# The Origin of the Elements between Iron and the Actinides – Probes for Red Giants and Supernovae

**I** Outline of scenarios for neutron capture nucleosynthesis (Red Giants, Supernovae) and implications for laboratory studies, status of available data

**II** Accelerator neutron sources, experimental techniques based on the time-of-flight method, state-of-the-art detectors

**III** Stellar spectra in the lab, activation method for *s*- and *p*-process studies, observational constraints.

# Heidelberg, main street 59

# nucleosynthesis 1900

# milestones of nucleosynthesis

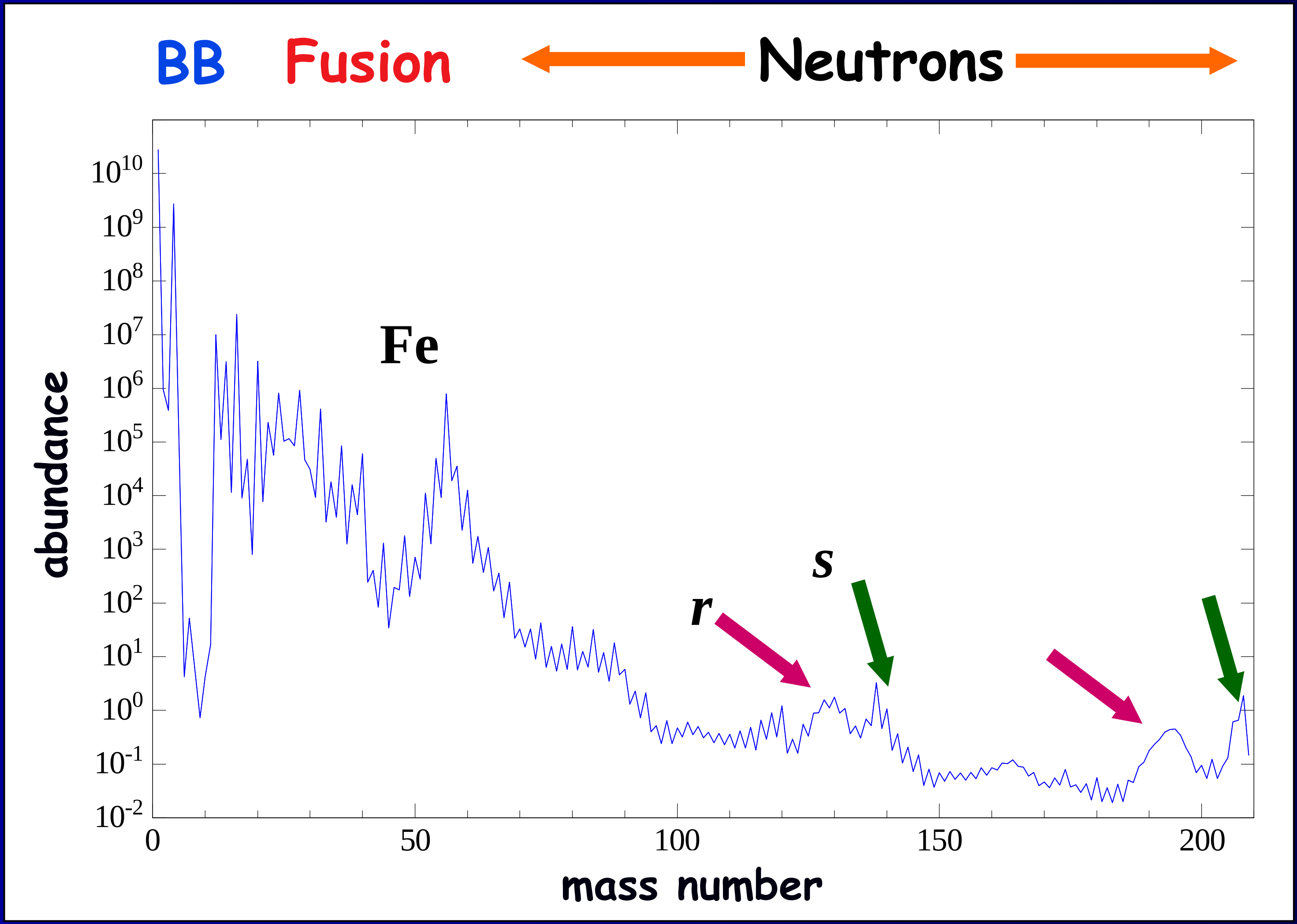
**1937** first systematic tabulation of solar abundances by Goldschmidt

**1937 - 39** pp chain and CNO cycle identified as stellar energy sources by Bethe & Critchfield and by von Weizsäcker

**1952** discovery of Tc in Red Giant stars by Merrill: evidence for stellar nucleosynthesis

**1957** fundamental paper on nucleosynthesis by Burbidge, Burbidge, Fowler & Hoyle ($B^2FH$) Rev. Mod. Phys. 29, 547 (1957)

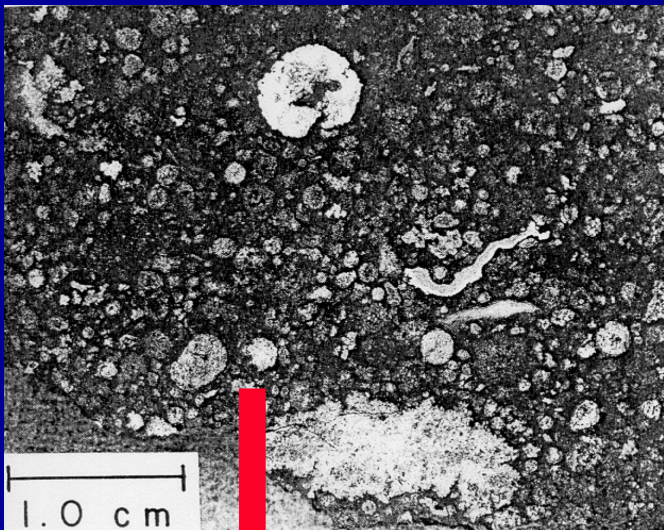
# abundances beyond Fe – ashes of stellar burning and SNe

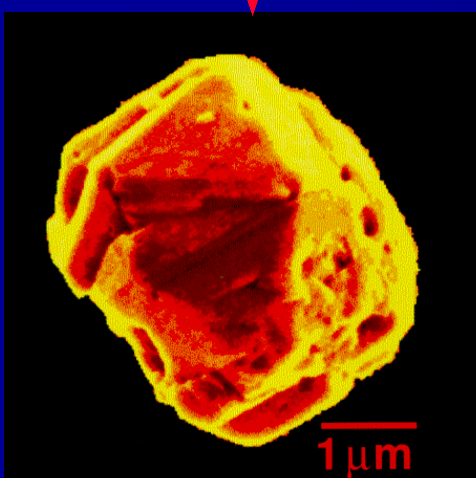


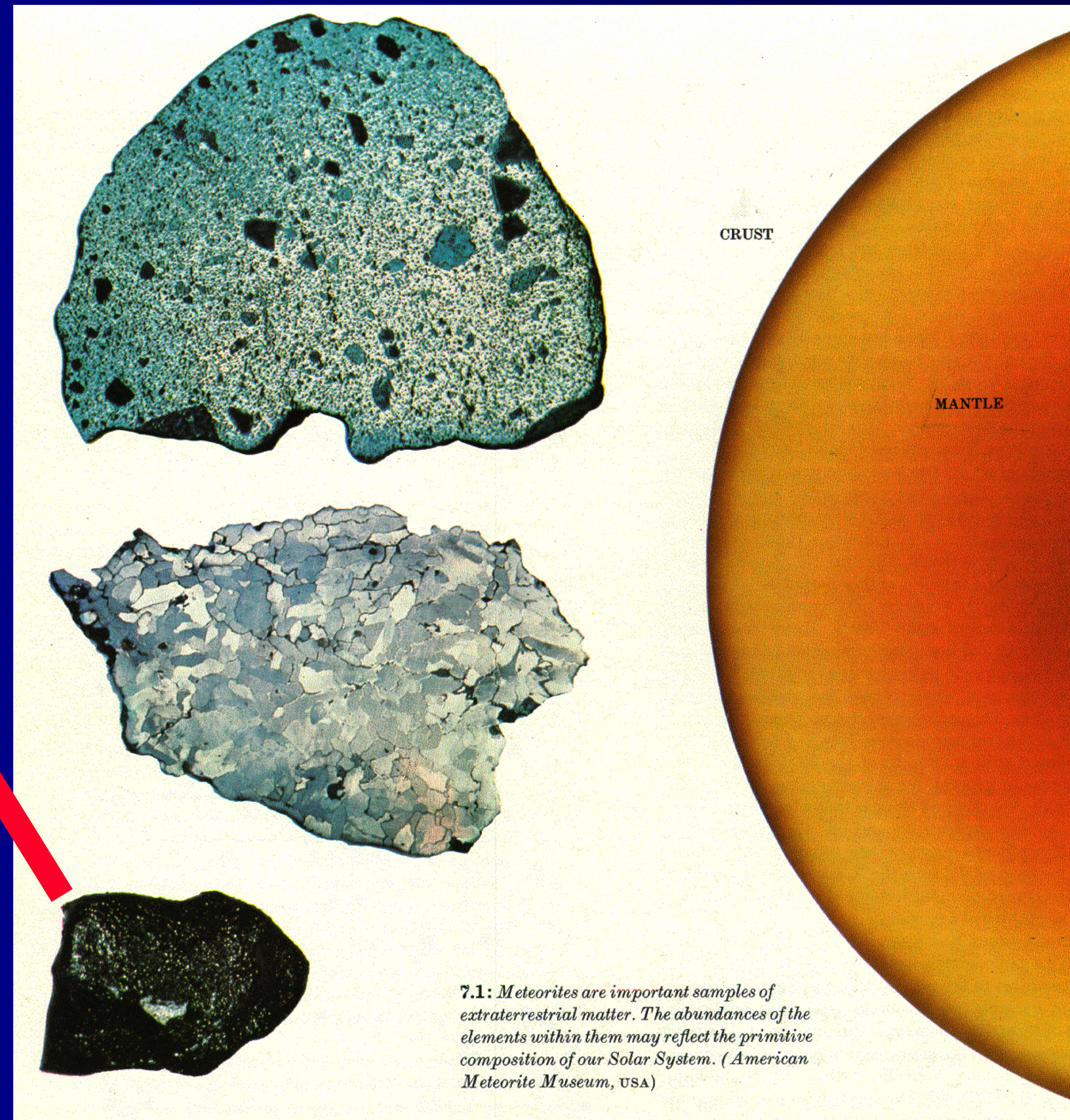

| | |
|---|---|
| H | 30 000 |
| C | 10 |
| Fe | 1 |
| Au | $2\ 10^{-7}$ |

neutrons produce 75% of the stable isotopes, but only 0.005% of total abundances

# sources of abundance information




**7.1:** *Meteorites are important samples of extraterrestrial matter. The abundances of the elements within them may reflect the primitive composition of our Solar System. (American Meteorite Museum,* USA)

