京都大学大学院理学系研究科物理学第二教室、２０１０年１０月１３－１５日

宇宙ハドロン核物理学

元素とニュートリノ

（１）宇宙・銀河の化学進化：元素組成の時間発展にみる宇宙の進化
（２）ビッグバン元素合成と暗黒物質：SUSY粒子モデル
（３）ニュートリノ質量と宇宙の構造形成、宇宙背景放射ゆらぎ

（４）ニュートリノ振動の物理
（５）ニュートリノ振動と超新星元素合成
（６）超新星爆発、ガンマ線バーストにおけるRプロセス

（７）談話会：原子核の弱電相互作用と超新星ニュートリノ：
ニュートリノ温度および振動パラメータの決定方法の提案

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宇宙の進化 vs. 物質の起源

宇宙

=

時間・空間、天体

宇宙の進化

膨張宇宙・活動天体の時空構造を直接観測し研究する。

⇕

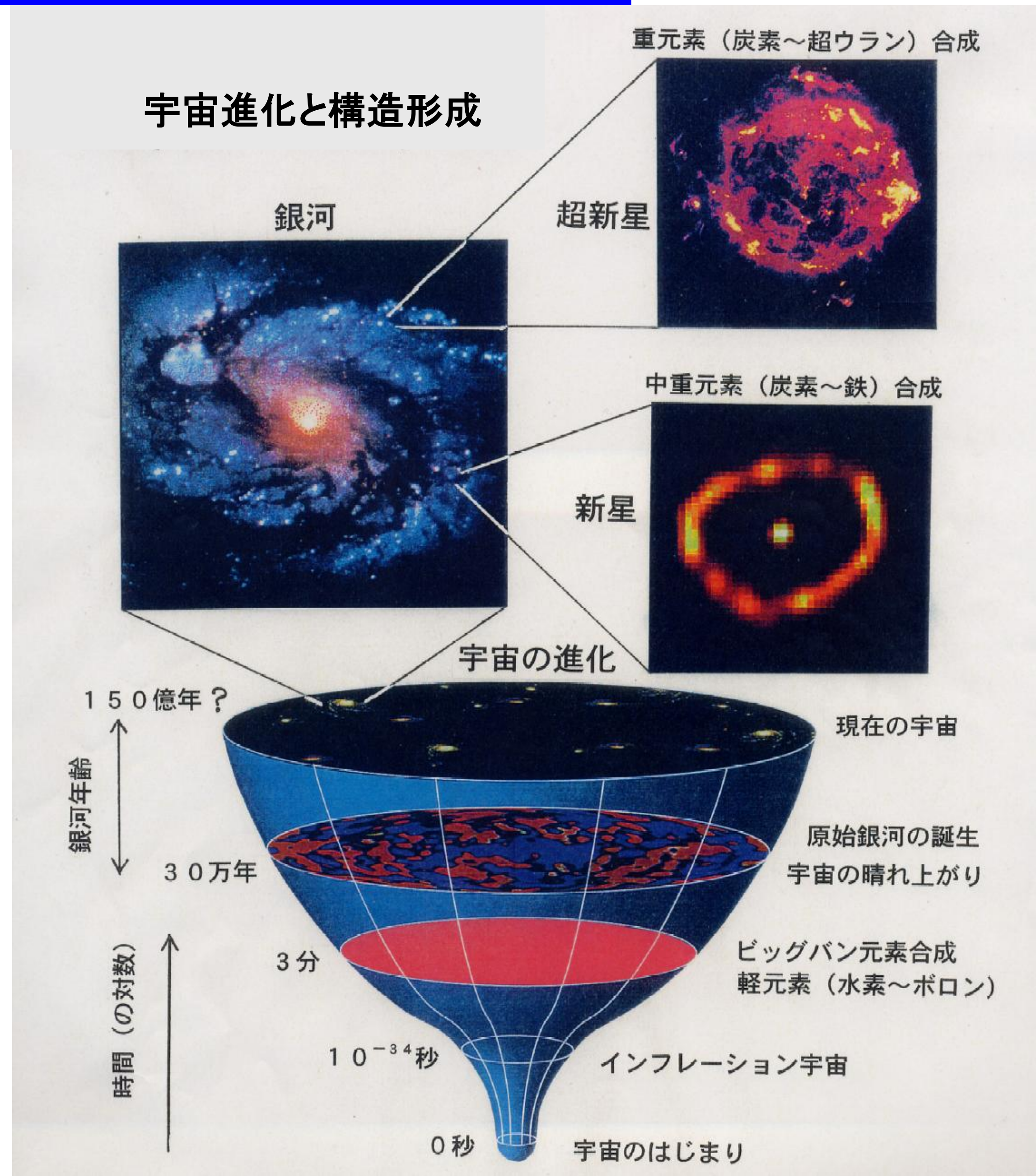
素粒子・原子核の性質や物理状態を精密に研究する。

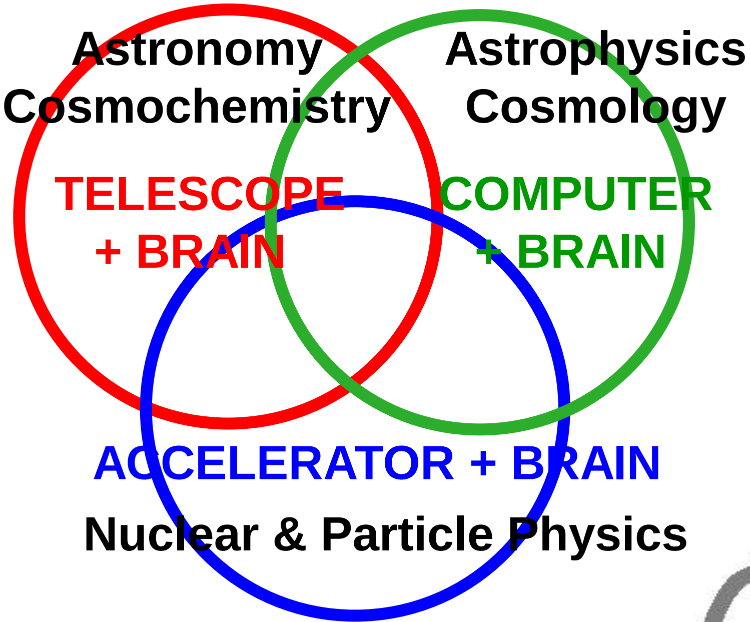
物質の起源

素粒子、原子核

=

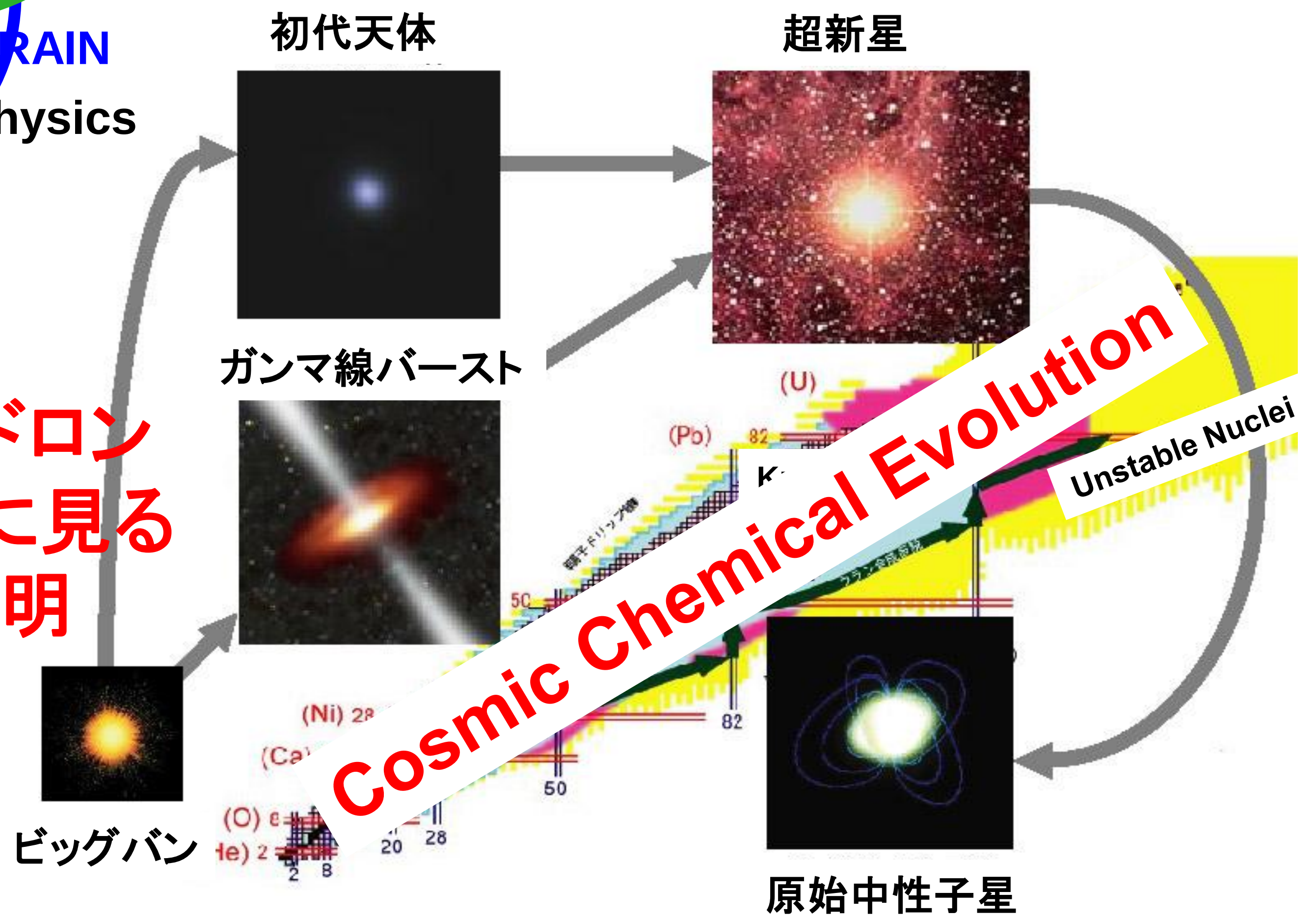
物質





宇宙ハドロン核物理

目的
元素合成量とハドロン過程の時間発展に見る宇宙進化の解明



量子ビーム実験＋宇宙天体観測＋理論（脳みそ）による宇宙ハドロン核物理

（1）宇宙･銀河の化学進化

元素組成の時間発展にみる宇宙の進化
Galactic Chemical Evolution

Taka KAJINO

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太陽系組成(安定核) ⇒ 爆発的元素合成(不安定核)

