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

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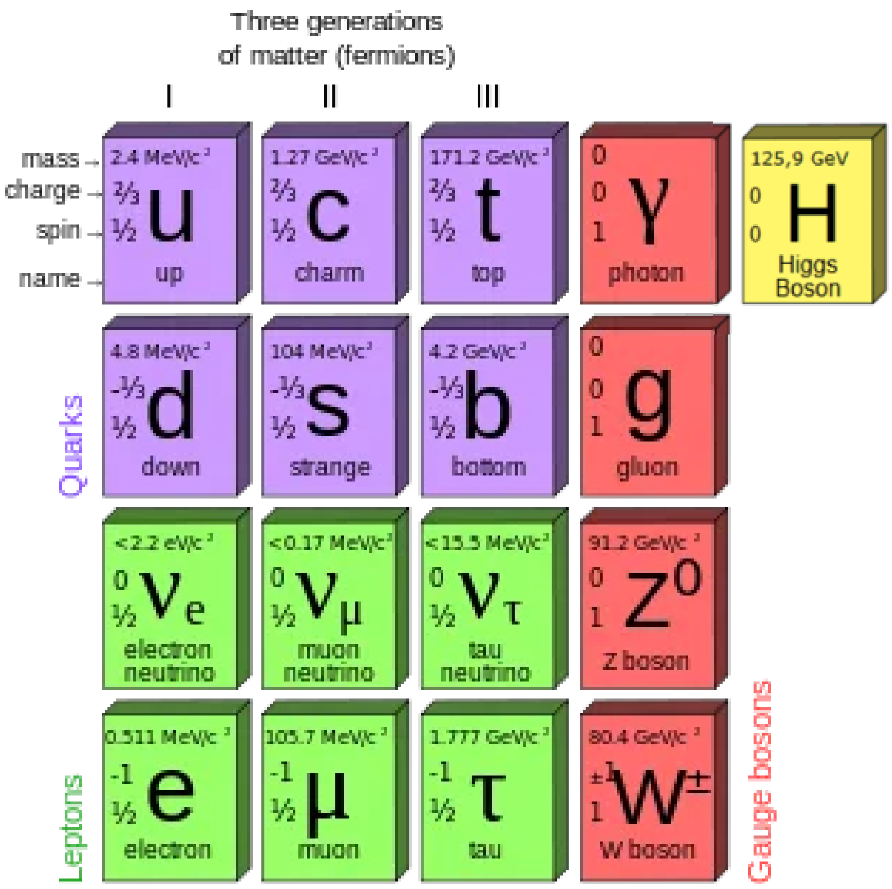
GANIL laboratoire commun CEA/DRF spiral2 CNRS/IN2P3

The very famous Standard Model

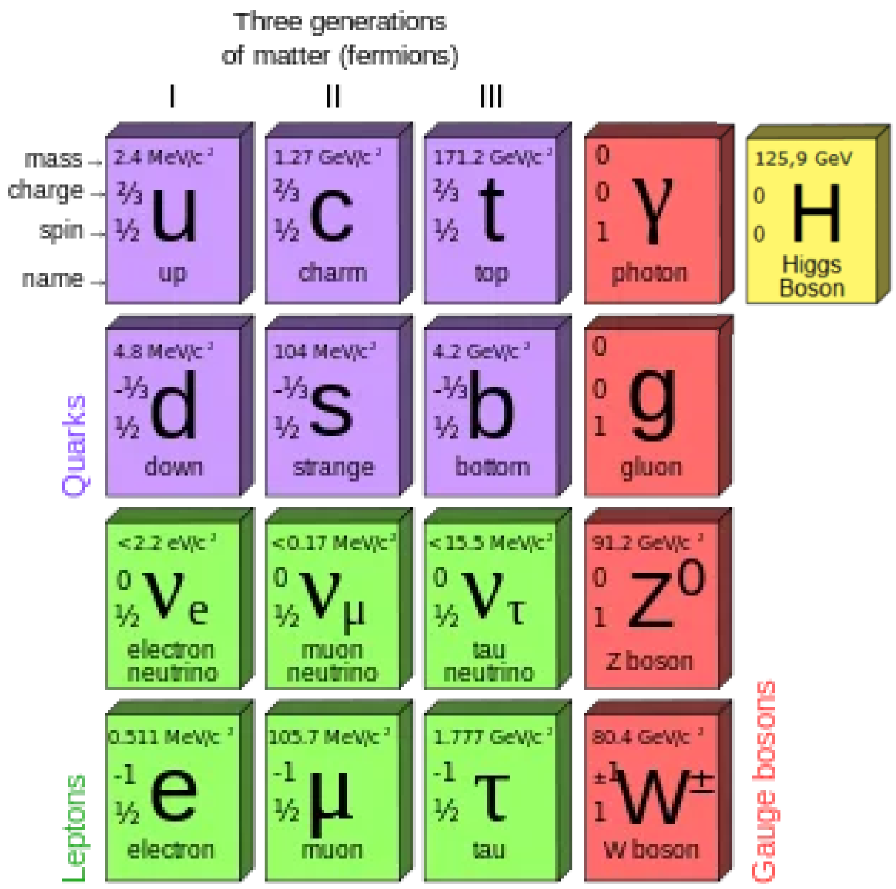


- Explains how the elementary particles : quarks, leptons, guage bosons
- Interact via the strong, weak, electromagnetic forces
- Higgs boson: generation of mass

Also said to be a *theory of almost everything*

Image Credit: Wikipedia.

Why beyond Standard Model physics?



Excellently describes the visible world around us.

But has limitations

- Baryon asymmetry in universe
- Dark matter, dark energy
- Neutrinos ……
- ...

Image Credit: Wikipedia.

