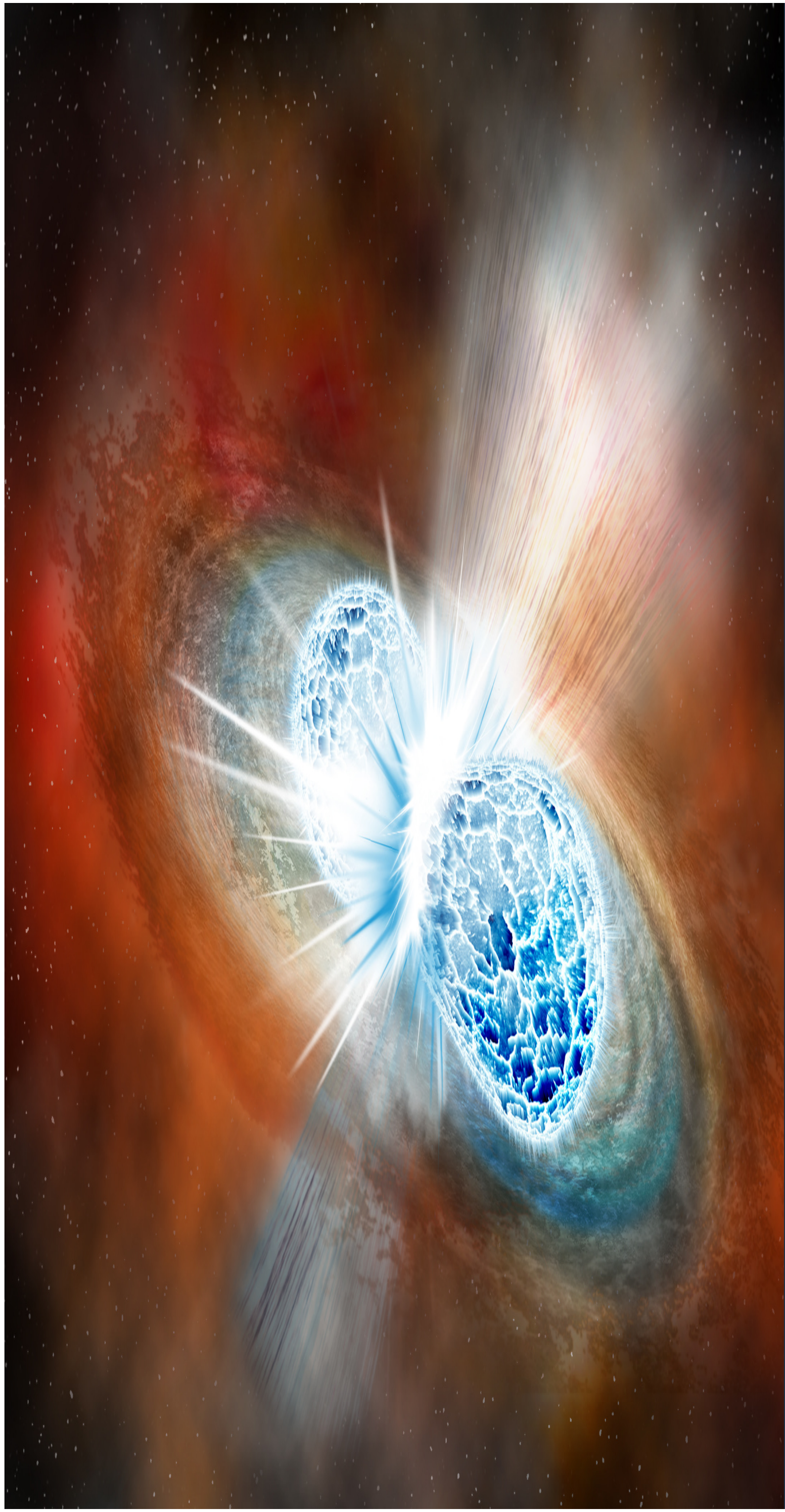
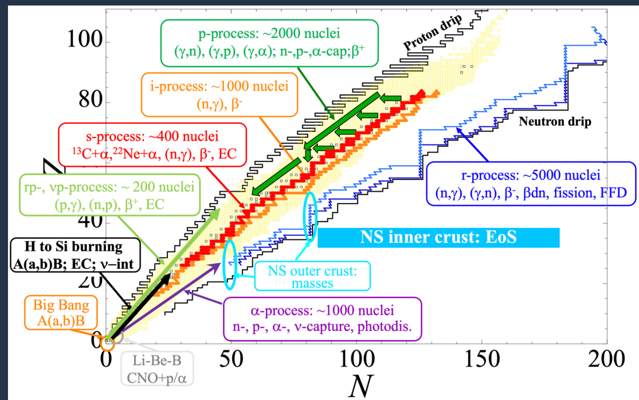


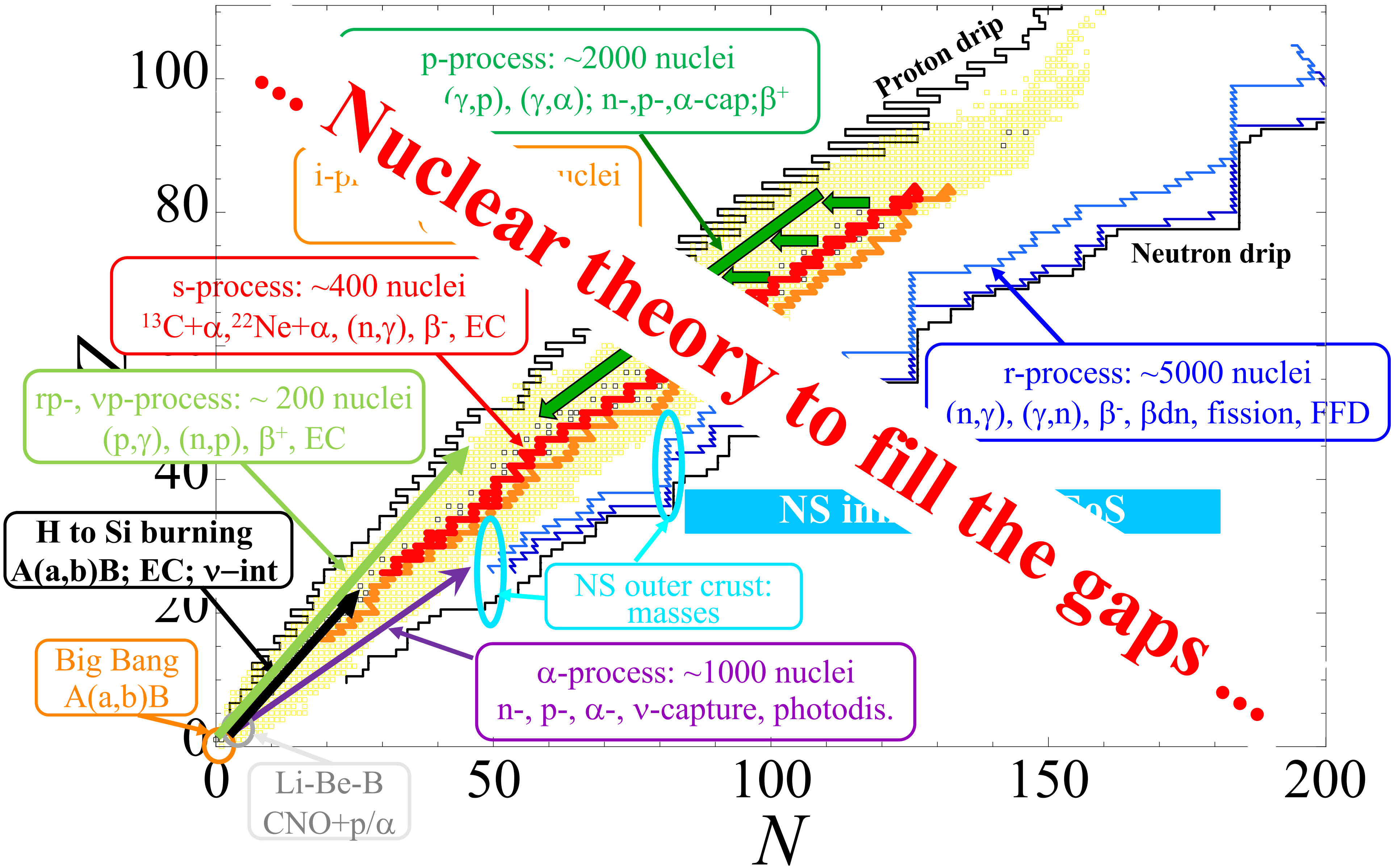
Progress & Challenges in nuclear theory for astrophysics applications



S. Goriely (IAA-ULB)

In collaboration with
W. Ryssens, A. Sanchez, S. Martinet, A. Choplin, G. Grams,
S. Hilaire, S. Péru, O. Just, A. Bauswein

Nuclear Astrophysics: a field with high NP demands



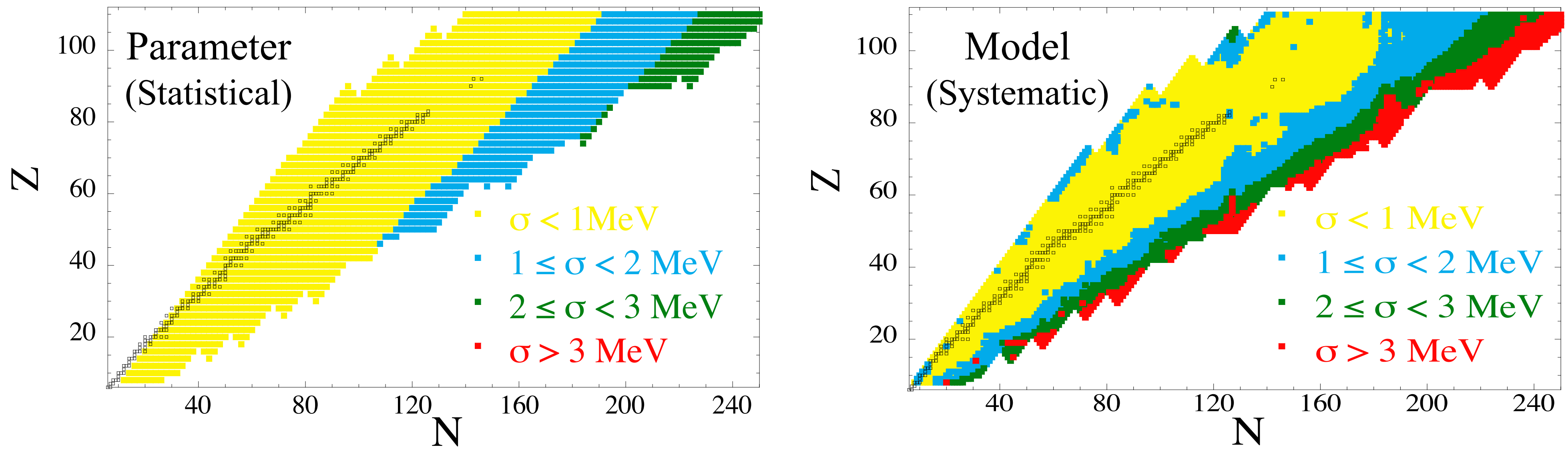
How accurate should the predictions be ?

How do nuclear uncertainties affect astrophysics observables ?

