r-process enrichment traced by Pu and Ba near the sun and in the Draco

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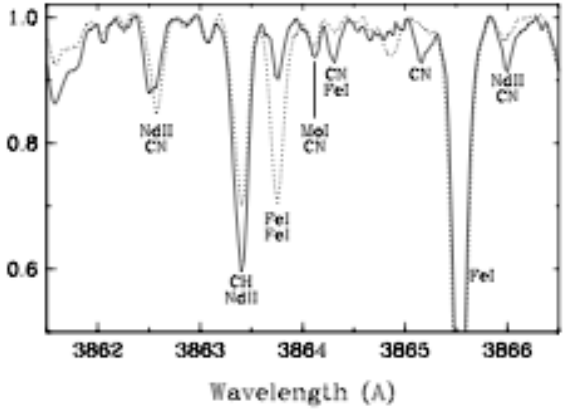
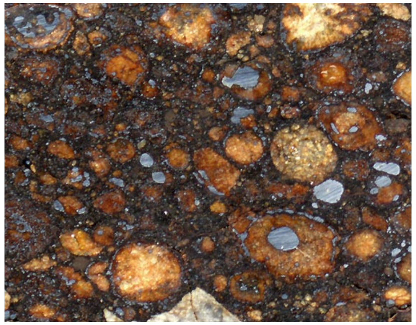
capturing electromagnetic waves



stellar spectra

earth archives



meteorites

deep-sea crusts

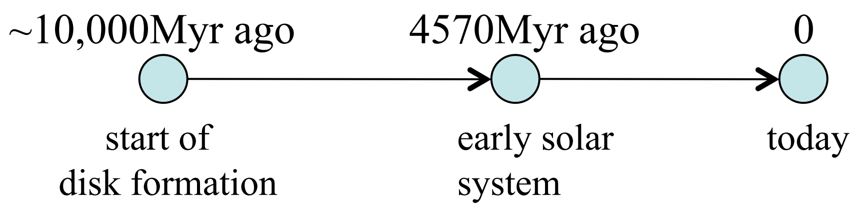
r-process site/nucleosynthesis

Observational Signatures of r-process nucleosynthesis in neutron star mergers
on August 1st, 2017

Talk outline

I. Pu near the sun

✓short-radioactive nuclei ^{244}Pu evolution in the solar vicinity



✓*event frequency & propagation of neutron star merger (ejecta)*

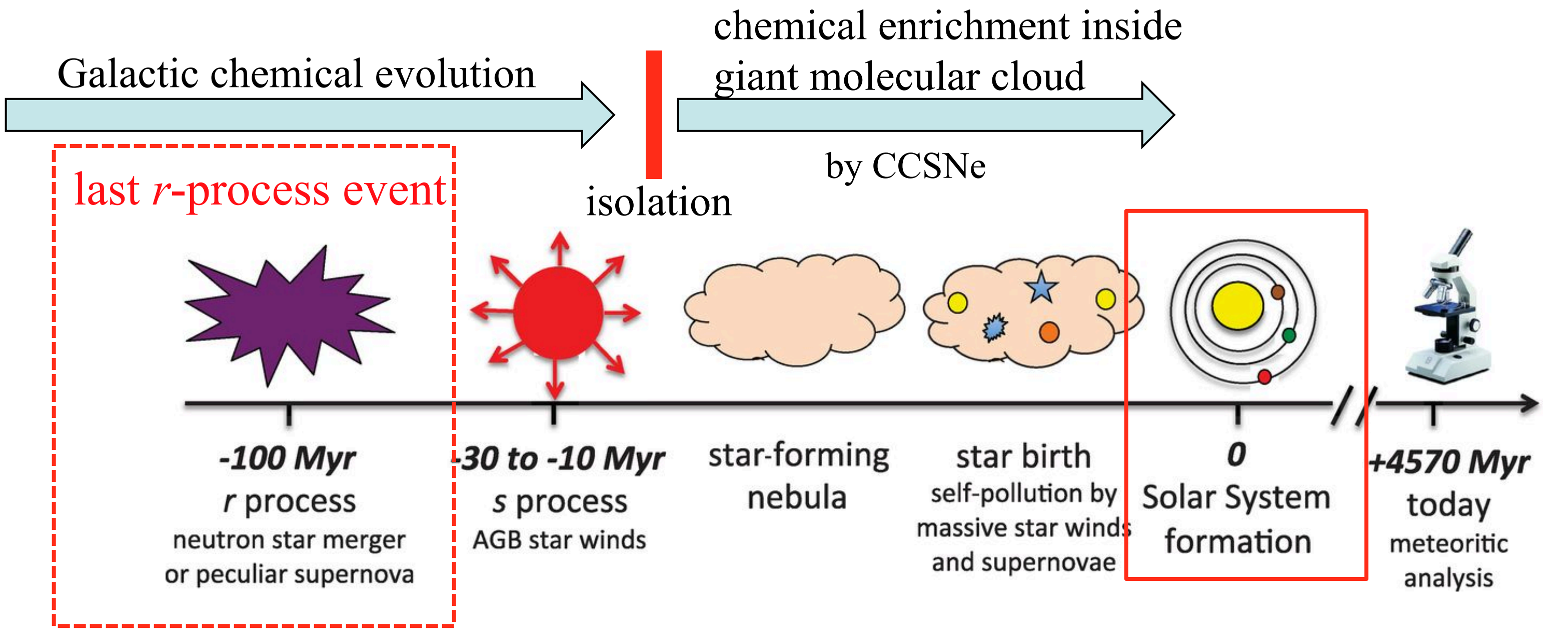
II. Ba in the Draco

✓The Milky Way satellite galaxies are the excellent testbed for the *r*-process study

✓*two distinct r-process events in the early Draco*

last r-process event at the early solar system

from short-lived radioactive nuclei



Lugaro et al. 2014

meteoritic abundances unstable/stable	production ratio	time interval between last r-process event and the solar system formation
$^{247}Cm/^{235}U = (1.1\text{-}2.4)\times10^{-4}$ (1.56×10^{7} yr)	0.4	123 Myr (Lugaro+ 2014)
$^{129}I/^{127}I = 1.19\pm0.20\times10^{-4}$ (1.57×10^{7} yr)	1.35	109 Myr (Lugaro+ 2014)
$^{244}Pu/^{238}U \sim 0.008$ (8.1×10^{7} yr)	0.53	100 Myr (Dauphas 2005)

On the other hand, meteoritic abundances of radionuclides originated form CCSNe such as

^{26}Al (half-life:1.03Myr)

^{60}Fe (half-life:2.2Myr)

imply the injection from a nearby CCSN

since their abundances are higher than the steady-state abundance inferred from γ-ray observations

last event of CCSNe $\ll$ 100 Myr

⇒ *r*-process production events may occur much less frequently than CCSNe

⇓

the whole evolution of ^{244}Pu abundance in the solar vicinity

a nice paper by Hotokezaka et al. (2015): neutron star merger = the *r*-process site

^{244}Pu evolution in the solar system

1. the early solar system (ESS) from meteorites
   ✓ $^{244}Pu/^{238}U \sim 0.008$ at 4570Myr ago from meteorites

2. the present from deep sea
   ✓current abundance of ^{244}Pu from deep sea measurement

Wallner et al. 2015

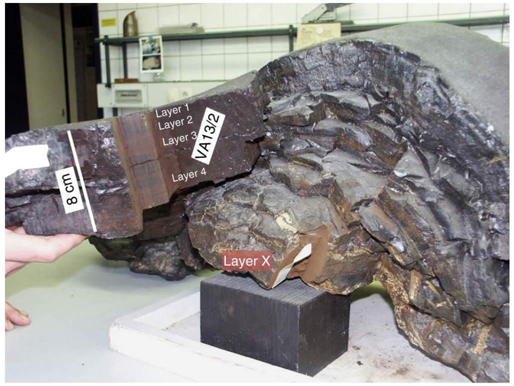
very low, compared with at the ESS

~0.15 × ESS value from a sediment

~0.01 × ESS value from a crust

Table 1 | ^{244}Pu detector events and corresponding ISM flux compared with galactic chemical models assuming steady state.