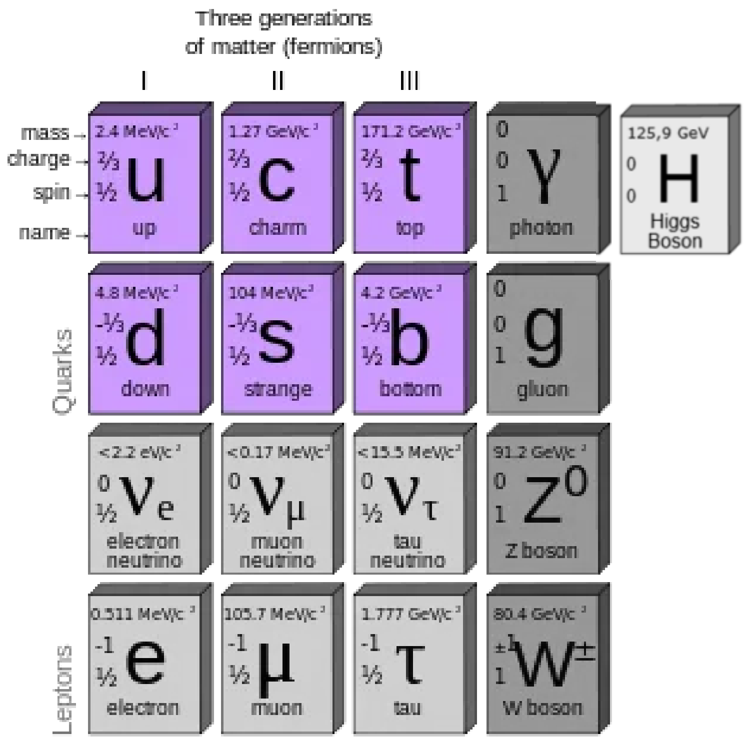
Nuclear β decays: probes of BSM physics

$$\mathcal{H} = \frac{G_F V_{ud}}{\sqrt{2}} \sum_{i=V,A,S,T,P} \left(\overline{\Psi_p} O_i \Psi_n\right)\left[\overline{\Psi}_e O^i (C_i + C_i'\gamma_5)\Psi_\nu\right] + h.c.$$

Unitarity of the CKM matrix

Correlation measurements

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**

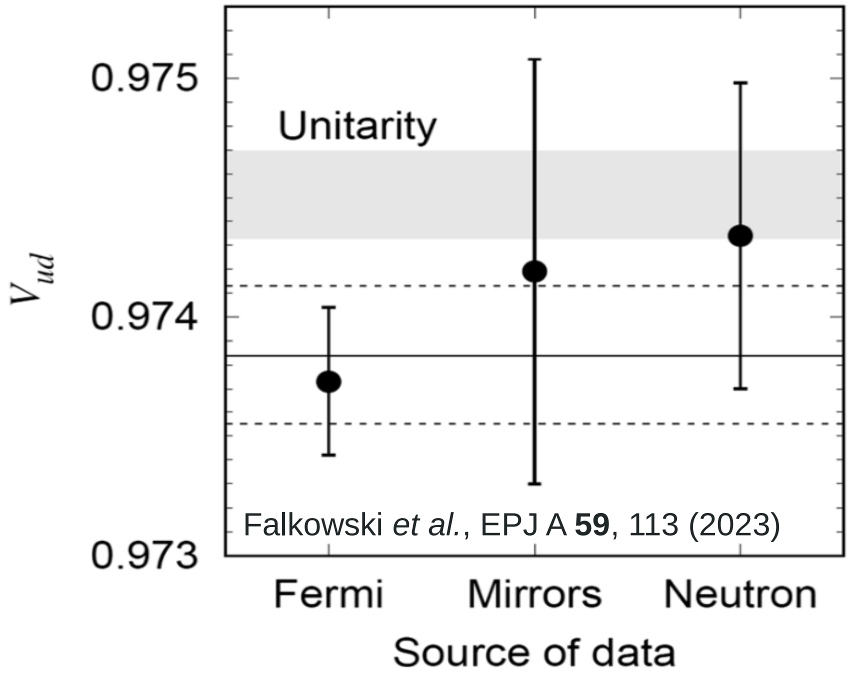
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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

