r-process enrichment in the Milky Way and nearby dwarf galaxies

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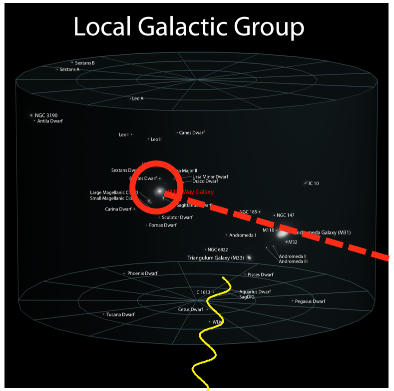
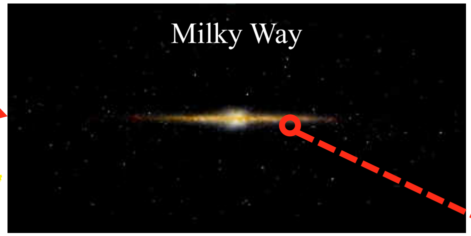
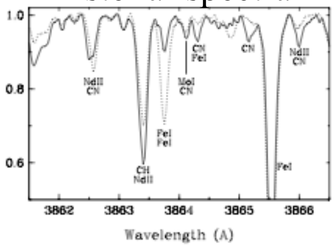


I. nearby dwarf galaxies

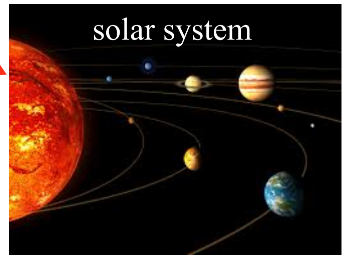


II. the Milky Way

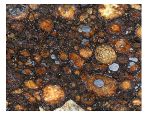
stellar spectra



III. the early and current solar system



chondrule

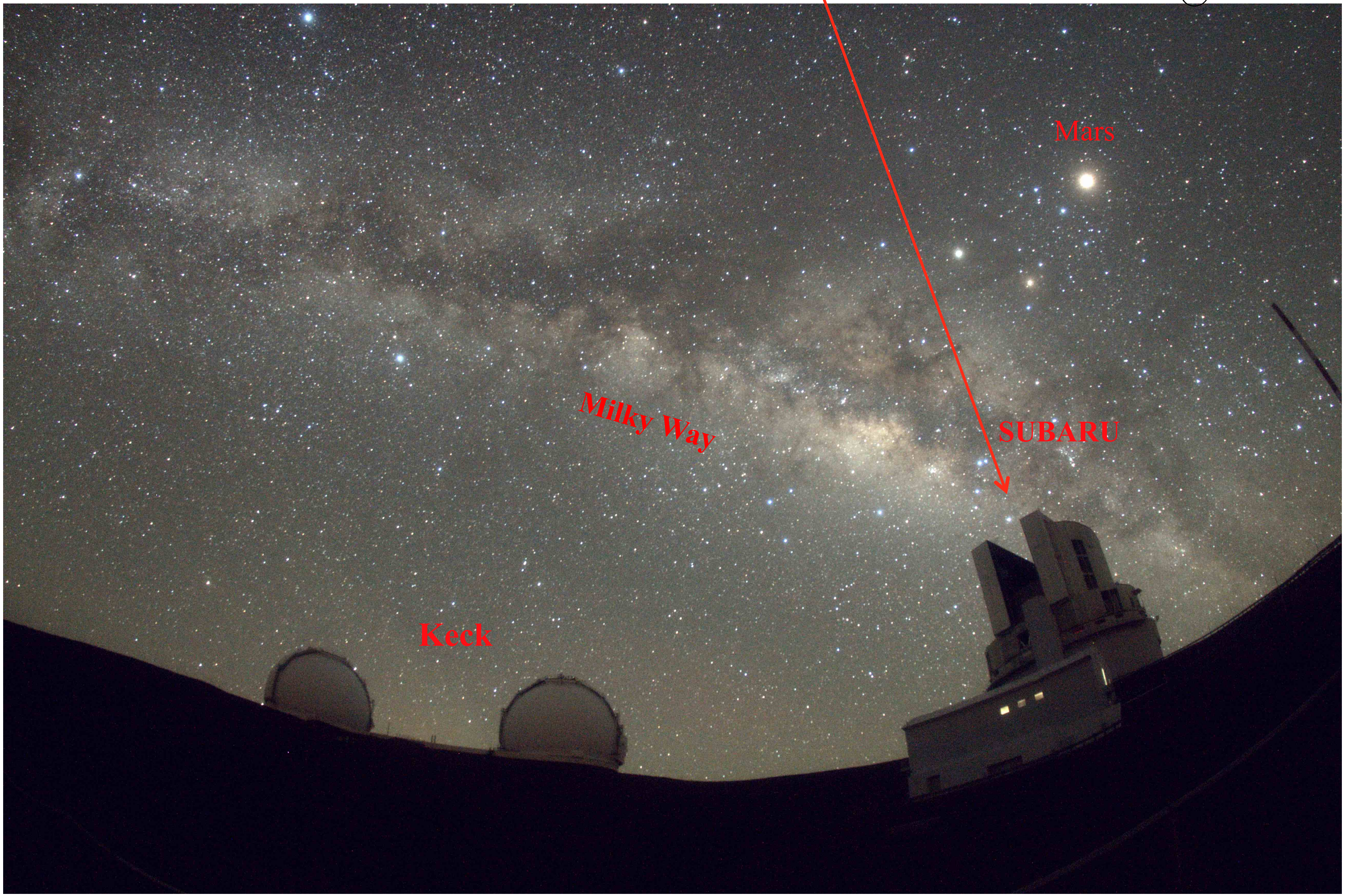


deep sea archives

The Milky Way and its environment, at IAP on September 21, 2016

We were measuring *r*-process abundance in the Draco dSph galaxy from here

May 30, 2016
@Matsuno



