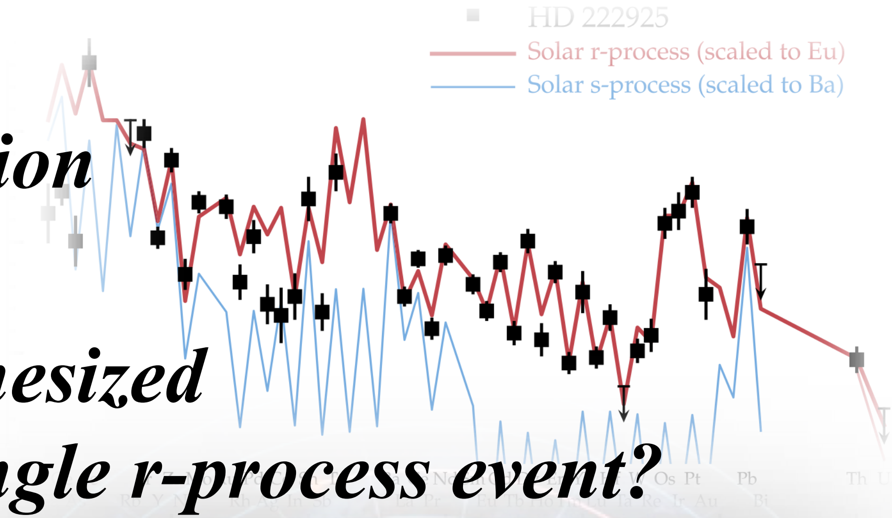
太陽近傍データで迫るr過程元素の起源と進化

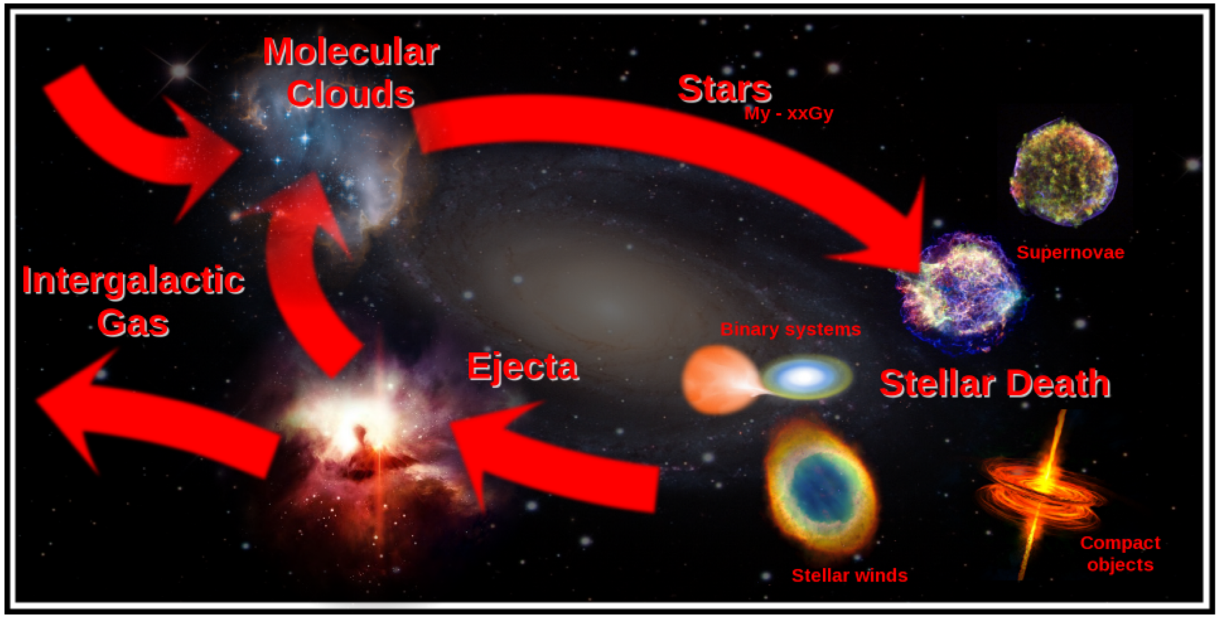
辻本拓司 (国立天文台)



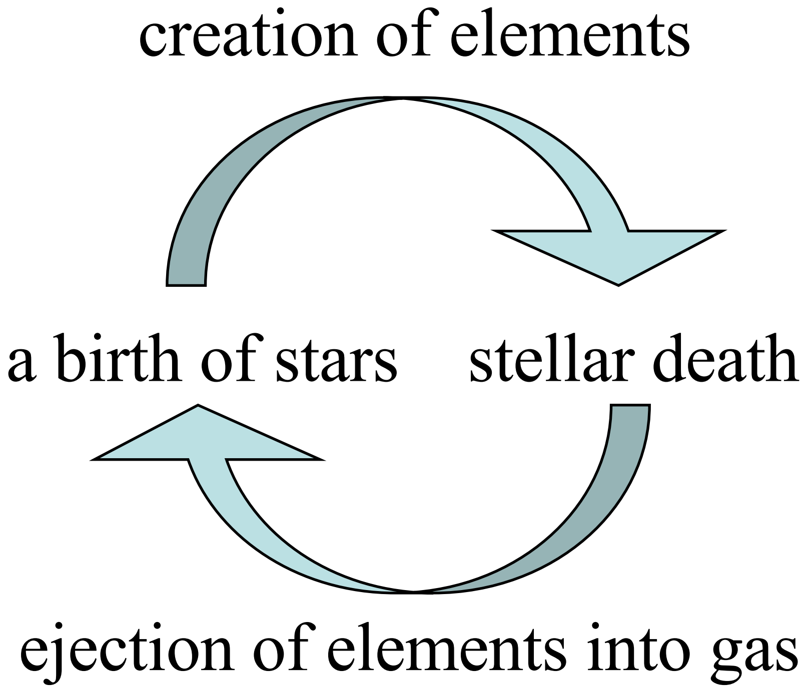
- *Galactic Chemical evolution*
- *Which elements are synthesized by a single r-process event?*
- *A rarity of r-process event*
- *r-Process enrichment in the Milky Way*

Galactic Chemical Evolution

Calculation of the evolutionary change in the mass fraction, Z_i, of each heavy element, i, in gas



@Longland



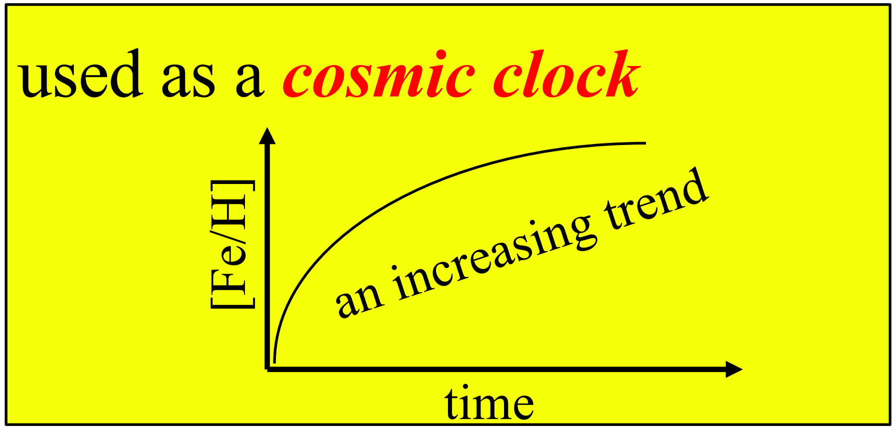
Each time's Z_i of gas can be recorded as **stellar Z_i** at each time (at a stellar surface)

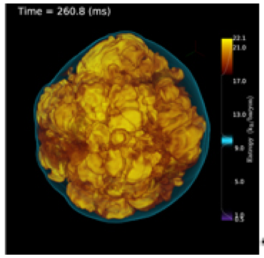
can be compared with the **observed Z_i of long-lived stars** ($M<0.8\ M_\odot$)

stellar abundances

$[Fe/H] = \log (Fe/H)_{star} - \log (Fe/H)_{\odot}$: used as a ***cosmic clock***

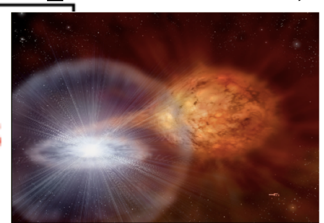
$[X/Fe] = \log (X/Fe)_{star} - \log (X/Fe)_{\odot}$



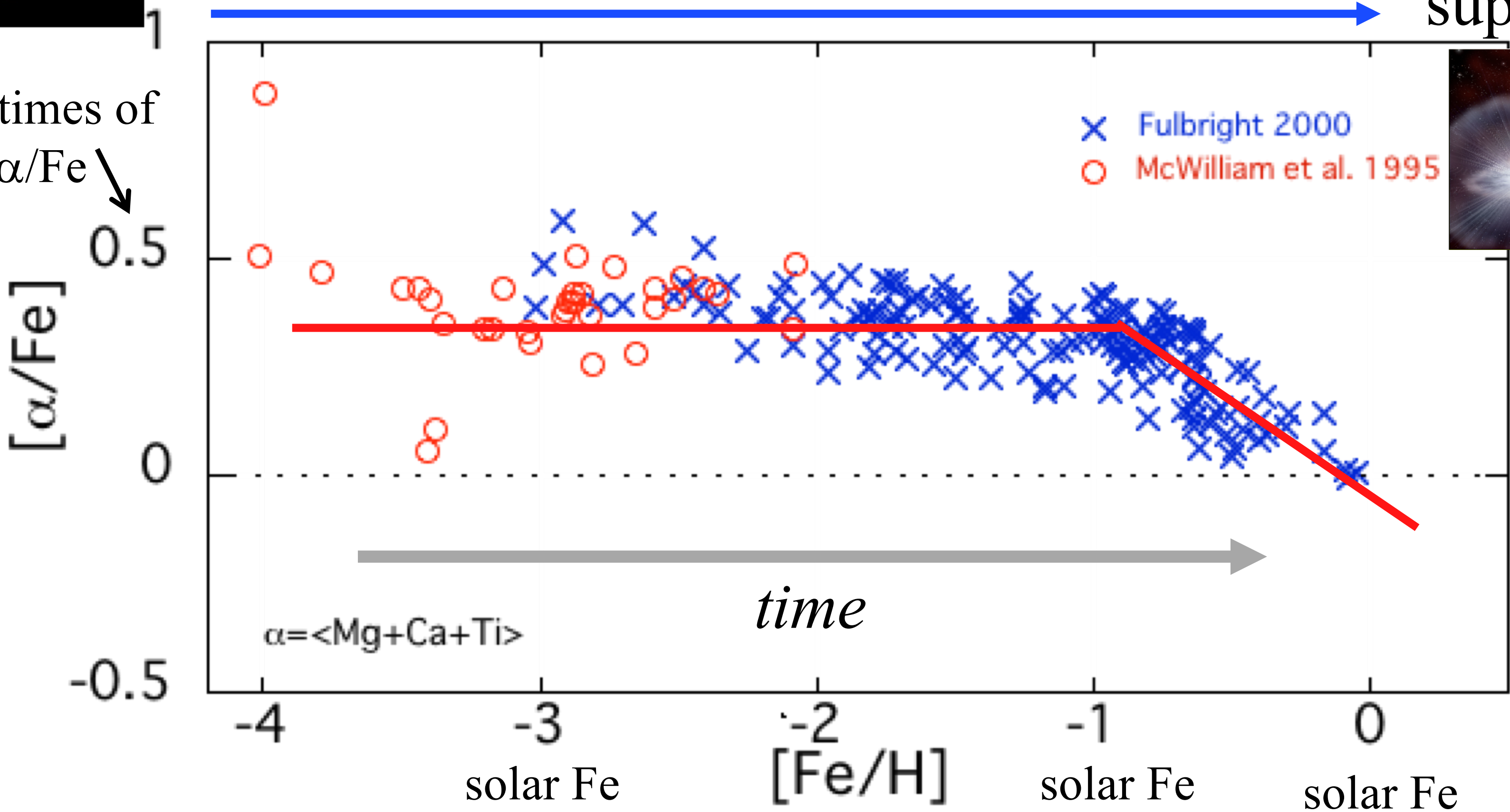


(core-collapse supernovae)
CCSNe

SNe Ia (type Ia supernovae)



