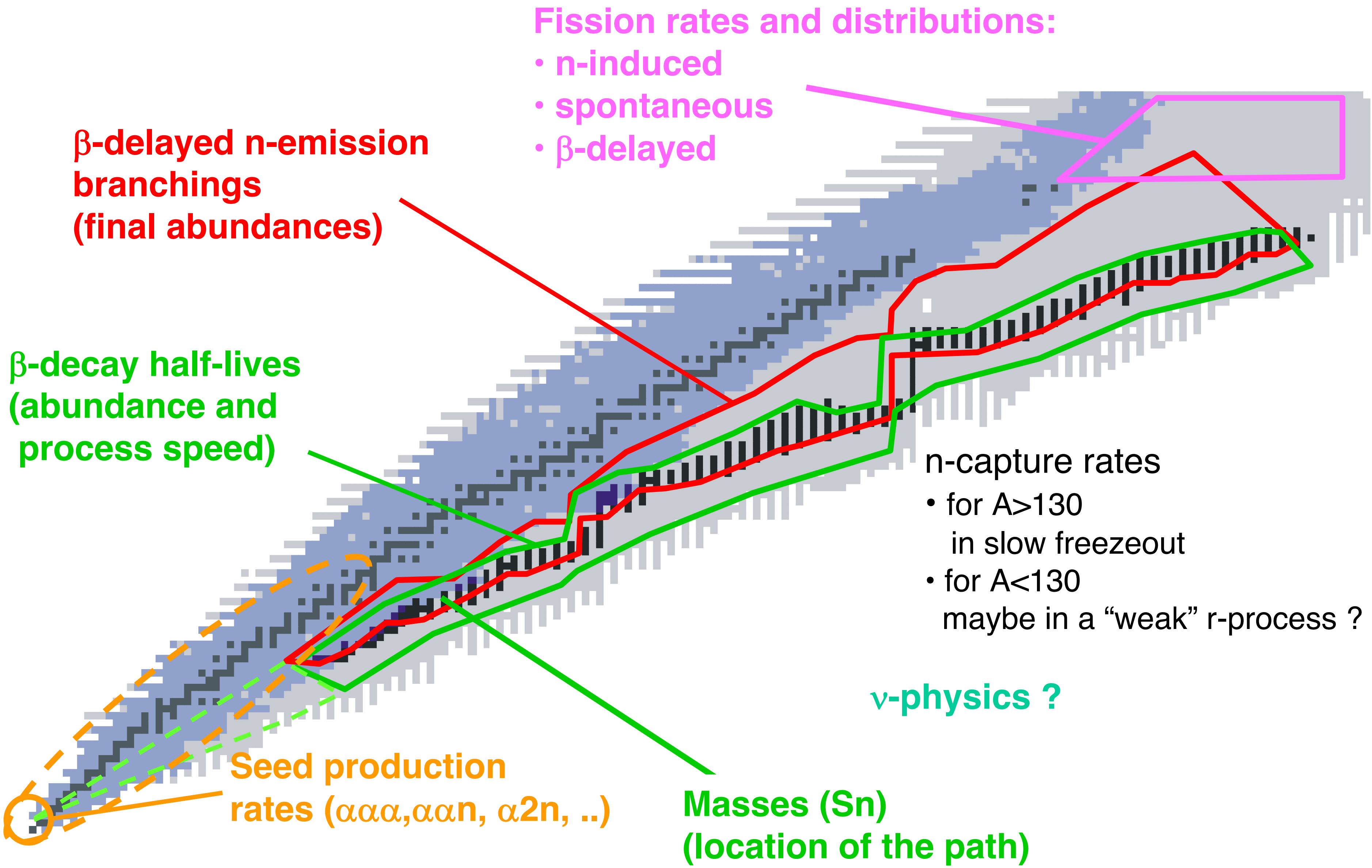
Microscopic calculations of β-decay rates for r-process

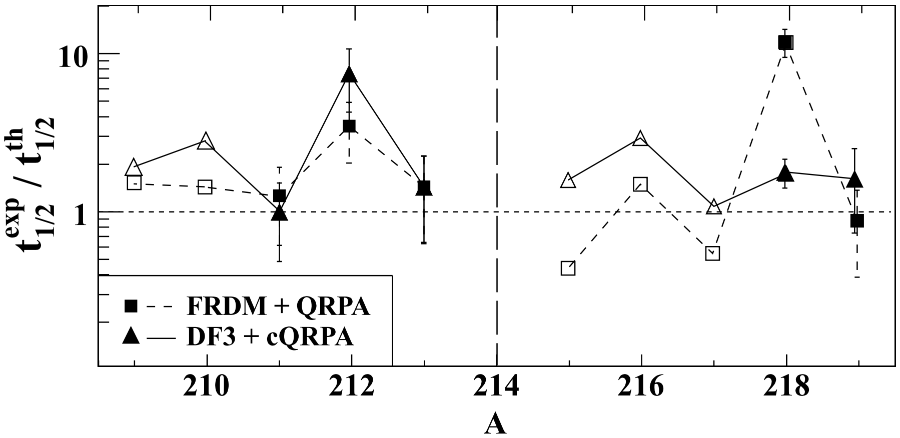
T. Marketin

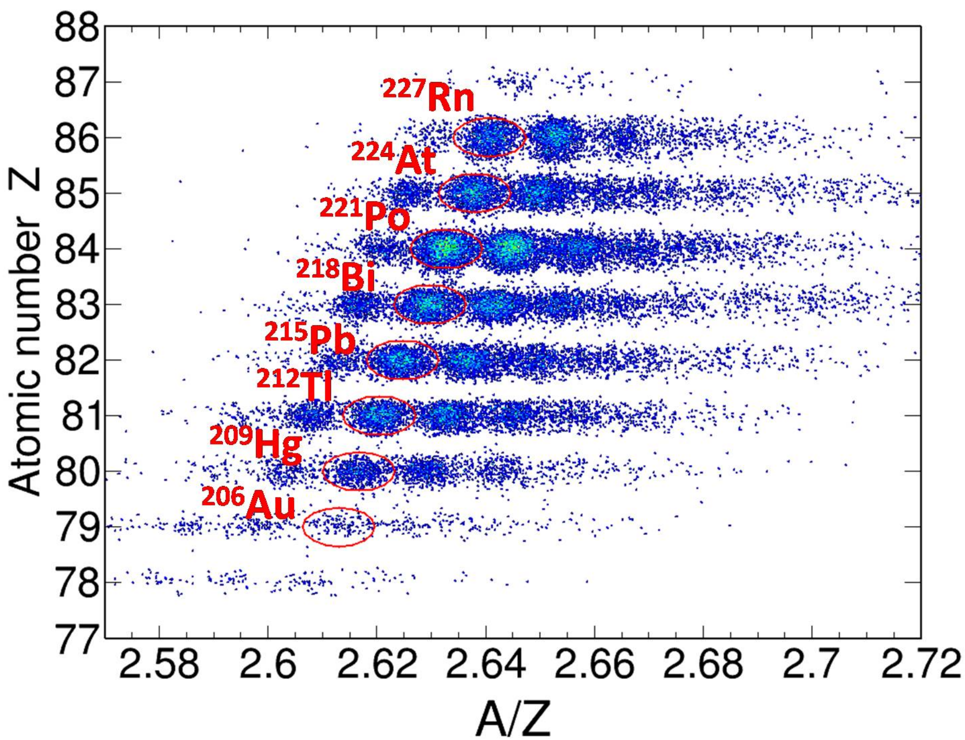
NAVI Physics Days

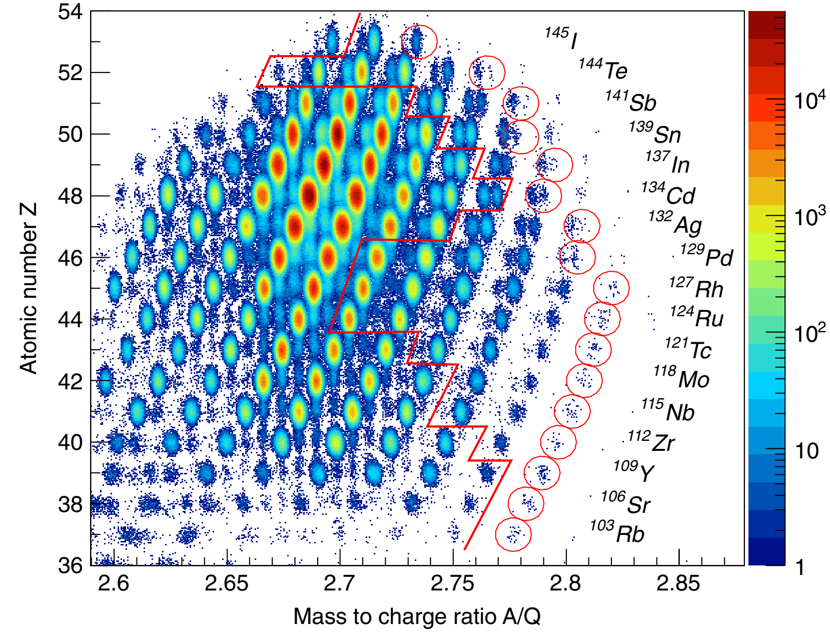
GSI, January 2016.

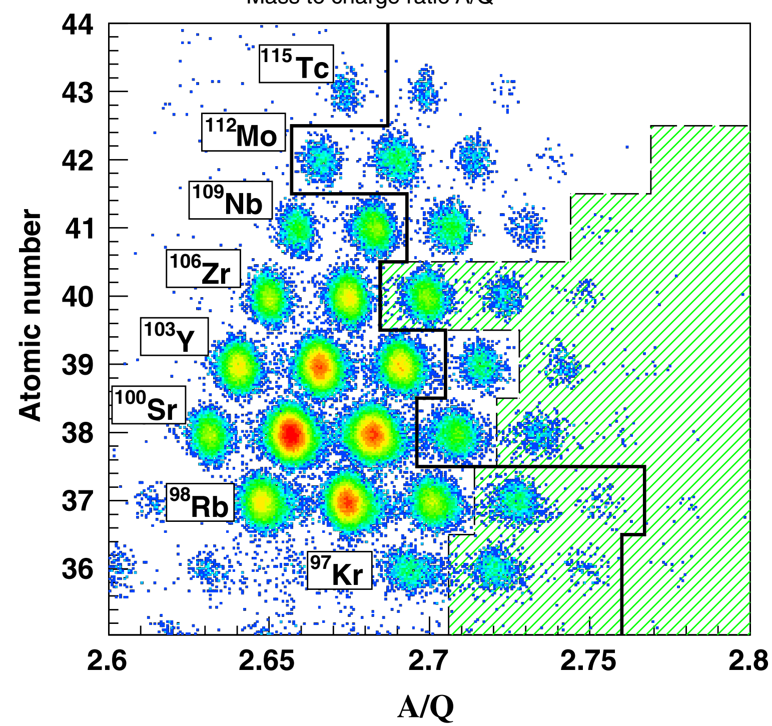


Fission rates and distributions:
• n-induced
• spontaneous
• β-delayed
β-delayed n-emission branchings (final abundances)
β-decay half-lives (abundance and process speed)
n-capture rates
• for A>130 in slow freezeout
• for A<130 maybe in a “weak” r-process ?
ν-physics ?
Seed production rates (ααα,ααn,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

