Decay properties of neutron-rich nuclei

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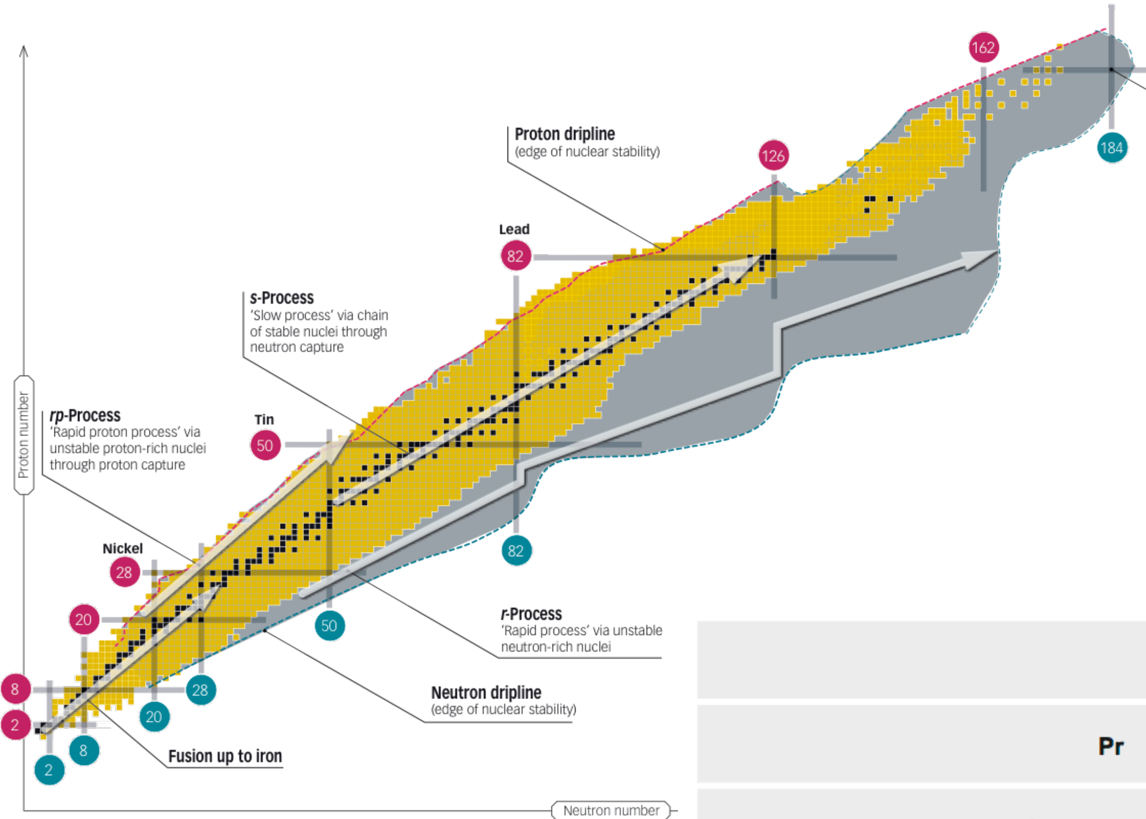
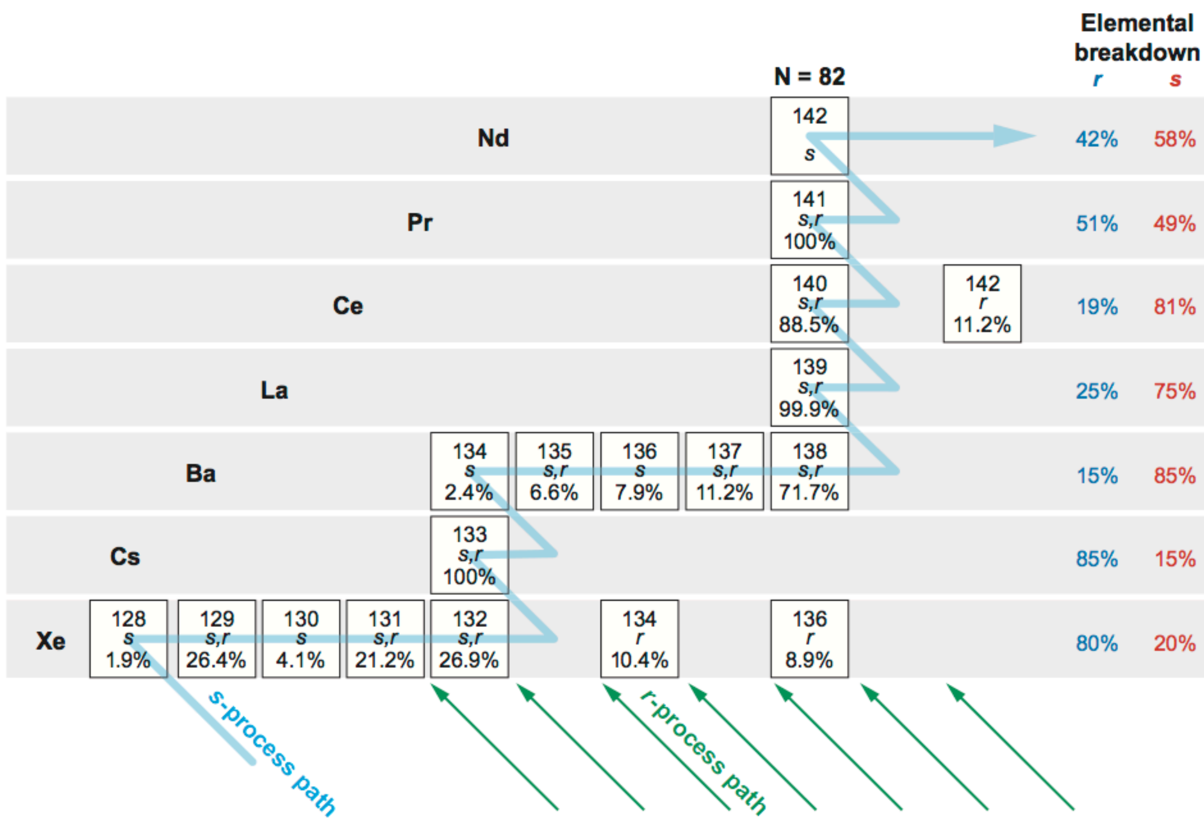
Observational Signatures of r-process Nucleosynthesis in Neutron Star Mergers

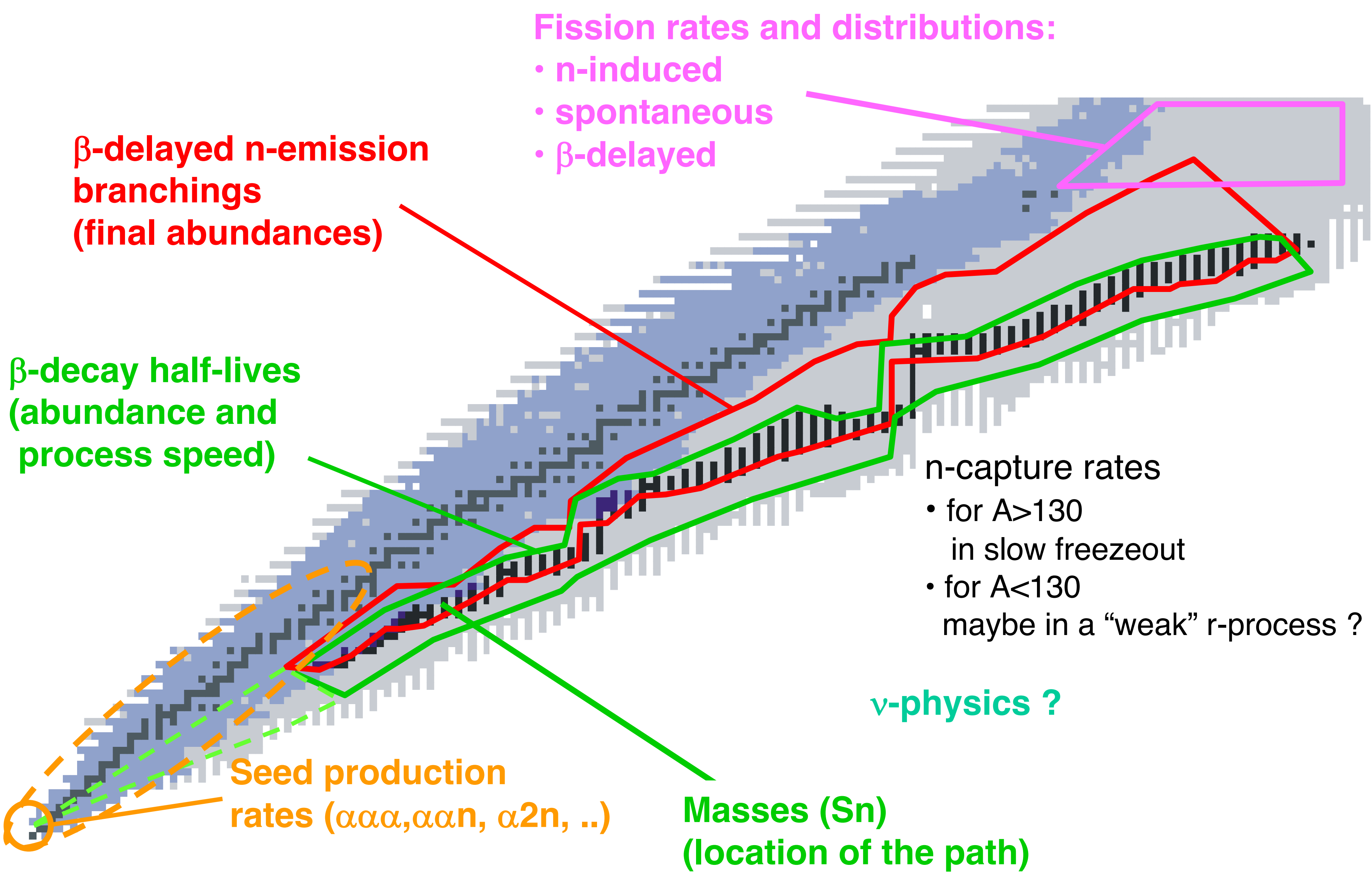
Seattle, August 2017.



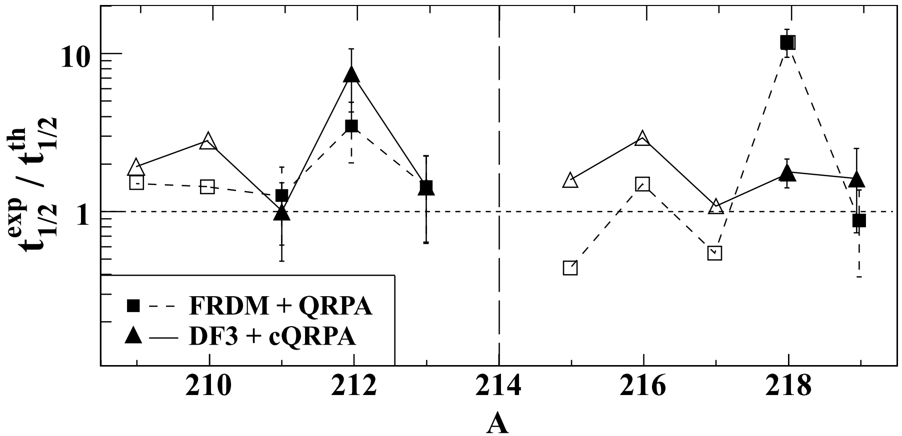
The s-process follows the valley of stability as the neutron captures and beta decay have comparable probabilities.

