銀河の化学進化から探る
*r*過程元素を作り出す超新星の個性

辻本拓司 (国立天文台)

What is "characteristic" here ?

Its frequency depends on "metallicity"

How?

Supernovae producing *r*-process elements strongly favor a low-metallicity ([Fe/H]<-0.7) environment

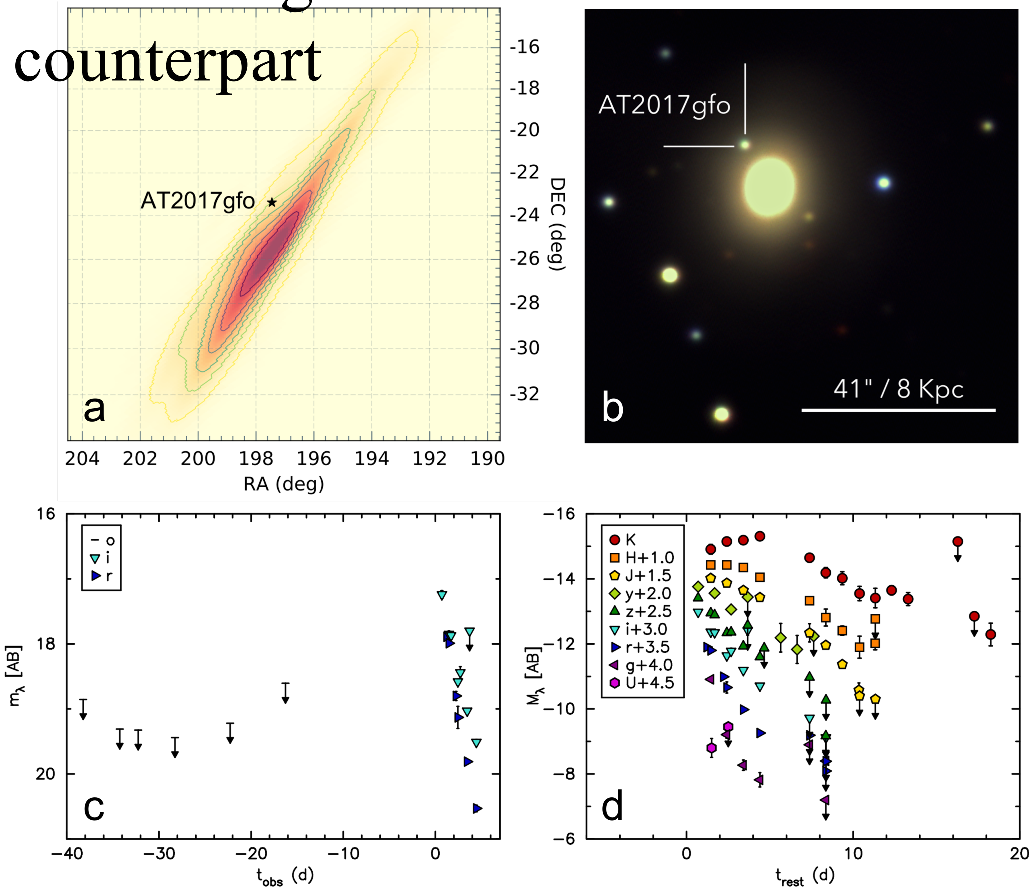
第10回超新星ニュートリノ研究会, 2月29–3月1日 at 岡山大学

Background

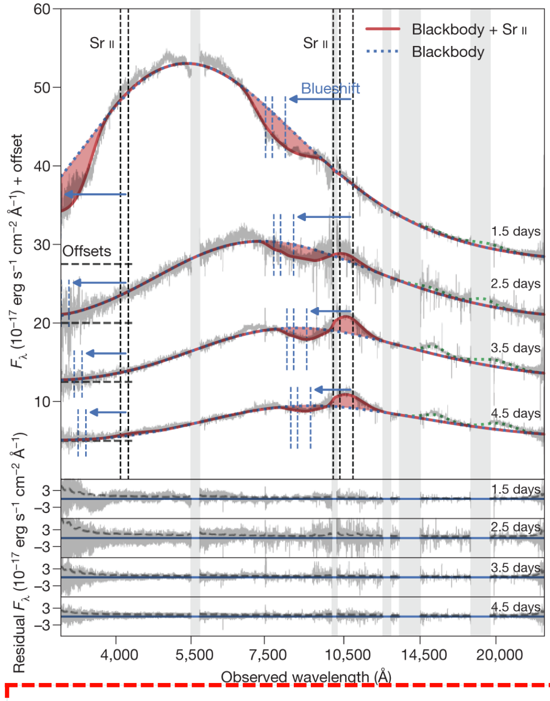
-two major updates to our understanding of the r-process-

GW170817 : GW from a binary neutron star merger

electromagnetic counterpart



(Smartt+ 2017)

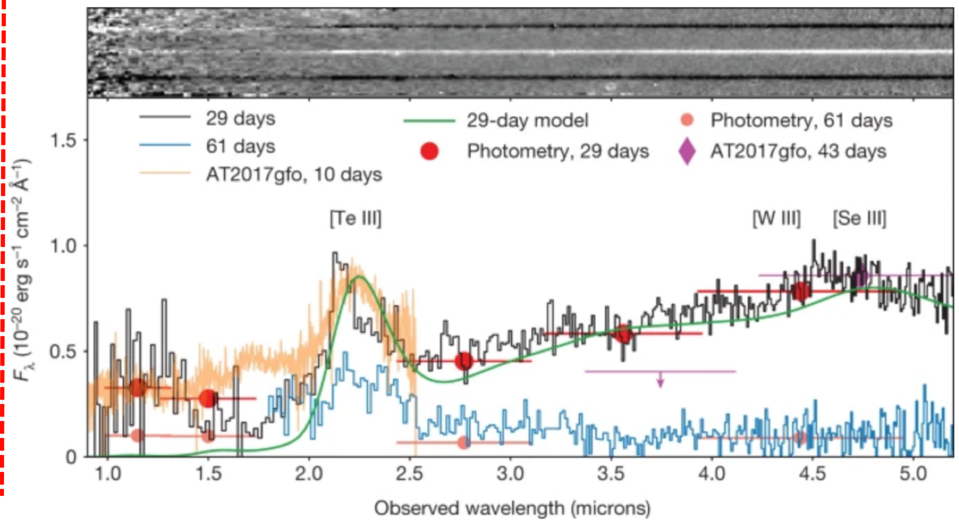


Sr is identified in the spectrum

(Watson+ 2019)

