Level densities and γ-strength functions for astrophysics applications

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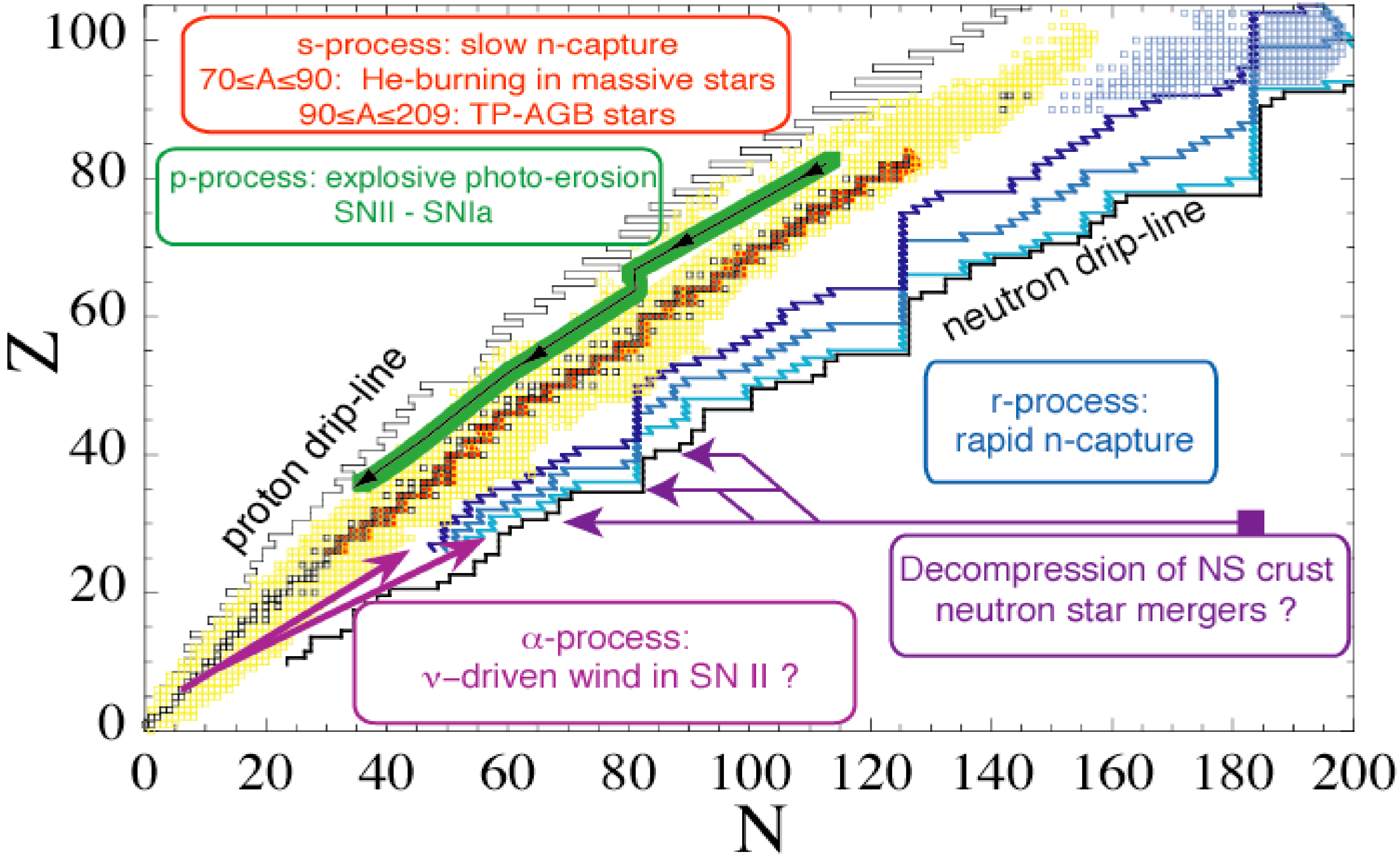
1. Nuclear needs for nuclear astrophysics calculations: Some astrophysics aspects of
    - the p-process nucleosynthesis: type-Ia and type-II Supernovae
    - the r-process nucleosynthesis: ν-driven wind of type-II supernovae, decompression of Neutron Star matter
2. Impact of the nuclear ingredients on reaction rates and nucleosynthesis predictions
    - γ-ray strength
    - Nuclear Level densities

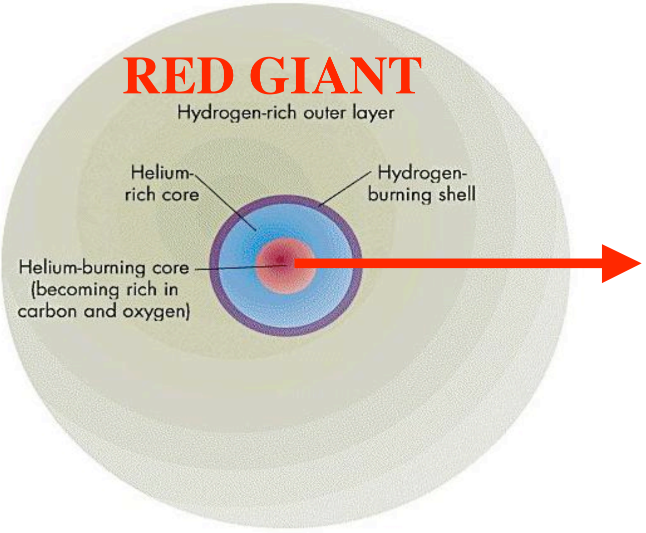
The s-, r- and p-processes of nucleosynthesis



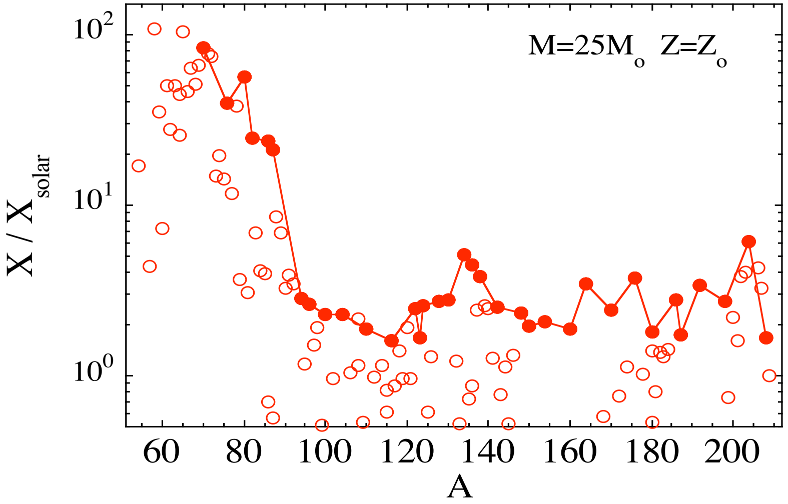
The identification of some of the astrophysical sites are still very much disputed
(in particular, where can neutrons be produced to give rise to a succesful s- or an r-process ?)

P-process in Ne/O-rich layers during SNII explosion of massive stars

1. s-process during core He-burning by ^{22}Ne(α,n)^{25}Mg



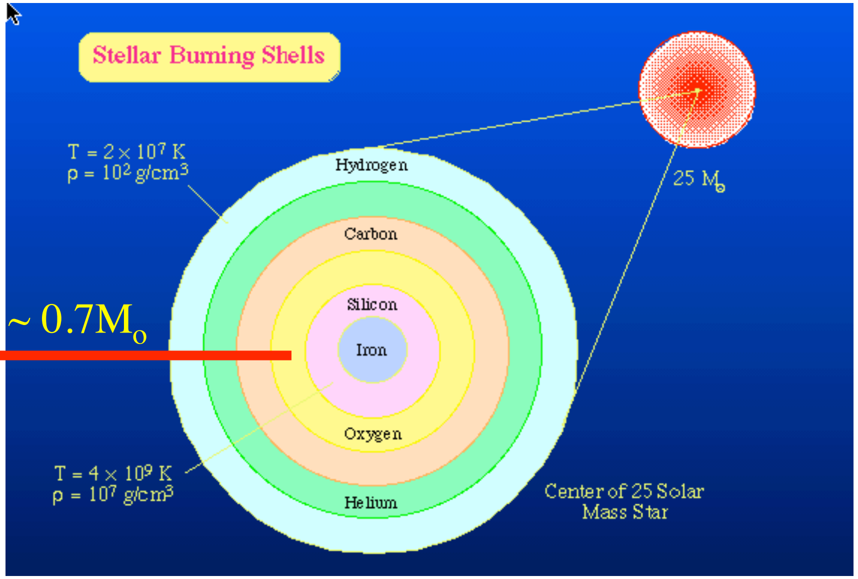
enrichment
in
s-elements
$70 \leq A \leq 90$



2. p-process in O/Ne layers

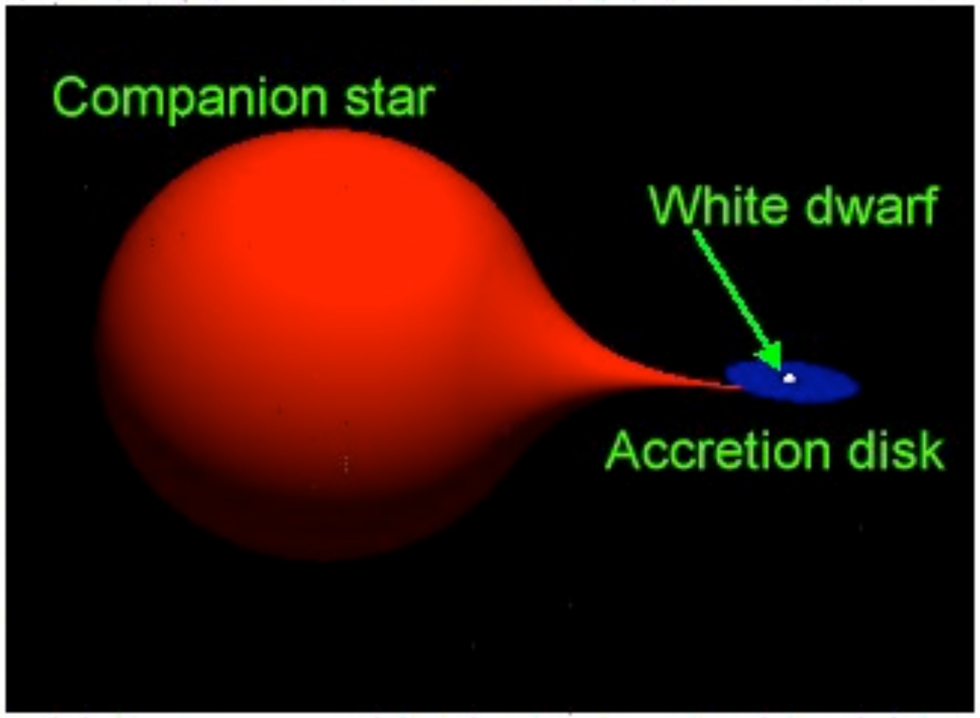
(hydrostatic pre-supernova as well as explosive supernova phases)

Heating at T=2–3 10^9 K of the s-enriched & r-seeds (~0.7M$_o$)



Accreting White Dwarf models for type Ia Supernovae

Matter accreted onto the surface of a White Dwarf (possibly enriched in s-elements during the AGB phase) from its binary companion causes regions in its interior to become unstable to thermonuclear runaway.

