Towards more accurate and reliable predictions for nuclear applications

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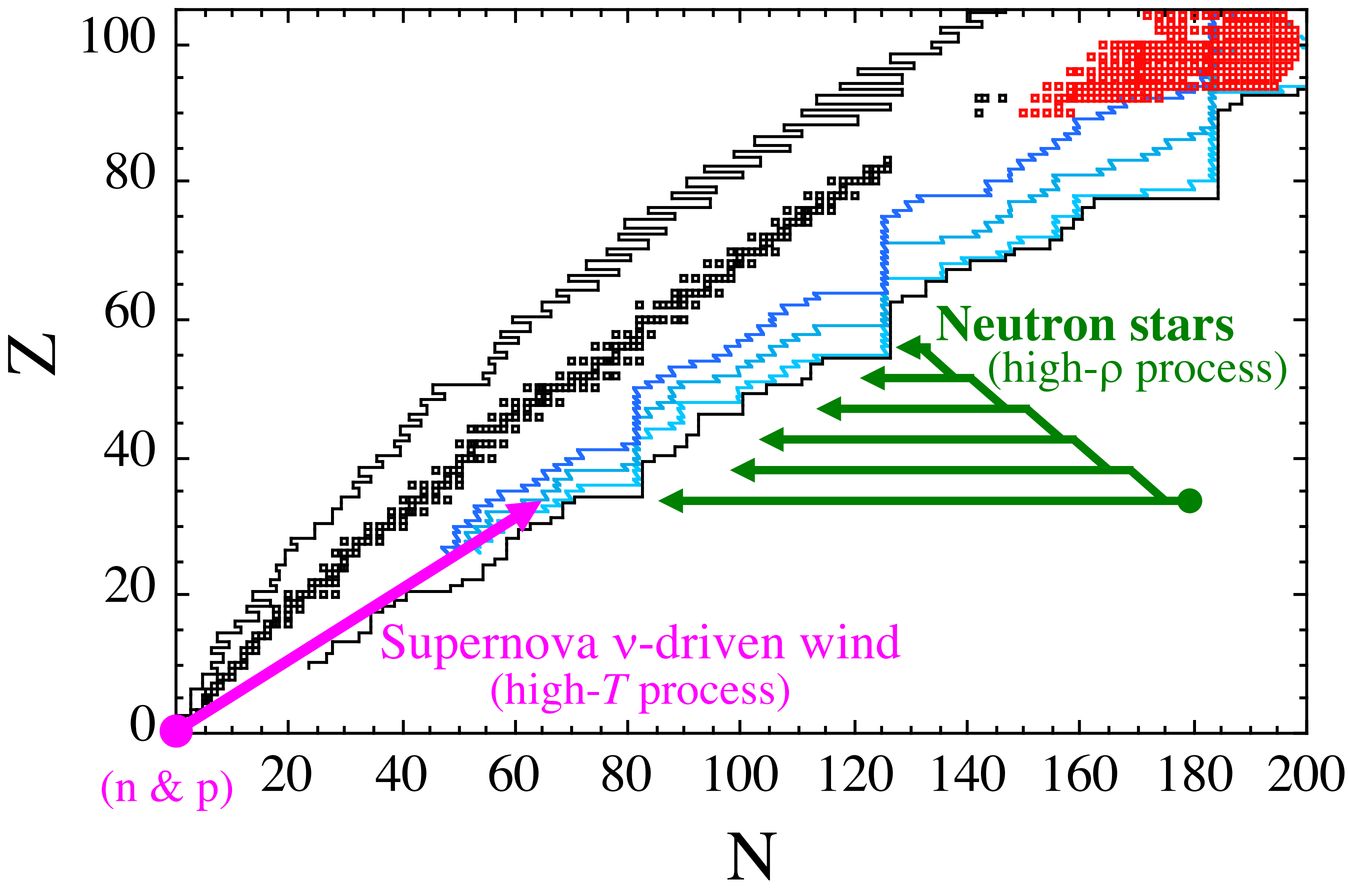
The r-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics

… the r-process site remains to be confirmed ...

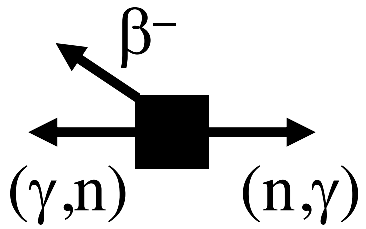


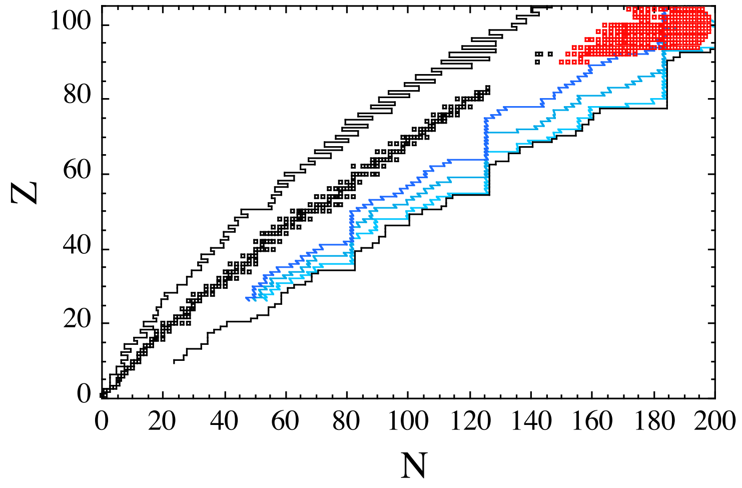
Nuclear physics input for r-process applications

(n,γ) – (γ,n) – β competition & Fission recycling

Main needs

- β-decay
- (n,γ) and (γ,n) rates
- Fission (nif, sf, βdf) rates
- Fission Fragments Distributions





Nucleosynthesis requires RATES for some 5000 nuclei !

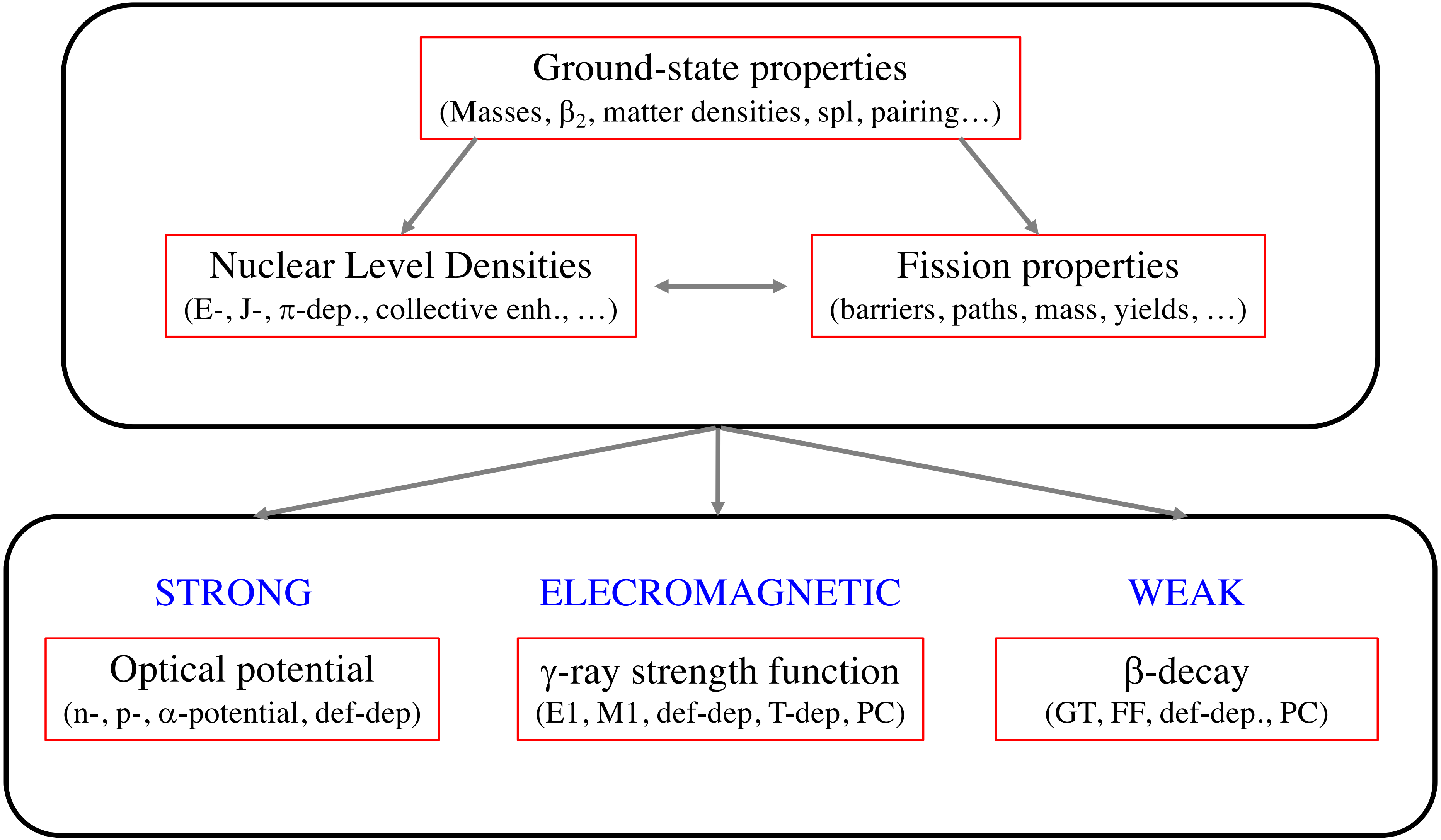
(and not only masses or β-decay along the oversimplified so-called “r-process path”)