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

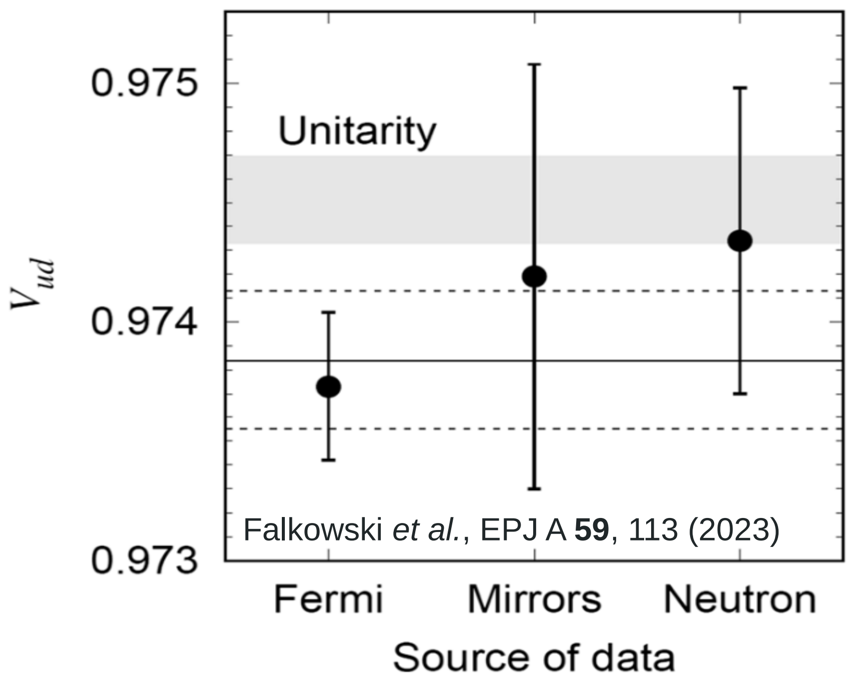


V_{ud} largest + most precise top-row element

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

Superallowed β decays: link to BSM physics

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



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

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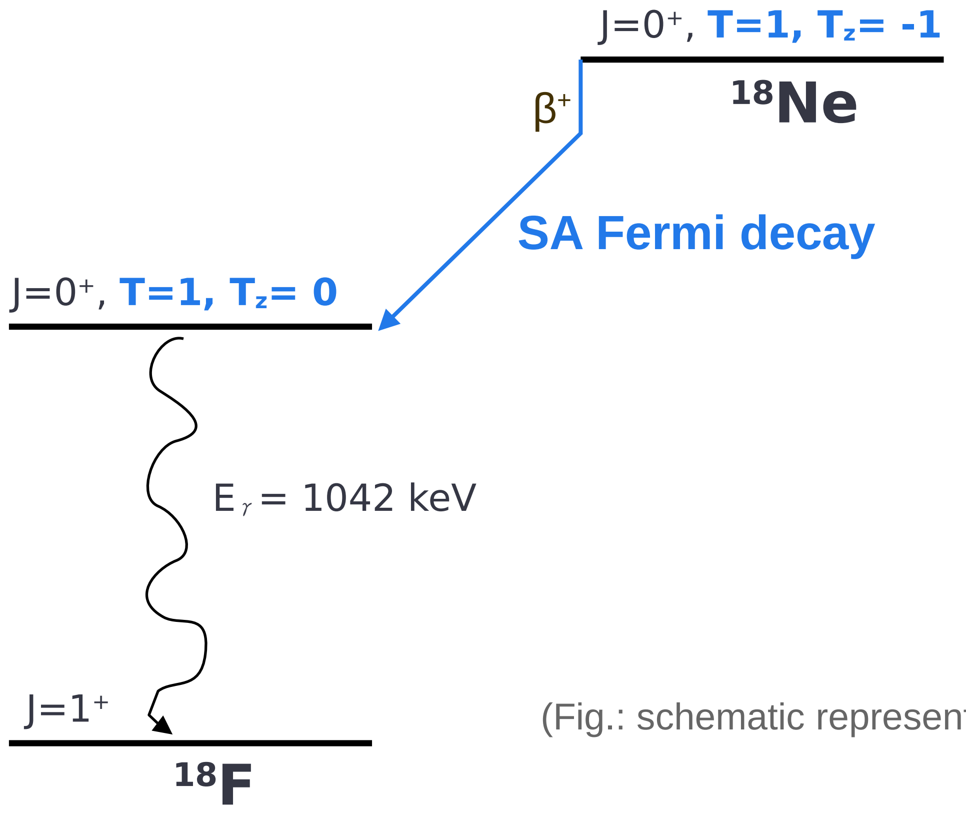
SA beta decay: β decays between **isobaric analog states (IAS)** => $J_i = J_f$



(Fig.: schematic representation)

Mirrors, neutron decays

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

Fermi decays

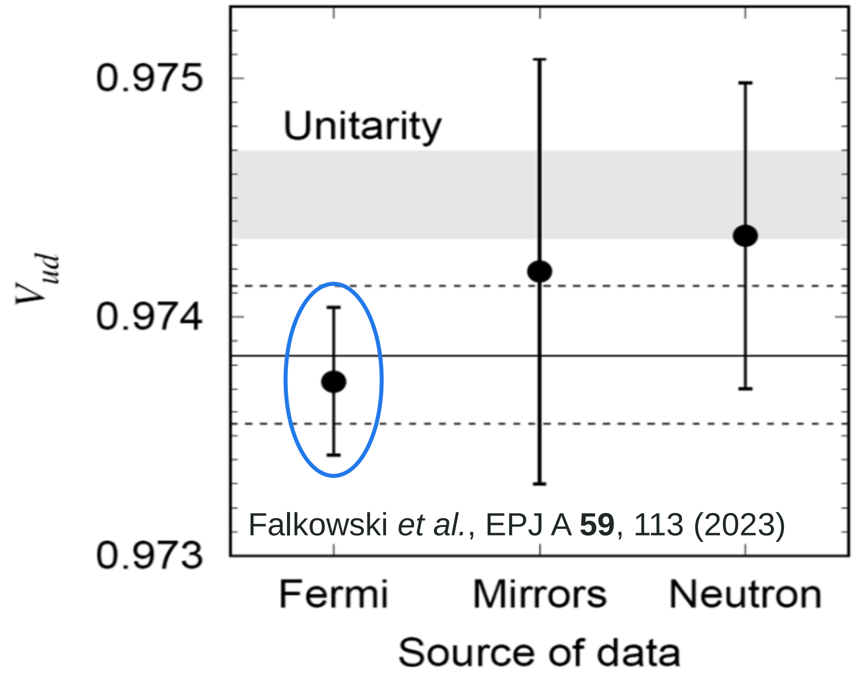
- T = 1 isospin triplet
- $J_i = J_f = 0^+$