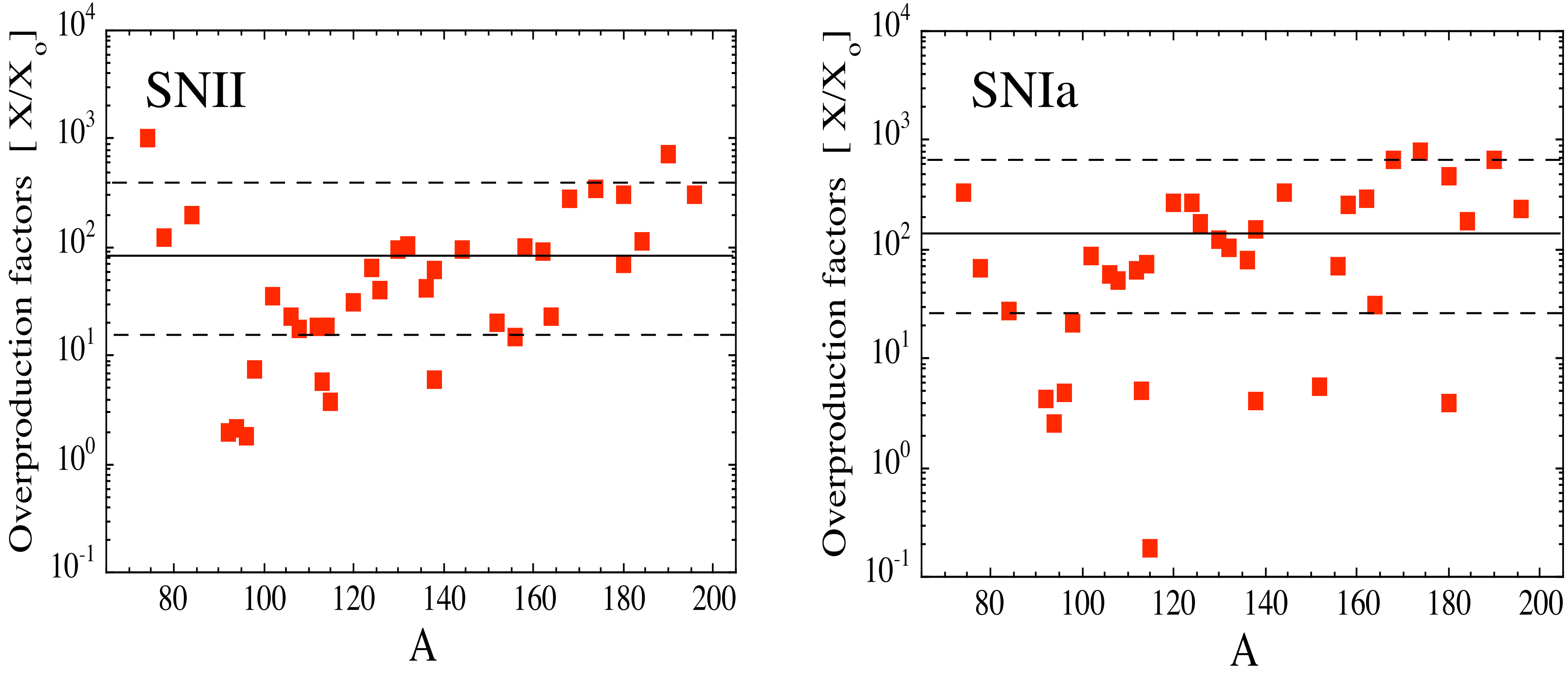


Carbon deflagration and/or detonation

(3D models available !!)

p-process nucleosynthesis in layers heated at T=2–3 10^9 K (initial composition C+O+Ne)

p-element overabundance distribution

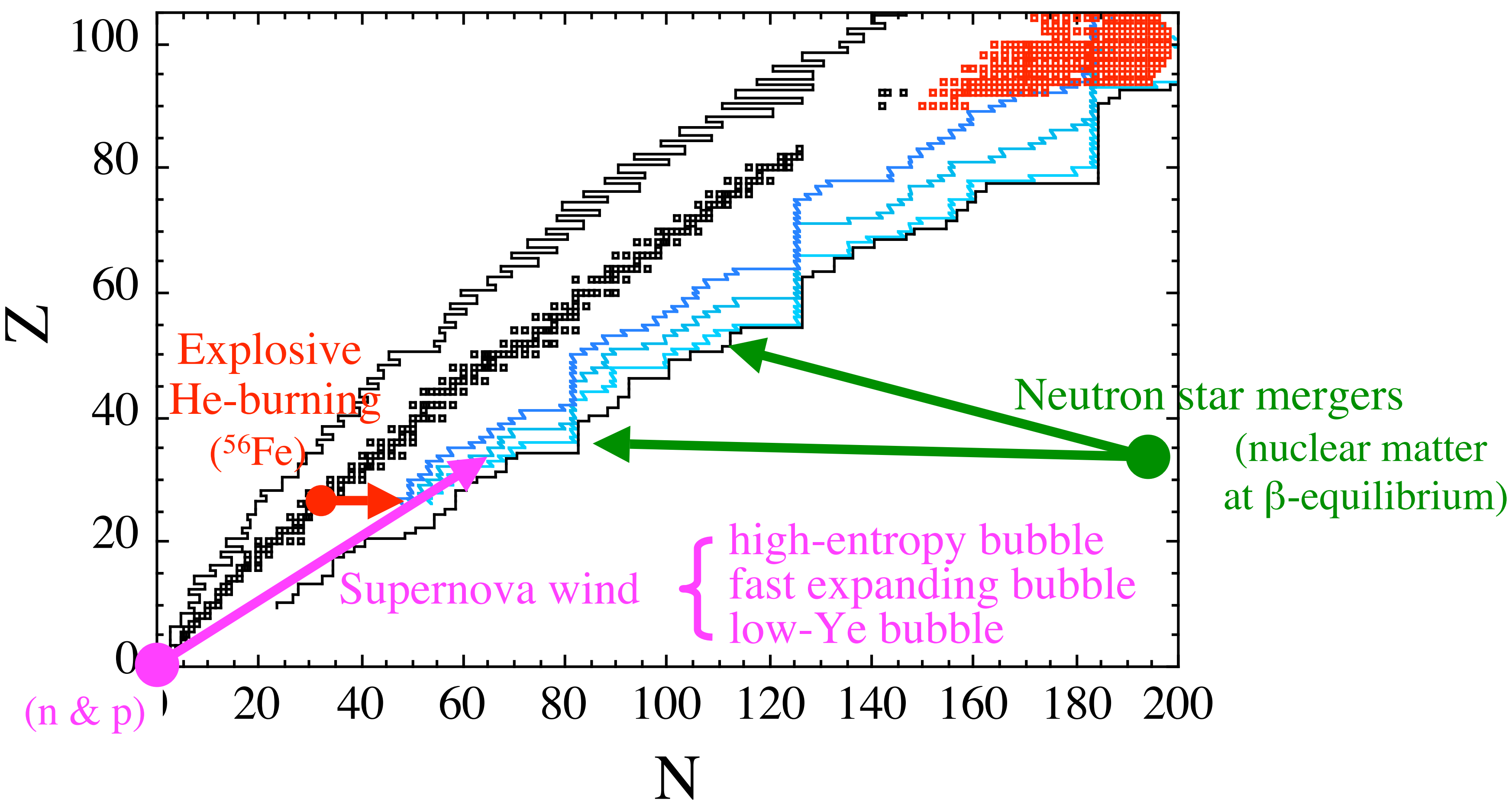


Nuclear needs:
- Photodisintegration rates
- Neutron-, proton, alpha-capture rates
- β^+-decay rates
- ν-nucleus interaction rates

For about 2000 neutron-deficient (and neutron-rich in some sites) nuclei

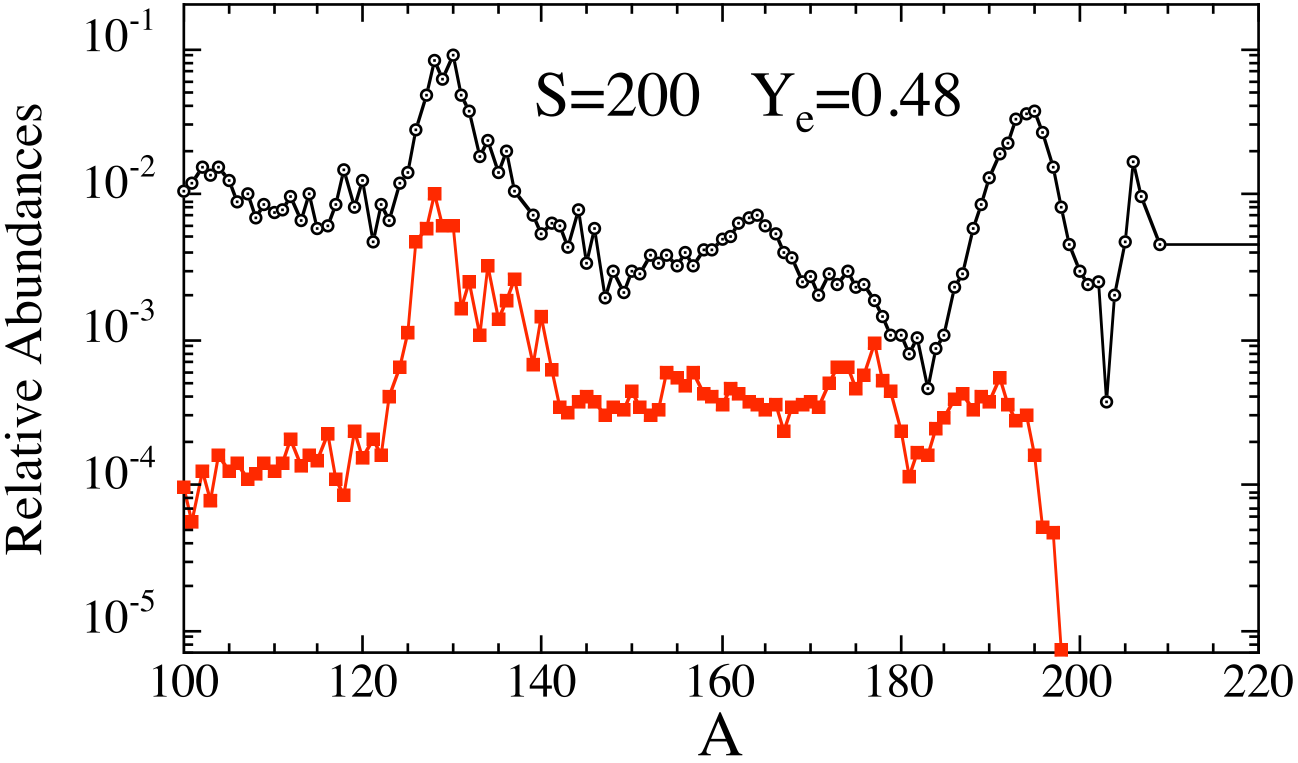
The r-process nucleosynthesis

one of the still unsolved puzzles in astrophysics
… the r-process site remains unknown ...



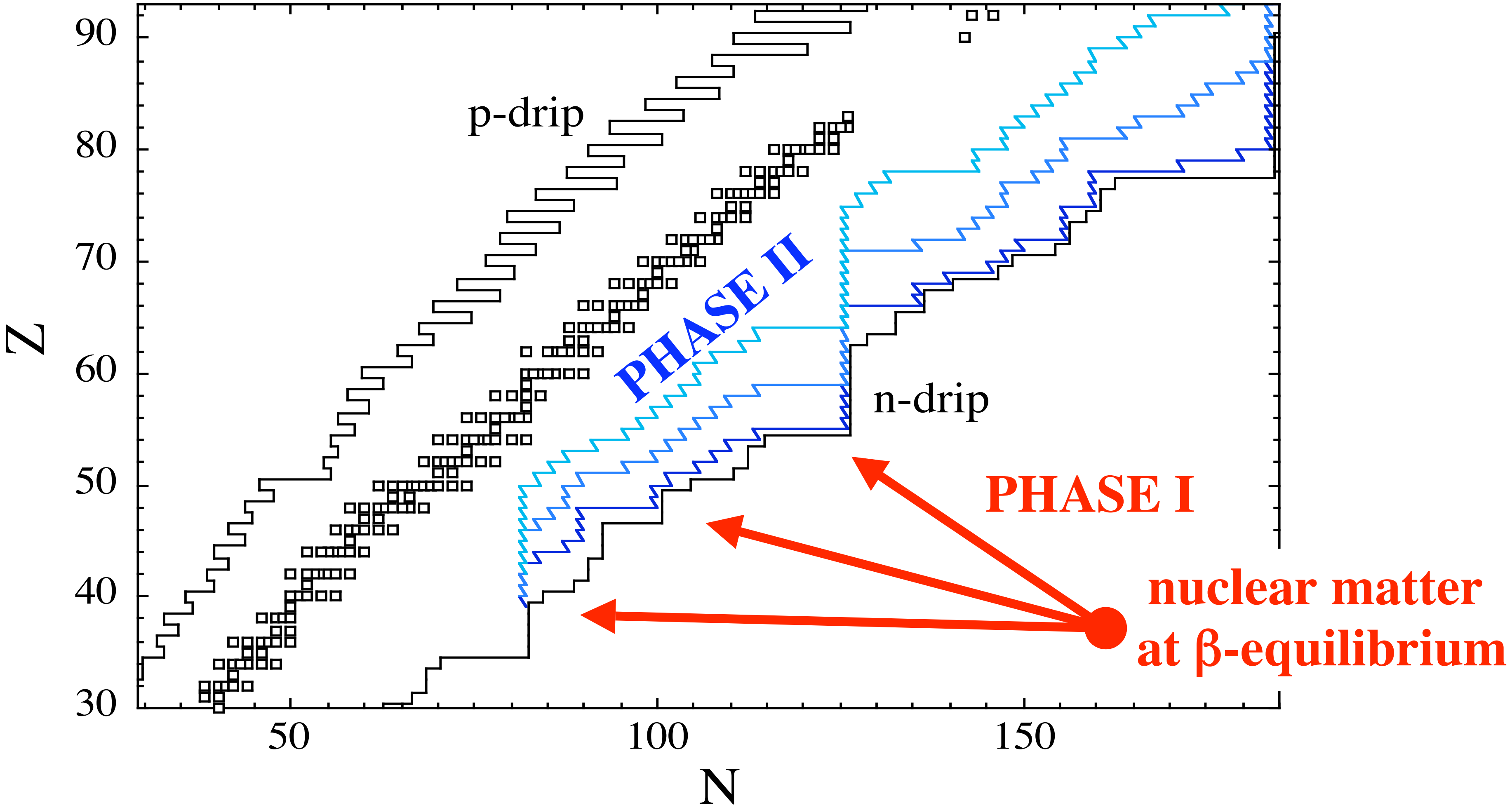
r-abundance distribution in the ν-driven wind

