

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

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DESIR WORKSHOP @ GANIL  
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# 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

# Superallowed beta decays and BSM physics

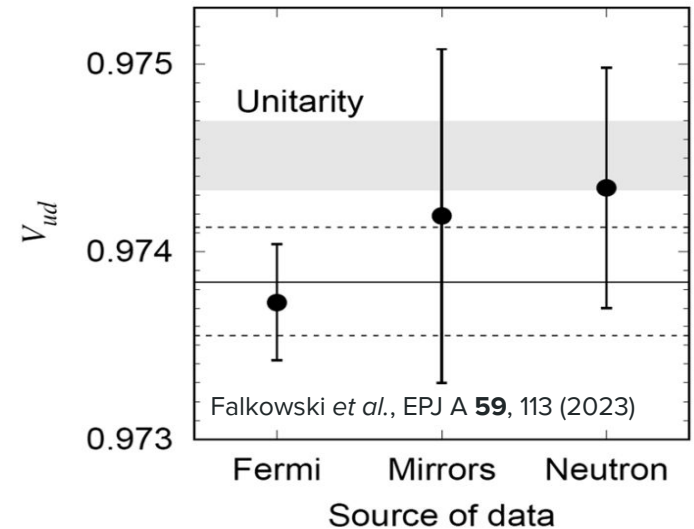
Unitarity of the CKM matrix : **crux** of the current Standard Model

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

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

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weak eigenstates                      CKM matrix                      mass eigenstates



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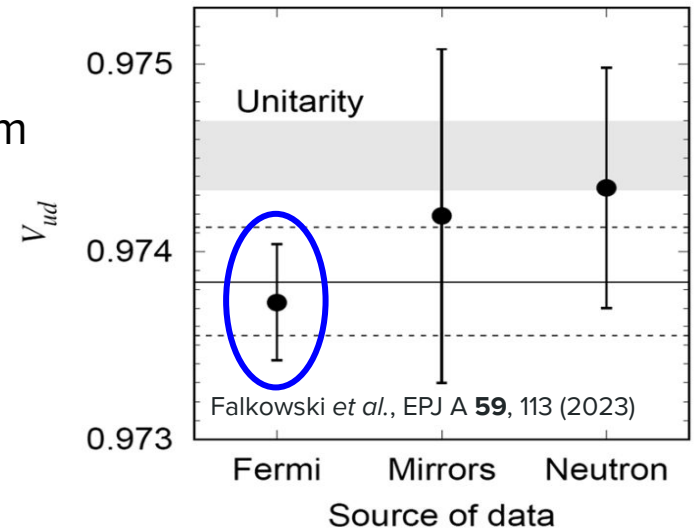
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To date : most precise determination of  $V_{ud}$  comes from **from Ft from superallowed  $0^+ \rightarrow 0^+$  beta decays**

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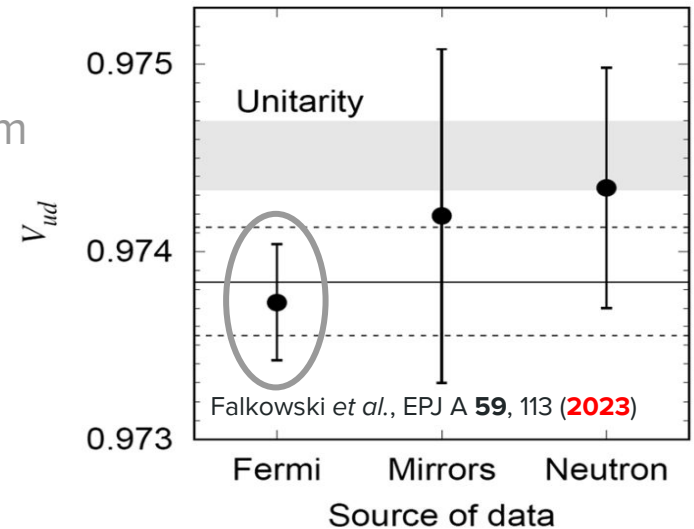
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Unitarity  $V_{ud}^2 + V_{us}^2 + V_{ub}^2 \neq 1$  **violated** at the  **$2\sigma$  level**.

