Experiments related to i and r process nucleosynthesis

-> the role of neutron-capture cross sections

O. Sorlin (GANIL, France)

I. r abundances in the solar system
II. r process in extremely meta-poor stars (EMP)
III. Evidences of neutron-capture processes in meteorites / grains

I. (d,p) reactions as a surrogate for (n,γ) around closed shells
II. Oslo method to constrain level density and gamma strengths
III. A neutron - RIB collider to measure direct neutron-capture rates

With materials from V. Hill, A-C. Larsen, M. Pignatari, R. Reifarth and M. Spite

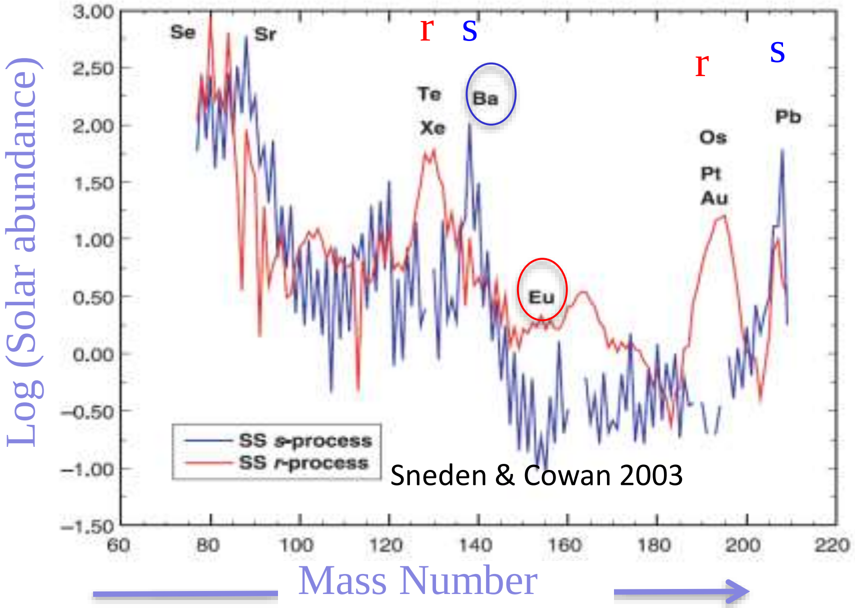
EURISOL DF Nov 15th

Elemental breakdown in r and s components

In the solar system:

Eu is a pure r element

Ba is mainly an s element



Sneden & Cowan 2003

Solar system abundance curve of heavy elements likely results from a mixture of different neutron-capture processes

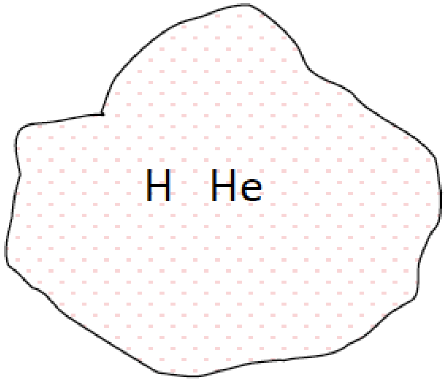
r process curve is obtained after subtraction of s process abundances deduced from measured neutron-capture cross sections

To compare calculated r process abundances with observations, one needs to ensure that observations do not come from several contributions

-> find stars in which abundances come from a ‘single’ process....

Enrichment in elements over time ?

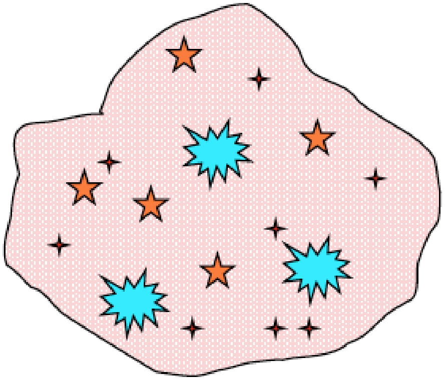
> Galactic chemical evolution



Formation of the Galaxy (primordial material)

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

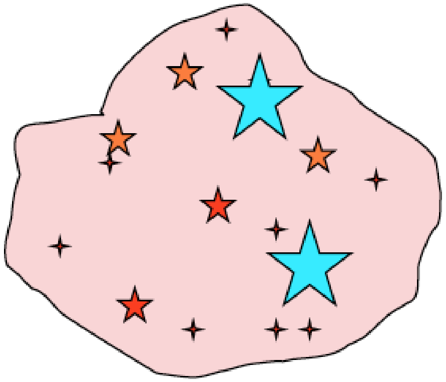
($[Fe/H] = -3$:
1000 times less Fe than sun)



stars are formed, they explode, and enrich the matter with their products (**stellar winds, supernovae**)

↓

A lot of Fe, possibly heavy elements as well



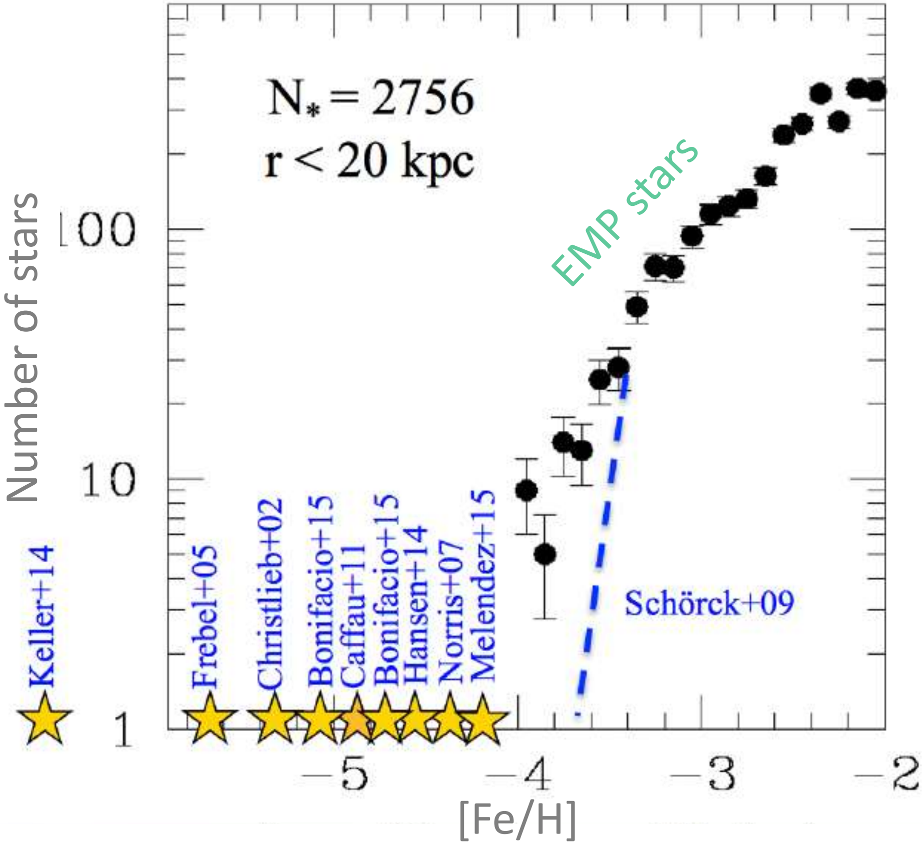
New stars are formed, explode, little by little the matter becomes richer in elements formed inside the stars...

Fe content is a good tracer of the enrichment of stars from earlier exploded ones

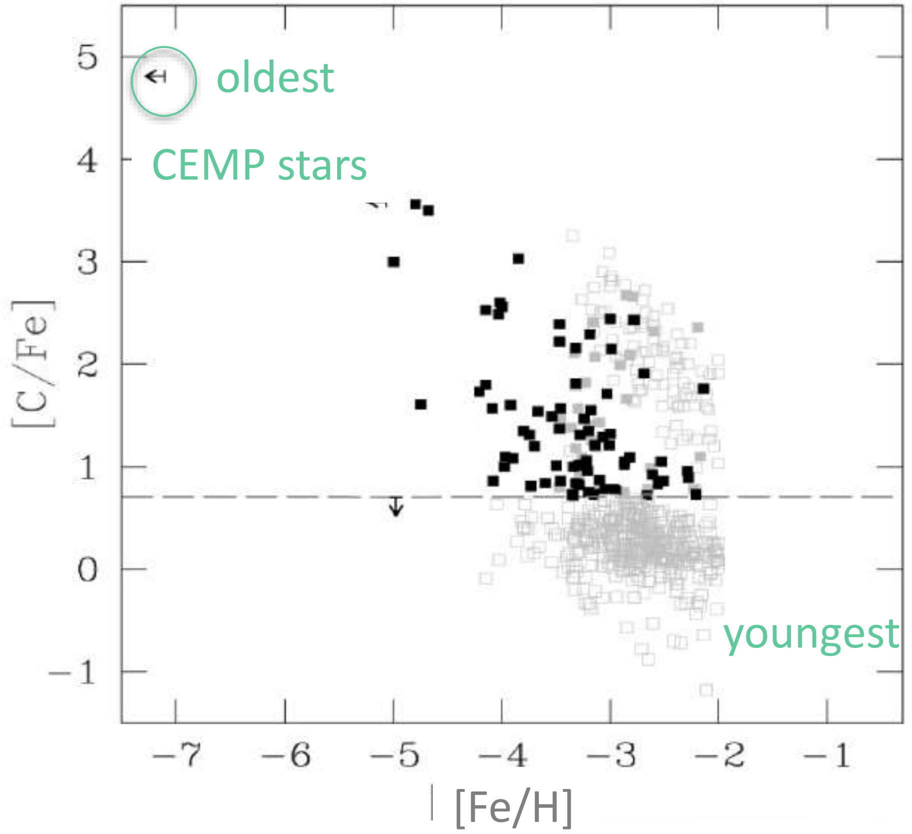
Extremely Metal-Poor stars reveal the content of early, fewly mixed, nucleosynthesis

Observations in the Galaxy

Metallicity Distribution Function



Carbon-Enhanced Metal-Poor stars

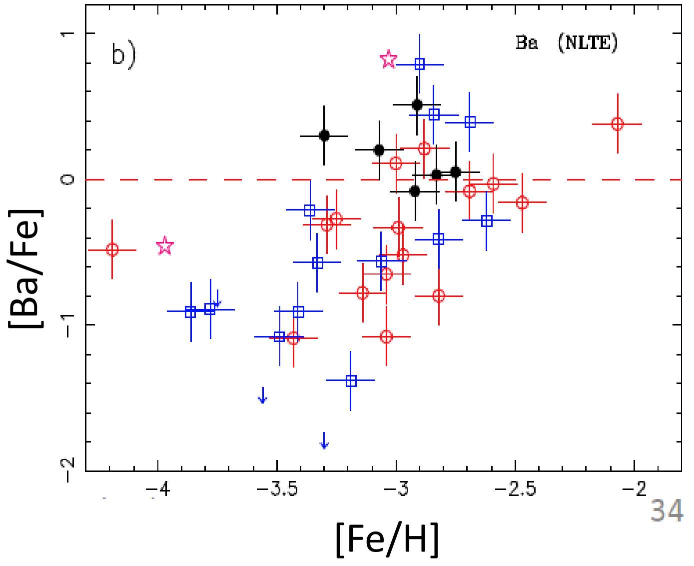


Metallicity distribution show a sharp decline and then a drop at [Fe/H]<-4

Most of the stars with [Fe/H]<-4 are C rich -> CEMP stars

Heavy neutron capture elements in metal-poor stars

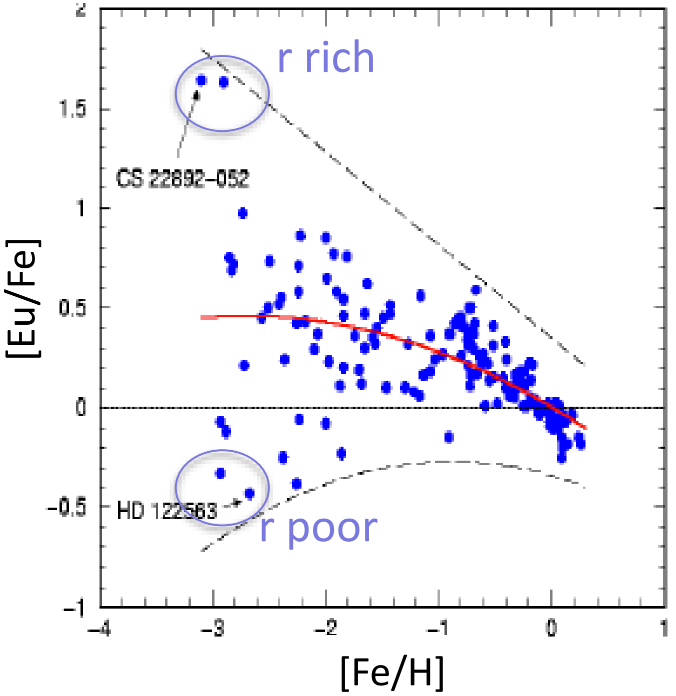
Ba abundance increase with [Fe/H]
-> Need Fe to increase in abundance
-> confirmed to be of secondary process



A large scatter of [Eu/Fe] ratio is observed:
r rich and r poor.

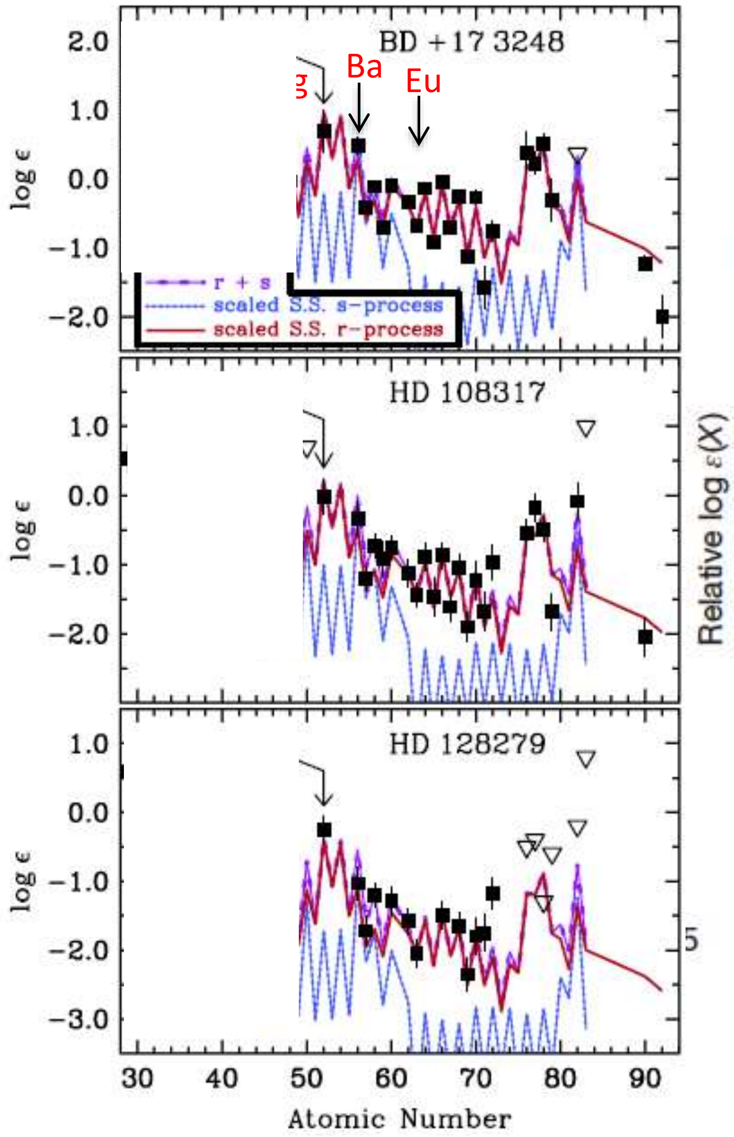
This suggests that the r process can be very well produced in few first generations of stars.

It is however a rare process, otherwise no such scatter in abundance

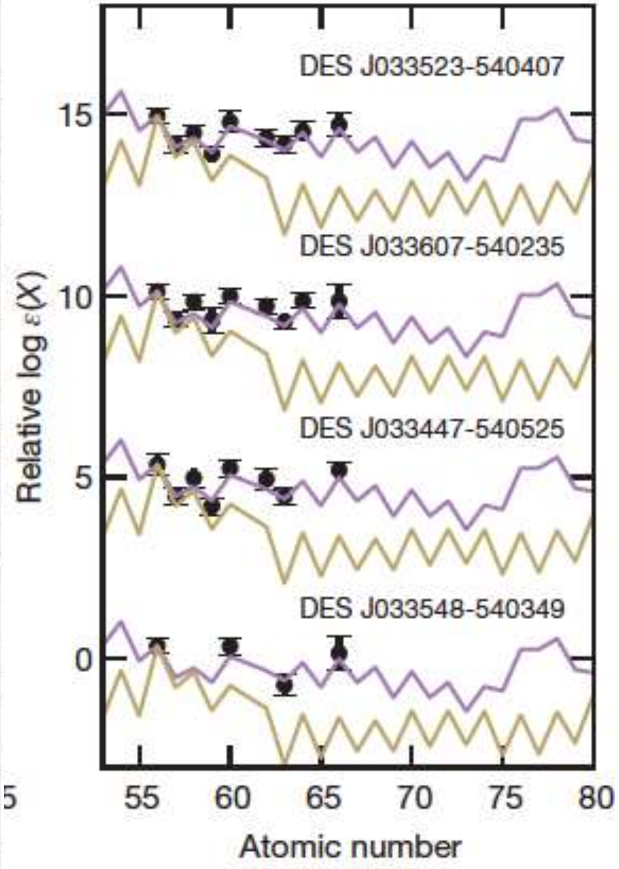


A universal r process ?

Galactic halo Roederer 2012 Hubble



Ret II : Ji et al. Nature 2016



Above Z≈52

Very robust pattern

Top & bottom galactic halo

Globular cluster stars

Dwarf galaxy Ret II

Below Z=52

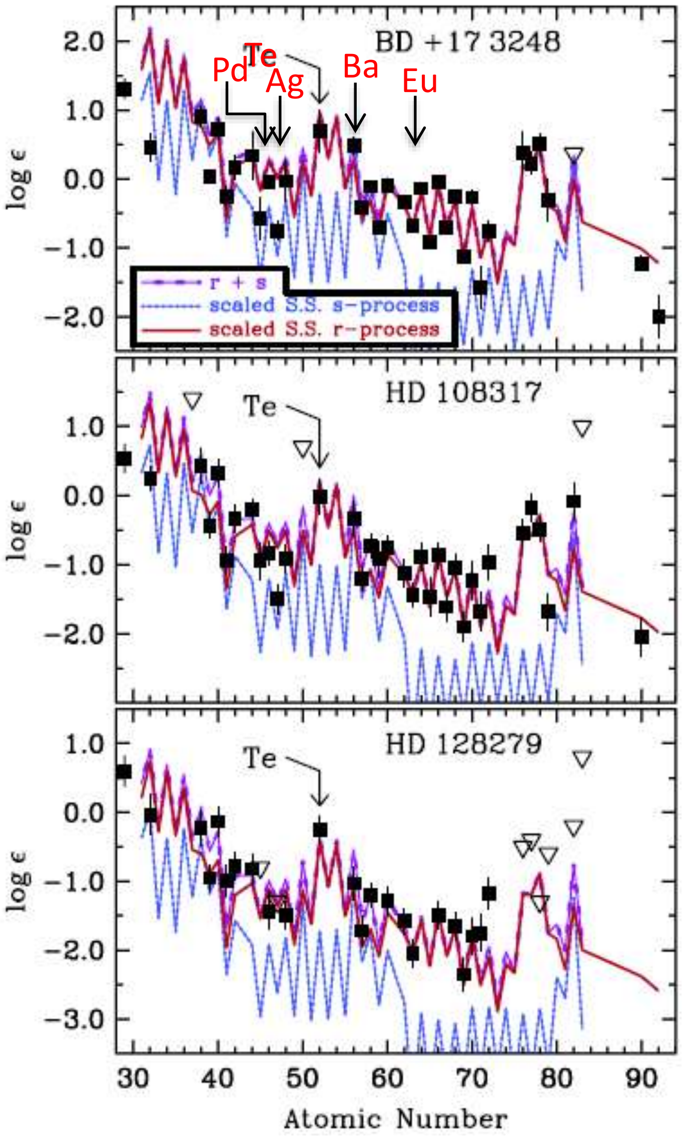
Less robust pattern

Another (weak) process

Two categories of r process elements: light and heavy elements

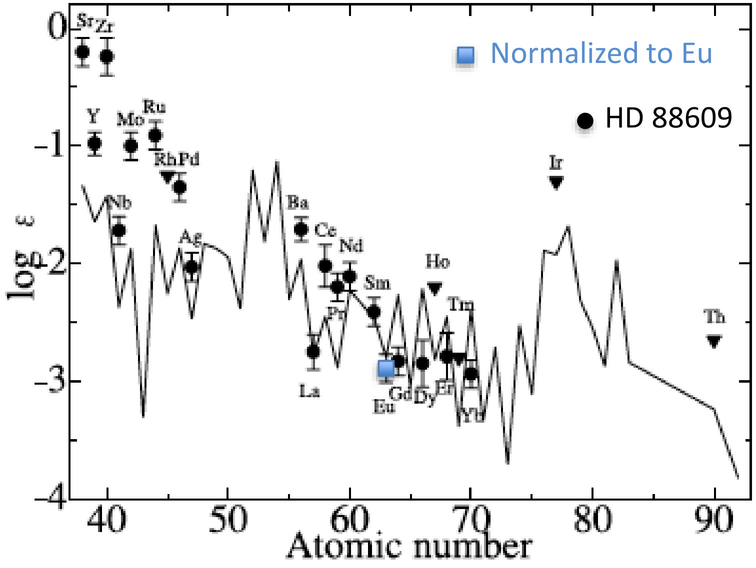
Existence of a low element primary process (LEPP)

Roederer 2012 Hubble



Eu-rich EMP stars display the same solar-like pattern for Z>50 -> main r process

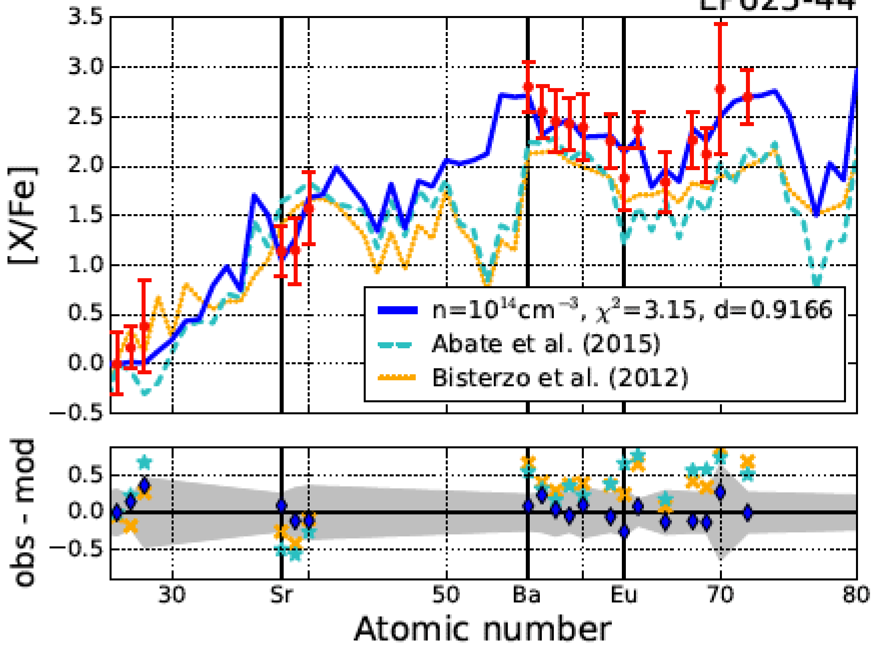
(Honda et al., ApJ 666 (2007))



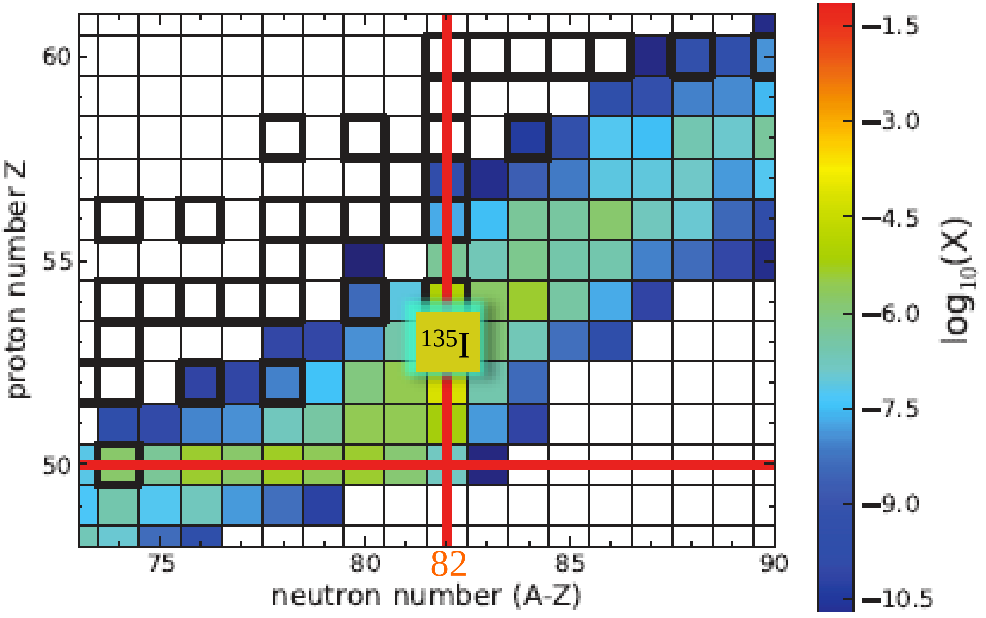
Other EMP stars display enrichments in low-mass elements -> weak r process

Carbon-enhanced metal-poor stars: an intermediate i-process

One of the 20 CEMP stars



i-process progenitors



Several CEMP stars of the galactic halo display enrichments associated with both s and r process (e.g. Ba and Eu, resp). This is puzzling as s and r process differ by 10 orders of magnitude in neutron densities and occur in very different sites.
(e.g. Roederer et al. ApJ. 2016, Denissenkov et al. Ap.J. L 2017 Mishenina et al. MNRAS 2015).

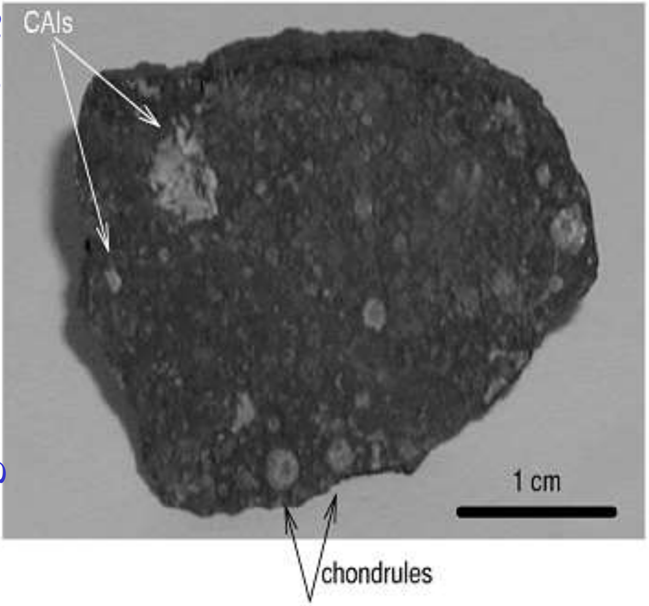
An intermediate process (10^{15} cm^{-3}), found in explosive He shells, could account for these observations. (e.g. Bertolli 2013, Pignatari 2016, Hampel 2017).

-> Neutron capture rates on unstable nuclei relatively close to stability are needed.