Extremely sensitive to the (unknown) thermodynamic profiles (S, Y_e, τ_{exp})



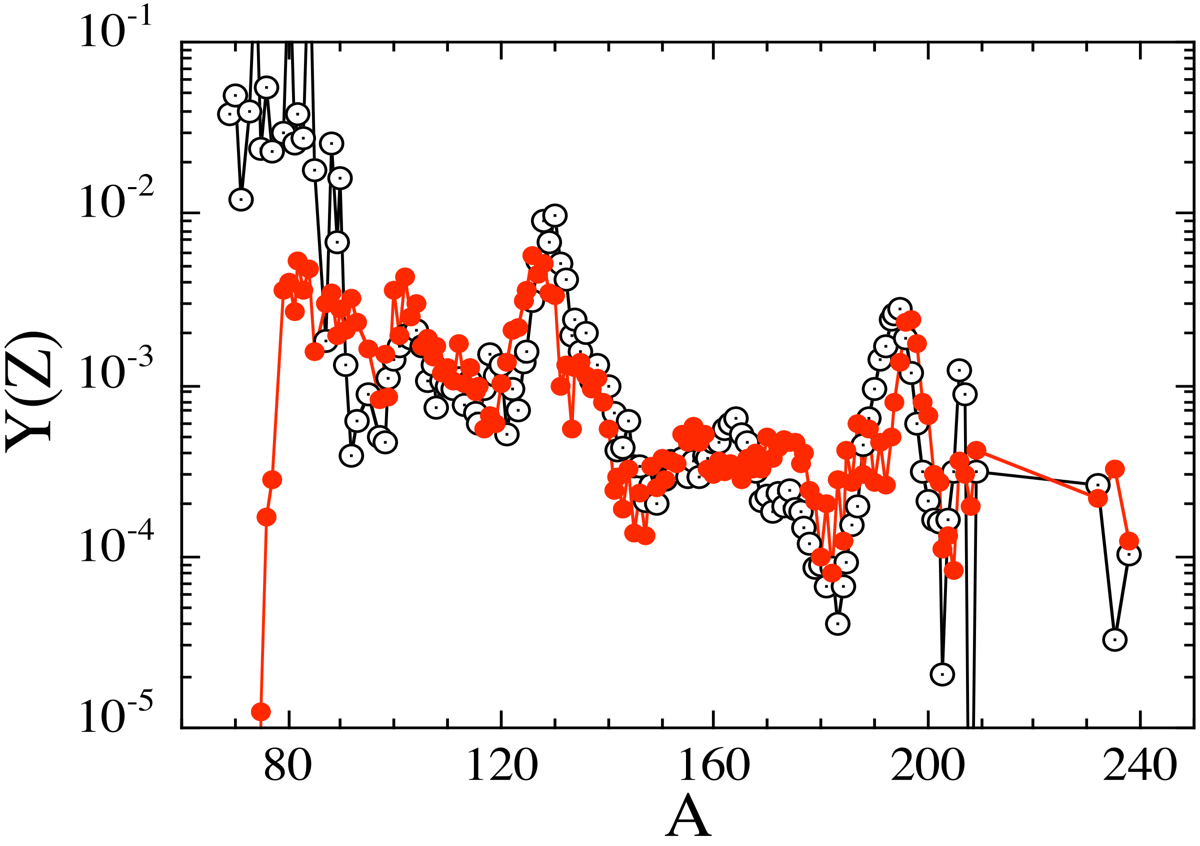
Nuclear needs:
- neutron capture versus photodisintegration **rates**
- β-decay rates (including delayed processes)
- ν-induced (NC, CC) reaction rates
- Fission properties ?

Decompression of initially cold NS matter



Total distribution for matter ejected from a radial column

material with n=0.00020 to 0.00080 fm^{-3}



Nuclear needs:
- neutron capture **rates** (up to the n-dripline !)
- β-decay rates (including delayed processes)
- no ν-induced reactions !
- Fission properties

Nucleosynthesis calculations require

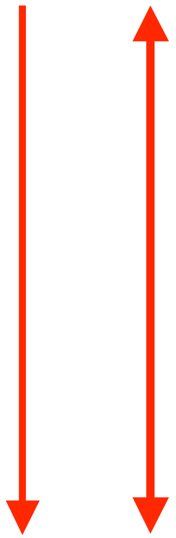
ACCURATE AND RELIABLE

CROSS SECTIONS

- **Nuclear structure properties**
- **Nuclear level densities**
- **γ-ray strength**
- **Optical potential**

γ-ray strength function

Global models available for γ-ray strength functions:

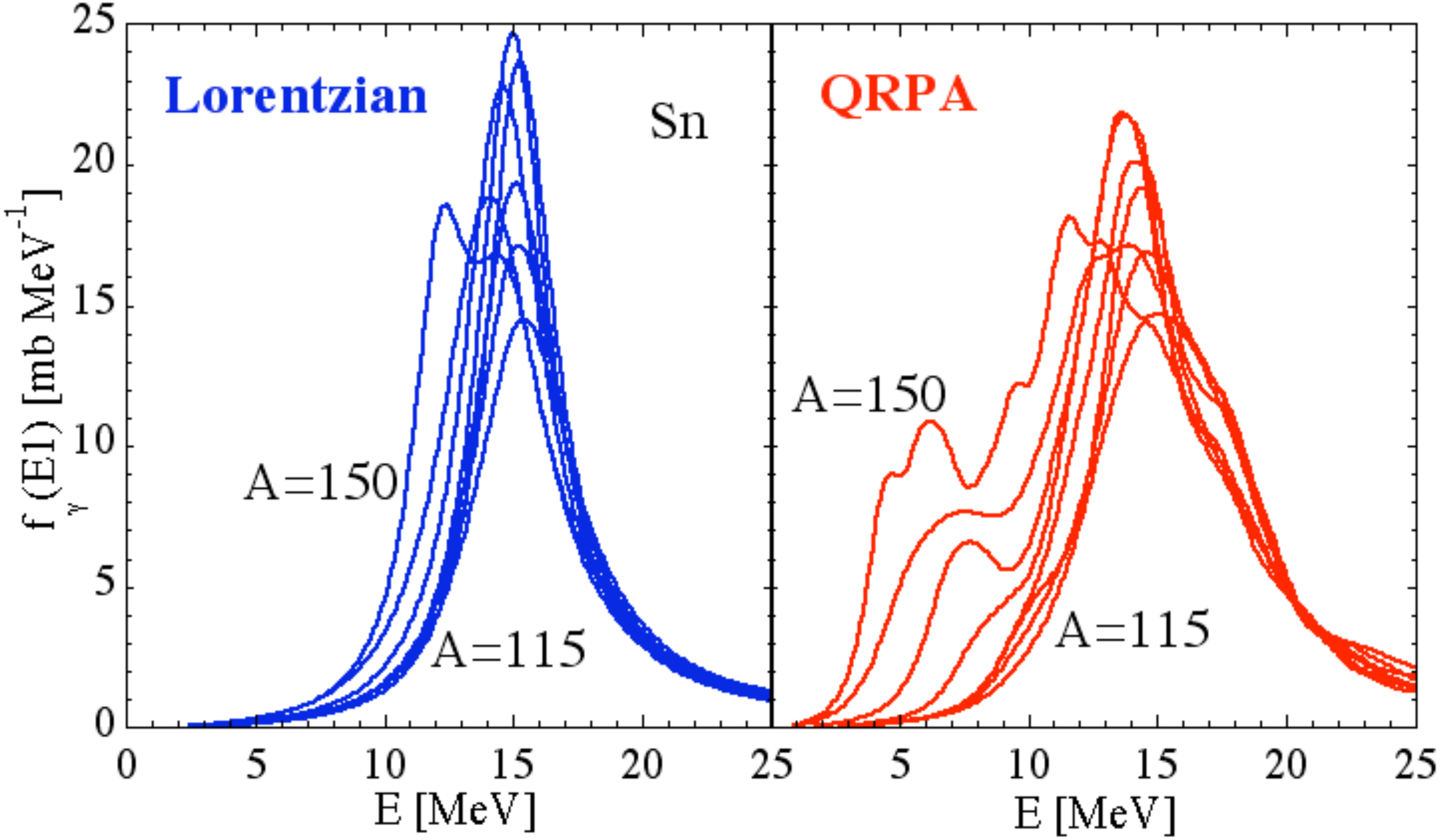


	Reliability	Accuracy
• Classical Approaches		
Lorentzian model & Liquid Drop vibration	–	+
Lorentzian model with E-dependent width	–	+
• Semi-Classical Approaches		
Lorentzian model with E- & T-dependent width	– +	+
(GLO, EGLO, MLO, GFL, Therm. Pole App., Hybrid, …)		
Semi-Microscopic Model		
HFB+QRPA model	+	+

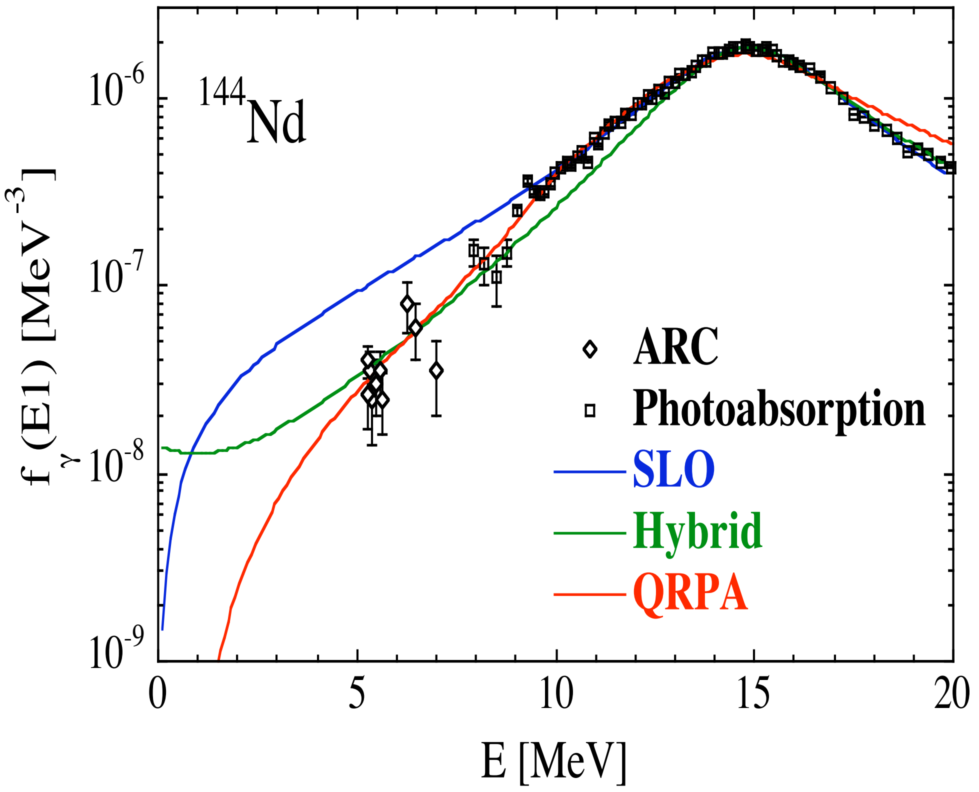
Experimental constraints

- ~84 photoabsorption data,
- ~50 low-energy strengths from resolved resonances or thermal capture measurements,
- (γ,n), (γ,γ') experiments
- (^{3}He, αγ) experiments (NLD-model dependent)