→ simulations rely almost entirely on theoretical predictions

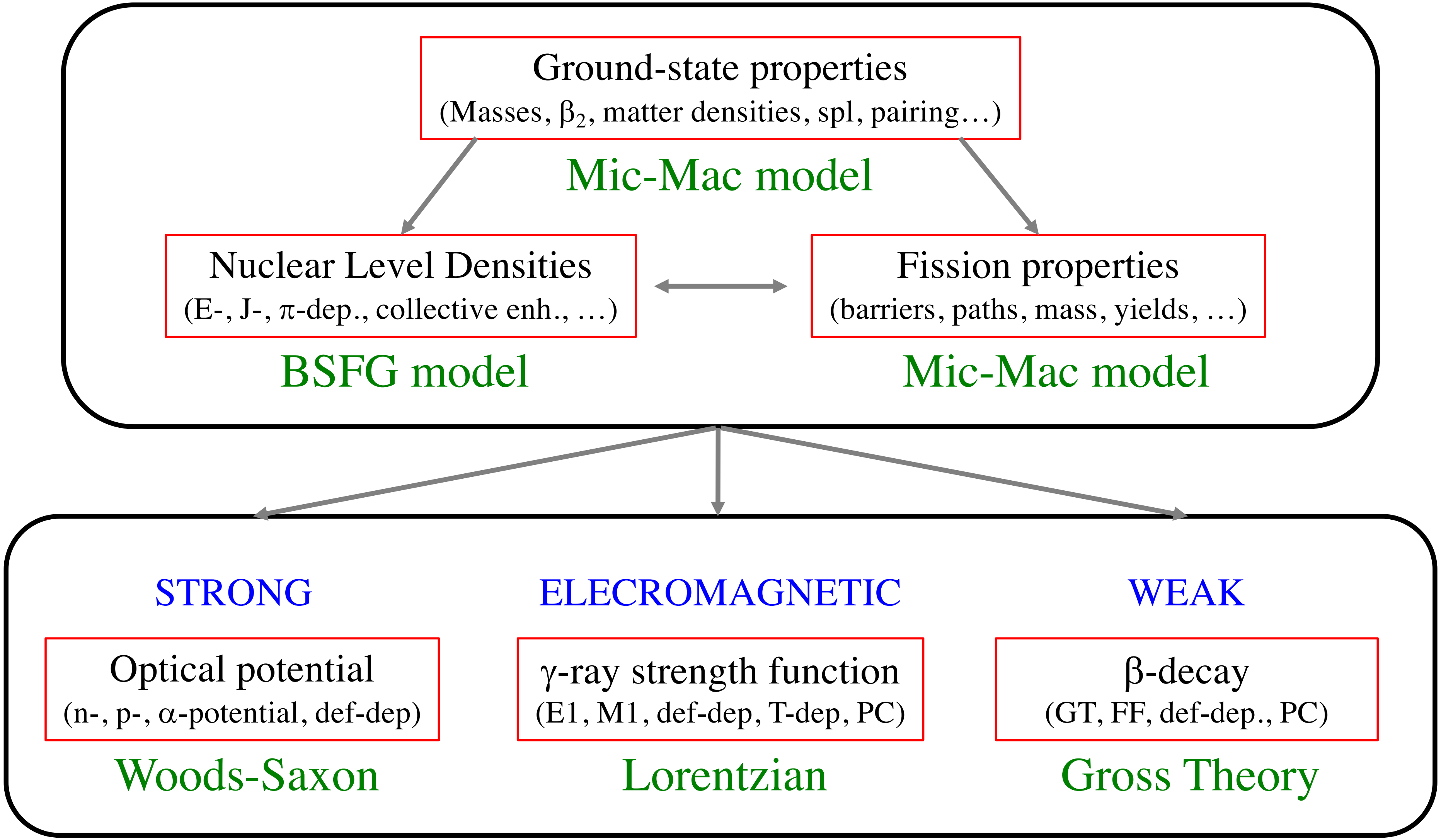
In turn, theoretical models are tuned on available experimental data

Ongoing progress on both theoretical and experimental sides

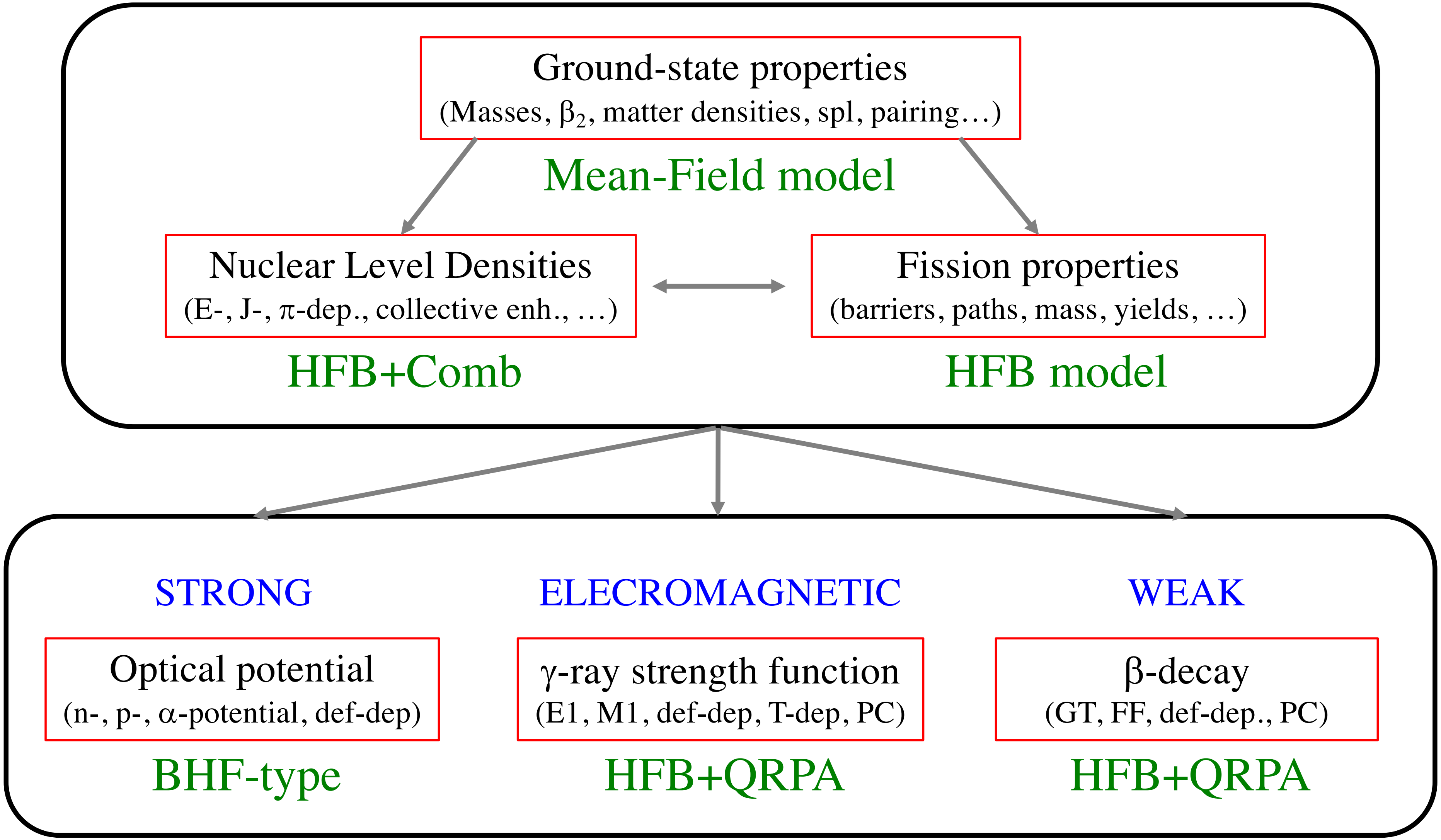
Nuclear inputs to nuclear reaction & decay calculations



Nuclear inputs to nuclear reaction & decay calculations



Nuclear inputs to nuclear reaction & decay calculations

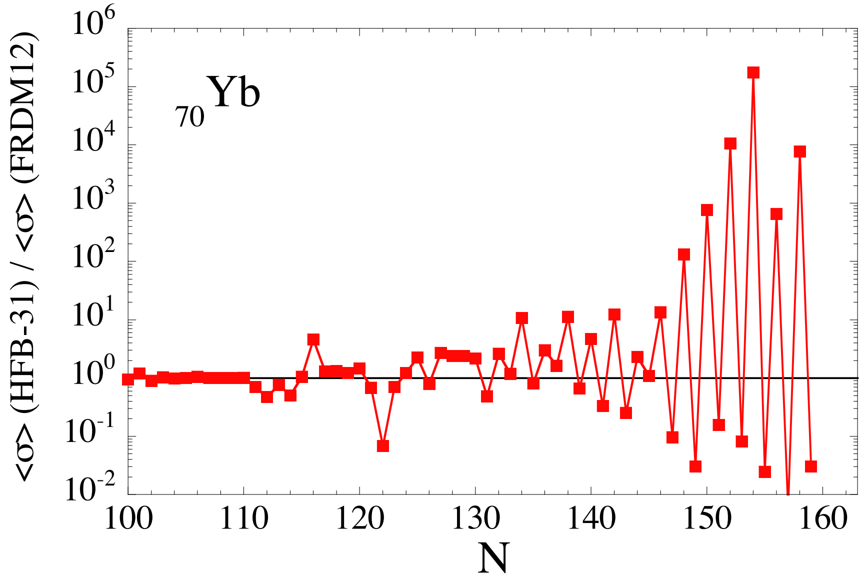


“Microscopic” approach is a necessary but not a sufficient condition !

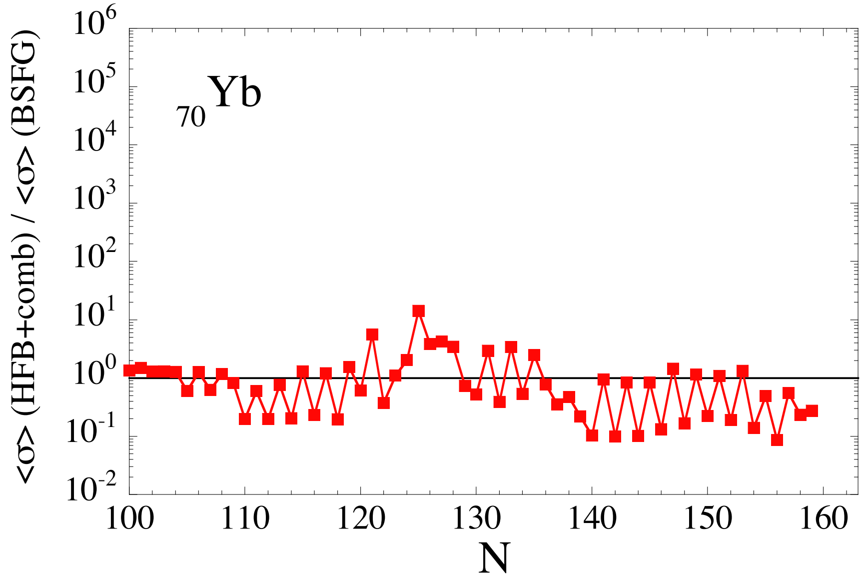
”(Semi-)Microscopic” models must be competitive in reproducing exp. data !

