Reaction Cross Sections for the *r*, *s*, and *p* Process

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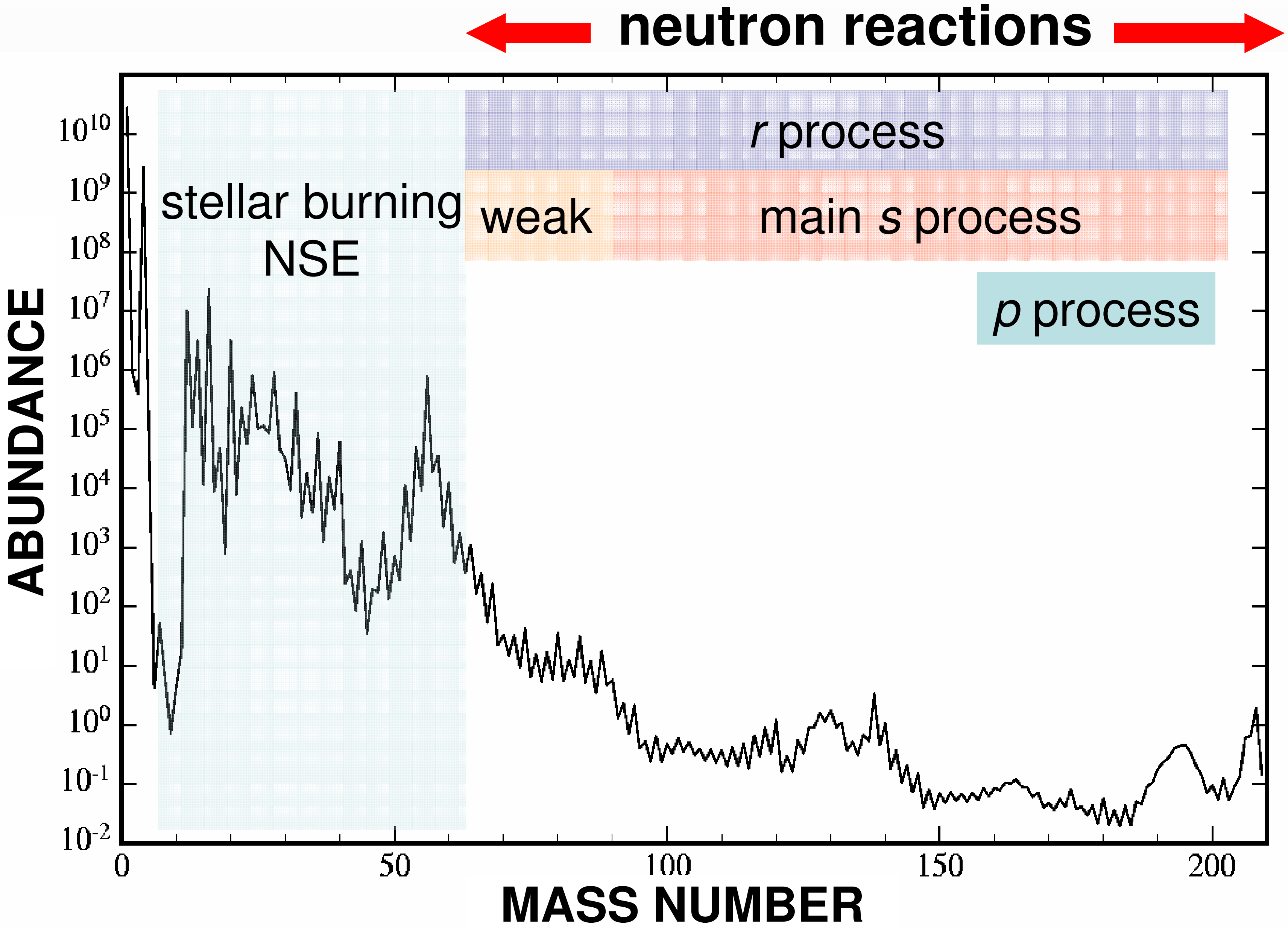
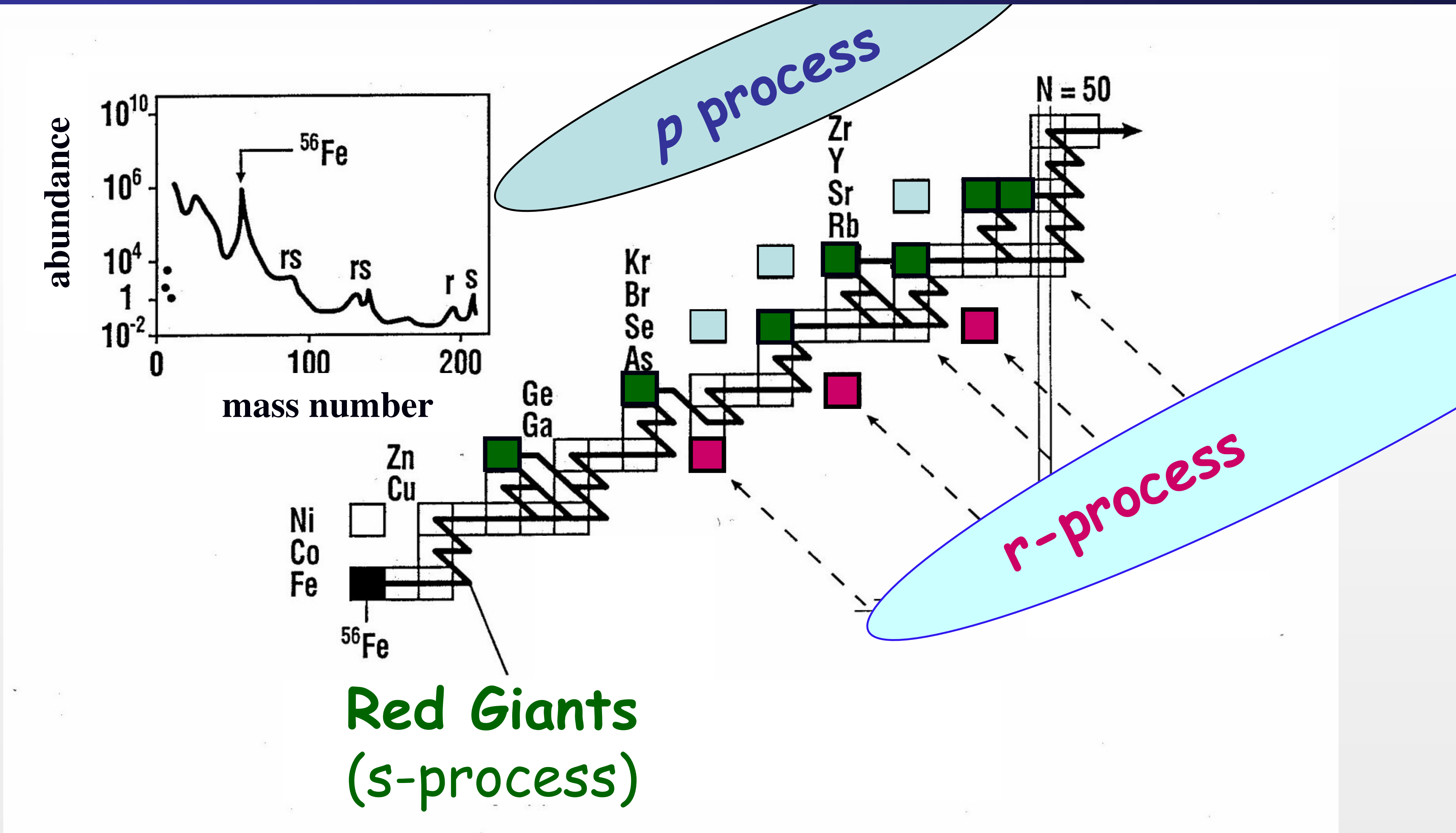
- *s* process: impact of (n, γ) reactions for the description of He burning scenarios
- explosive nucleosynthesis in the *r* and *p* processes: large reaction networks of unstable isotopes

components of the solar abundance distribution



s-, *r*-, and *p*-process mechanisms



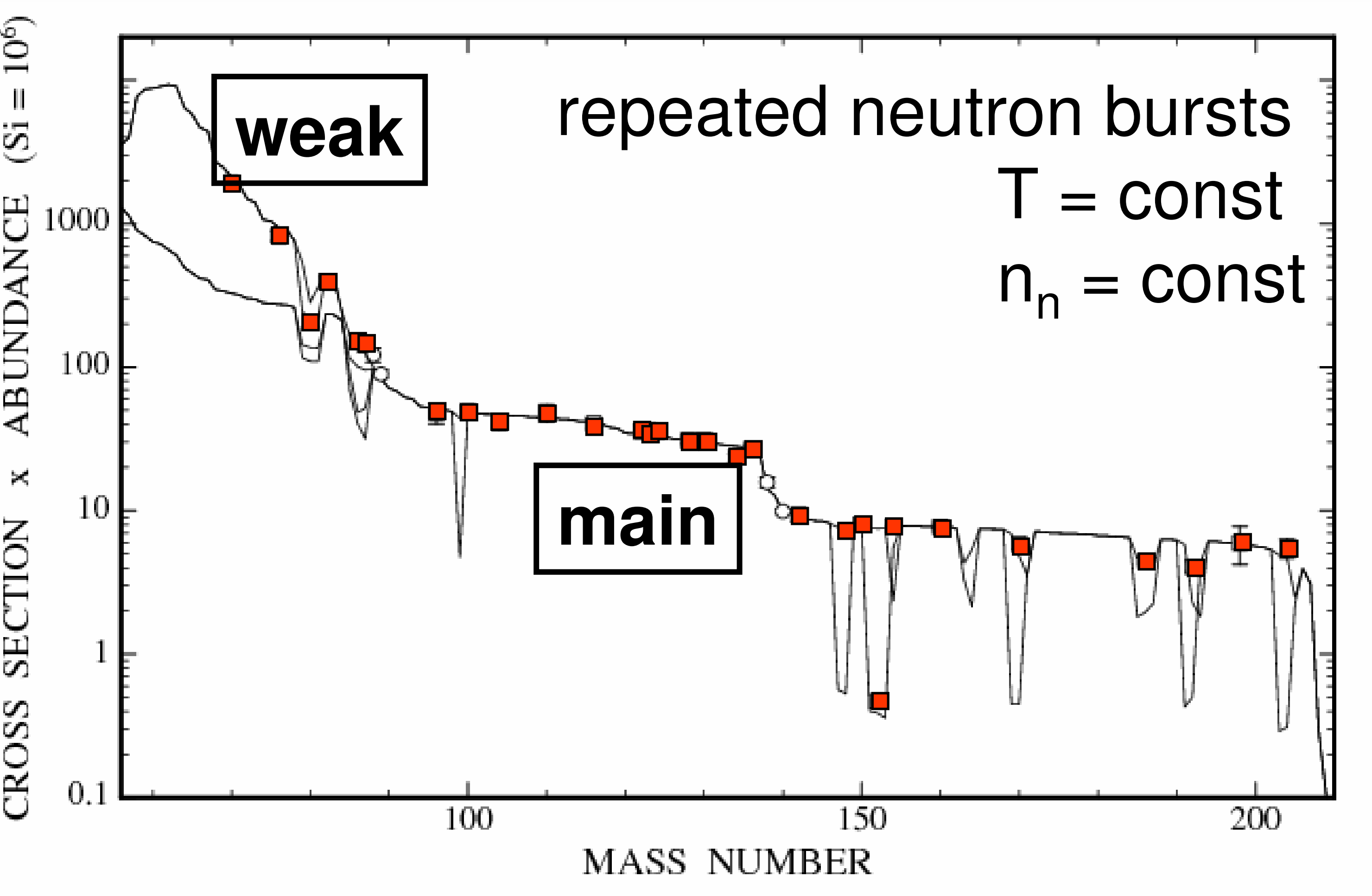
s-process abundance × cross section = σN_s = constant

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

classical approach: σN - curve



two processes:

A<90: not saturated

A>90: flow equilibrium

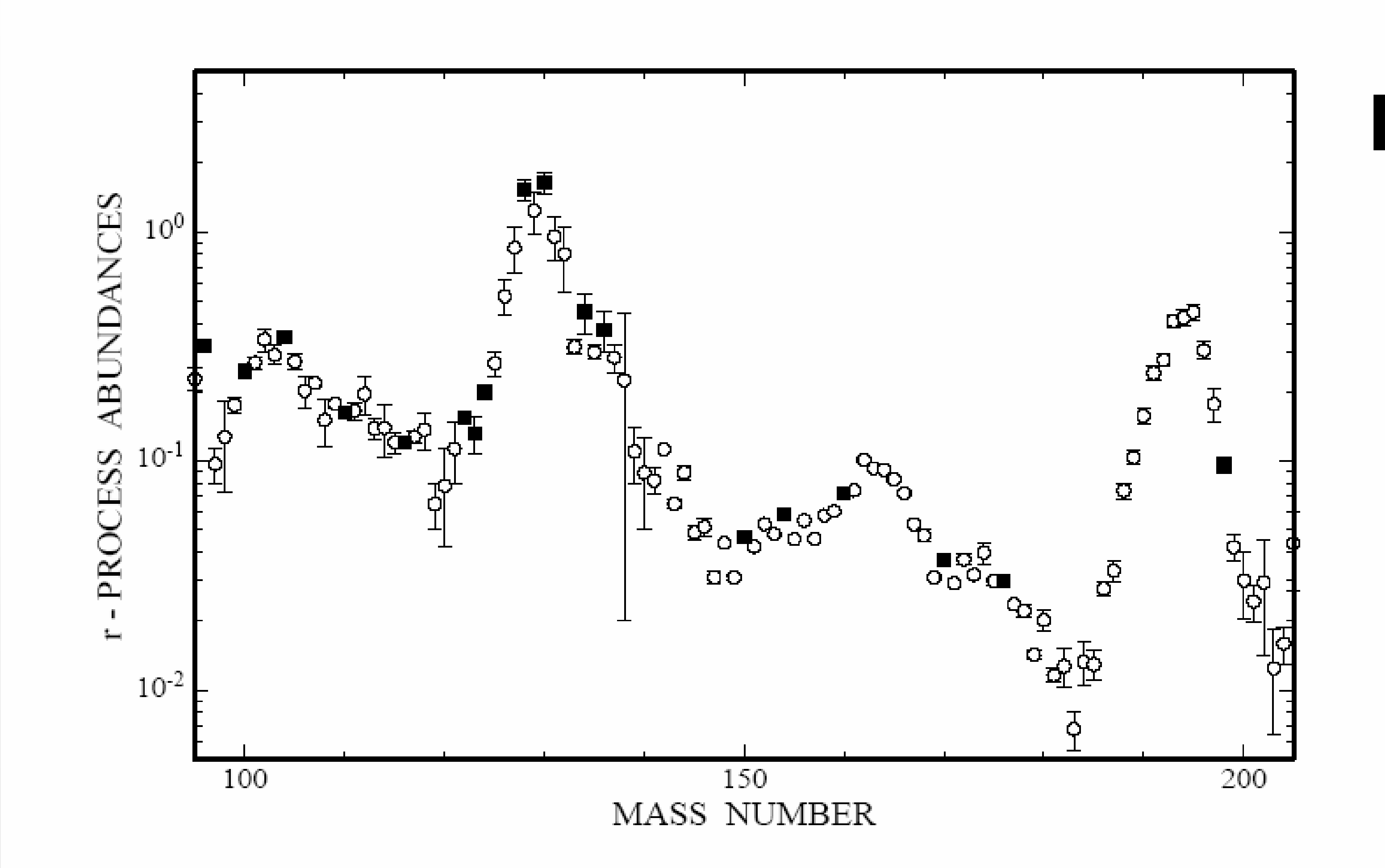
➡ different scenarios:

- **massive stars**
- **low-mass stars**

n-magic isotopes are bottlenecks

branchings provide n_n, T, ρ

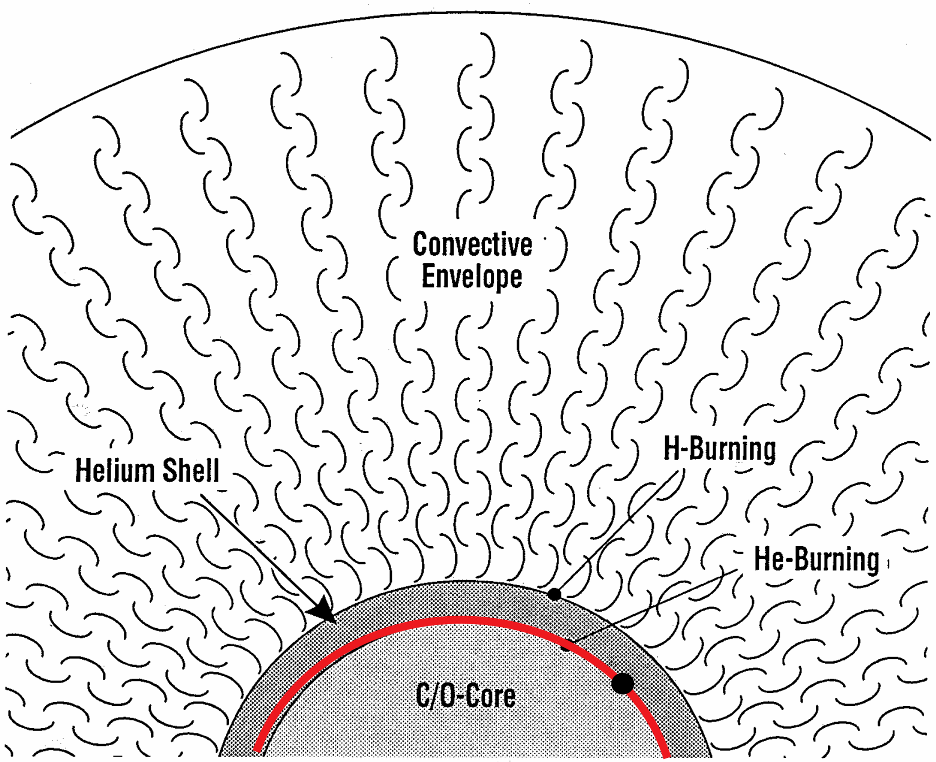
r-process residuals

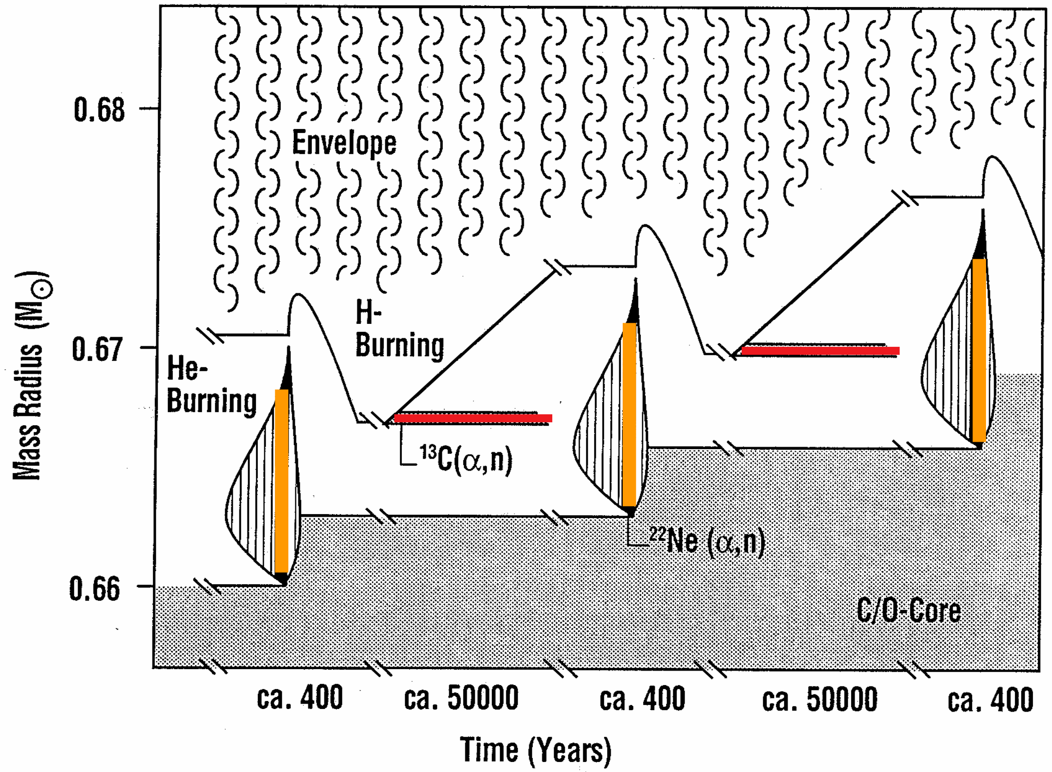


$$N_r = N_\odot - N_s$$

commonly used for comparison with *r*-process calculations

the *s* process in TP-AGB stars

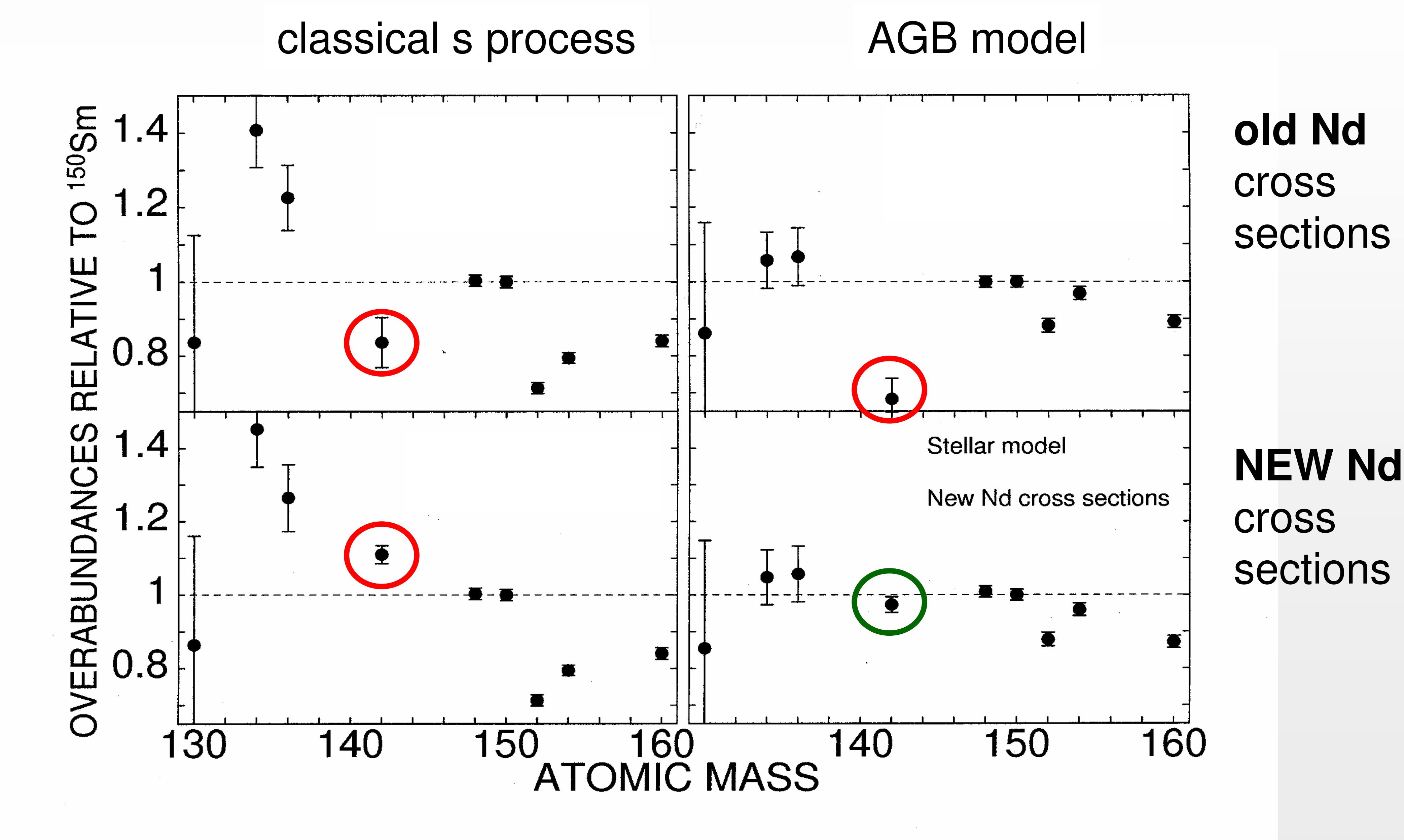




^{13}C(α,n) source operates during H-burning phase kT=8 keV

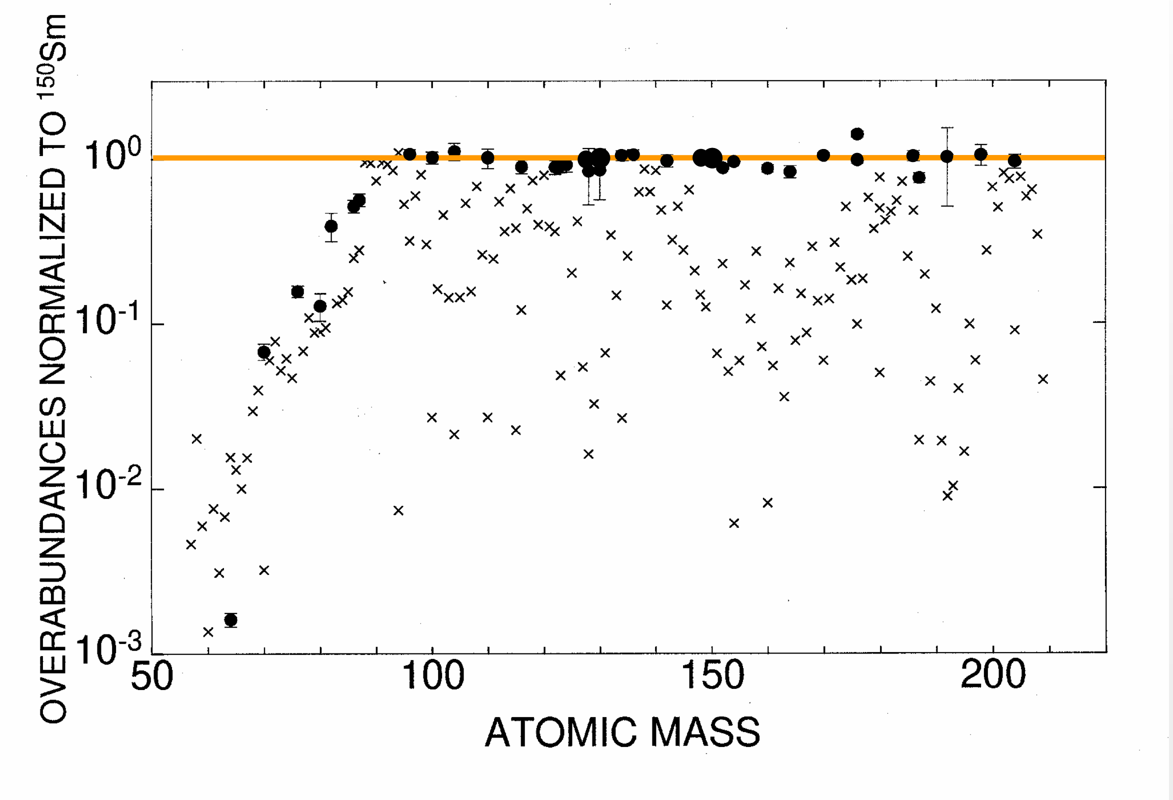
final abundance patterns via ^{22}Ne(α,n) during He shell flash kT=23 keV

