



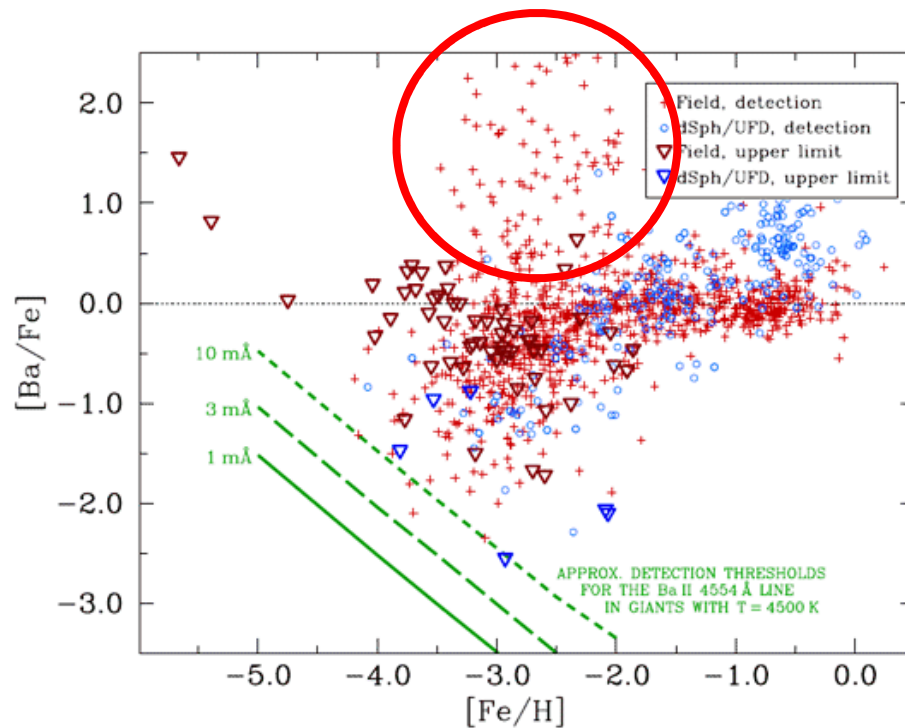
Double Beta Decays in Nucleosynthesis

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Double Beta Decays and Astro-Neutrino Interactions
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Barium is a typical s-element in solar-system, but is expected to be dominated by r-process in metal-poor (**MP**) stars.



I.U. Roederer, 2012

$$f_{\text{odd}} = \frac{N(^{135}\text{Ba}) + N(^{137}\text{Ba})}{N(\text{Ba})}$$

