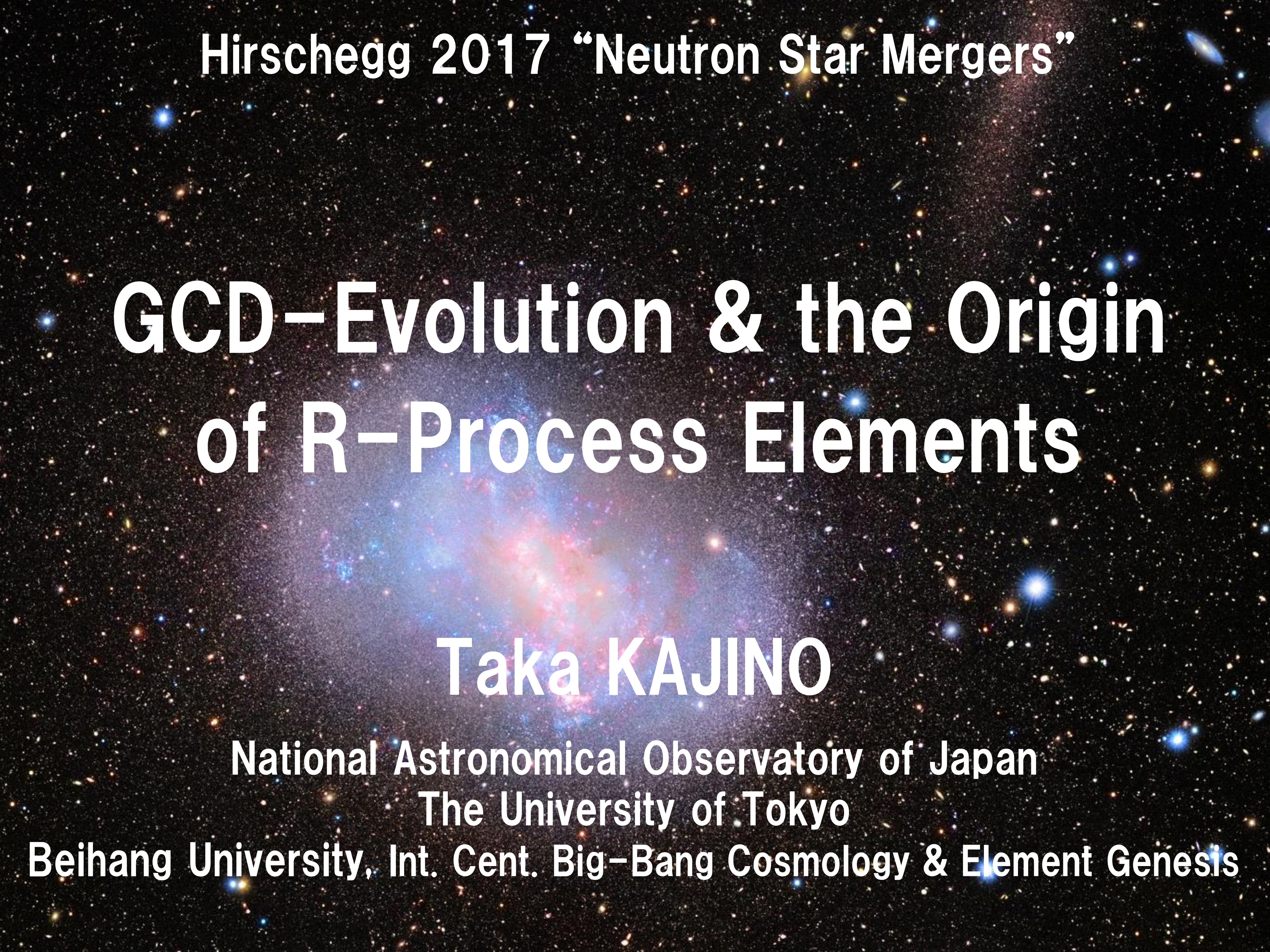
Hirschegg 2017 “Neutron Star Mergers”

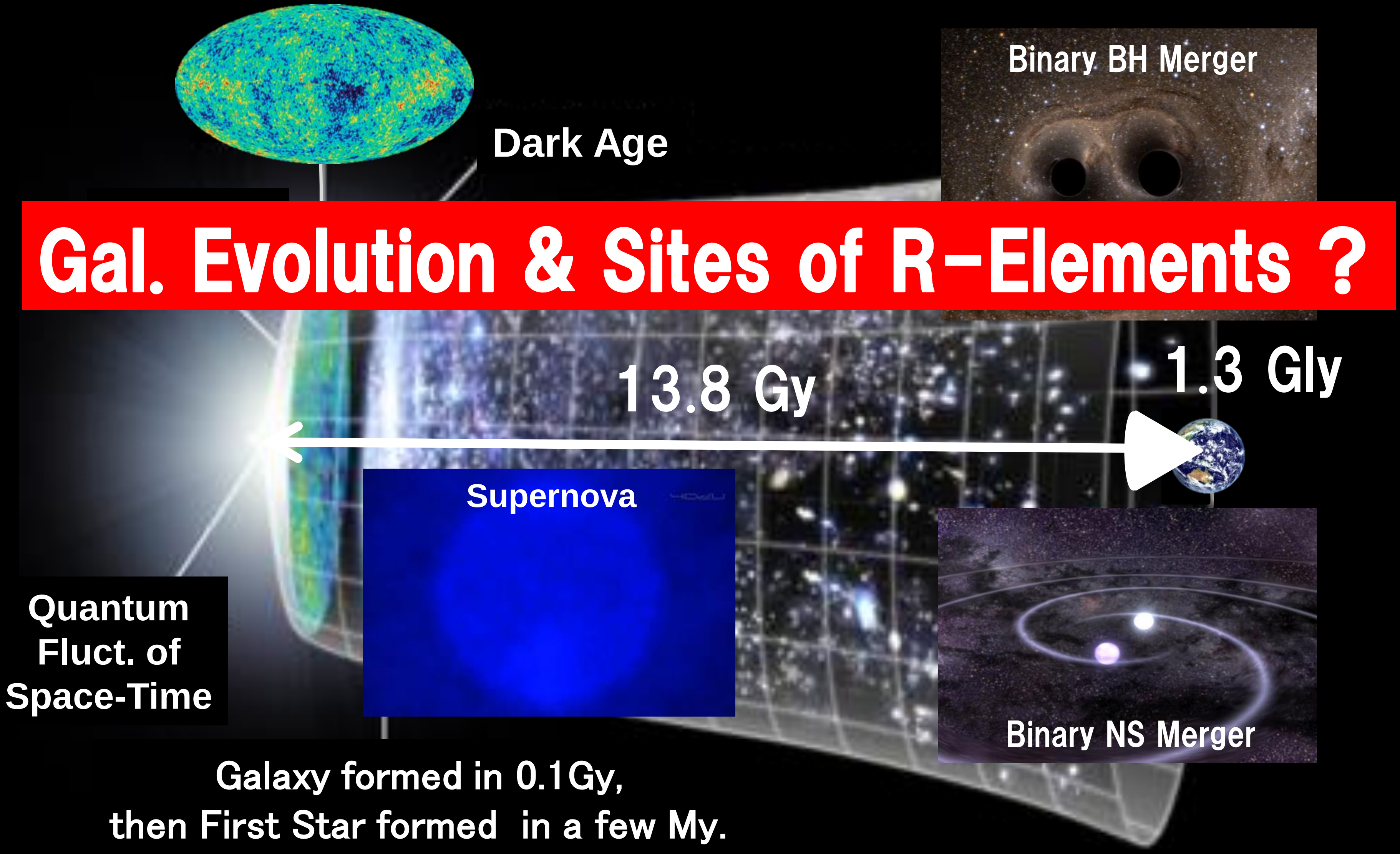


GCD-Evolution & the Origin of R-Process Elements

Taka KAJINO

National Astronomical Observatory of Japan
The University of Tokyo
Beihang University, Int. Cent. Big-Bang Cosmology & Element Genesis

Cosmic Evolution



Last Photon Scatt.
$3.8\text{x}10^5$ y

Dark Age

Binary BH Merger

Gal. Evolution & Sites of R-Elements ?

13.8 Gy

1.3 Gly

Supernova

Quantum
Fluct. of
Space-Time

Binary NS Merger

Galaxy formed in 0.1Gy,
then First Star formed in a few My.

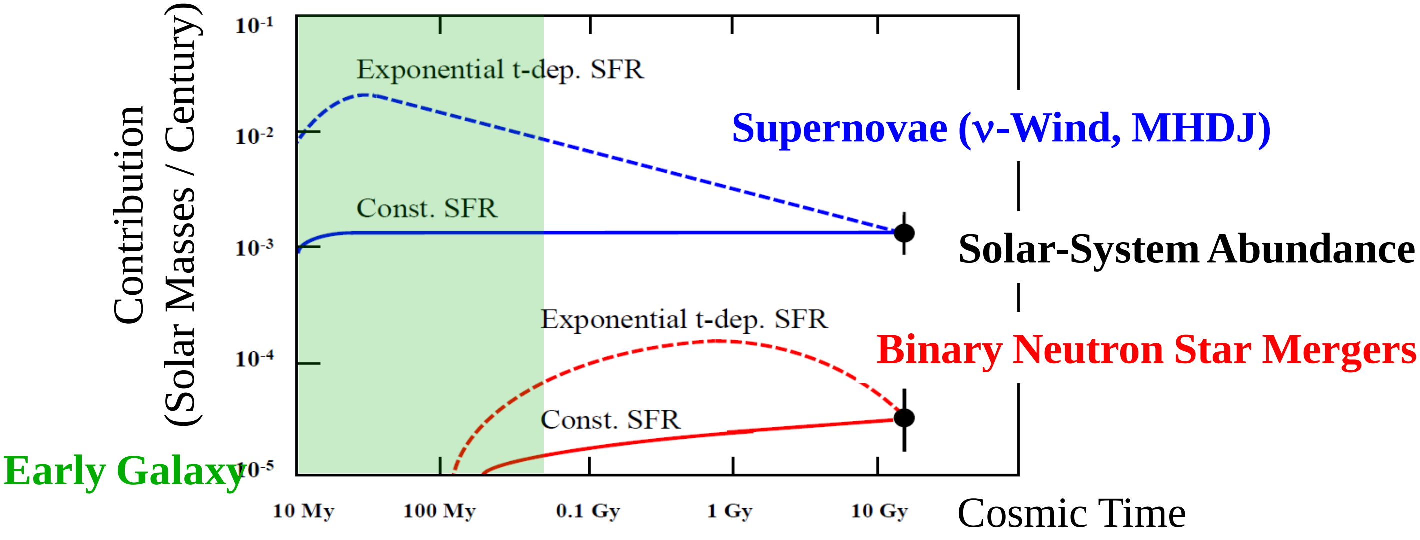
Galactic Chemo-Dynamical Evolution

Purpose

How to identify Astro. Sites for R-Elements, SNe or NSMs.

[1] Time-Scale Problem of NSMs in Galactic Chemical Evolution

⇒ Galactic Chemo-Dynamical Evolution

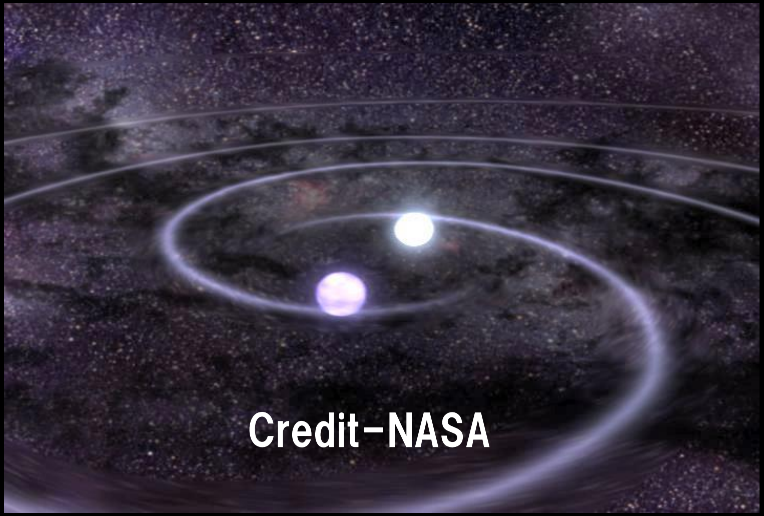


[2] R-Process Abundances of EMP☆ and S.S. ⇒ **UNIVERSALITY**

- Nuclear Physics
- Astron. Obs. of EMP☆ + Cosmochem. Analys. of Pre-Solar Grains

[3] ν-Matter Interactions in Explosion Dynamics and Flavor Oscillation

Binary Neutron-Star Mergers



Lattimer & Schramm, ApJ 192, L145 (1974),
Goriely, et al., ApJ 738, L32 (2011),
Korobkin, et al., MNRAS 426, 1940 (2012),
Bauswein, Goriely, & Janka, ApJ 773, 78 (2013),
Rosswog, et al., MNRAS 430, 2585 (2013),
Bauswein, et al., ApJ 773, 78 (2013),
Goriely, et al., PRL 111, 242502 (2013, 2015),
Piran, et al., MNRAS 430, 2121 (2013),
Wanajo, et al., ApJ 789, L39 (2014), ++

Time Scale Problem ?

$$100\mathrm{My} \lesssim \tau_c \lesssim 10\mathrm{Ty}$$

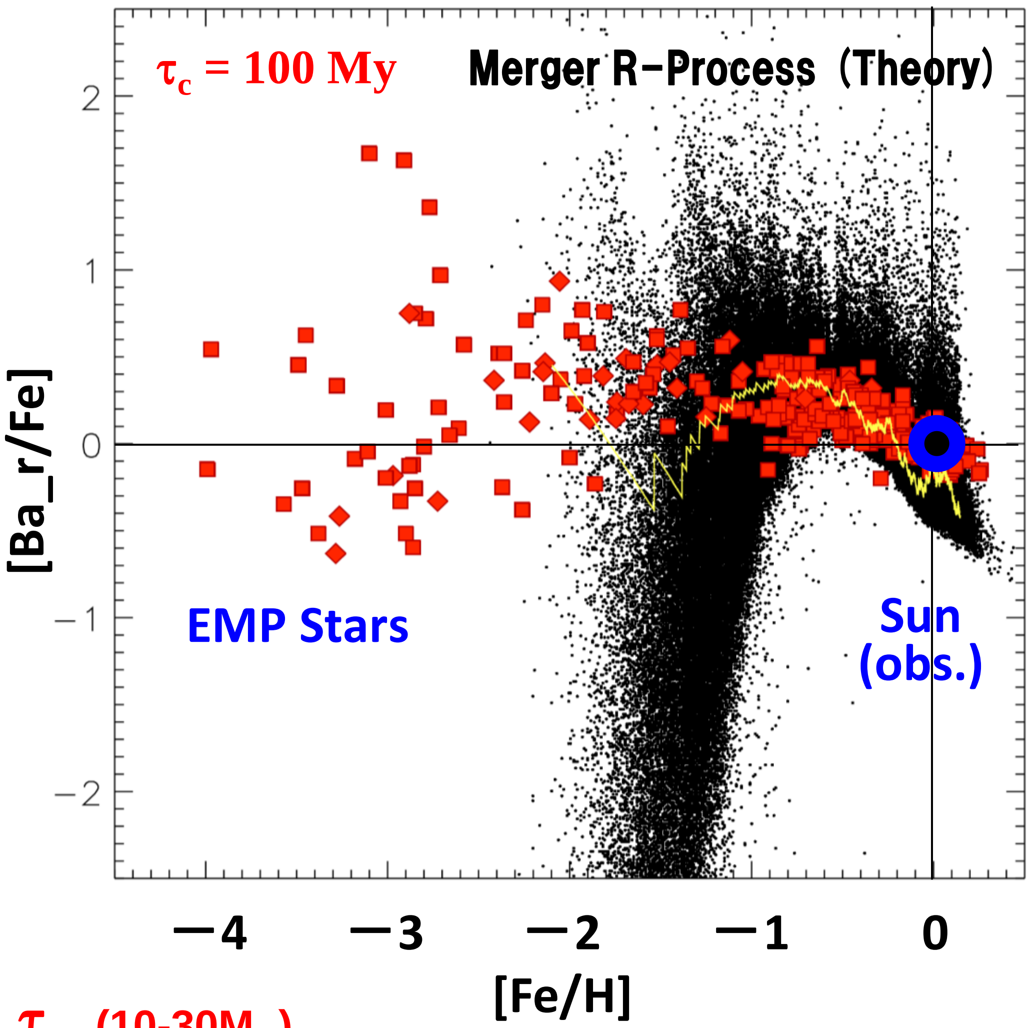
Binary NS Mergers have arrived too late in cosmic history !