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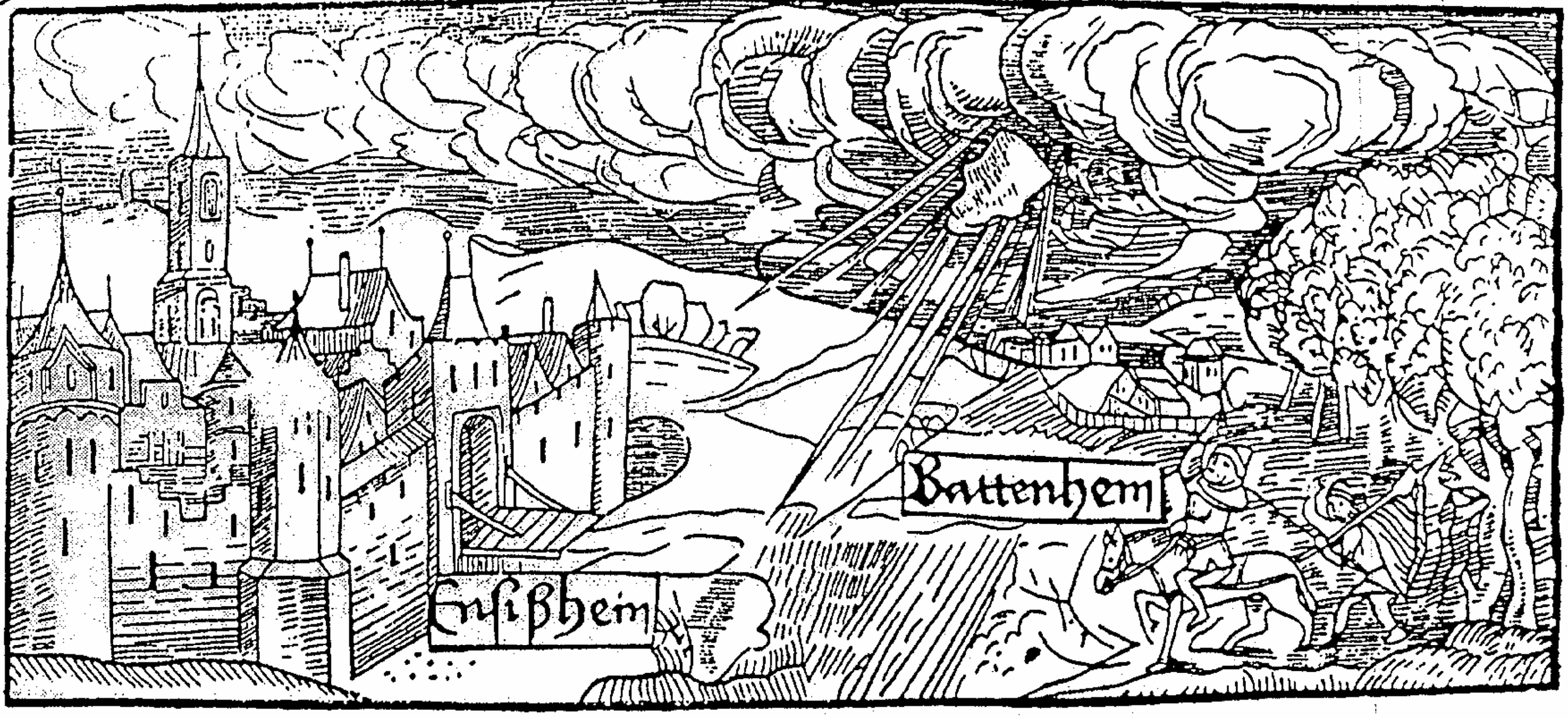
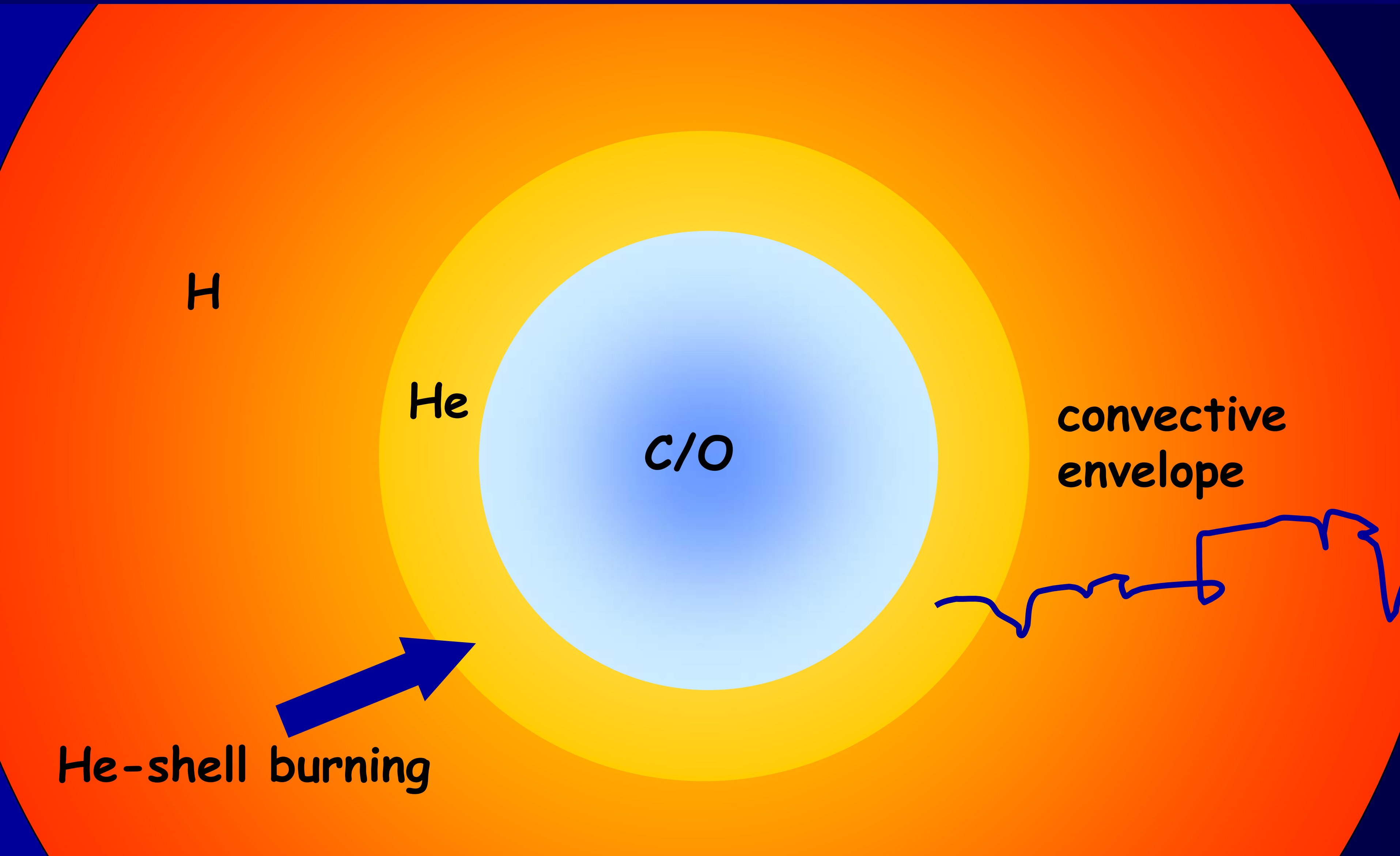
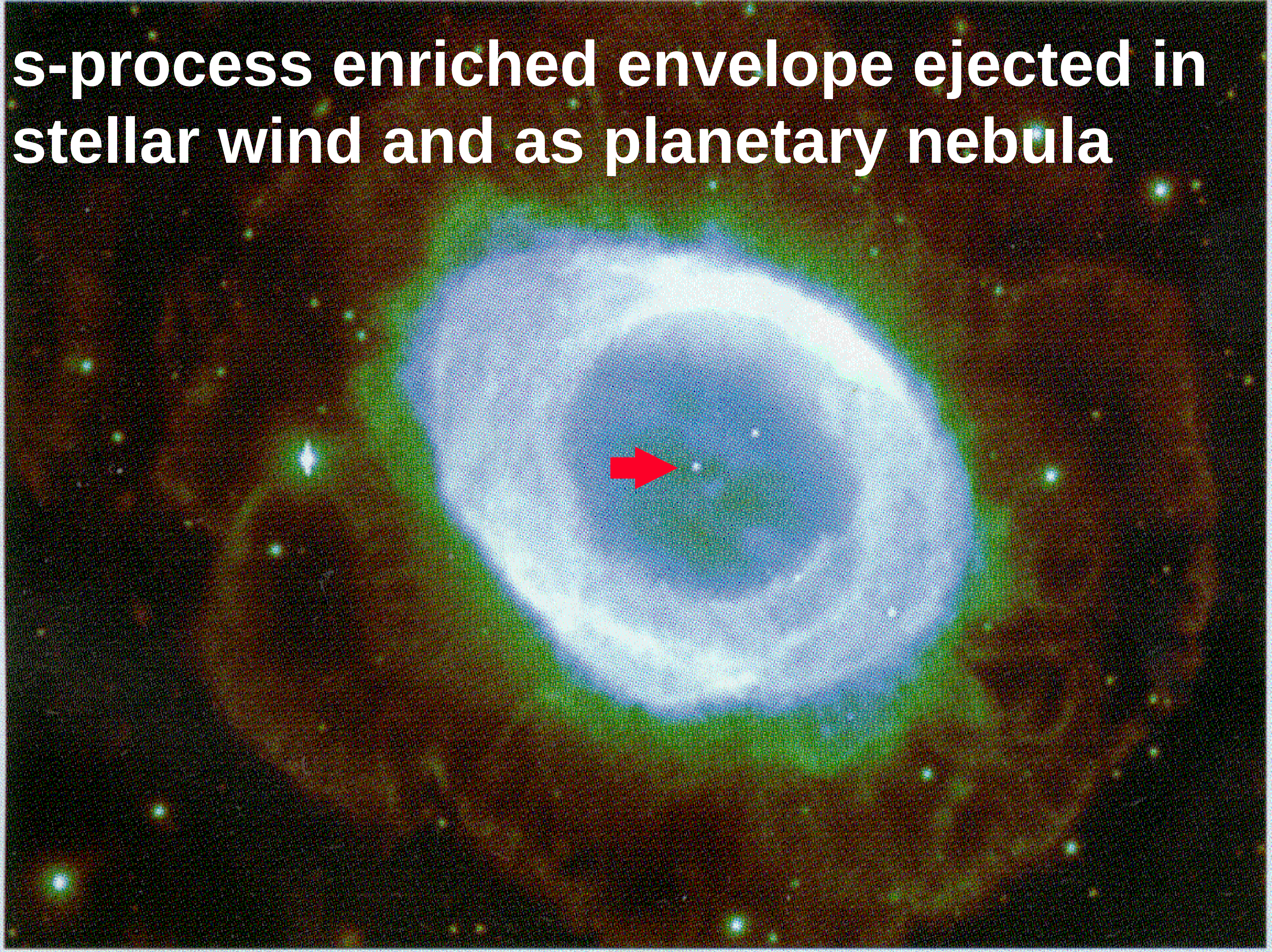