Information from stardusts collected on earth

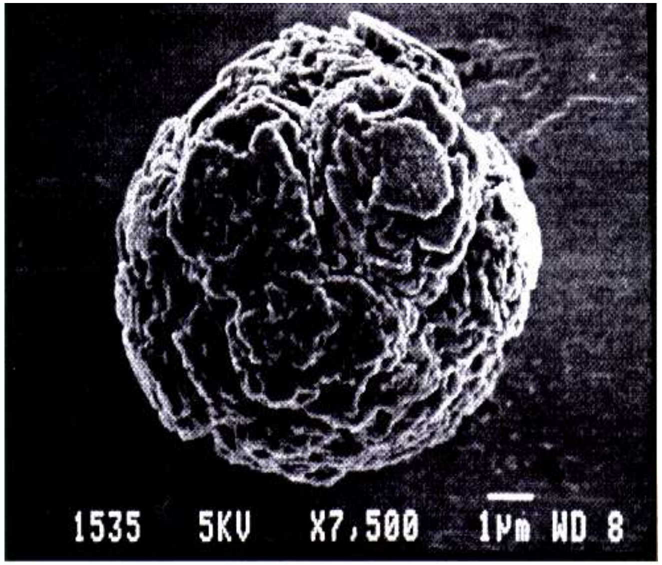
Ejected material from a precusor star
Travel throughout the galaxy, embedded in host material
Incorporated into the solar system
Collected on earth
Expected to keep fingerprints of of their formation site

CaAl-rich inclusions:
High T condensates
First solids formed into solar system
Moderate isotopic anomalies/solar
Embedded in a host solid rock



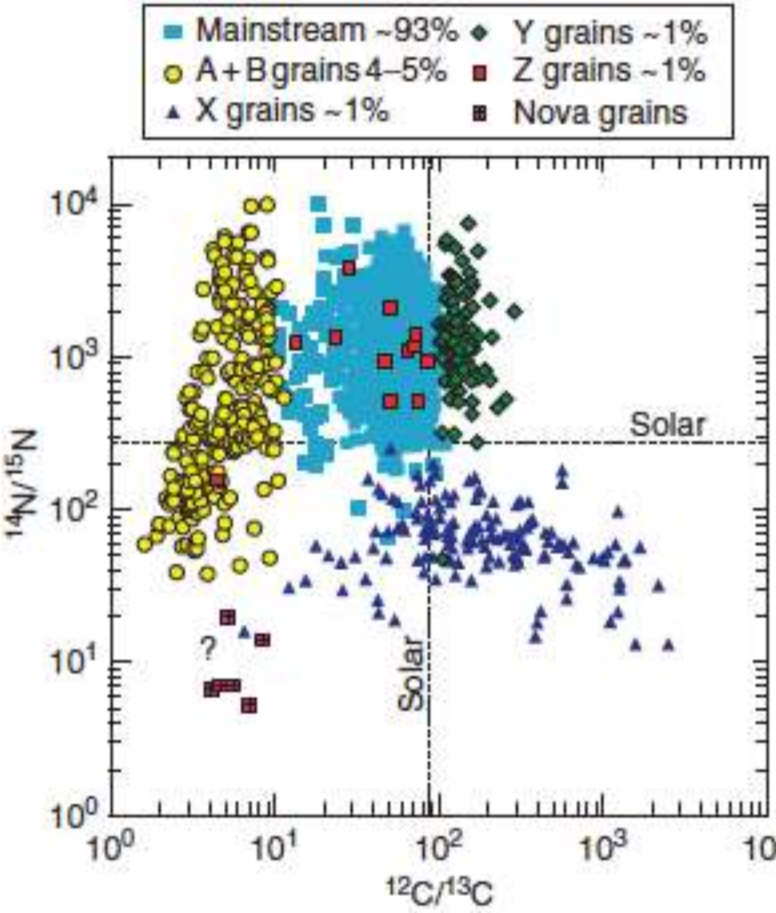
Fragment Allende meteorite

Si-C grains presolar grains:
Formed prior to the solar nebular
Huge isotopic anomalies/solar
Formed in supernovae (extinct ^{26}Al, ^{44}Ti)



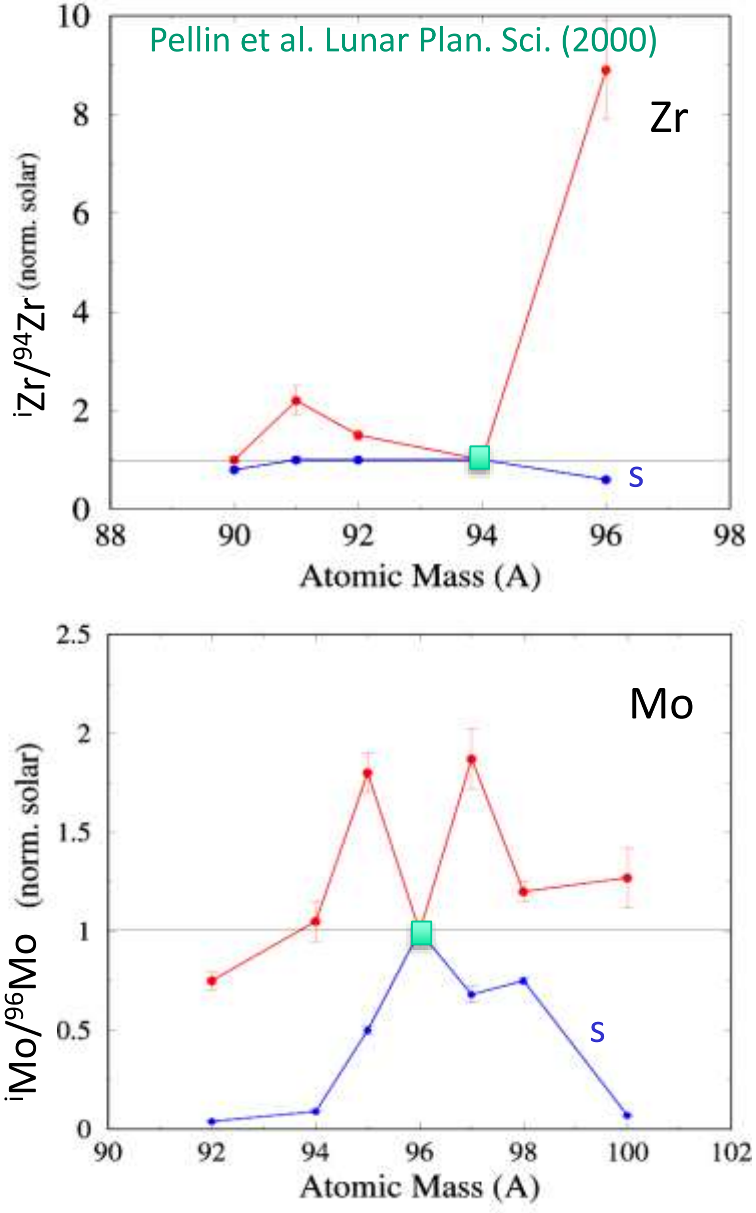
SiC- type X

Categories of Si-C grains



Zinner, Treatise on chemistry 2007

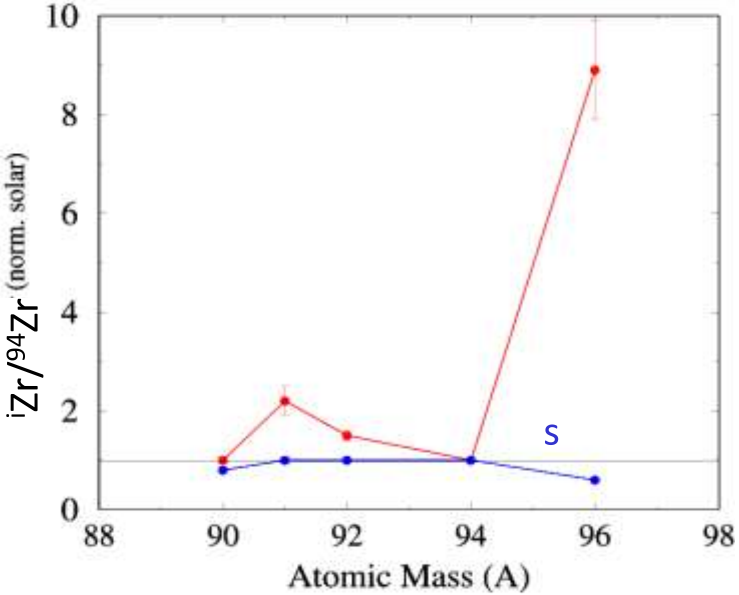
X grains

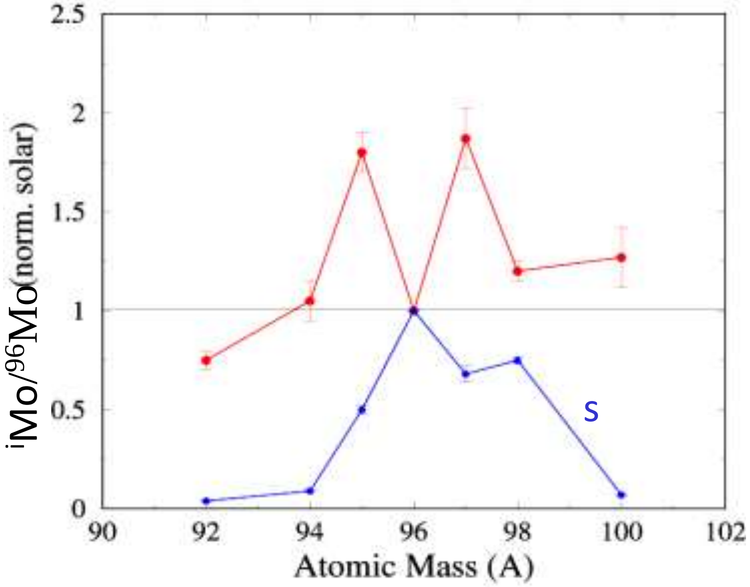

Pellin et al. Lunar Plan. Sci. (2000)

Isotopic compositions of mainstream grains differ significantly from solar ones (depleted in p and r) -> their origin is clearly extra solar. Their isotopic composition is typical of an s process.

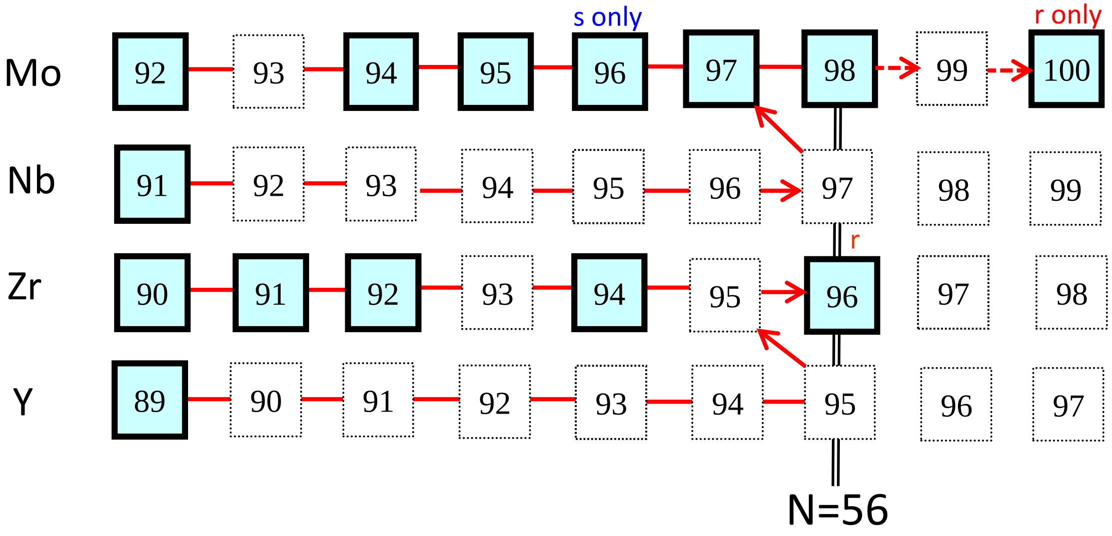
X grains likely come from supernovae explosions

Mo, Zr anomalies in Si-C presolar type x grains





Abundance patterns in Zr and Mo are intermediate between s and r: Pellin et al. Lunar Plan. Sci. (2000)



Neutron burst $10^{17}cm^{-3}$

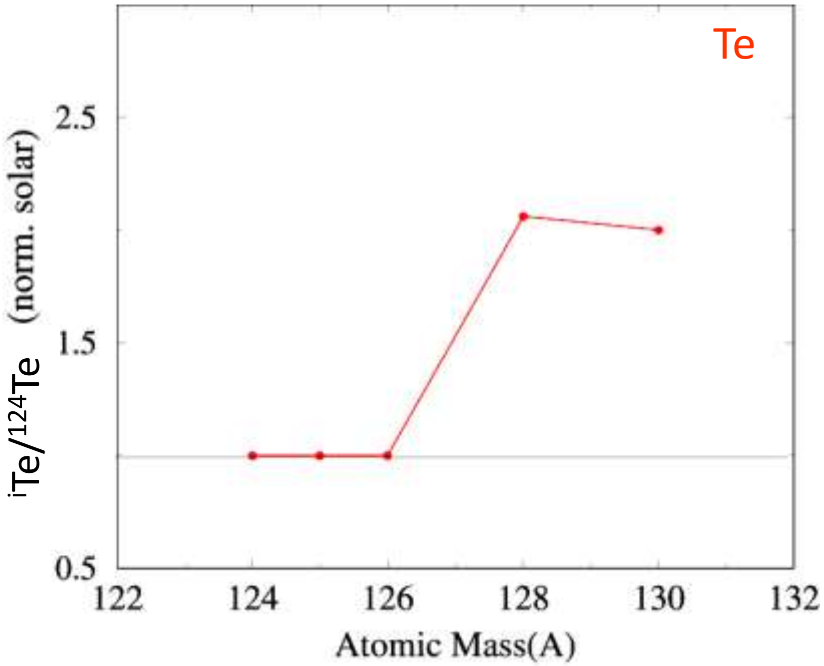
B. Meyer et al. Ap.J. L 540 (2000)

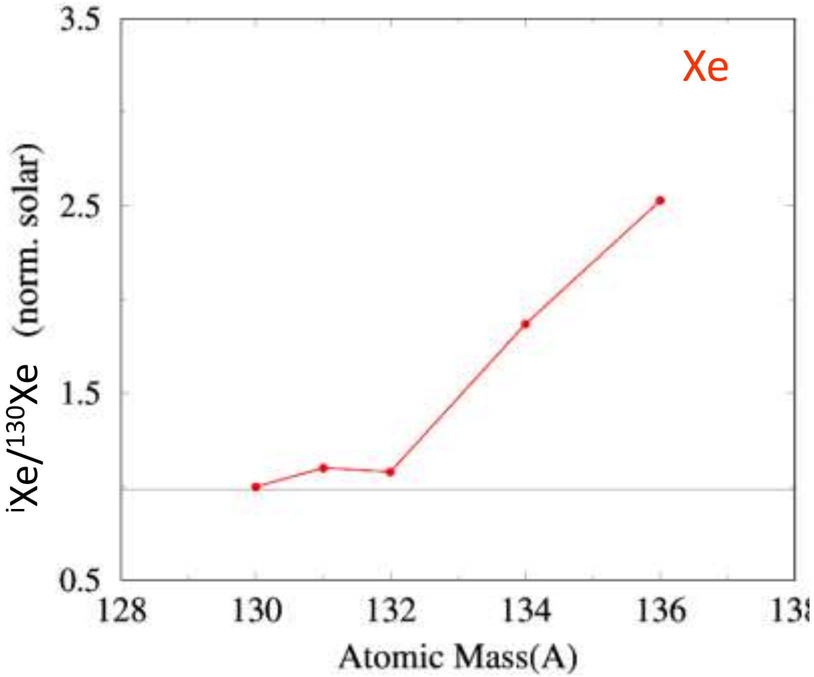
-> i process ?

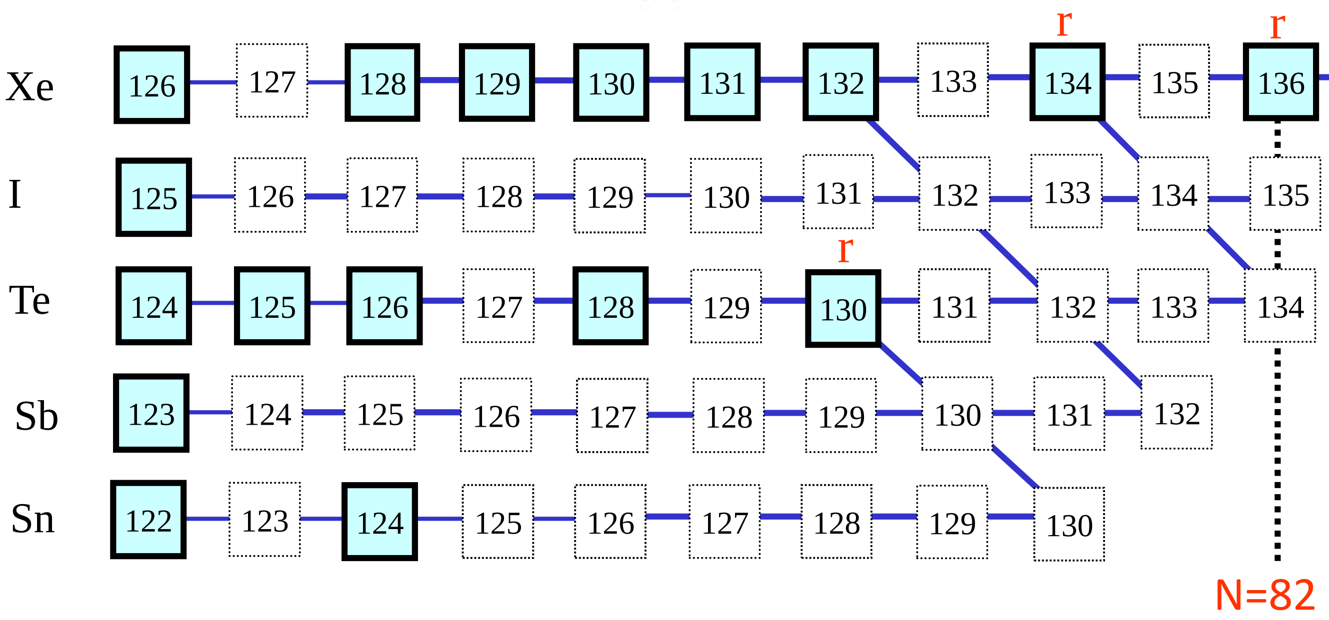
-> signature of N=56 subshell closure ?

-> Determine Nb, Y neutron captures

Te, Xe anomalies in diamond grains







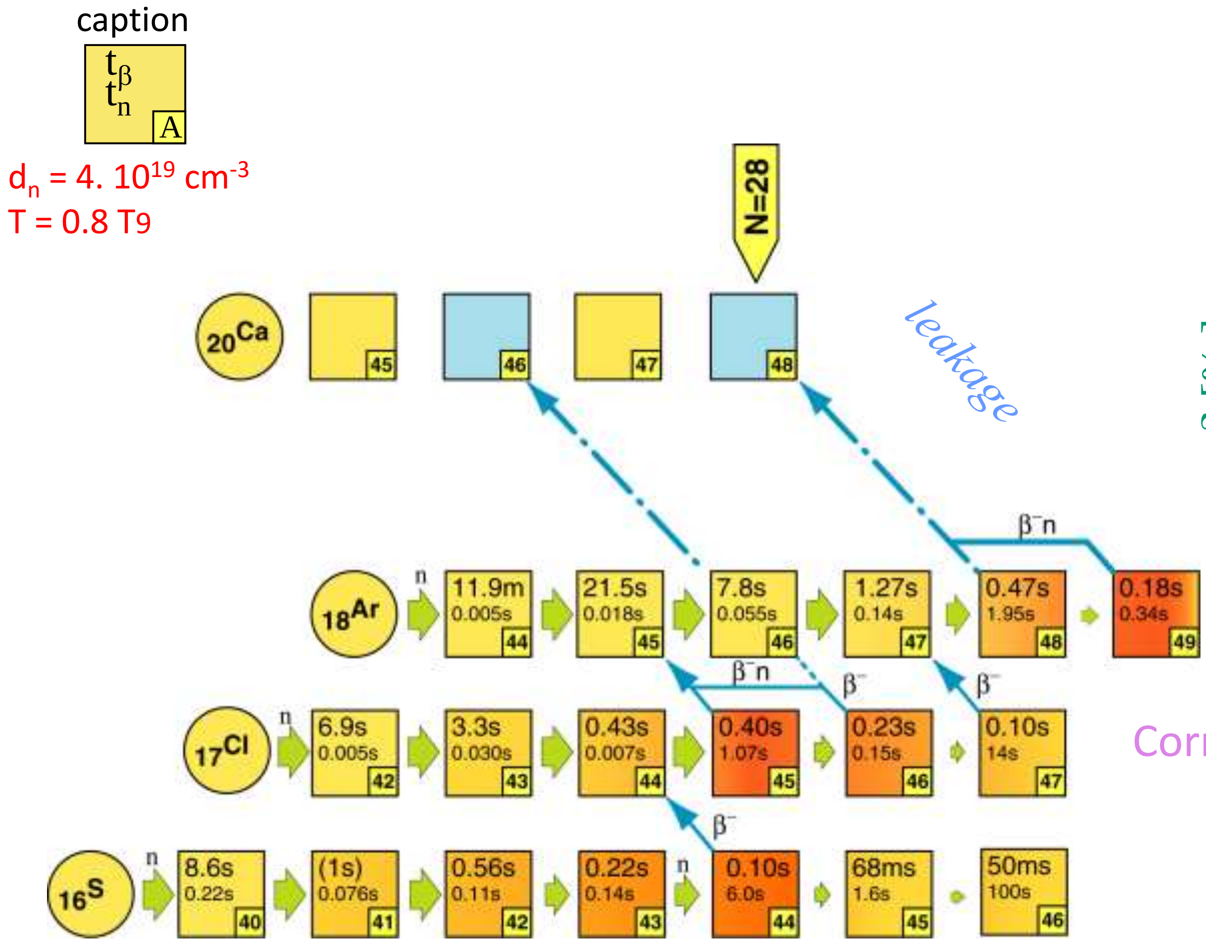
Neutron-rich scenario
Influence of N=82 shell closure
Abundances differ from solar r

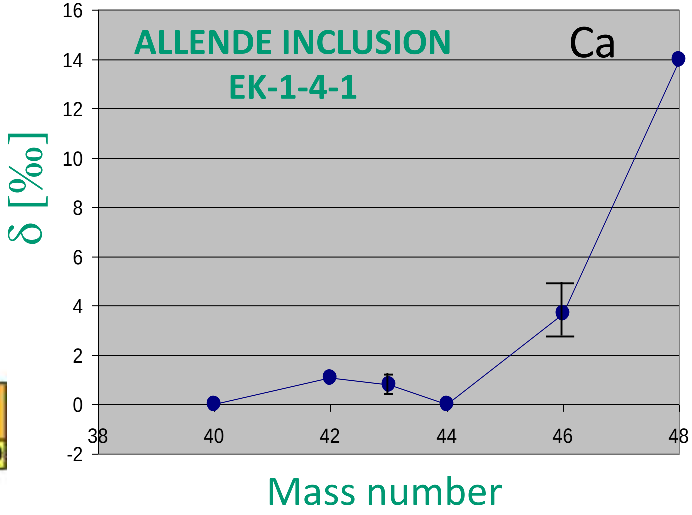
→ Neutron burst ?

Measure cross sections

Explain the abundance ratio ^{48}Ca/^{46}Ca ≈ 250

d_n = 4. 10^{19} cm^{-3}
T = 0.8 T9





Correlated over-abundances in ^{48}Ca-^{50}T
^{58}Fe-^{64}Ni

↓

Weak r process or SNI

➡ Determine experimental (n,γ) rates on unstable Ar nuclei.

Determination of neutron capture rates

What for ? : r process freeze-out, neutron bursts, cooling of neutron stars

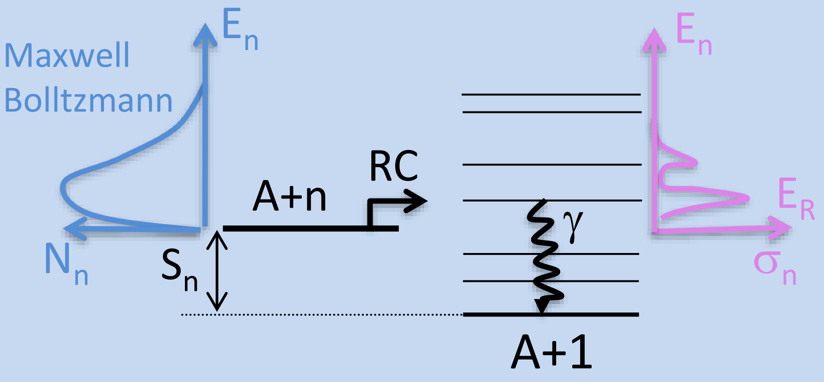
Far from stability, around closed shells

$E_n \approx kT \approx 100$ keV for $T \approx 10^9$K

- $S_n(A+1)$ is small
- Few states contribute, mainly low L
- Resonant or / and Direct capture

Other methods needed for nuclei in between shell closures -> level density and γ-strengths

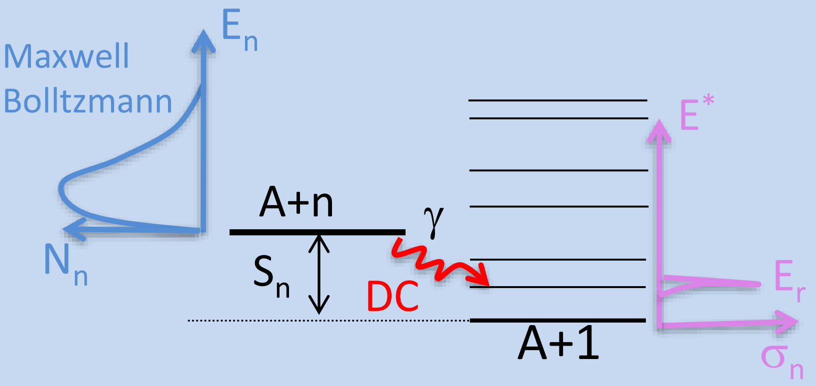
Resonant capture



$$\sigma_{BW}(E) = \omega(J_1,J_2,J)\,\pi\bar{\lambda}^2 \frac{\Gamma_n\Gamma_\gamma}{(E-E_R)^2+(\Gamma_{tot}/2)^2}$$

Measure E_R, Γ_n and Γ_γ

Direct capture



$$\frac{d\sigma}{d\Omega} \approx S\left|\int \Phi_f\, \theta_{EM}\, \Phi_i\, d\vec{r}\right|^2$$

Bound state

Folding potential

θ_{EM}: E1,M1 operators strongly dominant

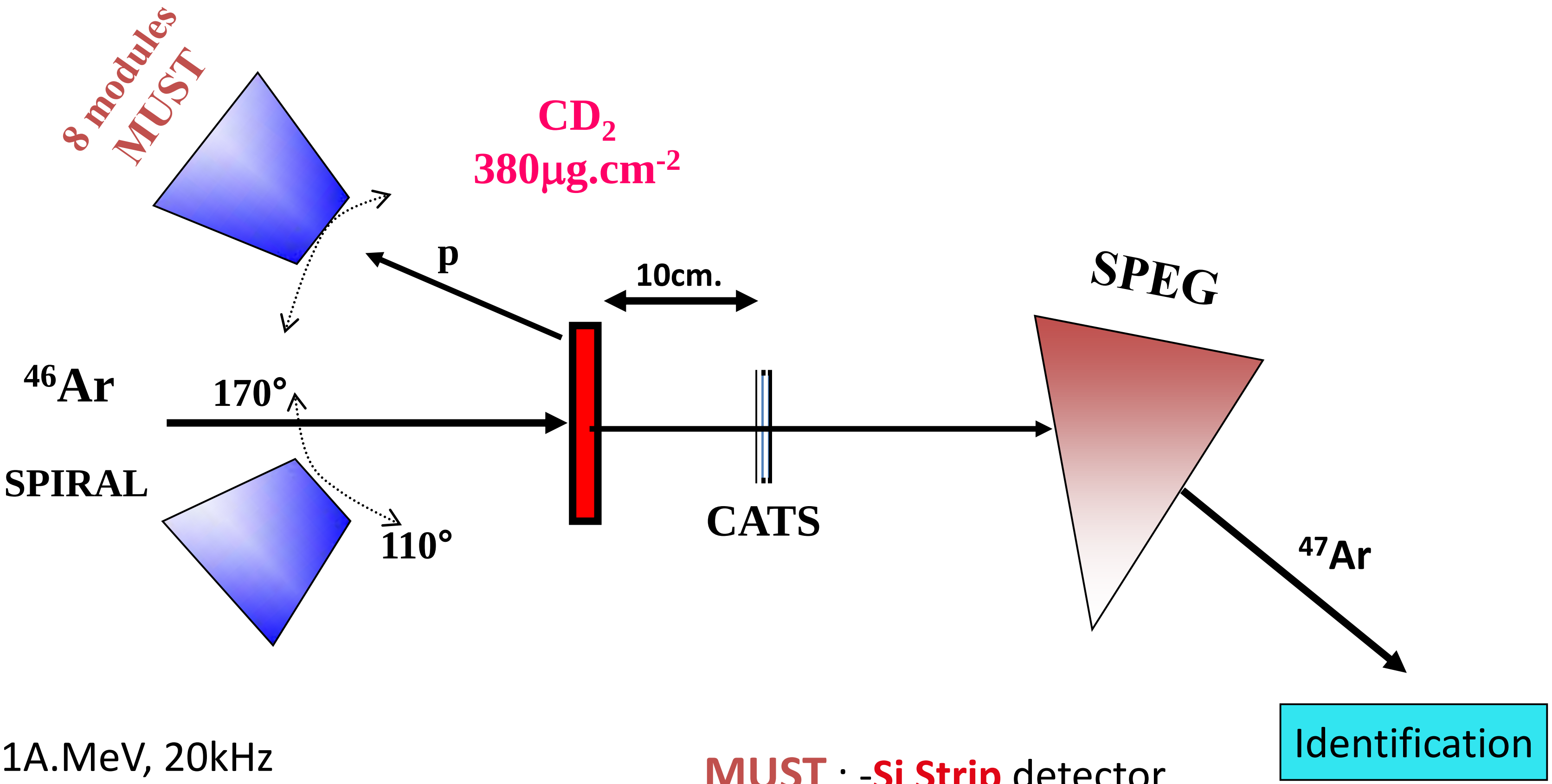
Determine J, L, S, E_r, S_n

Transfer (d,p) reactions can provide S_n, E, L, SF required for n captures

Comparison of (n,γ) versus (d,p)-derived cross section (Kraussmann et al. PRC 53 (1996))