Gal. Chem. Evolution (not Dynamical Simul.)

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

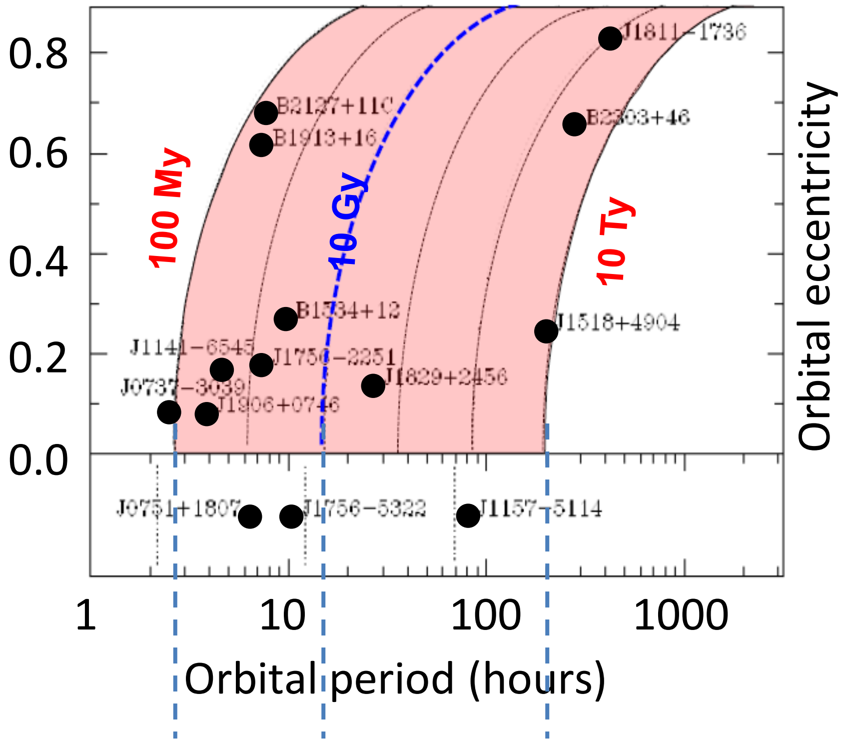
Time Scale Problem

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



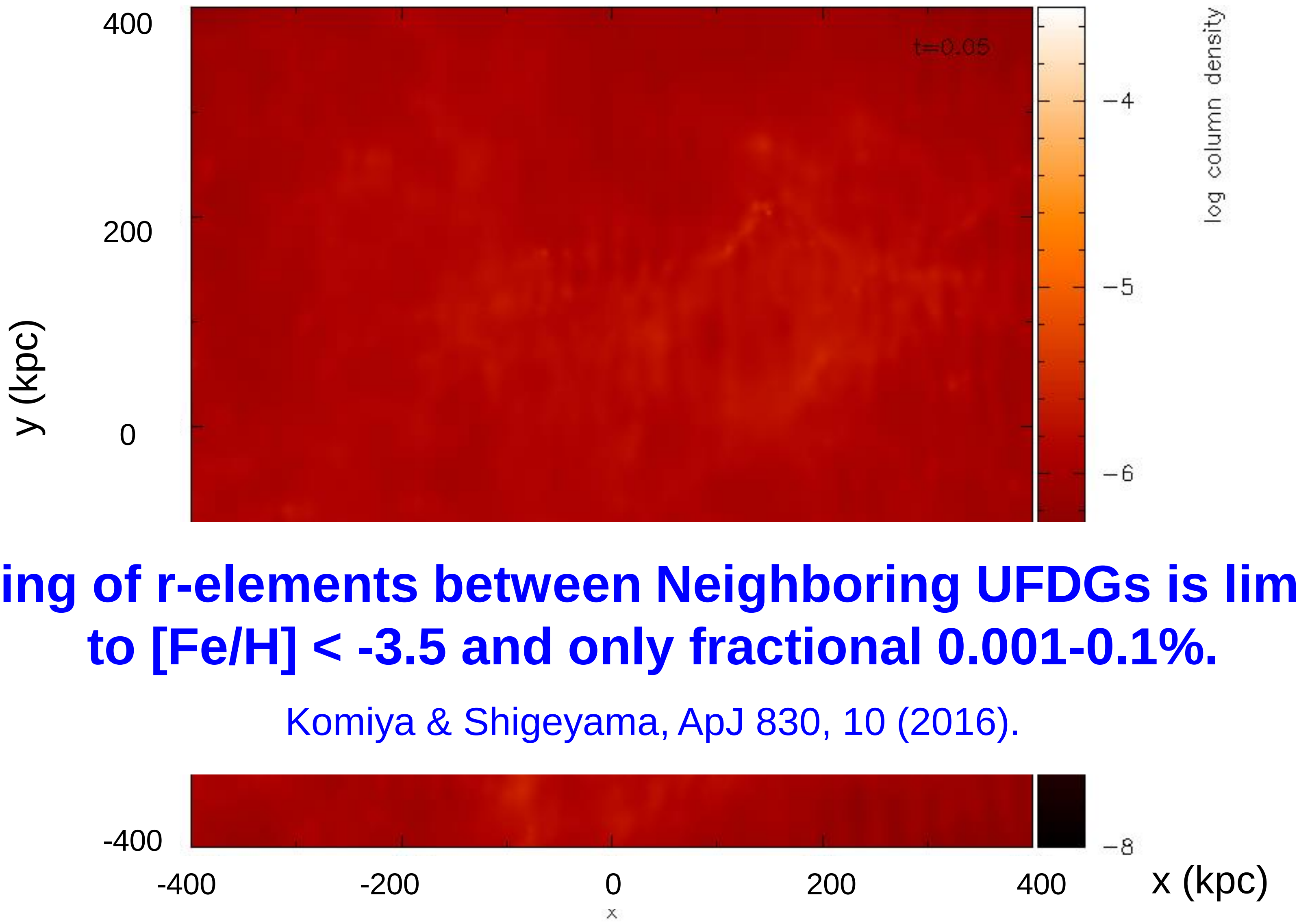
τ_{life} (10-30M$_\odot$)

1My 10My 100My ··· 10Gy

100My 10Gy 10Ty

Large Scale Structure Formation — Hierarchical

N-Body Simulation　　X. Zhao & G. Mathews (2014)



Mixing of r-elements between Neighboring UFDGs is limited to [Fe/H] < -3.5 and only fractional 0.001-0.1%.

Komiya & Shigeyama, ApJ 830, 10 (2016).

SUPERCOMPUTING of Galactic Chemo−Dynamical Evolution

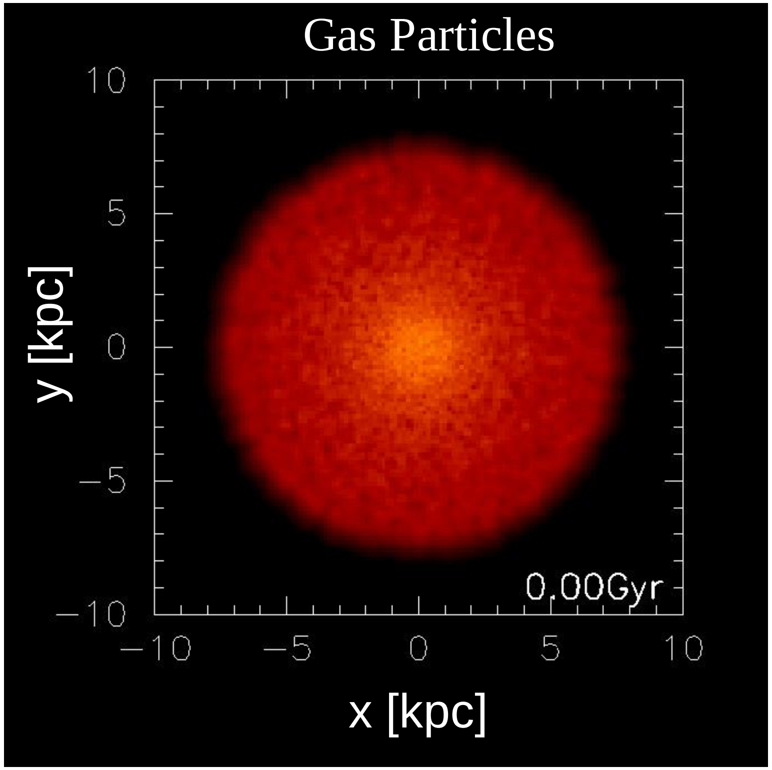
Dwarf Galaxies = Building Blocks of Milky Way Galaxy

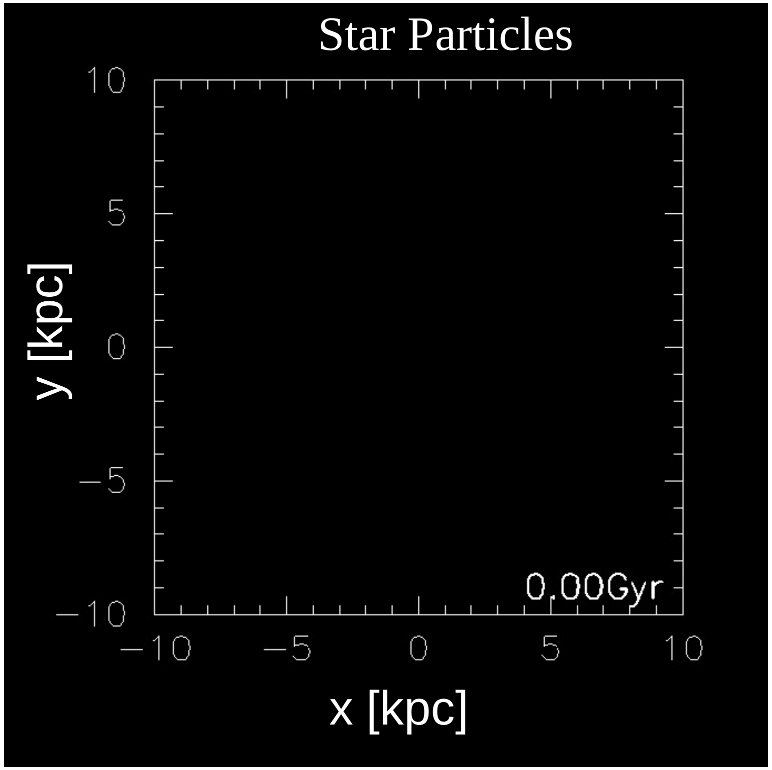
N−Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.
SNe = Metals ; NSM (τ_C=100My) = r−process elements. (n_H >100 cm^{-3} → ~10−100pc)

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

Yutaka Hirai et al., ApJ 814 (2015), 41 & MNRAS (2017), in press.

M_{tot} = 7x$10^8 M_{sun}$, N_i = 5x10^5 particles, $M_\bigstar$ = 100M_{sun}


Gas Particles


Star Particles

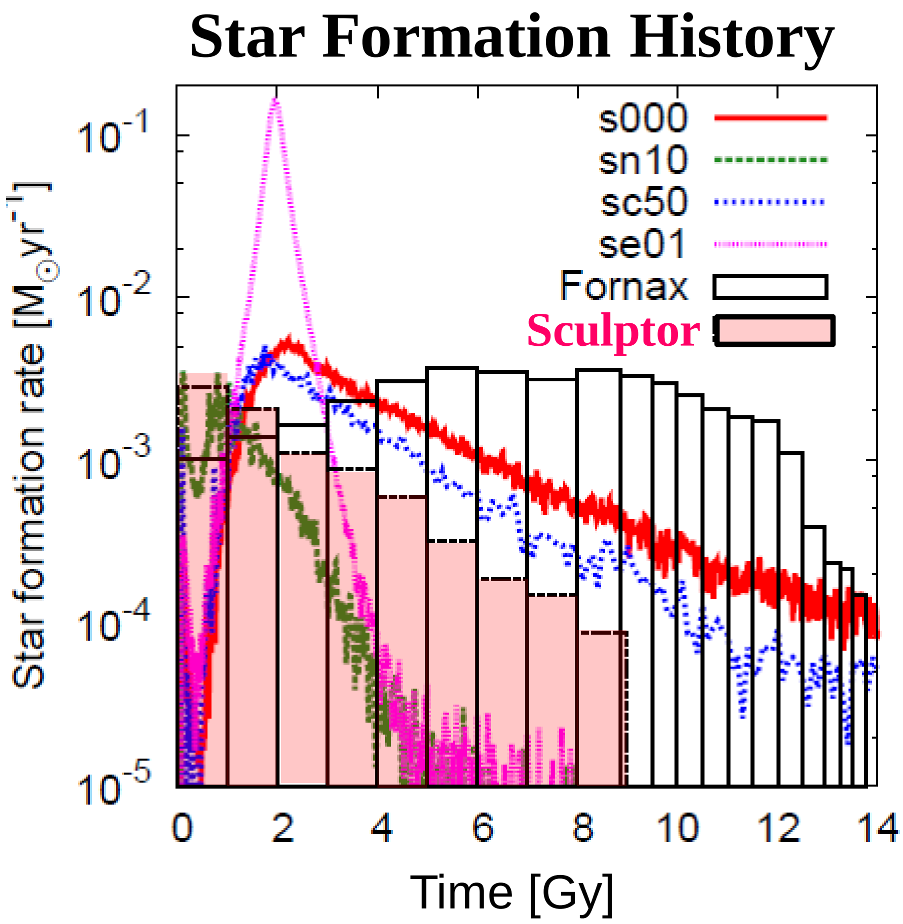
Galactic Chemo-Dynamical (N-Body/SPH) Simulation

