Linking stellar compositions and planet formation:
implications for stellar surface abundances and solar models

Masanobu Kunitomo (Kurume U., OCA 2023/11–2024/10)

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Lagrange seminar: 2023/Dec/12

Masanobu Kunitomo

- **2015** March: PhD @ Tokyo Tech., Japan
  (supervised by Shigeru Ida, M. Ikoma, T. Takeuchi, **Tristan**)

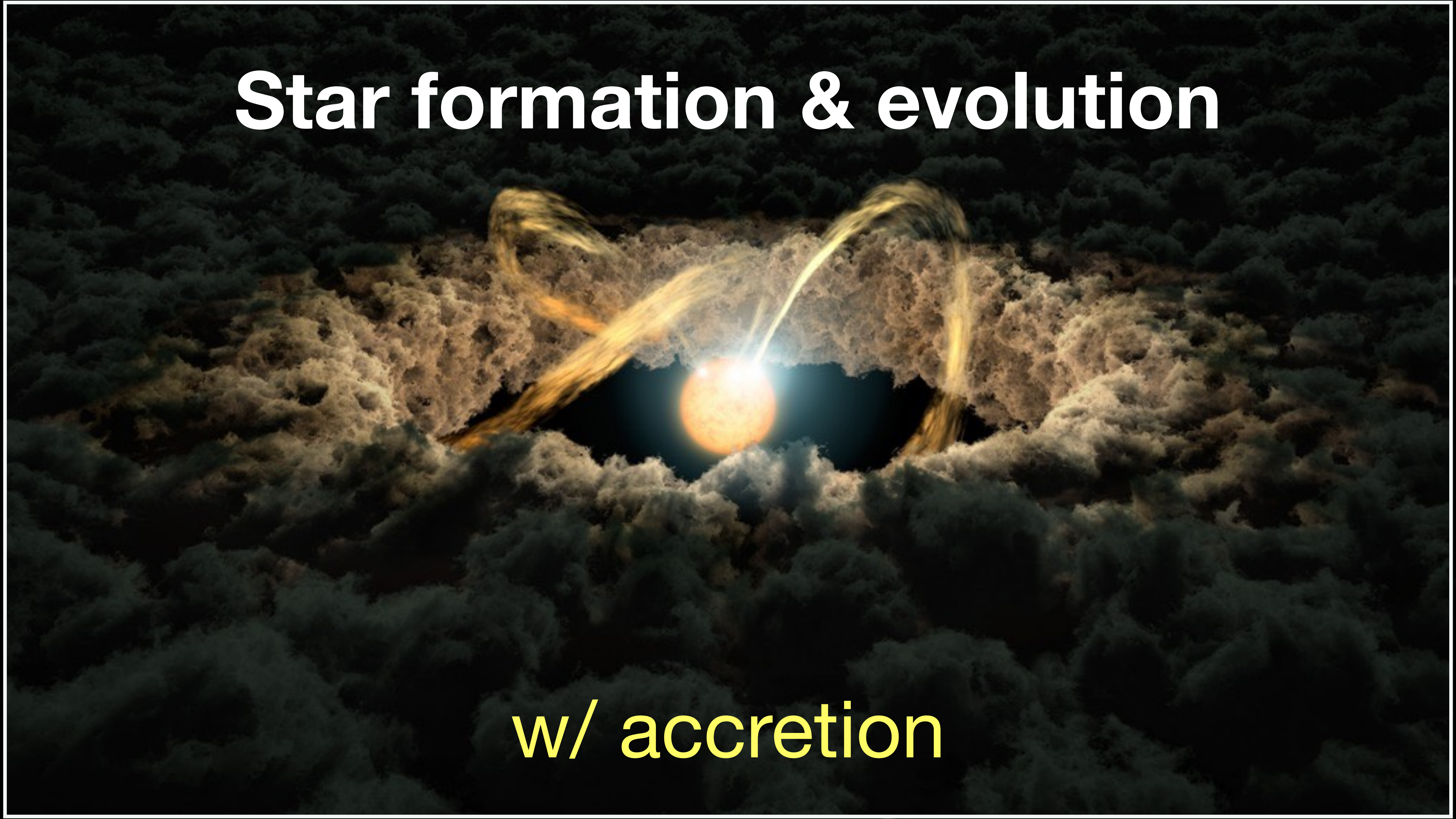
- **2015–2017**: Postdoc @ Nagoya U.
  (Shu-ichiro Inutsuka)

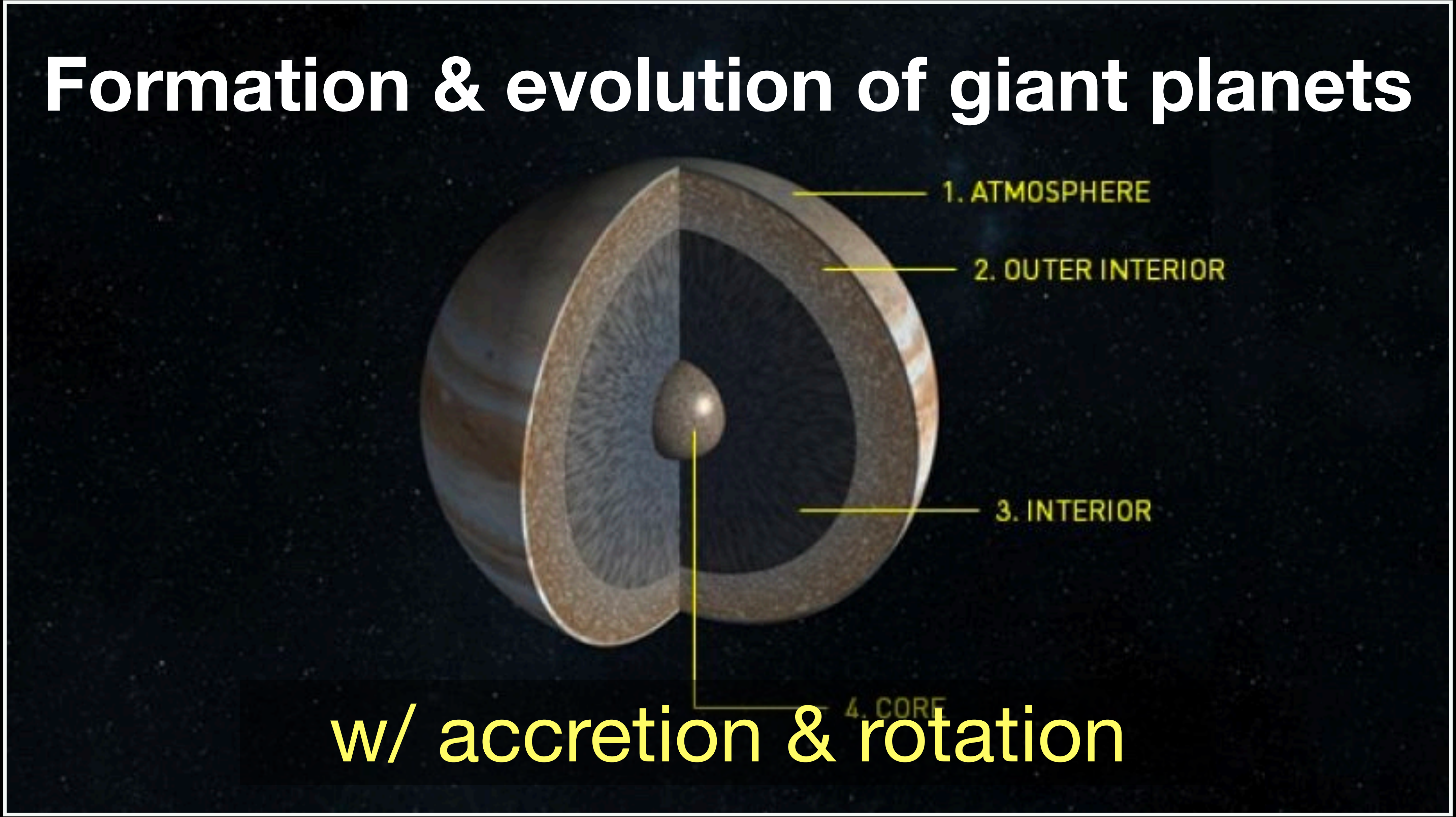
- **2017–2019**: Postdoc @ U. Tokyo
  (M. Ikoma; **JOVIAL** mission)

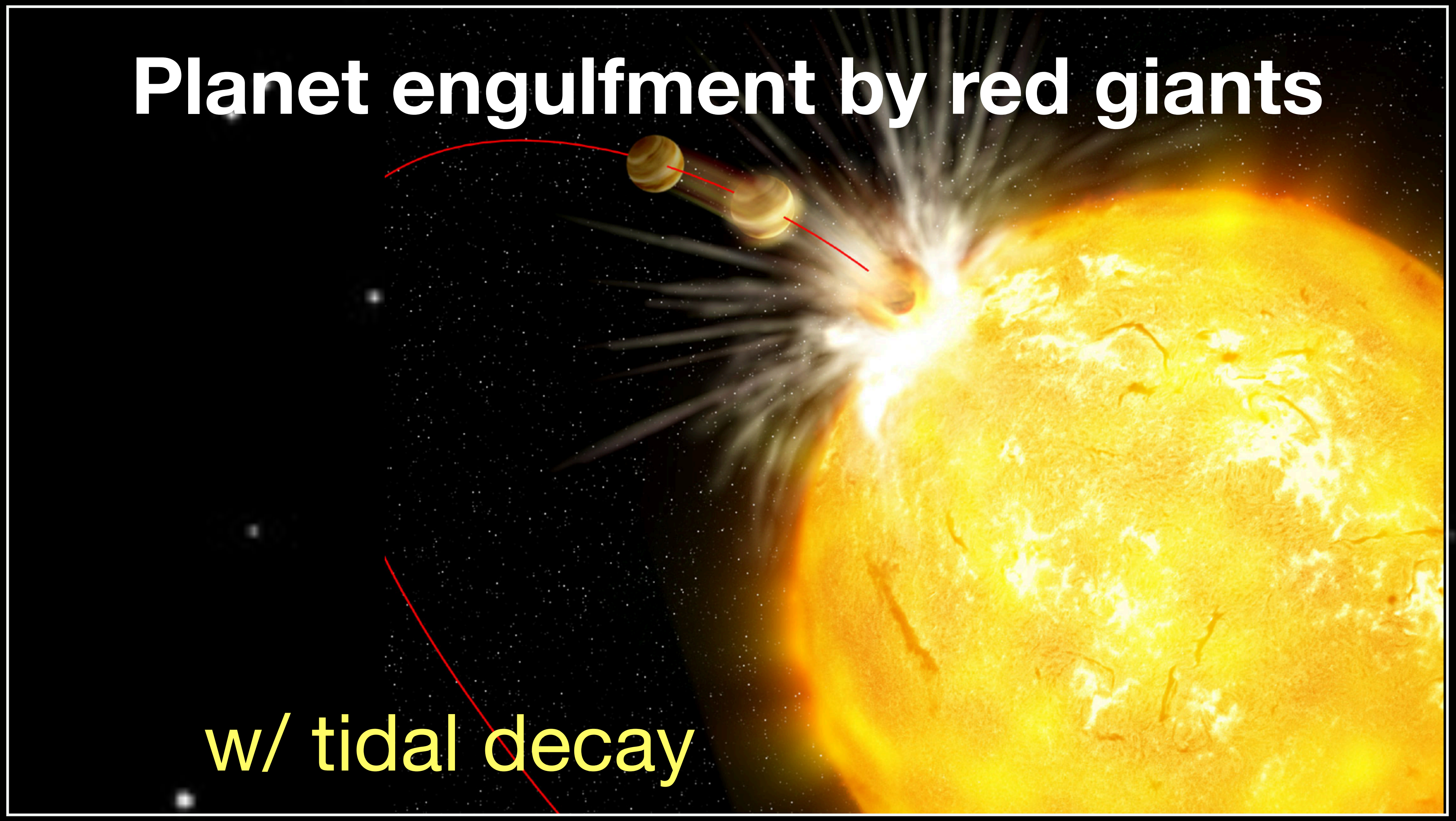
- **2019–**: Assistant prof. (→ Junior associate prof. from 2021) @ Kurume U.

- 2023/Nov–2024/Oct: Sabbatical @ OCA
  office: PHC building

Research interests







Contents of this talk

- Introduction
    - **Star formation** - accretion
    - **Stellar structure** - convective stability
    - **Planet formation** - “pebble wave”

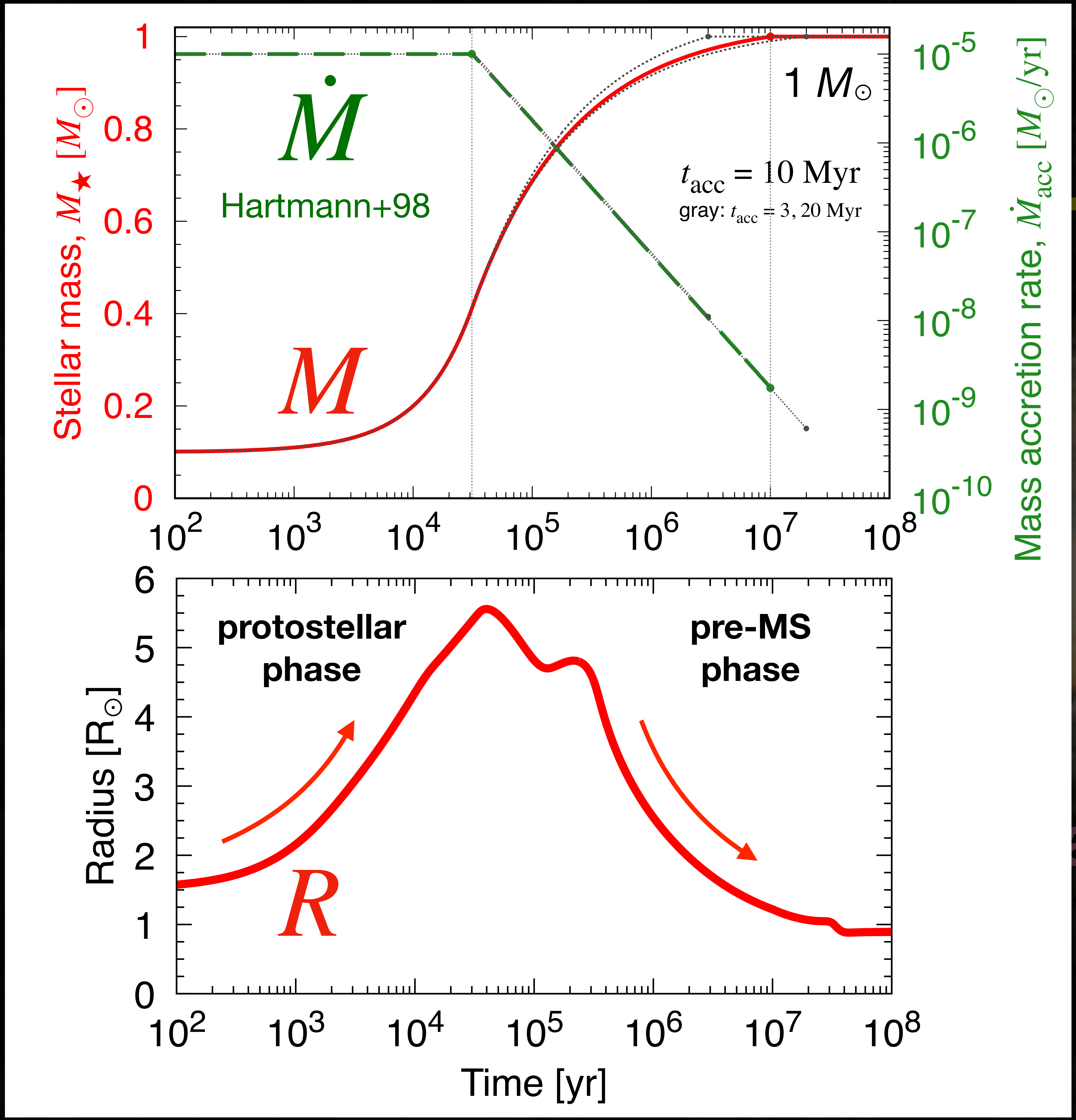
- **Consequences for stellar surface composition**
  - λ Boö stars, binary systems, solar twins, the Sun’s birthplace

- **Consequences for solar internal structure**
  - spectroscopicopy, helioseismology, neutrinos


Outflow
Cloud
observable
Protostellar Envelope
Forming disk
500 au
missing link
→ simulations
20000 au
protostar
pre-MS star
MS star
Protoplanetary disk
observable
observable
Planetary system
50 au
Credit: Bill Saxton, NRAO/AUI/NSF

Bird's eye view of 3D non-ideal MHD simulation


Protoplanetary disk
Accretion
chemical evolution
thermal evolution
Protostar
initially ~3 $M_{\rm Jup}$
© NASA/JPL-Caltech/R. Hurt



- Protostellar phase:
  - intense accretion ($\dot{M} \sim 10^{-5}\, M_\odot$/yr)
  - accretion injects energy
    ➔ expansion
- Pre-main-sequence phase:
  - weaker accretion ($\dot{M} \lesssim 10^{-7}\, M_\odot$/yr)
  - radiative energy loss dominates
    ➔ Kelvin-Helmholtz contraction

<u>Virial theorem</u>

$$\Delta E_{\mathrm{total}} = \underbrace{\Delta K}_{\text{thermal}} + \underbrace{\Delta V}_{\text{grav.}} = \frac{1}{2}\Delta V$$

Stellar structure

- ## Radiative zone
  - Energy flux is transported only by radiation
    where luminosity and opacity are low
  - Slow mixing by atomic diffusion (~Gyr timescale)

temperature gradient

$$\frac{d\ln T}{d\ln P} = \frac{3}{16\pi acG}\frac{P}{mT^4}\kappa l$$

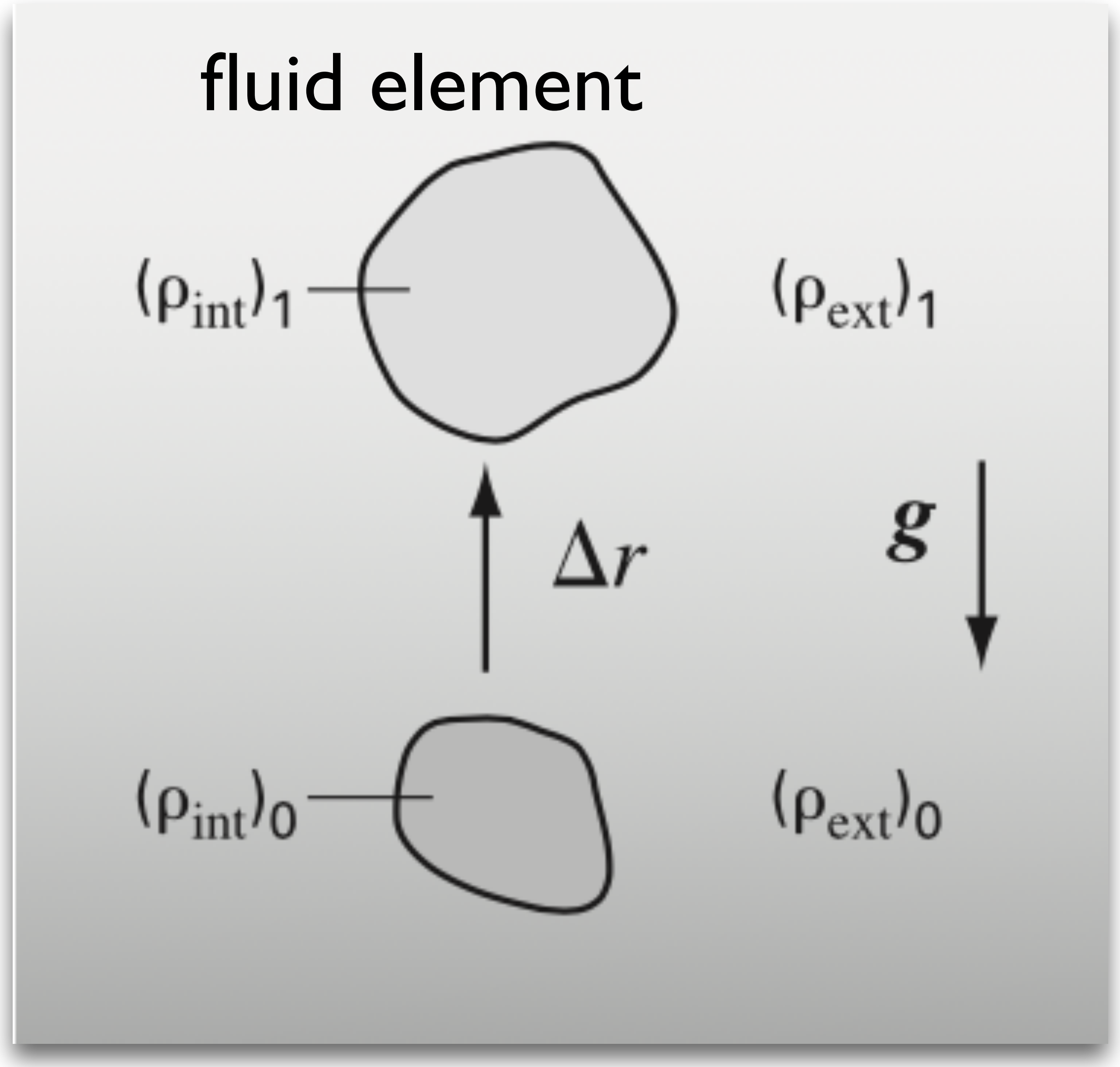
opacity

luminosity

- ## Convective zone
  - If the temperature gradient is too steep,
    convection sets in and transports a part of energy flux
  - **Fast mixing** (~10 days for the Sun)