Choose the appropriate energy for momentum matching (v/c~0.1) , RIB of ~10^5pps

Determine $^{46}Ar(n,\gamma)^{47}Ar$ using $^{46}Ar(d,p)^{47}Ar$ reaction



BEAM : 11A.MeV, 20kHz

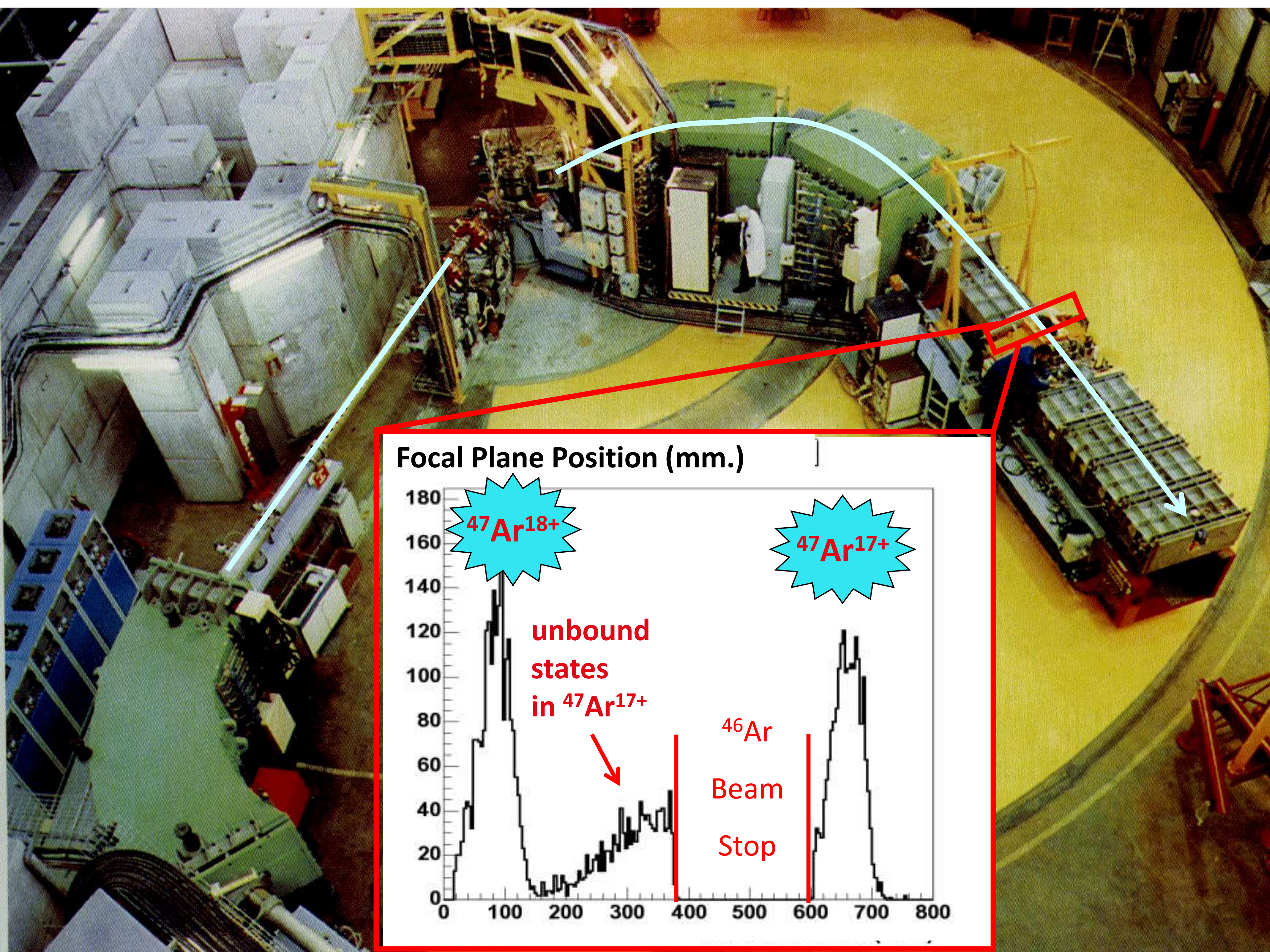
CATS : -**beam**-tracking detector

- Proton **emission point**.
  resolution : ~0.6 mm

MUST : -**Si Strip** detector
-Proton **impact localisation**
resolution : 1 mm
-Proton **energy** measurement.
resolution : 50 KeV
Efficiency >30%

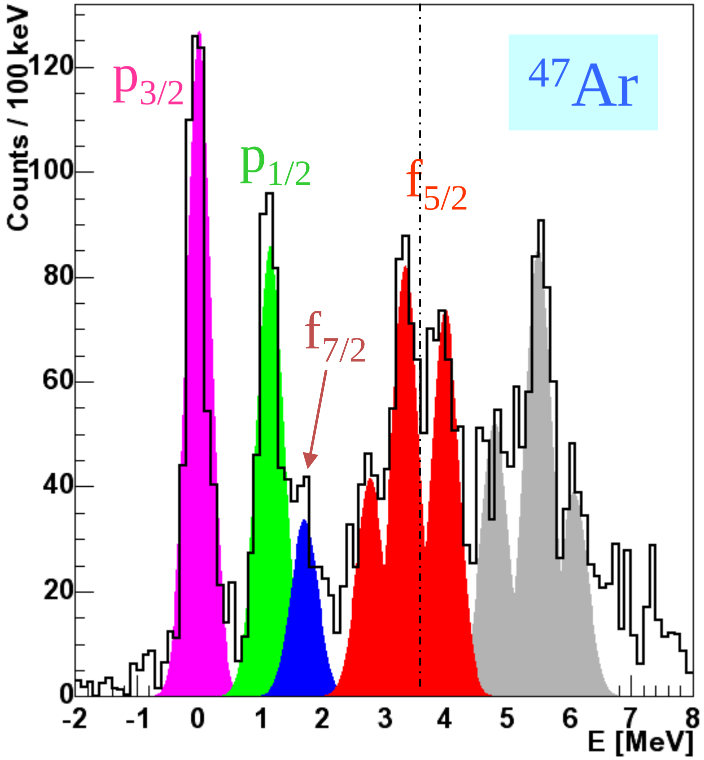
SPEG : Energy loss spectrometer : **recoil ion** identification →transfert-like products

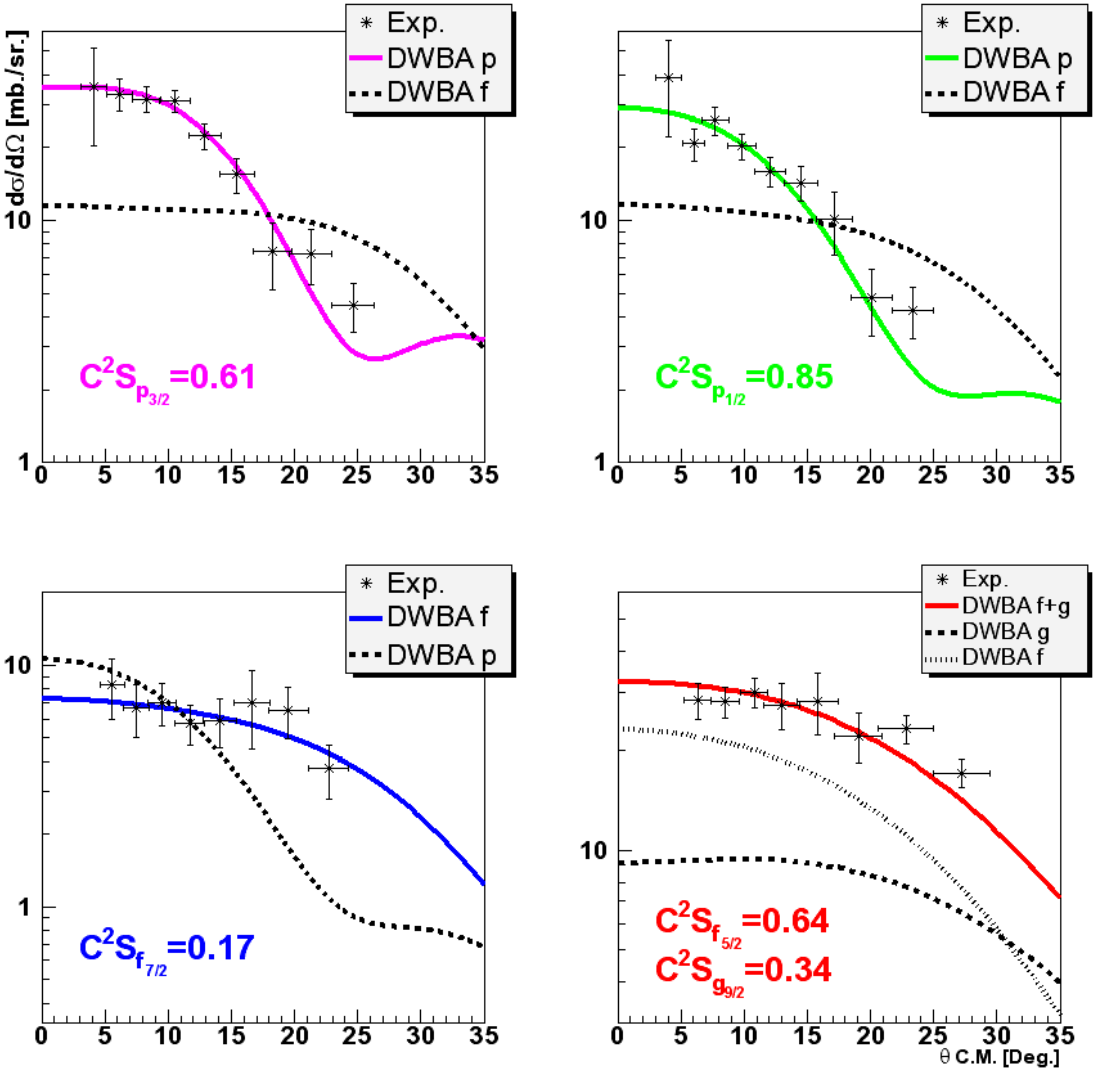
Future : use high-efficiency gamma-array and a liquid d target


Focal Plane Position (mm.)
$^{47}Ar^{18+}$
$^{47}Ar^{17+}$
unbound states in $^{47}Ar^{17+}$
^{46}Ar Beam Stop
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800

Excitation energy spectrum for ^{47}Ar

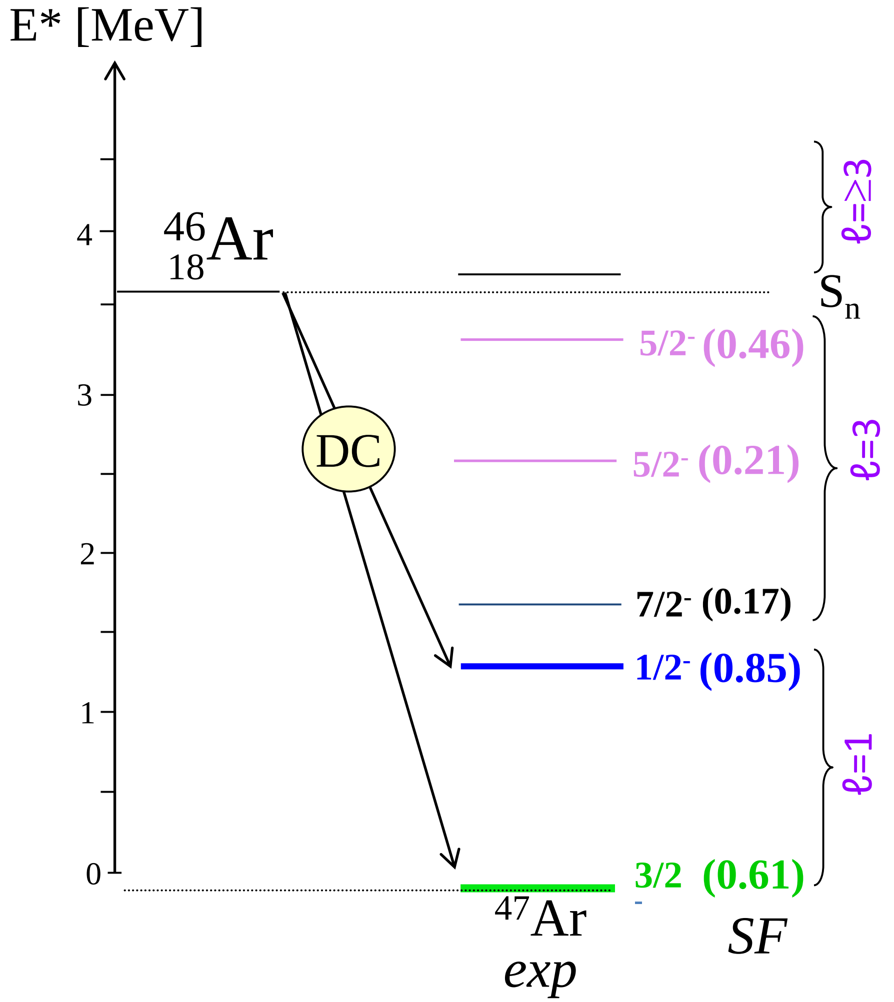
N=28 gap : 4.47(8)MeV
S_n=3.55(20)MeV
Gaudefroy et al. PRL (2006)

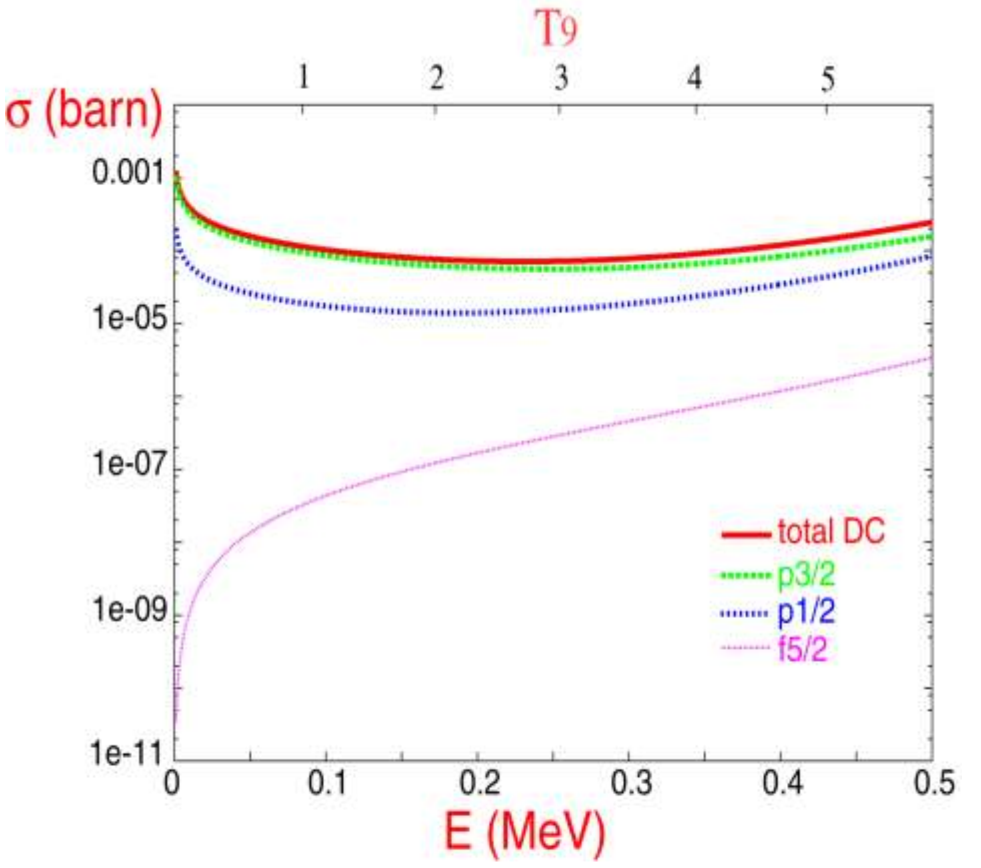




Use of spectrometer to suppress C induced background -> good mass resolution
Can be complemented by gamma-ray spectroscopy to achieve better energy resolution

Neutron capture rate at N=28 (^{46}Ar)





(d,p) access to E*, SF, spins → derive (n,γ) stellar rates

Direct capture (E1) with $\ell_n = 0$ on *p* states dominates

Speed up neutron-captures at the N=28 closed shell

Favor the enhancement of ^{48}Ca over that of ^{46}Ca using $d_n = 3\ 10^{19}$-^{21} cm^{-3}

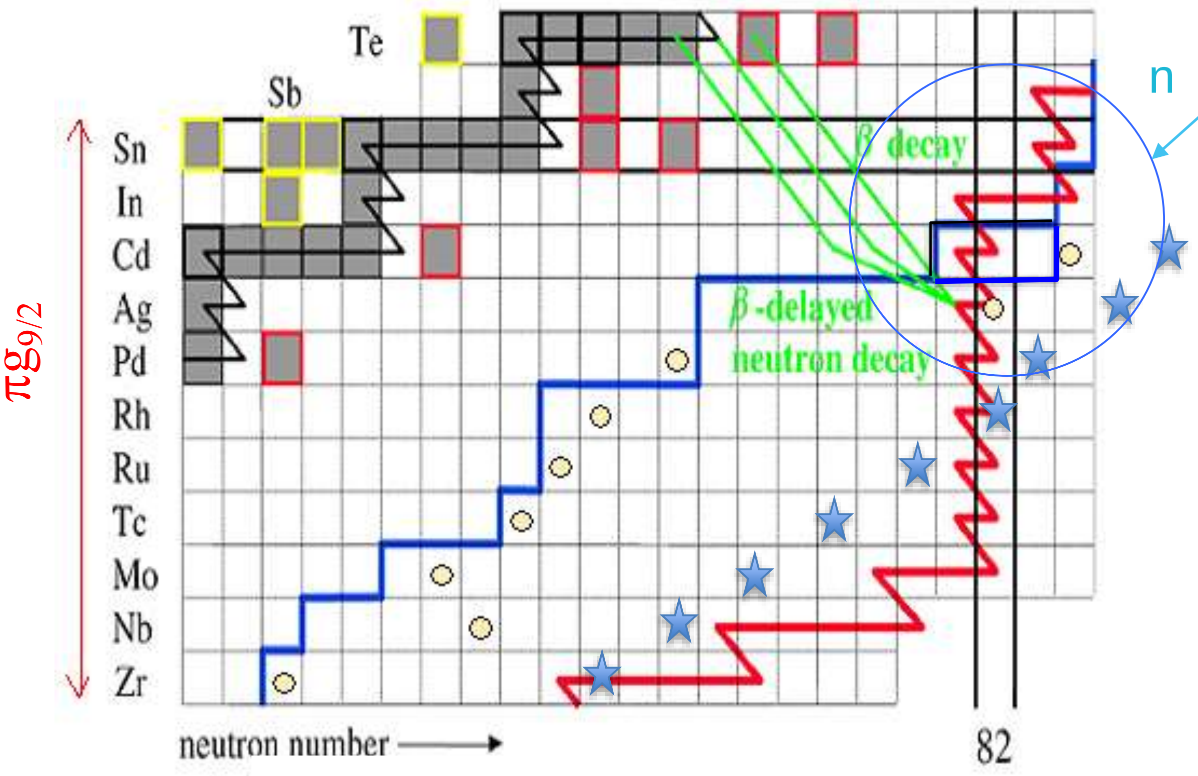
O. Sorlin et al. CR Phys 4 (2003)
L. Gaudefroy et al., EPJA (2006)

Neutron capture rate at N=82

Shuffle the material to more neutron-rich when the star expands

Could modify the shape of the r process peak

Play a role in weak r process conditions

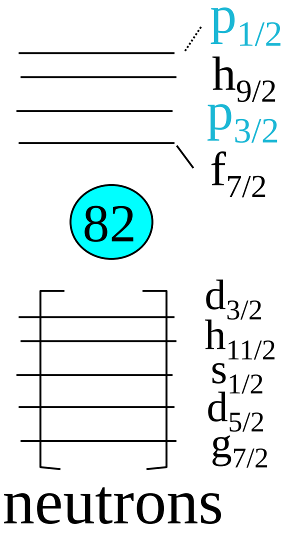


n capture rates important

○ $T_{1/2}$ until 2013

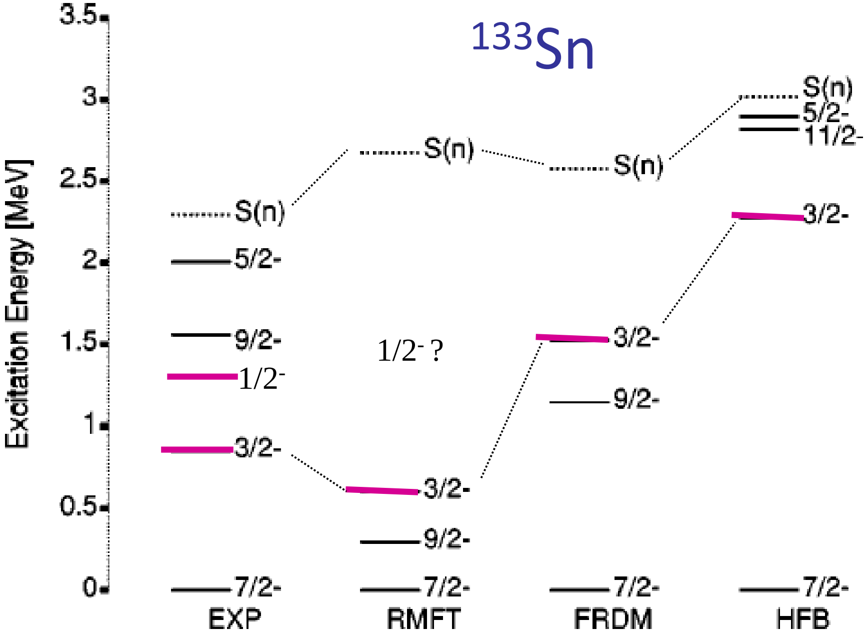
★ $T_{1/2}$ new RIKEN data

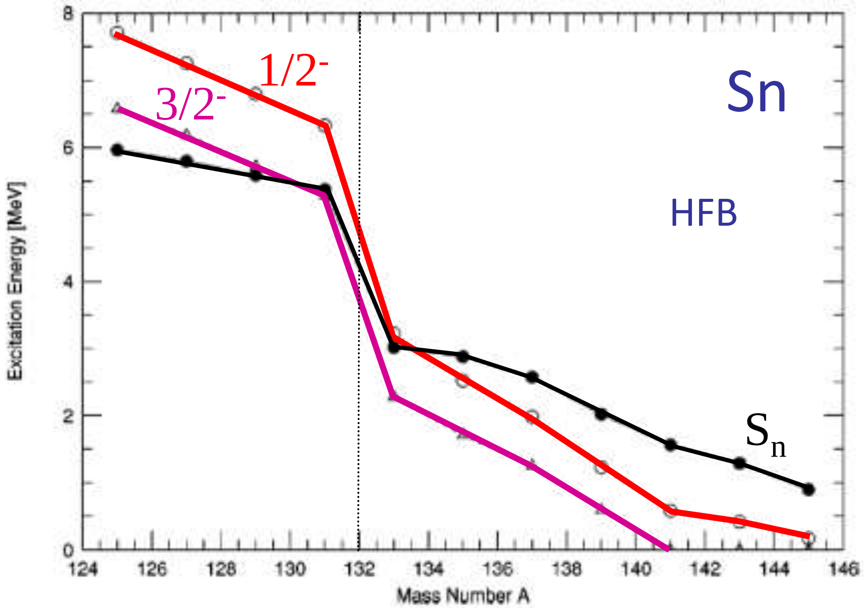
━ Limits of mass measurements

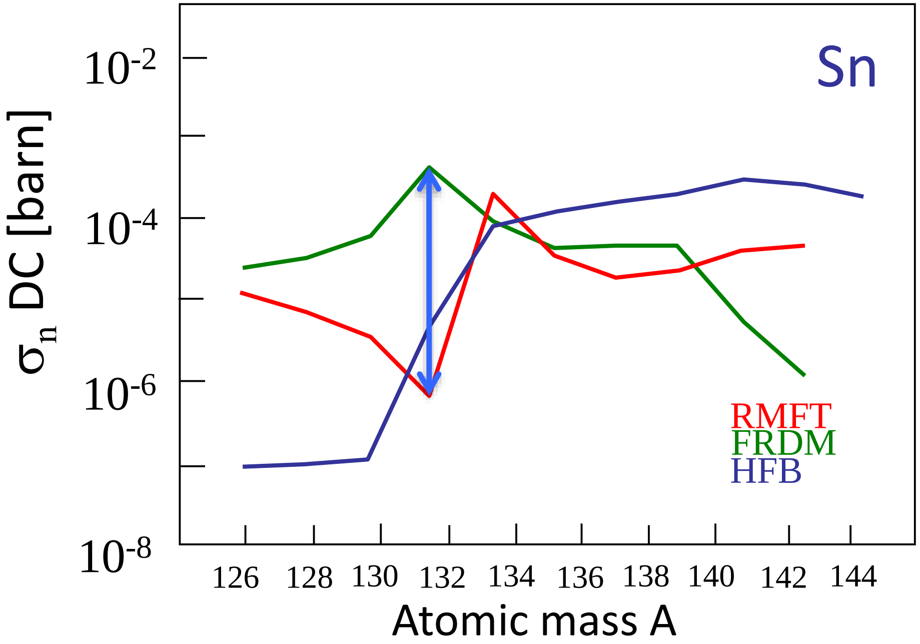


Same p orbits present …

Neutron captures at the N=82 shell closure







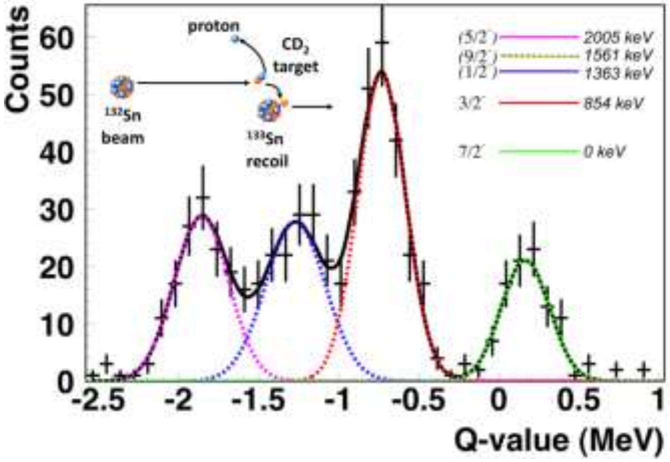
Same cross sections at ^{132}Sn, by chance !
Differ by more than factor 100 at ^{130}Sn

-> important role of DC on p orbits

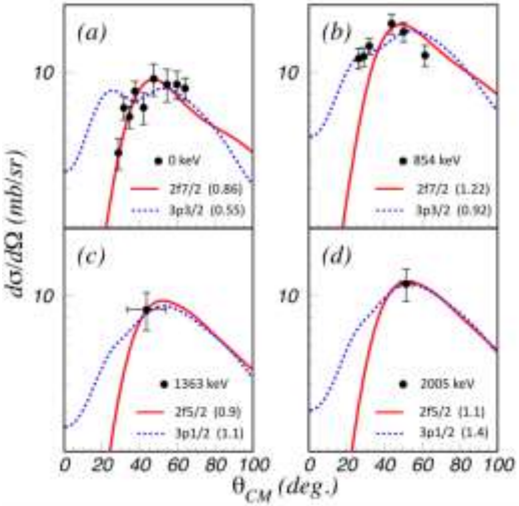
Rauscher et al. PRC 57(1998)

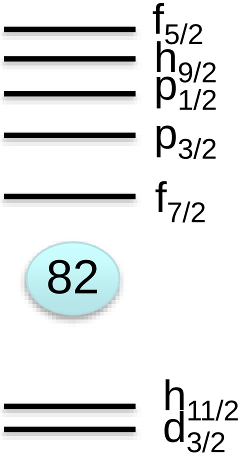
(d,p) reactions around the N=82 shell closure

^{132}Sn(d,p)^{133}Sn @ 4.8 Mev/A



Jones et al. Nature 465 (2010)





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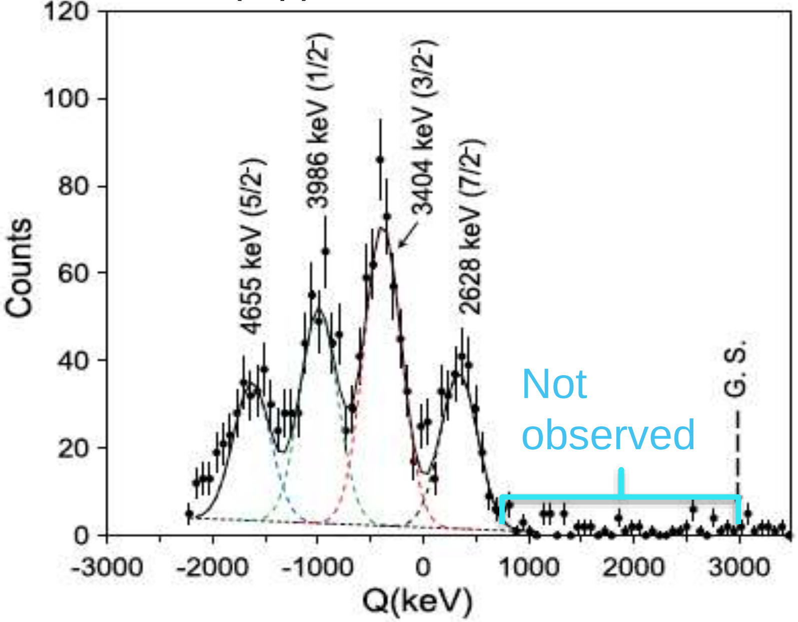
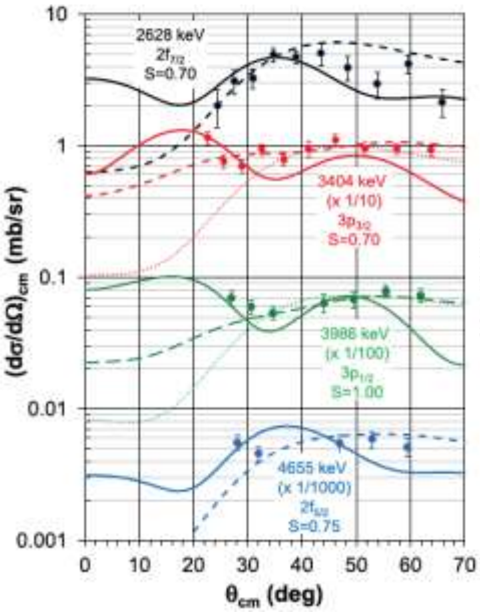
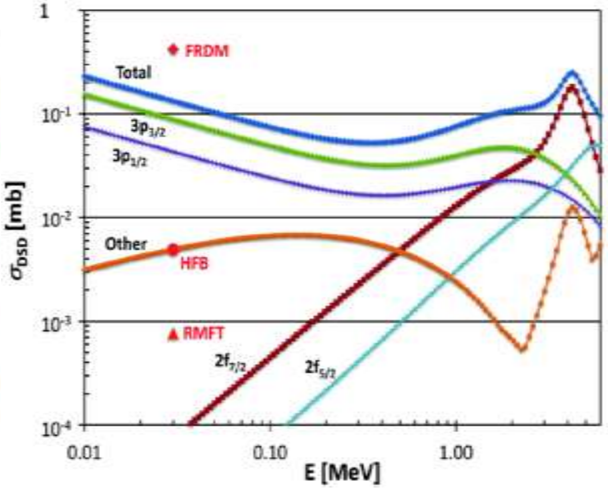
^{130}Sn(d,p)^{131}Sn @ 4.8 Mev/A



Kozub et al. PRL 109 (2012) 1724501



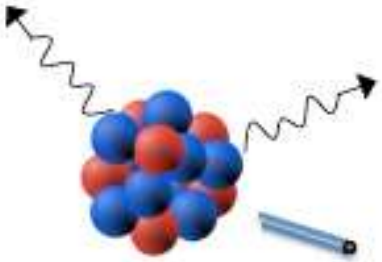
Summed cross sections



Go to heavier Sn or Cd in the future

Neutron captures closer to stability

The beta-Oslo method



1) Implant a neutron-rich nucleus (preferably with $Q_\beta \approx S_n$) in a *segmented* total-absorption spectrometer

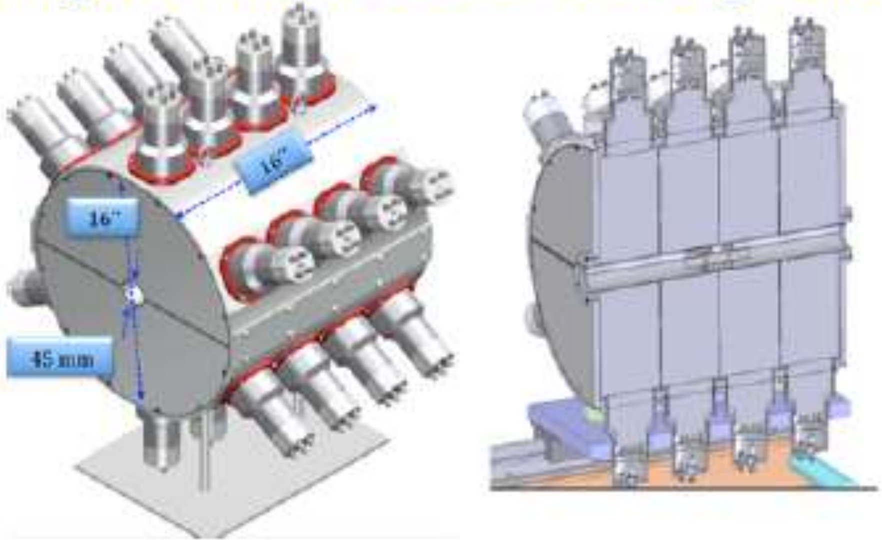
2) Measure β-particle in coincidence with γ's from the daughter nucleus

The segments give the individual γ rays,
the sum of all gives the initial Ex => need high efficiency!