1. Quantification of nuclear uncertainties

Some progress in considering "theoretical nuclear uncertainties" in NA

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



Model or parameter variations must be constrained by experimental data

e.g Only *parameter* variations s.t. $\sigma_{rms} < 0.8$ MeV ⟺ Only mass *models* s.t. $\sigma_{rms} < 0.8$ MeV

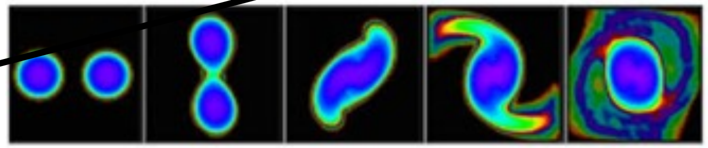
Only NLD/PSF *parameters* s.t. (n,γ) with $f_{rms} \leq 2$ ⟺ Only NLD/PSF *models* s.t. (n,γ) with $f_{rms} \leq 2$

Uncorrelated parameter variations

Masses/rates correlated by the model

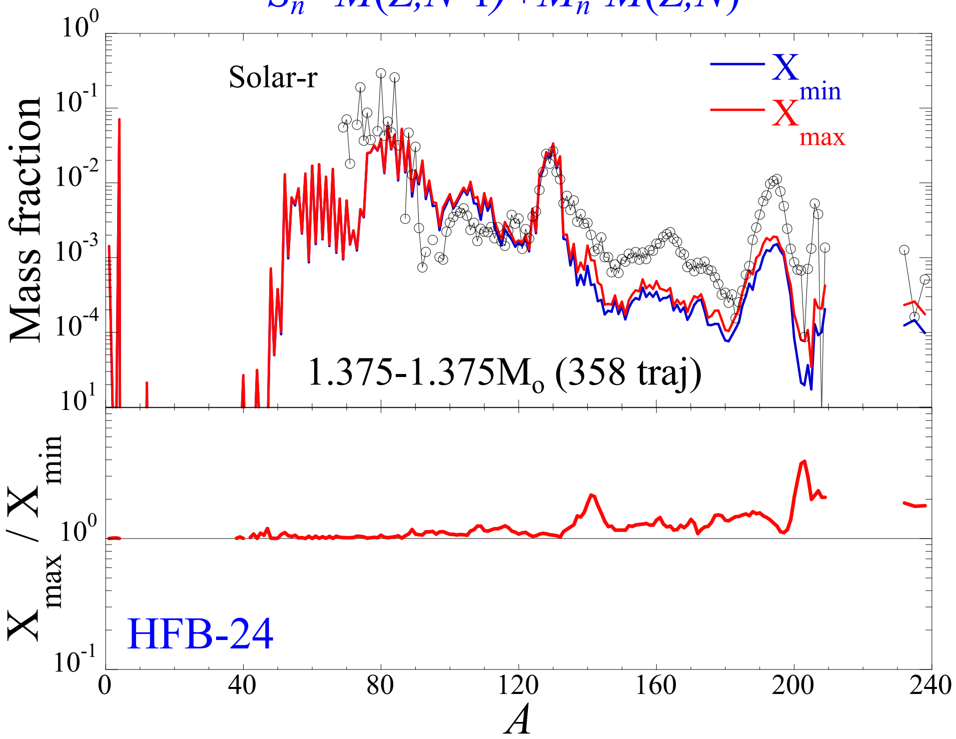
But what about their impact on astrophysical observables ?

2. Propagation of NP uncertainties into astrophysics simulations



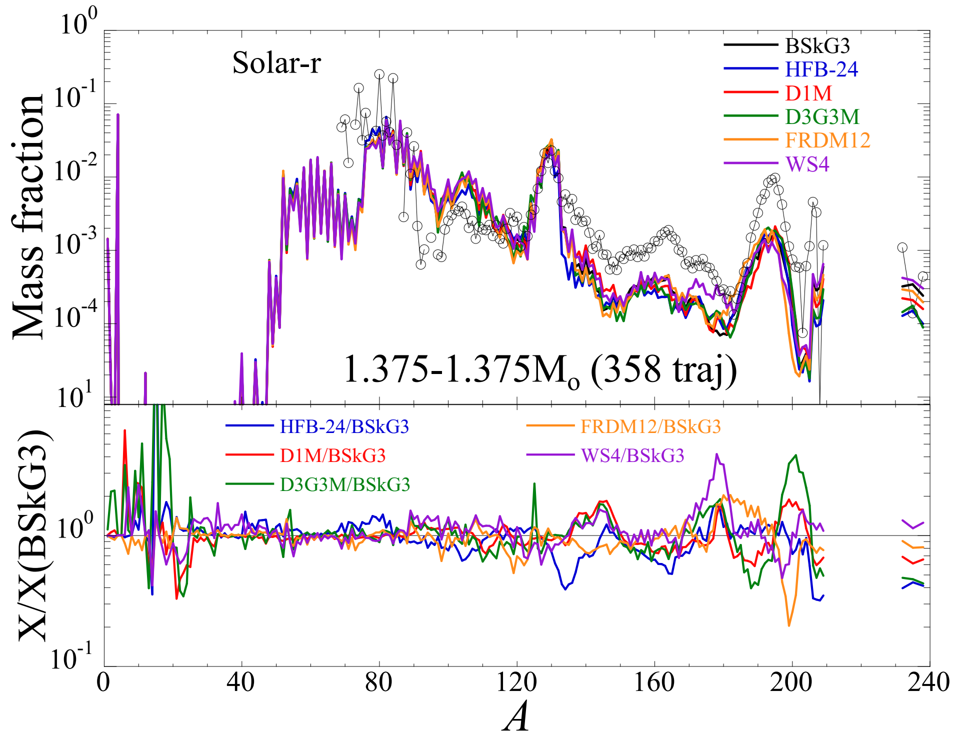
Parameter uncorrelated uncertainties

$S_n = M(Z,N\text{-}1) + M_n - M(Z,N)$



- Additional correlations may exist, e.g S_n and M
- MC approach if uncorrelated uncertainties
- Still parameters changes constrained by exp

Model-correlated uncertainties



- MC approach not correct
- Coherent model-correlated uncertainties
- Each model is affected by parameter unc.

if correlations or experimental constraints underestimated, impact is overestimated

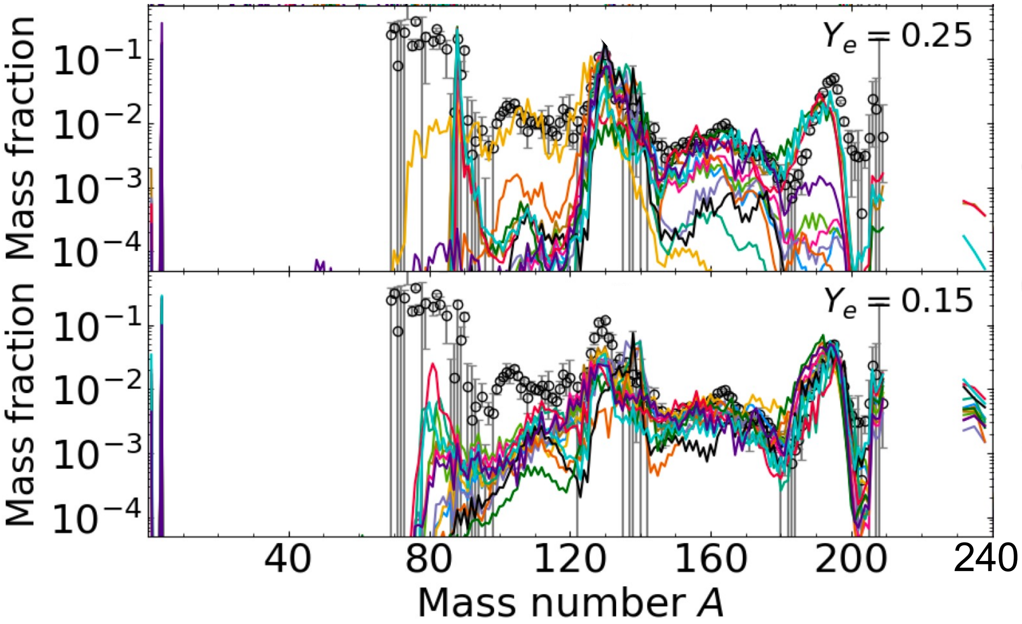
Impact of nuclear *model* uncertainties on the composition of NSM ejecta

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

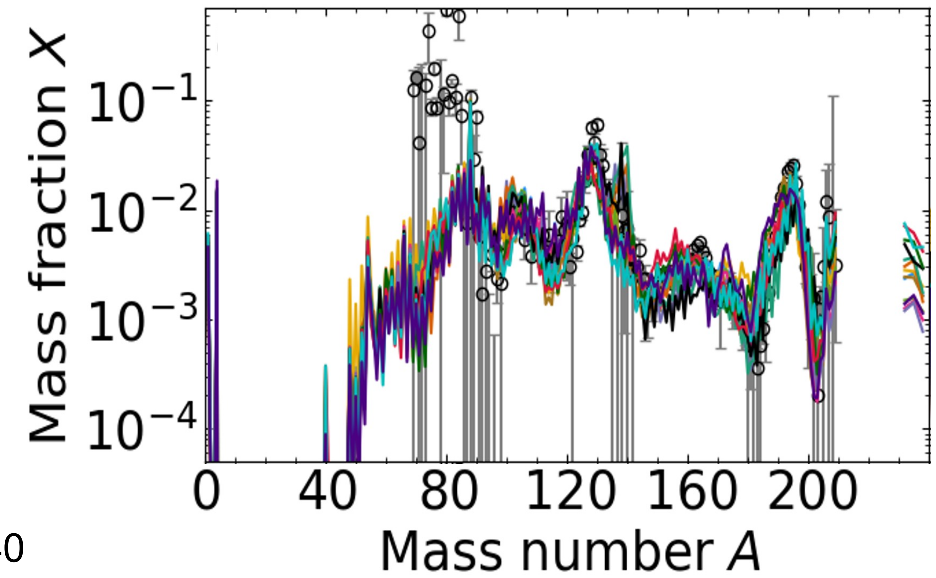
Kullmann et al. (2022)

Prompt dynamical ejecta: 1.35-1.35M_o (Bauswein 2022)

Single trajectory



Multiple trajectories



Global & Local discrepancies

Local (correlated) discrepancies

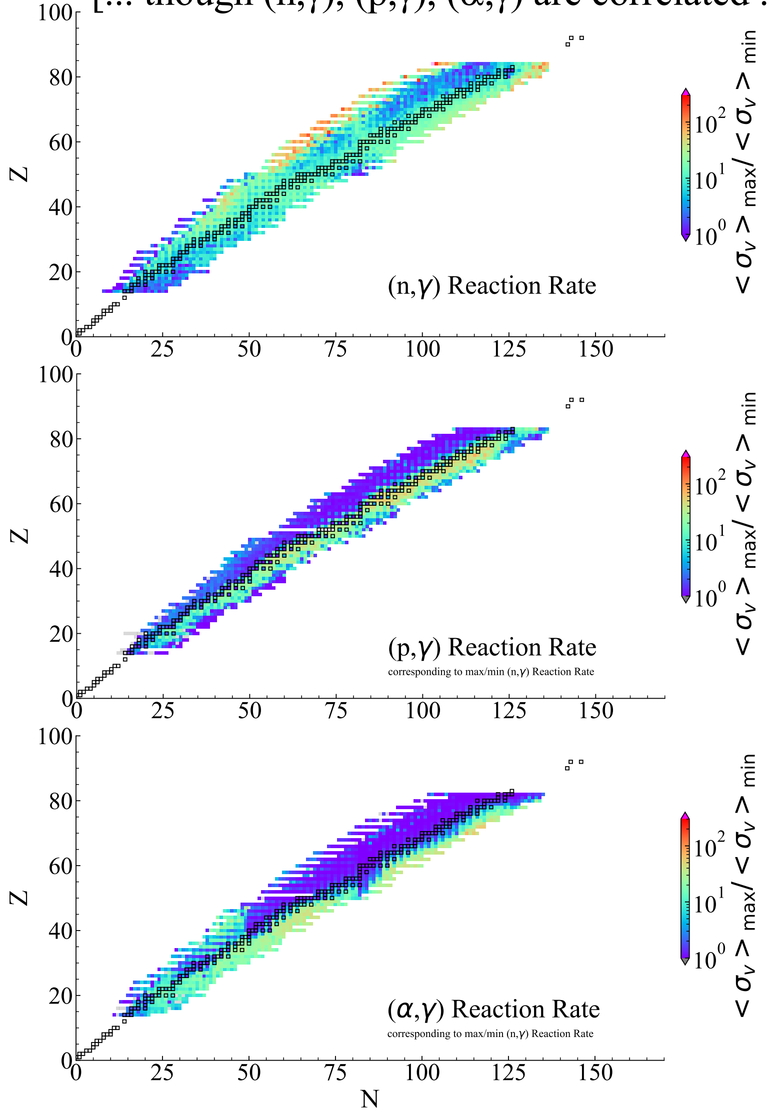
Astrophysical models evolve and may still not be robust
(what is "important" today may not be next year)

Uncertainty propagation must be applied to a *representative sample* of trajectories

