Nuclear astrophysics with real photons

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CASSIOPEIA A,
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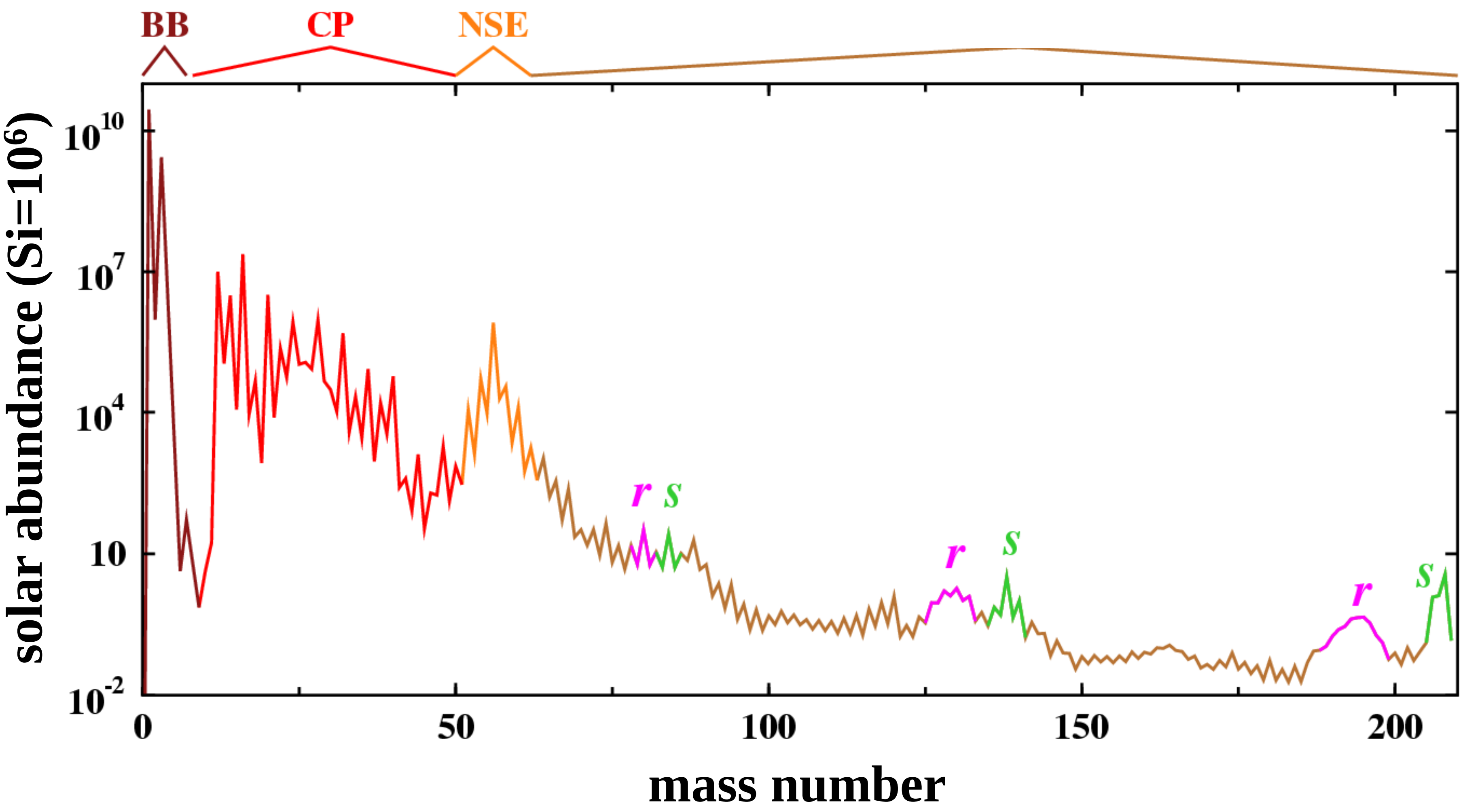
Contents

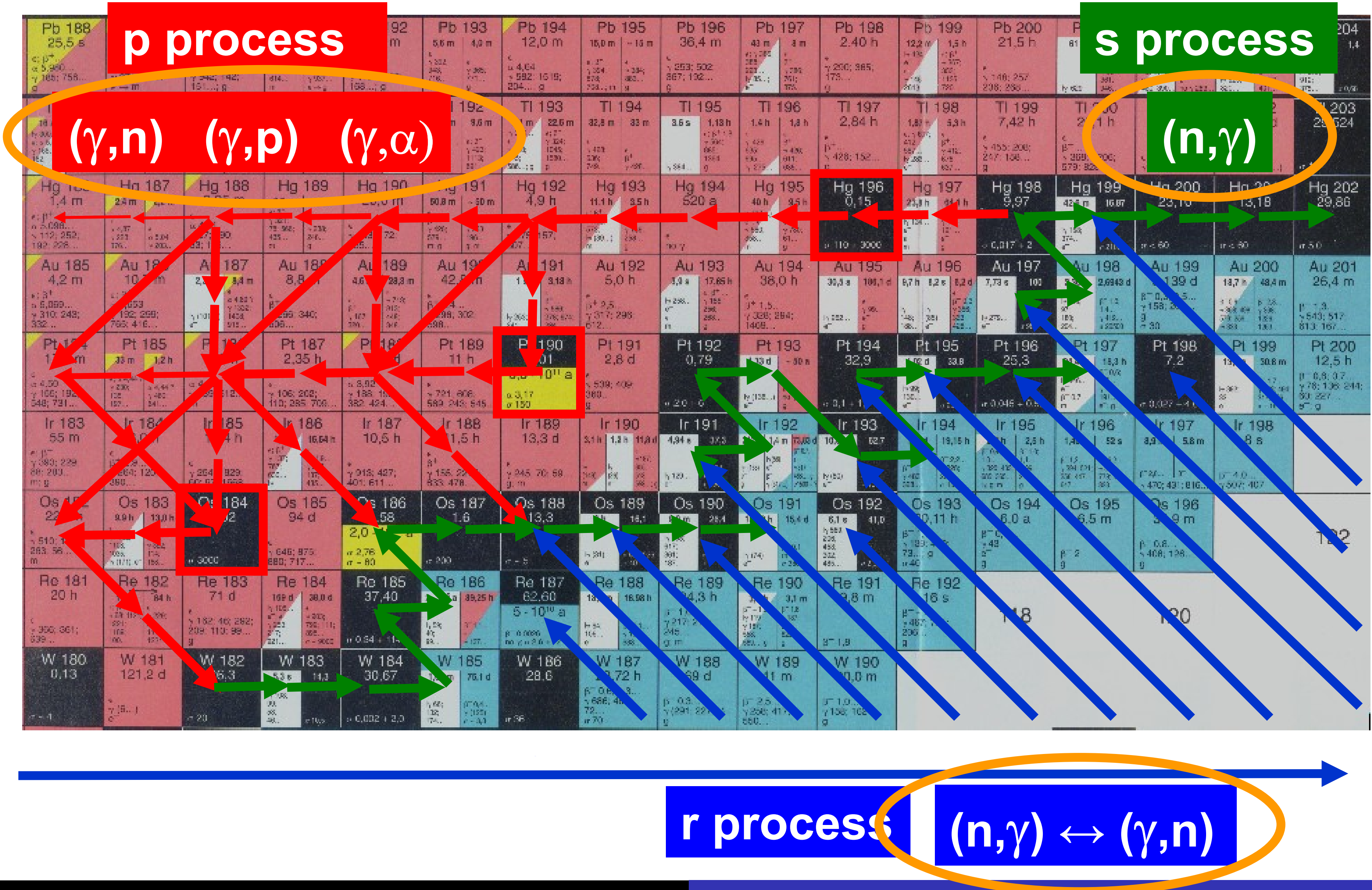
- Real photons and the nucleosynthesis of heavy elements
- Real photon experiments and astrophysical implications
  - Branching points in the *s* process
  - Photodissociation rates for the *p* process
- Experiments with tagged photons

Nucleosynthesis and solar abundance



Moreover: *p* process, *νp* process, *rp* process, ...

Nucleosynthesis of heavy elements



Reaction rates for nucleosynthesis networks

Direct measurements of reaction rates provide best reliability

Huge number of reaction rates needed

Many **unstable** isotopes along the reaction flow

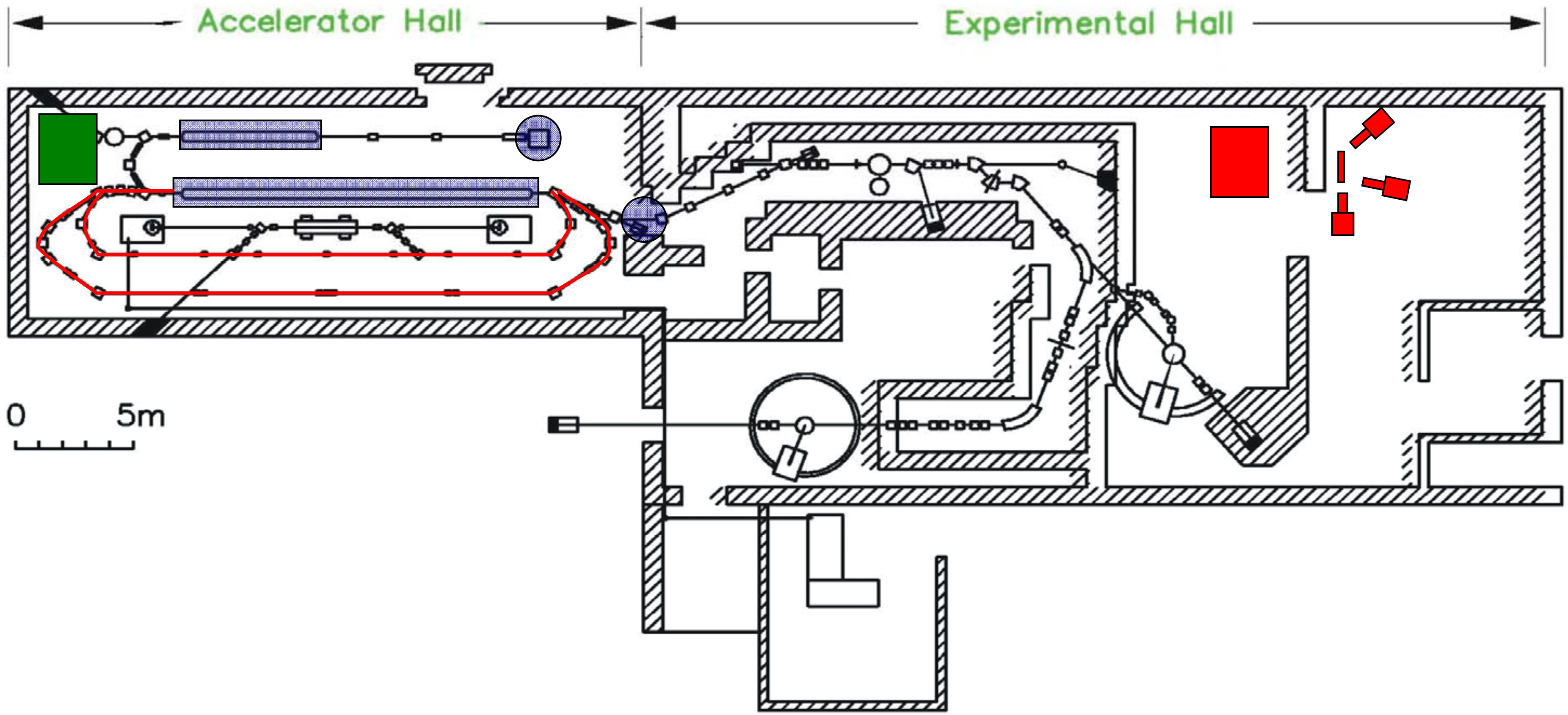
Strong **thermal excitation** of isotopes ($T \sim 10^8$-10^9 K)

Theoretical predictions of reaction rates are mandatory

Test predictive power experimentally

Improve nuclear input parameters
(photo-induced reactions:
optical potential, γ-strength function,
level densities,…)

