「重力波天体の多様な観測による
宇宙物理学の新展開」勉強会
2013.1.8. 熱海

銀河における元素量の観測

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銀河における元素量の観測

- 中性子星合体によってどのような元素合成が起こるか？

  とくにr-processのサイトか？

- 化学進化への影響は？

化学組成と金属量

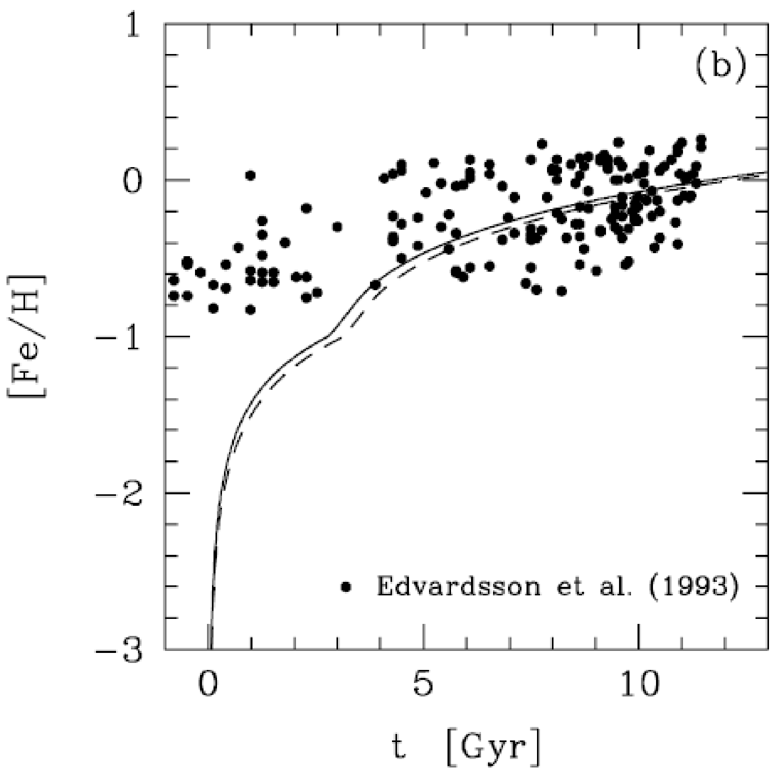
- 化学組成（元素量）
  chemical composition, (chemical) abundances
  元素の組成比（同位体組成はなかなか測れない）
  水素に対する組成比(個数密度比)、あるいは2元素の組成比
  [X/Y]=log(X/Y)-log(X/Y)sun
  例：[Fe/H]=-2.0 → 鉄組成が太陽の1/100
  　　[Eu/Fe]=+0.5 → 　Eu/Fe比が太陽の約3倍
- 金属量
  水素、ヘリウム以外の元素の（水素に対する）組成比
  鉄組成（[Fe/H]）で代表することが多い
  大雑把には化学進化の進行の程度（→経過時間）を表す

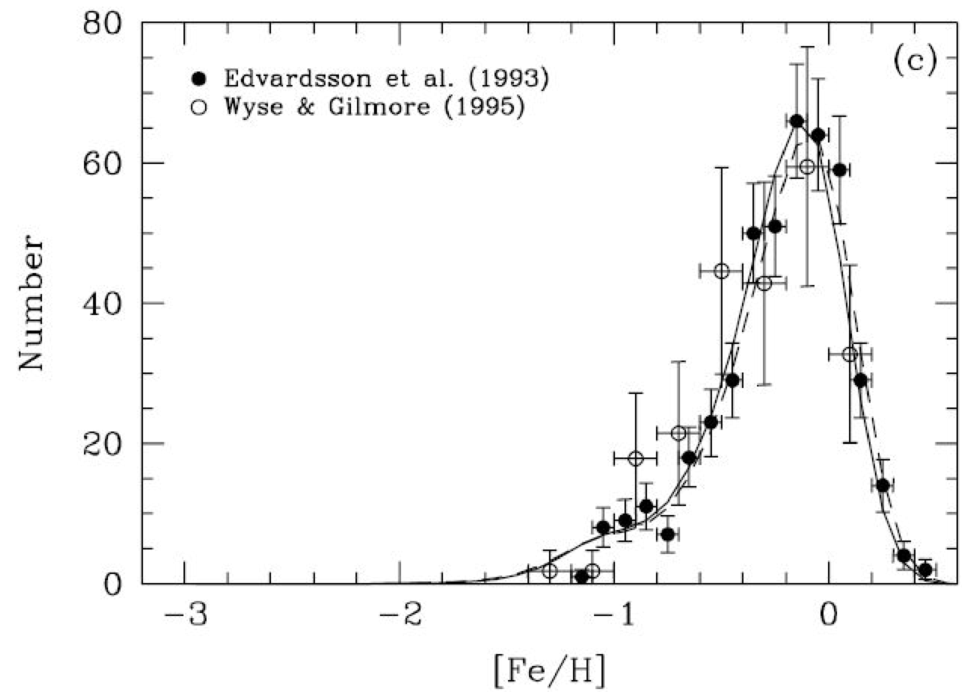
化学進化～銀河(宇宙)のなかでの金属量や元素組成の変遷の解明

- 星形成率(SFR)
- 星の質量関数(IMF)
- 元素合成
- …

→

- 星の金属量分布
- 星の金属量･年齢関係
- 化学組成比
- …





Kobayashi et al. (2006)

元素合成と化学進化:
例: α 元素と鉄族元素

大質量星でのCa,Fe合成

Ia型超新星でのFe合成

“knee”

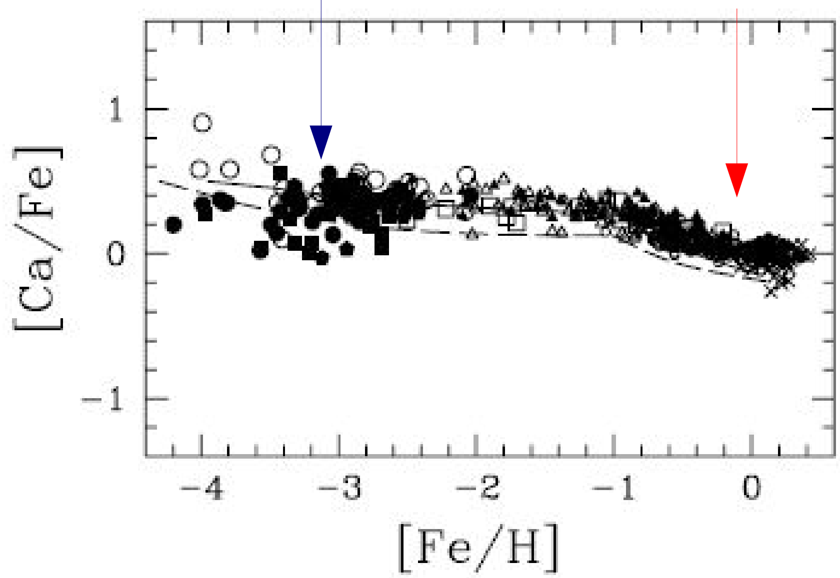
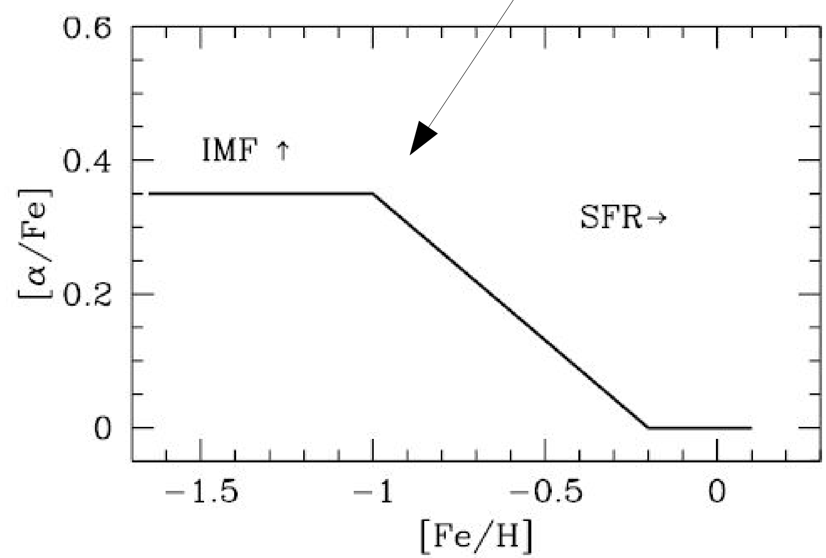


Fig. 12.—Same as Fig. 10, but for [Ca/Fe]-[Fe/H] relation. [*See the electronic edition of the Journal for a color version of this figure.*]



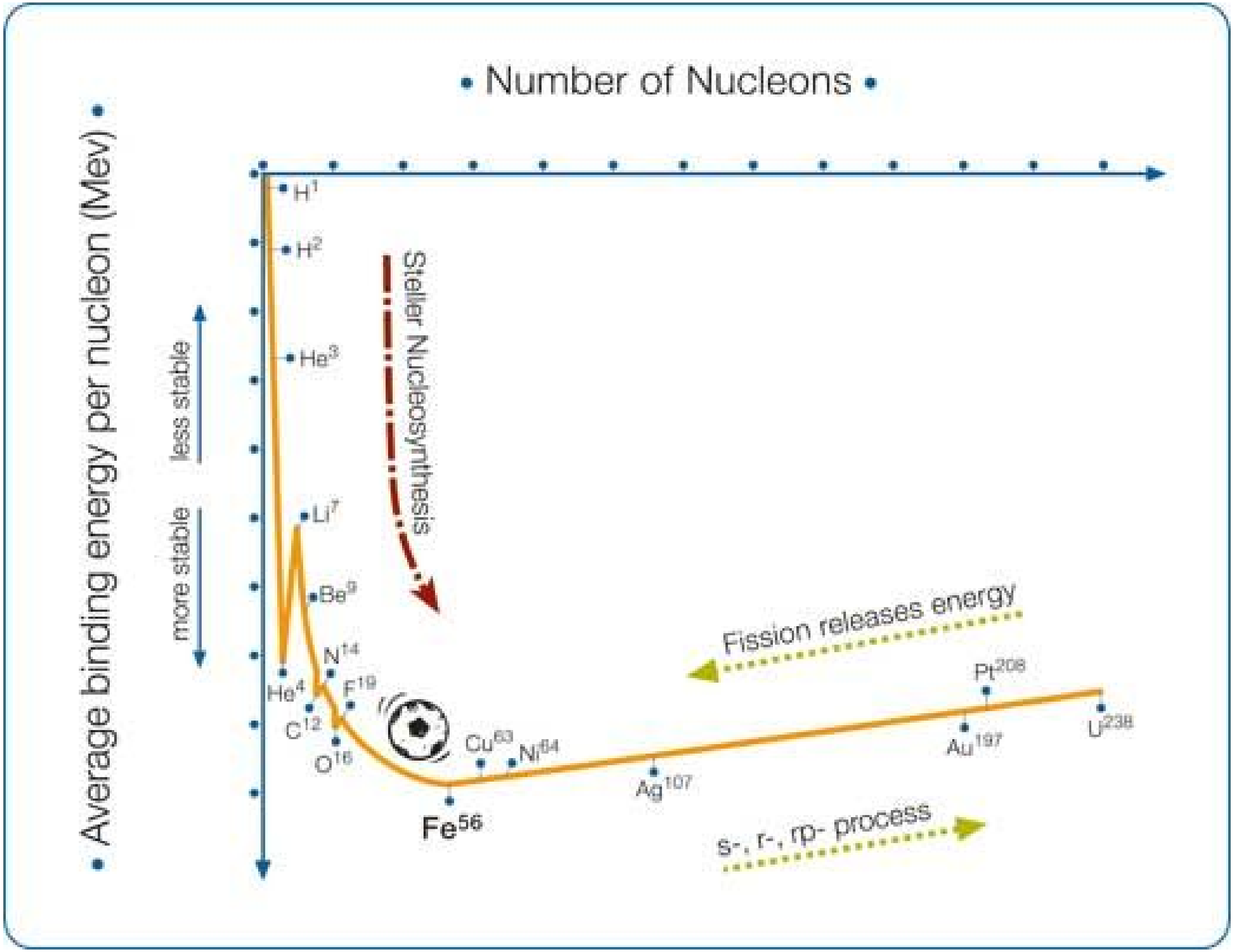
ure 1 A schematic diagram of the trend of α-element abundance with metallicity. Increased ial mass function and star formation rate affect the trend in the directions indicated. The knee ... he diagram is thought to be due to the onset of type Ia supernovae (SN Ia).

Kobayashi et al. (2006)

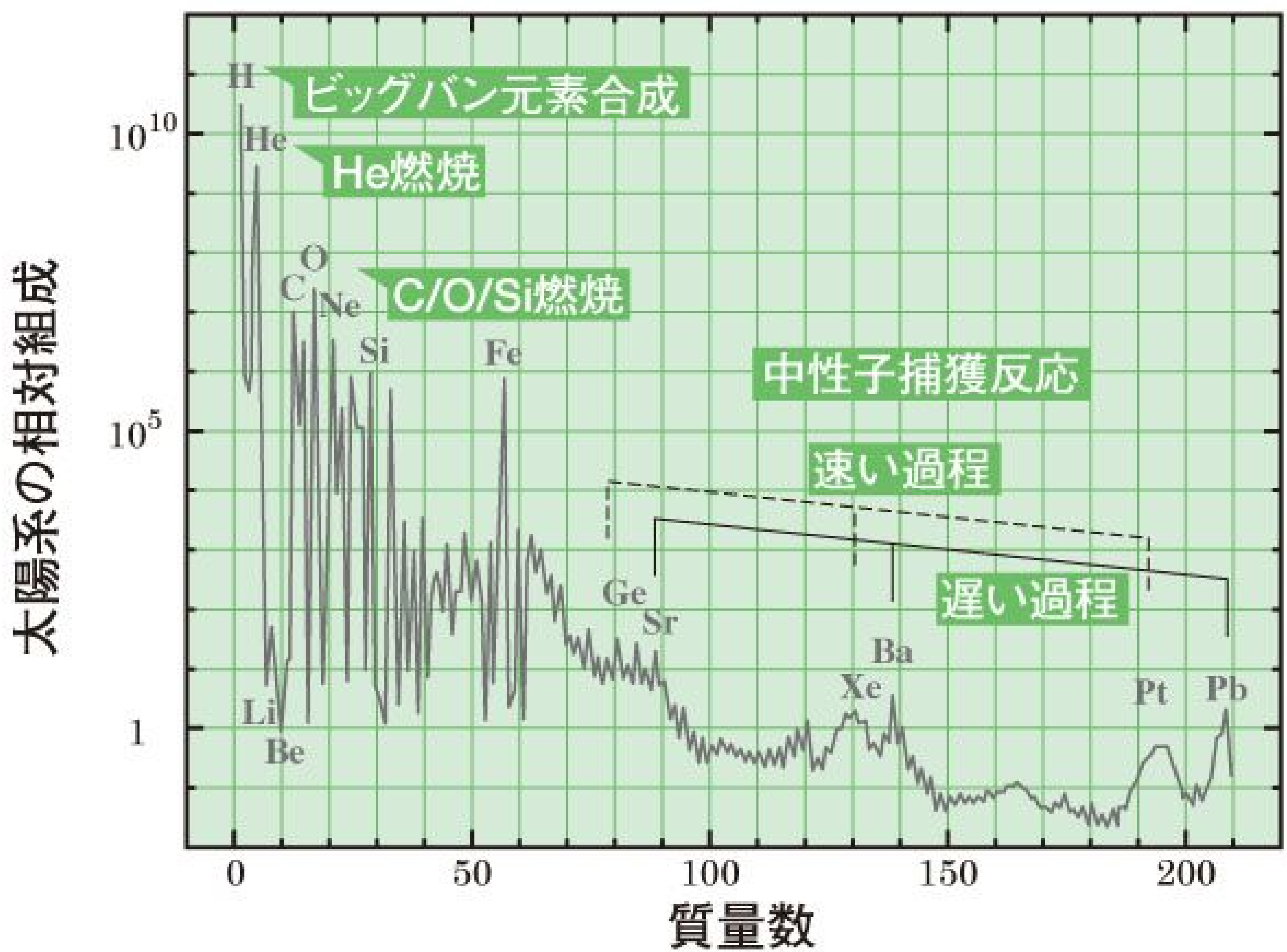
McWilliam et al. (1997)


