Special Lectures V
Theoretical Astronomy & Astrophysics

1. Cosmic & Galactic Evolution and Origin of Matter

Particle Cosmology
Dynamical Large-Scale Structure (LSS) Formation
Evolution of Matter (Chemical Evolution)

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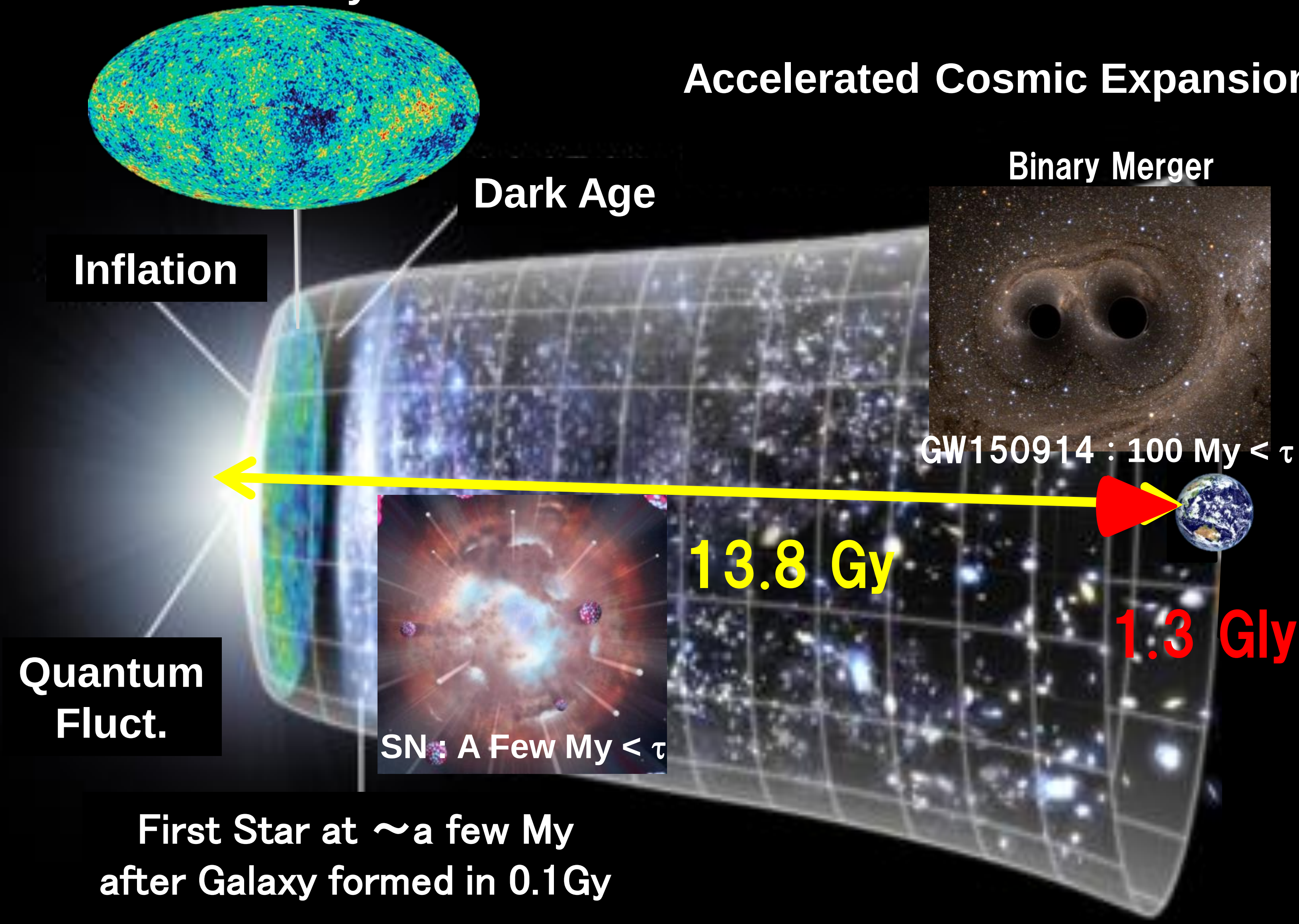
Cosmic Evolution



Photon Last Scatt.
3.8×10^5 y

Accelerated Cosmic Expansion

Dark Age

Inflation

Binary Merger

GW150914 : 100 My < τ

13.8 Gy

1.3 Gly

Quantum Fluct.

SN : A Few My < τ

First Star at ∼a few My
after Galaxy formed in 0.1Gy

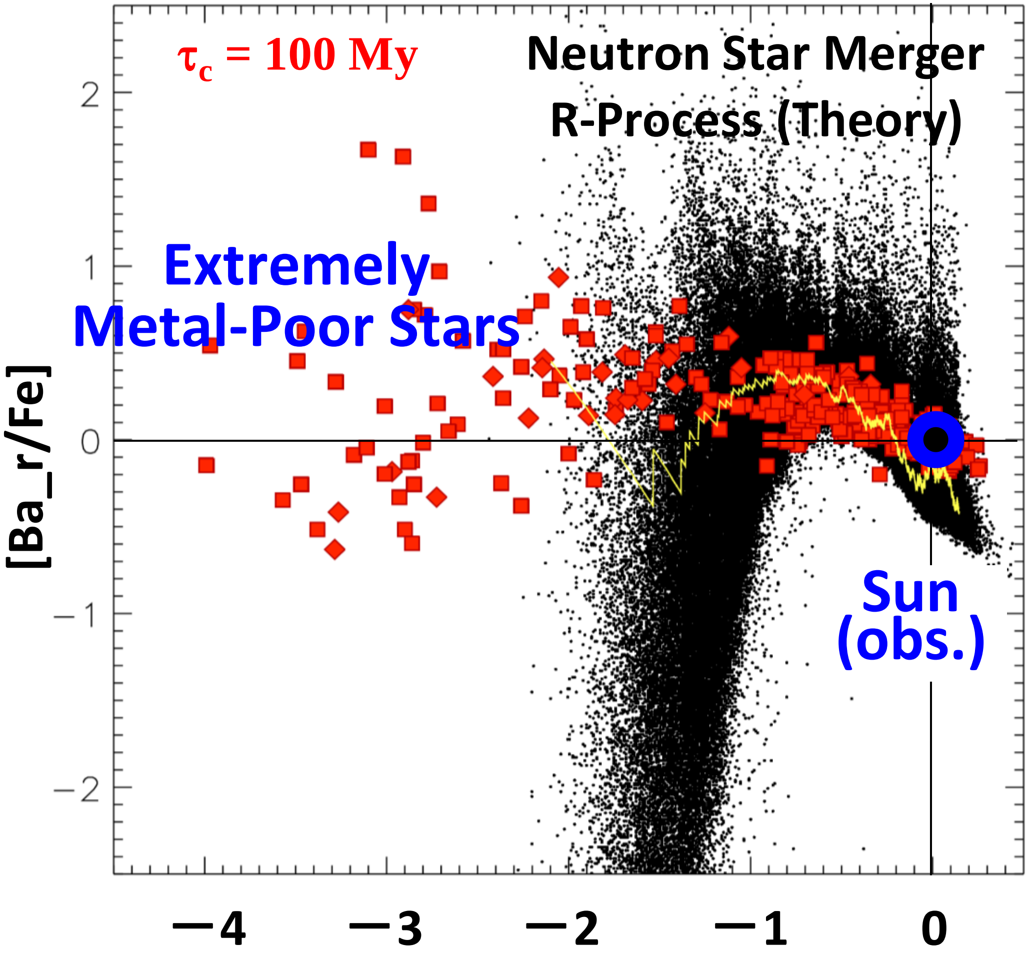
Galactic Chemo–Dynamical Evolution

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

Time Scale Problem

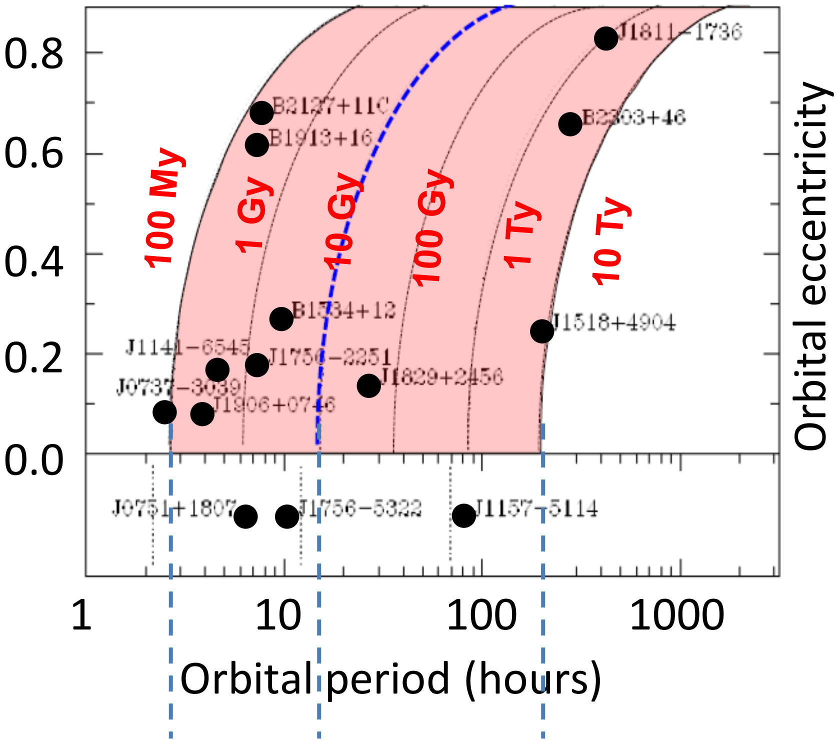
Argast, et al., A&A 416 (2004), 997,
Wehmeyer et al., MNRAS 452 (2015), 1970.

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

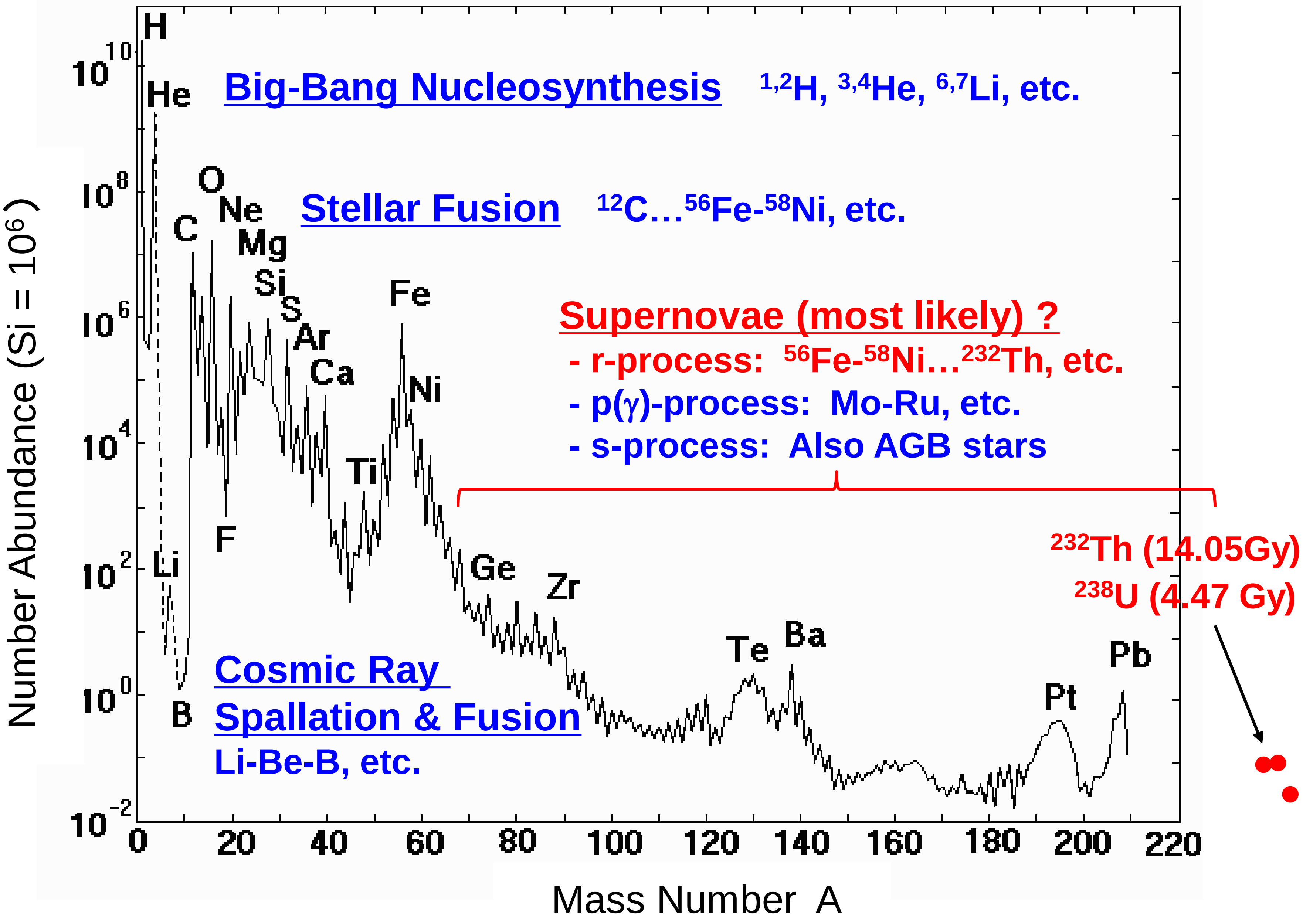


Life of Massive stars (20$M_\odot$)

1My 10My **100My ··· 10Gy**

100My 10Gy 10Ty

Atomic Nuclides – Solar System Abundance



Big-Bang Nucleosynthesis ^{1,2}H, ^{3,4}He, ^{6,7}Li, etc.

