26th INPC 2016, Adelaide in Australia
July 11-16, 2016

Quest for the Origin of R-Process in Nuclear Physics and Galactic Evolution

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Astrophysical sites for the r-process ?

Core-Collapse Supernovae?

MHD-Jet
- Nishimura, et al., ApJ 642, 410 (2006).
- Fujimoto, et al., ApJ 680, 1350 (2008).
- Winteler, et al., ApJ 750, L22 (2012).
- Nishimura et al., ApJ, 810, 109 (2015)

ν-DW ?
- Woosley, et al., ApJ 433, 229 (1994). +

Long-GRB
- Nakamura, et al, A&Ap 582 A34 (2015)

τ =1-10My

Underproduction, off peaks ?

Explosion Condition(Ω, B)?

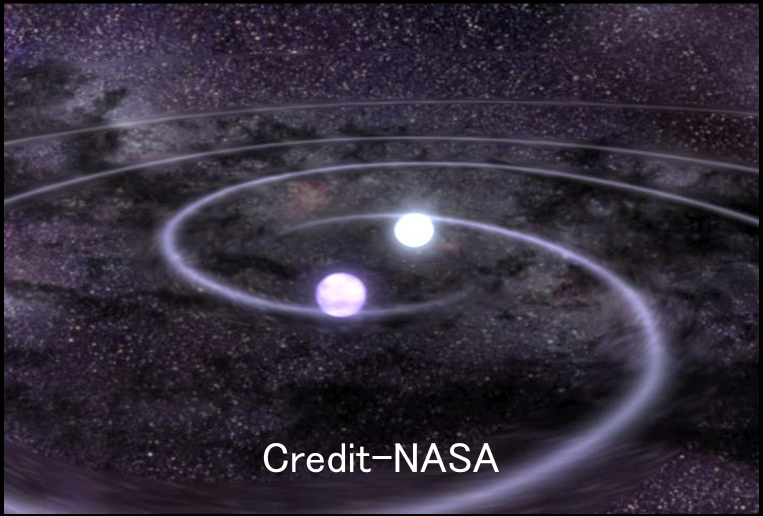
Binary Neutron-Star Mergers?

- Goriely, et al., ApJ 738, L32 (2011).
- Korobkin, et al., MNRAS 426, 1940 (2012).
- Rosswog, et al., MNRAS 430, 2585 (2013).
- Goriely, et al., PRL 111, 242502 (2013), (2015).
- Piran, et al., MNRAS 430, 2121 (2013).
- Wanajo, et al., ApJ 789, L39 (2014).

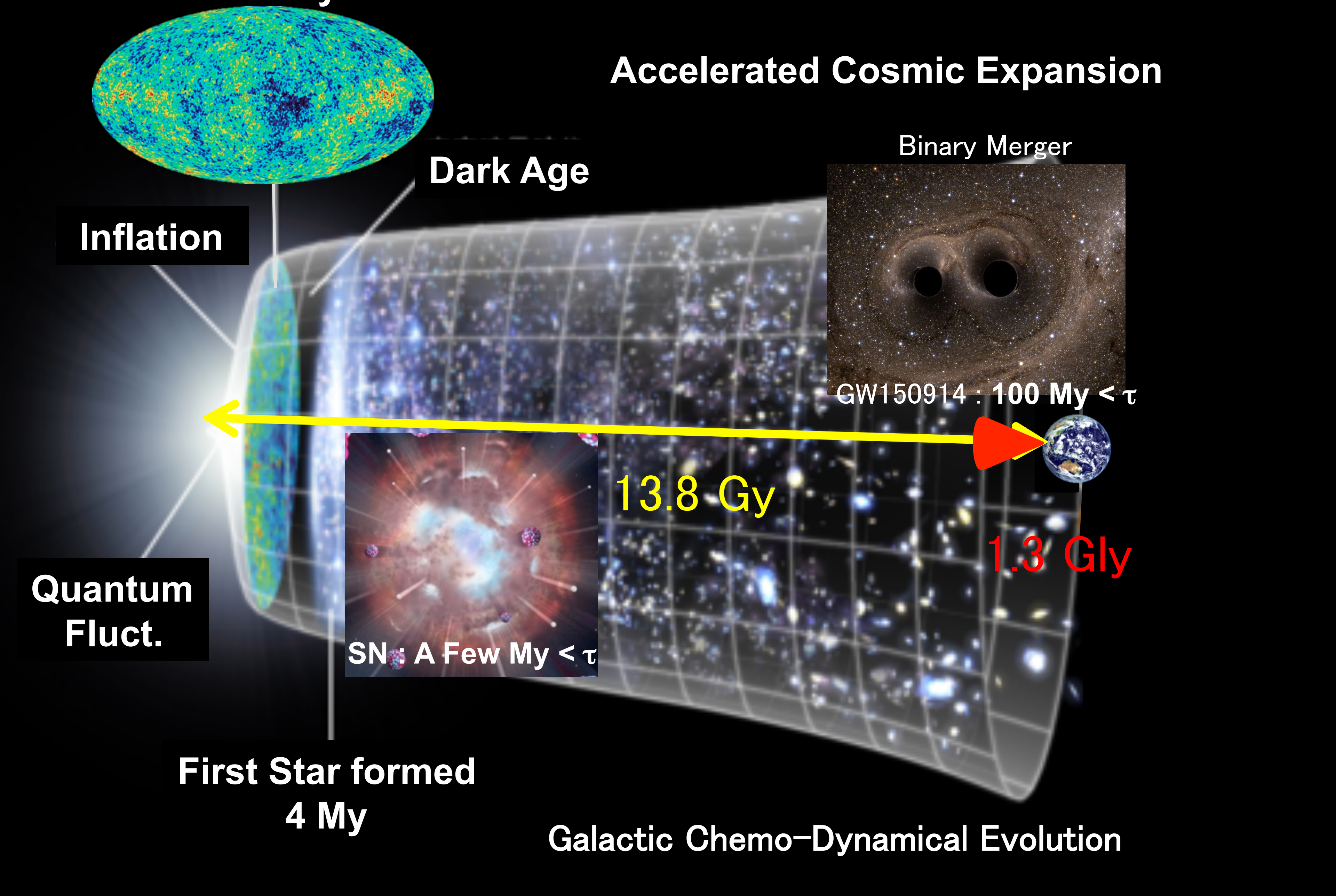
100My $\lesssim \tau_c \lesssim$ 10Ty

Binary NSs arrive too late ?

Time Scale Problem ?



Cosmic Evolution

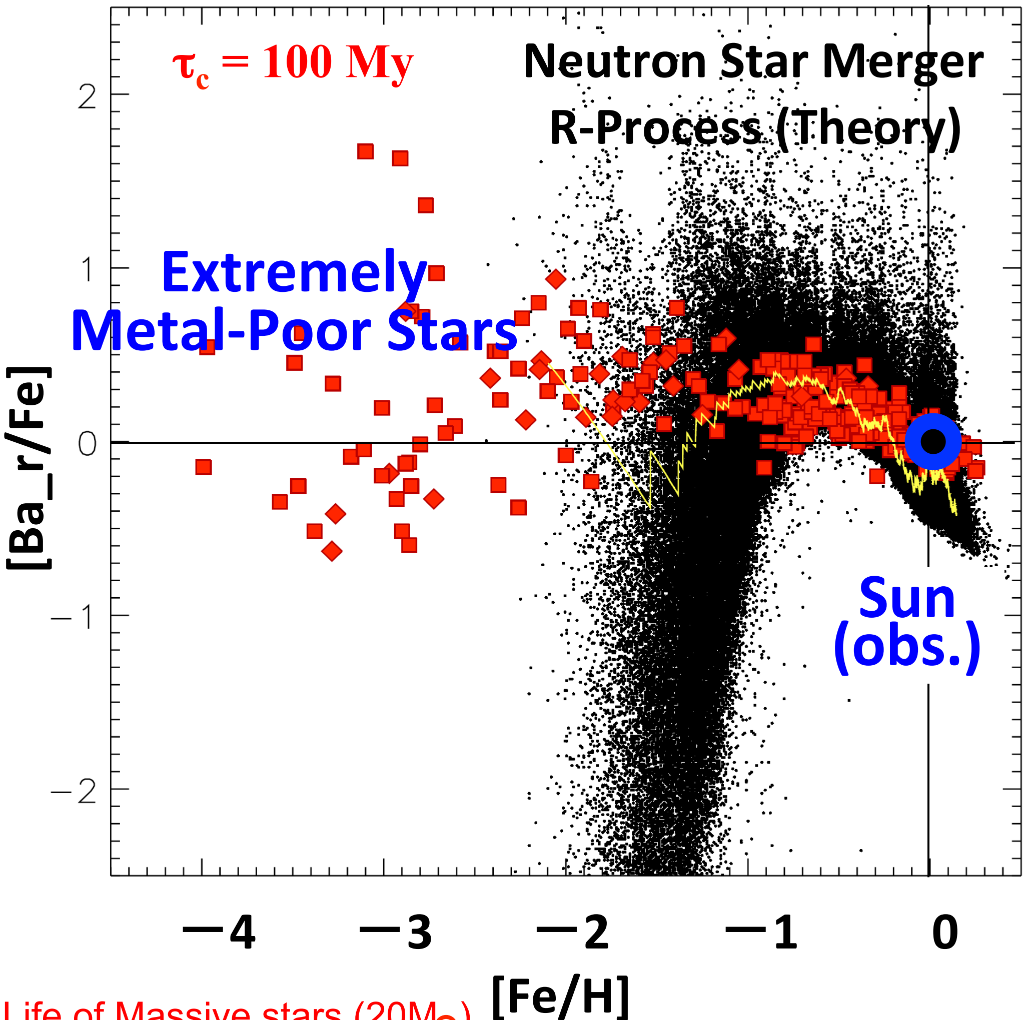


Wanderman & Piran (2014), τ_C = 4 Gy (arXiv:1405.5878)

Time Scale Problem

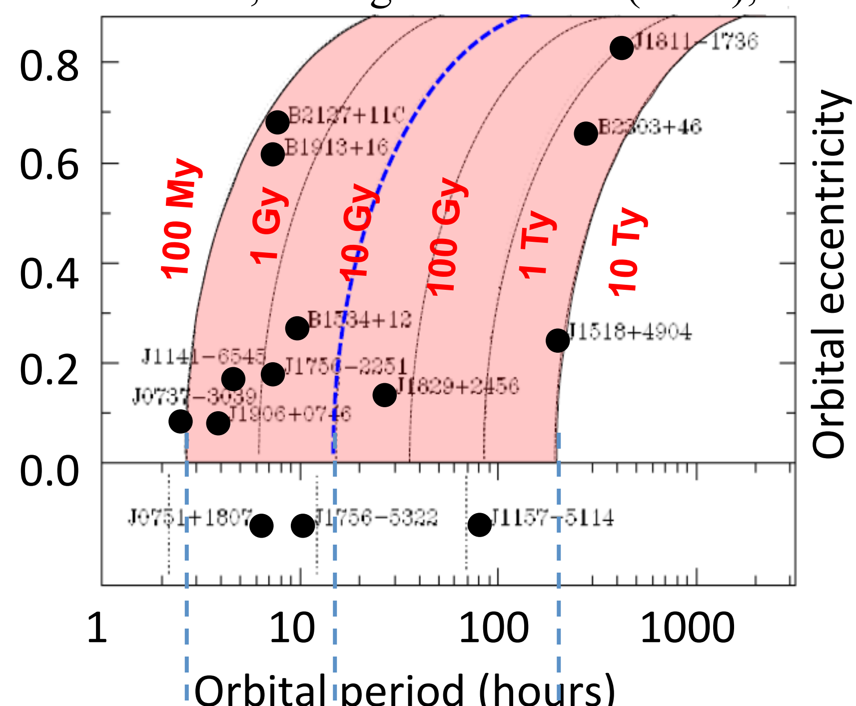
Argast, et al., A&A 416 (2004), 997,
Wehmeyer et al., MNRAS 452 (2015), 1970.

Merging, too slow for GW rad.: 100My < τ_c



$$\tau_c \simeq 9.83 \times 10^6 \text{ yr} \left(\frac{P_b}{\text{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$$

Lorimer, Living Rev. Rel. 11(2008), 8



Life of Massive stars ($20M_\odot$)

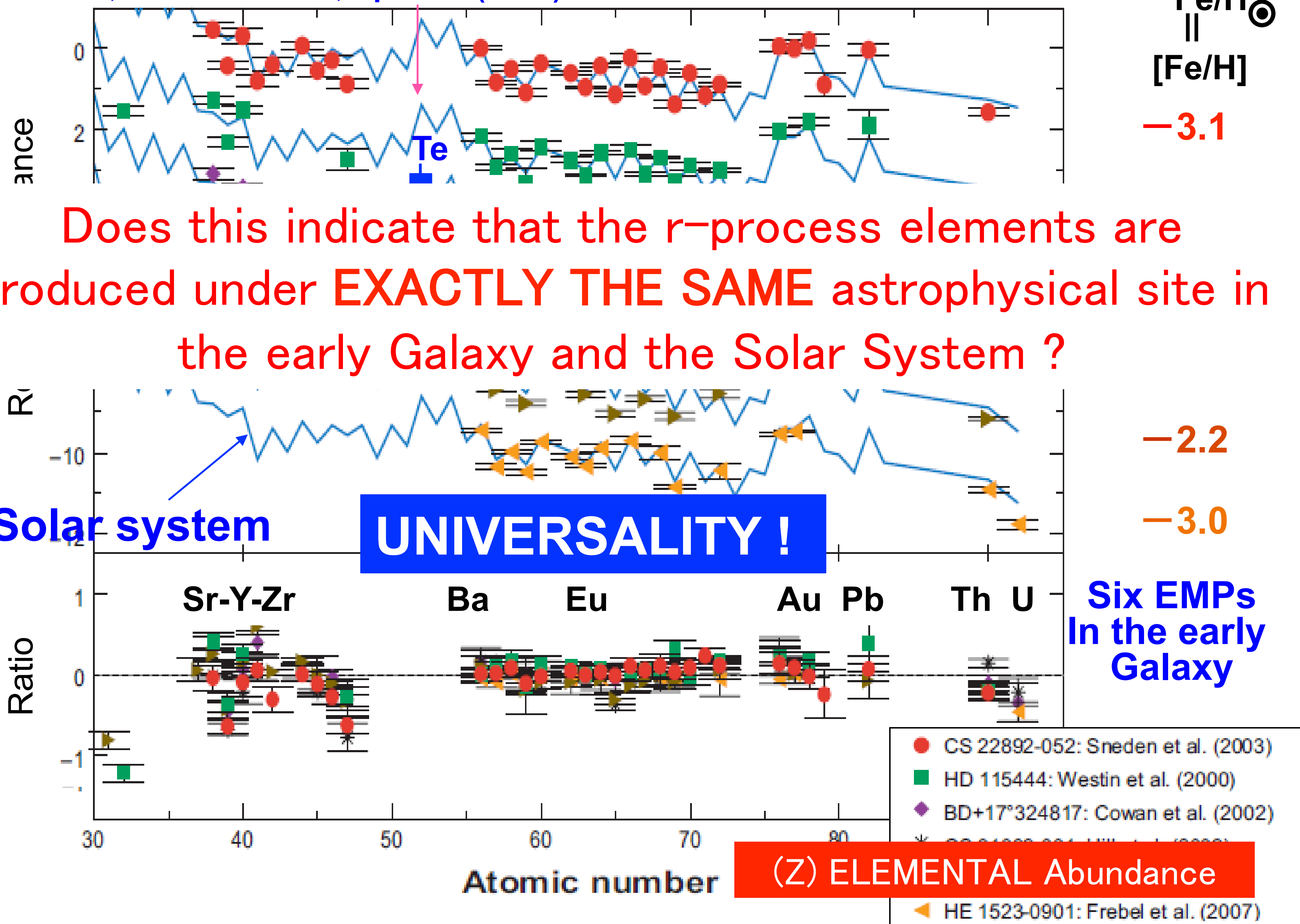
1My 10My 100My ··· 10Gy

100My 10Gy 10Ty

Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

HST-obs., Roederer et al., ApJ 747 (2012) L8.

$\frac{t}{10^{10}y} \fallingdotseq 10^{[Fe/H]}$ $\log \frac{Fe/H_{☆}}{Fe/H_{⊙}} = [Fe/H]$



Does this indicate that the r−process elements are produced under **EXACTLY THE SAME** astrophysical site in the early Galaxy and the Solar System ?

UNIVERSALITY !

(Z) ELEMENTAL Abundance

Purpose

Solve Time-Scale Problem of binary NSMs, still satisfying the UNIVERSALITY of the r-process elemental abundance pattern in the early Galaxy and the Solar System.

⇩

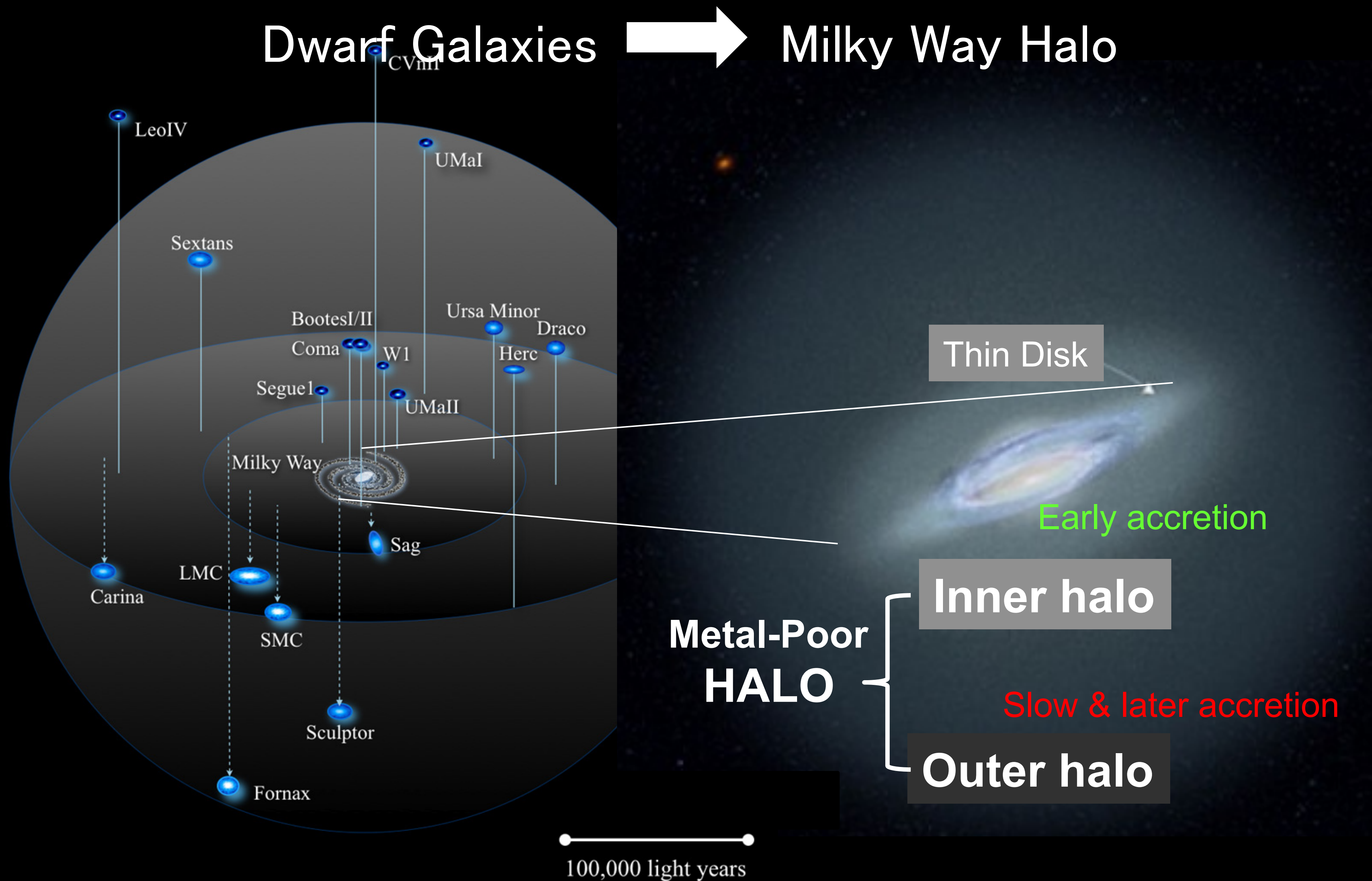
Identify the roles of SNe(MHD-Jet) in r-process.

Construct evolution model of Galactic structure formation and chemistry, i.e. r-process elements from both NSMs and SNe.