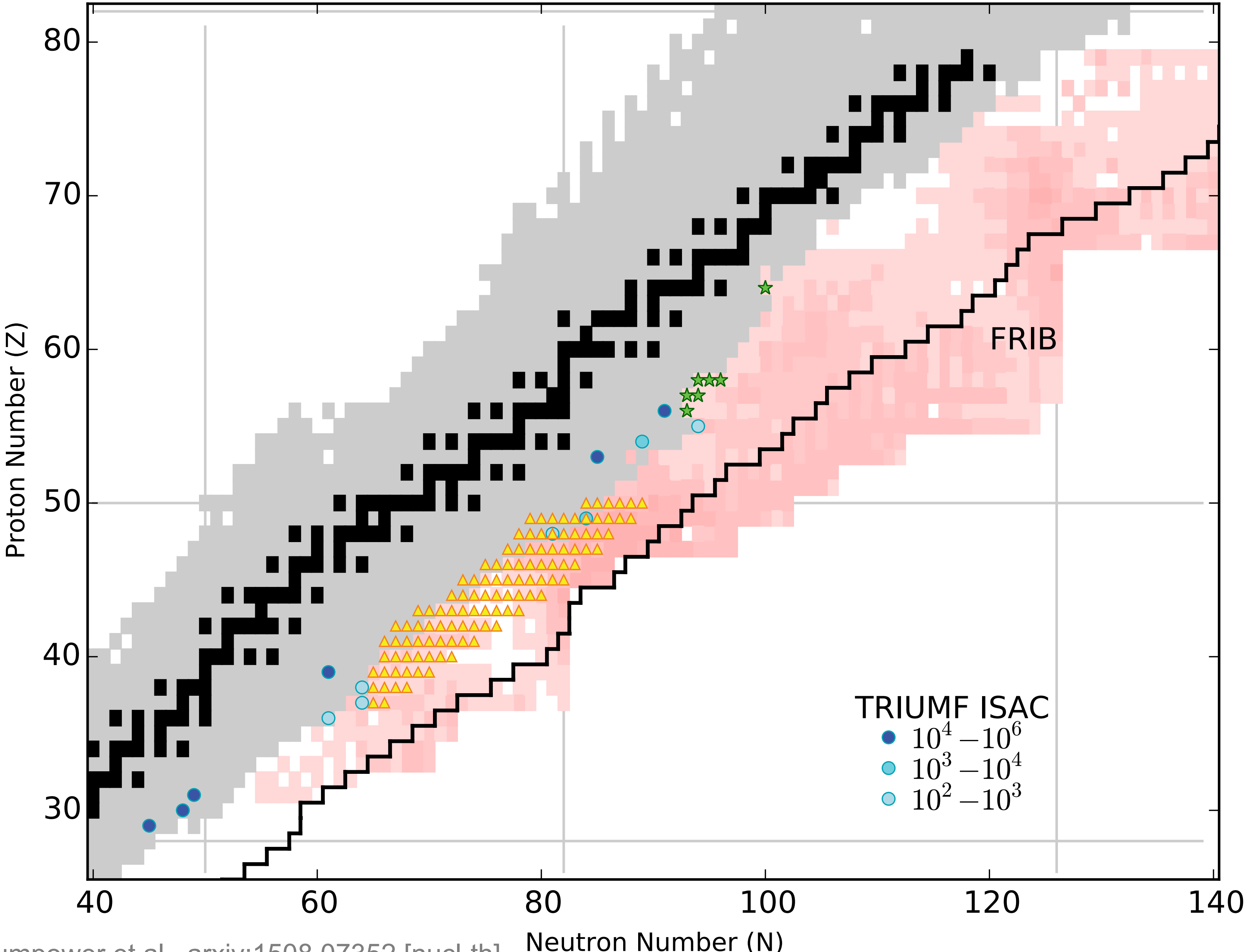




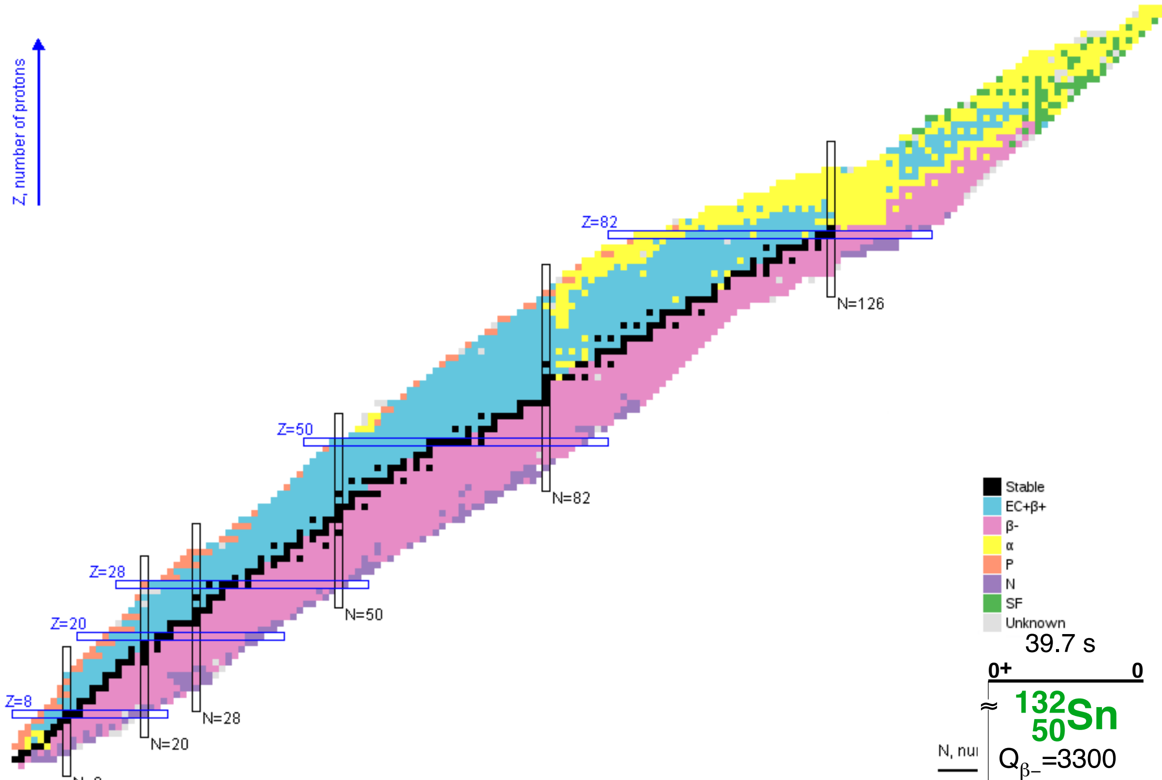


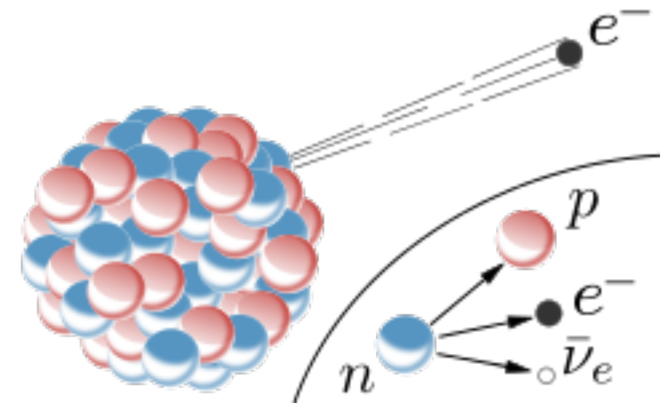


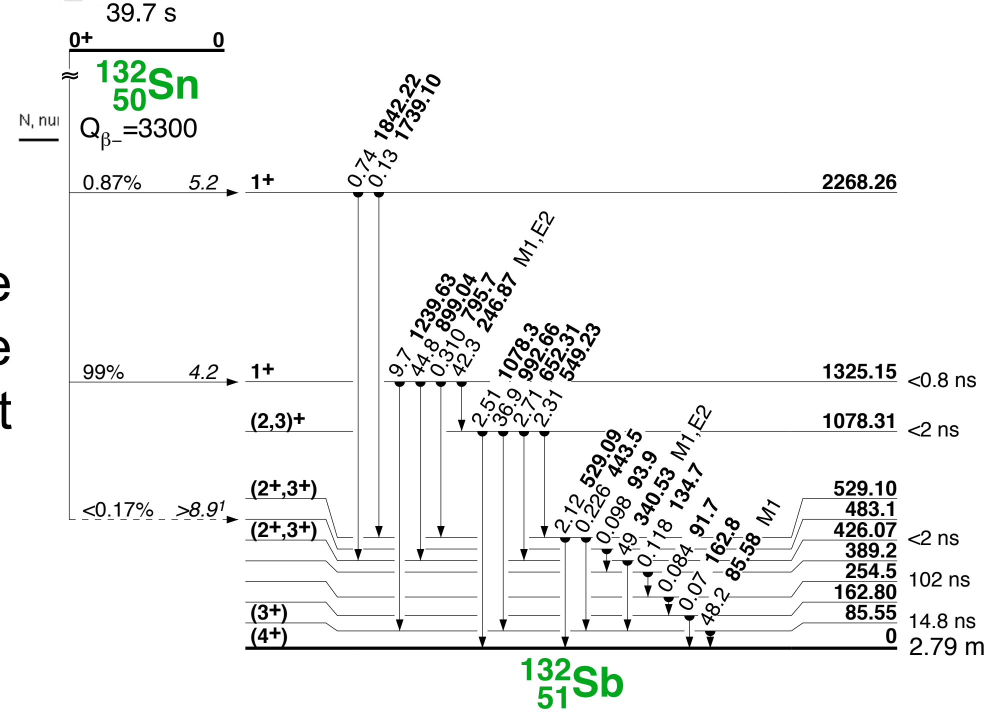
G. Lorusso et al., PhysRevLett 114, 192501 (2015)
R. Caballero-Folch et al., arxiv:1511.01296 [nucl-ex]
S. Nishimura et al., Phys. Rev. Lett. 106, 052502 (2011)



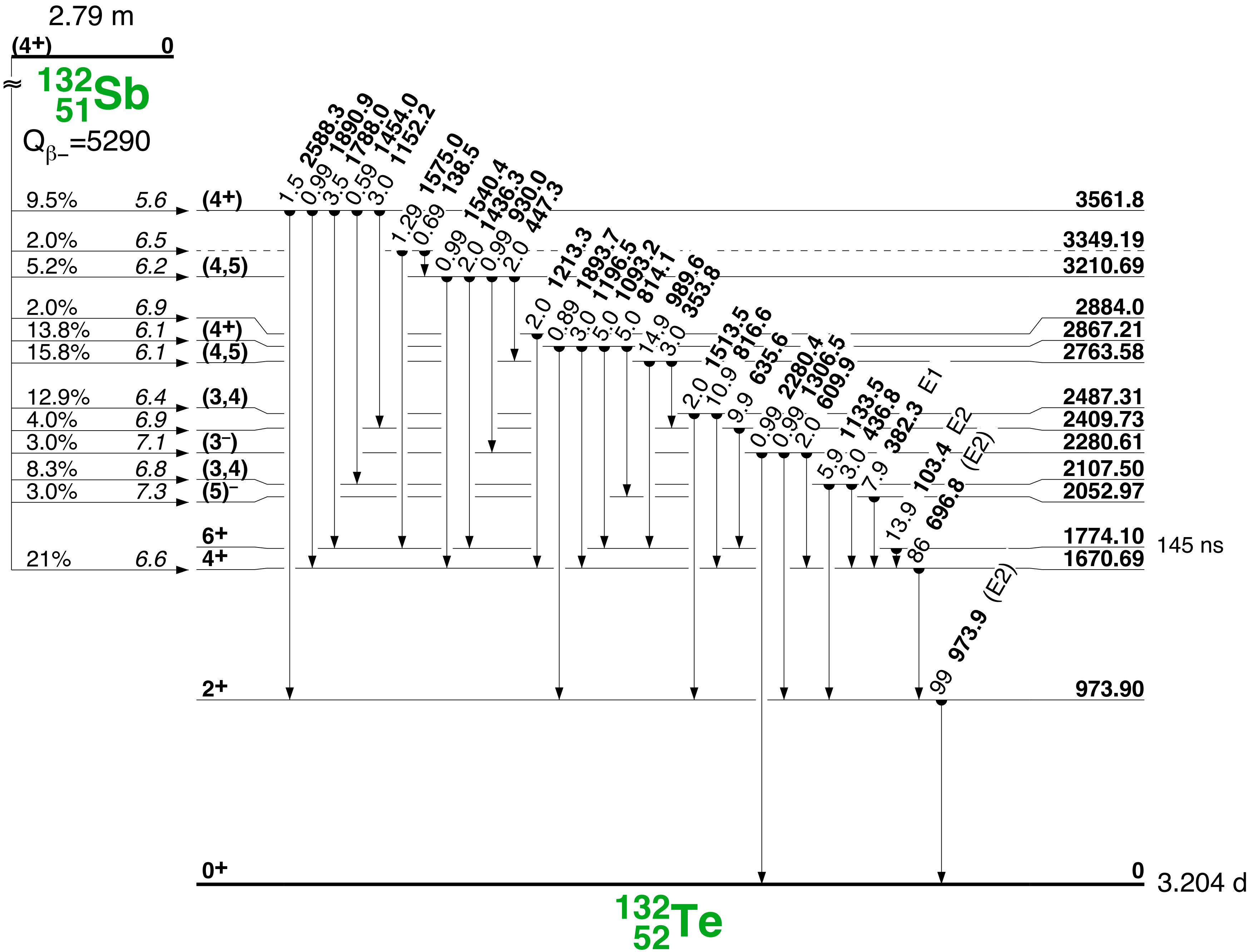
M. Mumpower et al., arxiv:1508.07352 [nucl-th]



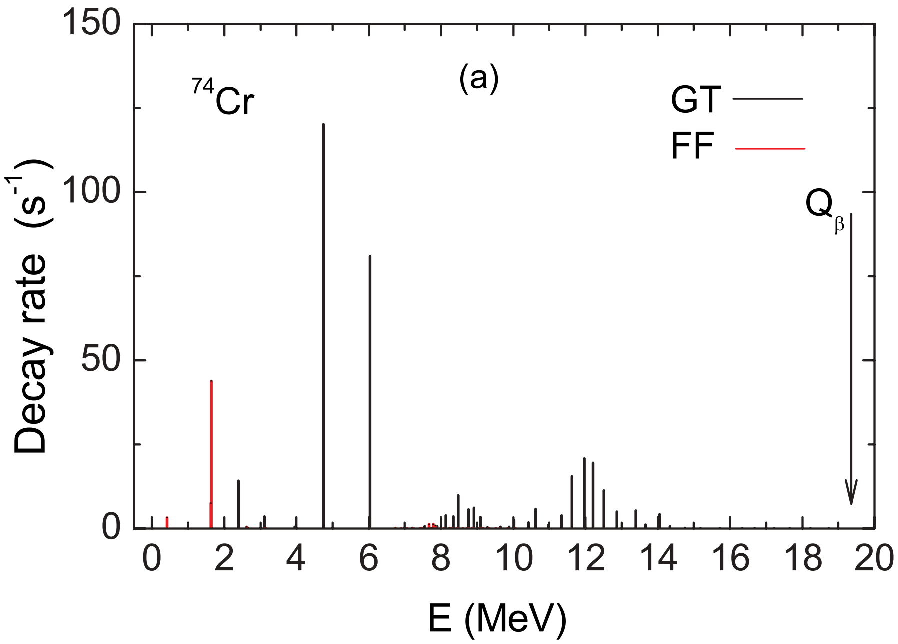


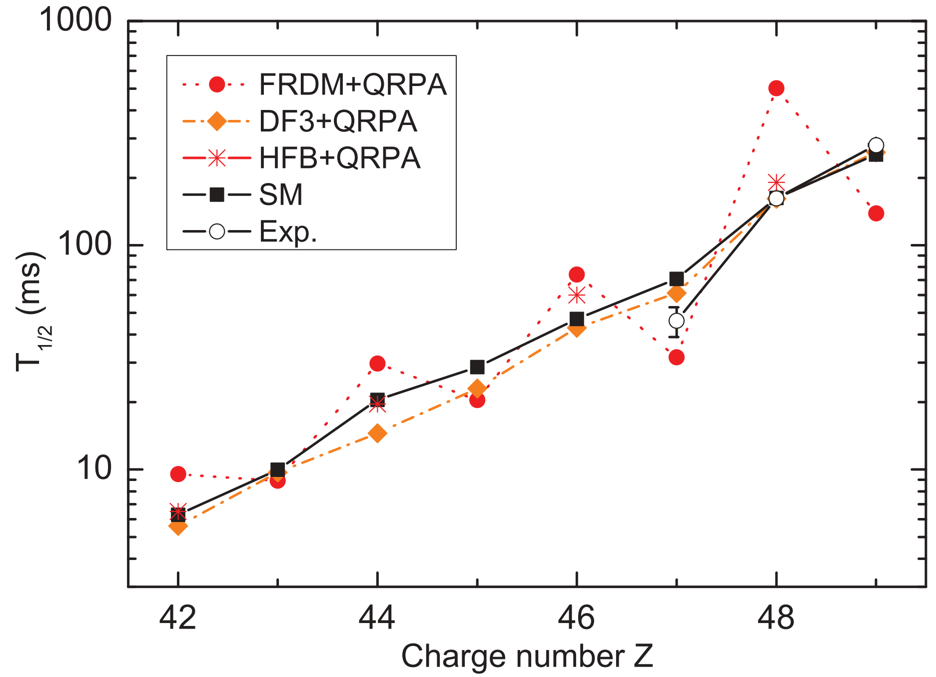


In some nuclei the decay is quite simple and is dominated by a single allowed transition from the parent ground state.

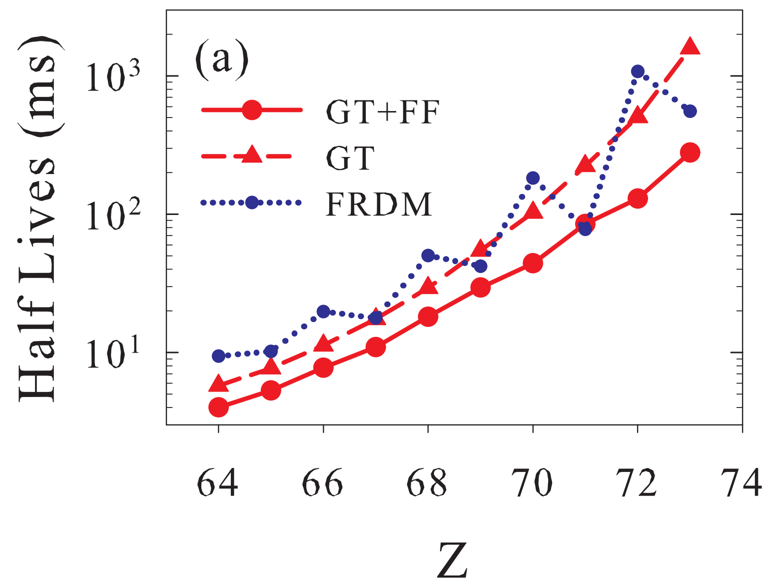


2.79 m
(4+) 0
132 51 Sb
Qβ−=5290
9.5% 5.6
2.0% 6.5
5.2% 6.2
2.0% 6.9
13.8% 6.1
15.8% 6.1
12.9% 6.4
4.0% 6.9
3.0% 7.1
8.3% 6.8
3.0% 7.3
21% 6.6
(4+)
(4,5)
(4+)
(4,5)
(3,4)
(3−)
(3,4)
(5)−
6+
4+
2+
0+
3561.8
3349.19
3210.69
2884.0
2867.21
2763.58
2487.31
2409.73
2280.61
2107.50
2052.97
1774.10
1670.69
973.90
0
145 ns
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
E2
103.4 (E2)
13.9
86 696.8
99 973.9 (E2)
132 52 Te





Shell model calculations are usually precise – but limited to nuclei around the closed proton and neutron shells.



Q. Zhi et al., Phys. Rev. C 87, 025803 (2015)
T. Suzuki et al., Phys. Rev. C 85, 015802 (2012)

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

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

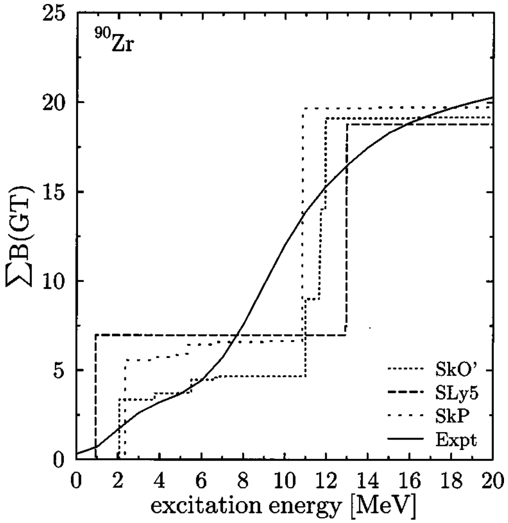
$$T_{1/2} = \frac{\ln 2}{\lambda}, \qquad D = \frac{(G_F V_{ud})^2}{2\pi^3}\frac{\left(m_e c^2\right)^5}{\hbar}$$

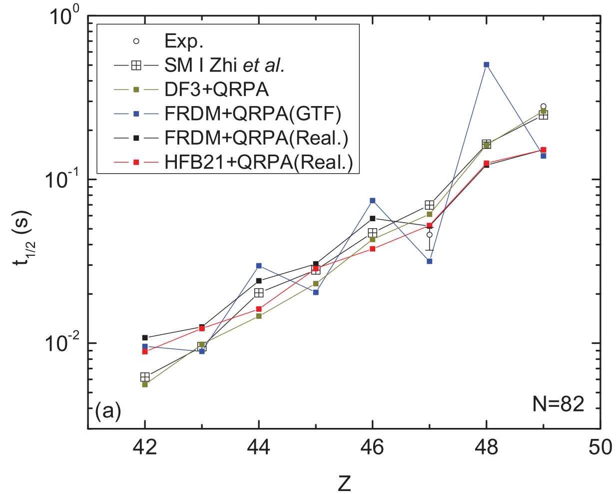
Allowed decay shape factor:

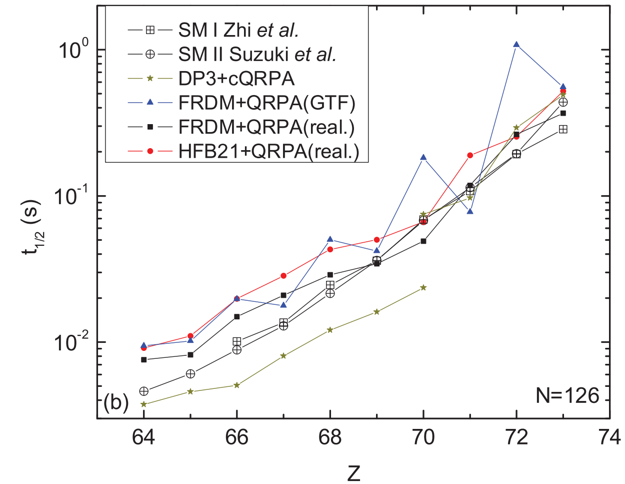
$$C(W) = B(GT)$$

First-forbidden transitions shape factor

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

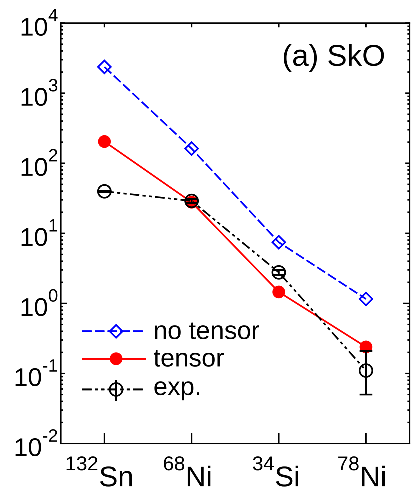


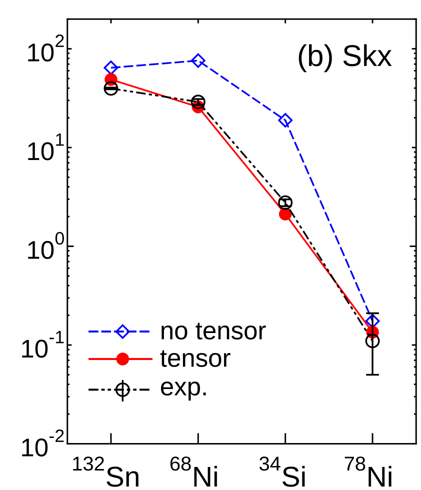




QRPA calculations are numerically less expensive – method of choice for large scale calculations.

