Precision measurements in superallowed $0^+ \rightarrow 0^+$ nuclear beta decays: opportunities at DESIR

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DESIR WORKSHOP @ GANIL
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laboratoire commun CEA/DRF CNRS/IN2P3

Superallowed beta decays and BSM physics

Unitarity of the CKM matrix : **crux** of the current Standard Model

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — CKM matrix — mass eigenstates

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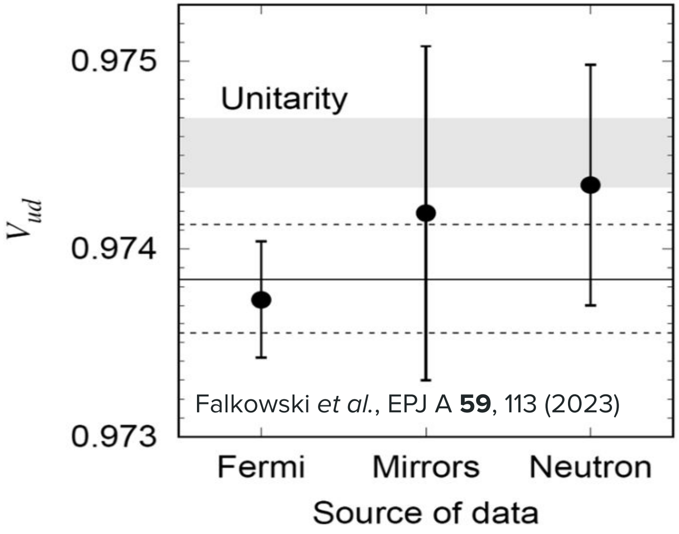
weak eigenstates — CKM matrix — mass eigenstates

V_{ud}: accessible via nuclear beta decays is by far the largest element of the first row (meson decays, $|V_{ub}|^2$ of the order 10^{-5})



Falkowski *et al.*, EPJ A **59**, 113 (2023)

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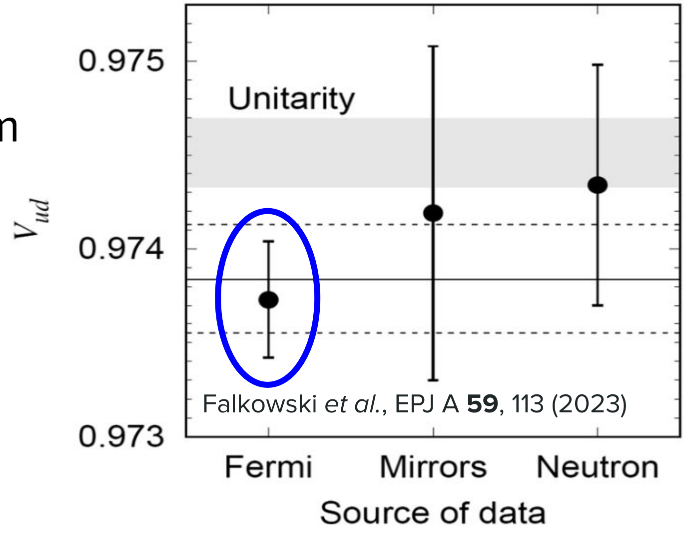
To date : most precise determination of V_{ud} comes from **from Ft from superallowed $0^+ \rightarrow 0^+$ beta decays**



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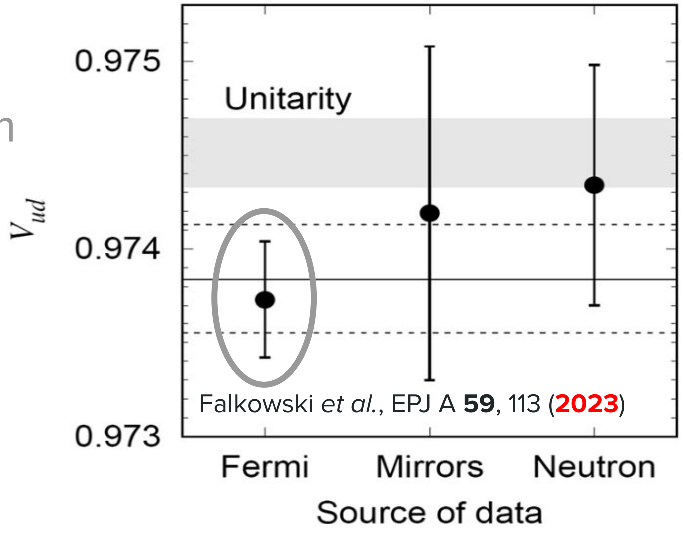
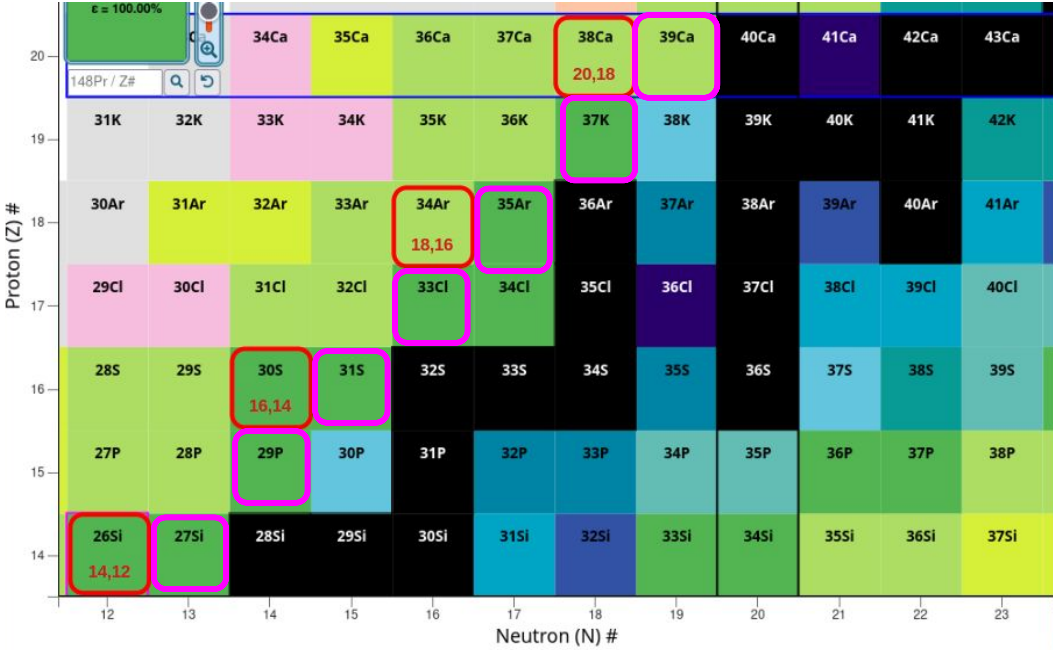


