Precision measurements in superallowed $0^+ \rightarrow 0^+$ β decays at GANIL

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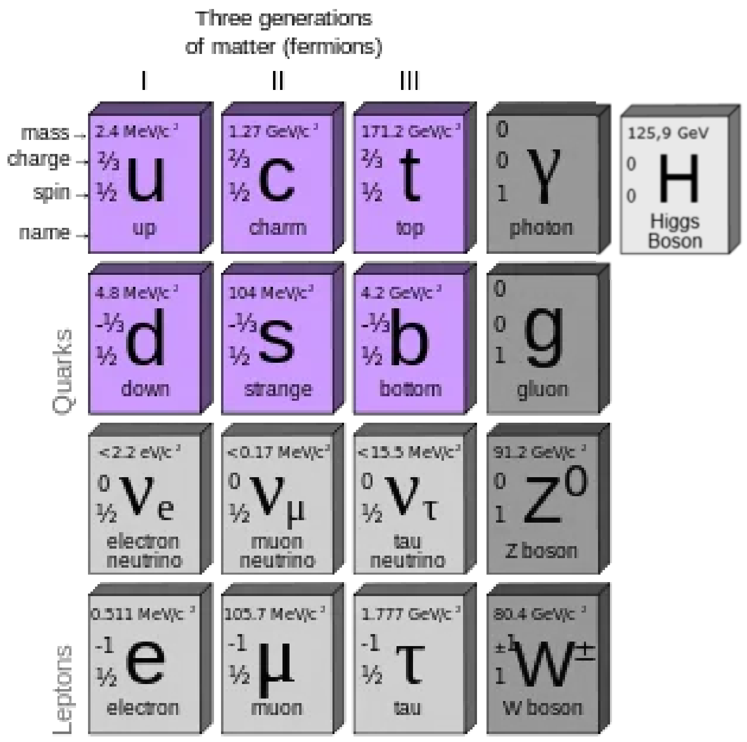
(On behalf of B. Rebeiro)

GDR Intensity Frontier
Annual Workshop 2025

12-14 November 2025

laboratoire commun CEA/DRF CNRS/IN2P3

Superallowed β decays: link to BSM physics



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

weak eigenstates **CKM matrix** **mass eigenstates**

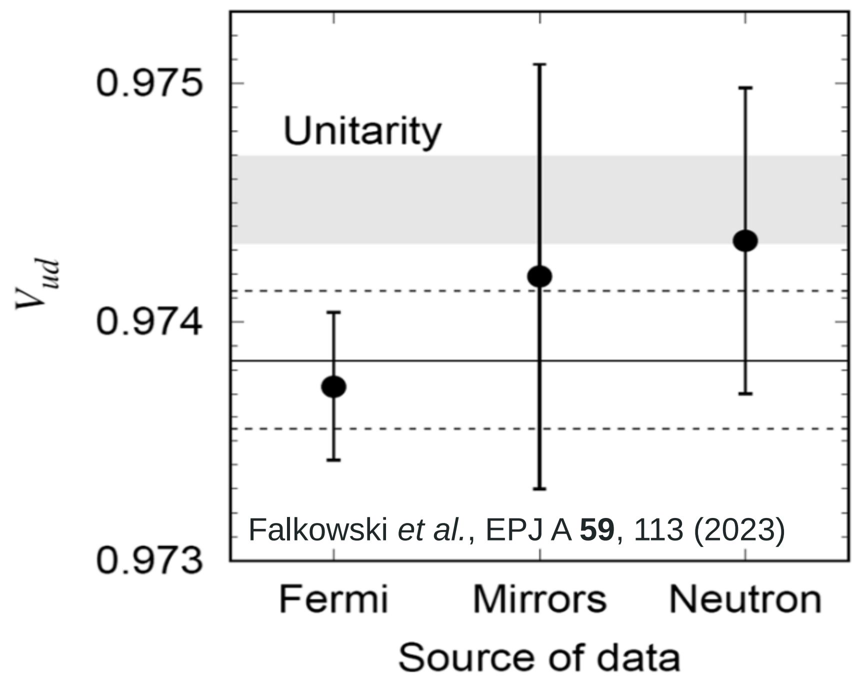
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Cabibbo-Kobayashi-Maskawa quark mixing matrix

- Describes relation between flavor eigen states and mass eigen states
- 3 quark generations = 3x3 matrix
- **Unitarity of CKM matrix** is fundamental to Standard Model

Superallowed β decays: link to BSM physics

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

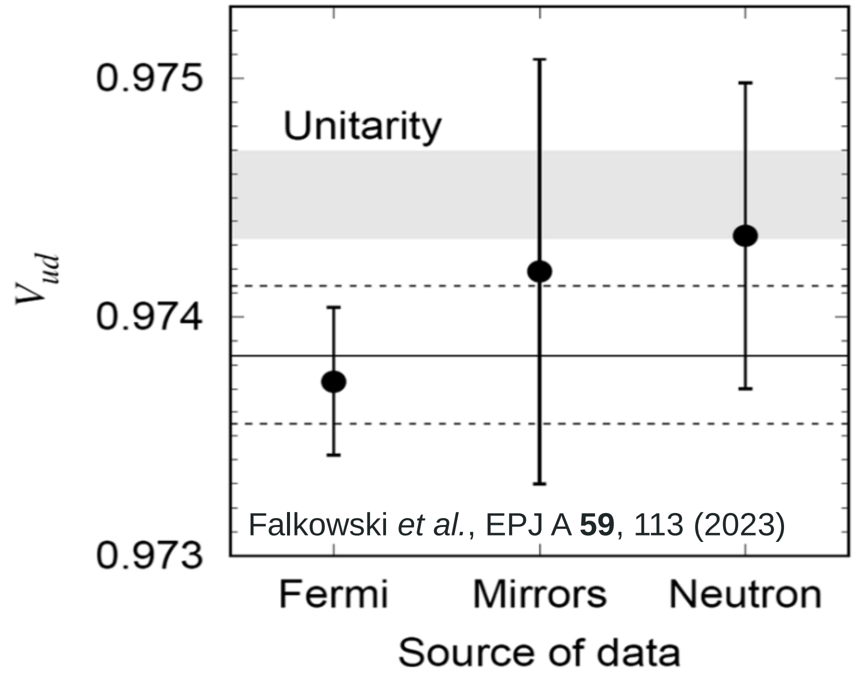


V_{ud} largest + most precise top-row element

- Contribues **strongly to unitarity tests**
- Accesible via superallowed beta decays

Superallowed β decays: link to BSM physics

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



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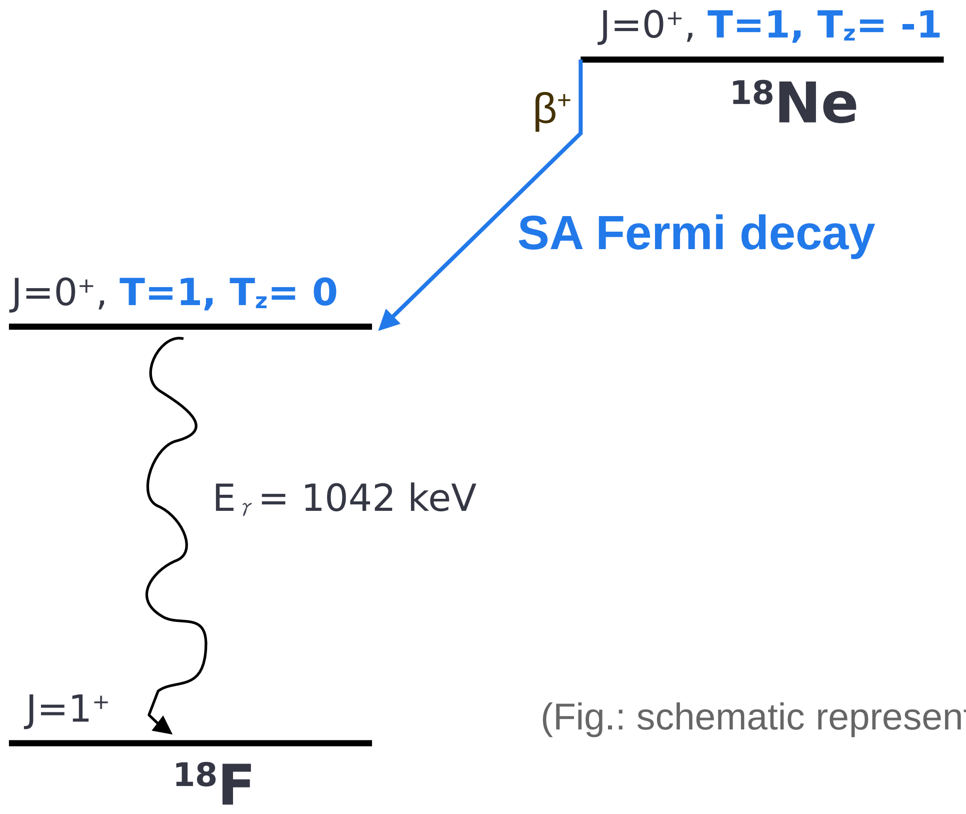
SA beta decay: β decays between **isobaric analog states (IAS)** => $J_i = J_f$



(Fig.: schematic representation)

Mirrors, neutron decays

- T = ½ isospin doublet
- $J_i = J_f = ½^+$

Fermi decays

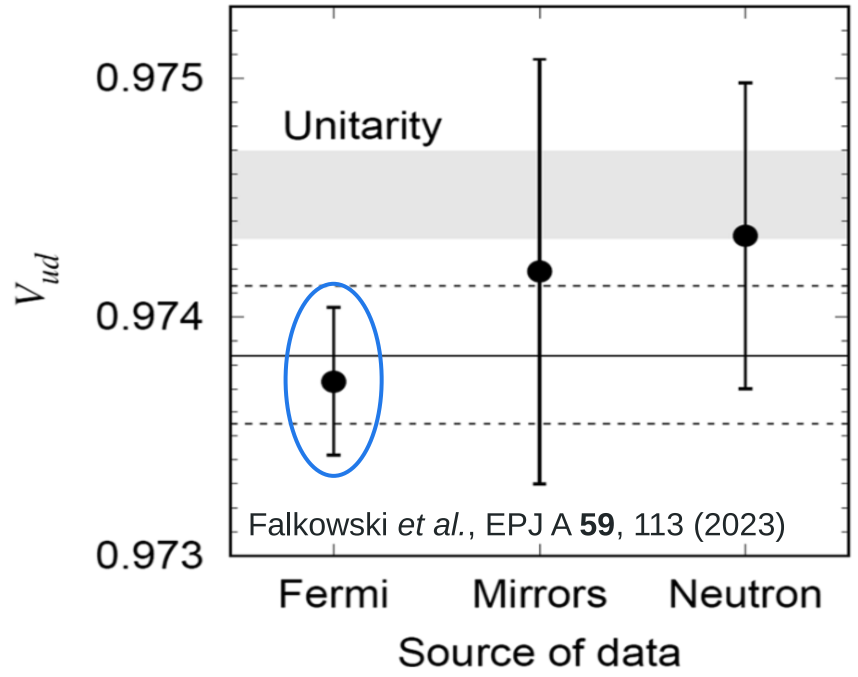
- T = 1 isospin triplet
- $J_i = J_f = 0^+$