First test @ NSCL/MSU, details:
^{76}Ge primary beam,
130 MeV/nucleon
on thick Be target => ^{76}Ga

Through gas cell => 30 keV ^{76}Ga (no contaminants) implanted on Si detector in the center of SuN, ≈ 500 pps

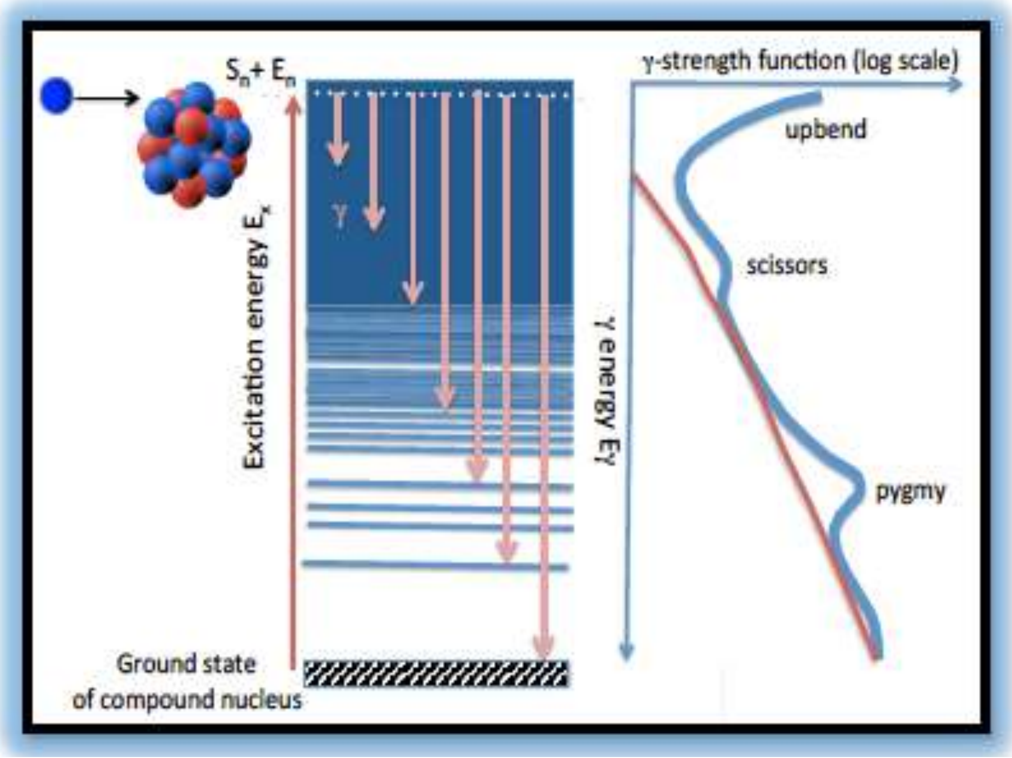
Efficiency of SuN: ≈85% @ 662 keV



Segmented, total absorption spectrometer SuN

Neutron captures closer to stability

Methods for measuring level density & γ strength of radioactive nuclei



Level density (at high Ex!):

Oslo method in inverse kinematics

beta-Oslo method

Gamma strength (at high Ex!):

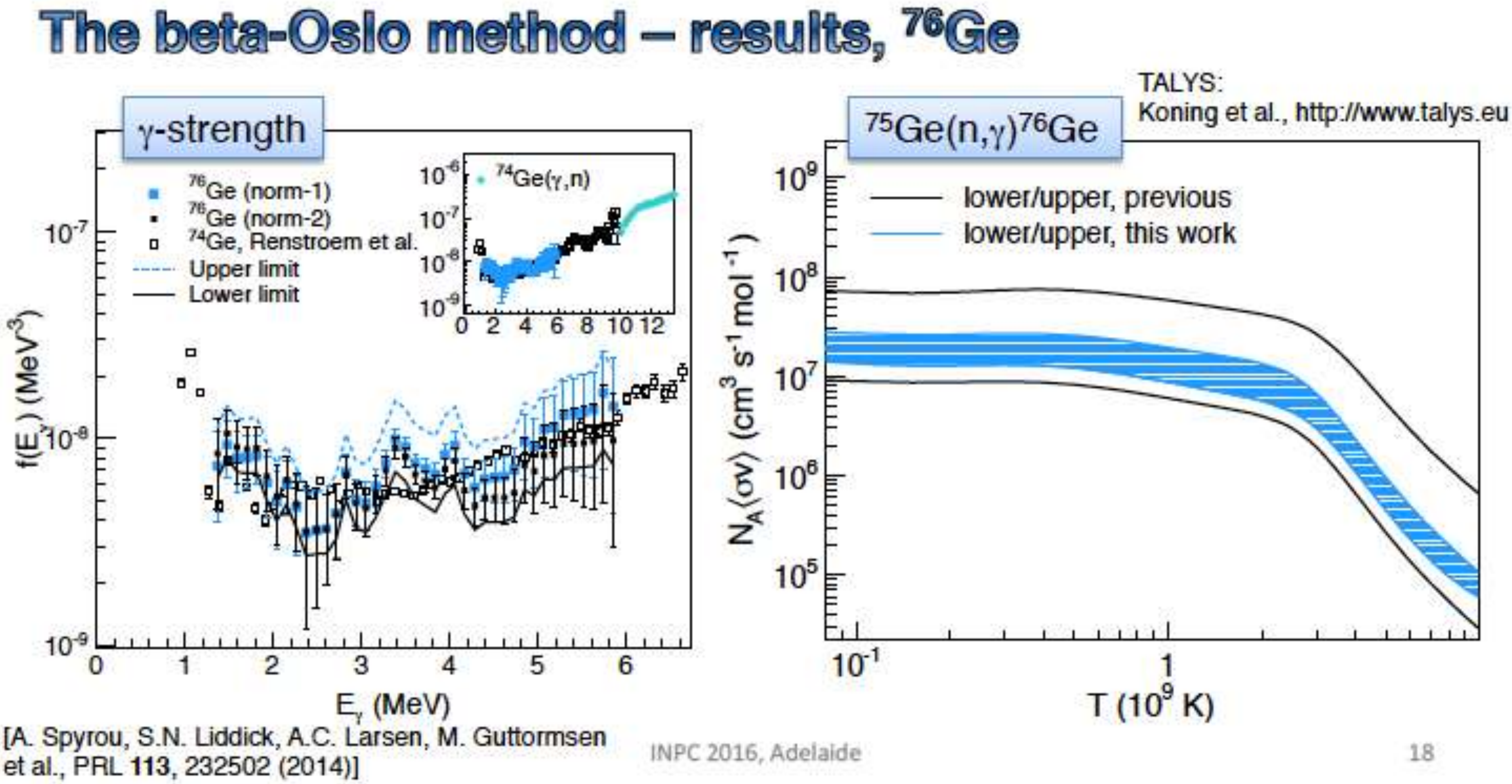
Coulomb excitation/dissociation

[see e.g. P. Adrich et al., PRL **95**, 132501 (2005),
O. Wieland et al., PRL **102**, 092502 (2009)
and D.M. Rossi et al., PRL **111**, 242503 (2013)]

Oslo method in inverse kinematics

beta-Oslo method

Neutron captures closer to stability

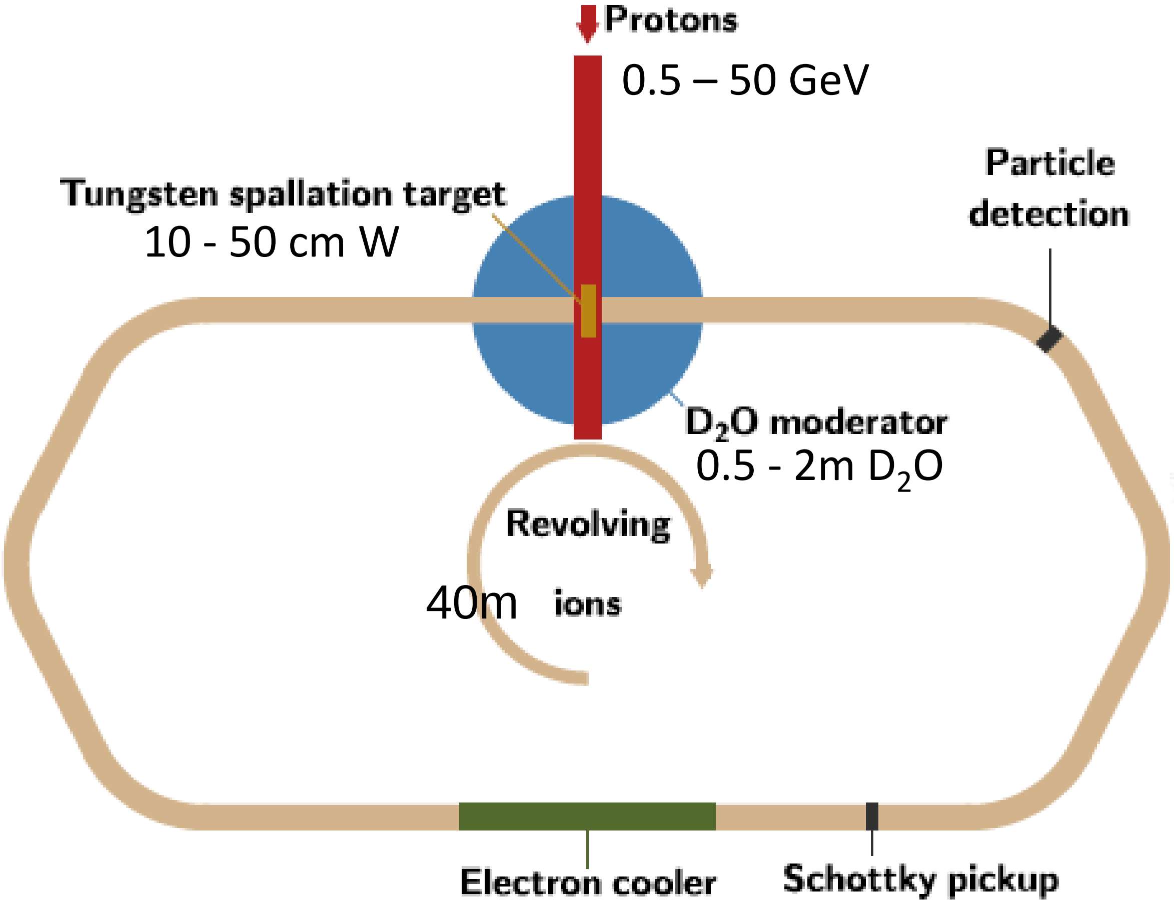


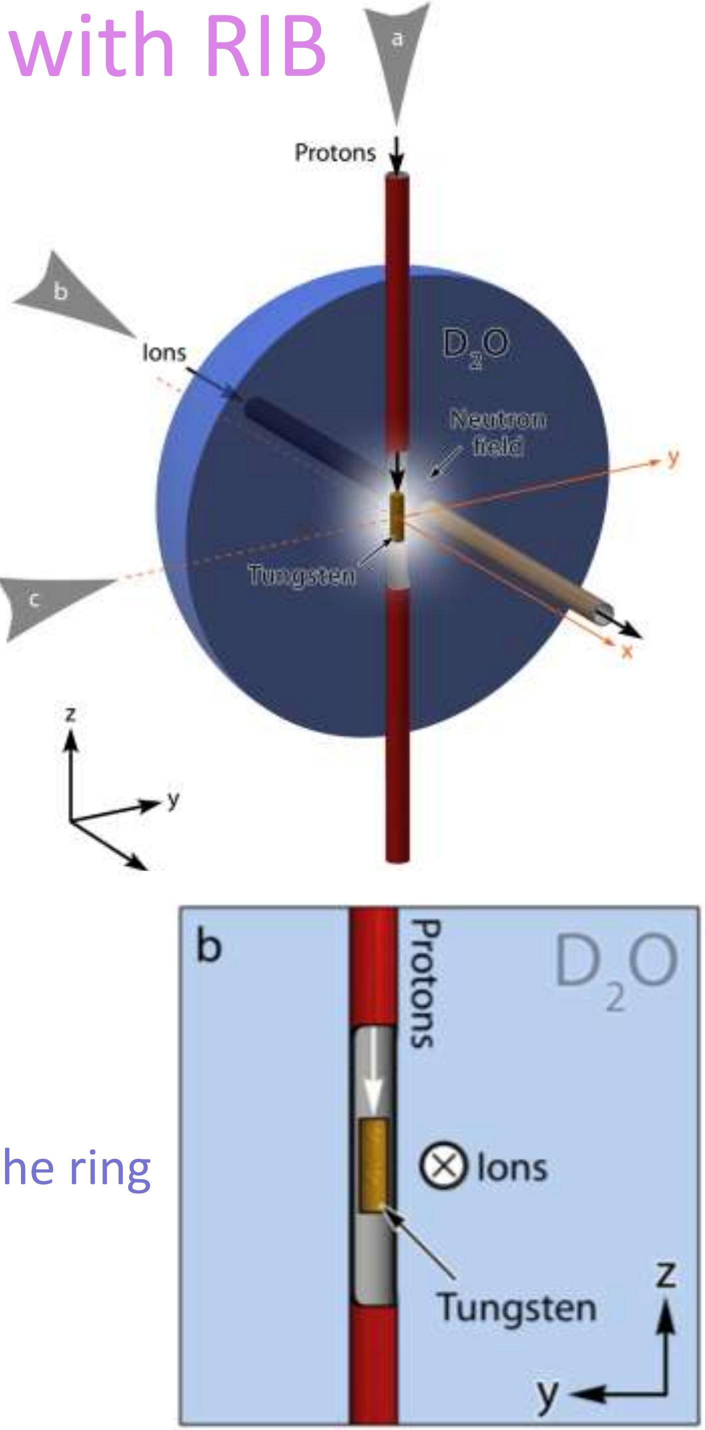
The beta-Oslo method – results, ^{76}Ge

TALYS:
Koning et al., http://www.talys.eu

[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL **113**, 232502 (2014)]

Future? : Colliding neutrons with RIB

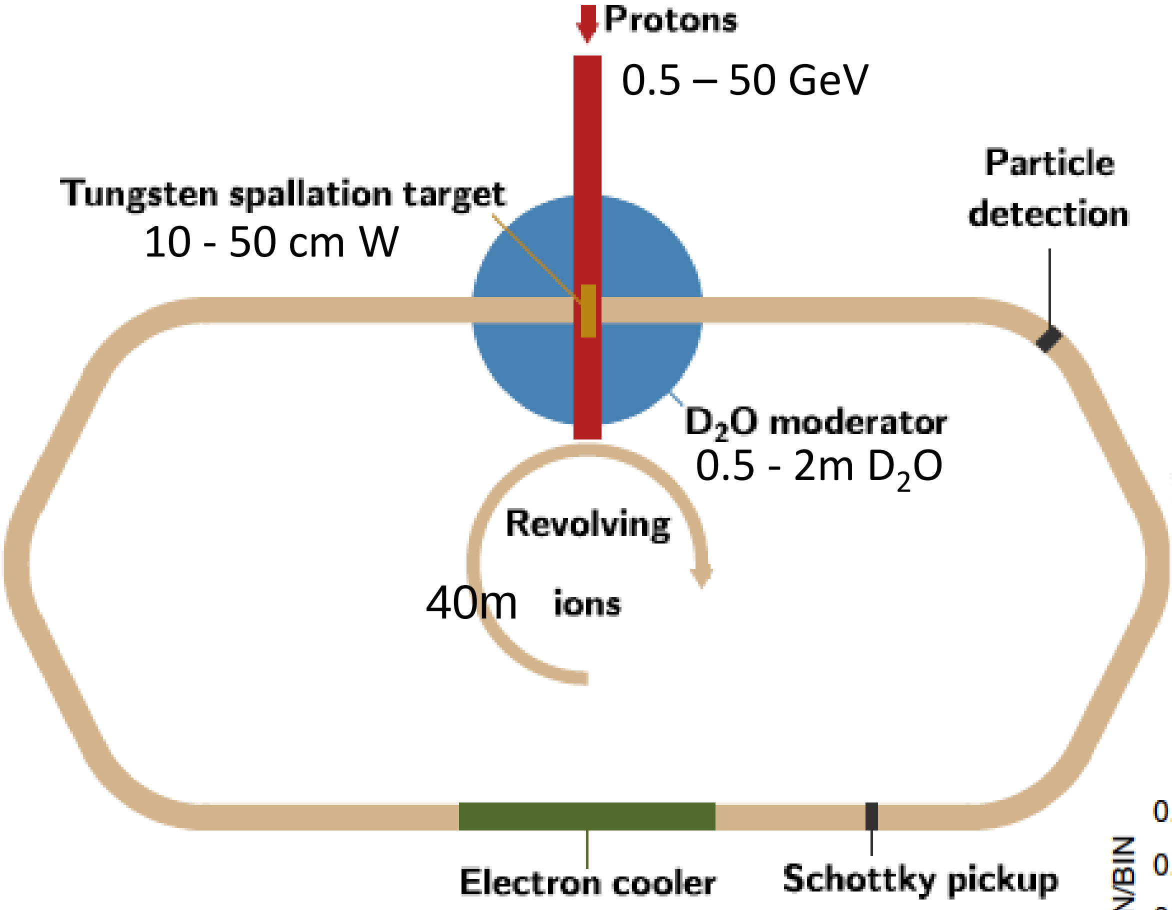




Interaction between thermalized neutrons with RIB in the ring

Reifarth et al, Phys. Rev ST Accelerator and Beams, 20, 044701 (2017)

Spallation-based neutron target



Protons

0.5 – 50 GeV

Tungsten spallation target

10 - 50 cm W

Particle detection

D_2O moderator

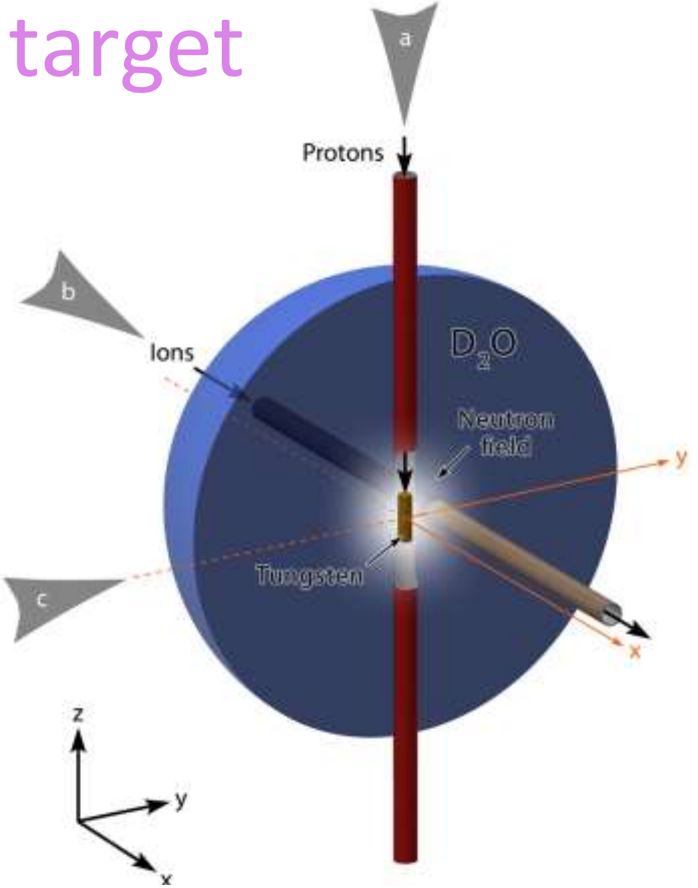
0.5 - 2m D_2O

Revolving

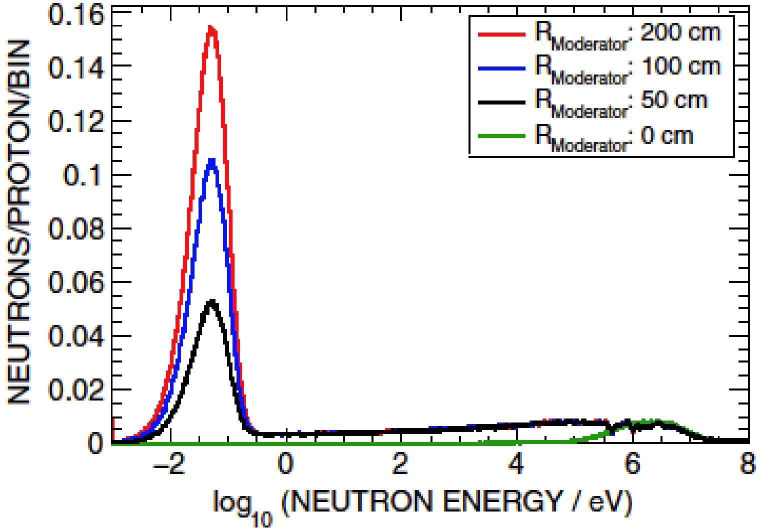
40m **ions**

Electron cooler

Schottky pickup

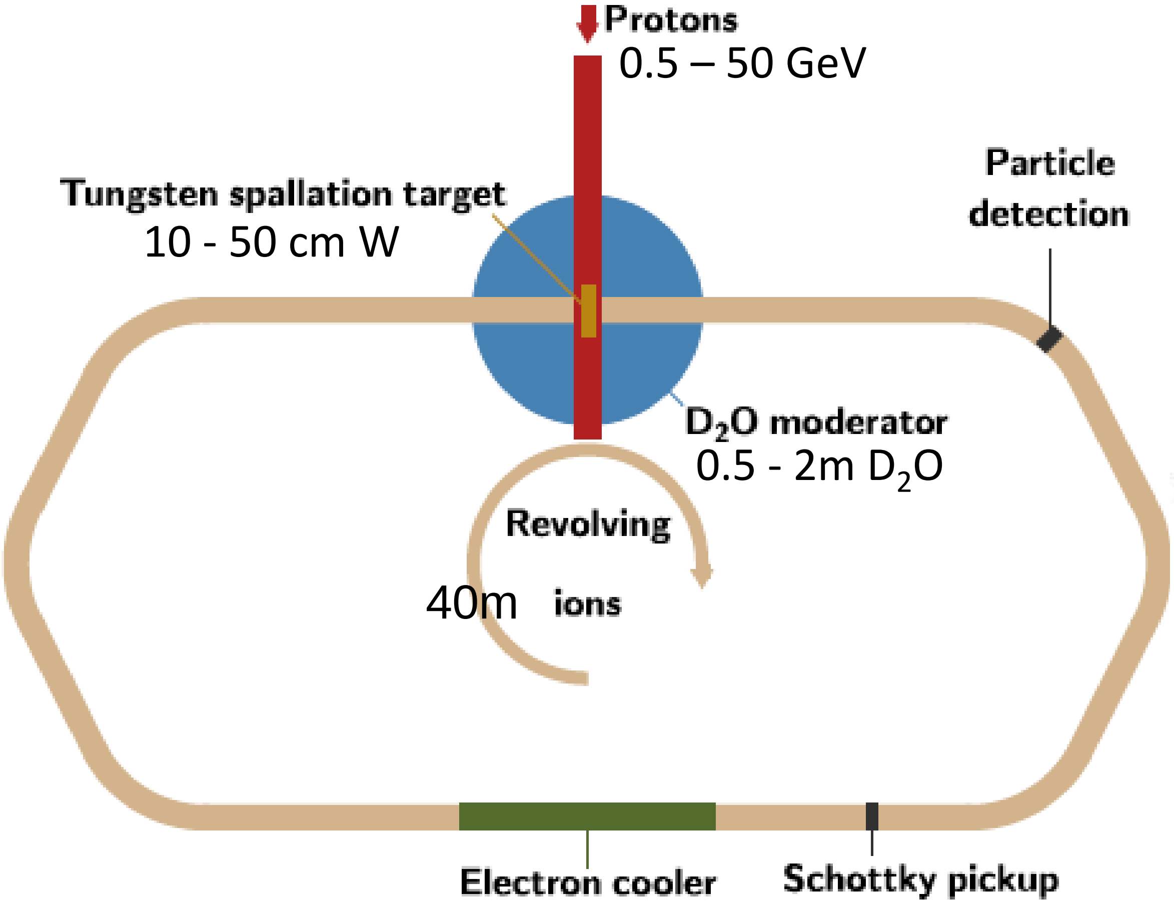


Energy of the ions fixes the energy of the reaction



Reifarth et al, Phys. Rev ST Accelerator and Beams, 20, 044701 (2017)

Spallation-based neutron target



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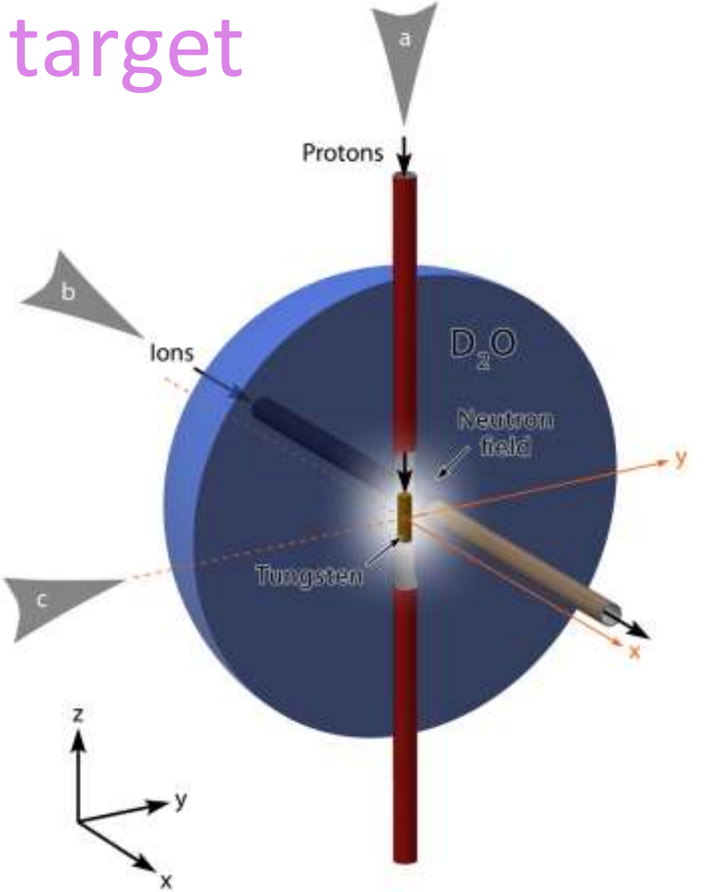
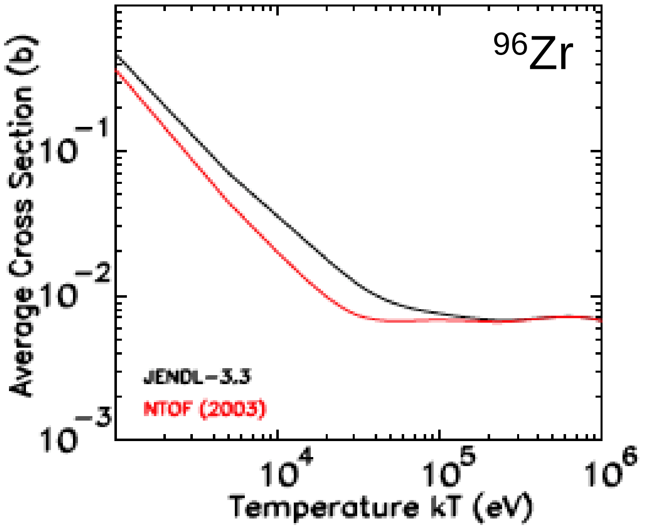




Protons: 100 μA @ 1 GeV, D_2O moderator radius: 2 m

Neutron target: 10^{10} n/cm^2 ,

With stored ions 10^7, revolution 1 MHz -> 10^{13} ions s^{-1}

Counts per day: 10 σ(mb)

Reifarth et al, Phys. Rev ST Accelerator and Beams, 20, 044701 (2017)