Unitarity $V_{ud}^2 + V_{us}^2 + V_{ub}^2 \neq 1$ violated at the 2σ level.

Is there new physics???

Quick primer on SA beta decays

- β^+ decays between isobaric analog states (IAS) in mirror nuclei with no change in nuclear spin : $J_i = J_f$
- Two class of SA decays
  - Fermi decays
    - $J_i = J_f = 0^+$
    - T = 1 isospin multiplets
  - Mirror decays
    - $J_i = J_f \neq 0$
    - T = ½ isospin multiplets
- Found on the neutron deficit side of the nuclear chart



High precision $ft^{0+ \to 0+}$ values

$$\frac{K}{2V_{ud}^2 G_F^2 \boxed{\times \text{ corrections}}} = ft^{0^+\to 0^+} \boxed{\times \text{ corrections}}$$

Statistical rate function

$$f = \int_1^{W_0} F(Z,W)S(Z,W)pW(W_0 - W)^2 dW$$

Partial half-life

$$t = \frac{t_{1/2}}{BR}\left(1 + \frac{P_{EC}}{P_{\beta+}}\right)$$

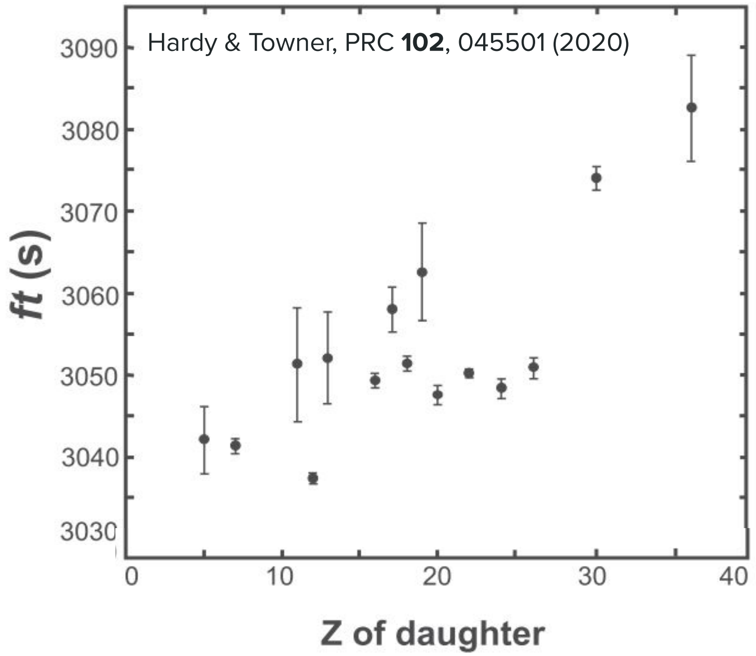


Fig. ft values of the 15 most precise SA $0^+ \to 0^+$ decays

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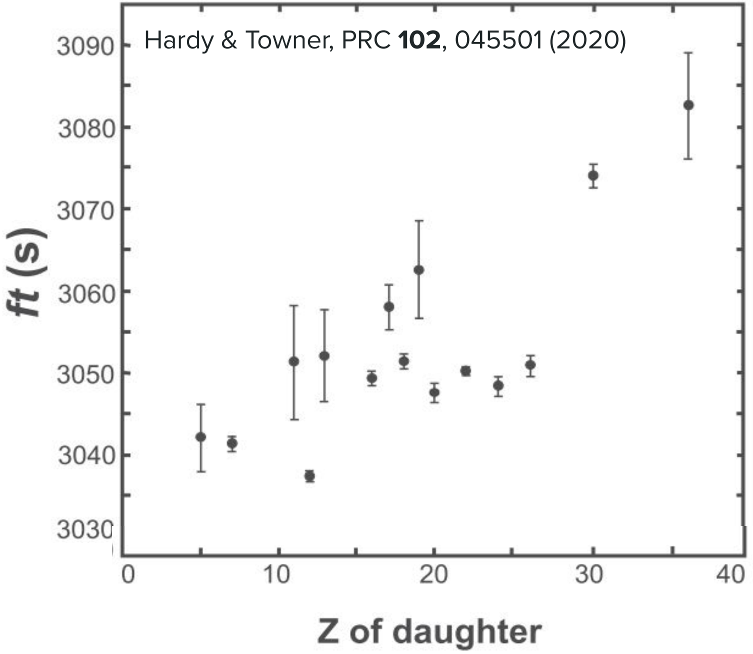


