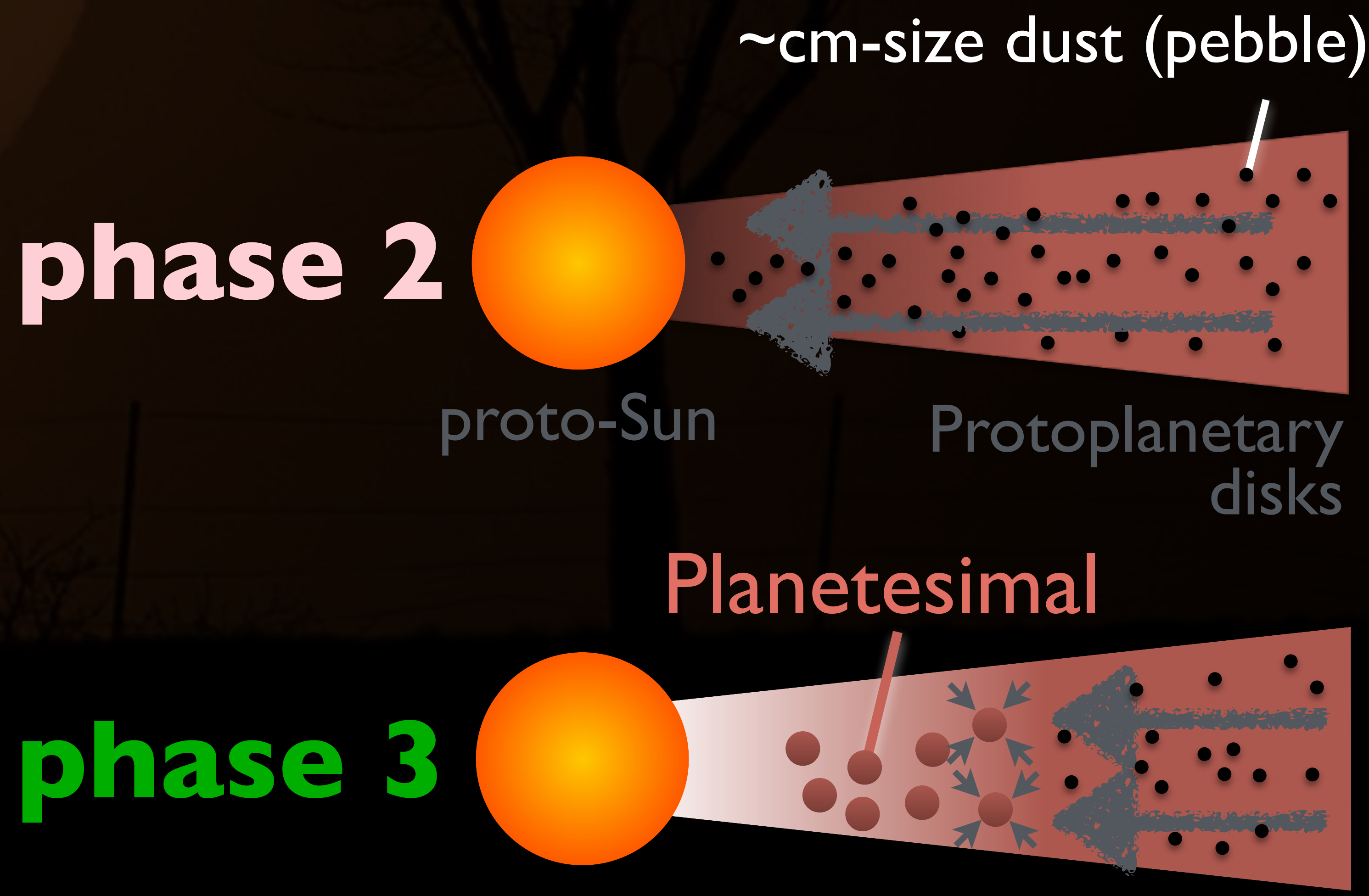
Garaud+07, Guillot+14, Applegren+20, Elbakyan+20