three times of solar α/Fe

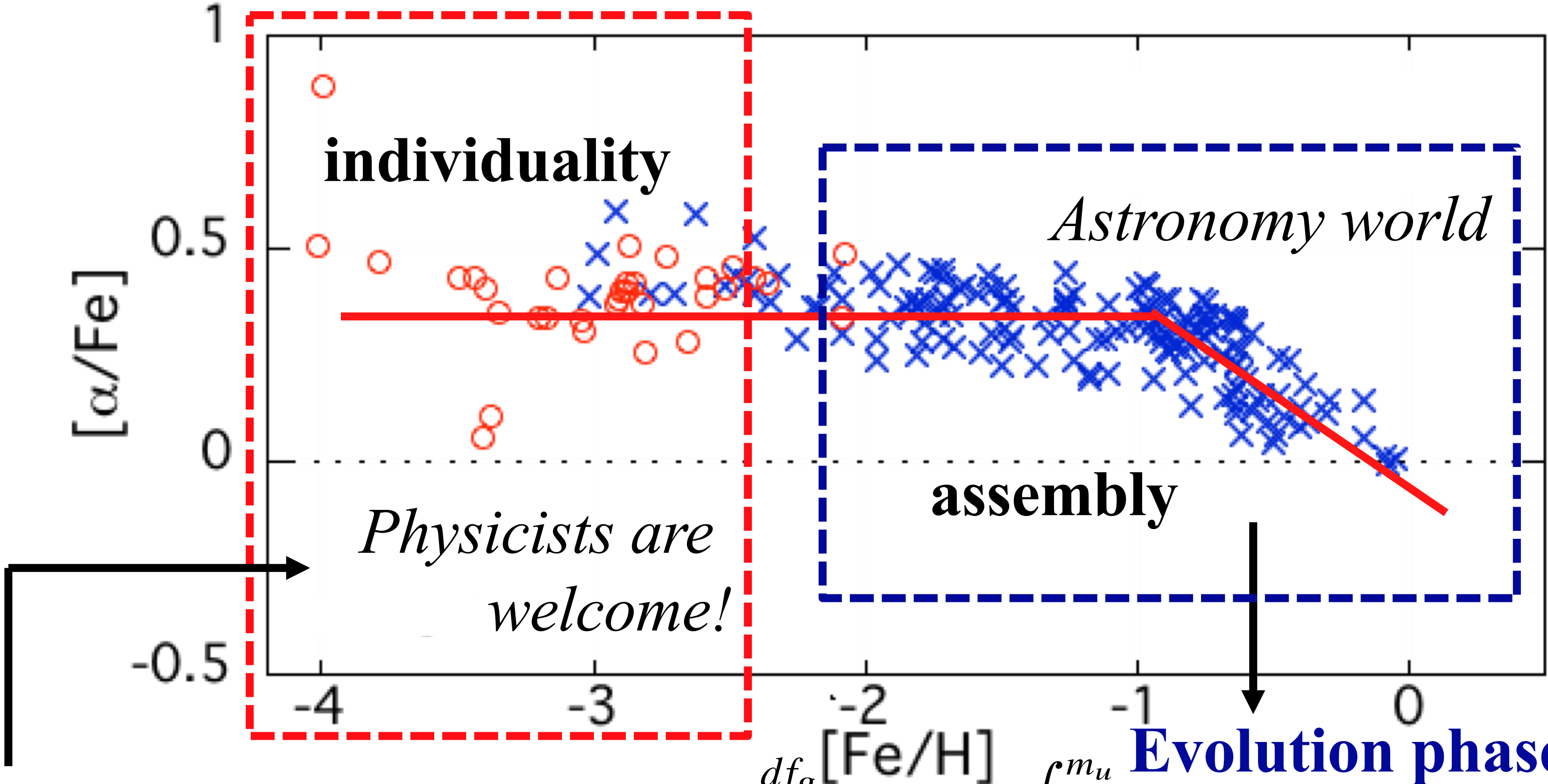


solar Fe × 1/1000

solar Fe × 1/10

solar Fe

Two domains of stellar abundances



Evolution phase

Nucleosynthesis phase

Individual stellar abundances may reflect each nucleosynthesis event

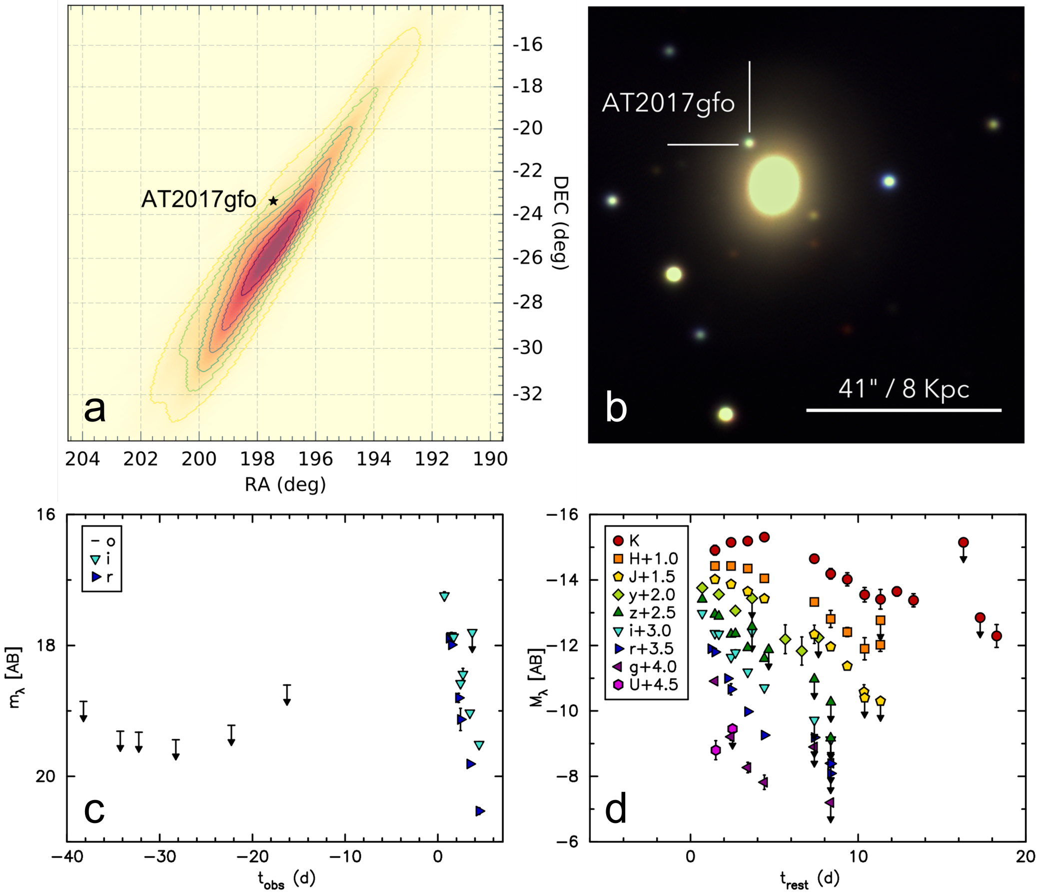
$$\frac{df_g}{dt} = -\psi(t) + \int_{\max(m_l, m_t)}^{m_u} dm\phi(m)r(m)\psi(t - t_m) + A(t)$$

$$\frac{d(Z_i f_g)}{dt} = -Z_i(t)\psi(t) + \int_{\max(m_l, m_t)}^{m_u} dm A\psi(m) y_{\mathrm{Ia},i} \times \int_0^t dt_{\mathrm{Ia}} g(t_{\mathrm{Ia}})\psi(t - t_{\mathrm{Ia}}) + \int_{\max(m_l, m_t)}^{m_u} dm(1 - A)\phi(m)[y_{\mathrm{cc},i} + Z_i(t - t_m) r_w(m)]\psi(t - t_m) + Z_{A,i}(t)A(t)$$