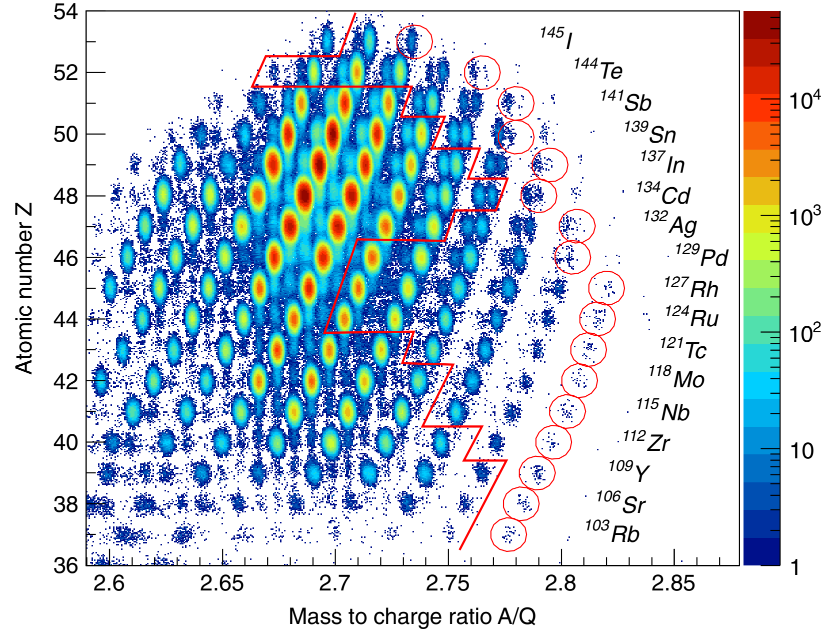


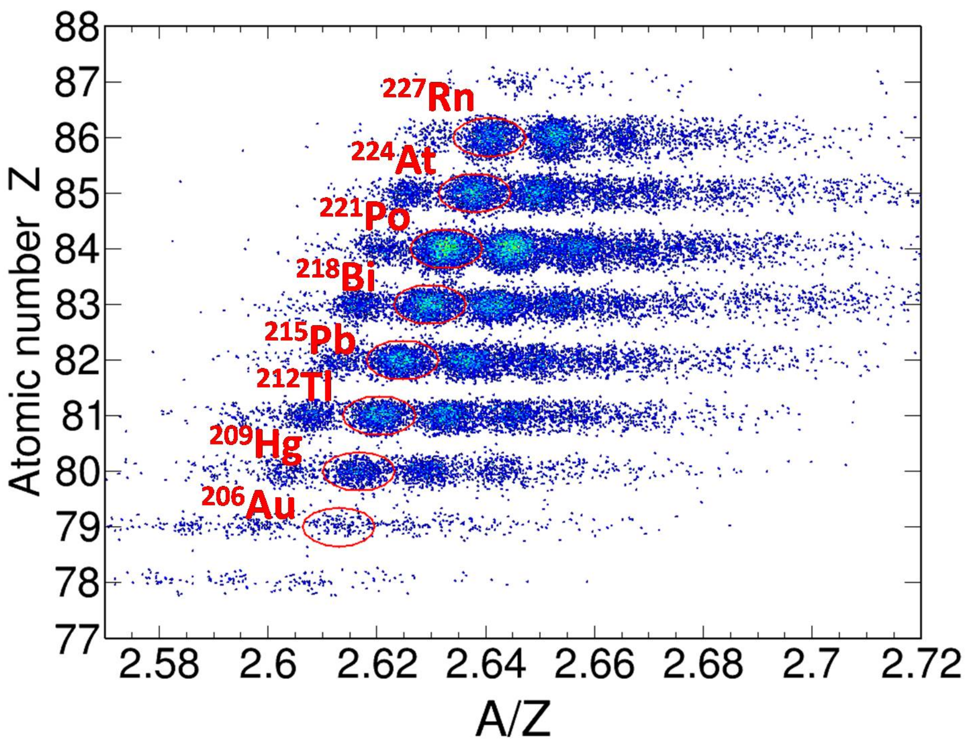
The path of the r-process lies very far from stability, exploring extreme nuclei at the limits of nuclear interaction.

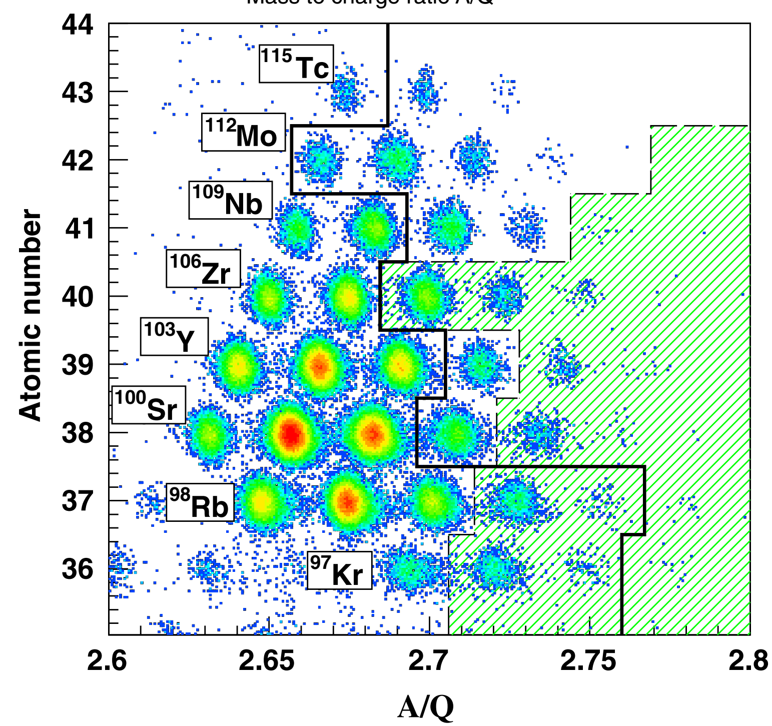


Fission rates and distributions:
• n-induced
• spontaneous
• β-delayed
β-delayed n-emission
branchings
(final abundances)
β-decay half-lives
(abundance and
process speed)
n-capture rates
• for A>130
in slow freezeout
• for A<130
maybe in a “weak” r-process ?
ν-physics ?
Seed production
rates (ααα,ααn, α2n, ..)
Masses (Sn)
(location of the path)

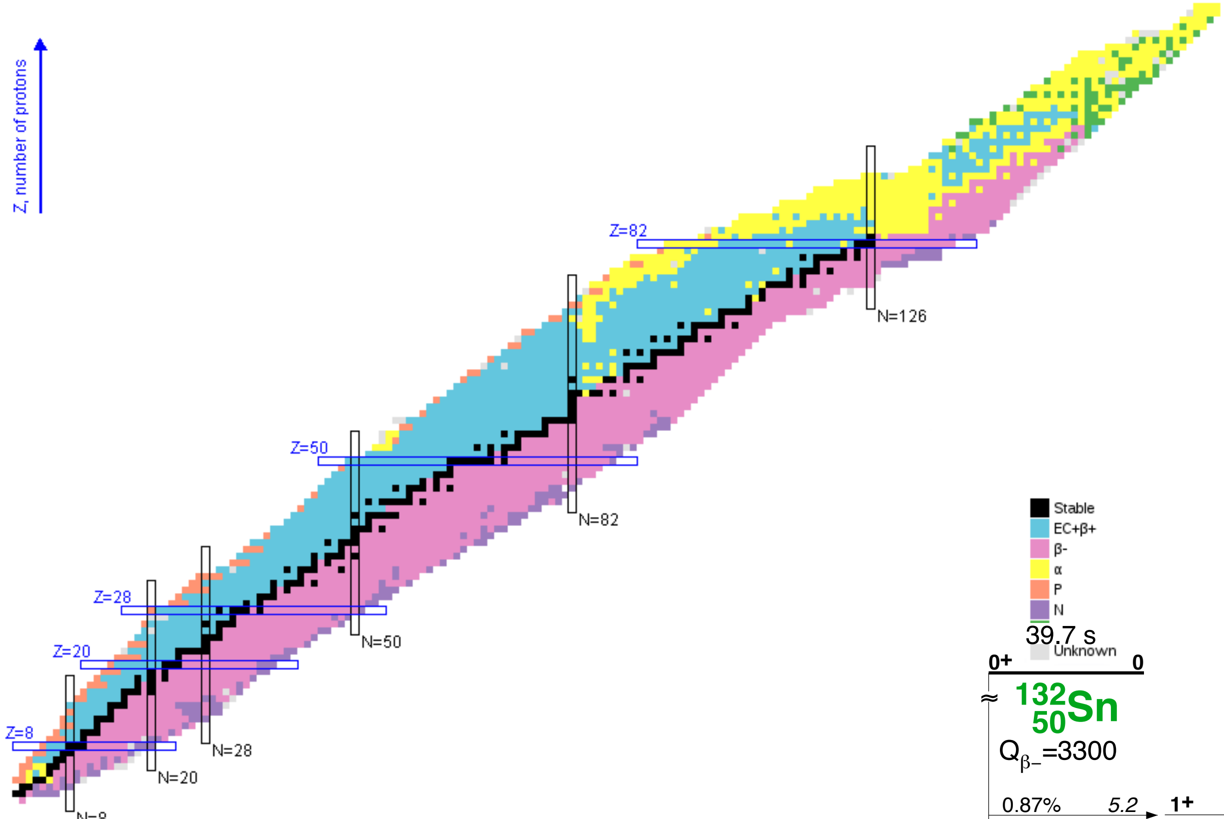


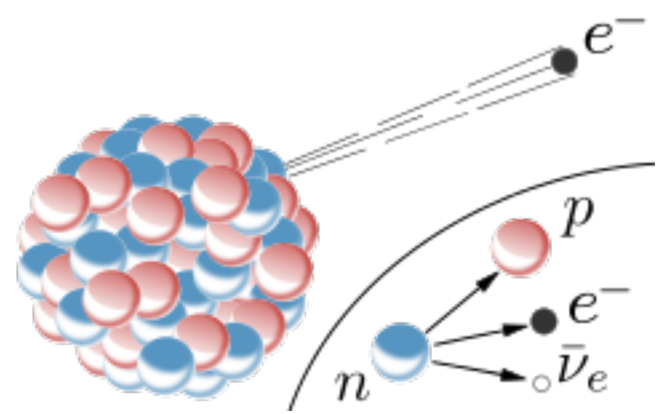




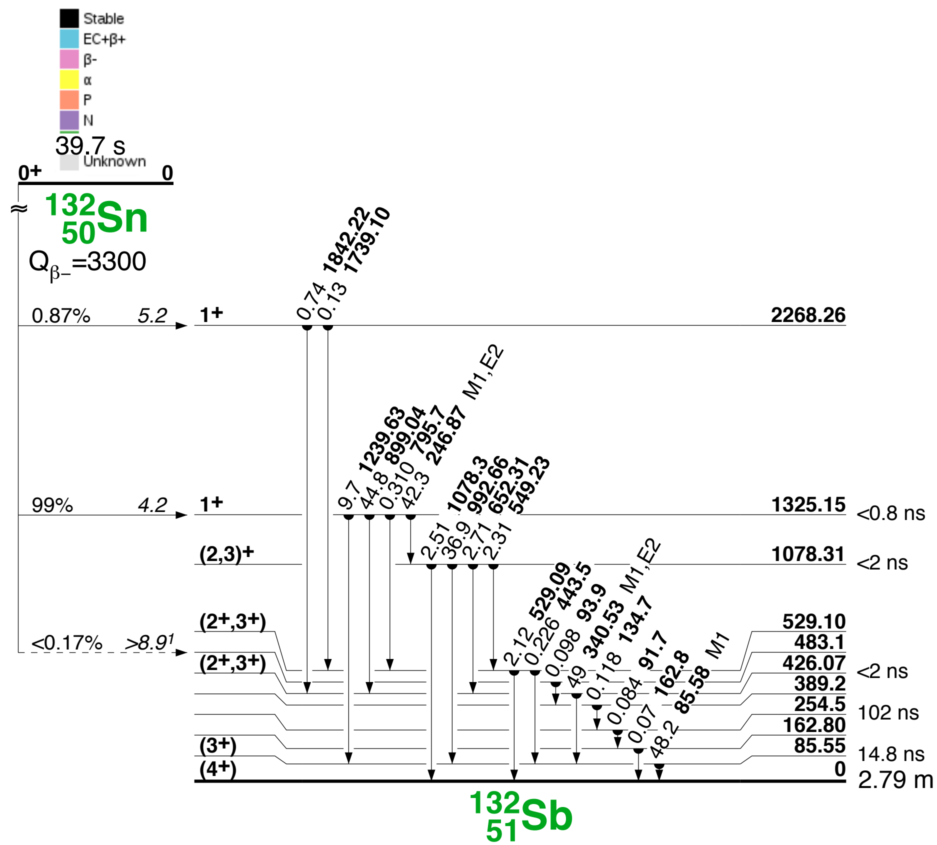


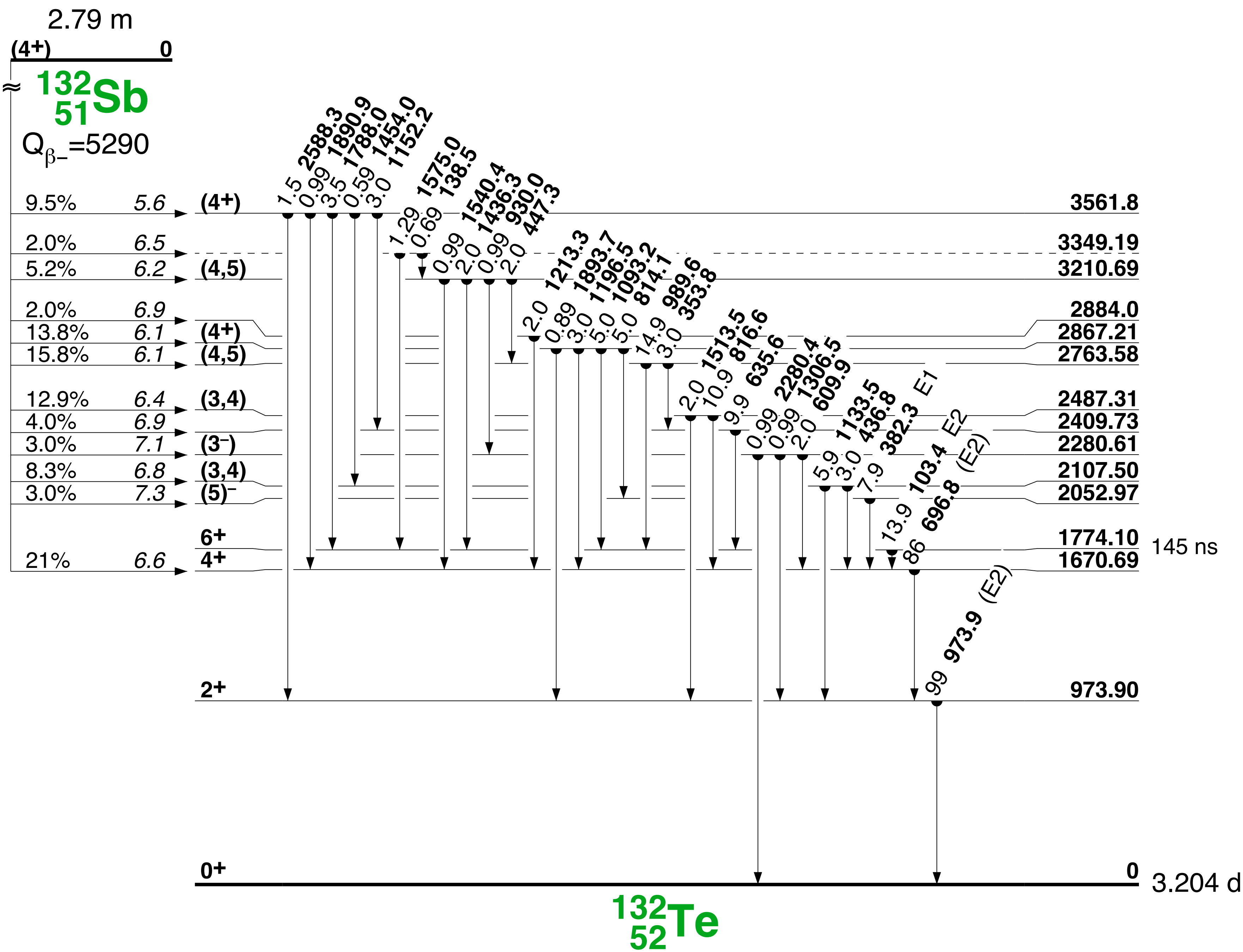
G. Lorusso *et al.*, Phys. Rev. Lett. 114, 192501 (2015)
R. Caballero-Folch *et al.*, Phys. Rev. Lett. 117, 012501 (2016)
S. Nishimura *et al.*, Phys. Rev. Lett. 106, 052502 (2011)