Fig. ft values of the 15 most precise SA $0^+ \rightarrow 0^+$ decays

High precision for V_{ud} requires low uncertainty on $ft^{0+ \rightarrow 0+}$

- Total transition energy $Q_{EC} < 0.02\%$
- Half-life of the decaying state, $t_{½} < 0.03\%$
- Beta branching ratio to the 0^+ IAS state, $BR < 0.3\%$

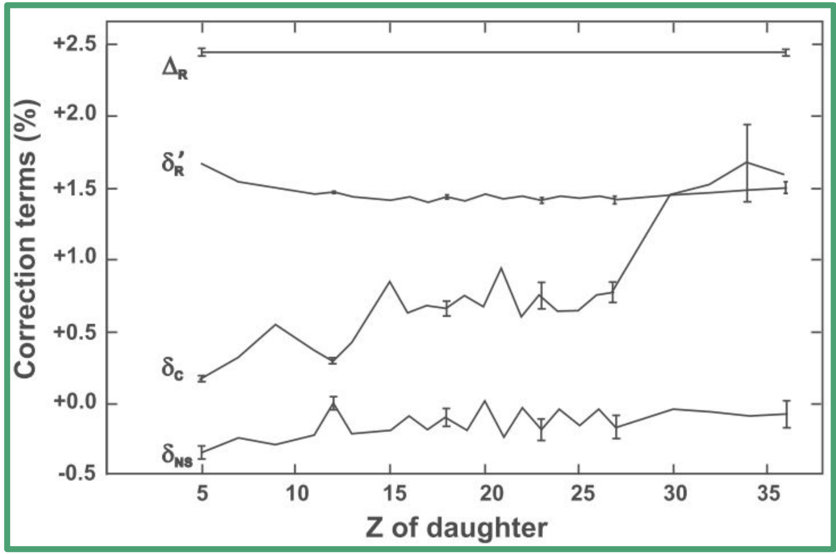
ft value + corrections = Ft

$$\mathcal{F}t^{0^+\to 0^+} = ft^{0^+\to 0^+}(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2V_{ud}^2 G_F^2(1+\Delta_R)}$$

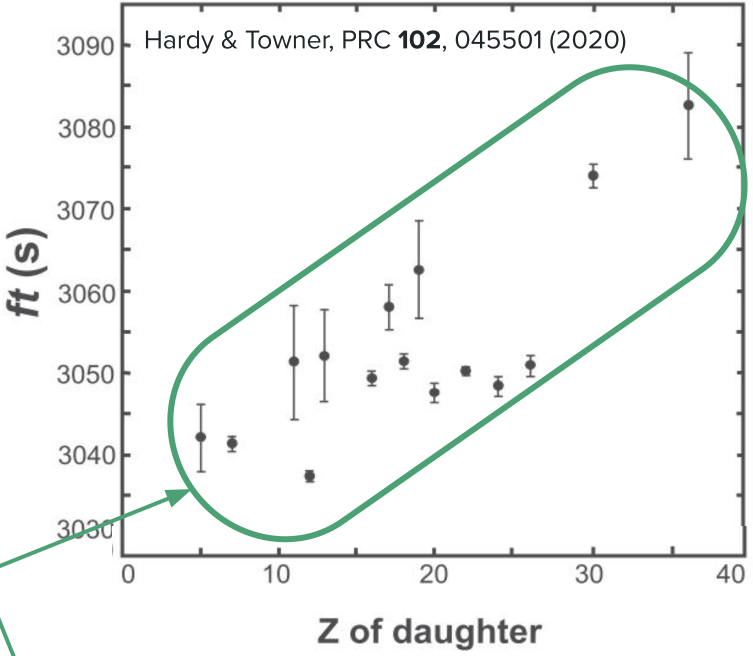
Δ_R: nucleus independent radiative corrections

δ'_R and δ_{NS}: transition/structure dependent radiative correction

δ_C: transition dependent isospin symmetry breaking corrections



Corrections of order of few %



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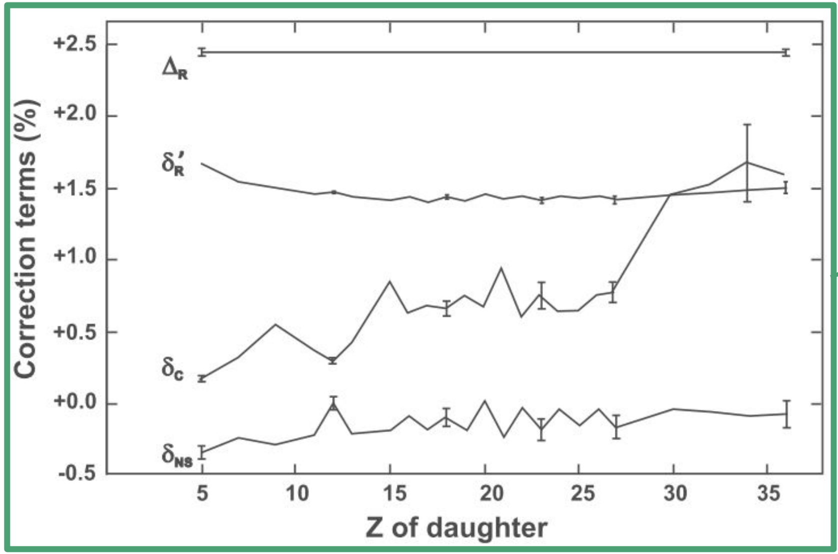