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

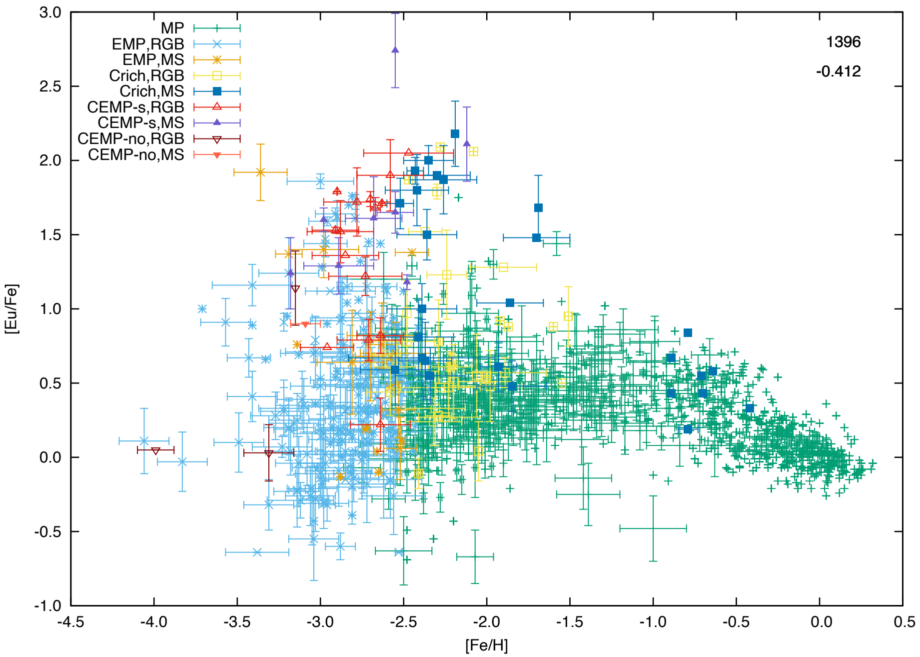
(Levan+ 2024)



JWST' result: **GRB230307A:** Te and other lanthanides are also identified

Galactic chemical evolution suggests supernovae must contribute to the r-process enrichment

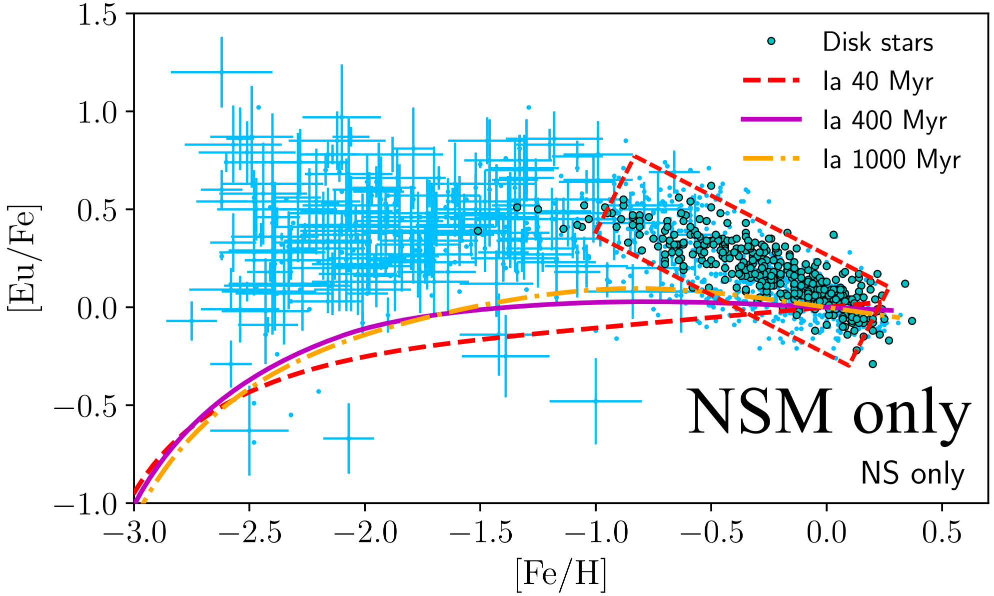
Halo

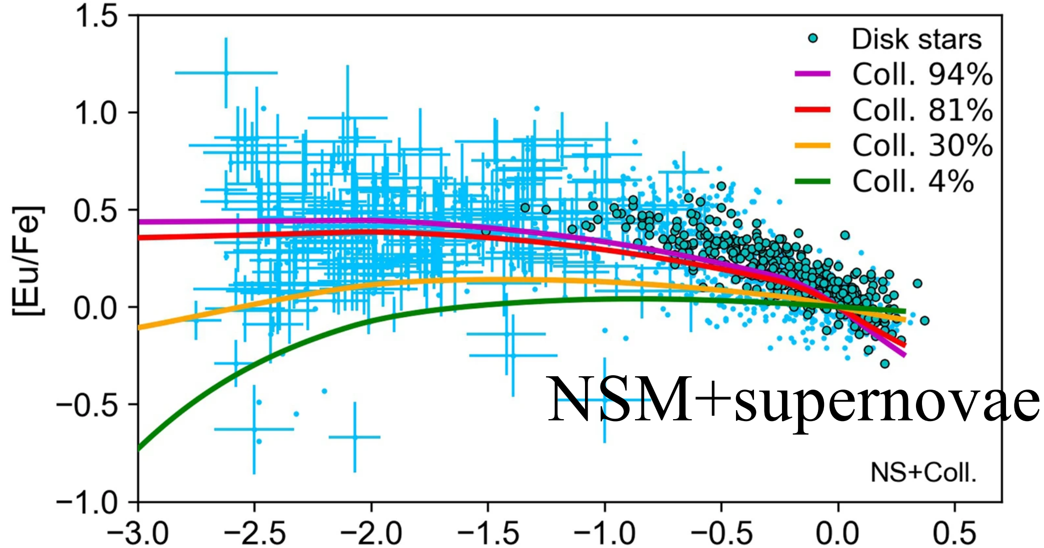


(from SAGA database)