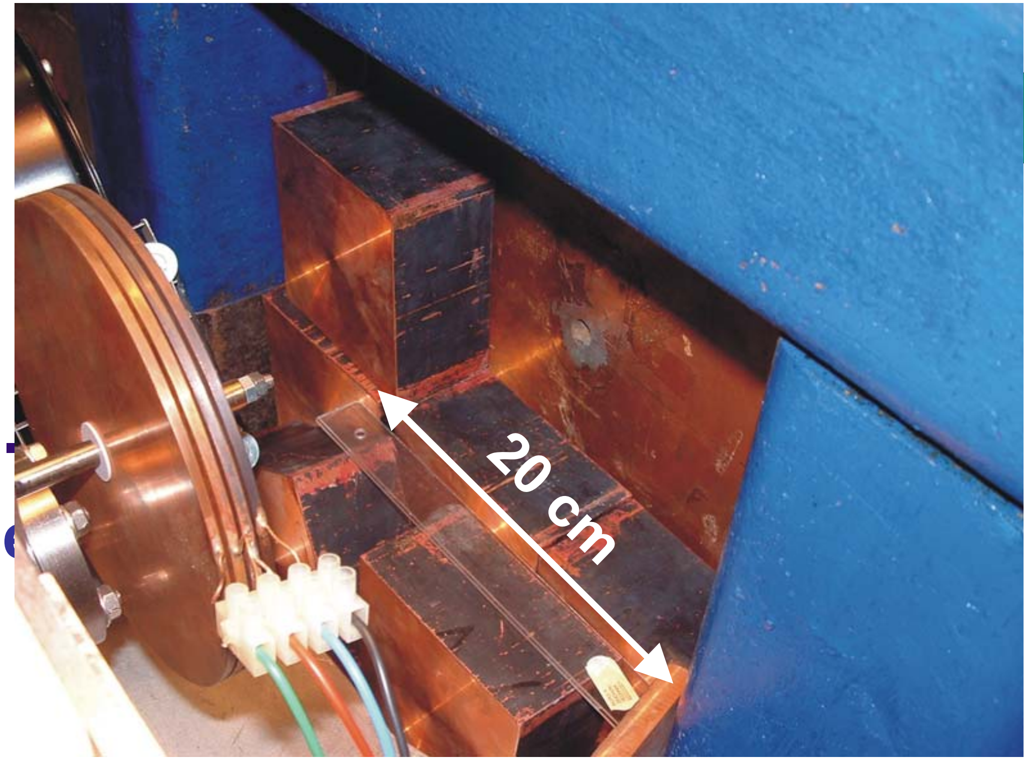
Experiments at the S-DALINAC

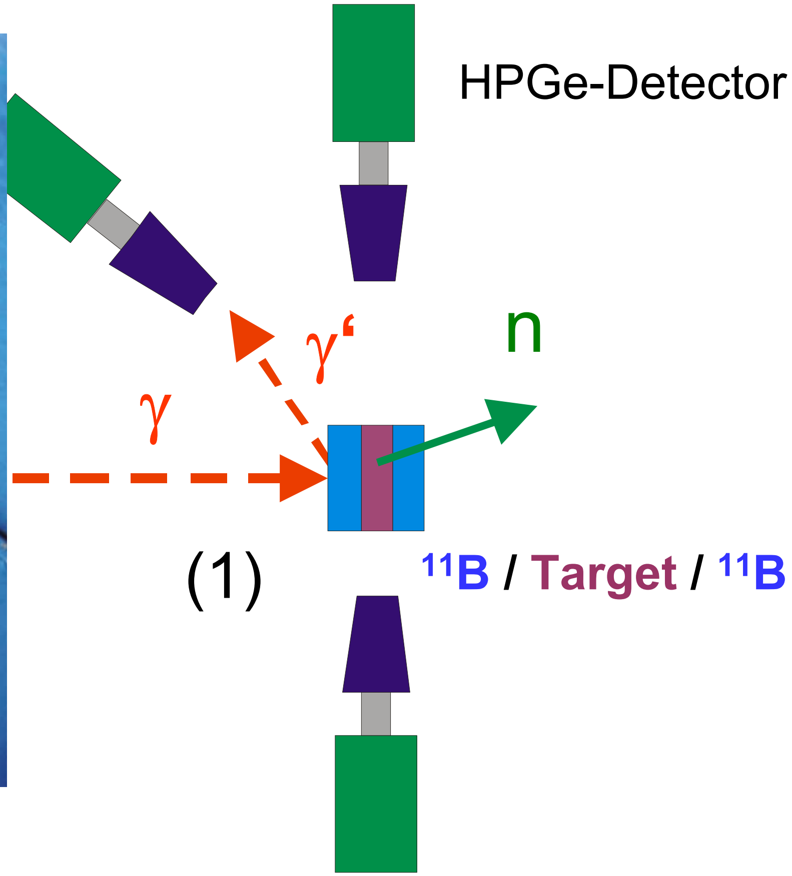


High intensity photon setup **$E_\gamma < 11$ MeV** **$n_\gamma \sim 10^5 - 10^7\ \gamma$ / (keV s cm^2)**

Photon tagging setup **$E_\gamma \sim 6\text{-}20$ MeV** **$n_\gamma \sim 10^3\ \gamma$ / (keV s cm^2)**

The experimental setup at the S-DALINAC

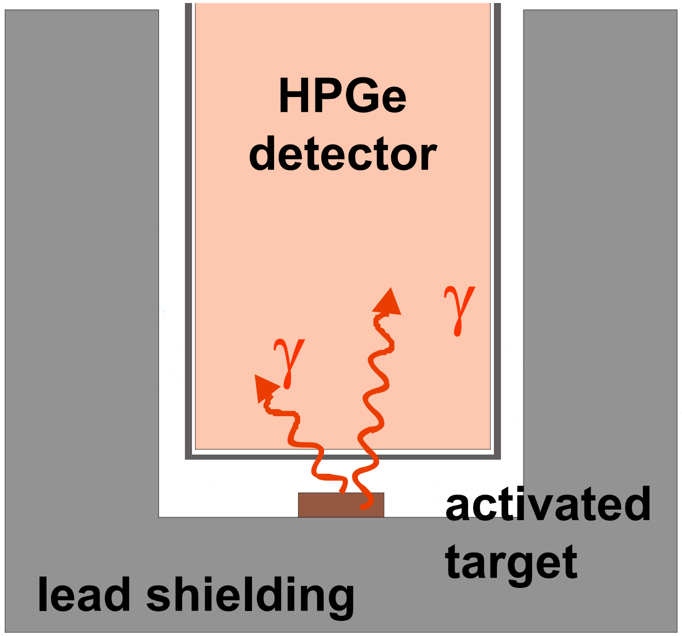




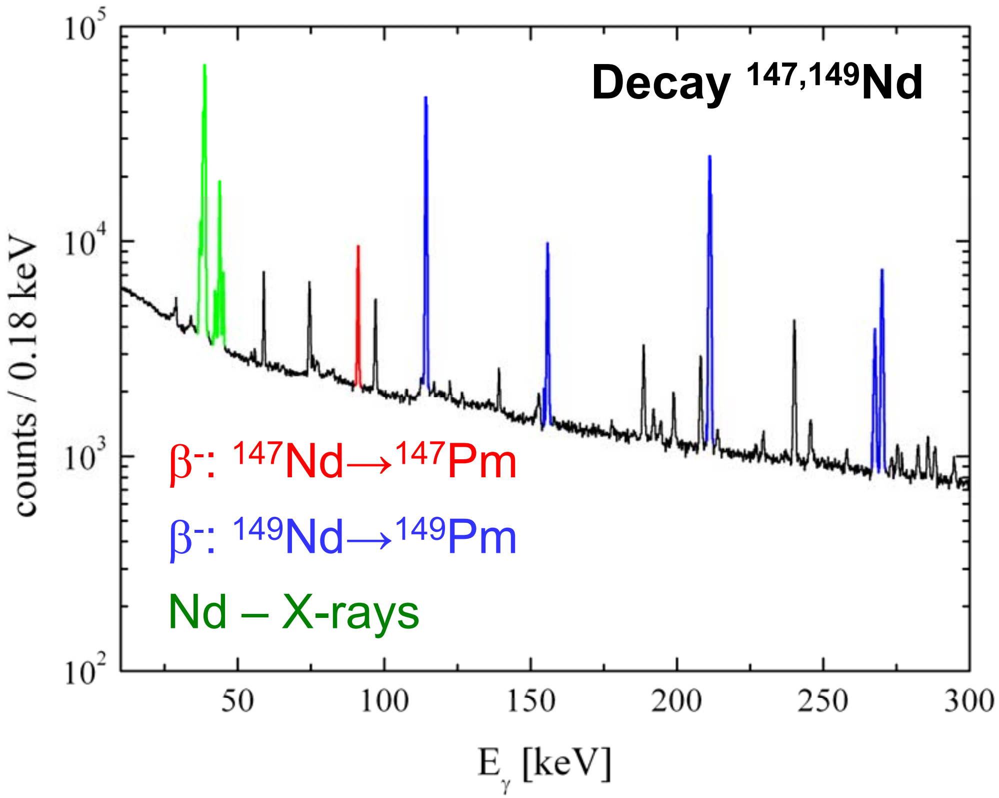
(1) Photon flux ~ 10^5 γ / (keV s cm^2)
Calibration of the photon flux via ^{11}B(γ,γ‘)

(2) Photon flux ~ 10^7 γ / (keV s cm^2)
Calibration of the photon flux via ^{197}Au(γ,n) and ^{187}Re(γ,n)

Determination of reaction yield



~ 2π geometry



Reaction yield: $Y \propto \int \sigma(E) n_\gamma(E) dE$

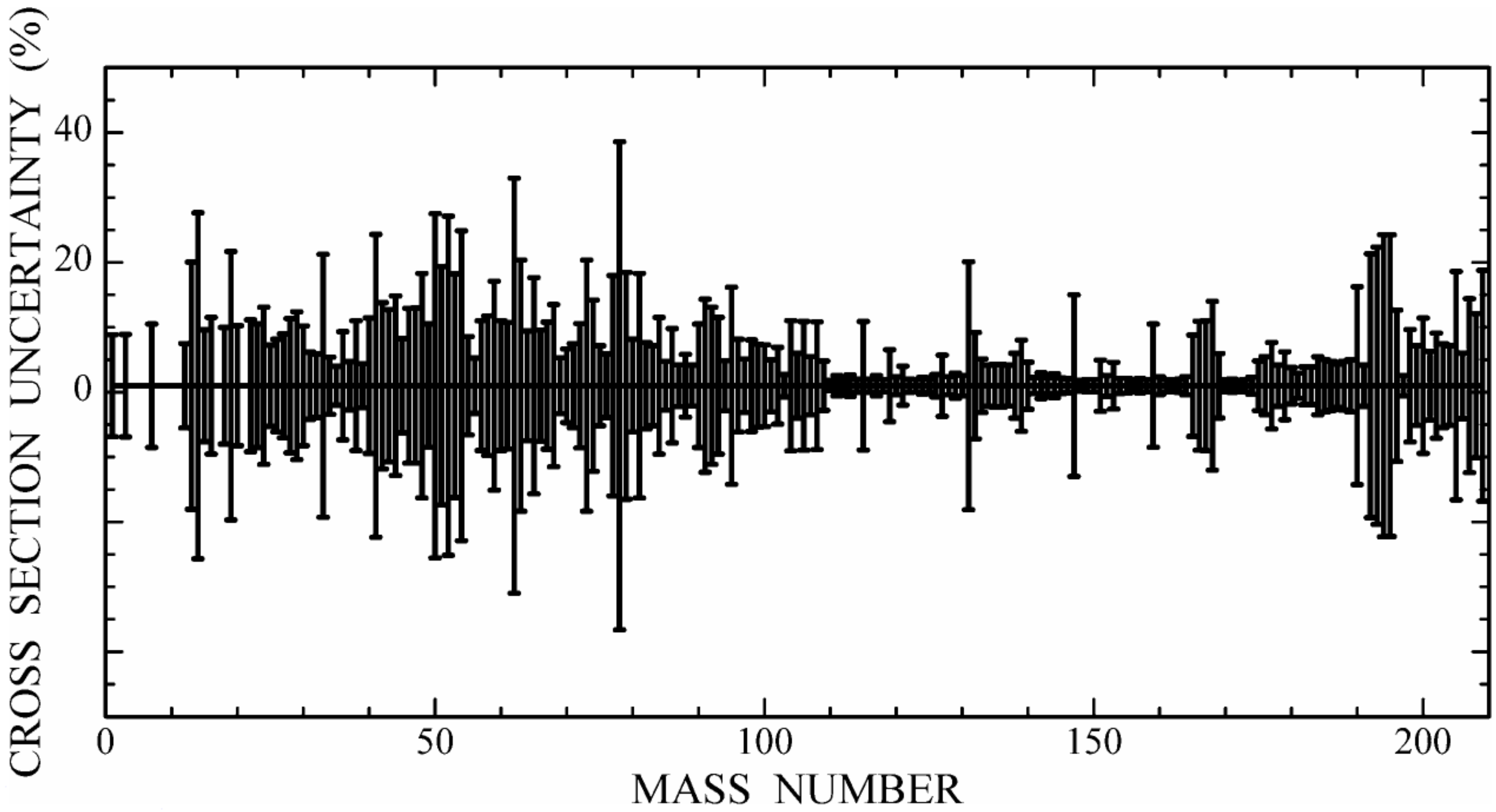
n_γ(E) is a continuous bremsstrahlung spectrum

⇒ Direct determination of ***σ(E)*** is **not** possible

The *s* process:

Investigations of branching points

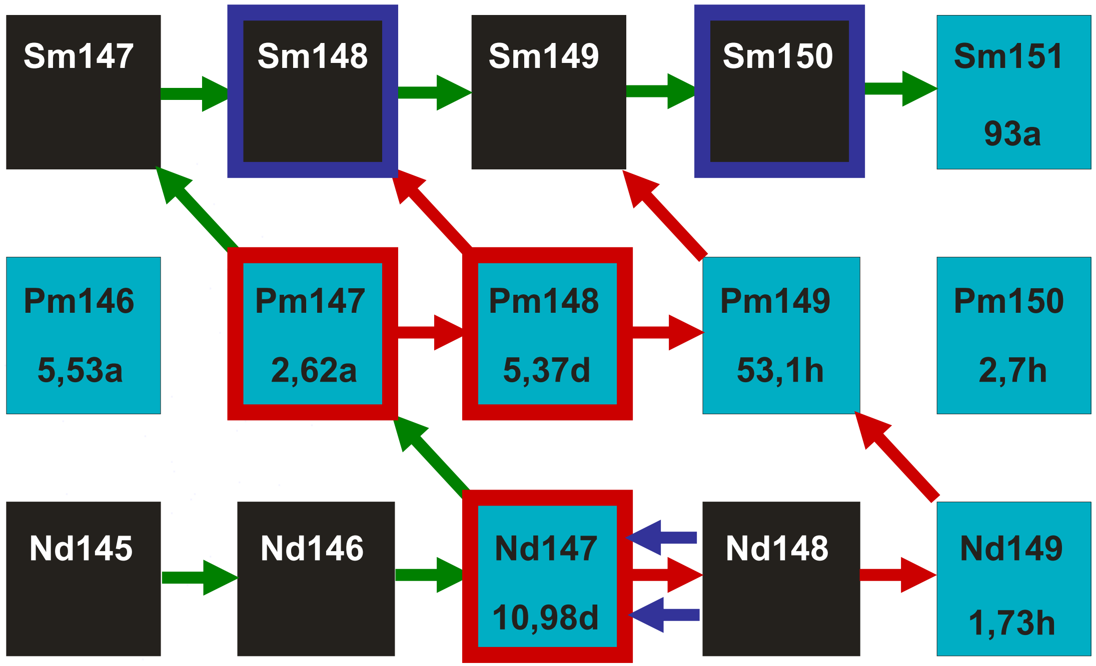
Measurements of neutron-capture cross section



F. Käppeler et al., NPA 777 (2006) 291

- Data from high-precision neutron-capture experiments available for a wide range of isotopes
- Neutron-capture experiments hardly possible for unstable isotopes ($\Rightarrow$ branching points)

Branching points: a probe for stellar conditions



$$\frac{N(^{148}\mathrm{Sm})}{N(^{150}\mathrm{Sm})} \sim \frac{\lambda_\beta}{\lambda_\beta + \lambda_n}$$ (branching ratio)