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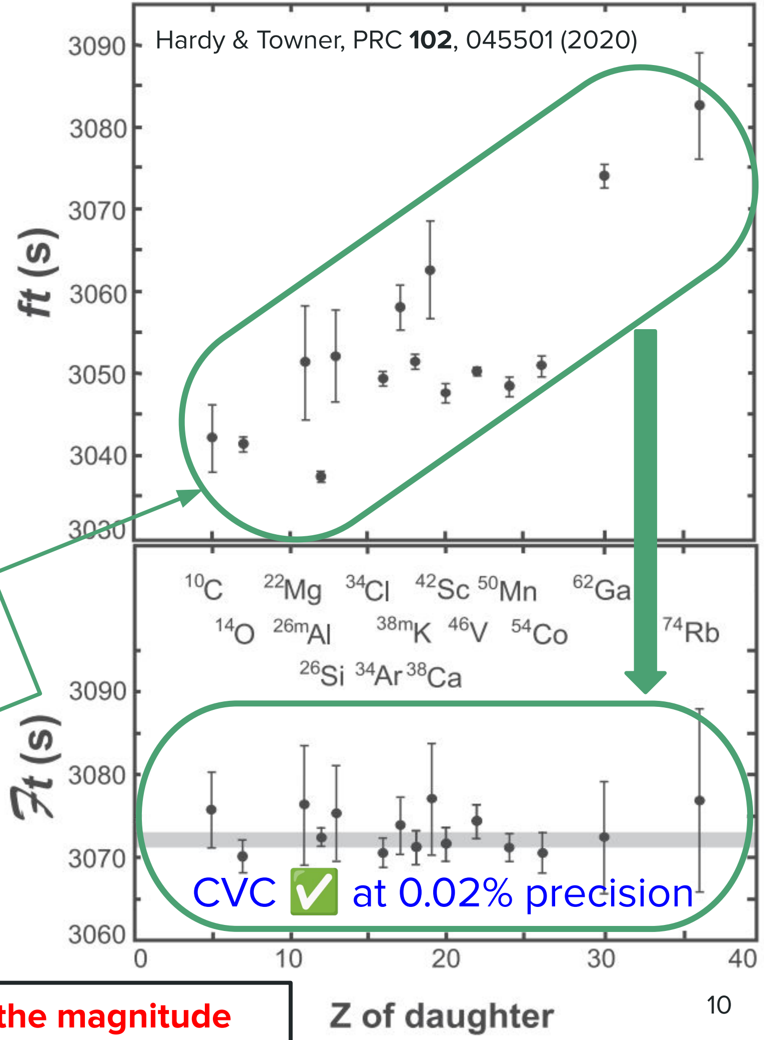


Average Ft defines value of Vud => corrections define the magnitude

Isospin symmetry breaking (ISB) corrections

$$\mathcal{F}t^{0^+\to0^+} = ft^{0^+\to0^+}(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2V_{ud}^2G_F^2(1+\Delta_R)}$$

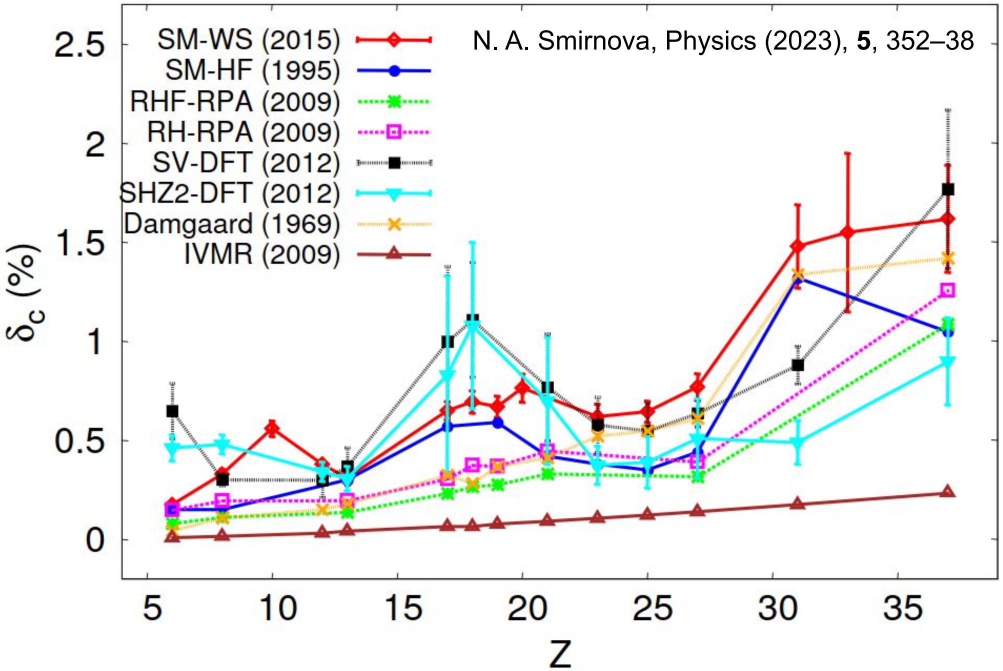
$\boldsymbol{\delta_C = \delta_{C1} + \delta_{C2}}$: isospin symmetry breaking corrections

- $\boldsymbol{\delta_{C1}}$: configurations mixing of the 0^+ IAS with non-analogue 0^+ states
- $\boldsymbol{\delta_{C2}}$: imperfect radial overlap between parent & daughter

➔ δ_C increases with Z

➔ Several δ_C corrections using different models.