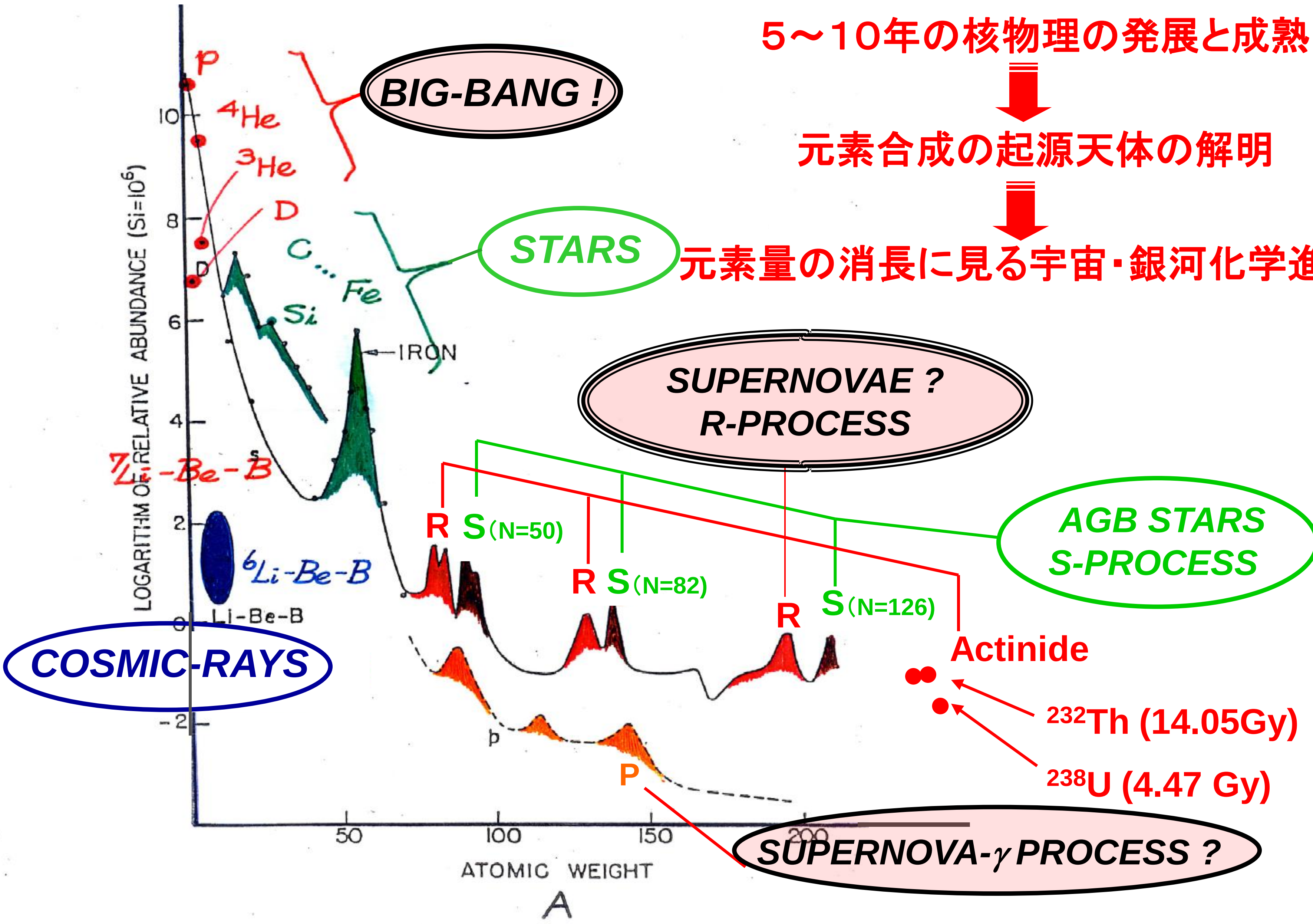
5～10年の核物理の発展と成熟

⇓

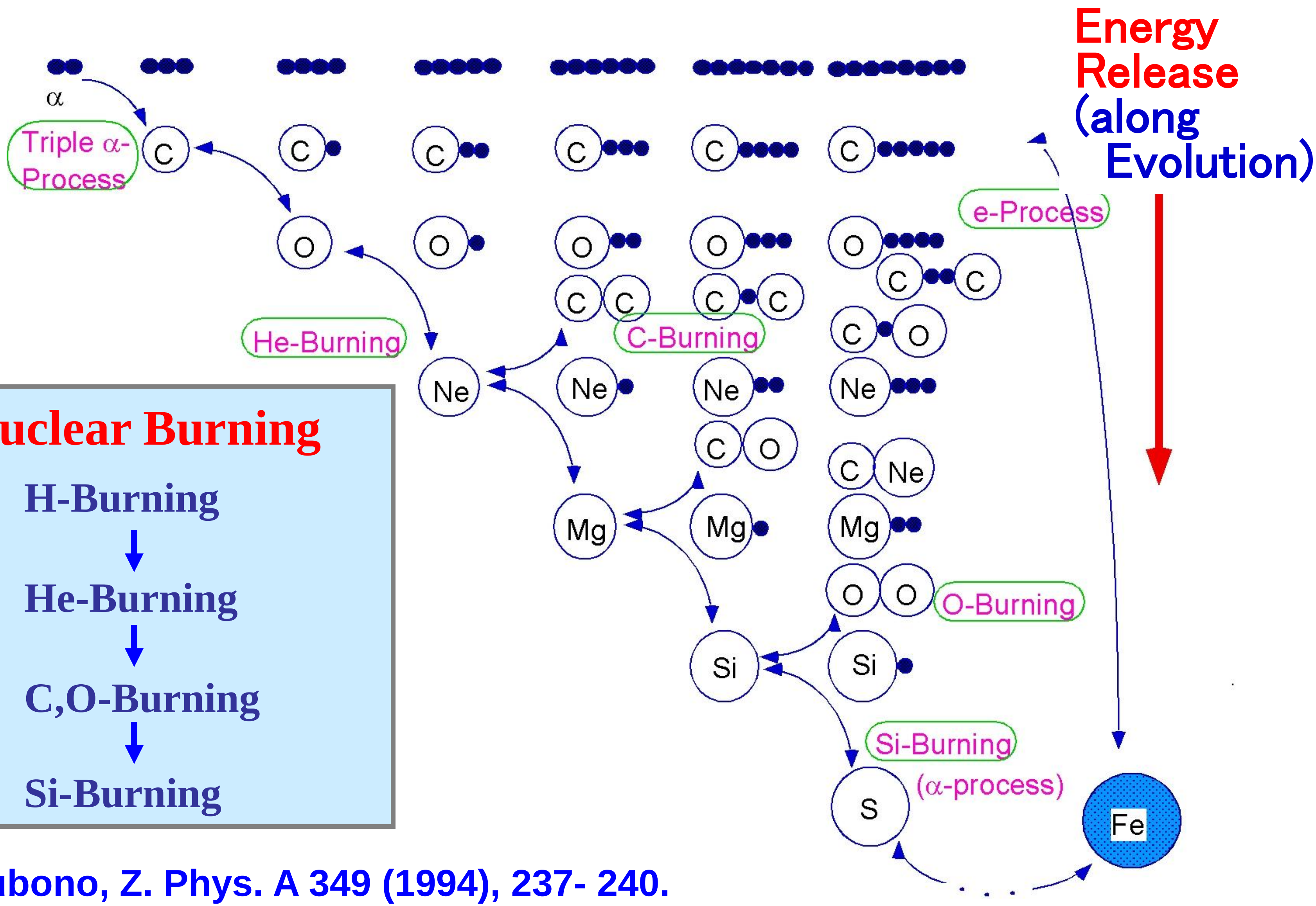
元素合成の起源天体の解明

⇓

元素量の消長に見る宇宙・銀河化学進化



Cluster Nucleosynthesis Diagram (CND)



Nuclear Burning

H-Burning

↓

He-Burning

↓

C,O-Burning

↓

Si-Burning

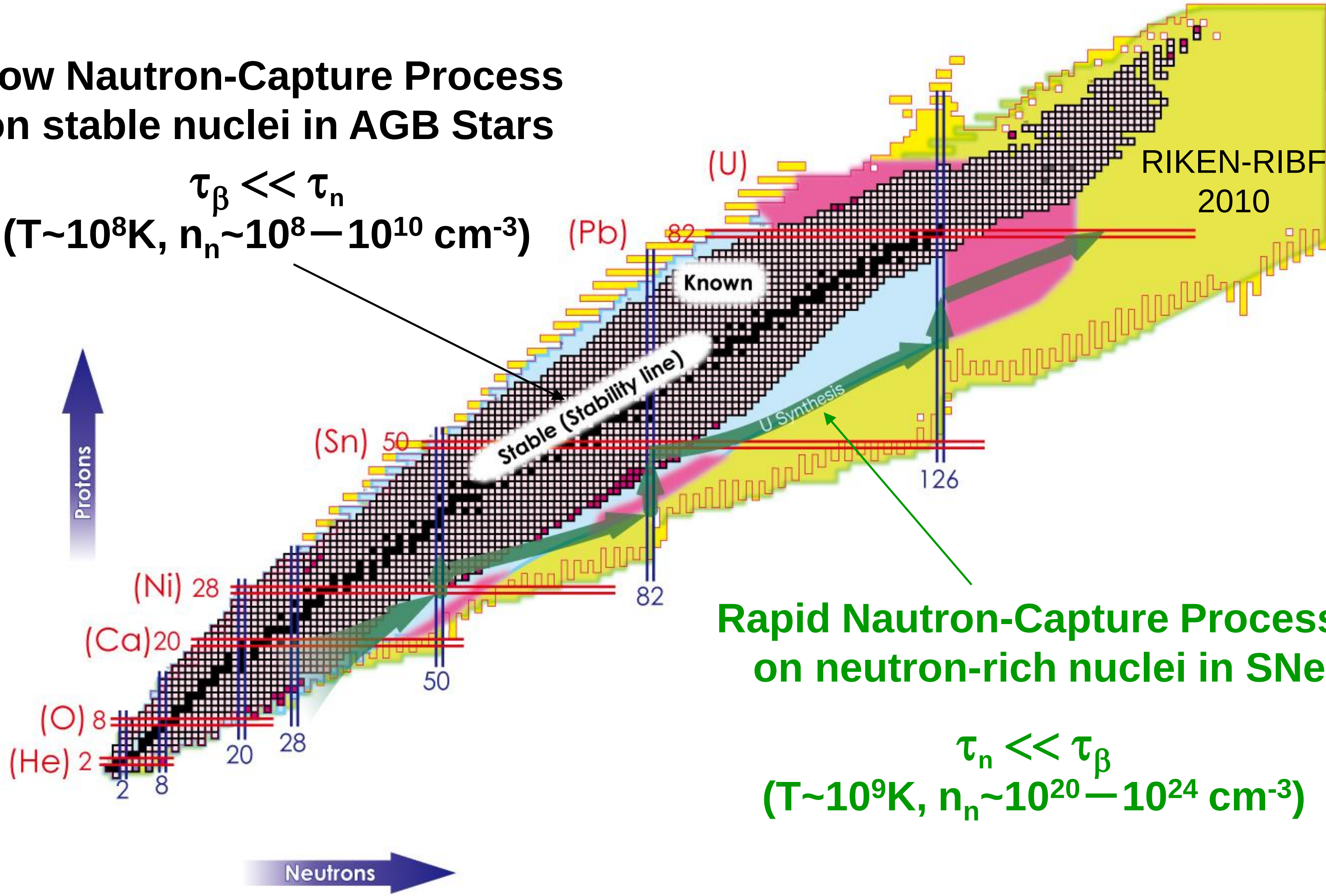
S. Kubono, Z. Phys. A 349 (1994), 237- 240.

Magic Number and Slow- & Rapid Neutron-Capture Processes

Slow Nautron-Capture Process on stable nuclei in AGB Stars

$\tau_\beta \ll \tau_n$

(T~10^8K, n_n~$10^8 - 10^{10}$ cm^{-3})

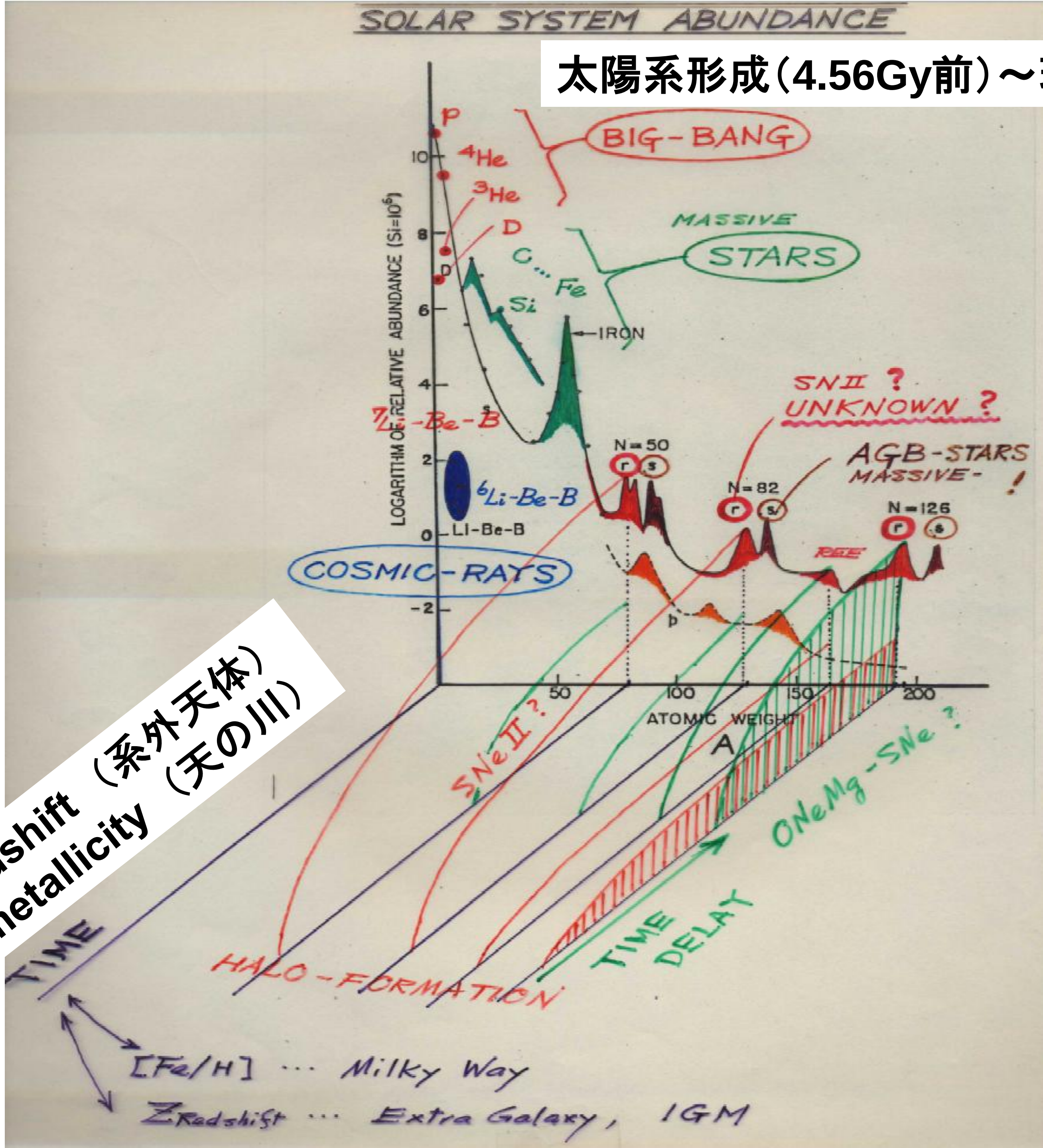


Rapid Nautron-Capture Process on neutron-rich nuclei in SNe

$\tau_n \ll \tau_\beta$

(T~10^9K, n_n~$10^{20} - 10^{24}$ cm^{-3})