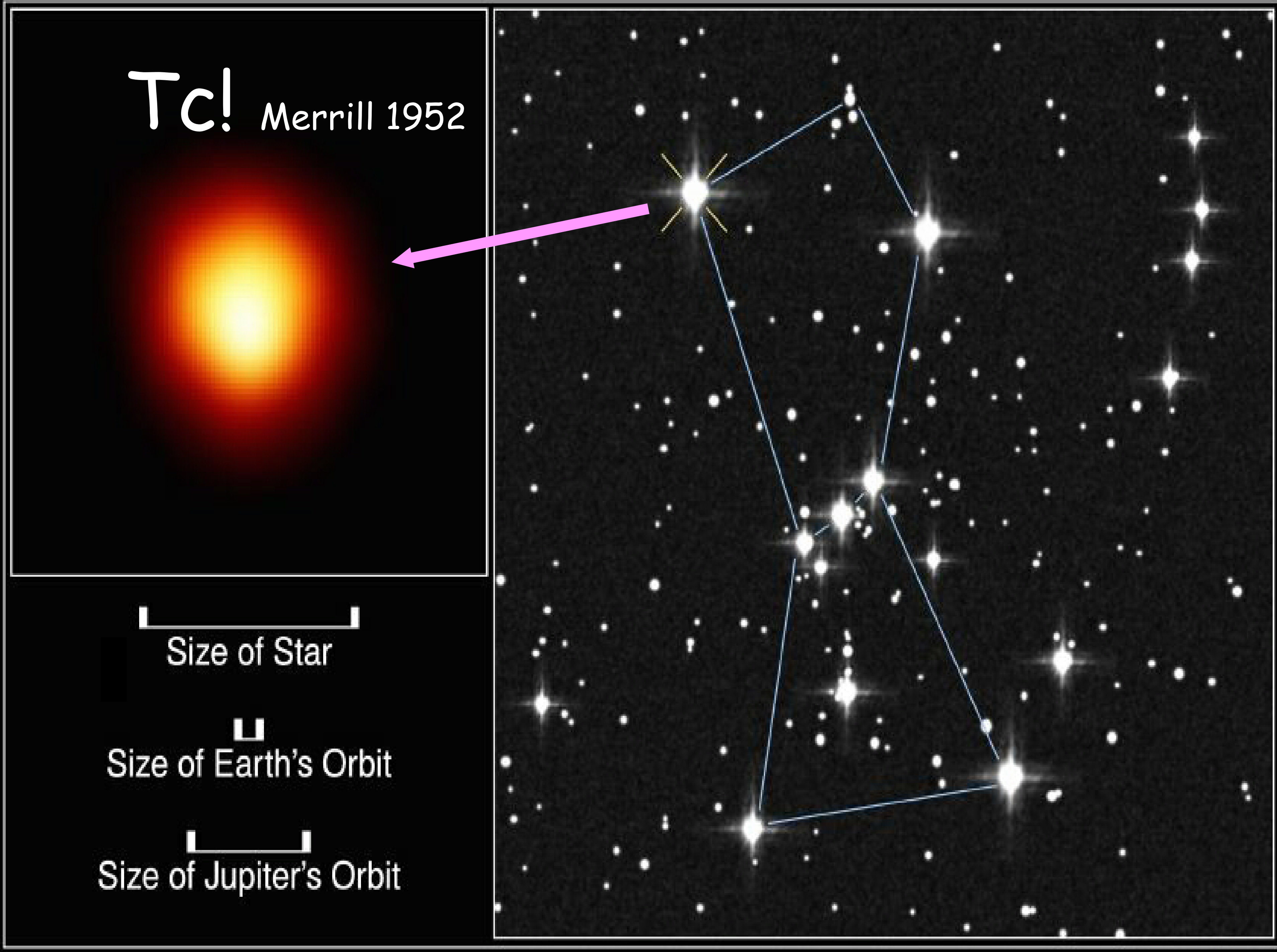

carbonaceous chondrites represent composition of homogenized protosolar nebula, but the most refractory stellar grains survived and witness stellar nucleosynthesis by CNO cycle, during He burning, and in the ***s*** and ***r*** processes

# element synthesis in Red Giants: production and transport to surface



# s-process enriched envelope ejected in stellar wind and as planetary nebula




Tc! Merrill 1952
Size of Star
Size of Earth's Orbit
Size of Jupiter's Orbit

# how do we know all this?

- observation of site-specific abundance signatures
  - stellar spectroscopy (IR, visible, UV, X- and $\gamma$-rays)
  - presolar dust grains
  - composition of solar system

- comparison with abundances obtained by detailed models of astrophysical processes
  - stellar physics
  - full nuclear reaction network

➡ *accurate laboratory measurements!!*

# new observations:
# meteoritic grains and high resolution spectroscopy

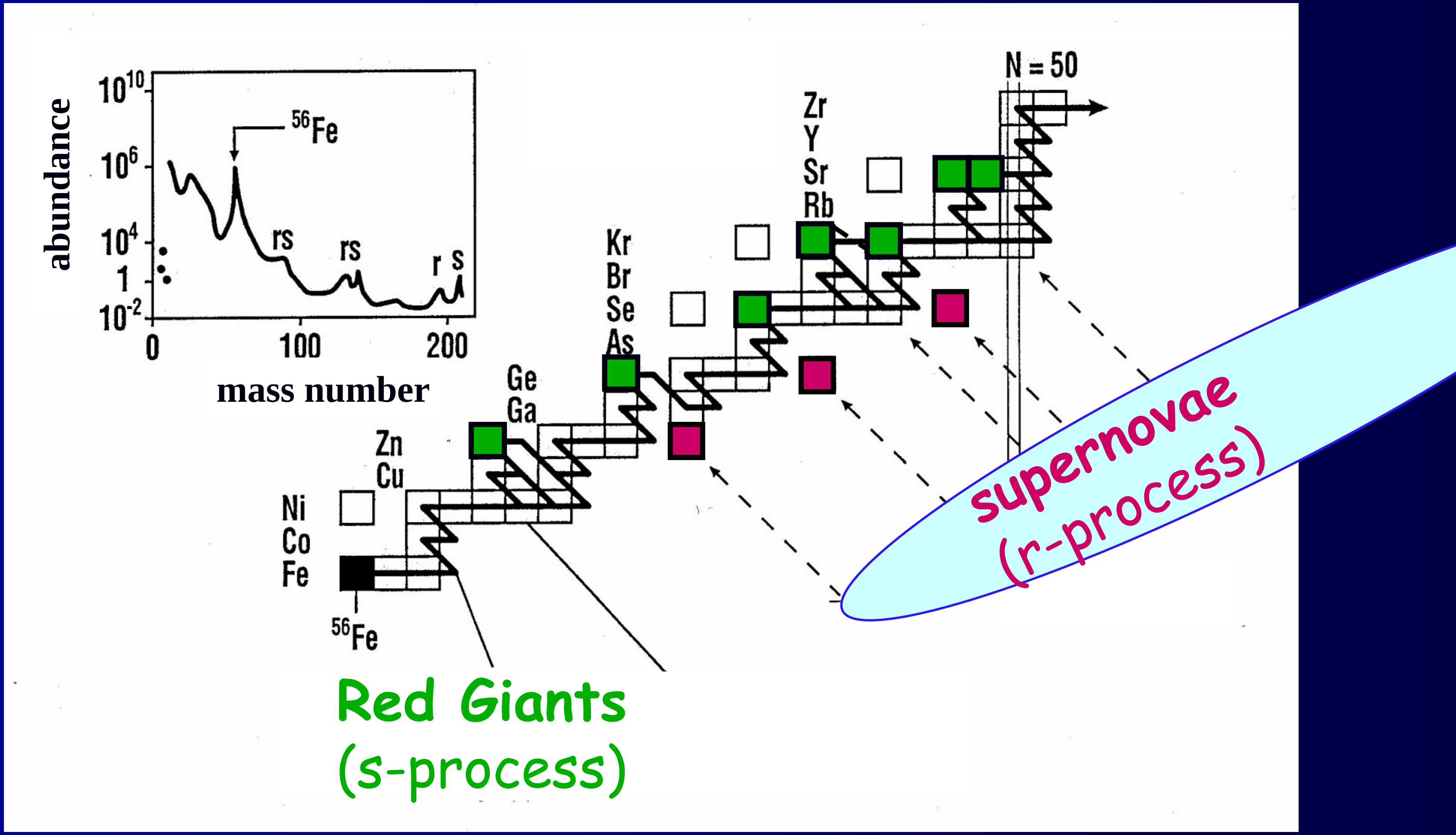
presolar grains from stellar outflows and  supernova ejecta

information on stellar and galactic evolution, nucleosynthesis, mixing in supernovae, the composition of stellar atmospheres, and processes on meteoritic parent bodies

