

太陽系大移動とスノーボールアース

辻本拓司(国立天文台)

I. A new paradigm of Galactic dynamics

*Stars radially move on the disk
when they encounter spiral arms.*

“radial migration”

II. Impact of radial migration on Galactic chemical evolution

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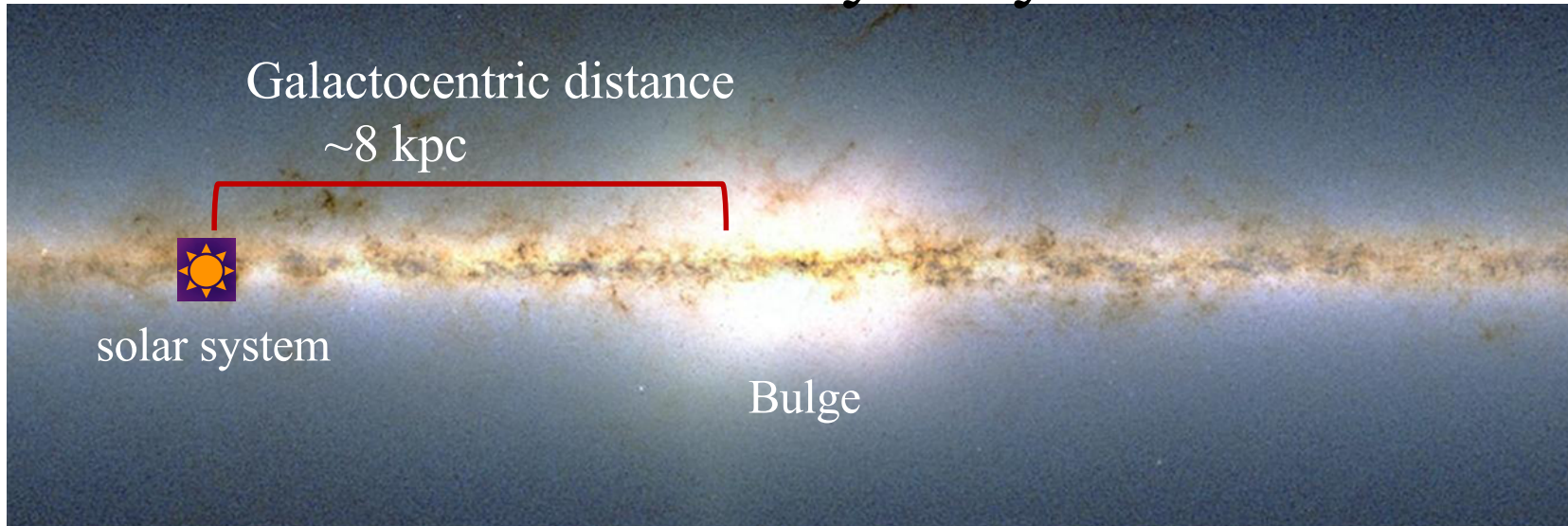
III. Migration of the solar system

IV. Snowball Earth and records on meteorites (!?)

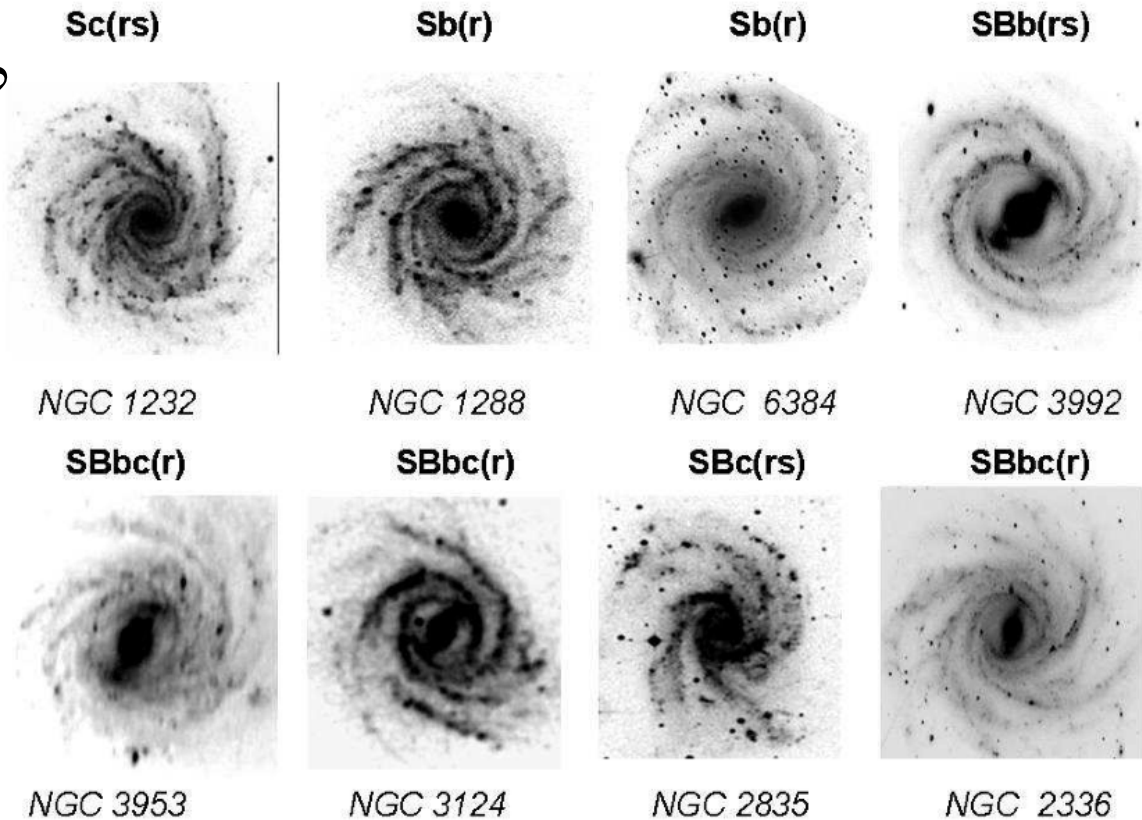
宇宙線で繋ぐ文明・地球環境・太陽系・銀河

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The Milky Way



Milky Way analogues



spiral arm:
A prominent
dynamical
structure

I. A new paradigm of Galactic dynamics

the remarkable progress in the last ~15 years

the controversy over spiral arm since 1960s

“**wave pattern** or **material structure**”

Lin & Shu (1964, 1966)

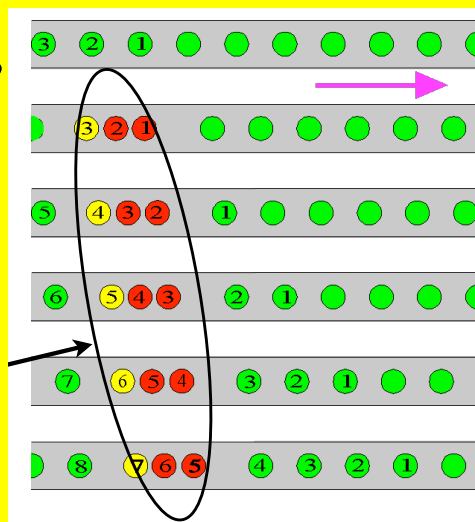
Lindblad, Kalnajs, Bertin

:

(quasi-) **stationary** density wave

“density wave theory”

the place of traffic congestion slowly propagates with changes of member cars



Goldreich & Lynden-Bell (1965)

Toomre

:

transient recurrent spiral

the structure that a high stellar density region formed by self-gravity is stretched by a differential (galactic) rotation

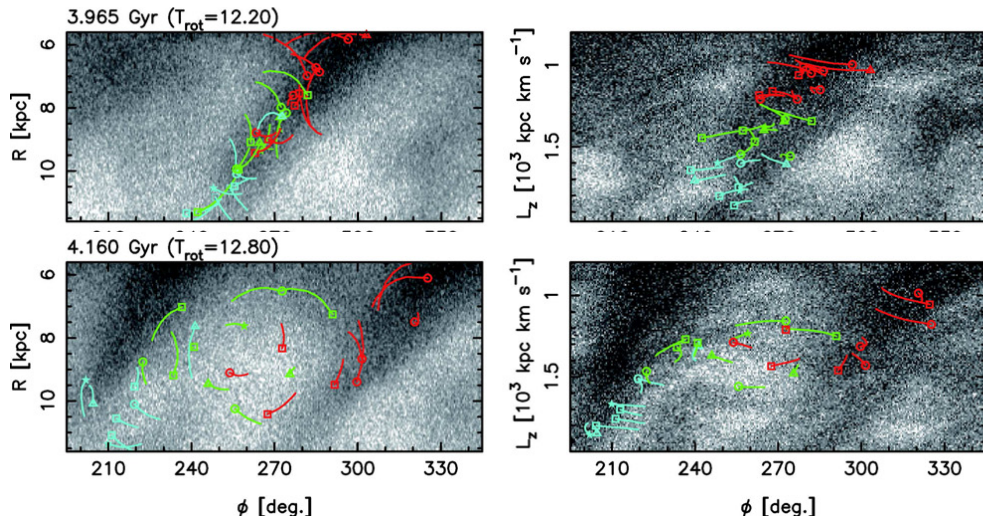
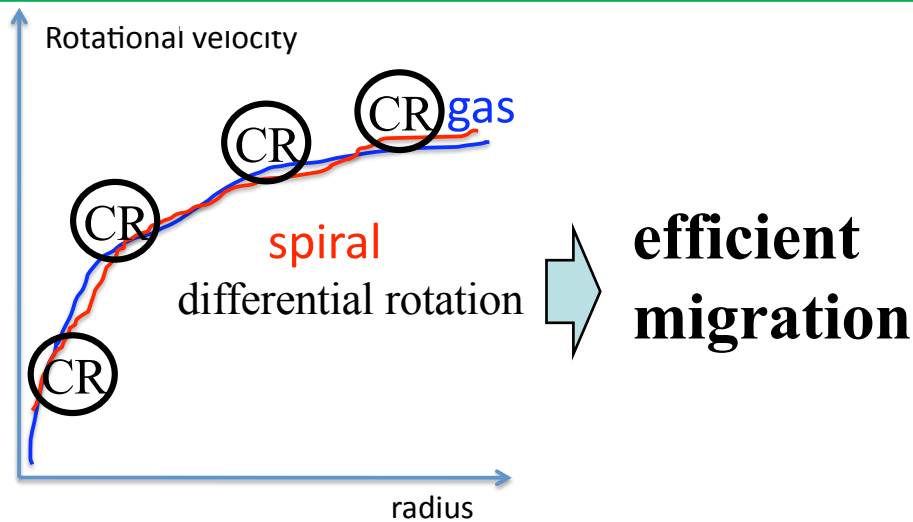
✓ a short lifetime ($\sim 1-2 \times 10^8$ yrs)

✓ repeatedly generate and die out

A paradigm shift from “wave pattern” to “material structure”

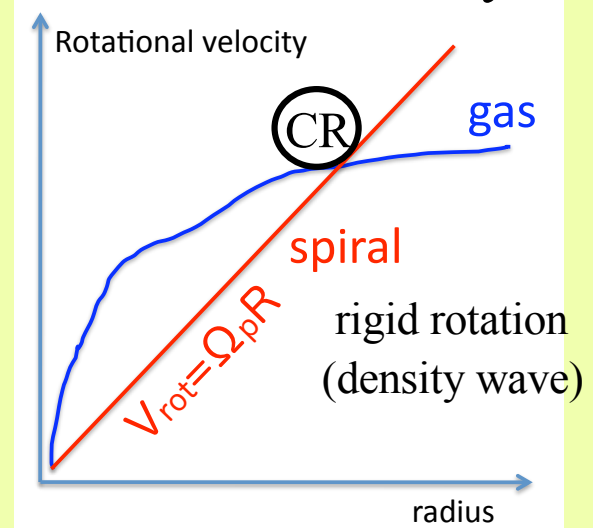
❑ Spirals induce radial migration of stars ❑

Stars radially move via a gravitational interaction with transient recurrent spirals by losing or gaining angular momentum: **This happens around the corotation radius.**



(Baba+ 2013)