Deep-sea archive	Time period (My)	Sample area (cm^2)	Sample mass (g)	Integral sensitivity (eff. × area × time period) (cm^2 My)	^{244}Pu detector events (2σ limit)*	^{244}Pu flux into terrestrial archive (atoms per cm^2 per My)	^{244}Pu flux ISM at Earth orbit (atoms per cm^2 per My)†
Crust_modern	0–0.5	227.2	80	0.006	16	—	—
Layer X	Blank	~100	364	—	0	—	—
Layer 2	0.5–5	227.2	473	0.016	0 (<3)	<188	<3,500
Layer 3	5–12	227.2	822	0.075	1 (<5)	13^{+53}_{-12} (<66)	$247^{+1,000}_{-235}$
Layer 4	12–25	142.2	614	0.060	1 (<5)	17^{+66}_{-15} (<83)	$320^{+1,250}_{-300}$
Crust	**0.5–25**	**182**	**1,909**	**0.151**	**2 (<6.7)**	13^{+31}_{-11} **(<44)**	250^{+590}_{-205}
Sediment	**0.53–2.17**	**4.9**	**101**	**0.0013**	**1 (<5)**	$750^{+3,000}_{-710}$	$3,000^{+12,000}_{-2,850}$
Model and satellite data‡				**Steady-state model and ISM flux data at 1 AU from satellite Cassini**			**20,000–160,000**



FeMn crust with a total thickness of 25cm was sampled in 1976 from the Pacific Ocean at 4,830m water depth.

How to calculate ^{244}Pu evolution

step1. the ejected mass of ^{244}Pu per volume per event

meteoritic abundances of **short-lived radioactive nuclei** hold **the information on one last *r*-process event**

$^{244}Pu/^{238}U \sim 0.008$ & meteoritic abundance of ^{238}U

⇨ $^{244}Pu = 2\times10^{-12}$: mass fraction by one event in the ISM

step 2. the total event number till the solar system formation

solar abundances (meteorites) of **stable nuclei** hold **the information on an accumulation of all *r*-process events till the ESS**

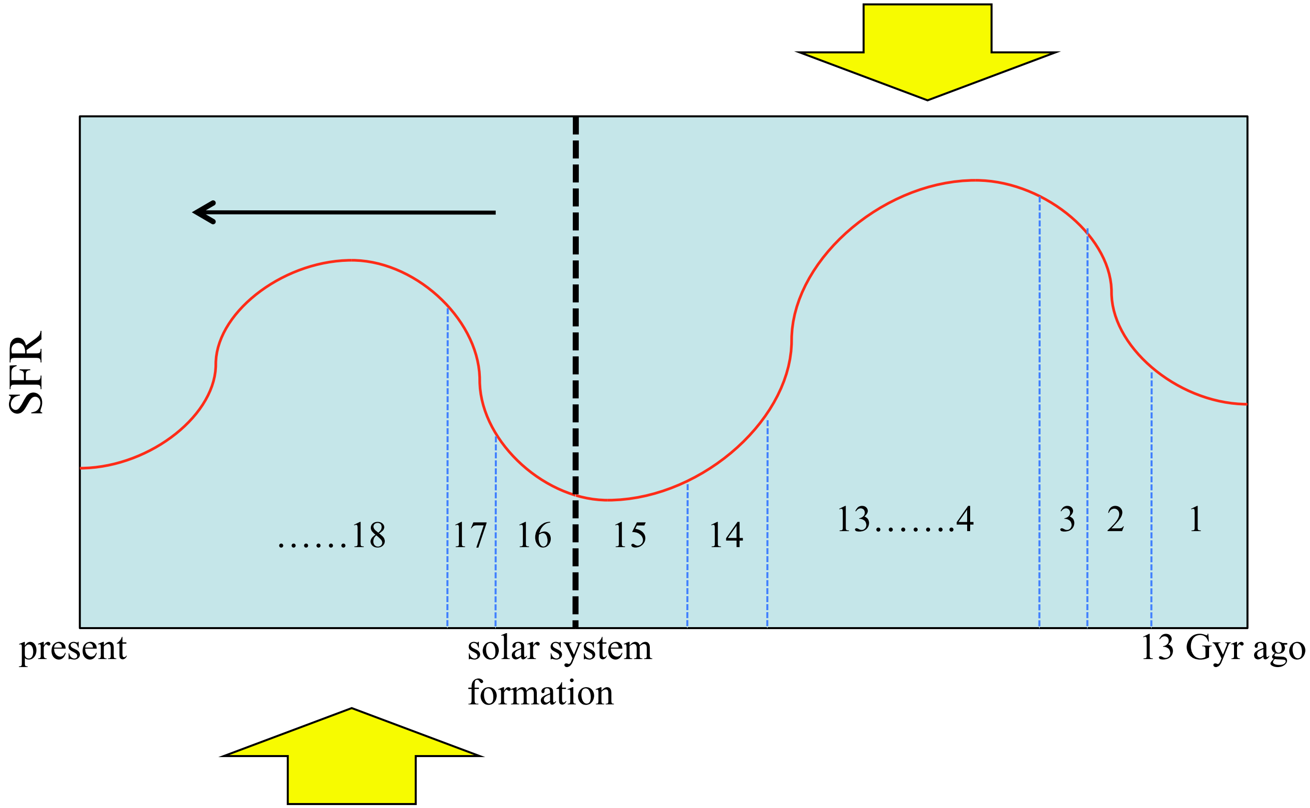
an ejected mass of Eu per one event per cm^3=2.5×10^{-11} ← $^{244}Pu/^{238}U=0.33$

(Goriely & Janka 2016, Eichler et al. 2015)

⇨ $3.7\times10^{-10}/2.5\times10^{-11}$ ~15

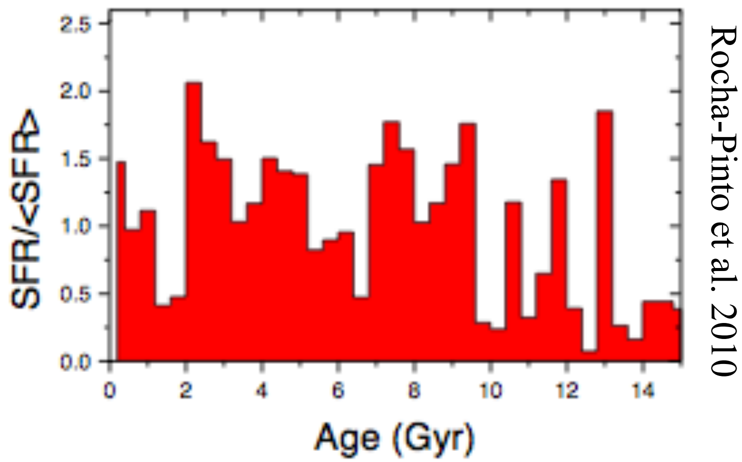
step 3. dating of individual events using a star formation history

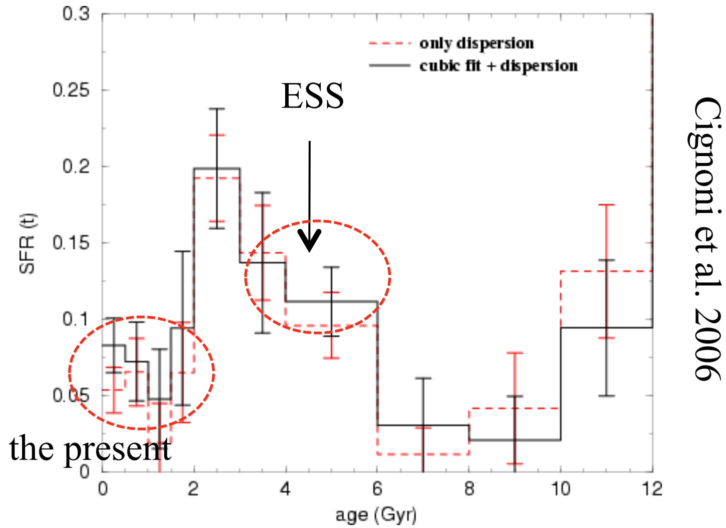
(i) We integrate the SFR from the beginning of the Galaxy to the time of ESS and bin by the inferred number (~15) of contributing r-process events during that time.