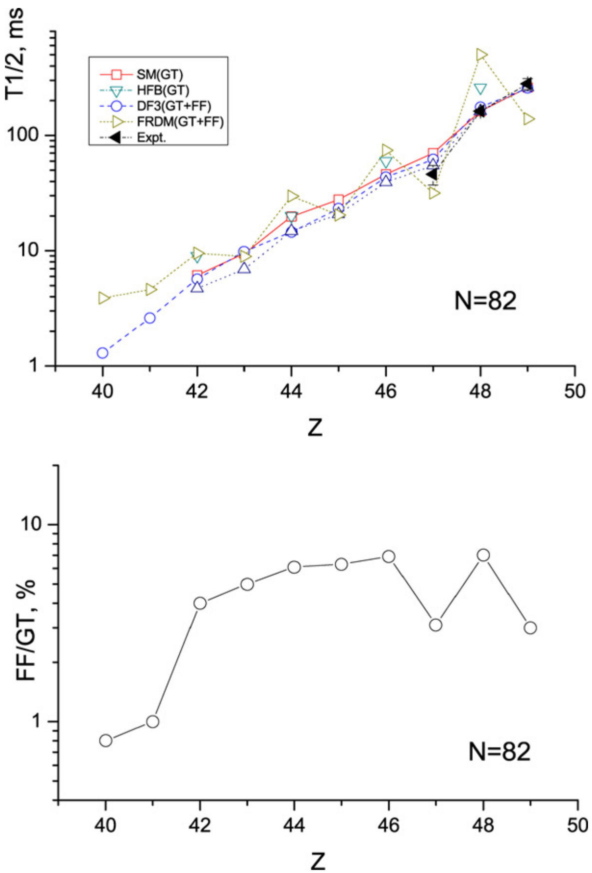
Self-consistent calculations are able to use a single interaction. Choice of interaction is critical for a good description of decay half-lives.

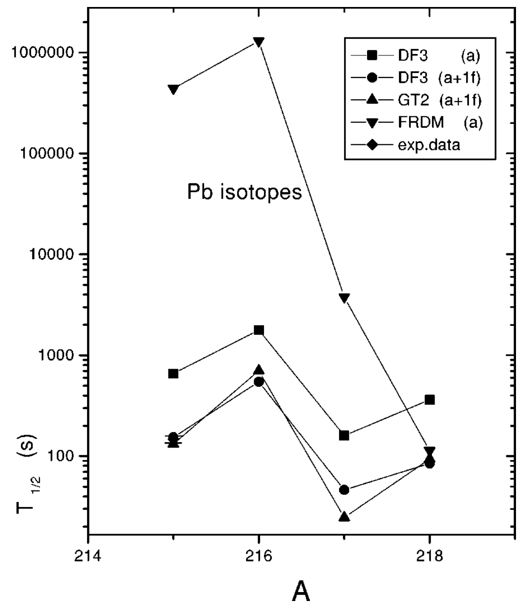


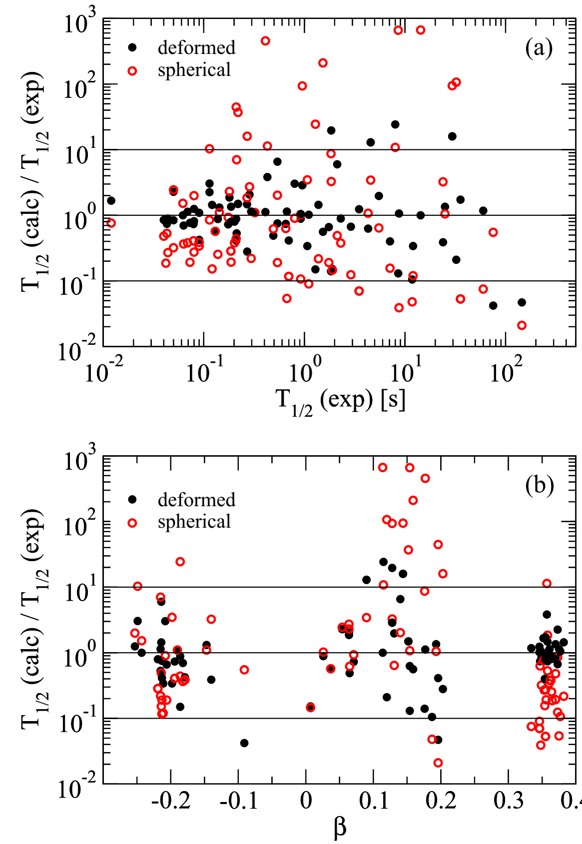


J. Engel et al., Phys. Rev. C 60, 014308 (1999)
D.-L. Fang et al., Phys. Rev. C 88, 034304 (2013)
F. Minato and C. L. Bai, Phys. Rev. Lett 110, 122501 (2013)

First-forbidden transitions can contribute a large part of the total decay rate in particular regions of the nuclear chart.

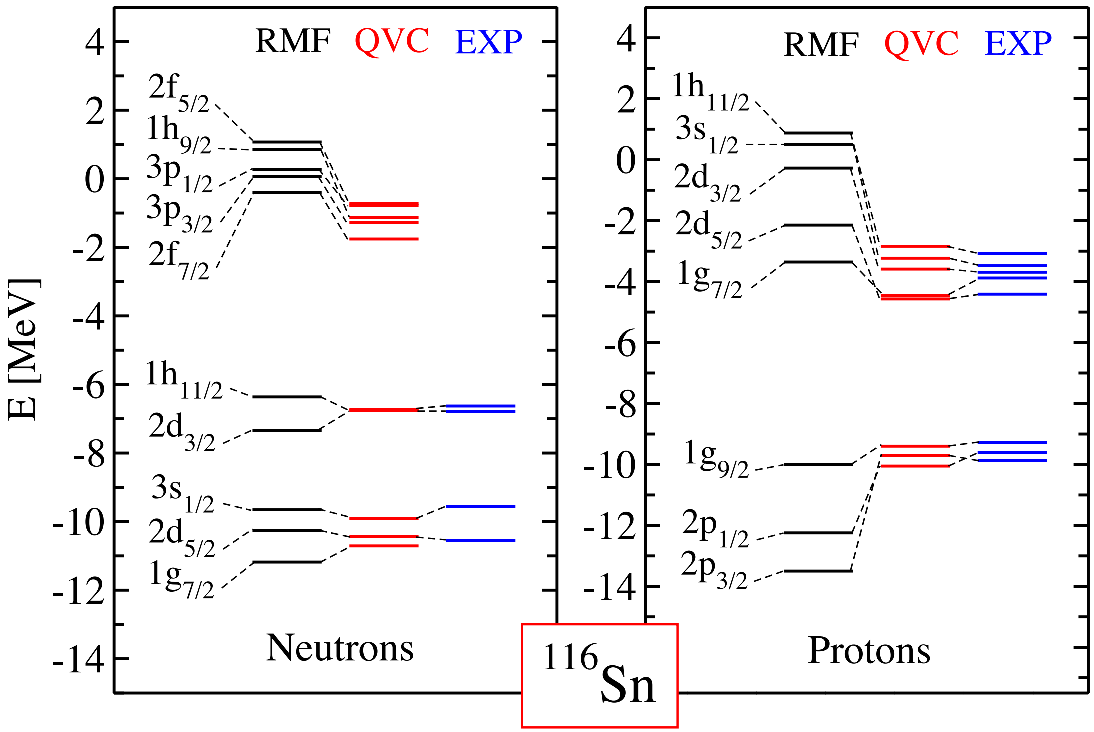






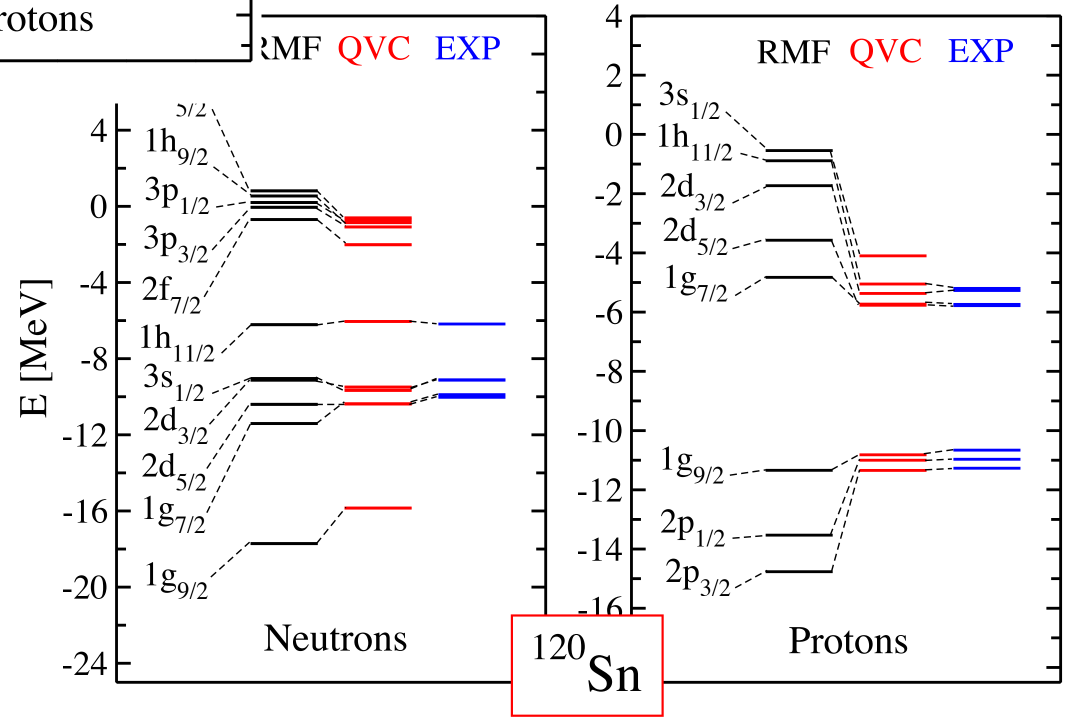
Deformation of the nuclear ground state impacts the decay properties of nuclei – an important, but difficult effect to include.

P. Sarriguren, Phys. Rev. C 91, 044304 (2015)
I. Borzov et al., Nucl. Phys. A 814, 159 (2008)
I. Borzov, Phys. Rev. C 67, 025802 (2003)

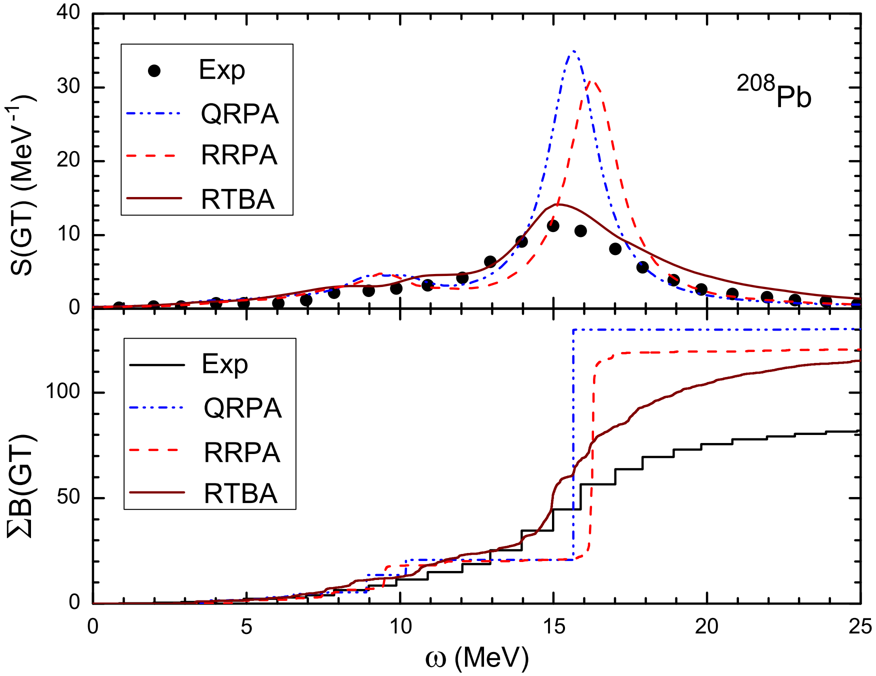


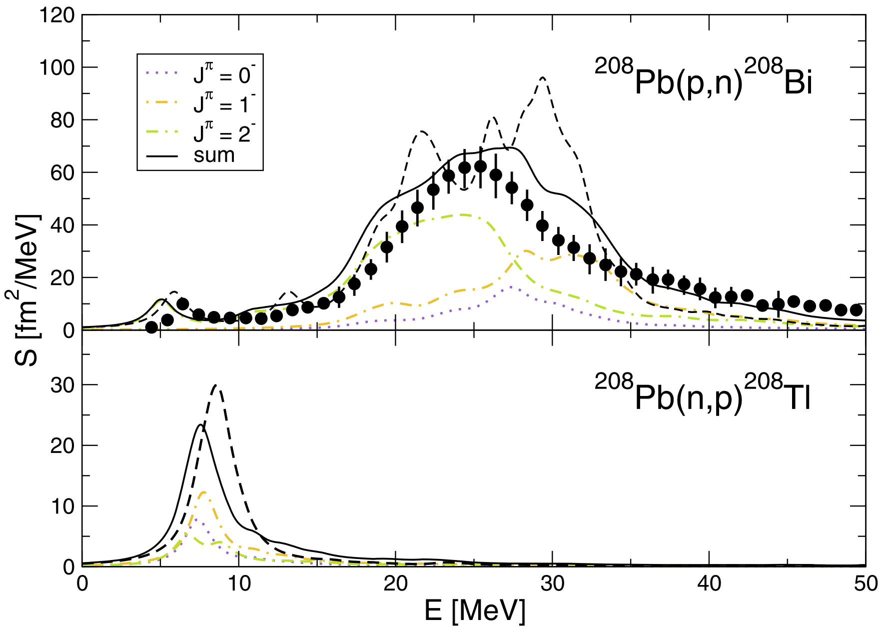
QVC correlations push states towards the Fermi energy – enhancing the density of states in vicinity of the FE.