A single *r*-process event makes all *r*-nuclei

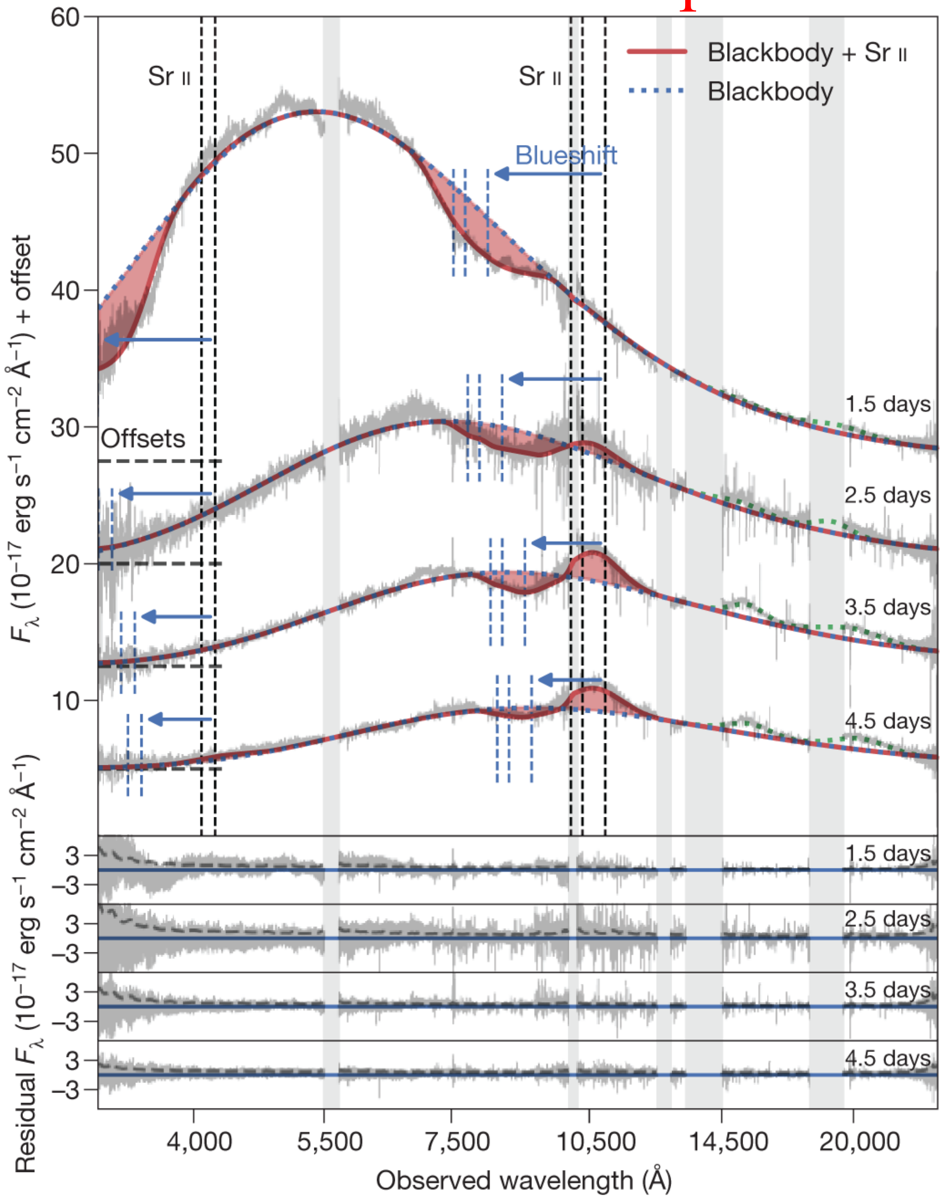
(Se ~ U)

GW170817 : GW from a binary neutron star merger



(Smartt+ 2017)

Sr is identified in the spectrum !

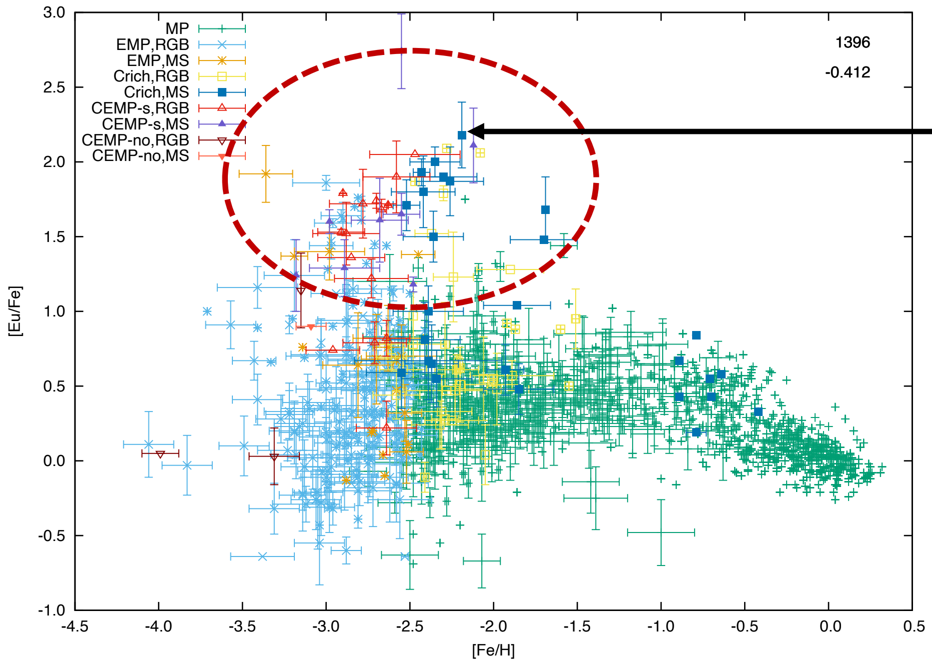


(Watson+ 2019)

kilonova: a strong indication of
r-process-element production

recent advance by Domoto+ 2022:
La and Ce as well (yesterday's talk)

r-process enhanced stars (*r*-II stars) in the Galactic halo



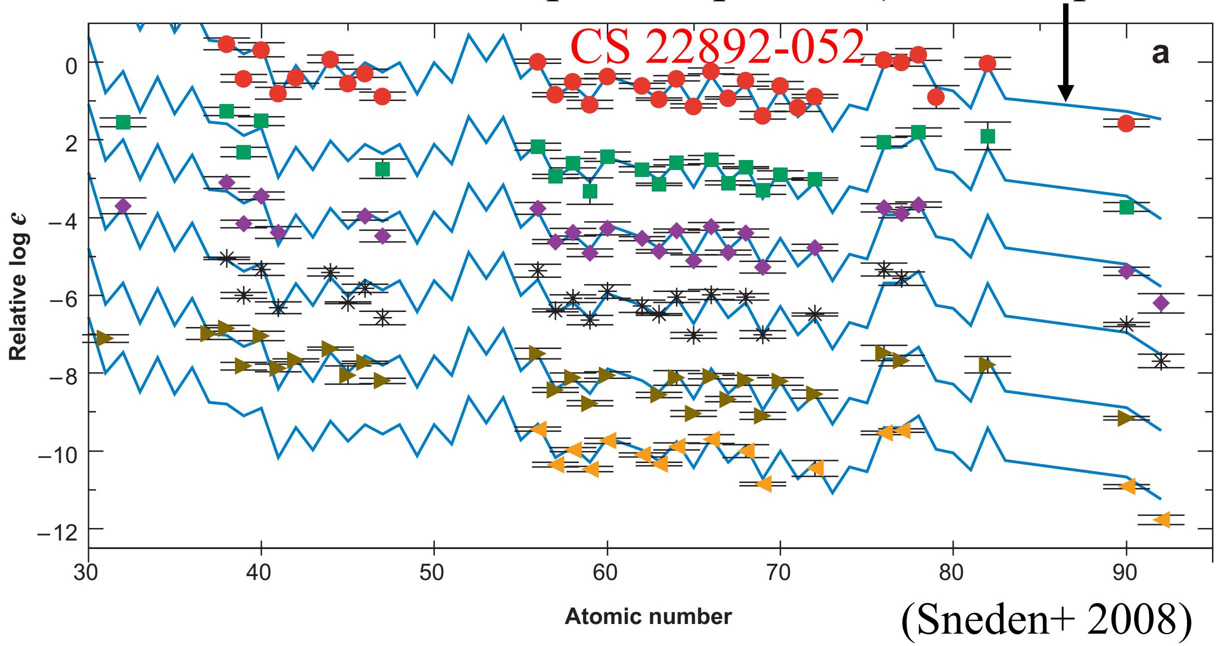
r-II stars ([Eu/Fe] >1)

Individual *r*-process patterns, in particular Z≥ 56, match the solar *r*-process pattern

presumably,
- ❑ a huge amount
- ❑ rarity

Individual *r*-process patterns likely reflect ones by a single *r*-process event

solar *r*-process pattern (solar – *s*-process)



(Sneden+ 2008)

✓ All *r*-process elements are synthesized

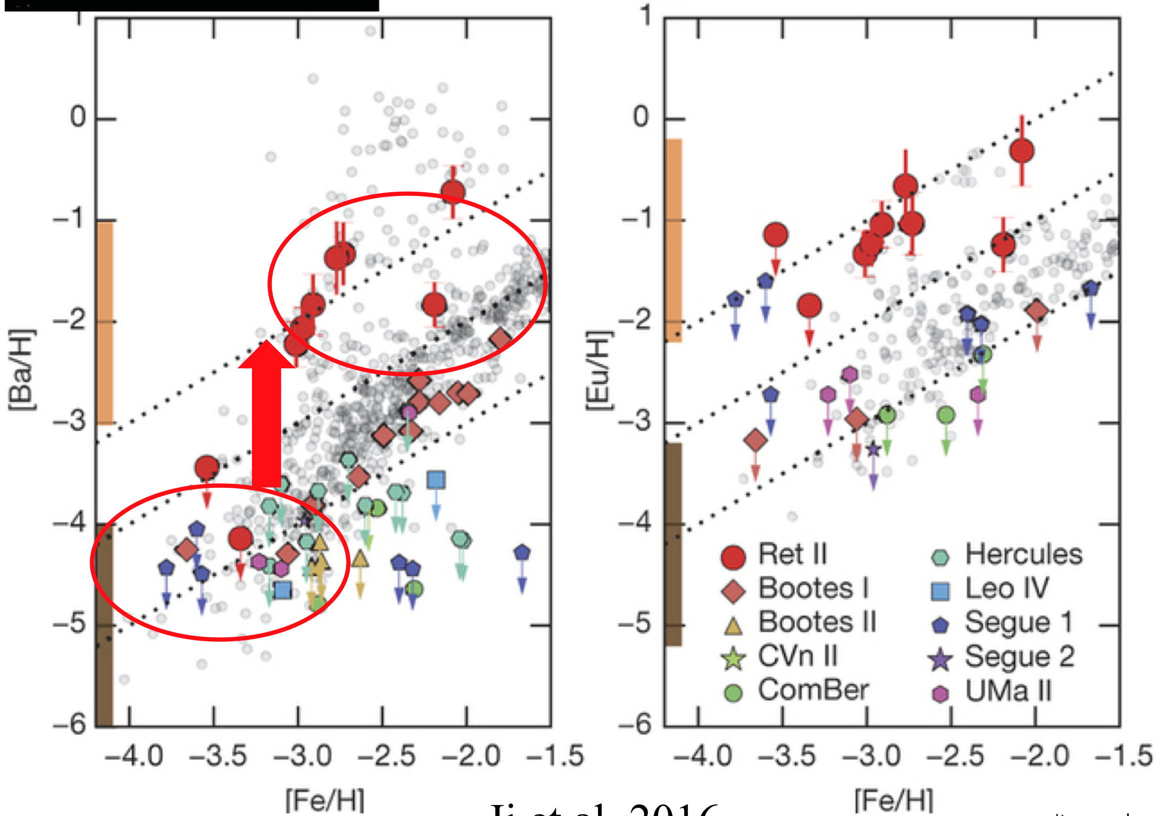
✓ little difference in nucleosynthesis among events

(universality)

Really, a single event?

A single *r*-process event is verified !

