Kilonova & Nuclear Physics Discussion

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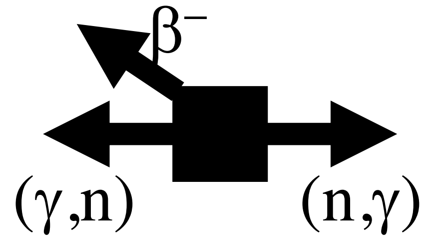
Food For Thoughts

- The importance of **rates** for the r-process nucleosynthesis
- The reaction model
  - Optical model potential
  - Direct radiative capture
  - The Resolved Resonance Region
- The various ingredients to the calculations of rates
  - Masses
  - γ-ray strength function
  - Nuclear level densities
- Fission
  - Fission paths and probability estimates
  - Fission fragment distribution (nb of ejected neutrons)

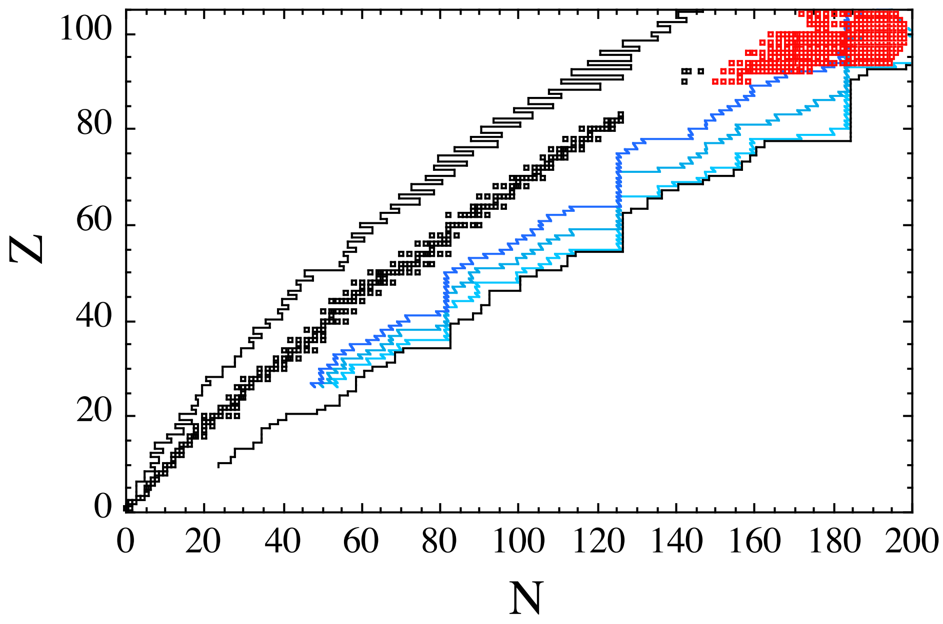
Nuclear needs for r-process nucleosynthesis

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



- β-decay
- (n,γ) **rates** and (γ,n) **rates**
- Fission (nif, sf, βdf) rates
- Fission products distribution
- ν-nucleon interaction

(+ NP associated with initial cond.)

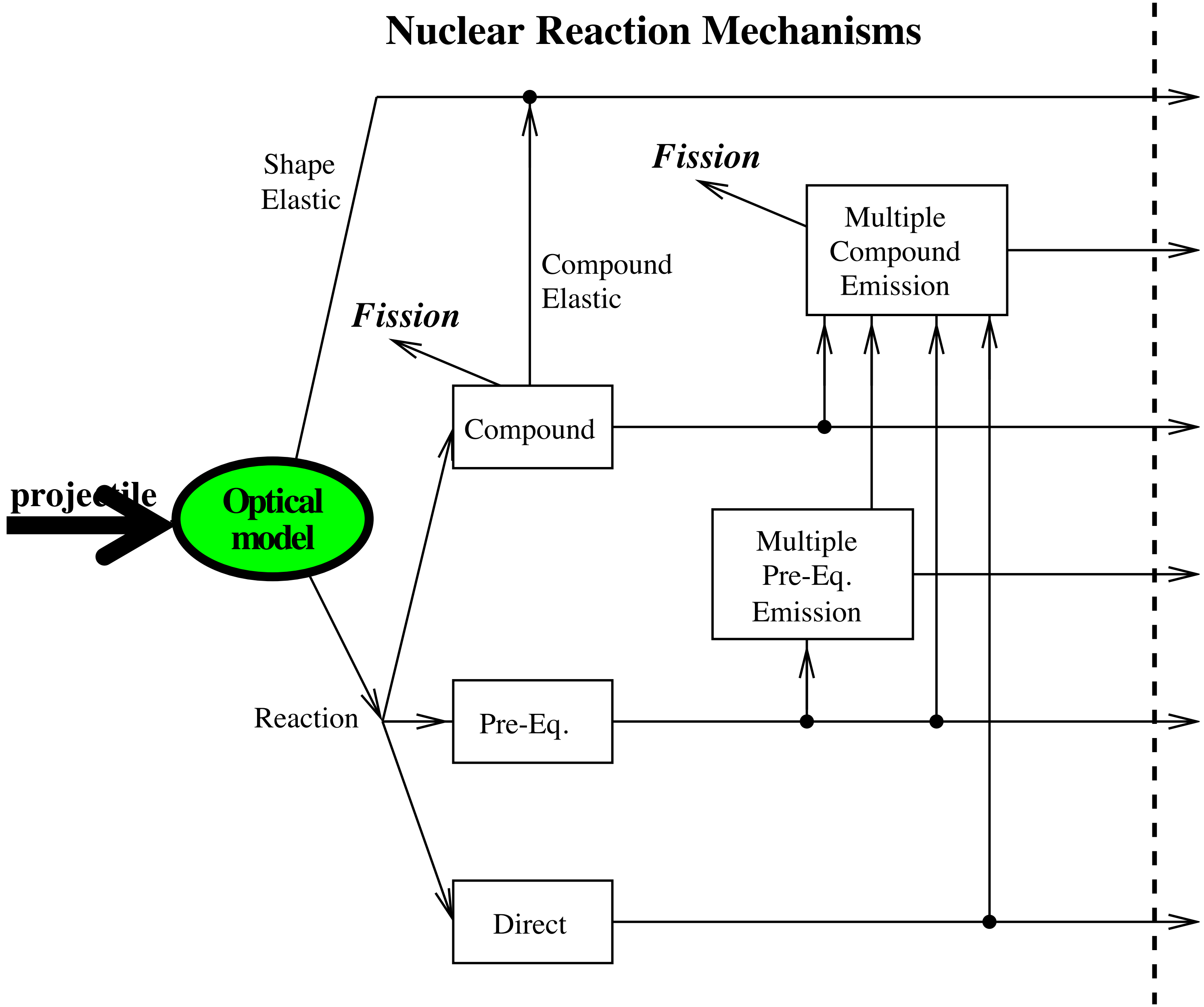


In all cases, nucleosynthesis requires RATES for some 5000 nuclei !

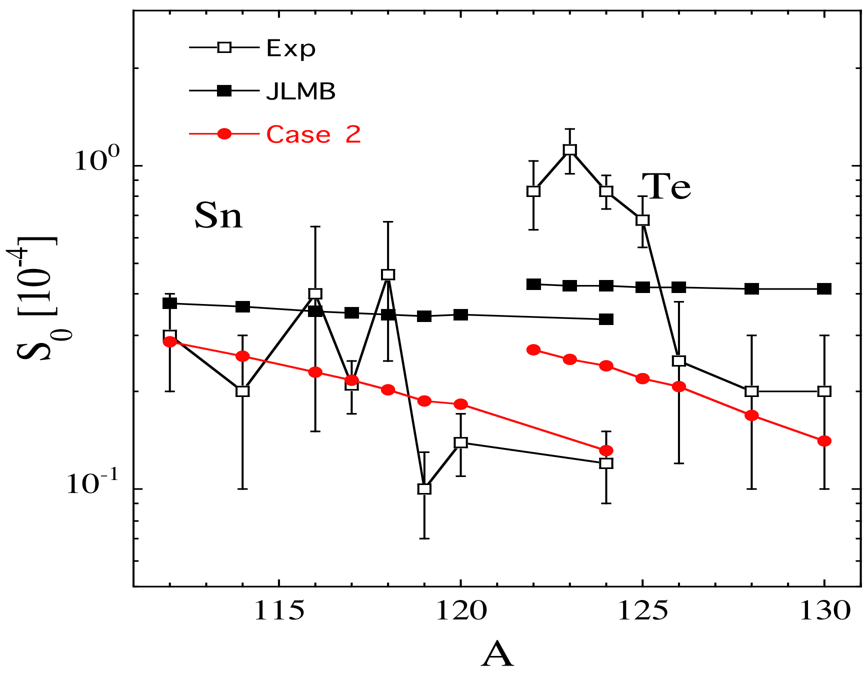
(and not only e-e nuclei, nor only spherical ones, nor those along the oversimplified so-called "r-process path")

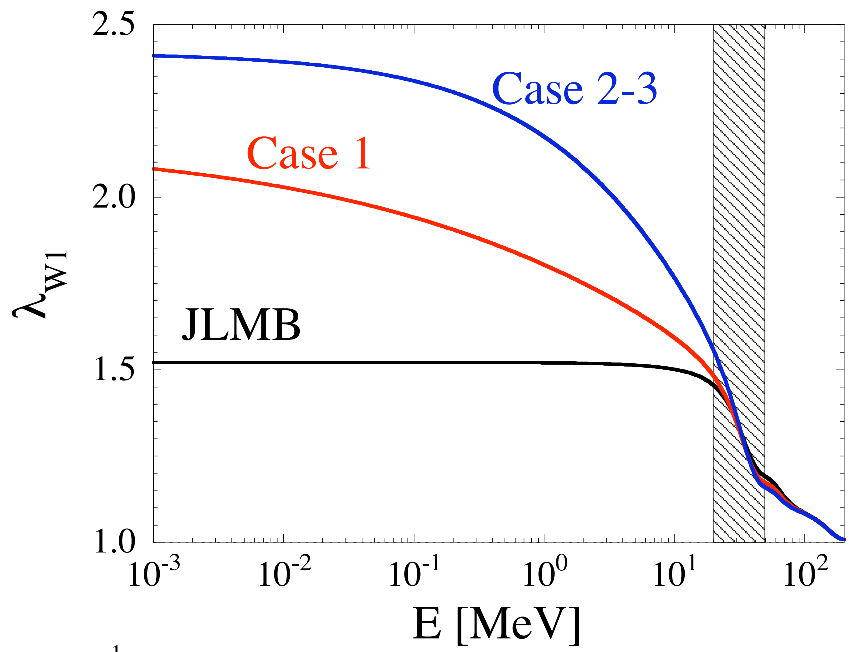
⟹ **simulations rely almost entirely on theoretical predictions**

Models sequence

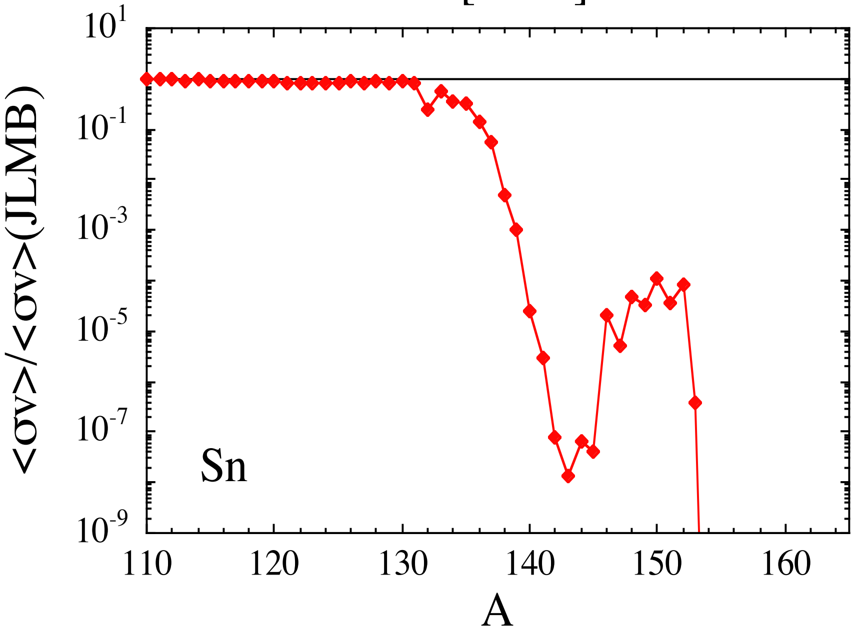


Re-renormalization of the isovector imaginary potential on S-wave neutron strength data

