Nuclear reactions relevant to nuclear astrophysics, status and perspectives

S. Goriely

In collaboration with

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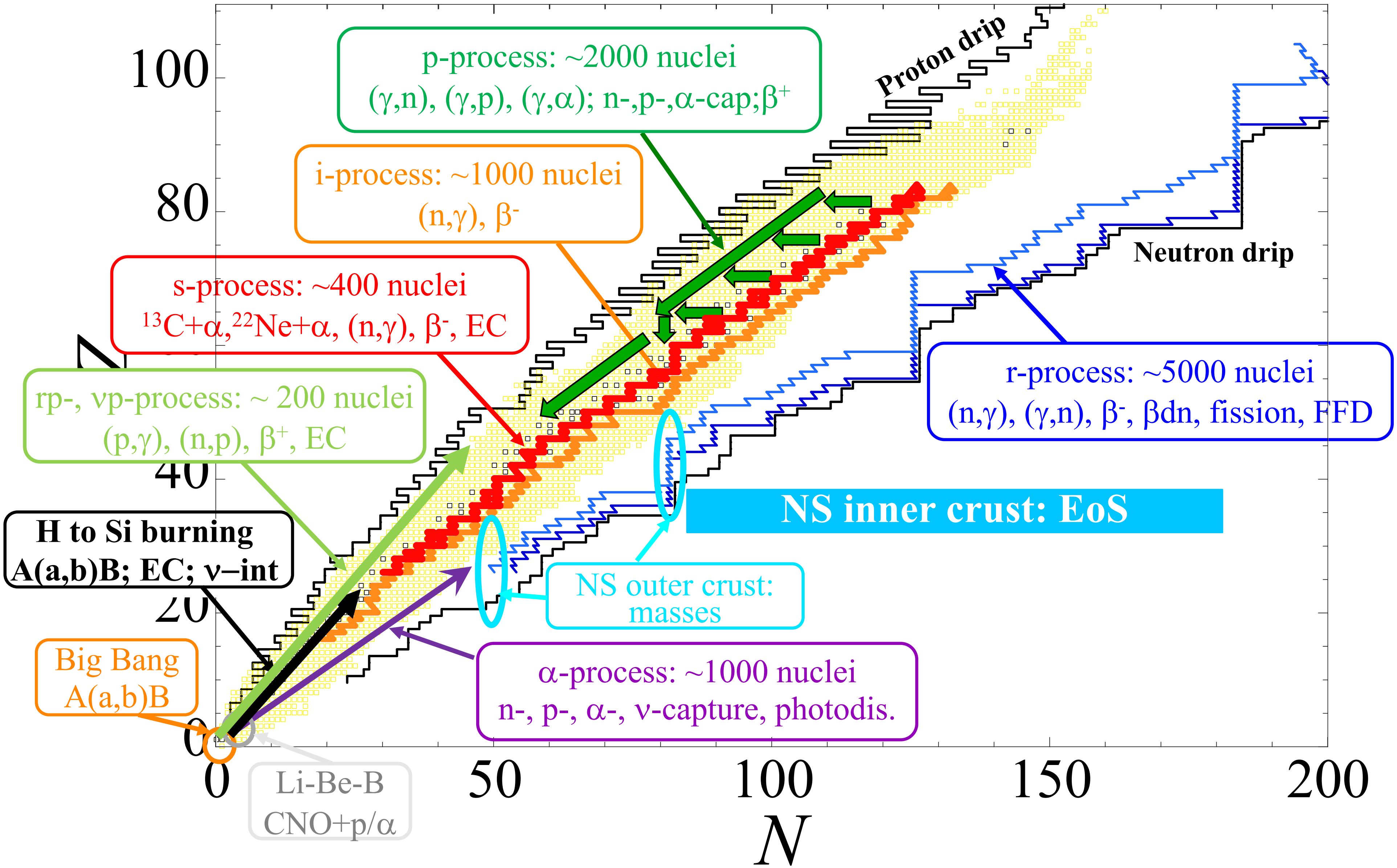
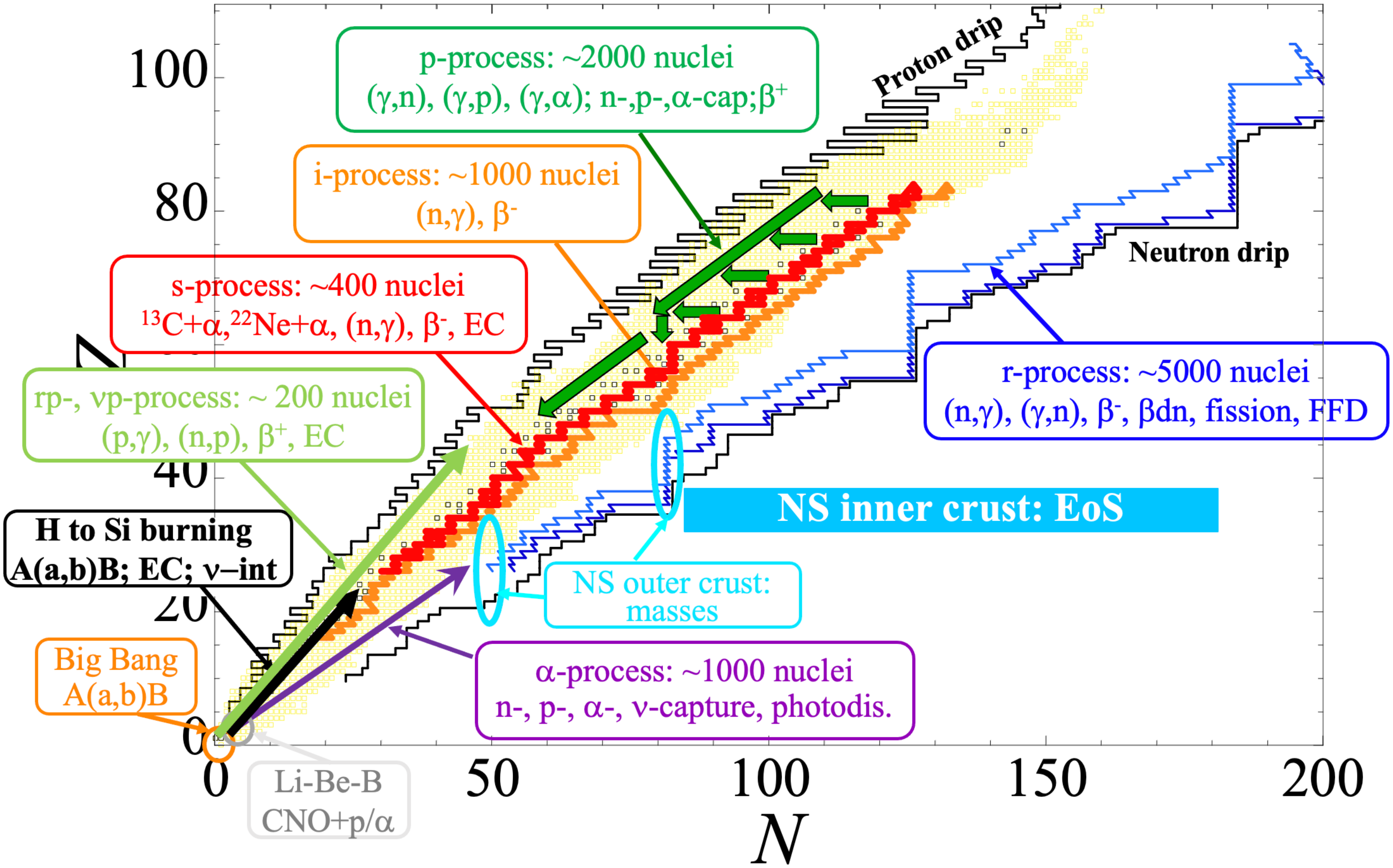
Nuclear Astrophysics: a field with high NP demands



Relatively limited amount of direct experimental data → Theory needs to fill the gaps

Nuclear Astrophysics: a field with high NP demands



What are the most relevant nuclear inputs / reactions ? (cf A. Ratkiewicz)

How do they affect astrophysics observables ?

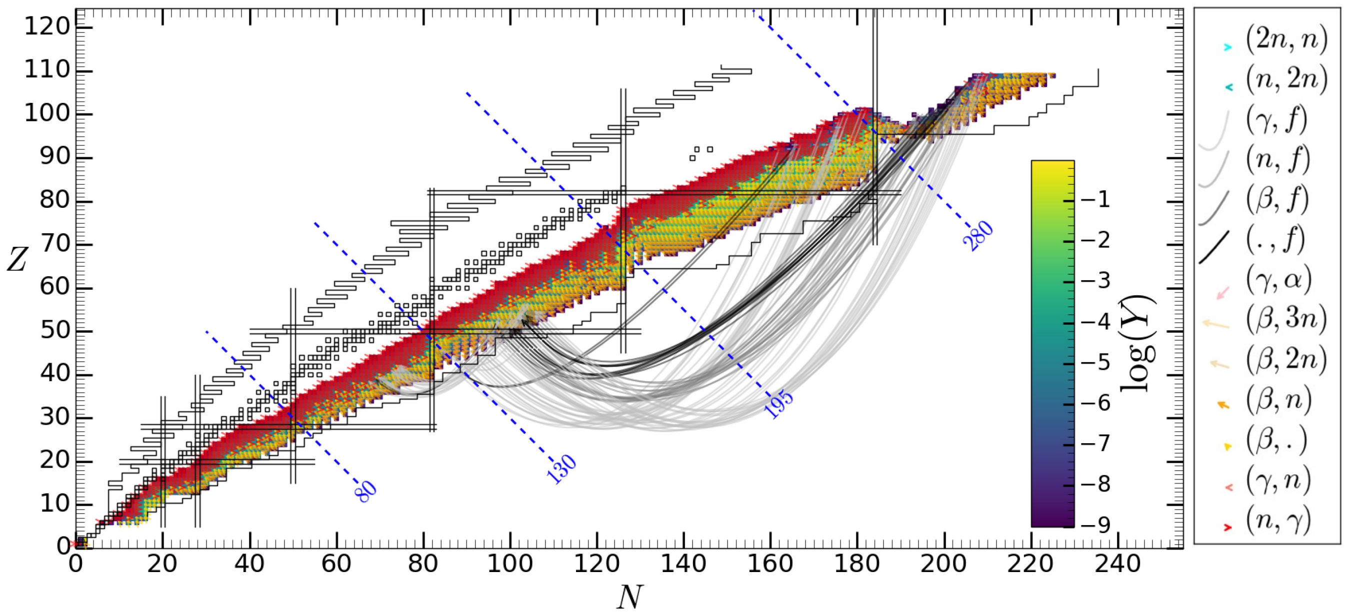
Nuclear physics input to the *r*-process nucleosynthesis

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

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

} Still many open questions

some 5000 nuclei with $Z \leq 110$ on the n-rich side – essentially no exp. data

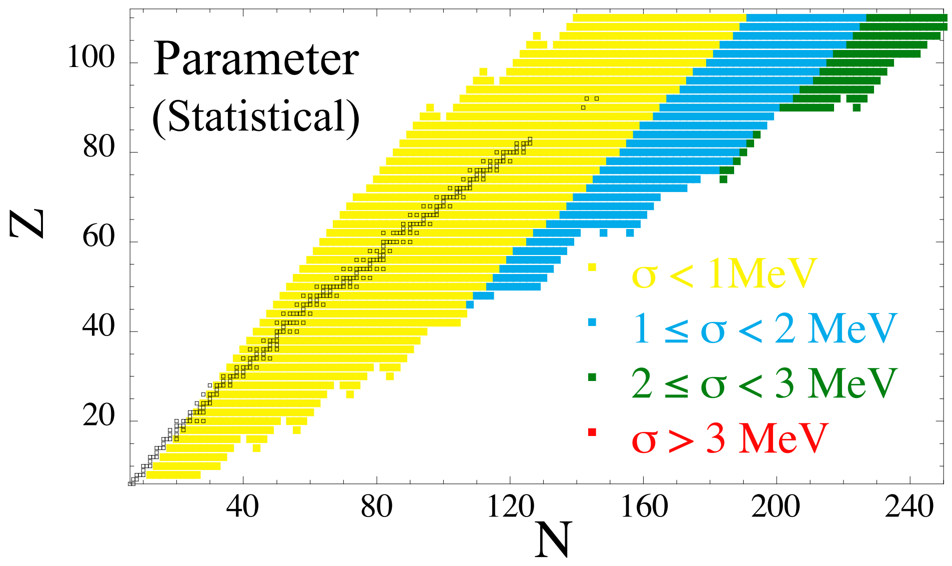


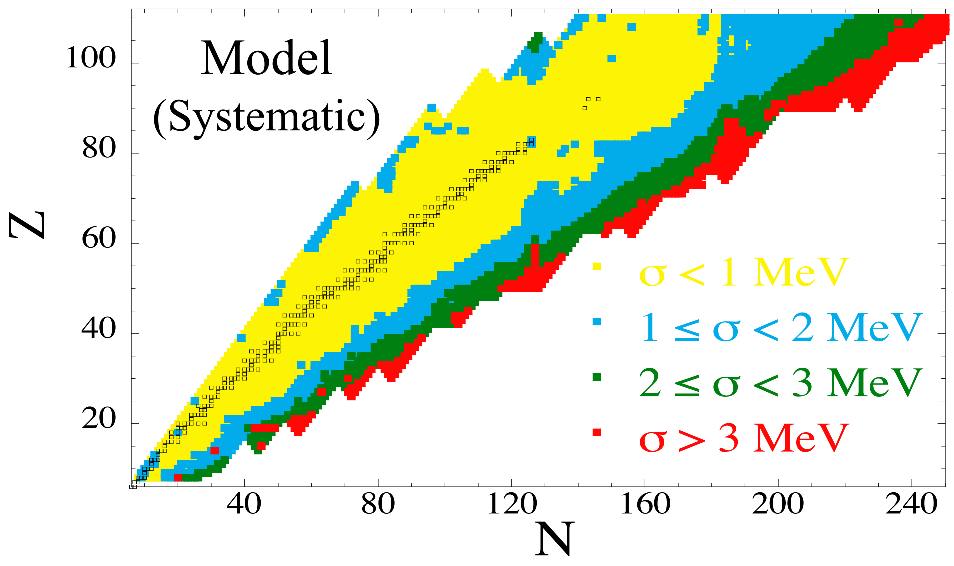
"Realistic" astrophysical model only available for Neutron Star Mergers

Nuclear uncertainties

Some Progress in considering "theoretical uncertainties" in NA

Two types of uncertainties affecting nuclear inputs (e.g Masses)



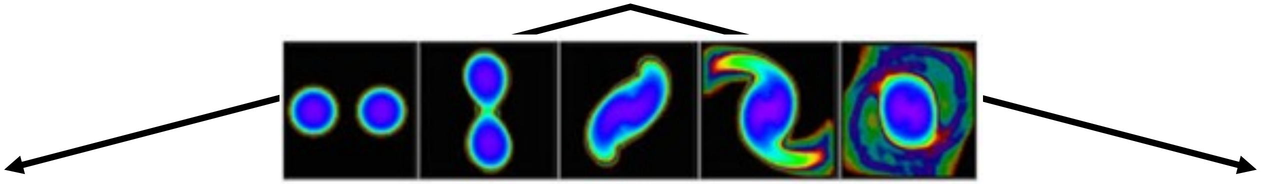


Model or parameter variations must be constrained by experimental data

e.g. mass models with $\sigma_{rms} < 0.8$ MeV or (n,γ) models with $f_{rms} \leq 2$

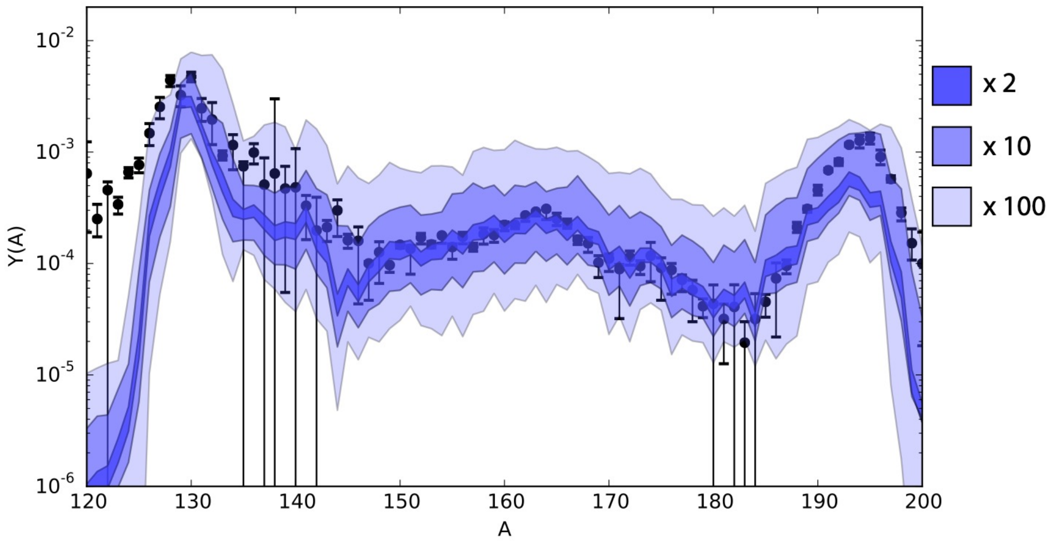
But what about their impact on astrophysical observables ?

How to propagate such NP uncertainties into astrophysics simulations ??