high resolution spectroscopy of stellar atmospheres

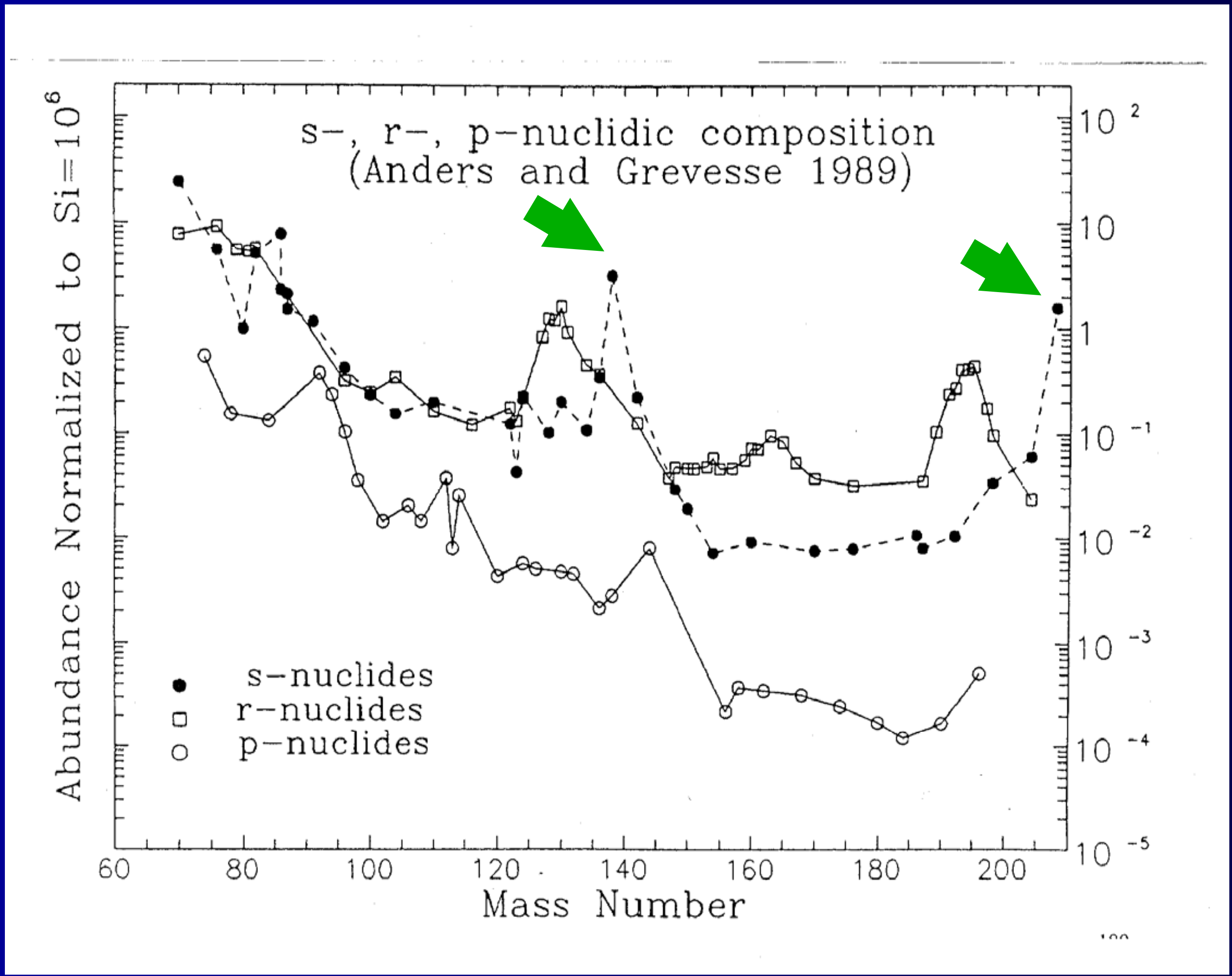
direct  identification of the isotopic mix of nucleosynthesis products via hyperfine structures of molecular bands - the basic link between stellar spectroscopy and nucleosynthesis models

# from Fe to U: s- and r-process

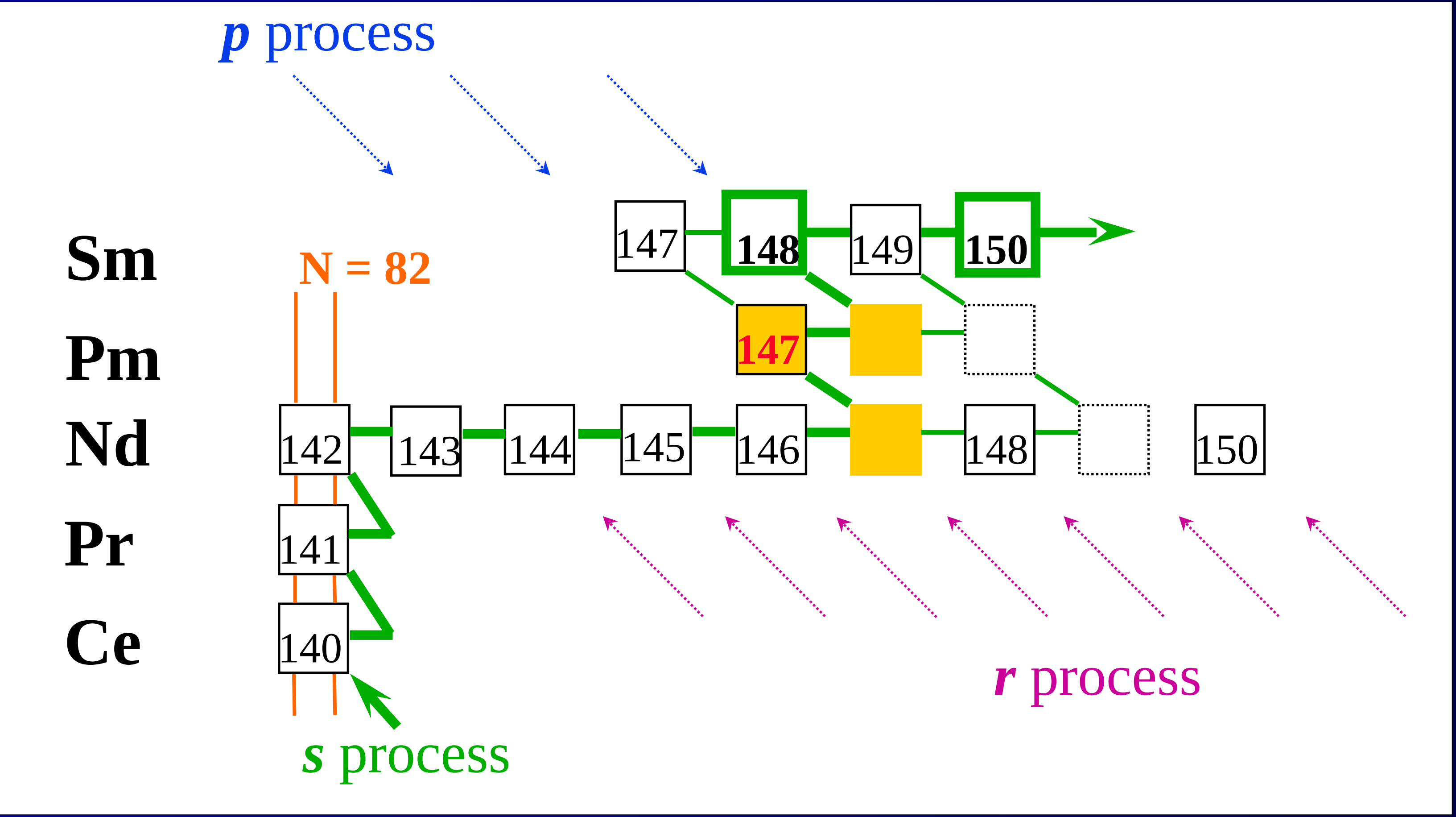



s-abundance × cross section = N σ = constant

# decomposition of solar abundances



# the *s*-process path:
# flow equilibrium ($N\sigma$ = const),
# magic neutron numbers & branchings



# nuclear physics for the s-process

- He burning at 100 – 300 MK (kT=10 – 30 keV)

  - abundances anti-correlated with $(n,\gamma)$ cross sections
  - specific abundance signatures in branchings
  - direct evidence via stellar spectroscopy and by analysis of presolar dust grains

- detailed models of stellar processes available
  - reliable nuclear reaction network

main input experimental:

**$(n,\gamma)$ cross sections and $\beta$-decay rates**

# Maxwellian averaged cross sections

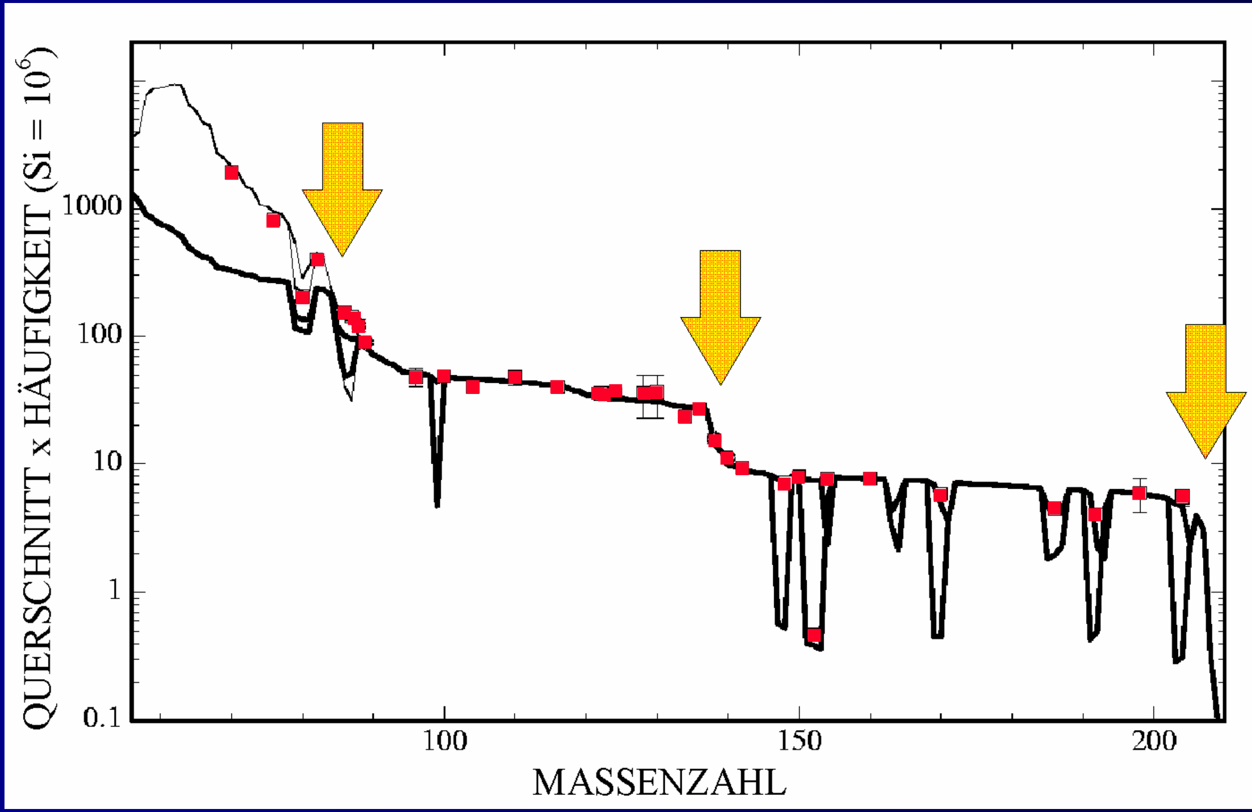
- measure $\sigma(E_n)$ by time of flight, $0.3 < E_n < 300$ keV,
  determine average for stellar spectrum
  correct for SEF
- produce thermal spectrum in laboratory,
  measure stellar average directly by activation
  correct for SEF