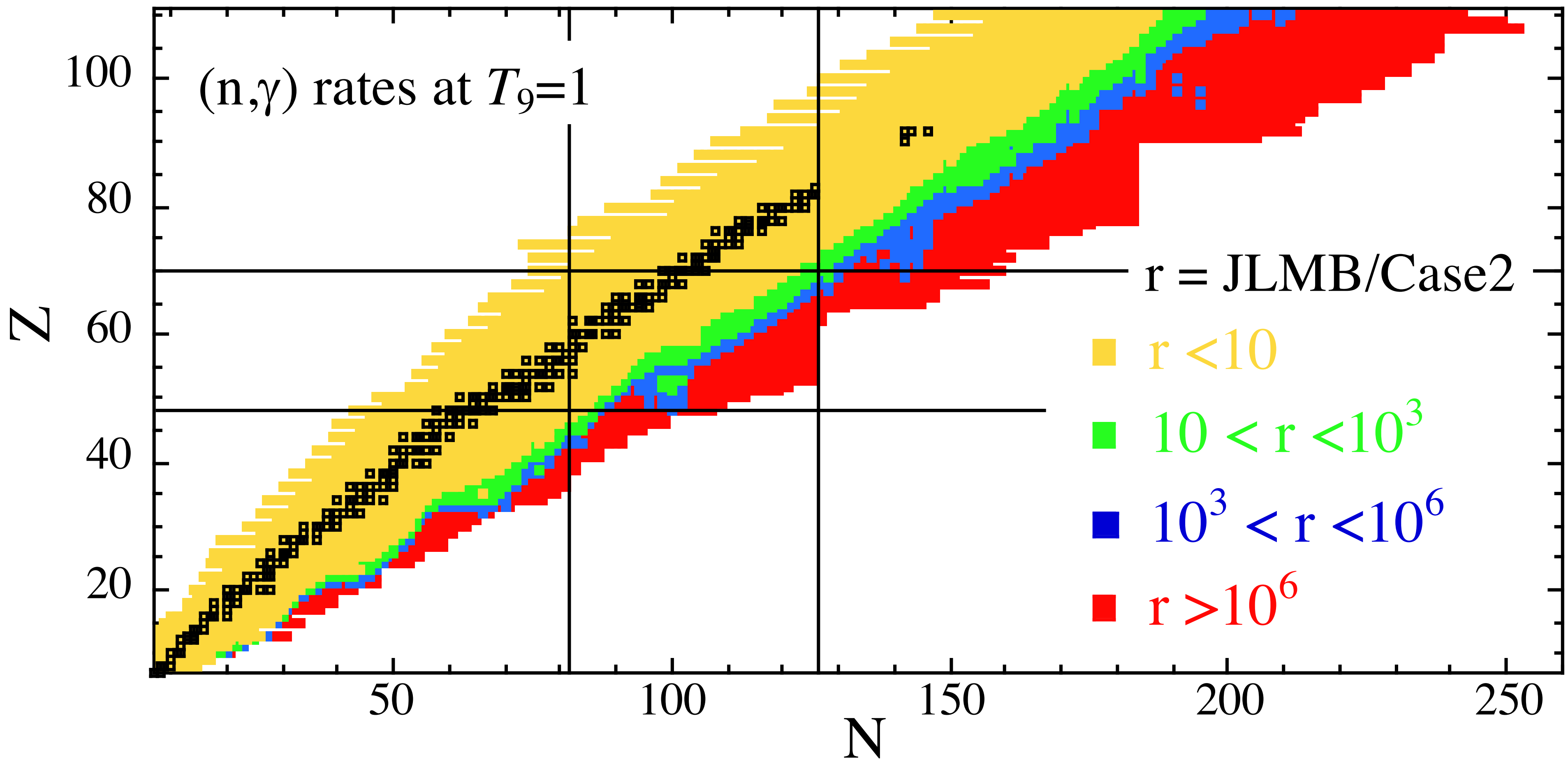




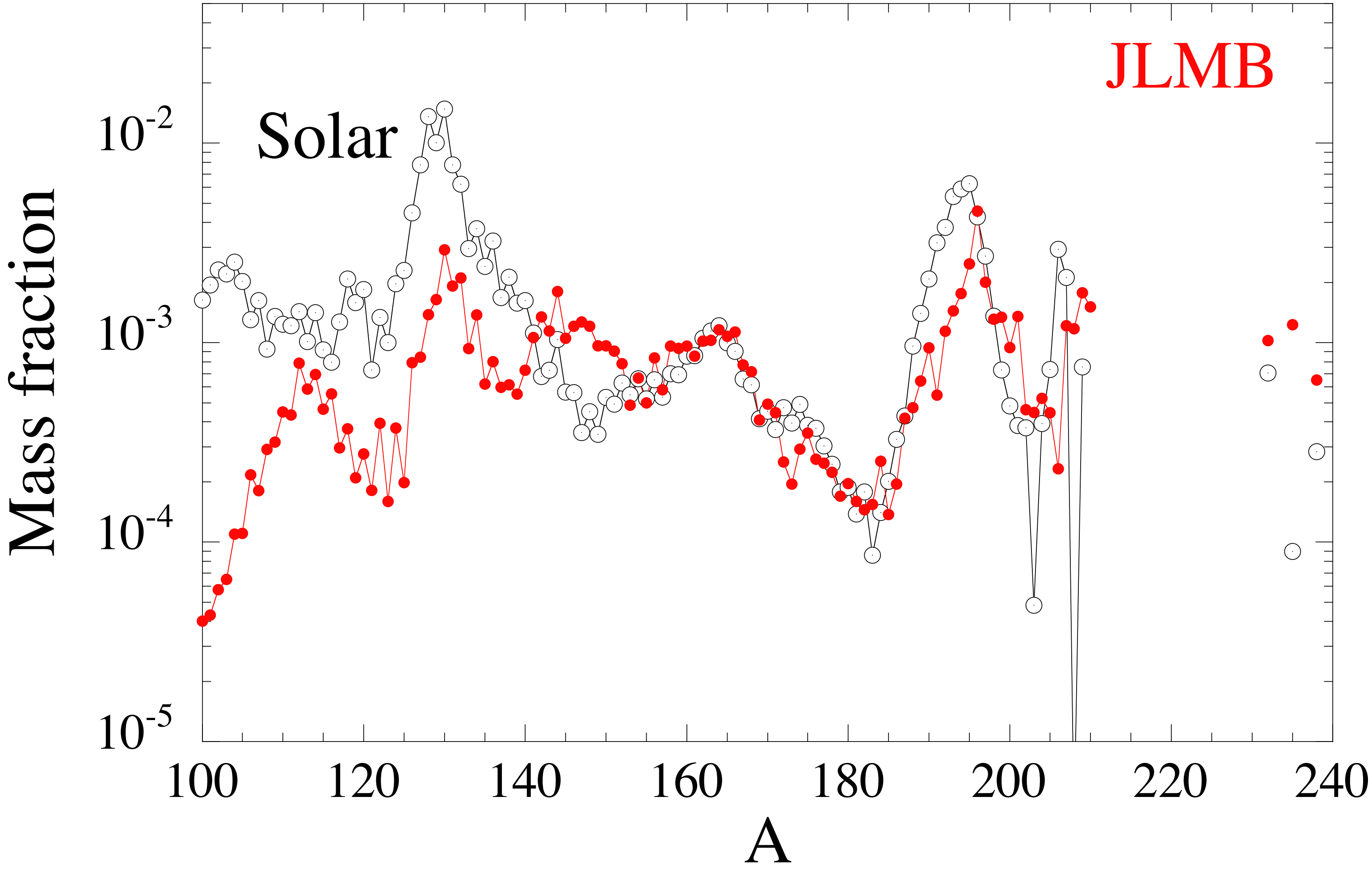
Impact on radiative neutron capture:
large reduction of the radiative capture by exotic n-rich nuclei

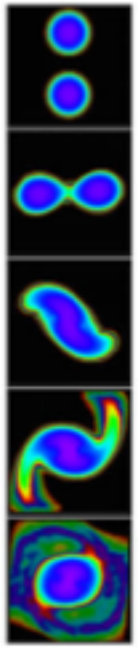


Drastic impact on the resonant capture by exotic neutron-rich nuclei



Impact on the r-process in the dynamical ejecta of binary NS mergers





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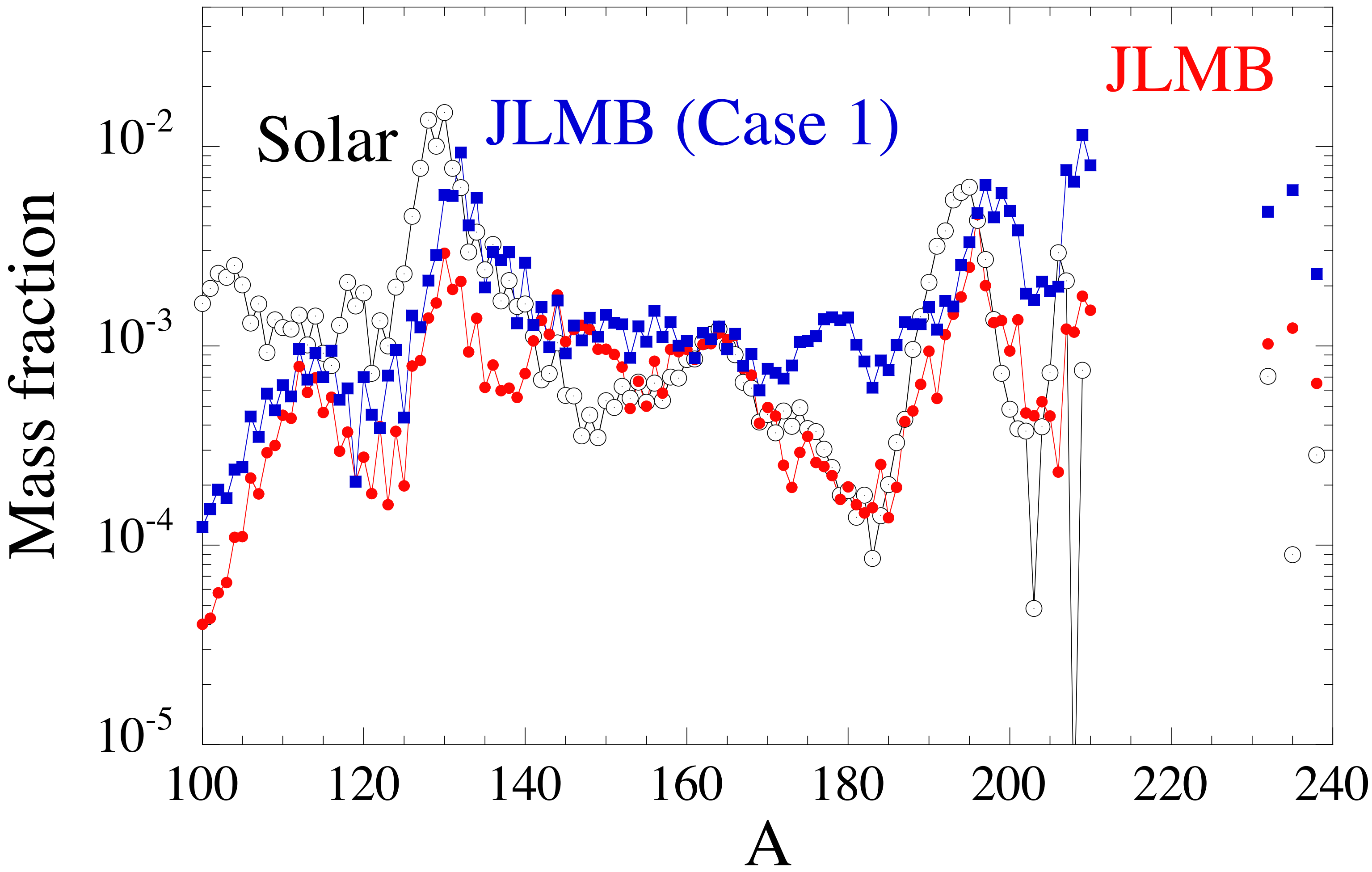