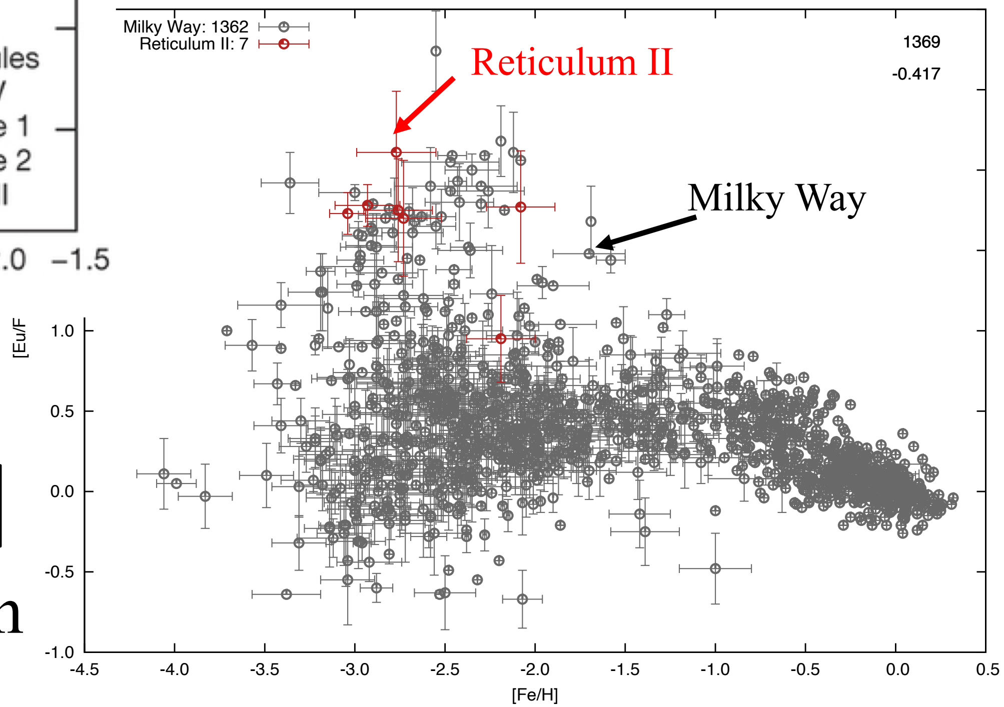
in an ultra-faint galaxy, Reticulum II [galaxy mass ~2500 solar mass]



Ji et al. 2016

Abundance jump by more than two orders is detected.

A r-process event emerged around [Fe/H]~ *-3.*



Individual abundance patterns of *r*-II stars can be compared with results of nucleosynthesis calculation

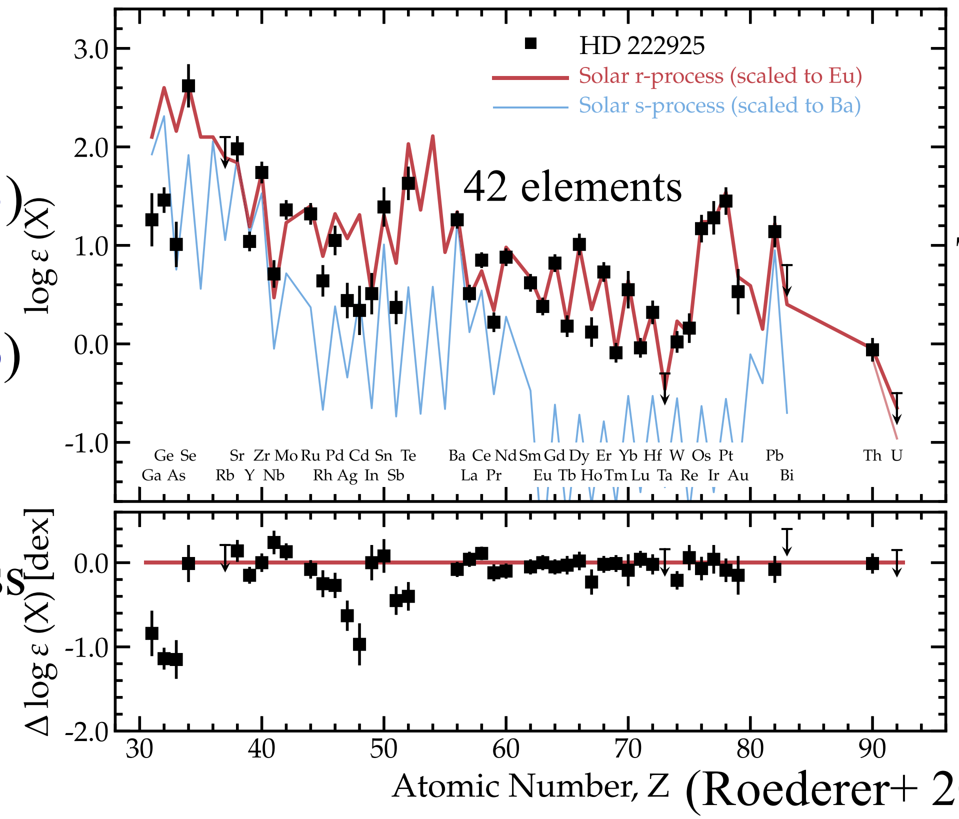
A very bright *r*-II star HD222925

V=9 mag

(CS22982-052:V=13)

(a brightest star in Reticulum II: V=16)

The lightest *r*-process element is **Se**?



(Roederer+ 2022)

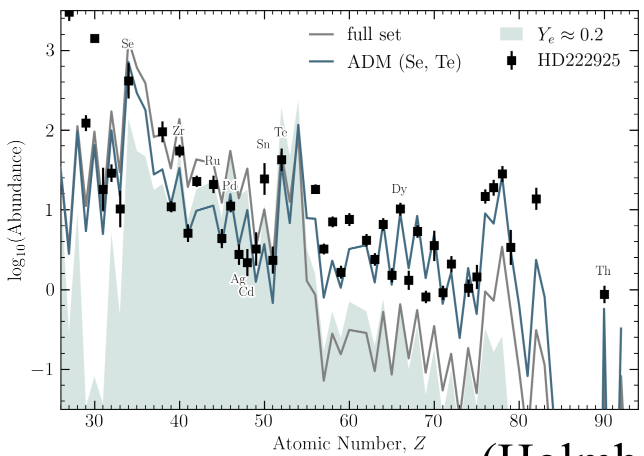
But, caution!!

This star is relatively metal-rich ([Fe/H]≈-1.5)

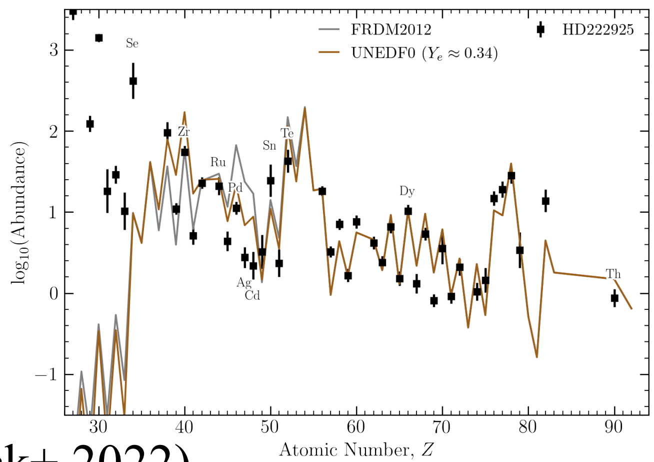
Gas where the star is born must be polluted, thus

≠ nucleosynthesis of a single *r*-process event

cold model



different nuclear mass model



(Holmbeck+ 2022)

no nuclear reheating
(low entropy+high velocity)
or
revised nuclear data

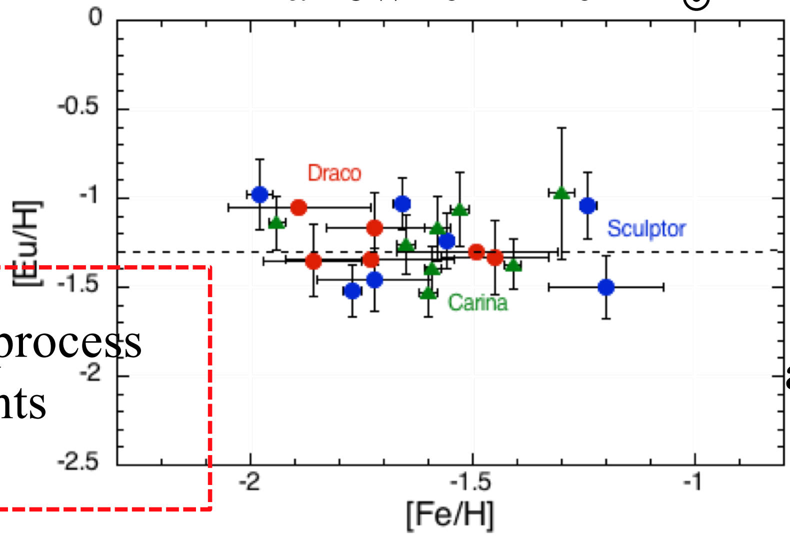
r-Process events should be rare

Regular CCSNe can not be a candidate
(ν-driven CCSNe) of the *r*-process site

Argument based on abundances in dwarf galaxies

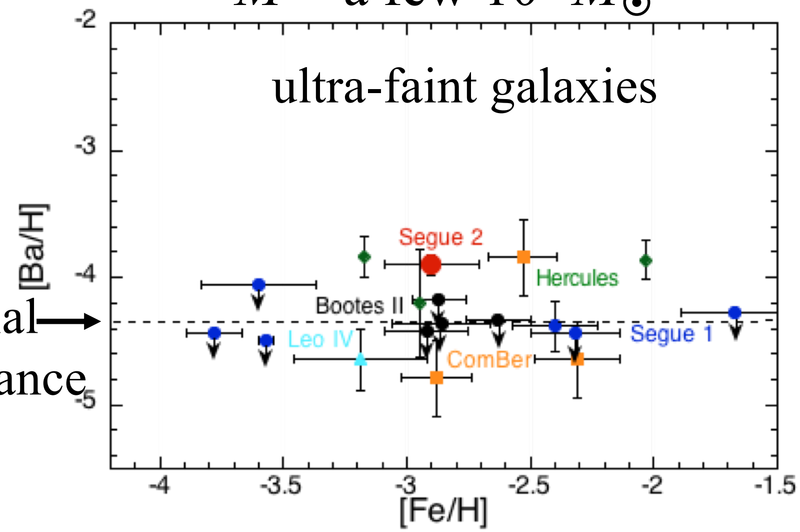
I. faint (small-mass) dwarf galaxies : **no *r*-process event is detected while Fe increases**