Impact of the various ingredients on the radiative neutron capture (E_n~100keV)

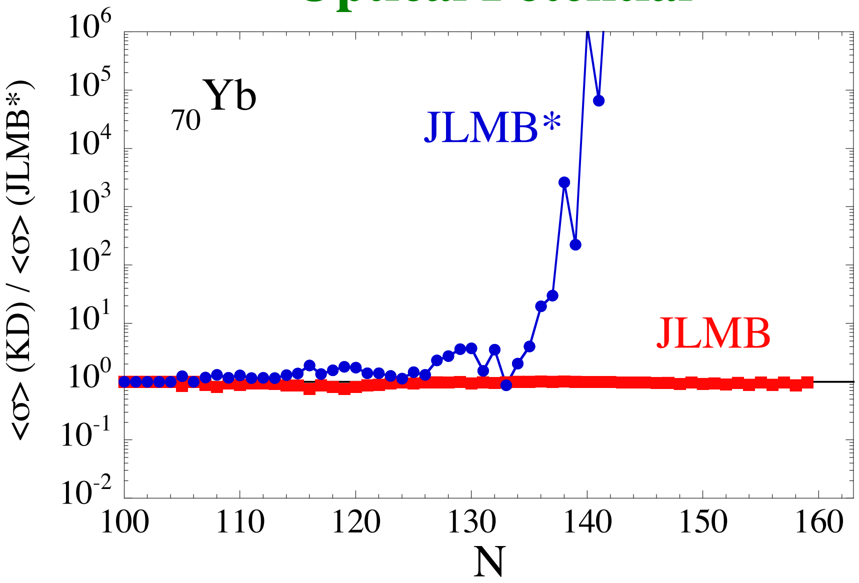
Masses



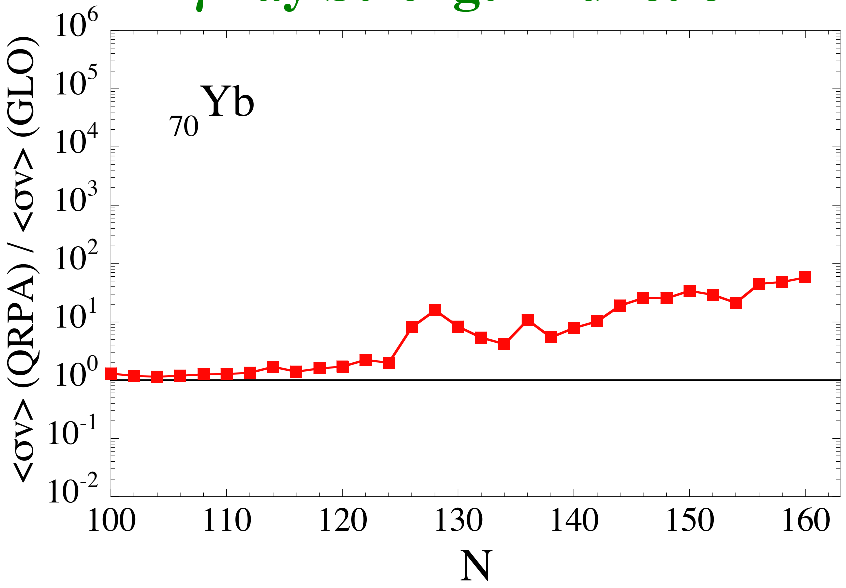
Nuclear Level Densities



Optical Potential



γ-ray Strength Function



Mean Field mass models

$$E = E_{MF} - E_{coll} - E_W - E_{b\infty}$$

E_{MF} : HFB or HF-BCS (or HB) main Mean-Field contribution

E_{coll}: Quadrupole Correlation corrections to restore broken symmetries and include configuration mixing

E_W : *Wigner* correction contributes significantly only for nuclei along the $Z \sim N$ line (and in some cases for light nuclei)

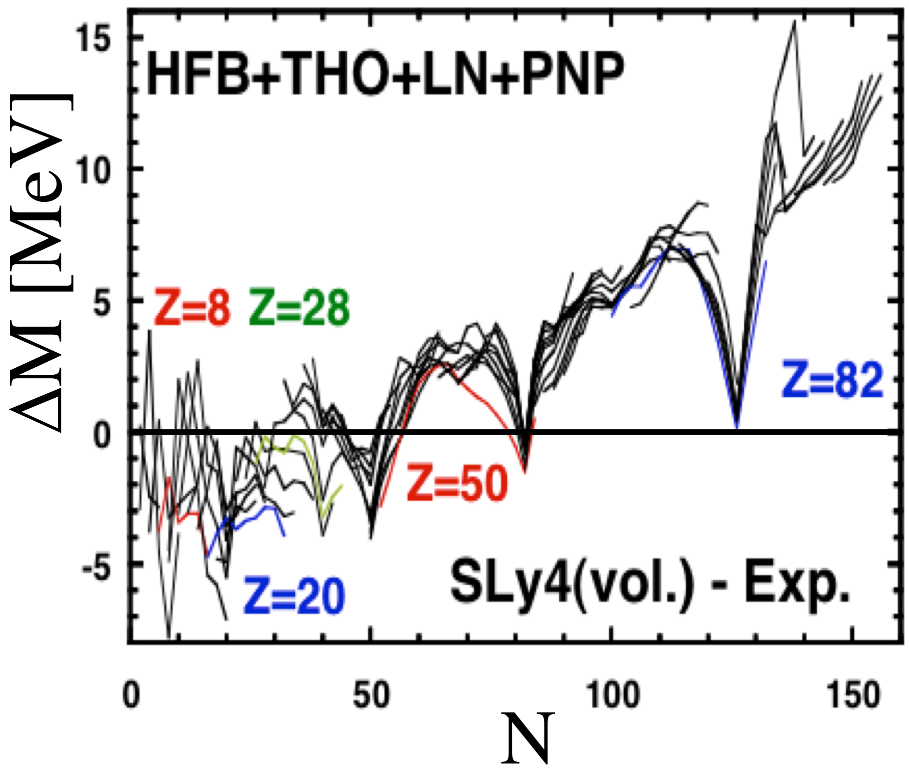
$E_{b\infty}$: Correction for infinite basis

Skyrme-HFB	Gogny-HFB	Relativistic MF
rms ~ 0.5-0.8MeV	rms ~ 0.8MeV	rms > 1.1MeV

Nuclear masses and their impact on the r-abundance distribution

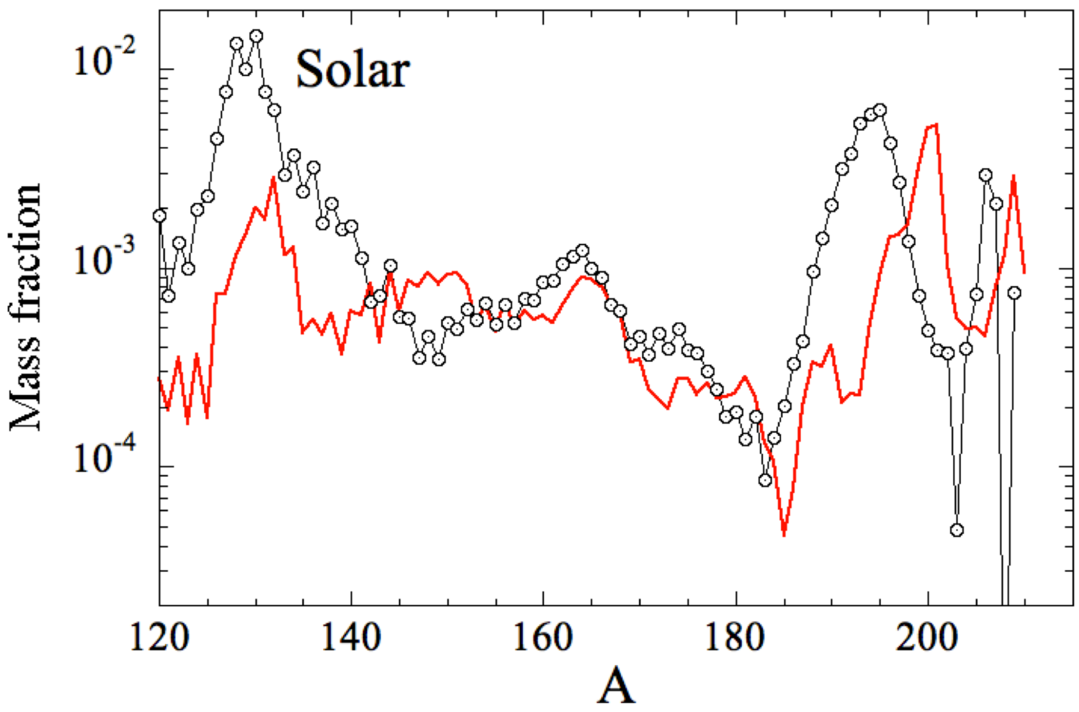
Nuclear masses driving the (n,γ) ⟷ (γ,n) competition

