Solar models with the evolving composition of accretion

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Kunitomo & Guillot (2021) A&A, 655, A51
Kunitomo, Guillot & Buldgen (2022), A&A, 667, L2

The future of solar modelling
2023/Sep/7 @ Sierre

Credit: Bill Saxton, NRAO/AUI/NSF


Accretion
Young Sun
Protoplanetary disk
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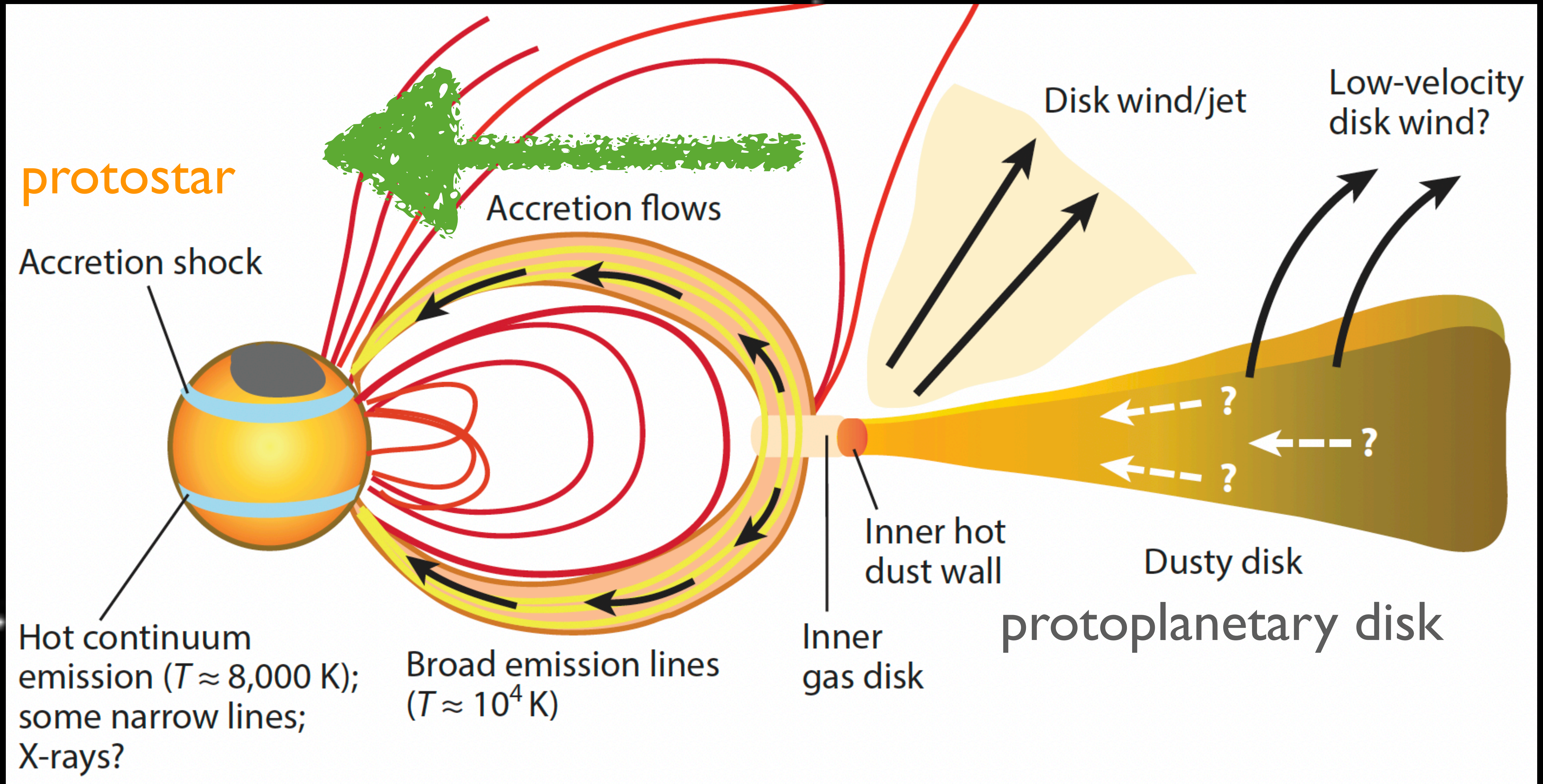
Coevolution of protostar and disk/planet

entropy
materials → thermal / chemical structures of stars

e.g., Hartmann+1997, Hosokawa+2011, Baraffe+2009, 2010, 2012, Tognelli+2016



Hartmann+2016

Kunitomo+2017

- Luminosity spreads in clusters
  e.g., Hillenbrand2009, Jeffries2012, Cao+2021

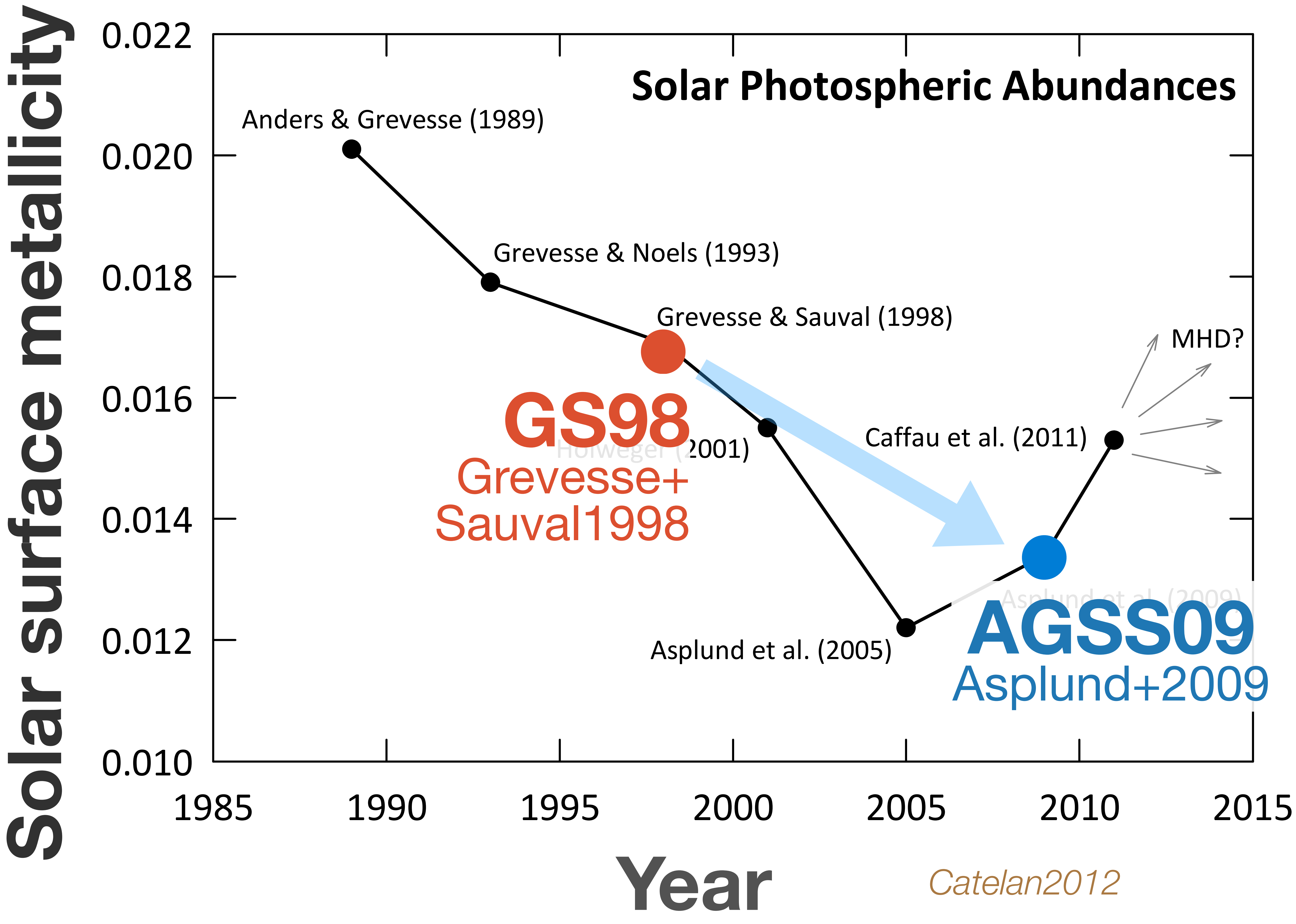
Kunitomo+2018

- λ Boo stars e.g., Murphy+Pauzen2017
- Solar twins e.g., Meléndez+2009
- Binaries e.g., Spina+2021

Kunitomo+2021, 2022

- Solar modeling problem

Revision of the solar surface composition

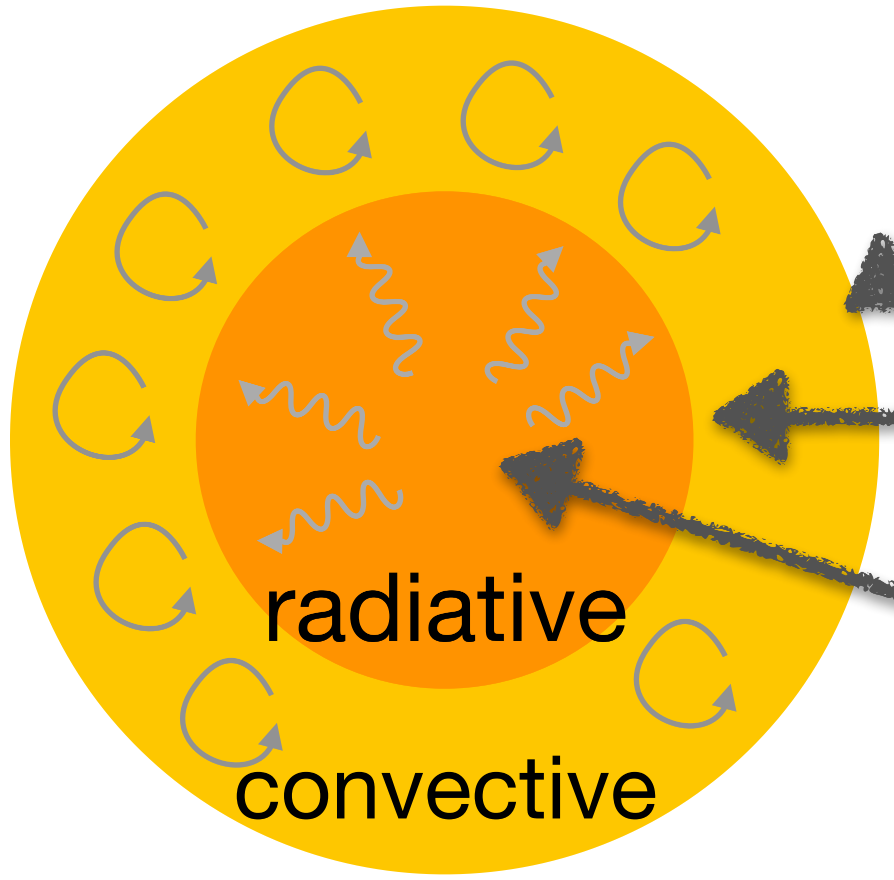


Decrease by ~30% (!)

due to updates in atm. models (e.g., **1D** → **3D**, non-LTE)

See also Asplund+2021

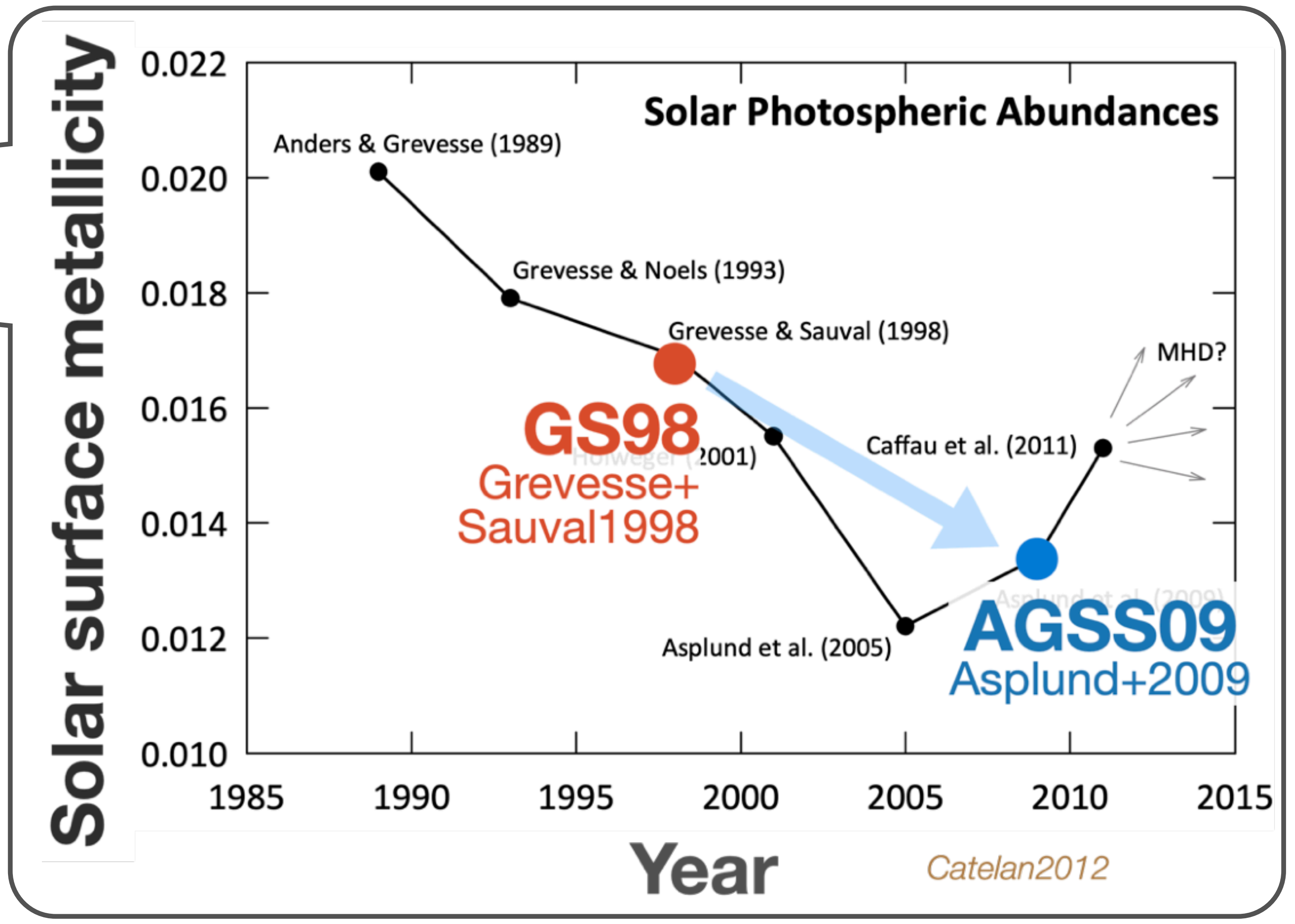
“Solar abundance problem”



Spectroscopy

Helioseismology

Neutrinos



Models w/ GS98

✔ Helioseismology

✔ Neutrinos

→

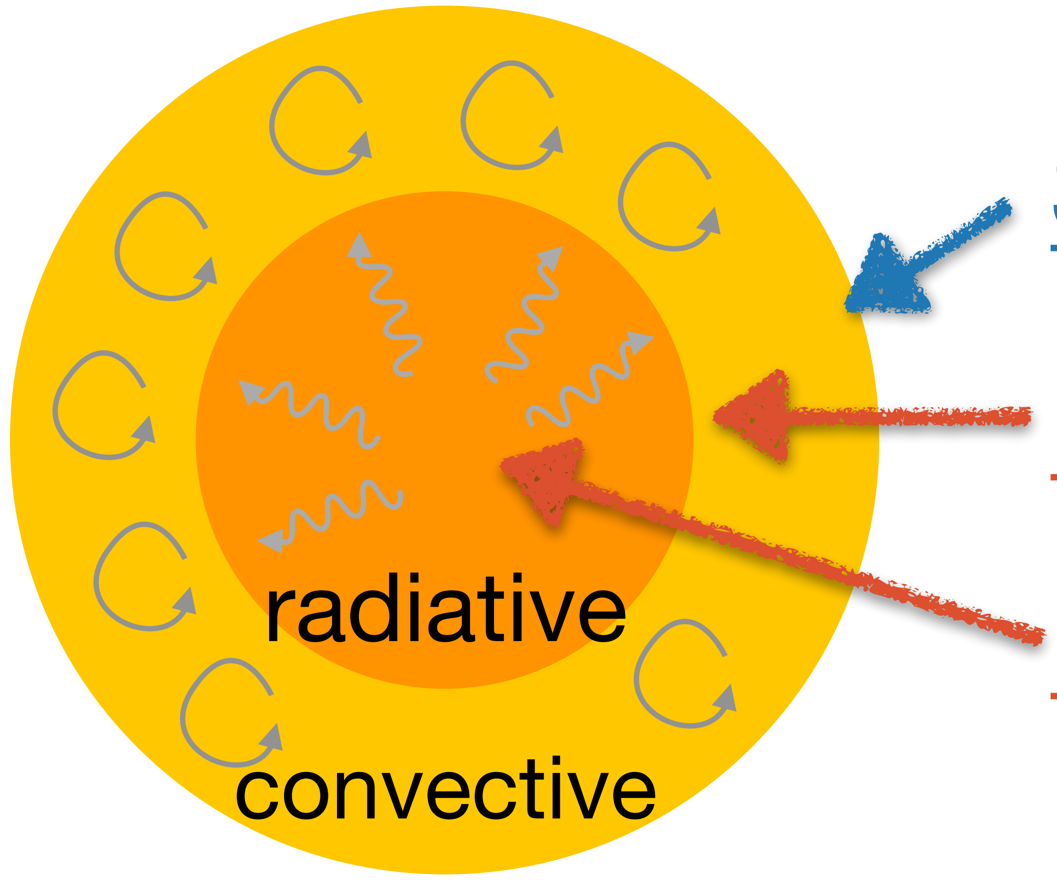
Models w/ AGSS09

✖ Helioseismology

✖ Neutrinos

Montalban+2006, Basu+Antia 2008, Buldgen+2019, Orebi Gann+2021, Christensen-Dalsgaard 2021

Our idea: composition gradient?



Spectroscopy: low-*Z*

Helioseismology: high-*Z*

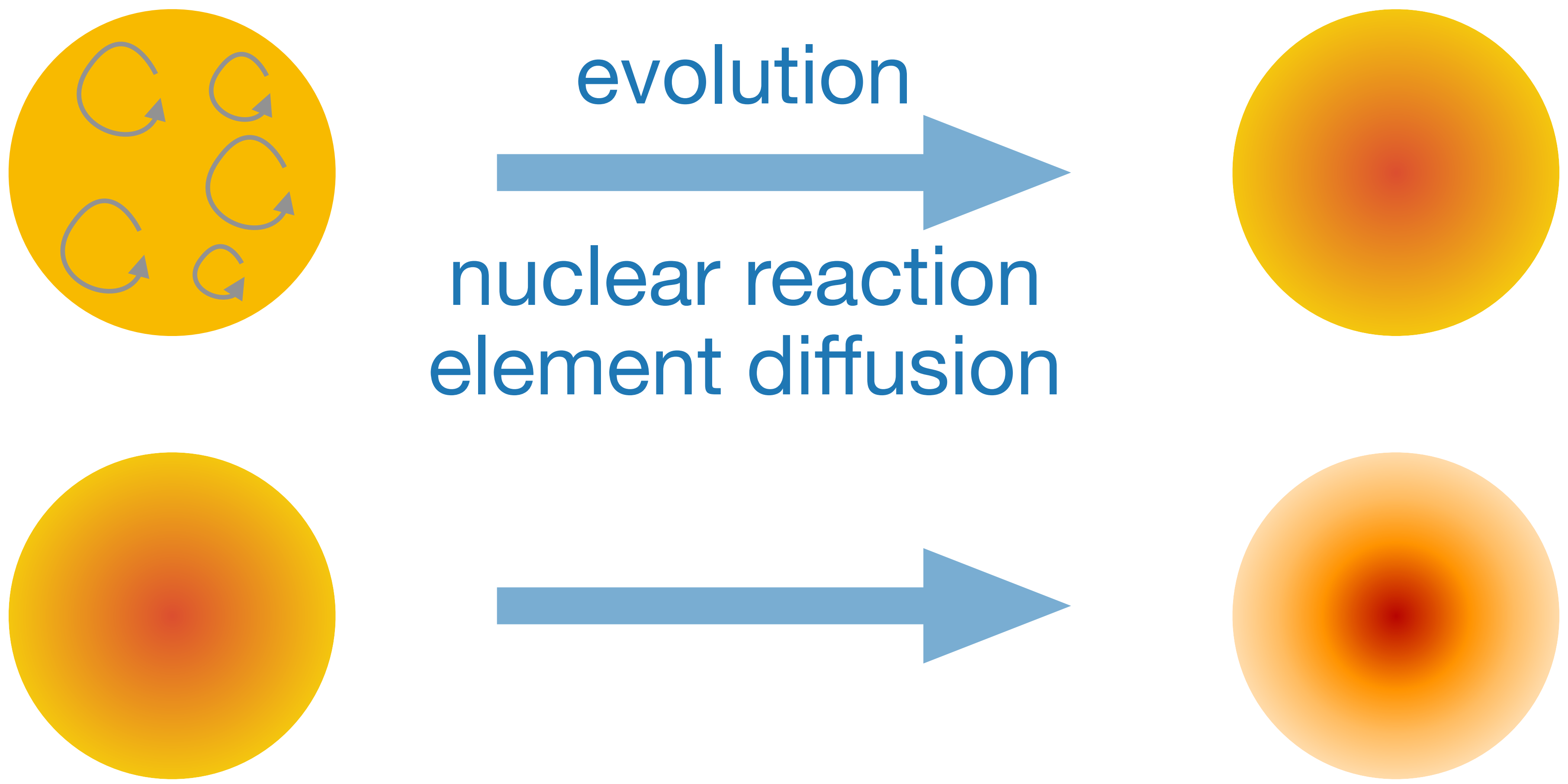
Neutrinos: high-*Z*

Composition gradient
in the solar interior?

proto-Sun | present day

standard solar models

this study



Small composition gradient

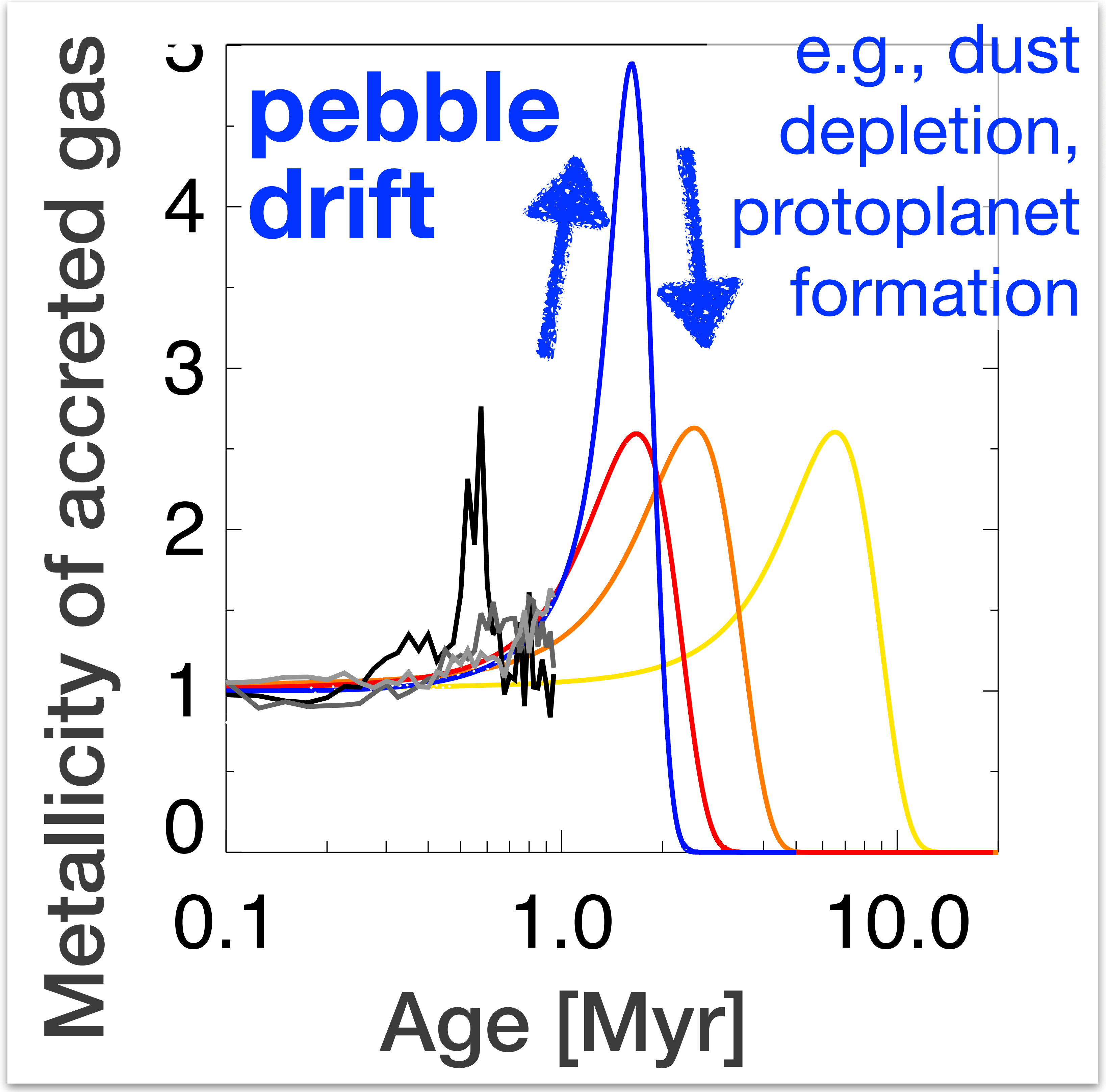
Larger gradient due to **star formation processes?**