**Is there new physics???**

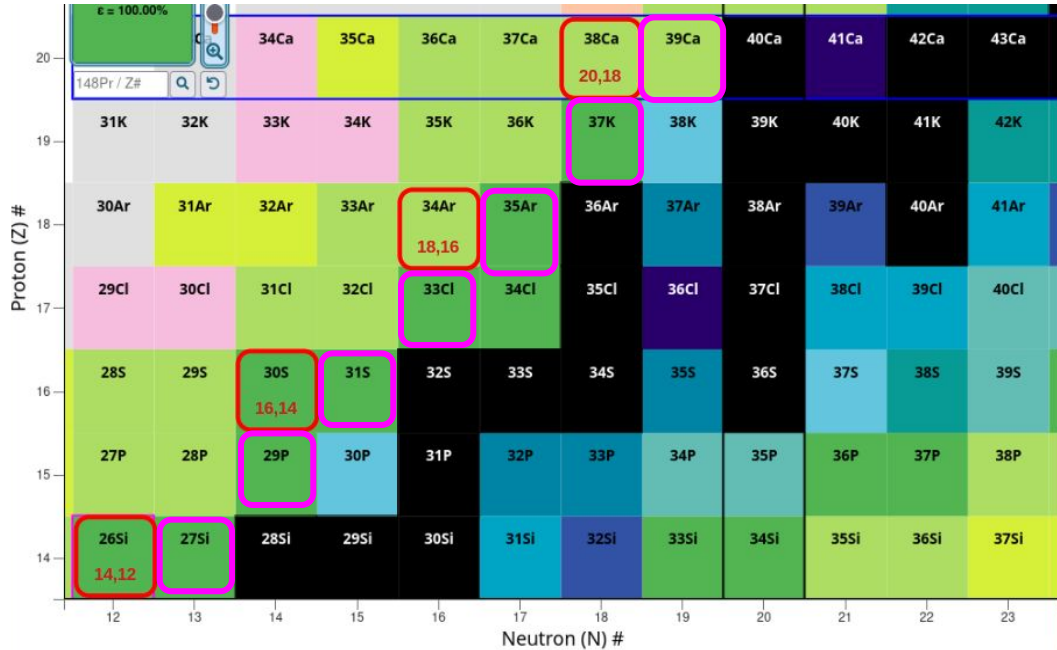
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weak eigenstates                      CKM matrix                      mass eigenstates



# Quick primer on SA beta decays

- $\beta^+$  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
    - $J_i = J_f \neq 0$
    - $T = 1/2$  isospin multiplets
- Found on the neutron deficit side of the nuclear chart



# High precision $ft^{0^+ \rightarrow 0^+}$ values

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

Statistical rate function

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

Partial half-life

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

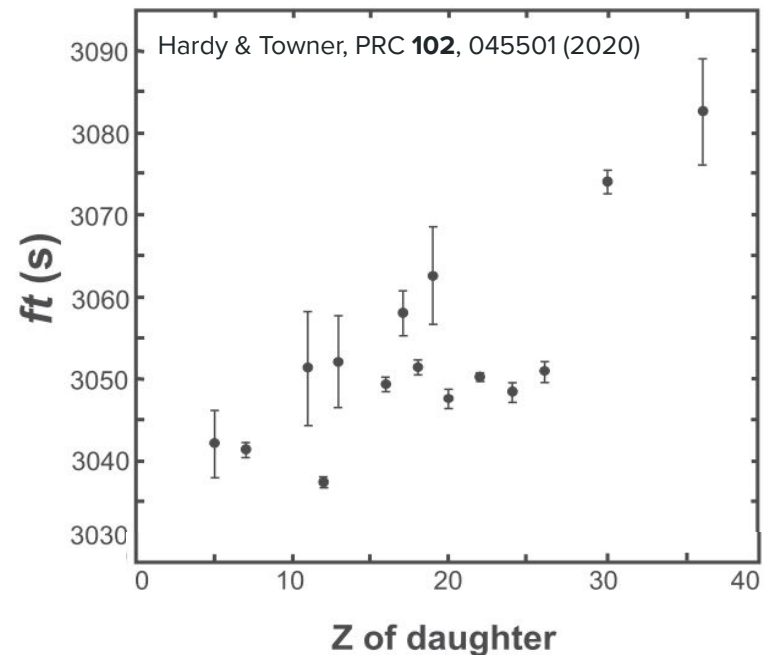


Fig.  $ft$  values of the 15 most precise SA  $0^+ \rightarrow 0^+$  decays

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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,  $t_{1/2} < 0.03\%$
- Beta branching ratio to the  $0^+$  IAS state,  $BR < 0.3\%$