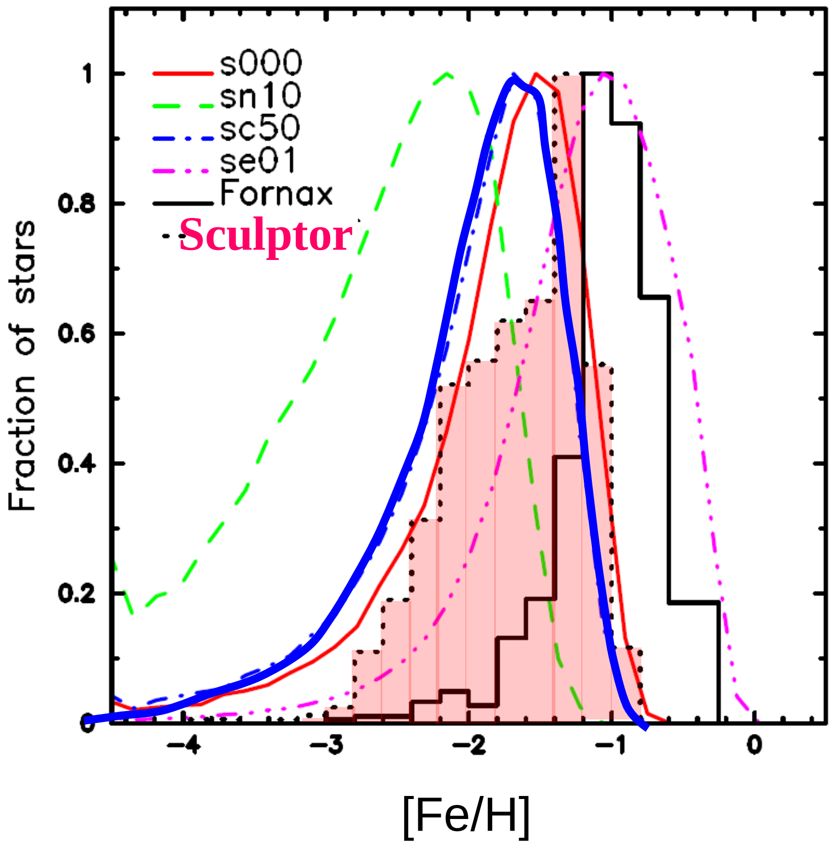
No need of introducing artificial parameters!

Hirai, Ishimaru, Saitoh, Fujii, Hidaka & Kajino, ApJ 814 (2016), 41; MNRAS (2017), in press.

Time-scale for STAR FORMATION ~ 1-2Gy (1000My)

Binary NSMs (100My<τ_C) can contribute from the epoch of INHOMOGENEOUS mixing !


Star Formation History



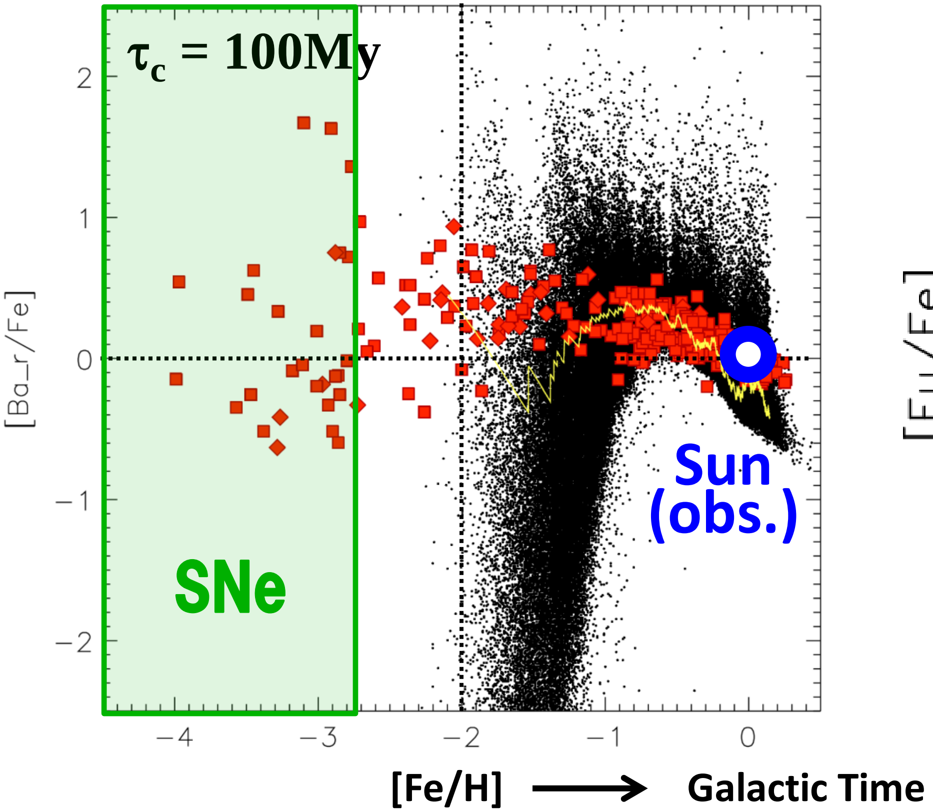
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

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)

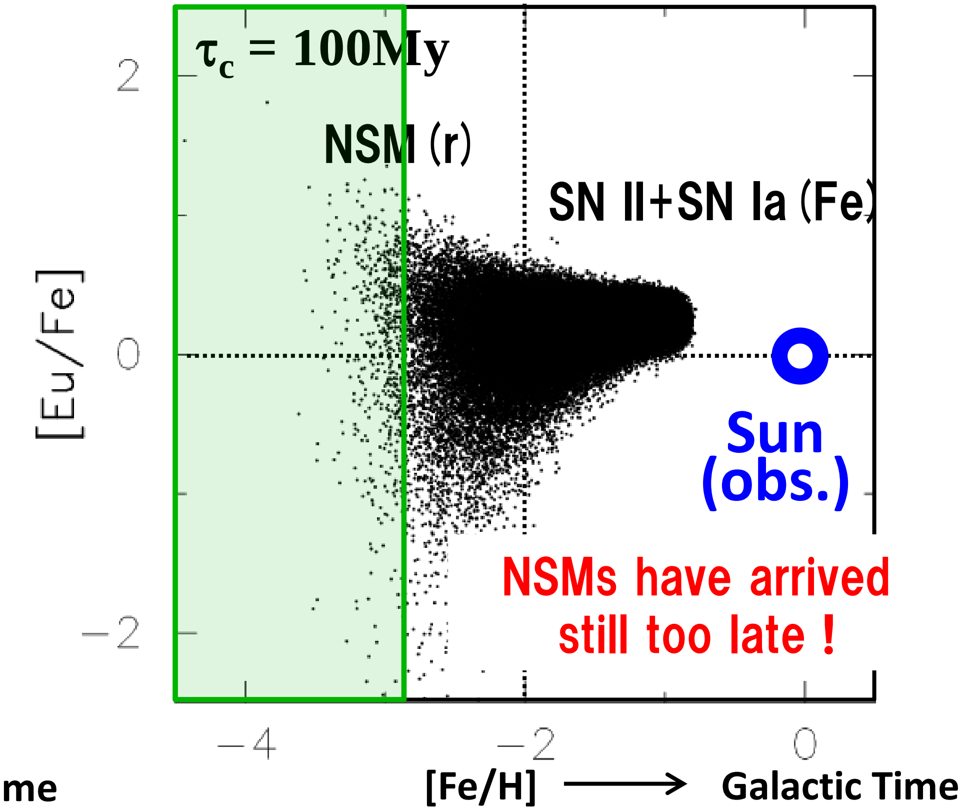
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino, ApJ 814 (2015), 41; MNRAS (2017) in press.

Without GAS MIXING

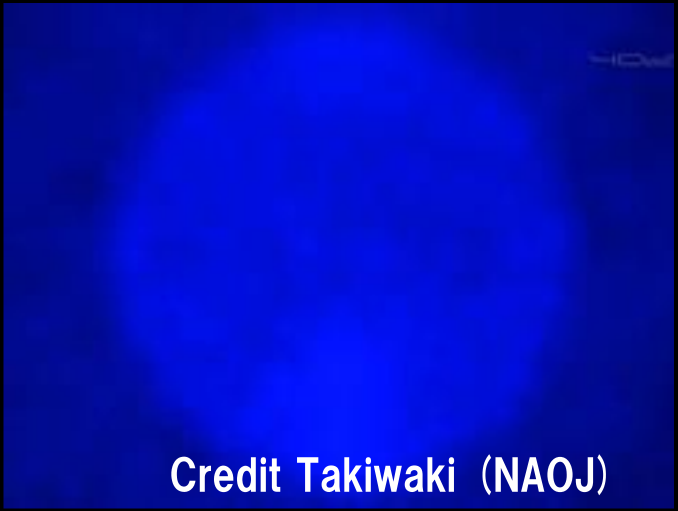


With GAS MIXING



NSMs have arrived still too late !

Core-Collapse Supernovae



Credit Takiwaki（NAOJ)

ν-Driven Winds ⇒ Up to 1st R-Peak

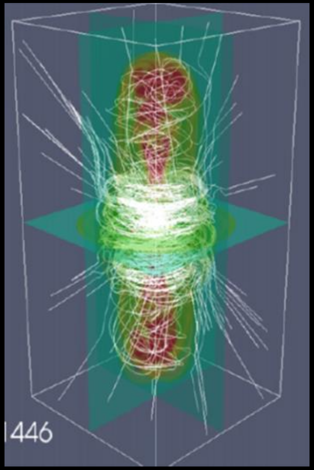
Meyer, et al., ApJ, 399, 656 (1992),
Woosley, et al., ApJ 433, 229 (1994),
Qian & Woosley, ApJ, 471, 331 (1996),
Witti, et al., A&A, 286, 842 (1994),
Otsuki, Kajino, et al., ApJ 533, 424 (2000) ++

Long-GRBs（Collapsar) ⇒ Peculiar R-Pattern

Nakamura, Kajino, et al., A&A 584, A34 (2015).

MHD-Jet

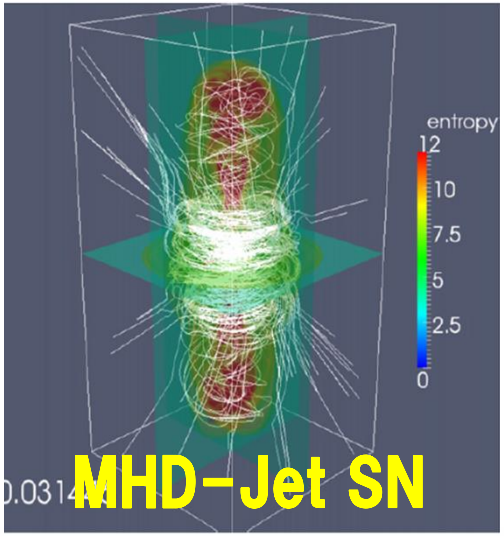
Nishimura, et al., ApJ 642, 410 (2006),
Fujimoto, et al., ApJ 680, 1350 (2008),
Winteler, et al., ApJ 750, L22 (2012),
Nishimura, Kajino, et al., ApJ, 810, 109 (2015) ++