Uncorrelated MC approach

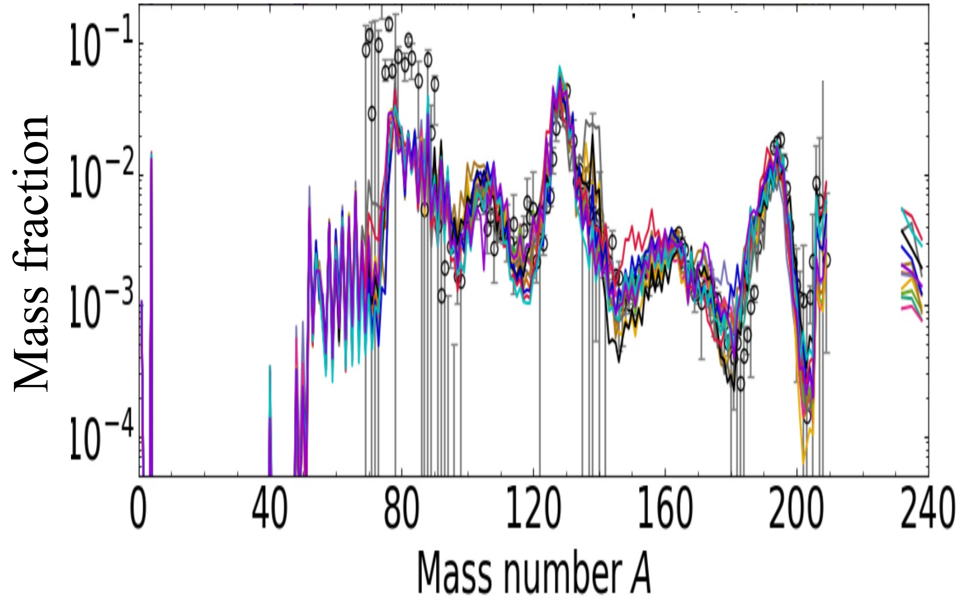
Mumpower et al. (2016); Nikas et al. (2020)



- Rates within an arbitray factor of 2, 10, 100
- Neglect correlations between uncertainties
- Overestimates impact – Often unphysical

Model-correlated approach

Sprouse et al. (2020); Kullmann et al. (2022)



- Coherent model-correlated uncertainties
- Only parameter or model uncertainties
- Overestimates impact if not exp-constrained

In all cases, propagation must be applied to a large representative sample of trajectories

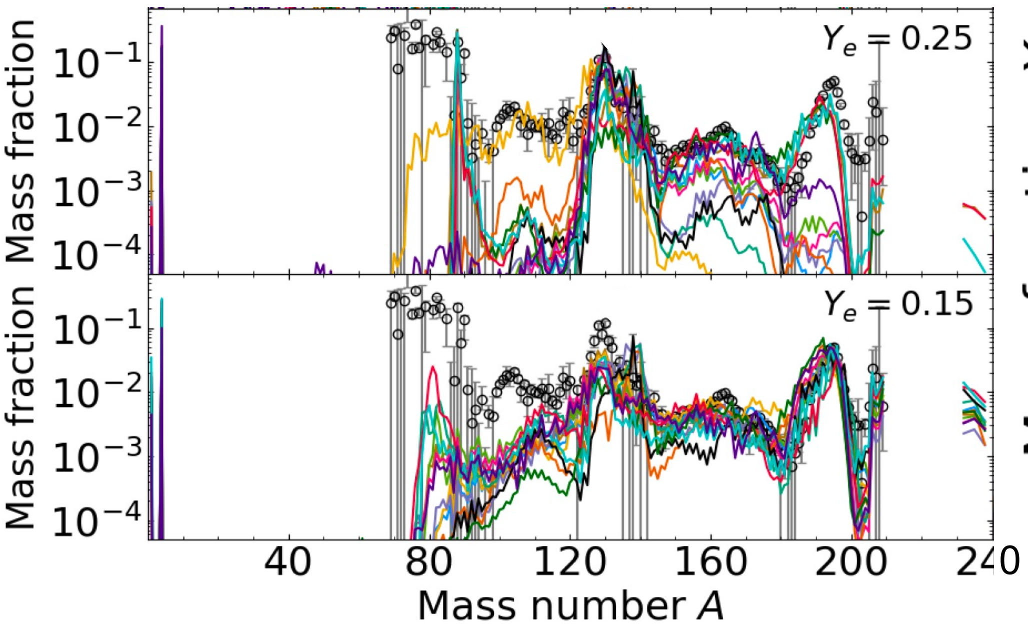
Impact of nuclear *model* uncertainties on the composition of NSM ejecta

15 different "acceptable" sets of nuclear inputs (masses, β-decay, n-capture, fission)

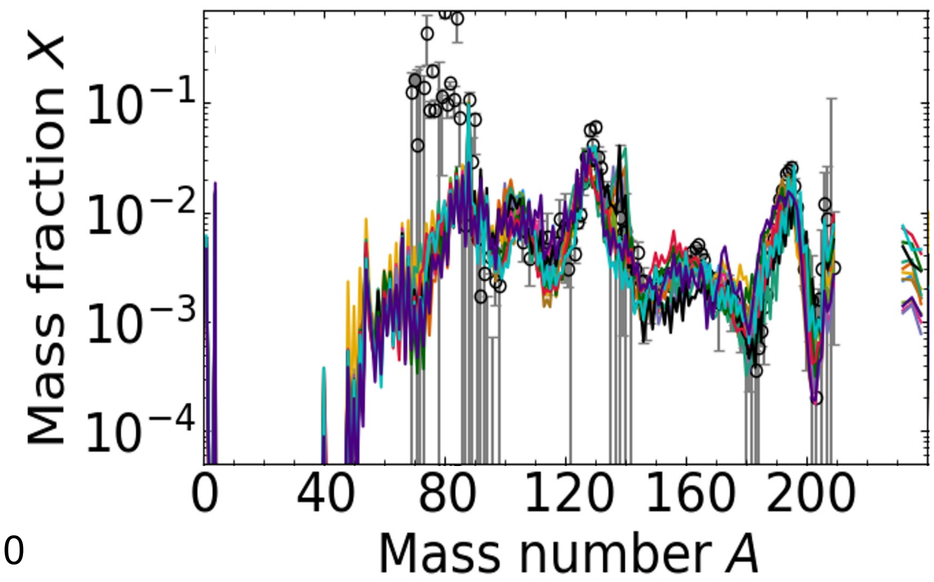
Kullmann et al. (2022)

Prompt dynamical ejecta: SFHo 135-135

Single trajectory



Multiple trajectories

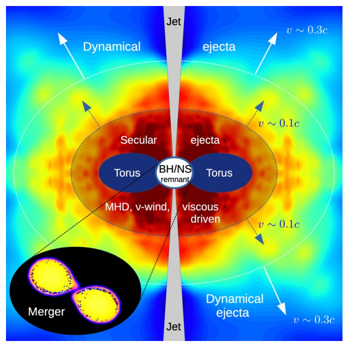


Global & Local discrepancies

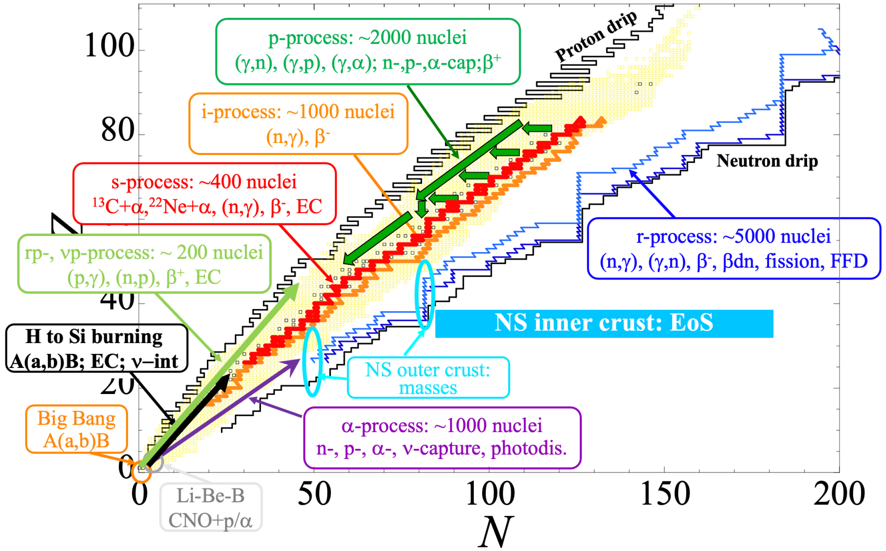
Local (correlated) discrepancies

Astrophysical models evolve and may still not be robust
(what is "important" today may not be next year)

→ Remain extremely critical about propagation of nuclear uncertainties into astrophysical models



Nuclear Astrophysics: a field with high NP demands



Still huge Nuclear Physics needs for ...

→ Dedicated experimental (and theoretical) work on key reaction
in particular: $^{12}C+\alpha$, $^{12}C+^{12}C$, $^{22}Ne+\alpha$, $^{17}O+\alpha$, ... (not all are "crucial")

→ A regularly-updated library of cross sections / rates
in particular: n-, p-, α-captures, $\beta^{\pm}$/EC/α decay

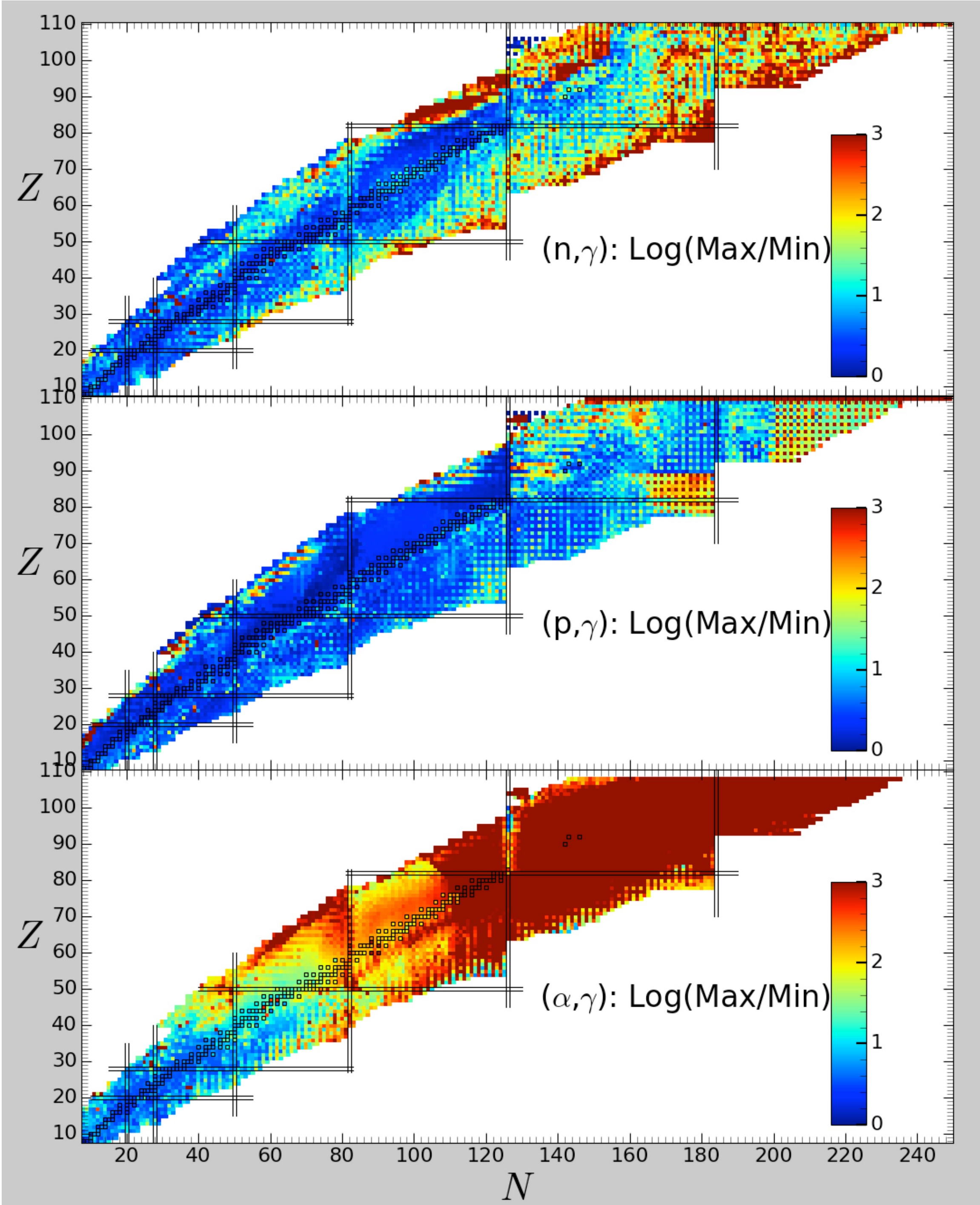
→ A regularly-updated library of evaluated input parameters
in particular: M, R_c, β_2, J^π, B_f, D_0, S_0, $<\Gamma_\gamma>$, PSF, NLD, OMP, ...

→ Experimental / theoretical insights of physical properties that could have a significant impact on xs predictions (esp. extrapolations):
for example: n skin, shell effects, PSF upbend/PR, α-OMP, IV n-OMP, ...

Large astrophysics uncertainties ("realistic" 3D vs parametrized unconfirmed sites)
→ the role of NP is to provide the most reliable exp/th data for astrophysics

Model uncertainties in the HF astrophysical rates
at T=2 10^9K due to "decent" models of

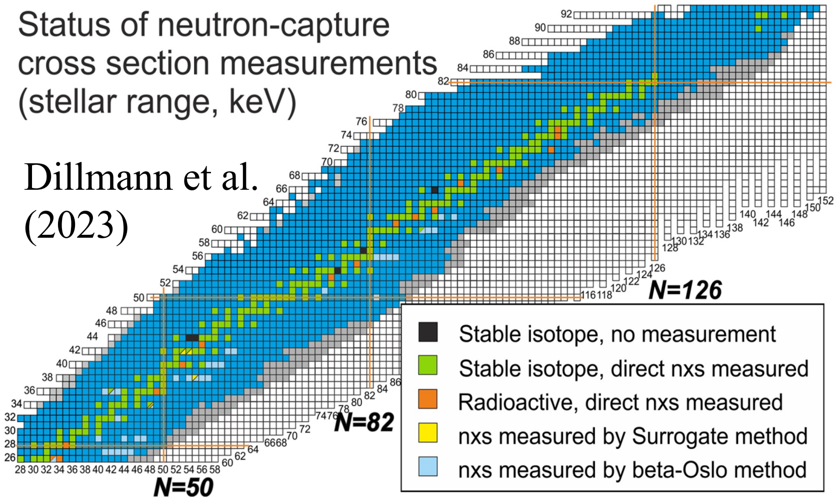
- Masses, deformations
- Nuclear Level Densities
- Photon Strength Functions
- Optical Potentials

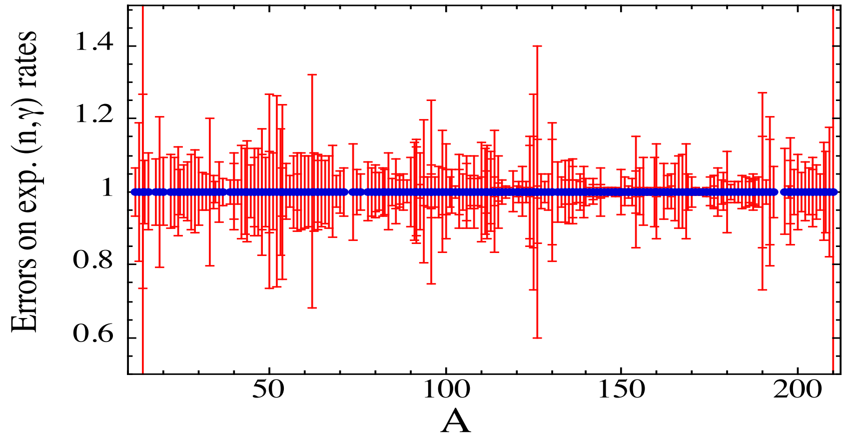


Experimental information on (n,γ) cross sections

Status of neutron-capture cross section measurements (stellar range, keV)

Dillmann et al. (2023)

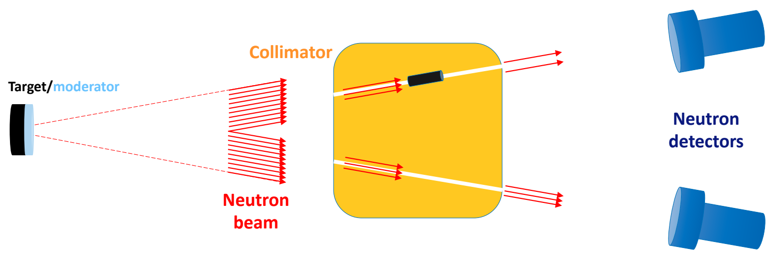




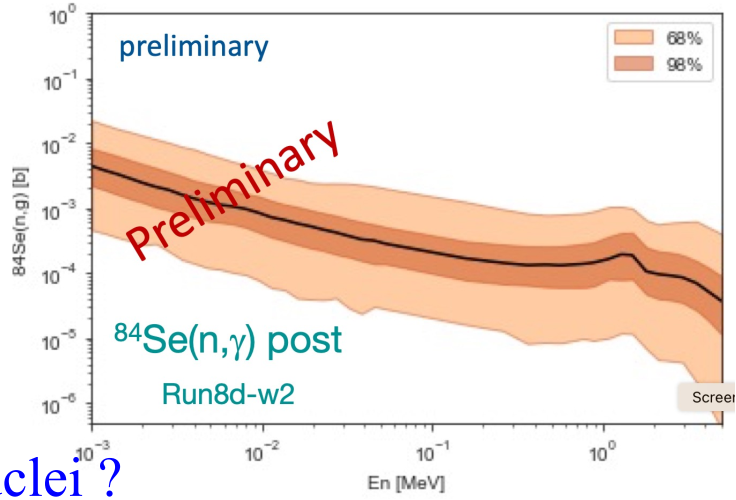
MACS available for some ~270 nuclei (s-process)

New experimental techniques to derive (n,γ) cross sections for unstable nuclei

New instrument DICER at LANSCE to constrain n-capture on radionuclides (cf Stamatopoulos)



β-Oslo or Surrogate (d,p) method

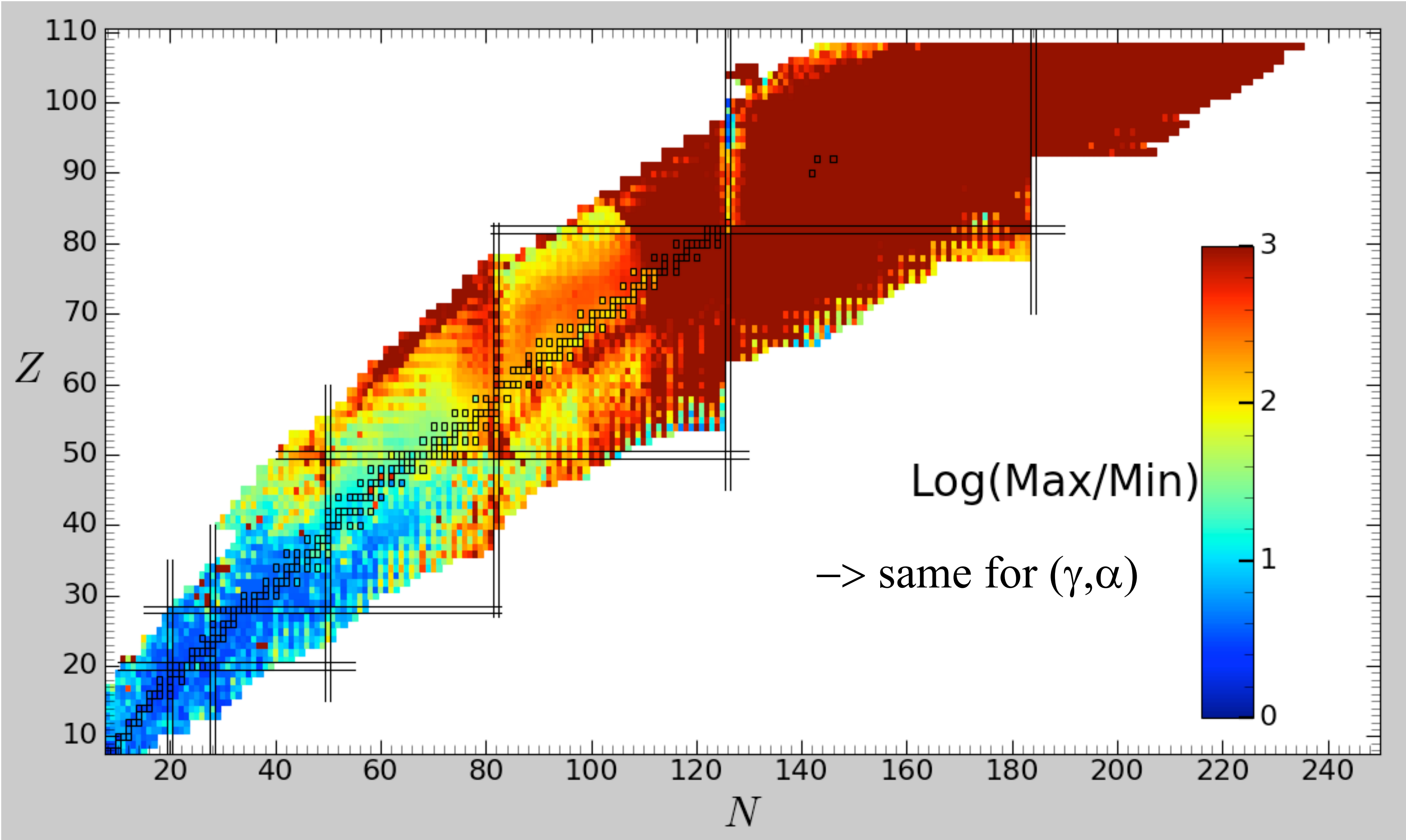


- Do we control (model-dep) uncertainties ?
- Can we learn about PSF, NLD, DC for n-rich nuclei ?