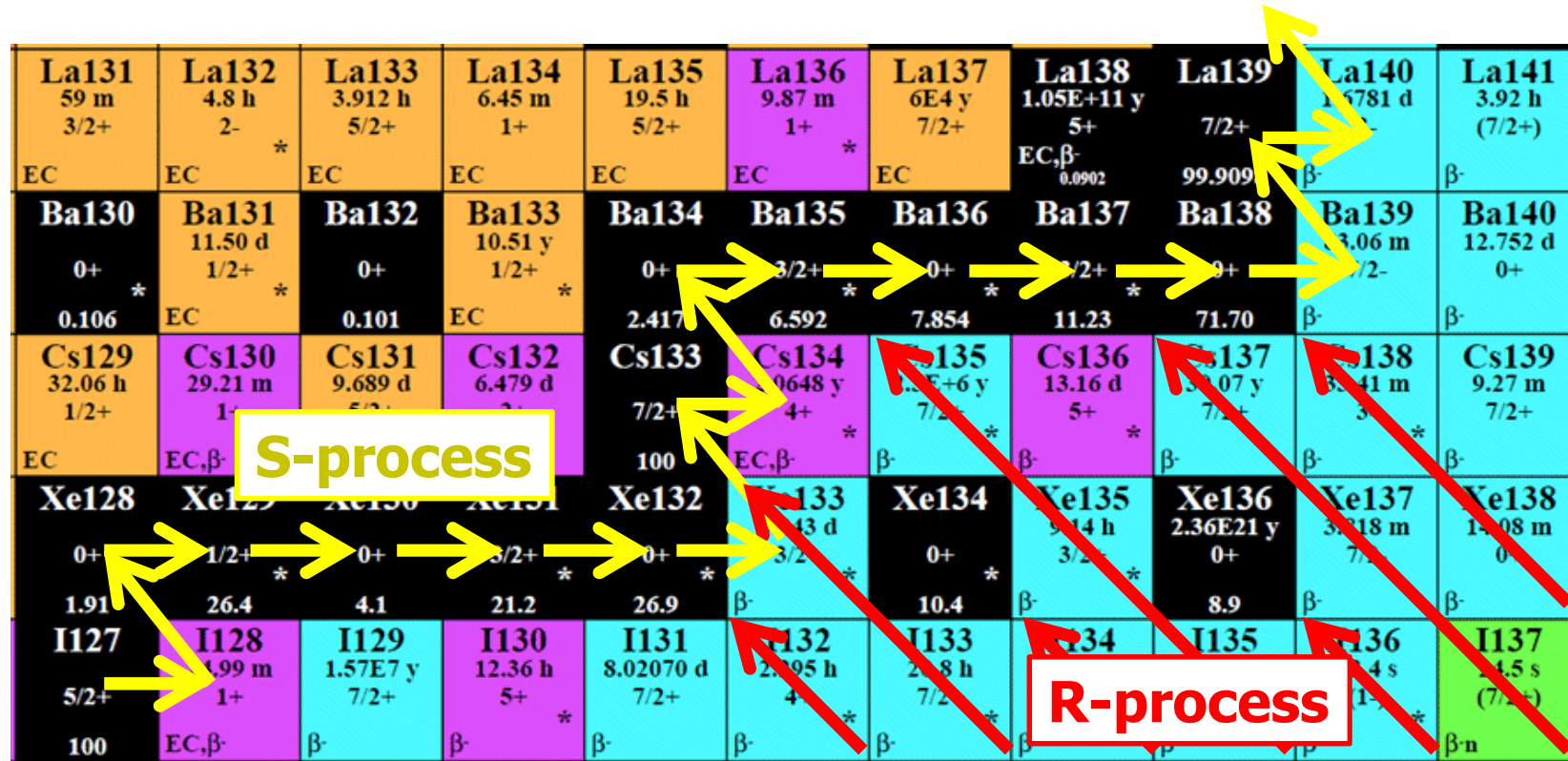
$= 0.11 \pm 0.01$ for s-only

0.46 ± 0.06 for r-only

0.17 in solar system

(Anders & Grevesse 1989)

Stellar s- and r-process paths



Note. f_{odd} becomes large for r-process,
because ^{134}Ba and ^{136}Ba are shielded by
 ^{134}Xe and ^{136}Xe , respectively.

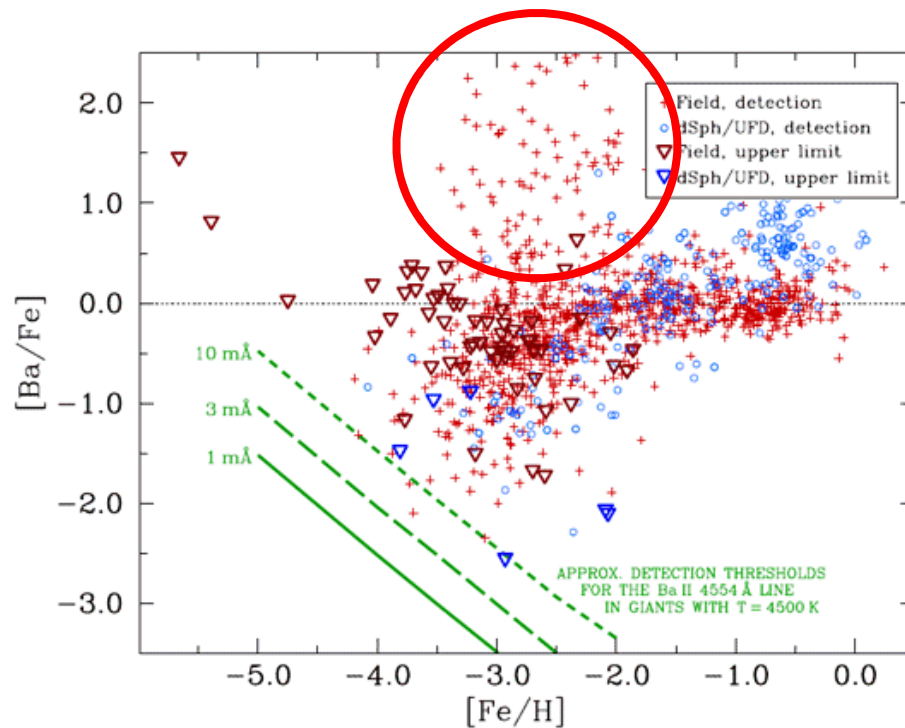


Slow neutron-capture processes

	Main process	Weak process
Atomic mass region	$A > 90$	$56 < A < 90$
Neutron density [cm^{-3}]	$10^7 \sim 10^{10}$	$10^6 \sim 10^7$
Duration [y]	~ 20000 /pulse	$10^5 \sim 10^6$
Astrophysical site	He-shell burning in Low-mass AGB* ($M = 1.5 \sim 3 M_{\odot}$)	Core He-burning in Massive star ($M > 10 M_{\odot}$)

