The r-process nucleosynthesis: astrophysics and nuclear physics challenges

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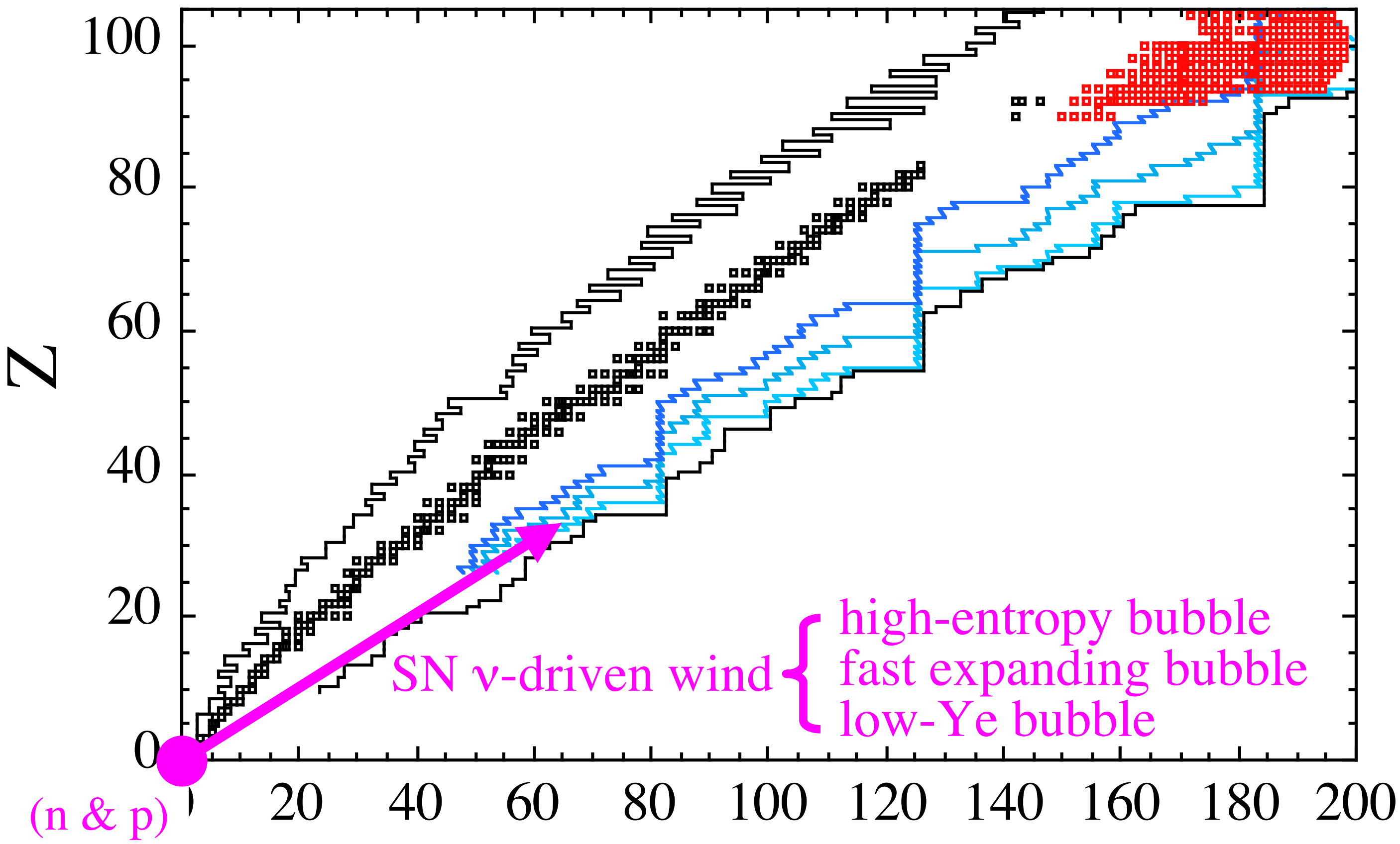
1. Astrophysics considerations: SN & NS
2. Nuclear models of relevance for astrophysics applications
   - Mass models
   - Fission rates

The r-process nucleosynthesis

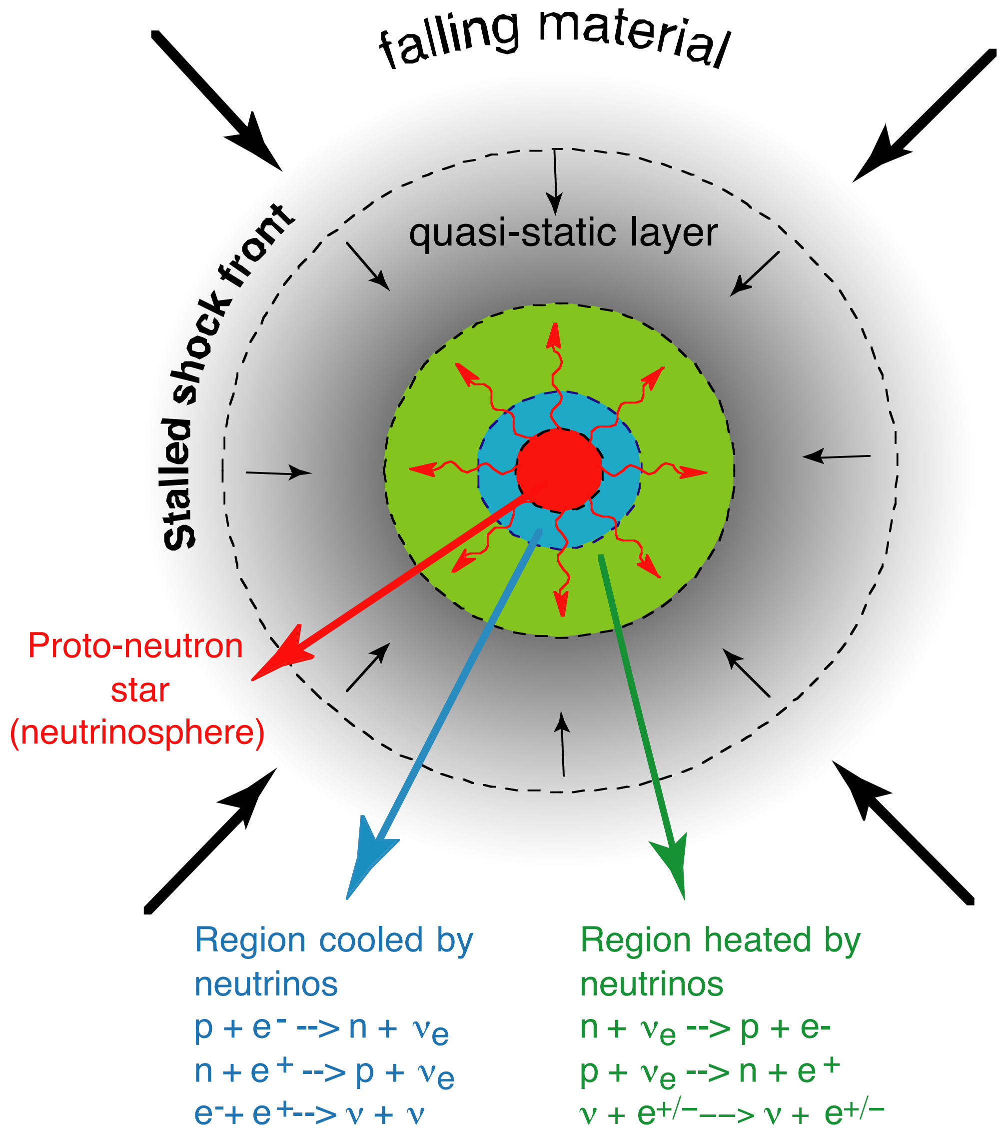
one of the still unsolved puzzles in astrophysics
… the r-process site remains unknown ...



Supernovae: the favoured r-process site ??

Many subjective interpretations, unconfirmed speculations, fast conclusions, …

The favorite r-process site: the ν-driven wind in SNII



Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6 g/cm^3$

↓ NSE

^{4}He recombination

↓ $\alpha\alpha n$-^{9}Be(α,n)

^{12}C bottleneck

↓ (α,γ) & (α,n)

$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

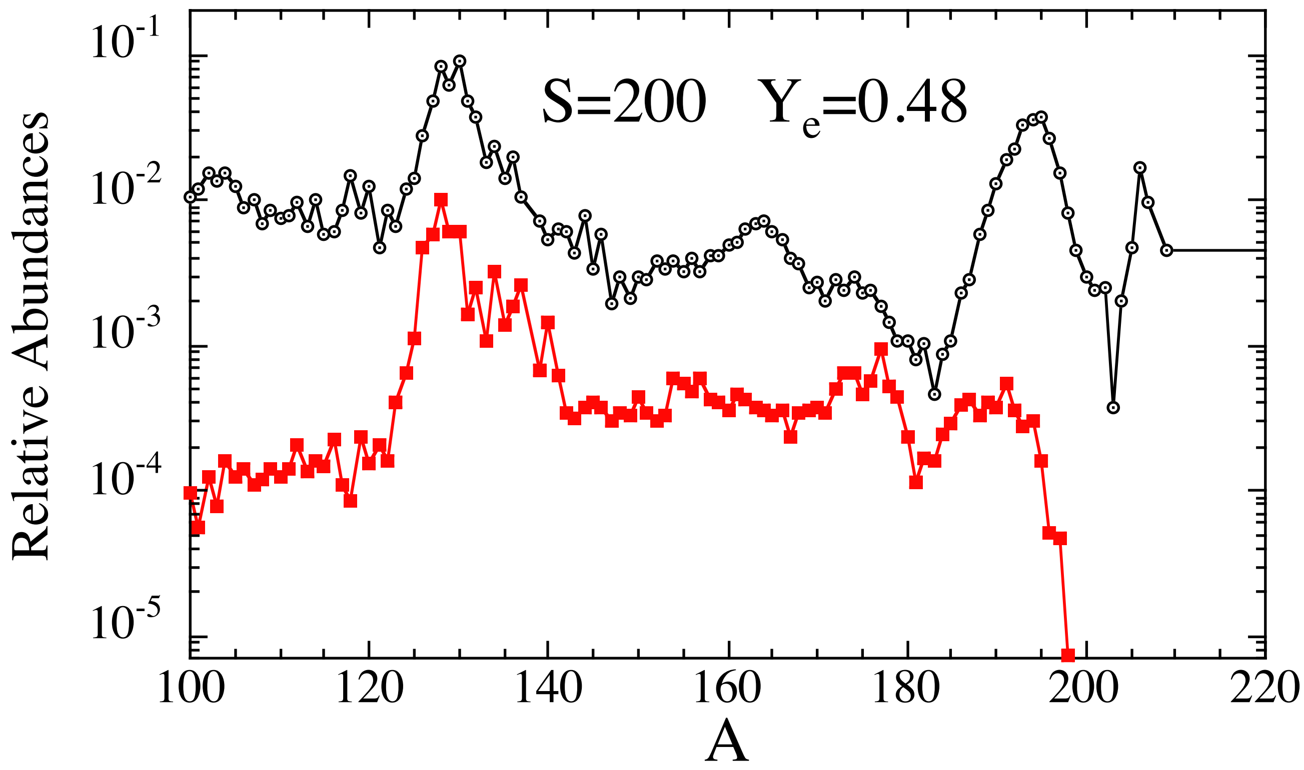
r-process

if Y_n/Y_{seed} large enough !!

Artificially large S, small Y_e, τ_{ex}

r-abundance distribution in the ν-driven wind

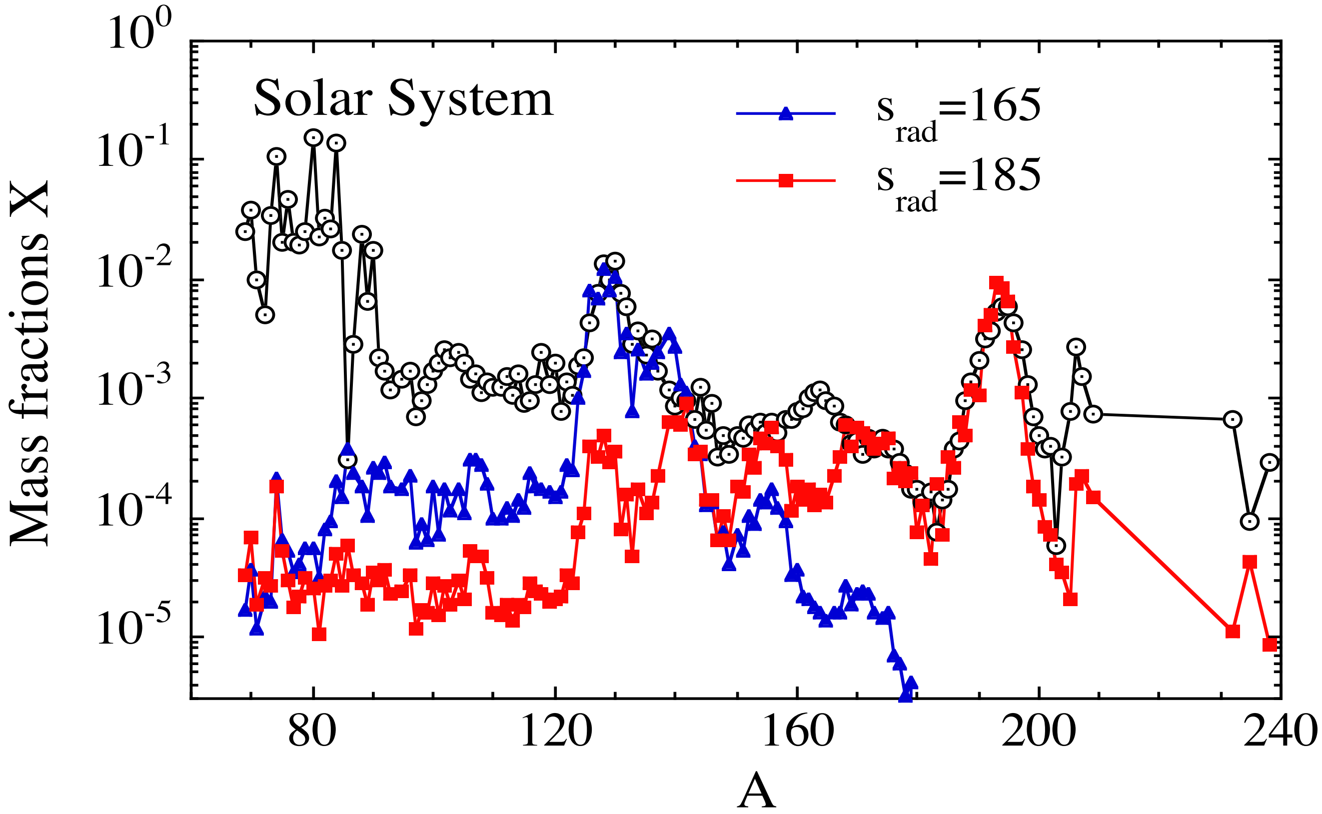
Extremely sensitive to the (unknown) thermodynamic profiles (S, Y_e, τ_{exp})



Sensitivity of the r-process nucleosynthesis to the wind conditions

Wind model of Janka & Takahashi (1997):same initial Y_e=0.48

same mass loss rate: dM/dt=6 10^{-6} M_o/s
different entropies



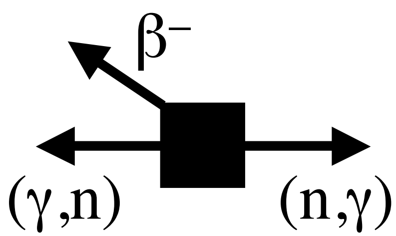
only hydrodynamic simulations can tell

… but the explosion has to be under control first …

Sensitivity to nuclear physics inputs

Nuclear needs

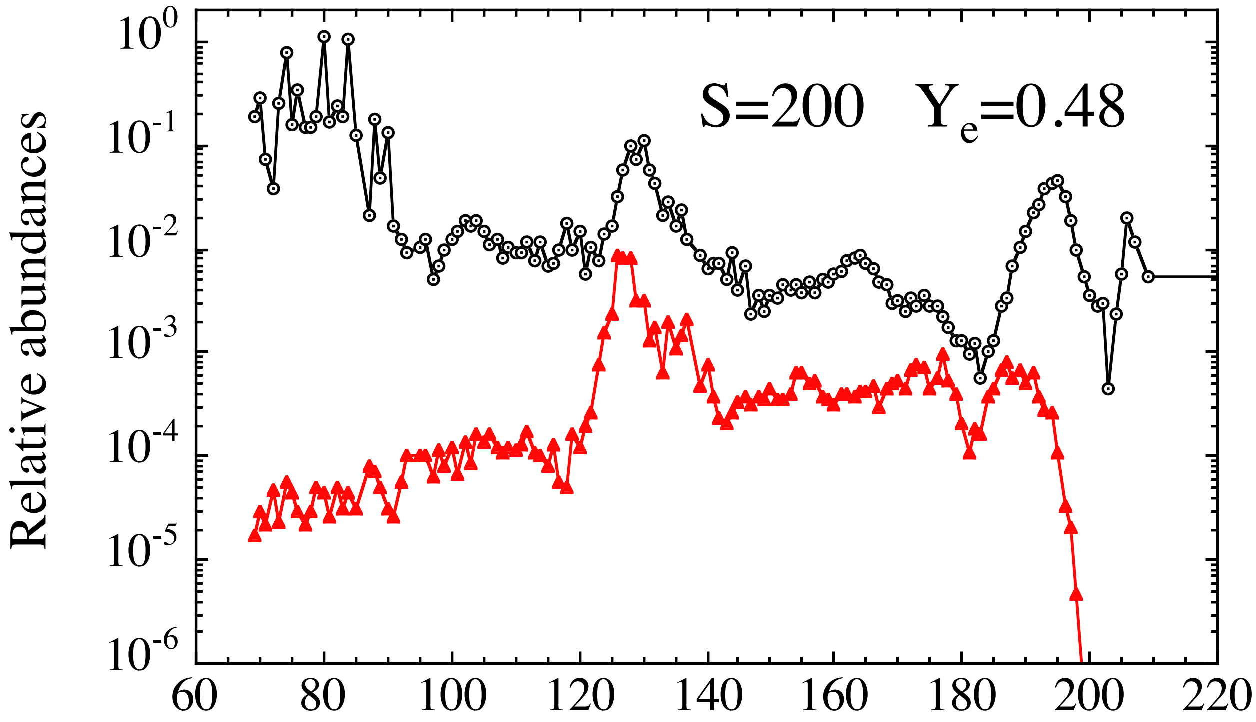
- all n- p-, α- captures and inverse rates for the initial α-process
- ν-nucleus (CC, NC) interactions (close to the proto-NS)
- radiative neutron capture & photodisintegration rates (cold versus hot ν-driven winds)
- β-decay rates
- fission probabilities (if any !?)



Sensitivity to nuclear masses and corresponding rates

Comparison for 3 differents mass models:

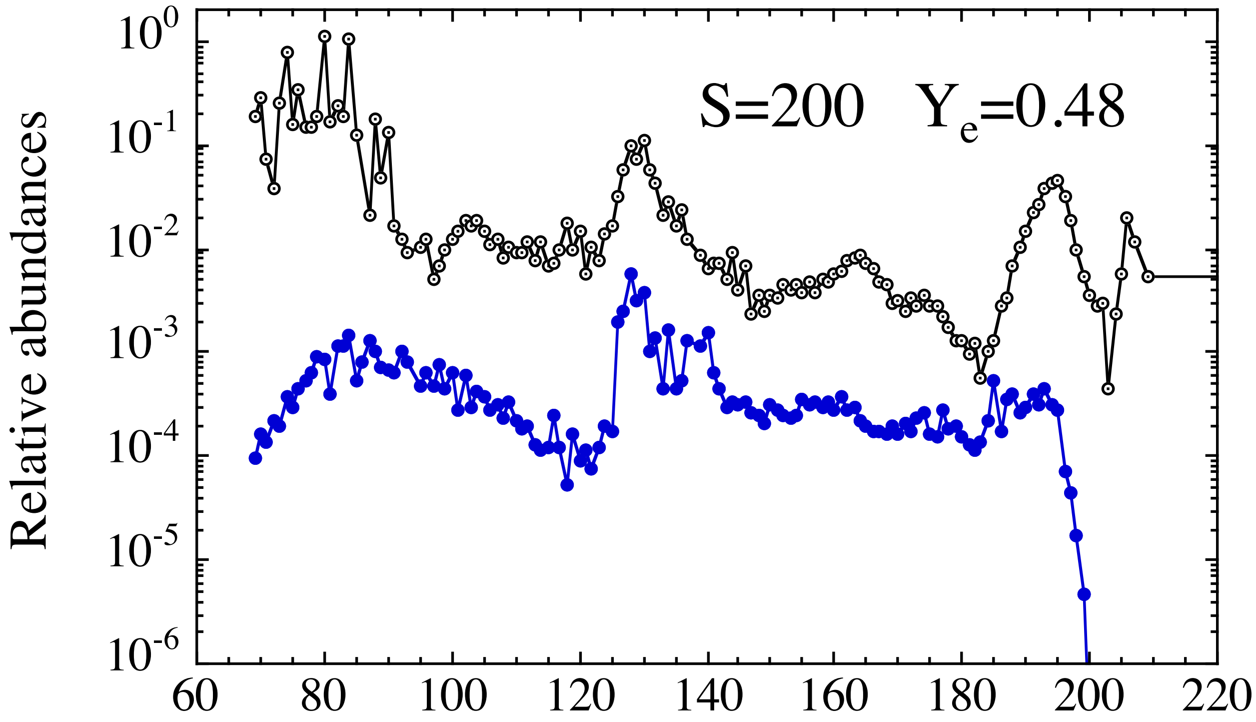
HFB-18: Skyrme HFB mass model σ(2149 nuclei)=585keV



Sensitivity to nuclear masses and corresponding rates

Comparison for 3 differents mass models:

HFB-D1M: Gogny HFB mass model σ(2149 nuclei)=798keV

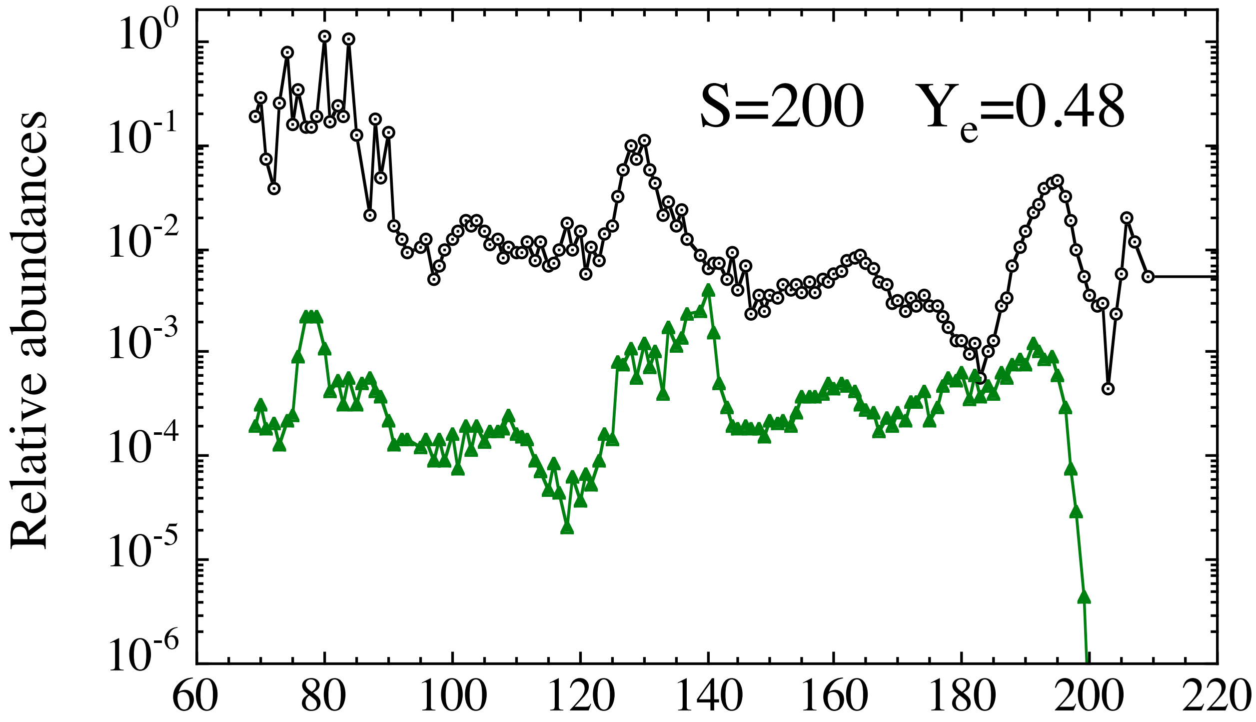


Sensitivity to nuclear masses and corresponding rates

Comparison for 3 differents mass models:

FRDM: mic-mac mass model

σ(2149 nuclei)=656keV



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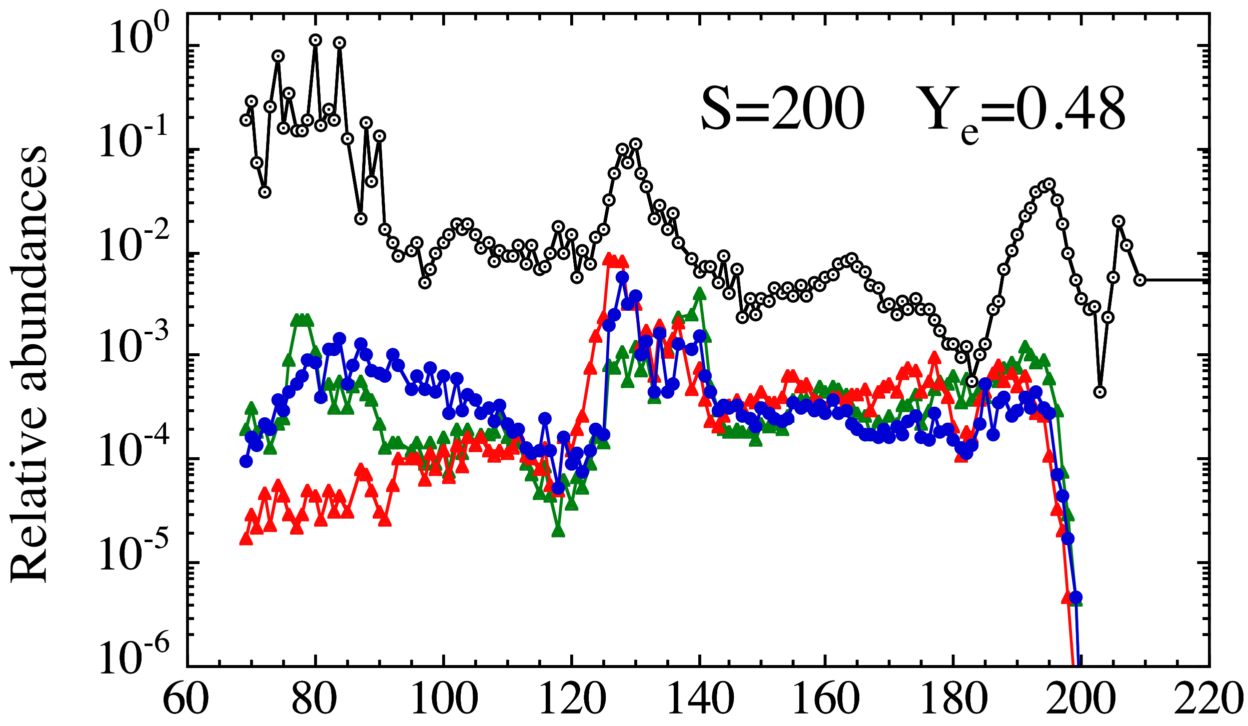
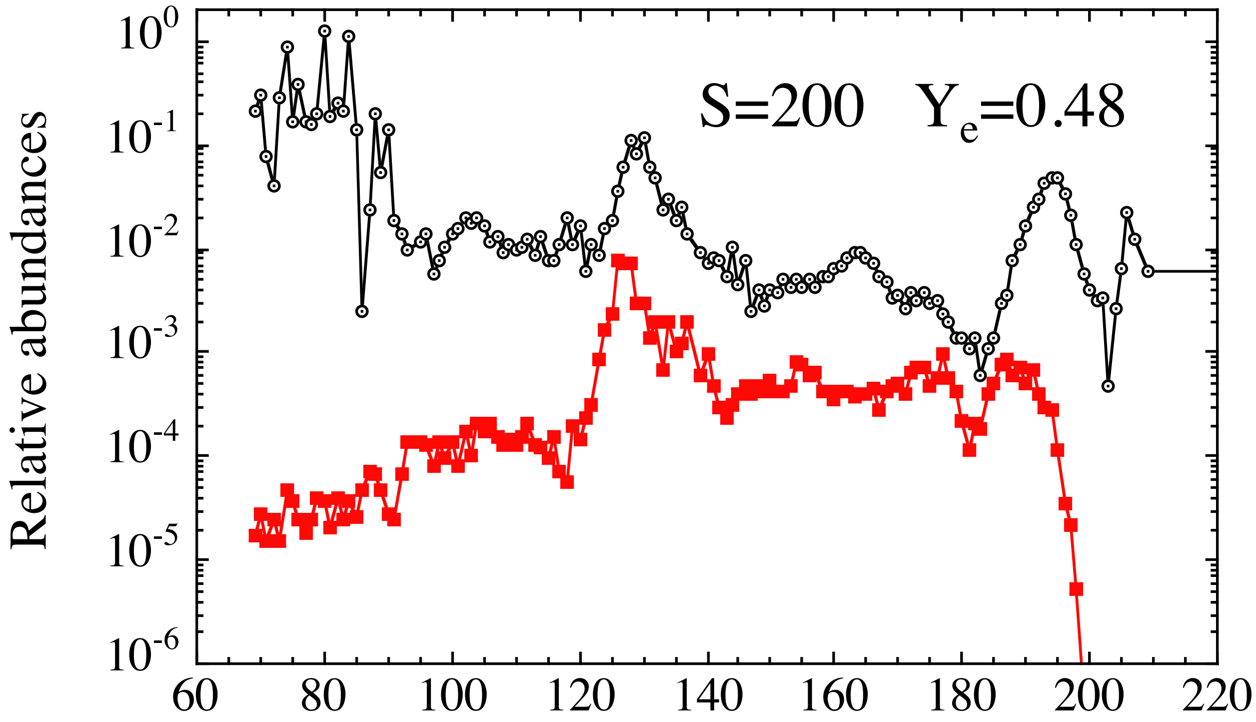


Sensitivity to β-decay rates

Comparison for 3 differents β-decay models:

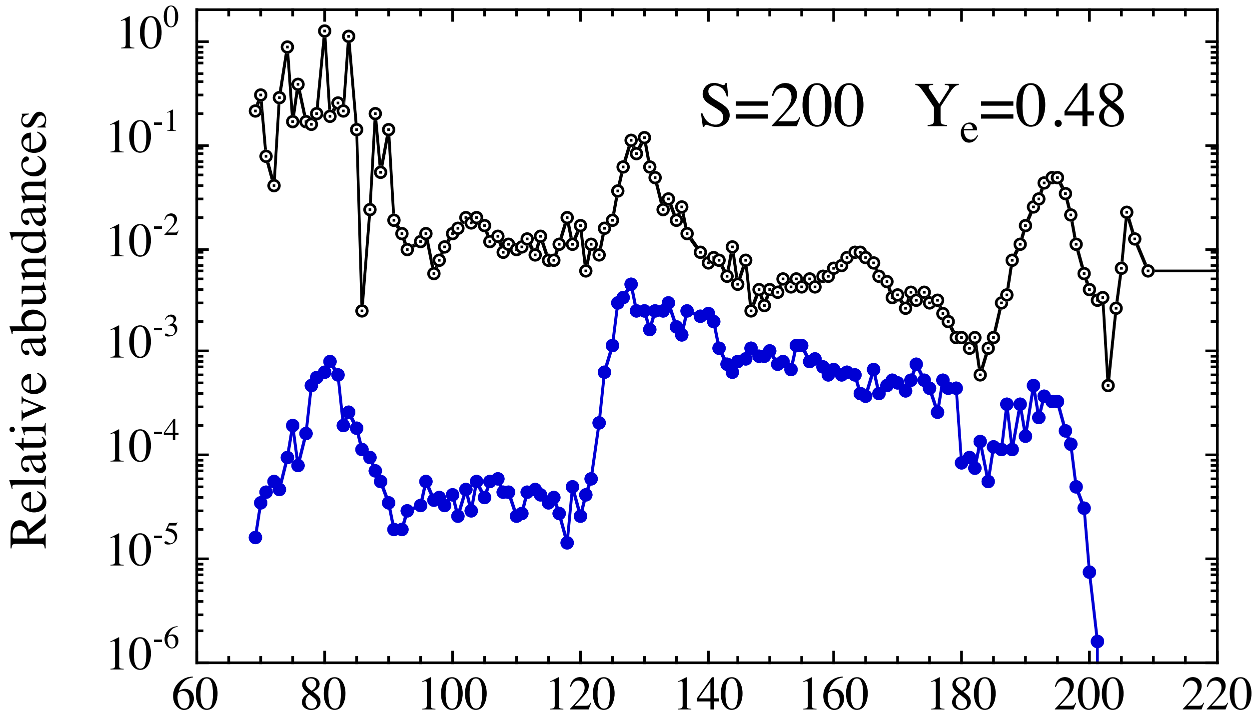
Gross Theory (GT2)



Sensitivity to β-decay rates

Comparison for 3 differents β-decay models:

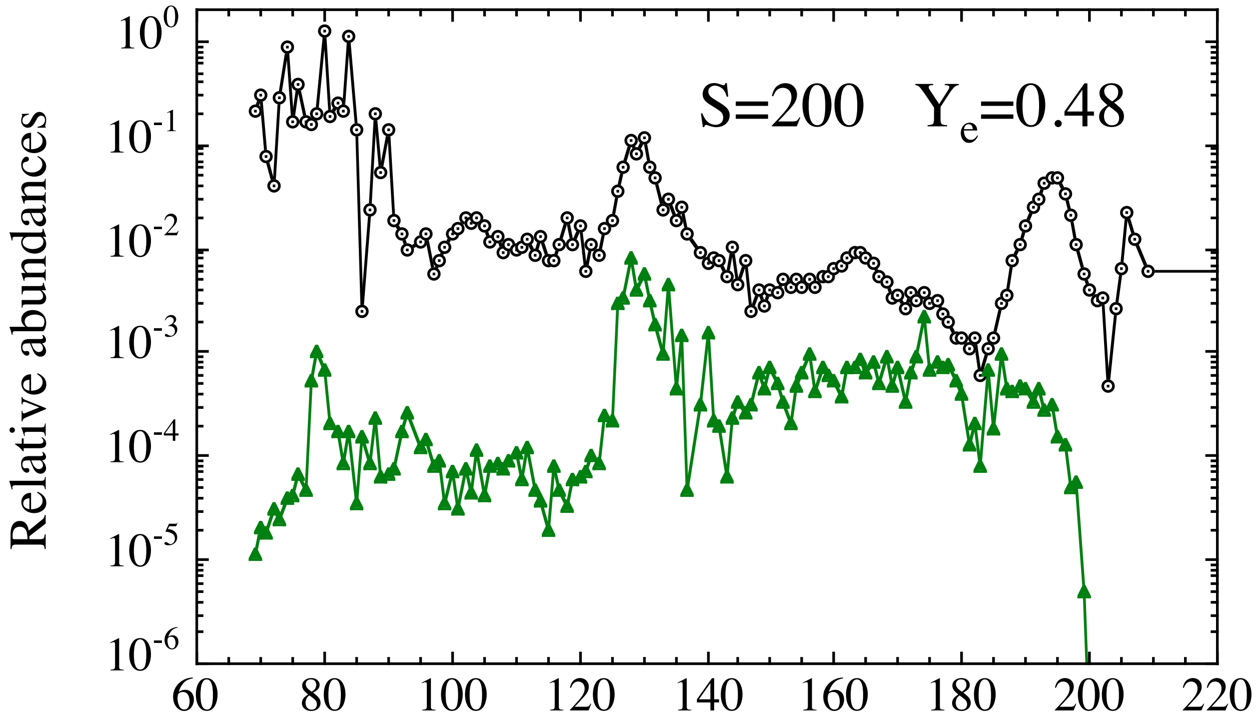
Klapdor et al. (TDA)



Sensitivity to β-decay rates

Comparison for 3 differents β-decay models:

FRDM+QRPA



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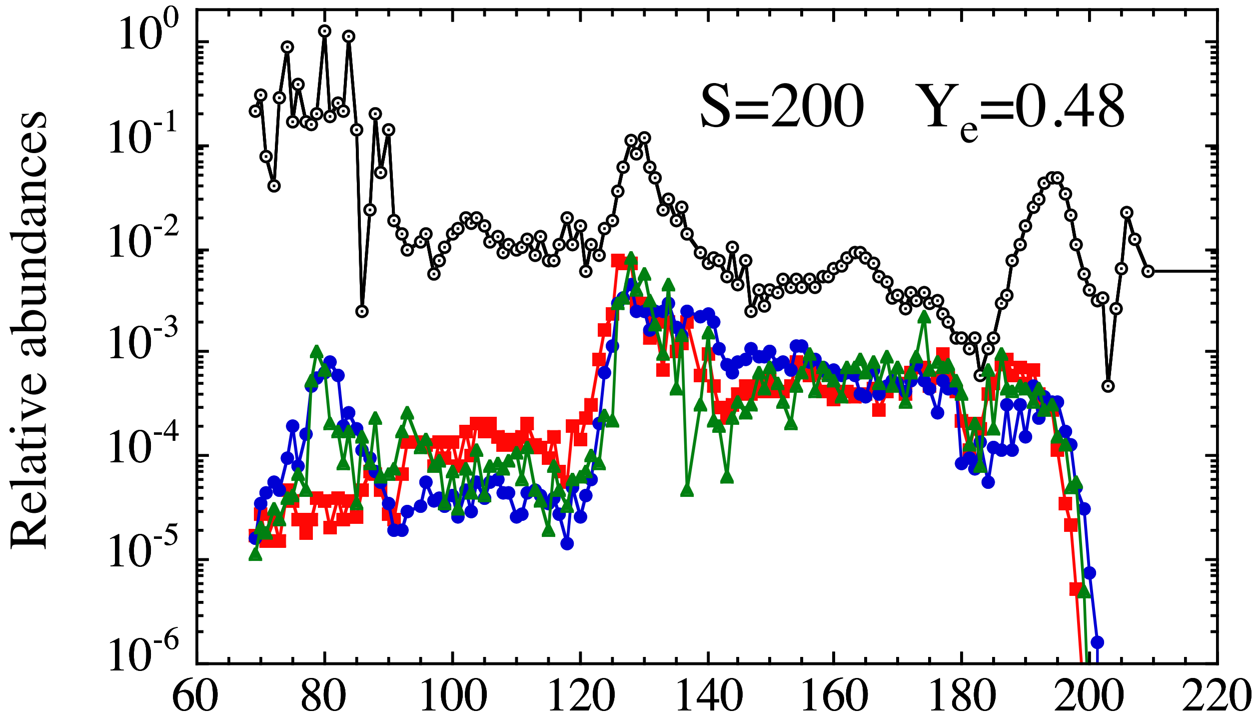
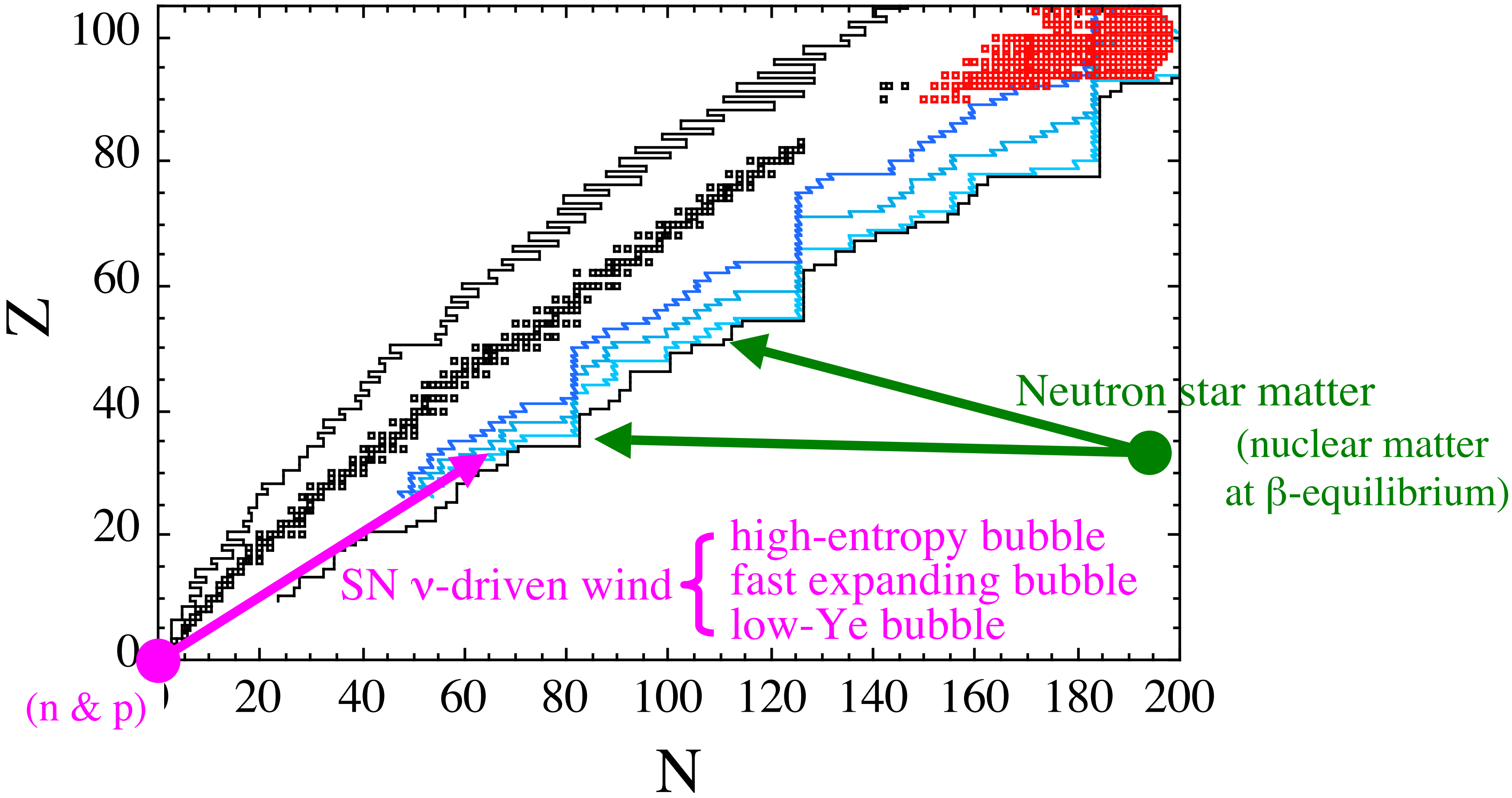


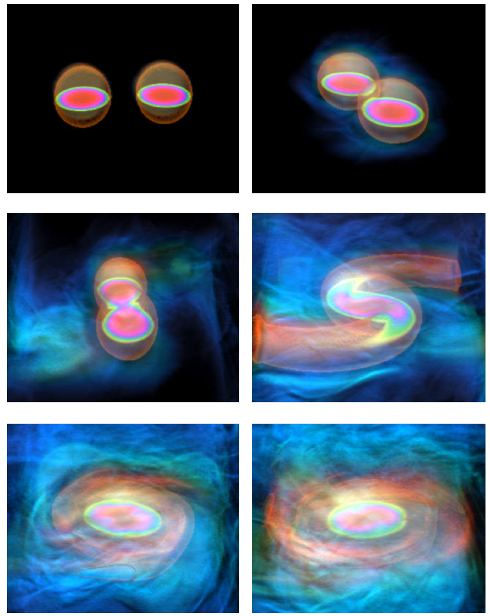
An alternative r-process scenario: the decompression of NS matter

(initial conditions: high-density matter)



Decompression of neutron star matter

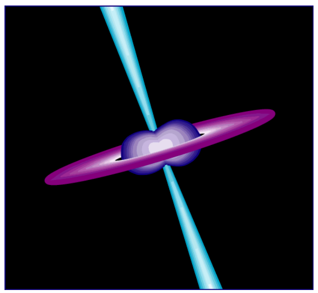
-Neutron star mergers (NS-NS or NS-BH)



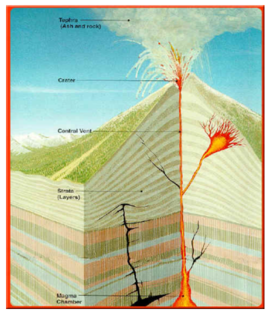
-Explosion of neutron stars below
minimum mass (e.g by mass transfer)

-Other speculative sites:

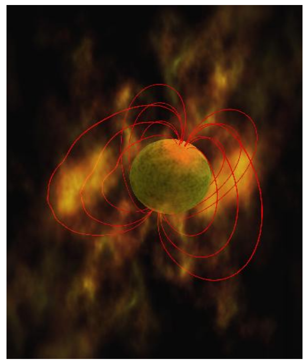
• Post-merger flows



• Volcano eruptions



• Magnetar outflows

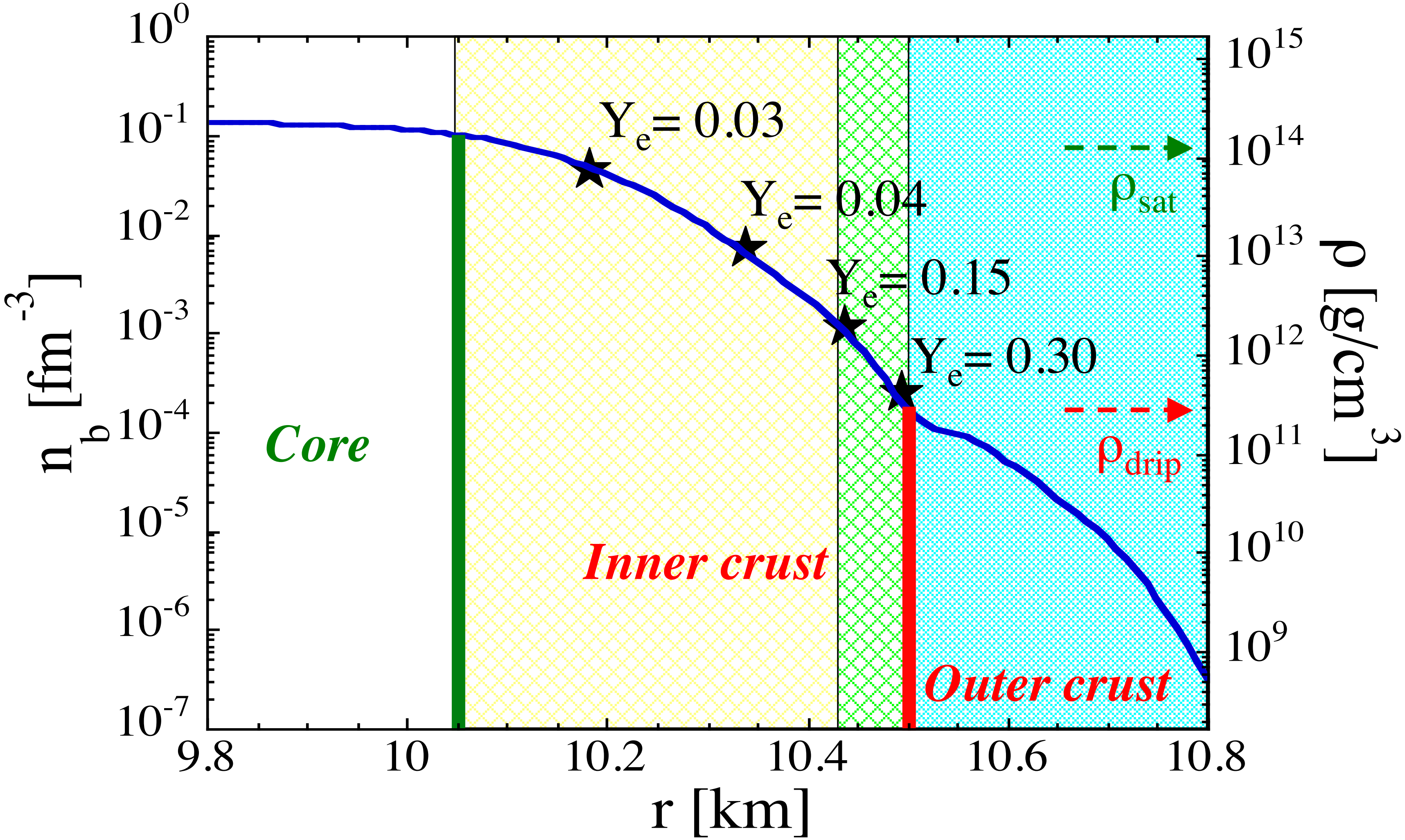


Decompression of the NS crust material

$\rho \leq 4.2\ 10^{11}$ g/cm^3 : Outer crust

$4.2\ 10^{11} \leq \rho \leq 10^{12}$ g/cm^3 : Reduced $Y_n/Y_{seed} < 100$

$10^{12} \leq \rho \leq 10^{14}$ g/cm^3 : Large $Y_n/Y_{seed} \sim 100 - 1000$



The NS outer crust at $T > 0$

Assuming the hot NS (β-equilibrated) outer crust cools down to a T_9~10

Establishment of a Nuclear Statistical Equilibrium at a given T & high ρ

- No time for β-equilibrium at $T<10^{10}$K: $Y_e=Y_e(T\sim10^{10}\text{K})$
- Coulomb effect of significant importance: must be included in the NSE equations at high ρ:

$$Q_{Z,A} = \Delta m_{Z,A} c^2 + \mu^C_{Z,A} - Z\mu^C_p$$

μ_C: Coulomb correction to the chemical potential

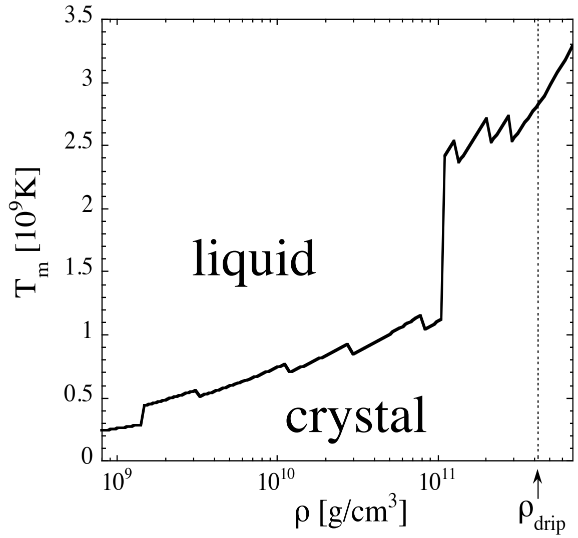
where $\mu^C_{Z,A} = k_B T \; f_C(\Gamma_{Z,A})$ function of the Coulomb-coupling constant Γ

(e.g Bravo & Garcia-Senz, 1999)

Coulomb liquid / crystal depending on the lattice melting temperature:

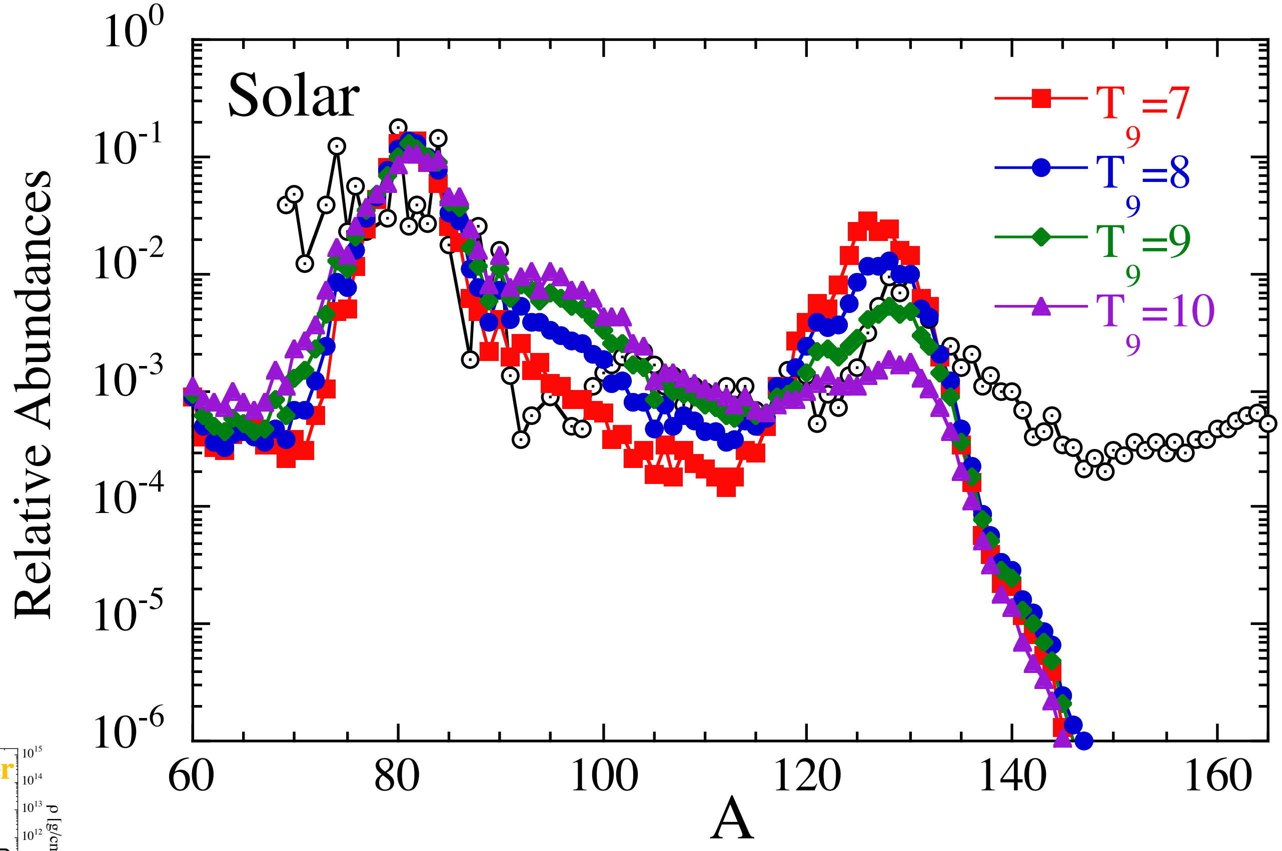
$$T_m = \frac{Z^2 e^2}{k_B r_{WS} \Gamma_m} \quad \Rightarrow \quad T_m \sim 0.15 Z^2 n_b [\text{fm}^3]^{1/3} 10^9 \text{K}$$

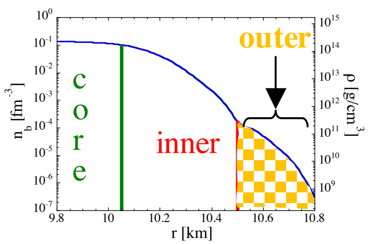
Solid-liquid phase transition for $\Gamma_m \sim 175.0 \pm 0.4$



Abundance distribution of the whole TOV-integrated outer crust cooling down from a β-equilibrium at T=10^{10}K and reaching NSE at a temperature T

Outer crust: $\rho \leq 4.2\ 10^{11}$ g/cm^3





Decompression of the outer crust initially at NSE at a temperature T

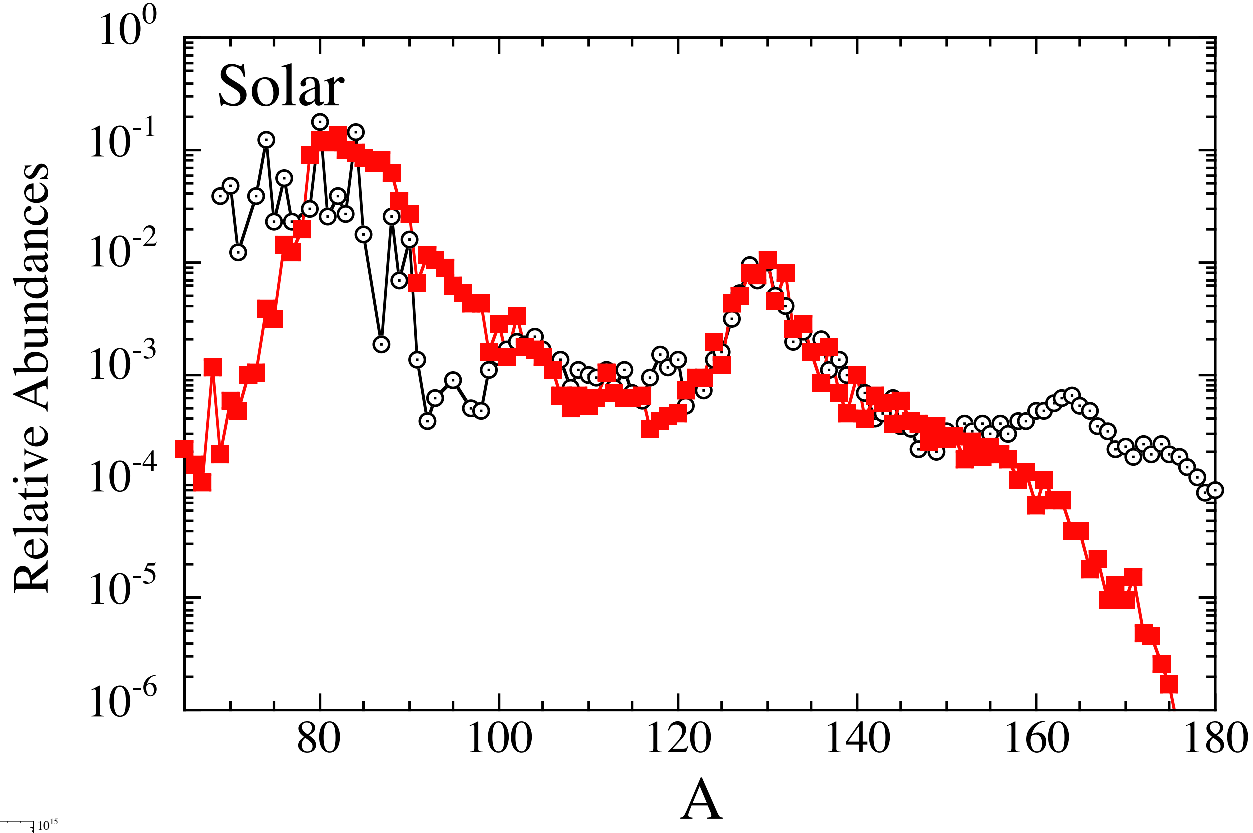
For $\rho << \rho_{drip}$, no free neutrons (except from β-delayed n-emission)

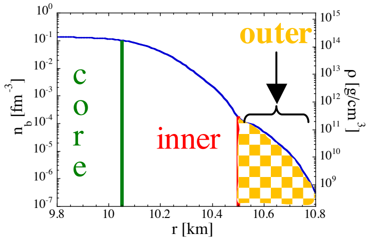
--> essentially similar distribution (smoothing)

For $\rho \sim \rho_{drip}$, free neutrons from heating … up to about ~ 10 n/seed

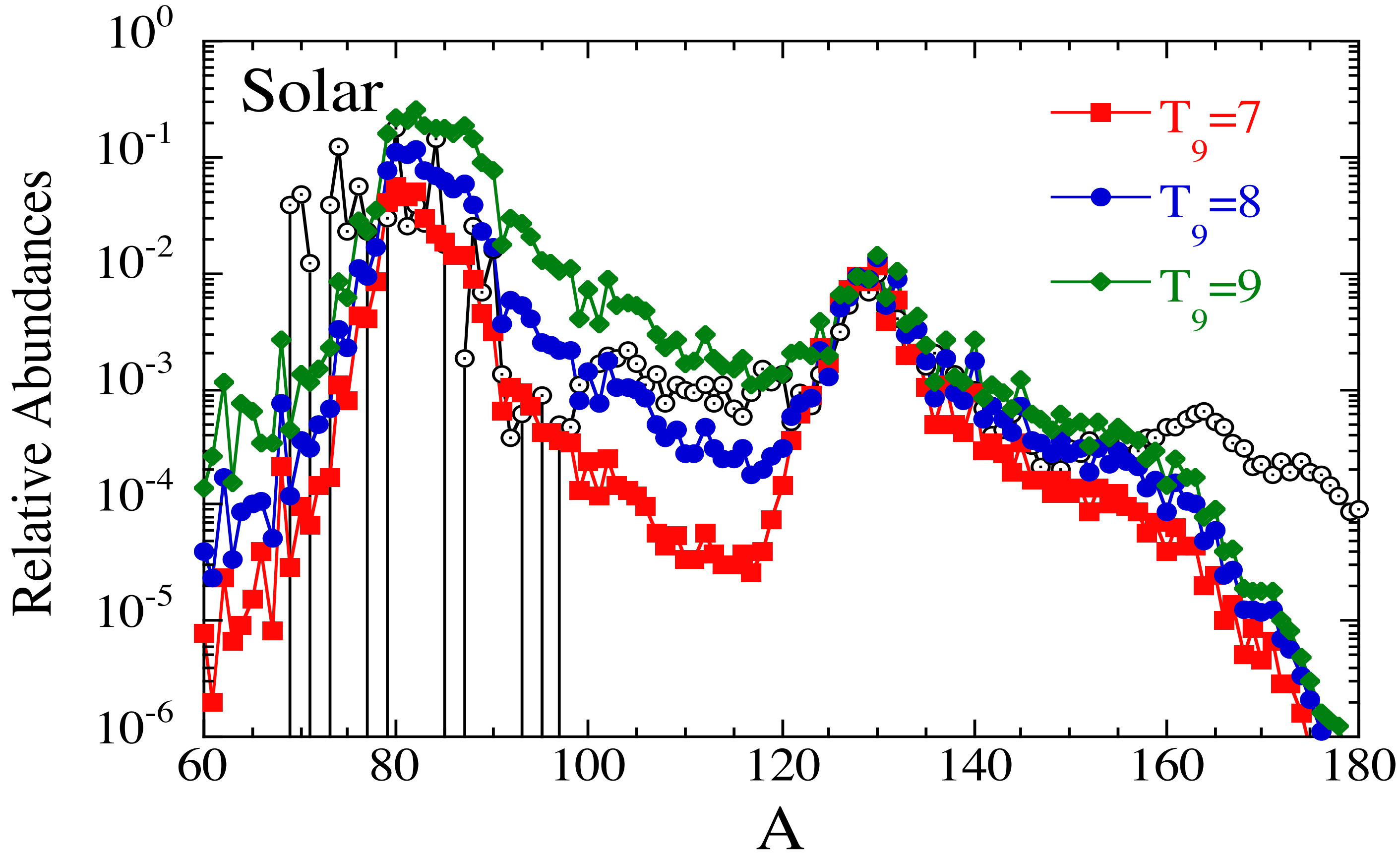
--> modification of the *A*-distribution

Final abundance distribution after decompression of the whole TOV-integrated outer crust initially at NSE at T=8.5 10^9K





Final abundance distribution sensitive to initial NSE temperature

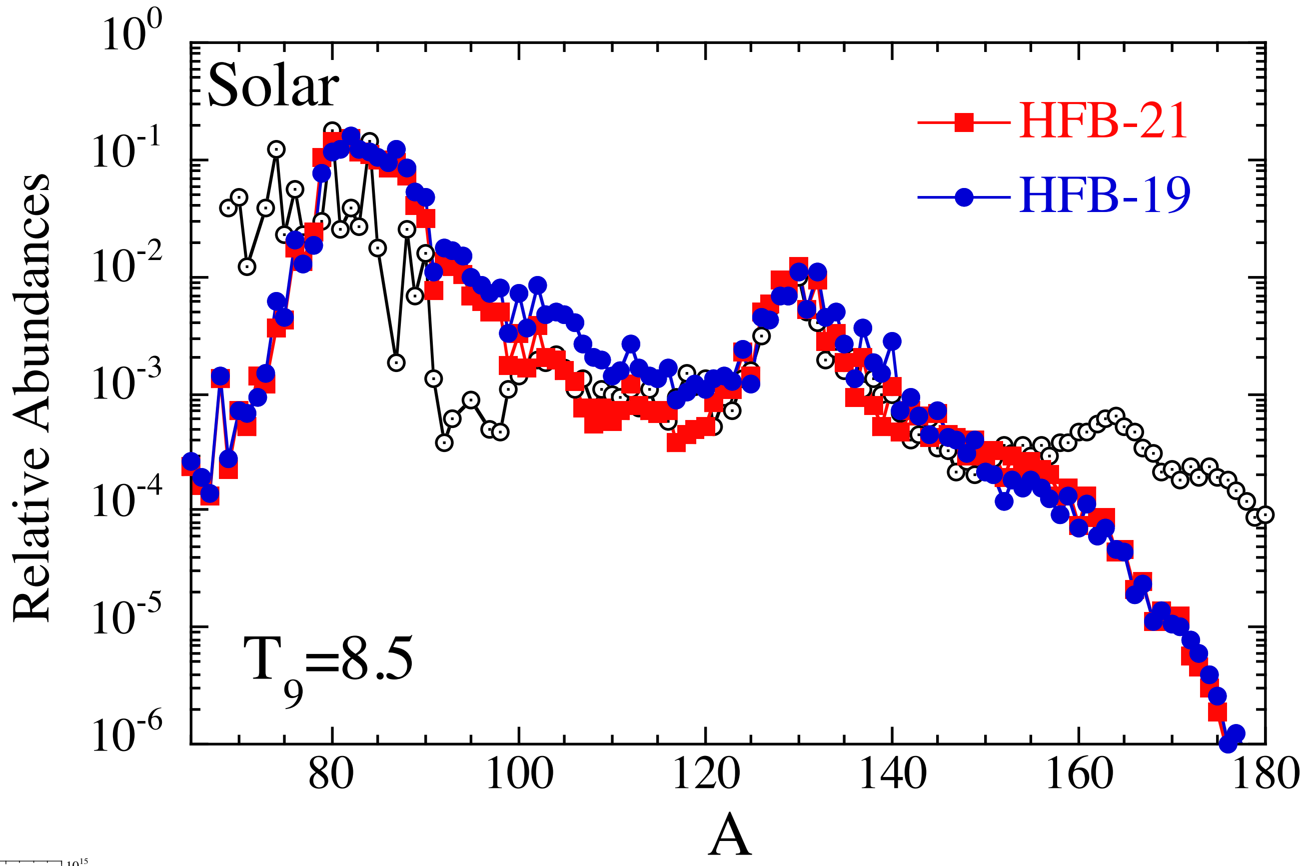


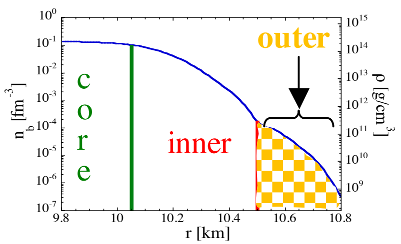
But NSE most likely to be achieved around T_9=8-9: $\tau_{NSE} \sim$ 1-20 ms at T_9=8

$\tau_{NSE} <$ 0.2 ms at T_9=9

Sensitivity to nuclear mass models

AME (2010) + theoretical masses for unknown nuclei





NSE --> essentially sensitive to masses !