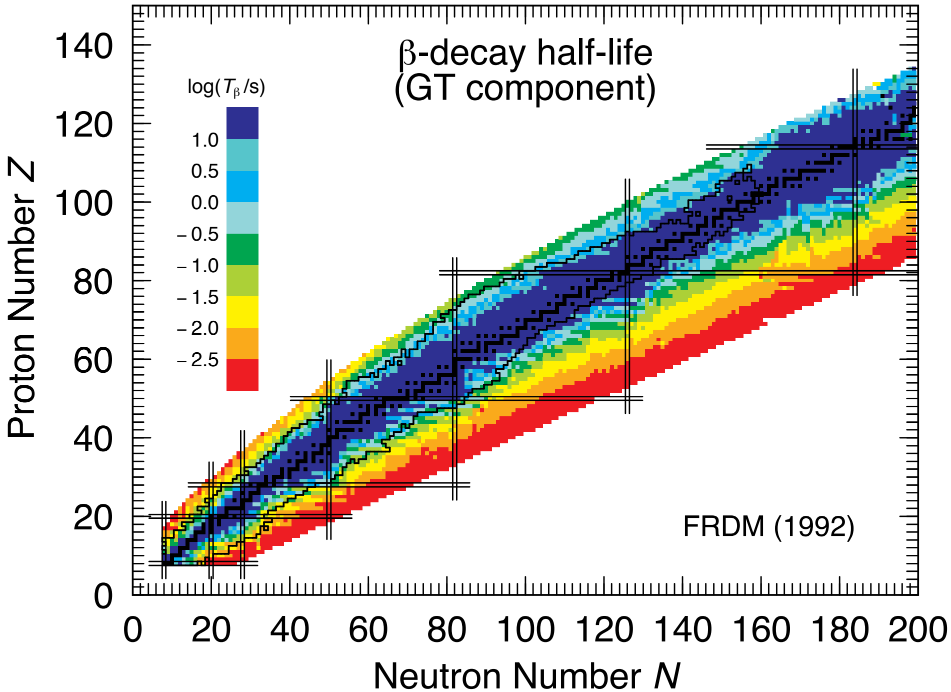


In some nuclei the decay is quite simple and can be described with just one state.

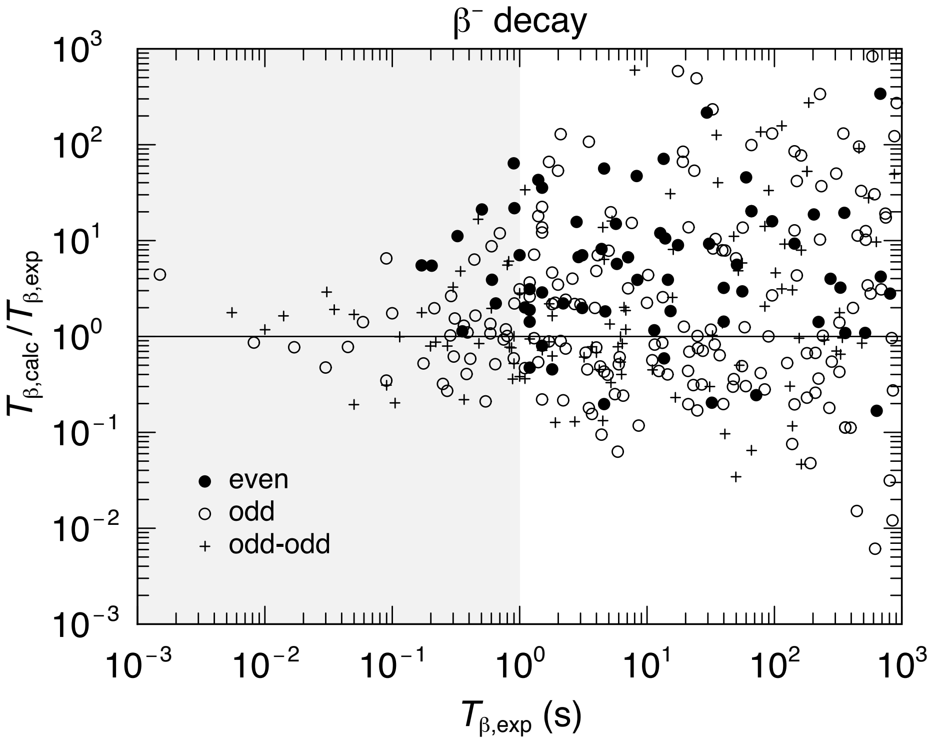



2.79 m
(4+) 0
132 51 Sb
Qβ−=5290
9.5% 5.6 (4+) 3561.8
2.0% 6.5 3349.19
5.2% 6.2 (4,5) 3210.69
2.0% 6.9 2884.0
13.8% 6.1 (4+) 2867.21
15.8% 6.1 (4,5) 2763.58
12.9% 6.4 (3,4) 2487.31
4.0% 6.9 2409.73
3.0% 7.1 (3−) 2280.61
8.3% 6.8 (3,4) 2107.50
3.0% 7.3 (5)− 2052.97
6+ 1774.10 145 ns
21% 6.6 4+ 1670.69
2+ 973.90
0+ 0 3.204 d
1.5 2588.3
0.99 1890.9
3.5 1788.0
0.59 1454.0
3.0 1152.2
1.29 1575.0
0.69 138.5
0.99 1540.4
2.0 1436.3
0.99 930.0
2.0 447.3
2.0 1213.3
0.89 1893.7
3.0 1196.5
5.0 1093.2
5.0 814.1
14.9 989.6
3.0 353.8
2.0 1513.5
10.9 816.6
9.9 635.6
0.99 2280.4
0.99 1306.5
2.0 609.9
5.9 1133.5
3.0 436.8
7.9 382.3 E1
13.9 103.4 E2
86 696.8 (E2)
99 973.9 (E2)
132 52 Te

Large-scale calculations

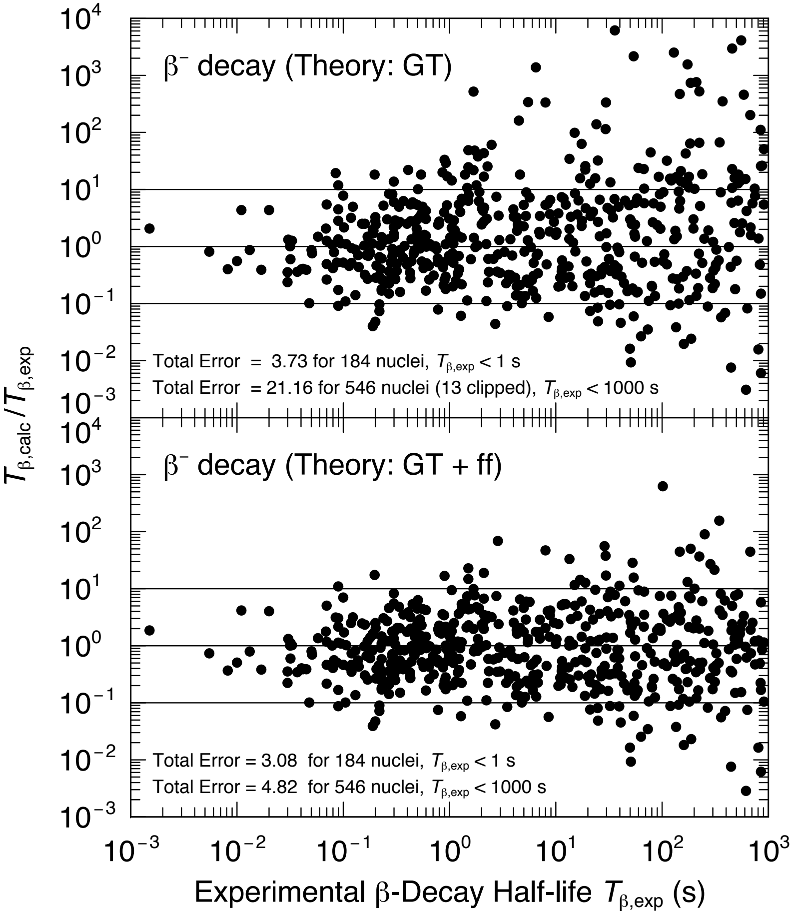


Nucleosynthesis simulations require data on a large number of nuclei – systematic calculations are needed.

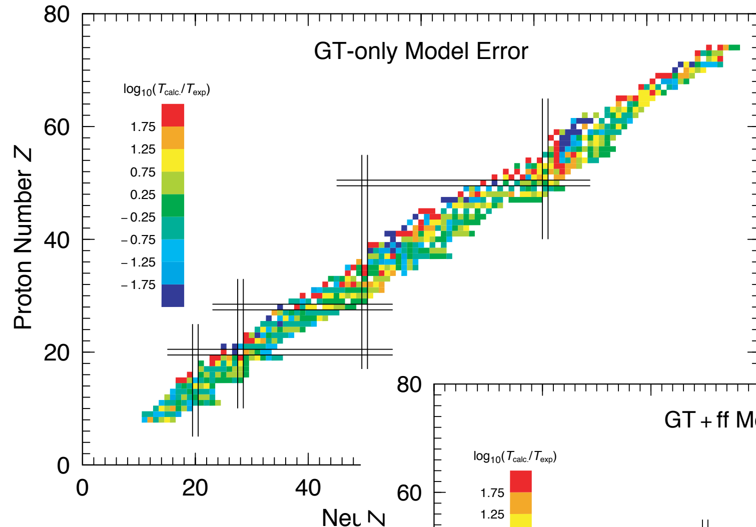


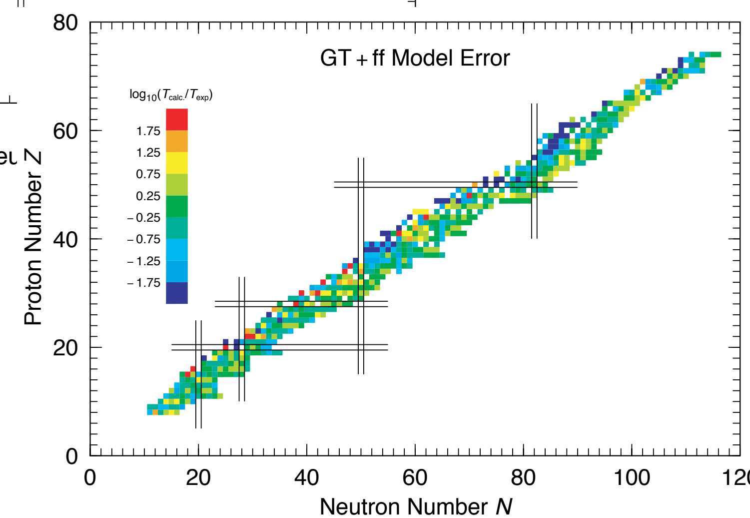
In 1997. the first large scale calculation of beta-decay half-lives was published based on finite range droplet model + QRPA.

P. Möller *et al.*, At. Data Nucl. Data Tables 66, 131 (1997)



In 2003. the reference dataset is published, again based on the FRDM + QRPA, but also including the first-forbidden transitions using a gross statistical calculation.





The first-forbidden transitions contribute to the decay rate mostly in nuclei close to the valley of stability.

