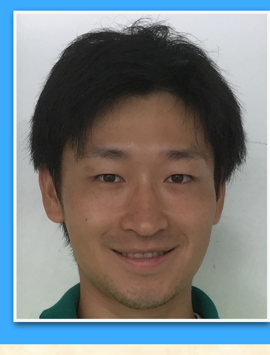
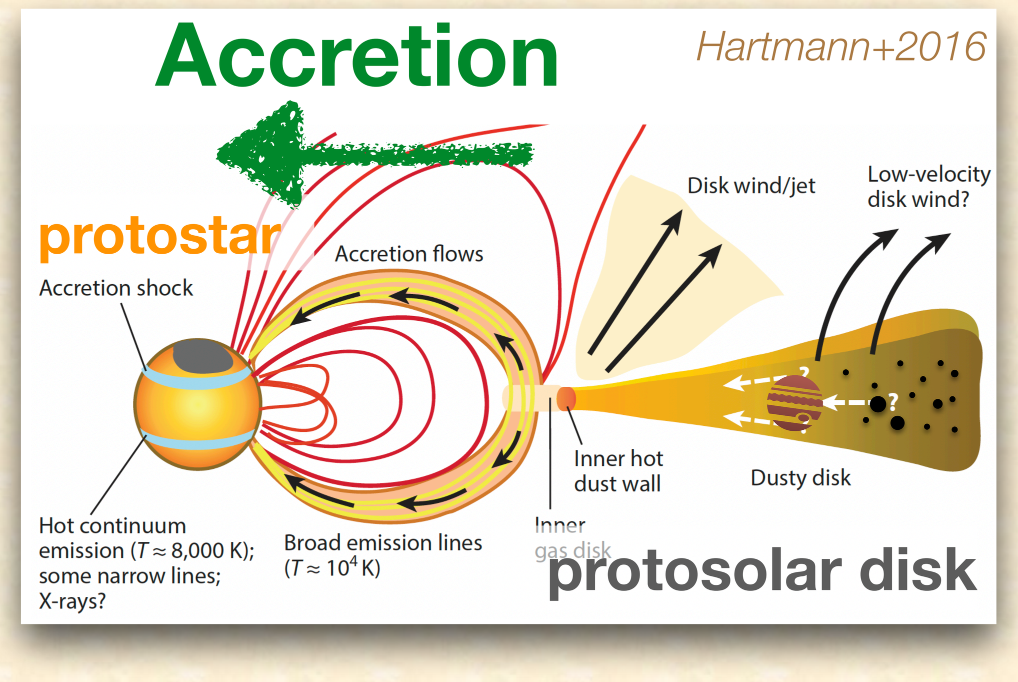
Evidence of a signature of planet formation processes from solar neutrino fluxes

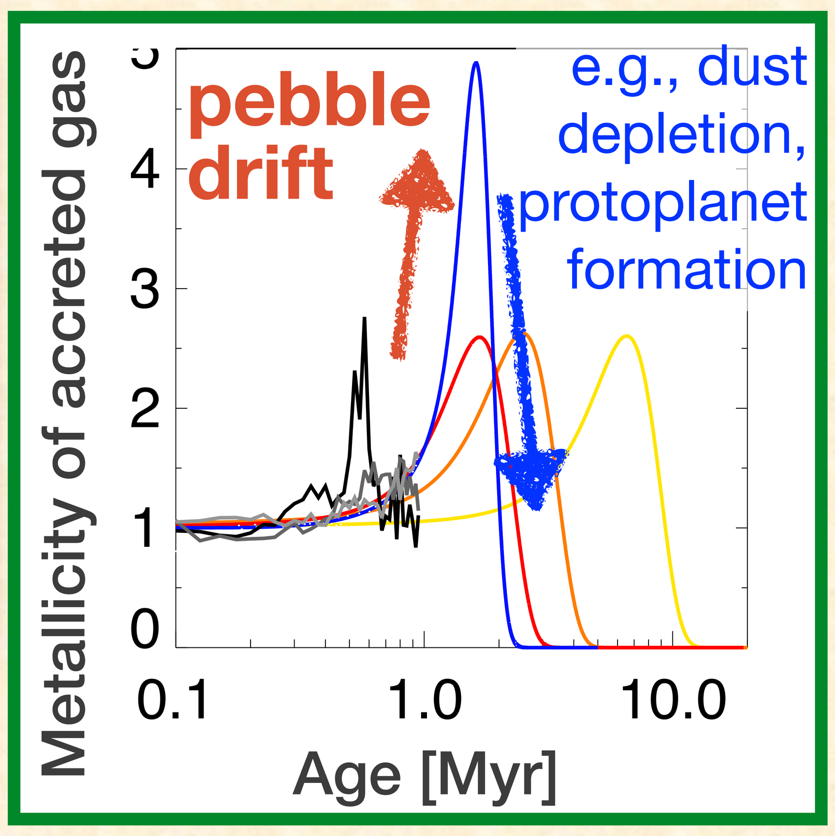
M. Kunitomo (Kurume U.), T. Guillot (OCA), G. Buldgen (U. Geneva)