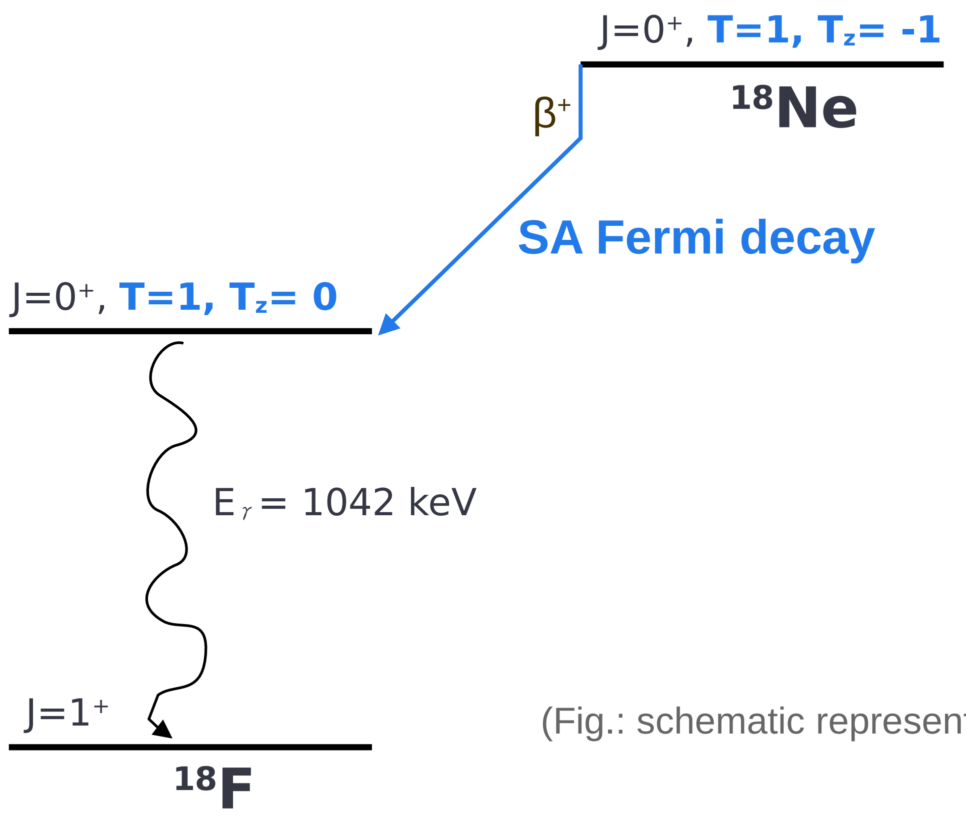
aka SA $0^+ \rightarrow 0^+$ β decay

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

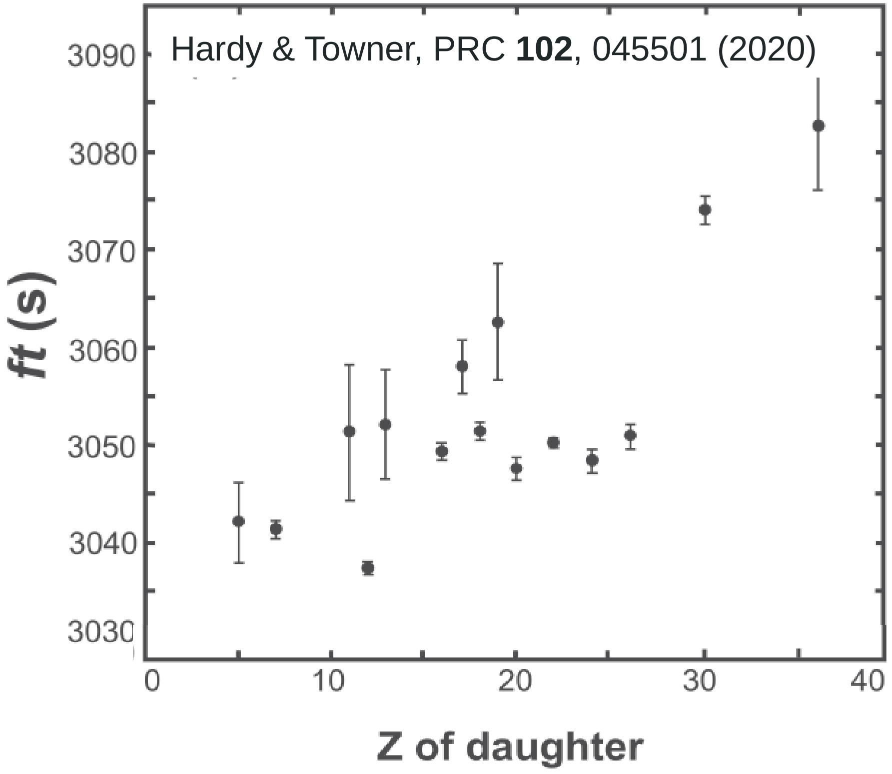
$$\frac{K}{2V_{ud}^2 G_F^2 (corrections)} = ft^{0^+\to 0^+}(corrections)$$

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, $BR < 0.3\%$

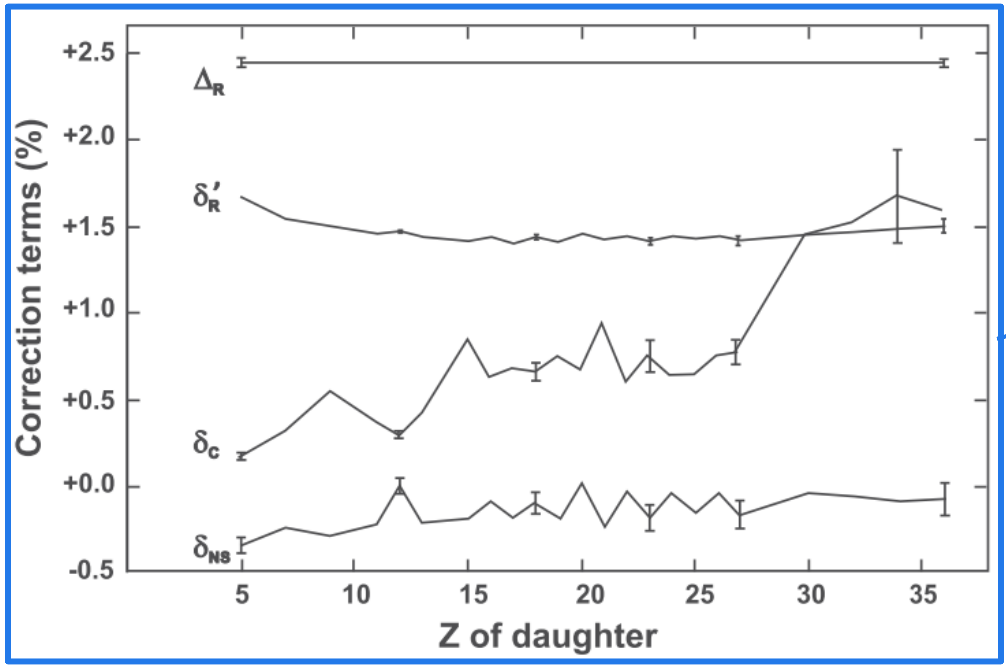
ft values + corrections = *Ft*

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

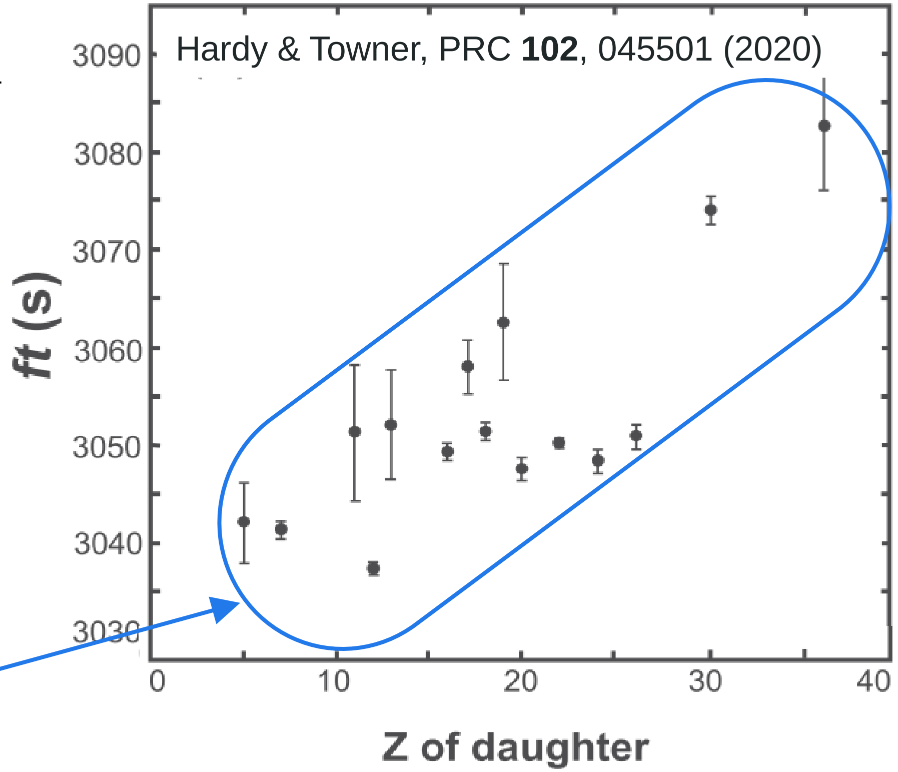
Δ_R: nucleus independent radiative corrections