➔ Large corrections near shell closure in $T_z = -1$ parents e.g. ^{18}Ne, ^{30}S, ^{42}Ti



To date : Ft computed using only one theory model

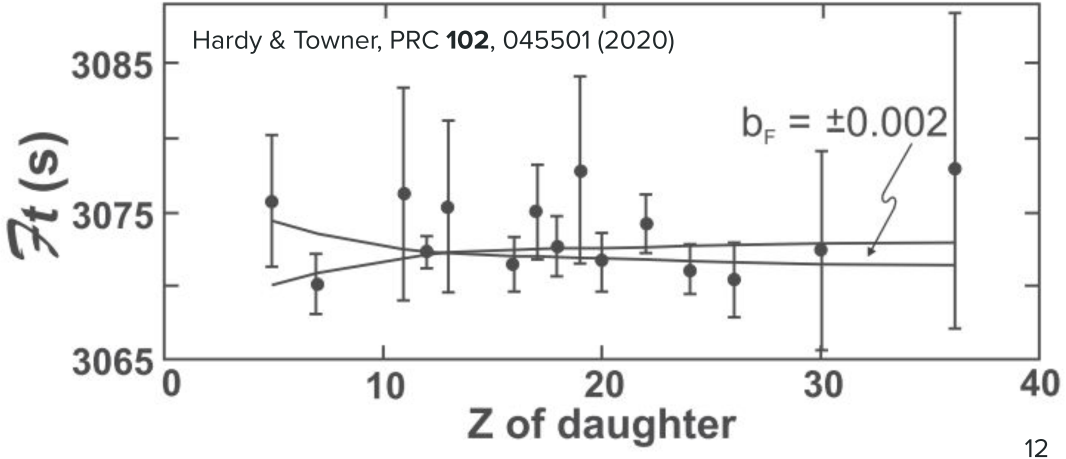
But that's not all ...

Ft values good probe for BSM physics : look for a non-zero Fierz term (b_F)

- Deviation of Ft from a constancy
- b_F depends on transition energy and highest sensitivity in low Z emitters: ^{10}C, ^{14}O

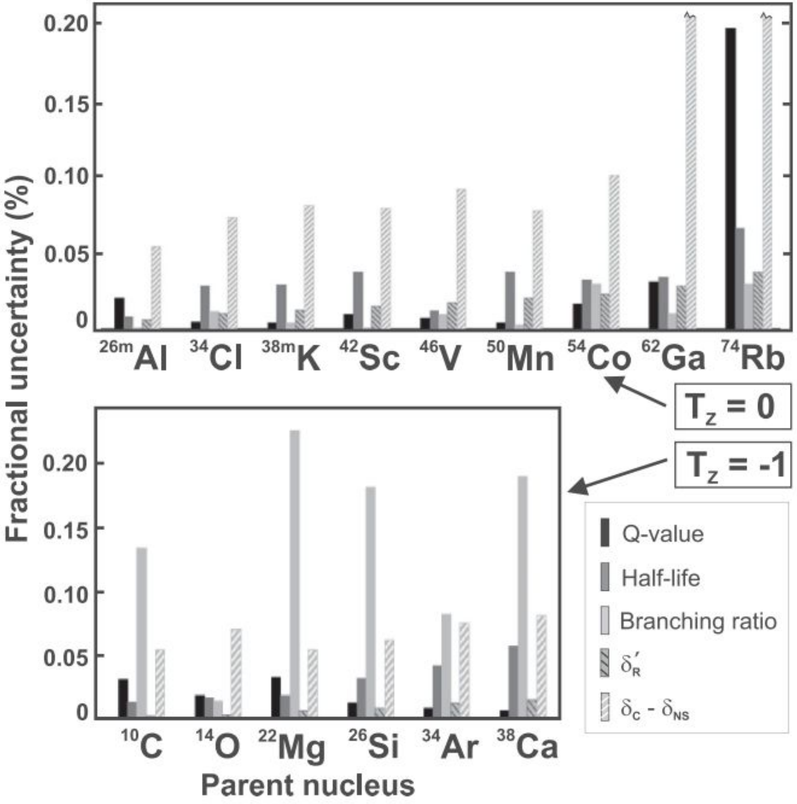
$$\mathcal{F}t_{\mathrm{BSM}}^{0^+\to 0^+} \approx \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)} \frac{1}{1+b_F\gamma\langle 1/W\rangle}$$

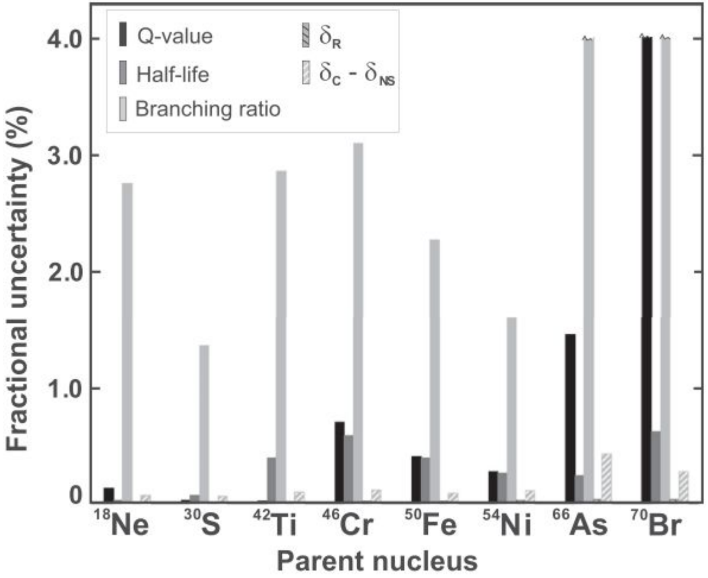
To constrain b : improve precision on all ft



