Recent studies on the nuclear physics input for the r-process nucleosynthesis

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NAVI Nuclear Astrophysics Virtual Institute

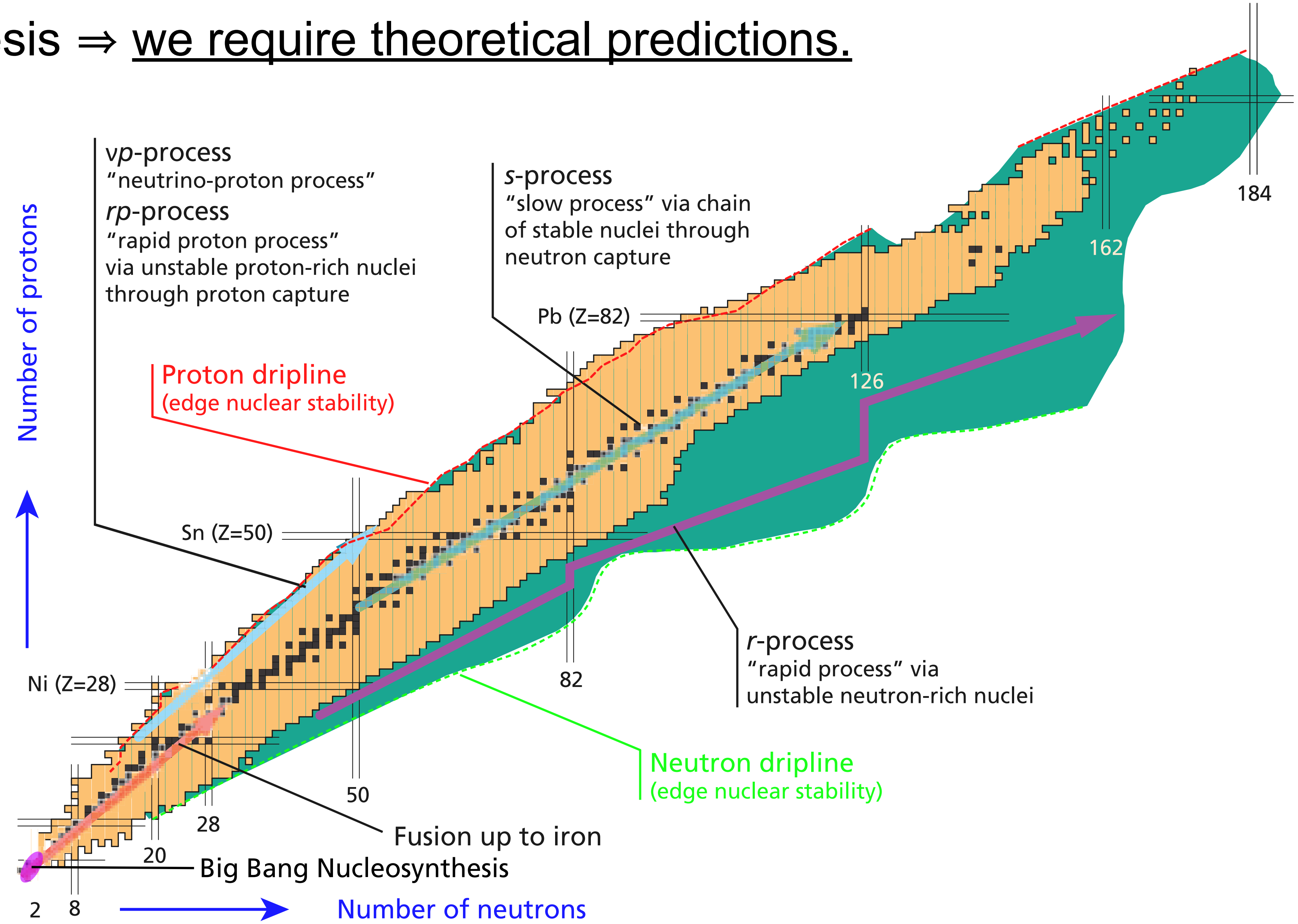
HIC for FAIR Helmholtz International Center

Outline

- Introduction.
- Results on beta decay half-lives.
- Developments in microscopic nuclear mass models.
- Summary and outlook

Motivation

Only some nuclei are/will be experimentally explored in the relevant region for r-process nucleosynthesis ⇒ we require theoretical predictions.



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

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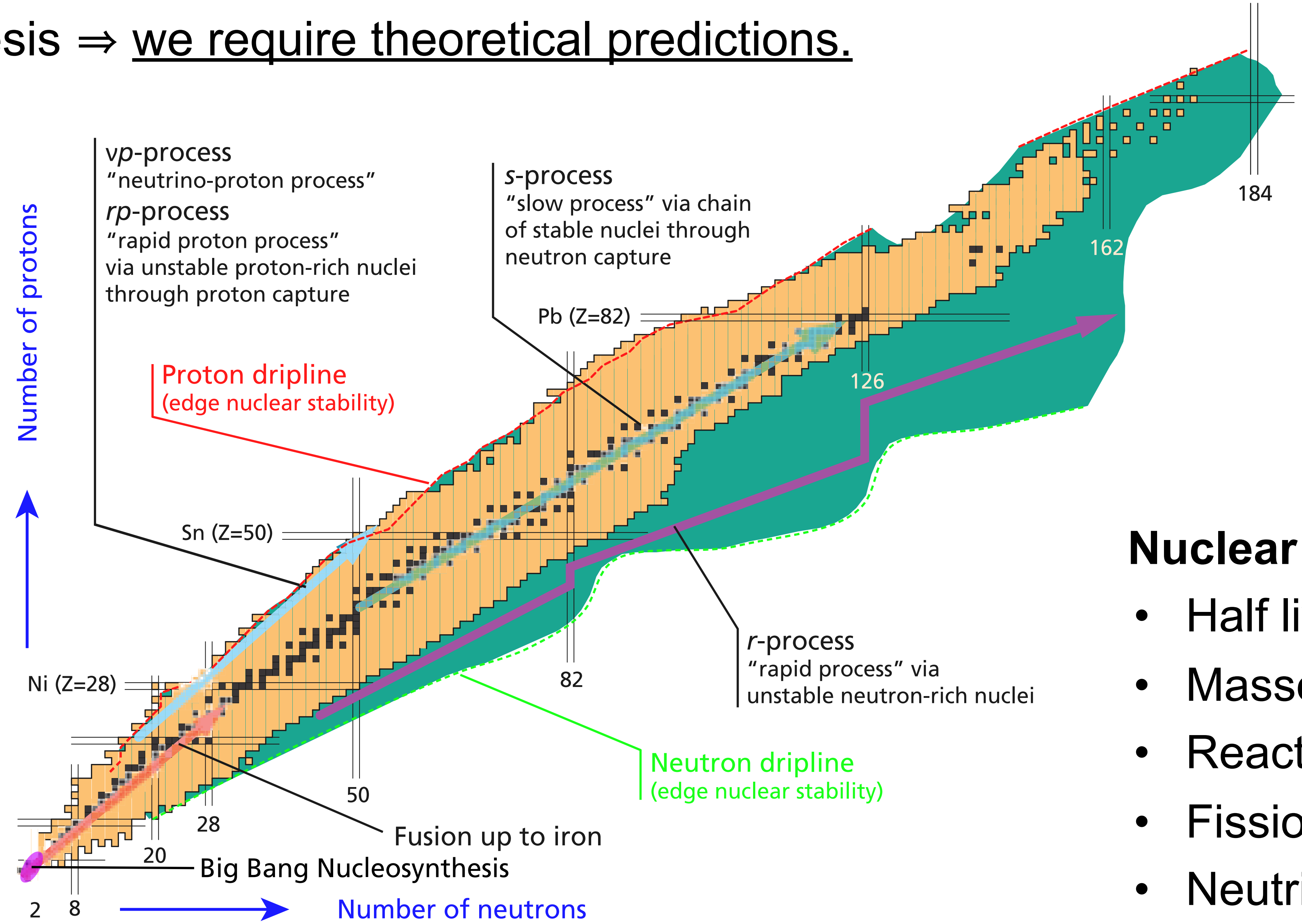

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Nuclear physics input:

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

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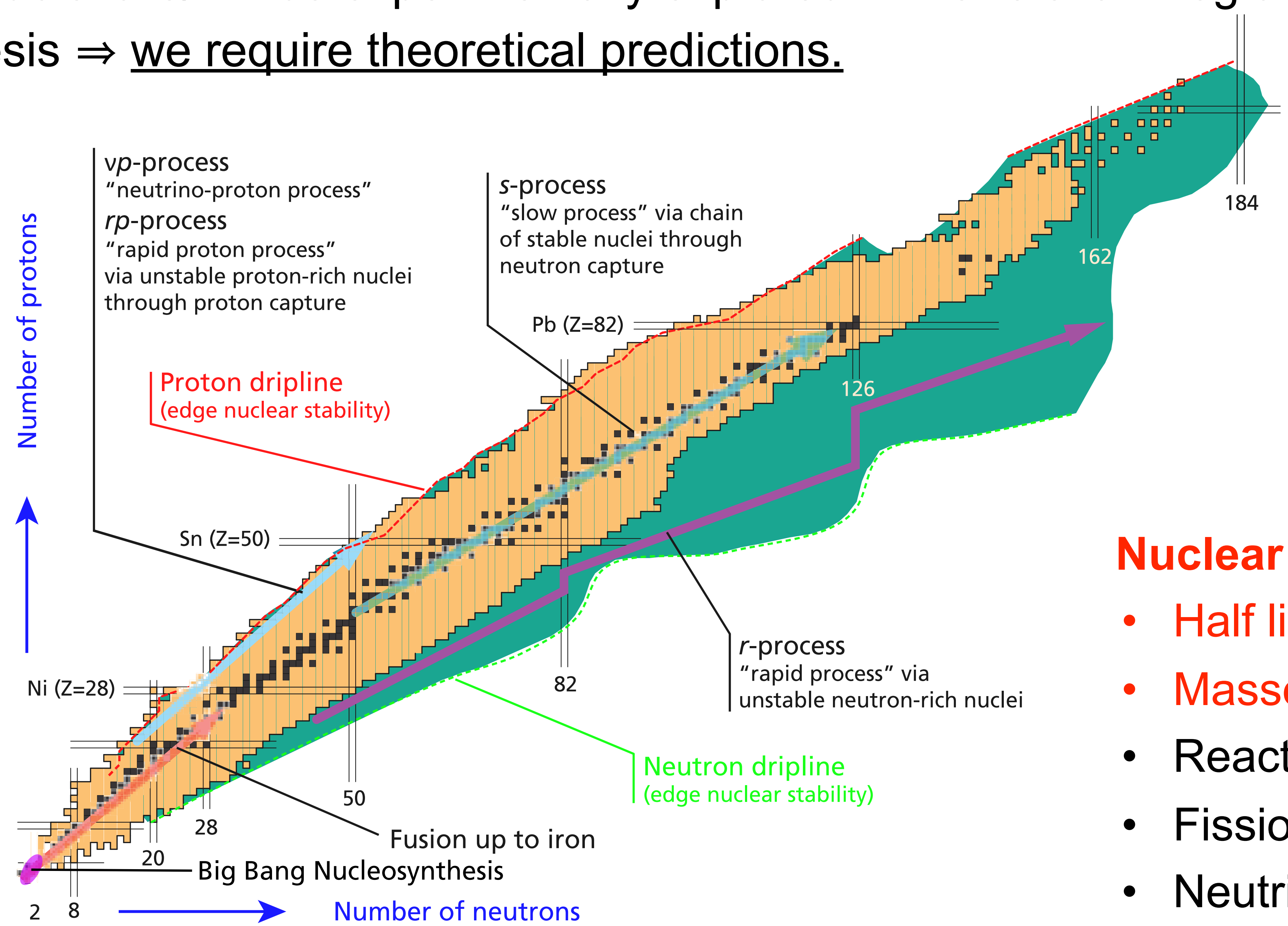

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Nuclear physics input:

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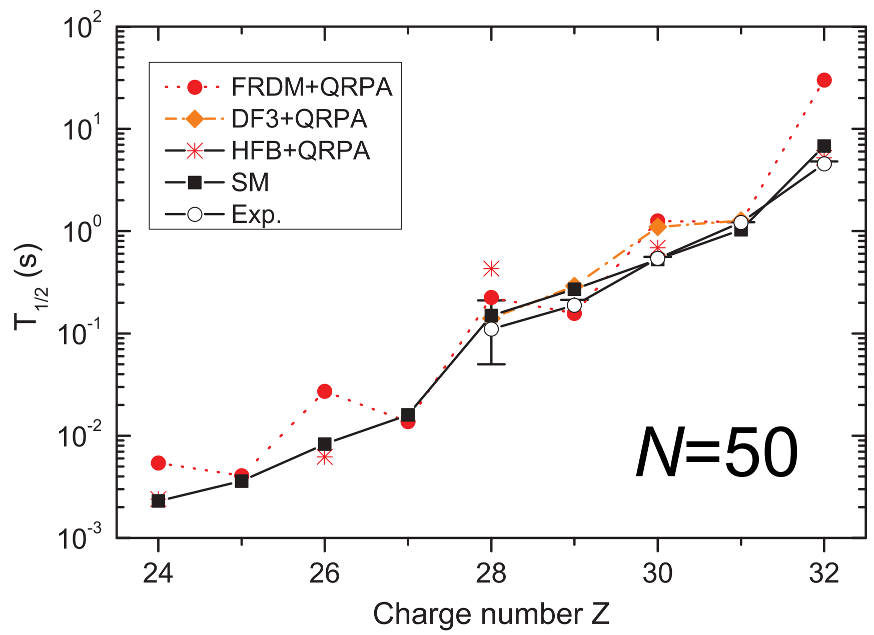
Beta-decay half-lives

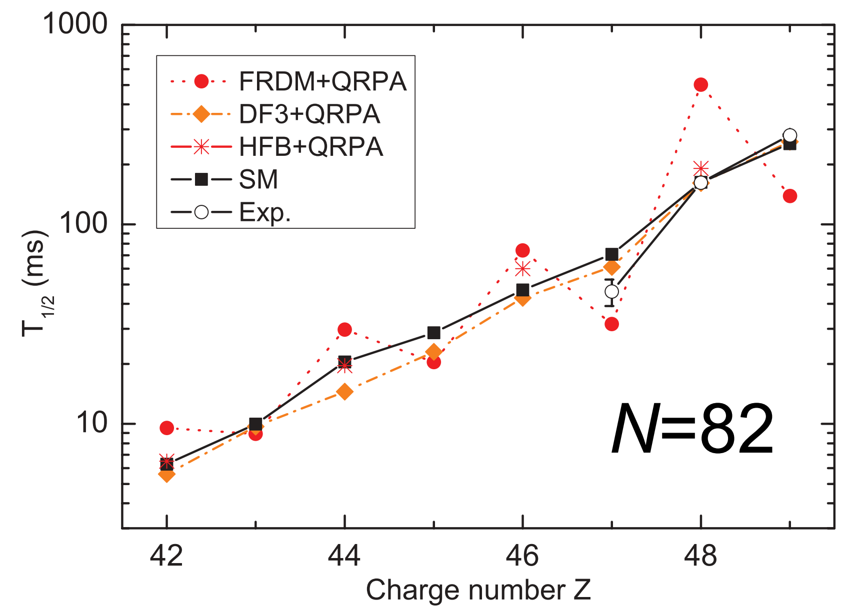
- Beta decay half-lives determine the time scale in r-process nucleosynthesis

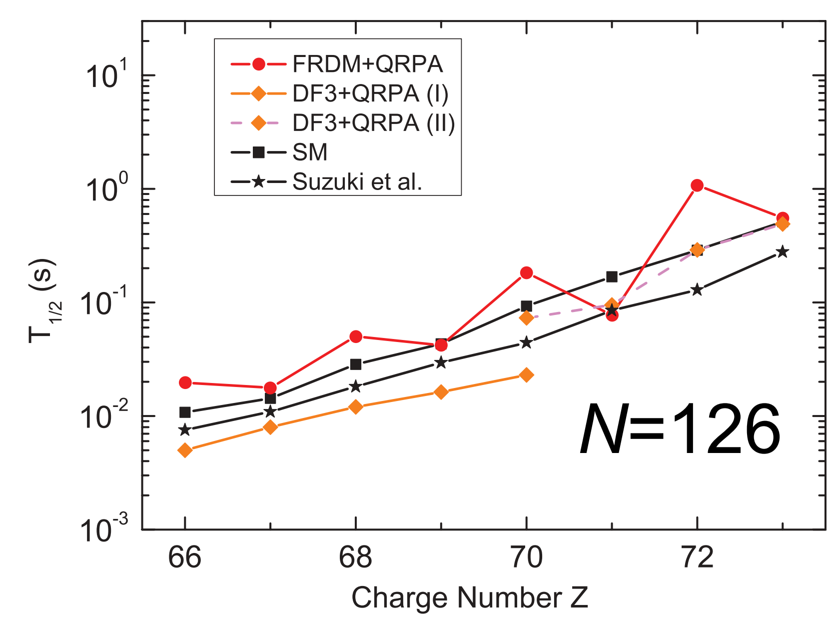
- Beta decay half-lives have been computed on FRDM model so far and the calculations show several problems:
  - Inconsistent treatment of first-forbidden transitions.
  - Overestimation of half-lives.
  - Strong odd-even effects.