Stellar Fusion ^{12}C…^{56}Fe-^{58}Ni, etc.

Supernovae (most likely) ?

- r-process: ^{56}Fe-^{58}Ni…^{232}Th, etc.
- p(γ)-process: Mo-Ru, etc.
- s-process: Also AGB stars

^{232}Th (14.05Gy)
^{238}U (4.47 Gy)

Cosmic Ray Spallation & Fusion
Li-Be-B, etc.

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) ?

MHD Jet SNe ?

Winteler et al. (2012)

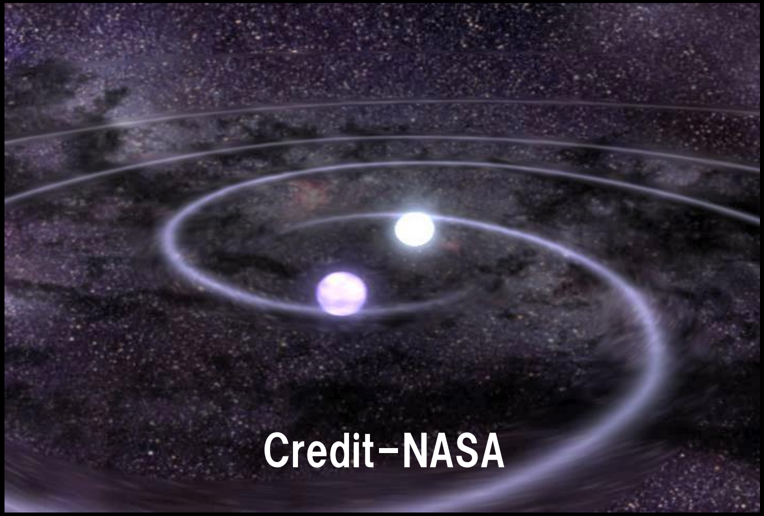
Binary Neutron-Star Mergers?

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).

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

Binary NSs arrive too late ?

Time Scale Problem ?



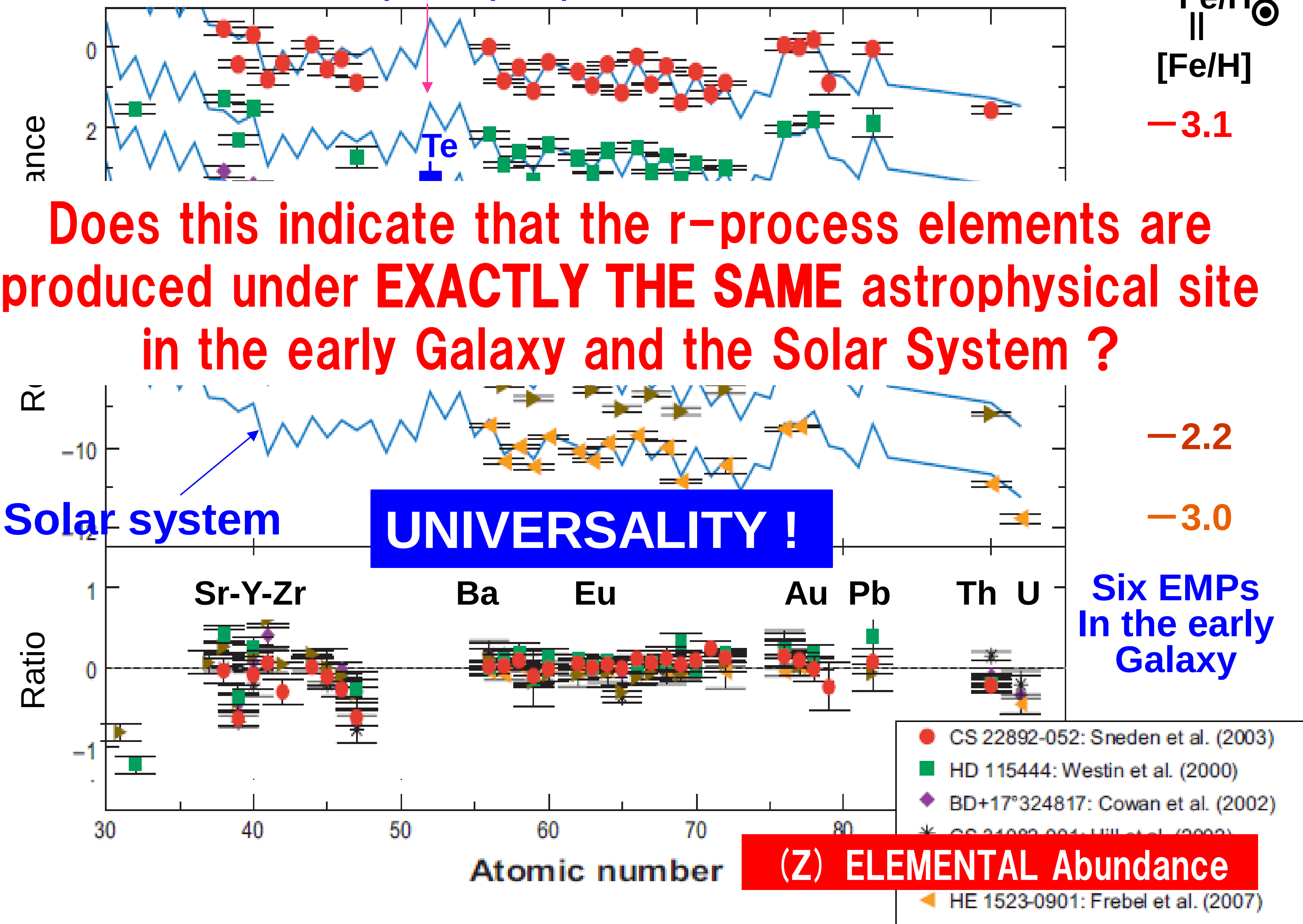
Credit-NASA

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

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

$$\frac{t}{10^{10}\mathrm{y}} \fallingdotseq 10^{[\mathrm{Fe/H}]}$$

$$\mathrm{Log}\ \frac{\mathrm{Fe/H}_{\star}}{\mathrm{Fe/H}_{\odot}} = [\mathrm{Fe/H}]$$



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

Solar system

UNIVERSALITY !