SLy4 : σ_{rms}=5.1MeV on 570 e-e nuclei



Stoitsov et al. 2003

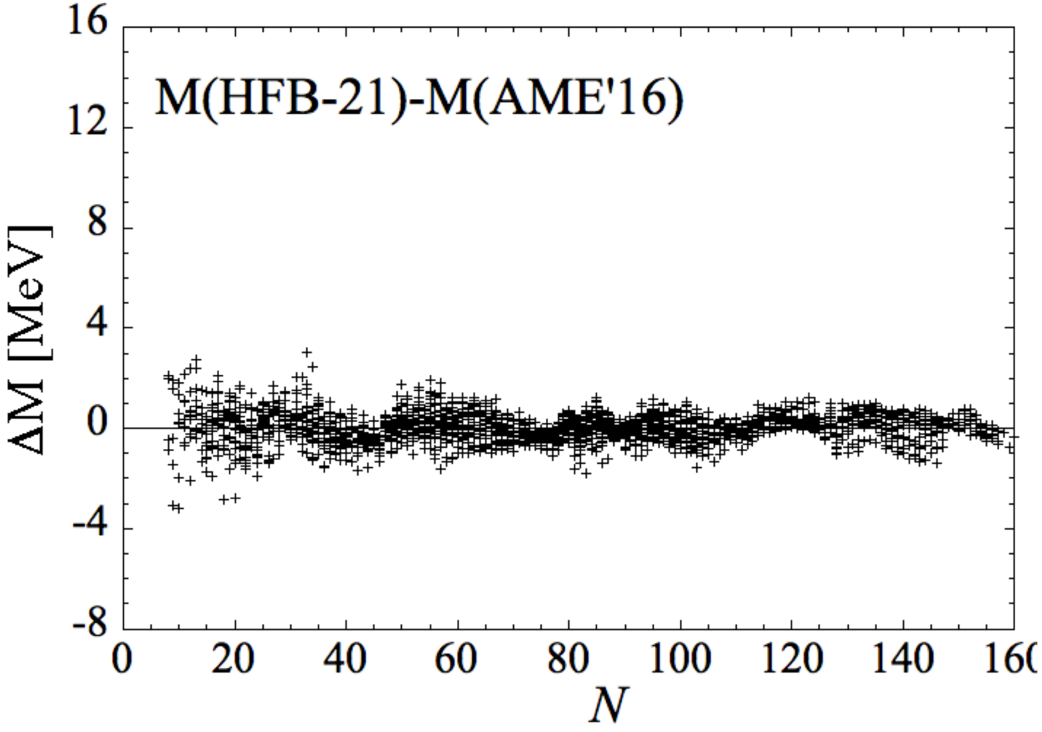
Dynamical ejecta of NSM



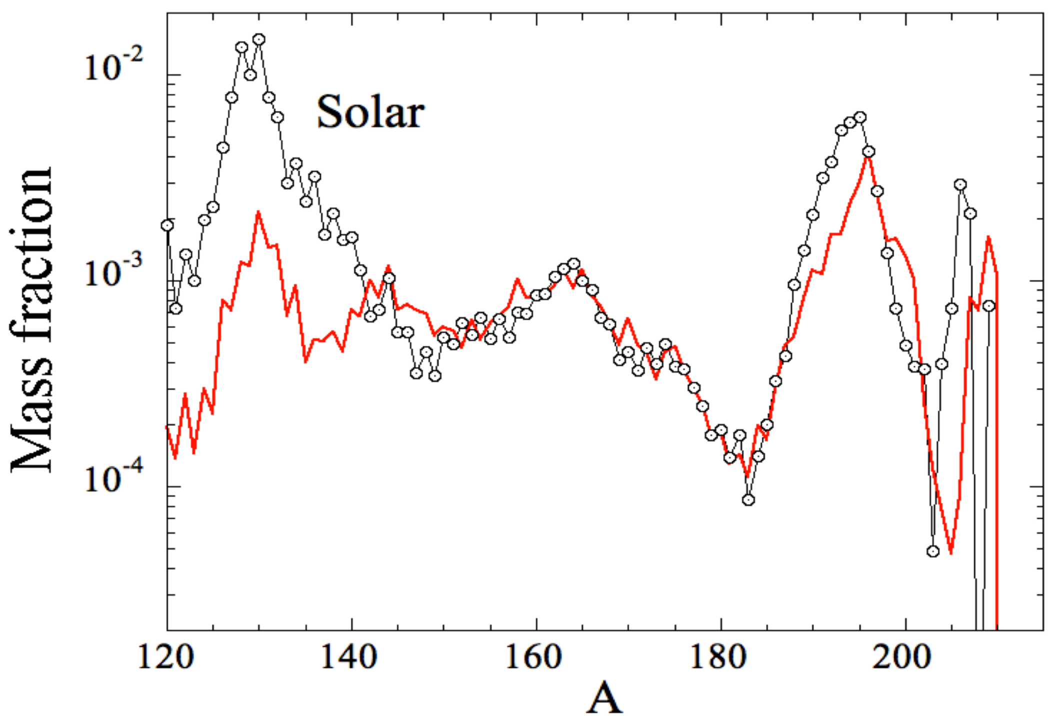
Nuclear masses and their impact on the r-abundance distribution

Nuclear masses driving the (n,γ) ⟷ (γ,n) competition

HFB-21 : σ_{rms}=0.59MeV on 2408 nuclei



Dynamical ejecta of NSM



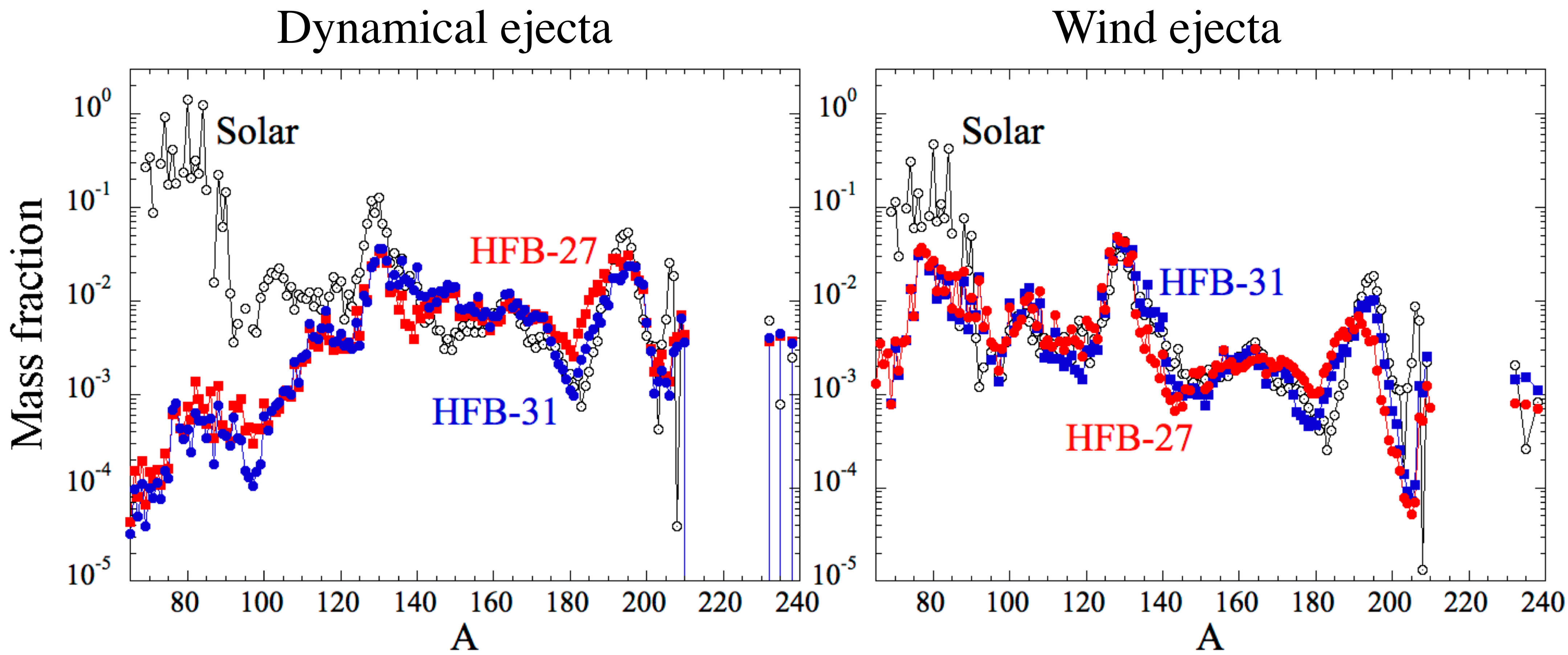
Good mass fit (rms <0.8MeV) is a necessary condition, but not a sufficient one

Nuclear masses and their impact on the r-abundance distribution

Nuclear masses driving the (n,γ) ⟷ (γ,n) competition

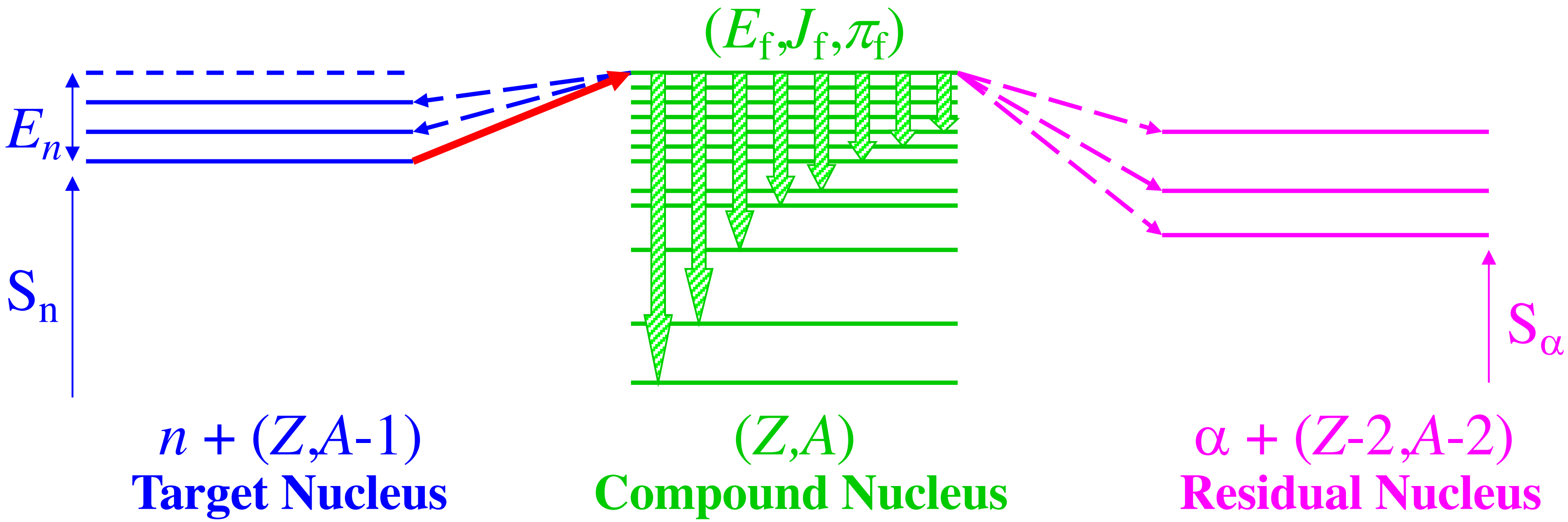
2 HFB mass models: HFB-27: Standard Skyrme σ_{rms}=0.50MeV

HFB-31: Generalized Skyrme σ_{rms}=0.56MeV



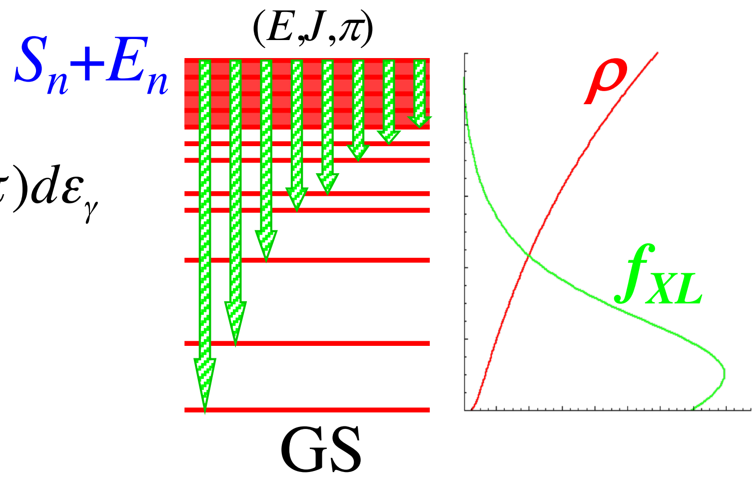
→ Need further "microscopic" calculations beyond mean-field