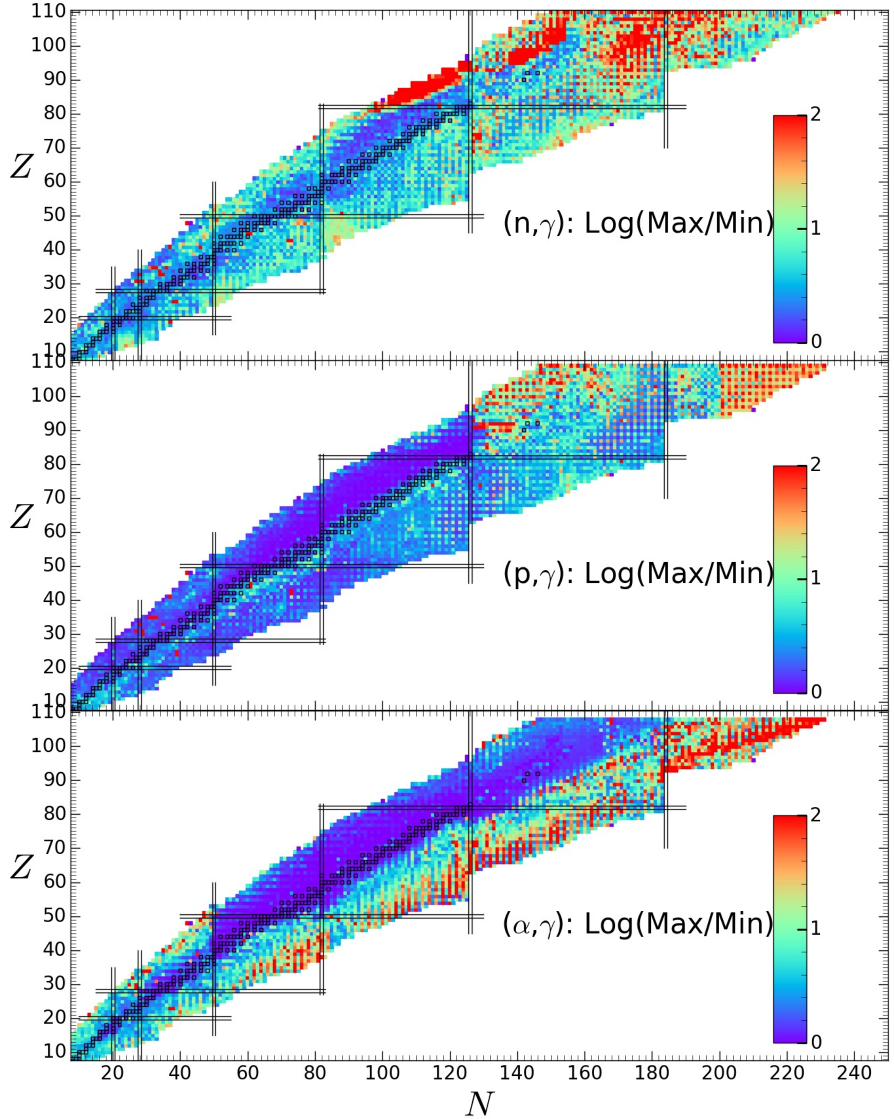
Impact of NLD/PSF uncertainties on the (n,γ), (p,γ), (α,γ) rates

Uncorrelated parameter uncertainties

[... though (n,γ), (p,γ), (α,γ) are correlated ...]



Correlated model uncertainties



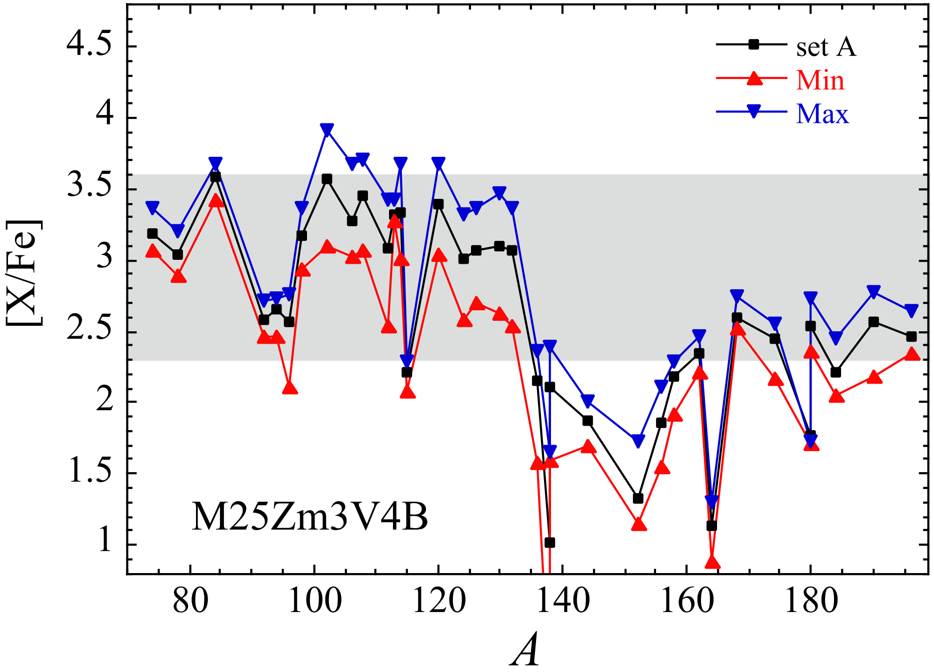
Impact of NLD/PSF uncertainties on the p-process nucleosynthesis

Overproduction of p-nuclei in the core of an exploding $25M_{o}$ Z=0.001 v/v_c=0.4 star

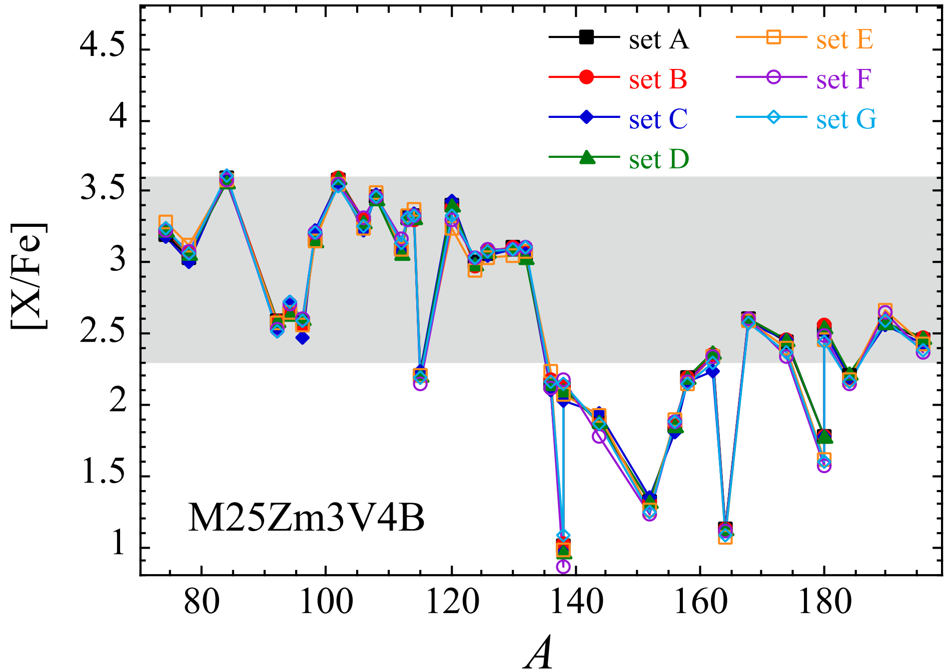
(Choplin et al. 2022)

Uncorrelated parameter uncertainties

Highly dominated by (γ,n) parameter uncertainties



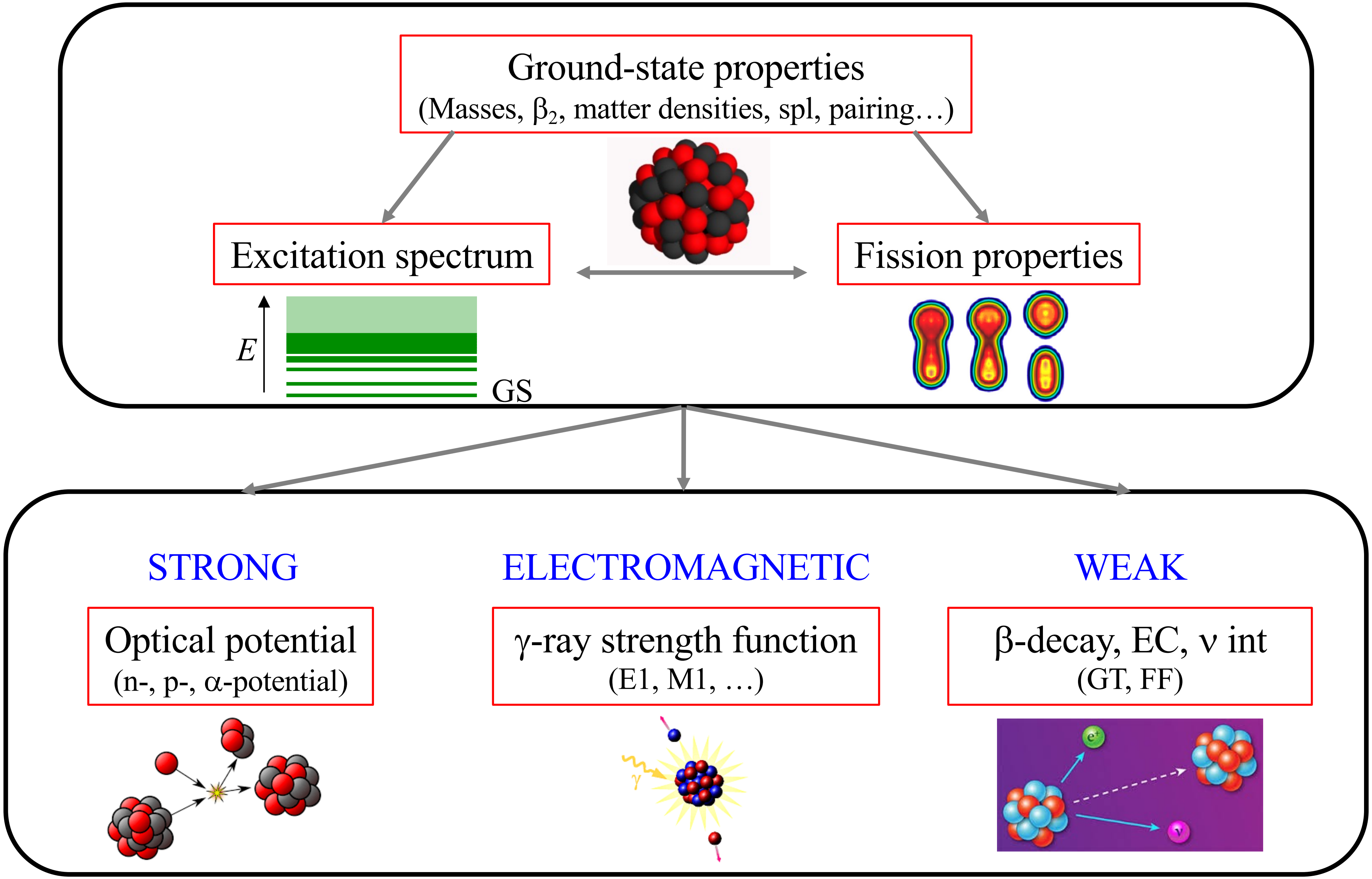
Correlated model uncertainties



Reduction of the model & parameter uncertainties through

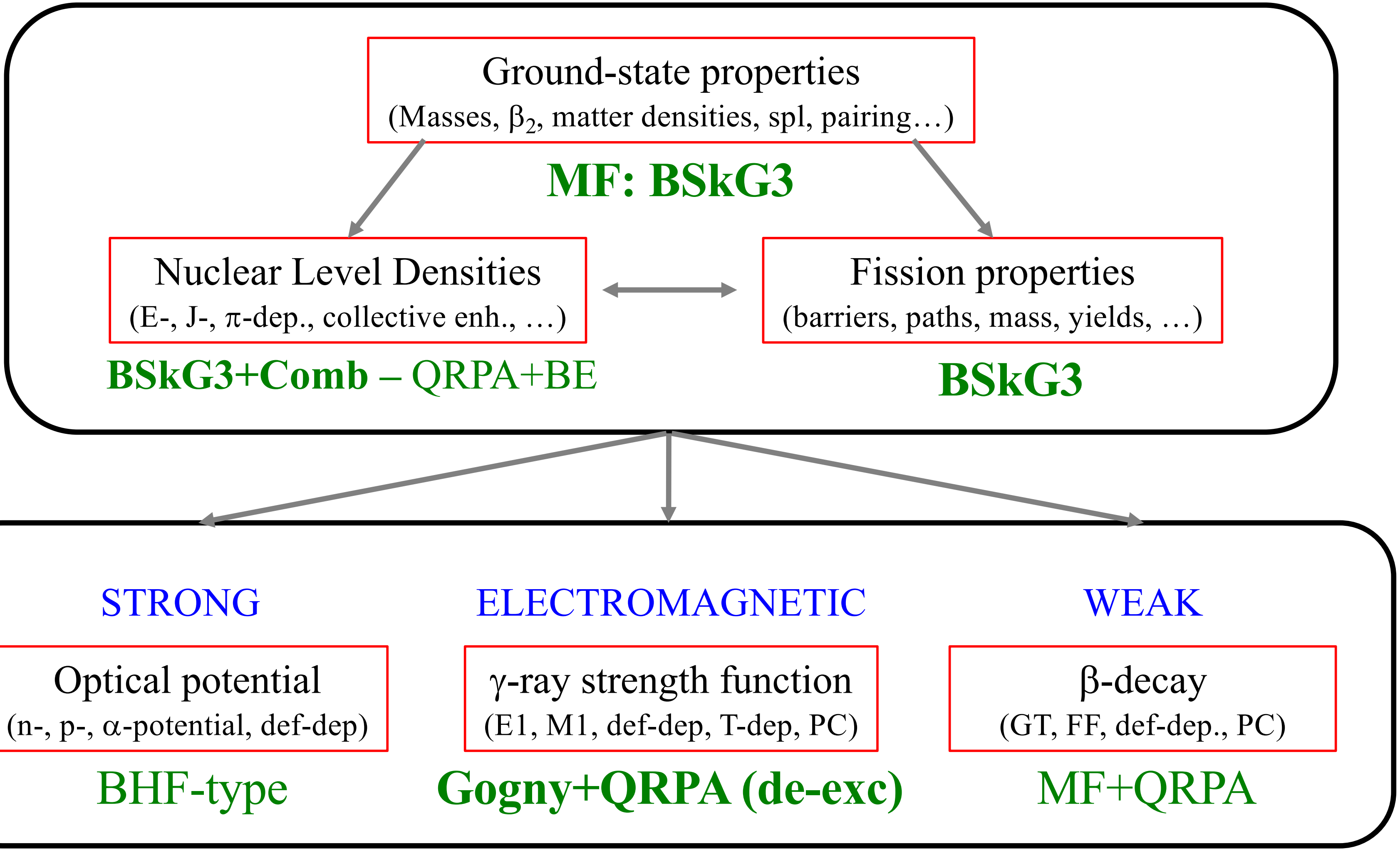
- More experimental constraints
- **Improved nuclear models**
  - ➢ Their **reliability**, *i.e.* their physical robustness
  - ➢ Their **accuracy**, *i.e.* their capacity to reproduce experimental data