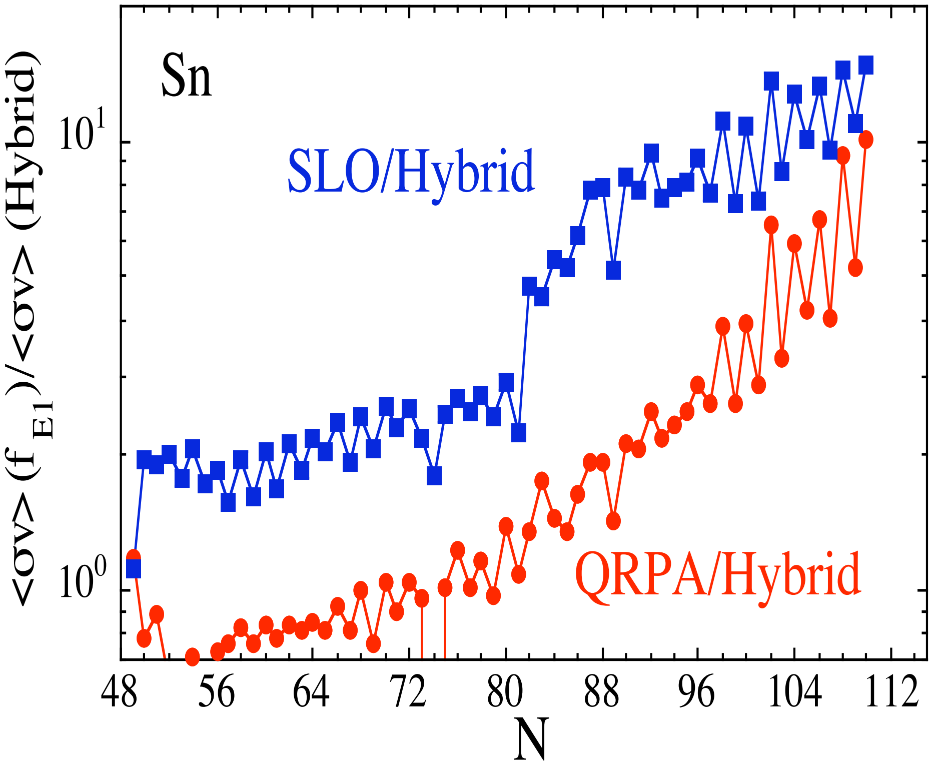
Far away from stability



E1 strength models



Radiative n-capture rate at T=10^9K

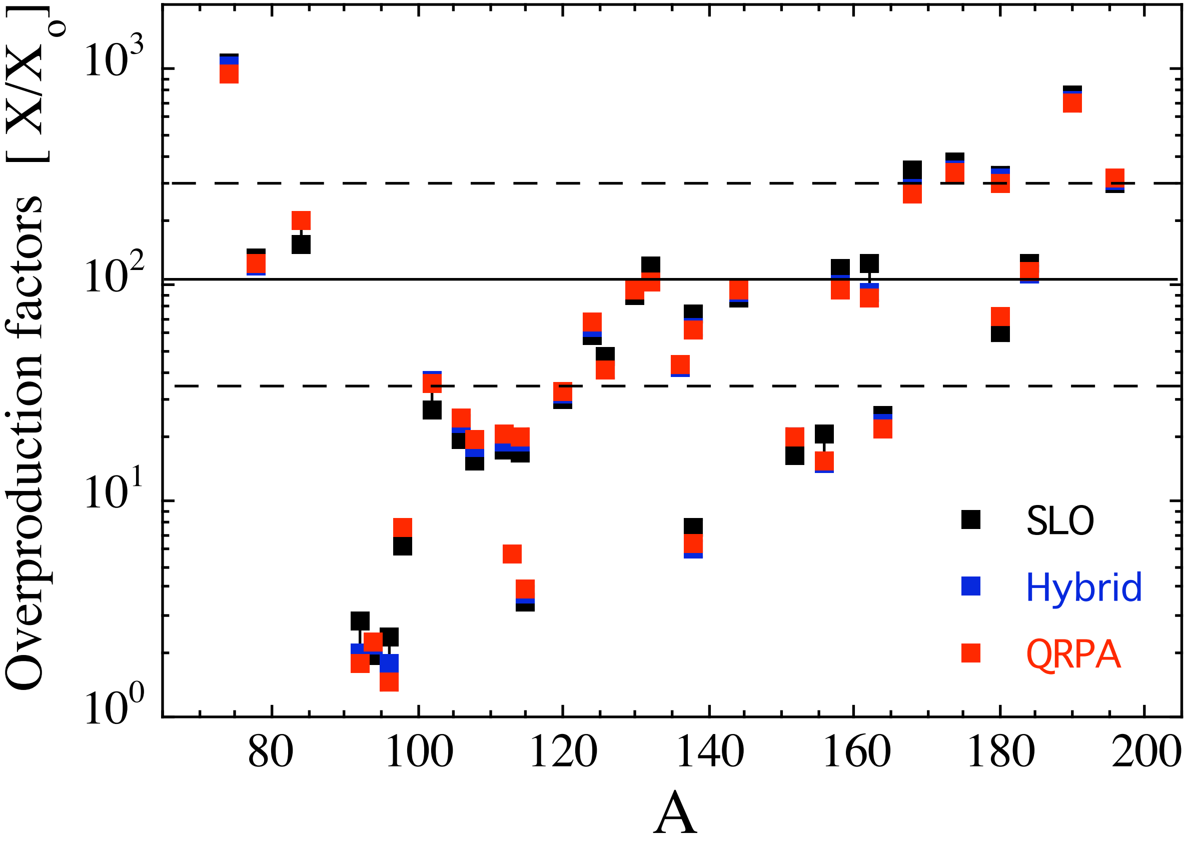


~ factor of 2 in the n-deficient region

~ factor of 10 in the n-rich region

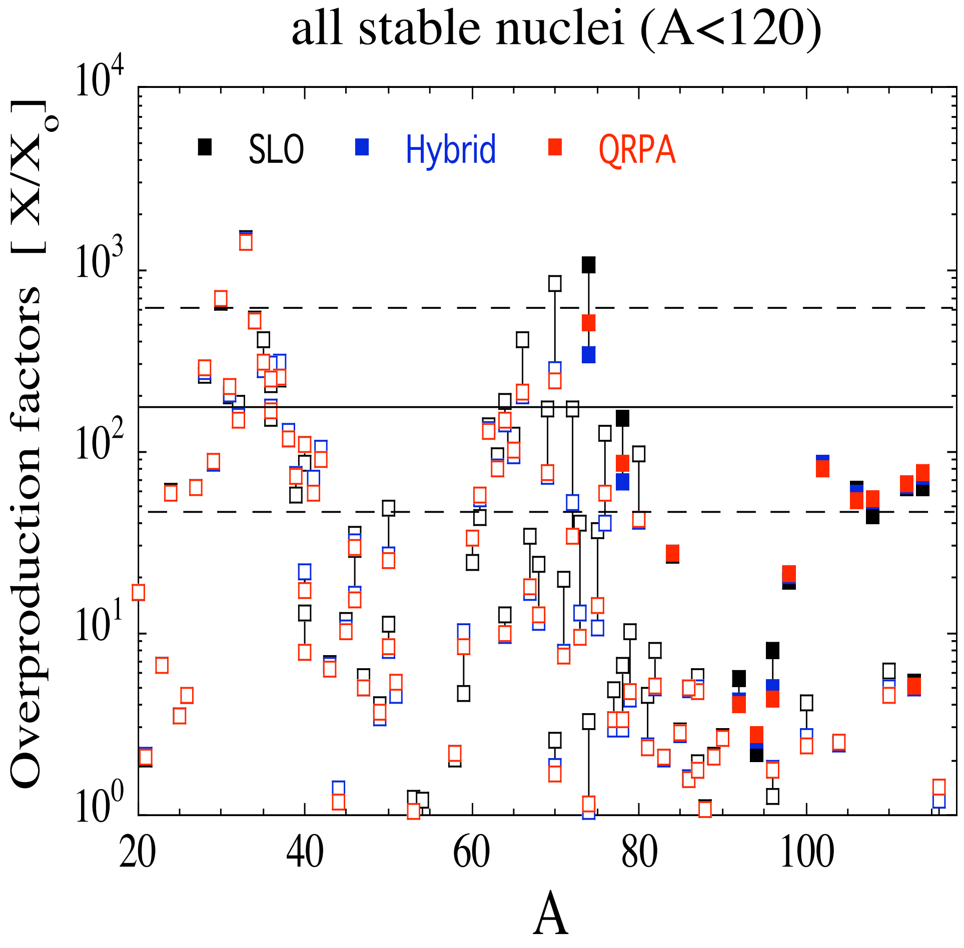
Impact on the p-process nucleosynthesis

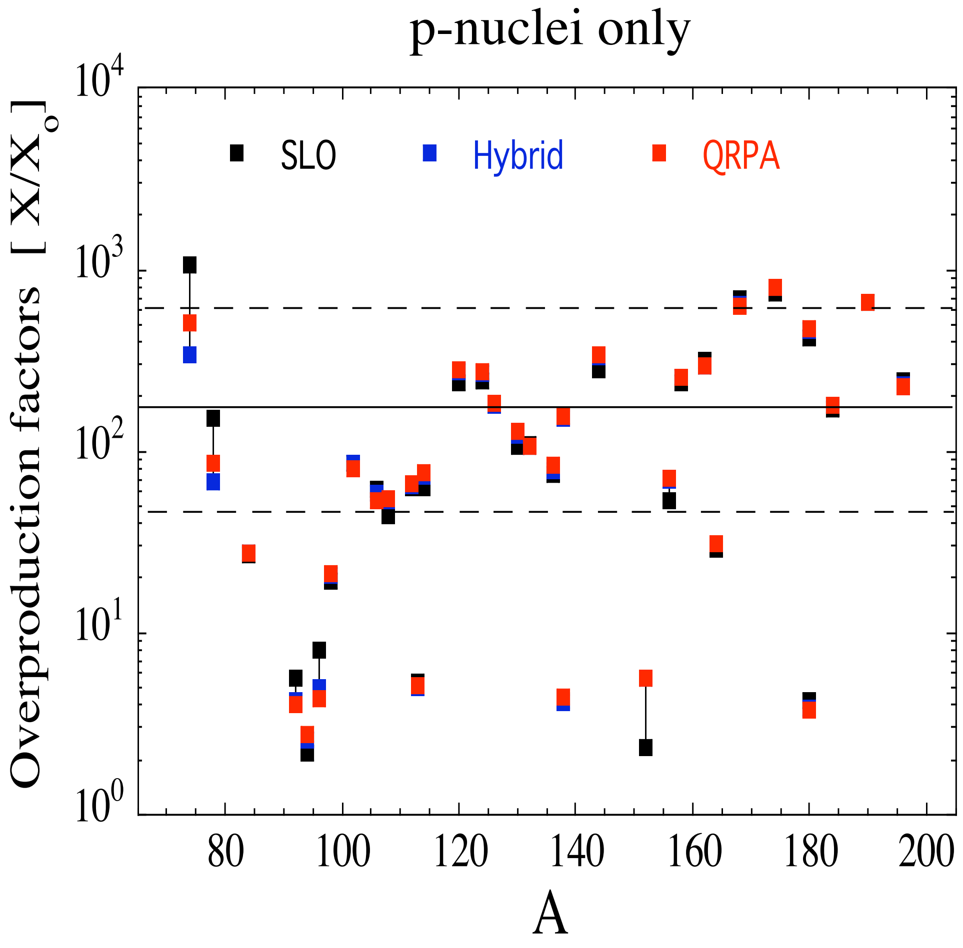
P-process in the O-Ne-rich layers of SNII (25M$_o$)



P.S. all n-, p-, α-capture rates coherently estimated with corresponding E1 strength, all other inputs being equal.

