NIC School
2023.9.12.

Observations. 2. Lithium and r-process

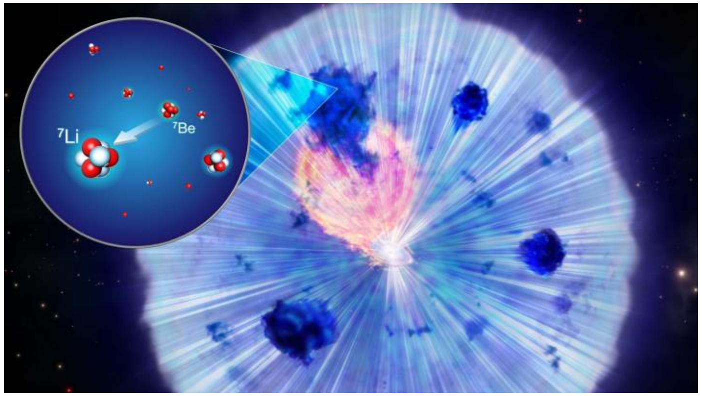
Wako Aoki

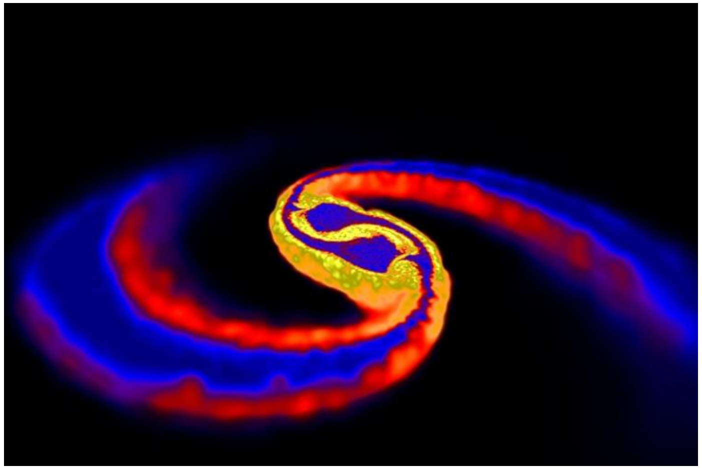
National Astronomical Observatory of Japan

SOKENDAI (Graduate University for Advanced Studies)

Observations. 2. Lithium and r-process

- **Li in the cosmos**
  - **Constraint from chemical evolution models**
  - **Li measurements for novae**
- **r-process**
  - **Direct measurement for merging event of binary neutron stars**
  - **Constraint from solar abundances**
  - **Constraint from stellar abundances**





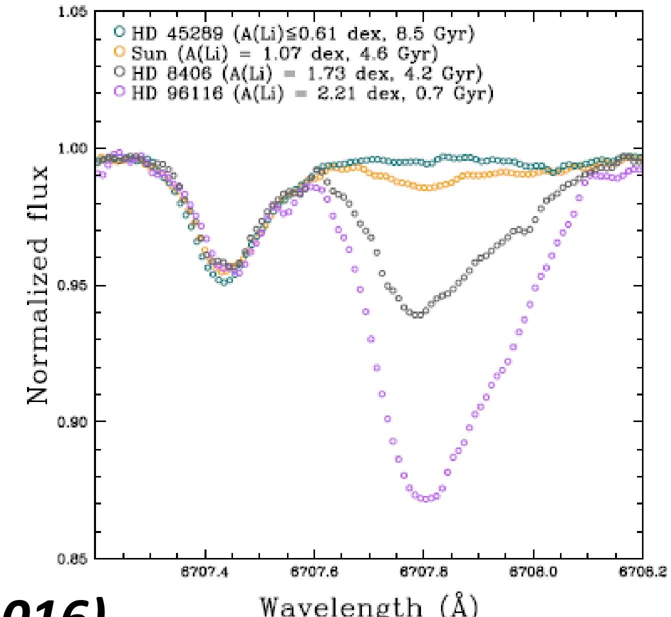
Lithium sources in the Cosmos

- A variety of origins
- Destruction inside of stars

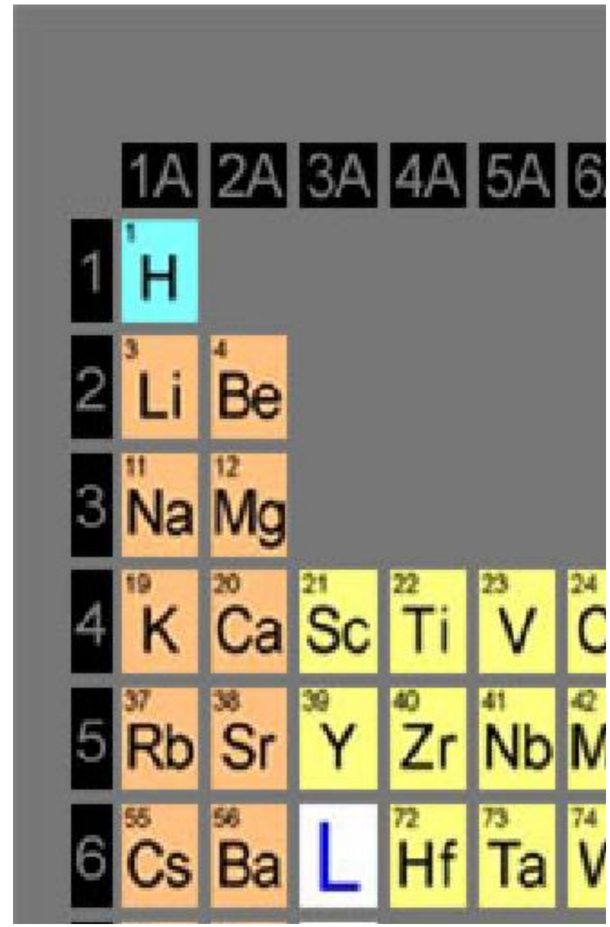
1. Big Bang nucleosynthesis
2. Cosmic-ray spallation
3. Low-mass stars (AGB stars)
4. nova explosions
5. Supernova explosions

Li isotopes in the solar-system

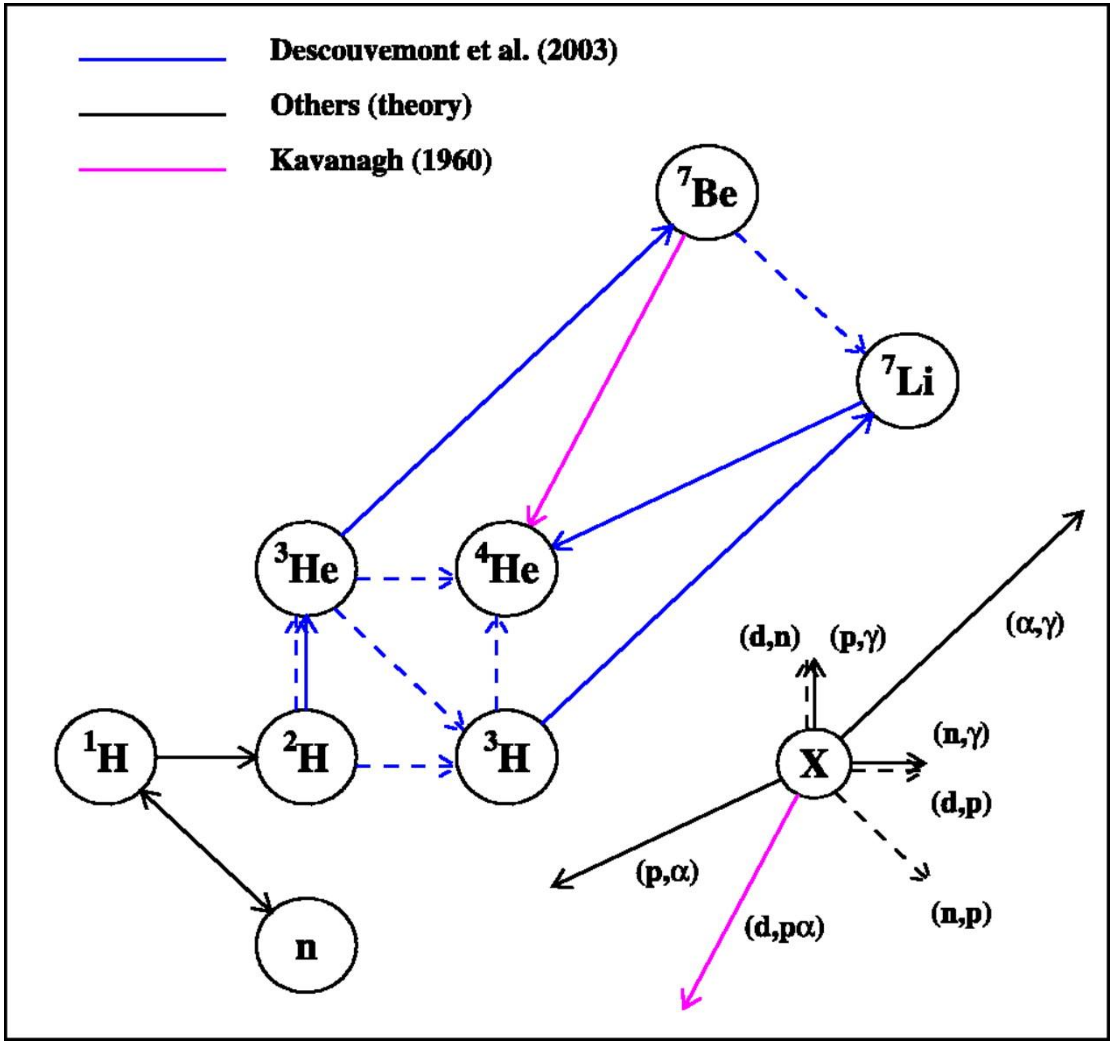
- **Meteorite:**
  $\log \varepsilon(\mathrm{Li}) = \log(N_{\mathrm{Li}}/N_{\mathrm{H}})+12$
  $= 3.26$
  $^{7}\mathrm{Li}/^{6}\mathrm{Li}=12.5$
- **Photosphere:**
  $\log \varepsilon(\mathrm{Li}) = 1.05$



Carlos et al. (2016)

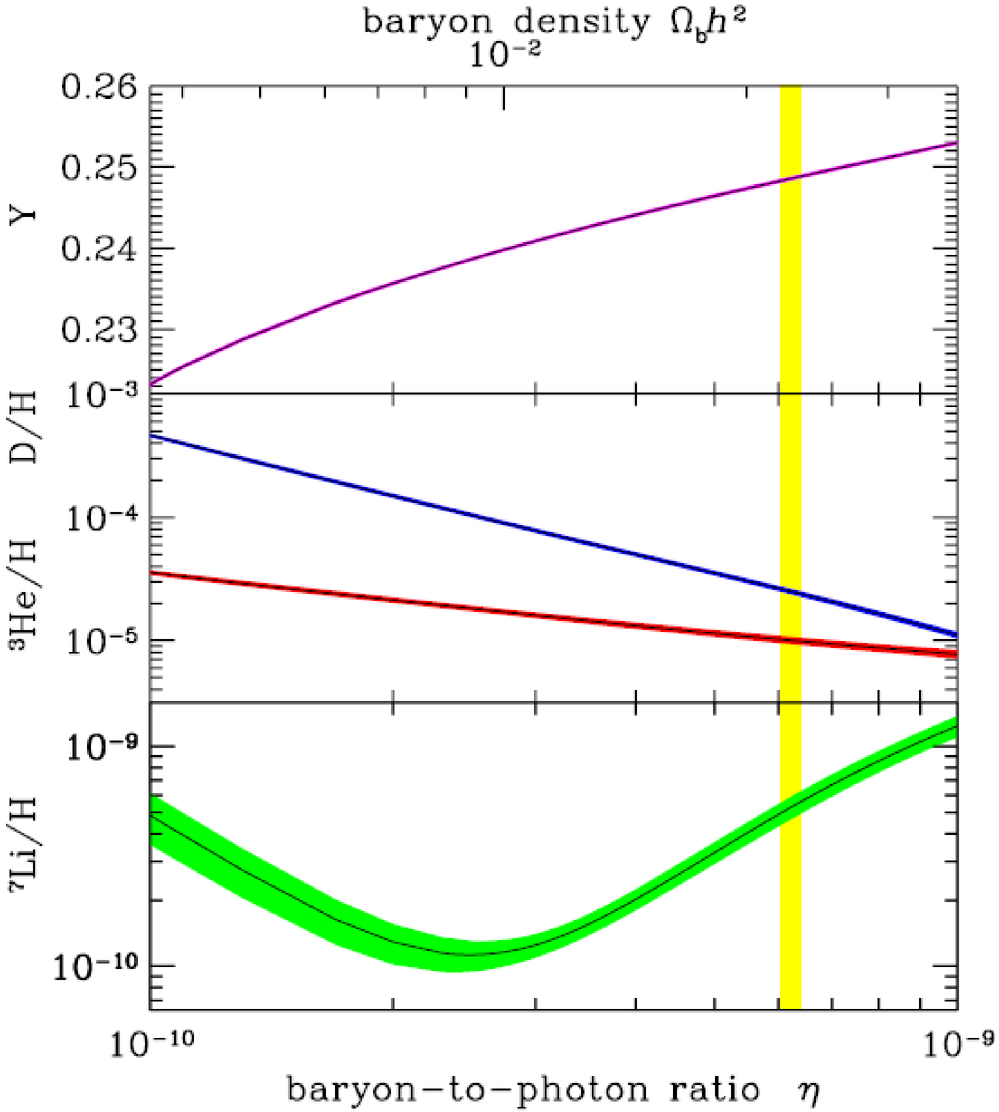


1. Li production in Big-Bang nucleosynthesis



Coc et al. (2004)

Big-Bang nucleosynthesis



Cyburt et al. (2008)
cf. review by Cyburt et al. (2015)

Lithium sources in the Cosmos

2. Li production by Cosmic-ray (CR) spallation

- CR (CNO) + ISM(pα)
  'primary'
- ISM(CNO) + CR(pα)
  'secondary'
- α + α → ^{6}Li

^{7}Li/^{6}Li～2

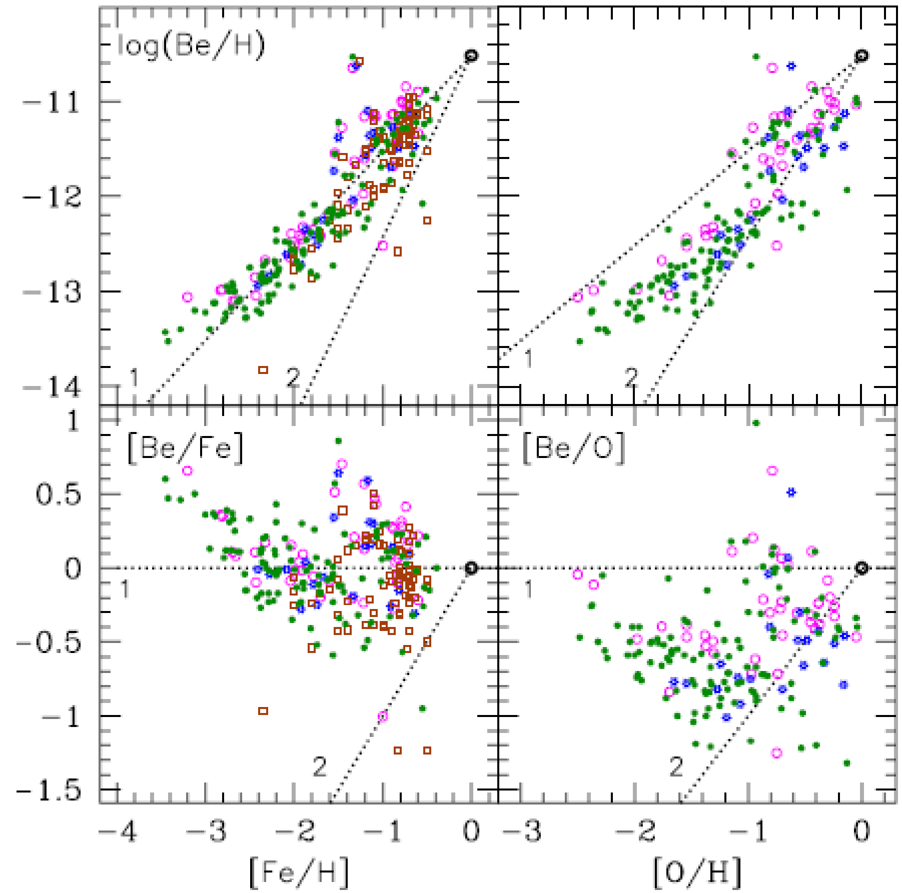


Fig. 1. Observations of Be vs. Fe (*left*) and vs. O (*right*). In all panels, dotted lines indicate slopes of 1 (primary) and 2 (secondary). Data are from Primas (2010, circles), Tan et al. (2009, asterisks), Smiljanic et al. (2009, open squares), and Boesgaard et al. (2011, dots).