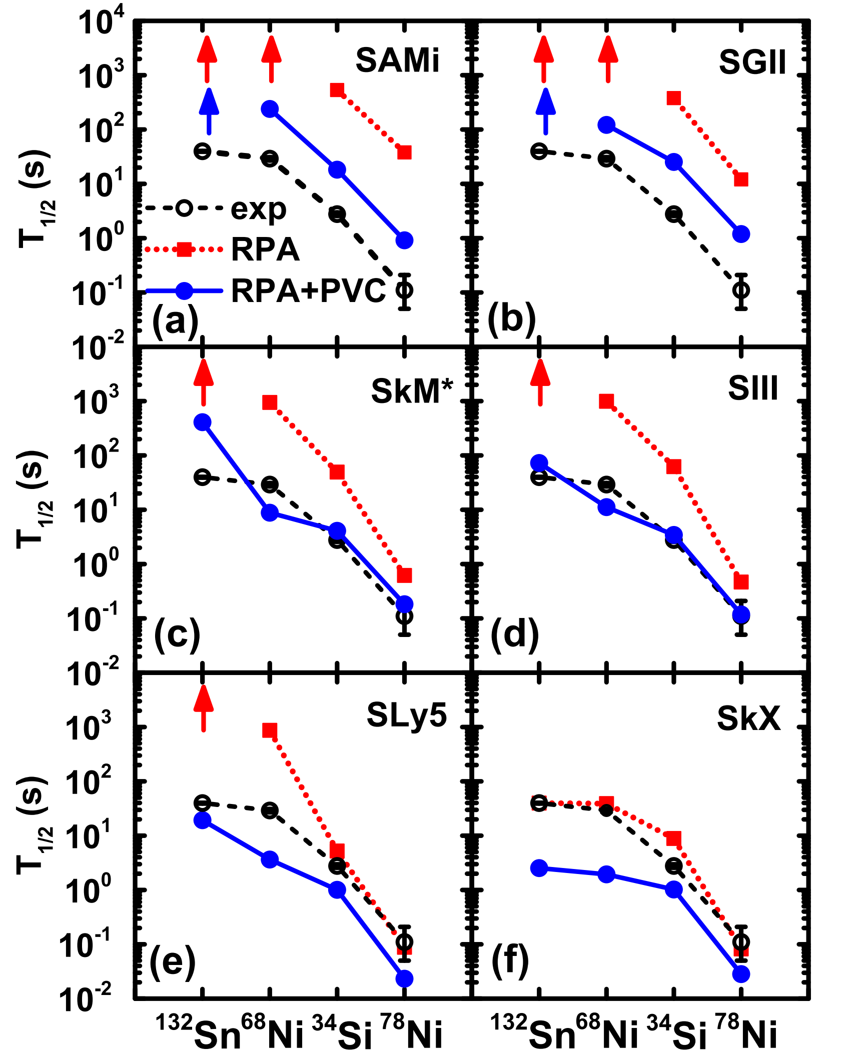
Phonon coupling enriches the RPA spectrum with additional transitions leading to significant fragmentation of the giant resonances.



E. Litvinova, Phys. Rev. C 85, 021303(R) (2012)

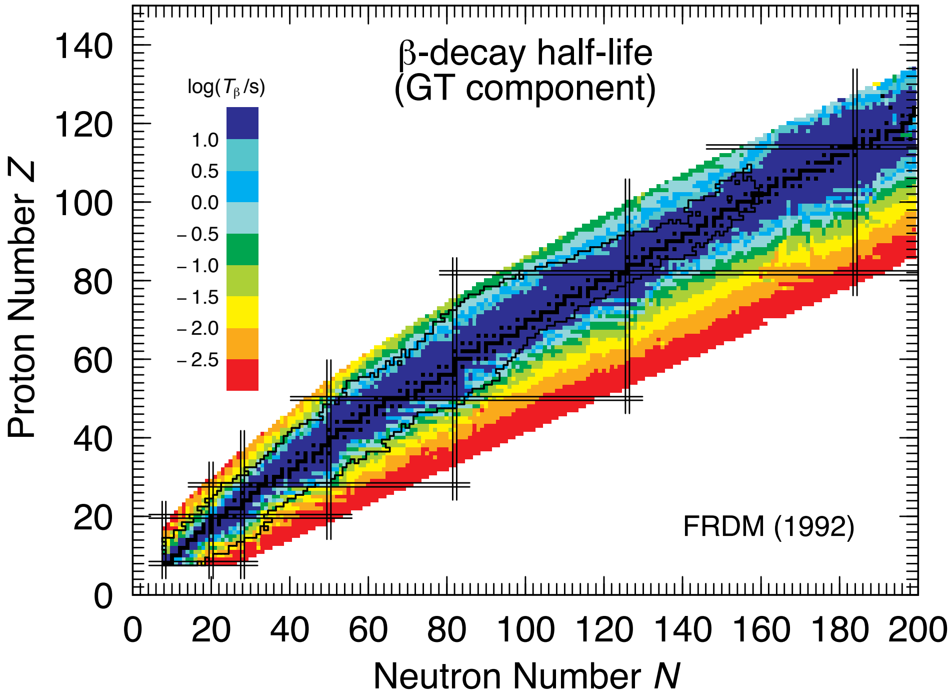




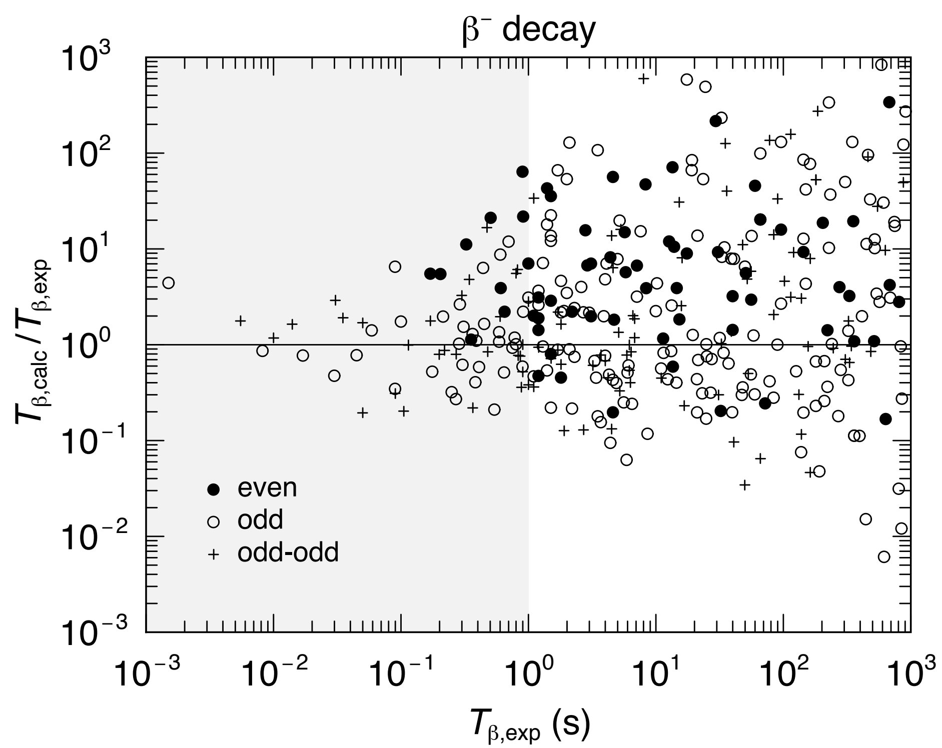


T. M. et al., Phys. Lett. B 706, 477 (2012)
E. Litvinova et al., Phys. Lett. B 730, 307 (2014)
Y. F. Niu et al., Phys. Rev. Lett 114, 142501 (2015)

Large-scale calculations

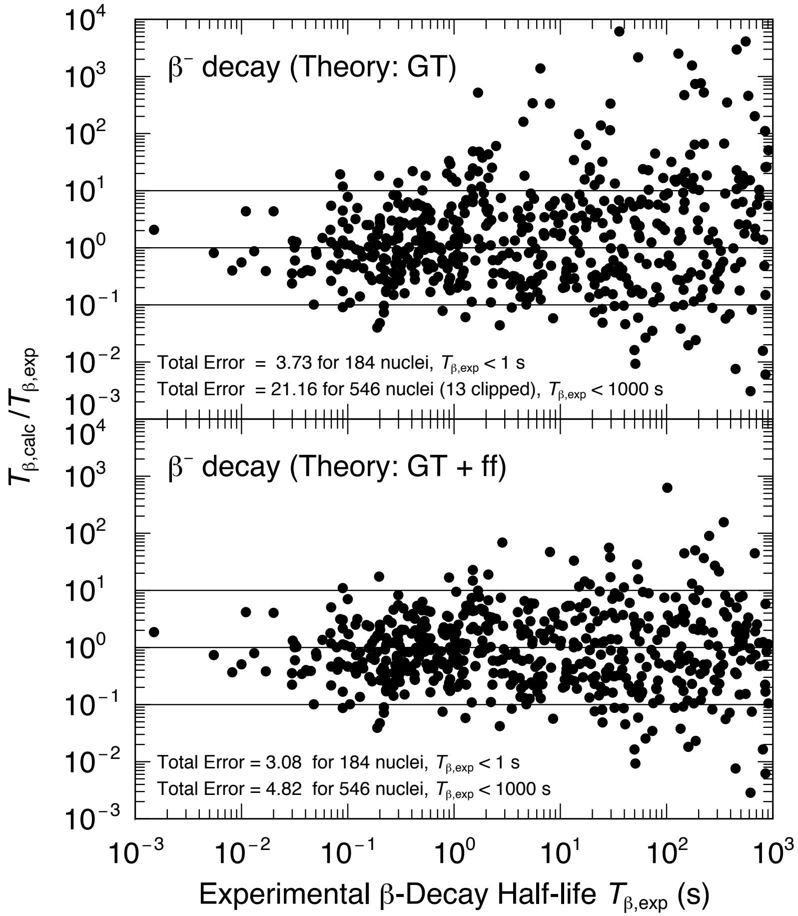


In 1997. the first large scale calculation of beta-decay half-lives was published based on finite range droplet model + QRPA.

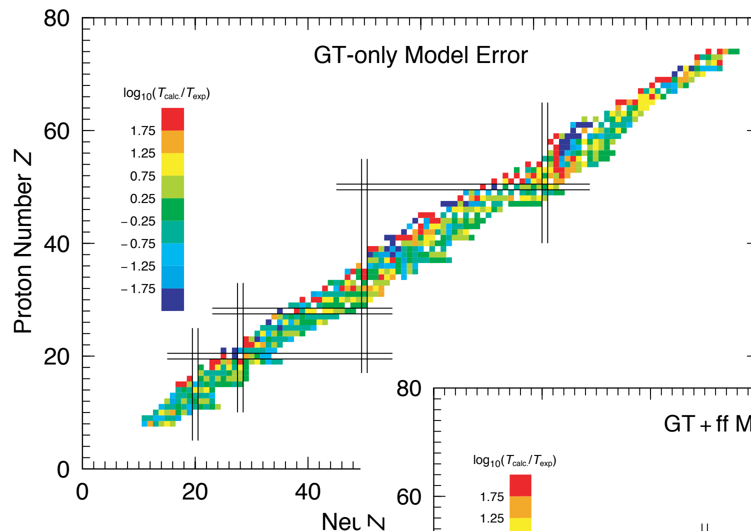


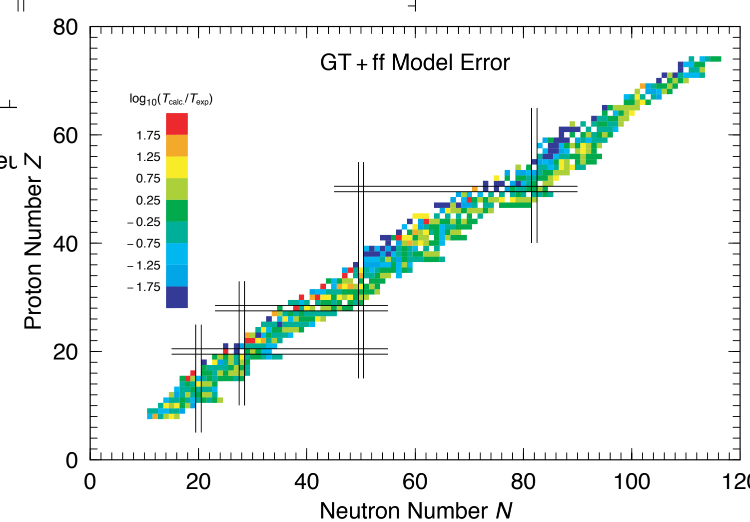
Deviations from the experimental values are reduced for very unstable nuclei + systematically underestimated rates for even-even nuclei.

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.

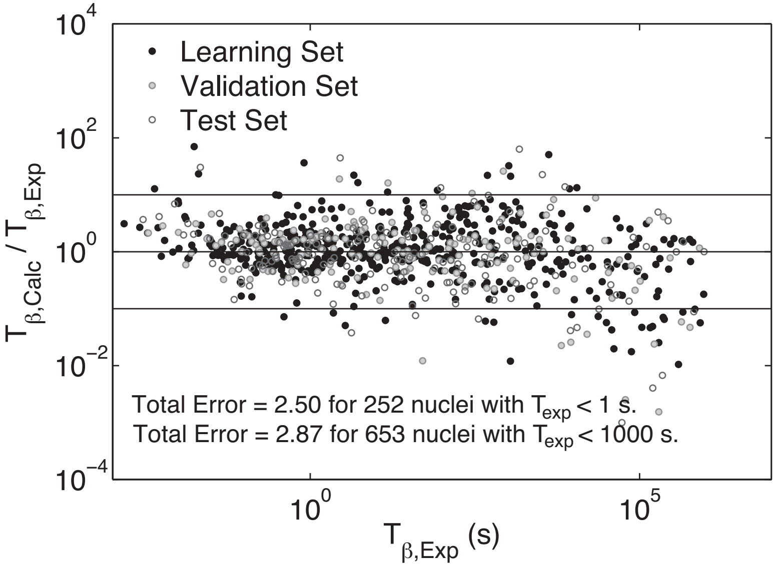


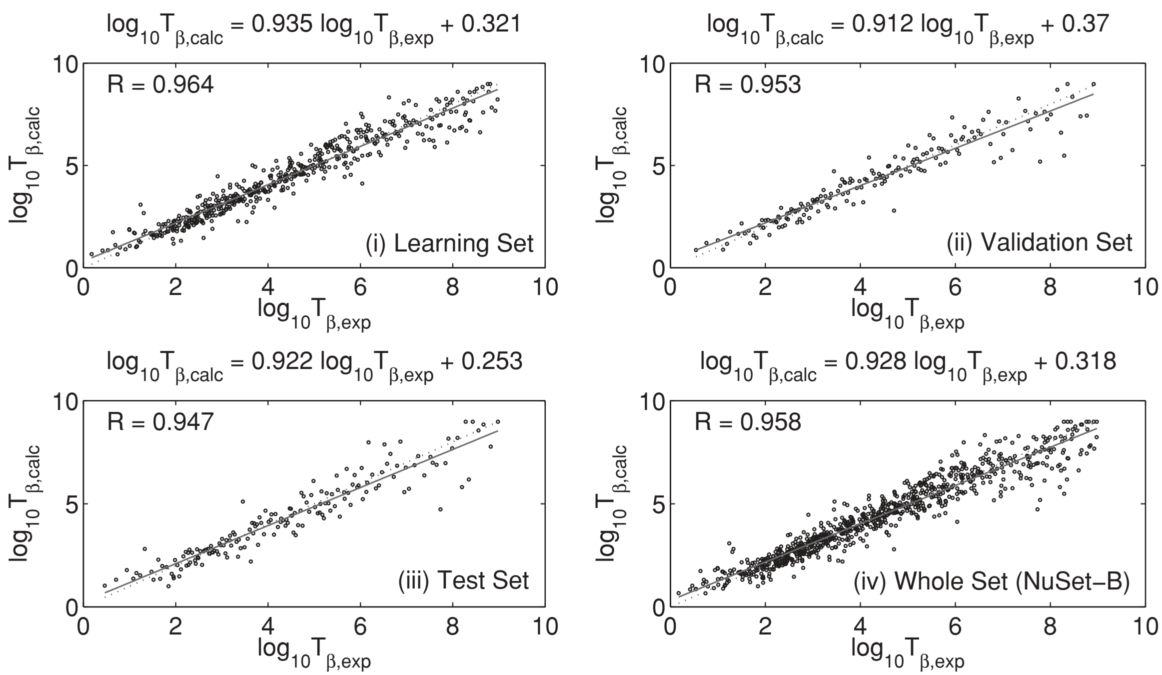


The first-forbidden transitions contribute to the decay rate mostly in nuclei close to the valley of stability.

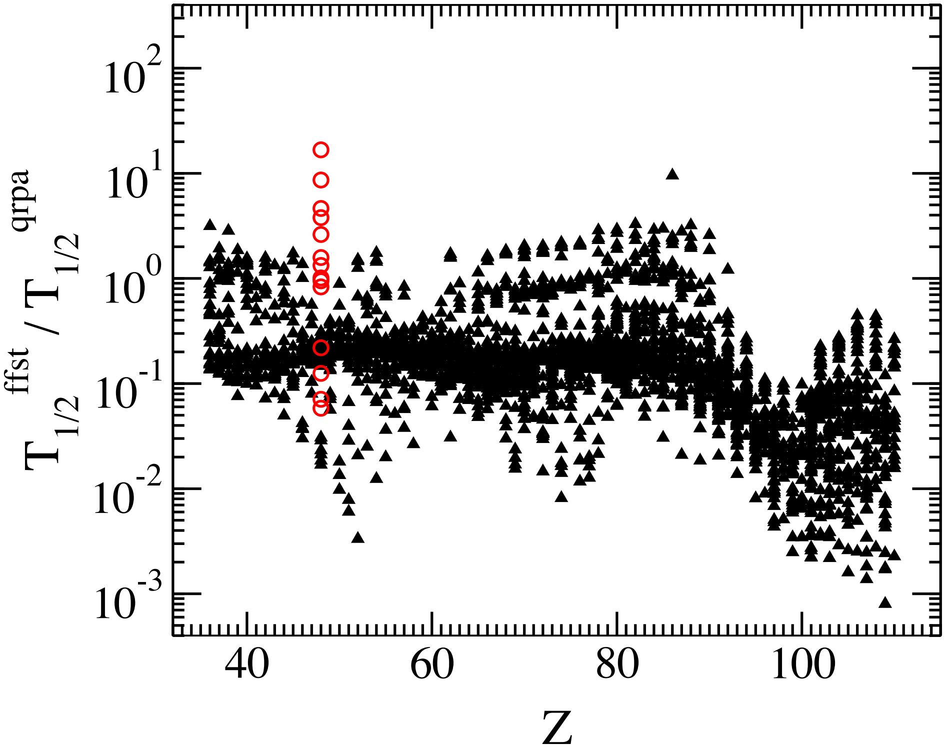
Statistical learning methods have also been applied to the problem of beta-decay half-lives.