Schwarzschild criterion

$$\frac{d\ln T}{d\ln P} > 0.4$$

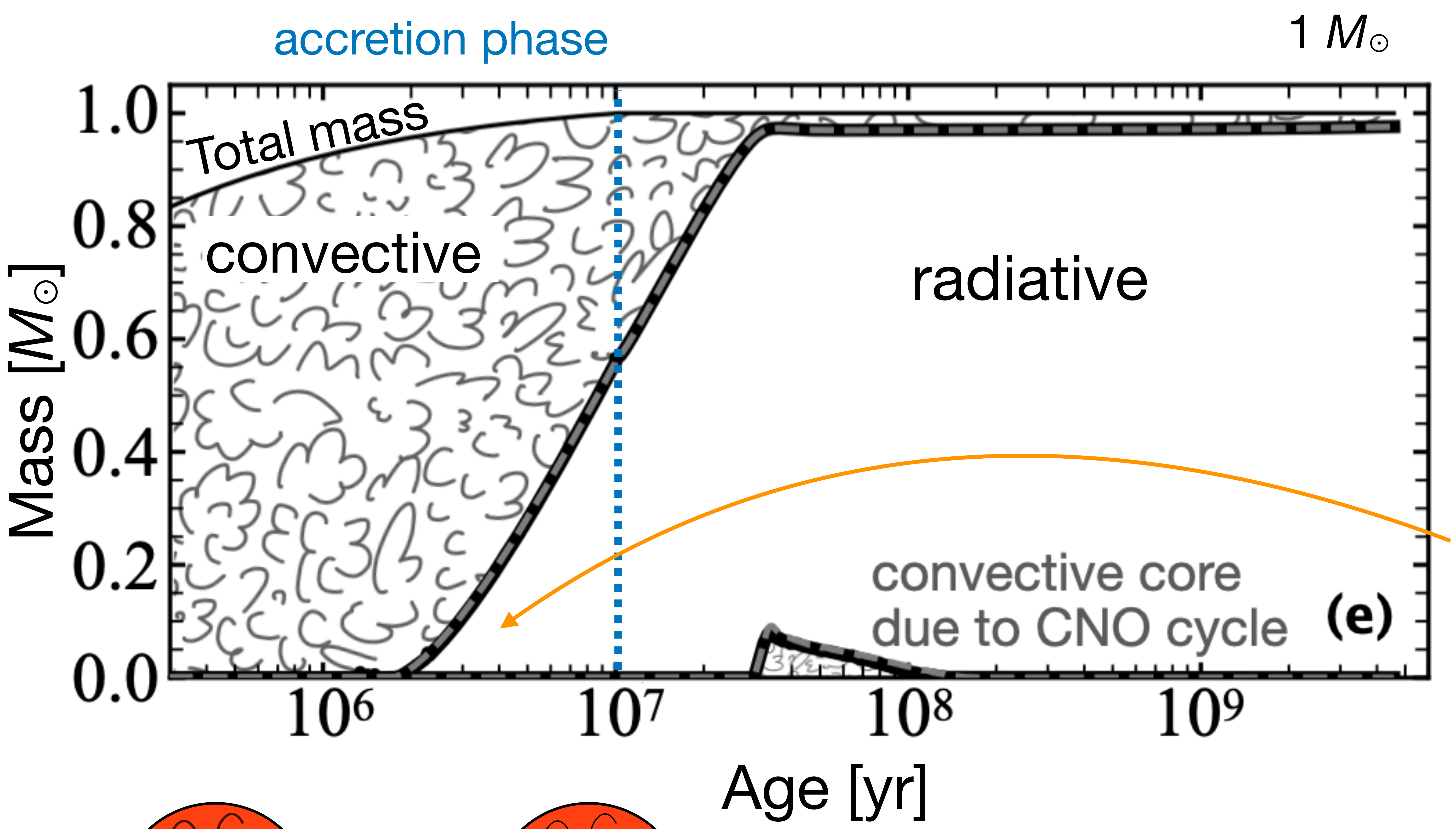


Palla+Stahler05

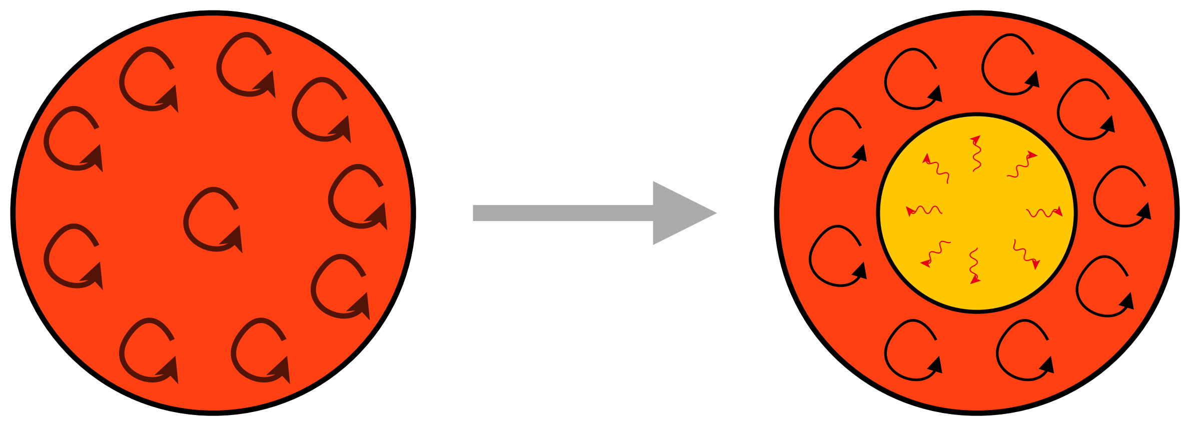
+ degeneration, overshooting, semiconvection


the Sun
~0.7 $R_\odot$
© NASA/SDO
2016 Sep 19 09:30:38.000 (TAI)
Data taken by Jaime de la Cruz Rodriguez & Jorrit Leenaarts at the Swedish 1-m Solar Telescope
Visualization generated by NASA's Scientific Visualization Studio

Evolving structure of young stars



Kunitomo+2022



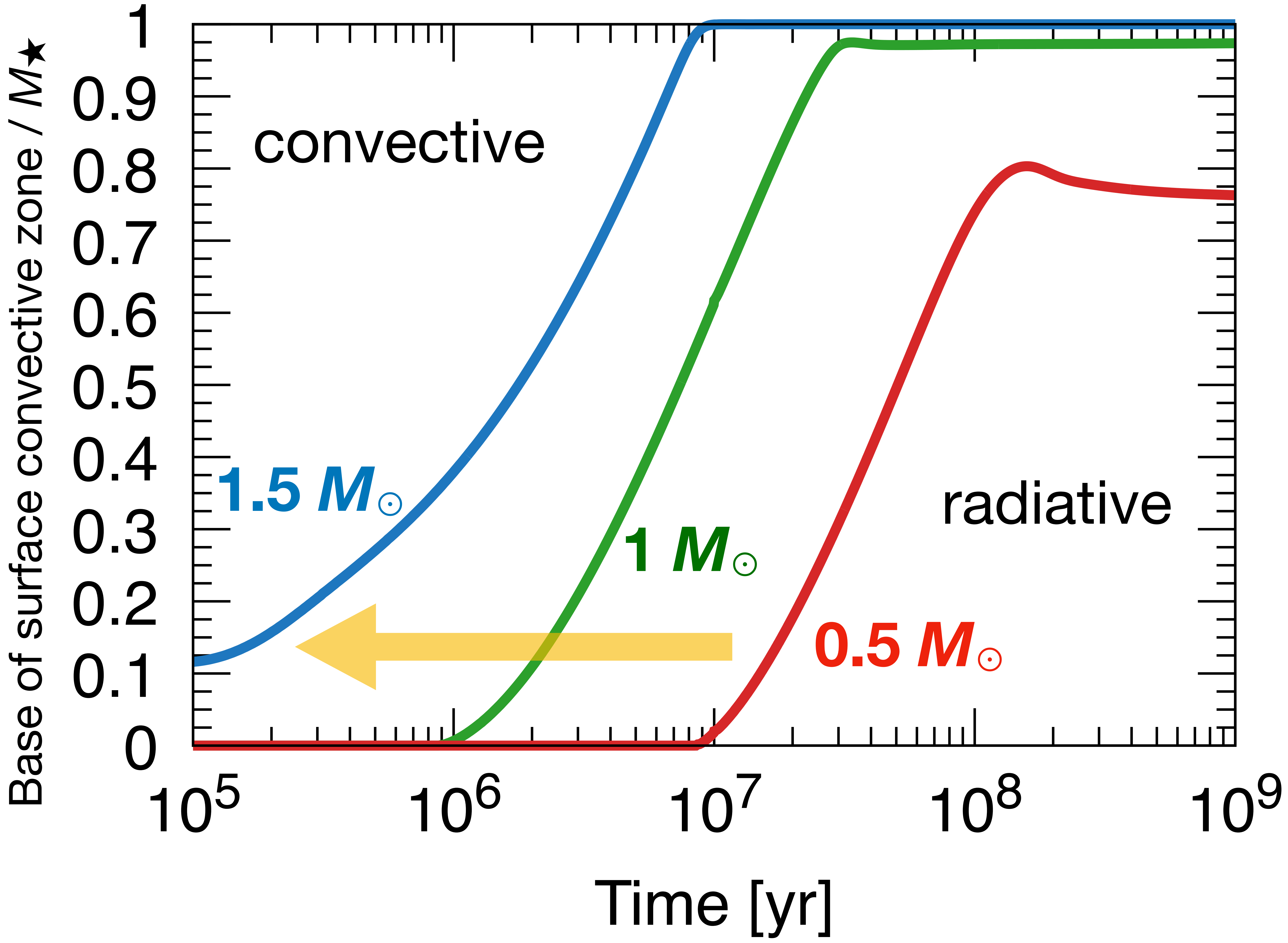
- **Fully convective at first**
  - Higher energy due to accretion
    → lower temperature
    → higher opacity ($\kappa \propto T^{-3.5}$)
  - "Hayashi phase" *Kramers law*
- **Radiative core develops**
  - K-H contraction → higher temperature
    → lower opacity

Virial theorem

$$\Delta E_{\mathrm{total}} = \Delta K + \Delta V = -\Delta K$$

thermal grav.

Evolving structure of young stars



- **Fully convective at first**
  - Higher energy due to accretion
    → lower temperature
    → higher opacity ($\kappa \propto T^{-3.5}$)
  - "Hayashi phase"

Kramers law

- **Radiative core develops**
  - K-H contraction → higher temperature
    → lower opacity
  - **more rapidly for higher-mass stars**

Virial theorem

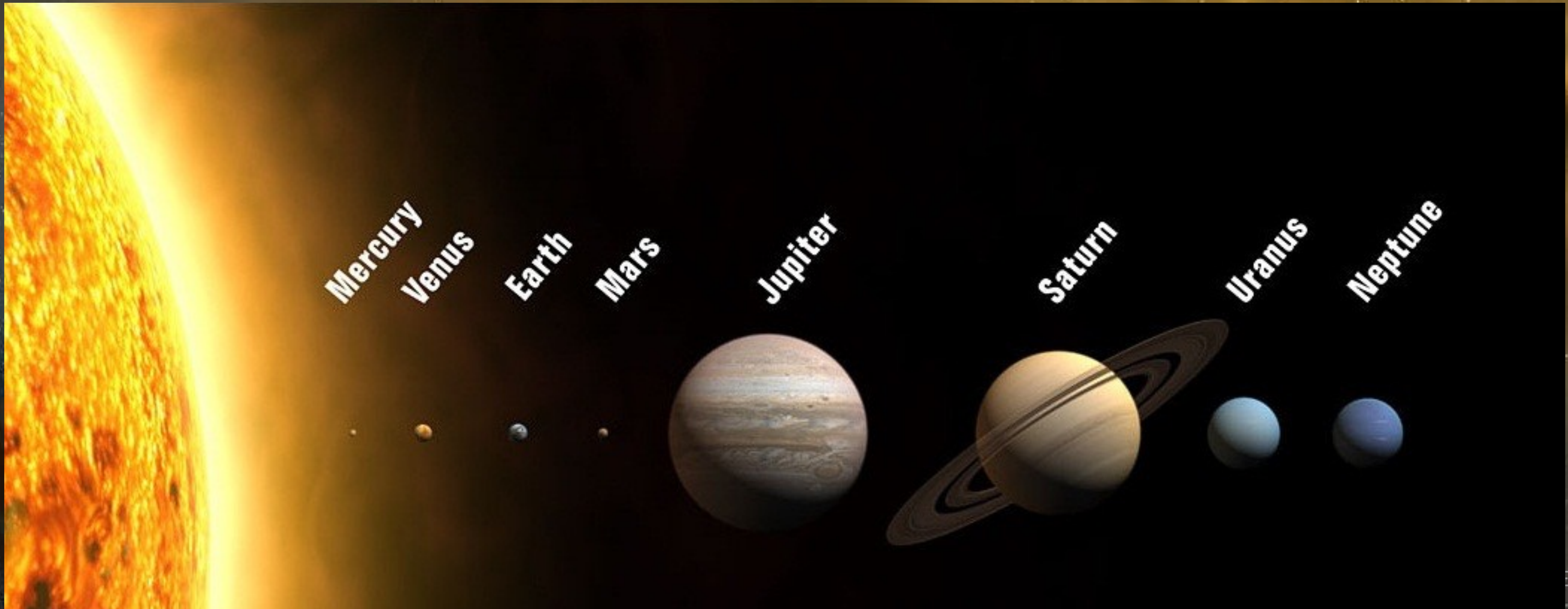
$$\Delta E_{\rm total} = \Delta K + \Delta V = -\Delta K$$

thermal grav.

Solar-System planets

~150 $M_\oplus$ solids were used for planet formation processes in the early Solar System

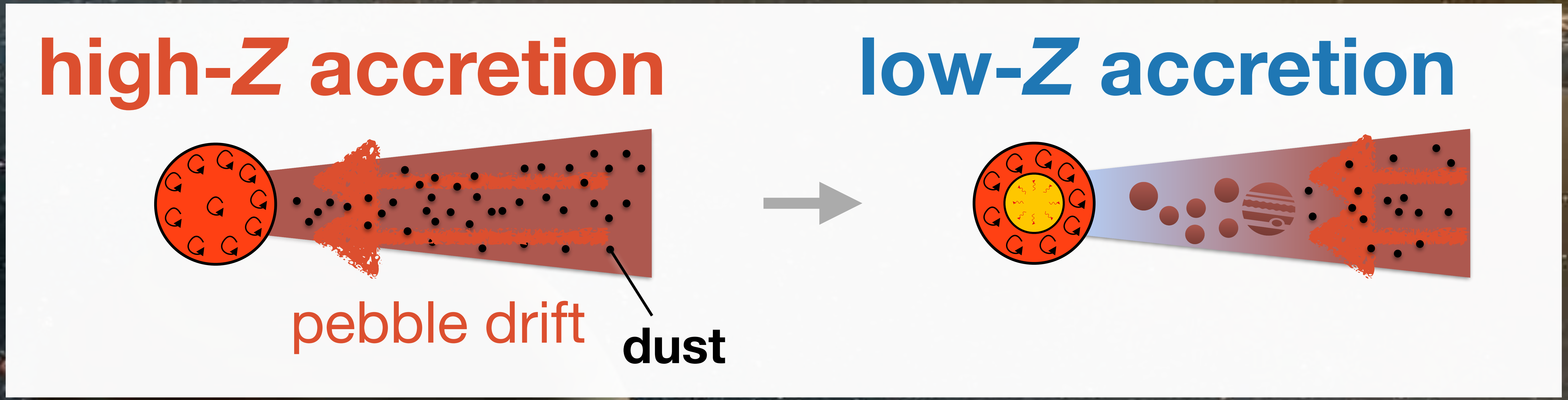
cf. **~5000 $M_\oplus$** metals in the Sun



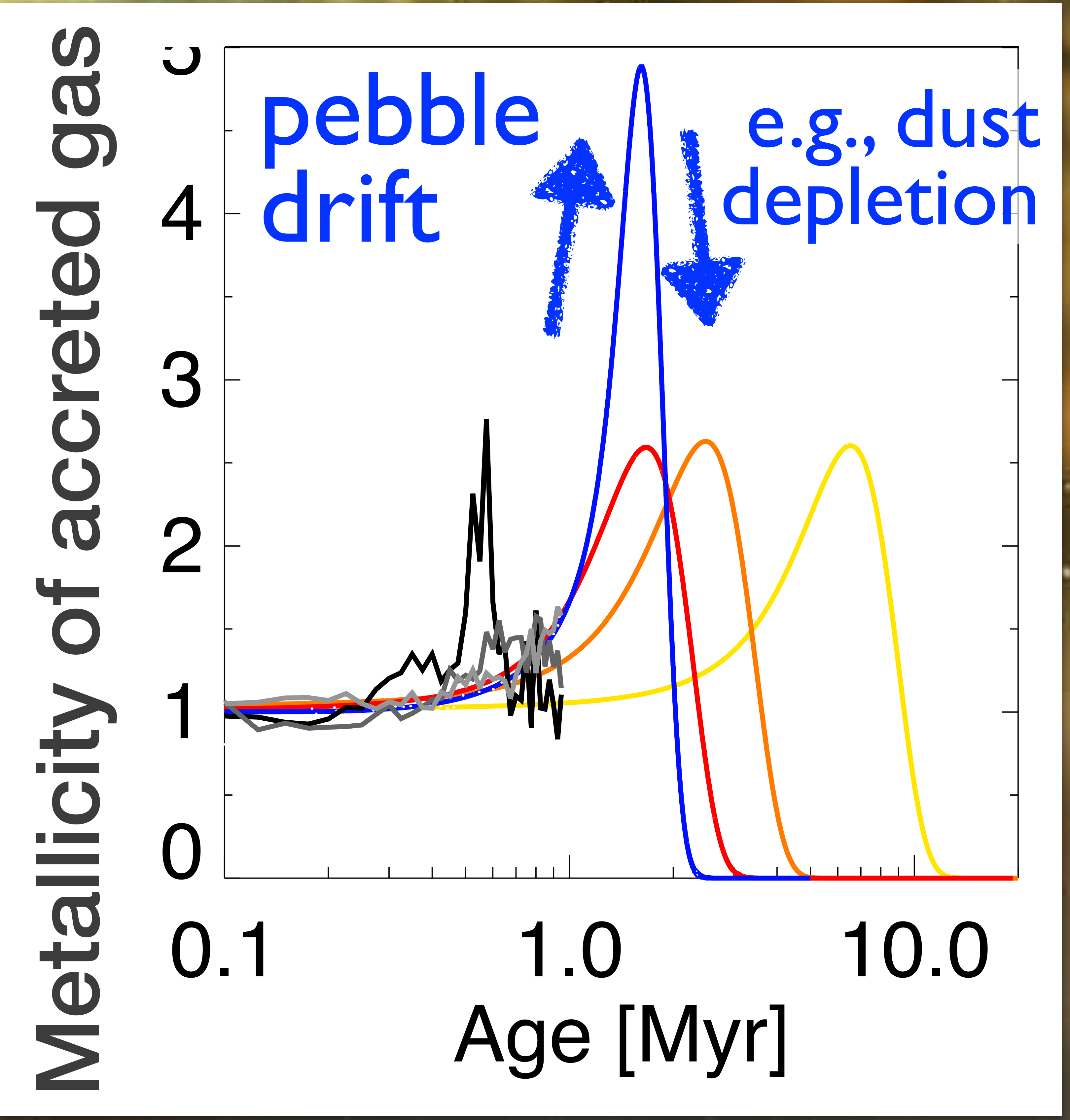
E/Lynette Cook

Evolving composition of disk gas

Evolving composition of disk gas



Garaud+2007, Guillot+2014, Applegren+2020, Elbakyan+2020

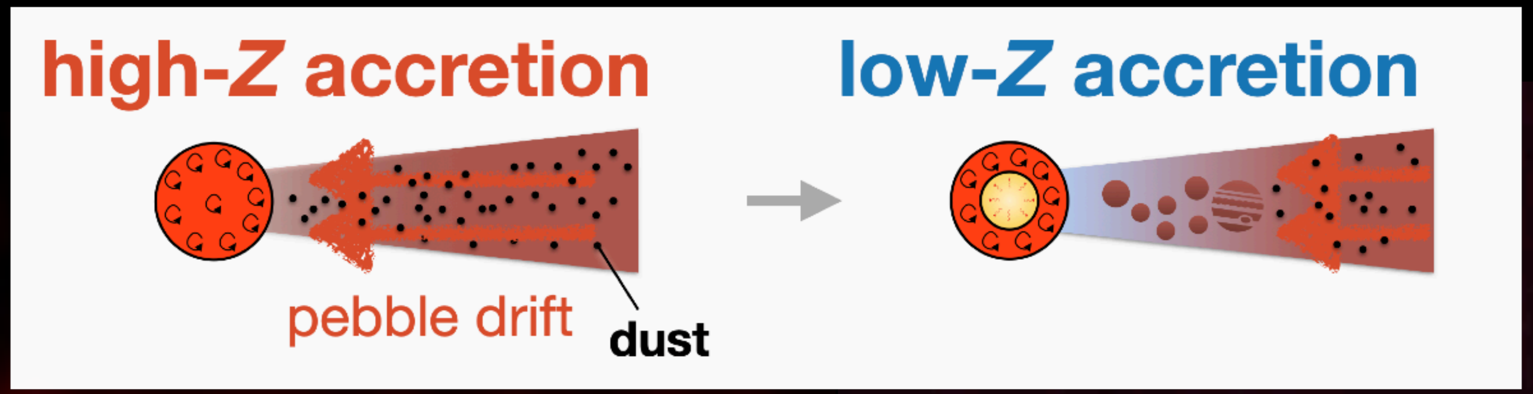


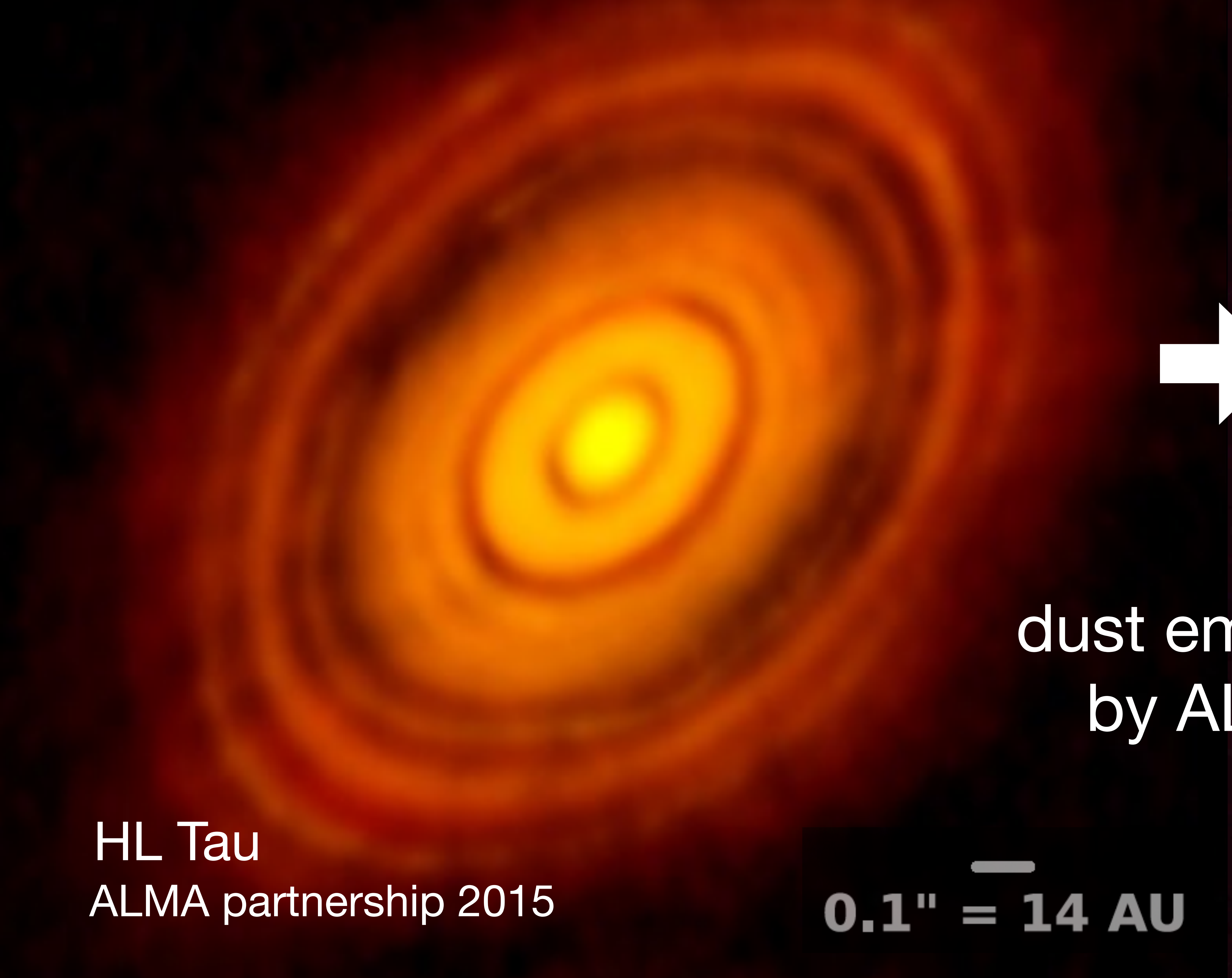
Kunitomo+Guillot 2021

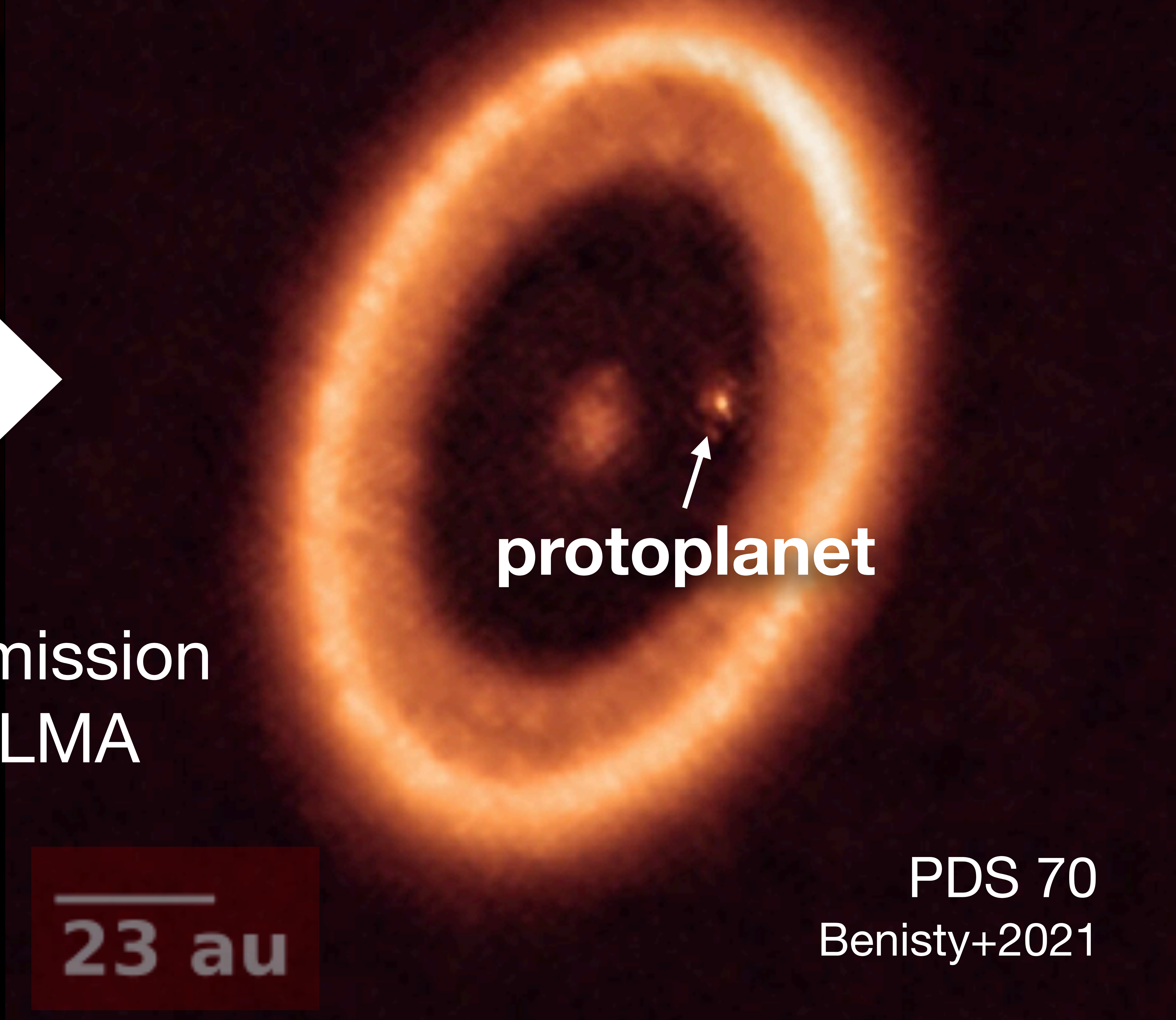
NASA/FUSE/Lynette Cook

Early phase: *dusty* accretion (high-*Z*)