* Asymptotic Giant Branch

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MP

0.18 ± 0.08

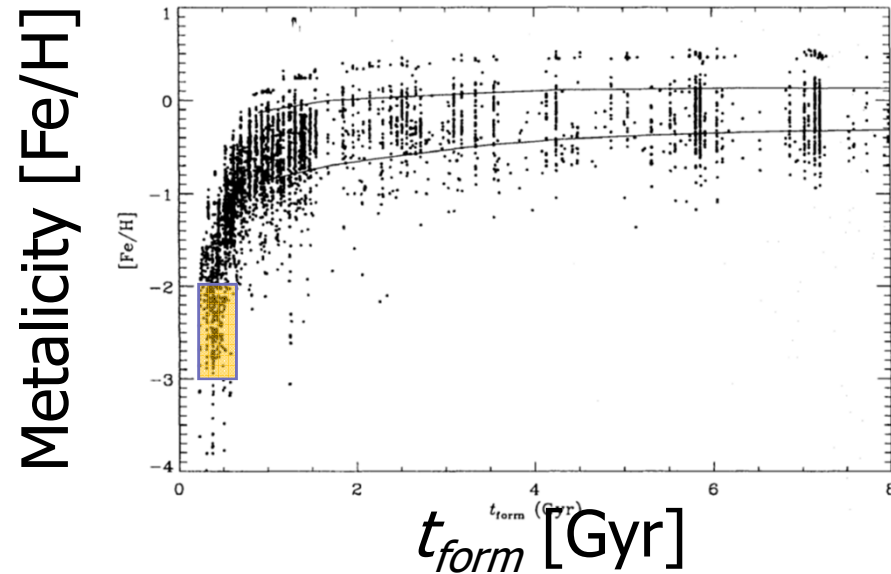
Gallagher, Aoki, Honda et al. 2012

0.15 ± 0.12

Collet, Asplund, Nissen 2009

★ Age-metallicity relation

C.M. Raiteri et al., A&A 315, 105-115 (1996)



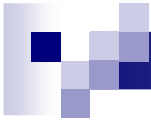
$[\text{Fe}/\text{H}] = -2.15 \sim -3.07$
Gallagher, Aoki, Honda et al. 2012

$[\text{Fe}/\text{H}] = -2.50$
Collet, Asplund, Nissen 2009

➡ $t_{\text{form}} = 0.3 \sim 0.6 \text{ Gyr}$

★ Lifetime of stars; $\tau_{\text{MS}} = 7 \times 10^9 \left[\frac{M}{M_{\odot}} \right]^{-3} [\text{yr}]$

➡ $\tau_{\text{MS}} = 0.26 \sim 2.1 \text{ Gyr for } M = 1.5 \sim 3 M_{\odot}$



- Observation discovered old stars with enhanced abundances of ^{134}Ba and ^{136}Ba .
- ^{134}Ba and ^{136}Ba are produced mainly by main s-process.
- Main s-process occurs in AGB phase of low-mass stars, which take long time to enter He-burning stage.

Is there any unknown type of s-process ?