On the other hand, in the case of density wave,

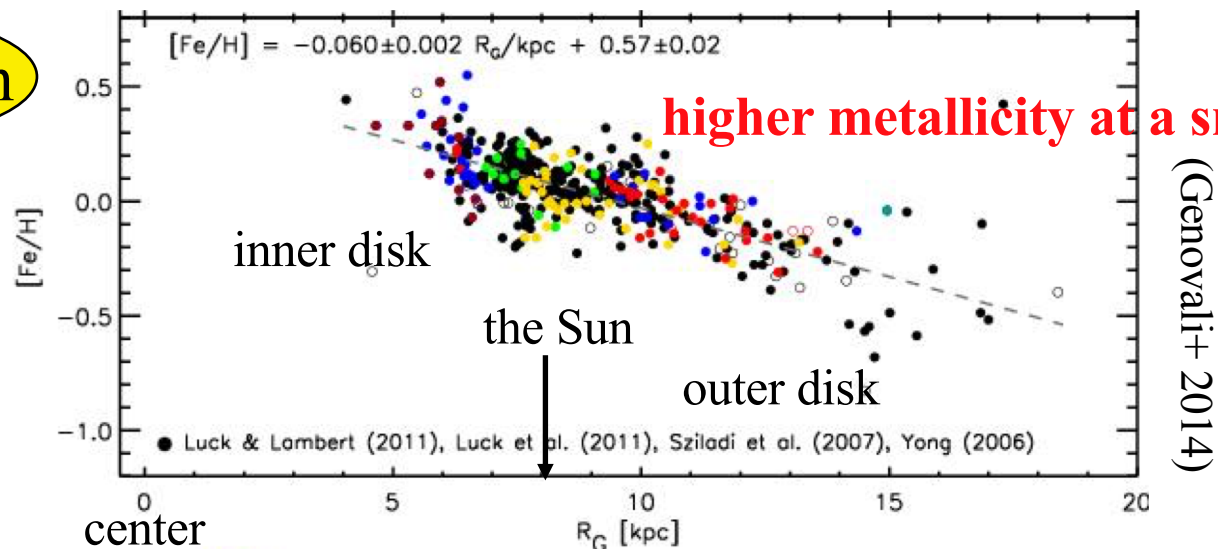


Stars just go across spirals

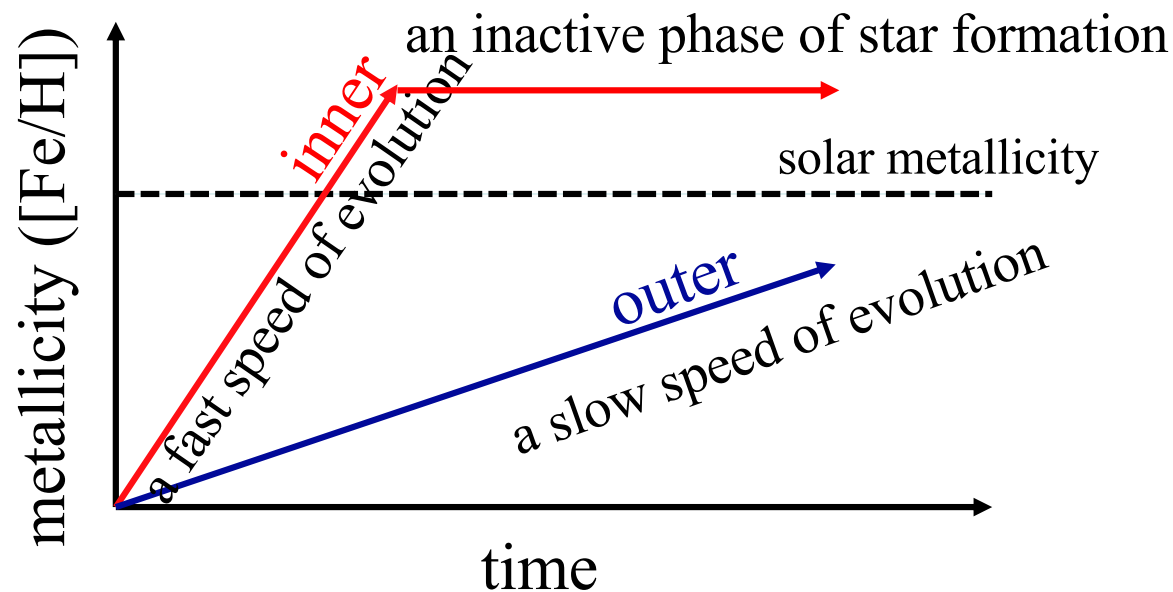
II. Impact of radial migration on Galactic chemical evolution

The chemical evolution of the disk **differs** in accordance with Galactocentric distance (R_{GC})

Observation



Theory



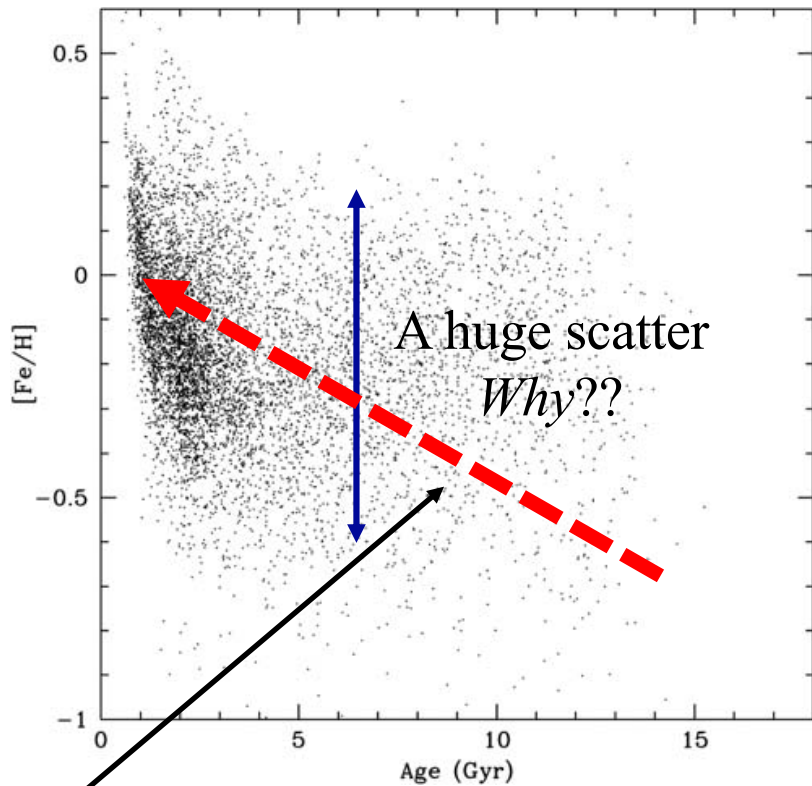
“inside-out scenario”

Observational fact well explained I

Age-metallicity ([Fe/H]) relation

Observation

(Nordstrom+2004)

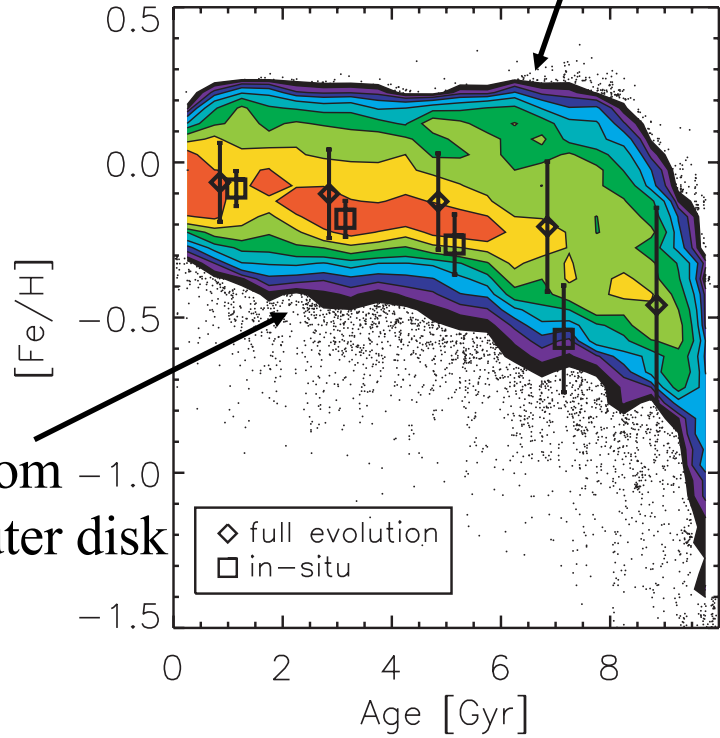


Such a trend ought to be seen

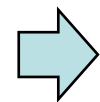
Theory

stars from the inner disk

stars from the outer disk



(Roskar+2008)