# the classical *s*-process: **100-300 MK**

flow equilibrium ($\sigma N = \text{const}$),
magic neutron numbers & branchings

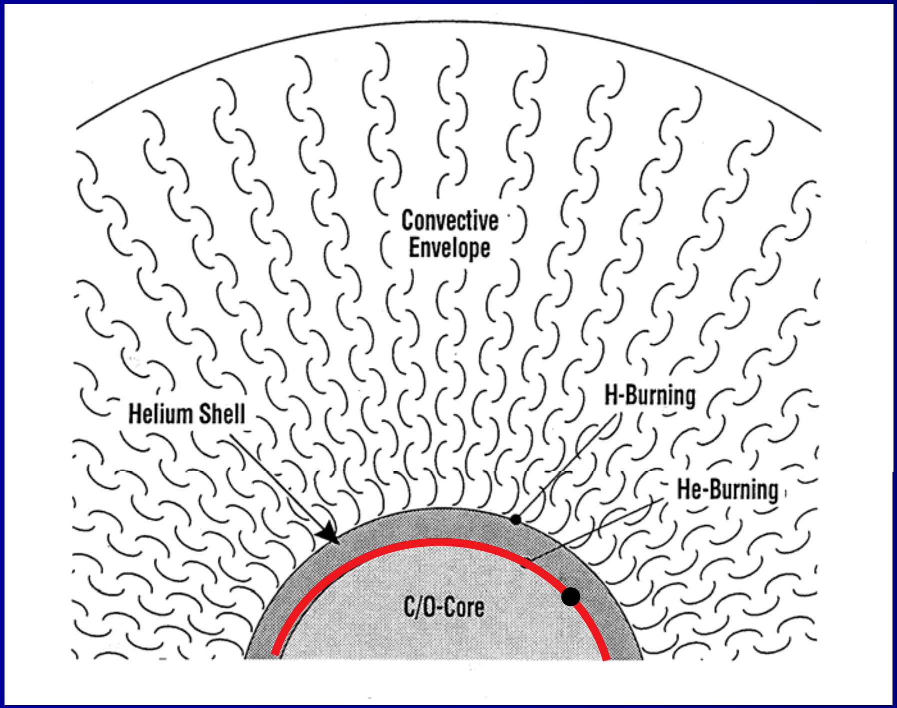
*abundances determined by*

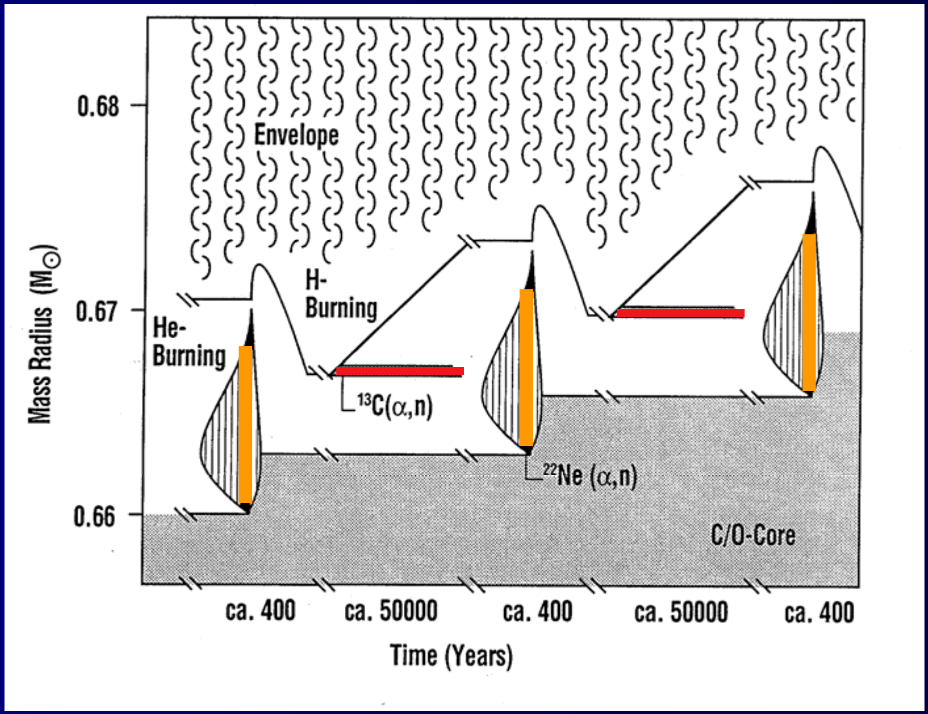
- **seeds (Fe)**
- **exposure**
- $\sigma$




two different *s* processes: main component in low mass AGB stars
weak component in massive stars