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

Beta-decay half-lives. Shell Model



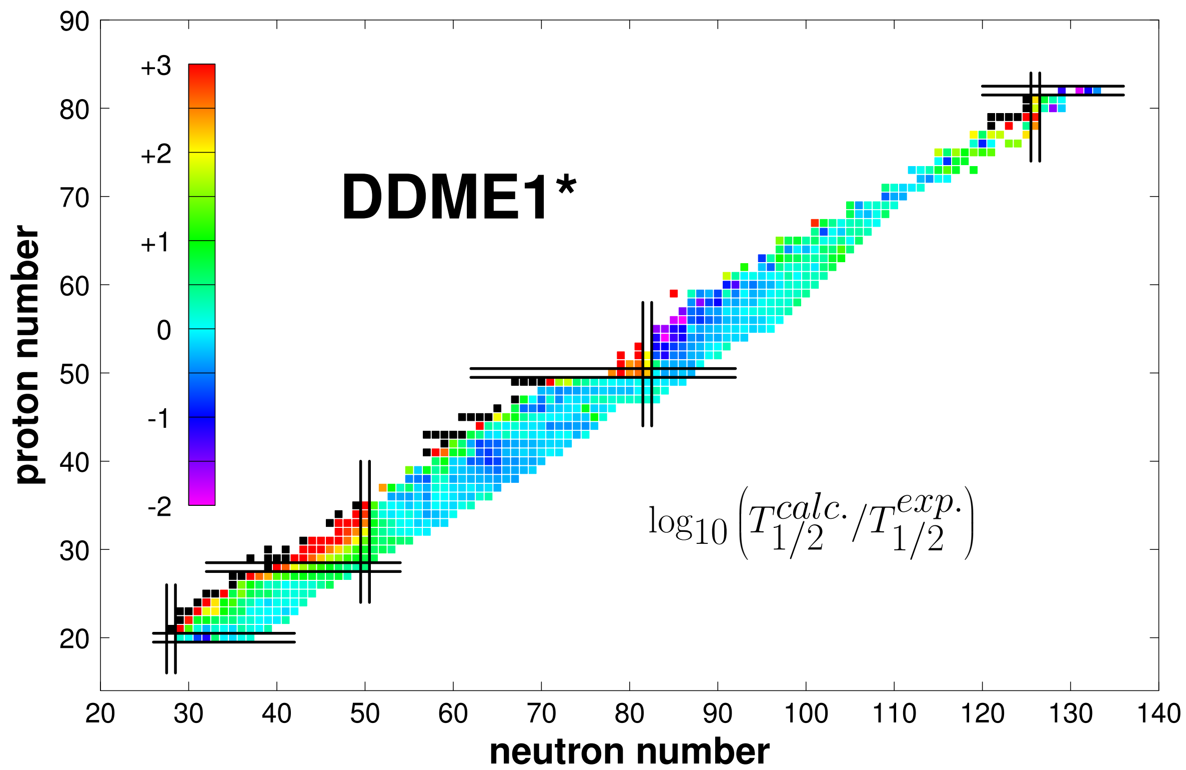


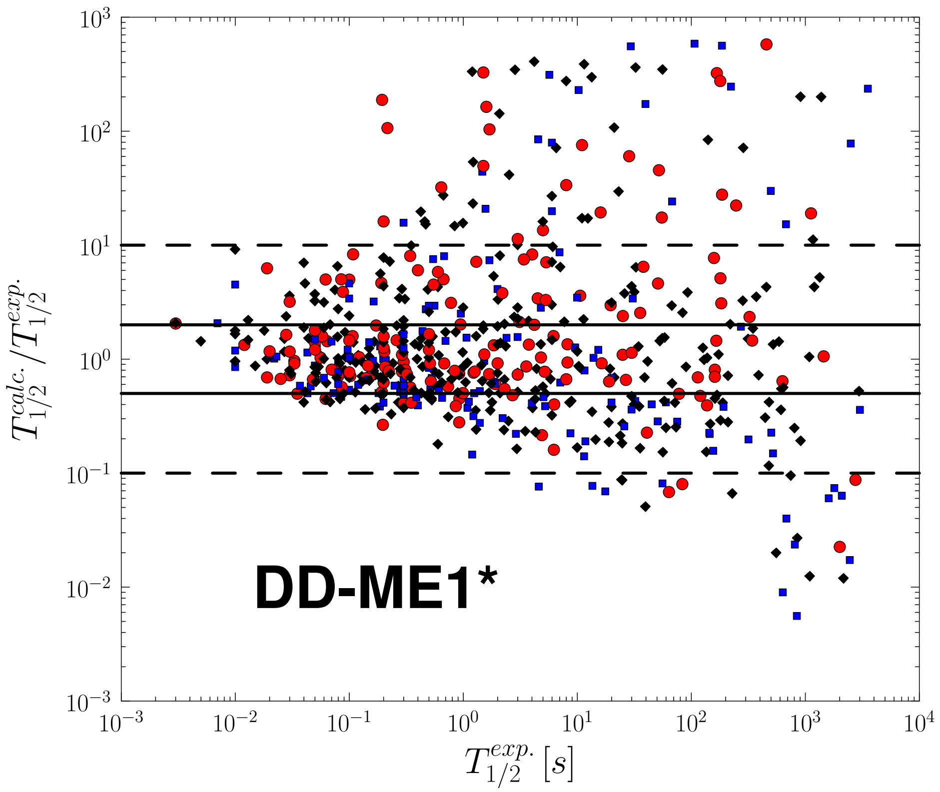


- Shell Model calculations including first forbidden transitions for N = 50, 82, 126.
- Very good agreement with the available experimental data
- Less significant odd-even effects than in FRDM model

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. CDFT method

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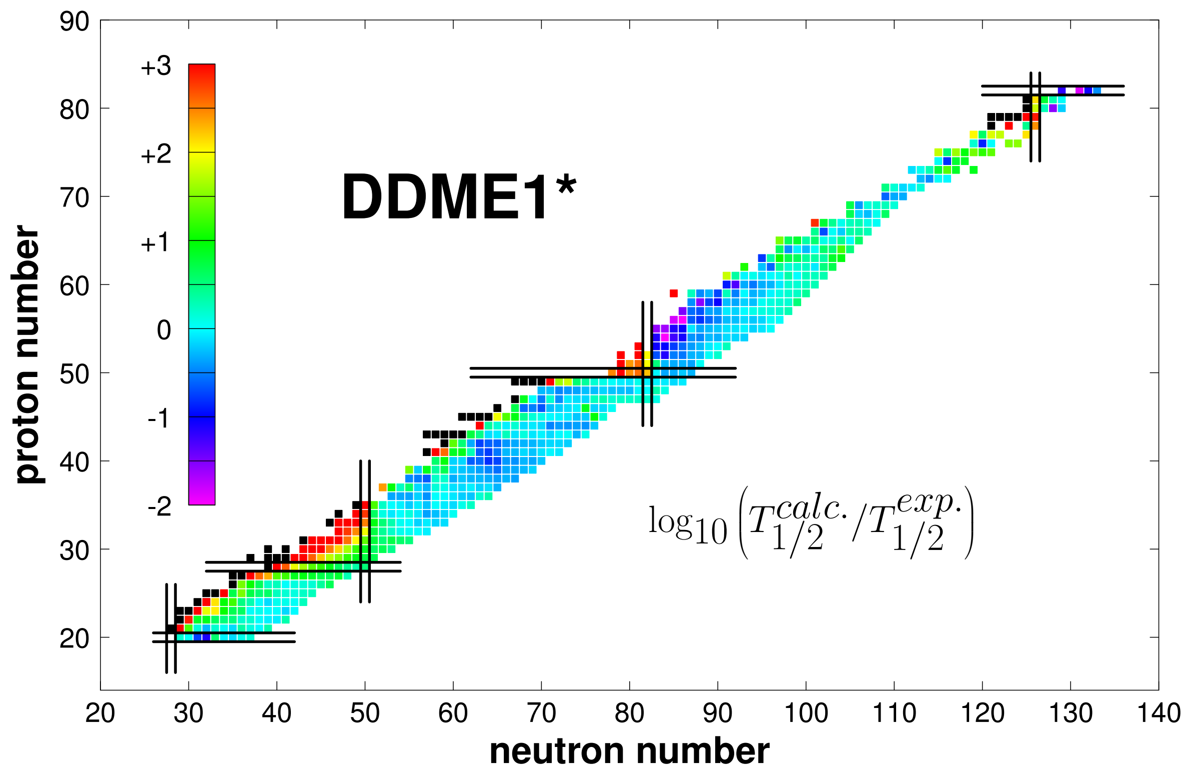

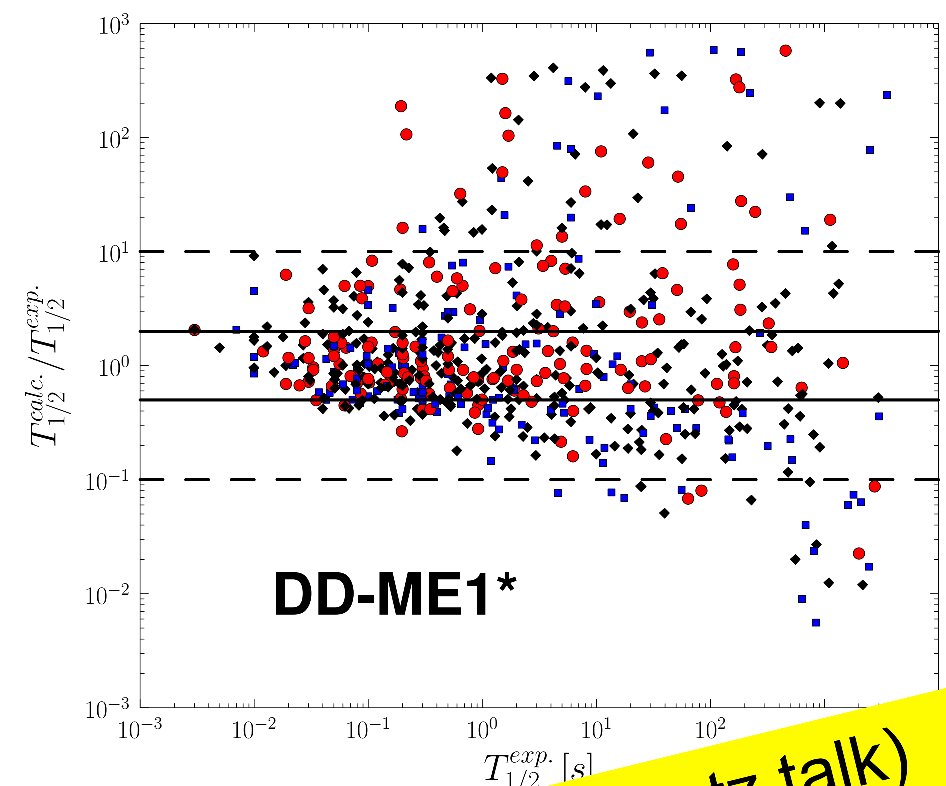

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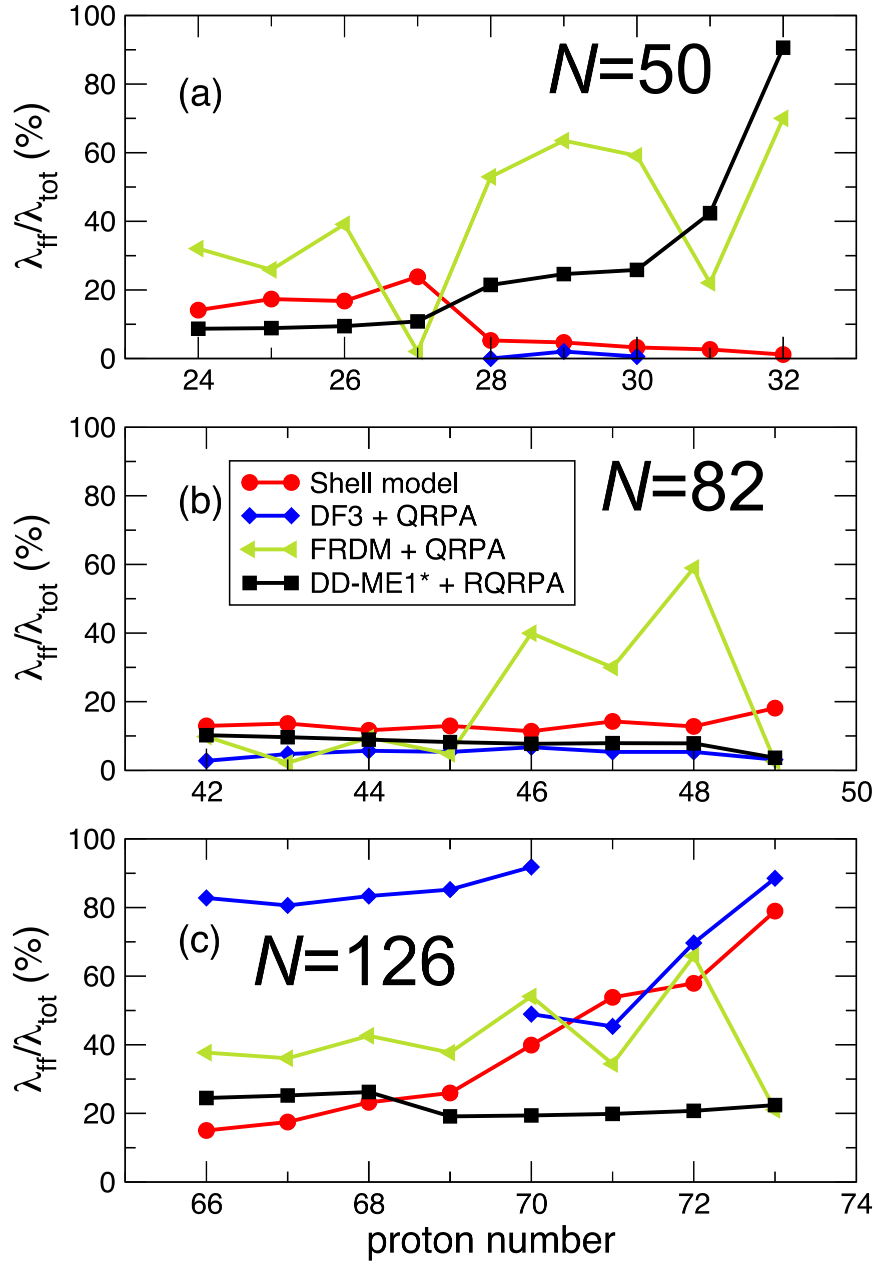
See also Fang and Brown QRPA calculations (see H. Schatz talk)

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 dor CDFT.
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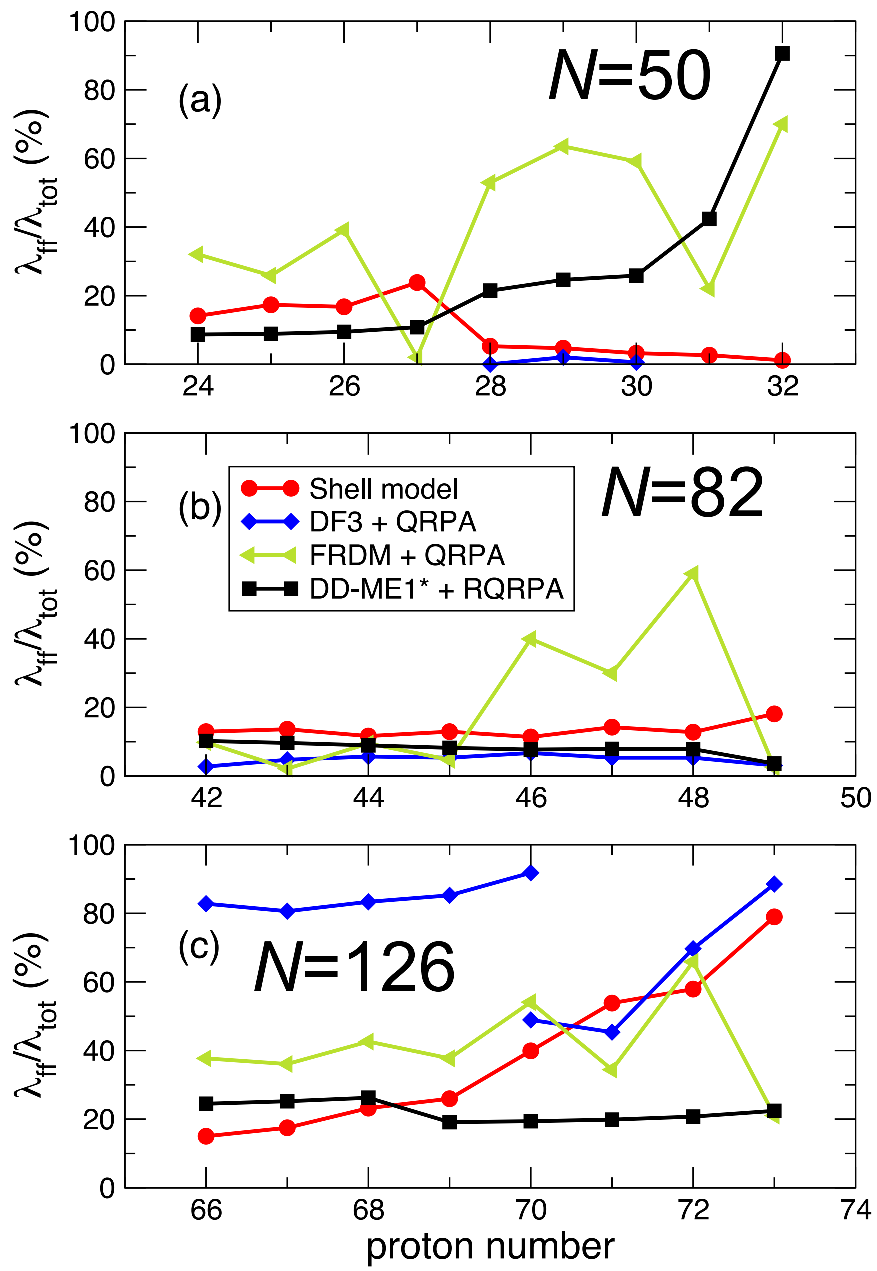