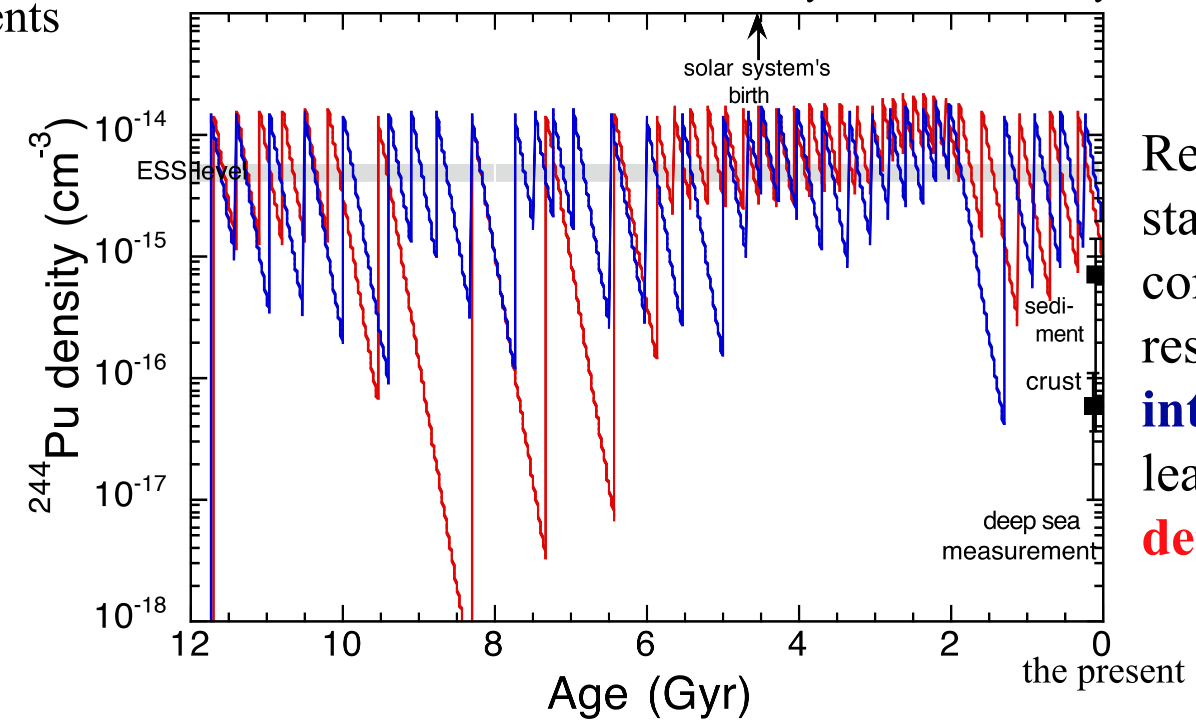
(ii) We integrate the SFR forward from the ESS time to the present, and at any time that the integrated number of newly formed stars reaches the threshold number, ^{244}Pu is ejected into the ISM.

star formation history: never constant but has a bursting feature





time interval of NSM events → Δt~ 200Myr Δt~ 400Myr



Relatively current low star formation rate compared with at ESS results in **a longer time interval of events** and leads to **a low Pu detection** in deep sea.

(TT et al. 2017)

the frequency of *r*-process production event

by counting the number of supernovae
for the current interval of ~400Myr

step 1. the present-day local supernova rate

✓ from the local present-day star formation rate: 0.48-1.1$M_\odot$/Gyr/pc^2

the relation between SFR and CCSN rate
SFR=1.65/yr & CCSN rate=2.3/century in the Galaxy

→ one per 2.1-4.8 Myr per 100 pc-radius disk region

✓ **from ^{60}Fe detection in deep sea crusts** (Wallner et al. 2016)

Two supernovae occurs at 1.5-3.2 Myr ago and 6.5-8.7 Myr ago
at distances up to 100 pc

⇨ **one CCSN per 4Myr per 100pc-radius disk region**

step 2. the volume where a NSM propagates

+ synthesized Pu mass

The volume contains gas of ~3.5×10^6 M$_\odot$ ← ^{244}Pu density

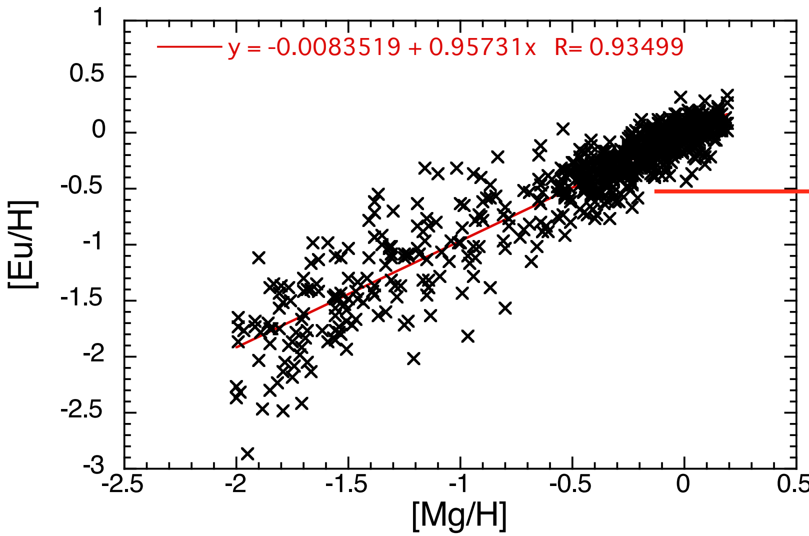
⇨ **~370 pc-radius disk region** ~100 x SNR