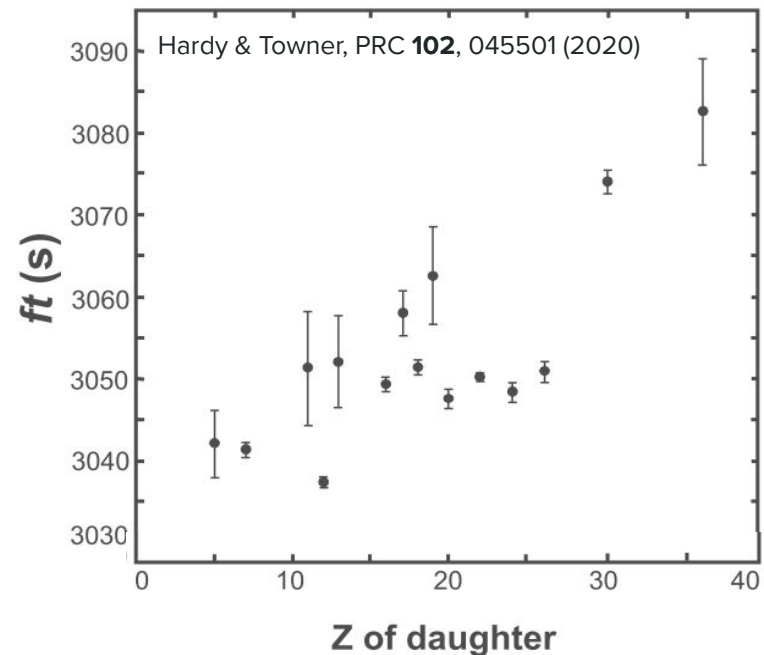


Fig.  $ft$  values of the 15 most precise SA  $0^+ \rightarrow 0^+$  decays



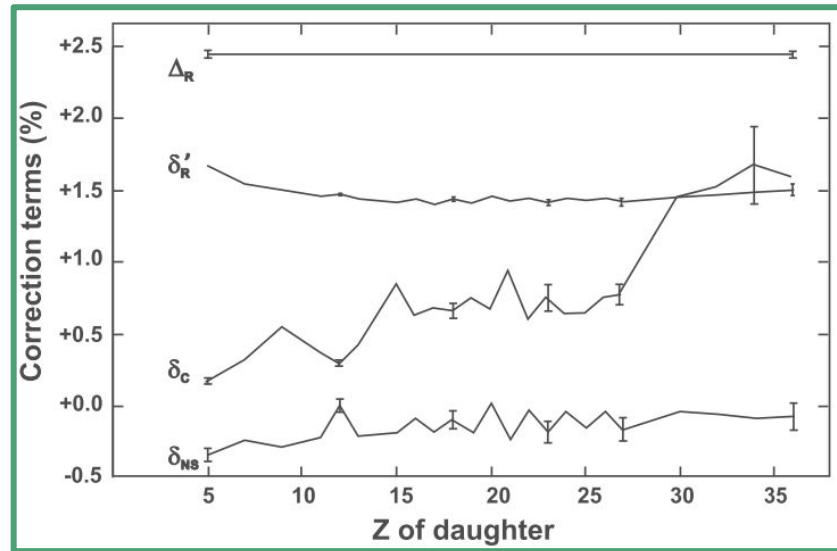
# ft value + corrections = Ft

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

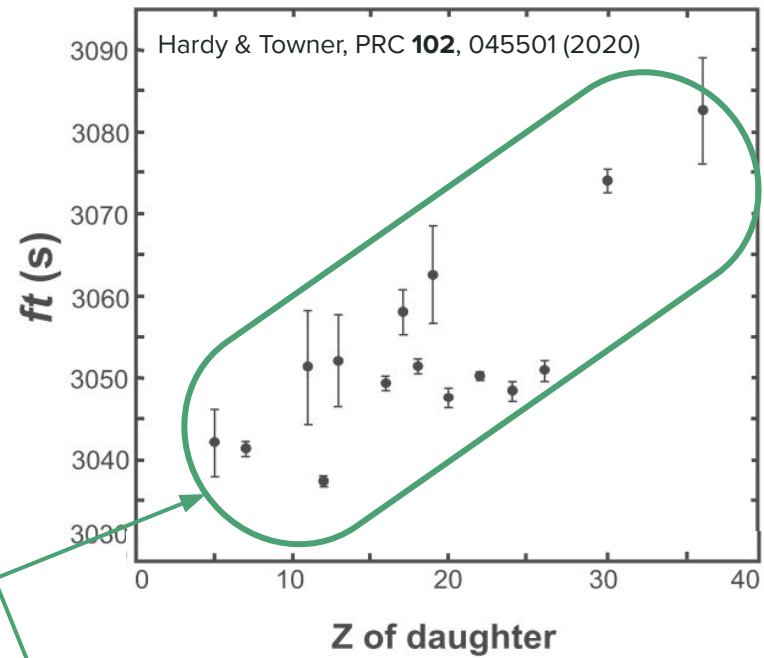
$\Delta_R$ : nucleus **independent** radiative corrections

$\delta'_R$  and  $\delta_{NS}$ : transition/structure **dependent** radiative correction