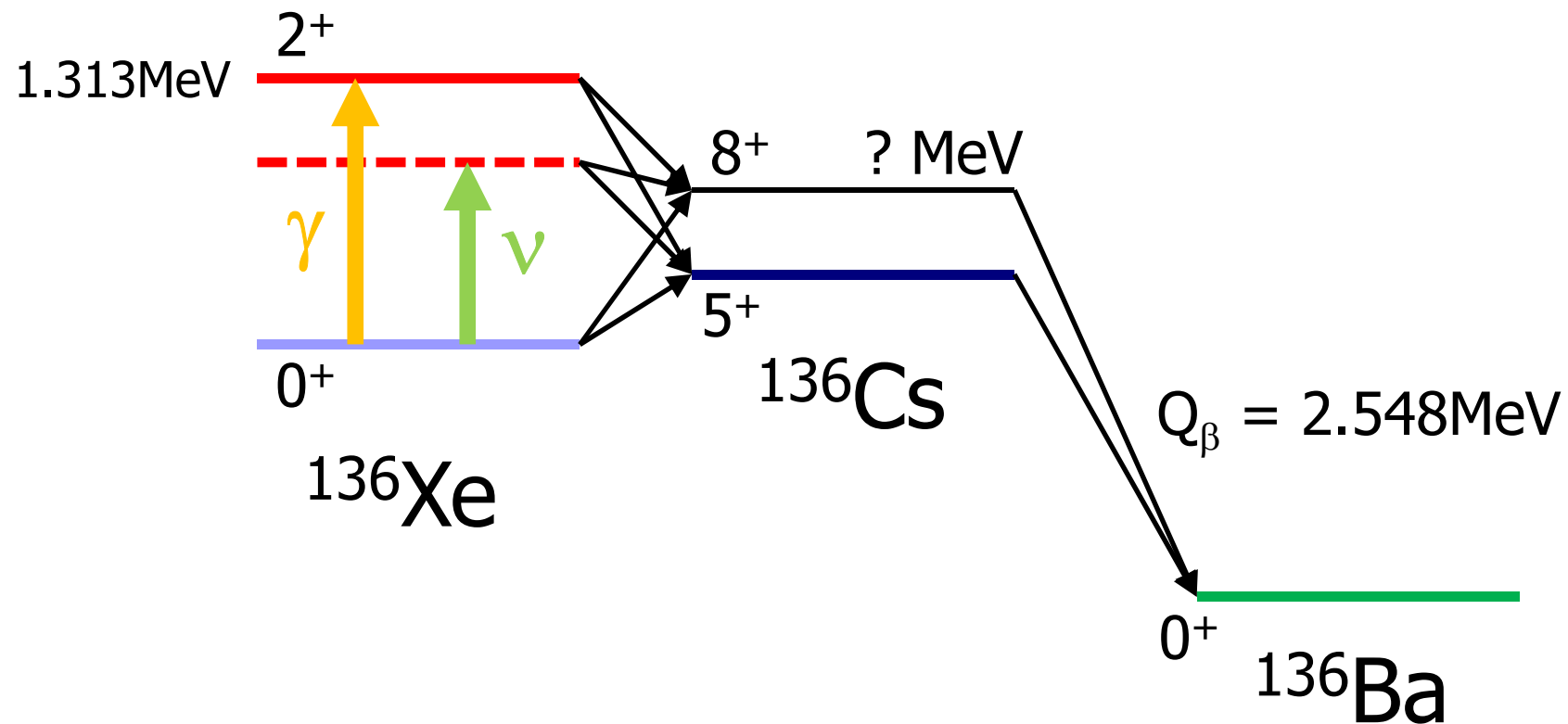
Is there any unknown effect in r-process ?