◎ Galactic Chemo-Dynamical Evolution

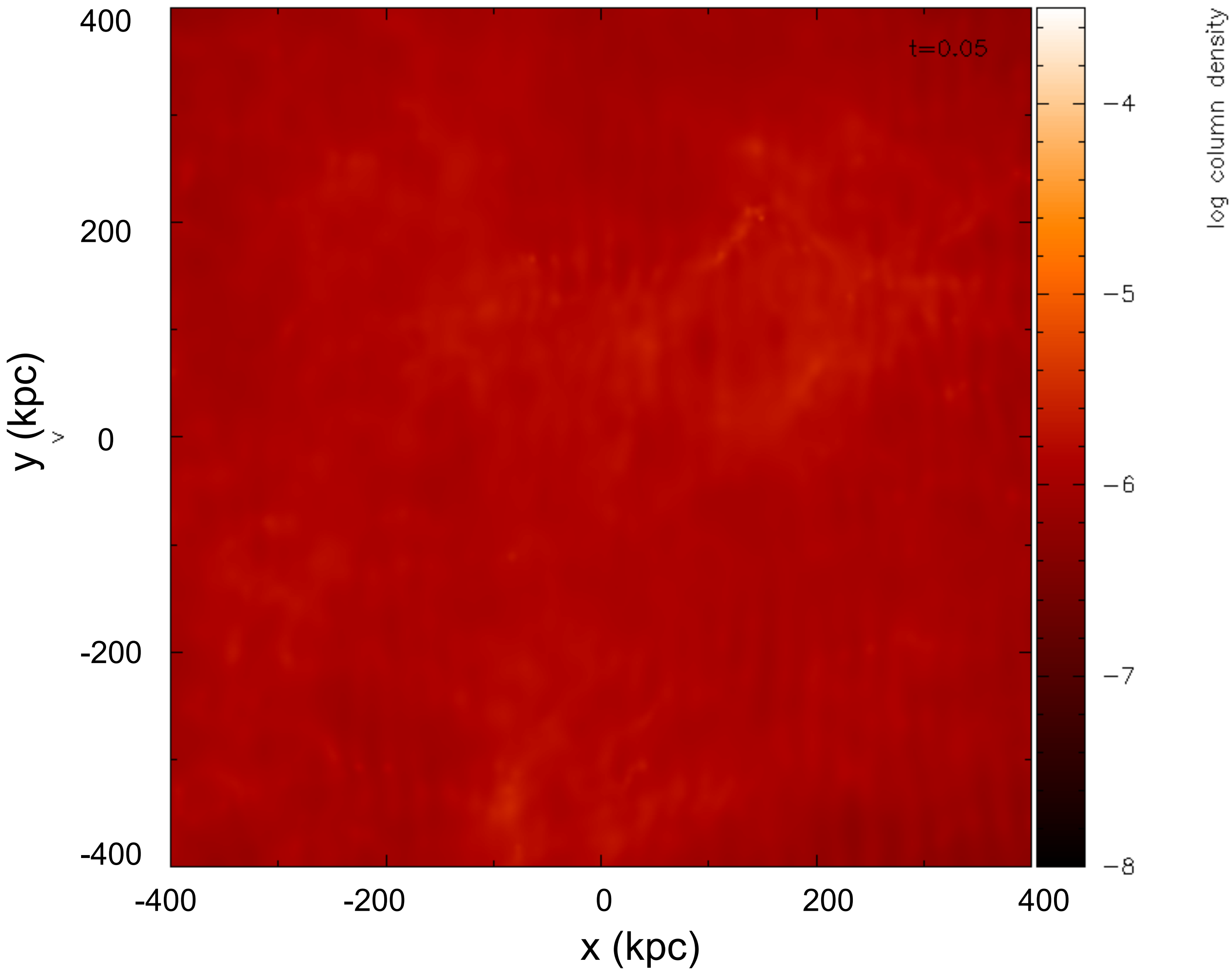
◎ Nuclear Physics of Unstable Nuclei

Hierarchical Galactic Structure Formation



N–Body Simulation of LSS Formation

X. Zhao & G. Mathews (2014)



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution

Dwarf Galaxies = Building Blocks of Milky Way Galaxy

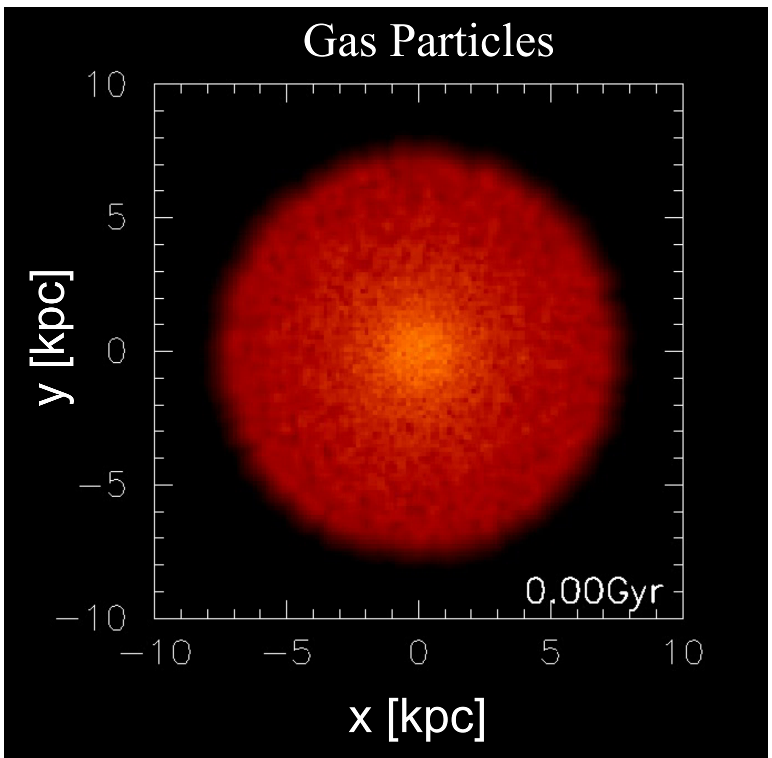
N-Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.

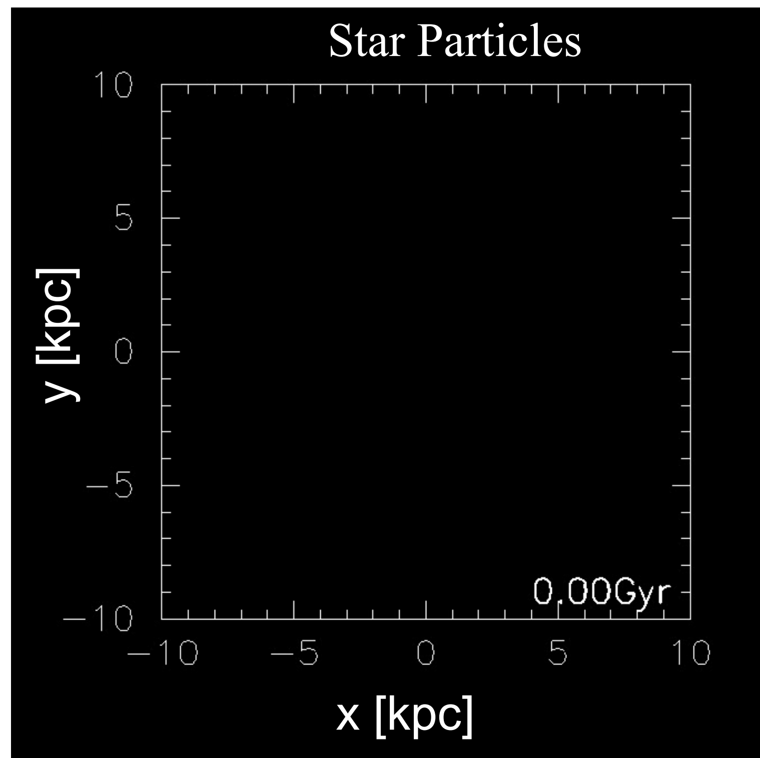
SNe = Metals ; NSM(τ_c=100My)= r-process elements. (n_H >100 cm^{-3} → ~10-100pc)

SPH code = ASURA (Saitoh et al., PASJ 60 (2008), 667; PASJ 61 (2009), 481)

Yutaka Hirai et al., (COSNAP), ApJ 814 (2015), 41.

$M_{tot} = 7x10^8 M_{sun}$, $N_i = 5x10^5$ particles, $M_\star = 100 M_{sun}$





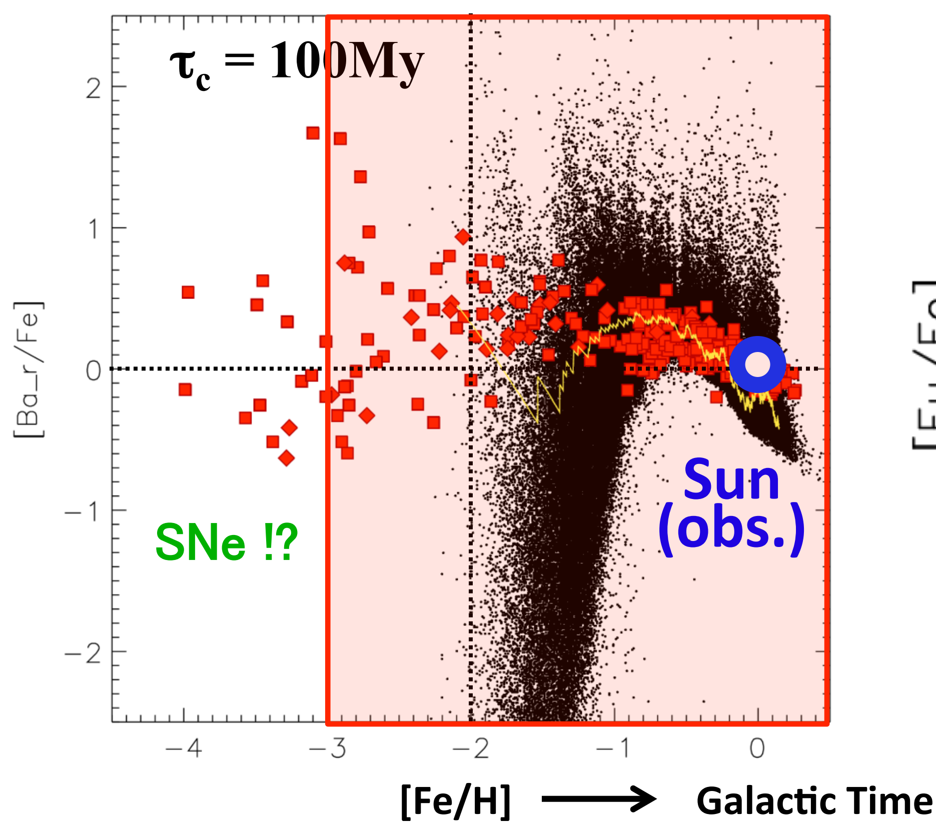
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Spheroidals

N-Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.
SNe = Metals ; NSM(τ_c=100My)= r-process elements. (n_H >100 cm^{-3} → ~10-100pc)

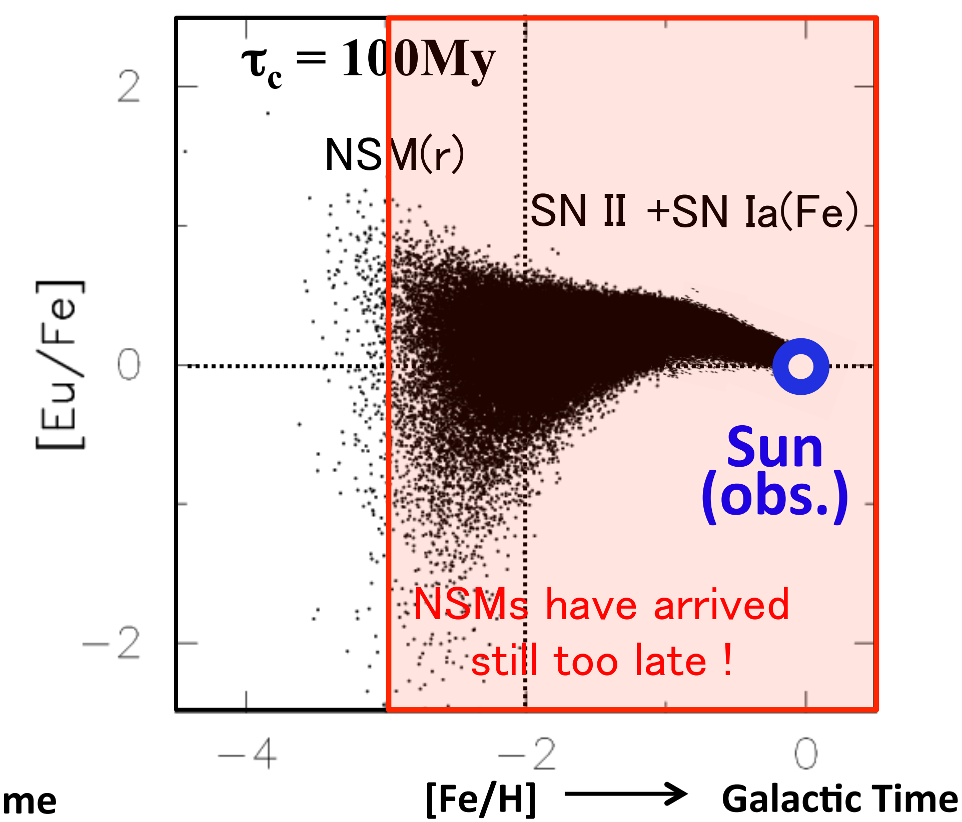
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino, ApJ 814 (2015), 41.