Sensitivity to nuclear mass models

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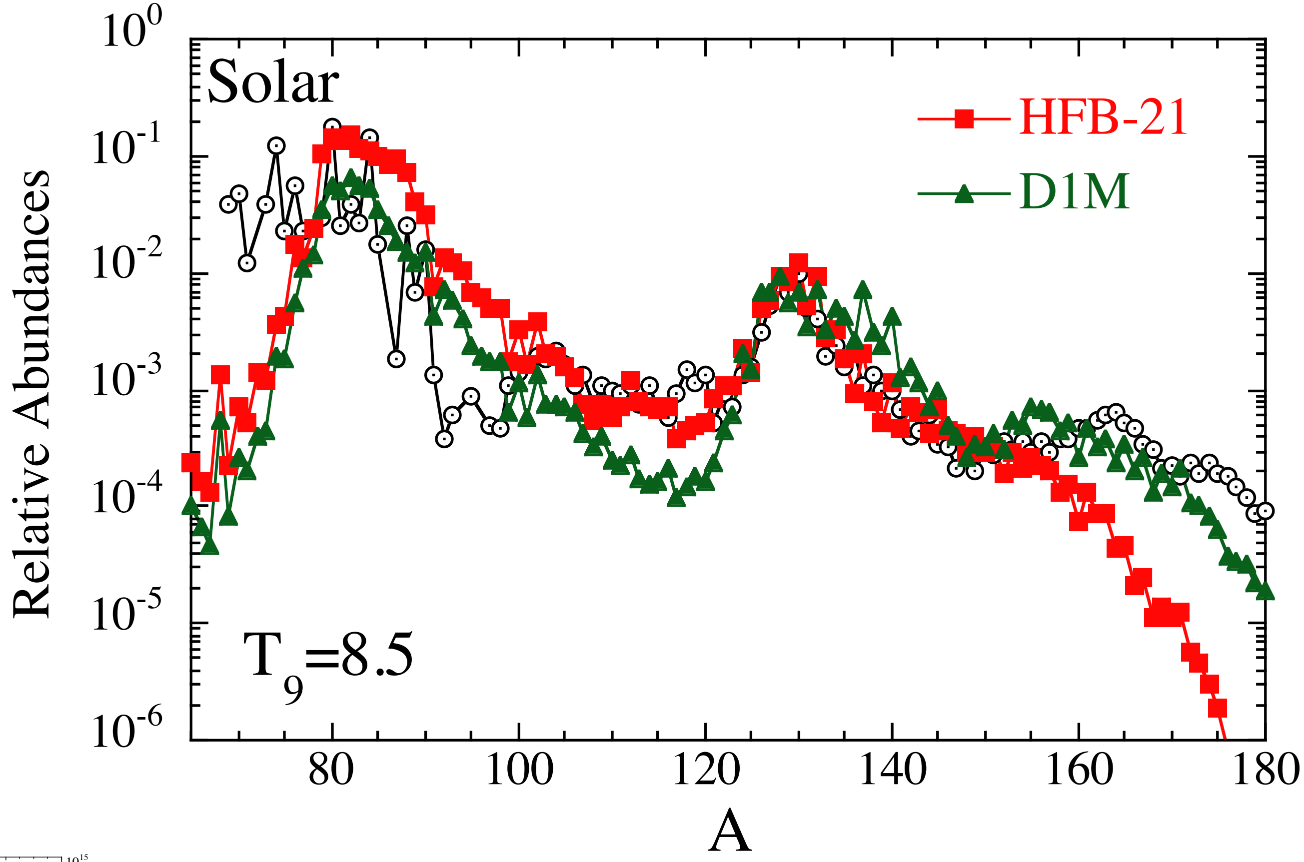

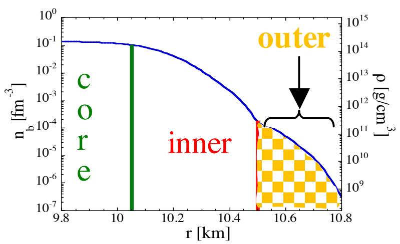

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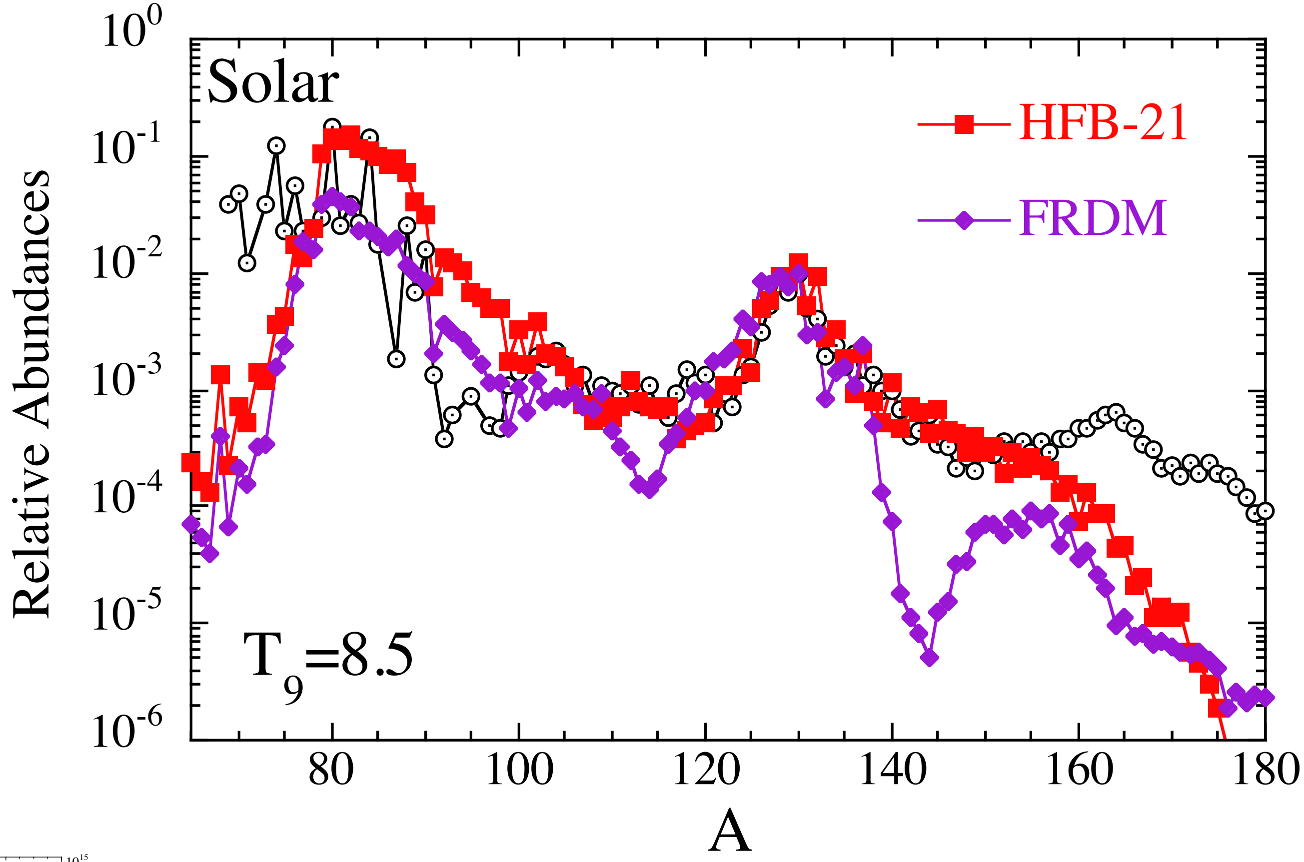
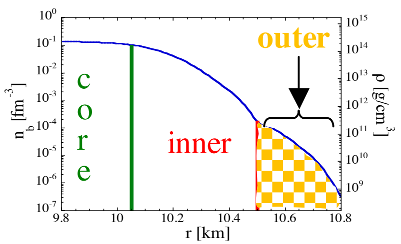
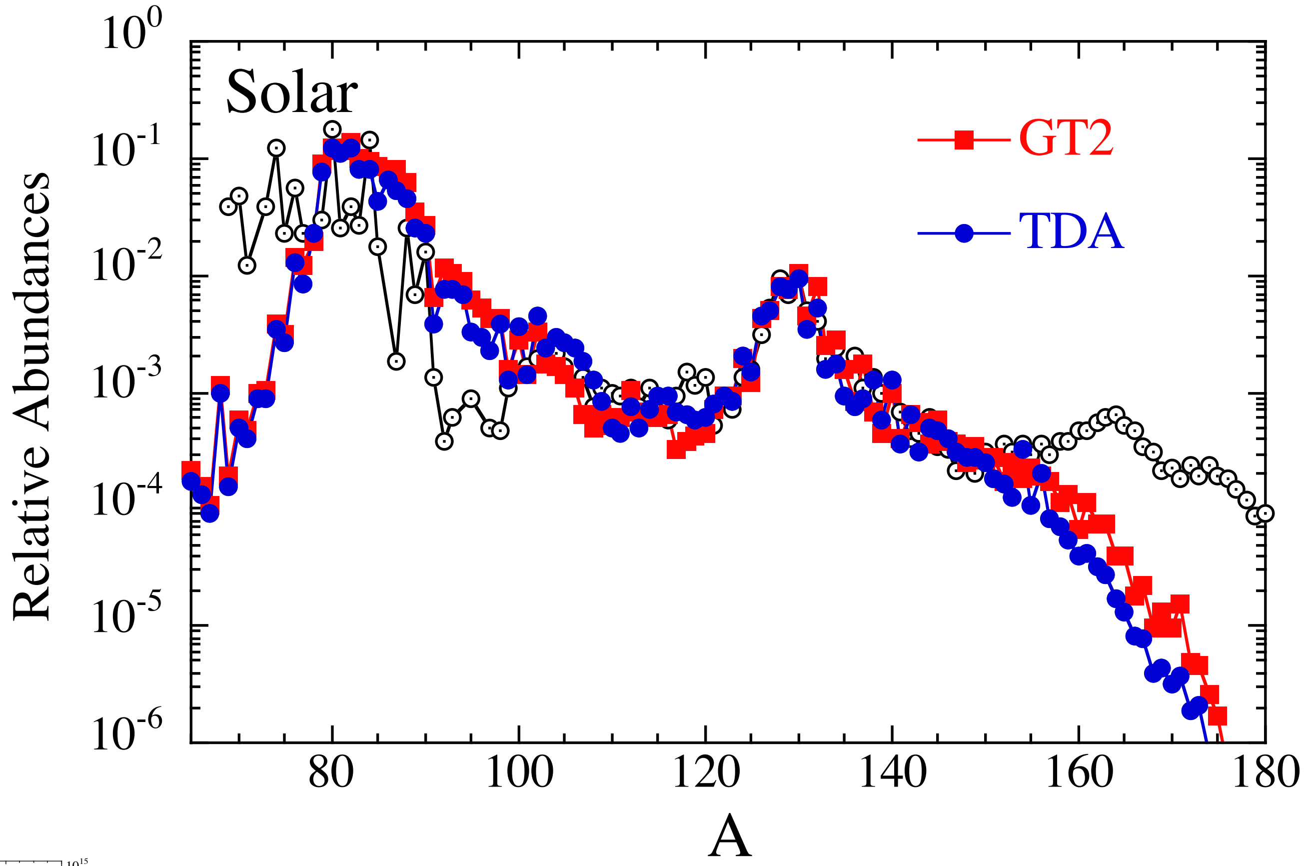
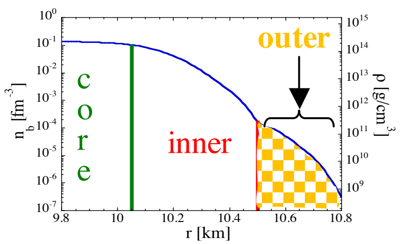




Sensitivity to β-decay rates

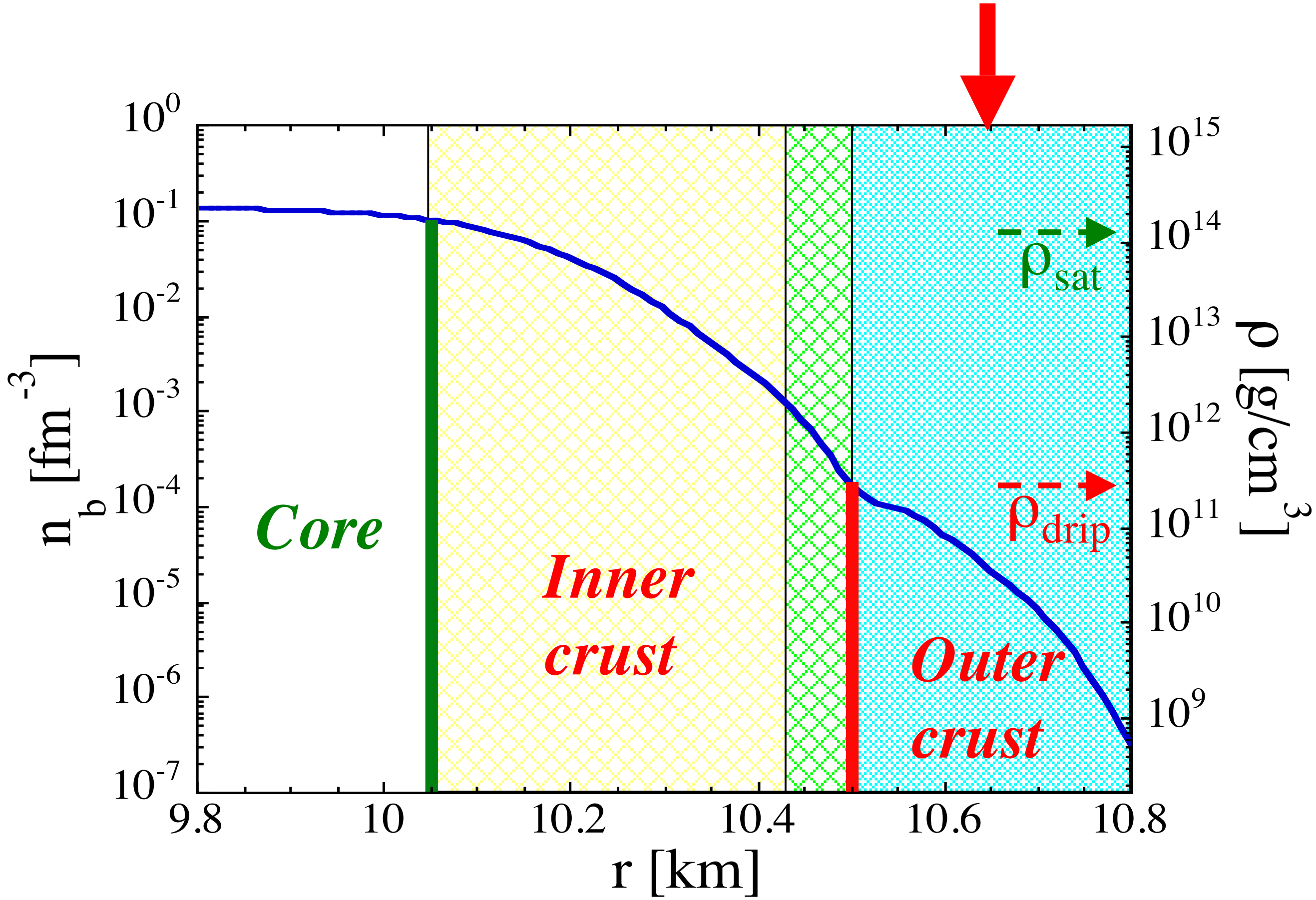




BUT the outer crust ~ 5 $10^{-5}M_o$ --> contribution to Galactic enrichment ??

→ **very unlikely to contribute to NS merger ejecta even if the whole outer crust would be ejected: M_{ej}(Merger)>$10^{-3}M_o$**

→ **Other mechanisms of NS mass ejection, e.g magnetars ??**

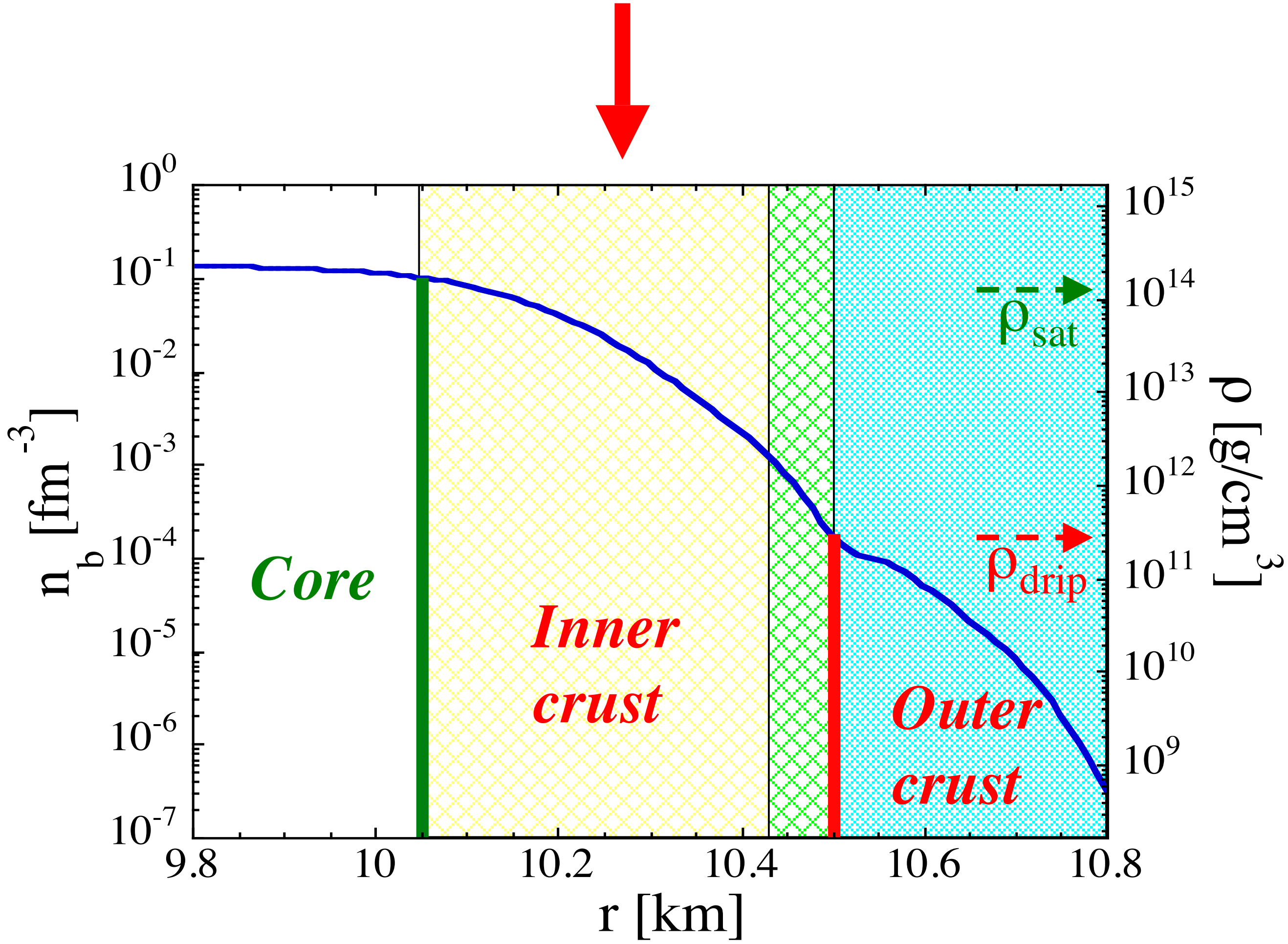


What about the composition of the ejected inner crust material ??

$M \sim 3\ 10^{-3}\ M_o$

(for a 1.35 –1.35 M_o NS merger)

The deeper in the inner crust, the more free neutrons, the larger Y_n/Y_{seed} for r-process



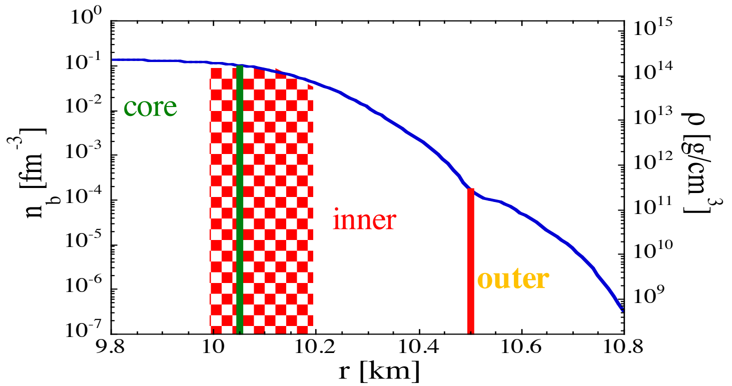
Decompression of the ejected particles from NS merger (~ 3 $10^{-3} M_o$)

(hydro models from Bauswein & Janka)

Initial densities within a factor 5 around the saturation density:

minimun $\rho = 6.7\ 10^{13}$ g/cm^3

maximun $\rho = 1.9\ 10^{14}$ g/cm^3



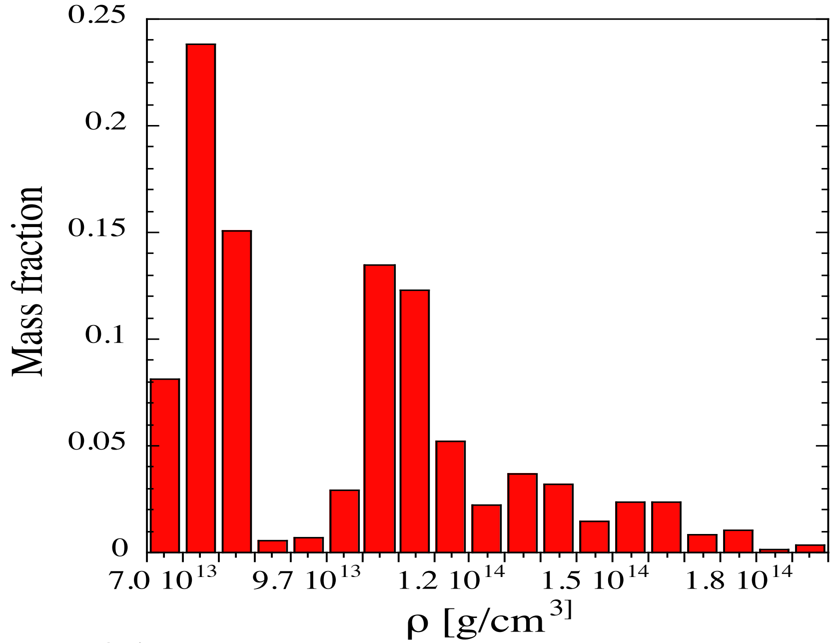
essentially the deep inner crust (outer crust not resolved)