Extremely metal-poor stars are enriched by *r*-process elements

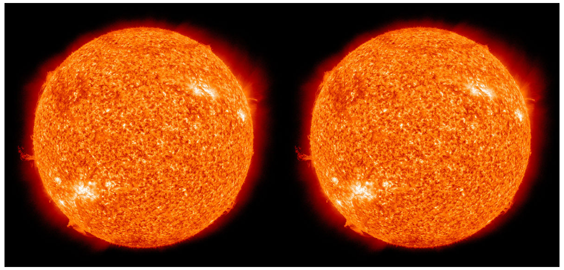
Disk





(Siegel+ 2019)

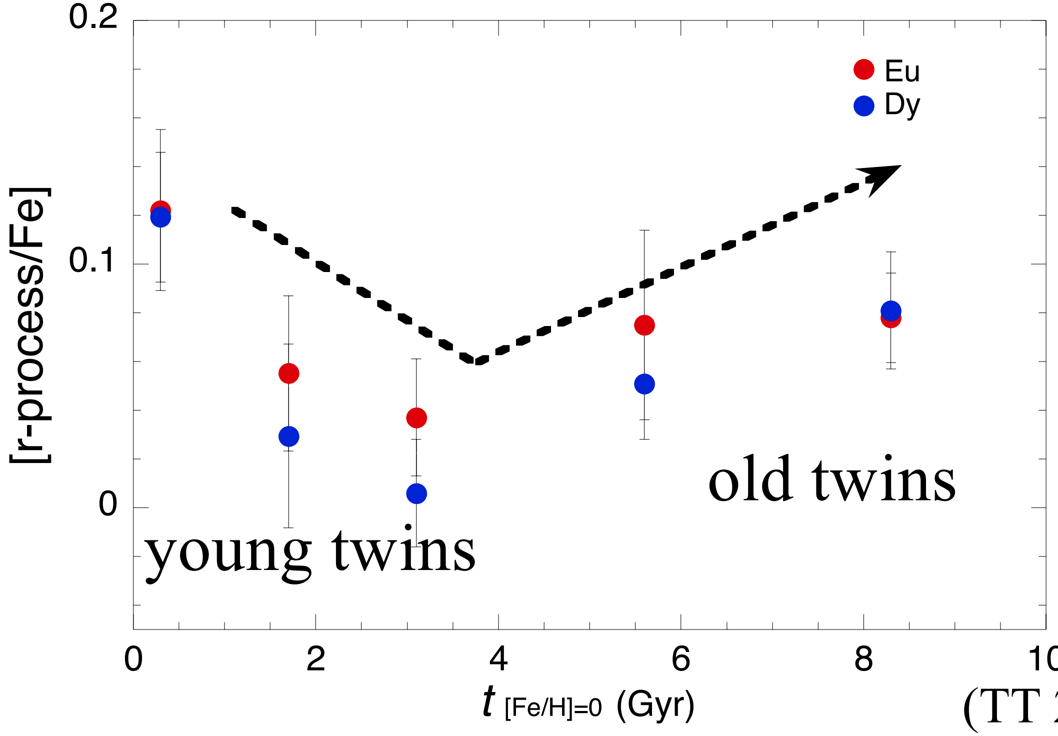
solar twins



stars which exhibit stellar atmospheric characteristics
quite similar to the solar values

an effective temperature (≤ 100K), surface gravity (log g: ≤ 0.1), [Fe/H] ratio (≤ 0.1 dex)

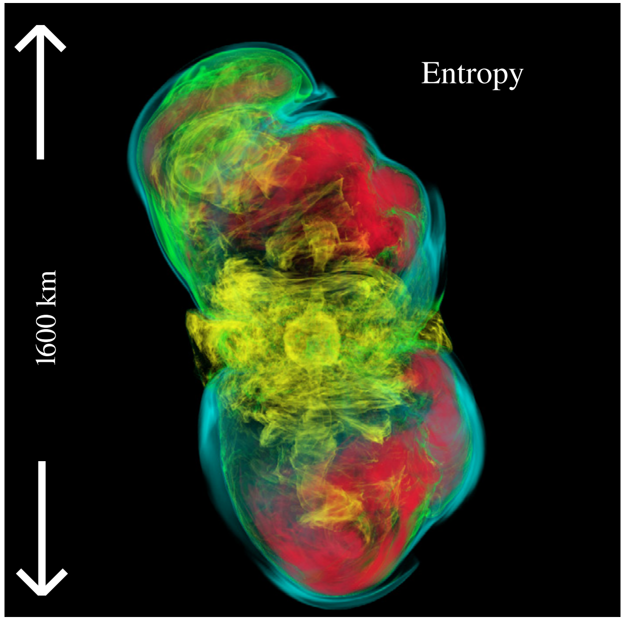
[r-process/Fe] ratios don't follow the monotonous trend



(TT 2021)

suggesting two sites of *r*-process whose delay times are different

Candidates of *r*-process CCSNe



(Mosta+ 2014)

1. Magnetorotational SNe

✓ An explosion triggered by fast rotation and high magnetic fields

(e.g., Takiwaki+09, Kuroda+20)