Prantzos (2012)

3. Li production in low-mass stars

'beryllium transport (Cameron-Fowler) mechanism'

- **He shell:**
  $^3He + \alpha \rightarrow {}^7Be$
- **Stellar surface:**
  $^7Be + e \rightarrow {}^7Li$

(half-life of ^7Be is 53 days)

Abia et al. (1999)

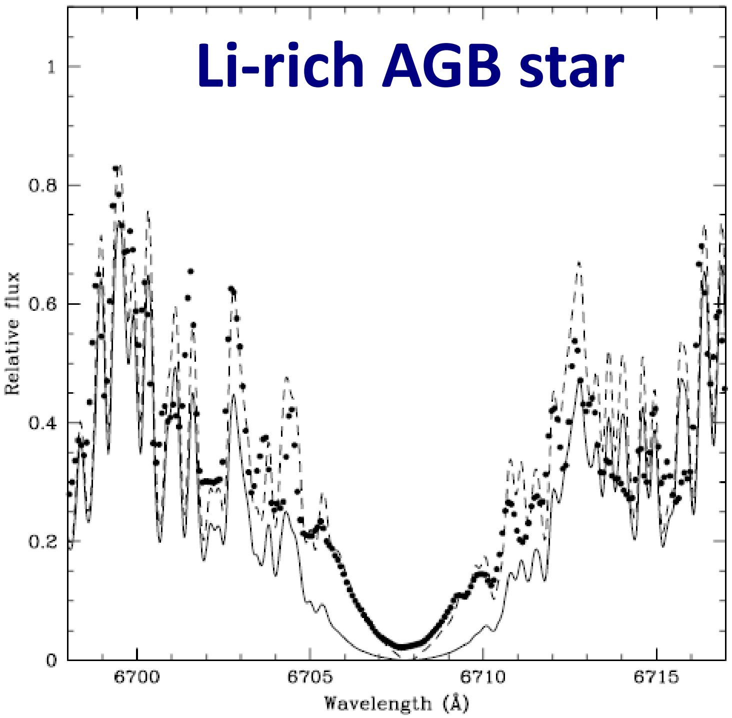
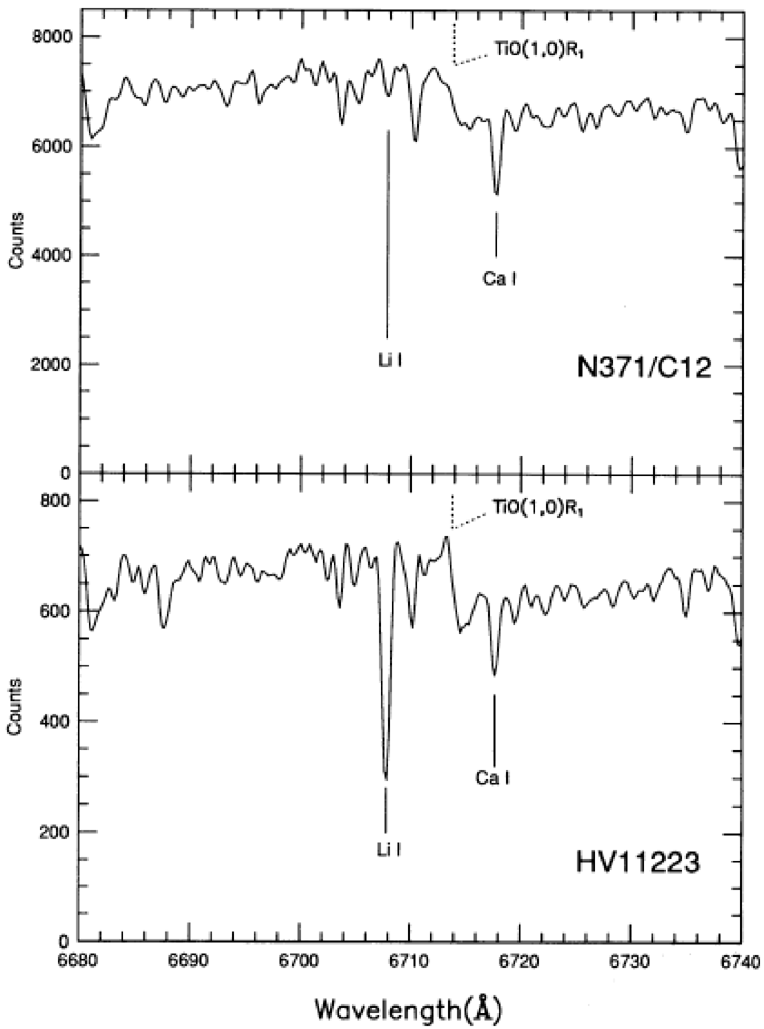


Fig. 5. As Fig. 4 in the λ6708 Å spectral domain of WZ Cas for log ϵ(Li)=5.0

Contribution to Li in the Galaxy is unclear, because (1) the Li-rich phase in stellar evolution would be short, and (2) mass-loss rate during the Li-rich phase is uncertain.

Lithium sources in the Cosmos

Li-rich giant (AGB) stars in Magellanic clouds



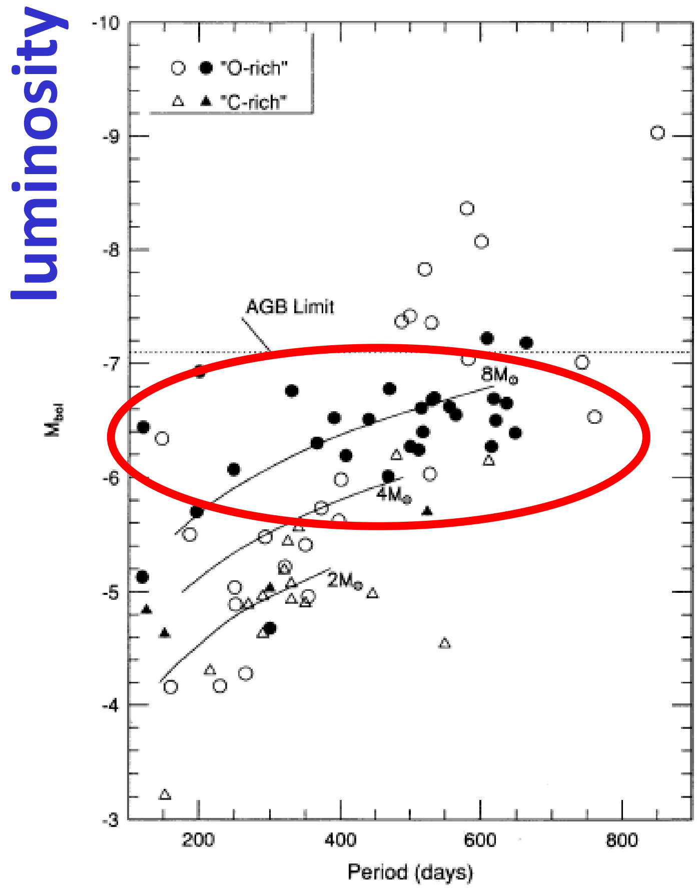


FIG. 6.—Combined M_{bol}-P diagram for the Magellanic Clouds with the filled symbols denoting the Li-strong stars. The segregation of the Li-strong stars to the most luminous of the AGB stars is striking. Note that no AGB stars with detectable Li I are found at luminosities significantly exceeding the AGB limit. A few AGB stars with $M_{bol} > -6$ show detectable Li I lines. The solid curves denote evolutionary tracks for AGB stars taken from the equations given in Wood et al. (1983) for fundamental pulsators.

Plez et al. (1993)

Smith et al. (1995)

4. Li production in novae

e.g. Boffin et al. (1993)

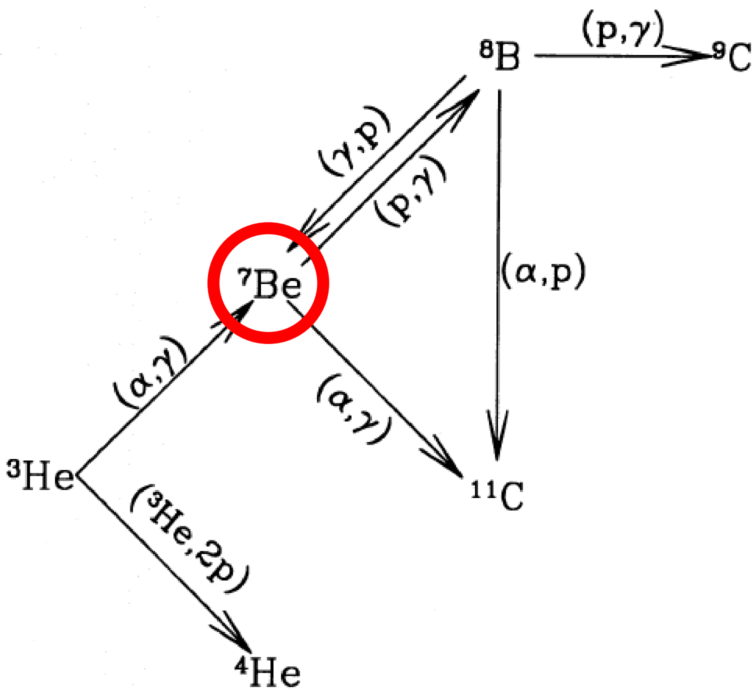


Fig. 1. Main nuclear reactions involved in the synthesis of ^{7}Be for typical explosive hydrogen burning conditions. The post-freeze-out ^{7}Be($e^-\nu$)^{7}Li transformation is not indicated

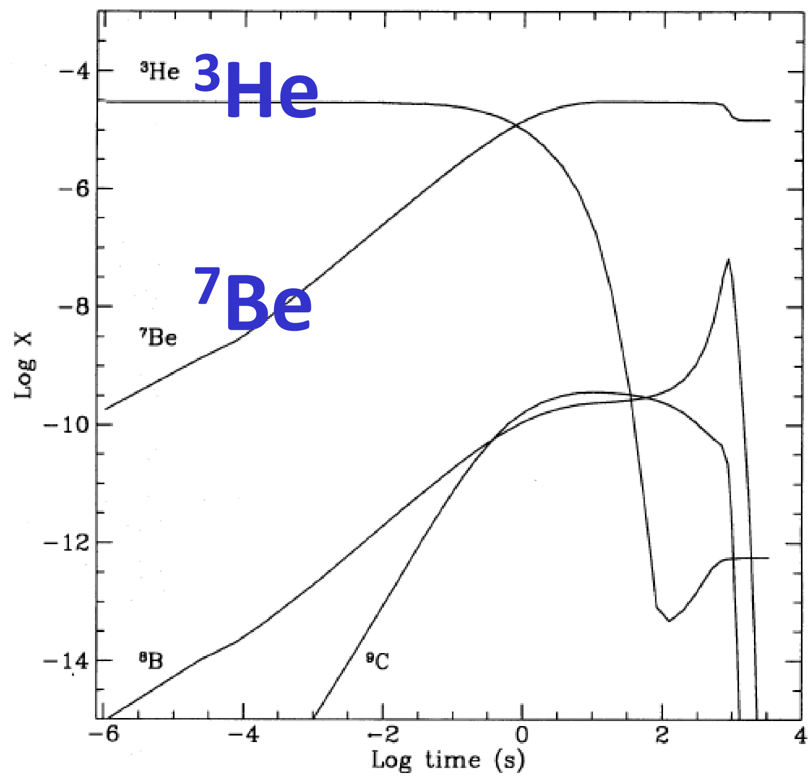
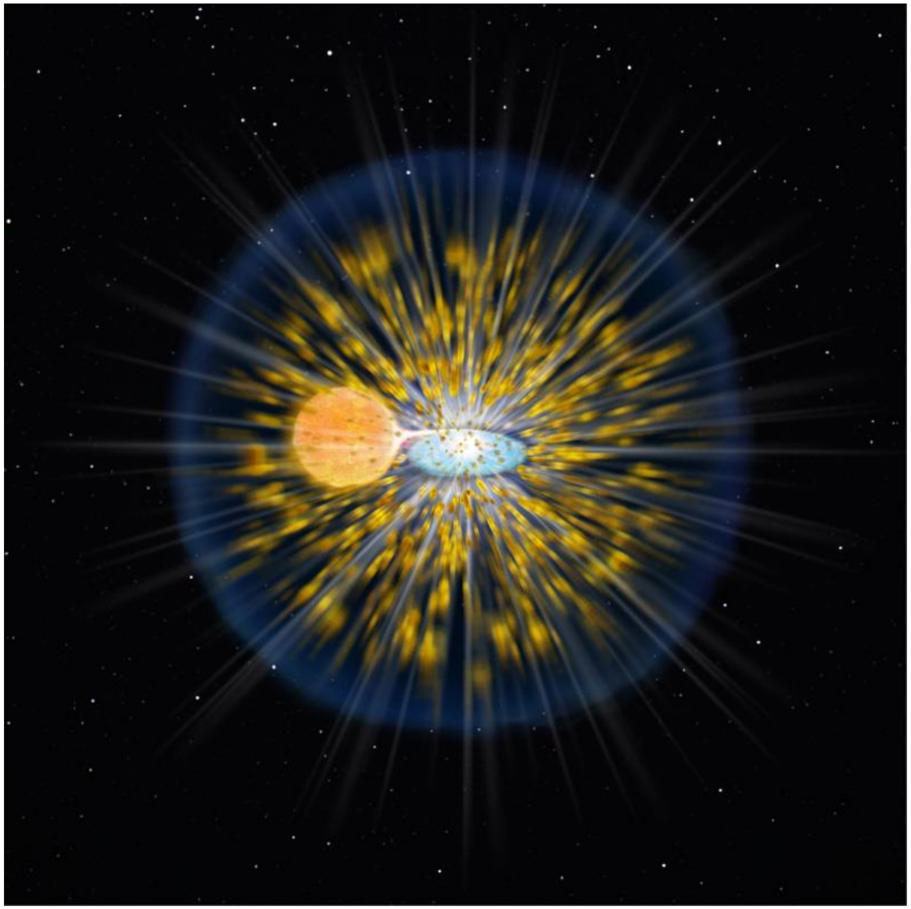


Fig. 4. Time evolution of the mass fractions of ^{3}He, ^{7}Be, ^{8}B, and ^{9}C for the case T_0 = 3 10^8 K, ρ = 100 gcm^{-3}, and τ_{ex} = 300 s

Classical novae



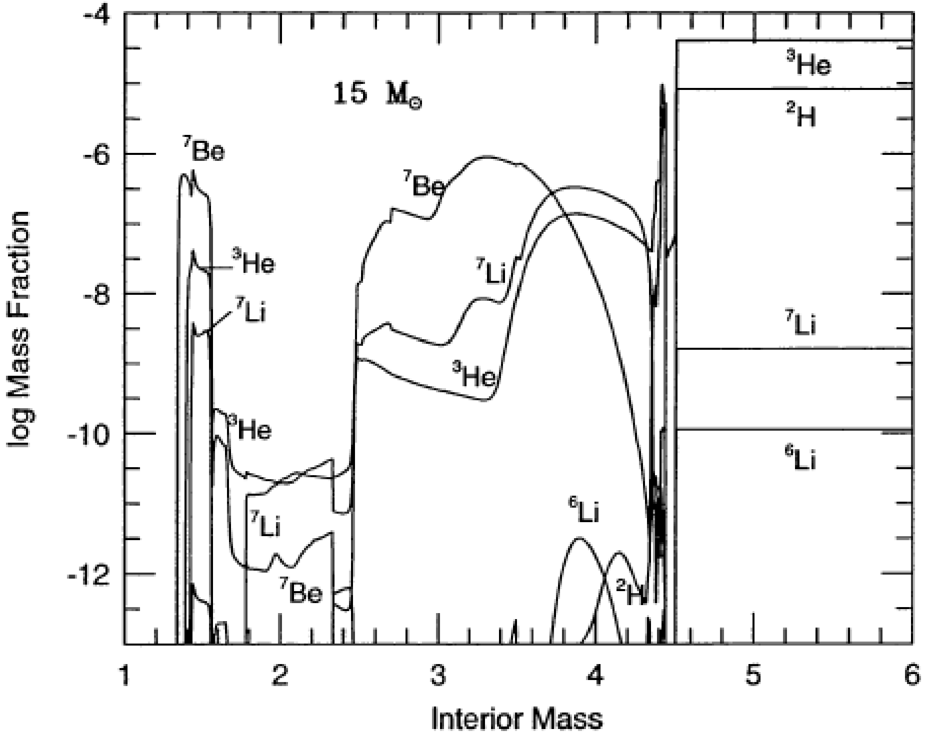
5-10 events per year observed in the Milky Way

- **Binary system with a white dwarf and a main-sequence star or a red giant**
- **Mass accretion from a companion to white dwarf through accretion disc**

Igniting nuclear fusion when the gas layer becomes sufficiently hot and dense →explosive reaction ejecting the gas layer

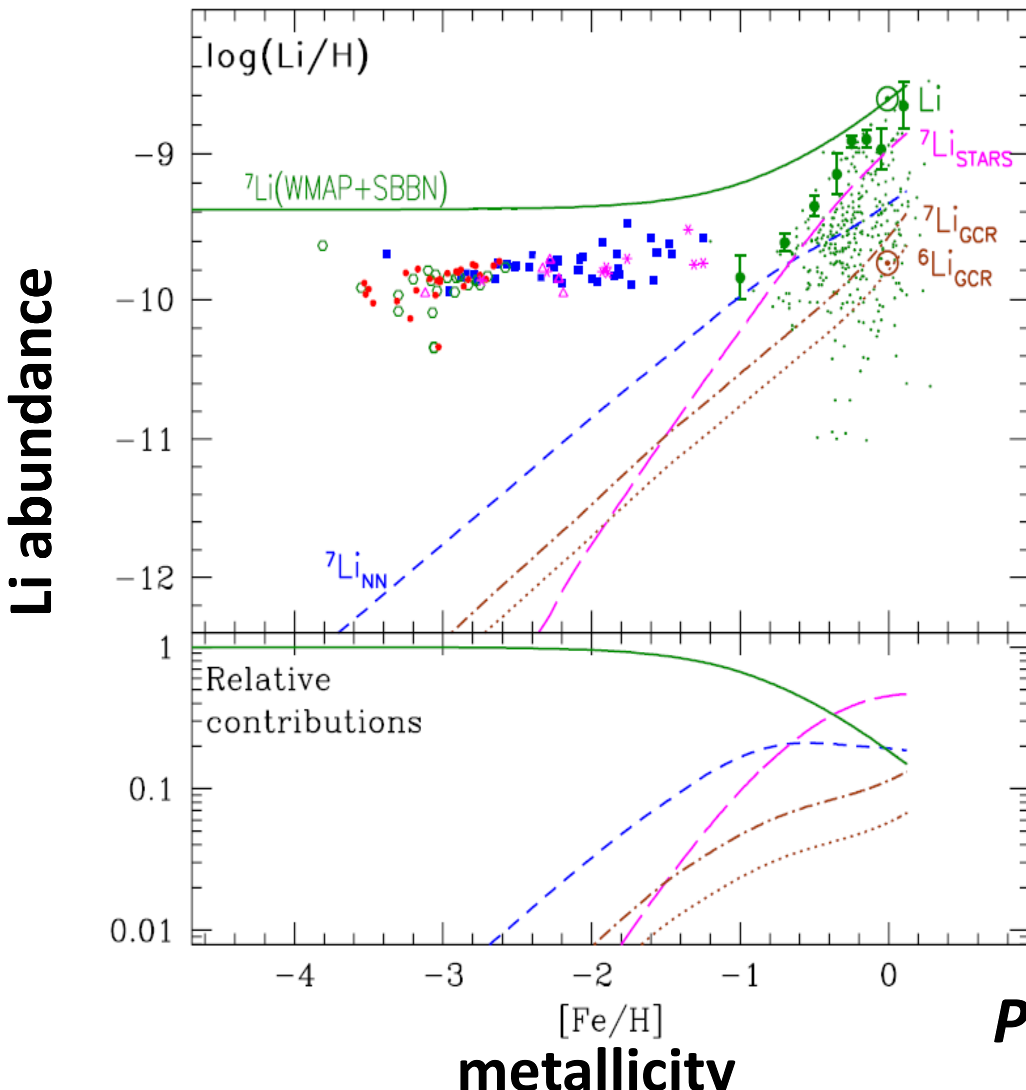
5. Li production in Supernovae -- ν-process

ex. $^{4}He(\nu,\nu' p)^{3}H(\alpha,\gamma)\ ^{7}Li$



Woosley & Weaver (1995)

Modeling of the evolution of Li in the Galaxy



- **Observational data for unevolved stars (main-sequence stars)**
- **Large scatter of Li abundances in metal-rich stars**
- **Almost constant Li abundance (Li plateau) in metal-poor stars**

Prantzos (2012)