Late phase: *dust-poor* acc. (low-*Z*)







dust emission
by ALMA

HL Tau
ALMA partnership 2015

PDS 70
Benisty+2021

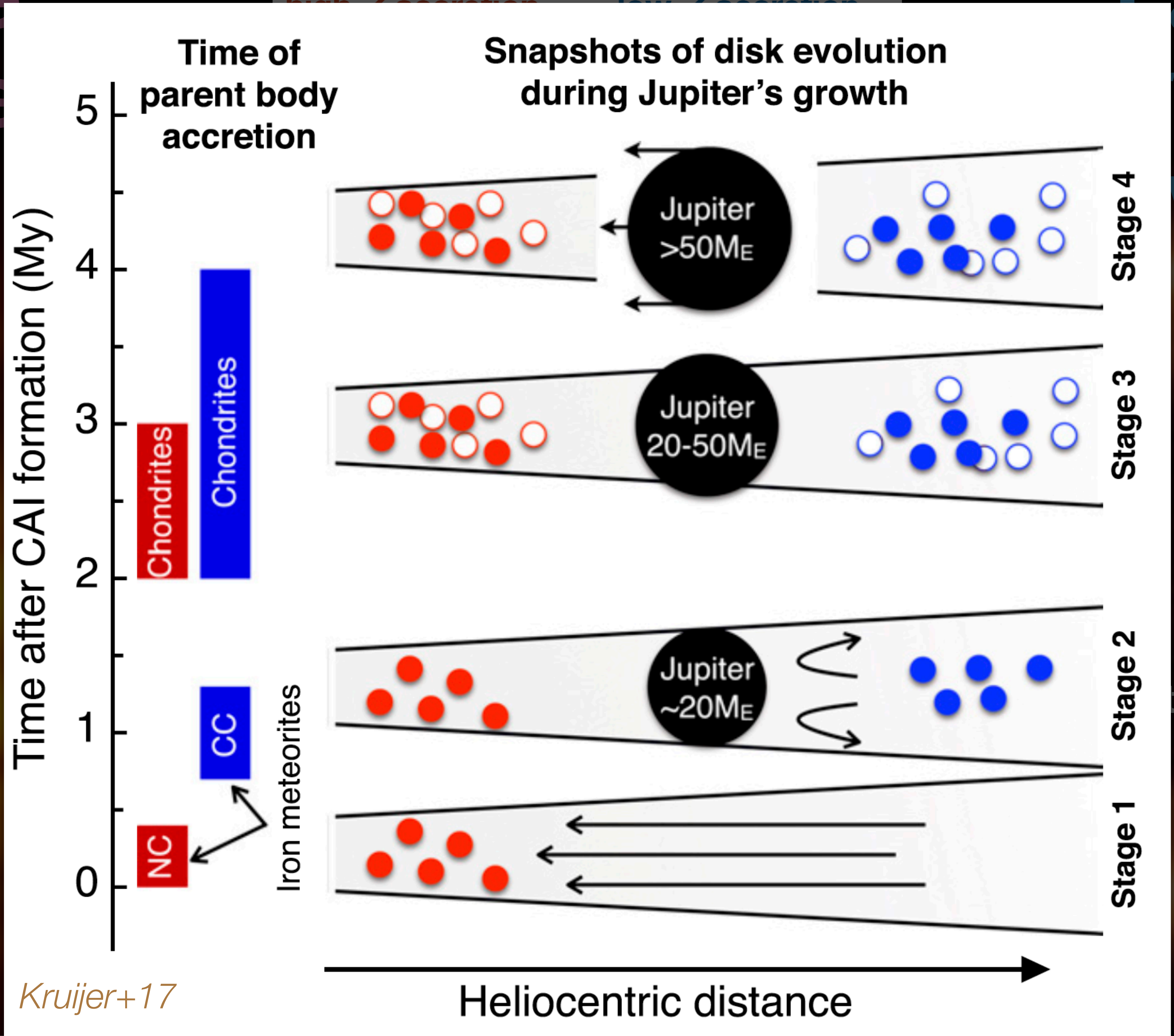
Early phase: *dusty* **accre**

(high-*Z*)

Late phase: *-poor* **acc.**

w-*Z*)

Time



toplanet

HL Tau

ALMA partnership 2015

0.1" = 14 AU

23 au

PDS 70

Benisty+2021

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  - spectroscopicopy, helioseismology, **neutrinos**

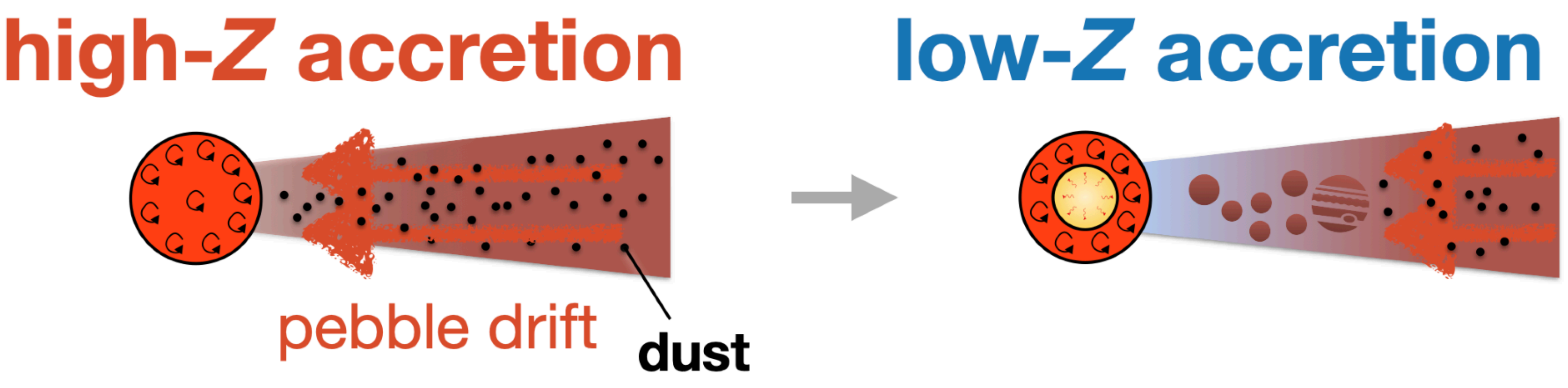
Stellar evolution models w/ accretion

Stellar evolution calculation

- 1D MESA code solves the eqs. of:
  - continuity
  - momentum (quasi-hydrostatic)
  - energy (nuclear reaction, accretion energy)
  - temperature (mixing-length theory)
  - composition (nuclear reaction, mixing)

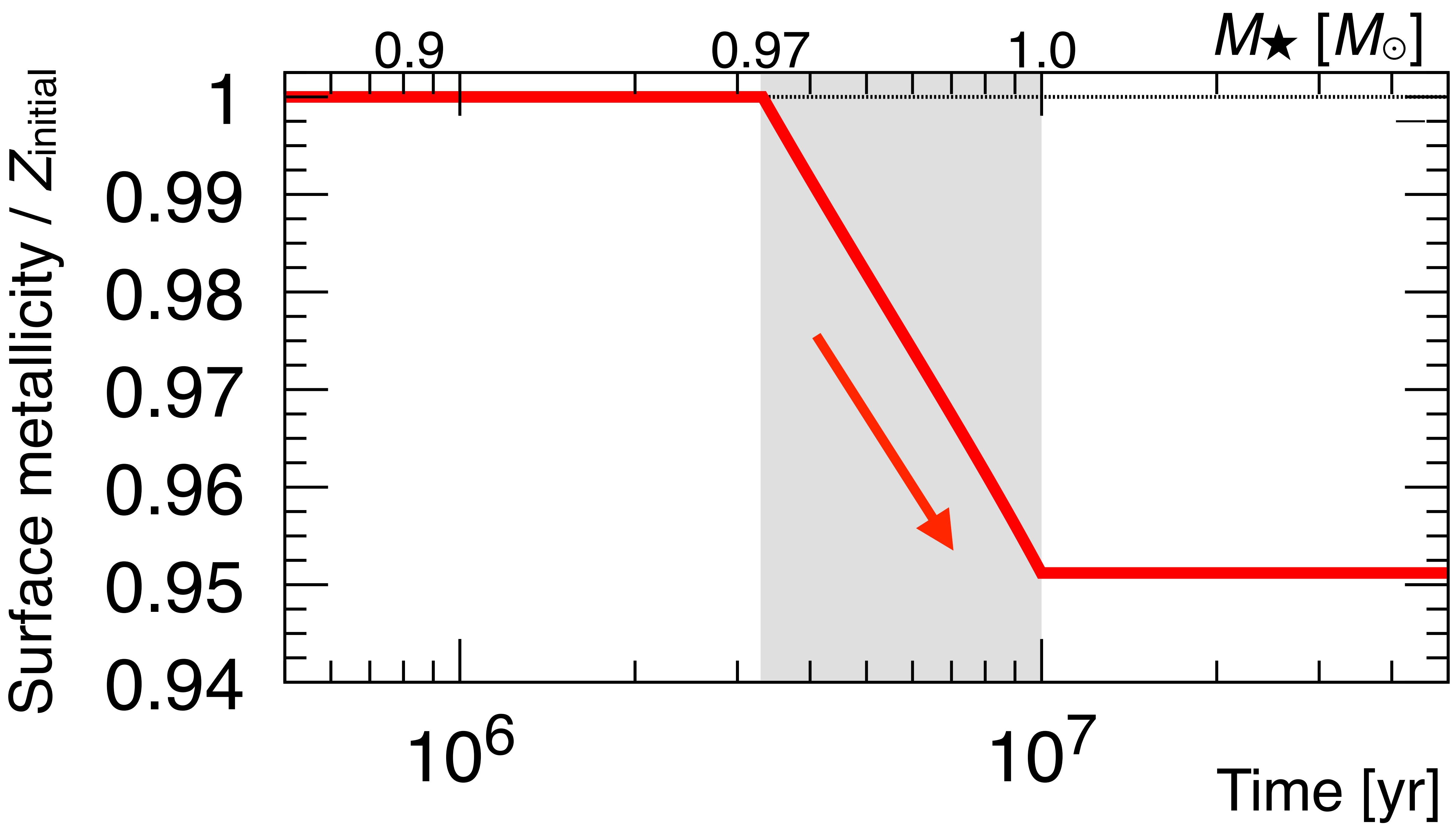
Accretion

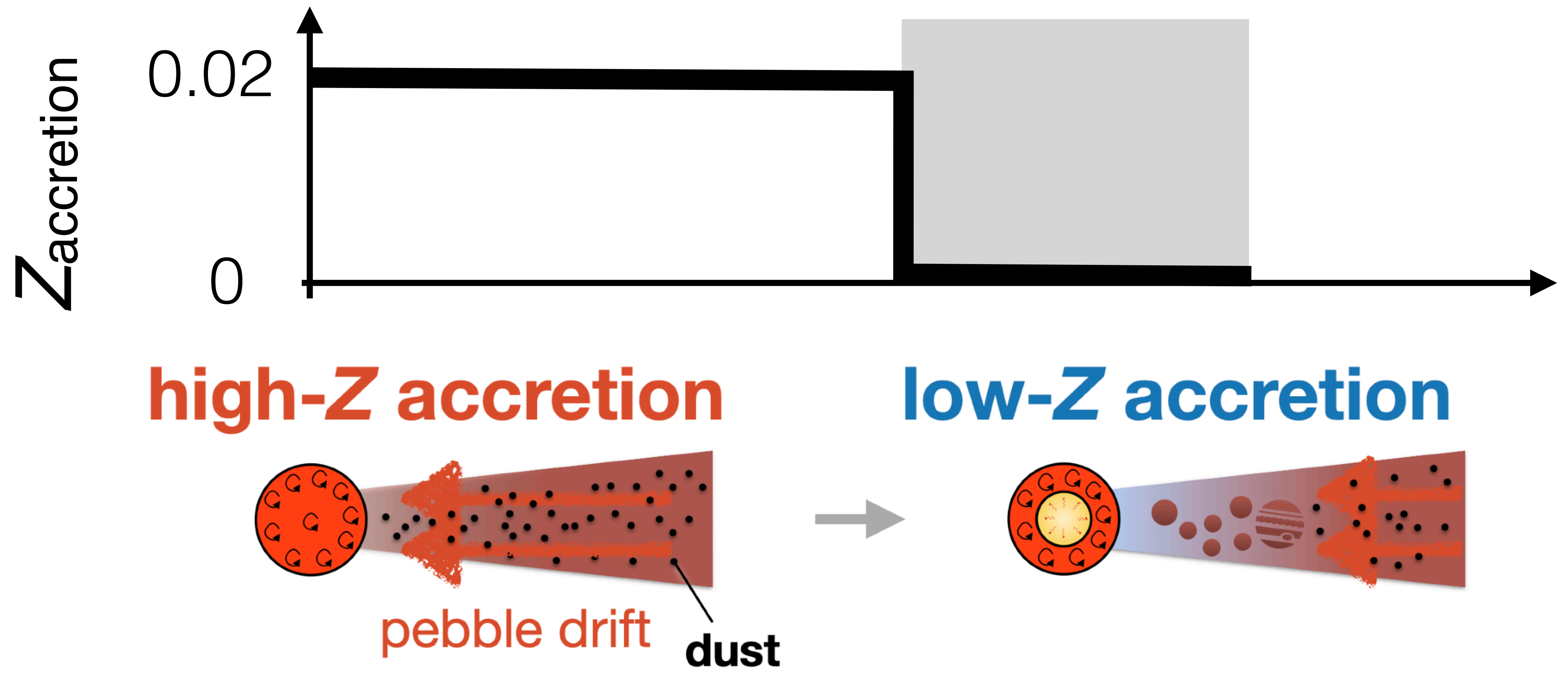
- Mass accretion rate
  - observed $\dot{M} \propto t^{-1.5}$
  - from protostellar phase
- Composition
  - high-Z in the early phase → low-Z



Paxton+11, Kunitomo+17, 18

Stellar surface composition evolution

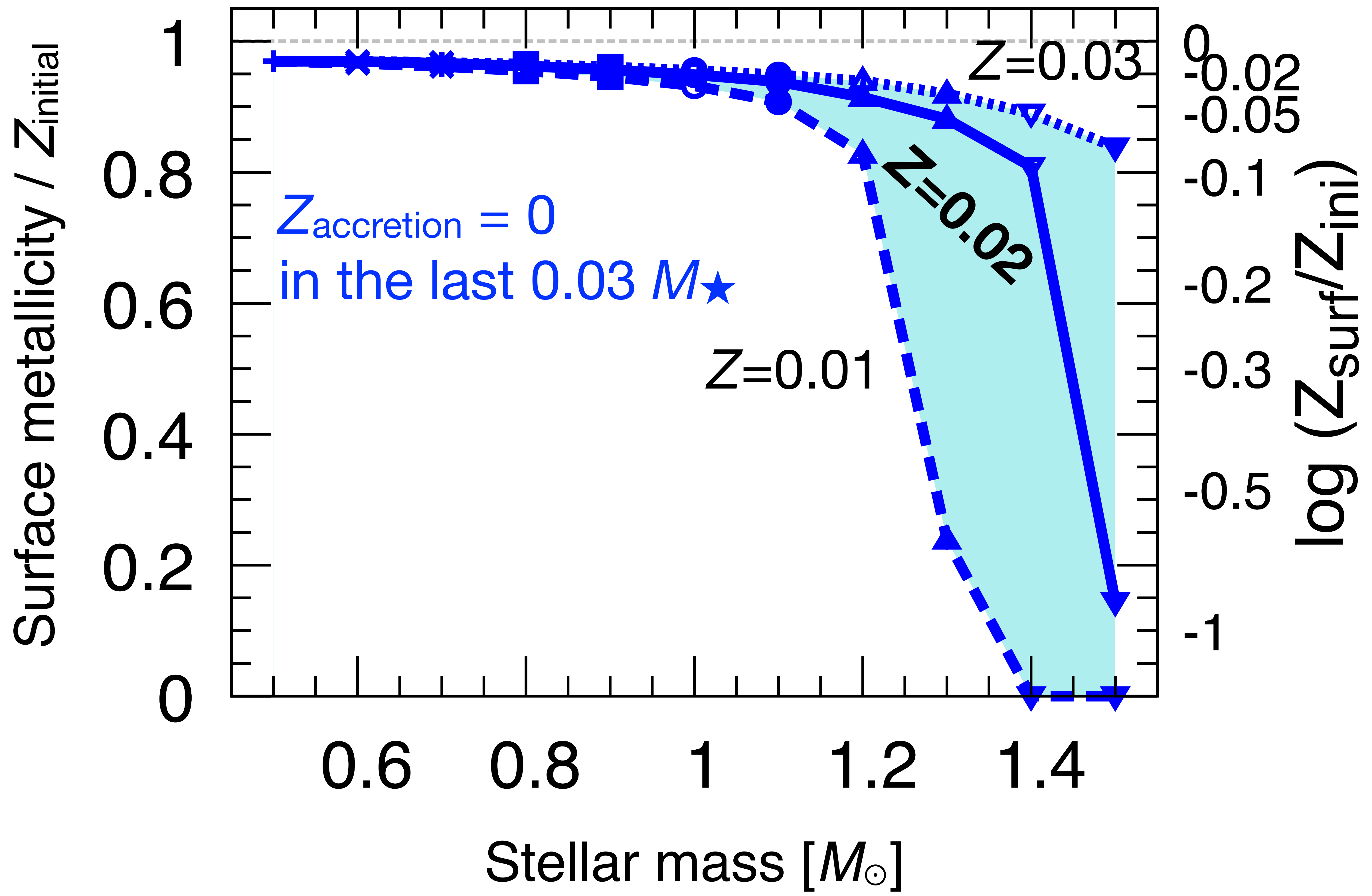




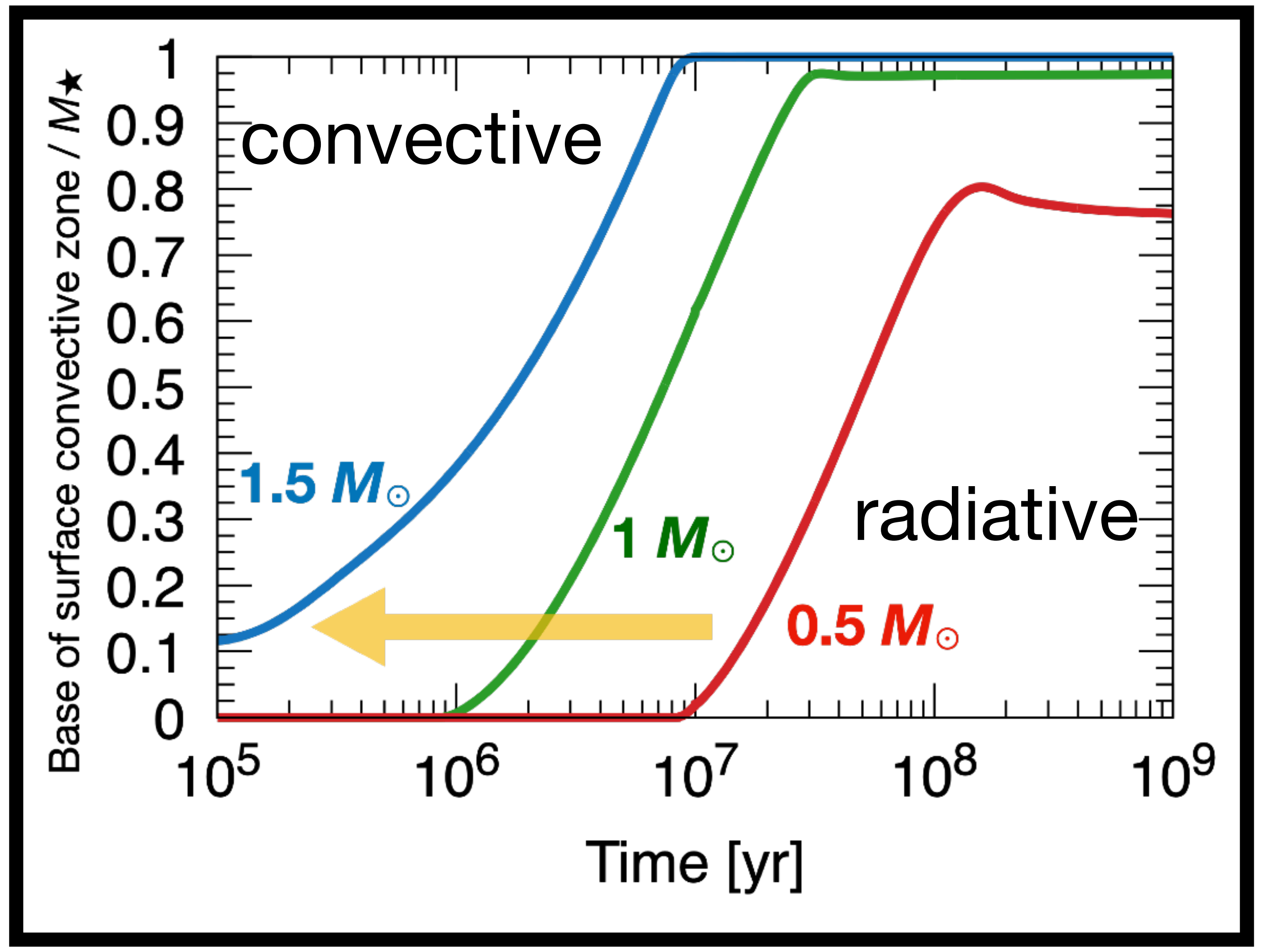
- Here we assume a metal-free accretion in the last **0.03 $M_\odot$**
  - ~150 $M_\oplus$ solids were used in the early Solar System
- Low-Z accretion in the late phase *dilutes* the stellar surface: The surface metallicity decreases by ~5%