P. Möller *et al.*, Phys. Rev. C 67, 055802 (2003)

QRPA calculations

Transitions are obtained by solving the pn-(R)QRPA equations

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = E_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix}$$

Residual interaction is derived from the Lagrangian density

$$\mathcal{L}_{\rho+\pi} = -g_\rho \bar{\psi} \gamma_\mu \vec{\rho}^\mu \vec{\tau} \psi - \frac{f_\pi}{m_\pi} \bar{\psi} \gamma_5 \gamma^\mu \partial_\mu \vec{\pi} \vec{\tau} \psi$$

Total strength of a particular transition

$$B_{\lambda,J}(GT) = \left| \sum_{pn} \left\langle p \left\| \hat{O}_J \right\| n \right\rangle \left(X_{pn}^{\lambda,J} u_p v_n - Y_{pn}^{\lambda,J} v_p u_n \right) \right|^2$$

Decay rate is of the form

$$\lambda_i = D \int_1^{W_{0,i}} W\sqrt{W^2 - 1}\,(W_{0,i} - W)^2\, F(Z,W)C(W)dW$$

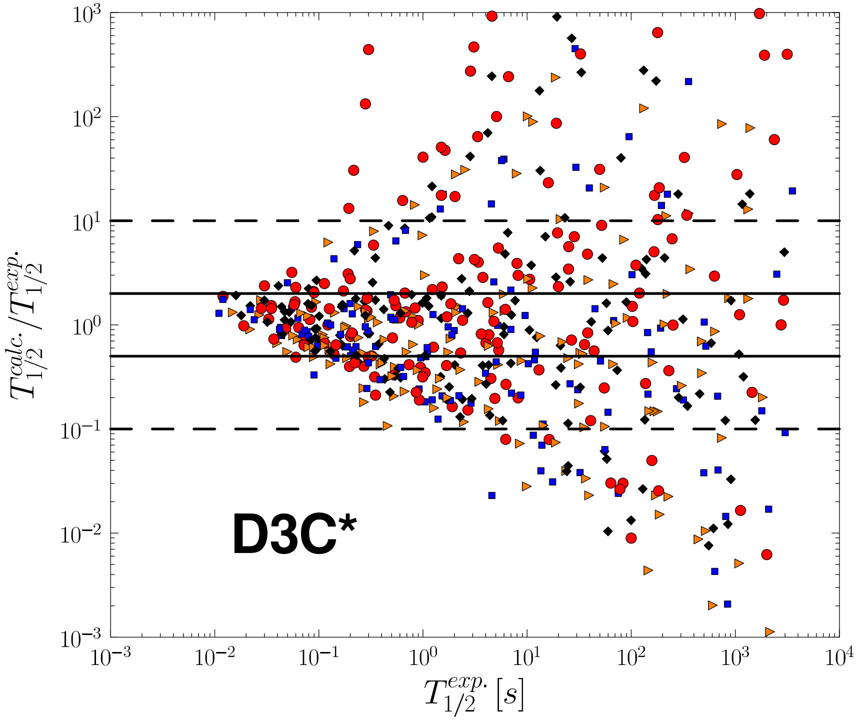
$$T_{1/2} = \frac{\ln 2}{\lambda}, \qquad D = \frac{(G_F V_{ud})^2}{2\pi^3}\frac{\left(m_e c^2\right)^5}{\hbar}$$

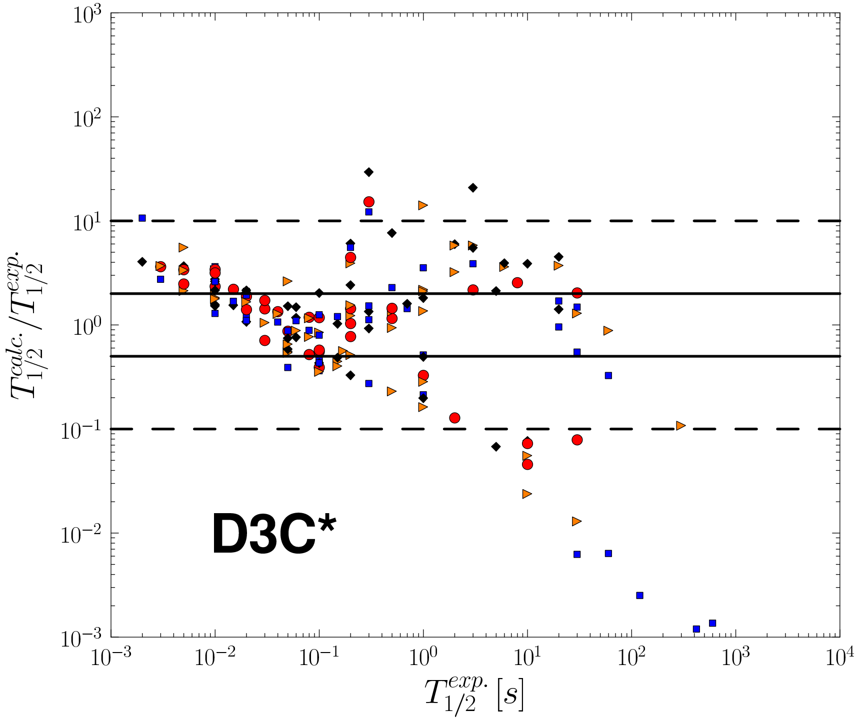
Allowed decay shape factor:

$$C(W) = B(GT)$$

First-forbidden transitions shape factor

$$C(W) = k\left(1 + aW + bW^{-1} + cW^2\right)$$

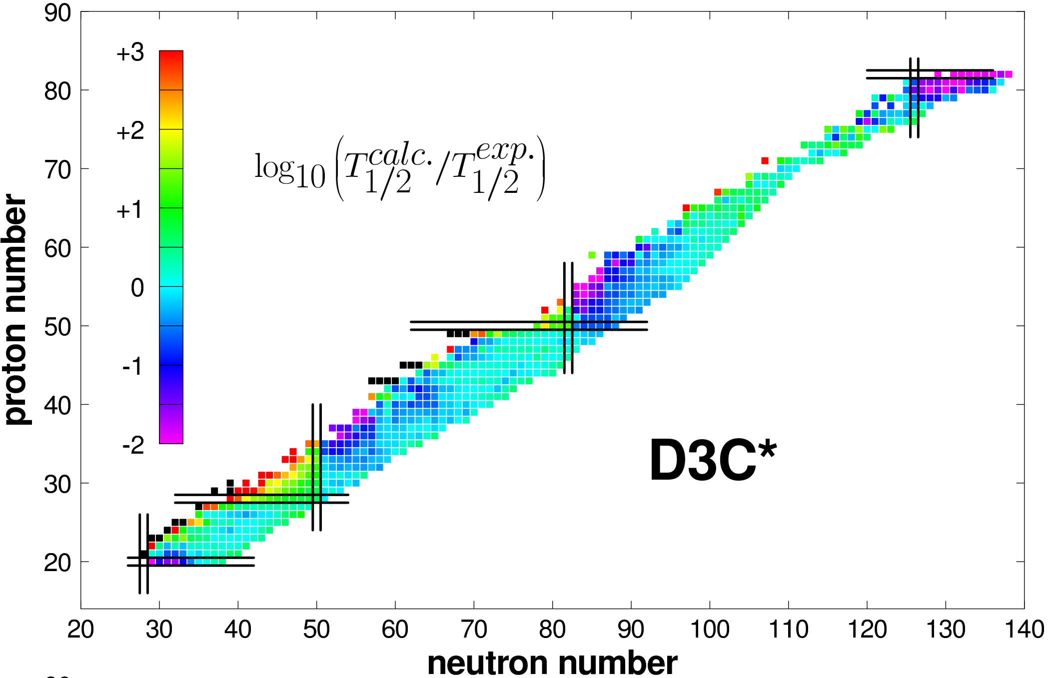




$$\bar{r} = \frac{1}{N}\sum_i \log\frac{T_{calc.}}{T_{exp.}}$$

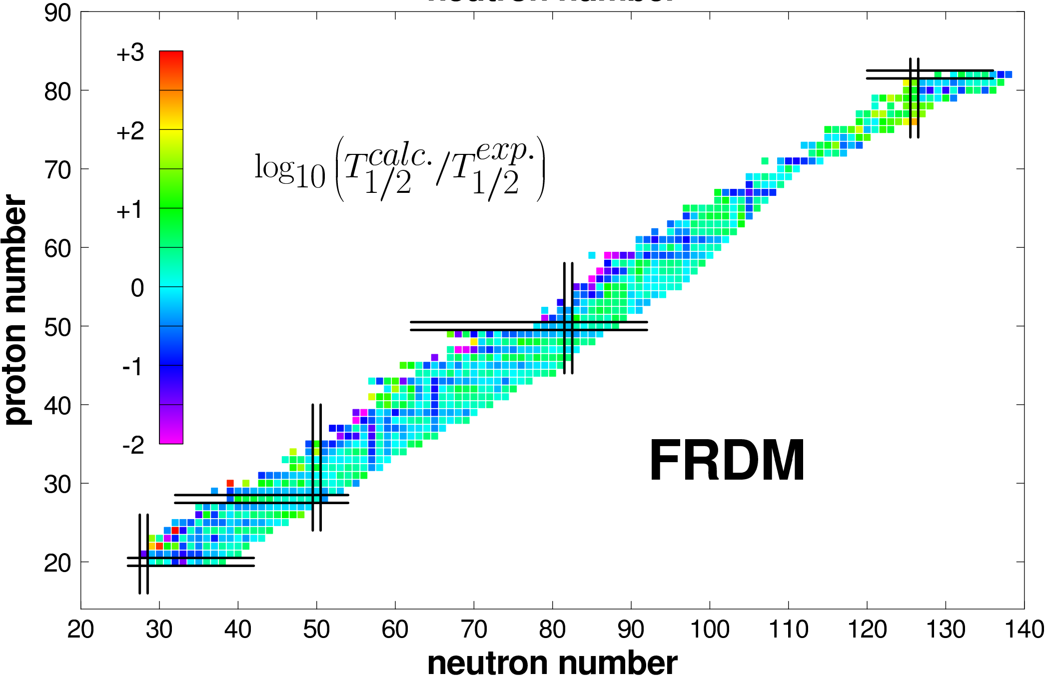
$$\sigma = \left[\frac{1}{N}\sum_i (r_i - \bar{r})^2\right]^{1/2}$$

	D3C*		FRDM	
$T_{\rm exp.}$ [s]	$\bar{r}$	σ	$\bar{r}$	σ
< 1000	0.011	0.889	0.021	0.660
< 100	0.057	0.791	0.040	0.580
< 10	0.061	0.645	0.046	0.515
< 1	0.011	0.436	0.019	0.409
< 0.1	0.041	0.195	0.021	0.354



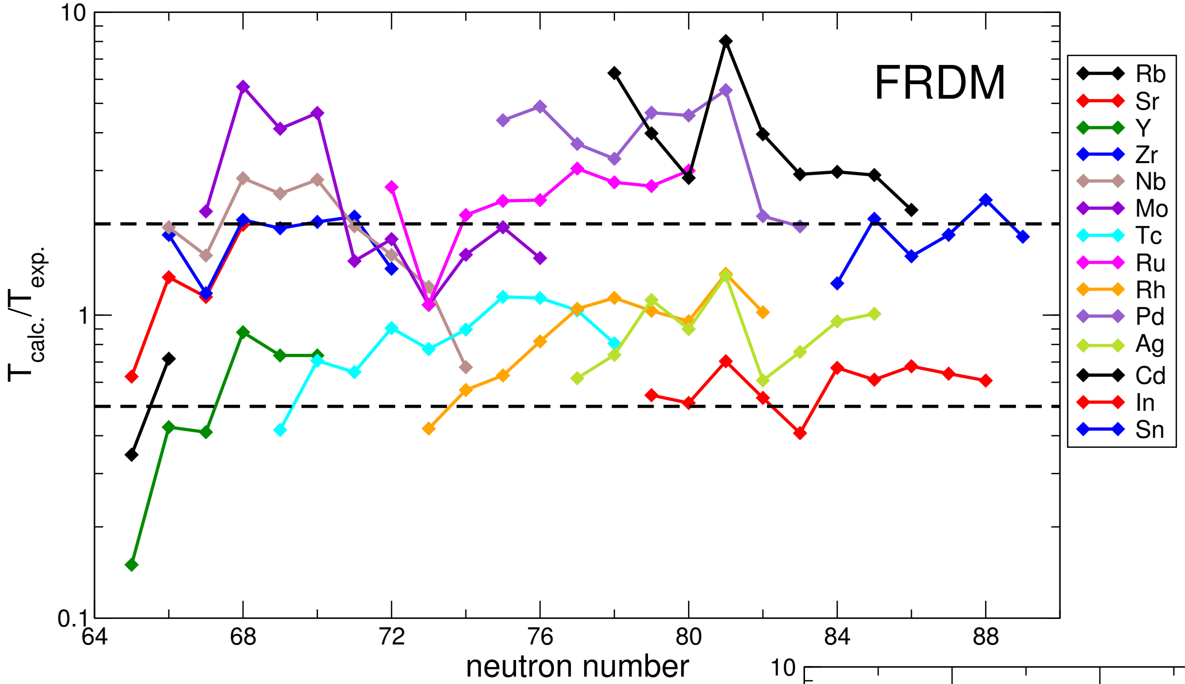
D3C*

	$\bar{r}$	σ
even-even	-0.037	0.331
odd-Z	0.054	0.328
odd-N	-0.086	0.387
odd-odd	0.089	0.582
total	0.011	0.436