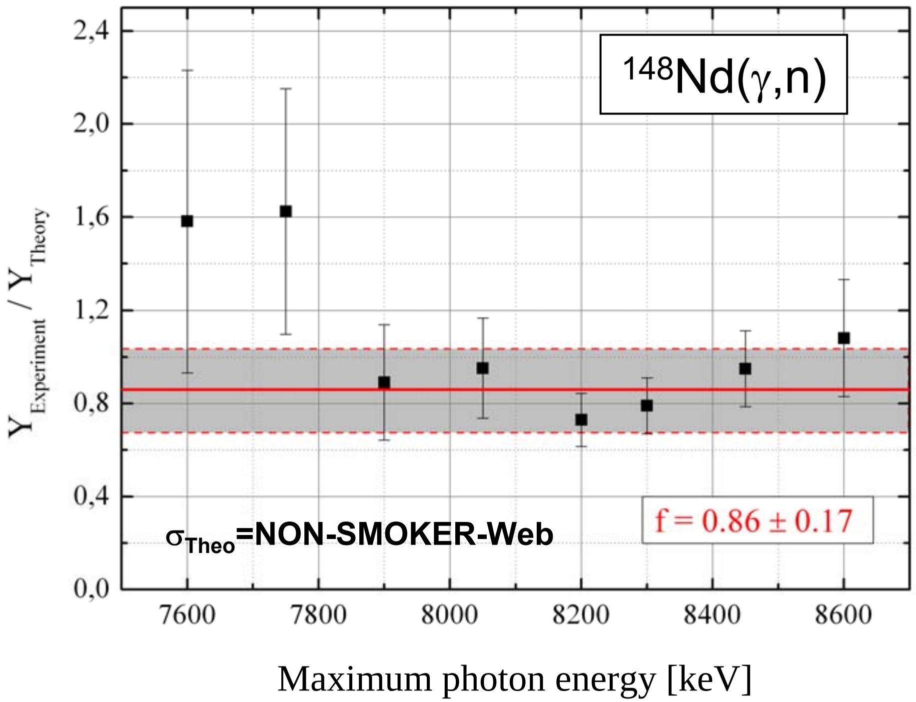
λ_n depends on:
- *neutron capture cross section*
- *neutron density* and *temperature* in stellar environment

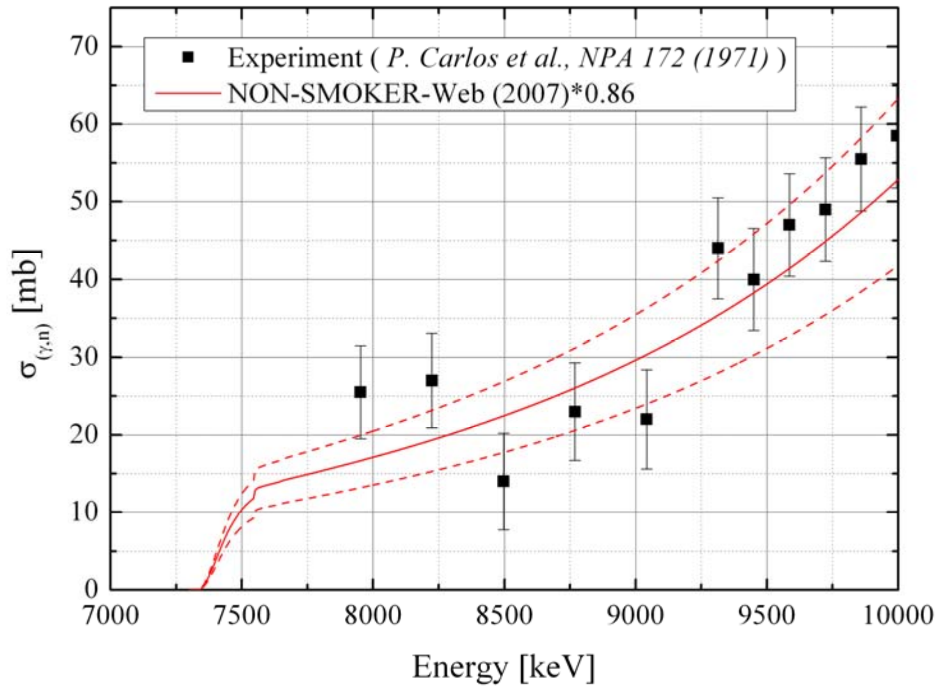
$\sigma(\gamma,n) \leftrightarrow \sigma(n,\gamma)$

Test of theoretical predictions for (γ,n) cross section

$$\sigma(E) = f \cdot \sigma_{theo}(E)$$

$$Y \propto \int \sigma(E) n_\gamma(E) dE \;\Rightarrow\; f = \frac{Y_{\text{Experiment}}}{Y_{\text{Theory}}}$$





J. Hasper, submitted to PRC

(γ,n) versus (n,γ)

Principle of Detailed Balance:

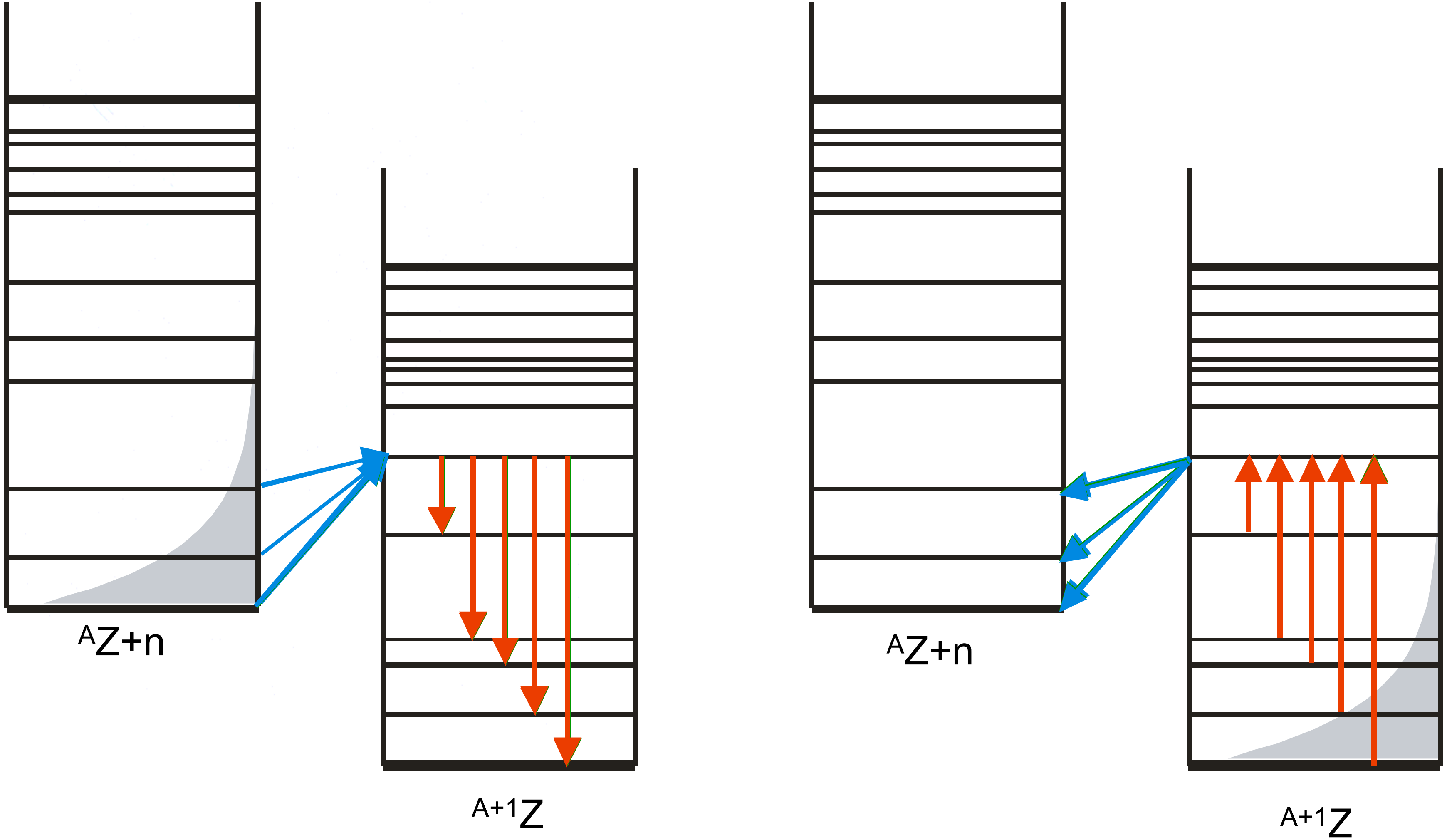
$$\lambda^*_{(\gamma,n)} = \frac{(2J_n+1)(2J_i+1)}{(2J_f+1)} \frac{1}{1+\delta_{12}} \left(\frac{G_n G_i}{G_f}\right) \left(\frac{A_n A_i}{A_f}\right)^{3/2} \left(\frac{kT}{2\pi N_A \hbar^2}\right)^{3/2} \langle \sigma v \rangle^*_{(n,\gamma)} \exp\left(-\frac{Q}{kT}\right)$$

Only applicable under stellar conditions !!!

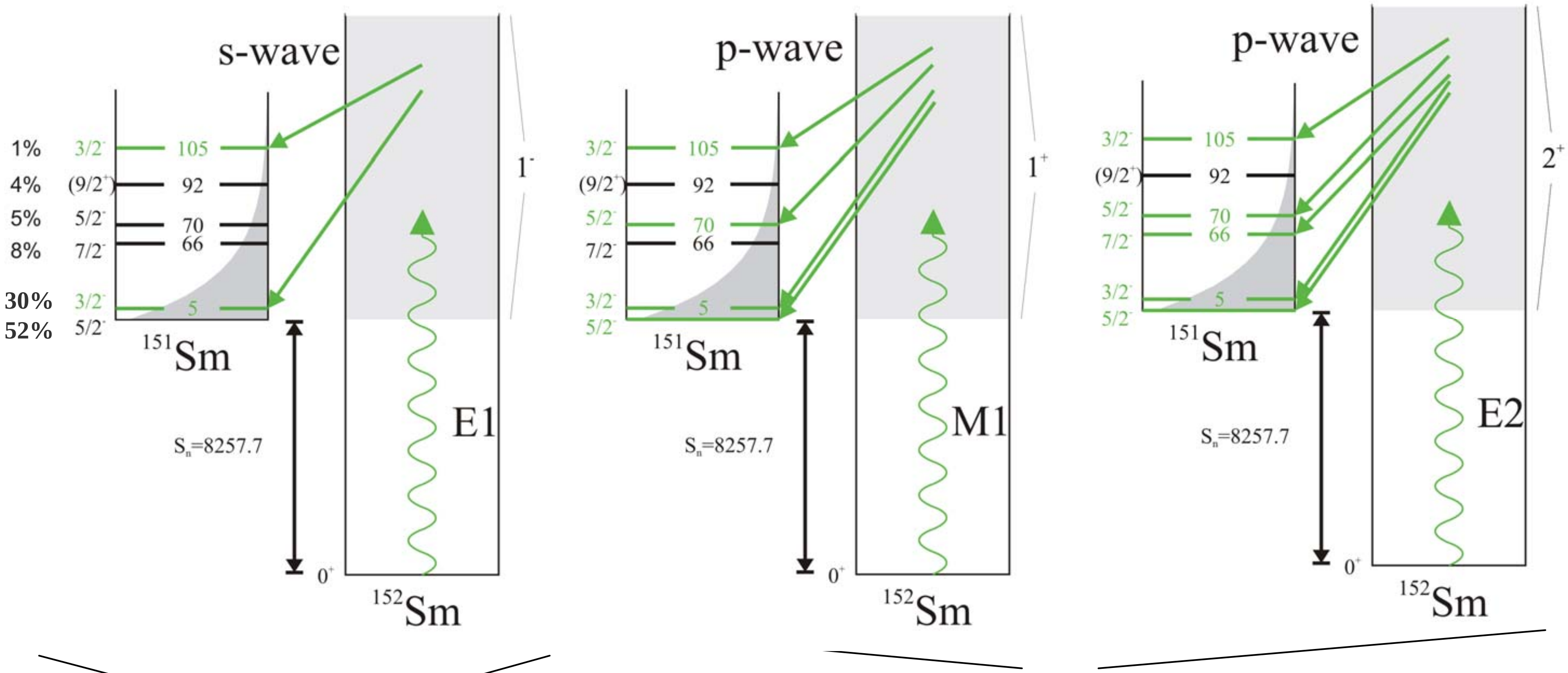
T. Rauscher et al., ADNDT 75 (2000) 1

Principle of „Detailed Balance“

Stellar conditions (T ≈ 10^8 K) ⟨)



The Branching Point ^{151}Sm



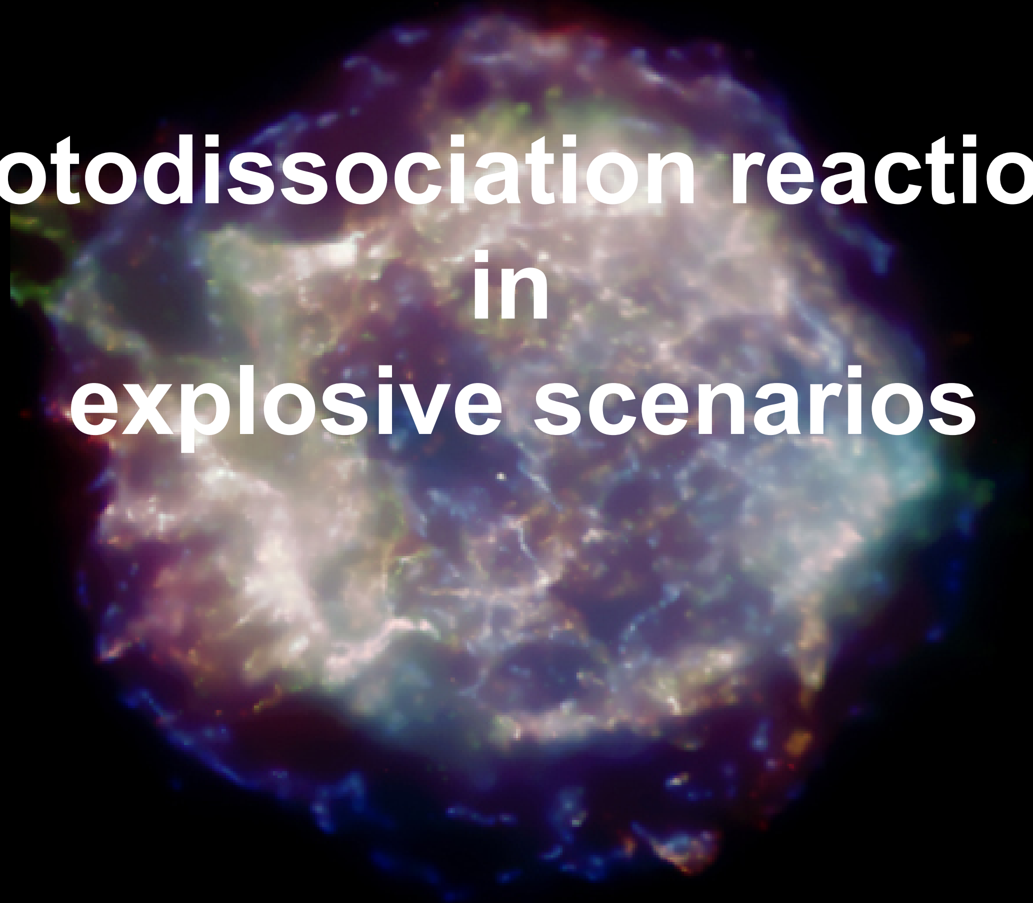
No ground state transition

Surpression due to angular momentum barrier in the exit channel and higher multipolarity in the entrance channel