$\delta_C$ : transition **dependent** isospin symmetry breaking corrections



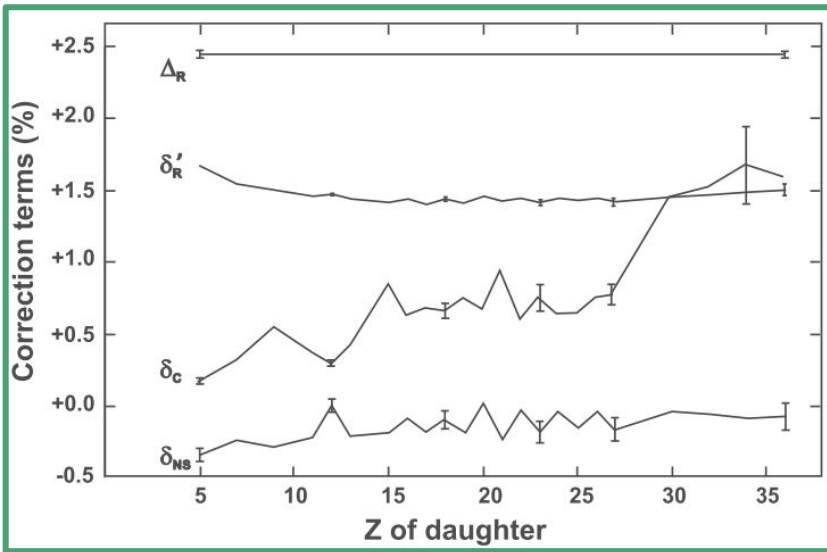
Corrections of order of few %



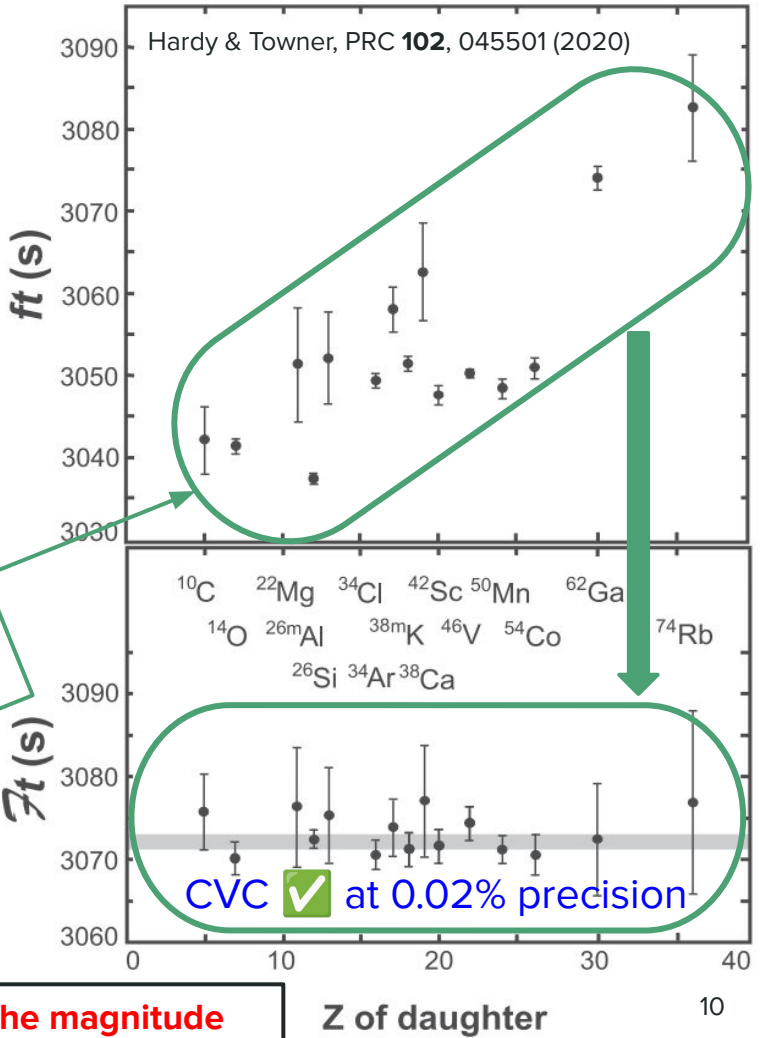
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- $\Delta_R$ : nucleus independent radiative corrections
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Corrections of order of few %



Average Ft defines value of  $V_{ud}$  => corrections define the magnitude

Z of daughter 10

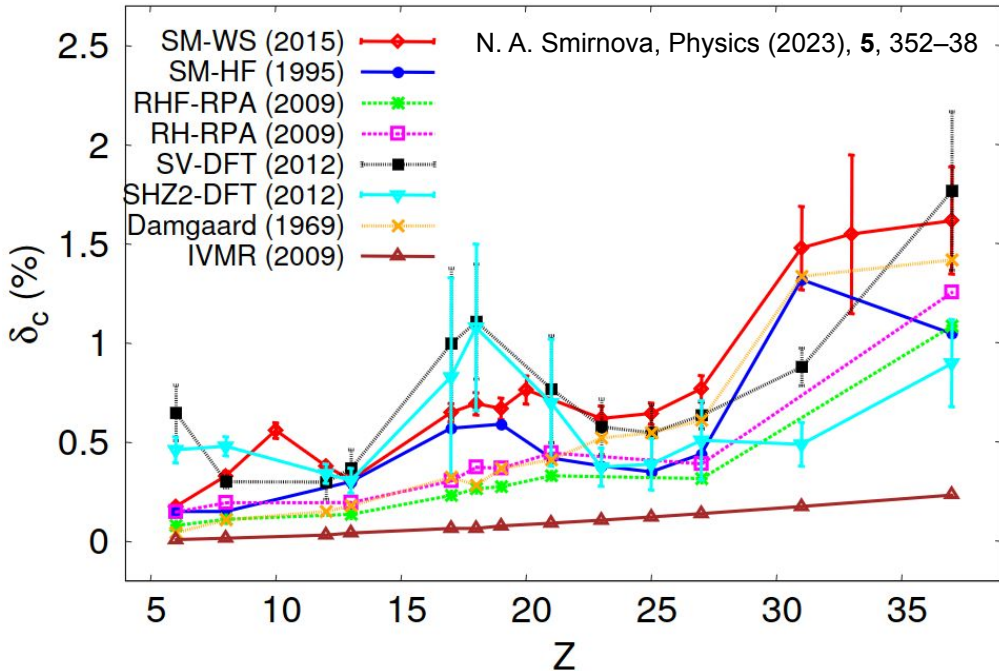
# Isospin symmetry breaking (ISB) corrections

$$Ft^{0^+ \rightarrow 0^+} = ft^{0^+ \rightarrow 0^+} (1 + \delta'_R) (1 + \delta_{NS} - \delta_C) = \frac{K}{2V_{ud}^2 G_F^2 (1 + \Delta_R)}$$