Hauser-Feshbach model for radiative neutron capture reactions



$$\sigma_{(n,\gamma)} \propto \sum_{J,\pi} \frac{T_n(J^\pi)T_\gamma(J^\pi)}{T_n(J^\pi)+T_\gamma(J^\pi)} \approx \sum_{J,\pi} T_\gamma(J^\pi)$$ since $T_n(J^\pi) >> T_\gamma(J^\pi)$: E_n~keV

$$T_\gamma = \sum_{J^\pi XL} \int_0^{S_n+E_n} 2\pi\varepsilon_\gamma^{2L+1} f_{XL}(\varepsilon_\gamma)\rho(S_n+E_n-\varepsilon_\gamma, J, \pi)d\varepsilon_\gamma$$



Nuclear astrophysics apps require
NLDs & GSF for ~ 8000 nuclei

Mean Field + QRPA γ-ray strength function

*Large-scale E*1 Mean-Field + QRPA calculations

Skyrme-HFB + QRPA	Gogny-HFB + QRPA	RMF +QRPA

QRPA calculations can accurately reproduce experimental data, provided *empirical corrections* are made, *i.e.*

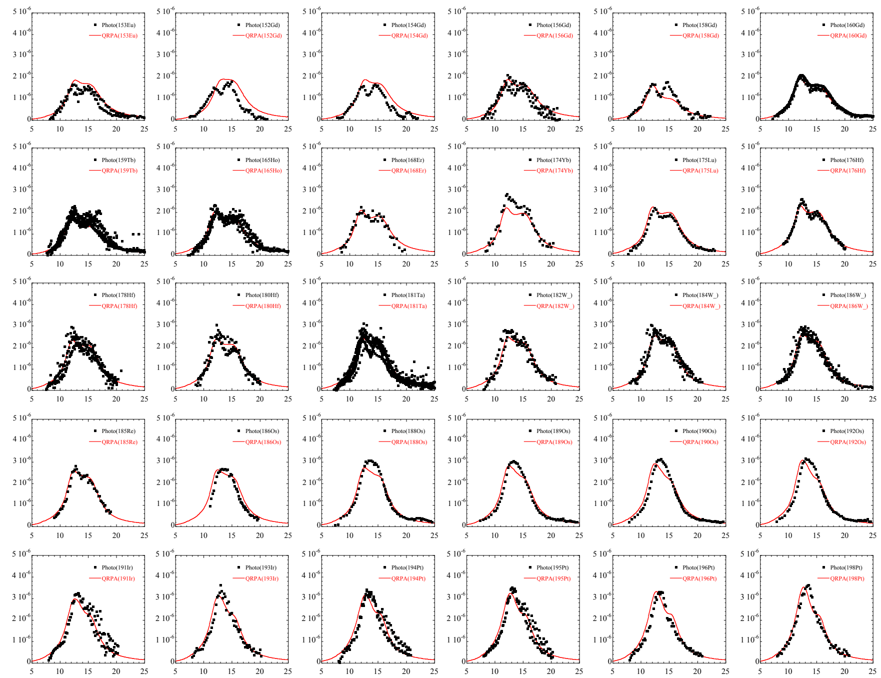
- Empirical Energy shift (beyond 1p-1h excitations and phonon couplings)
- Empirical damping of collective motions → broadening
- Empirical deformation effects for *spherical calculations*

Recent large-scale axially-deformed Gogny-HFB + QRPA calculations with D1M interaction
for ~2000 e-e nuclei with $8 \leq Z \leq 110$
(interpolation for odd-A & odd-odd nuclei)

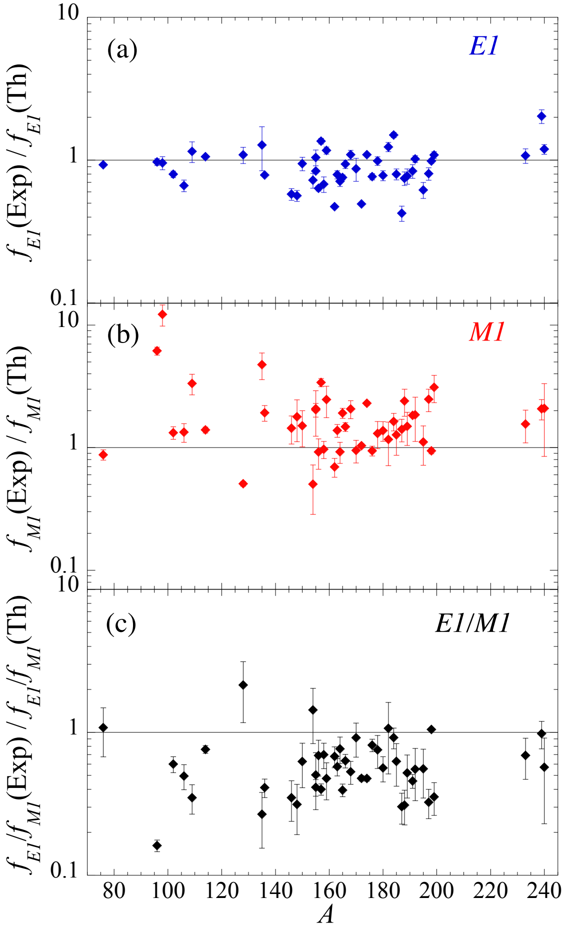
Gogny-HFB + QRPA *E*1 and *M*1 strength functions

QRPA calculations of the *E*1 & *M*1 strengths *empirically renormalized* on exp. data

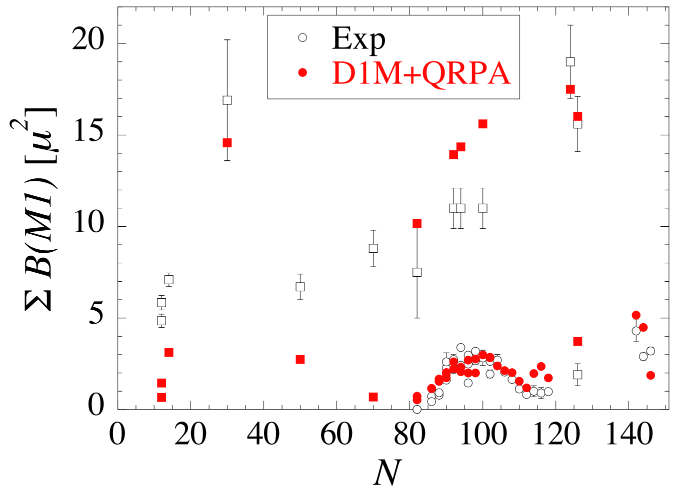
Photo data



ARC data



NRF data

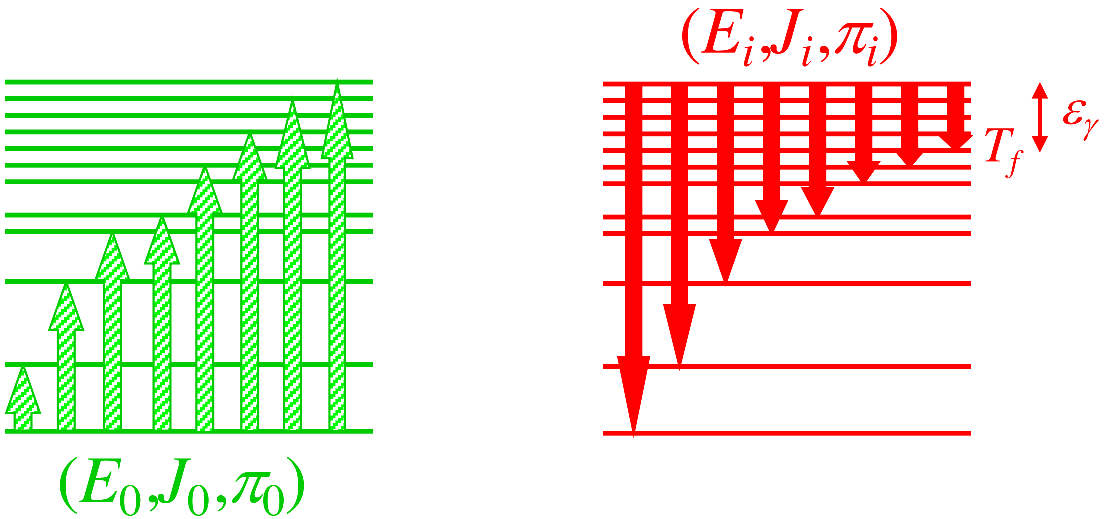


Presence and impact of a possible low-energy *M*1 upbend of the de-excitation strength function

Violation of the Brink hypothesis

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma) \neq \overrightarrow{f}_{E1}(\varepsilon_\gamma)$$

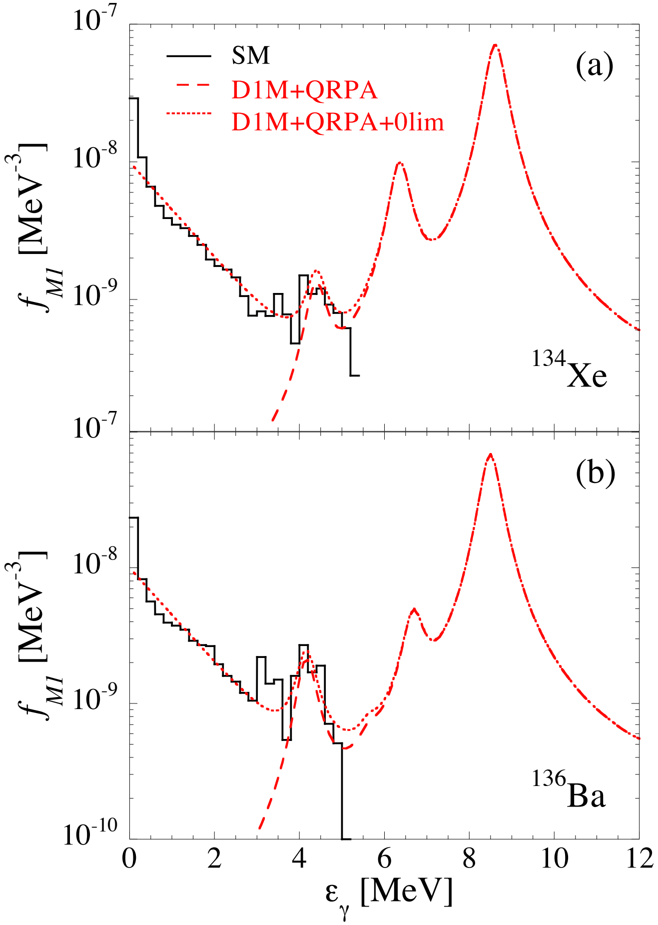
$$\overleftarrow{f}_{E1} = \overleftarrow{f}_{E1}(\varepsilon_\gamma, T_f)$$