local surface density of gas = 8 $M_\odot$ pc^{-2}

the number of CCSNe within 370pc-radius for 400 Myr: ~1400 CCSNe

NSM rate = one per ~1400 CCSNe at the current solar system

NS merger rate deduced from stellar abundances



a slope is determined by the ratio of the production rates between Eu and Mg

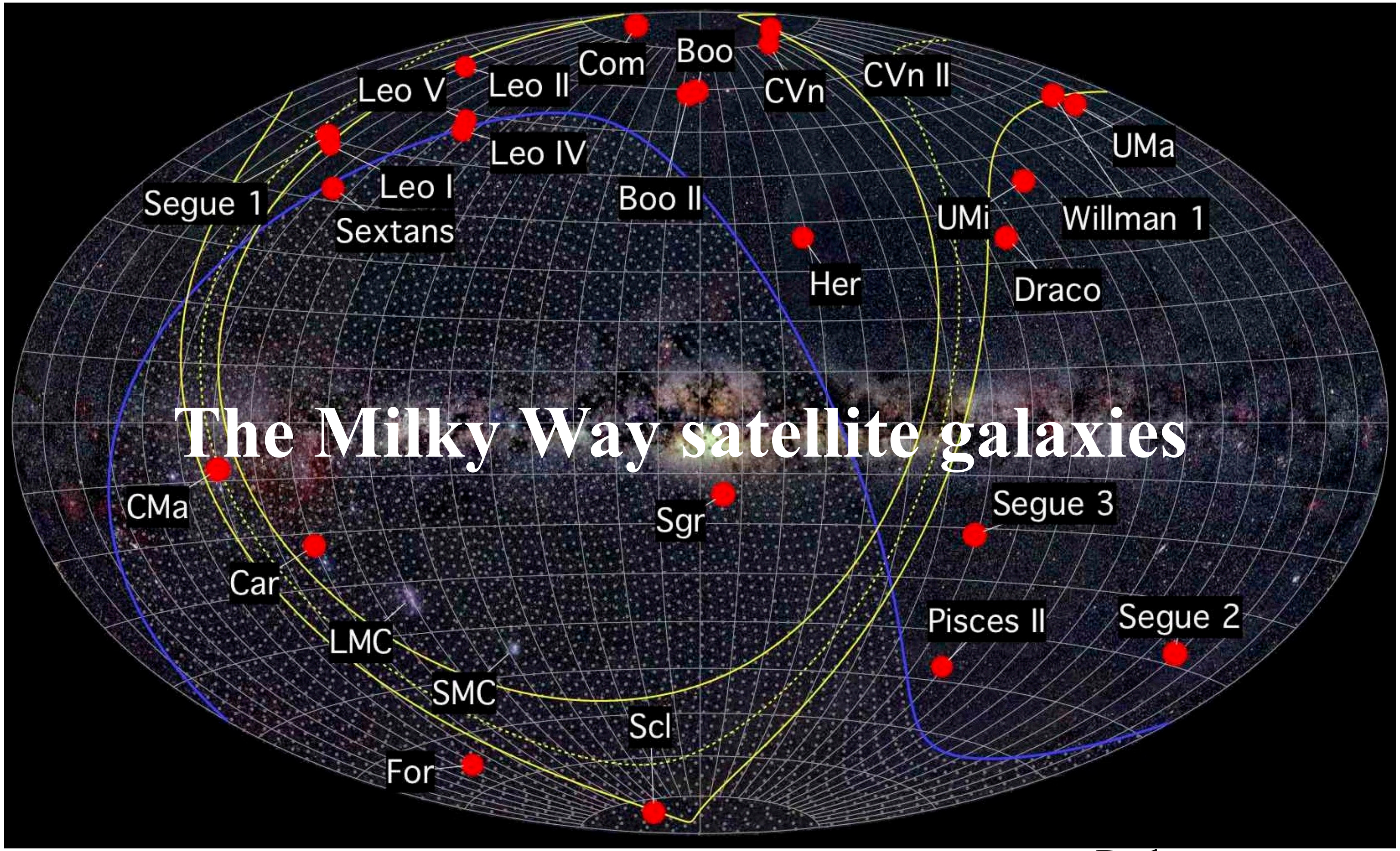
$$\text{slope} = \frac{\text{NSM Eu yield} \times \text{NSM rate}}{\text{supernova Mg yield} \times \text{supernova rate}}$$

$M_{Fe} \sim 0.07\,M_\odot$
(from light curve, Hamuy 2003)
&
$[Mg/Fe]_{halo}=0.4$
(from the observed halo ratio)

$Mg=0.1M_\odot$

$M_{NSM,ejecta}=0.01M_\odot$
+ the solar *r*-process pattern

NSM rate = one per ~1400 CCSNe



Dark energy survey
(credit: A. Frebel)

Why dwarf galaxies?

supernovae vs. NS mergers

rarity

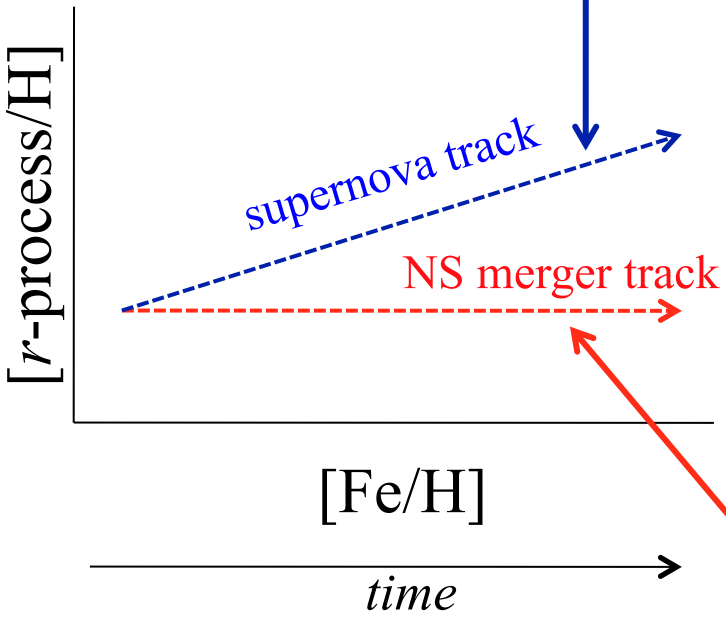
one NSM event per ~1000-2000 CCSNe

Some small galaxies can't host such a number of CCSNe

For instance, a dwarf galaxy with $10^5\ M_\odot$

~500 CCSNe in total

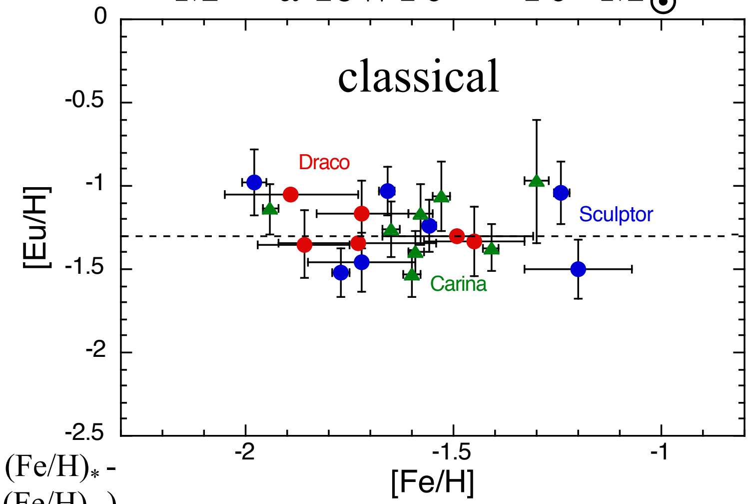
no NS Merger event in such a galaxy is predicted.



Note! the Milky way experiences more than 2×10^5 NS mergers.

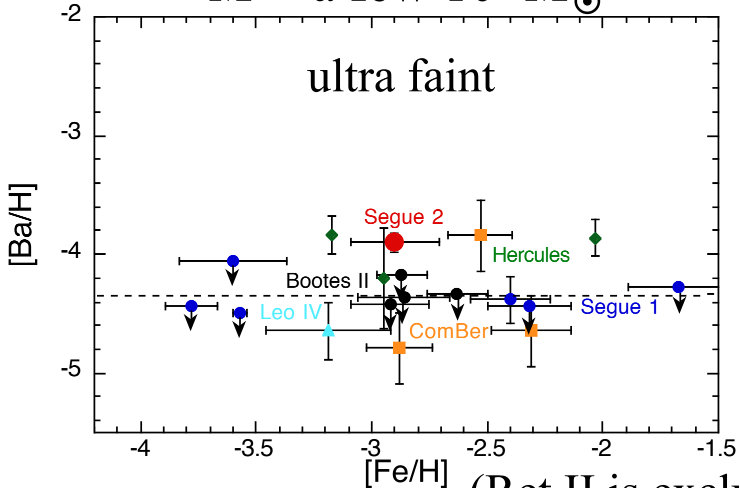
I. faint (small-mass) dwarf galaxies

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



([Fe/H]=log $(Fe/H)_*$ - log $(Fe/H)_\odot$)