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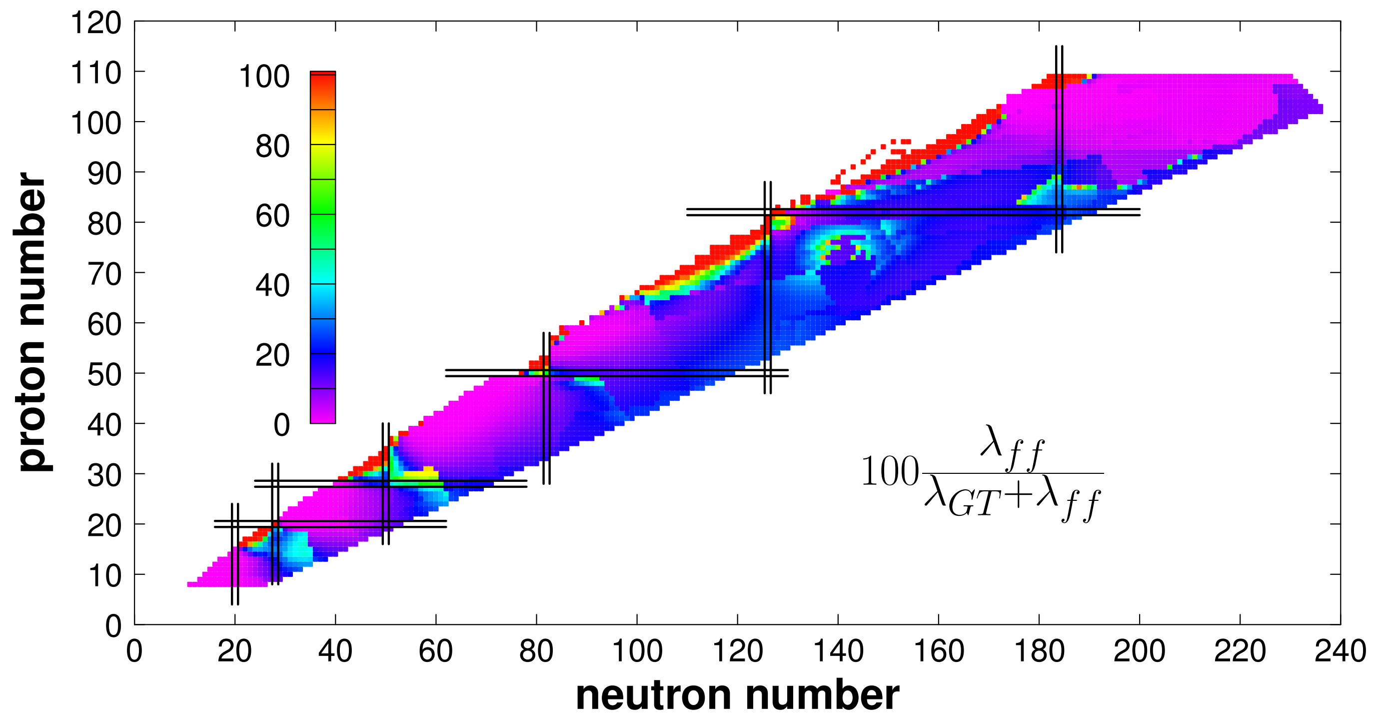
- Systematics of the first forbidden contributions can be performed within the CDFT framework.



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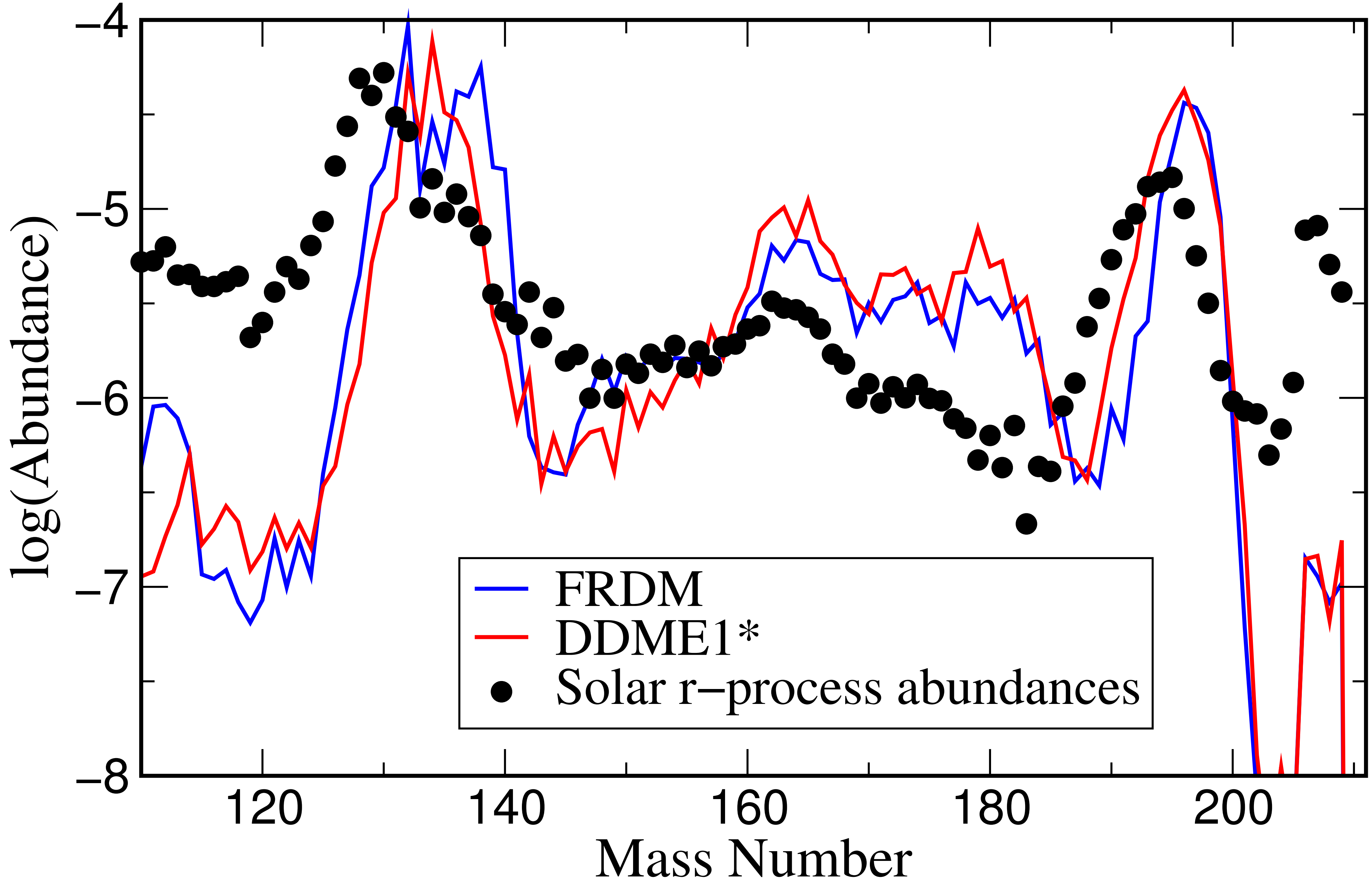
Beta-decay half-lives.
Impact on r-process nucleosynthesis



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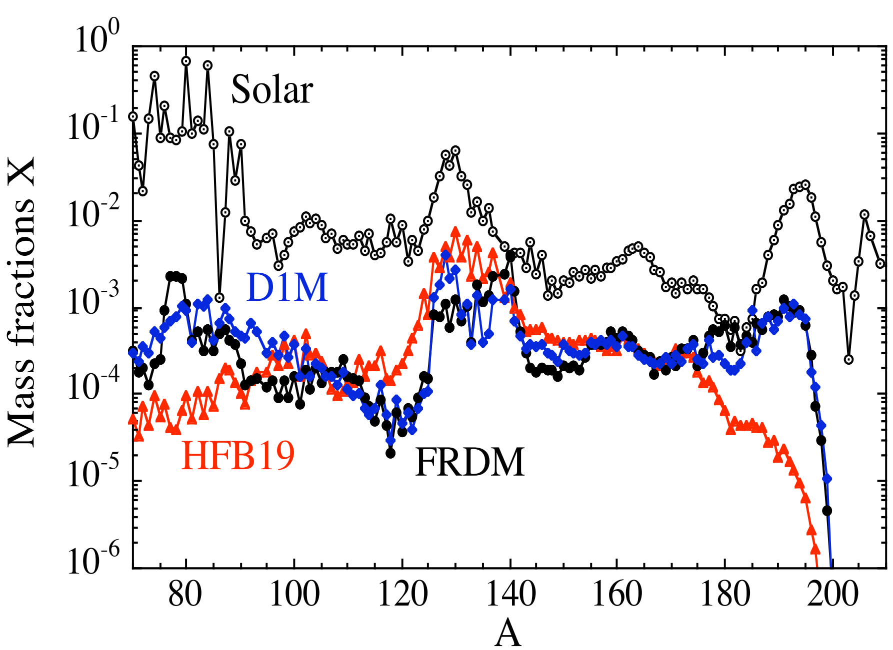
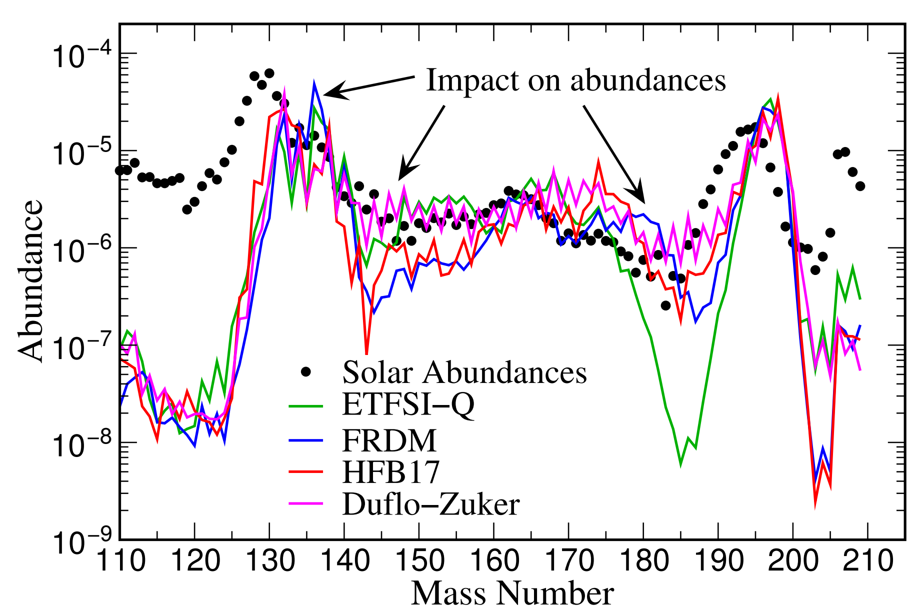
Nuclear masses

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

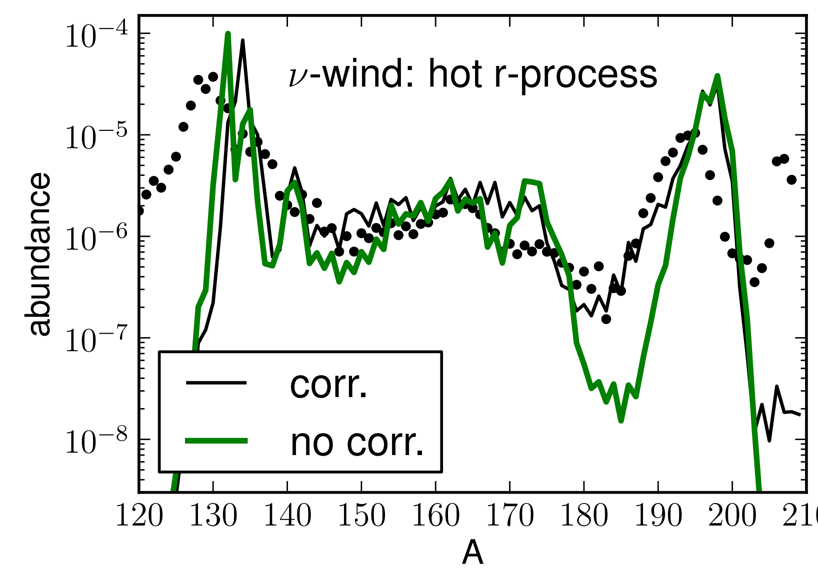
Final abundances depend on the mass model used (for the same astrophysical conditions)



Goriely et al.



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



Arcones and Bertsch, PRL 108, 151101(2012)

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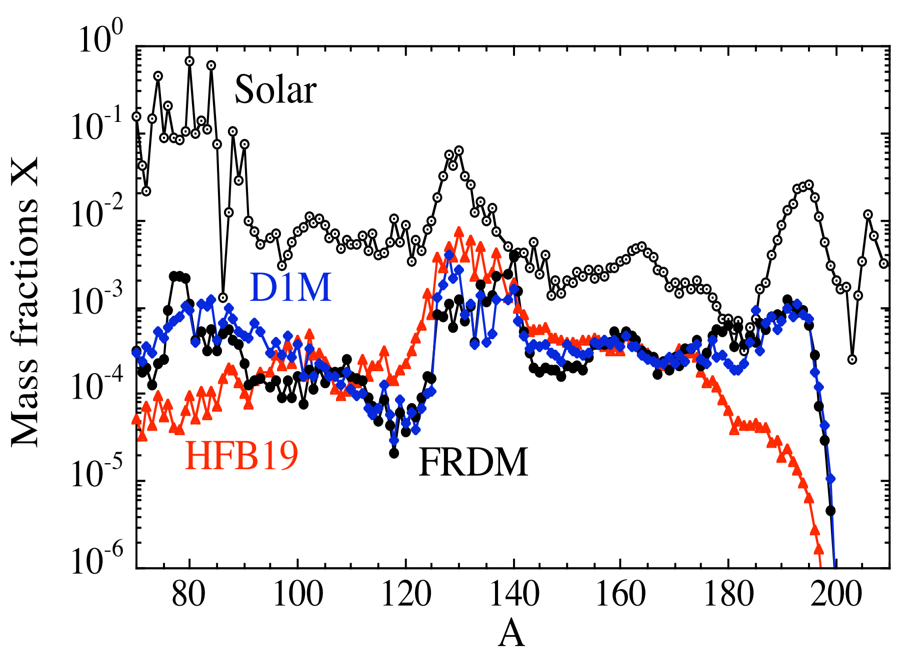

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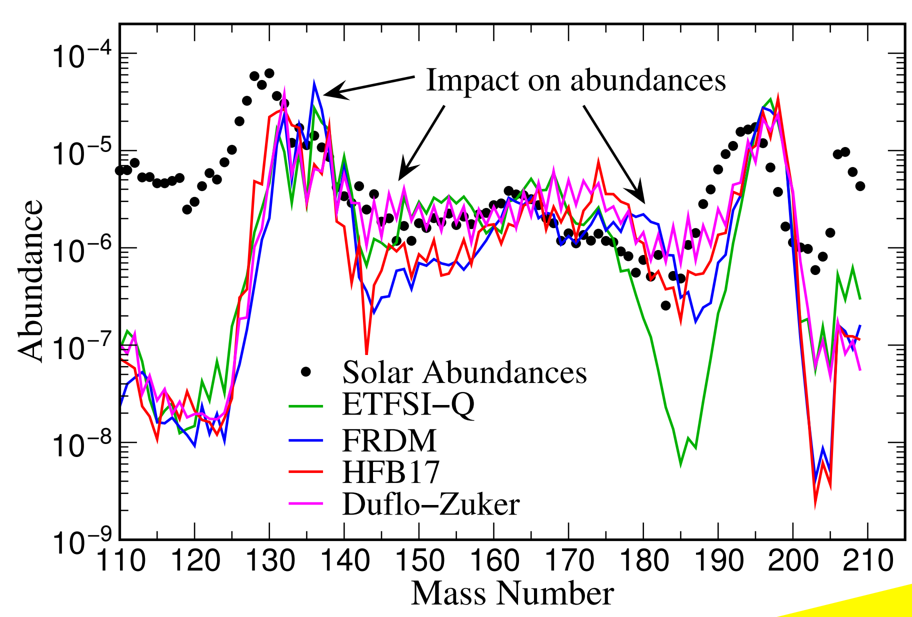