元素の周期表
ビッグバン元素合成、宇宙線破砕反応等
星の中の核融合
中性子捕獲反応

原子核として最も安定なのは鉄



鉄より重い元素の組成は格段に低い



中性子捕獲による重元素の合成

- 原子核どうしの結合では鉄より重い元素はほとんど合成されない

- 中性子捕獲(neutron-capture)なら重い原子核の合成が可能
 ←中性子過剰な環境が必要

「核図表」～原子核の構成･特性を整理した図

陽子数→

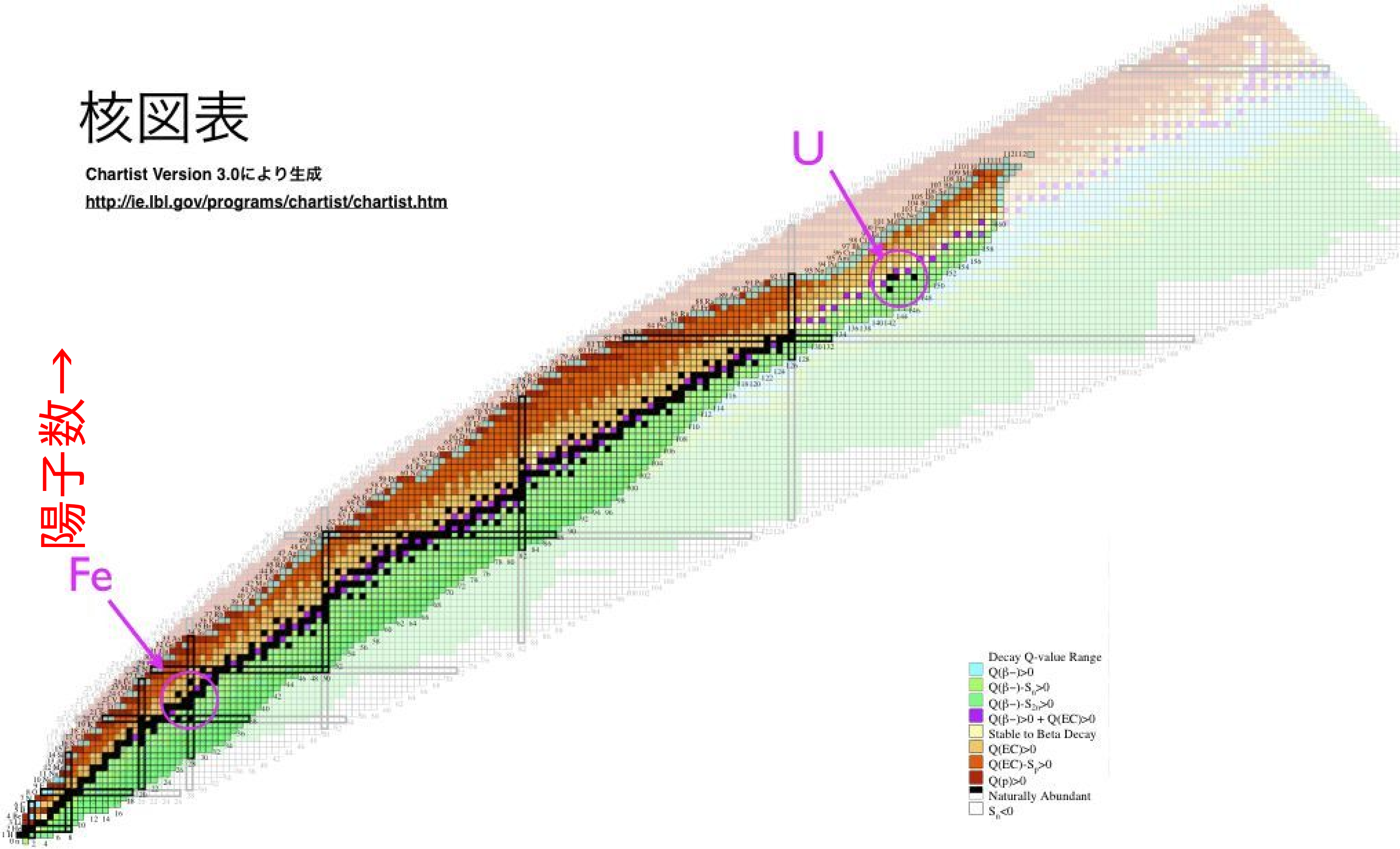
16											S 26 0.012s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s
15											P 25 0.0368s	P 26 0.0437s	P 27 0.26s	P 28 0.2703s	P 29 4.142s
14									Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297
13									Al 21 0.0428s	Al 22 0.0911s	Al 23 0.446s	Al 24 2.053s	Al 25 7.183s	Al 26 7.17e+05y	Al 27 100
12								Mg 19 4e-12s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10	Mg 26 11.01
11								Na 18 0.0347s	Na 19 0.435s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.603y	Na 23 100	Na 24 15h	Na 25 59.1s
10							Ne 16	Ne 17 0.1092s	Ne 18 1.666s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m
9							F 15 0.14s	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s	F 22 4.23s	F 23 2.23s
8						O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.757	O 17 0.038	O 18 0.205	O 19 26.88s	O 20 13.51s	O 21 3.42s	O 22 2.25s
7						N 11 0.09s	N 12 0.011s	N 13 9.965m	N 14 99.632	N 15 0.368	N 16 7.13s	N 17 4.173s	N 18 0.619s	N 19 0.271s	N 20 0.13s	N 21 0.095s
6				C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07	C 14 5700y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
5					B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0125s	B 15 0.0105s		B 17 0.00508s		B 19 0.00292s
4					Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0213s		Be 14 0.00484s				
3					Li 6 7.59	Li 7 92.41	Li 8 0.8399s	Li 9 0.1783s		Li 11 0.0087s						
2			He 3 0.000137	He 4 99.9999		He 6 0.8067s		He 8 0.1191s								
1		H 1 99.9885	H 2 0.0115	H 3 12.32y												
0			n 1 10.23m													

中性子数→

核図表

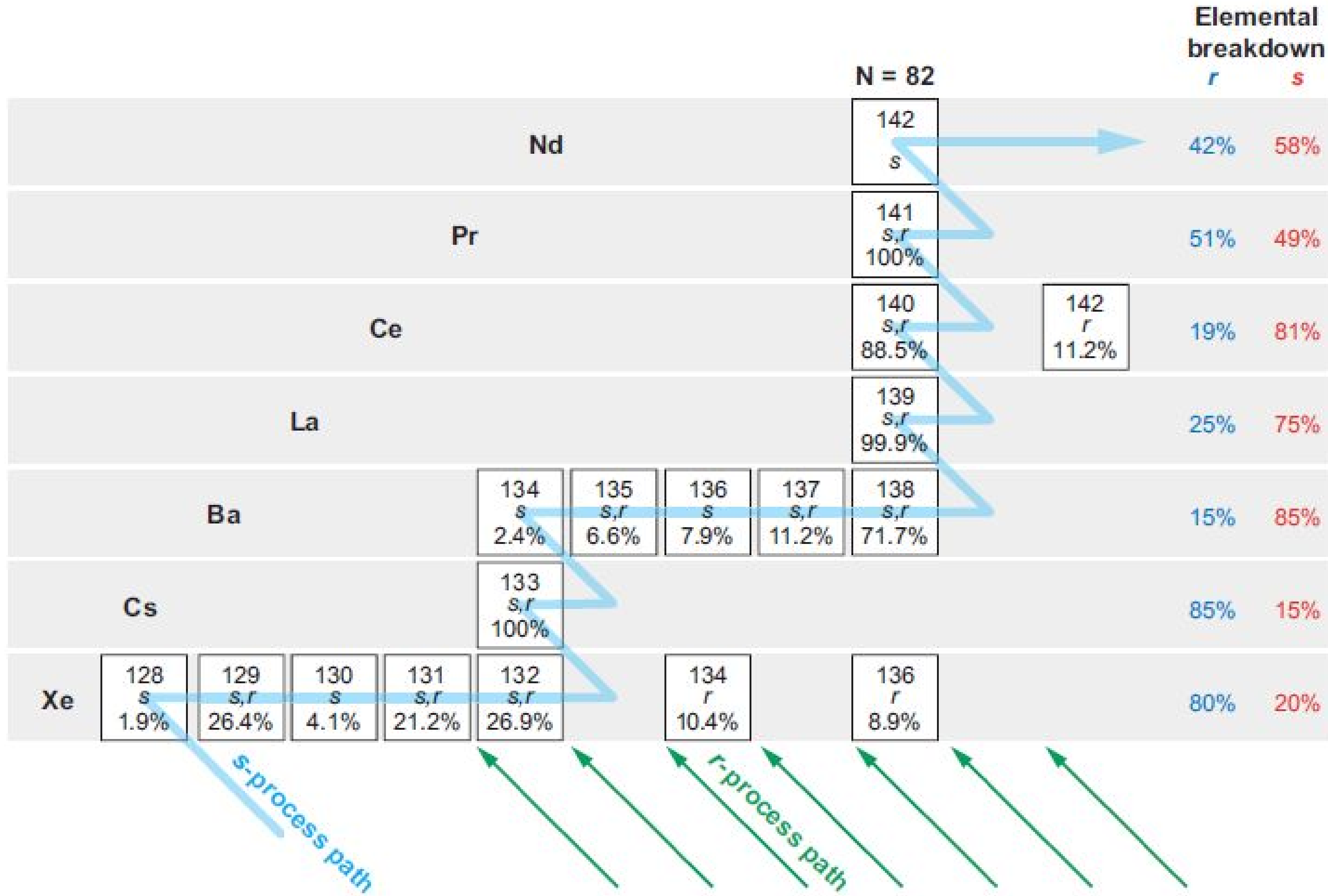
Chartist Version 3.0により生成

http://ie.lbl.gov/programs/chartist/chartist.htm



中性子数→

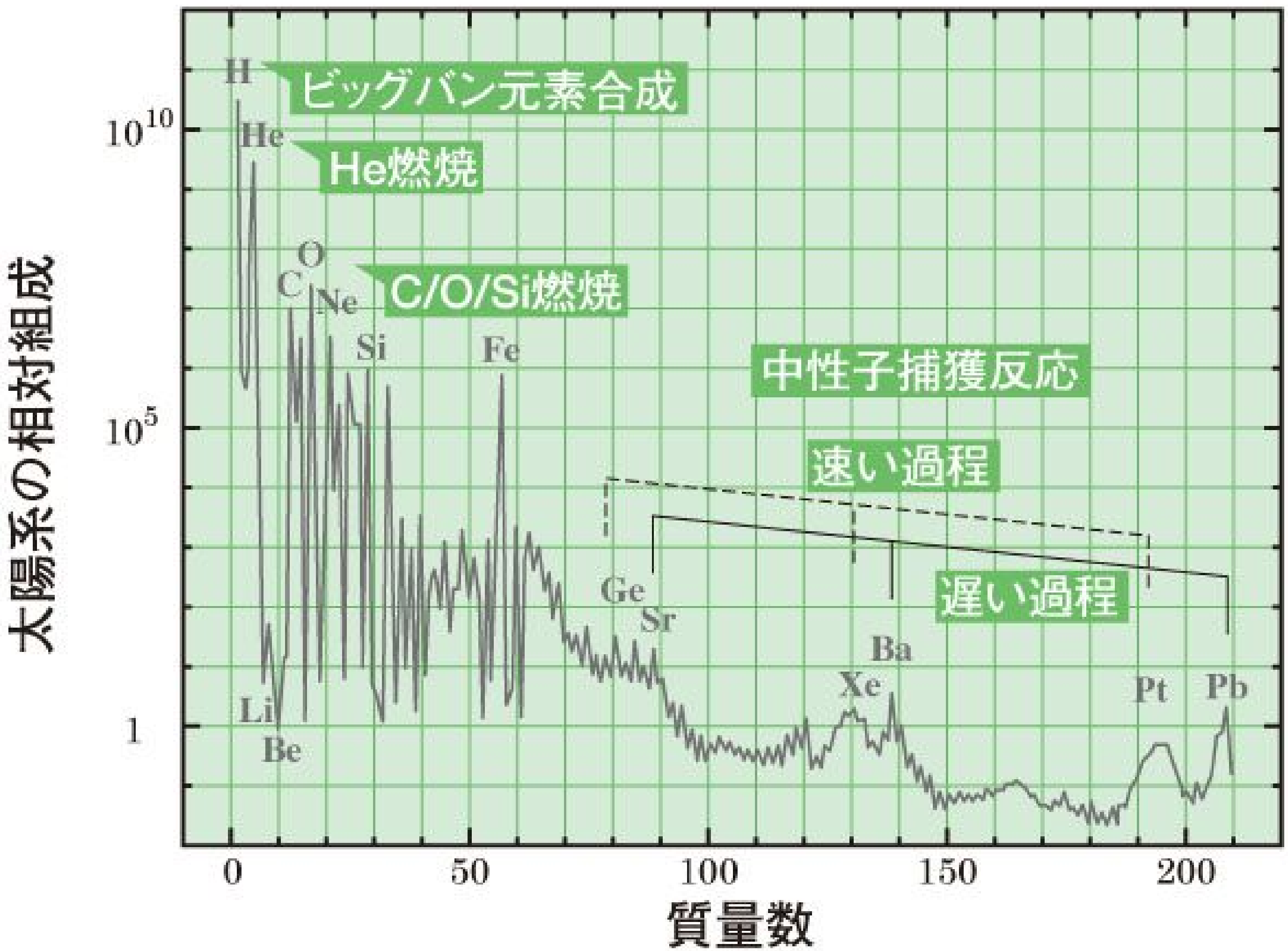
s-process と r-process



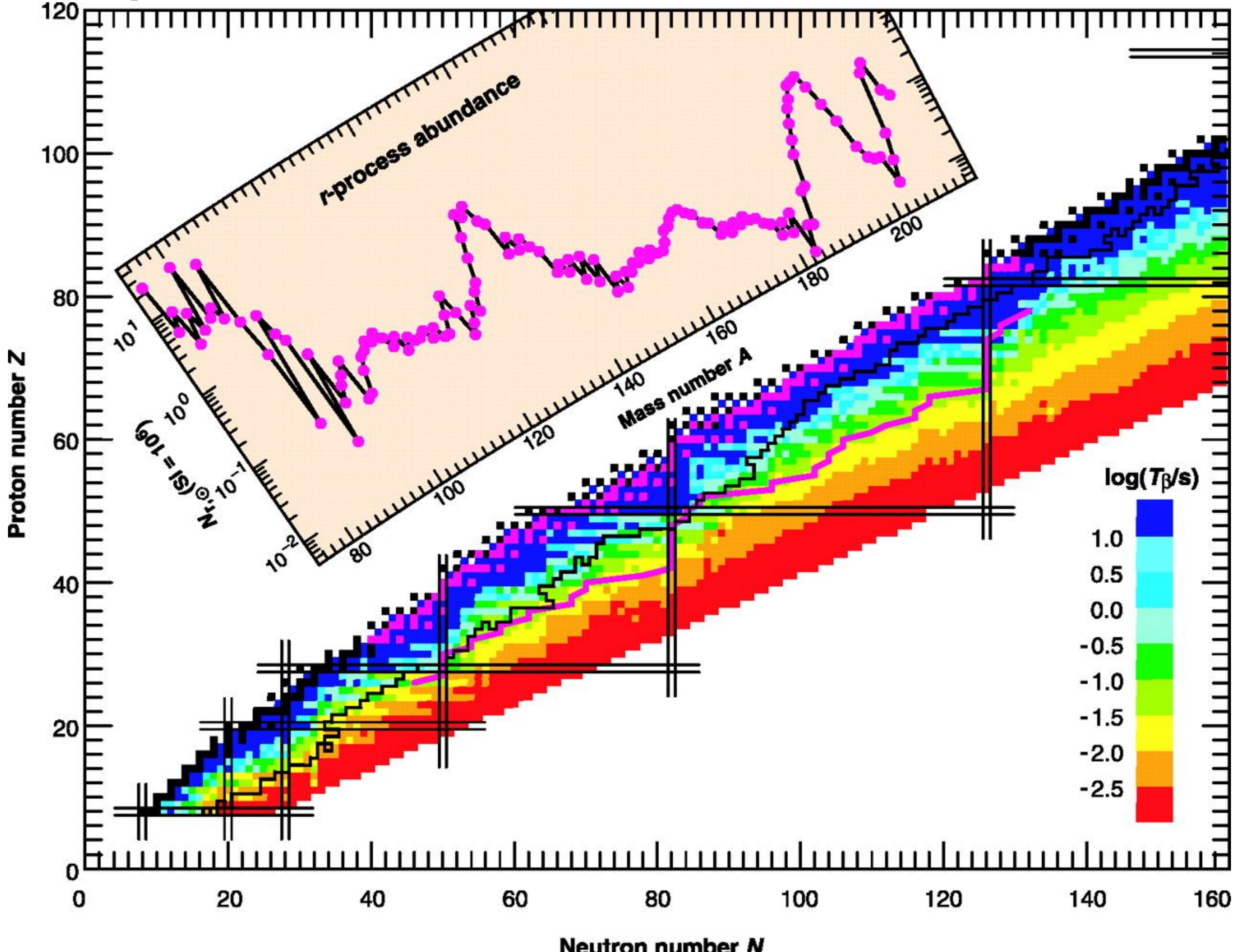
Sneden et al. (2008)

中性子の魔法数に対応した2つの組成のピークが存在→2つのプロセスが存在

s-proces & r-process



r-process



Sneden et al. (2008)

r-process: 爆発的な重元素合成

- r-process:1秒程度で終了する、急速な中性子捕獲反応
→不安定原子核を経由した反応の解明へ

- r-process がどこで起こっているかは、依然未解明
  候補:重力崩壊型超新星、中性子星の合体...