Refractory-poor stellar surface by accretion

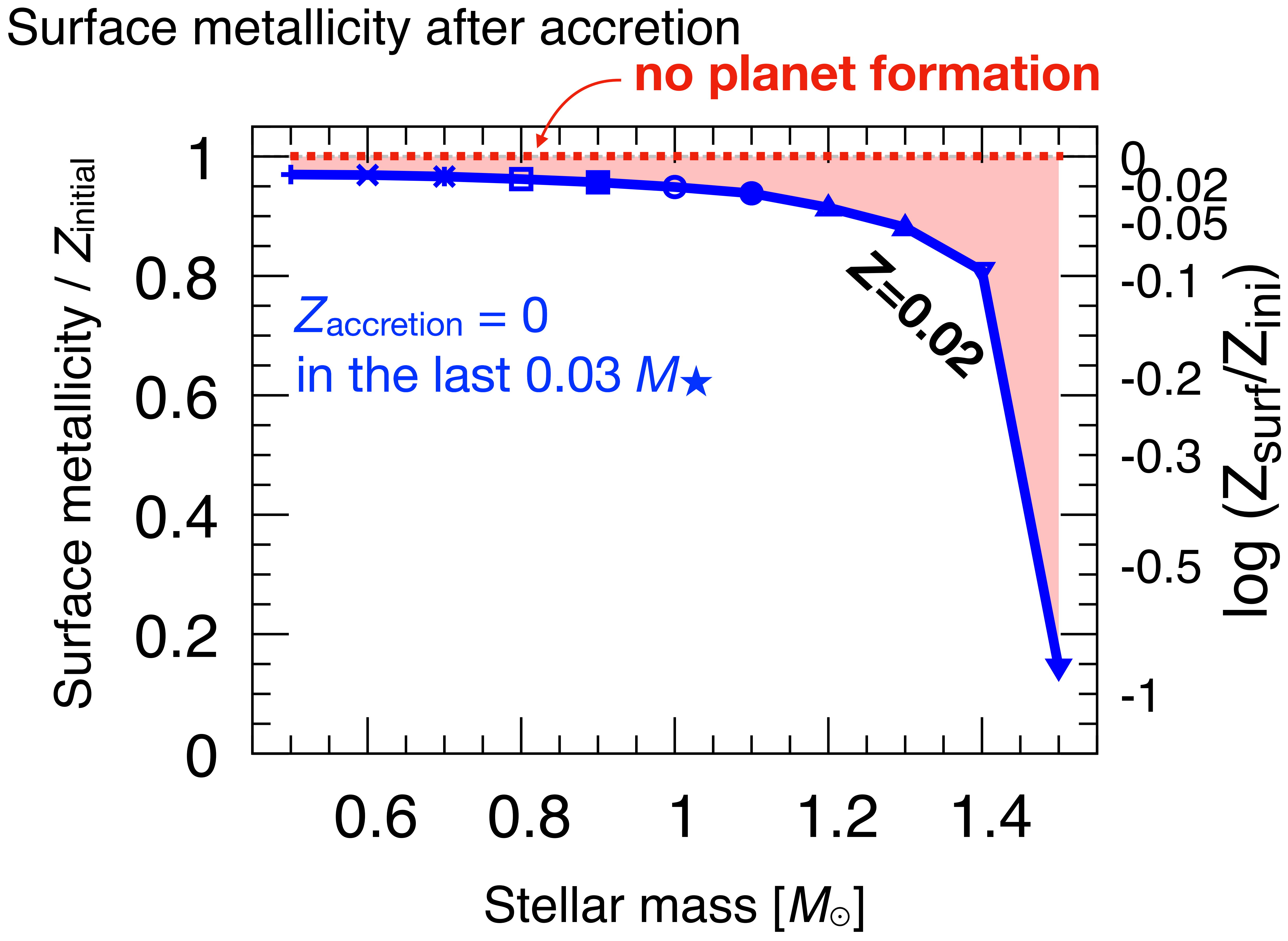
Surface metallicity after accretion



- **Higher-mass, metal-poor stars are more affected by the accretion**
  - radiative core develops **more rapidly**
  - K-H timescale $\propto GM^2/RL \propto M^{-1}$
  - low-Z star has a lower opacity



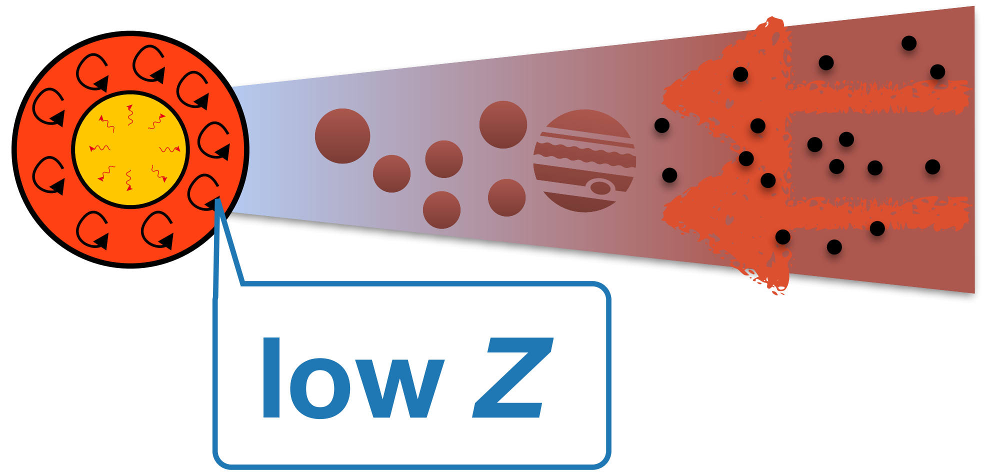
Refractory-poor stellar surface by accretion



- **Higher-mass, metal-poor stars are more affected by the accretion**
  - radiative core develops **more rapidly**
  - K-H timescale $\propto GM^2/RL \propto M^{-1}$
  - low-Z star has a lower opacity

- **The variety in planet formation processes yields the variety in the stellar surface metallicity**

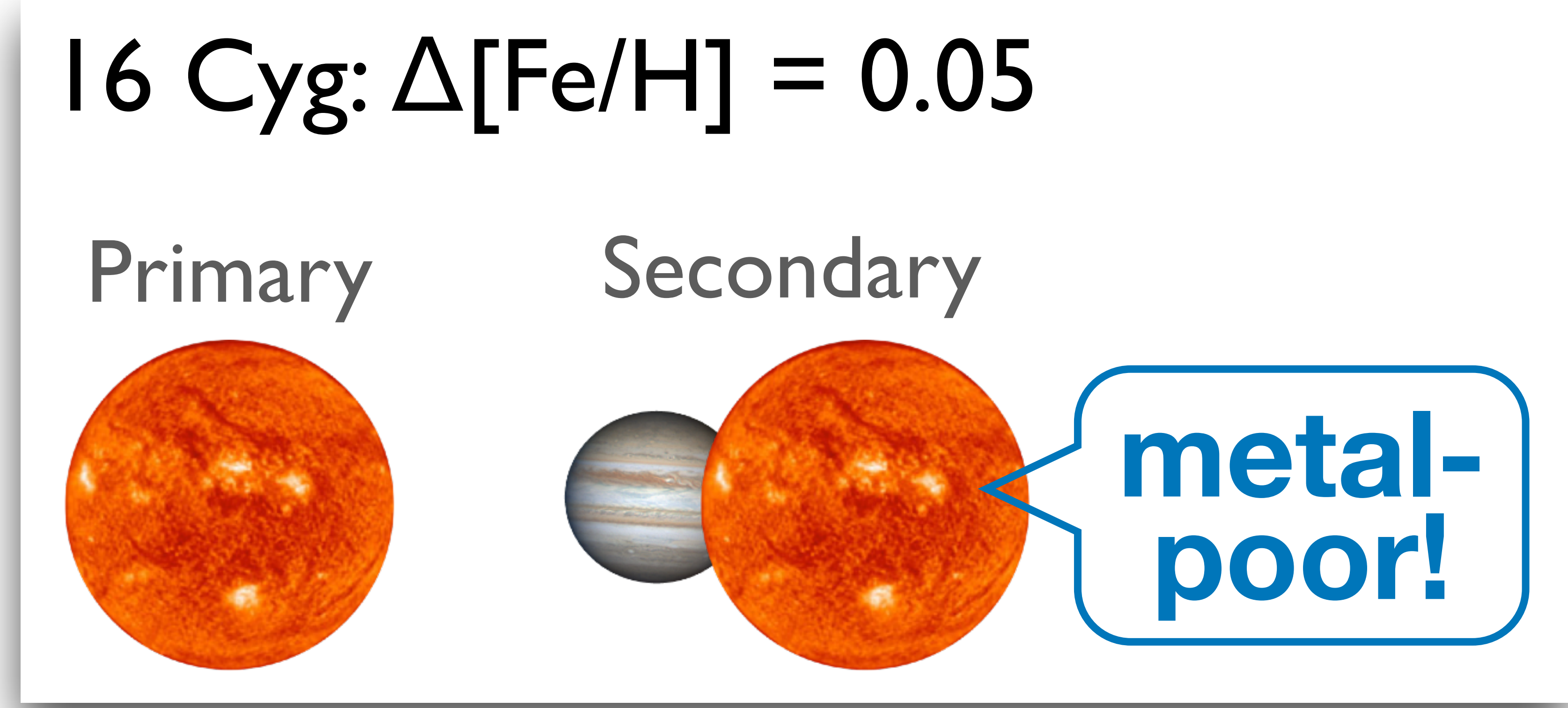
Implications for observed puzzles



Composition anomaly in binaries

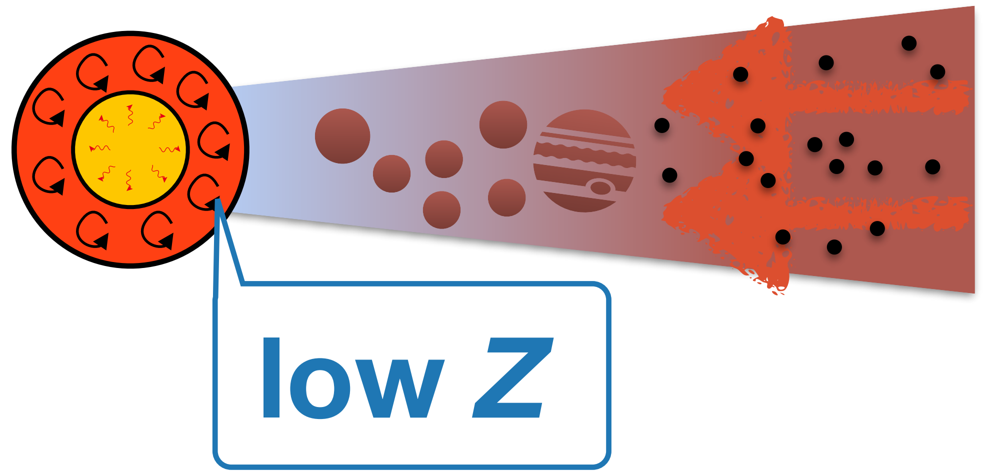
- λ Boö stars: refractory-poor A stars
- Composition anomaly in solar twins

e.g., Ramirez+11; Damasso+15

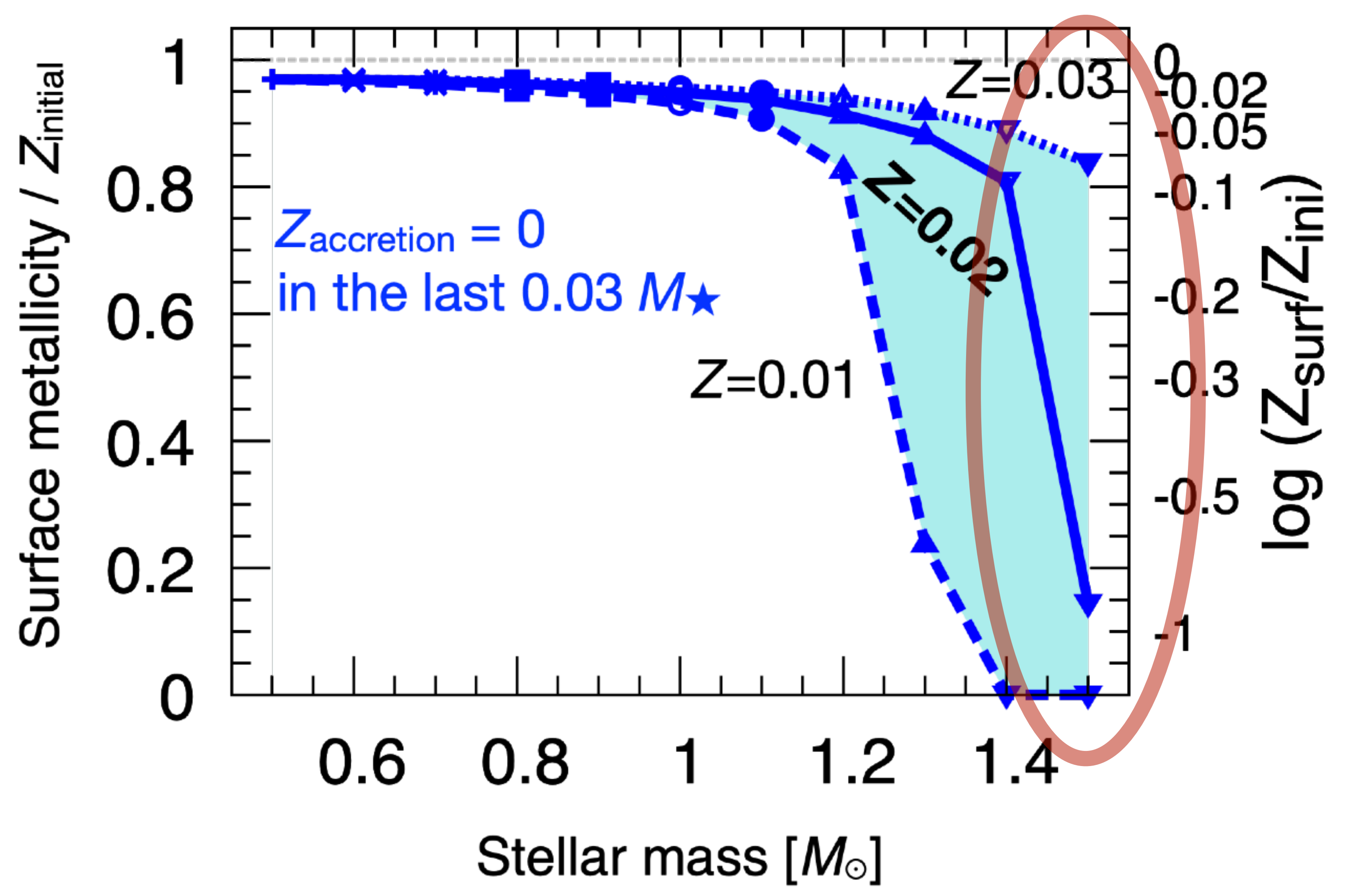


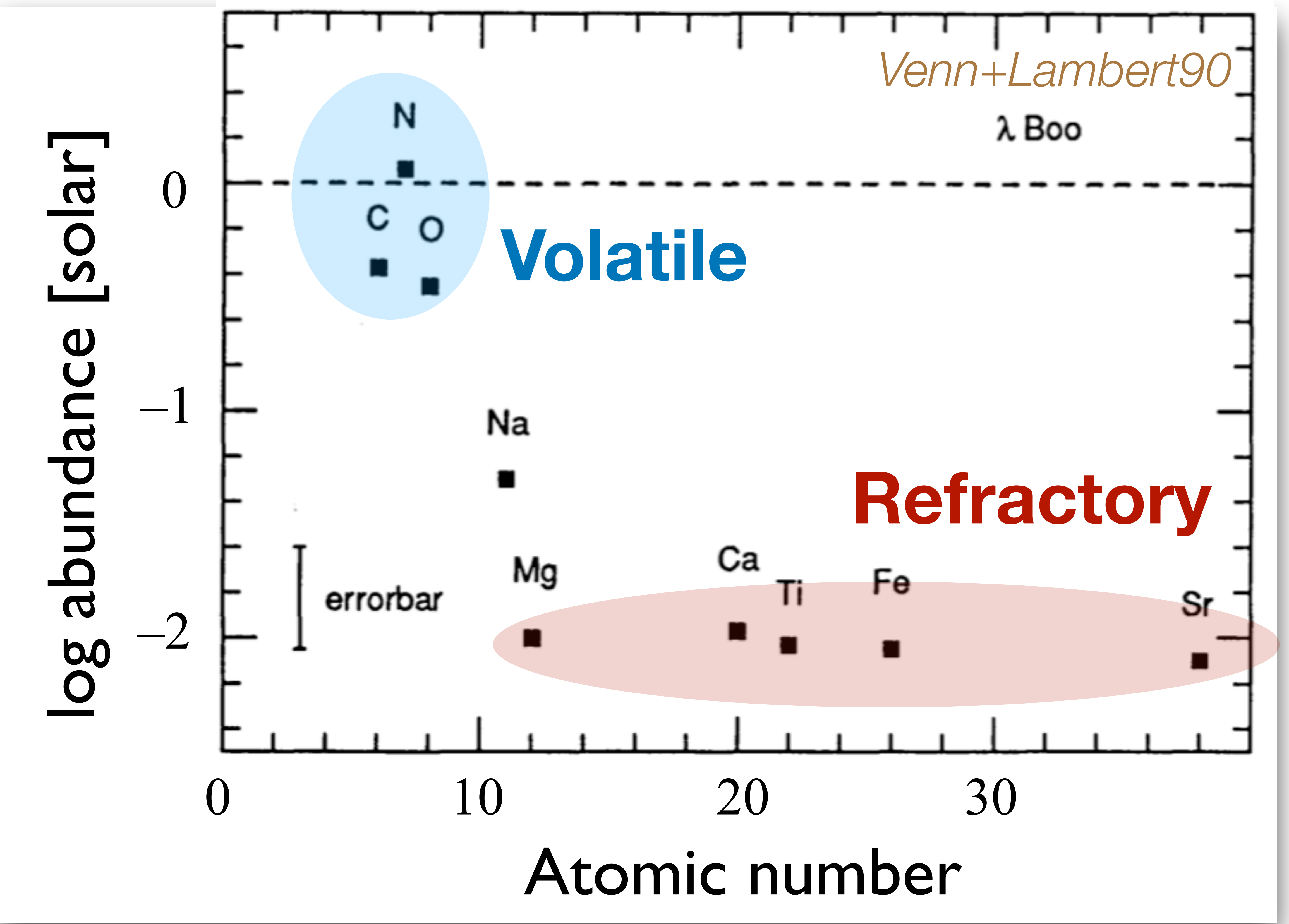
Name	Δ[Fe/H] in dex	Planet	$T_{\rm eff}$ [K]	Dilution?
16 Cyg A	+0.047	-	5830	consistent
B	0	2.4 $M_{\rm Jup}$	5751	
XO-2 N	+0.054	0.6 $M_{\rm Jup}$	≈ 5300	consistent
S	0	0.3 + 1.4 $M_{\rm Jup}$	≈ 5300	
ζ^1 Ret	+0.02	-	5710	consistent
ζ^2 Ret	0	debris disk	5854	
WASP-94 A	+0.01	0.45 $M_{\rm Jup}$	≈ 6200	inconclusive
B	0	0.62 $M_{\rm Jup}$	≈ 6100	
HD133131 A	−0.03	1.43 + 0.63 $M_{\rm Jup}$	≈ 5800	inconclusive
B	0	2.5 $M_{\rm Jup}$	≈ 5800	
HAT-P-4 A	+0.11	0.7 $M_{\rm Jup}$	6036	inconsistent
B	0	-	6037	
HD 80606	+0.013	4 $M_{\rm Jup}$	≈ 5600	inconsistent
80607	0	-	≈ 5500	

Implications for observed puzzles

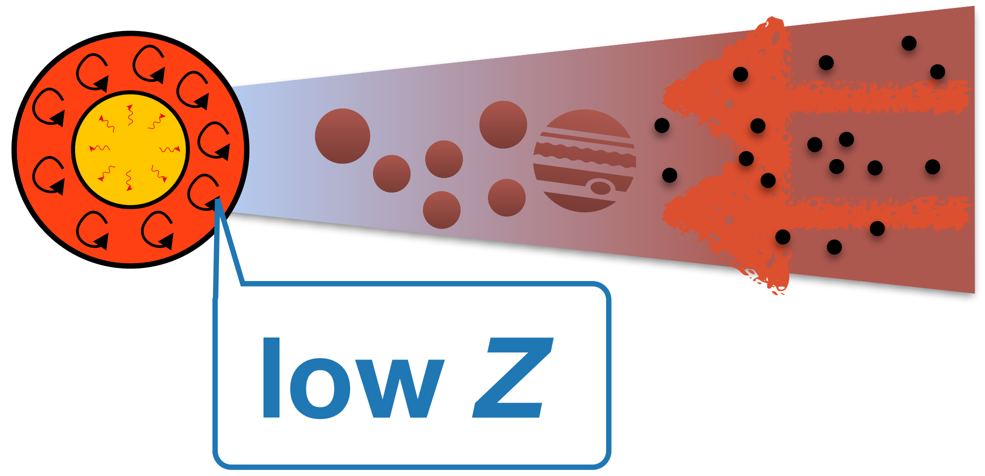


- ✔ Composition anomaly in binaries
- ✔ **λ Boö stars: refractory-poor A stars**
- Composition anomaly in solar twins