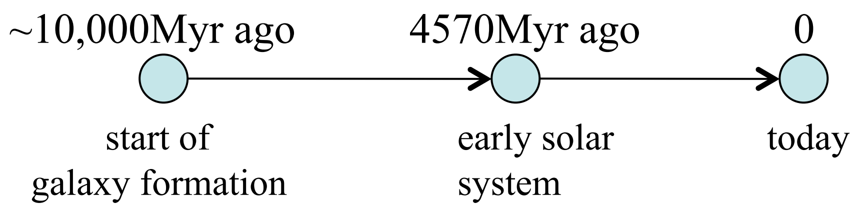
Talk outline

✓narrowing down the astrophysical site of *r*-process from dwarf galaxies

✓event frequency estimated from the Milky Way

✓early *r*-process enrichment in dwarf galaxies

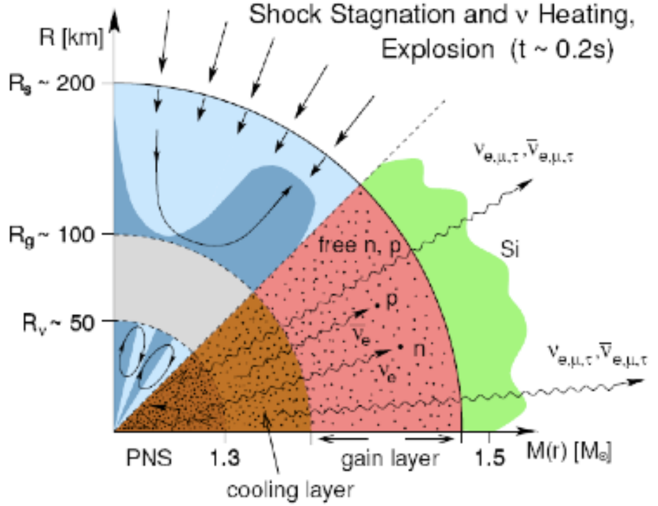
✓short-radioactive nuclei ^{244}Pu evolution in the solar system



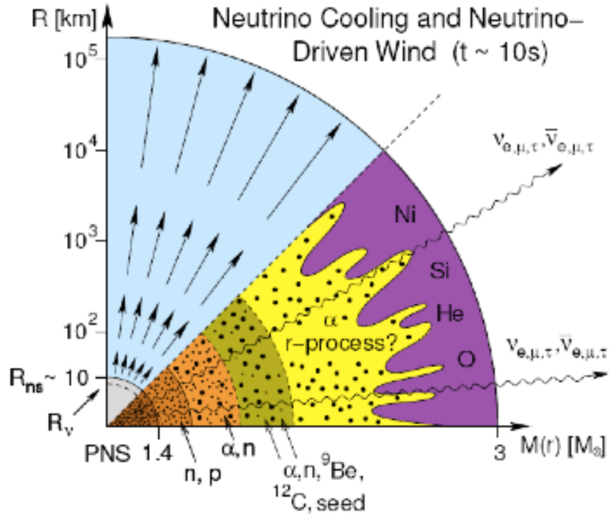
What is the astrophysical object producing *r*-nuclides in the Universe?

Since *r*-process nucleosynthesis demands an extremely neutron-rich environment, the possible astrophysical sites are limited to two events

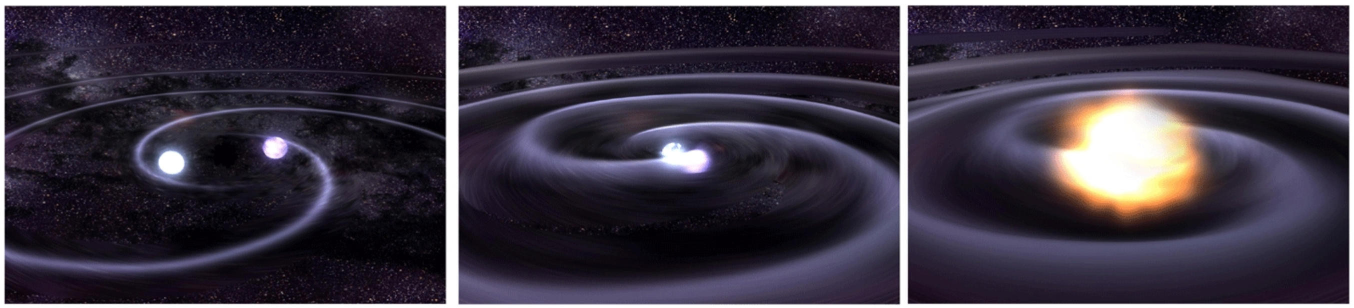
core-collapse supernova (CCSN)



vs.