contact me!

1. Compositional star-disk interaction





Stars are formed by the accretion from a protoplanetary disk where planets are formed. Planet formation processes (dust growth & drift) leads to **variable composition** of accreting materials:

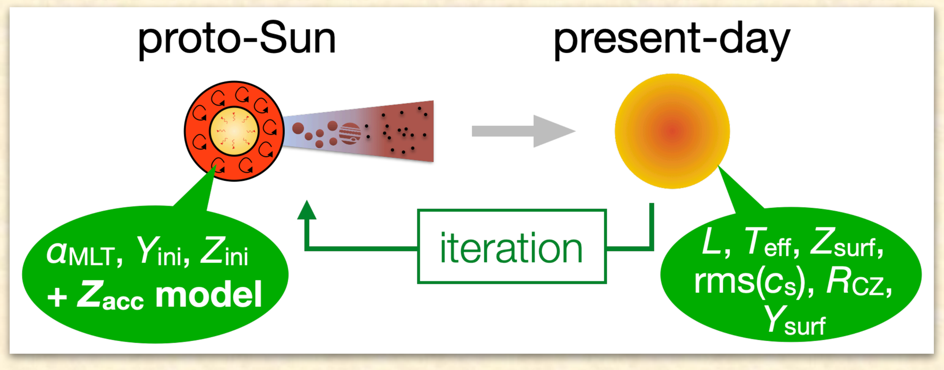
- ~cm-sized grains ("pebbles") rapidly fall on to the proto-Sun → high-Z accretion
- dust depletion or planetary gap → low-Z accretion

e.g., Garaud+2007, Guillot+2014, Kobayashi+Tanaka2021

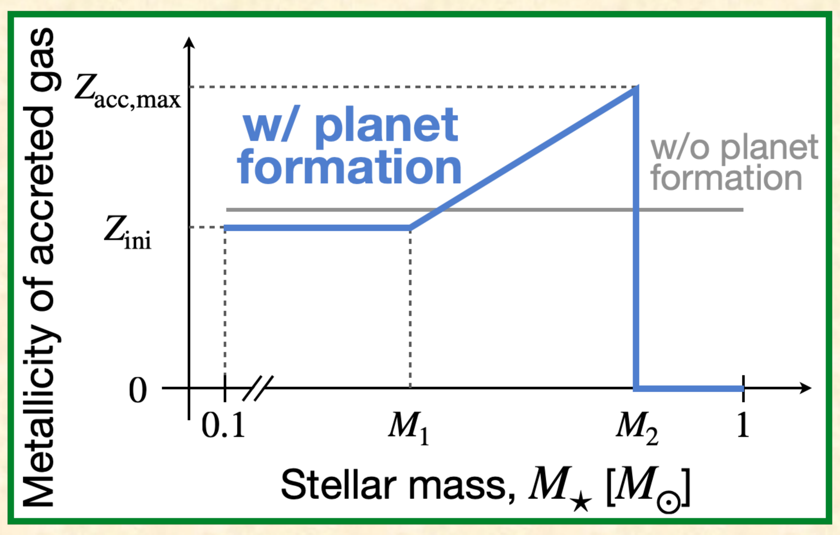
How does accretion affect the chemical structure of the Sun?