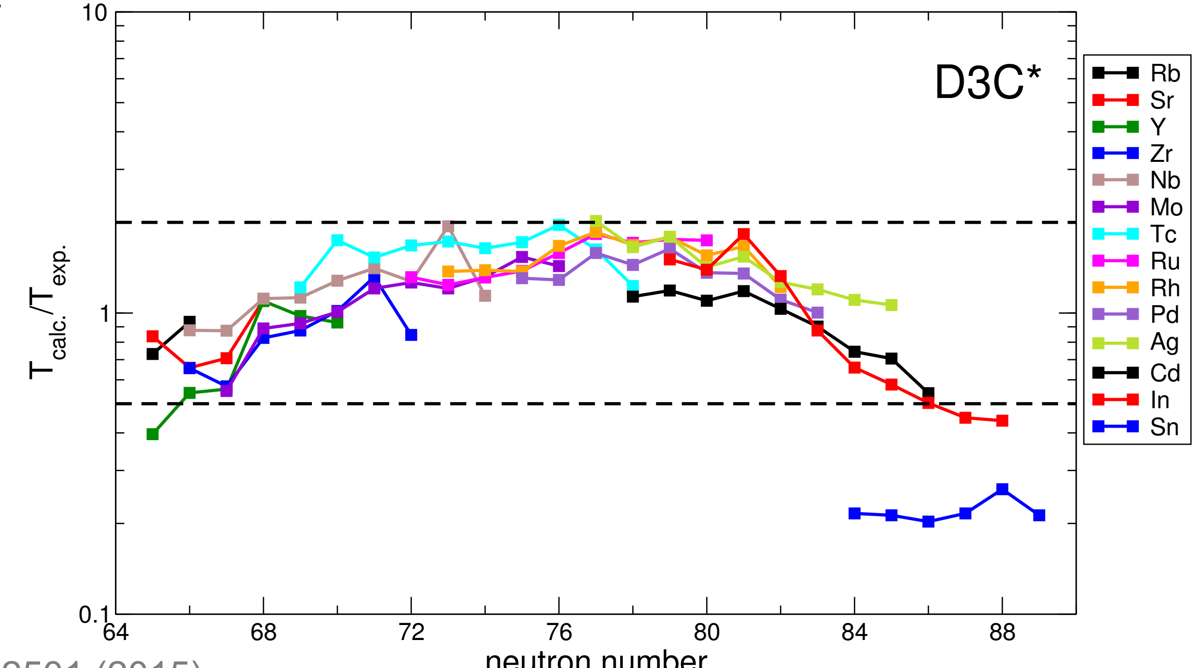


FRDM

	$\bar{r}$	σ
even-even	0.333	0.226
odd-Z	-0.128	0.288
odd-N	0.124	0.436
odd-odd	-0.179	0.409
total	0.019	0.409

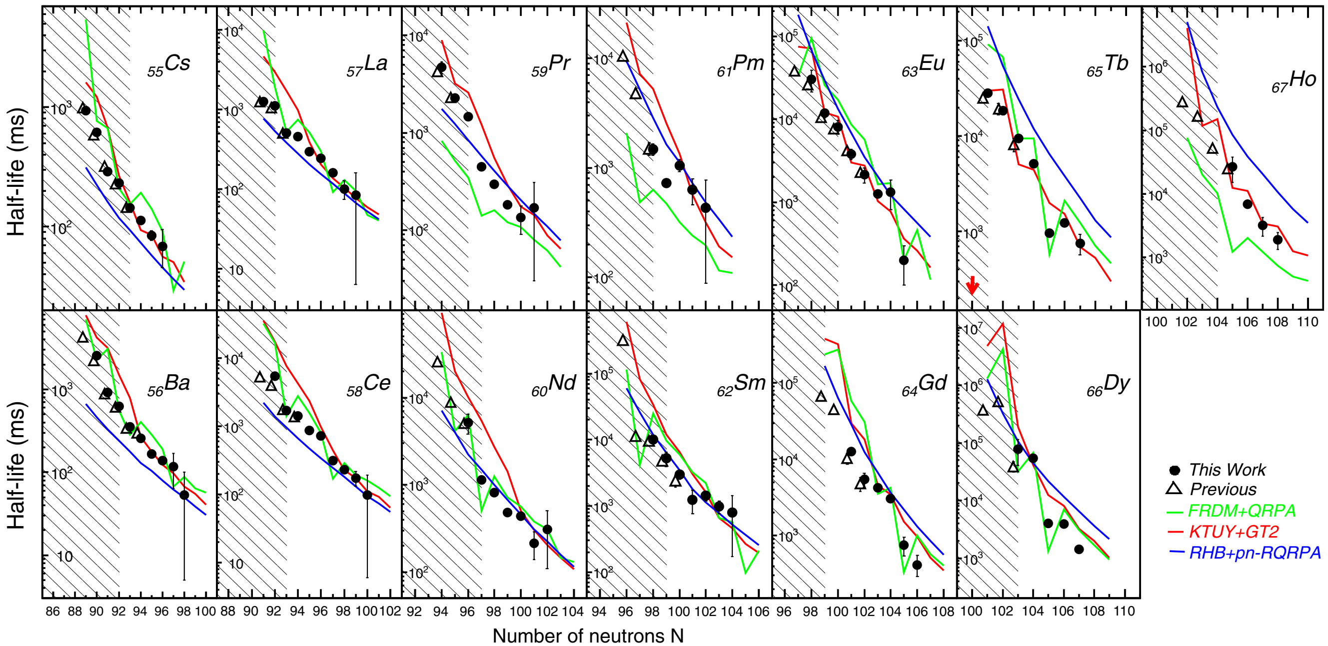


- recent experiment with 110 half-lives
- 40 new measurements



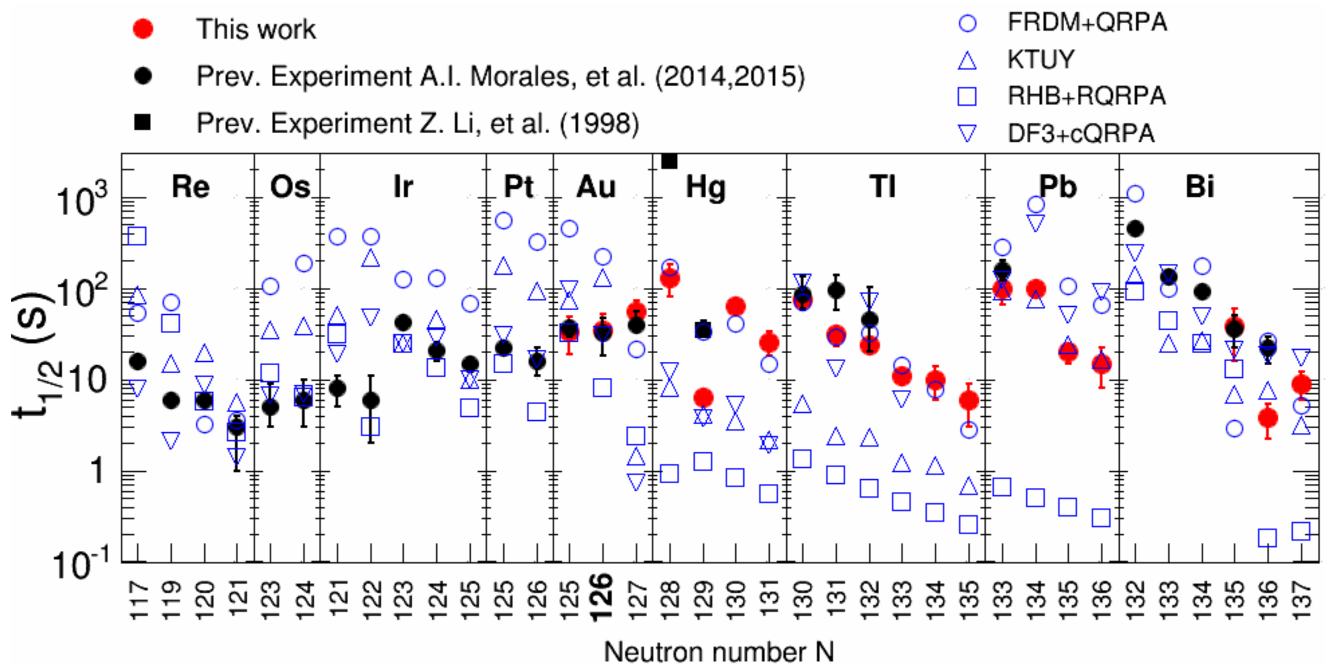
Comparison with the latest measurements is consistent with the previous results.

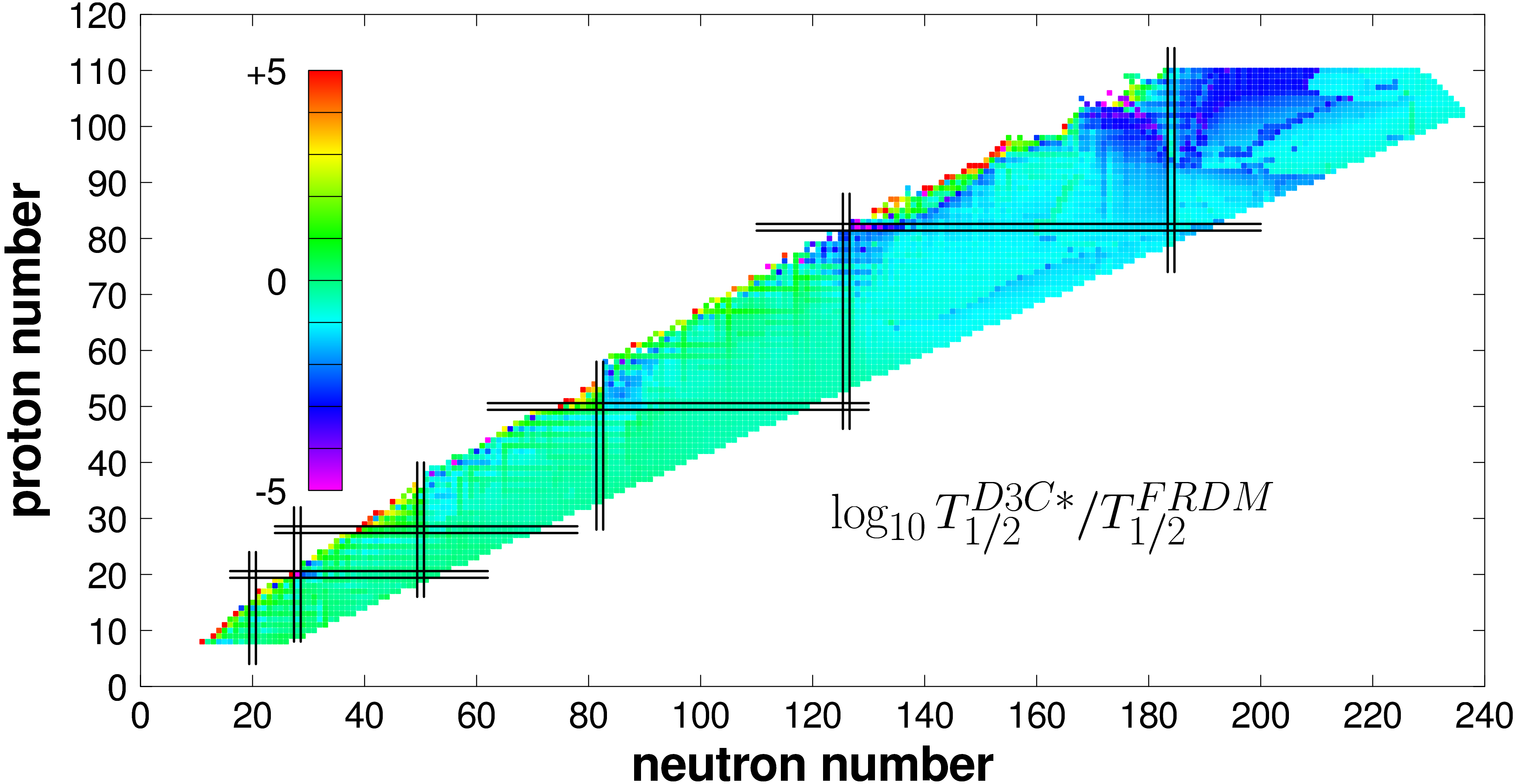
G. Lorusso *et al.*, Phys. Rev. Lett. 114, 192501 (2015)



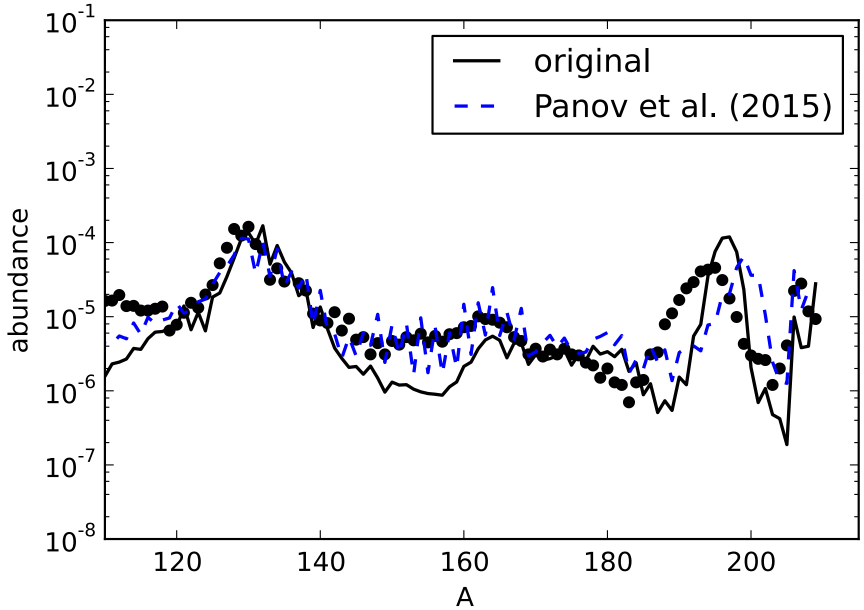
94 measured half-lives from Cs ($Z = 55$) to Ho ($Z = 67$).