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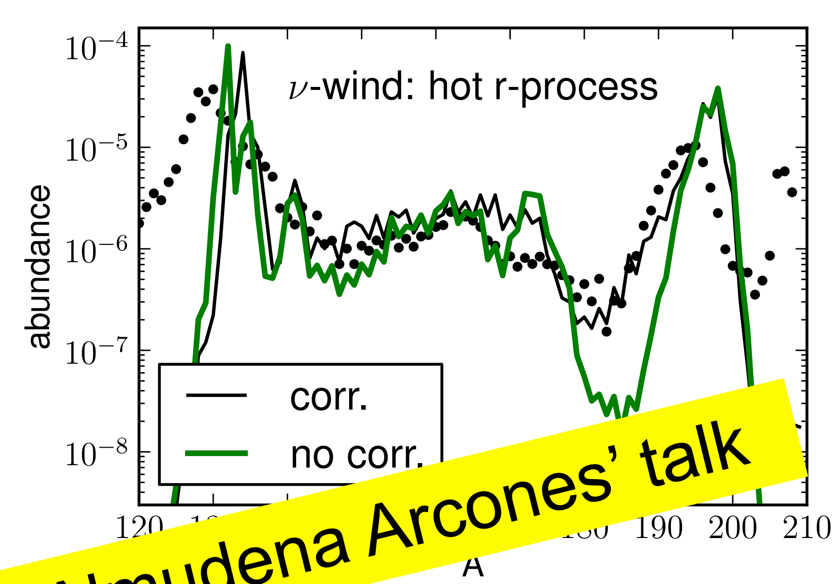

see Almudena Arcones' talk

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Ab-initio nuclear masses

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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)

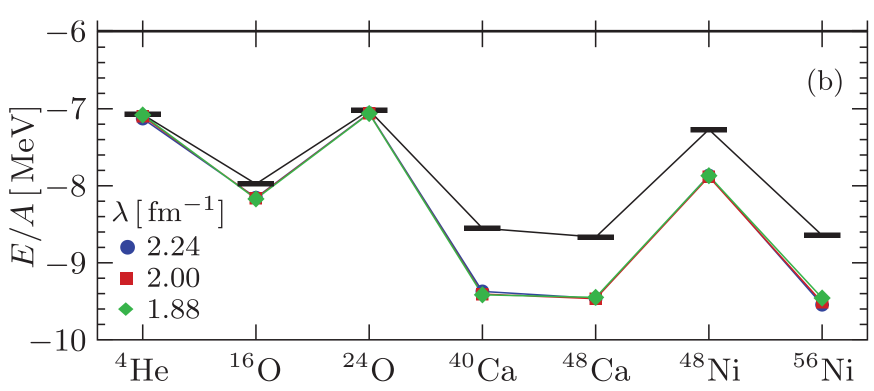
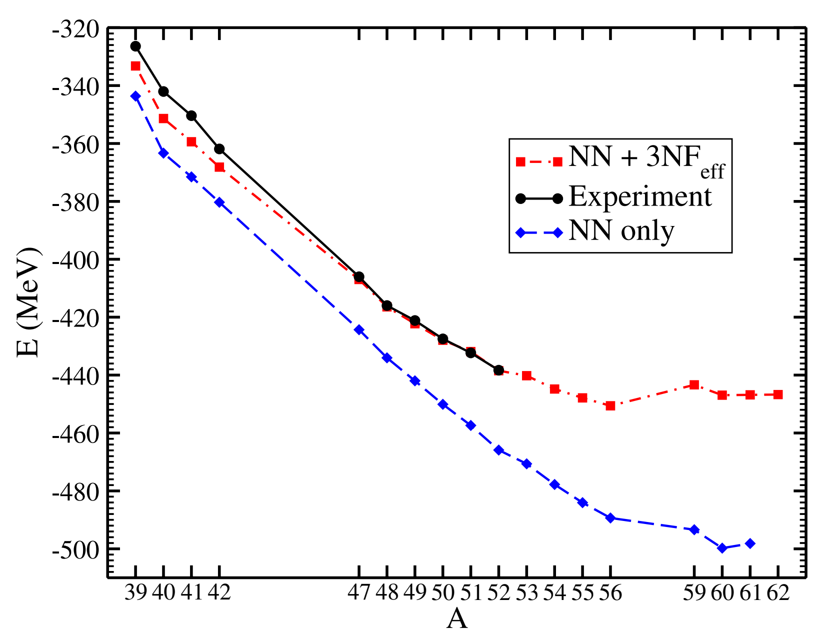
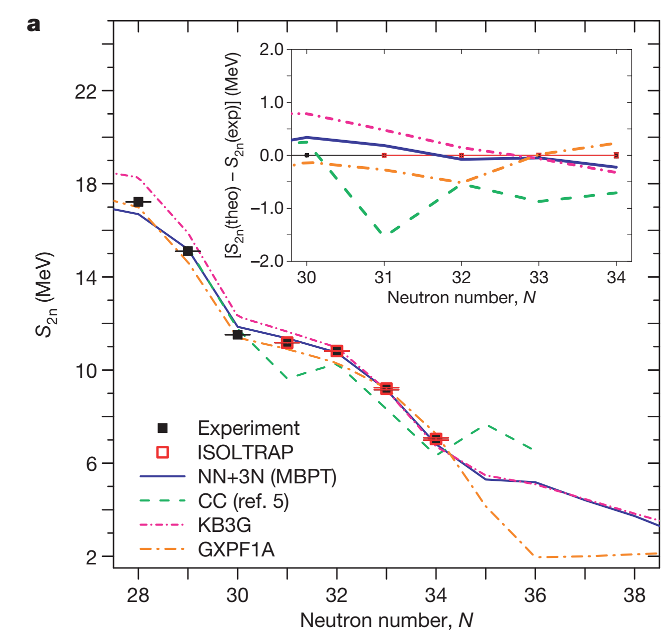


FIG. 7. (Color online) IM-SRG(2) ground-state energy per nucleon of closed-shell nuclei for $NN + 3N$-induced (top) and $NN + 3N$-full Hamiltonians (bottom) at different resolution scales λ. Energies are determined at optimal $\hbar\Omega$ for $e_{\mathrm{Max}} = 14$. Experimental energies (black bars)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

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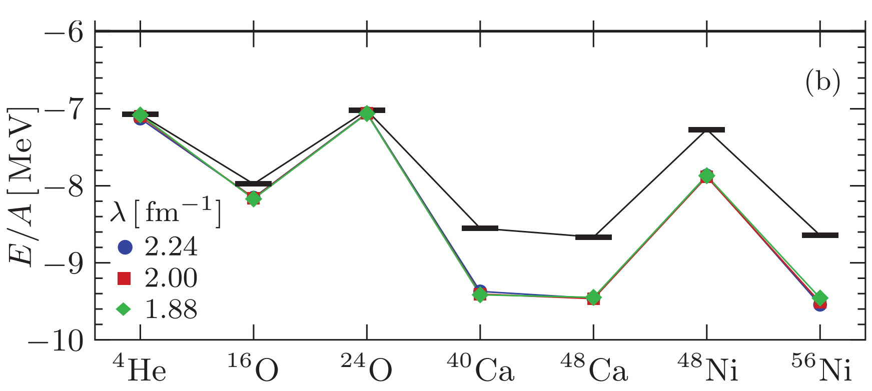

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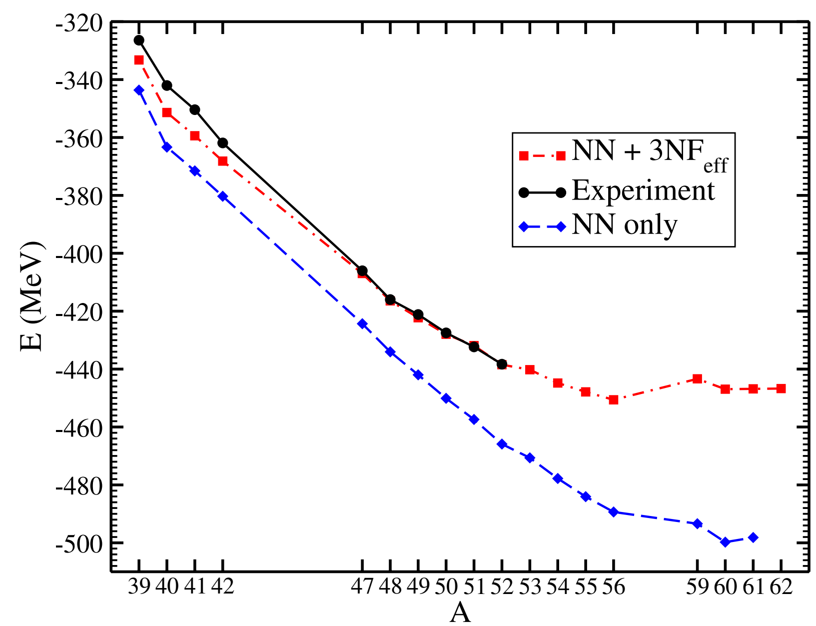

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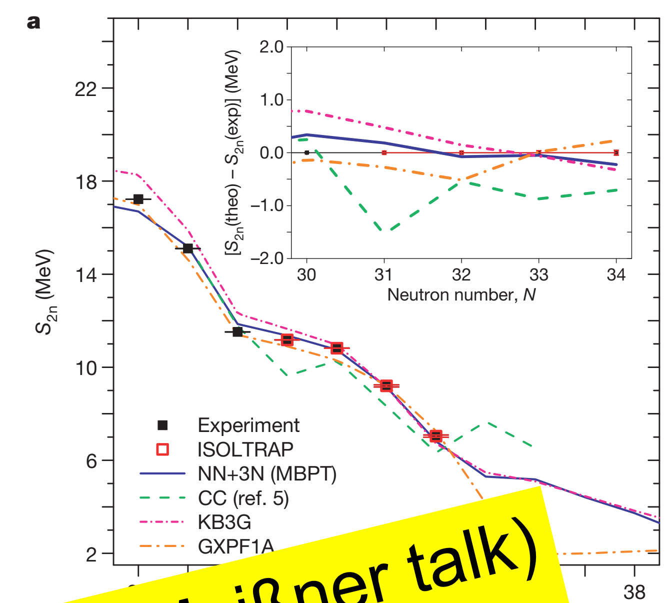

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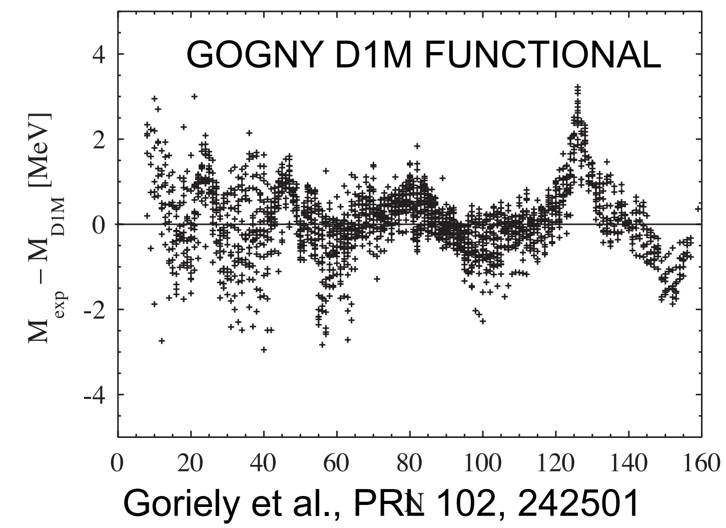
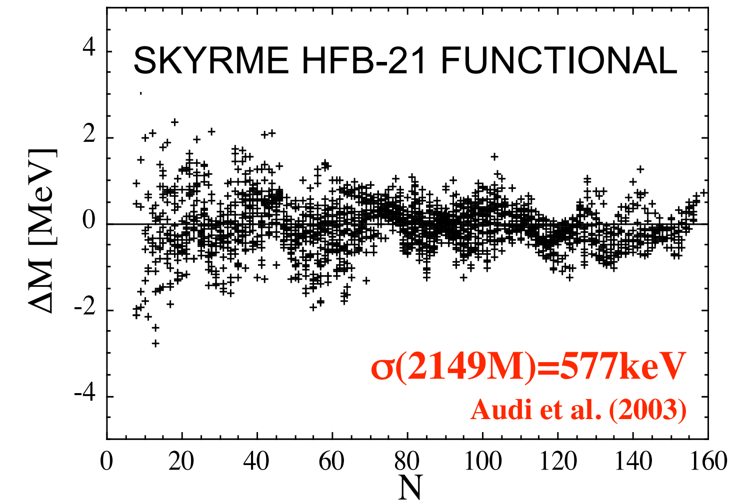
- Nuclear physics calculations on the lattice (see Ulf G. Meißner talk)
- FMD with UCOM (see T. Neff's talk)

Microscopic mass models with effective interactions

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

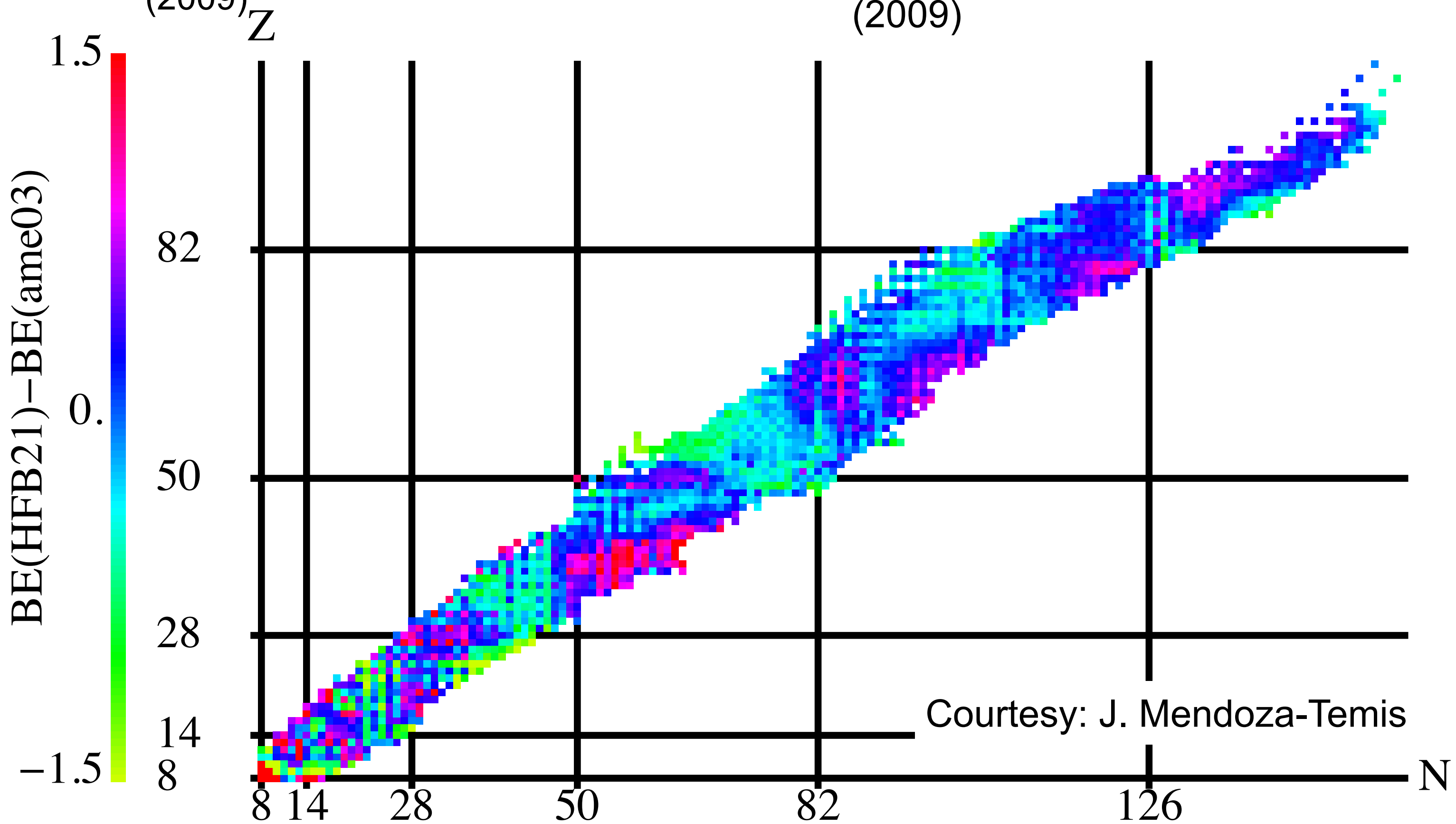


Goriely et al., PRL 102, 242501 (2009)