Nuclear inputs to nuclear reaction & decay calculations



Some new efforts to improve the nuclear predictions for astrophysical applications

Nuclear inputs to nuclear reaction & decay calculations



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

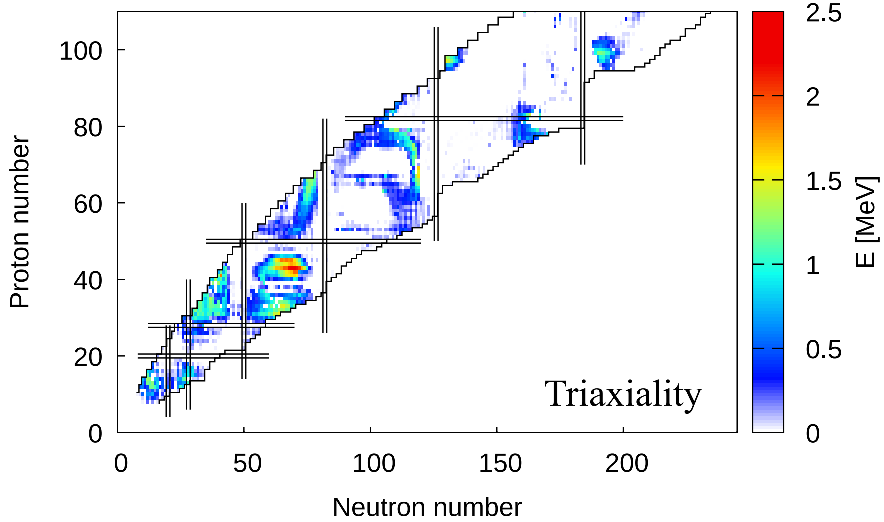
”(Semi-)Microscopic” models must be competitive in reproducing exp. data !

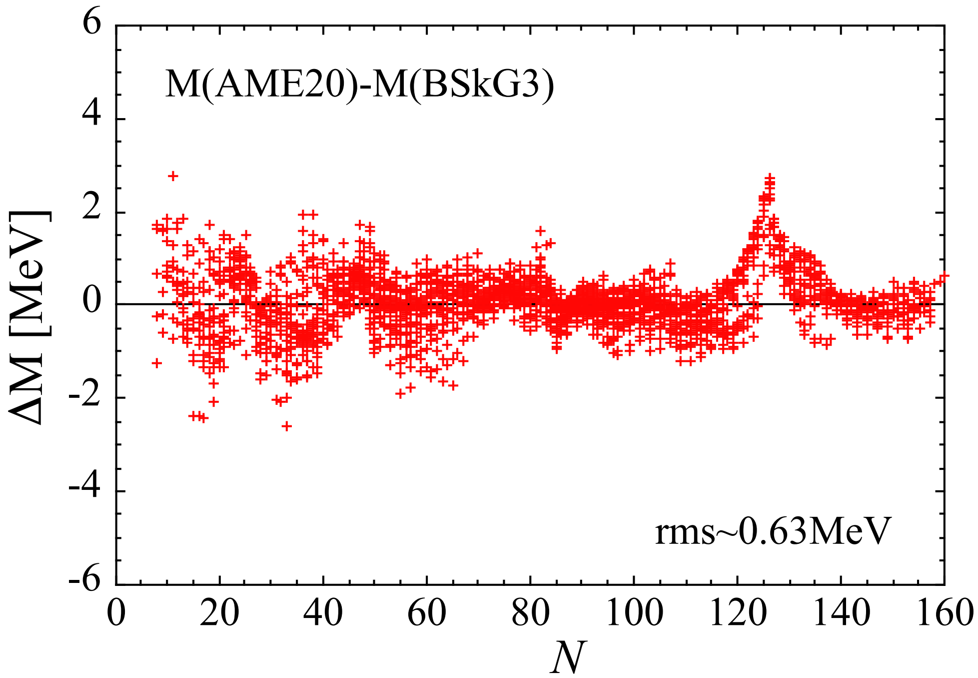
BSkG3 HFB nuclear mass models

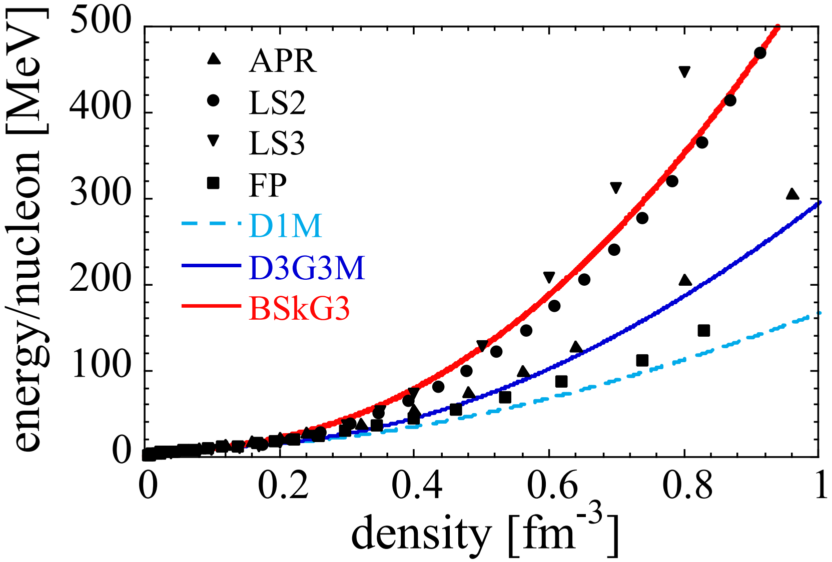
Grams, Ryssens et al. (EPJA 59, 270, 2023)

Recent Skyrme-HFB mass model: BSkG3

- Triaxiality, time-reversal symmetry breaking & octupole GS deformation
- Microscopic pairing from “realistic” calculations
- Stiff EoS
- Accurate masses: σ(2457*M*)=0.63MeV



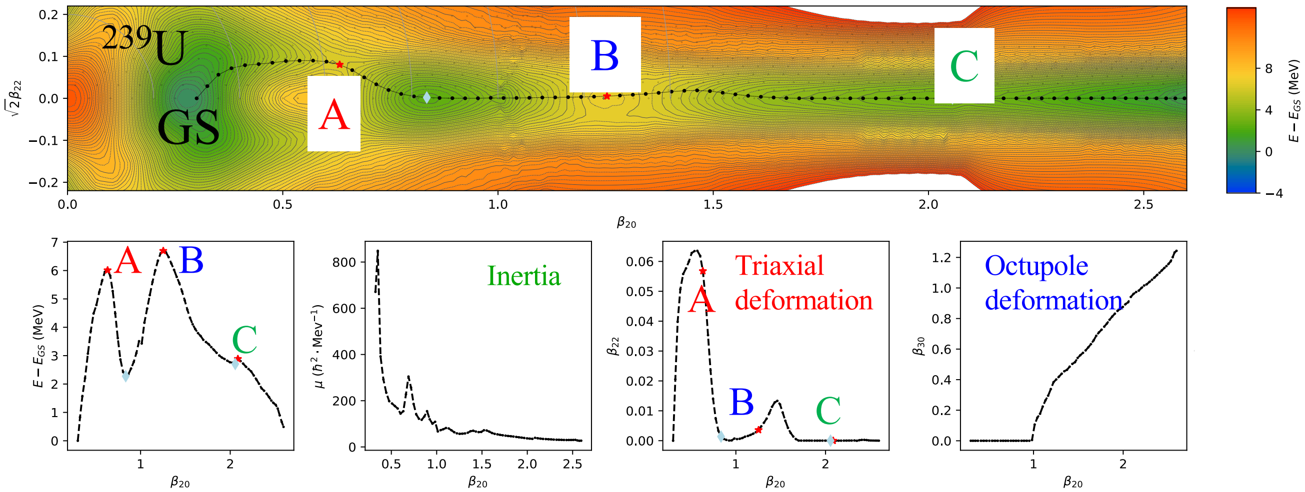




BSkG3: Remarkable description of fission properties

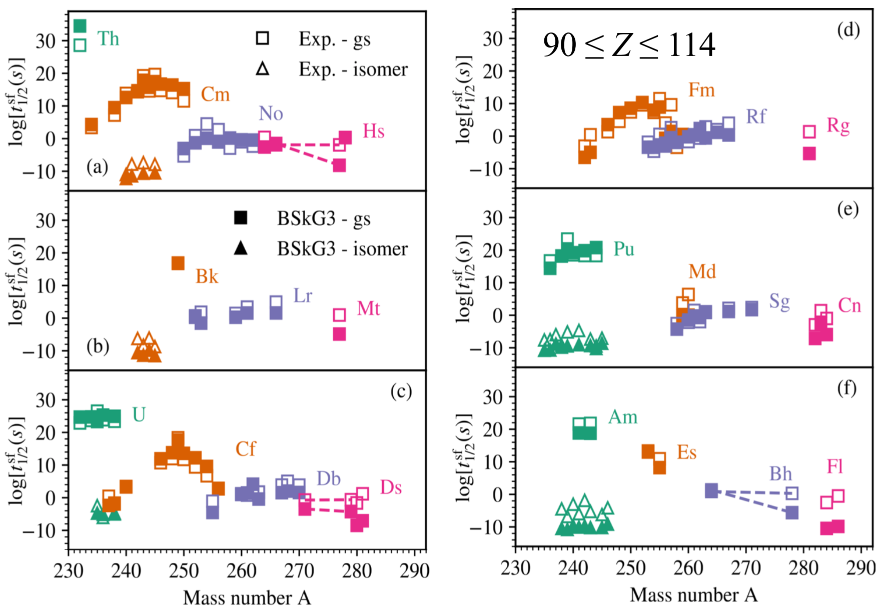
cf Sánchez Fernández et al. (poster #160)

- Fission barriers



rms	σ(B_I) [MeV]
BSkG3	**0.33**
HFB-14	0.60
FRLDM	0.81
BCPM	1.48

- Spontaneous fission half-lives



For GS:
107 $t_{1/2}$: f_{rms}=1.5 10^3

For fission isomers:
29 $t_{1/2}$: f_{rms}=5.3 10^3

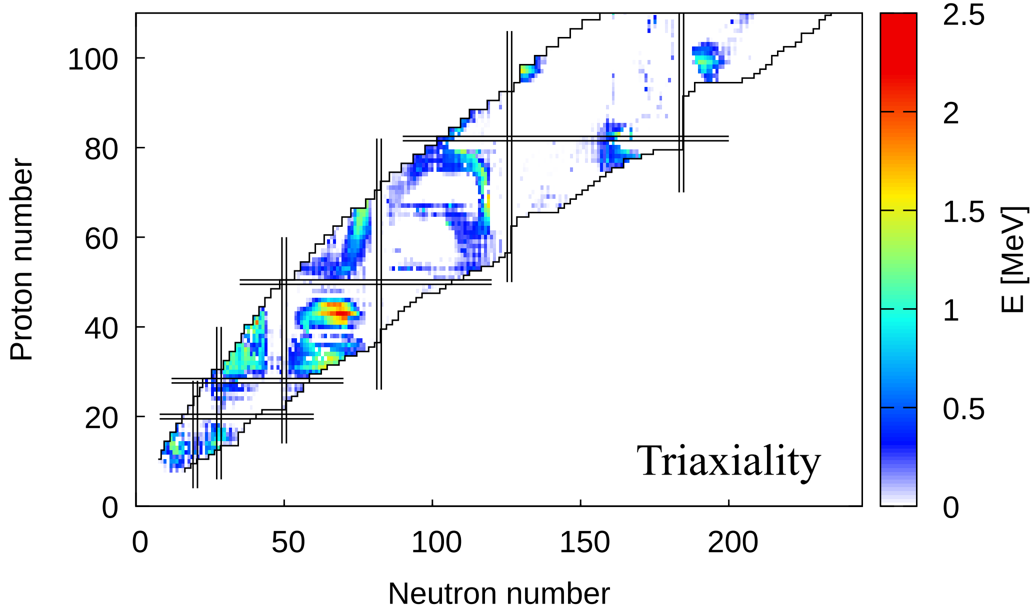
$$f_{\rm rms} = \exp\left[\frac{1}{N}\sum_i^N (\ln r_i)^2\right]^{1/2}$$