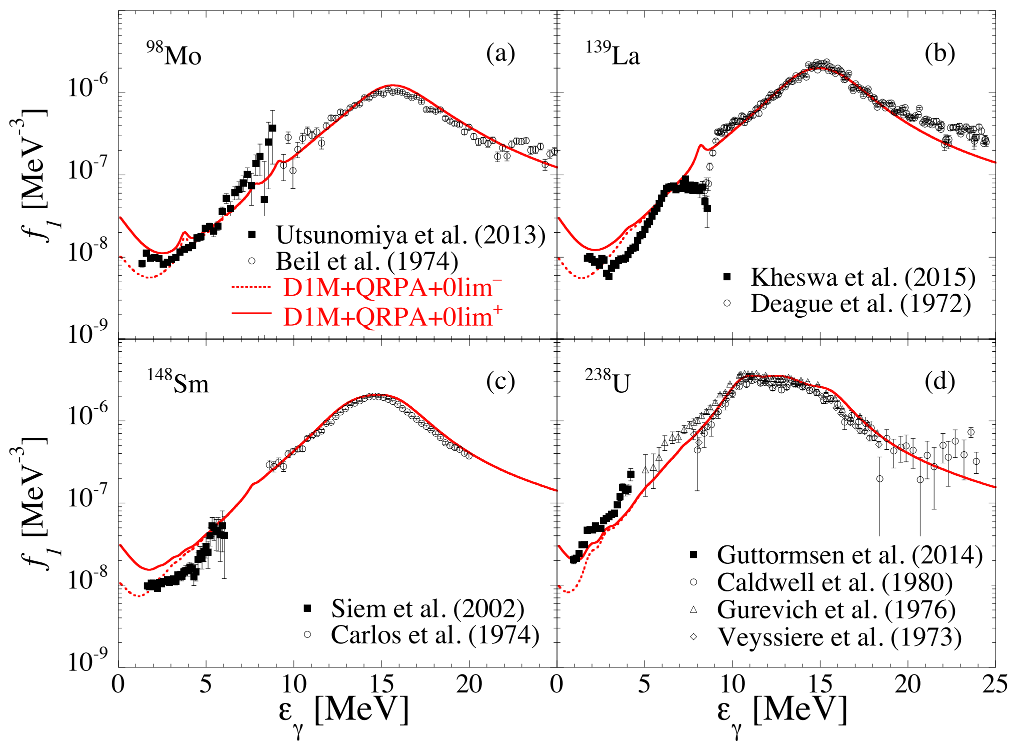
SM-inspired low-energy correction of the de-excitation strength

$$f_{E1} = f_{E1}^{QRPA} + f_{E1}(\varepsilon_\gamma \to 0)$$ Non-zero limit of the *E1* strength at $\varepsilon_\gamma \to 0$

$$f_{M1} = f_{M1}^{QRPA} + f_{M1}(\varepsilon_\gamma \to 0)$$ Upbend of the *M1* strength at $\varepsilon_\gamma \to 0$



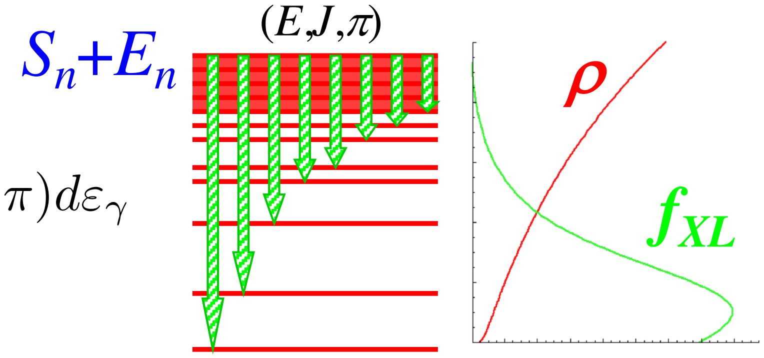
Oslo data



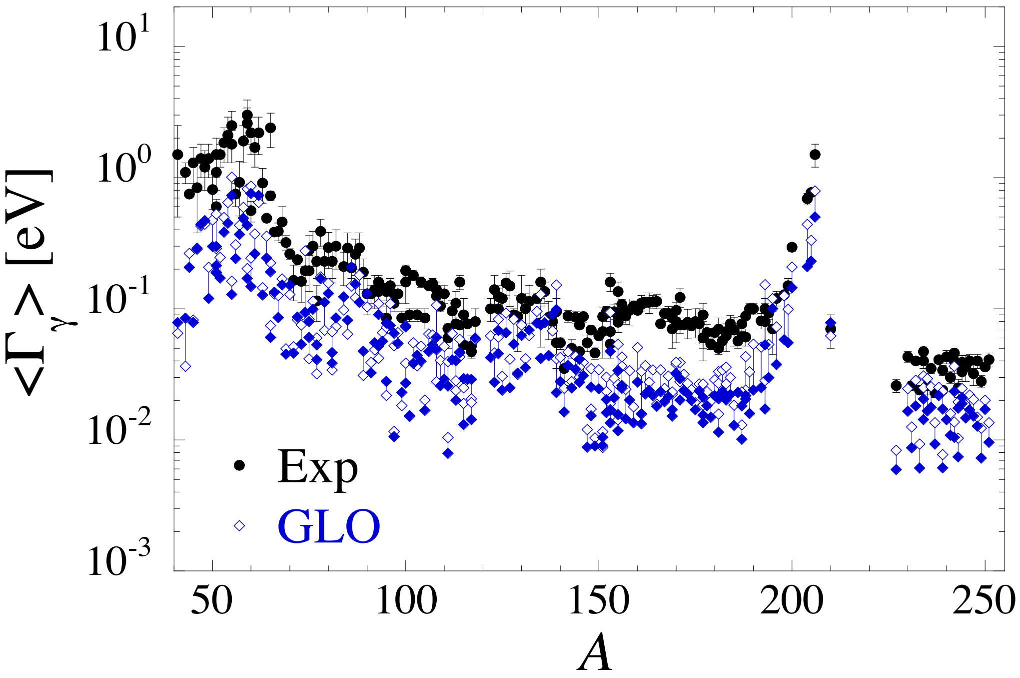
See also Litvinova talk (this workshop)

The long-standing problem of the average radiative width $<\Gamma_\gamma>$

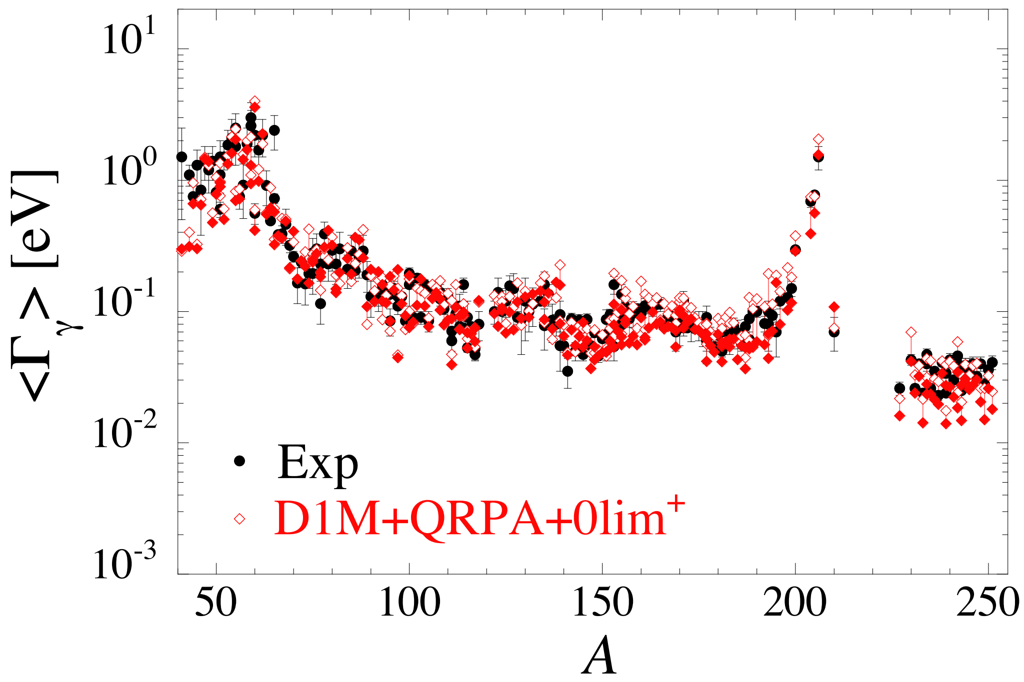
$$\langle \Gamma_\gamma \rangle = \frac{D_0}{2\pi} \sum_{X,L,J,\pi} \int_0^{S_n+E_n} T_{XL}(\varepsilon_\gamma) \times \rho(S_n + E_n - \varepsilon_\gamma, J, \pi) d\varepsilon_\gamma$$