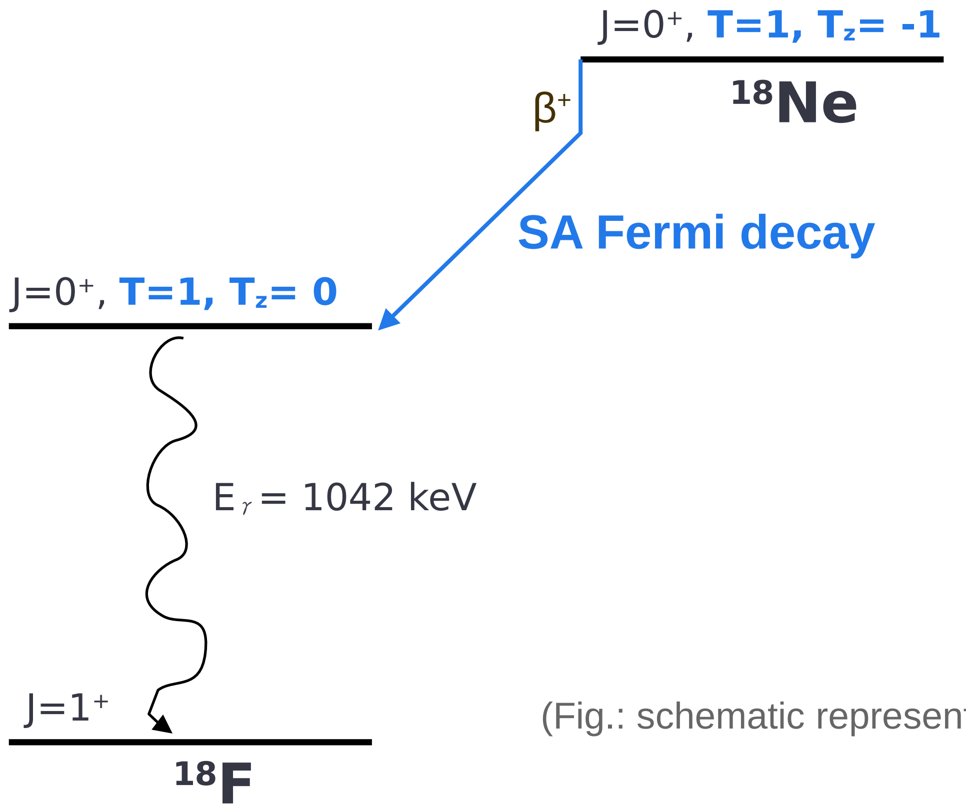
aka SA $0^+ \rightarrow 0^+$ β decay

Superallowed β decays: link to BSM physics

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

$$|0.97373(31)|^2 + |0.22430(80)|^2 + |0.00382(20)|^2 < 1^{[1]}$$





(Fig.: schematic representation)

To date most precise determination of $|V_{ud}|$ is from

Ƒt values of SA $0^+ \rightarrow 0^+$ beta decays

[1] J. C. Hardy and I. S. Towner, PRC, **102**, 045501, (2020)

High precision *ft* values

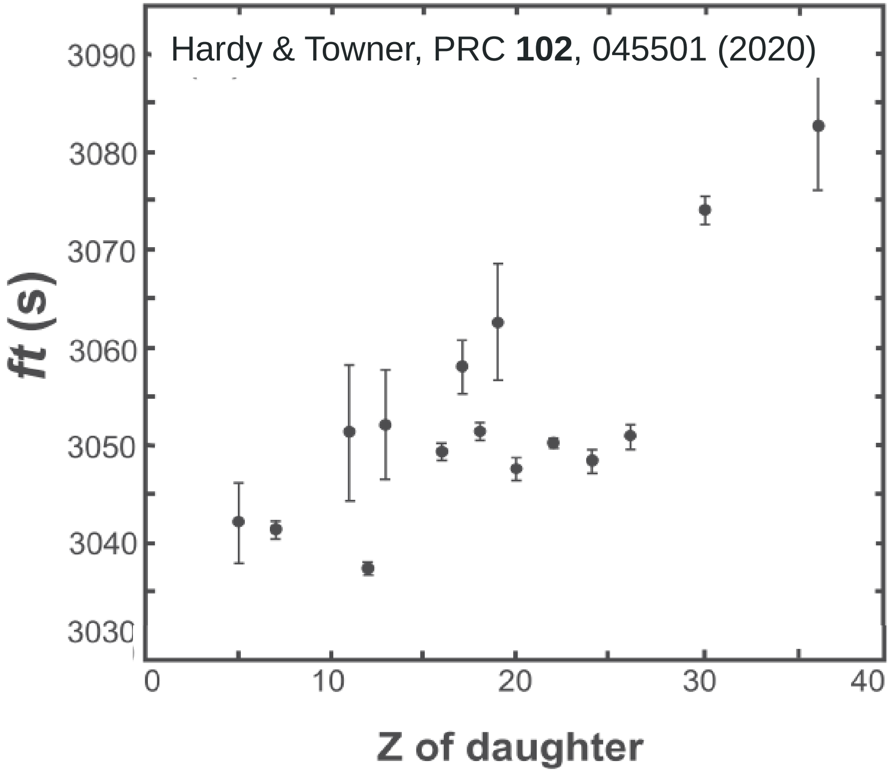
$$\frac{K}{2V_{ud}^2 G_F^2 (corrections)} = ft^{0^+ \to 0^+}(corrections)$$

Statistical rate function

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

Partial half-life

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



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

- 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, $BR < 0.3\%$

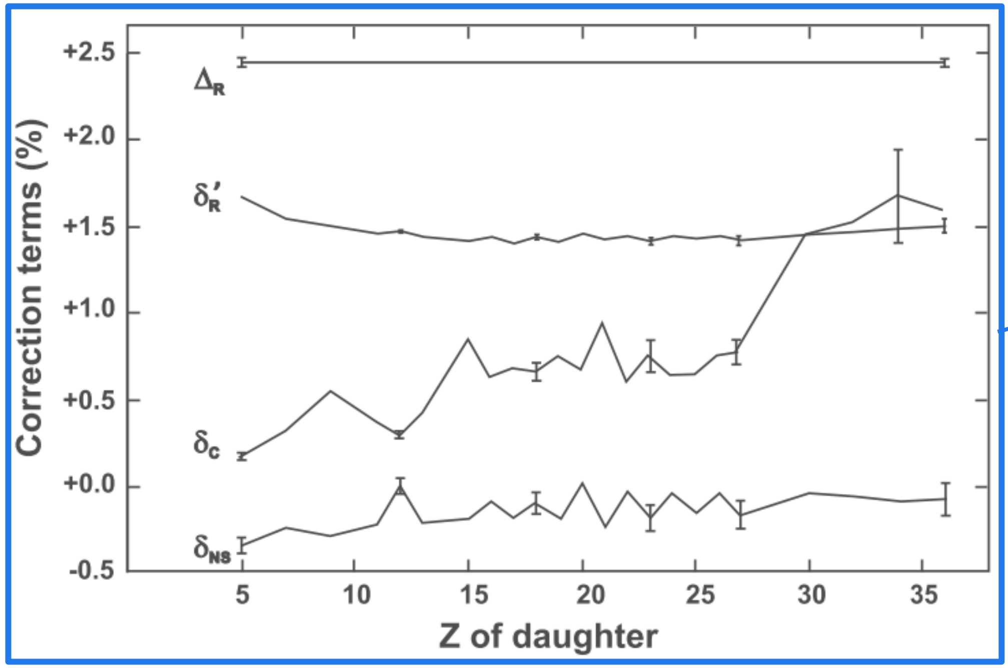
ft values + corrections = Ƒt

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

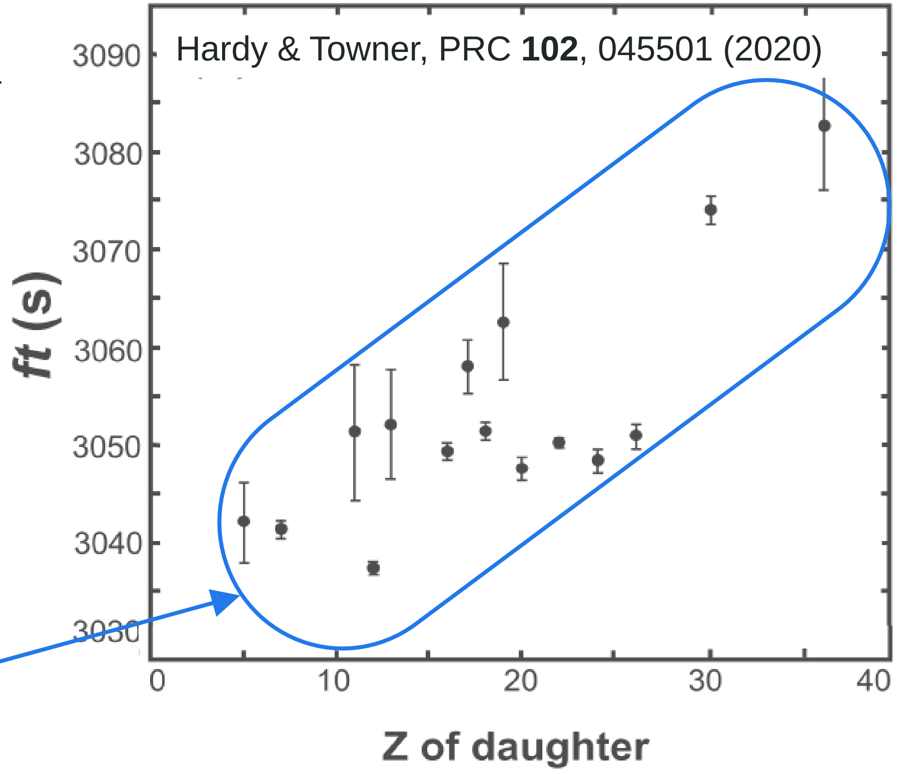
Δ_R: nucleus independent radiative corrections