- 太陽系組成のr-process 成分は、s-process 成分で説明できない成分から推定される。

r-process についての観測からの制限

(1) Chemical abundance patterns of r-process enhanced stars

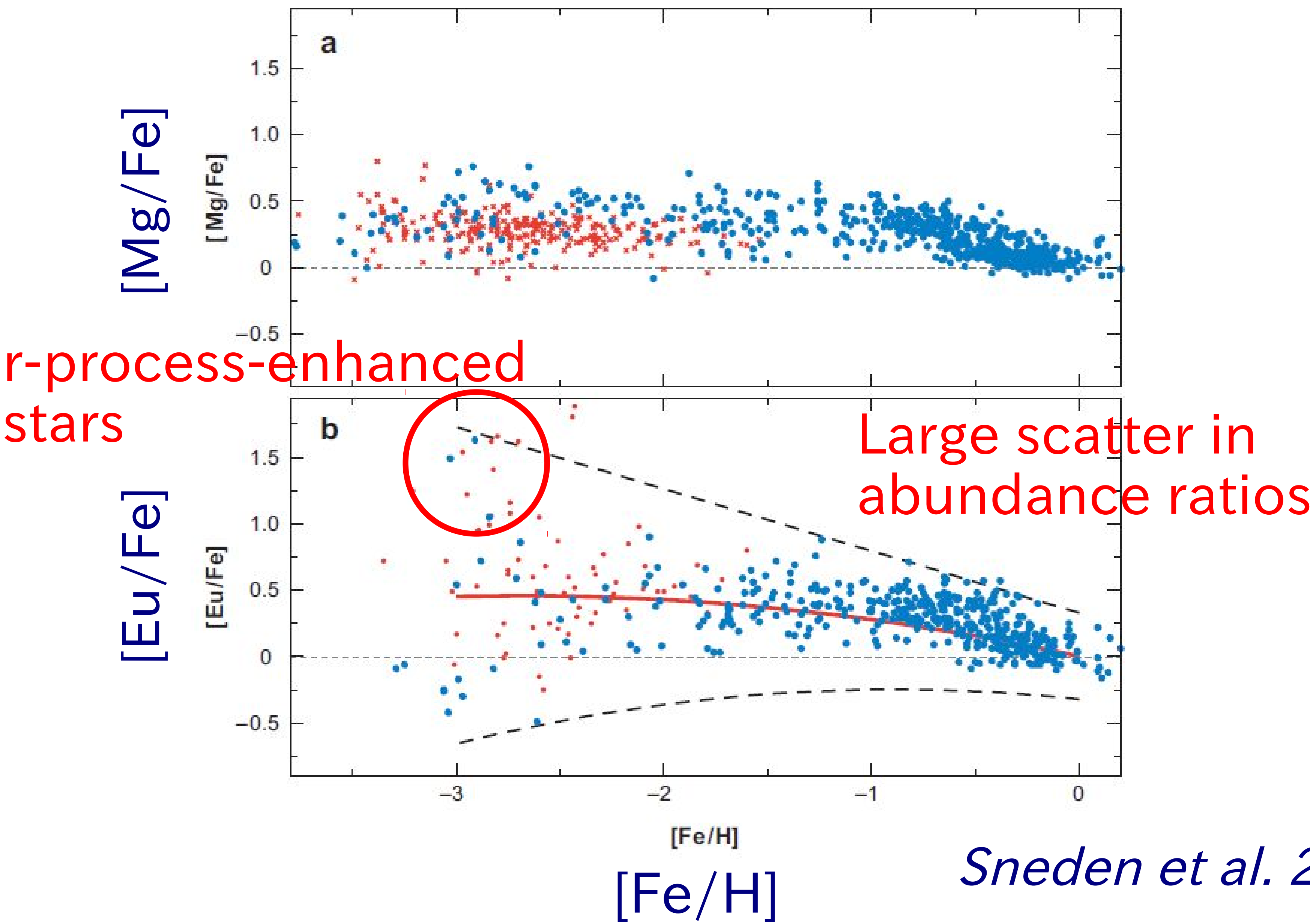
(2) Abundance distribution/trend of heavy elements
 -large scatter of Eu abundance ratios
 -distribution of Sr and Ba abundance ratios
 -heaviest elements: Th and Pb
 -(No) correlation with lighter elements

(3) Searches for r-process elements in supernova remnants

(4) Other systems
 -globular clusters
 -dwarf galaxies

Summary and discussion

Eu（ユーロピウム、r-process でつくられる元素のひとつ）の組成比にみられる大きな分散



Sneden et al. 2008

Eu（ユーロピウム、r-process でつくられる元素のひとつ）の組成比にみられる大きな分散

銀河初期では個々のr-process の結果が星間物質中で十分混ぜられていない

→金属量の低い星は個々のr-processの結果を直接反映している
→組成比の分散の程度は、個々のr-processのyieldの大きさと星間物質中での混合の程度を反映

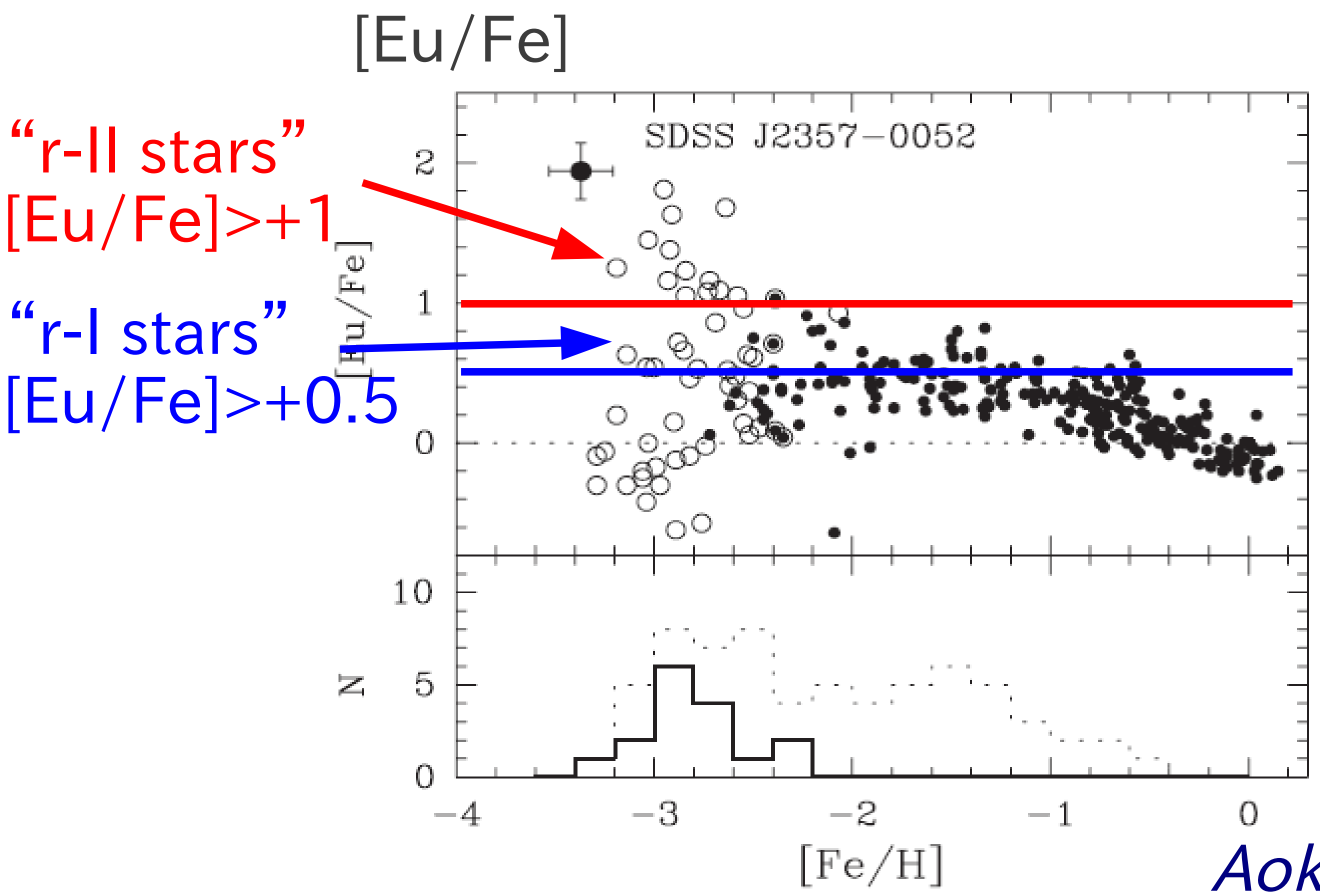
組成を測定する対象天体は?

- 銀河系内の星
  金属量の低い星のほとんどはハロー構造の星
  近傍の銀河の星も最近は研究対象に

- 小質量星
  太陽の0.8倍程度の質量
  主系列・準巨星または赤色巨星

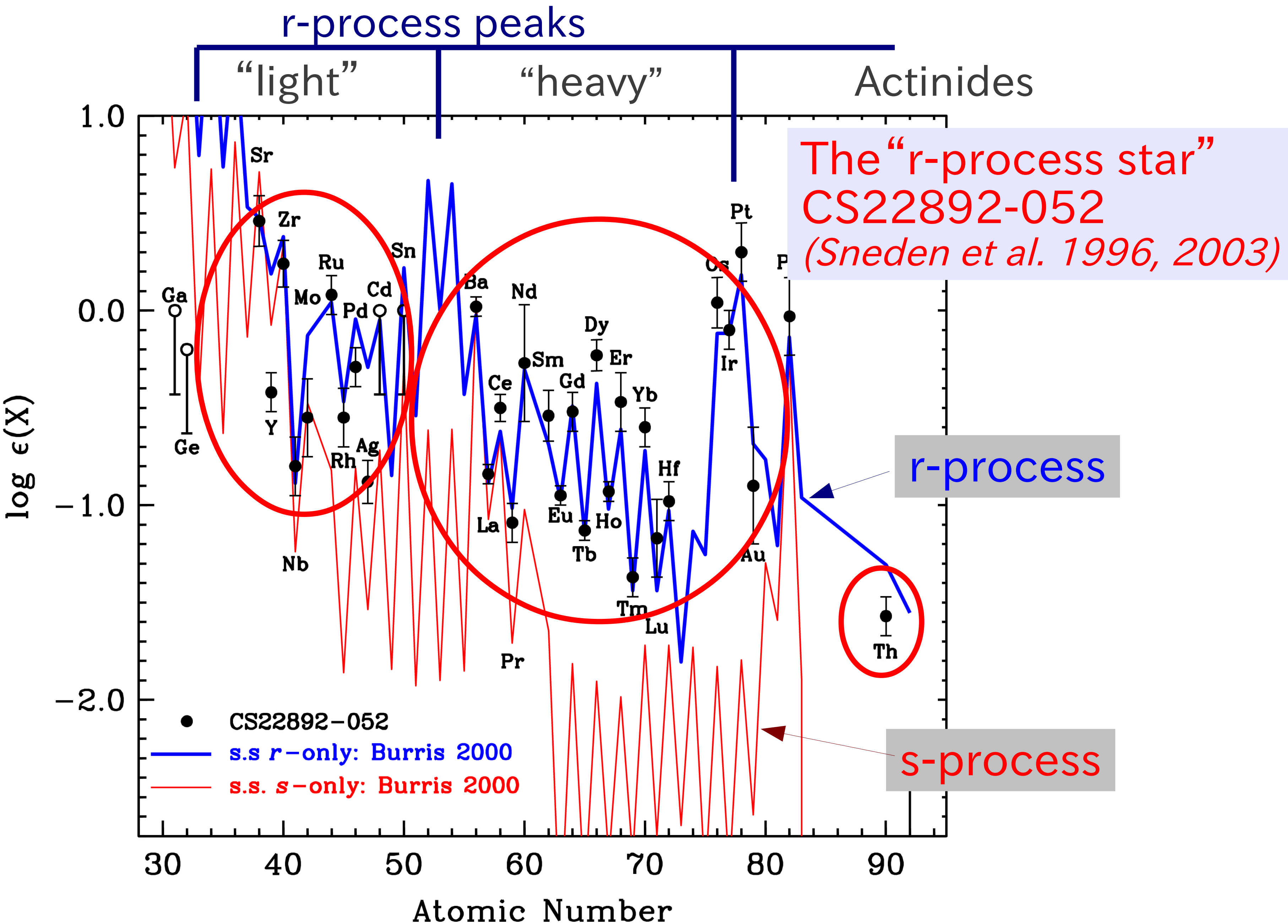
- 表面組成は誕生時の組成をほぼ保持
  一部の元素は内部の元素合成の結果を反映
  伴星からの質量降着を受けている星もある

(1) Constraints from abundance patterns of r-process enhanced stars

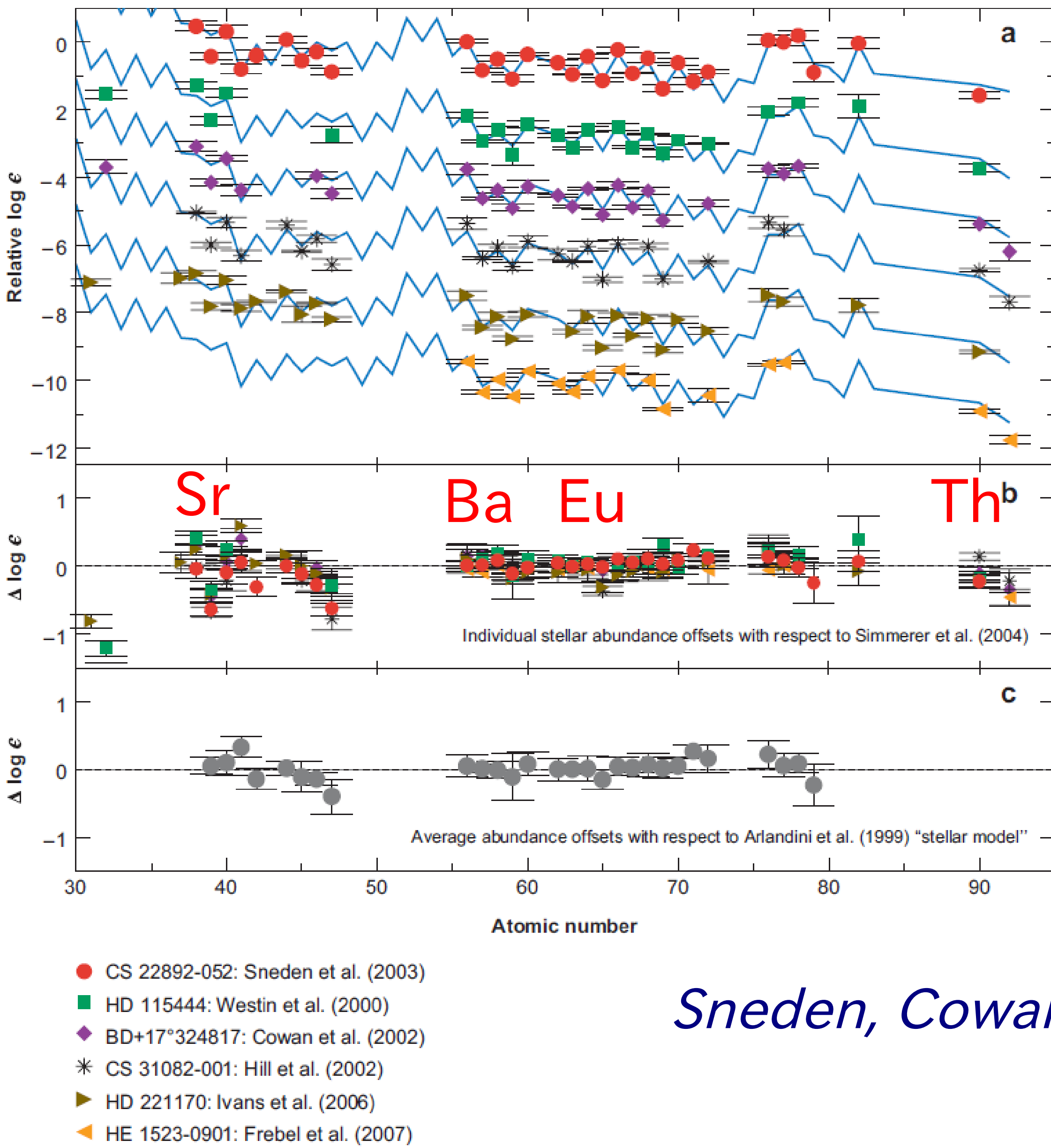


Aoki et al. 2010

r-process-enhanced stars



Similar abundance patterns are also found for other r-process-enhanced stars

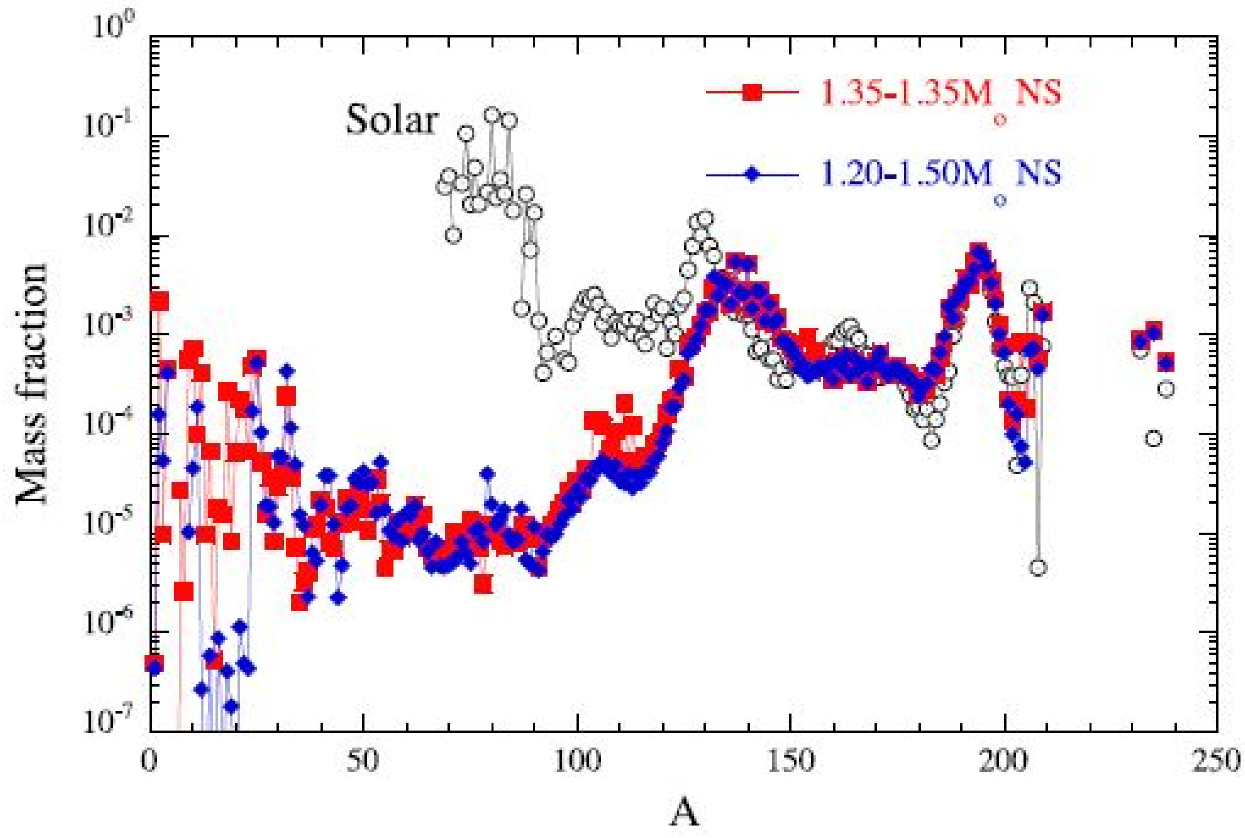


Comparisons with solar-system r-process pattern

Sneden, Cowan, Gallino 2008

中性子星合体におけるr-processのモデル計算

Goriely et al. (2011)