Li abundances in stellar atmospheres

- **Destruction of lithium**

  ^{7}Li destruction with *T>2.5* Million K

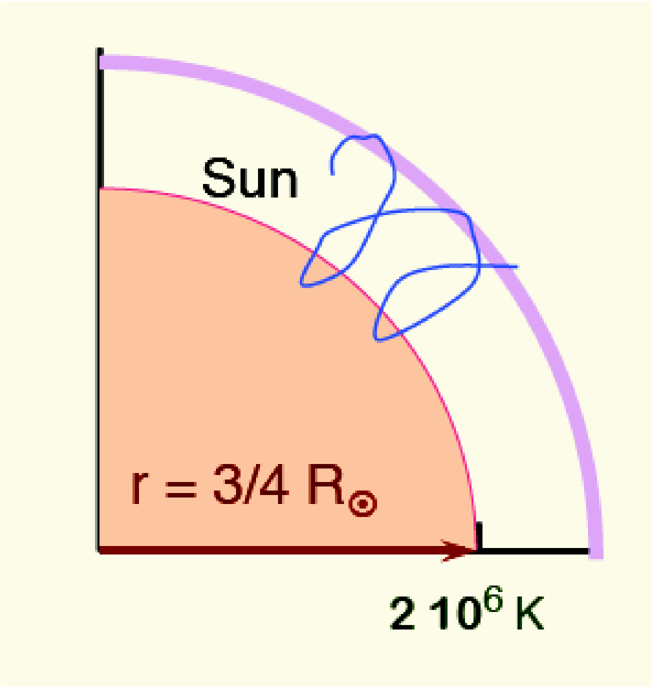
  $^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

  ^{6}Li destruction with *T>2* Million K

  $^{6}Li + D \rightarrow {}^{4}He + {}^{4}He$

  $^{6}Li + p \rightarrow {}^{4}He + {}^{3}He$

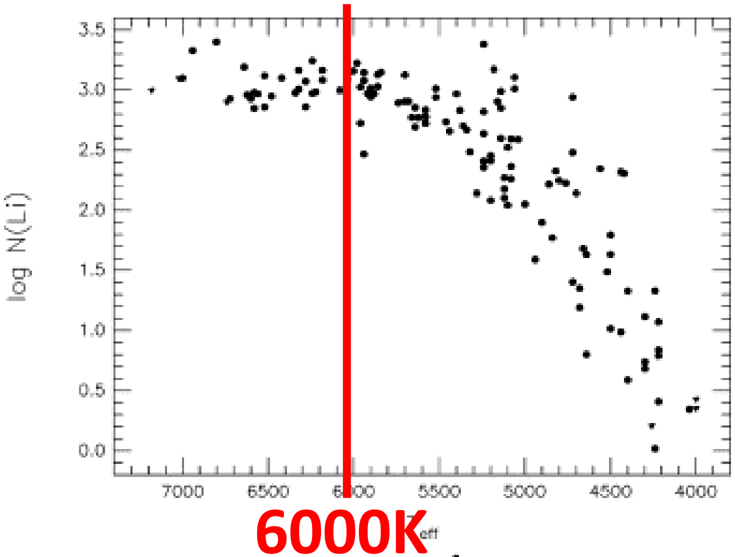
- **Li is depleted at the surface of stars in which convective envelope is sufficiently thick.**



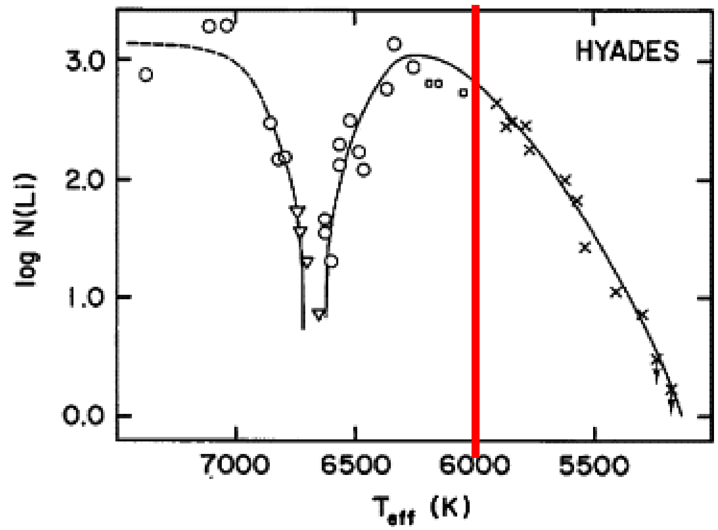
Spite (Li in the Cosmos)

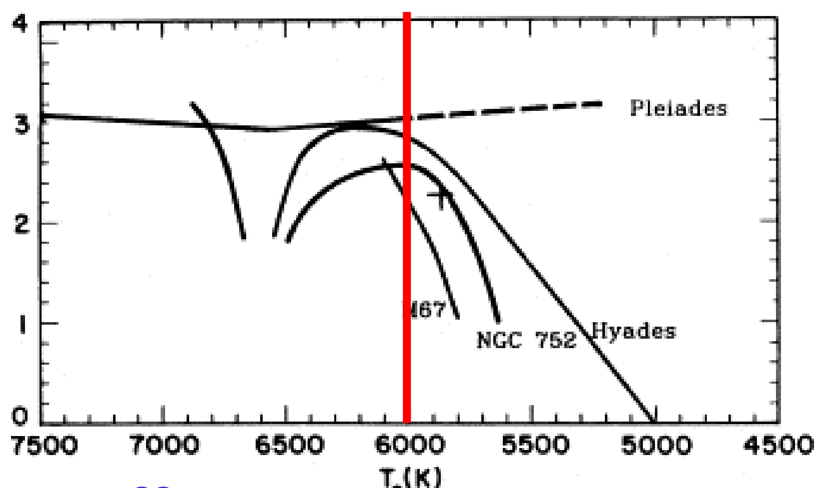
Lithium in main-sequence stars in clusters

Pleiades: a young cluster (80Myr)



Hyades: an"old" cluster (600Myr)



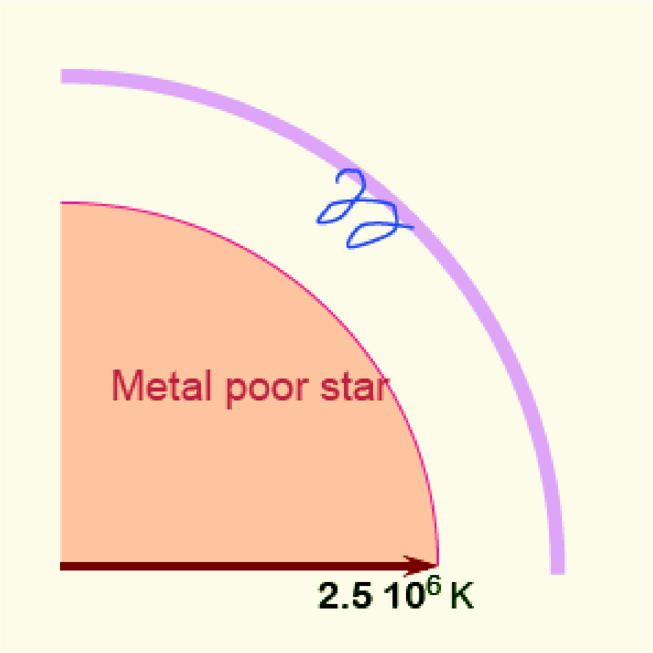


Effective temperature

Hobbs (2000)

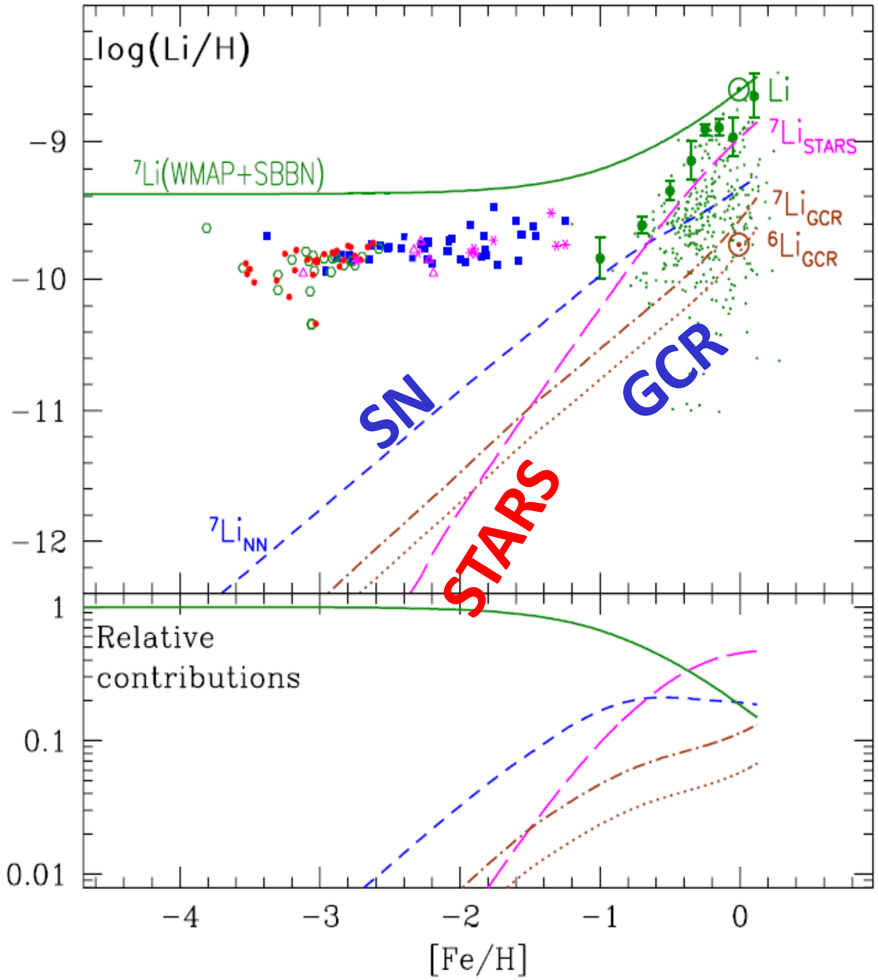
Lithium in metal-poor stars

Shallow convective layer in metal-poor stars →small depletion of lithium



Spite (Li in the Cosmos)

Modeling of the evolution of Li in the Galaxy



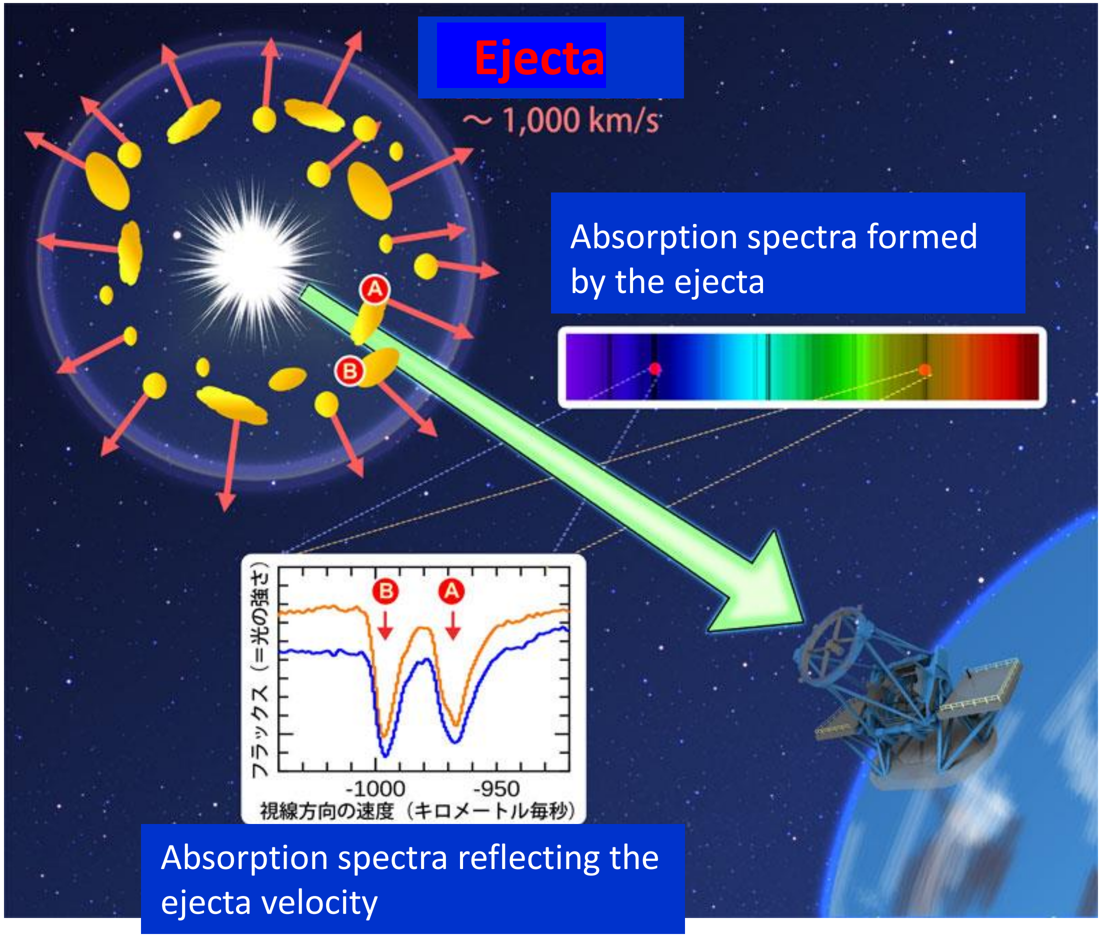
- **Big Bang nucleosynthesis 'SBBN'**
- **Low-mass stars: 'STARS' including novae**
- **Cosmic rays: 'GCR'**
- **Supernovae: 'SN'**

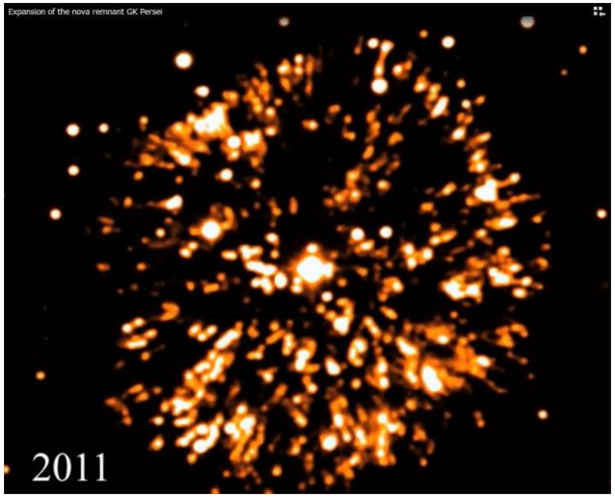
Prantzos (2012)

Li abundances observed in stars indicates Li production in low-mass stars and nova explosions, which have long time scale. However, there was no direct observational evidence until 2015.

Lithium production in nova explosions

High velocity absorption lines in nova spectra





Liimets et al., (2012)

Nova 1901 Per (GK Per)
110 years after the explosion

Absorption by gas clumps ejected from the white dwarf surface by explosion

Lithium production in nova explosions

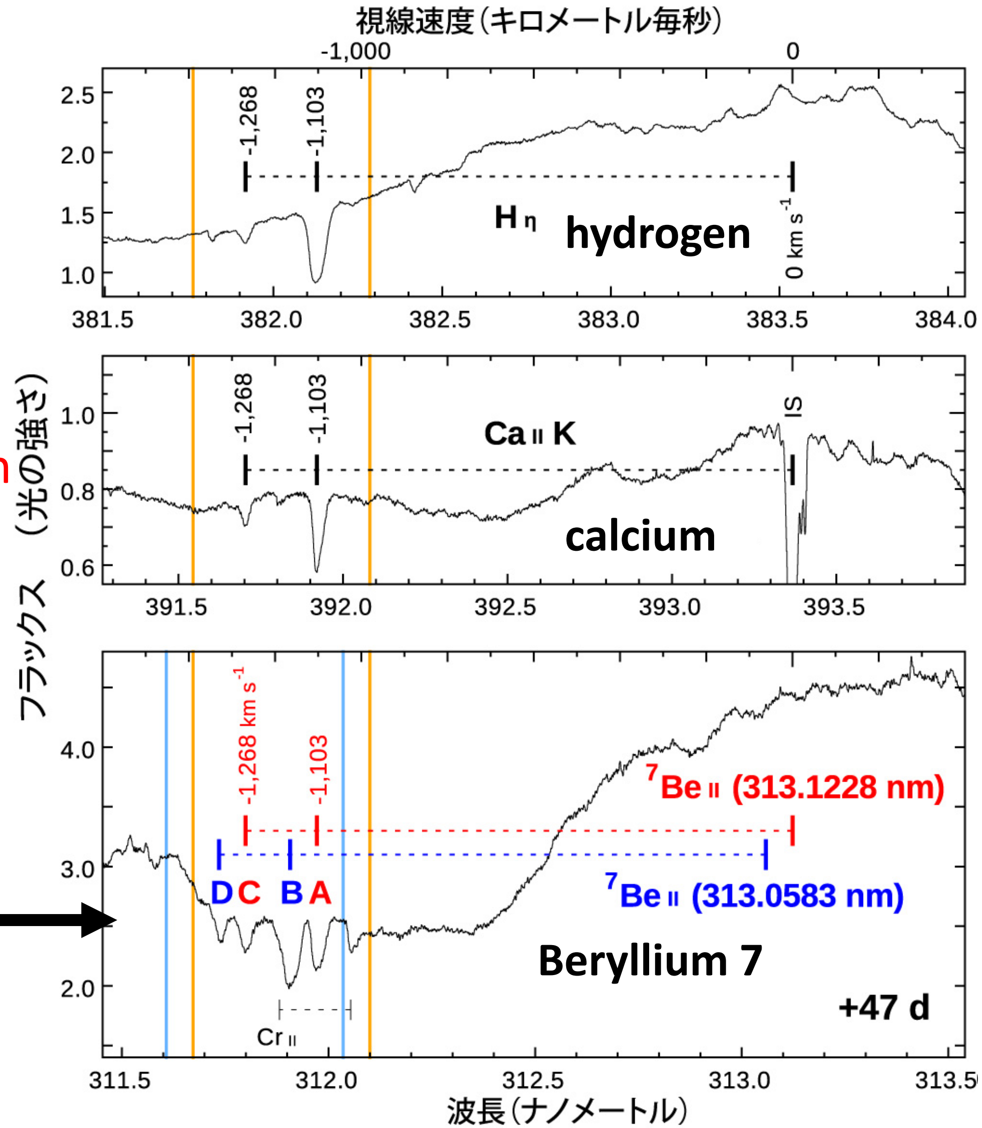
Discovery of ^{7}Be in a nova spectrum

Tajitsu et al.(2015, Nature 518, 381)

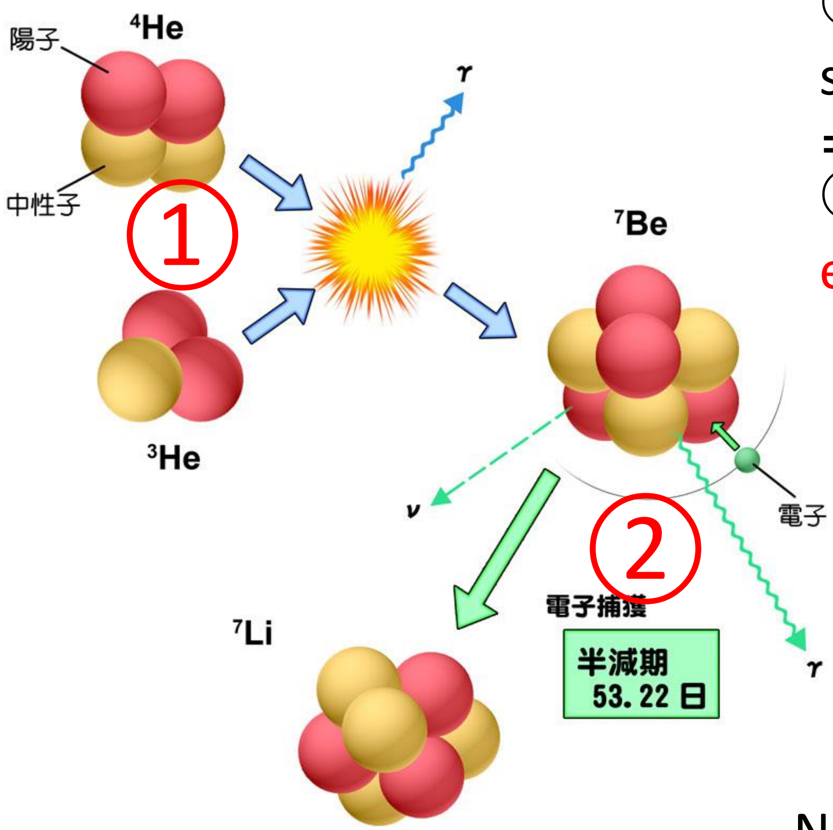
- 47 days after the explosion
- Two high velocity absorption components at
  -1,103 km/s
  -1,268 km/s

Detection of doublet ^{7}Be absorption line at 312nm (UV region)

Velocity is adjusted by one of the ^{7}Be II doublet lines (shown by red: A and C), which agrees the velocity estimated for H and Ca lines



^{7}Li production in classical novae



①hydrogen burning at the surface of a white dwarf
⇒ ^{3}He(α,γ)^{7}Be reaction
②electron capture forming ^{7}Li in ejected gas

Short half life of 7Be (53.2 days) indicates that it is synthesized in the object very recently.