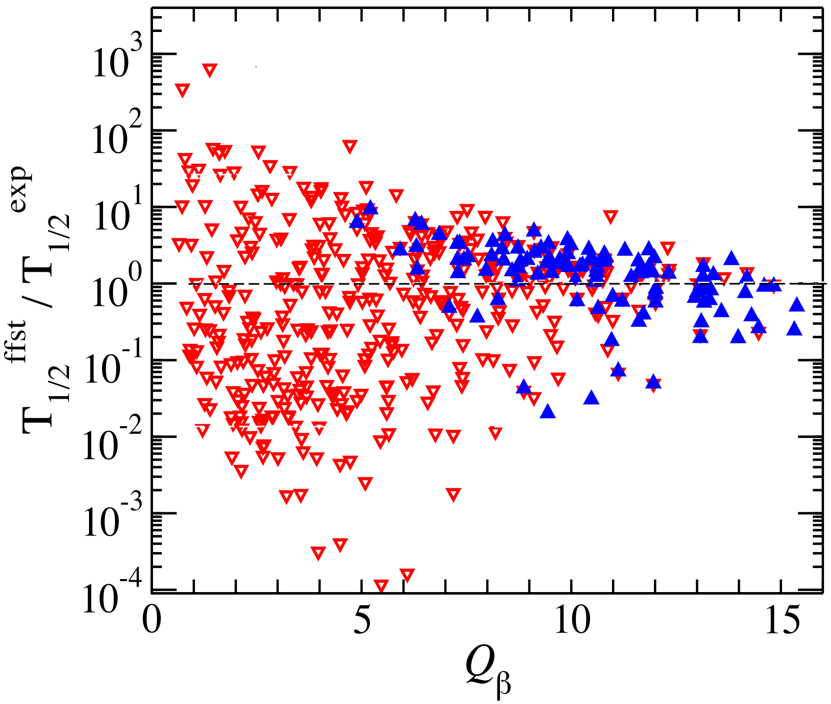
Model is based on a fully connected artificial neural network attempting to learn the behaviour of nuclear decay properties.



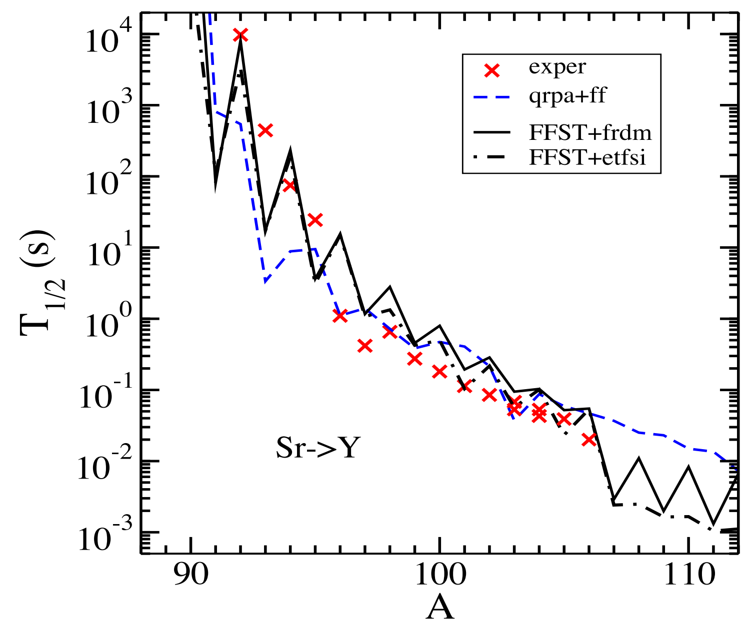


Deviations do not show any dependence on the experimental half-lives – all data have the same weight in the learning process.

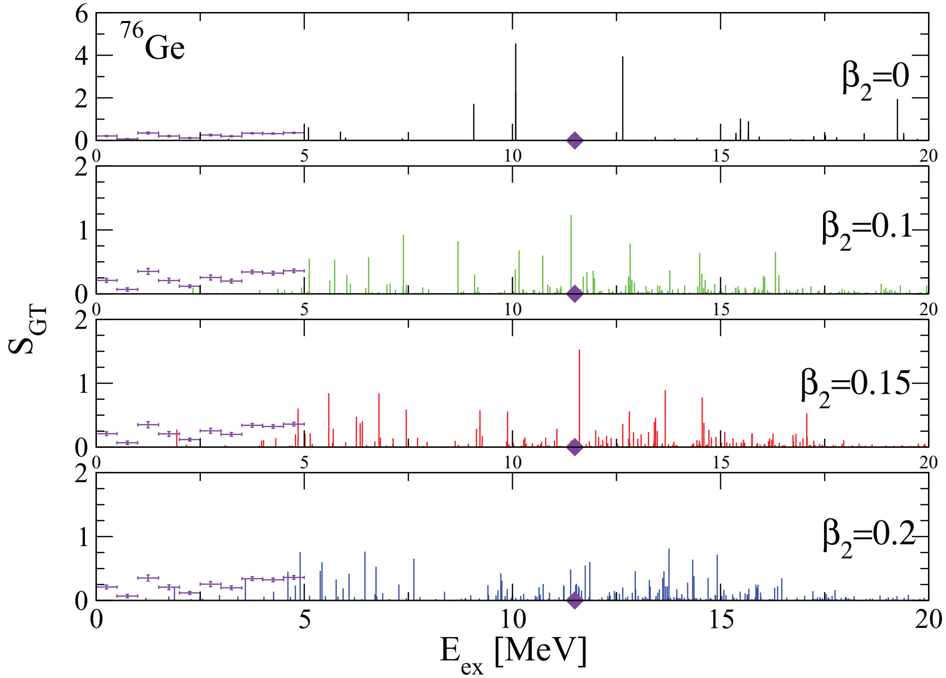


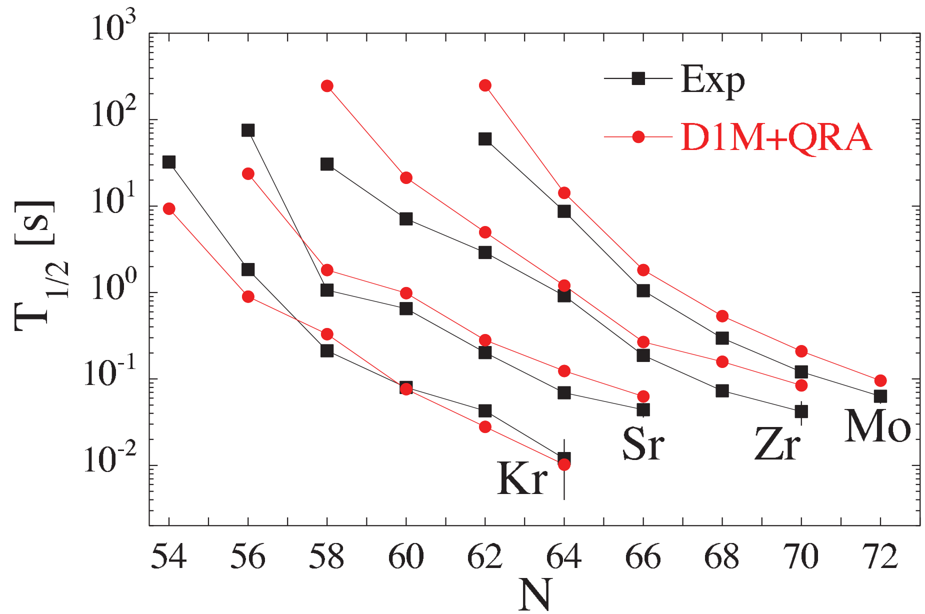


Calculation based on the Finite Fermi system theory. The results display a very strong odd-even staggering in the decay rates which is not visible in the data.



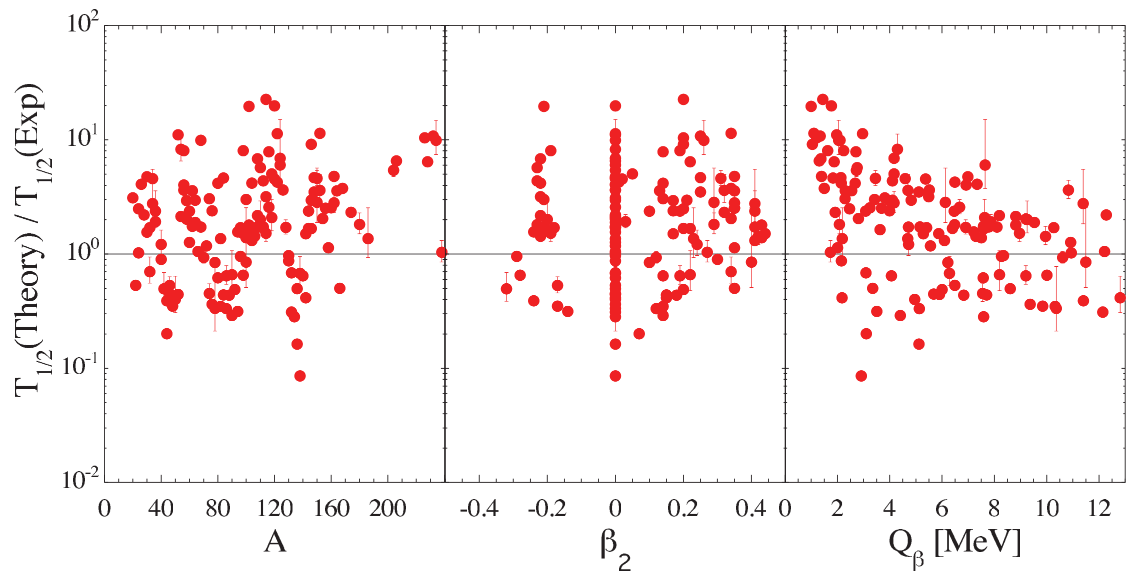
I. V. Panov et al., Nucl. Phys. A 947, 1 (2016).



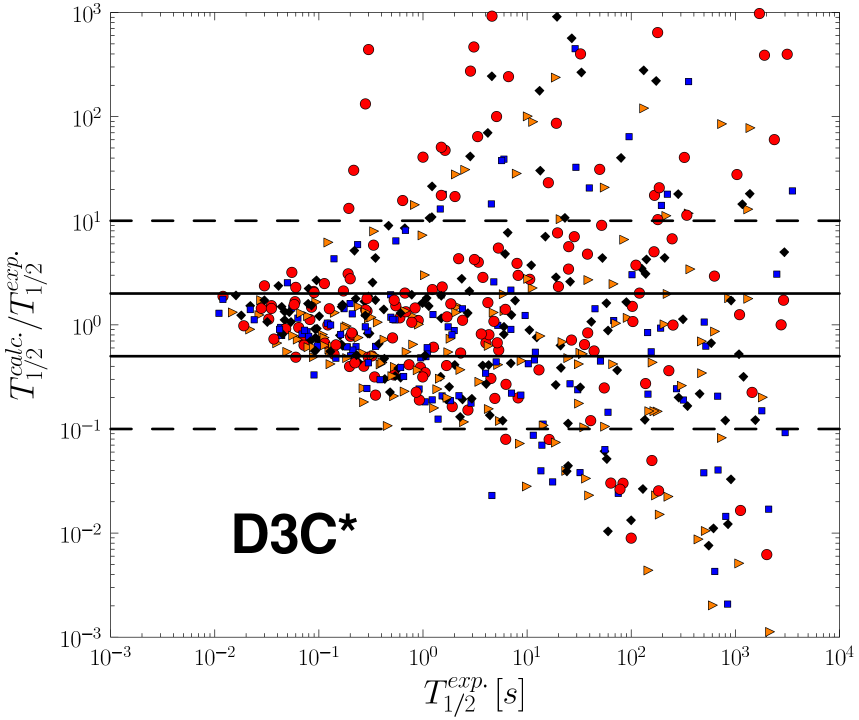


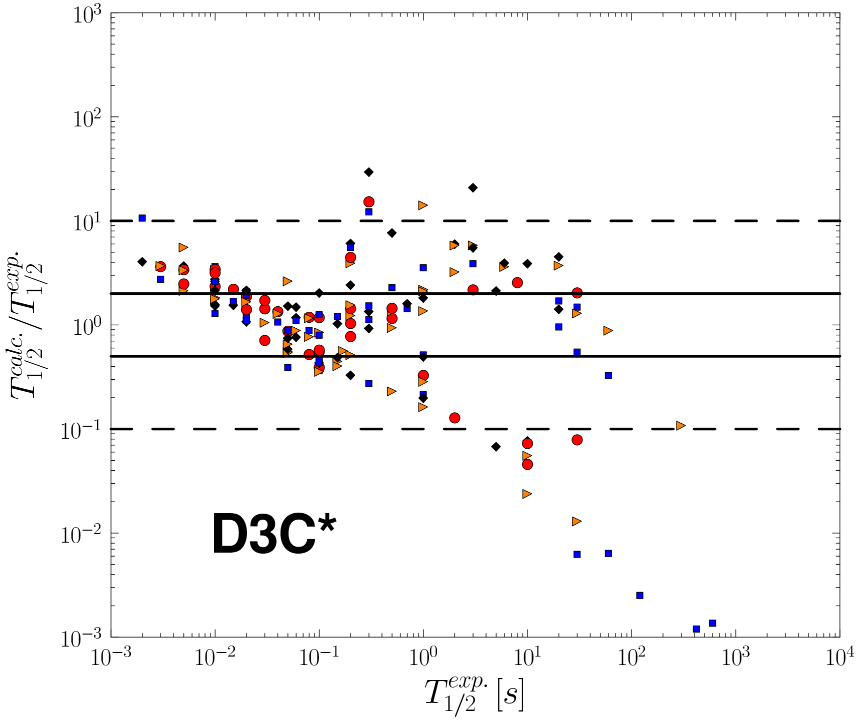
Explicit treatment of deformations using an axially deformed QRPA code based on the Gogny interaction.

Significant enrichment of the spectrum with larger deformations.



M. Martini, S. Péru, and S. Goriely, Phys. Rev. C 89, 044306 (2014)

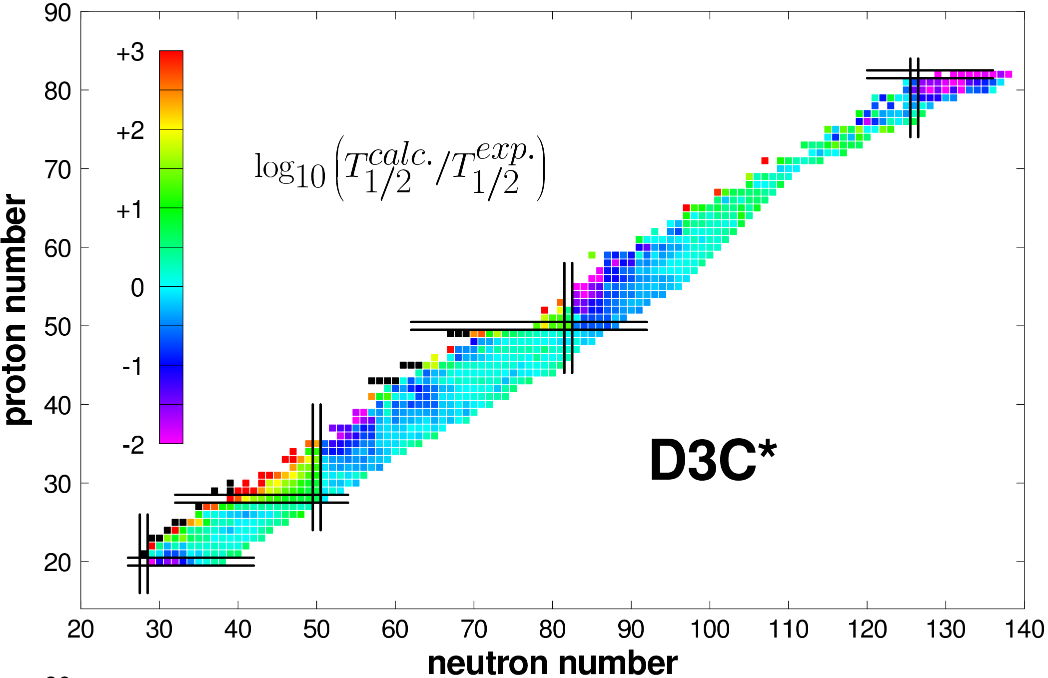




$$\bar{r} = \frac{1}{N}\sum_i \log \frac{T_{calc.}}{T_{exp.}}$$

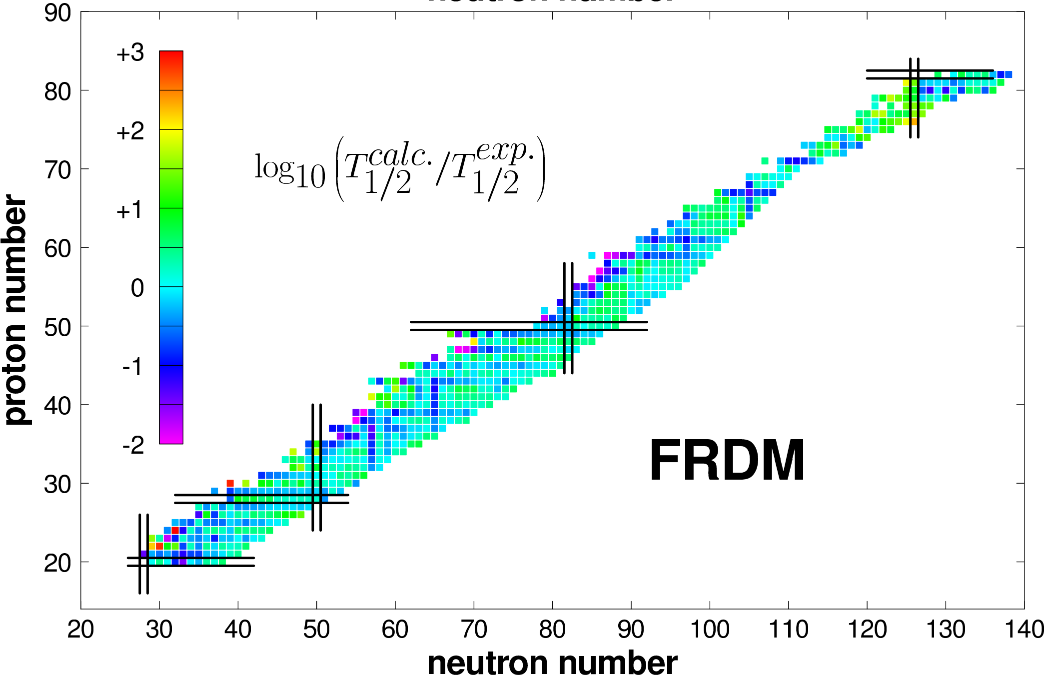
$$\sigma = \left[\frac{1}{N}\sum_i (r_i - \bar{r})^2\right]^{1/2}$$