−3.1

−2.2

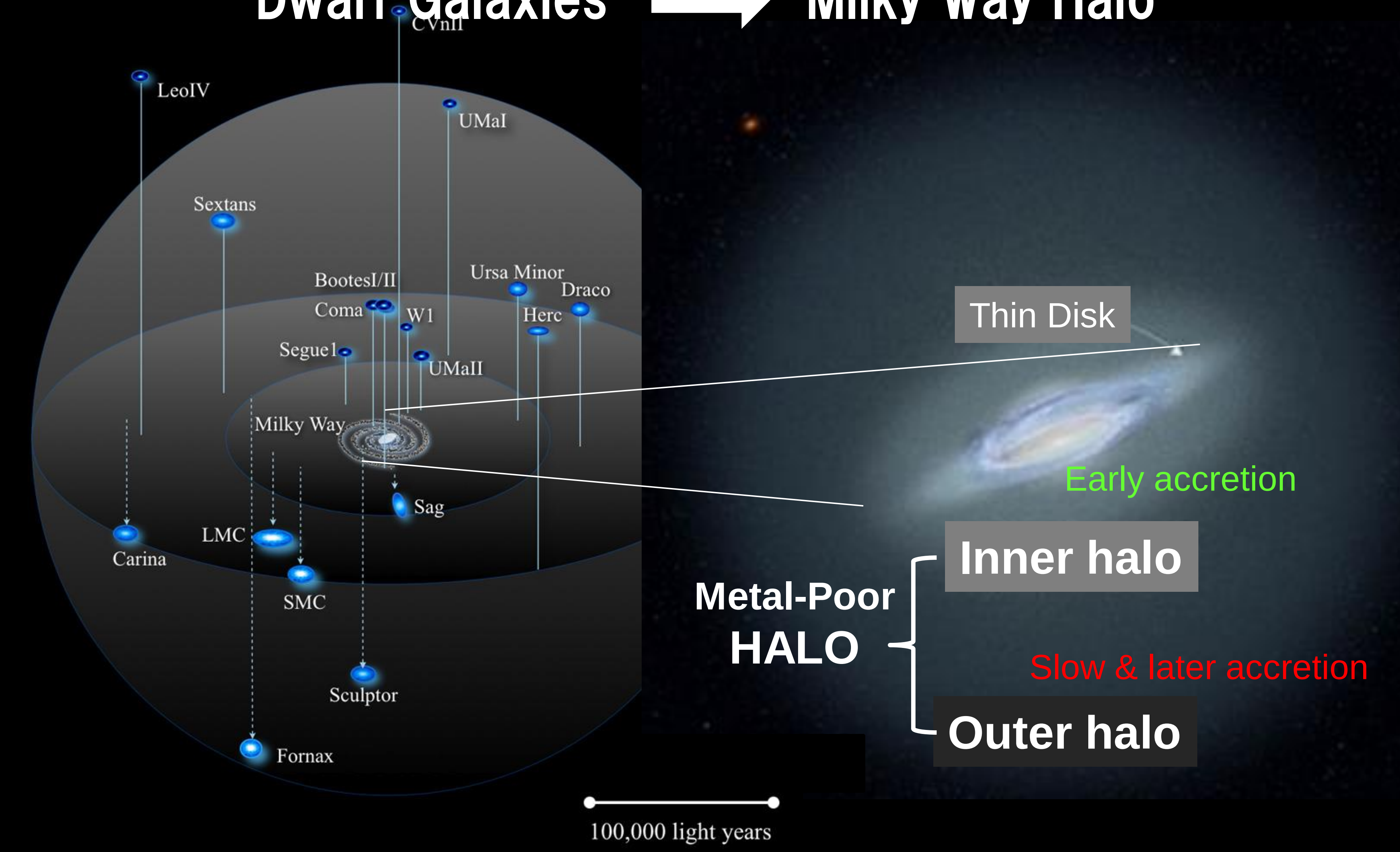
−3.0

Six EMPs In the early Galaxy

(Z) ELEMENTAL Abundance

Hierarchical Galactic Structure Formation

Dwarf Galaxies → Milky Way Halo



Thin Disk

Early accretion

Inner halo

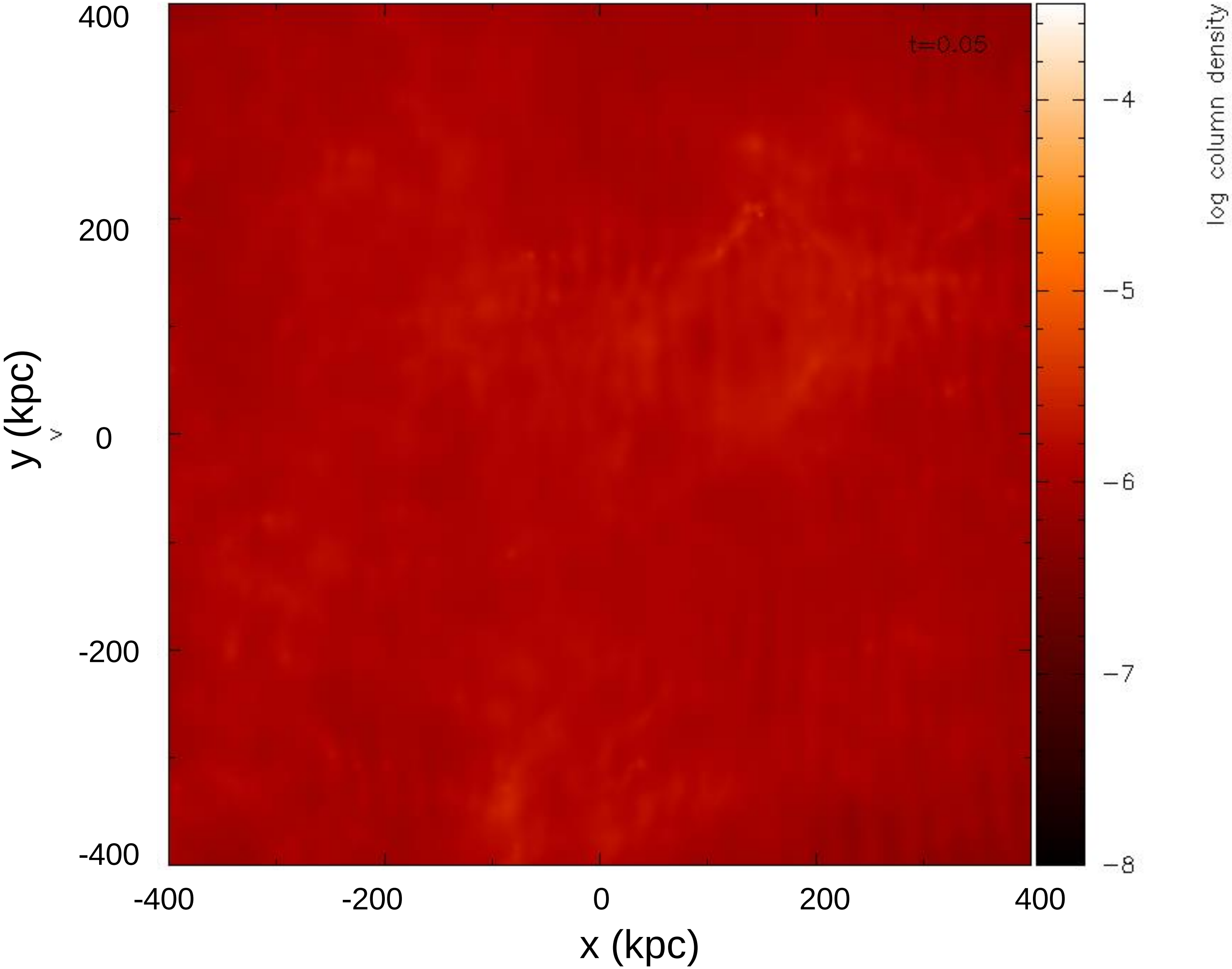
Metal-Poor
HALO

Slow & later accretion

Outer halo

N-Body Simulation of LSS Formation

X. Zhao & G. Mathews (2014)



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution

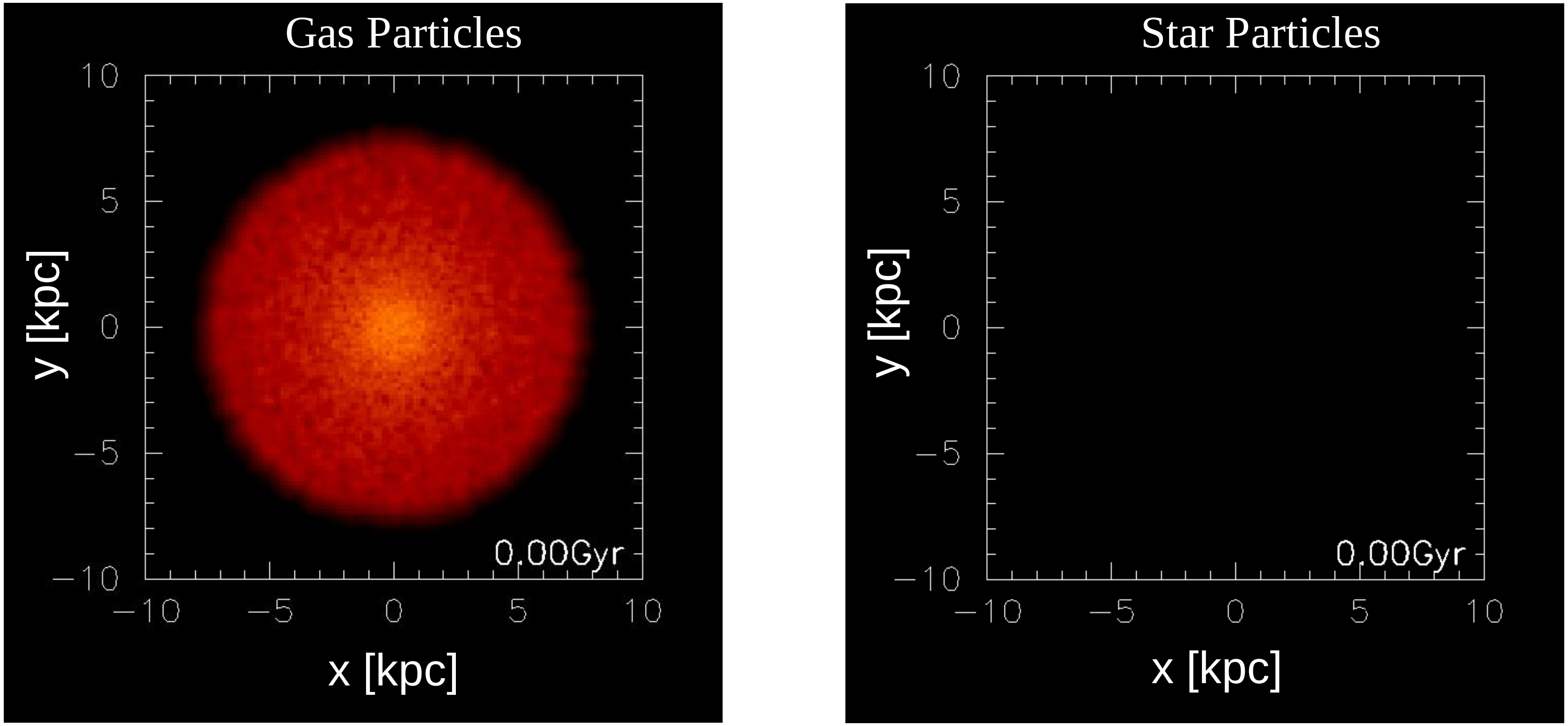
Dwarf Galaxies = Building Blocks of Milky Way Galaxy

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



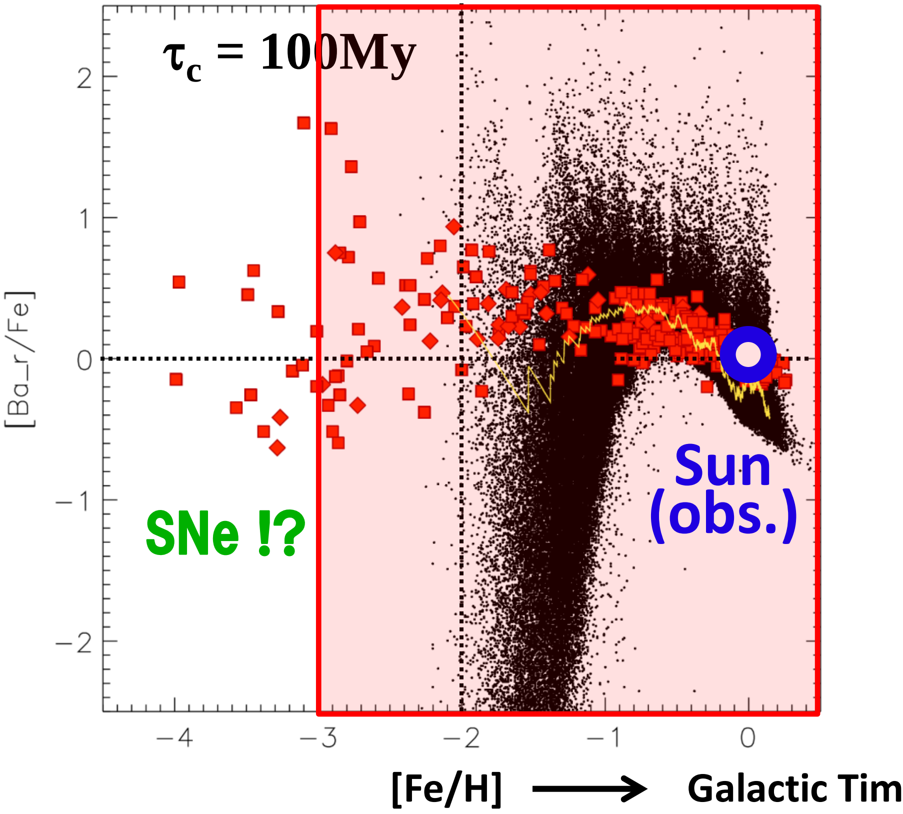
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Spheroidals

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)

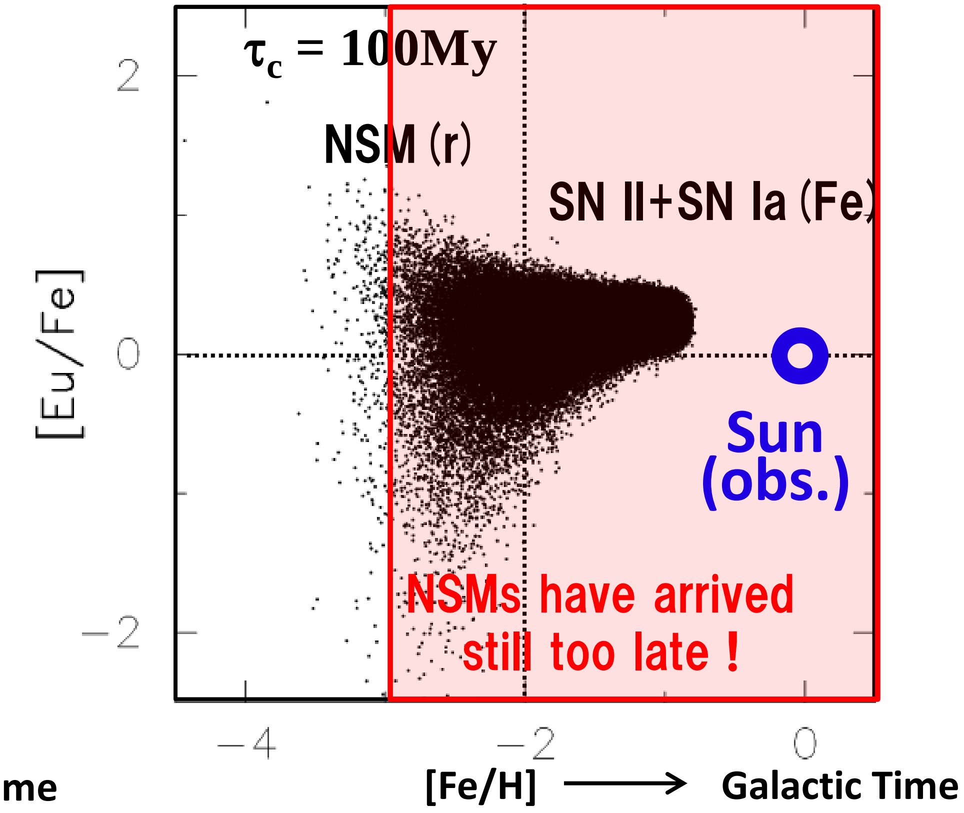
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