Extended to ~3000 nuclei ($80 \leq Z \leq 118$) for r-process simulations ... cf impact on Adrian's poster

Nuclear Level densities

New *combinatorial* predictions based on the BSkG3 nuclear structure properties

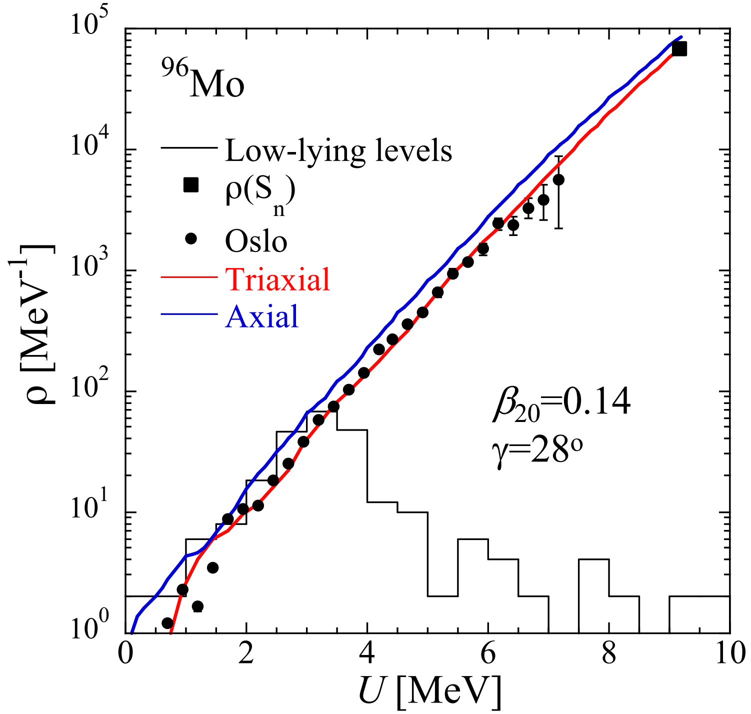
- Improved nuclear structure properties
- Inclusion of triaxial degree of freedom

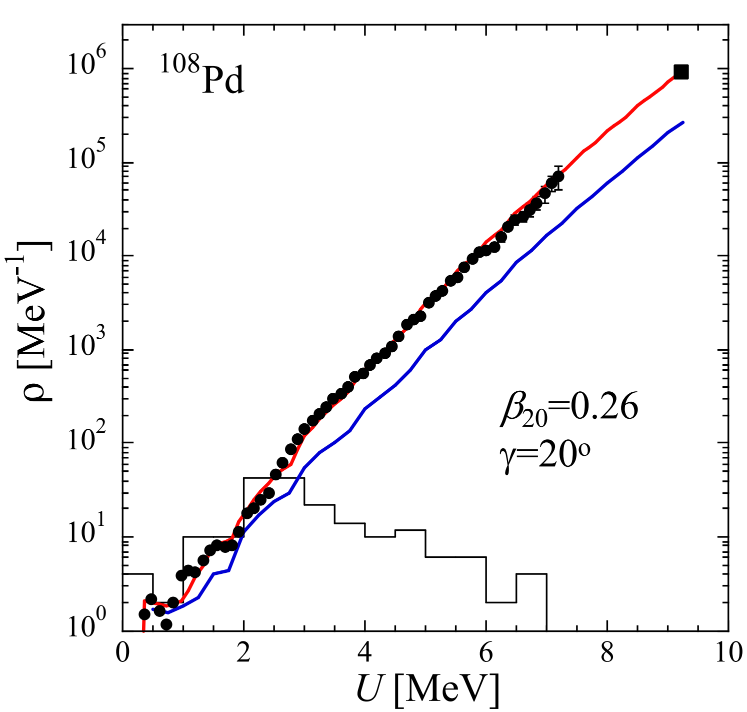


Effects of traxiality on BSkG3+Combinatorial NLD

Main impact of the triaxiality on the NLD:

- Reduction of the spl density → Lower intrinsic NLD
- Additional collective enhancement → Increase total NLD



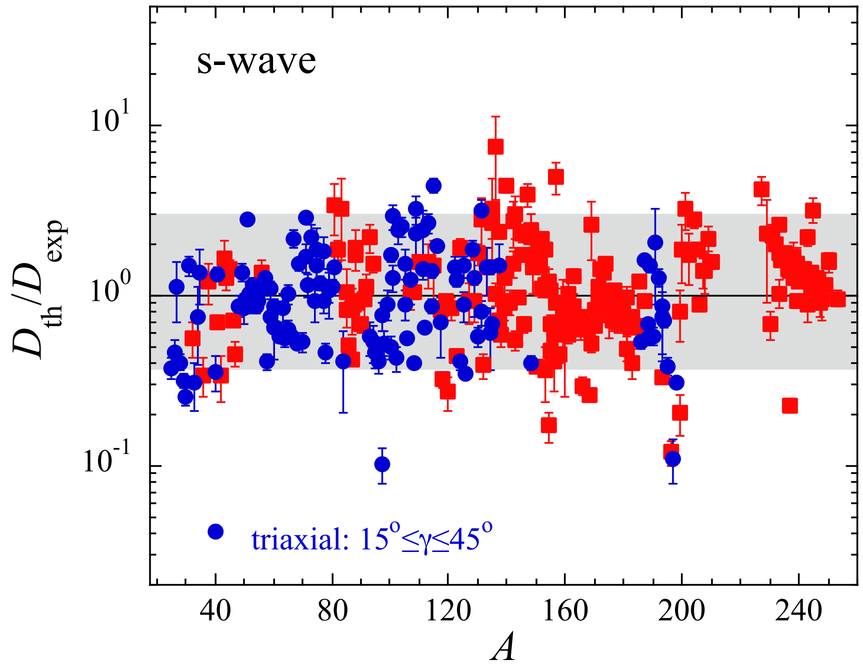


For modestly deformed nuclei:
Decrease of NLD

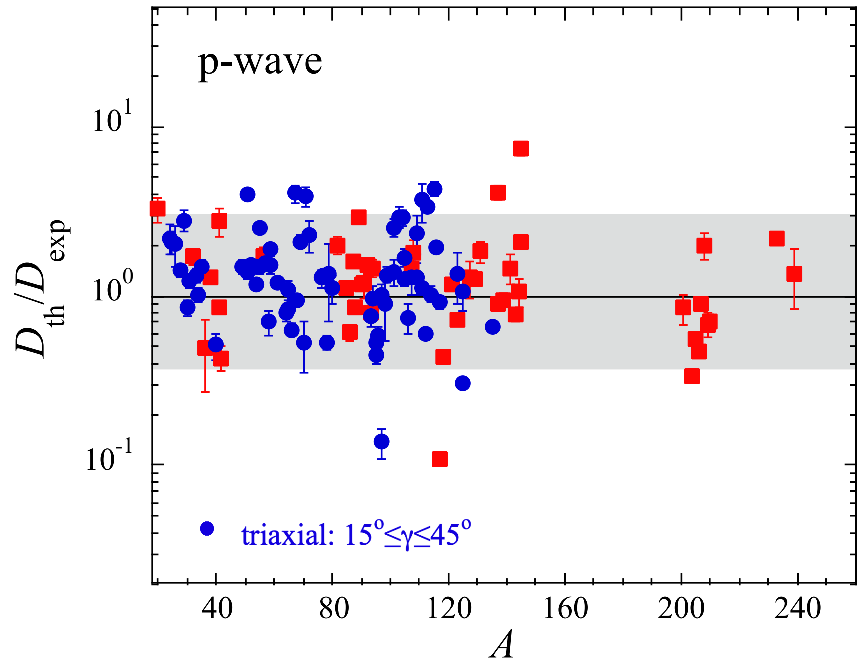
For well deformed nuclei:
Increase of NLD

Comparison with RIPL-3 resonance spacings

D_0 = *s*-wave neutron resonance spacings



D_1 = *p*-wave neutron resonance spacings



299 nuclei: f_{mean}=1.03 - f_{rms}=1.96

BSk14+comb (2008): f_{rms}=2.34

116 nuclei: f_{mean}=1.21 - f_{rms}=1.99

BSk14+comb (2008): f_{rms}=2.24

Also in good agreement with low-lying states, Oslo data, ...

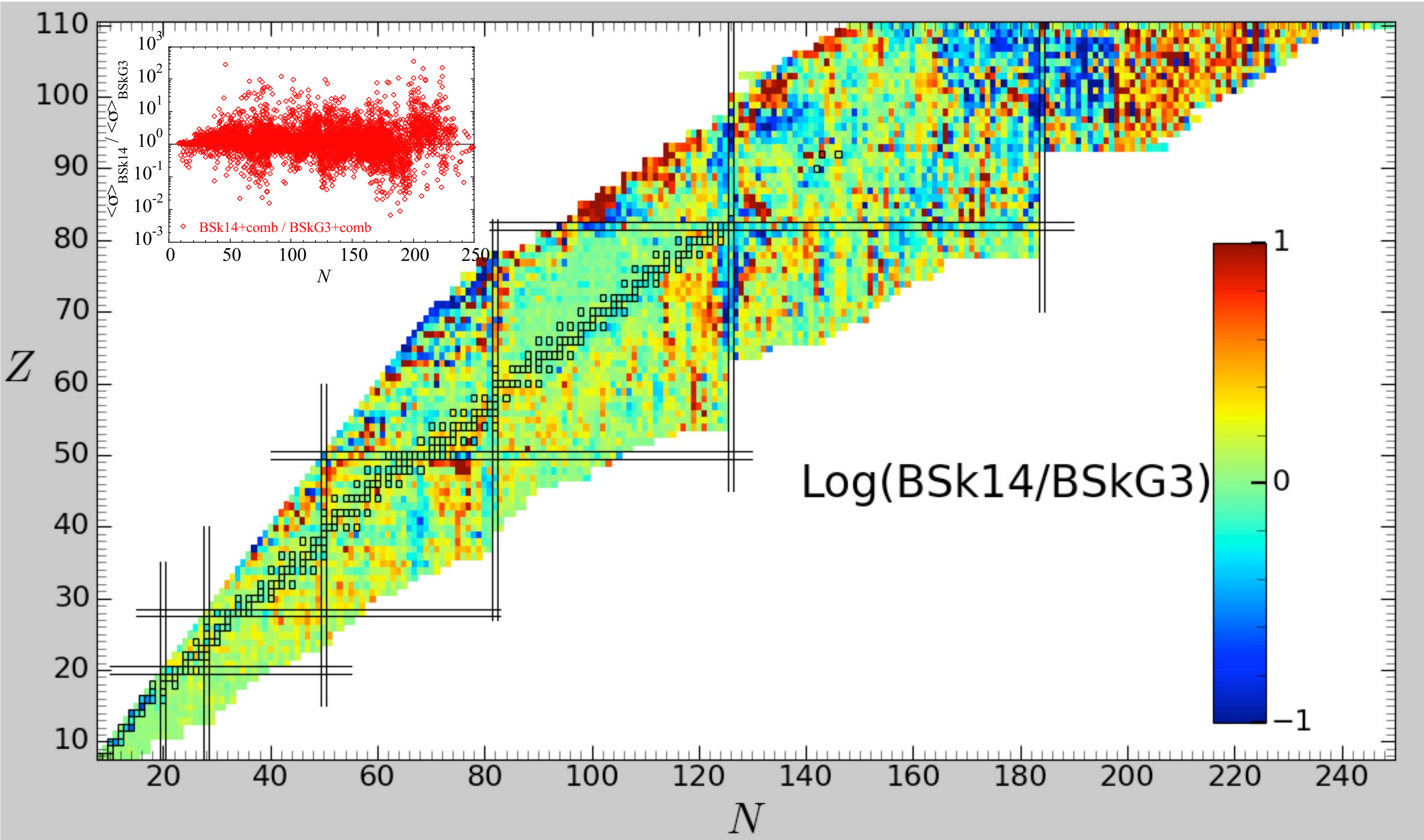
$$f_{\rm rms} = \exp\left[\frac{1}{N_e}\sum_{i=1}^{N_e}\ln^2\frac{D^i_{\rm th}}{D^i_{\rm exp}}\right]^{1/2}$$