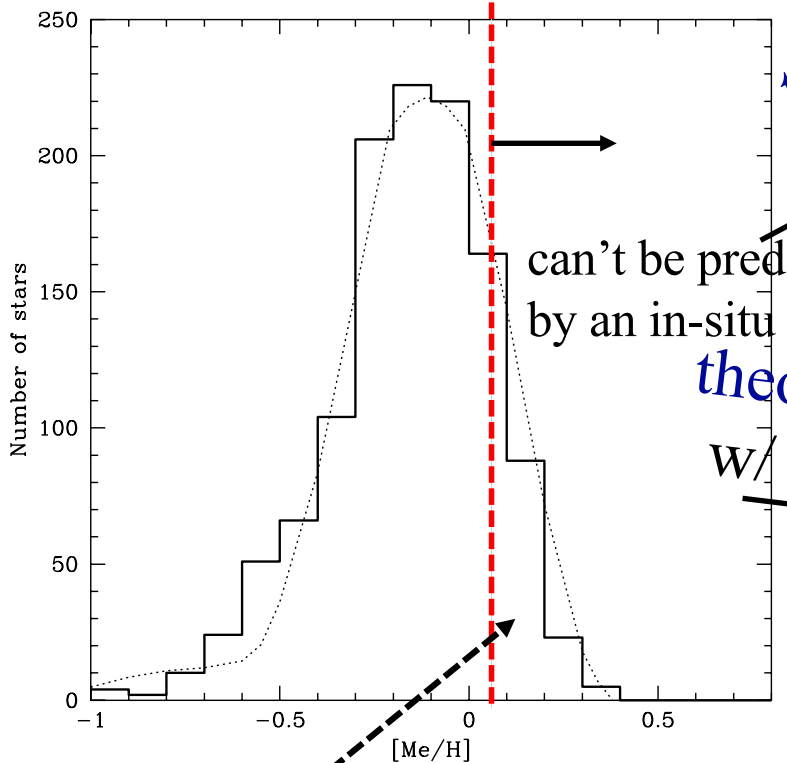


A mixture of stars with various age-[Fe/H] relations makes this trend unseen

Observational fact well explained II

the presence of super metal-rich stars

Observation



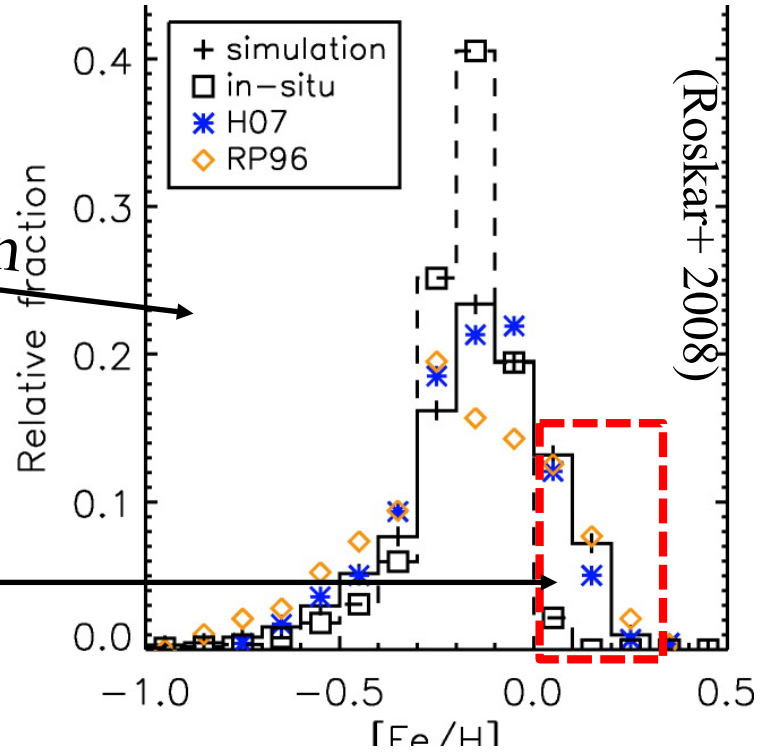
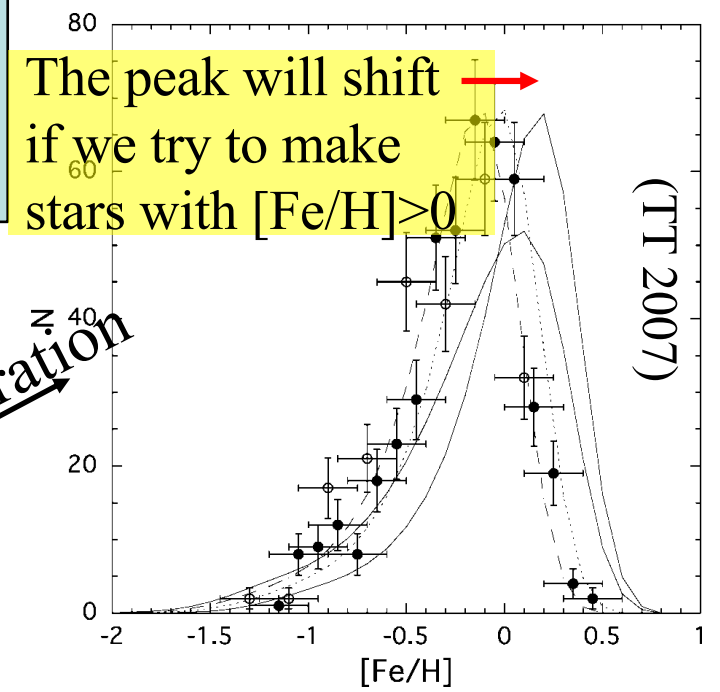
(Nordstrom+2004)