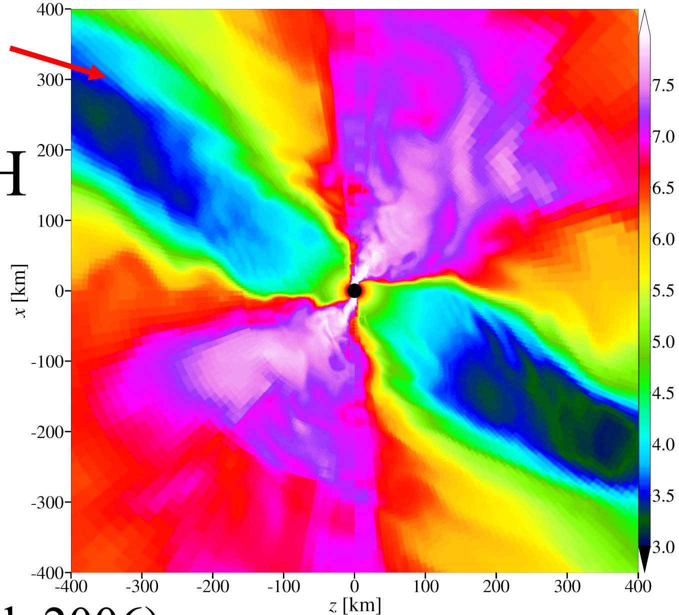
✓ *r*-process nucleosynthesis

(e.g., Winteler+12, Nishimura+15)

✓ associated with magnetars, superluminous SNe (?)

2. Collapsars

torus around BH



(Gottlieb+2022)

✓ Powered by energy from the rotating BH

(MacFadyen & Woosley 99)

✓ *r*-process nucleosynthesis

(Siegel+ 19)

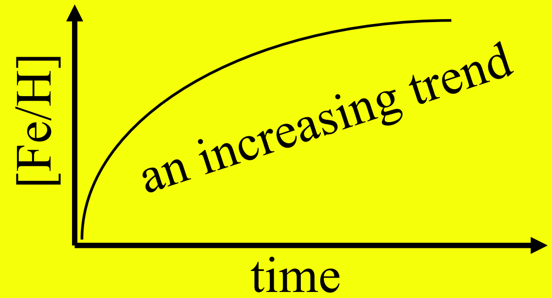
✓ associated with long GRB (?)

(Woosley & Heger 2006;Yoon et al. 2006)