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

δ_C: structure dependent isospin symmetry breaking corrections



Corrections of few %



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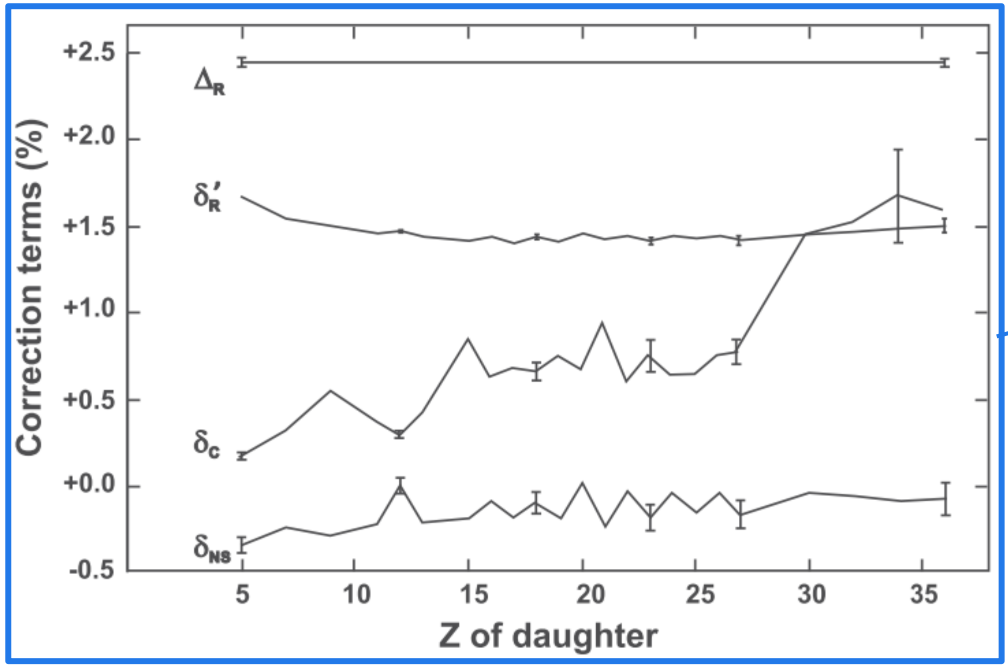

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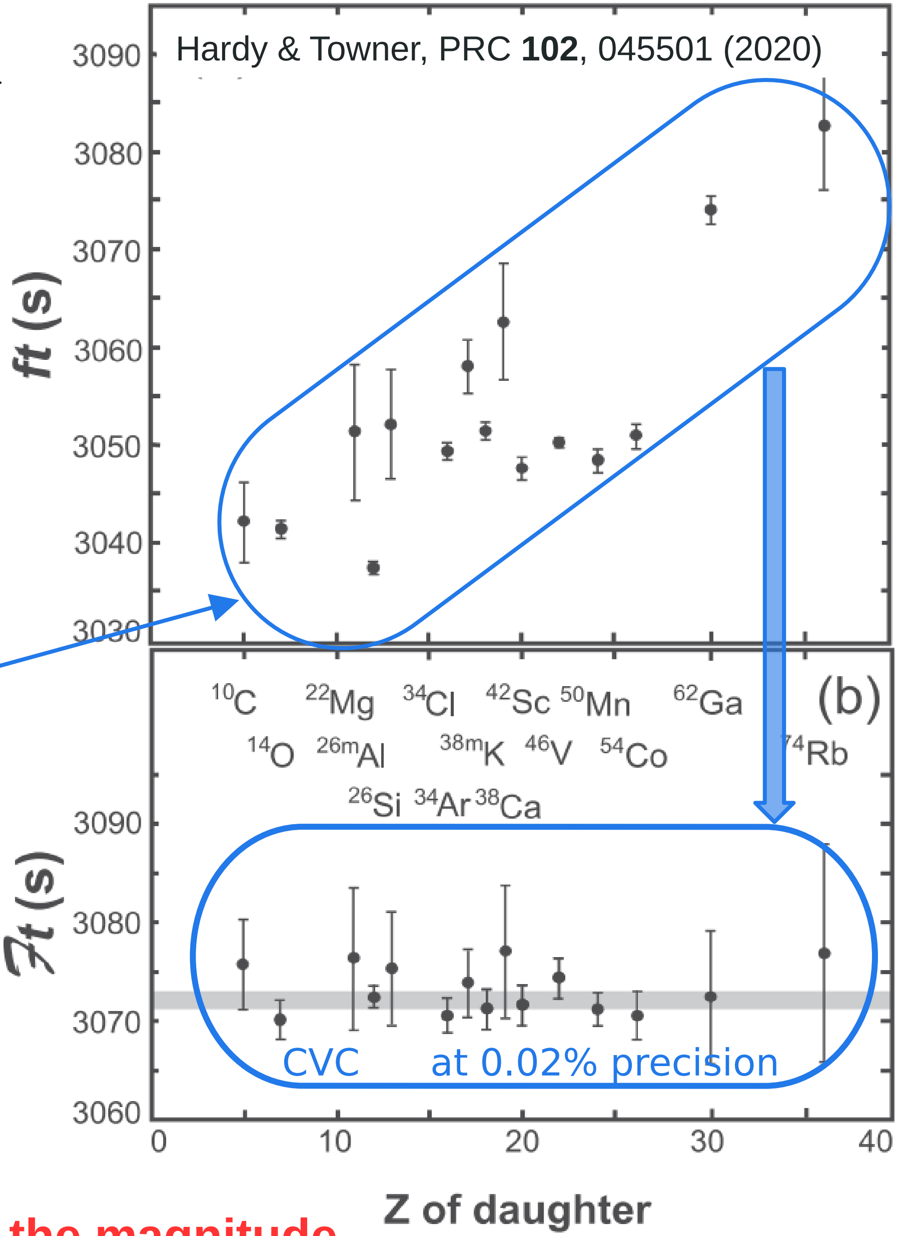
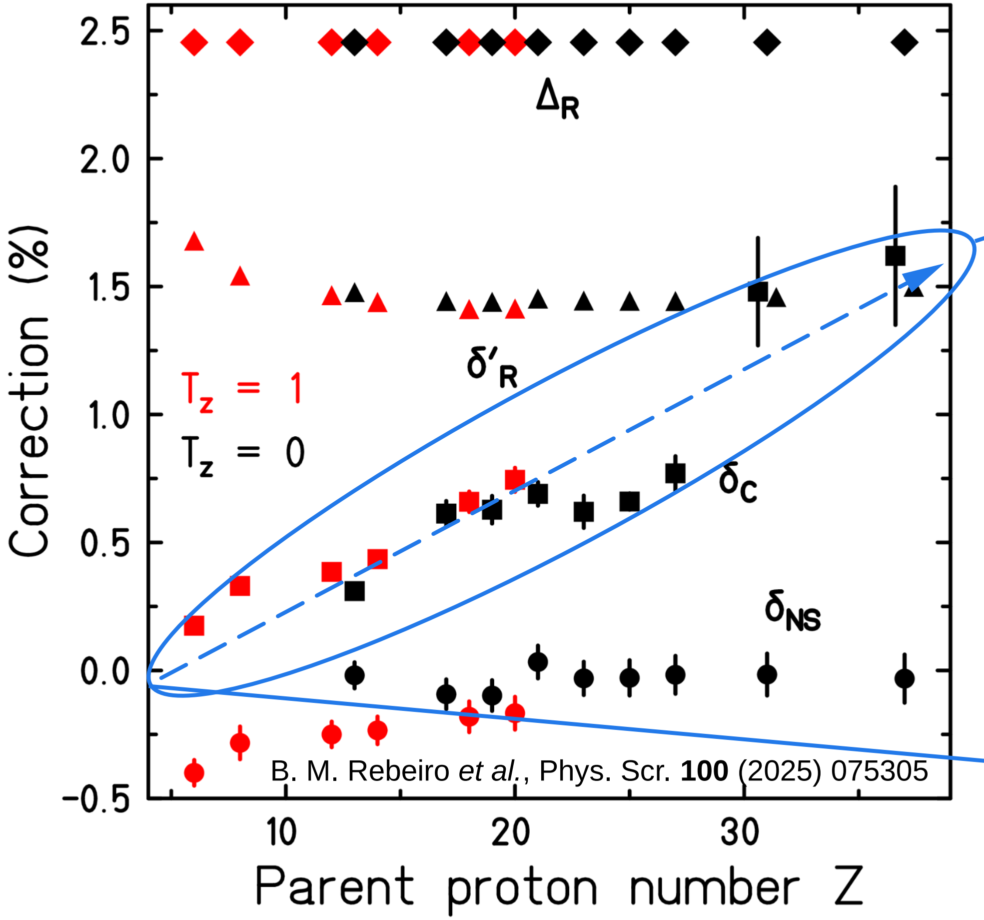