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

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

- $\delta_C$  increases with Z
- Several  $\delta_C$  corrections using different models.
- Large corrections near shell closure in  $T_z = -1$  parents e.g.  $^{18}\text{Ne}$ ,  $^{30}\text{S}$ ,  $^{42}\text{Ti}$



**To date : Ft computed using only one theory model**

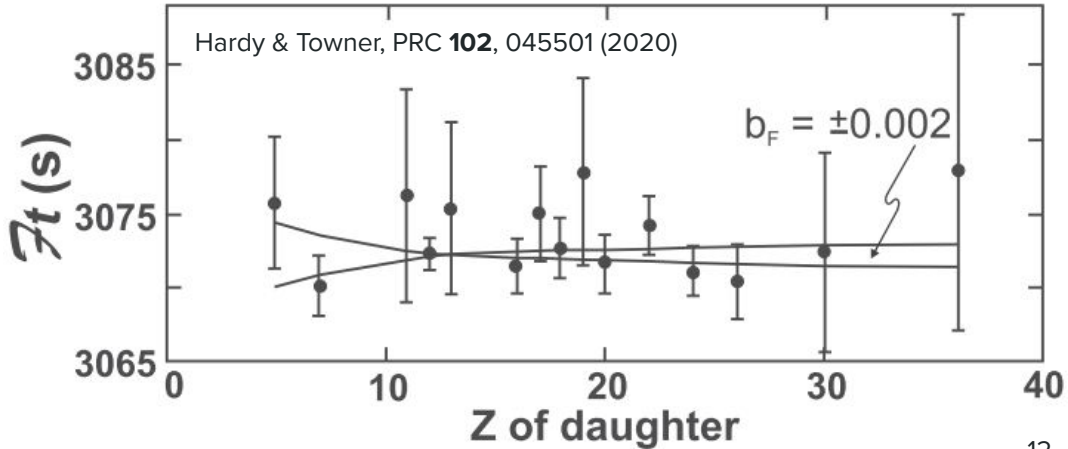
# But that's not all ...

**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:  $^{10}\text{C}$ ,  $^{14}\text{O}$

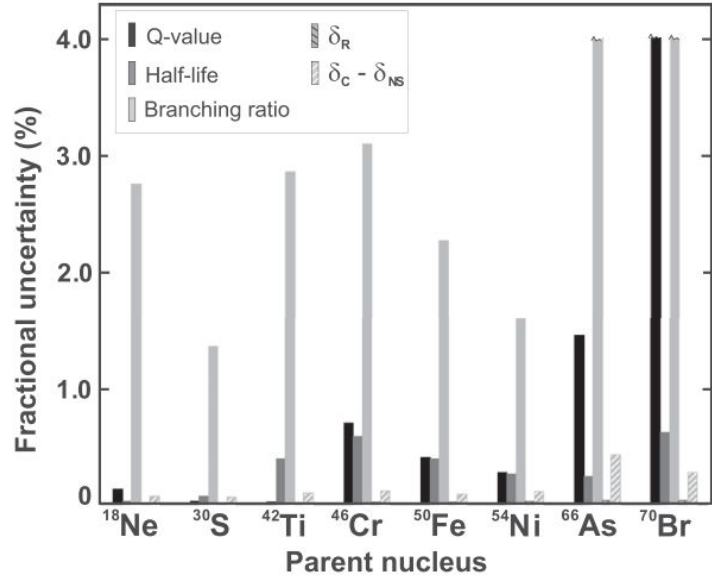
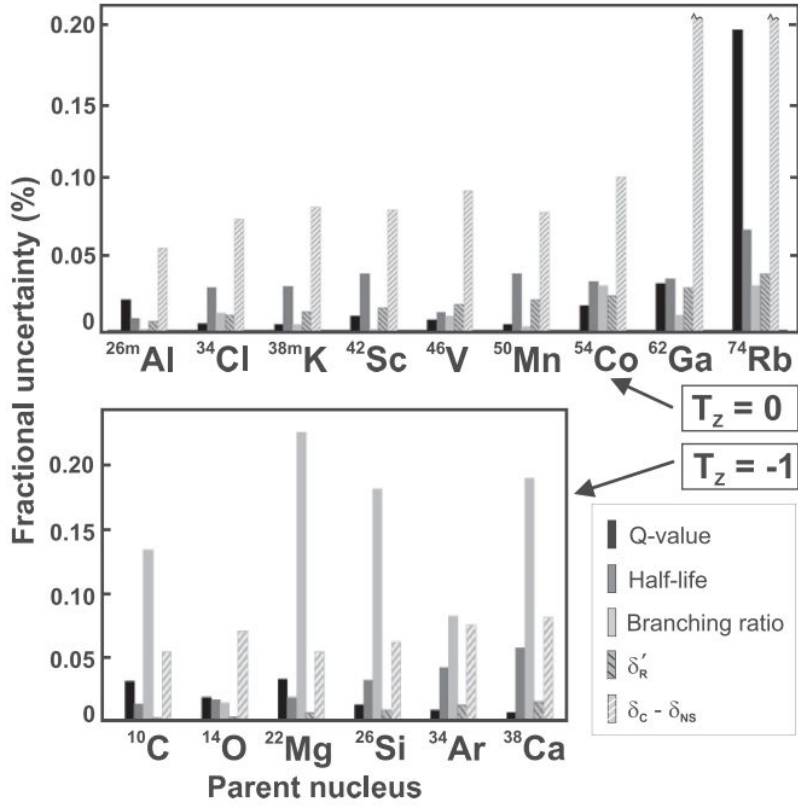
$$\mathcal{F}t_{\text{BSM}}^{0^+ \rightarrow 0^+} \approx \frac{K}{2G_F^2 V_{ud}^2 (1 + \Delta_R^V)} \frac{1}{1 + b_F \gamma \langle 1/W \rangle}$$