	D3C*		FRDM	
$T_{\text{exp.}}$ [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



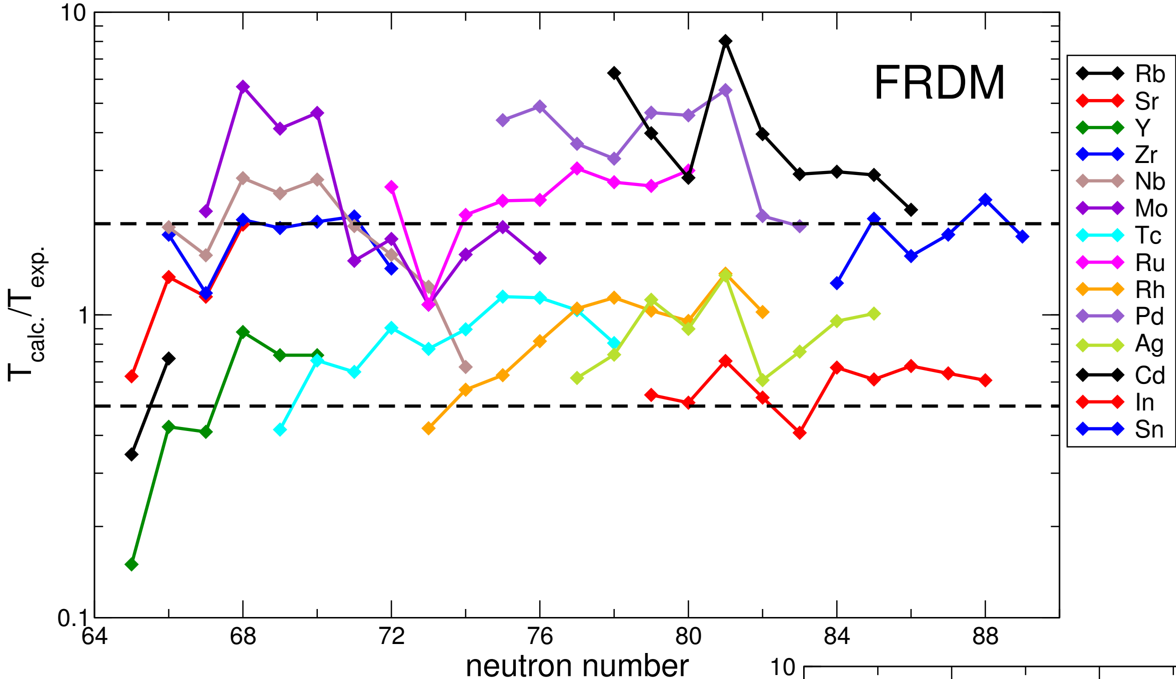
D3C*

	$\bar{r}$	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



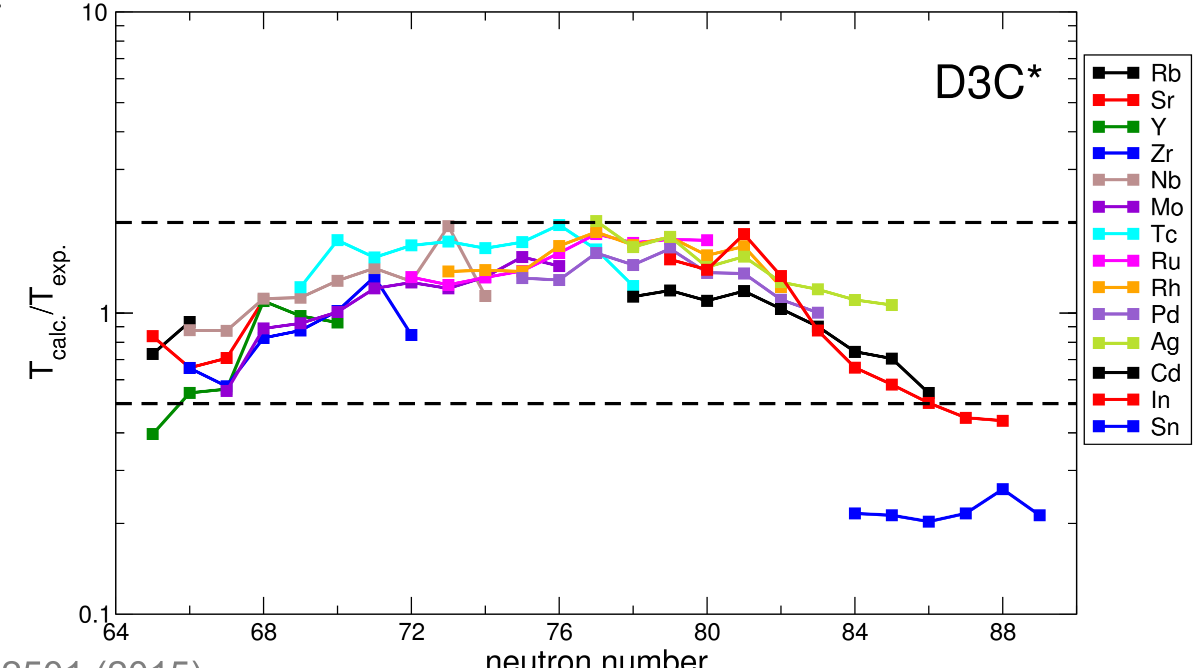
FRDM

	$\bar{r}$	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

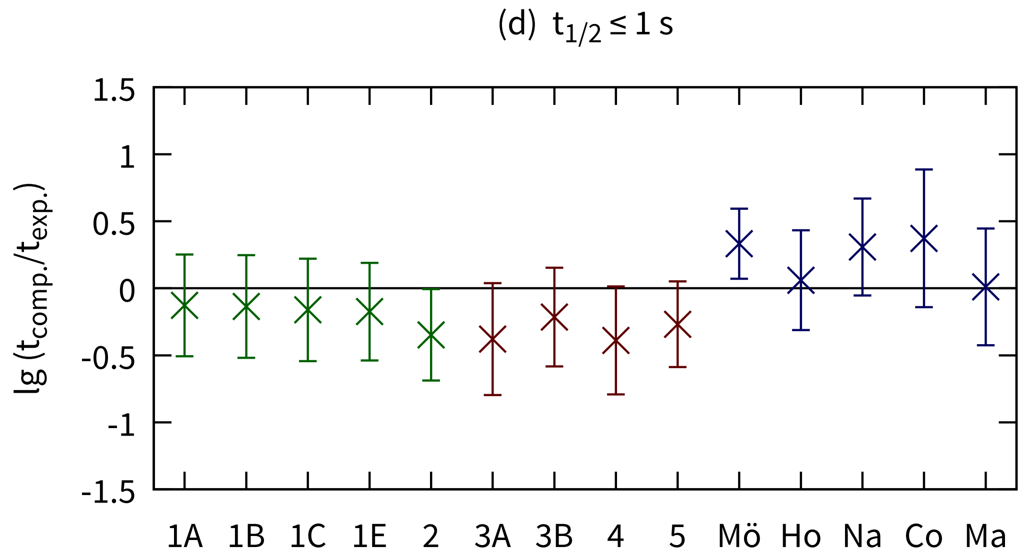
Comparison with the latest measurements is consistent with the previous results.

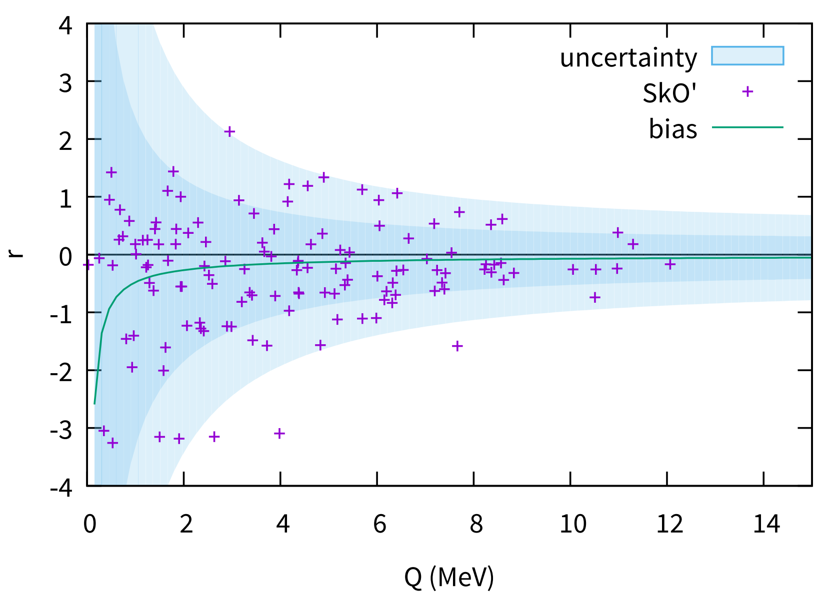


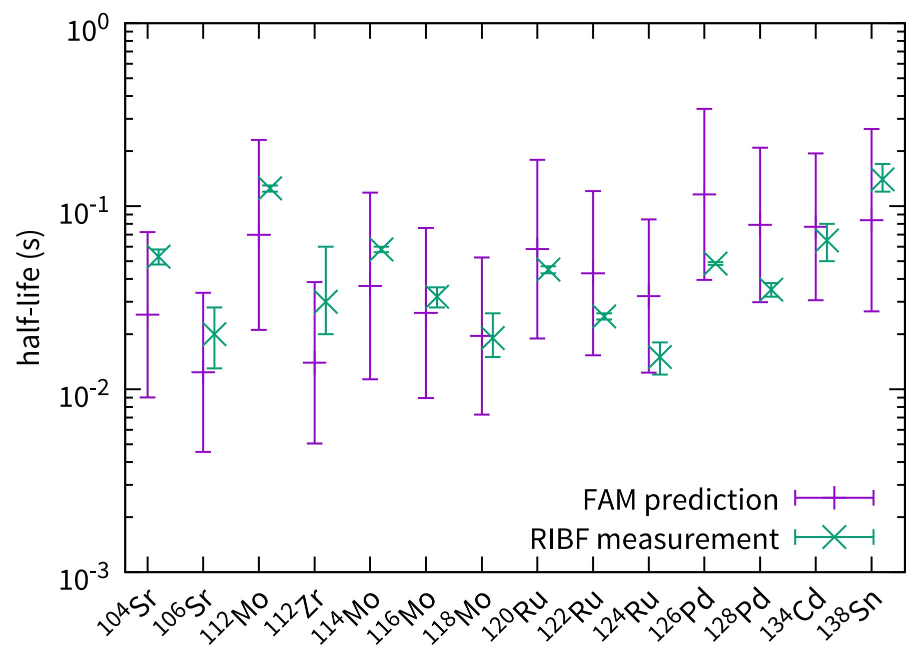
G. Lorusso et al., Phys. Rev. Lett. 114, 192501 (2015)

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

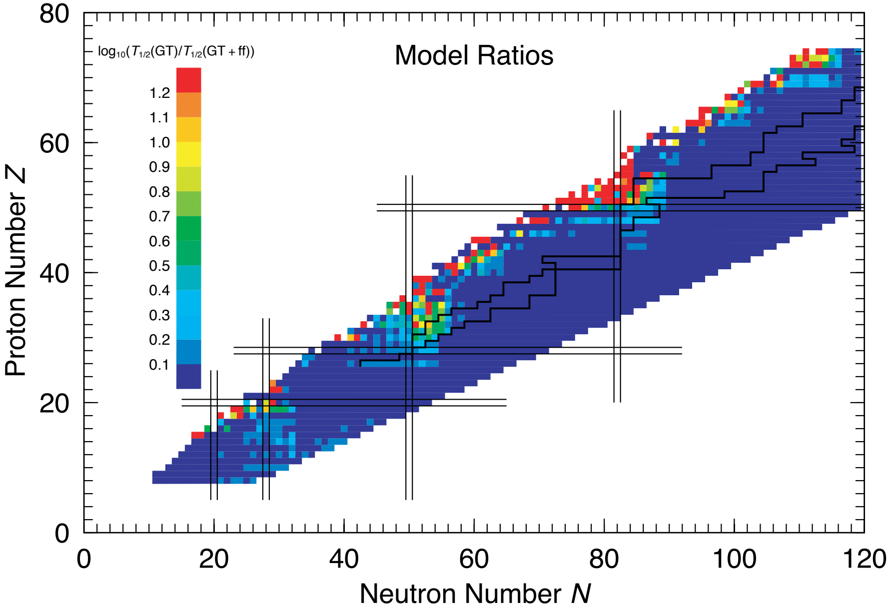
The interaction was also adjusted to dynamic properties of select nuclei – improved description of decay properties.