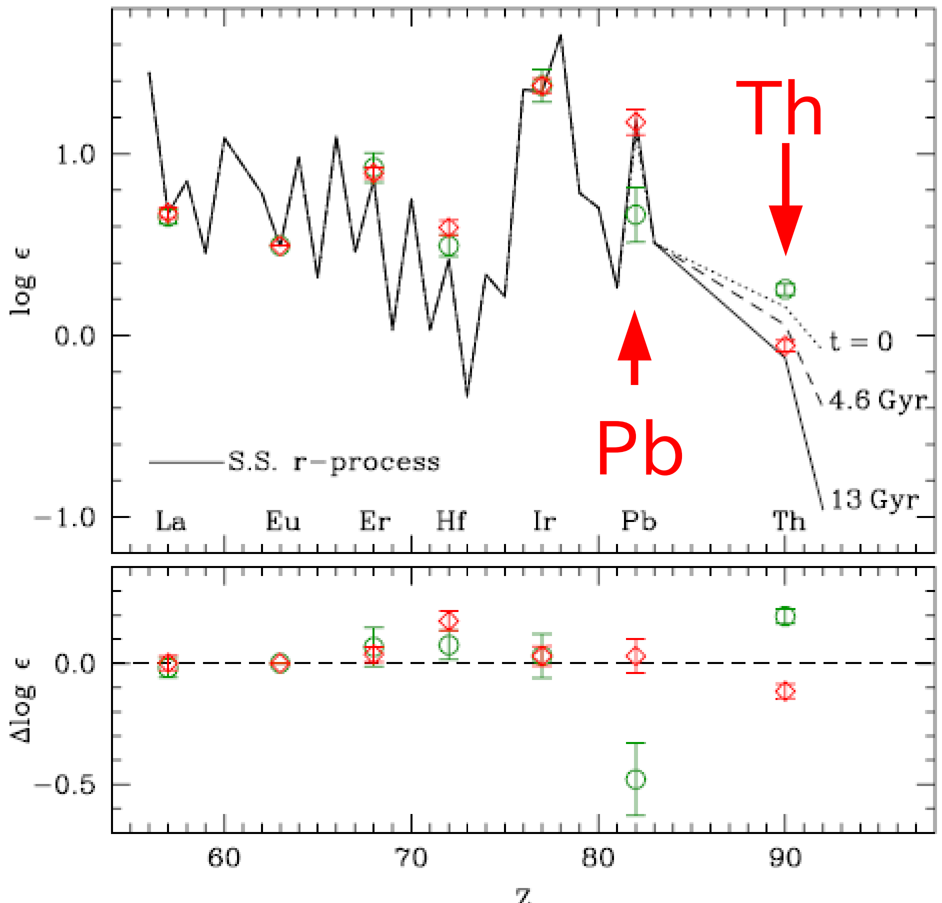


Heaviest elements: Th and Pb

- Scatter exists in the actinides abundance ratios (e.g. Th/Eu), but that is small (<0.5 dex).

- Pb abundances are low in r-process-enhanced stars (?)

○"standard" r-enhanced stars
○"actinide-boost" stars



Roederer et al. 2009

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○"standard" r-enhanced stars
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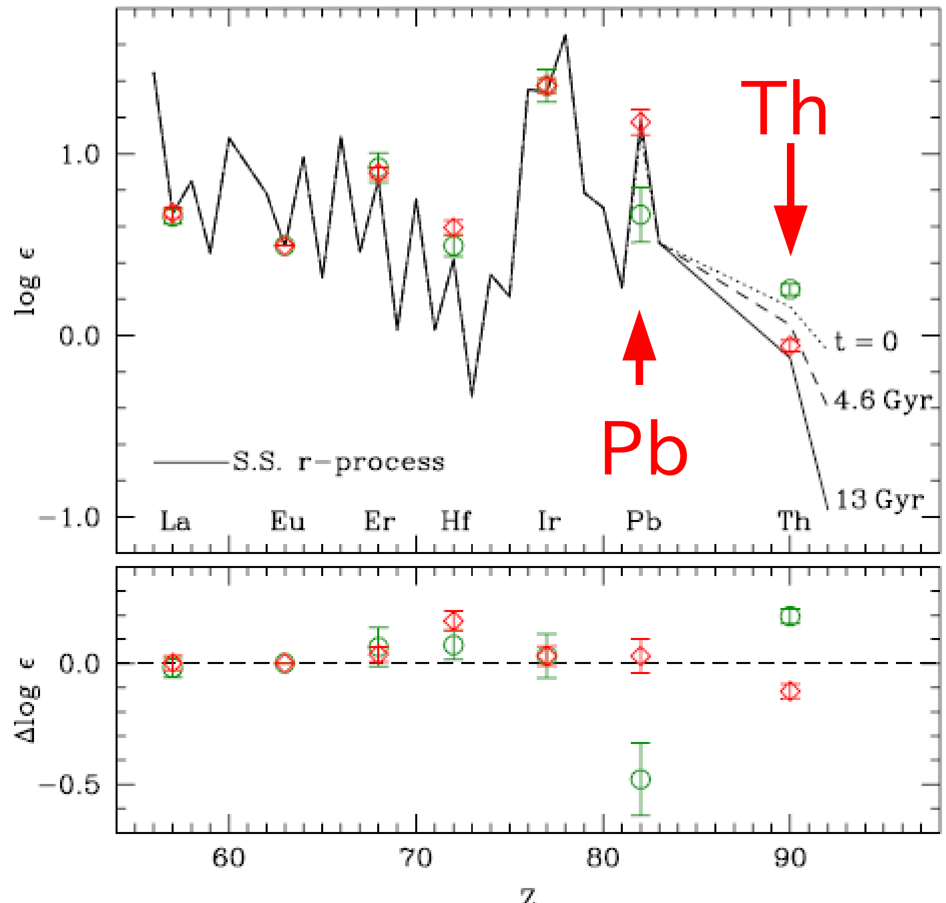
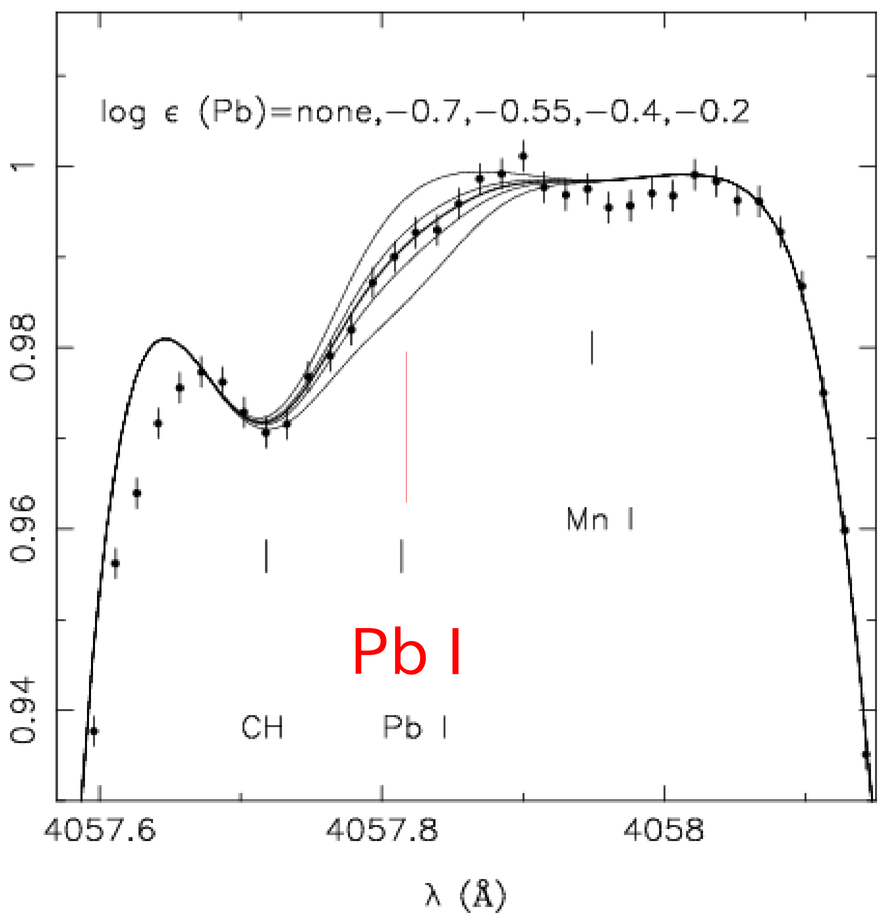


Roederer et al. 2009

Heaviest elements: Pb problem



Plez et al. (2004)

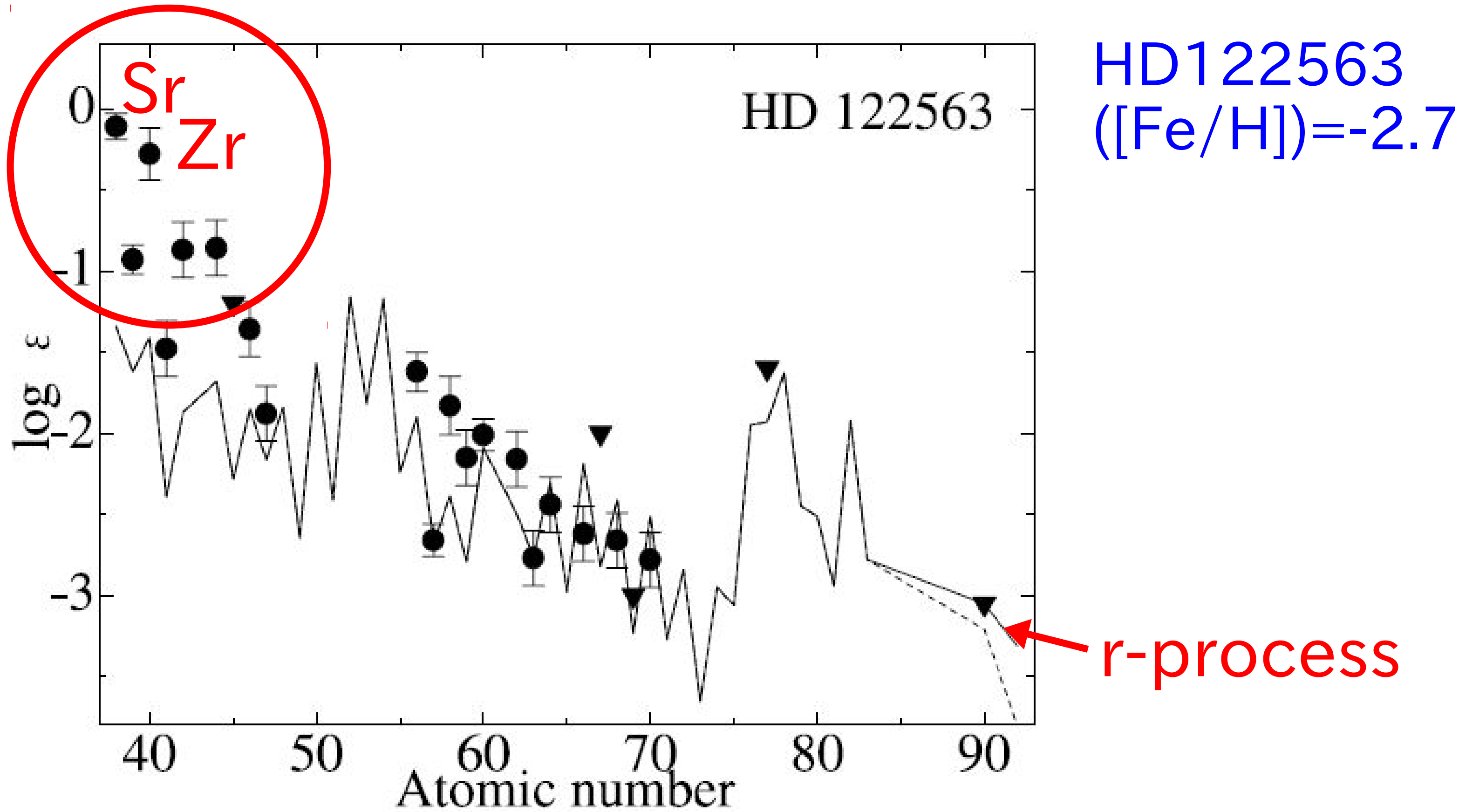
r-process-enhanced star CS31082-001
→Pb abundance is much lower than expected from Th, U abundances

Pb is also deficient in another r-II star (HE1523-0901: Frebel et al. 2007)

cf. Wanajo et al. (2007)
"cold r-process"?

Notice for discussion from abundance patterns

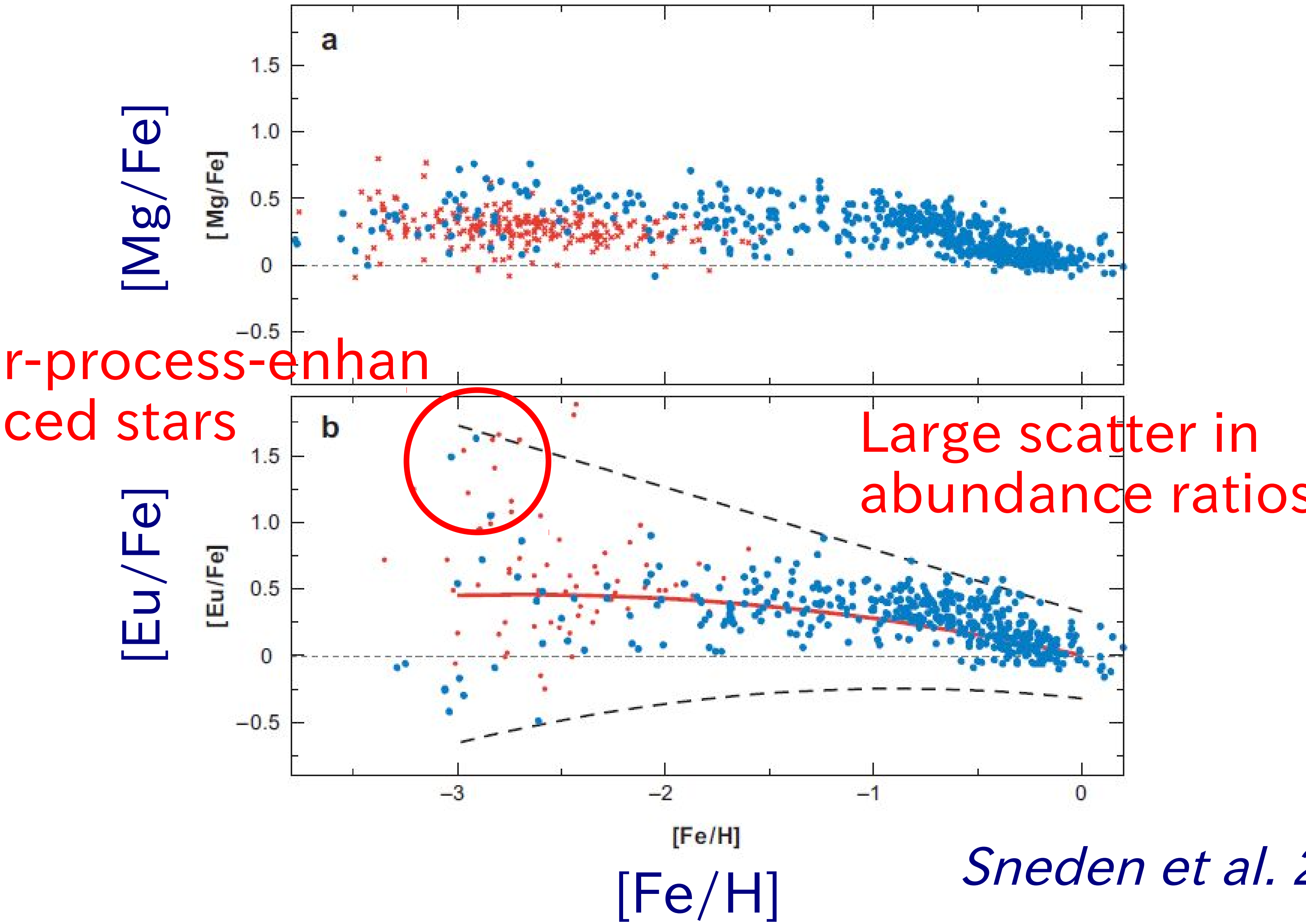
- "r-II stars" may be special class
- There are many "r-process-poor" stars. Some of them show large excesses of light (1[st] peak) neutron-capture elements.