$M \sim$ a few$10^5 - 10^6\ M_\odot$



a few *r*-process events

$M <$ a few $10^4\ M_\odot$

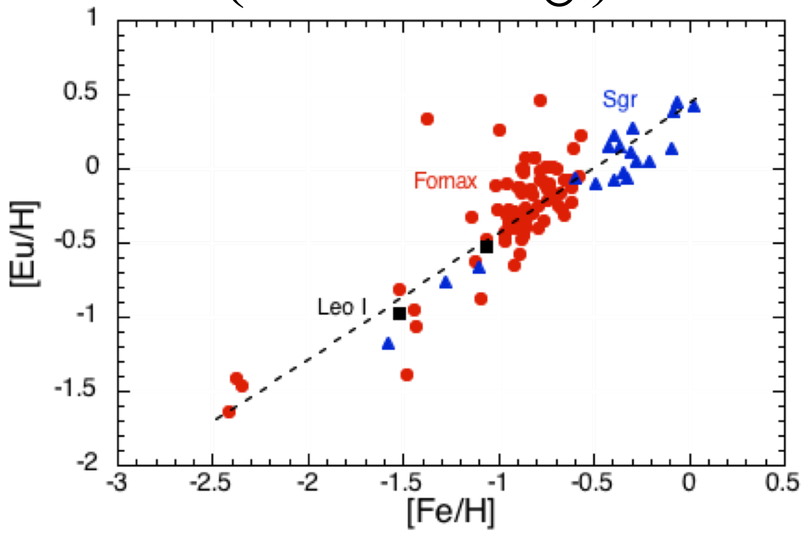


initial abundance →

(TT & Shigeyama 2014)

(excluding Reticulum II)

II. massive ($M > 10^7\ M_\odot$) dwarf galaxies



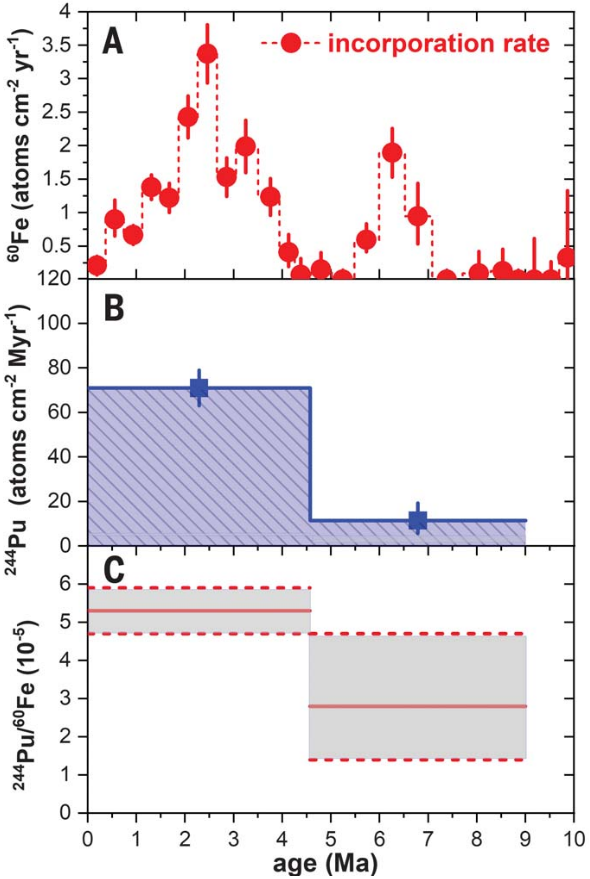
An increasing Eu/H trend is reasonable since NSMs happened ~100 times in total in the Fornax dSph ($4 \times 10^7\ M_\odot$).

NSM: neutron star merger

Can we completely exclude regular CCSNe from a candidate?

^{60}Fe

^{244}Pu



(Wallner+ 2021)

Maybe, a very small contribution (a few % or less) from regular CCSNe could be OK.

FeMn crust from the Pacific Ocean at 4,830m water depth

But, the measurement result can explain ~20-70% of actinides in the Universe by regular CCSNe !

Thus, something wrong (Diehl+ 2022)

~~might relate their sources~~; but, alternatively, it might be related to how ejecta flow through the interstellar medium on long time scales, and could thus point to a common driver for a simultaneous presence in the terrestrial record. The radioactive decay time of ^{244}Pu is 30 times longer than that of ^{60}Fe, so that ^{244}Pu would be sampled much further back in time. ~~Even if found in the same terrestrial deep-~~

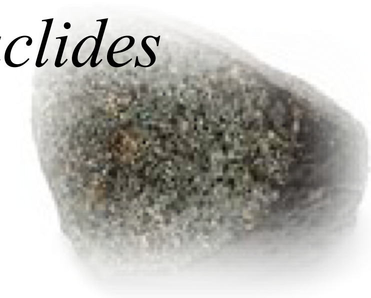
suggests co-production of ^{60}Fe and ^{244}Pu

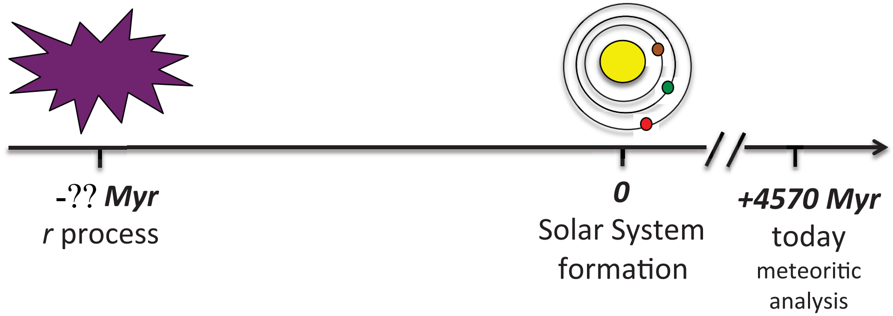
a different propagation of different ejecta?

Last *r*-process event at the early solar system

Short-lived radionuclides
in ***meteorites***

(1960~)





half-lives: ^{247}Cm: 1.56×10^{7} yr, ^{129}I: 1.57×10^{7} yr, ^{244}Pu: 8.1×10^{7} yr

meteoritic abundances unstable/stable	production ratio	time interval between last *r*-process event and the solar system formation
$^{247}\mathrm{Cm}/^{235}\mathrm{U} = (1.1\text{-}2.4) \times 10^{-4}$	0.4	123 Myr (Lugaro+ 2014)
$^{129}\mathrm{I}/^{127}\mathrm{I} = 1.19 \pm 0.20 \times 10^{-4}$	1.35	109 Myr (Lugaro+ 2014)
$^{244}\mathrm{Pu}/^{238}\mathrm{U} \sim 0.008$	0.53	100 Myr (Dauphas 2005)

The last *r*-process event occurred **~100 Myr ago**, which can be compared to **~2-3 Myr ago** for the last CCSN event

(^{129}I/ ^{247}Cm can constrain *r*-process model: Cote+ 2021)

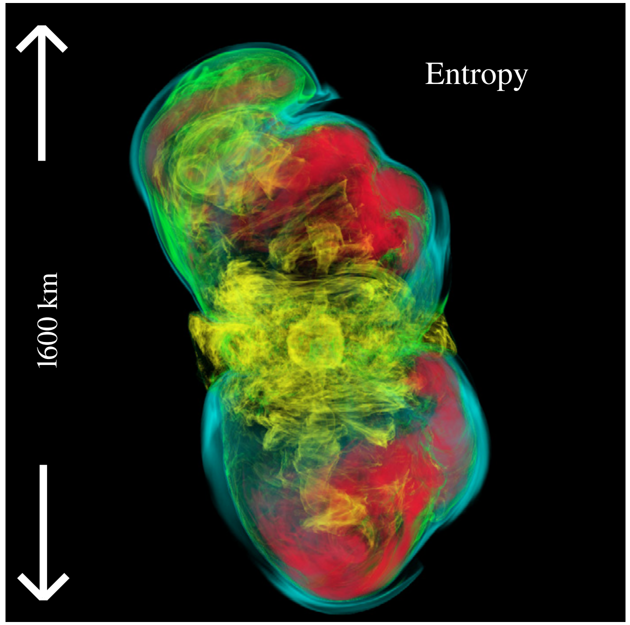
Candidates of *r*-process CCSNe

1. Magnetorotational SNe

✓ An explosion triggered by fast rotation and high magnetic fields
(e.g., Takiwaki+09, Kuroda+20)

✓ *r*-process nucleosynthesis
(e.g., Winteler+12, Nishimura+15)

✓ associated with magnetars (?)



(Mosta+ 2014)

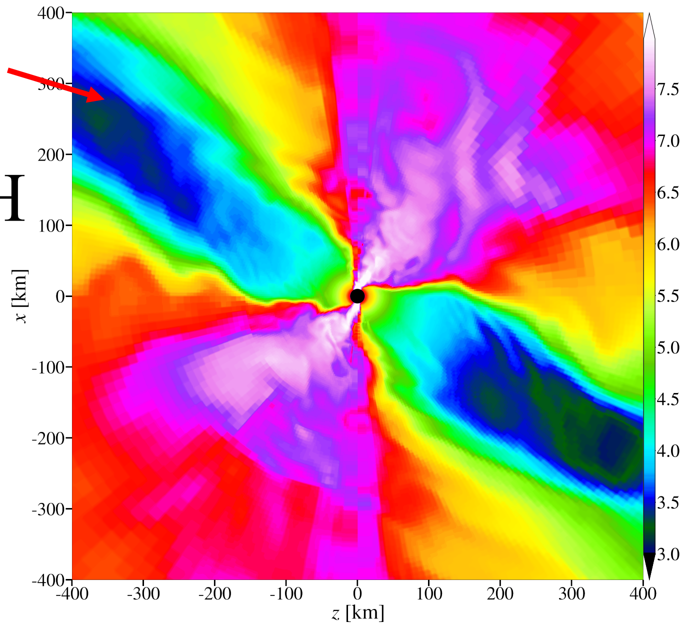
2. Collapsars

✓ Powered by energy from the rotating BH
(MacFadyen & Woosley 99)

✓ *r*-process nucleosynthesis
(Siegel+ 18)

✓ associated with long GRBs (?)