search for an abundance signature in AGB stars

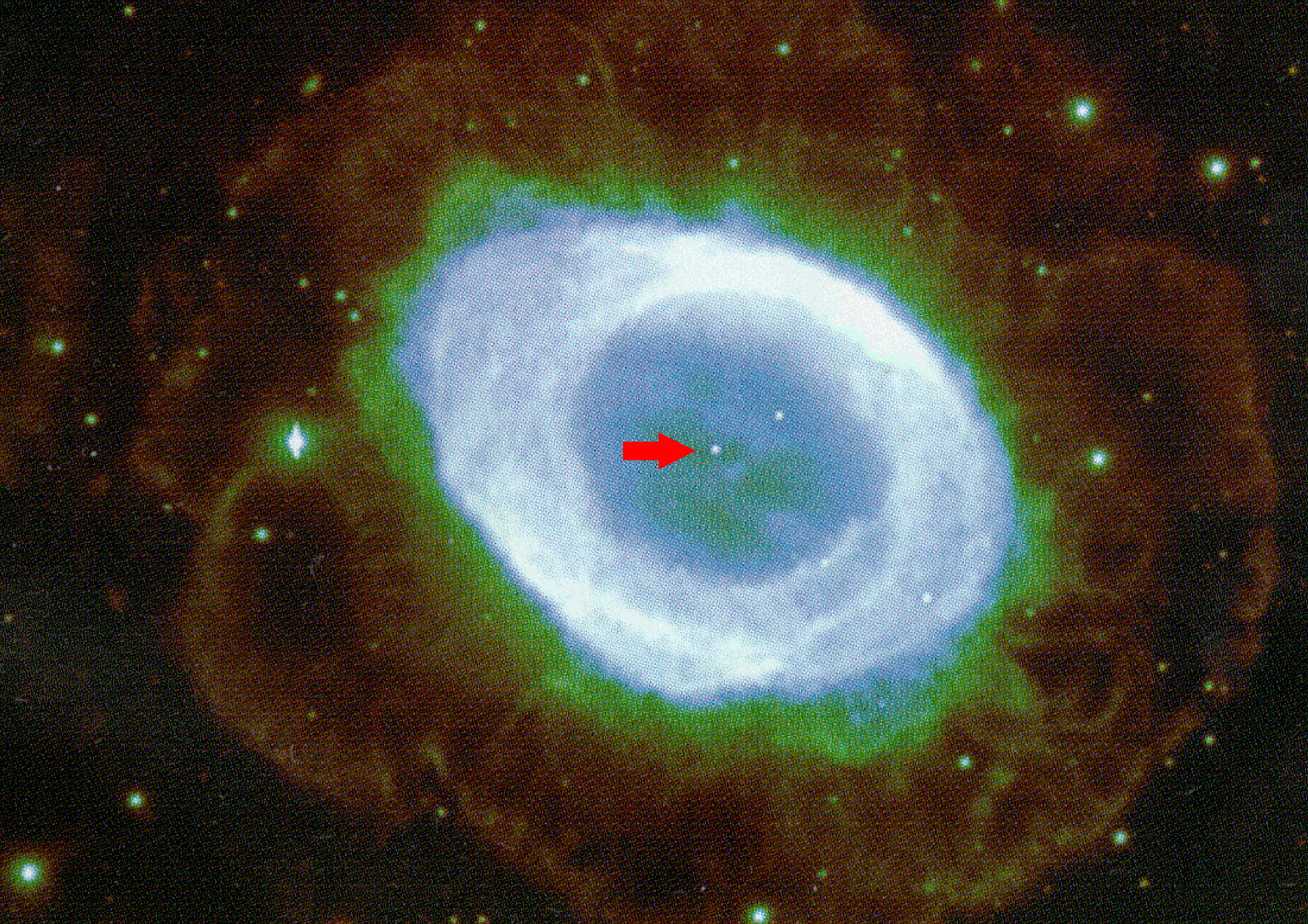


the new *s* process – main component

success of the main *s* process in TP-AGB stars of 1- 3 $M_\odot$

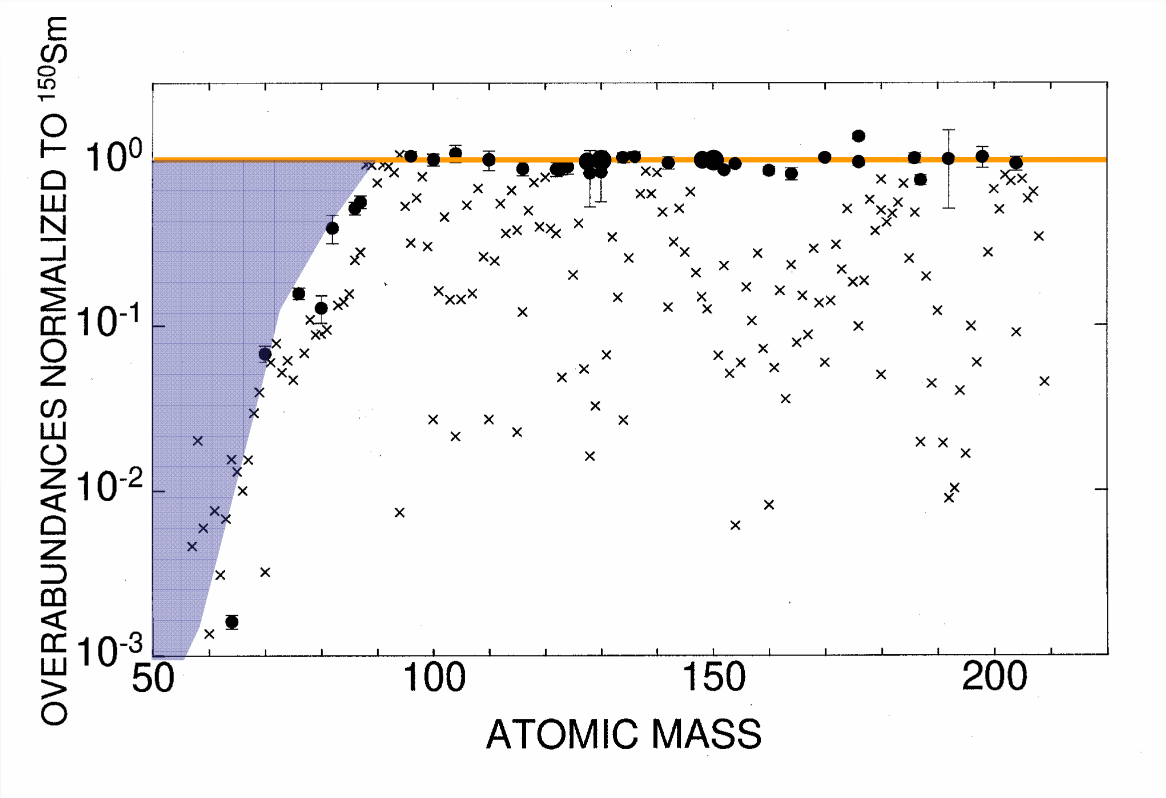


Arlandini et al. ApJ 525 (1999) 886



the *s* process – weak component

main *s* process limited to mass region from Zr to Bi



weak s process – conditions at stellar site

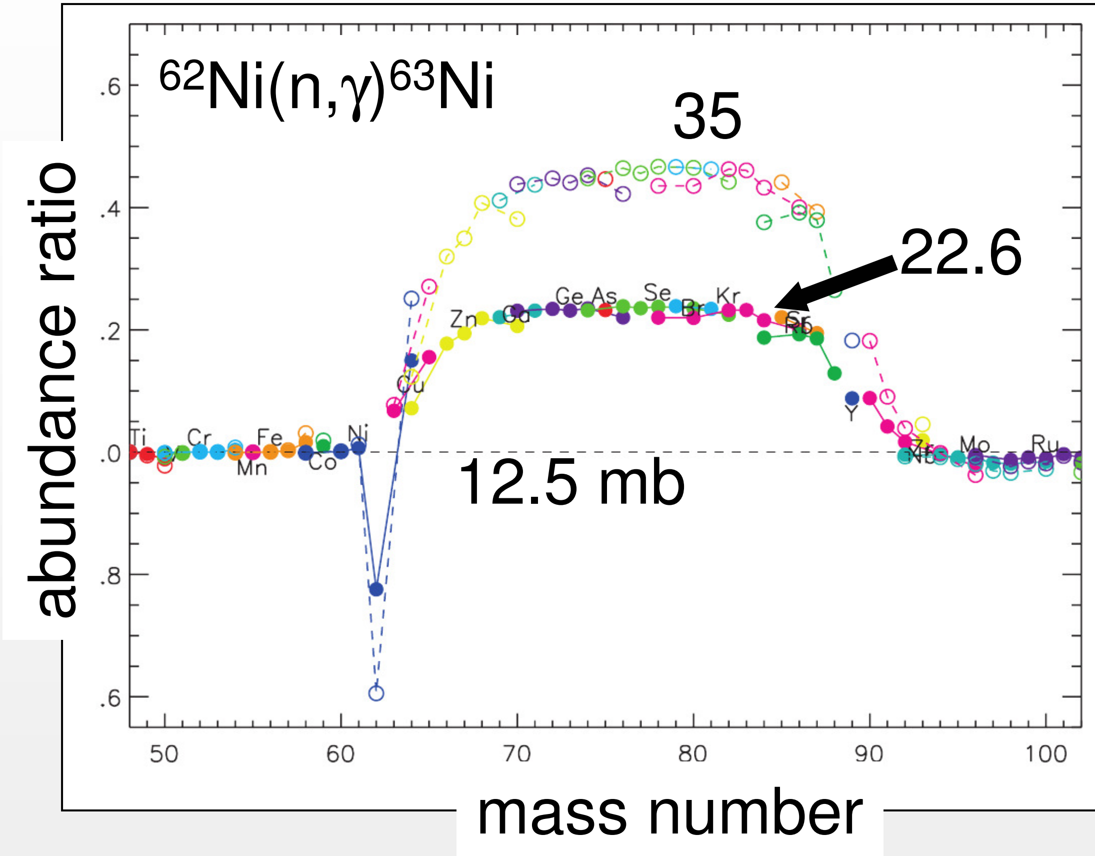
stellar site: **massive stars with $M > 8\ M_\odot$**

	core He-burning	shell C-burning
temperature	$3\text{-}3.5 \cdot 10^8$ K	$\sim 1 \cdot 10^9$ K
neutron density	10^6 cm^{-3}	$10^{11}\text{-}10^{12}$ cm^{-3}
neutron source	$^{22}Ne(\alpha,n)$	**$^{22}Ne(\alpha,n)$,** $^{13}C(\alpha,n)^{16}O$