Neutrino-induced $\beta\beta$ decay

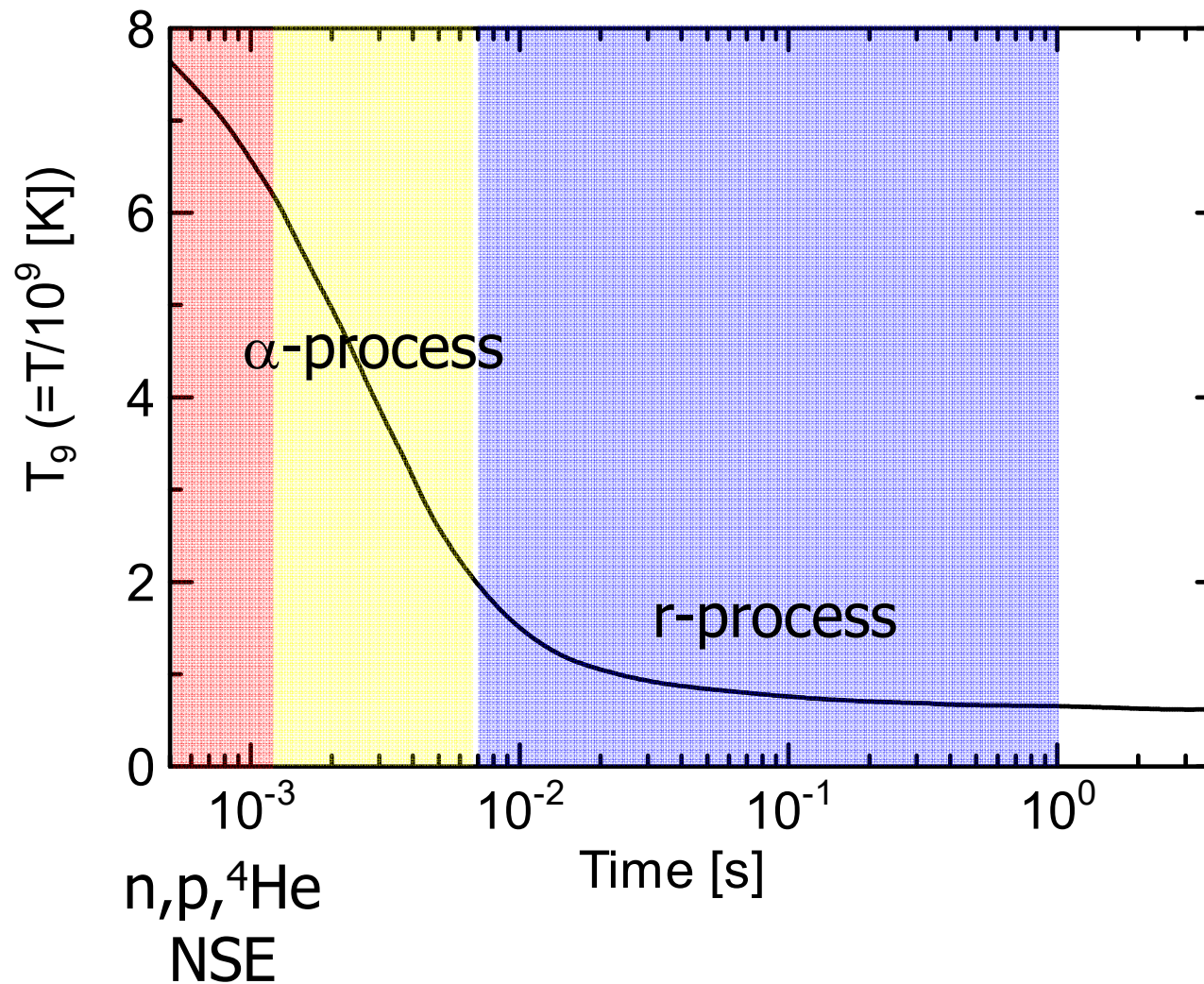
La131 59 m 3/2+ EC	La132 4.8 h 2- EC *	La133 3.912 h 5/2+ EC	La134 6.45 m 1+ EC	La135 19.5 h 5/2+ EC	La136 9.87 m 1+ EC *	La137 6E4 y 7/2+ EC	La138 1.05E+11 y 5+ EC, β^- 0.0902	La139 7/2+ 99.9098	La140 1.6781 d 3- β^-	La141 3.92 h (7/2+) β^-
Ba130 0+ 0.106 *	Ba131 11.50 d 1/2+ EC *	Ba132 0+ 0.101	Ba133 10.51 y 1/2+ EC *	Ba134 0+ 2.417 *	Ba135 3/2+ 6.592 *	Ba136 0+ 7.854 *	Ba137 3/2+ 11.23 *	Ba138 0+ 71.70	Ba139 83.06 m 7/2- β^-	Ba140 12.752 d 0+ β^-
Cs129 32.06 h 1/2+ EC	Cs130 29.21 m 1+ EC, β^- *	Cs131 9.689 d 5/2+ EC	Cs132 6.479 d 2+ EC, β^-	Cs133 7/2+ 100	Cs134 2.648 y 4+ EC, β^- *	Cs135 2.3E+6 y 7/2+ β^- *	Cs136 1.516 d 5- β^- *	Cs137 30.0 7/2- β^-	Cs138 7/2- 30.0	Cs139 9.27 m 7/2+ β^-
Xe128 0+ 1.91	Xe129 1/2+ 26.4 *	Xe130 0+ 4.1	Xe131 3/2+ 21.2 *	Xe132 0+ 26.9 *	Xe133 5.243 d 3/2+ β^- *	Xe134 0+ 10.4 *	Xe135 9.14 h 3/2+ β^- *	Xe136 2.36E21 y 0+ 8.9	Xe137 3.818 m 7/2- β^-	Xe138 14.08 m 0+ β^-
I127 5/2+ 100	I128 24.99 m 1+ EC, β^-	I129 1.57E7 y 7/2+ β^-	I130 12.36 h 5+ β^- *	I131 8.02070 d 7/2+ β^-	I132 2.295 h 4+ β^- *	I133 20.8 h 7/2+ β^- *	I134 52.5 m (4)+ β^- *	I135 6.57 h 7/2+ β^-	I136 83.4 s (1-) β^- *	I137 24.5 s (7/2+) β^- n

Neutrino-induced double-beta decays of $^{134,136}\text{Xe}$ may play crucial roles in production of $^{134,136}\text{Ba}$ in r-process.