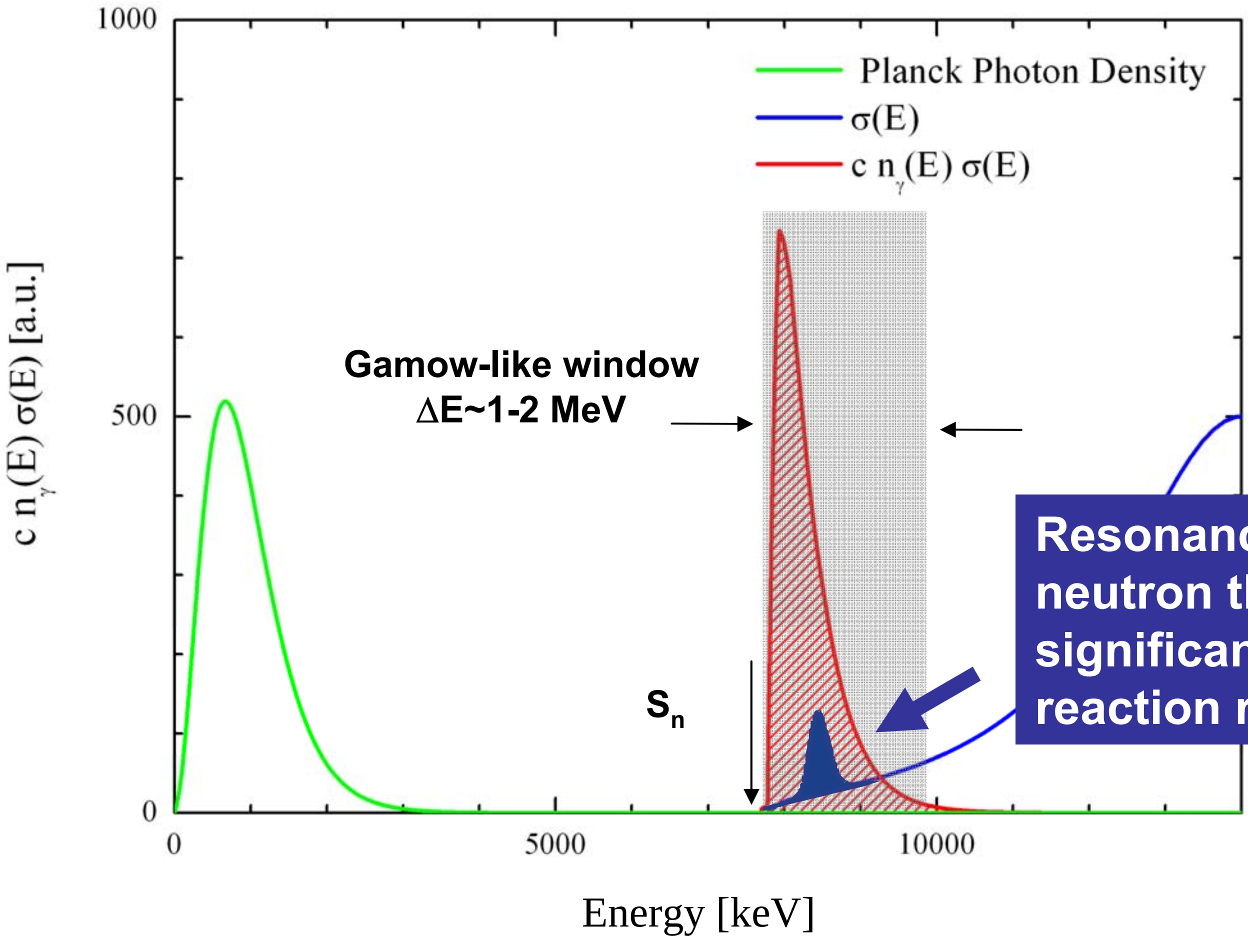
$\Rightarrow$ **High sensitivity of (γ,n) reaction to the transition into 1st excited state**

The *p* process:

Photodissociation reactions
in
explosive scenarios

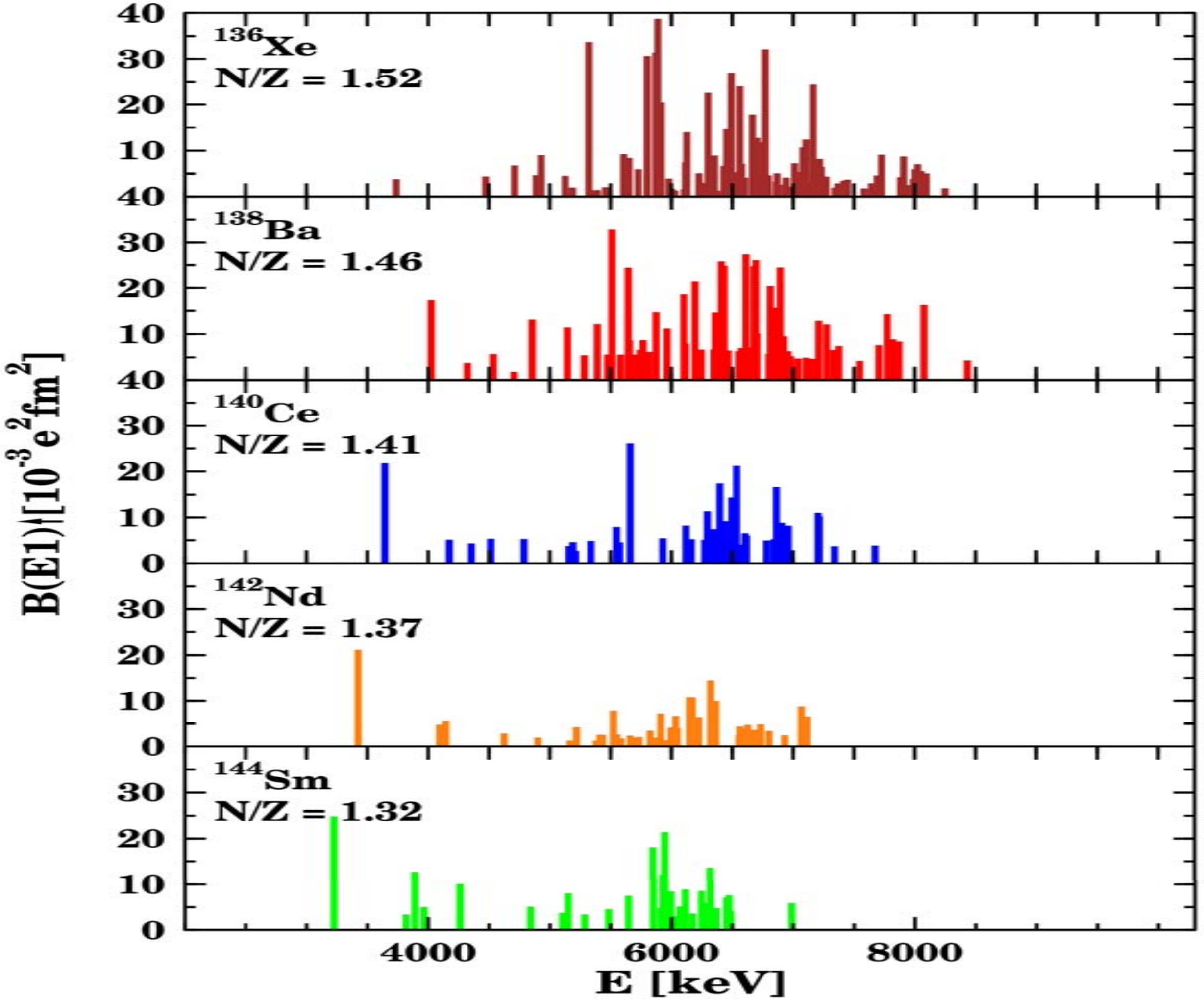


Reaction rate: $$\lambda(T) = c \int n_\gamma(E)\, \sigma(E)\, dE$$



Resonance close to neutron threshold would significantly increase reaction rate

PDR *below* the neutron threshold ((γ,γ') @ S-DALINAC)

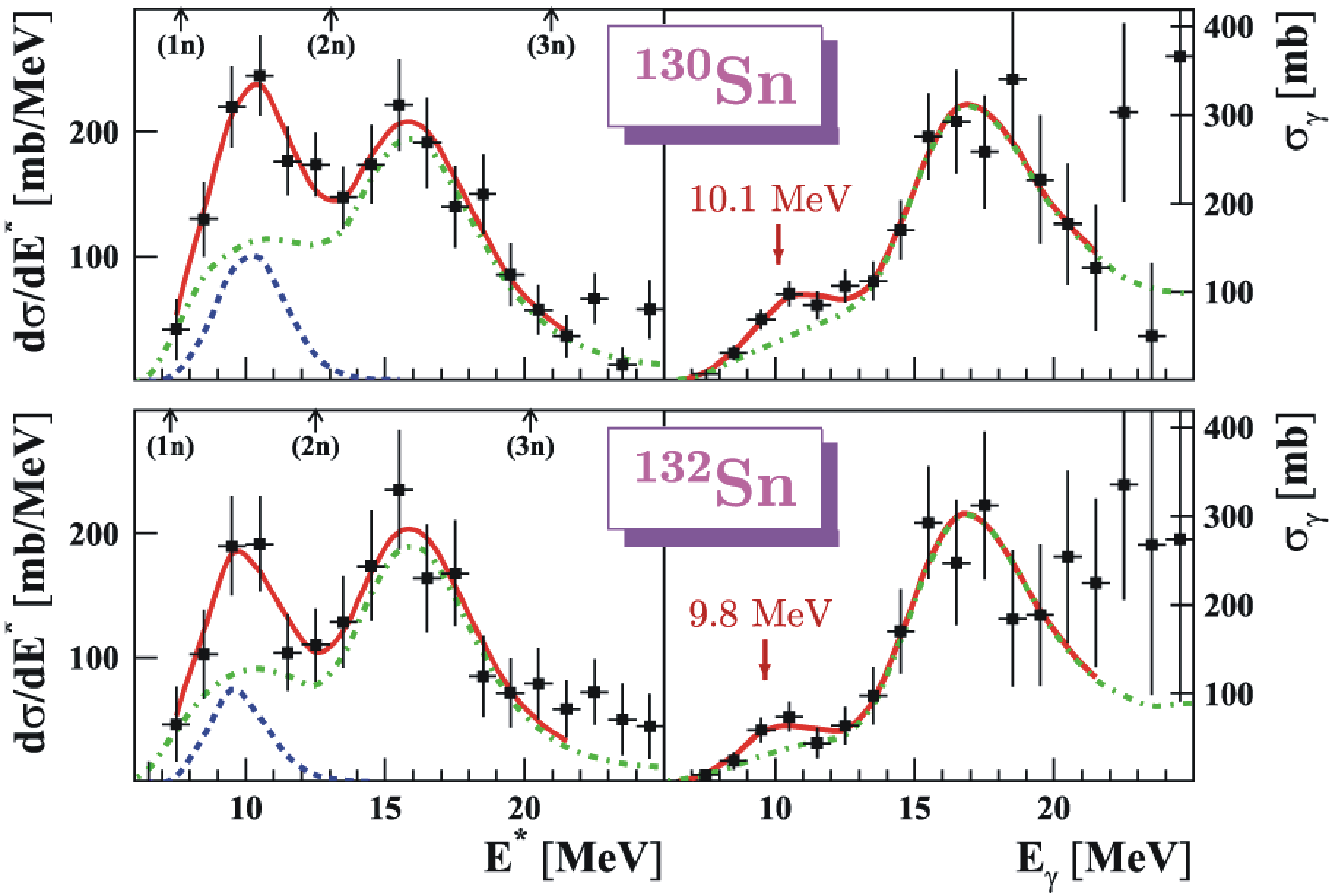


A. Zilges et al., PLB 542 (2002) 43
S. Volz et al., Nucl. Phys. A 779 (2006) 1

Is there also a resonant structure above the threshold?