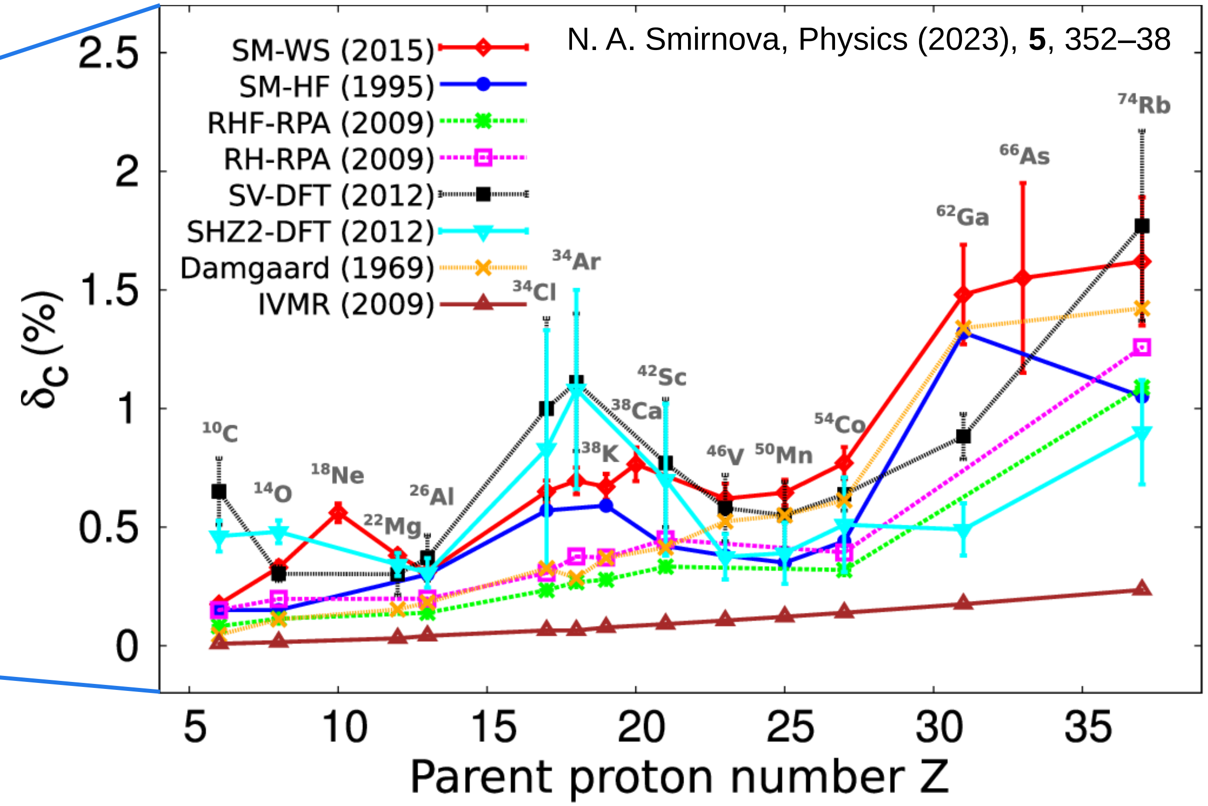
Average Ƒt defines value of V_{ud} => corrections define the magnitude

BSM physics or model effect?

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



δ_c: Isospin symmetry breaking correction



Ƒt values computed using only one δ_C theory model: SM-SW (2015)