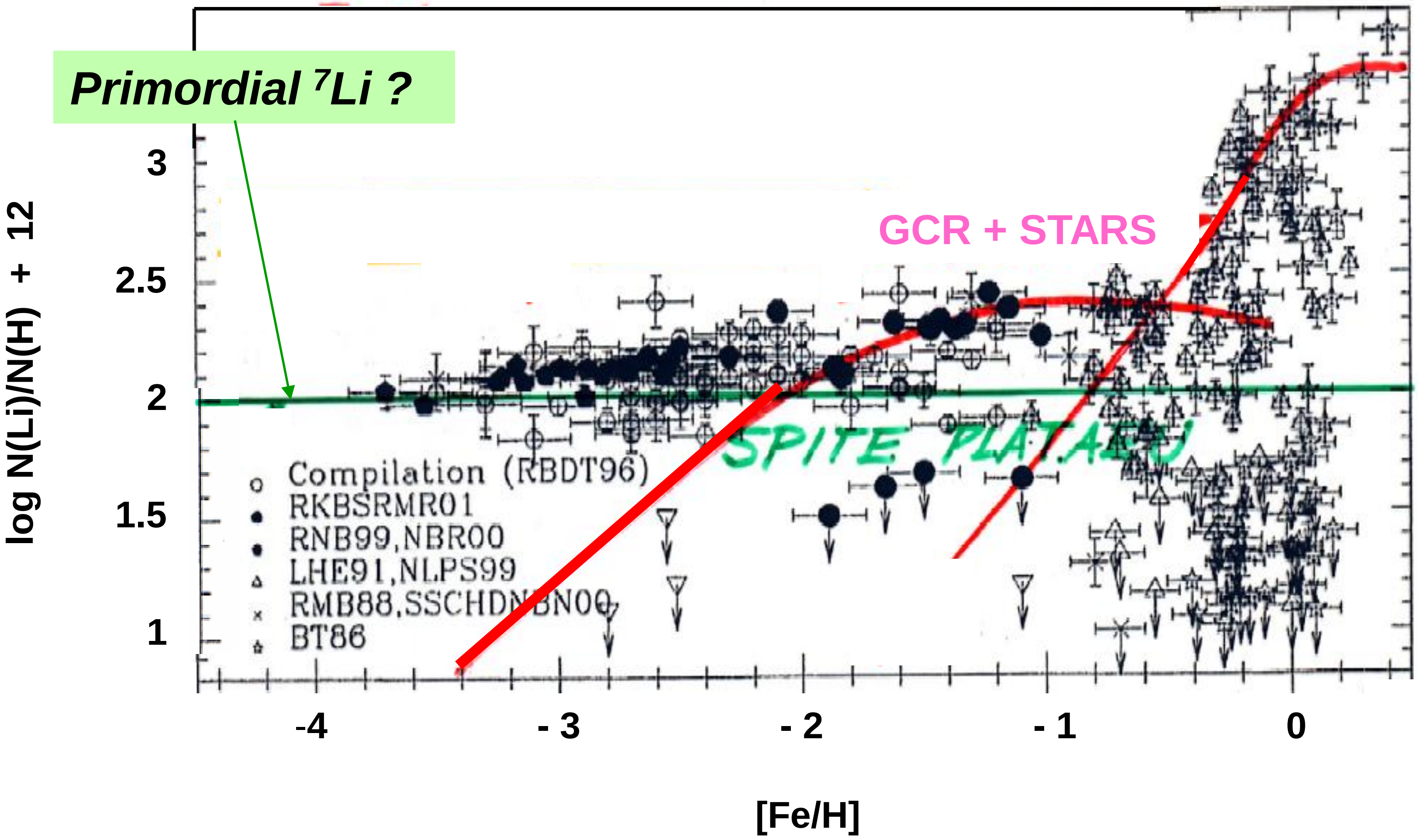
太陽系形成（4.56Gy前）～現在



実時間：redshift（系外天体）
元素量：metallicity（天の川）

^{7}Li Abundance vs. Neutrino Process

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



目的

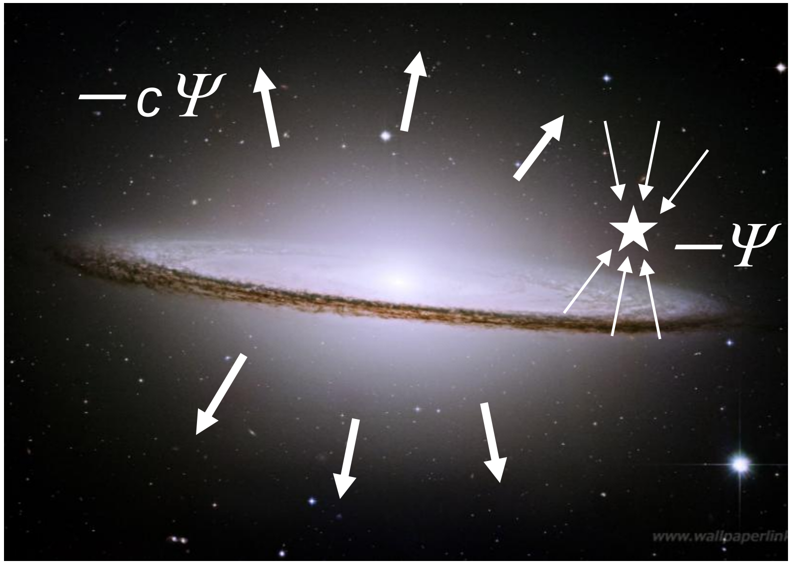
宇宙での物質循環の連鎖が、元素量・ハドロン過程と宇宙進化の関係を解明する鍵を握る。

宇宙開闢（時間0）→ビッグバン元素合成（3分）
→宇宙の晴れ上がり（38万年）
→初代天体の形成（約10億年）
→恒星進化と元素合成→超新星爆発→星間質量放出→次世代の天体形成→ ・・・ →太陽系形成（約100億年）

「元素量」と「宇宙・銀河進化時間」の関係を構築。

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 $R = \sum R_i Z_i$

$$\frac{dM_{tot}}{dt} = -c\Psi \quad (1)$$

$$\frac{dM_G}{dt} = -(1-R+c)\Psi \quad (2)$$

$$\frac{d(M_G Z_i)}{dt} = y_i \Psi - (1-R_i+c)\Psi Z_i \quad (3)$$

$$\frac{d(M_G Z_L)}{dt} = y_L \Psi + \sum_j Z_j \left(\frac{A_L}{A_j}\right) \langle \sigma_{jL} \phi \rangle - (1-R_L+c)\Psi Z_L \quad (4)$$

Stellar Production

GCR production

Local → Global Model

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

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

Three-ASSUMPTIONS in simple GCE Model

(1) Instantaneous Recycling & Homogeneous Mixing

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

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

$$- Z_i \psi(t)$$

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

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

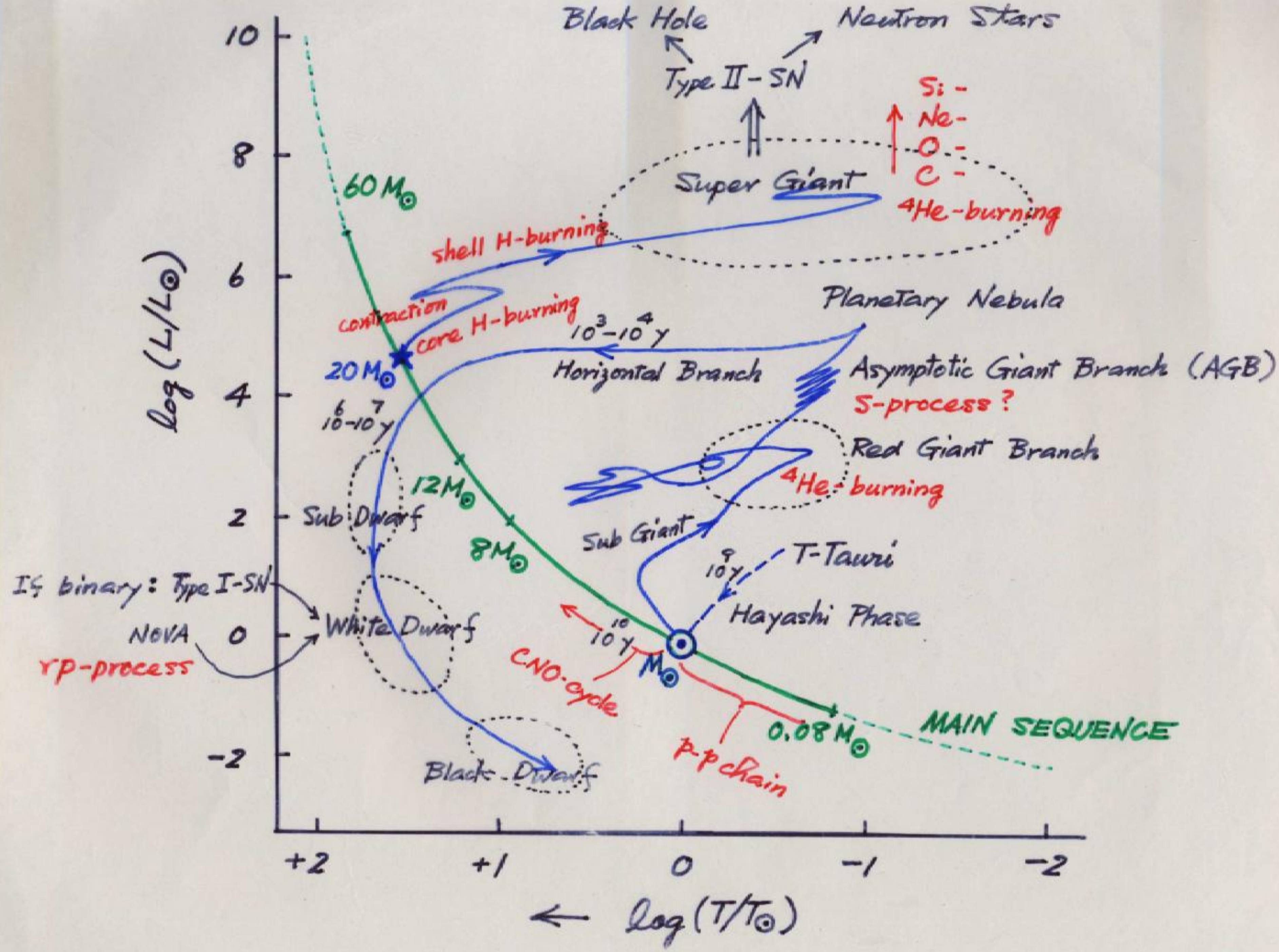
$$- \frac{1}{\tau_i} M_G Z_i + \sum_{j \neq i} \frac{1}{\tau_j} M_G Z_j$$

Biggest contribution from MASSIVE STARS (SNe)

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

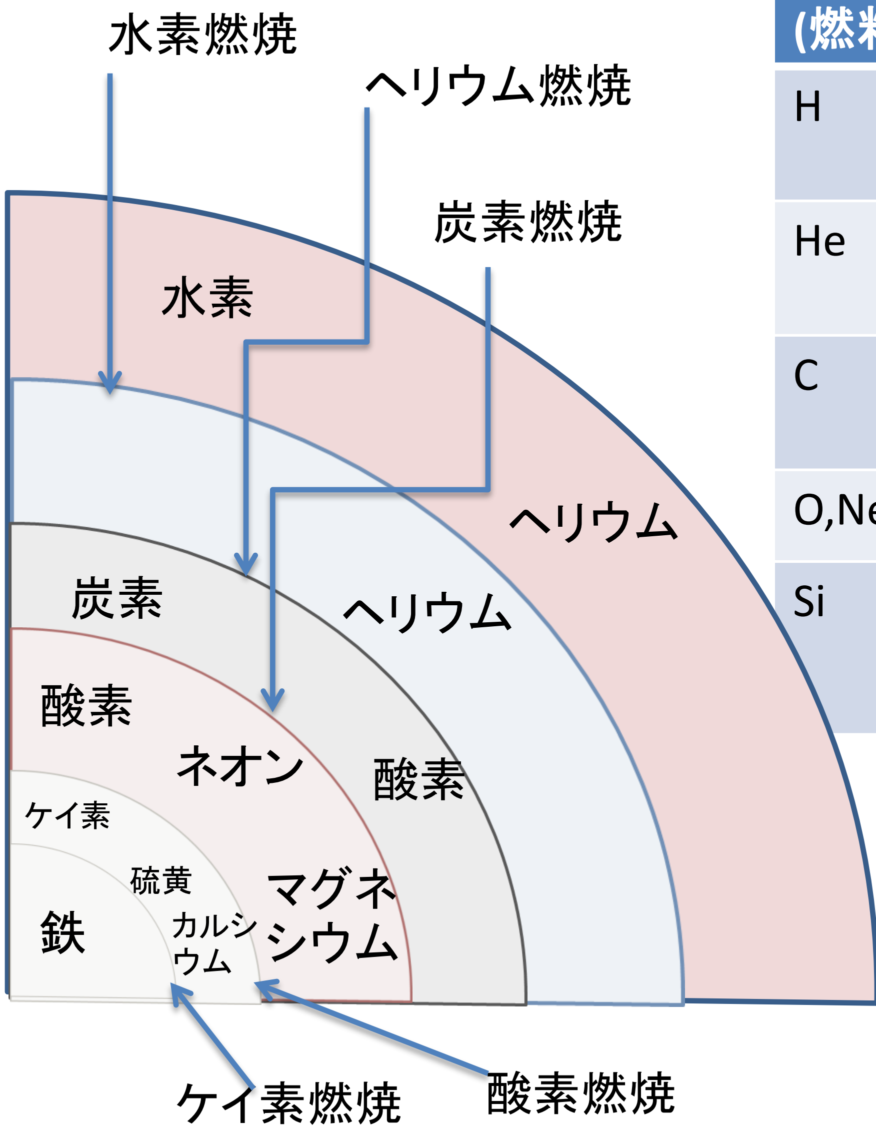
$$\frac{d(M_G Z_i)}{dt} \approx \underbrace{\left[\int dm \left(q_i - q_i^{(rem)} \right) \phi_{IMF}(m) \right]} \times \psi(t)$$

y_i = elemental production yield



Black Hole
Neutron Stars
Type II - SN
Si -
Ne -
O -
C -
4He-burning
Super Giant
shell H-burning
60 M⊙
contraction
core H-burning
10³-10⁴ y
Planetary Nebula
20 M⊙
Horizontal Branch
Asymptotic Giant Branch (AGB)
S-process ?
10⁶-10⁷ y
Red Giant Branch
4He-burning
12 M⊙
Sub Dwarf
Sub Giant
8 M⊙
T-Tauri
10⁹ y
If binary: Type I-SN
Hayashi Phase
White Dwarf
NOVA
rp-process
10¹⁰ y
CNO-cycle
M⊙
0.08 M⊙
MAIN SEQUENCE
Black-Dwarf
p-p chain
log (L/L⊙)
10
8
6
4
2
0
-2
+2
+1
0
-1
-2
← log (T/T⊙)

