Nuclear physics input for r-process studies

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EURISOL meeting

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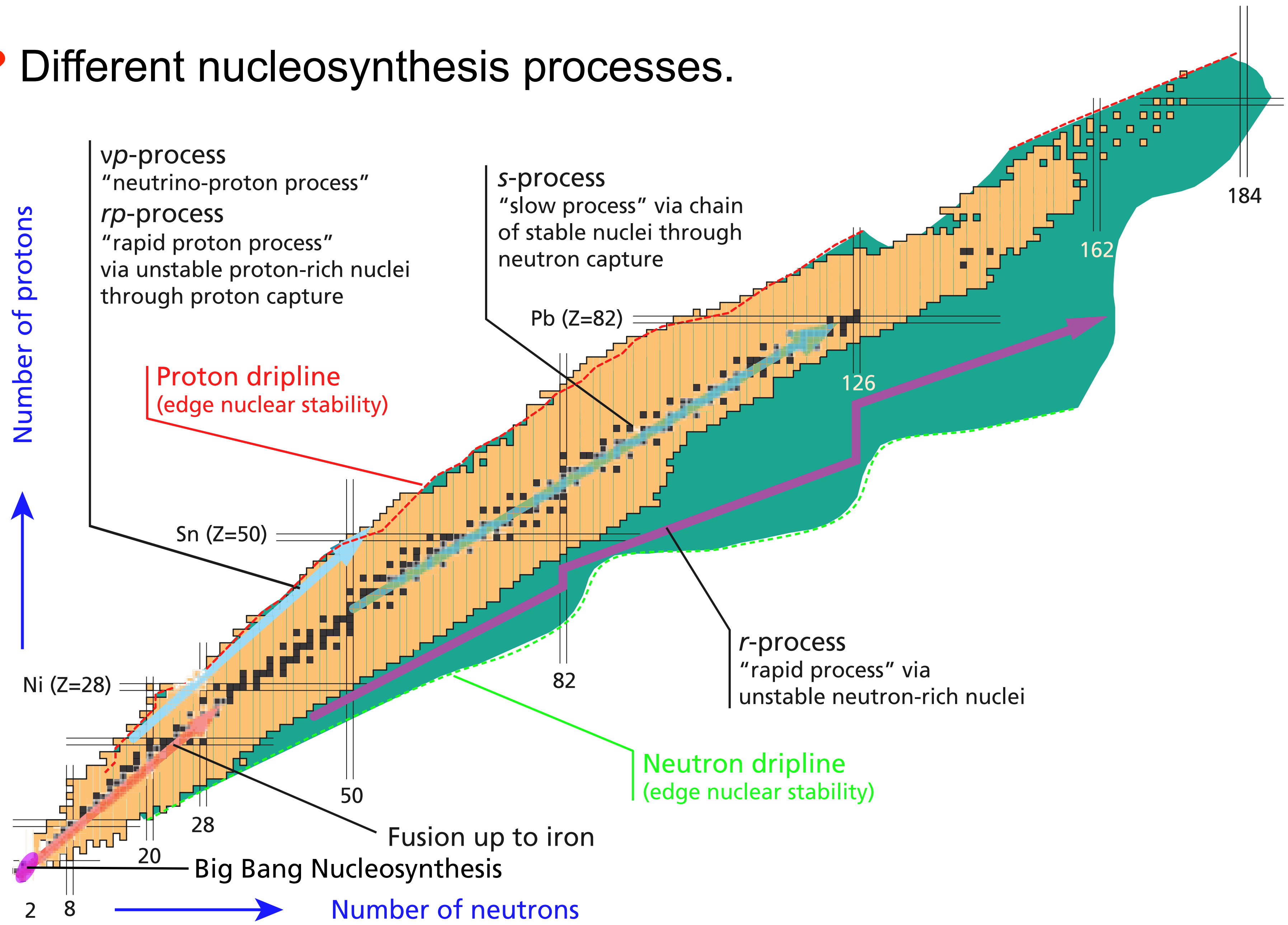
Outline

- Introduction.
- Nuclear masses.
- Beta decay half-lives.
- Summary and outlook.

Motivation

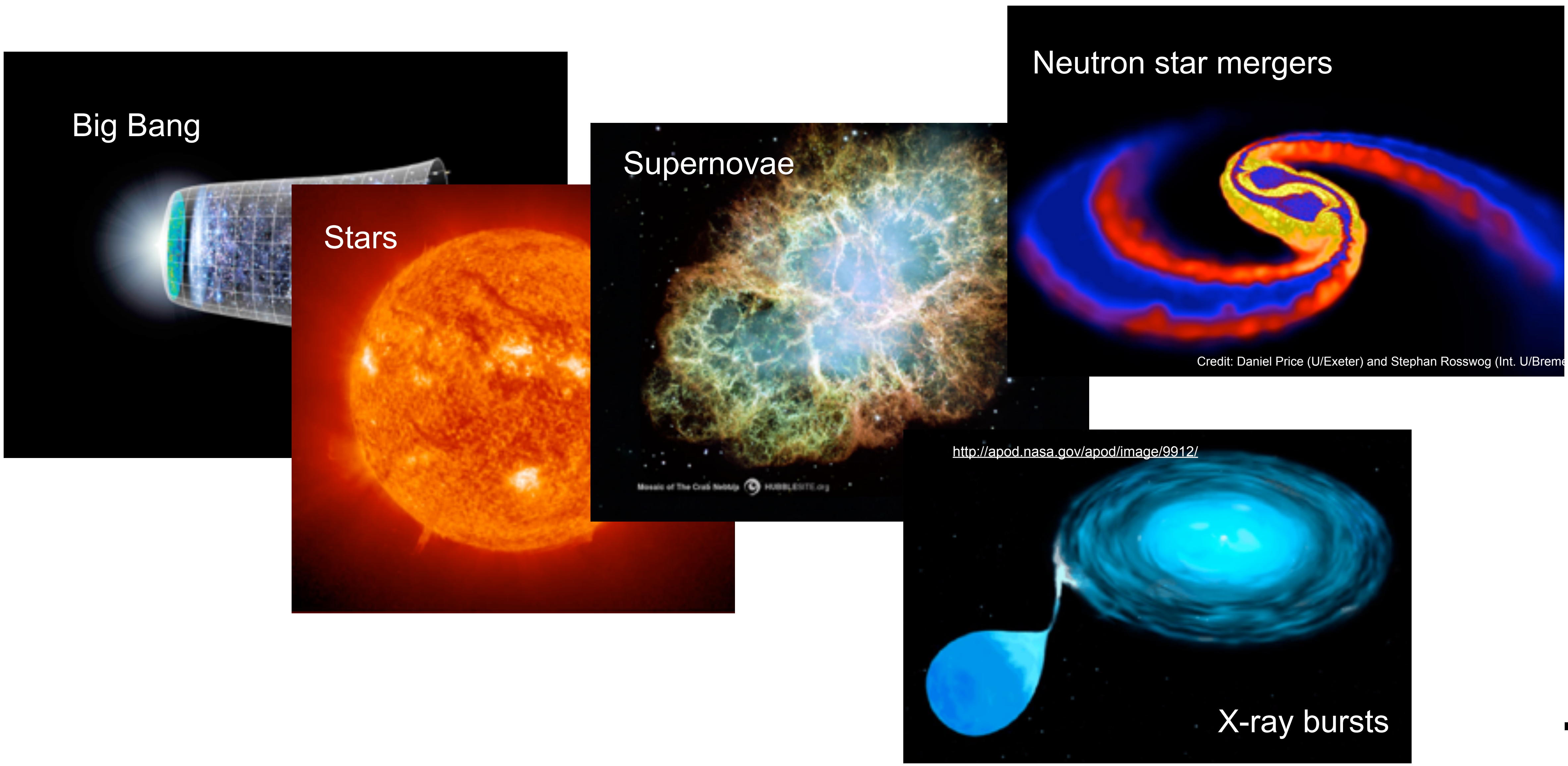
- What is the **origin of the elements**?
  - **HOW?** Different nucleosynthesis processes.



Credits: GSI-FAIR webpage/G. Martínez-Pinedo

Motivation

- What is the **origin of the elements**?
  - **WHERE?** Different astrophysical scenarios.



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Motivation

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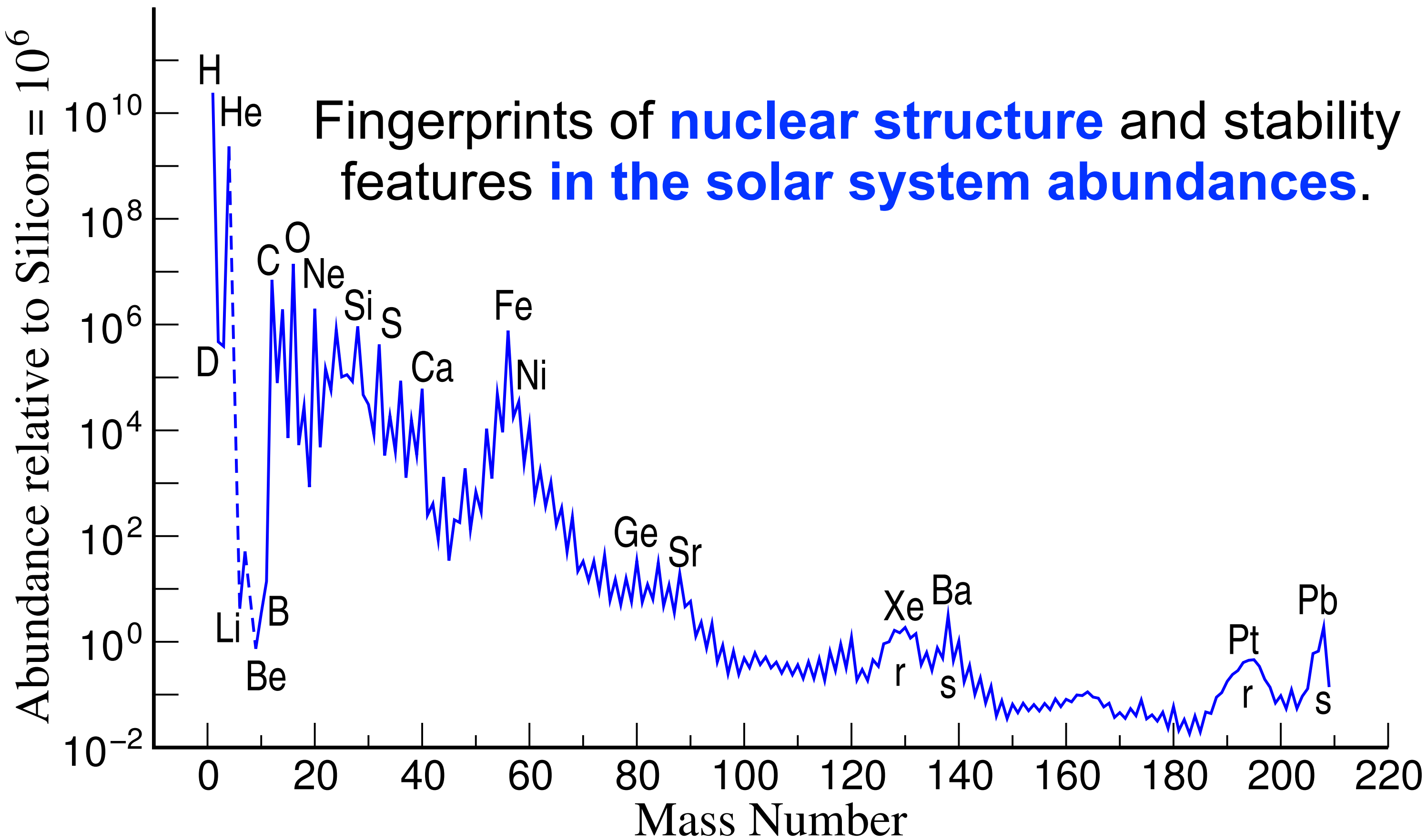
- What is the **origin of the elements**?
  - **HOW?** Different nucleosynthesis processes.
  - **WHERE?** Different astrophysical scenarios.
  - **Observables**: Elementary abundance pattern in stars.
    Light curves in explosive events.