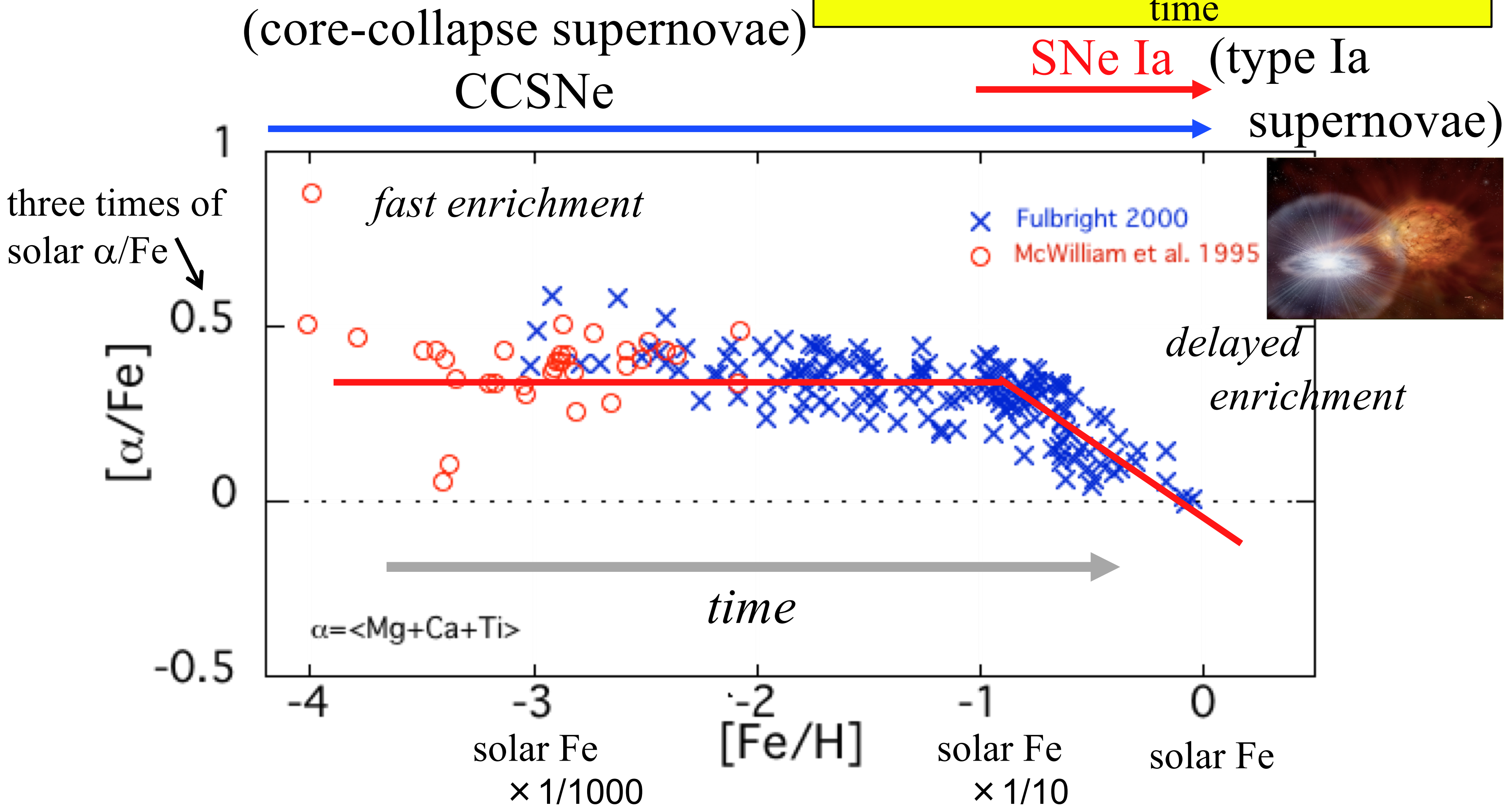
Basic concepts of chemical evolution

stellar abundances

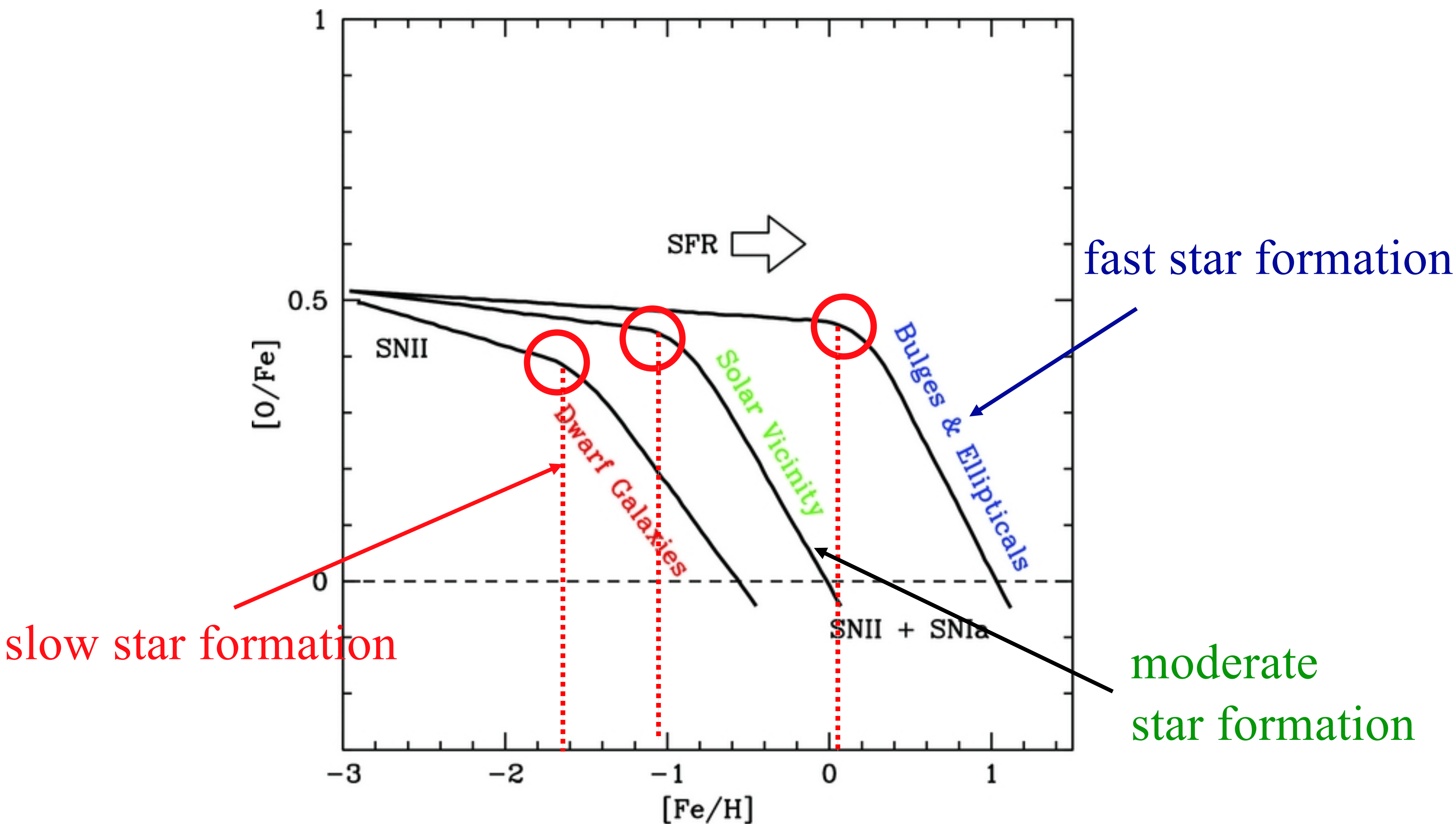
$[Fe/H] = \log (Fe/H)_{star} - \log (Fe/H)_{\odot}$: used as a ***cosmic clock***