PDR *above* the neutron threshold (Coulex @ GSI)

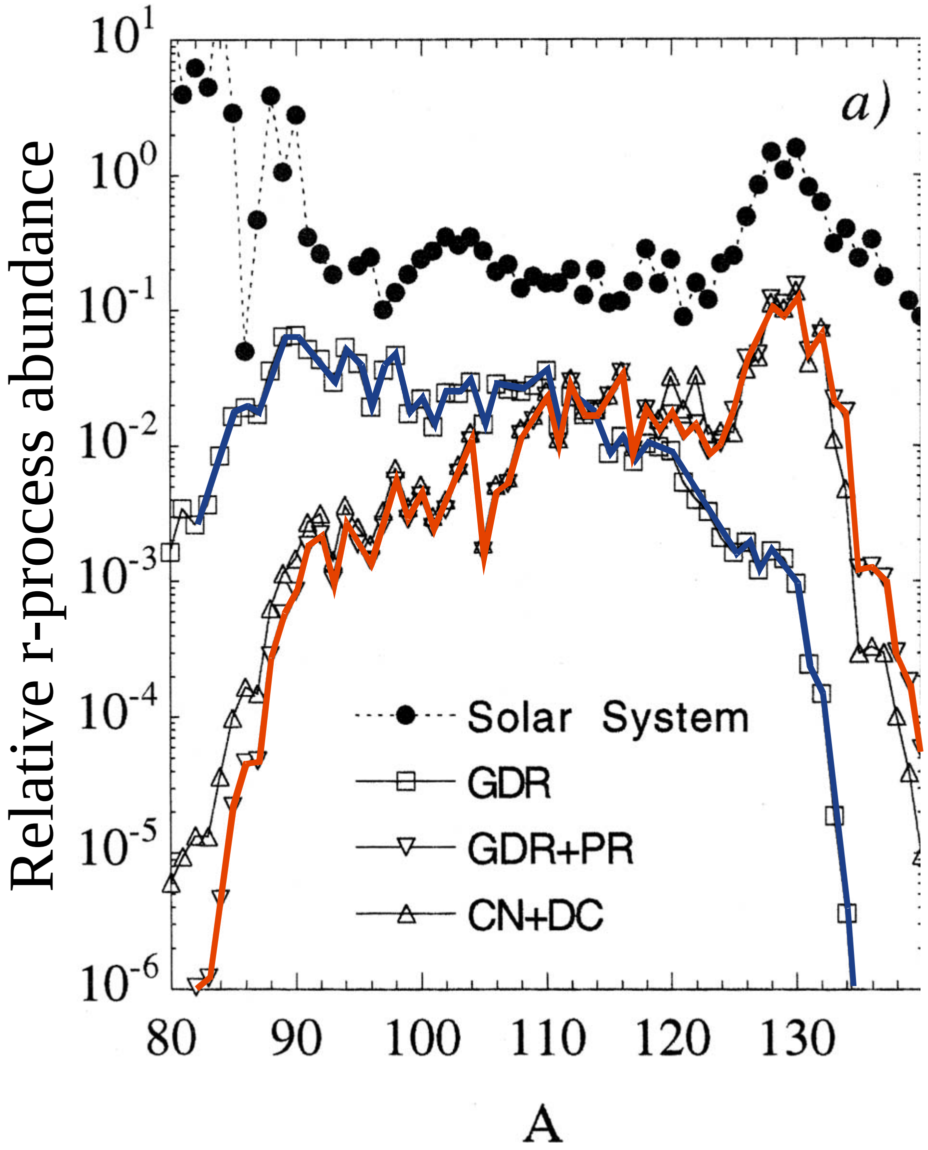
Electromagnetic-excitation cross section	Photo-neutron cross section



P. Adrich et al., PRL 95 (2005) 132501
T. Aumann, EPJ A 26 (2005) 441

Impact of PDR on nuclear astrophysics

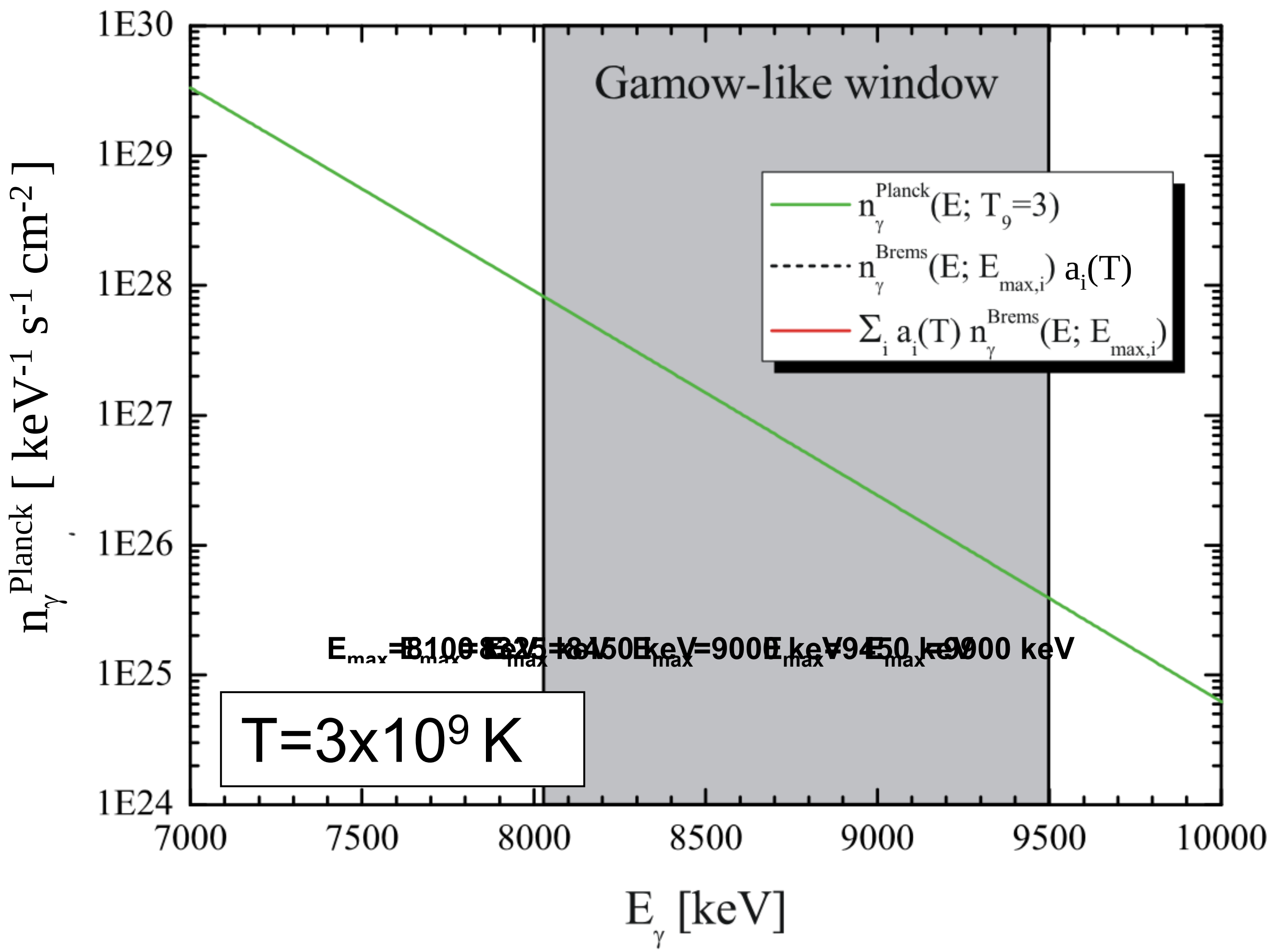
- PDR *above* threshold has a direct impact on reaction rates for nuclear astrophysics
- PDR *below* neutron threshold shifted to *above* the threshold at high temperatures (Brink's hypothesis)
- PDR has significant impact on explosive nucleosynthesis (T ~ 10^9 K)



S. Goriely, PLB 436 (1998) 10

Approximation of Planck Spectrum

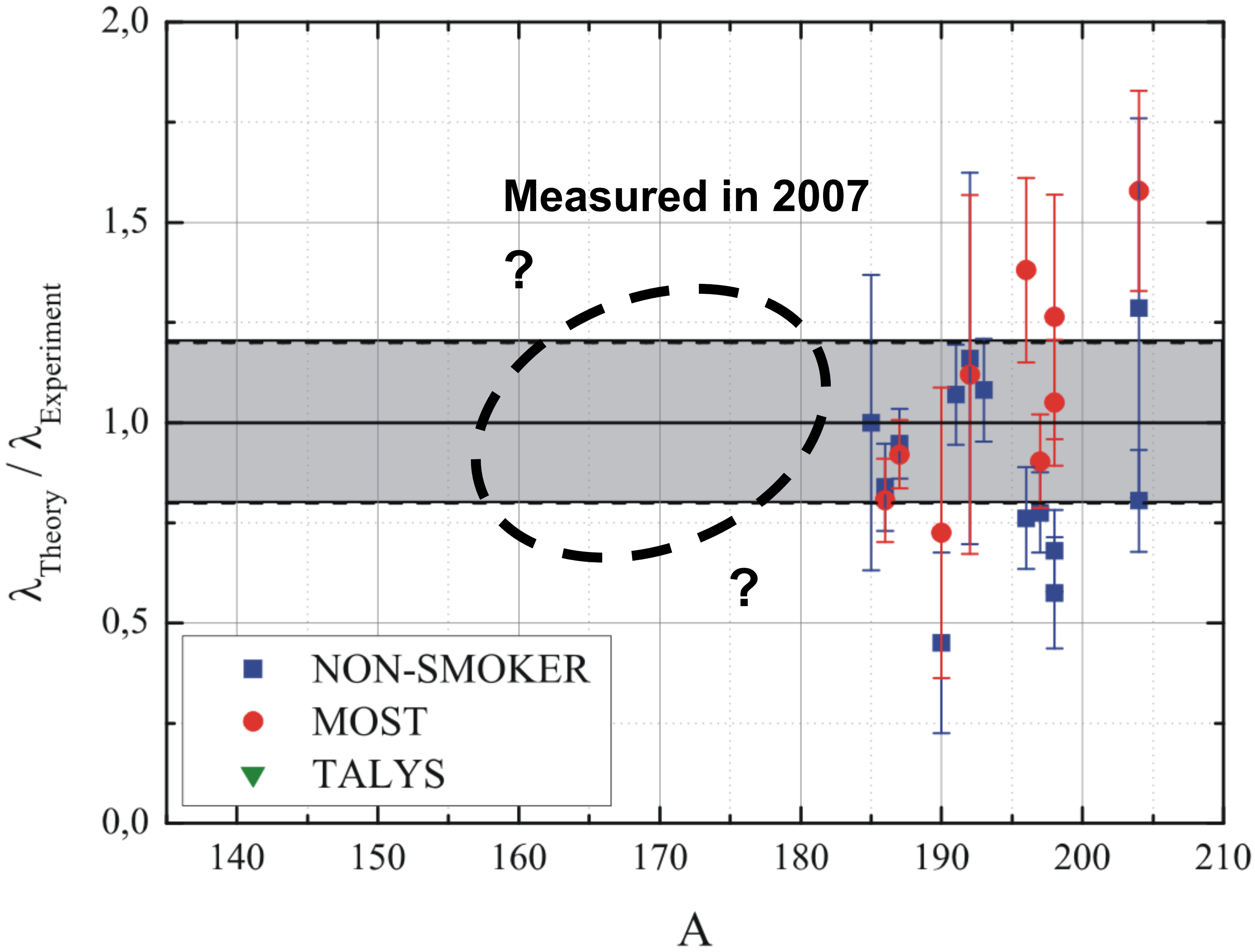
$$\lambda(T) = c \int n_\gamma(E)\, \sigma_{(\gamma,n)}(E)\, dE \approx \sum a_i(T) Y_i$$



P. Mohr et al., Phys. Lett. B 488 (2000) 127

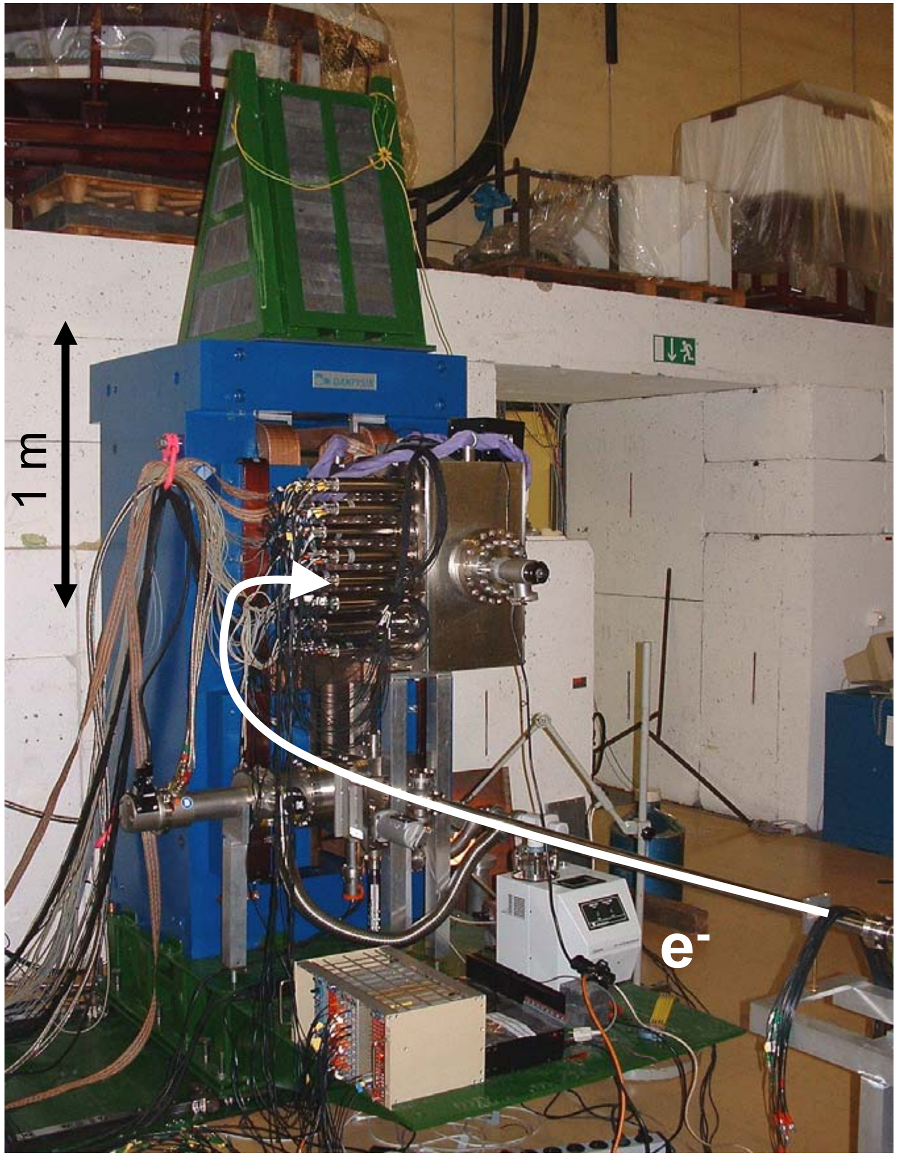
A. Zilges et al., Prog. Part. Nucl. Phys. 44 (2000) 39

Results for ground-state reaction rates (T = 2.5 x 10^9 K)



M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1
T. Rauscher and F.-K. Thielemann, ADNDT 75 (2000) 1
A. J. Koning et al., AIP 769 (2004) 1154

Direct measurements with tagged photons



energy of each photon known

- **Direct measurement** of photodissociation cross sections (γ,n), (γ,p), (γ,α) with **high energy resolution** (ΔE~25 keV)

  (> 100 keV above threshold for (γ,n))

- First production run in 2008

Summary

- Photo-induced reactions have significant implications for the nucleosynthesis of heavy elements (*s*, *r* and *p* process)
- Input from nuclear physics mandatory to improve astrophysical models
  - Measurements of reaction rates
  - Study of nuclear physics parameters
- New experimental techniques will open new fields of research
  - Photon tagging → photo-induced reactions with high resolution
  - Extension of investigation to (γ,p) and (γ,α) reactions
  - Radioactive beam facilities → investigation of unstable isotopes

Many thanks to...