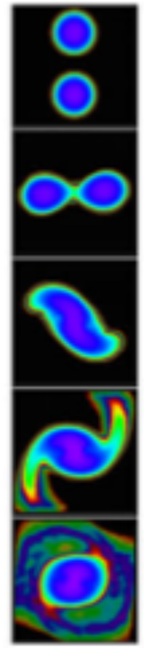

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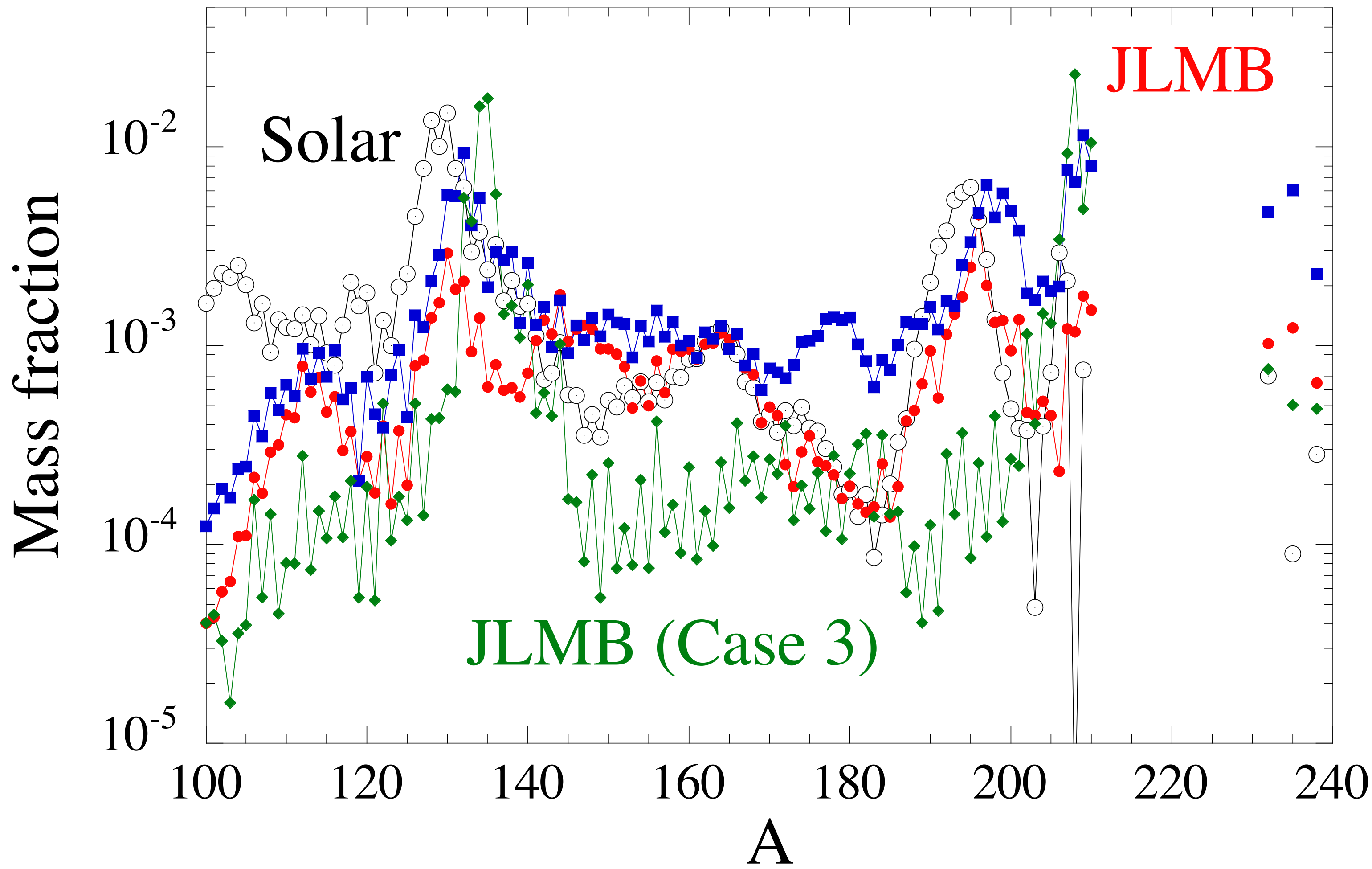
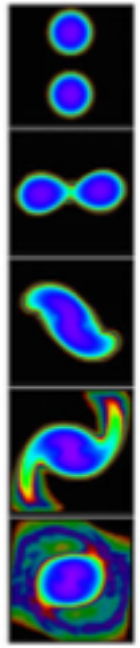
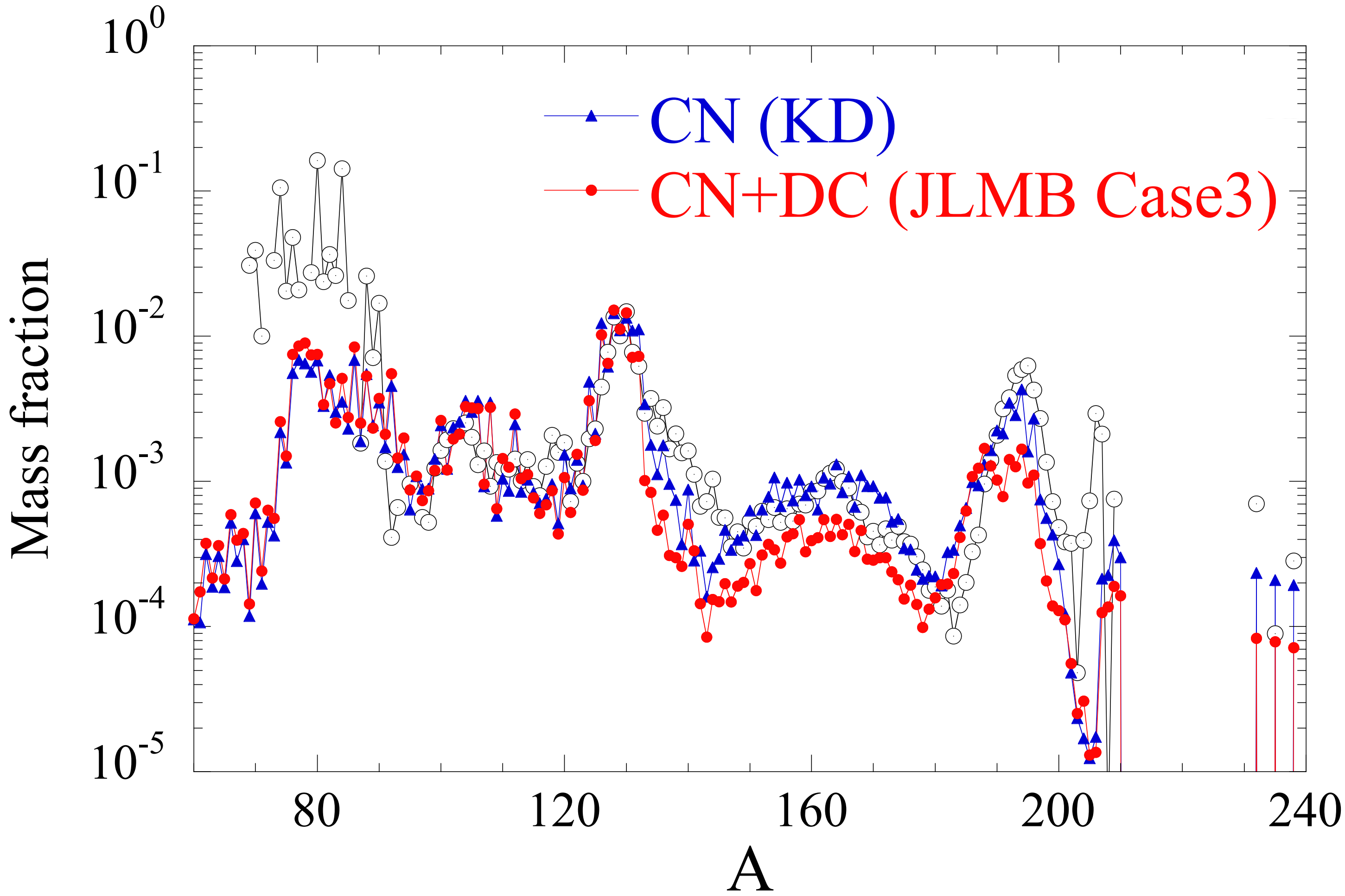
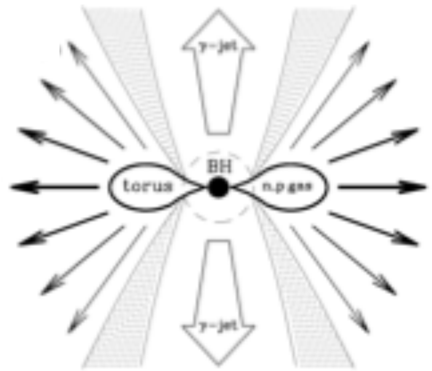