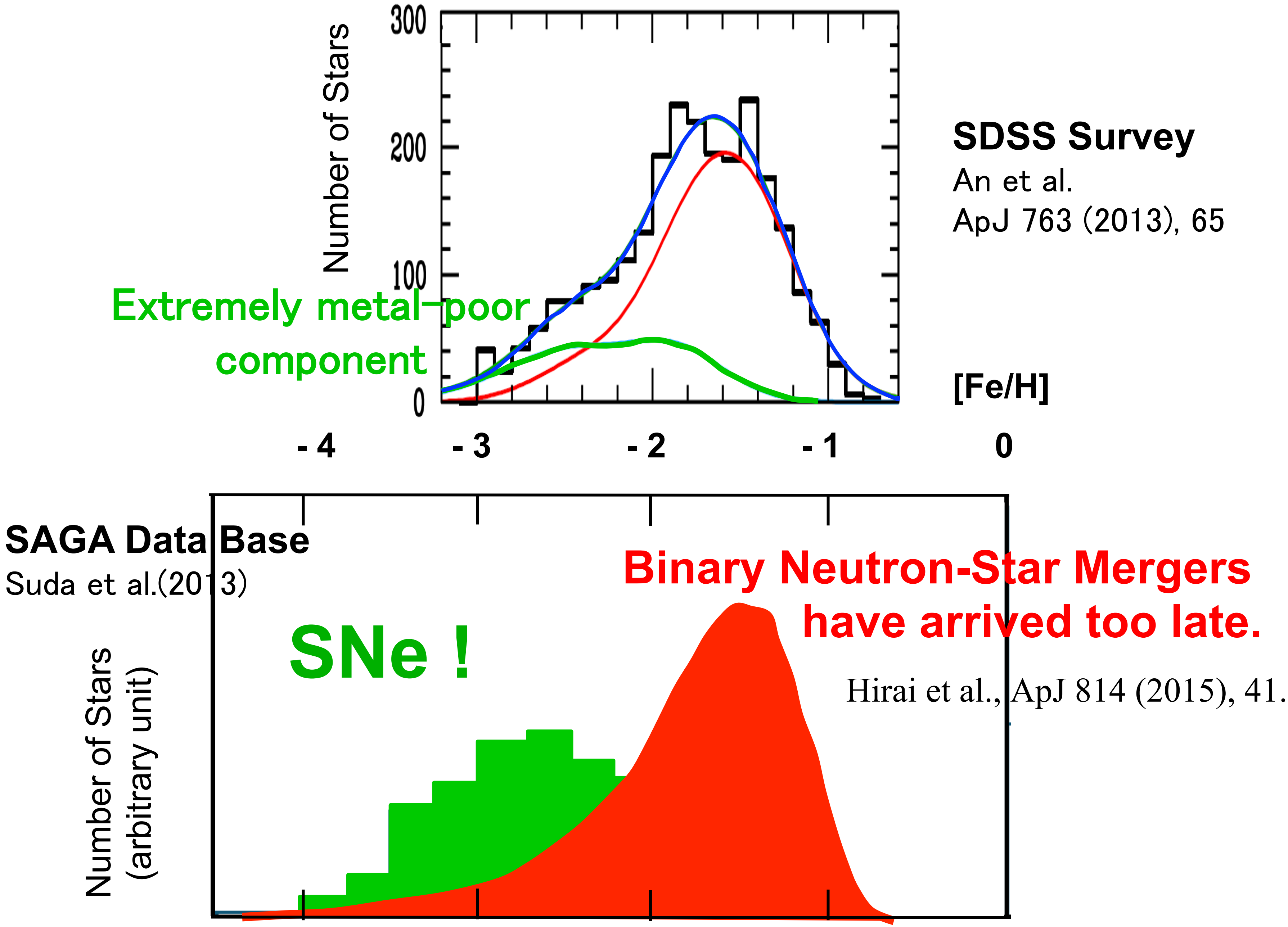
Without GAS MIXING

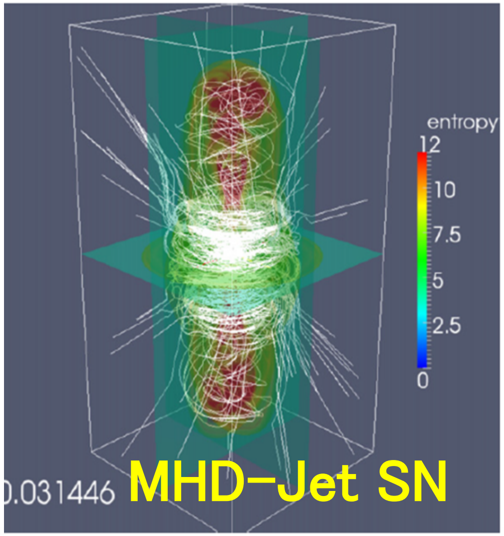


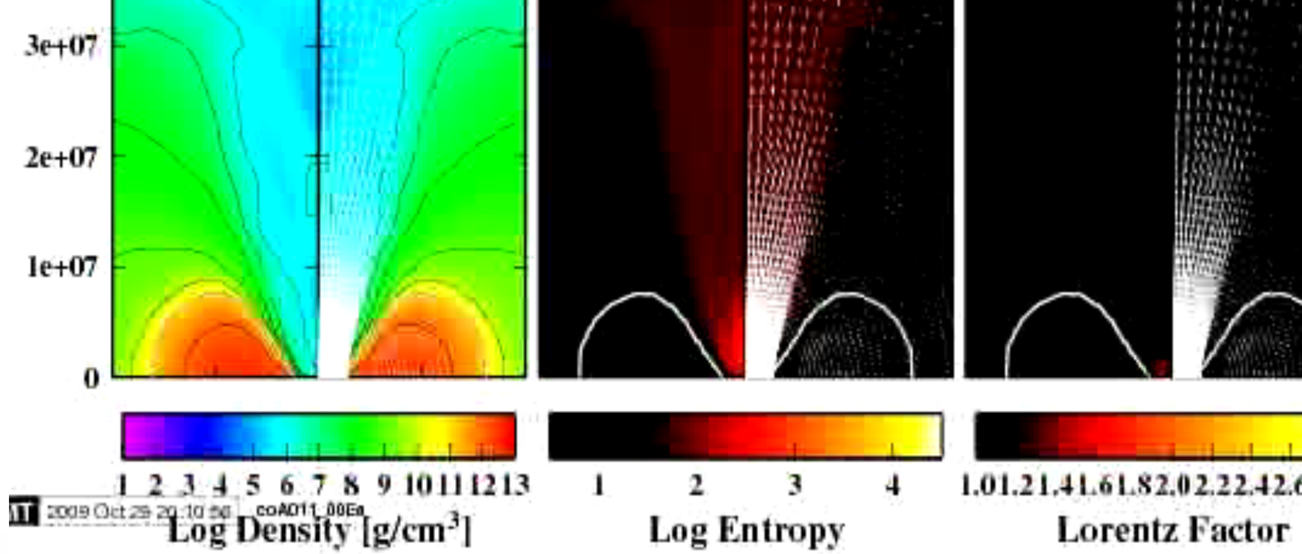
With GAS MIXING

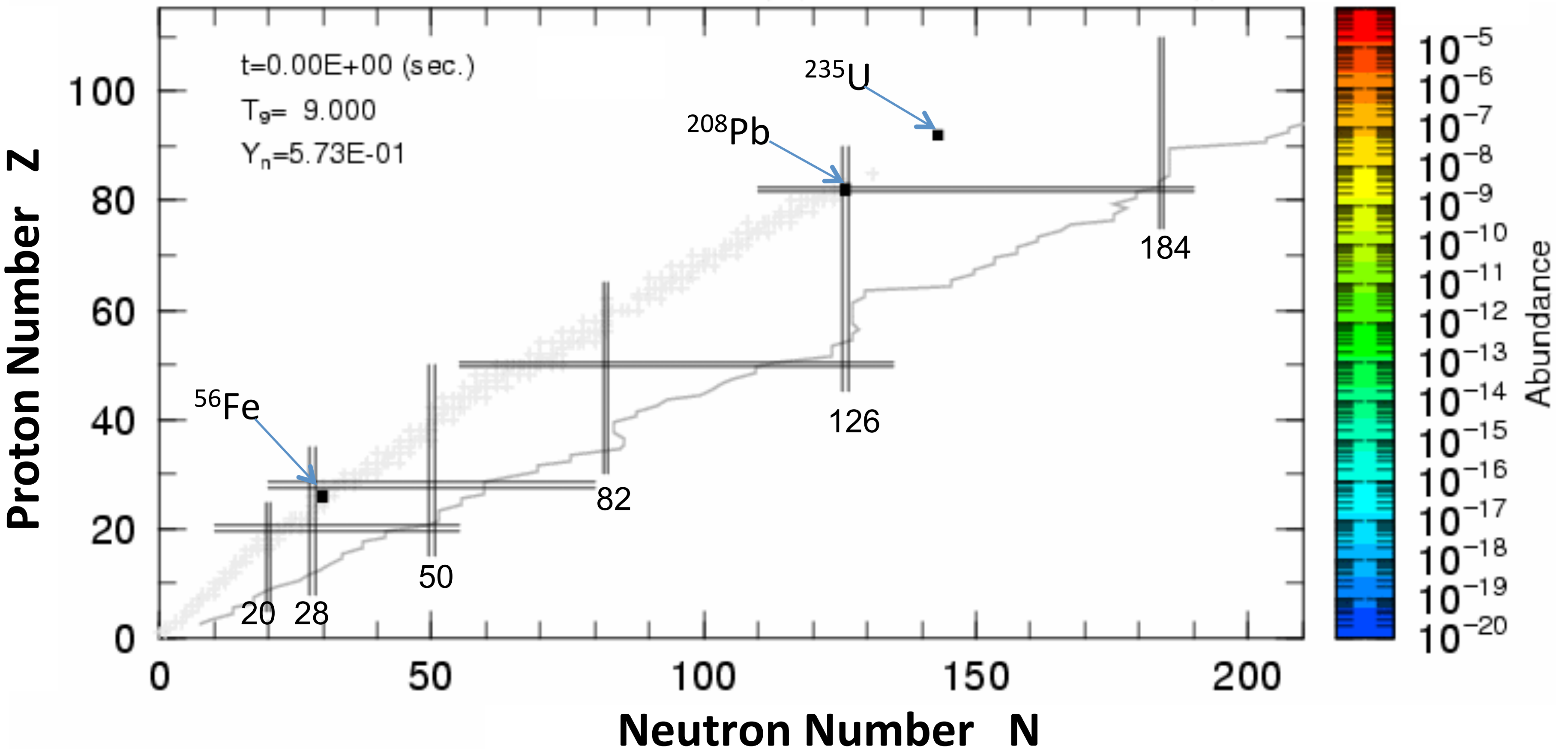


Observational Data of Milky Way HALO



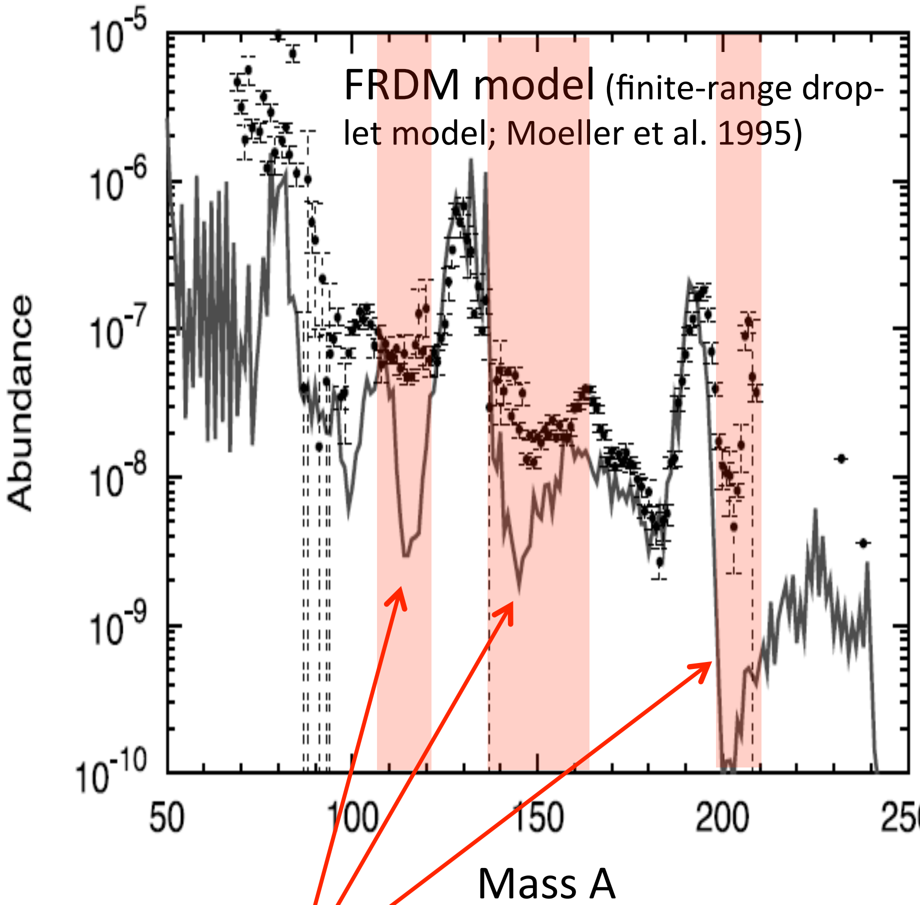

entropy
12
10
7.5
5
2.5
0
.031446
MHD-Jet SN


3e+07
2e+07
1e+07
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Log Density [g/cm³]
1 2 3 4
Log Entropy
1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
Lorentz Factor


t=0.00E+00 (sec.)
T₉= 9.000
Yₙ=5.73E-01
235U
208Pb
56Fe
20
28
50
82
126
184
Proton Number Z
Neutron Number N
0
20
40
60
80
100
0
50
100
150
200
Abundance
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰

CCSN: Magneto–Hydrodynamic Jets

S. Nishimura, et al., ApJ , 642, 410 (2006) ; T. Takiwaki, K.Kotake and K. Sato, ApJ 691, 1360 (2009); C. Winteler, et al., ApJ 750, L22 (2012).



the rotational axis is found to be good for r
peak, ETFSI model (Extended Thomas-Fermi + Strutinsky; Goriely 2003) ed r
strong n th
uniform rotation and magnetic field model,
is obtained in the direction of the equatorial
to be limited to the reproduction of the *r*-ele
ond peak. Moreover, it is found that globa
duced *r*-elements does not qualitatively depe
form of ρ and T after the last stage of NSE, a
features in the abundance production are ra

Underproduction PROBLEM ! → **Possible Solutions** Nucl. Phys. – Shell Quenching ?

RIKEN-RIBF : Decay Spectroscopy around A = 100–145

G. Lorusso et al., PRL 114 (2015), 192501.

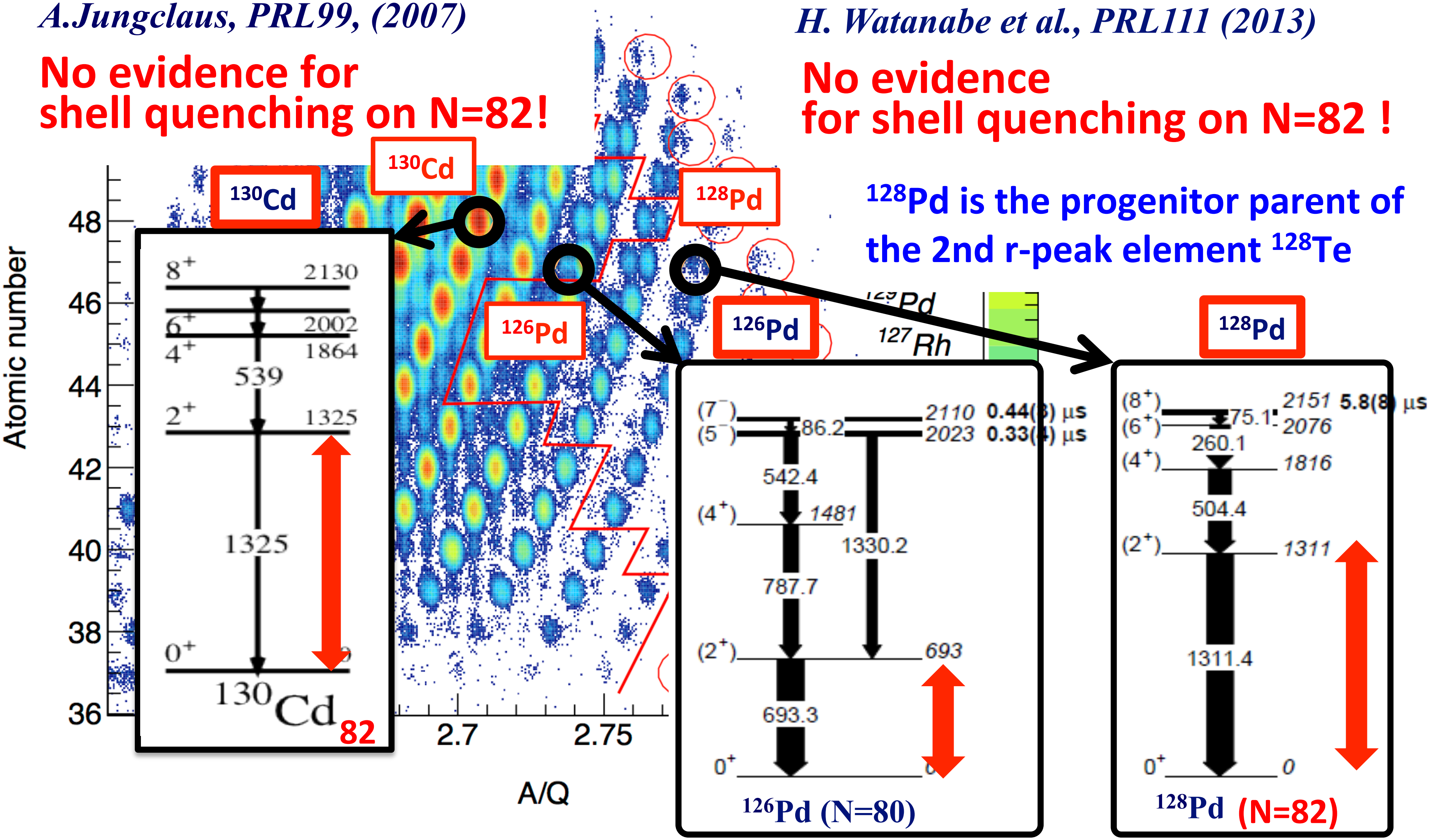
A.Jungclaus, PRL99, (2007)

No evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

No evidence for shell quenching on N=82 !

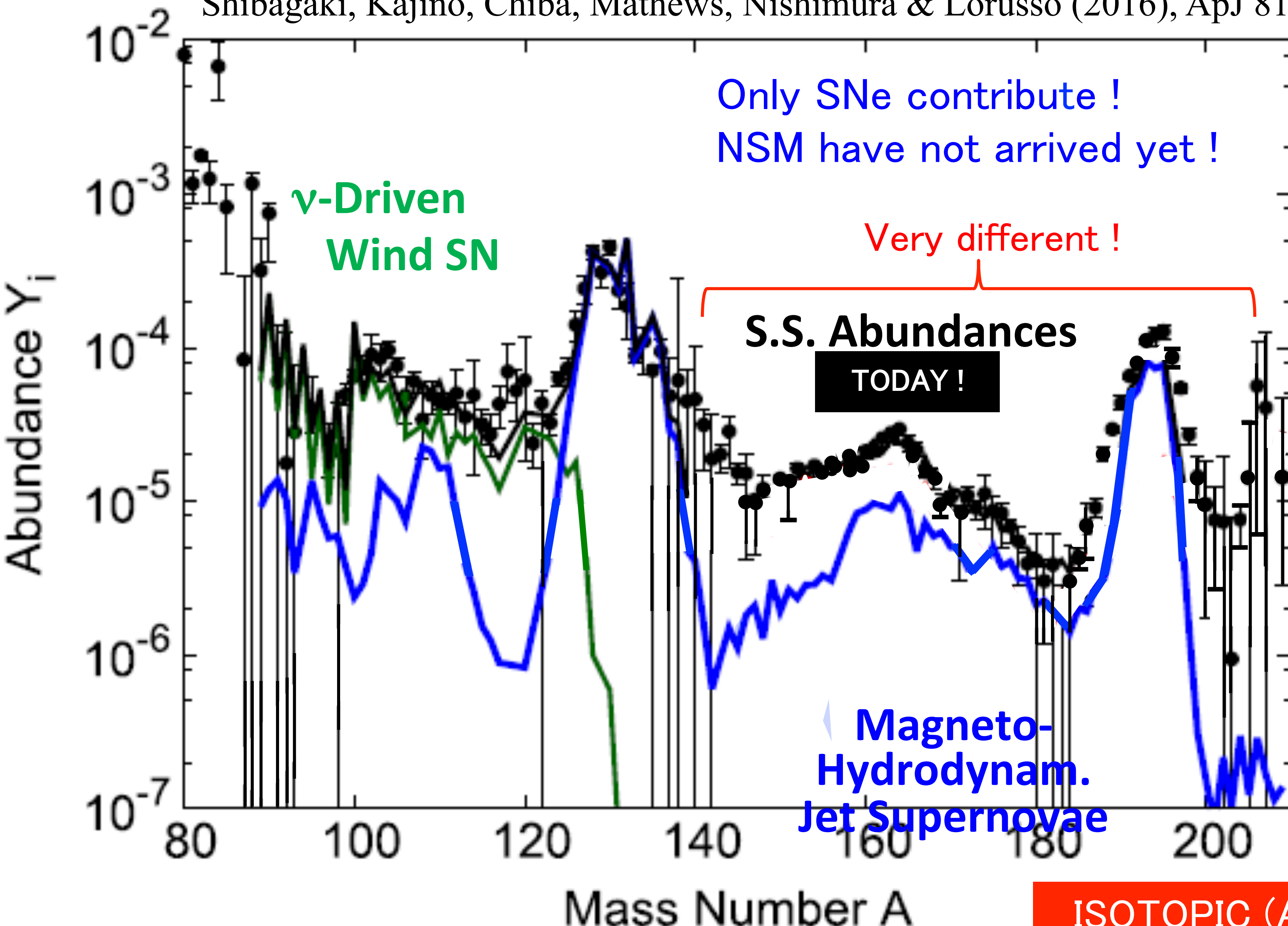
^{128}Pd is the progenitor parent of the 2nd r-peak element ^{128}Te



Solar System r–Process Abundance

Early Galaxy !

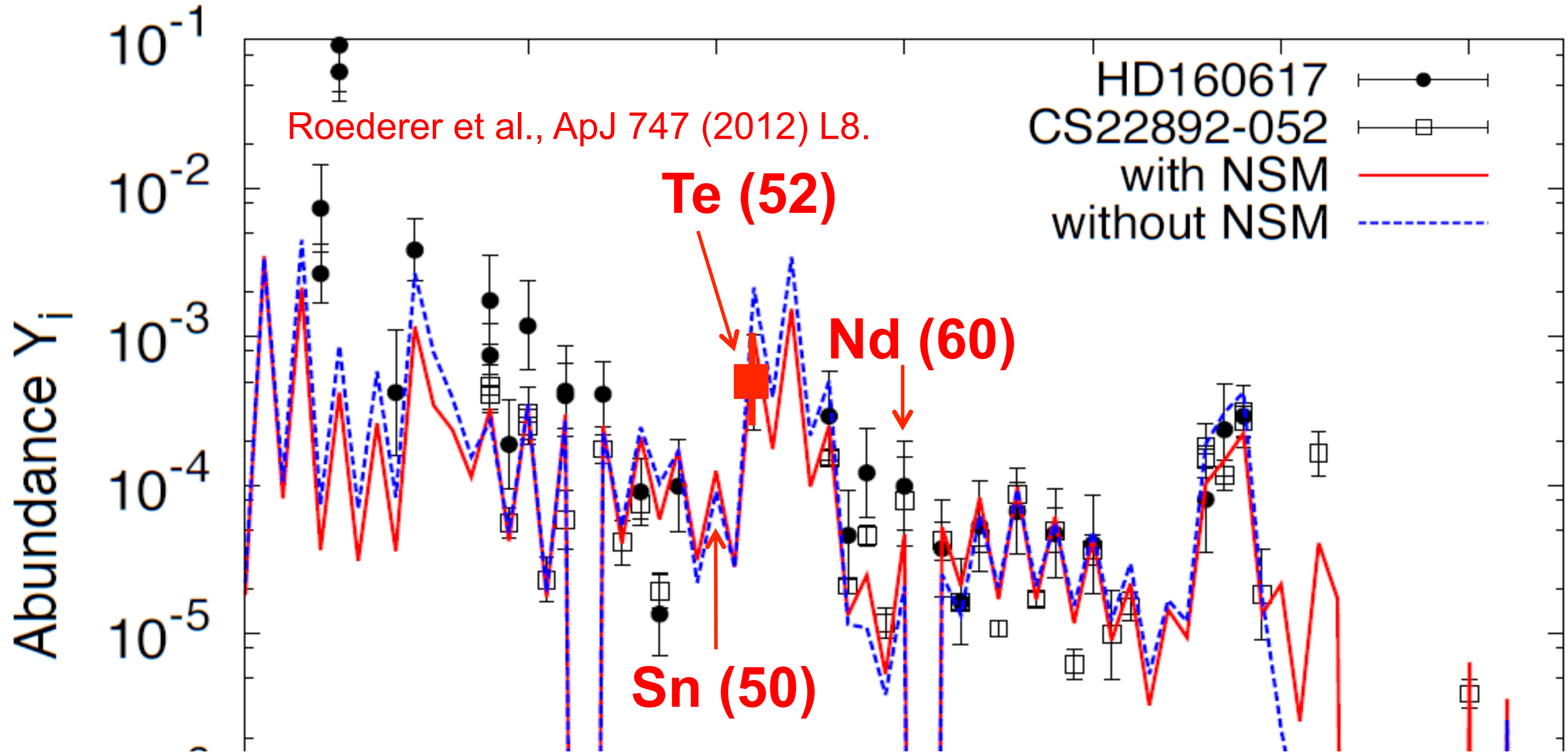
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.



ISOTOPIC (A) !

UNIVERSALITY !

Early Galaxy !