Standard GLO

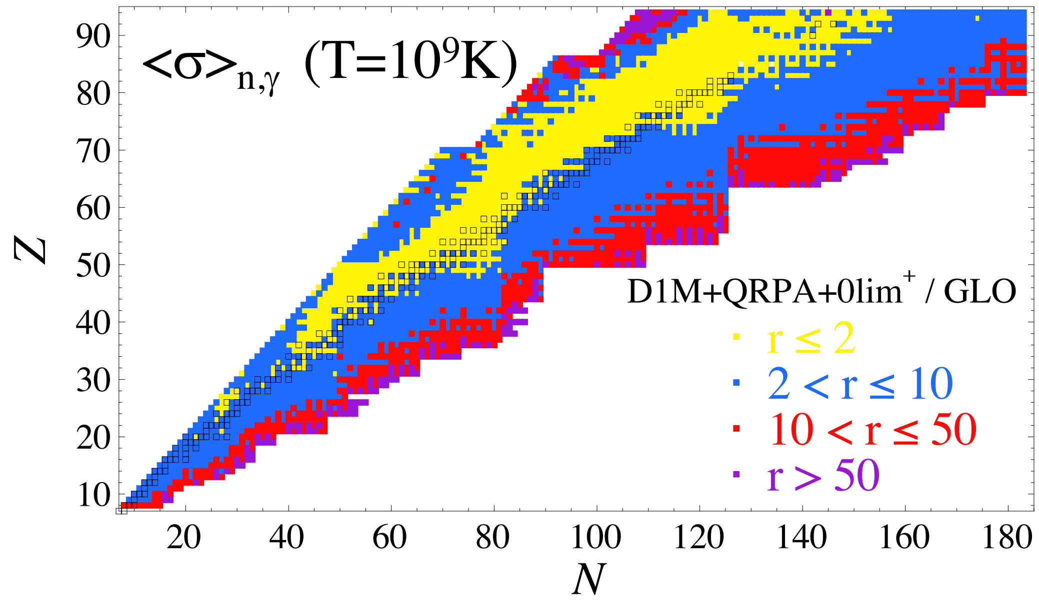


New D1M+QRPA+0lim



Theoretical error bars correspond to different NLD prescriptions

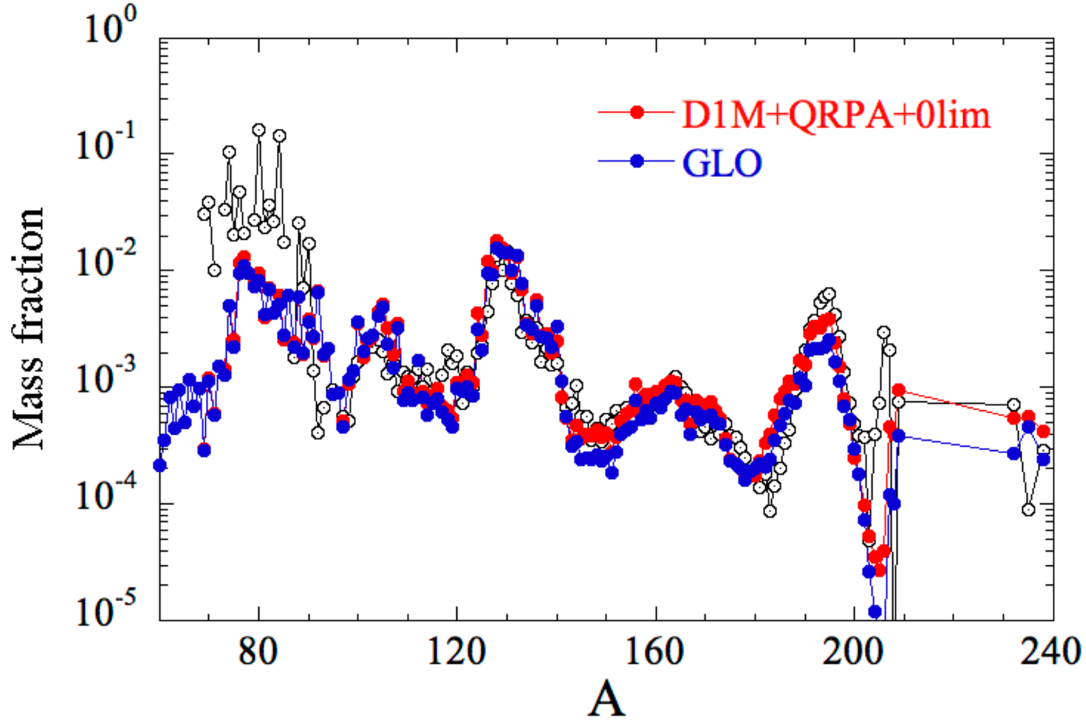
Impact of the new E1/M1 strength on the radiative n-capture rate of astrophysical interest



Increase of <σ> due to low-energy

- *E*1 QRPA low-E strength
- *M*1 scissors & upbend

Impact of the new E1/M1 strength on the r-process nucleosynthesis in the NSM disk ejecta



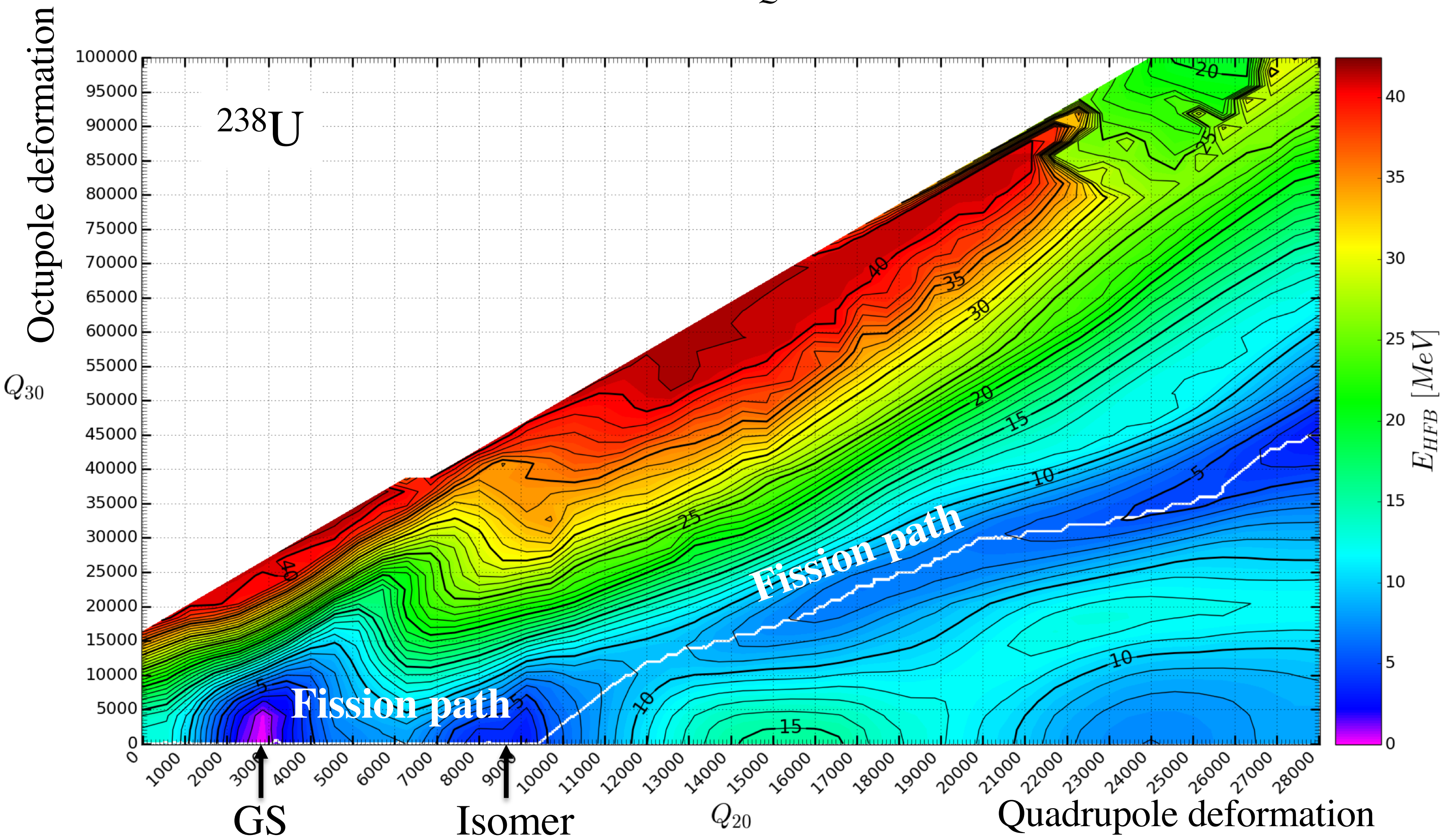
Increase production of

- Lanthanides & 3rd peak
- Actinides & chronometers

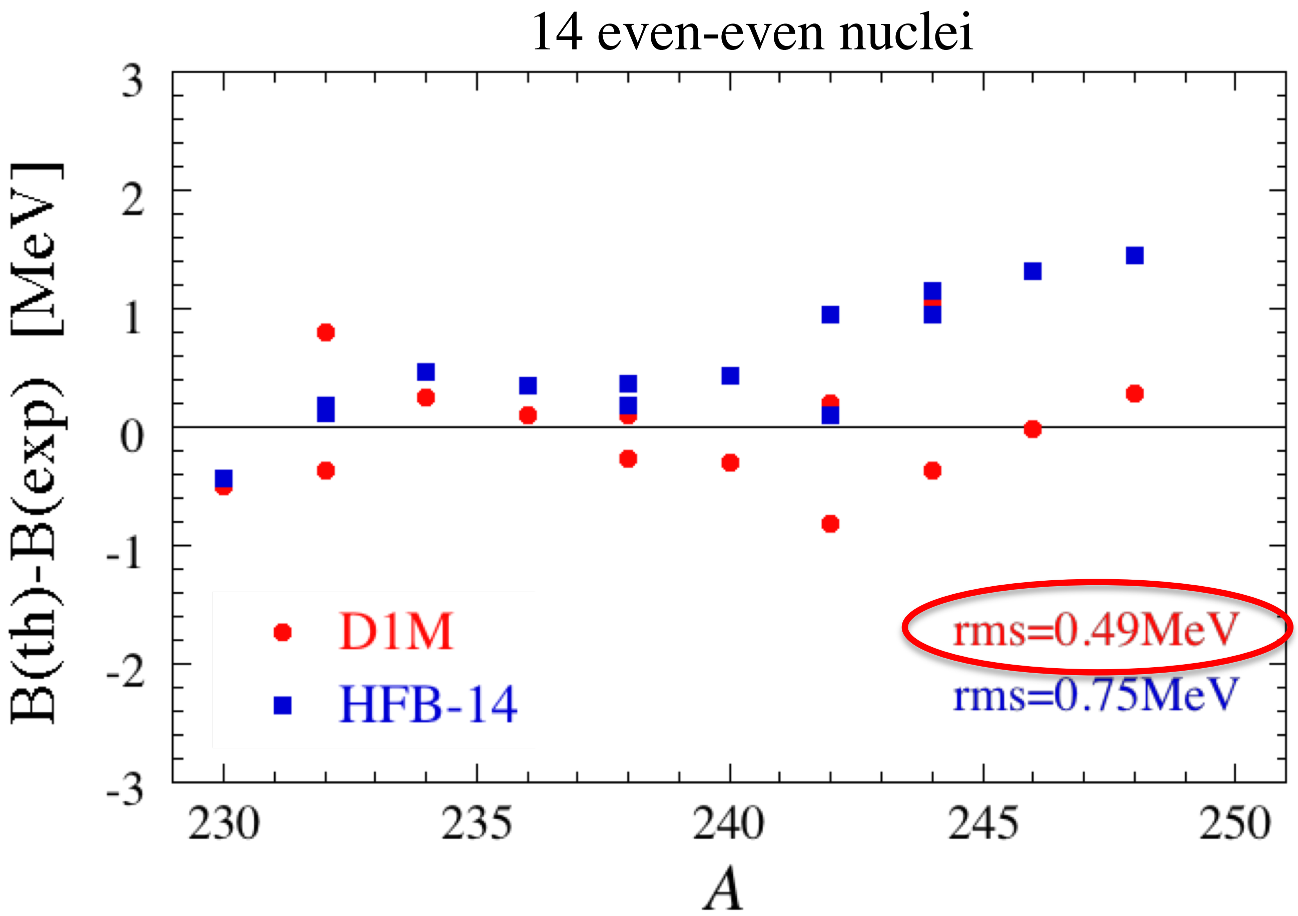
Calculation of the Gogny-HFB fission paths