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

δ_C: structure dependent isospin symmetry breaking corrections



Corrections of few %



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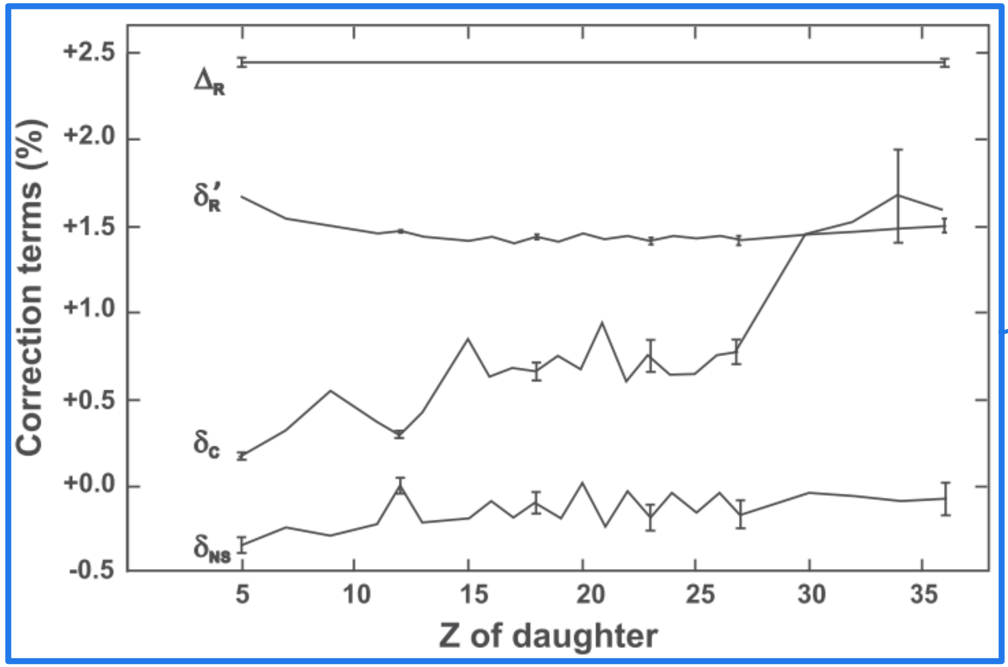
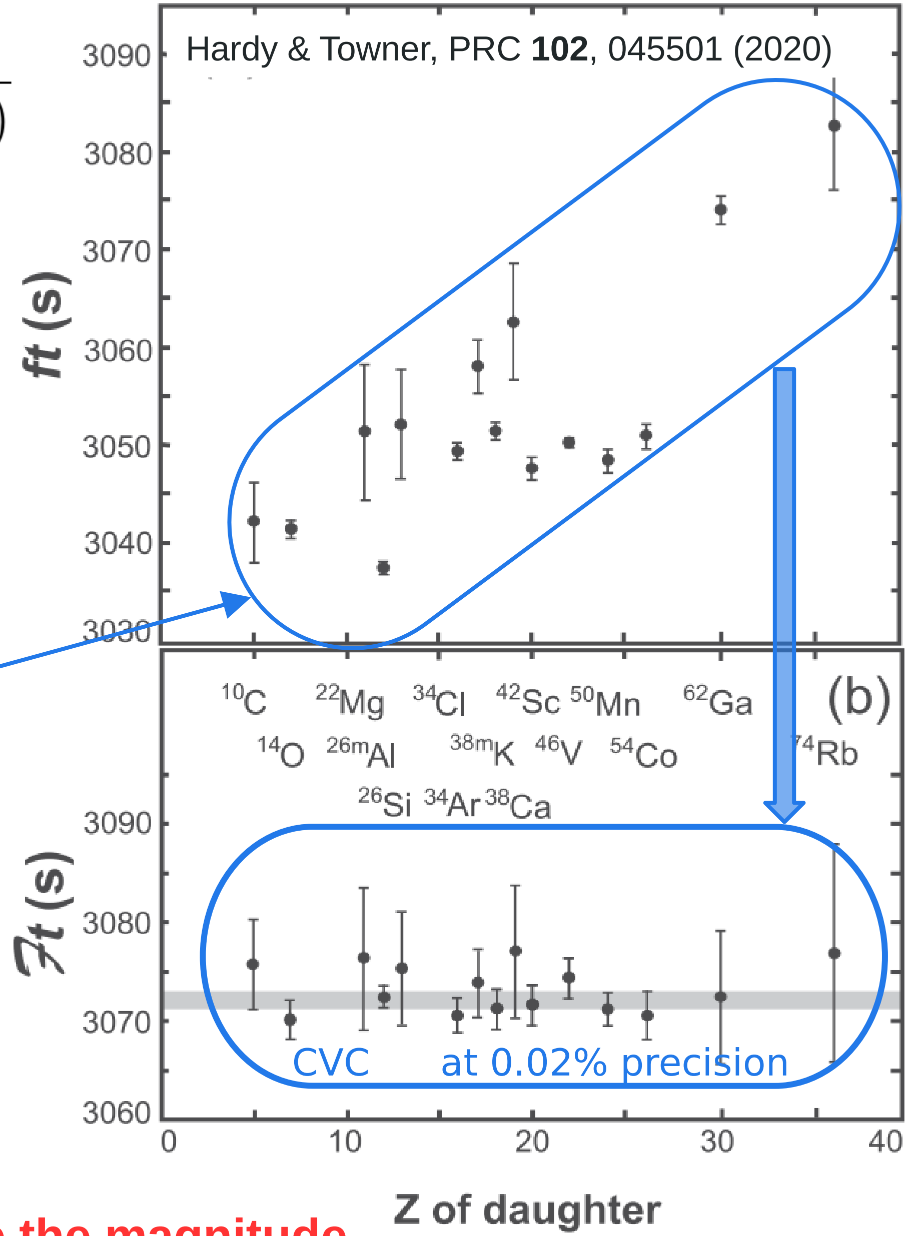


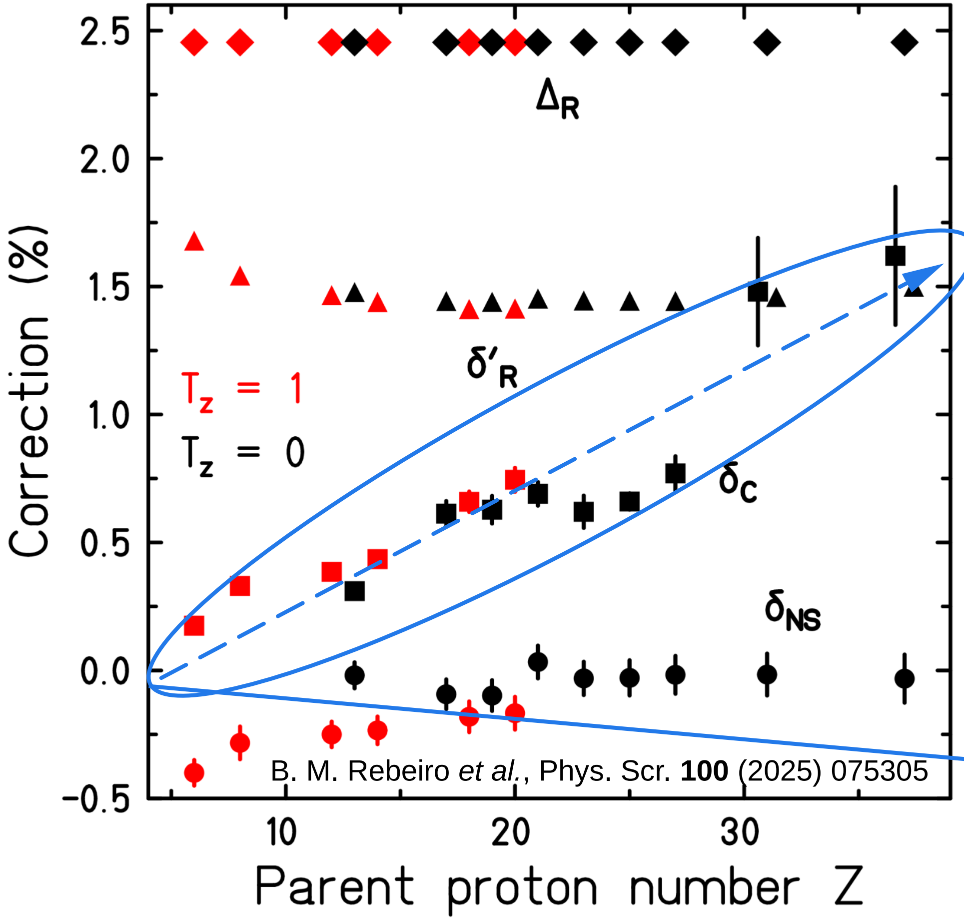
Corrections of few %



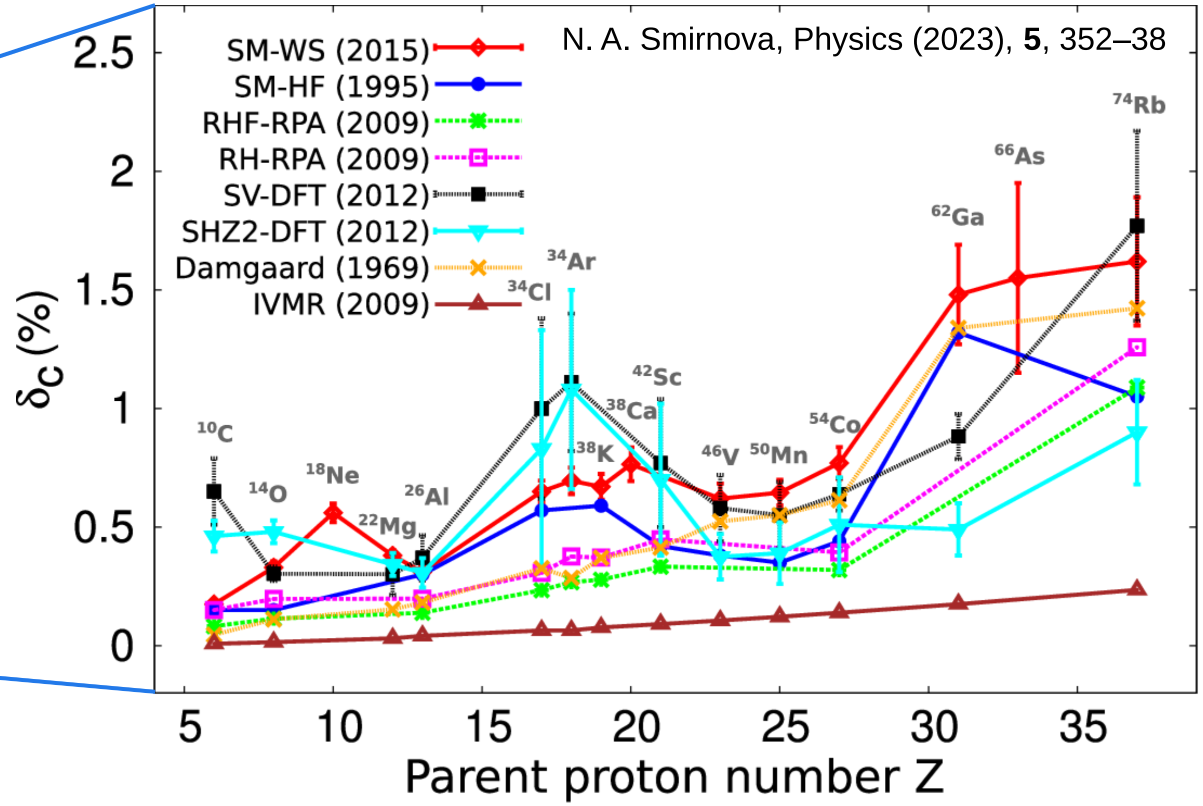
Average Ƒt defines value of V_{ud} => corrections define the magnitude

BSM physics or model effect?

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



δ_c: Isospin symmetry breaking correction



$\mathcal{F}t$ values computed using only one δ_C theory model: SM-SW (2015)

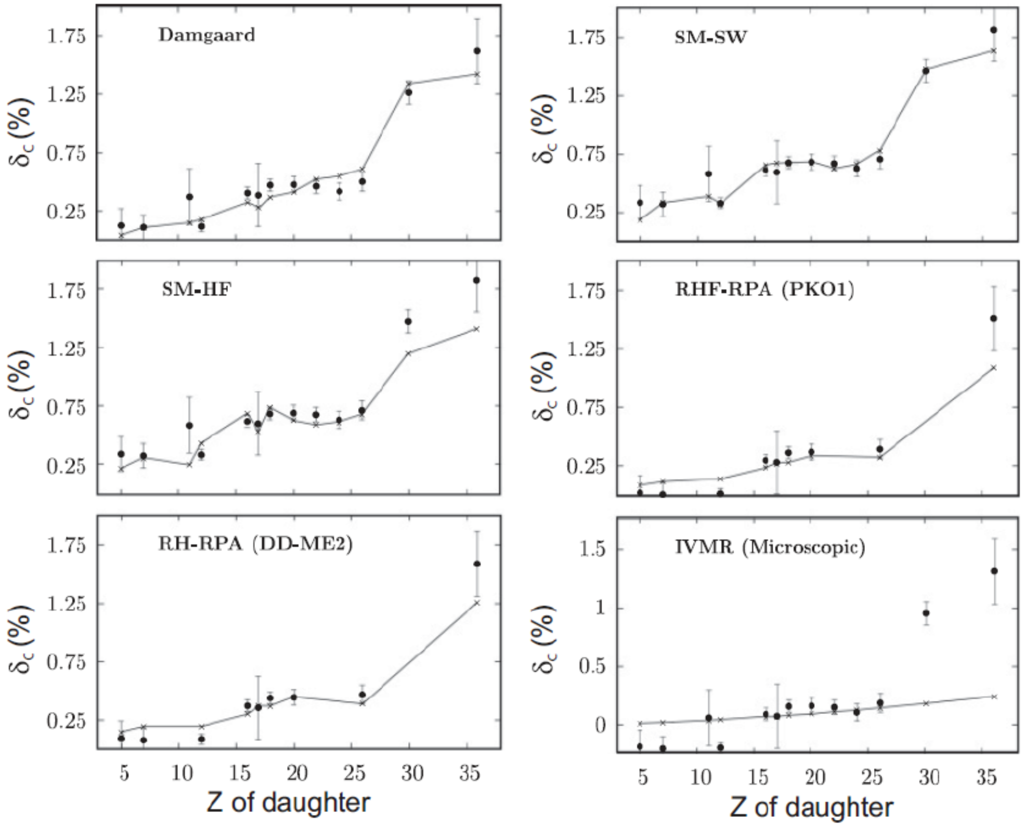
BSM physics or model effect?