Accretion onto the proto-Sun

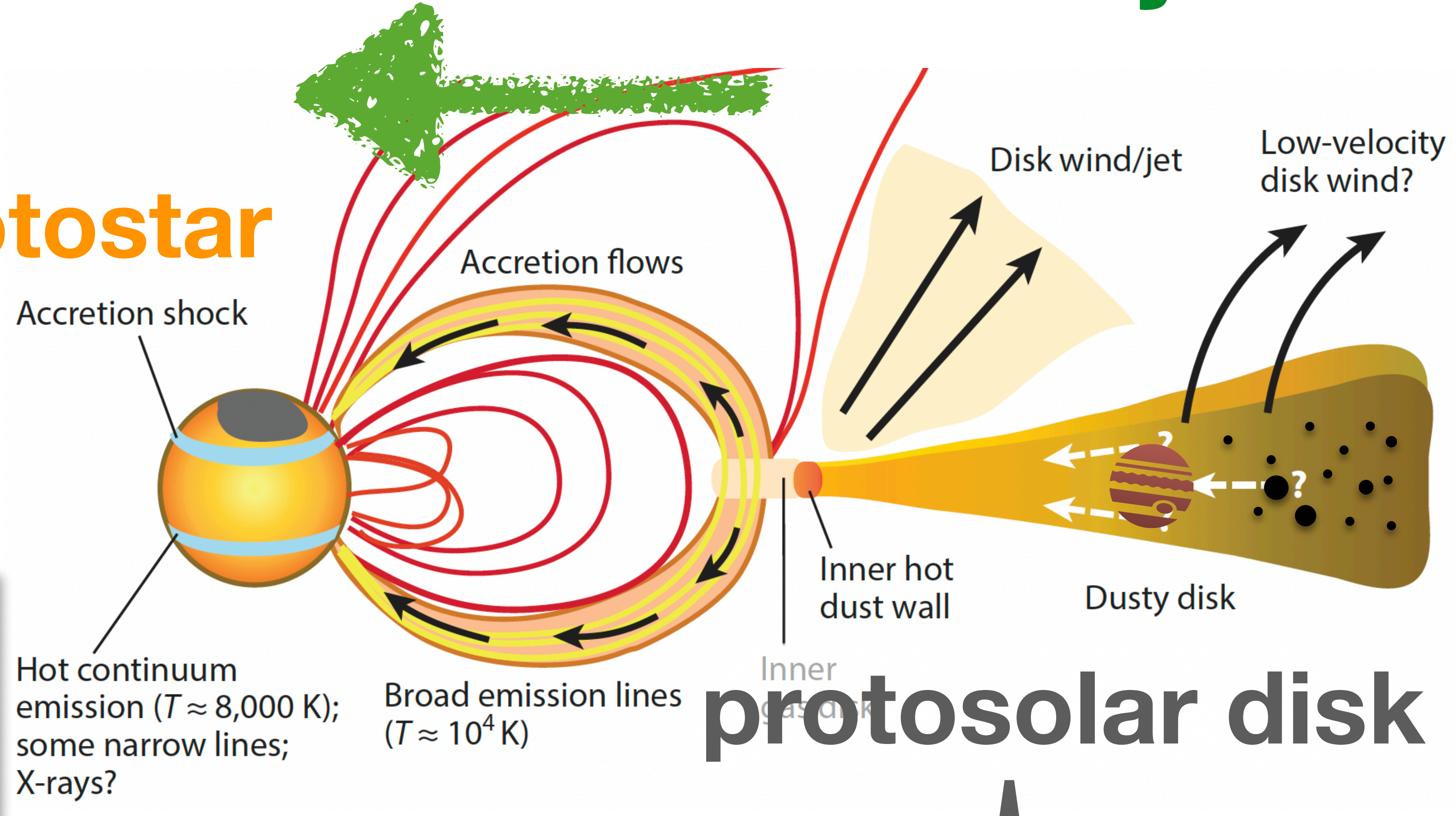
Accretion = injection of disk matter

see also Garaud+2007, Guillot+2014, Applegren+2020, Elbakyan+2020, Kobayashi+Tanaka2021

Kunitomo+Guillot 2021



protostar



protosolar disk

Hartmann+2016; see also Hosokawa+Omukai2009, Machida+2010, Inutsuka2012, Tomida+2013

Planet formation processes

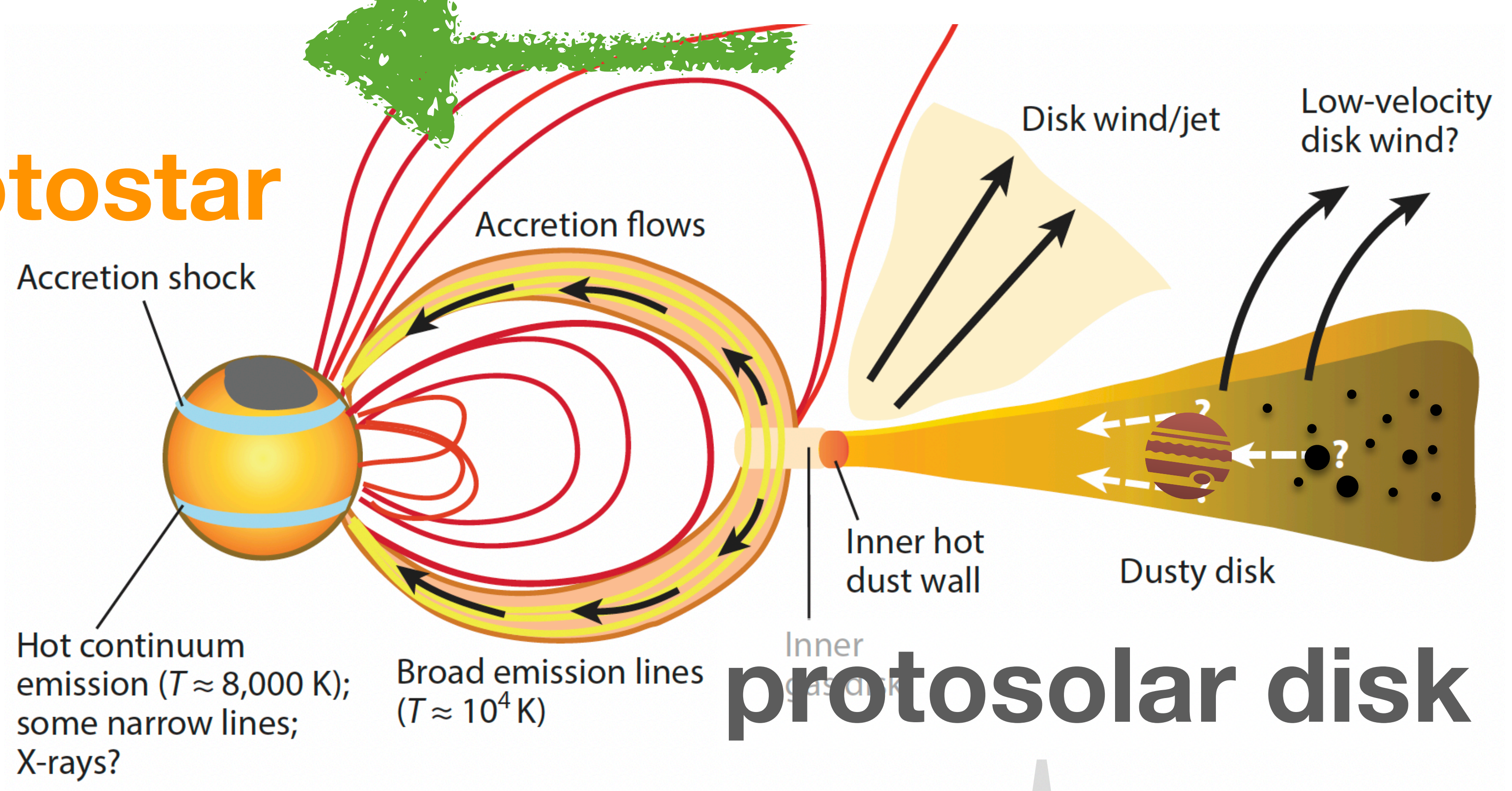
~μm dust grains | **~cm *“pebbles”*** | ~km planetesimals | planets

rapidly fall onto the star *Adachi+1976*

Accretion onto the proto-Sun

Accretion = injection of disk matter

protostar



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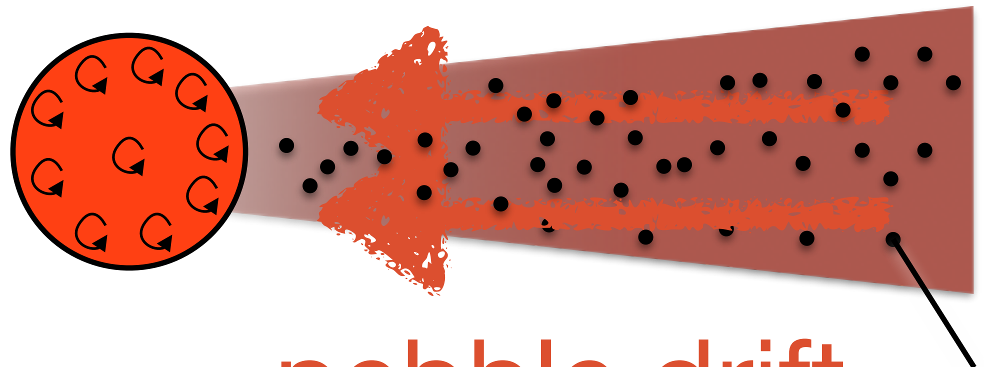
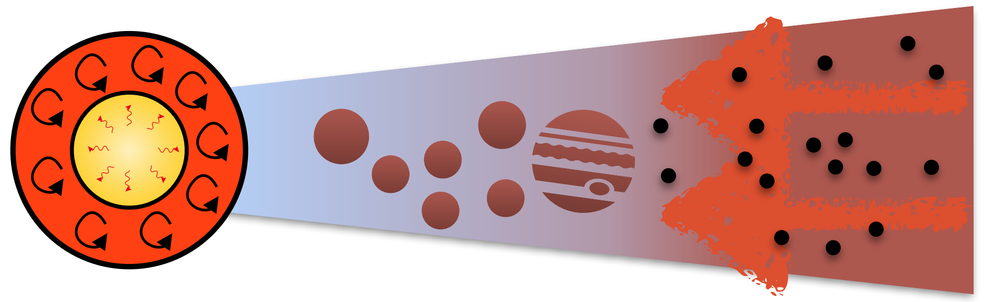
high-*Z* accretion



pebble drift

dust



low-*Z* accretion

Planet formation processes

~μm dust grains

~cm "pebbles"

~km planetesimals

planets

Evolving composition of accretion flow

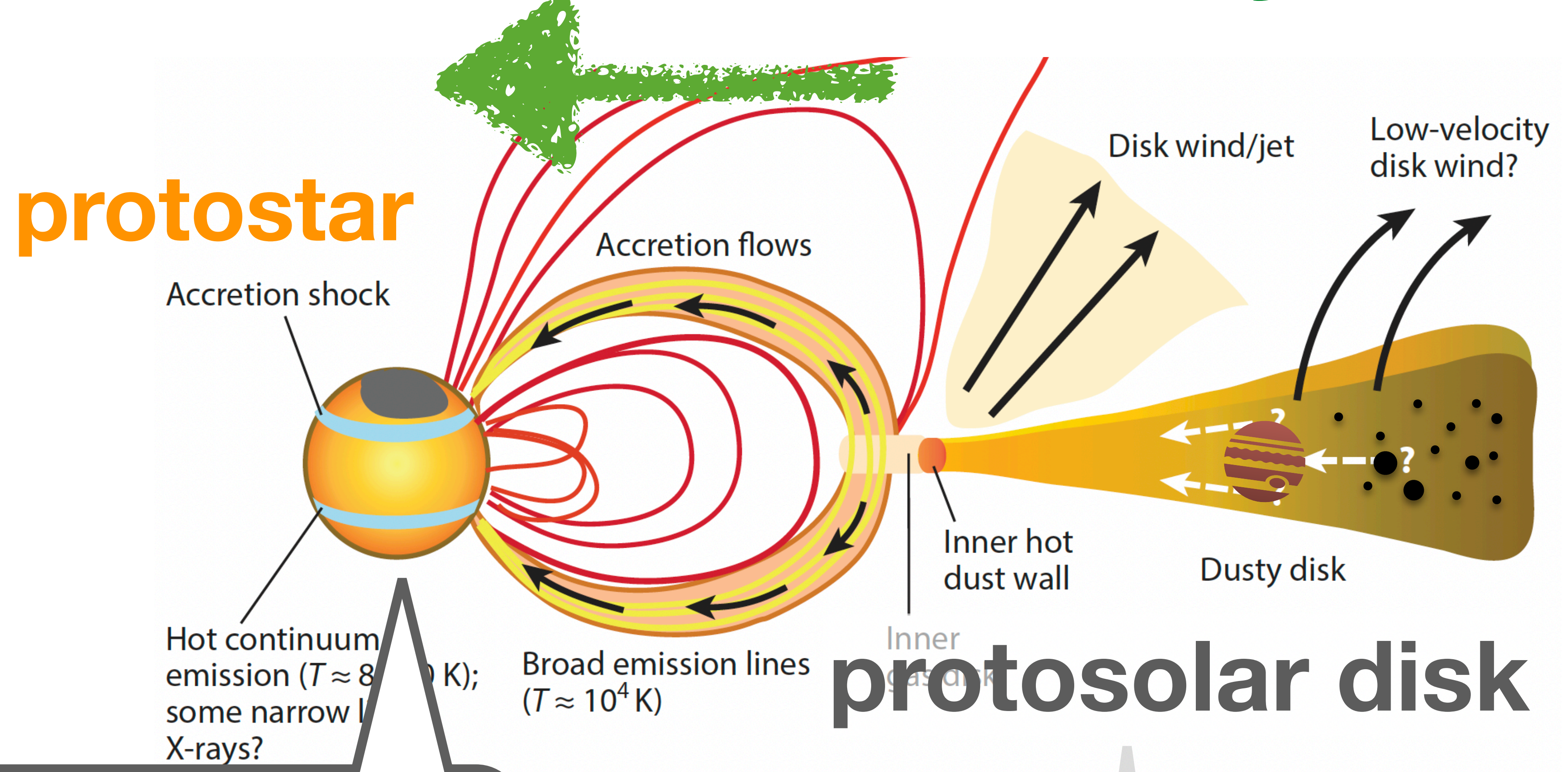
rapidly fall onto the star *Adachi+1976*


Early phase:
dusty accretion
(high-Z)
Late phase:
dust-poor accretion
(low-Z)
planet
HL Tau
ALMA partnership 2015
dust emission
PDS 70
Benisty+2021

Accretion onto the proto-Sun

Accretion = injection of disk matter

Hosokawa+Omukai2009, Machida+2010, Inutsuka2012, Tomida+2013



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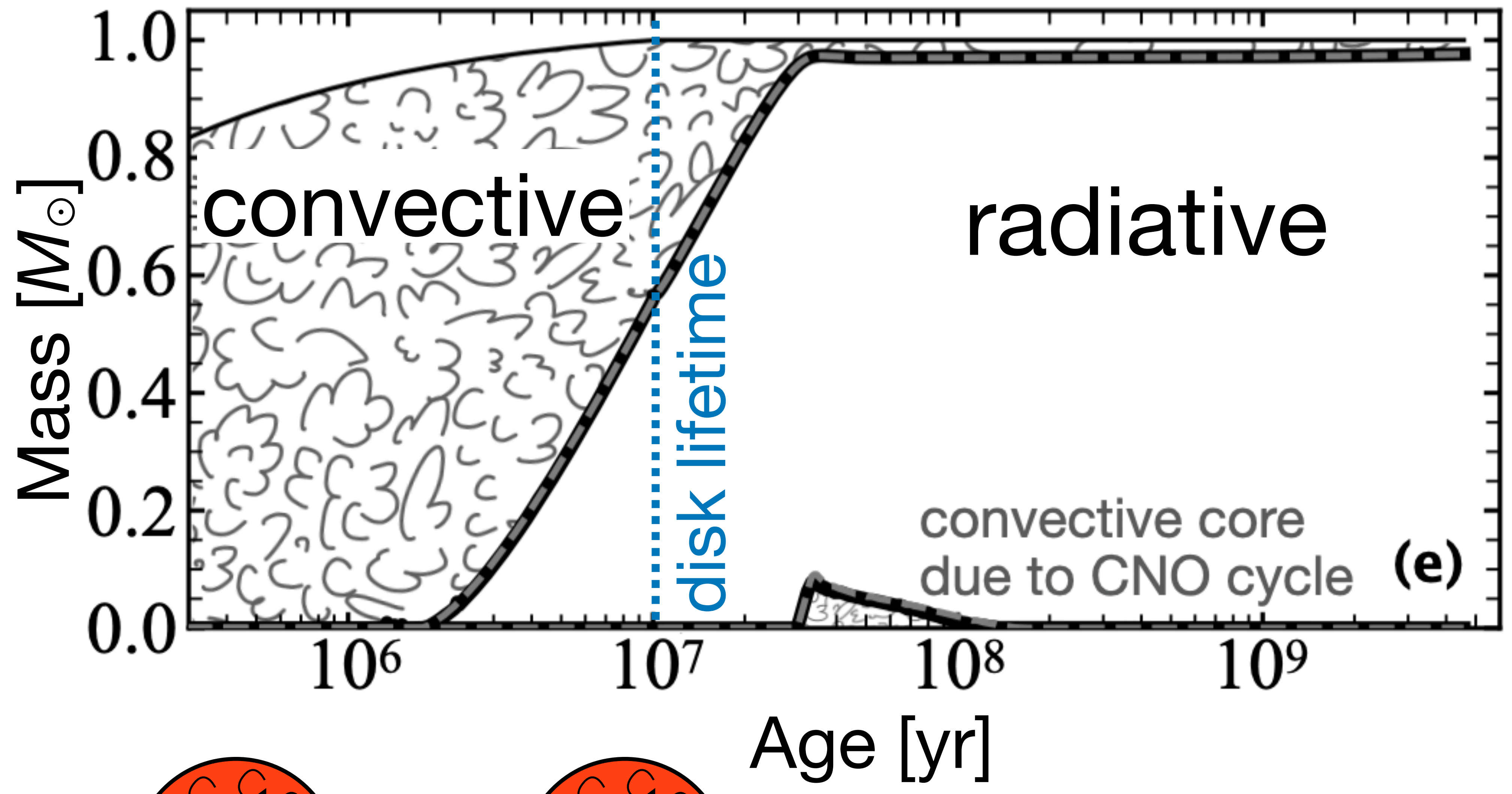
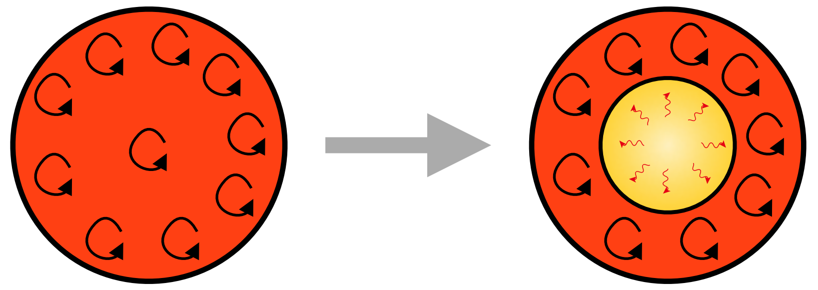
Star formation





Kunitomo+2022

Planet formation processes

~µm dust grains | ~cm "pebbles" | ~km planetesimals | planets

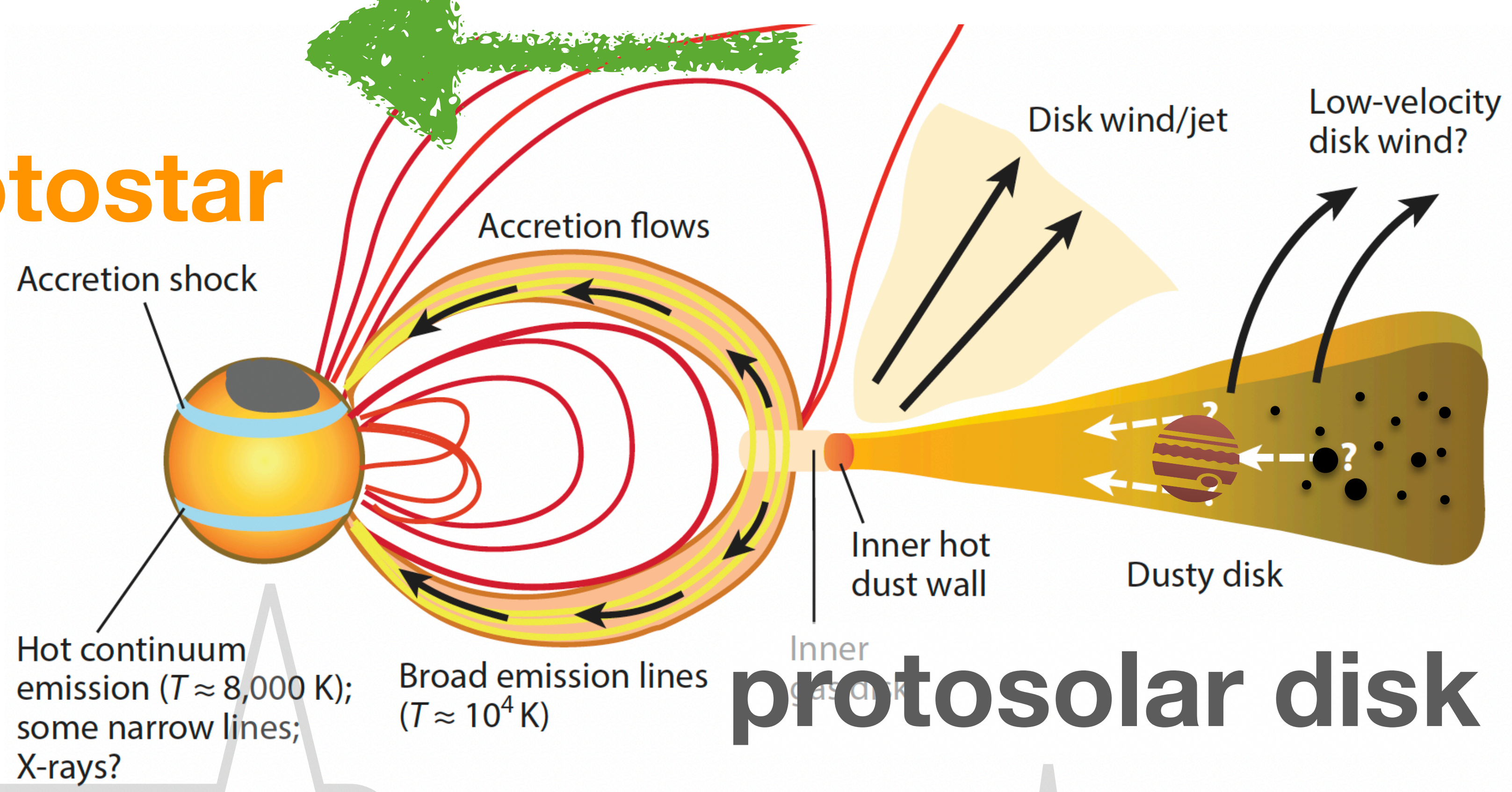
Evolving composition of accretion flow

rapidly fall onto the star *Adachi+1976*

Accretion onto the proto-Sun

Accretion = injection of disk matter

protostar



protosolar disk

Hosokawa+Omukai2009, Machida+2010, Inutsuka2012, Tomida+2013

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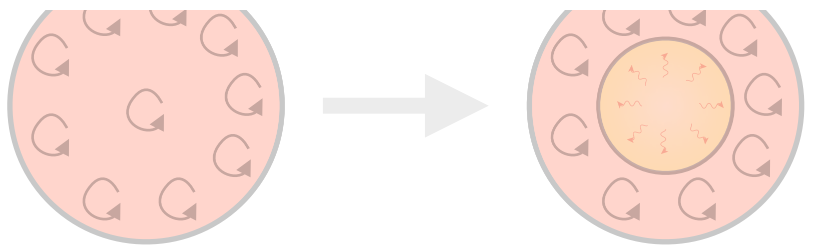
Star formation