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

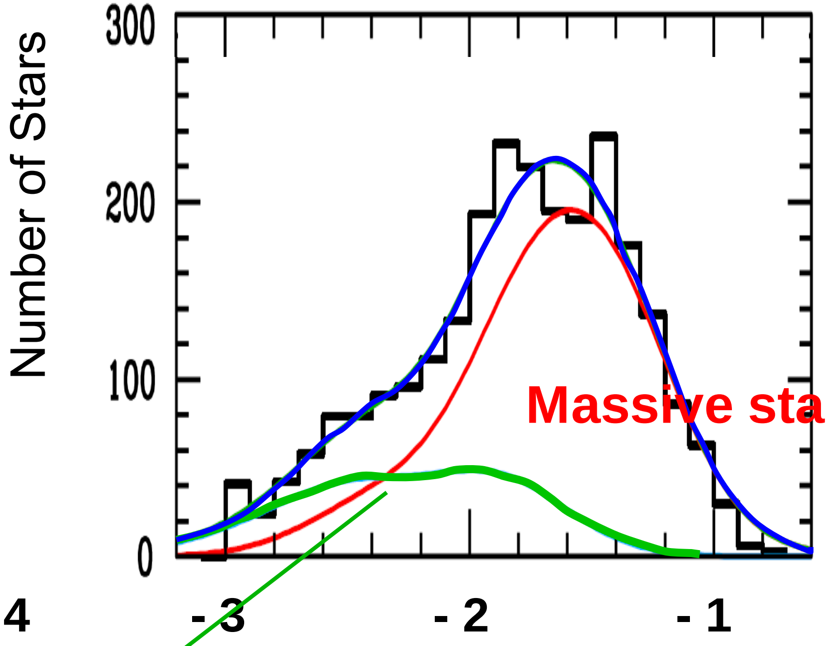
Without GAS MIXING



With GAS MIXING



Observational Data of Milky Way HALO



SDSS Survey
An et al.
ApJ 763 (2013), 65

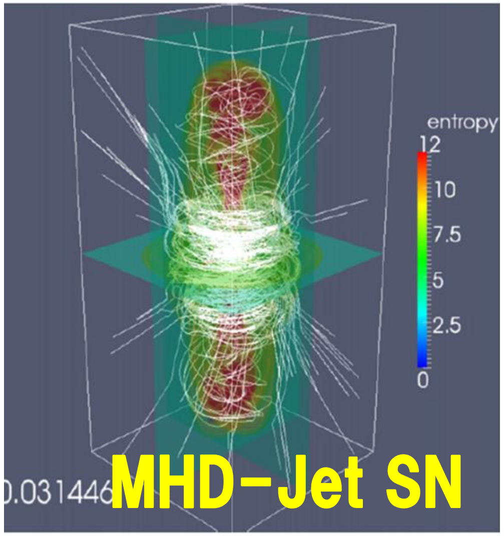
Massive stars ⇒ SNe & NSMs

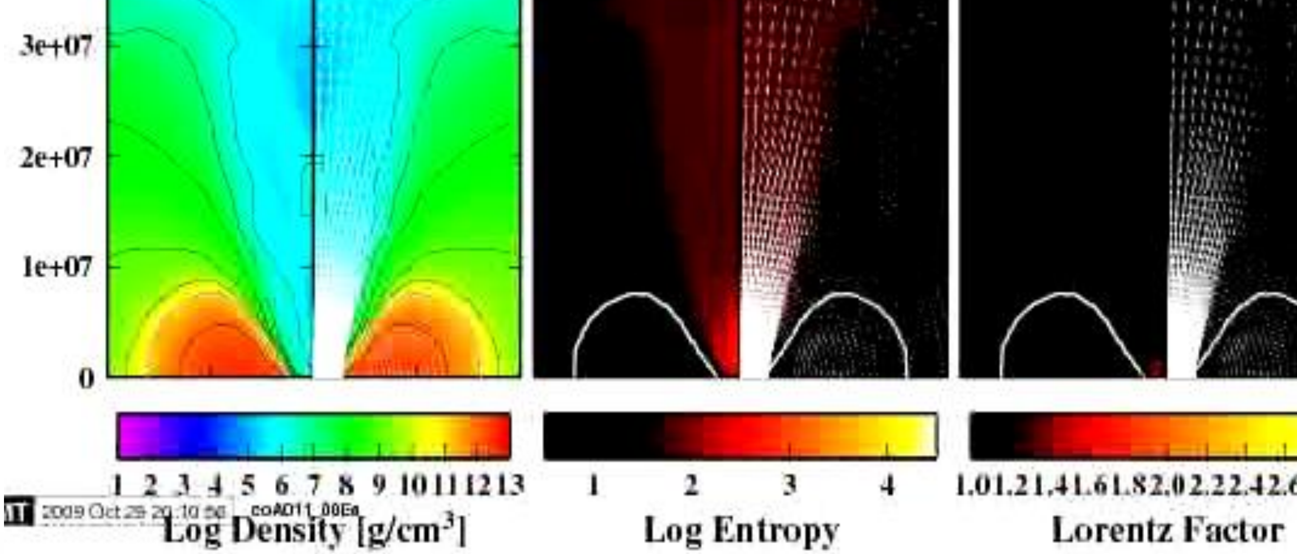
Extremely metal-poor component

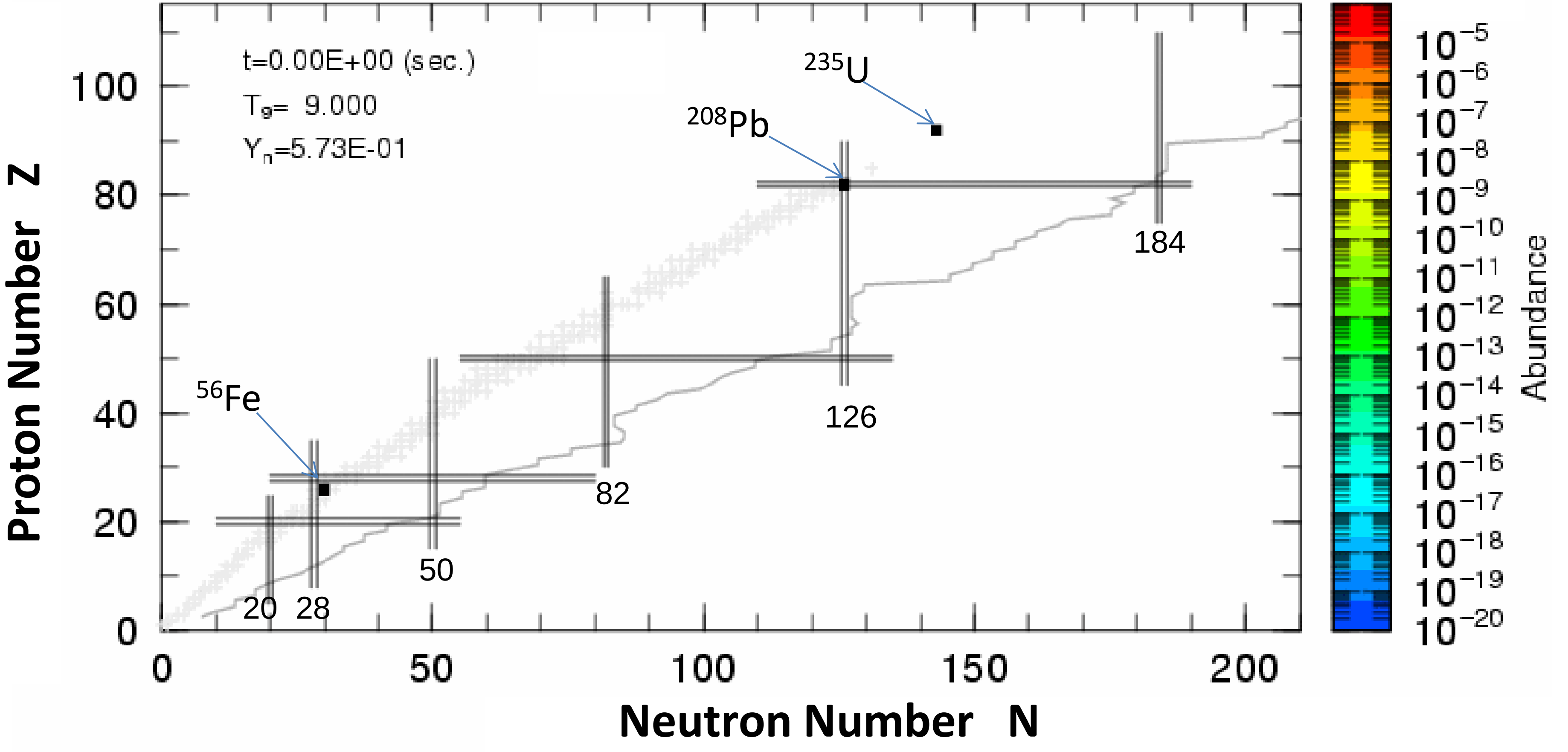
Binary Neutron-Star Mergers have arrived too late.

SNe !

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


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

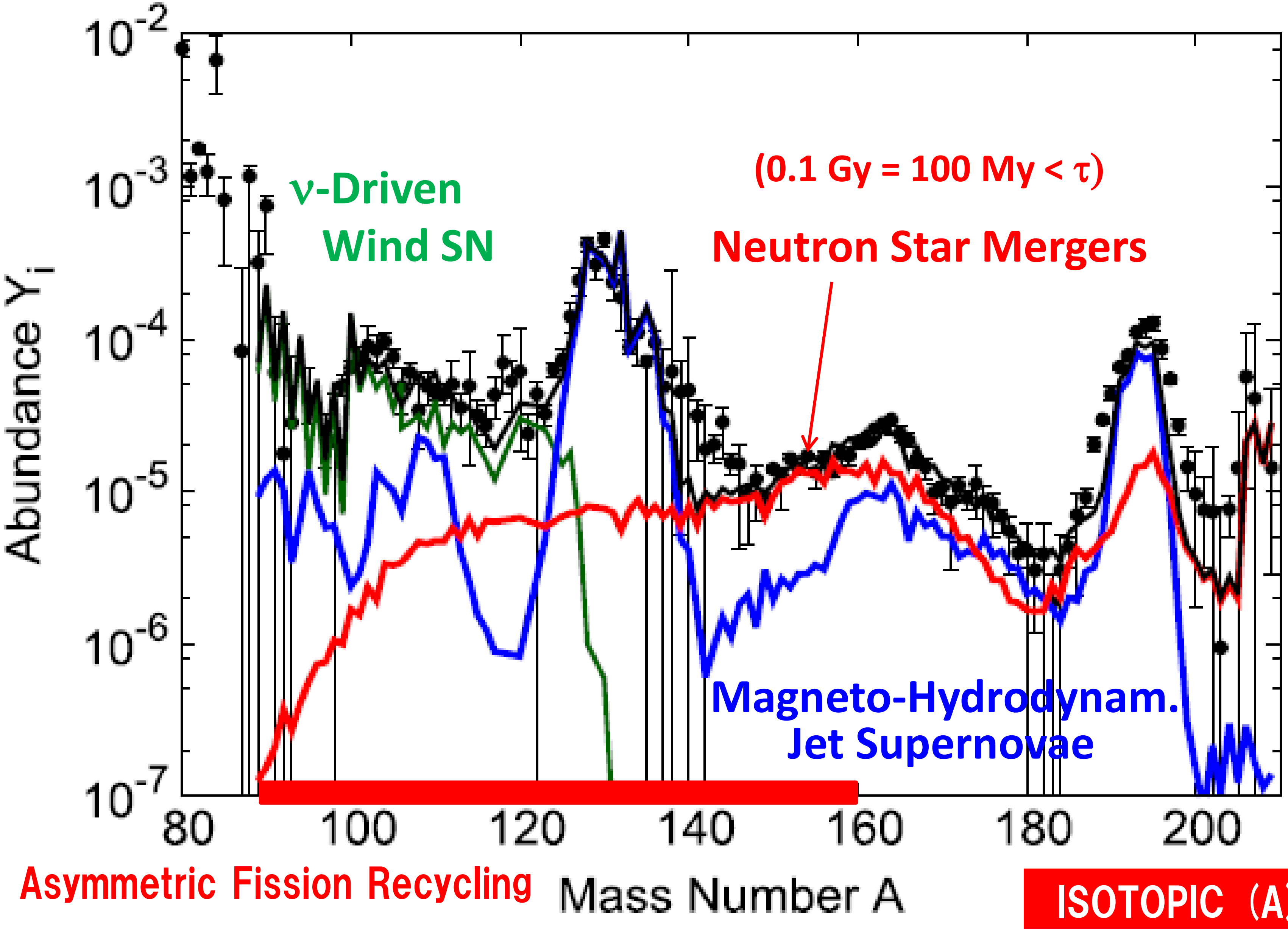

3e+07
2e+07
1e+07
0
1 2 3 4 5 6 7 8 9 10 11 12 13
1 2 3 4
1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
2009 Oct 28 20:10:58 coA011_00Ea
Log Density [g/cm³]
Log Entropy
Lorentz Factor


t=0.00E+00 (sec.)
T₉= 9.000
Yₙ=5.73E-01
²³⁵U
²⁰⁸Pb
⁵⁶Fe
20
28
50
82
126
184
0
20
40
60
80
100
0
50
100
150
200
Proton Number Z
Neutron Number N
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
Abundance

Solar System r-Process Abundance

TODAY t = 13.8Gy

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



ν-Driven Wind SN

(0.1 Gy = 100 My < τ)

Neutron Star Mergers

Magneto-Hydrodynam. Jet Supernovae

Asymmetric Fission Recycling

ISOTOPIC (A) !

Basics of Theoretical Astronomy and Astrophysics – 1
Sept. 26, 2016

Galactic Chemical Evolution

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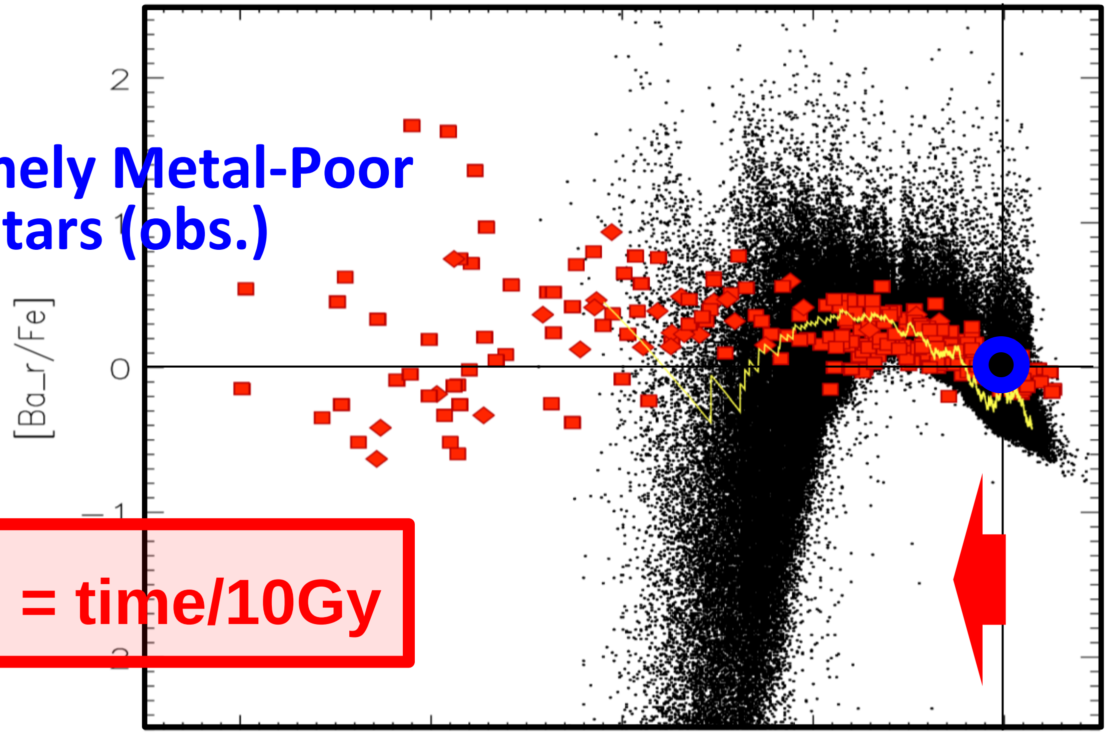


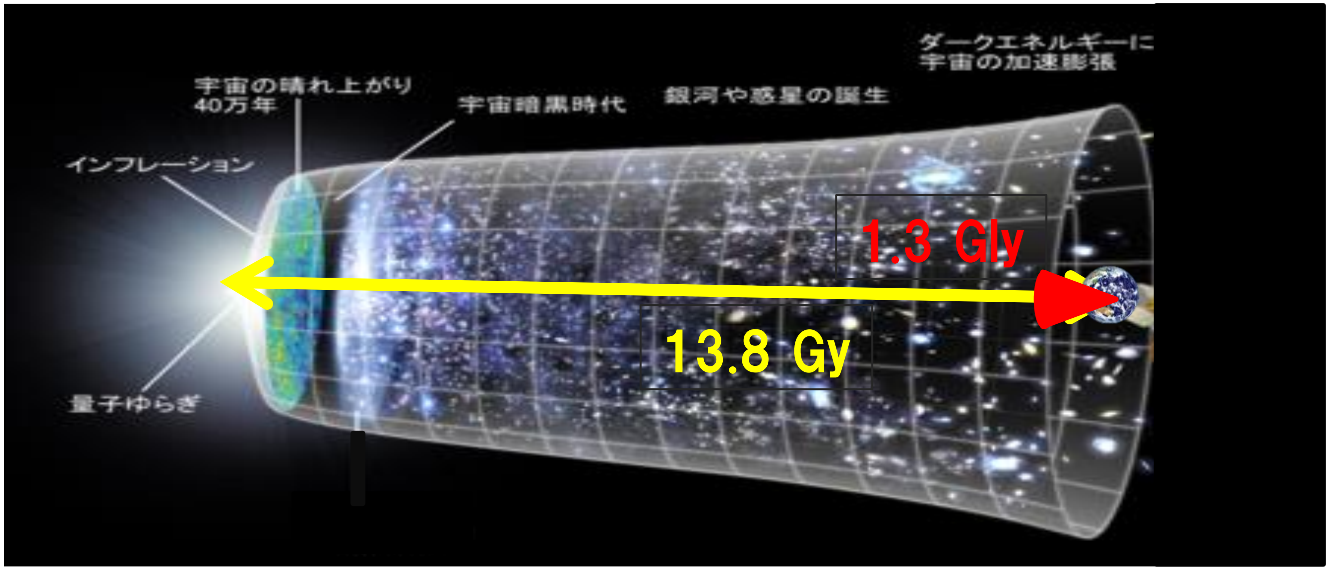
Extremely Metal-Poor Stars (obs.)