P-process in accreting White Dwarf models for SNIa


all stable nuclei (A<120)

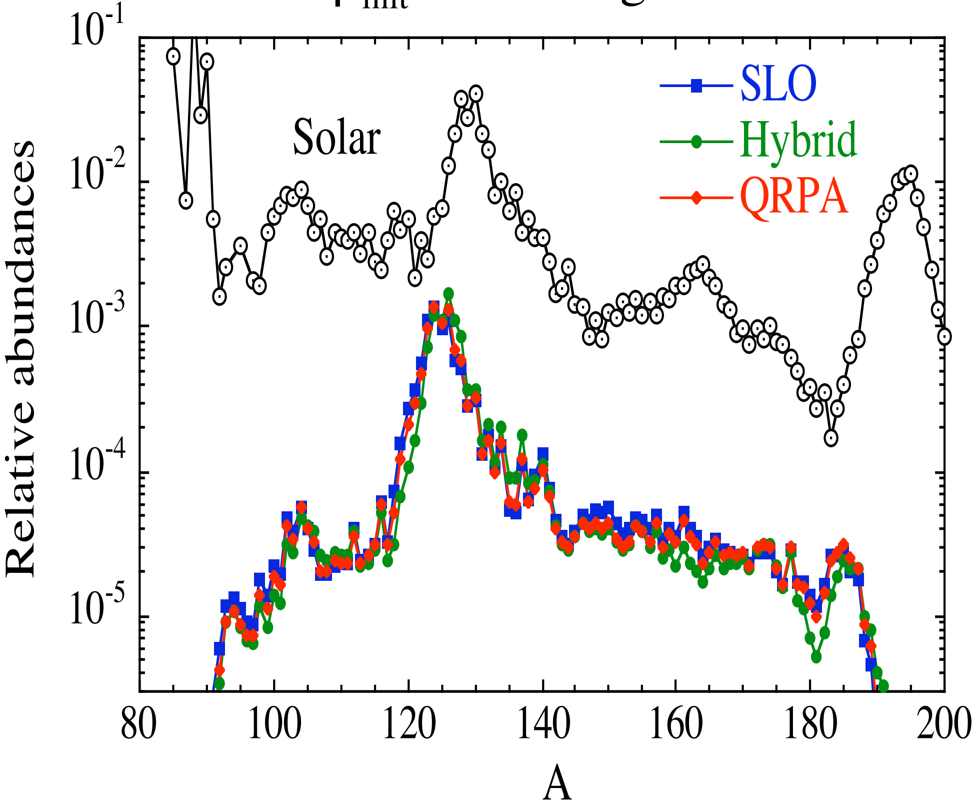

p-nuclei only

Sensitivity similar for different initial AGB s-abundance distributions

Impact on the r-process nucleosynthesis

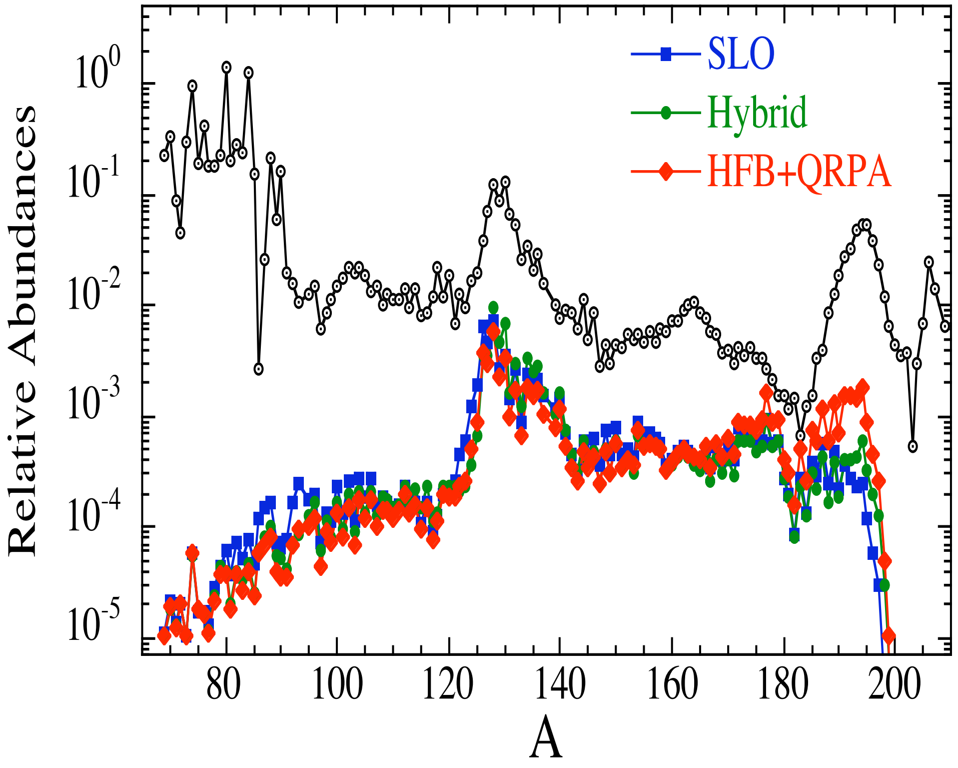
decompressing NS matter

ρ_{init}=7.5 10^{11} g/cm^3



ν-driven wind of SNII

S=200, Y_e=0.48, dM/dt=$10^{-6}M_o s^{-1}$, f_E=2



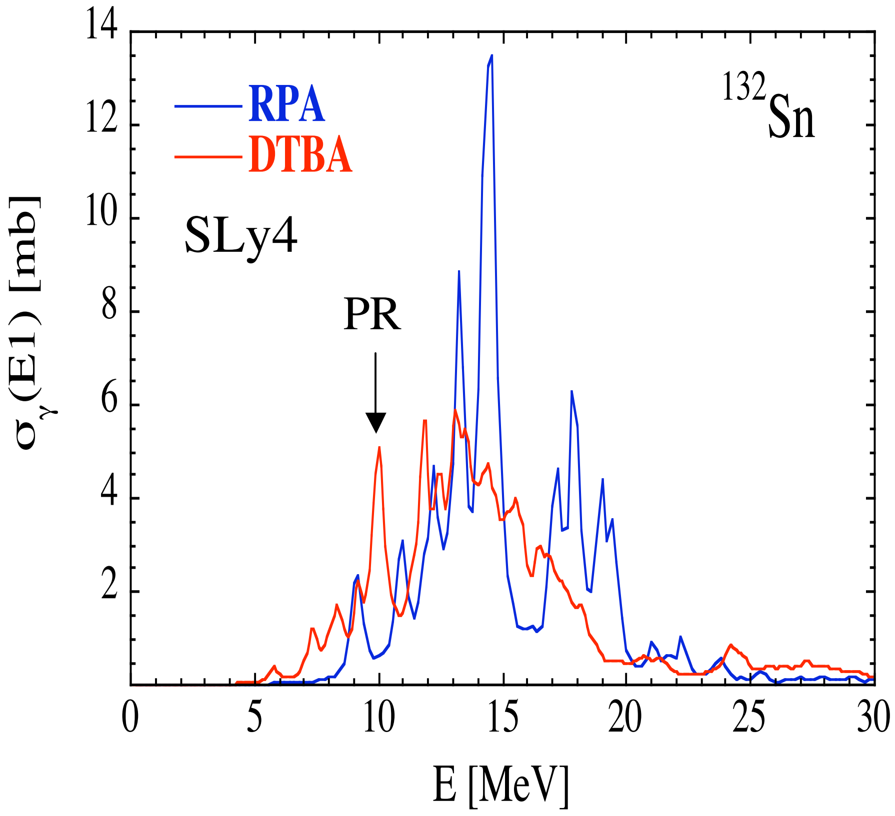
P.S. all n-, p-, α-capture rates coherently estimated with corresponding E1 strength, all other inputs being equal.

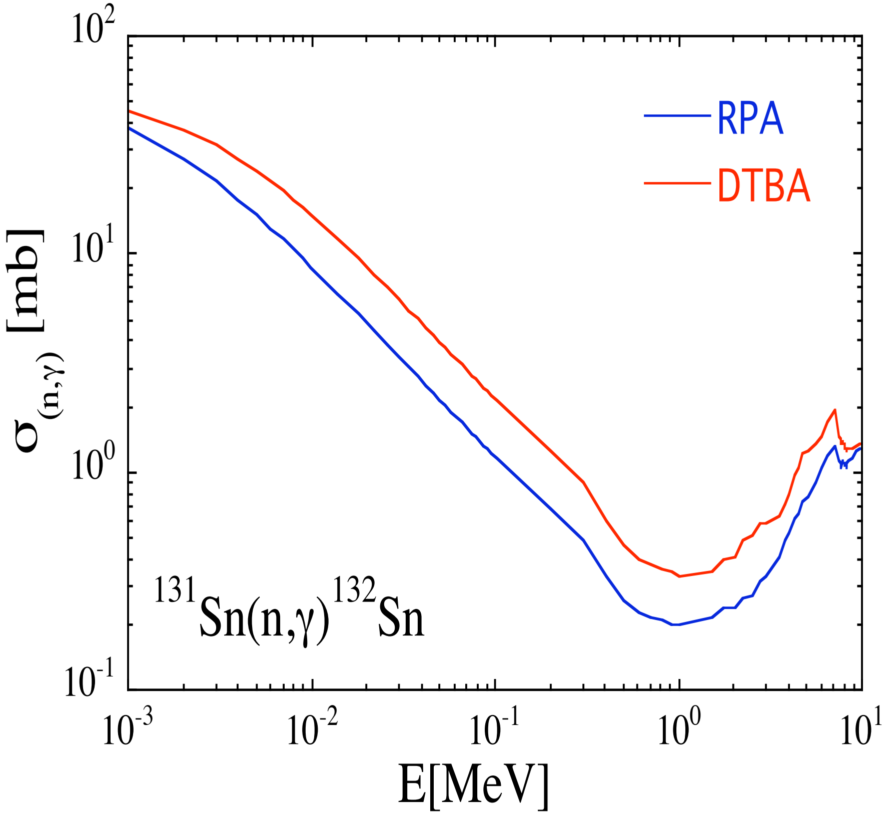
Self-consistent microscopic theories taking into account the single-particle continuum and phonon coupling (1p1h x phonon and 2p2h x phonon)

DTBA: Discrete Time Blocking Approximation

Avdeyenkov et al.