Honda et al. 2006

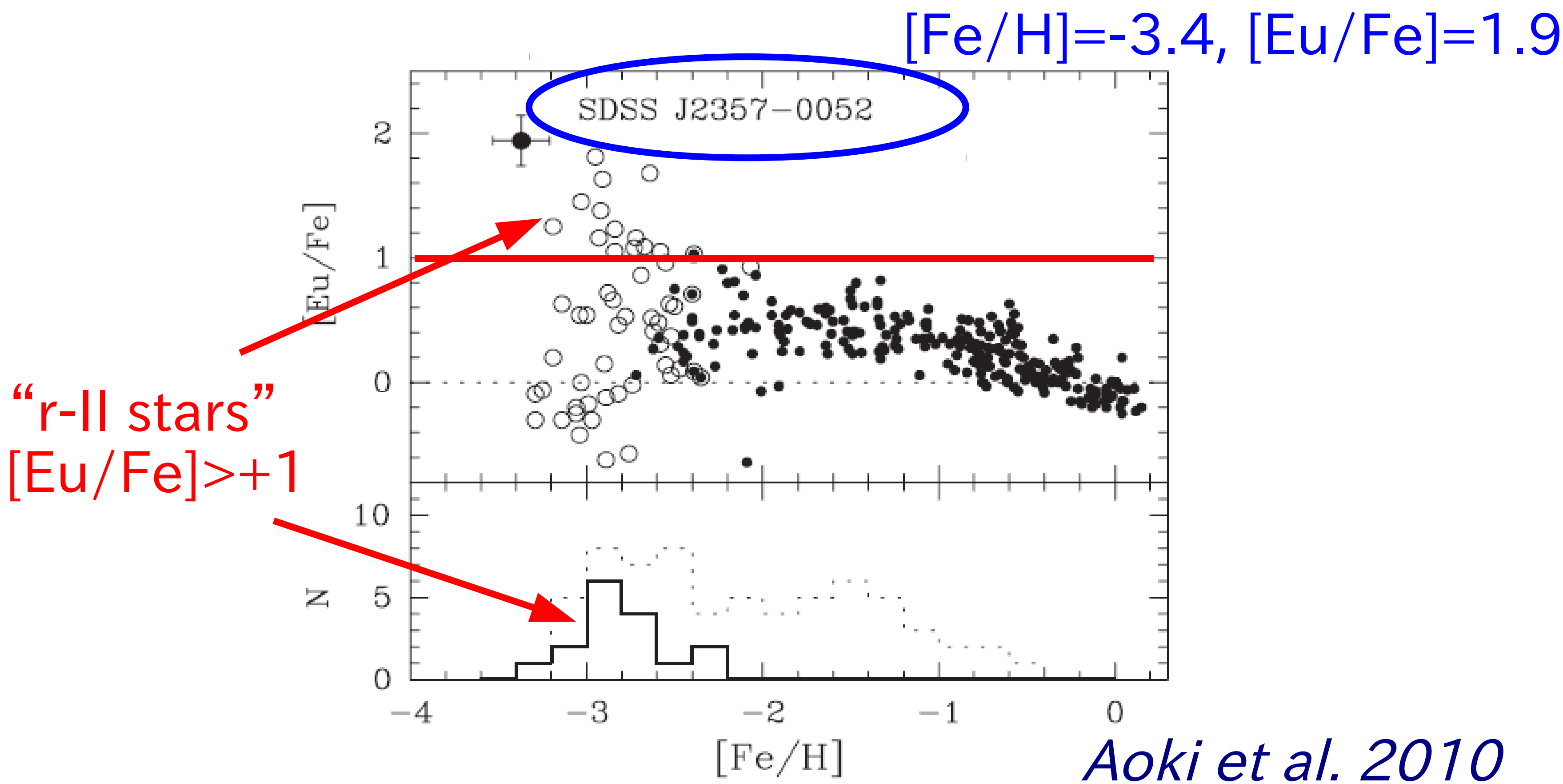
(2) Abundance distribution / trend of heavy elements

(2-1) Large scatter of the r-process abundance ratios



Sneden et al. 2008

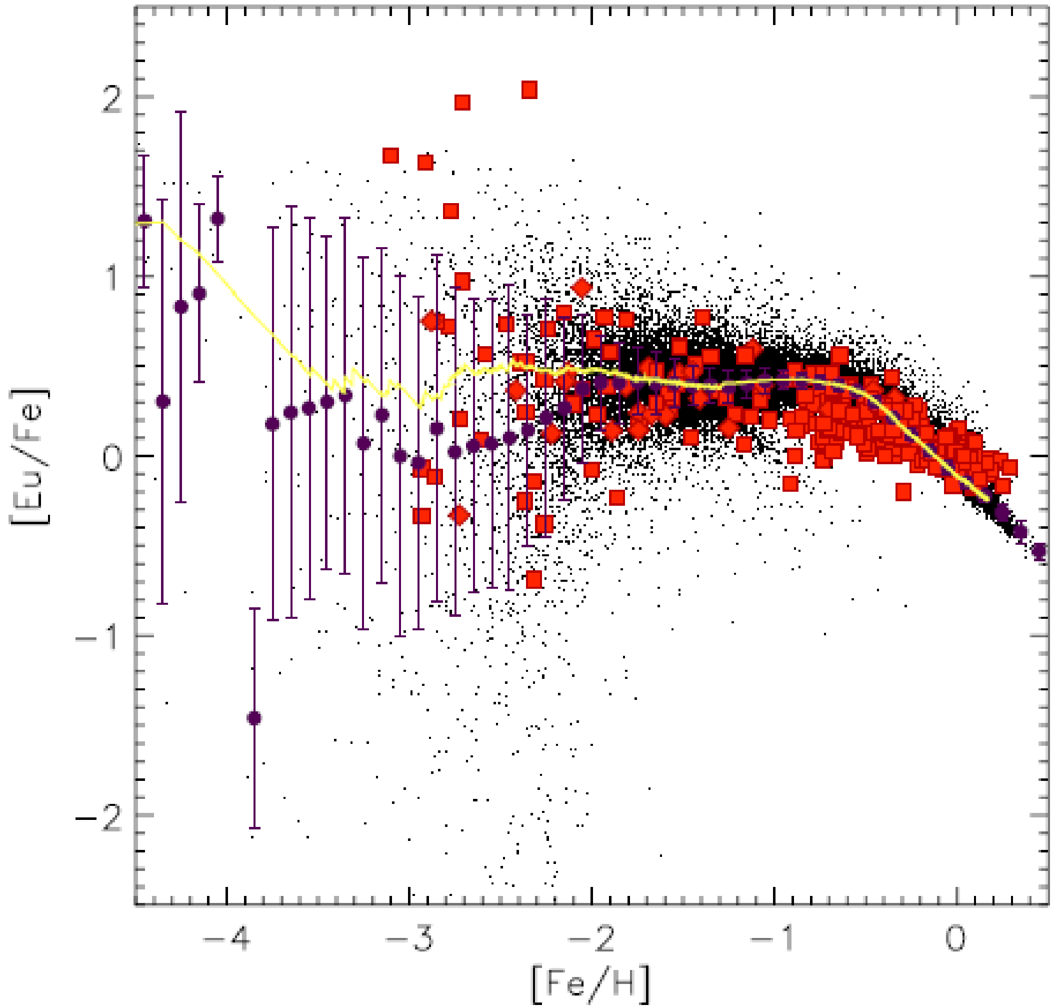
Metallicity distribution of r-process-enahnced stars



Eu is the best indicator of the (main) r-process, but spectral lines are too weak in extremely metal-poor stars

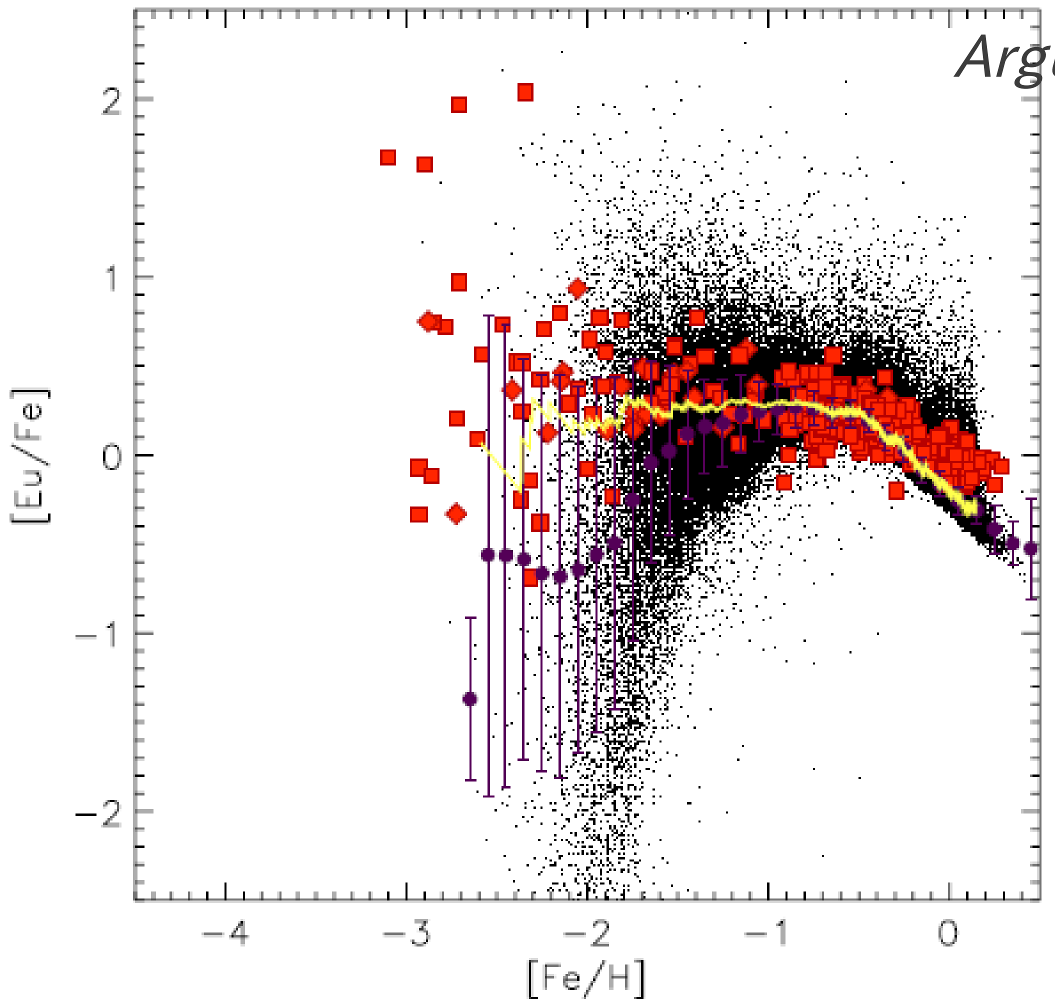
r-process サイトをII型超新星と仮定した場合の化学進化

Argust et al. (2004)



r-process サイトを中性子星合体と仮定した場合の化学進化

発生率2x10^{-4} yr^{-1}、発生のタイムスケール10^{6}年、yields 10^{-3}M$_{sun}$



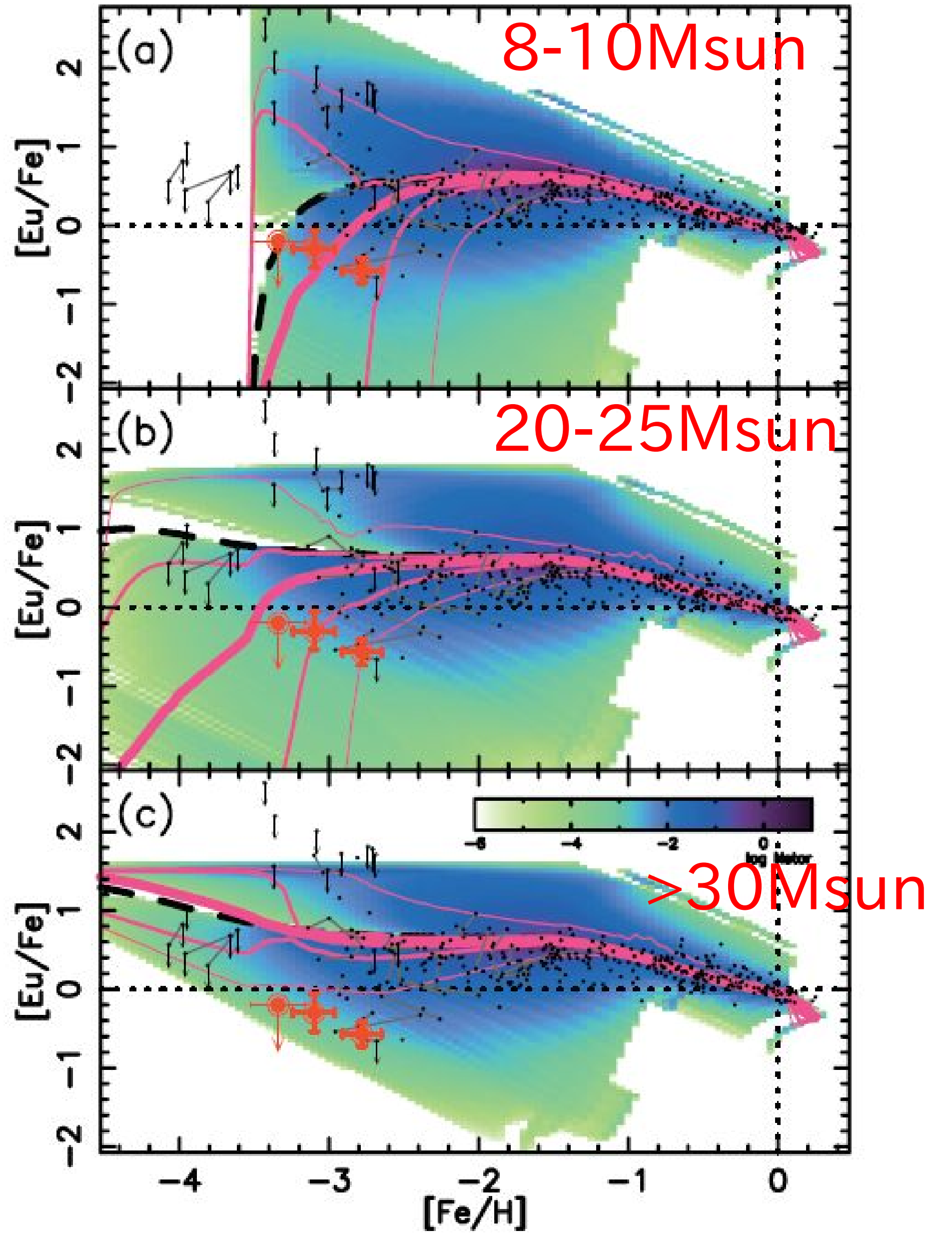
Argust et al. (2004)

Metallicity dependence of abundance ratios as a probe of the astrophysical sites

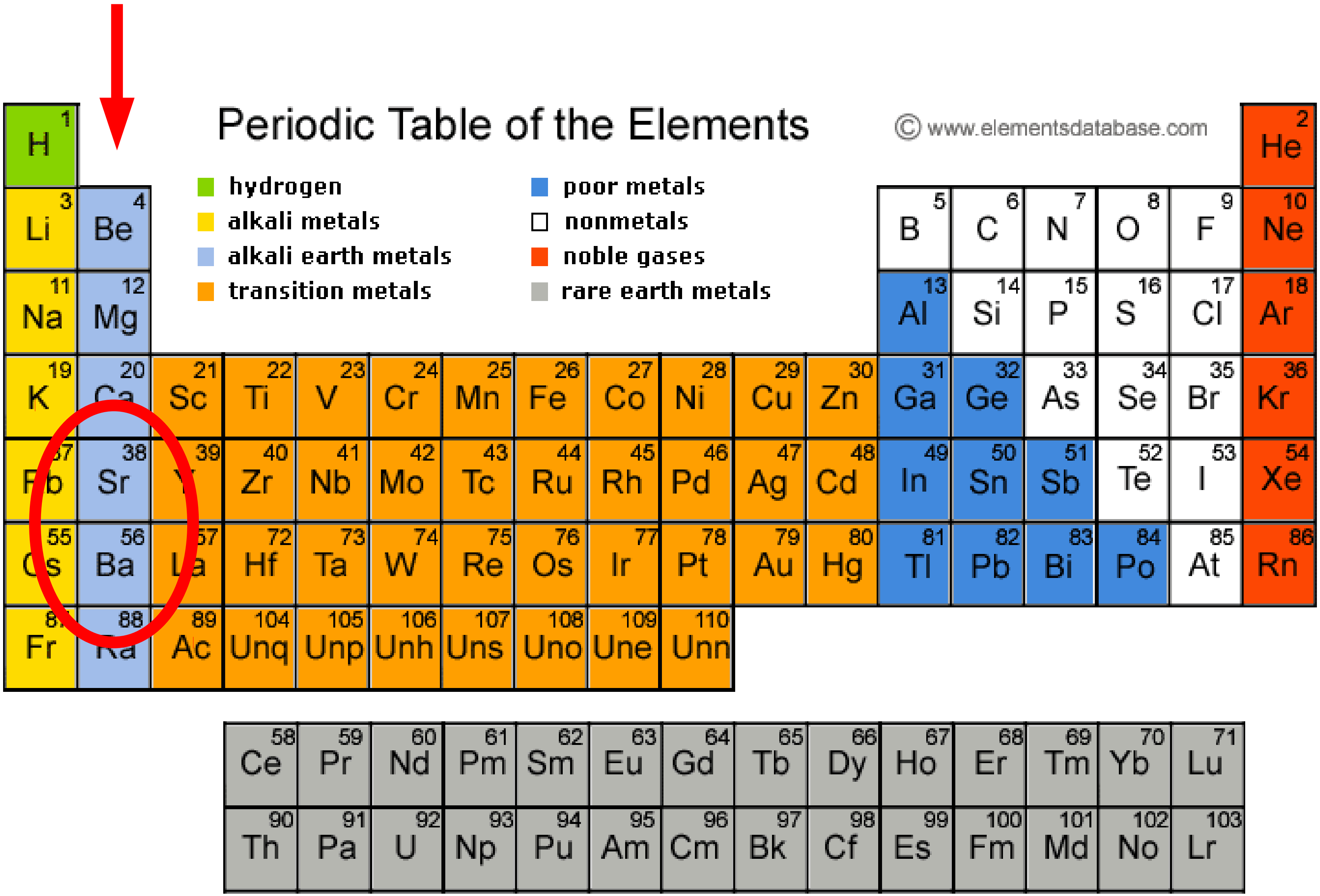
Metallicity dependence
→indirect estimate for mass of progenitors (model dependent)

Example:
Trend and scatter of Eu abundances
→ less massive stars (8-10 Msun) are preferable as astrophysical sites of the main r-process.