2. Remark on δ_c for the pure Fermi $0^+ \rightarrow 0^+$ transitions:

Towner and Hardy concluded that the(ir) SM-SW values are best because these,

“when combined with the experimental *ft* values, produce corrected *Ft* values that agree best with the CVC hypothesis over the full range of *Z* values”.

One can question this approach as they later use the constancy of these *Ft* values to test to which precision the CVC hypothesis holds …



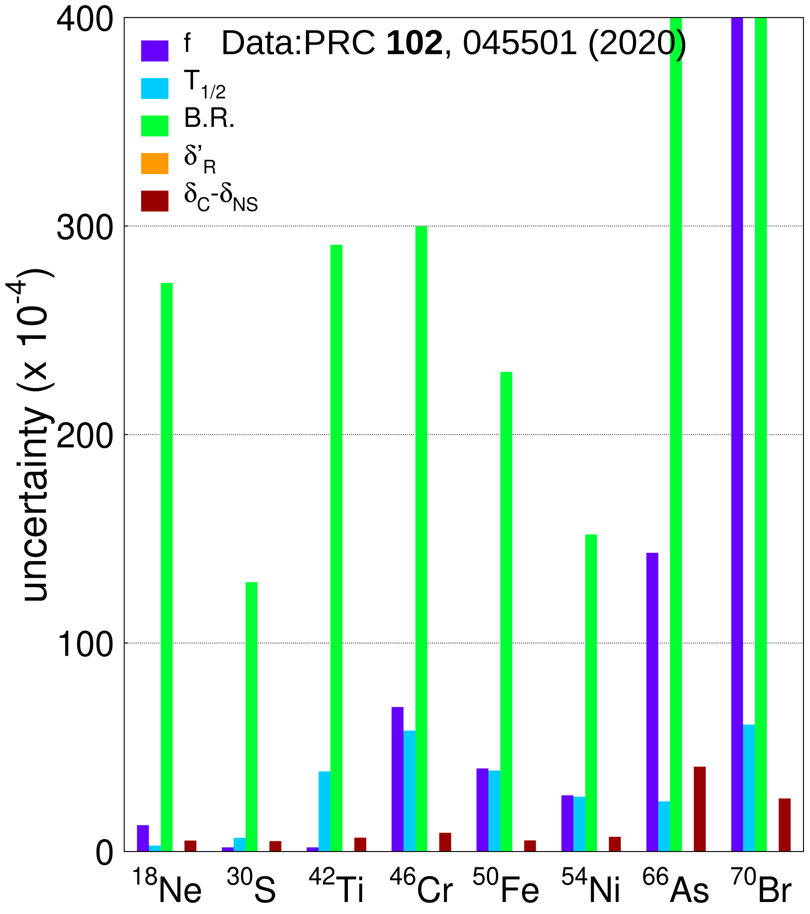
I.S. Towner and J.C. Hardy, Phys. Rev. C 82, 065501 (2010)

KU LEUVEN

Slide taken from Nathal Severijns' PSI 2025 talk

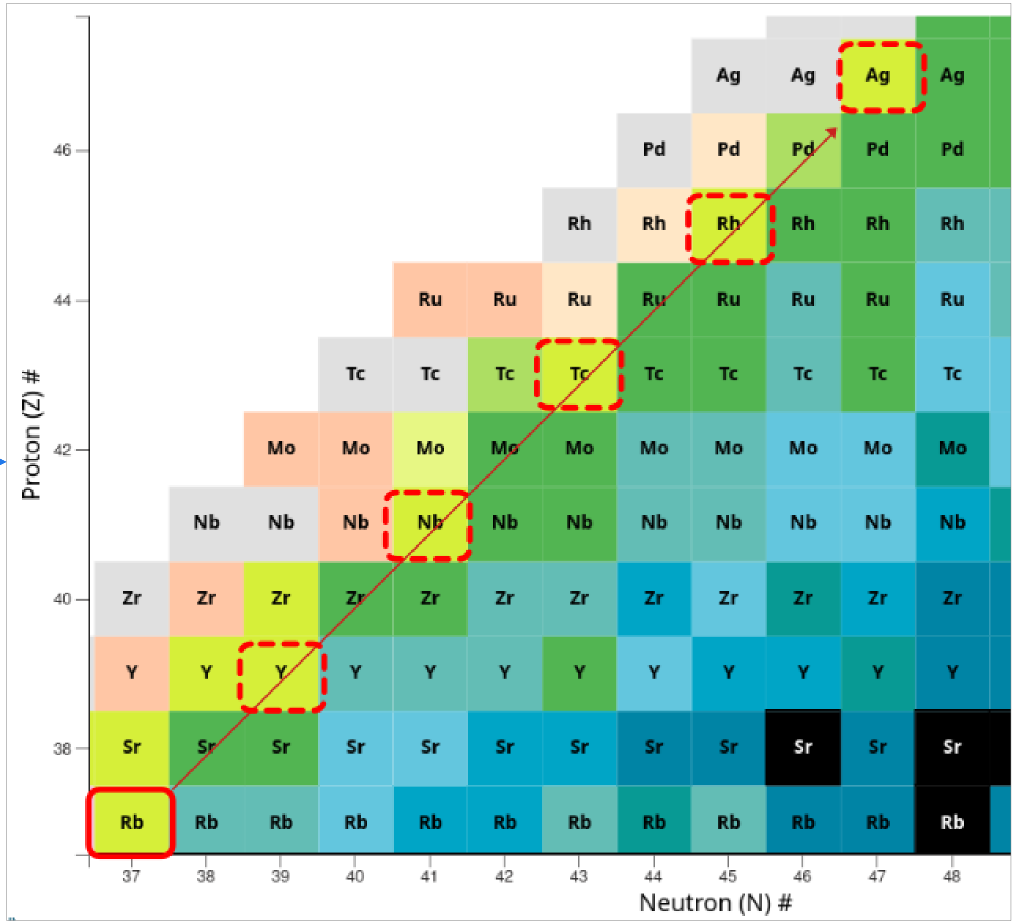
Superallowed program at GANIL

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



High precision
Half life, branching ratio & masses

Constrain ISB corrections
&
Test ISB models for larger variation of Z



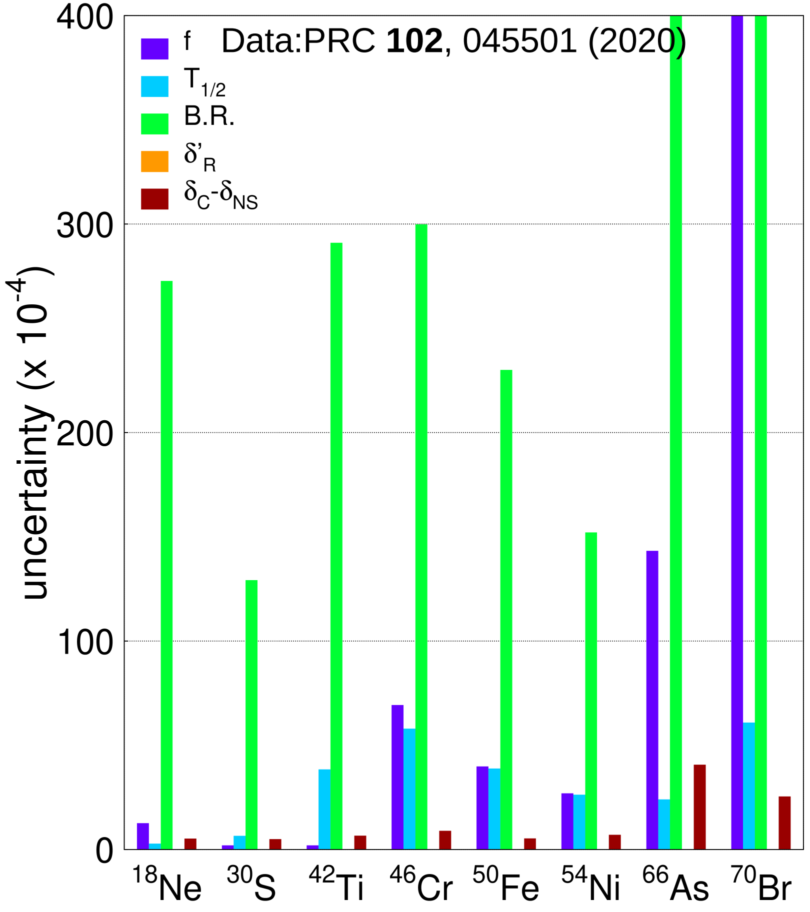
Phase 1: Expts at SPIRAL1 & LISE

Phase 2: Expts at DESIR & S^3-LEB

Superallowed program at GANIL

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

B M Rebeiro et al., Phys. Scr. 100 (2025) 075305
Superallowed $0^+ \to 0^+$ β decay studies at GANIL and upcoming opportunities with DESIR and S^3-LEB



High precision
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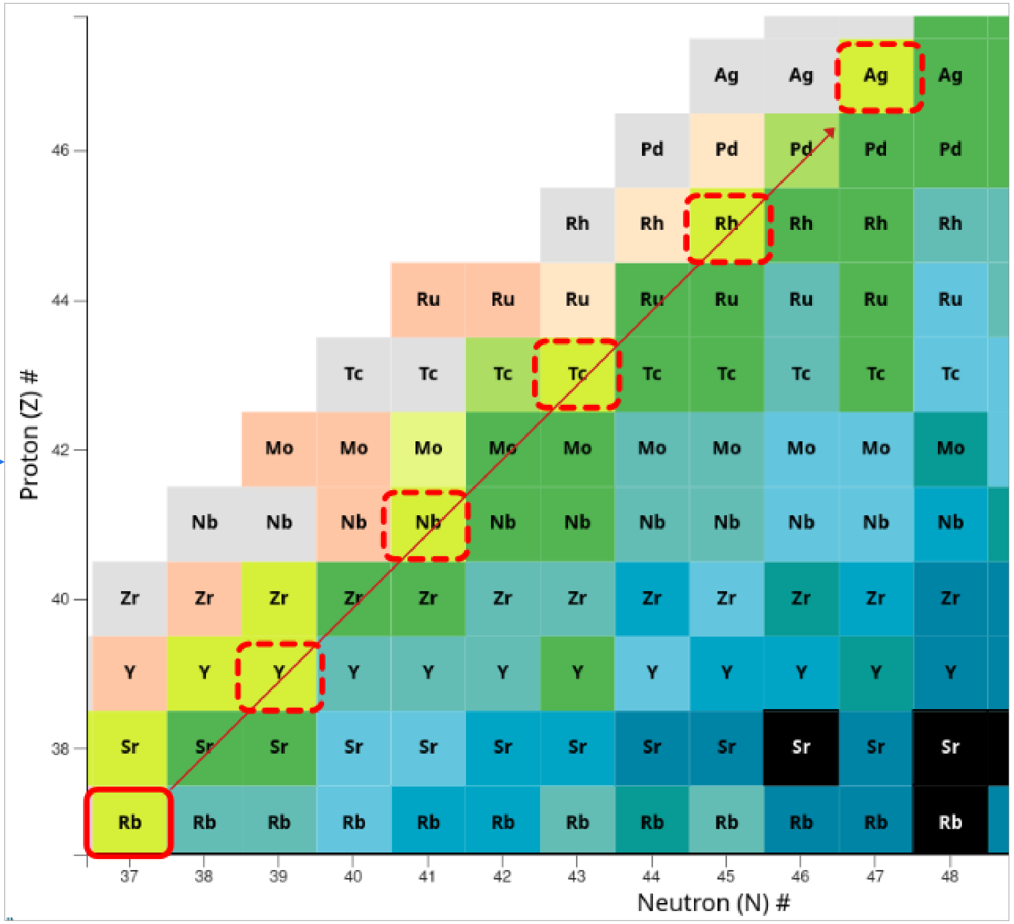
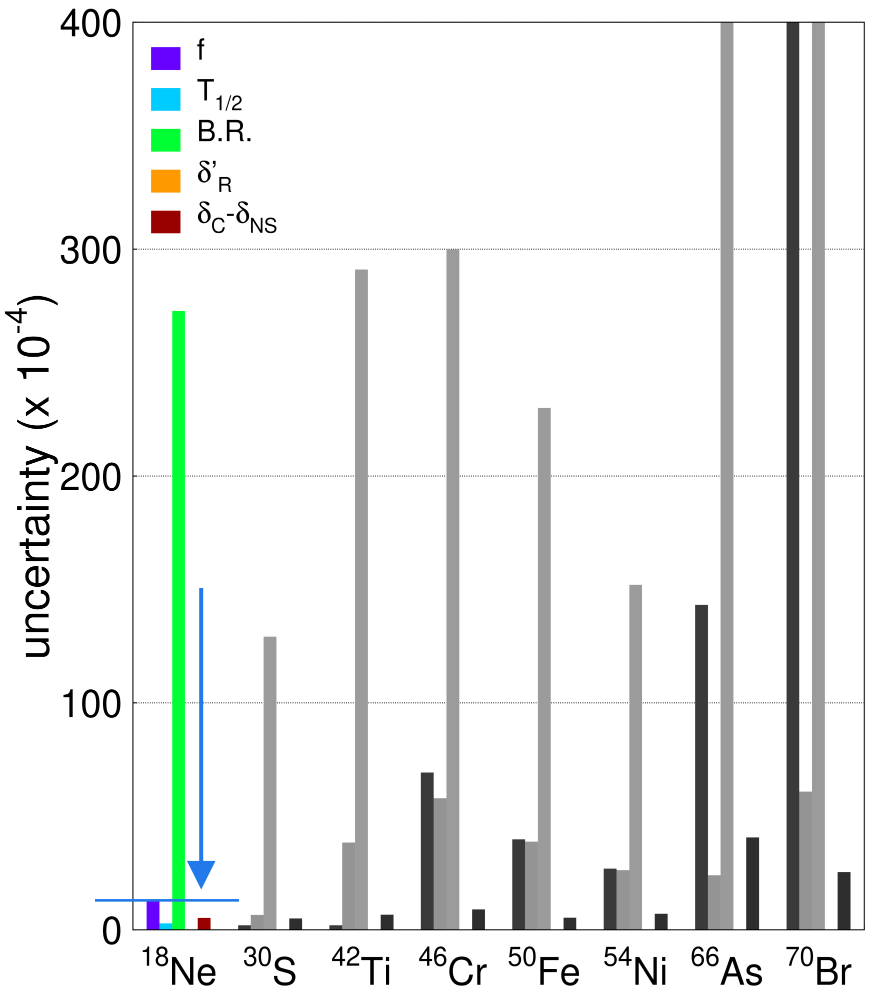