(May not be of direct astro relevance but well indirect !)

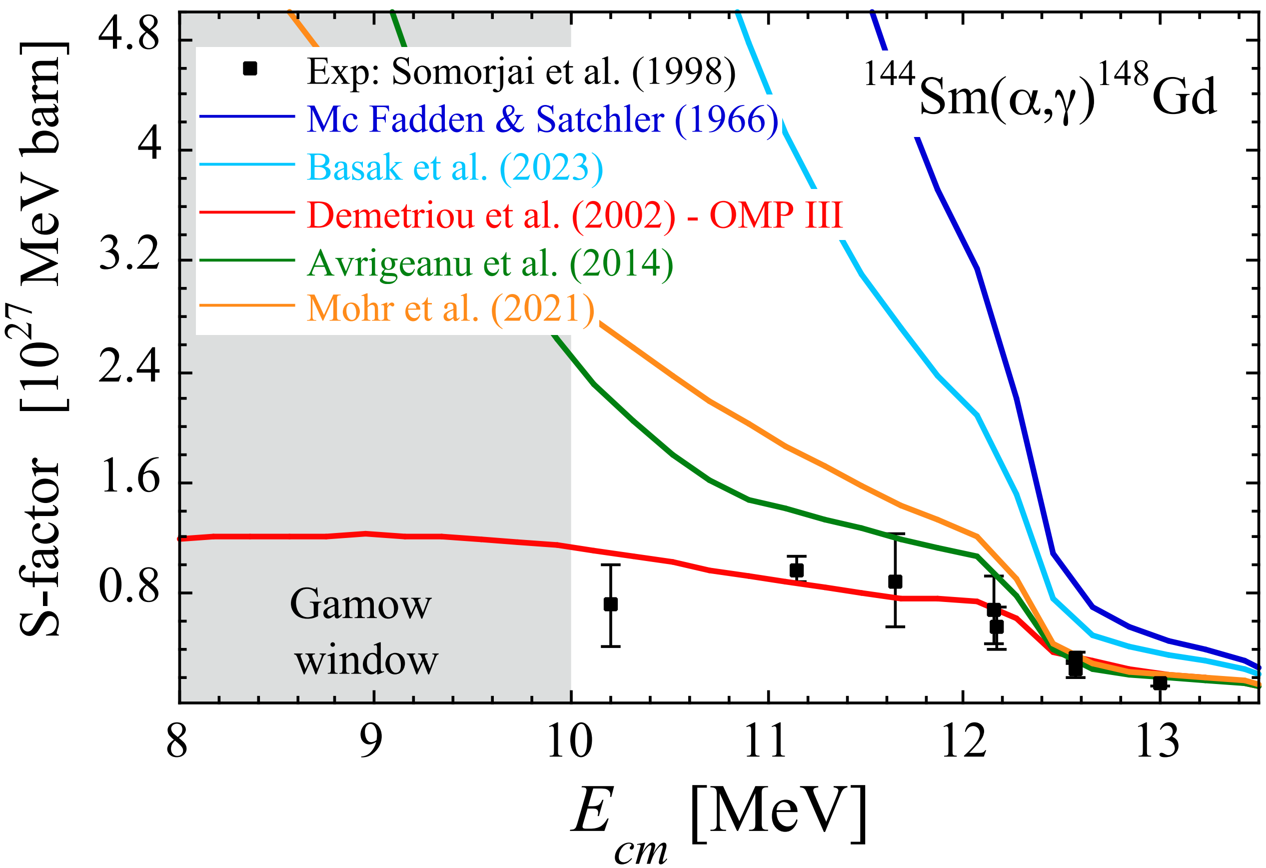
Uncertainties in the (α,γ) rates predictions at T=2 10^9K

Uncertainties associated with masses, **α-OMP**, NLD, PSF



Uncertainties in the (α,γ) rates predictions

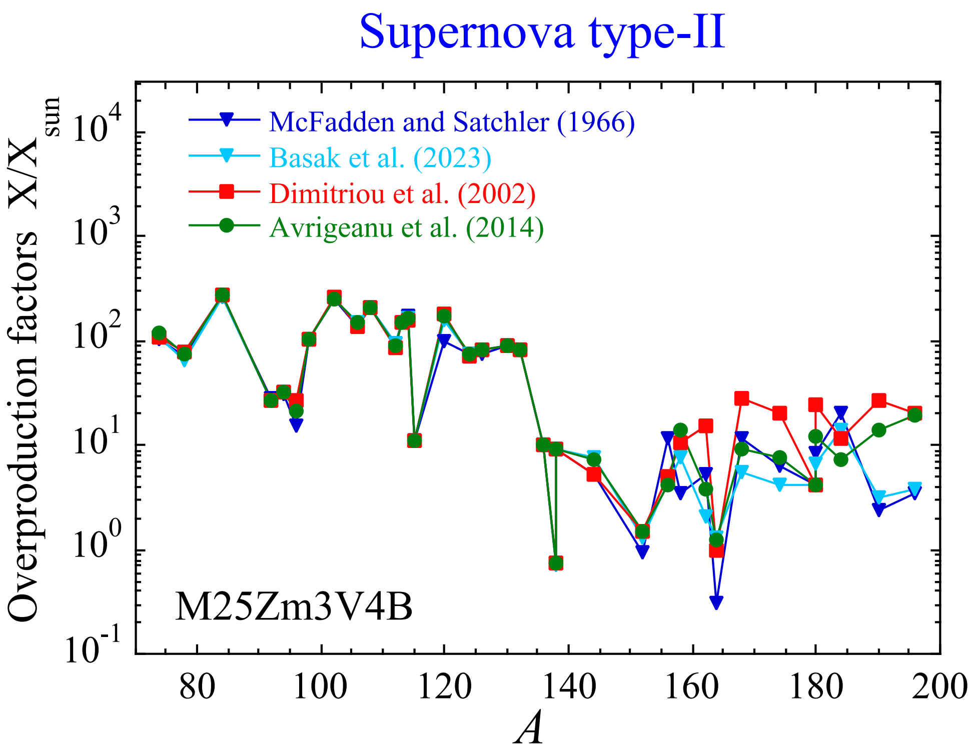
Uncertainties associated with **α-OMP:** The stringent test of $^{144}Sm(\alpha,\gamma)^{148}Gd$

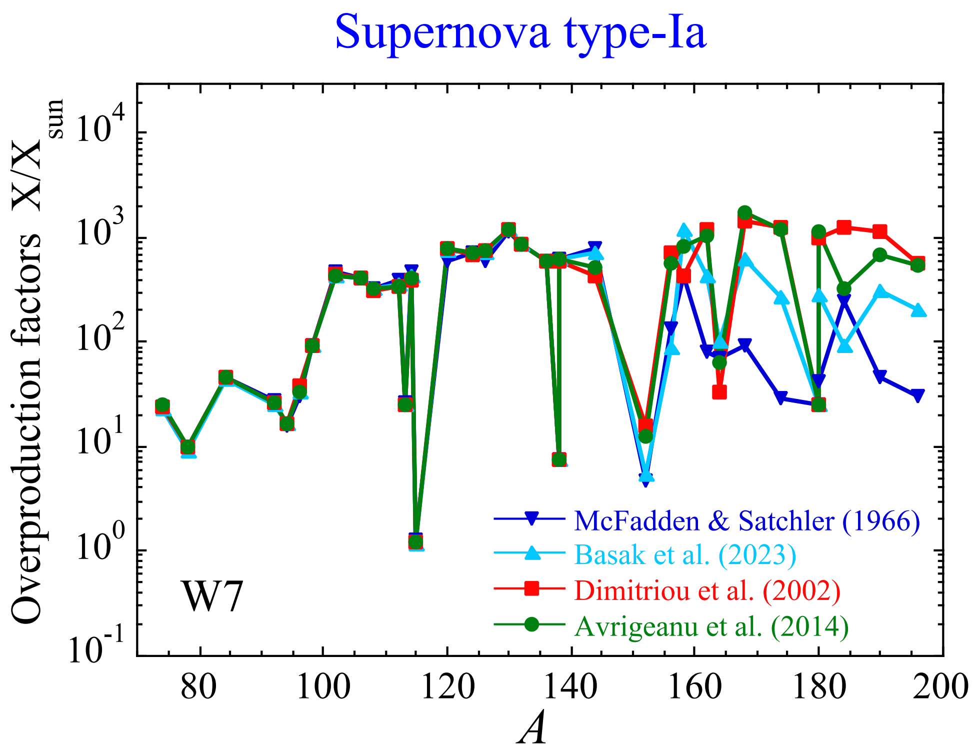


Sensitivity of the p-process enrichment to the α-nucleus optical potential

Sensitivity of the heavy p-nuclei production to the α-OMP mode uncertainties

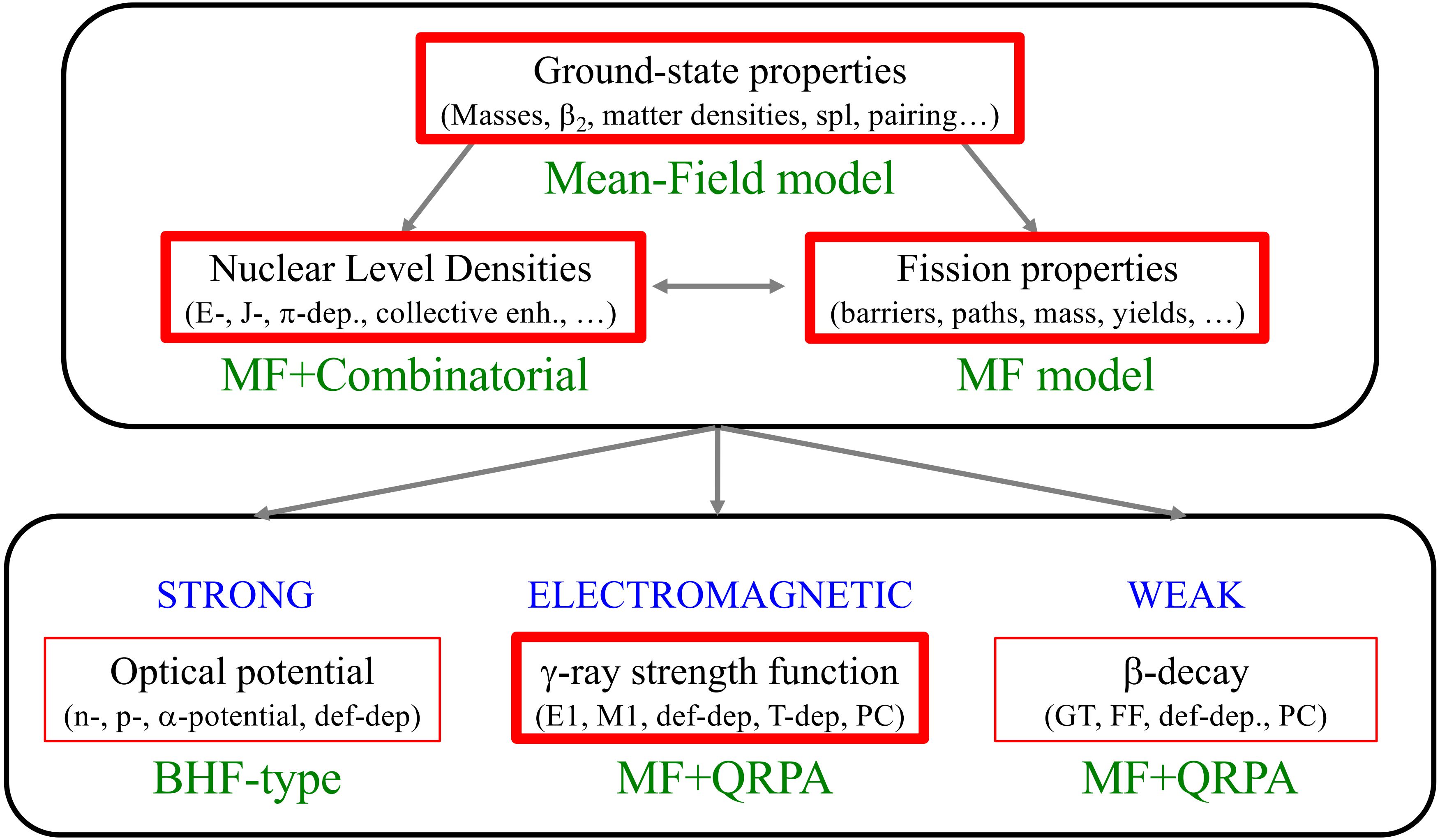
(No estimate of the parameter uncertainties available yet)





- Need for (α,γ), (n,α), ... on heavy targets far below the Coulomb barrier
- Need for improved dispersive optical potential
- Need for global analysis of all available data

Nuclear inputs to nuclear reaction & decay calculations



"Microscopic" approach is a necessary but not a sufficient condition !

Large-scale "(semi-)microscopic" models must be competitive in reproducing exp. data !

Mean Field mass models

Mass models do not only provide masses, but all GS structure properties !

$$E = E_{MF} - E_{corr}$$

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

$\boldsymbol{E_{corr}}$**:** Beyond-Mean-Field corrections to restore broken symmetries, include configuration mixing, ...

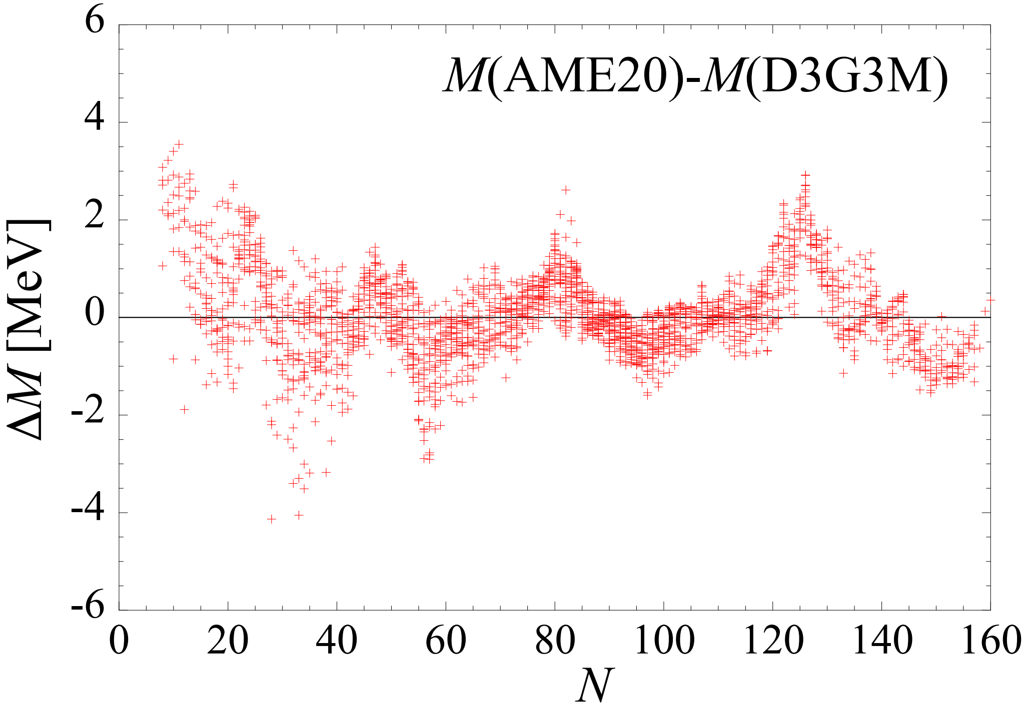
Skyrme-HFB	Gogny-HFB	Relativistic MF
rms ~ 0.5-0.8MeV	rms ~ 0.8MeV	rms > 1.1MeV