super metal-rich ($[Fe/H] > 0$) stars:
~20 % of nearby stars

theory1:
w/o radial migration

theory2:
w/ radial migration

stars migrated
from the inner
disk

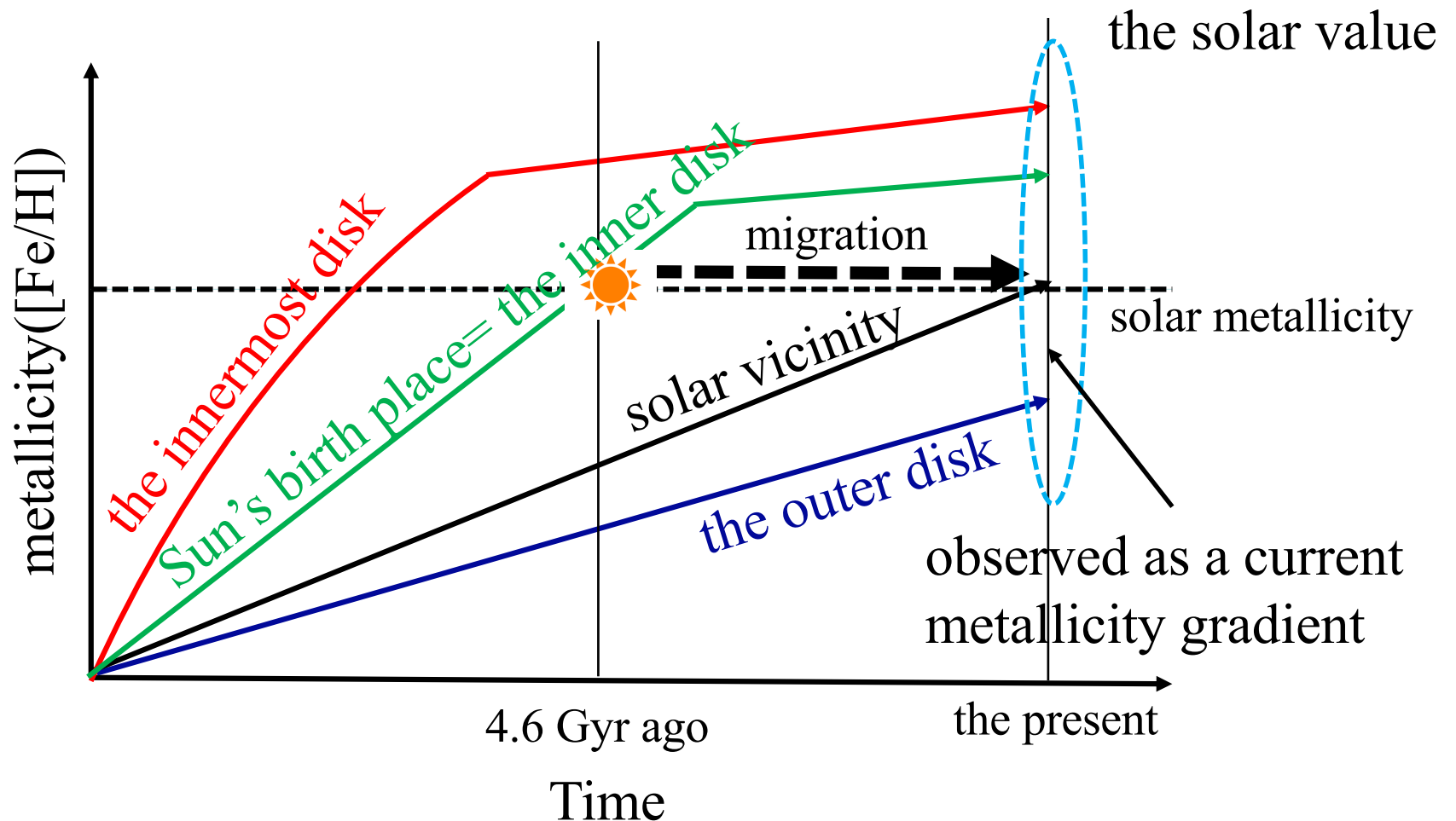


III. Migration of the solar system

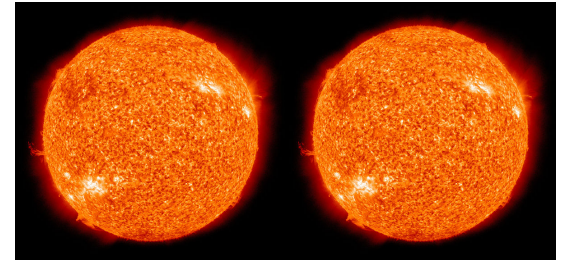
The solar system was born in the inner region than the present locus

- ❑ The solar system gained the solar metallicity 4.6 Gyr ago
- ❑ But, the metallicity in the solar vicinity currently achieves

(Wielent+ 1996)