2. Computation method

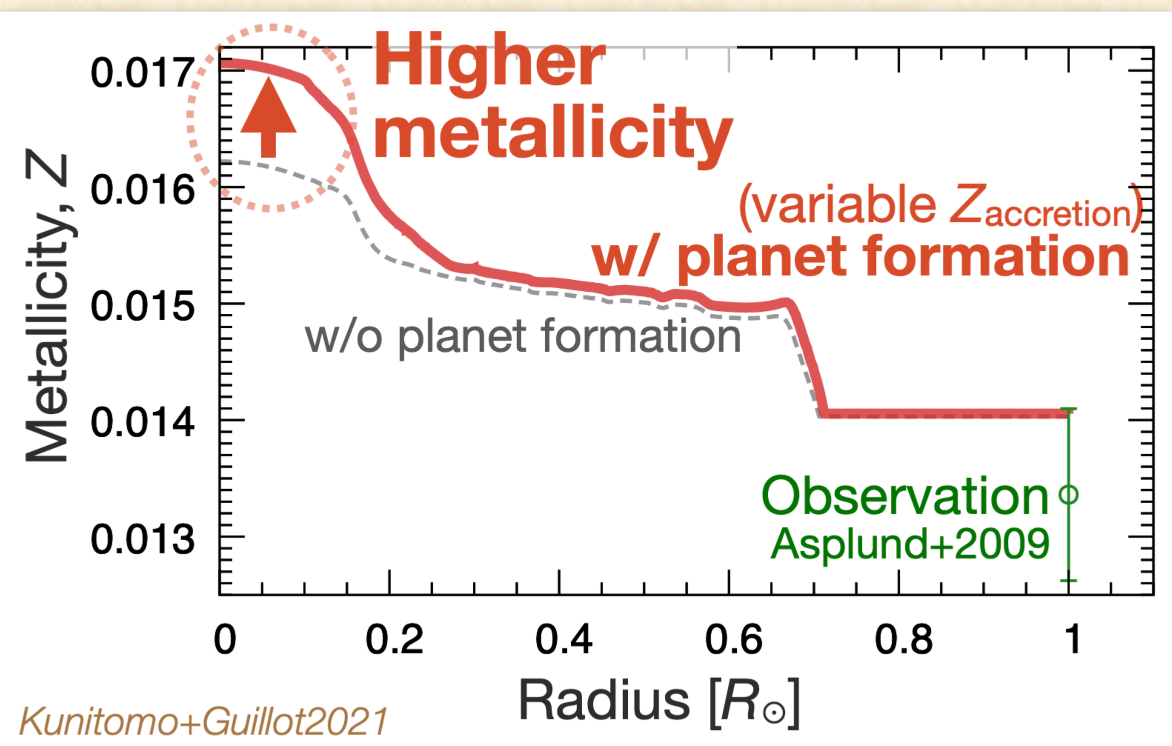
- MESA code (Paxton+2011–2019, Kunitomo+2017, 2018, 2021, 2022)
- Initial mass: 0.1 $M_\odot$, disk lifetime: 10 Myr, solar age: 4.567 Gyr
- **Optimization**: simplex method (Nelder-Mead 1965)
  - target: six observables (surface composition, L, $T_{\rm eff}$, rms(c_s), $R_{\rm CZ}$)
  - input: initial & accretion composition, convection parameters
- **Variable composition of accretion**: a simple model capturing the key features of simulation results (pebble drift & dust depletion)



best model: $M_1 \approx 0.90\,M_\odot$, $M_2 \approx 0.96\,M_\odot$, $Z_{\rm ini} \approx 0.014$, $Z_{\rm acc,max} \approx 0.065$