Ishimaru et al. 2004

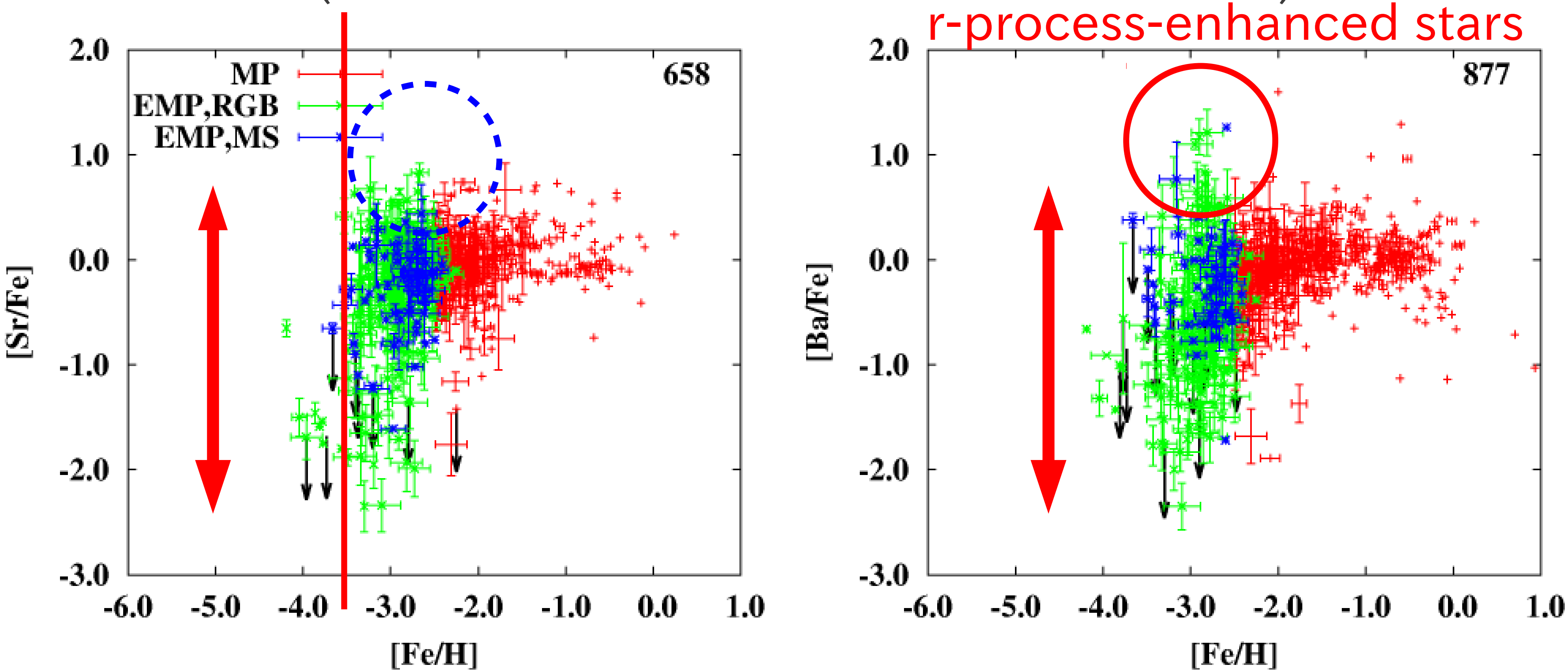


(2-2) Sr and Ba: representatives of light and heavy neutron-capture elements



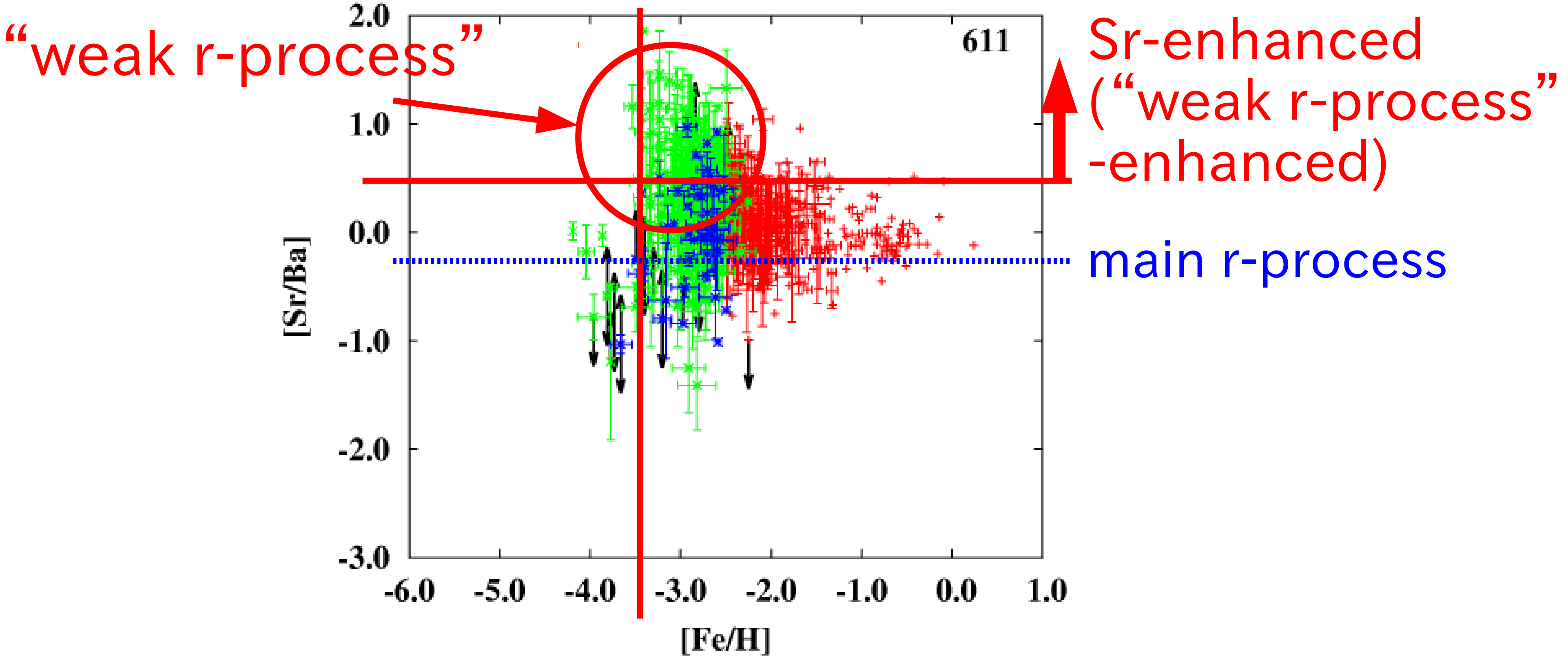
Trend and scatter in abundance ratios of Sr and Ba from SAGA database

(Carbon-enhanced stars are excluded)



- Very large scatter in [Sr/Fe] and in [Ba/Fe] in [Fe/H]<-2.5.
- A group of stars show very high [Ba/Fe] at [Fe/H]=-3.. Such stars are not found in the [Sr/Fe] diagram.

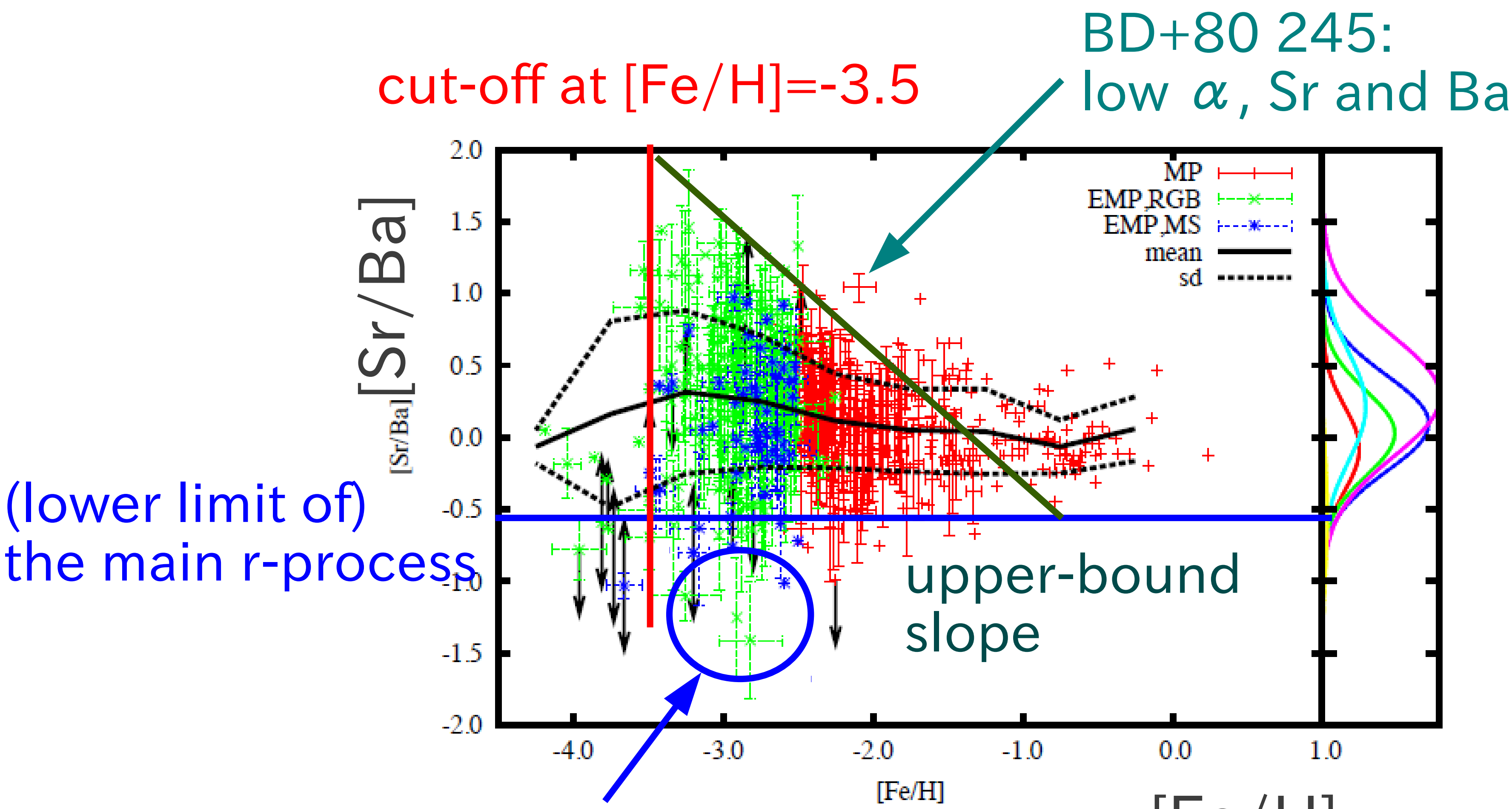
Trend and scatter in Sr/Ba abundance ratios of from SAGA database



A tentative definition of Sr-enhanced stars:

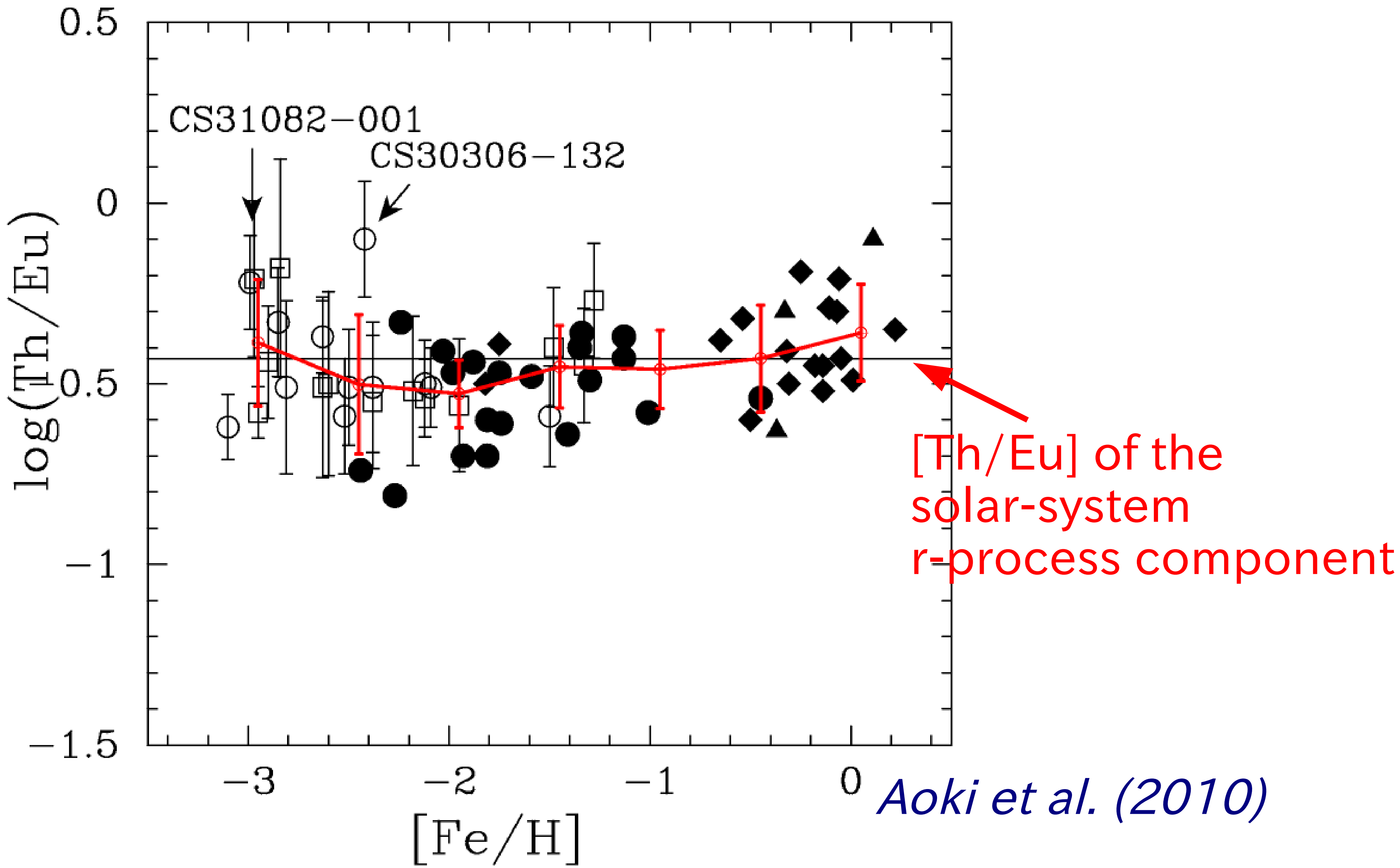
[Sr/Ba]> +0.5 → "weak r-process"-enhanced stars

Sr/Ba diagam … in more detail



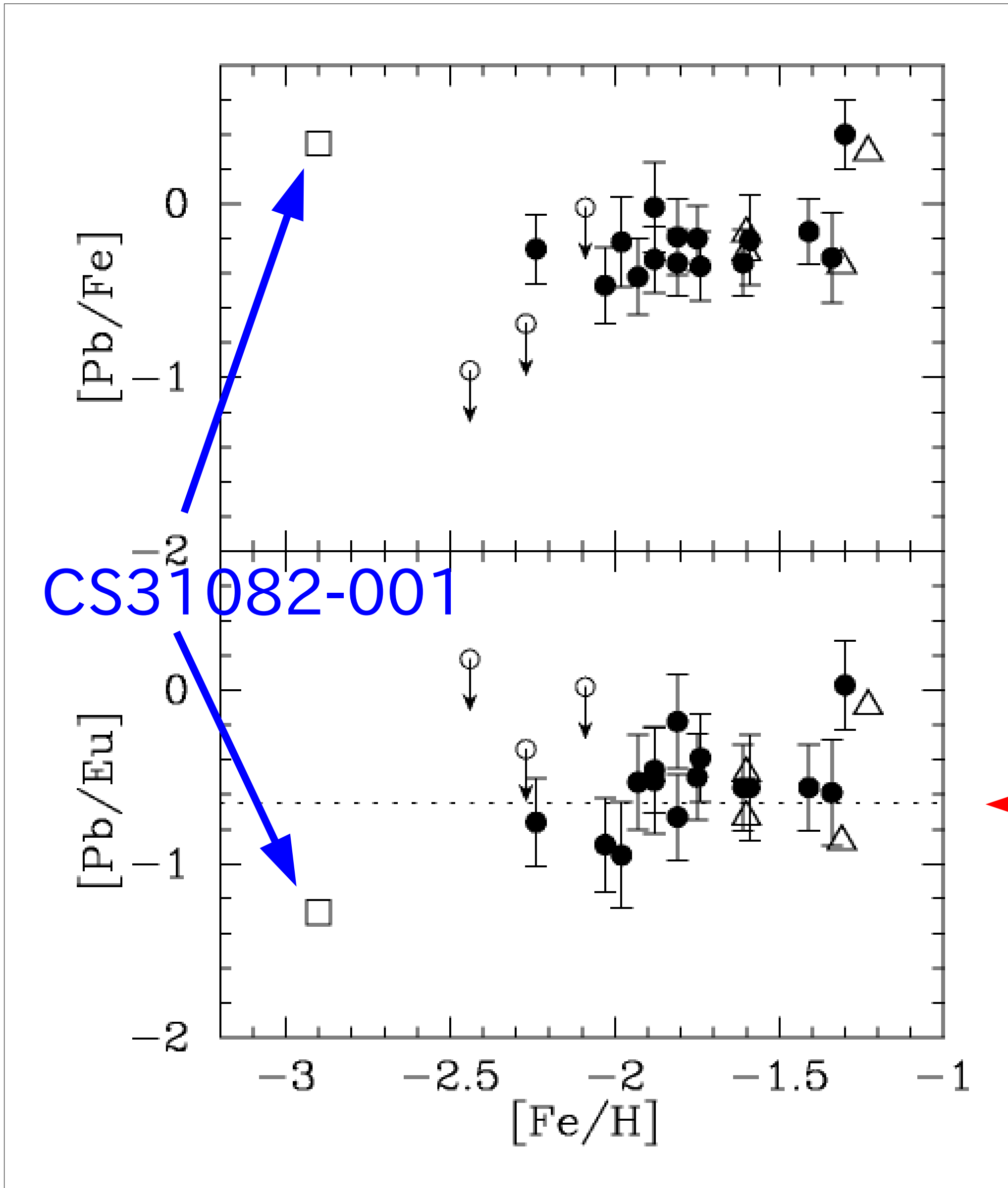
Moderately C-rich and/or binary
… affected by s-process

(2-3) Heaviest elements: Th



Aoki et al. (2010)

(2-3) Heaviest elements: Pb



Carbon-enhanced stars are not included.