Evolution of solar structure



Kunitomo+2022

Planet formation processes

~μm dust grains | ~cm "pebbles" | ~km planetesimals | planets

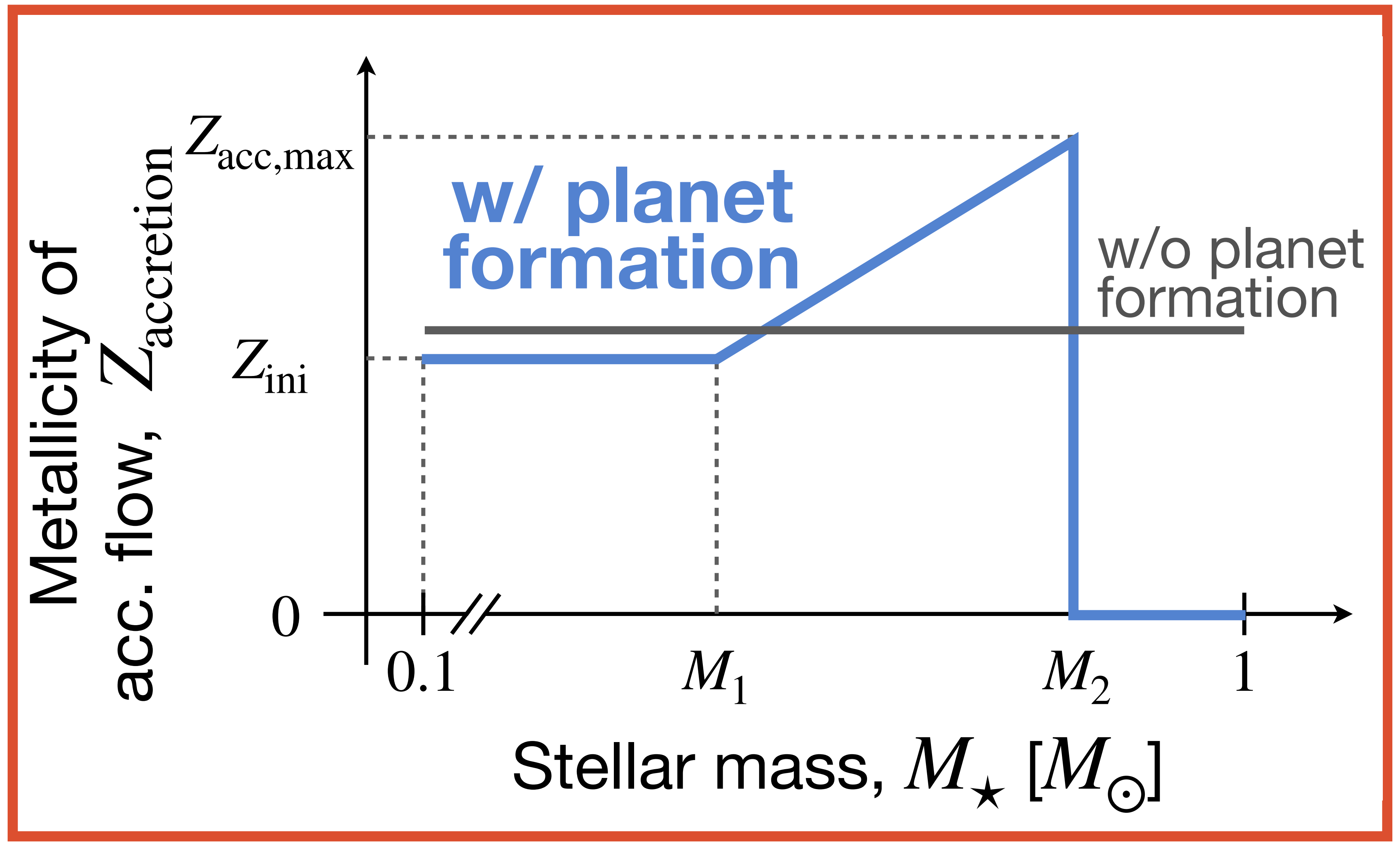
Evolving composition of accretion flow

rapidly fall onto the star *Adachi+1976*

Method

Evolving composition of accretion

- based on planet formation processes
- initial: 0.1 $M_\odot$, $\dot{M}$: Hartmann+1998



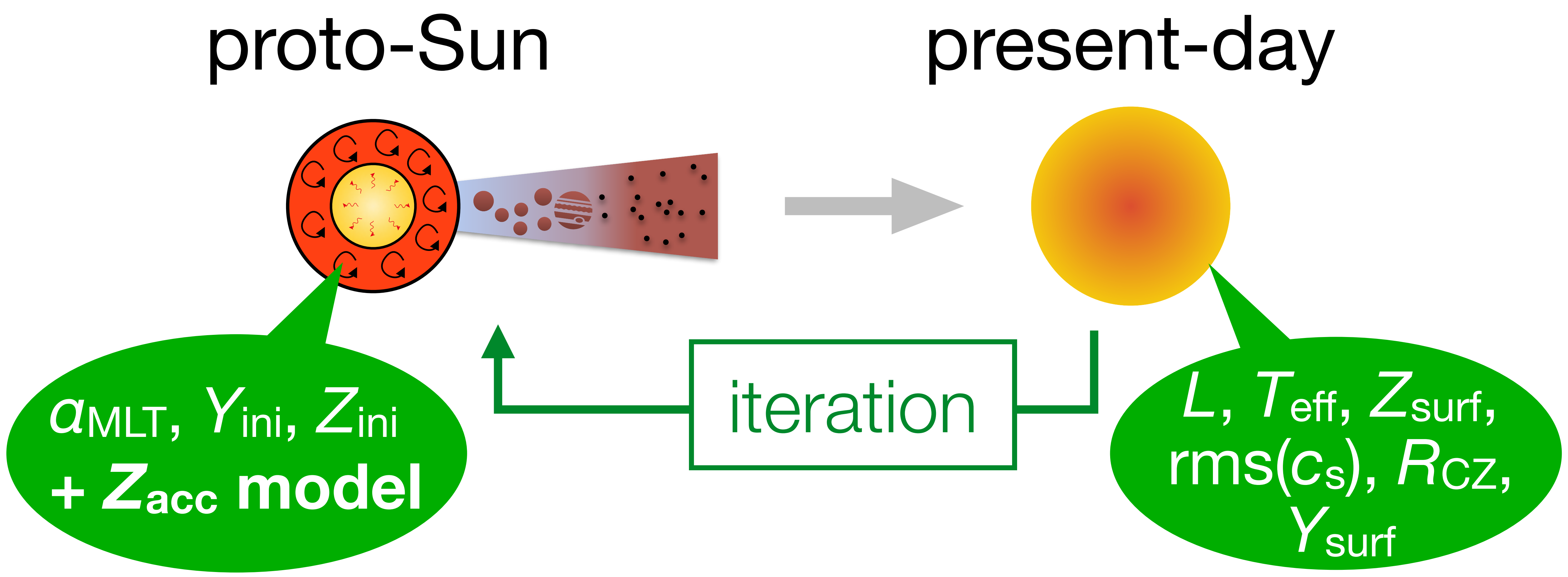
Simulation

- stellar evolution code MESA + accretion (Paxton+2011, Kunitomo+2017, 2018, 2021)
- optimization w/ Simplex method *Nelder+Mead 1965*

Input parameters

- input: convection, initial composition, **evolving composition of accretion**
- target: L, $T_{\rm eff}$, surface composition, helioseismic constraints

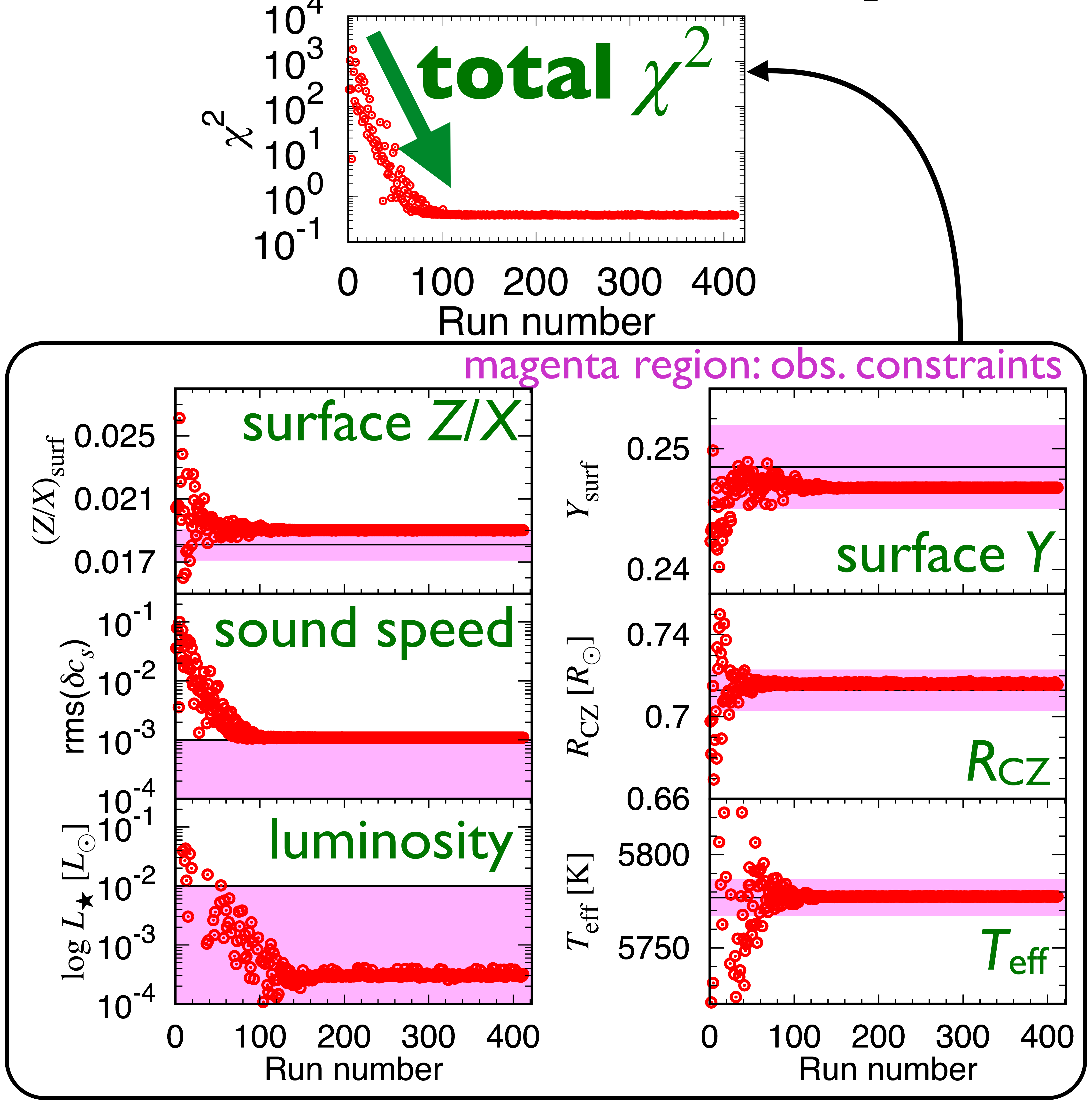
see Ayukov+Baturin2017 "extended calibration"



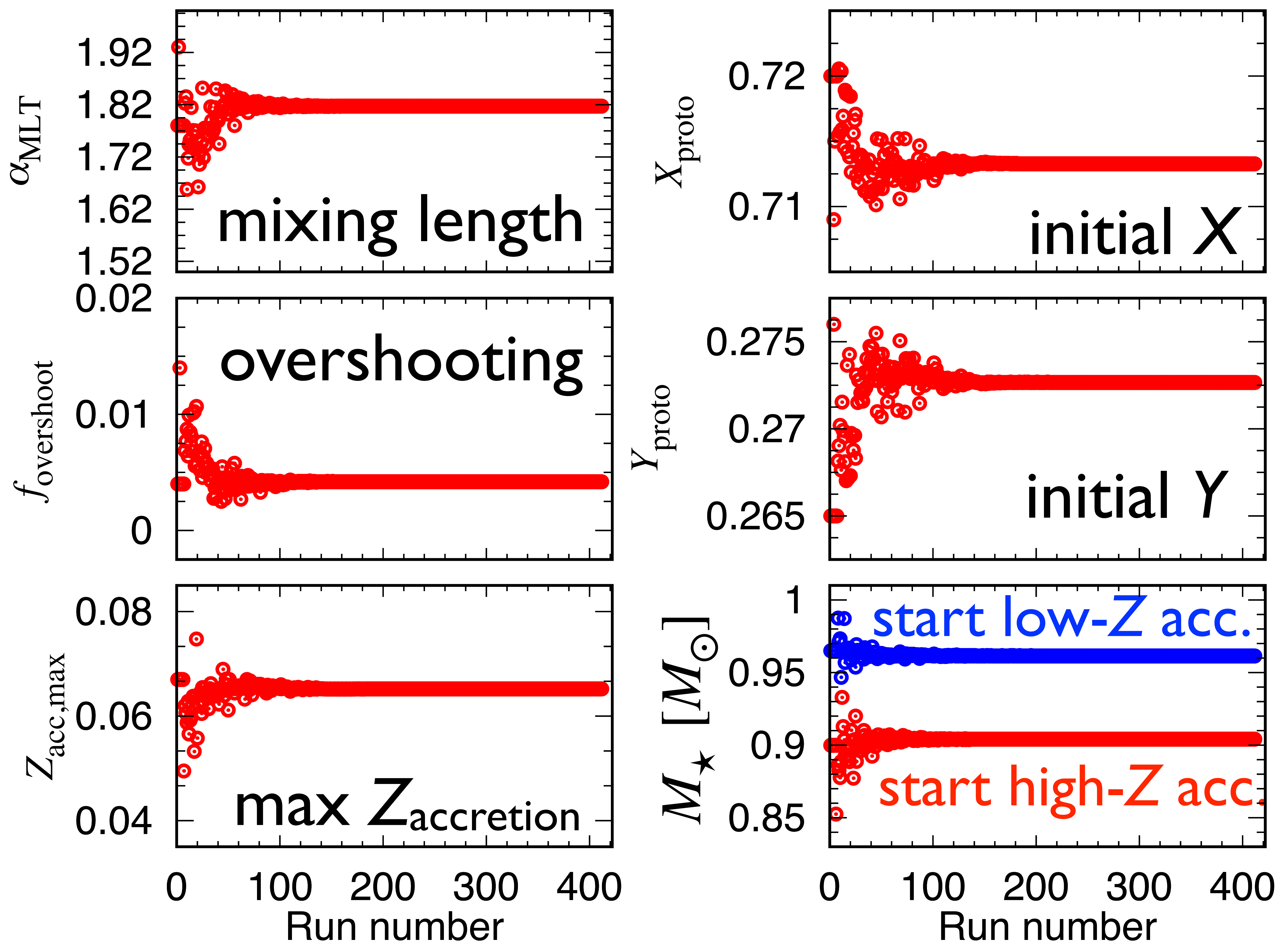
“Extended calibration”

cf. Ayukov+Baturin 2017

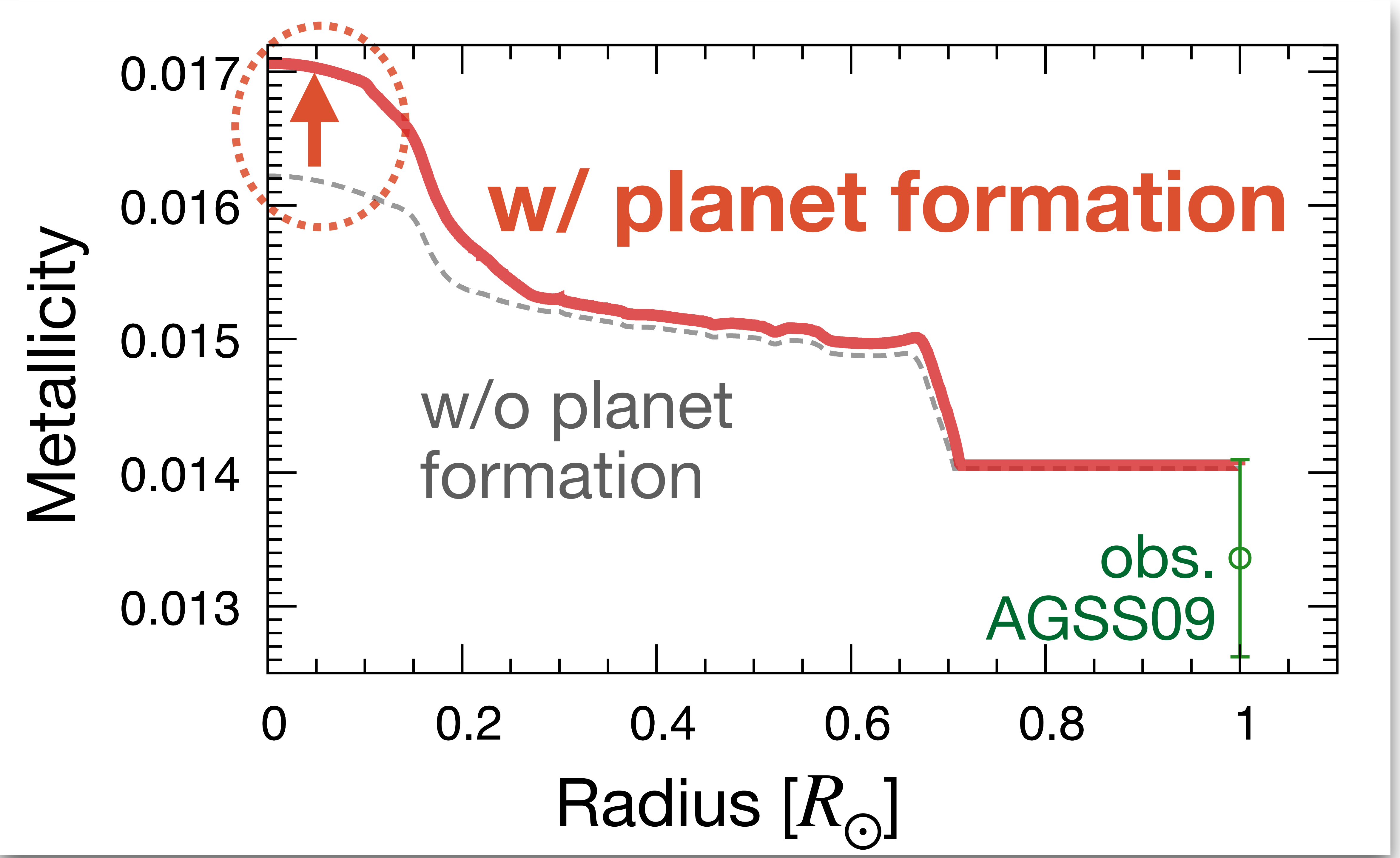
Results at 4.567 Gyr



Input parameters



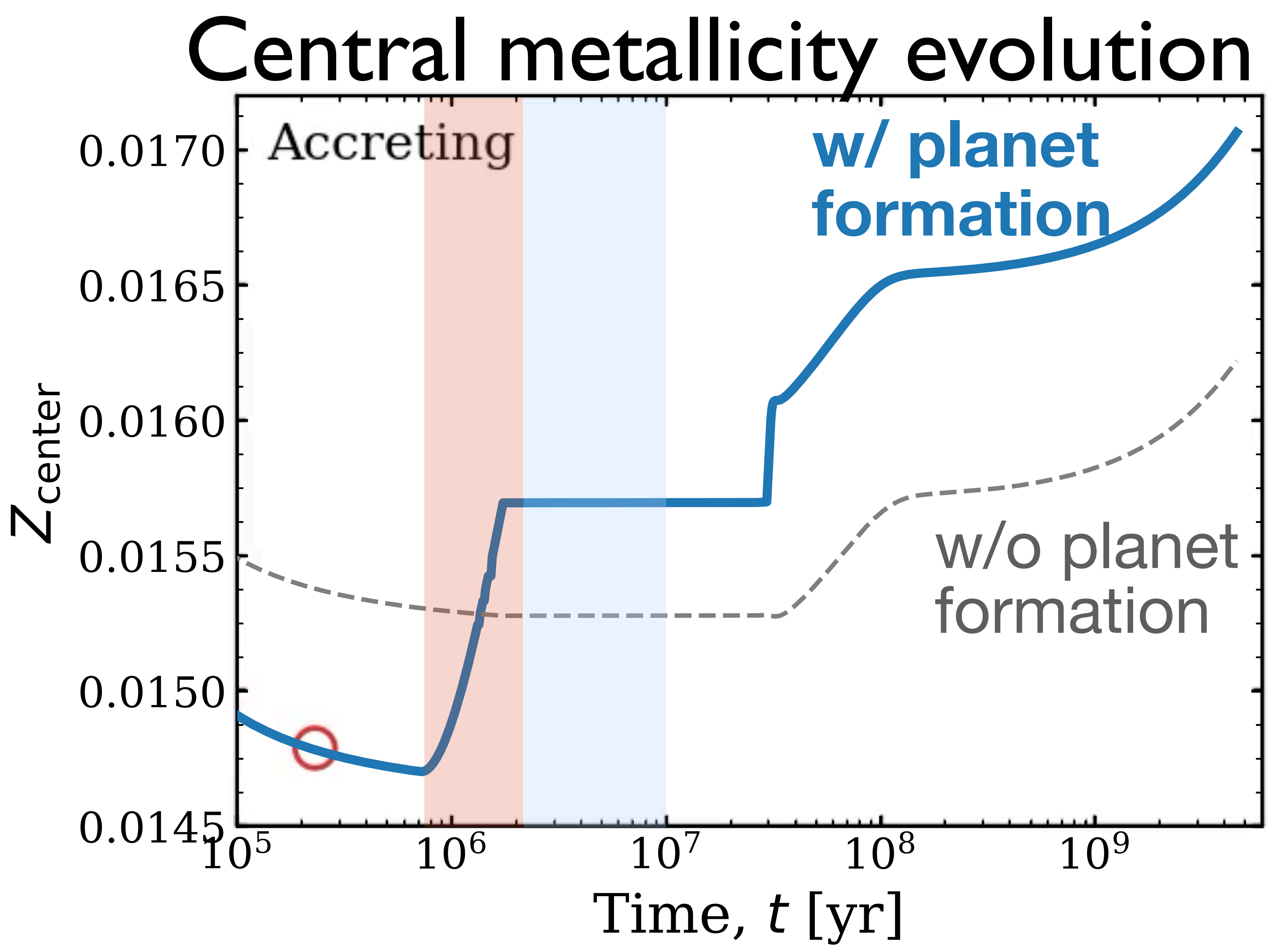
Metallicity profile of the present-day Sun