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



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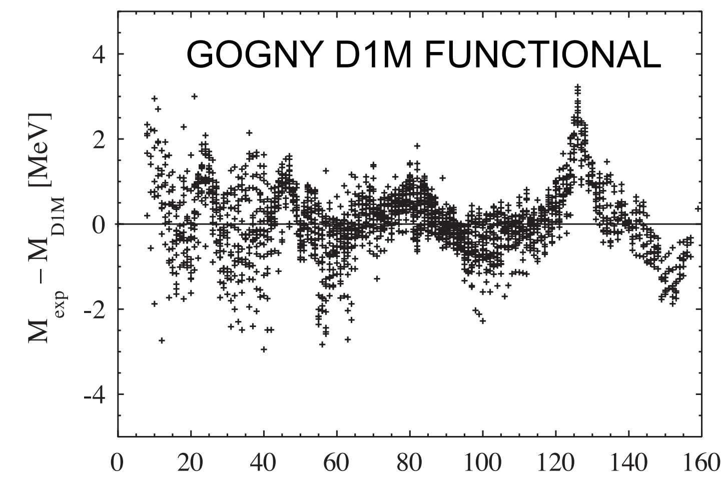

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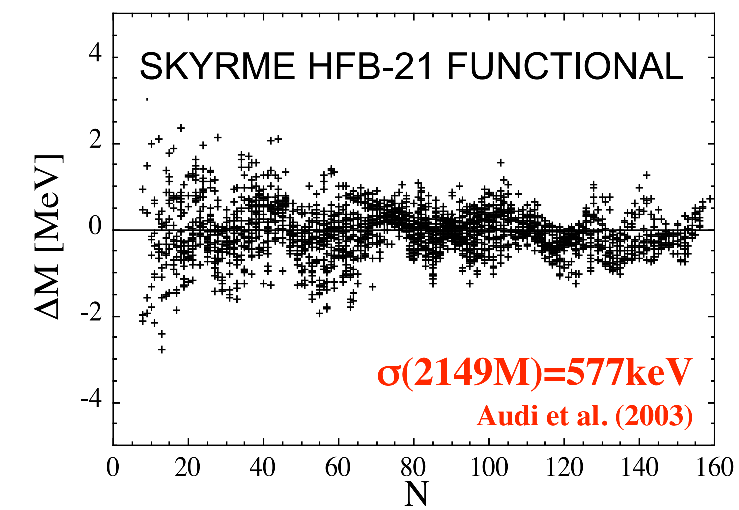

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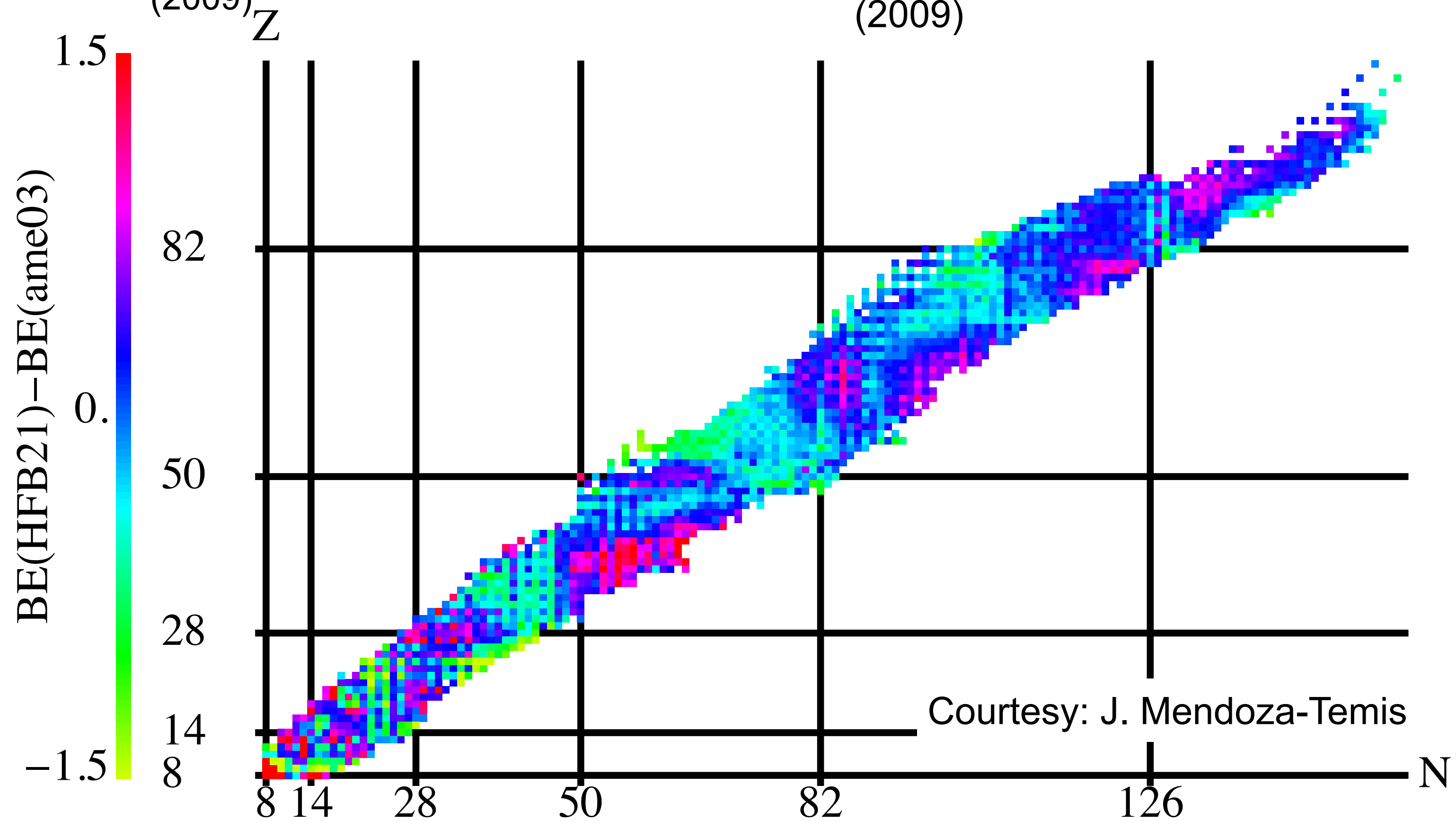

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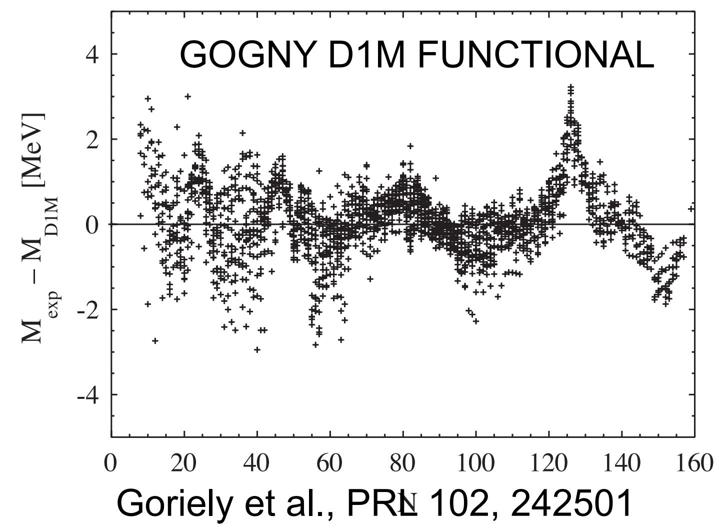

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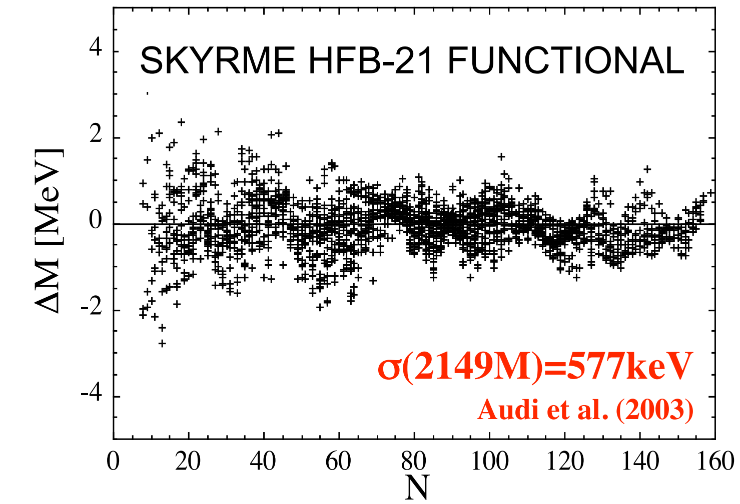

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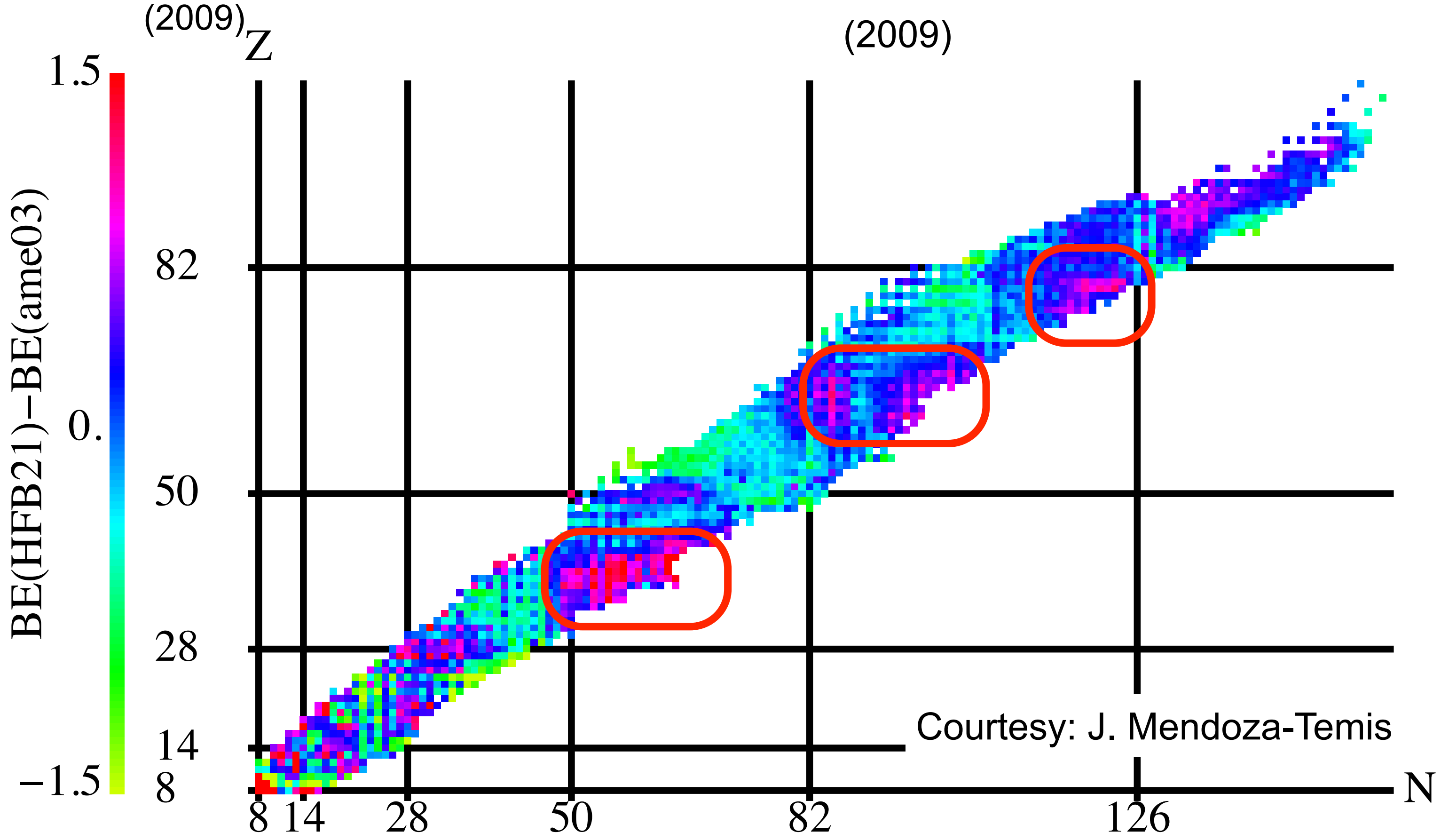

Self-consistent (beyond) mean field description

- **Effective nucleon-nucleon interaction:**

Gogny force (D1S-D1M) that is able to describe properly many phenomena along the whole nuclear chart.

$$V(1,2)=\sum_{i=1}^{2} e^{-(\vec{r}_1-\vec{r}_2)^2/\mu_i^2}\left(W_i+B_iP^\sigma-H_iP^\tau-M_iP^\sigma P^\tau\right)$$
$$+iW_0(\sigma_1+\sigma_2)\vec{k}\times\delta(\vec{r}_1-\vec{r}_2)\vec{k}+t_3(1+x_0P^\sigma)\delta(\vec{r}_1-\vec{r}_2)\rho^\alpha\left((\vec{r}_1+\vec{r}_2)/2\right)$$
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central term

$$+iW_0(\sigma_1+\sigma_2)\vec{k}\times\delta(\vec{r}_1-\vec{r}_2)\vec{k} + t_3(1+x_0P^\sigma)\delta(\vec{r}_1-\vec{r}_2)\rho^\alpha\left((\vec{r}_1+\vec{r}_2)/2\right)$$

spin-orbit term

density-dependent term

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$$+iW_0(\sigma_1+\sigma_2)\vec{k}\times\delta(\vec{r}_1-\vec{r}_2)\vec{k}$$ spin-orbit term

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- **Methods of solving the many-body problem:** **Variational approaches**

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- **Methods of solving the many-body problem:** **Variational approaches**

➡**Parameters of the effective interaction are fitted to reproduce experimental data solving the many-body problem at certain level of approximation (mean field normally).**

Hartree-Fock-Bogoliubov (HFB)

Variational space: $\{|\Phi(\vec{q})\rangle\}$ set of **product-type** wave functions which fulfill:

- Quasiparticle vacua: $$\alpha_k(\vec{q})|\Phi(\vec{q})\rangle = 0$$
- Most general linear combination of the arbitrary single particle basis: $$\alpha_k^\dagger(\vec{q}) = \sum_l U_{lk}(\vec{q})c_l^\dagger + V_{lk}(\vec{q})c_l$$
- Fermionic operators: $$\{\alpha_k^\dagger(\vec{q}), \alpha_{k'}(\vec{q})\} = \delta_{kk'}; \{\alpha_k^\dagger(\vec{q}), \alpha_{k'}^\dagger(\vec{q})\} = \{\alpha_k(\vec{q}), \alpha_{k'}(\vec{q})\} = 0$$

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Variational principle: $\delta\left[E'^{\mathrm{HFB}}(\vec{q}) = \langle\Phi(\vec{q})|\hat{H} - \lambda_N\hat{N} - \lambda_Z\hat{Z} - \vec{\lambda}_{\vec{q}}\hat{\vec{Q}}|\Phi(\vec{q})\rangle\right]_{|\Phi(\vec{q})\rangle = |\mathrm{HFB}(\vec{q})\rangle} = 0$

$\lambda_N(\vec{q}) \rightarrow \langle\Phi(\vec{q})|\hat{N}|\Phi(\vec{q})\rangle = N$

$\lambda_Z(\vec{q}) \rightarrow \langle\Phi(\vec{q})|\hat{Z}|\Phi(\vec{q})\rangle = Z$

$\lambda_{\vec{q}}(\vec{q}) \rightarrow \langle\Phi(\vec{q})|\hat{\vec{Q}}|\Phi(\vec{q})\rangle = \vec{q}$

Self-consistent mean field in a nutshell

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$\lambda_Z(\vec{q}) \rightarrow \langle\Phi(\vec{q})|\hat{Z}|\Phi(\vec{q})\rangle = Z$

$\lambda_{\vec{q}}(\vec{q}) \rightarrow \langle\Phi(\vec{q})|\hat{\vec{Q}}|\Phi(\vec{q})\rangle = \vec{q}$

$$E^{\mathrm{HFB}}(\vec{q}) = \langle\Phi(\vec{q})|\hat{H}|\Phi(\vec{q})\rangle$$

$|\mathrm{HFB}(\vec{q})\rangle$ **Product Type**

Hartree-Fock-Bogoliubov (HFB)

Variational space: $\{|\Phi(\vec{q})\rangle\}$ set of **product-type** wave functions which fulfill:

- Quasiparticle vacua: $$\alpha_k(\vec{q})|\Phi(\vec{q})\rangle = 0$$

- Most general linear combination of the arbitrary single particle basis: $$\alpha_k^\dagger(\vec{q}) = \sum_l U_{lk}(\vec{q})c_l^\dagger + V_{lk}(\vec{q})c_l$$

1. finite basis!! convergence?