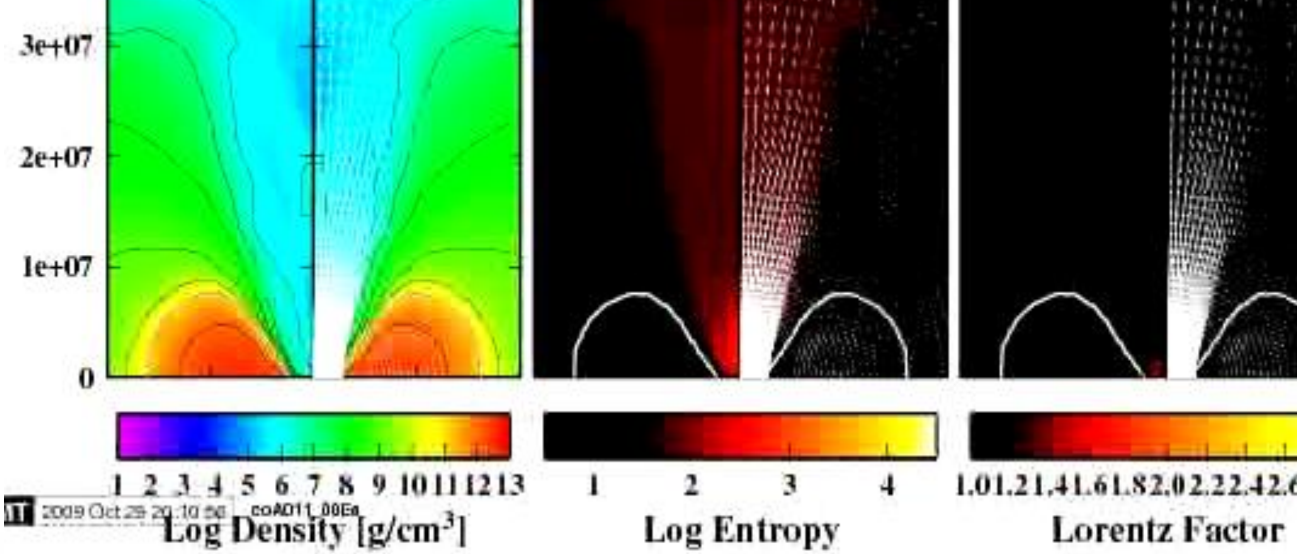


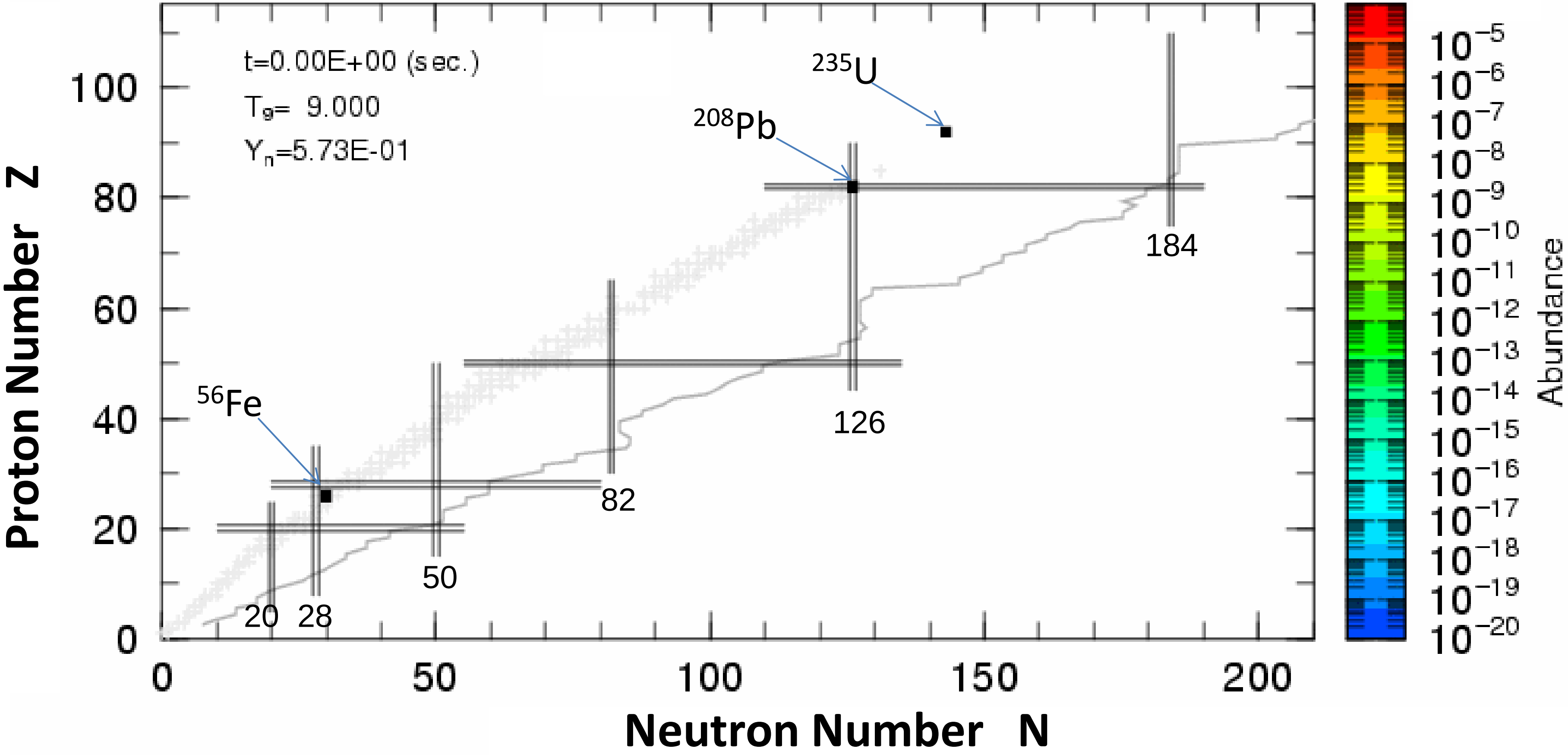
Explosion Condition, still unclear?

τ =1-10My

Underproduction, off R-Peaks ?

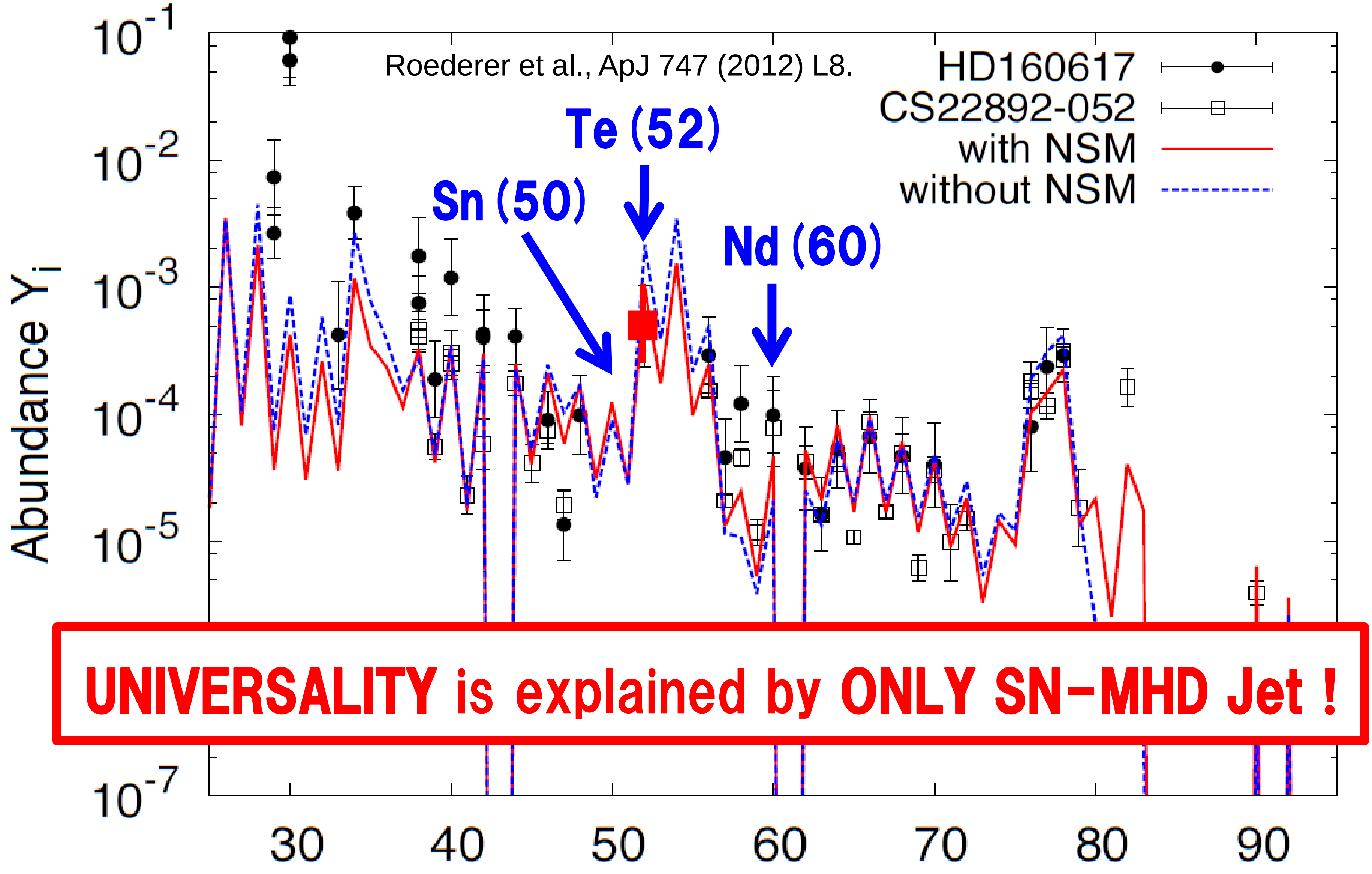

entropy
12
10
7.5
5
2.5
0
0.0314
MHD-Jet SN


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
2009 Oct 29 20:10:58
coA011_00Ea


t=0.00E+00 (sec.)
T₉= 9.000
Yₙ=5.73E-01
²³⁵U
²⁰⁸Pb
⁵⁶Fe
20
28
50
82
126
184
Proton Number Z
0
20
40
60
80
100
Neutron Number N
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

UNIVERSALITY !

Early Galaxy !

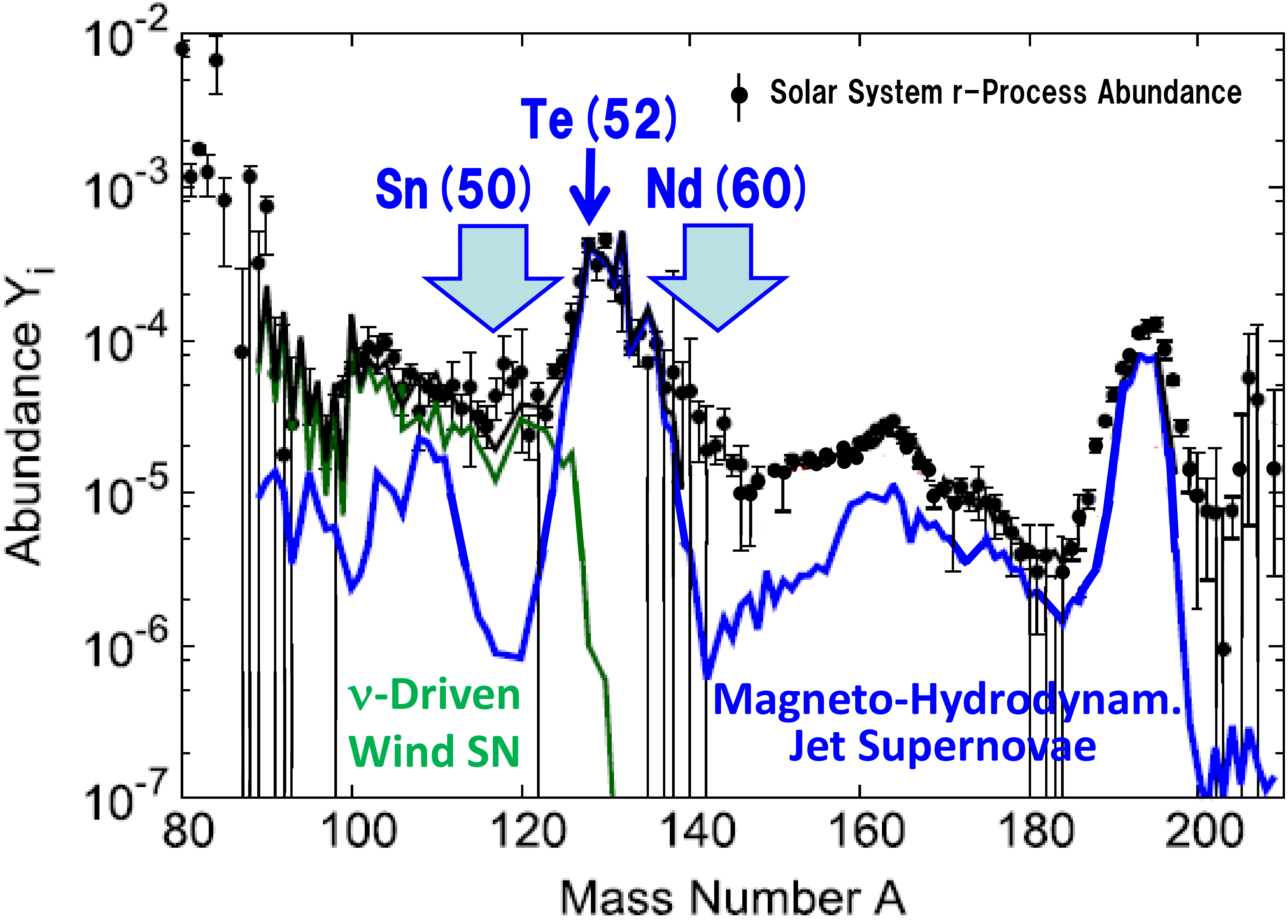


UNIVERSALITY is explained by ONLY SN-MHD Jet !

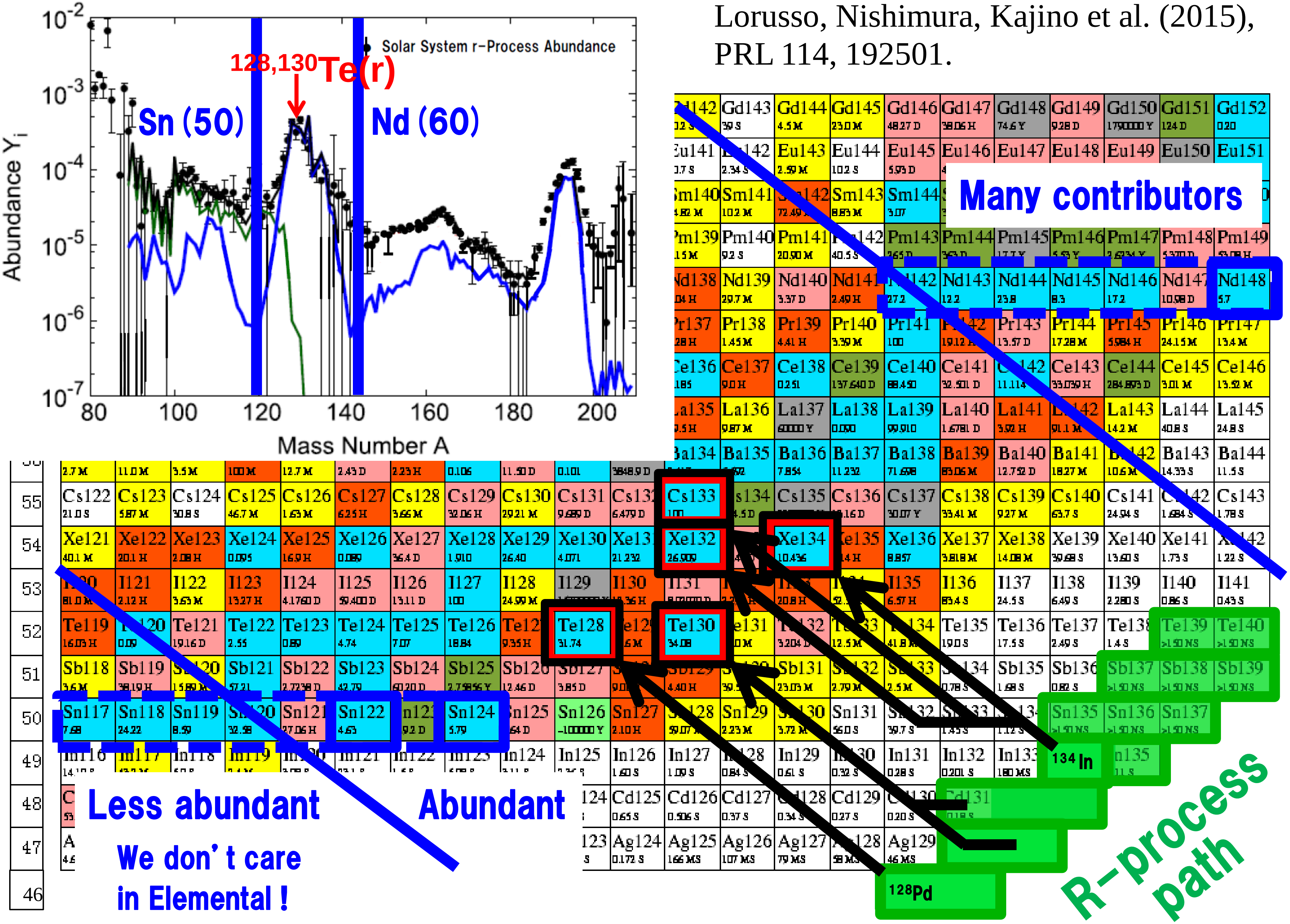
Astron. Obs. Doesn’t separate ISOTOPES !

ELEMENTAL (Z)

Early Galaxy !



Lorusso, Nishimura, Kajino et al. (2015),
PRL 114, 192501.