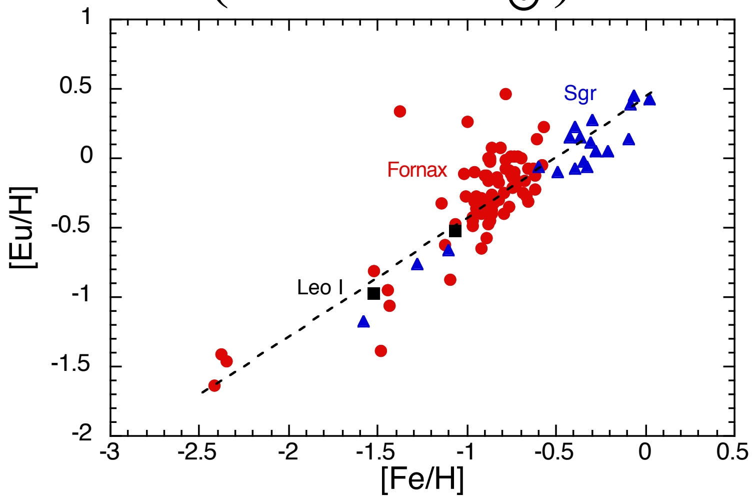
$M <$ a few $10^4 M_\odot$



(Ret II is excluded)

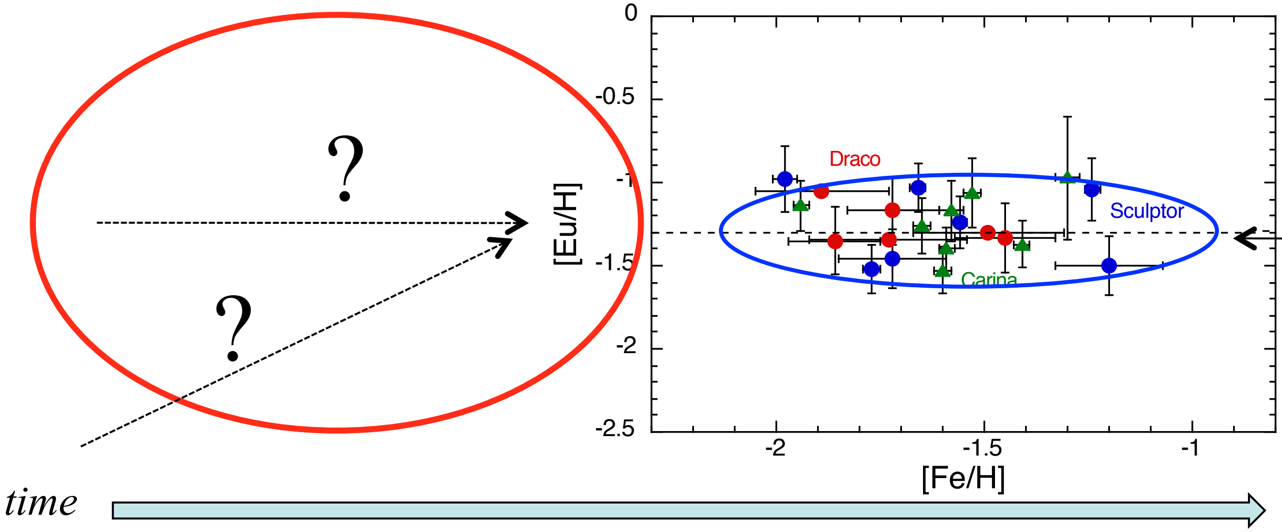
No increase in *r*-process abundance strongly suggests **a NS merger is the *r*-process origin**.

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

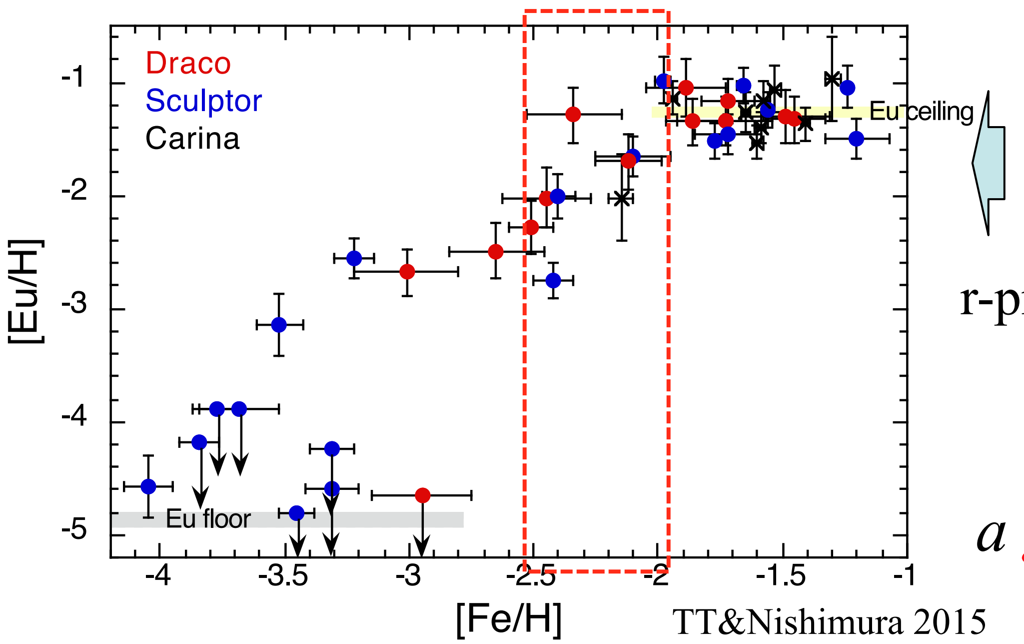


An increasing Eu/H trend is reasonable since NS mergers happened ~100 times in total in the Fornax galaxy ($2\times10^7 M_\odot$).

Very early *r*-process enrichment in faint dwarf galaxies



Where Eu comes from?



TT&Nishimura 2015

Most of [Eu/H] values for [Fe/H]<-2 are derived from [Ba/H] assuming the pure r-process Ba/Eu ratio.