important: reaction flow NOT in equilibrium

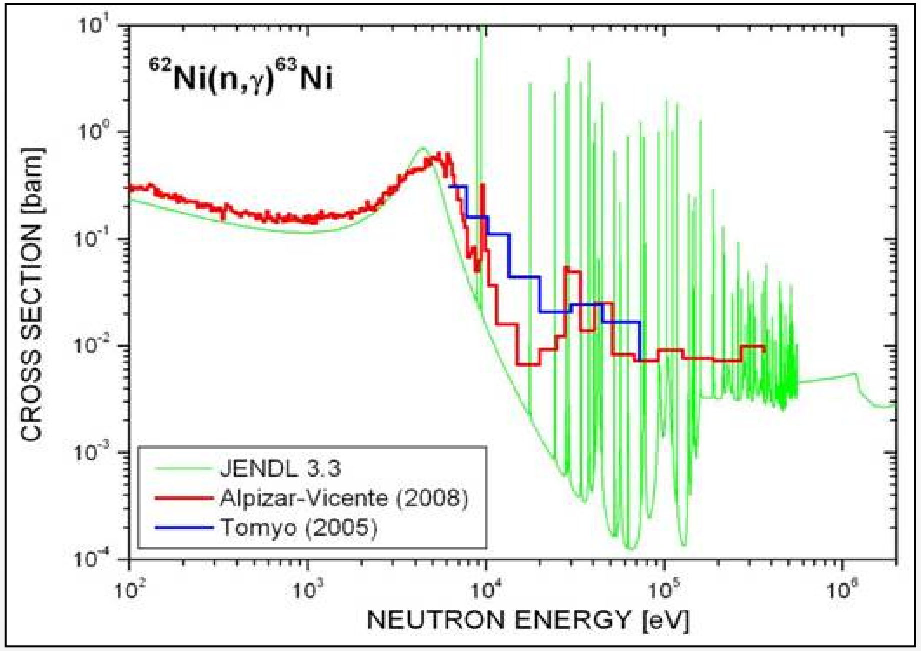
weak s process in massive stars

- reaction flow not in equilibrium
  ➡ propagation waves

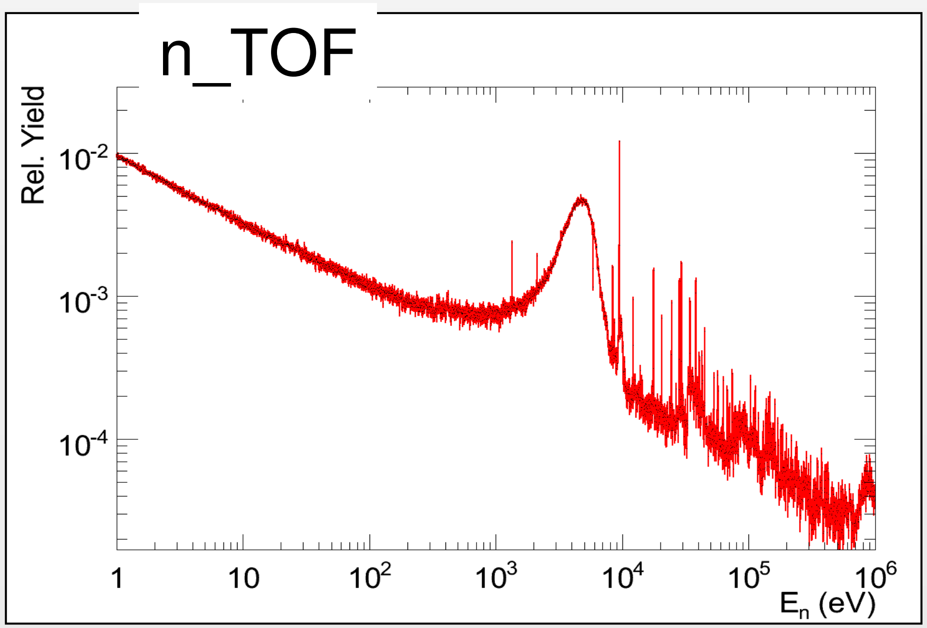


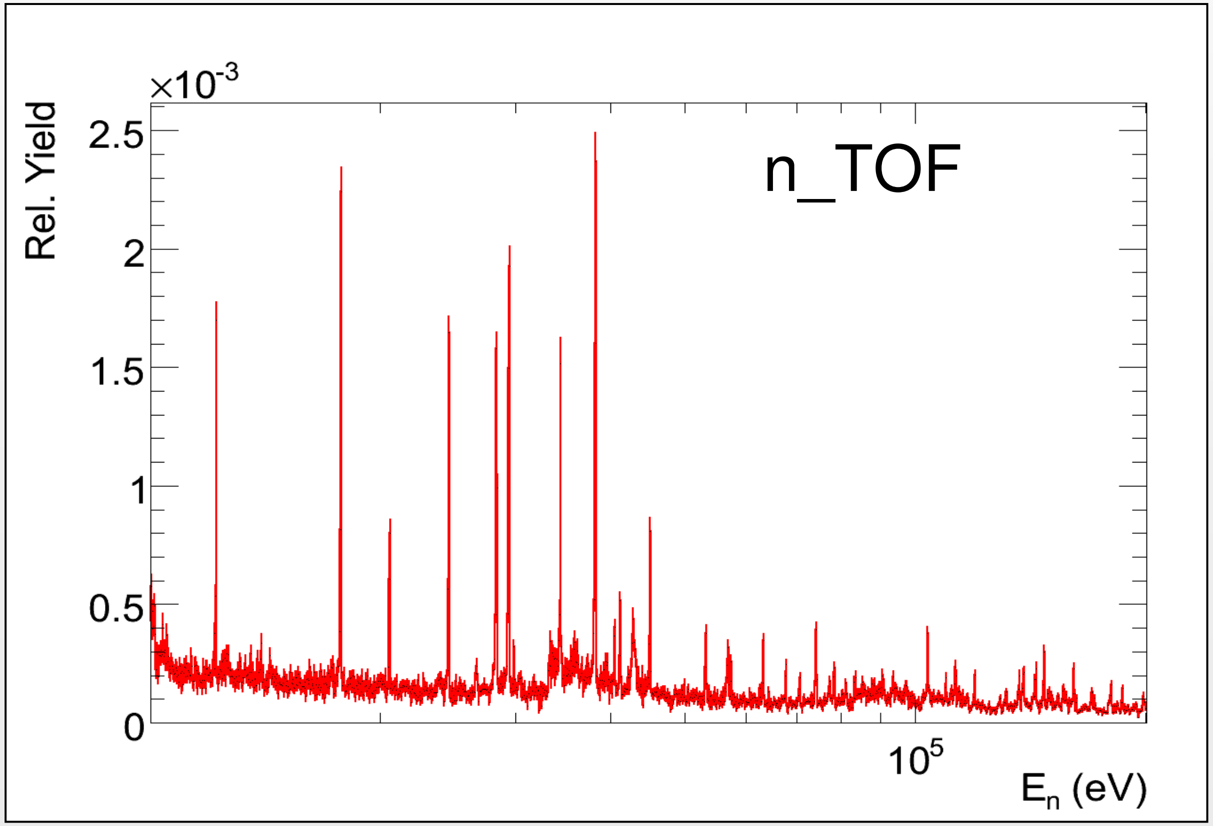
accurate (n,γ) measurements for all stable Fe and Ni isotopes under way at CERN by the n_TOF collaboration

n_TOF first results: $^{62}Ni(n,\gamma)$

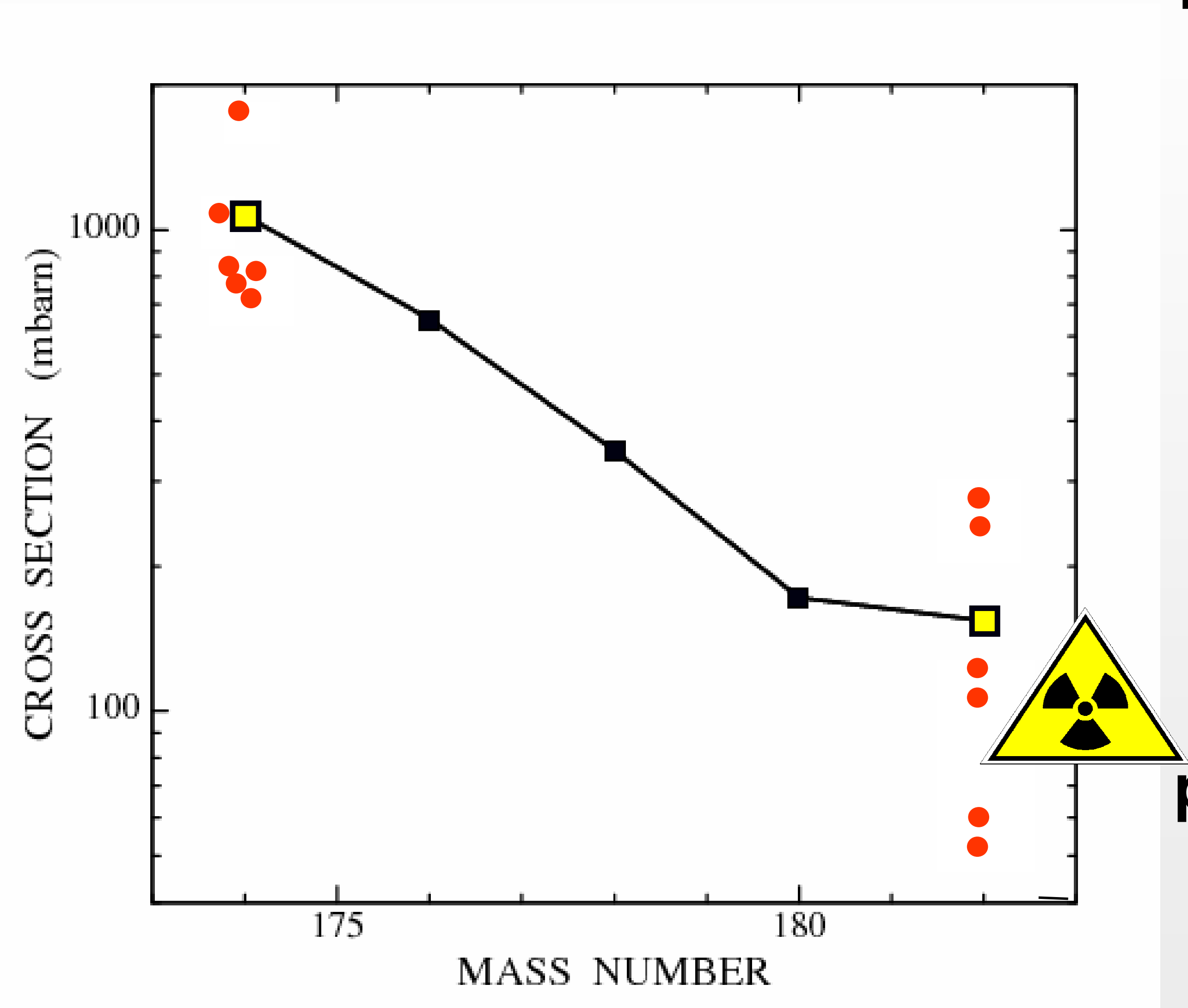


previous TOF measurements
(courtesy I. Dillmann)





what about theory ?



^{176}Hf, ^{178}Hf, ^{180}Hf:

MACS

uncertainties

1 - 2%

exercise joined

by 6 leading groups:

calculate MACS of

^{174}Hf and ^{182}Hf

prior to measurement

but theory indispensable for stellar corrections

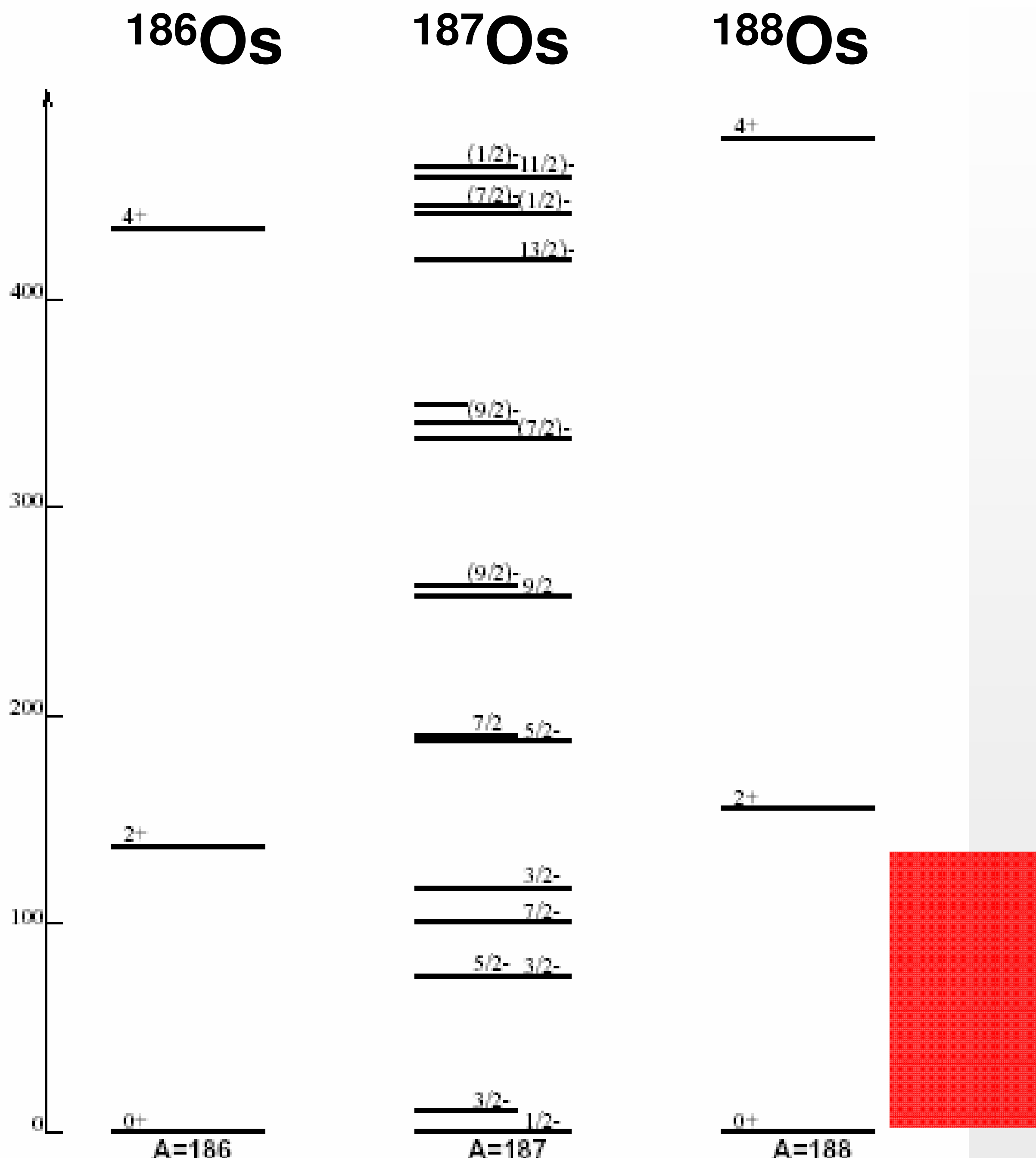
thermal population of nuclear states

$$P(E_k) = \frac{(2J_k + 1)e^{-E_k/kT}}{\sum_m (2J_m + 1)e^{-E_m/kT}}$$

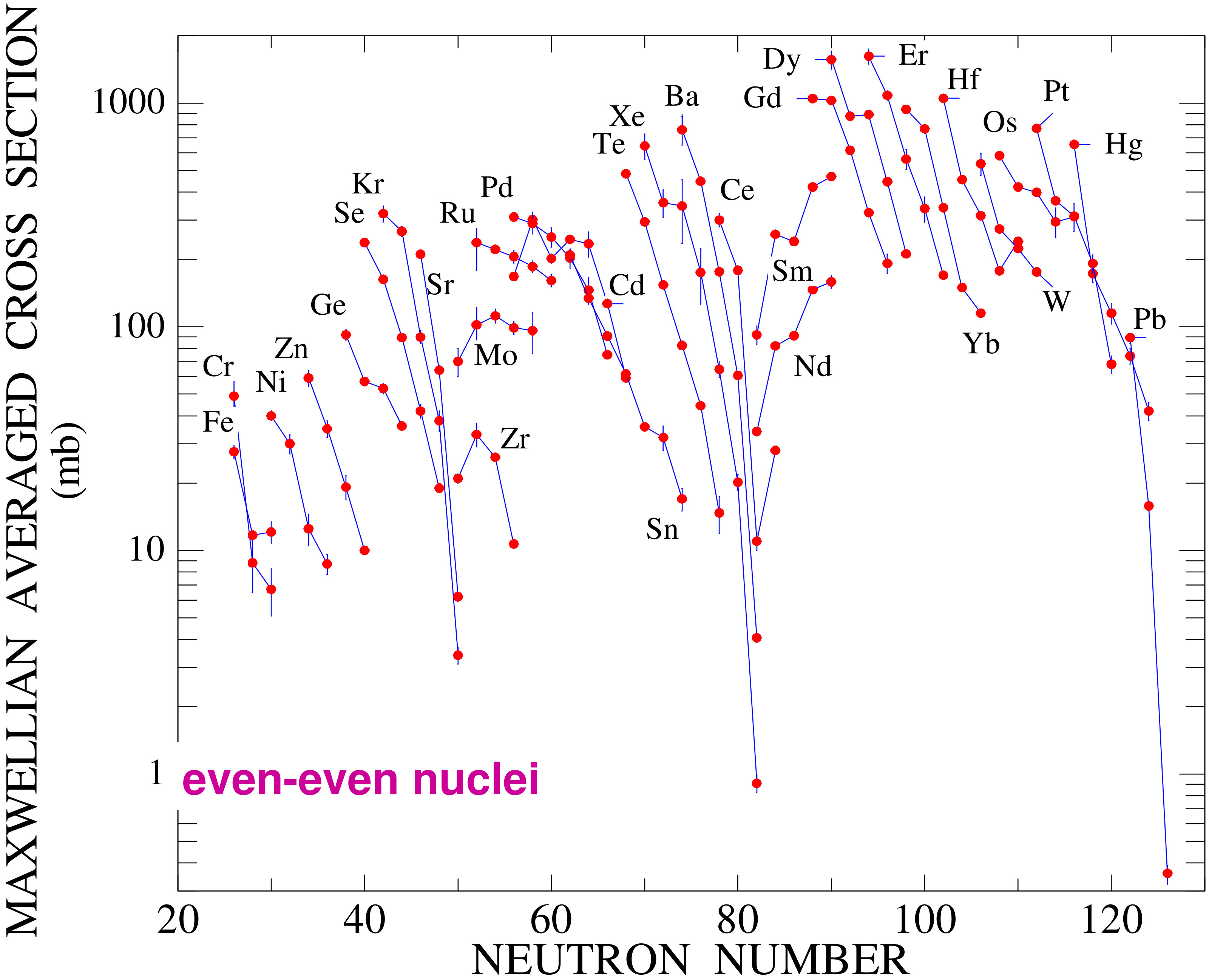
in ^{187}Os at $kT = 30$ keV

P(gs) = 33%
P(1st) = **47%**
P(all others) = 20%

stellar enhancement factor
SEF = σ^* / σ_{exp} = 1.2



MACS data @ kT = 30 keV

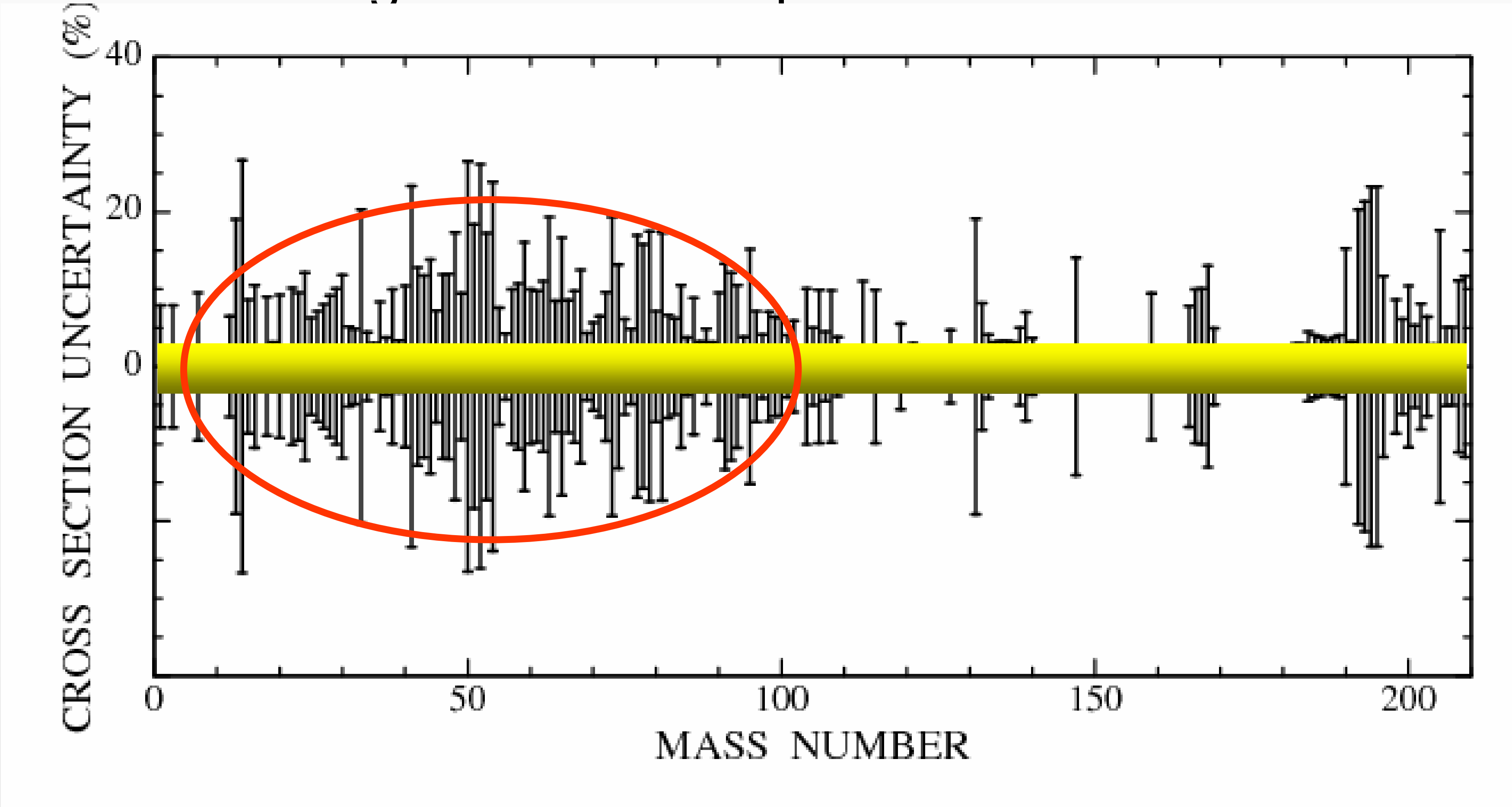


data from www.kadonis.org

I Dillmann, R Plag

status of MACS for *s* process

needed: cross sections with uncertainties between **1** and **5%**
for complete set of isotopes from ^{12}C to ^{210}Po,
including unstable samples



quests for *s*-process data

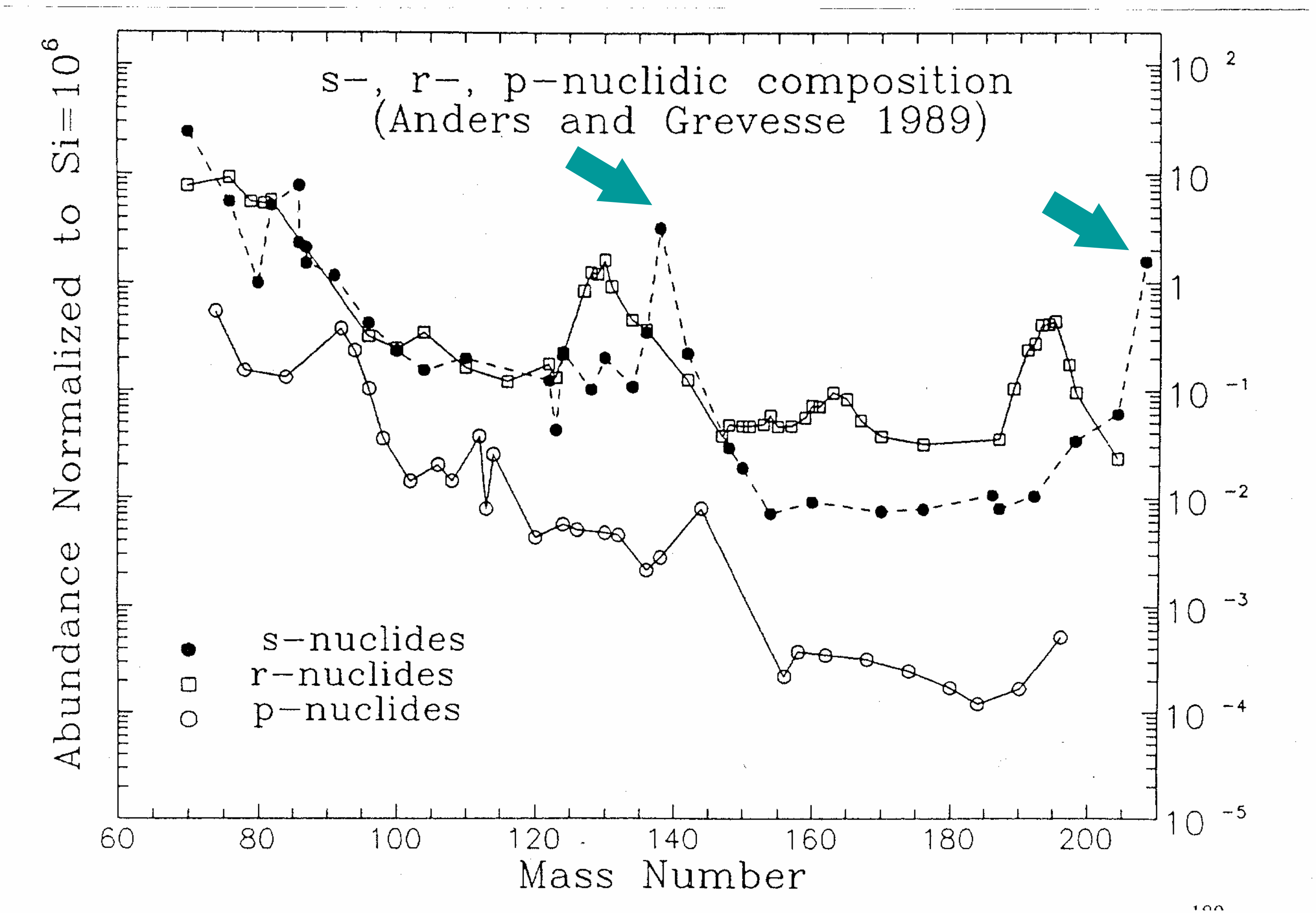
weak s process

- **propagation effects, extended network**
- **branchings at ^{63}Ni, ^{79}Se, ^{85}Kr (n_n, T)**

main *s* process

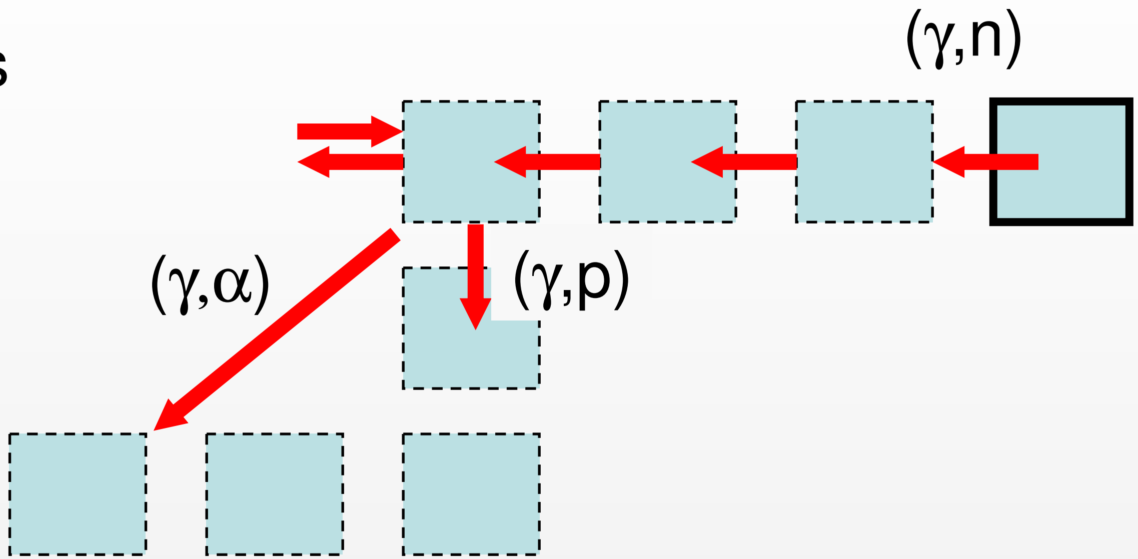
- ***s*-only isotopes for overall distribution**
- **unstable branch point isotopes (n_n,T, ρ)**
- **presolar grains involving 75 isotopes**
- **bottle neck reactions; neutron poisons**
- **neutron source reactions (^{13}C and ^{22}Ne)**
- **thermally excited states: scattering data**

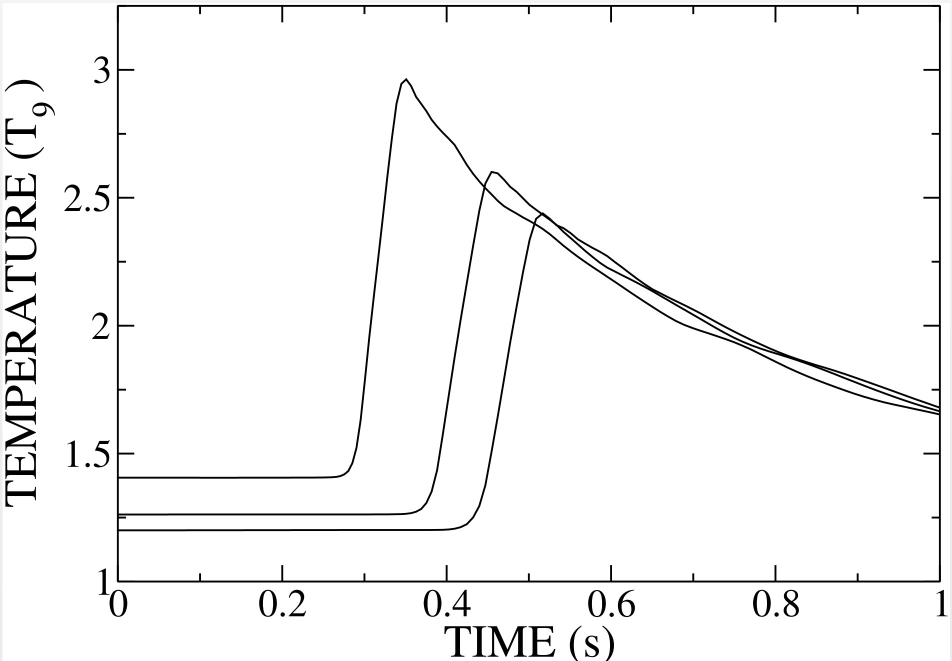
decomposition of solar abundances

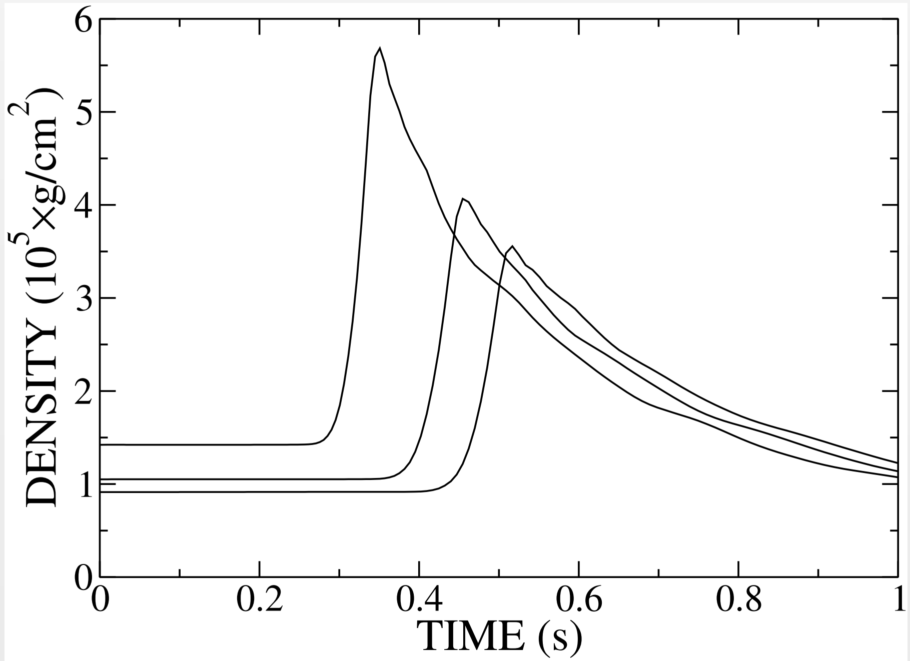


p process: mechanisms and sites

- SN shock front heating O-Ne layers to $T_9 = 1 - 3$
- time scale 1 s
- network of γ-induced reactions