Impact on the r-process in the disk ejecta of binary NS mergers





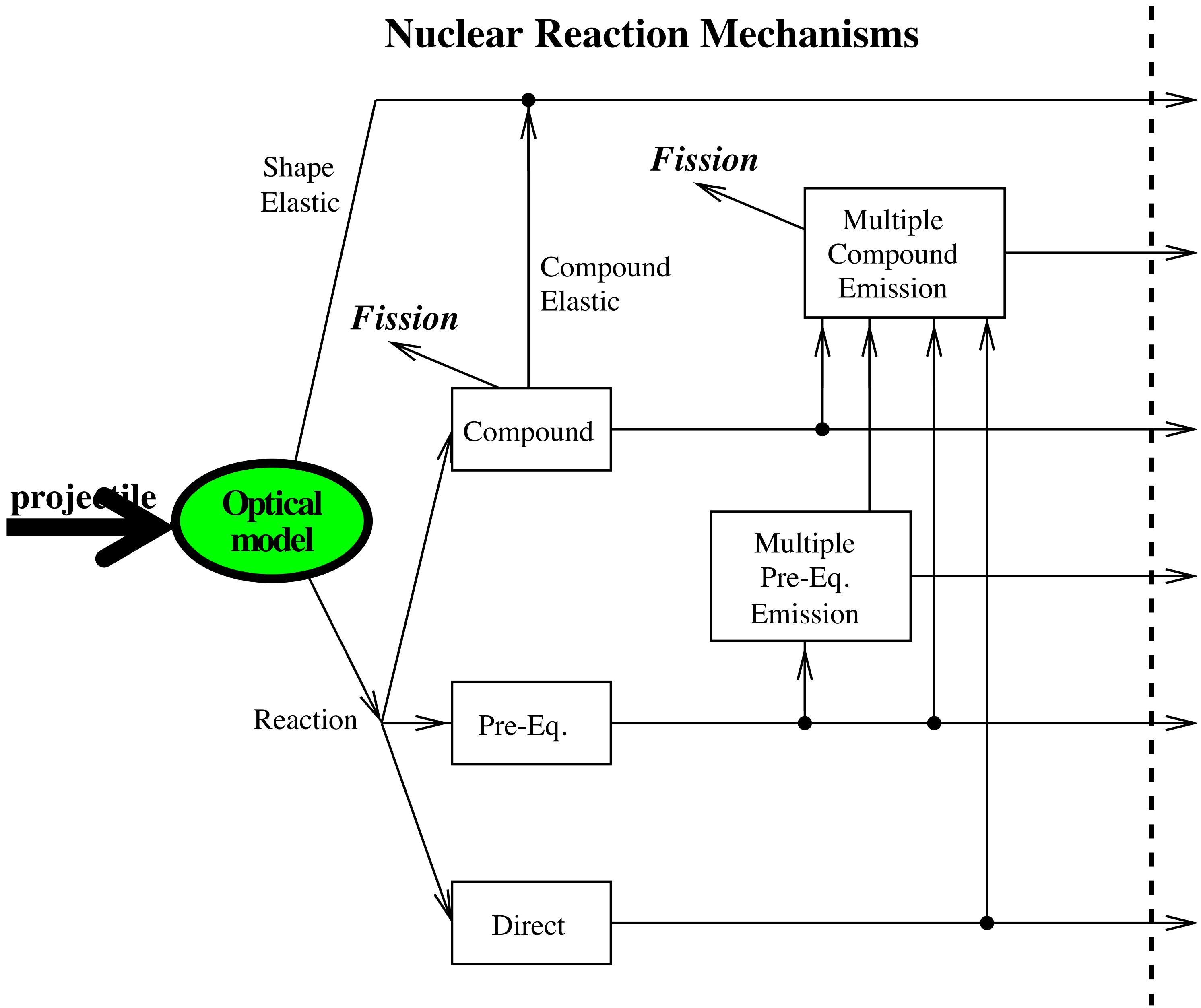
$M_{BH}=3M_o$
$M_{torus}=0.1M_o$

Masses: HFB24
β-rates: RRPA

Questions raised

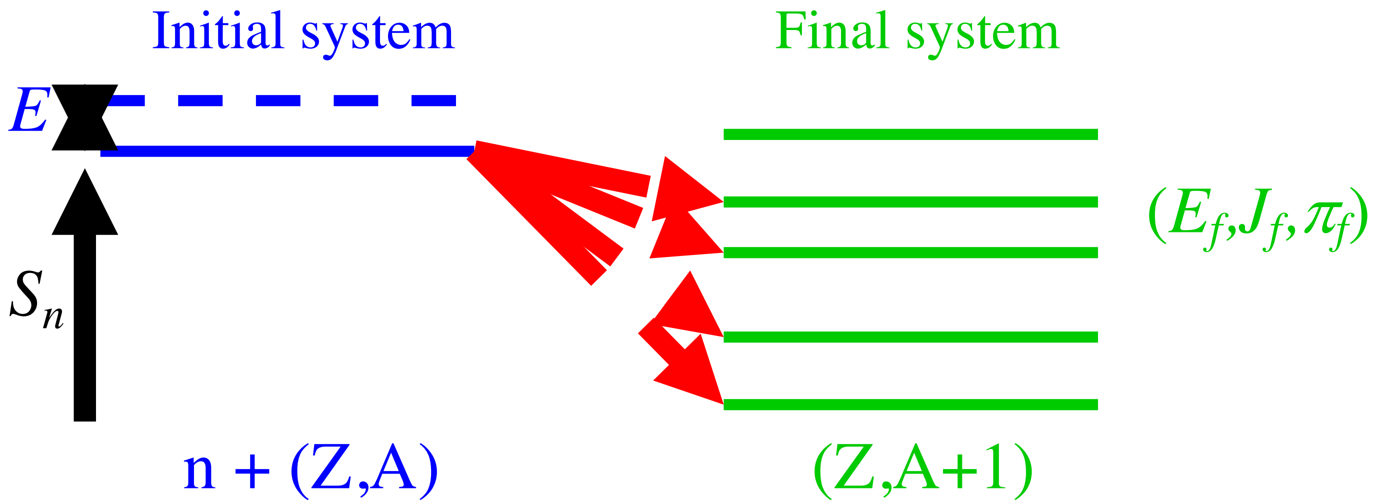
1. What is the neutron absorption (Imaginary W) by n-rich nuclei ?

Models sequence



Direct captures

Direct scatter of incoming neutrons into a bound state without formation of a Compound Nucleus (particularly important for light and low-S_n n-rich nuclei)



Direct capture cross section calculated within the potential model

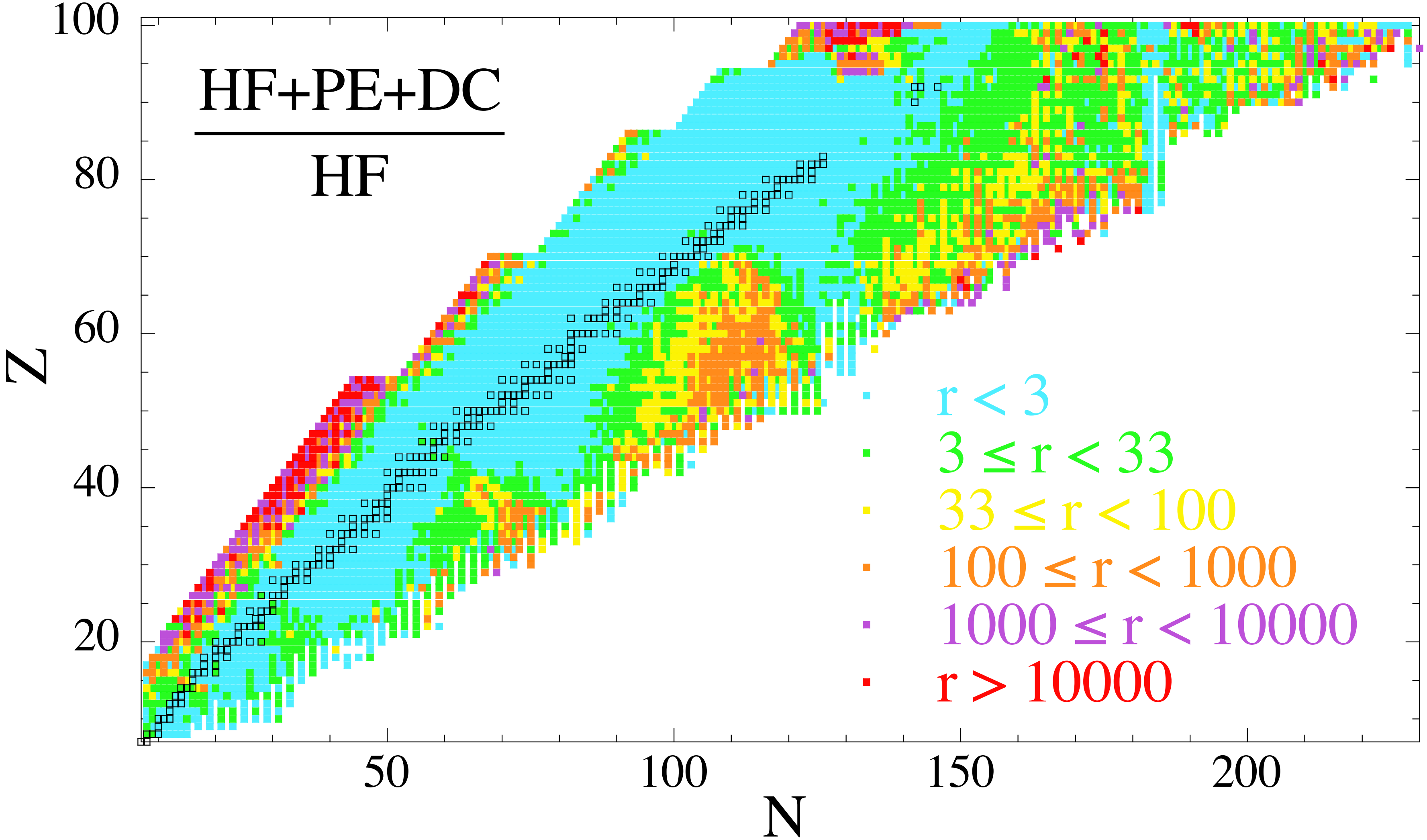
$$\sigma_f^{DC}(E) = \frac{16\pi}{9\hbar}\, k_\gamma^3\, \bar{e}^2\, \mid Q_{i\to f}^{E1}(E) \mid^2 \quad \text{with} \quad Q_{i\to f}^{E1}(E) = \langle \Psi_f \mid T^{E1} \mid \Psi_i(E) \rangle$$

→ reliable model, but requires a proper description of

- n-nucleus potential
- excitation spectrum (E_f, J_f, π_f)
- spectroscopic factor C^2S

Impact of the DC & PE on the HF (n,γ) rates

TALYS calculation



So far no r-process calculation including DC contribution !

Questions raised

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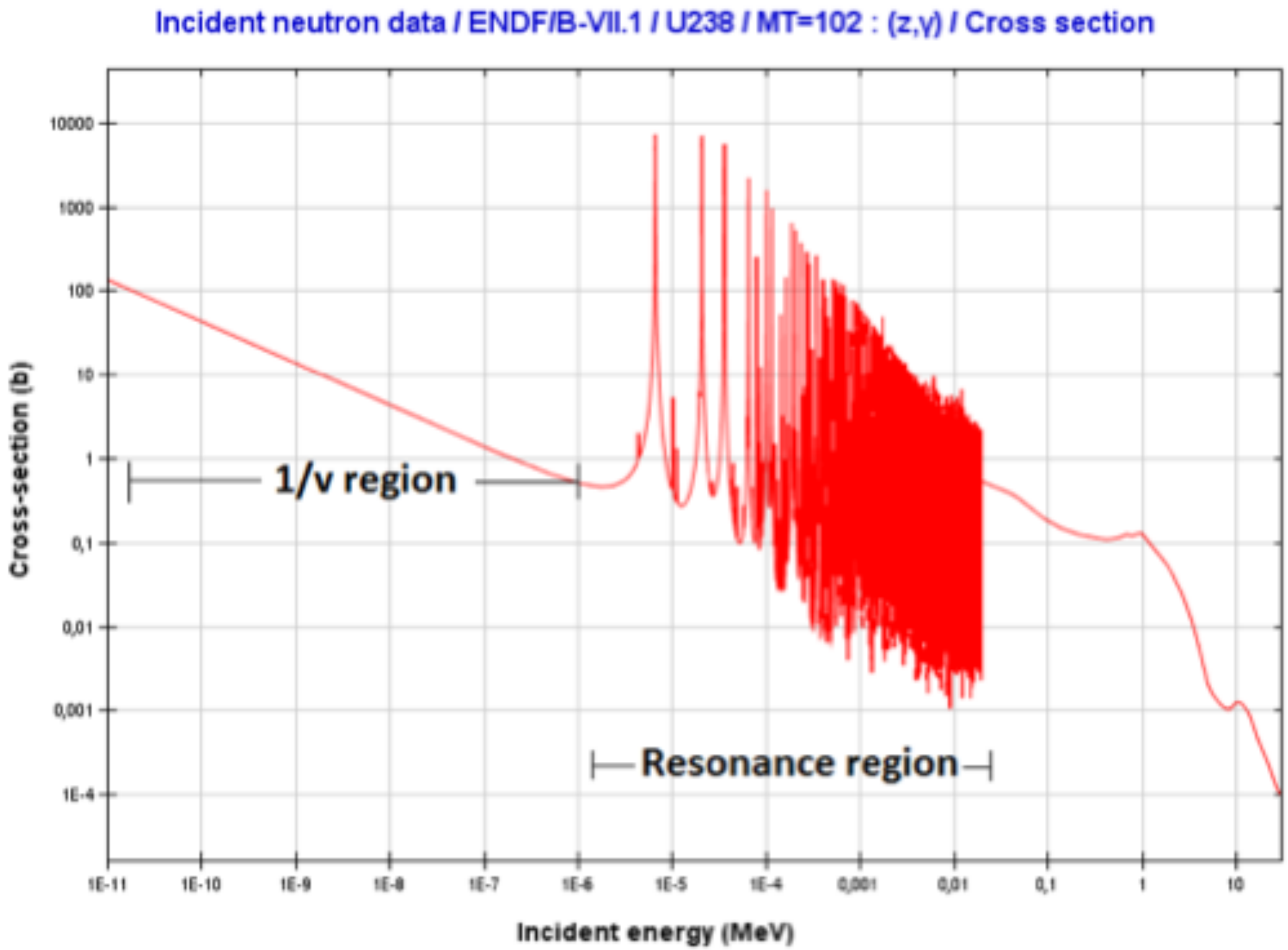
2. What is the direct capture (and PE) contribution to the neutron-capture rates ?