torus around BH



(Gottlieb+2022)

r-Process enrichment in the Milky Way

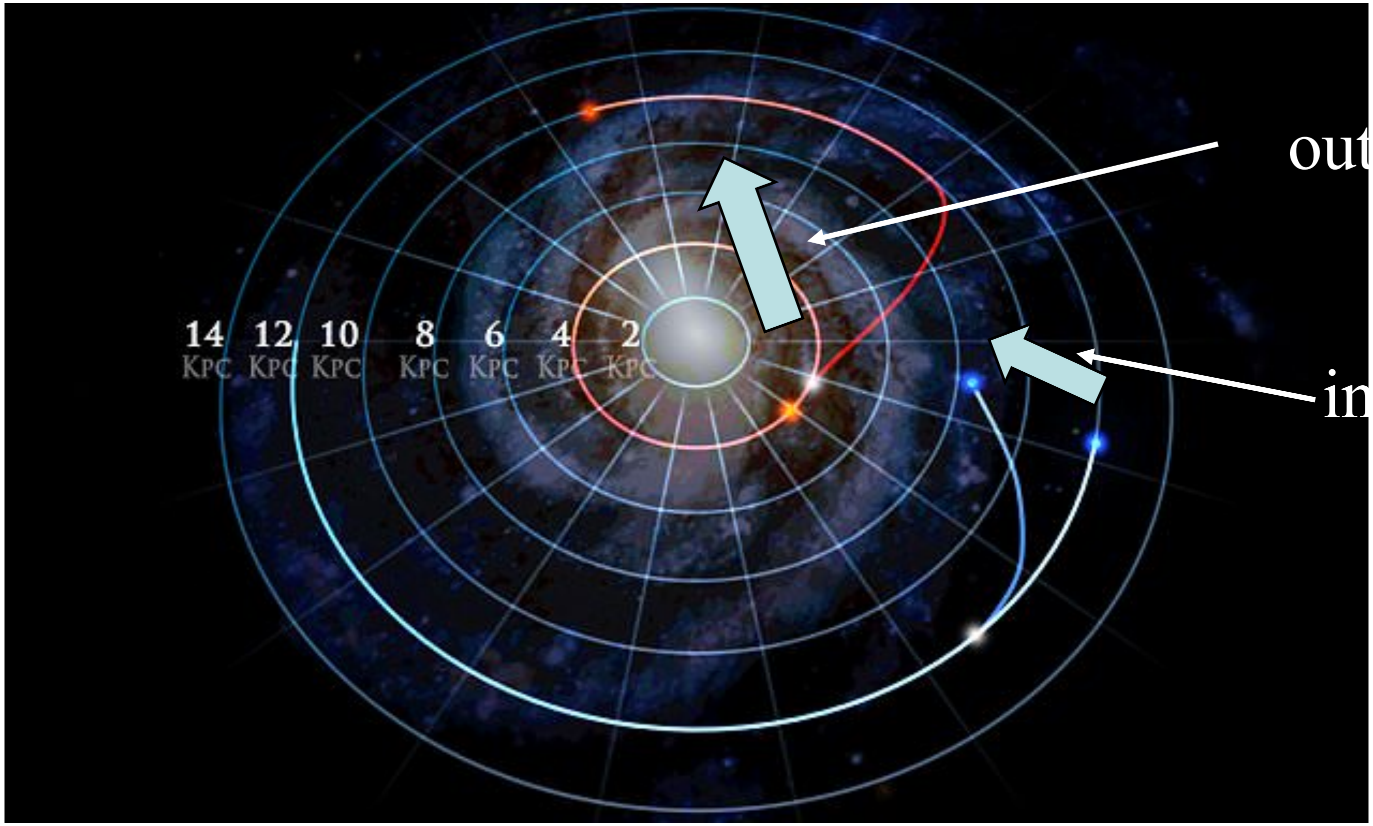
Identifying
the production sites of r-process

Based on

- radial migration
- solar twins

A new paradigm of Galactic dynamics

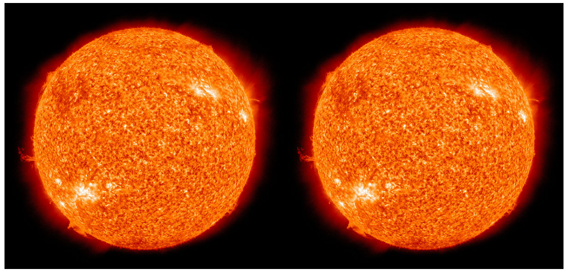
Stars radially move on the Galactic disk : ***radial migration***



@Danna Berry

This theory predicts that the stars in the solar vicinity represent the mixture of stars born at various Galactocentric distances over the disk.

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!**

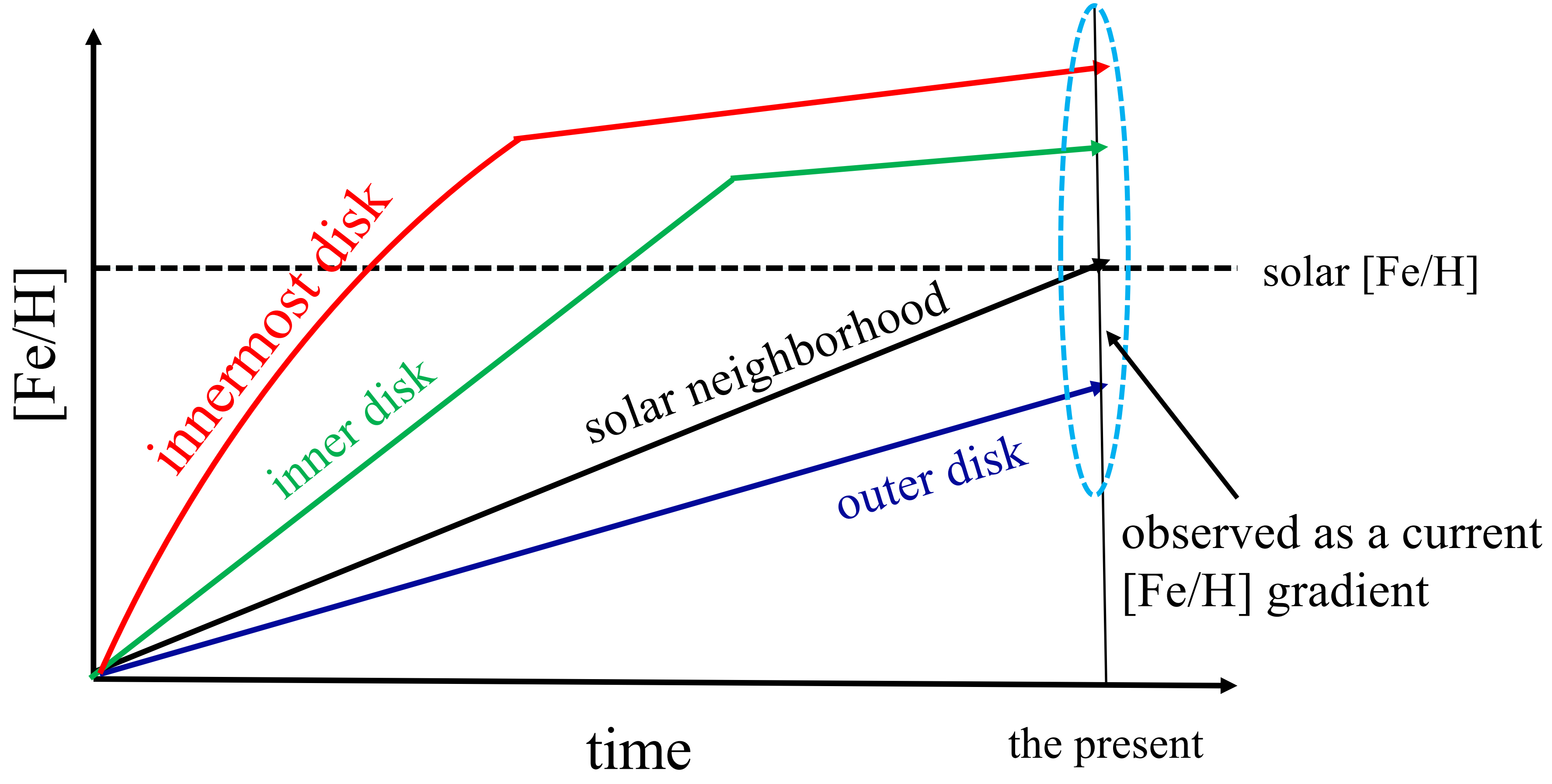
⇨ There is a large span in ages among the stars having the same metallicity

The ages of solar twins are widely distributed over 0-10 Gyr

Locally identified solar twins might be the assembly of stars migrating from various R_G in the inner disk

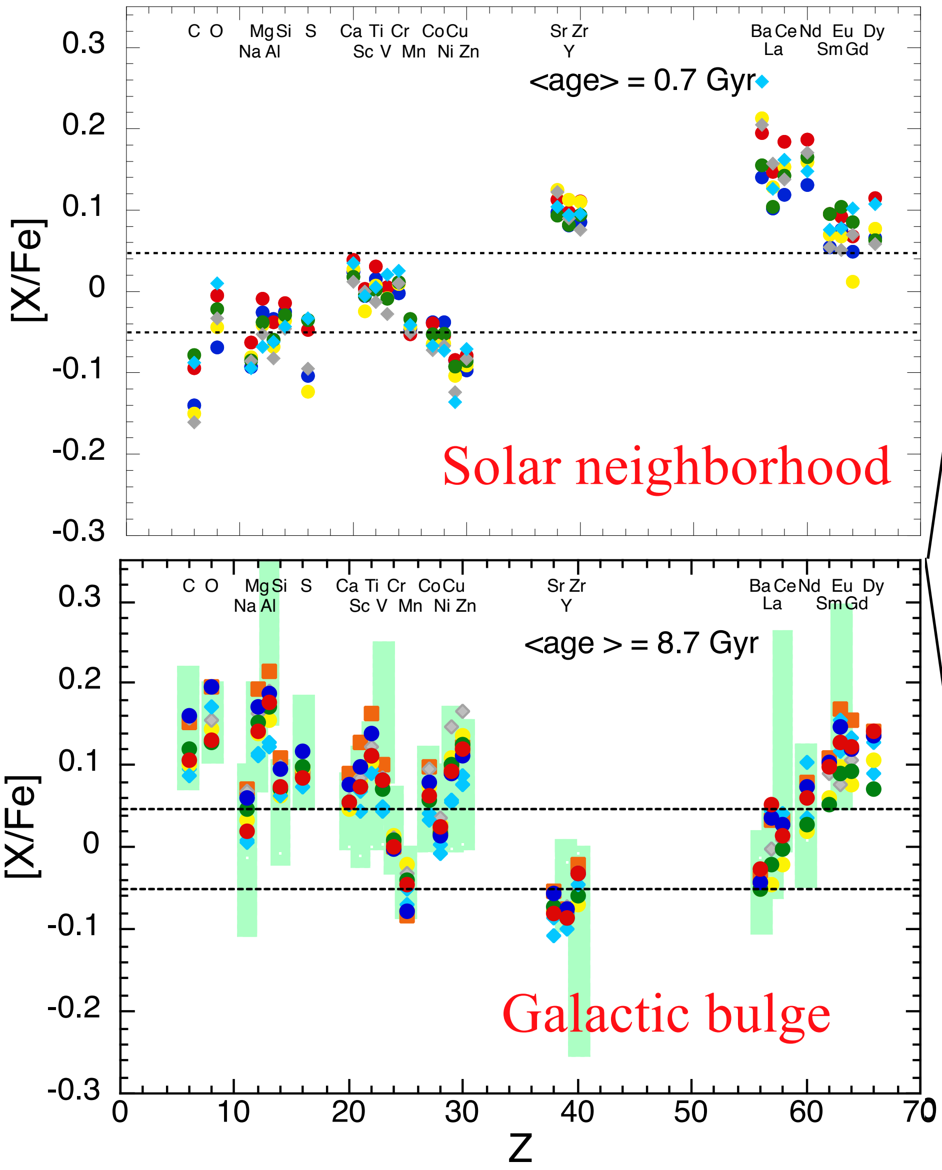
—— *consistent with the view on radial migration* ——