solar twin stars

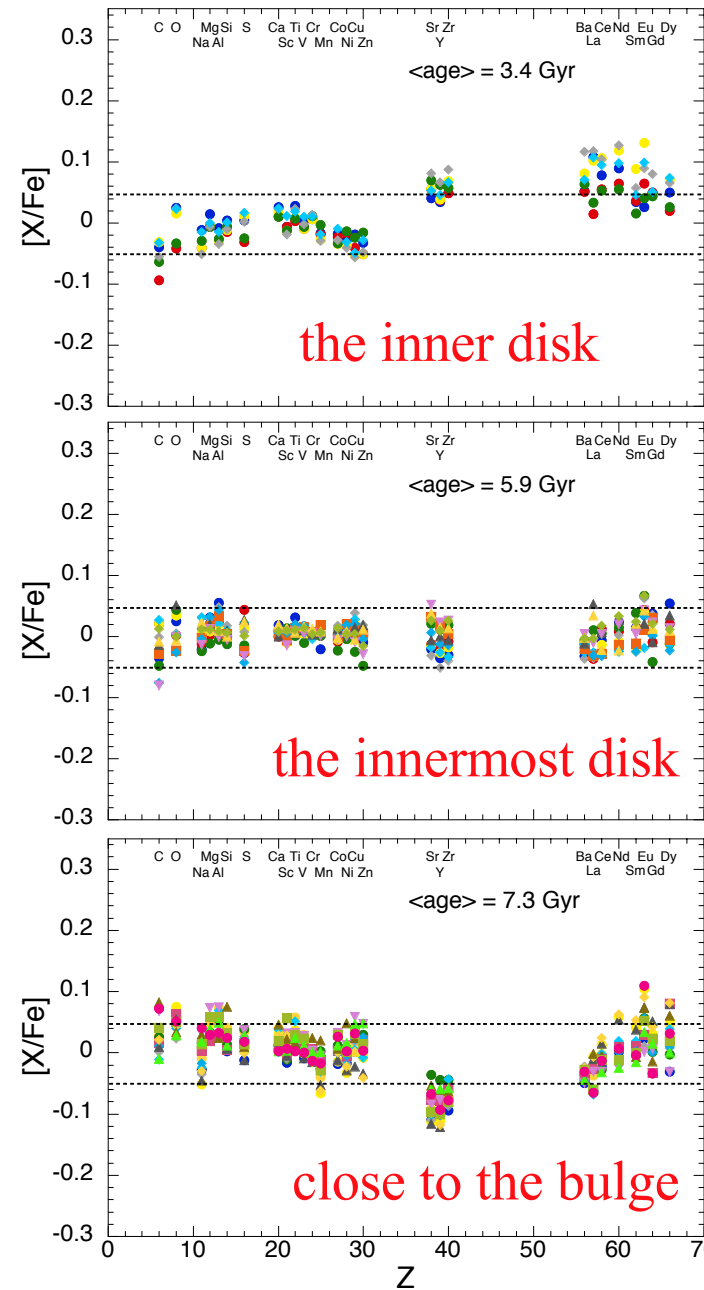
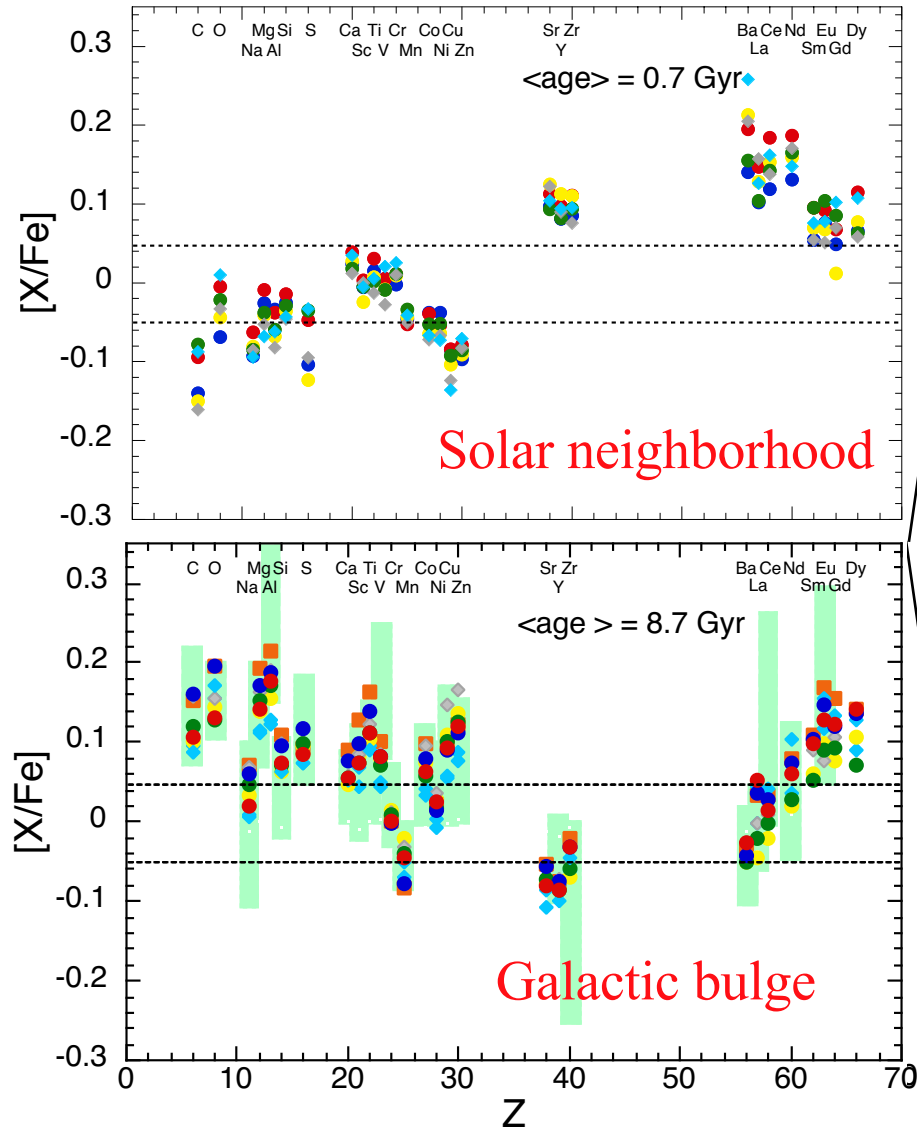


- ✓ stars that are nearly identical to the Sun
an effective temperature (≤ 100 K),
a logarithmic surface gravity (≤ 0.1), **[Fe/H] ratio (≤ 0.1)**
- ✓ 79 twins in the solar vicinity (≤ 100 pc)
- ✓ precise age determination (an uncertainty of 4×10^8 yrs) together
with high-quality chemical abundances (an error of < 0.01 dex)
- ✓ **the ages are widely distributed over 0 – 10 Gyr!**
 - ⇒ implying the assembly of stars migrating from various R_{GC}
in the inner disk
- ✓ chemical abundances play a role of identification
 - ⇒ identify the birth environment



Elemental abundance patterns of different age group at different R_{GC} as the birth place