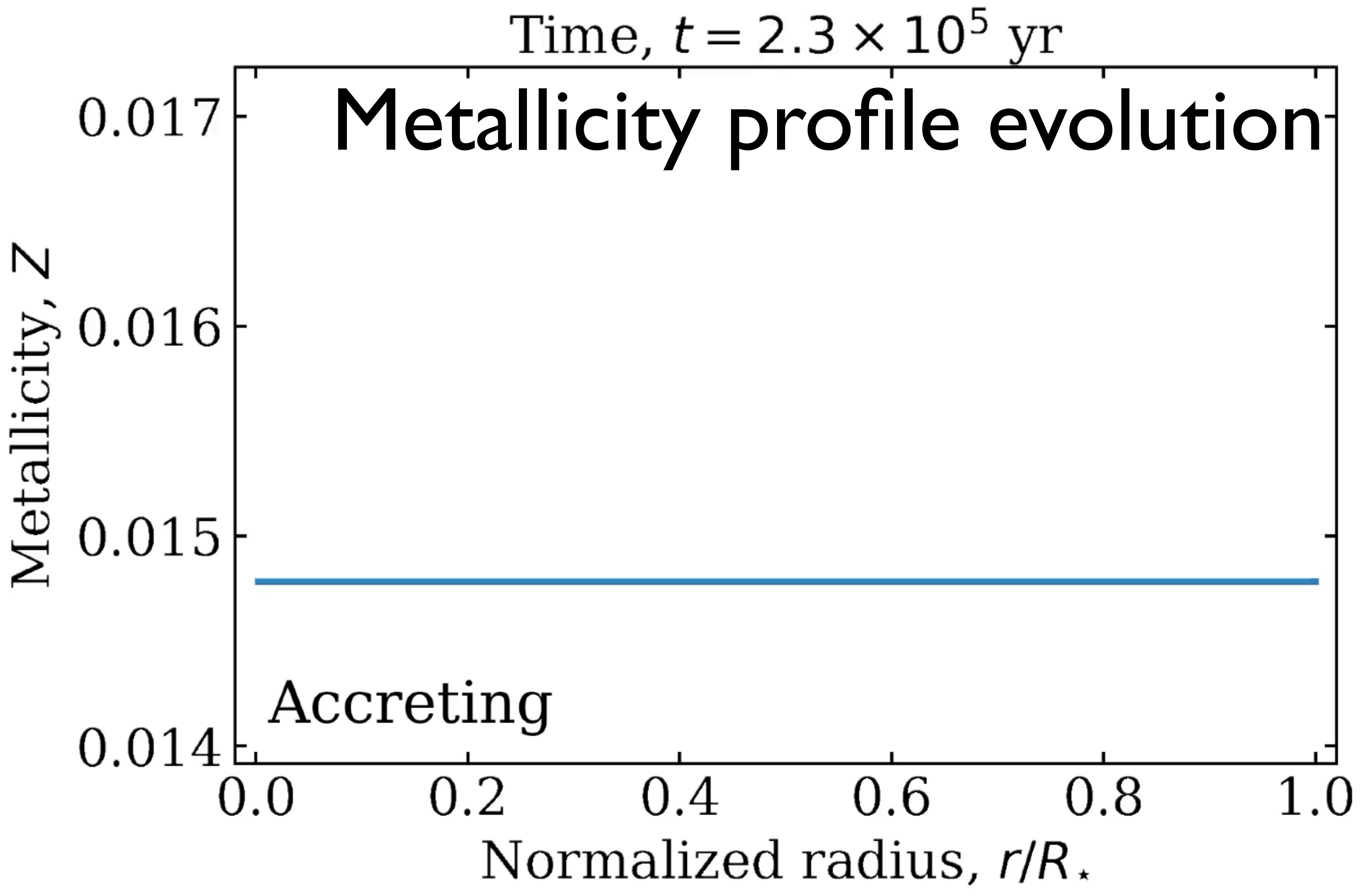


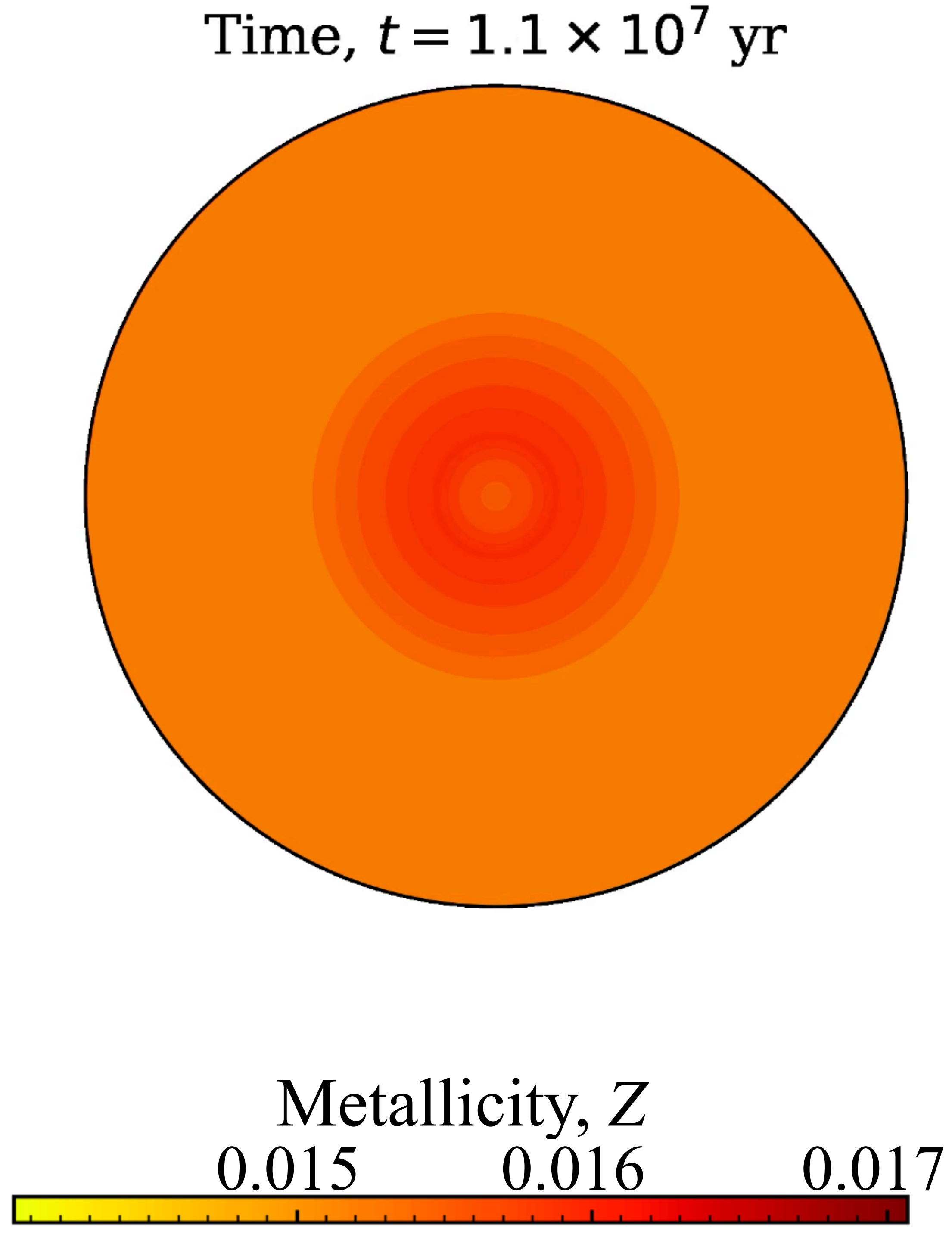
Kunitomo+Guillot 2021

- **central metallicity increases by ~5%**
- only in the central region ($\lesssim 0.2\ R_\odot$)

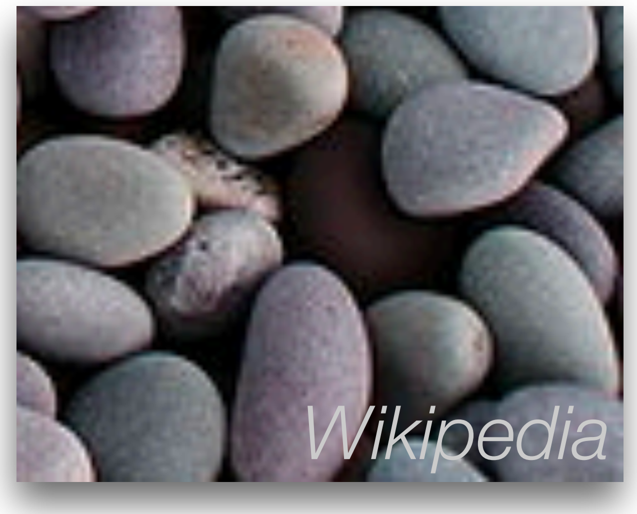
What governs the central metallicity?



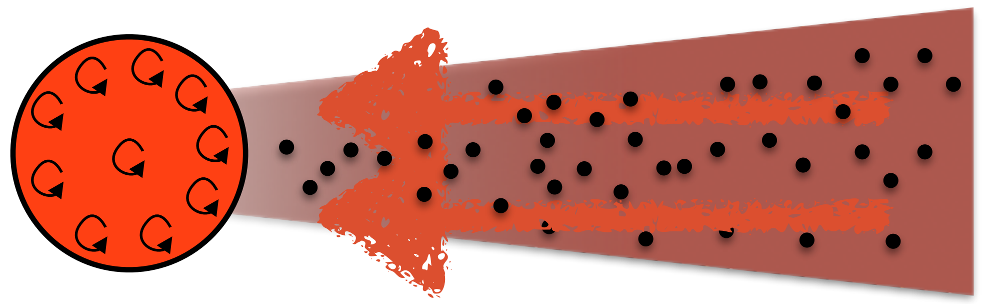




high-Z accretion **low-Z accretion**



pebble drift

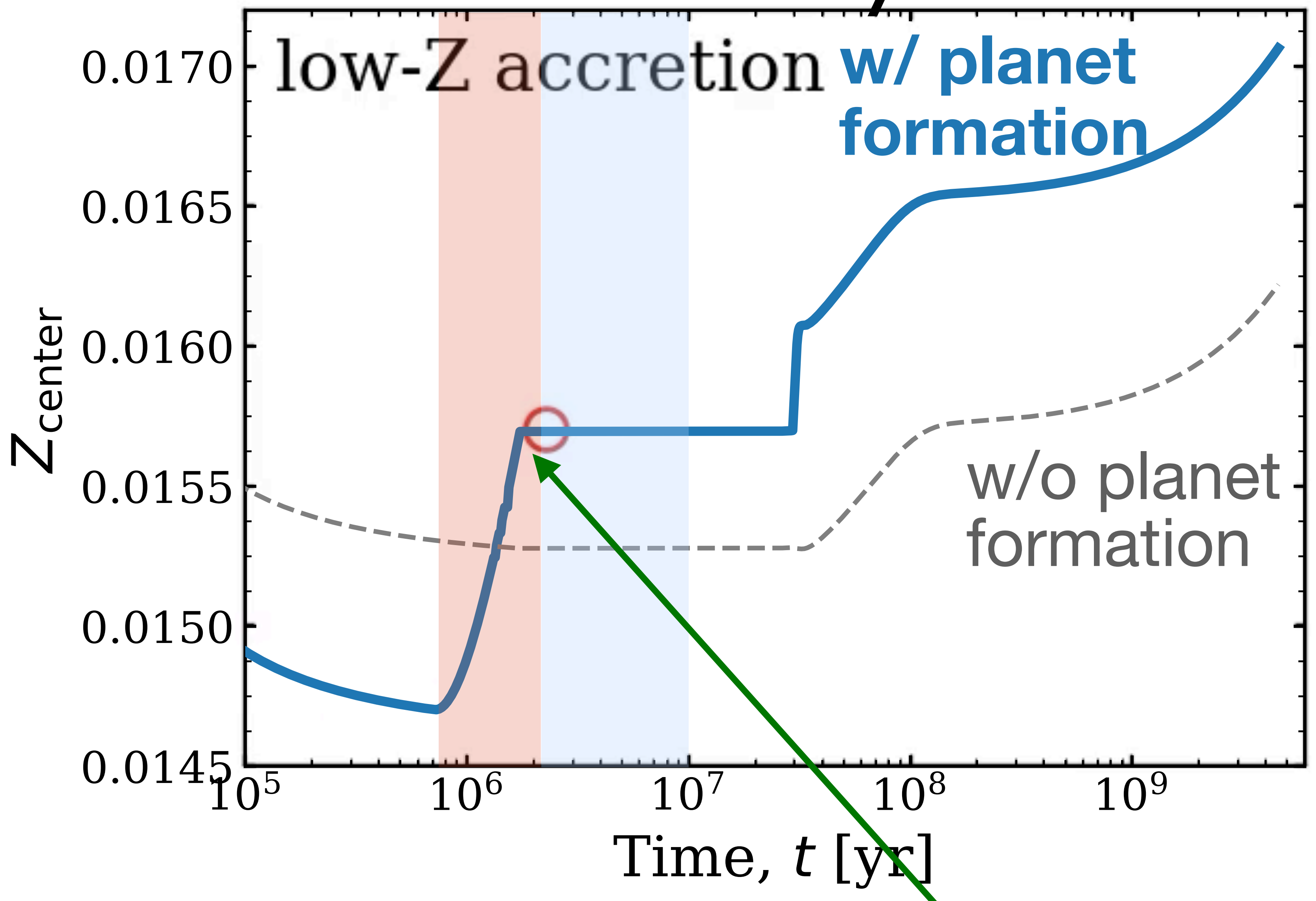


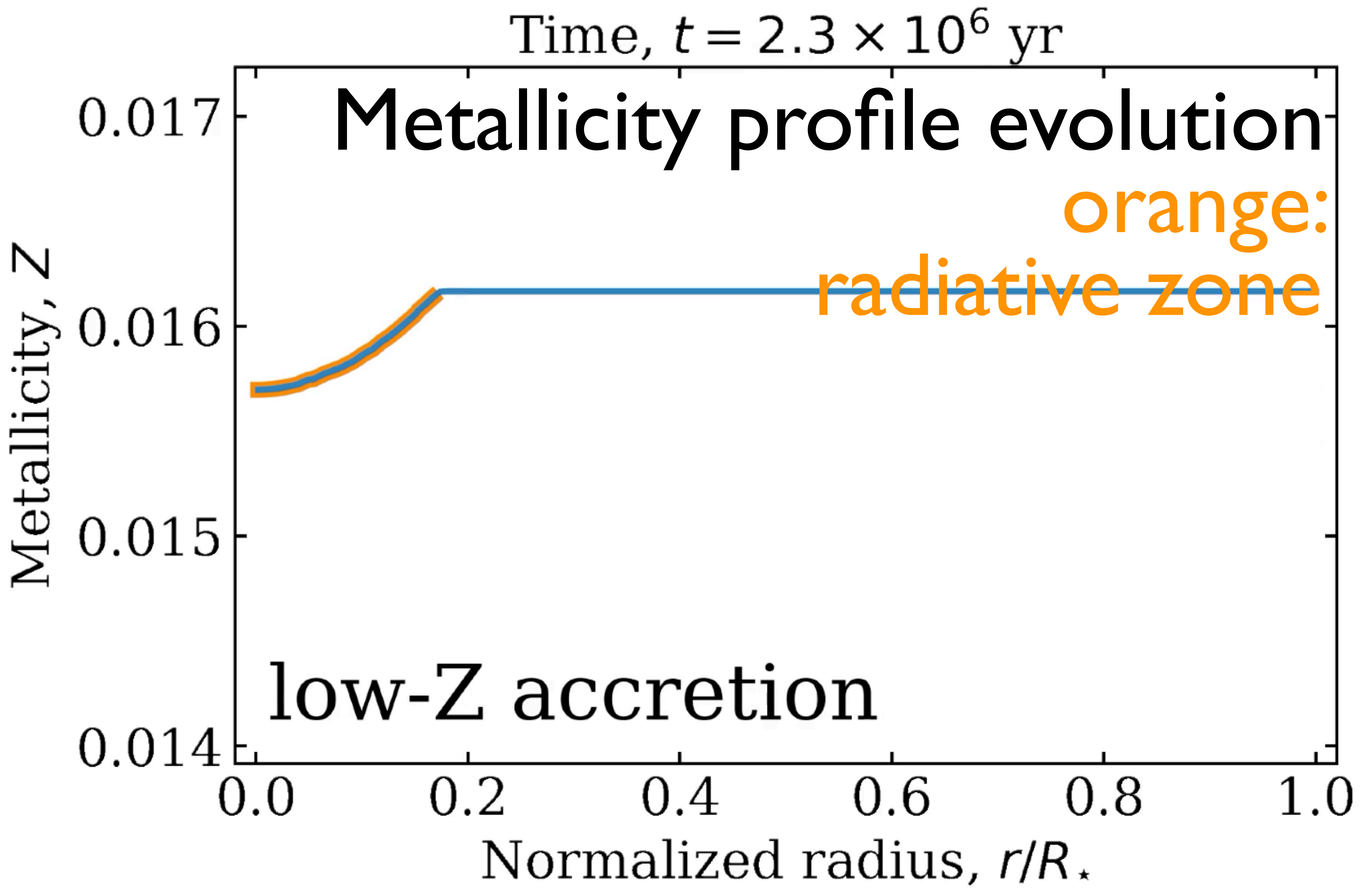
~cm dust rapidly fall

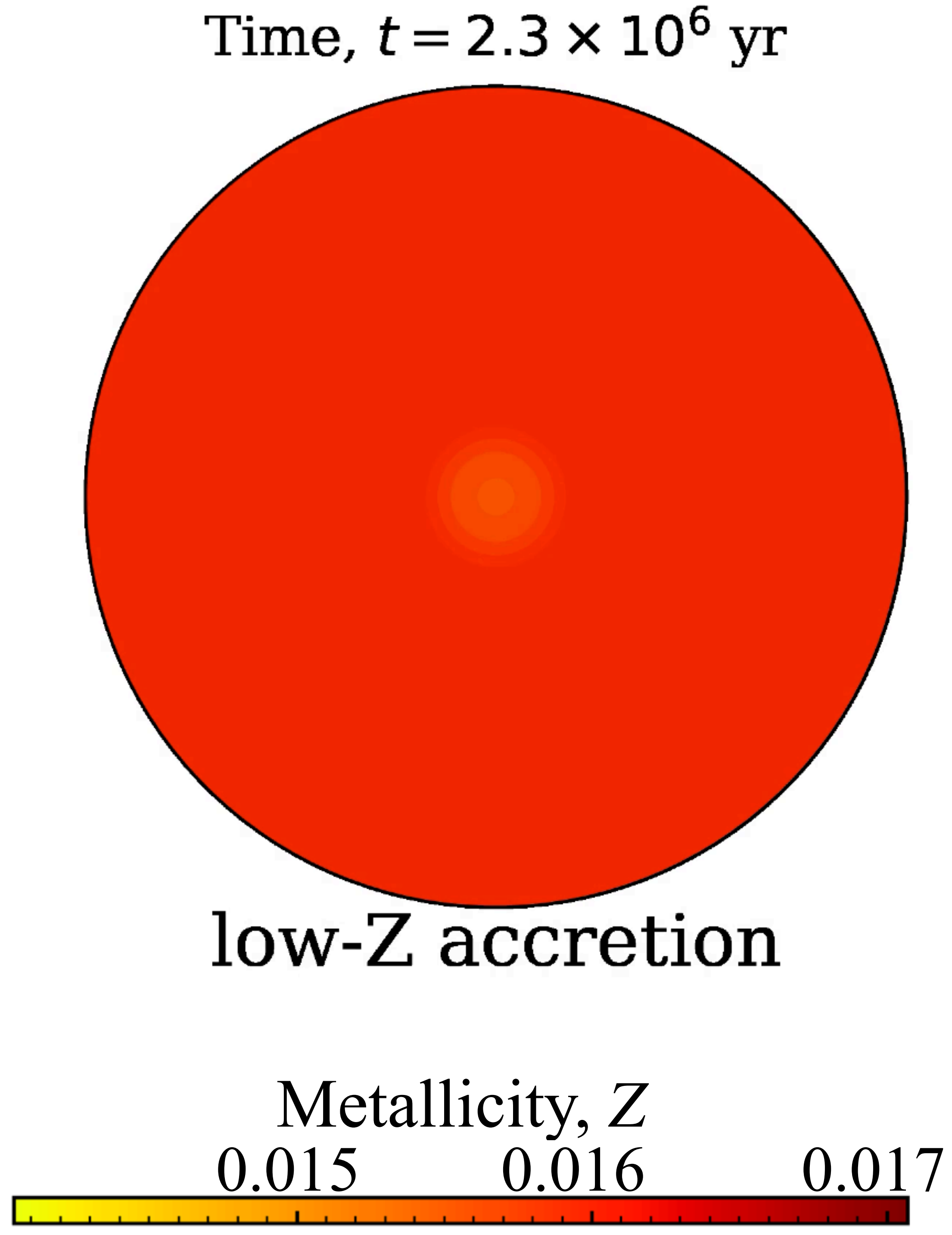
high-Z accretion + fully convective
→ high-Z from center to surface

What governs the central metallicity?