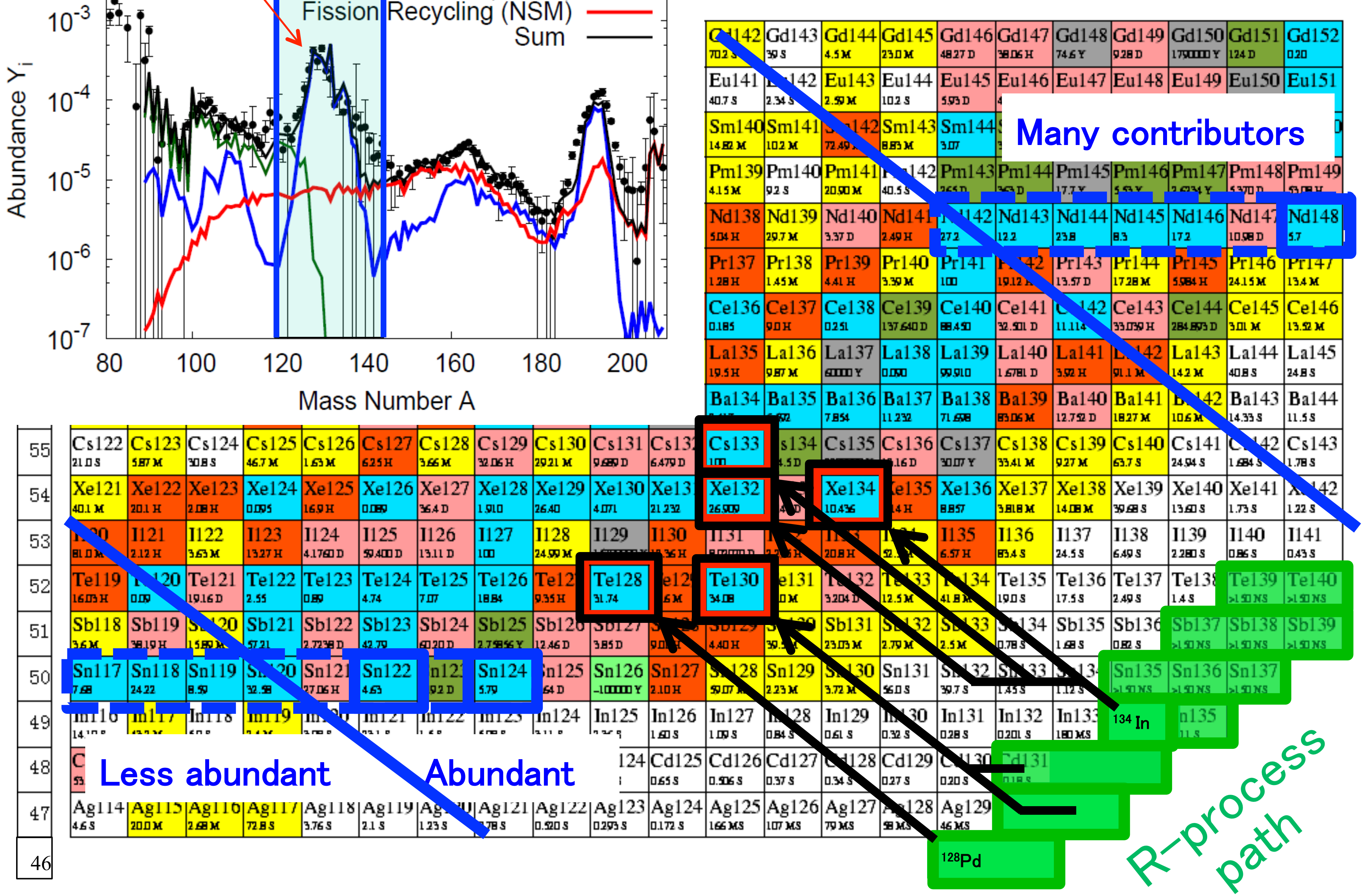
UNIVERSALITY does **NOT** necesarily indicate that the r–process elements are produced under **EXACTLY THE SAME** astrophysical site in the early Galaxy and the Solar System.

Astron. Obs. Doesn't separate ISOTOPES !

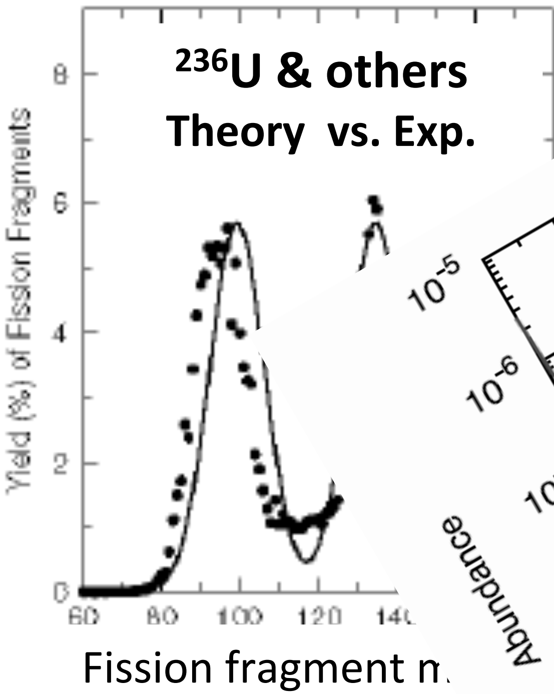
Atomic Number Z

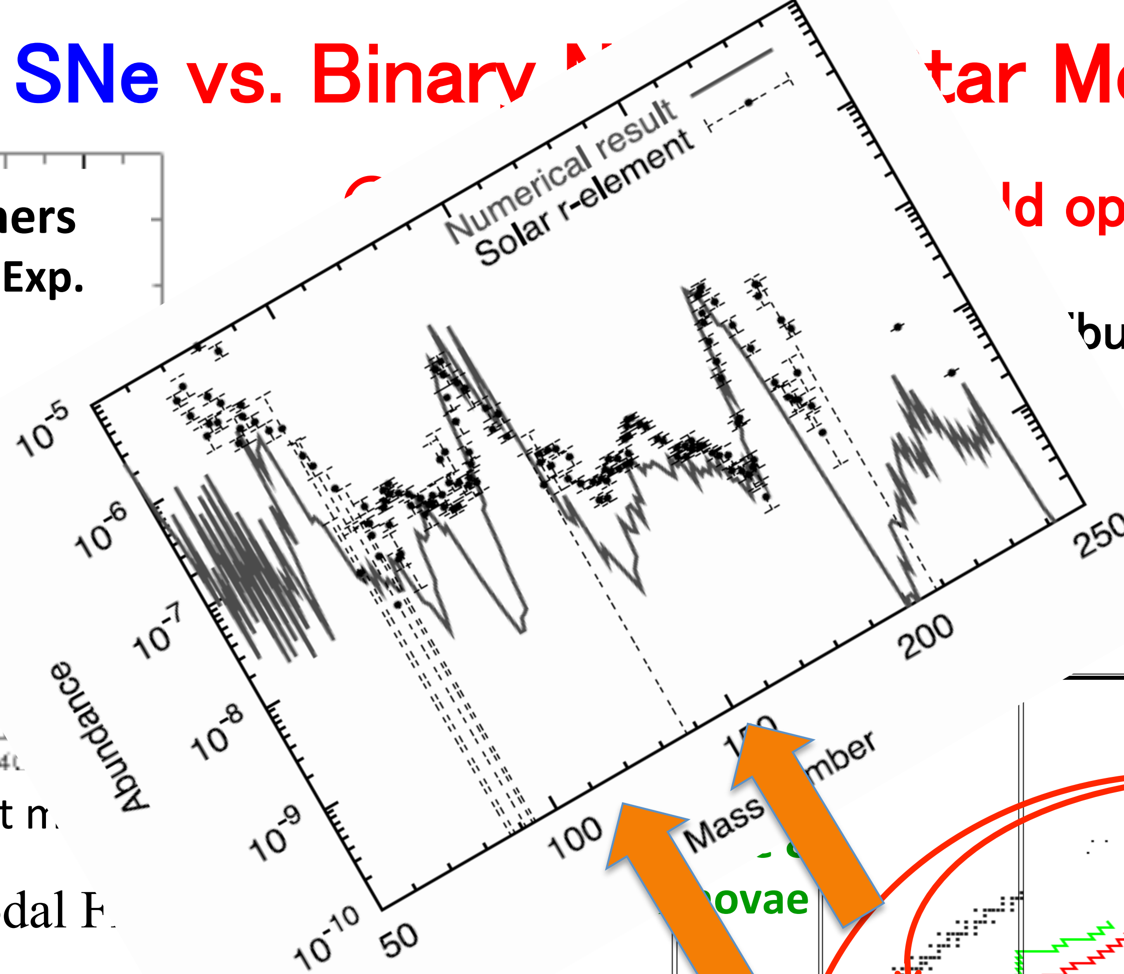
ELEMENTAL (Z)

Lorusso et al. with Kajino (2015), PRL 114, 192501. (COSNAP + RIKEN Collab.)



MHD-Jet SNe vs. Binary N… …tar Mergers





…'d operate!

…'bution

…e, France, (2007)
…8).

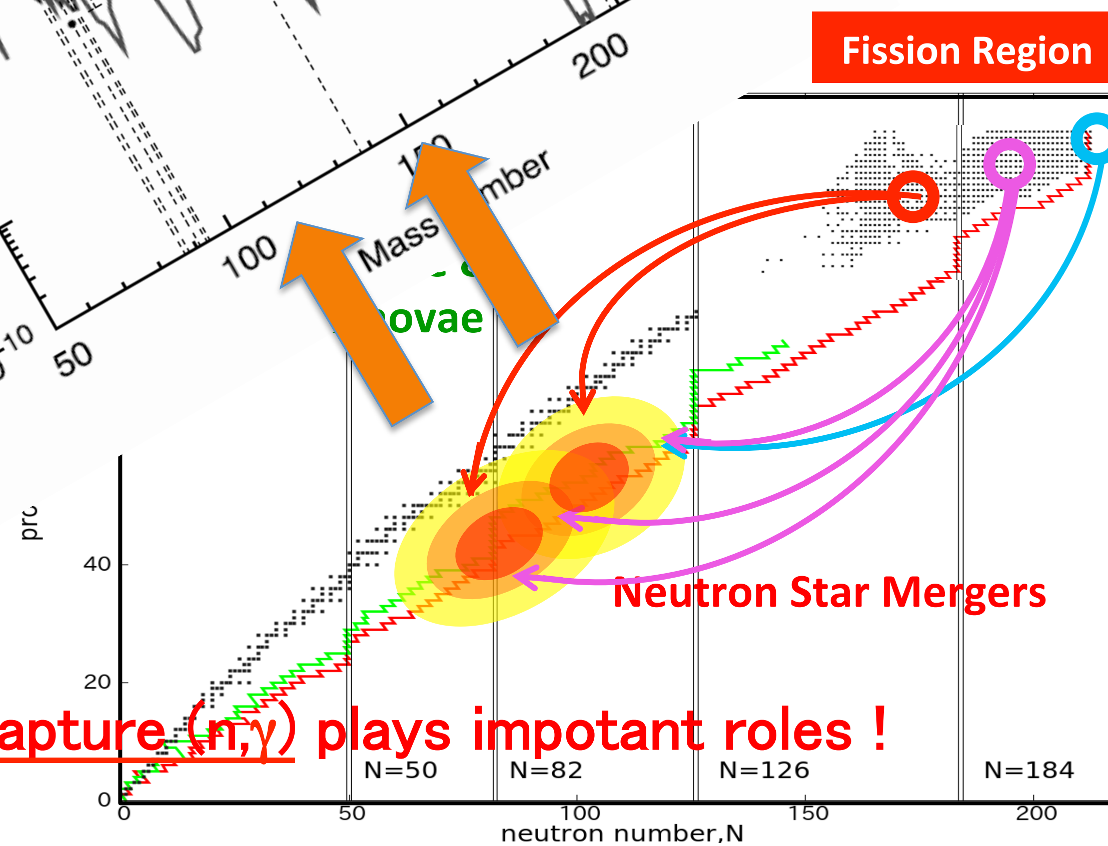
Bimordial or Trimodal F…

$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi\sigma}} W_i \exp\left(\frac{-(A \ldots}{2\ldots}\right.$$

$$A_H = (1+\alpha)(A_p - N_{loss})/2$$

$$A_L = (1-\alpha)(A_p - N_{loss})/2$$

$$A_M = (A_H + A_L)/2$$

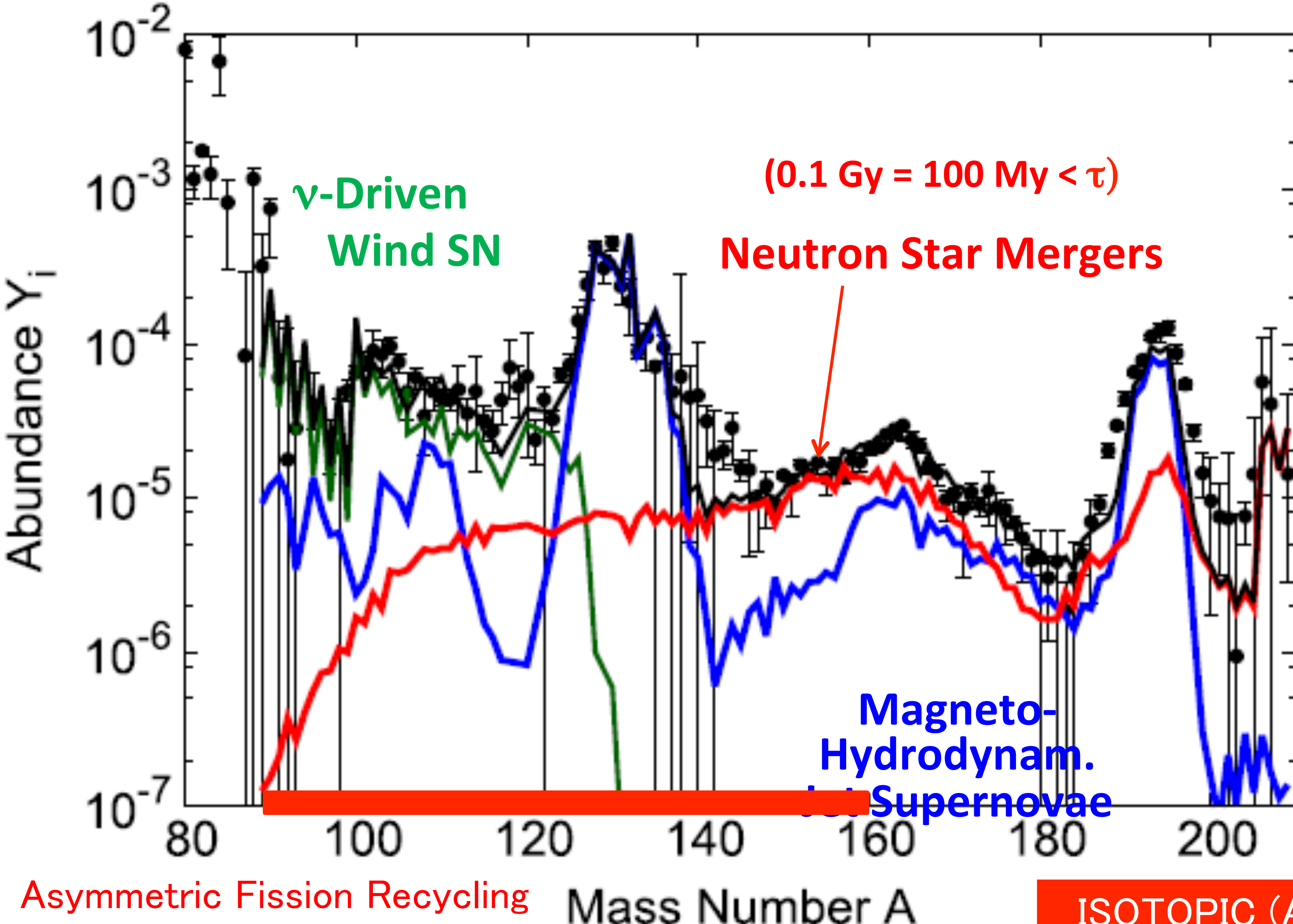


◎ Neutron capture (n,γ) plays impotant roles !

Solar System r-Process Abundance

TODAY t = 13.8Gy

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.



ISOTOPIC (A) !

Observed Galactic event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]				
νSN (Weak r)	=	7.4×10^{-4}	x	(1.9±1.1) [a]
MHD Jet SNe	=	0.6×10^{-2}	x	((0.03±0.02) x (1.9±1.1)) [b]
Binary NSMs	=	$(2\pm1) \times 10^{-2}$	x	$(1\text{-}28)\times10^{-3}$ [c]

Observations a 1.9±1.1 Diehl, et al., Nature 439, 45 (2006).

b 0.03±0.02 Winteler, et al., ApJ 750, L22 (2012).

Obs. Estimate c $(1\text{-}28) \times 10^{-3}$ Kalogera, et al., ApJ 614, L137 (2004).

Galactic Evolution including Binary Evolution

$$\frac{dM_i}{dt} = P_i(t) + E_i(t) + X_{in} f_{in}(t) - X_i[f_{out}(t) + B(t)]$$

Ejection rate of species i into the ISM

$$E_i(t) = \int_{m(t-\tau_m)}^{m_u} (m_i) X_i(t-\tau_m)(m - m_r - m_i)\varphi(m)\psi(t-\tau_m)\,dm$$

Production rate of newly synthesized species i into the ISM

$$P_{Fe}(t) = m_{Fe}(Ia)R_{Ia} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

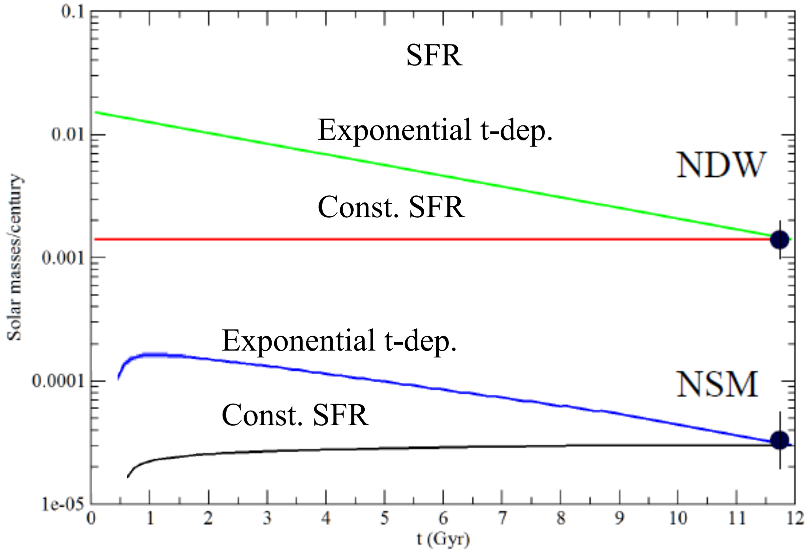
$$P_{rNSM}(t) = m_r(NSM)R_{NSM} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

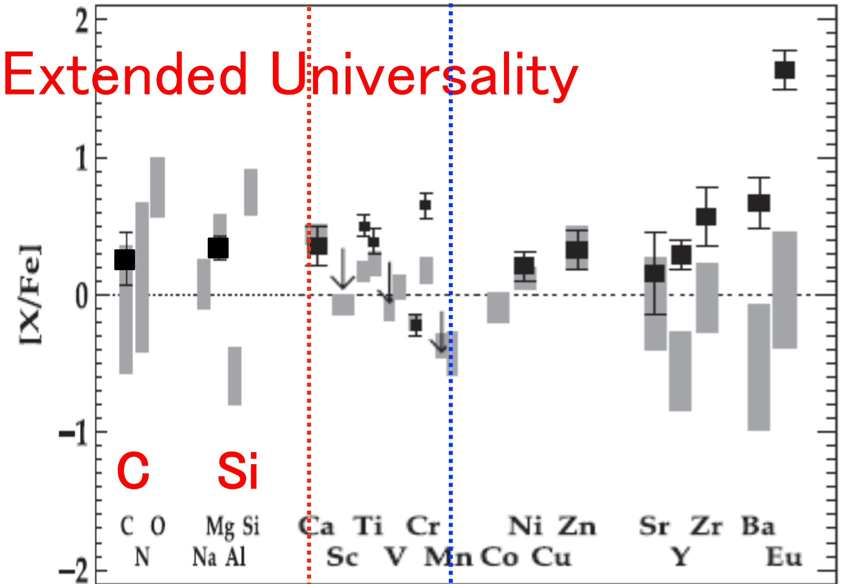
$$P_{rNDW}(t) = m_r(NDW)R_{SNII}$$

$$P_{rMHDJ}(t) = m_r(MHDJ)\epsilon_{MHDJ}R_{SNII}$$

$$R_{NSM} = \int_{m_l}^{m_h} dM_B\,\varphi(M_B) \int_{q_l}^{1} dq f(q) \int_{a_l}^{a_h} da P(a)\psi(t-\tau_{m2}-t_G)$$