Sun (obs.)

BH Merger
at d=1.3 Gly

$10^{[Fe/H]}$ = time/10Gy

−∞	−4	−3	−2	−1	0	[Fe/H]
Big-Bang	1My	10My	100My	1Gy	13.8Gy	time



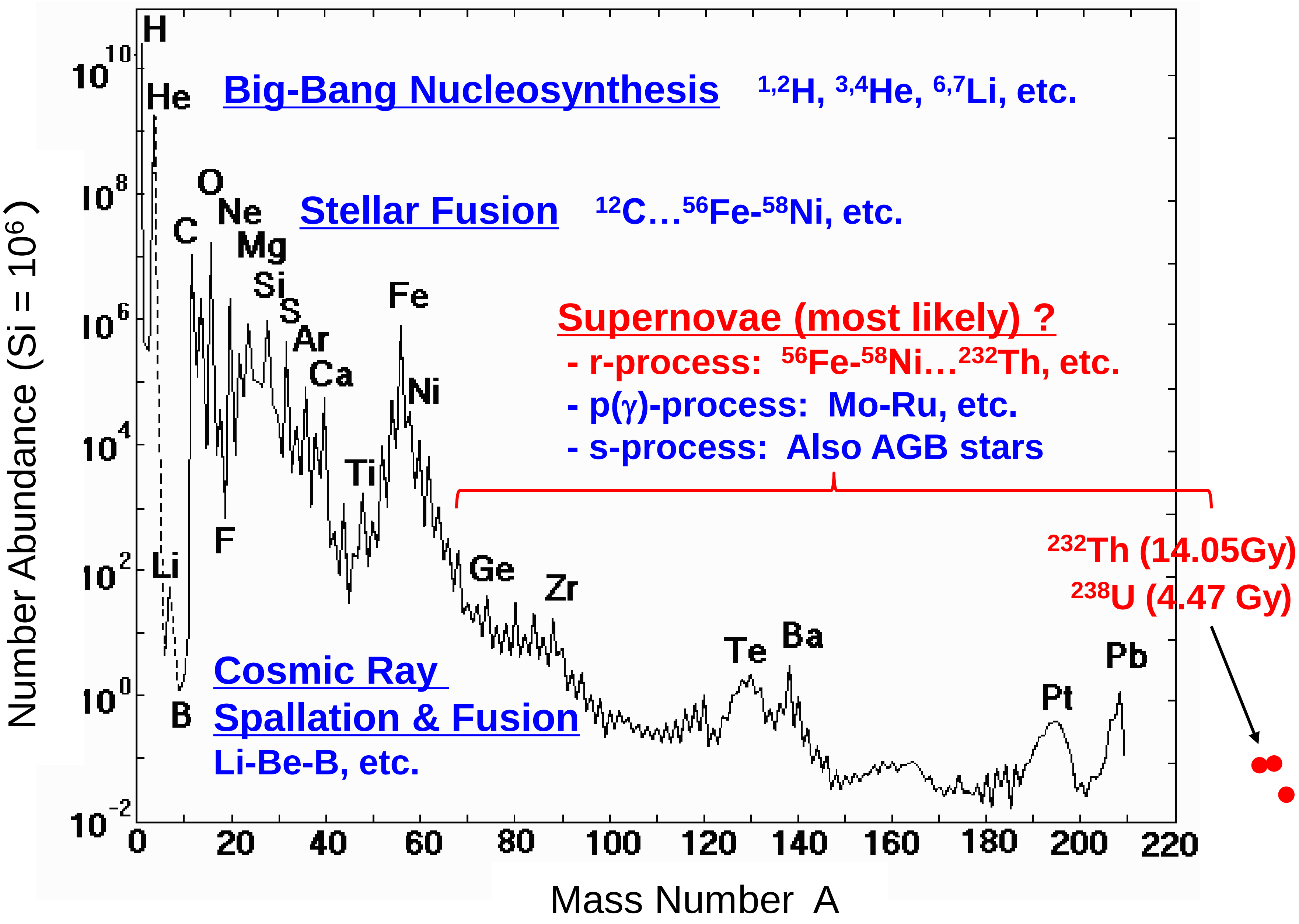
TIME SCALE of Cosmic & Galactic Evolution

Variation of elemental abundances takes the keys
to solve Cosmic Chemical Evolution!

Birth of the Universe (t=0) → Big-Bang Nucleosynthesis (3m)
→ Photon Last Scattering ($3.8\text{x}10^5$y) → 1st Stars (1Gy)
→ Stellar Evolution → Supernovae → 2nd gen. Stars → ・・・
→ Formation of the Solar System (10Gy)

Today' s Purpose:-
is to construct a relation between
"Elemental Abundances" and "Cosmic Time" !

Solar System Abundance



Big-Bang Nucleosynthesis ^{1,2}H, ^{3,4}He, ^{6,7}Li, etc.

Stellar Fusion ^{12}C…^{56}Fe-^{58}Ni, etc.

Supernovae (most likely) ?

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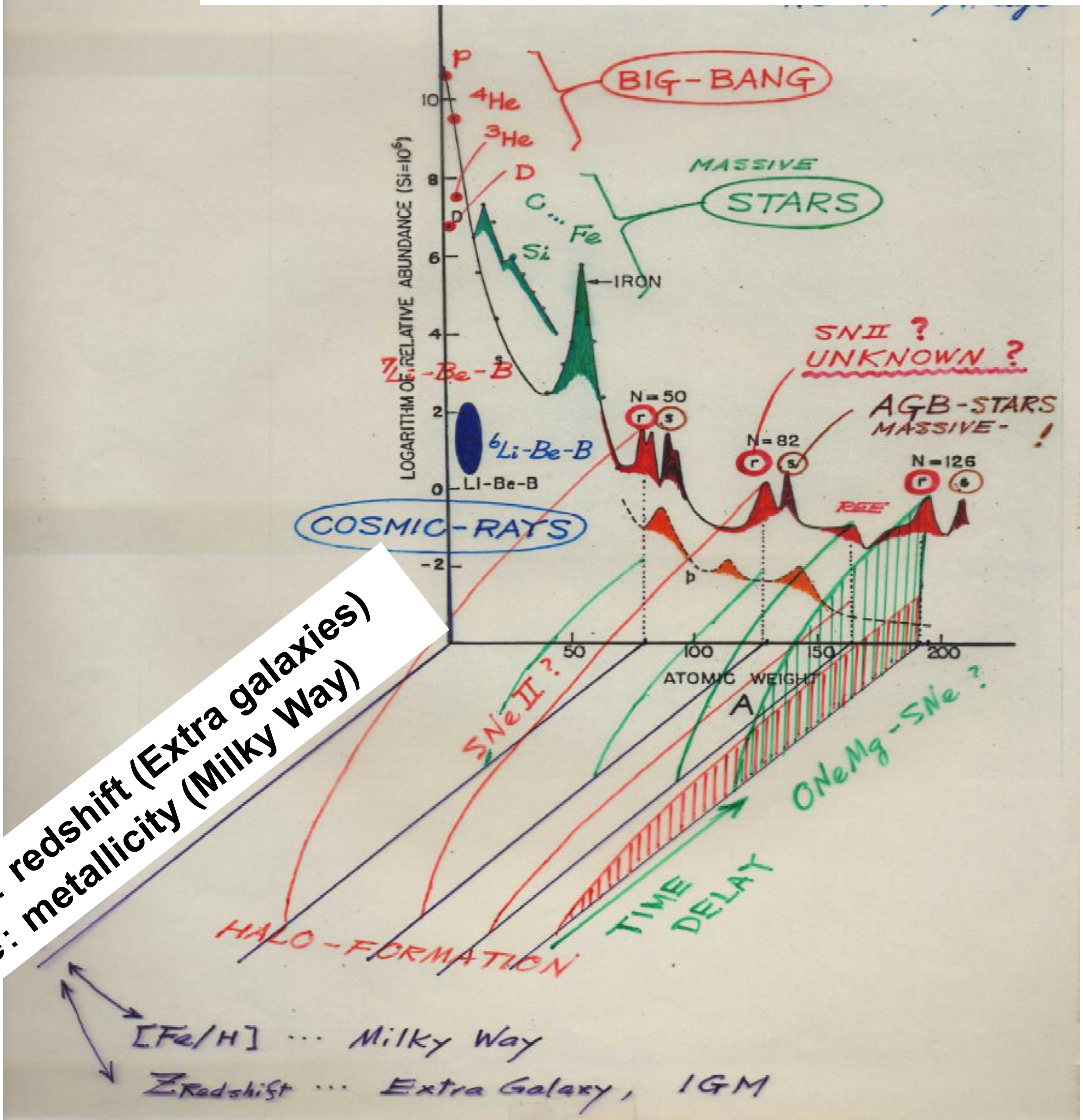
- s-process: Also AGB stars

^{232}Th (14.05Gy)
^{238}U (4.47 Gy)

Cosmic Ray Spallation & Fusion
Li-Be-B, etc.

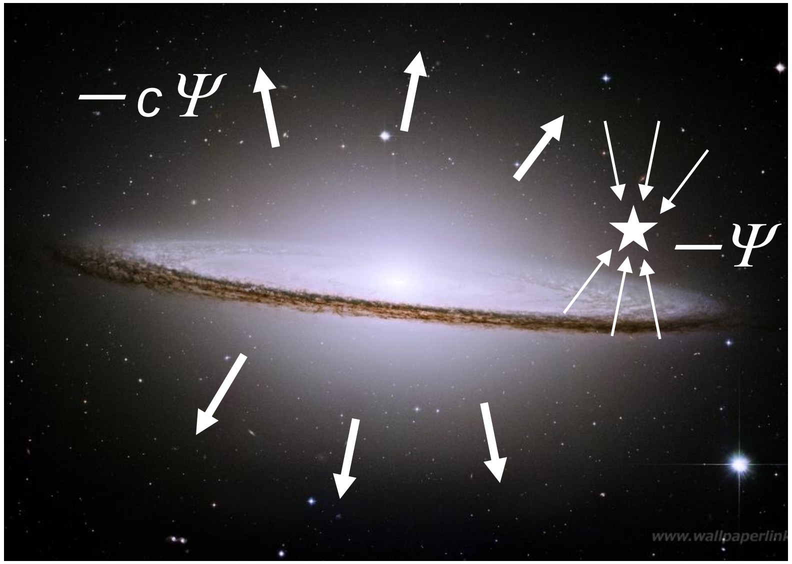
Solar system formation（before4.56Gy）～present



Cosmic time：redshift (Extra galaxies)
Abundance：metallicity (Milky Way)

Simple Galactic Chemical Evolution (GCE) Model

http://www.kabegamilink.com/act/0704/03242.html



Halo-Gas (M_G) and **Stars** ($M_{tot} - M_G$)

- Z_i = Mass Fraction of Nucleus-*i*
- y_i = Stellar Production Yield
- Ψ = Star Formation Rate
- ϕ = Galactic Cosmic Ray
- $c\Psi$ = Galactic Wind
- R = Returned Fraction $R = \sum R_i Z_i$

$$\left\{\begin{aligned}
&\frac{dM_{tot}}{dt} = -c\Psi && (1)\\
&\frac{dM_G}{dt} = -(1-R+c)\Psi && (2)\\
&\frac{d(M_G Z_i)}{dt} = y_i\Psi - (1-R+c)\Psi Z_i && (3)\\
&\frac{d(M_G Z_L)}{dt} = y_L\Psi + M_G \sum_j Z_j\left(\frac{A_L}{A_j}\right)\langle\sigma_{jL}\phi\rangle - (1-R+c)\Psi Z_L && (3')
\end{aligned}\right.$$

Stellar Production

GCR production

Local → Global Model

$$\Psi(t) = \iiint_{HALO} \varphi(\vec{r},t)\, d\vec{r}, \qquad M_G(t) = \iiint_{HALO} \rho_G(\vec{r},t)\, d\vec{r}$$

$[M_\odot/y]$ $[M_\odot/y/L^3]$

Three-ASSUMPTIONS in simple GCE Model

(1) Homogeneous Mixing & Instantaneous Recycling

SNe evolve rapidly in 10^6—10^7y which is much shorter than the time scale of Cosmic and Galactic chemical evolution 10^9 – 10^{10}y.