●○*Aoki et al. (2008)*
△*Yong et al. (2006, 2008)*

[Pb/Eu] trend agrees with the solar-system r-process component in general. But the [Pb/Eu] of the r-II star CS31082-001 is exceptionally low.

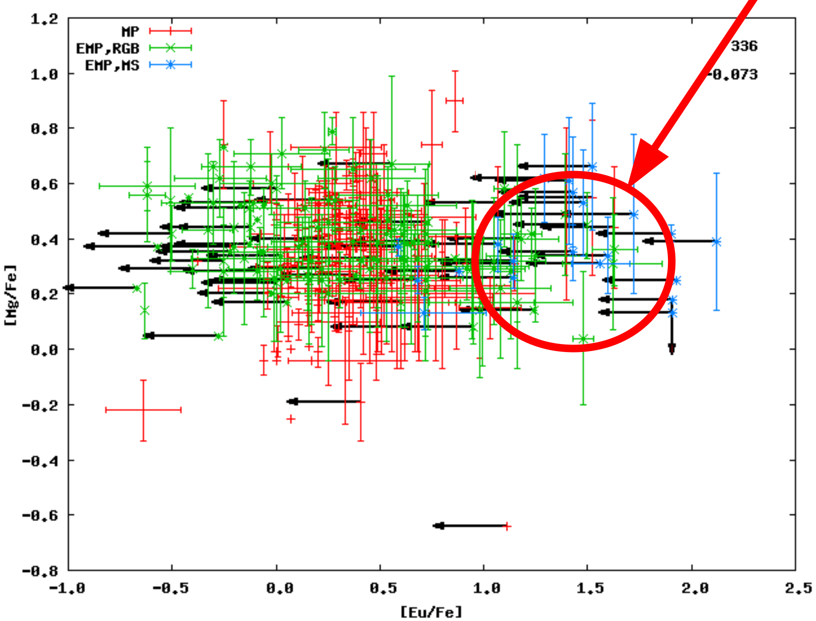
[Pb/Eu] of the solar-system r-process component (uncertain)

(2-4) NO correlation between neutron-capture elements and lighter elements (within the current measurement accuracy)

r-II stars

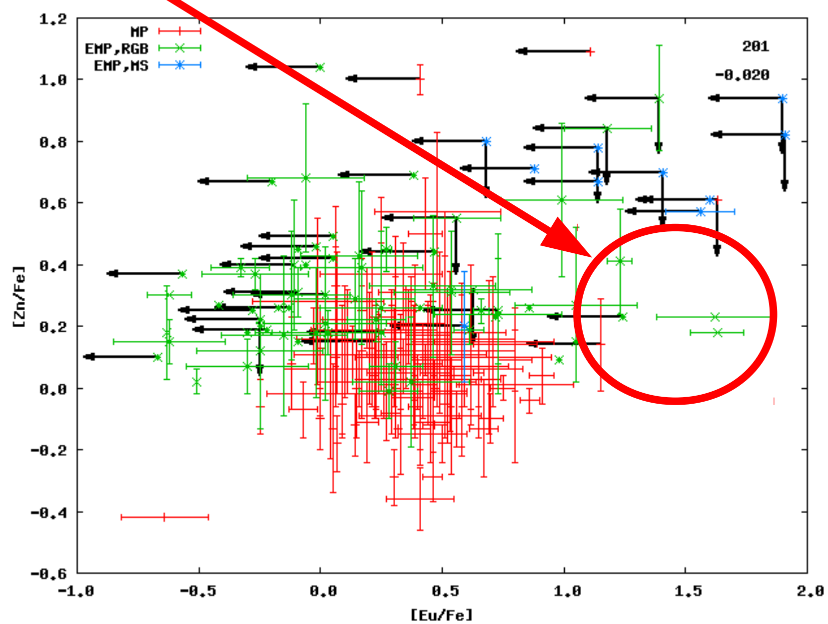
SAGA database

[Mg/Fe]



[Eu/Fe]

[Zn/Fe]



[Eu/Fe]

(3) r-process elements in supernova remnants?

Wallerstein et al. (1995)

A SEARCH FOR *r*-PROCESS ELEMENTS IN THE VELA SUPERNOVA REMNANT[1]

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Received 1994 November 28; accepted 1995 March 6

ABSTRACT

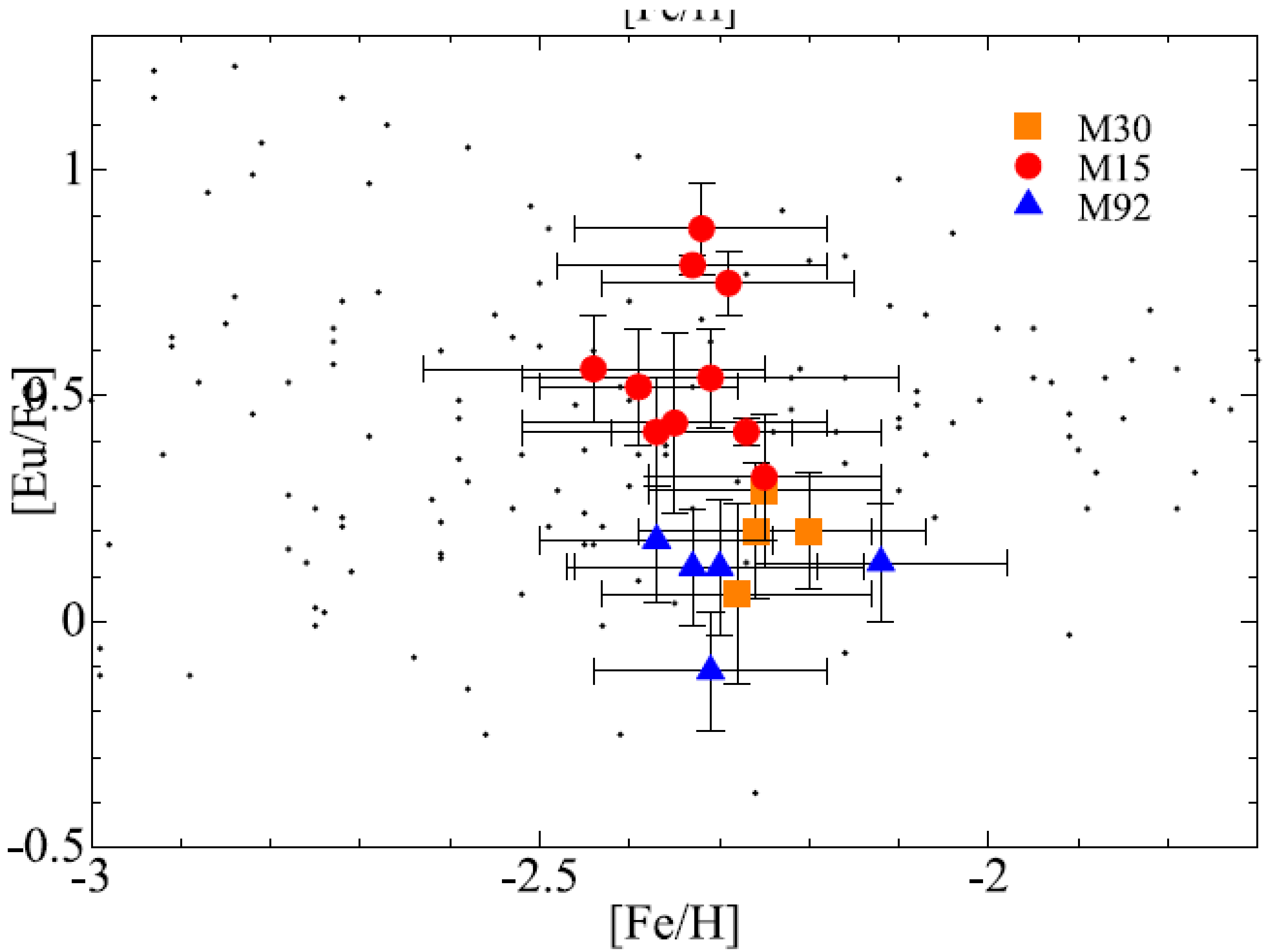
After a description of recent developments in the physics of rapid neutron capture in Type II supernovae and a discussion of the detectability of supernovae ejecta, we present the data from a search for Ge, Kr, Yb, Os, and Hg in five stars behind or within the Vela remnant. Only Ge II was detected, but its column density and the upper limits of the other species show no excess above the estimated contribution of ambient gas. Finally, we discuss the extent that clumping and the improved performance of the GHRS may make *r*-process ejecta from Vela detectable in the future.

(4) r-process elements in other systems

- Globular clusters
  - -overabundance of r-process elements
  - -scatter in abundance ratios in a cluster

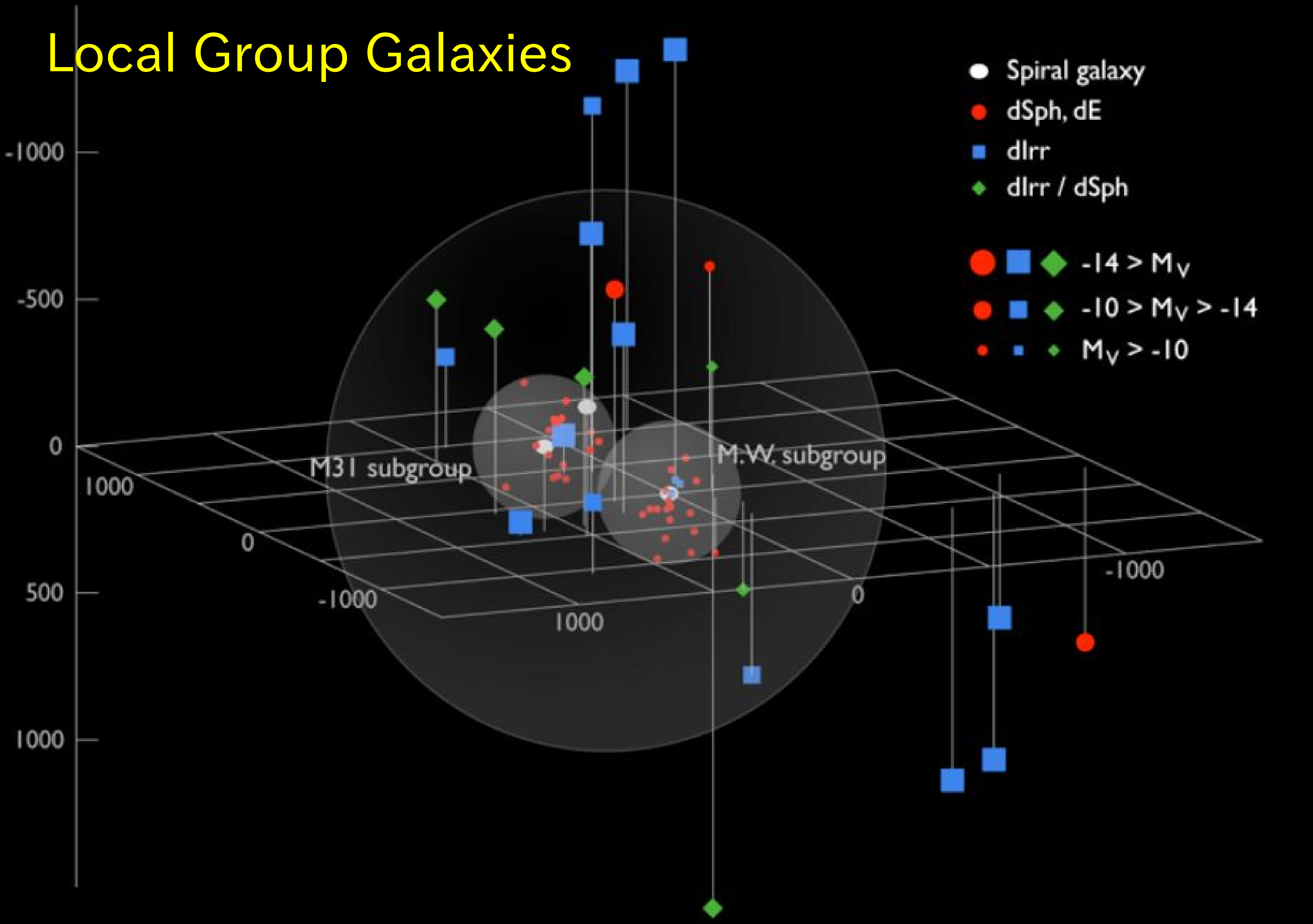
- Dwarf galaxies around the Milky Way
  - -different chemical evolution from the Milky Way (halo)
  - -surviver of building blocks of the halo?

R-process elements in very metal-poor globular clusters



Honda et al. (in prep.)

Local Group Galaxies



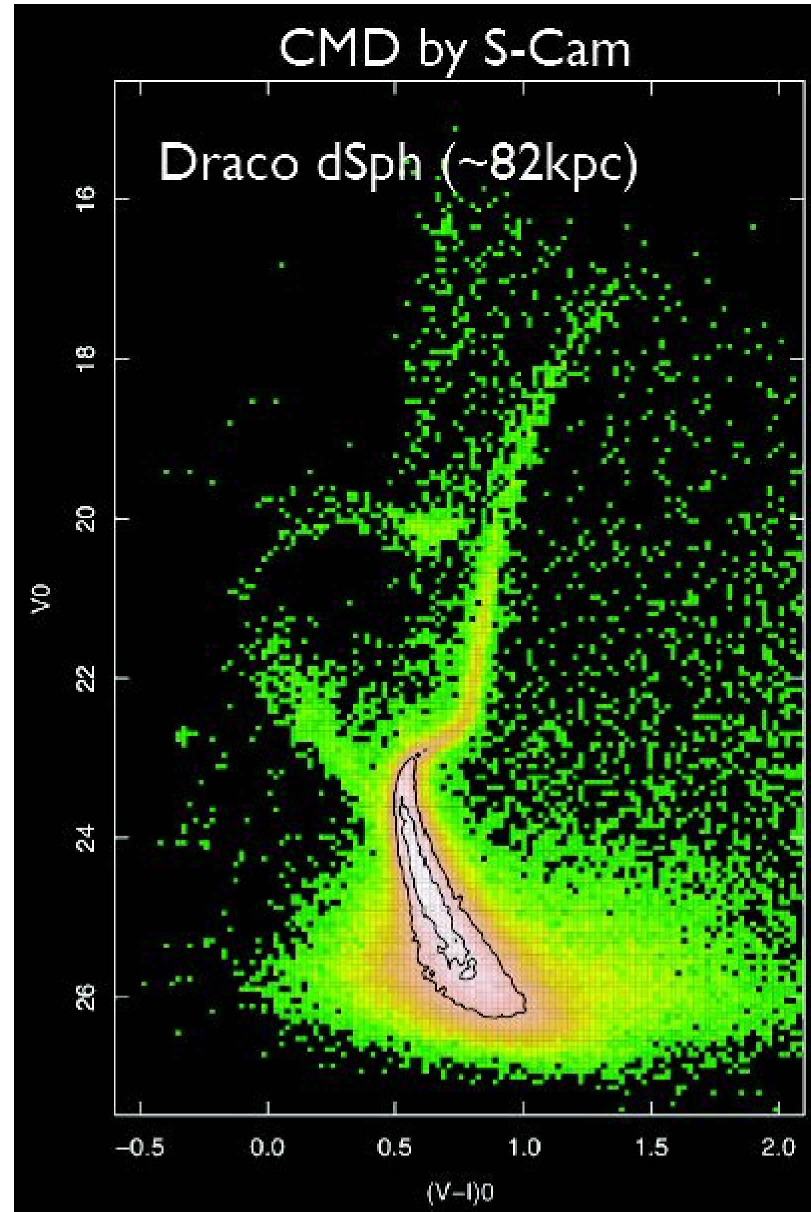
courtesy of S. Okamoto

Dwarf galaxies around the Milky Way

Short distance + low stellar density
→not easy to identify as a galaxy
→possible to observe individual stars

Draco (82kpc)

Okamoto et al. 2008



Ultra-Faint Dwarf Galaxies (UFDG) newly found by SDSS (and Subaru follow-up)