- Natural spreading of the strength
- Even more strength at low-energy wrt RPA





Exp:	E=16.1MeV	Γ=4.7MeV
DTBA:	E=14.3MeV	Γ=3.7MeV

The ε_γ --> 0 tail of the γ-strength function

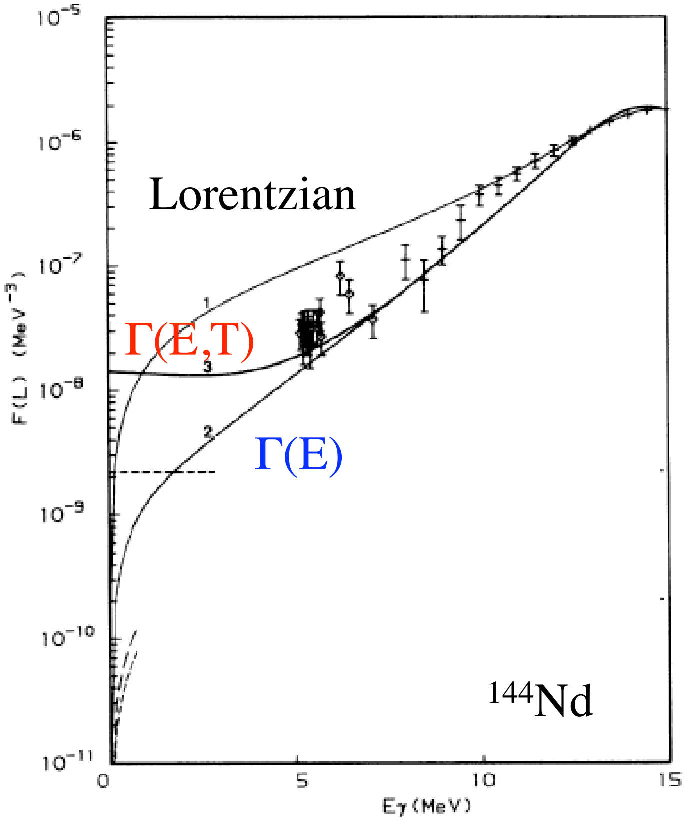
- Standard Lorentzian
- Lorentzian with E-dependent width (e.g McCullagh et al. 1981) $\Gamma = \Gamma_0 \left(\frac{E}{E_0} \right)^{1/2}$
- Generalized Lorentzian with T- and E-dep. width (e.g Kopecky & Uhl 1990)

The E- and T-dependent width is essentially derived from the theory of Fermi liquids (e.g Kadmenski et al. 1982) and also suggested by exp. ARC data

$$\Gamma = \frac{\Gamma_0}{E_0^{\,2}} \left(E^2 + 4\pi^2 T^2 \right)$$

decay of p-h states into more complex states

collisions between quasi-particles



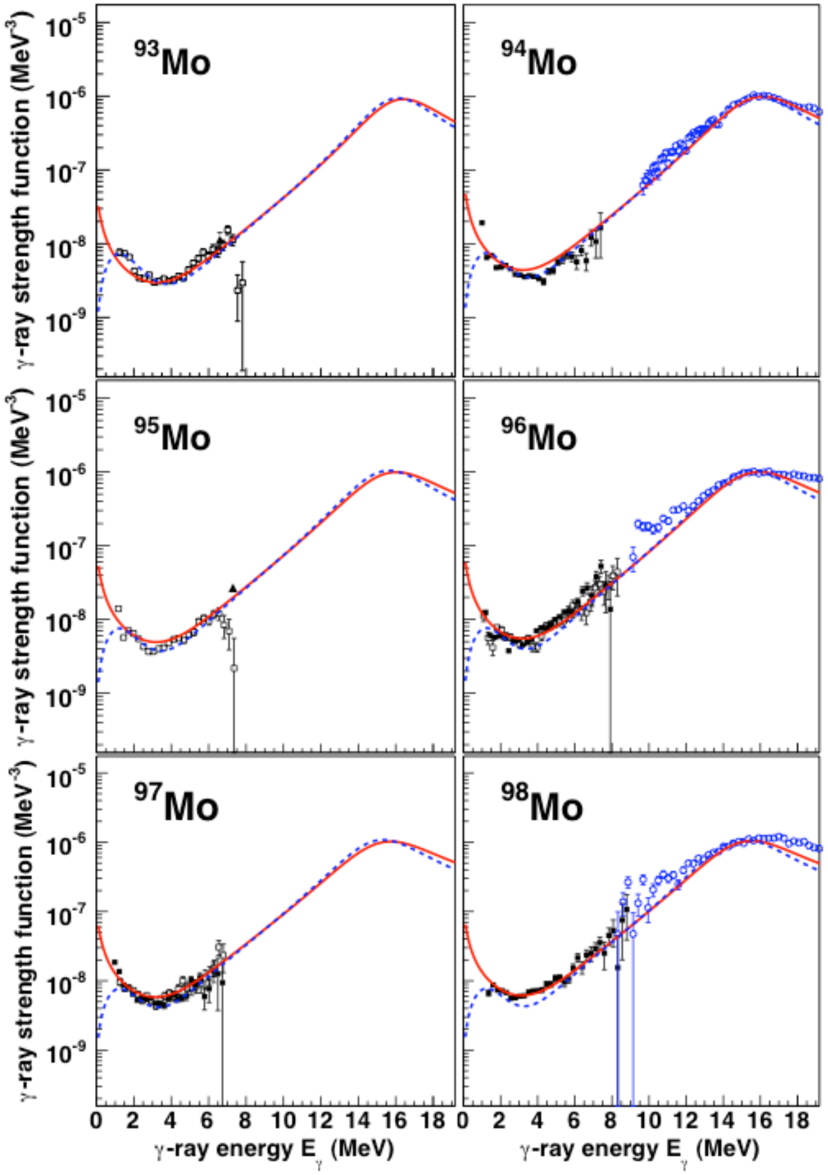
At the basis of the GLO, EGLO, MLO, GFL, Hybrid, … models

But not many exp. data at low energy to confirm this behaviour

Kopecky & Uhl (1990)

The low-energy upbend structure determined experimentally in Oslo

(at least for ^{44,45}Sc, ^{50,51}V, ^{56,57}Fe, $^{93\text{-}98}$Mo,
but not for Sn, Sm, Dy, Er or Yb)



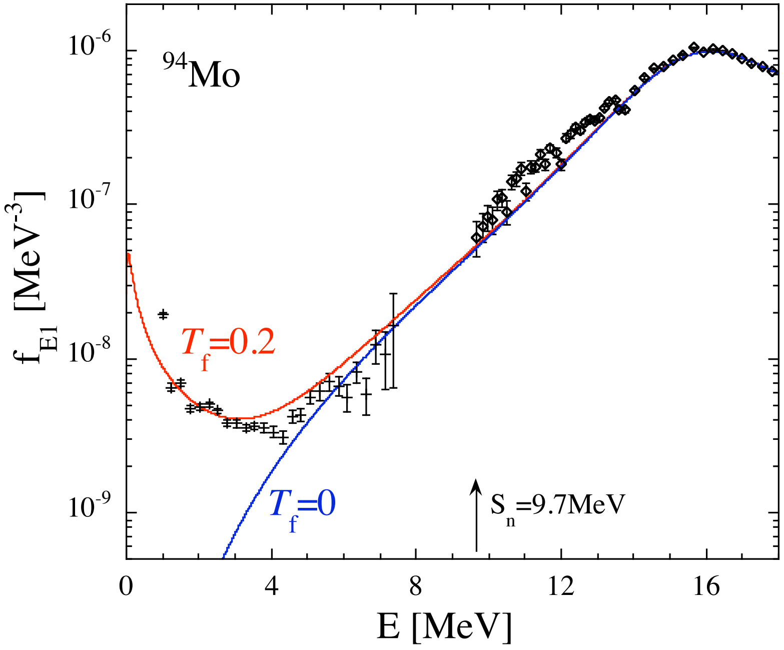
A.-C. Larsen et al. (2009)

Assuming an E1 character, the upbend can be described by a simple phenomenological formula (modified version of the Hybrid model):

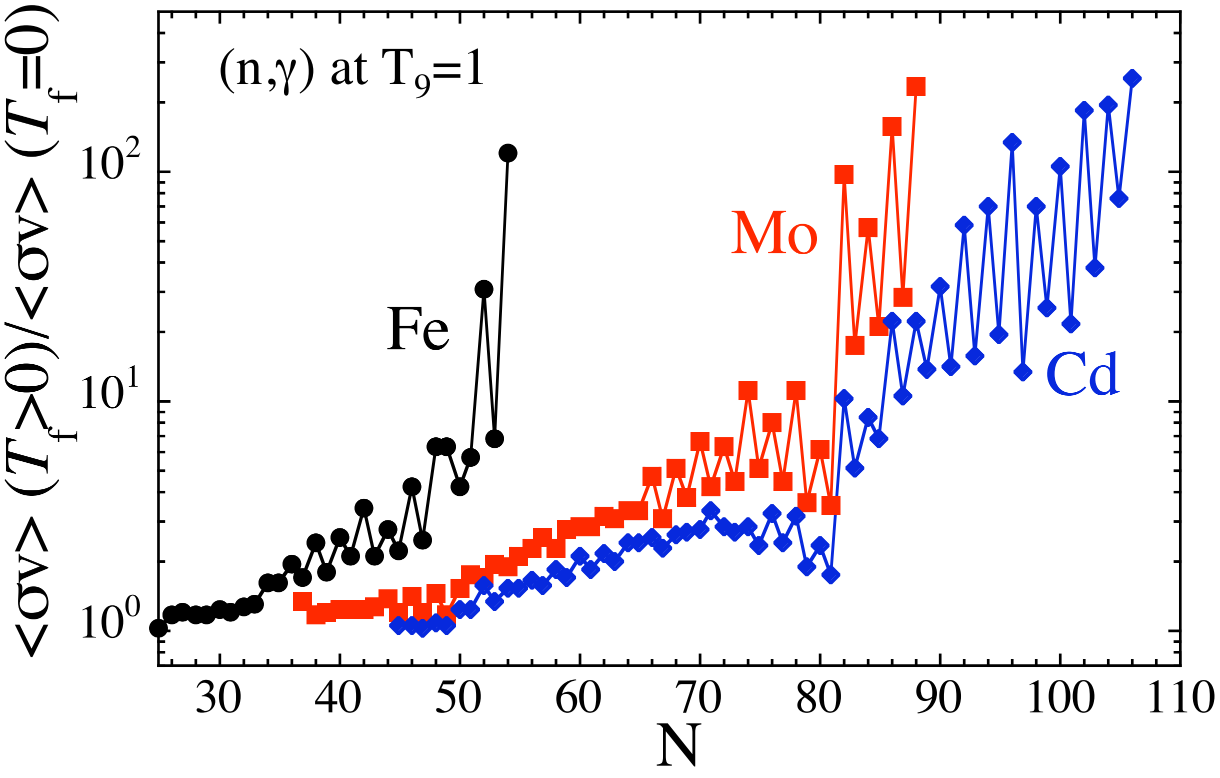
Generalized Lorentzian with E-, T-dep. width

$$f_{E1}(E_\gamma) = 8.68 \times 10^{-8} \frac{\sigma_0 E_\gamma \Gamma(E_\gamma) \Gamma_0}{(E_\gamma^2 - E_0^2)^2 + \Gamma_0 \Gamma(E_\gamma) E_\gamma^2}$$

with $$\Gamma(E_\gamma) = \frac{\Gamma_0}{E_0^2} \left[E_\gamma^2 + 4\pi^2 T_f^2 \frac{E_0^2}{E_\gamma^2} \right]$$



Impact of the upbend pattern on the radiative n-capture rate

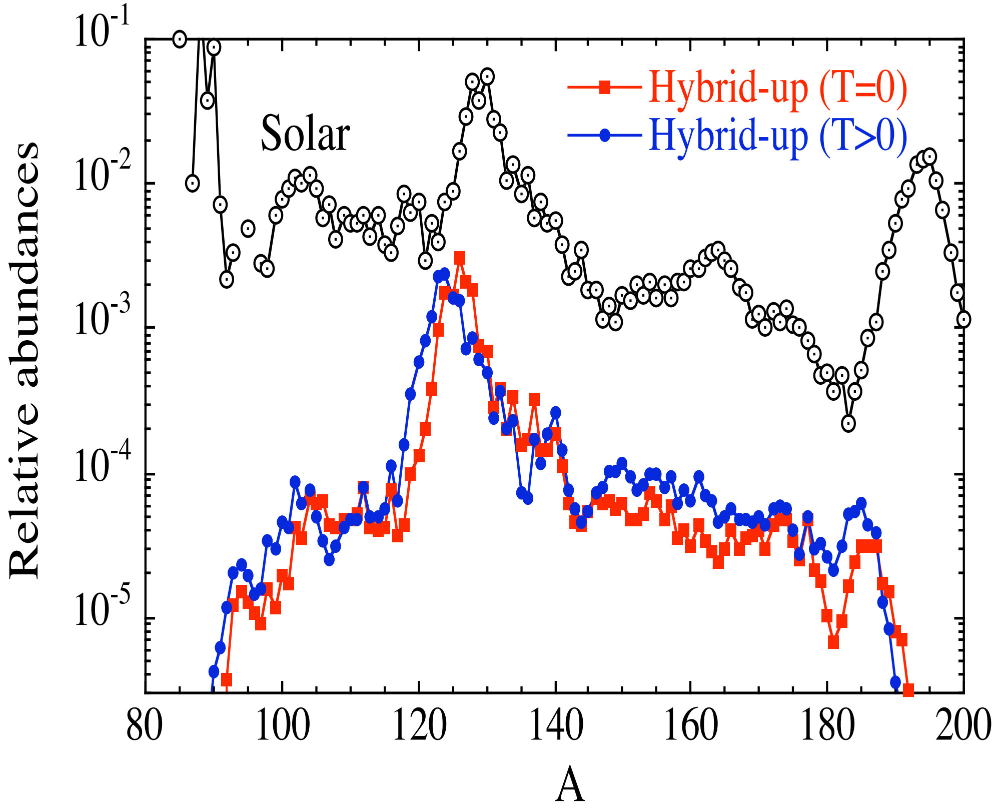


Small impact on the stable nuclei (~ factor of 2 at most)