(2) Star formation rate (SFR=Ψ) ∝ (Gas-Mass=M_G)^n

n=1: Tinsley’s law for the halo stars
n=2; Schmidt’s law for the disc stars

(3) Cosmic Ray=Φ ∝ SFR=Ψ

$$\frac{d(M_G Z_i)}{dt} = \int_{0.08 M_\odot}^{60 M_\odot} dm \left(q_i(m) - q_i^{(rem)}(m) \right) \phi_{IMF}(m)\, \psi(t - \tau(m))$$

$$- Z_i \psi(t)$$

$$+ R Z_i \psi(t)$$

$$- c Z_i \psi(t)$$

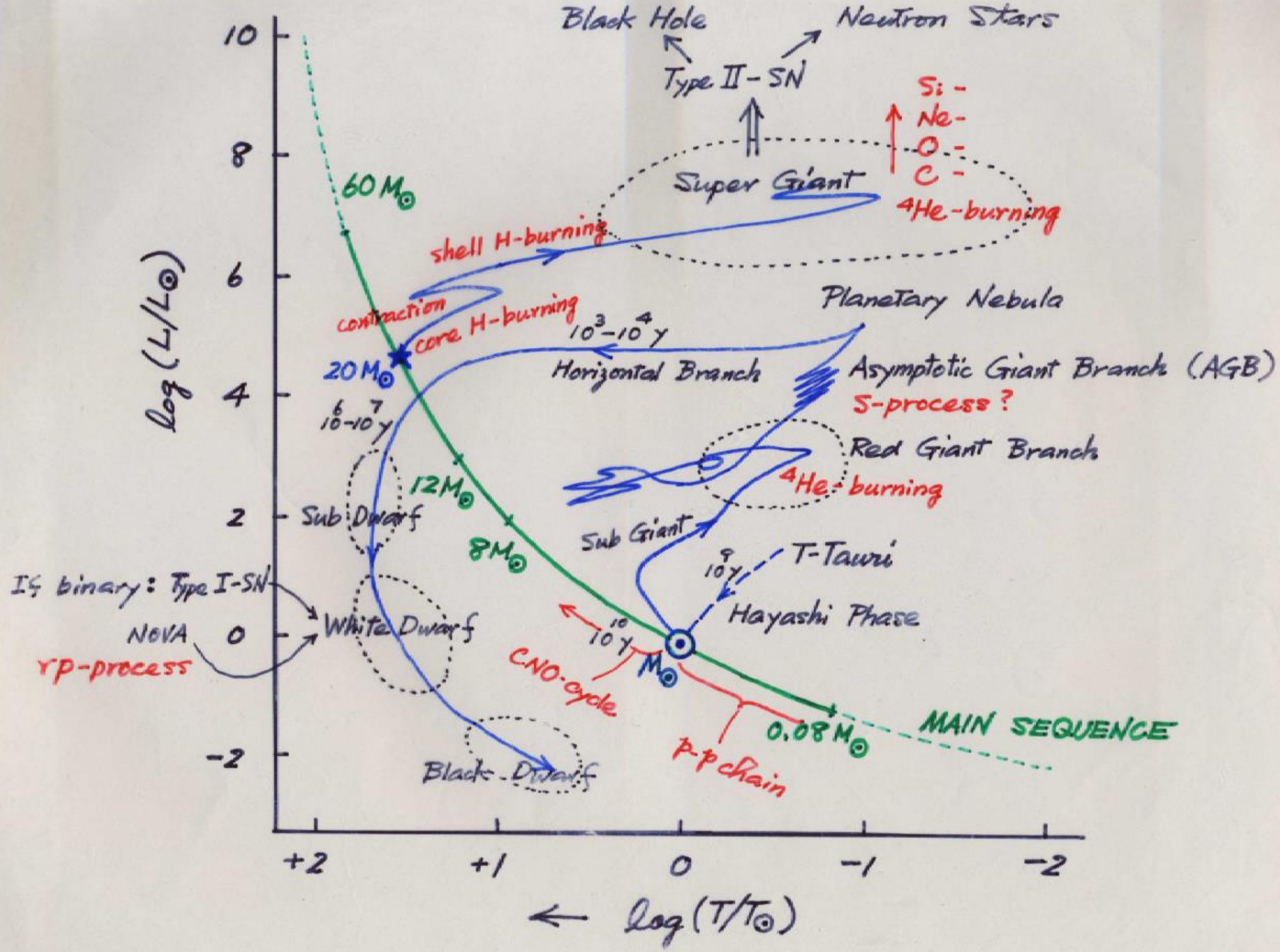
$$- \frac{1}{\tau_i} M_G Z_i + \sum_{j \neq i} \frac{1}{\tau_j} M_G Z_j$$

Biggest contribution from MASSIVE STARS (SNe)

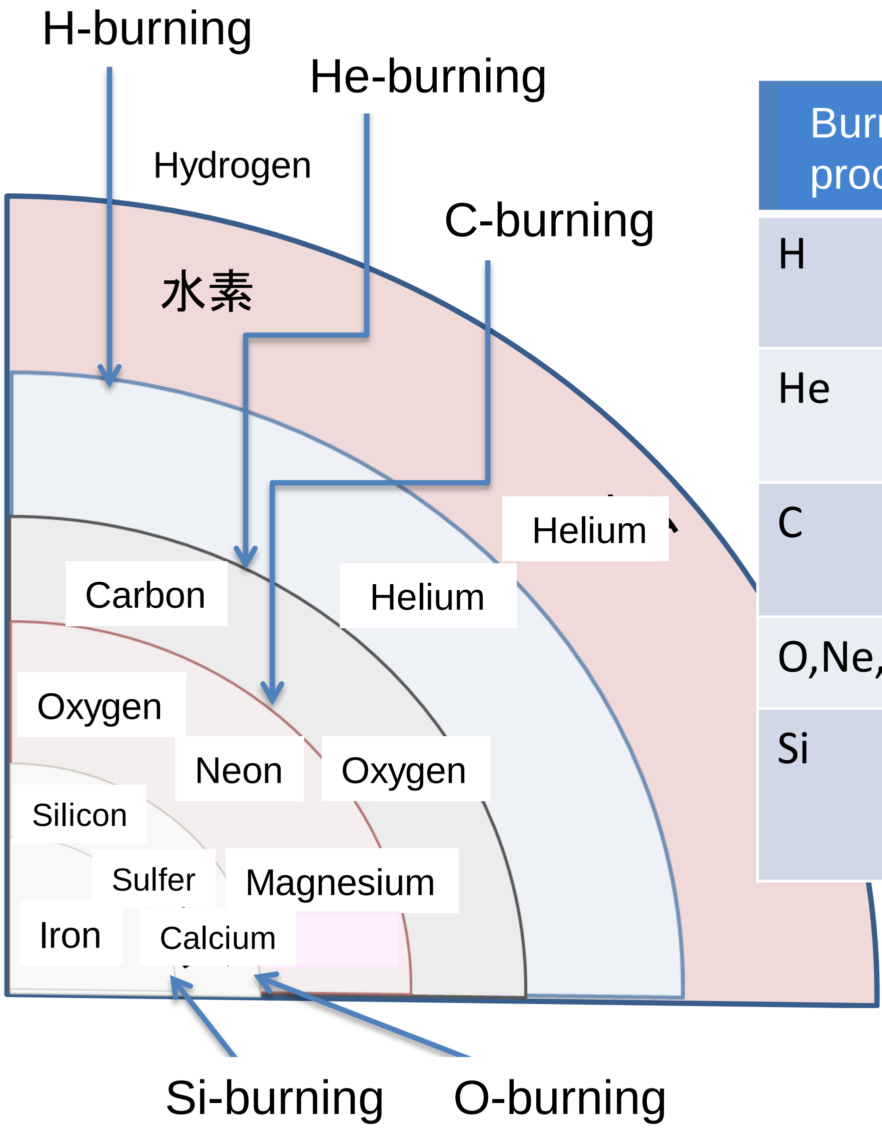
with $\tau(m)=10^6$-10^7 y << t ~ 10^{10} y → **Instanteneous Recycling**

$$\frac{d(M_G Z_i)}{dt} \approx \underbrace{\left[\int dm \left(q_i - q_i^{(rem)} \right) \phi_{IMF}(m) \right]}_{} \times \psi(t)$$

y_i = elemental production yield

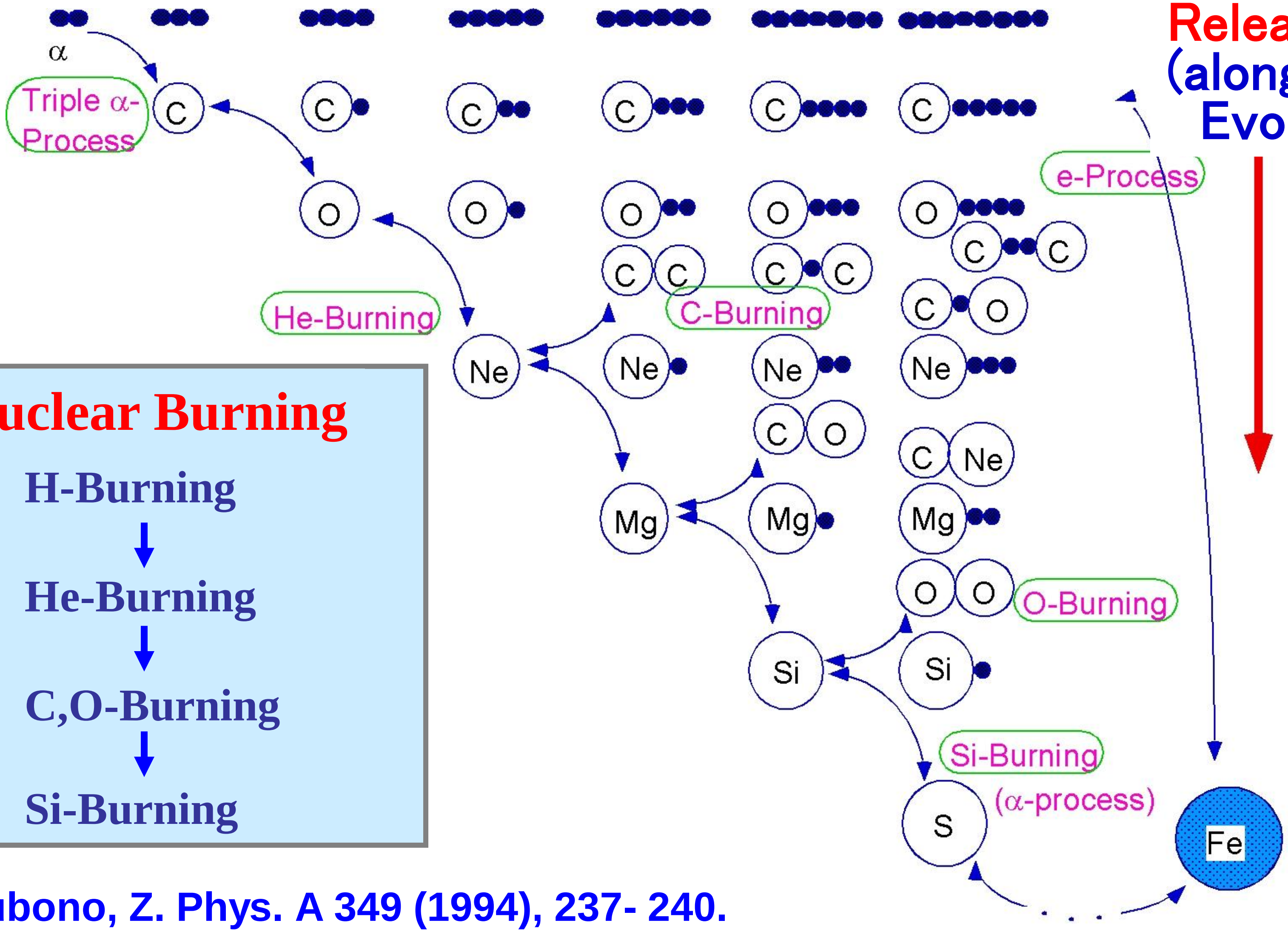

Black Hole
Neutron Stars
Type II - SN
Si -
Ne -
O -
C -
Super Giant
4He-burning
shell H-burning
60 M⊙
Planetary Nebula
contraction
core H-burning
10^3 - 10^4 y
Horizontal Branch
Asymptotic Giant Branch (AGB)
S-process ?
20 M⊙
10^6 - 10^7 y
Red Giant Branch
4He-burning
12 M⊙
Sub Dwarf
Sub Giant
8 M⊙
10^9 y
T-Tauri
If binary: Type I-SN
Hayashi Phase
NOVA
rp-process
White Dwarf
10^10 y
CNO-cycle
M⊙
0.08 M⊙
MAIN SEQUENCE
p-p chain
Black Dwarf
log (L/L⊙)
10
8
6
4
2
0
-2
+2
+1
0
-1
-2
← log (T/T⊙)

Stellar Evolution of Massive Stars
→ Supernova Explosion



Burning process	Main reaction processes	Final product	T (10^8K)
H	pp chain CNO cycle	^{4}He	0.15 0.2
He	$3\alpha \rightarrow {}^{12}\mathrm{C}$ ${}^{12}\mathrm{C}+\alpha \rightarrow {}^{16}\mathrm{O}$	^{12}C ^{16}O	1.5
C	${}^{12}\mathrm{C}+{}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne}+\alpha$ $\rightarrow {}^{24}\mathrm{Mg}$	^{20}Ne ^{24}Mg	7
O,Ne,Mg	${}^{16}\mathrm{O}+{}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si}+\alpha$	^{28}Si	>15
Si	${}^{28}\mathrm{Si}+\alpha \rightarrow {}^{32}\mathrm{S}$	^{56}Fe	40

Cluster Nucleosynthesis Diagram (CND)



Energy Release (along Evolution)