Phase 1: Expts at SPIRAL1 & LISE

Phase 2: Expts at DESIR & S^3-LEB

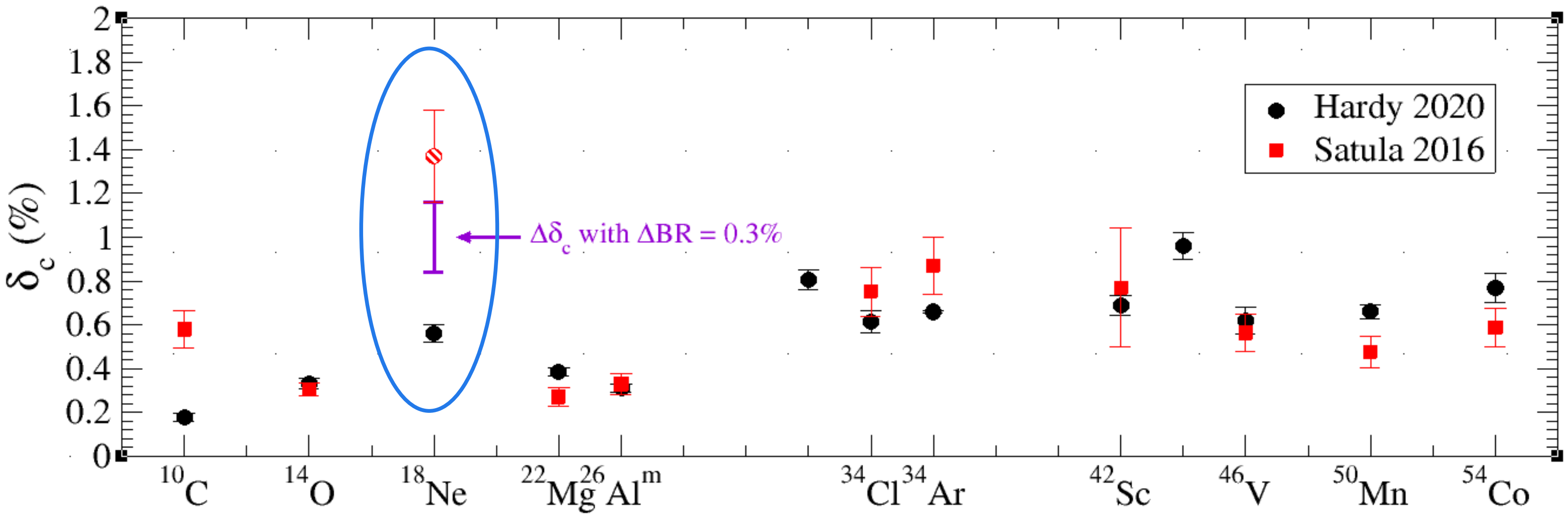
First experiment of Phase 1: ^{18}Ne @ SPIRAL1 (GANIL)



Data:PRC **102**, 045501 (2020)

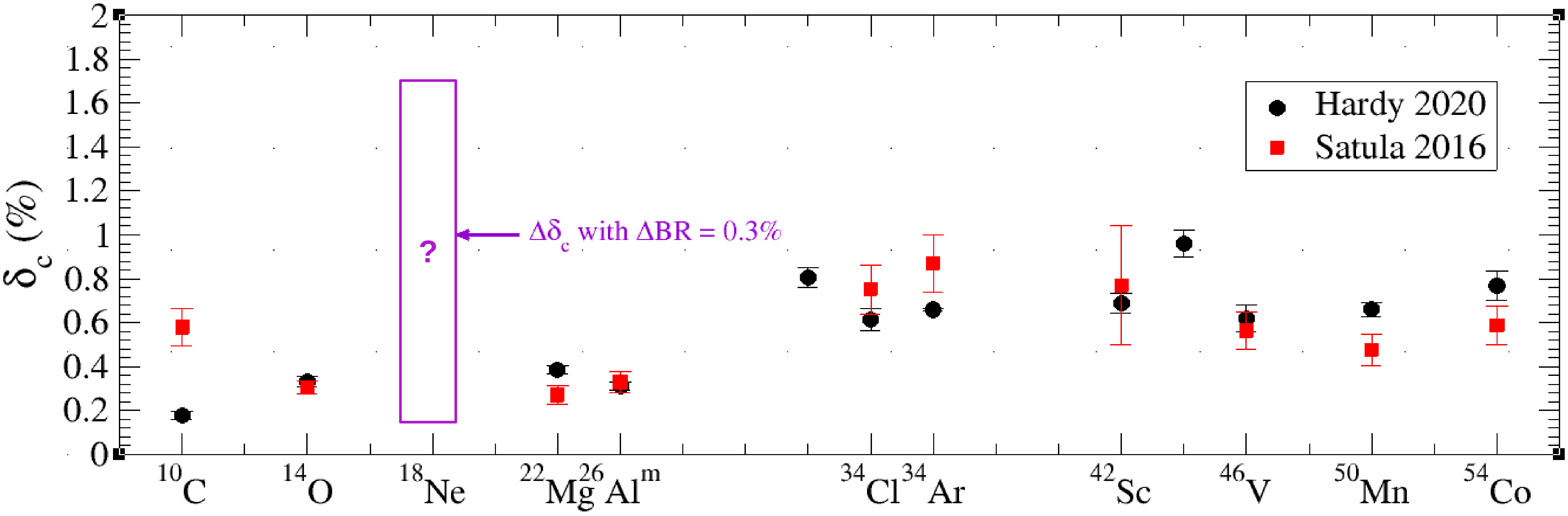
GOAL

- Reduce uncertainty on SA branching ratio to **0.3%**
- Sensitive to differentiate between models for ISB corrections



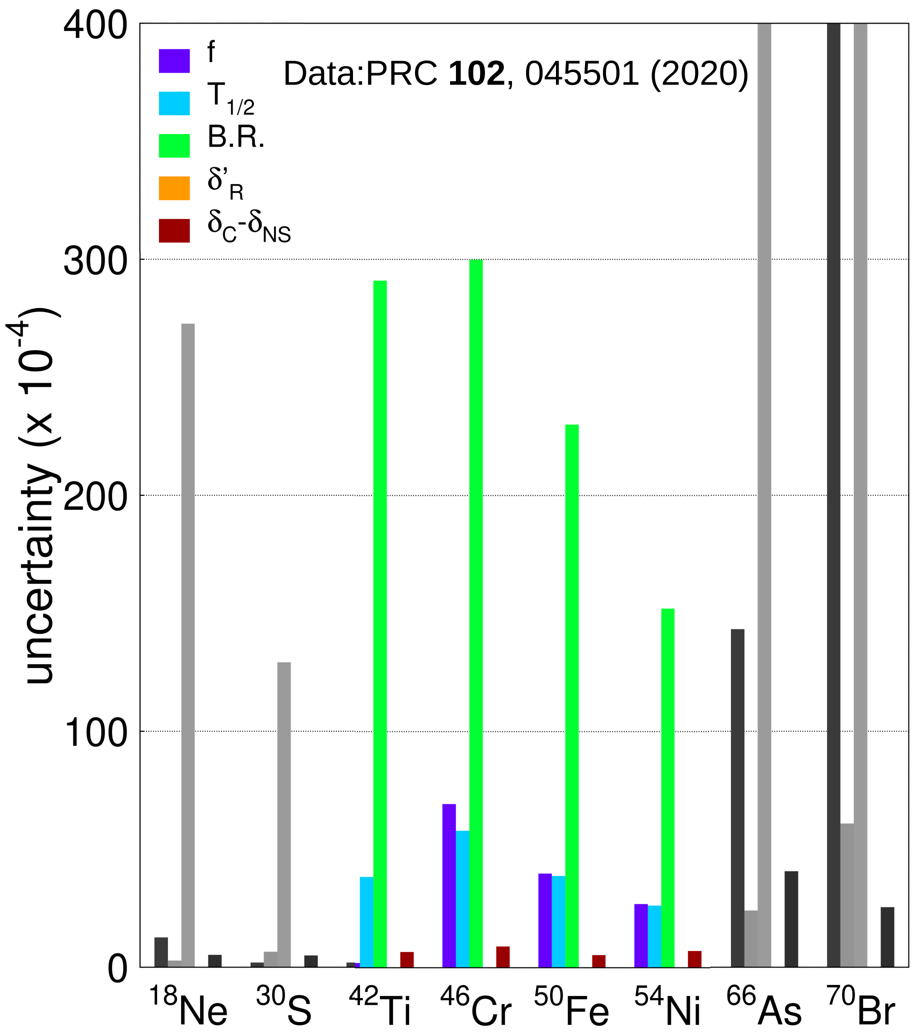
Experiment done in June 2025, analysis ongoing...