Many contributors

												d142 2 S	Gd143 39 S	Gd144 4.5 M	Gd145 23.0 M	Gd146 48.27 D	Gd147 38.06 H	Gd148 74.6 Y	Gd149 9.28 D	Gd150 1790000 Y	Gd151 124 D	Gd152 0.20
												u141 .7 S	E 142 2.34 S	Eu143 2.59 M	Eu144 10.2 S	Eu145 5.93 D	Eu146 4	Eu147	Eu148	Eu149	Eu150	Eu151
												m140 .82 M	Sm141 10.2 M	142 72.49	Sm143 8.83 M	Sm144 3.07	S					0
												m139 15 M	Pm140 9.2 S	Pm141 20.90 M	P 142 40.5 S	Pm143 265 D	Pm144 363 D	Pm145 17.7 Y	Pm146 5.53 Y	Pm147 2.6234 Y	Pm148 5.370 D	Pm149 53.08 H
												d138 04 H	Nd139 29.7 M	Nd140 3.37 D	Nd141 2.49 H	142 27.2	Nd143 12.2	Nd144 23.8	Nd145 8.3	Nd146 17.2	Nd147 10.98 D	Nd148 5.7
												r137 28 H	Pr138 1.45 M	Pr139 4.41 H	Pr140 3.39 M	Pr141 100	P 42 19.12 H	Pr143 13.57 D	Pr144 17.28 M	Pr145 5.984 H	Pr146 24.15 M	Pr147 13.4 M
												e136 185	Ce137 9.0 H	Ce138 0.251	Ce139 137.640 D	Ce140 88.450	Ce141 32.501 D	C 142 11.114	Ce143 33.039 H	Ce144 284.893 D	Ce145 3.01 M	Ce146 13.52 M
												a135 .5 H	La136 9.87 M	La137 60000 Y	La138 0.090	La139 99.910	La140 1.6781 D	La141 3.92 H	L 42 91.1 M	La143 14.2 M	La144 40.8 S	La145 24.8 S
	2.7 M	11.0 M	3.5 M	100 M	12.7 M	2.43 D	2.23 H	0.106	11.50 D	0.101	3848.9 D	a134	Ba135 .592	Ba136 7.854	Ba137 11.232	Ba138 71.698	Ba139 83.06 M	Ba140 12.752 D	Ba141 18.27 M	B 42 10.6 M	Ba143 14.33 S	Ba144 11.5 S
55	Cs122 21.0 S	Cs123 5.87 M	Cs124 30.8 S	Cs125 46.7 M	Cs126 1.63 M	Cs127 6.25 H	Cs128 3.66 M	Cs129 32.06 H	Cs130 29.21 M	Cs131 9.689 D	Cs13 6.479 D	Cs133 100	s134 .5 D	Cs135	Cs136 .16 D	Cs137 30.07 Y	Cs138 33.41 M	Cs139 9.27 M	Cs140 63.7 S	Cs141 24.94 S	C 42 1.684 S	Cs143 1.78 S
54	Xe121 40.1 M	Xe122 20.1 H	Xe123 2.08 H	Xe124 0.095	Xe125 16.9 H	Xe126 0.089	Xe127 36.4 D	Xe128 1.910	Xe129 26.40	Xe130 4.071	Xe13 21.232	Xe132 26.909		Xe134 10.436	e135 14 H	Xe136 8.857	Xe137 3.818 M	Xe138 14.08 M	Xe139 39.68 S	Xe140 13.60 S	Xe141 1.73 S	X 42 1.22 S
53	I 20 81.0 M	I121 2.12 H	I122 3.63 M	I123 13.27 H	I124 4.1760 D	I125 59.400 D	I126 13.11 D	I127 100	I128 24.99 M	I129	I130 .36 H	I131	I	I 20.8 H	I 52.	I135 6.57 H	I136 83.4 S	I137 24.5 S	I138 6.49 S	I139 2.280 S	I140 0.86 S	I141 0.43 S
52	Te119 16.03 H	T 20 0.09	Te121 19.16 D	Te122 2.55	Te123 0.89	Te124 4.74	Te125 7.07	Te126 18.84	Te12 9.35 H	Te128 31.74	e12 .6 M	Te130 34.08	e131 .0 M	T 32 3.204 D	T 33 12.5 M	134 41.8 M	Te135 19.0 S	Te136 17.5 S	Te137 2.49 S	Te13 1.4 S	Te139 >150 NS	Te140 >150 NS
51	Sb118 3.6 M	Sb119 38.19 H	S 120 15.89 M	Sb121 57.21	Sb122 2.7238 D	Sb123 42.79	Sb124 60.20 D	Sb125 2.75856 Y	Sb126 12.46 D	Sb127 3.85 D	9.0	Sb129 4.40 H	39.5	Sb131 23.03 M	S 32 2.79 M	S 33 2.5 M	134 0.78 S	Sb135 1.68 S	Sb136 0.82 S	Sb137 >150 NS	Sb138 >150 NS	Sb139 >150 NS
50	Sn117 7.68	Sn118 24.22	Sn119 8.59	S 20 32.58	Sn121 27.06 H	Sn122 4.63	n12 .92 D	Sn124 5.79	n125 .64 D	Sn126 ~100000 Y	Sn127 2.10 H	128 59.07	Sn129 2.23 M	130 3.72 M	Sn131 56.0 S	S 32 39.7 S	S 33 1.45 S	134 1.12 S	Sn135 >150 NS	Sn136 >150 NS	Sn137 >150 NS	
49	In116 14.	In117	In118	In119	In 20	In121	In122	In123	In124	In125	In126 1.60 S	In127 1.09 S	128 0.84 S	In129 0.61 S	130 0.32 S	In131 0.28 S	In132 0.201 S	In133 180 MS	^{134}In	n135 11 S		
48	C 53.									124	Cd125 0.65 S	Cd126 0.506 S	Cd127 0.37 S	128 0.34 S	Cd129 0.27 S	C 130 0.20 S	Cd131					
47	A 4.6									123 S	Ag124 0.172 S	Ag125 166 MS	Ag126 107 MS	Ag127 79 MS	128 58 MS	Ag129 46 MS						
46																^{128}Pd						

Less abundant

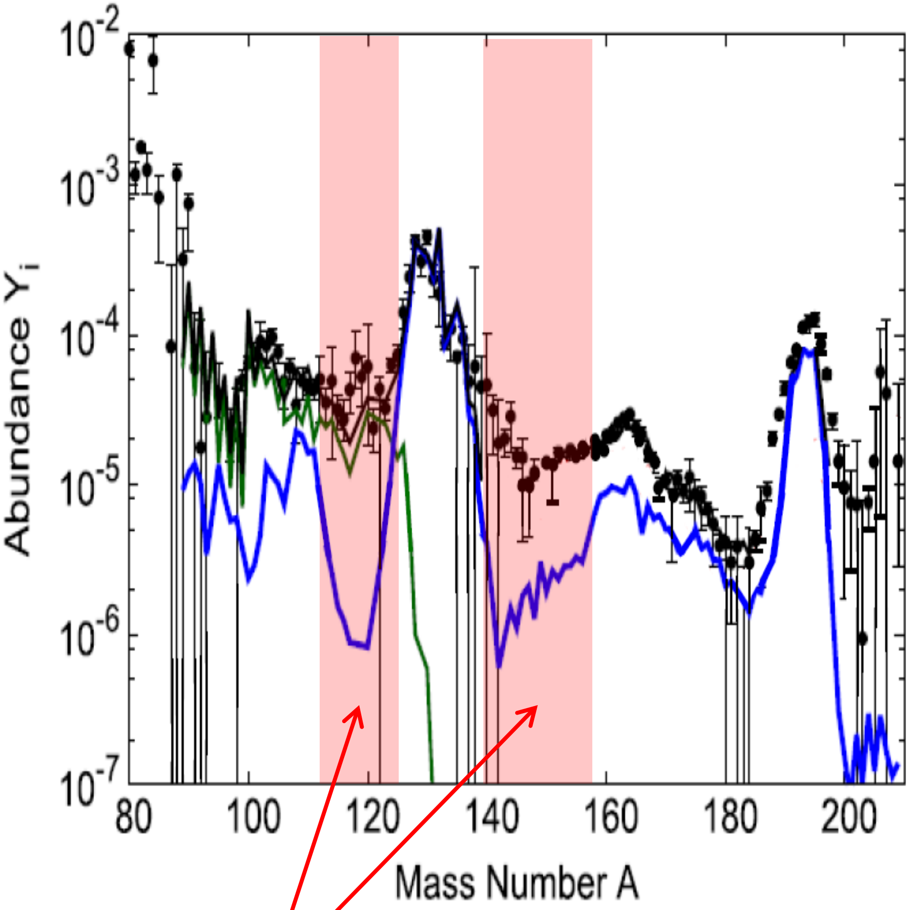
Abundant

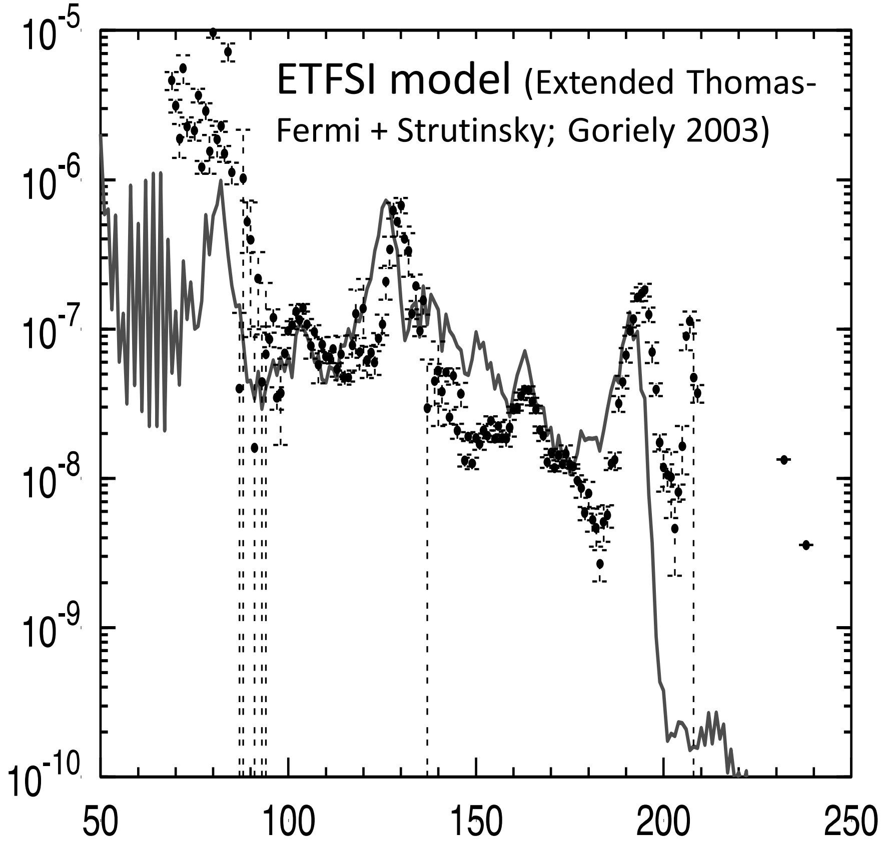
We don' t care
in Elemental !

R-process path

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).





Underproduction PROBLEM ! → **Possible Solutions**

Nucl. Phys. - Shell Quenching ?

or

Another Site （NSM） !

S.S. abundance has no Time-Scale Problem.

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

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

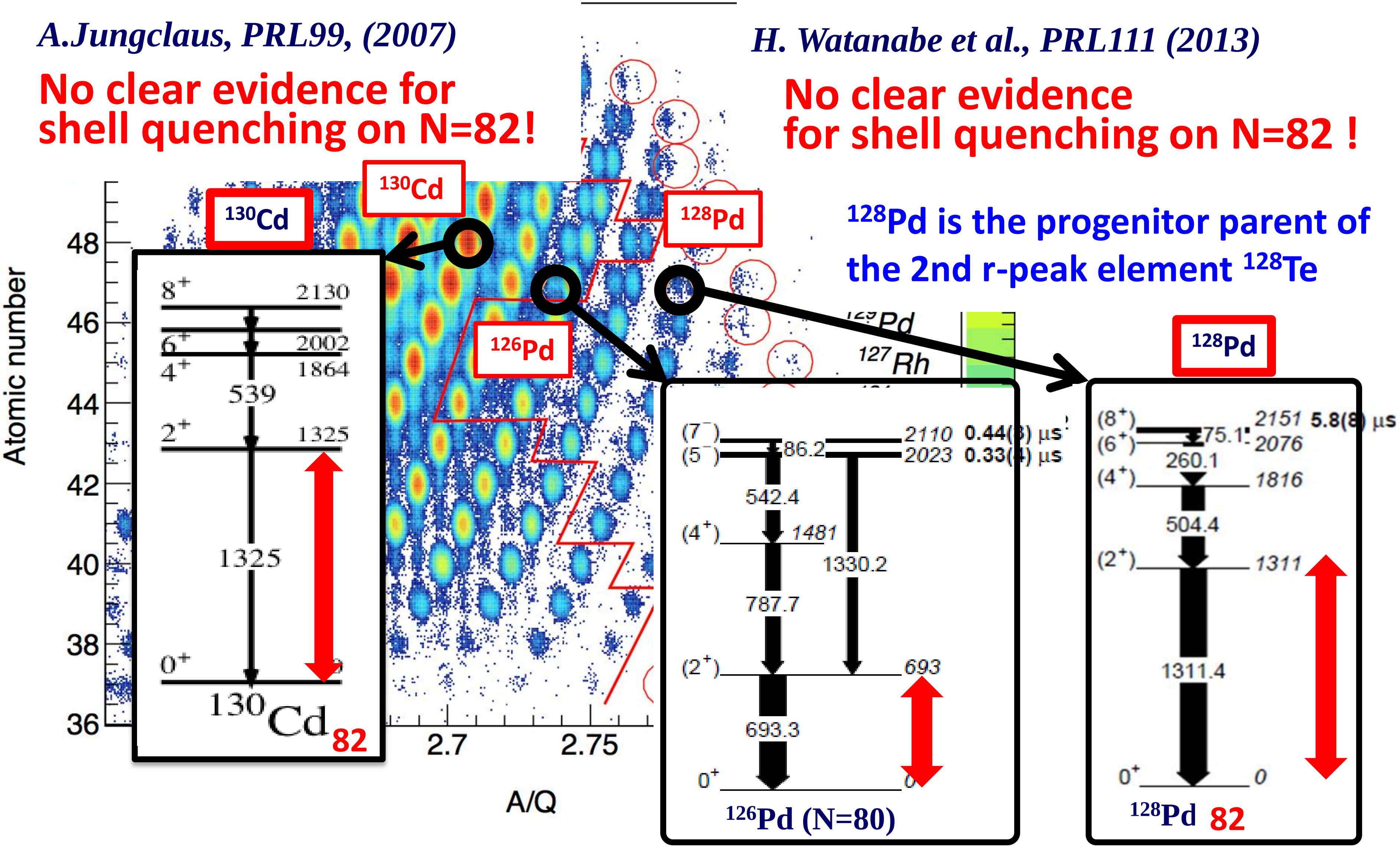
A.Jungclaus, PRL99, (2007)

No clear evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

No clear evidence for shell quenching on N=82 !