Nuclear Burning

H-Burning
↓
He-Burning
↓
C,O-Burning
↓
Si-Burning

S. Kubono, Z. Phys. A 349 (1994), 237- 240.

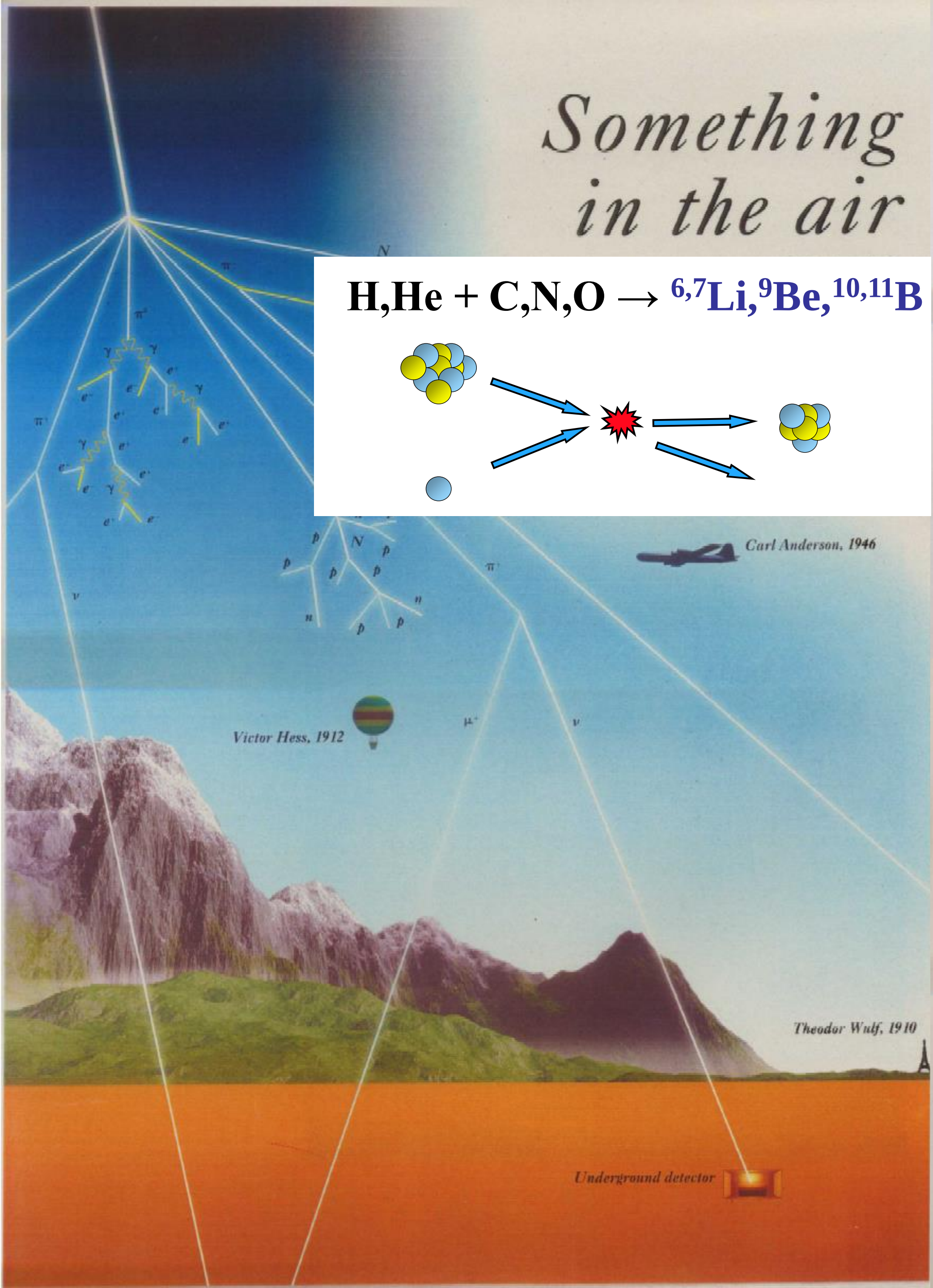
Time – Metallicity Relation Observable Measure.

$$[\mathrm{Fe/H}] = \log(\mathrm{Fe/H}) - \log(\mathrm{Fe/H})_\odot$$

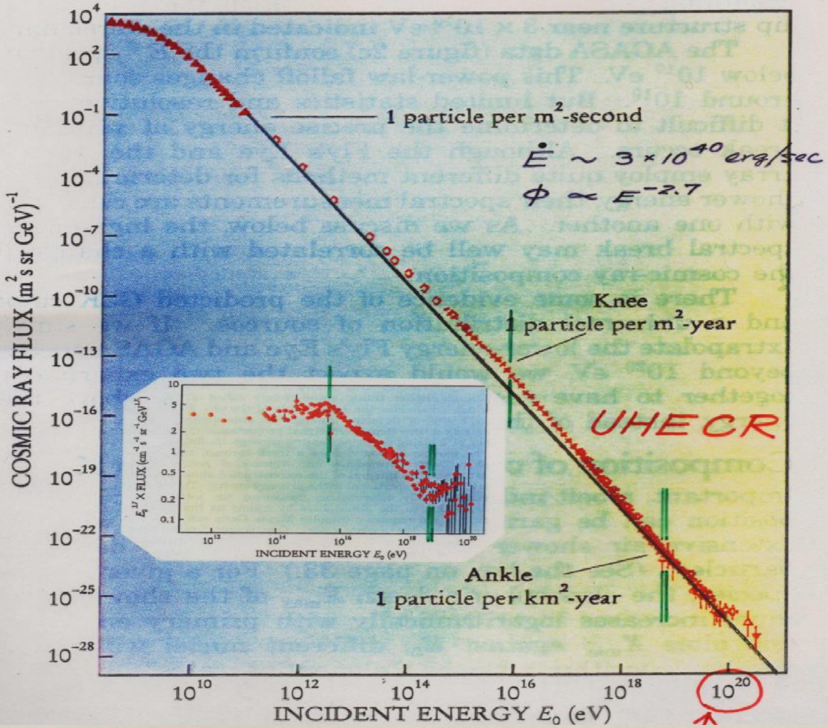
4.56 Gy

[Fe/H]	- ∞ ···	-5.4	-3	-2	-1	0
Cosmic time = t	0 ···	Early Universe	10My	100My	1Gy	10Gy
Redshift = z	+ ∞ ···	~1000	~100	~20	~4	0

$$a \propto (1+z)^{-1} \propto t^{2/3} \quad \therefore \ (t/13.7\mathrm{Gy})^{2/3} = 1/(1+z)$$



$H,He + C,N,O \rightarrow {}^{6,7}Li, {}^{9}Be, {}^{10,11}B$



$\dot{E} \sim 3 \times 10^{40}$ erg/sec

$\phi \propto E^{-2.7}$

UHECR

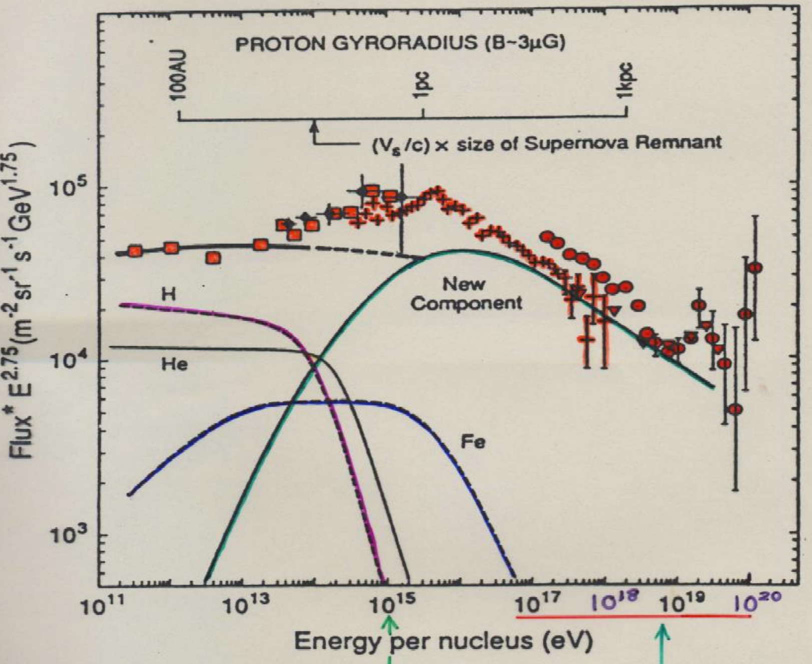


Fig. 6. All-particle spectrum (E per nucleus)

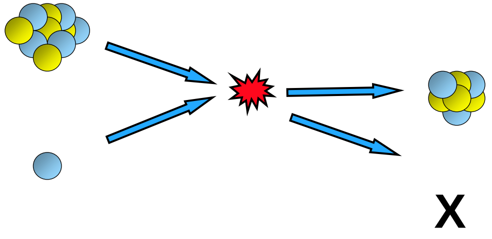
LiBeB-Production in Spallation or Fusion Reactions

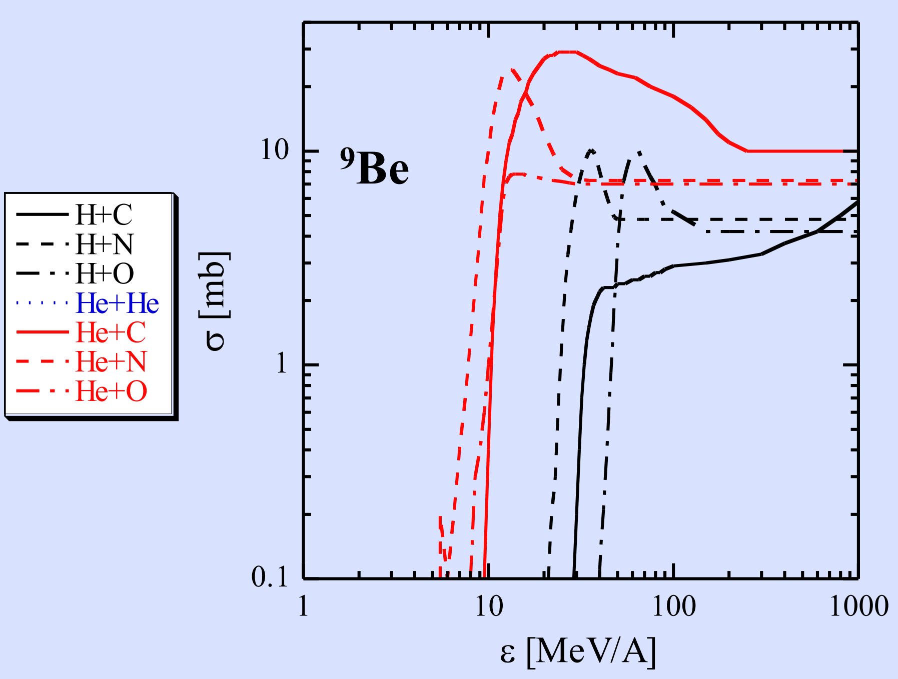
Example: O+H → Be

$$\left[\frac{d(M_G Z_L)}{dt}\right]_{GCR} = \sum_j Z_j \left(\frac{A_L}{A_j}\right) \int \sigma_{jL}\, \phi\, dE$$

Target Nucleus in ISM *Cross Section* *GCR Flux Energy Spectrum*

H,He + C,N,O → ^{6,7}Li, ^{9}Be, ^{10,11}B





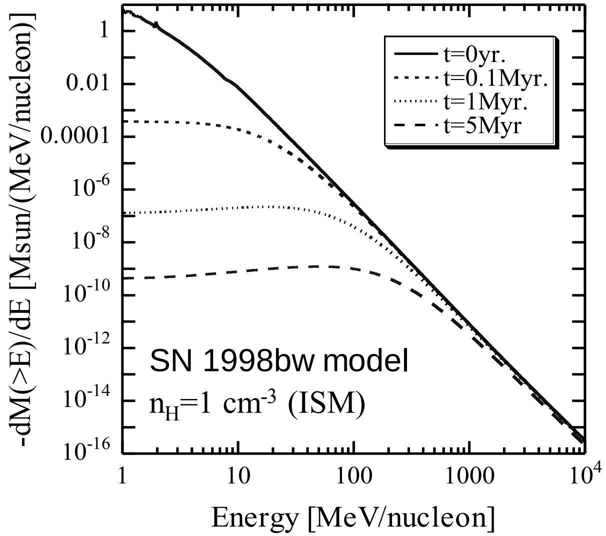
Cross sections
(Read & Viola 1984; Mercer+ 2001)

Transport equation

$$\frac{\partial F_i(E,t)}{\partial t} = \frac{\partial[\omega_i(E)F_i(E,t)]}{\partial E} - \frac{F_i(E,t)}{\Lambda}\rho v_i(E)$$

ω_i : energy loss rate (ionization)

Λ : loss length (spallation & escape)



GALACTIC COSMIC-RAY PROPAGATION

$$\begin{cases} \text{EVOLUTION} : & \tau_G \sim 1\ \text{Gyr} \sim 10^9\ \text{yr} \\ \text{PROPAGATION} : & \tau_p \sim \dfrac{10\ \text{kpc}}{c} \sim 10^4\ \text{yr} \end{cases}$$