- Grain growth is likely to occur in the protostellar phase (class 0/I)
  Tsukamoto+17, Manara+18

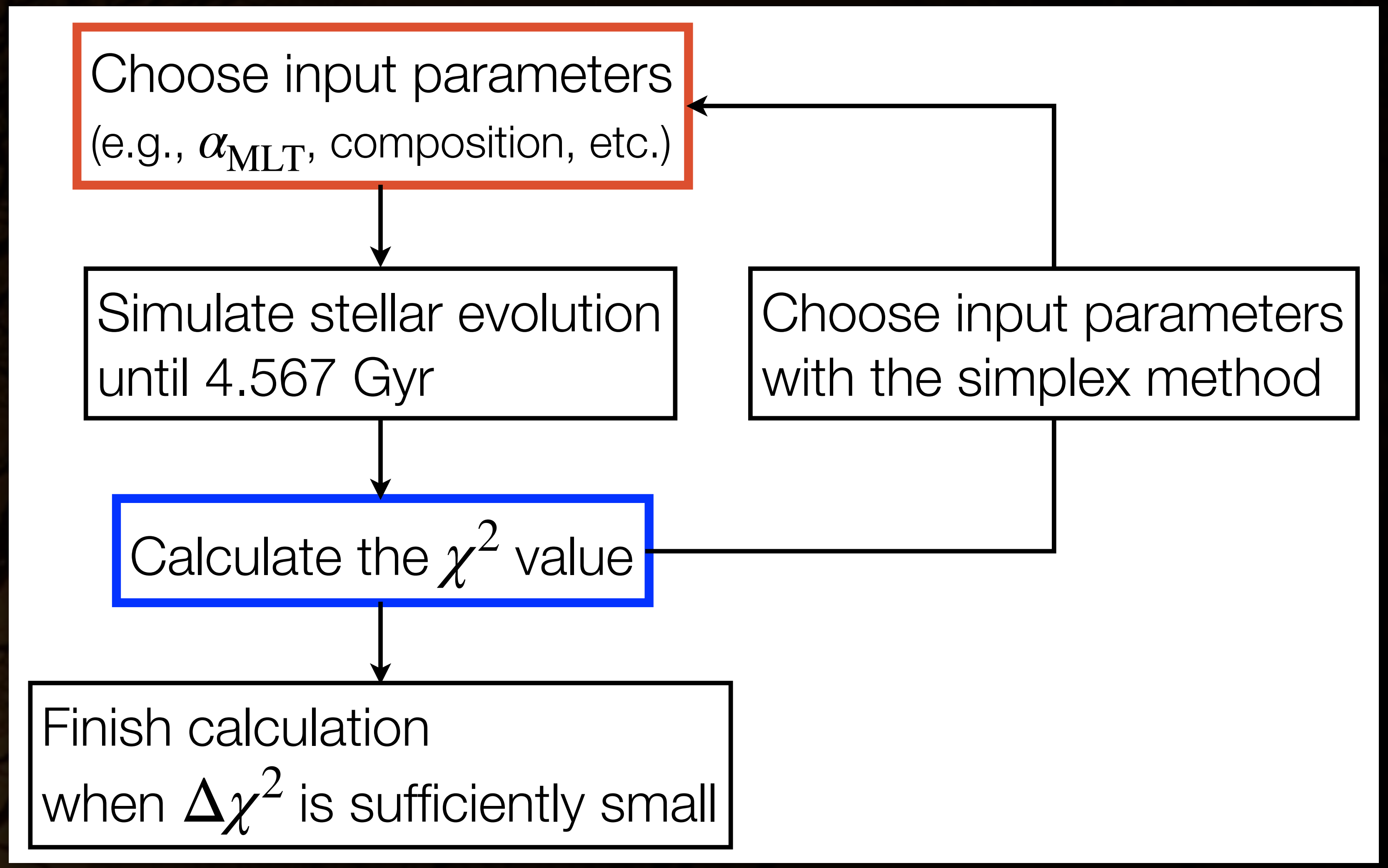
➔ We investigate solar models including planet formation in the **protostellar phase**

- $M_1 = [0.8, 0.99]\,M_\odot$, $M_2 = [0.9, 0.99]\,M_\odot$
- Previous studies investigated solar models with pre-main-sequence accretion and showed that it does not solve the solar abundance problem.