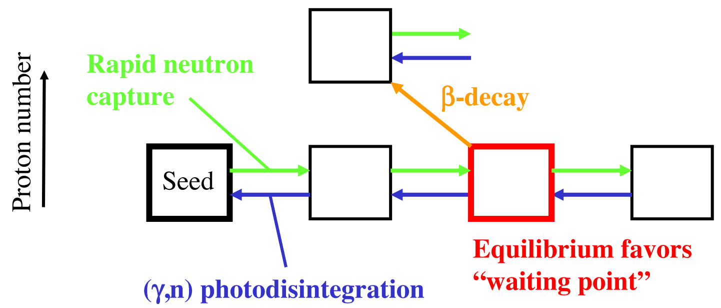
Nuclear physics input:

- Masses
- β-Half lives
- Reaction rates
- Fission
- Neutrino reactions

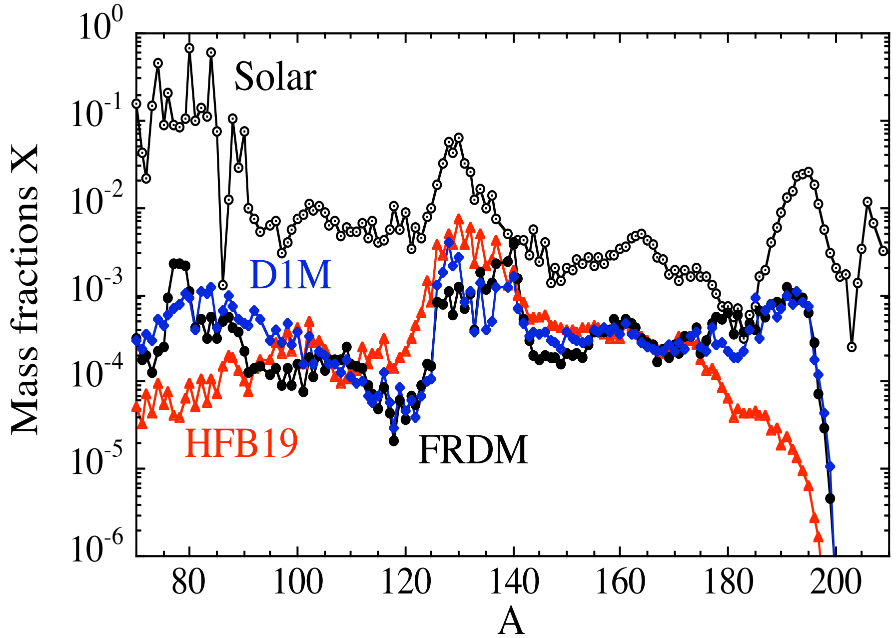
Taken from **experiments** and... **theory!!**

Impact of nuclear masses on r-process simulations

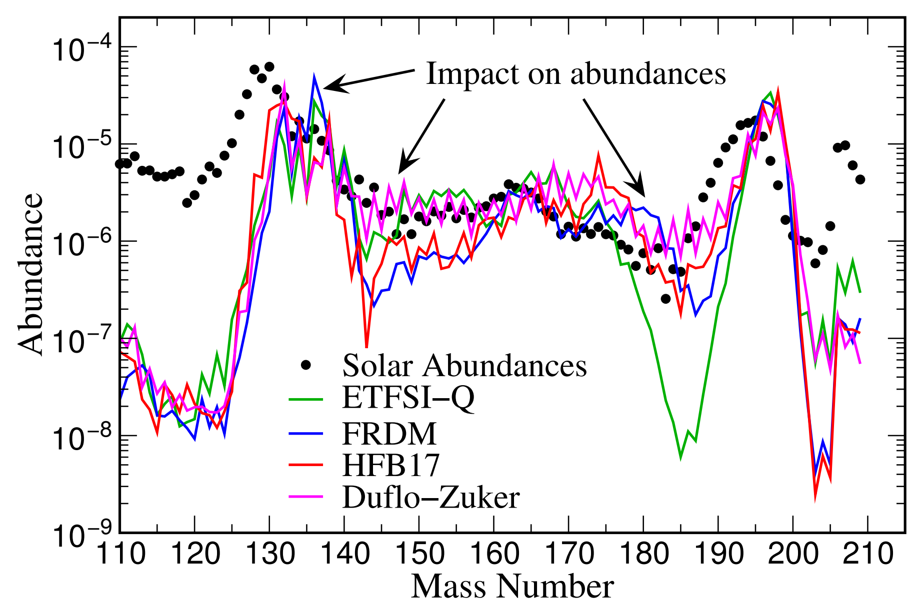
- Nuclear masses determine in r-process nucleosynthesis:
  - Neutron capture rates/photo-disintegration.
  - Beta decay Q-values.



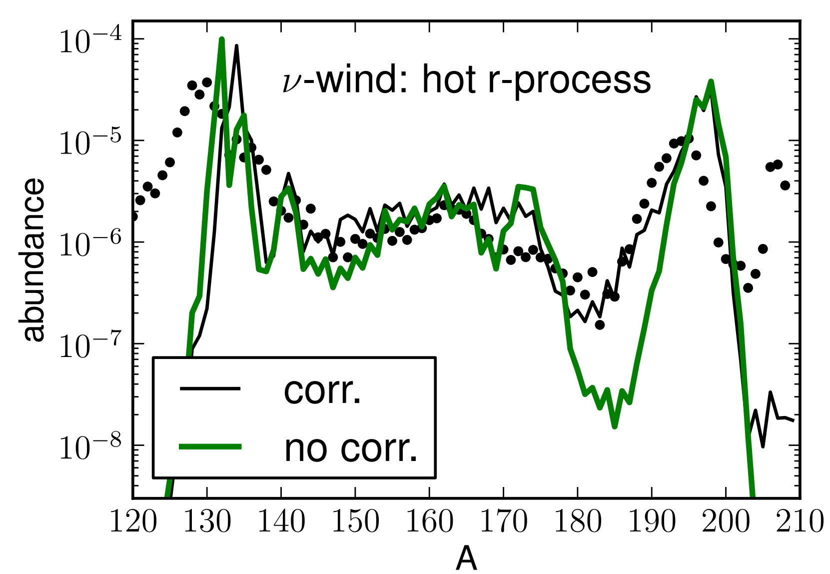
Final abundances depend on the mass model used (for the same astrophysical conditions)



S. Goriely et al.



A. Arcones and G. Martínez-Pinedo, PRC 83, 045809 (2011)



A. Arcones and G.F. Bertsch, PRL 108, 151101(2012)

See also S. Wanajo et al., Astrophys. J. 606, 1057 (2004)

Impact of nuclear masses on r-process simulations

- Nuclear masses determine in r-process nucleosynthesis:
  - Neutron capture rates/photo-disintegration.
  - Beta decay Q-values.

- Changes in the final r-process abundances produced by a 25% variation of the separation energies have been studied globally.

- Most sensitive nuclei are those near to the neutron magic numbers.

S. Brett et al., Eur. Phys. J. A 48, 184 (2012)

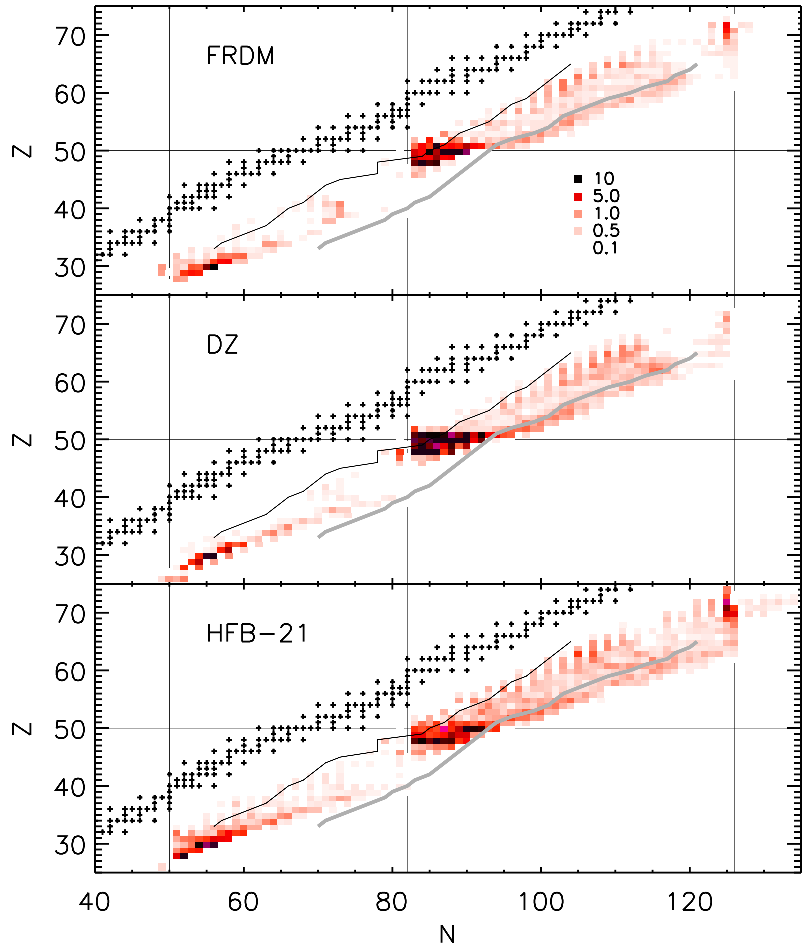
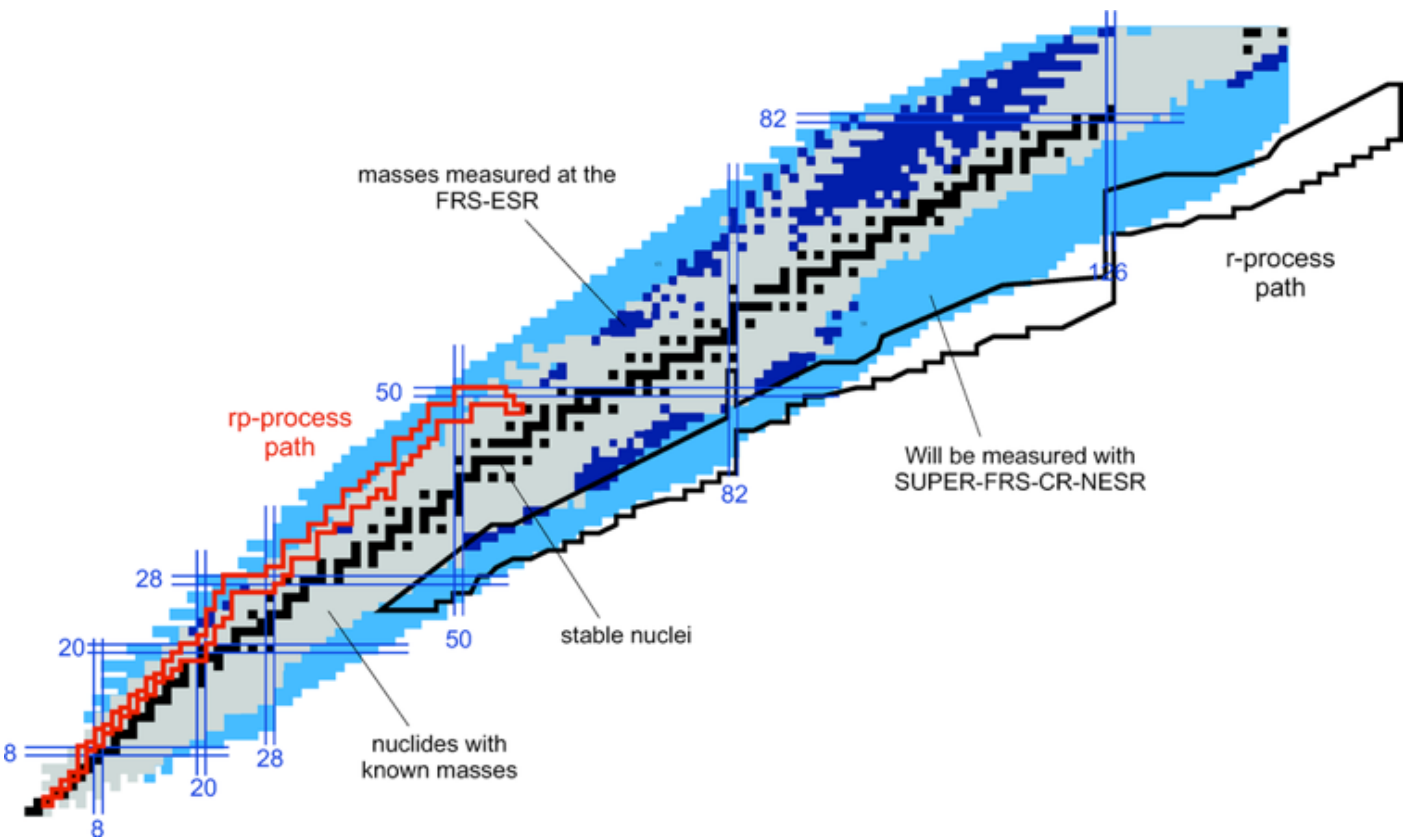


Fig. 3. Comparison of the sensitivity to mass values determined by eq. (2). The separation energies far from stability were generated by the FRDM [25], Duflo-Zuker [26], and HFB-21 [27]. The scale is from white to dark red, indicating regions with a small change to a substantial change in the resulting abundances. For reference, stable nuclei have been included as black crosses and the magic numbers have been indicated by thin lines. Superimposed on the sensitivity results are the limits of accessibility by CARIBU [28] and the proposed FRIB intensities [29]. In both cases, we have plotted the conservative limits of what can be produced and measured in mass measurements.