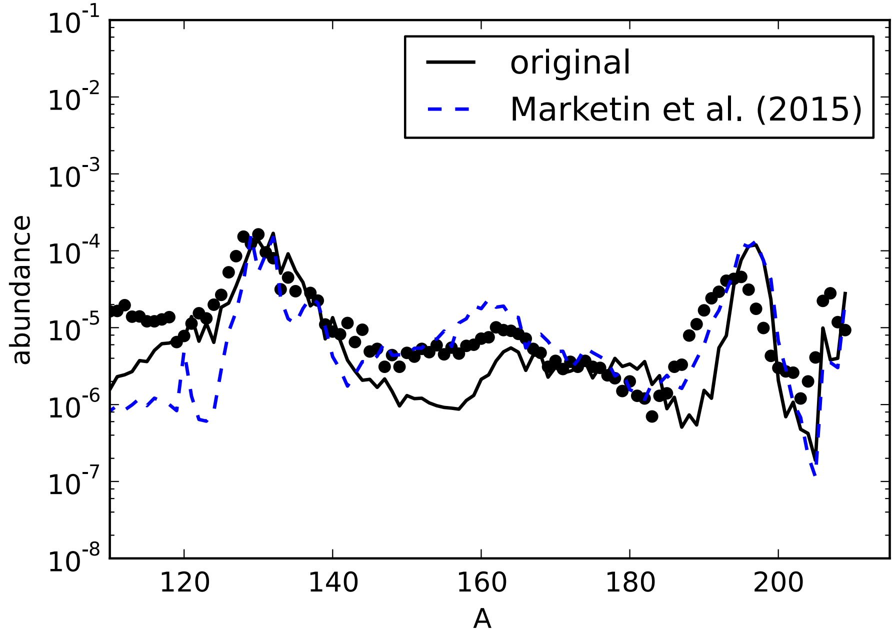
20 half-lives of heavy elements from Au to Bi.





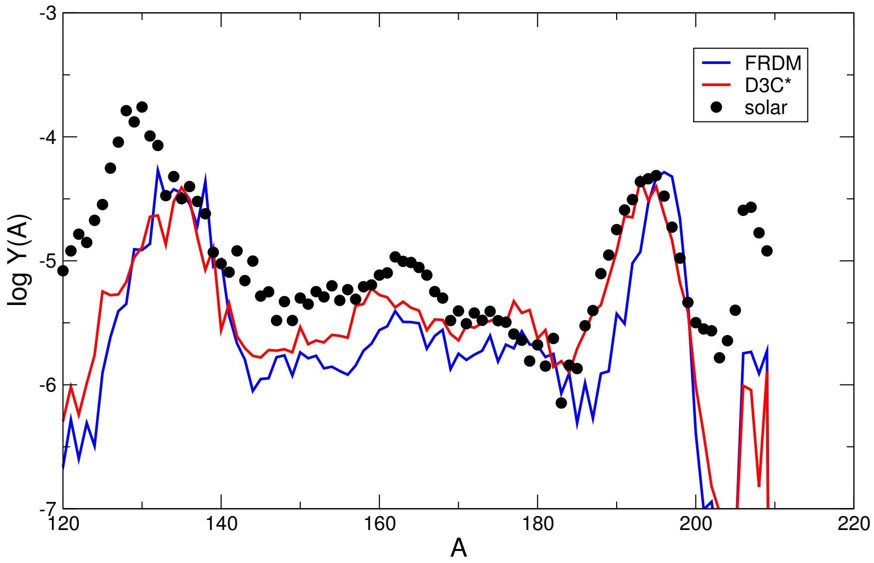
proton number
neutron number
+5
0
-5
$\log_{10} T_{1/2}^{D3C*}/T_{1/2}^{FRDM}$





Position of the peak around A ≈ 190 depends critically on the amount of neutrons available after freeze-out.

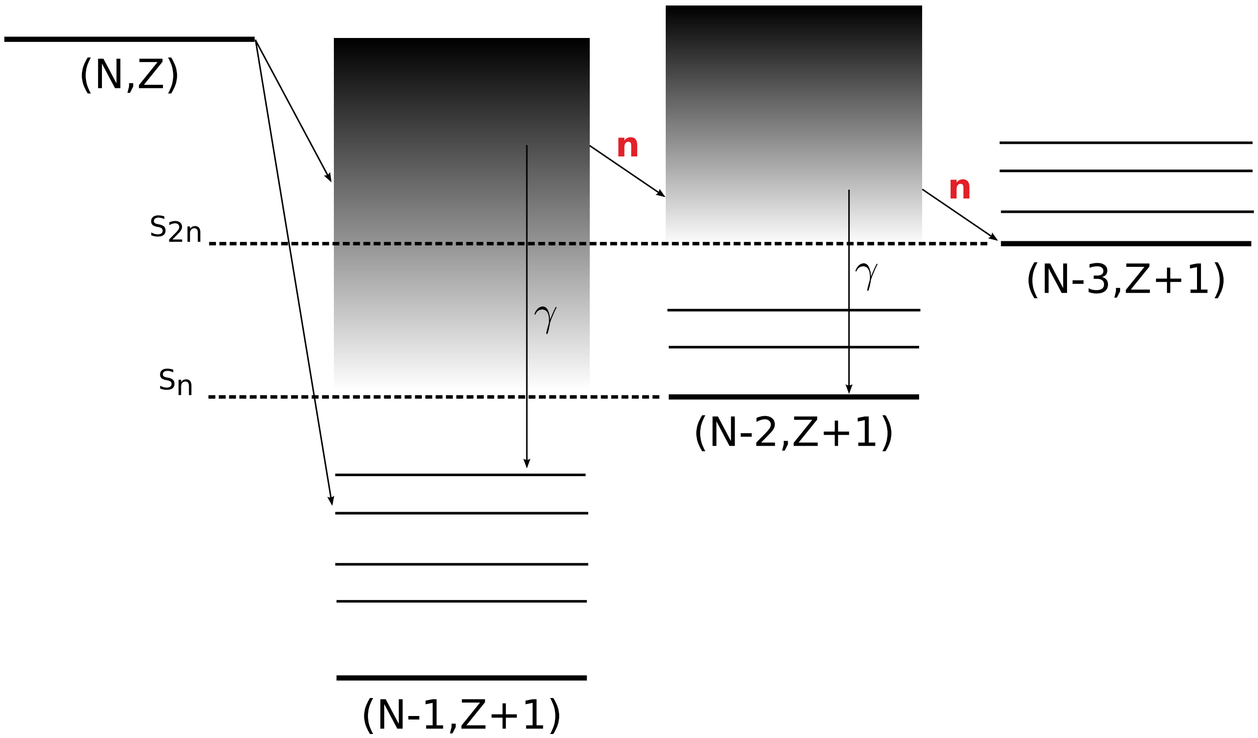
Latest calculations provide systematically shorter half-lives in the region of heavy nuclei – significant consequences for the r-process.



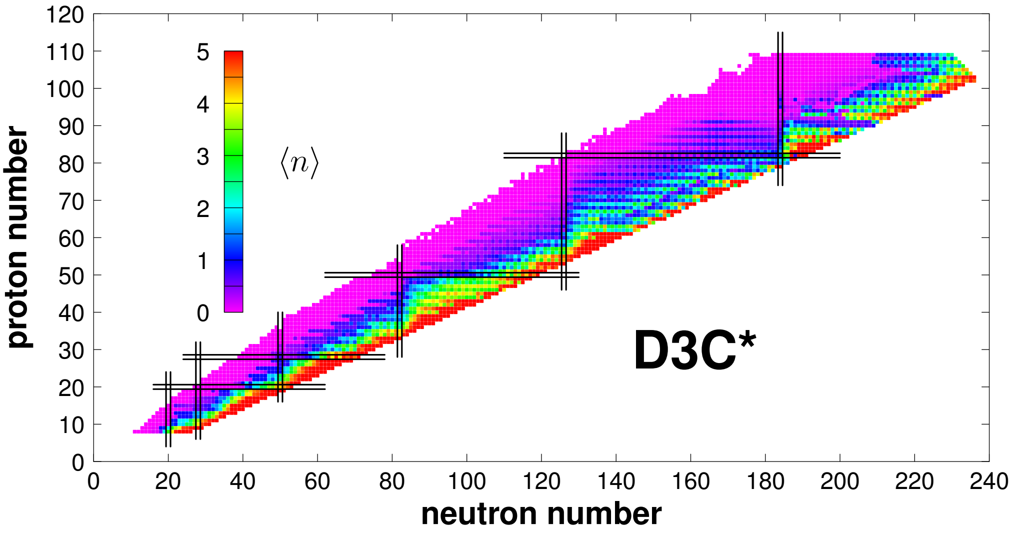
M. Eichler *et al.*, Astrophys. J. 808, 30 (2015)

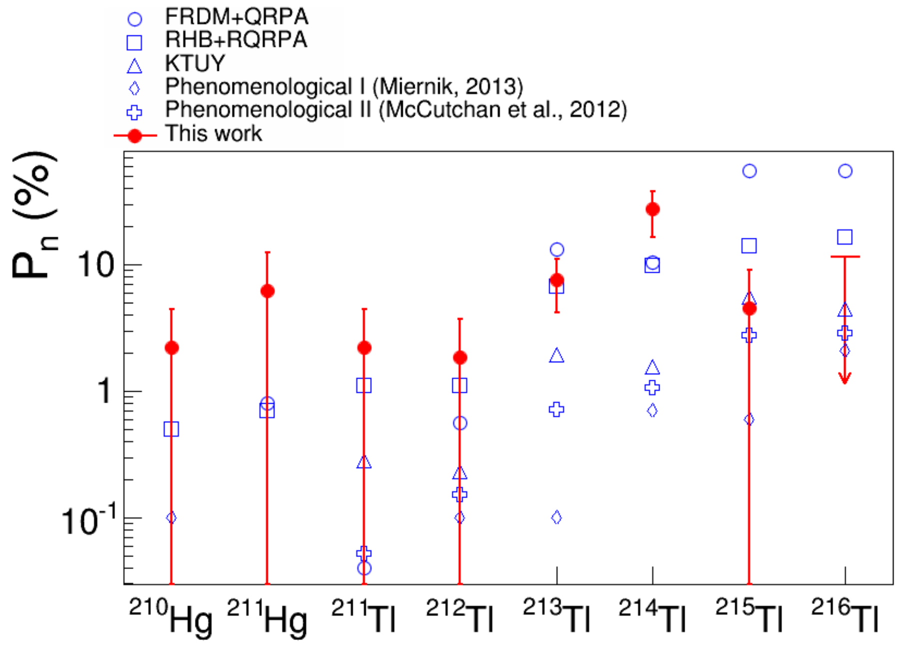
Beta-delayed neutron emission

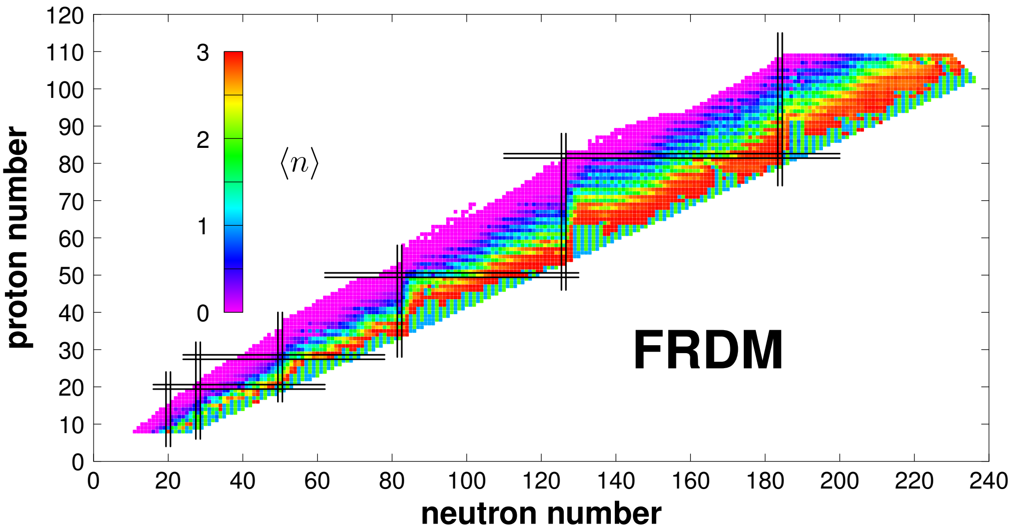
In nuclei with small S_n an additional process is possible:



Beta-delayed neutron emission contributes neutrons at the late stages of the r-process, after the initial neutron flux has dissipated.