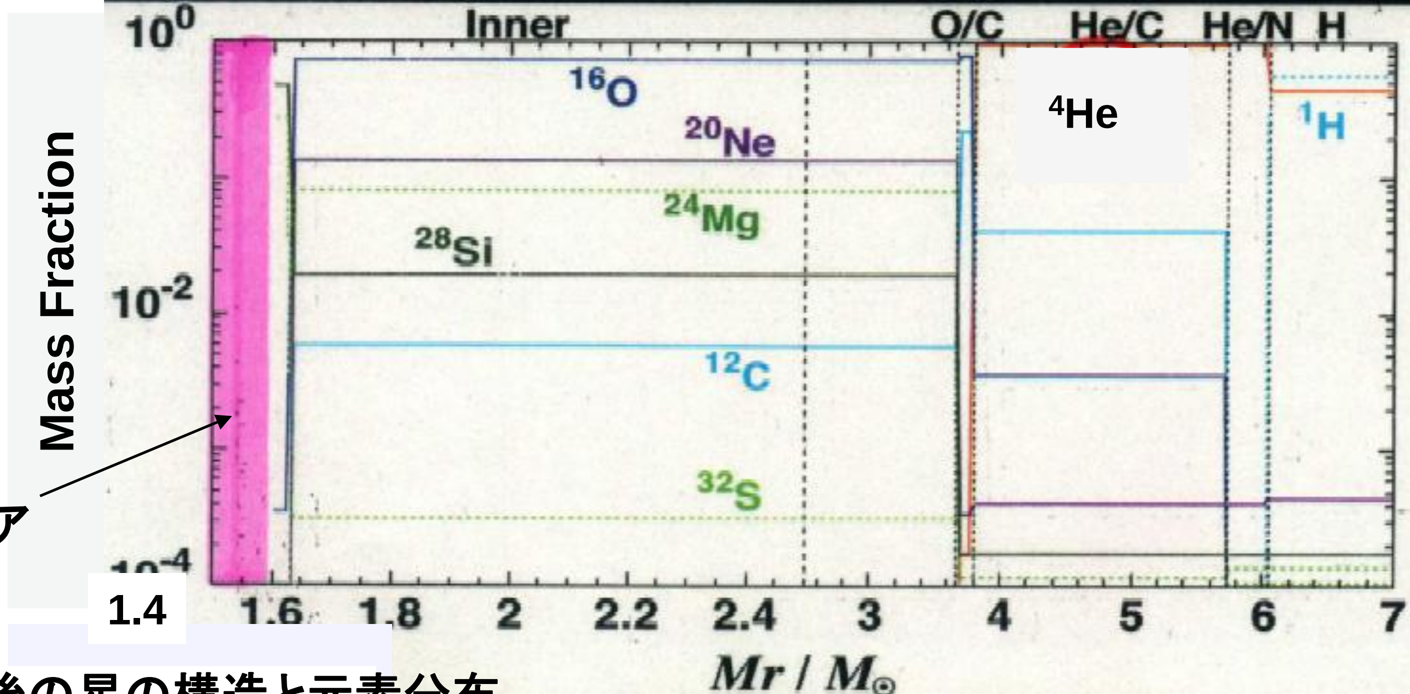
恒星の構造進化と元素合成



燃焼過程(燃料)	主な反応	最終生成物	温度(10^8K)
H	ppチェイン CNOサイクル	^{4}He	0.15 0.2
He	$3\alpha \rightarrow {}^{12}$C ^{12}C+$\alpha \rightarrow {}^{16}$O	^{12}C ^{16}O	1.5
C	^{12}C+^{12}C$\rightarrow$^{20}Ne+α $\rightarrow$^{24}Mg	^{20}Ne ^{24}Mg	7
O,Ne,Mg	^{16}O+^{16}O$\rightarrow$^{28}Si+α	^{28}Si	>15
Si	^{28}Si+$\alpha \rightarrow {}^{32}$S ・・・・ ・・・・	^{56}Fe	40

爆発直前

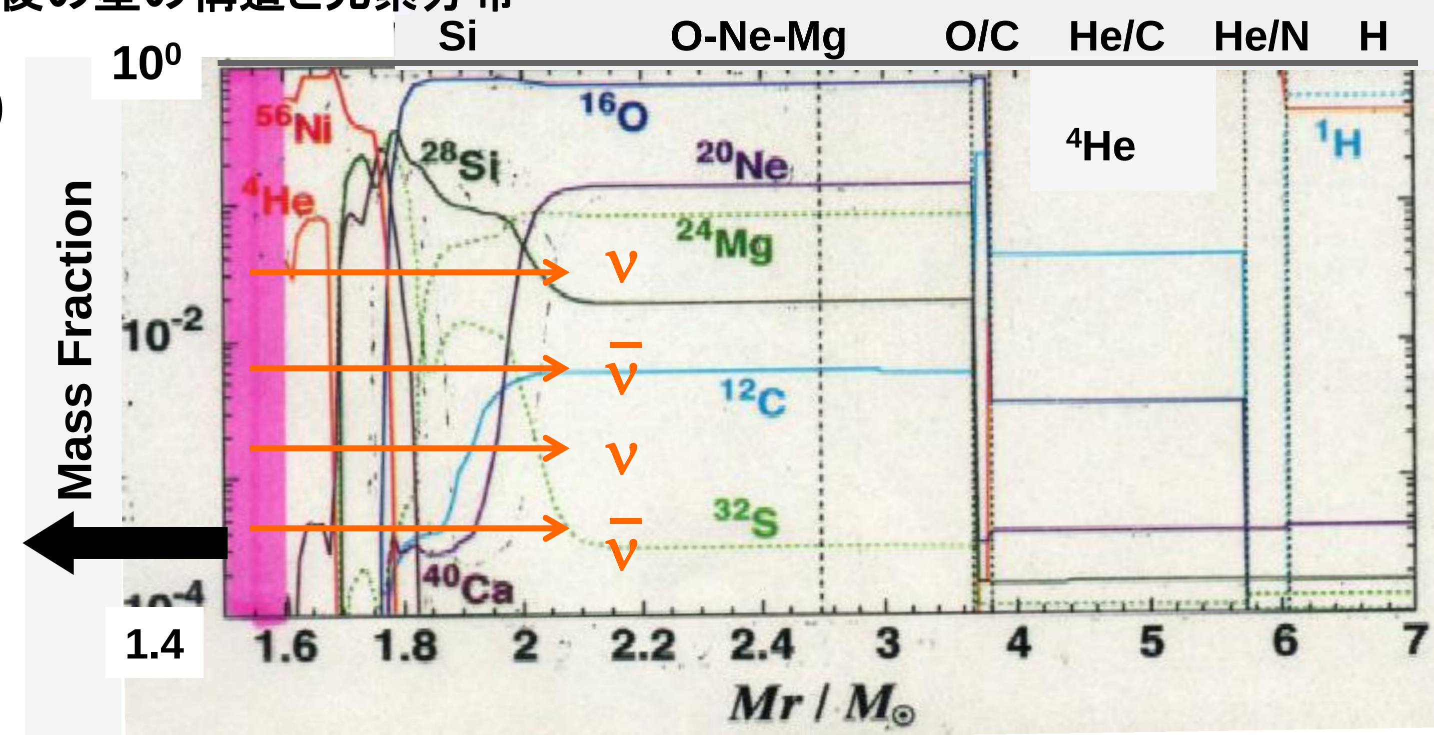
鉄・コバルト・ニッケルのコア



超新星爆発前後の星の構造と元素分布
Yoshida and Kajino (2005)

爆発直後
(約10秒)

中性子星に
重力崩壊
1.4 $M_\odot$



金属量は宇宙銀河進化の時間発展を示す
Observable Measure.

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

4.56 Gy ↓

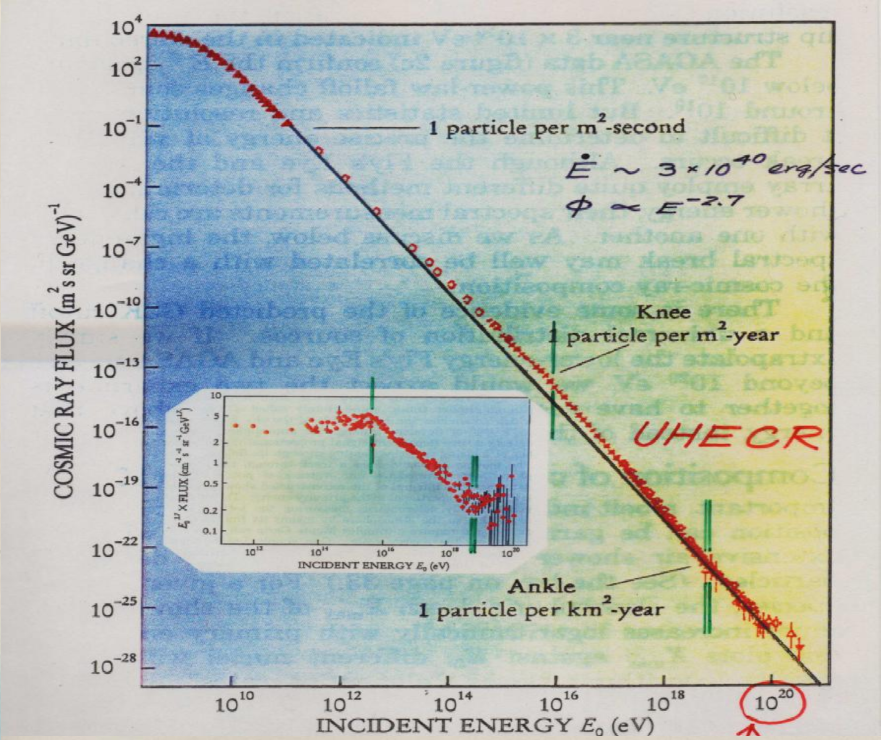
[Fe/H]	- ∞ ···	-5.4	-3	-2	-1	0
Cosmic time = t	0 ···	Early Universe	10My	100My	1Gy	10Gy
Redshift = z	+ ∞ ···	~1000	~100	~20	~4	0

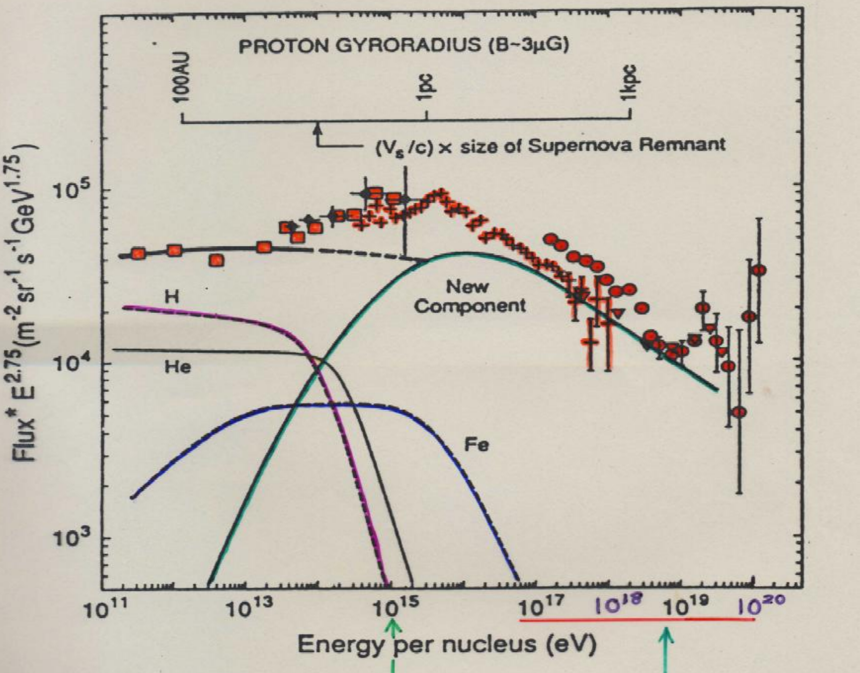
$$a \propto (1+z)^{-1} \propto t^{2/3} \quad \therefore (t/13.7Gy)^{2/3} = 1/(1+z)$$

Something in the air

COSMIC RAYS

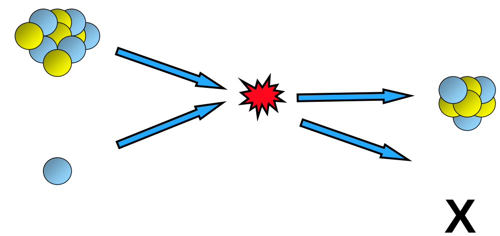
After the discovery of radioactivity, physicists found a new penetrating radiation, this time coming from outer space. They called it cosmic rays, and in the 1920s it set the stage for the next surprise.