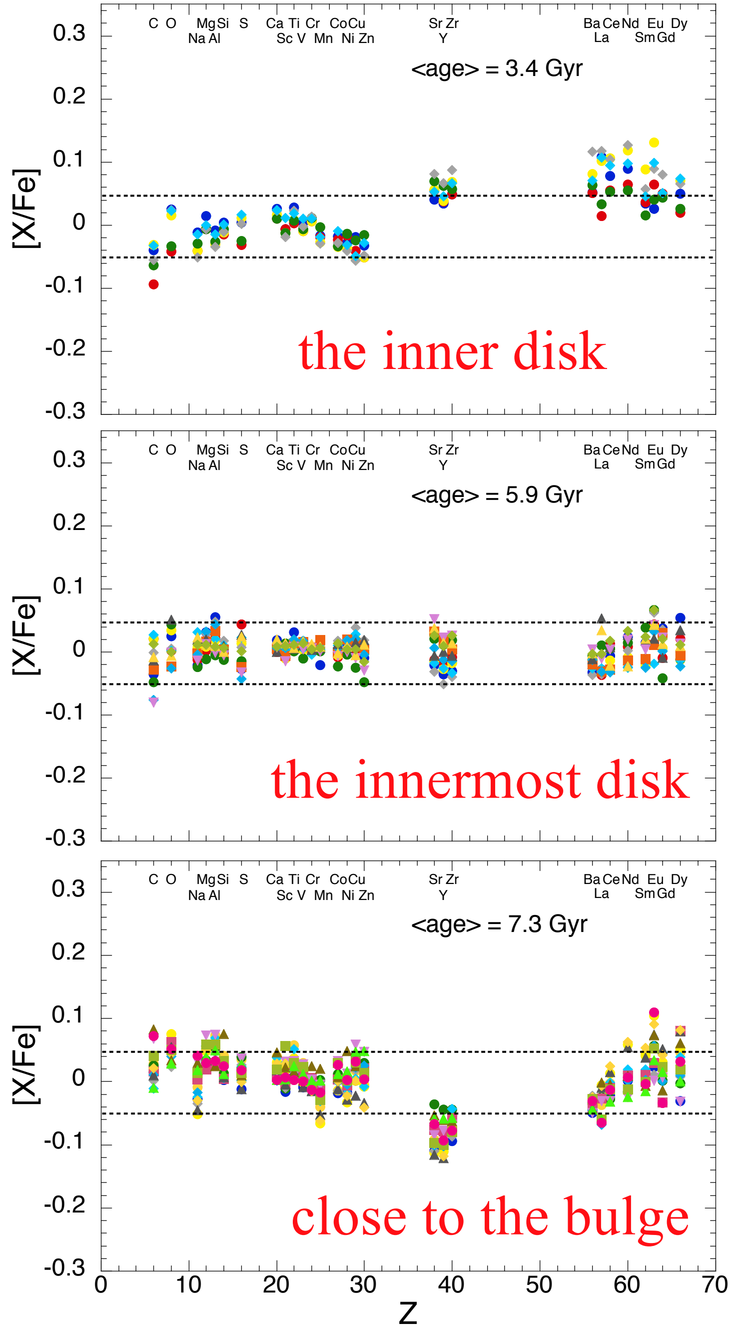
Older twins were born at the disk closer to the center



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

older ages = smaller R_{GC}

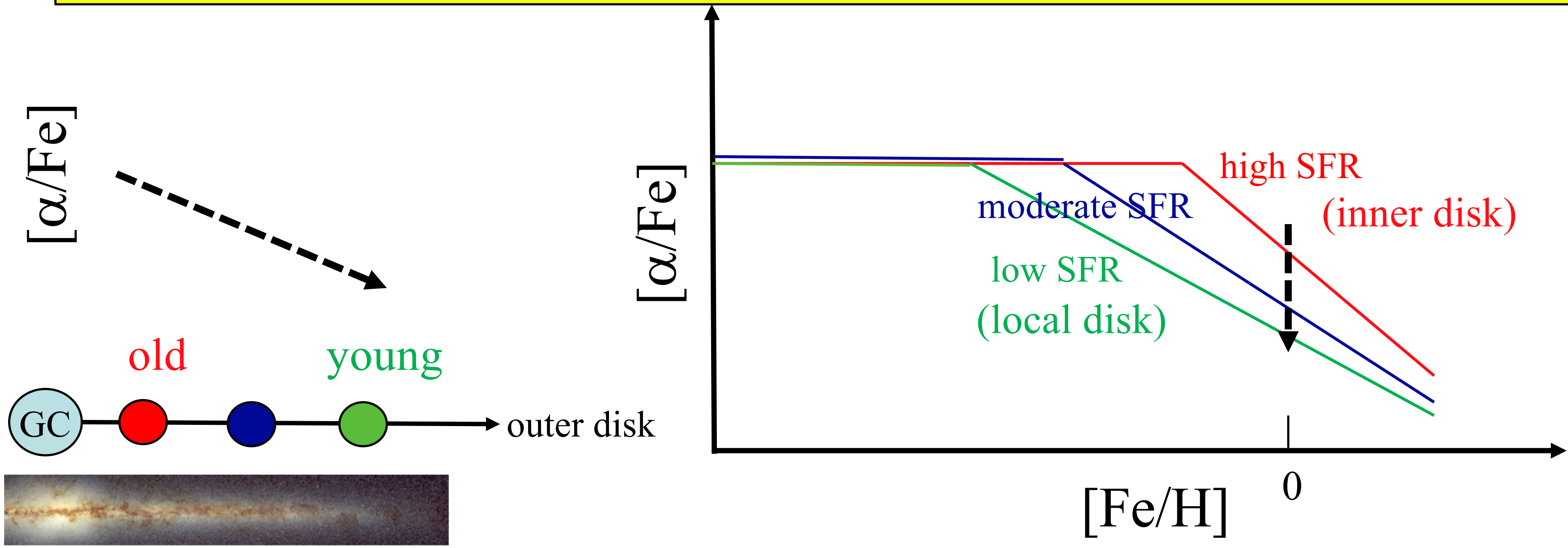


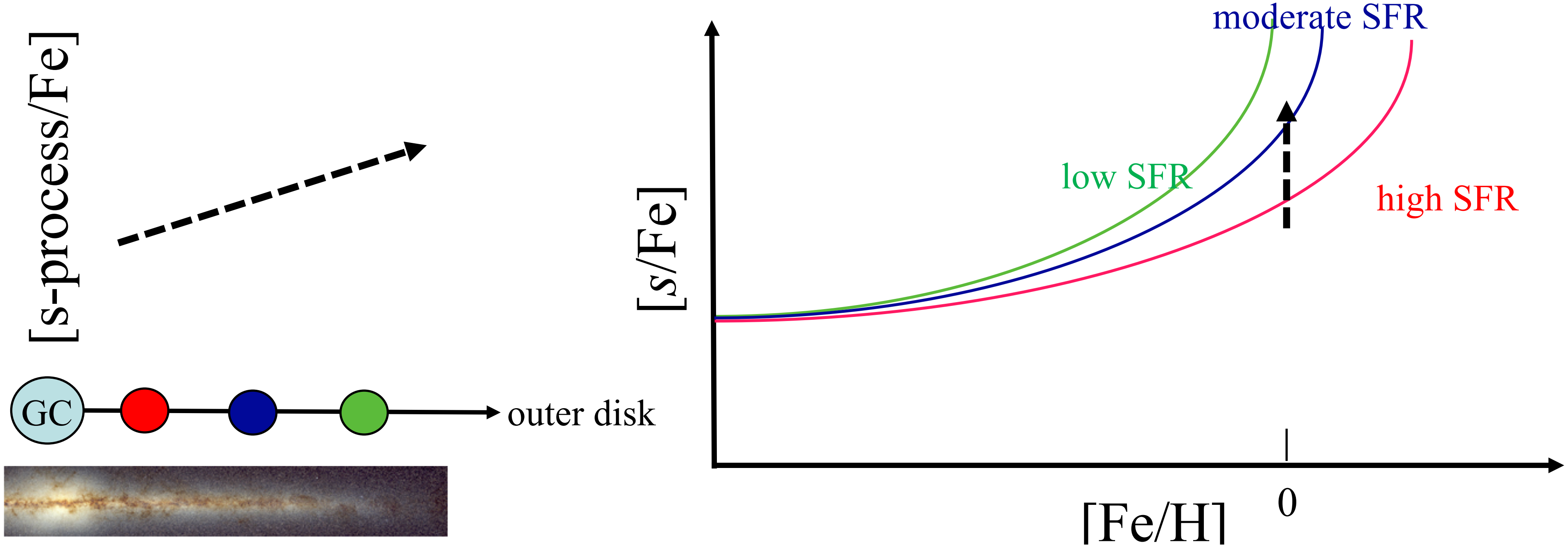


including the Sun

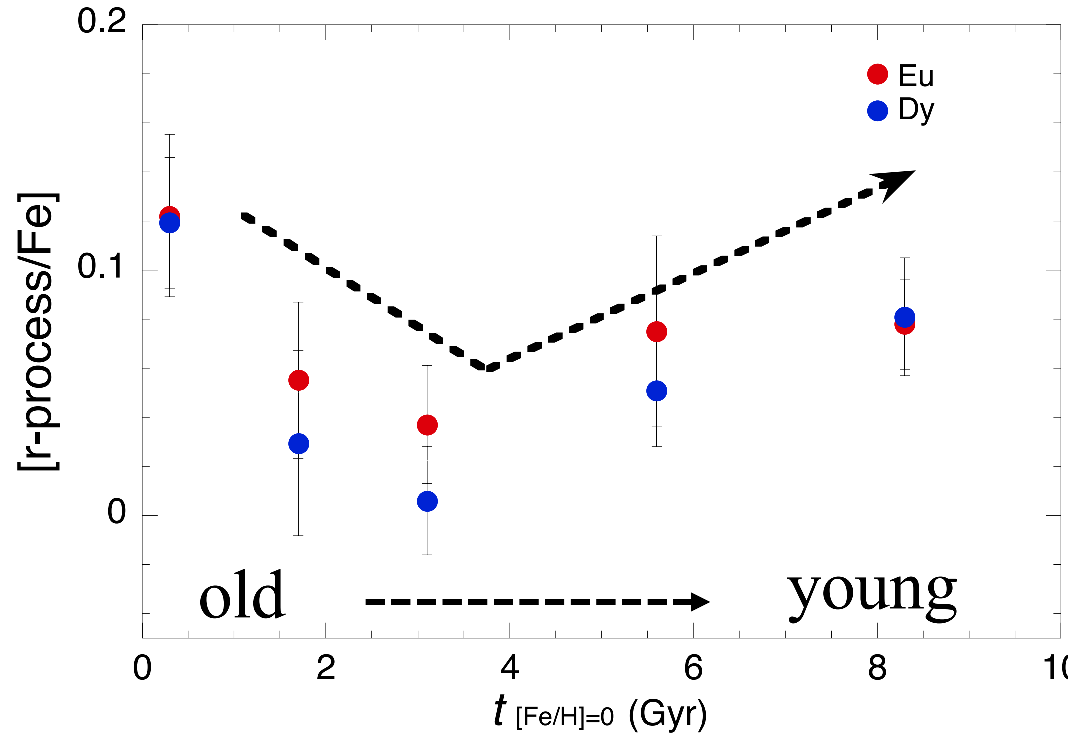
(TT 2021)