**To constrain  $b$  : improve precision on all ft**



# Current scenario...

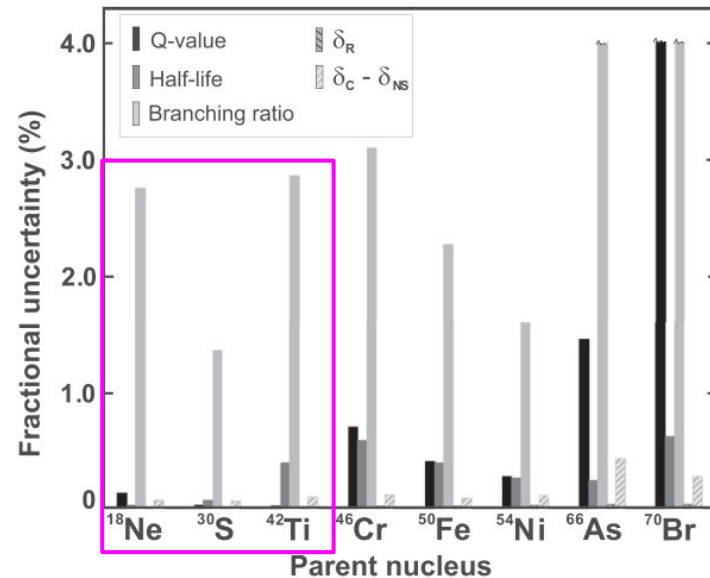
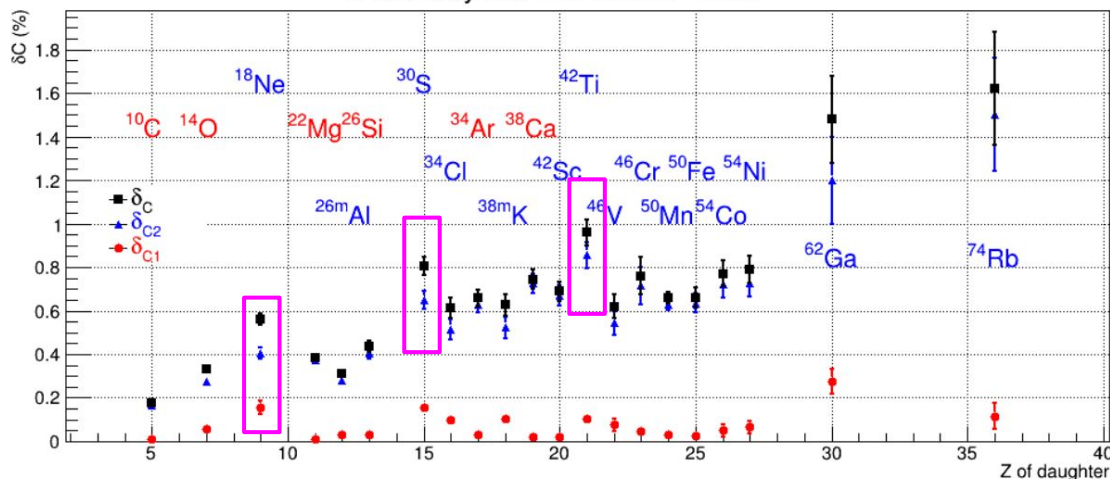
23 known cases, but precision  $\approx 0.3\%$  or better for **only 15** transitions