Central metallicity evolution



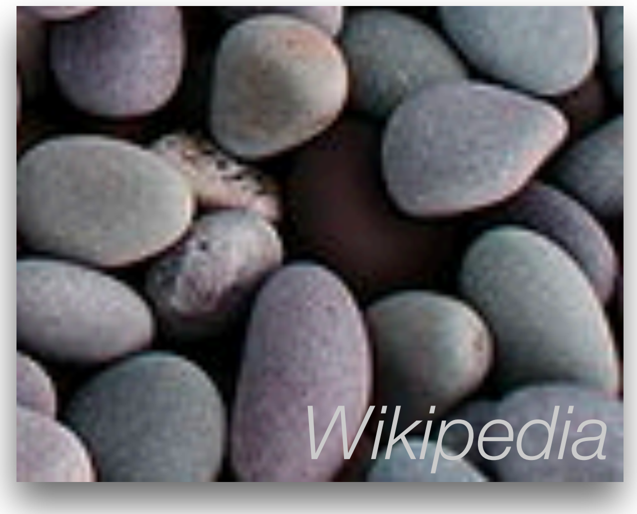




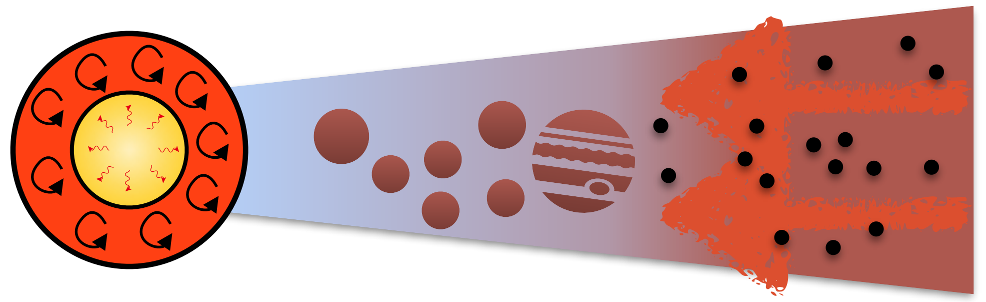
high-Z accretion | low-Z accretion

Radiative core develops

➔ central Z is preserved



pebble drift

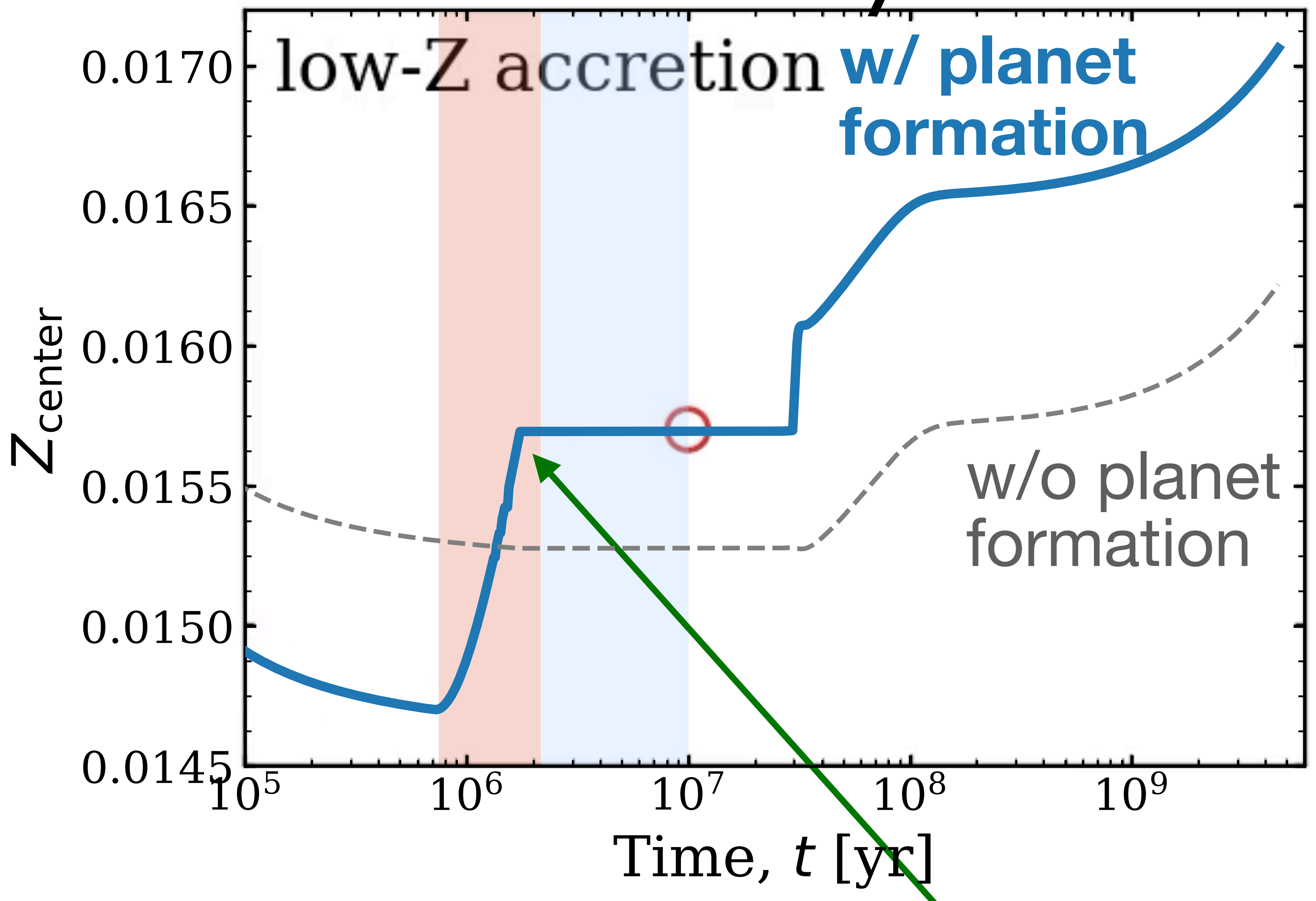


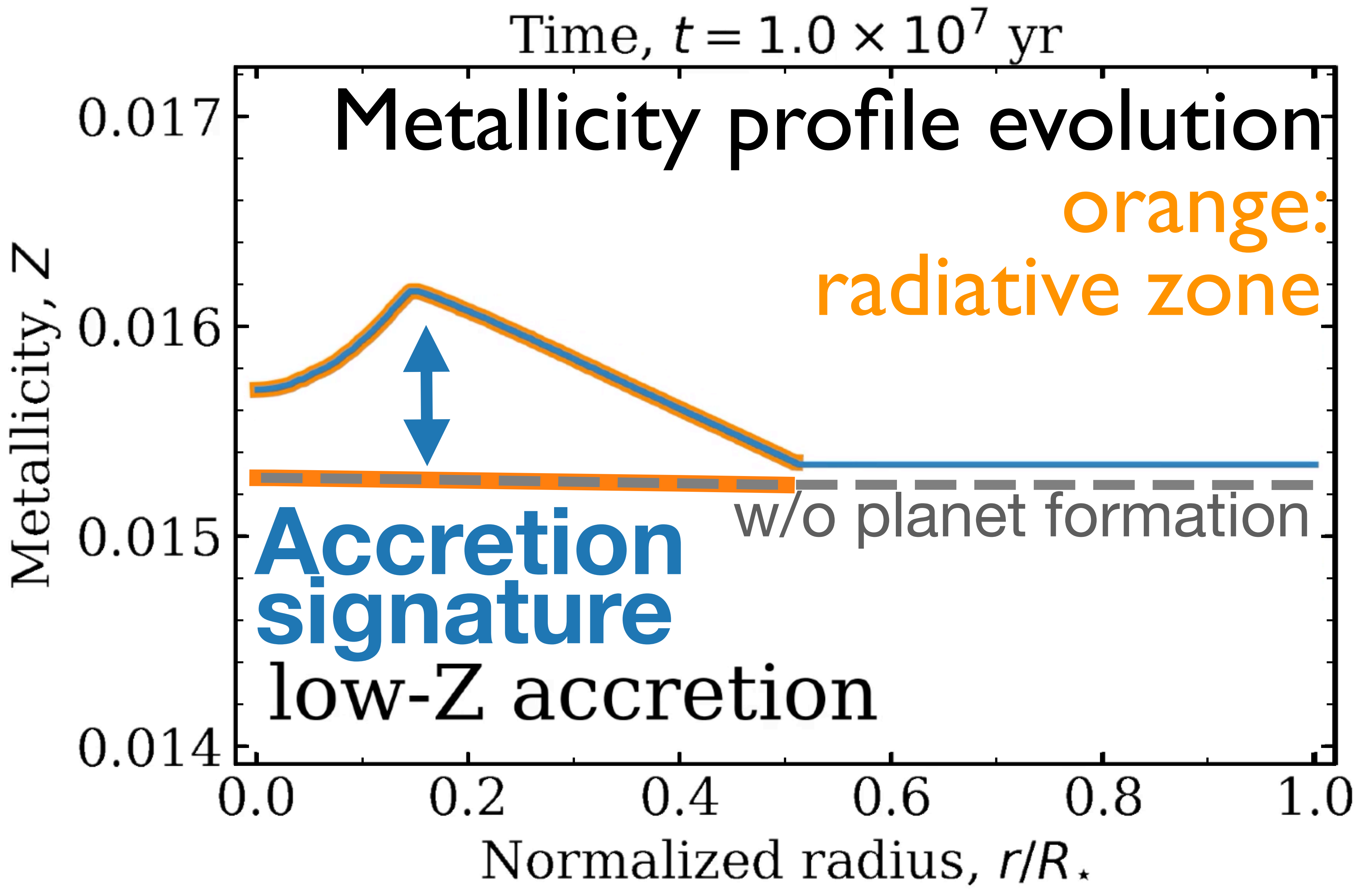
protoplanet formation & dust depletion

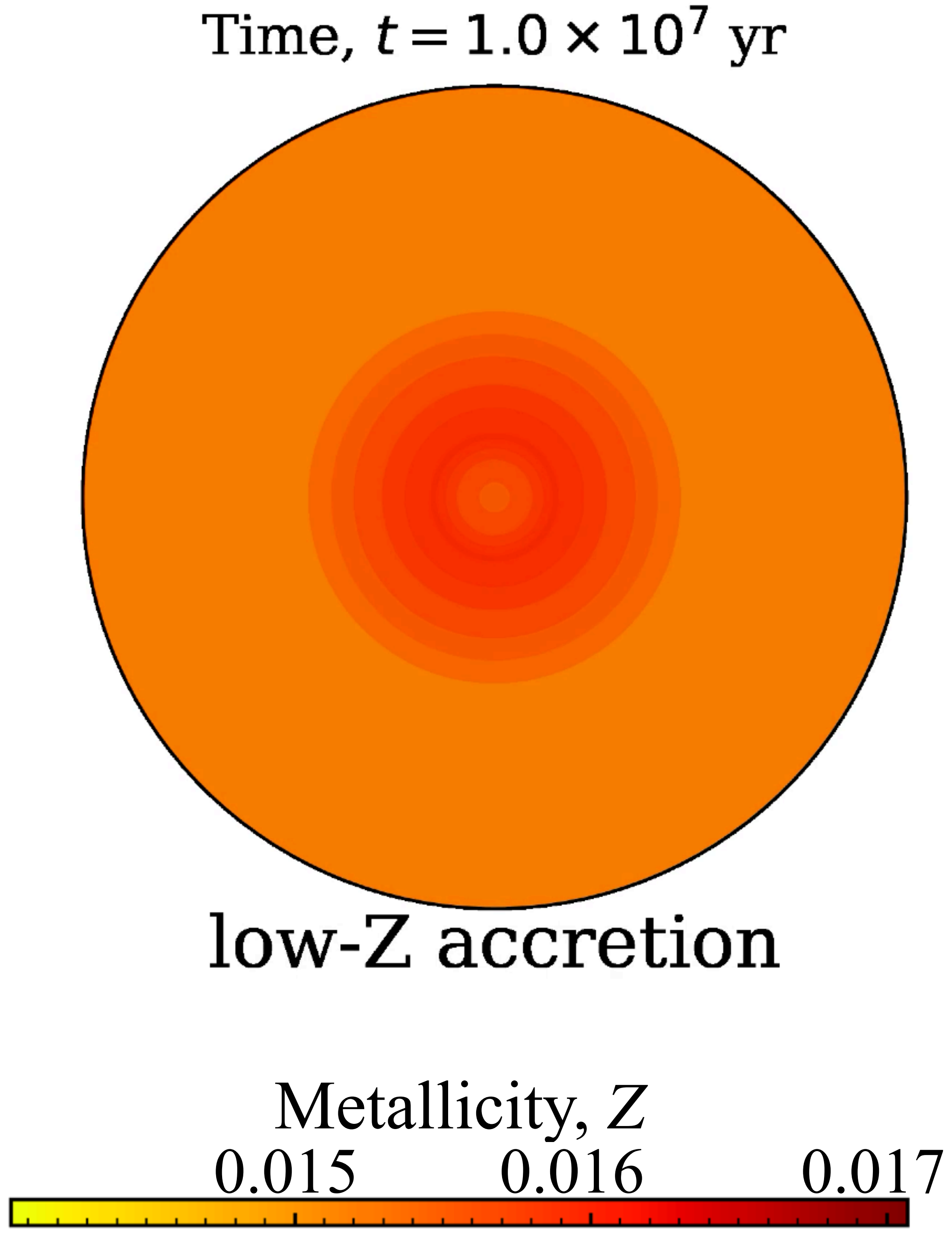
- **high-Z structure remains in the central radiative core**
- **low-Z accretion ➔ low-Z surface**

What governs the central metallicity?

Central metallicity evolution

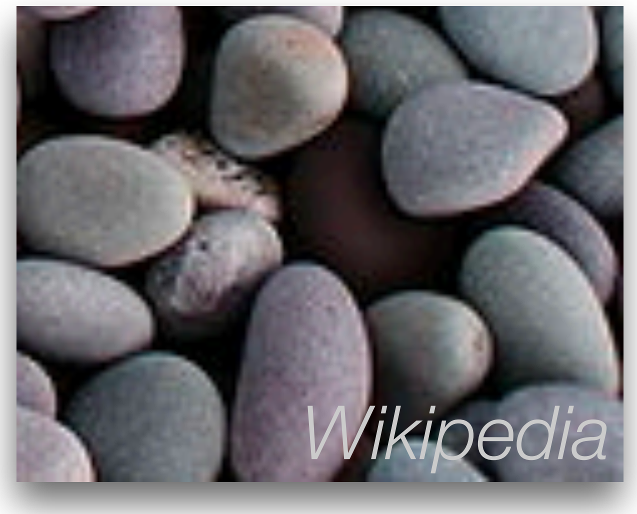






high-Z accretion | low-Z accretion

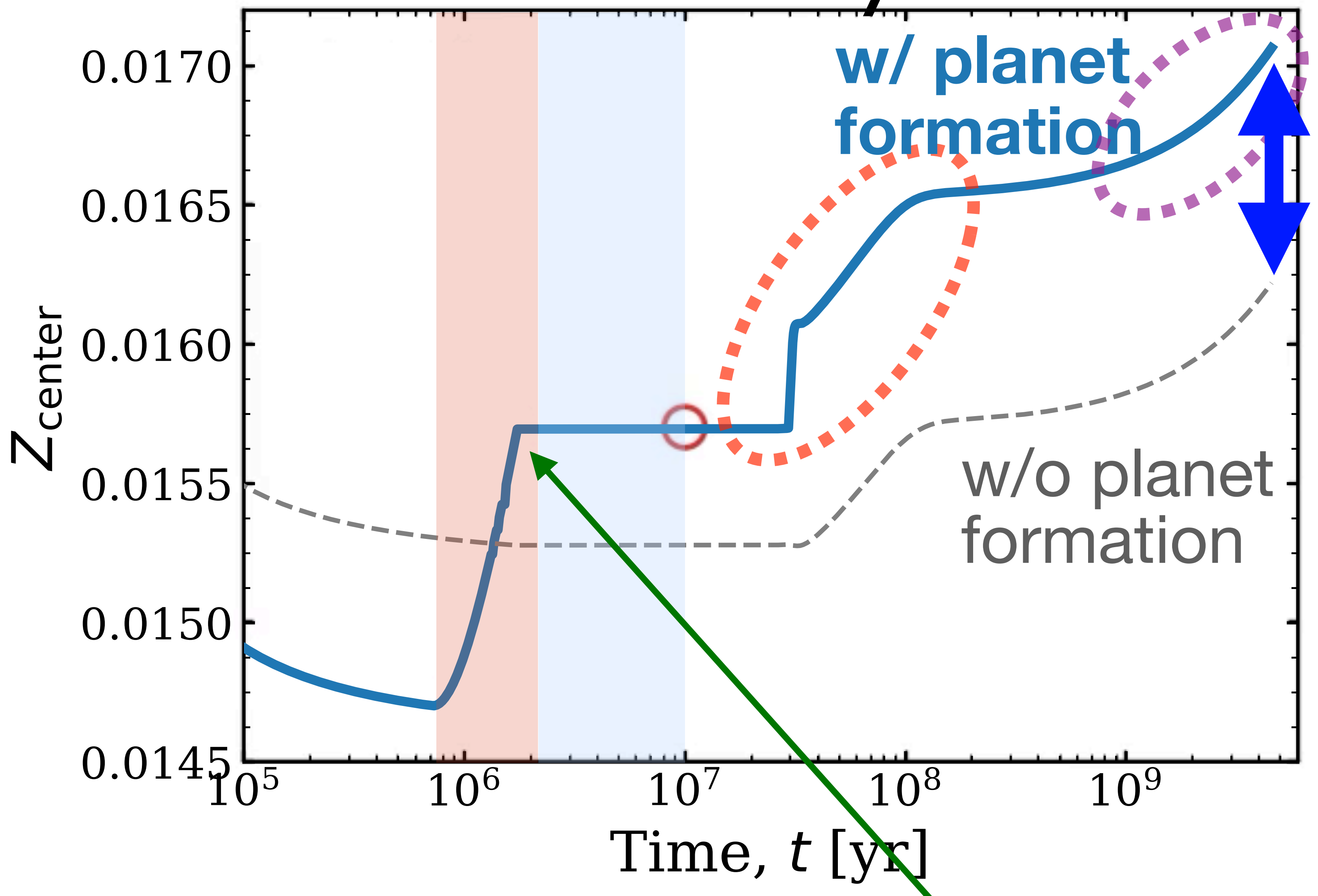
Radiative core develops
➔ central Z is preserved

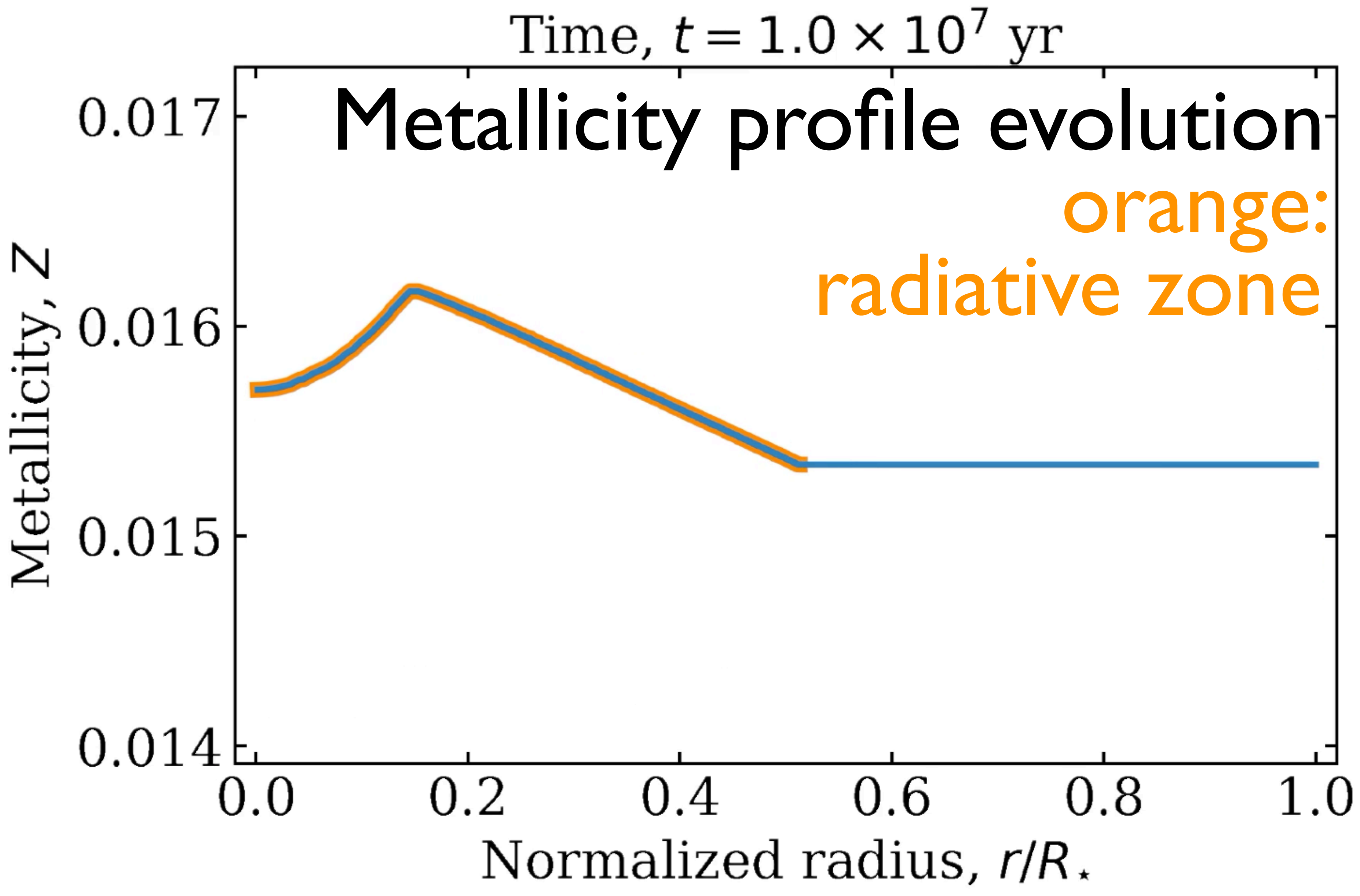


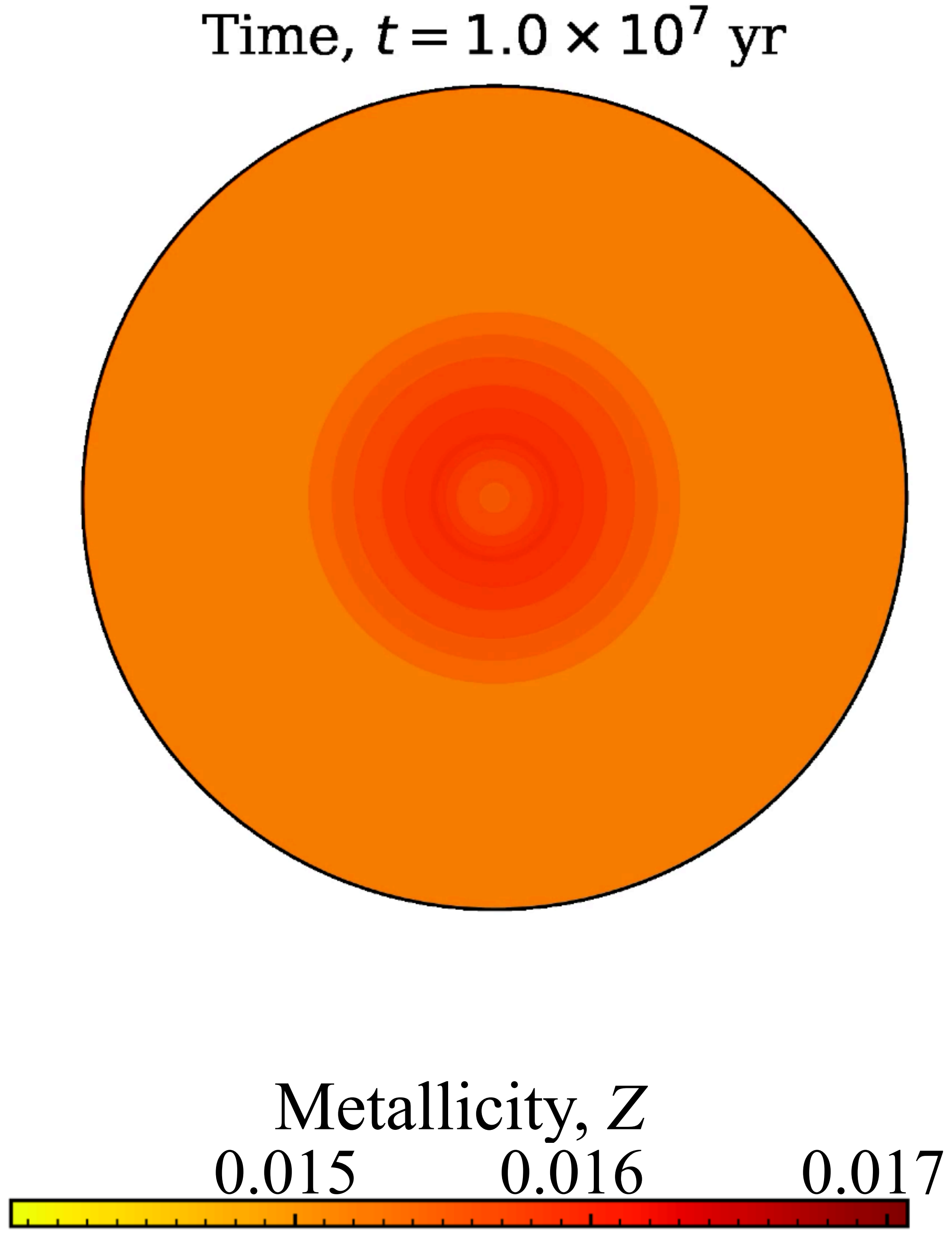
pebble drift

What governs the central metallicity?

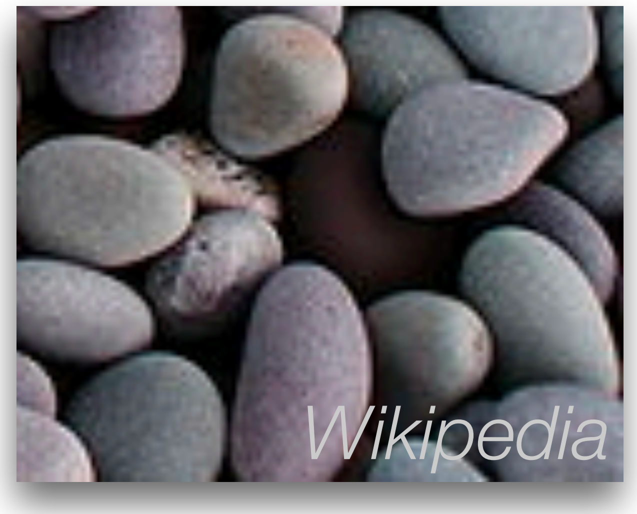
Central metallicity evolution







high-Z accretion **low-Z accretion**



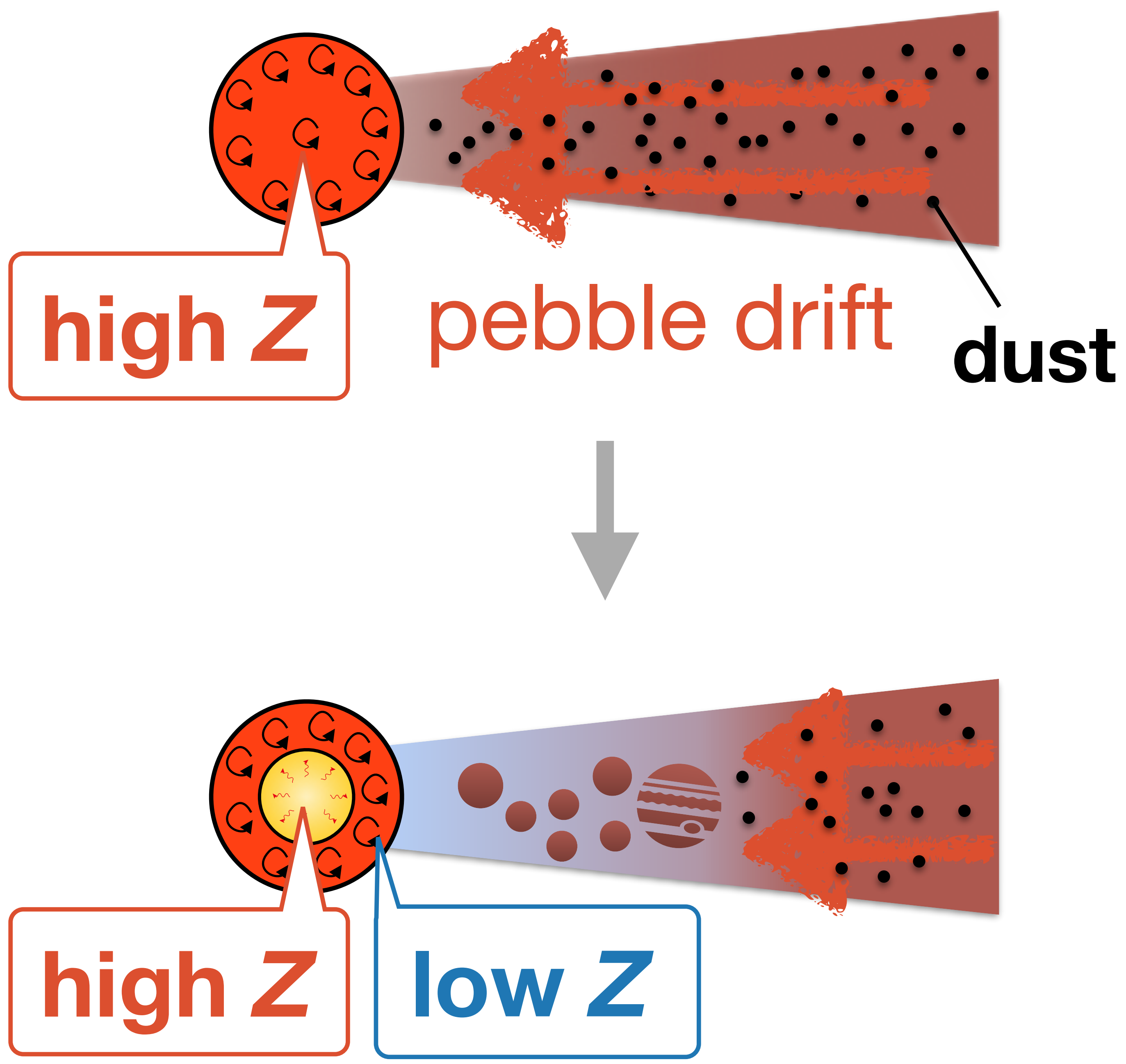
pebble drift

Radiative core develops
➔ central Z is preserved

"Incomplete CNO cycle" ($^{12}C + 2p \rightarrow {}^{14}N$)
➔ central Z increases & convective core

Gravitational settling ➔ central Z ↑ & surface Z ↓

What governs the central metallicity?