$$R_{SNII} = \int_{m_l}^{m_h} \varphi(m)\psi(t-\tau_m)\,dm$$

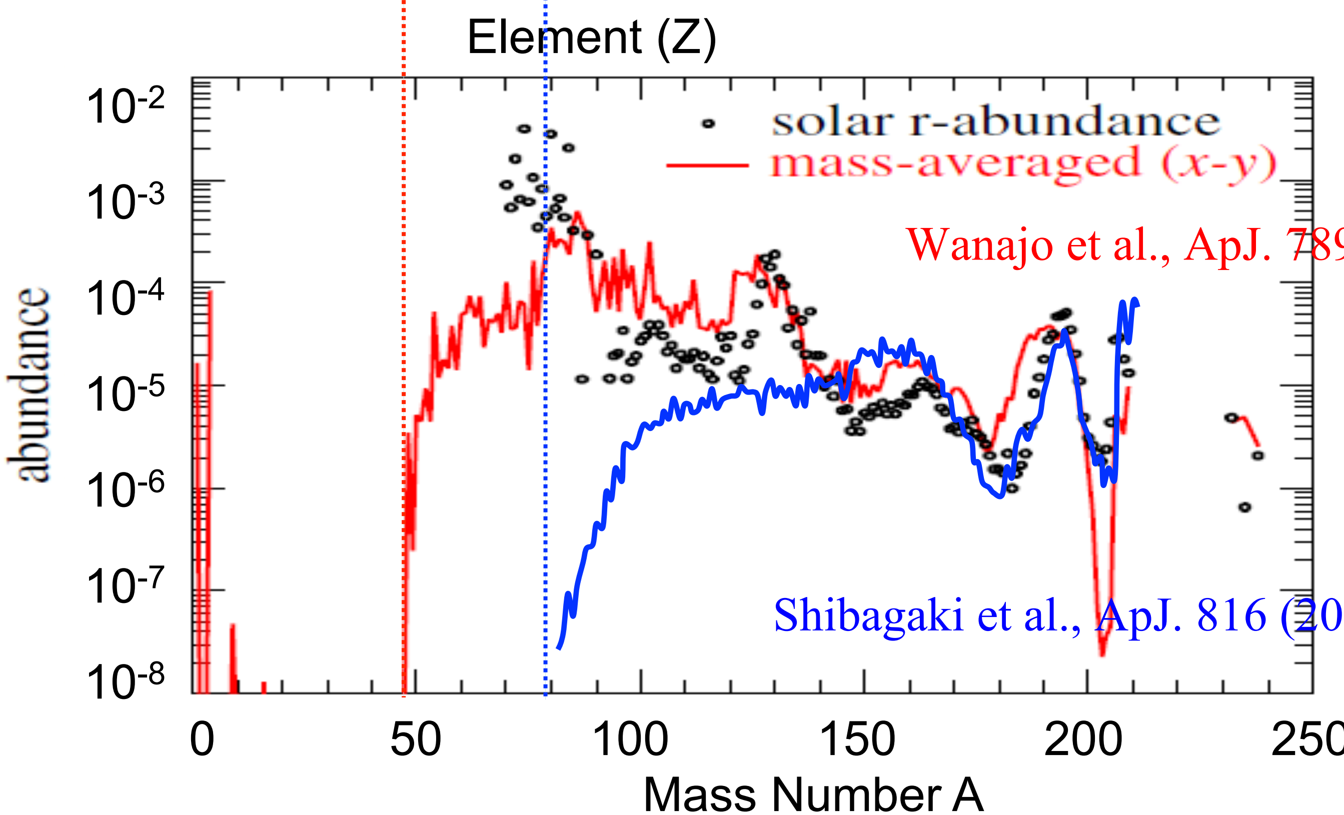




Ultra-Faint warf Galaxy: Ret. II

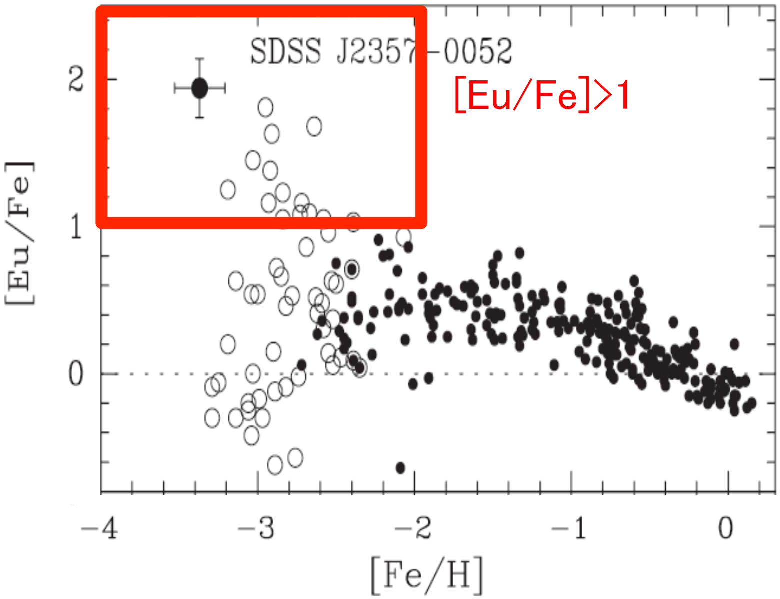
Ian U. Roederer et al., ApJ. 151 (2016), 82.

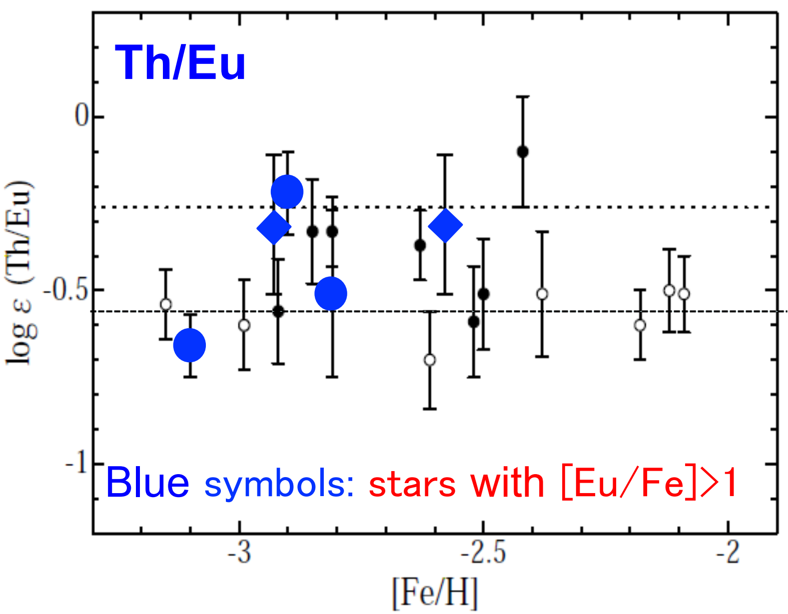
Neutron Star Merger r-process cannot produce A < 50 !



Theor. Cal.
NSM r-Process

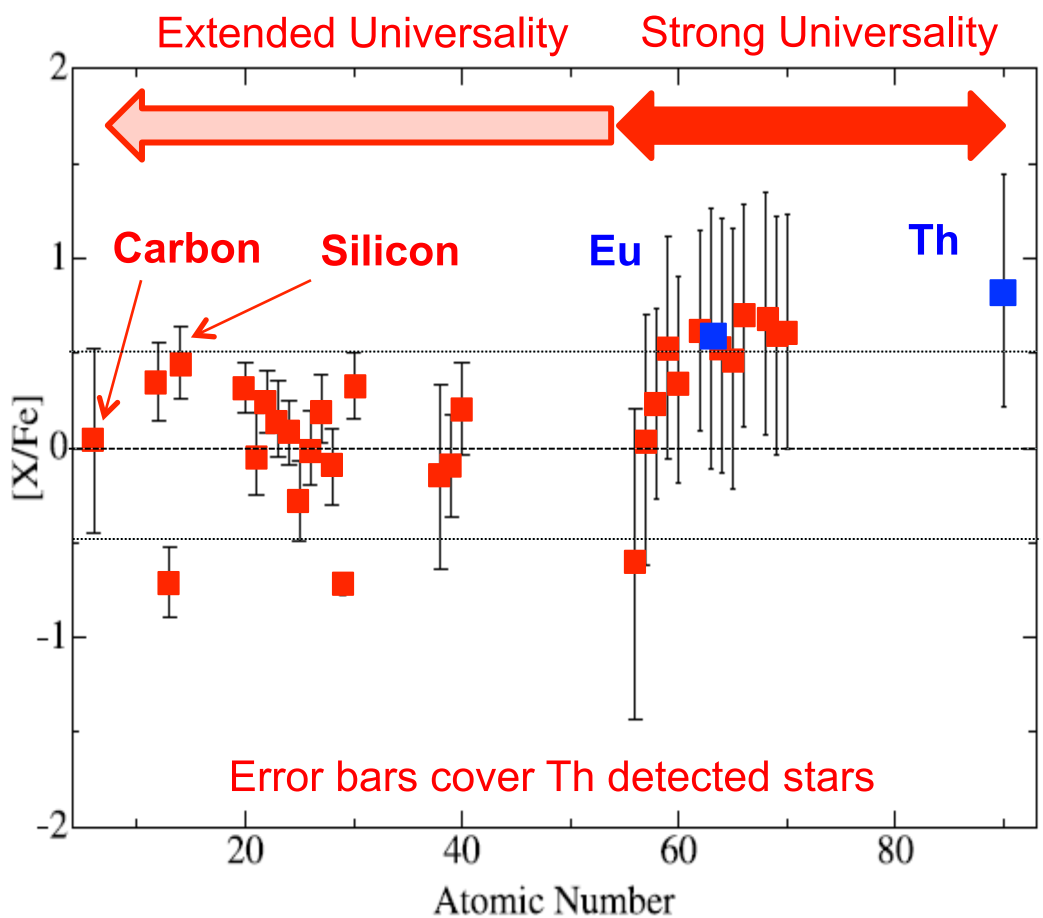
Milky Way Halo Stars





EXTENDED UNIVERSALITY

Honda, Aoki, Kajino, Beers, et al.,
(SUBARU-HDS Collaboration),
ApJ 607 (2004), 474; ApJS 152 (2004) 113.



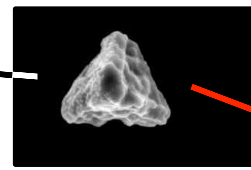
QUEST for Cosmo-Chemistry and Astronomy

:– to measure "EXTENDED UNIVERSALITY for A < 50"
even in the Solar System ([Fe/H]=0)

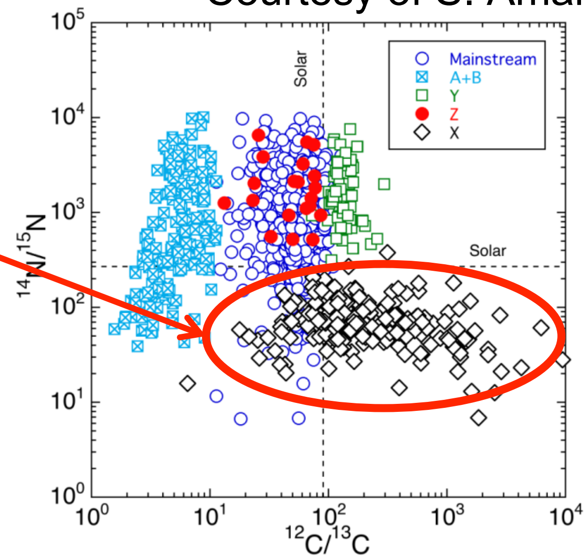
Supernova Grains e.g. Murchison Meteorite

–

SiC X-grains



Courtesy of S. Amari

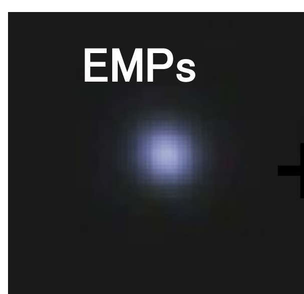


SiC X-grains are made of CC-SN Dust !

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)

Spectr. Astron. Obs.

Detection of C, Si & r-Elements simultaneously !



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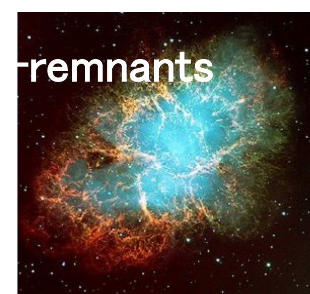


QUEST for NUCLEAR PHYSICS

Nuclear Reactions:

– Fission modes & Fission Fragment Distributions (FFD);
Spontaneous, β–delayed, n–capture induced

–(n, γ) cross sections

Nuclear Structure:

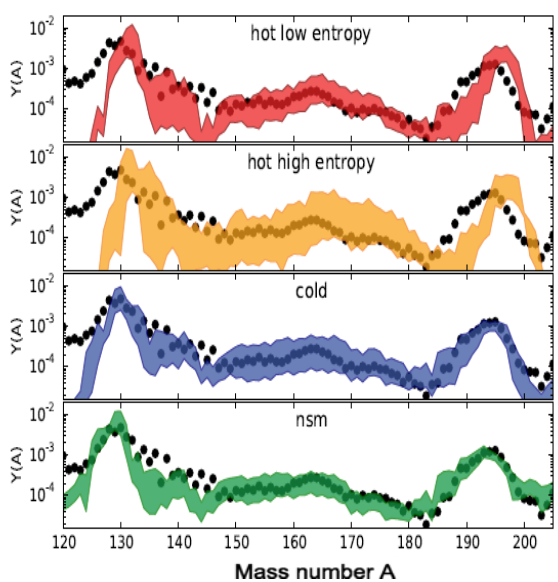
– Shell quenching(i.e. robustness of magic number)

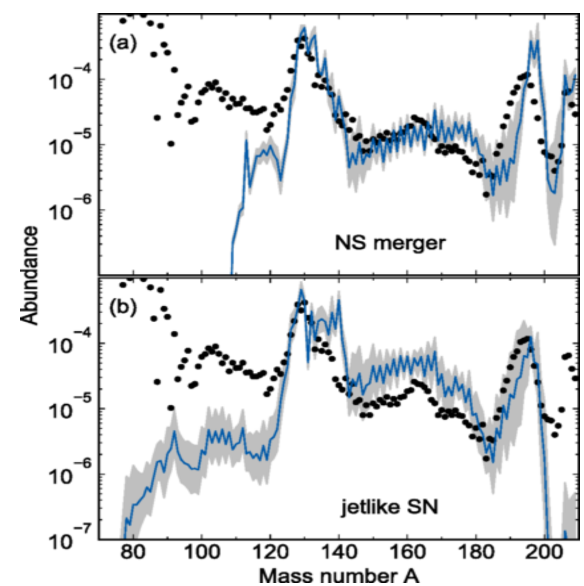
– Nuclear masses; Q_n for $\sigma(n, \gamma)$, Q_β for $\tau_{1/2} \propto (Q_\beta - E^*)^5$
β–delayed neutron emission; $E1 \propto (Q_\beta - E^*)^3$

Nuclear Uncertainty:

— Surman's talk

- Mumpower, M, et al.
  PPNP 86 (2016), 86
  PR C92 (2015), 035807
- Martin, et al.
  PRL 116 (2016), 121101
  \+





SUMMARY

Origin (Astrophys. Site) of R-Process Elements

- NUCLEOSYNRHESIS in SNe

R-process in ccSNe(MHD Jet & ν-driven) alone satisfies the universality for extremely metal-poor halo stars in the early Galaxy.

- TIME-SCALE PROBLEM in Binary NSMs

Although NSMs have arrived too late ($100My < \tau$) in MW halo and dwarf galaxies, they contribute to the S.S.($\tau \sim$ 10Gy) abundance which are the admixture of both SN & NSM r-process elements.

- DISPERSION PROBLEM in GCD-Evolution

Abundance scatter arises from the balance between;

1. Turbulent Mixing in star forming regions and SN Feedback,
2. Inhomogeneous star formation & ejecta from both SNe and NSMs.

OBSERVATIONAL QUEST

:– to measure ”ISOTOPIC” as well as “ELEMENTAL” !

◎“STRONG UNIVERSALITY”(above 2nd peak) is in **ELEMENTAL** abundances ratios(as a function of atomic number Z).

:– Binary NSMs have arrived too late for TIME SCALE PROBLEM, 100My < t_{NSM},
⇒ ISOTOPIC(A) ratios, different from ELEMENTAL(Z) ratios.

◎Time &[Fe/H] evolution of **ISOTOPIC** abundance ratios (as a function of mass number A) could clearly indicate SN dominance in the early Galaxy.

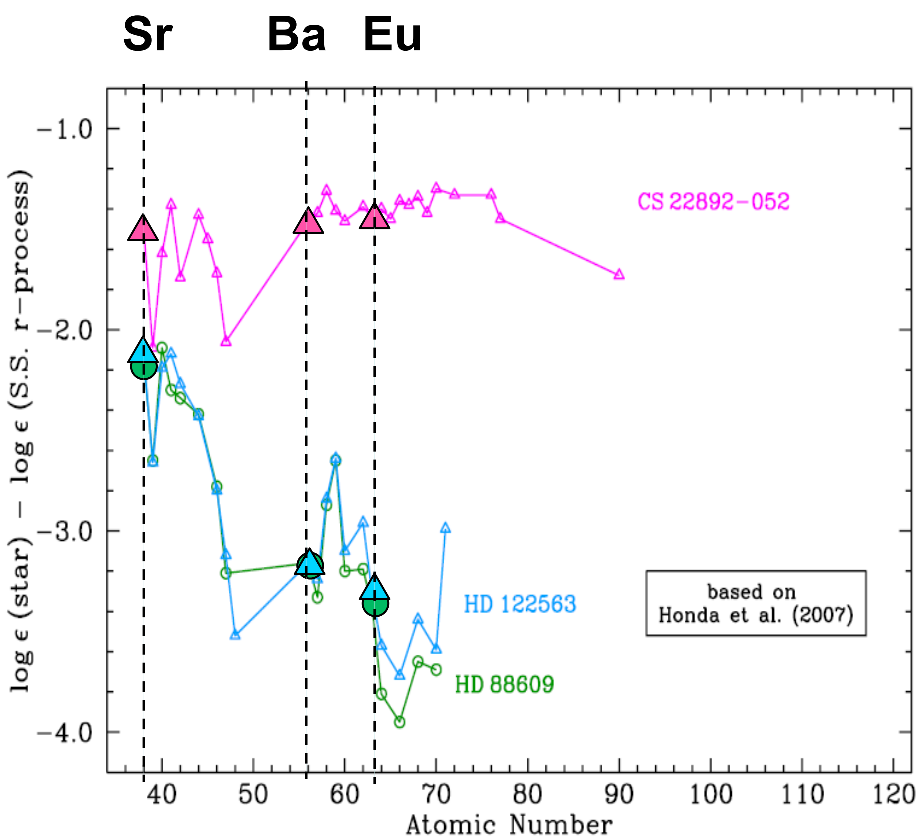
:– to measure ”EXTENDED UNIVERSALITY” !

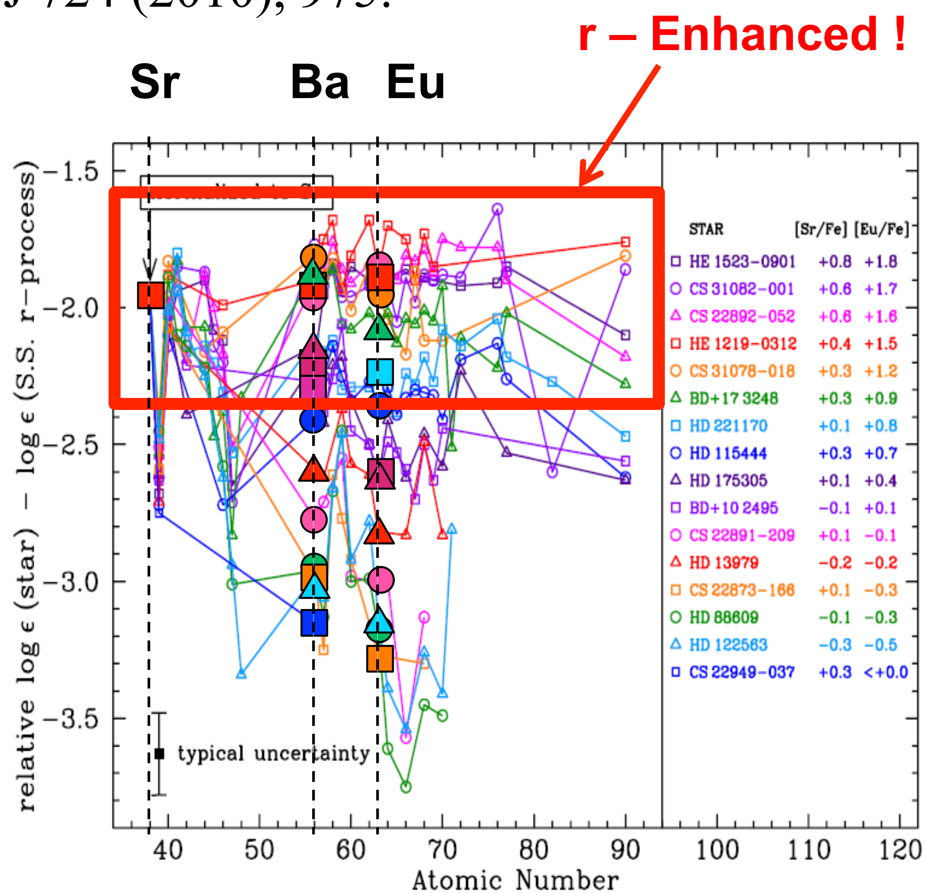
◎”EXTENDED UNIVERSALITY” between C–Si–Fe & r–elements !