Large impact on exotic n-rich nuclei ($N>N_{mag}$: up to a factor ~100)

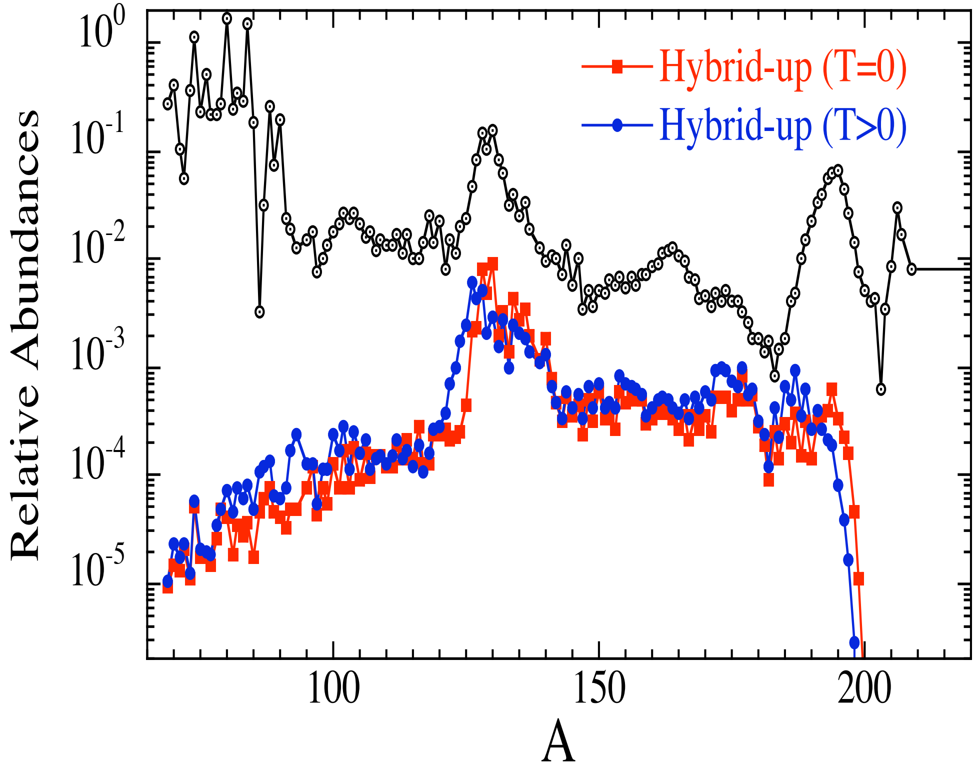
--> The upbend structure, but if true, its impact is far from being negligible

Impact of the low-energy E1 upbend on the r-abundance distribution



decompressing NS matter

$\rho_{init}=7.5\ 10^{11}\ g/cm^3$



ν-driven wind of SNII

$S=200,\ Y_e=0.48,\ dM/dt=10^{-6}M_o s^{-1},\ f_E=2$

Nuclear Level Densities

Global models available for nuclear level densities:

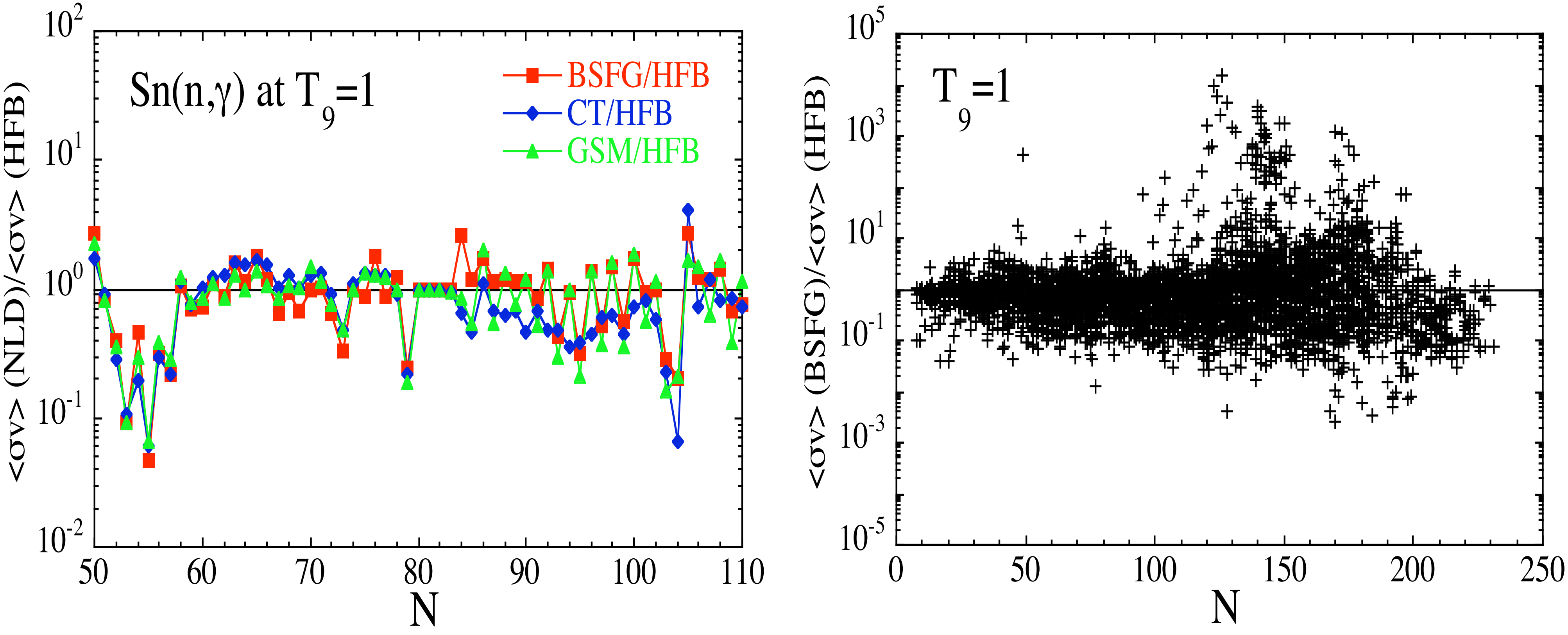
	Reliability	Accuracy
• **Macroscopic-Microscopic Approaches**		
Back-Shifted Fermi Gas model	– –	+ +
Shell-dependent BSFG model with(out) coll. Enh.	– –	+ +
Generalized Superfluid Model	+ –	+ +
• **Semi-Microscopic Model**		
Statistical Model	+ +	+ +
Combinatorial Model	+++	+ +

Extensive literature on microscopic models but not much of practical use for nuclear applications

Experimental constraints:

- ~295 s-wave neutron spacing at $U=S_n$
- low-lying states for 1200 nuclei,
- Many model-dependent data exist (e.g Oslo data from (^{3}He,αγ) and (^{3}He,^{3}He'γ))

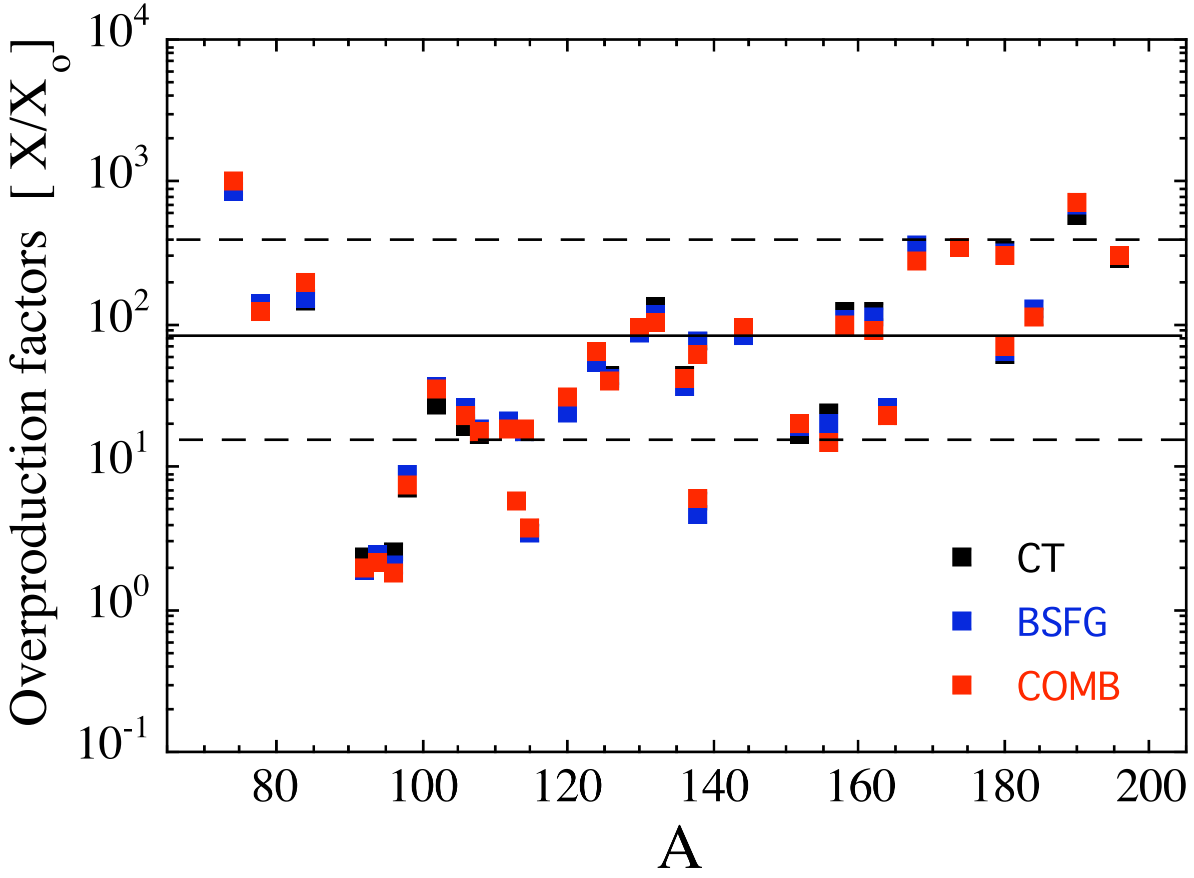
Impact of different NLD models on the radiative n-capture rate