Early phase (≲1.7 Myr)

- **high-*Z* accretion** due to pebble drift
- **fully convective** proto-Sun

→ homogeneously **high-*Z* solar interior**

Late phase (2–10 Myr)

- **low-*Z* accretion** (e.g., dust depletion)

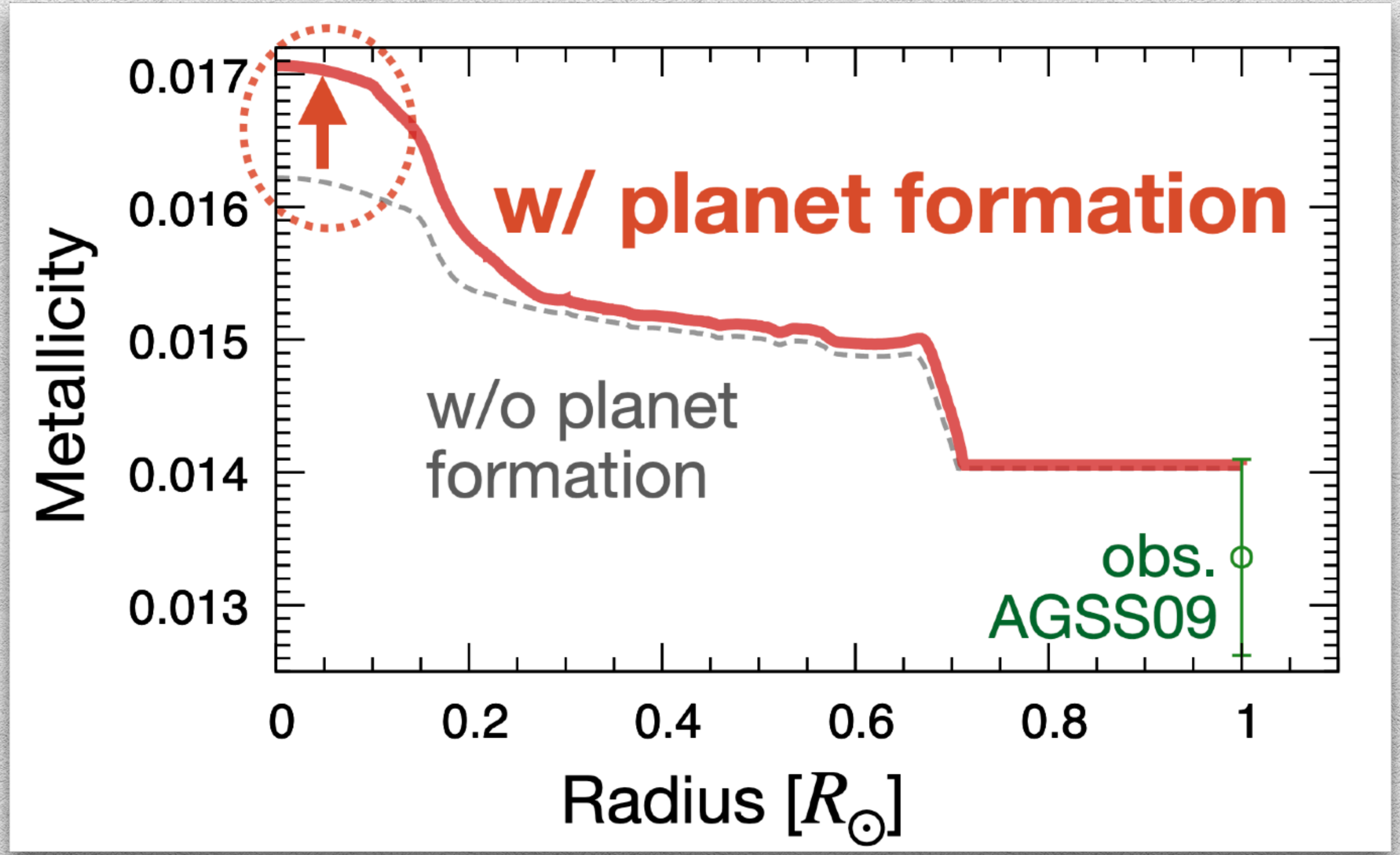
→ **low-*Z* solar surface**

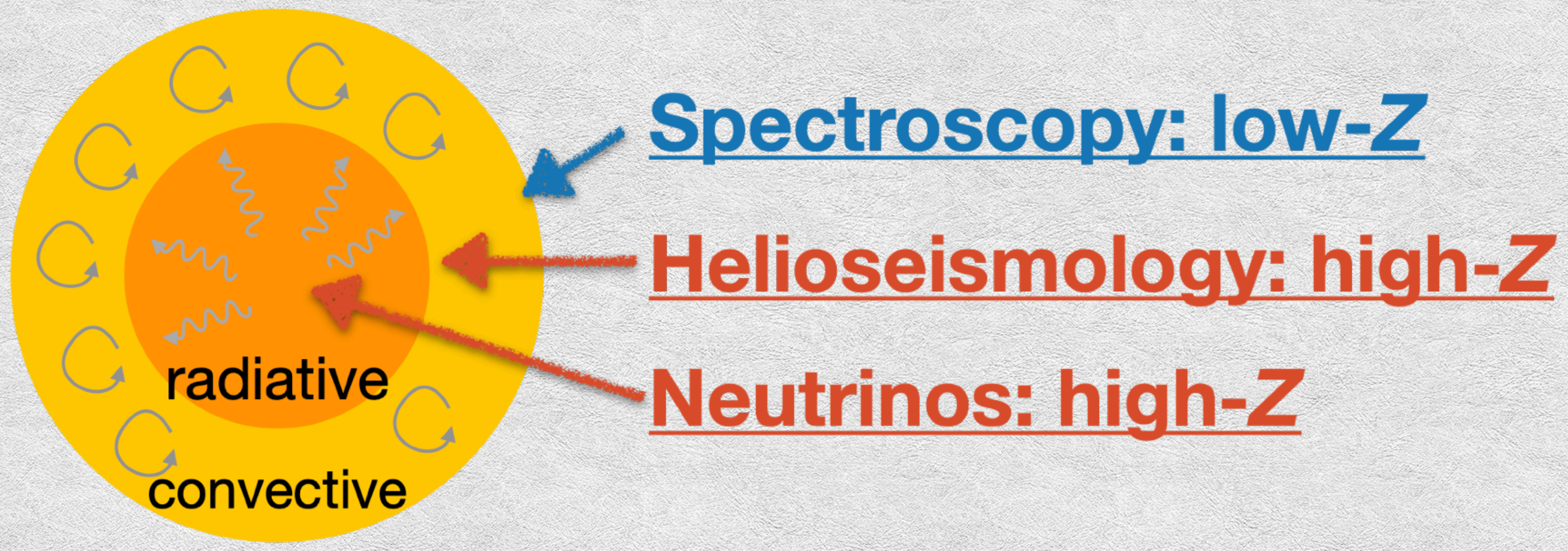
- central region becomes **radiative**

→ **high-*Z* core** remains

composition gradient!

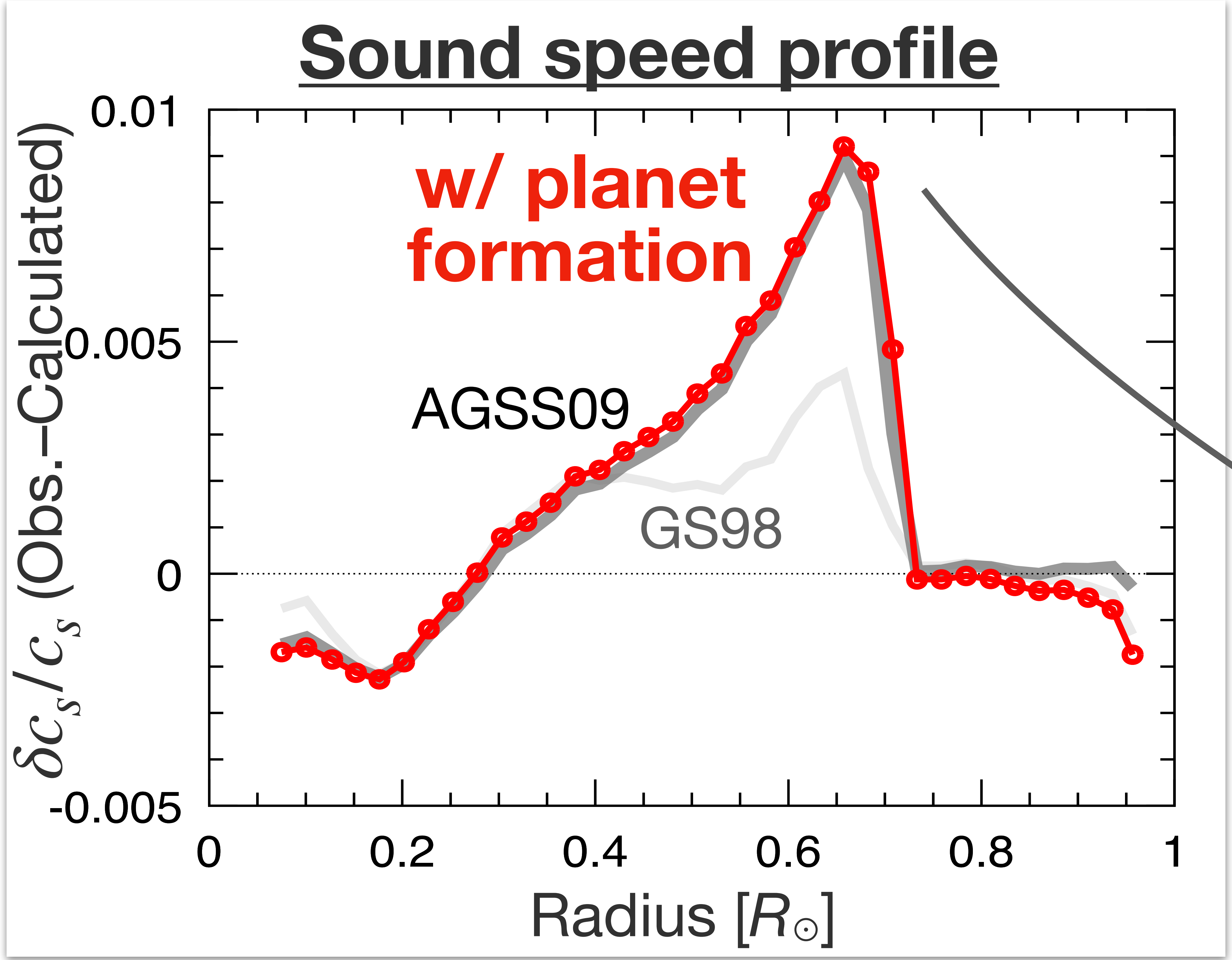
only in the radiative central region





Does the compositional gradient affect the sound speed profile and neutrino fluxes?

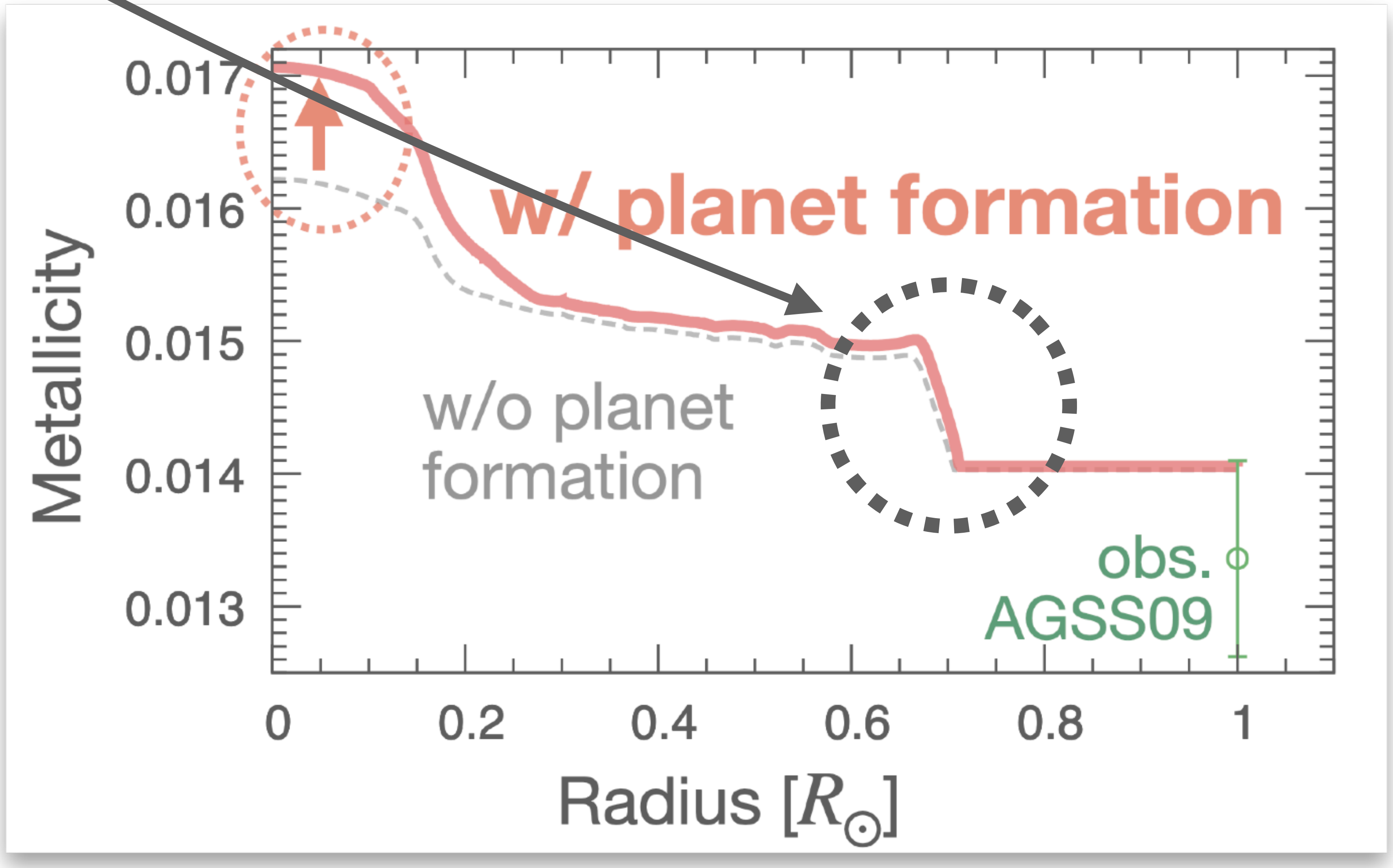
Sound speed profile is not affected



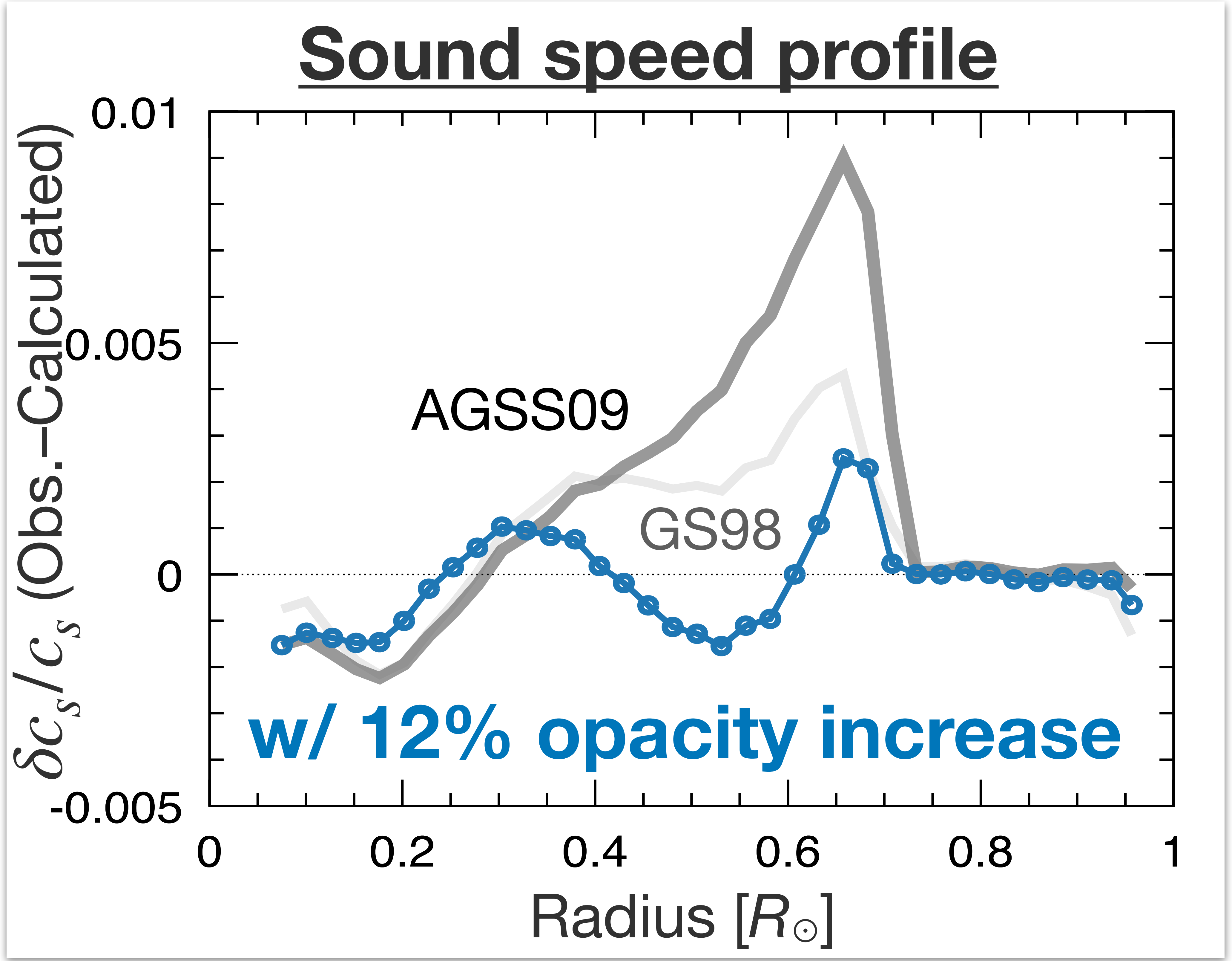
Kunitomo+Guillot 2021

The sound speed anomaly at ~0.7 $R_\odot$ is not improved

Planet formation processes affect composition only in the central region



Opacity increase improves the c_s profile



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Planet formation processes affect composition only in the central region

~12–18% opacity increase improves the profile even better than the GS98 SSM

Compatible with the recent experiments

Bailey+2015, Nagayama+2019

see also Christensen-Dalsgaard+2009, 2010, Serenelli+2009, Villante 2010, Buldgen+2019

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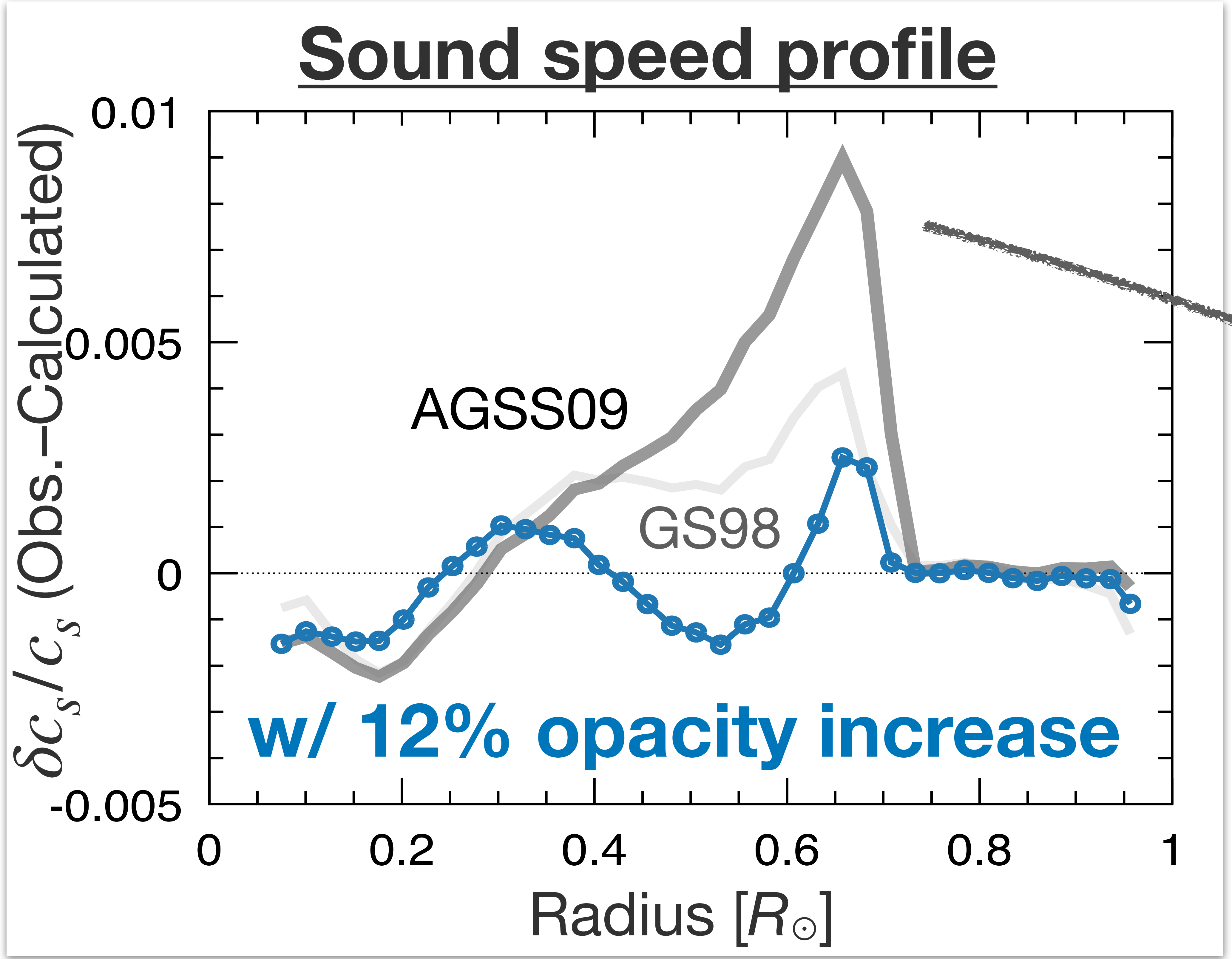