neutron star (NS) merger



Why dwarf galaxies?

supernovae vs. NS mergers

rarity

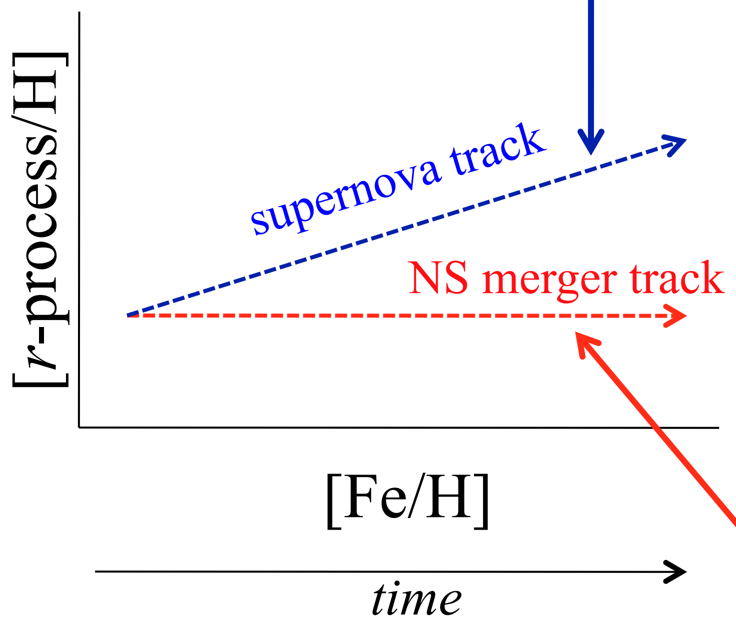
one NSM event per 1000-2000 CCSNe

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

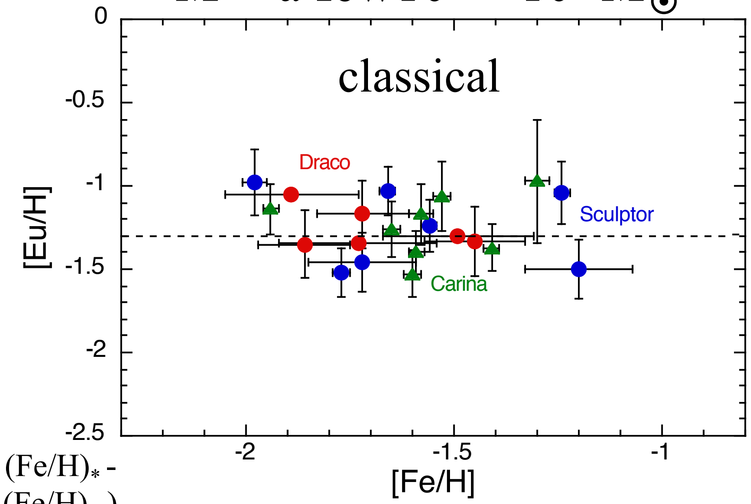
no NS Merger event in such a galaxy is predicted.



Note! the Milky way experiences more than 2×10^8 NS mergers.