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

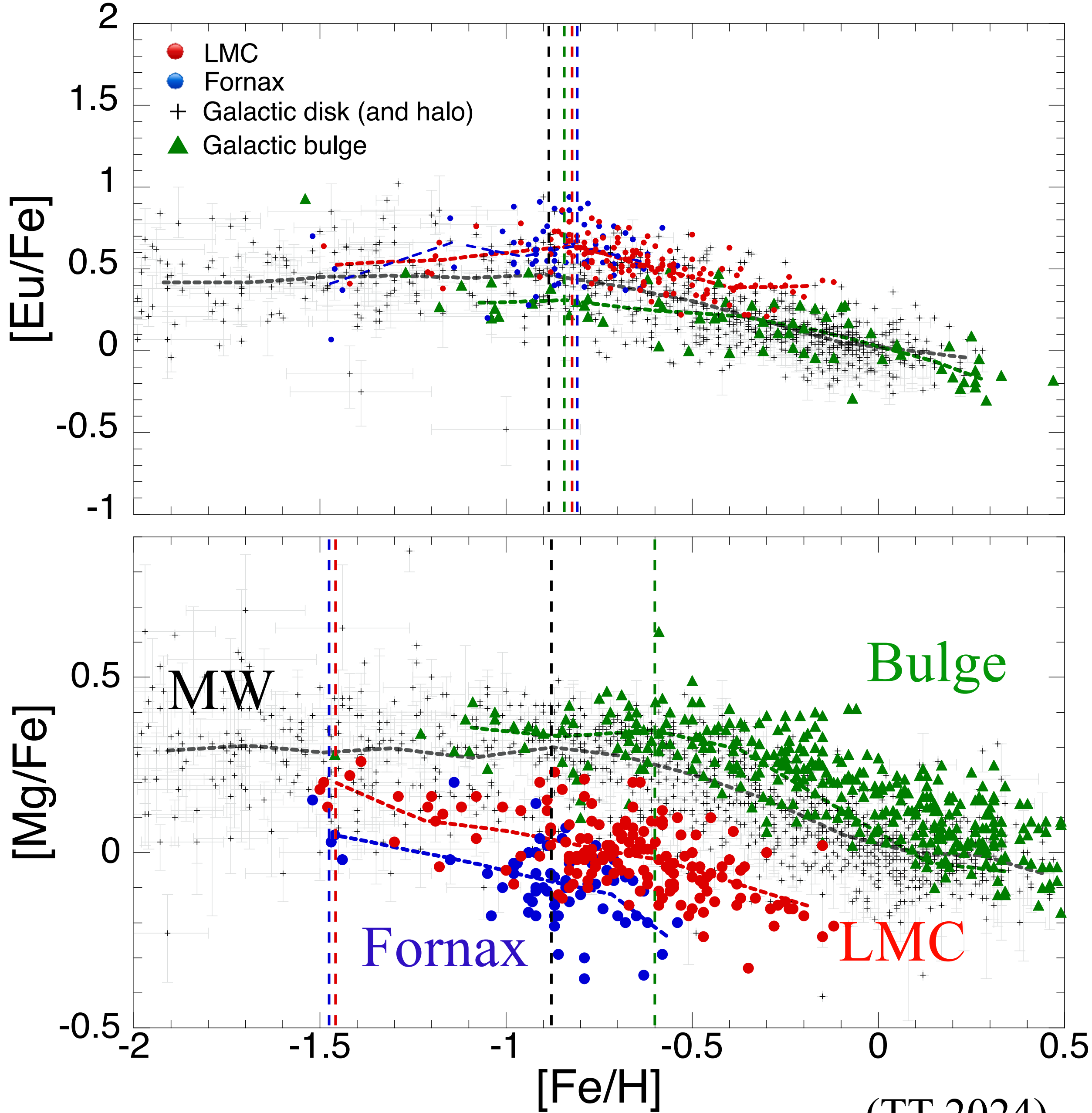


A locus of a decreasing start (knee) depends on the speed of star formation



Discussions

What causes the [Eu/Fe]-knee feature??



(TT 2024)

Fe release from SNe Ia
is unlikely

BUT

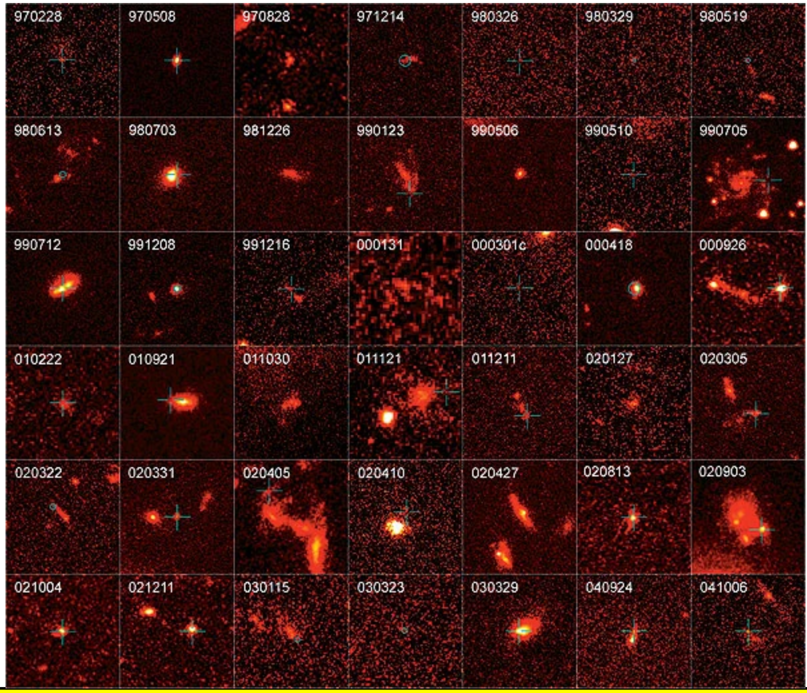
"**A metallicity threshold**
beyond which r-process
SNe cease to emerge"
is implied

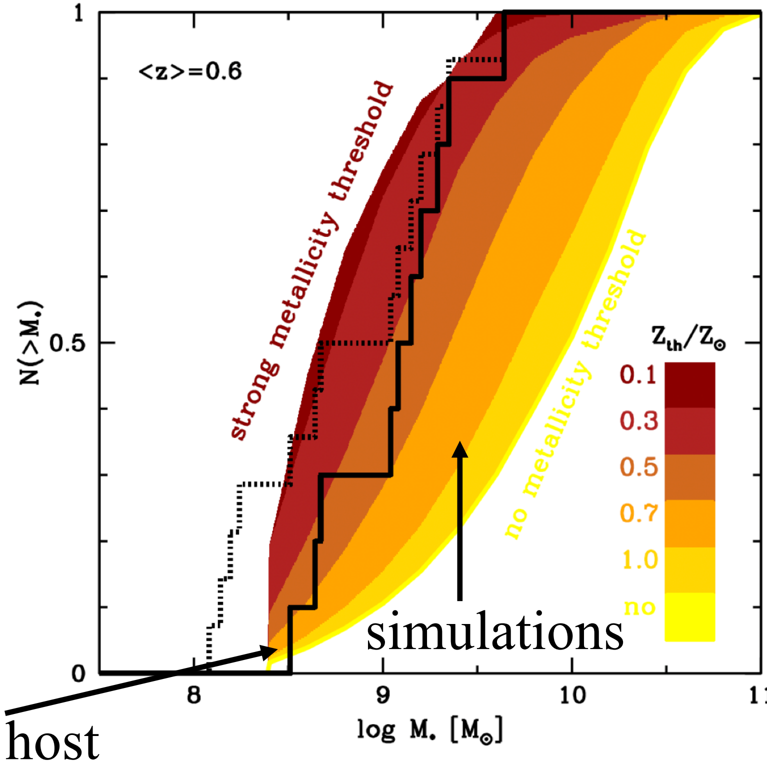
Long GRBs (≈ Collapsars) favor a low-metallicity environment

host galaxies: faint, irregular galaxies

"low-metallicity galaxies"

$Z < 1/3\ Z_\odot$ (Fruchter+ 2006)





(Vergeni+ 2015)

LGRB host distribution

$Z < 0.3\text{-}0.5\ Z_\odot$

Superluminous SNe, possibly identified with magnetorotational SNe, emerge in low-metallicity galaxies (e.g., Lunnan+ 2014)

Theoretically, a metallicity threshold should exist that retains enough angular momentum as $Z < 0.3\ Z_\odot$

(Woosley & Heger 2006)

How about a metallicity threshold for NSMs?