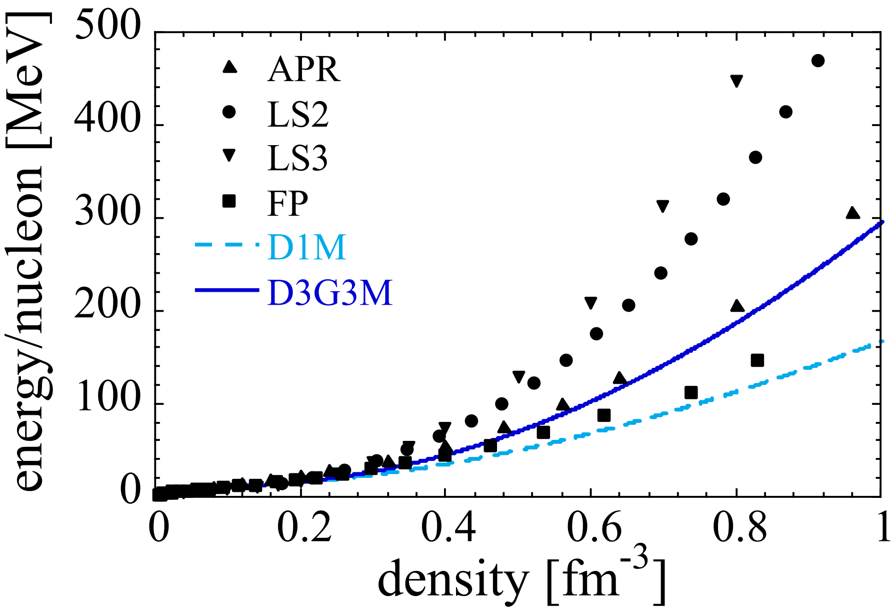
For astrophysical applications, only mass models with $\sigma_{rms} \lesssim 0.8$ MeV should be considered (even if "microscopic")

New HFB nuclear mass models

New Gogny-HFB mass model: D3G3M

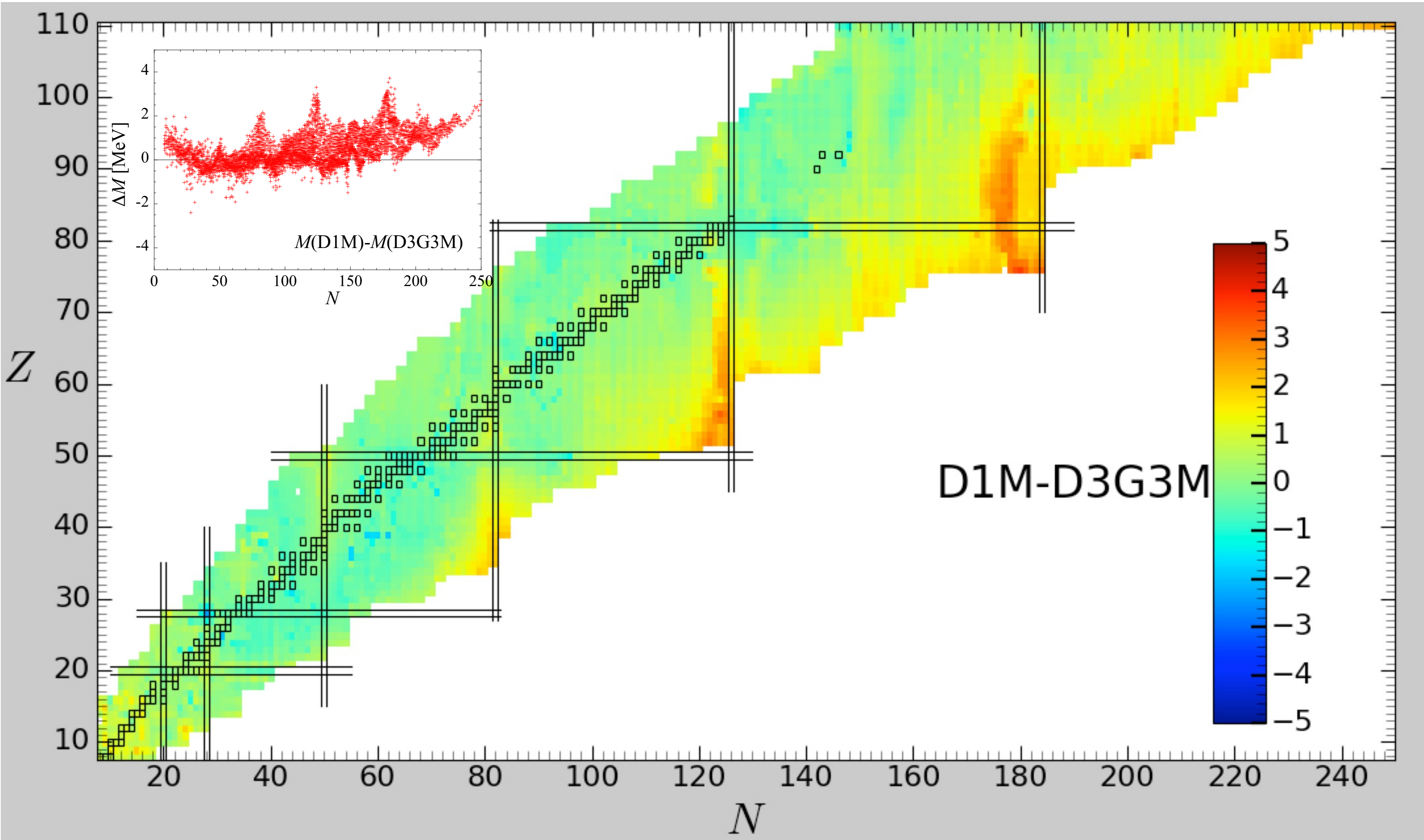
- Gogny interaction with 3 Gaussian terms
- Stiffer EoS than D1M (NS M_{max}~$2.14M_o$)
- Accurate masses: σ(2457*M*)=0.87MeV





Batail et al. (2024)

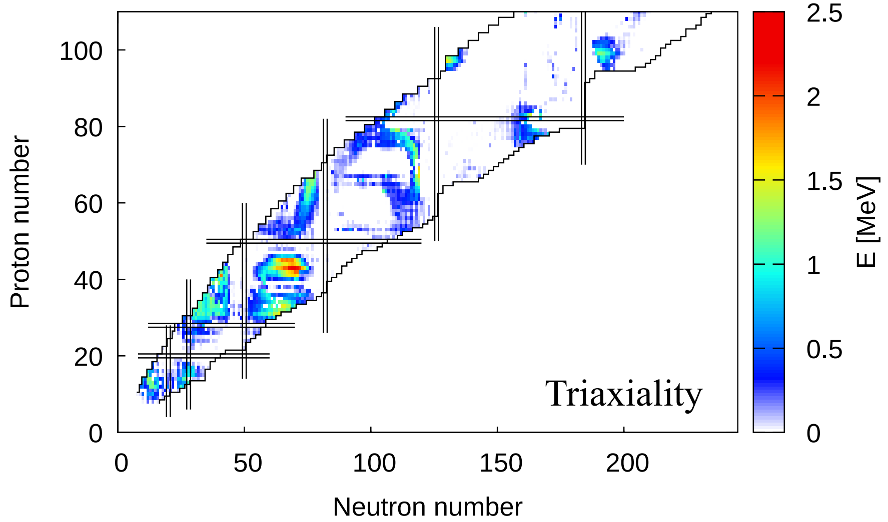
Differences in the mass predictions between D1M and D3G3M

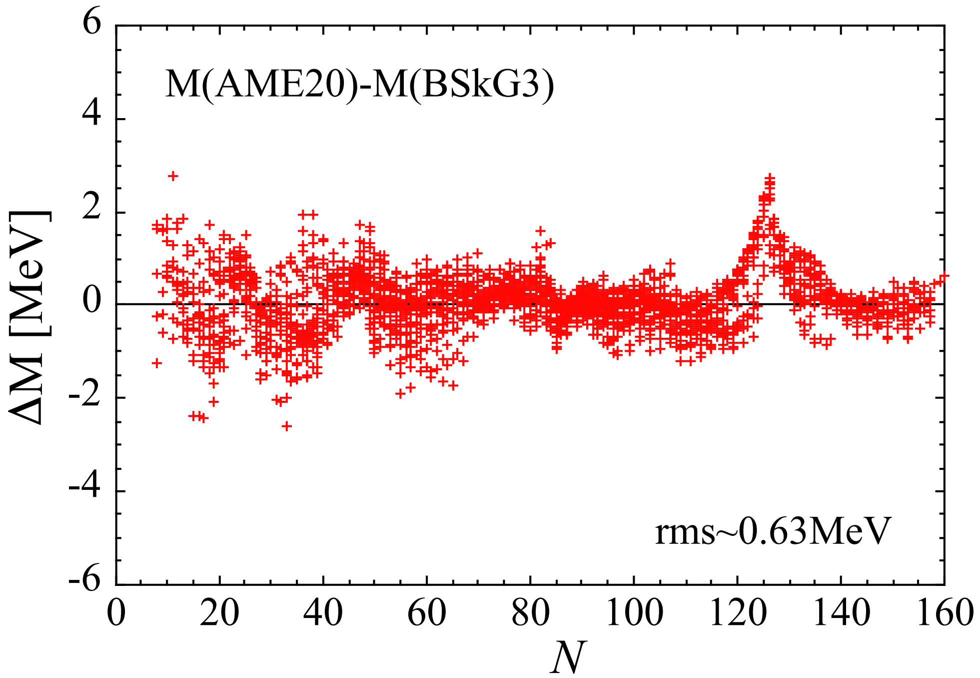


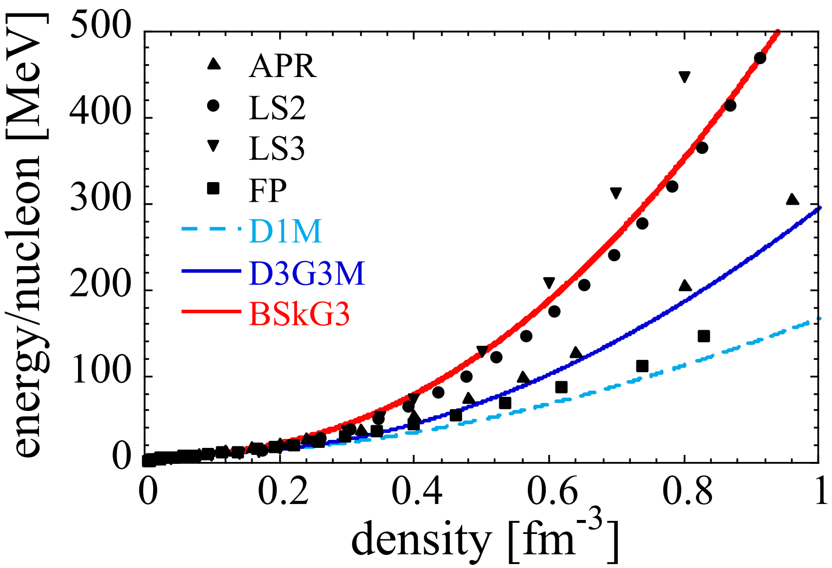
New HFB nuclear mass models

New Skyrme-HFB mass model: BSkG3

- Triaxiality, time-reversal symmetry breaking & octupole GS deformation
- Microscopic pairing from "realistic" calculations
- Stiff EoS (NS M_{max}~$2.26M_o$)
- Accurate masses: σ(2457*M*)=0.63MeV

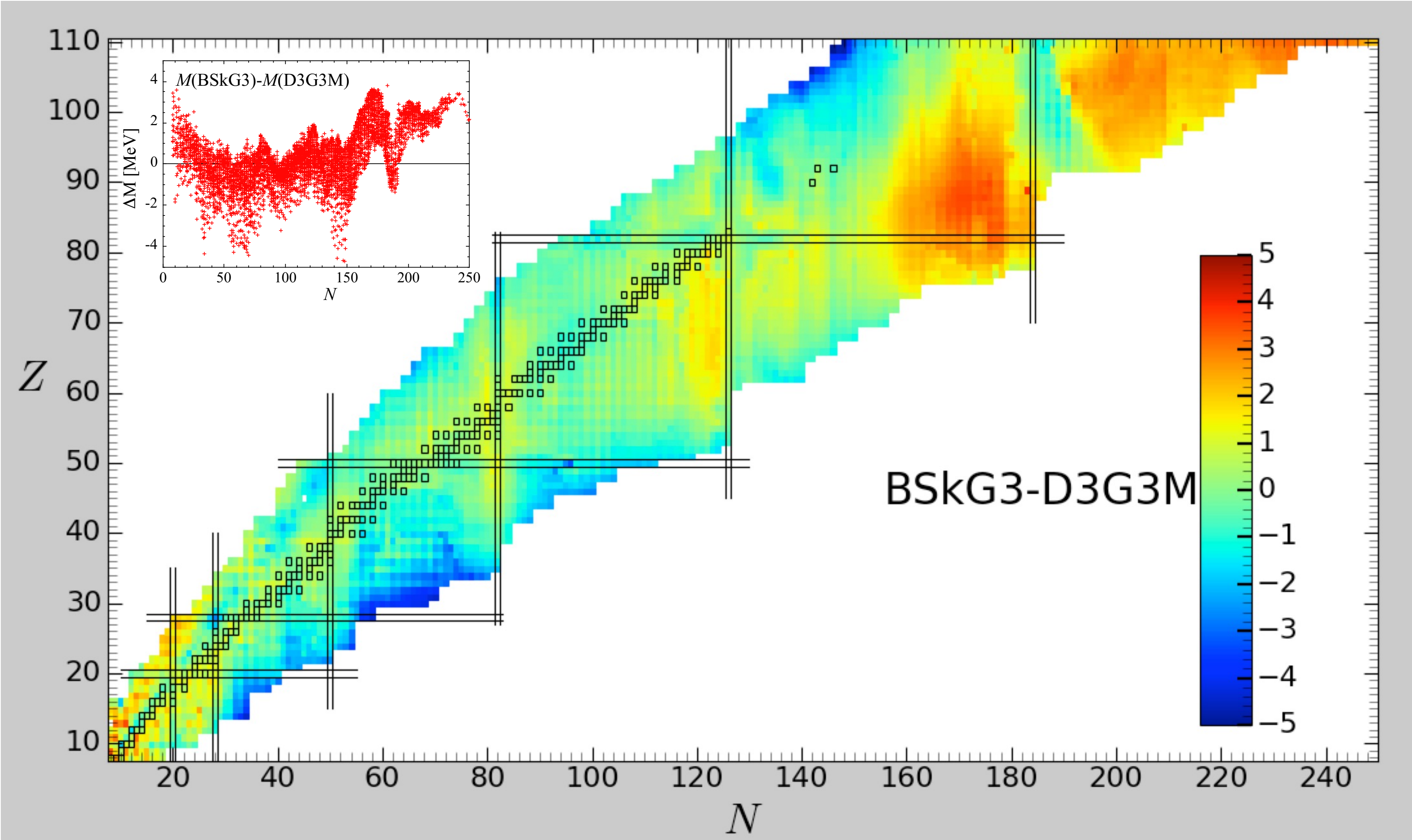


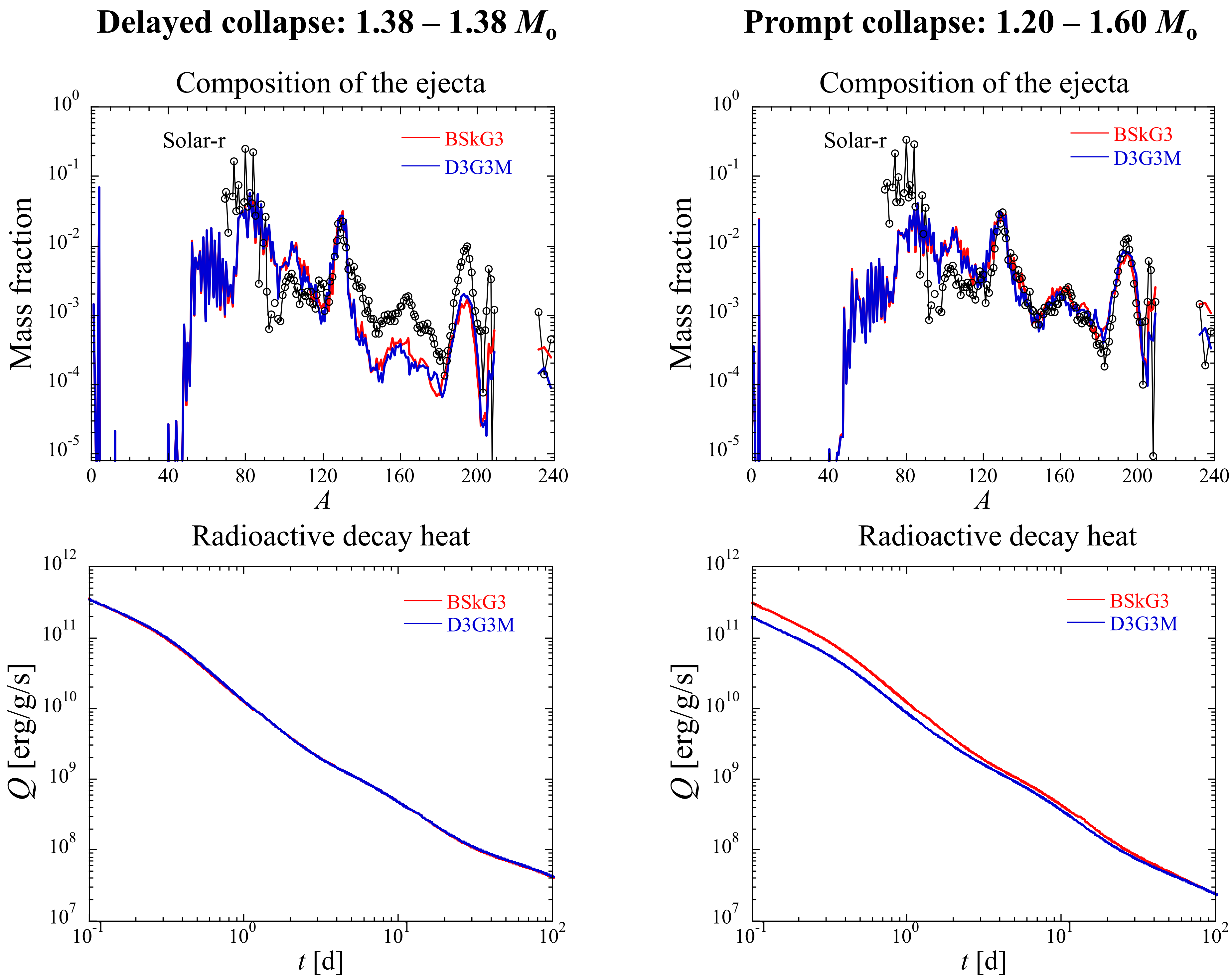




Grams, Ryssens et al. (EPJA 59, 270, 2023)