LiBeB-Production in Spallation or Fusion Reactions

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

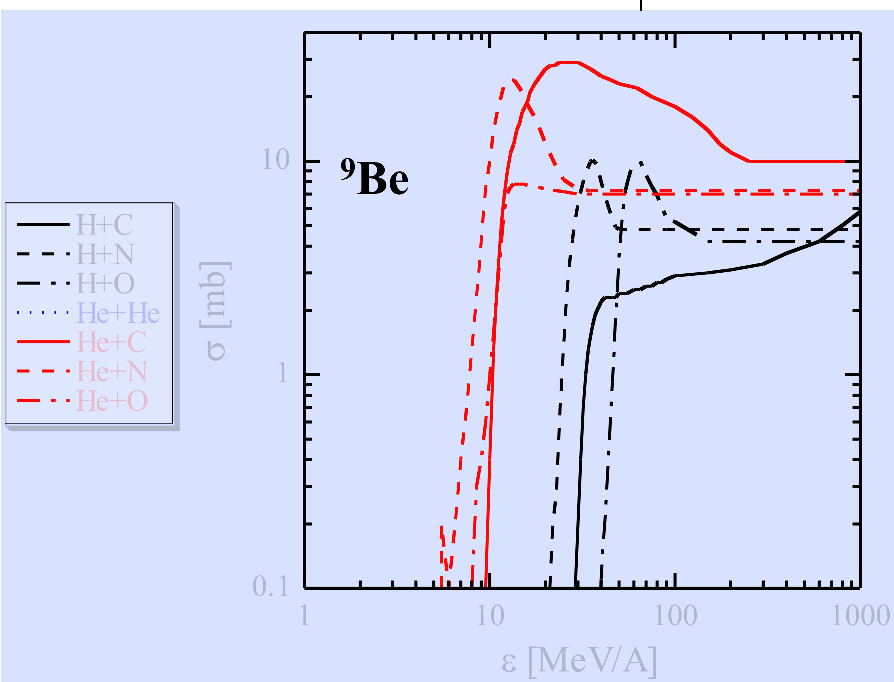


Example: O+H → Be

$$\frac{dN_{Be}}{dt} = \underbrace{n_H}_{} \int \underbrace{\sigma^{Be}{}_{O,H}(E)}_{} \underbrace{\frac{F_O(E,t)}{A_O m_H}}_{} v_O(E)\, dE$$

number density of **H** in ISM/CSM

number of **O** with energy ***E~E+dE*** at time ***t***



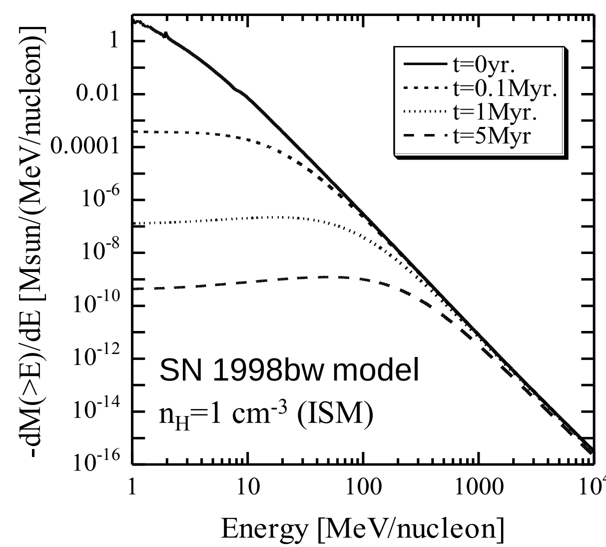
Cross sections
(Read & Viola 1984; Mercer+ 2001)

Transport equation

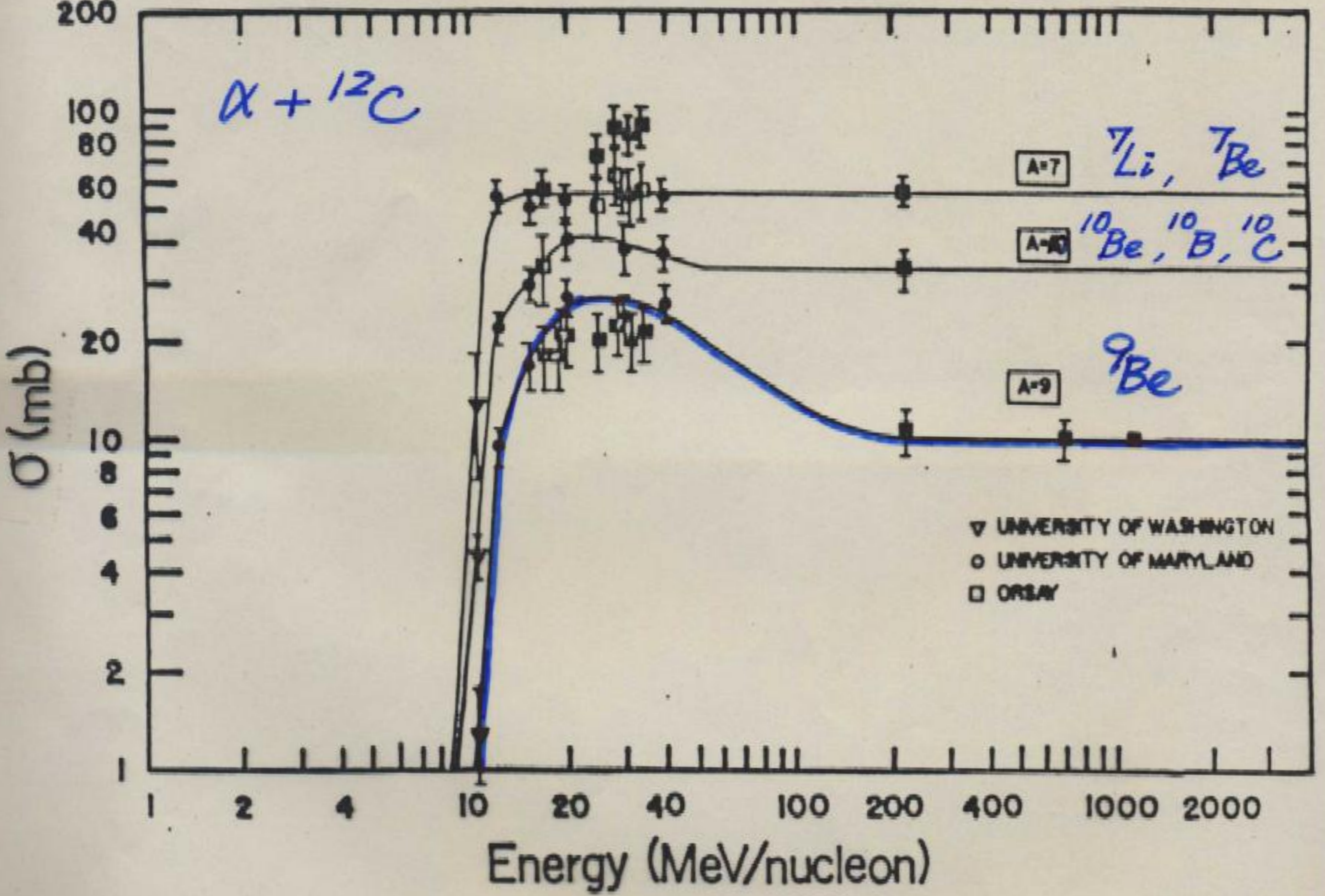
$$\frac{\partial F_i(E,t)}{\partial t} = \frac{\partial [\omega_i(E) F_i(E,t)]}{\partial E} - \frac{F_i(E,t)}{\Lambda} \rho v_i(E)$$

ω_i : energy loss rate (ionization)

Λ : loss length (spallation & escape)



Excitation Functions for Alpha on Carbon



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)

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

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

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

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

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

$$\Lambda_e = \rho\, v\, \tau_e$$

SOLUTION OF $(\star)$

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

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

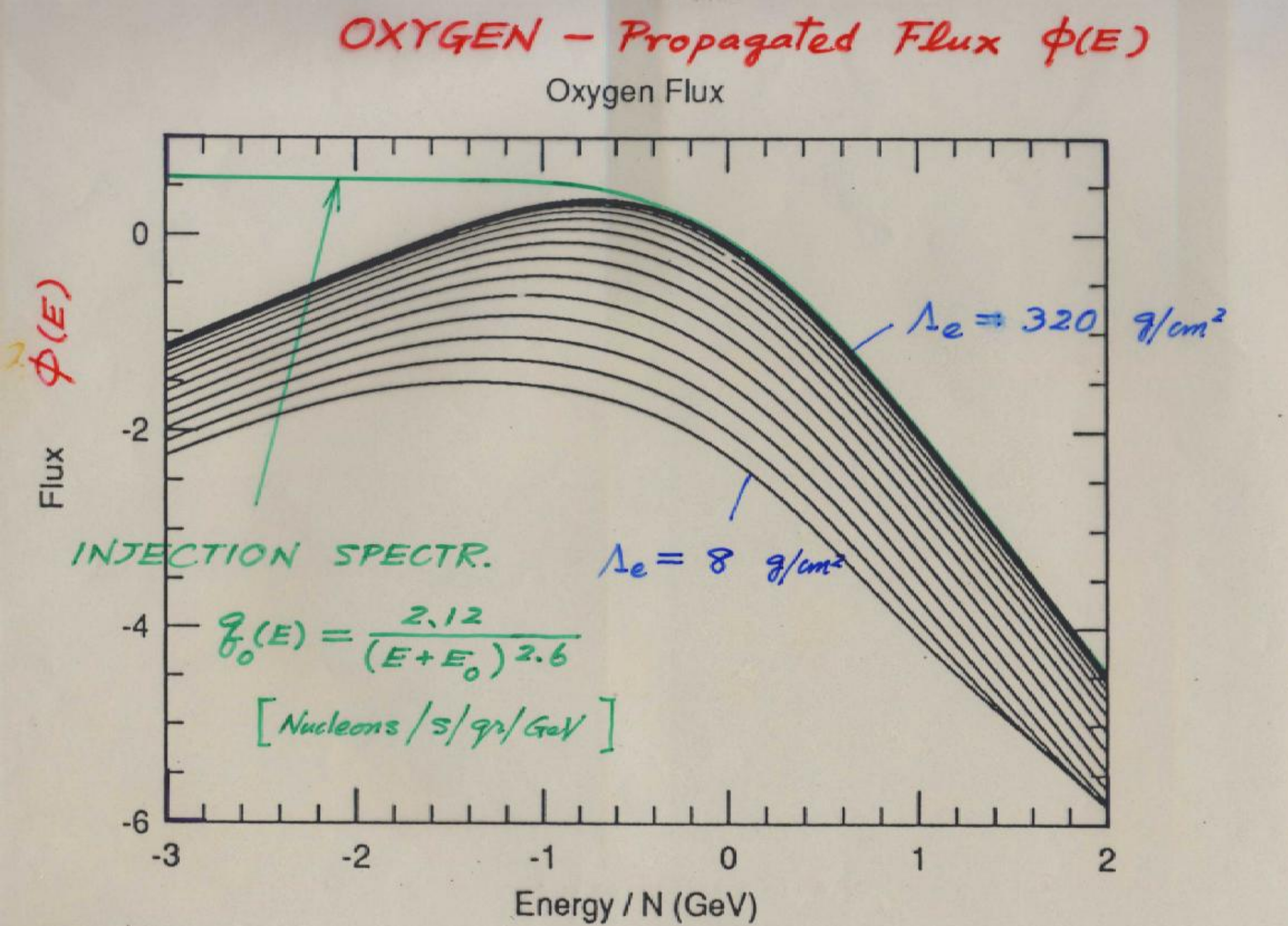
EVOLUTION

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

LIMIT:

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

HIGH-E $\quad \phi(E) \rightarrow \Lambda\, q(E)$



OXYGEN – Propagated Flux φ(E)
Oxygen Flux
Flux
φ(E)
0
-2
-4
-6
-3
-2
-1
0
1
2
Energy / N (GeV)
Λe = 320 g/cm²
Λe = 8 g/cm²
INJECTION SPECTR.
q0(E) = 2.12 / (E + E0)^2.6
[Nucleons / s / gr / GeV]

4.5.2. Energy Loss Mechanisms for High Energy Particles

4.5.2.1. Charged Particle Energy Loss by Ionization

When a charged particle passes through matter, it loses energy by exciting and ionizing atoms. The loss in the energy, E, of a particle of charge, eZ, is given by (BETHE, 1930, 1932; BLOCH, 1933)

$$-\frac{dE}{dx}=\frac{2\pi Z^2 e^4 N}{mv^2}\left[\ln\left(\frac{2mv^2\gamma^2 W_m}{I^2}\right)-2\beta^2+f\right] \quad (4\text{-}407)$$

$$\approx 2.54\times10^{-19} Z^2 N\sqrt{2/(\gamma-1)}\,[\ln(\gamma-1)+11.8]\ \mathrm{eV\ cm^{-1}}$$

for atomic hydrogen and $\gamma \ll 1$

$$\approx 2.54\times10^{-19} Z^2 N\left[3\ln\gamma+\ln\left(\frac{M}{m}\right)+19.5\right]\mathrm{eV\ cm^{-1}}$$

for atomic hydrogen and $\gamma \gg M/m$,

where dx is an element of unit length in the direction of particle motion, m is the electron mass, M is the mass of the incident particle whose velocity is v, the $\beta=v/c$, the $\gamma=(1-\beta^2)^{-1/2}=E/(Mc^2)$, the number density of electrons in the material is N, the ionization potential is I, and the maximum energy transfer, W_m, is given by Eq. (4-362). The density effect term, f, was first suggested by FERMI (1939, 1940), and is tabulated together with other constants in Eq. (4-407) by STERNHEIMER (1956) and HAYAKAWA (1969). Ionization potentials were given in Table 34.