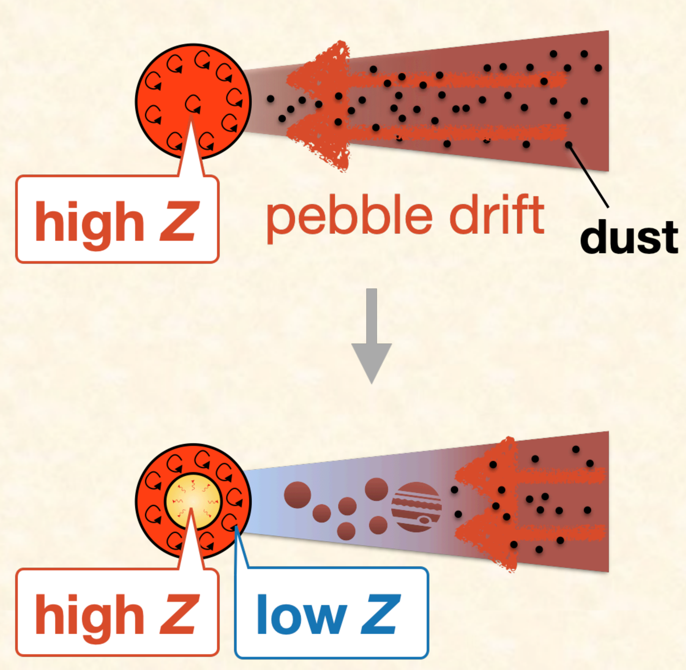


3. Chemical structure of the present-day Sun



- Variable composition of accretion leads to a **higher central metallicity** by 5%
- Compositional gradient exists only in the central region (≲0.2 $R_\odot$)

Why?



Early phase (≲1.7 Myr)

- **high-Z accretion**
- **fully convective** proto-Sun

→ **high-Z** in the entire solar interior

Late phase (2–10 Myr)