→ Tables of ρ(*U*,*J*,π) NLDs (*U*≤200MeV *J*<50) available for

- GS (triaxial, octupole) of ~ 8500 nuclei (8≤*Z*≤118)
  (including renormalisation coefficients (α,δ) on experimental D_{exp} & LLL, when available)
- Saddle points and shape isomers (triaxial, octupole) of ~ 3000 nuclei (80≤*Z*≤118)

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

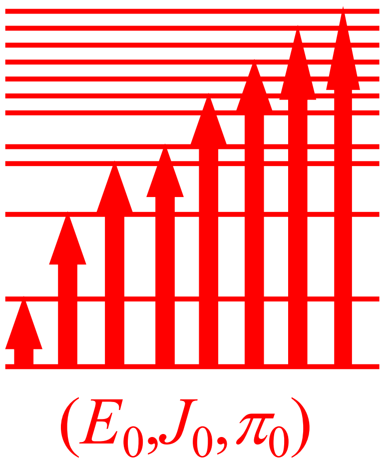
Comparison of BSk14+comb (2008) vs BSkG3+comb (2025) impact on <σ> at $T=10^9$K

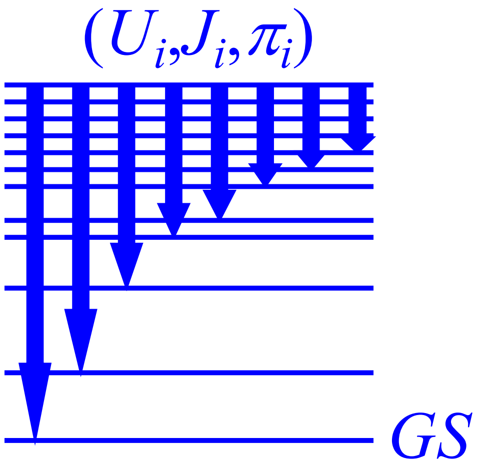


Photon Strength Function

New calculations of the **de-excitation** PSF

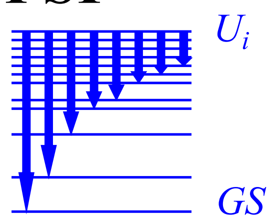
In particular: (γ,n), (γ,p), (γ,α) (n,γ), (p,γ), (α,γ)



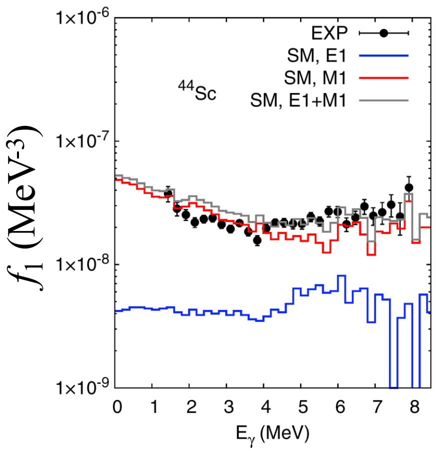


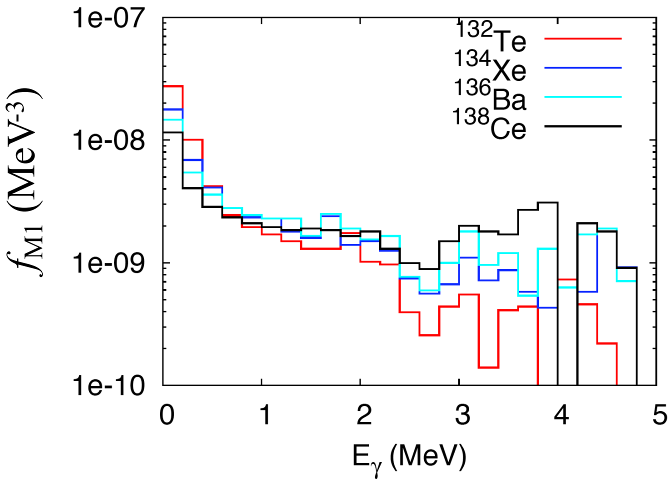
Shell Model prediction of the low-energy de-excitation PSF

Schwengner et al. (2013, 2017,2021), Brown et al. (2014), Sieja (2017, 2018), Karampagia et al. (2017), Midtbø et al. (2018), Mercenne et al. (2024), Chen et al,. (2025), Le Noan et al. (2025)

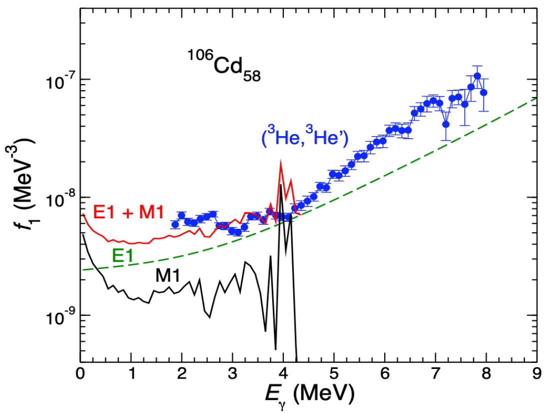


Sieja et al. (2017, 2018)

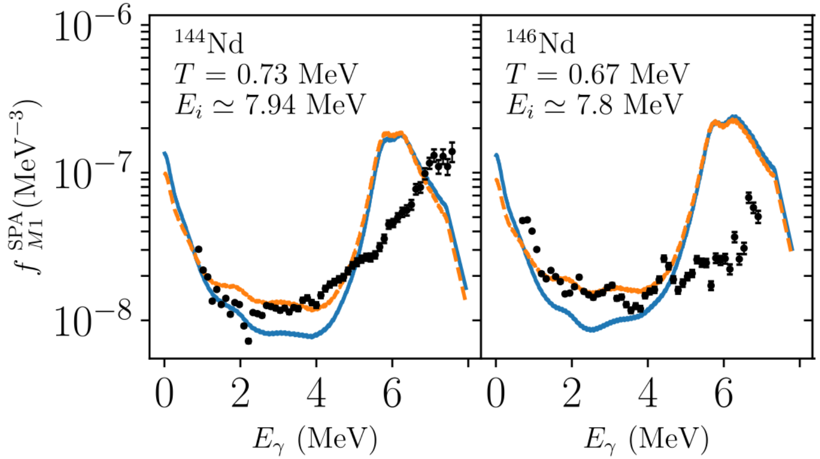




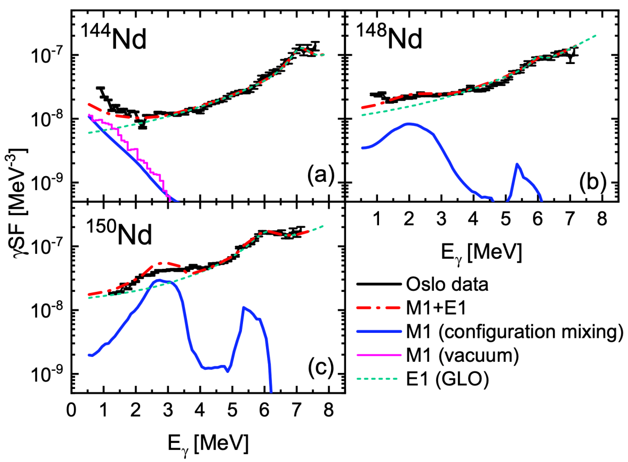
Schwengner (2021)



Mercenne et al. (2024)



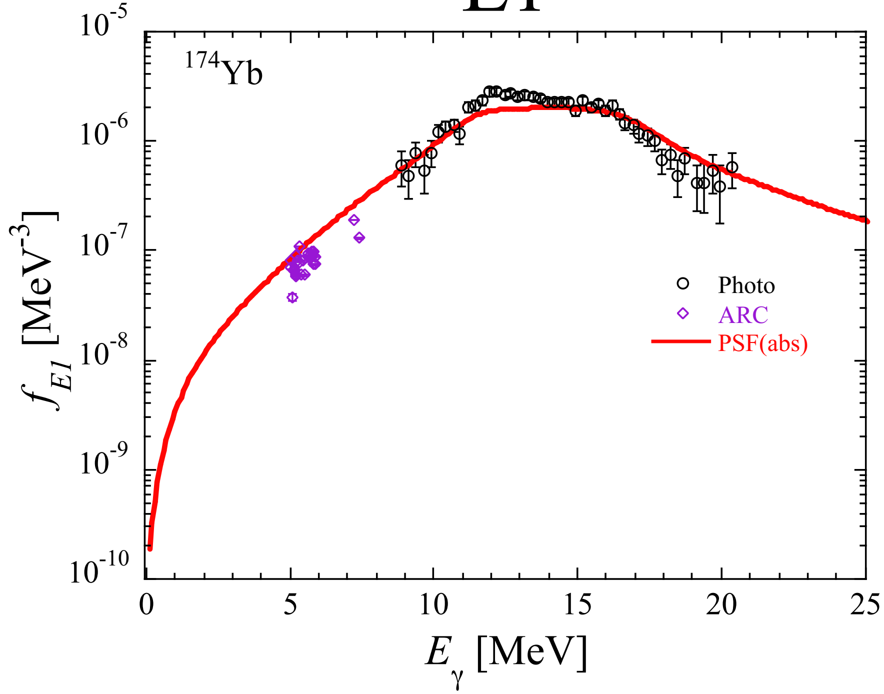
Chen et al. (2025)



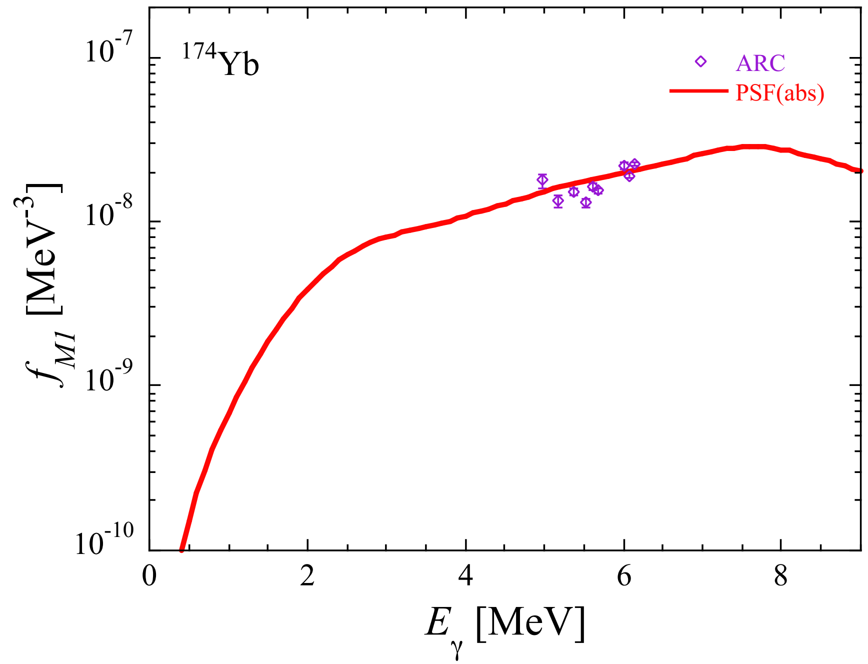
QRPA photoabsorption PSF from the GS

Gogny-HFB+QRPA

E1

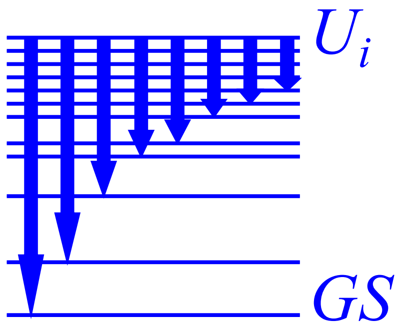


M1



Successful in describing photo, ARC, NRF, ... data

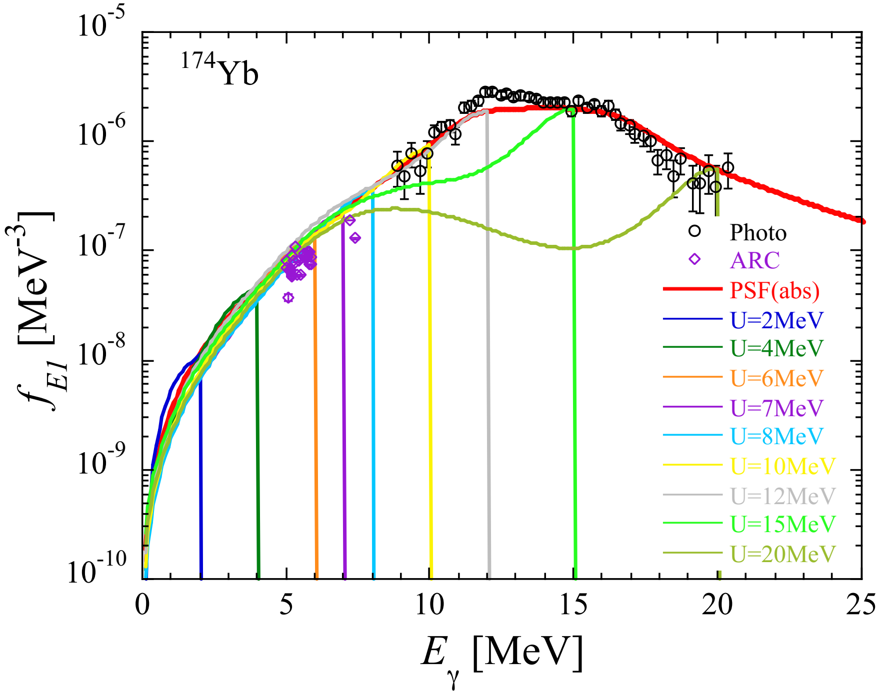
QRPA de-excitation PSF at an initial energy U_i