:– MHD–Jet SNe can, but NSMs cannot produce light elements 80 < A.

DIVERSITY of r-abundance pattern in MW-EMP stars

I. Roederer, et al., ApJ 724 (2010), 975.





Outflow winds & jets from NSM are well controlled by GENERAL RELATIVITY.

➡ NO DIVERSITY

My Score Sheet (cont')

5. Diversity of r-Elements

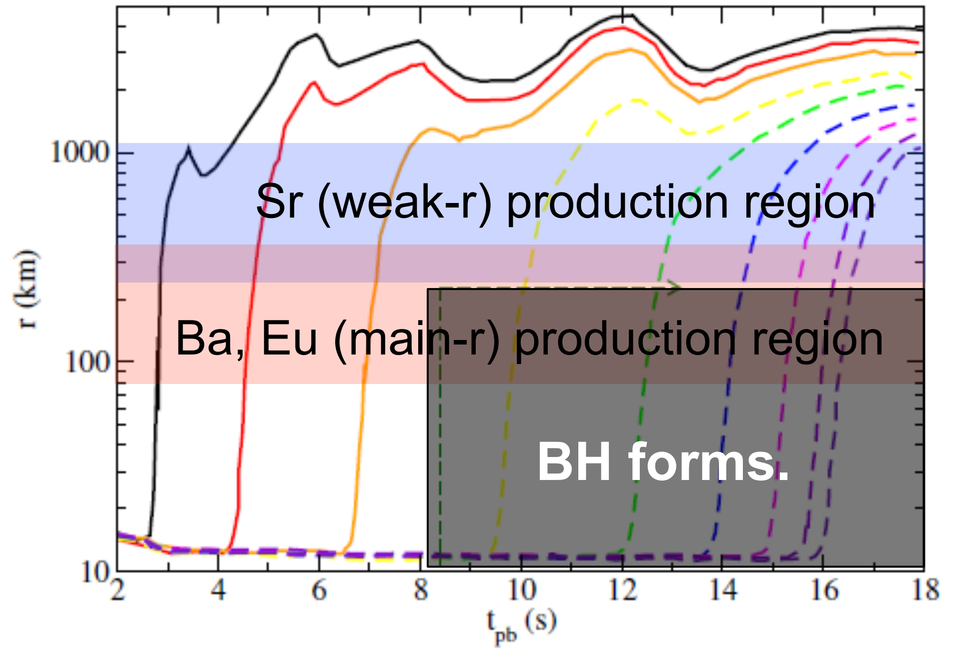
SN ! NSM ?

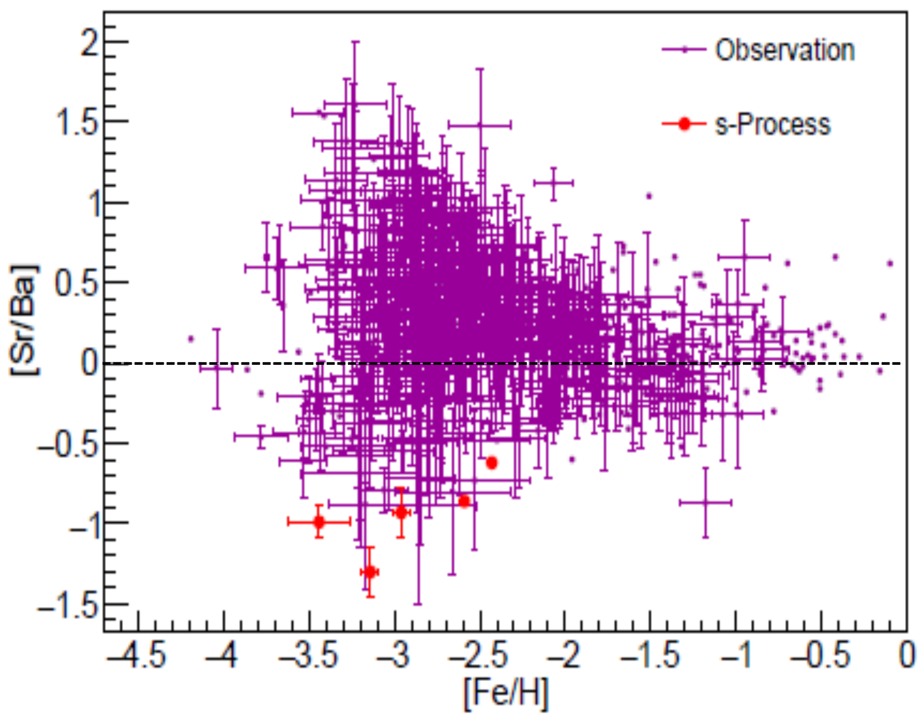
[Sr/Ba,Eu] in Failed SNe

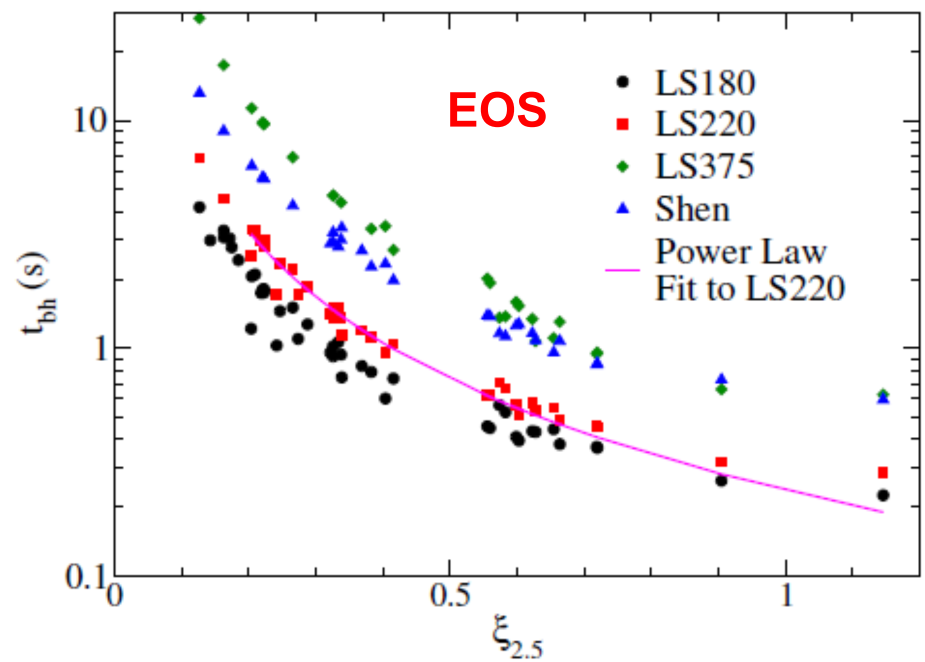
Dispersion due to Turbulent Mixing
in individual SN Ejecta

Dependence of the r-element dispersion
on **EOS** in Metal-Poor Halo Stars

Famiano, Kajino, Aoki and Suda,
ApJ (2016), submitted.

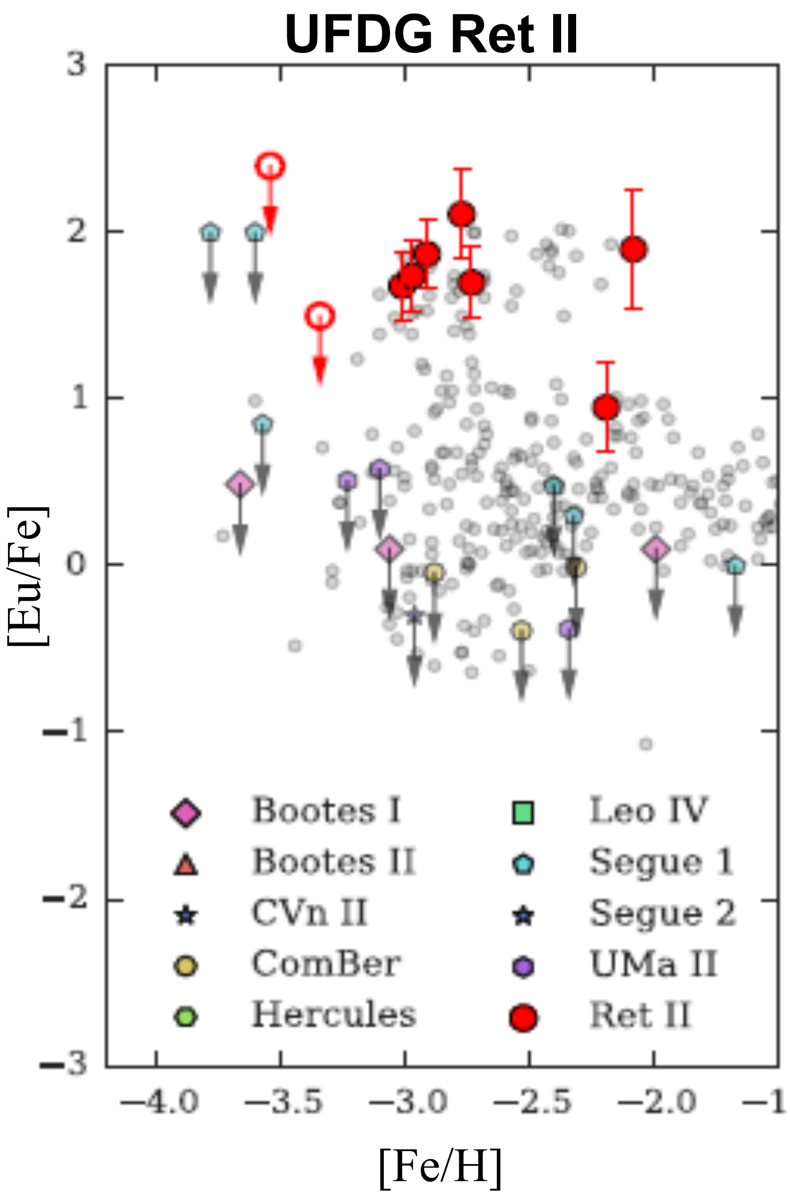






"Strong" & "Extended" Universality in Ultra-Faint Dwarf Ret. II

Ian U. Roederer et al., ApJ. 151 (2016), 82.
Alexander P. Ji, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610



My Score Sheet

R-process Site
SN (MHD-Jet) vs. Binary NSM?

1. Event Rate

UFDG Ret. II mass

IMF

$(2.6 +/- 0.2) x 10^3 M_\odot$

NSM/SN (0.1%)

MHDJ/SN (1-3%)

→ **~10 SNe**

→ **~(0.01-0.28)x10 NSM / MHDJ !**

SN !? NSM ?

2. Ejecta stops ? (in shallow grav. pot.)

SN ! NSM ?

3. UFDG, very old (Mean 13 +/-1 Gy)

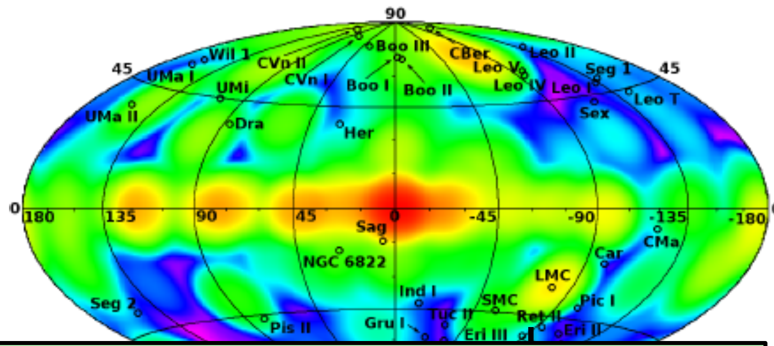
SN ! NSM !

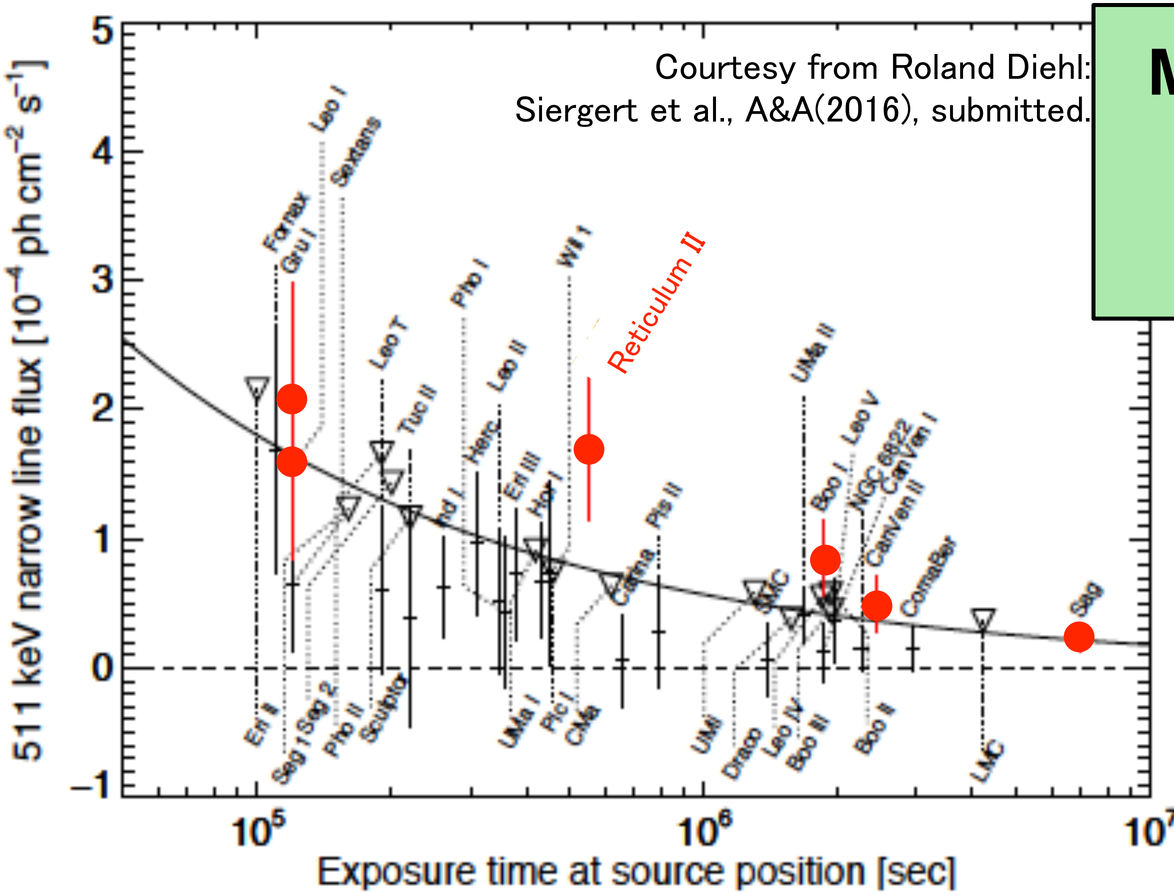
Search for 511 keV emission in nearby dSph galaxies (INTEGRAL)

– Dark Matter or Stellar e^+ ?

– No significant detection except for Reticulum II ⇒ Stellar e^+

Exposure map

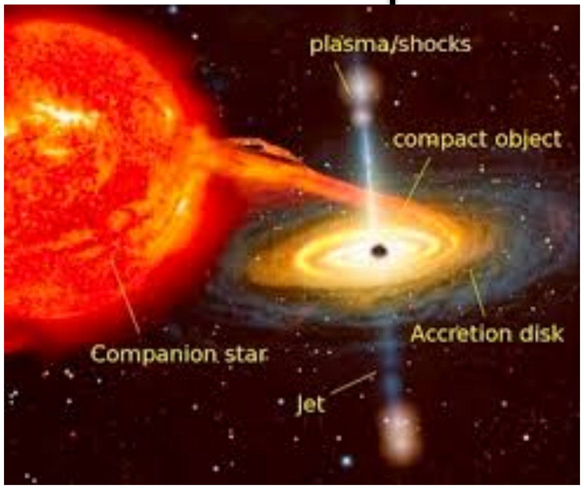




My Score Sheet (cont')

6. Stellar e+ 511 keV ?

SN ! NSM !



Microquasar ?

Fluid-Dynamical Model for Neutron Star Merger

Binary Neutron Star Merger

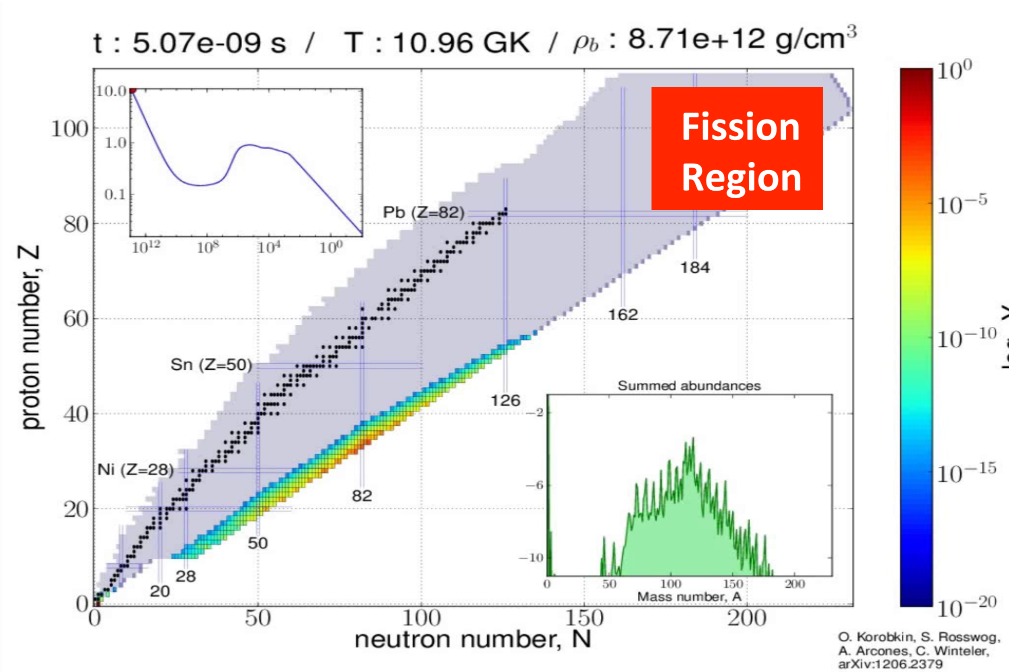
Korobkin et al., MNRAS 426 (2012), 1940; Rosswog et al., MNRAS 430 (2013), 2585.

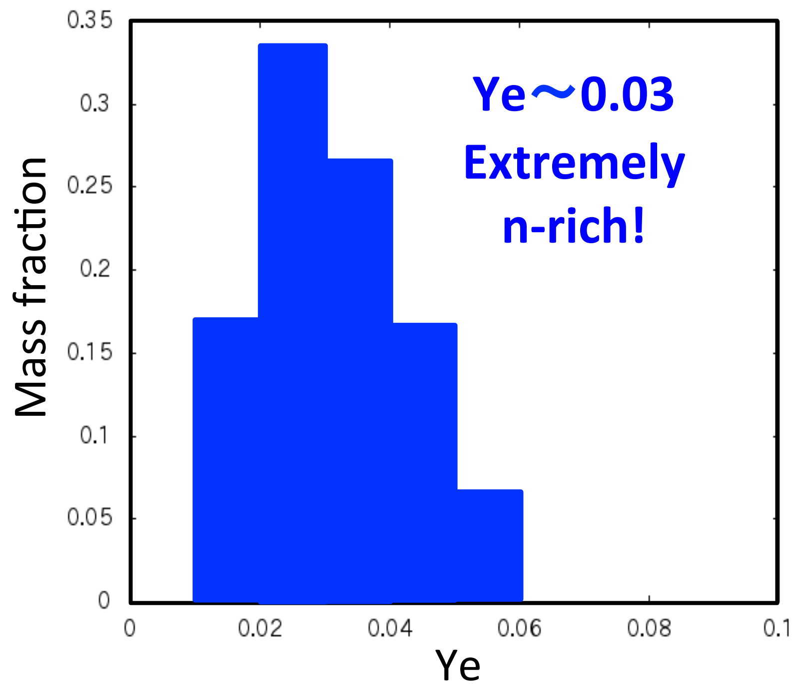
SPH Simulation: (Adiabatic Expansion)

Newtonian gravity, Neutrino Leakage scheme

Entropy, Ye, T, ρ Evolution: (Fission is a strong heat-source: $S \sim \dot{q}/T$)

We solved thermodynamic evolution of each trajectory from the initial conditions.





Nuclear Models
— sensitive to Fission —

Nuclear Mass Model :

Fission Barrier, Q_β

KTUY Model

Koura, Tachibana, Uno, Yamada,
PTP 113, 305 (2005).

One of the Best Models!