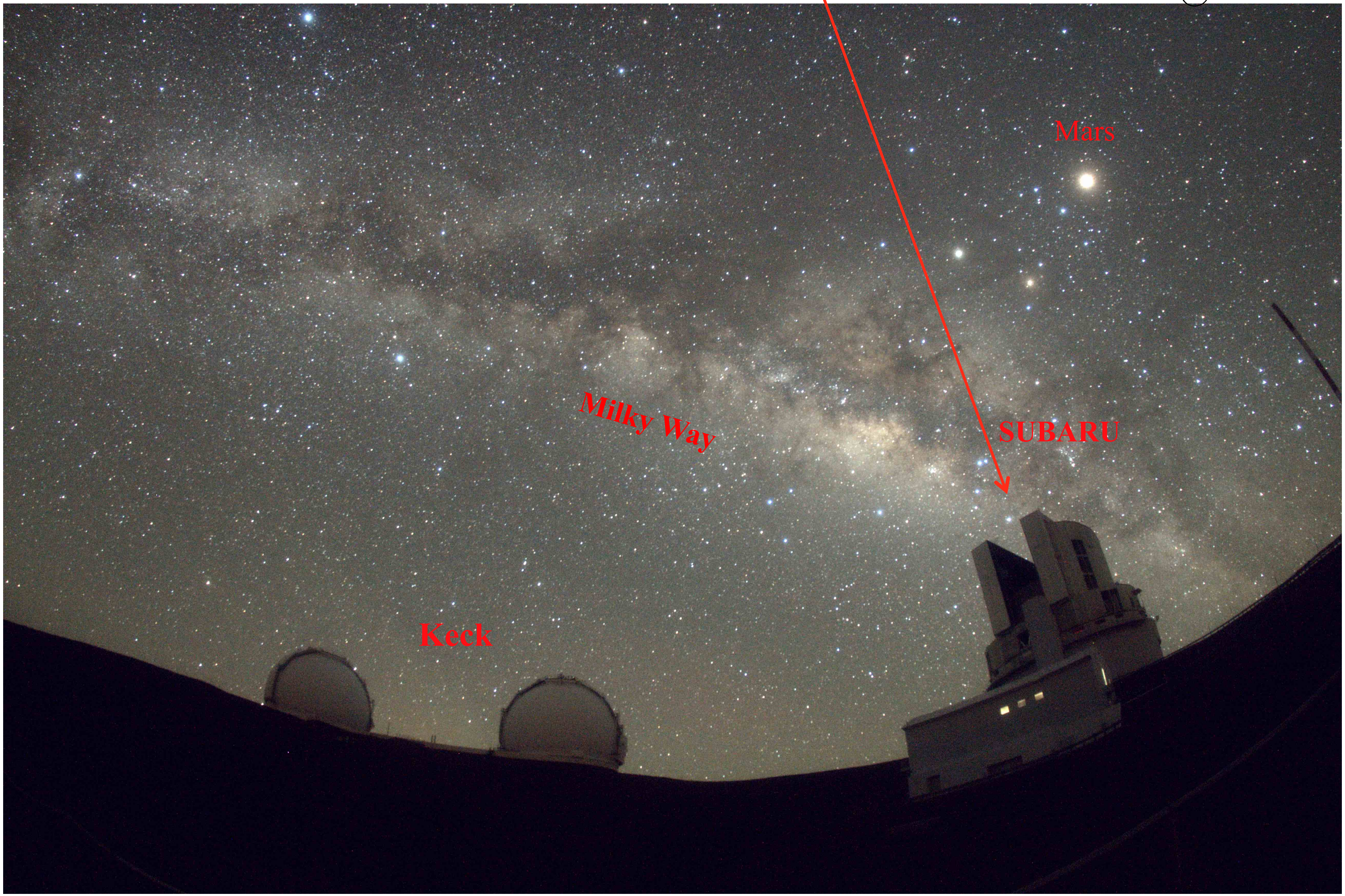
r-process abundance remarkably increases for [Fe/H]<-2

a gradual increase ?

or a sporadic increase?

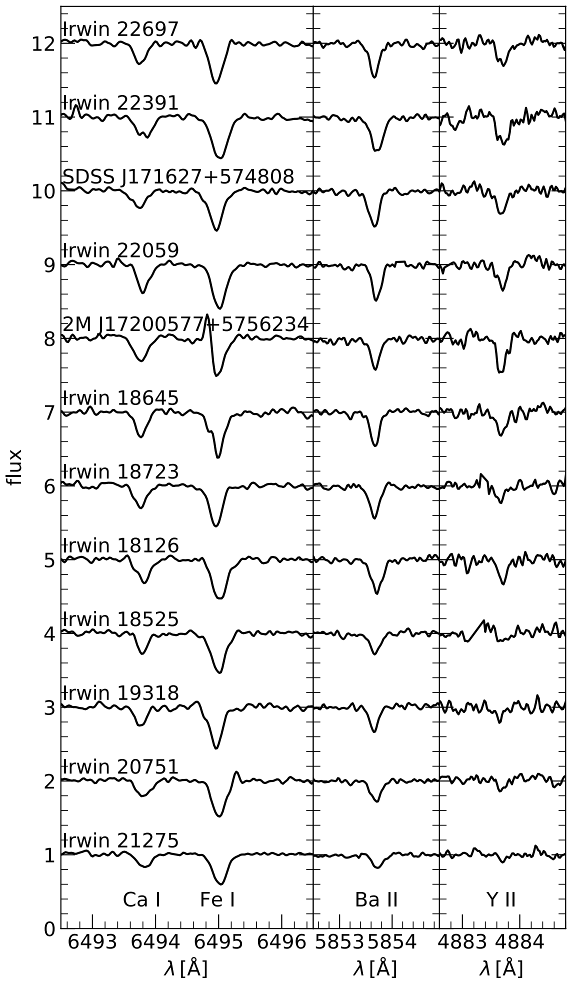
We measured *r*-process abundance in the Draco dSph galaxy from here!