Differences in the mass predictions between BSkG3 and D3G3M





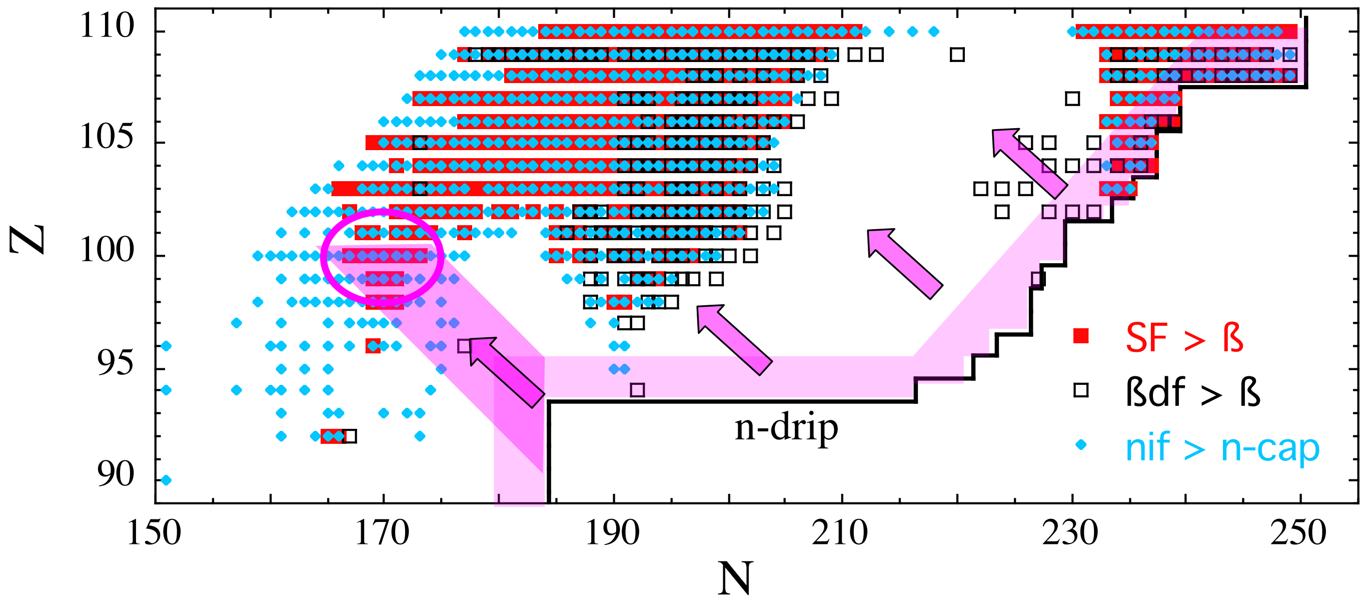
Delayed collapse: 1.38 – 1.38 M_o
Prompt collapse: 1.20 – 1.60 M_o
Composition of the ejecta
Solar-r
BSkG3
D3G3M
Mass fraction
A
Radioactive decay heat
Q [erg/g/s]
t [d]

Fission properties for r-process nucleosynthesis

Fission processes (spontaneous, β-delayed, neutron-induced) and fission fragment distribution of relevance for estimating the

- termination region of the r-process (recycling, heating, prod of SH)
- production of Pb-peak elements
- production of radiocosmochronometers (U, Th)
- production of light species (*A*~110-160) by fission recycling

Detailed calculation of fission probabilities (sf, nif, βdf) for about 2000 nuclei

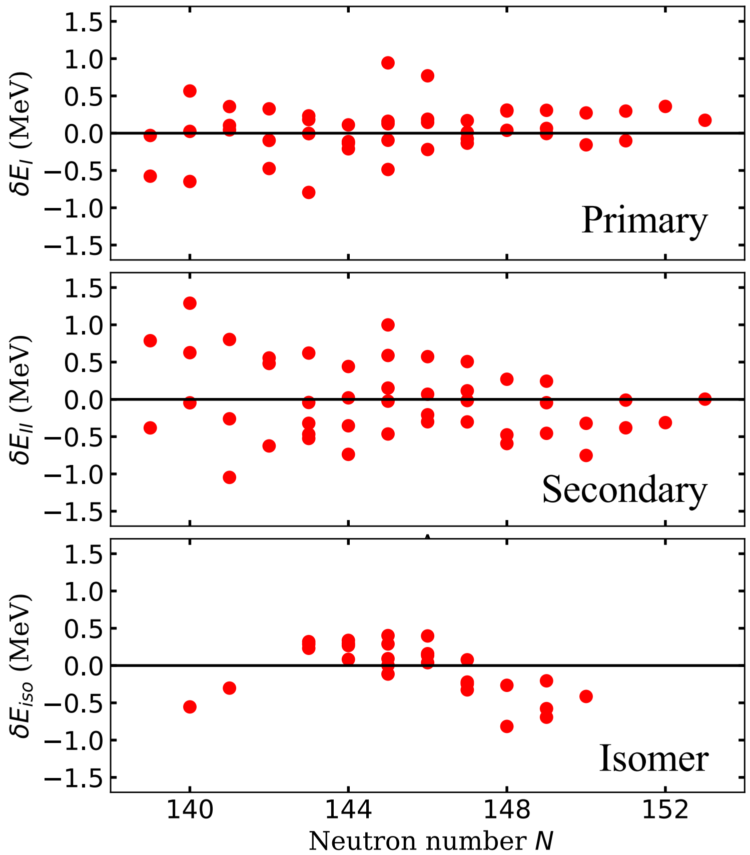


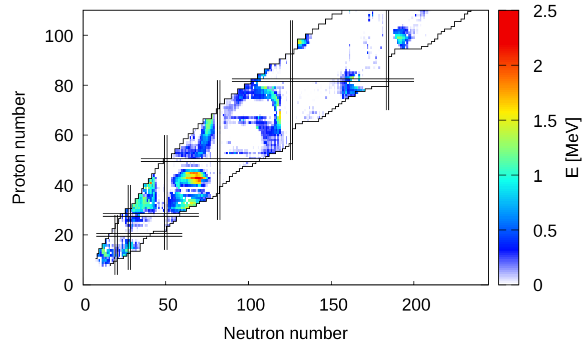
Fission properties

New BSkG3 predictions

Accurate fission barriers σ(45B_f)=0.33MeV including triaxial & octupole deformations **simultaneously**

B_f(BSkG3)- B_f(exp)





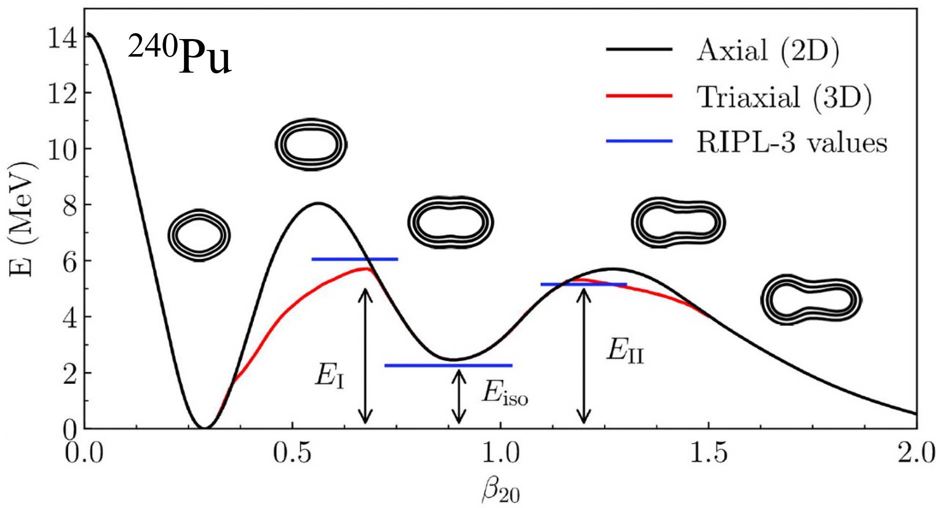
	BSkG3
σ(M) [MeV]	0.63
σ(E_I) [MeV]	**0.33**
σ(E_{II}) [MeV]	0.51
σ(E_{iso}) [MeV]	0.36

Including odd-*A* & odd-odd

BSkG3 fission paths

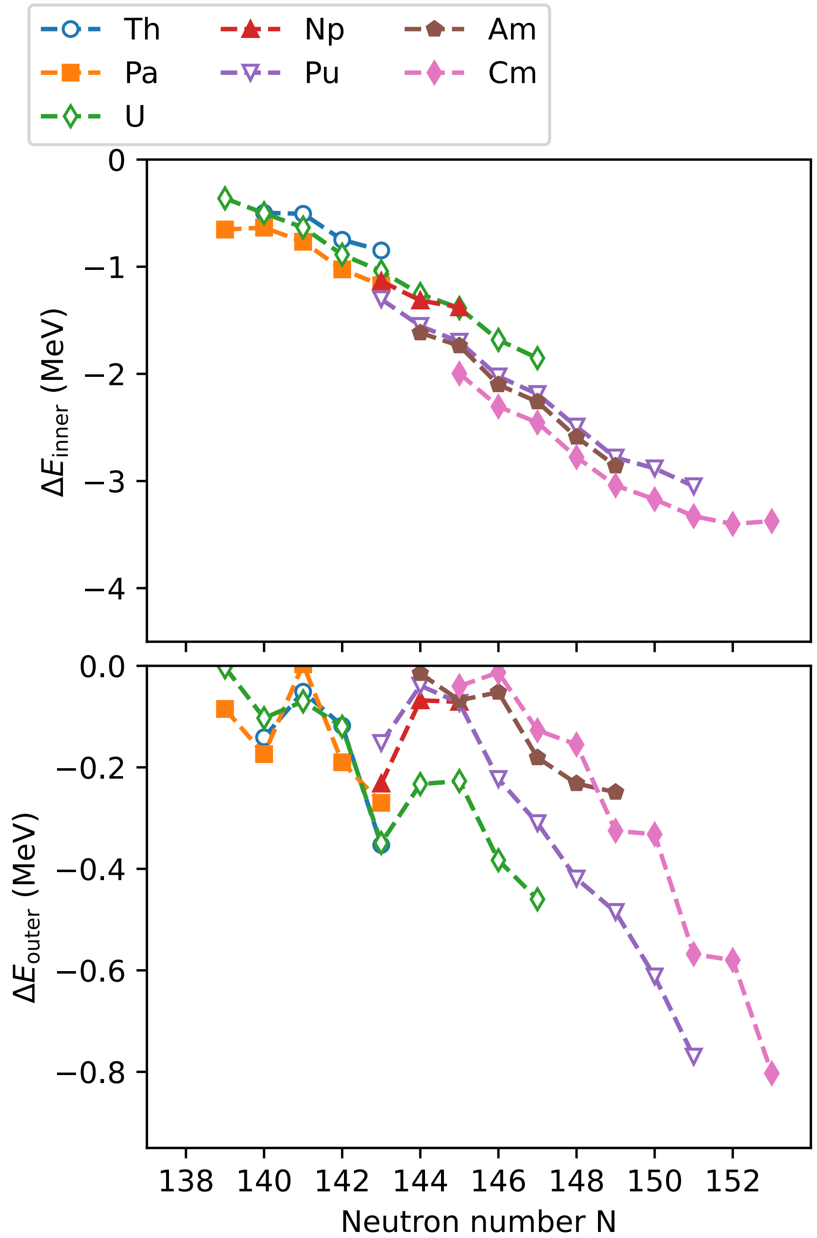
Effects of triaxiality on ***both***

- Triaxial inner barrier



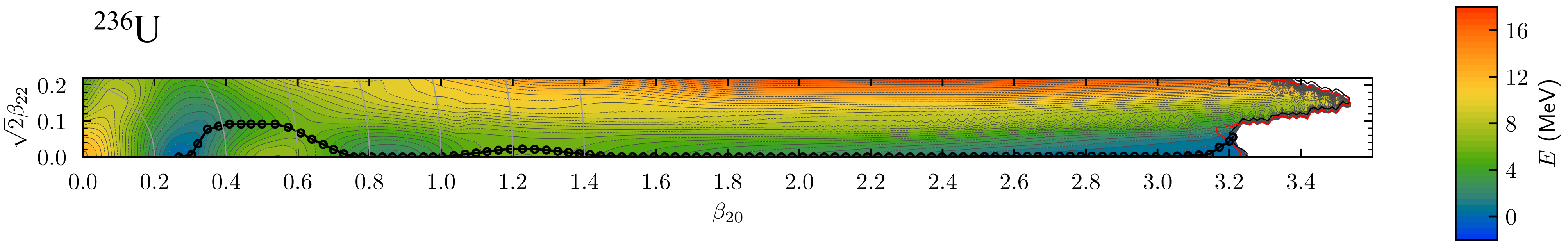
- Triaxial- and octupole-deformed outer barrier

  (also for odd-*A* and odd-odd nuclei)

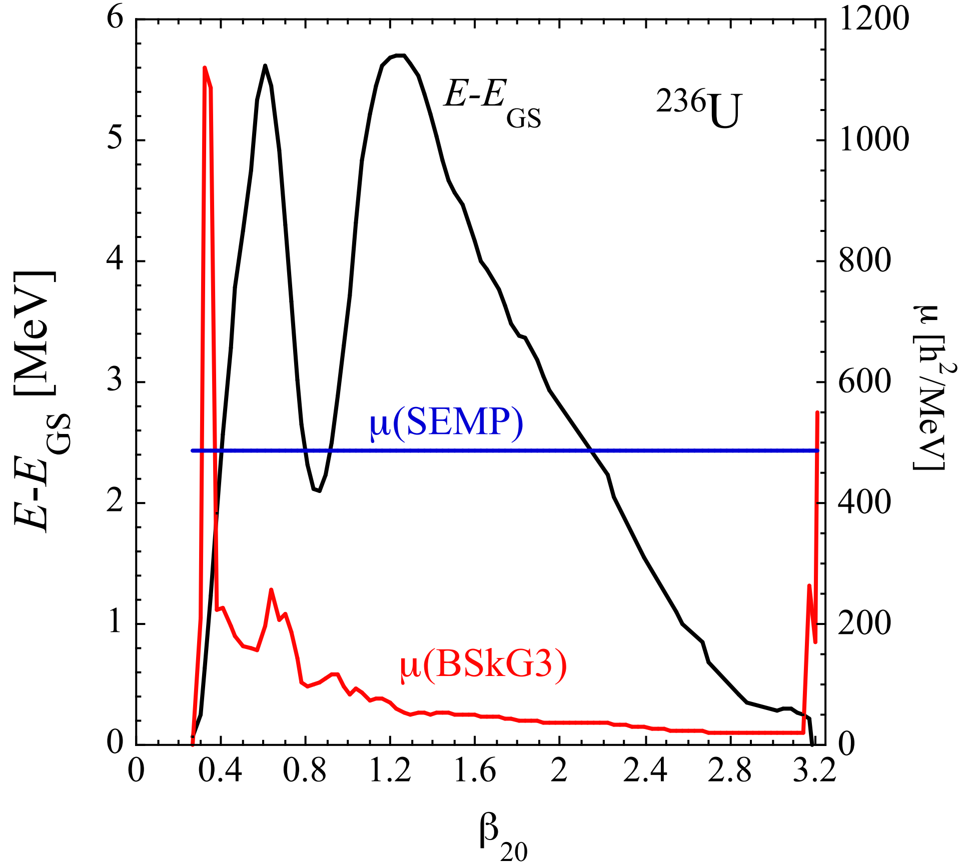


To be extended to 2000 nuclei for r-process simulations ...

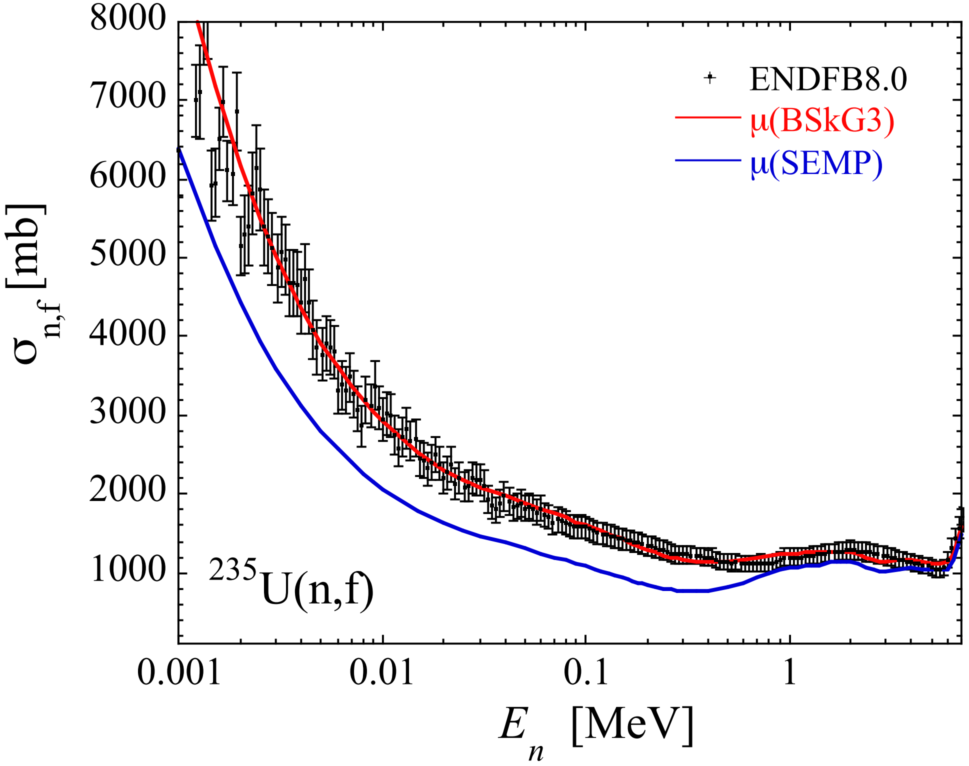
BSkG3 estimate of inertial masses and the least action path



Least action path ($\beta_{20},\beta_{22},\beta_{30},\beta_{32}$)