⇩

Reaction Rates:

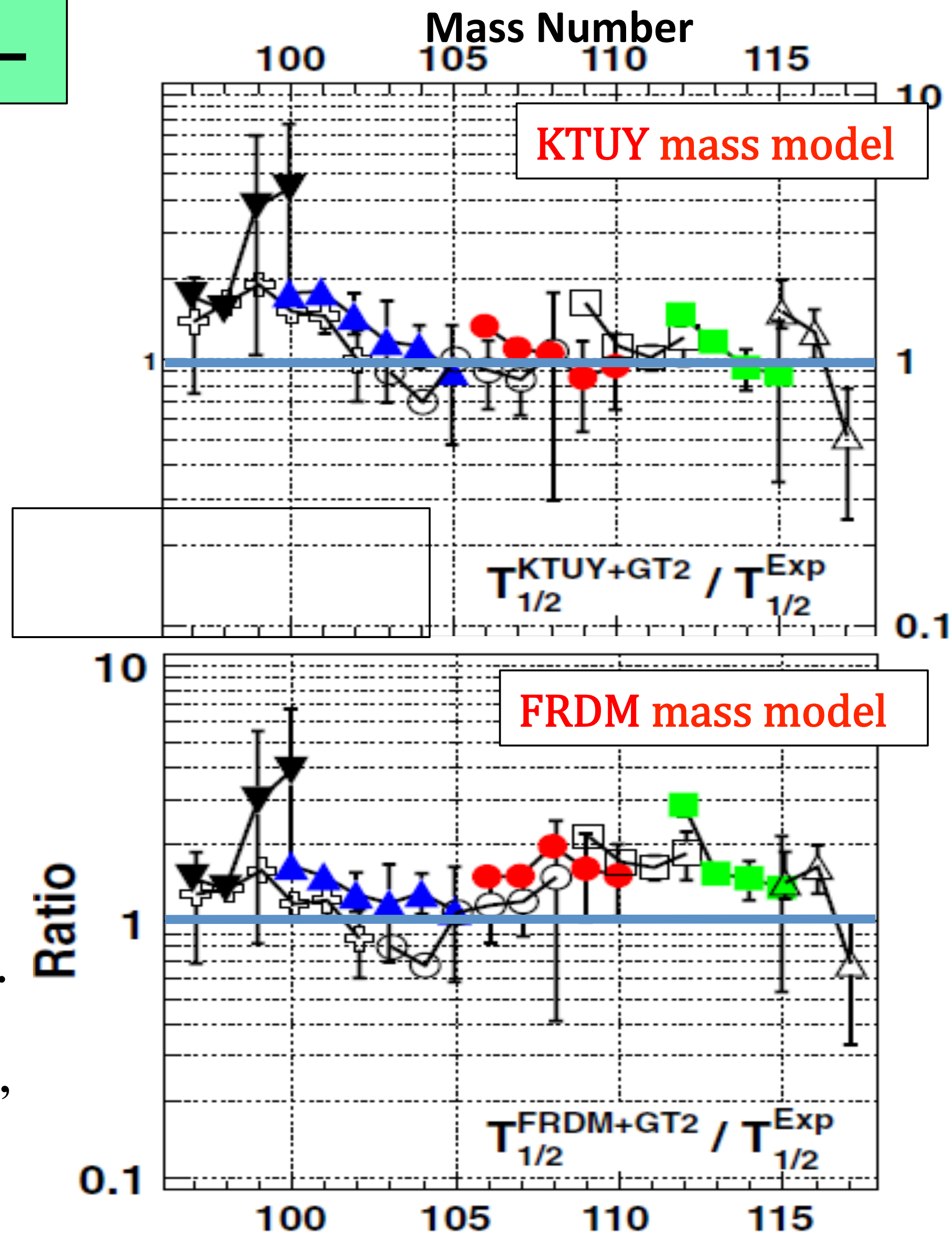
α-decay, β-decay, fission

H. Koura, AIP Conf. Proc. 704, 60, (2004).

M. Ohta et al., Proc. Int. Conf. on Nucl. Data for Science and Technology, Nice, France, (2007).

RIKEN β-Decay Experiment:

S. Nishimura et al., PRL 106, 052502 (2011).

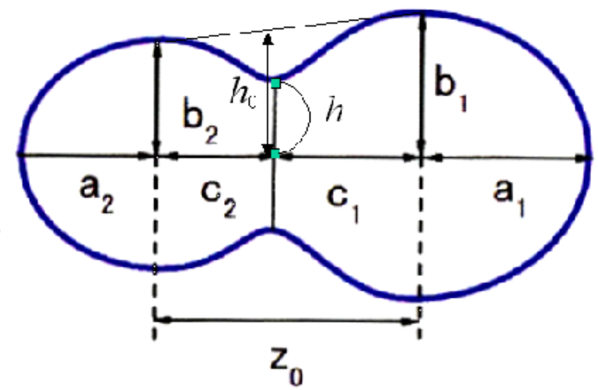


Fission Fragment Mass Distribution

M. Ohta et al., Proc. Int. Conf. on NDST, Nice, France, (2007)
S. Chiba et al., AIP Conf. Proc. 1016, 162 (2008).

Liquid Drop Model + Two center shell Model

Parameter { distance z, mass asymmetry α, deformation δ }



⇨ Potential Energy Surface

Fission Fragment Distribution

$$f(A) = \frac{1}{\sqrt{2\pi\sigma}}(1-\omega_s)(e^{-(A_H-A)^2/2\sigma^2} + e^{-(A_L-A)^2/2\sigma^2}) + \frac{2\omega_s}{\sqrt{2\pi\sigma}} e^{-((A_H+A_L)/2-A)^2/2\sigma^2}$$

Analysis of Potential Energy near the Scission Point

- Location of the depth of the asymmetric valley at δ=0.2, 0.3
  → mass asymmetry of fission fragment distribution(A_H,A_L)
- Depth of the asymmetric valley & Depth at α=0 and δ~0
  → ratio of the symmetric component and asymmetric component(ω_s)
- σ=7.0

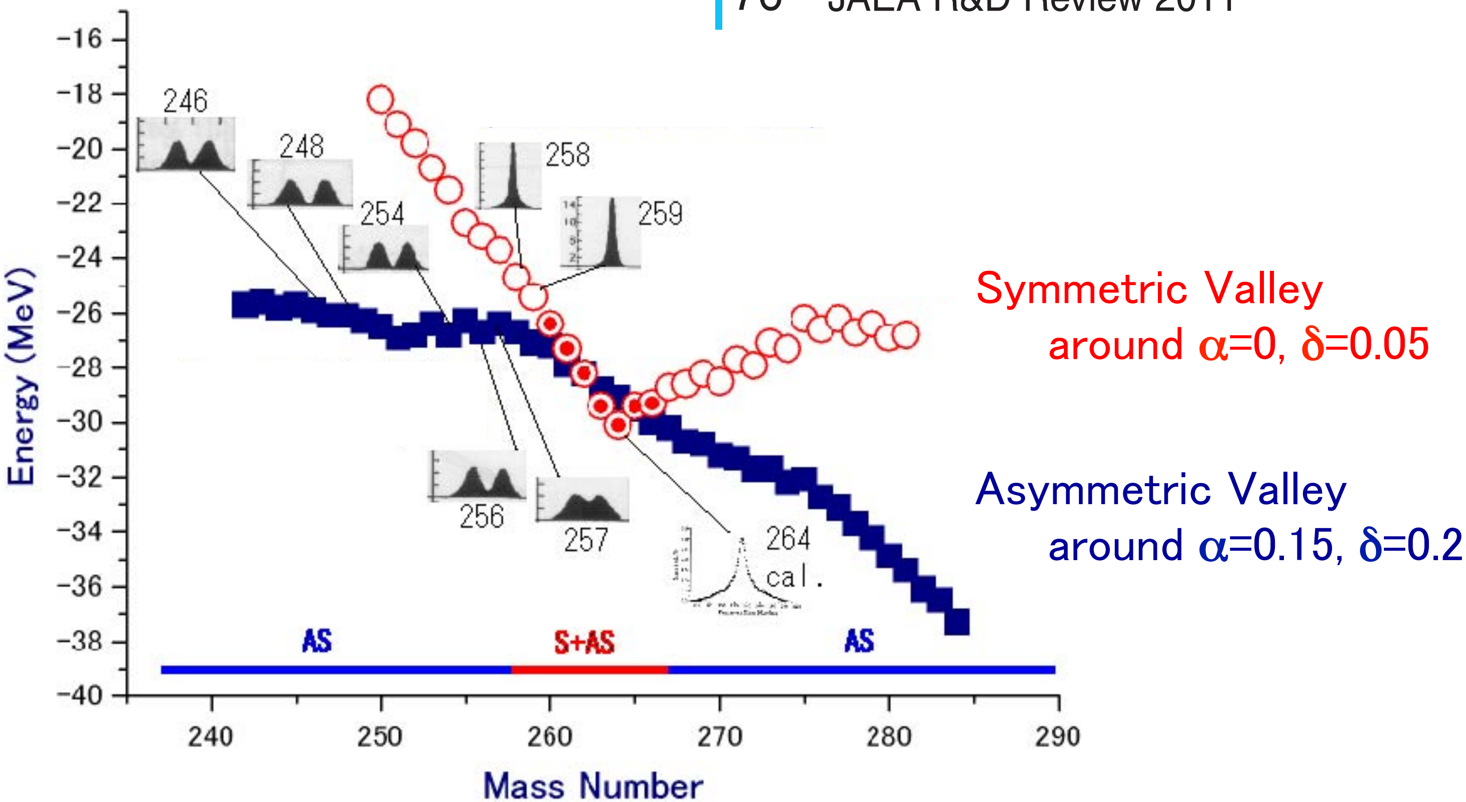
the first time, conducted an experiment to study the properties in such a light-nucleus region. According

Fission Path of Mercury

Reference

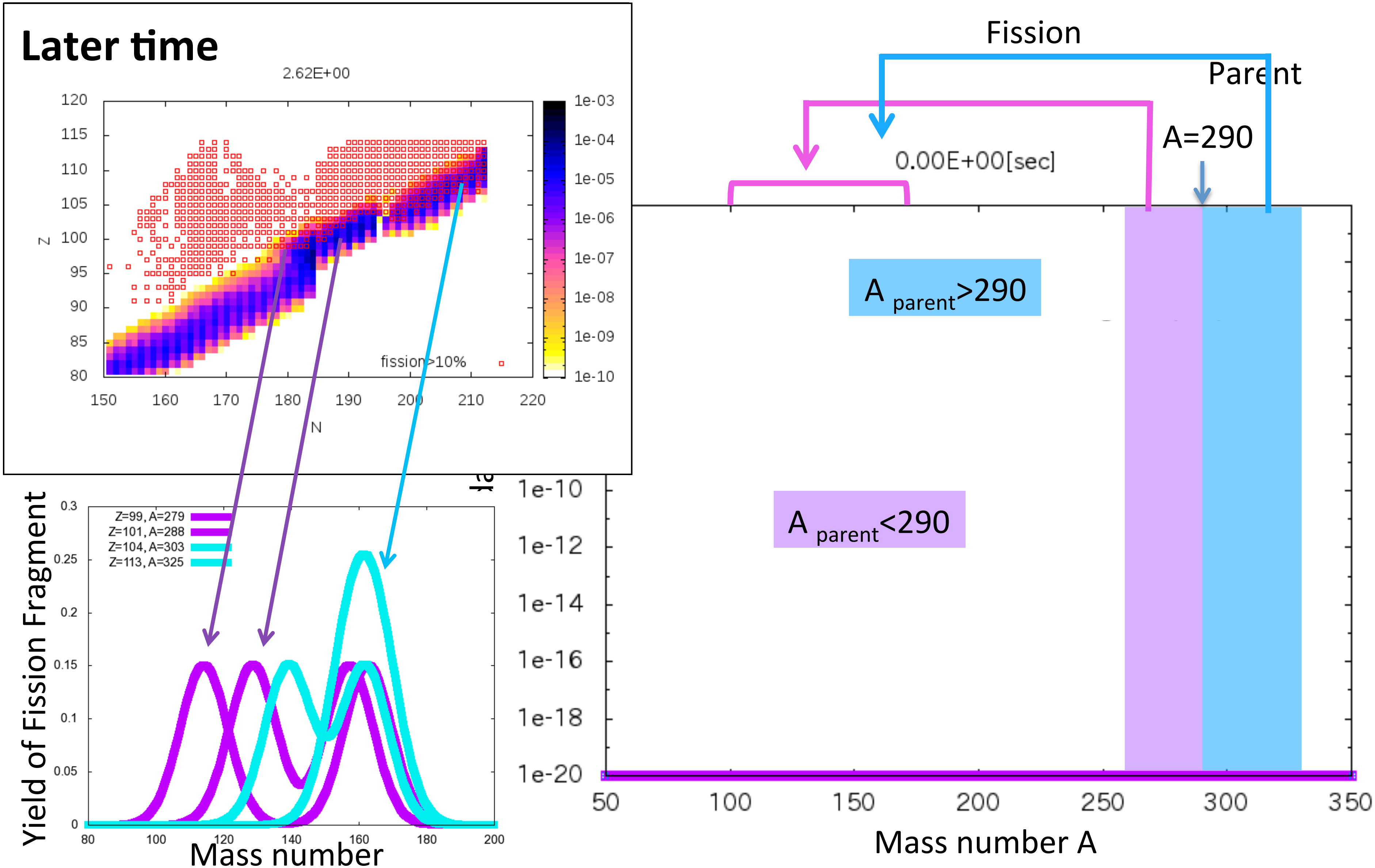
Andreyev, A.N., Nishio, K. et al., New Type of Asymmet
p.252502-1-252502-5.

Potential Depth of Fission Valley
(near Scission Point) of Fm isotopes



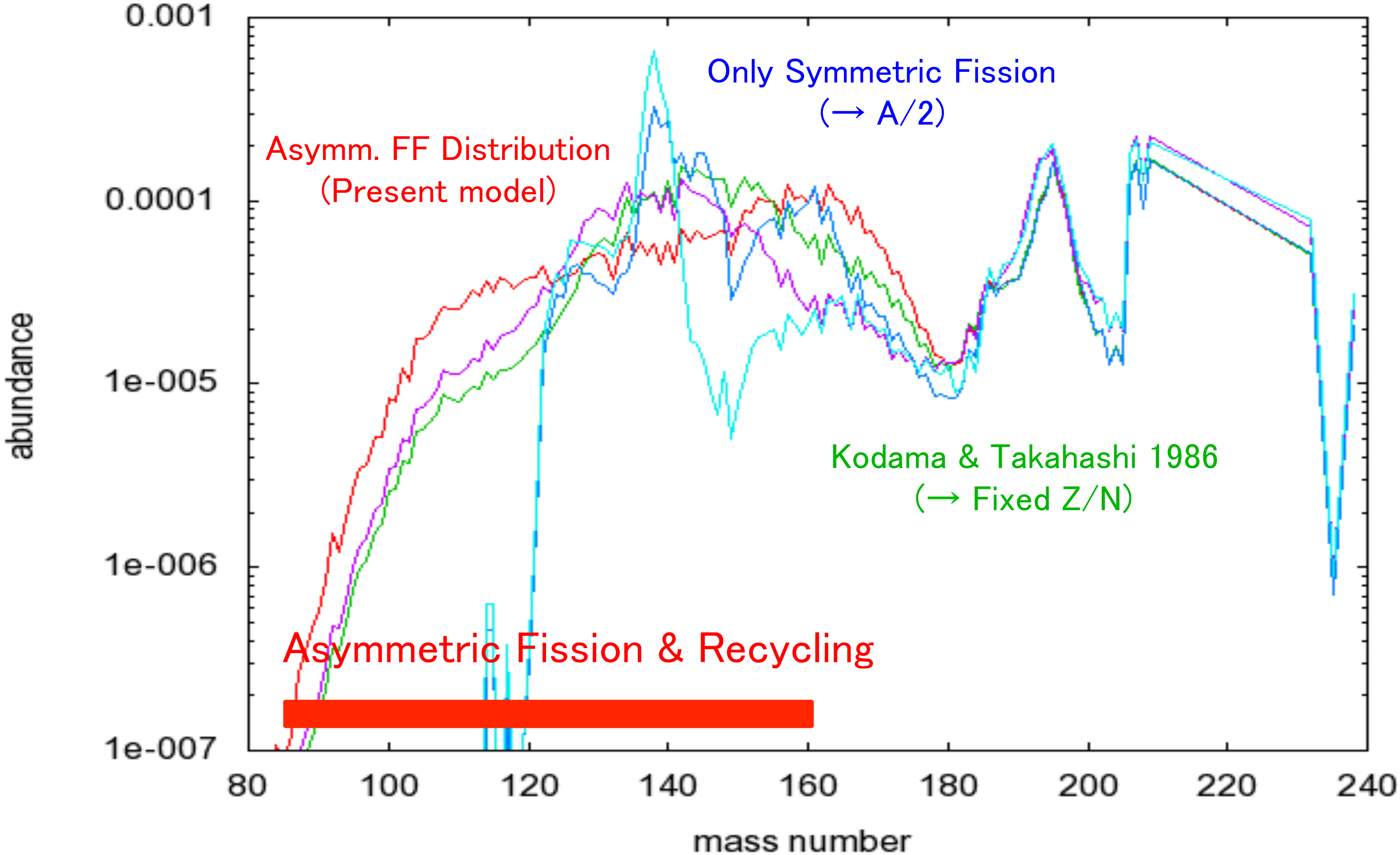
Abundance Evolution of Fission Recycling

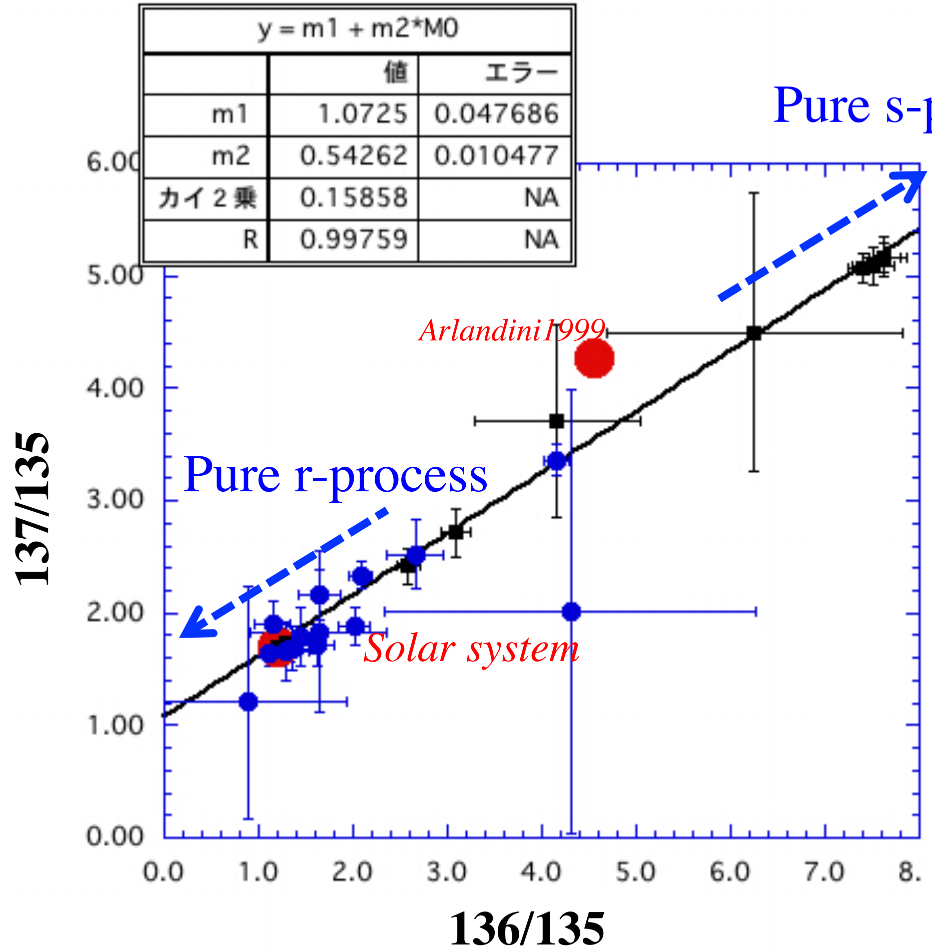
Binary Neutron Star Merger Model : SPH simulation – Newtonian gravity, Neutrino Leakage scheme
Korobkin et al., MNRAS 426 (2012), 1940.