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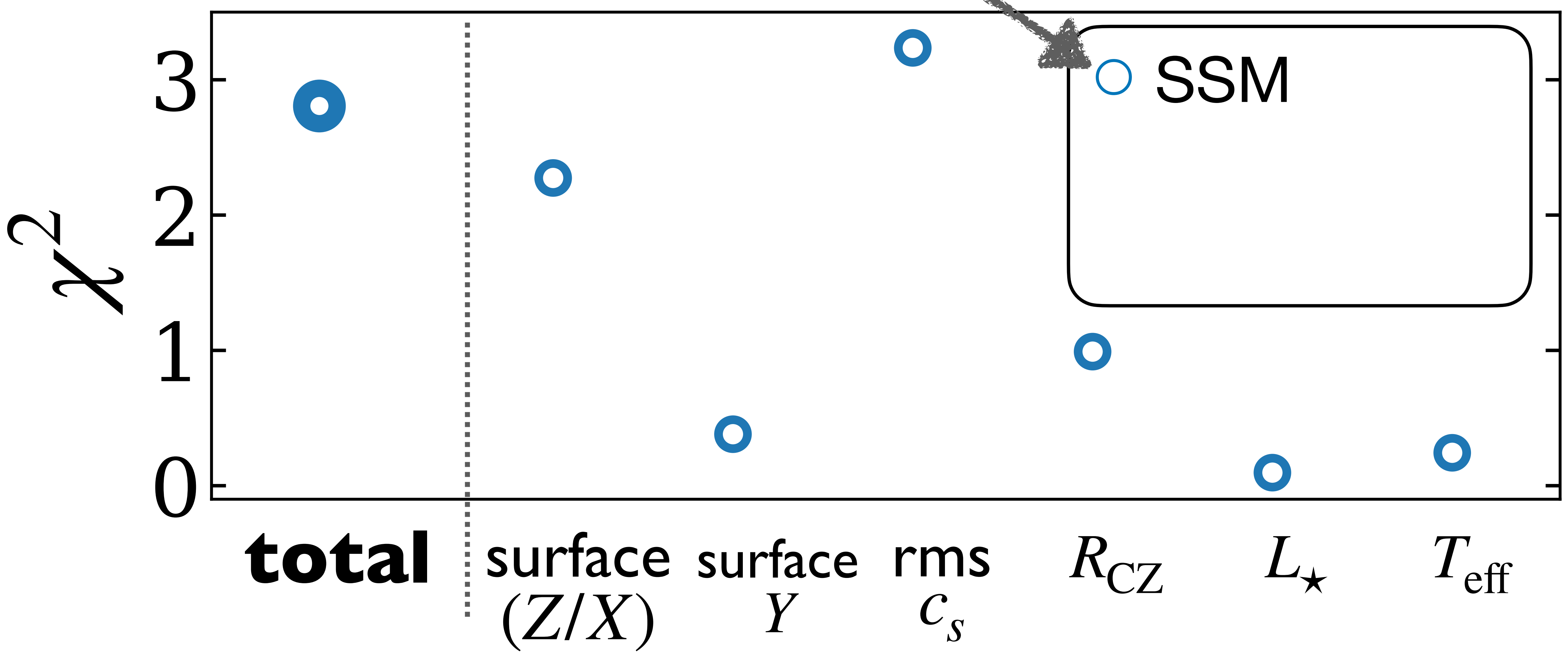

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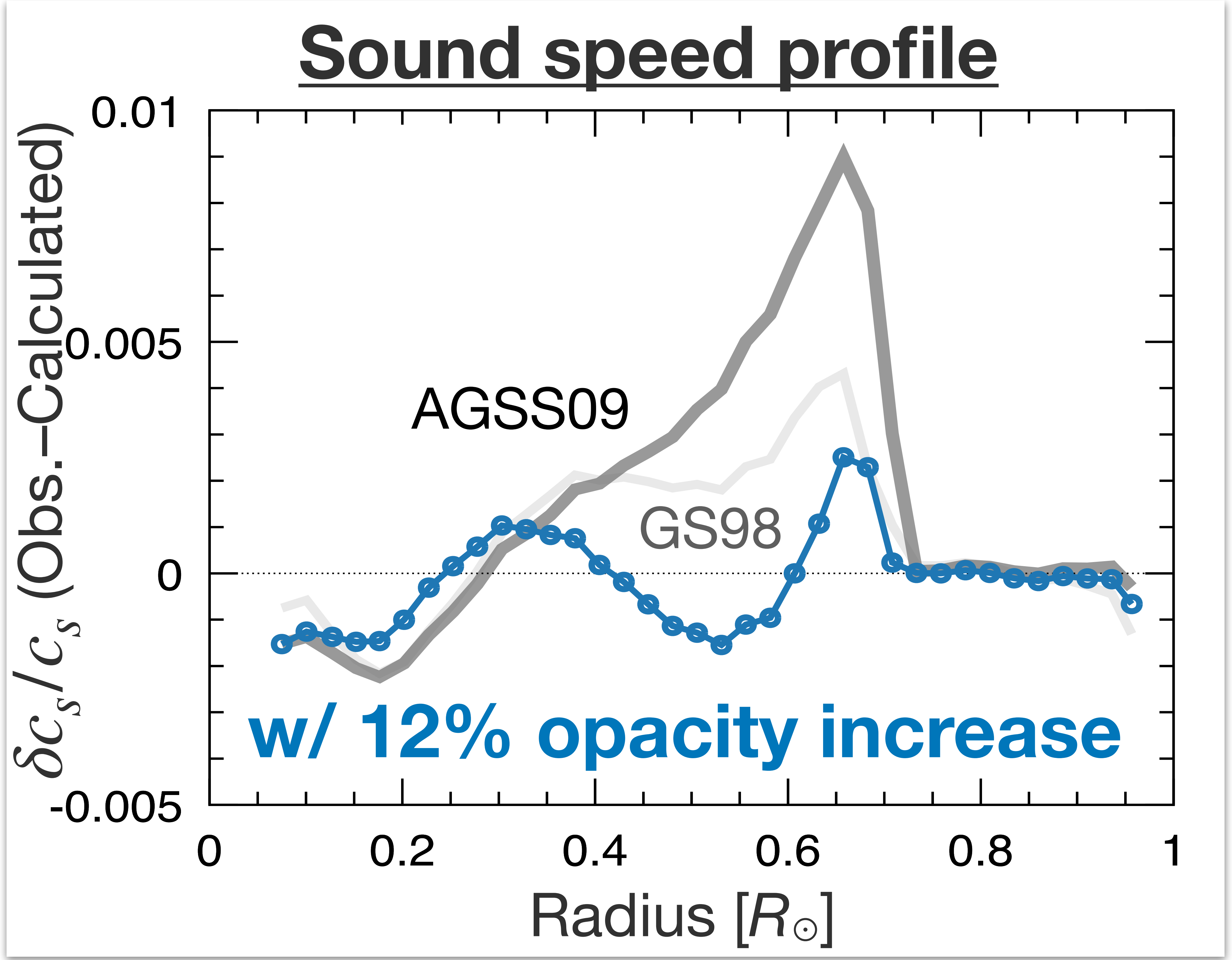

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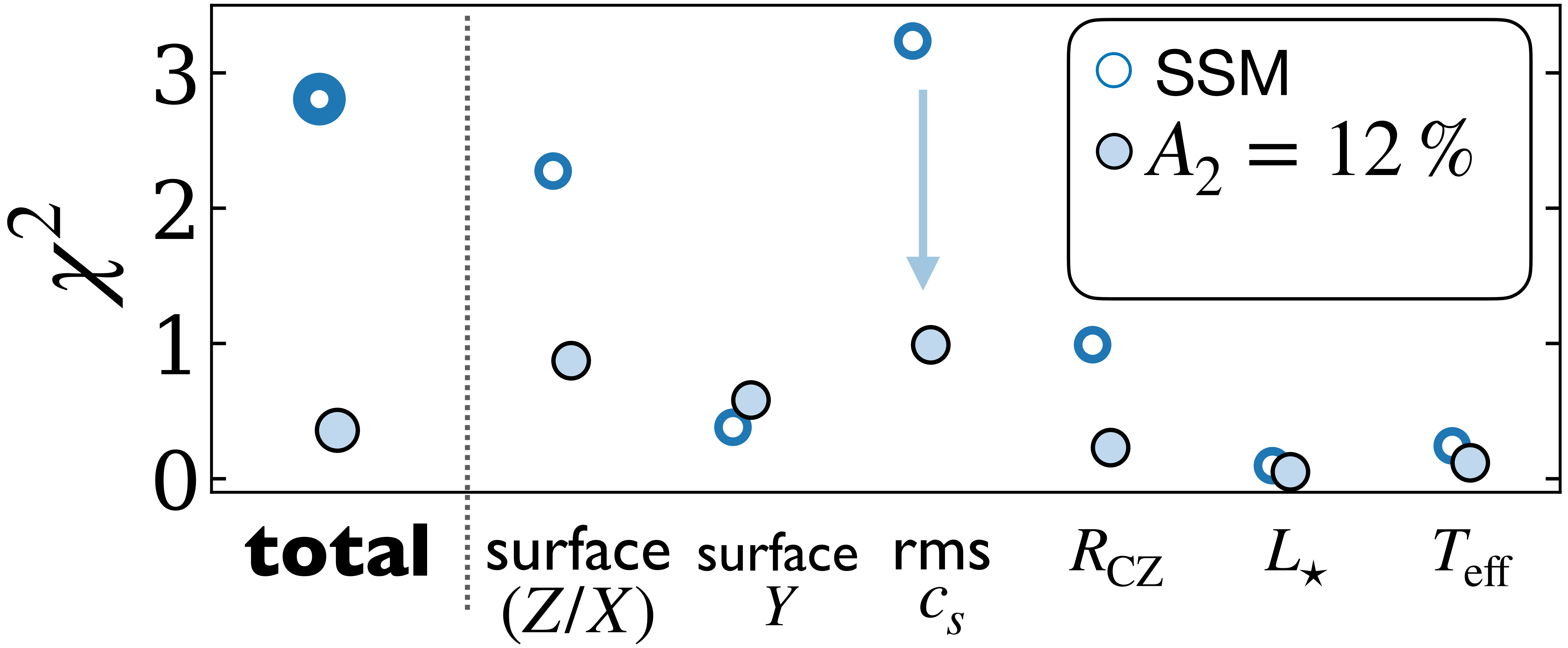

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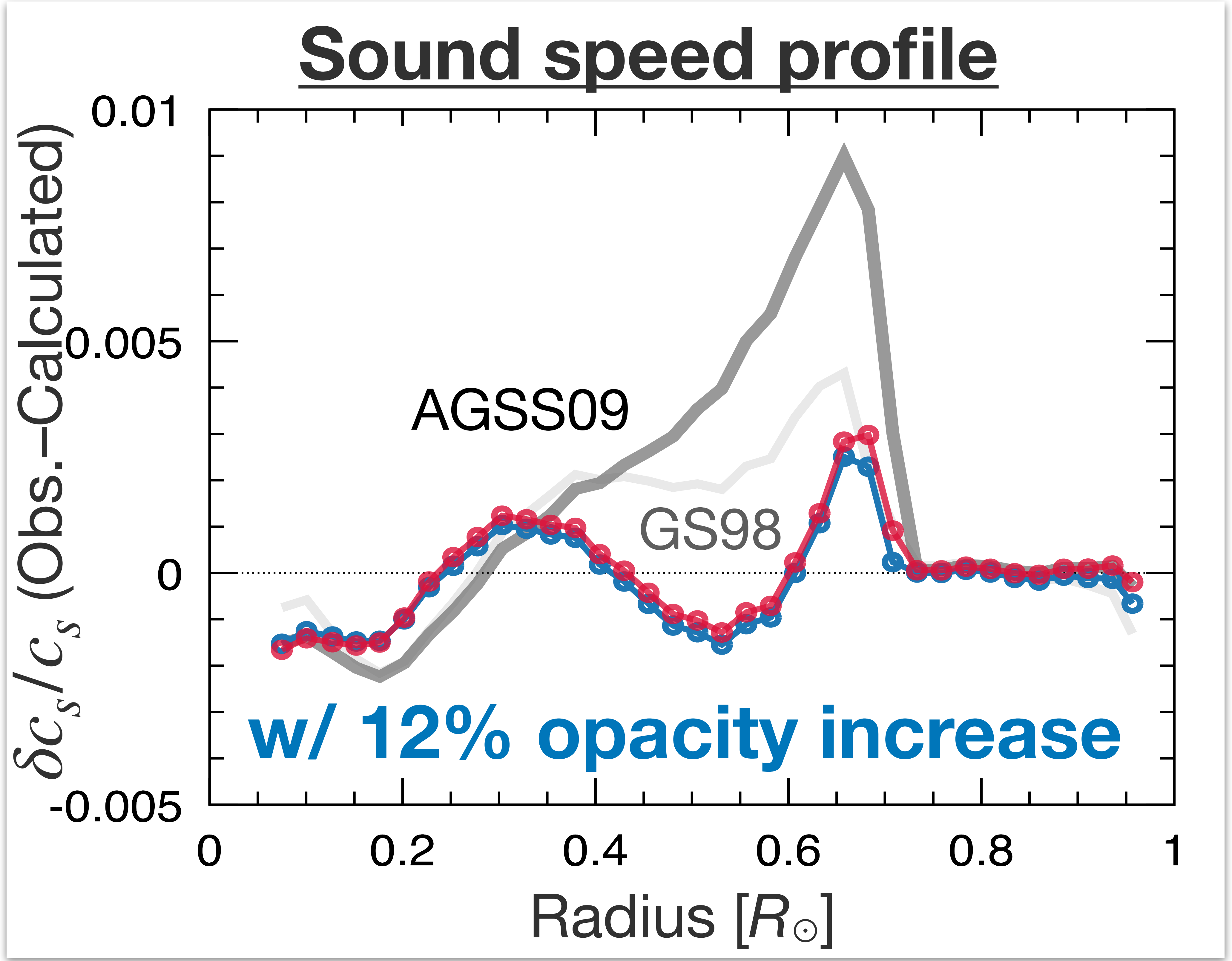

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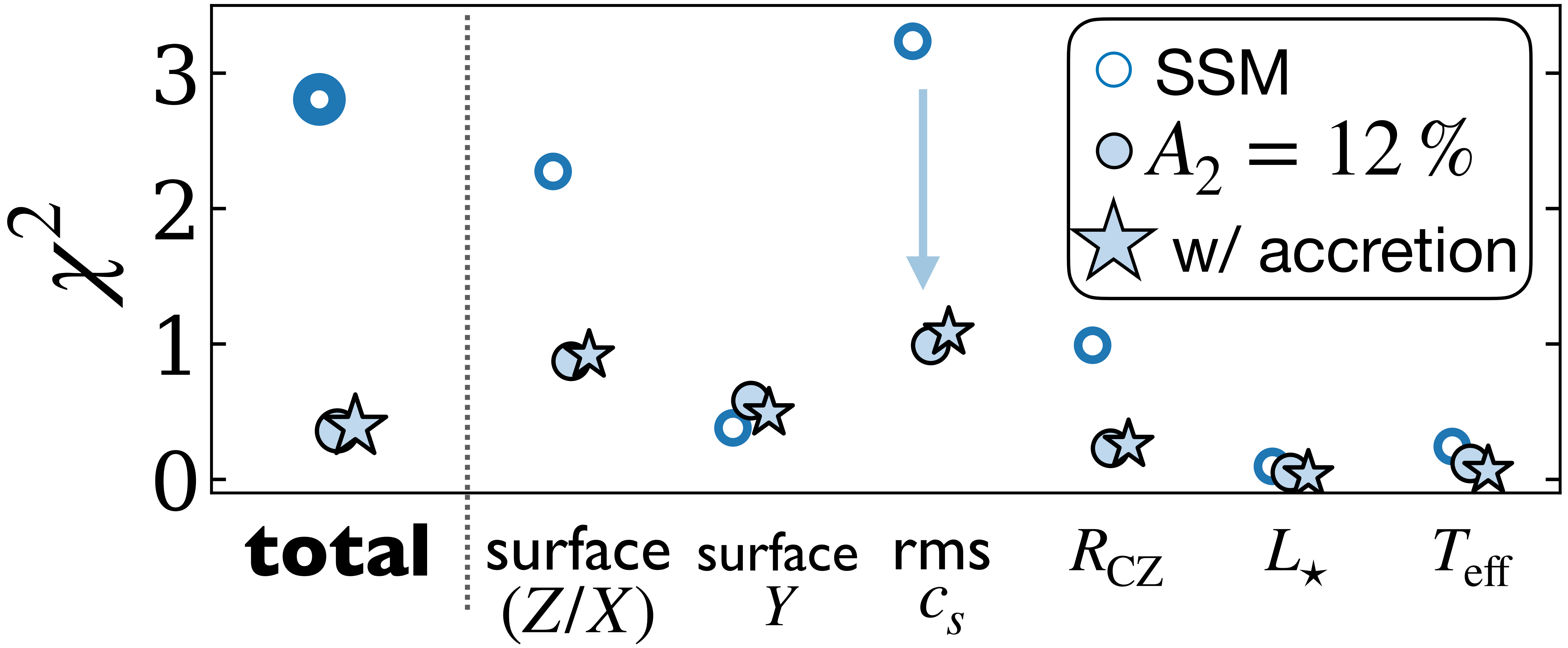
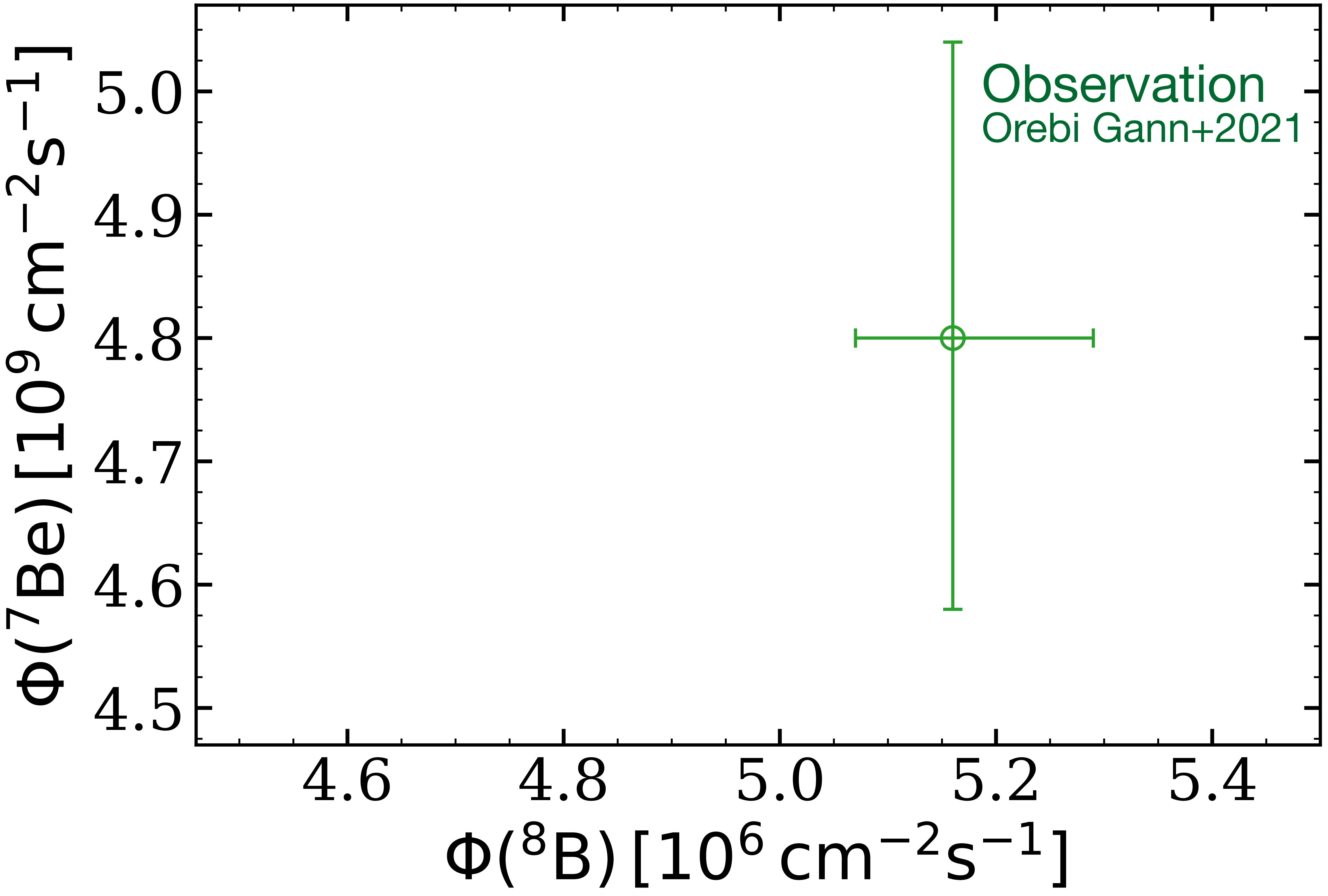
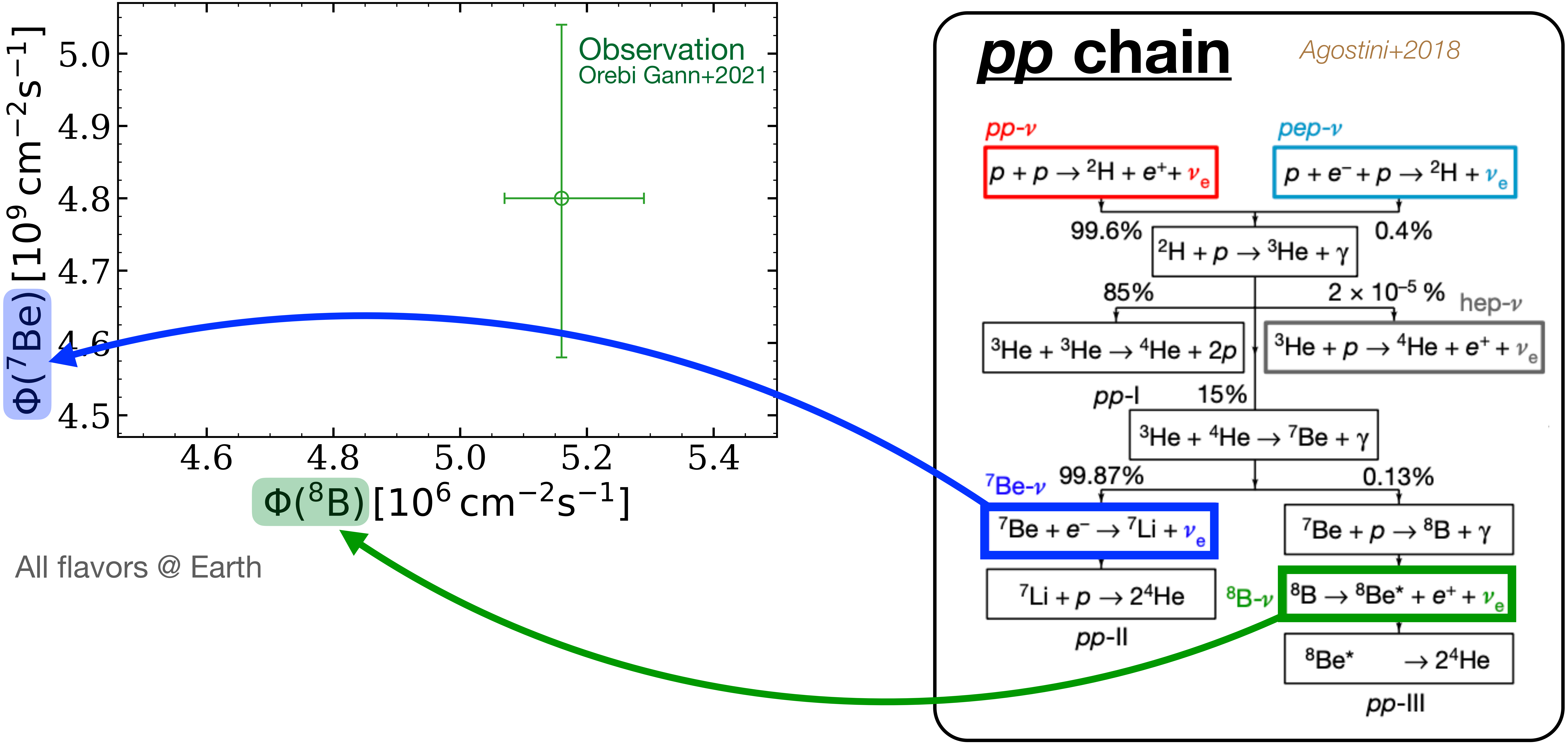