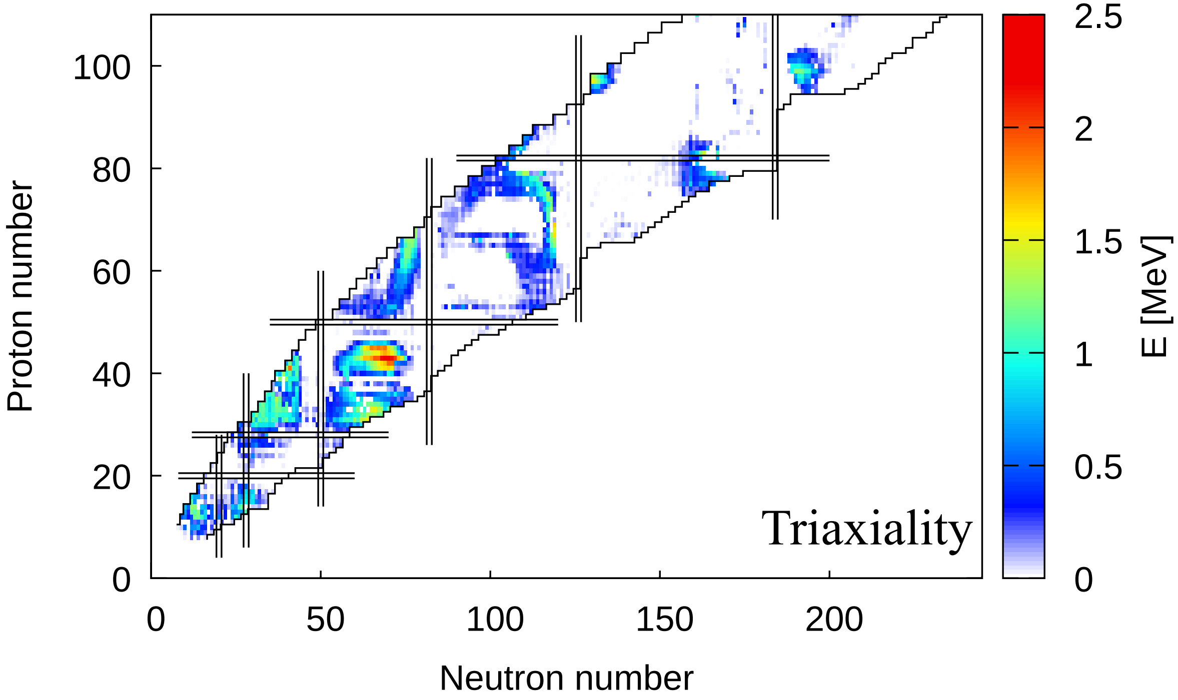
Impact of μ on (n,f) cross section



Normalisation of BSkG3 fission $B_{f\,(\sim2\%)}$ & NLD for ^{236}U

Nuclear Level densities

New combinatorial predictions with BSkG3 properties

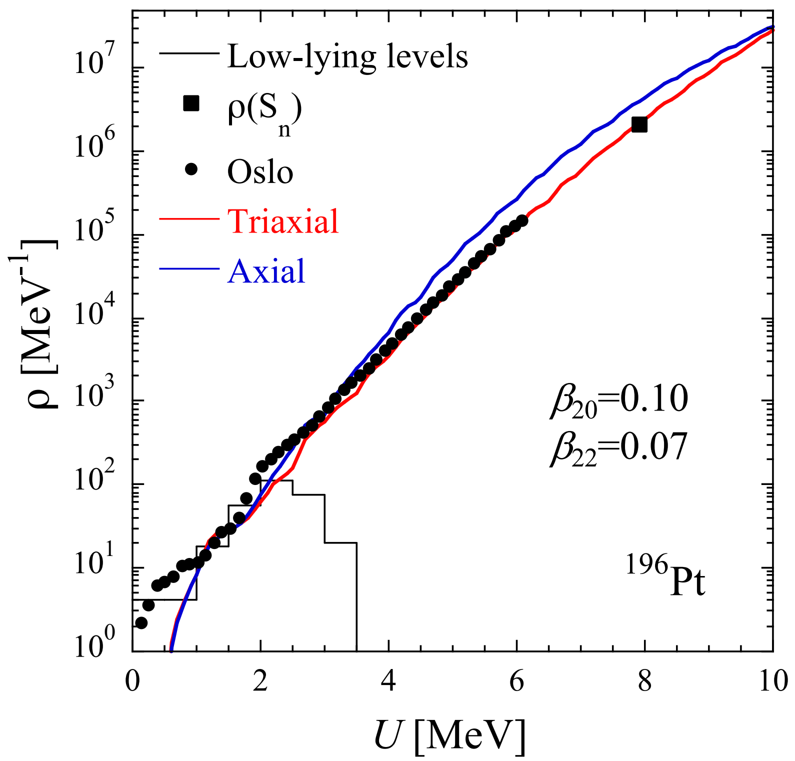


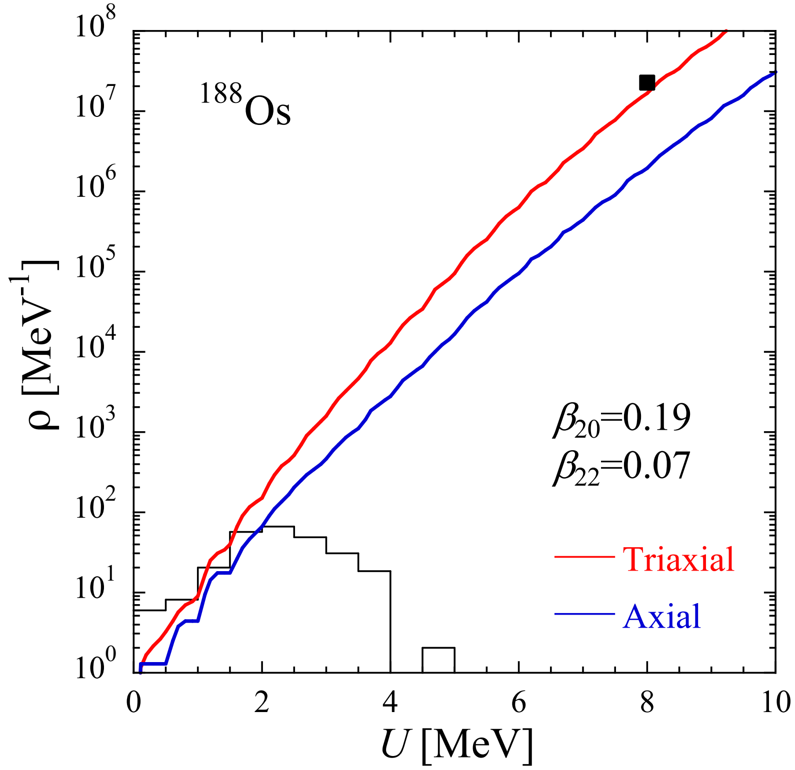
Cf S. Hilaire's talk

NLD within the triaxial HFB(BSkG3)+Combinatorial model

Main impact of the triaxiality on the NLD:

- Lower intrinsic NLD
- Additional collective enhancement





For modest deformation and MoI
→ Lower total NLD

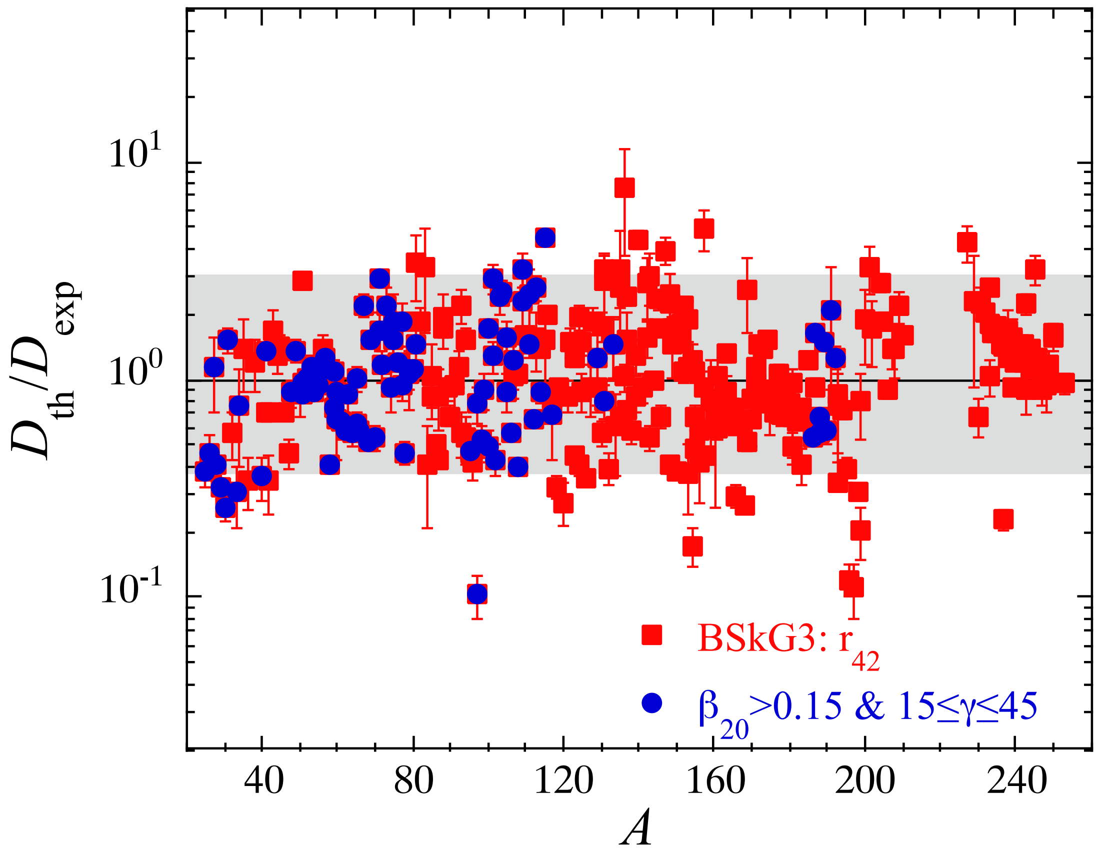
For large deformation and MoI
→ Larger total NLD

In both cases: modification of the *U*-dependence

New NLD calculations allowing for triaxial deformations

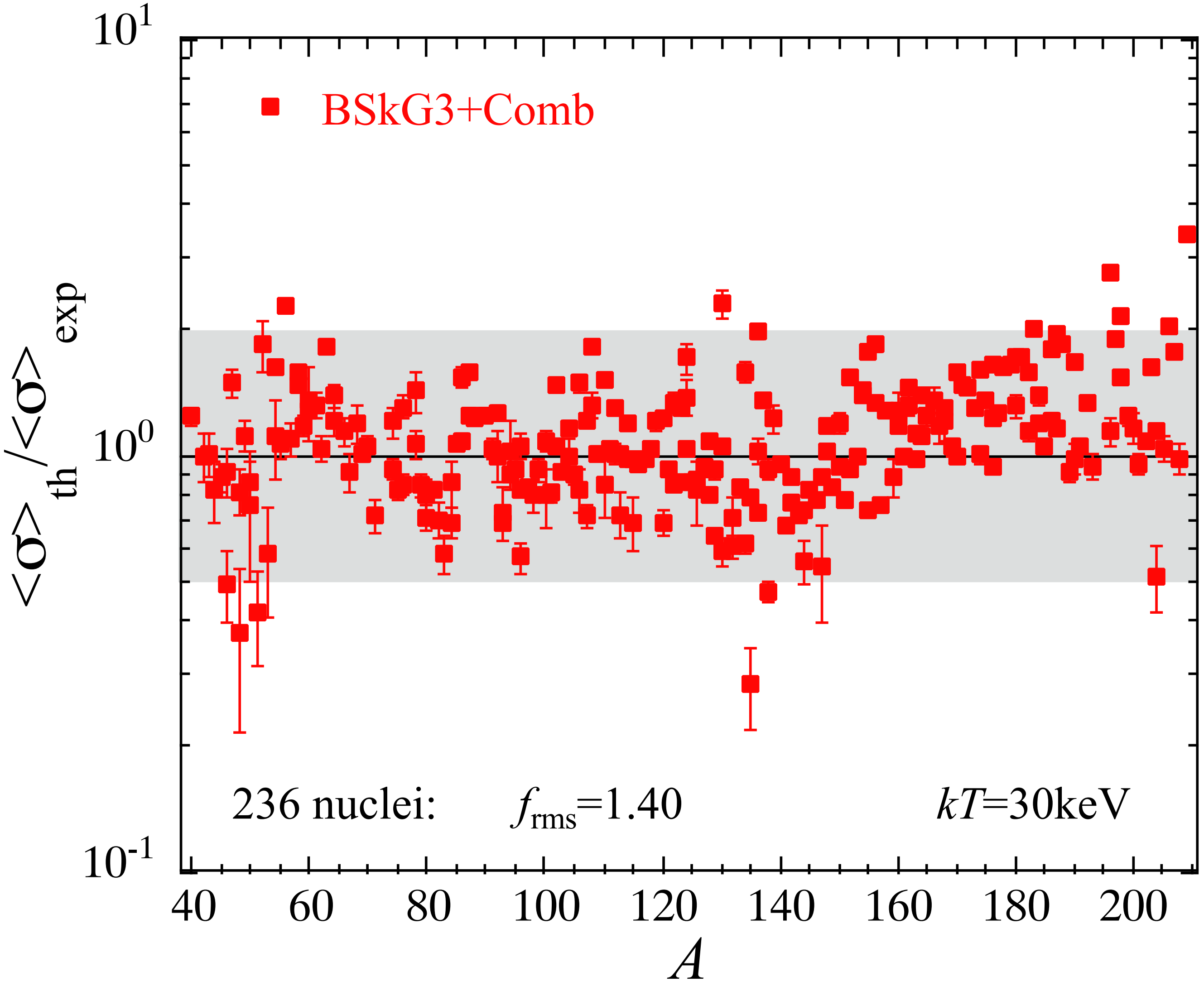
BSkG3 interaction (MOCCa code: Grams, Ryssens et al. 2023): σ(*M*)~0.63 MeV

299 nuclei: $f_{\rm rms}$=1.74 $$f_{\rm rms} = \exp\left[\frac{1}{N_e}\sum_{i=1}^{N_e}\ln^2\frac{D^i_{\rm th}}{D^i_{\rm exp}}\right]^{1/2}$$



D_0 = *s*-wave neutron resonance spacing : $D_0 = \dfrac{1}{\rho(S_n, J_0+1/2, \pi_0) + \rho(S_n, J_0-1/2, \pi_0)}$

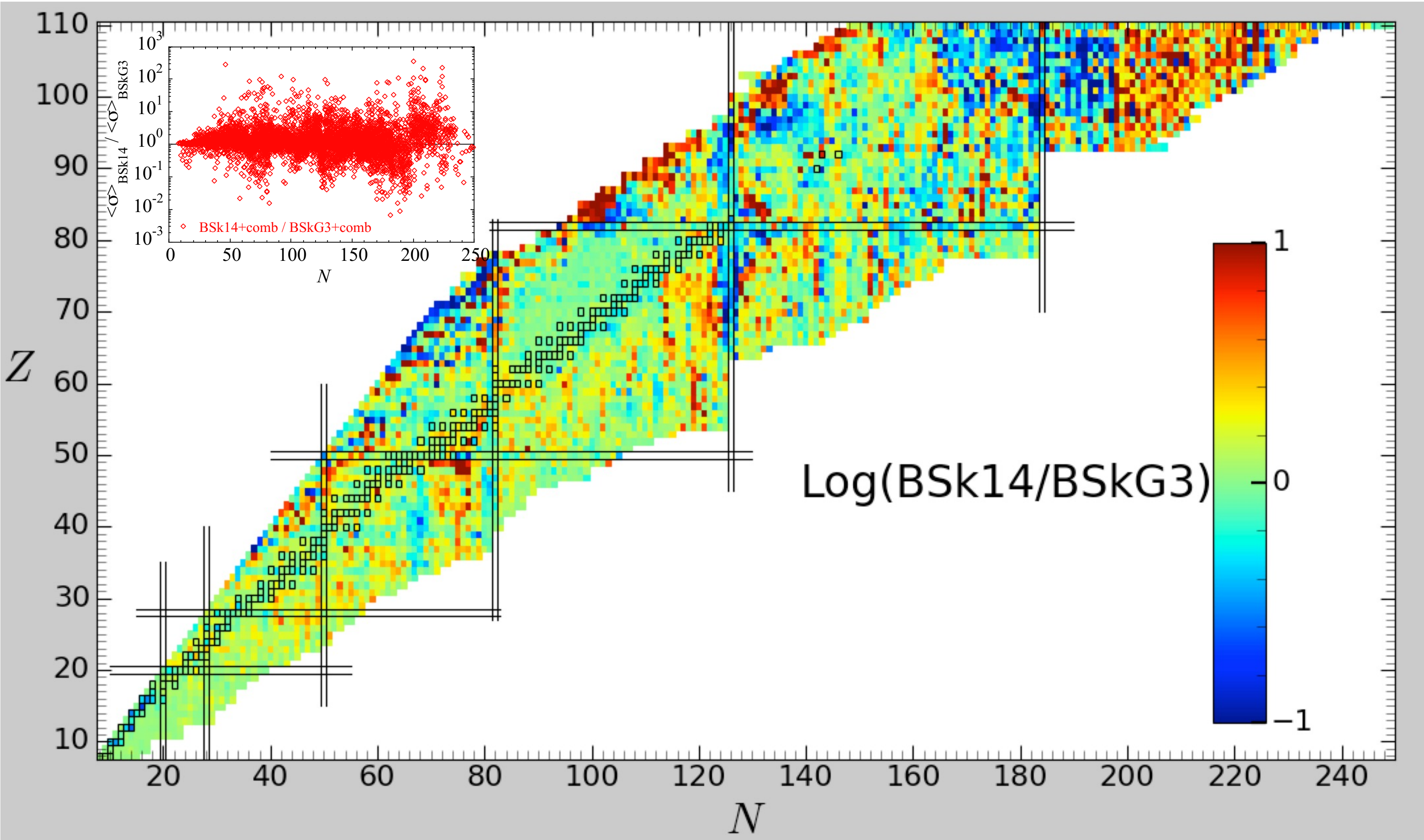
Application of the BSkG3+combinatorial NLD to cross section calculation



Energy-, spin- and parity-depencent NLD tables ready for use for 7677 nuclei ($8 \leq Z \leq 110$)
including renormalisation coefficients (α,δ) on experimental D_{exp} & LLL (when available)

Impact of the BSkG3+combinatorial NLD on HF (n,γ) reaction rates (T_9=1)

Comparison of BSk14+comb (2008) vs BSkG3+comb (2024) impact on N_a<σv>



Energy-, spin- and parity-depencent NLD tables ready for use for 7677 nuclei ($8 \leq Z \leq 110$) including renormalisation coefficients (α,δ) on experimental D_{exp} & LLL (when available)

QRPA + Boson Expansion Method: a conceptually new approach

Hilaire et al. PLB 843, 137989 (2023)

- **Deformed QRPA calculati** collective levels (***Bosons***) for various given multipolar u parities: $K=$ up to $9^{+/-}$ (Gogny D1M+C with a energy 200MeV

- **Boson Expansi** upling Boson neralized boson partition fun

$$\mathcal{Z}_{\text{boson}} = \ldots e^{-\lambda\mu} t^{\mu} p_{\lambda}]^{N_{\text{boson}}}$$