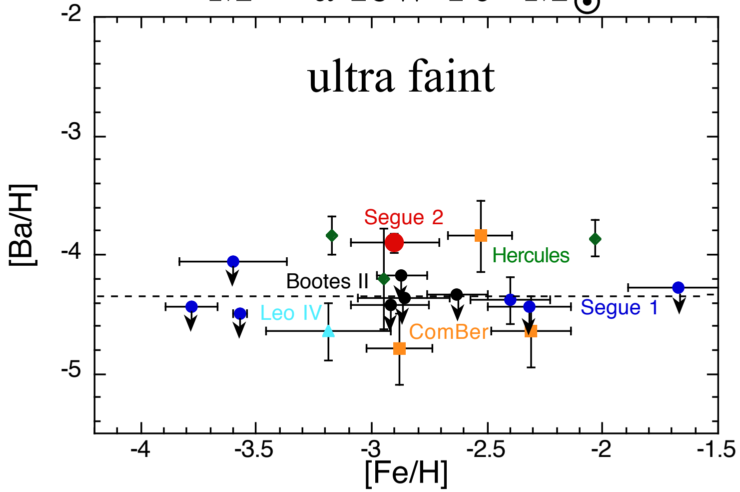
I. faint (small-mass) dwarf galaxies

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



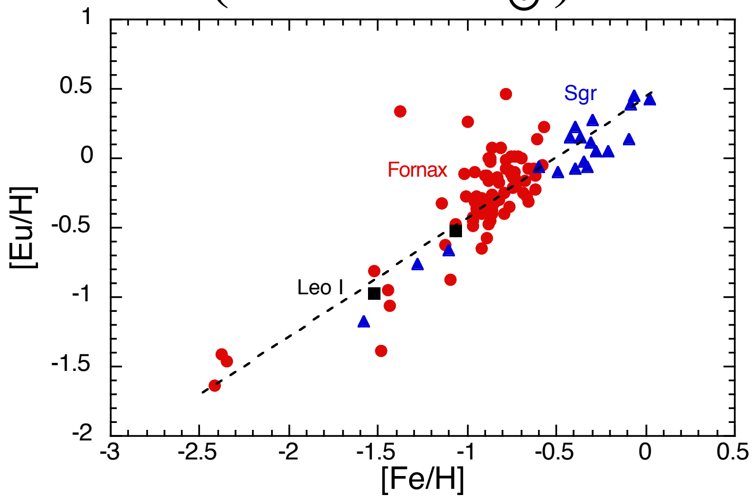
([Fe/H]=log (Fe/H)$_*$ - log (Fe/H)$_\odot$)

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



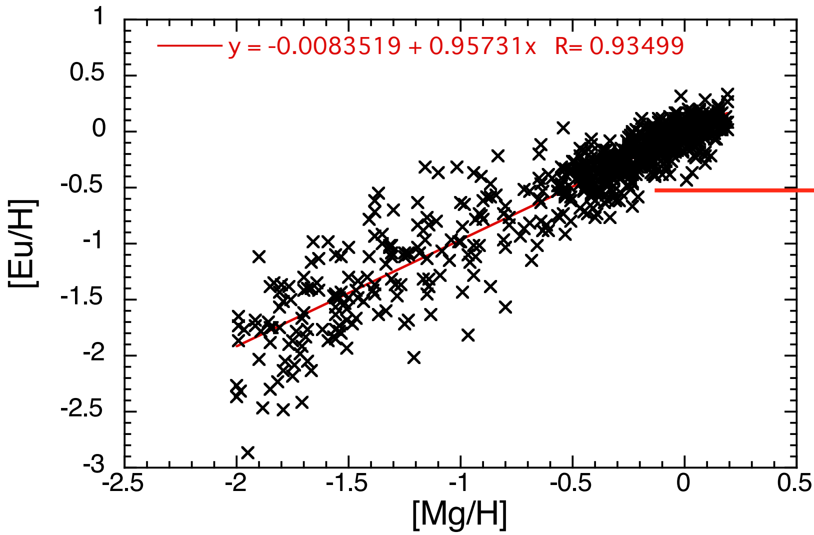
No increase in *r*-process abundance strongly suggests
a NS merger is the *r*-process origin.

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 ($2{\times}10^7\ M_\odot$).

NS merger rate deduced from the Milky Way



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

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

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

$\mathrm{Mg} = 0.4 M_{\odot}$

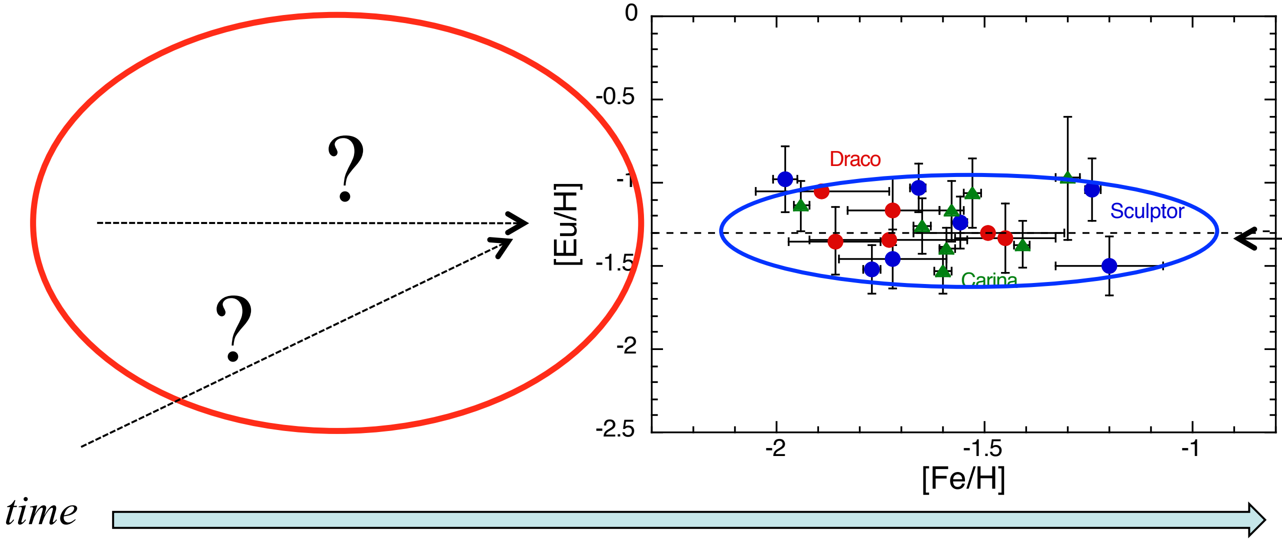
$M_{\mathrm{NSM,ejecta}} = 0.01 M_{\odot}$