Very unlikely

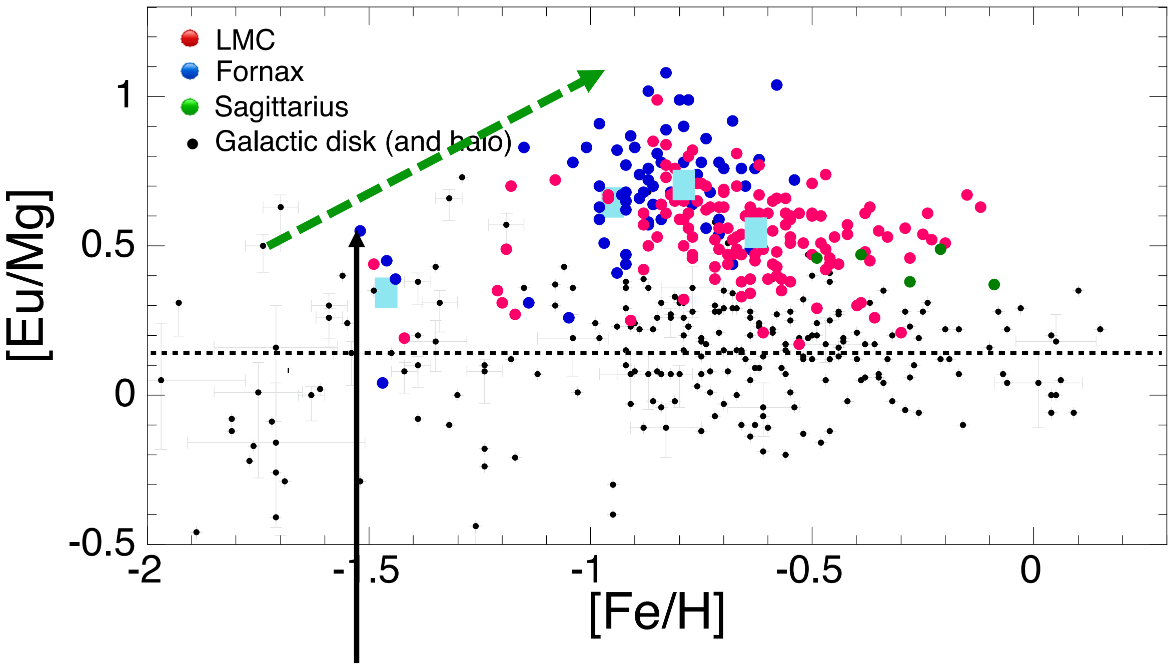
✓No theory

✓ the estimated high frequency rate of NSMs in the local Universe

$\mathcal{R}_{\rm BNS} = 320^{+490}_{-240}\ {\rm Gpc^{-3}\ yr^{-1}}$ (Abbott+ 2021)

✓ the presence of double NSs which will merge in the Milky Way

A signature of *r*-process enrichment by NSMS is visible



due to a delayed Eu release from NSMs

[Fe/H]<-0.7

Joint *r*-process enrichment by NSMs and *r*-process SNe

[Fe/H]>-0.7

NSMs only contribute to *r*-process enrichment

Modeling of chemical evolution
for
the LMC and the Milky Way

Common to all

- the sites of r-process elements: **two sites are considered**

  - NSMs

    DTD $\propto t_{\mathrm{delay}}^{-0.9}$, with a range of $0.03 \leq t_{\mathrm{delay}} \leq 10$ Gyr.