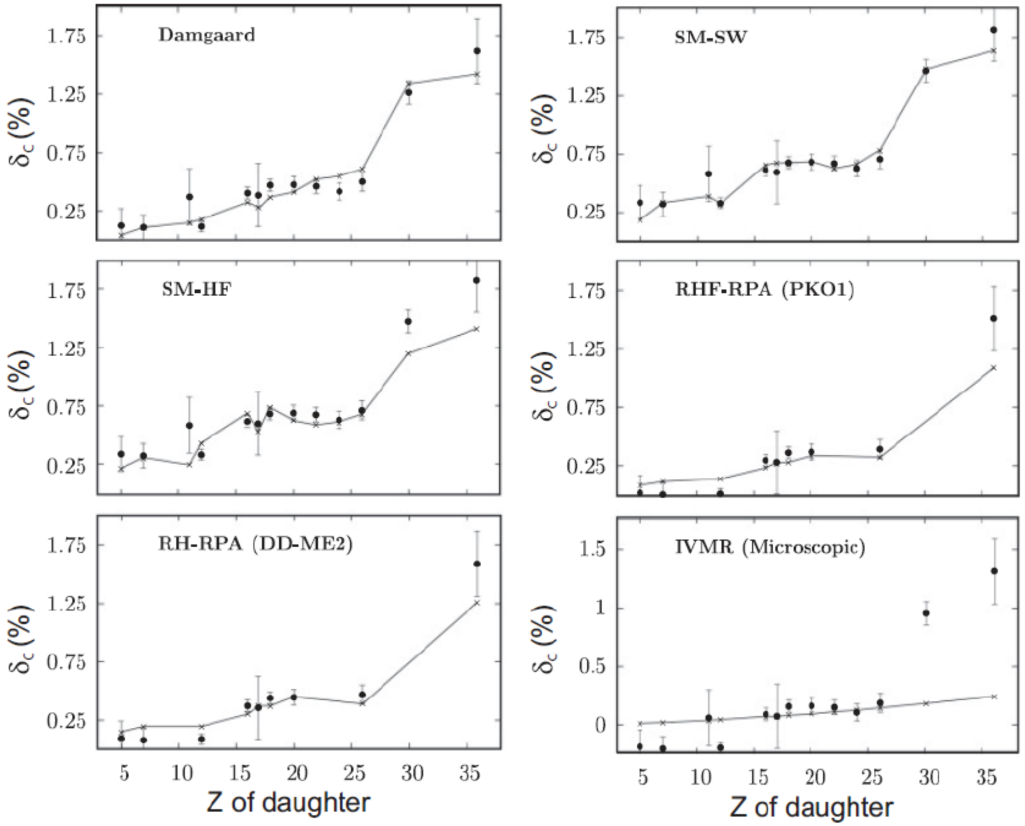
BSM physics or model effect?

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 …



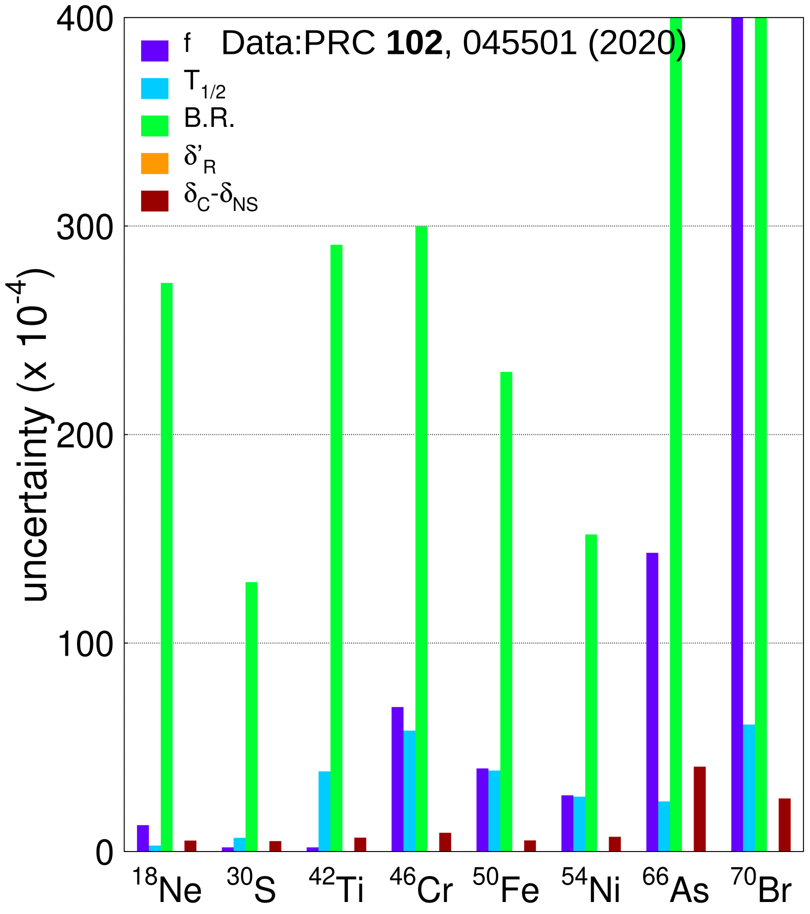
I.S. Towner and J.C. Hardy, Phys. Rev. C 82, 065501 (2010)