NSM rate = one per ~1400 CCSNe

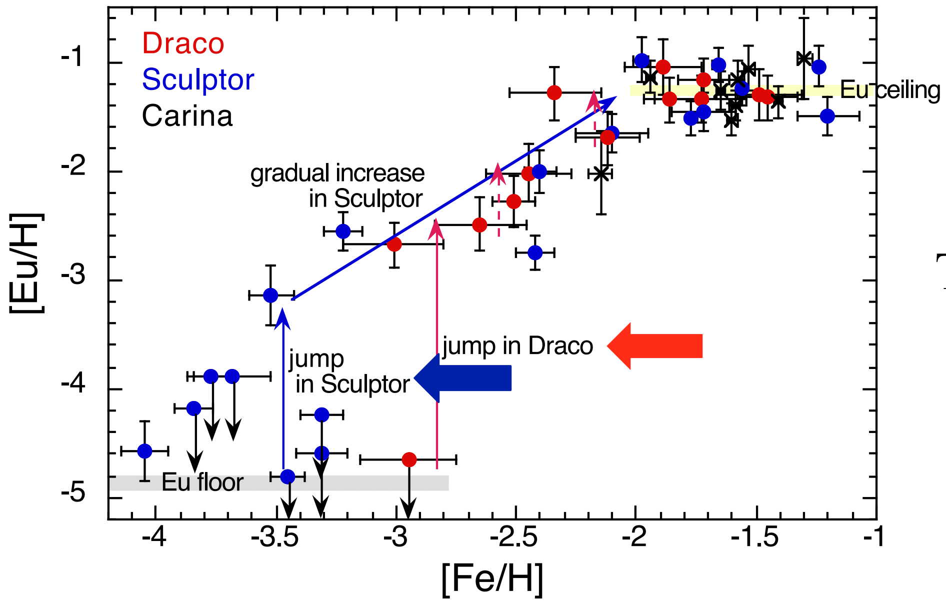
Galactic CCSNe rate
of 2.3SNe per century (Li et al. 2011)

~16 Myr^{-1} in the Galaxy

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



Where Eu comes from?



[Eu/H] remarkably increases for [Fe/H]<-2

There exists Eu producer inside early dSphs

What??

the feature of jump-like increases

What requires for Eu producer in the early faint galaxies?

✓more frequent than NS mergers, but much less frequent than CCSNe

✓a selective operation only in low-metallicity stars

a promising candidate = magneto-rotational SNe (MR-SNe)

an explosion triggered by fast rotations and high magnetic fields

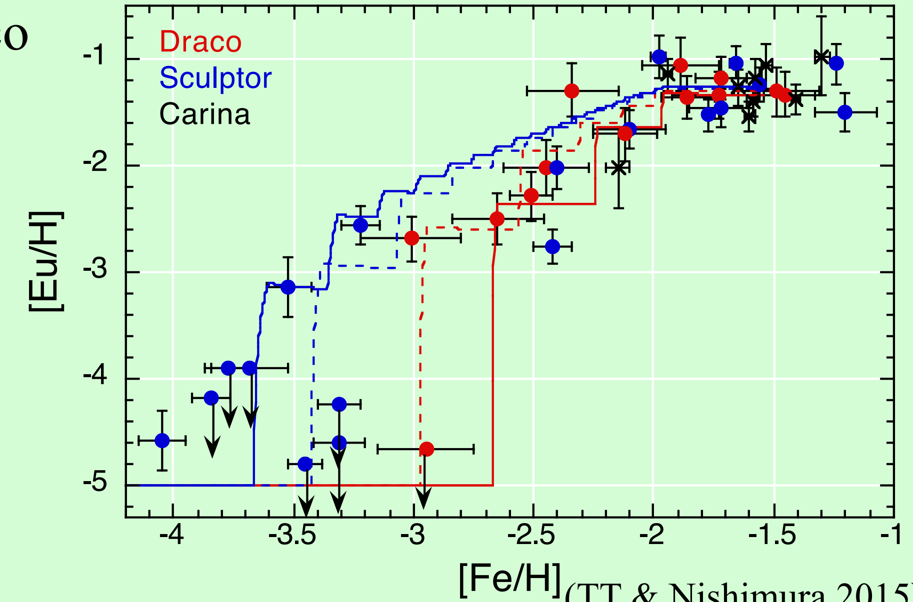
the emergence of MR-SNe is inclined toward very low-metallicity stars in which the rotational velocity is expected to be high