For a completely ionized gas and an ultrarelativistic incident particle, we have (GINZBURG, 1969)

$$f=\ln(1-\beta^2)+\ln\left(\frac{I^2}{\hbar^2\omega_p^2}\right)+1\,, \quad (4\text{-}408)$$

where the plasma frequency, ω_p, is given by

$$\omega_p=(4\pi e^2 N_e/m)^{1/2}\,,$$

and N_e is the free electron density. For the case of an ionized gas and an ultra-relativistic incident particle, Eq. (4-407) becomes

$$-\frac{dE}{dx}\approx 2.54\times10^{-19} Z^2 N_e\left[\ln\left(\frac{W_m}{mc^2}\right)-\ln N_e+74.1\right]\mathrm{eV\ cm^{-1}}, \quad (4\text{-}409)$$

where $W_m=E$ if $\gamma \gg (M/m)$ and $W_m=2E^2/(mc^2)$ for $1 \ll \gamma \ll (M/m)$.

For the special case of an electron incident upon neutral atoms,

$$-\frac{dE}{dx}=\frac{2\pi e^4 N}{mv^2}\left[\ln\left(\frac{mv^2\gamma^2 W_m}{I^2}\right)+\frac{9}{8}-\beta^2+f\right] \quad (4\text{-}410)$$

$$\approx 2.54\times10^{-19} N[3\ln\gamma+20.2]\ \mathrm{eV\ cm^{-1}} \quad \text{for hydrogen and } \gamma\ll 1.$$

When ultrarelativistic electrons are incident upon a fully ionized gas,

$$-\frac{dE}{dx}\approx 2.54\times10^{-19} N_e[\ln\gamma-\ln N_e+73.4]\ \mathrm{eV\ cm^{-1}}. \quad (4\text{-}411)$$

Bethe's formula of ionization energy loss

Electron energy losses by ionization and other processes are illustrated in Fig. 28 for the Galaxy and the intergalactic medium.

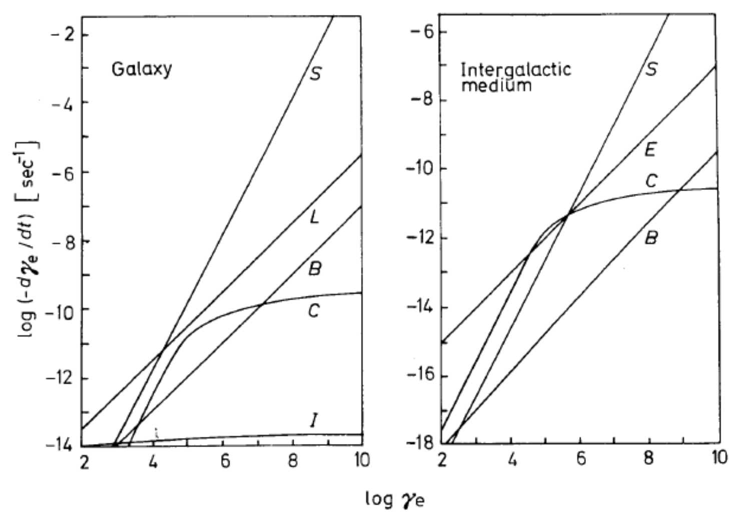
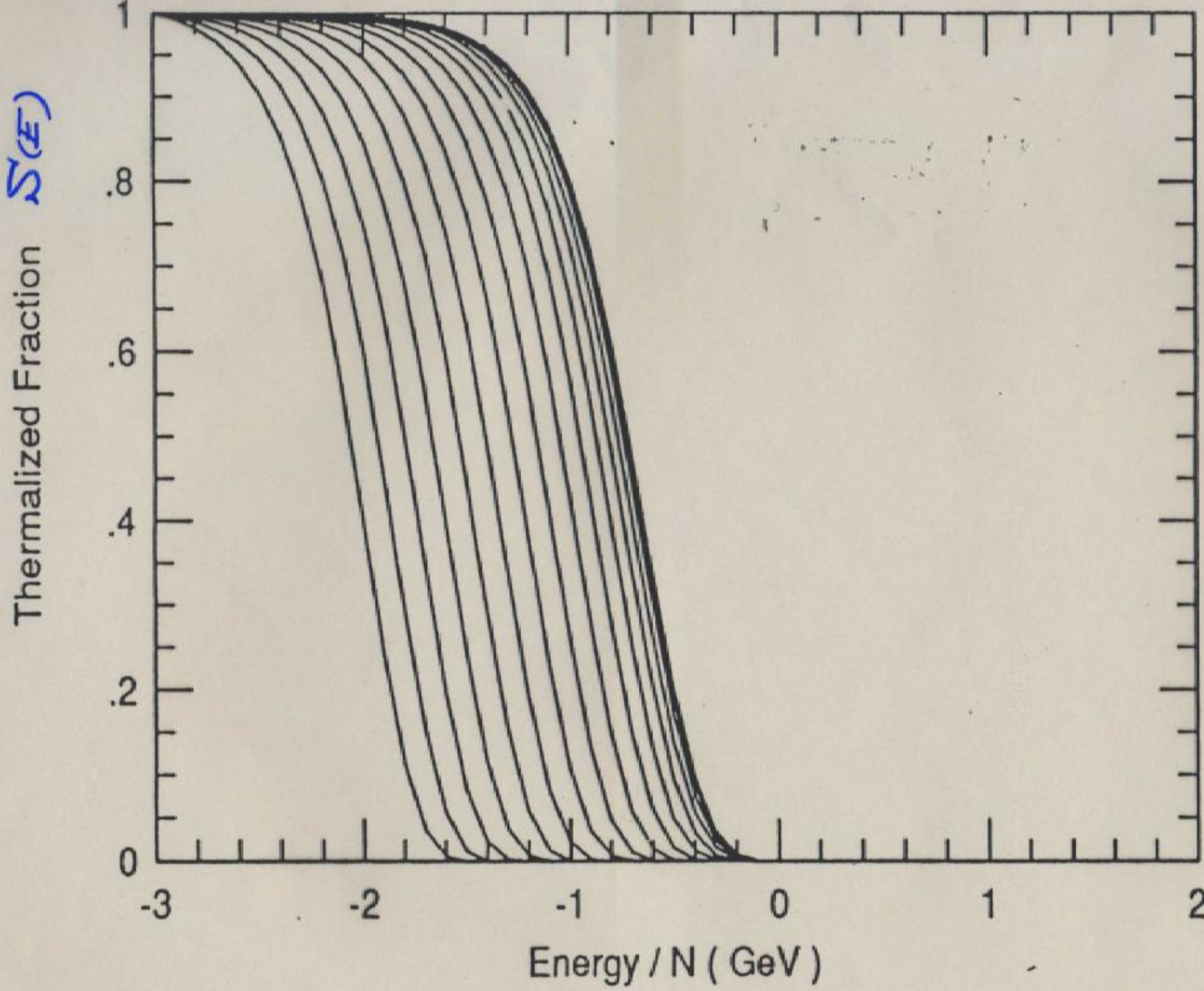


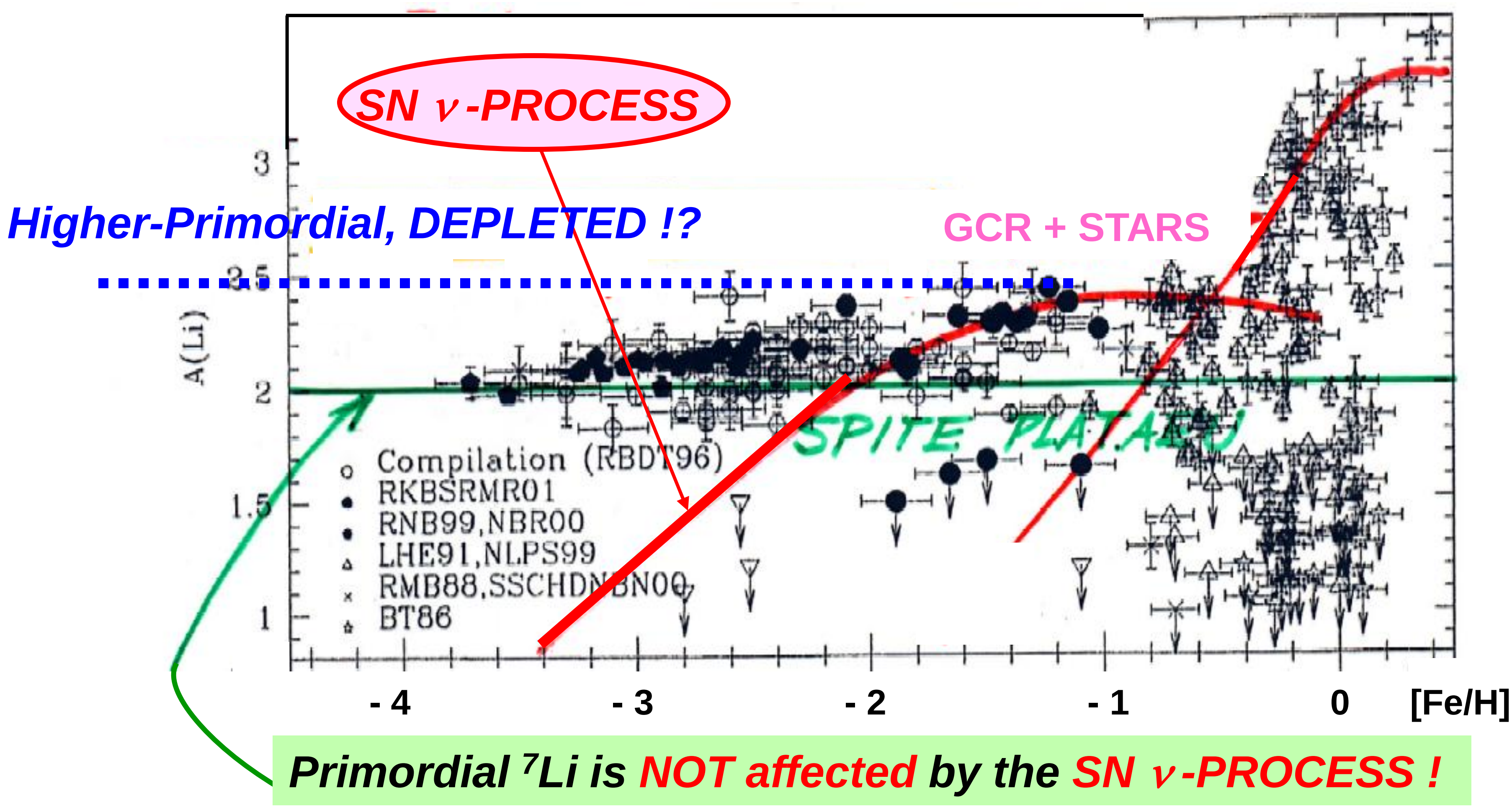
Fig. 28. Electron energy loss rates in the Galaxy and the intergalactic medium by synchrotron emission (S), cosmic expansion (E), leakage out of the halo (L), bremsstrahlung emission (B), Compton scattering (C), and ionization (I), (after BURBIDGE, 1966, by permission of Academic Press, Inc.). Here $\gamma=E/mc^2$ where E is the total energy of the electron. All energy loss rates are given in Sect. 4.5 except for the leakage loss rate $d\gamma/dt=\gamma lc/R^2$, and the expansion loss rate $d\gamma/dt=\gamma H_0$. Here the radius of the galactic halo is $R\approx5\times10^{22}$ cm, the mean free path for Brownian motion of interstellar gas clouds is $l\approx1$ kiloparsec $=3\times10^{21}$ cm, and the Hubble constant gives an age of $H_0^{-1}\approx10^{17}$ sec

Thermalization into ISM of the Produced ^{9}Be from $^{16}O+p \rightarrow {}^{9}Be+X$