Guzik+05, Serenelli+11, Hoppe+20



stellar evolution calculations + minimization



- Simulate the protostellar phase to the solar age (4.567 Gyr)
  - 1D quasi-static simulation with the MESA code *Paxton+11, 13, 15, 18, 19*
  - Three effects: **planet formation, opacity increase, overshooting**
  - Accretion: from 0.1 M⊙ to 1 M⊙ with $\dot{M} \propto t^{-3/2}$ *Hartmann+98*

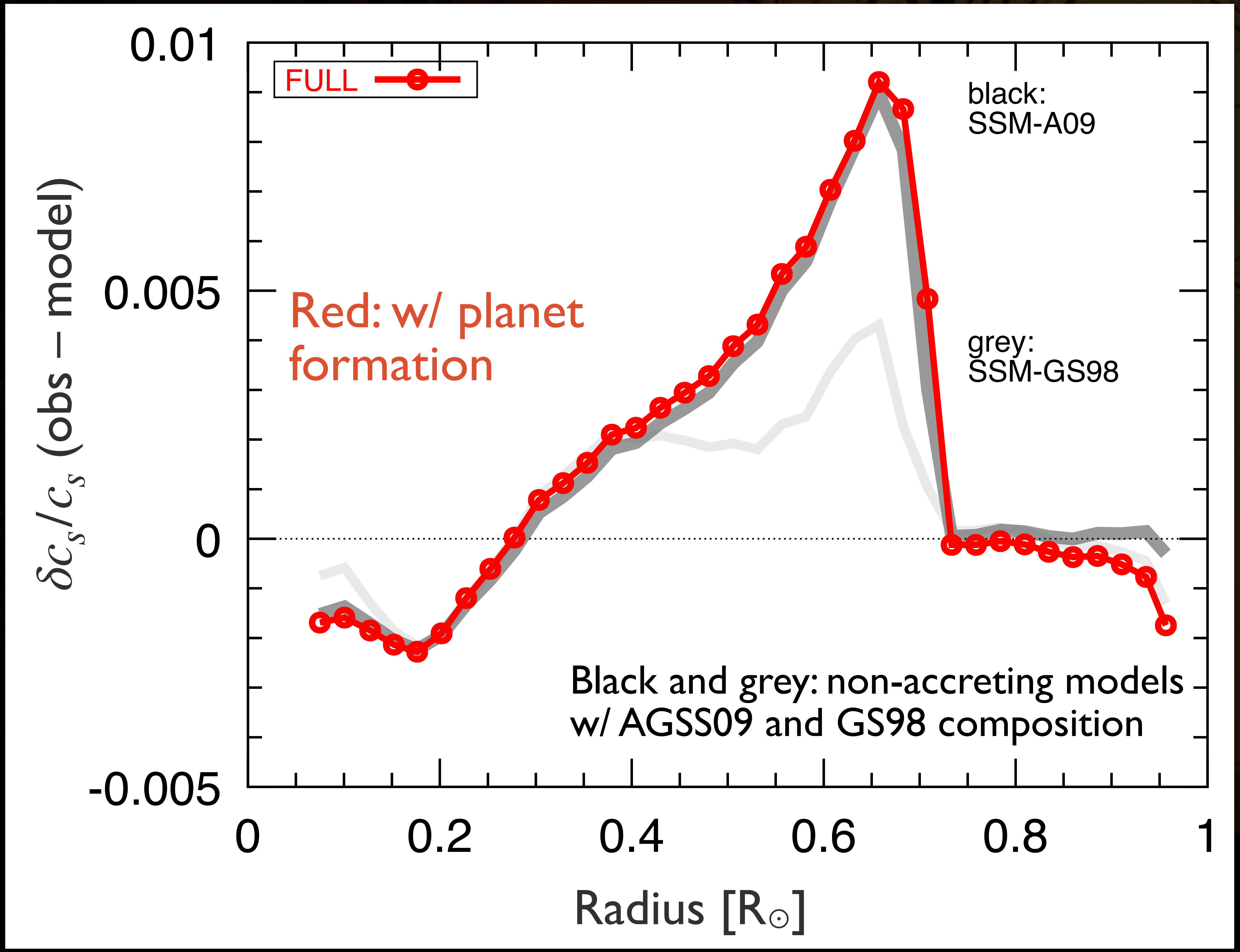
- Minimization of the χ^2 value with the simplex method *Nelder-Mead65*
  - When a simulation ends, we calculate the χ^2 value by comparing the result with observed values. By iterating this, we search for the best input parameters.
  - Inpur parameters:
    - mixing-length parameter $\alpha_{\rm MLT}$, overshooting parameter $f_{\rm overshoot}$, Initial composition ($Y_{\rm acc,ini}$, $Z_{\rm acc,ini}$) *Herwig00*
    - $+M_1$, M_2, $Z_{\rm acc,max}$ for planet formation
    - +opacity changes
  - Observational constraints:

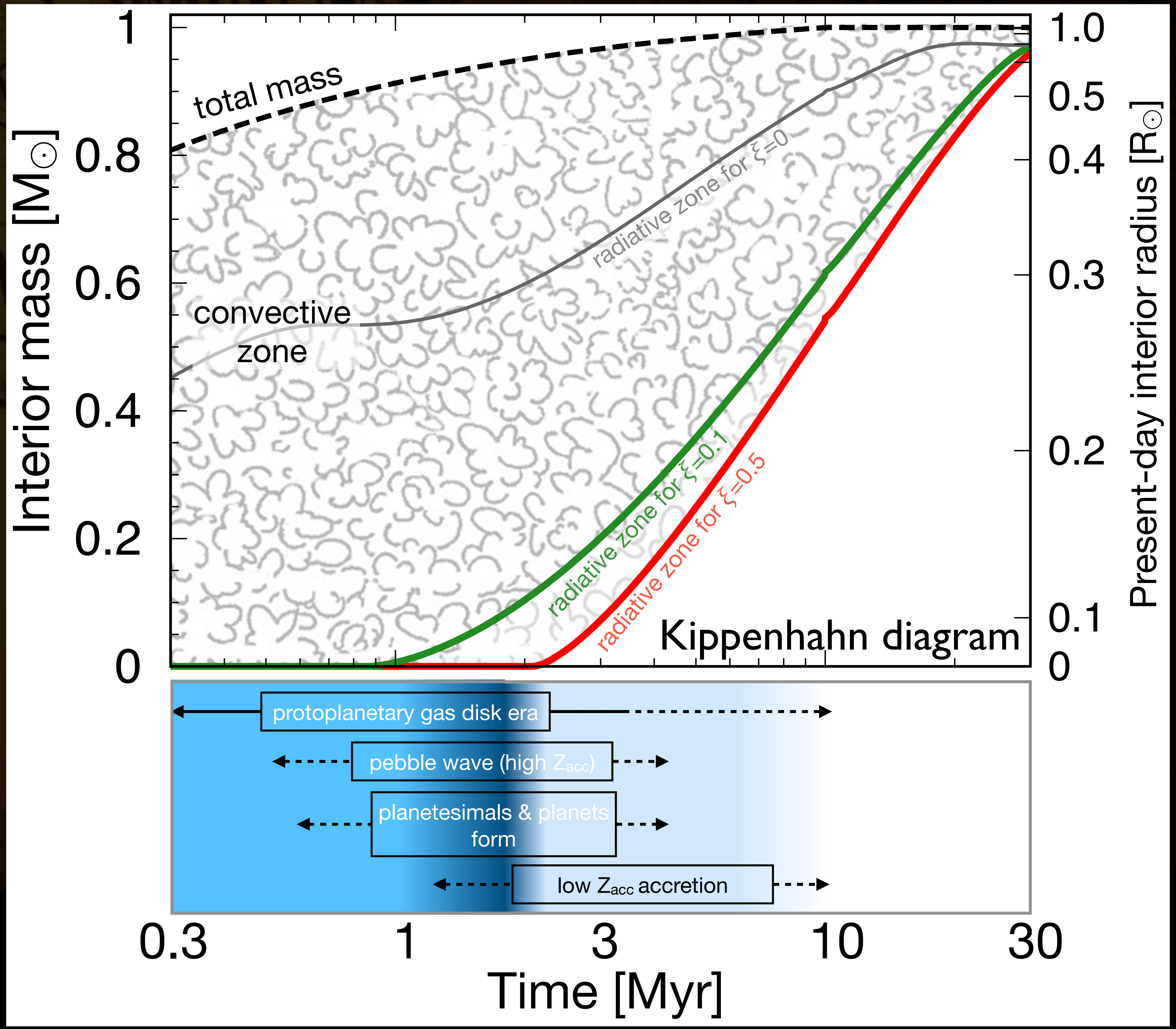
Name	Description	Value	Uncertainty
$(Z/X)_{\rm surf}$	Abundance ratio of metals to hydrogen[a]	0.0181	10^{-3}
		0.02292	10^{-3}
$Y_{\rm surf}$	Surface helium abundance	0.2485	0.0035
$R_{\rm CZ}$	Location of the convective-radiative boundary [R⊙]	0.713	0.01[b]
rms(δc_s)	Root-mean-square sound speed	0	10^{-3} [c]
log $L_\star$	Bolometric luminosity [L⊙]	0	0.01 dex[c]
$T_{\rm eff}$	Effective temperature [K]	5777	10[c]