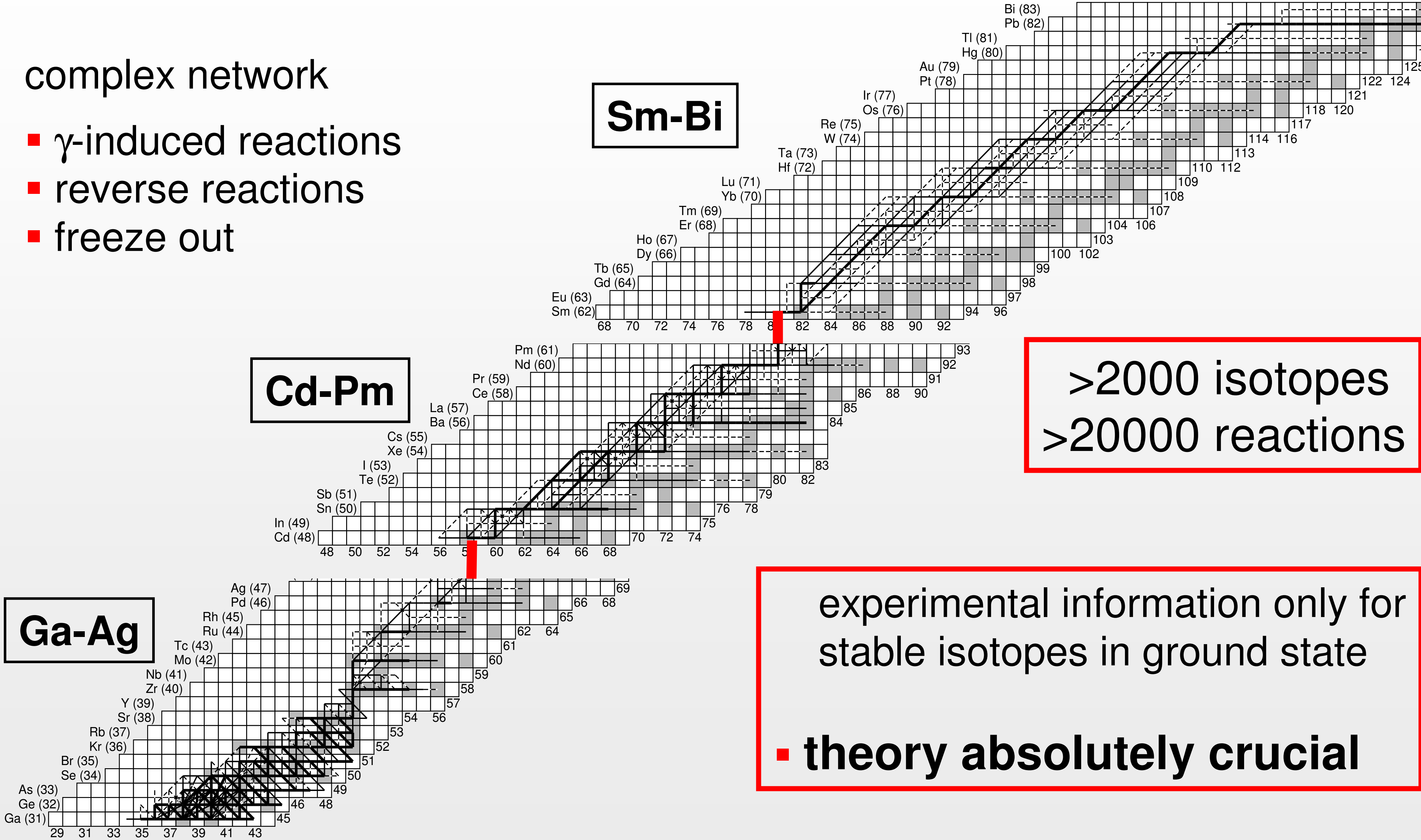




p-process network

complex network

- γ-induced reactions
- reverse reactions
- freeze out



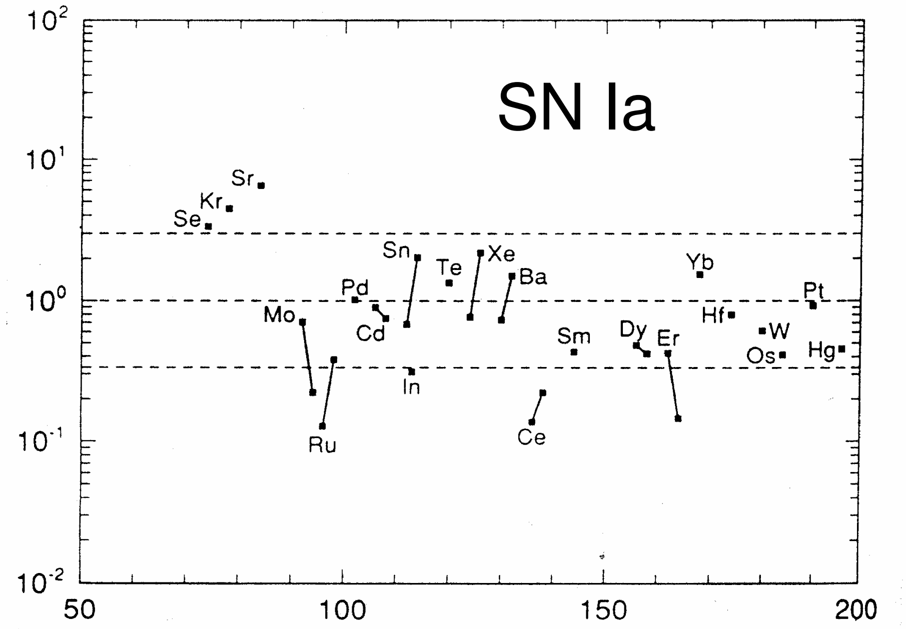
>2000 isotopes
>20000 reactions

experimental information only for stable isotopes in ground state

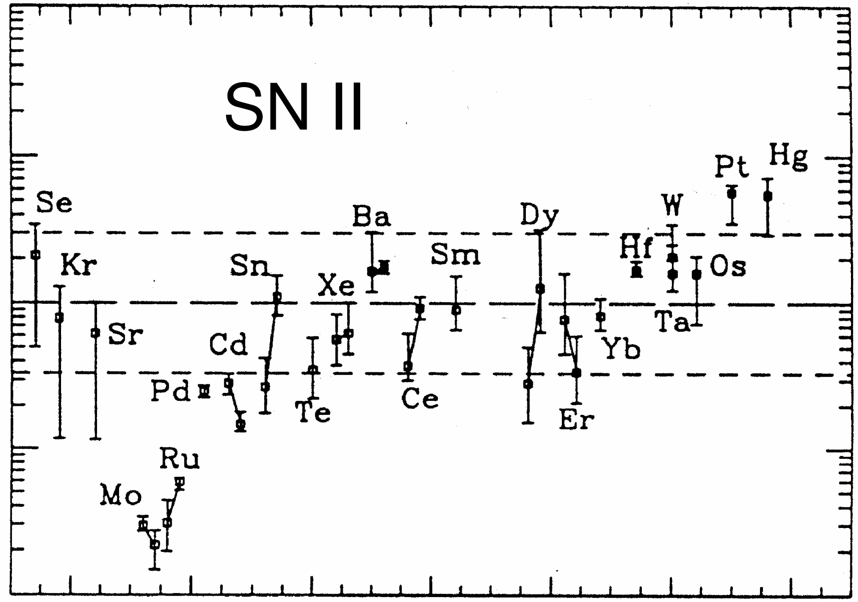
- **theory absolutely crucial**

the *p*-process problem with Mo and Ru

Howard et al., Ap. J. 309 (1991) L5

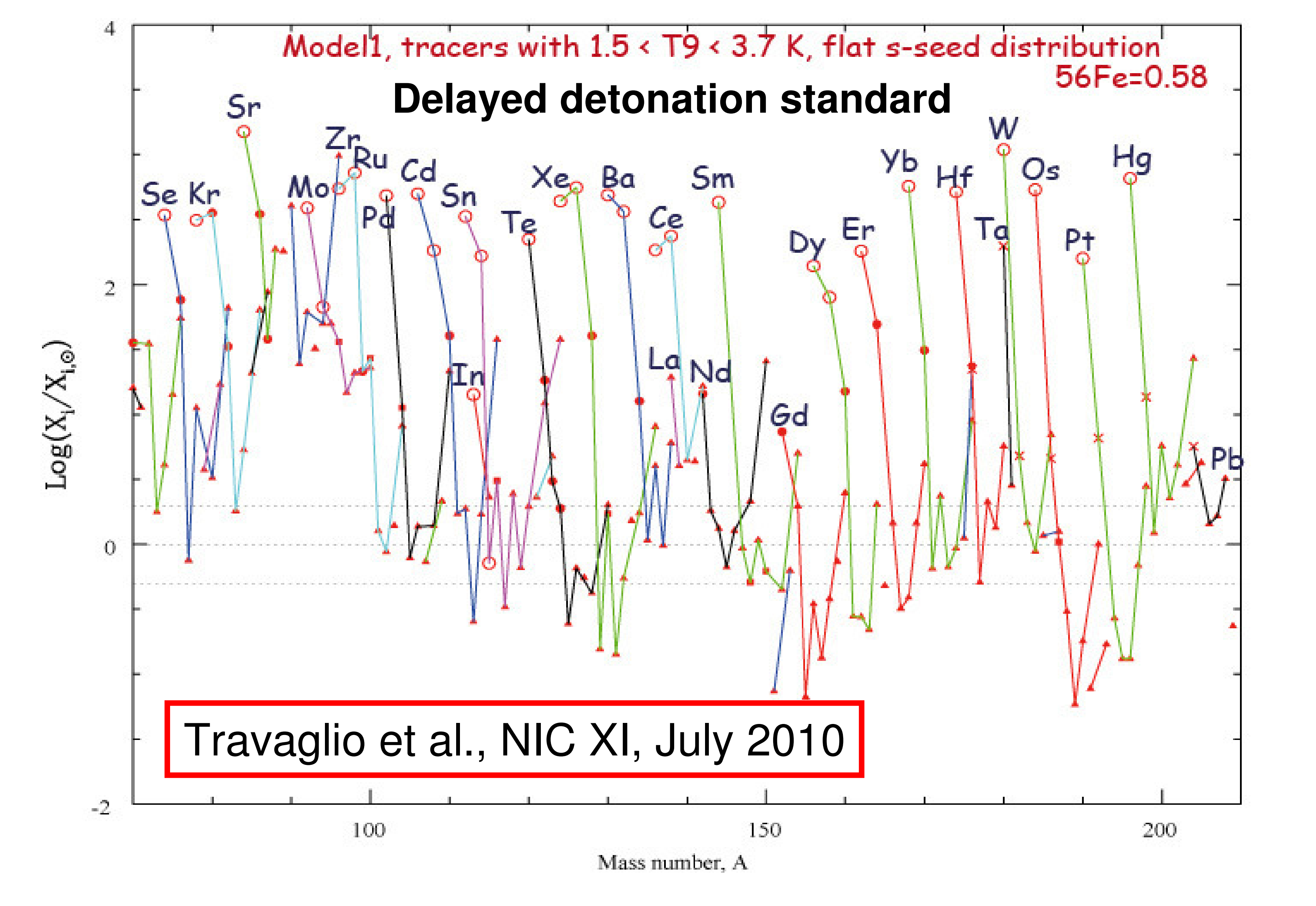


Rayet et al., A&A 298 (1995) 517



MASS NUMBER

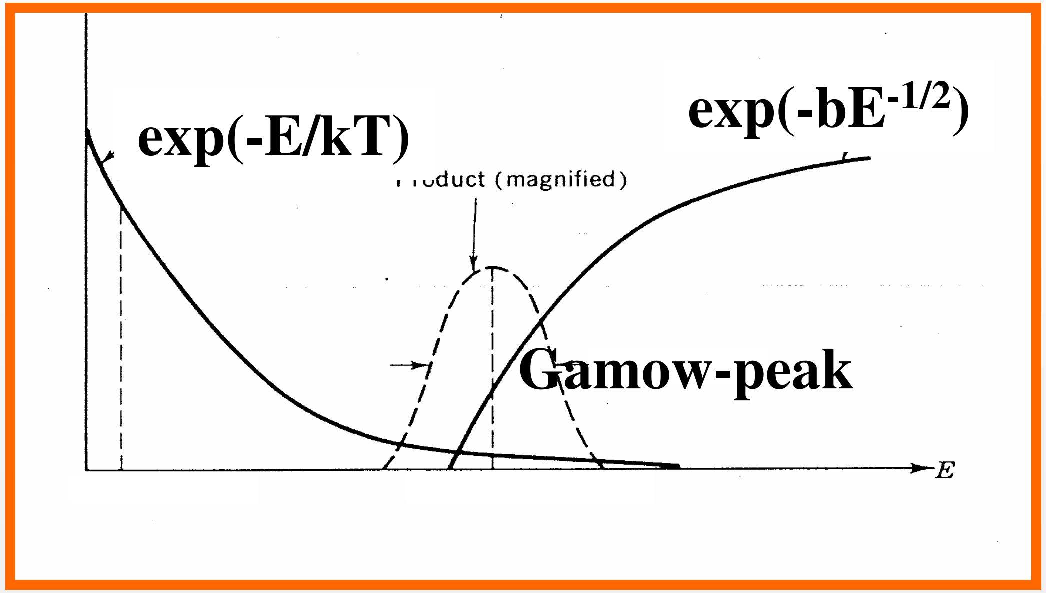
p process coupled to 3D calculation for SN Ia



p- and α-induced reactions

low energy cross section data needed
Gamow window:

E (T, Z) = 5 – 15 MeV



γ-induced reactions:
- bremsstrahlung + activation
- tagged photons
- Coulomb dissociation

p- and α-induced reactions:
- activation
- in-beam γ measurements

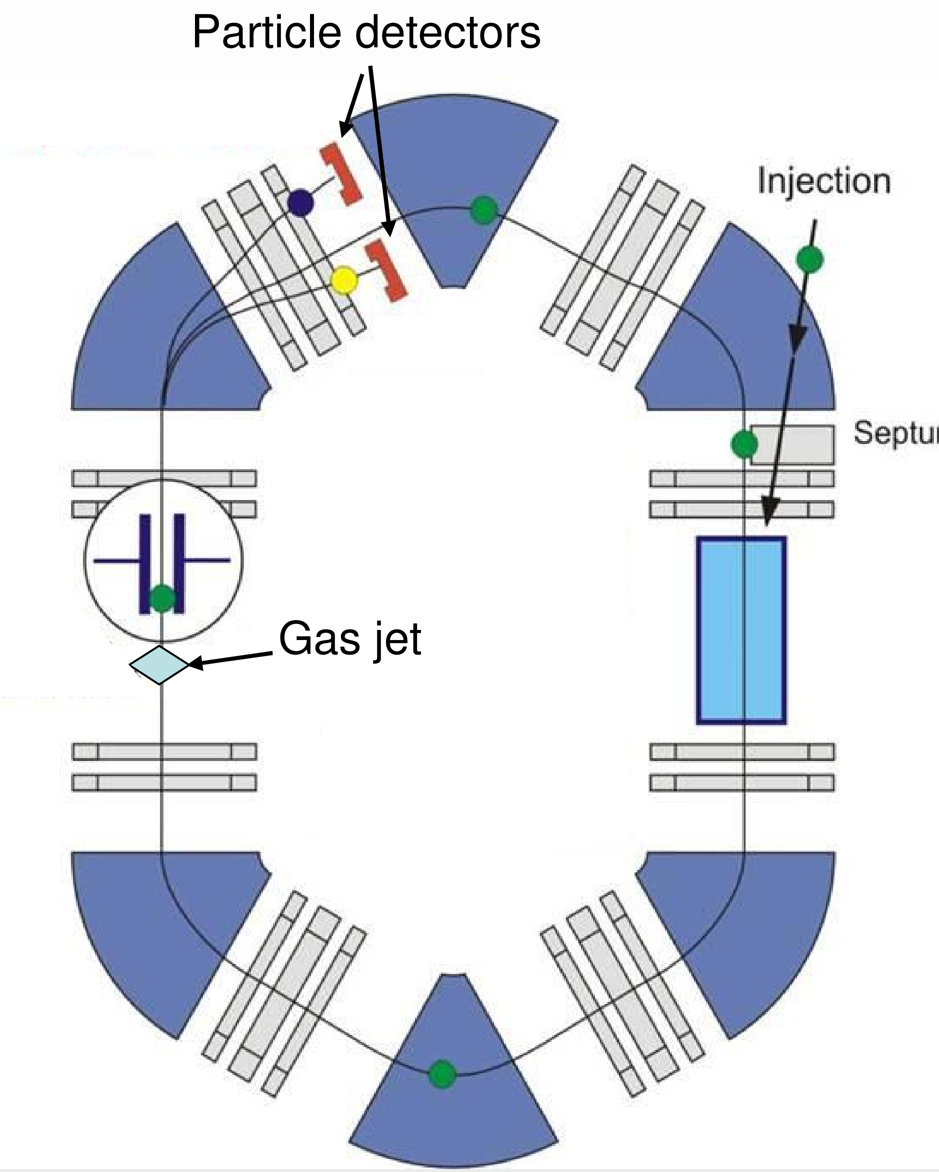
so far, all measurements on stable isotopes
➡ important for guiding statistical model calculations

reactions on unstable nuclei at the ESR

measurements of (p,γ) or (α,γ) rates in inverse kinematics.

- radioactive ions injected, decelerated, and cooled
- reactions studied with internal gas jet target

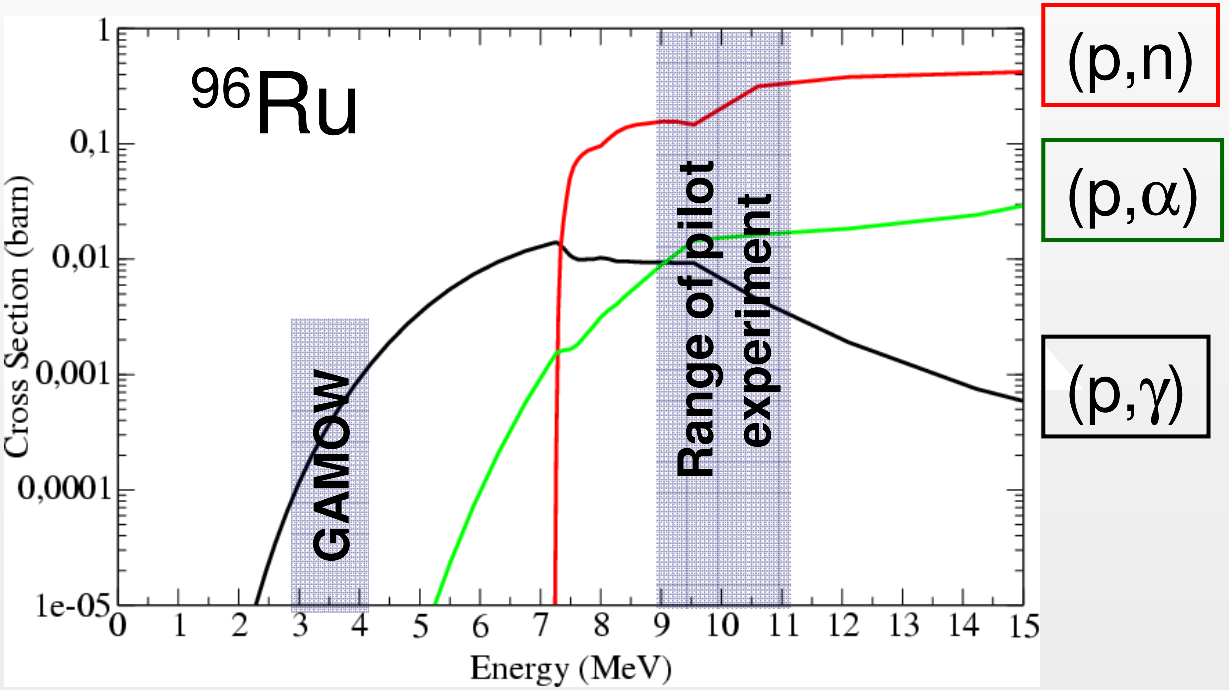
- applicable to radioactive nuclei and gases
- direct counting of reaction products by in-ring particle detectors (low background, high efficiency)



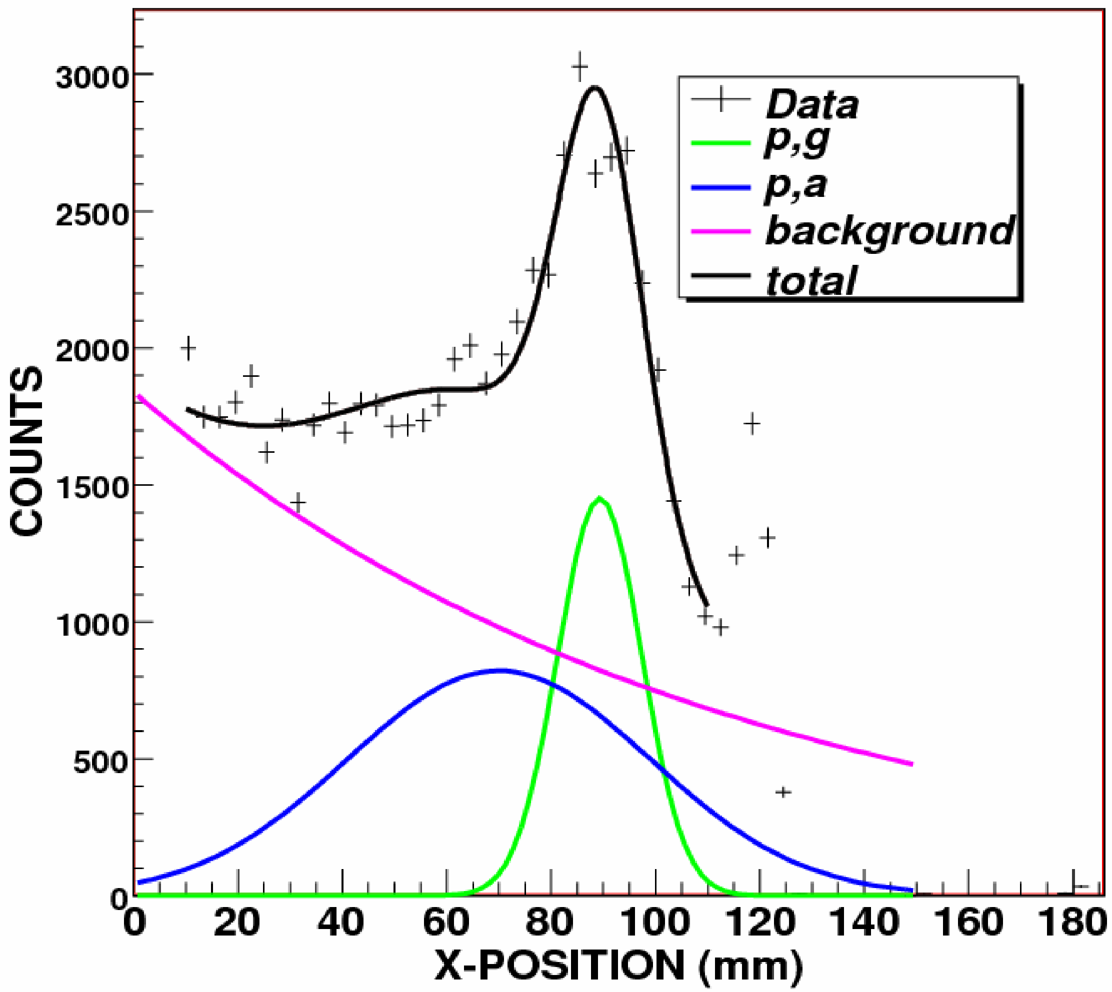
ESR

pilot experiment with stable ^{96}Ru beam

- measurement with stable beam at E_p = 9, 10, 11 AMeV
- $5 \cdot 10^6$ particles per spill,
- target density $1 \cdot 10^{13}$ atoms/cm^2, luminosity $2.5 \cdot 10^{25}$
- cross section of 1 mb ➡ ~100 counts/h



preliminary result @ 11 MeV



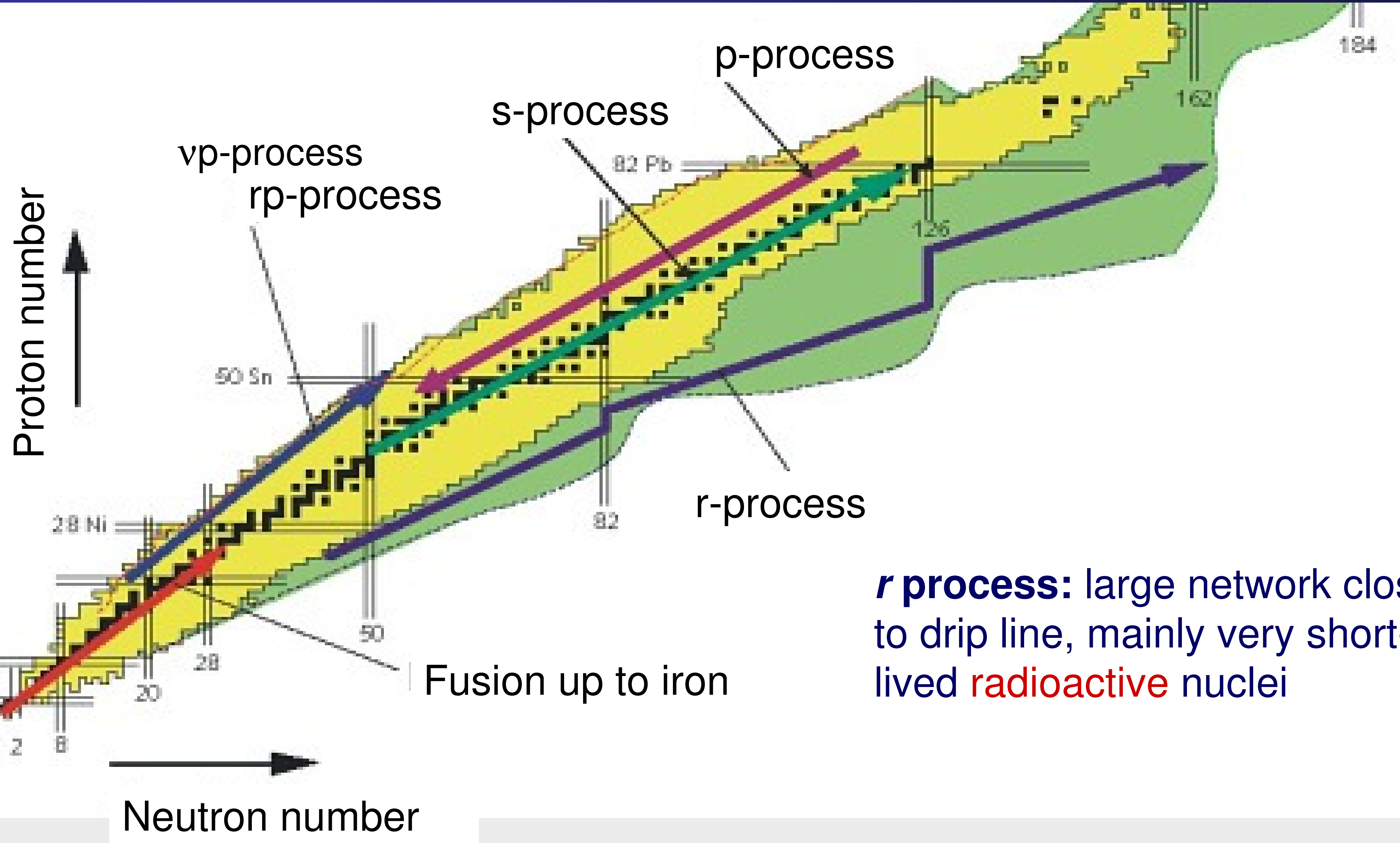
courtesy M. Heil, GSI

upper limit for (p,γ)
(without (p,n) component)