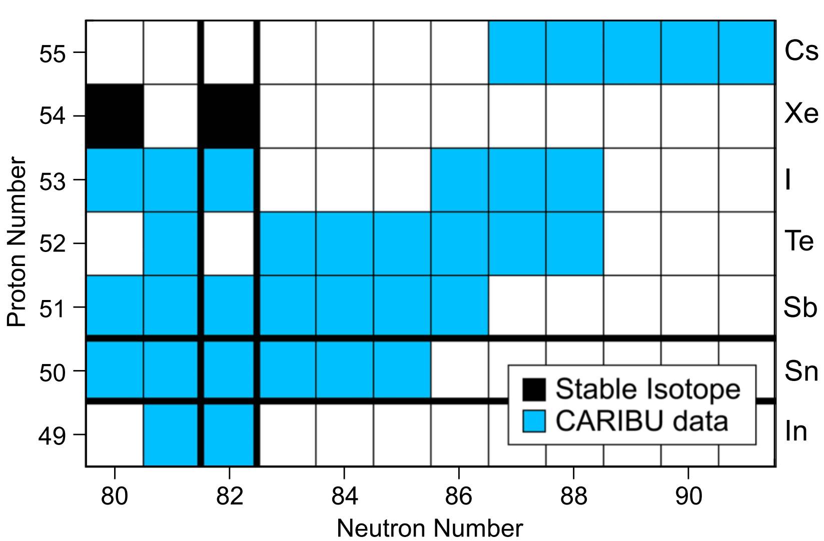
Masses@GSI/FAIR and the r-process path

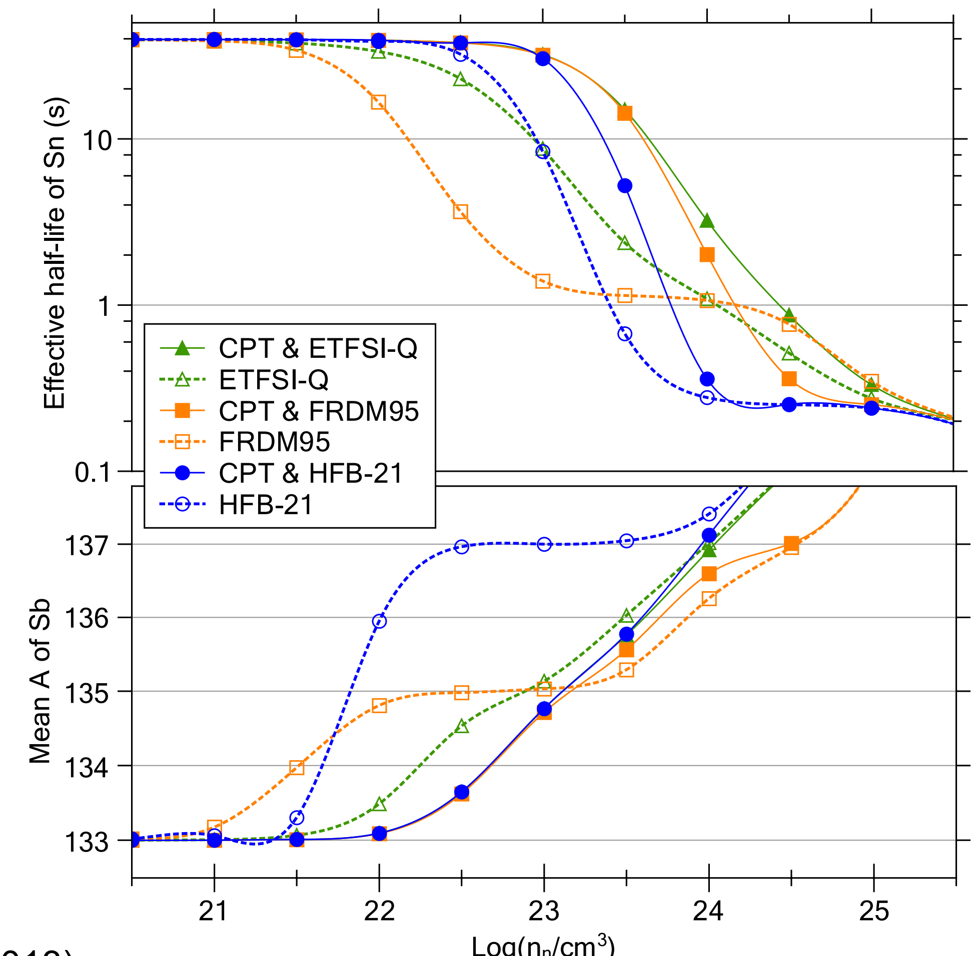


B. Sun et al., Nucl. Phys. A 812, 1 (2008), L. Chen et al., Nucl. Phys. A 882, 71 (2012)

New masses around ^{132}Sn

- JYFLTRAP@JYVÄSKYLÄ (J. Hakala et al., Phys. Rev. Lett. 109, 032501 (2012))
- ISOLTRAP@ISOLDE (C. Weber et al., Nucl. Phys. A 803, 1 (2008), G. Sikler et al., Nucl. Phys. A 763, 45 (2005), M. Dworschak et al., Phys. Rev. Lett. 100, 072501 (2008))
- FRS/ESR@GSI (B. Sun et al., Nucl. Phys. A 812, 1 (2008), L. Chen et al., Nucl. Phys. A 882, 71 (2012))
- CPT/CARIBU@ANL (J. Van Schelt et al., Phys. Rev. Lett. 111, 061102 (2013))





J. Van Schelt et al., Phys. Rev. Lett. 111, 061102 (2013)

Effect on r-process simulations

Neutron separation energies were overestimated in the mass models with respect to the experimental data, inhibiting (γ,n) reactions which would push material to longer-lived isotopes

Drastic transition from ^{133}Sb to ^{137}Sb in HFB-21 mass model not observed in the data including the new masses measured at CPT-CARIBU.

Nuclear masses used in r-process simulations

• Experimental masses where available: ~2300 (Audi *et al.* Chinese Phys. C 36, 1287 (2012)).

• Theoretical global nuclear mass models widely used in nucleosynthesis calculations:

➡ Finite Range Droplet Model (**FRDM**). (Möller et. al 1995, Möller et. al 2012)

➡ Extended Thomas-Fermi plus Strutinsky Integral (**ETFSI**). (Aboussir et al. 1995)

➡ Weizsäcker-Skyrme (**WS**). (N. Wang et al. 2010)

➡ Duflo-Zuker (**DZ**) functional based on Shell Model. (Duflo and Zuker 1995)

➡ Self-consistent mean field models based on Hartree-Fock-Bogoliubov approximations:

- **Skyrme HFB-*** (Goriely et al 2013)
- **Gogny D1M** (Goriely et al. 2009)

Typical r.m.s. deviation from the experimental data ~0.6 MeV

Ab-initio nuclear masses

Nuclear binding energies have been computed recently for heavier nuclei using chiral effective field theory interactions

H. Hergert et al., Phys. ev. C 87, 034307 (2013)

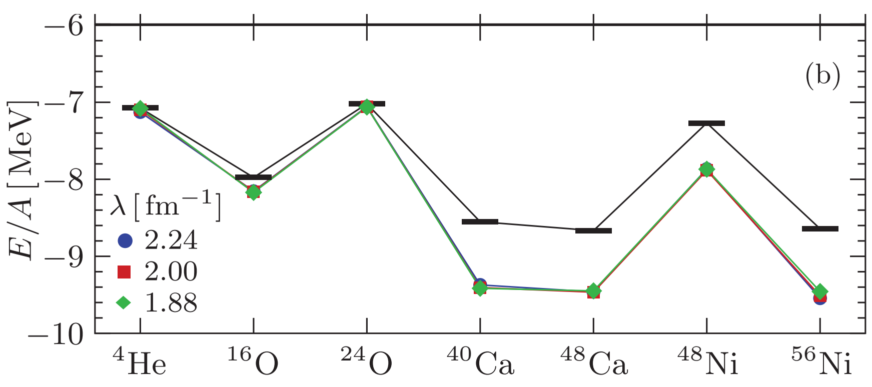
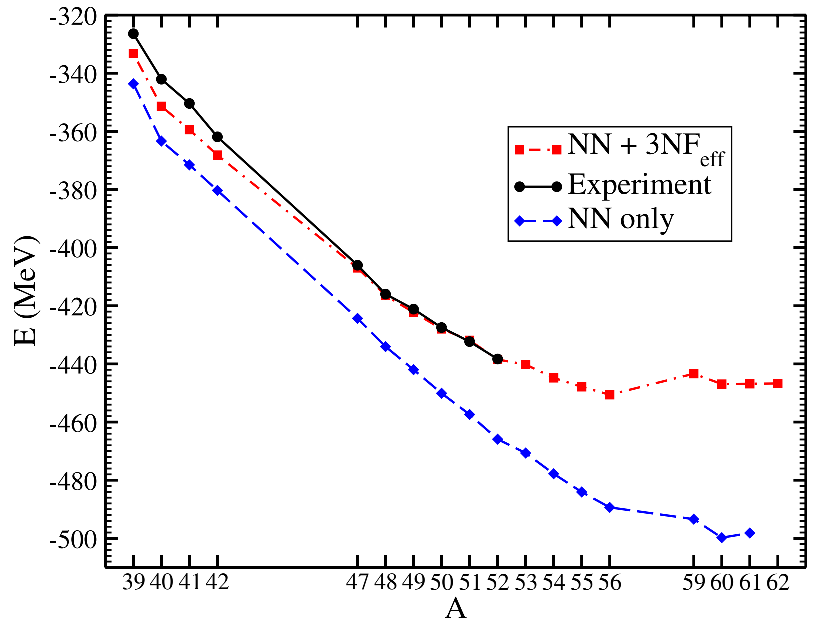
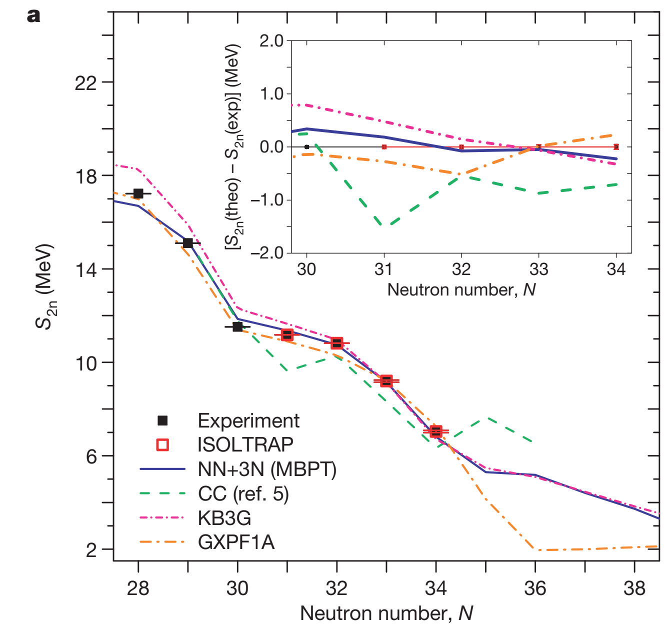


FIG. 7. (Color online) IM-SRG(2) ground-state energy per nucleon of closed-shell nuclei for $NN + 3N$-induced (top) and $NN + 3N$-full Hamiltonians (bottom) at different resolution scales λ. Energies are determined at optimal $\hbar\Omega$ for $e_{\mathrm{Max}} = 14$. Experimental energies (black bars) are taken from Ref. [44].

G. Hagen et al., Phys. Rev. Lett. 109, 032502 (2012)



F. Wienholtz et al, Nature 498, 346 (2013)



Ab-initio methods are far from being useful for nucleosynthesis simulations:

- Limited to magic or semi-magic nuclei.
- Limited accuracy so far (too much overbinding).
- Good results in some regions while in other regions are very bad.
- Missing many body forces, uncertainties in the three body coupling constants, etc.

Microscopic mass models with effective interactions

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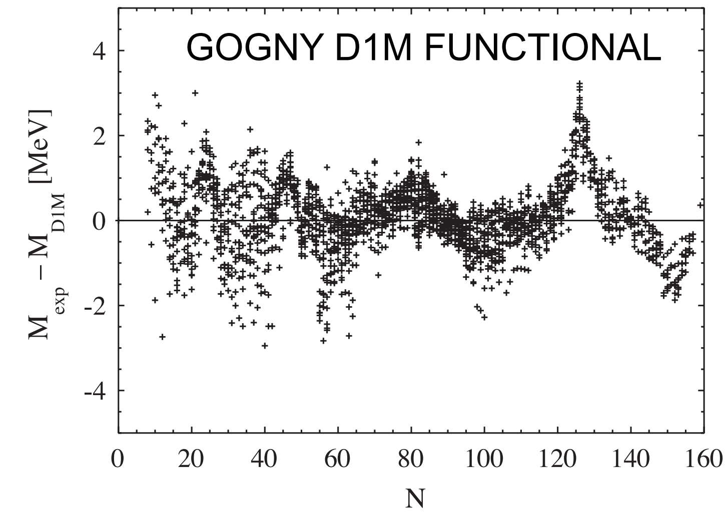
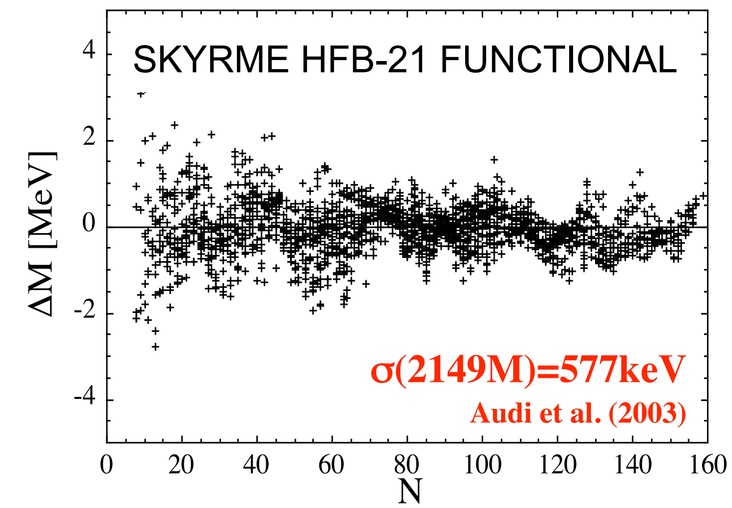
- Self-consistent mean field approximations provide a very good description of known data.