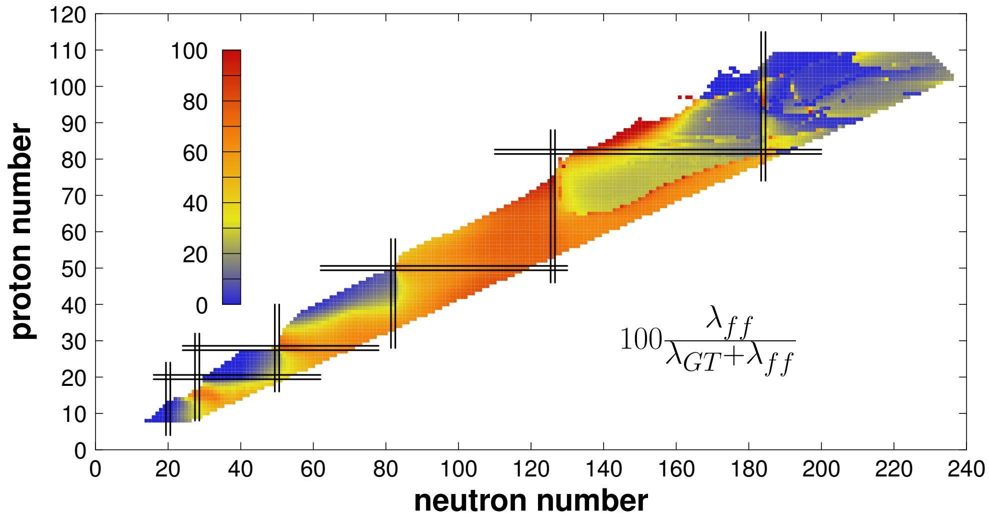




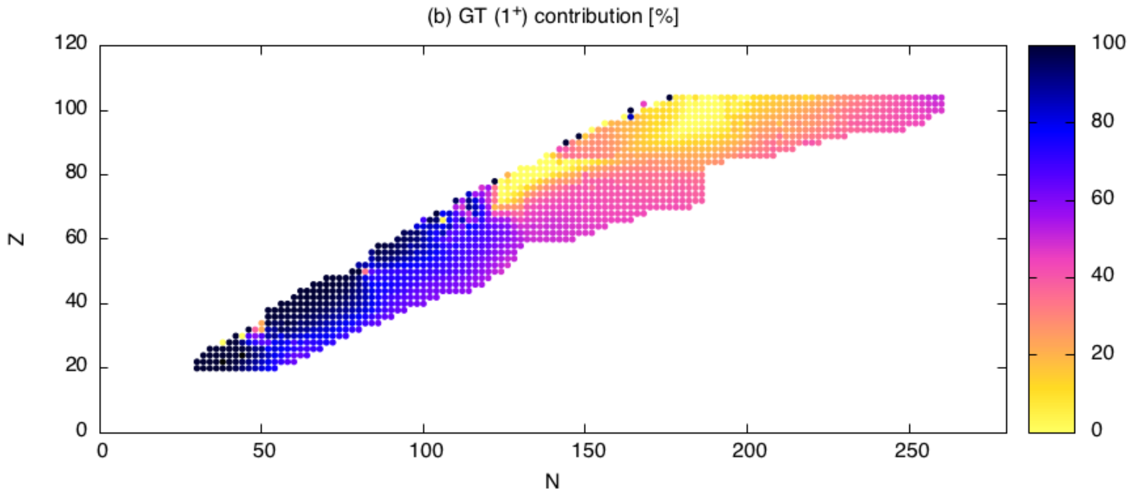


M. T. Mustonen and J. Engel, Phys. Rev. C 93, 014304 (2016)

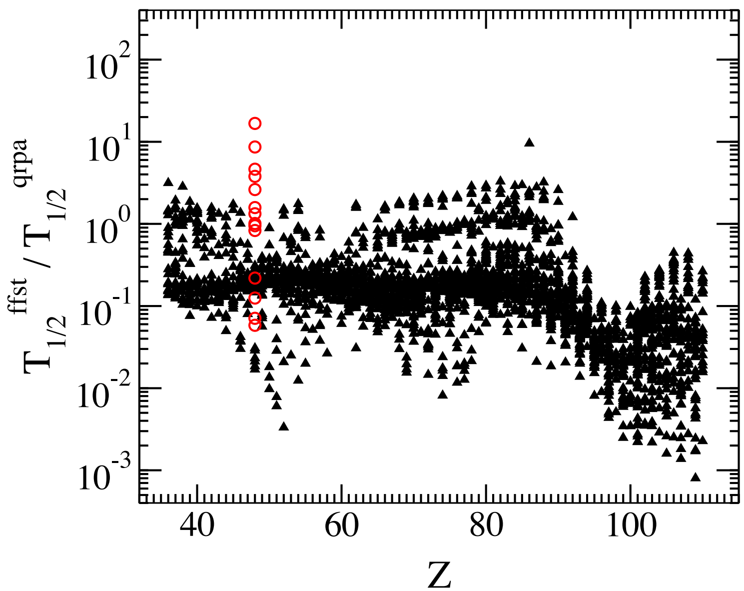


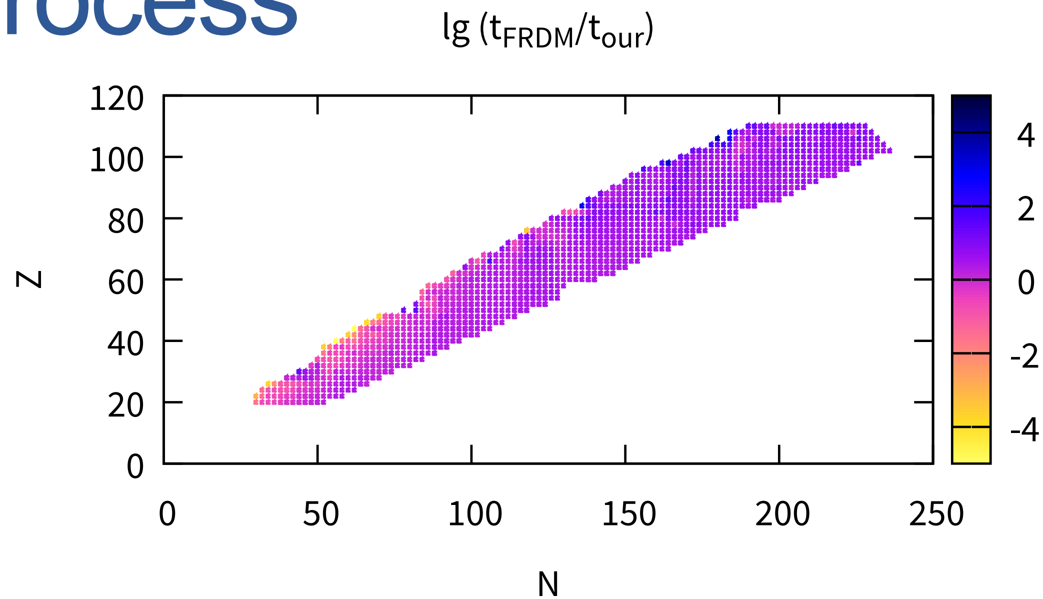


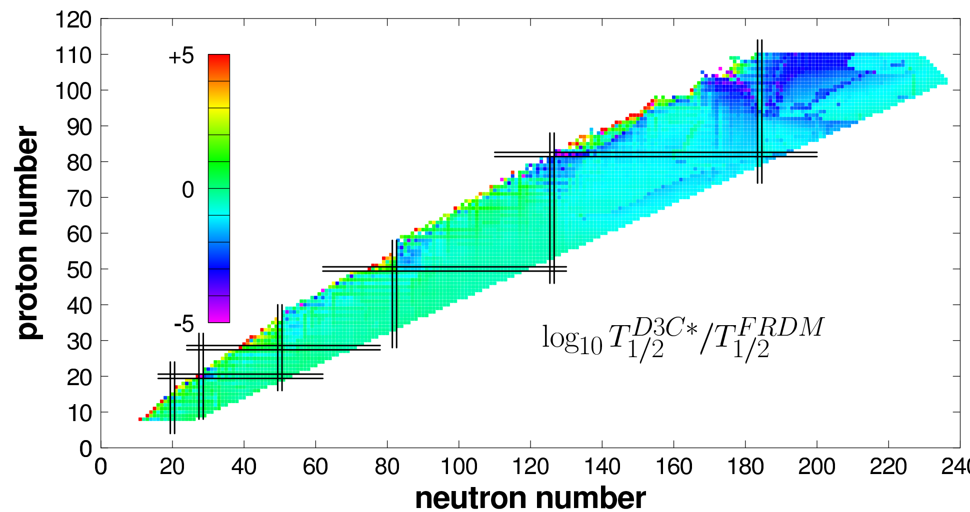
Contribution of ff transitions in different regions of the nuclear chart is still very much under debate.



Impact on the r-process







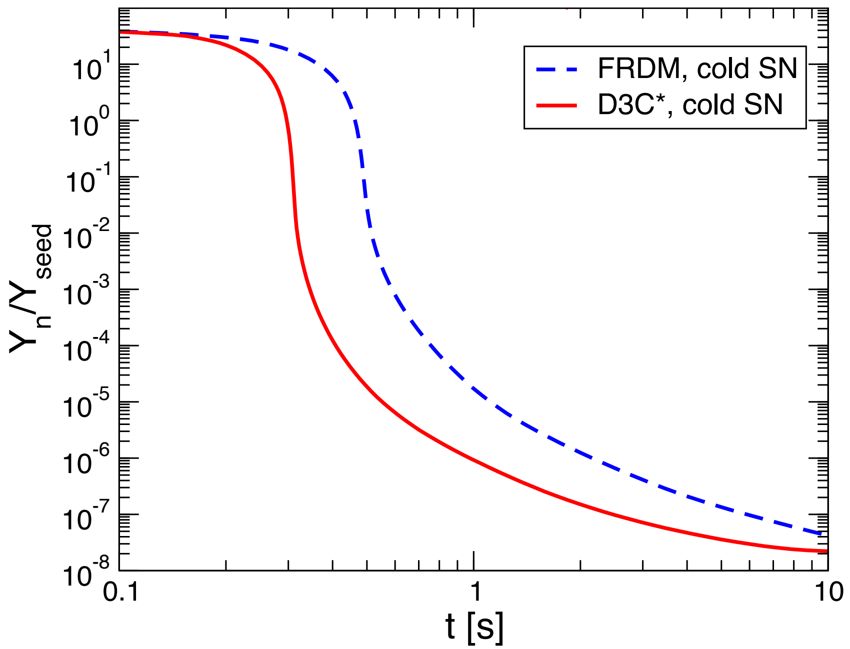
Latest calculations provide systematically different half-lives in particular regions of the nuclear chart – significant consequences for the r-process.

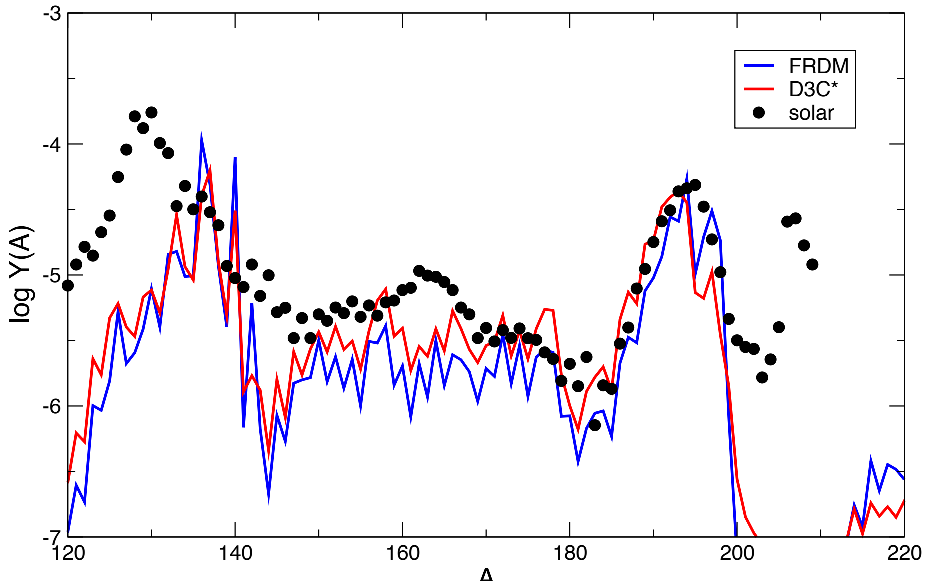
M. T. Mustonen and J. Engel, Phys. Rev. C 93, 014304 (2016)
I. V. Panov et al., Nucl. Phys. A 947, 1 (2016).

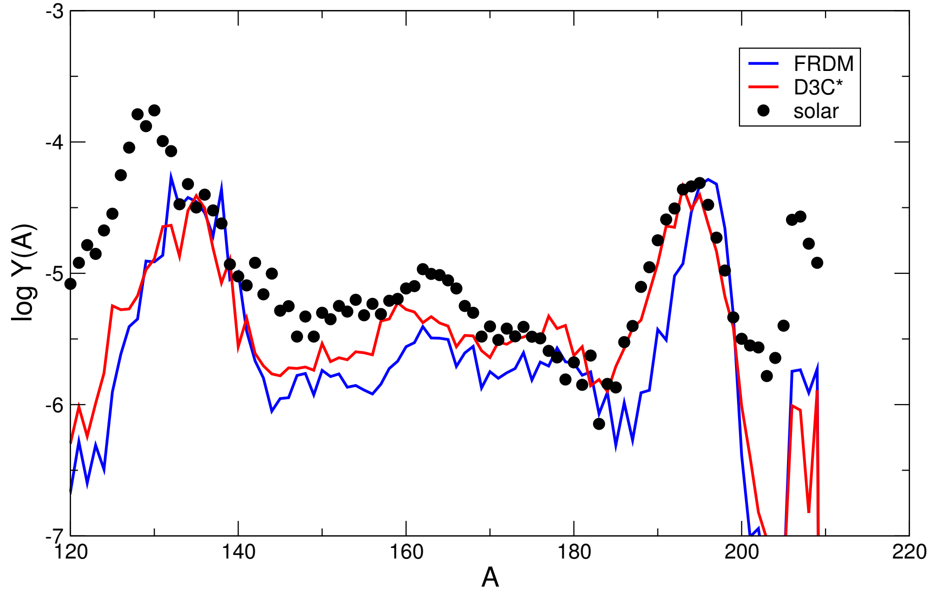
Half-lives have a significant impact on the abundance pattern.

Third peak is particularly sensitive to the changes.

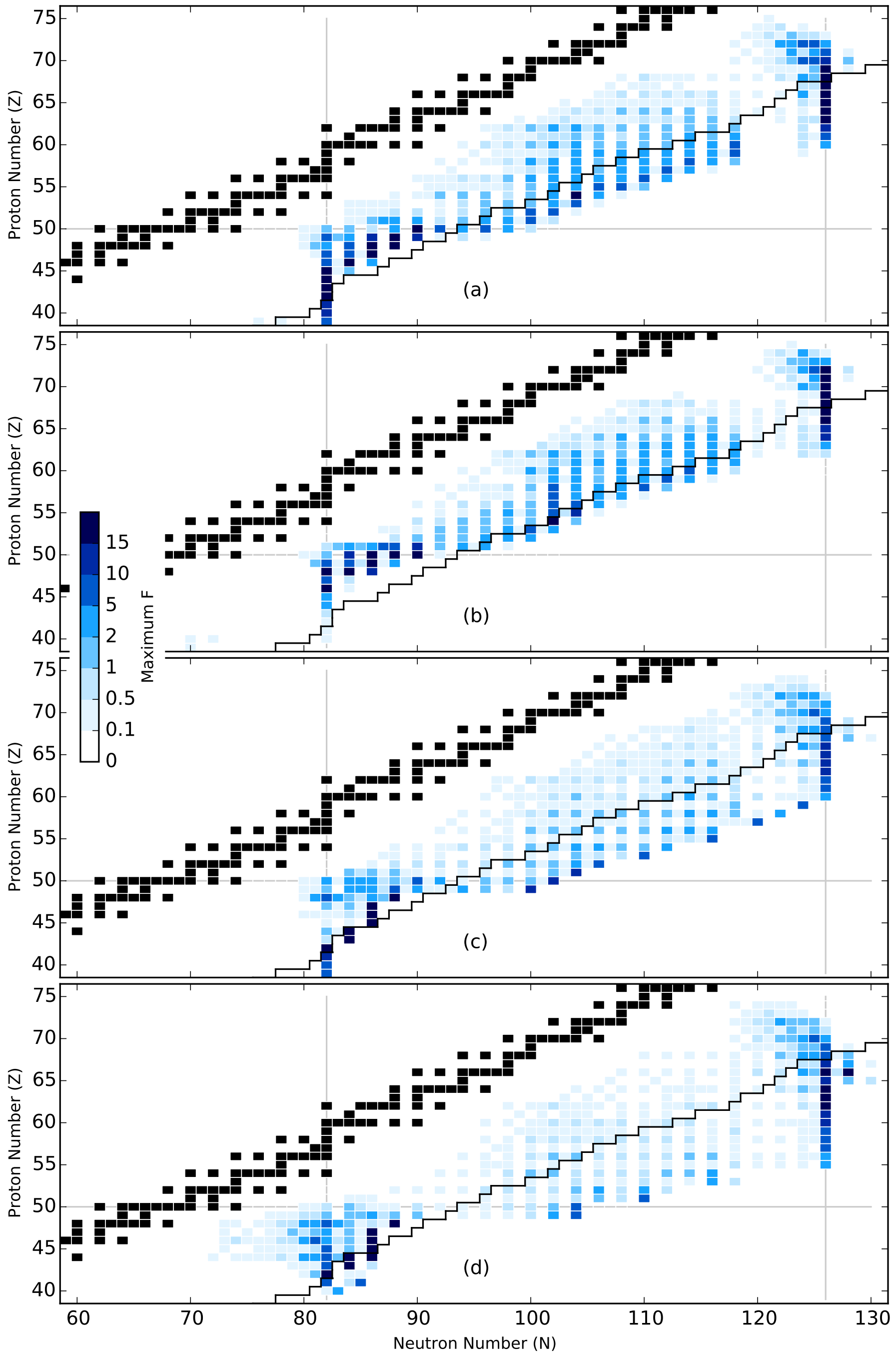
The result is valid for varying astrophysical conditions.







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



Sensitivity studies provide information on the importance of particular nuclei in the r-process simulations.

Variation of beta-decay half-lives of each nucleus produces changes in the total abundance pattern.