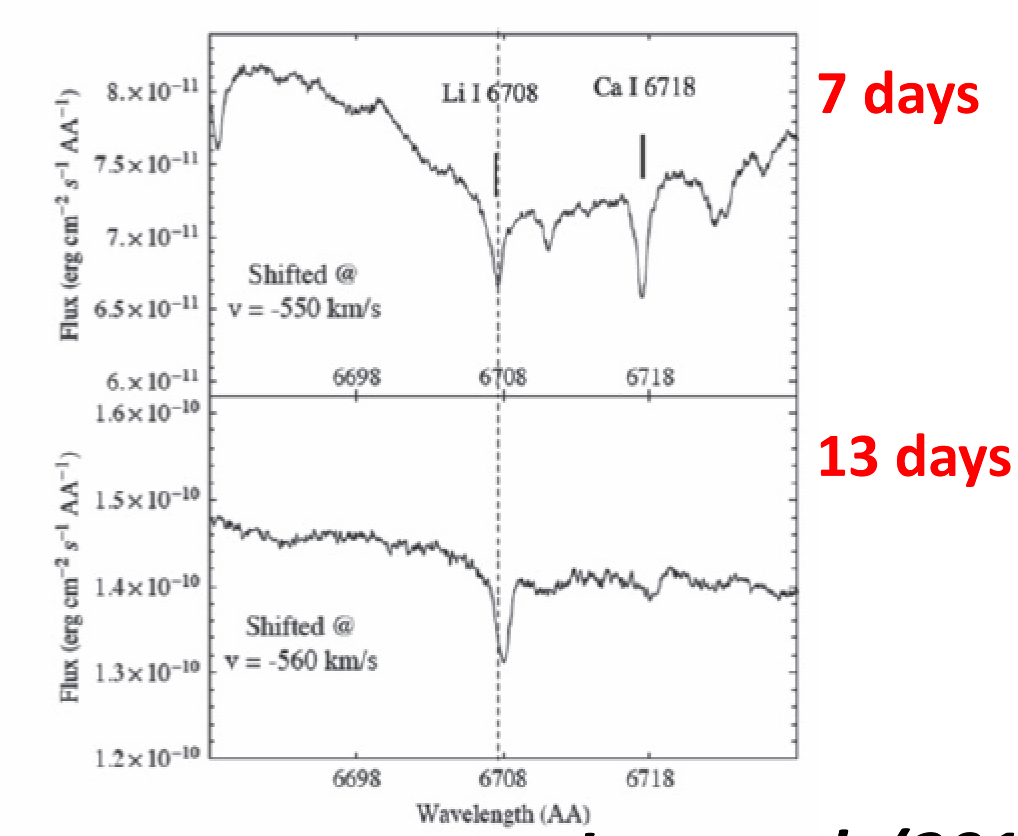
No observational evidence until 2015.
γ-ray emission at 478keV by electron capture has not yet been detected.

Another evidence: Li absorption line in classical nova spectra

Absorption line of neutral Li in spectra of earlier phase of (different) nova

Novae are certain site of Li production

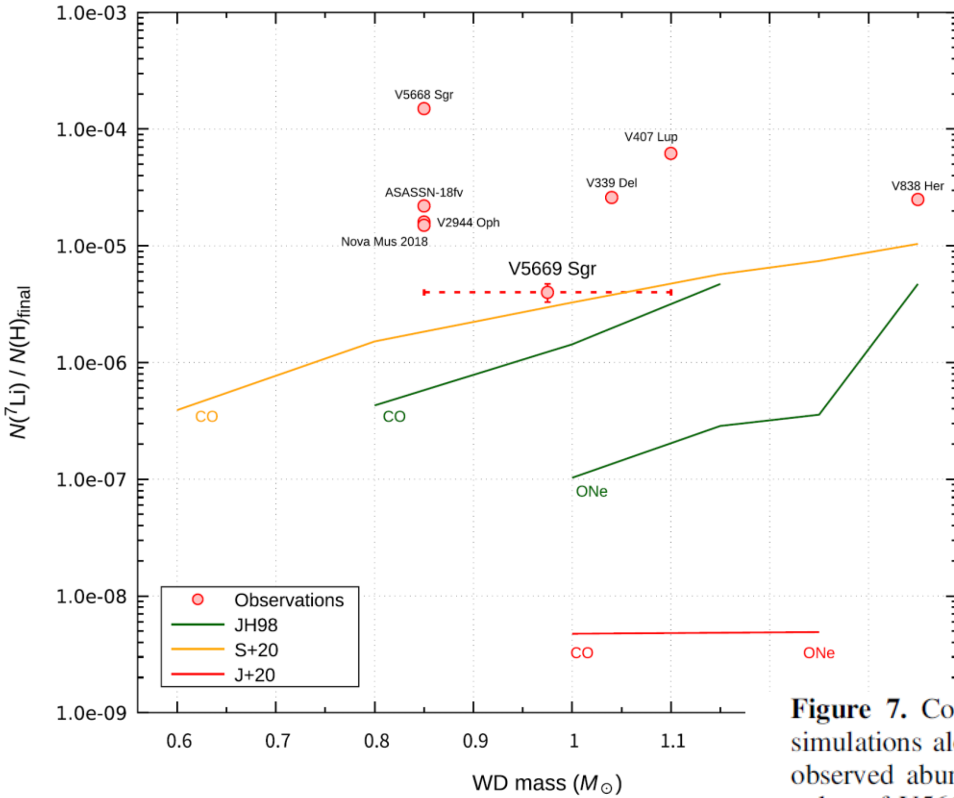
Nova 1369 Cen



Izzo et al. (2015)

Lithium production in nova explosions

^{7}Li abundances in nova ejecta estimated from ^{7}Be



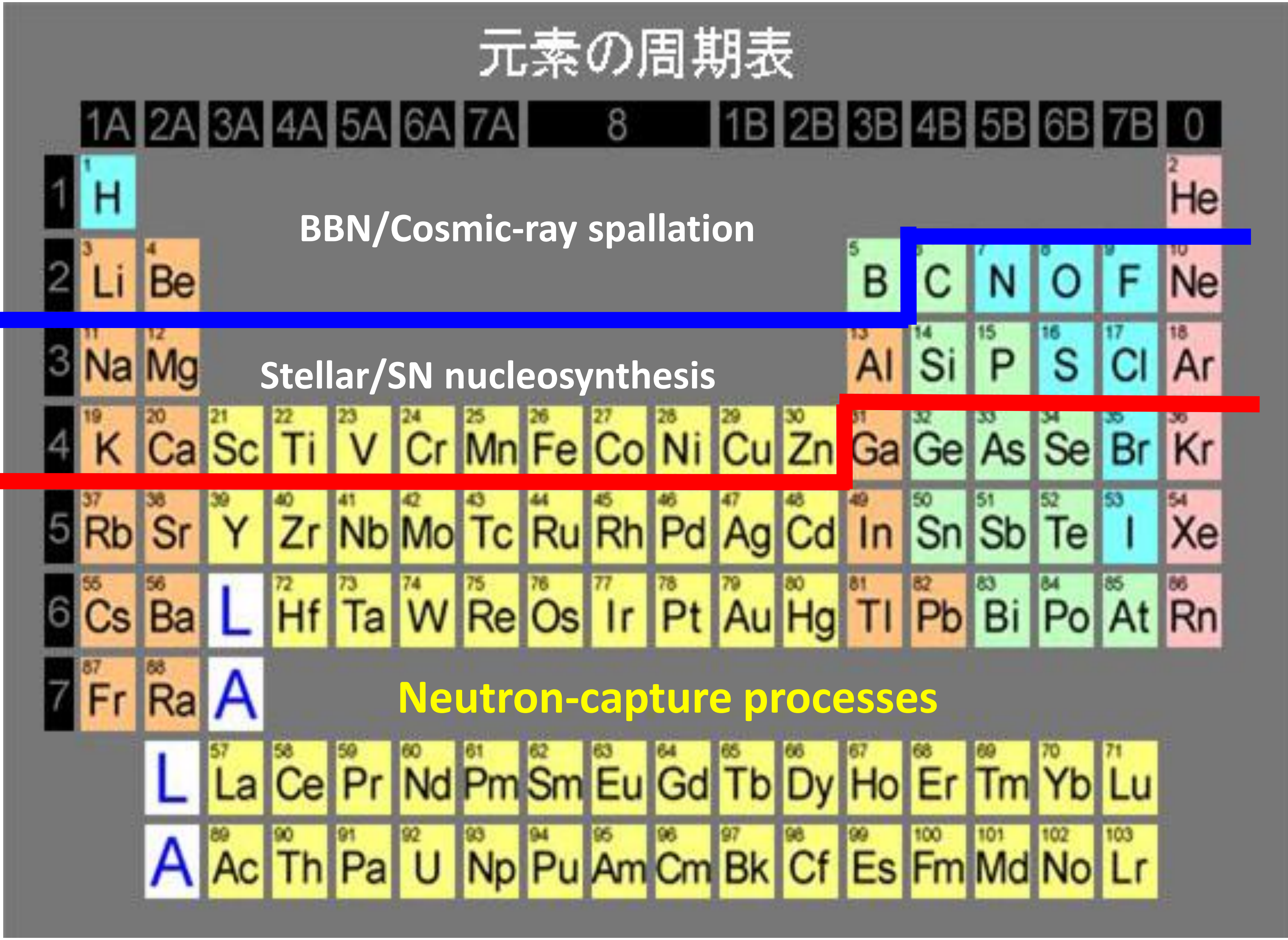
The estimates are quite uncertain, but suggest yields even larger than model predictions.

Arai et al. (2021)

Figure 7. Comparison with observed Li abundances and recent numerical simulations along with WD masses. Red bordered circles denote averages of observed abundances listed in Table 6. The dotted horizontal line with the value of V5669 Sgr shows the considerable WD mass range of V5669 Sgr. Note that WD masses for all observed novae, which have been estimated from the duration of their light curves, generally have similar large error bars. Since evaluating errors for each WD mass estimation is difficult, we simply plotted middle points of each estimated mass ranges for each observed nova. The green, orange, and red lines correspond to theoretical predictions; highest values for each WD mass in José & Hernanz (1998, JH98), the 25%–50% mixing model for only CO novae of Starrfield et al. (2020, S+20), and "123-321 models" of José et al. (2020, J+20), respectively.

r-process observations

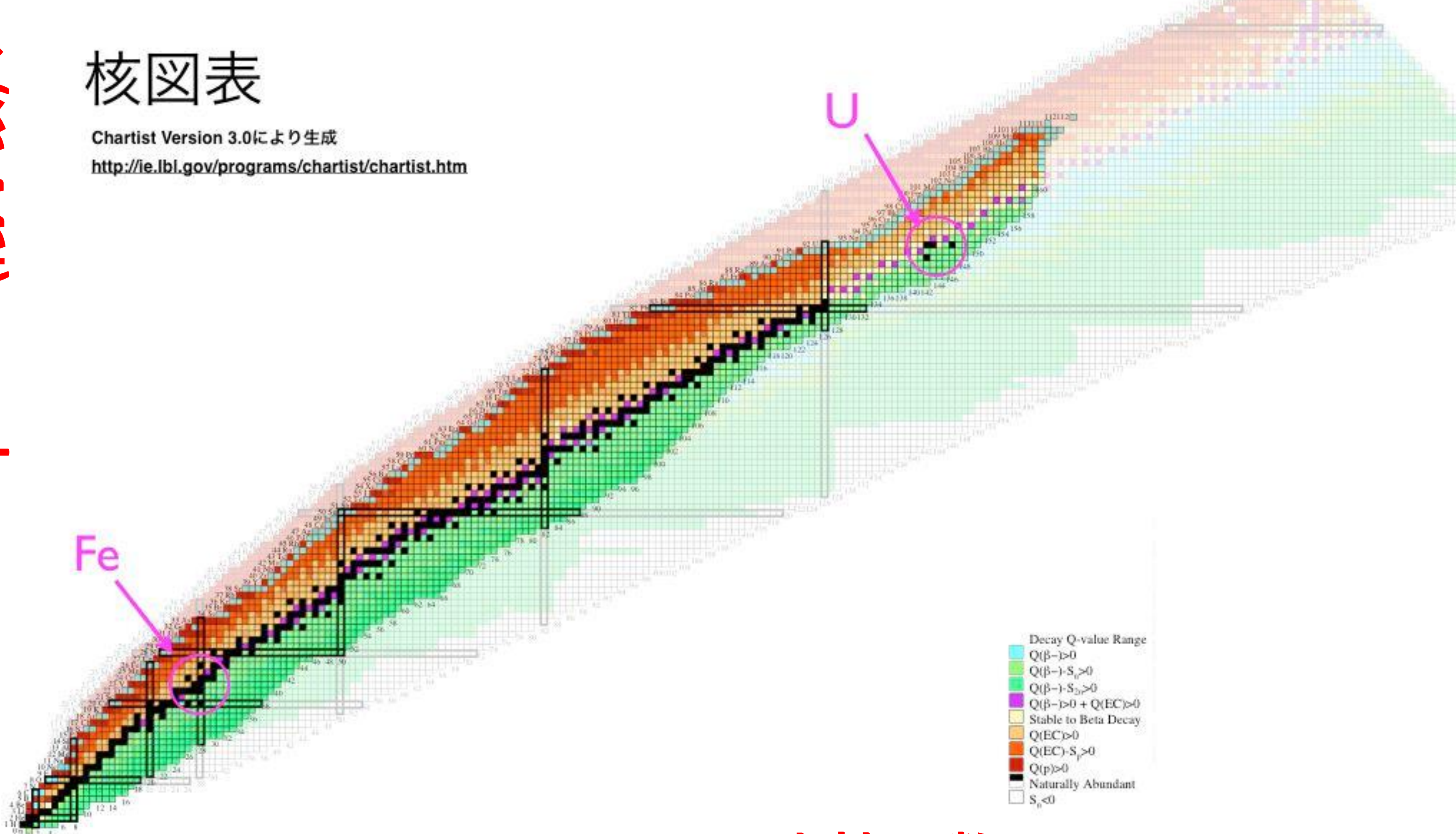
- Direct observations
- Solar abundances: r-process abundance pattern
- Stellar abundances
  - -Individual events recorded in extremely metal-poor stars
  - -Chemical evolution from large sample
  - -Constraints from dwarf galaxies
- Observations with LAMOST and Subaru


元素の周期表
1A 2A 3A 4A 5A 6A 7A 8 1B 2B 3B 4B 5B 6B 7B 0
1 H He
2 Li Be B C N O F Ne
3 Na Mg Al Si P S Cl Ar
4 K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
5 Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
6 Cs Ba L Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
7 Fr Ra A
L La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
A Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
BBN/Cosmic-ray spallation
Stellar/SN nucleosynthesis
Neutron-capture processes

r-process

Existence of actinides requests a neutron-capture process with very short time scale in explosive environment (r-process)

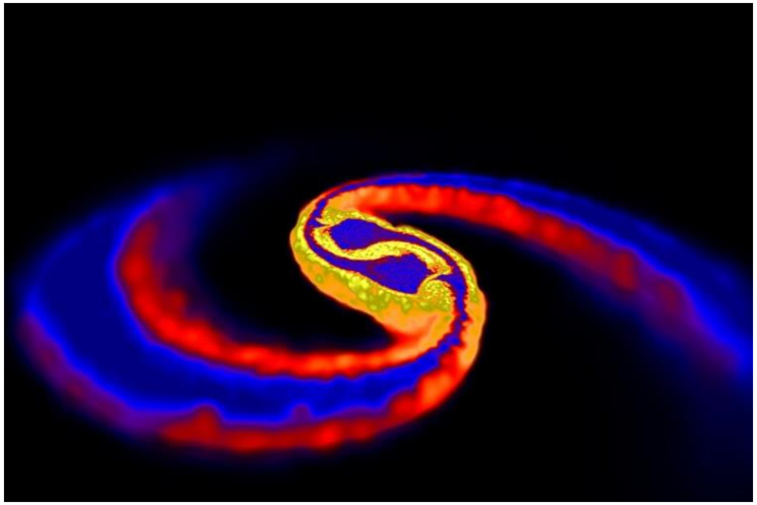
Number of proton (陽子数)→



Number of neutron (中性子数)→

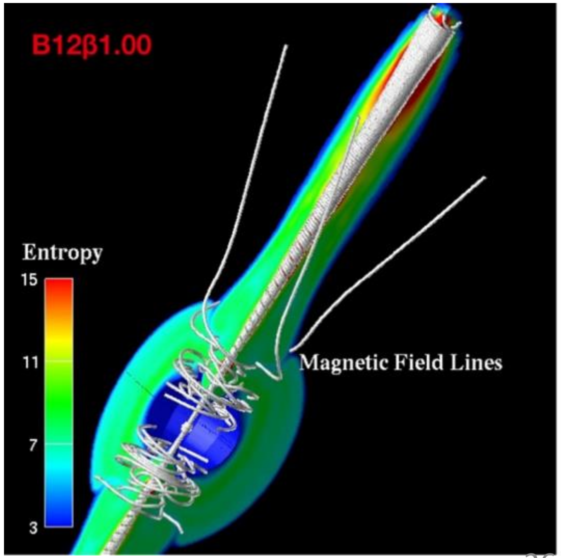
Candidates for r-process sites

- **Merger of binary neutron stars**
  e.g. Goriely et al. 2011;
  Rossborg et al. 2014;
  Wanajo et al. 2014



Price & Rossbwog

- **Special supernova explosions**
  e.g. magnetrotationally driven supernova (*e.g. Fujimoto et al. 2008; Nishimura et al. 2015*)



N. Nishimura et al. (2015)

r-process direct observations

Direct observations?