AGSS09
GS98

Planet formation alone does not solve the problem

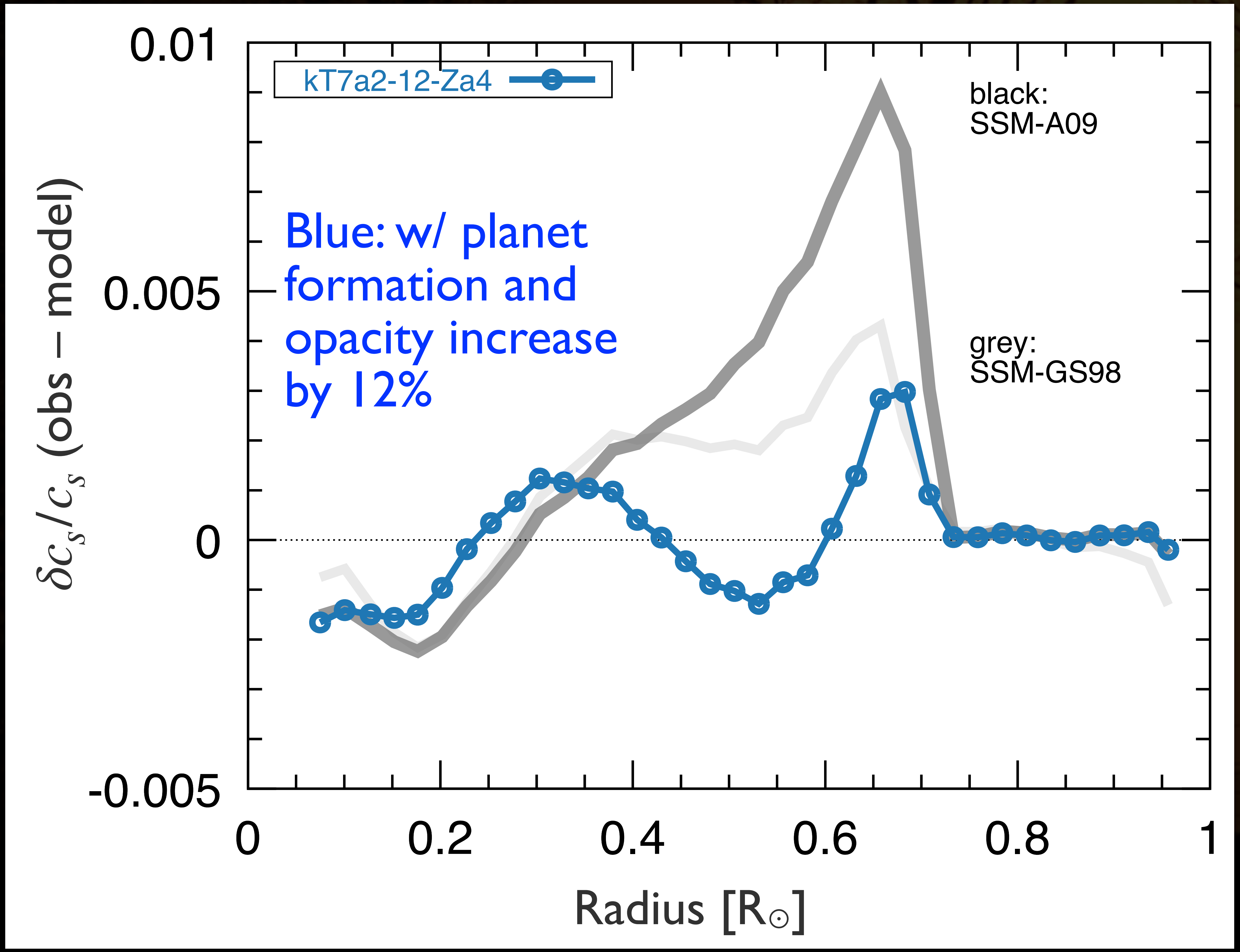
- Metal-poor accretion (by planet formation) does not improve the sound-speed profile
  - Low-mass protostar and pre-MS have a thick convective zone ➔ accreting materials are mixed and diluted