# the *s* process in AGB stars

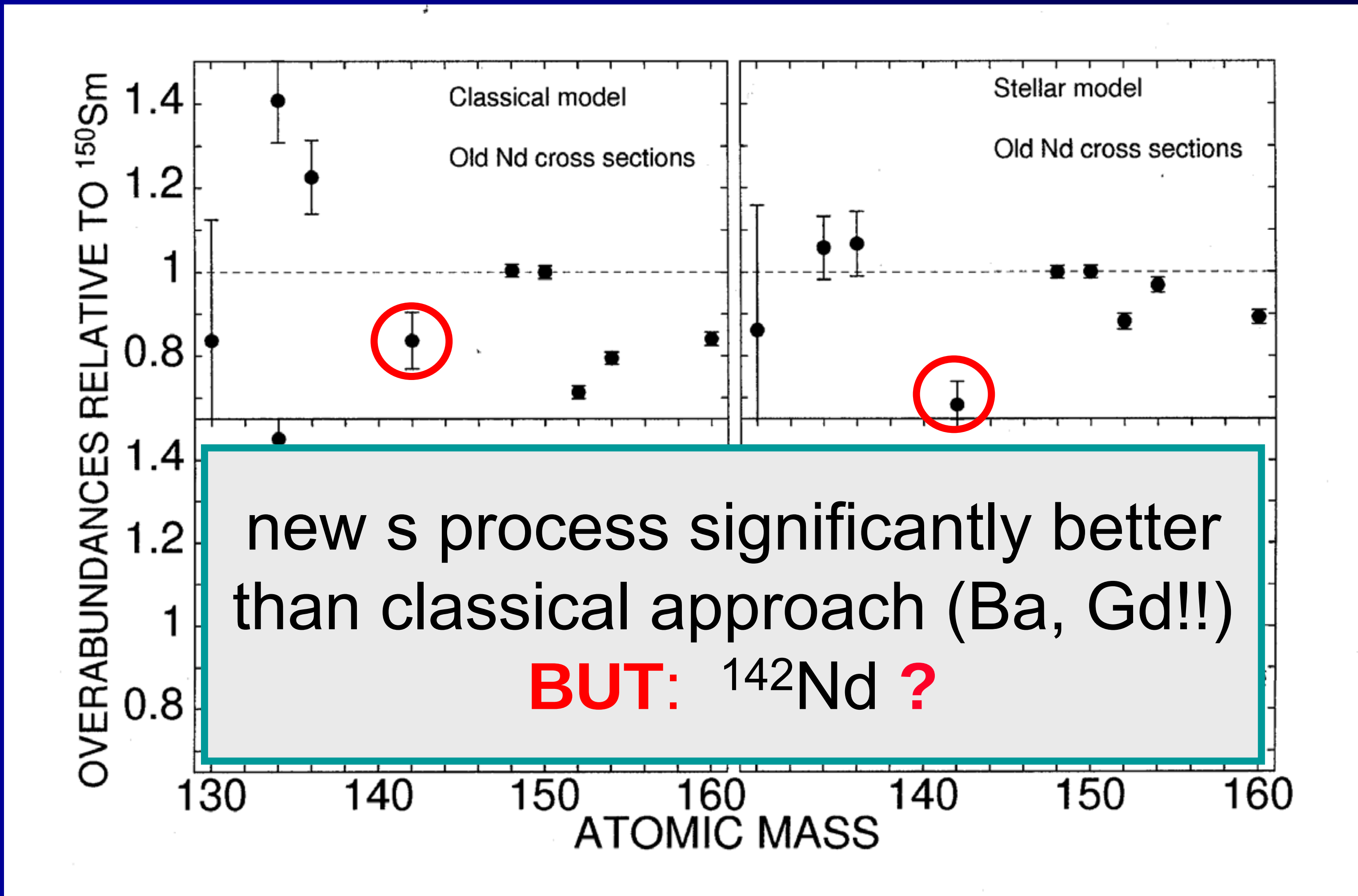



$^{13}C(\alpha,n)$ source operates during H-burning phase
kT=8 keV

final abundance patterns via $^{22}Ne(\alpha,n)$ during He shell flash
kT=23 keV

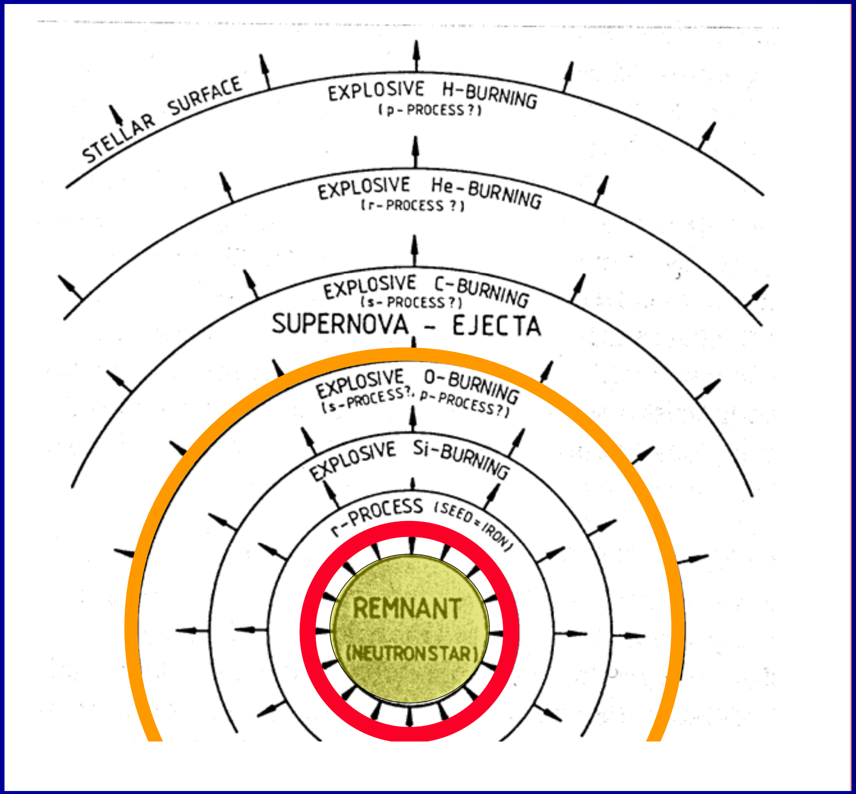
# the *s* process in AGB stars:
## search for an abundance signature

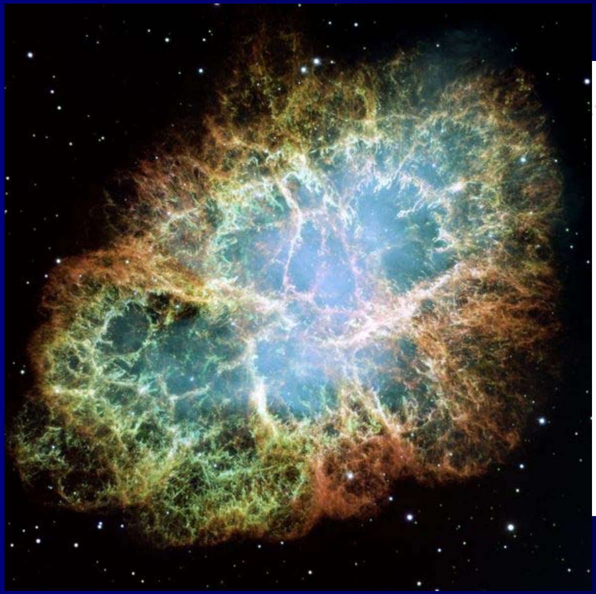


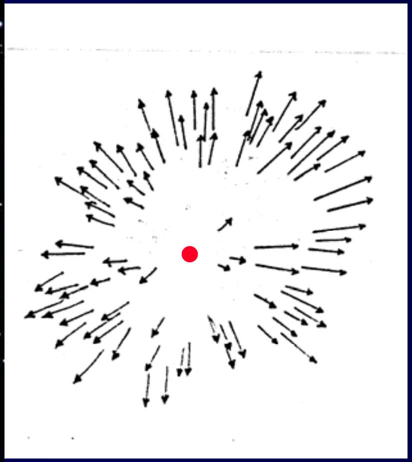

new s process significantly better than classical approach (Ba, Gd!!)

**BUT**: $^{142}$Nd **?**

# explosive nucleosynthesis in supernovae: the *r* and *p* process





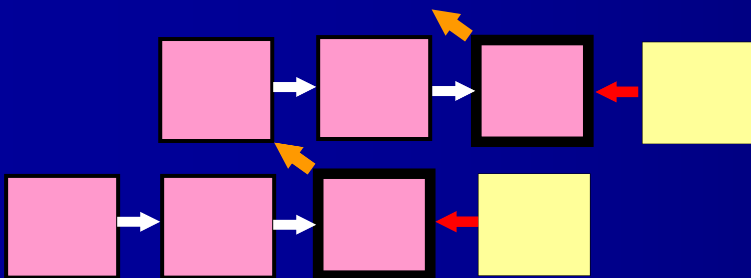
## *the p process*

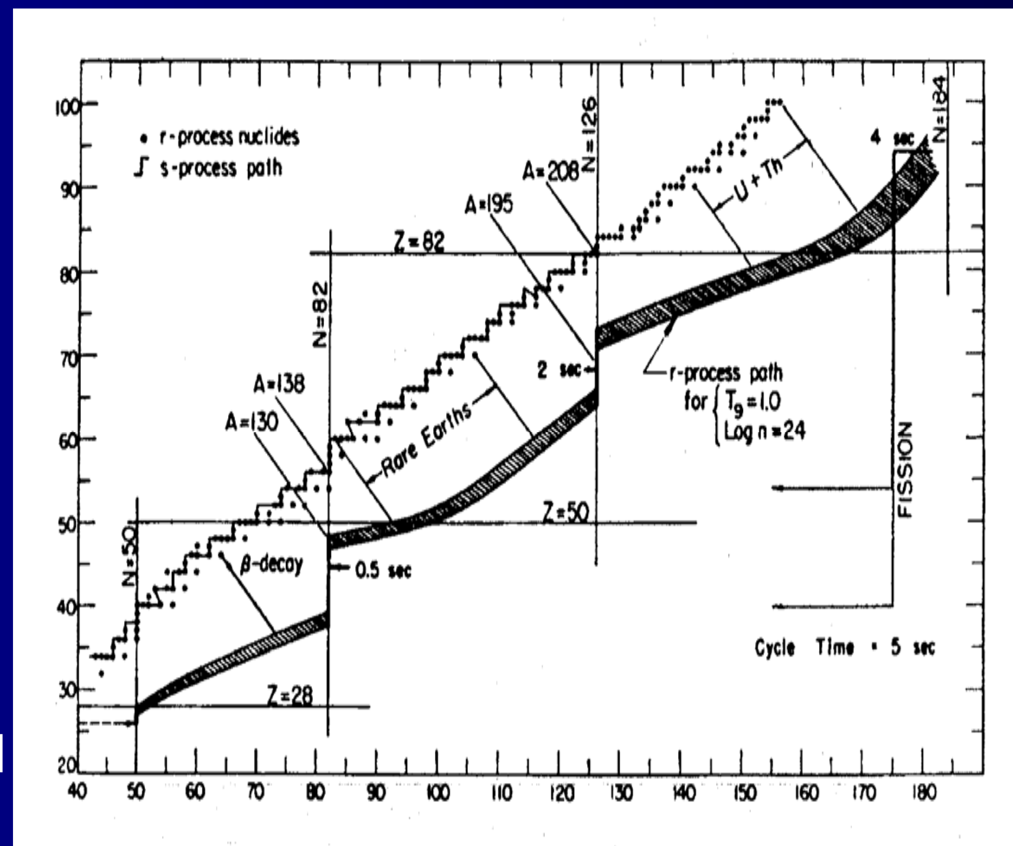
- high temperatures: $T_9 = 2 - 3$

## *the r-process*

- high neutron densities and temperatures:
  $T_9 = 1 - 2$; $n_n > 10^{20}$ cm$^{-3}$
- neutron capture times <1ms
- total duration 1 - 2 s

# the *r*-process

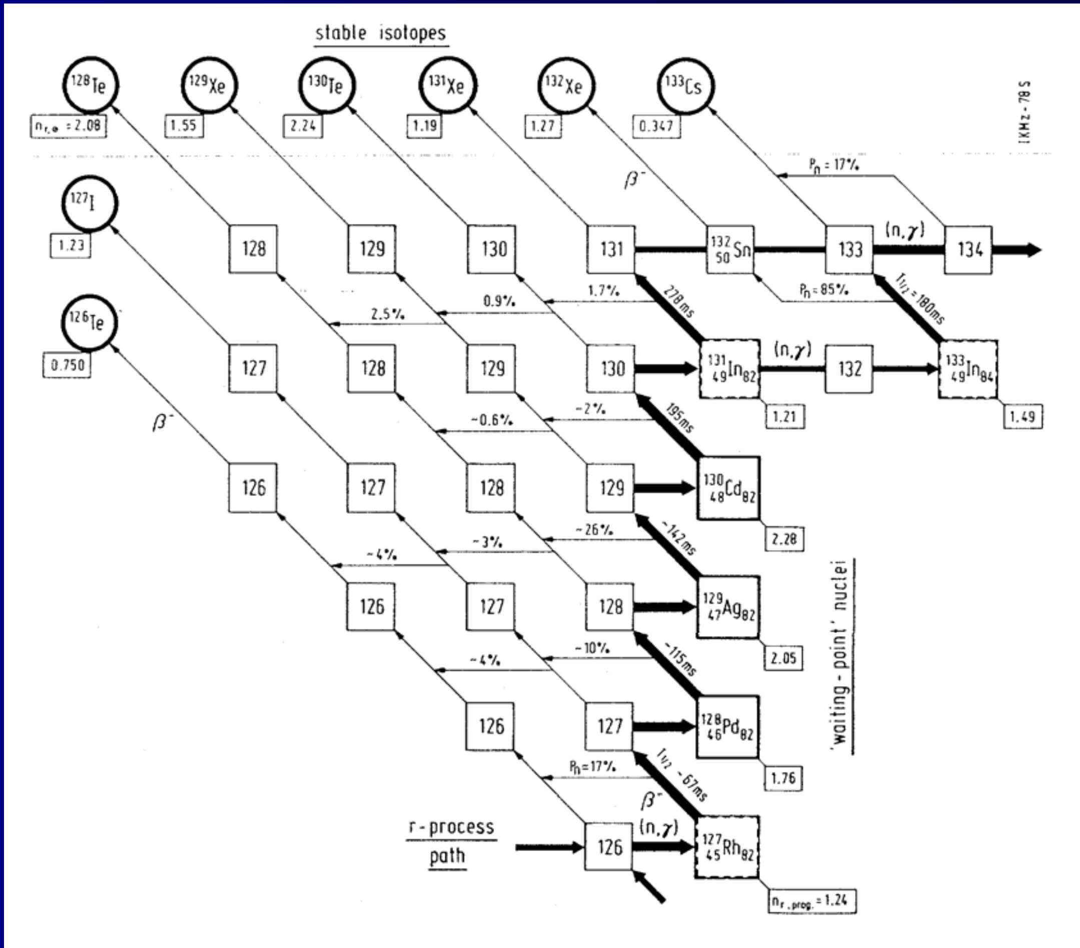





- reaction path defined by waiting points at $S_n$~2 MeV
- primary yields inversely proportional to $\lambda_\beta$ at waiting points
- abundance peaks at magic neutron numbers appear shifted after decay