- **NO direct evidence of r-process in supernova explosions**
- **Signature of r-process in merger of binary neutron stars**

r-process elements in supernova remnants?

Wallerstein et al. (1995)

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

GEORGE WALLERSTEIN AND ANDREW D. VANTURE[2]
Department of Astronomy FM-20, University of Washington, Seattle, WA 98195
EDWARD B. JENKINS
Princeton University Observatory, Princeton, NJ 08544-1001
AND
GEORGE M. FULLER
Department of Physics, University of California, San Diego, La Jolla, CA 92093-0319
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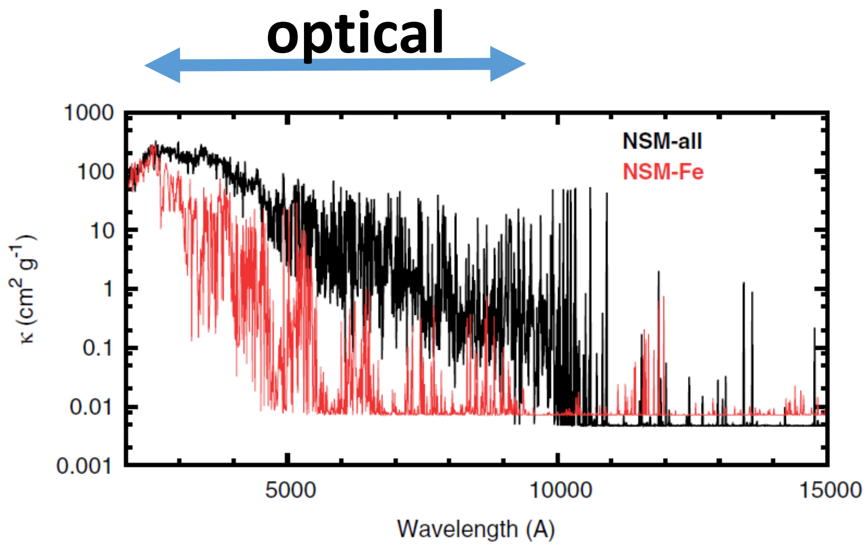
ABSTRACT

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.

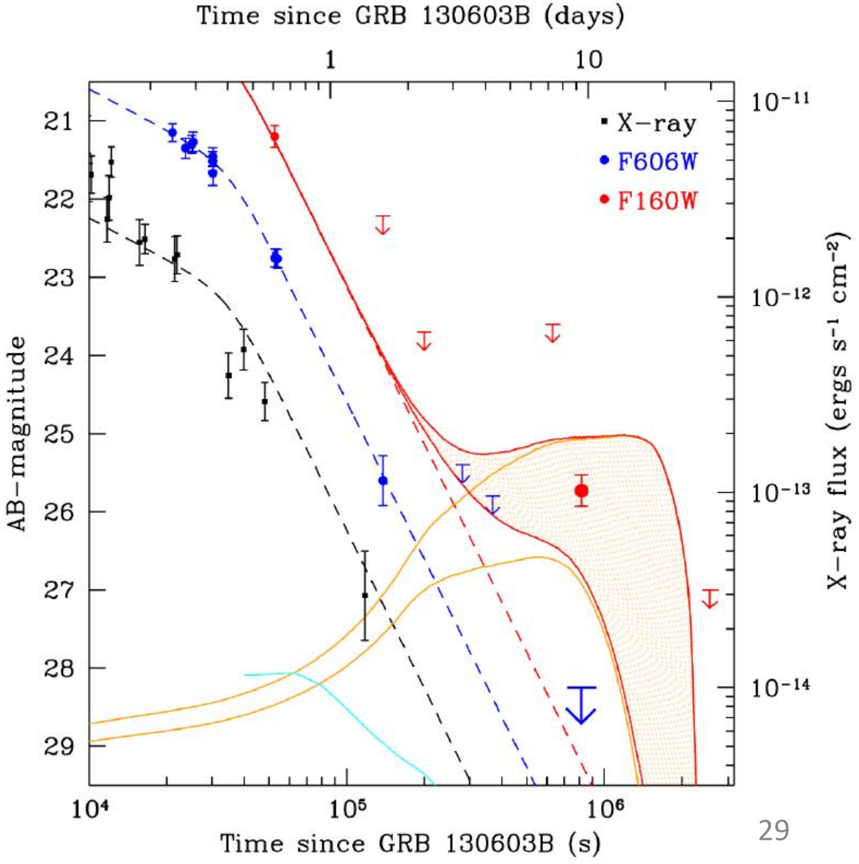
r-process elements in kilonova (=afterglow of a possible neutron star merger)?

- Excess of infrared flux in late phase is predicted by **including amount of lanthanides in opacity source**
- Excess of infrared flux is found in afterglow of a short GRB

Tanaka & Hotokezaka (2013)



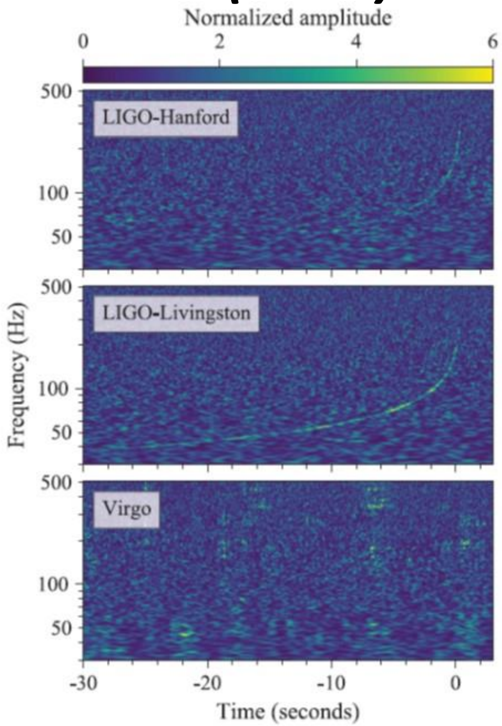
Tanvir et al. (2013)



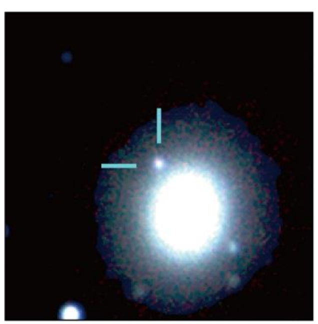
r-process direct observations

GW170817

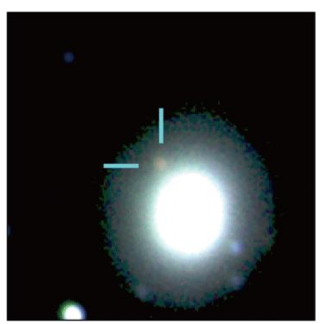
Abbott et al. (2017)



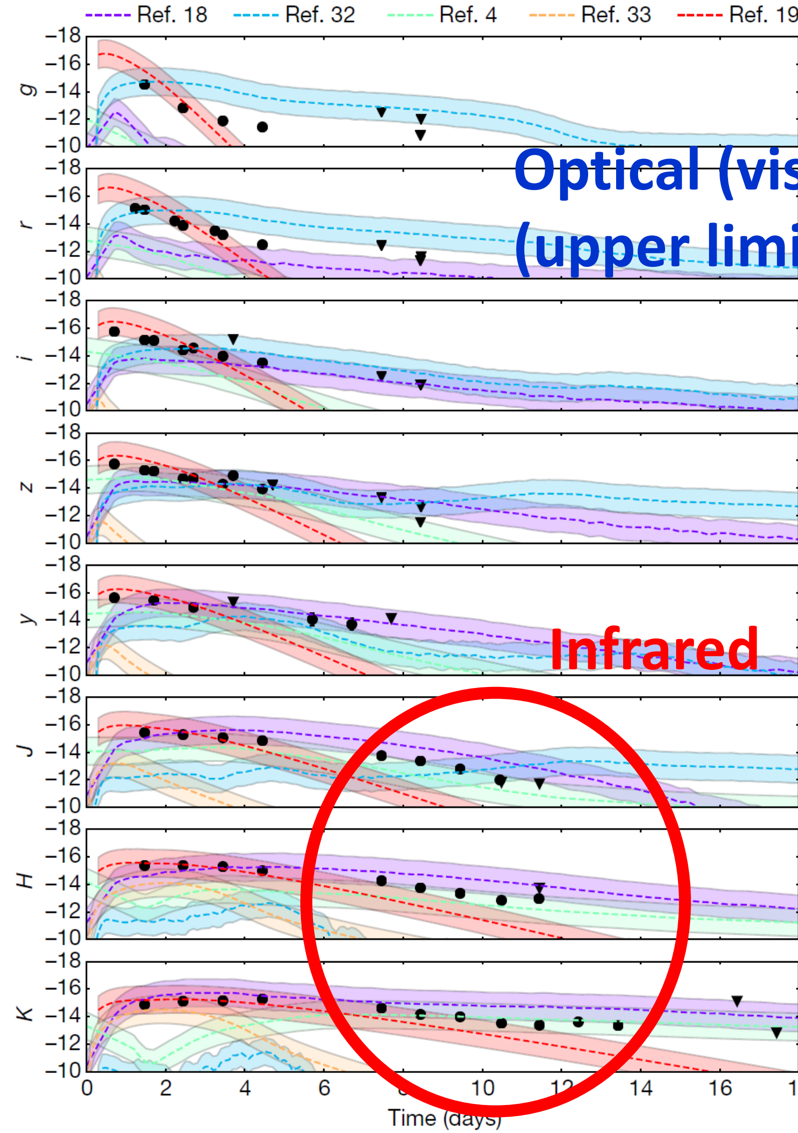
2017.08.18-19



2017.08.24-25

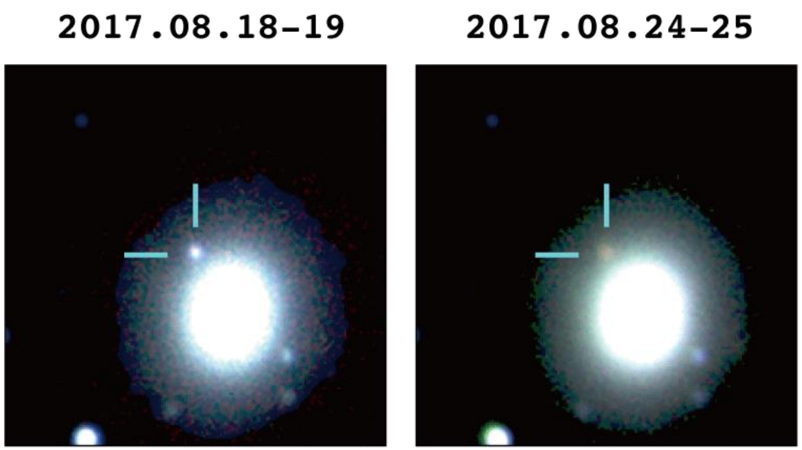


Smartt et al. (2017)

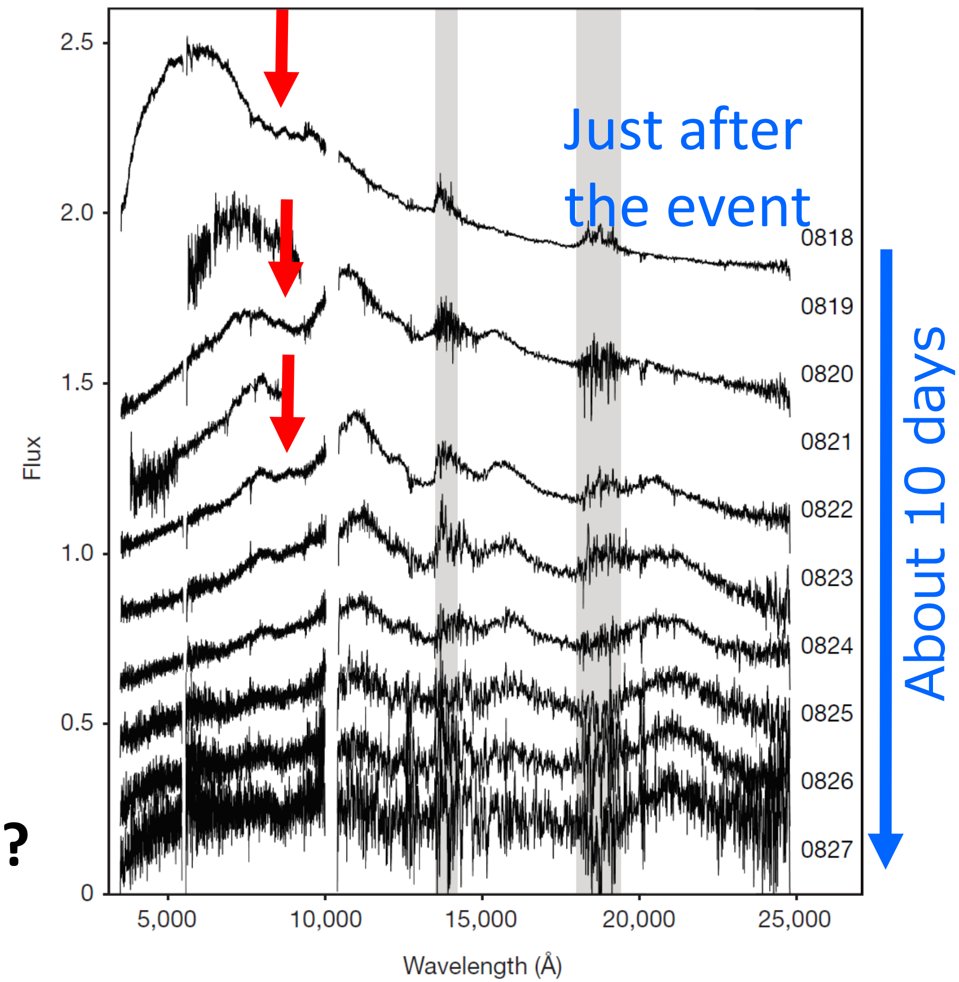


Gravitational wave and matter evolution

The gravitational wave event GW170817



Visual/infrared spectra of the gravitational wave event (merging of neutron stars) →signature of heavy elements?



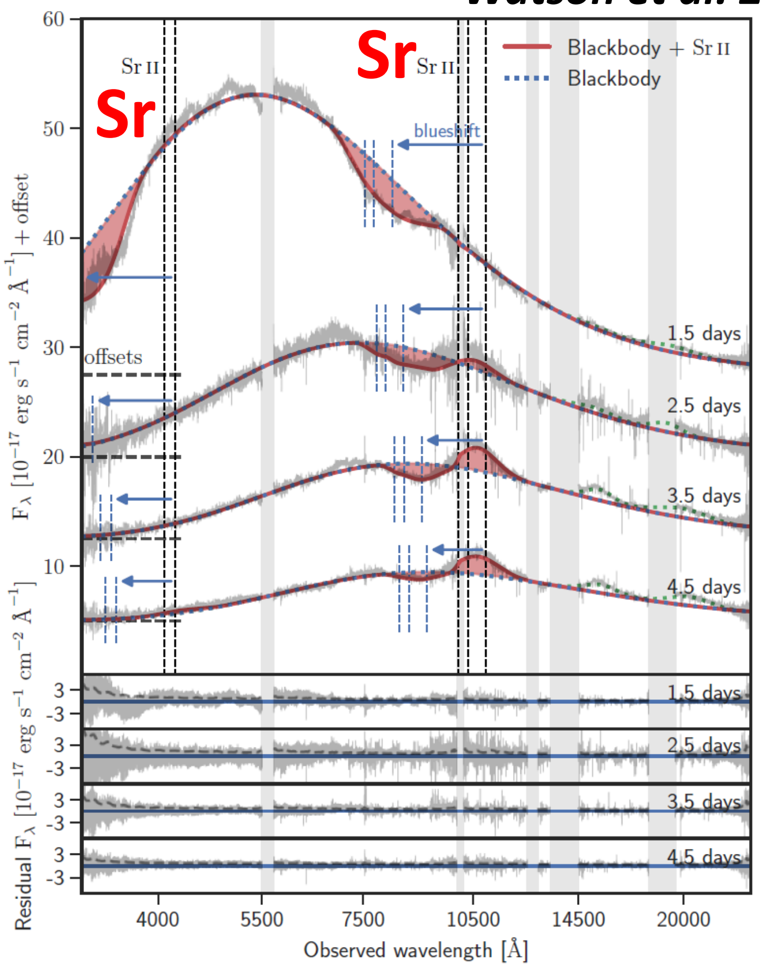
Pian et al. (2017, Nature)

r-process direct observations

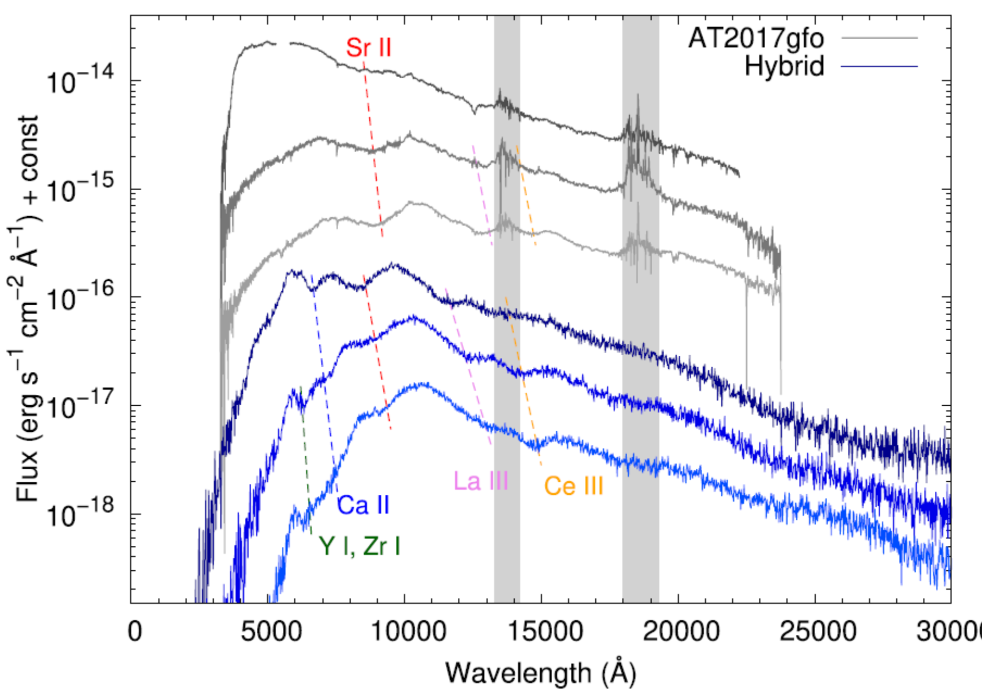
Spectroscopic observation of GW170817

Identification of strontium (Sr), Cerium (Ce) and Lantanum (La) in GW170817 absorption spectra, suggesting large production of light neutron-capture elements