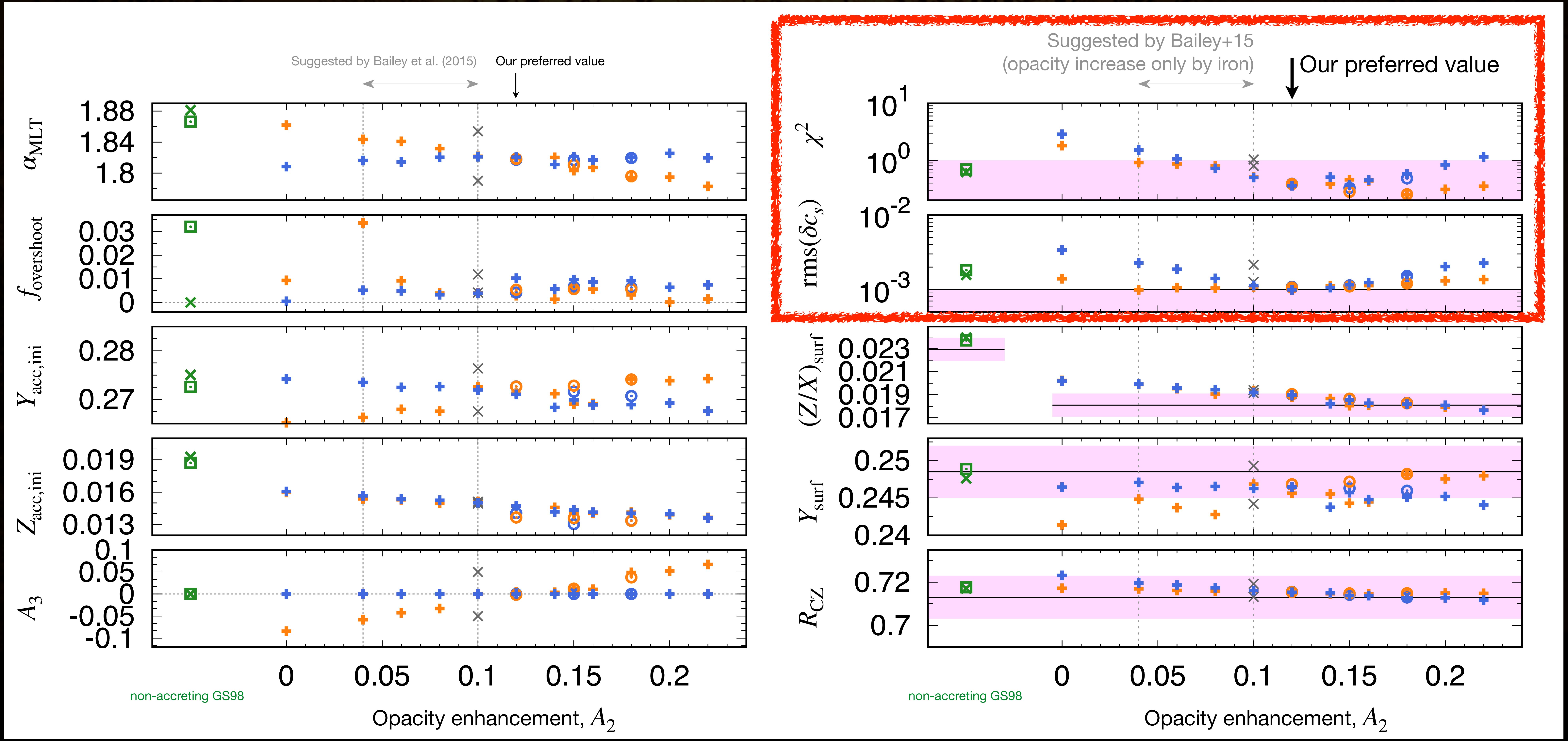
Opacity increase has a great effect

- Opacity increase improves the sound-speed profile, as suggested by previous studies *e.g., Christensen-Dalsgaard+09*
  - Opacity affects the stellar structure (e.g., the size of convective zone)
  - Opacity depends on metallicity
    ➔ Solar structure is reproduced even with the low metallicity, if opacity increase is considered



How much increase do we need?