Planet formation affects neutrino fluxes



All flavors @ Earth

Planet formation affects neutrino fluxes



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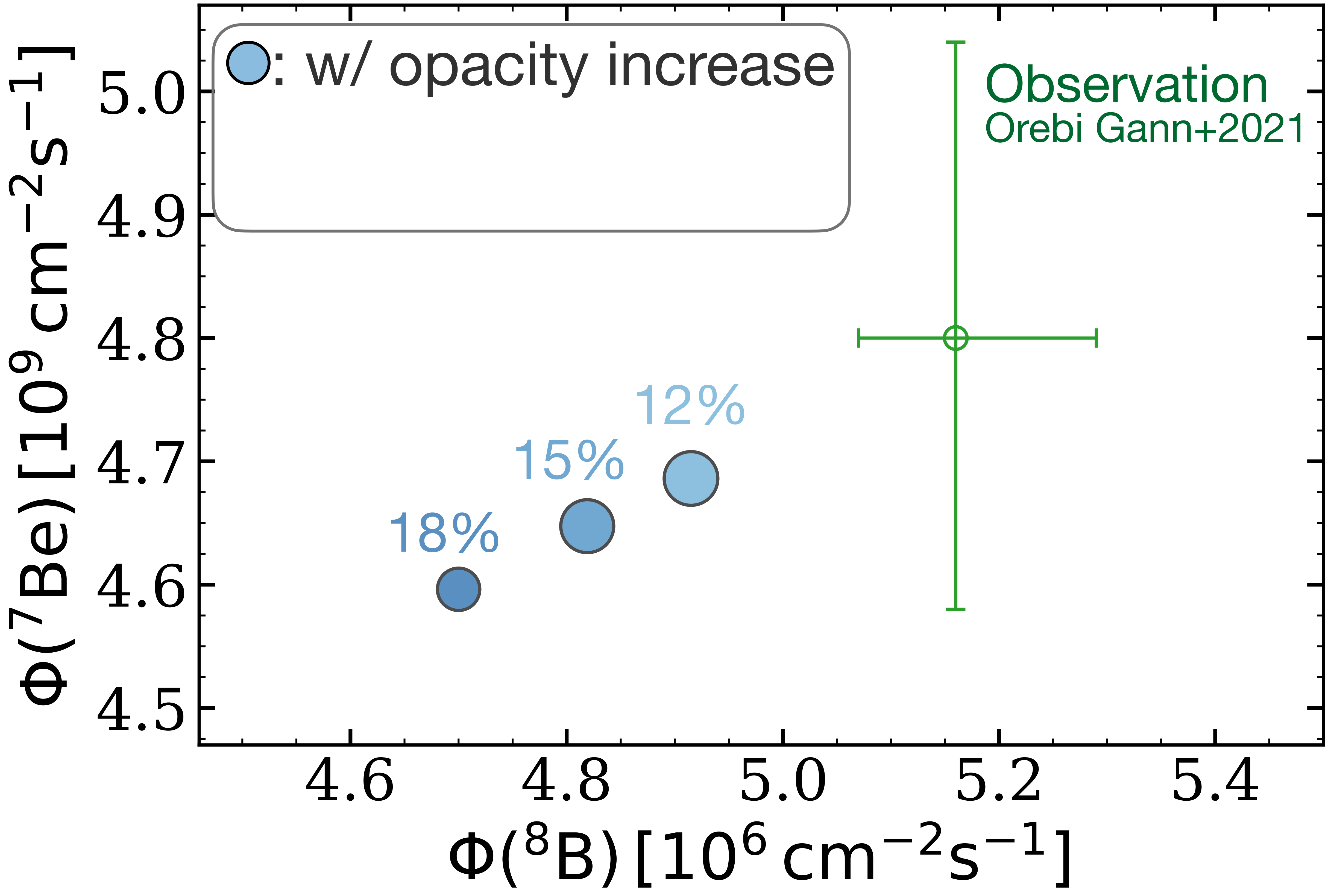


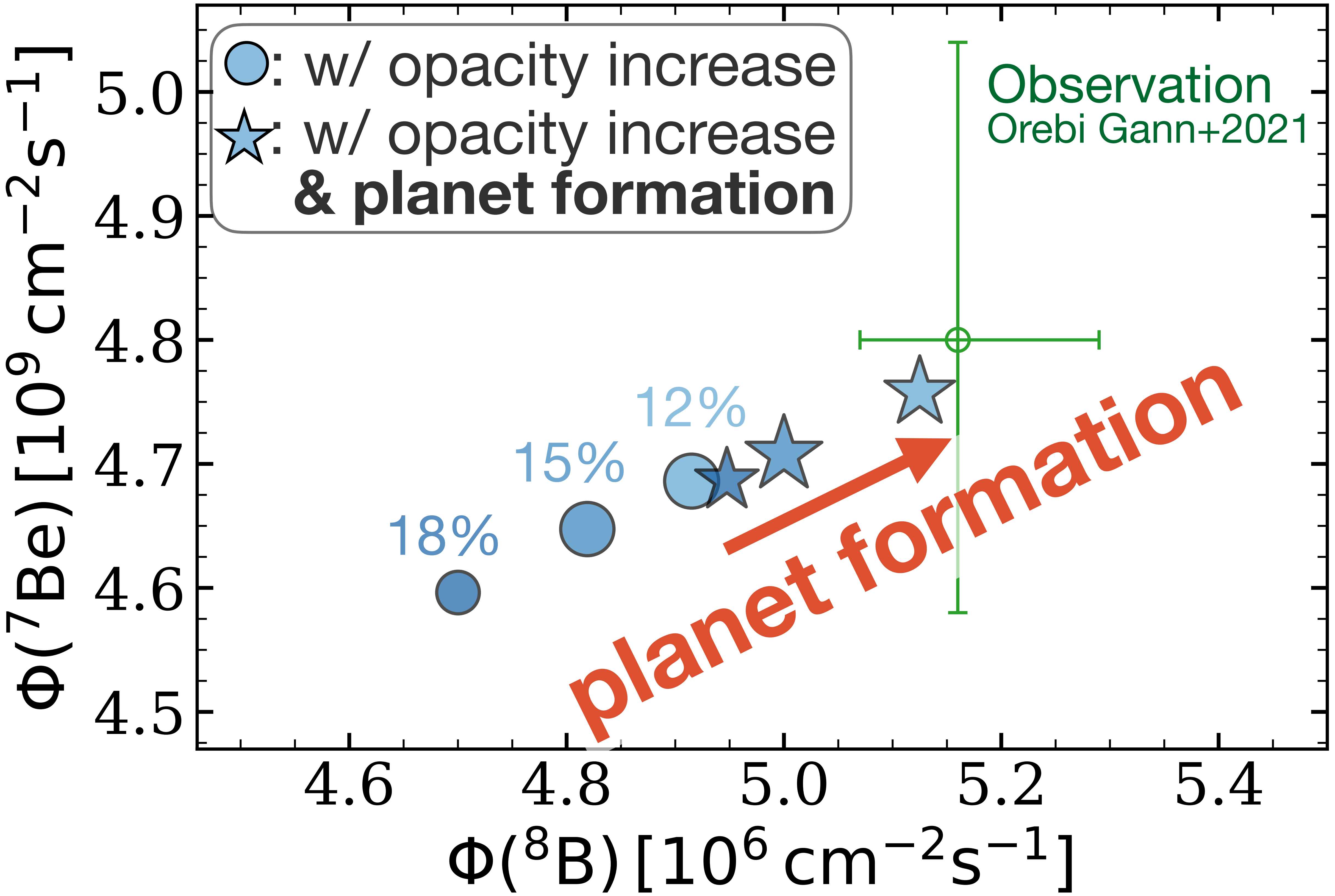
All flavors @ Earth

- With ~**12–18% opacity increase**, helioseismic and spectroscopic observations are well reproduced ($\chi^2 \lesssim$ **0.5**)

  Kunitomo+Guillot 2021; see also Bahcall+2005, Christensen-Dalsgaaard+2009, Bailey+2015, Buldgen+2019

- However, inconsistent with neutrino observation

Planet formation affects neutrino fluxes



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- However, inconsistent with neutrino observation

- Planet formation processes increase neutrino fluxes

→ consistent with neutrino obs.!

see also Serenelli+2011, Zhang+2019

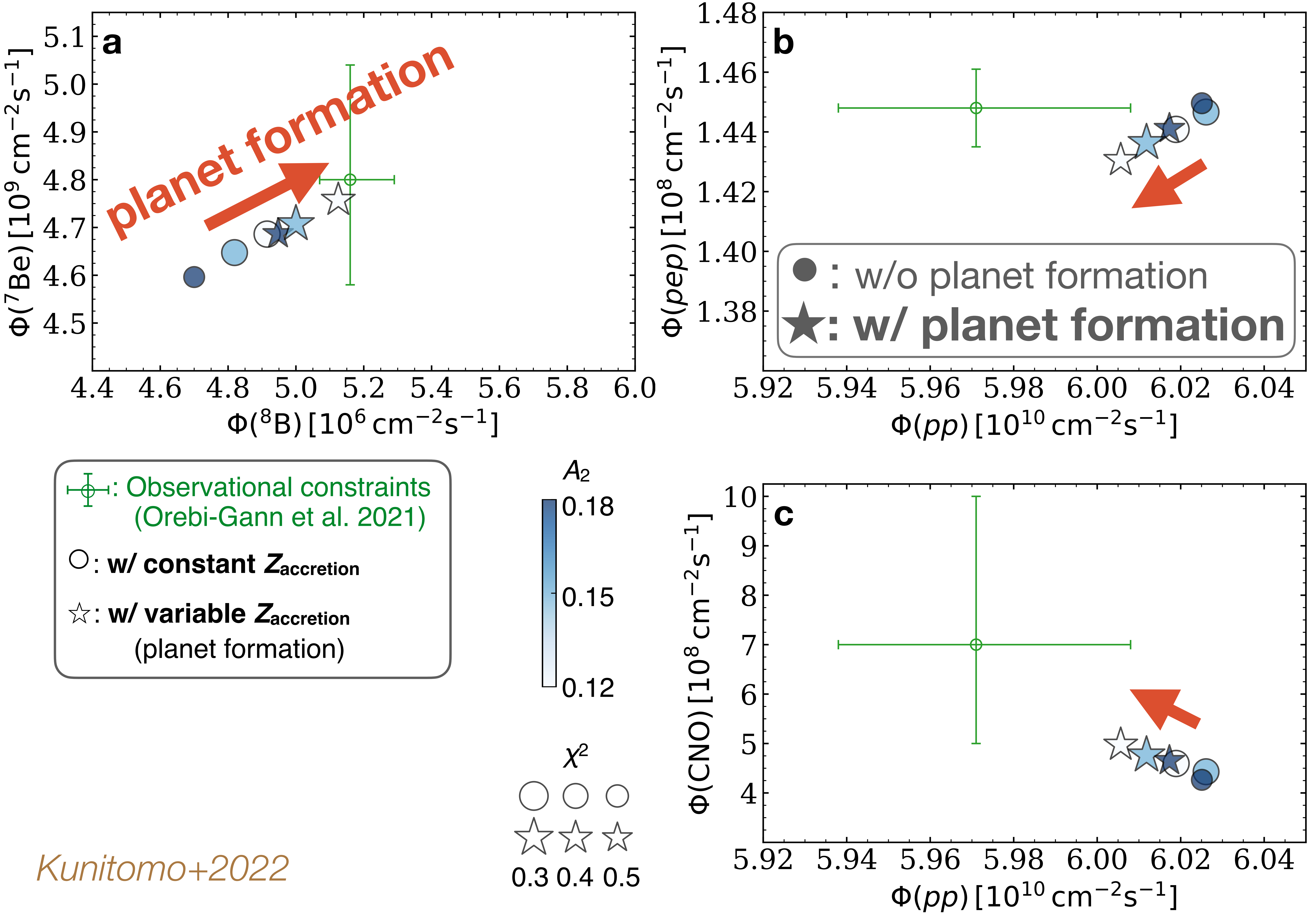
All flavors @ Earth

Kunitomo+2022

Neutrino, helioseismic & spectroscopic observations can be reproduced

Solar abundance problem can be solved by **star & planet formation processes**

Planet formation affects neutrino fluxes



Kunitomo+2022

- Higher ^{8}B, ^{7}Be, CNO and lower *pp*, *pep* fluxes due to planet formation processes

  see also Serenelli+2011, Zhang+2019

- **All the observed fluxes are reproduced within ~1σ**

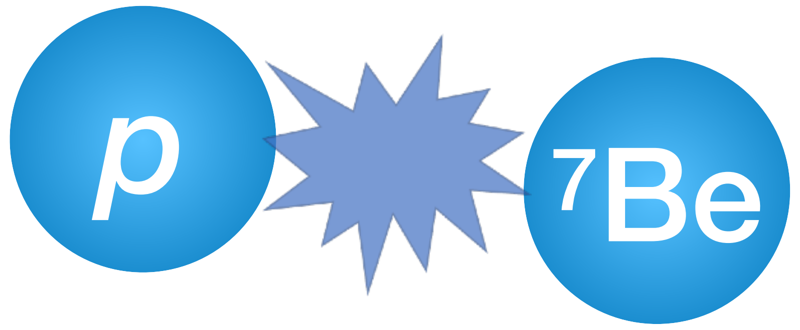
Why does planet formation affect neutrinos?

Neutrino fluxes
(= nuclear reaction rates) strongly
depend on **temperature**

$$\Phi(^8\mathrm{B}) \propto T_{\mathrm{center}}^{25}$$
$$\Phi(^7\mathrm{Be}) \propto T_{\mathrm{center}}^{11}$$
$$\Phi(\mathrm{CNO}) \propto T_{\mathrm{center}}^{20}$$

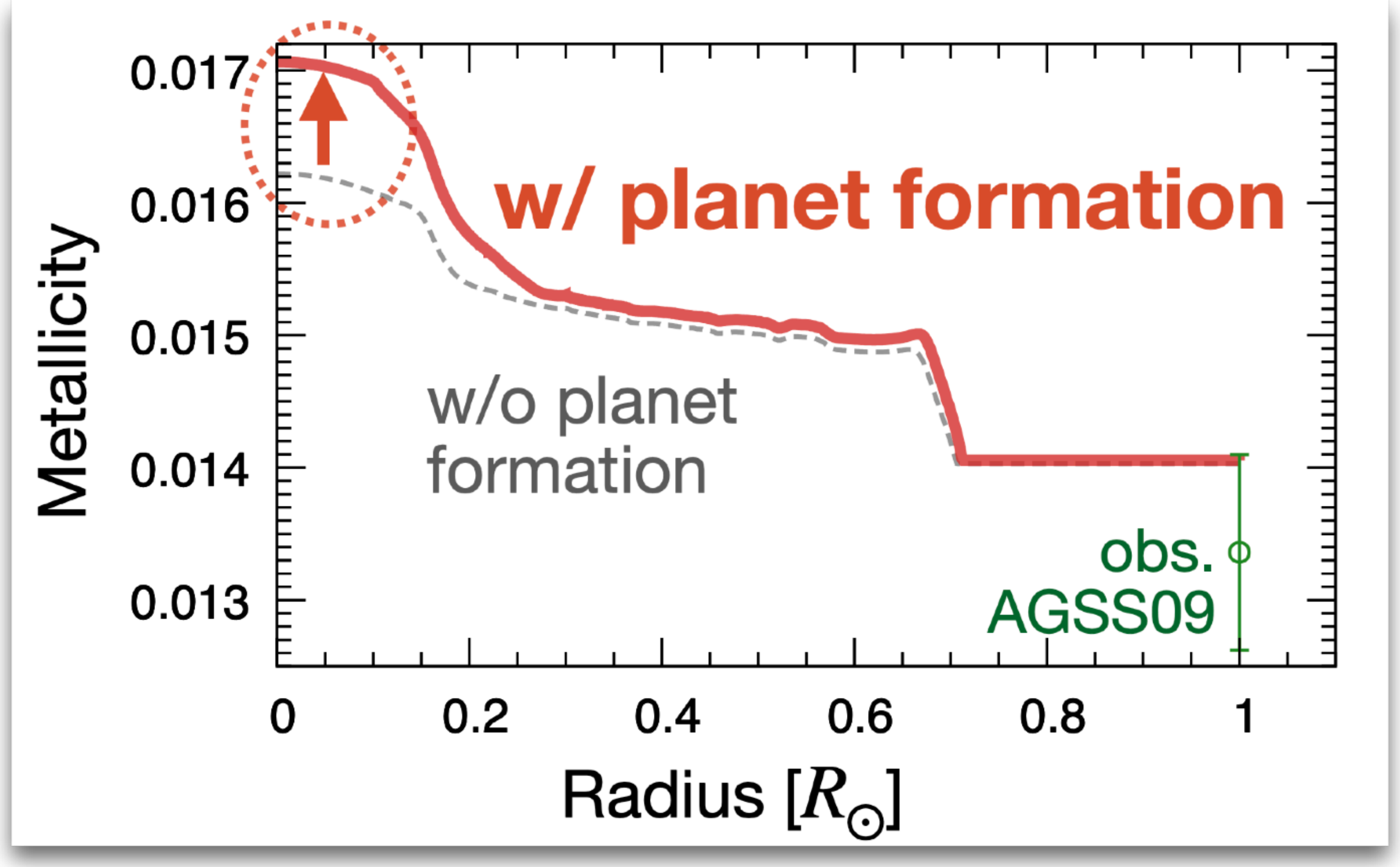
Bahcall+Ulmer1996

thermal energy ~ keV (~10^7 K)



~MeV Coulomb barrier vs **tunnel effect**

Planet formation processes induces
higher central metallicity
→ higher opacity
→ **higher temperature**
→ higher neutrino fluxes

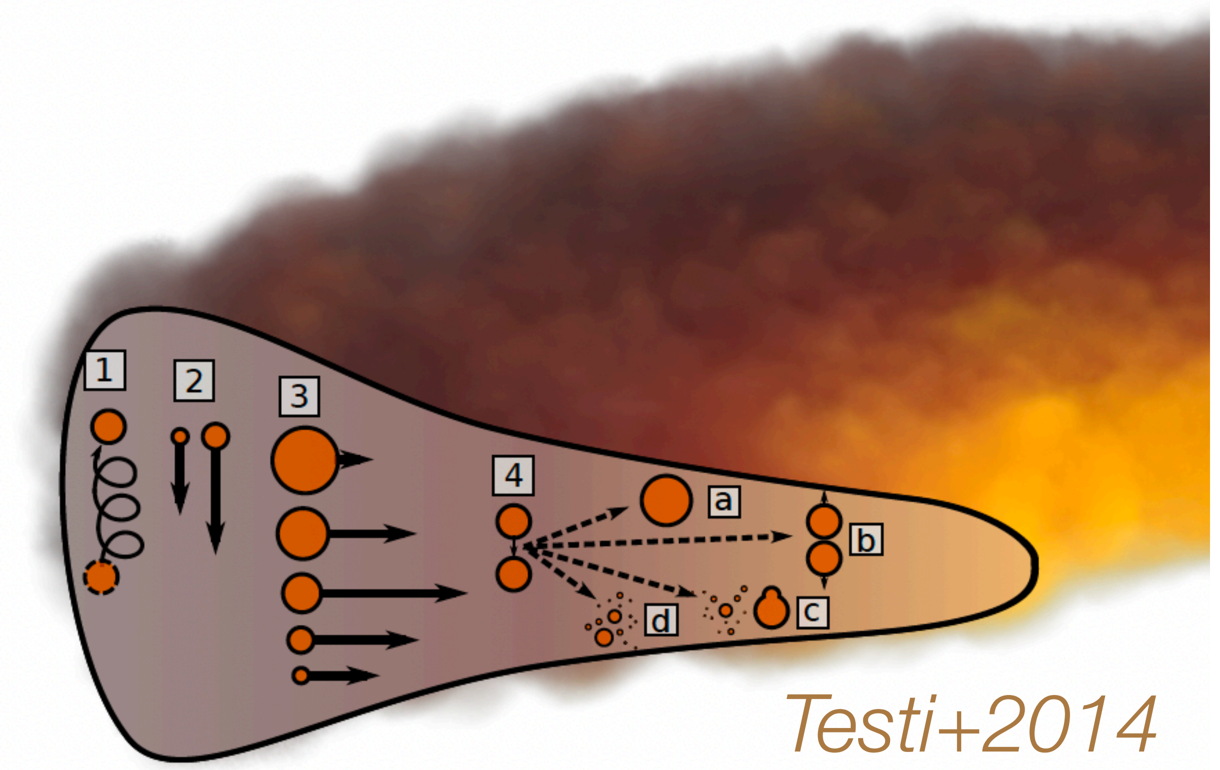


Future prospects

Realistic $Z_{accretion}$ model

- theory of dust coagulation & drift
- observational constraints

e.g., Kobayashi+Tanaka 2021, Roman-Duval+2020, Kama+2015



Testi+2014

More detailed comparison w/ obs.

- surface Li, rotation profile *Eggenberger+2022*

Additional input physics

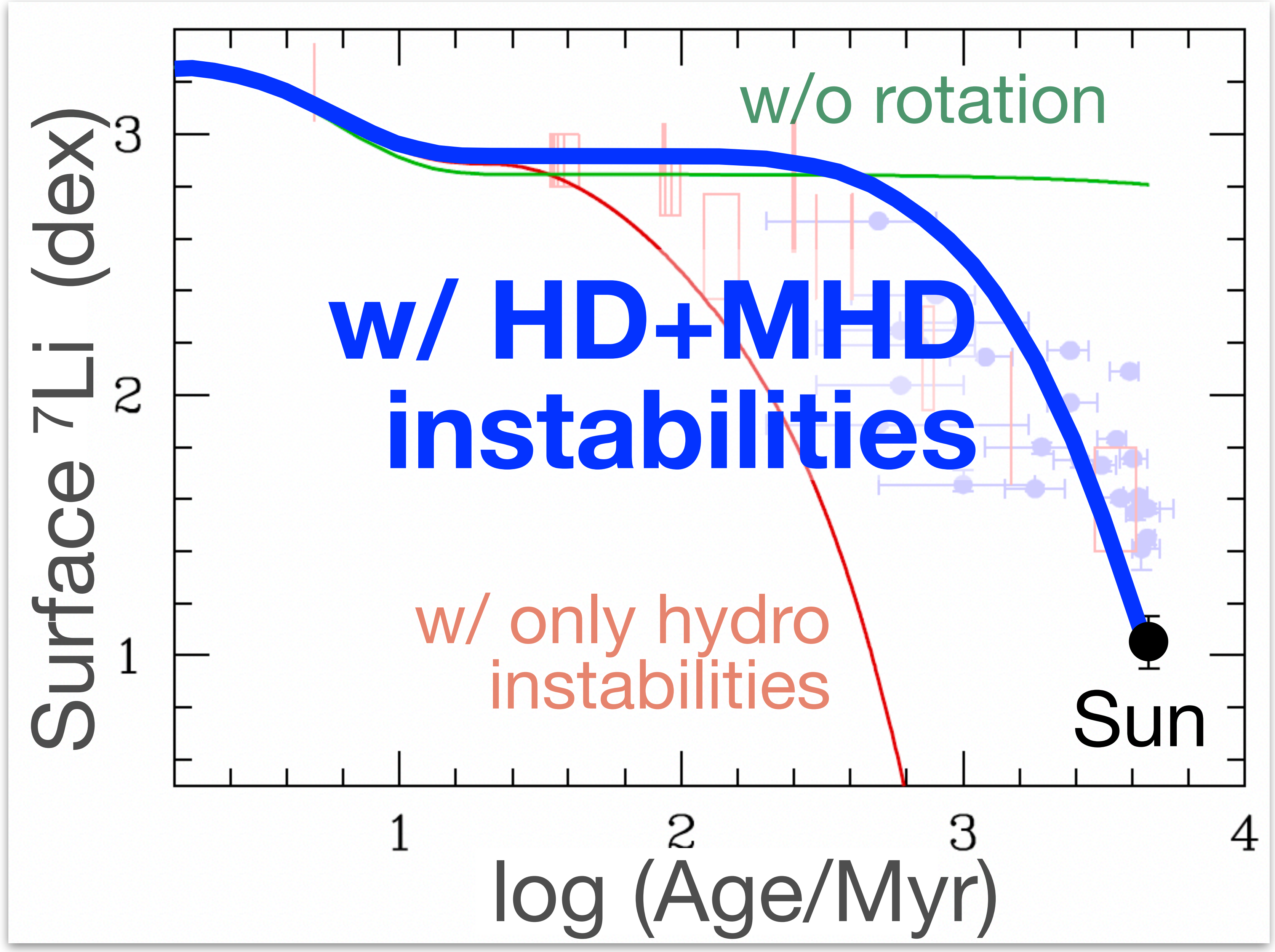
- rotational diffusion ((M)HD instabilities) *Yang2022*
- solar winds (~0.02 $M_{\odot}$ for 4.6 Gyr?)

Suzuki+2013, Zhang+2019

Implications for other stars

- solar twins (e.g., 16 Cyg), δ Scuti stars, etc.

Kunitomo+2018, Deal+2015, Steindl+2022



Eggenberger+2022

Summary

- We simulated the formation and evolution of the Sun focusing on the **evolving composition of accretion flow** and found
  - planet formation processes can increase the central metallicity by up to 5%
  - models including both **planet formation processes** and opacity increase **reproduce spectroscopic/helioseismic/neutrino constraints**

Kunitomo+2022, A&A