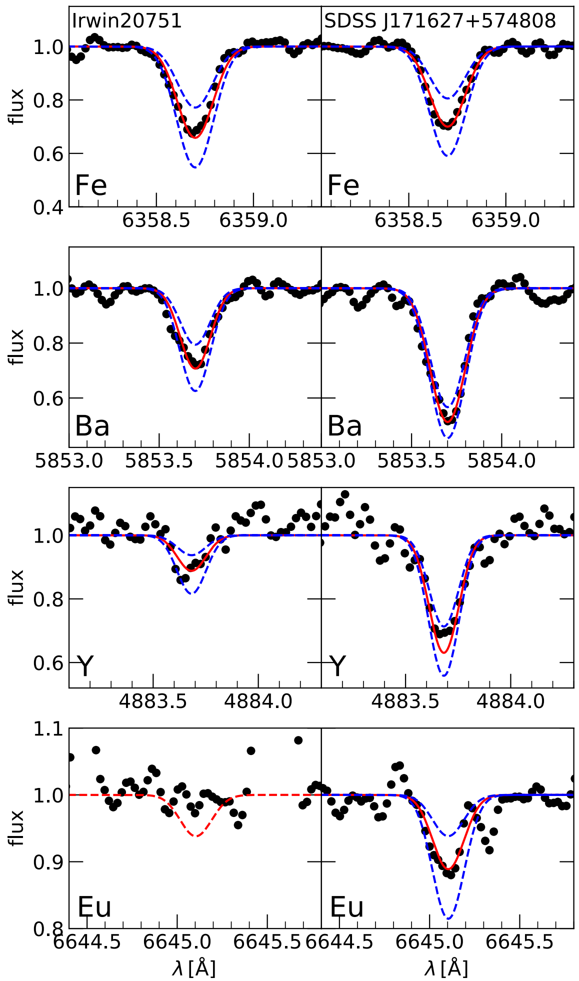
May 30, 2016
@Matsuno



Twelve Draco stars for -2.5 < [Fe/H] < -2

V~16.87
-17.35mag

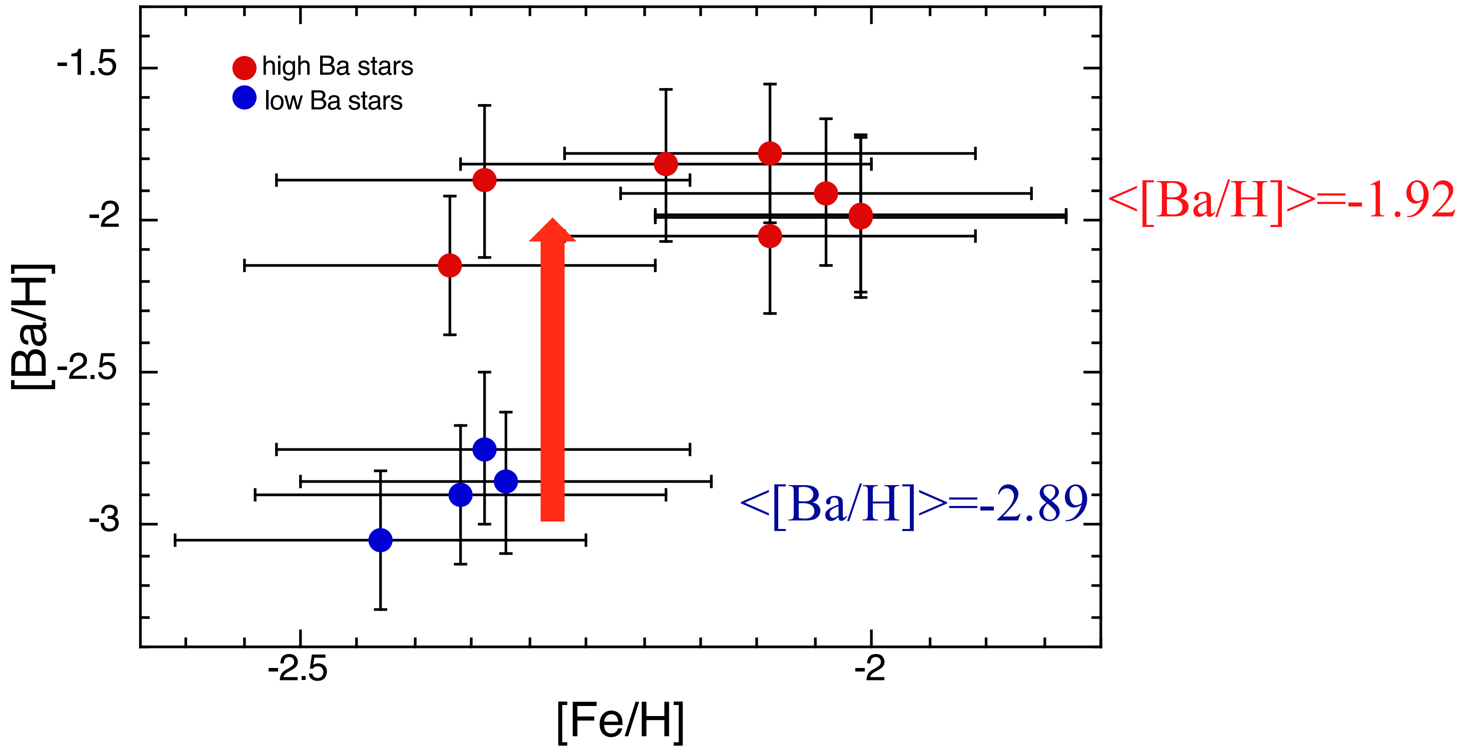




Whereas the Ca and Fe lines are quite similar, the strengths of the Ba and Y lines are different between the eight objects form the top and the other four objects.

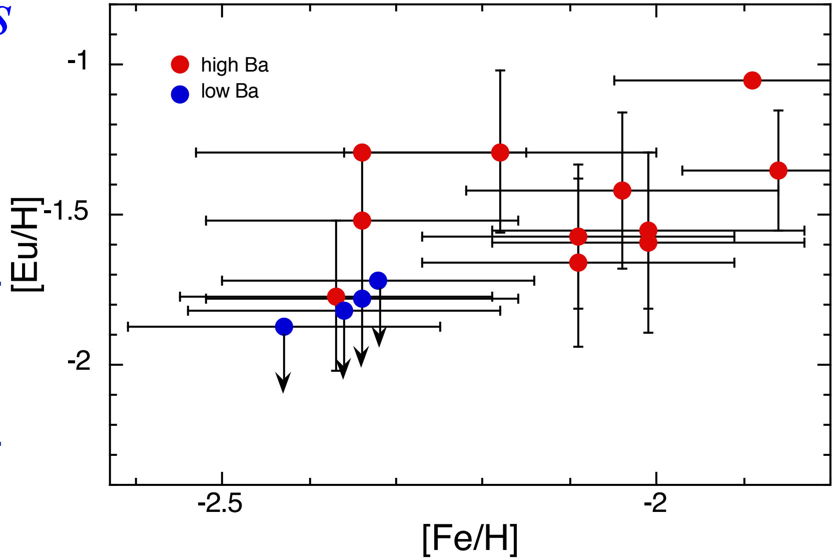
The two stars have similar stellar parameters but show the different Ba, Y, and Eu abundances.

Two distinct *r*-process populations



The occurrence of an episode boosting [Ba/H] by one order of magnitude around [Fe/H]≈-2.3.

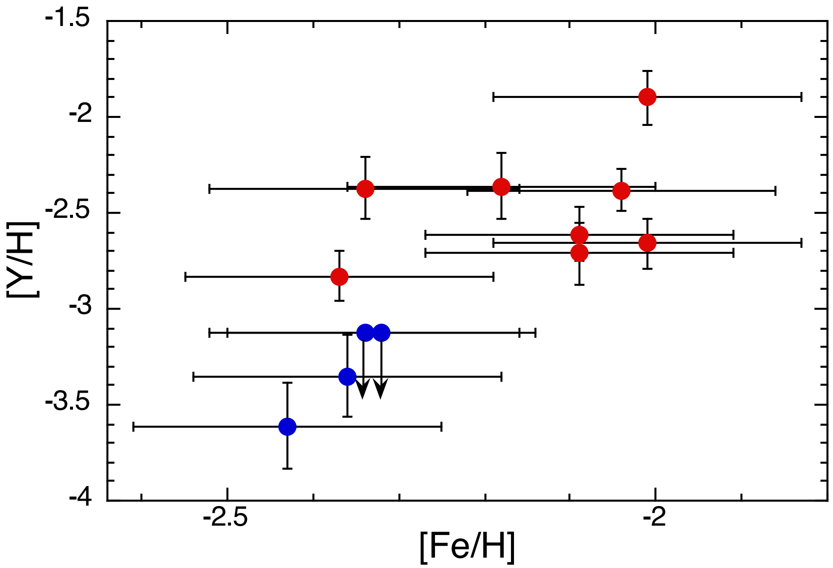
Two distinct r-process populations are also implied from their Eu abundances



spectral lines of Eu are not detected

nearly pure r-process Ba/Eu ratio

The abundance of a light neutron-capture element, Y, shows a feature similar to Ba and Eu



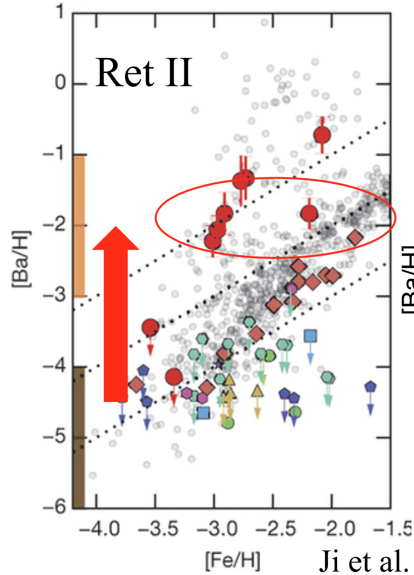
a jump-like increase in [Y/H] as large as that seen in [Ba/H]