Potential energy surface determined with D1M interaction from

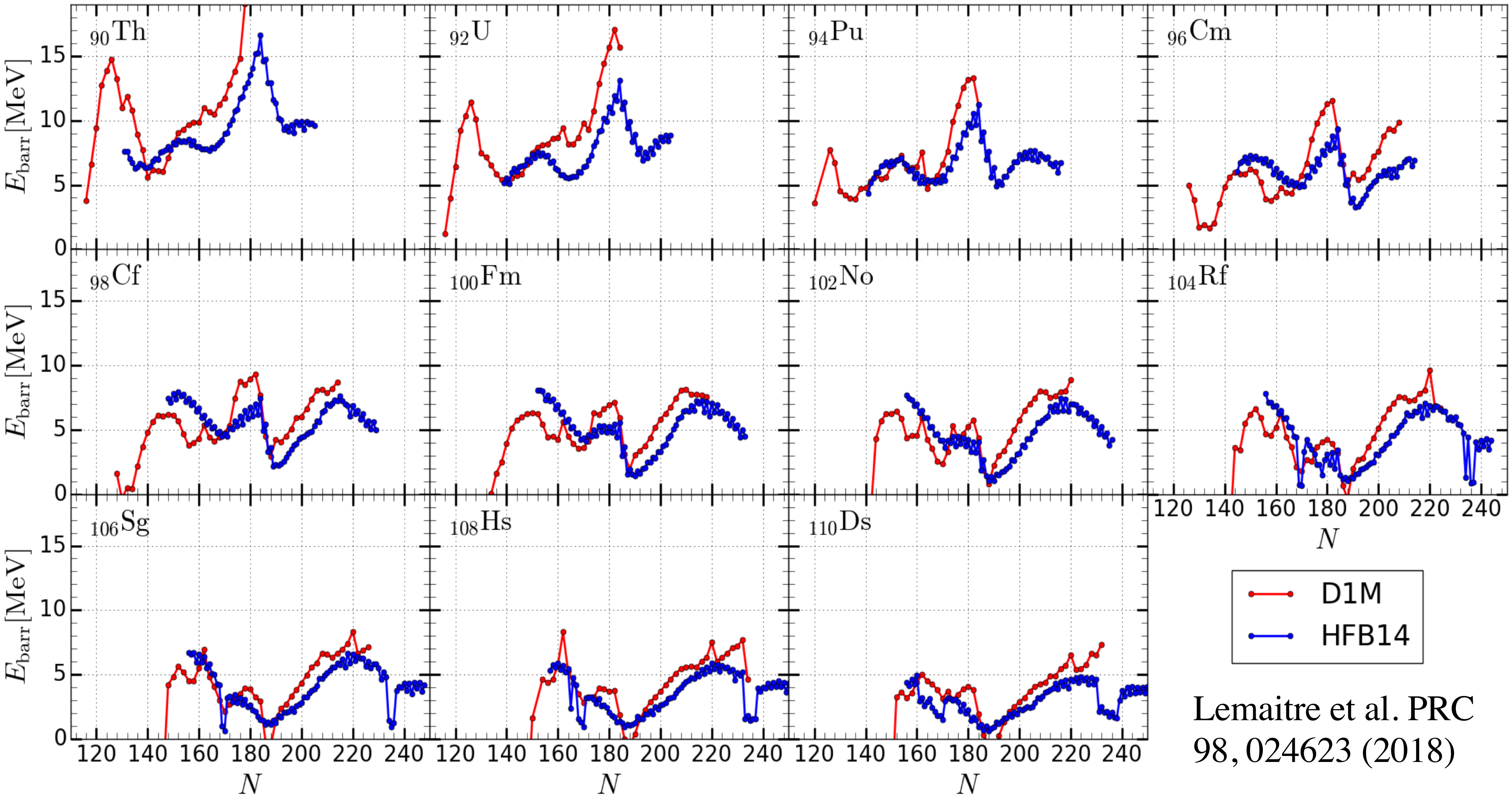
$$E(\beta_2, \beta_3) = E_{HFB} + \Delta E_{Quad} + \Delta E_{triax} + \Delta E_{ZPE}$$ (N. Dubray 2016)



Comparison of the *primary* barrier with empirical barriers (RIPL-3)



Comparison for 424 fission barriers of e-e 90≤Z≤110 nuclei

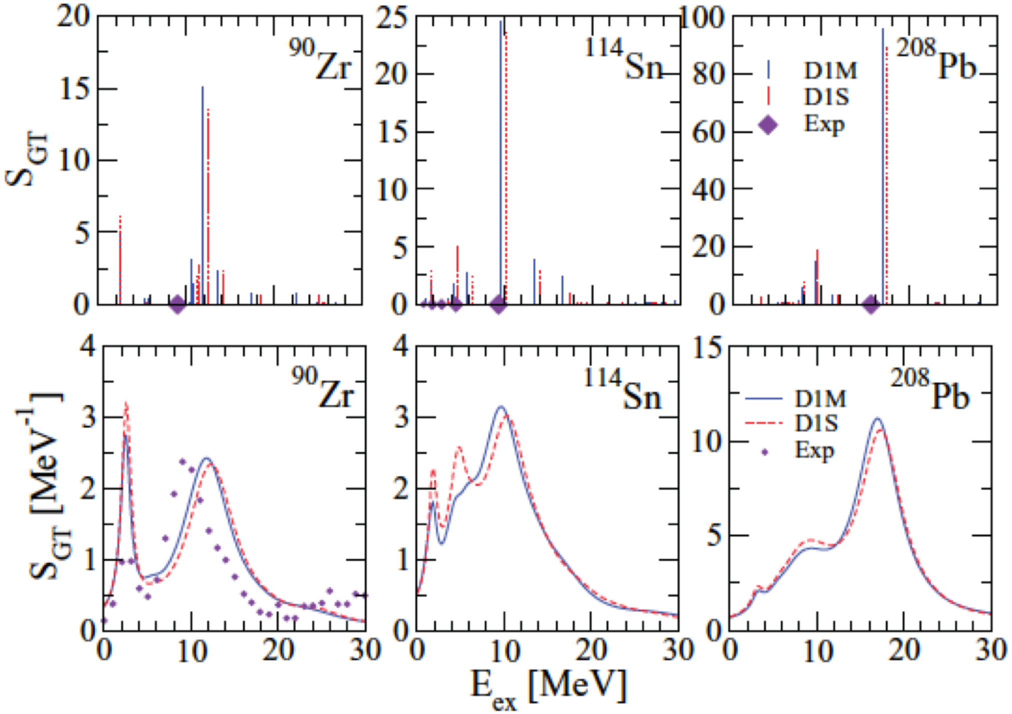


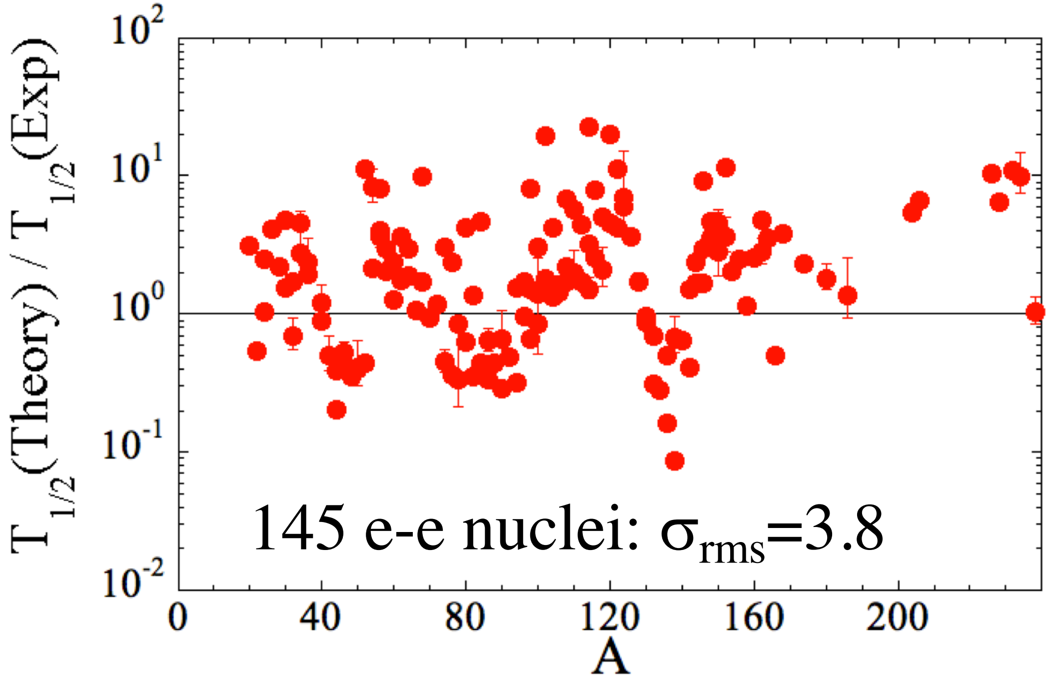
Lemaitre et al. PRC 98, 024623 (2018)

PES for odd nuclei under progress

β-decay rates

Calculation of the GT β-strength function within the axially deformed HFB+QRPA approach with D1M Gogny force (Martini, Peru, SG 2014)





$$\frac{\ln 2}{T_{1/2}} = \frac{(g_A/g_V)^2_{\rm eff}}{D}\int_0^{Q_\beta} f_0(Z,A,Q_\beta - E_{\rm ex}) S_{\rm GT}(E_{\rm ex})\, dE_{\rm ex}$$

Inclusion of odd nuclei under progress

Conclusions: still many open questions

1. How reliable are the present β-decay models (def, FF, odd-A,…) ?
2. How reliable are the present mass models ?
3. How well can we describe fission processes and FFD distributions ?
4. How reliable are NLD and PSF models for n-rich nuclei ?
5. What is the neutron absorption by n-rich nuclei (OMP) ?
6. What is the direct capture (and PE) contribution to the n-capture rates for exotic n-rich nuclei ?
7. What is the impact of the Resolved Resonance Region of n-rich nuclei on n-capture rates ?
8. How can we properly treat nuclear UNCERTAINTIES in *r*-process simulations ?

… Still a lot of nuclear physics questions to answer to …

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