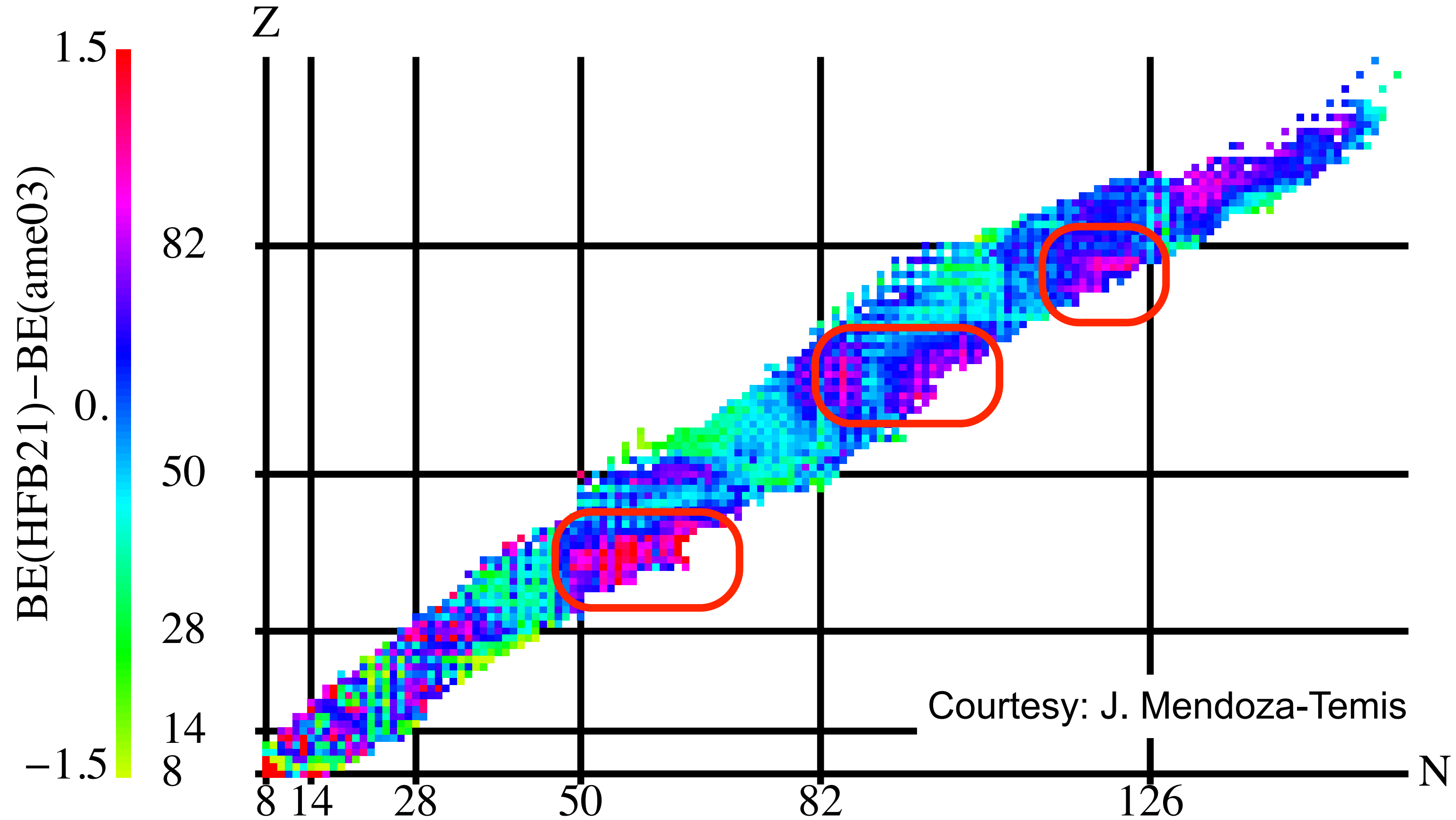


Goriely et al., PRL 102, 242501 (2009)



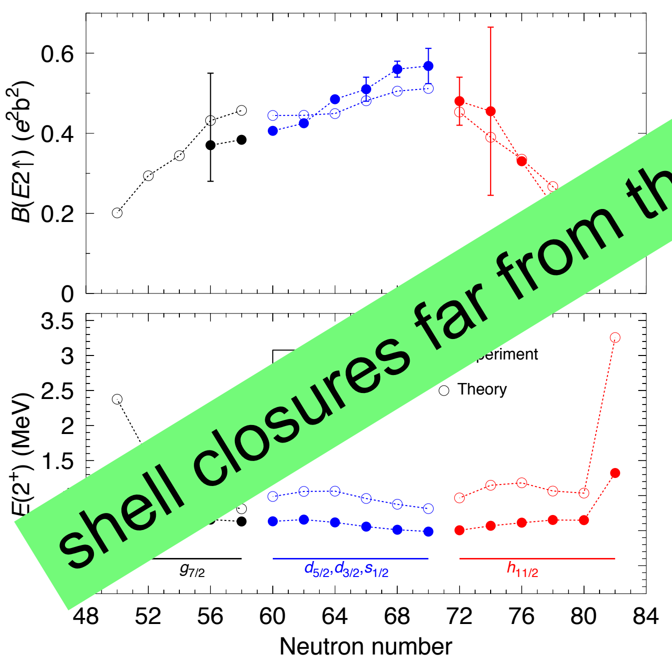
Goriely et al., PRL 102, 152503 (2009)

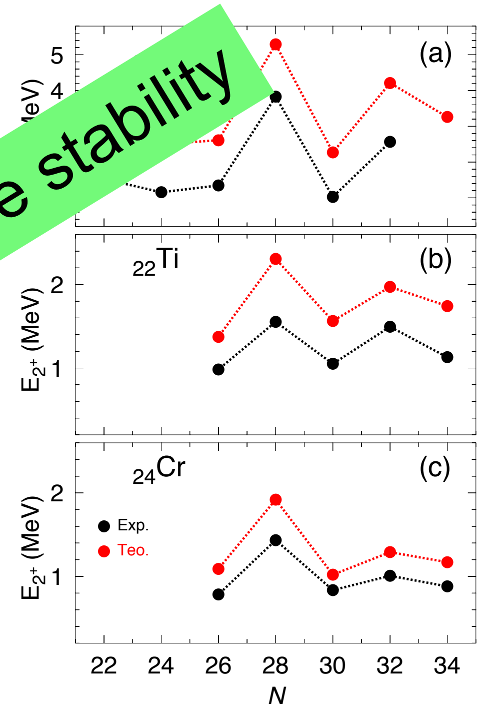
- There are still some problems in transitional regions and local uncertainties:
  - Numerical noise.
  - Some physics missing: Restoration of broken symmetries and configuration mixing.
  - Nuclei with odd number of protons/neutrons are not treated in equal footing as the even-even ones



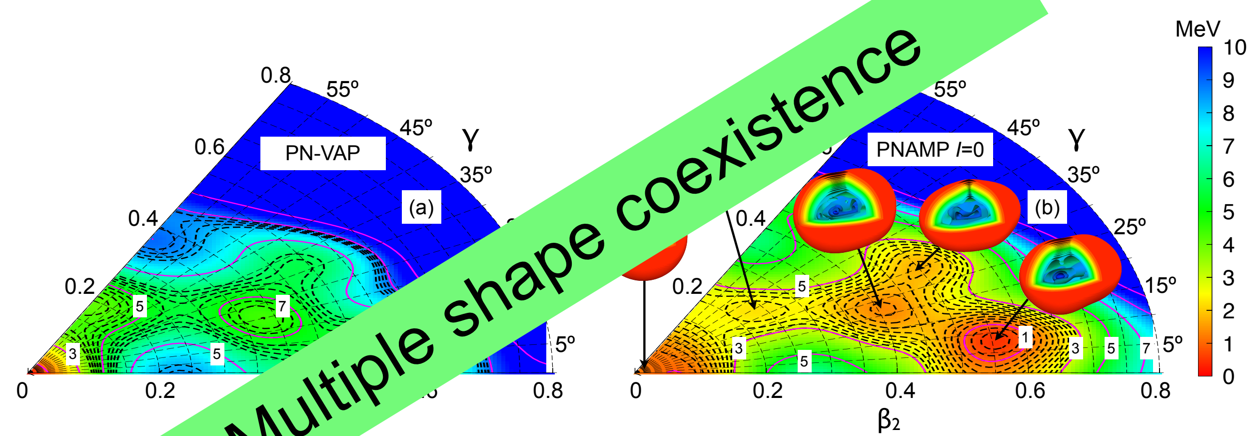
Self-consistent (beyond) mean field description