modeling the enrichment paths in the Draco and Sculptor

more frequent in Sculptor due to more massive galaxy

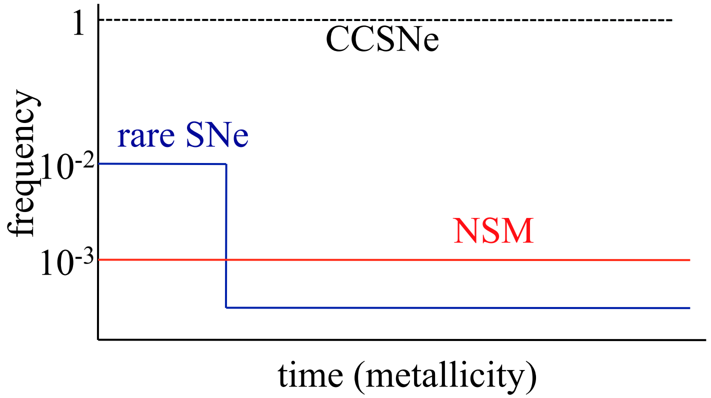
a frequency: one per 100-200 CCSNe

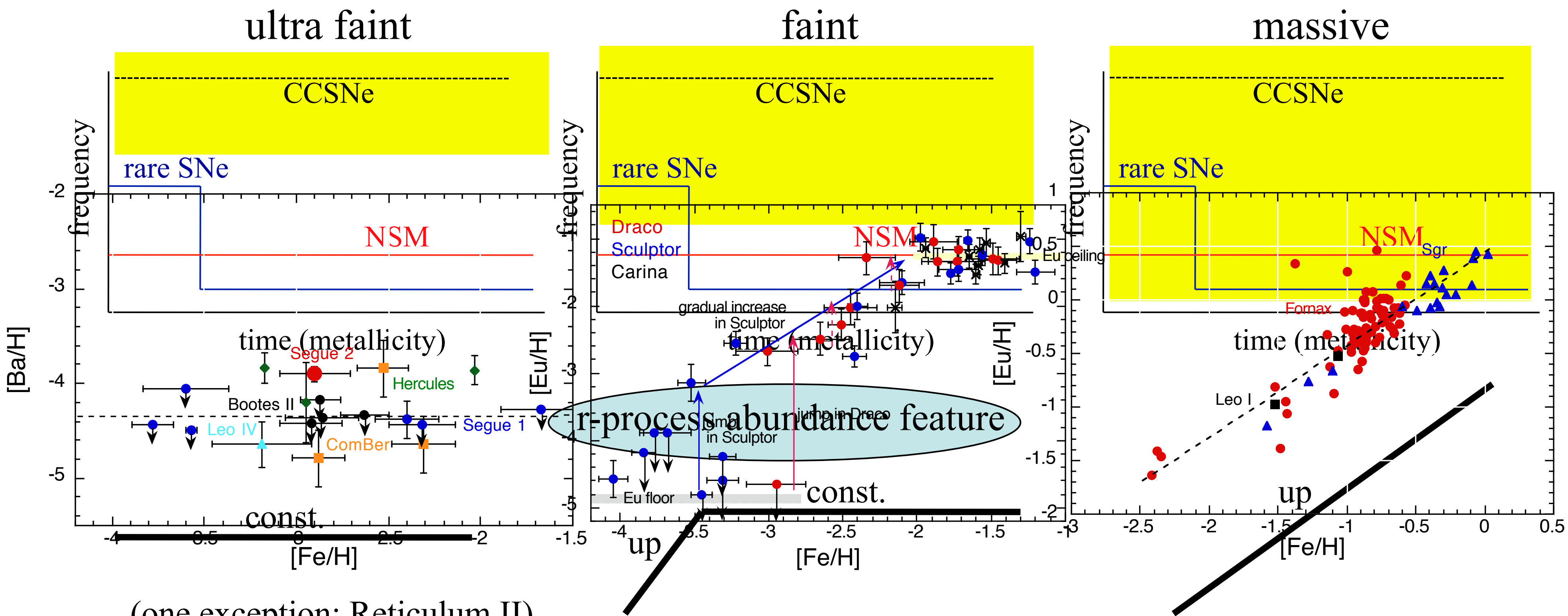
a Eu mass: ~1/10 of a NSM yield



(TT & Nishimura 2015)