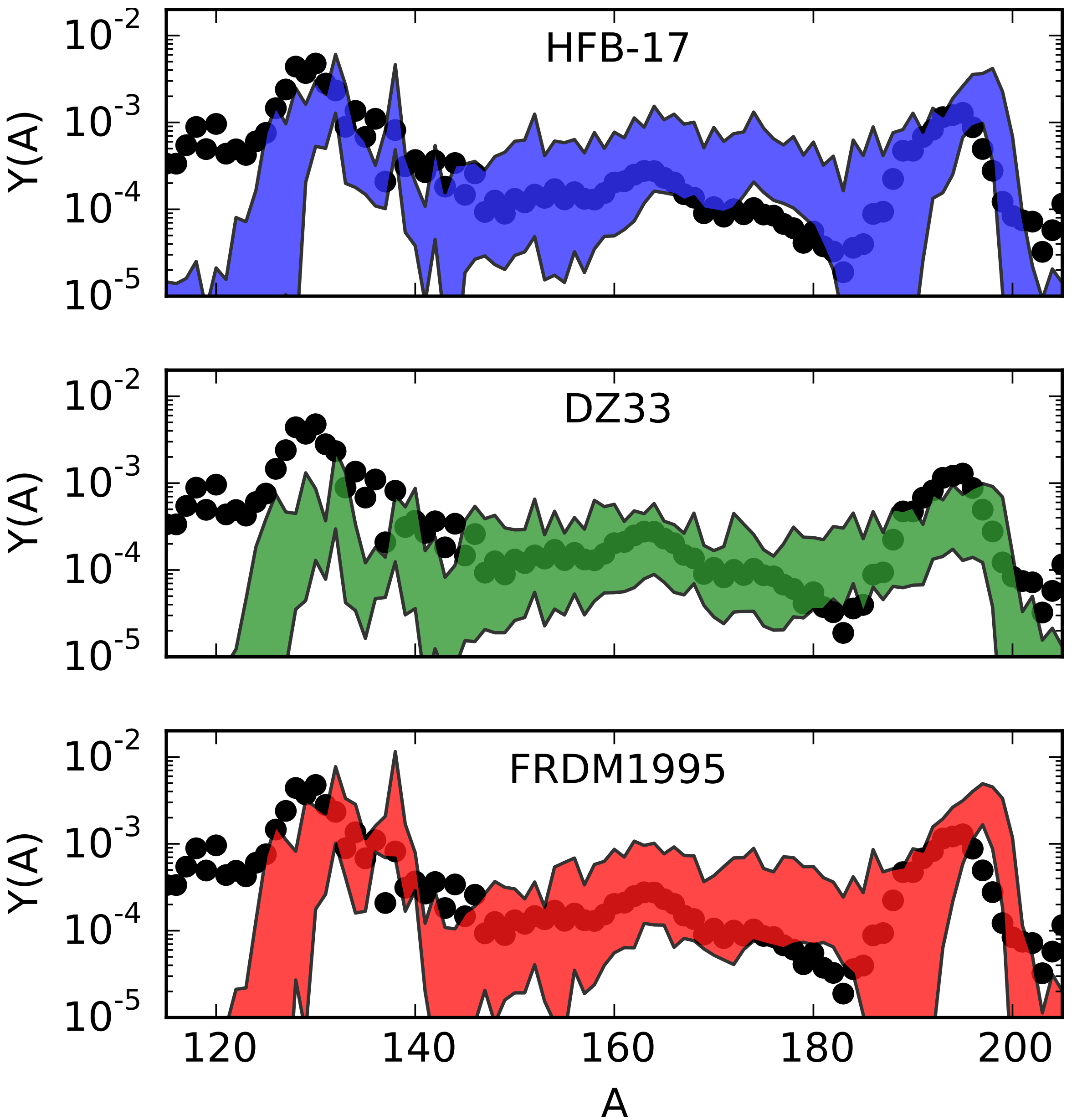
For different astrophysical scenarios, similar regions appear to be important in the description of heavy element creation.

M. Mumpower et al., arxiv:1508.07352 [nucl-th]

Monte Carlo methods applied to the study of the sensitivity of r-process abundances to beta-decay.

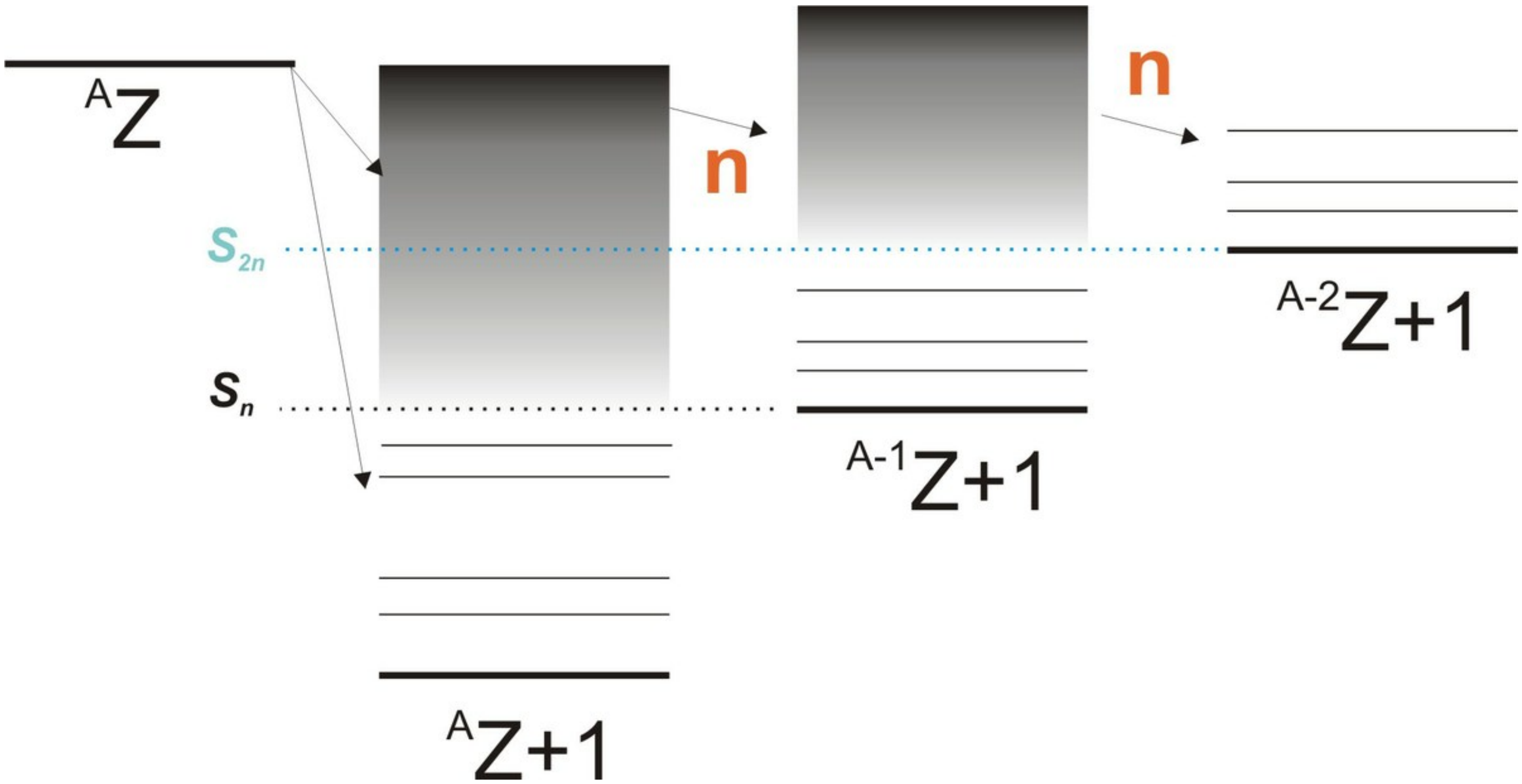
Even though general structure of the abundance pattern remains, changes in beta-decay half-lives produce a large variance in the abundance pattern.

Studies may help indicate which nuclear inputs are important for heavy element nucleosynthesis simulation.

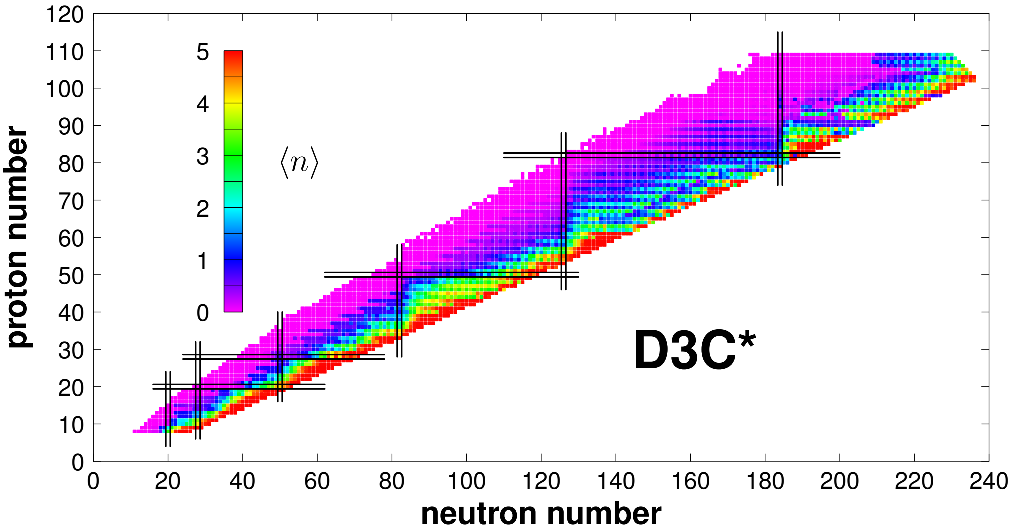


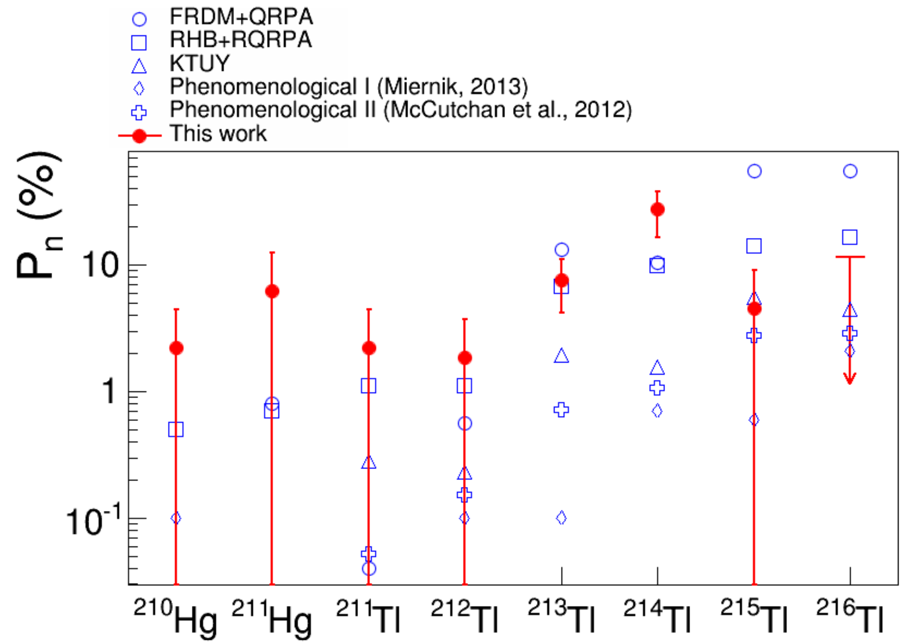
Beta-delayed neutron emission

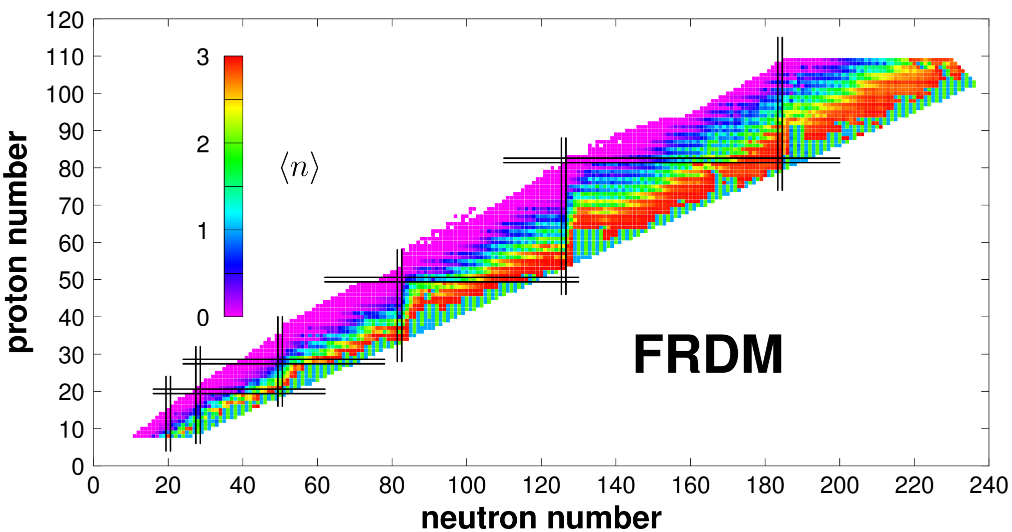
In nuclei with small S_n an additional process is possible.



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



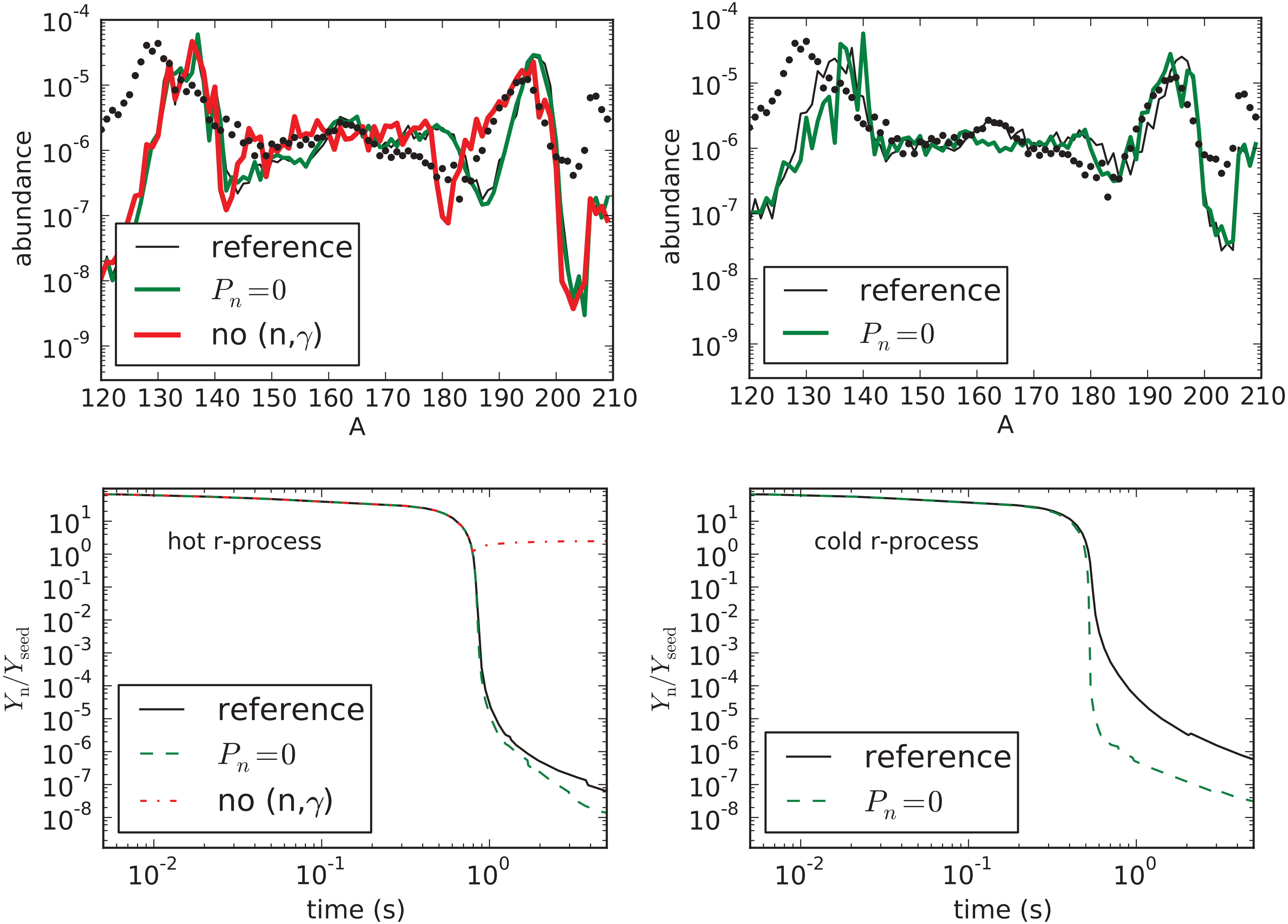




$$P_{xn} = \frac{1}{\lambda_{tot}} \sum_{E_i = S_{xn}}^{S_{(x+1)n}} \lambda_i$$

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

R. Caballero-Folch et al., arxiv:1511.01296 [nucl-ex]



A. Arcones and G. Martínez-Pinedo, Phys. Rev. C 83, 045809 (2011)

Conclusion and outlook

- Large-scale calculations of beta-decay rates are both computationally and theoretically demanding undertaking.
- Progress of experimental facilities provides data on increasingly exotic nuclei – extremely helpful in constraining models.
- Decay rates of neutron-rich nuclei have a significant effect on the r-process abundances – it is important to constrain them as much as possible.
- New theoretical approaches (finite amplitude method and particle-vibration coupling) will enable a more complete treatment of nuclear decay and provide a detailed description of transition spectra at low energies.