Conclusions

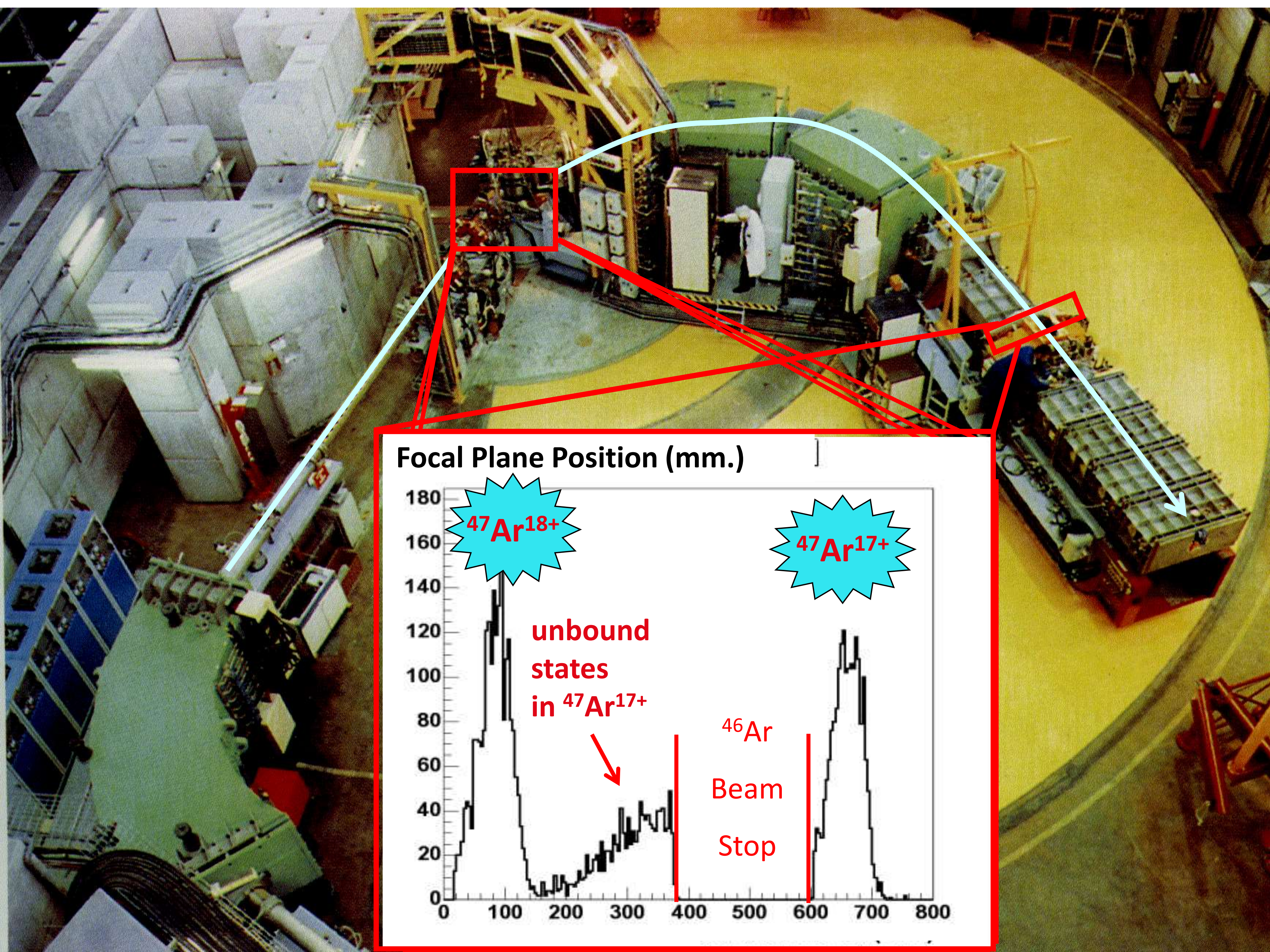
Measuring neutron-capture rates on unstable nuclei is not an easy and the techniques are case dependent (beta-delayed neutron spectroscopy could be used as well…)

Can be done in several Isolde facilities in Europe

Find weakly-mixed stars or grains in which neutron-rich nuclei are produced

Study the relevant properties of nuclei far from stability (masses, $T_{1/2}$, P_n, neutron-capture rates) to better understand which processes in stars can produce these abundances

With materials from V. Hill, A-C. Larsen, M. Pignatari, R. Reifarth and M. Spite

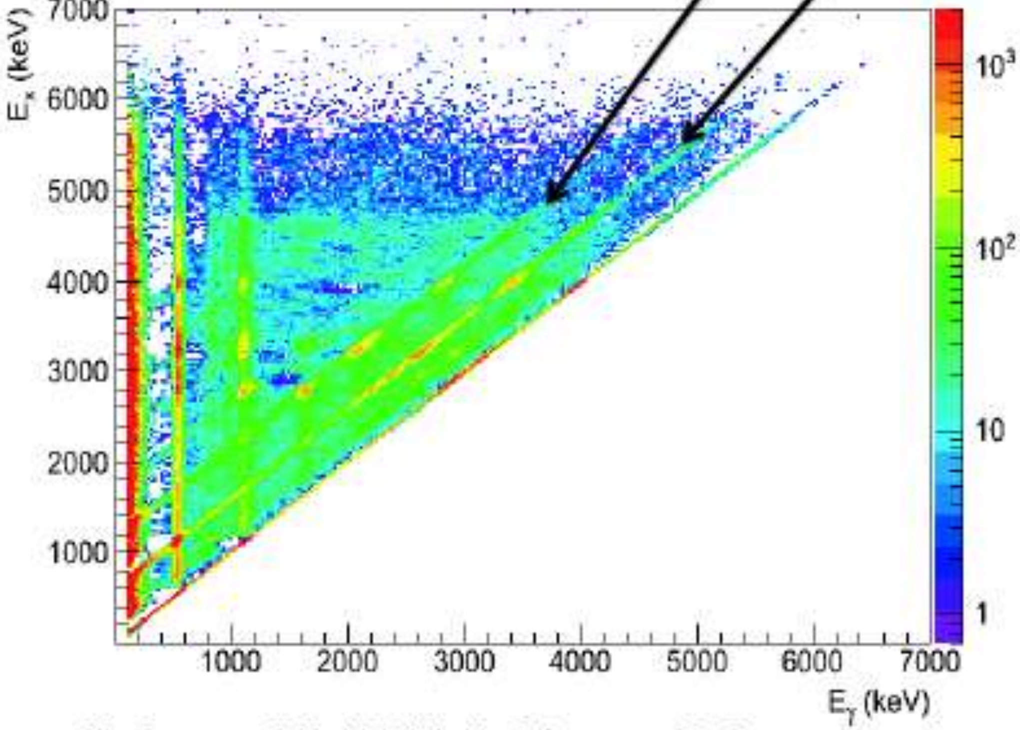

Focal Plane Position (mm.)
^{47}Ar^{18+}
^{47}Ar^{17+}
unbound states in ^{47}Ar^{17+}
^{46}Ar Beam Stop
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800

The beta-Oslo method – ^{76}Ge

^{76}Ga => ^{76}Ge – unfolded spectra

Decay to 2^+ @ 1108 keV

Decay to 2^+ @ 562.9 keV



[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., Phys. Rev. Lett. **113**, 232502 (2014)]

^{76}Ga $T_{1/2}$: 32.6 s

^{76}Ga $I^{\pi} = 2^{-}$

Beta-decay Q-value: 7.07 MeV

(feeds mostly levels below Ex ≈ 5 MeV)

S_n of ^{76}Ge: 9.428 MeV

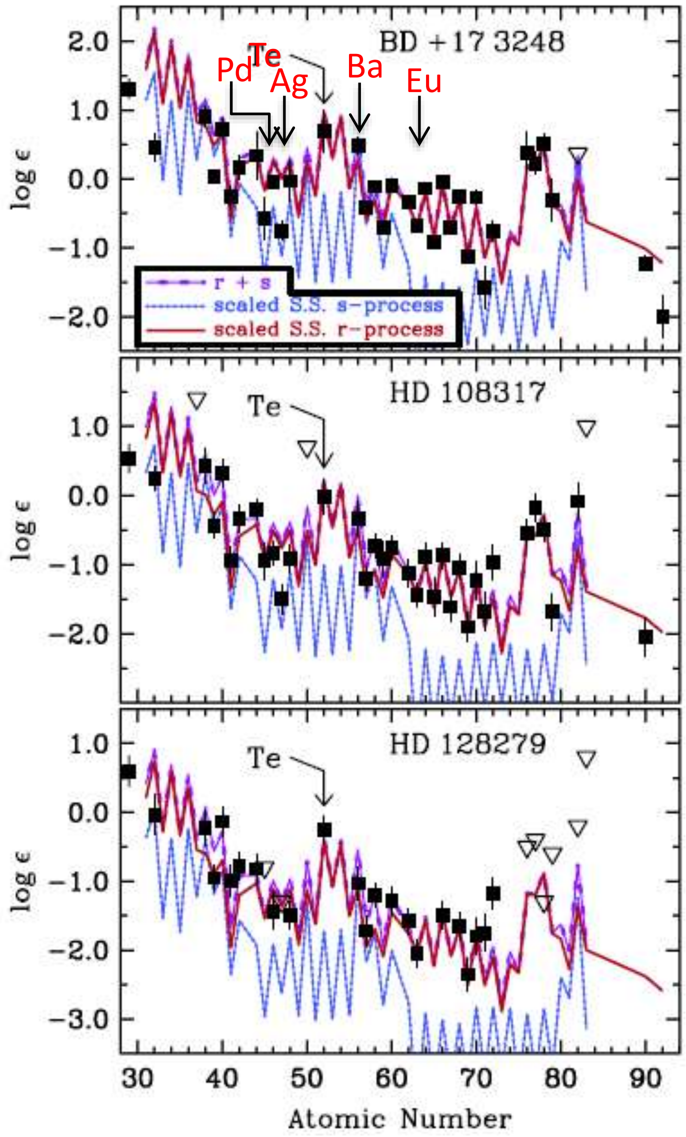
Initial spins, ^{76}Ge (Gamow-Teller): 1-,2-,3-

After one primary (dipole) transition:

0,1,2,3,4

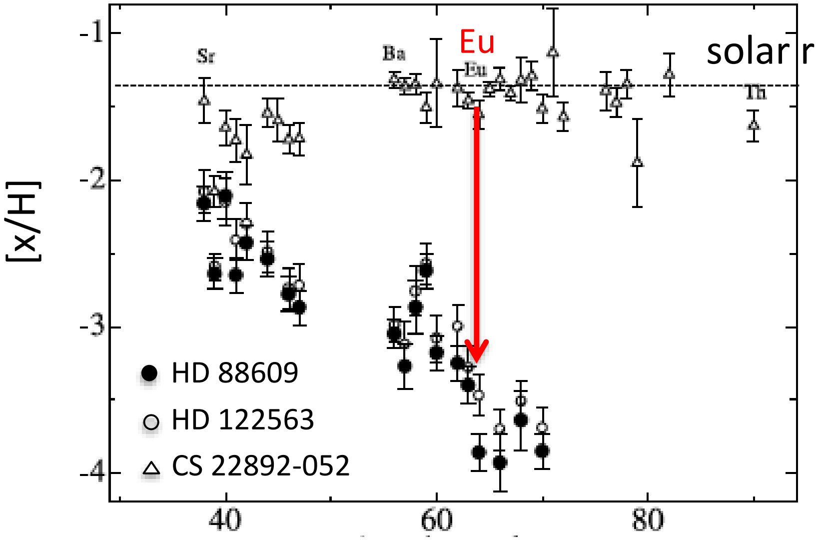
Existence of a low element primary process (LEPP)

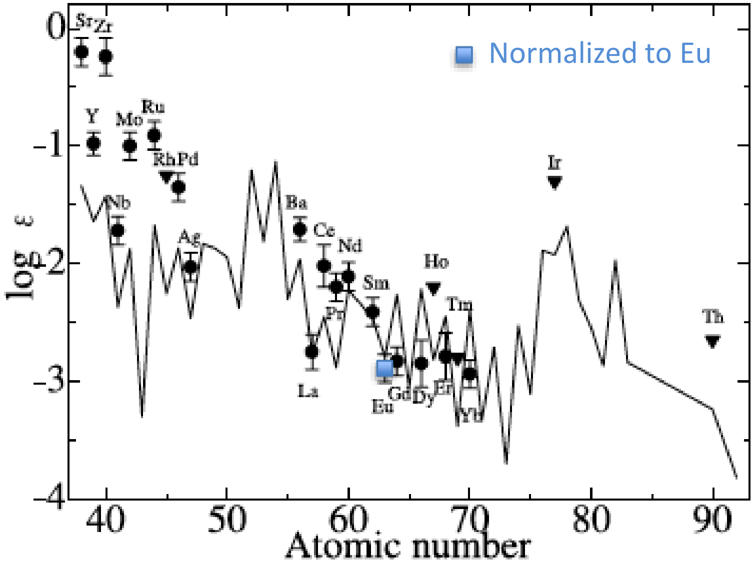
Roederer 2012 Hubble



Eu-rich EMP stars display the same solar-like pattern for Z>50 -> main r process

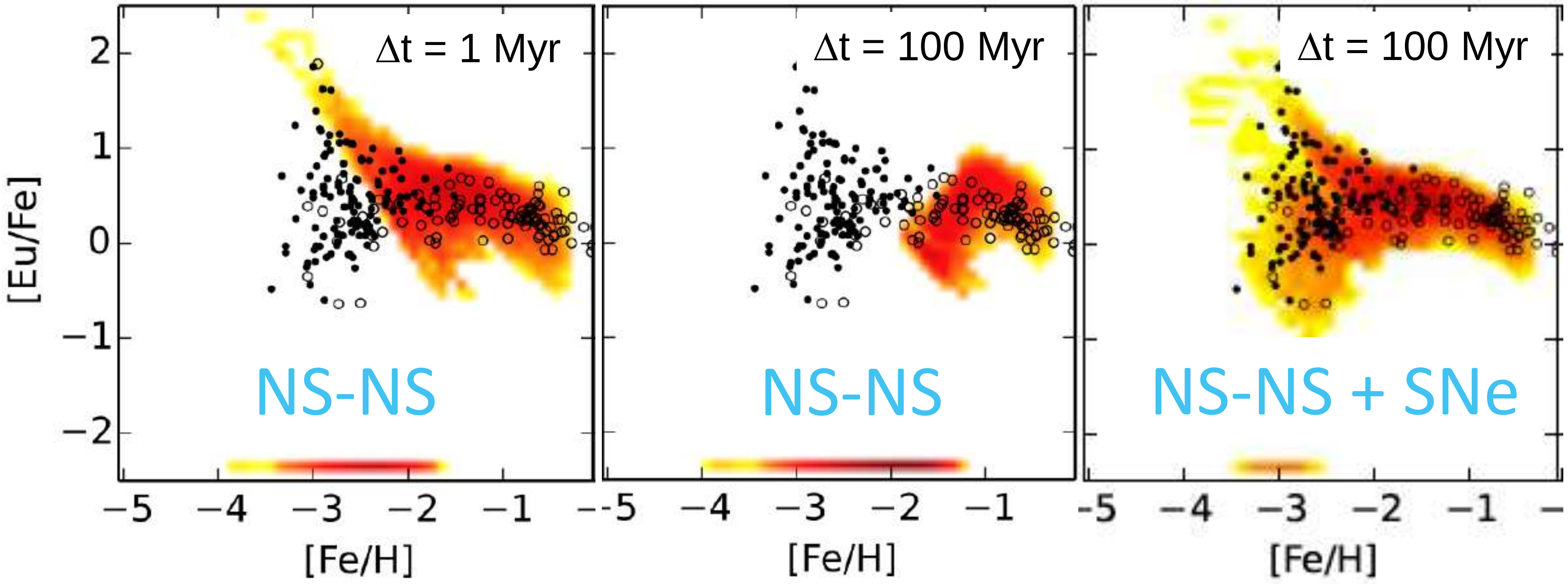
(Honda et al., ApJ 666 (2007))





Other EMP stars display enrichments in low-mass elements -> weak r process

r process in NS-NS: time scale problem

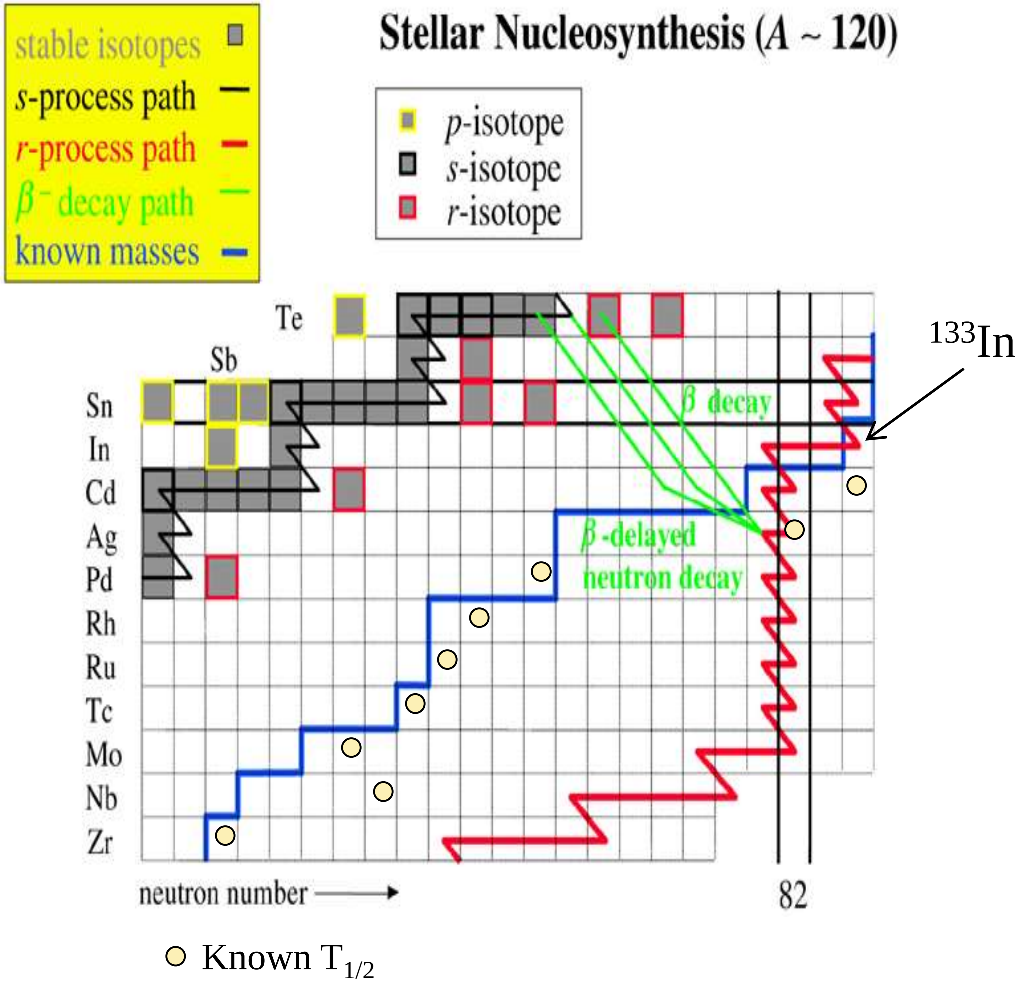


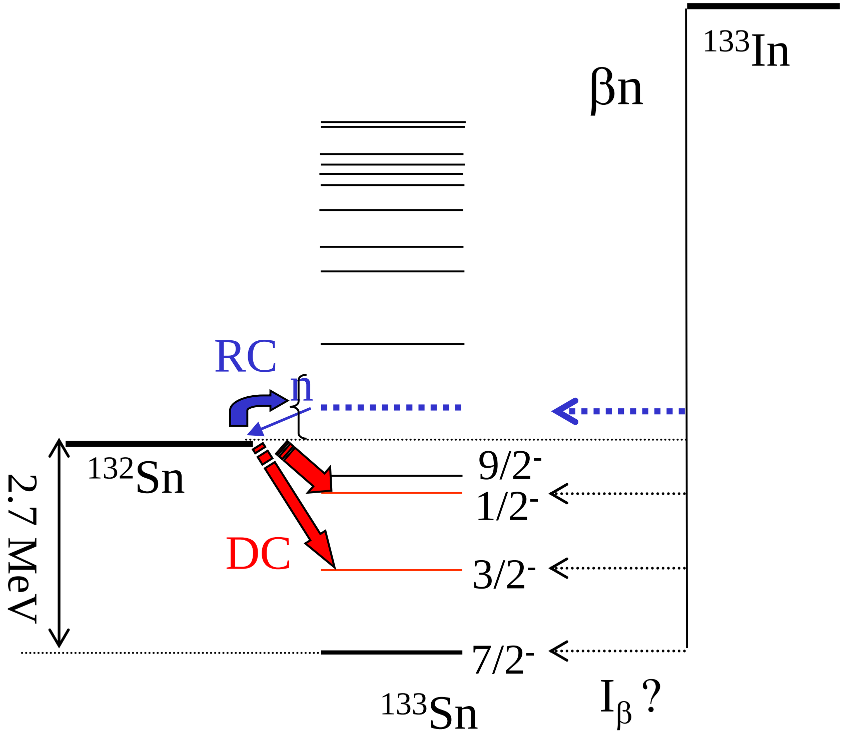
Cescutti et al. 2014

To make binary star mergers (NS-NS) as a contributor to the early galactic evolution, one needs to assume their very fast occurrence (much faster than commonly thought)

Add CCSNe contribution on top of NS-NS can better account for Eu early production

β decay and neutron spectroscopy





Search for s-wave resonances

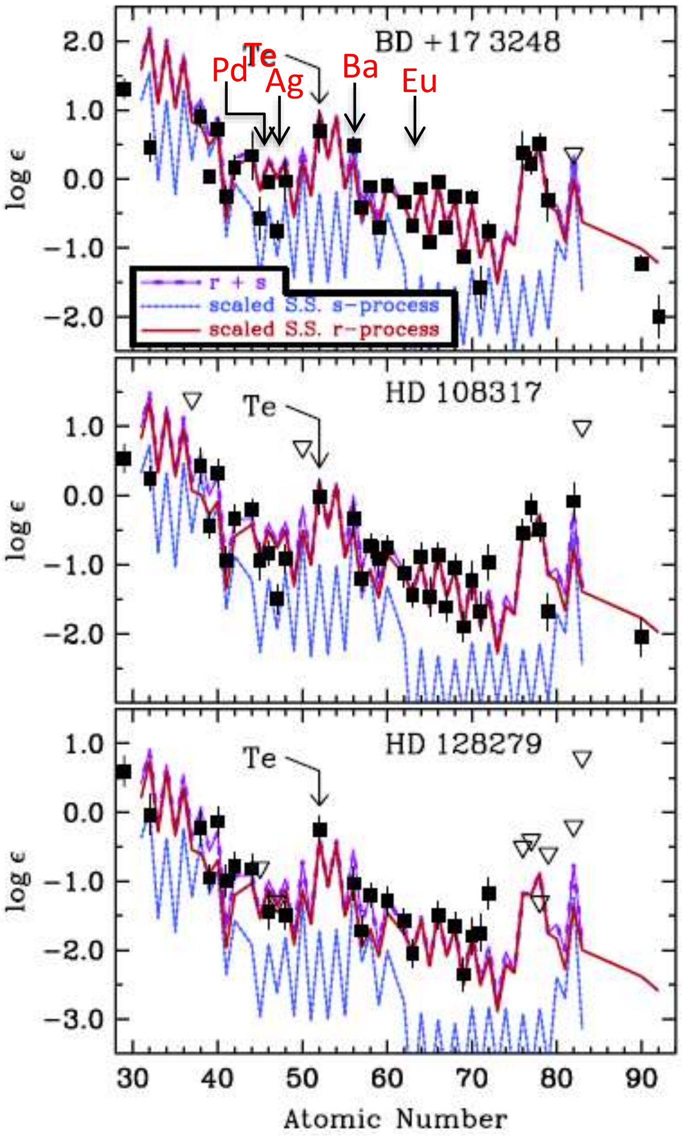
Search for p states

Lifetimes, P_n values, location of levels/resonances

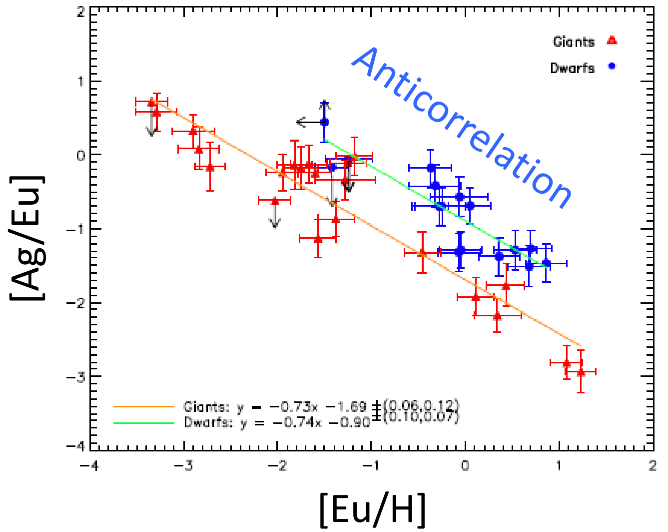
Should be performed in the In, Ag chains

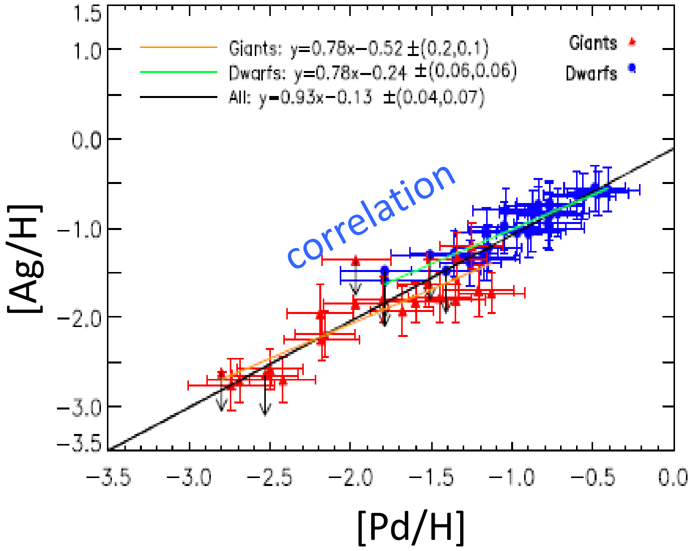
Correlations betwen light and heavy elements ?