Selected applications

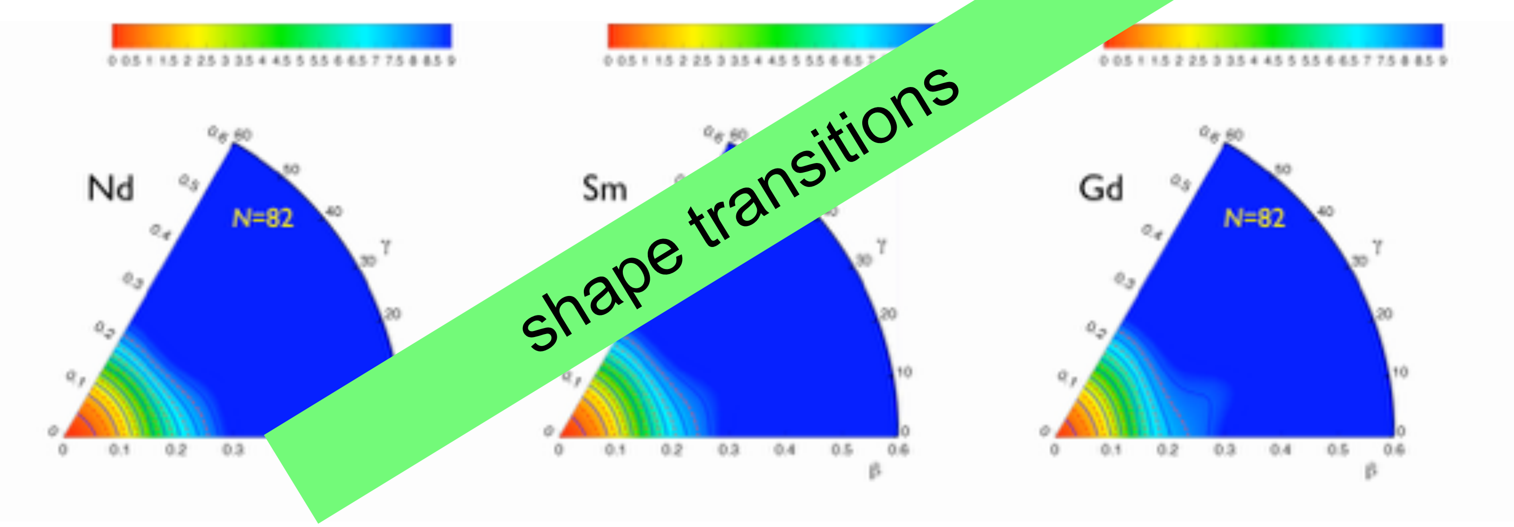




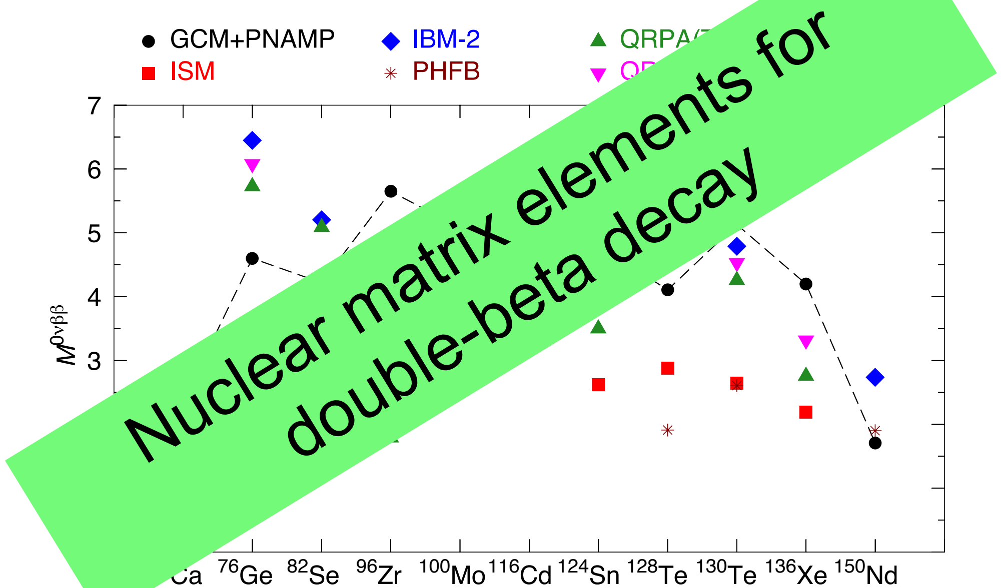
shell closures far from the stability



Multiple shape coexistence

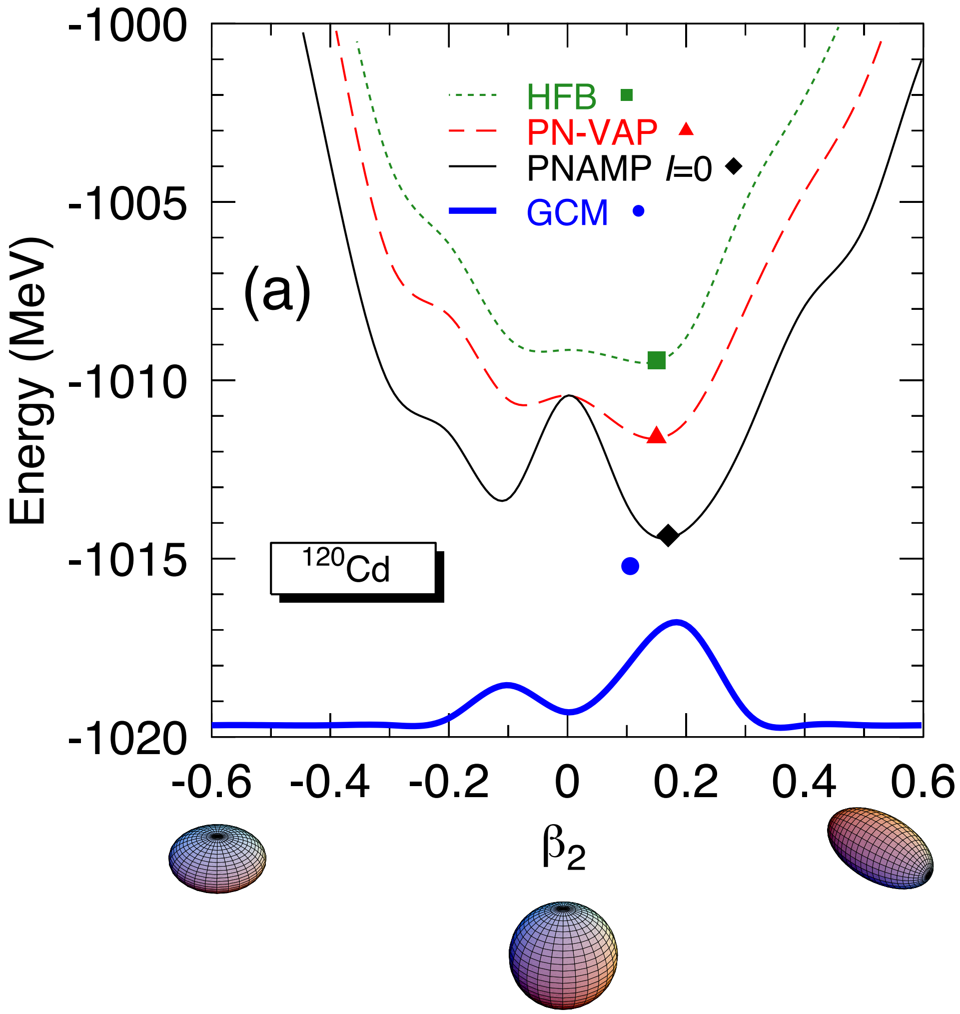


shape transitions

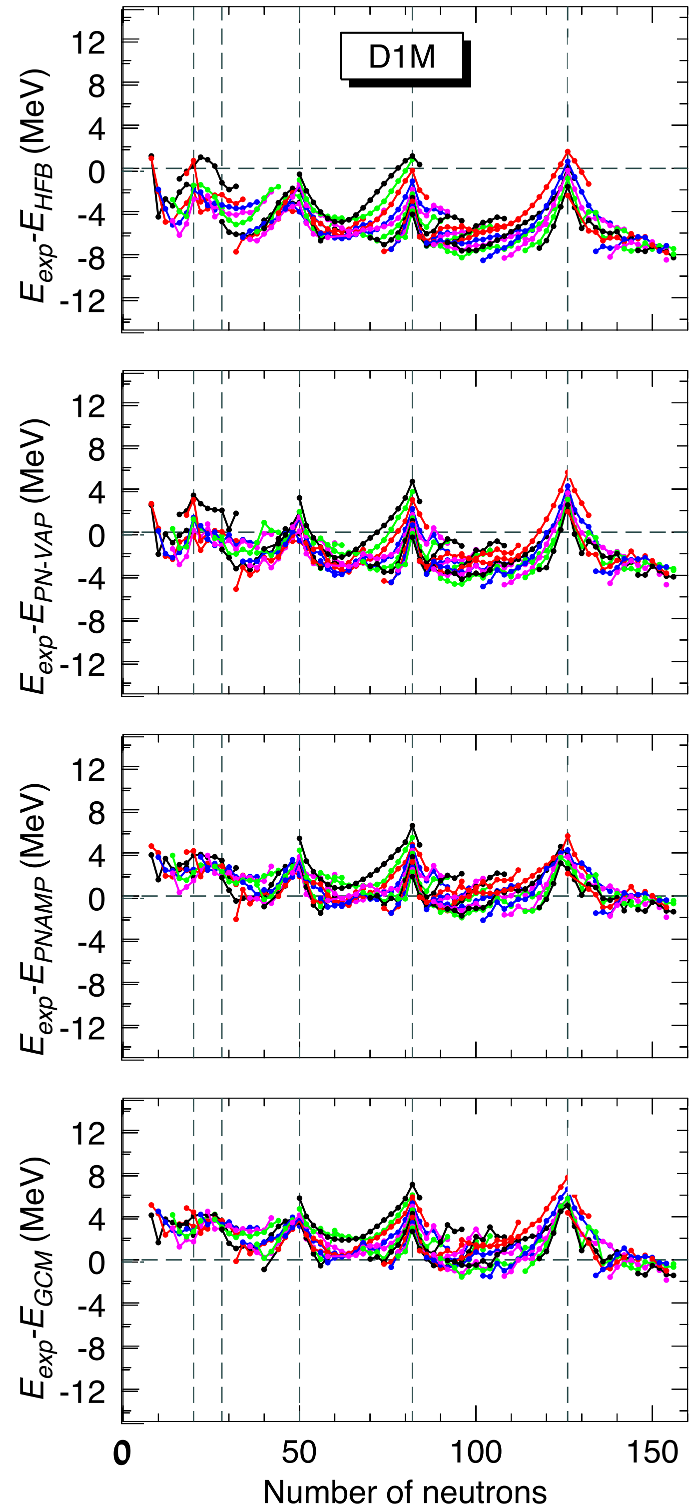


Nuclear matrix elements for double-beta decay

Microscopic mass models. Beyond mean field effects



Successive gain in energy by including more beyond-mean-field (variational) correlations



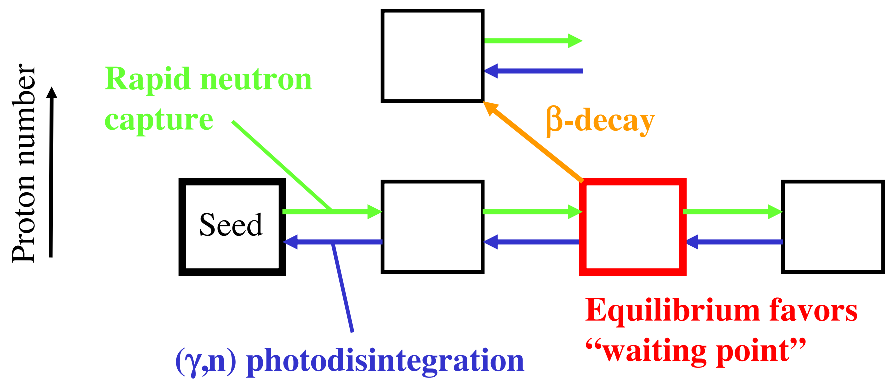
- BMF effects correct the under binding at the MF level but produces excess of binding energy → refit of the force
- BMF effects reduces the spread of the data, specially in the light nuclei
- Shell effects are present both at MF and BMF levels

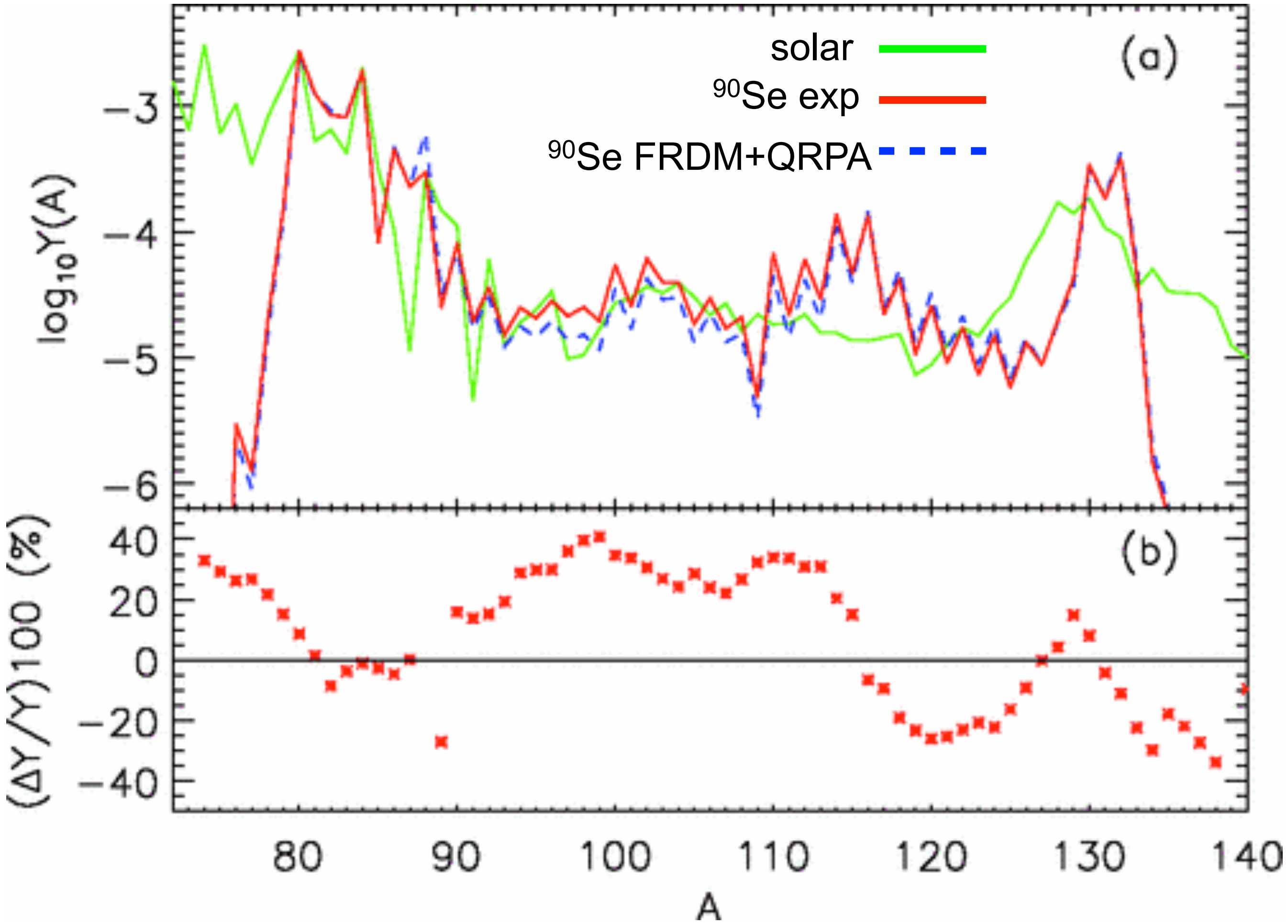
T. R. R. et al, arXiv 1407.7699 (2014)

See also M. Bender et al, PRC 73, 034322 (2006)

Impact of beta-decay half-lives on r-process simulations

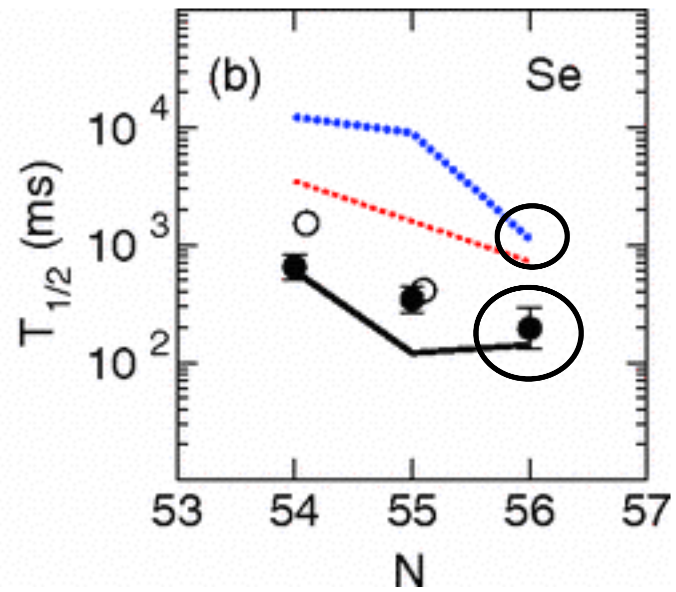
- Beta decay half-lives determine the time scale in r-process nucleosynthesis





M. Quinn et al, PRC 85, 035807 (2012)

Changing the half-life of a single element produces significant changes in the final abundances obtained in r-process simulations