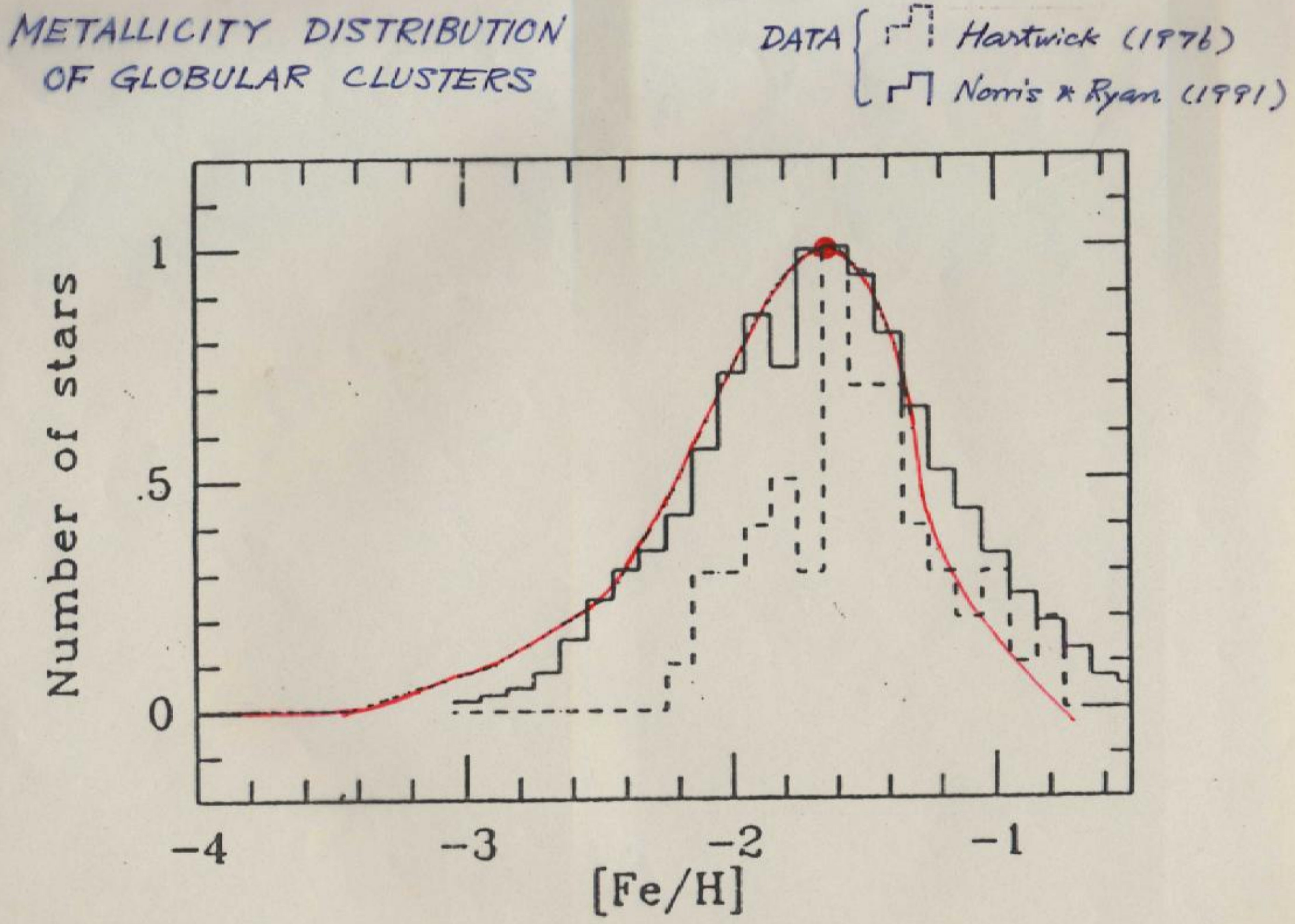
^{7}Li Abundance vs. Neutrino Process

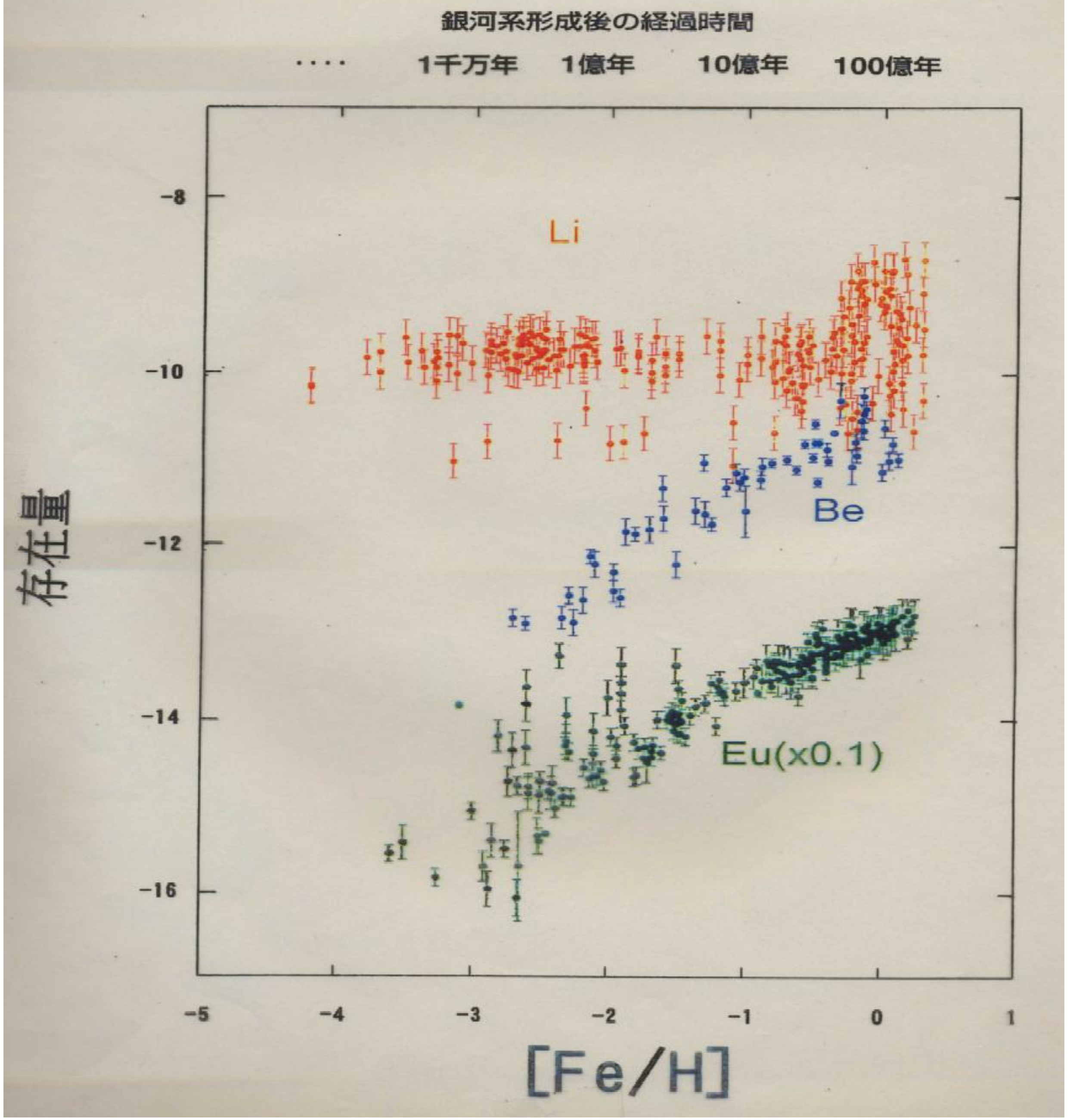
Ryan, Kajino, Beers, Suzuki, Romano, Matteucci & Rosolankova 2001, ApJ 549, 55.



Primordial ^{7}Li is NOT affected by the SN ν-PROCESS !

Primordial ^{7}Li is still PROBLEMATIC !

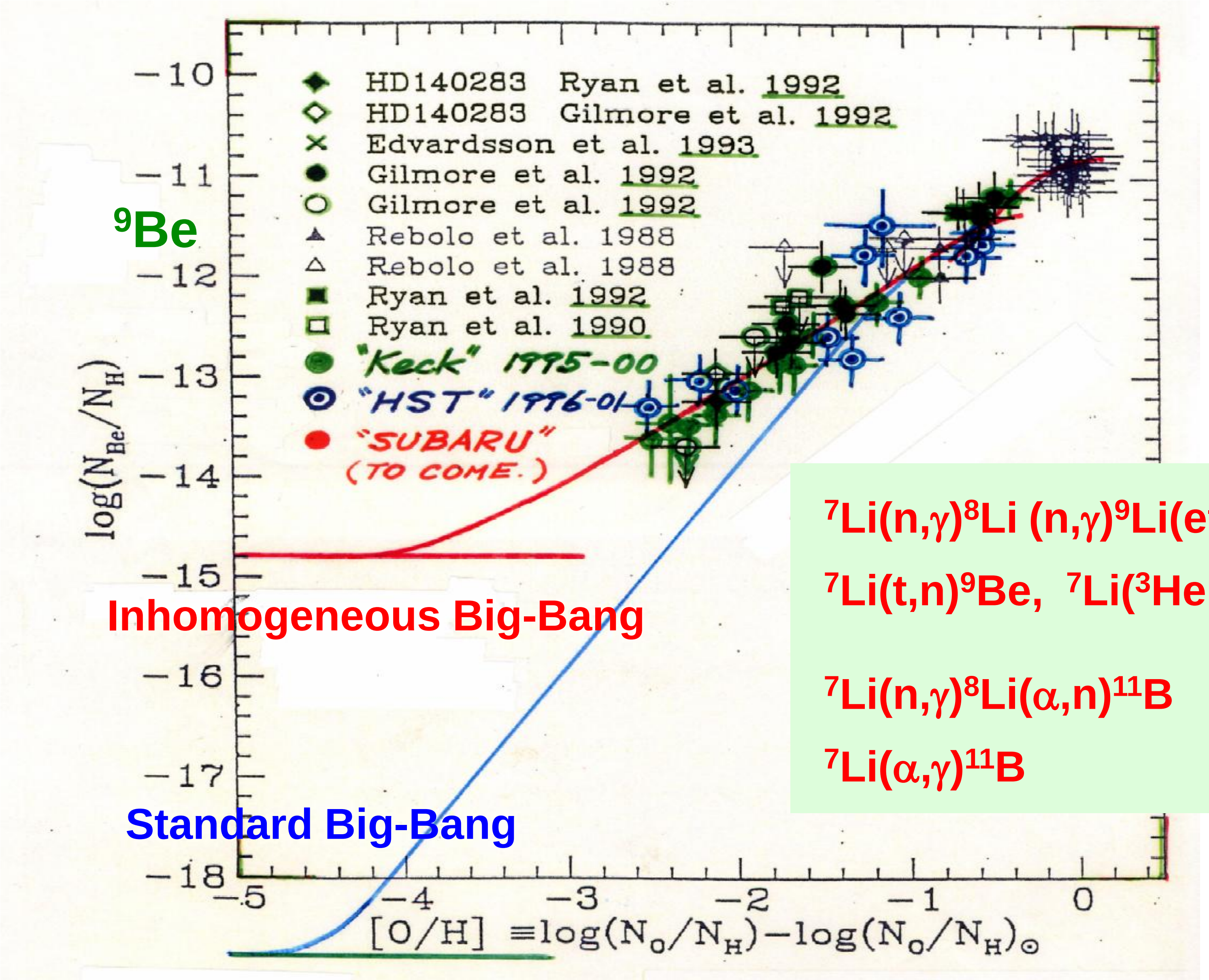

METALLICITY DISTRIBUTION
OF GLOBULAR CLUSTERS
DATA
Hartwick (1976)
Norris & Ryan (1991)
Number of stars
1
.5
0
−4
−3
−2
−1
[Fe/H]



銀河系形成後の経過時間
‥‥
1千万年
1億年
10億年
100億年
存在量
-8
-10
-12
-14
-16
Li
Be
Eu(x0.1)
-5
-4
-3
-2
-1
0
1
[Fe/H]

INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS

Kajino and Boyd, ApJ 359 (1990) 267; Orito, Kajino, Boyd & Mathews, ApJ 488 (1997) 515.



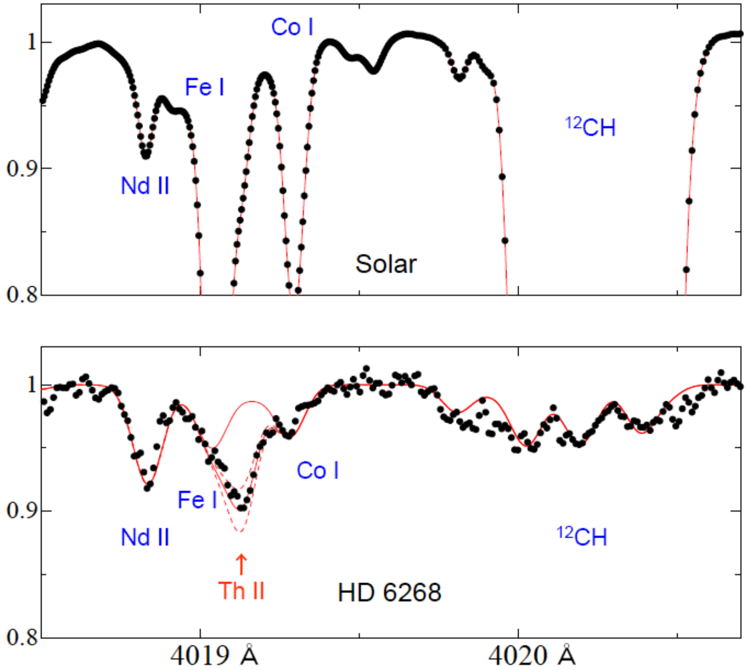
$^{7}Li(n,\gamma)^{8}Li\ (n,\gamma)^{9}Li(e^{-}\nu)^{9}Be$,