Current scenario…

23 known cases, but precision ≅0.3% or better for **only** 15 transitions



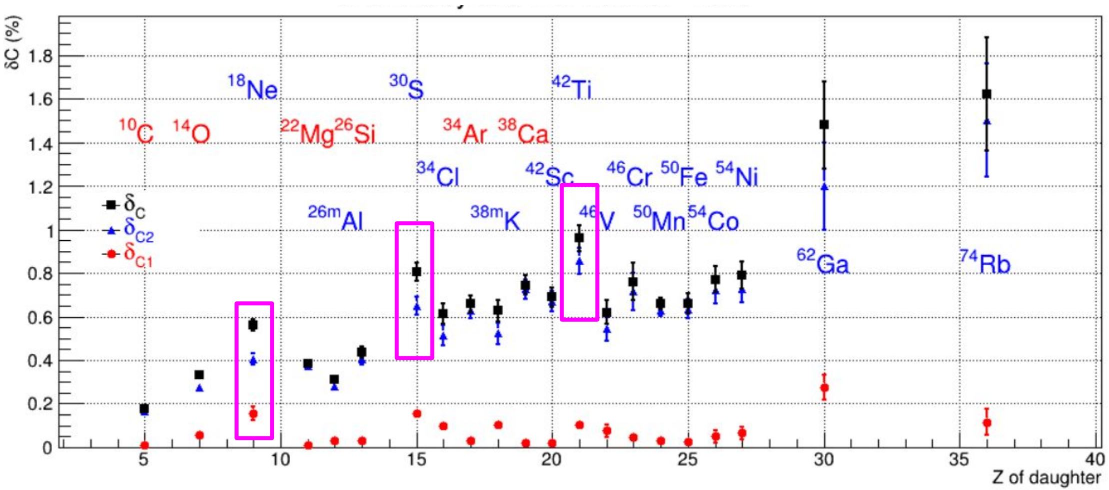


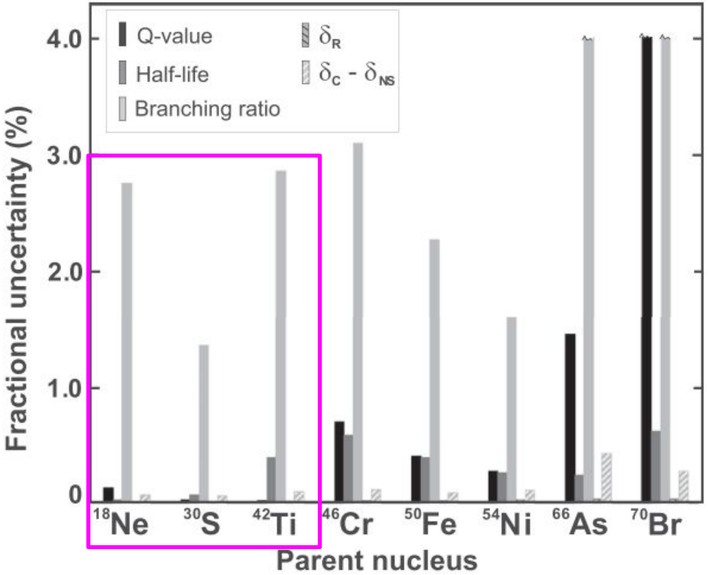
Remaining 8: require improved precision on experimental observables esp. BR

Images from Hardy & Towner, PRC **102**, 045501 (2020)

Superallowed program at GANIL : Current

- Proposal to remeasure the branching ratio of $^{18}Ne \rightarrow {}^{18}F$
- Analyzing the data to improve branching ratio and half-life for decay of $^{30}S \rightarrow {}^{30}P$
- Exploring production of ^{42}Ti at LISE