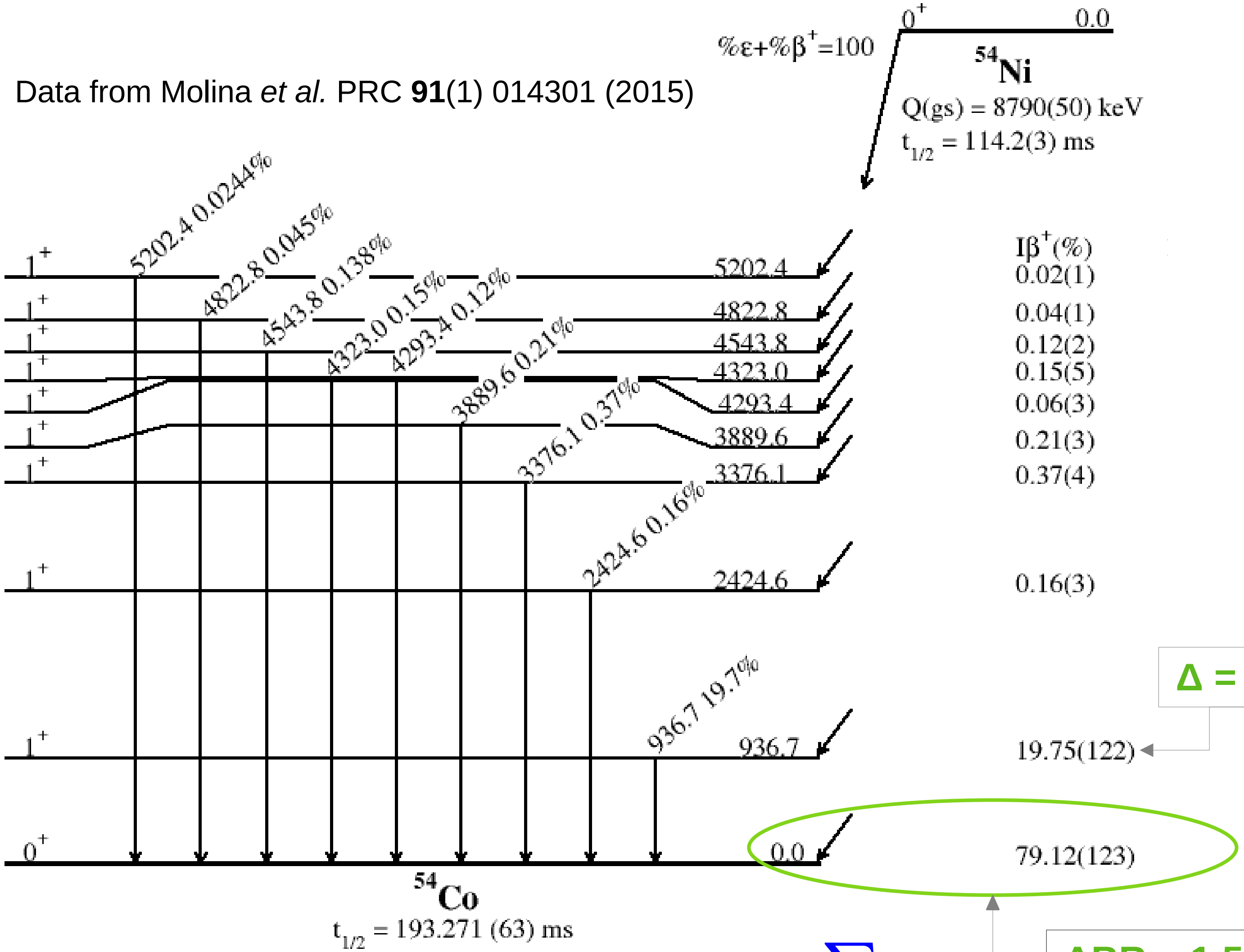
^{18}Ne analysis: Work in Progress...



Looking for theory collaborations for ISB corrections

Phase 1 (contd): ^{42}Ti, ^{46}Cr, ^{50}Fe, ^{54}Ni @ LISE (GANIL)





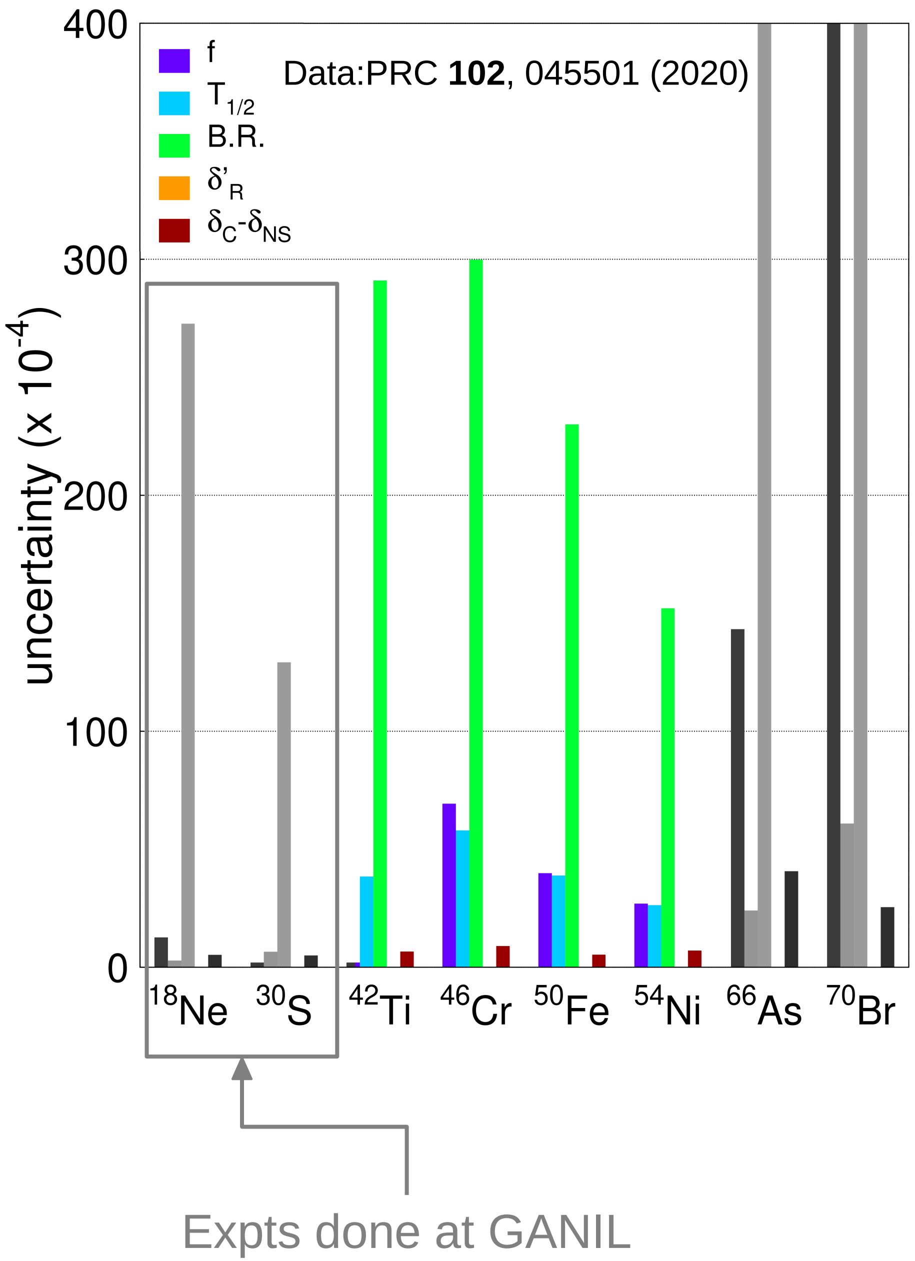
Δ = 6%

$$BR_{SA} = 1 - \sum_i BR_i$$

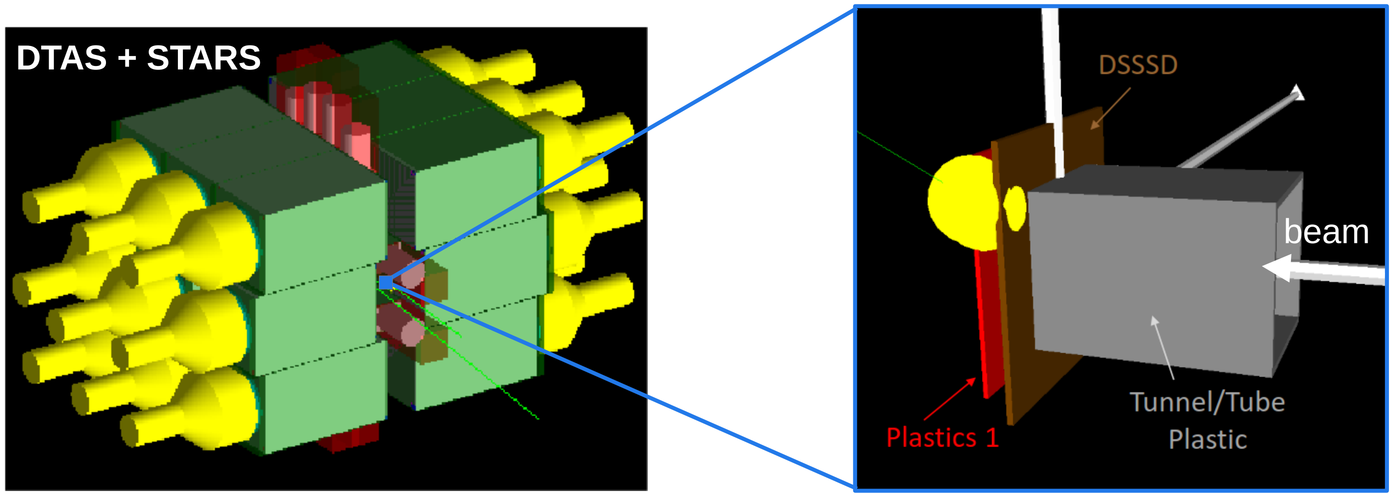
ΔBR = 1.5%,
Reqd Δ = 0.3%

- Largest uncertainty: SA branching ratio
- Several competing $0^+ \rightarrow 1^+$ transitions that need to be measured with high precision
- High energy, low intensity γ transitions => Possibly suffering from Pandemonium effect

Phase 1 (contd): ^{42}Ti, ^{46}Cr, ^{50}Fe, ^{54}Ni @ LISE with TAGS



- Produce SA parent RIB via in-flight fragmentation at **LISE**
- **Total absorption gamma spectroscopy** to address Pandemonium effect
- **DTAS** (18 NaI(Tl))/**Rocinante** (12 BaF_2) + **STARS** (16 $LaBr_3$:Ce)
  - High efficiency + high segmentation + good energy resolution + sub ns timing resolution
- **E891_23: TAGS @ LISE scheduled for 2026**
  - Proof of principle TAS of SA candidates as bonus from this expt.