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

# Superaligned program at GANIL : Current

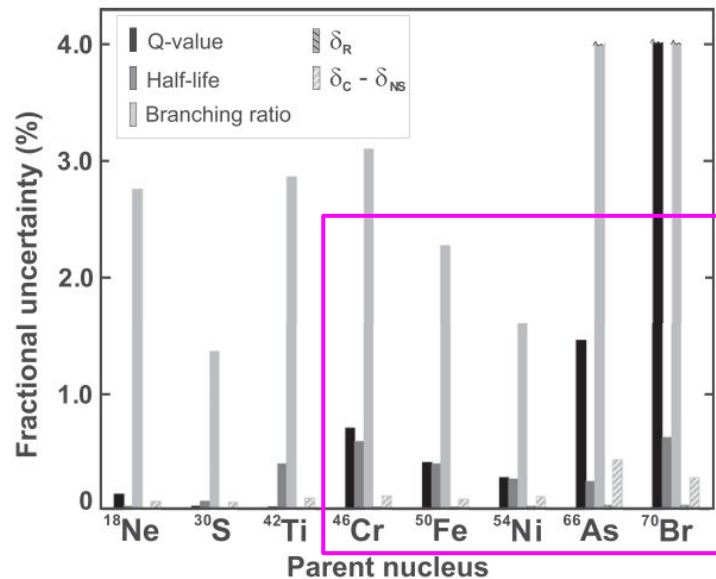
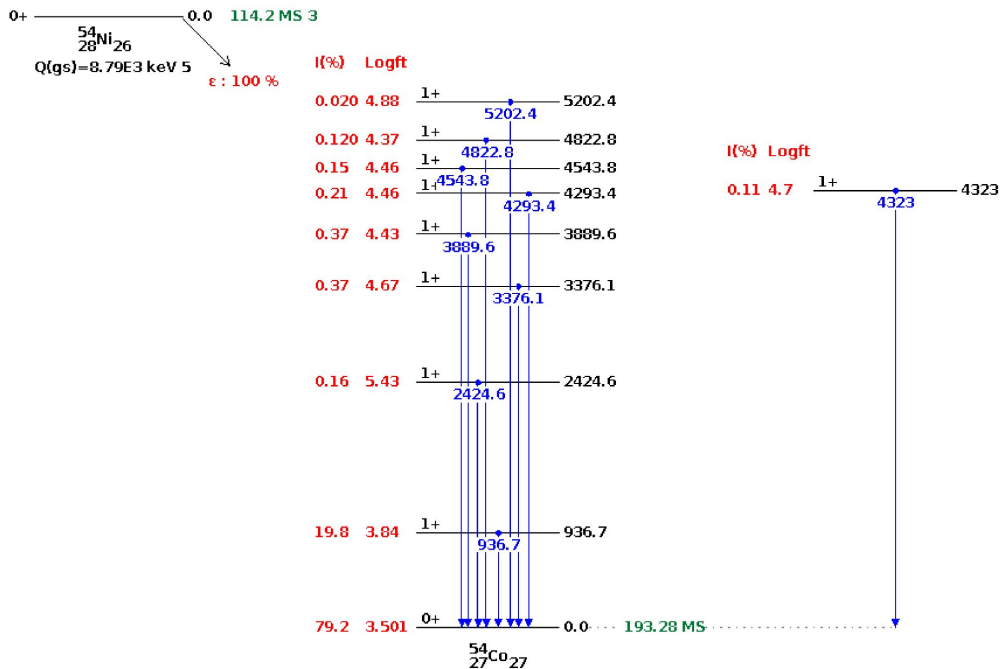
- Proposal to remeasure the branching ratio of  $^{18}\text{Ne} \rightarrow ^{18}\text{F}$
- Analyzing the data to improve branching ratio and half-life for decay of  $^{30}\text{S} \rightarrow ^{30}\text{P}$
- Exploring production of  $^{42}\text{Ti}$  at LISE