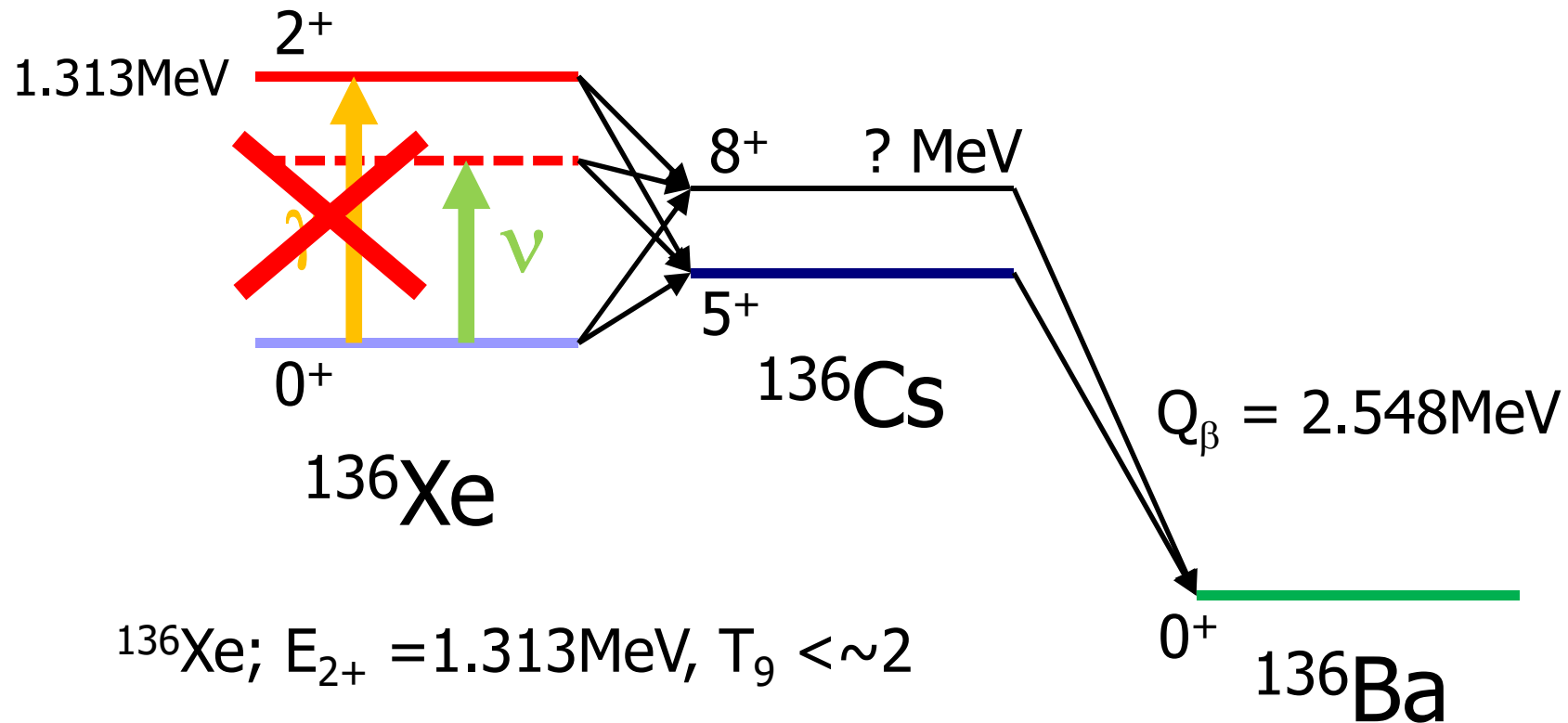
ν -induced $\beta\beta$ v.s. $\beta\beta$ from excited states



Temperature (Matter)