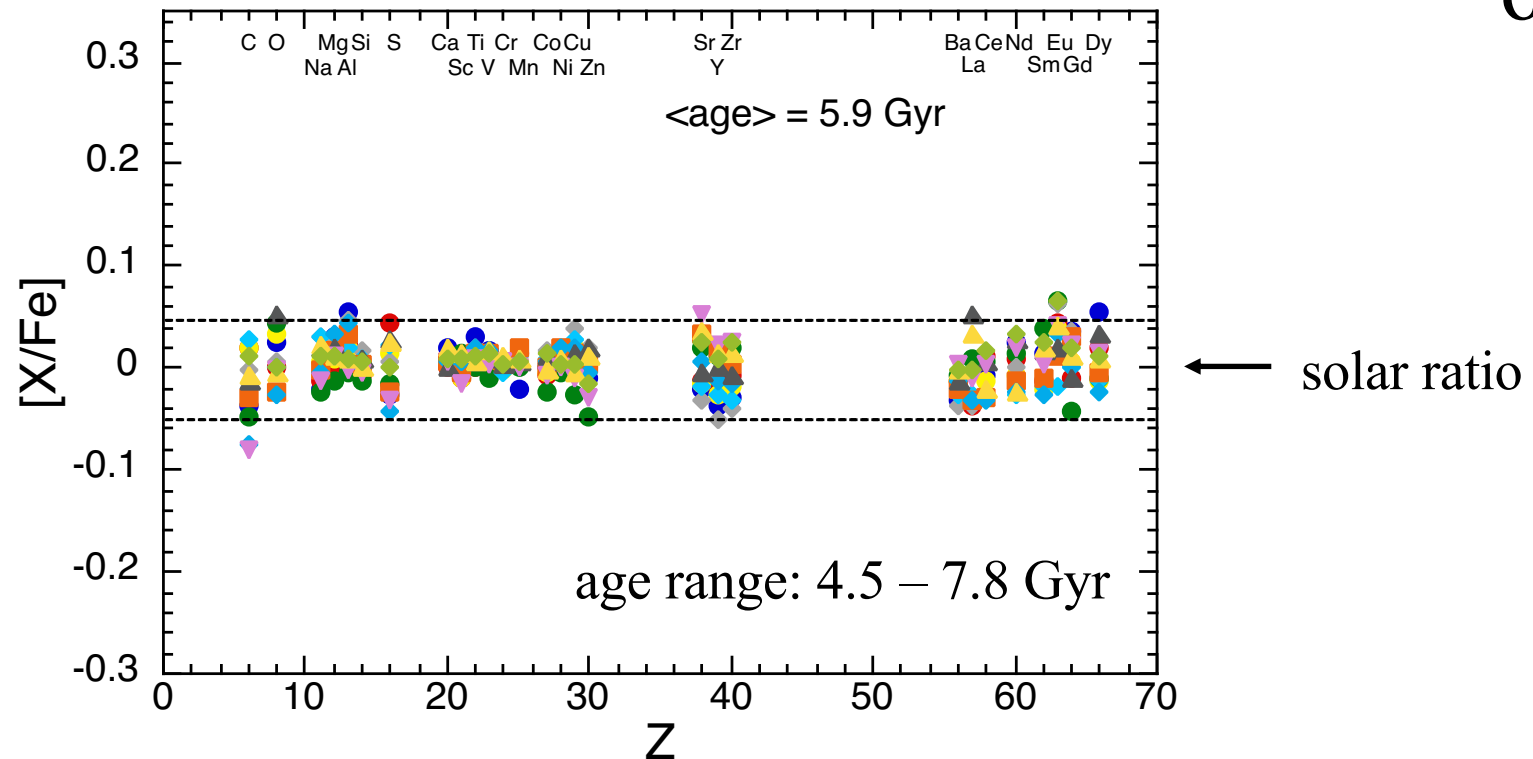
old ages = smaller R_{GC}



including the Sun

close to the bulge

Solar abundance is shared with twins of the age ~ 6 Gyr old



➡ The birthplace of the Sun might be shared with that for these old twins

➡ Where were these old twins born on the disk?

Note, the age of thin disk is $\sim 8-9$ Gyr old !

➡ **the innermost disk (approximately, $R_{GC} \approx 3-5$ kpc)**

IV. Snowball Earth and records on meteorites (!?)

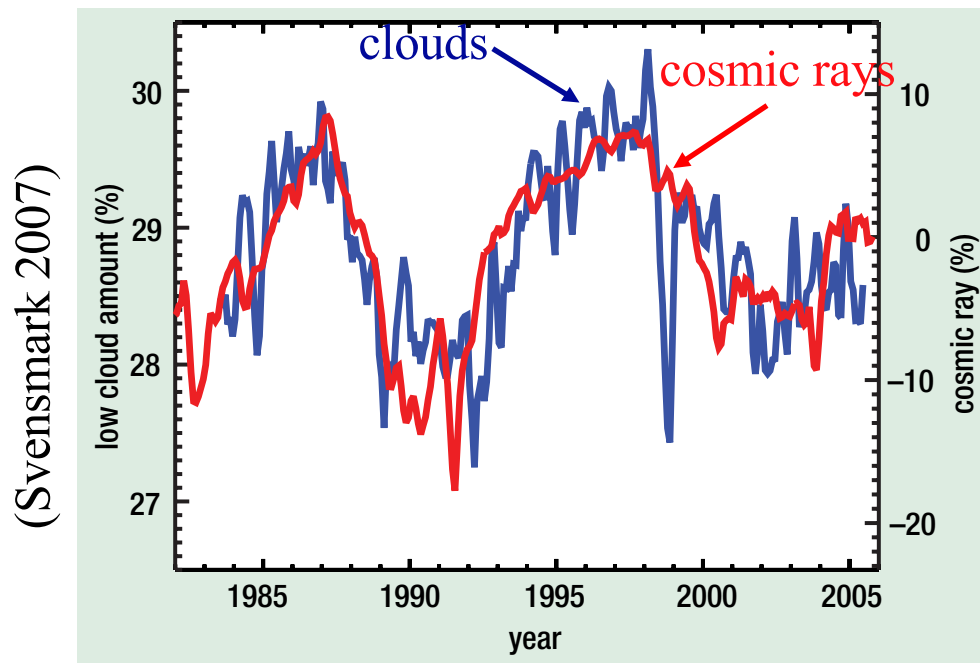
*The solar system migrated from the inner disk region,
experiencing encounters with spiral arms*

spiral arm : star-forming regions

→ the cradles of massive baby stars

→ the enormous flux of cosmic rays from supernovae

cosmic ray → cloud coverage → climate change



an increase in cosmic rays

→ ionization of the air

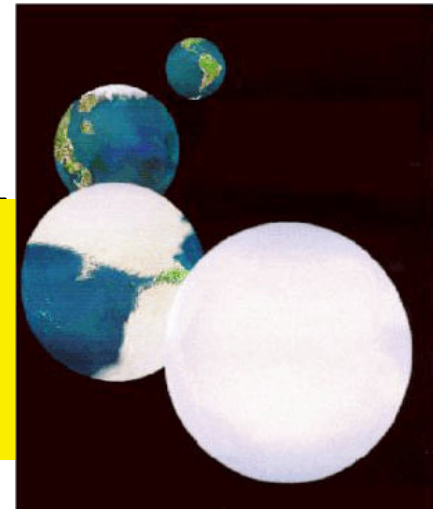
→ the aerosol particles

→ cloud condensation nuclei

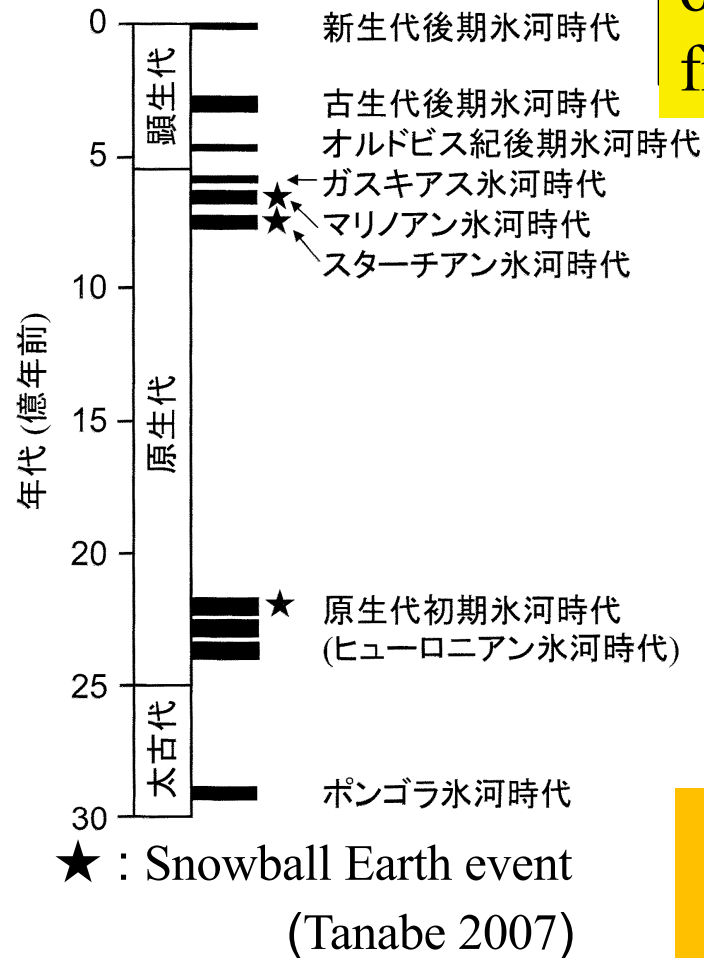
→ cloudiness

→ **a strong cooling effect**

Snowball Earth



Liquid water on the surface of the Earth was frozen entirely from pole to pole.