Watson et al. 2019



Domoto et al. 2022

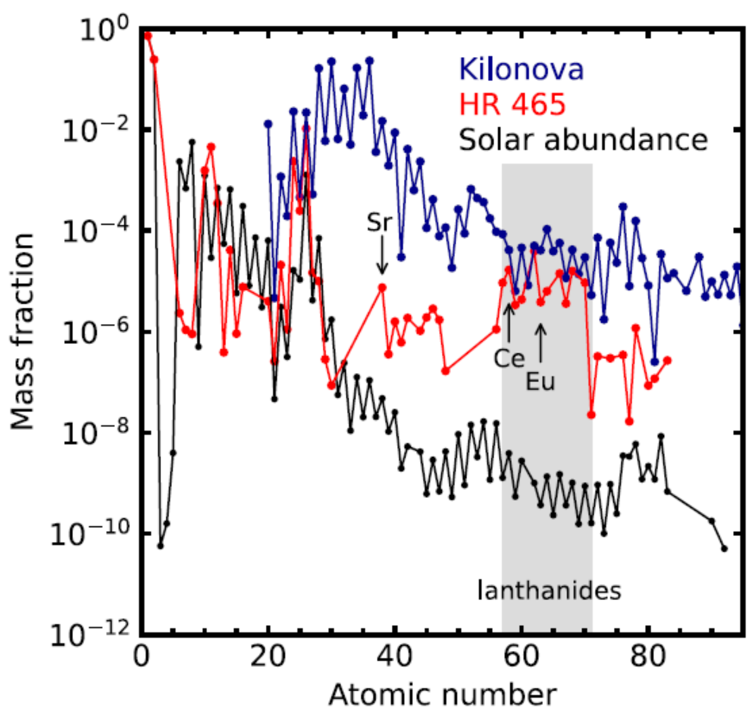


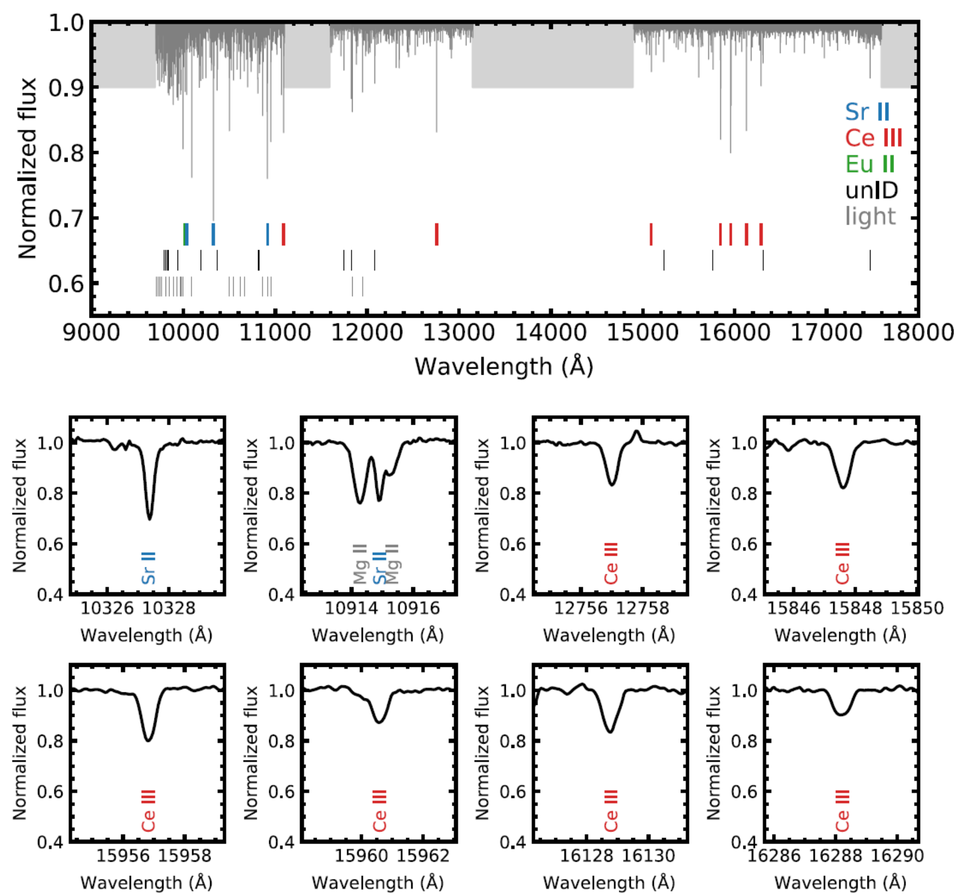
r-process direct observations

Investigation of infrared spectral lines of lanthanides

Spectral lines that contribute to infrared spectral features are searched for using spectra of "chemically peculiar stars" showing large excess of lanthanides.

Tanaka et al. 2022





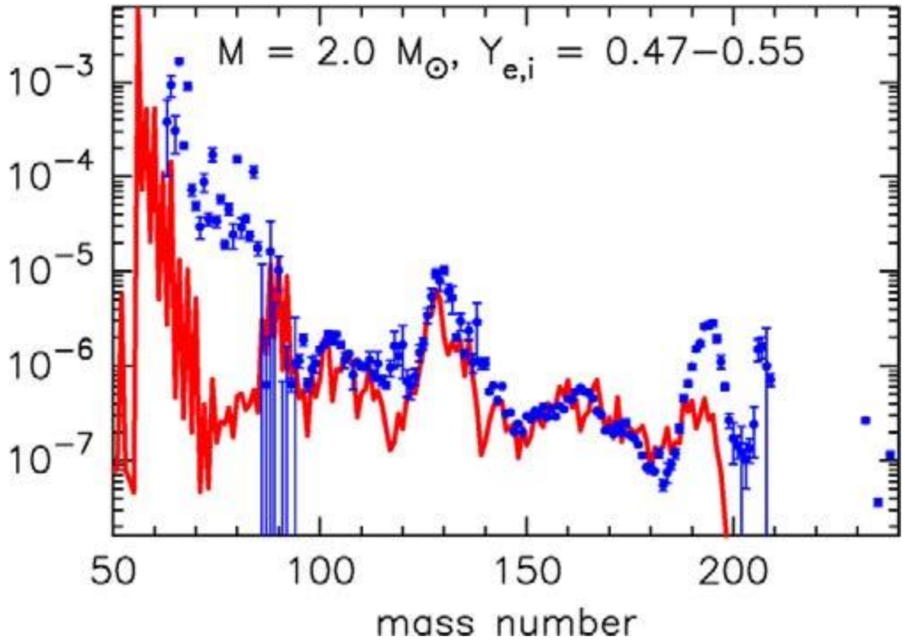
Solar-system r-process component

Solar system
r-process abundance pattern

Solar-system r-process component

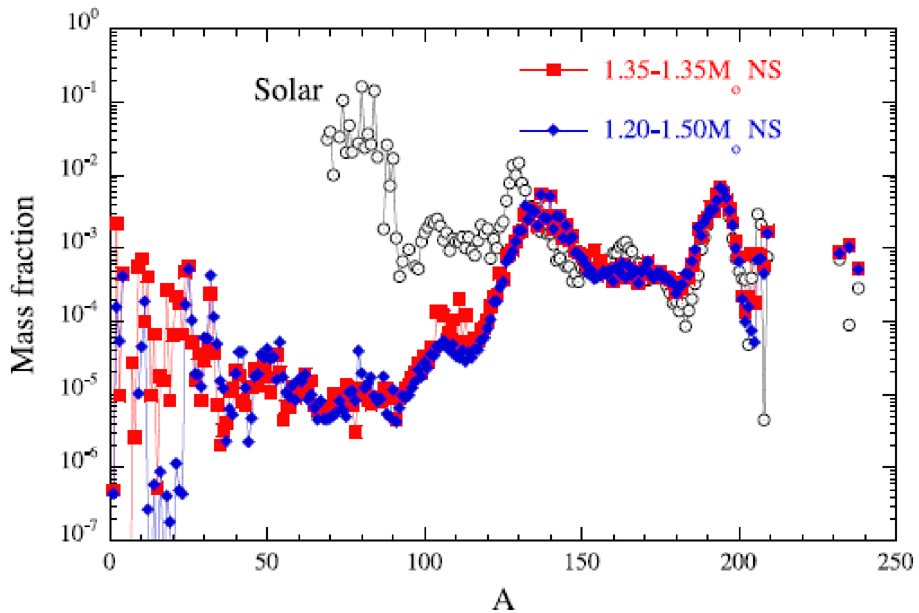
r-process models are compared with the abundance pattern of the r-process component of solar-system material, that is determined by *residual* of solar abundances from which s-process component is subtracted.

Core-collapse supernova



Wanajo & Ishimaru (2006)

Neutron-star merger



Goriely et al. (2011)

Solar abundances

- Determination of abundances by spectral line analysis (as for stars)
  - almost all elements including volatile elements C, N, O, …
  - advantage of solar spectral analysis
    - very high quality spectrum
    - accurate model parameters
    - spatially resolved spectra
- Determination of abundances from meteorites analysis
  - metal abundances
  - advantages
    - very accurate
    - isotope ratios
- Solar wind, corona etc.
  - noble gases He, Ne, Ar, …

Neutron-capture elements

Analysis using the updated atomic line data
→ better agreement with meteoritic results

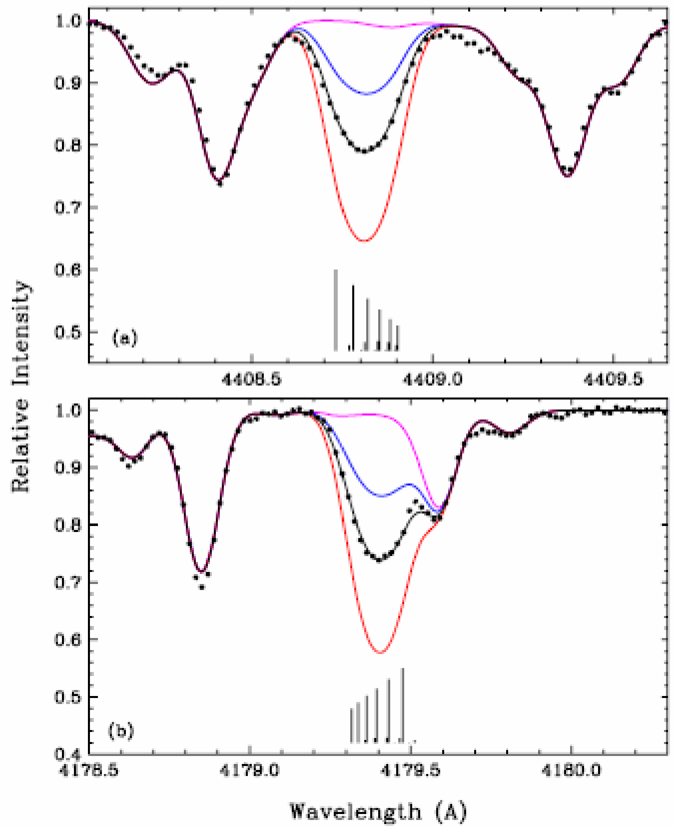


Figure 3. Observed and synthetic spectra in CS 31082−001 of two strong Pr II lines with wide hfs. In each panel, the points represent the observed spectrum. The magenta line is the spectrum computed with no contribution from Pr II; the black line is the best-fitting synthesis (with the Pr abundance given in Table 6); and the red and blue lines are the syntheses computed with Pr abundances altered by ±0.3 dex from the best value. The vertical lines have been drawn at the bottom of each panel to indicate the wavelengths and *relative* strengths (arbitrary overall normalization) of the hyperfine components that comprise the Pr II transitions.

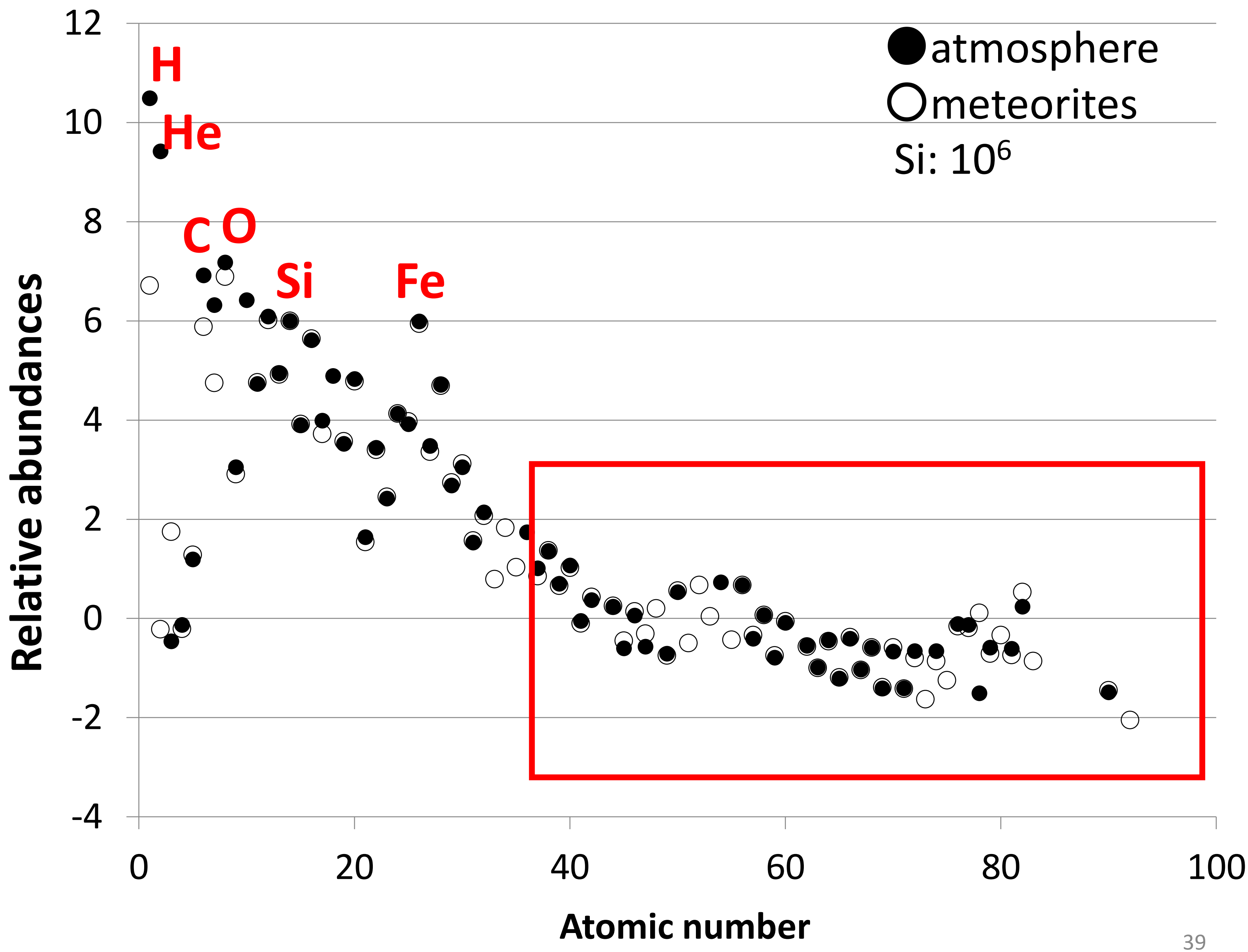
Sneden et al. (2009)

Solar-system r-process component

Recent measurements of transition probability for rare earth elements

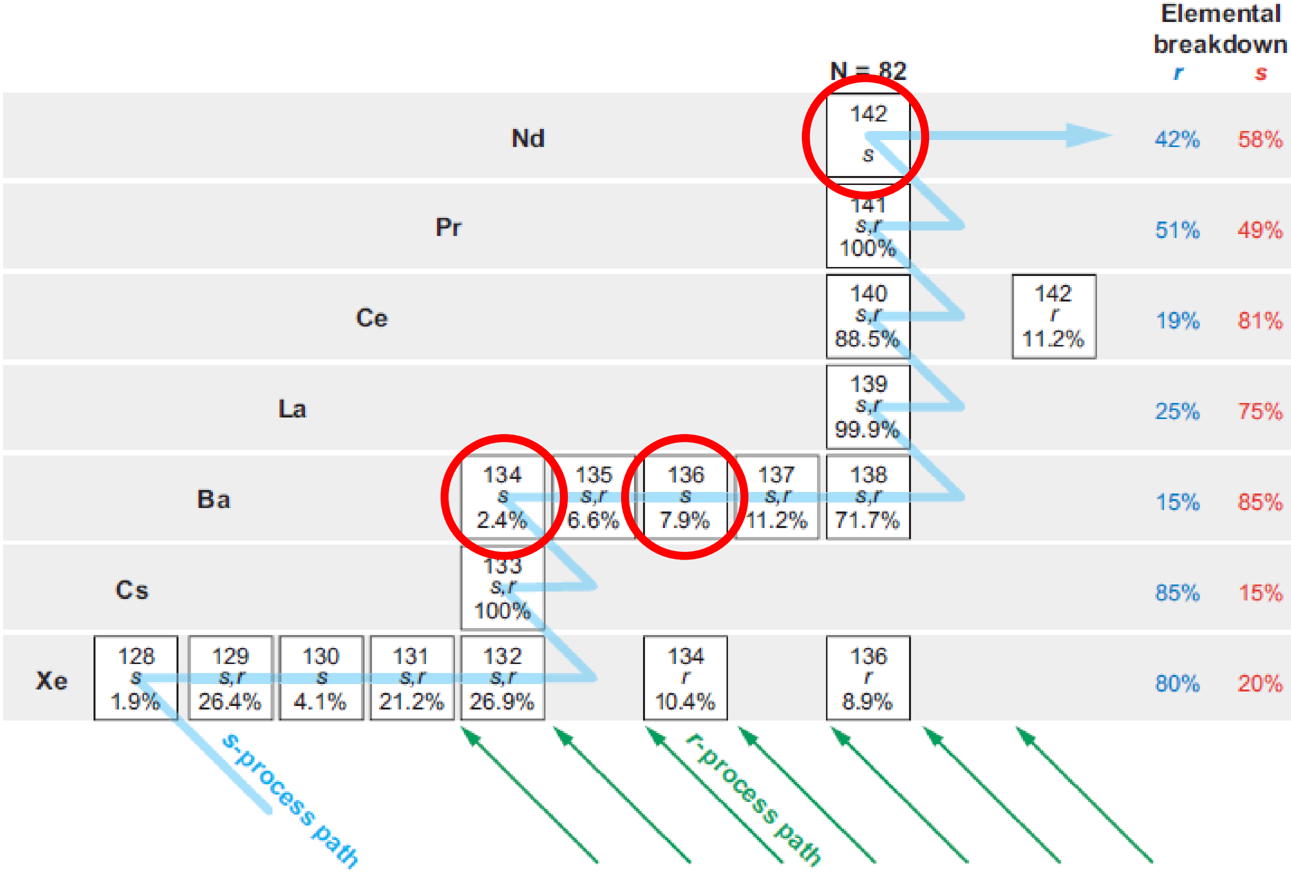
Experiments have been conducted from astronomical interests