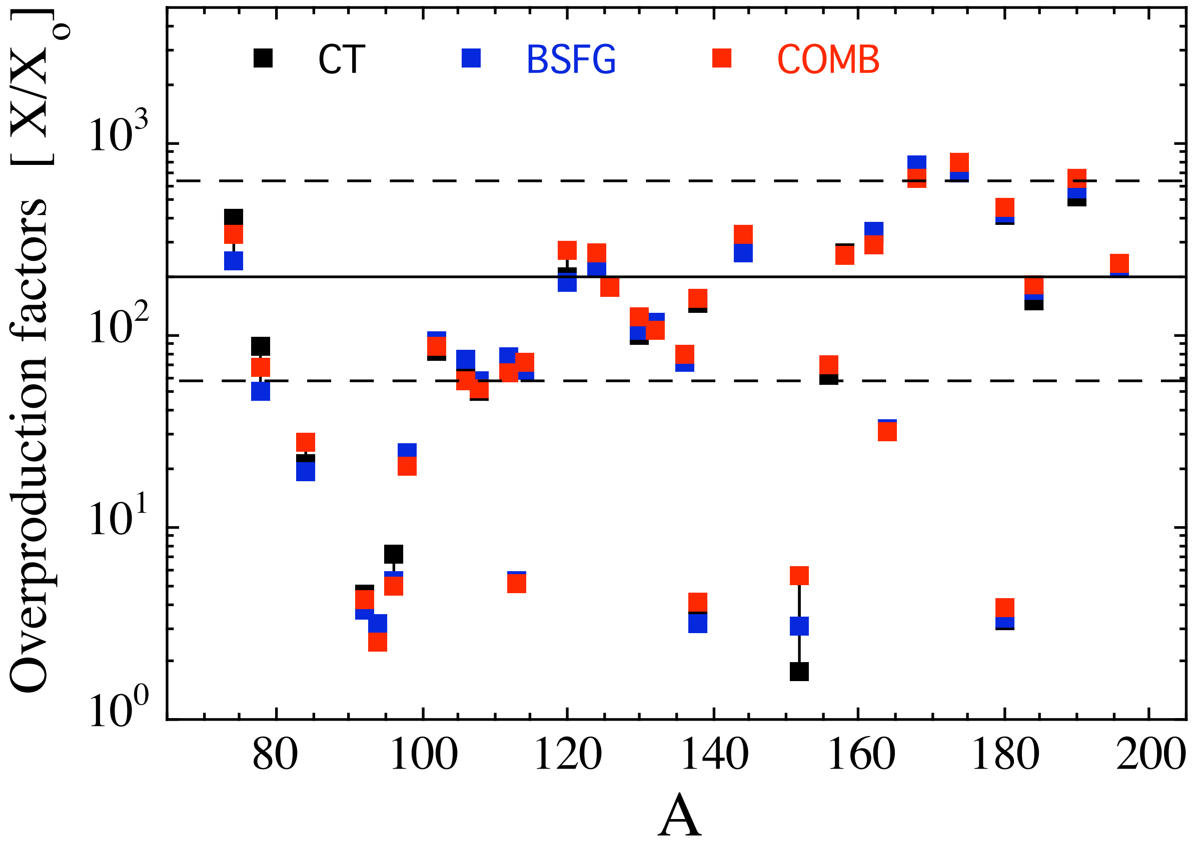
P.S. BSFG, CT and GSM models are shell-dependent and account explicitely for collective enhancement

Impact on the p-process nucleosynthesis

P-process in the O-Ne-rich layers of SNII (25M$_o$)



P-process in accreting White Dwarf models for SNIa



P.S. Sensitivity for 40≤A≤70 nuclei similar to the one affecting light p-nuclei

Impact on the r-process nucleosynthesis

decompressing NS matter

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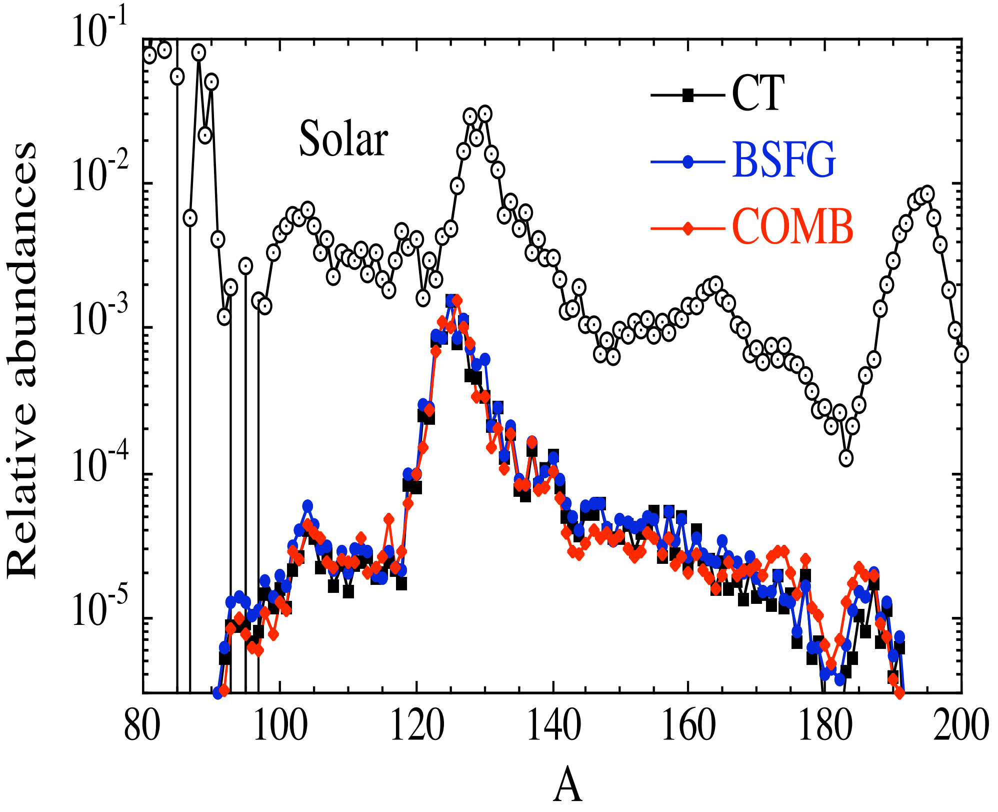

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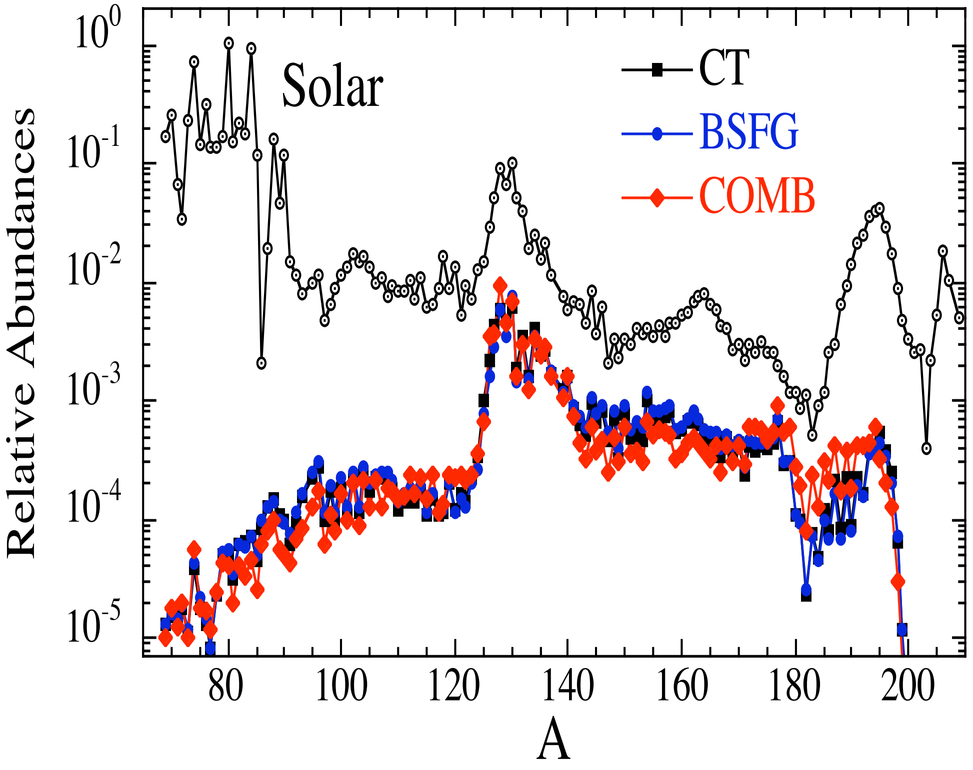
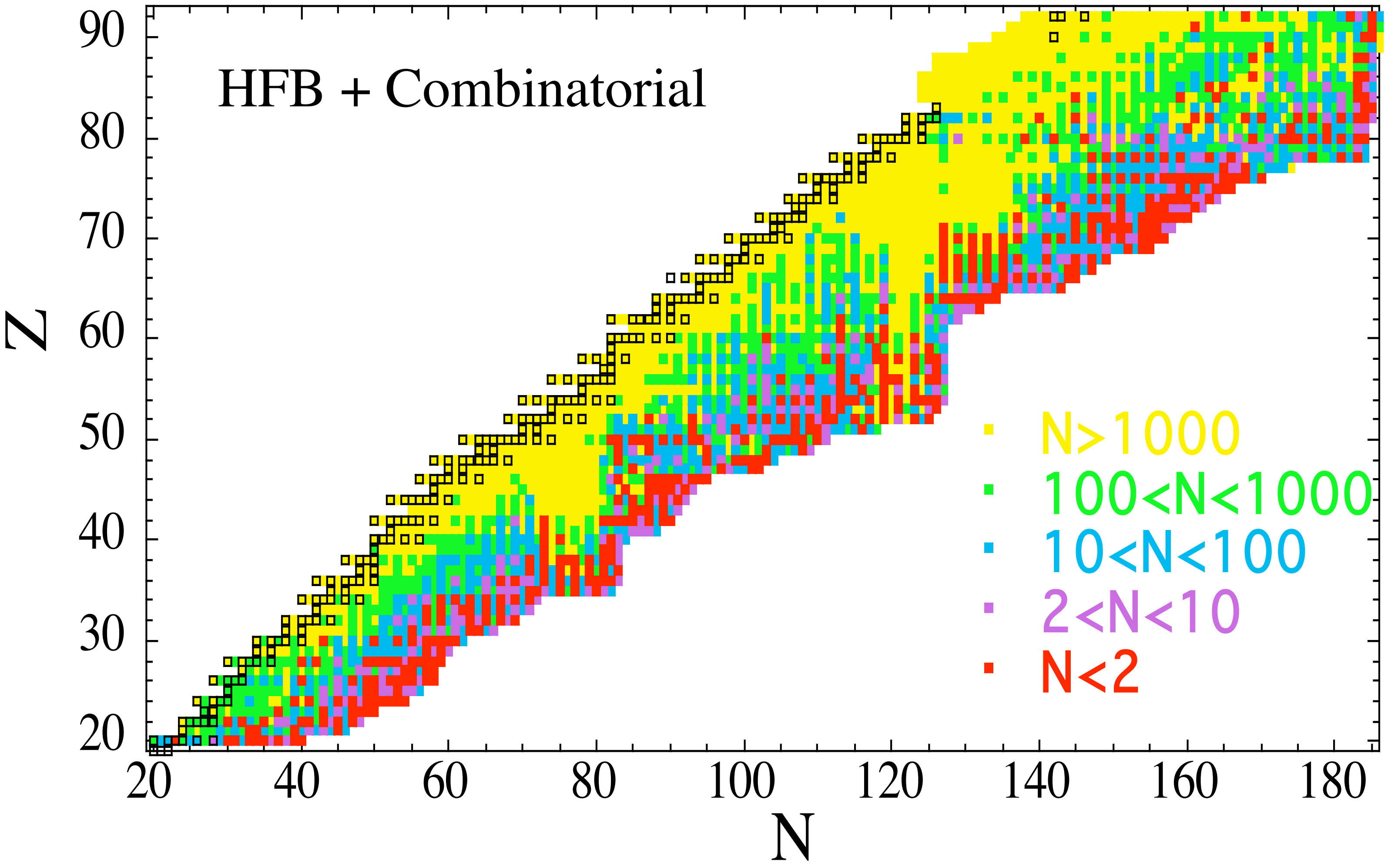


Number of levels (all spins and parities) available above U=Sn in a energy range of 2kT=0.250 MeV



Conclusions

Nuclear Level Densities and γ-strength functions play a key role for a reliable estimate of reaction rates of unstable nuclei

Still many open questions

- **γ-ray strength:**
  - **low-lying strength (E-, T-dep., PR, upbend) --> need more exp. data**
  - **Isospin dependence of the GDR parameters**
  - **M1 contribution**
- **NLD:**
  - **evolution of deformation with excitation energy**
  - **Low-Energy spectrum for exotic nuclei**

In the limits of the present models, the impact on

– the p-process is restricted to the lightest p-elements and medium-mass nuclei ($40 \leq A \leq 80$)

– the r-process is more difficult to ascertain, but in all cases the best nuclear physics (reproducing experimental data) is a necessary condition