- Fermionic operators: $$\{\alpha_k^\dagger(\vec{q}), \alpha_{k'}(\vec{q})\} = \delta_{kk'}; \{\alpha_k^\dagger(\vec{q}), \alpha_{k'}^\dagger(\vec{q})\} = \{\alpha_k(\vec{q}), \alpha_{k'}(\vec{q})\} = 0$$

Variational principle: $$\delta\left[E'^{\mathrm{HFB}}(\vec{q}) = \langle\Phi(\vec{q})|\hat{H} - \lambda_N\hat{N} - \lambda_Z\hat{Z} - \vec{\lambda}_{\vec{q}}\hat{\vec{Q}}|\Phi(\vec{q})\rangle\right]_{|\Phi(\vec{q})\rangle = |\mathrm{HFB}(\vec{q})\rangle} = 0$$

$$\lambda_N(\vec{q}) \to \langle\Phi(\vec{q})|\hat{N}|\Phi(\vec{q})\rangle = N$$

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Self-consistent mean field in a nutshell

TECHNISCHE UNIVERSITÄT DARMSTADT

Hartree-Fock-Bogoliubov (HFB)

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1. finite basis!! convergence?

2. Breaks the symmetries!!

Variational principle: $\delta\left[E'^{\mathrm{HFB}}(\vec{q}) = \langle\Phi(\vec{q})|\hat{H} - \lambda_N\hat{N} - \lambda_Z\hat{Z} - \vec{\lambda}_{\vec{q}}\hat{\vec{Q}}|\Phi(\vec{q})\rangle\right]_{|\Phi(\vec{q})\rangle = |\mathrm{HFB}(\vec{q})\rangle} = 0$

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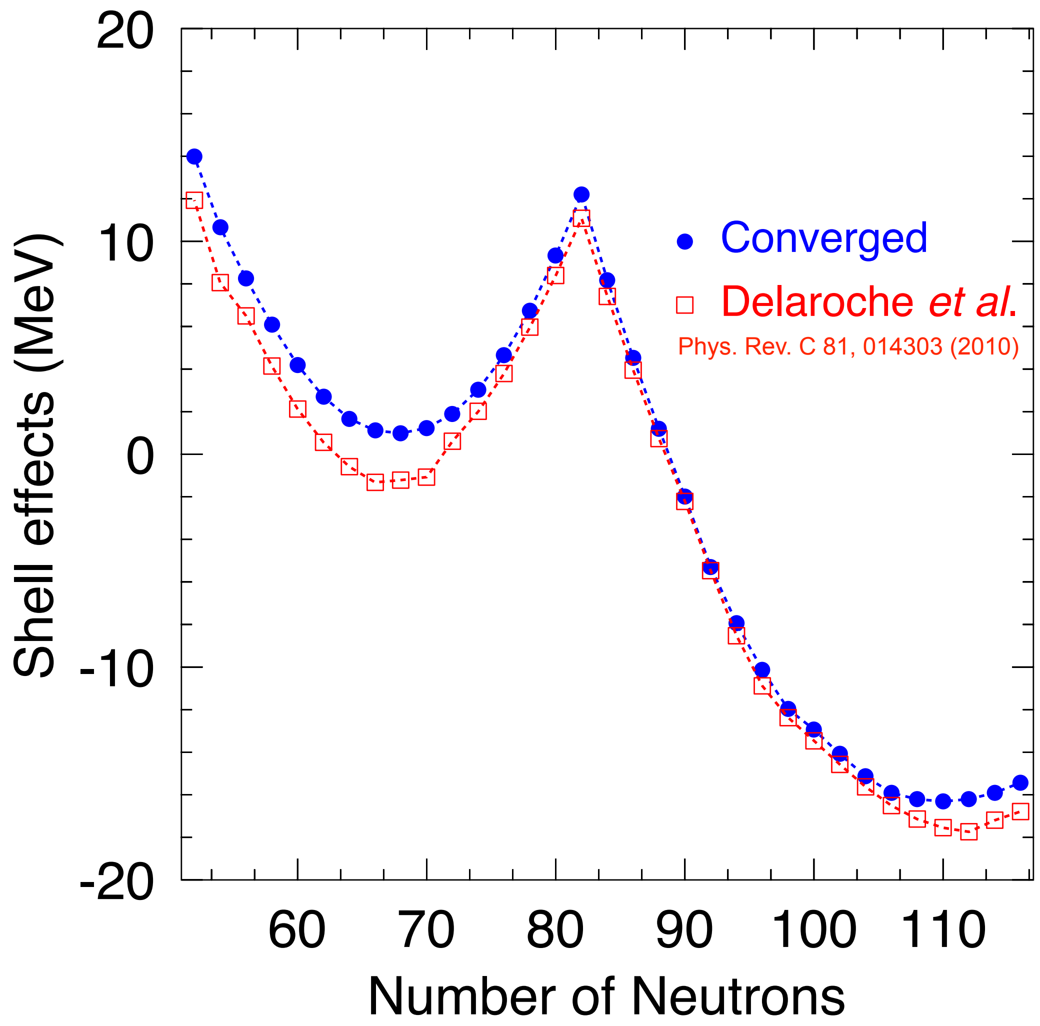
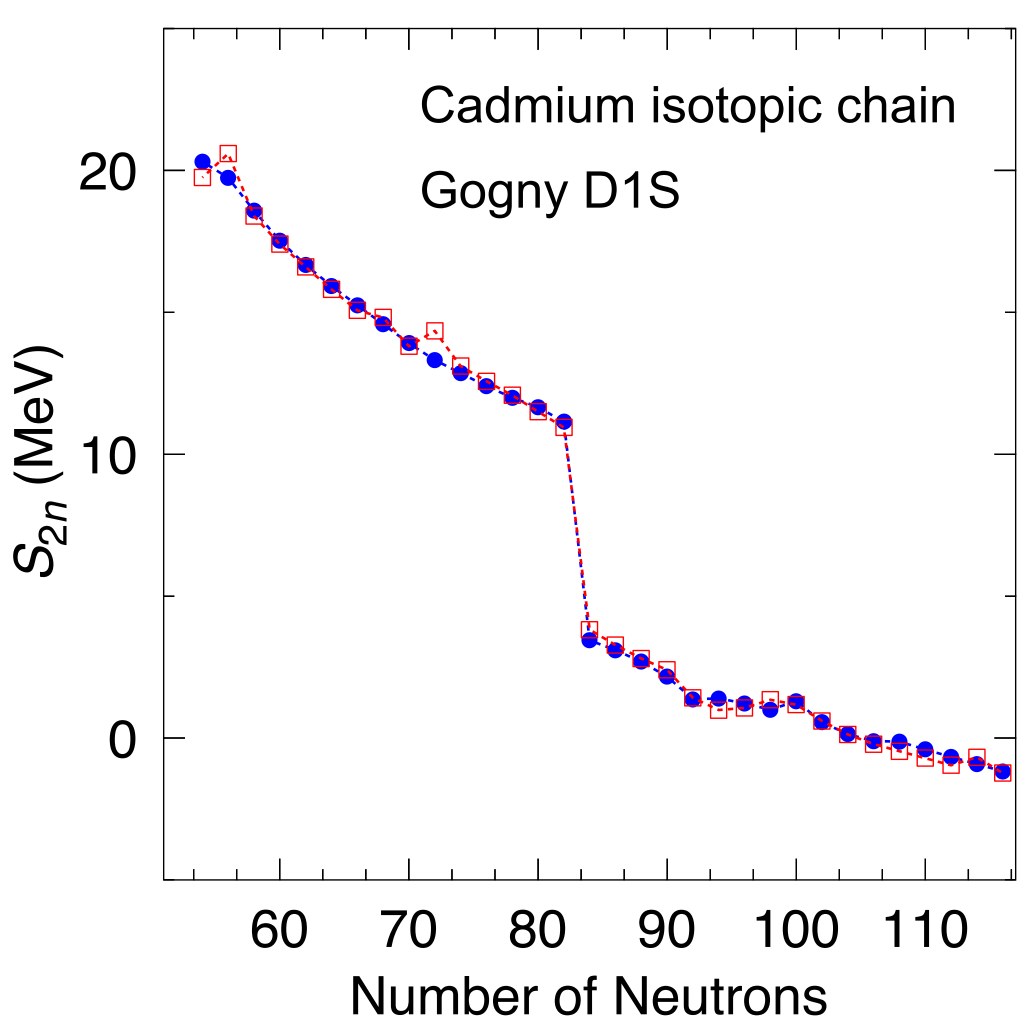
Convergence

- Published tables could contain some lack of convergence in the total binding energy.
- Two neutron separation energies are better converged.
- Artificial ‘jumps’ or ‘noise’ could appear in the S_{2n} due to lack of convergence.





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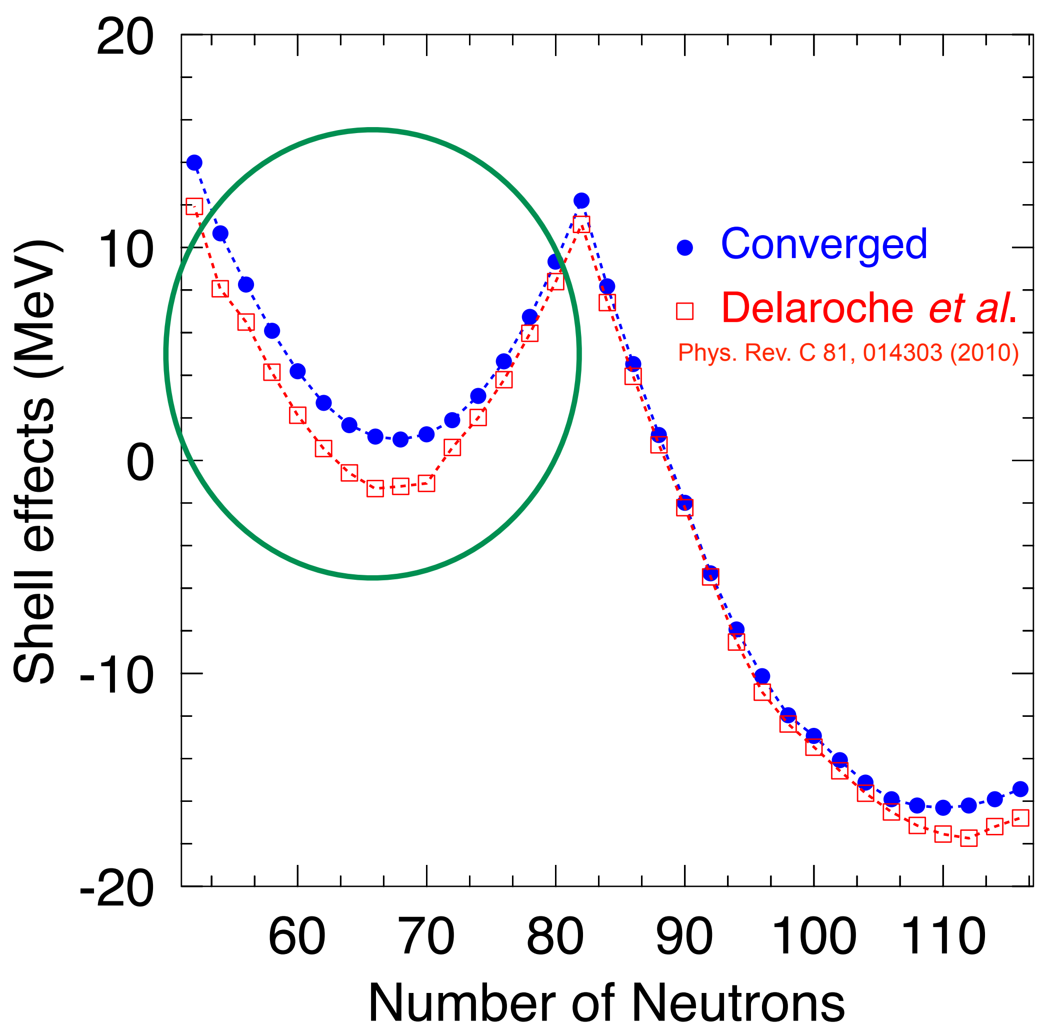

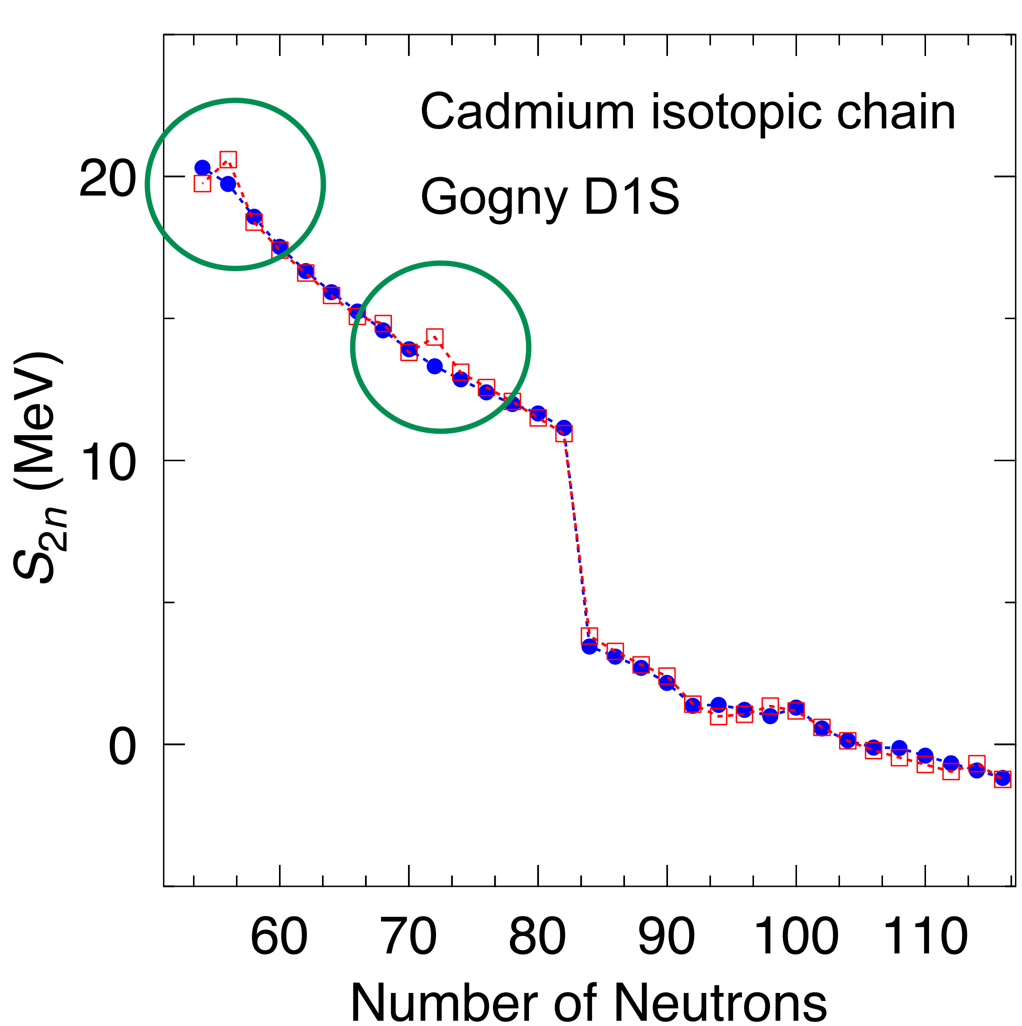

Convergence

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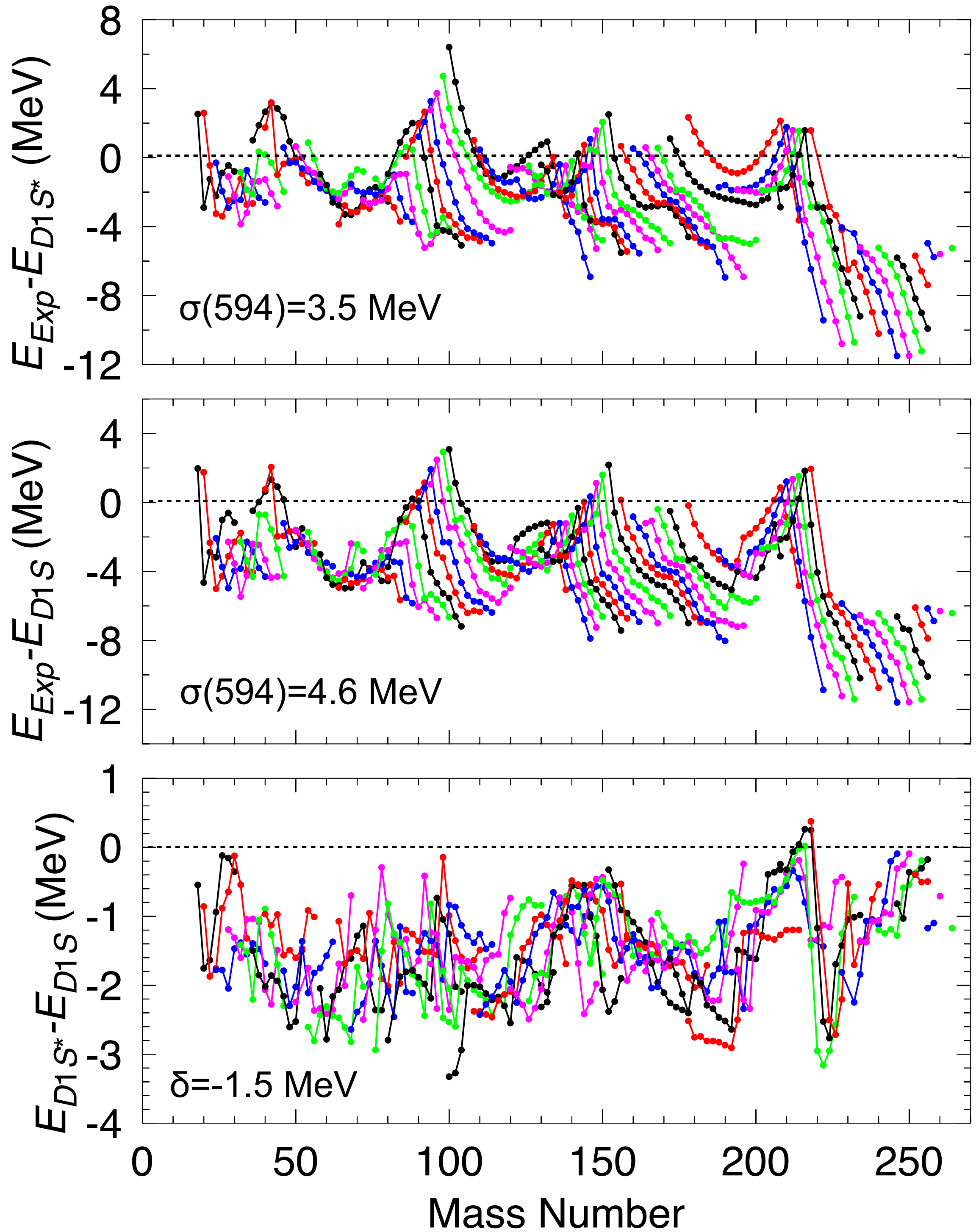


- Experimental data: AME12, only even-even.
- Gogny D1S: Delaroche et al., PRC 81, 014303 (2010).
- Gogny D1S*: N_{osc}=18, b optimized, β_2 explored.