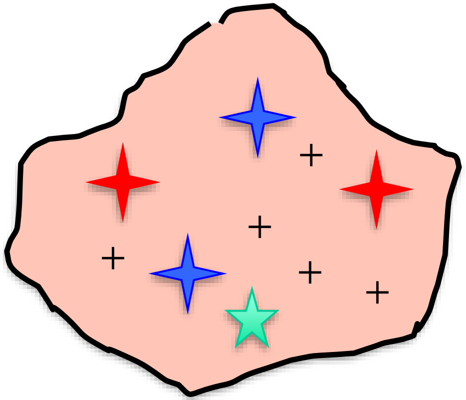
Roederer 2012 Hubble



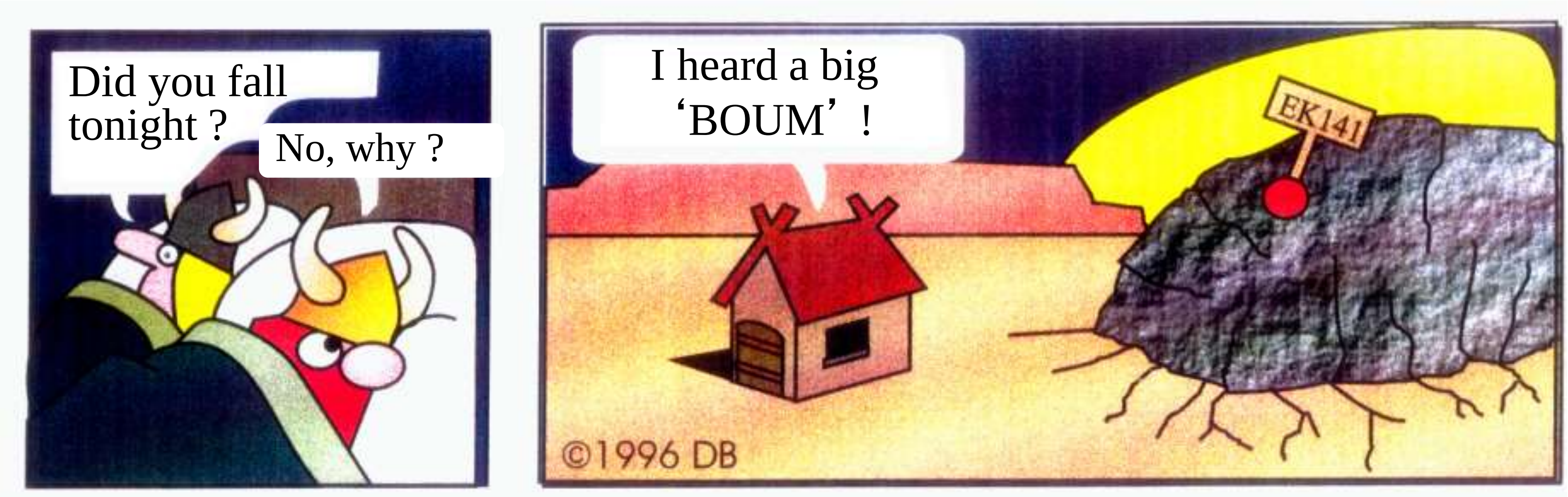
(PhD-thesis C.J. Hansen 2011)







^{48}Ca overabundance in EK 1-4-1 inclusion of meteorite



$^{48}Ca/^{46}Ca \approx 250$ (solar =53)

Allende meteorite:

fell in 1969

weight 2t

chondraneous carbide

several CaAl-rich inclusions

EK1-4-1 inclusion :

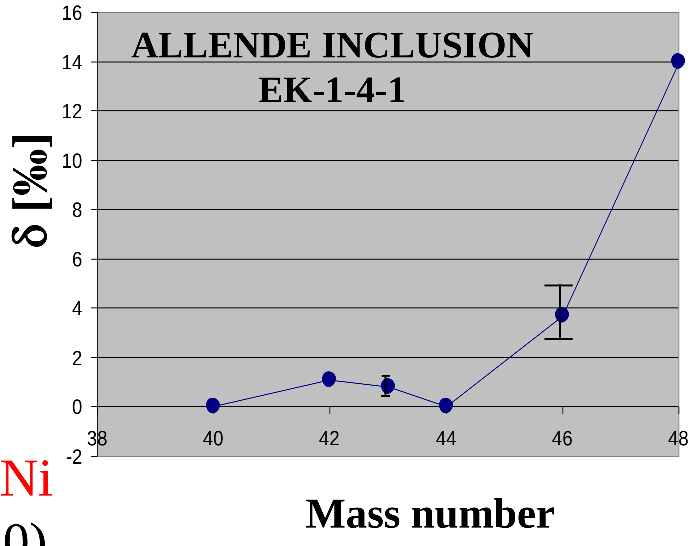
spherical shape, white colour

diametre 1cm

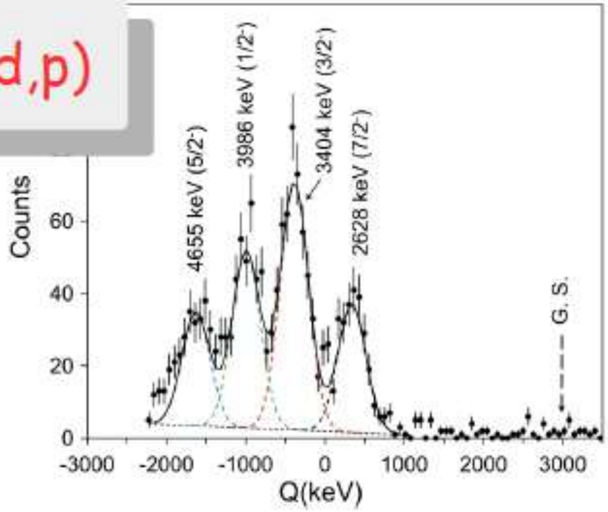
Fusion temperature 1500-1900K

Correlated over-abundances ^{48}Ca-^{50}Ti-^{54}Cr-^{58}Fe-^{64}Ni

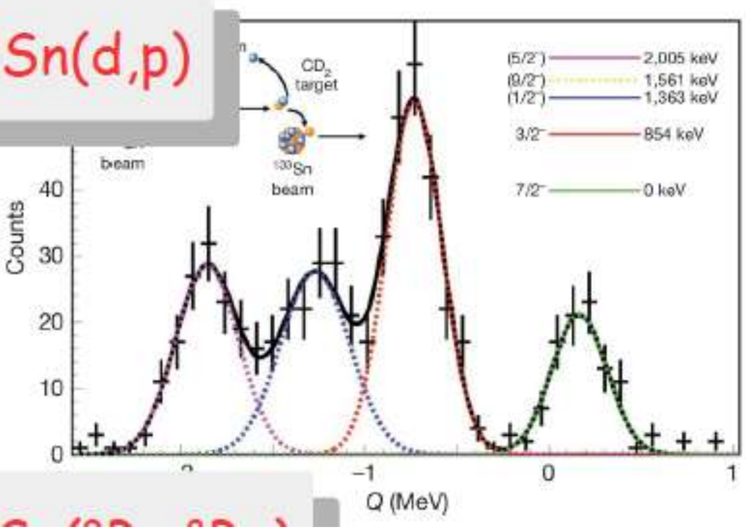
Underabundance of ^{66}Zn, r process Nd, Sm (A~150)



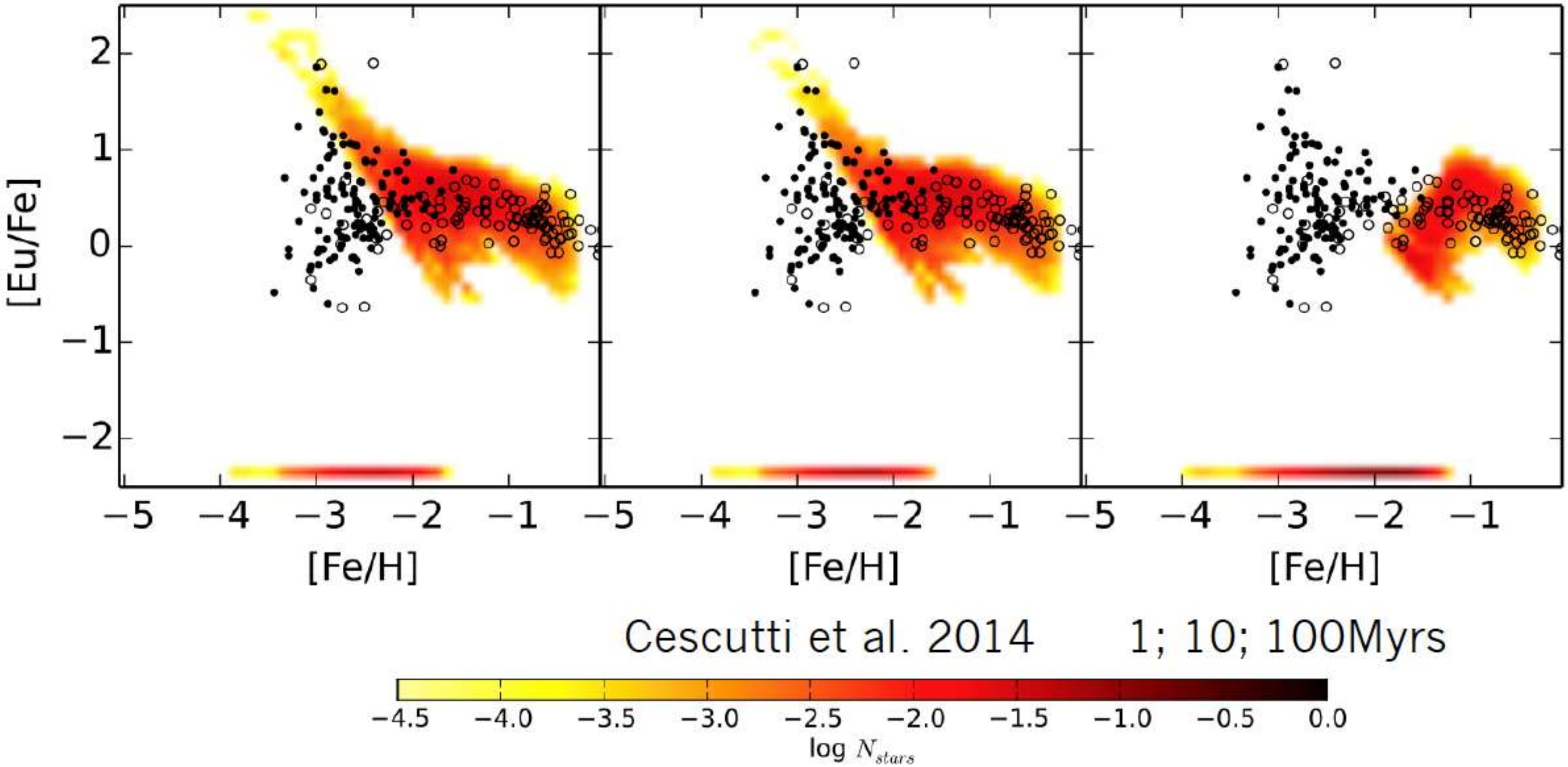
^{130}Sn(d,p)



^{132}Sn(d,p)



R process in NS-NS: timescale problem



To make binary star mergers (BNS, NS-NS) as a contributor to the early galactic evolution, one needs to assume their very fast occurrence (much faster than commonly thought) and add some CCSNe contribution on top as BNS cannot produce modest enhancements in Eu.

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

EMP stars

Extremely Metal Poor stars

The chemical composition of the atmosphere of the **old stars,** born at the very beginning of the Galaxy, is the witness of the chemical composition of the gas in the early matter.

How to find them ?

Since at their birth the matter was enriched by a very small number of supernovae, they are very metal-poor.

Metallicity is taken as a criterion of primevality

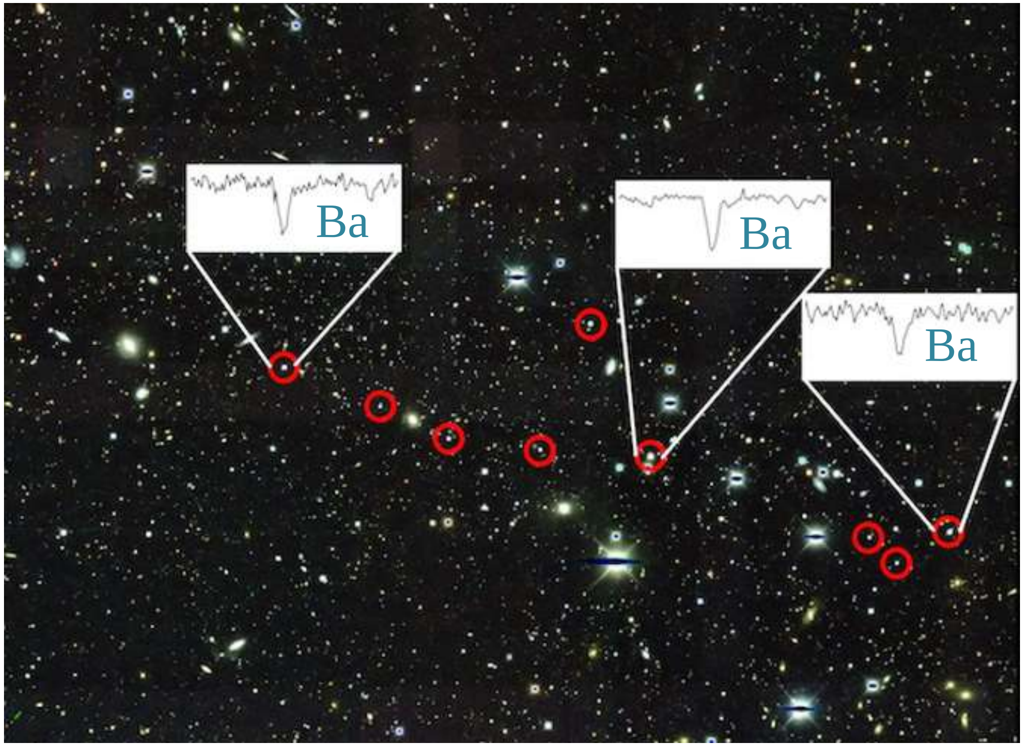
Definitions: $[Fe/H] = \log (Fe/H)_{\star} - \log (Fe/H)_{\odot}$

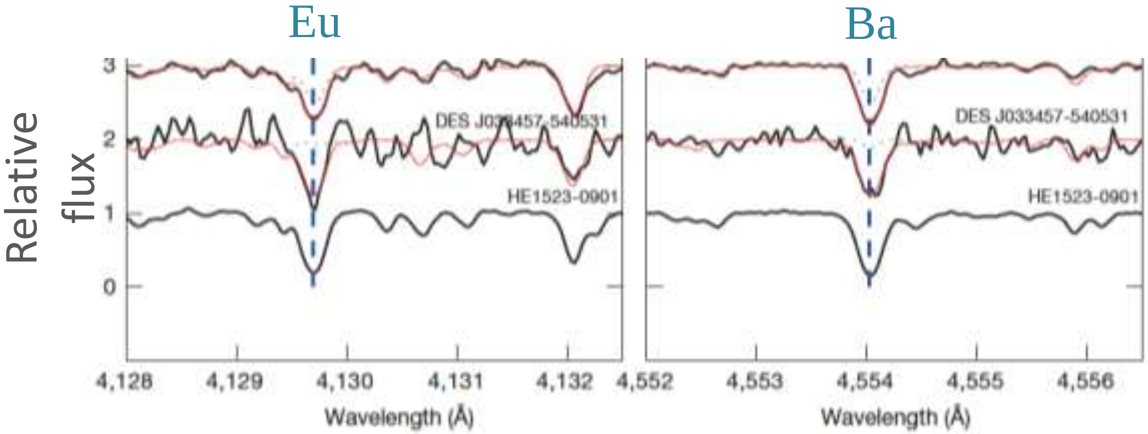
$([X/H] = \log (X/H)_{\star} - \log (X/H)_{\odot} \ldots)$

ex: $[Fe/H] = -2$ → 100 times less iron than the Sun

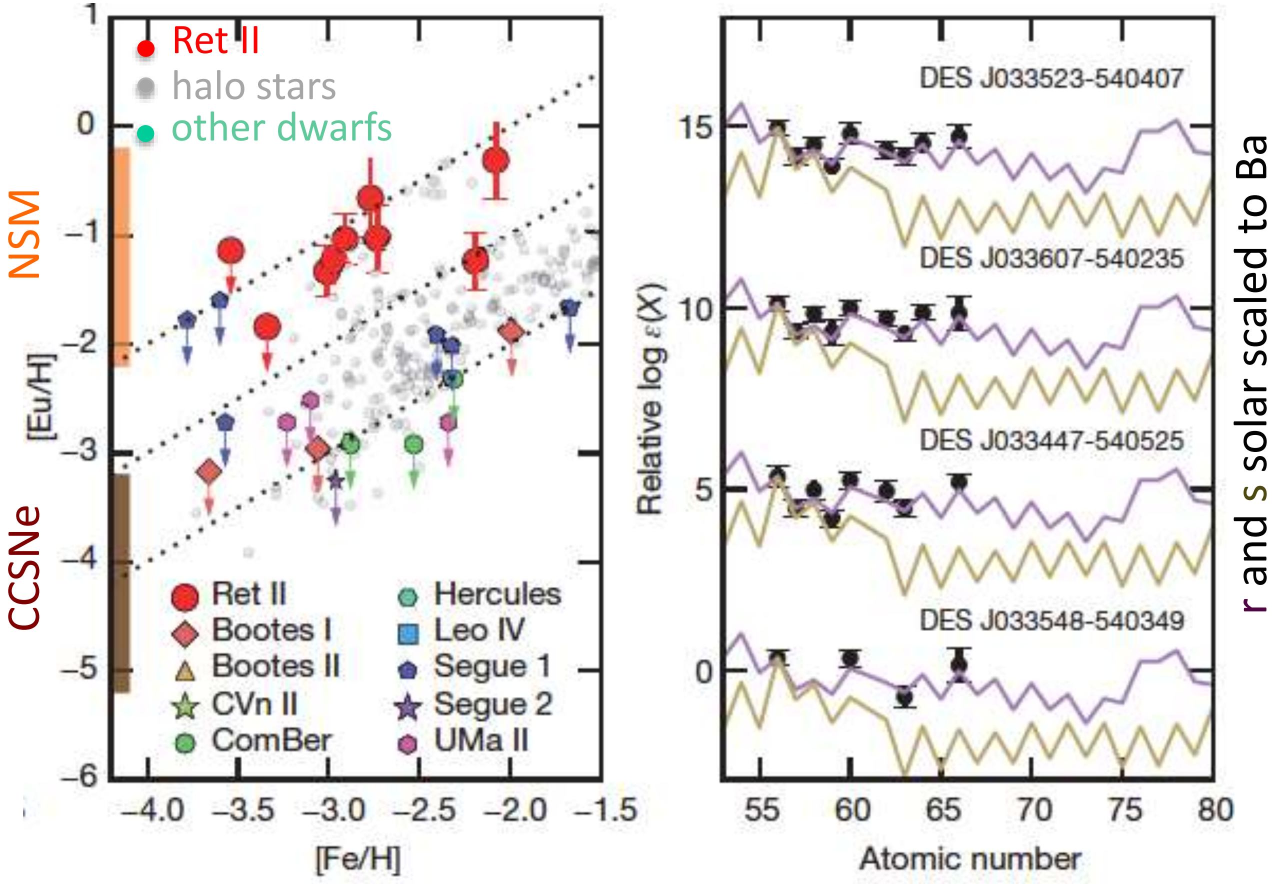
Clues from outside the galaxy

Dark energy Survey / Fermilab, ret II dwarf galaxy : Ji, Frebel et al.





Clues from outside the galaxy



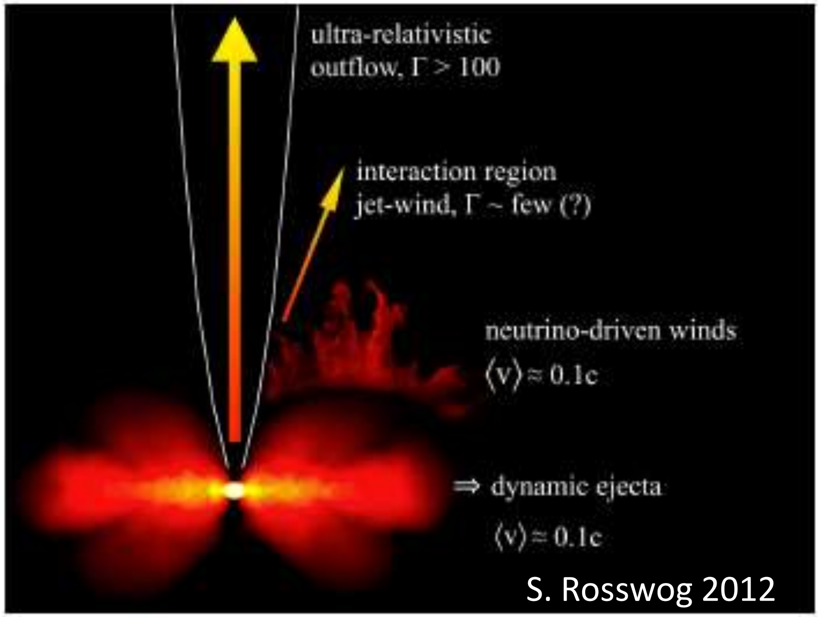
Ji et al. Nature 2016

Given the amplitude and constancy in r-process enrichment, a single event is the most likely. This implies a single large-mass r process, likely to originate from NS-NS binary (CCSNe gives much smaller mass rate).

r-process in stars: where ?

One of the biggest remaining question …

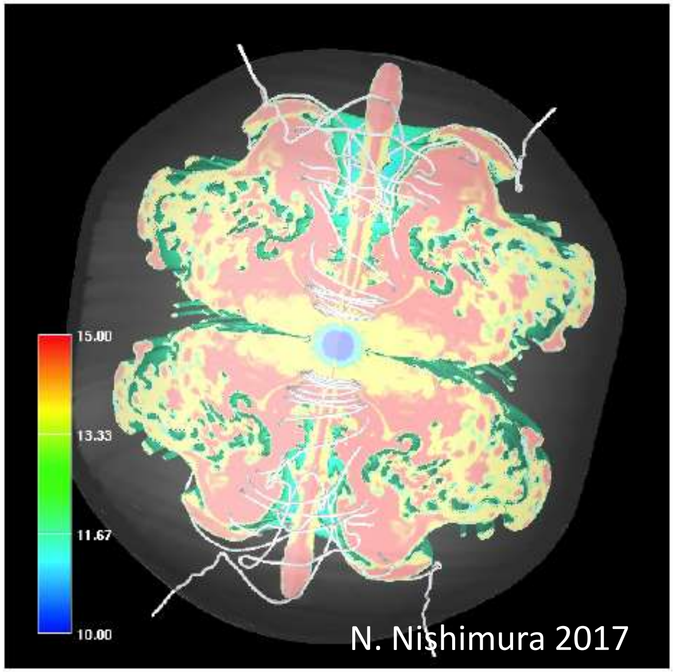
Binary neutron stars:
Matter ejection and r-process nucleosynthesis from dynamic ejecta and eutron driven wind



S. Rosswog 2012

Expected to produce and eject a lot of r elements. They are however rather rare events.

Highly-magnetized core-collapse supernovae

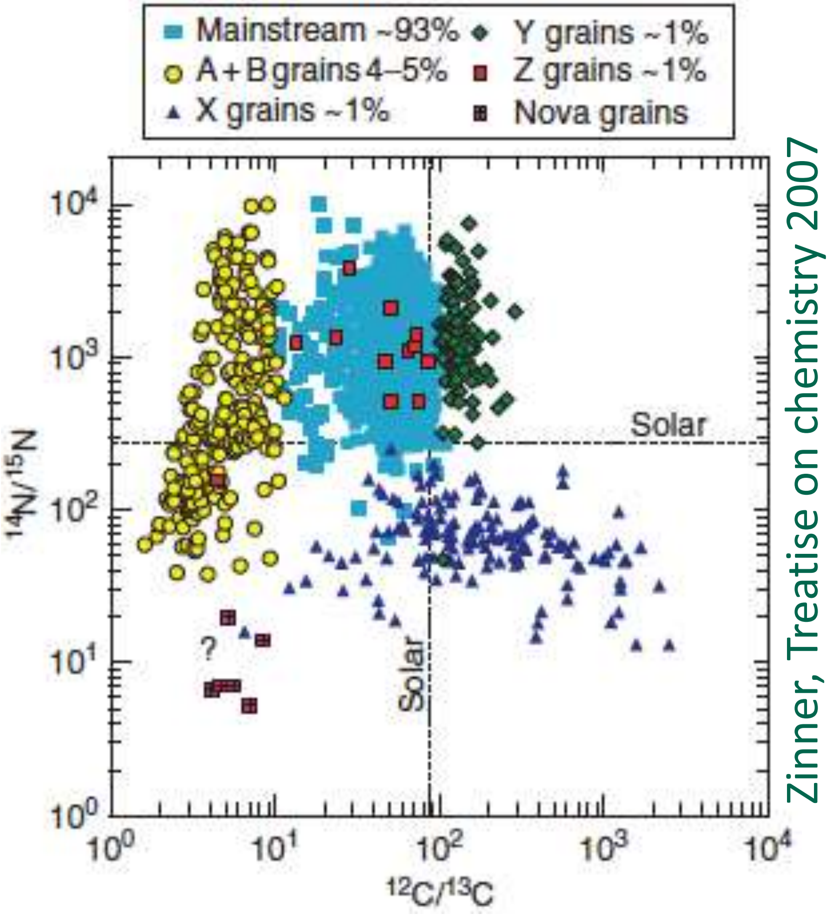


N. Nishimura 2017

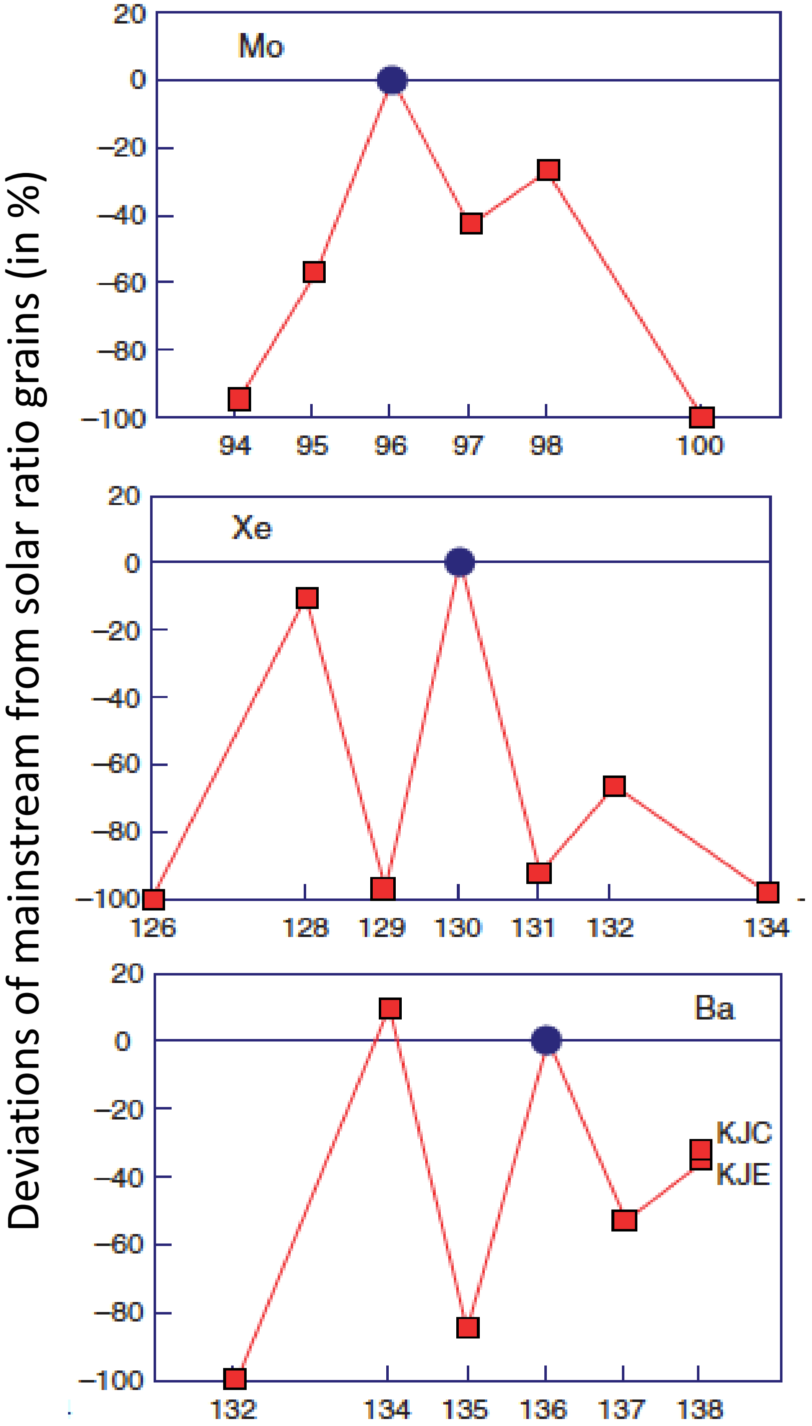
Only highly magnetized CCSNe may have suitable conditions to develop r process nucleosynthesis

Deduce the stellar site(s) of the r-process from observations of poorly-mixed stars

Categories of Si-C grains



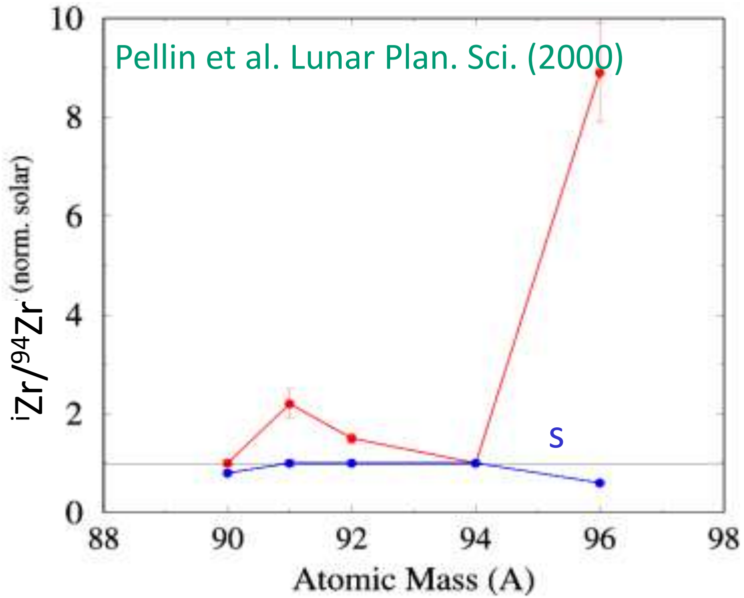
Zinner, Treatise on chemistry 2007

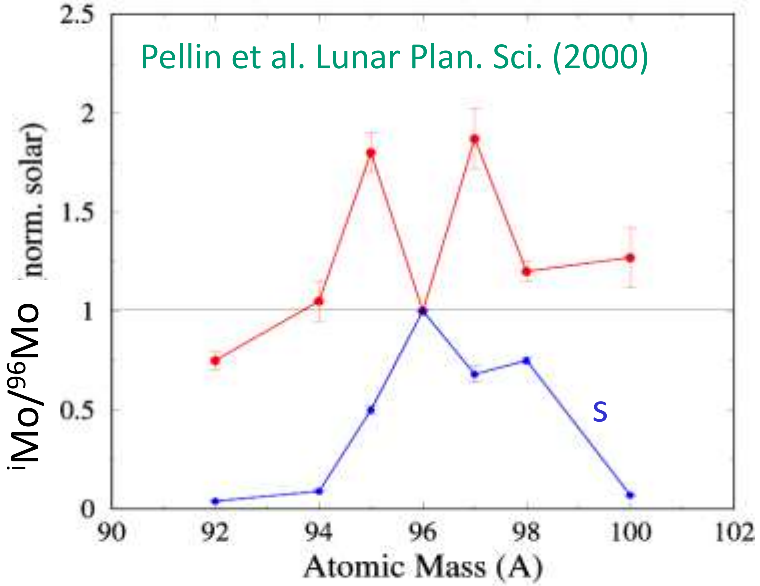


Isotopic compositions of mainstream grains differ significantly from solar ones (depleted in p and r) -> their origin is clearly extra solar. Their isotopic composition is typical of an s process.