$^{7}Li(t,n)^{9}Be$, $^{7}Li(^{3}He,p)^{9}Be$

$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

$^{7}Li(\alpha,\gamma)^{11}B$

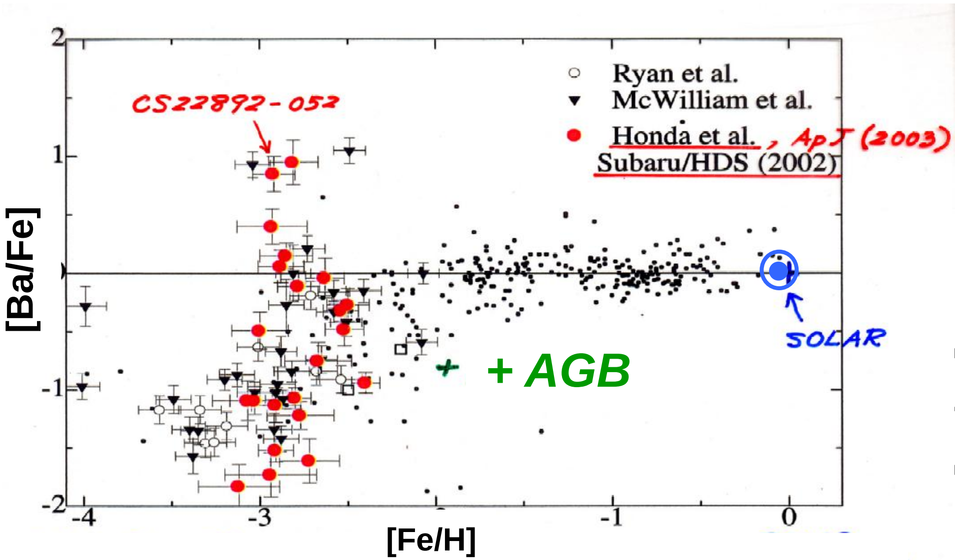
Subaru Telescope



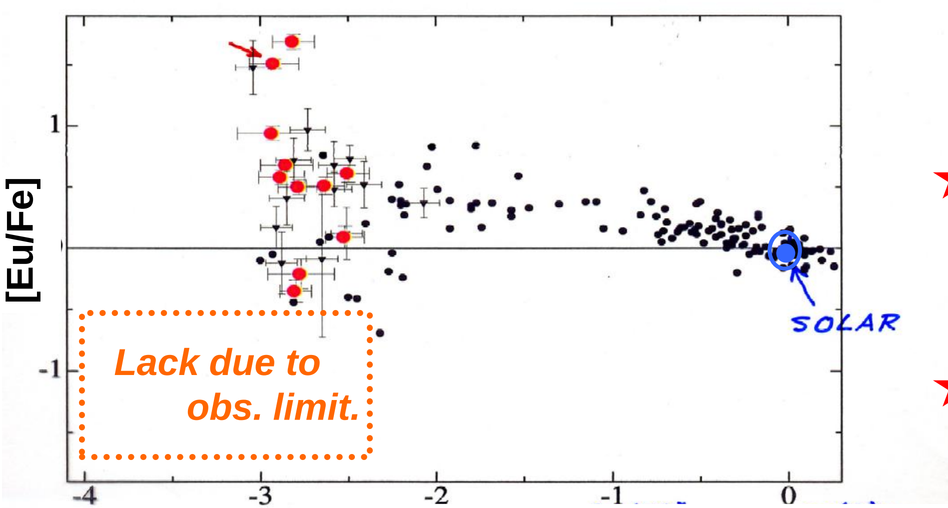
High-Dispersion Spectrograph

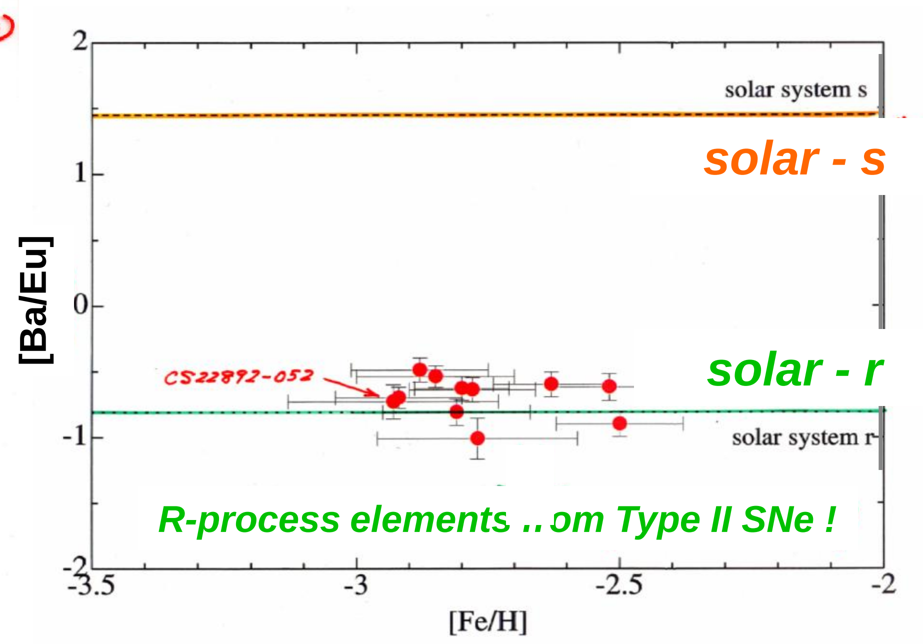
SUBARU Telescope HDS

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



SN II ⟵ ⟶ ⟵ SN I + II ⟶





Early Galaxy ⟵

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

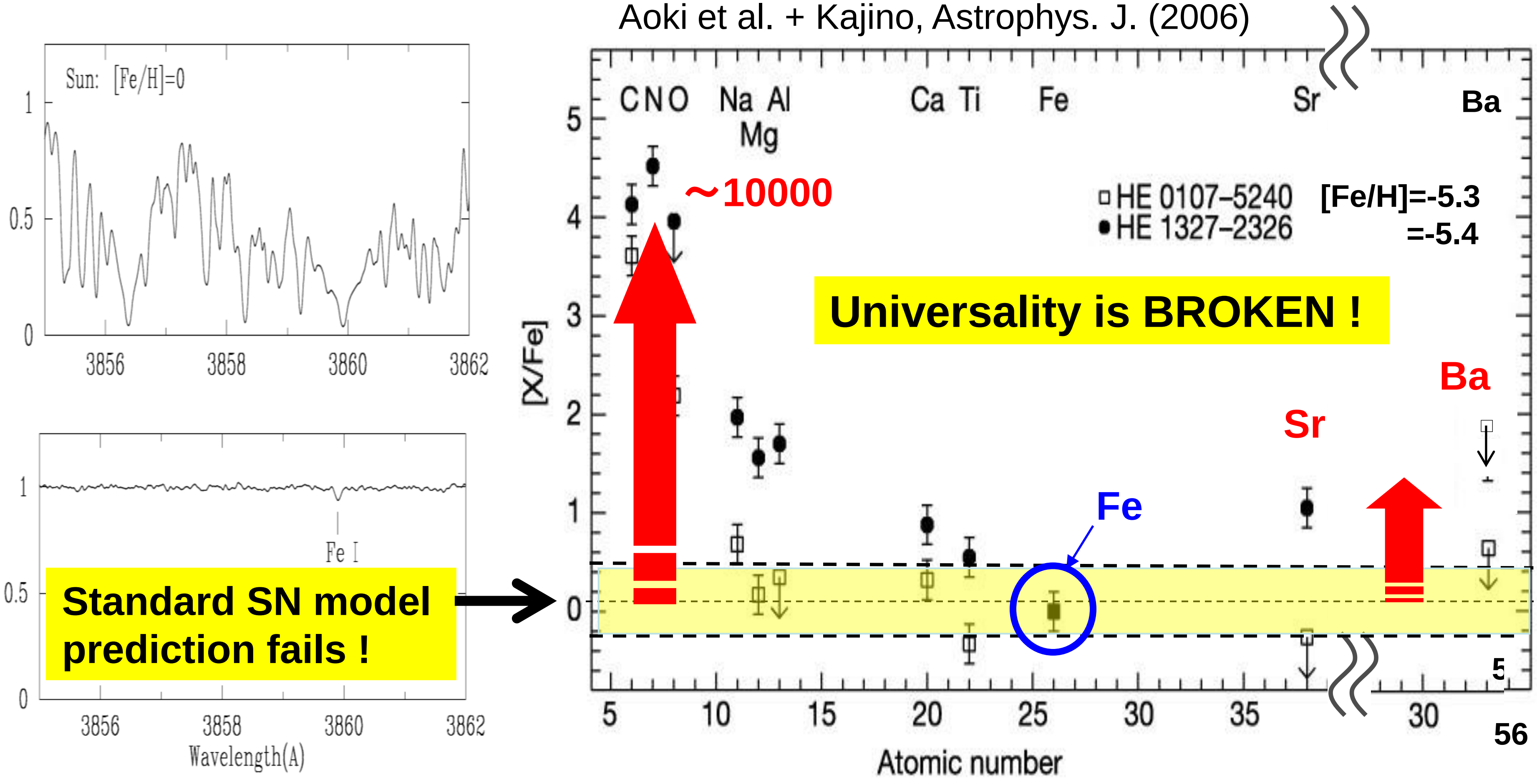
★ **Large abundance scatter at [Fe/H]<-2 is an evidence for INDIVIDUAL supernova episode.**

★ **Only Core-Collapse TYPE II SUPER-NOVAE are the likely astrophysical sites of the R-Process !**

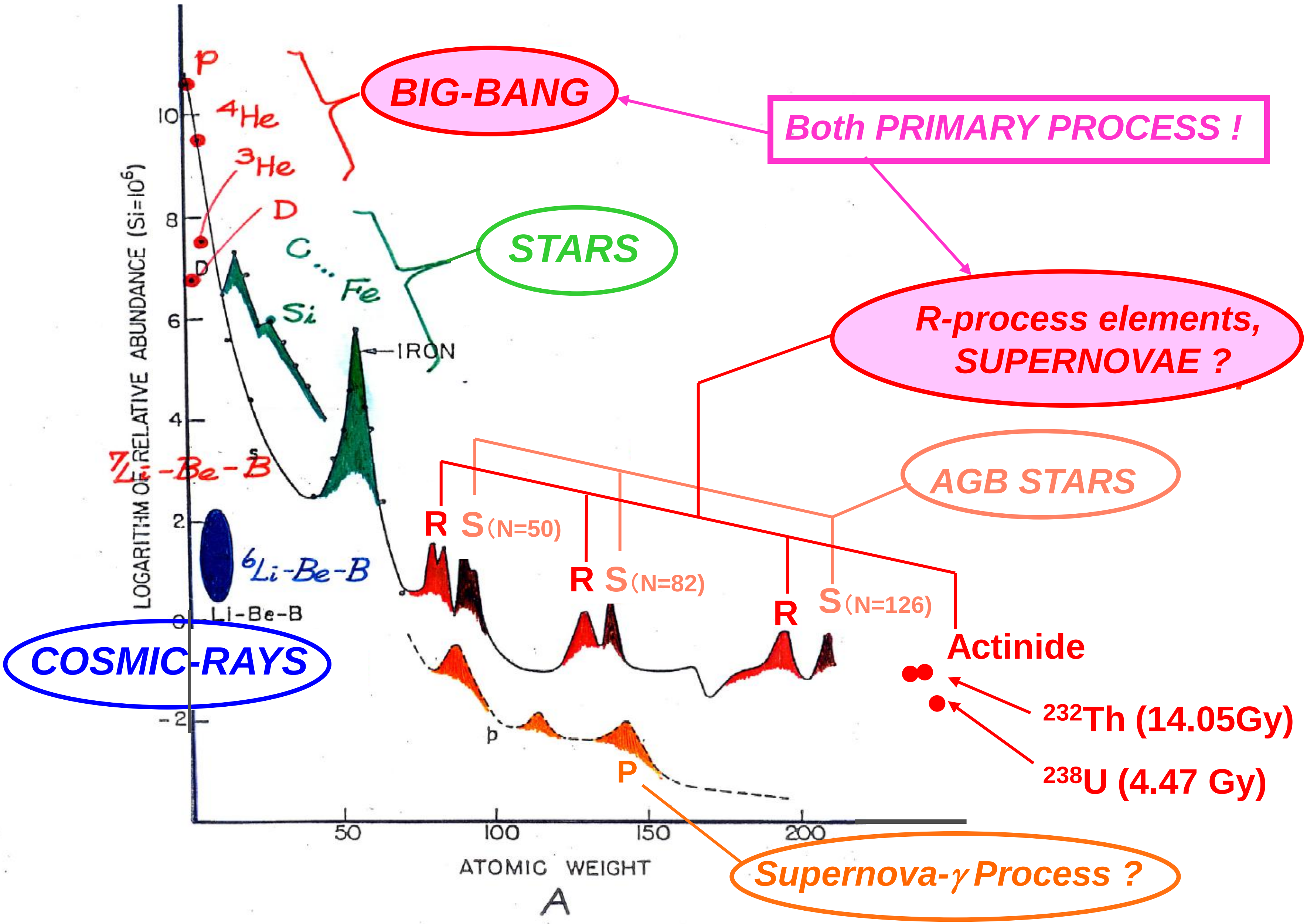
We SUBARU-HDS group discovered an oldest Pop. II Star in the Milky Way !

[Fe/H] = -5.4 ! ⟷ 1/250,000 x Solar-Fe

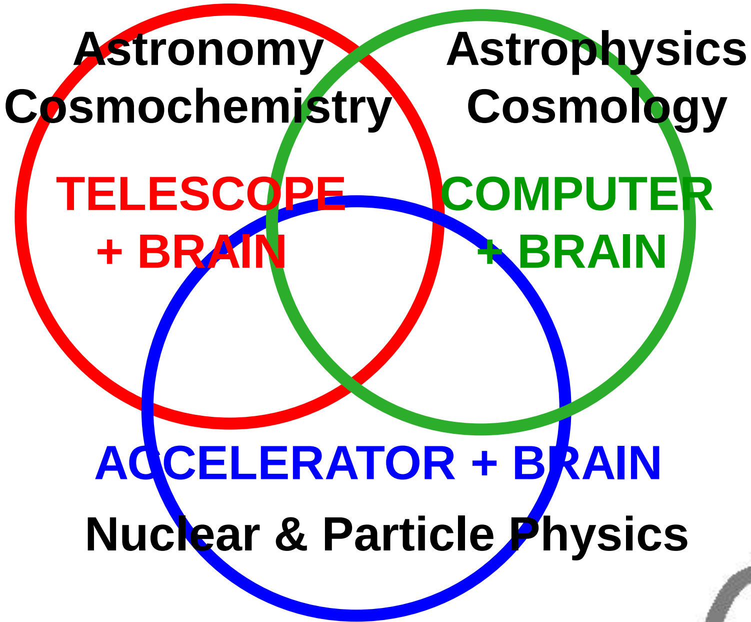
Frebel, Aoki, et al. + Kajino, Nature 434 (2005), 871,
Aoki et al. + Kajino, Astrophys. J. (2006)



Solar System Abundance



宇宙ハドロン核物理



目的
元素合成量とハドロン
過程の時間発展に見る
宇宙進化の解明