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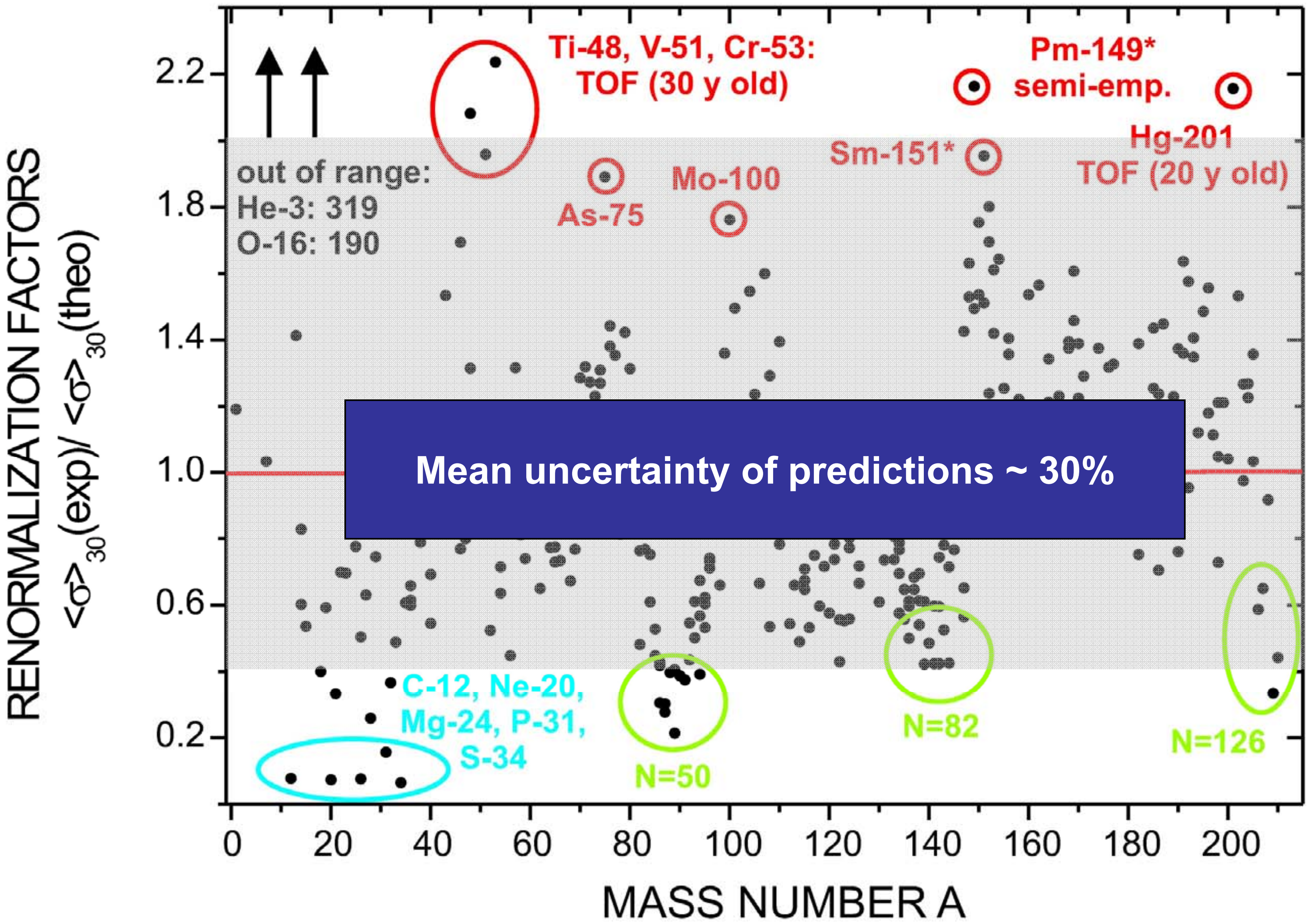
Thomas Rauscher, Basel, Switzerland

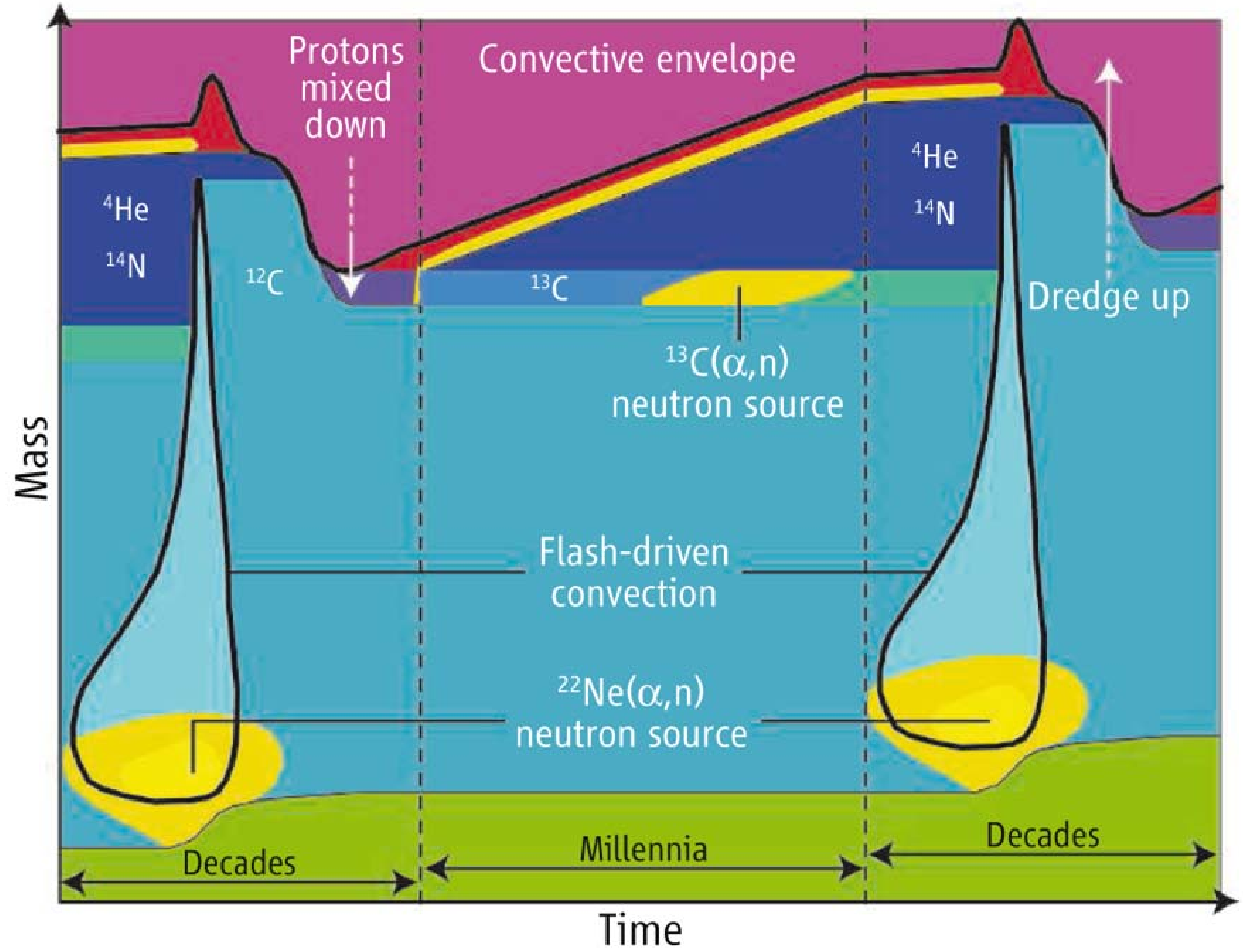
This project is supported by DFG SFB 634

Cross-section predictions from Hauser-Feshbach calculations



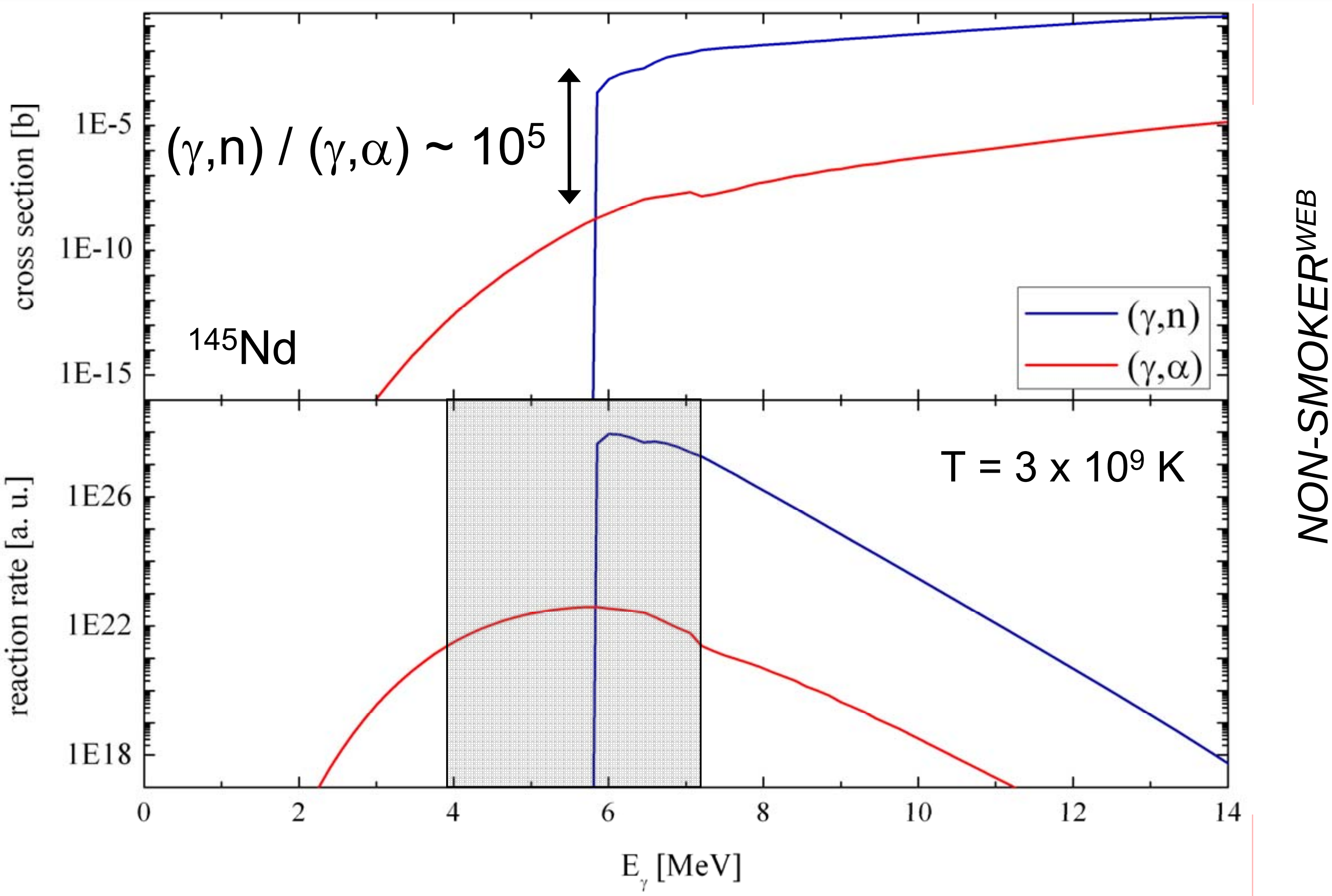
T. Rauscher

Nucleosynthesis in TP AGB-Stars



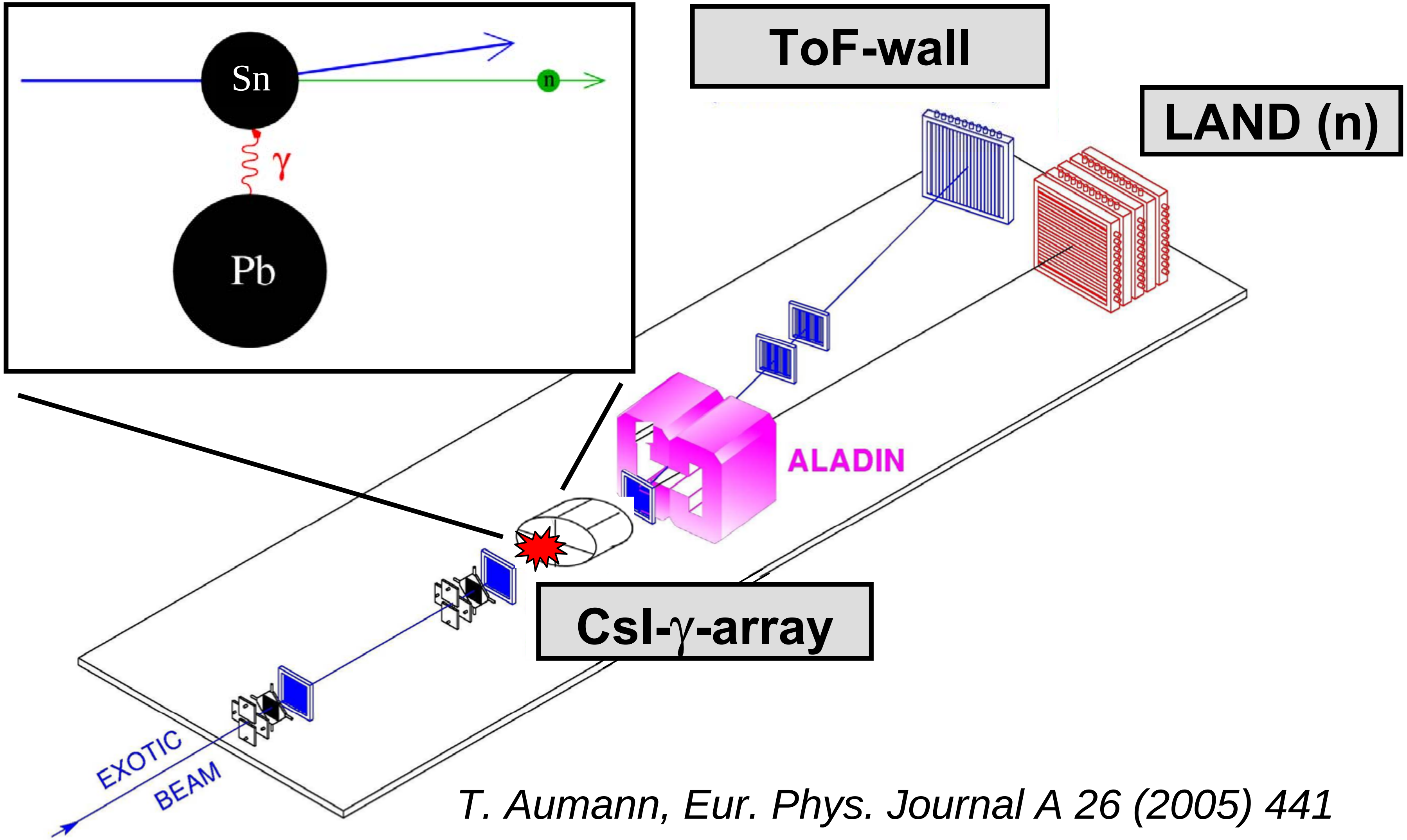
A. I. Boothroyd, SCIENCE 314 (2006) 1690