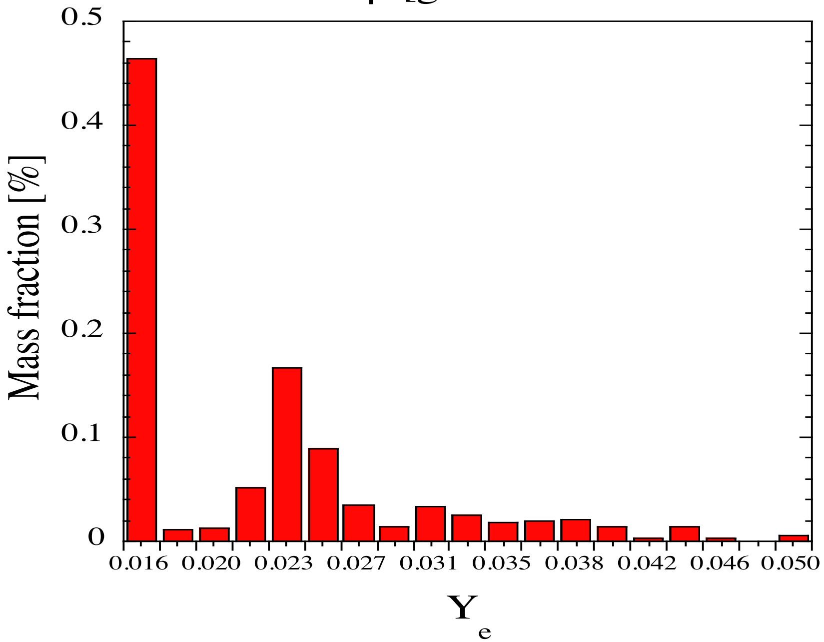
Distribution of initial Y_e:

minimum Y_e = 0.015

maximum Y_e = 0.051

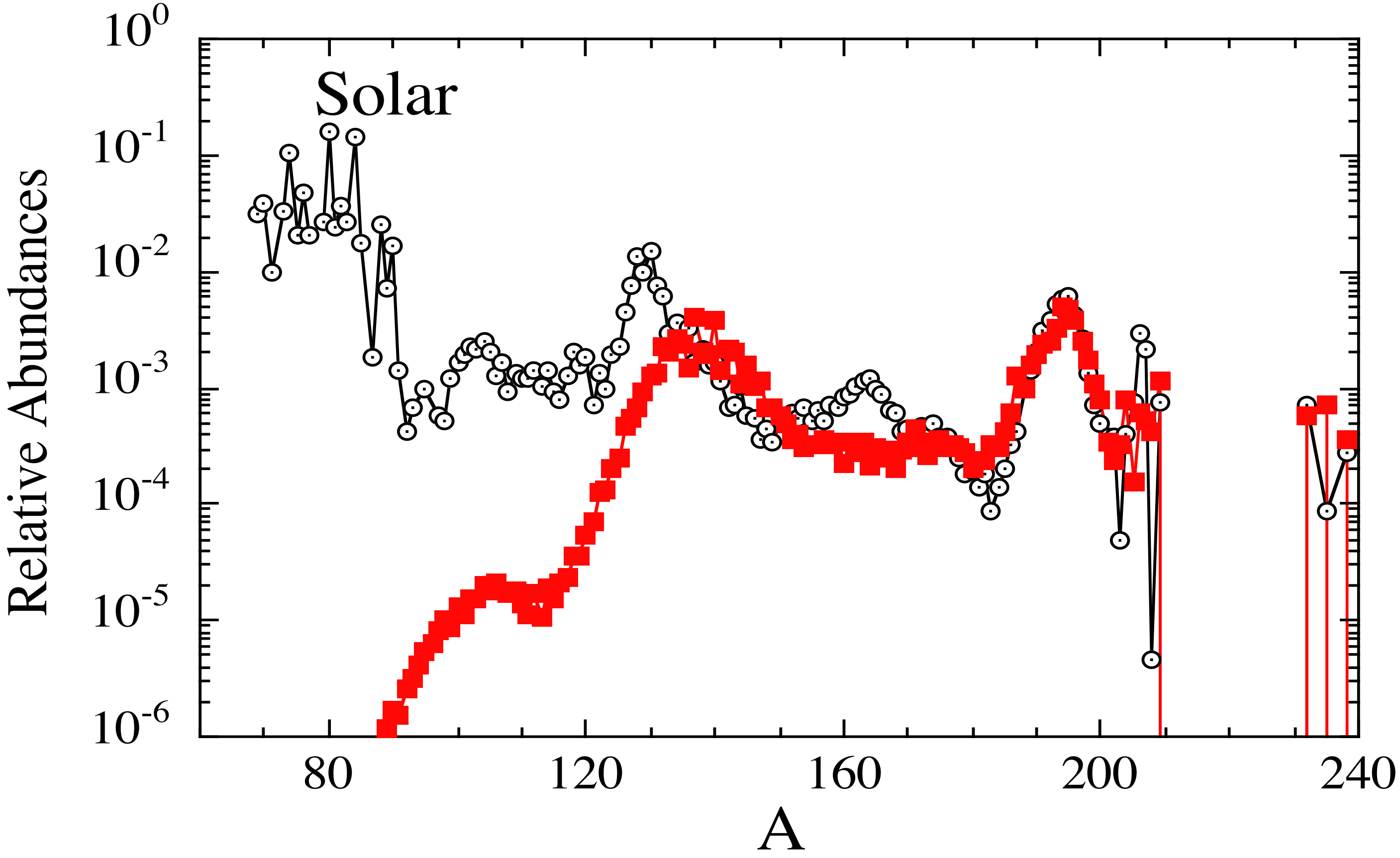
--> Y_n/Y_{seed} ~ 1000



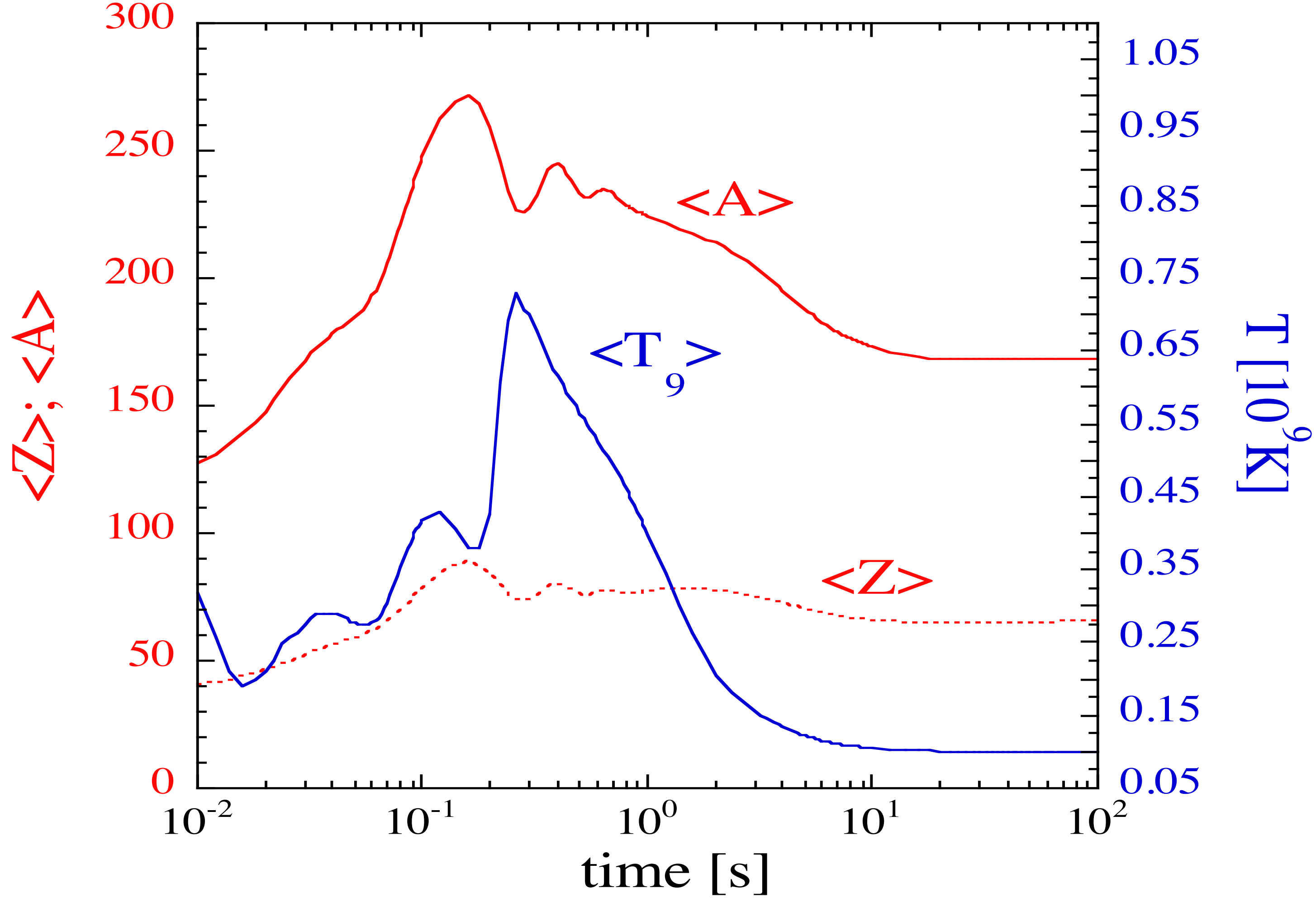


Final ejected r-abundance distribution

~1000 trajectories

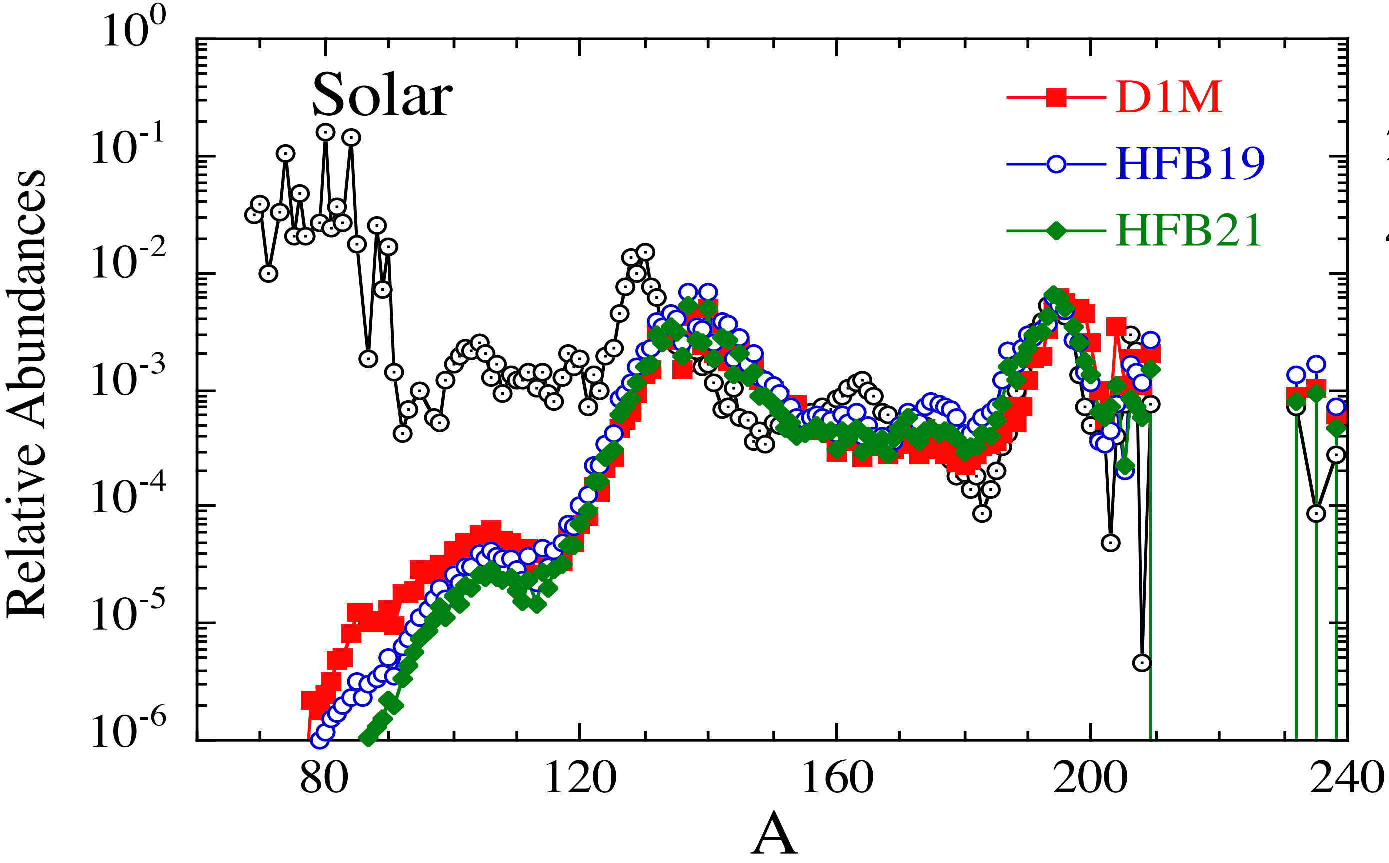


Average species and temperature



Sensitivity to the masses and corresponding reaction rates

- HFB-19 & HFB-21: Skyrme HFB mass tables (S.G. et al 2010)
- D1M: Gogny HFB mass tables (S.G et al 2009)

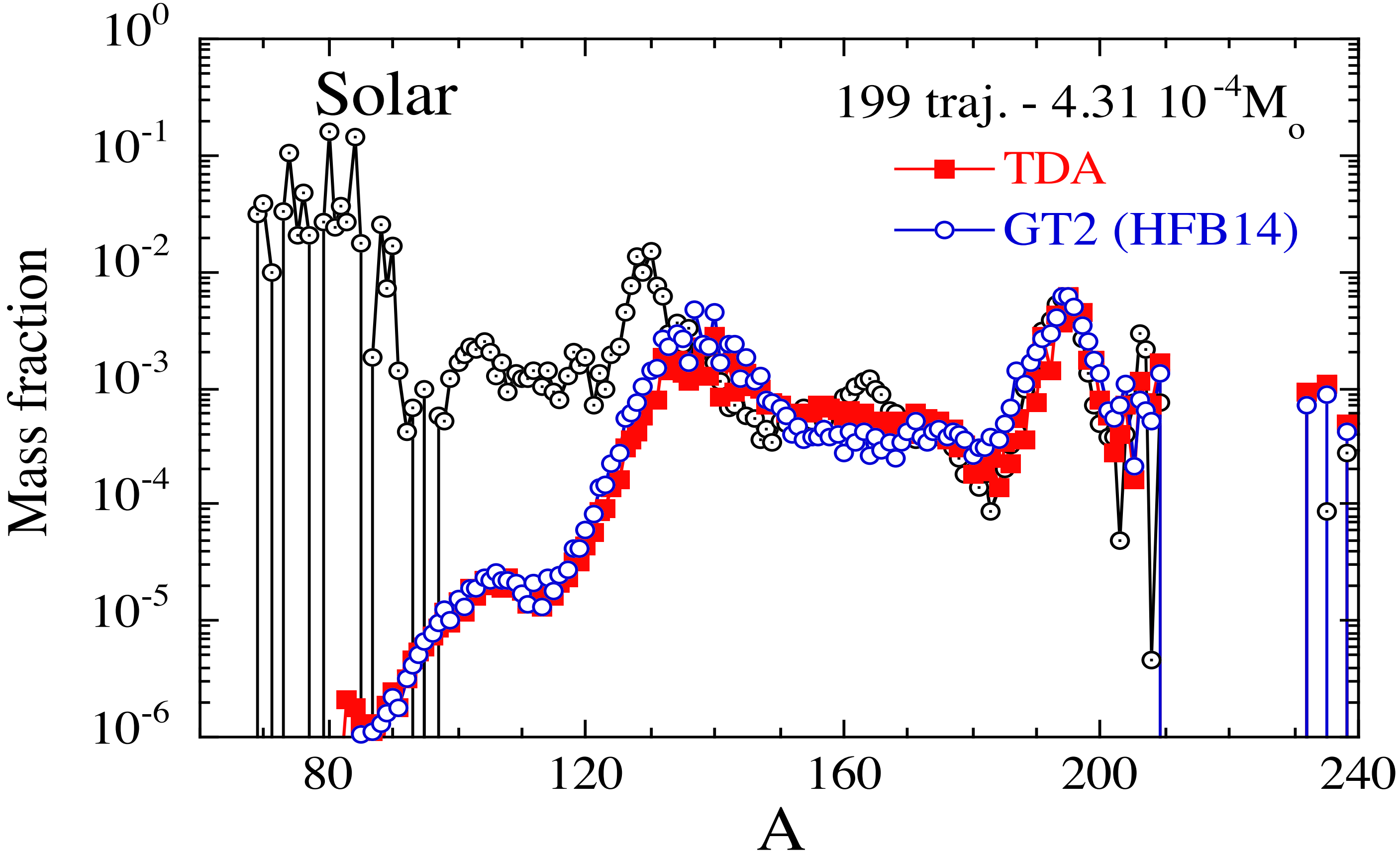


200 trajectories

4.3 $10^{-4}M_o$

Sensitivity to the β-decay rate

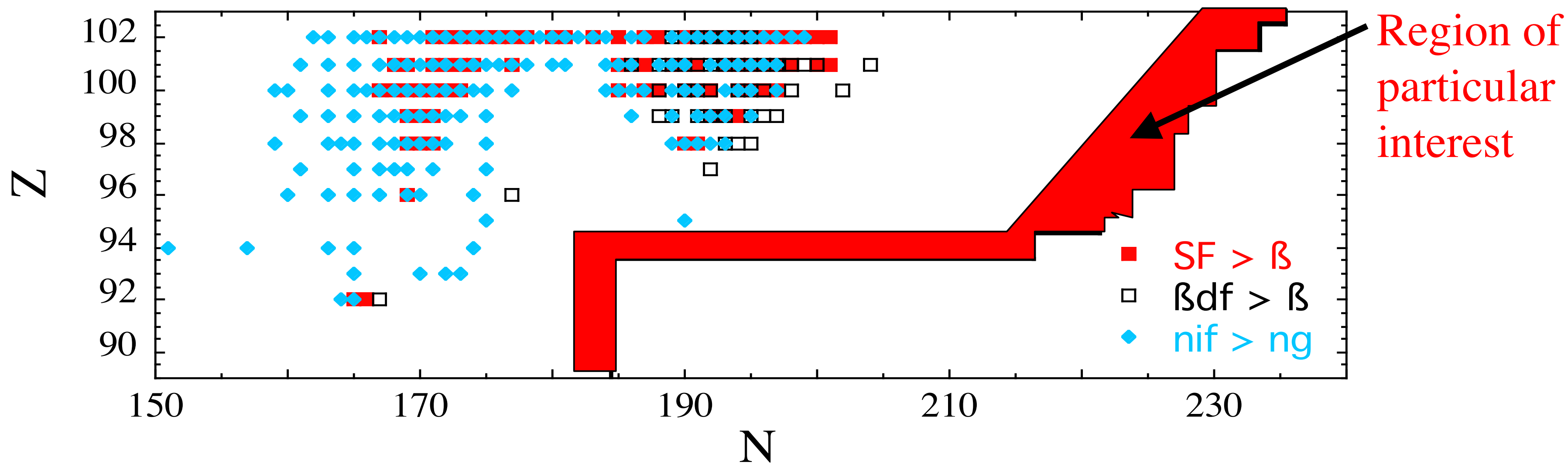
- Tamm-Dancoff Approximation (Klapdor et al. 1984)
- Gross Theory Version 2 (Tachibana et al. 1990) with HFB14 Q_β



Sensitivity to the fission scheme

Need for detailed fission probabilities (sf, nif, βdf):

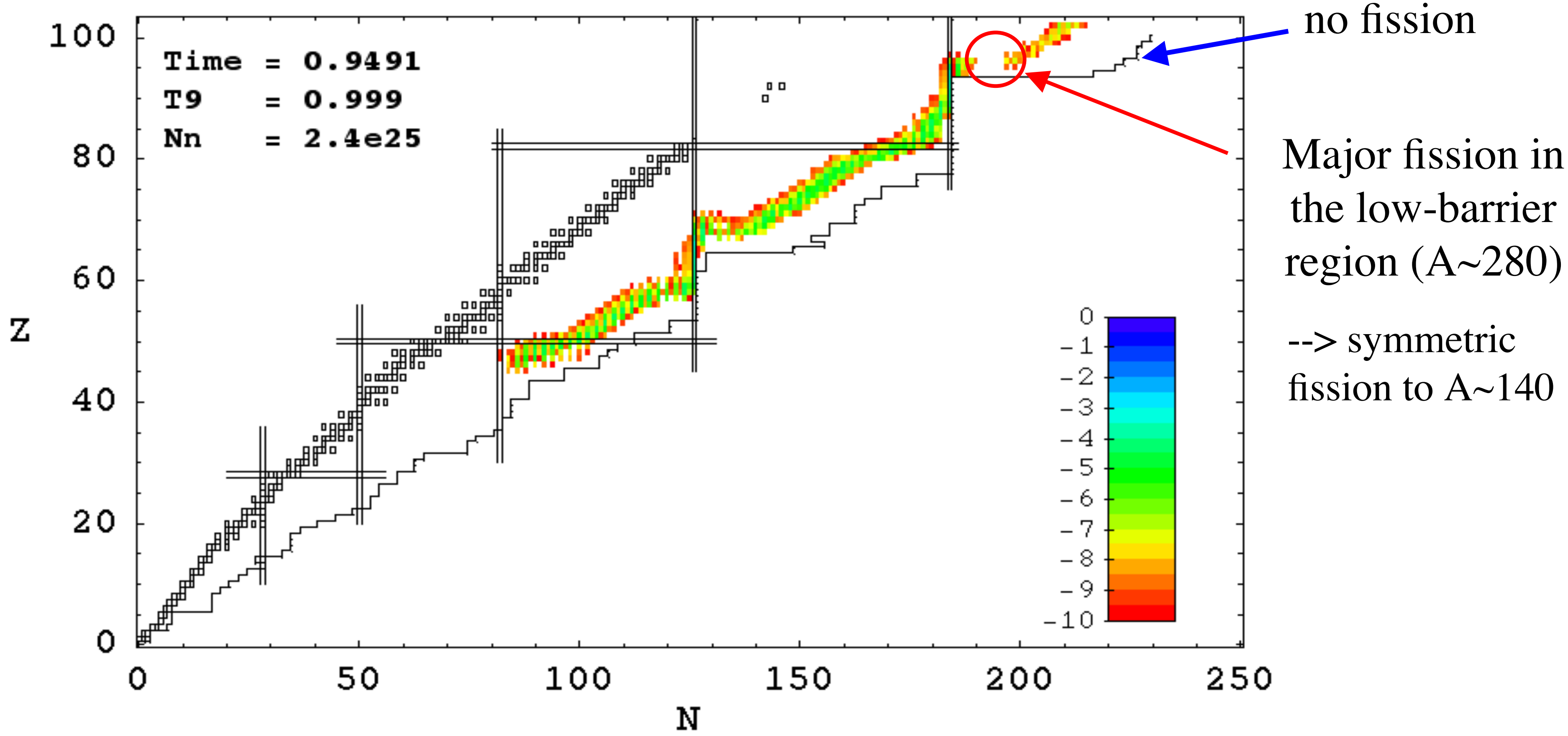
- sf: HFB-14 fission path and barrier penetration (updated TALYS T_f)
- nif: HFB-14 fission path and NLD included in TALYS
- βdf: HFB-14 fission path and GT β-strength function (updated TALYS T_f)



Need for fission fragment distribution:

- HFB-14 mass asymmetry
- Z- and A-distribution function ?