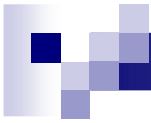


ν -induced $\beta\beta$ v.s. $\beta\beta$ from excited states

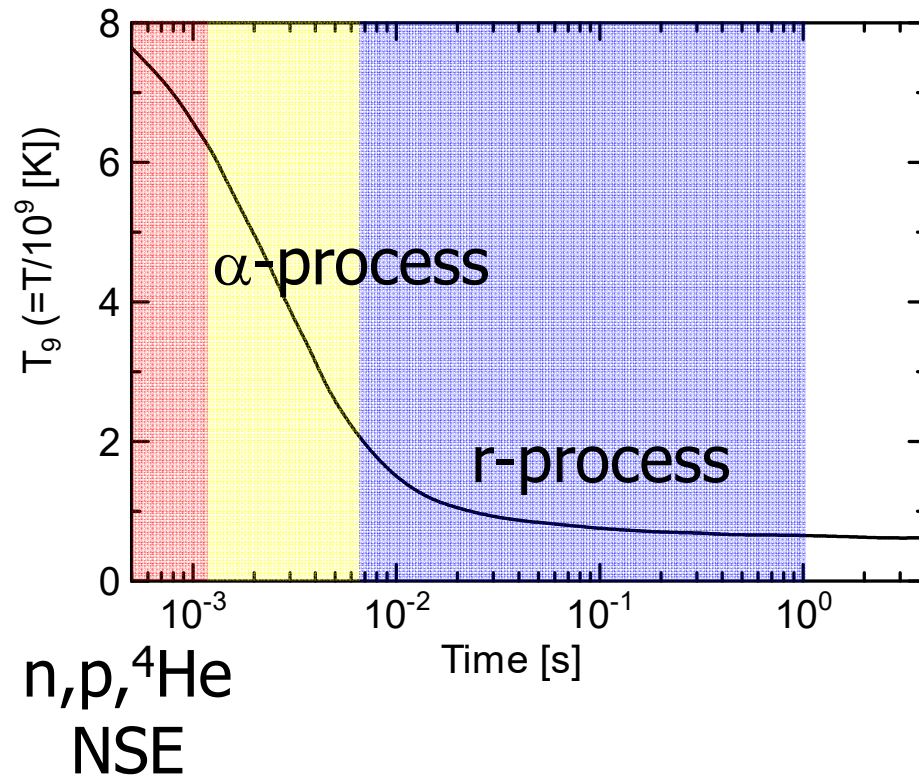


$^{136}\text{Xe}; E_{2^+} = 1.313\text{MeV}, T_9 < \sim 2$

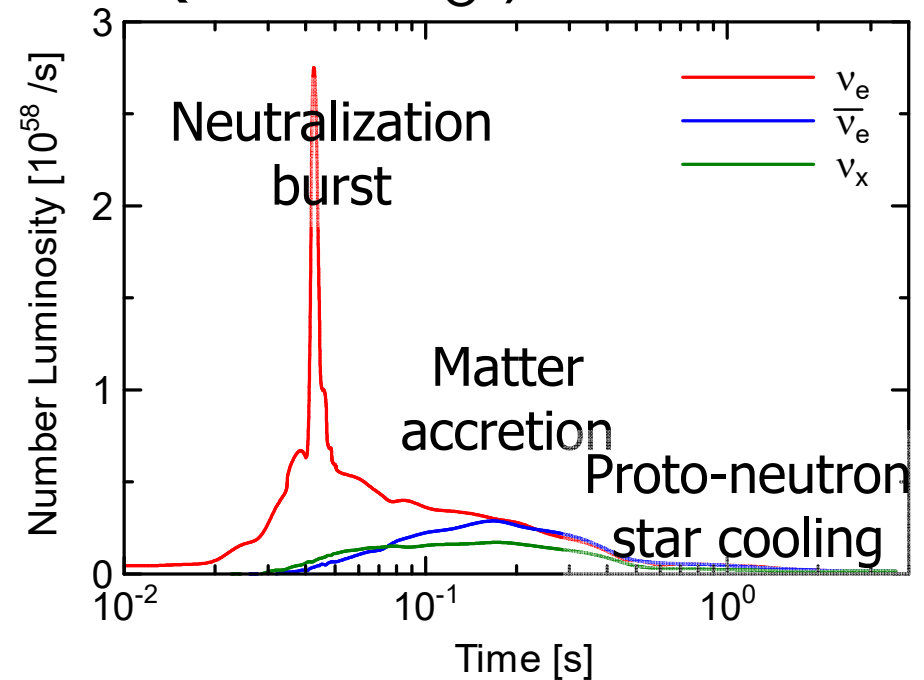
$\rightarrow P(2^+) < 5 \times 10^{-4}$



Temperature (Matter)



Neutrino Luminosity ($M=20M_{\odot}$)