Experimental beta-decay half-lives of neutron rich nuclei

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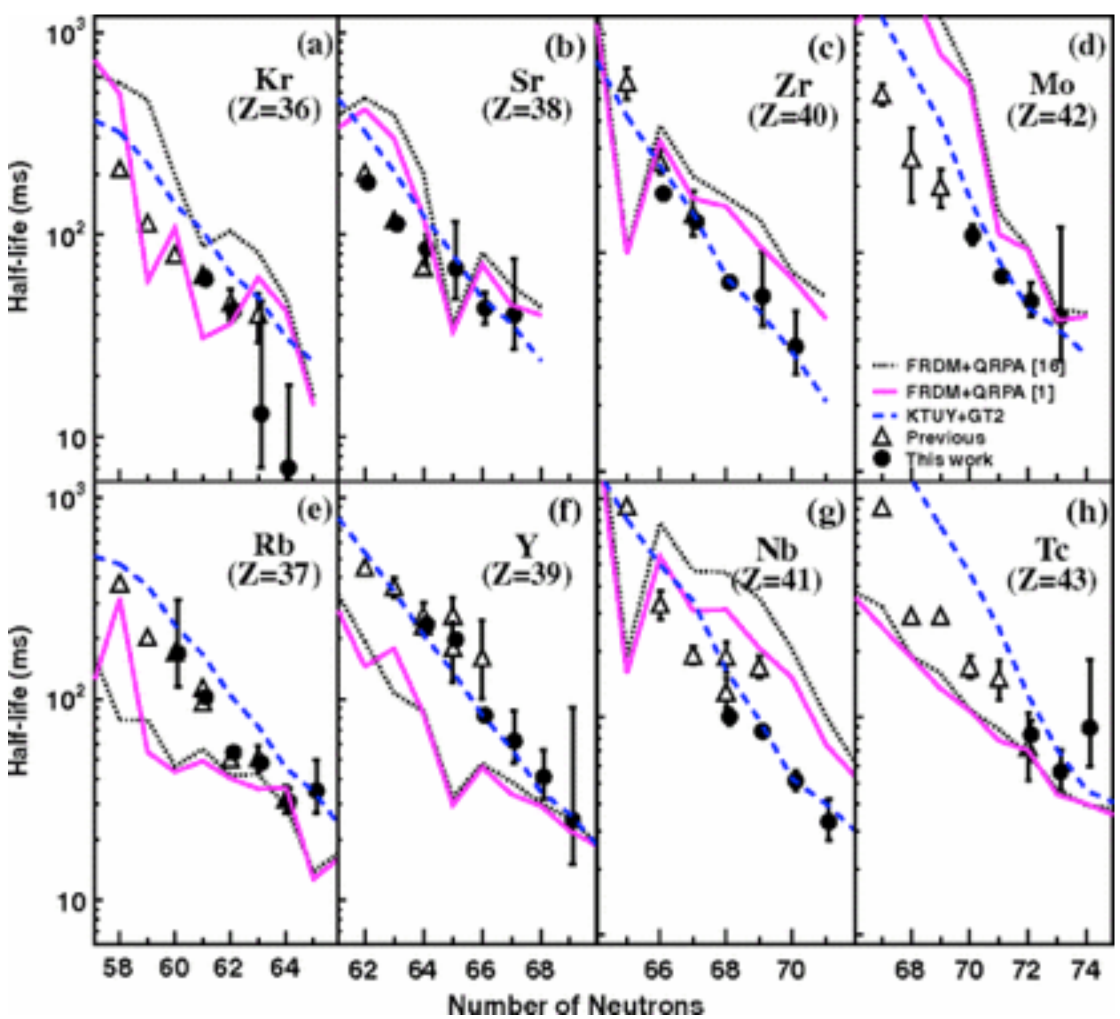
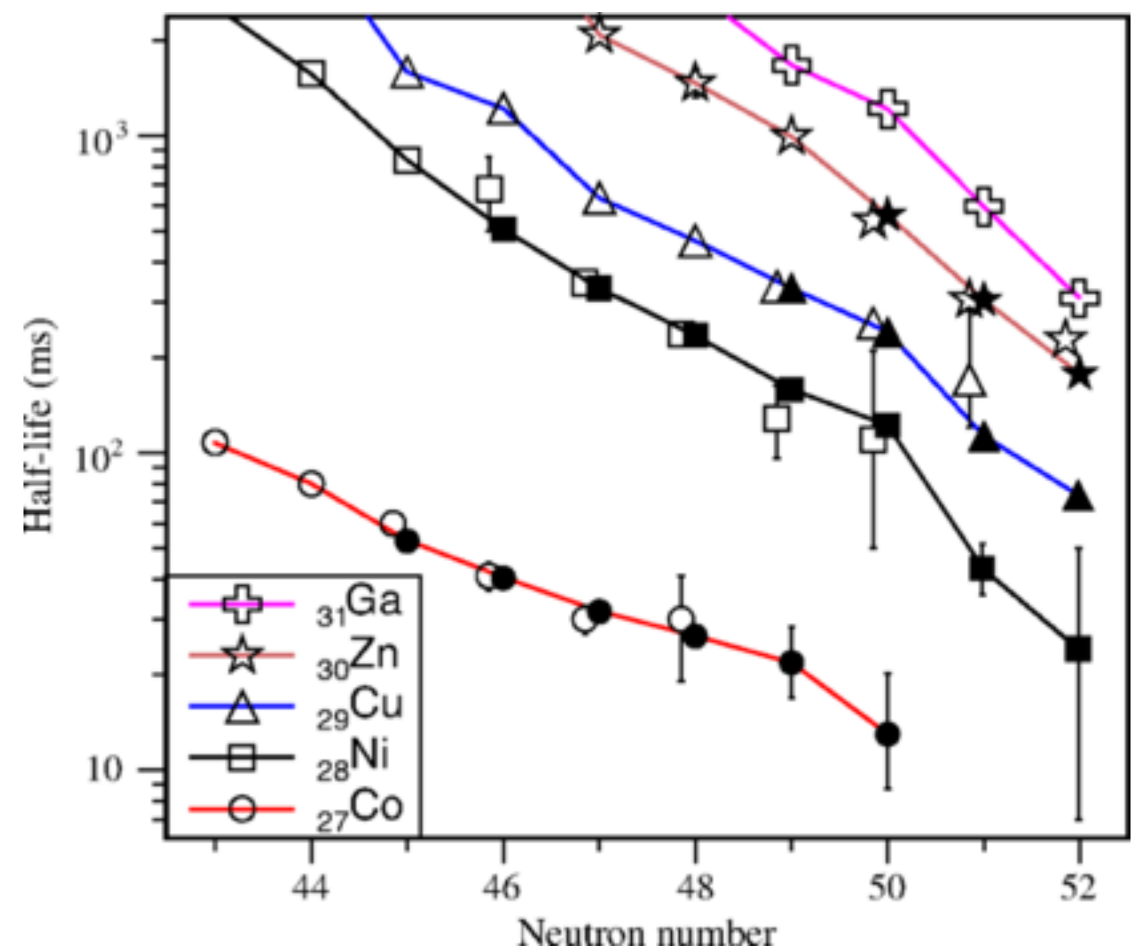
- Beta decay half-lives@RIKEN/RIBF



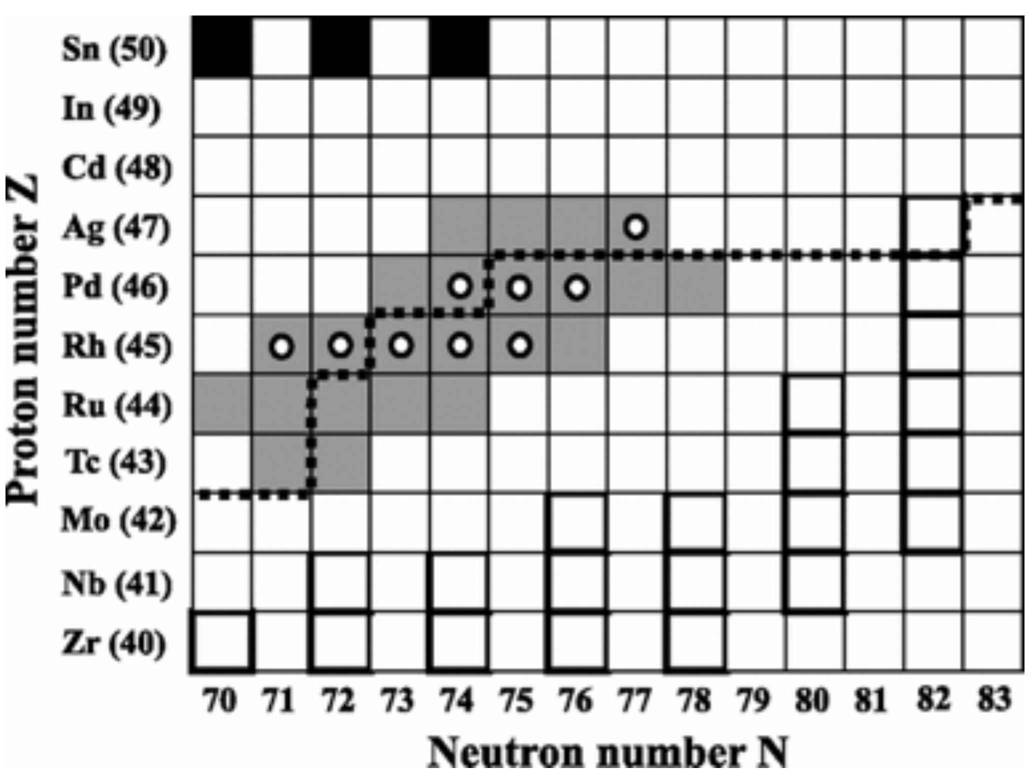
S. Nishimura et al, PRL 106, 052502 (2011)



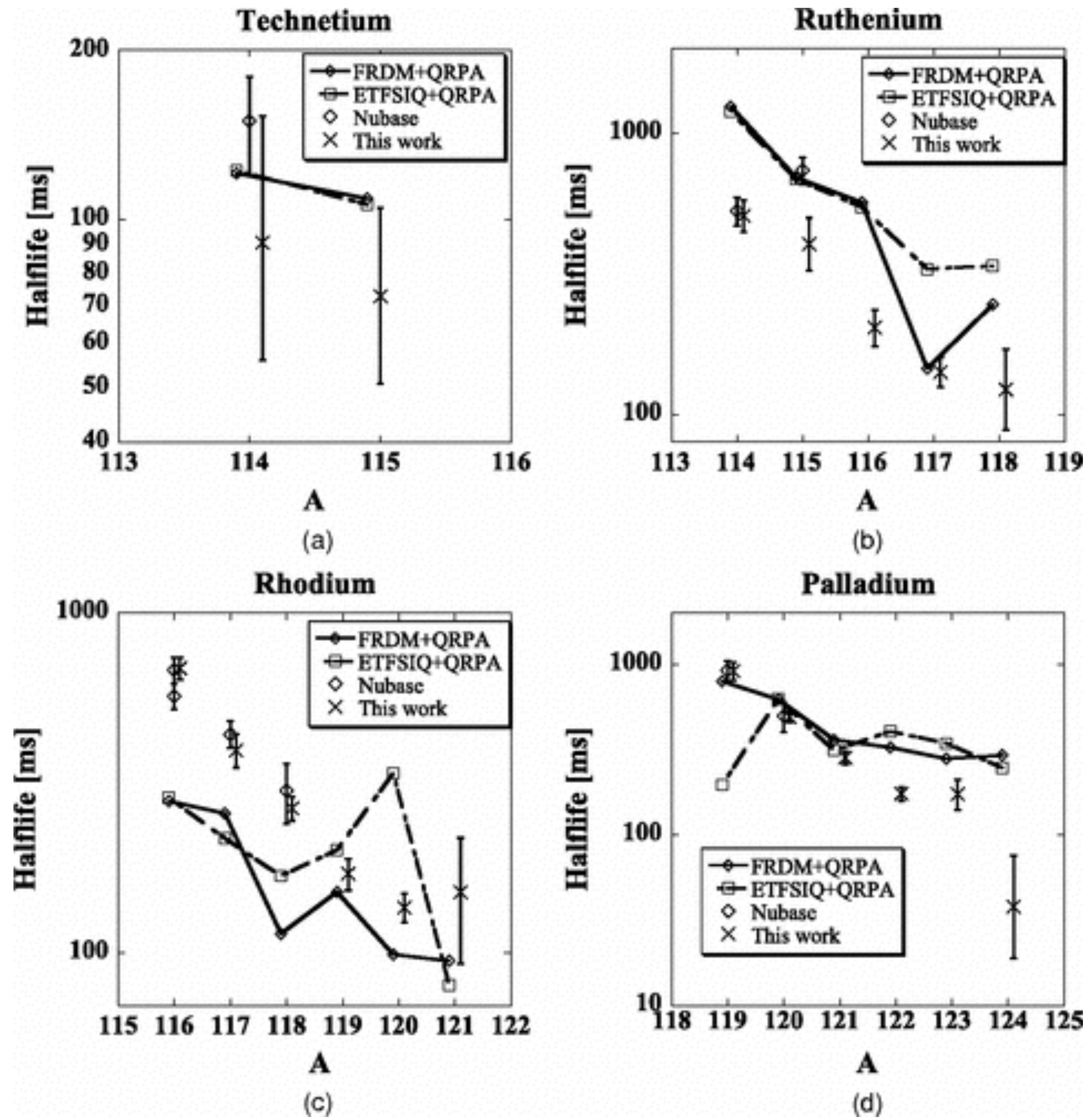
Z. Y Xu et al, PRL 113, 032505 (2014)