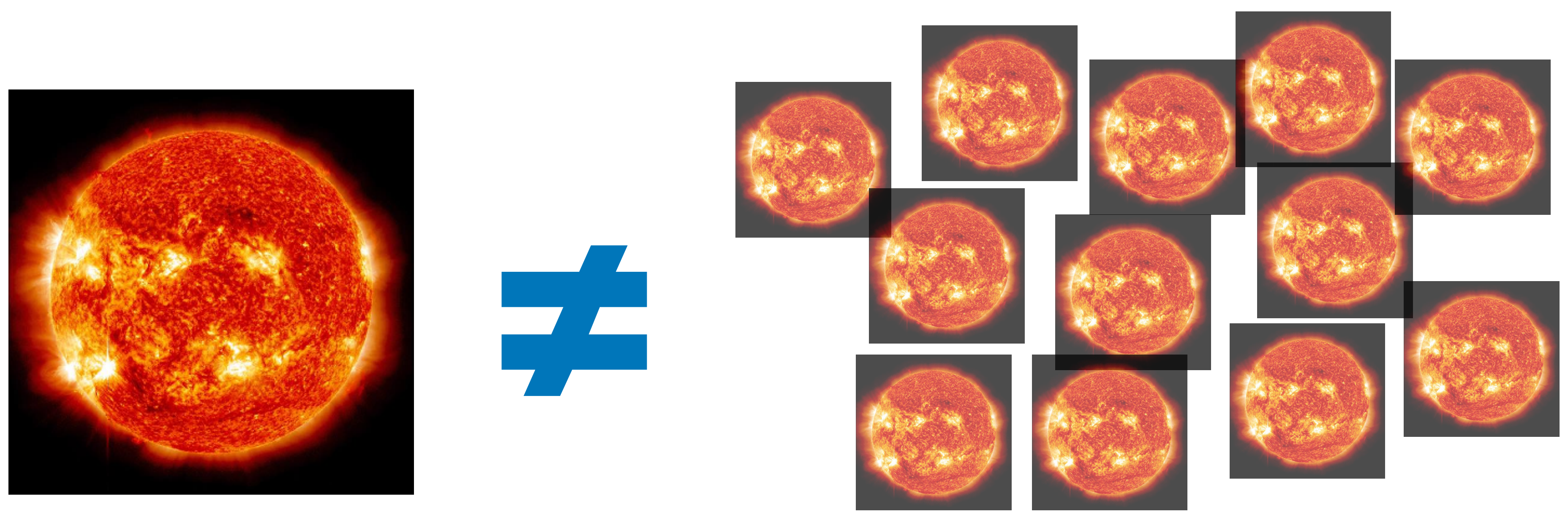




Implications for observed puzzles

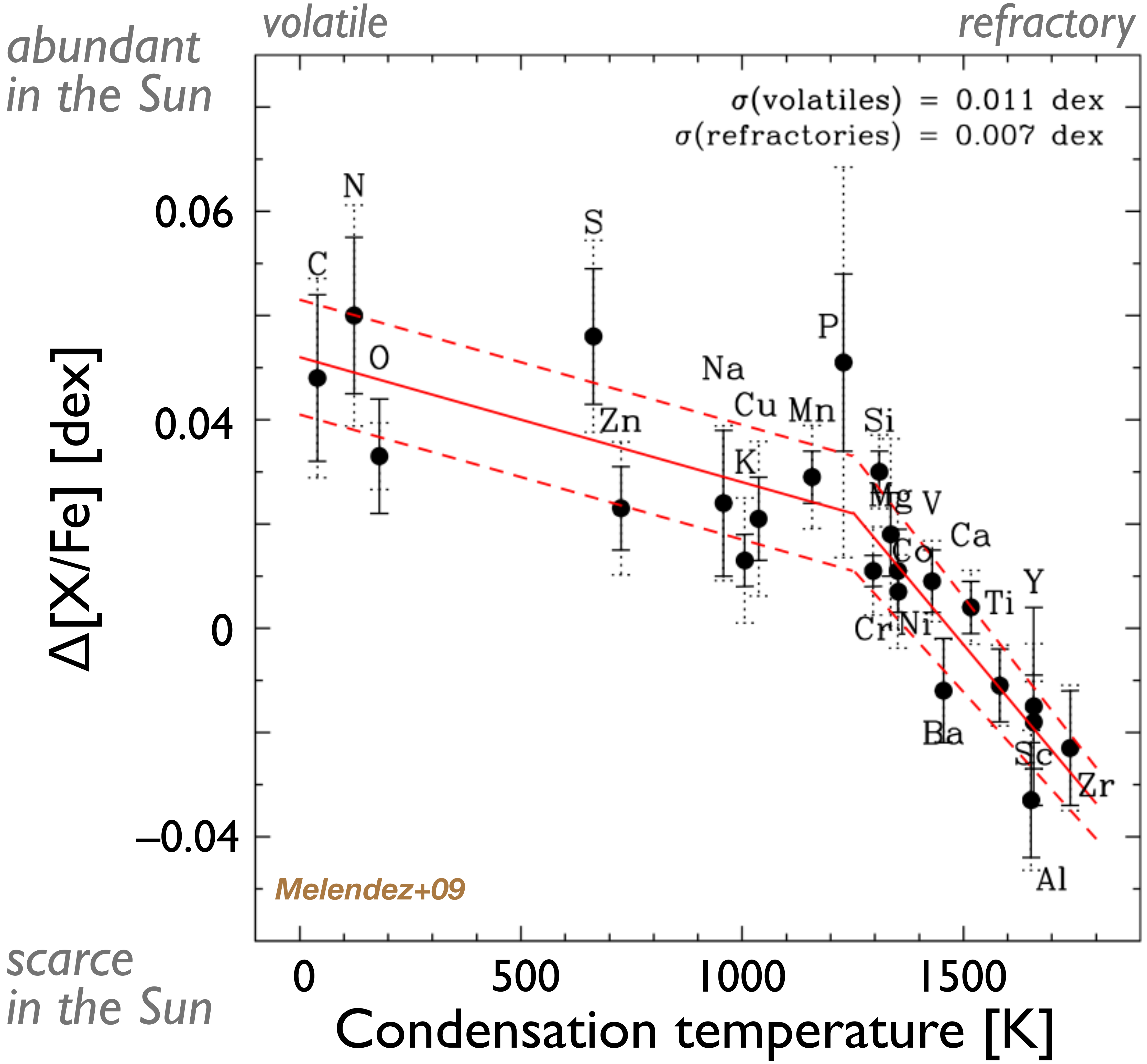


- ✔ Composition anomaly in binaries
- ✔ λ Boö stars: refractory-poor A stars
- △ **Composition anomaly in solar twins**

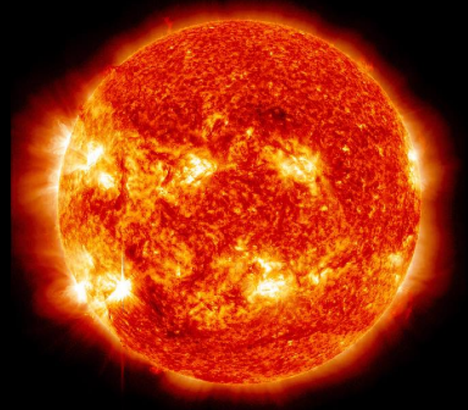


~10% solar twins (incl. the Sun!) have refractory-poor compositions

Solar abundances normalized by the average of solar twins



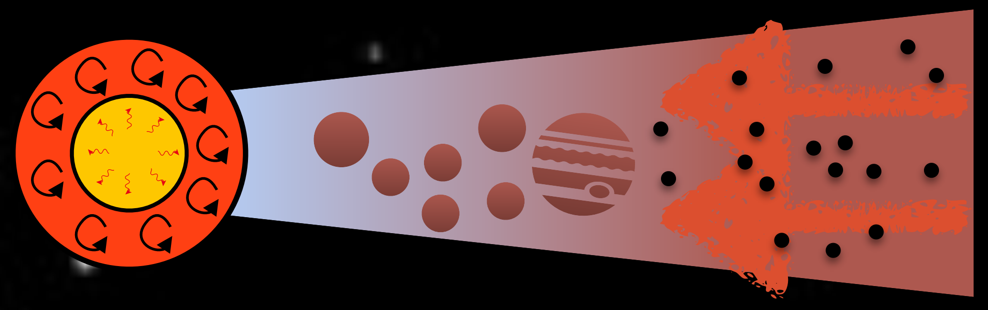
Two scenarios



Accretion signature?

Solar surface is diluted by the accretion of disk gas where many planets are formed?

low-*Z* accretion



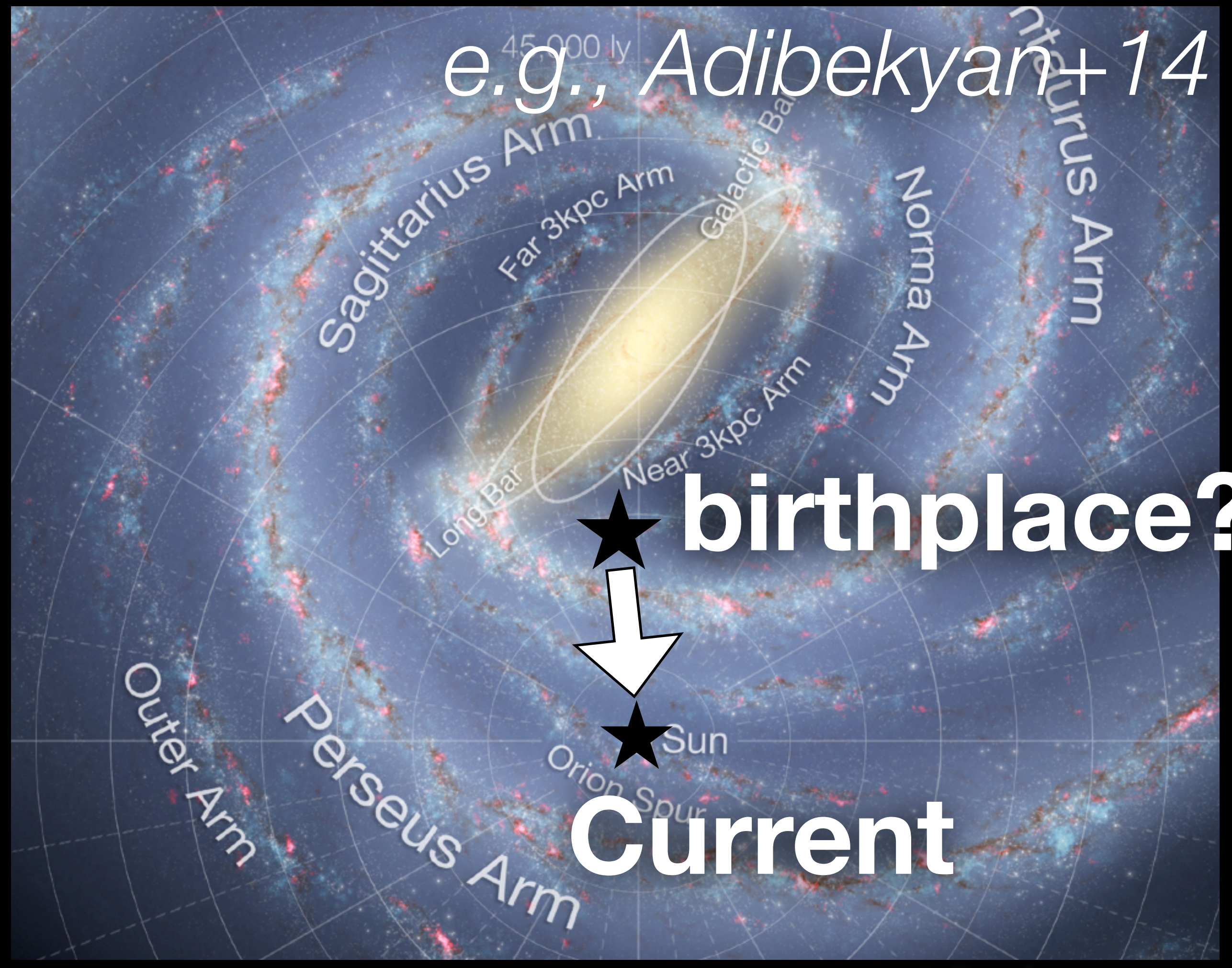
e.g., Chambers10

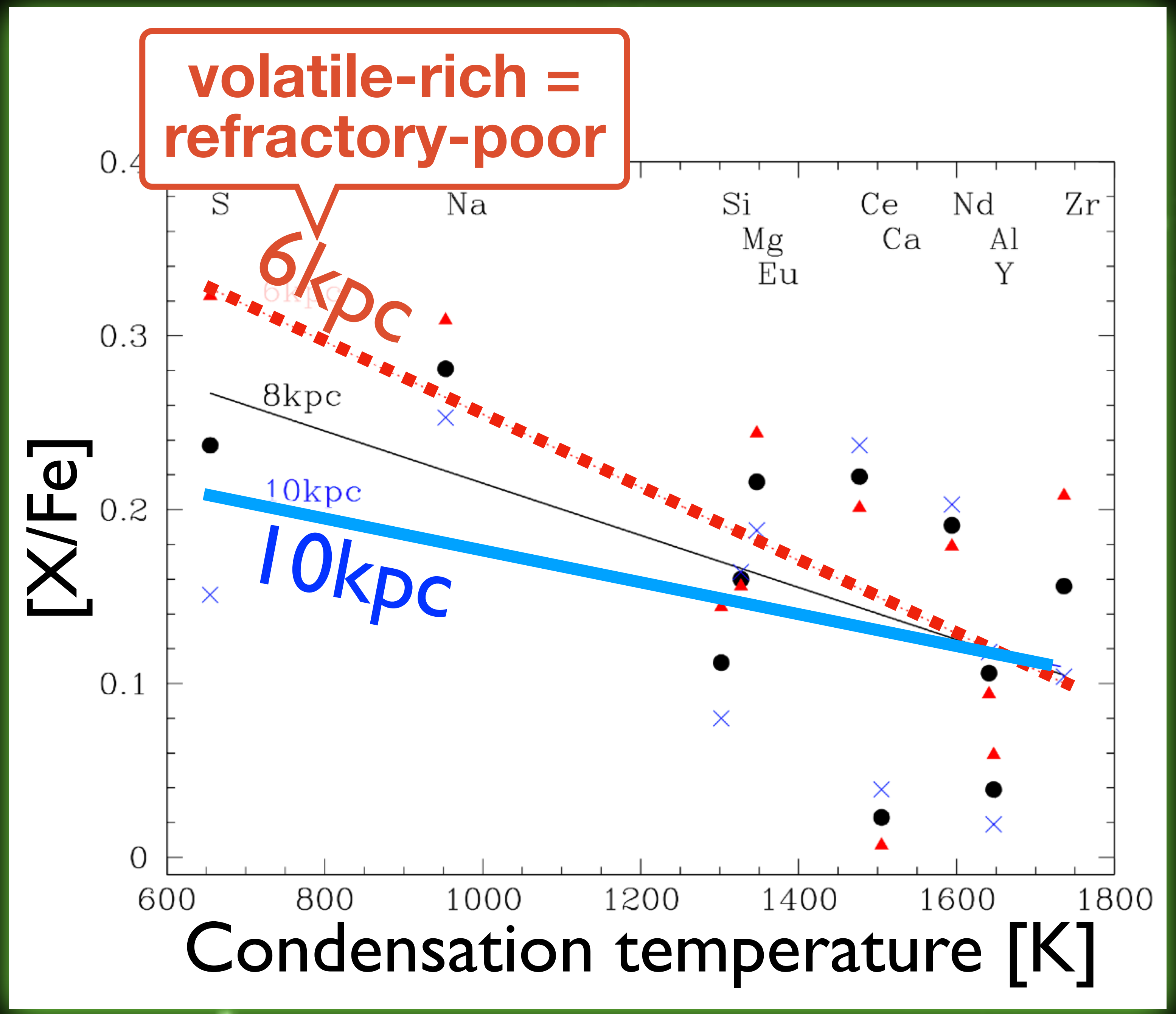
quantitatively not enough

Kunitomo+18

Galactic origin?

Inner Galaxy is refractory-poor
➔ Outward migration of the Sun induced the difference?





Adibekyan+14

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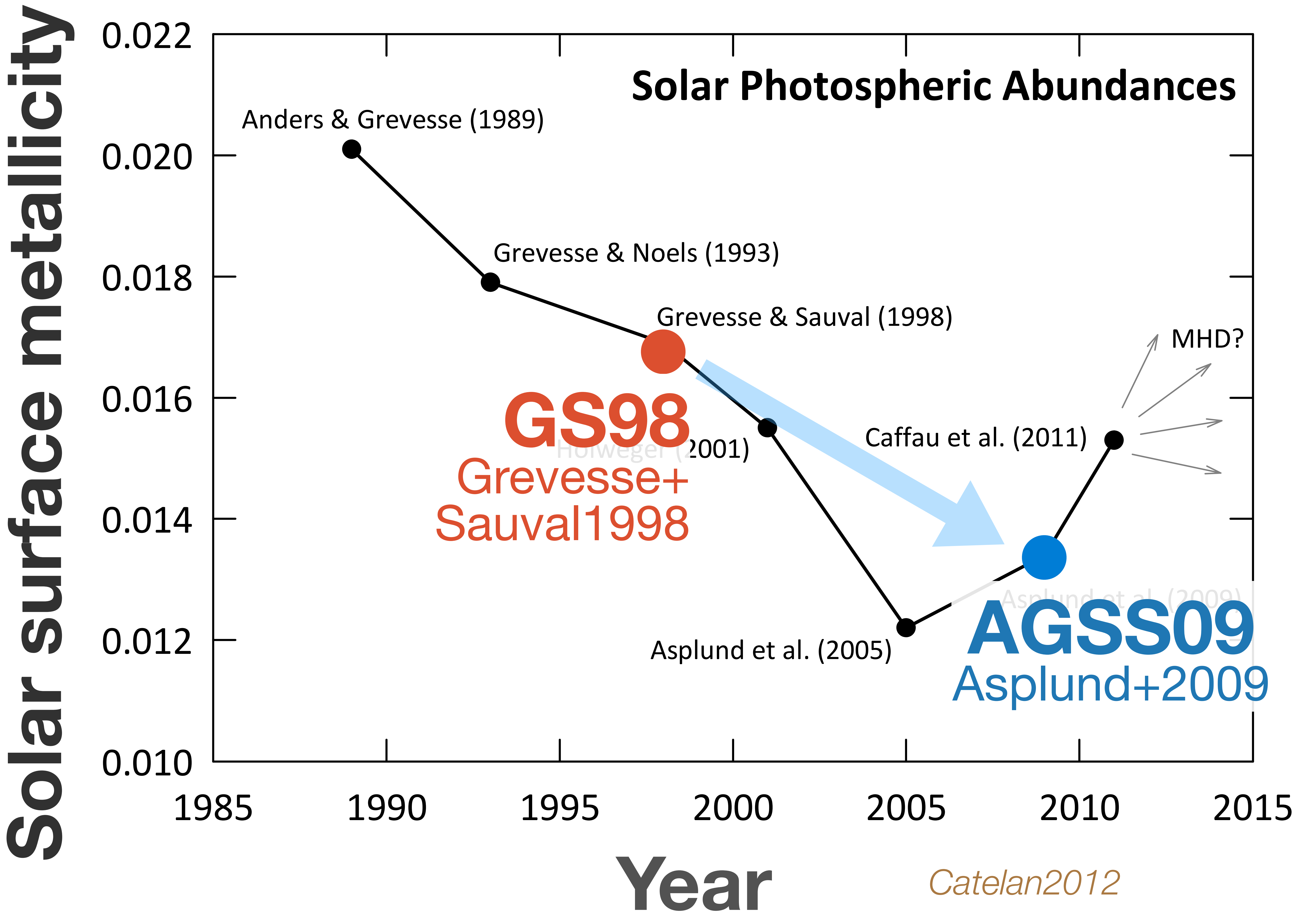
  - spectroscopicopy, helioseismology, **neutrinos**

Revision of the solar surface composition



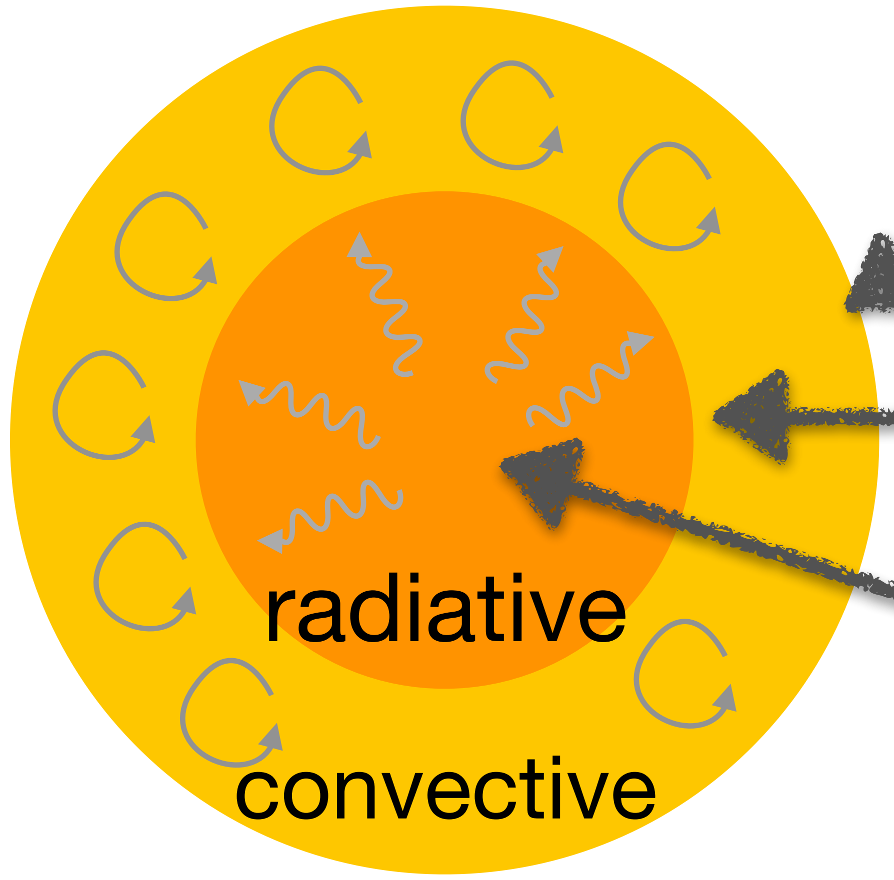
Catelan2012

Decrease by ~30% (!)