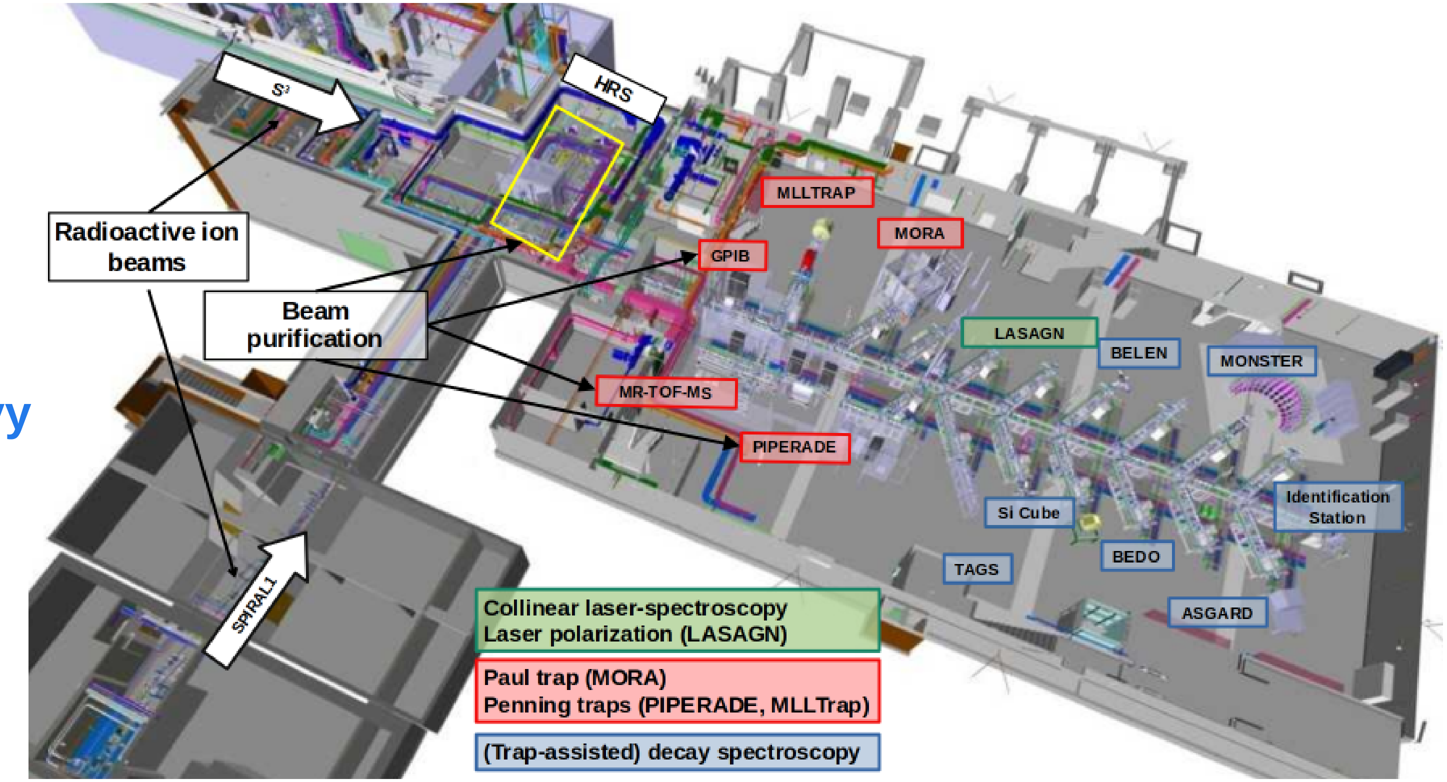


Images: M. Estienne, (NA)^{2}STARS kick-off Meeting, Dec 2024

Phase 2: Beyond ^{54}Ni towards ^{98}In

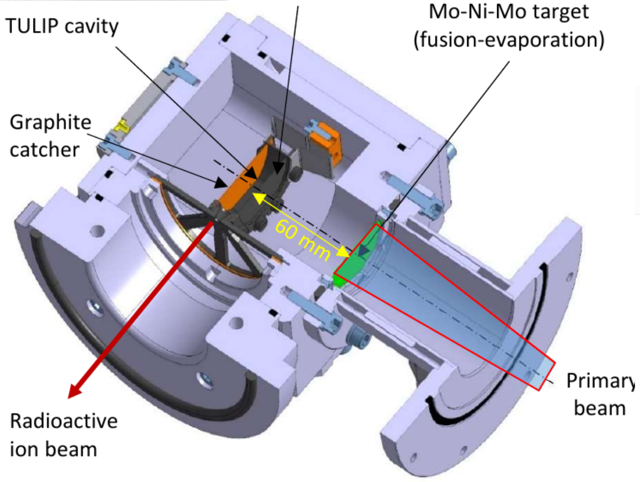
Tests δ_c models where most sensitive, i.e large Z

- **RIB from SPIRAL1 & SPIRAL2 (via S³-LEB)**
  - RIB production via fusion evaporation reaction => good for n-deficiet SA nuclei
- **Multiple purification devices**
  - HRS, GPIB, PIPERADE, MR-TOF: $m/\Delta m \sim 10^6$
- **Multiple experimental programs**
  - All in 1 room: decay spectroscopy, trapped ion studies, laser spectroscopy
- **TAS + STARS @ DESIR => ideal to study heavy SA beta decays**



First physics run with decay station: 2027

Phase 2: SA RIB Beyond ^{54}Ni with TULIP @ SPIRAL1



Projectile	^{20}Ne $^{10+}$
5.85 MeV/u	1000 pnA
Compound	^{78}Sr
Fragment	^{74}Rb
Target	Ni_{68} Ni_{26} Ni 4 µm

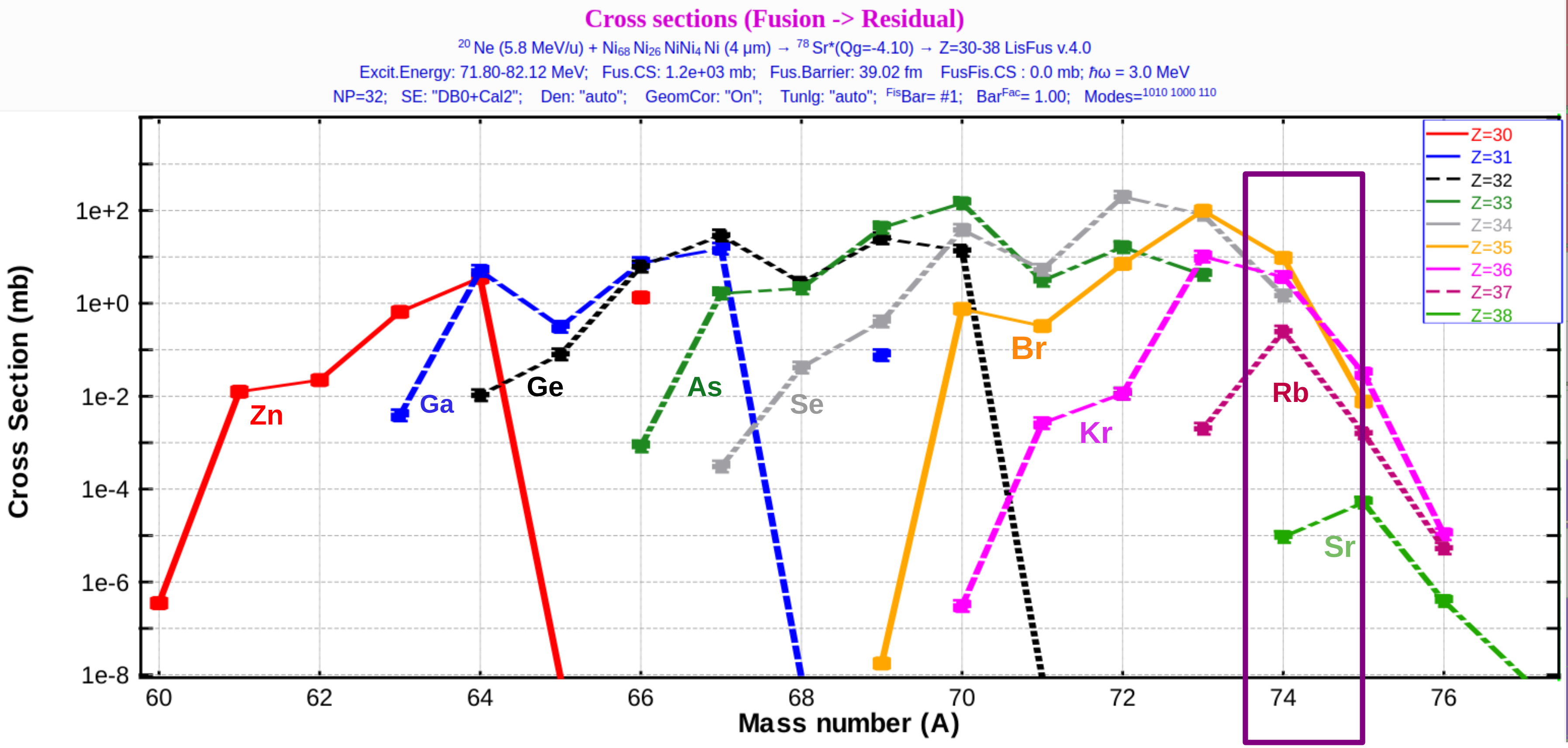
TULIP

anr

CES 31: Physique Subatomique (PRC)

AAPG ANR 2018 GANIL

TULIP (Target Ion Source for Short-Lived Isotope Production)



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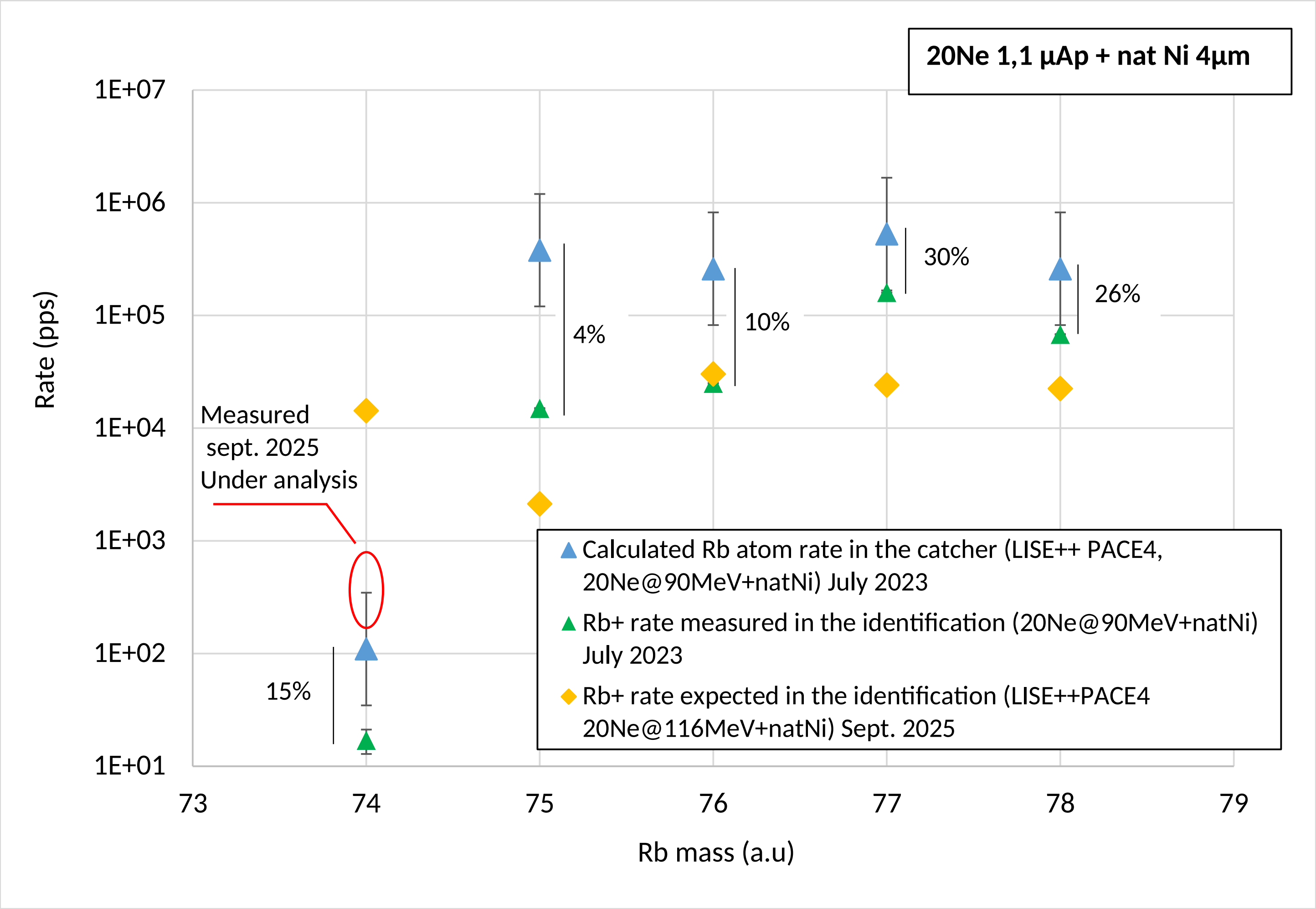