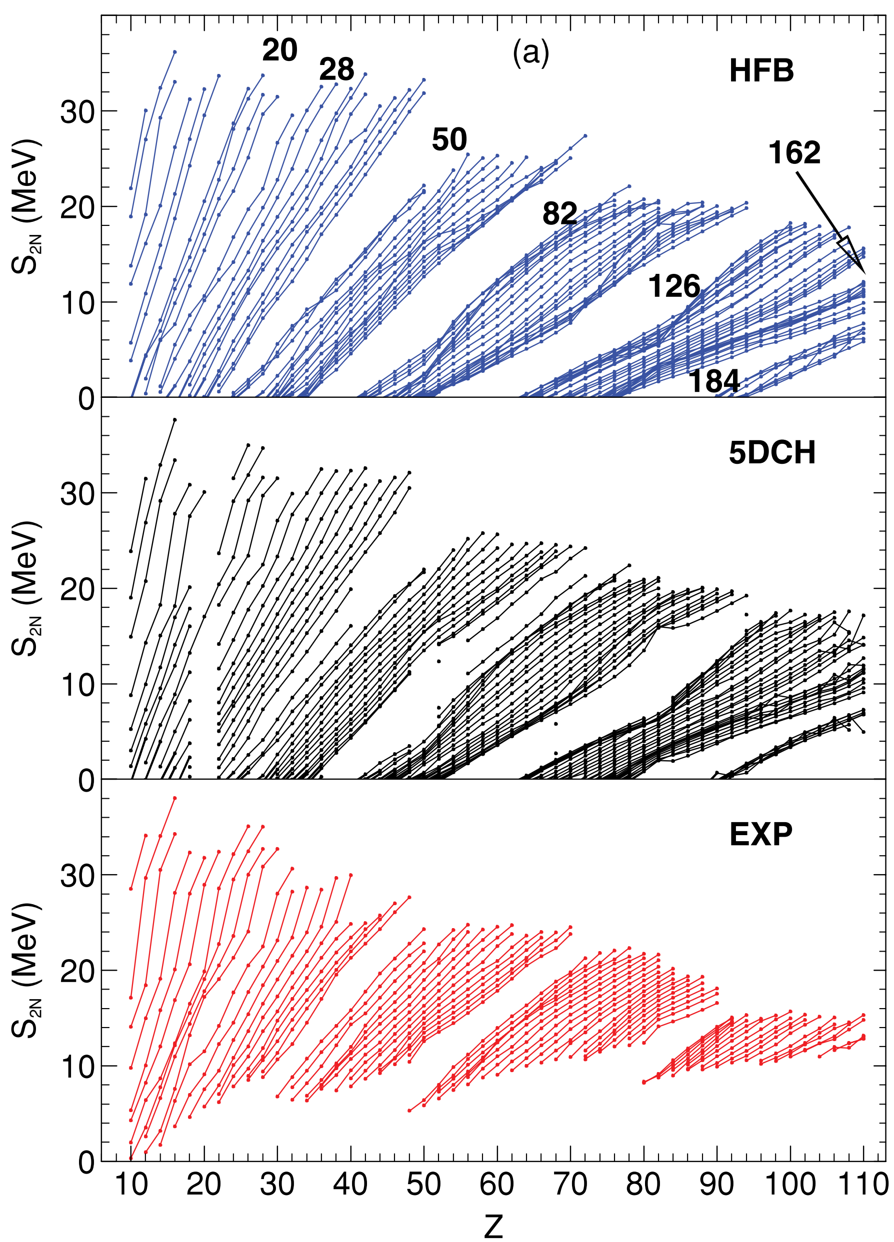
- Gogny D1S **is not** a good parametrization for masses (overbinding of double magic nuclei, underbinding of neutron rich nuclei, poor r.m.s.).

- Better convergence gives smaller r.m.s. and smoother behavior along the whole AME12 even-even data.
- ~1.5 MeV average gain in energy by improving the convergence.

A. Arzhanov, Master Thesis

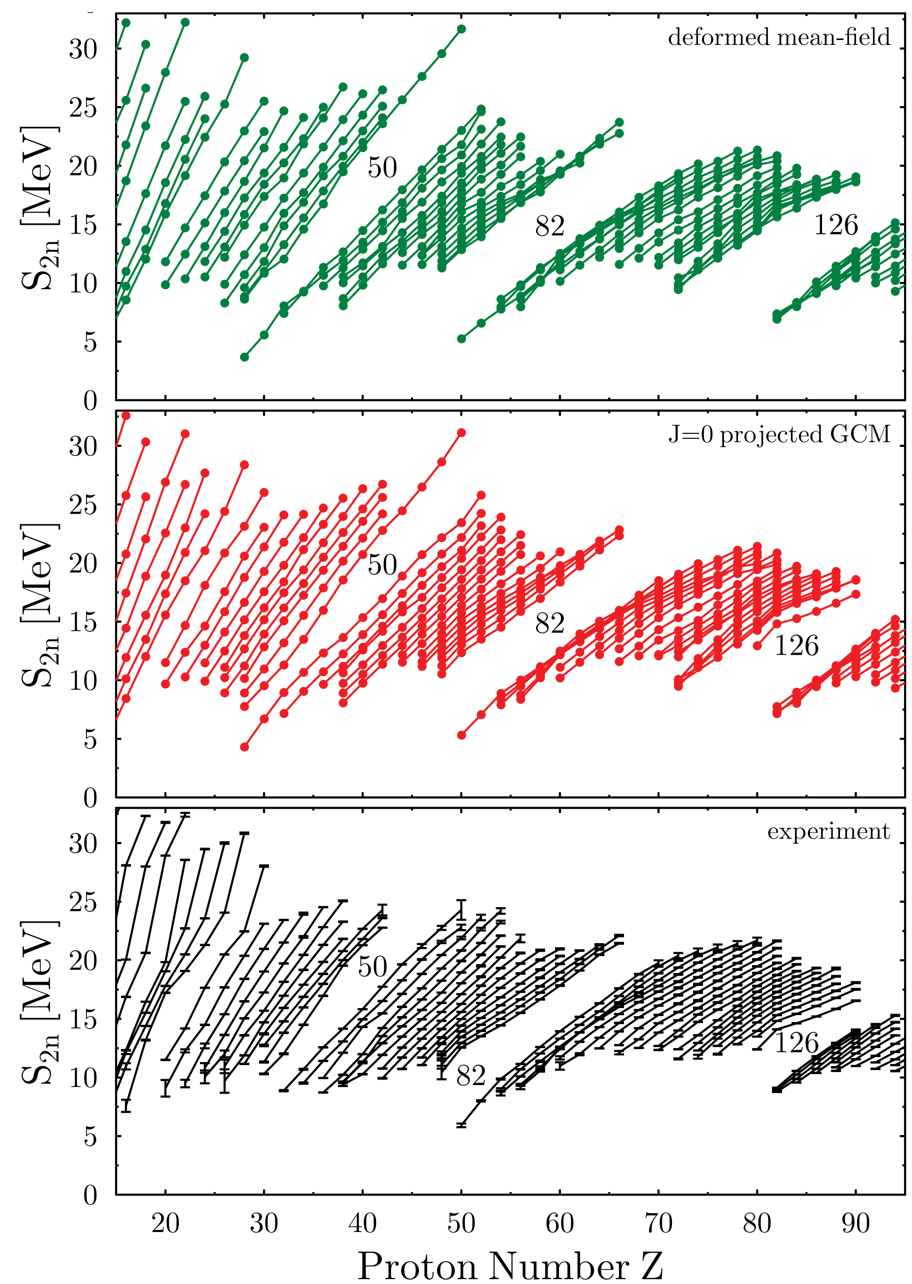
Mean field vs. Beyond mean field. Global systematics

Gogny D1S



Delaroche et al. PRC 81, 014303 (2010)

Skyrme SLy4

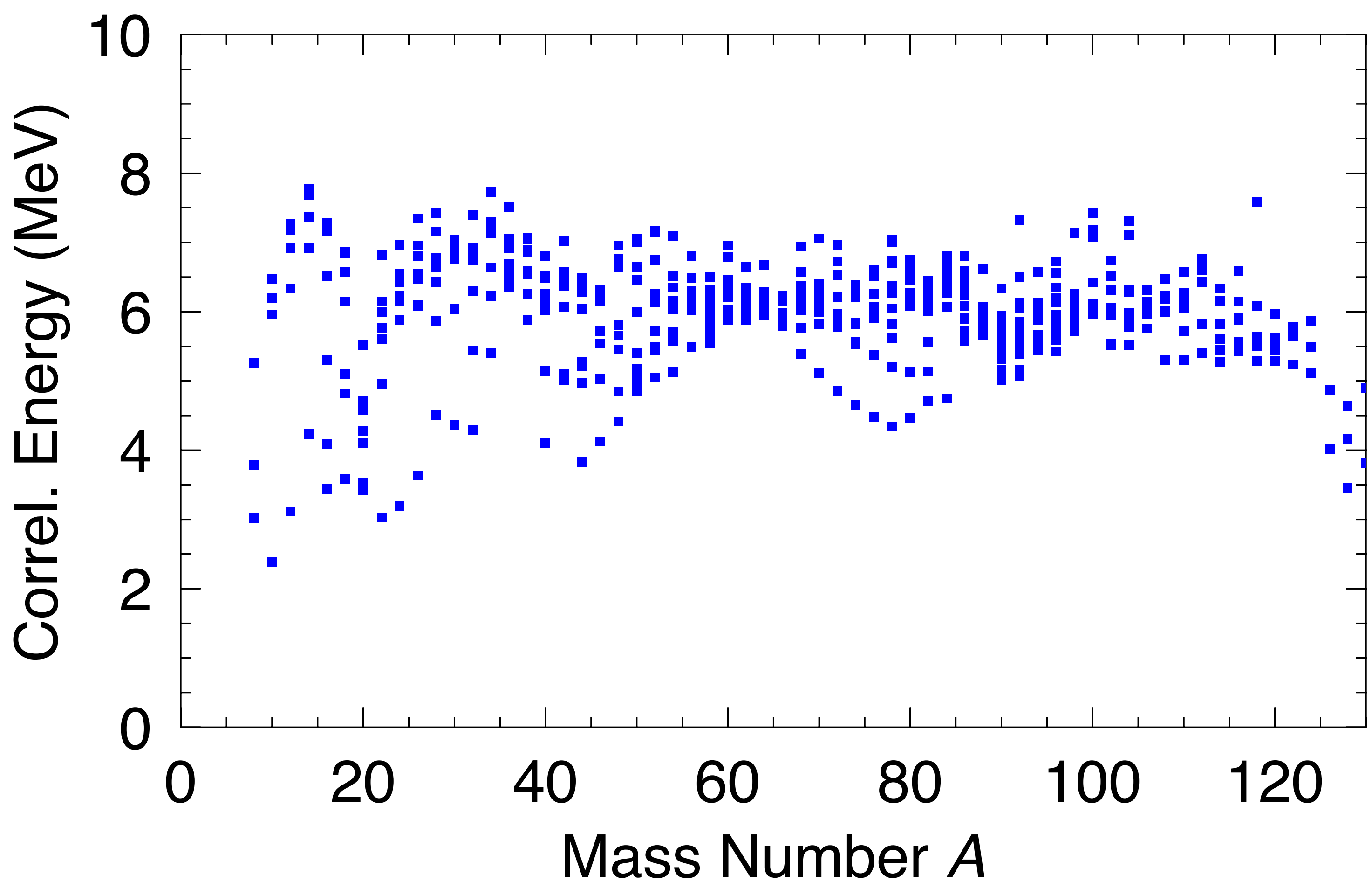


Bender et al., PRC 73, 034322 (2006)

- No **exact** projections/GCM but gaussian overlap approximations (GOA) are used: they are not variational
- Beyond mean field effects tend to reduce the shell gaps
- Separation energies are smoother when beyond mean field are included.

Mean field vs. Beyond mean field. Global systematics

Gogny D1S ~75000 h CPU time @GSI and @CSC-LOEWE



- **Exact** particle number (VAP) and angular momentum projections + **exact** GCM: there is always energy gain w.r.t. the mean field.

T. R. Rodríguez, A. Arzhanov, G. Martínez-Pinedo, in preparation

Mean field vs. Beyond mean field. Global systematics

TECHNISCHE UNIVERSITÄT DARMSTADT

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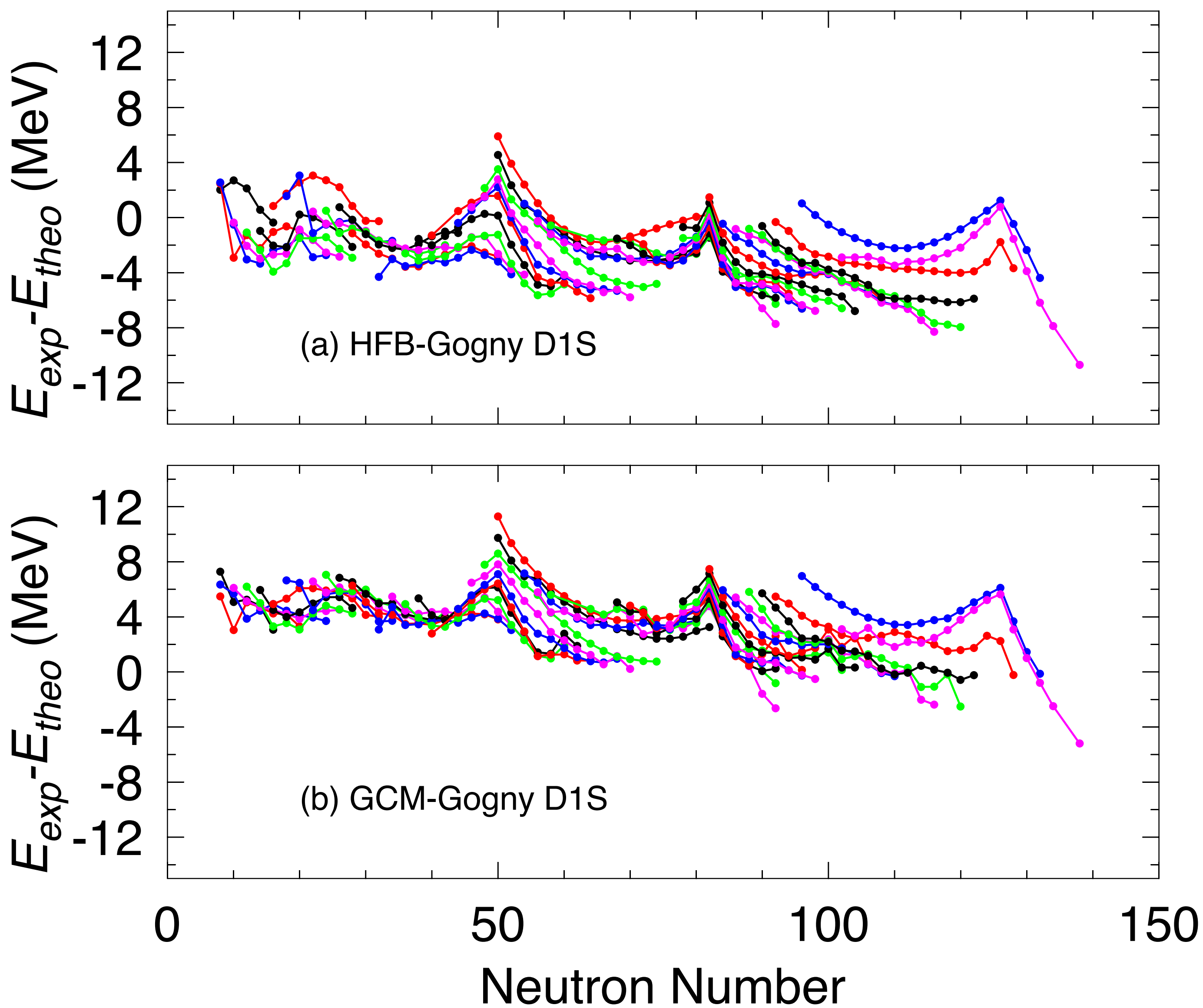

- **Exact** particle number (VAP) and angular momentum projections + **exact** GCM: there is always energy gain w.r.t. the mean field.