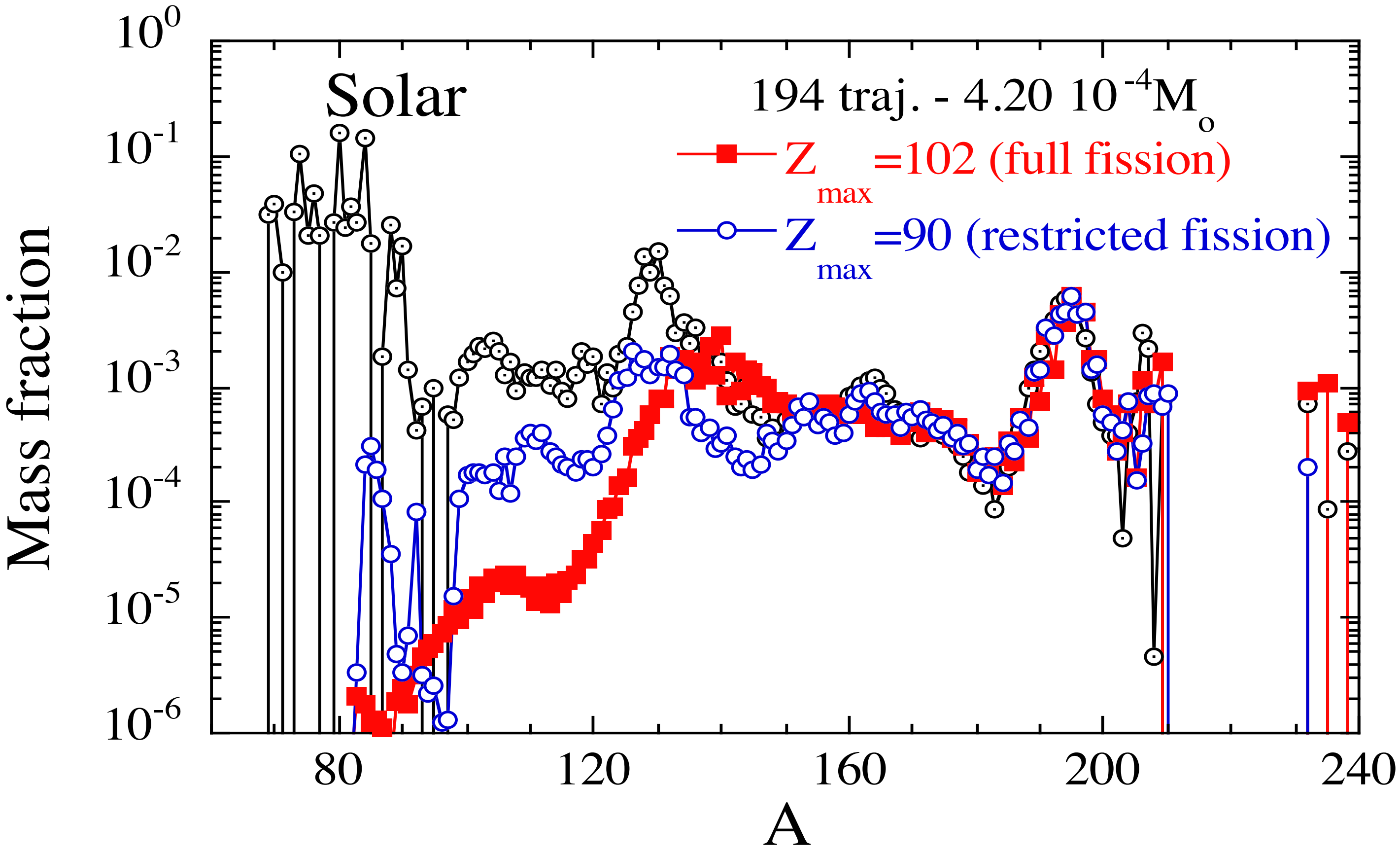
Sensitivity to the fission scheme



Fission plays a significant role in the decompression of the inner crust:

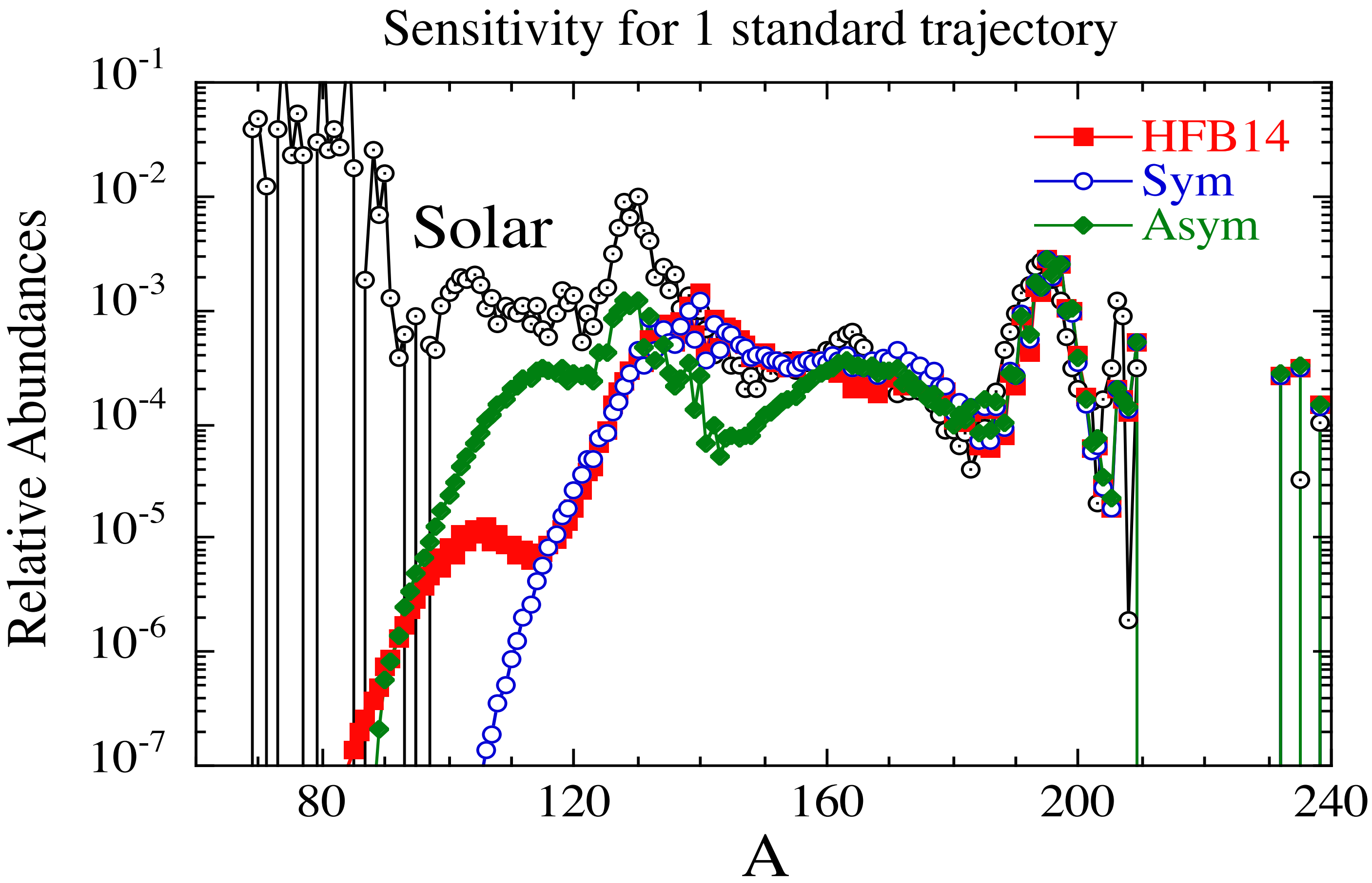
- where does the r-process stop (fission properties at the drip line) ?
- what is the dominant fission mode ?
- what is the impact of the recycling on the light (120≤A≤160) element production ?

- Restricted scheme: Z_{max}=90, essentially asymmetric spontaneous fission
- Full fission scheme: Z_{max}=102 with sf, βdf and nif coherently treated



Sensitivity to fission fragment distribution

- Fission with HFB14 mass asymmetry at saddle point
- Fission with symmetric or asymmetric distributions



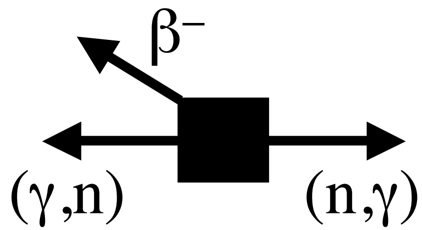
Nuclear needs for r-process nucleosynthesis

"hot" ν-driven wind	(n,γ)–(γ,n) equilibrium	β-decays and "masses" + *ν*-nucleus interaction + (n,γ) rates (?) + Fission (nif, sf, βdf) rates (?)
Inner crust of NS & "cold" ν-driven wind	(n,γ) <-> β competition & Fission recycling	β-decay & (n,γ) rates + Fission (nif, sf, βdf) rates + Fission Product distribution + EoS of asymmetric NM
Outer crust of NS	nuclear and β-equil. at non-zero T	Masses, EoS, Coulomb correction β-decay & EC rates

Nuclear Physics associated with the r-process

(Still large uncertainties in astrophysics modelling, hence nuclear needs !)

Competition between



- radiative neutron capture (n,γ)
- photo-neutron emission (γ,n)
- β-decay
- fission (n-induced, β-delayed, spont.) for the heaviest species
- ν-nucleus interaction properties (?)

FOR POTENTIALLY ALL NUCLEI (~ 5000) FROM THE VALLEY OF STABILITY TO THE NEUTRON DRIP LINE

(not only for the so-called "waiting points")

We know these quantities will enter the problem but as long as the r-process site will remain unknown, we cannot judge
- *quantitatively* about the *importance* of a given ingredient, hence
- even less about the *quality* of the nuclear input (from astro simulations)

Challenge in theoretical nuclear physics
(essential for r-process applications)

PHENOMENOLOGICAL DESCRIPTION

↓

UNIVERSAL GLOBAL MICROSCOPIC DESCRIPTION

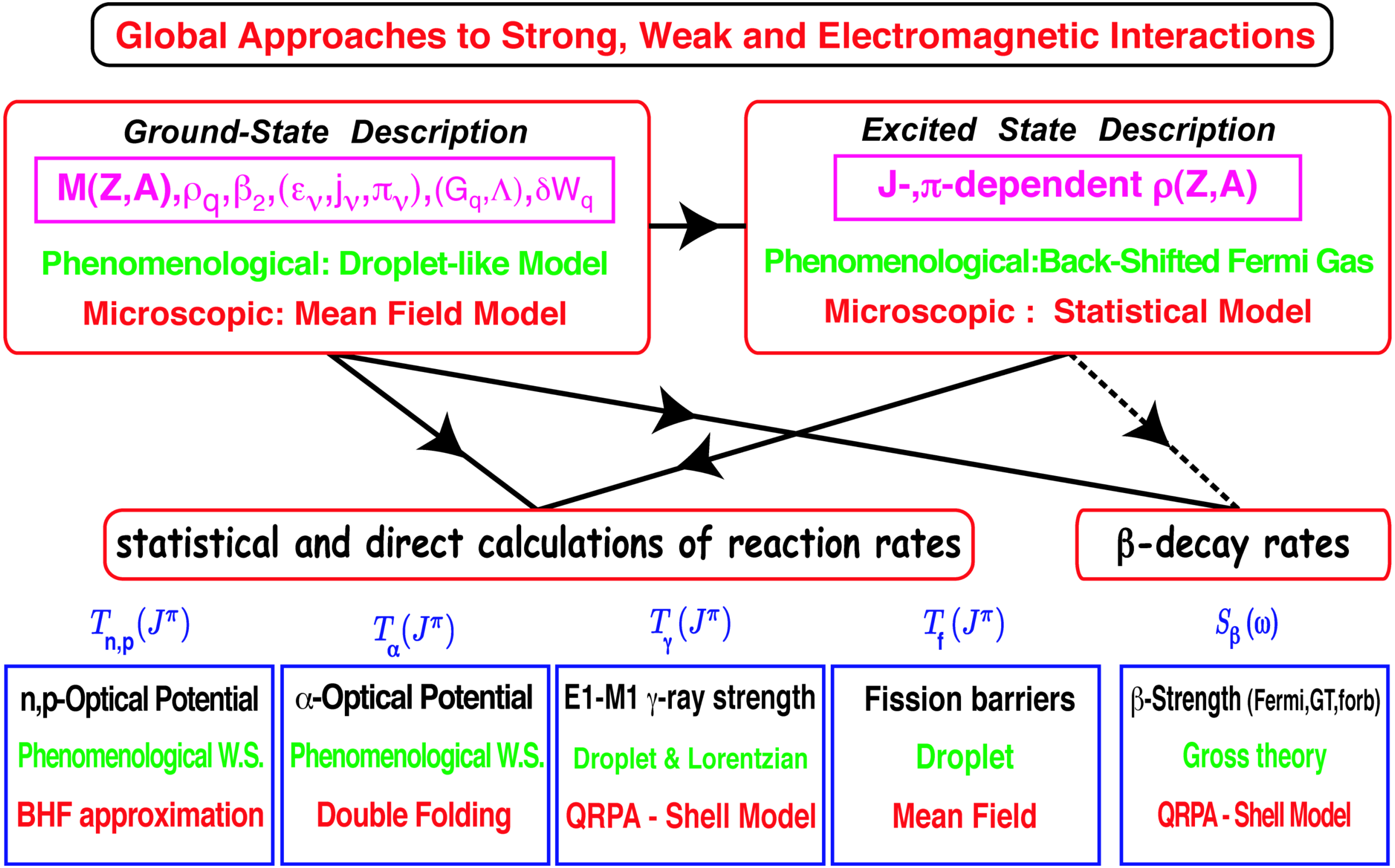
UNIVERSAL: capable of predicting *all properties* of relevance

GLOBAL: capable of predicting the properties of *all nuclei*

MICROSCOPIC: for more *reliable extrapolations* from valley of stability to drip lines

A necessary condition for a true predictive power

A challenge that will require a continued effort…



--> Still large uncertainties for exotic nuclei: (n,γ) rates: factor ~ $10^2 - 10^6$

β-decay rates: factor ~ 10 (?)

fission ??????

Nuclear mass models

Nuclear mass models provide all basic nuclear ingredients:

Mass excess (Q-values), deformation, GS spin and parity

but also

single-particle levels, pairing strength, density distributions, … in the GS as well as non-equilibrium (e.g fission path) configuration

Building blocks for the prediction of ingredients of relevance in the determination of nuclear reaction rates and β-decay rates, such as

- nuclear level densities
- γ-ray strengths
- fission probabilities
- etc …

as well as for the nuclear/neutron matter Equation of State **(NEUTRON STARS)**

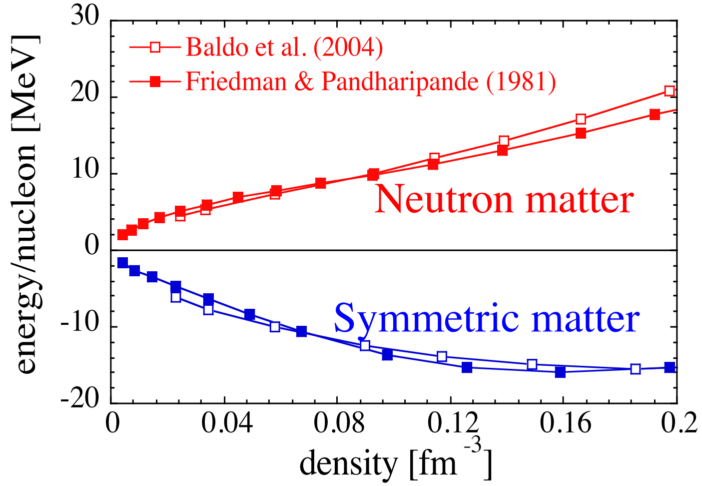
The criteria to qualify a mass model should NOT be restricted to the rms deviation wrt to exp. masses, but also include (in particular when universality is aimed at)

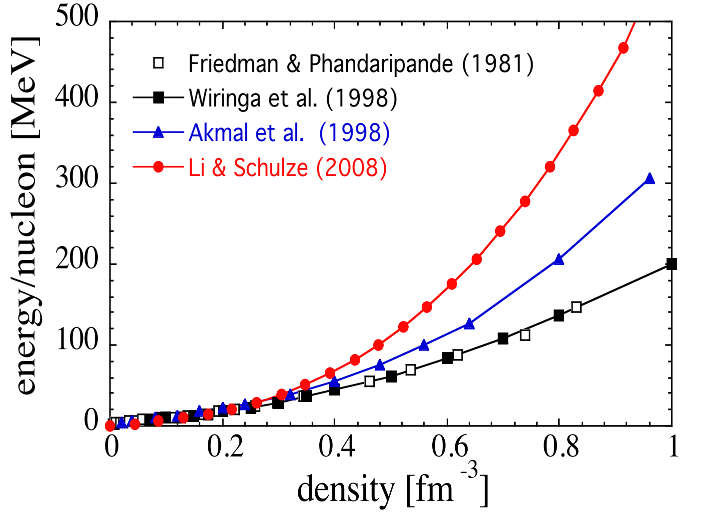
- the quality of the underlying physics (sound, coherent, "microscopic", …)

- all the observables of relevance in the specific (astrophysics) applications

Observables considered

- 2149 experimental masses from Audi et al. (2003)
- 782 exp. charge radii from Angeli et al (2004)
- Symmetric nuclear matter properties
  - $m^* \sim 0.6$ - 0.8 (BHF, GQR) & $m^*_n(\beta) > m^*_p(\beta)$
  - $K \sim 230$ - 240 MeV (breathing mode)
  - E_{pot} from BHF calc. & in 4 (S,T) channels
  - Landau parameters $F_0(S,T)$, $F_1(S,T)$
    - stability condition: $F_l^{ST} > -(2l+1)$
    - empirical $g_0 \sim 0$; $g_0' \sim 0.9$-1.2
    - sum rules $S_1 \sim 0$; $S_2 \sim 0$
  - Pairing gap (with/out medium effects)
- Neutron matter properties
  - $J \sim 29 - 32$MeV
  - E_n/A from realistic BHF-like calculations
  - Pairing gap
  - Stability of neutron matter at all polarizations
- Giant resonances
  - ISGMR, IVGDR, ISGQR
- Additional model-dependent properties
  - Nuclear Level Density (pairing-sensitive)
  - Isomers & Fission barriers (scan large deformations)
  - Properties of the lowest 2+ levels (519 e-e nuclei)
  - Moment of inertia in superfluid nuclei (backbending)





Hartree-Fock-Bogolyubov model predictions

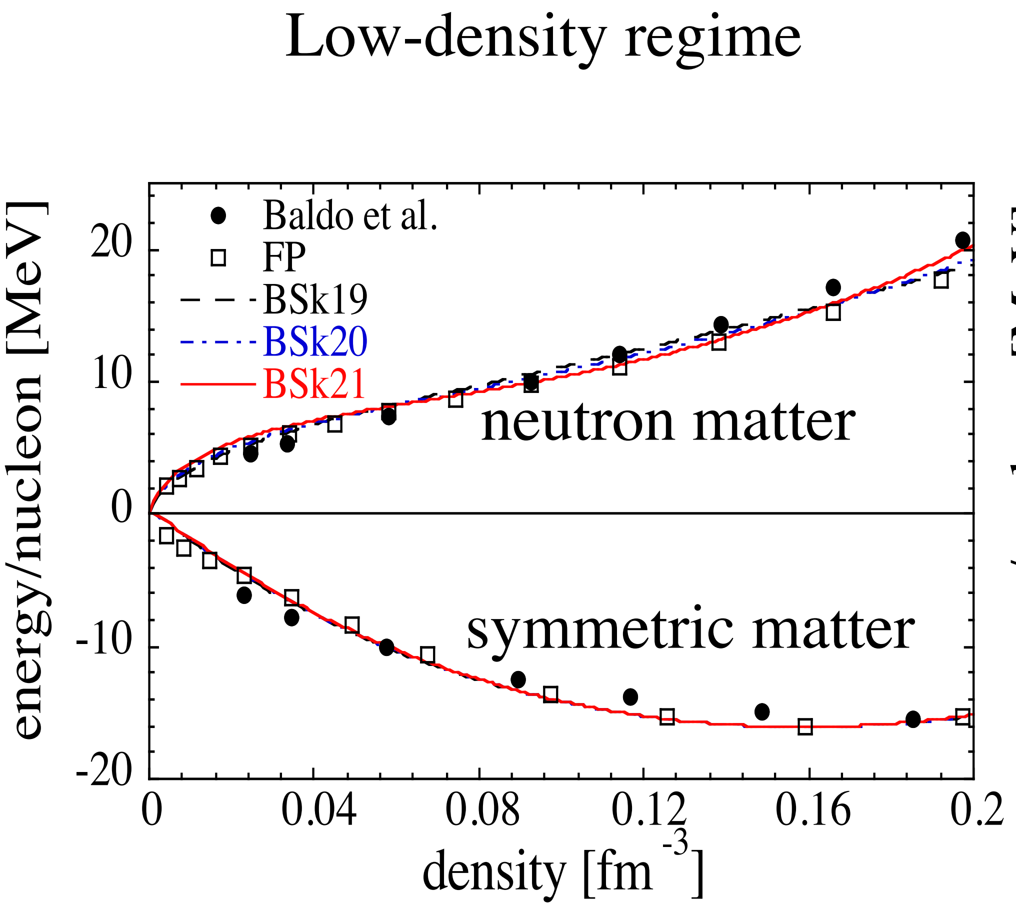
The long road in the HFB mass model development		σ_{rms} **(2149 nuc)**	
HFB-1-2:	Possible to fit all 2149 exp masses Z≥8	**659 keV**	
HFB-3:	Volume versus surface pairing	**635 keV**	
HFB-4-5:	Nuclear matter EoS: M^*=0.92	**660 keV**	
HFB-6-7:	Nuclear matter EoS: M^*=0.80	**657 keV**	
HFB-8:	Introduction of number projection	**635 keV**	
HFB-9:	Neutron matter EoS - J=30 MeV	**733 keV**	
HFB-10-13:	Low pairing & NLD	**717 keV**	~
HFB-14:	Collective correction and Fission B_f	**729 keV**	~
HFB-15:	Including Coulomb Correlations	**678 keV**	
HFB-16:	with Neutron Matter pairing	**632 keV**	
HFB-17:	with Neutron & Nuclear Matter pairing	**581 keV**	
HFB-18-21:	Non-Std Skyrme (t_4-t_5 terms) - Fully stable	**577 keV**	