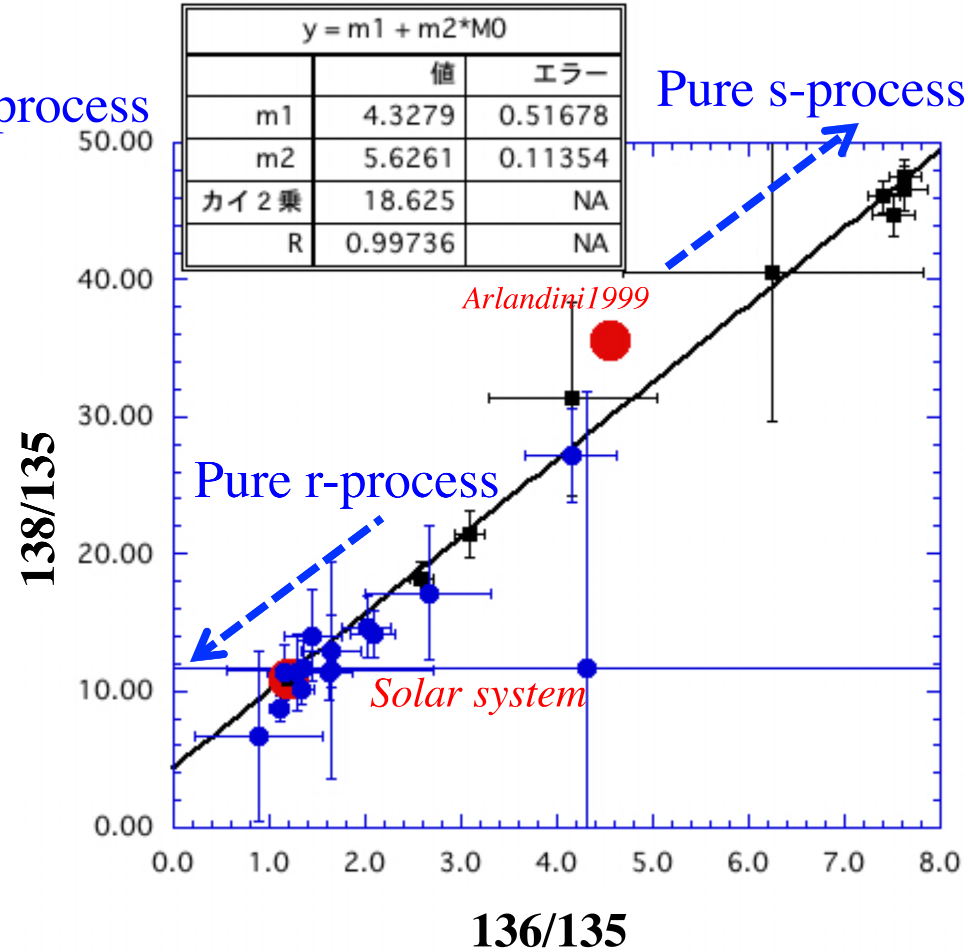


Symmetric fission makes sharp 2nd & 3rd peaks.

Asymmetric fission & recycling wash out the 2nd peak, still keeping the REE hill and the 3rd peak.







^{136}Ba=s-only: In the limit of ^{136}Ba→0, pure r-component is extracted.

Isotopic ratios	Wanajo et al. et al. (2014)	Shibagaki et al. (2014)		Giuseppe et al. (2015)
	NSM	**NSM**	**MHD-jet**	**ν-DW**
137/135=1.07 ± 0.05	**0.218**	**1.0**	**0.2**	**2.23**
138/135=4.33 ± 0.52	**0.294**	**1.1**	**0.18**	**3.46**

Galactic Chemo-Dynamical (N-Body/SPH) Simulation

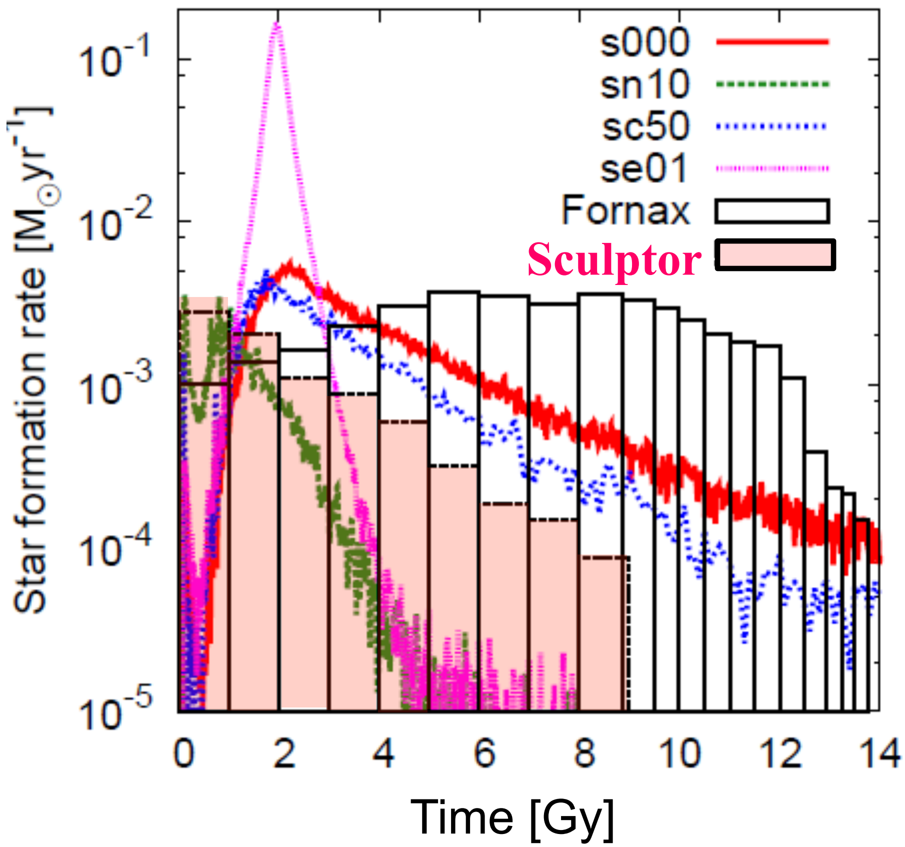
No need of introducing artificial parameters!

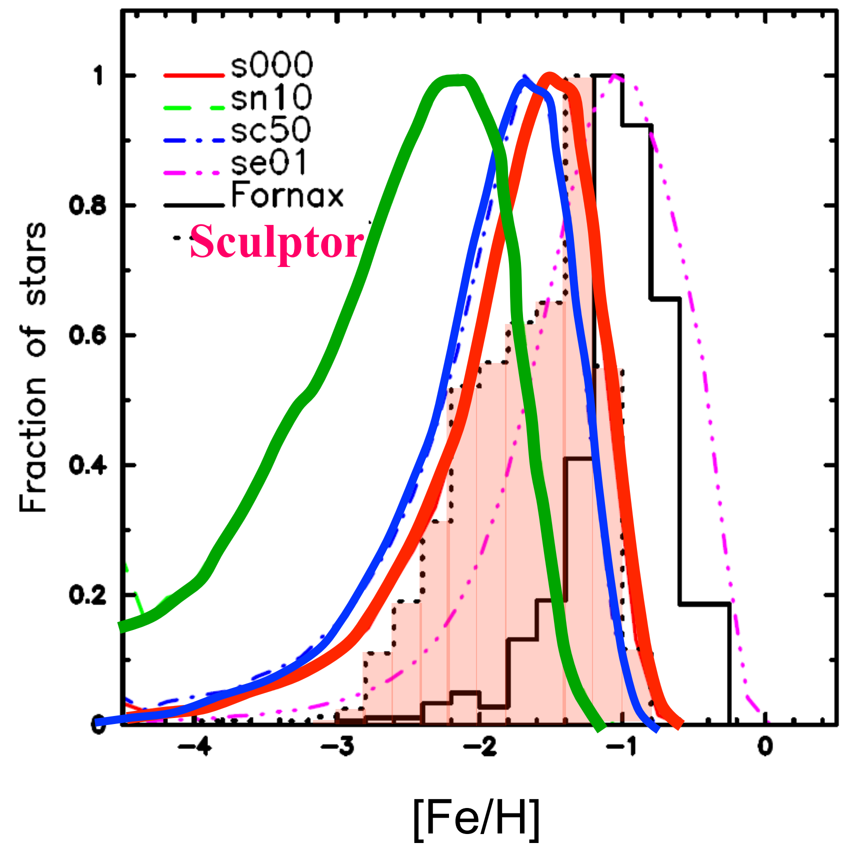
Hirai, Ishimaru, Saitoh, Fujii, Hidaka & Kajino, ApJ 814 (2016), 41.

* Early Accretion ⇒ Inner Halo
* Slow & Late Accretion ⇒ Dwarf Spheroidals & Outer Halo

Time-scale for SF = 1Gy(1000My) >> τ_C(NSM) = 100 ⇒ Binary NSMs can contribute !

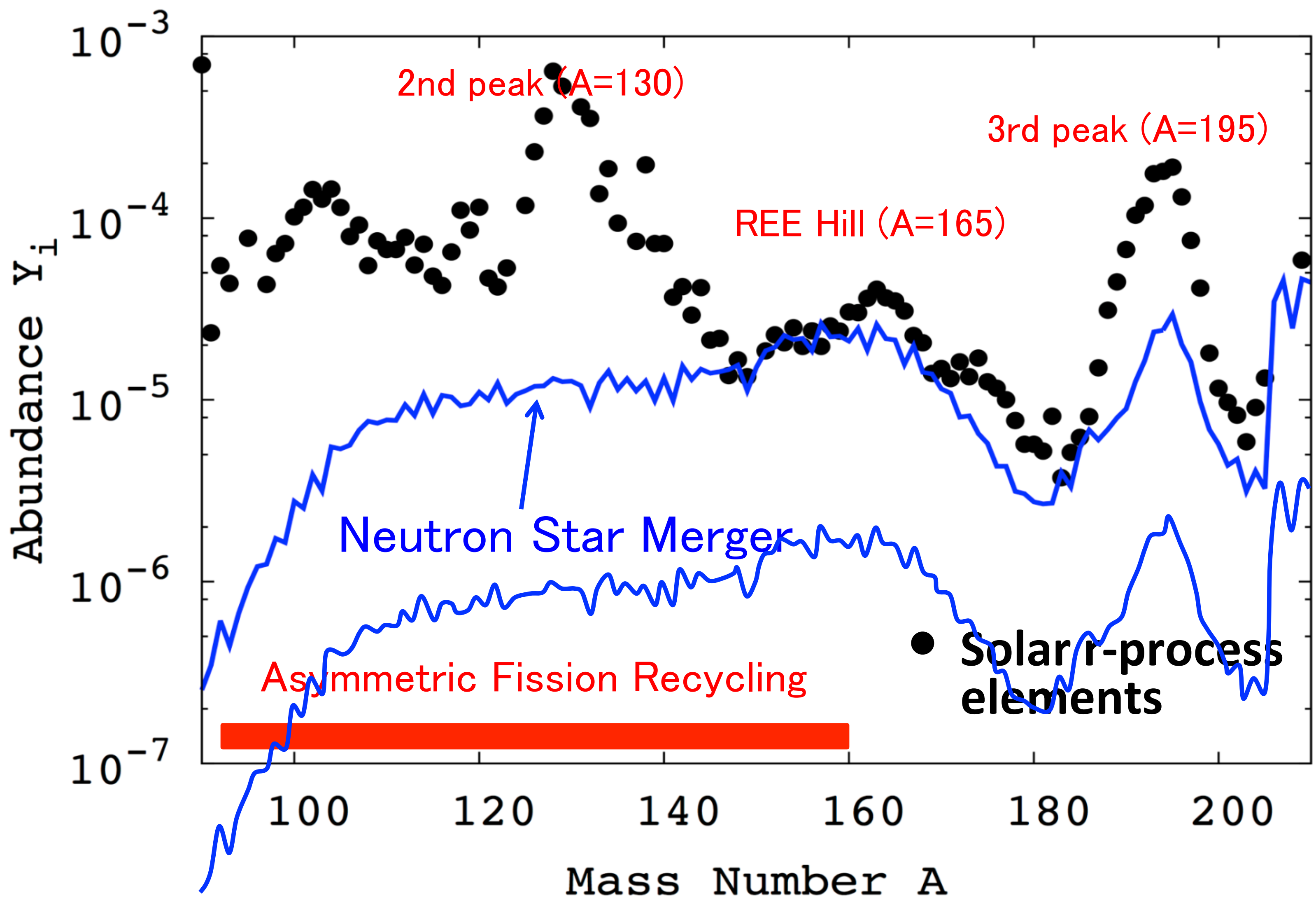
Star Formation History





Contribution from Neutron Star Merger

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.



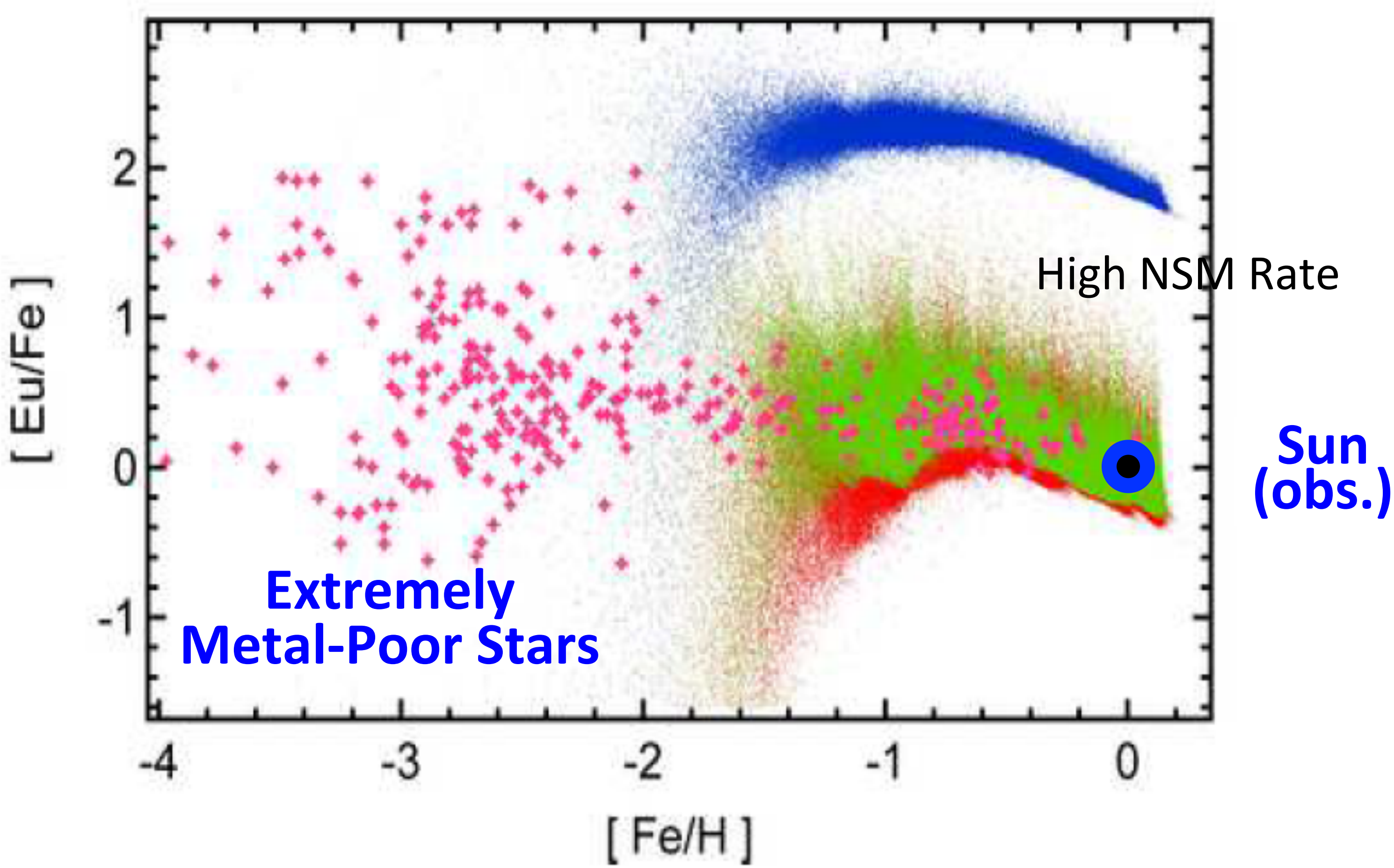
Inhomogeneous GCE does not solve "Time Scale Problem".

(GCE = Galactic Chemical Evolution)

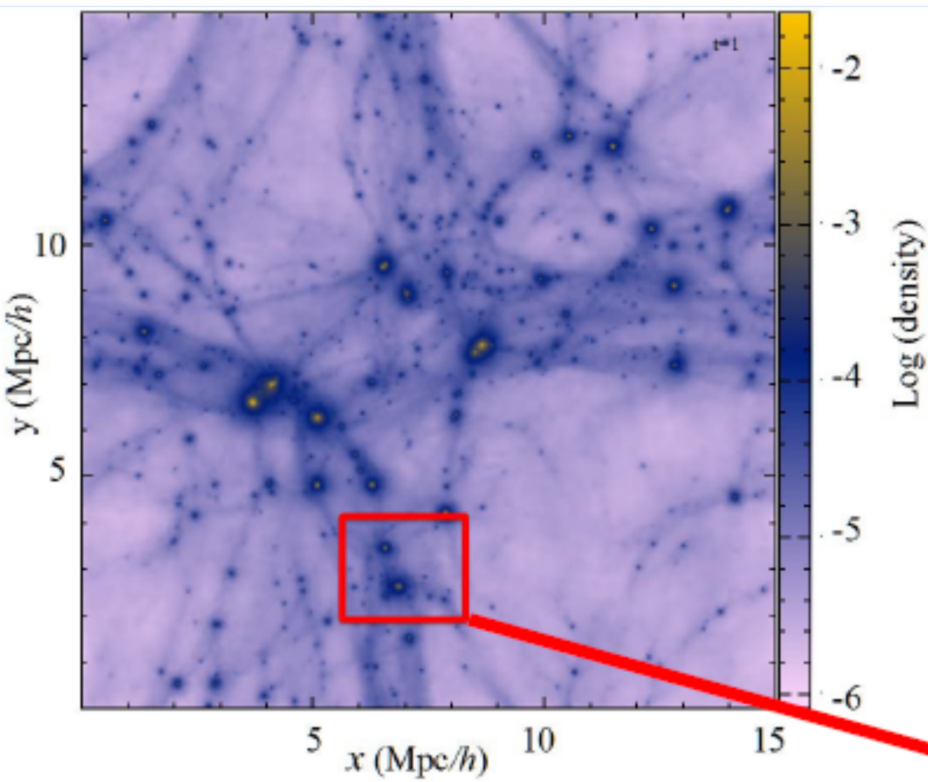
We should study DYNAMICAL Evolution + GCE.

(Galaxy Structure Formation)

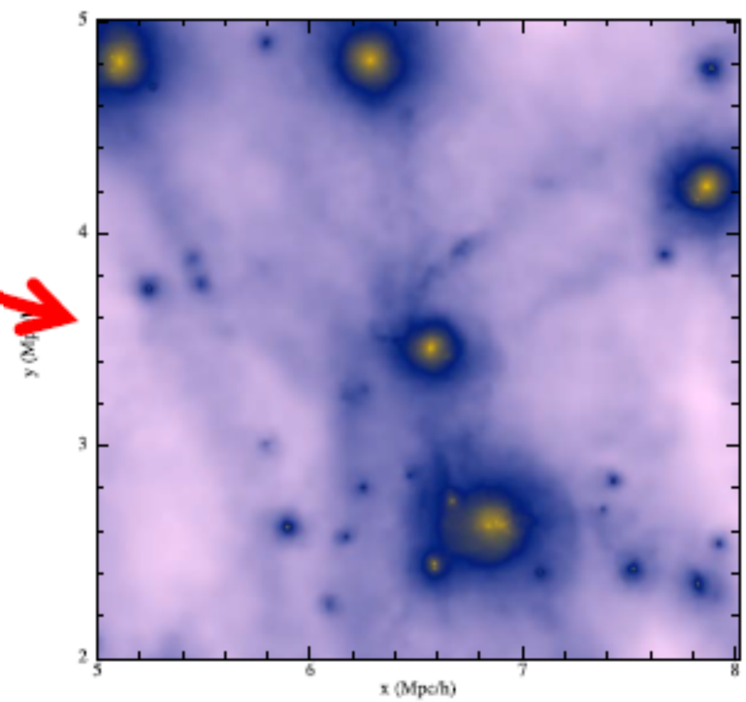
Wehmeyer, Pignatari, and Thielemann, MNRAS 452 (2015), 1970.



Hierarchical Galaxy Formation Scenario



Arrival of r-process material
in Milky Way halo requires
Chemo-Dynamical Evolution



X. Zhao & G. Mathews (2014)