# waiting point approximation

- reaction path defined by waiting points at $S_n$~2 MeV
- waiting point abundances defined by: $\lambda_\beta N_r = const$
- final abundances modified by beta delayed neutron emission and (n,γ)/(ν,x) reactions
- contribution to mass region 70 < A < 238



# nuclear physics for the *r*-process

- explosive nucleosynthesis (supernovae?) at < 1 GK (<100 keV)

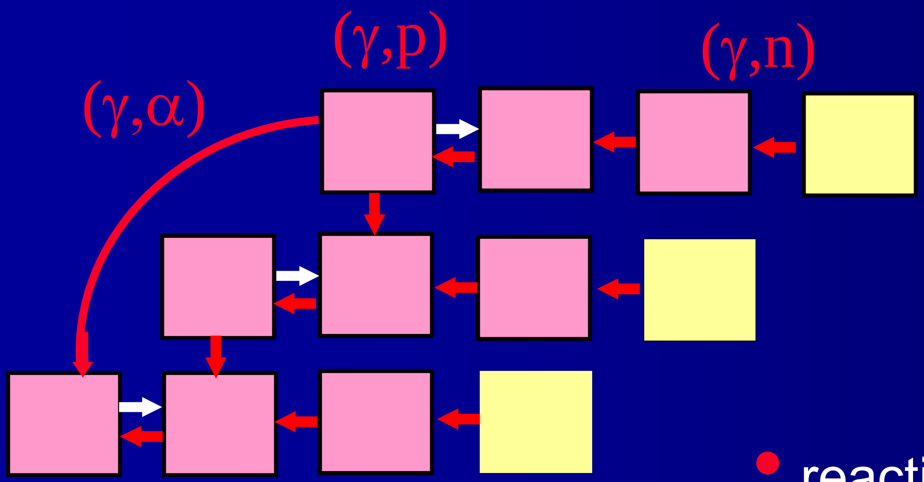
  - $\beta$-decay rates near neutron drip line

    exotic radioactive nuclei

- r-process models uncertain, problems
  - with explosion mechanism
  - nuclear data for reaction network

main input: *mostly theoretical, great challenge!*

# the *p*-process




- reaction path defined by temperature and neutron separation energies
- seed nuclei from s- and r-distributions
- neutron capture during freeze-out

# nuclear physics for the *p*-process

- explosive nucleosynthesis (supernovae?) at < 2 - 3 GK (<200 keV)

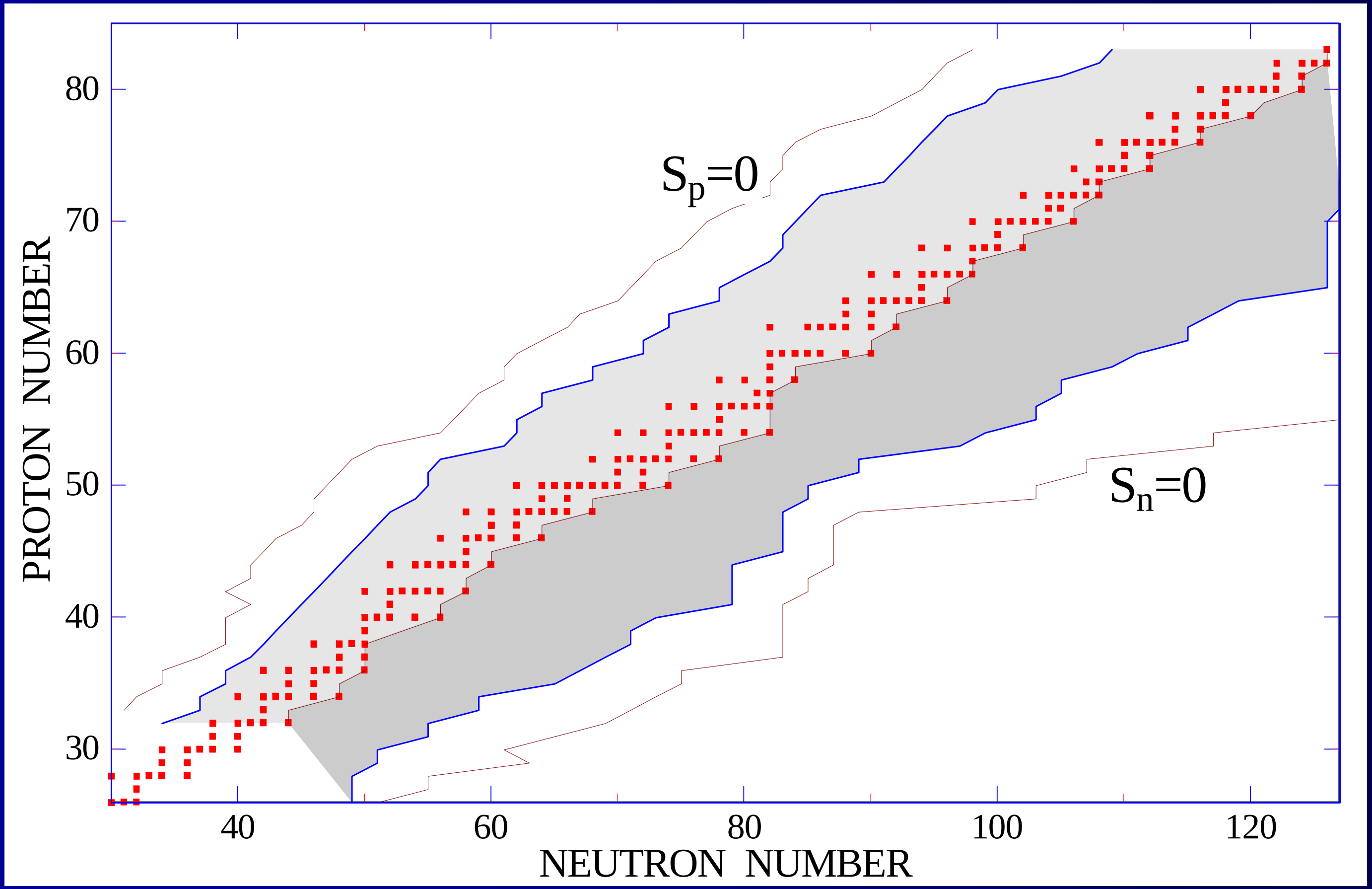
  - reaction flow via $\gamma$-induced reactions a few mass units from stability valley

    exotic proton-rich nuclei

- *p*-process models uncertain,
  - problems with nuclear data for reaction network
  - origin of $^{92,96}$Mo and $^{96,98}$Ru unclear

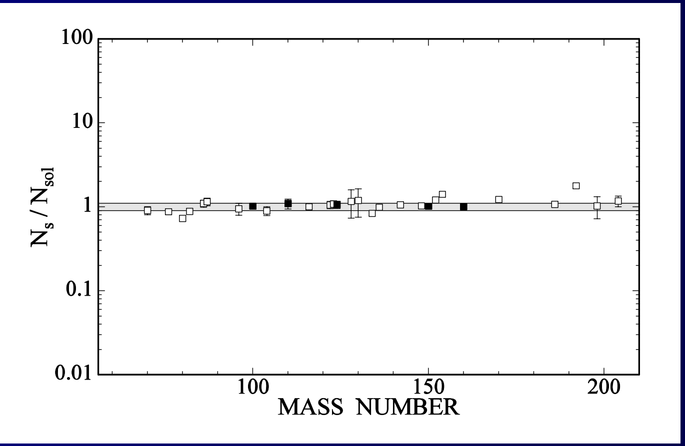
main input: mostly theoretical, great challenge!