The High-Fidelity Resonance vs Hauser-Feshbach method to predict radiative n-capture cross section

HFR method: average parameters (the scattering radius, level spacing, reduced neutron width and the radiative width) are used to generate resolved resonances



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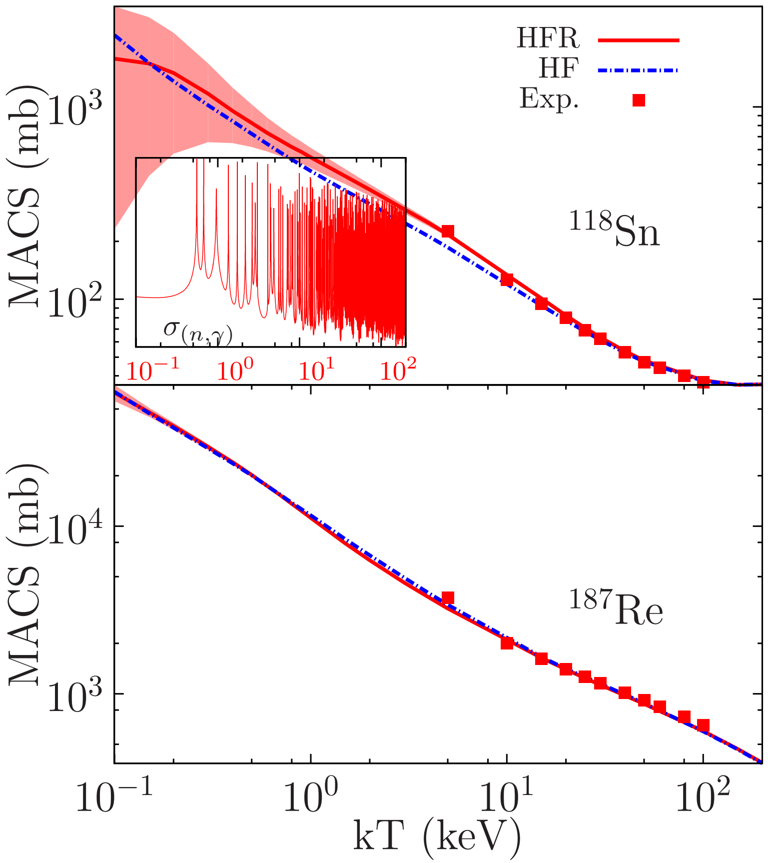
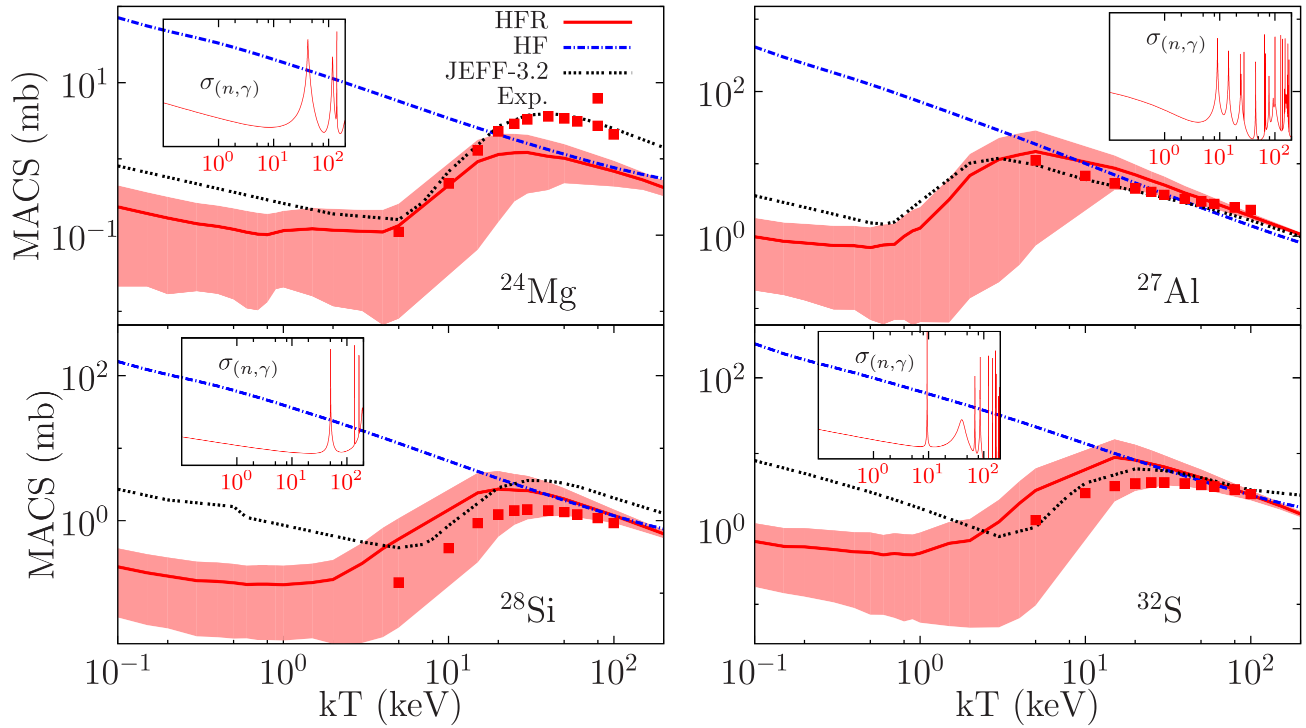
Similar to HF to heavy nuclei



Improved description of MACS of light nuclei



Rochman et al. PLB 764, 109 (2017)

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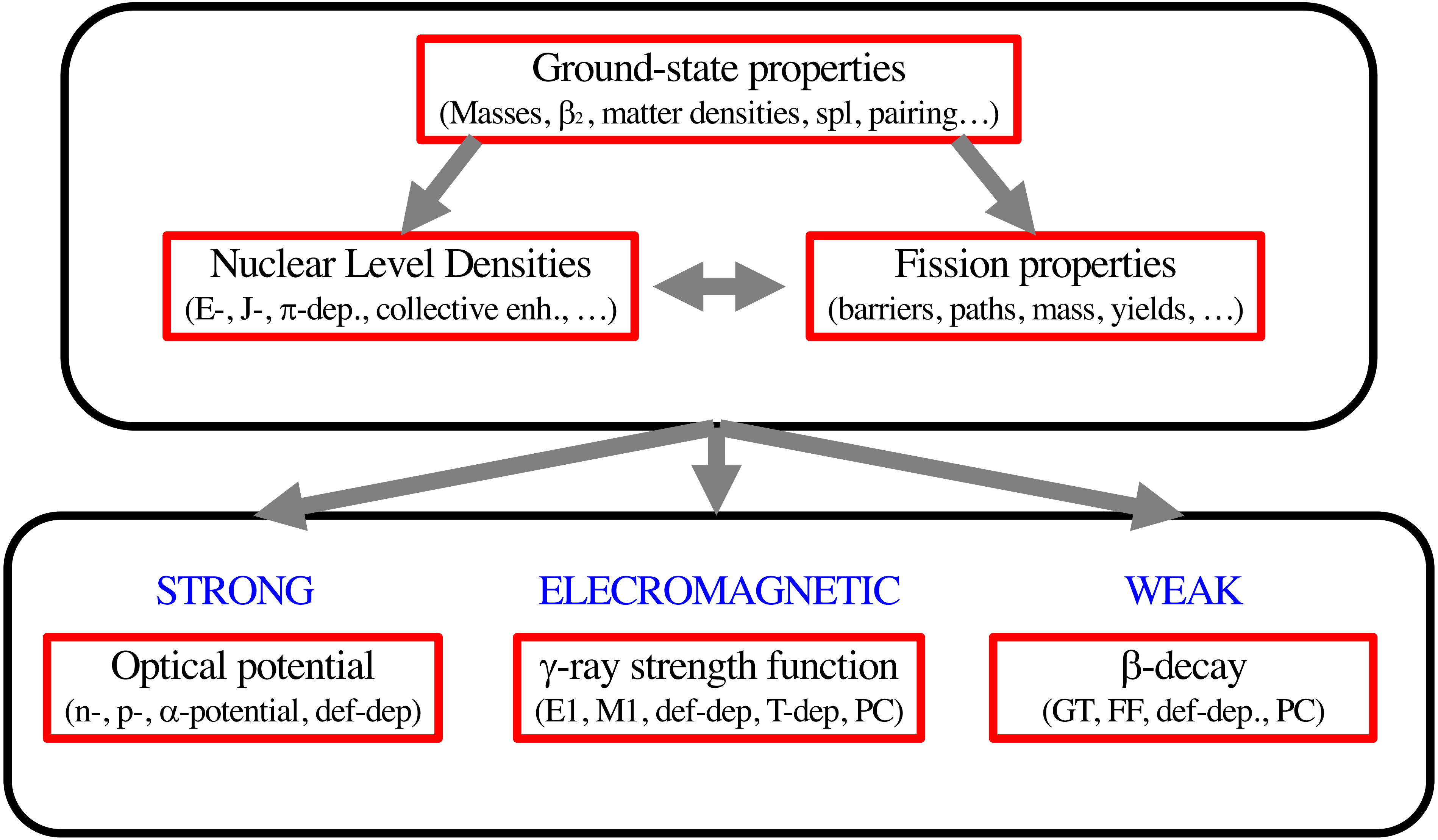
Nuclear inputs to nuclear reaction & decay calculations