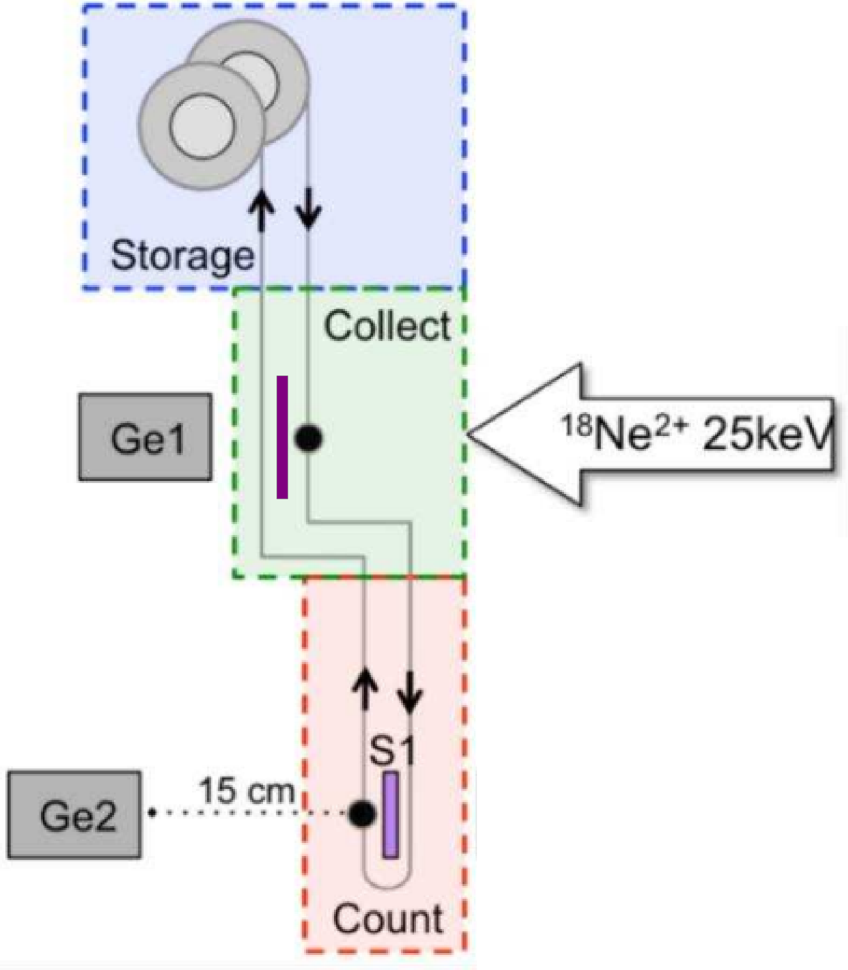
- Expected ion rate of $^{74}Rb^{+}$: ~10^4 pps
- Obtained : few hundreds per second for 1 pµA of ^{20}Ne (under analysis)
  - Cause: entrance window probably broken. No confinment of atoms or ions in the cavity.
- Next test run next week

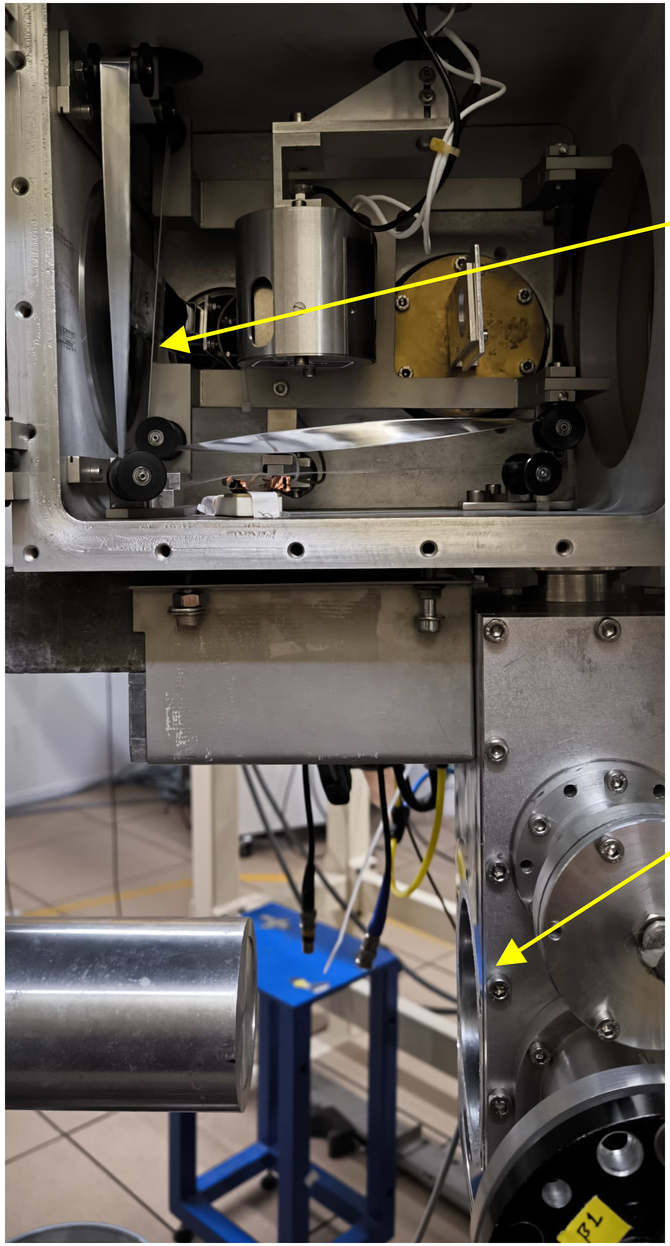
Test run done 3-7 Sept 205

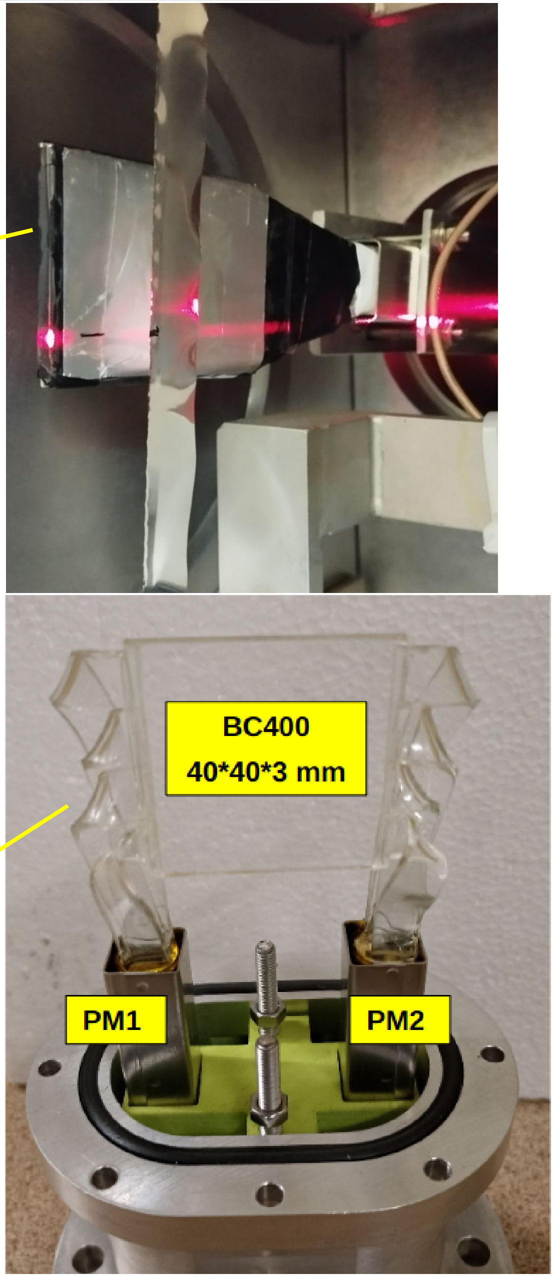
Thank you for your time and this opportunity to share our work.

ANY

^{18}Ne @ GANIL : experimental setup

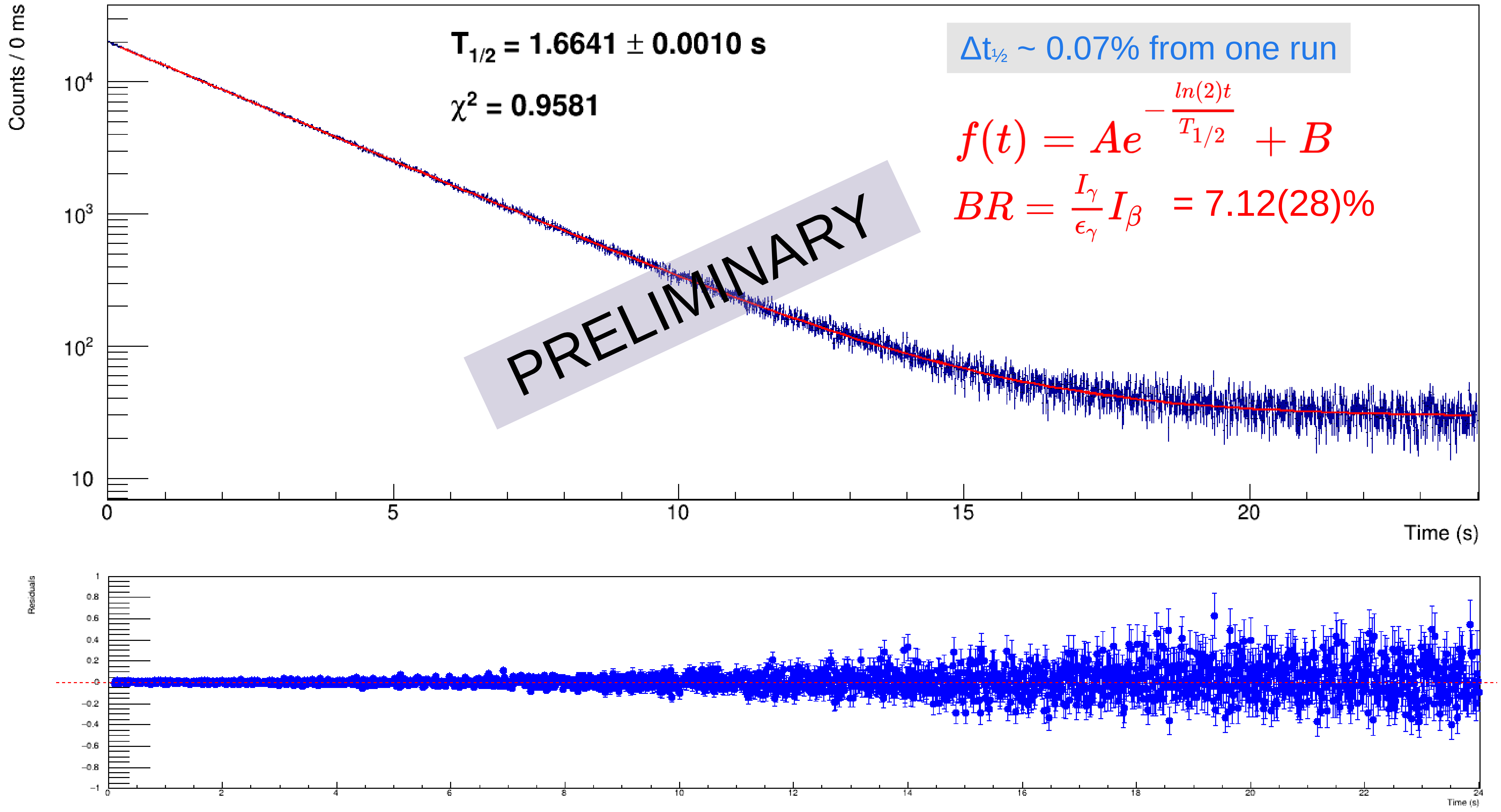






- $^{18}Ne^{+2}$ ISOL beam from SPIRAL1
- Beam on – beam off structure

^{18}Ne half-life from online data analysis



Slide by Samuel Lecanuet, LP2i Bordeaux