deformed ^{174}Yb

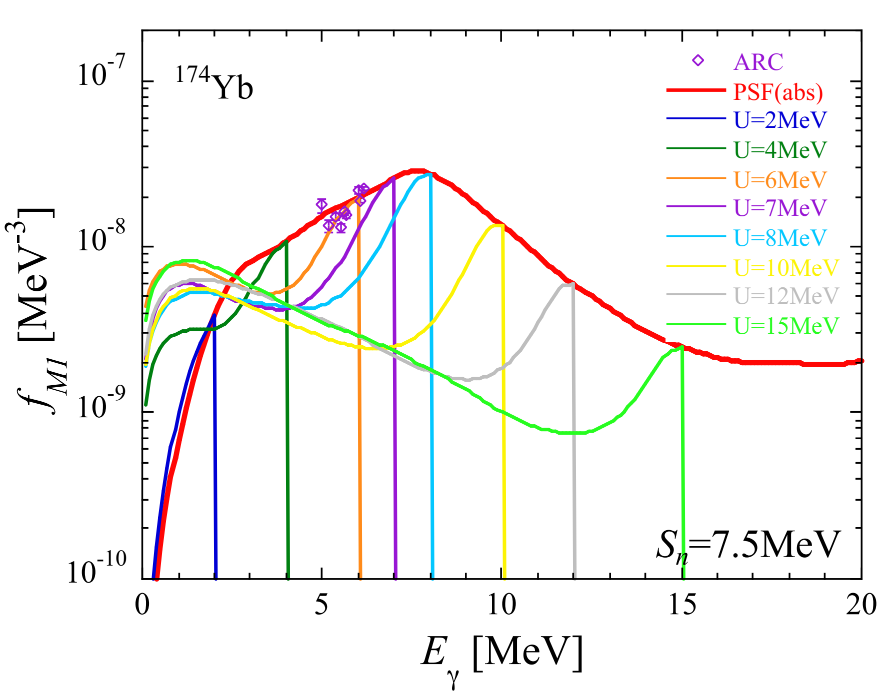
Gogny-HFB+QRPA

E1



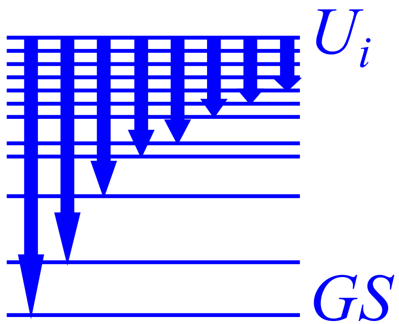
Negligible low-energy E1 enhancement

M1



Significant low-energy M1 enhancement (“upbend”) but also reduction at higher E_γ

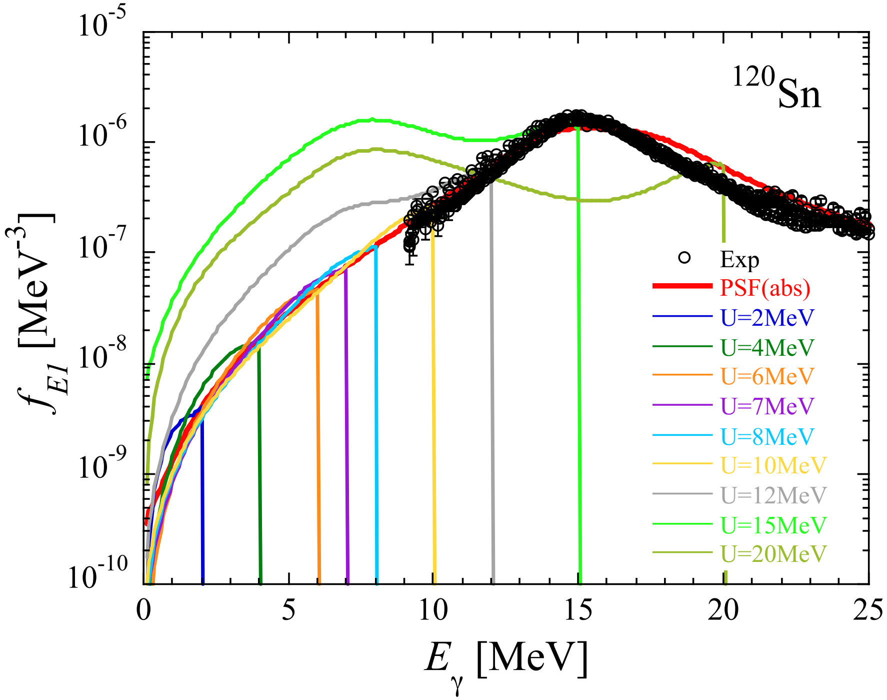
QRPA de-excitation PSF at an initial energy U_i



spherical ^{120}Sn

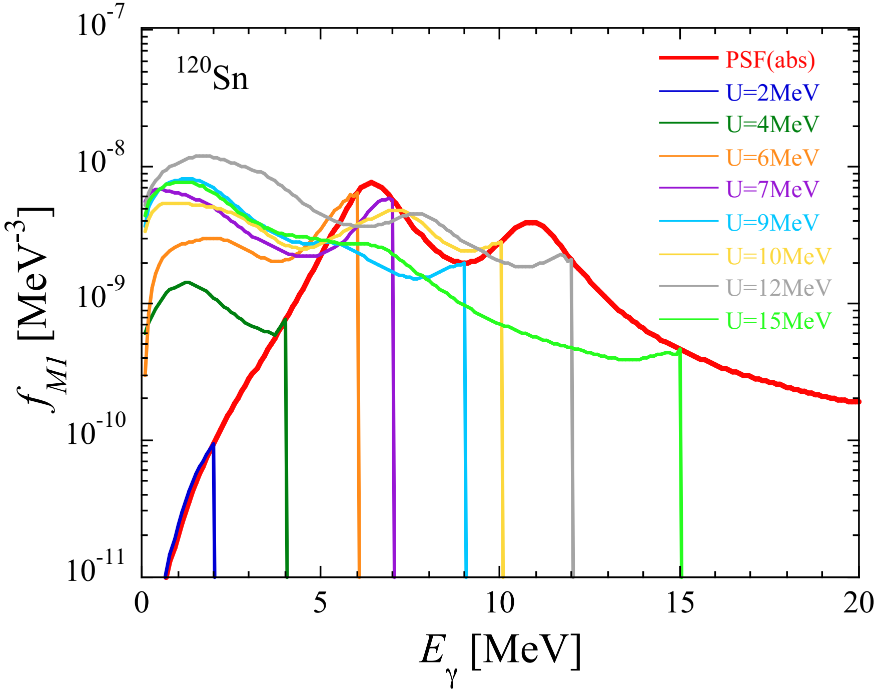
Gogny-HFB+QRPA

E1



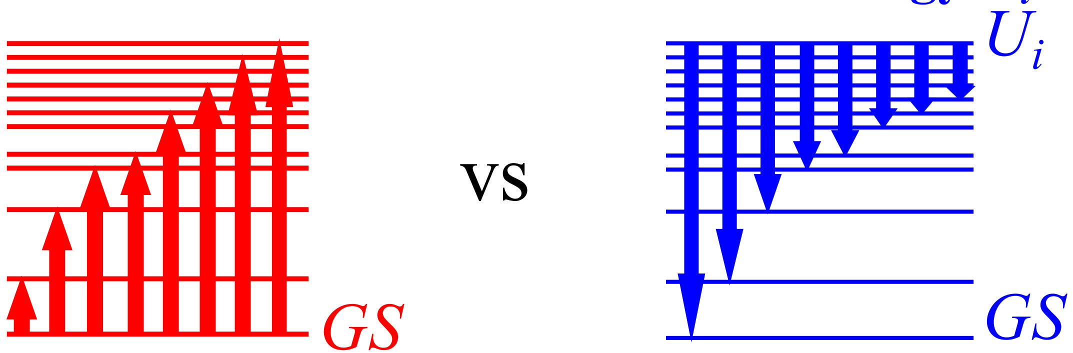
Non-negligible low-energy E1 enhancement at E_γ>10MeV

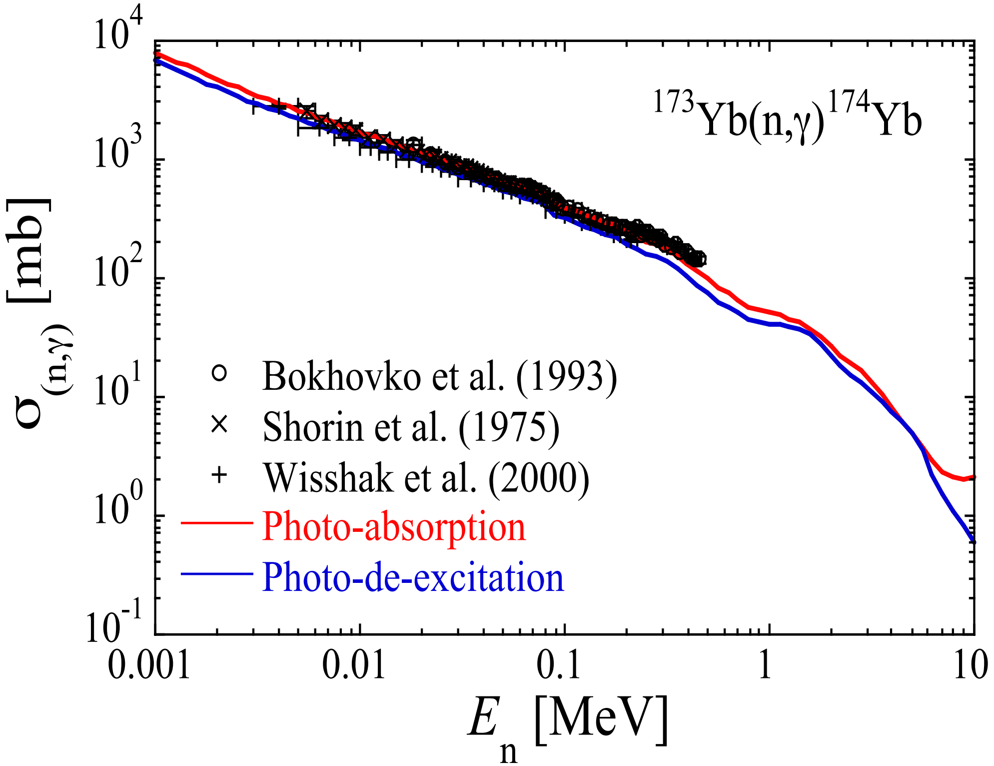
M1

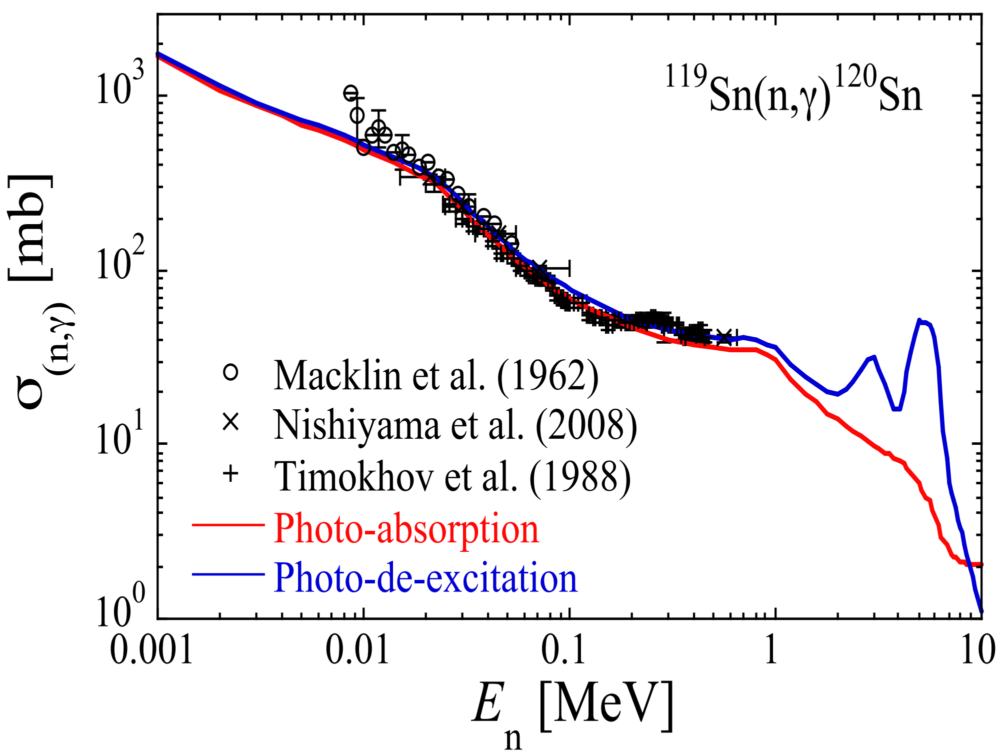


Significant low-energy M1 enhancement (“upbend”) but also reduction at higher E_γ