Experimental beta-decay half-lives of neutron rich nuclei

- Beta decay half-lives@NSCL/MSU

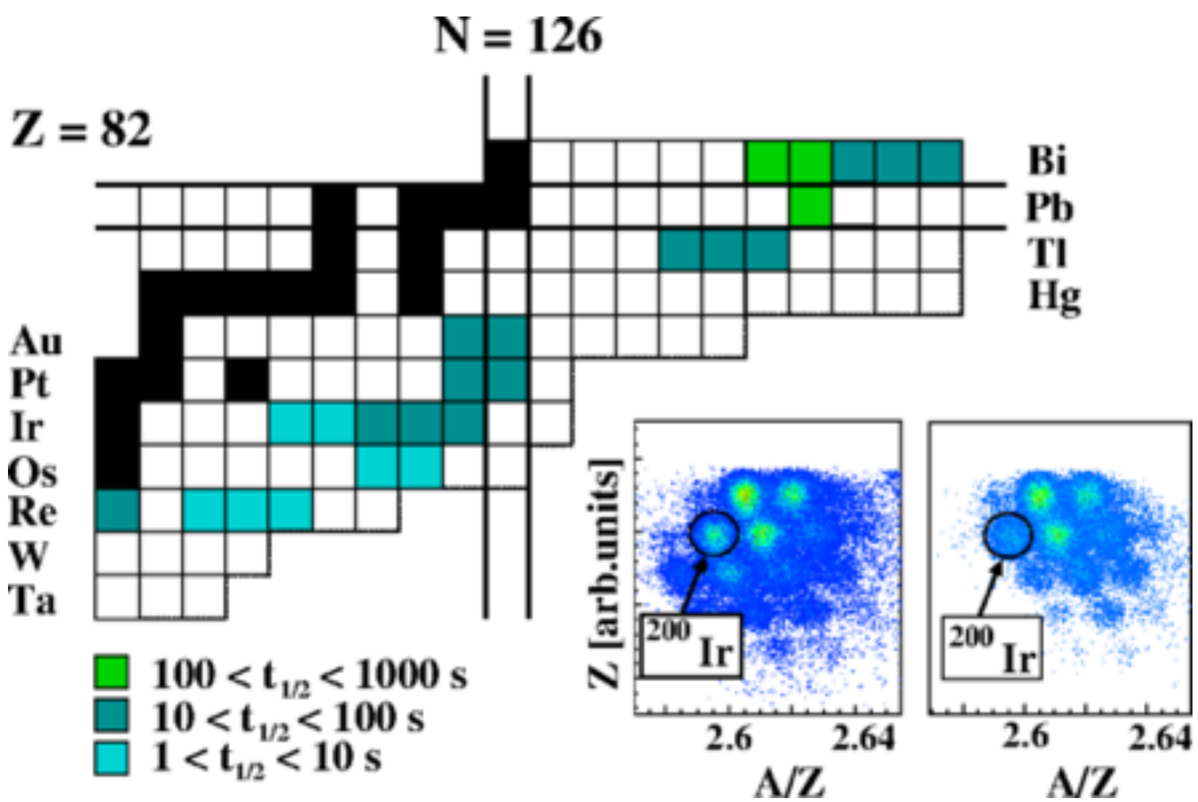


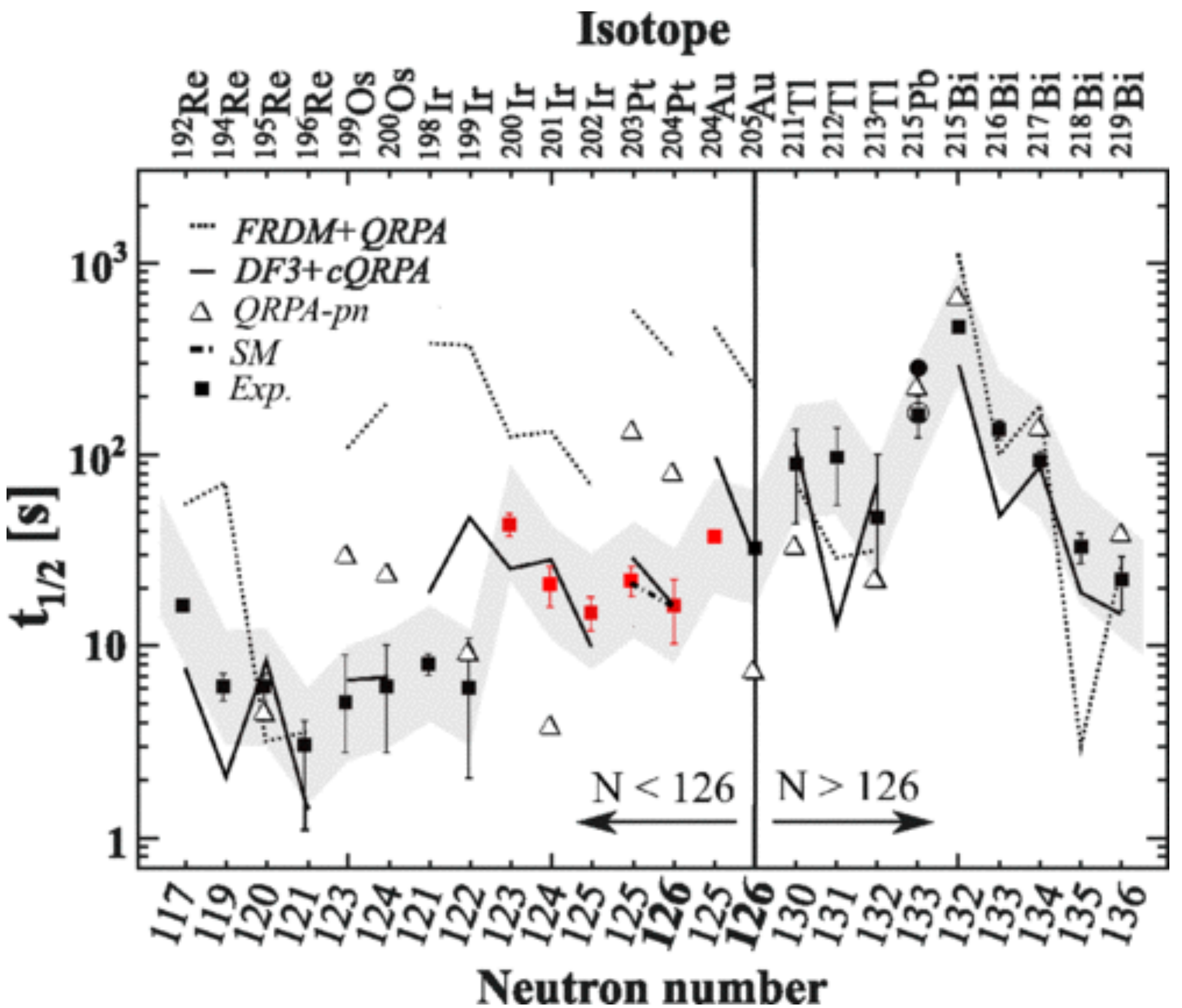
F. Montes et al, PRC 76, 035801 (2006)



Experimental beta-decay half-lives of neutron rich nuclei

- Beta decay half-lives@RISING/GSI





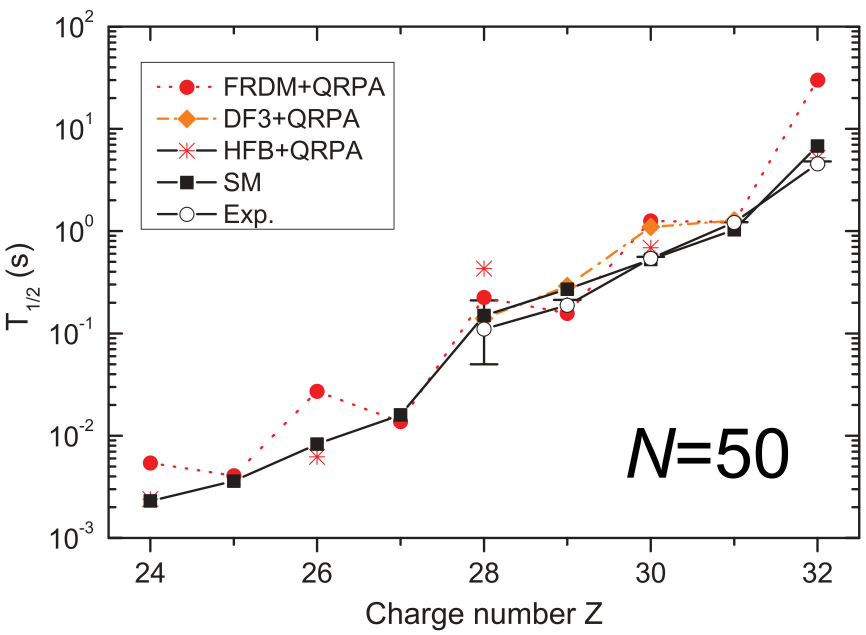
A. I. Morales et al, PRL 113, 022702 (2014)

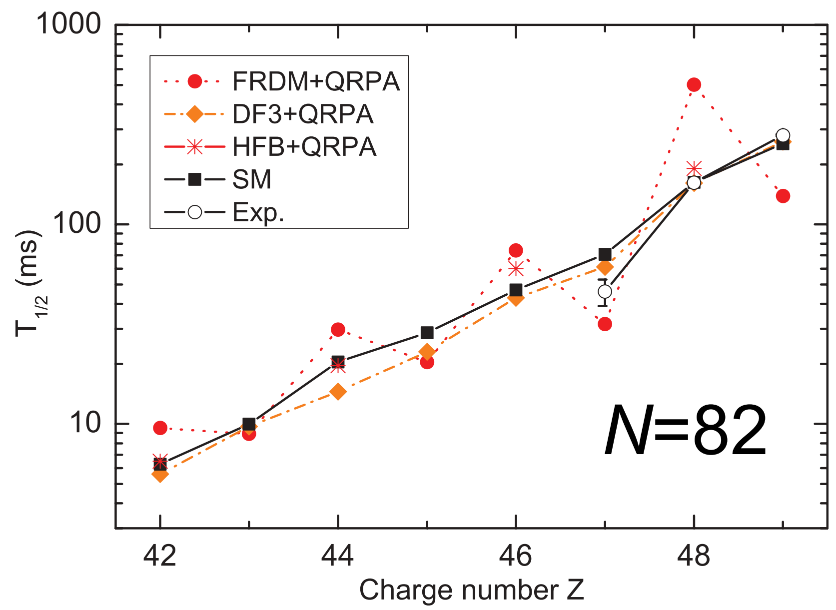
Calculation of beta-decay half-lives

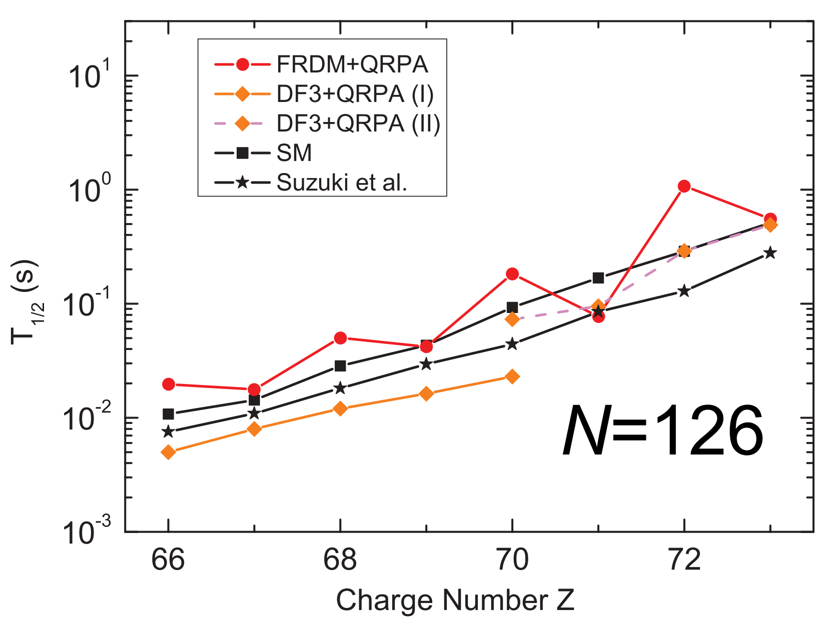
- Beta decay half-lives have been computed on FRDM model so far and the calculations show several problems:
  - Inconsistent treatment of first-forbidden transitions.
  - Overestimation of half-lives.
  - Strong odd-even effects.

- Recent microscopic calculations including Gamow-Teller and first forbidden transitions:
  - Shell Model for N = 50, 82, 126.
  - Non-relativistic DFT+QRPA
  - Global calculations within the Covariant Density Functional Theory, using the spherical QRPA method.

Beta-decay half-lives. Shell Model



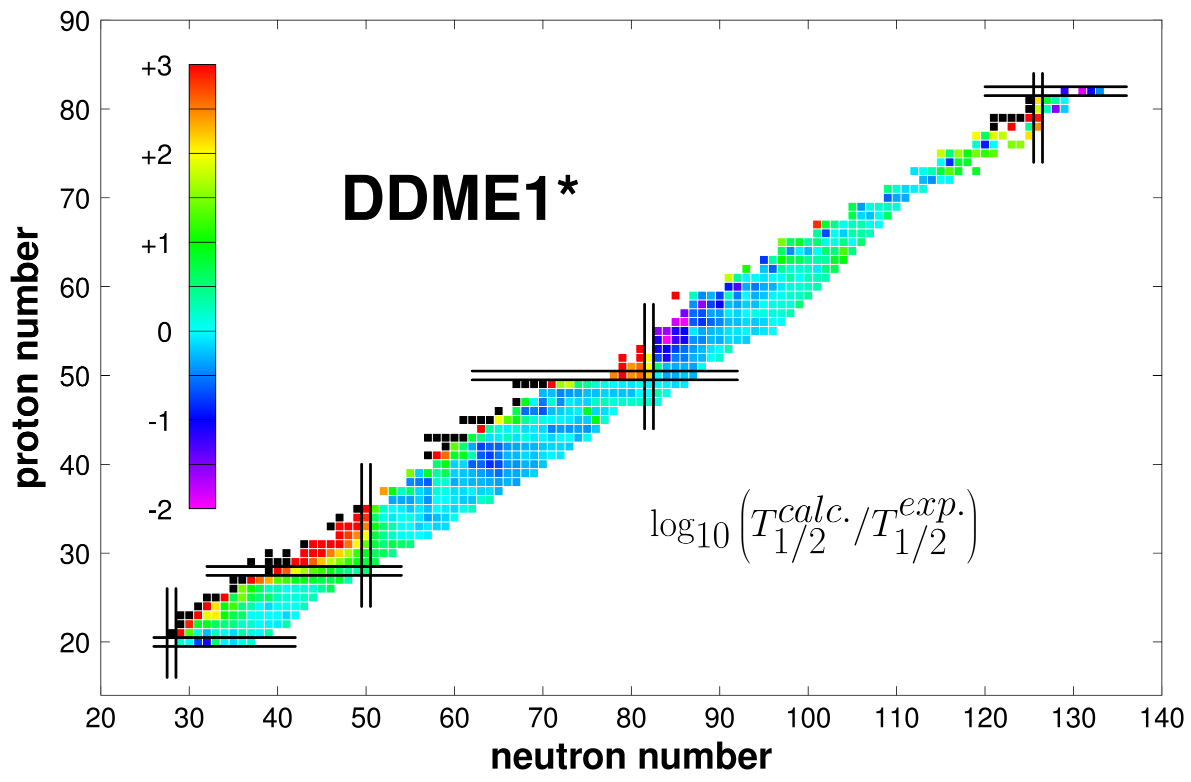


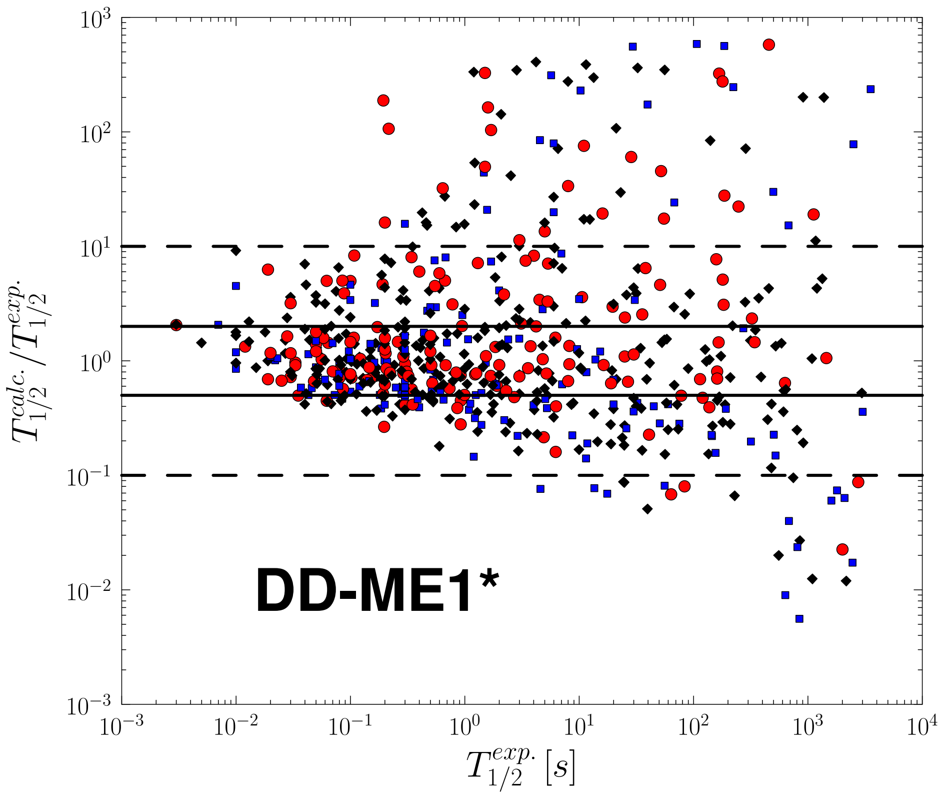


- Shell Model calculations including first forbidden transitions for N = 50, 82, 126.
- Very good agreement with the available experimental data
- Less significant odd-even effects than in FRDM model