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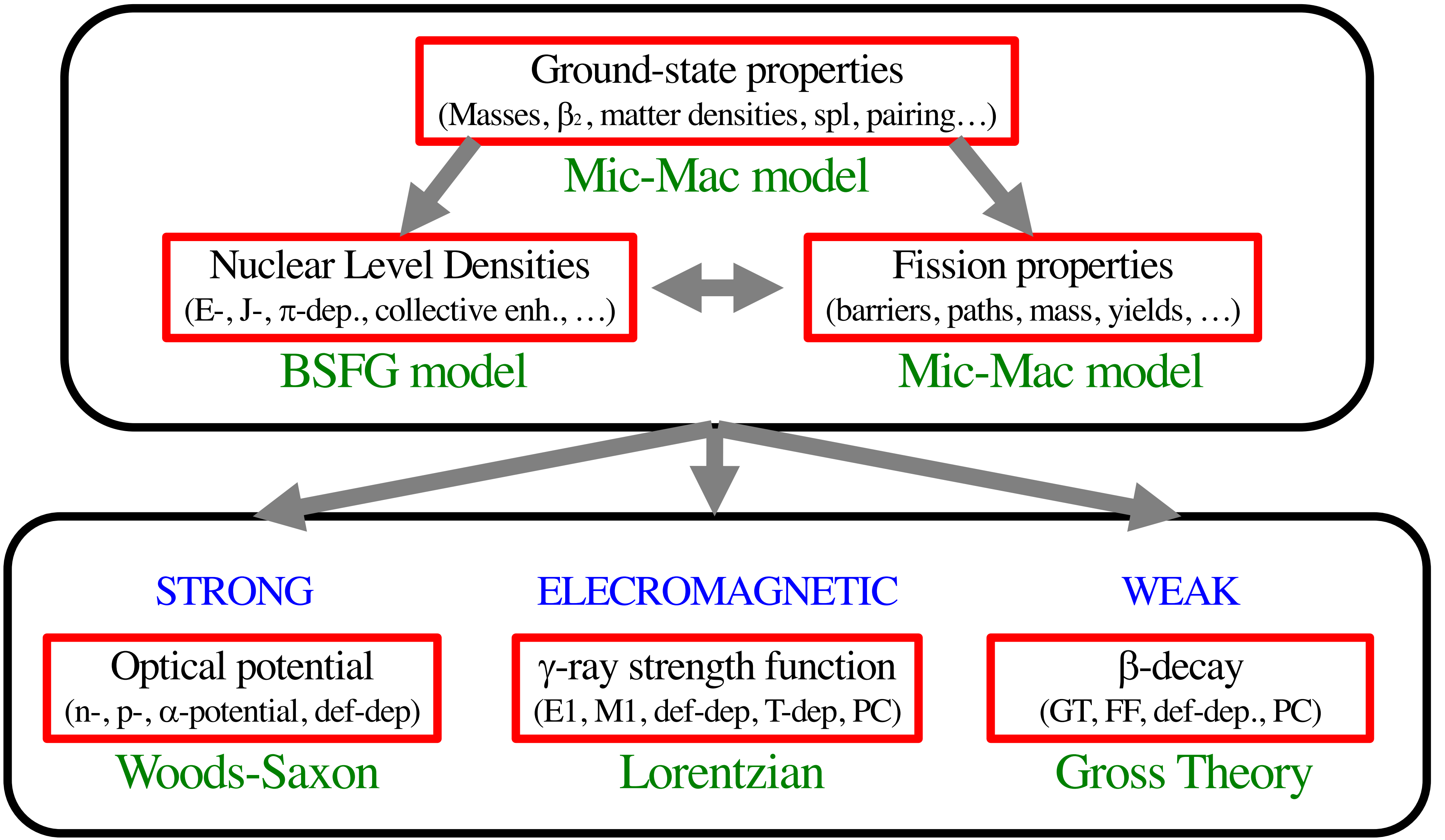

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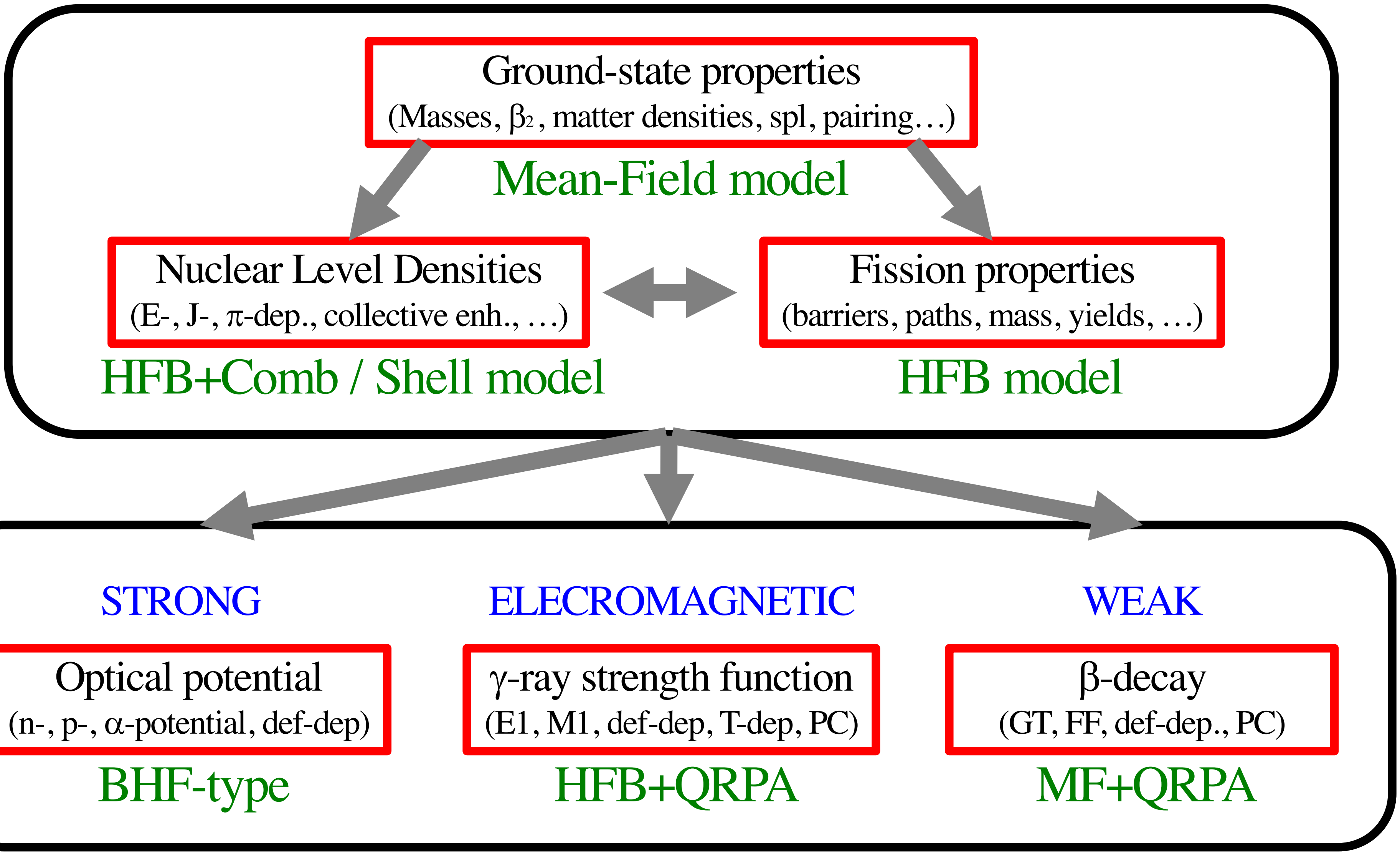
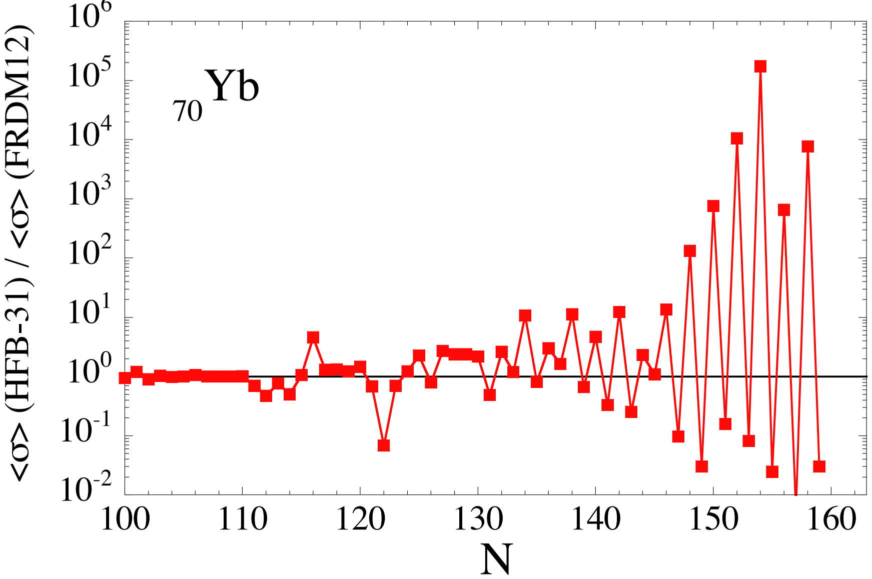
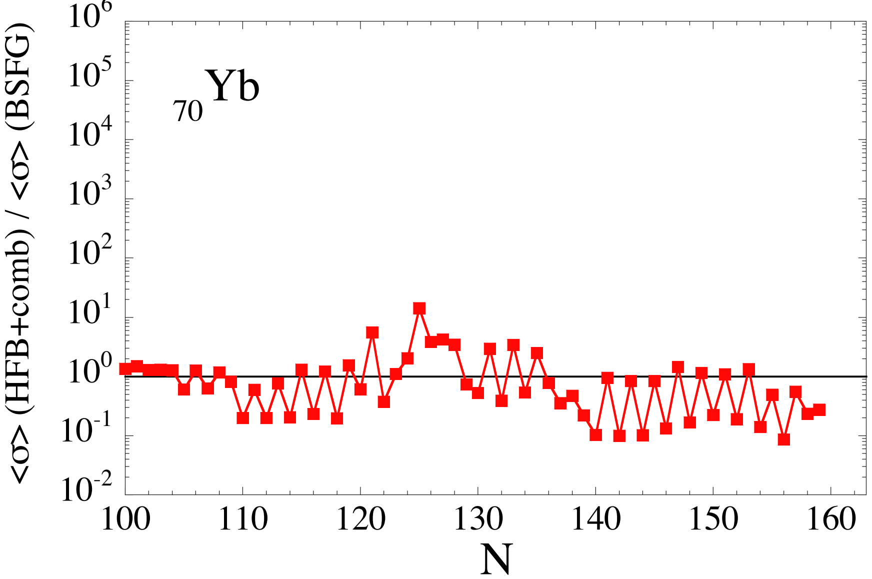


Impact of the various ingredients on the radiative neutron capture (E_n~100keV)

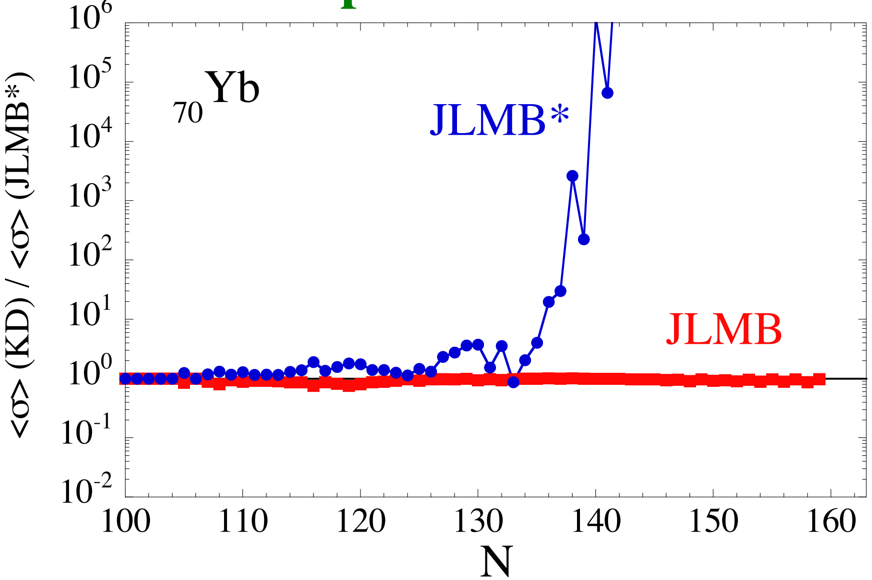
Masses



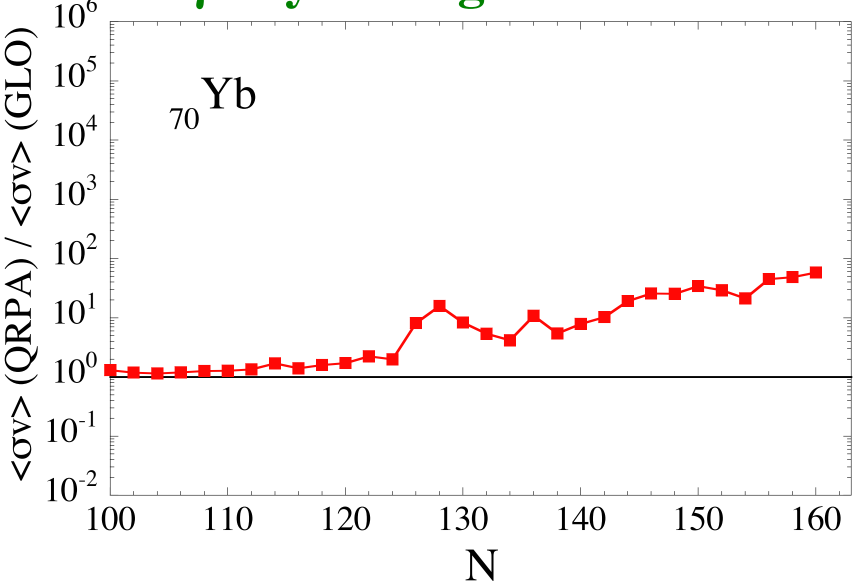
Nuclear Level Densities



Optical Potential



γ-ray Strength Function



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4. Is it needed to develop competing “microscopic” models to replace macroscopic-type models ?