- BMF effects reduces the spread of the data, specially in the light nuclei

T. R. Rodríguez, A. Arzhanov, G. Martínez-Pinedo, in preparation

Mean field vs. Beyond mean field. Global systematics

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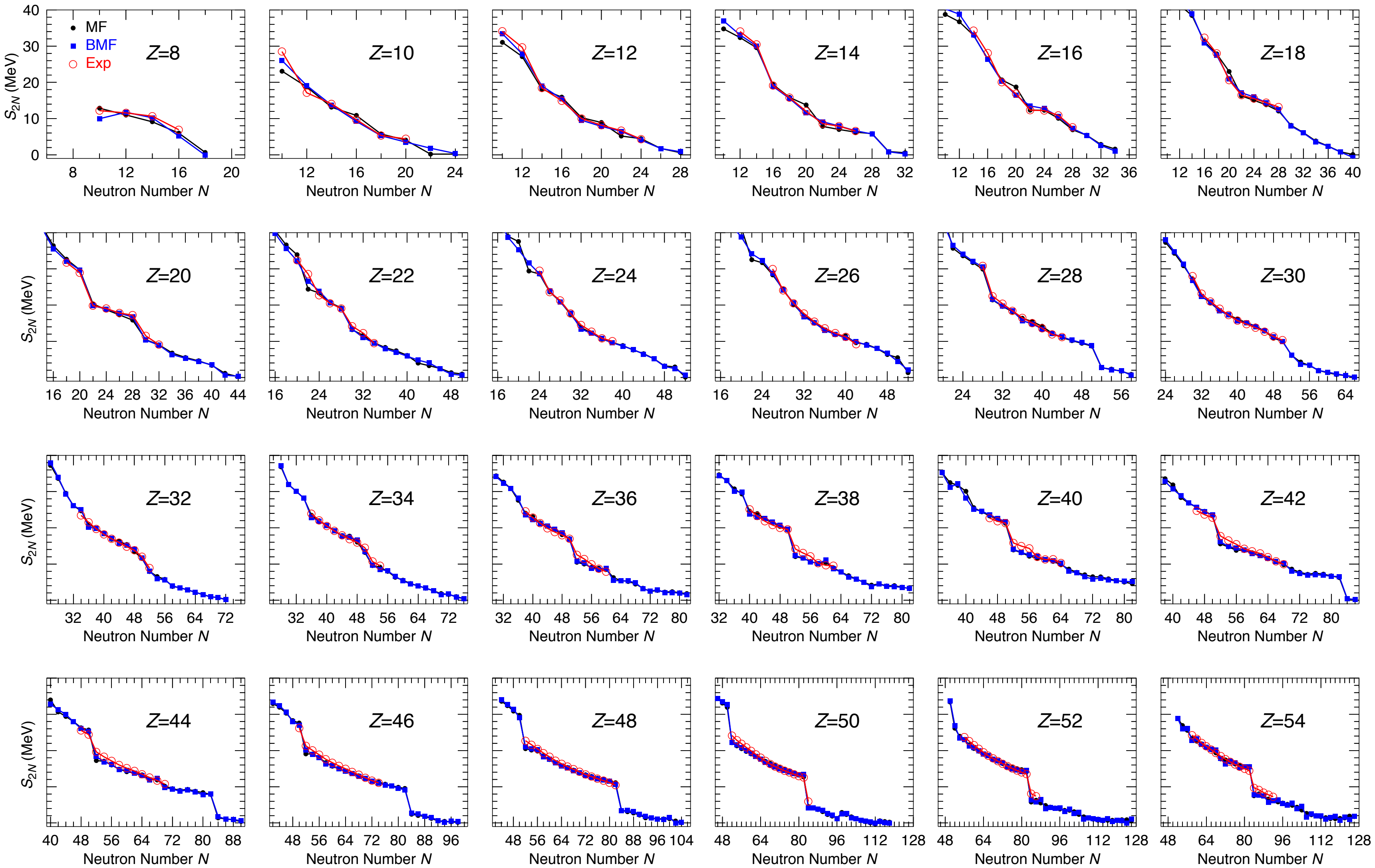

- **Exact** particle number (VAP) and angular momentum projections + **exact** GCM: there is always energy gain w.r.t. the mean field.
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- BMF and MF separation energies are rather similar (a bit smoother and in better agreement with data when BMF effects are included).

T. R. Rodríguez, A. Arzhanov, G. Martínez-Pinedo, in preparation

Mean field vs. Beyond mean field. Global systematics

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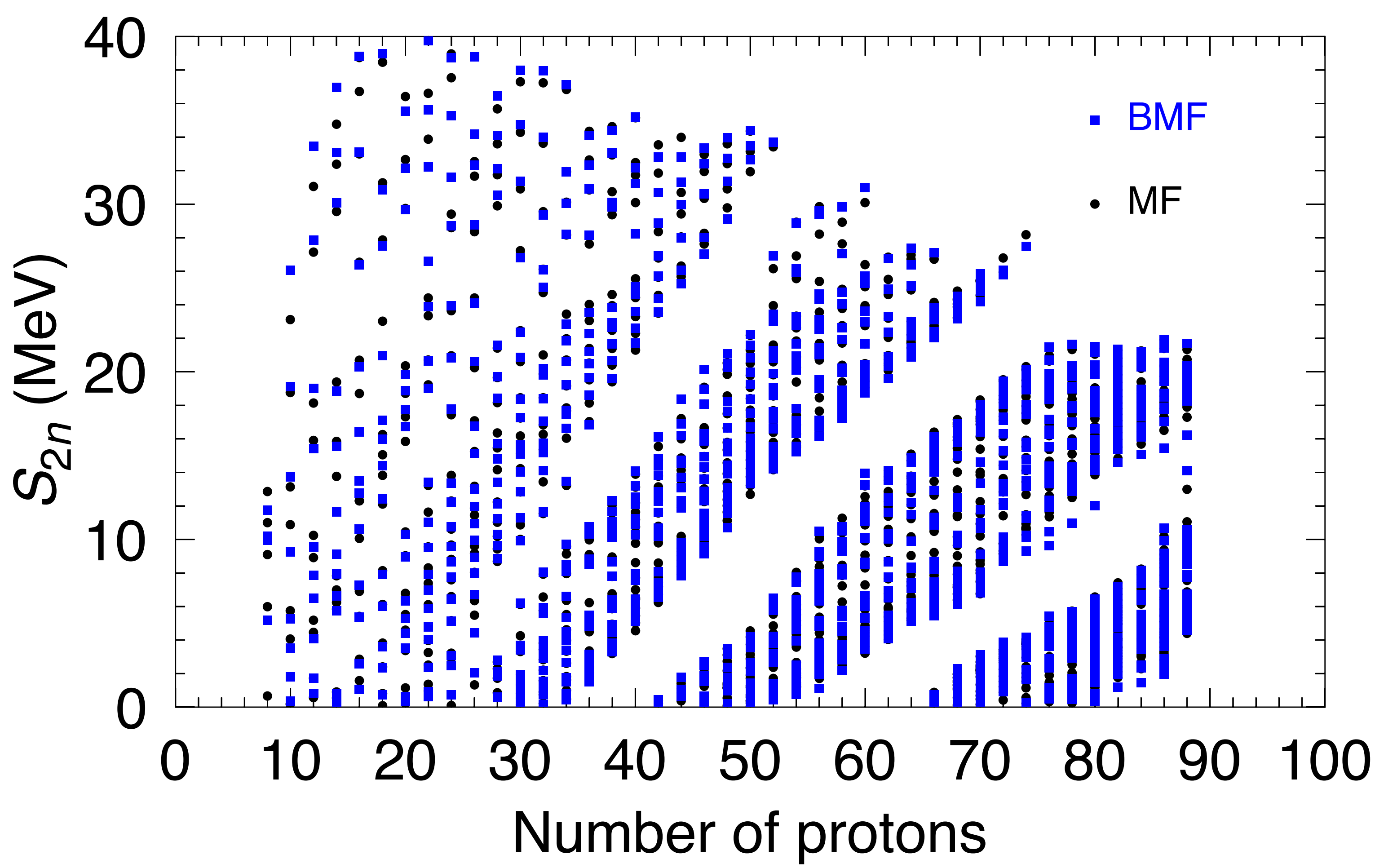
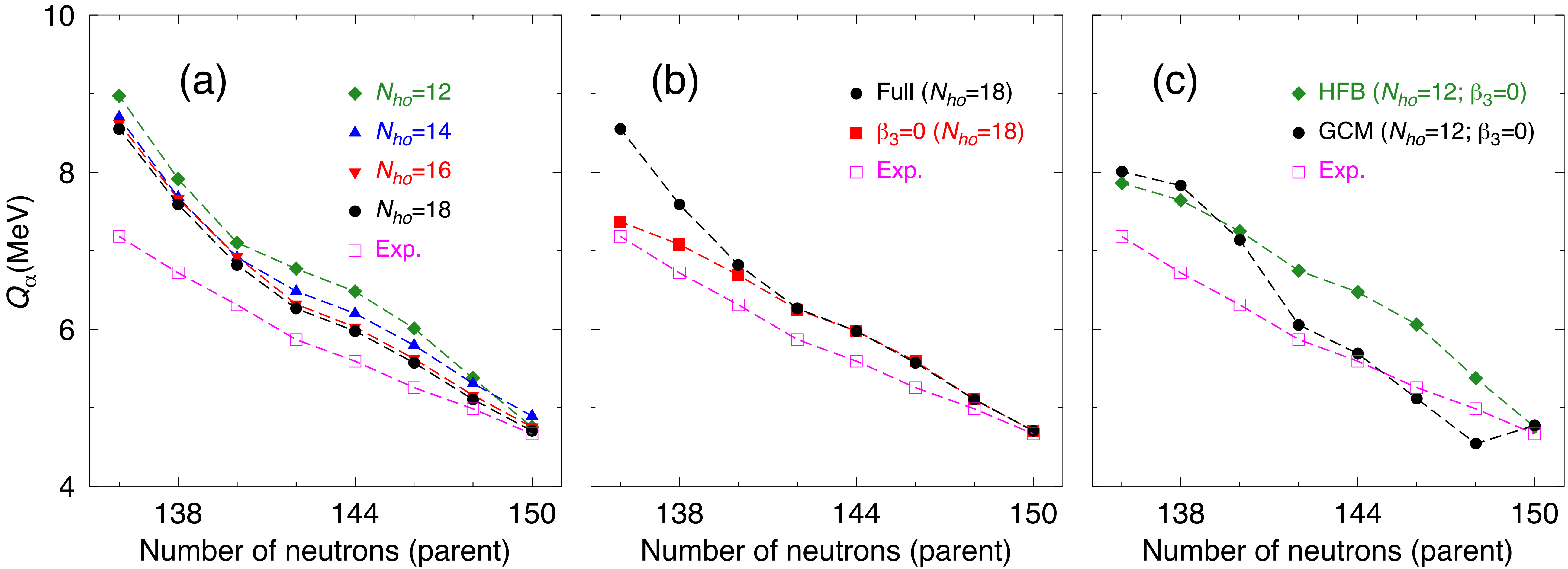


T. R. Rodríguez, A. Arzhanov, G. Martínez-Pinedo, in preparation

- **Exact** particle number (VAP) and angular momentum projections + **exact** GCM: there is always energy gain w.r.t. the mean field.
- BMF effects reduces the spread of the data, specially in the light nuclei
- BMF and MF separation energies are rather similar (a bit smoother and in better agreement with data when BMF effects are included).
- Reduction of the shell gaps are not evident.

Pu isotopes. Gogny D1M parametrization



Convergence affects the results

Addition of new degrees of freedom affects the results

Beyond mean field effects affects the results

Need to reduce the ***physical*** and ***numerical*** uncertainties in energy density functional calculations

T. R. Rodríguez, GSI report 2013

Summary and outlook

- Beta-decay half-lives including Gamow-Teller and first-forbidden contributions are now available with Shell Model and Covariant Density Functional Theory.

- Microscopic nuclear models for masses have to take carefully into account:
  - Convergence with respect to the working basis.
  - Beyond-mean-field effects calculated without approximations.

Summary and outlook

- Beta-decay half-lives including Gamow-Teller and first-forbidden contributions are now available with Shell Model and Covariant Density Functional Theory.

- Microscopic nuclear models for masses have to take carefully into account:
  - Convergence with respect to the working basis.
  - Beyond-mean-field effects calculated without approximations.

- 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).
- Development of reliable **extrapolation** schemes to infinite working basis.
- Comparison to new **experimental data**.
- Impact on **nucleosynthesis** simulations.

Credits

Credits

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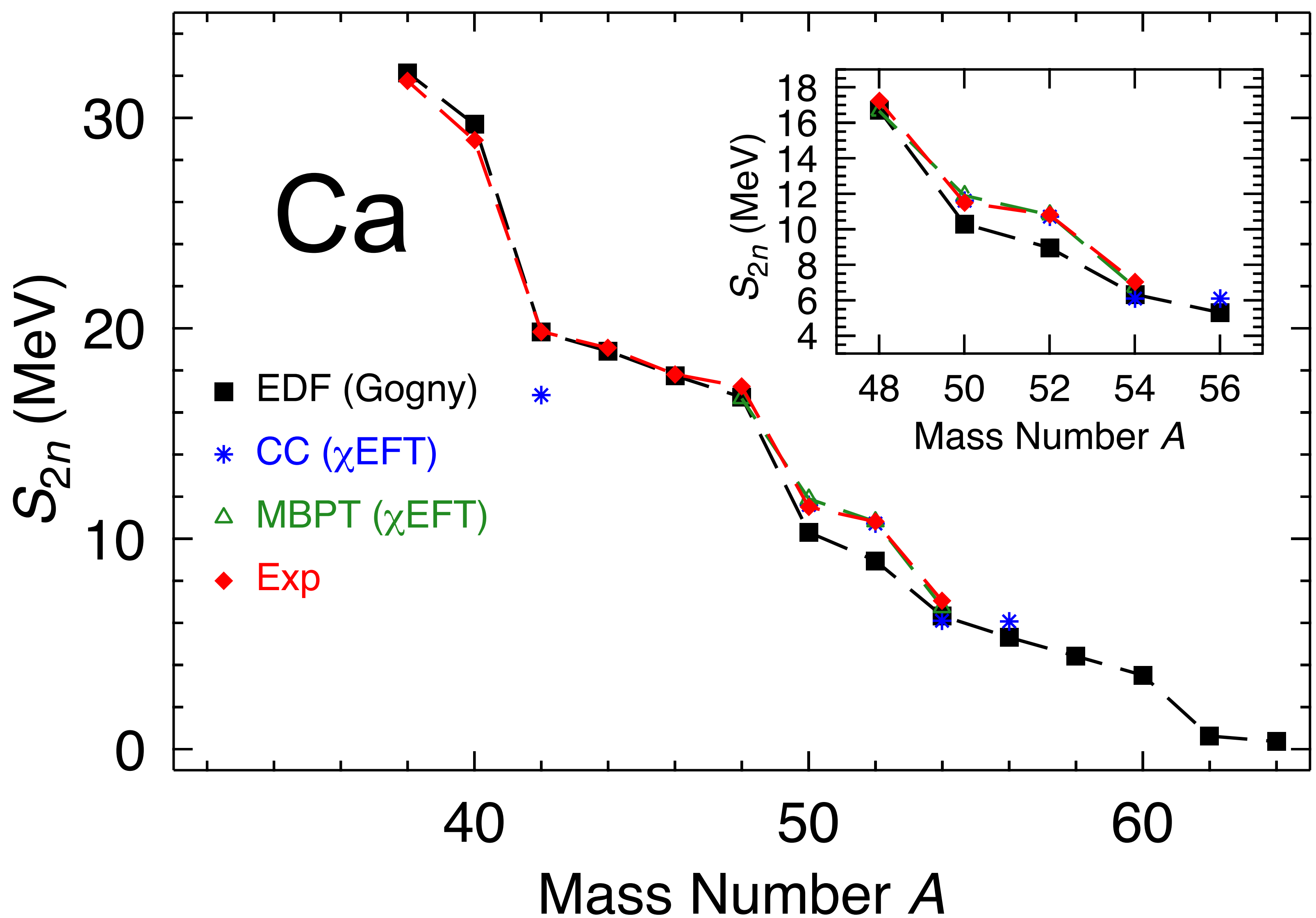

Ca
S_{2n} (MeV)
30
20
10
0
40
50
60
Mass Number A
EDF (Gogny)
CC (χEFT)
MBPT (χEFT)
Exp
18
16
14
12
10
8
6
4
48
50
52
54
56