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



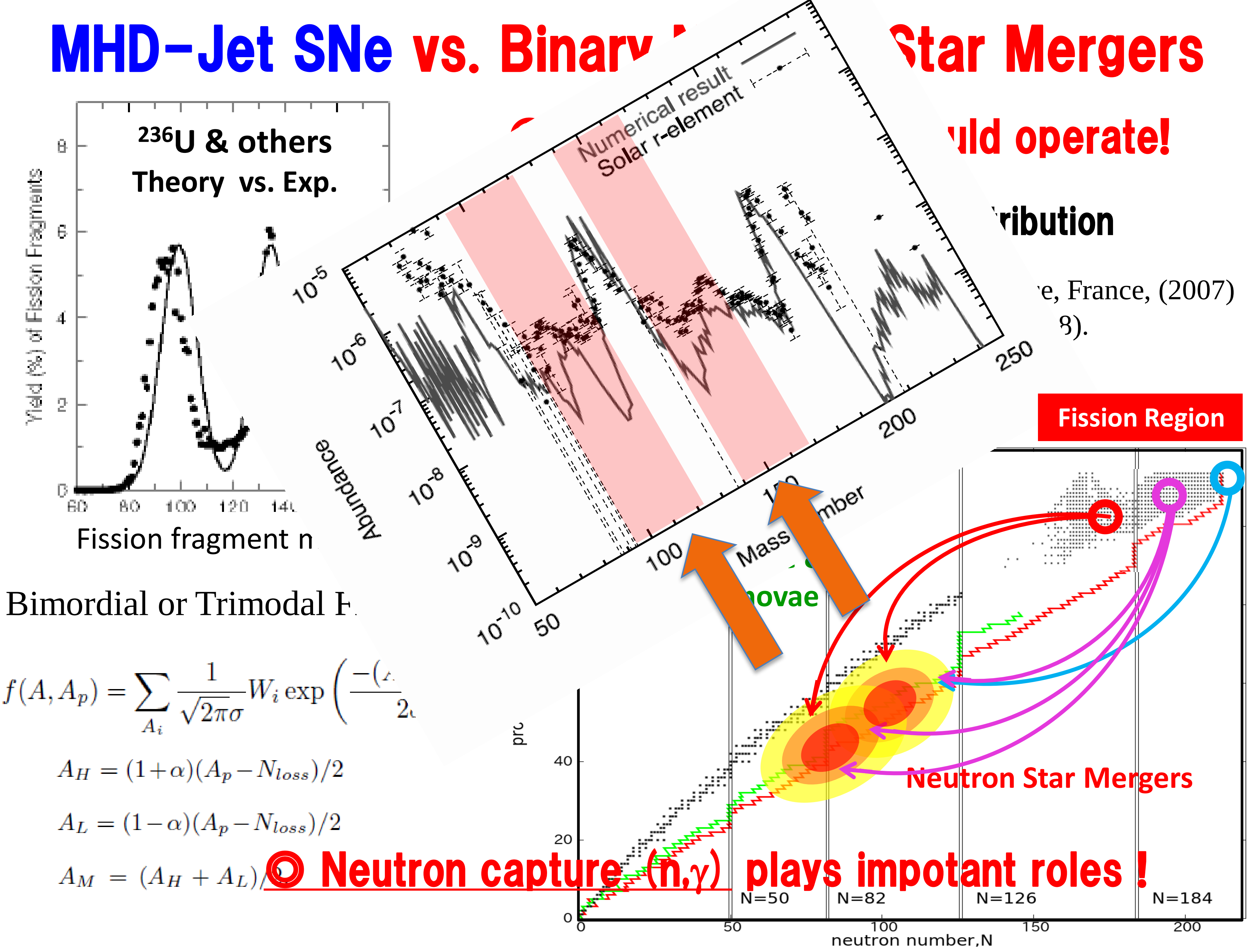
MHD-Jet SNe vs. Binary N Star Mergers

uld operate!

ribution

e, France, (2007)

8).



Bimordial or Trimodal F

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

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

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

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

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

Fluid-Dynamical Model for Neutron Star Merger

Binary Neutron Star Merger

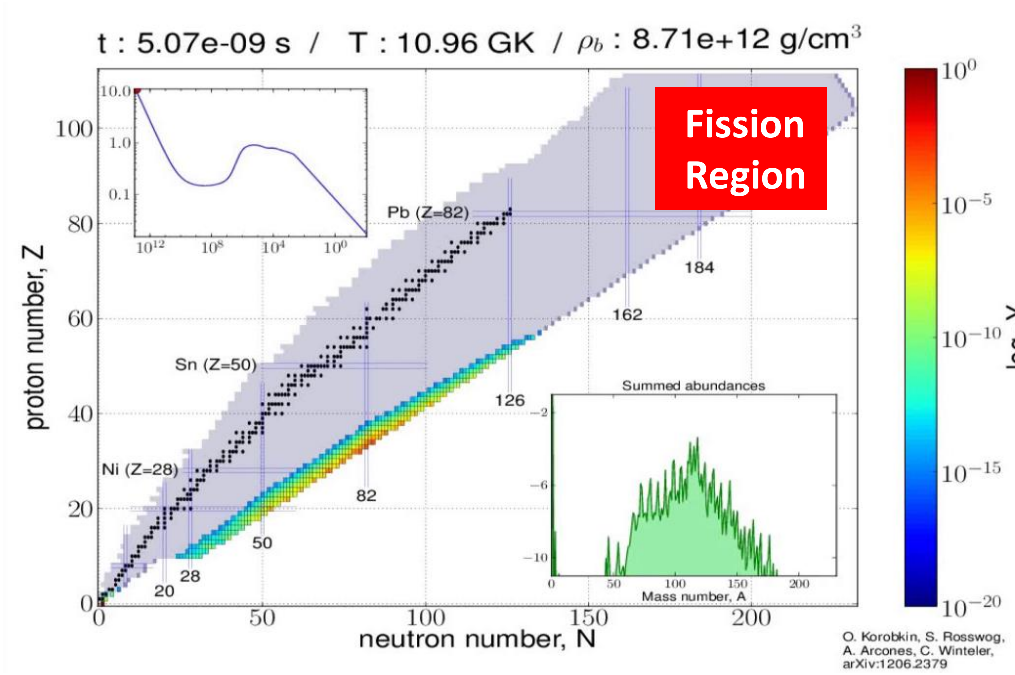
Korobkin et al., MNRAS 426 (2012), 1940; Rosswog et al., MNRAS 430 (2013), 2585.

SPH Simulation: (Adiabatic Expansion)

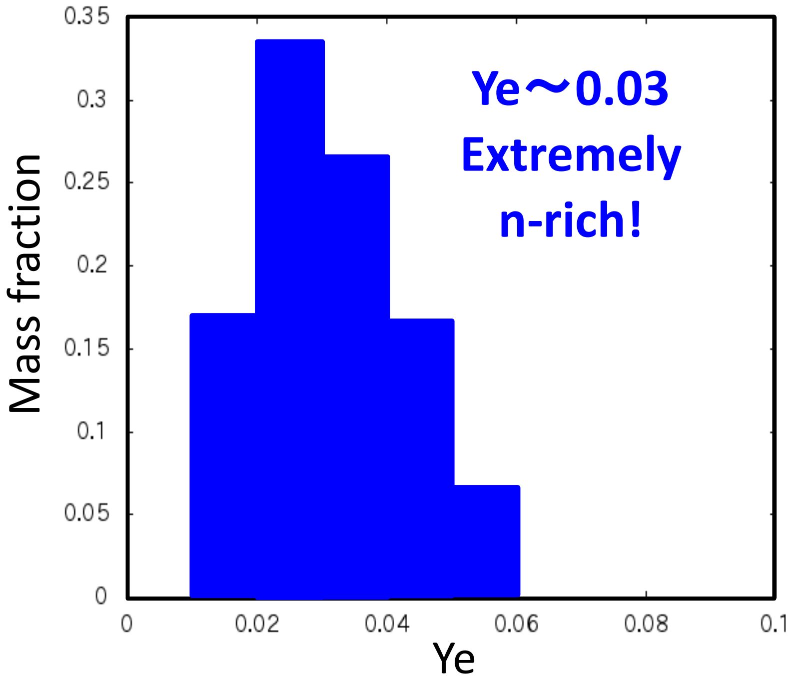
Newtonian gravity, Neutrino Leakage scheme

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.



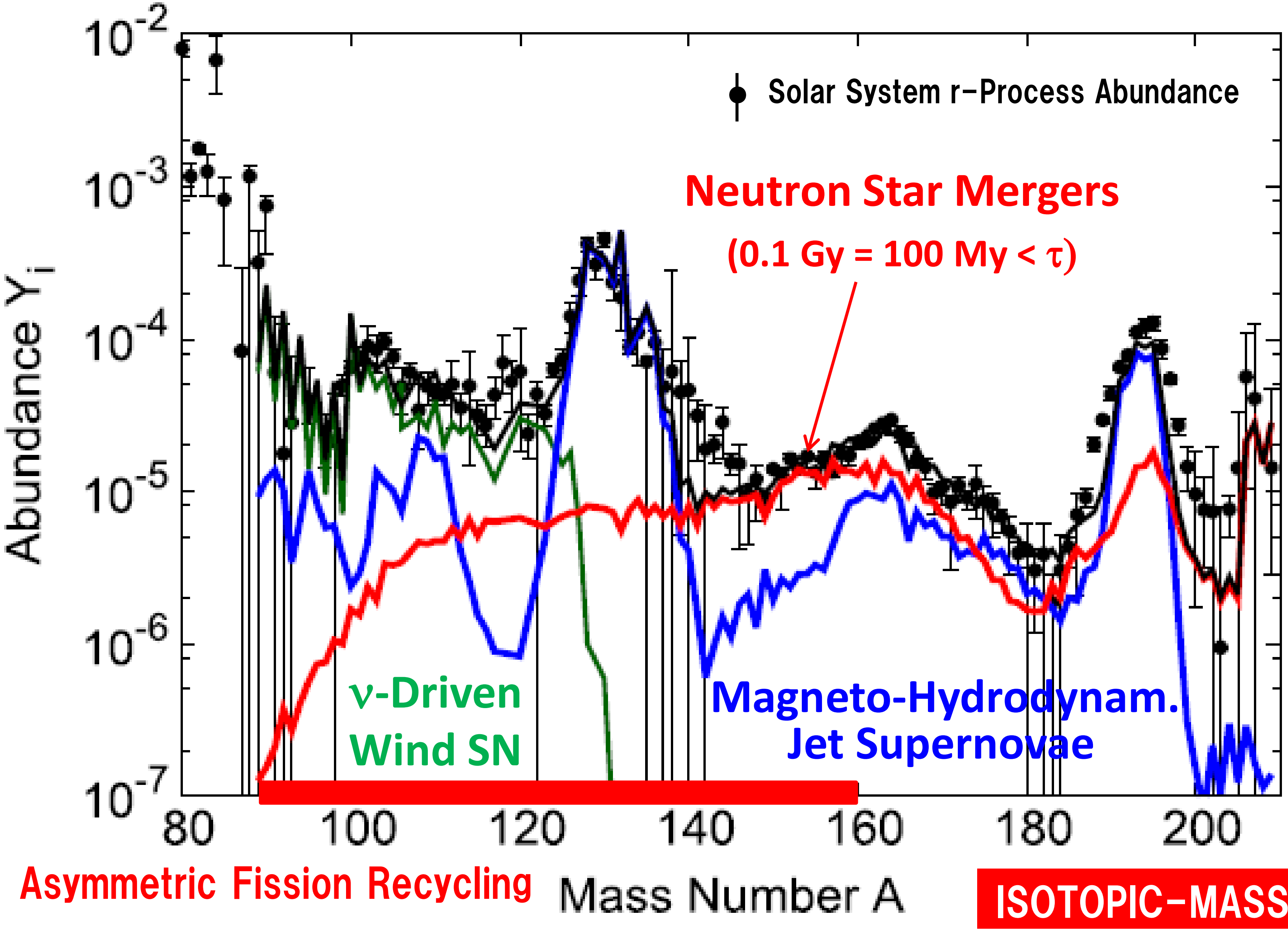
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379



Solar System r-Process Abundance

Present t = 13.8Gy

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



ISOTOPIC-MASS (A)

Observed Galactic event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]

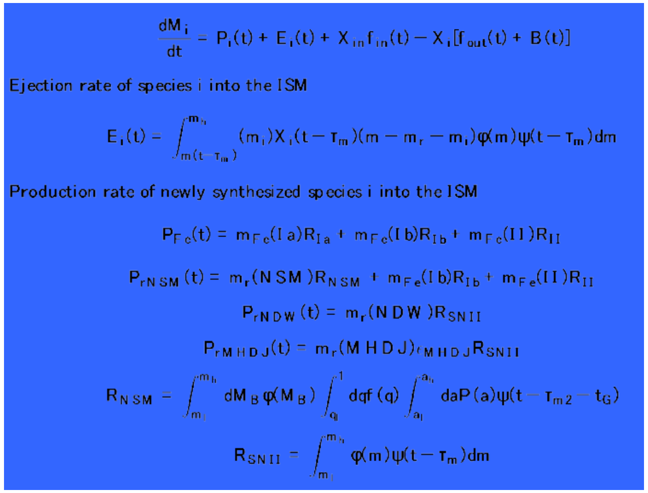
νSN (Weak r) = 7.4 x 10^{-4} x (1.9±1.1) [a]

MHD Jet SNe = 0.6 x 10^{-2} x ((0.03±0.02) x (1.9±1.1)) [b]

Binary NSMs = (2±1) x 10^{-2} x (1-28)x10^{-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	(1-28) x 10^{-3}	Kalogera, et al., ApJ 614, L137 (2004).