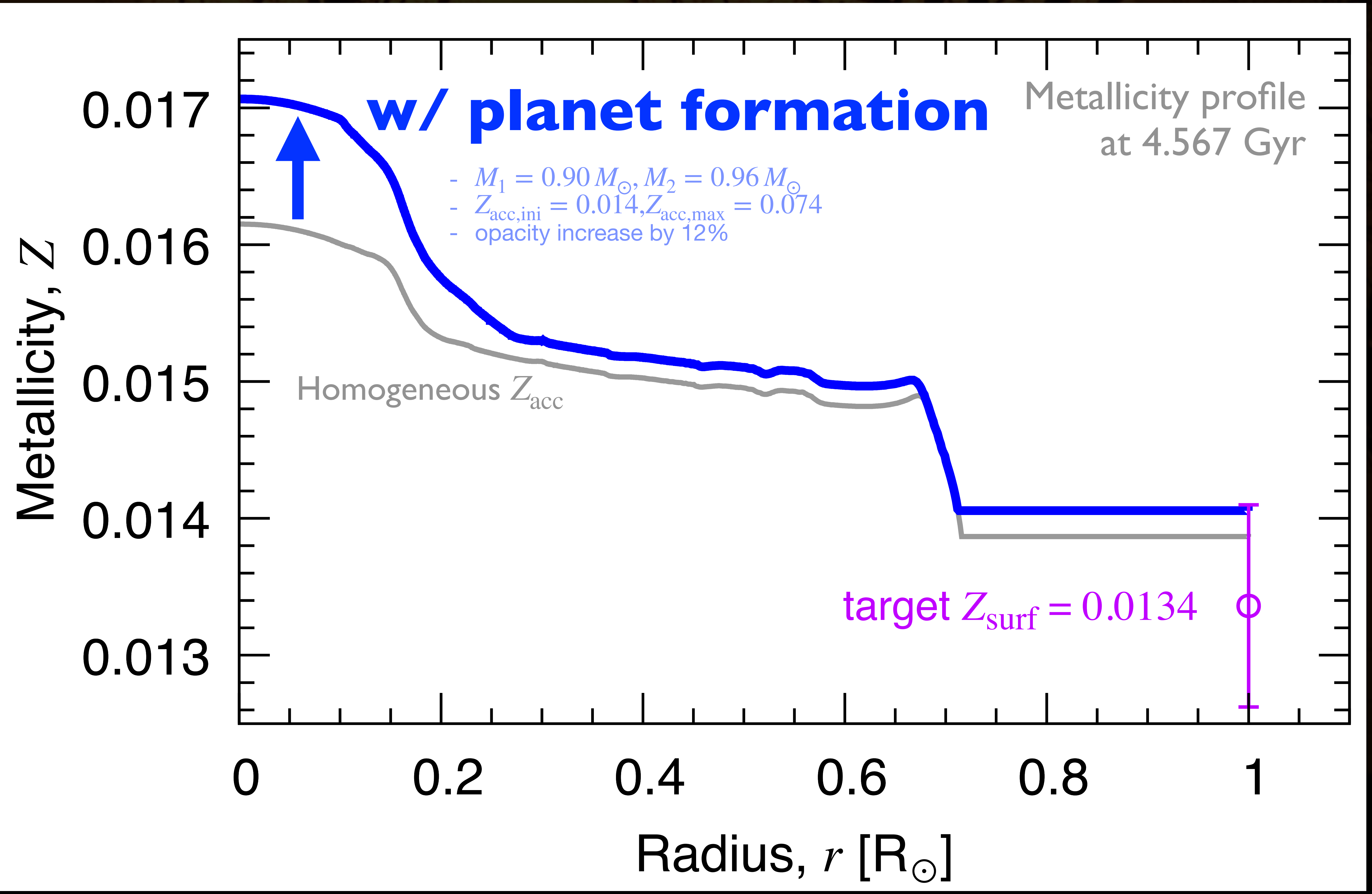
- ~12–18% opacity increase at around ~3×10⁶ K
- Recent experiments at Los Alamos suggested 7±3% increase (Bailey+15; only by iron opacity increase). Our solution is slightly larger but qualitatively in good agreement.



Solar neutrino: imprint of planet formation?

Agostini+18, Borexino Collaboration 20

- Planet formation can increase **the solar central metallicity**
  - Recent neutrino observations have suggested a metal-rich solar core ➔ consistent!
  - Detailed comparison with neutrino fluxes is our future work



Summary

- In the 2000s, the estimate of the solar surface metallicity decreased considerably, but both helioseismic and neutrino observations have suggested the old metal-rich composition
- We investigated the effect of planet formation (metal-poor accretion) on the solar abundance problem by performing a large number of stellar evolutionary simulations
- We found that
    - planet formation has little impact on the sound-speed profile, whereas opacity increase has a great impact
    - the required opacity increase is ~12–18%
    - planet formation, instead, has a great impact on the solar central metallicity, which is important for neutrino fluxes

Future work:

- Finding a solution that is quantitatively consistent with both helioseismic and neutrino observations
- Optimization using MCMC instead of the simplex method