Change in abundance ratios as a function of age (i.e., R_{GC}) can be explained by the models with a different speed of star formation



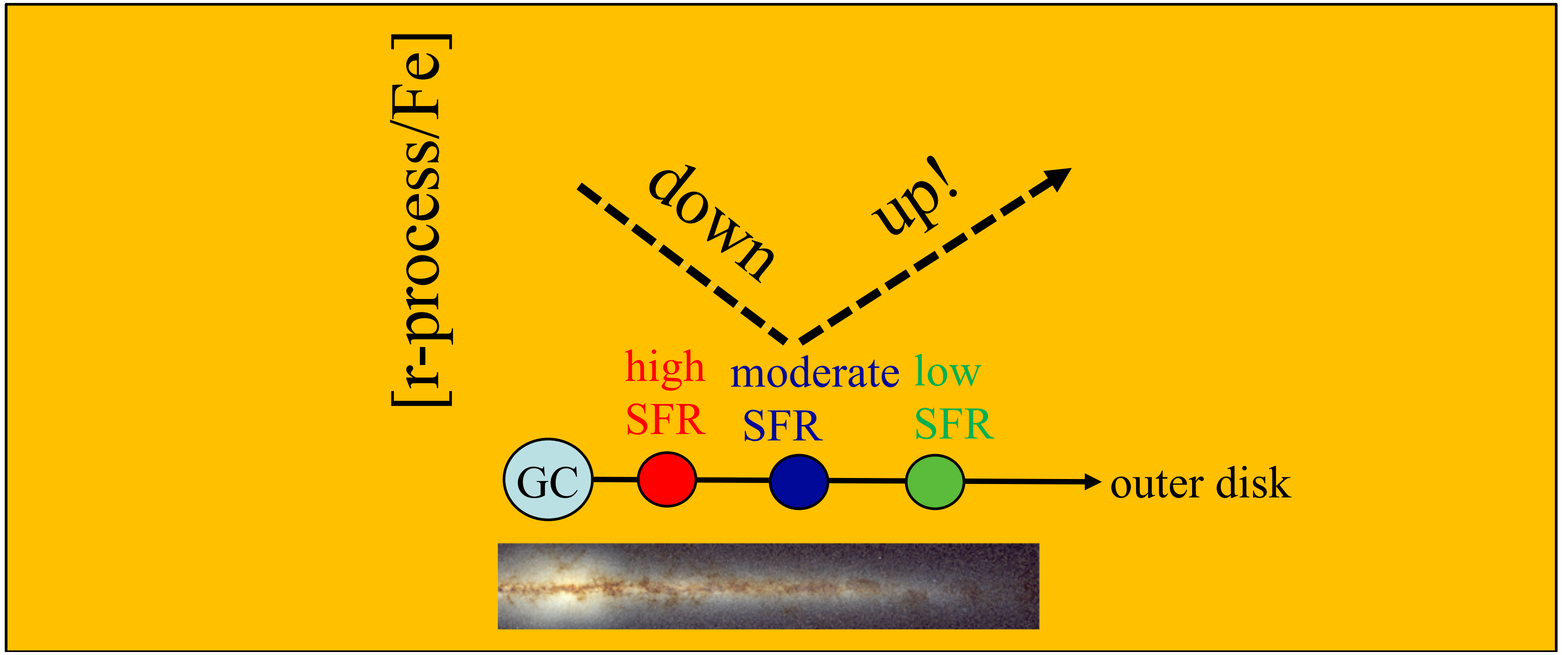


[*r*-process/Fe] ratios don’t follow the monotonous trend



$t_{\text{[Fe/H]=0}}$:
elapsed time for the chemical enrichment up to [Fe/H]=0 from the start of star formation

(= an age of the Galactic disk – twin’s age)

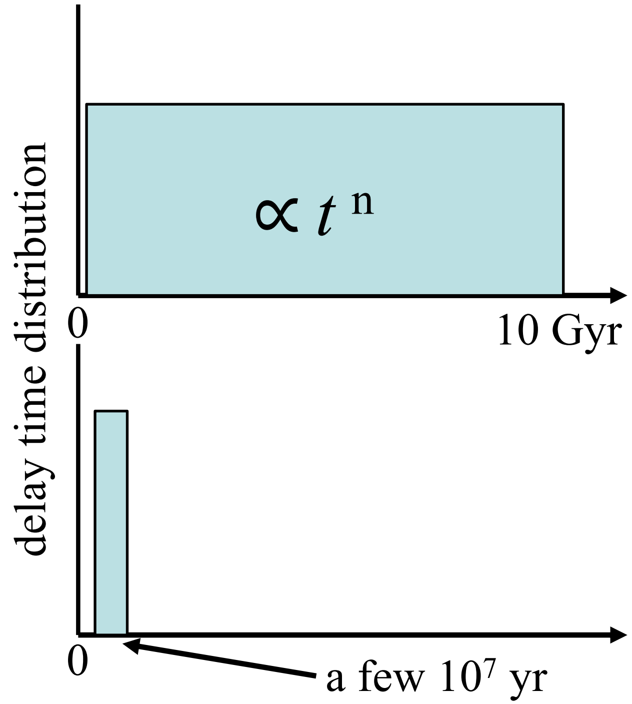


the possible sites of r-process elements

- neutron star mergers (NSMs)

  the sole site or not?

- specific core-collapse supernovae (CCSNe)
  - ✓ magneto-rotational supernovae
  - ✓ collapsars



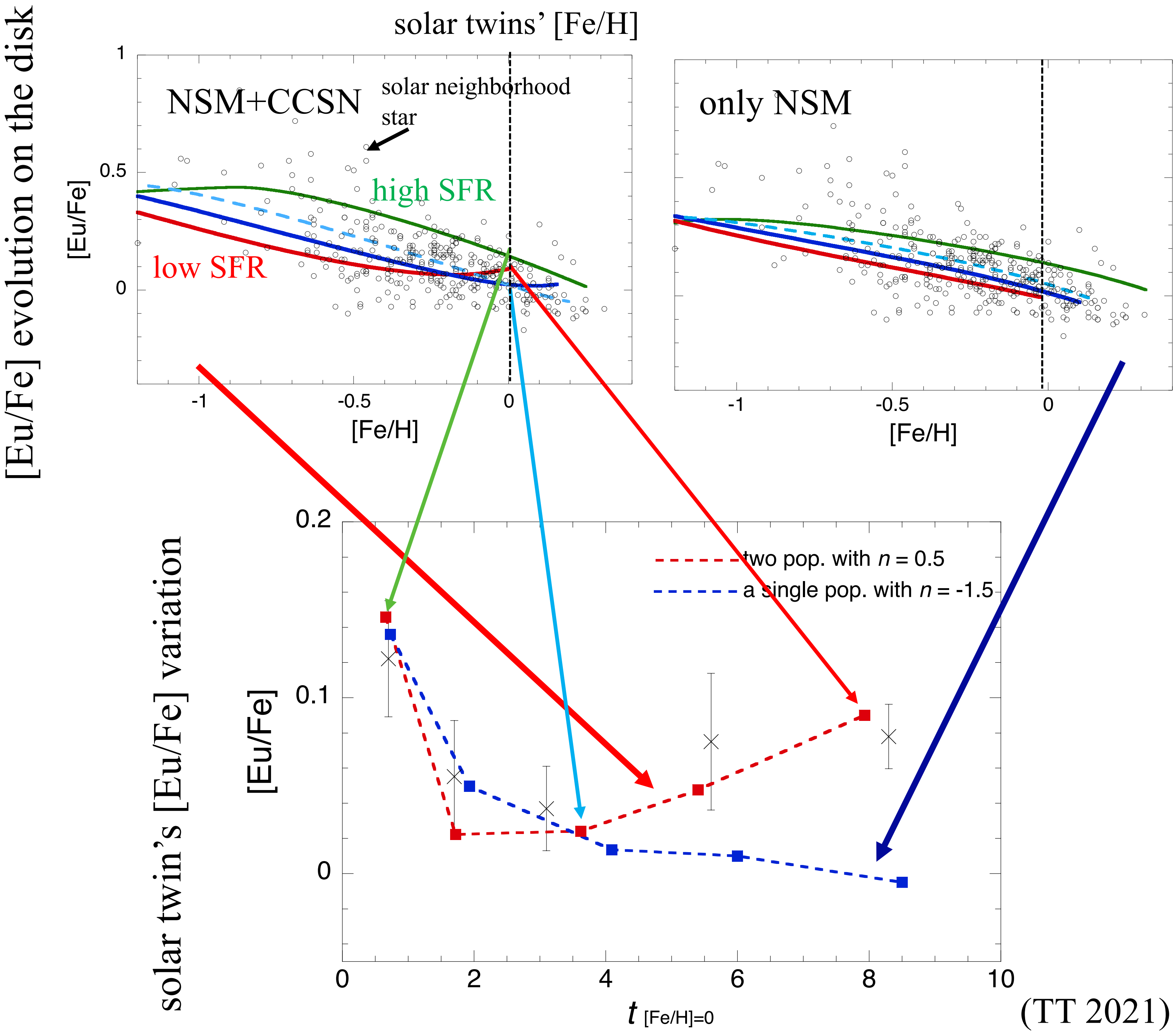
To explain the trend of [*r*-process/Fe] (down&up) on the Galactic disk

⇩

two sites with largely different delay times (short&long) is indispensable

⇩

major contribution from both CCSNe and NSMs is suggested



[Eu/Fe] evolution on the disk
solar twins' [Fe/H]
NSM+CCSN
solar neighborhood star
high SFR
low SFR
only NSM
[Eu/Fe]
[Fe/H]
1
0.5
0
-1
-0.5
solar twin's [Eu/Fe] variation
two pop. with n = 0.5
a single pop. with n = -1.5
0.2
0.1
2
4
6
8
10
t [Fe/H]=0
(TT 2021)

Summary

- A single *r*-process event makes all *r*-nuclei (Se ~ U).

- *r*-Process events should be rare. Thus, regular (i.e.neutrino-driven) CCSNe can not be a candidate of the *r*-process site.

- Enrichment of *r*-process elements for solar twins in the Milky way strongly implies, *r*-process elements are synthesized in not only neutron star mergers but also in a subclass of CCSNe.