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

See also Asplund+2021

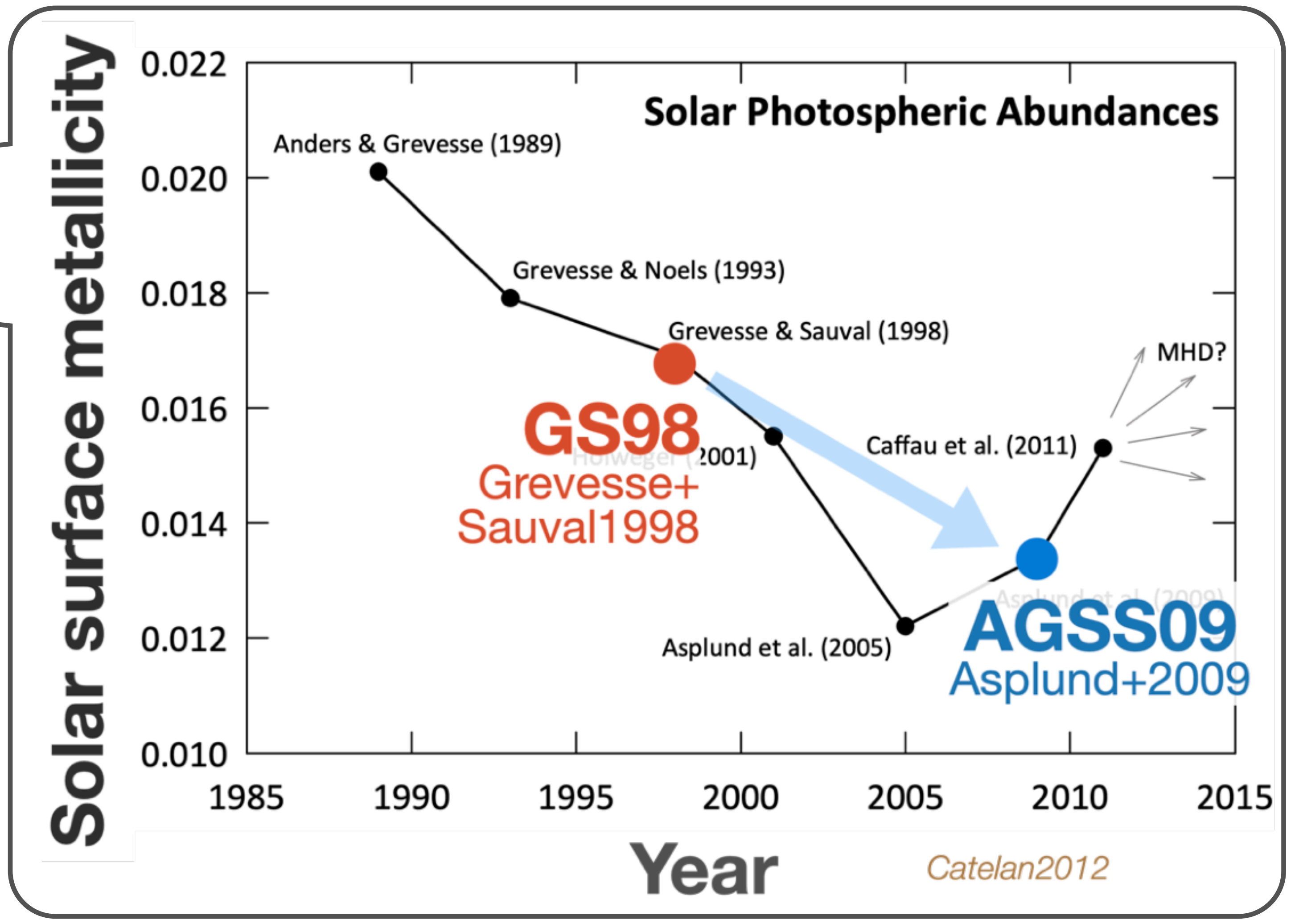
“Solar modeling problem”



Spectroscopy

Helioseismology

Neutrinos



Models w/ **GS98**

✓ Helioseismology

✓ Neutrinos

→

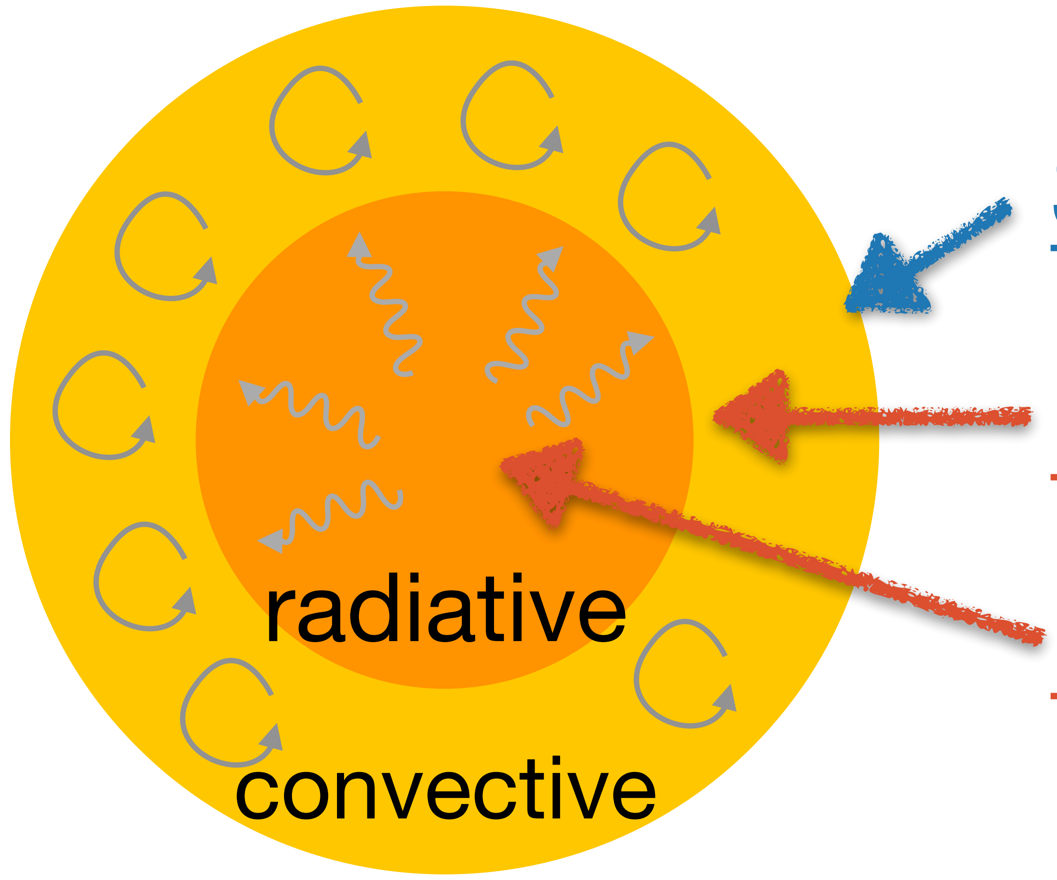
Models w/ **AGSS09**

✗ 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

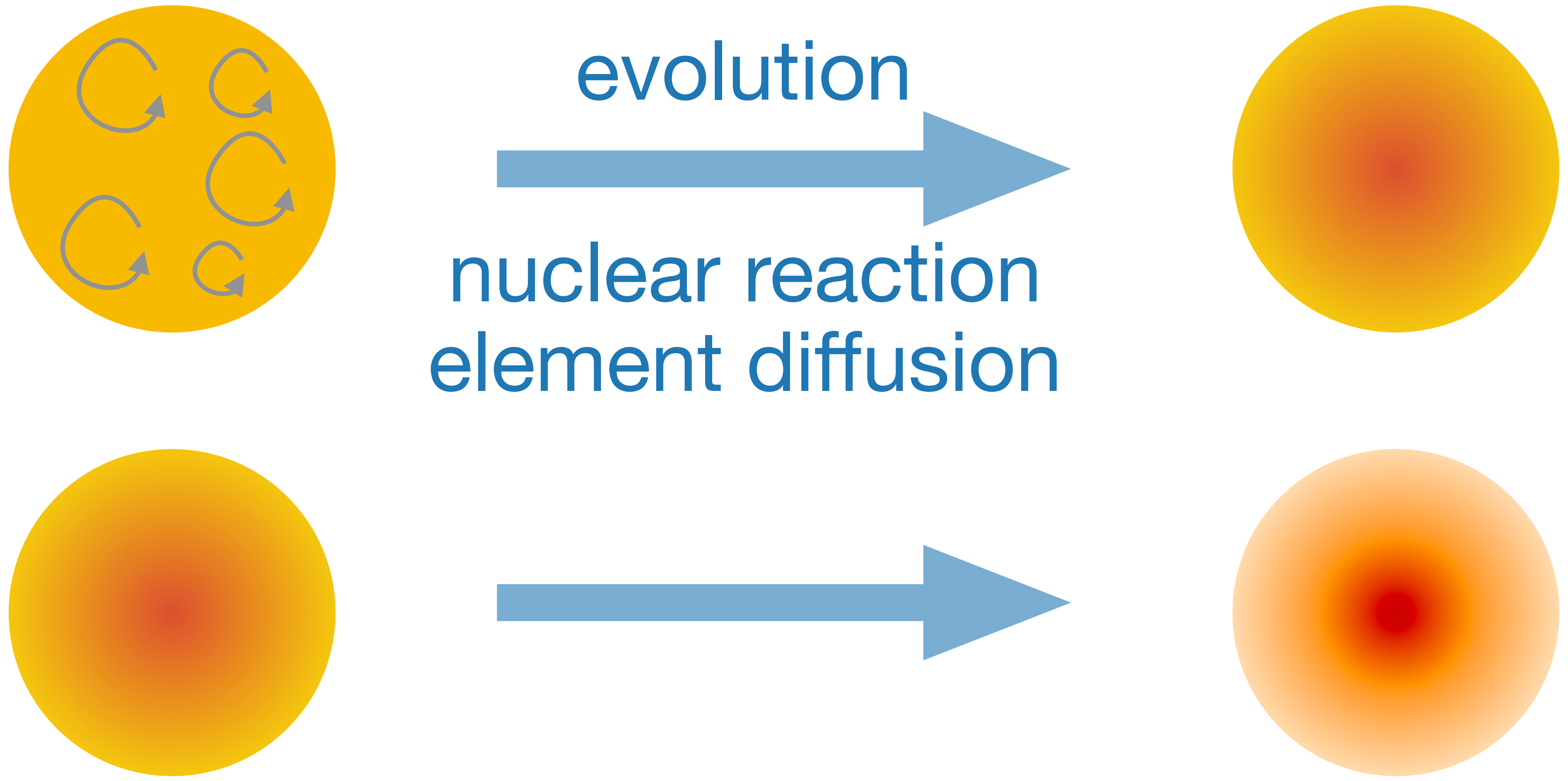
Neutrinos: high-Z

Composition gradient
in the solar interior?

proto-Sun | present day

standard solar models

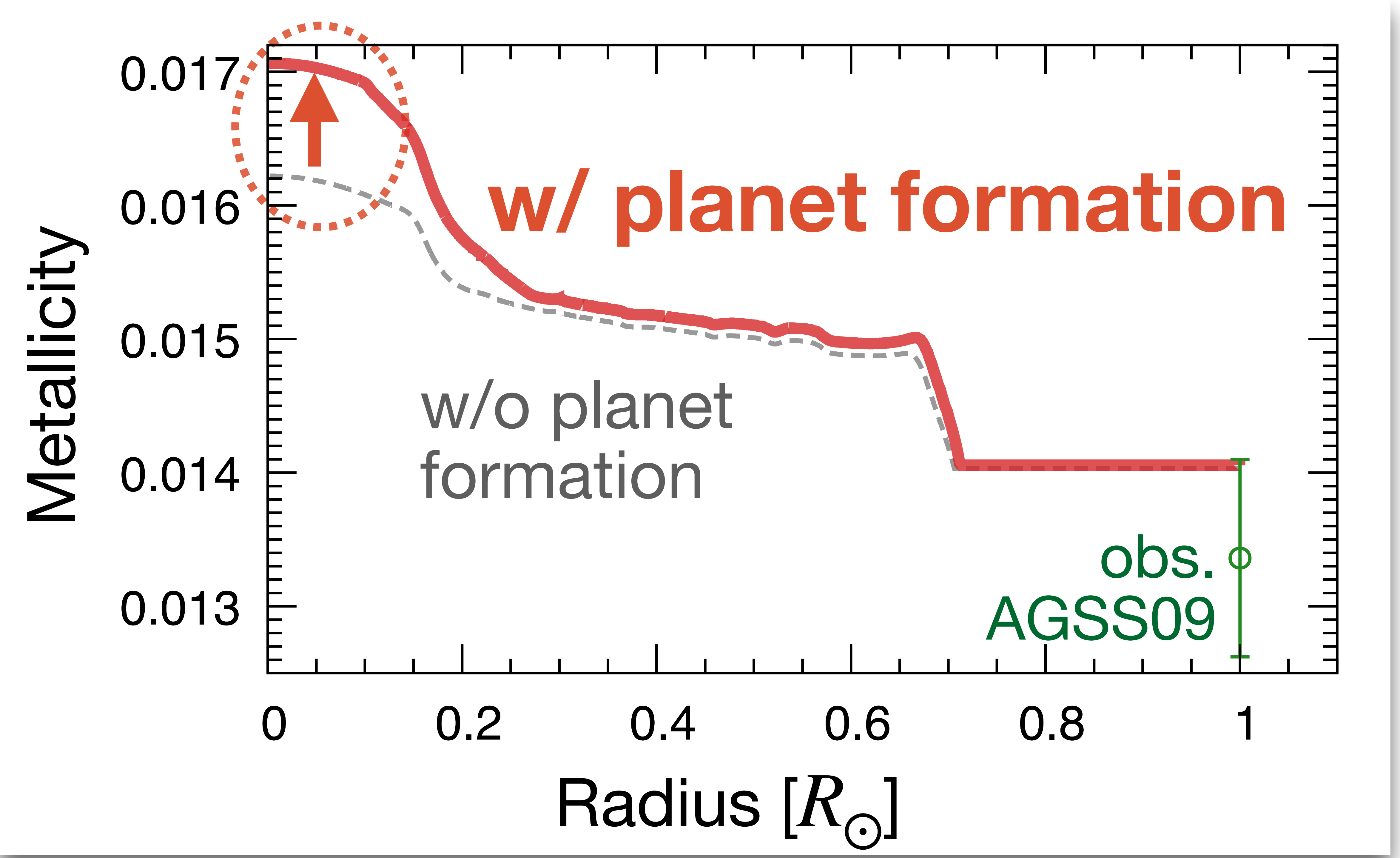
this study



Small composition gradient

Larger gradient due to
star formation processes?

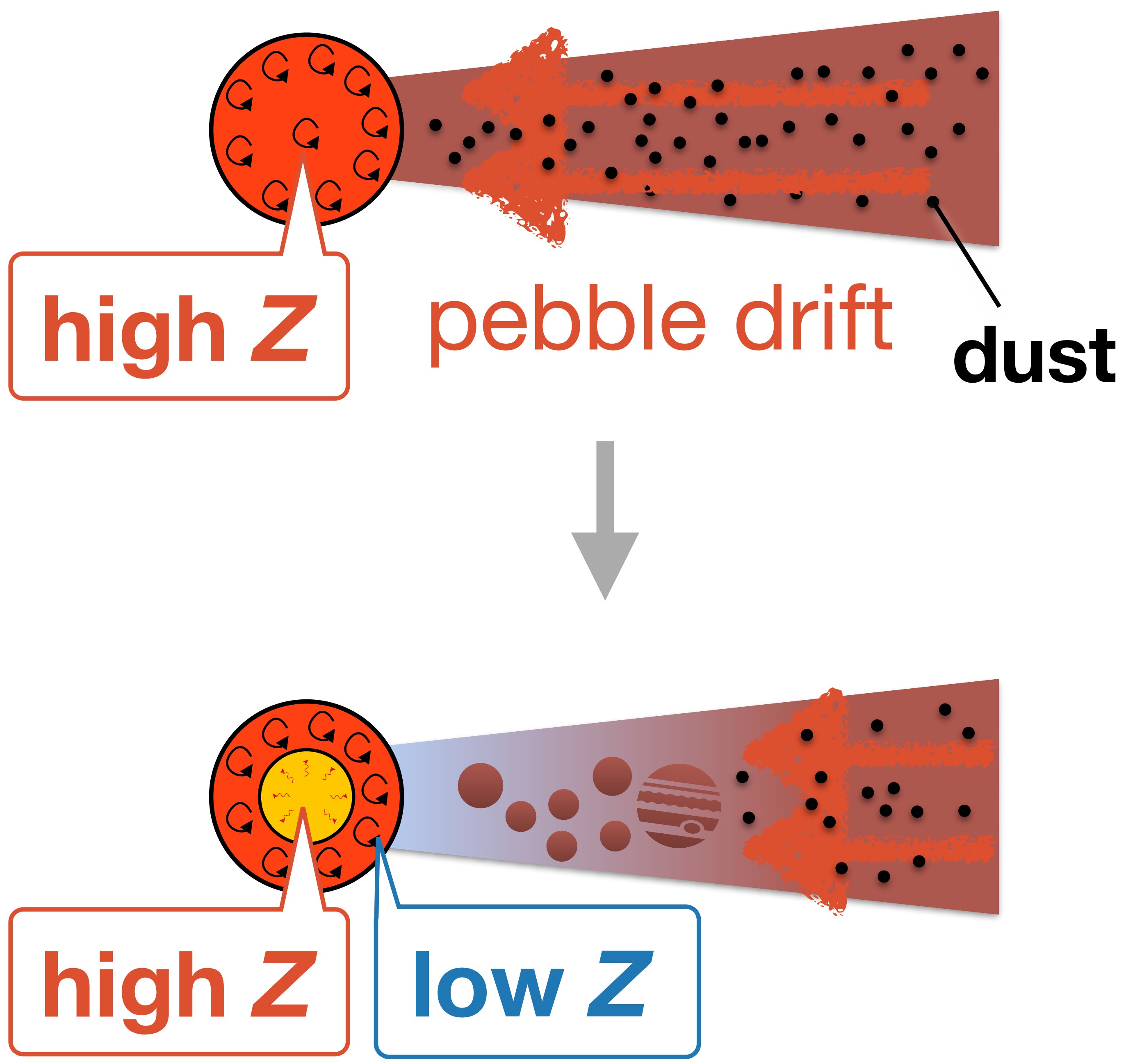
Metallicity profile of the present-day Sun



Kunitomo+Guillot 2021

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

What governs the central metallicity?



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)

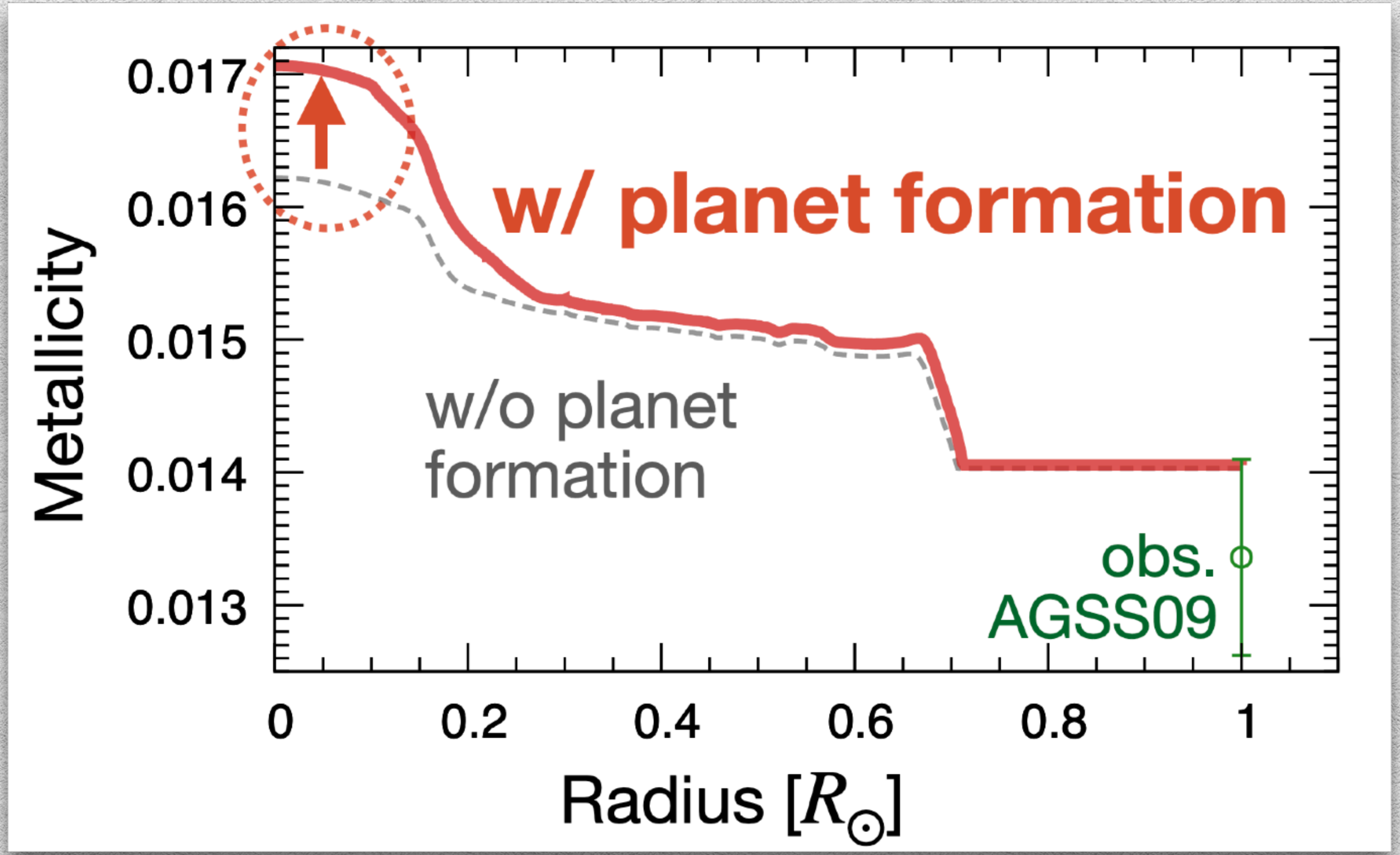
➔ **low-Z solar surface**

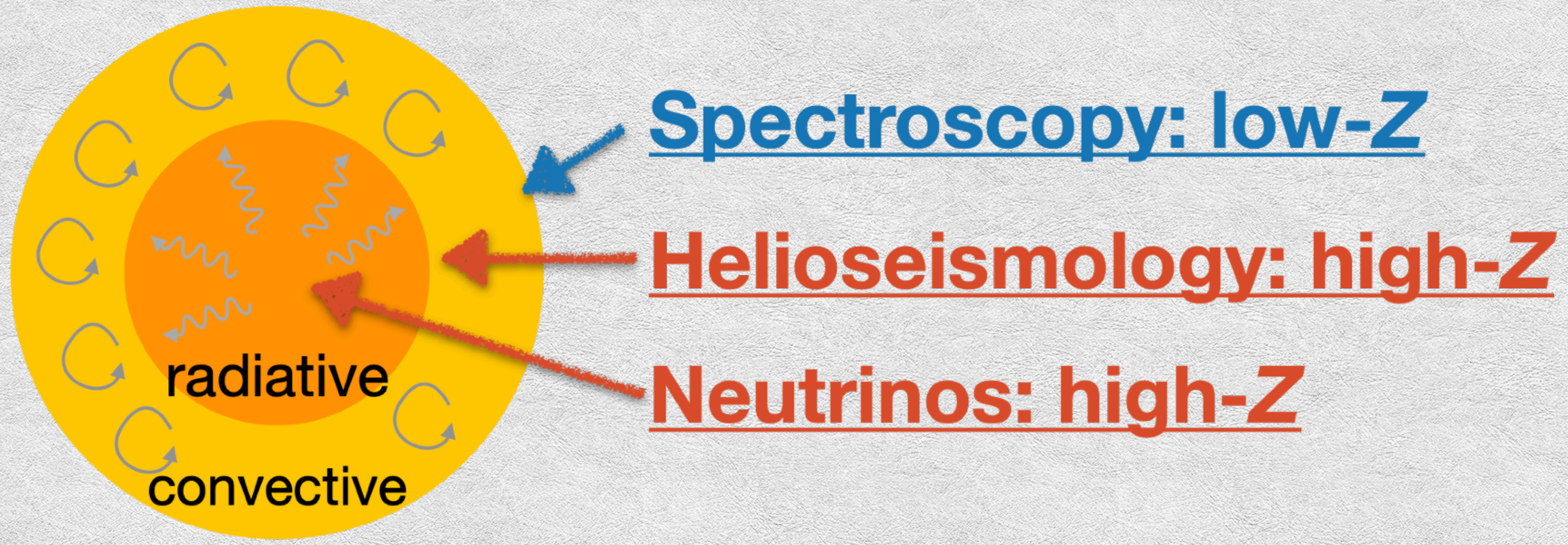
- central region becomes **radiative**

➔ **high-Z core** remains

composition gradient!