QRPA de-excitation PSF at an initial energy U_i



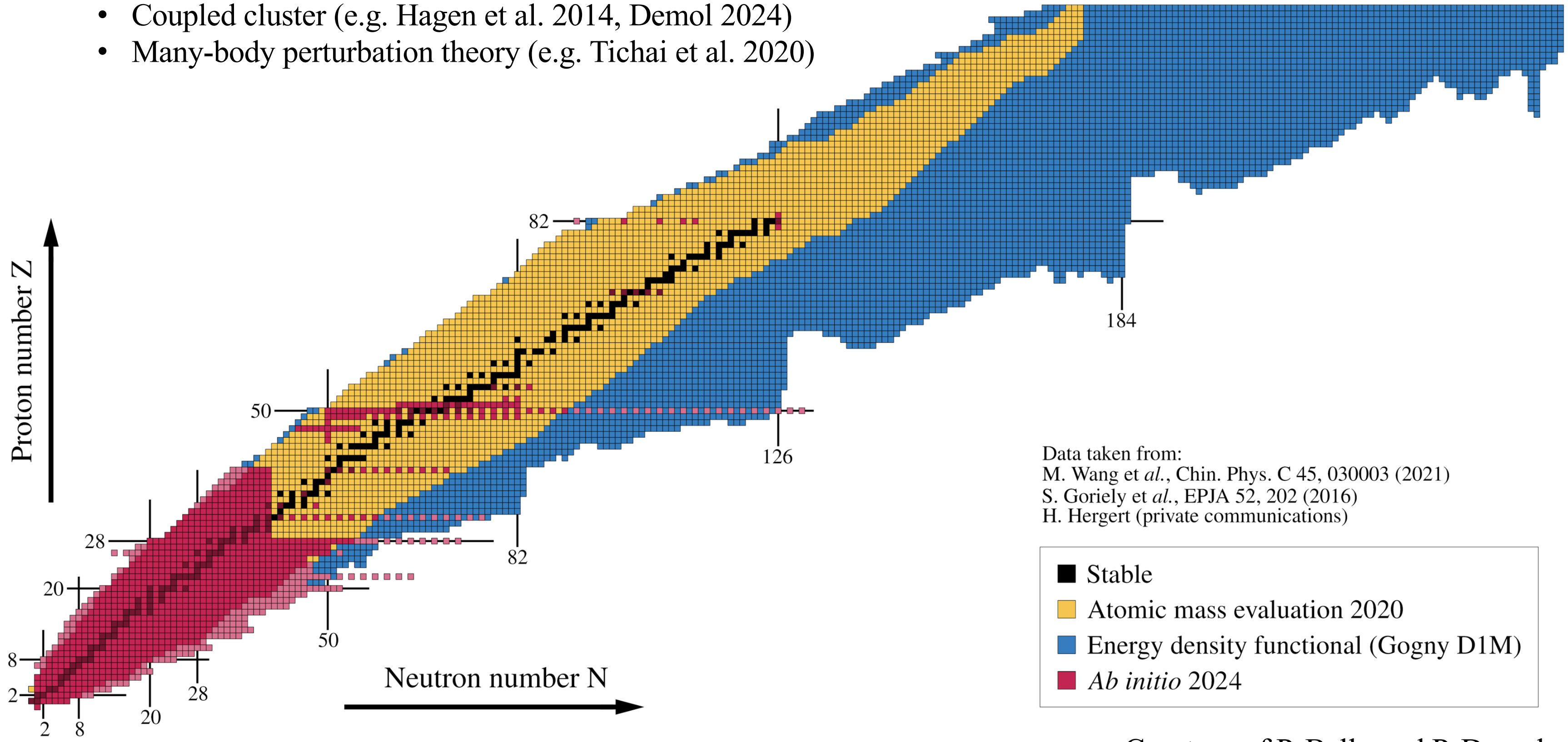




Application to cross section calculations and implication for nucleosynthesis still ongoing

Impressive progress in *Ab-initio* models

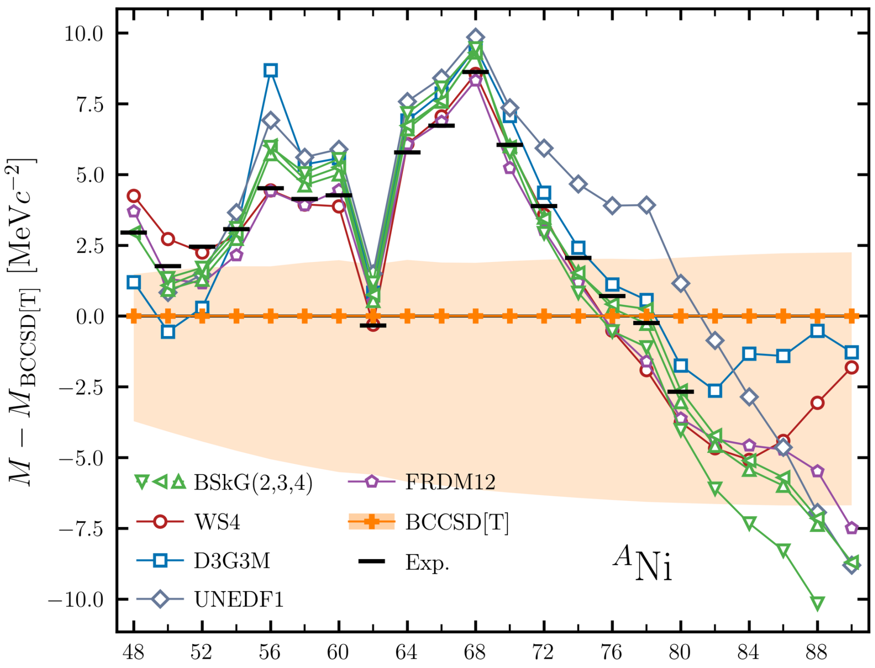
- Self-consistent Green's function (e.g. Soma, 2002; Barbieri et al. 2022)
- In-medium similarity renormalization group (e.g. Hergert et al. 2016)
- Coupled cluster (e.g. Hagen et al. 2014, Demol 2024)
- Many-body perturbation theory (e.g. Tichai et al. 2020)



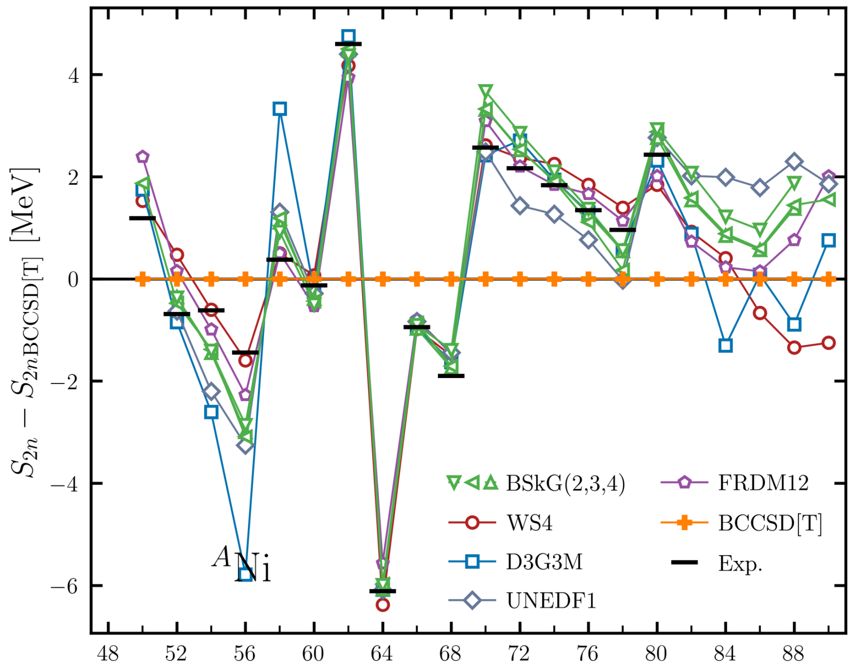
Courtesy of P. Bally and P. Demol

Comparison between BCCSD[T] *ab-initio* predictions with mass models

Ni isotopes: **Masses**



Ni isotopes: ***S_2n***

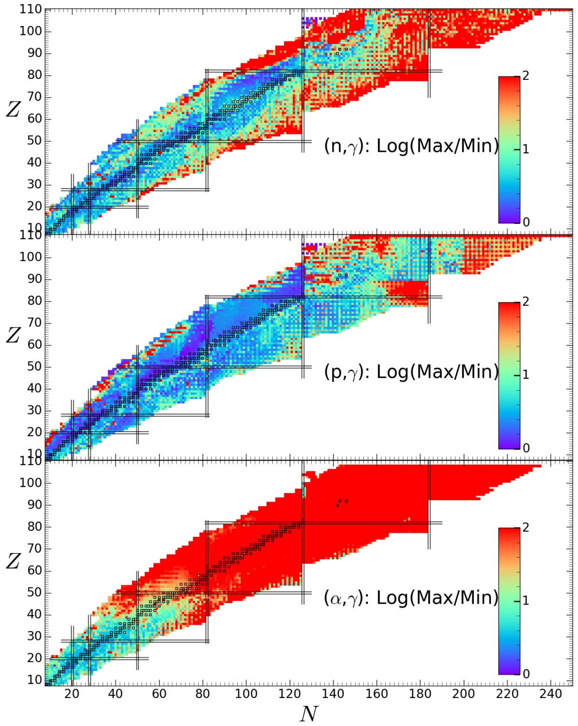


Courtesy of P. Demol

Future developments may allow us to use *ab-initio* models
as reference calculation far away from experimentally known regions

Still many uncertainties associated with NP inputs

- **Improved MF models for nuclear inputs to the reaction model**
  - GS properties: correlations, odd-*A*, triaxiality
  - Fission: 3D fission paths, NLD at the saddle points, FFD
  - E1/M1-strength functions: PR, ε_γ=0 limit, *T*-dep, PC, J^π-dep
  - Nuclear level Densities: low-*E*, correlations, pairing, vib-rot
  - Optical potential: low-*E* isovector imaginary n-OMP, α-OMP below Coulomb barrier



- **Reaction model**
  - HF vs RR vs Direct capture

- **β-decay model (including βdn, βdf, EC)**
  - Forbidden transitions, deformation, odd-*Z*/*N*, Beyond MF

    (cf Robin & Martinez-Pinedo, 2024; Alvear Terrero et al. this conference)

Conclusions

- **Major progress achieved and efforts ongoing**
  - Reaction model (e.g. TALYS)
  - MF, beyond MF, QRPA/FAM, SM, ab-initio
- **Selection of models for astrophysics application according to**
  - Their reliability, *i.e.* their physical robustness

    e.g. avoid extrapolation with "macroscopic" models (or ML algorithms)
  - Their accuracy, *i.e.* capacity to reproduce experimental data

    e.g. SLO, GLO models of PSF should not be used

- **Updated experimental libraries to reduce parameter uncertainties**

  → 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, ...

If we can describe relatively accurately known reaction/decay rates,
we are still far from being able to predict ***reliably***
n-, p- or α-captures, β-decay, and even less, fission of exotic nuclei
BUT progress is being made