  - r-process supernovae

    the metallicity threshold at [Fe/H]=-0.7

Vary between MW and LMC

- star formation

  slower star formation for the LMC

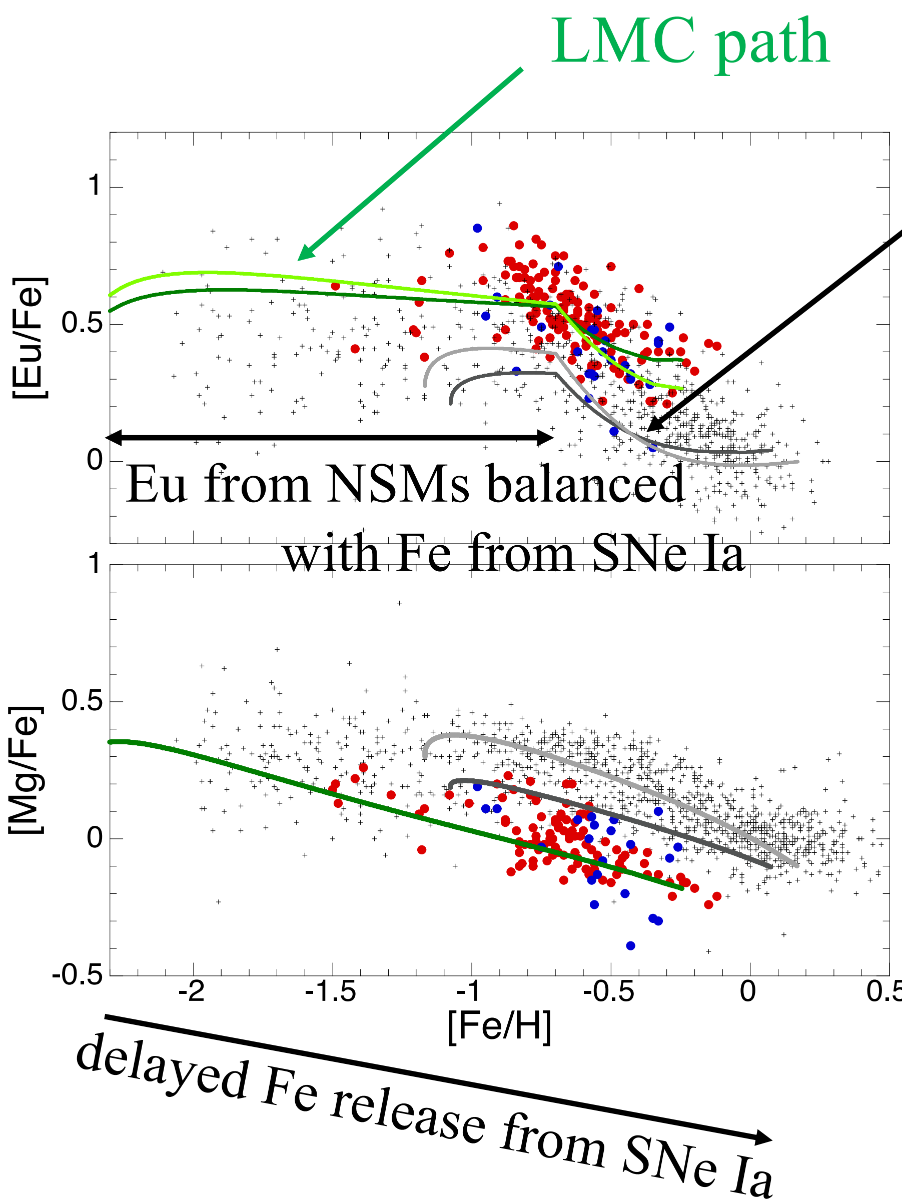
- yields from CCSNe and SNe Ia

  less amounts of release from them for the LMC

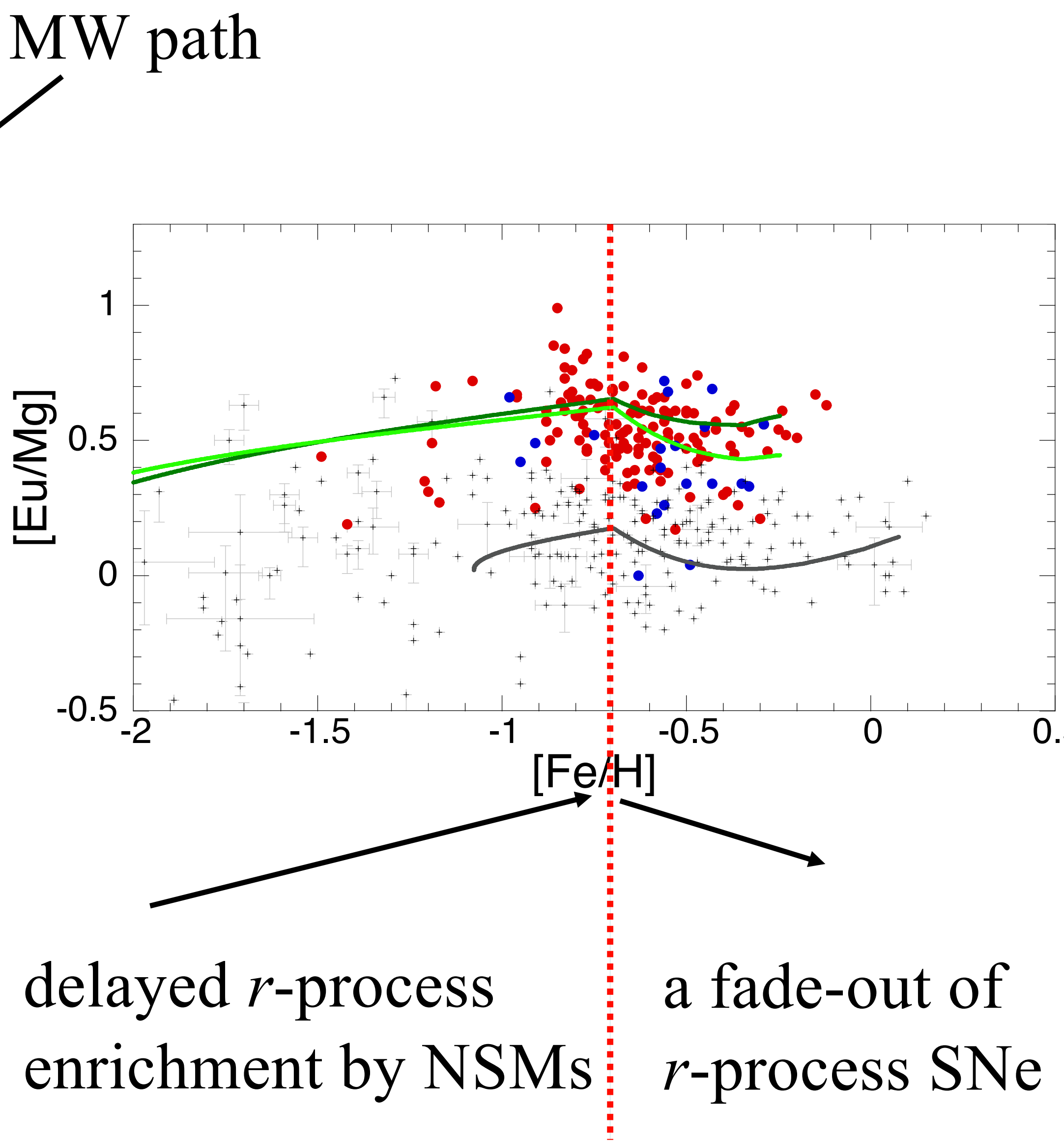
  ✓a smaller number of massive stars

  ✓a less frequency of SNe Ia

Results



LMC path
MW path
[Eu/Fe]
[Mg/Fe]
[Fe/H]
Eu from NSMs balanced
with Fe from SNe Ia
delayed Fe release from SNe Ia



[Eu/Mg]
[Fe/H]
delayed *r*-process
enrichment by NSMs
a fade-out of
r-process SNe

Summary

- Generally, the [X/Fe]-knee feature is considered to be caused by delayed Fe release from SNe Ia
- But, this is not the case for [*r*-process/Fe]
- The [*r*-process/Fe]-knee feature must be caused by a metallicity threshold at [Fe/H]≈-0.7 for CCSNe producing r-process elements
- Delayed r-process enrichment by NSMs is visible at an early stage of chemical evolution in dwarf galaxies

Accordingly, we propose

joint *r*-process enrichment by supernovae with a metallicity threshold and neutron star mergers