- **low-Z accretion**

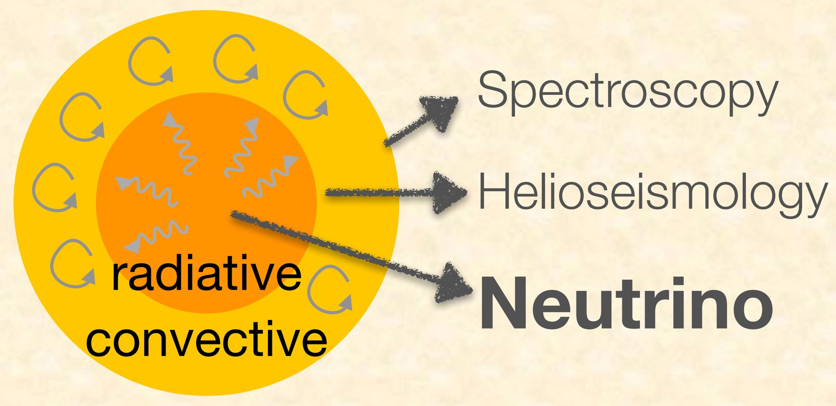
→ **low-Z solar surface**

- central region becomes **radiative**

→ **high-Z core** remains

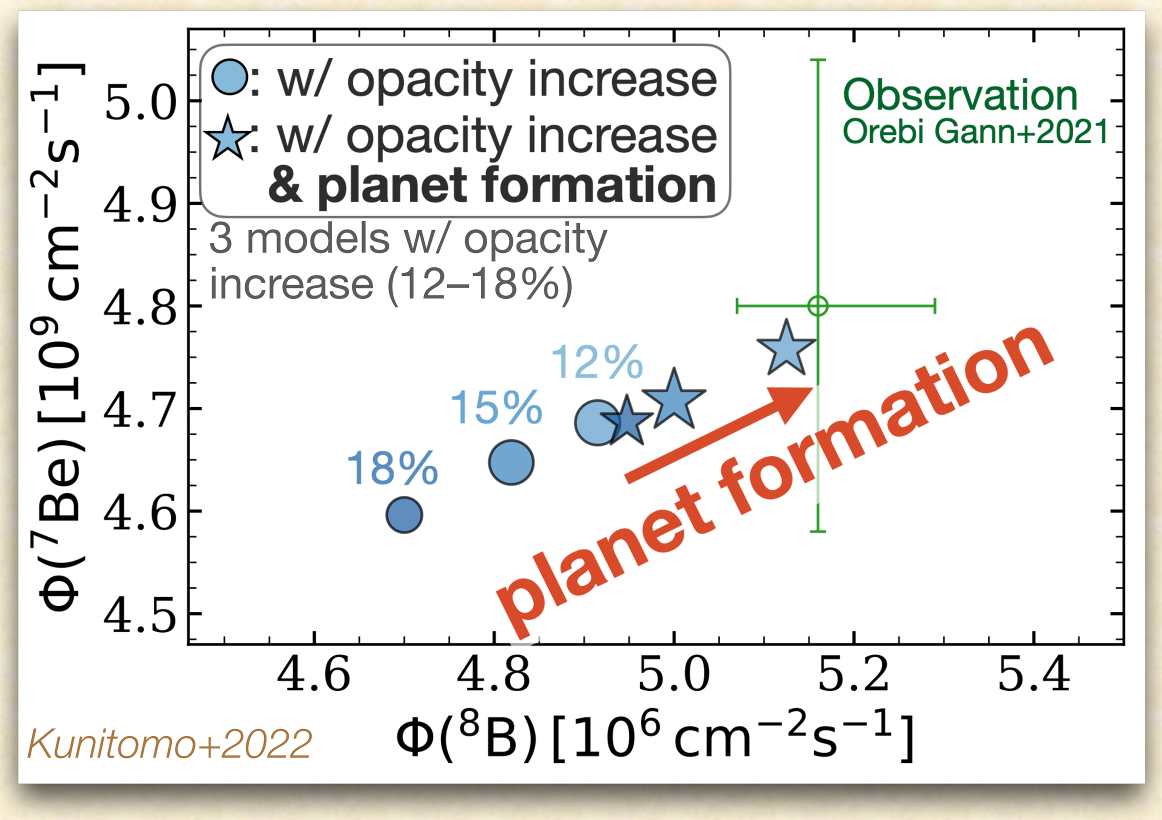
4. Observations favor the high-Z solar core

Three ways to see the solar interior



Solar central region is traced by neutrinos emitted by nuclear reactions. **Is the high-Z core in our models consistent with neutrino observations?**

Neutrino fluxes



12–18% opacity increase needed for helioseismic and spectroscopic observations (Bailey+2015, Buldgen+2019, Kunitomo+Guillot2021)

- Models w/o planet formation predict low fluxes → inconsistent w/ observations
- Planet formation processes increase neutrino fluxes → **consistent w/ observations!**
- Other fluxes (*pp*, *pep*, CNO neutrinos) are also reproduced within ~1σ

For a realistic solar model, star and planet formation processes should be considered!

Why?

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

Bahcall+Ulmer1996

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

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

5. Future prospects

Realistic $Z_{\rm accretion}$ model

- detailed model of dust coagulation & drift (e.g., Kobayashi+Tanaka 2021)
- observational constraints (e.g., ULLYSES; Roman-Duval+2020, Kama+2015)

More detailed comparison w/ observations

- surface Li, rotation profile (Eggenberger+2022)

Additional input physics

- rotational diffusion (HD/MHD instabilities; Yang2022)
- solar winds (~0.02 $M_\odot$? Suzuki+2013, Zhang+2019)

Implications for other stars

- solar twins, δ Scuti stars (Kunitomo+2018, Deal+2015, Steindl+2022)

Take-home messages:

- **Planet formation processes lead to the variable composition of accretion**
- **Planet formation results in a metal-rich solar core and high neutrino fluxes in agreement w/ observations**

download paper: Kunitomo et al. (2022), A&A