The challenge to measure (γ,α)-reactions

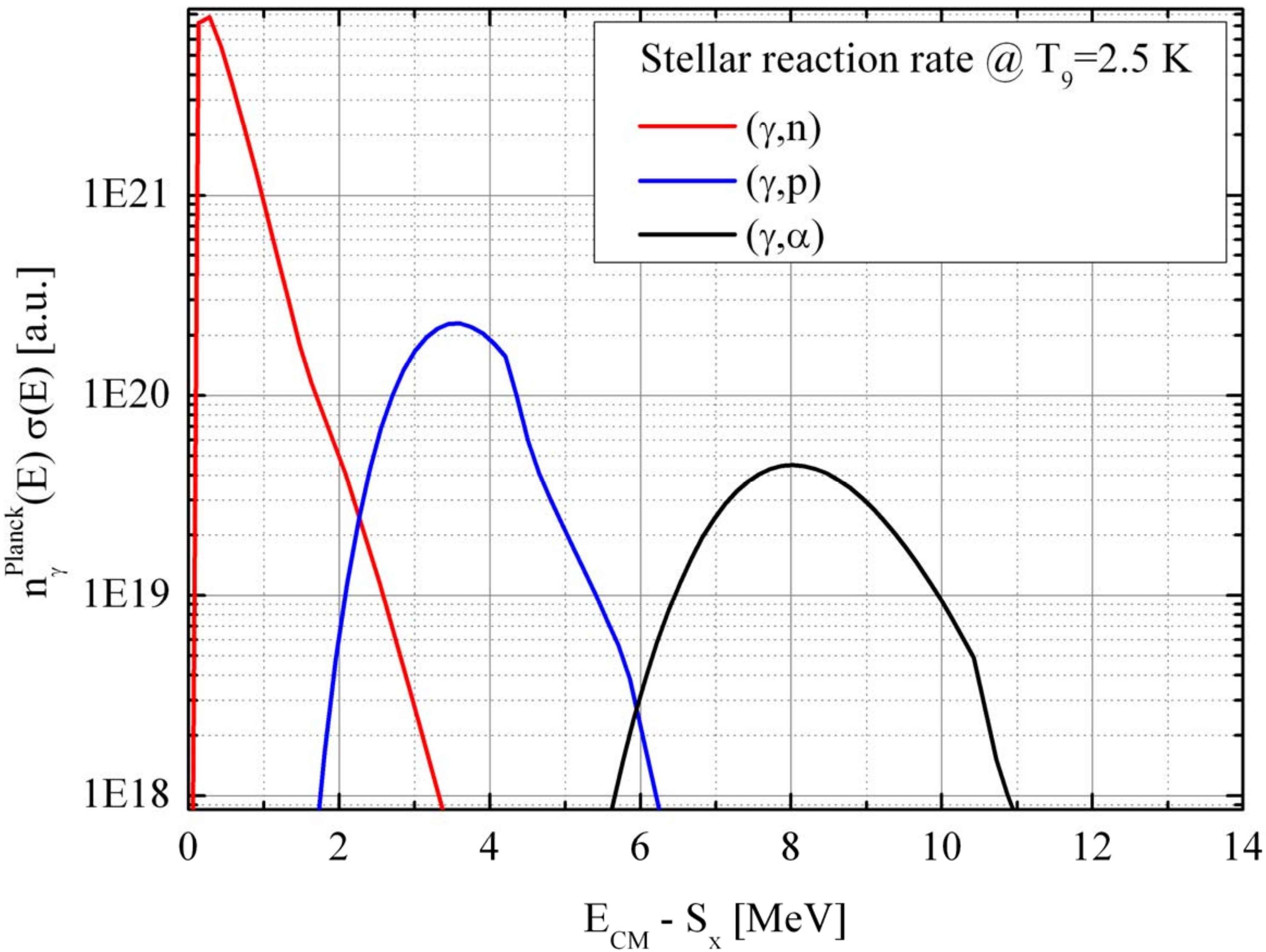


- Very low reaction yield → low activity measurements
- Decay spectra dominated by competing reactions

Experiments in inverse kinematics: FRS/LAND setup @ GSI

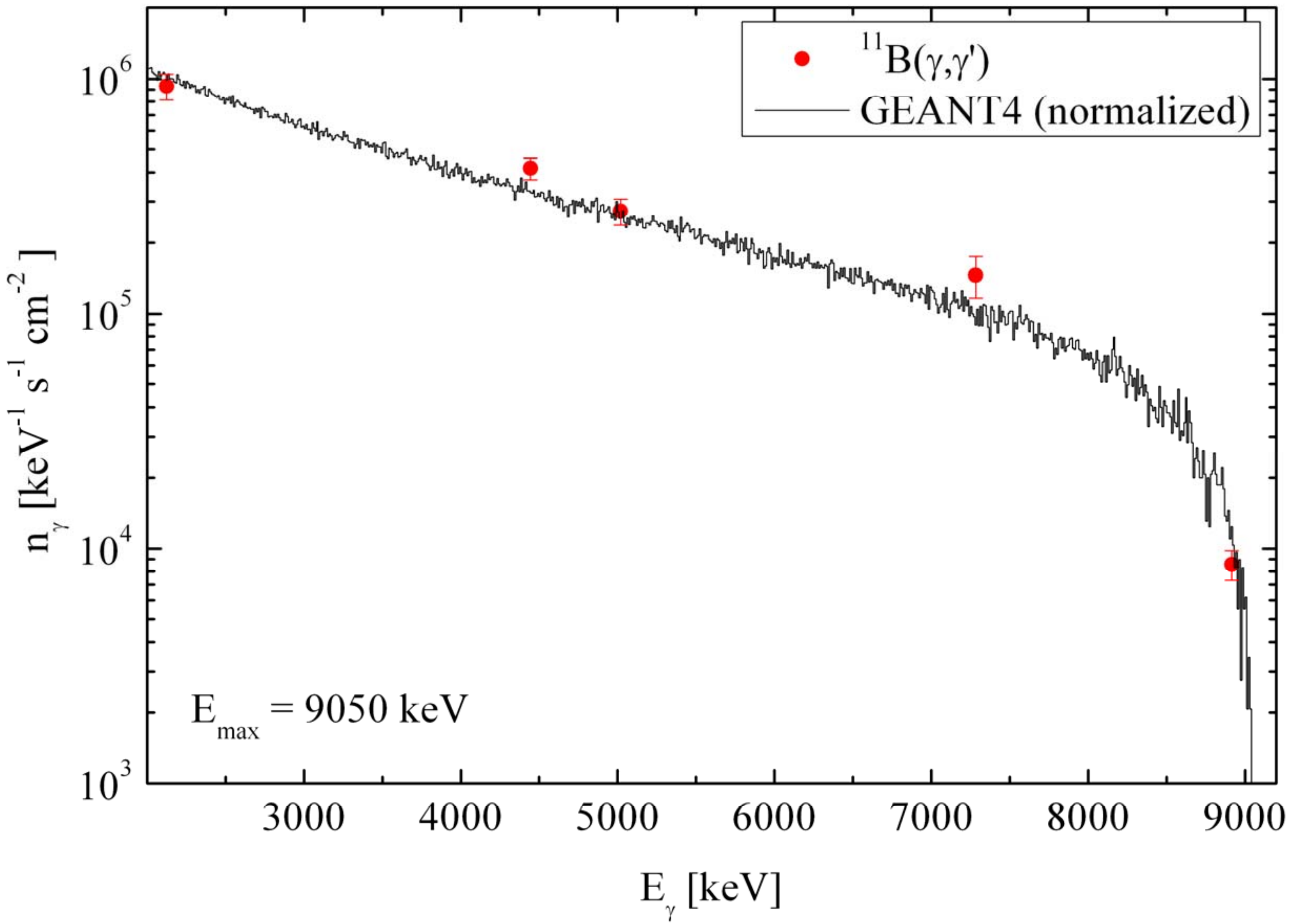


T. Aumann, Eur. Phys. Journal A 26 (2005) 441



Stellar reaction rate @ T9=2.5 K
(γ,n)
(γ,p)
(γ,α)
1E21
1E20
1E19
1E18
0
2
4
6
8
10
12
14
$n_\gamma^{Planck}(E)\ \sigma(E)$ [a.u.]
$E_{CM} - S_x$ [MeV]

Calibration of the Photon Flux



Big Bang Nukleosynthese – BB

- Produktion von H:
  $T \approx 7.5 \cdot 10^9$ K, p:n ≈ 7:1
- Produktion von D:
  $T \approx 10^9$ K, $p + n \rightarrow d + \gamma$
- Produktion von ^{3}He:
  $T \approx 10^9$ K, z.B. $d + p \rightarrow {}^3He + \gamma$
- Produktion von ^{4}He:
  $T \approx 10^9$ K, z.B. ${}^3He + n \rightarrow {}^4He + \gamma$
- Produktion von ^{7}Li:
  $T \approx 10^9$ K, z.B. ${}^3He + \alpha \rightarrow {}^7Be + \gamma$ und Elektroneneinfang zu ^{7}Li

	Elementhäufigkeit
D/H	0.238 ± 0.005
^{3}He/H	$(2.78 \pm 0.29) \cdot 10^{-5}$
^{4}He/H	$(1.2 – 1.5) \cdot 10^{-5}$
^{7}Li/H	$(0.59 – 4.1) \cdot 10^{-10}$

Stellare Nukleosynthese – CP

– CP: charged particle reactions

– Wasserstoffbrennen: $4p \rightarrow {}^{4}He + 2e^{+} + 2\nu$
realisiert im p-p-Zyklus, CNO-Zyklus, NeNa-, MgAl-Zyklus

– Heliumbrennen: $3\alpha \rightarrow {}^{12}C$
außerdem: ${}^{12}C(\alpha,\gamma)$, ${}^{16}O(\alpha,\gamma)$

– Kohlenstoffbrennen: ${}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha$

– Neonbrennen: ${}^{20}Ne(\alpha,\gamma){}^{24}Mg$

– Sauerstoffbrennen: ${}^{16}O + {}^{16}O \rightarrow {}^{28}Si + \alpha$

– Siliziumbrennen: ${}^{28}Si + 7\alpha \rightarrow {}^{56}Ni$

Nukleosynthese im thermischen Gleichgewicht – NSE

– NSE: nuclear statistical equilibrium

– Photodesintegration und Einfangreaktion im Gleichgewicht

– Reaktionsmechanismus:

$^{28}Si + \alpha \leftrightarrow {}^{32}S + \gamma$

$^{32}S + \alpha \leftrightarrow {}^{36}Ar + \gamma$

$^{36}Ar + \alpha \leftrightarrow {}^{40}Ca + \gamma$

...

$^{52}Fe + \alpha \leftrightarrow {}^{56}Ni + \gamma$

$\rightarrow$ nur die stabilsten Kerne „überleben“

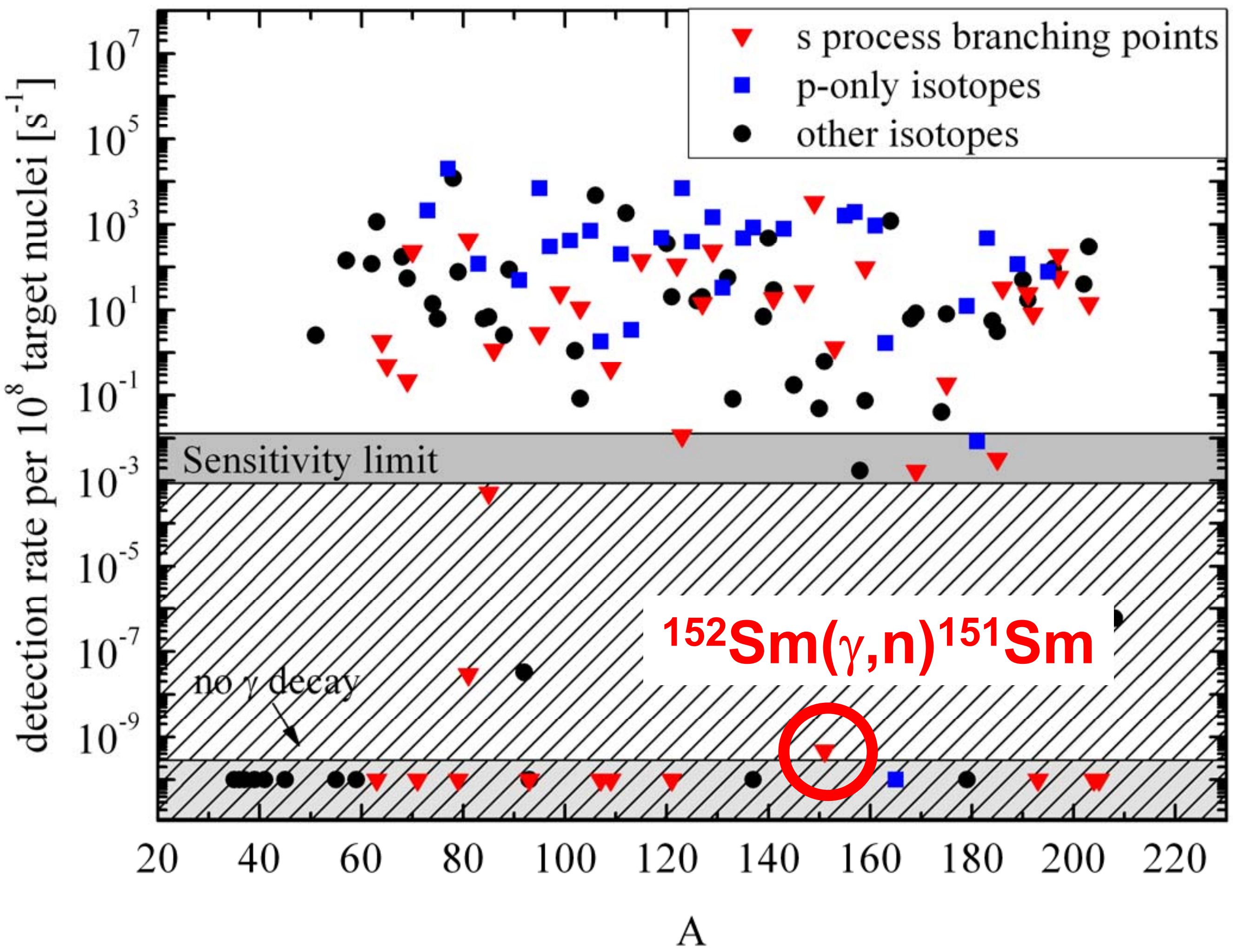
Results for ground state reaction rates (T_9 = 2.5)