Galactic Evolution including Binary Evolution
Kajino, Mathews et al. (2017)



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

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

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

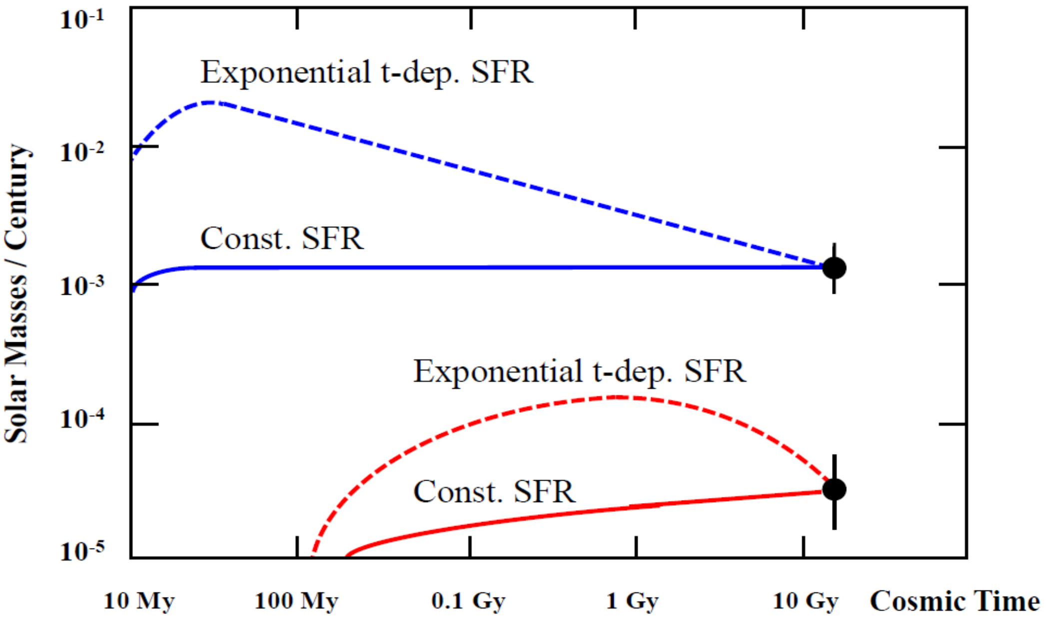
$$P_{rNSM}(t) = m_r(NSM)R_{NSM} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

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

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

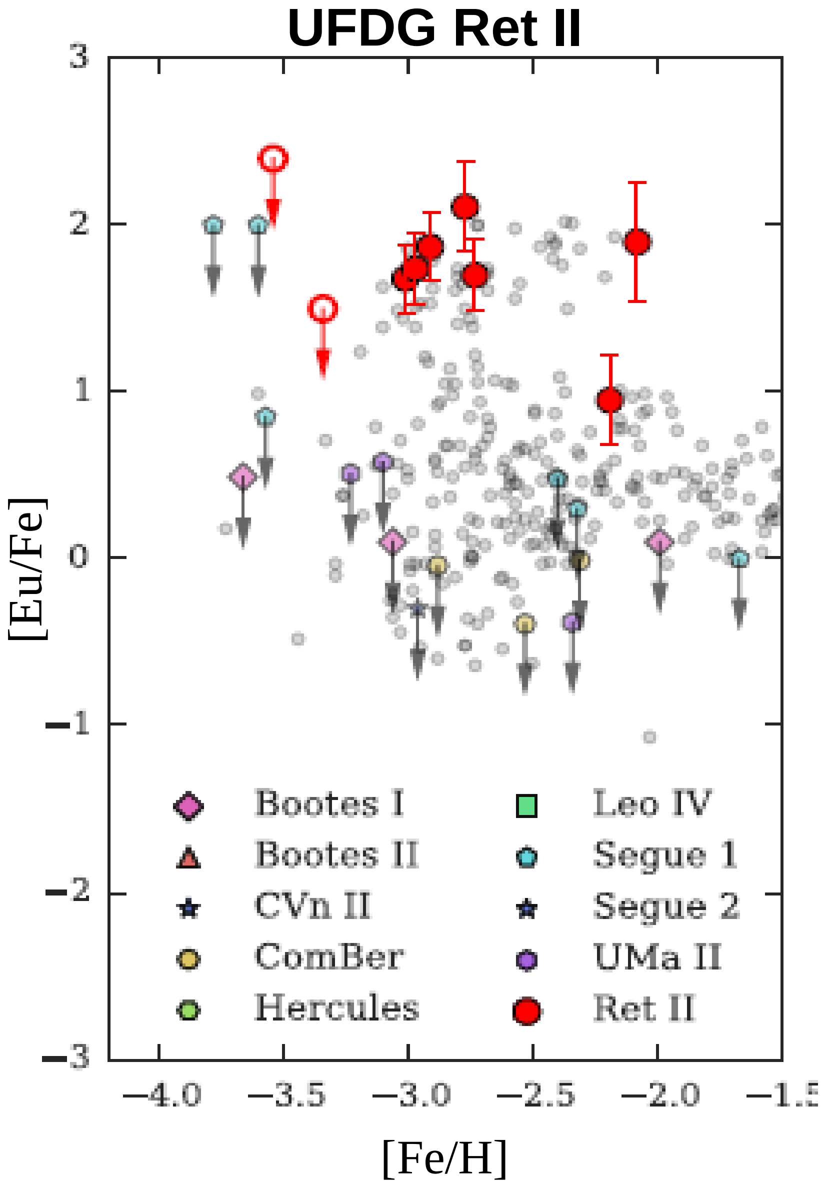
$$R_{NSM} = \int_{m_l}^{m_u} dM_B\,\varphi(M_B) \int_{q_l}^{1} dq f(q) \int_{a_l}^{a_u} da P(a)\psi(t-\tau_{m2}-t_G)$$

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



Strong 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.



Which is likely r-process site, MHD-Jet SN or Binary NSM?

Product. Yield ~ 10^{-2} $M_\odot$ /event

1. Event Rate, too small?

(2.6 +/- 0.2)x$10^3 M_\odot$ Ret. II baryon mass

⟶ ~10 SNe IMF

⟶ ~(0.01-0.3)x10 NSM/SN (0.1%)
MHDJ/SN (1-3%)

SN ! NSM !

2. Very old ?

SN ! NSM !

3. Extended Universality ?
Dust forms ?

SN ! NSM ?

4. Ejecta escape from shallow pot. ?

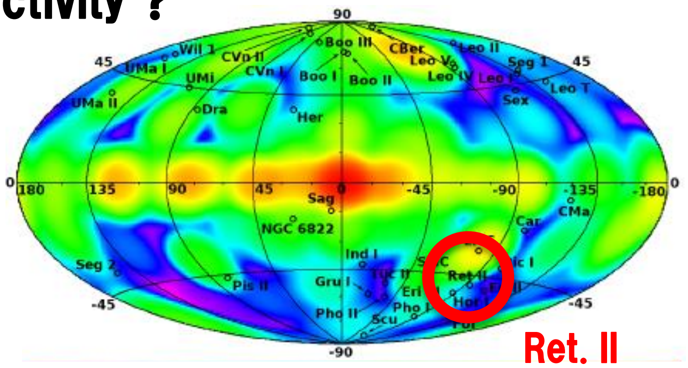
SN ! NSM ?

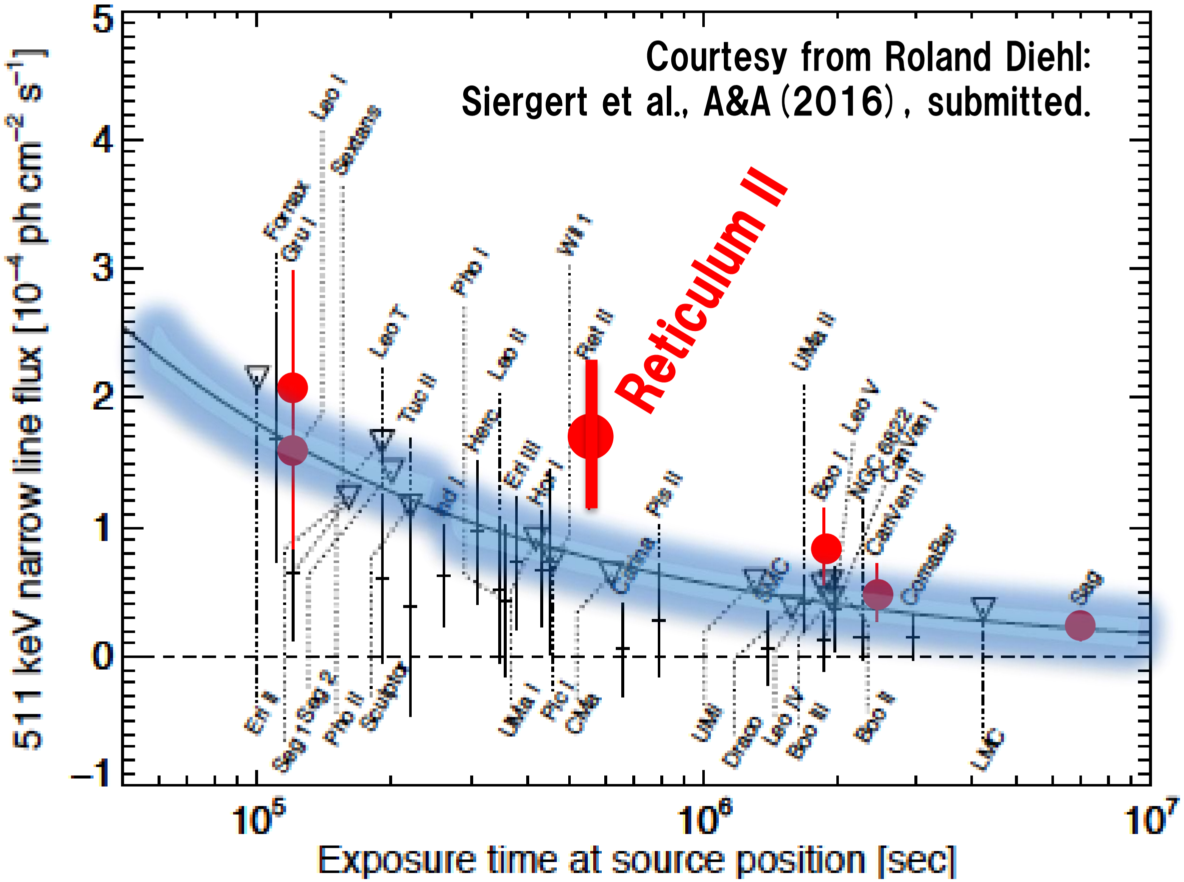
Ret. II should be very old !

INTEGRAL Mission（γ-Ray Satellite）detects 511 keV Emission Line.

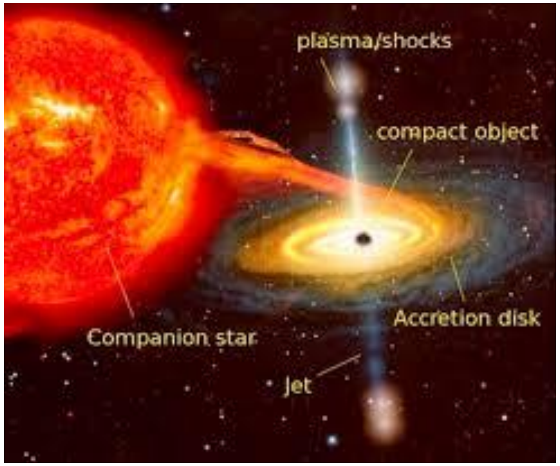
- Does e⁺⁻ come from DM-annihilation or Stellar Activity ?
- No significant detection except for Reticulum II

Exposure map



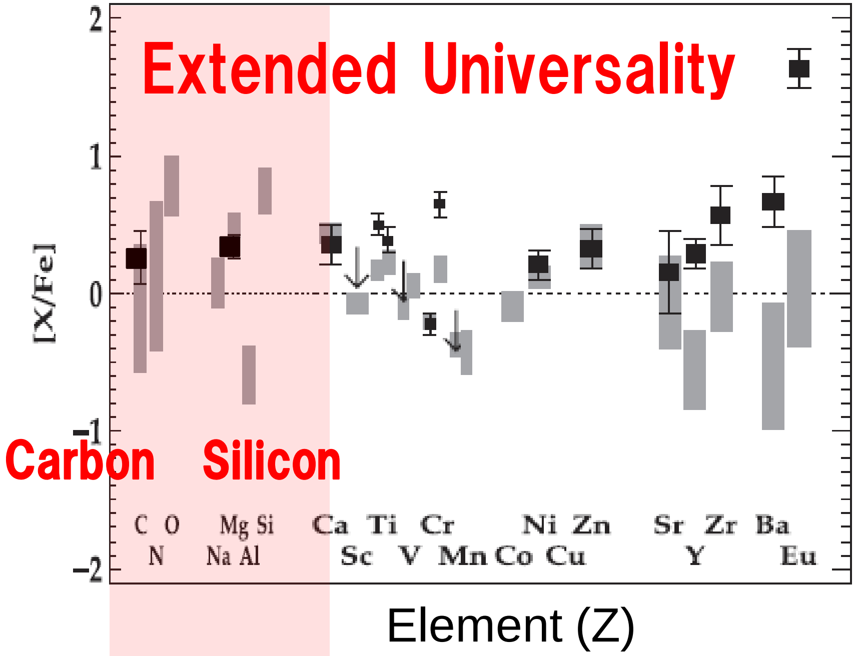


Courtesy from Roland Diehl:
Siergert et al., A&A (2016), submitted.



Micro-quasar !
links to
MHDJ-SN or NSM ??

Ultra-Faint warf Galaxy: Ret. II



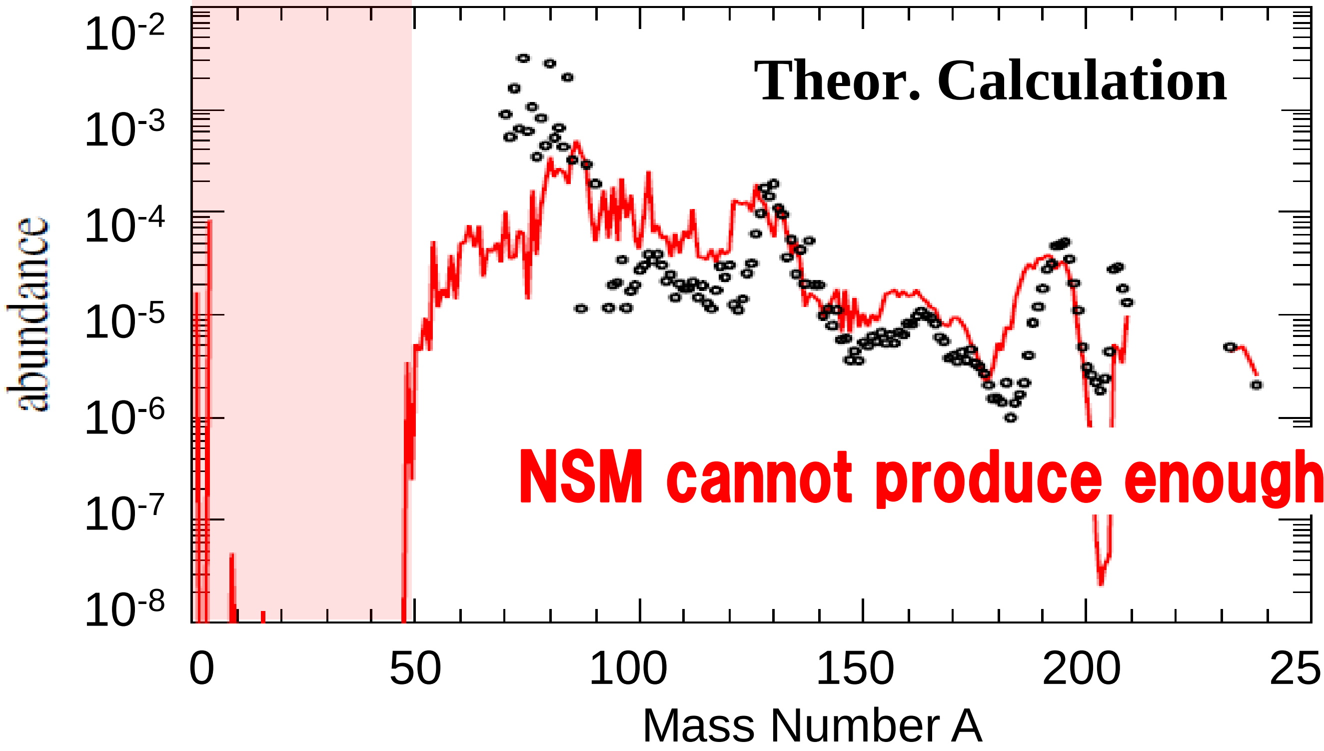
Extended Universality

Carbon Silicon

Astron. Observation

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

Wanajo et al., ApJ. 789 (2014), L39.
Shibagaki et al., ApJ. 816 (2016), 79; (2017)

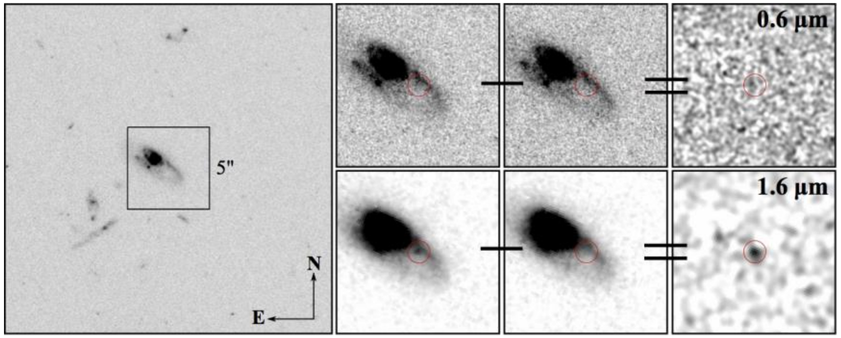


Theor. Calculation

Goriely, et al., ApJ 738, L32 (2011); Korobkin, et al., MNRAS 426, 1940 (2012); Bauswein, et al., ApJ 773, 78 (2013); Rosswog, et al., MNRAS 430, 2585 (2013); Goriely, et al., PRL 111, 242502 (2013), (2015): Piran, et al., MNRAS 430, 2121 (2013).