- **Con n of spin- ar ndent NLD**

spherical nuclei: $\ldots_{\text{tot}}(U, M=J, \pi) - \omega_{\text{tot}}(U, M=J+1, \pi)$

well deformed nu $= \frac{1}{2}\left[\sum_{K=-J, K\neq 0}^{J} \omega_{\text{tot}}(U - E_{rot}^{J,K}, K, \pi)\right] + \omega_{\text{tot}}(U - E_{rot}^{J,0}, 0, \pi)$

Cf Hilaire's talk

No independent particle approximation

- **Phenomenologic ng** between spherical and well deformed nuclei

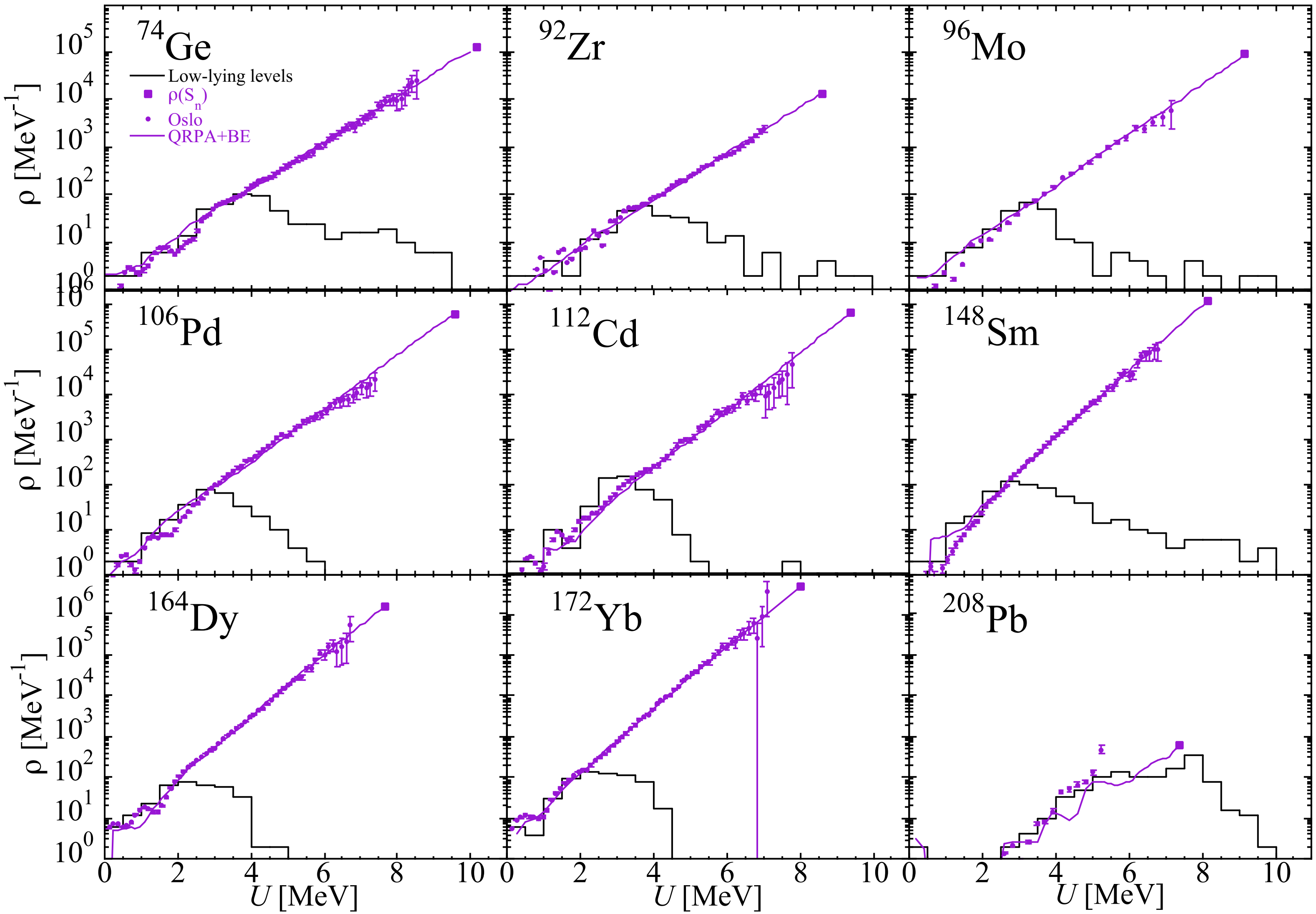
$$\rho(U,J,\pi) = \left[1-\mathcal{F}\right]\rho_s(U,J,\pi) + \mathcal{F}\rho_d(U,J,\pi) \quad \text{where} \quad \mathcal{F} = 1 - \left[1 + e^{(r_{42} - 2.90)/0.35}\right]^{-1}$$

$r_{42}=E(J=4)/E(J=2)=3.3$ rotator

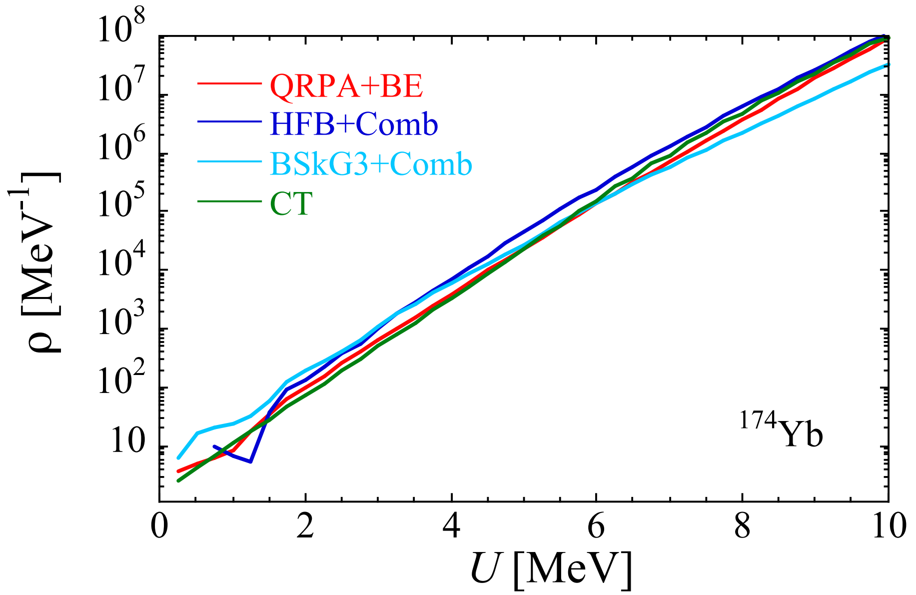
2.0 vibrator

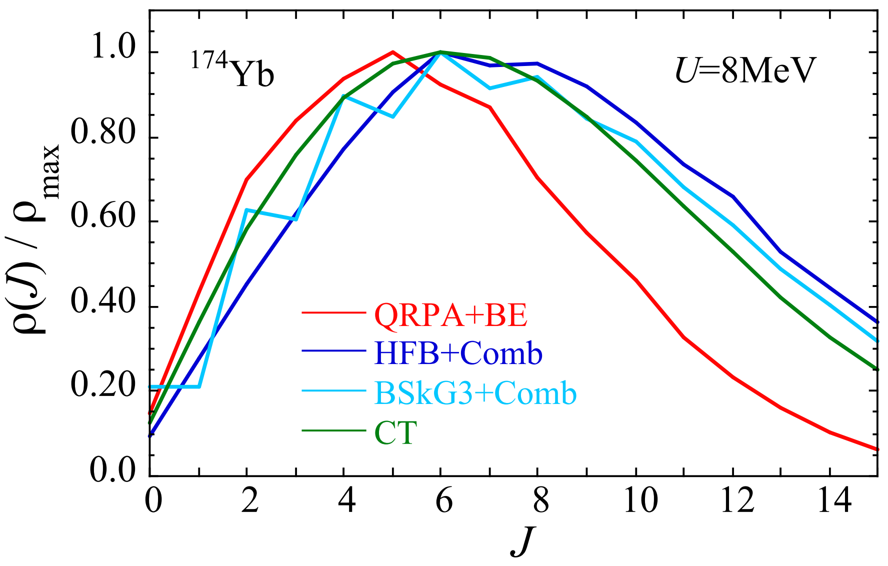
Comparison of the QRPA + BE Method with Oslo data

Normalisation of the QRPA+BE energies on D_0 & Oslo data on theoretical NLDs

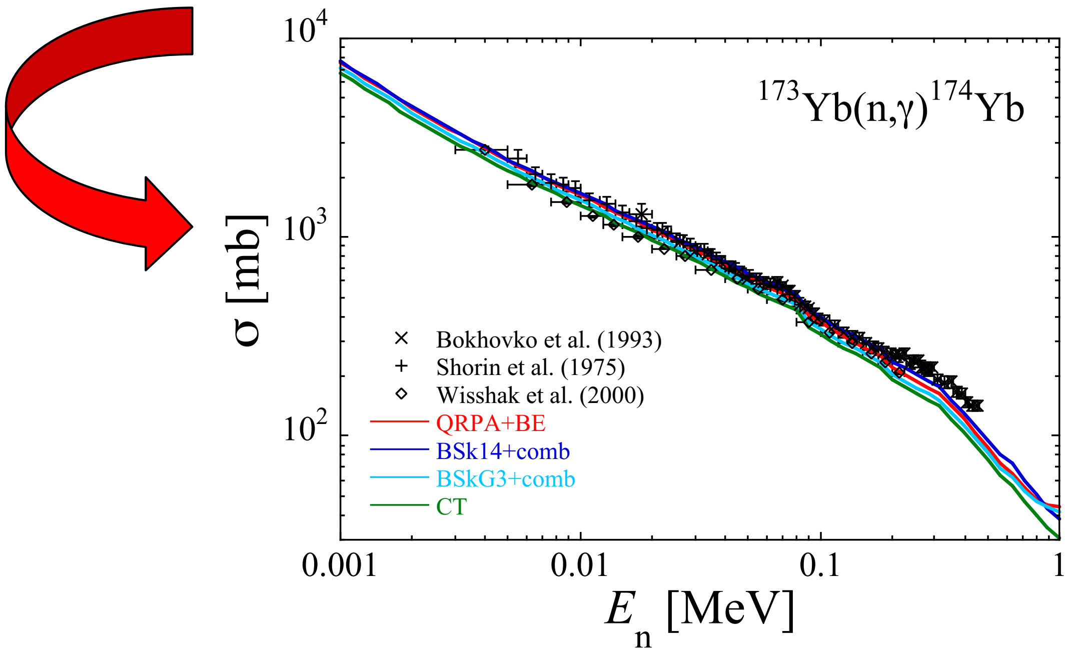


Application to reaction cross section: ^{173}Yb(n,γ)^{174}Yb



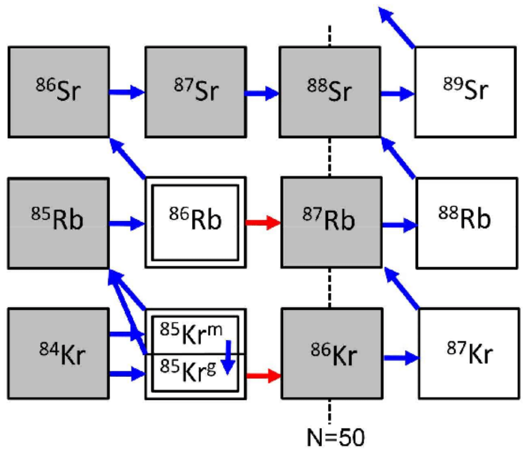


Narrow spin distribution



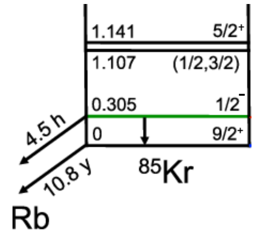
Cannarozzo, Pomp et al. (2023)
"We find that a significant **reduction of the spin width distribution** improves the agreement between calculated and experimentally observed isomeric yield ratios" from de-excitation of fission fragments

Application to $^{84}Kr(n,\gamma)^{85}Kr$



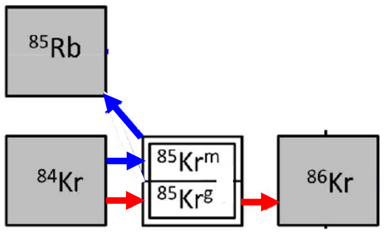
Non-thermalisation of $^{85}Kr^m$ in a low-T (s-process) plasma

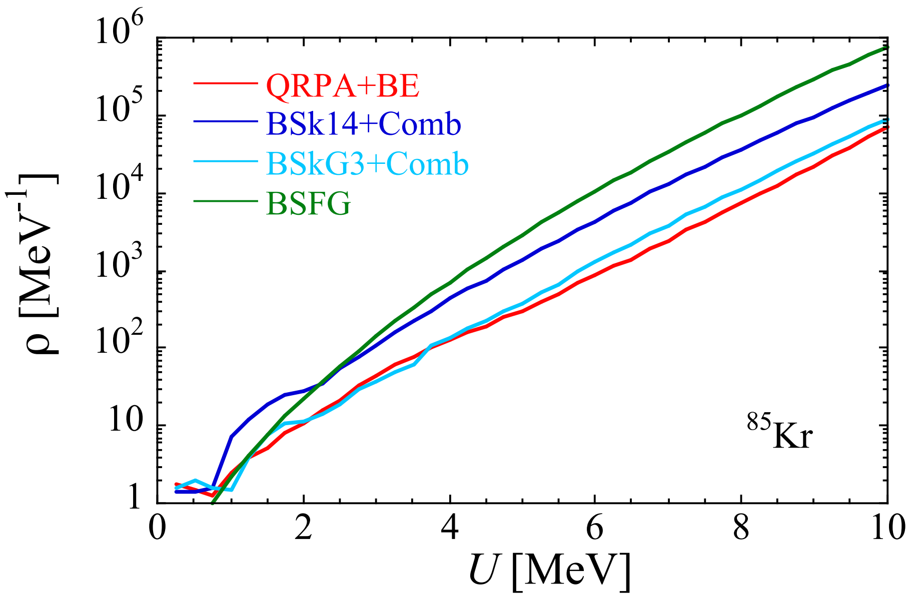
→ Branching:

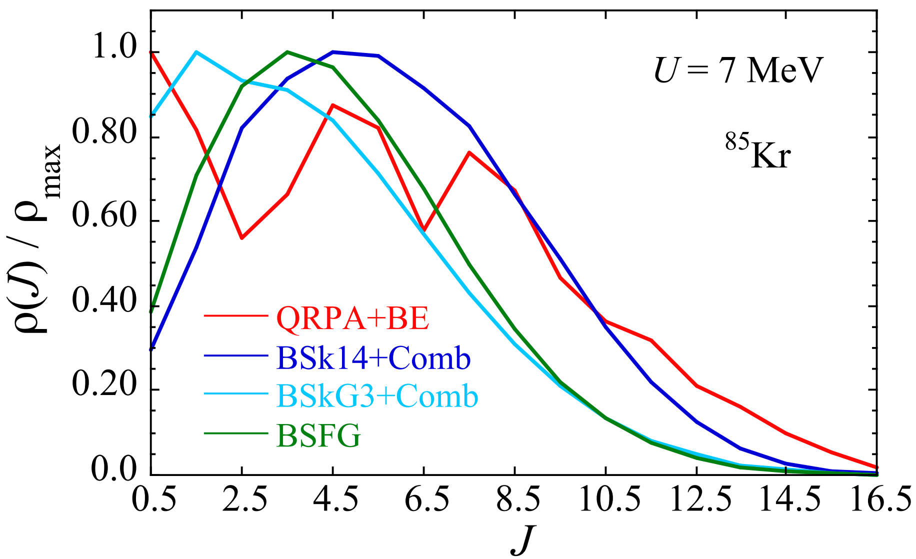


$^{84}Kr(n,\gamma)^{85}Kr^m(\beta^-)^{85}Rb$

$^{84}Kr(n,\gamma)^{85}Kr^g(n,\gamma)^{86}Kr$

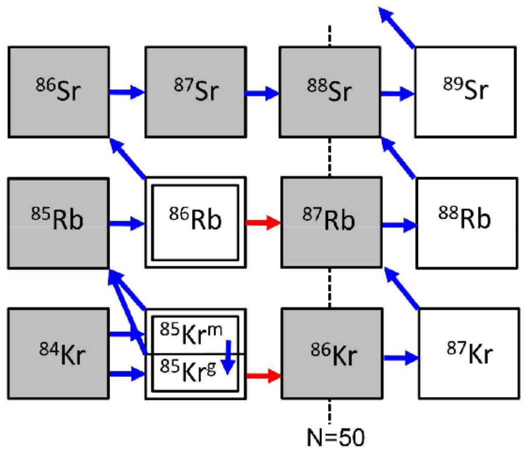






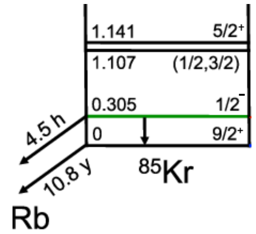
Non-statistical J-distribution in ^{85}Kr

Application to $^{84}Kr(n,\gamma)^{85}Kr$



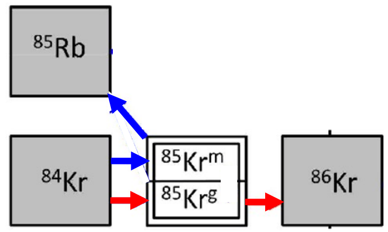
Non-thermalisation of $^{85}Kr^{m}$ in a low-T (s-process) plasma

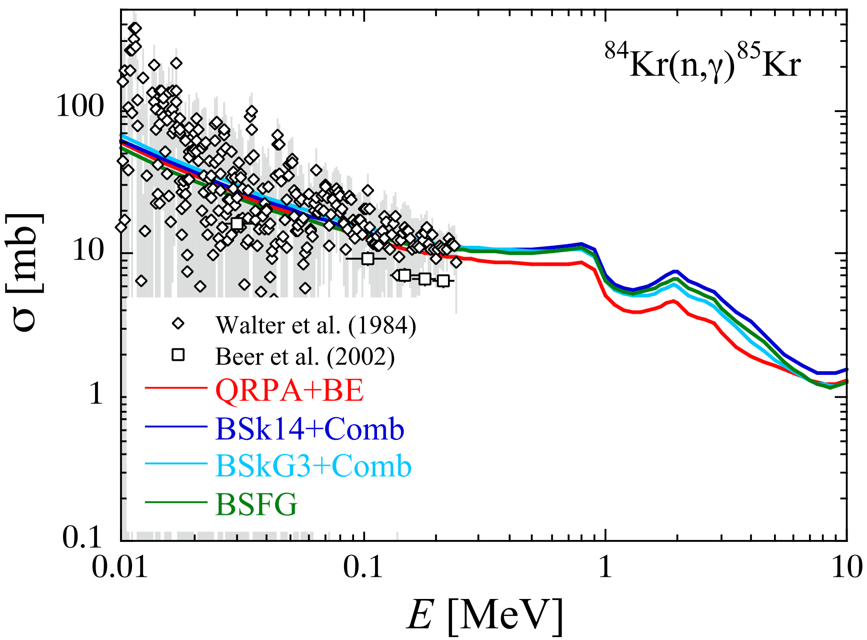
→ Branching:

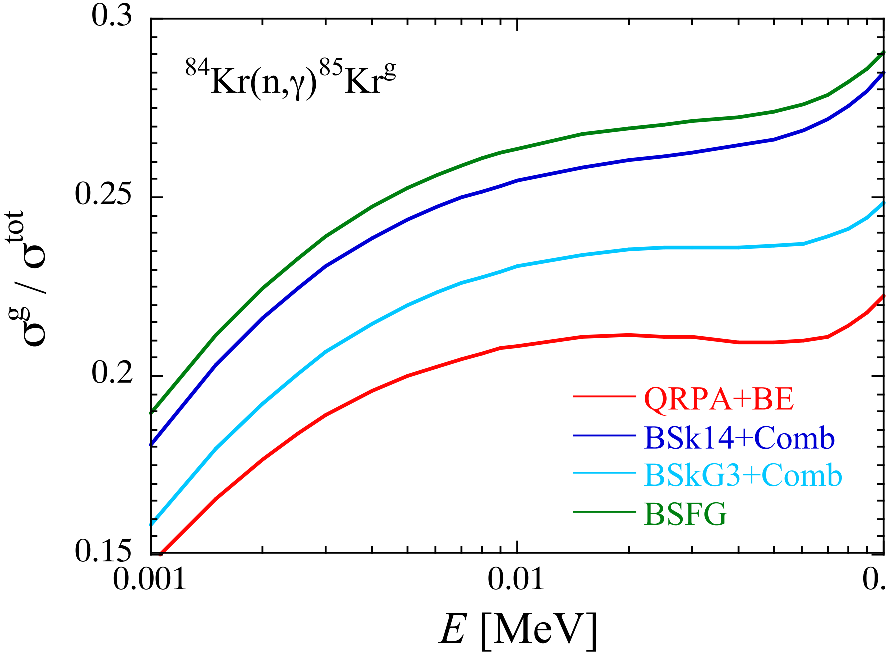


$^{84}Kr(n,\gamma)^{85}Kr^{m}(\beta^{-})^{85}Rb$

$^{84}Kr(n,\gamma)^{85}Kr^{g}(n,\gamma)^{86}Kr$



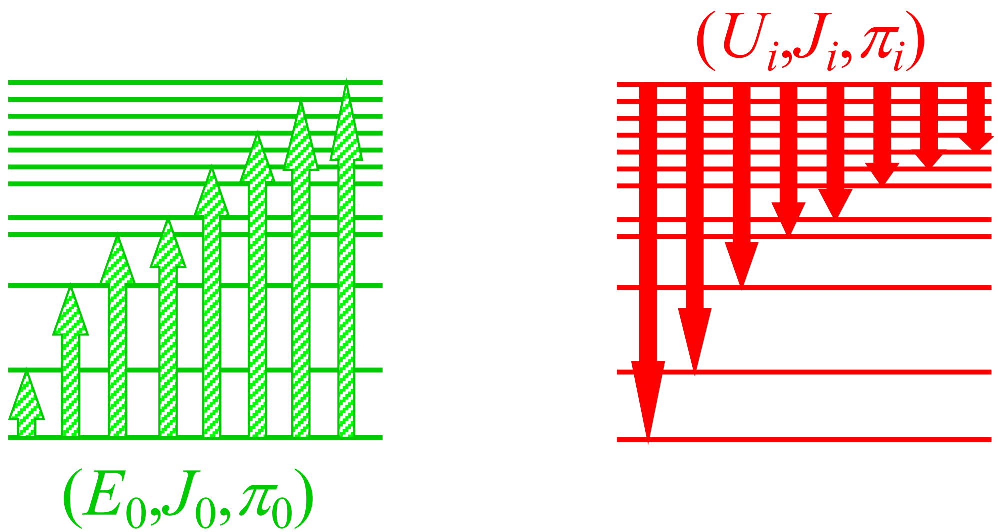




NLD renormalised on low-lying levels and D_0

Photon Strength Function

New D1M+QRPA calculations of the **de-excitation** PSF

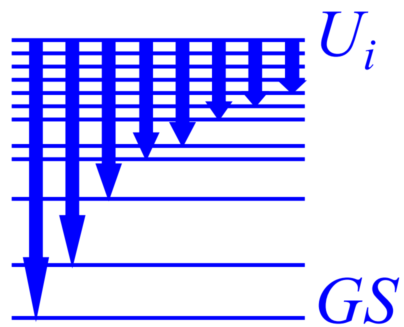


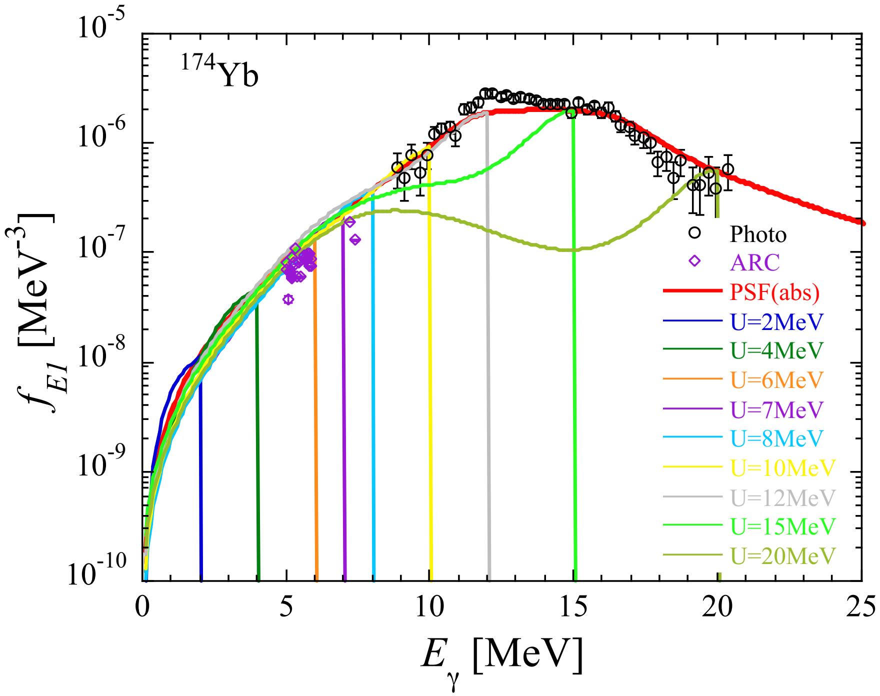
cf Péru's talk

QRPA de-excitation PSF at an initial energy U_i

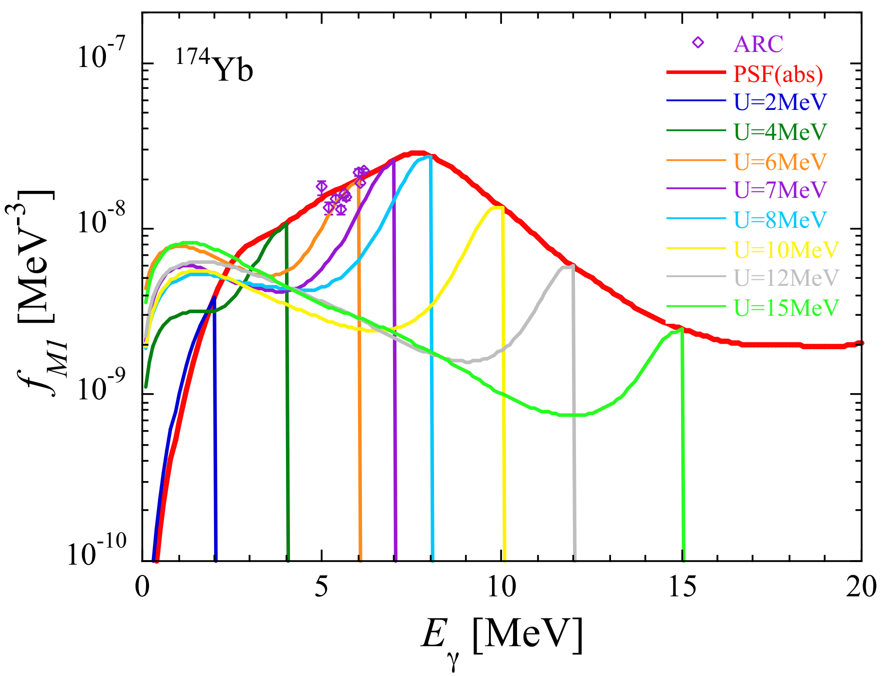
$$f_{E1}(E) = \int_{-\infty}^{+\infty} L(E,\omega) S_{E1}(\omega)\, d\omega \quad \text{with}$$

$$L(E,\omega) = \frac{1}{\pi\Gamma} \frac{\Gamma^2 E^2}{\left[E^2 - (\omega-\Delta)^2\right]^2 + \Gamma^2 E^2}$$





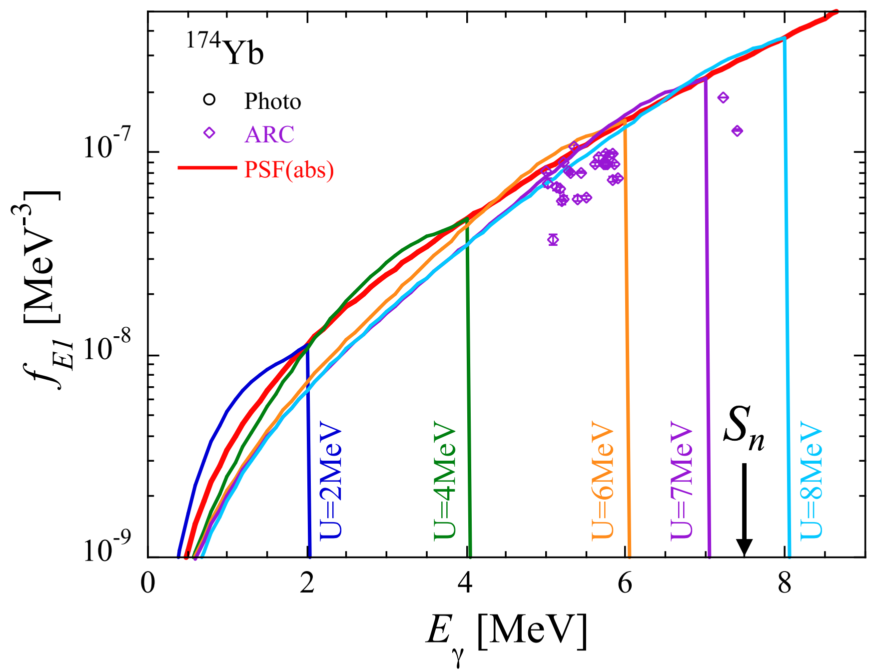
Negligible low-energy E1 enhancement

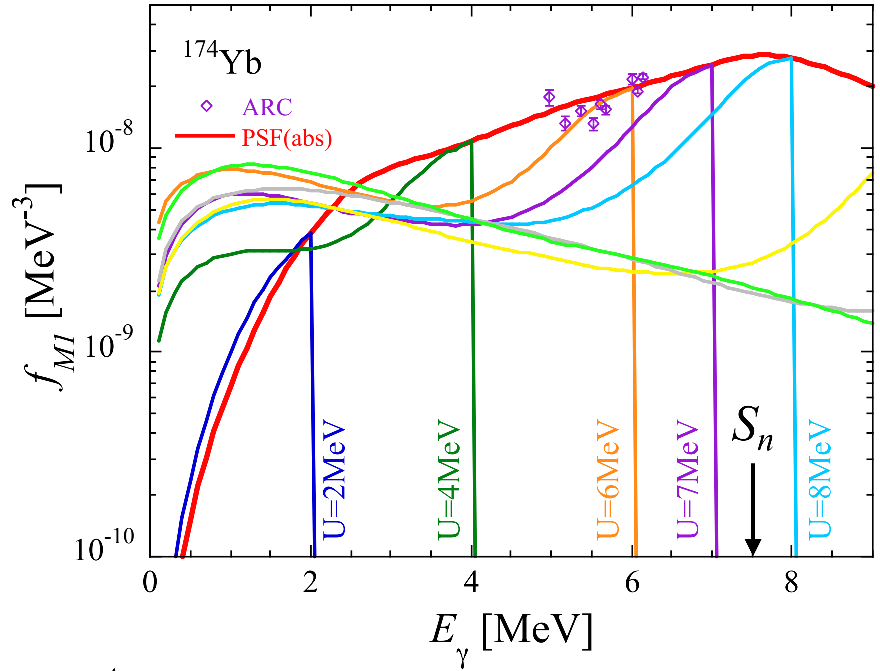


Significant low-energy M1 enhancement

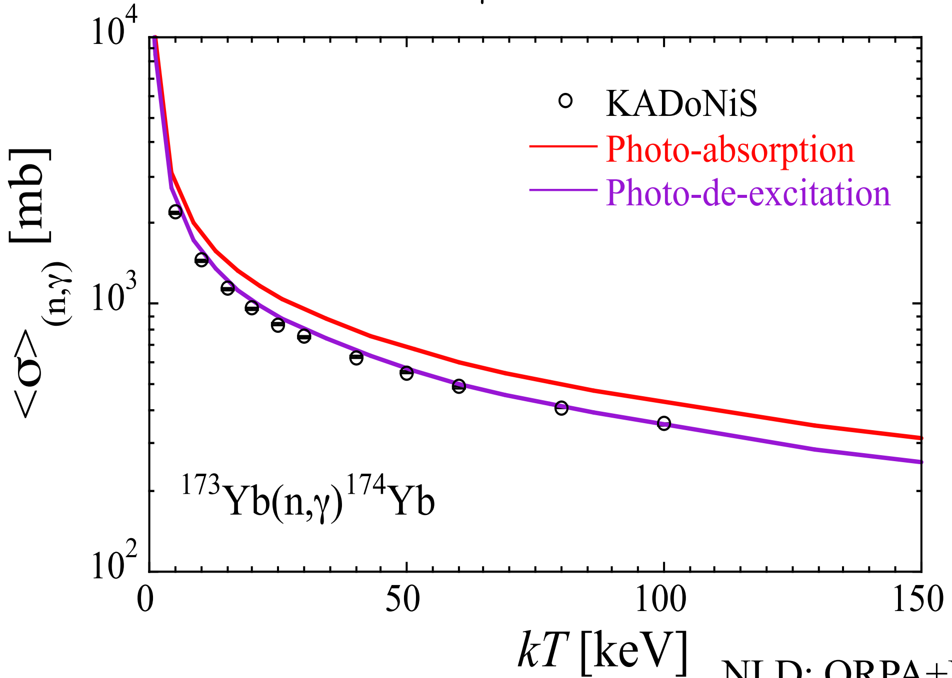
→ impact on low-S_n n-capture

Impact of the de-excitation PSF on radiative n-capture cross sections





Decrease of the (n,γ) cross section when including the de-excitation PSF with respect to the photo-absorption PSF

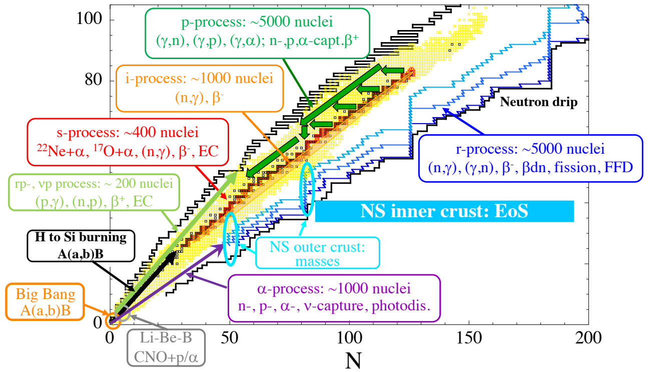


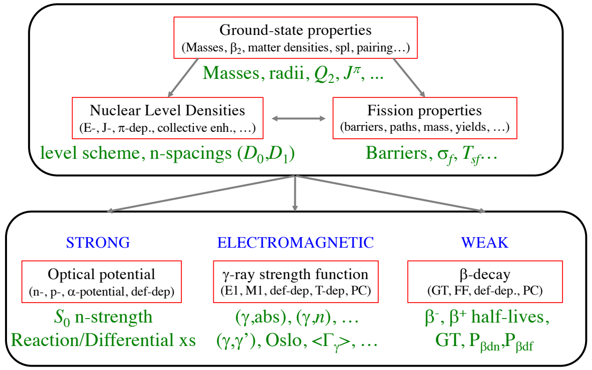
NLD: QRPA+BE

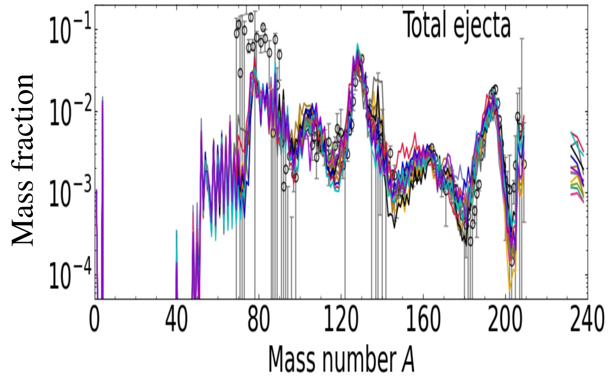
Conclusion: Progess in Nuclear Astrophysics

Despite impressive progress for the last years, Nuclear Astrophysics still requires

- **Dedicated experimental work** on
  - key reactions (^{12}C+α, ^{12}C+^{12}C, ^{22}Ne+α, ...)
  - reactions (n,γ), (p,γ), (α,γ), (n,f), ... for stable and unstable targets (RIB, Oslo, surro)
  - key properties (M, R_c, NLD, PSF, OMP, ...) for stable as well as unstable nuclei
- **Dedicated theoretical work** based on as “microscopic” as possible models for experimentally unavailable nuclei (mean-field, shell model, ab-initio)
- **Detailed account of uncertainties** that need to be properly propagated into astrophysical observables.
- **Remain critical about impact** of NP on astrophysics observables







THANK YOU
FOR
YOUR ATTENTION