Nuclear mass models

Nuclear mass models provide all basic nuclear ingredients:

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

but also the major nuclear structure properties

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 cross sections and β-decay rates, such as

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

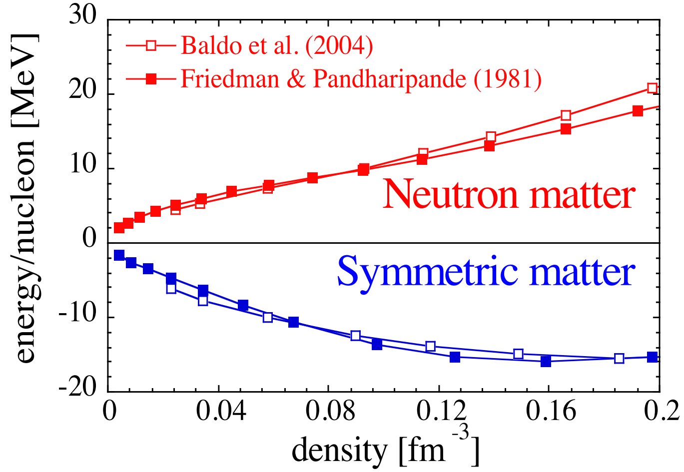
as well as for the $(n,\gamma)/(\gamma, n)$ ratio & nuclear/neutron matter Equation of State

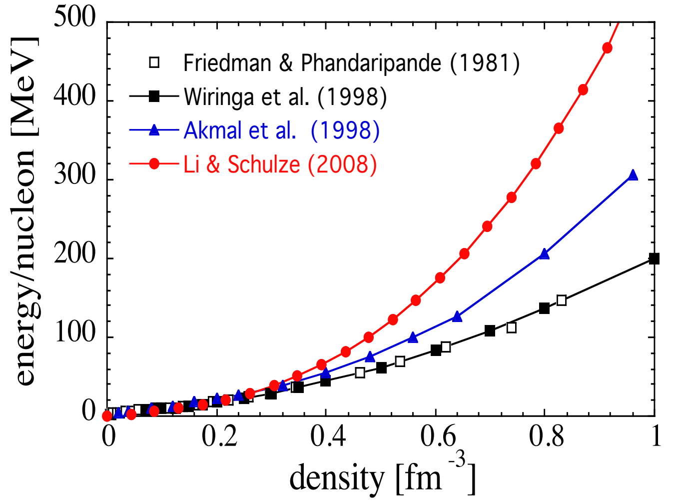
The criteria to qualify a mass model should NOT be restricted to the rms deviation wrt to exp. masses, but also include
- the quality of the underlying physics (sound, coherent, "microscopic", …)
- all the observables of relevance in the specific applications of interest (e.g astro)

Challenge for modern mass models: to reproduce as many observables as possible

- **2408 experimental masses** from AME'2016 → rms ~ 500-800keV
- 782 exp. charge radii (rms ~ 0.03fm), charge distributions, as well as ~26 n-skins
- Isomers & Fission barriers (scan large deformations)
- Symmetric infinite nuclear matter properties
  - $m^* \sim 0.6 - 0.8$ (BHF, GQR) & $m^*_n(\beta) > m^*_p(\beta)$
  - $K \sim 230 - 250$ MeV (breathing mode)
  - E_{pot} from BHF calc. & in 4 (S,T) channels
  - Landau parameters $F_l(S,T)$
    - stability condition: $F_l^{ST} > -(2l+1)$
    - empirical $g_0 \sim 0$; $g_0' \sim 0.9\text{-}1.2$
    - sum rules $S_1 \sim 0$; $S_2 \sim 0$
  - Stability at finite momentum q
  - Pairing gap (with/out medium effects)
  - Pressure around 2-3ρ_0 from heavy-ion collisions
- Infinite 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)
  - Properties of the lowest 2^+ levels (519 e-e nuclei)
  - Moment of inertia in superfluid nuclei (back-bending)

~ model-dependent





Recent Mic-Mac mass models

$$E = E_{LD} + E_{micro}$$

- FRDM'12 : update from FRDM'95 (Möller 2012)
  - σ_{rms} = 0.599 MeV (2408 nuclei in AME'16)

- WS mass formula (Ning Wang et al. 2011)
  - WS3: σ_{rms} = 0.343 MeV (2408 nuclei in AME'16)
  - WS4: σ_{rms} = 0.302 MeV (2408 nuclei in AME'16)

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

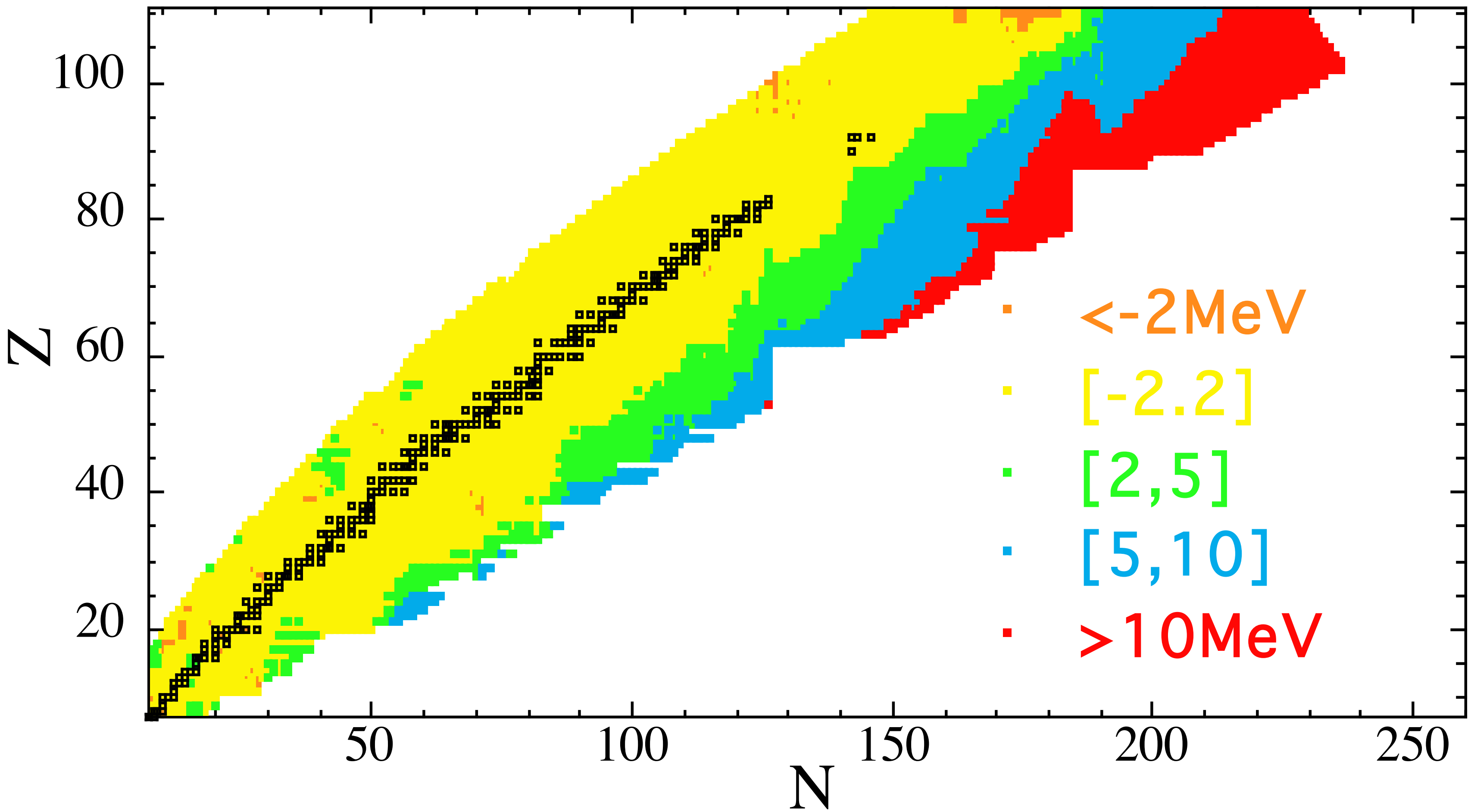
E_{coll}: Quadrupole Correlation corrections to restore broken symmetries and include configuration mixing

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

ΔM=M(FRDM)–M(HFB-21)



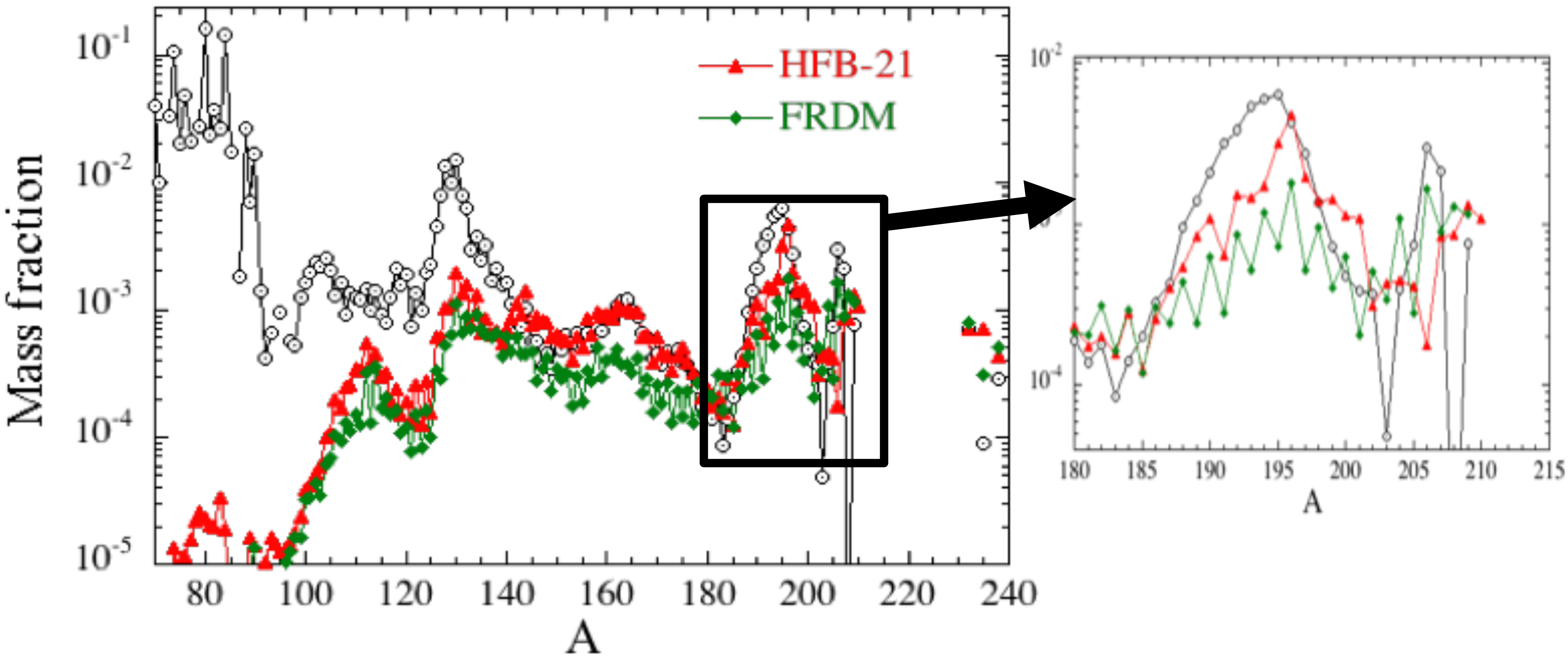
Relative agreement between HFB and FRDM

Major differences around magic numbers N~126 and N~184

but also odd-even pairing effects → affecting $Q(n,\gamma)$, hence cross sections