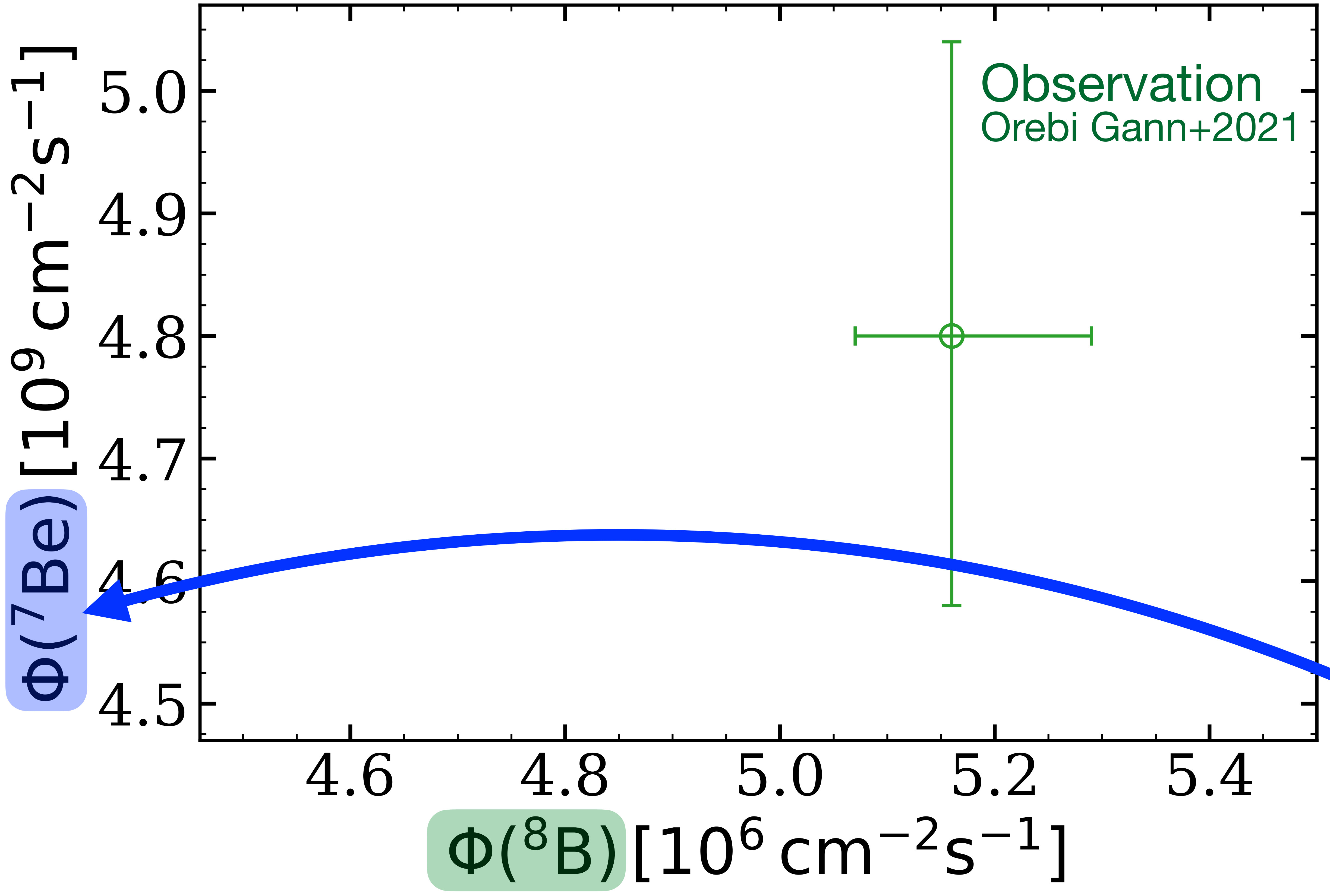
only in the radiative central region



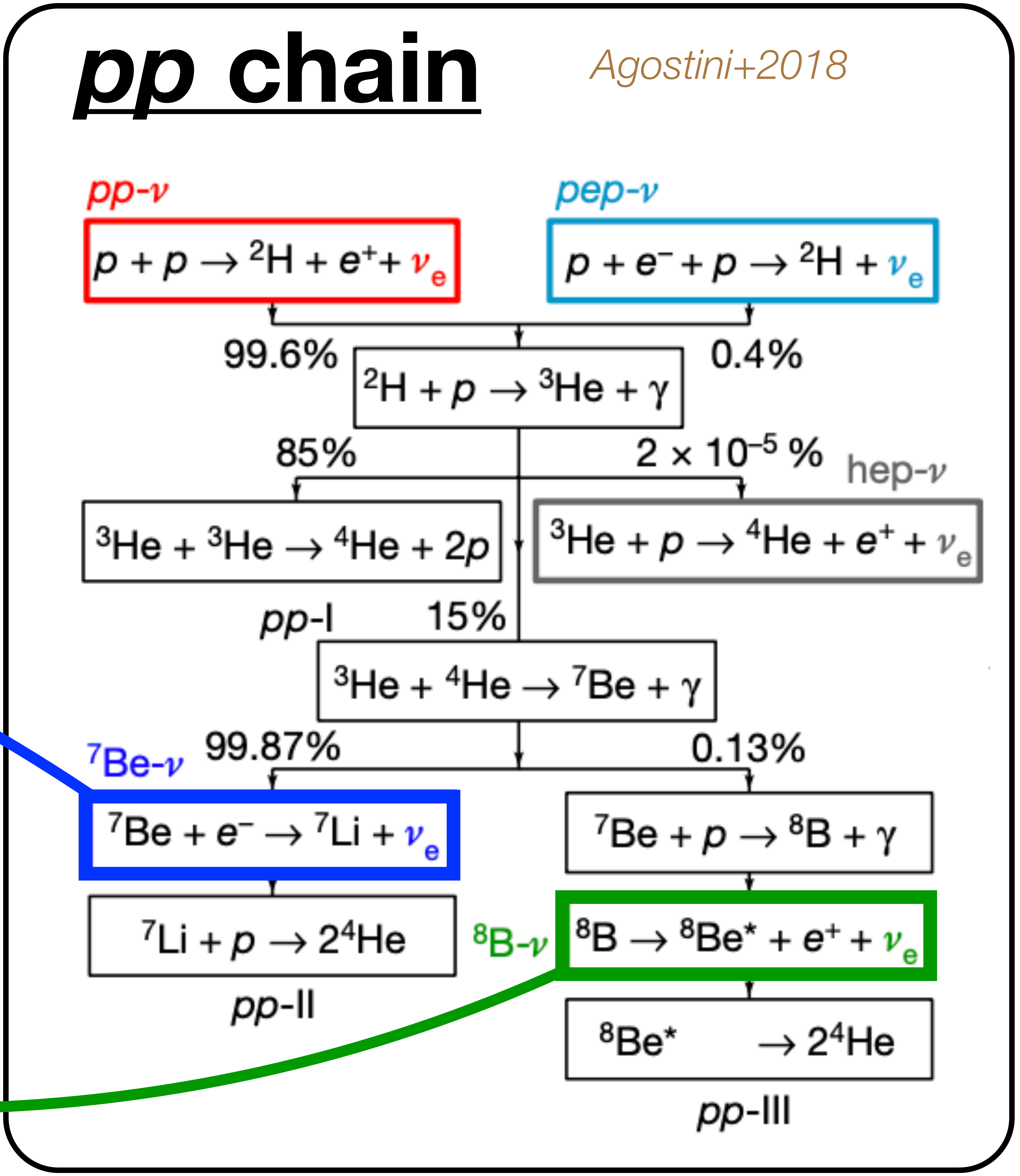


Does the compositional gradient affect solar neutrino fluxes?

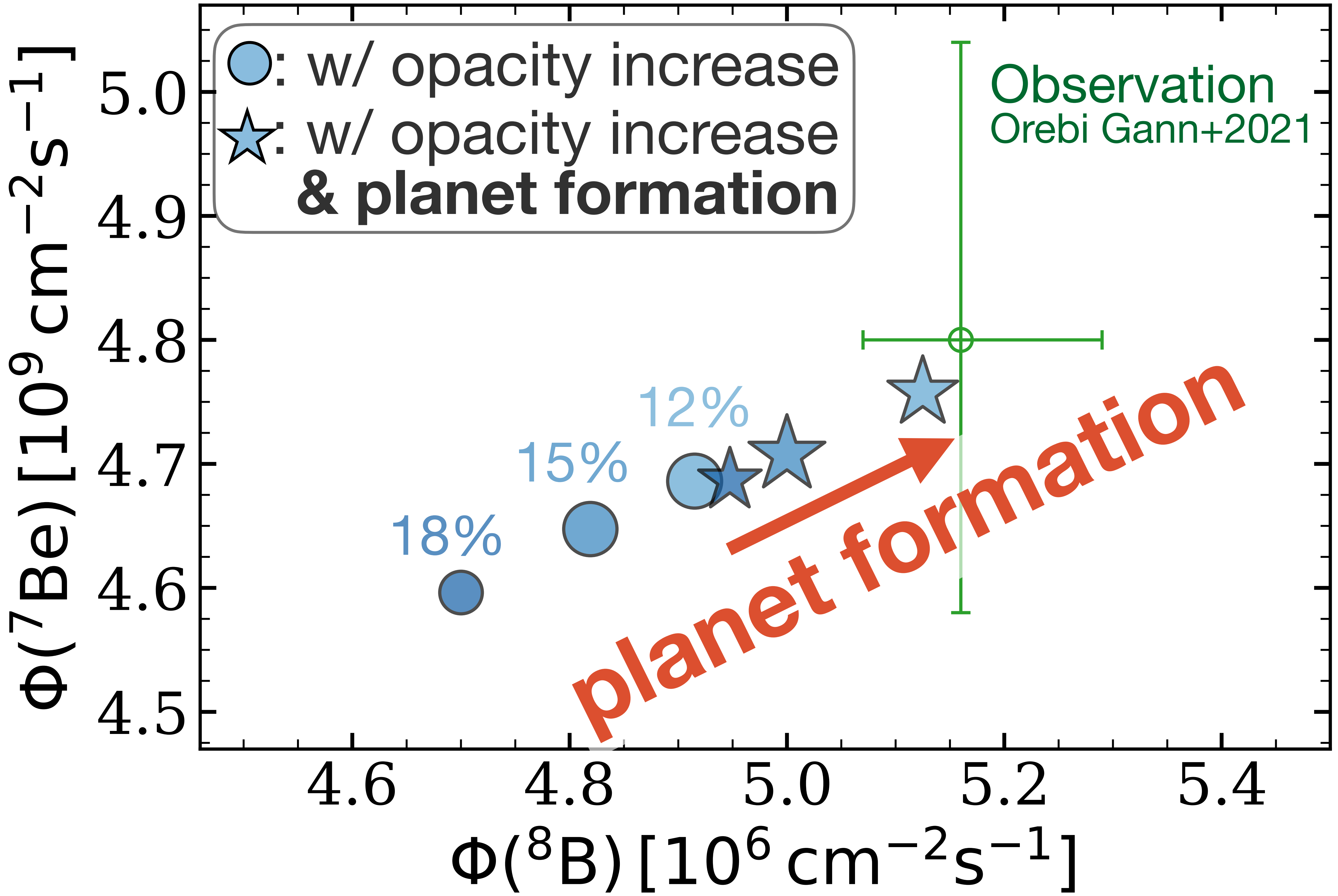
Planet formation affects neutrino fluxes



All flavors @ Earth



Planet formation affects neutrino fluxes



All flavors @ Earth

Kunitomo+2022

- 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 processes increase neutrino fluxes

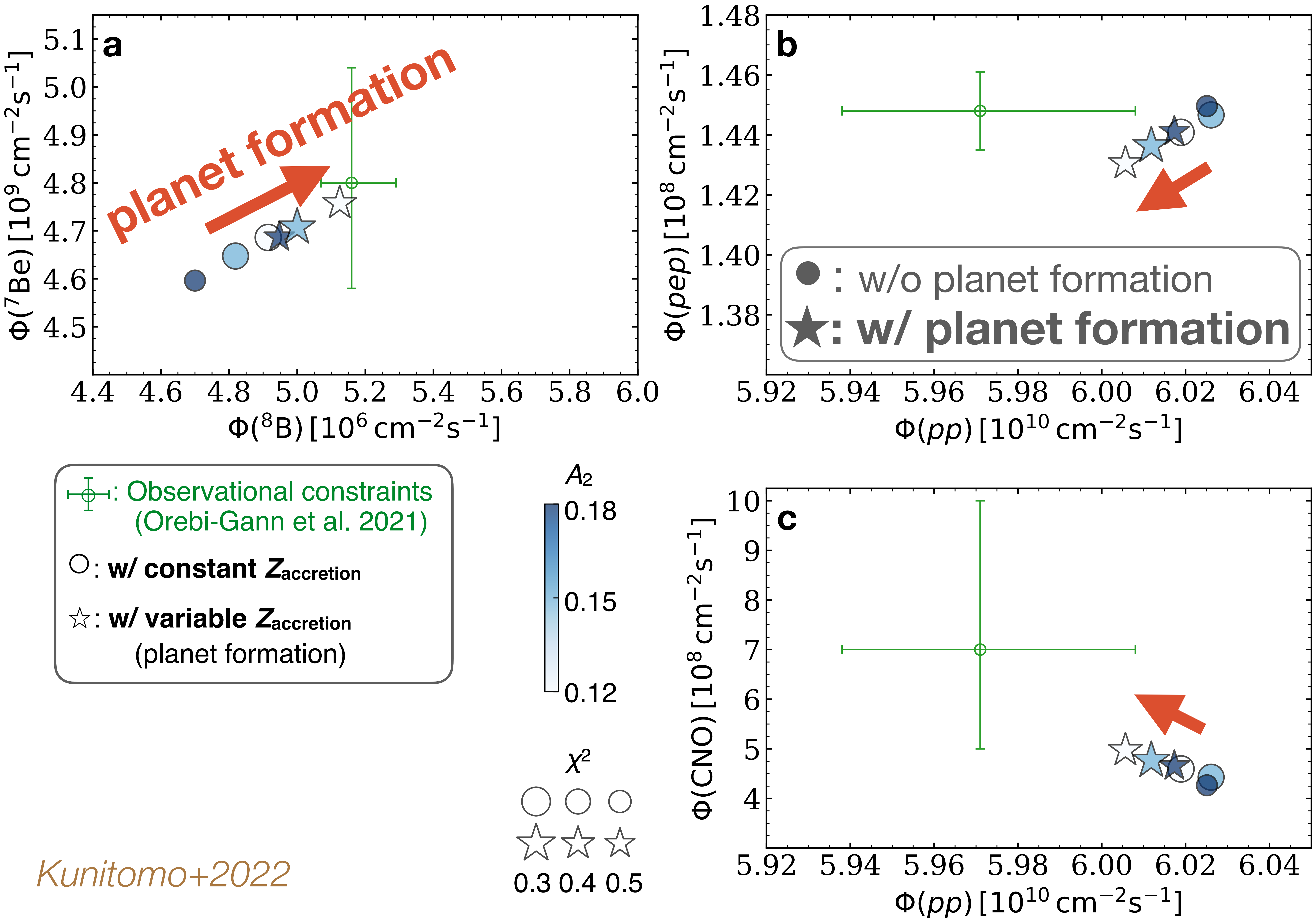
  → **consistent with neutrino obs.!**

  see also Serenelli+2011, Zhang+2019

Neutrino, helioseismic & spectroscopic observations can be reproduced

Solar modeling 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?

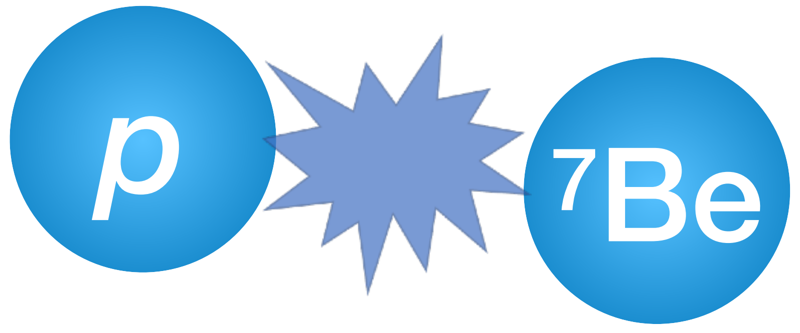
Neutrino fluxes
(= nuclear reaction rates) strongly
depend on **temperature**

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

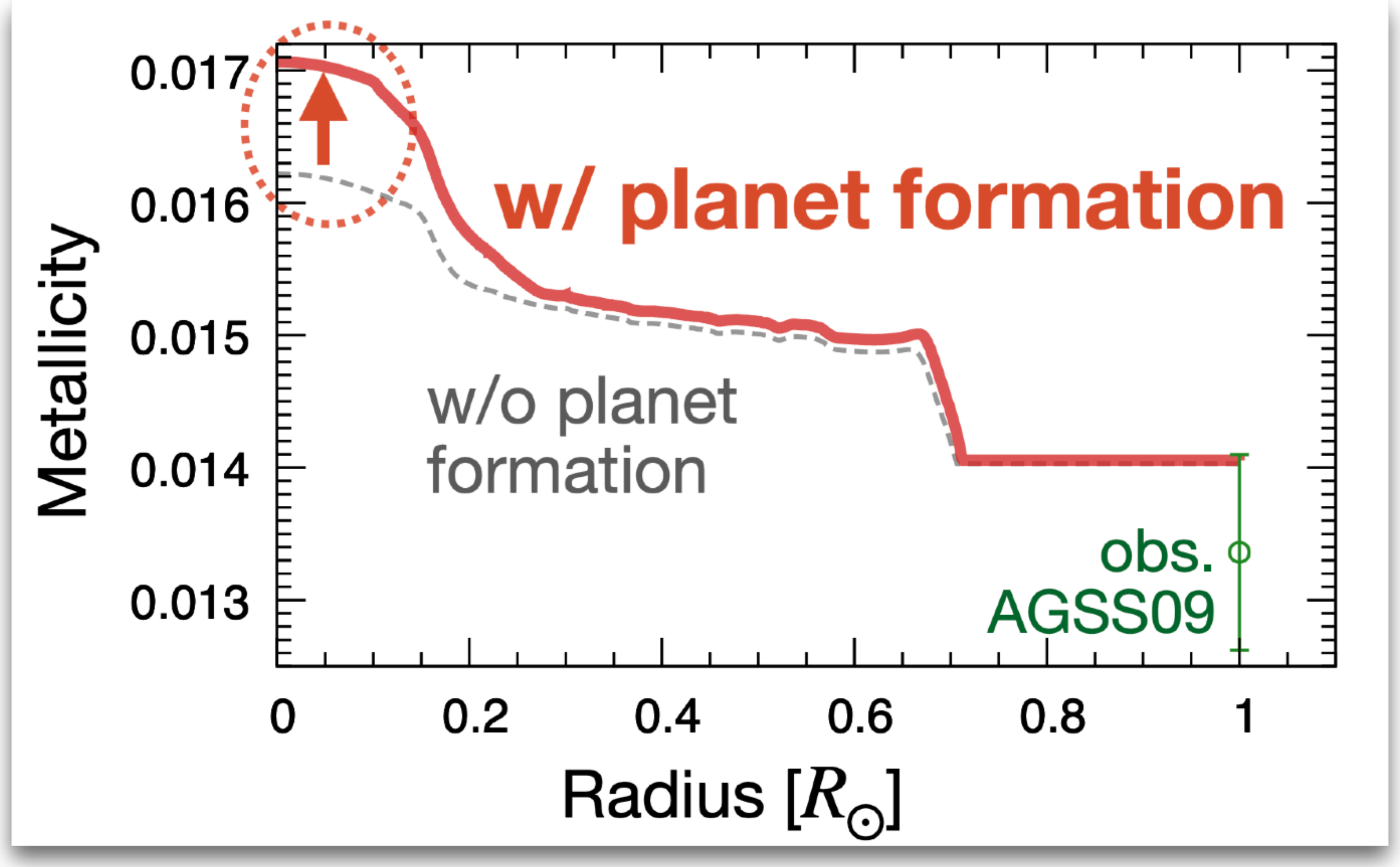
Bahcall+Ulmer1996

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

thermal energy ~ keV (~10^7 K)



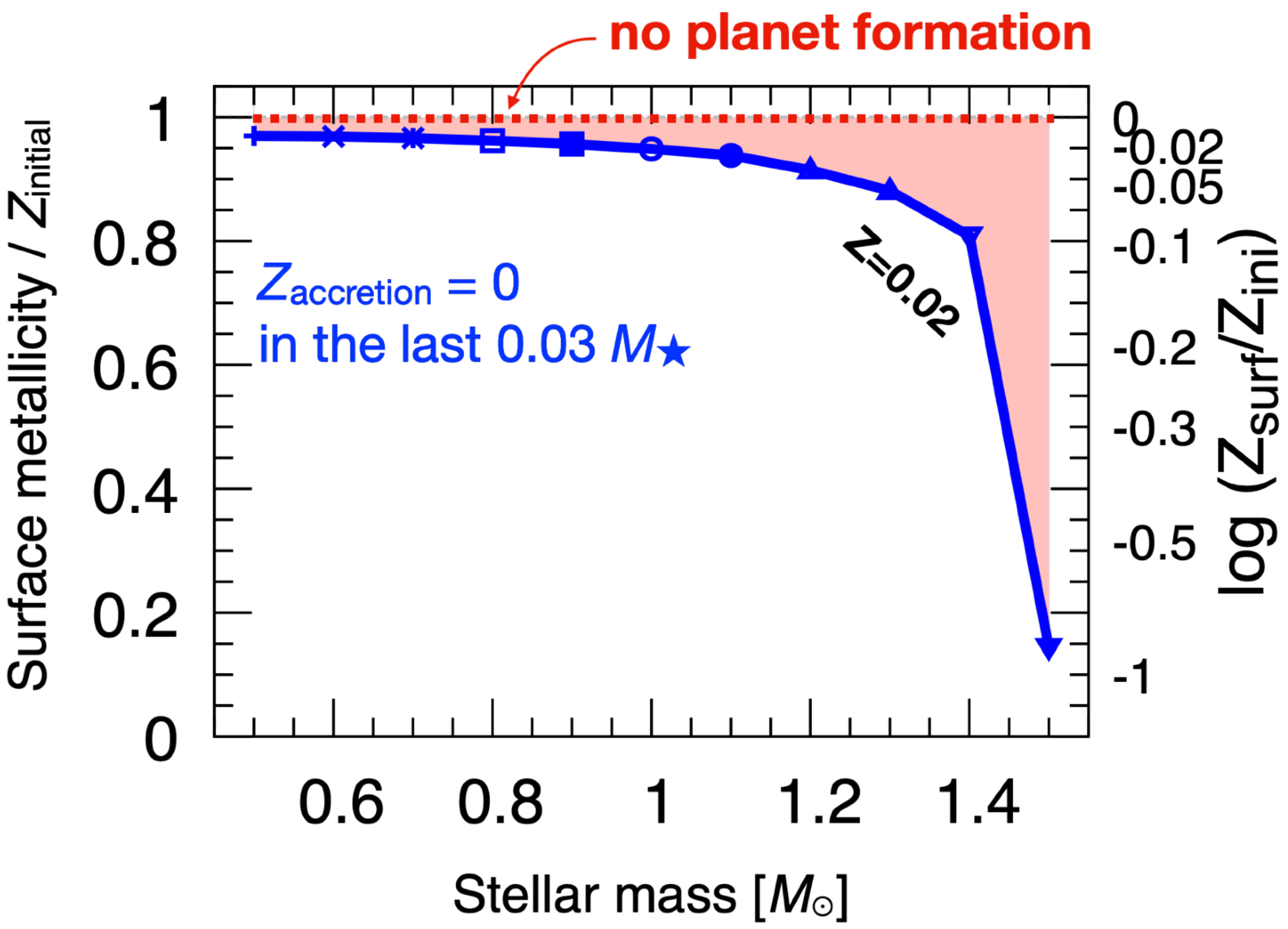
~MeV Coulomb barrier vs **tunnel effect**