NSM cannot produce enough A < 50 !

Another DIFFICULTY for R-Process in Binary NSMs

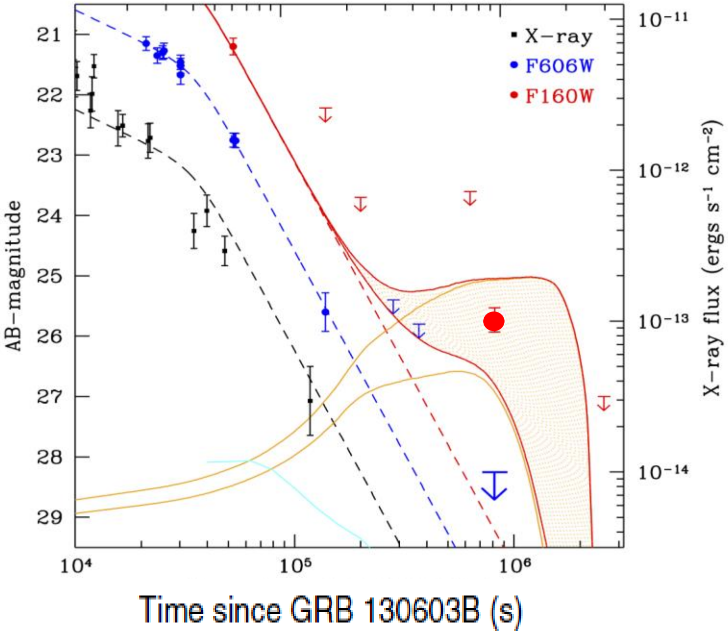


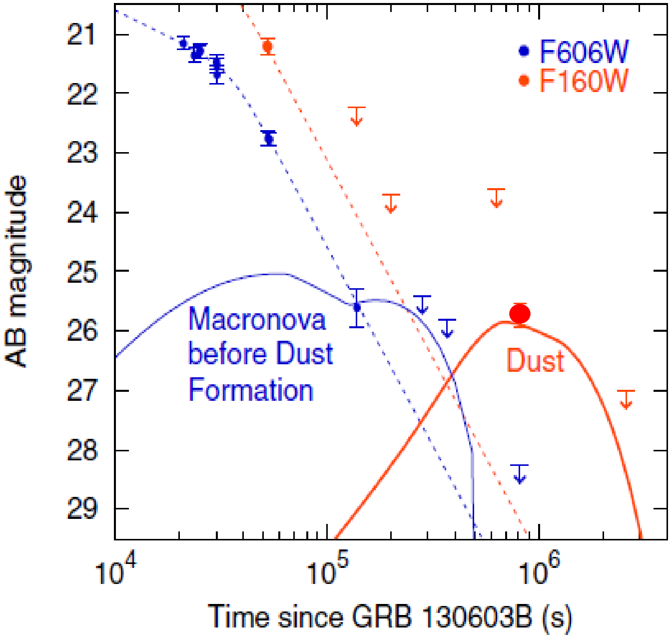
Macronova（Kilonova)

Tanvir, Levan, Fruchter, et al., Nature 500, 547 (2013)

Dust is hard to form for deficient Carbon and other lighter elements.

Takami, Nozawa & Ioka, ApJ 786, L5 (2014).





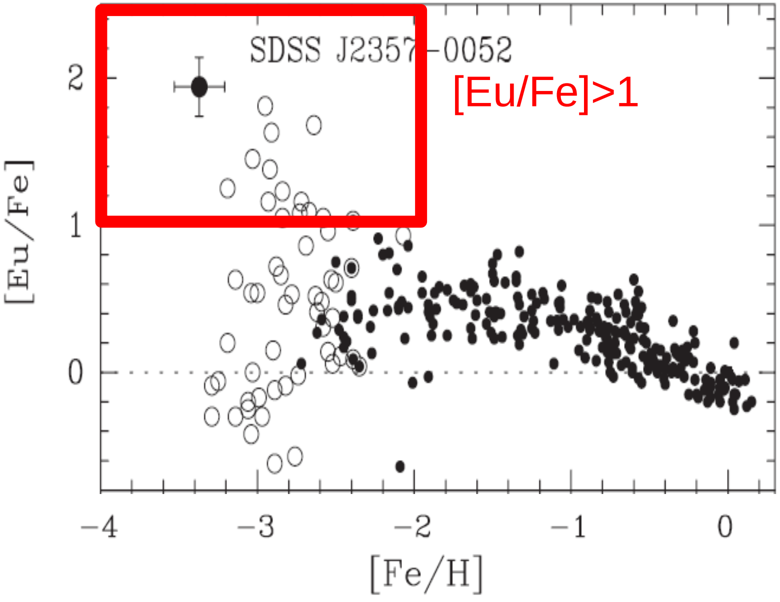
Dust formation becomes even more difficult when one includes more complete opacity table for heavy actinide elements.

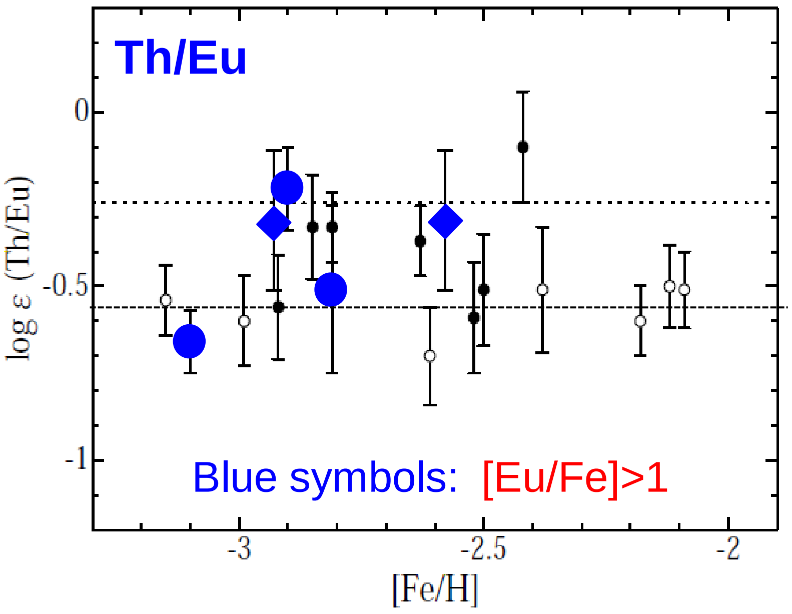
Milky Way Halo Stars

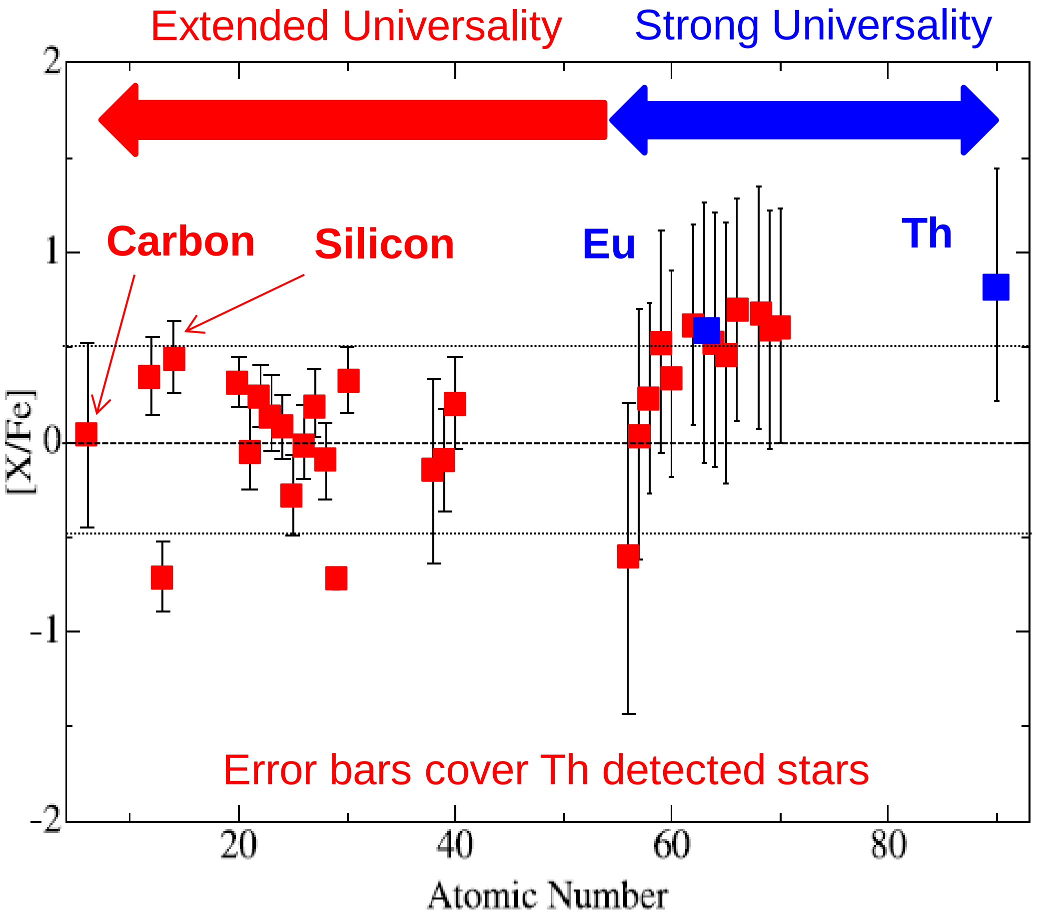
EXTENDED UNIVERSALITY

Honda, Aoki, Kajino, Beers, et al.,
(SUBARU-HDS Collaboration),

ApJ 607 (2004), 474; ApJS 152 (2004) 113.





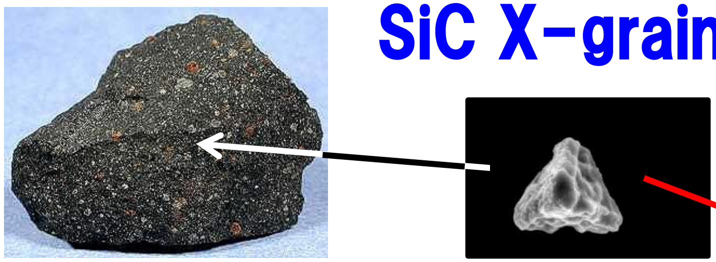


QUEST for Cosmo-Chemistry and Astronomy:

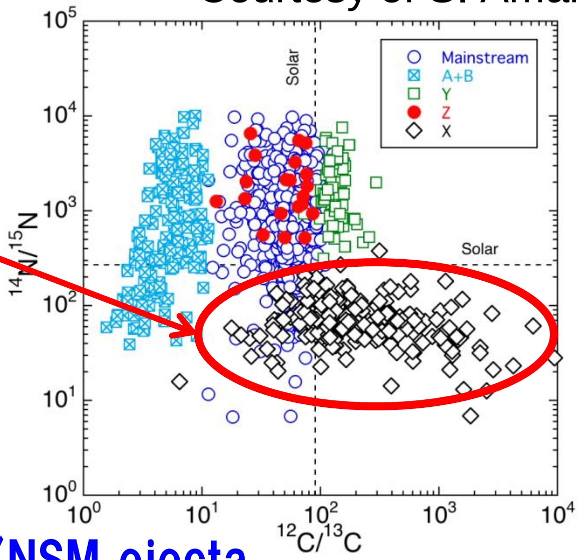
to find/confirm “EXTENDED UNIVERSALITY”

◎ Supernova Grains e.g. Murchison Meteorite

SiC X-grains



Courtesy of S. Amari



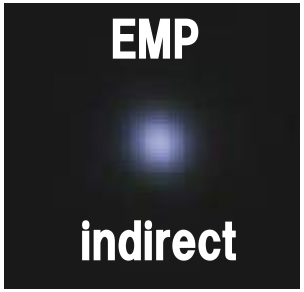
- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}=60$yr)

Pre-solar X-grains condense and form in SN/NSM ejecta.

- If SiC X-grain incl. much r-elements → NSM ? SN !
- If extended Universality manifests in [r/C-Si-Fe] = 0 → SN !
- If diversity in [r/C-Si-Fe] exists → SN !

◎ Spectr. Astron. Obs.

Direct detection of C, Si & r-elements simultaneously !



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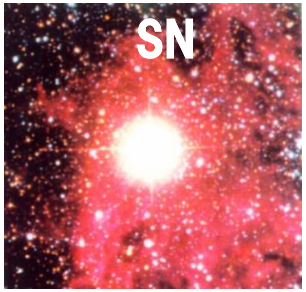

SUMMARY

★ **TIME-SCALE PROBLEM** of NSMs remains.
Galactic Chemo-Dynamical Evolution can PARTIALLY resolve this problem.

★ **UNIVERSALITY** in EMP☆ is satisfied only by SNe (νDW+MHDJ).

★ **S.S. r-elements need both SNe and NSMs.**

➡ **Evolution of ISOTOPIC Abundances takes the key !**

➡ **Pre-solar X-Grains (SiC+r nuclei) should be an evidence !**

⇒ Quest for Astronomy, Astrophysics and Cosmology

⇒ Quest for Nuclear Physics

SYNERGY among Astronomy, Cosmochemistry

and Nuclear Physics is highly desirable !