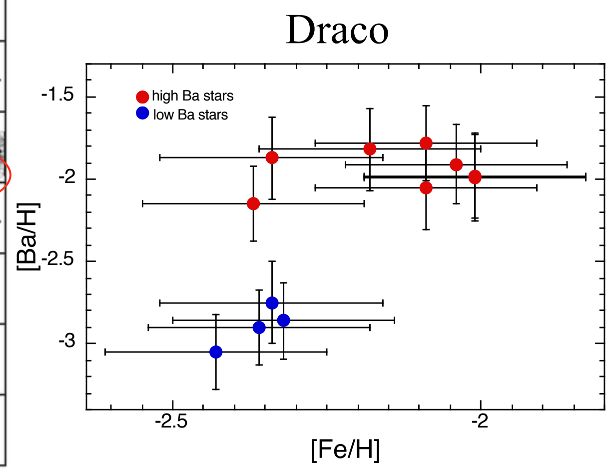
~ 1 dex jump

Similarities to *r*-process event in Reticulum II

I. A single r-process event in both galaxies increases [Ba/H] up to approximately the same level, i.e., [Ba/H]~ -2.

similar amount

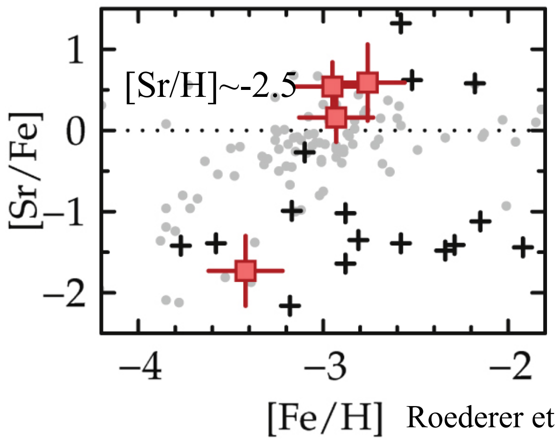


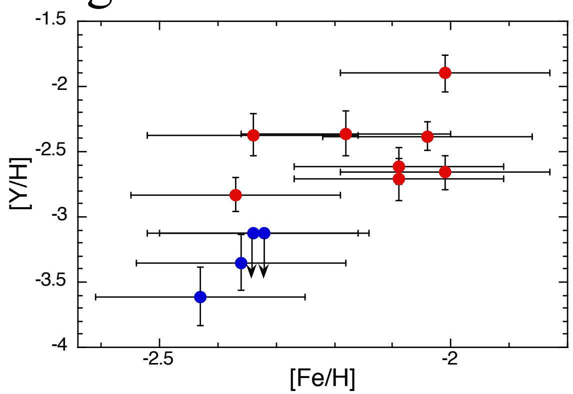


Ji et al. 2016

II. This increase in [Ba/H] is accompanied with an increase in the abundance of light neutron-capture element, Sr and Y, by the same magnitude as the increase of Ba

similar pattern





Roederer et al. 2016

the mass of Ba ejected from the r-process event in the Draco

$$\Delta[\mathrm{Ba/H}] = \frac{\text{the ejected Ba mass}}{M_{\mathrm{ISM}}}$$

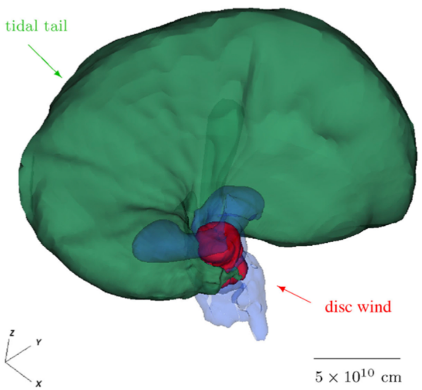
[Ba/H] from -2.9 to -1.9

Chemical evolution model gives ~$2\times10^{6}\ M_{\odot}$

Ba mass ~ $3\times10^{-4}\ M_{\odot}$

Who is the r-process producer?

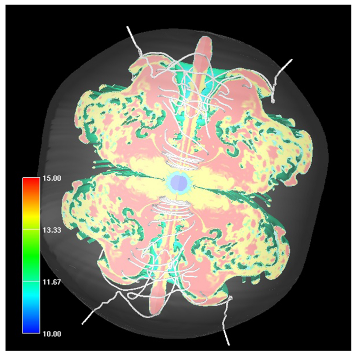
a NS merger



the ejecta composed of elements with A≥ 89 including Y with a mass of $0.01M_{\odot}$ contain the Ba mass of $3.2\times10^{-4}M_{\odot}$, assuming the solar *r*-process pattern.

a magneto-rotational supernova

The latest results suggest Ba production as much as $2.8\times10^{-4}\ M_{\odot}$.

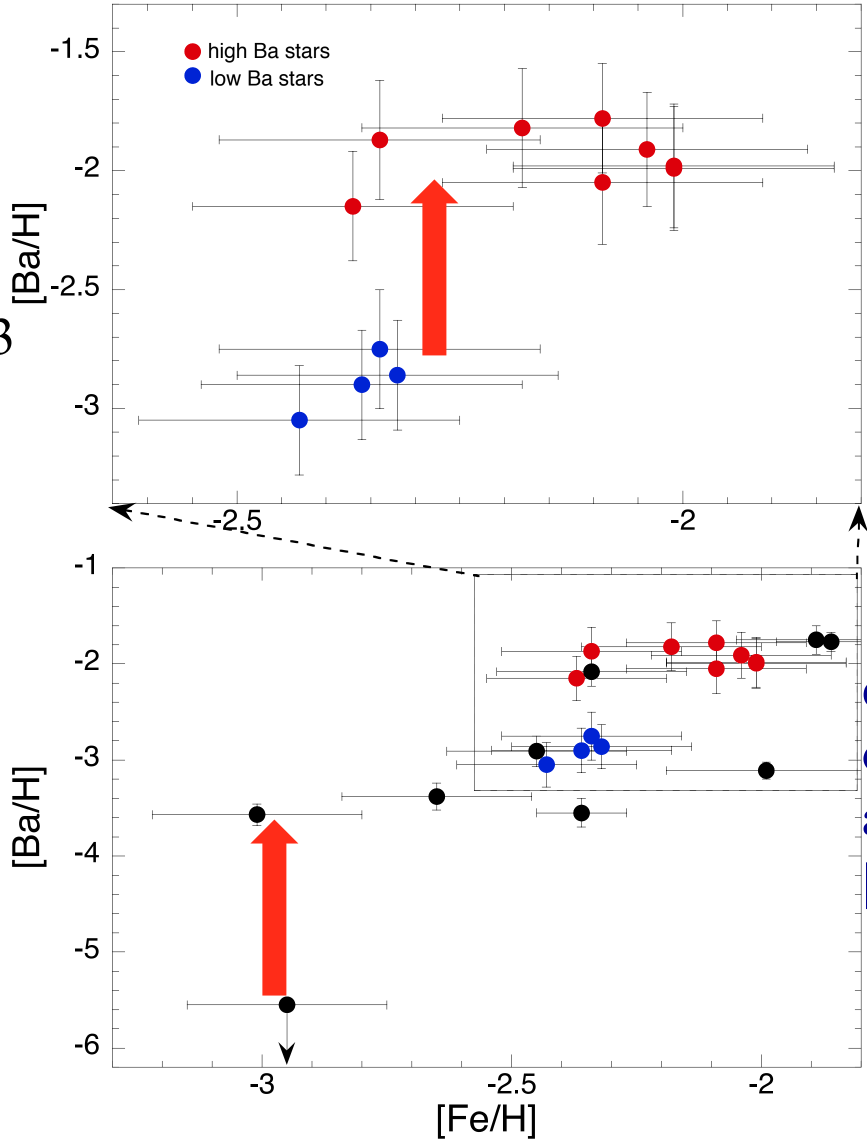


Nishimura et al. 2017

Two types of *r*-process events

lifting [Ba/H] up to
~ -2 at [Fe/H] ≈ -2.3

lifting [Ba/H] up to
~ -3.5 at [Fe/H] ≈-3



eject a large amount of
r-process elements

identical to the one
in the Ret II

eject a much smaller amount
of *r*-process elements as low
as <10% of the event around
[Fe/H]=-2.3

not found in the Ret II

two types of r-process events differing at least one order of magnitude
in the degree of enrichment of ISM

Keep in mind :

r-process events are not necessarily associated with the high production.

Open question :

The presence of two *r*-process events may suggest **the same site generates a different amount of nucleosynthesis products** owing to, e.g., a large variety of ejecta mass of NS mergers or *r*-process yields in magneto-rotational SNe ??

or

it implies the presence of **two distinct *r*-process sites** ??

"We witness a neutron star merger and a supernova! ??"

Conclusions

✓ ^{244}Pu evolution in the solar system

method: short-radioactive & stable *r*-process elements
meteorites & deep-sea archives

r-process site: *neutron star mergers*

event frequency: *one per ~1400 core-collapse supernovae*

ejecta spread: ~100 × SN ejecta

✓Ba abundance feature in the Draco dwarf galaxy

method: high-dispersion spectroscopy

Two distinct r-process events

which are associated with high and low r-process yields