# nucleosynthesis networks



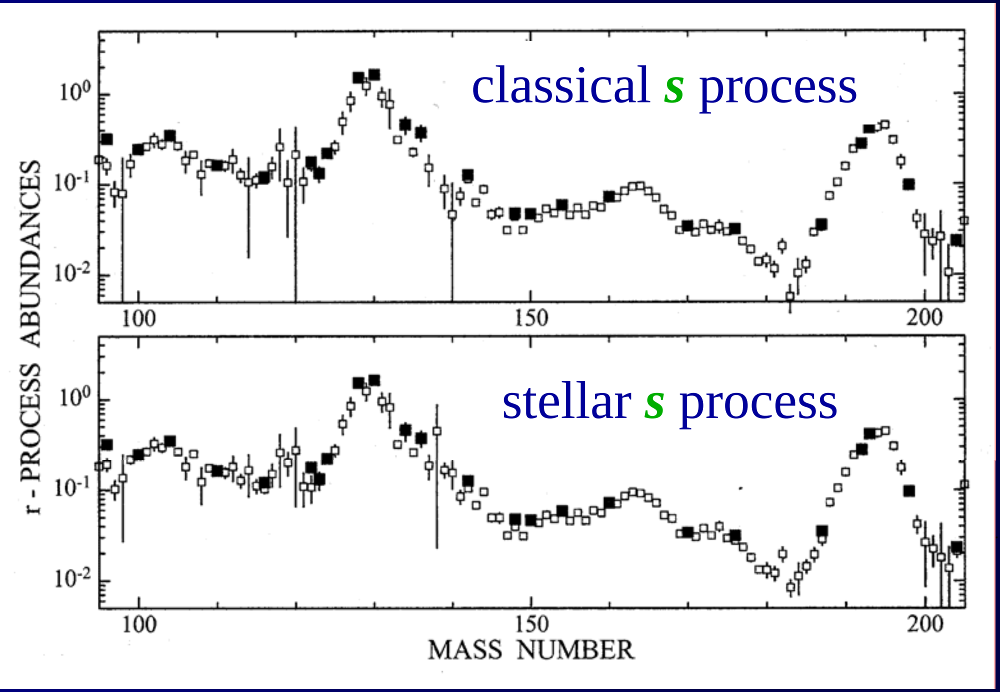
# the *s*- and *r*-process abundances

***s*** abundances are well defined
by experimental cross sections

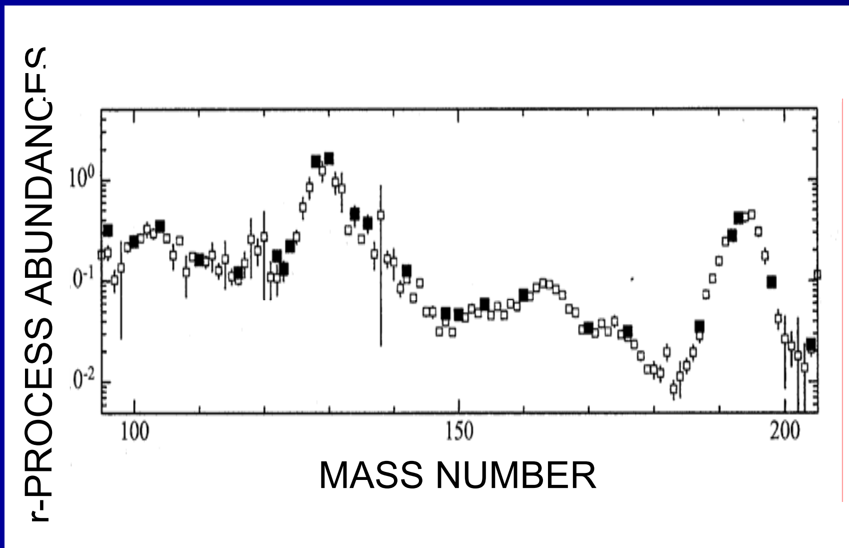


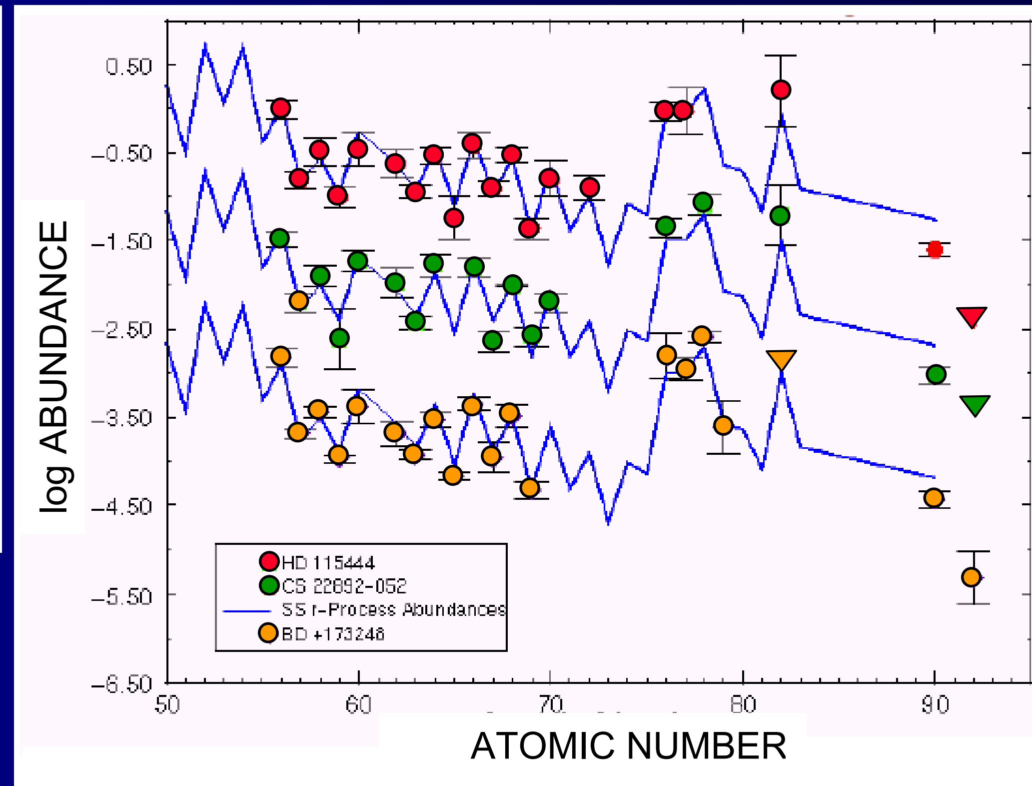

***r*** abundances obtained as

$$N_r = N_{\odot} - N_s$$



# very metal-poor stars show only *r* process

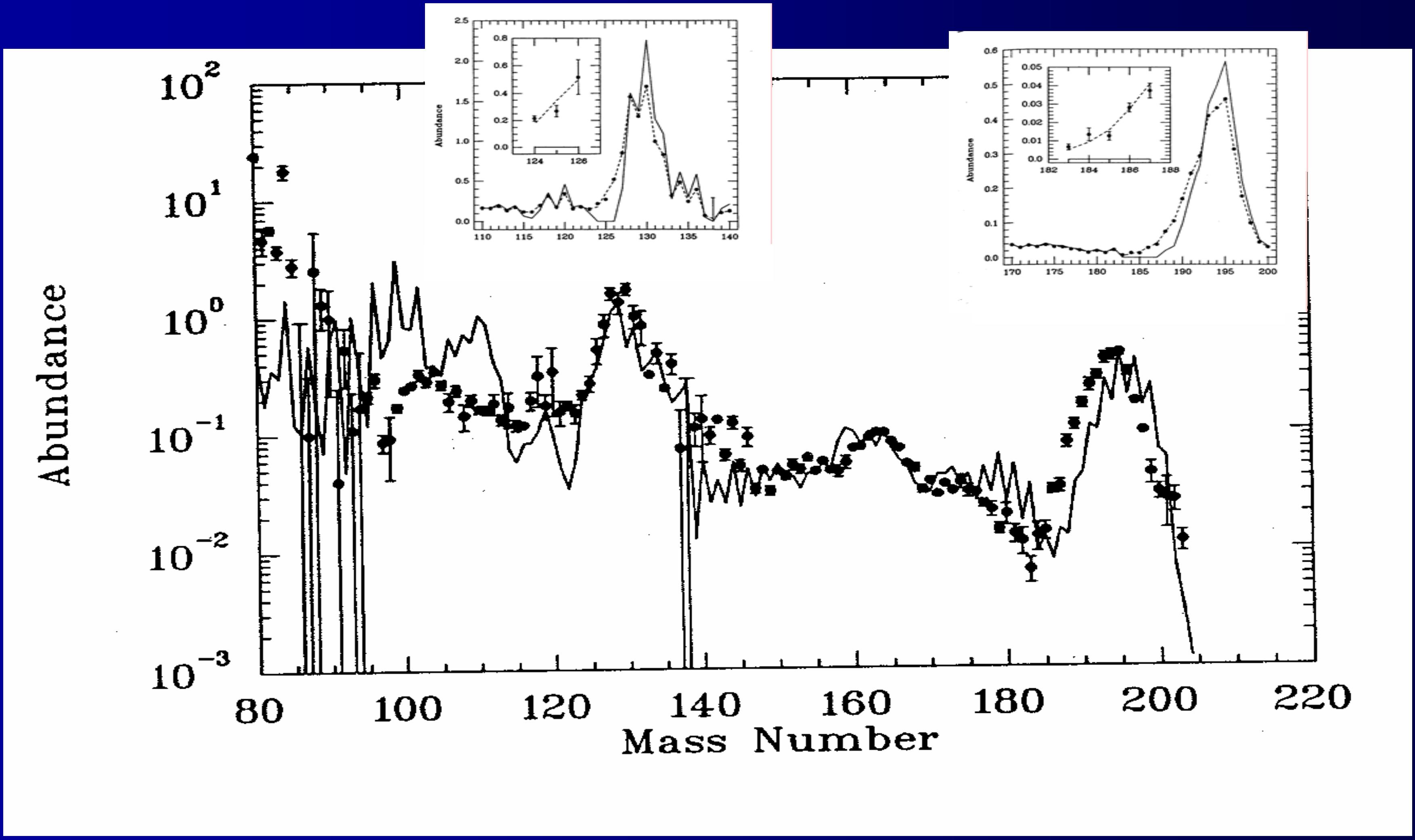



**oldest stars contain 1000 times less heavy elements,**
**but relative abundances from Ba to Pb are exactly solar**

→ **two *r*-processes?**

# r-process abundances and $\nu$-induced modifications



# neutron reactions: origin of the heavy elements

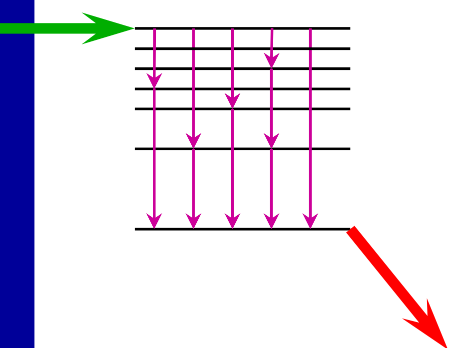
***s* process:** Red Giant stars, $(\alpha,n)$ reactions, Fe - Bi,
$(n,\gamma)$ cross sections for $T_8$ = 1-3, $E_n$=0.3-300 keV
reaction path follows stability valley

***r* process:** supernova at mass cut, Zr - U;
$(n,\gamma)$ cross sections for freeze-out,
$E_n$= 0.3-300 keV
reaction path close to neutron drip line

***p* process:** supernova in O/Ne shell, $(\gamma,n)$ reactions,
Fe - Bi, $(n,\gamma)$ cross sections for freeze-out,
$E_n$ up to 1 MeV,
reaction path in proton rich region

# detection of neutron capture events

(n,γ):



## prompt γ-rays + TOF-method

| | | |
|---|---|---|
| single γ´s | * Moxon-Rae | $\varepsilon_\gamma$ ~ 1% |
| | * PH-weighting | ~ 20% |
| | * Ge, NaI | < 1% |
| all cascade γ´s | * 4π $BaF_2$ | ~100% |

## activation in quasi-stellar spectrum

most sensitive — * small cross sections, $10^{14}$ atoms sufficient

selective — * natural samples or low enrichment