La II: Lawler et al. (2000, ApJ, 556, 452)
Eu II: Lawler et al. (2001, ApJ, 563, 1075)
Tb II: Lawler et al. (2000, ApJS, 137, 341)
Nd II: Den Hartog et al. (2003, ApJS, 148, 543)
Ho II: Lawler et al. (2004, ApJ, 604, 850)
Pt I: Den Hartog et al. (2005, ApJ, 619, 639)
Sm II: Lawler et al. (2006, ApJS, 162, 227)
Gd II: Den Hartog et al. (2006, ApJS, 167, 292)
Hf II: Lawler et al. (2007, ApJS, 169, 120)
Er II: Lawler et al. (2008, ApJS, 178, 71)
Ce II: Lawler et al. (2009, ApJS, in press)
Pr II, Dy II, Tm II, Yb II, Lu II: Sneden et al. (2009, ApJS)
....



atmosphere
meteorites
Si: 10^6
H
He
C
O
Si
Fe
Relative abundances
Atomic number
12
10
8
6
4
2
0
-2
-4
0
20
40
60
80
100

Estimate of s-process / r-process components



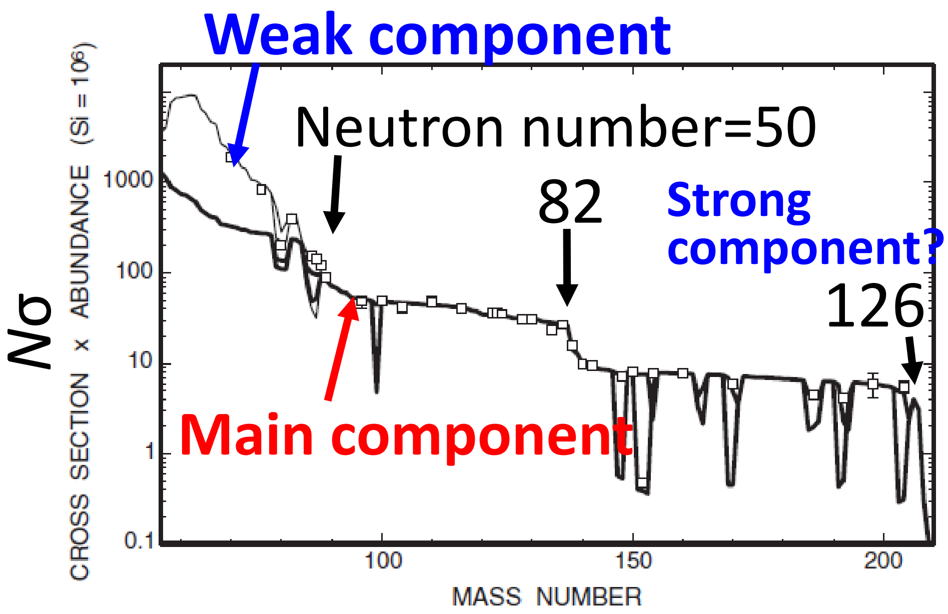
Sneden et al. (2008)

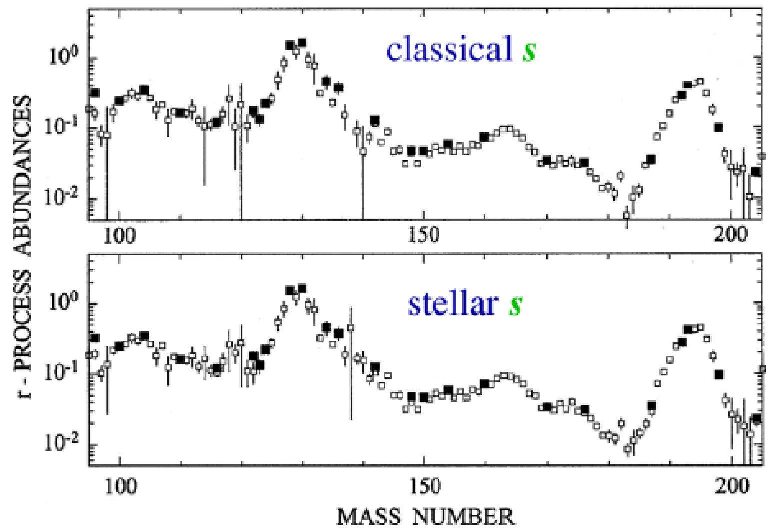
Estimate of s-process / r-process components

Steady flow neutron-capture → $N\sigma$～constant (σ: neutron-capture cross section)

Kaeppeler et al. (2011)

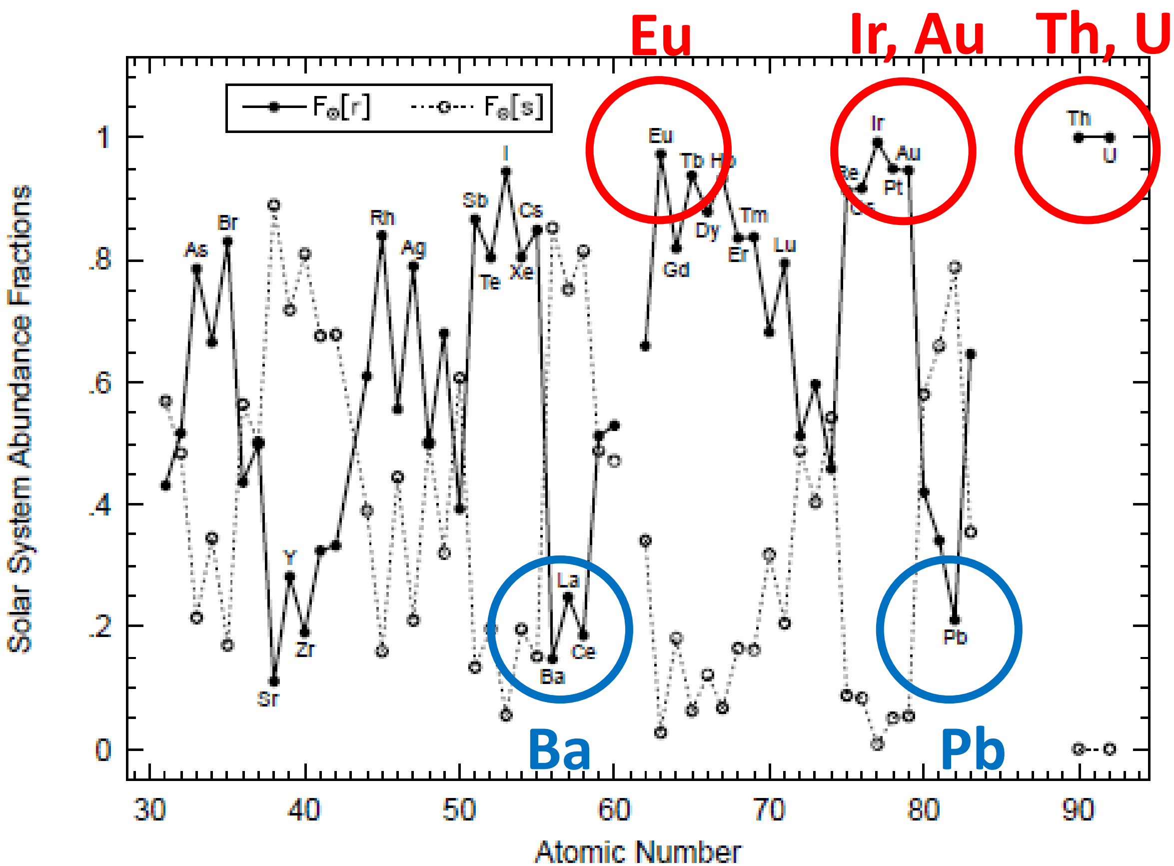
Residual = the r-process component





Analysis of solar abundance: s-process v.s. r-process

Burris et al. (2000)



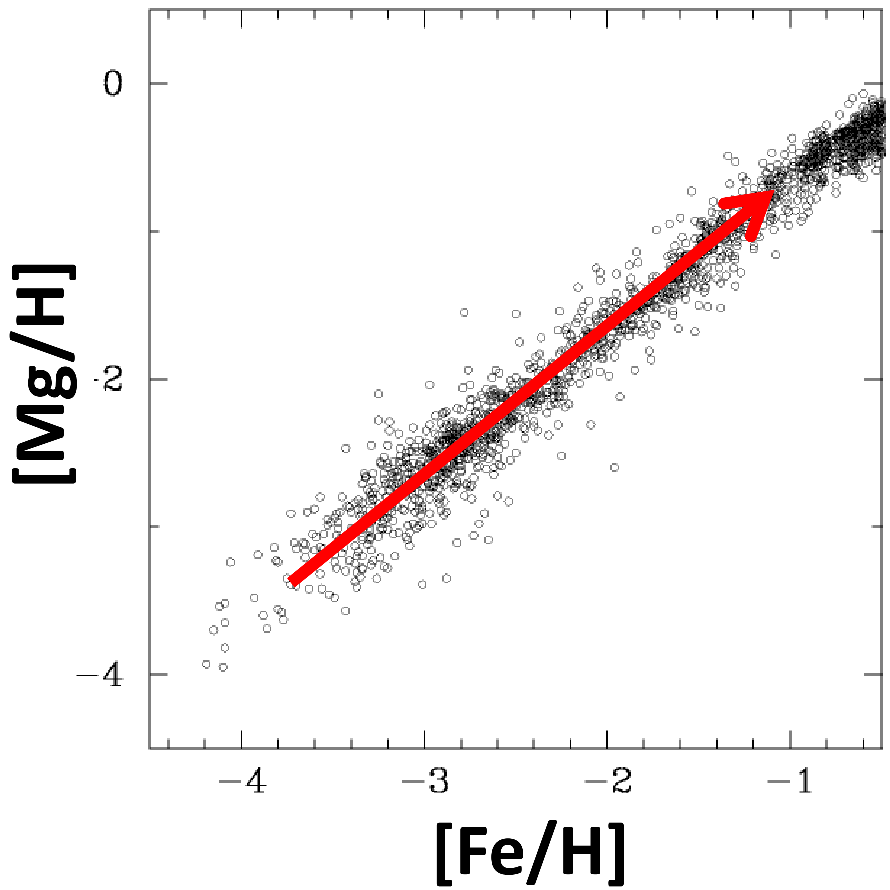
Stellar abundances

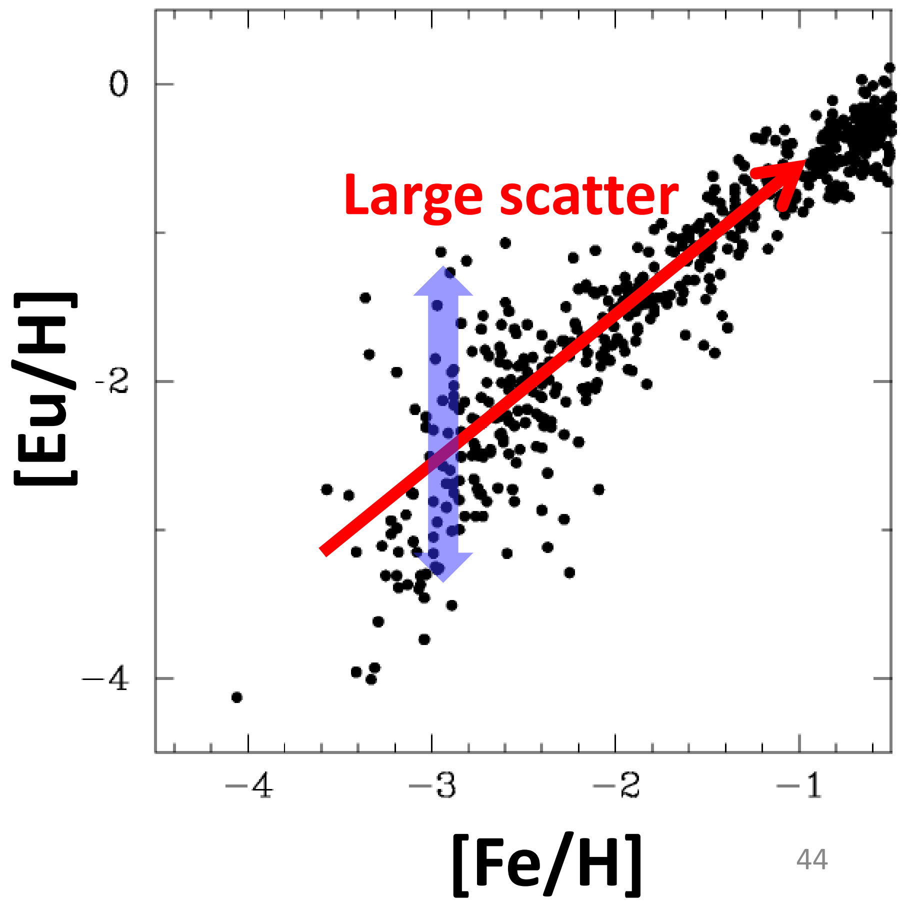
- Individual events recorded in extremely metal-poor starts
- Chemical evolution from large sample

Chemical abundances of metal-poor stars

$$[X/H]=\log_{10}(X/H)-\log_{10}(X/H)_{\odot}$$

SAGA database of metal-poor stars (*Suda et al. 2008, 2017*)

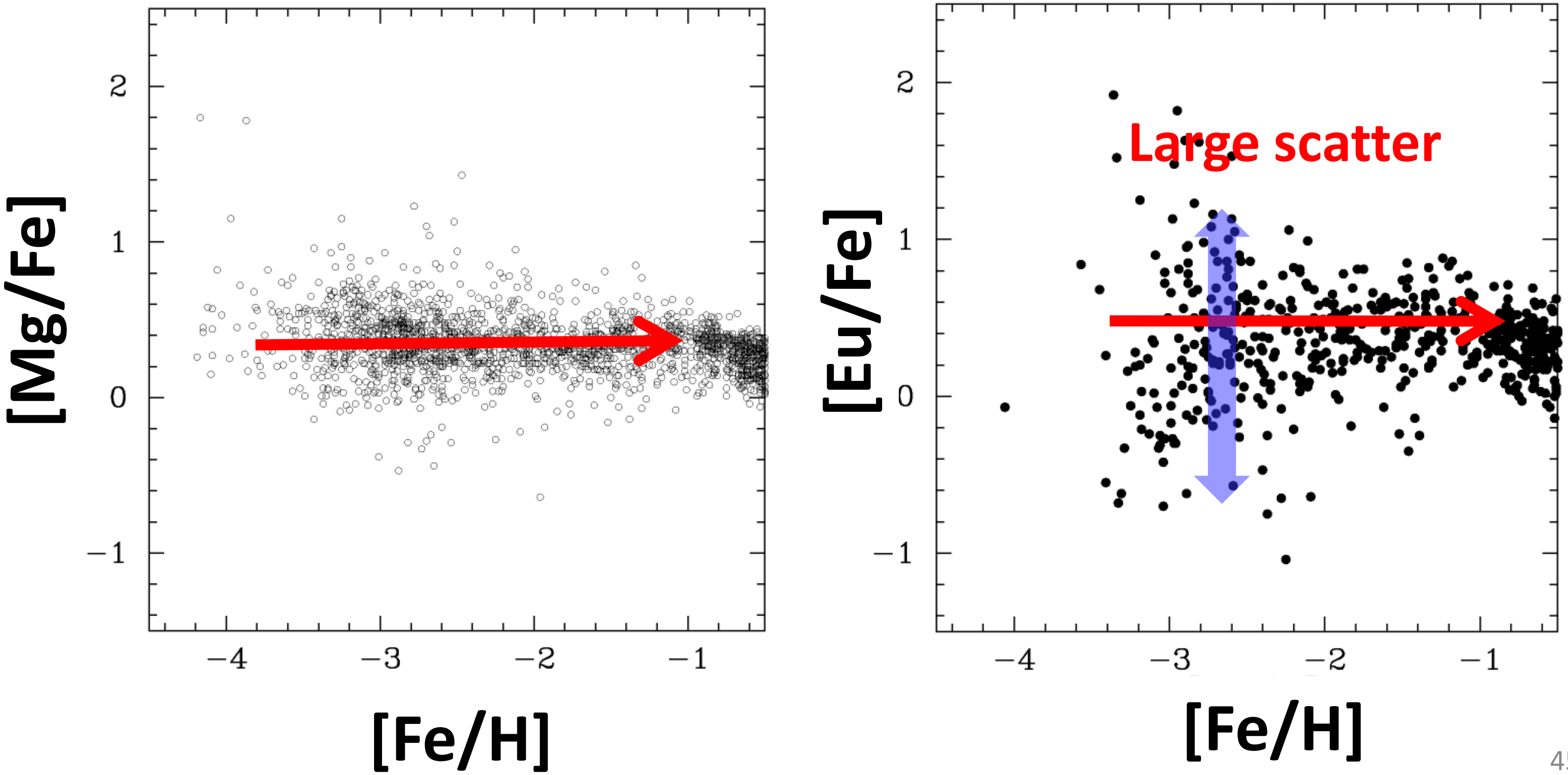




Chemical abundances of metal-poor stars

$[X/Fe]=\log_{10}(X/Fe)-\log_{10}(X/Fe)_{\odot}$

SAGA database of metal-poor stars (*Suda et al. 2008, 2017*)