Isotope	$\lambda_{exp,gs}$	Reference
^{186}W	310(40)	K. Sonnabend et al., ApJ 583 (2003) 506
^{185}Re	19(7)	S. Müller et al., Phys. Rev. C 73 (2006) 025804
^{187}Re	76(7)	
^{190}Pt	0.4(2)	K. Vogt et al., Phys. Rev. C 63 (2001) 055802
^{192}Pt	0.5(2)	
^{198}Pt	87(21)	
^{197}Au	6.2(8)	K. Vogt et al., Nucl. Phys. A 707 (2002) 241
^{196}Hg	0.42(7)	K. Sonnabend et al., Phys. Rev. C 70 (2004) 035802
^{198}Hg	2.0(3)	
^{204}Hg	57(21)	
^{204}Pb	1.9(3)	
^{191}Ir	4.3(5)	J. Hasper, to be published
^{193}Ir	13.5(16)	

M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1

T. Rauscher and F.-K. Thielemann, ADNDT 75 (2000) 1

Possible (γ,n) reactions in photoactivation experiments



Use Accelerator Mass Spectrometry where detection rate is too low

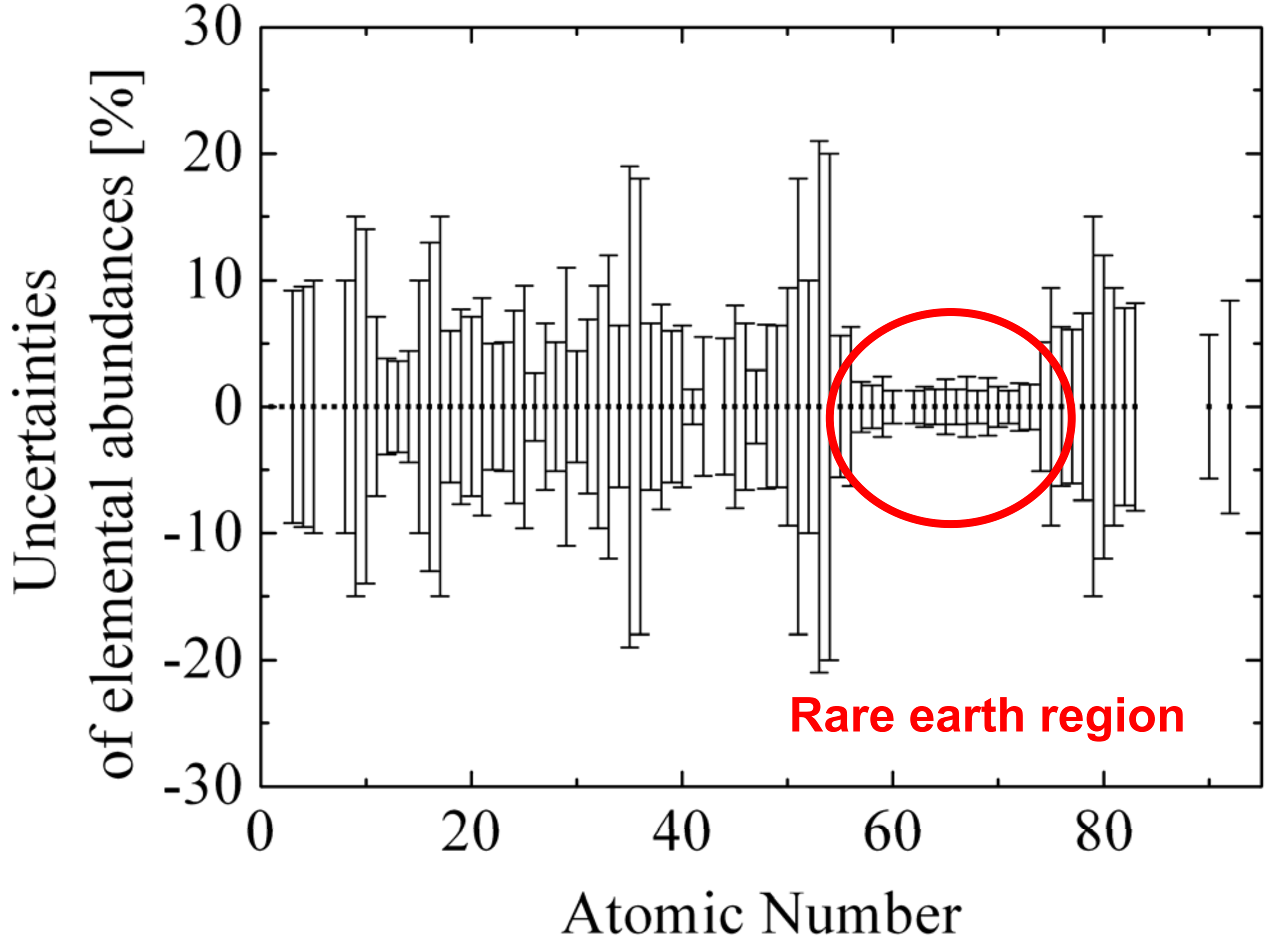
p process contributions to *s*-isotope abundance

s-only isotope	*p* process contribution [%]
^{70}Ge	9.7
^{76}Se	9.7
^{80}Kr	15.0
^{82}Kr	3.0
^{86}Sr	5.6
^{104}Pd	9.0
^{110}Cd	7.0
^{116}Sn	2.6
^{122}Te	3.6
^{124}Te	2.0
^{134}Ba	4.2

s-only isotope	*p* process contribution [%]
^{136}Ba	1.3
^{142}Nd	9.3
^{148}Sm	1.1
^{150}Sm	1.7
^{152}Gd	33.0
^{154}Gd	5.0
^{160}Dy	2.4
^{164}Er	9.0
^{170}Yb	4.3
^{186}Os	1.1
^{192}Pt	1.8

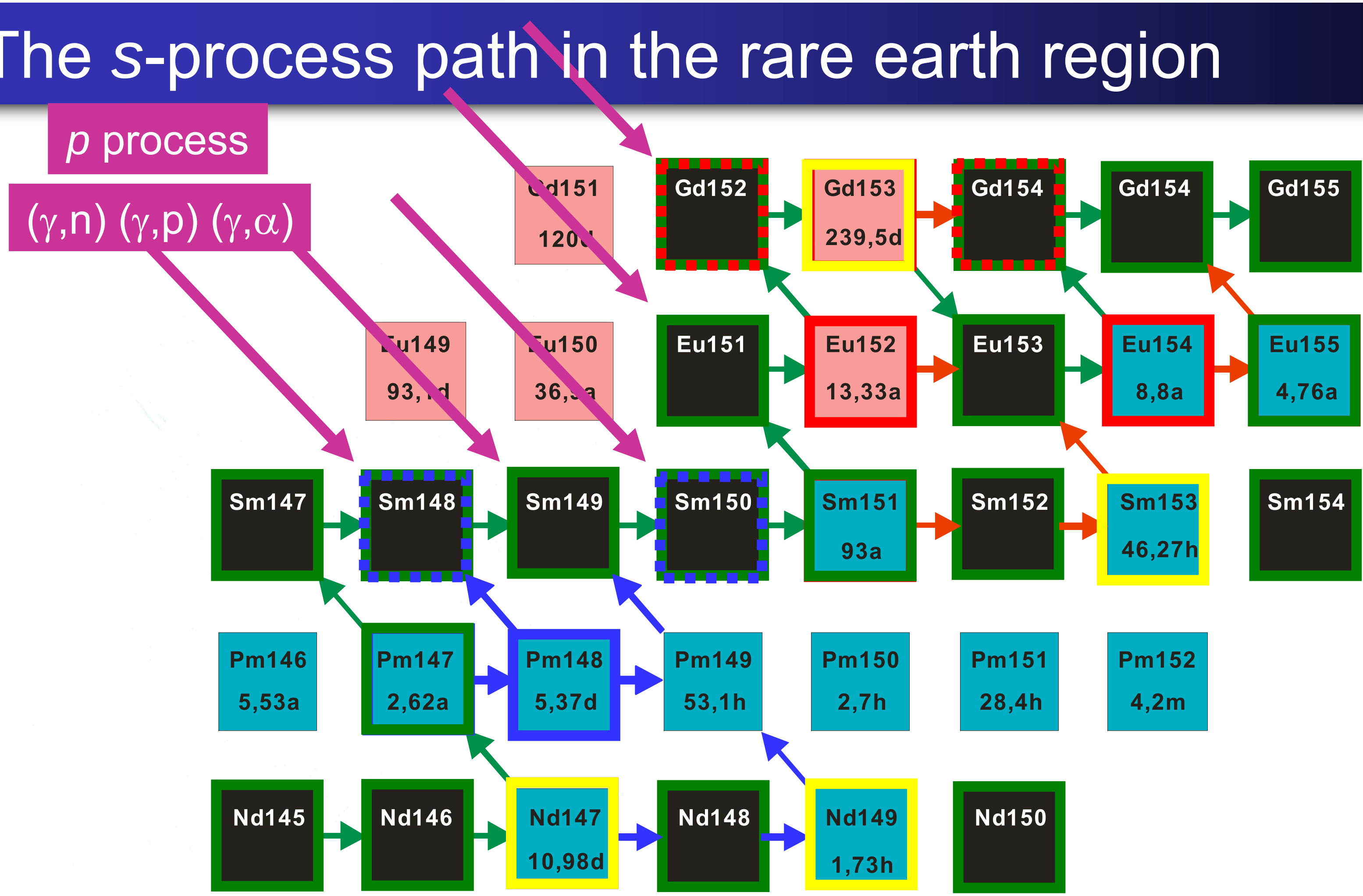
F. Käppeler et al., APJ 354 (1990) 630

Uncertainties of Elemental Abundances



E. Anders and N. Grevesse, Geochim. Cosmochim. Acta 53 (1989) 197

The *s*-process path in the rare earth region



Measured in neutron capture experiments (Karlsruhe, n_TOF,…)

short-lived isotopes

(γ,n) ↔ (n,γ)

Modelling the stellar nucleosynthesis

Stellar Evolution

- Evolutionary models
- Spectral observations

$\Rightarrow$ ***Physical conditions***

Galactic Evolution

- Averaging over stars with various metallicity and mass

stellar nucleosynthesis

Nuclear Physics Input

- Cross sections and reaction rates
- Decay rates of unstable isotopes
- Influence of thermal excitations

$\Rightarrow$ ***Reaction flow***

Elemental Abundances

- High-resolution spec-troscopy and investigation of meteorides

Astrophysical site of the *s* process

Weak component	**Main component**
– A ≈ 56 – 90	– 85 < A < 209
– massive stars (> 10 M_{solar})	– He-shell burning in TP AGB-Stars (1–3 M_{solar})
– neutron source: **^{22}Ne(α,n)**	– two neutron sources:
– He burning: **$n_n \approx 10^6$ cm^{-3}**, **$T \approx 2 - 3 \cdot 10^8$ K**	**^{13}C(α,n): $n_n \approx 10^7$ cm^{-3}**, **$T \approx 10^8$ K**, ≈ 10.000 yr
– C-shell burning: **$n_n \approx 10^{11}$ cm^{-3}**, **$T \approx 10^9$ K**	**^{22}Ne(α,n): $n_n \approx 10^{11}$ cm^{-3}**, **$T \approx 3 \cdot 10^8$ K**, ≈ 10 yr

Time scale for neutron capture: 0.1 yr – 100 yr

Branching points and stellar neutron density

Branching points	n_n (10^8 cm^{-3})	Reference
^{95}Zr	4^{+3}_{-2}	Käppeler et al., ApJ 354 (1990)
^{147}Nd / ^{147}Pm / ^{148}Pm	$3.0^{+1.1}_{-1.1}$	Käppeler et al., ApJ 354 (1990)
	$4.9^{+0.6}_{-0.5}$	Reifarth et al., ApJ 582 (2003)
^{169}Er / ^{170}Tm	$1.8^{+4.5}_{-0.8}$	Käppeler et al., ApJ 354 (1990)
^{185}W / ^{186}Re	$4.1^{+1.2}_{-1.1}$	Käppeler et al., ApJ 366 (1991)
	$3.8^{+0.9}_{-0.8}$	Sonnabend et al., ApJ 583 (2002)
^{191}Os / ^{192}Ir	$0.7^{+0.05}_{-0.02}$	Koehler et al., ApJ

The *s* process: Overview

- Astrophysical sites: **massive stars** (> 10 M_{solar})
  TP AGB-Stars (1–3 M_{solar})
- Neutron sources: **$^{22}Ne(\alpha,n)$, $^{13}C(\alpha,n)$**
- Moderate physical conditions: **$T \sim 10^8$ K**
  $n_n \sim 10^6$-10^{11} cm^{-3}
- Time scale for neutron capture: **0.1 yr – 100 yr**

_S_-process path follows the valley of stability

The *p* process: Overview

- 35 stable proton-rich isotopes can not be produced in neutron capture processes
- Photodisintegration process
  - (γ,n), (γ,p), (γ,α) reactions
  - about 10000 reaction rates involved
  - starts from seed nuclei produced in *s*,*r* process
- Astrophysical site: Typ II supernovae
  - T~ 2-3 GK