To benchmark  $\delta_c$  calculations : need high precision experimental data

# Superaligned program at GANIL : Future

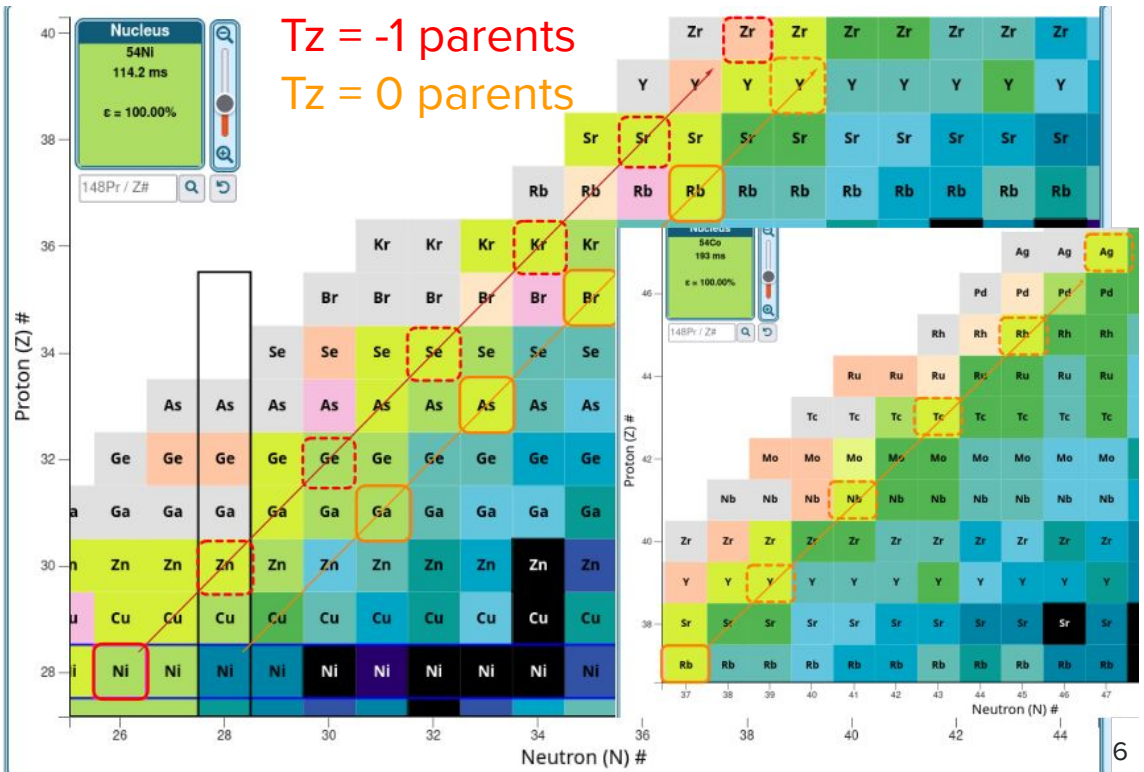
- Improve precision on remaining 5 cases
- Require beams from upcoming S3 facility
- Branching ratio measurement with Total Absorption spectroscopy (TAS)



# Superaligned program at GANIL : Future

## Extend range of nuclei to test CVC for heavier super allowed $\beta^+$ emitters

- Beams from upcoming S<sup>3</sup> facility.
- Couple with HRS/PIPERADE @ DESIR for ultrapure samples
- Mass measurements using PIPERADE/MLLTRAP
- BR,  $t_{1/2}$  using decay tape station and TAS or other decay spectroscopy setups.





# Superaligned program at GANIL : Challenges

## DESIR beams via S<sup>3</sup>-LEB

- t<sub>1/2</sub> for know (heavier) SA emitters <sup>54</sup>Ni - <sup>70</sup>Br : **115 ms and less**
  - Current gas cell extraction time 300-600 ms (projected to 50 ms)
  - Could be a major bottleneck

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

1 H 1.008	2 He 4.003	Studied by laser spectroscopy										13	14	15	16	17	2 He 4.003
3 Li 6.941	4 Be 9.012	To be studied in the current/new RI facilities										5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.999	10 Ne 20.180
11 Na 22.990	12 Mg 24.305	3	4	5	6	7	8	9	10	11	12	13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.789
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.95	43 Tc [98]	44 Ru 101.07	45 Rh 102.91	46 Pd 106.43	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57-71 * #	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po [209]	85 At [210]	86 Rn [222]
87 Fr [223]	88 Ra [226]	89-103 #	104 Rf [265]	105 Db [268]	106 Sg [271]	107 Bh [270]	108 Hs [277]	109 Mt [276]	110 Ds [281]	111 Rg [280]	112 Cn [285]	113 Nh [286]	114 Fl [289]	115 Mc [289]	116 Lv [293]	117 Ts [294]	118 Og [294]
* Lanthanide series		57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [145]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.91	68 Er 167.26	69 Tm 168.91	70 Yb 173.05	71 Lu 174.97	
# Actinide series		89 Ac [227]	90 Th 232.01	91 Pa 231.04	92 U 238.03	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]	103 Lr [262]	

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

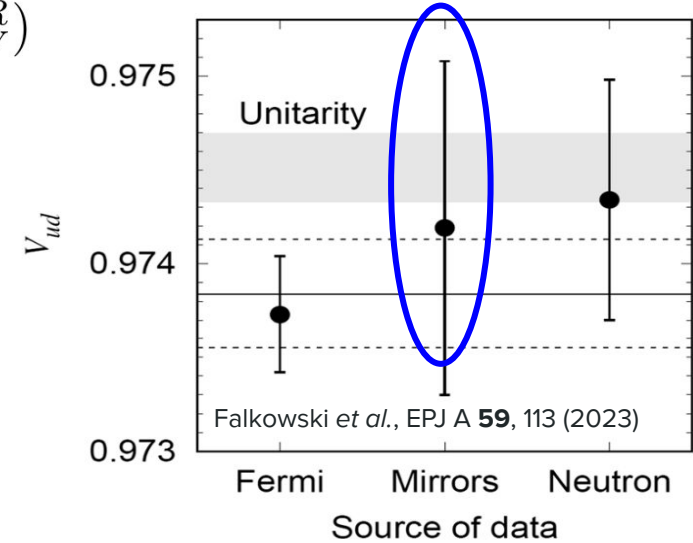
# Superaligned program at GANIL : Day 1 cases

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

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

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

- In addition to BR,  $t_{1/2}$  and masses require  $\rho$  = Gamow-Teller/Fermi mixing ratio
- Requires correlation measurements => MORA
- Beta asymmetry ( $A_\beta$ ) : 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!**