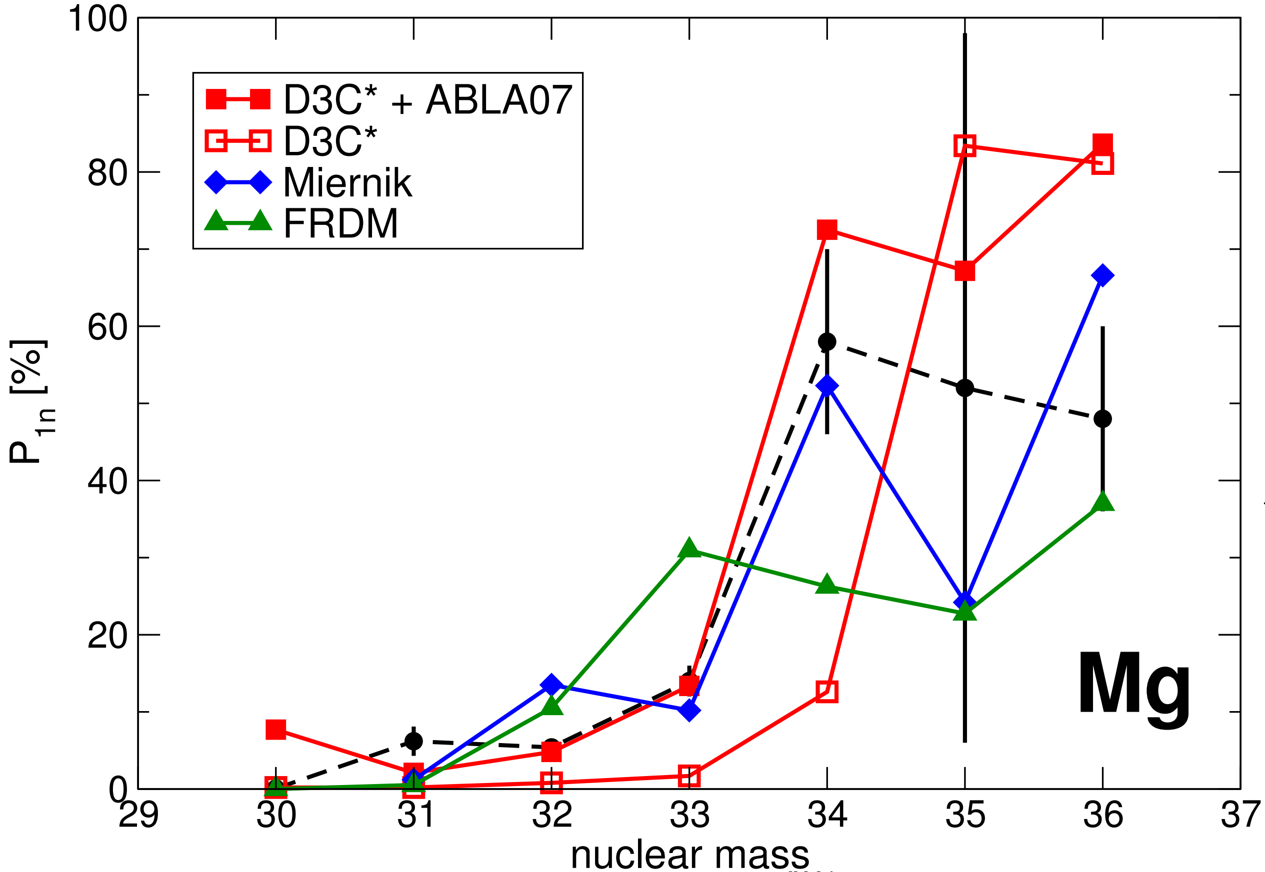




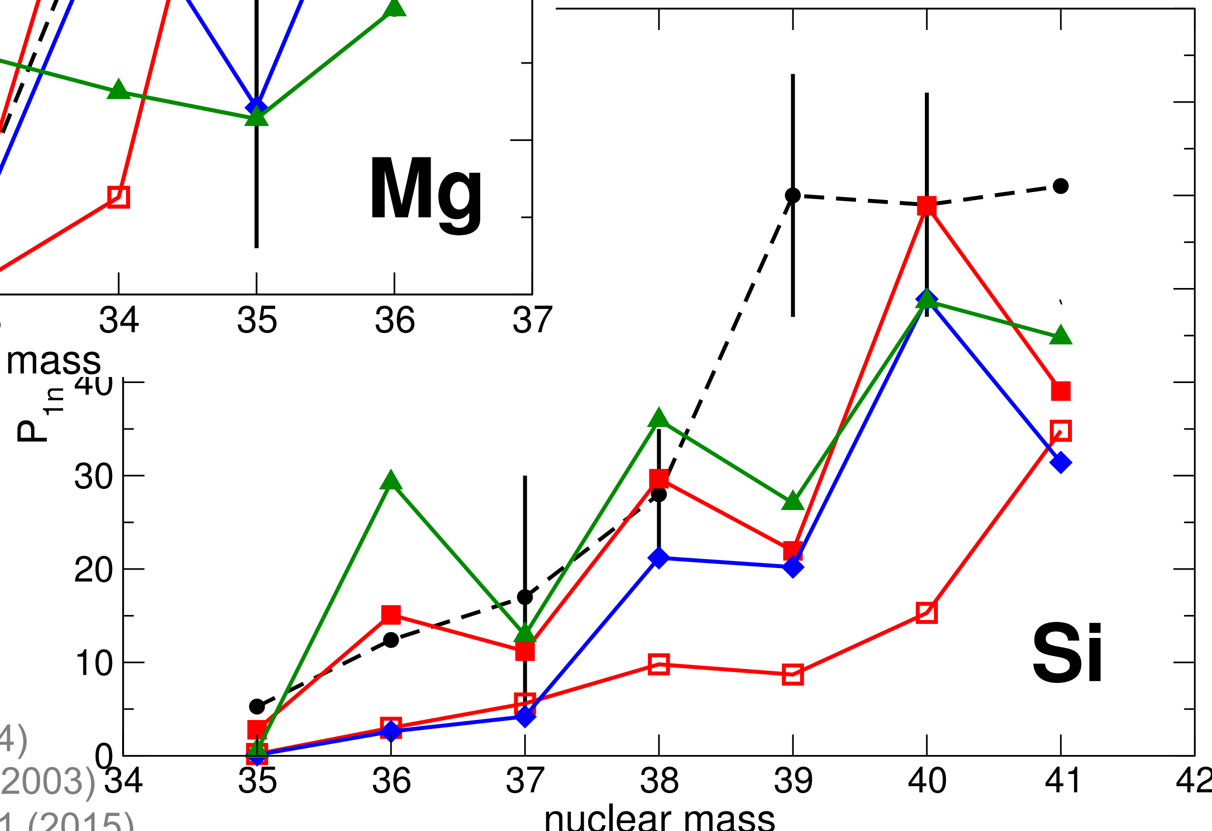
$$P_{xn} = \frac{1}{\lambda_{tot}} \sum_{E_i = S_{xn}}^{S_{(x+1)n}} \lambda_i$$

$$\langle n \rangle = \sum_k k \times P_{kn}$$

R. Caballero-Folch *et al.*, Phys. Rev. Lett. 117, 012501 (2016)

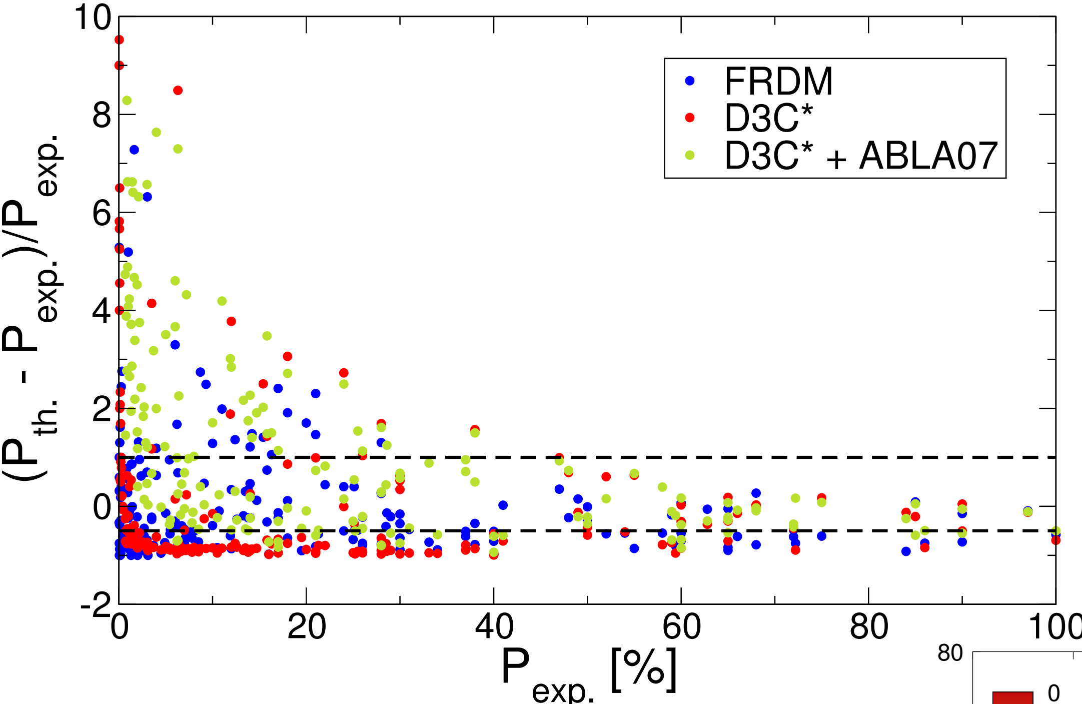


Combining beta-decay branching ratios and energies with ABLA07 γ- and neutron emission cross-sections.



Better agreement with available data, and competitive with other models.

K. Miernik, Phys. Rev. C 90, 054306 (2014)
P. Möller *et al.*, Phys. Rev. C 67, 055802 (2003)
M. Birch *et al.*, Nucl. Data Sheets 128, 131 (2015)

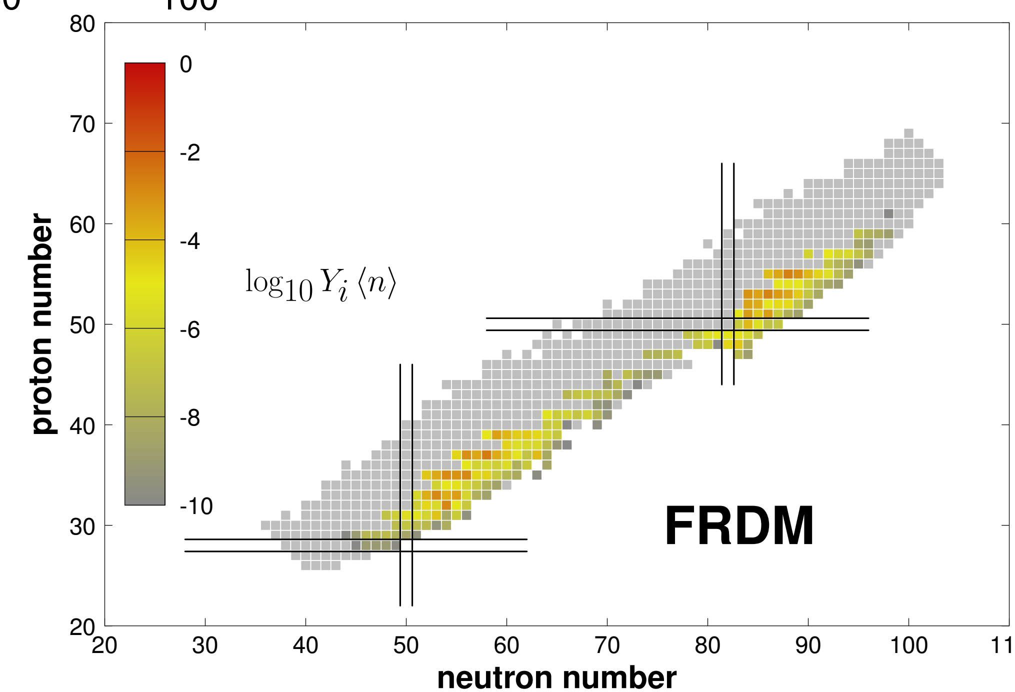


	avg.	st. dev.
FRDM	-0.320	0.581
D3C*	-0.315	0.756
D3C* + ABLA07	0.057	0.689

Data mostly available for nuclei with relatively small Q values – small emission probabilities.