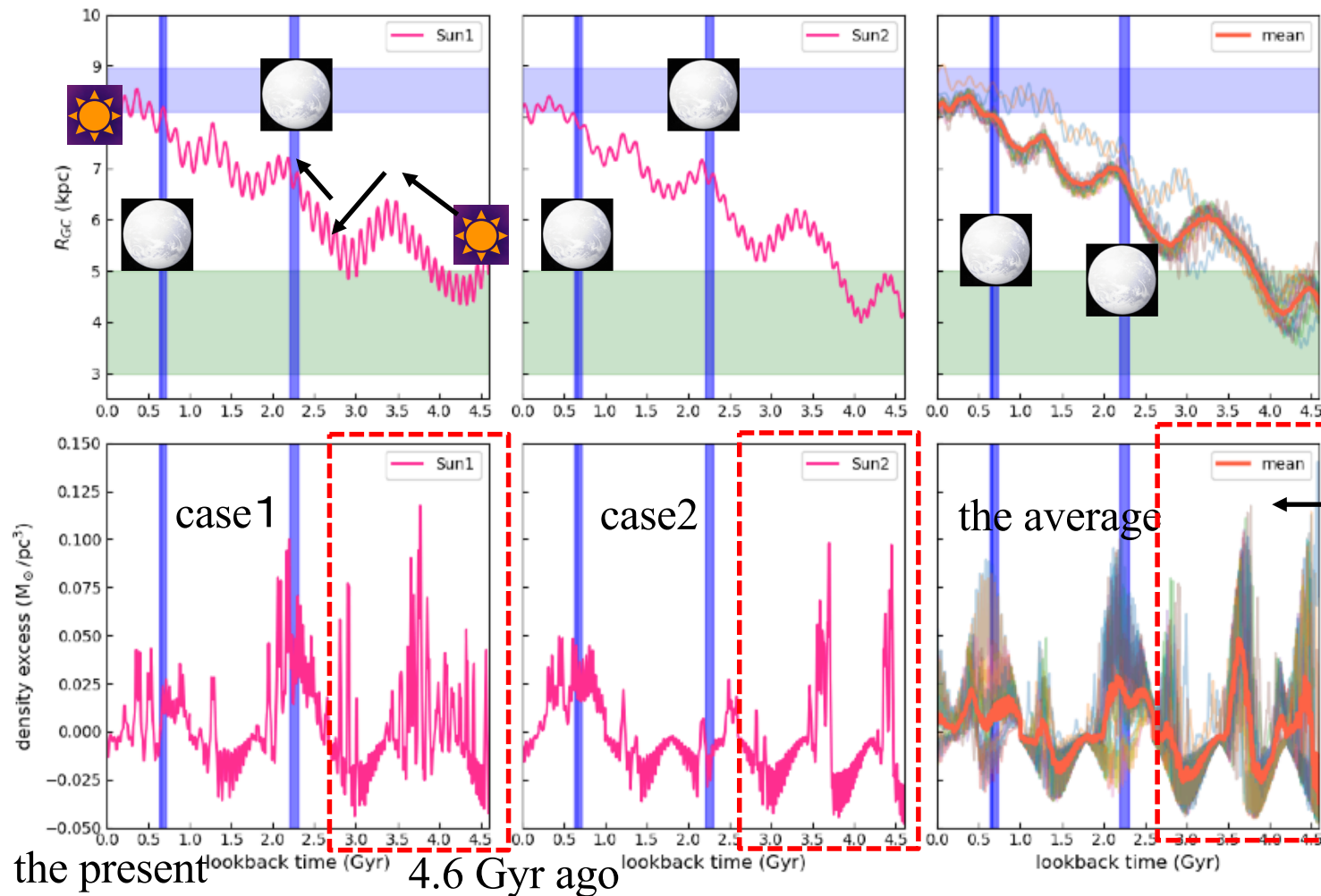
3 times during the history of the Earth

- 24.3 100Myr ago (Huronian glaciation)
 - 7.17 100Myr ago (Sturtian glaciation)
 - 6.50 100Myr ago (Marinoan glaciation)
- (Hoffman 2019)

The trigger responsible for this event is still under debate, including the hypothesis of “the Great Oxidation event” for the first one (Kirschvink+ 2000)

The lifetime trajectory of the solar system connected to Snowball Earth events by numerical simulations

(TT & Baba 2020)



the blocking of cosmic rays by high solar magnetic activity

The mechanism for two events in rapid succession (650 Myr ago, 720 Myr ago) was puzzling.



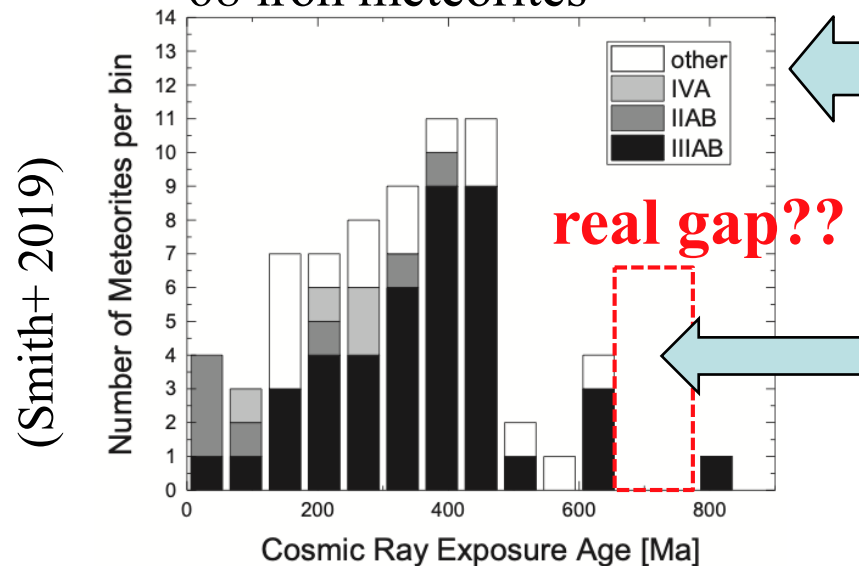
Vertically oscillating stellar motion during spiral-arm passage occasionally leads to a split into two discrete passage episode

A possible evidence for the connection between spiral-arm passages and Snowball Earth events

Intensive cosmic ray (CR) flux at ~650-700 Myr ago is recorded in **meteorites**??

CR exposure age: measure the duration of a meteorite was exposed to CRs from e.g., $^{41}\text{K}/^{40}\text{K}$, assuming the CR flux history was constant
“Thus, a linear change in the integrated flux corresponds to a linear change in age”

CR exposure age histogram of 68 iron meteorites



The ages of iron meteorites are widely distributed over 1000 Mys.

Intensive CR at ~650My ago, If exists, will cause some gap of age histogram after this epoch.