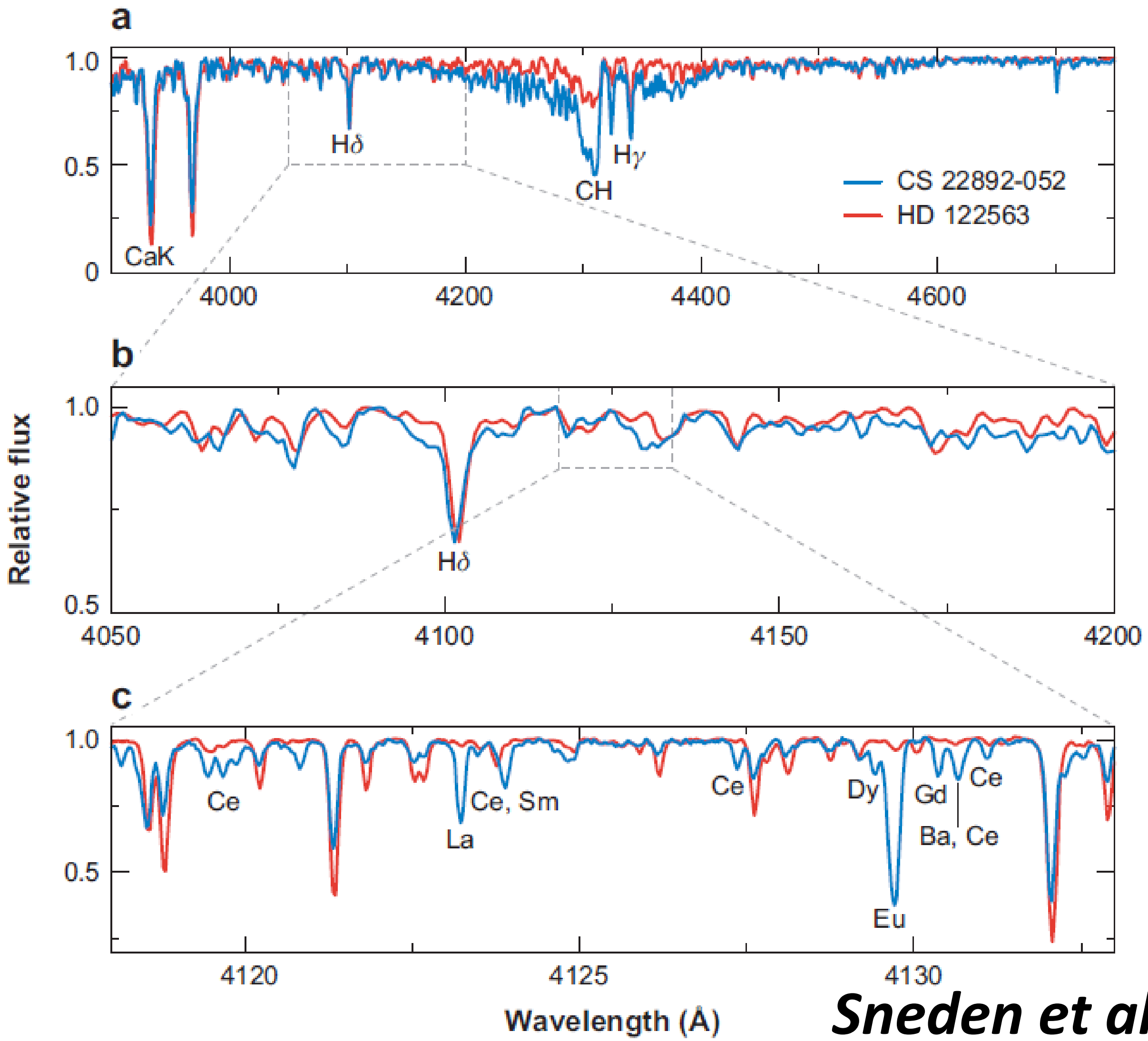
Indication of large scatter in [Eu/Fe]

- r-process (producing Eu) is (almost) **independent of the process yielding Fe** (i.e. supernovae general).
- r-process is associated with **rare events** compared with supernovae general.

Eu-rich (r-process-rich) metal-poor stars are ideal targets to study details of the r-process.

Stellar abundances of r-process elements

“r-process-enhanced star”

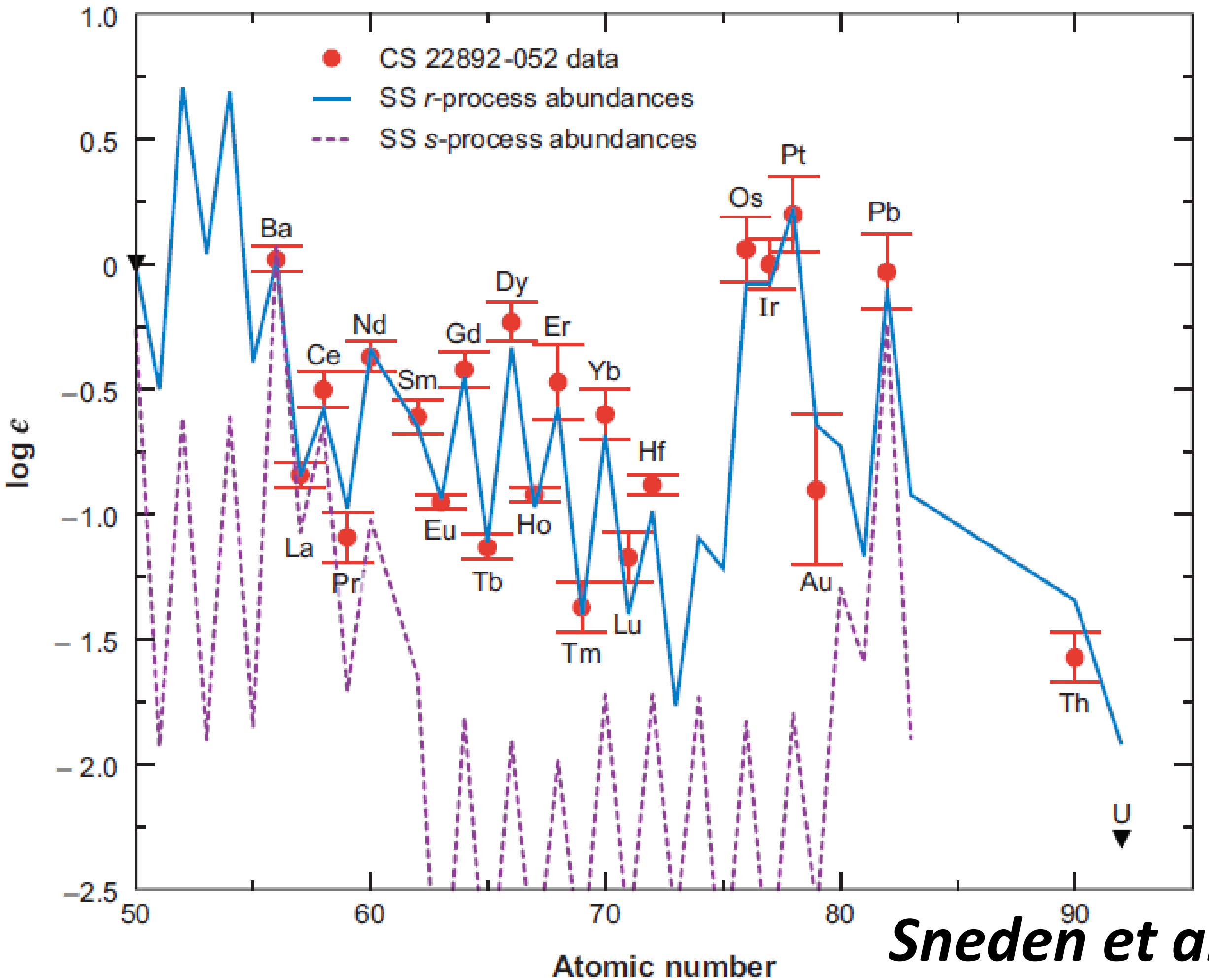


Sneden et al. (2008)

Stellar abundances of r-process elements

"r-process-enhanced" very metal-poor stars

- •Records of (single) r-process event in the early Galaxy
- •Similar to the solar-system r-process abundance pattern



Sneden et al. (2008)

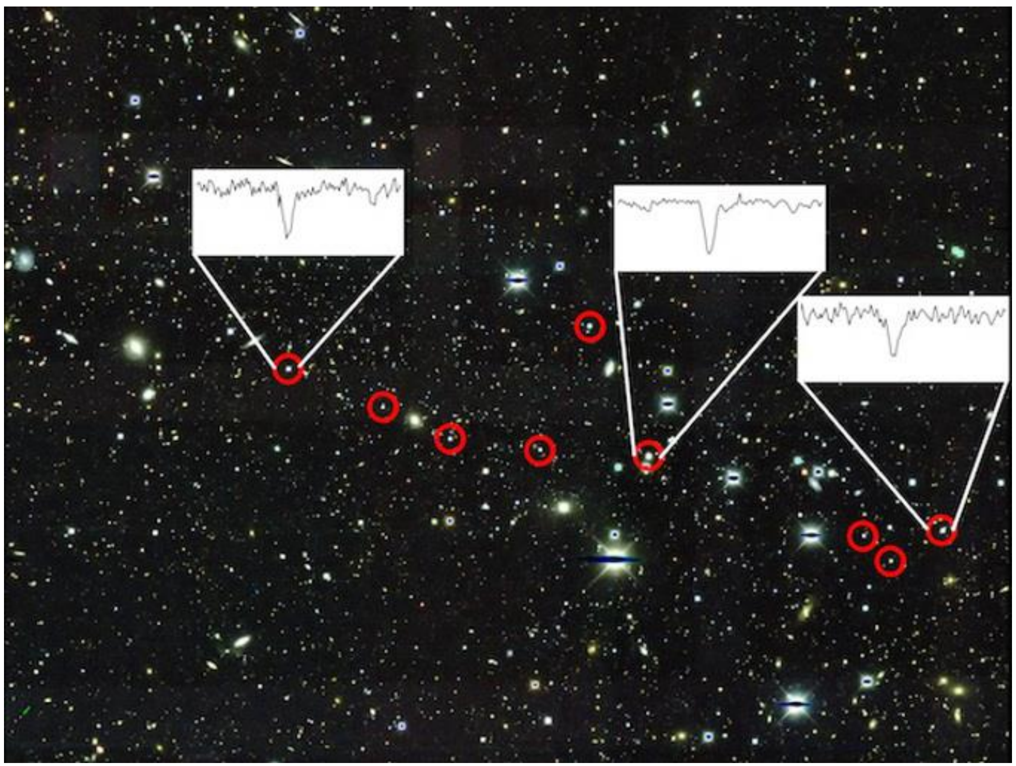
Stellar abundances of r-process elements

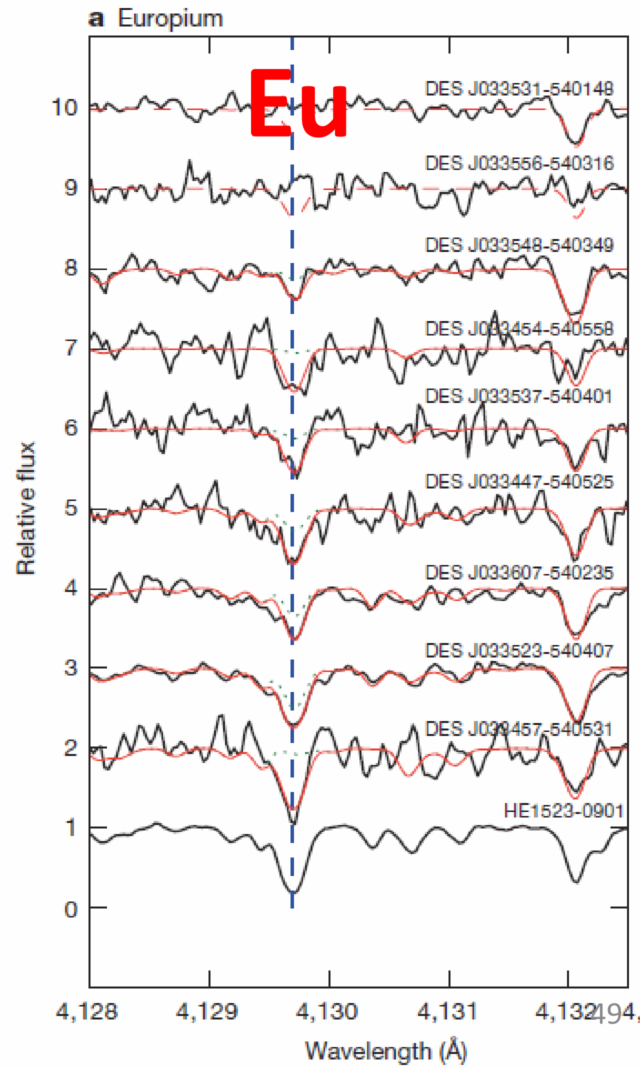
Discovery of an r-process-enhanced dwarf galaxy Reticulum II

Ji et al. (2016)

Roederer et al. (2016)

Ji et al. (2016)



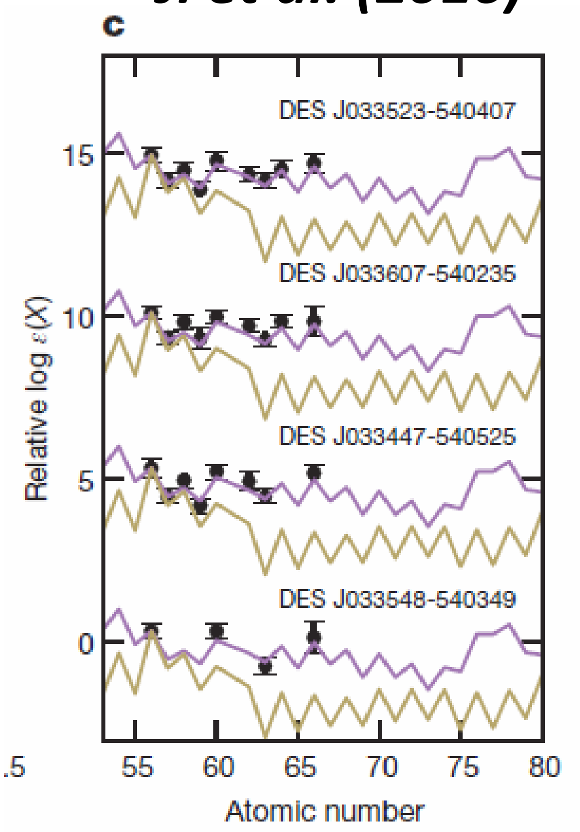


Stellar abundances of r-process elements

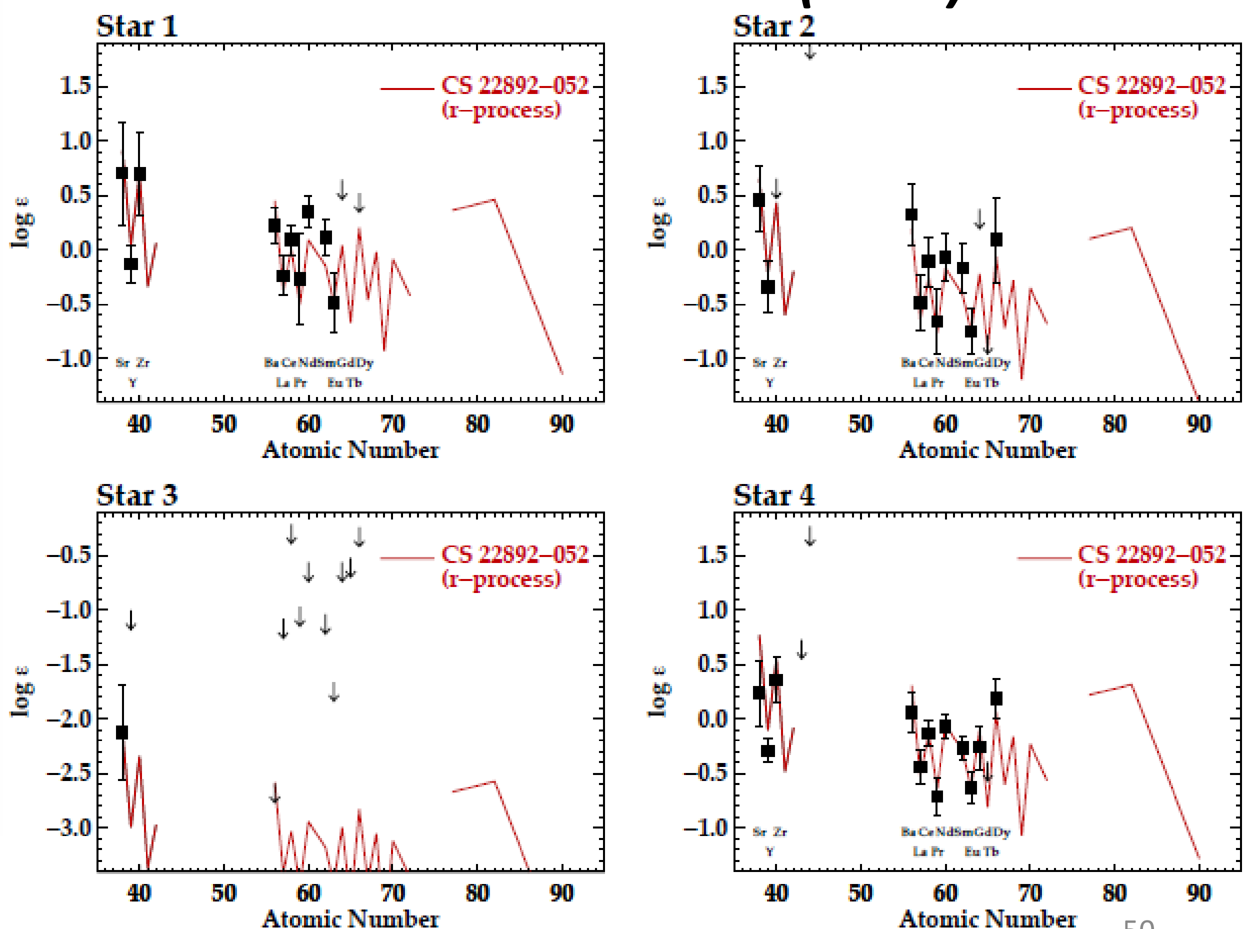
r-process-enhanced stars in the ultra-faint dwarf galaxy Reticulum II

Heavy elements trace the solar-system r-process abundance pattern

Ji et al. (2016)



Roederer et al. (2016)



The Milky Way Galaxy has been formed from small stellar systems (mergers of mini-halos).

Observations. 2. Lithium and r-process Summary

Li in the cosmos

- **Li is produced through many processes (e.g., Big Bang, high energy particle, nova and supernova explosions), and useful to examine chemical evolution models.**
- **Li production in nova explosions is observationally established, indicating novae are major source of Li in the current Galaxy.**

r-process

- **Production of heavy elements by r-process in mergers of binary neutron stars is suggested by direct observations of a kilonova.**
- **r-process yields are recorded in r-process-enhanced metal-poor stars in the Galaxy. Such stars could be formed in dwarf galaxies affected by a (single) r-process events, and later accreted into the Galaxy.**

Question and comments are welcome:

aoki.wako@nao.ac.jp