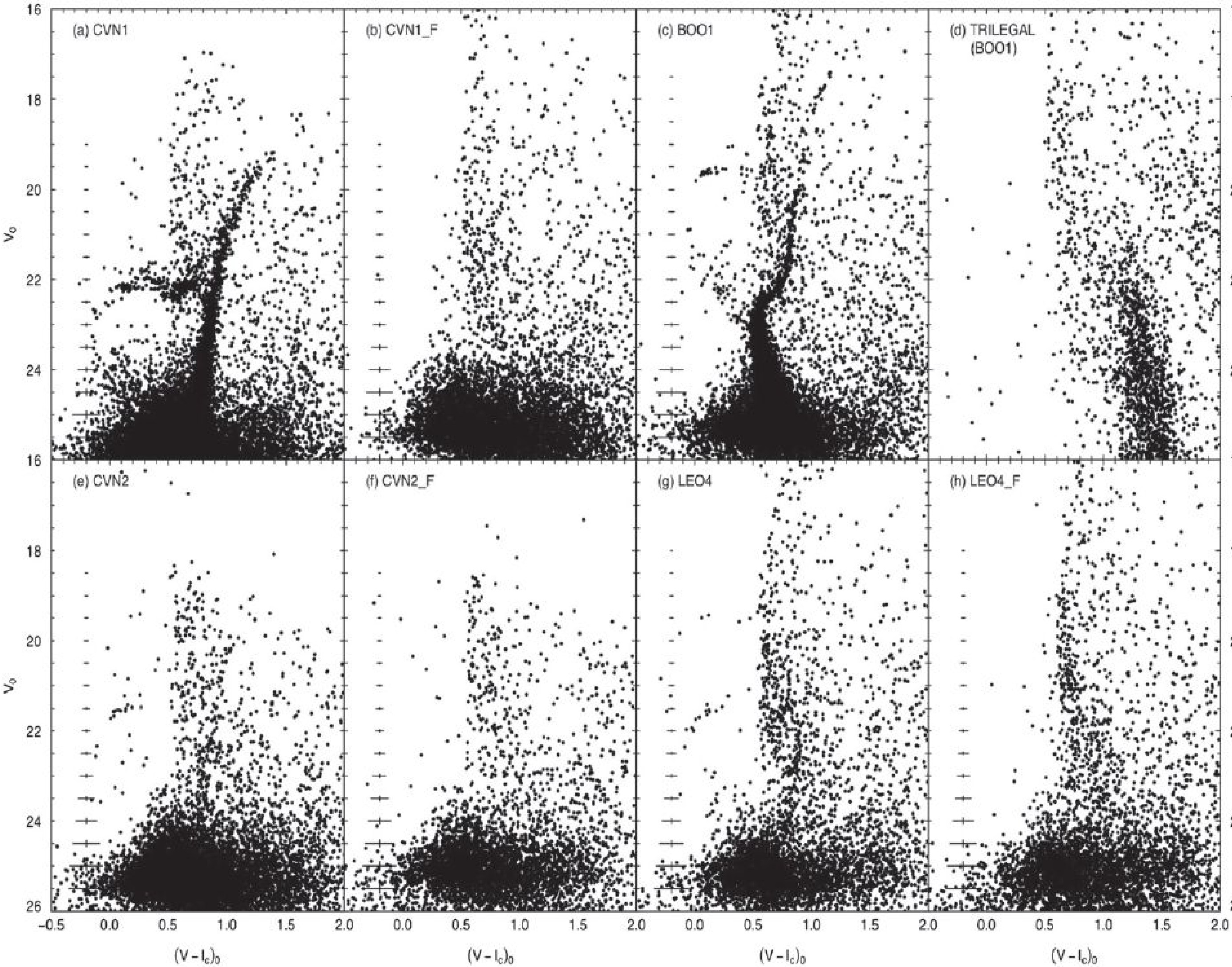
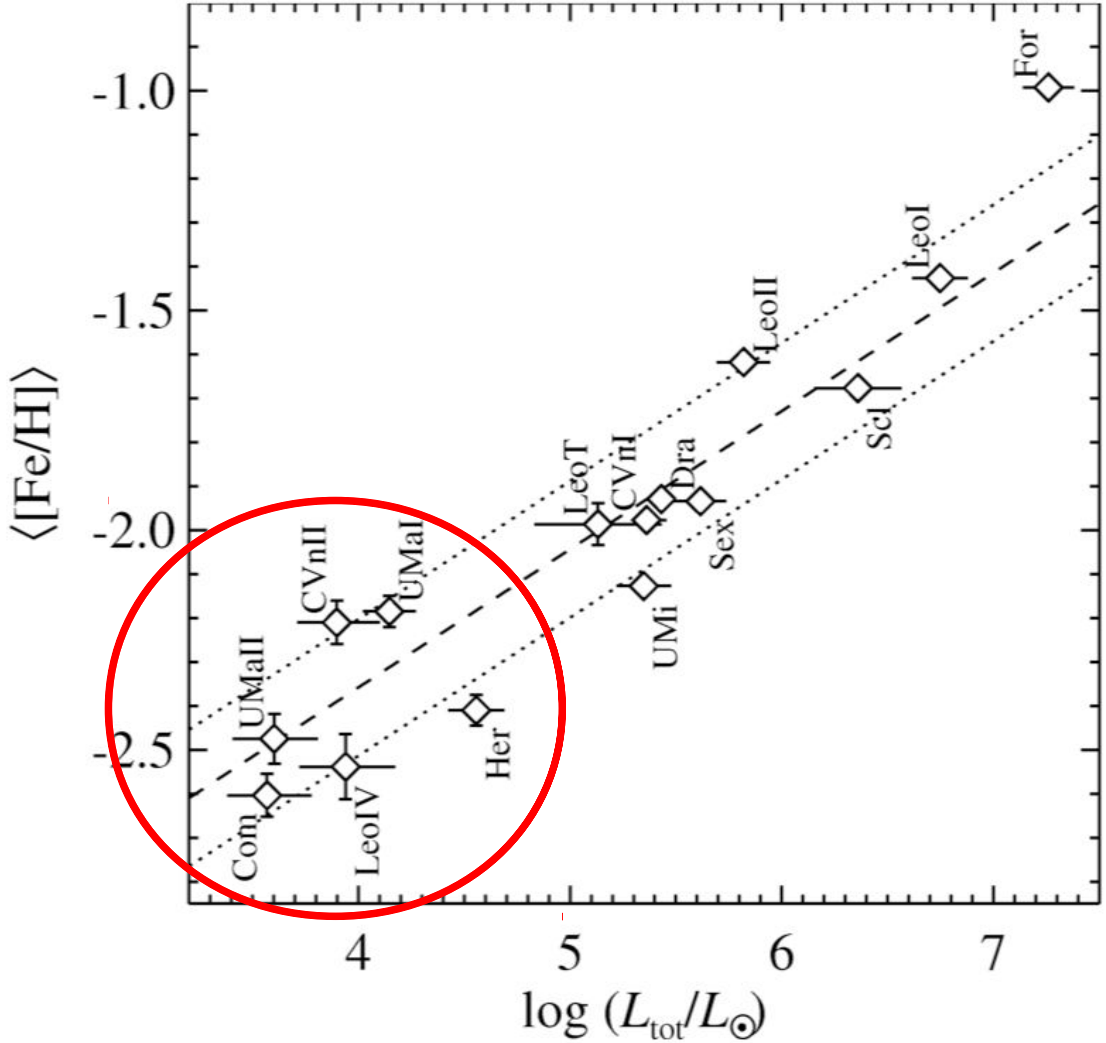


Figure 3. CMDs of the star-like objects in all observed fields and the simulated CMD. The magnitude errors are estimated by the artificial star test. In panel (d), the TRILEGAL model is used to simulate the CMD of Galactic foreground stars in the direction of the BOO1 field.

Okamoto et al. (2012)

Fainter galaxies (with smaller stellar mass) have lower metallicity

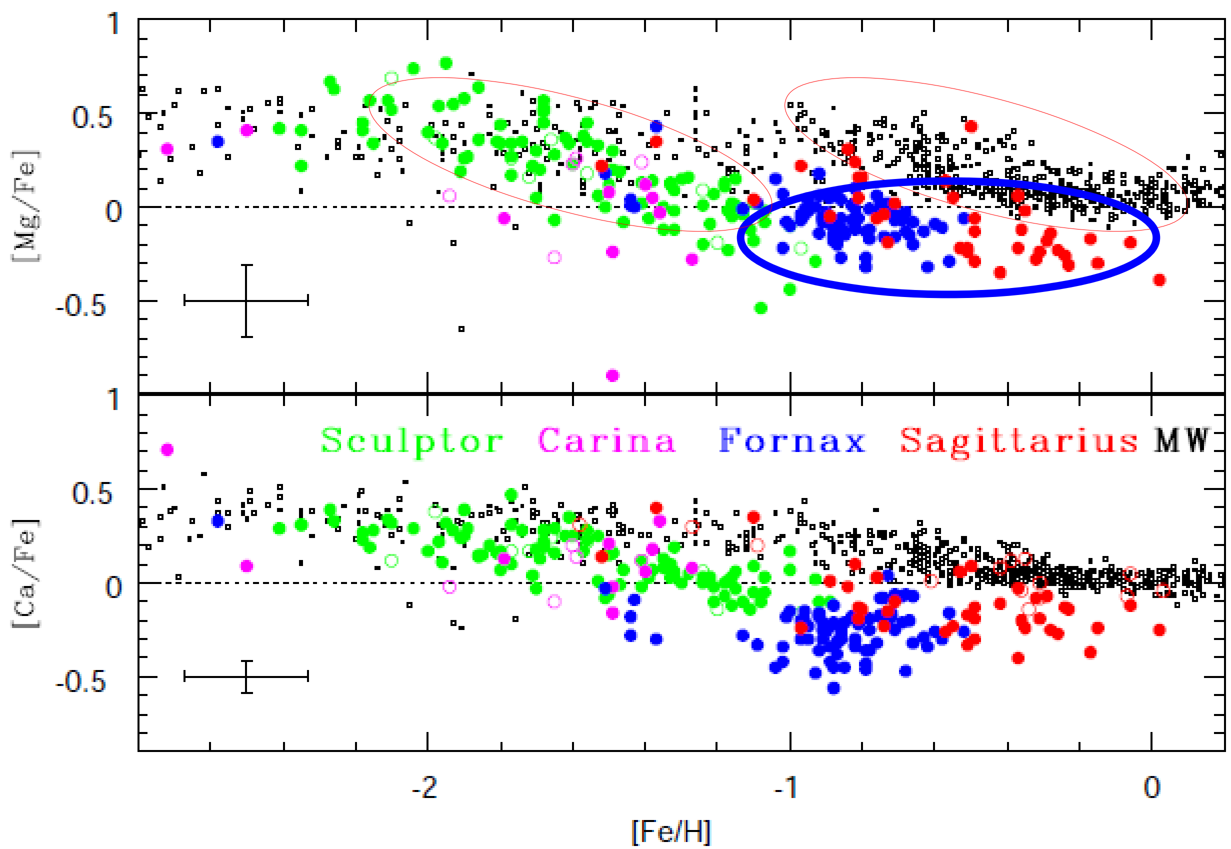


Kirby et al. (2008), updated by Frebel et al. (First Stars IV)

Dwarf galaxy stars have different abundance trend from Milky Way stars

[Mg/Fe]

[Ca/Fe]



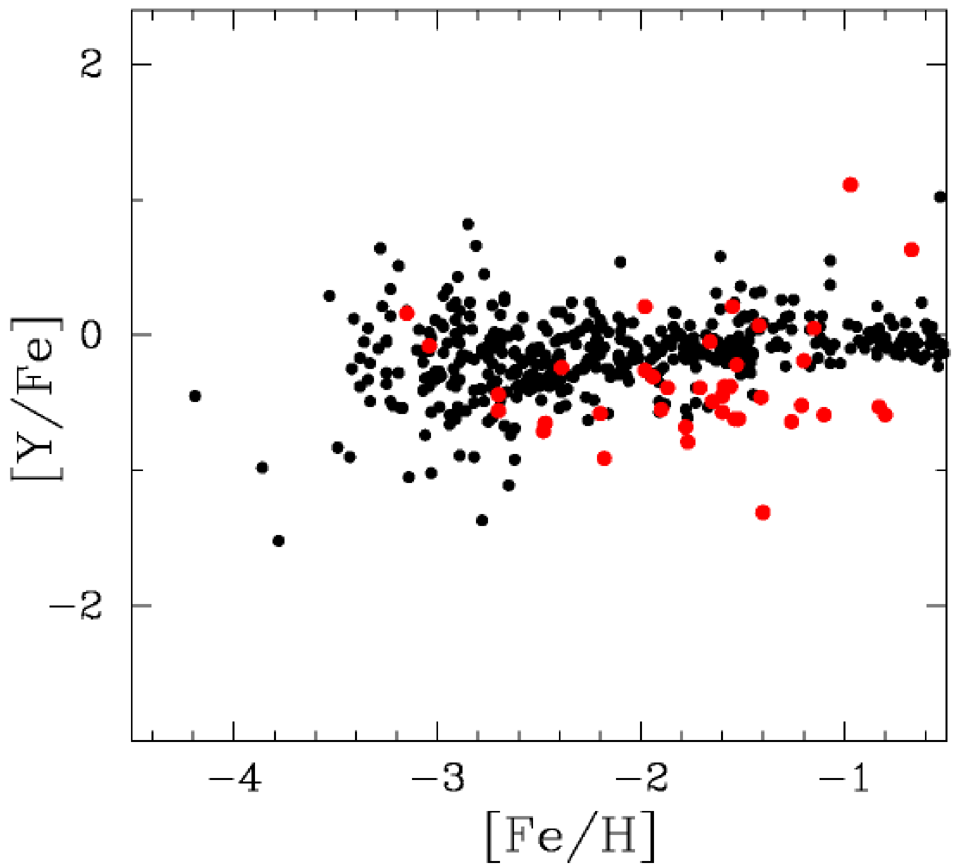
Milky Way disk stars

dwarf galaxies

Tolstoy et al. (2009, ARAA)

Neutron-capture elements in dwarf galaxies

- We are extending the SAGA database to dwarf galaxy stars (T. Suda, J. Hidaka, W. Aoki)
- There are significant differences of abundance trend between dwarf galaxies and Milky Way.

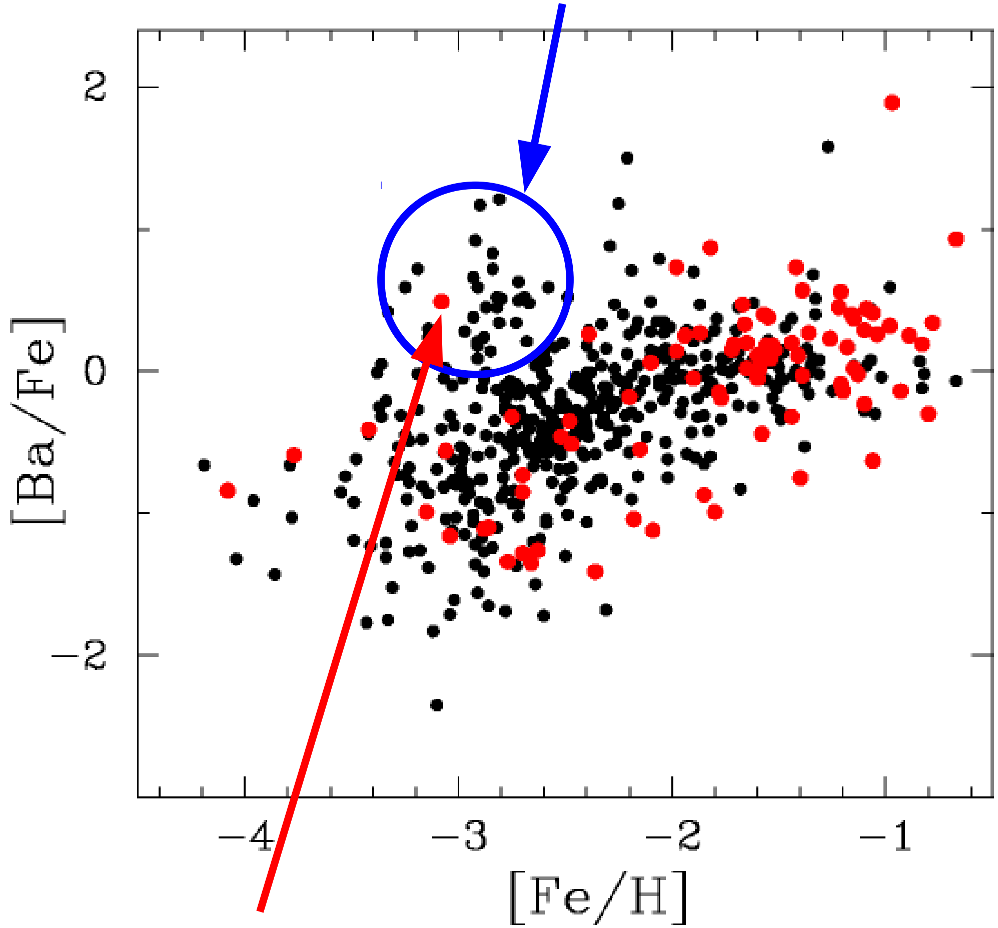


●:dwarf galaxy stars
●:field stars

Y is under-abundant in dwarf galaxies
→smaller contribution by weak s-process (+weak r-process?) from very massive stars?

Neutron-capture elements in dwarf galaxies

r-process-enhanced stars in the Milky Way



●:dwarf galaxy stars
●:field stars

※carbon-enhanced stars are excluded
→Ba is mostly r-process origin

Ba is more under-abundant in dwarf galaxies
→no r-process-enhanced stars in dwarf galaxies?

The Ba of this object is attributed to s-process (Honda et al. 2011)

r-processについての観測からの制限(1)

- “main r-process”については、作られる組成パターンに普遍性(Universality)がみられる。

-”r-process enhanced stars”の組成パターン(1^{st} ～ 3^{rd} peakまで)がよく揃っている。それは太陽系組成のr-process成分のパターンともよく合う(1^{st} peakあたりは合わない)。

-actinides と他の元素の組成比(Th/Eu)にも大きな分散は見られない → 何らかのメカニズムでアクチノイド合成が制御されている?

-いくつかの”r-process enhanced stars”の鉛(Pb)組成が低い → ”r-process enhanced stars”は本当に典型的なr-processを代表しているか?

r-processについての観測からの制限（2）

- 金属欠乏星（[Fe/H]<-2）全体では重元素組成比(Eu/Feなど)に大きな分散
 →r-process の起源は一部のごく限られた天体

- もっとも低い金属量の星にもSr,Ba はほとんどの場合検出される
 →r-process は宇宙のごく初期から普遍的に存在（？）

- Sr/Ba に大きな分散 → 1st peak をつくる別のプロセスが存在

- r-process 元素は他の元素組成比（Mg/Fe, Zn/Feなど）とは何の相関も見られない
→ r-process は他の元素合成とは独立に起きている?

- 今のところ超新星残骸にr-process の証拠は見つかっていない。

r-processについての観測からの制限(3)

- 球状星団の星でも[Eu/Fe] に分散が見られるものがある
→ 球状星団形成と r-process のタイムスケールが近い(?)

- 矮小銀河の金属欠乏星ではr-process元素が欠乏?
(現状ではデータ量が不足)