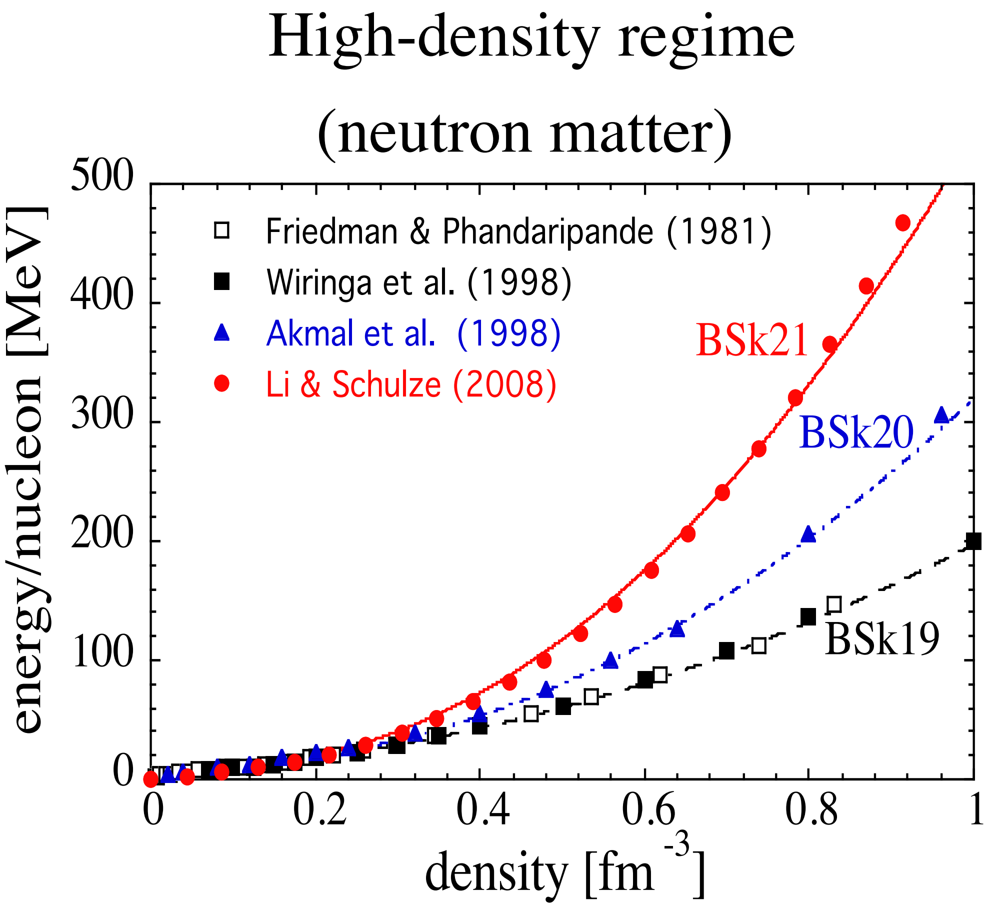
Maximum Constraints on both Nuclei and Infinite Nuclear Matter

But also **fission barriers, shape isomers, NLD, GR**

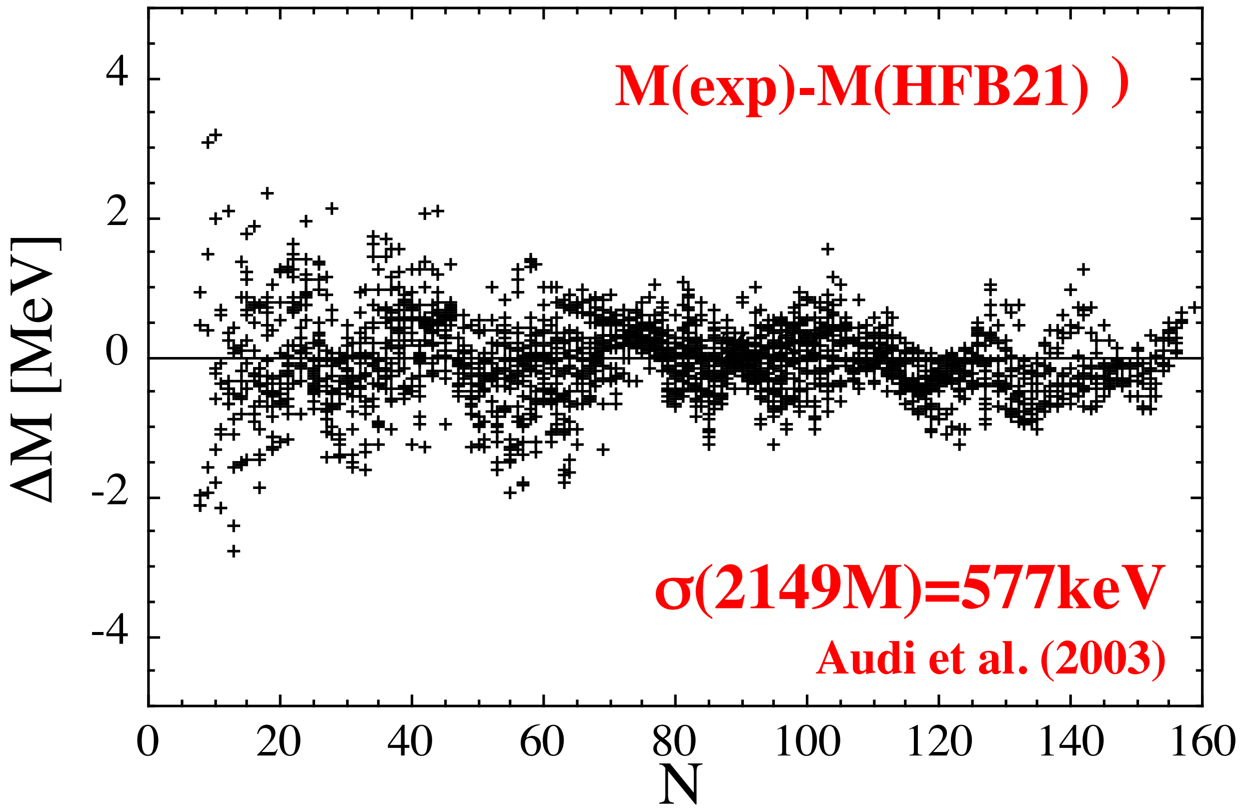
(in the spirit of practical applications for astrophysics)

HFB19-21: Stiffness of the neutron matter energy density





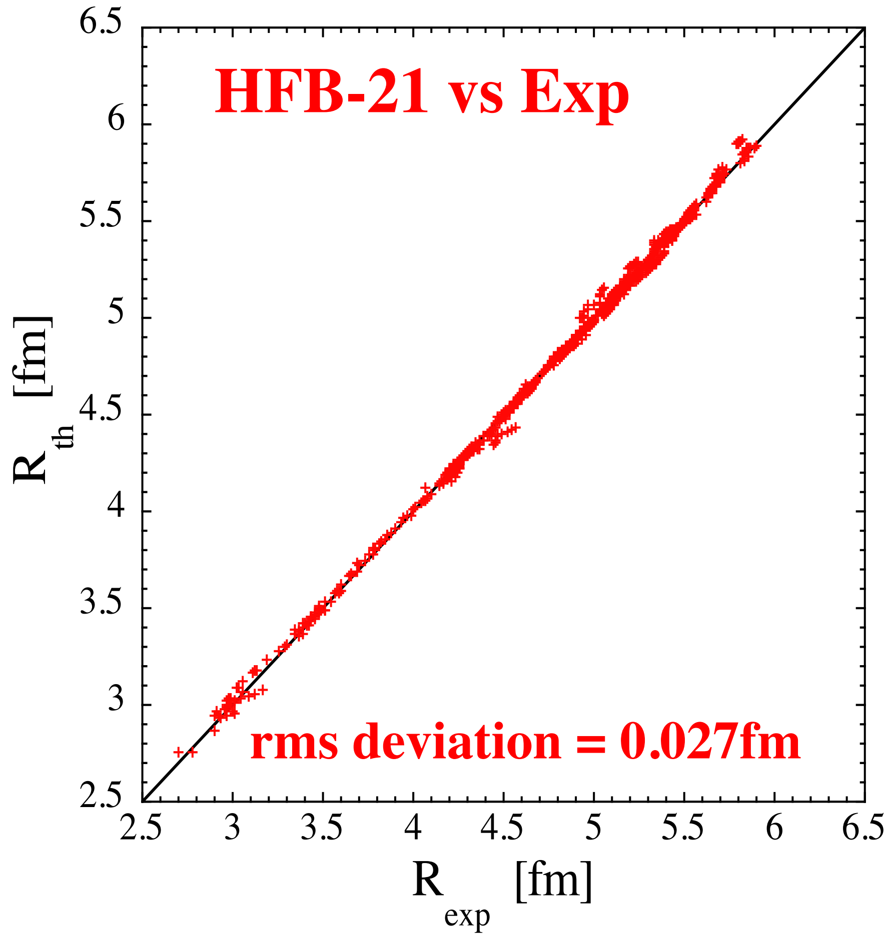
Comparison with experimental masses



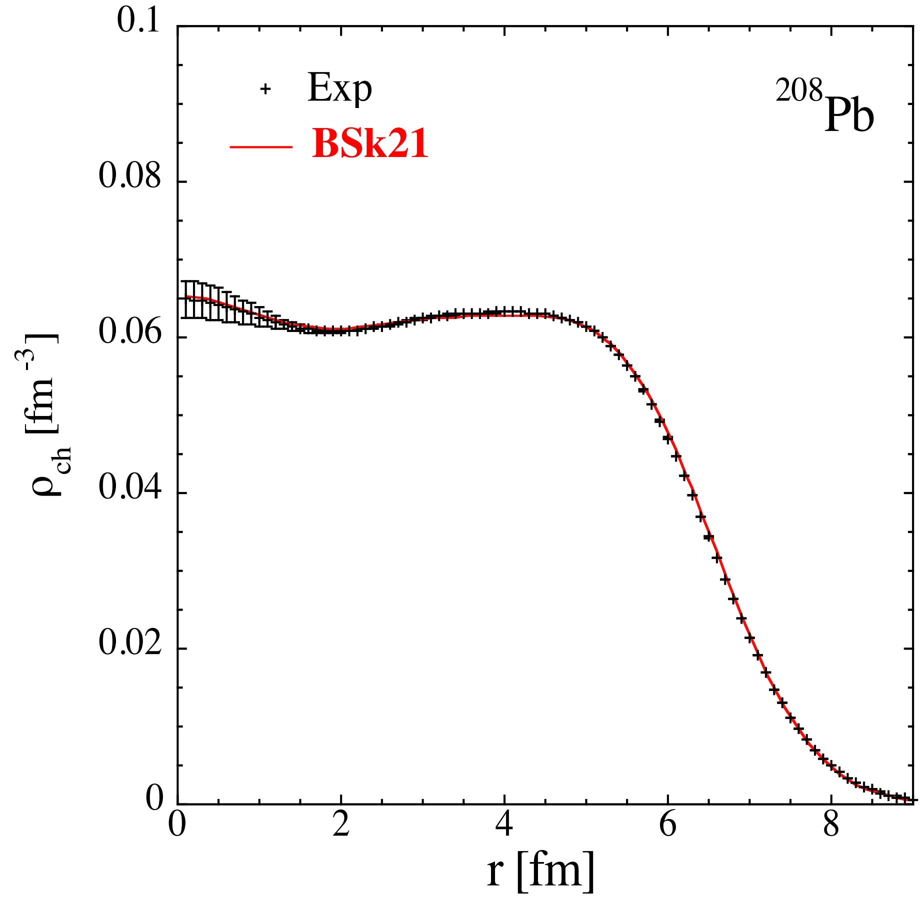
	σ(HFB20)	σ(HFB21)	σ(FRDM)
434 masses (36≤Z≤85, p-rich) at GSI (2005)	**397 keV**	**388 keV**	**429 keV**
119 masses (28≤Z≤46, n-rich) at JYFLTRAP (2009)	**453 keV**	**625 keV**	**694 keV**

Some examples for nuclear structure properties of interest for applications

Charge radii for 782 nuclei



Charge distribution of ^{208}Pb



Skyrme-HFB mass models: a first step towards “microscopic” models for practical applications

… but there is obviously still room for many improvements:

- Pairing interaction (contact force, cut-off dependence)
- Improved treatment of odd nuclei
- Phenomenological Wigner correction
- Finite-range forces of Gogny-type
- Correlation effects beyond mean field
- Etc…

A new generation of mass models

Gogny-HFB mass table beyond mean field !

close collaboration with Bruyères-le-Châtel
(S. Hilaire & M. Girod)

Beyond the mean field, the total binding energy is estimated from

$$E_{tot} = E_{HFB} - E_{Quad}$$

where • E_{HFB}: deformed HFB binding energy obtained with a *finite range* standard **Gogny-type** force

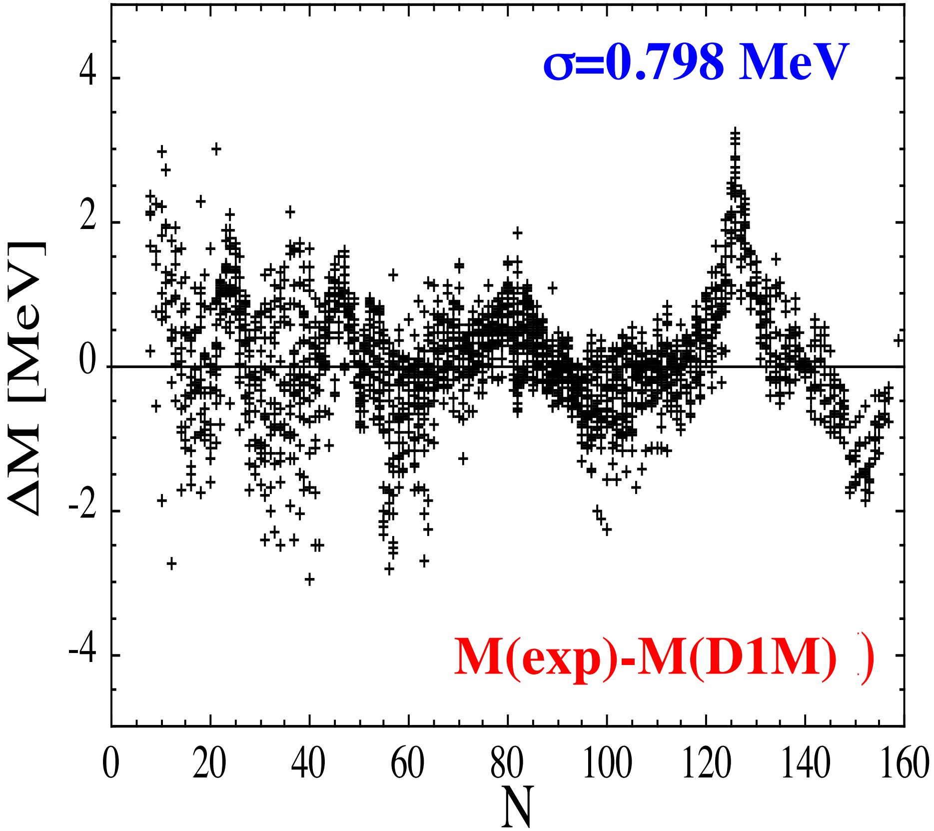
$$V(1,2) = \sum_{j=1,2} e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_j^2}} (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau)$$
$$+ t_0 (1 + x_0 P_\sigma) \delta(\vec{r}_1 - \vec{r}_2) \left[\rho\left(\frac{\vec{r}_1 + \vec{r}_2}{2}\right)\right]^\alpha$$
$$+ i W_{LS} \overleftarrow{\nabla}_{12} \delta(\vec{r}_1 - \vec{r}_2) \times \overrightarrow{\nabla}_{12} . (\vec{\sigma}_1 + \vec{\sigma}_2) .$$

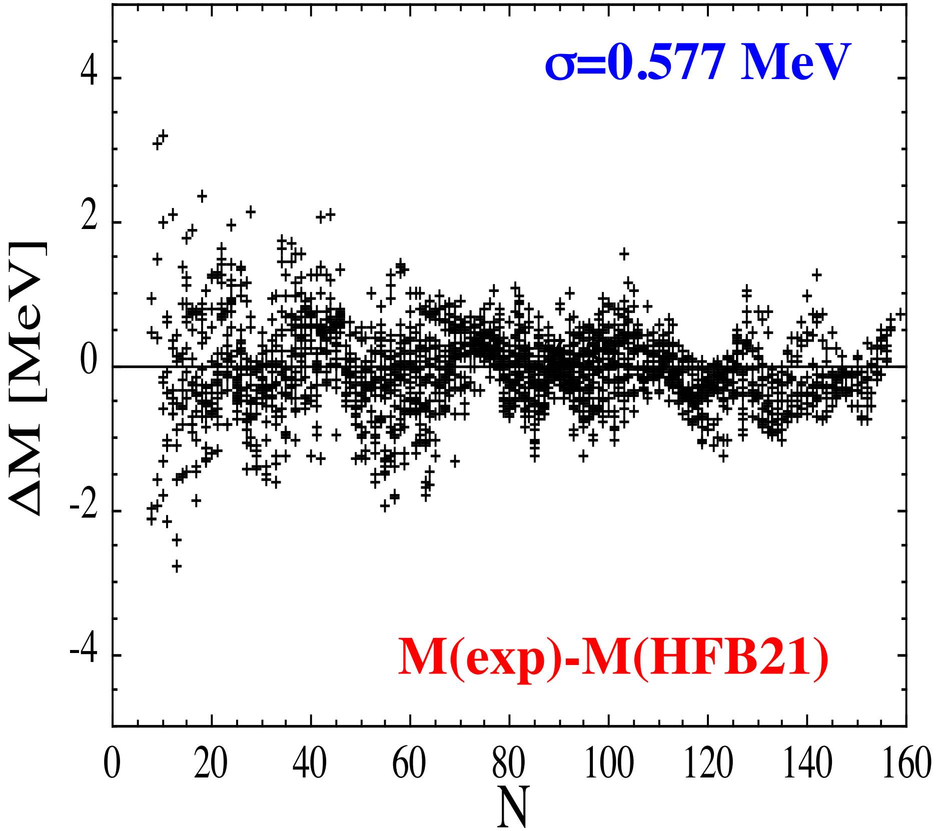
• E_{Quad} : quadrupolar correction energy determined with the *same* Gogny force (no "double counting") in the framework of the 5D-Bohr Hamiltonian model for the five collective quadrupole coordinates, i.e. rotation, quadrupole vibration and coupling between these collective modes (axial and triaxial quadrupole deformations included)

Girod, Berger, Libert, Delaroche

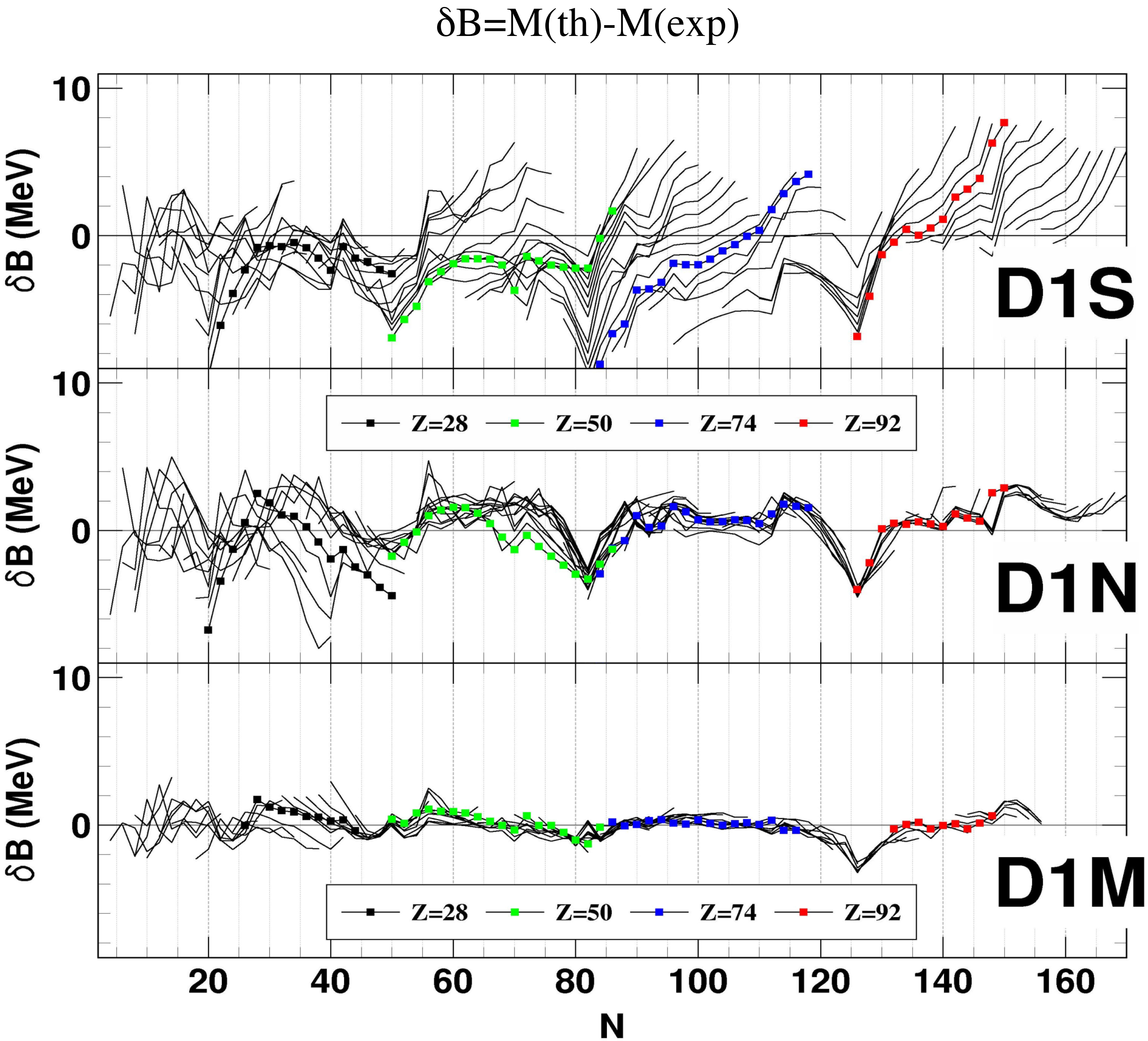
First Gogny-HFB mass formula (D1M force)

2149 Masses: ε=0.126 MeV σ=0.798 MeV
with coherent E_{Quad} & E_{HFB} !
707 Radii: ε=-0.008 fm σ=0.031 fm (with Q corrections)