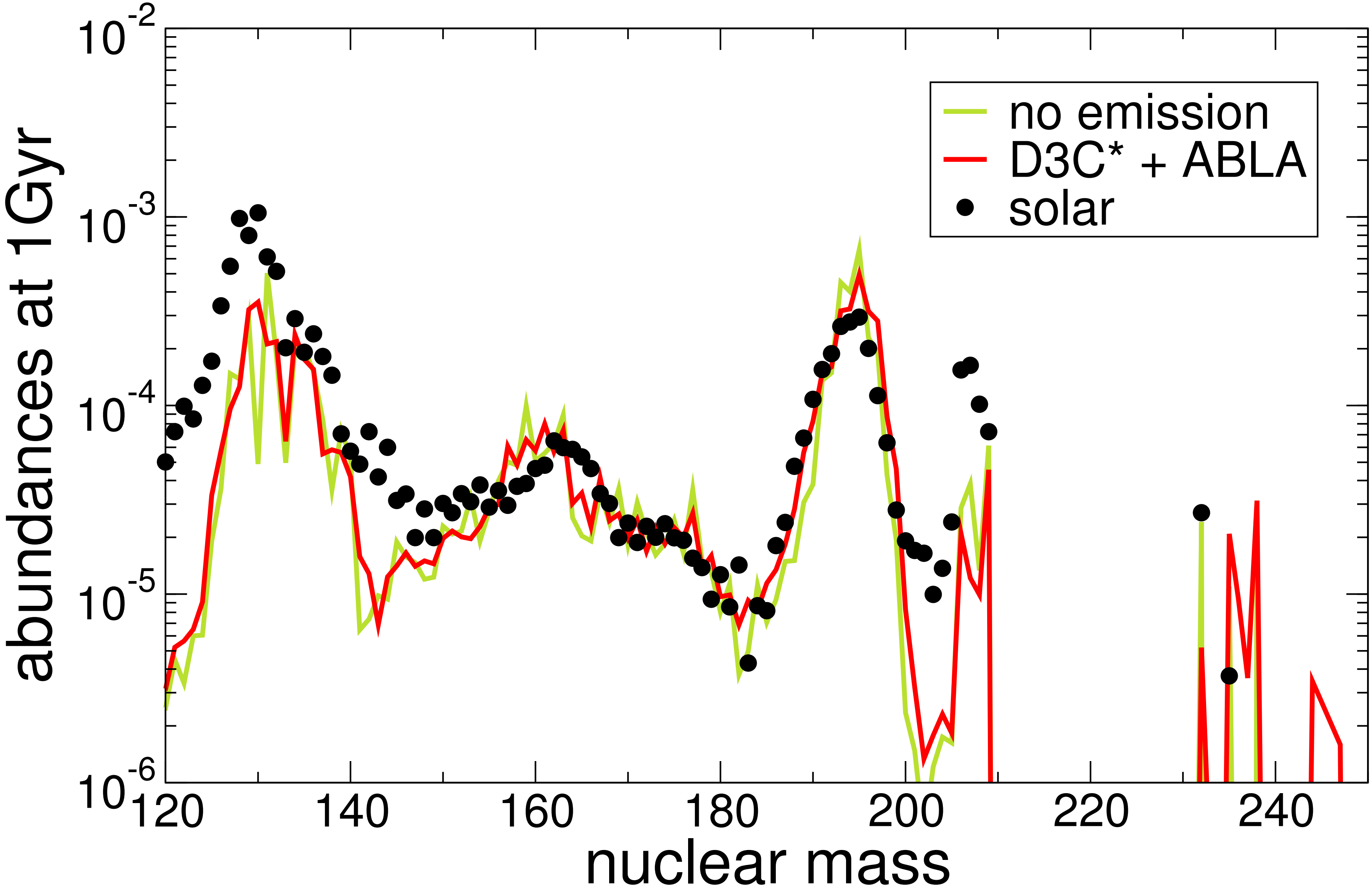
Other observables are available – avg. number of delayed neutrons from fission of ^{235}U.

$$\langle n \rangle^{^{235}U} = 0.0158 \pm 0.0005$$



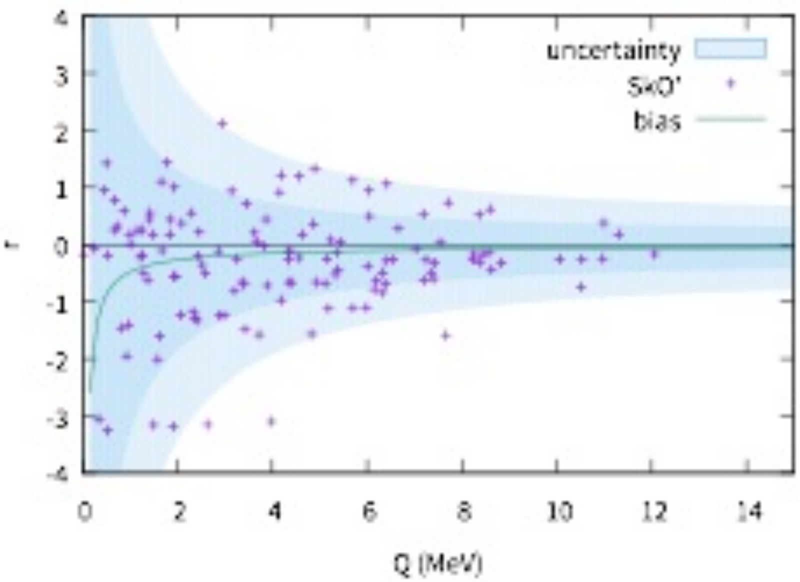
G. R. Keepin *et al.*, Phys. Rev. 107, 1044 (1957)

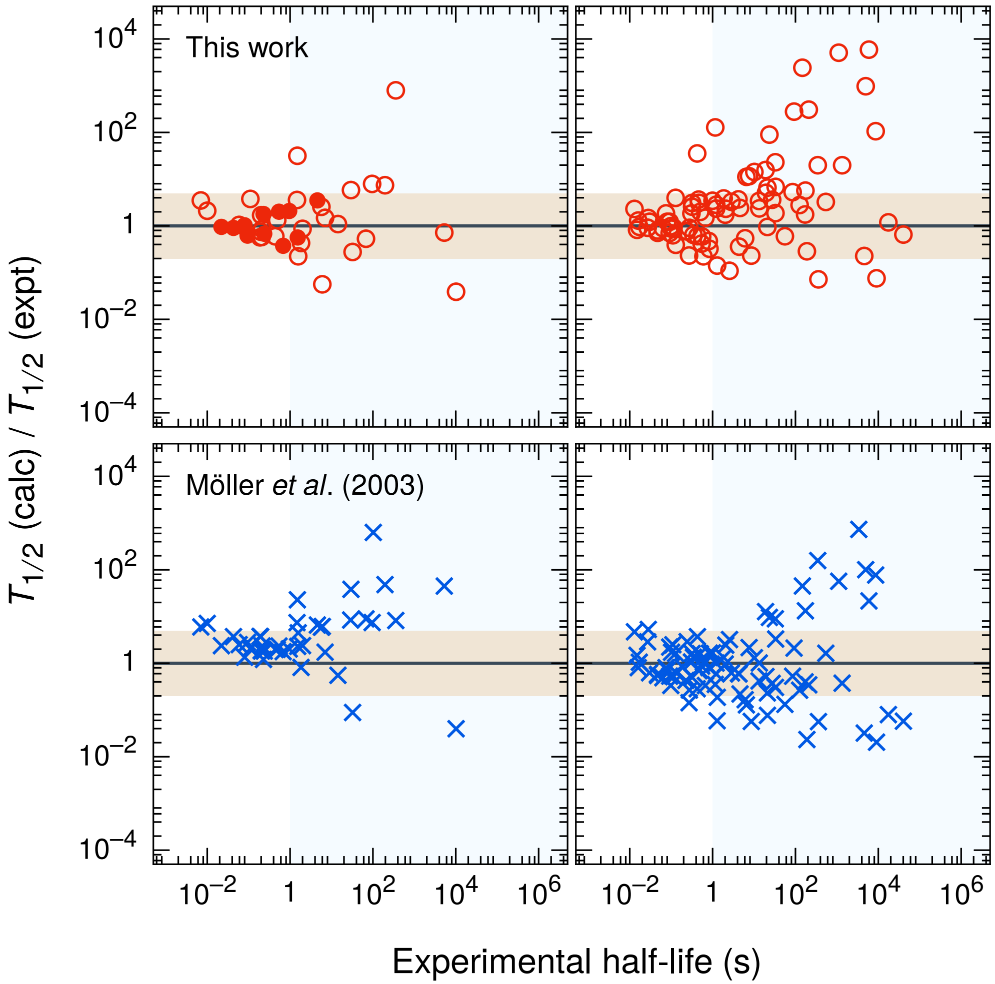
Beta-delayed neutron emission does affect the resulting abundance pattern.



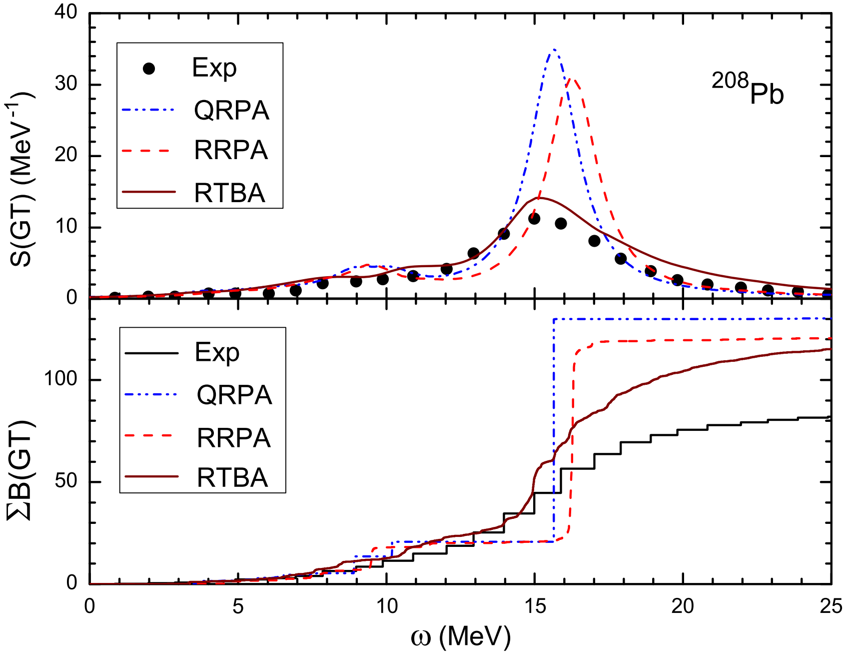
Calculation based on the finite amplitude method (FAM) – a formulation of the QRPA which allows for a quick determination of the nuclear response.

The interaction was also adjusted to dynamic properties of select nuclei – improved description of decay properties.



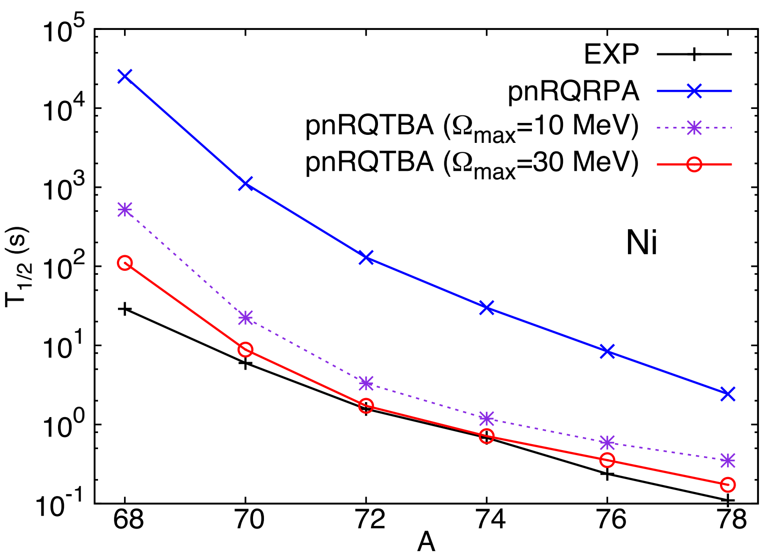


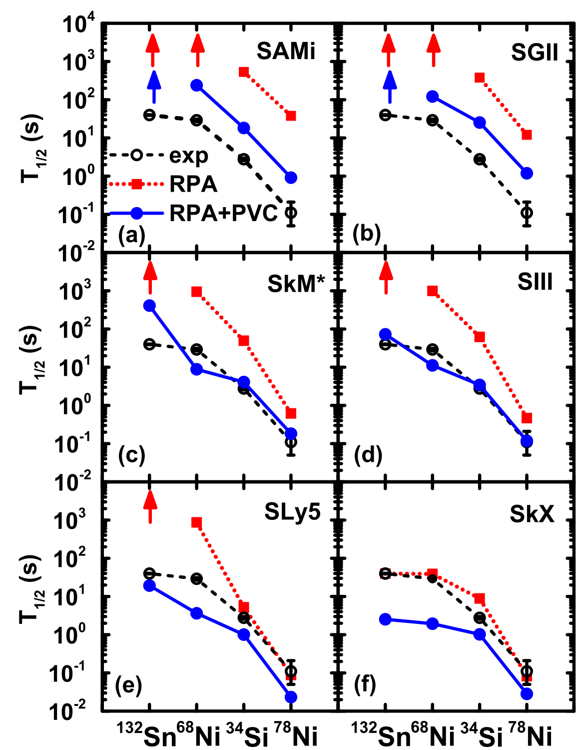
M. T. Mustonen and J. Engel, Phys. Rev. C 93, 014304 (2016)
T. Schafer *et al.*, arXiv: 1606.05909 [nucl-th]



QVC correlations push states towards the Fermi energy – enhancing the density of states in vicinity of the FE.

Excellent description of GT resonance in ^{208}Pb and half-lives of the Ni chain.





E. Litvinova, Phys. Rev. C 85, 021303(R) (2012)
E. Litvinova *et al.*, Phys. Lett. B 730, 307 (2014)
C. Robin and E. Litvinova, Eur. Phys. J. A 52, 2015 (2016)
Y. F. Niu et al., Phys. Rev. Lett. 114, 142501 (2015)