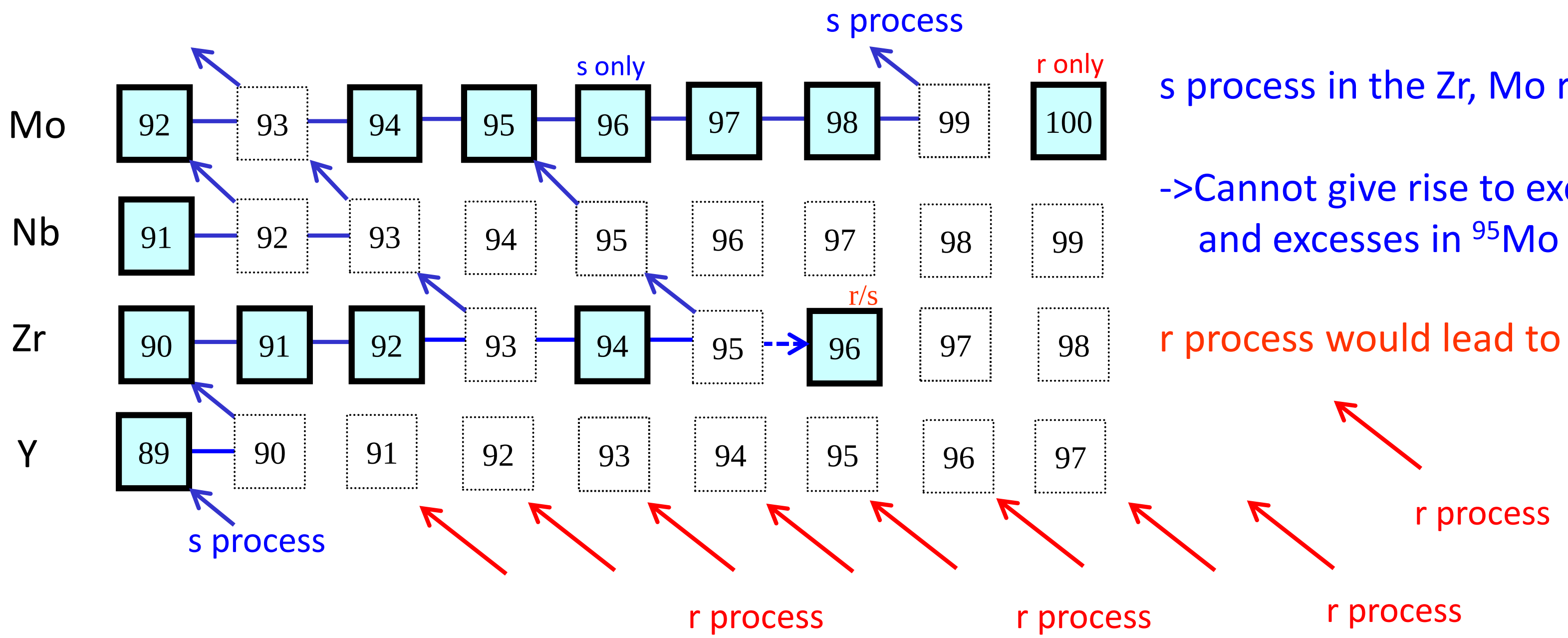
X grains likely come from supernovae explosions

Mo, Zr anomalies in Si-C presolar type x grains





Abundance patterns in Zr and Mo are intermediate between s and r



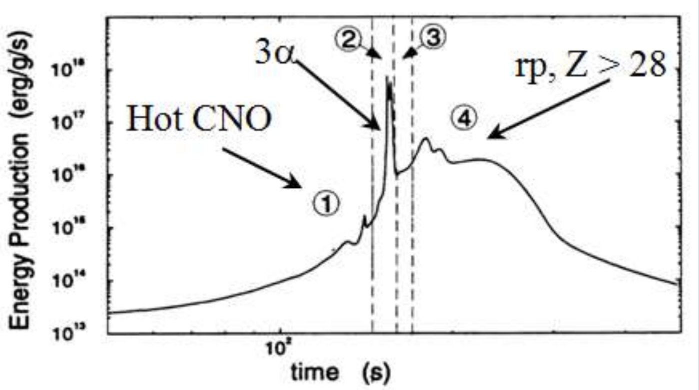
s process in the Zr, Mo region

->Cannot give rise to excess in ^{96}Zr and excesses in ^{95}Mo and ^{97}Mo.

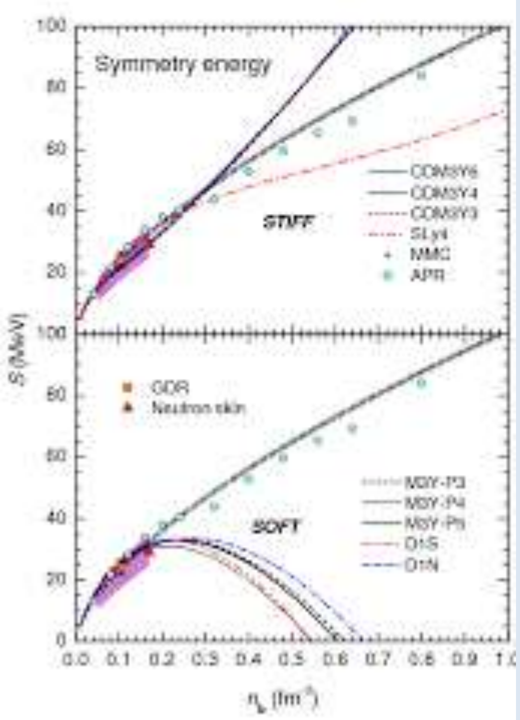
r process would lead to enhanced ^{100}Mo

Nuclear astrophysics

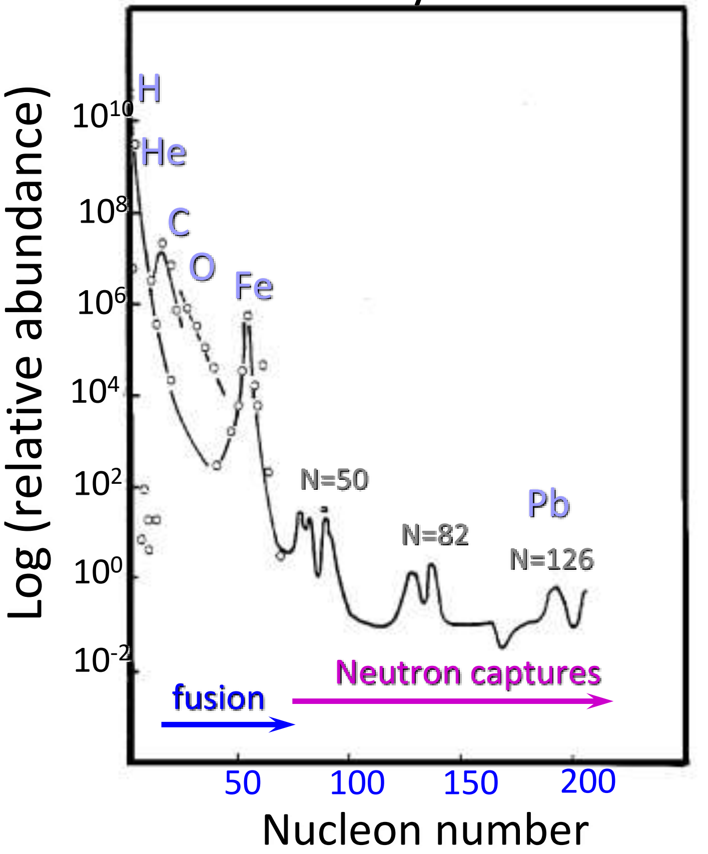
Nuclear reactions in stars



EOS of nuclear matter



Nucleosynthesis



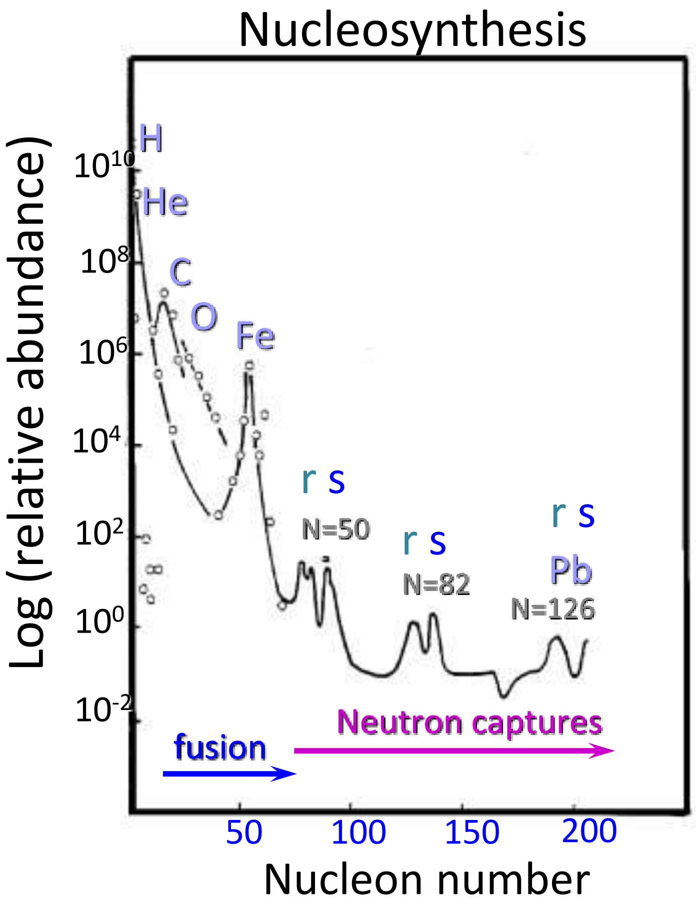
Strong connexions with:

Stellar hydrodymanics

Astronomy, geocosmochemistry

Galactic chemical evolution

Abundance curve of the elements in solar sytem



Decreasing trend / reduced fusion cross section

Fe peak -> stronger binding energy per nucleon

Flat component afterwards -> neutron captures

Double peaks -> (at least) 2 classes of processes connected to closed shells

Decomposition of the 2 processes (r,s)

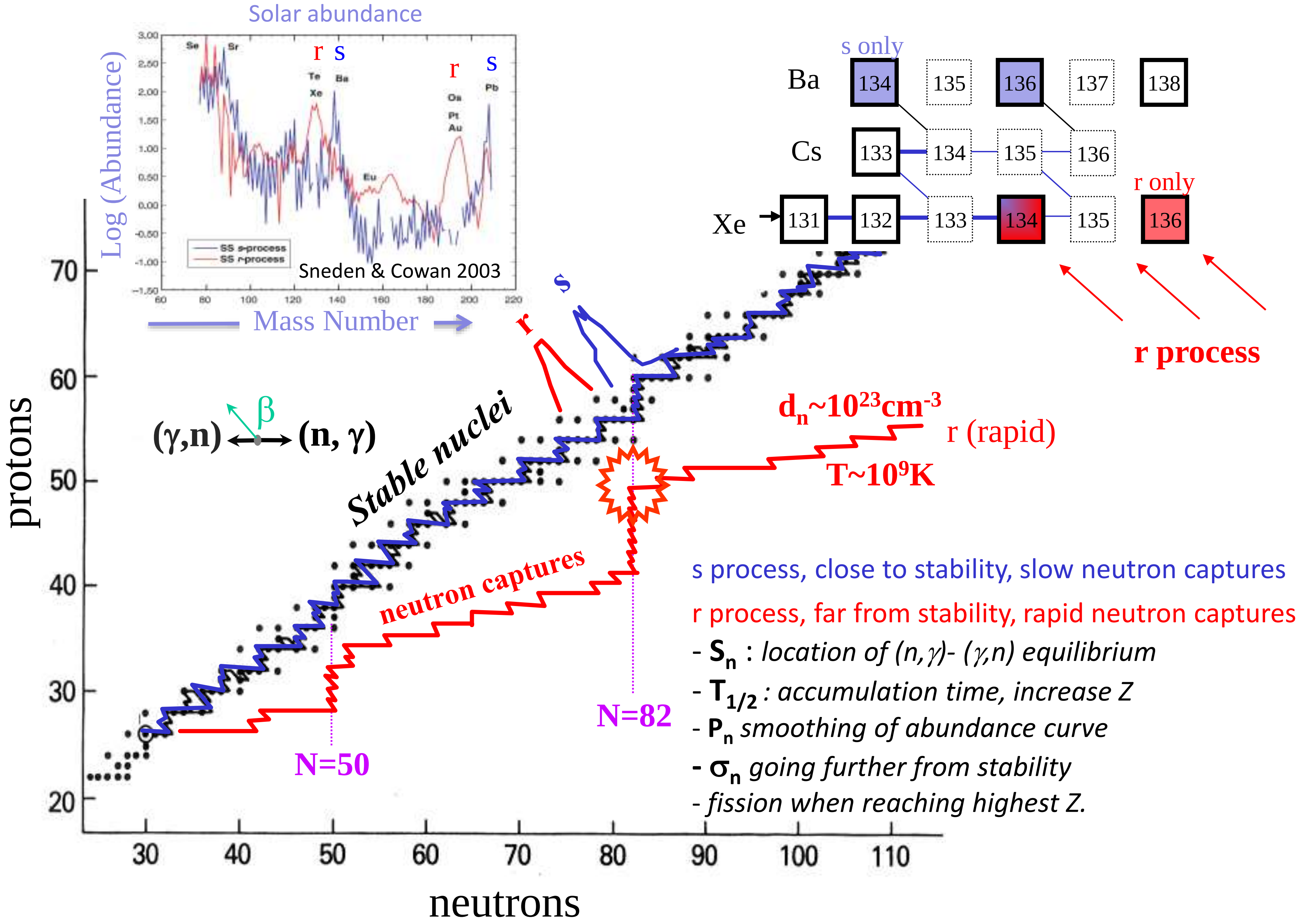
Abundance in SS may come from many successive enrichments of different elemental patterns

Search for ‘young’ stars:
 -> less mixing
-> Hopefully disentangle between s and r processes

Do young stars still exist ?

Where / how to find them ? Which composition ?

Neutron capture processes: classical picture



s process, close to stability, slow neutron captures

r process, far from stability, rapid neutron captures

- **S_n** : *location of (n,γ)- (γ,n) equilibrium*
- **$T_{1/2}$** : *accumulation time, increase Z*
- **P_n** *smoothing of abundance curve*
- **σ_n** *going further from stability*
- *fission when reaching highest Z.*

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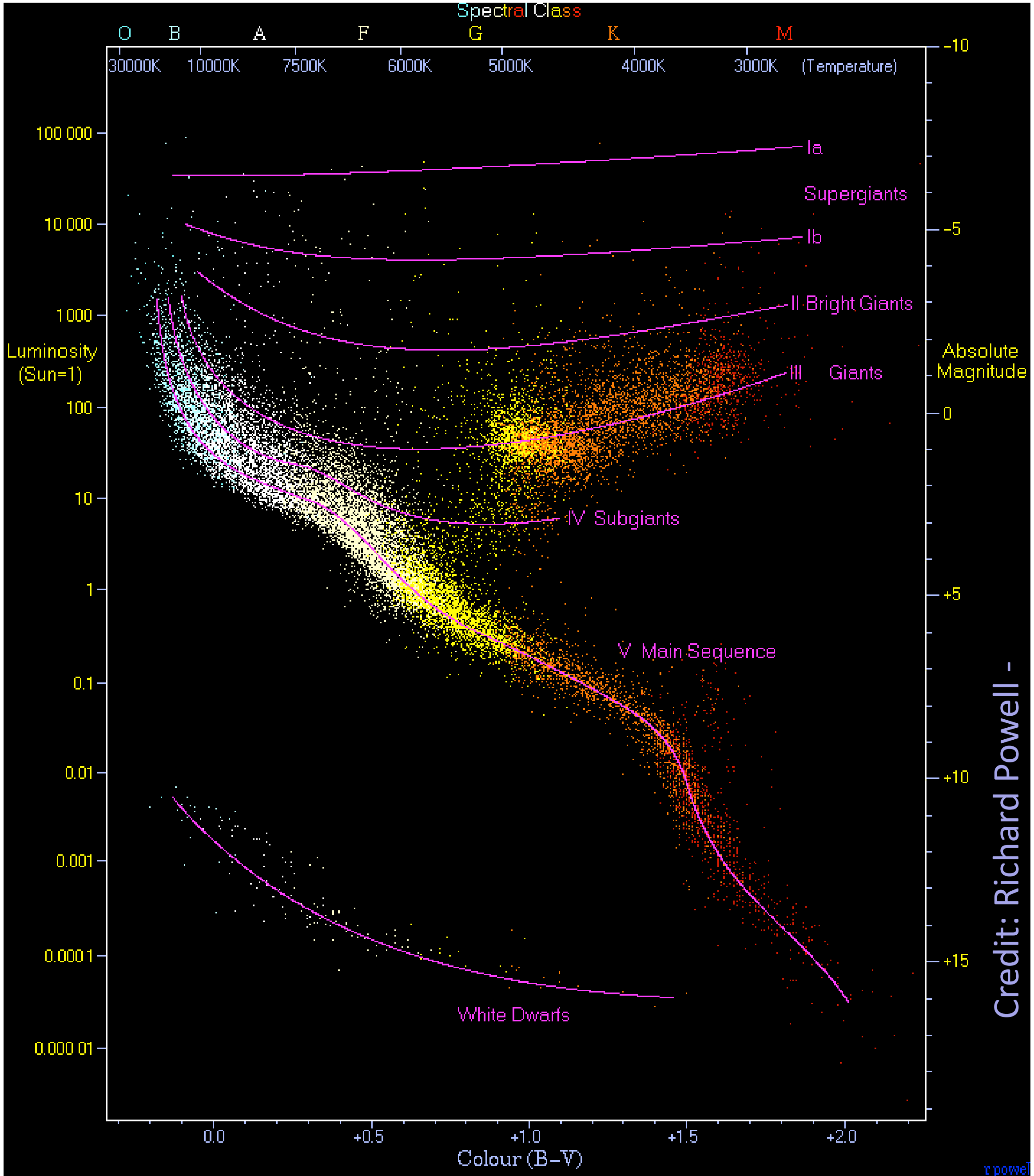
With materials from V. Hill, M. Spite and M. Pignatari

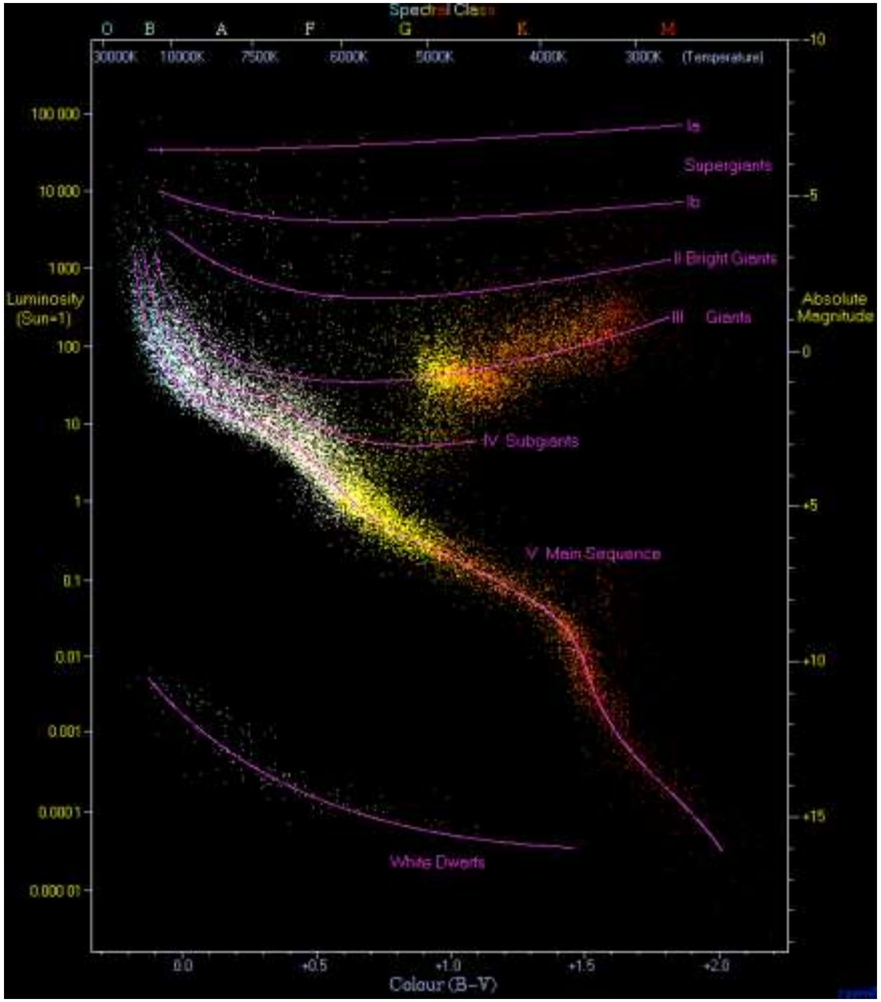
The Hertzprung – Russel diagram



Credit: Richard Powell -

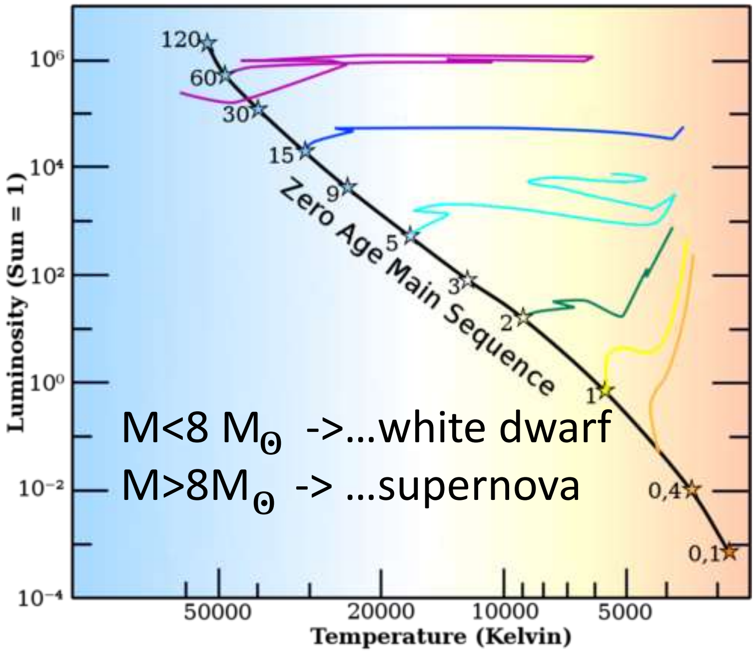
A simplistic history of stellar evolution

The Hertzprung – Russel diagram



Credit: Richard Powell -

← Log (Temperature) —



$M<8\ M_{\odot}$ ->…white dwarf

$M>8M_{\odot}$ -> …supernova

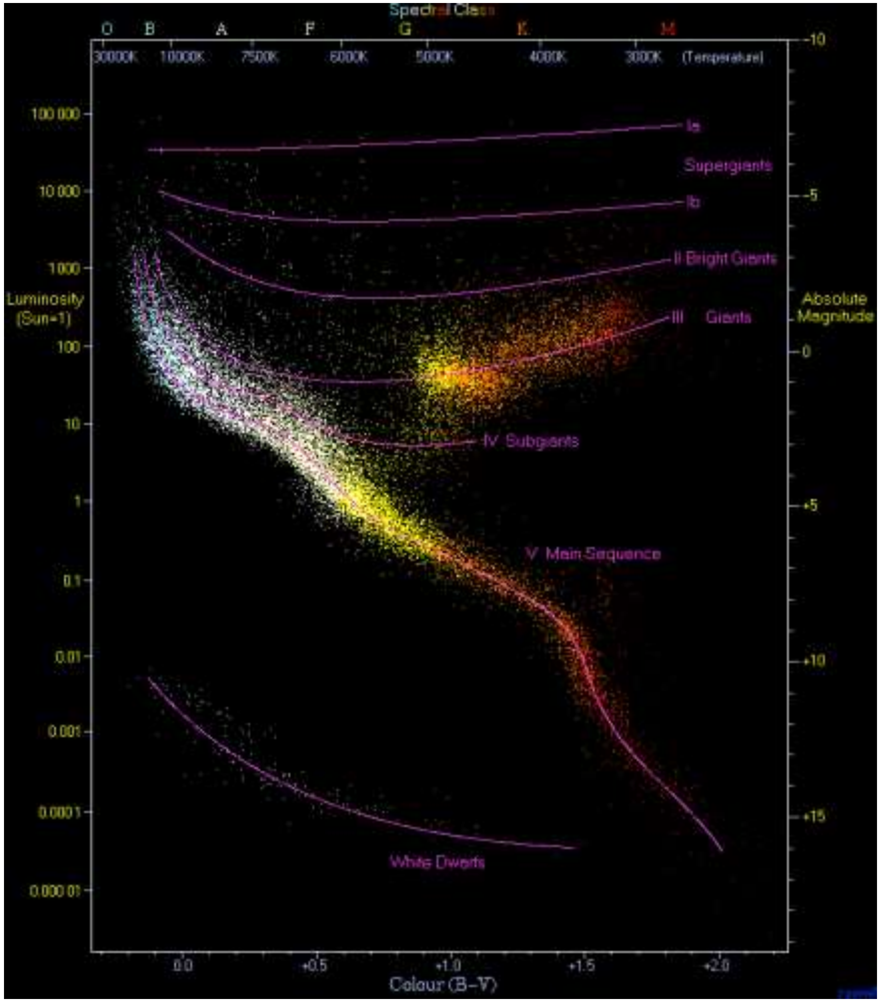
Stars leave the MS when a large fraction of H has fused. It contracts and initiate more H to fuse, thus becoming brighter. It increases its radius, making its surface cooler (more red).

When the star’s mass is large enough, He start to burn and the star moves on the AGB phase. In this phase outer layer can mix with interior

At the end of their life stars that cannot ignite C burning end up in WD, otherwise in SN

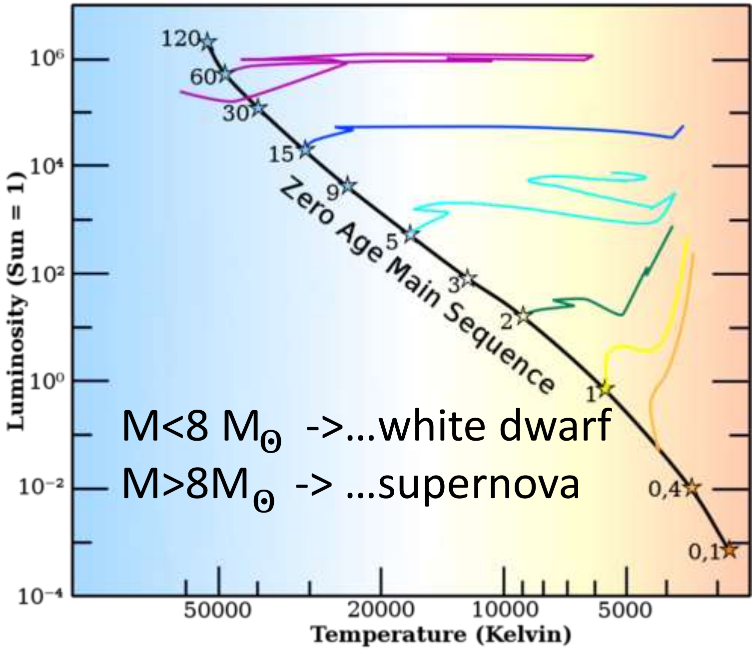
A simplistic history of stellar evolution

The Hertzprung – Russel diagram



Credit: Richard Powell -

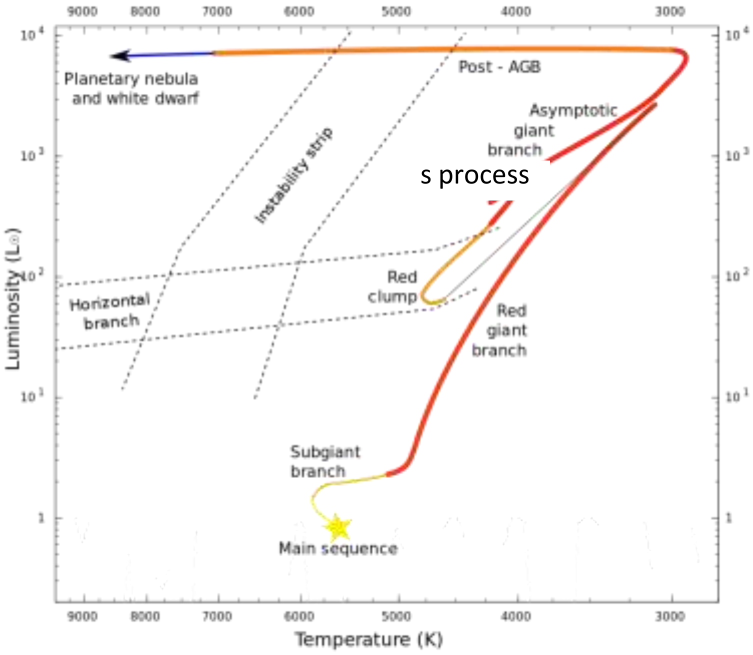
← Log (Temperature) —



$M<8\ M_\odot$ ->…white dwarf

$M>8M_\odot$ -> …supernova

Evolution of a 1 $M_\odot$ star



s process

Planck : age of the Universe 13 800 x10^6 yr

lifetime of the stars

luminosity ~∝ $\mathcal{M}^4$
quantity of fuel ∝ $\mathcal{M}$

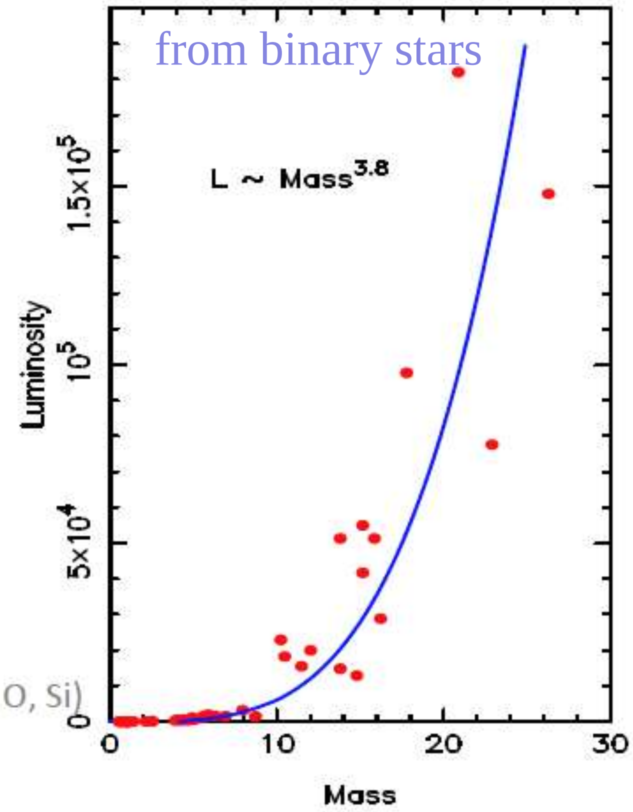
➔ **More a star is massive more its lifetime is short…**

	lifetime
0.8 $\mathcal{M}_\odot$	15 000 x10^6 yr
1 $\mathcal{M}_\odot$	10 000 x10^6 yr
6 $\mathcal{M}_\odot$	113 x10^6 yr

$\mathcal{M} < 8\ \mathcal{M}_\odot$
core becomes degenerate after
He burning phase → white dwarfs

10 $\mathcal{M}_\odot$	31 x10^6 yr
30 $\mathcal{M}_\odot$	2 x10^6 yr
60 $\mathcal{M}_\odot$	0.4 x10^6 yr

$\mathcal{M} > 8\ \mathcal{M}_\odot$
succession of burnings (H, He, C, Ne, O, Si)
an iron core is formed.
The core collapse → SNII