Impact of masses on the r-process nucleosynthesis in NS mergers

- GT2 β-decay rates with consistently estimated Q_β
- n-capture rates estimated within the HF+PE+DC model (TALYS)



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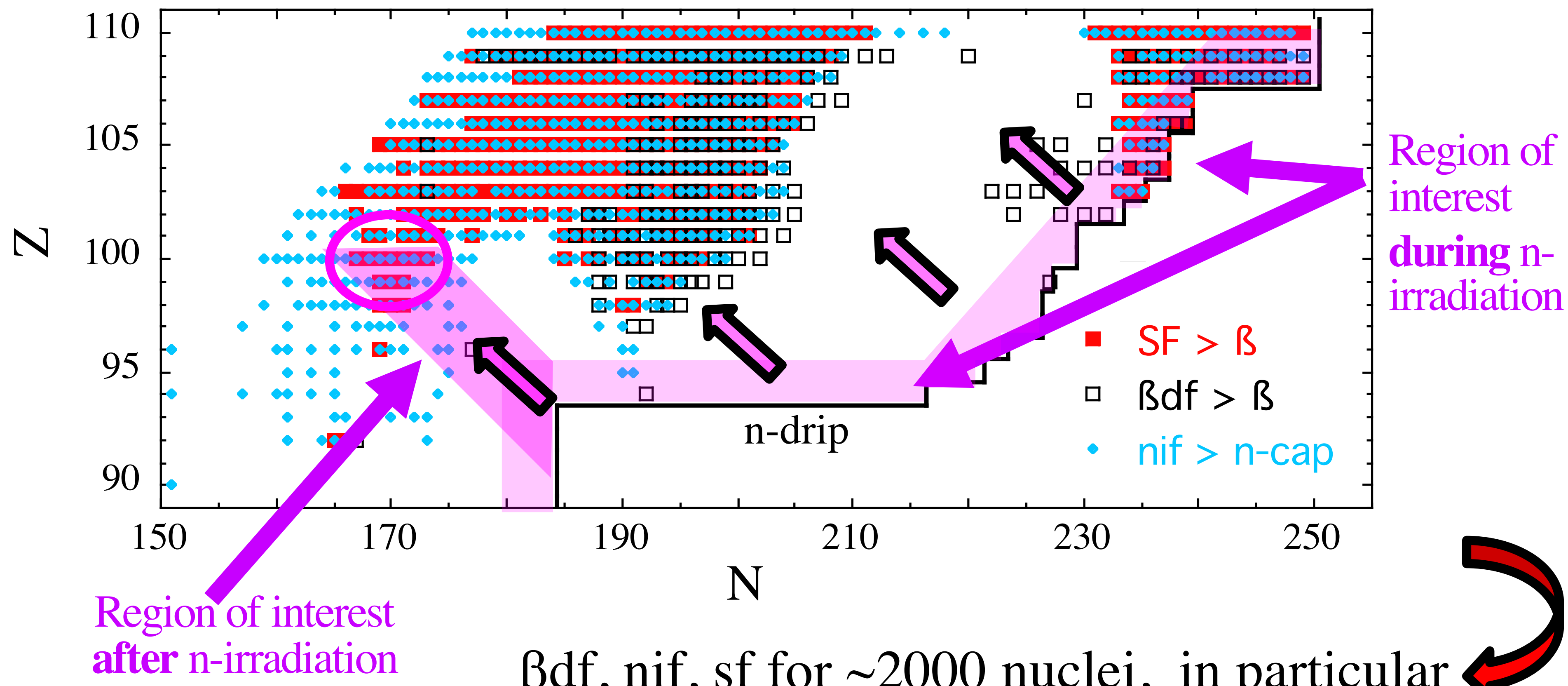
5. How reliable are the present mass models ? What are the next steps ?

Fission properties and the r-process



βdf, nif, sf for ~2000 nuclei, in particular along the n-drip line

Production of Super-Heavy nuclei ?

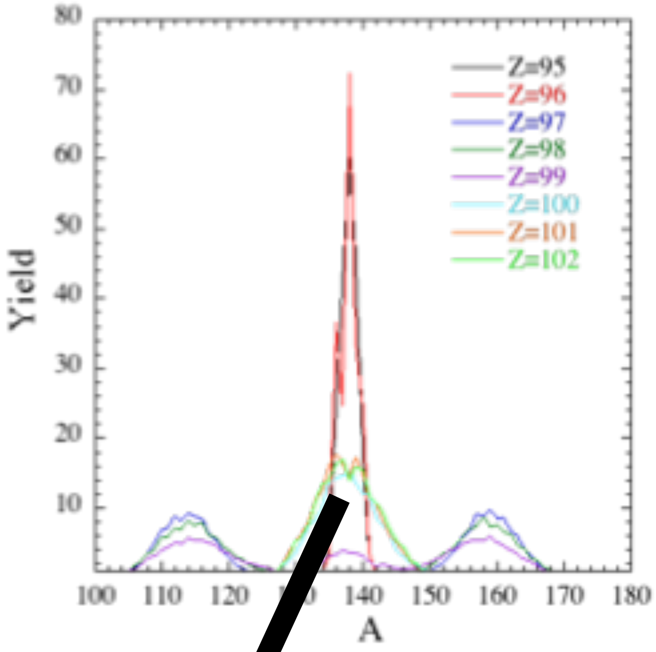
Special emphasis on the FFD for the *A*~278 isobars

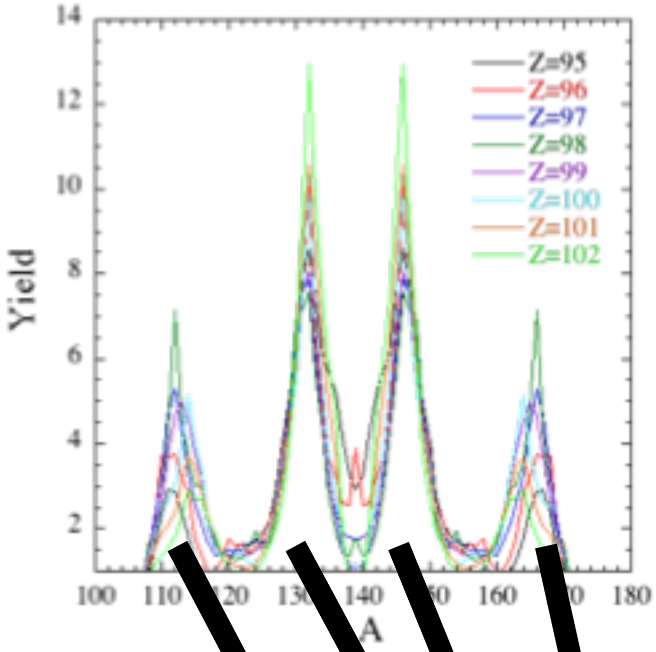
Sensitivity to the fission fragment distribution

along the A=278 isobar (from the N=184 closed shell)

GEF v1.4
K. Schmidt et al. (2013)

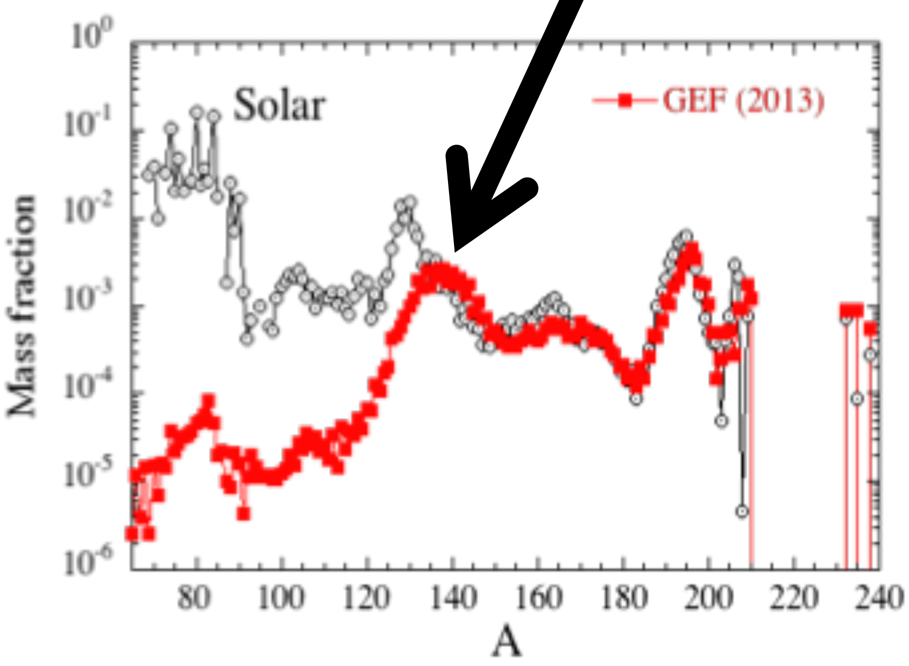
Semi-empirical mic-mac Scission Point model

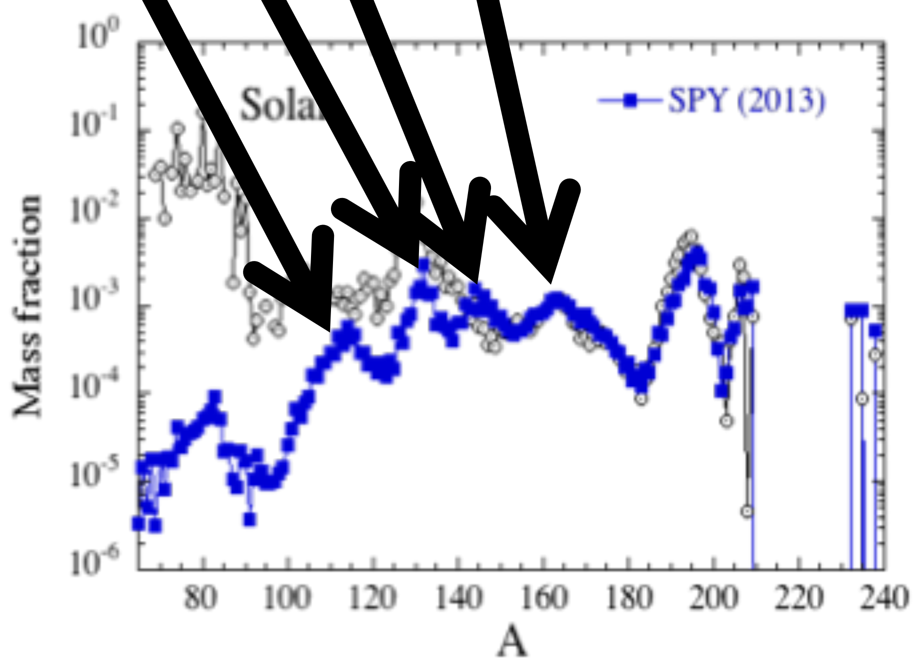




SPY:
S. Panebianco et al. (2013)

Parameter-free Scission Point model based on D1S potential energy surfaces





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7. How to properly treat UNCERTAINTIES ?

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…Still some work to be done …