A unified scheme of r-process enrichment in dwarf galaxies

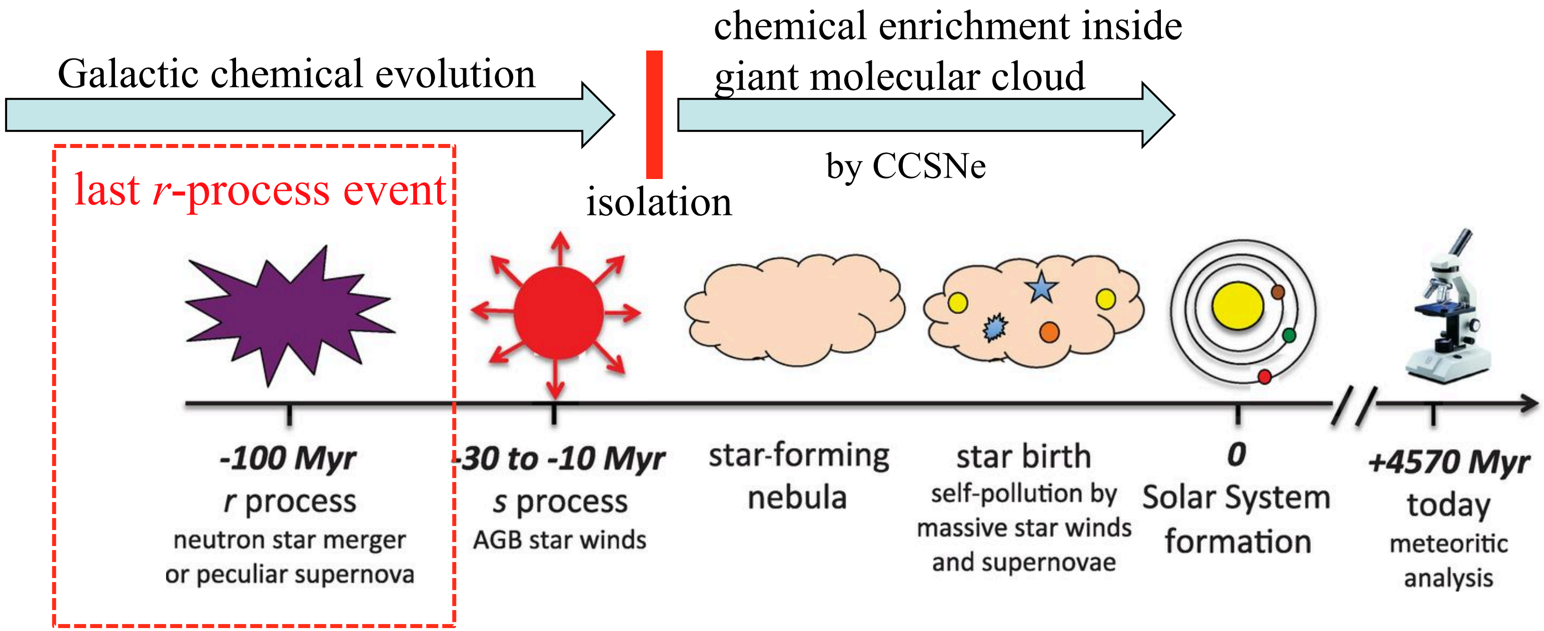




(one exception: Reticulum II)

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
$^{247}Cm/^{235}U = (1.1\text{-}2.4)\times10^{-4}$ $(1.56\times10^{7}$ yr)	0.4	123 Myr (Lugaro+ 2014)
$^{129}I/^{127}I = 1.19\pm0.20\times10^{-4}$ $(1.57\times10^{7}$ yr)	1.35	109 Myr (Lugaro+ 2014)
$^{244}Pu/^{238}U \sim 0.008$ $(8.1\times10^{7}$ yr)	0.53	100 Myr (Dauphas 2005)

^{244}Pu evolution in the solar system

1. the ESS from meteorites
   ✓ ^{244}Pu/^{238}U ~ 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

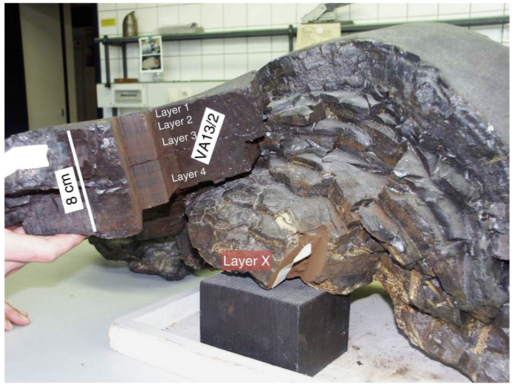
very low, compared with the early solar system

~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

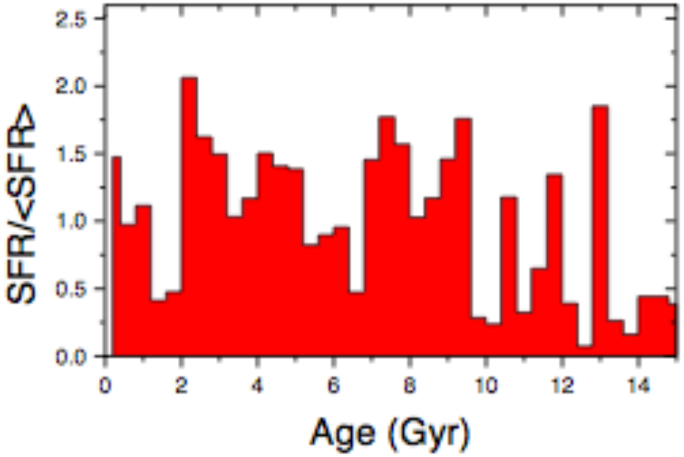
solar abundances (meteorites) of **stable nuclei** hold **the information on integration of the past**