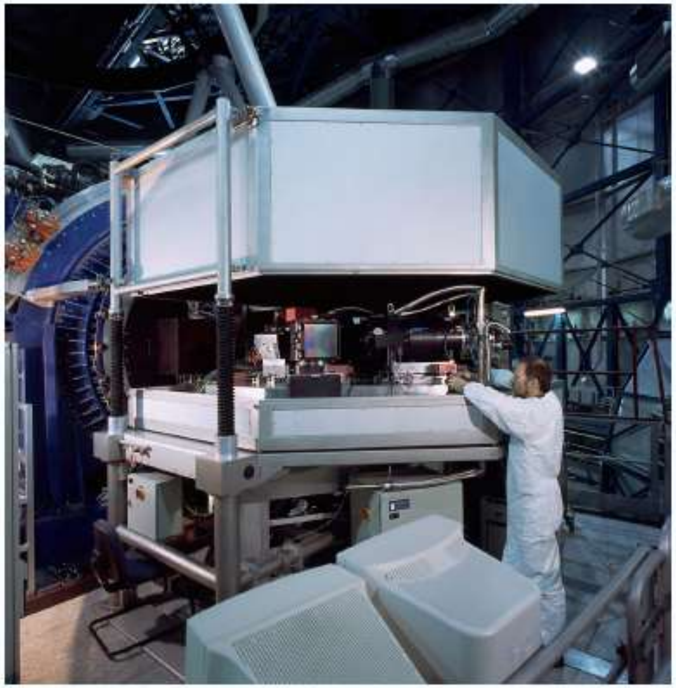
from binary stars

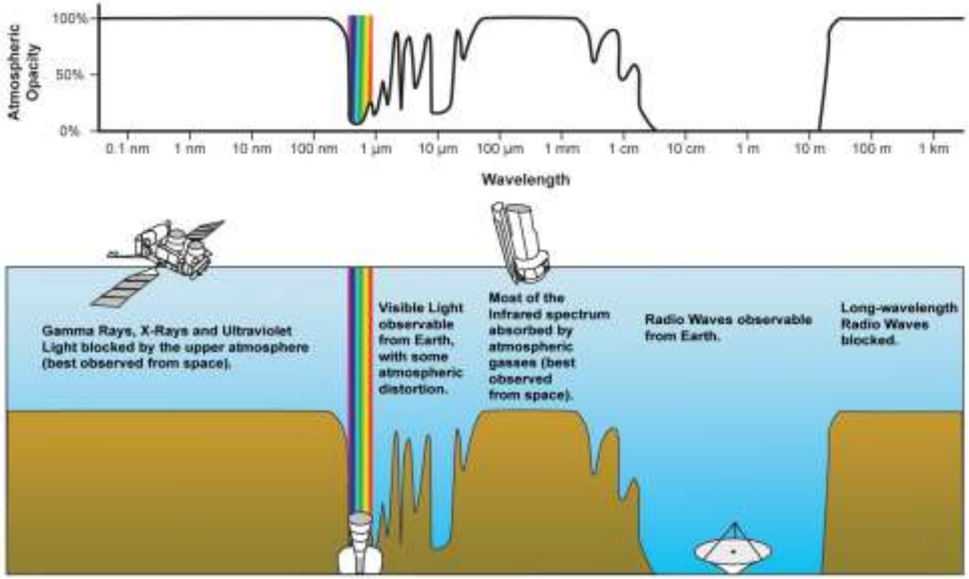
t_{MS} (yrs) ≈ 10^{10} $(M/M_\odot)^{-2.8}$

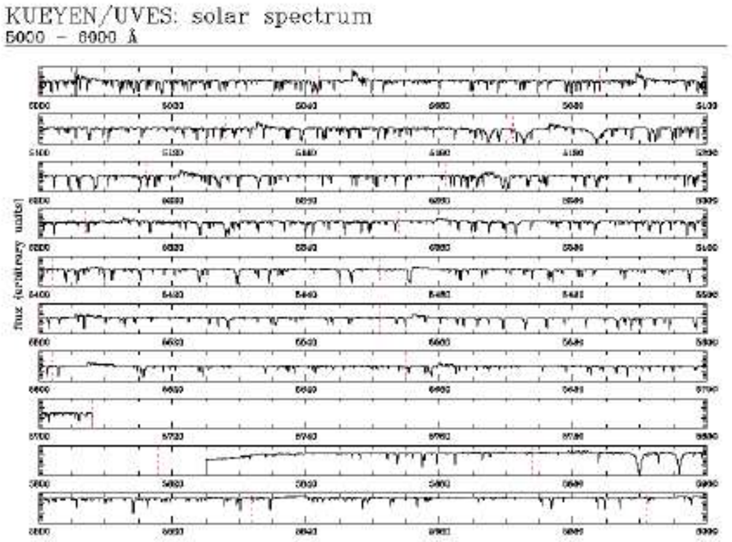
- **If in the first Gyr, stars were formed with $\mathcal{M} < 0.9\ \mathcal{M}_\odot$, they are still shining today** (main sequence stars or giants)

- **In this first Gyr only massive stars $\mathcal{M} > 5\ \mathcal{M}_\odot$ had time to enrich the matter**

How to measure elemental abundances in stars ?



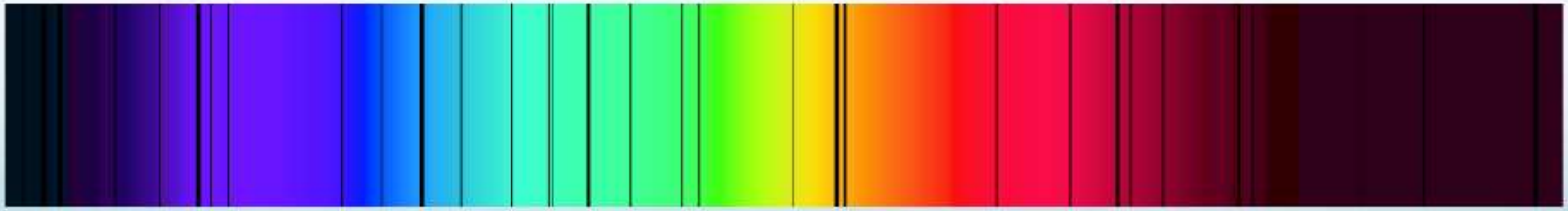




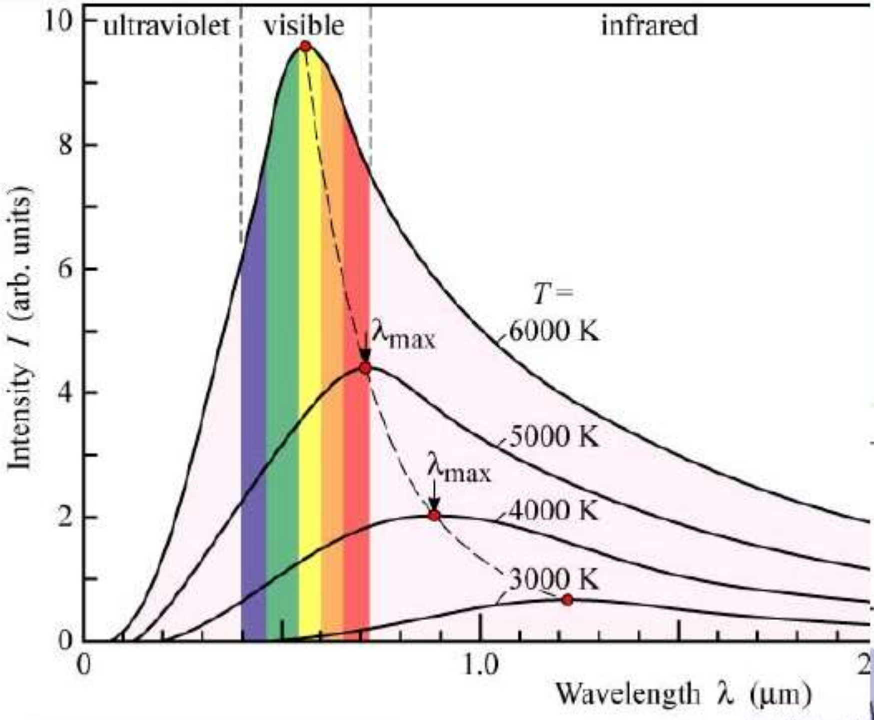
Absorption Spectra

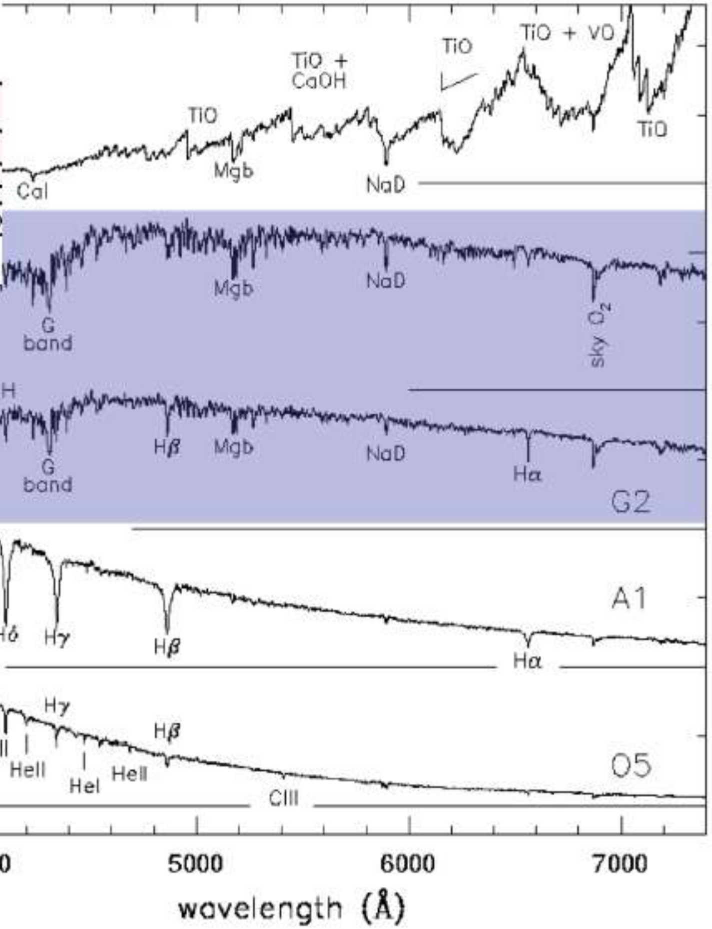
Absorption spectra occur when electromagnetic radiation from a background star passes through a relatively cold gas. Long lived stars ("fossils") mostly belong to this case, and have Teff up to ~6500K.

- Radiation at specific wavelengths from the star interacts with (is absorbed by) atoms in the cold gas, causing their electrons to gain energy and enter excited states.
- These electrons quickly de-excite and emit photons at the same wavelengths. However, the direction of the emitted light is random and this leads to the appearance of dark lines (or missing light) in the resulting spectra, corresponding to the wavelengths that were absorbed by the gas. These lines are known as absorption lines.



Temperature drives the spectra appearance





T ~ 4000K

Molecules!

Mainly neutral metal lines

T ~ 6000K

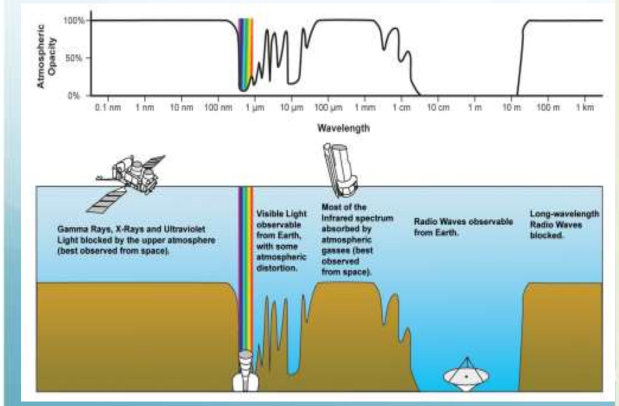
Ionised Metal lines

T < 11 000K

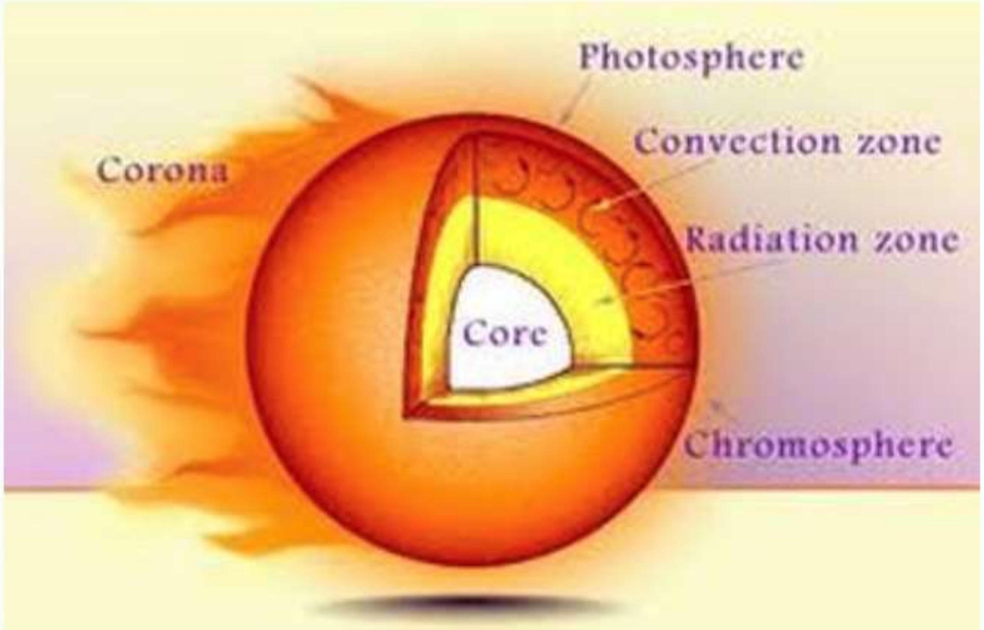
Dominated by neutral H

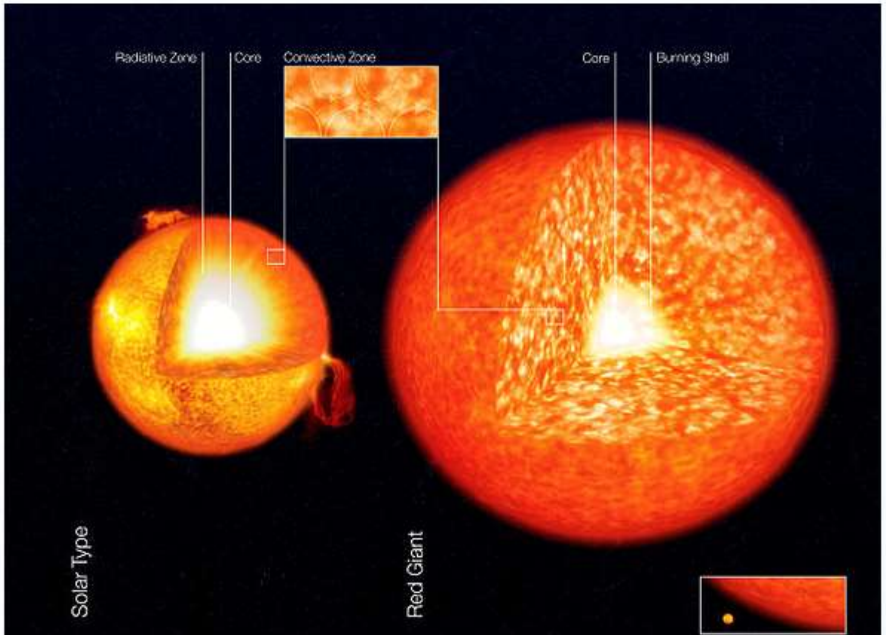
T ~ 30 000K

Highly ionised species



What part of the star do we "see"?





Stellar light emitted at the solar photosphere radiates through the stellar atmosphere where absorption lines are formed. Hence, observation probe the composition at the surface of the star

In low-mass stars (about 1 solar mass) , the convective zone does not reach the very center of the star where nuclear reaction take place -> the surface contain the initial composition at the birth of the star or that of the initial gas in which it formed

In giant stars, mixing episodes can occur when the star leaves the main sequence. It implies that some internally products isotopes can be dredged up to the surface (^{13}C, ^{14}N), while some more fragile ones can be depleted at the surface (Li).

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

Neutron sources in the s process

Low mass AGB stars < 3 $M_\odot$

Low temperature 10^8 K

${}^{12}\mathrm{C}(p,\gamma){}^{13}\mathrm{N}(\beta^-){}^{13}\mathrm{C}(\alpha,n)$

Flux 10^8 n cm^{-3}

Duration 10^5 y, A > 80

Main component

Intermediate mass AGB > 3 $M_\odot$

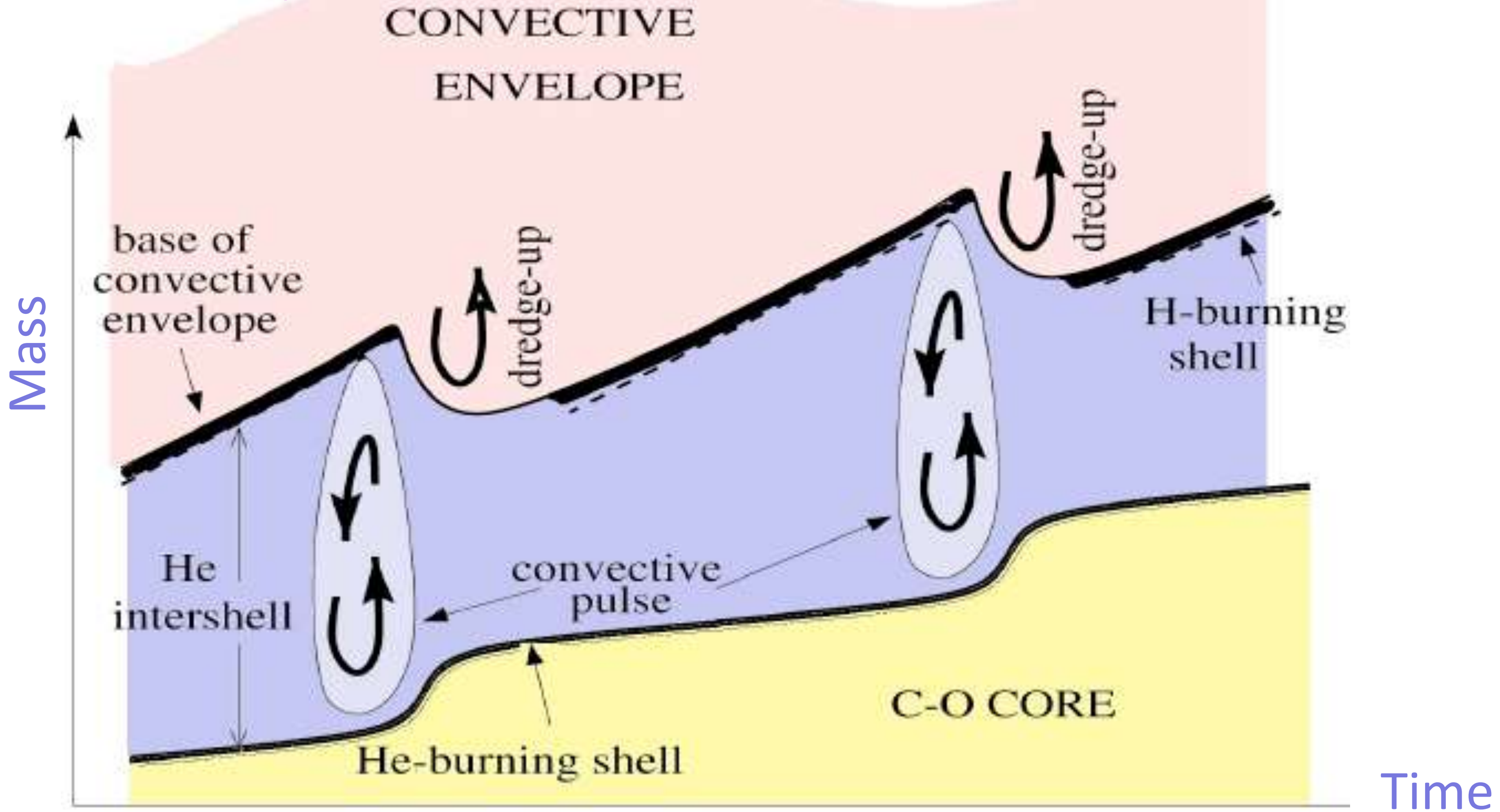
Higher temperature 3 10^8 K

${}^{14}\mathrm{N}(\alpha,\gamma){}^{18}\mathrm{F}(\beta^+){}^{18}\mathrm{O}(\alpha,\gamma){}^{22}\mathrm{Ne}(\alpha,n)$

Flux 10^{13} n cm^{-3}

Duration 10 y, A ≈ 60-80

Weak component

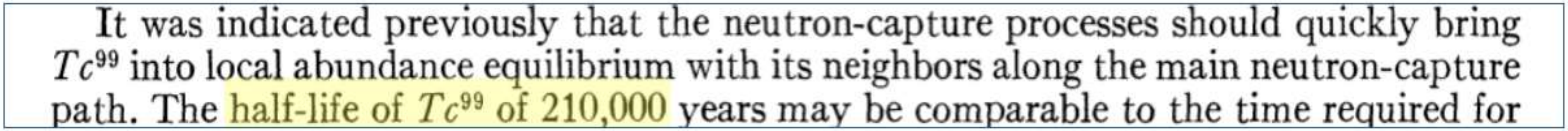


s-process n-captures ongoing in stars

1952 Merrill find Tc lines in S stars (AGB stars)

Tc is a short period radioactive element **not observed**
on earth
in the meteorites
in the Sun

1955 Cameron shows that neutron captures on iron seeds are able to explain the presence of Tc in S stars



It was indicated previously that the neutron-capture processes should quickly bring Tc^{99} into local abundance equilibrium with its neighbors along the main neutron-capture path. The half-life of Tc^{99} of 210,000 years may be comparable to the time required for

-> s process nucleosynthesis

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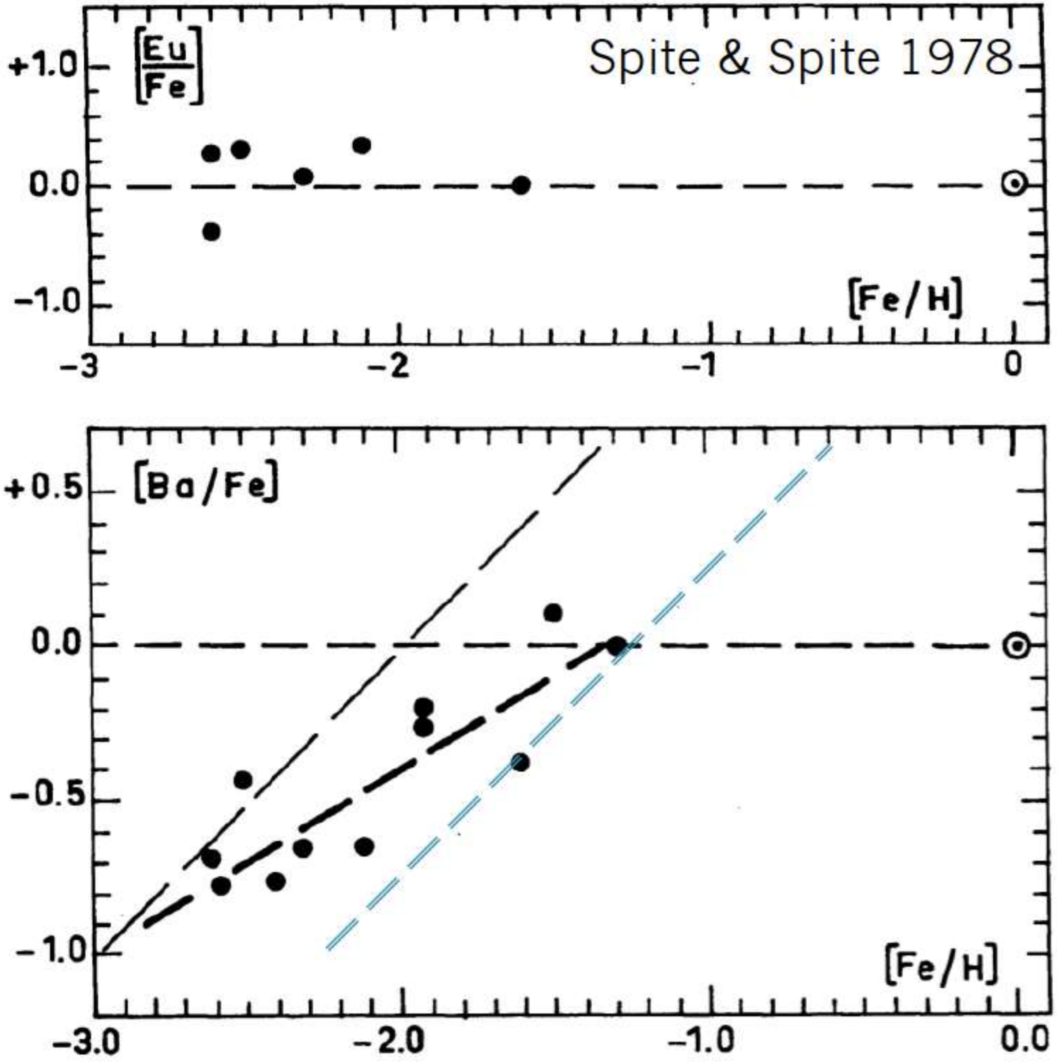
Heavy n-captures in metal-poor stars



- Eu (almost pure r-process nuclei in the Sun), is slighlty enhanced in low metallicity stars unlike Ba, Y which decreases at low metallicities
- Ba and Y "s-process" nuclei have a different trend with [Fe/H] than a secondary process would allow.
- Truran (1981) was the first to propose a coherent picture of the s- and r-process elements in the galaxy, where the r- process occurs in a primary way in short-lived contributors.

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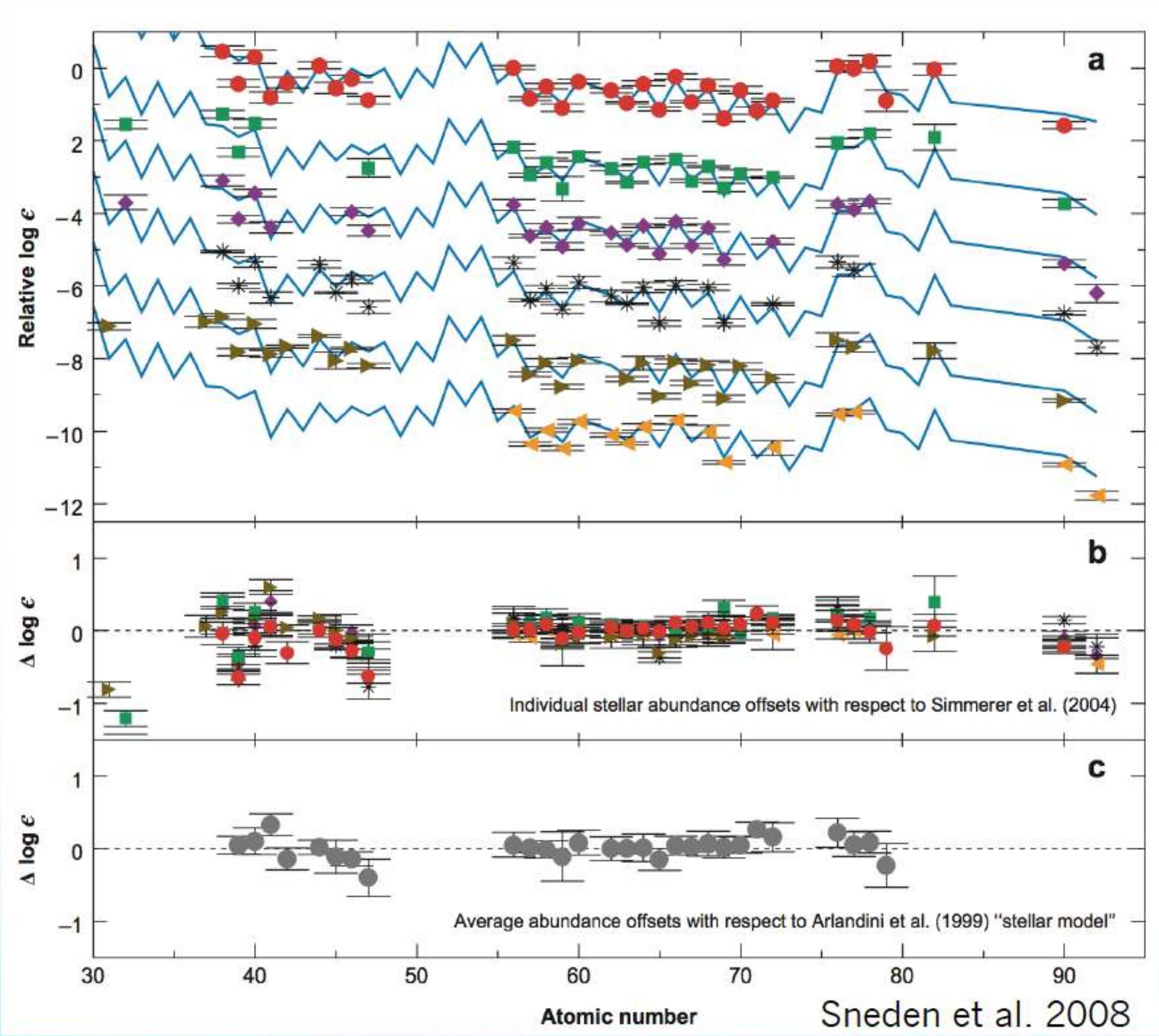
A universal r-process?



Sneden et al. 2008

Above Z=56

Very robust pattern

Top & bottom galactic halo

Globular cluster stars

Outside the galaxy

Below Z=56

Less robust pattern

Another process ?

Correlations between them ?

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End of Lecture I.

Take away messages:

Elements heavier than Fe are produced by neutron capture processes

There exists two major categories of processes with low and high densities

s-process nucleosynthesis is observed and ongoing in AGB stars

r-process site(s) is so far unknown: supernova, neutron star mergers…

Observation in EMP display similar pattern above Z=56 -> robust r

Below Z=56, many more fluctutaions -> weak r process

Other signature of weak r process exist in CEMP-i stars and in meteorites