Q. Zhi *et al.*, Phys. Rev. C 87, 025803 (2013)

Beta-decay half-lives. CDFT method

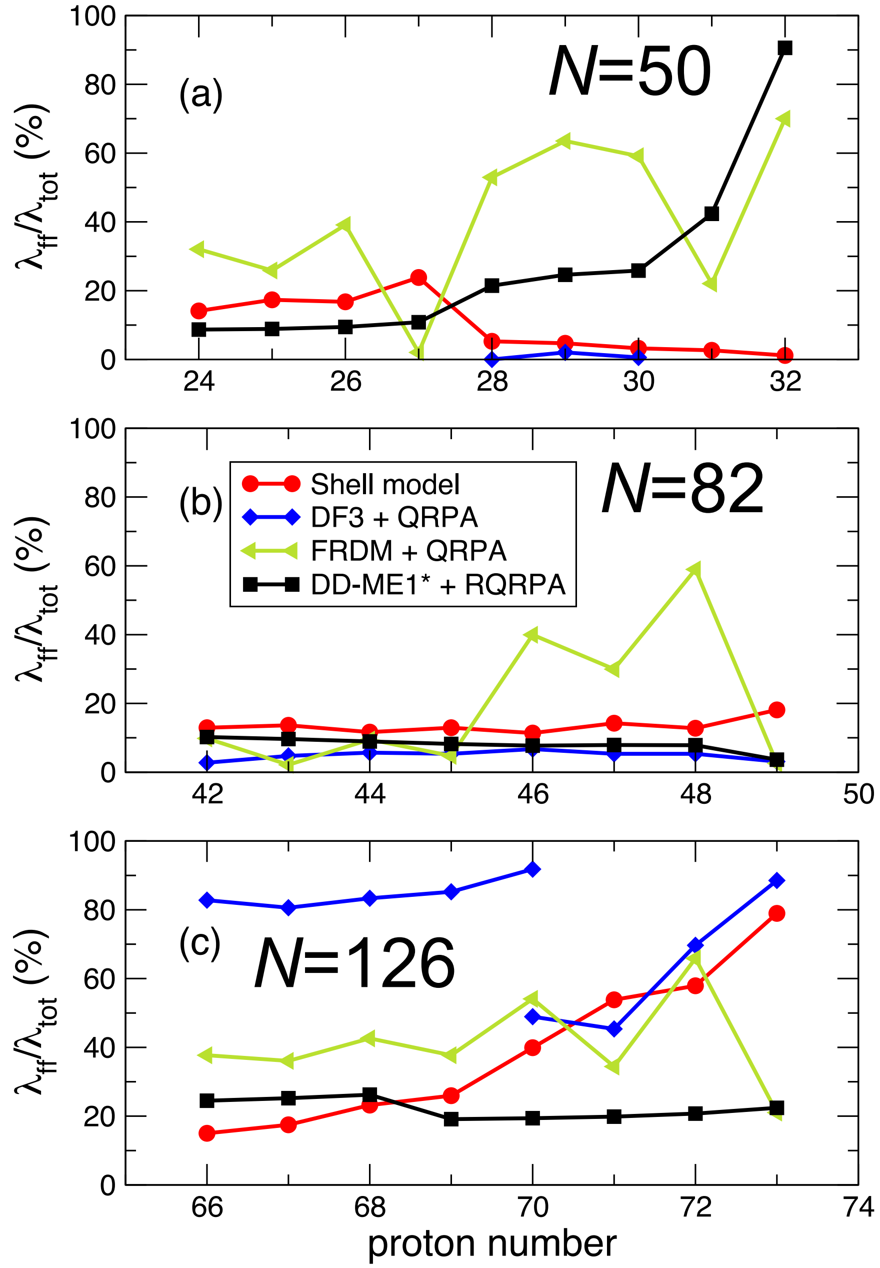




- Global calculations using spherical covariant DFT+pnQRPA calculations.
- Good agreement with the experimental data, particularly in short-lived nuclei.

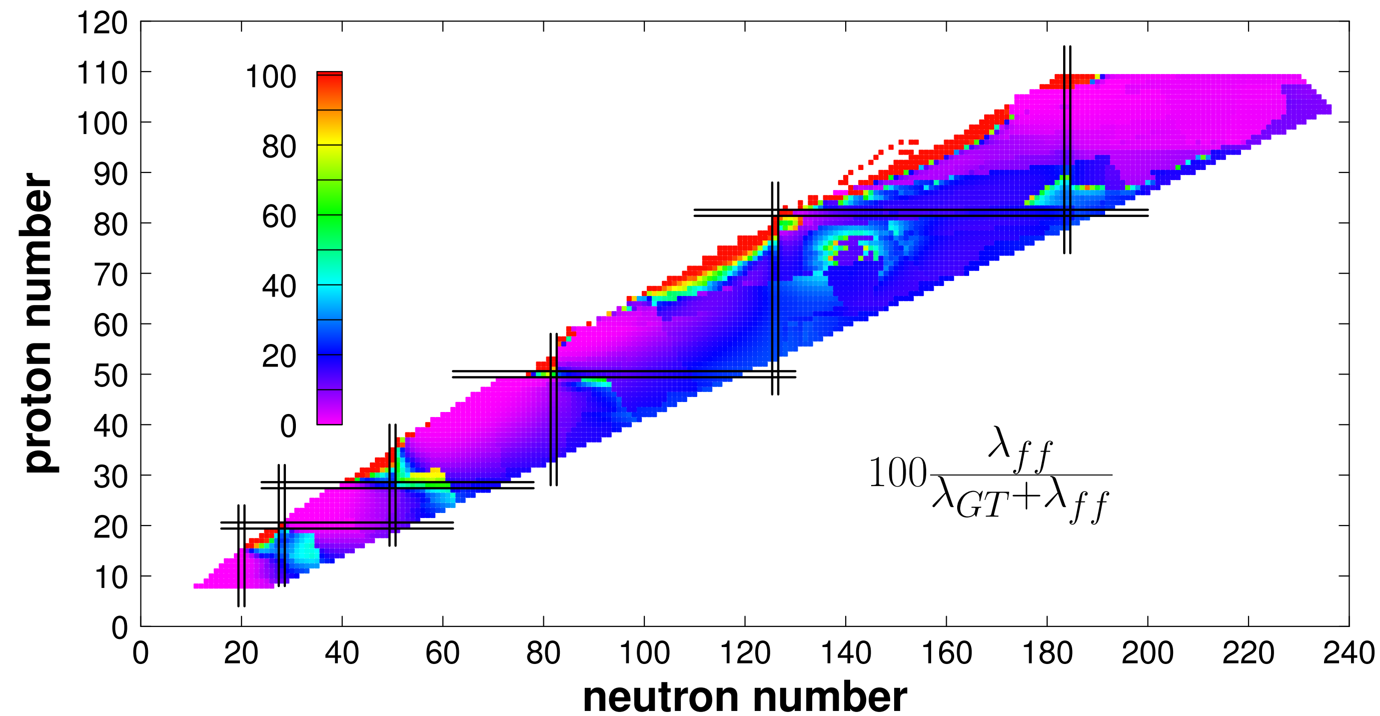
T. Marketin *et al.*,, in preparation

Beta-decay half-lives. First forbidden contribution



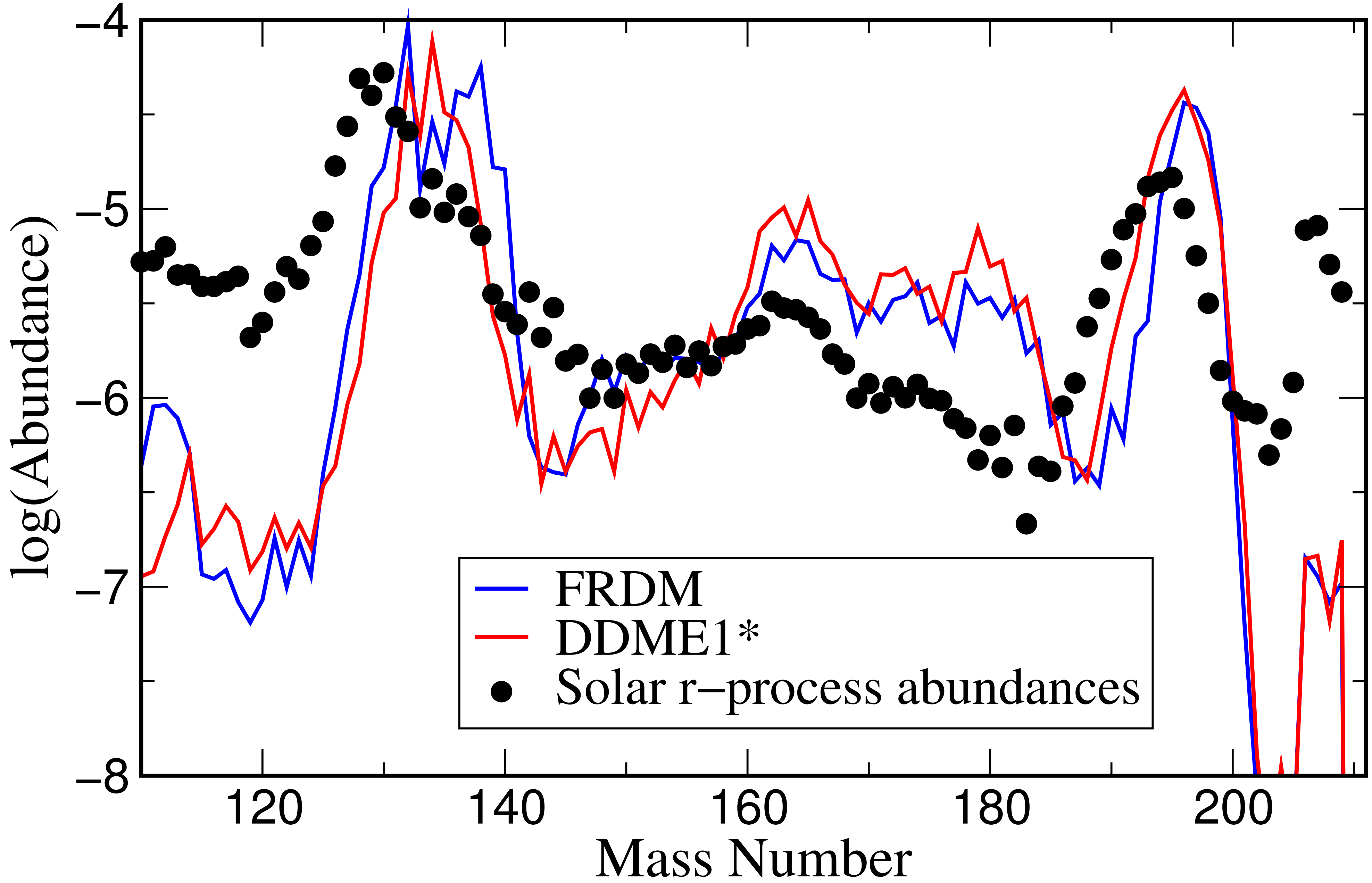
- For *N*=50, first forbidden contributions increase above Z=28 for CDFT calculations while they are negligible for SM.
- For *N*=82, first forbidden contributions remain small both for CDFT and SM calculations.
- For *N*=126, first forbidden contributions increase with proton number in SM while remain constant for CDFT.
- For FRDM, a less smooth result is obtained.

- Systematics of the first forbidden contributions can be performed within the CDFT framework.



T. Marketin *et al*.,, in preparation

Beta-decay half-lives. Impact on r-process nucleosynthesis



T. Marketin *et al.*,, in preparation

Summary and outlook

Experiments for nuclear masses, beta decay half-lives, beta delayed neutron emission, etc:

THE MORE THE BETTER

However, not all nuclei belonging to the r-process path will be experimentally accessible:

THEORETICAL UNCERTAINTIES

- ***Ab-initio* methods** are still far away from being usable in astrophysical applications.
- **Shell model** cannot be applied extensively either.
- We have to rely upon mic/mac approaches and/or **energy density functional** methods (also for **fission** studies).

Summary and outlook

Improving energy density functional methods for nuclear astrophysics applications:

- Study of **odd-systems** on the same footing as the even-even ones (masses and beta-decays).
- Development of **parametrizations** of the interaction fitted with BMF functionals (now becoming available thanks to the new computational resources).
- Including all possible **degrees of freedom** within the theoretical framework (multipoles, single particle excitations,…).
- Solving technical problems such as providing reliable **extrapolation** schemes to infinite working basis.

Further improvements are (will be) possible thanks to the combined experimental and theoretical efforts.

Best is (hopefully) yet to come…