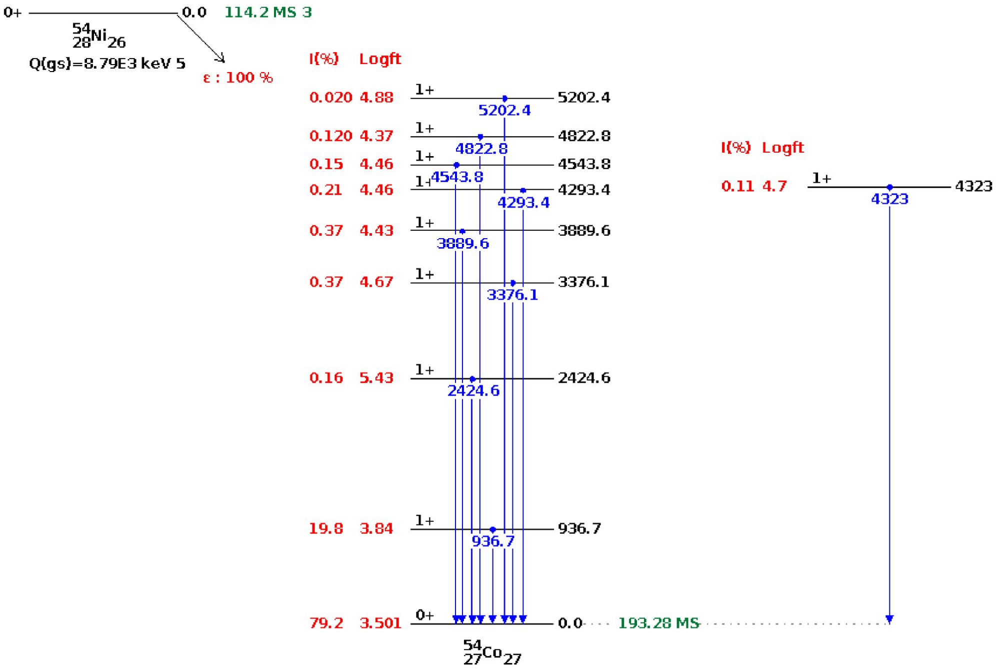


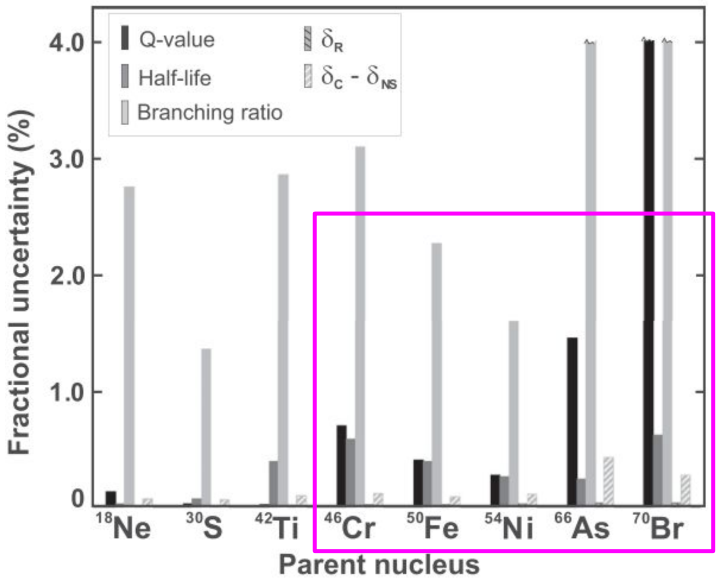


To benchmark δ_c calculations : need high precision experimental data

Superallowed program at GANIL : Future

- Improve precision on remaining 5 cases
- Require beams from upcoming S3 facility
- Branching ratio measurement with Total Absorption spectroscopy (TAS)

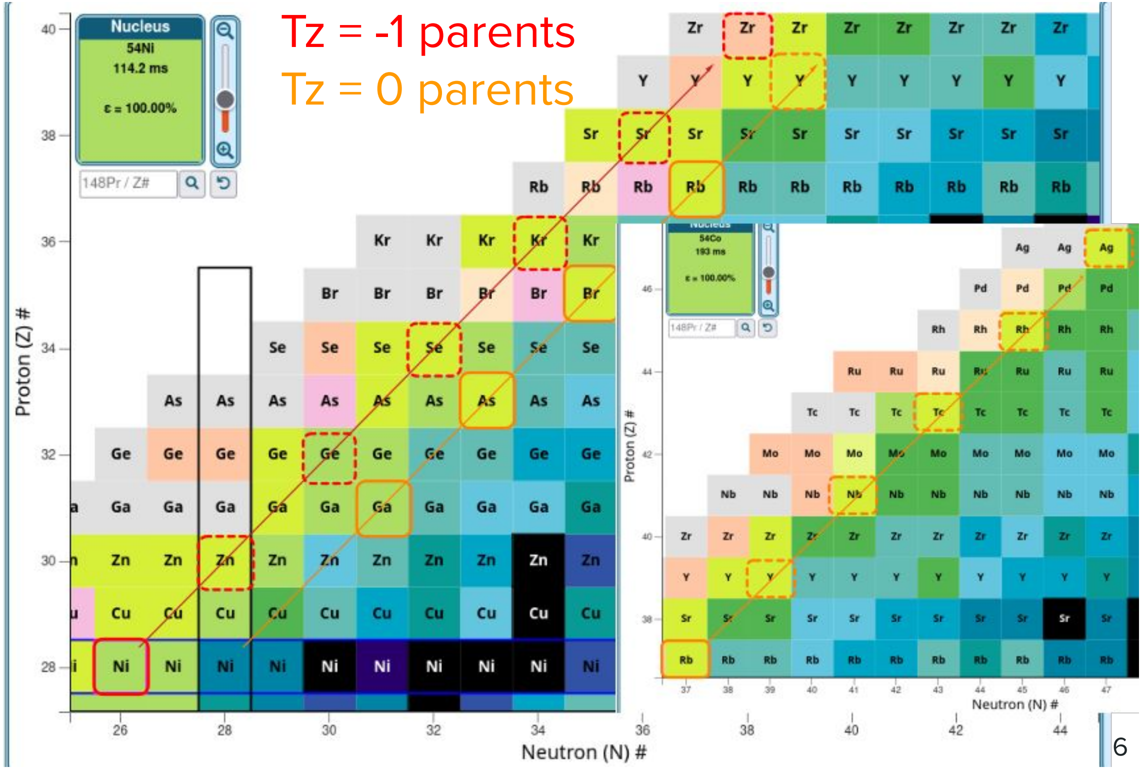




Superallowed program at GANIL : Future

Extend range of nuclei to test CVC for heavier super allowed β^+ emitters

- Beams from upcoming S^3 facility.
- Couple with HRS/PIPERADE @ DESIR for ultrapure samples
- Mass measurements using PIPERADE/MLLTRAP
- BR, $t_{½}$ using decay tape station and TAS or other decay spectroscopy setups.