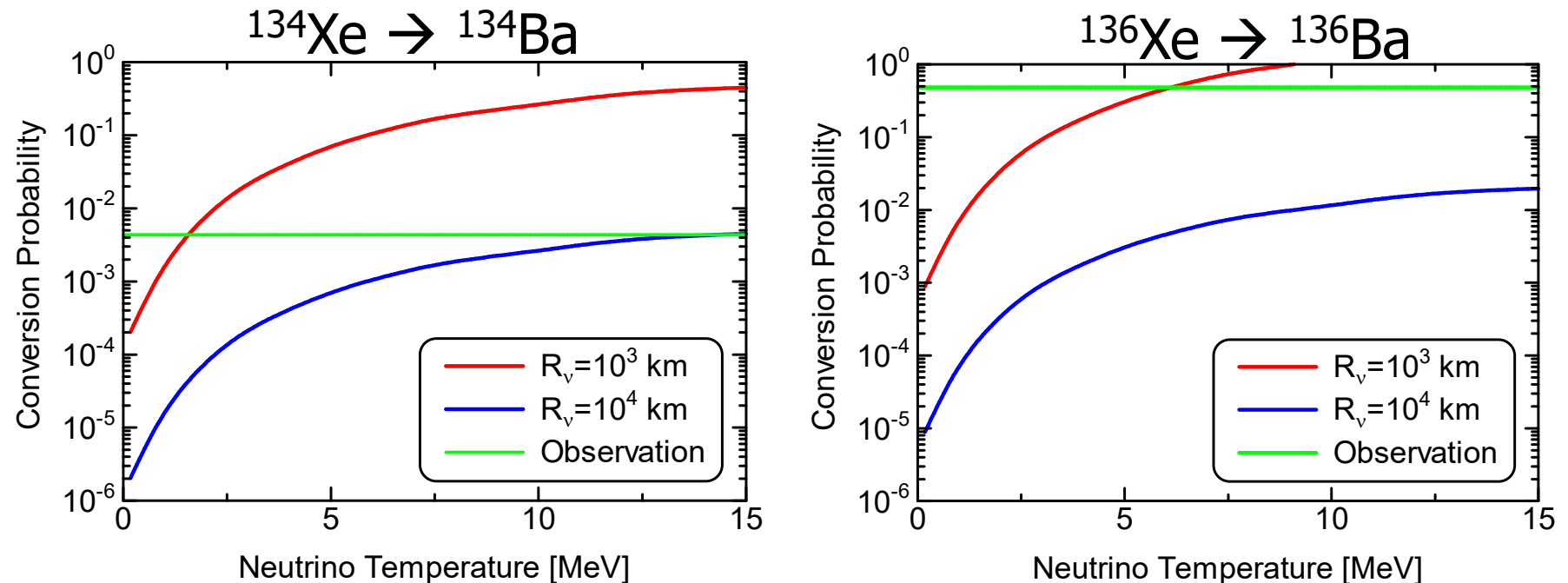
$$\langle E_{\nu_e} \rangle \sim 10 \text{ MeV} \quad \langle E_{\bar{\nu}_e} \rangle \sim 15 \text{ MeV}$$

$$\langle E_{\nu_x} \rangle \sim 23 \text{ MeV}$$

T. Totani, K. Sato, H.E. Dalhed, J.R. Wilson,
ApJ 496, 216-225 (1998)

Probability of $^{134,136}\text{Ba}$ production via ν - $\beta\beta$ process

Assuming total energy of emitted neutrinos to be 3.5×10^{53} erg, ν_e will have total energy of $\sim 6 \times 10^{52}$ erg or $\sim 3.7 \times 10^{58}$ MeV.



Given realistic reaction rates, temperature and radius of ν - $\beta\beta$ region can be constrained.



Summary

- Some metal-poor stars indicate large enhancement in even-even Ba isotopes.
- Heavier ($\sim 3M_{\odot}$) component of low-mass AGB stars may contribute. Another possibility will be $\beta\beta$ -decays of $^{134,136}\text{Xe}$ induced by absorptions of neutrinos or photons.
- γ -induced $\beta\beta$ -decays of $^{134,136}\text{Xe}$ are unlikely due to too small population of 1st excited states at r-process temperature; $T_9 < 2$.
- On the other hand, ν -induced $\beta\beta$ -decay is still possible.
- Since β -decay lifetimes of ^{134}I and ^{136}I are much longer than r-process duration, ν - $\beta\beta$ process cannot occur in single r-process episode.
- For quantitative analysis, reliable calculation for ν - $\beta\beta$ rate is necessary.