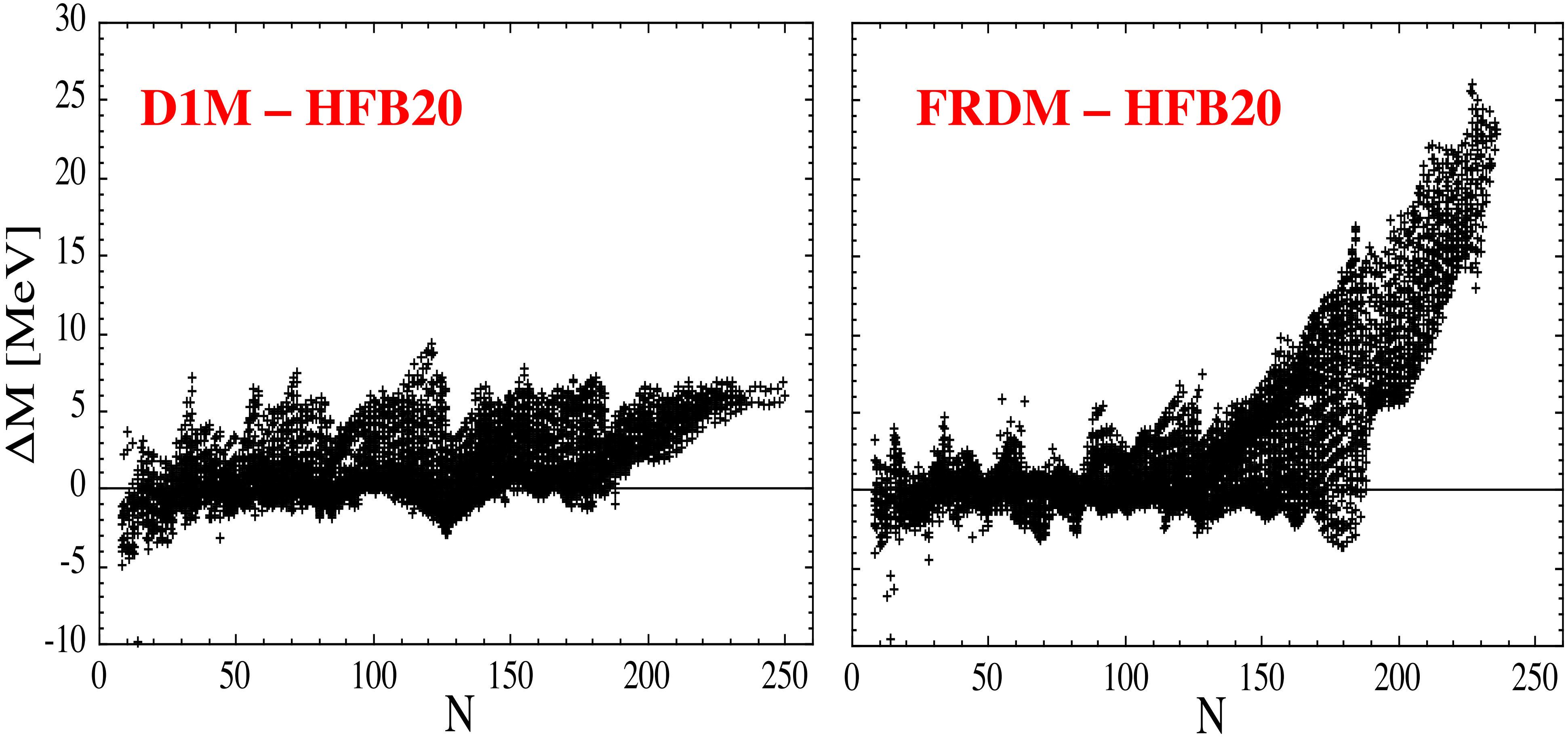


--> It is possible to adjust a Gogny force to reproduce all exp masses accurately



δB=M(th)-M(exp)
δB (MeV)
D1S
D1N
D1M
Z=28
Z=50
Z=74
Z=92
N

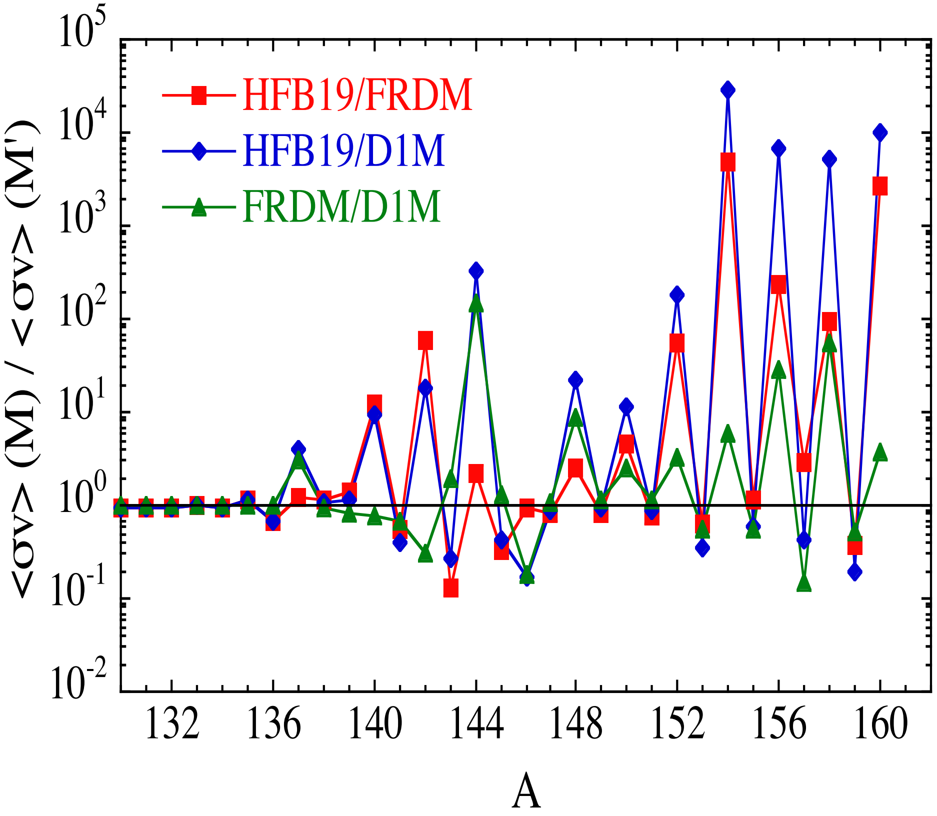
Comparison between Skyrme-HFB, Gogny-HFB and FRDM masses



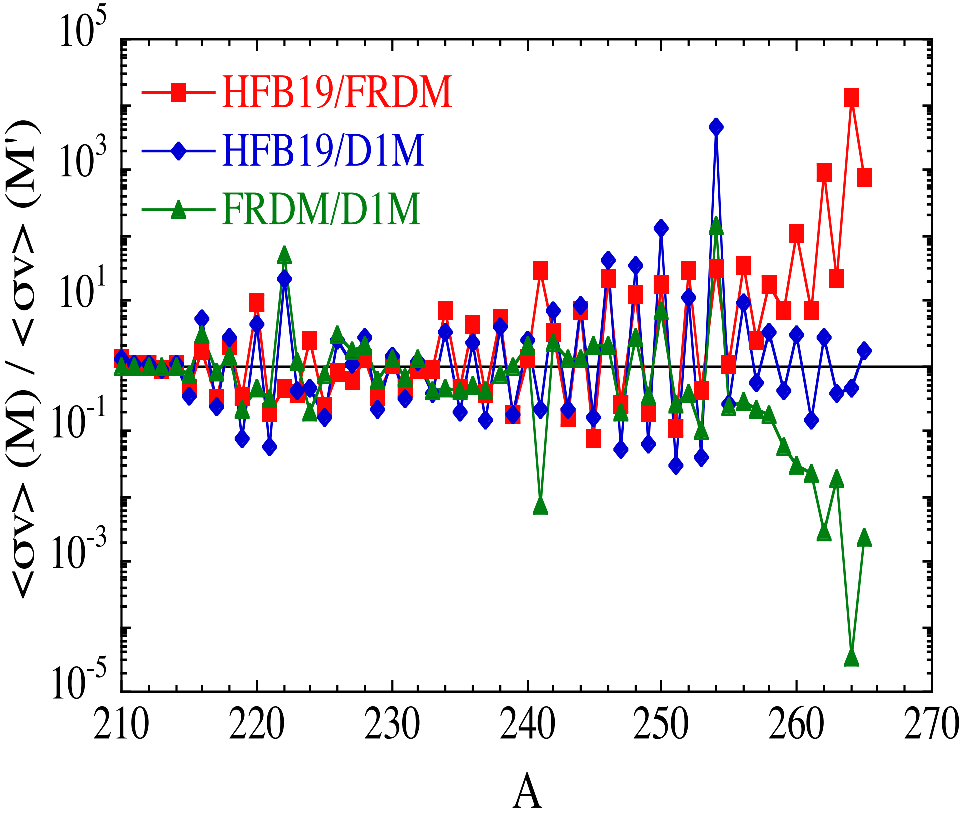
Impact of nuclear masses on the (n,γ) reaction rate at T=10^{9}K

(~ cross section around 100keV - Calculation within the HF reaction model)

Sn isotopes

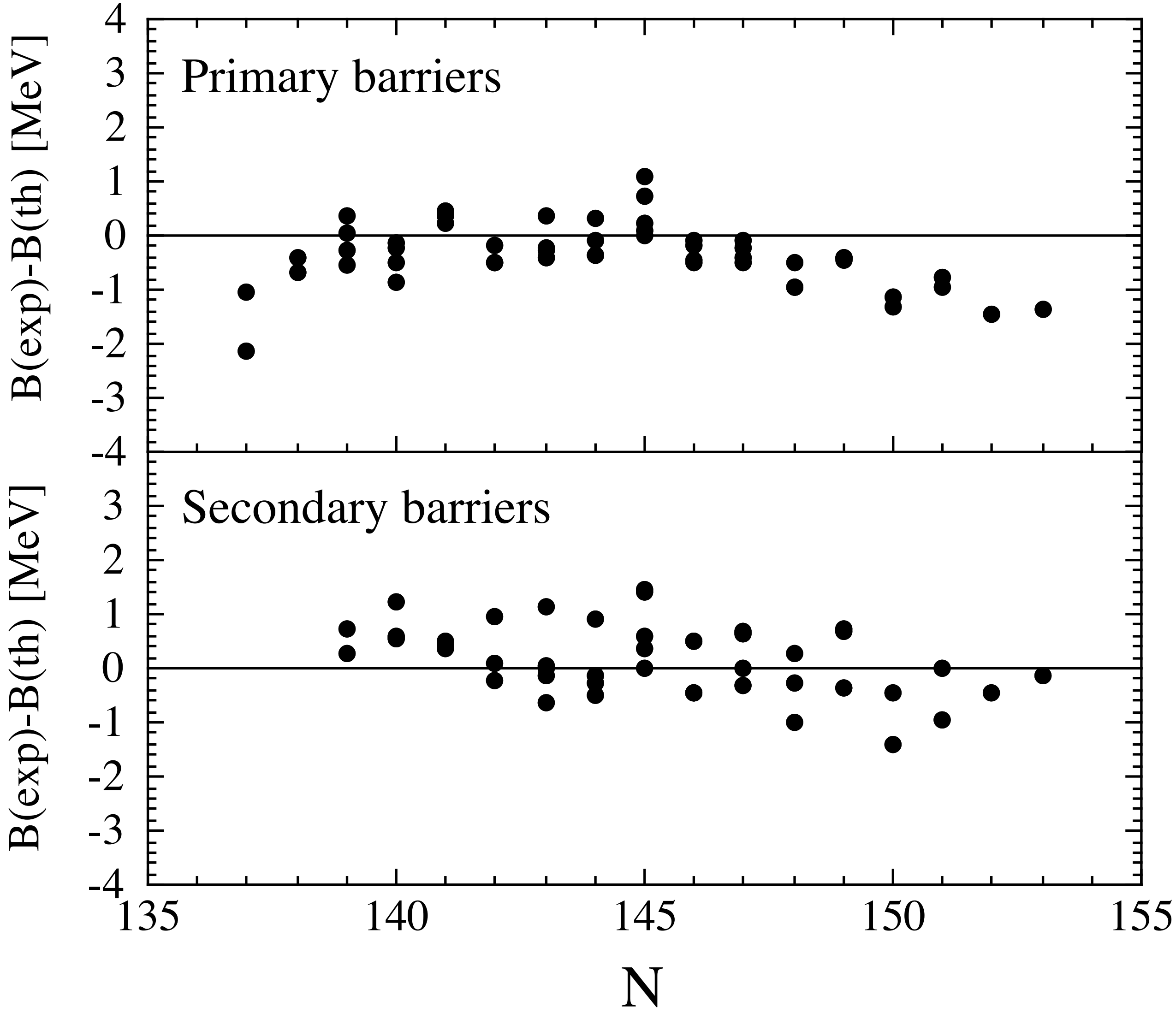


Pb isotopes



Extension to large deformations
Comparison of HFB fission barriers with « experimental » data

HFB-14 mass model



B_{1st} (Exp) – B_i (HFB)

52 nuclei with Z ≥ 88

rms = 0.67 MeV

B_{2nd} (Exp) – B_i (HFB)

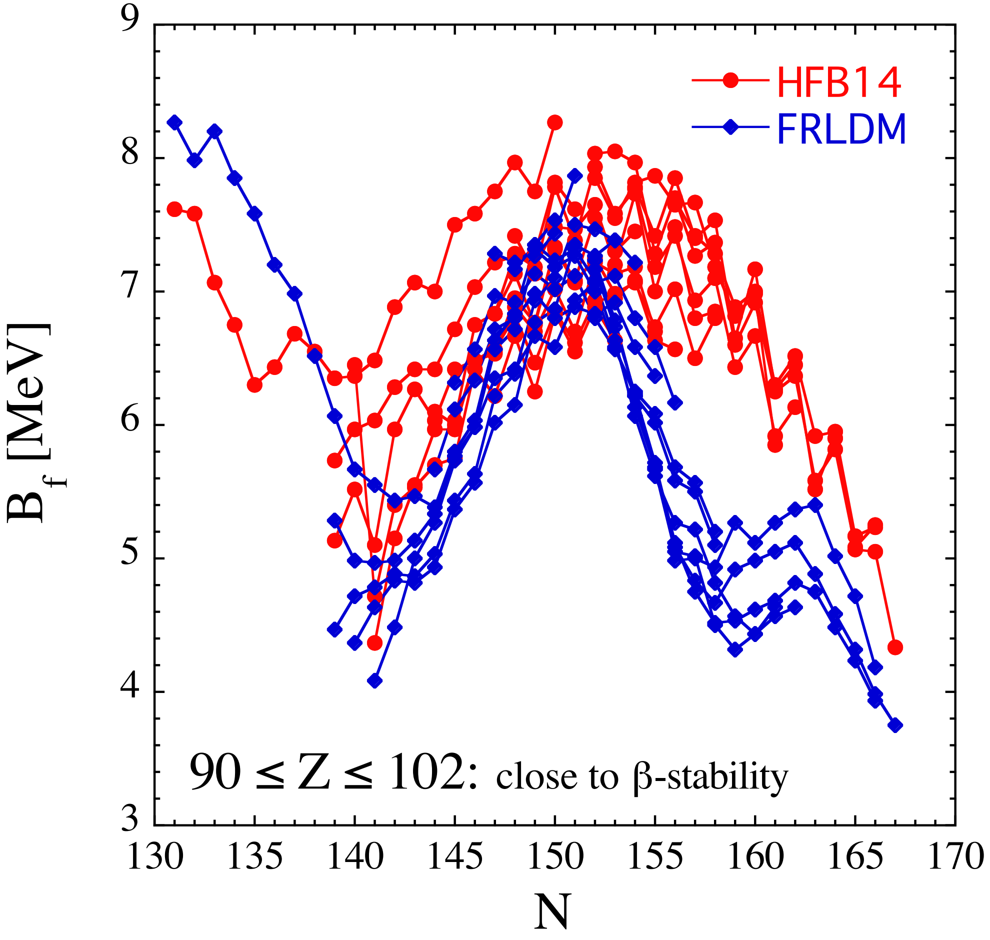
45 nuclei

rms = 0.65MeV

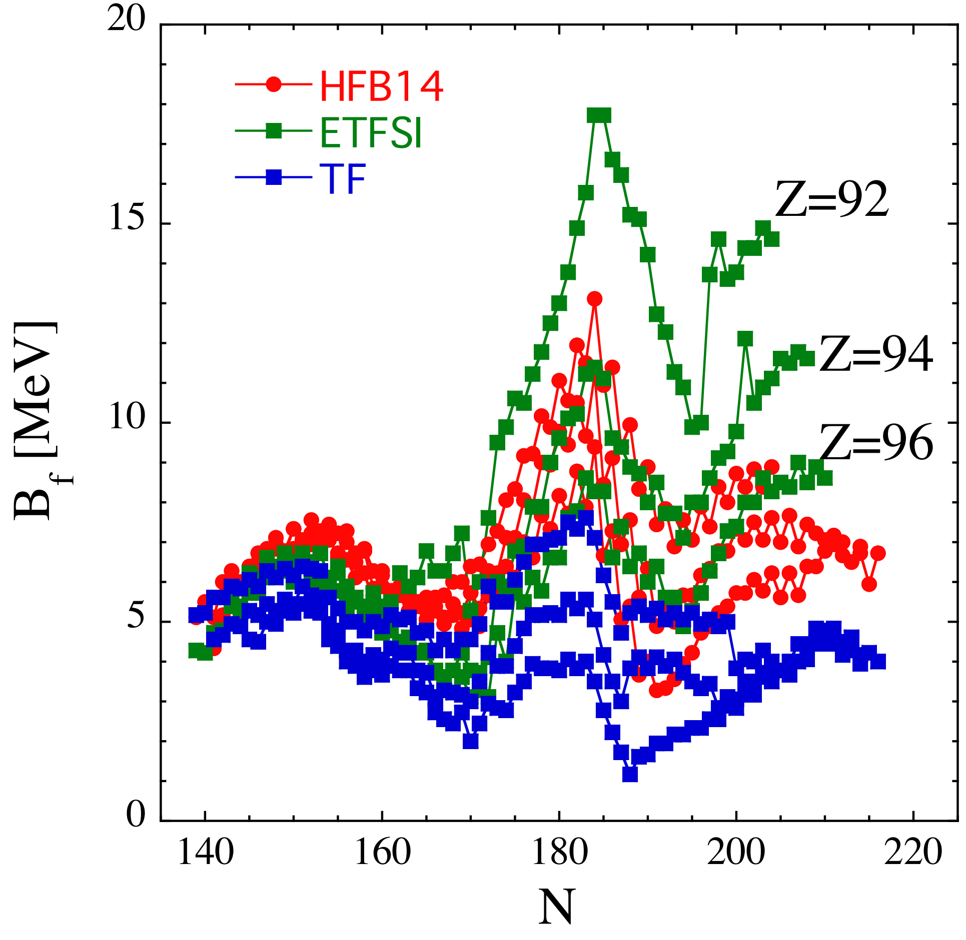
Global predictions of fission barriers

1000 HFB fission paths (90 ≤ Z ≤ 102) (available at www-astro.ulb.ac.be)
(as well as coherently determined combinatorial NLD at saddle points)

Close to β-stability



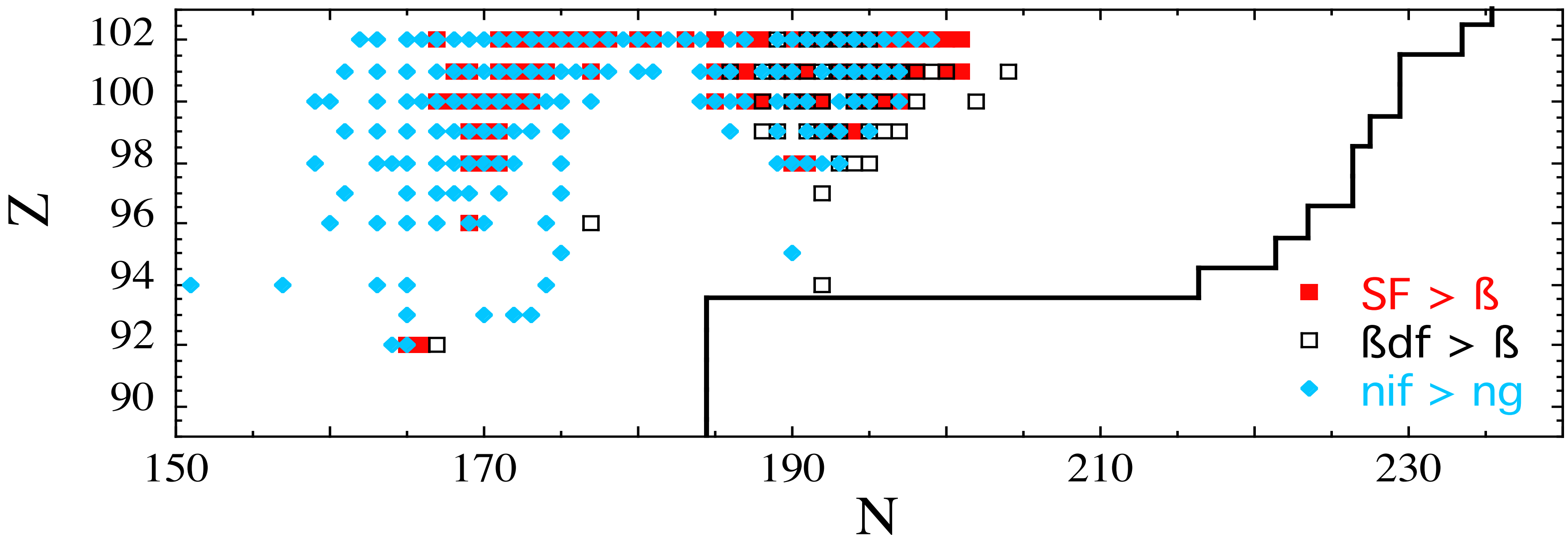
Far away from β-stability



Fission probabilities

Determination of fission probabilities (sf, nif, βdf): updated calculation of

- sf: HFB-14 fission path and barrier penetration (updated TALYS T_f)
- nif: HFB-14 fission path and corresponding NLD included in TALYS
- βdf: HFB-14 fission path and GT β-strength function (updated TALYS T_f)



But is the fission symmetric or asymmetric ?

What is the Z- and A-distribution of the fission fragments ?

Conclusions

The r-process puzzle remains, first of all, an *astrophysics* problem

?? what is the astrophysics site hosting the r-process ??

- **Decompression of initially hot material (SN/GRB ν-driven wind)**
  appealing but …where, how? high-S, low-Ye, Fast expansion, …?

- **Decompression of initially cold material (NS mergers, NS outflows ?)**
  appealing but …contribution to GCE, details of mass ejection,…

… or maybe some very different sites with other types of nuclear mechanisms …???

Solution will come from *hydrodynamic simulations*

(r-process conditions, amount of matter ejected, event rate)

plus some hints from *observations*, eventually

Conclusions

A continued effort is required

- **to improve the predictions of nuclear structure properties within "*microscopic*" models (masses, deformations, …)**
- **to improve the coherent calculations of reaction & β-decay rates for experimentally unknown nuclei**
  - **Reaction model: equilibrium, pre-equilibrium, DC**
  - **β-decay model: allowed, forbidden transitions, …**
  - **Nuclear ingredients:**
    - **GROUND-STATE properties**
    - **nuclear level densities**
    - **optical potentials**
    - **γ-ray strength functions**
    - **β-strength functions**
    - **FISSION properties**

We are still far from being capable of estimating ***reliably*** the radiative neutron capture and β-decay of exotic n-rich nuclei

(and fission properties even of known nuclei)

Theoretical as well as Experimental works are definitely needed