an ejected mass of Eu per one event per $cm^3 = 2.5\times10^{-11}$

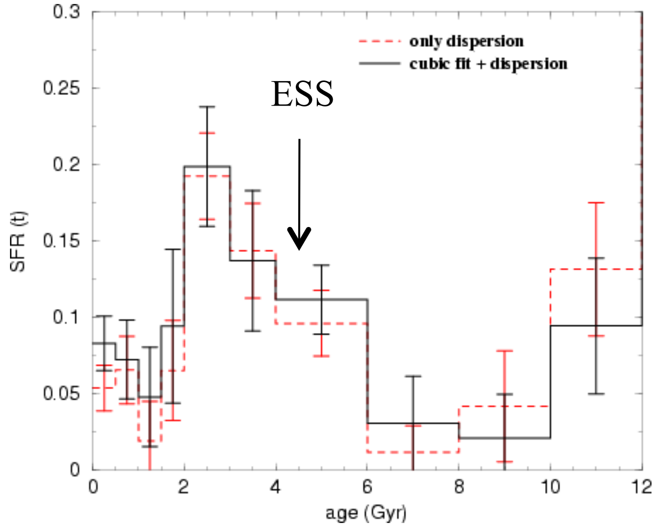
⇒ $3.7\times10^{-10}/2.5\times10^{-11}$ ~ 15

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

star formation history: never constant but has a bursting feature

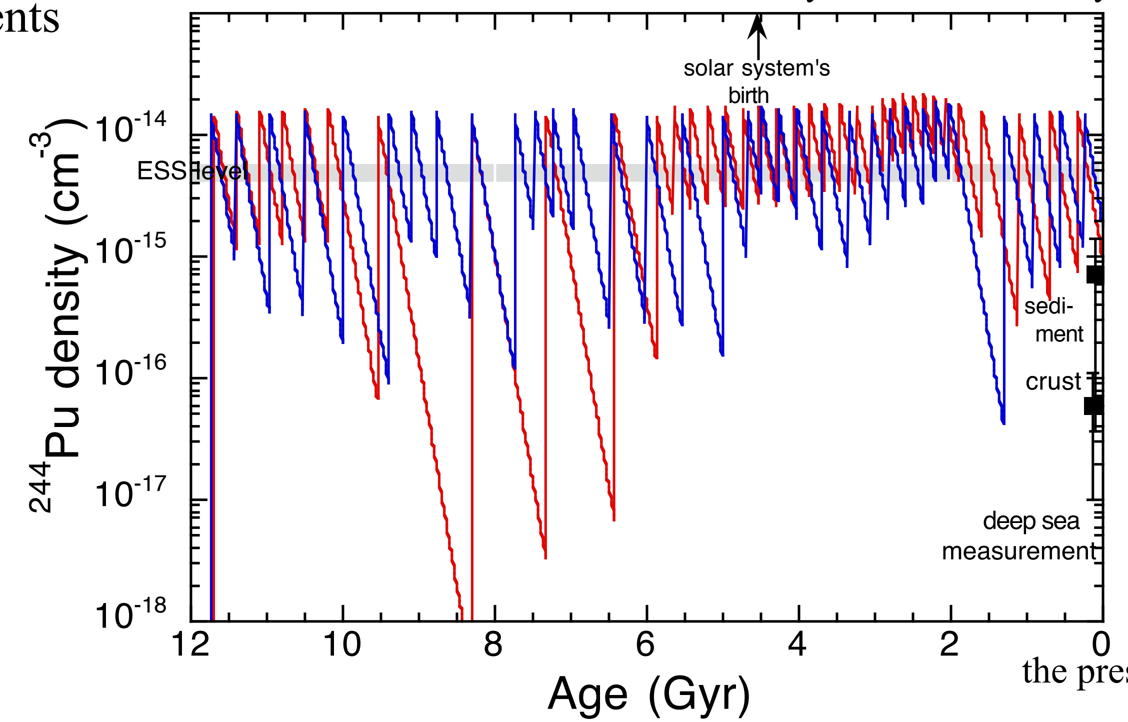


Rocha-Pinto et al. 2010



Cignoni et al. 2006

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.

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

→ 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

the volume contains gas of ~3.5×10^6 $M_{\odot}$ ← ^{244}Pu density

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

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

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

Conclusions

✓narrowing down the astrophysical site of *r*-process from dwarf galaxies

Answer: *neutron star mergers*

✓event frequency estimated from the Milky Way

Answer: *one per ~1400 core-collapse supernovae*
= ~16 Myr^{-1} in the Milky Way

✓the site of *r*-process in the early dwarf galaxies

Answer: magneto-rotational *supernovae*

✓^{244}Pu evolution in the solar system

traces a local star formation history and confirms "neutron star mergers as the site of r-process"