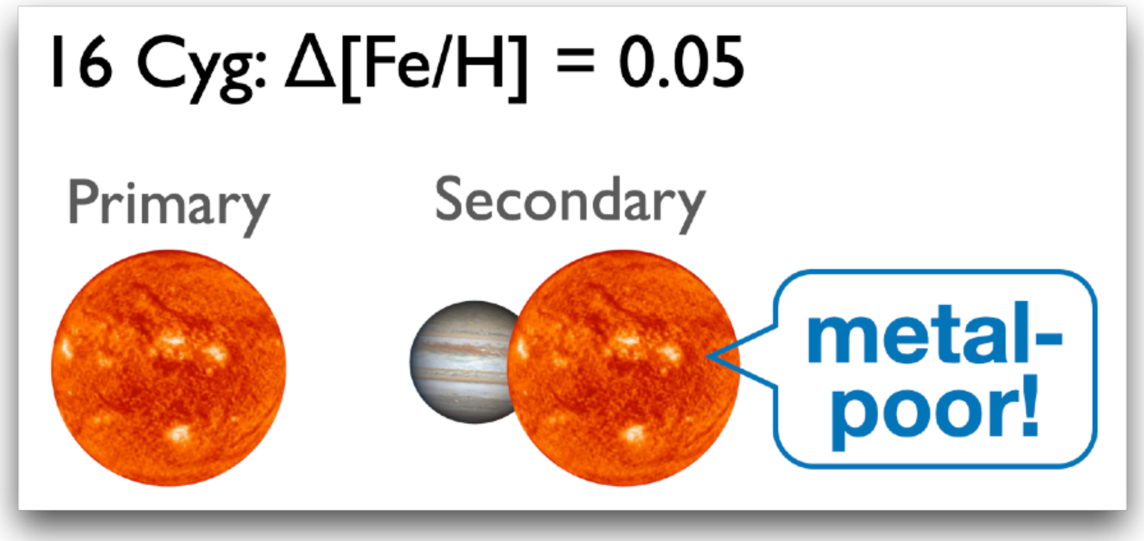
Future prospects

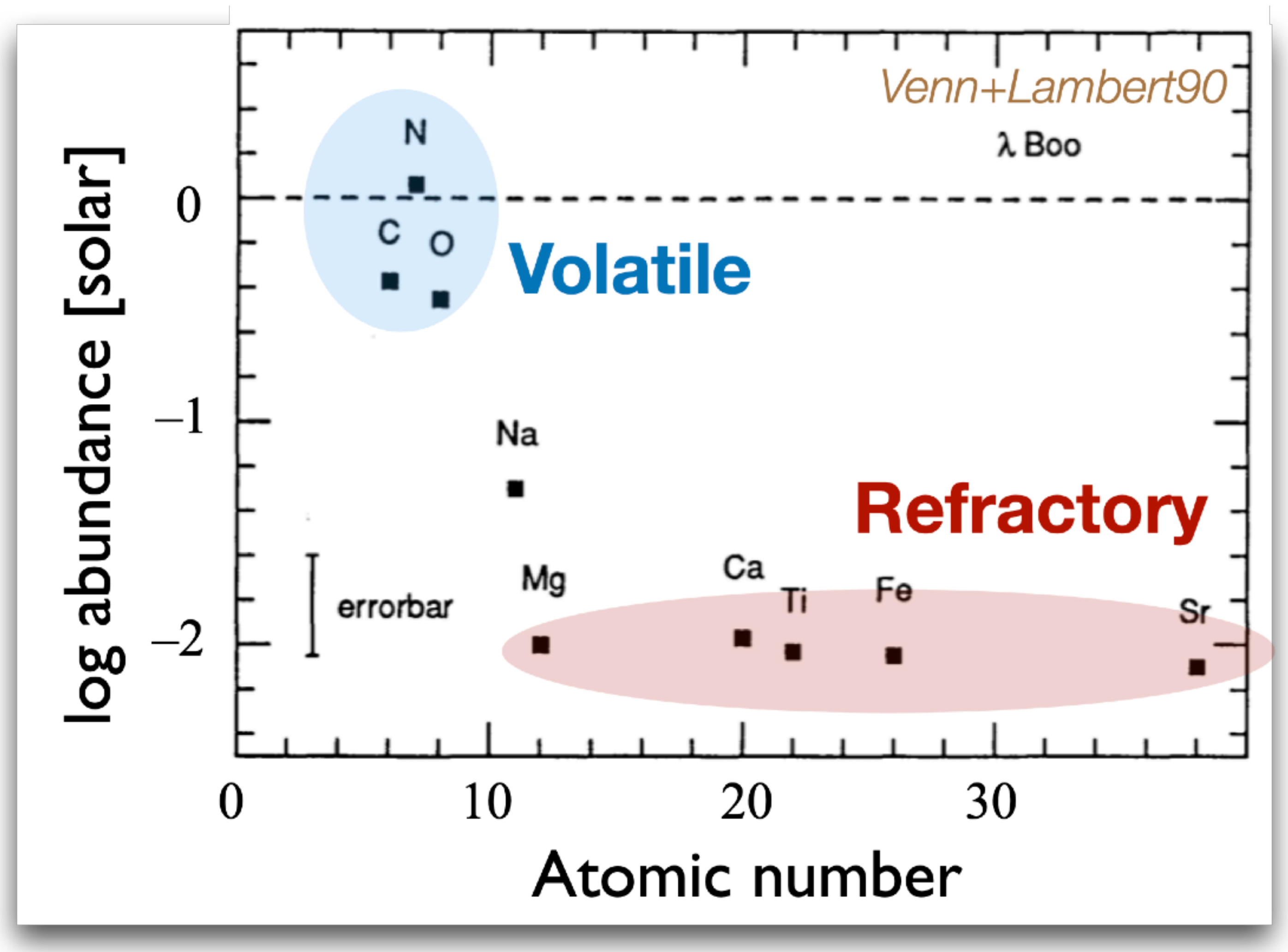
Comparison w/ large samples

- Surface Z by GAIA, planet population by PLATO



- Scatter in the shaded region?
- Correlation with planets?





Future prospects

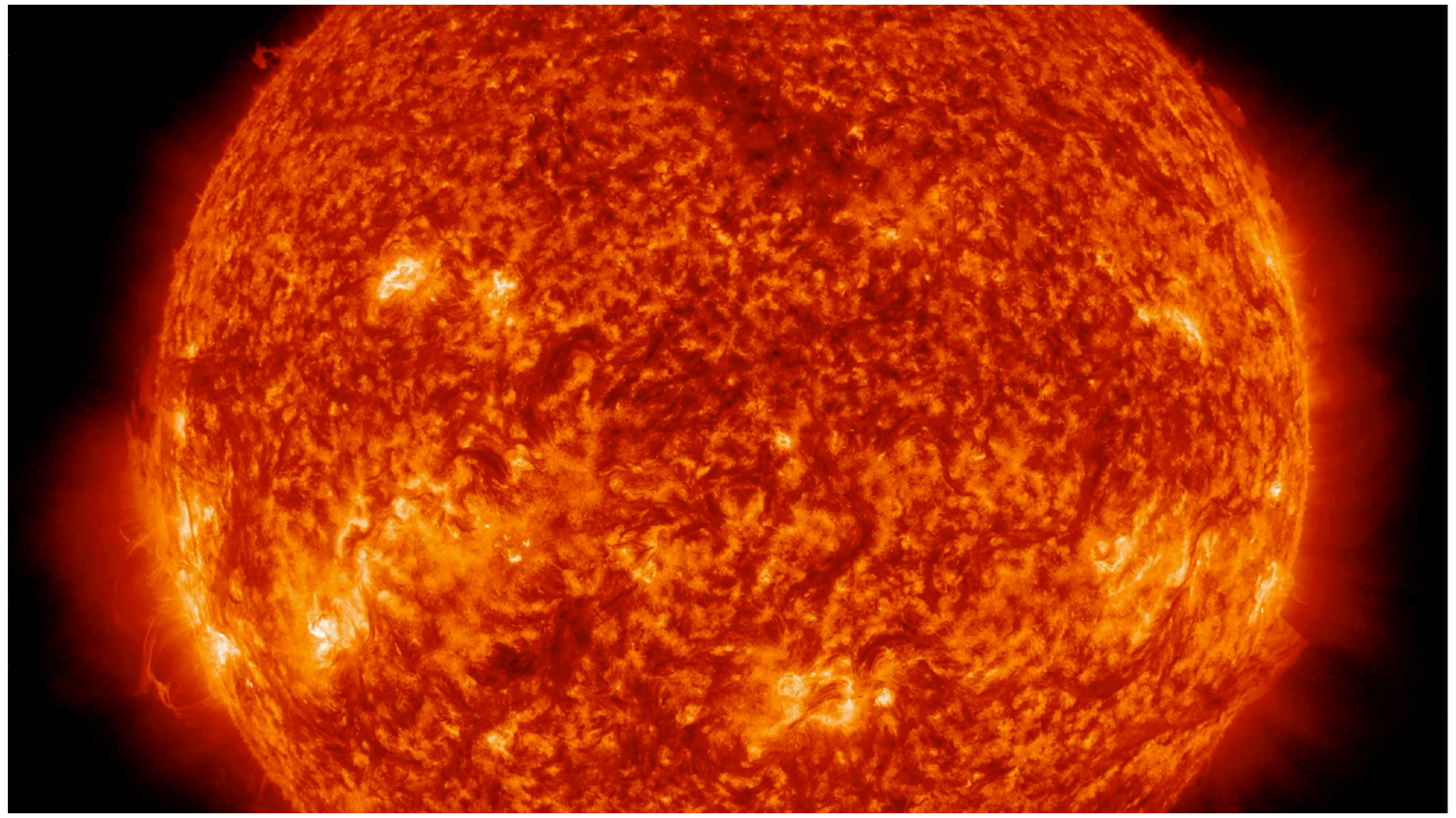
Comparison w/ large samples

- Surface Z by GAIA, planet population by PLATO

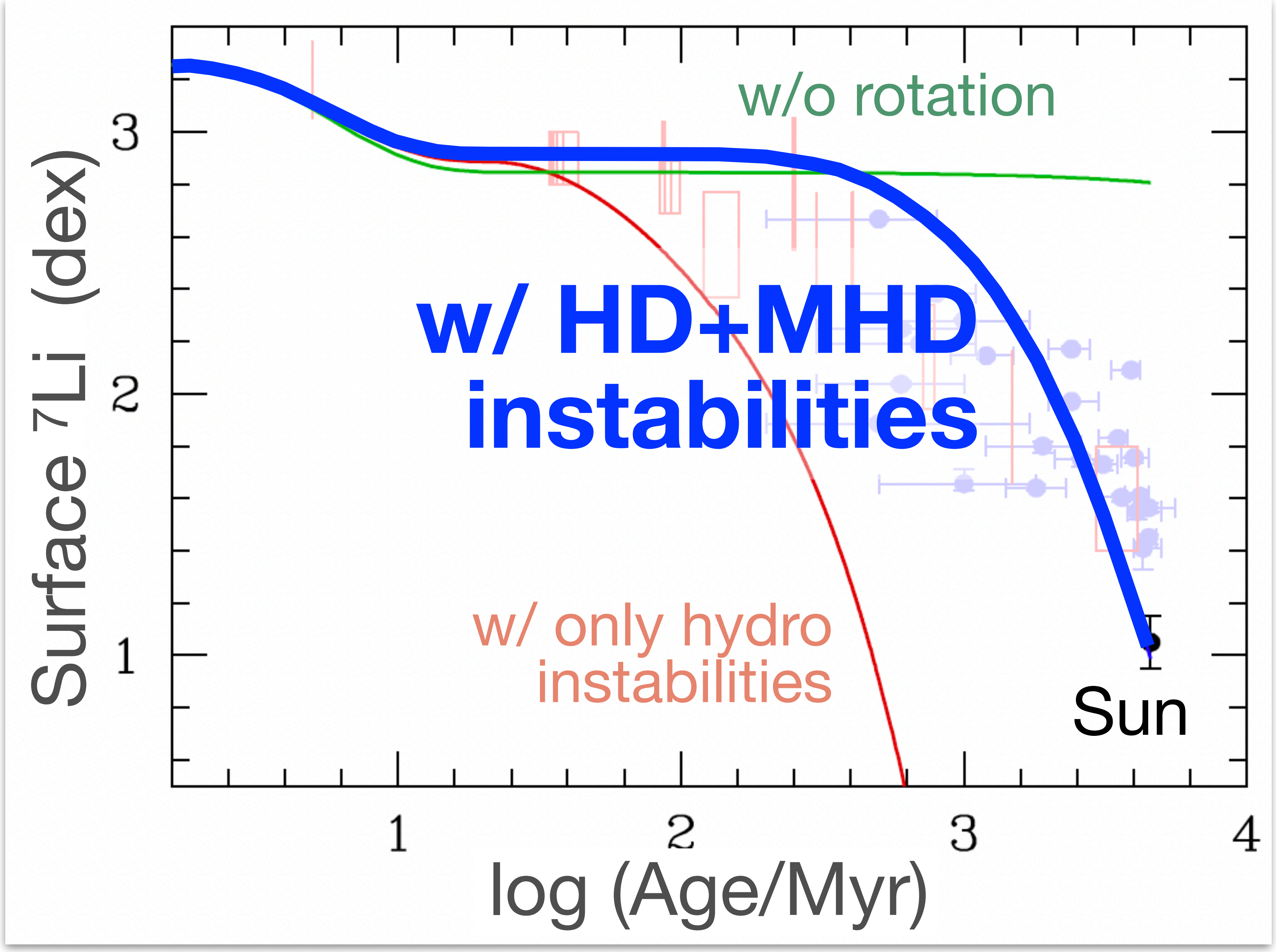
Additional input physics

- rotational diffusion ((M)HD instabilities)
- stellar winds (~0.02 $M_\odot$ for 4.6 Gyr?)

The present-day Sun rotates with ~28 days
but **young stars rotate with ~1 day**



Eggenberger+2022



Future prospects

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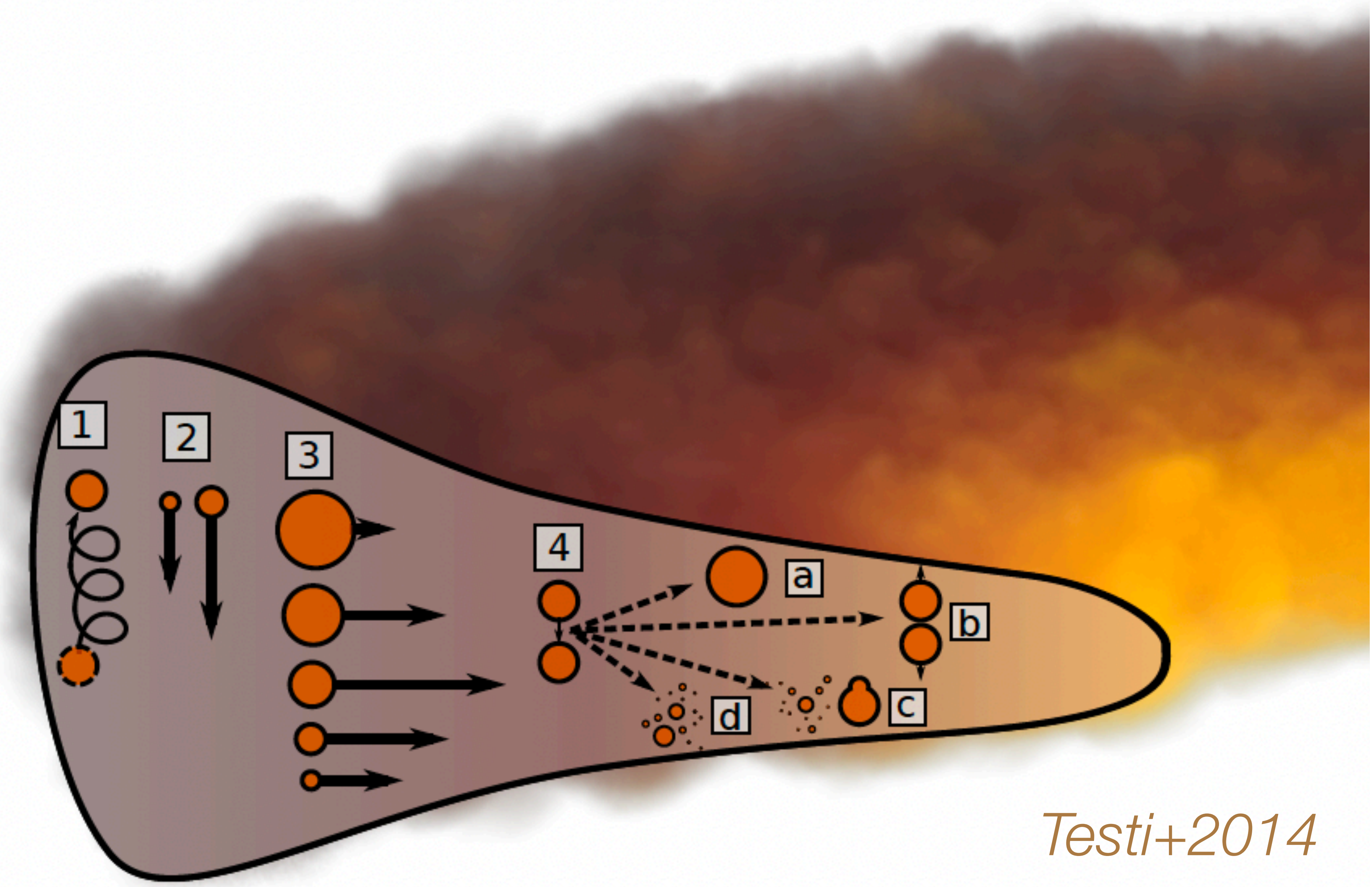
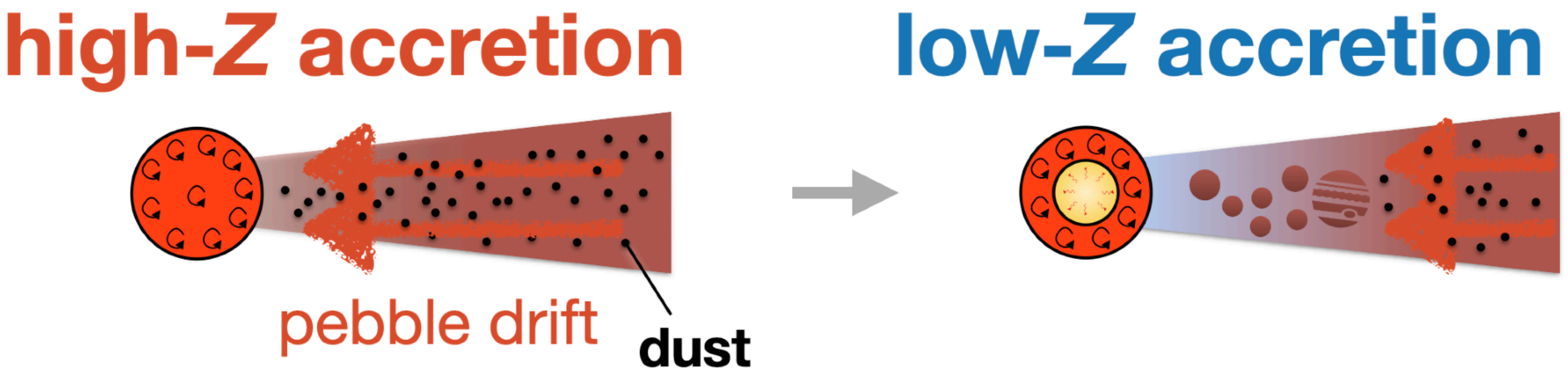
Realistic $Z_{\mathrm{accretion}}$ model

- theory of dust coagulation & drift
- observational constraints

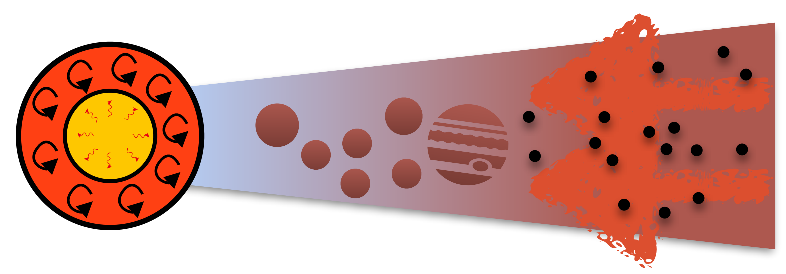
e.g., Kobayashi+Tanaka 2021, Roman-Duval+2020, Kama+2015

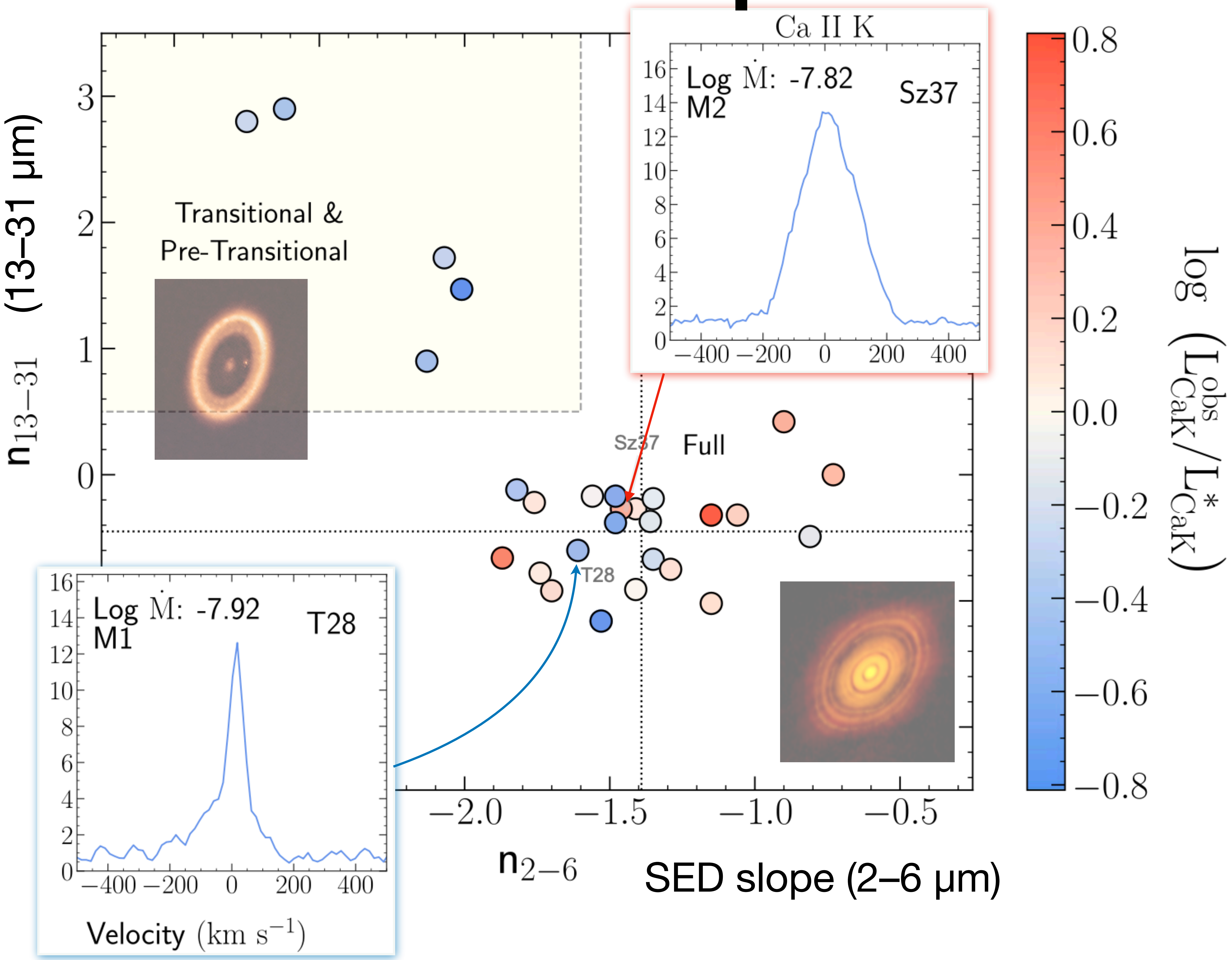


Testi+2014



Observed compositions of accretion flow





- X-shooter/VLT observations of Chamaeleon I star-forming region
- **Color** shows how much Ca II K line is weaker than expected from Hα
- **All the (pre-)transition disks and some full disks have deficit in Ca**
- T28 inner disk has a Ca abundance of **~17% solar**

Micolta+23

Summary

- We simulated the formation and evolution of stars focusing on the **evolving composition of accretion flow** and found
  - planet formation processes can decrease the stellar surface metallicity and explain chemical peculiarities in λ Boö stars and binaries Kunitomo+18
  - the solar central metallicity can be increased by up to 5% and neutrino fluxes are reproduced Kunitomo+21, 22