⇒ STEADY STATE APPROX. (for p & α)

$$\frac{\partial N(E)}{\partial t} \approx 0 \approx -\frac{N(E)}{\tau_e} - \frac{\partial}{\partial E}\left[b(E)N(E)\right] + Q(E)$$

$$\cancel{-\left\{\sigma_{\alpha i}(E)\, n_{He} + \sigma_{pi}\, n_H\right\}\cdot v \cdot N(E)} \quad \text{small}$$

$$\phi(E) = N(E)\cdot v$$

$$\therefore\ 0 \approx -\frac{\phi(E)}{\Lambda} + \frac{\partial(W\phi)}{\partial E} + q(E) \text{ ——— } (\bigstar)$$

$$\frac{1}{\Lambda} \equiv \frac{1}{\Lambda_e} + \cancel{\left\{\frac{\sigma_{pi} + \frac{n_{He}}{n_p}\sigma_{\alpha i}}{m_p + \frac{n_{He}}{n_p} m_\alpha}\right\}}, \quad q(E) \equiv \frac{Q(E)}{\underline{\underline{\rho}}}$$

$$\Lambda_e = \underline{\underline{\rho}}\, v\, \tau_e$$

SOLUTION OF $(\bigstar)$

$$\phi(E) = \frac{1}{W(E)}\int_E^\infty dE'\, q(E')\, \exp\left[-\frac{R(E') - R(E)}{\Lambda}\right]$$

$$R(E) \equiv \int_0^E dE'/W(E')$$

EVOLUTION

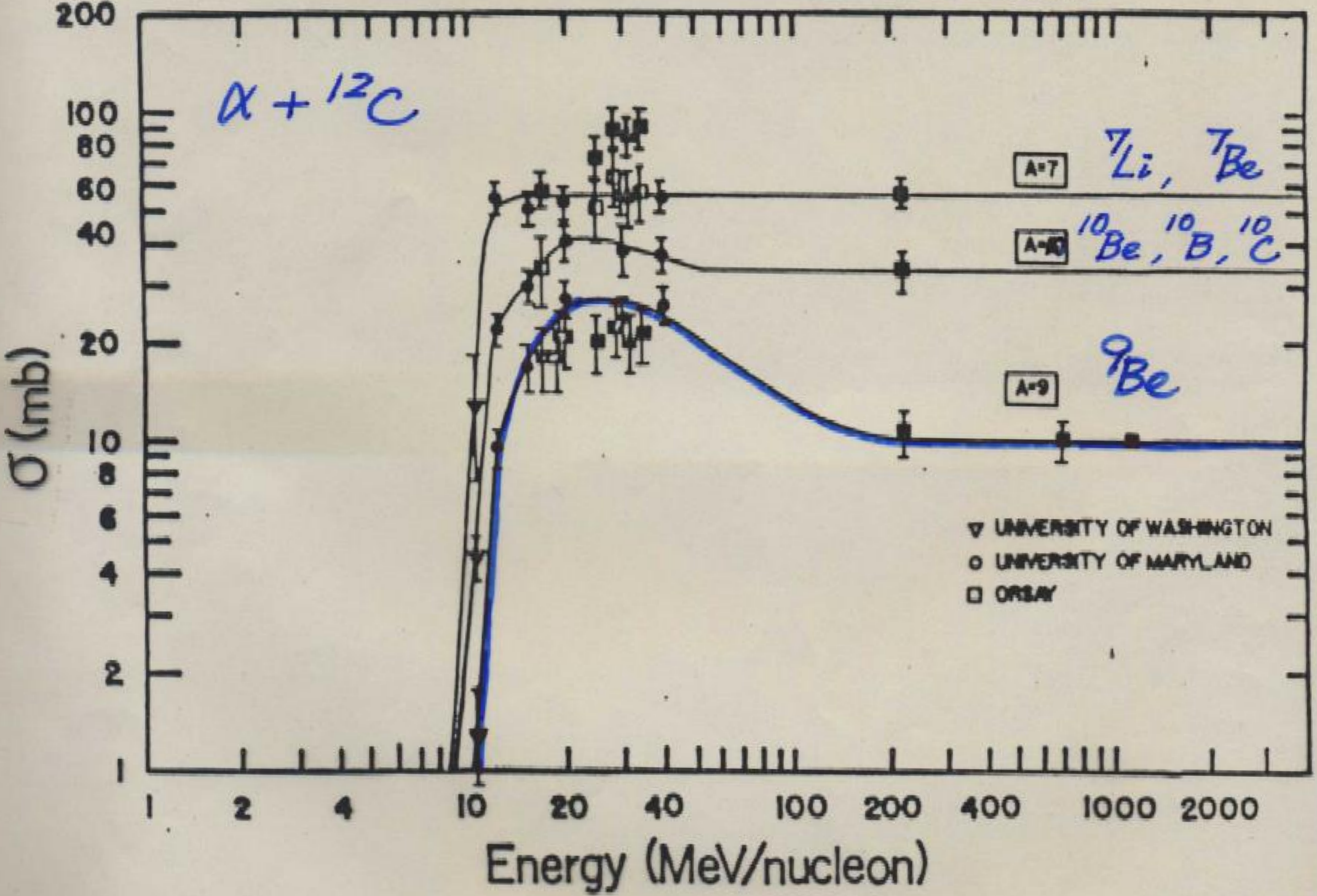
$$\Lambda q = \Lambda \frac{Q}{\rho} \propto \psi_{\text{SFR}}$$

LIMIT :

LOW-E $\quad \phi(E) \longrightarrow \int^\infty q_i(E')\, dE'/W(E')$

HIGH-E $\quad \phi(E) \longrightarrow \boxed{\Lambda\, q(E)}$

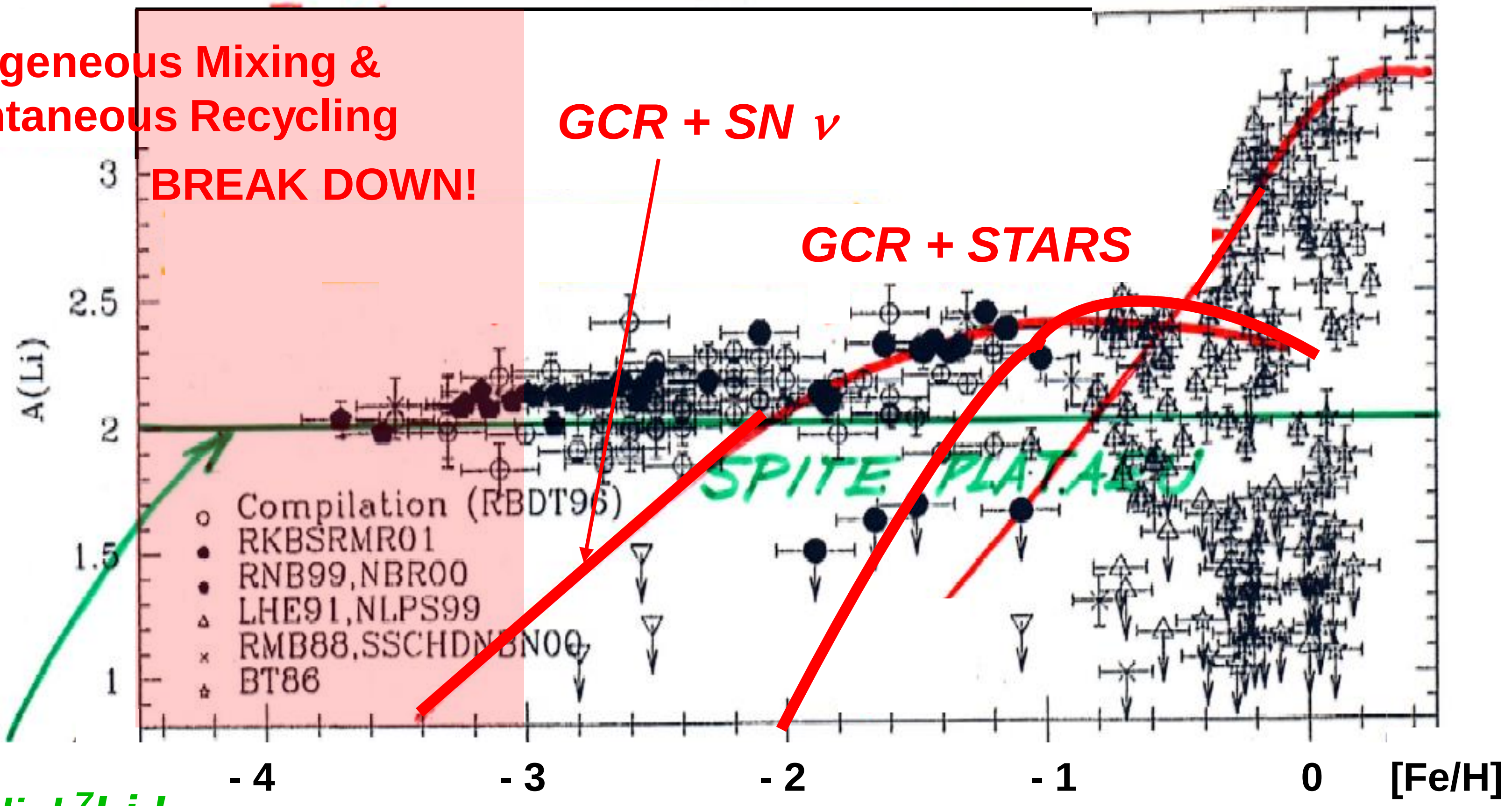
Excitation Functions for Alpha on Carbon



Analytic Solution of Eqs. (1) – (3)’

Big-Bang → Galaxy Forms → Star Forms

Ryan, Kajino, Beers, Suzuki, Romano,
Matteucci & Rosolankova 2001, ApJ 549, 55.



Homegeneous Mixing &
Instantaneous Recycling

BREAK DOWN!

GCR + SN ν

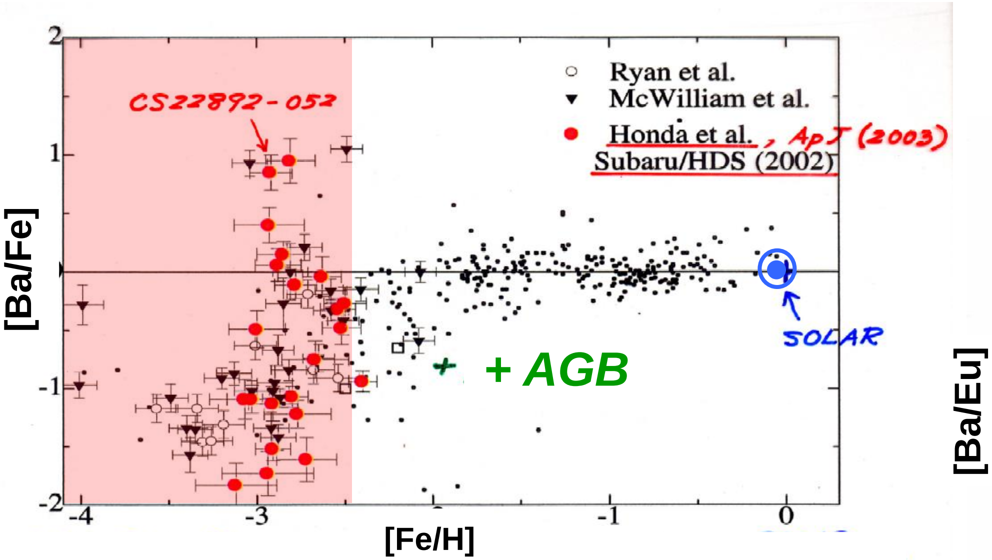
GCR + STARS

Primordial ^{7}Li !

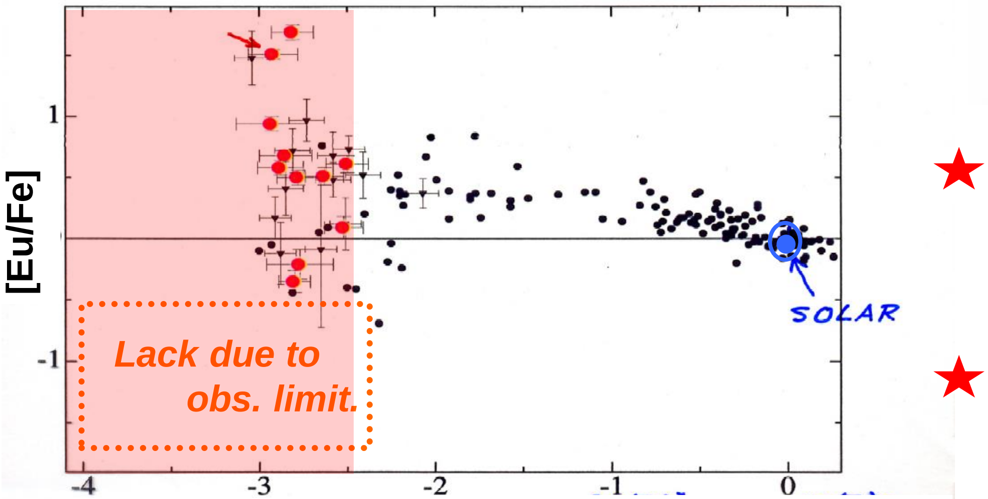
Early Universe **10My** **100My** **1Gy** **10Gy** ***TIME***

SUBARU Telescope HDS

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

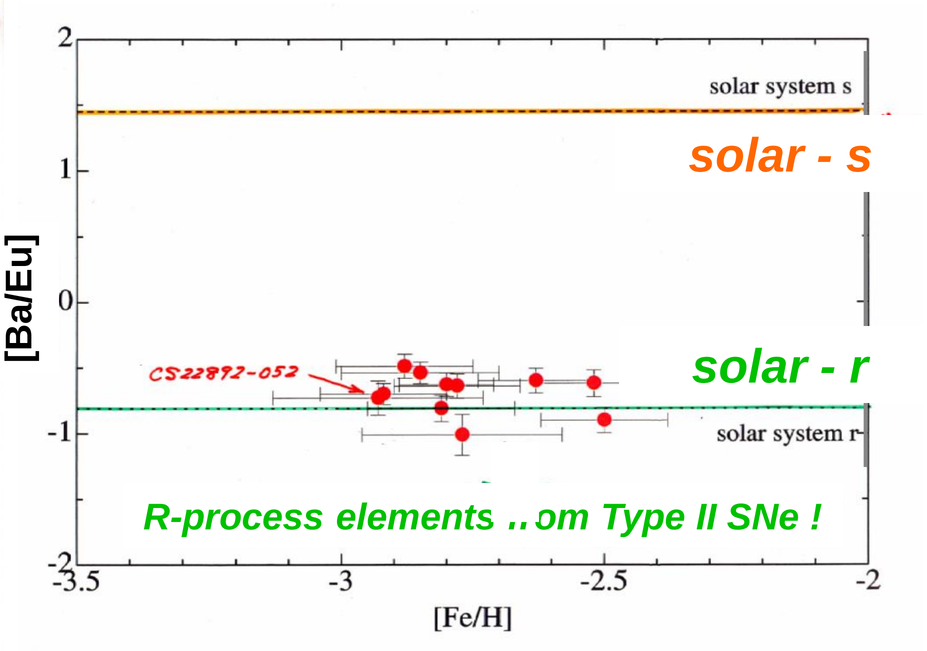


SN II ⟷ **SN I + II**



Early Galaxy ⟵

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



- ★ Large abundance scatter at [Fe/H]<-2 is an evidence for INDIVIDUAL supernova episode.
- ★ Only Core-Collapse TYPE II SUPER-NOVAE are the likely astrophysical sites of the R-Process !