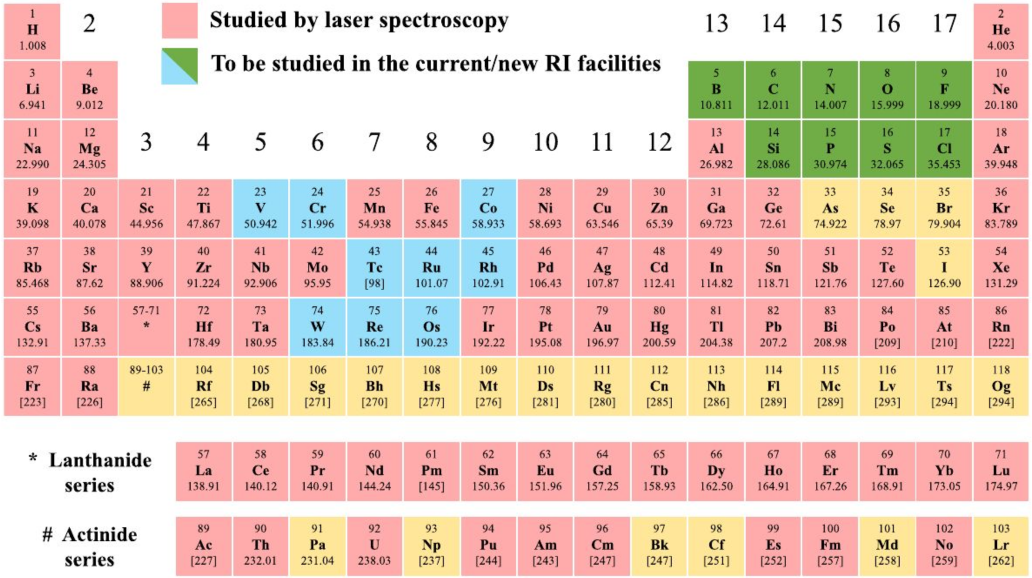


Superallowed program at GANIL : Challenges

DESIR beams via S^3-LEB

1. $t_{½}$ for know (heavier) SA emitters ^{54}Ni - ^{70}Br : **115 ms and less**
   - Current gas cell extraction time 300-600 ms (projected to 50 ms)
   - Could be a major bottleneck

2. LASER ionization schemes currently not available for all SA emitters
   - Need support from LASER community to develop efficient laser ionization schemes



X.F. Yang, *et al.* Prog. Part. Nucl. Phys. **129** (2023) 104005.

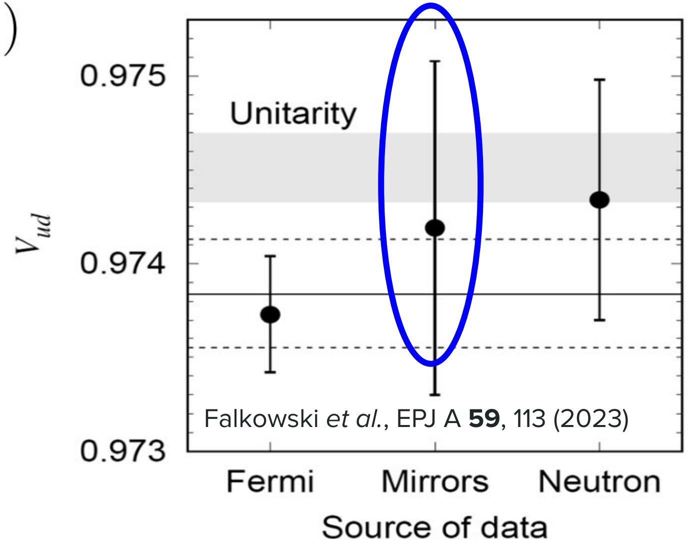
Superallowed program at GANIL : Day 1 cases

SA pair	$t_{1/2}$ (ms)	Laser spectroscopy ?	SPIRAL1 beam yield	S^3 beam yield
$^{42}Ti \rightarrow {}^{42}Sc$	208.65	Yes	No	1.6E05
$^{46}Cr \rightarrow {}^{46}V$	260	Not yet	No	2.6E03
$^{50}Fe \rightarrow {}^{50}Mn$	155	Yes	No	1.2E02
$^{54}Ni \rightarrow {}^{54}Co$	114.2	Yes	No	8.0E02
$^{66}As \rightarrow {}^{66}Ge$	95.77	No	No	2.2E03
$^{70}Br \rightarrow {}^{70}Se$	79.1	No	5.4E01	6.5E02

Beyond superallowed $0^+ \rightarrow 0^+$ towards mirror decays

$$2\mathcal{F}t^{0^+\rightarrow 0^+} = \mathcal{F}t^{mirror}(1+\frac{f_A}{f_V}\rho^2) = \frac{K}{2V_{ud}^2 G_F^2 \,(1+\Delta_V^R)}$$

- In addition to BR, $t_{½}$ and masses require
  ρ = Gamow-Teller/Fermi mixing ratio
- Requires correlation measurements => MORA
- Beta asymmetry (A_β) : sensitive to right-handed currents



Conclusion

- Superallowed beta decays are excellent probes for beyond Standard Model physics
- Observables require high precision to set any BSM limits
- DESIR : excellent for these studies
- Few roadblocks that need attention
  - (Efficient) laser schemes not available
  - Short half-lives => require faster ejection out of the gas cell

Thank you for your attention!