$\sigma_{p\gamma}$ < 4.0 mb

Non-Smoker: 3.5 mb

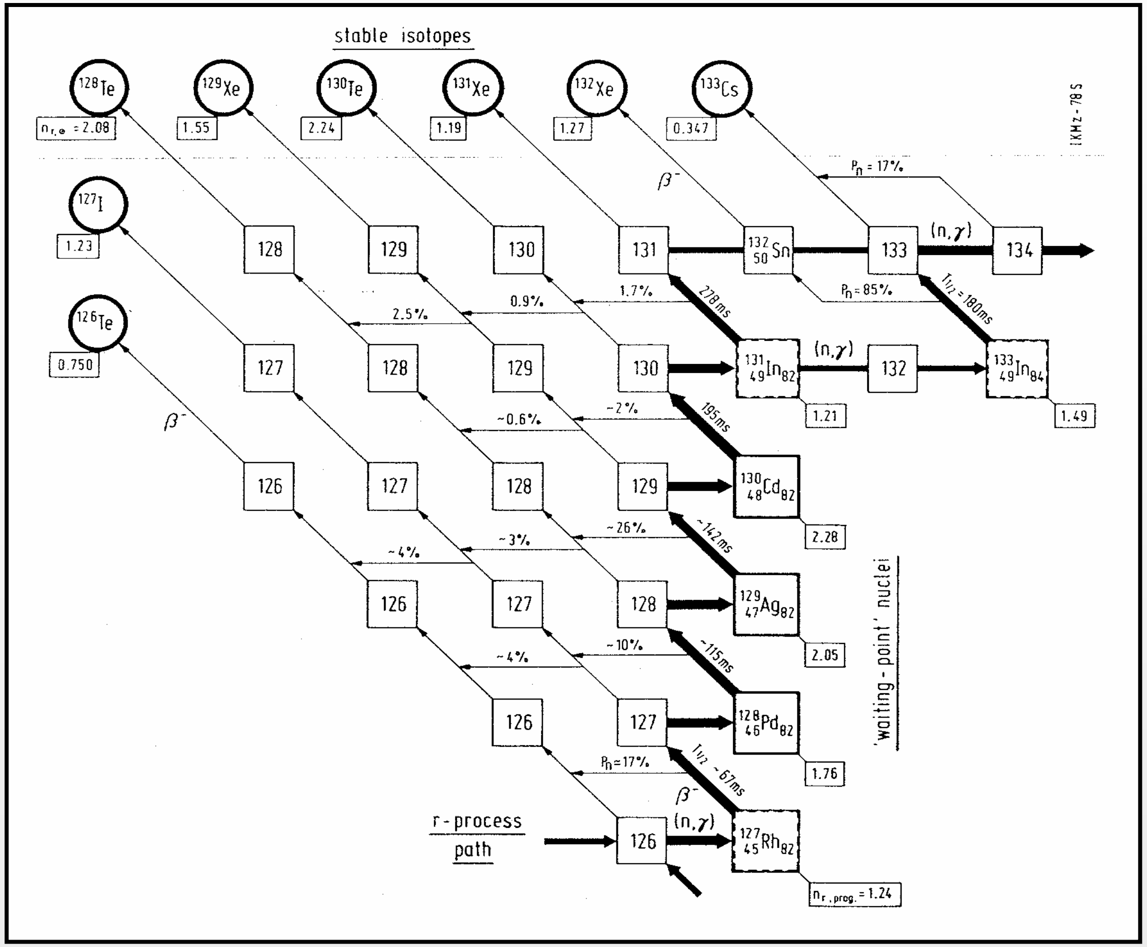
nucleosynthesis in the *r* process



***r* process:** large network close to drip line, mainly very short-lived radioactive nuclei

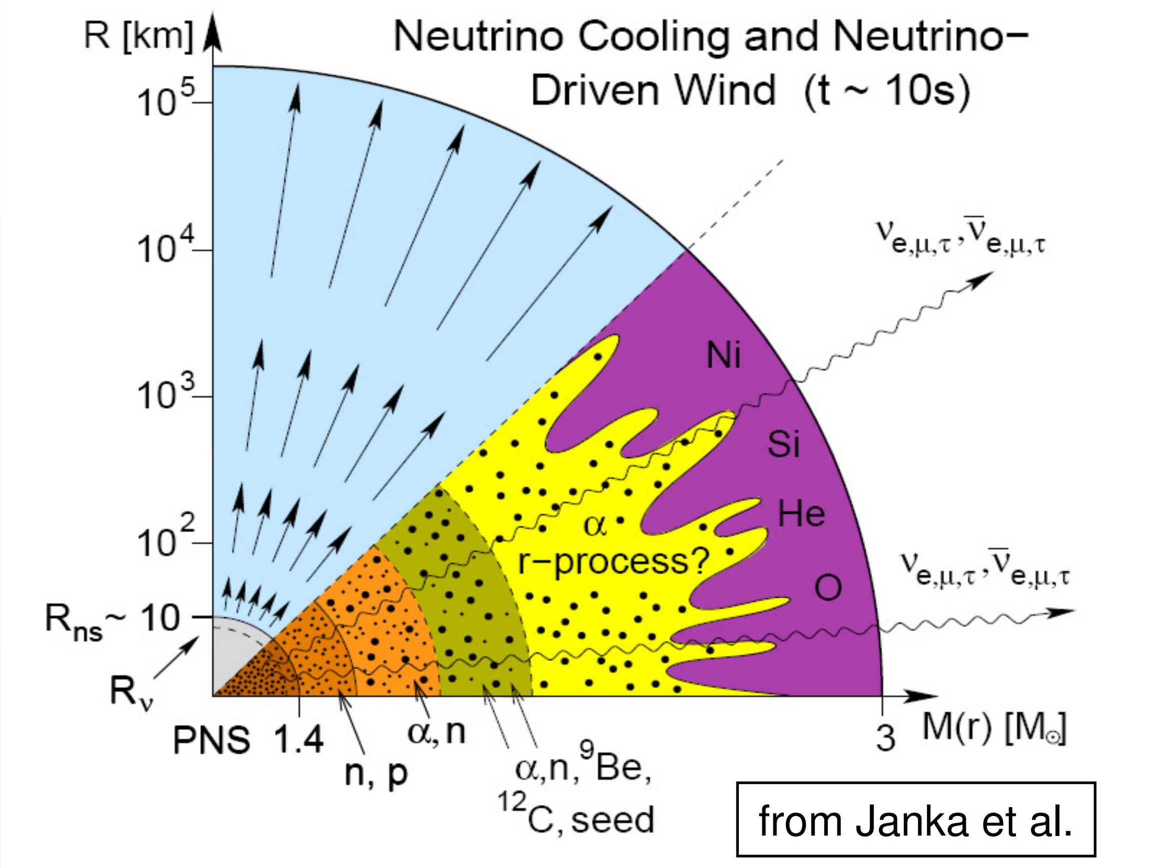
waiting point approximation

- reaction path defined by waiting points at S_n~2 MeV
- waiting point abundances defined by: $t_{1/2} N_r = \text{const}$
- final abundances modified
  - beta delayed neutron emission
  - $(n, \gamma)/(\nu, x)$ reactions



current *r*-process scenario

ν-driven wind model of core collapse supernovae (SN II)

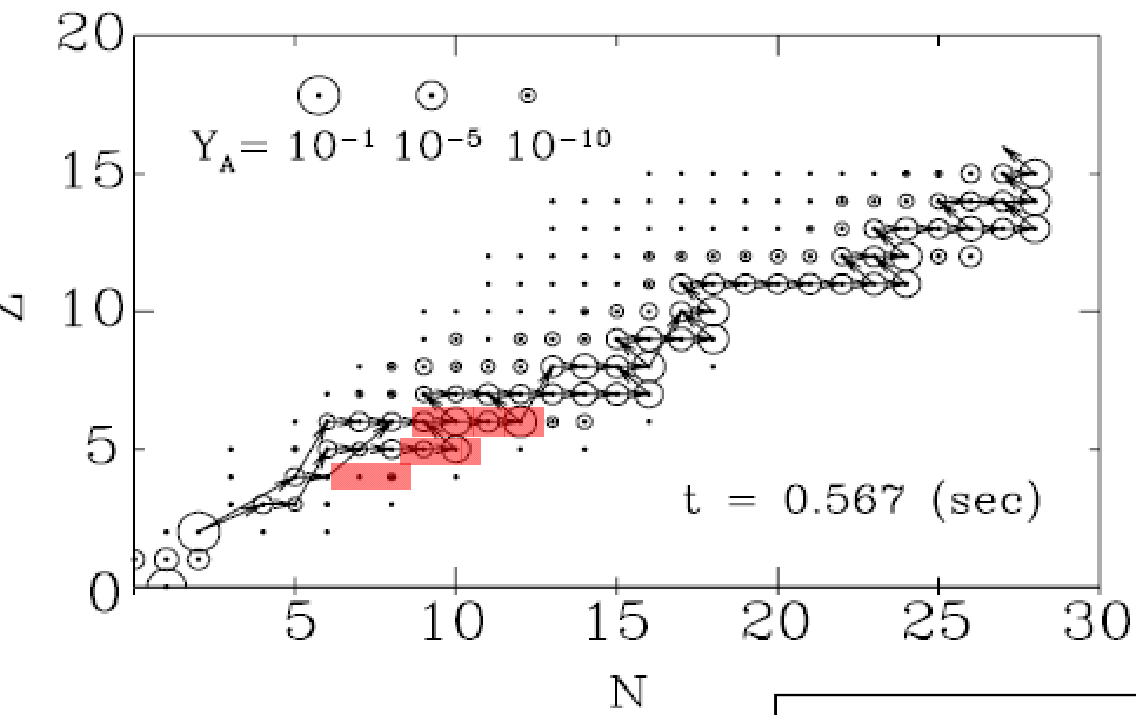


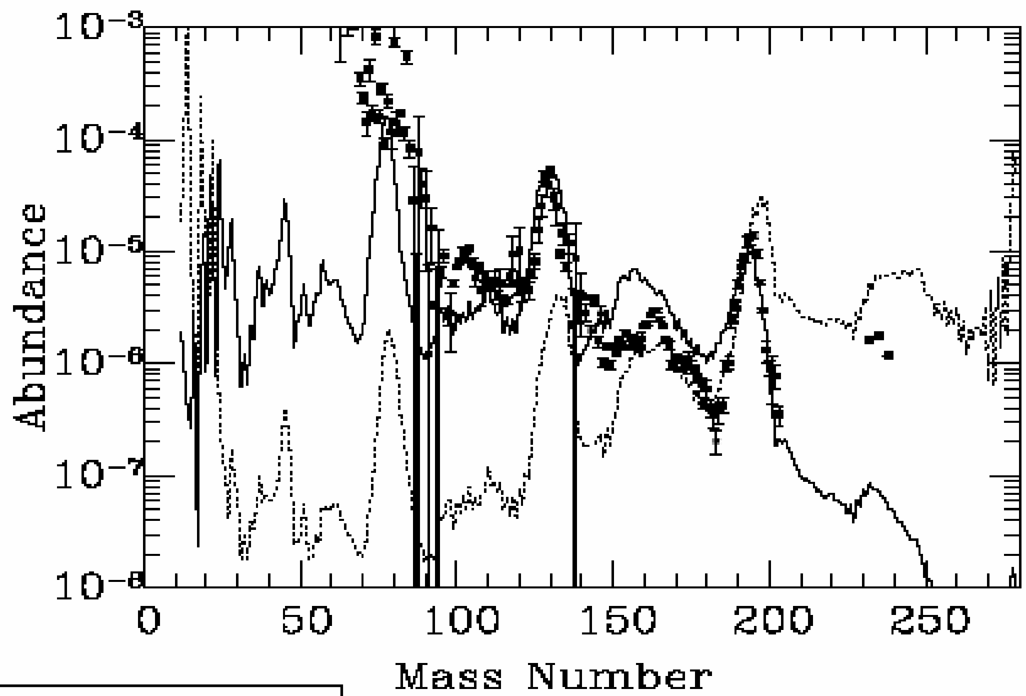
- formation of seed nuclei by charged-particle-induced reactions (α process)
- *r* process path about 15 mass units from stability

(n,γ) cross sections for the *r* process ?

direct (n,γ) measurements in or near the *r*-process path presently out of reach (small σ, short $t_{1/2}$)

but (n,γ) data on n-rich light isotopes could contribute to the *r*-process efficiency in short-dynamic-time-scale models

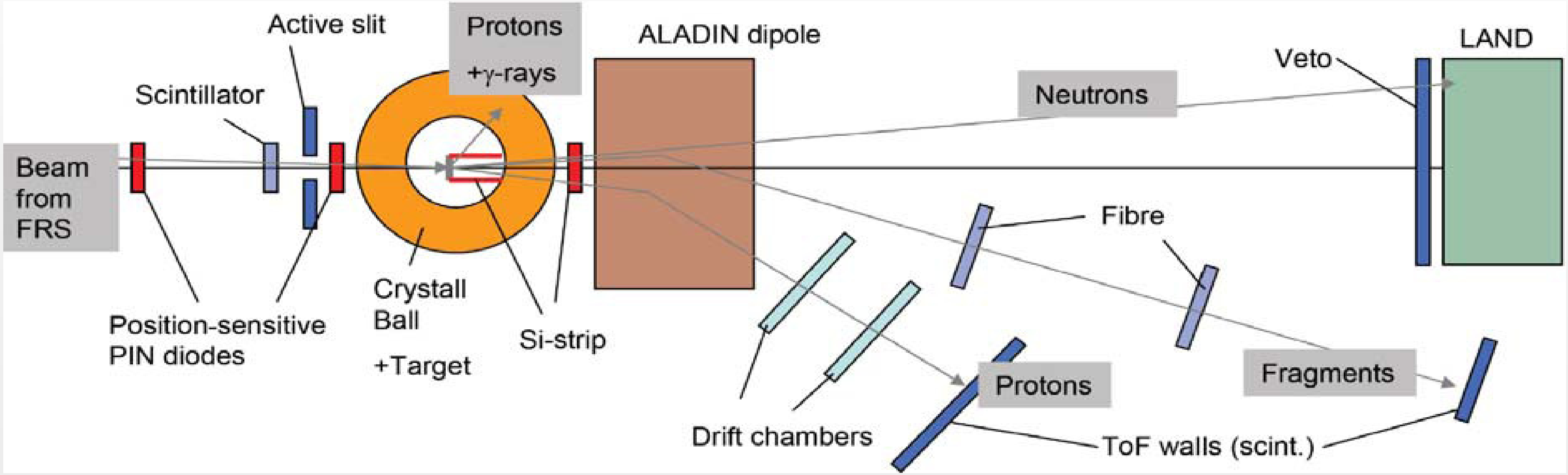




Terasawa et. al. APJ 562, 470, 2001

Coulomb dissociation at LAND

measurements of (γ,n) cross sections proposed on carbon isotopes up to ^{18}C(γ,n), ^{14,15}B, and ^{11,12}Be



Courtesy M. Heil

summary

s process during stellar evolution:

- experimental data for stable isotopes available, but need accuracy
- SEF corrections under control
- challenges for unstable branch points

explosive nucleosynthesis:

- huge networks, mostly unstable nuclei, large SEF corrections
  ➡ theory absolutely crucial
- experimental approaches for *p* process at RIB facilities
- cross sections for the *r* process only in exceptional cases