KU LEUVEN

Slide taken from Nathal Severijns' PSI 2025 talk

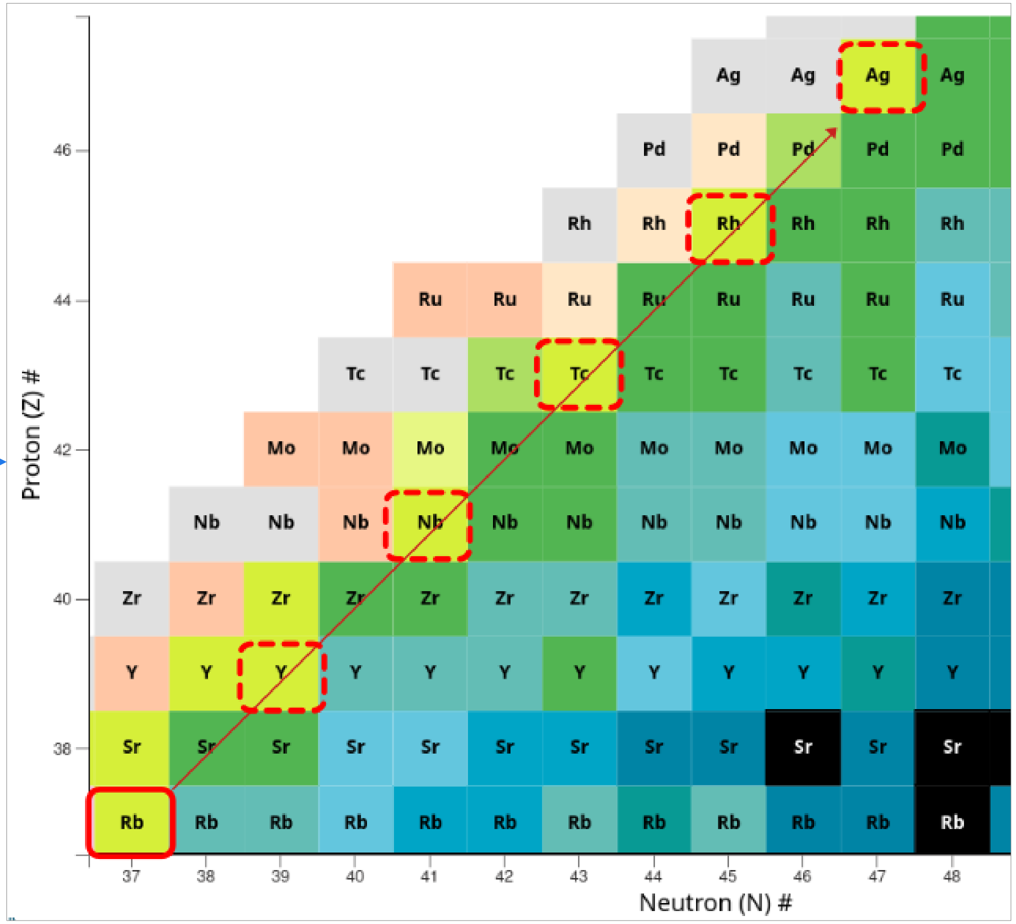
Superallowed program at GANIL

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



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

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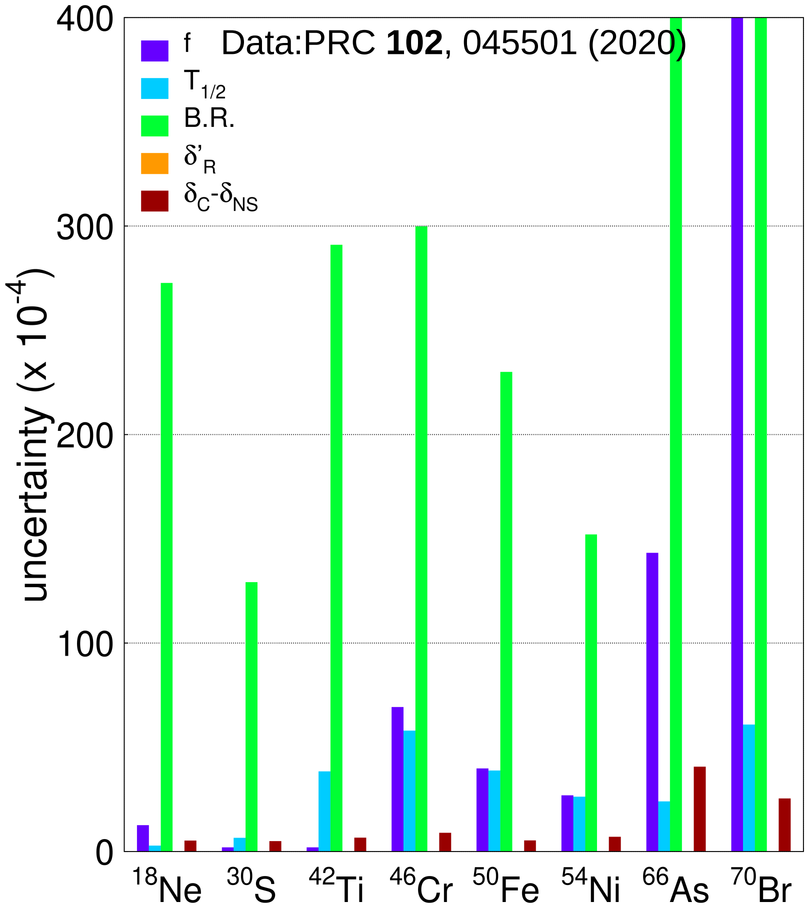
B M Rebeiro et al., Phys. Scr. 100 (2025) 075305

Superallowed $0^+ \to 0^+$ β decay studies at GANIL and upcoming opportunities with DESIR and S^3-LEB



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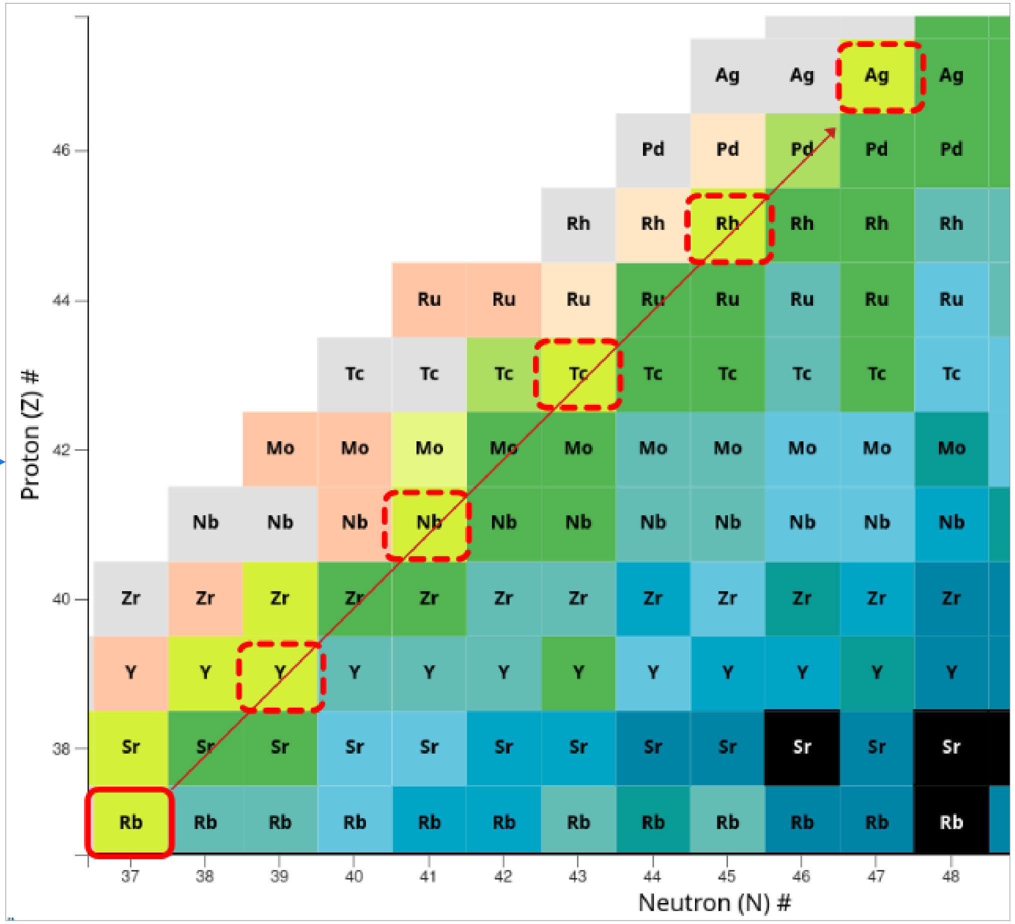
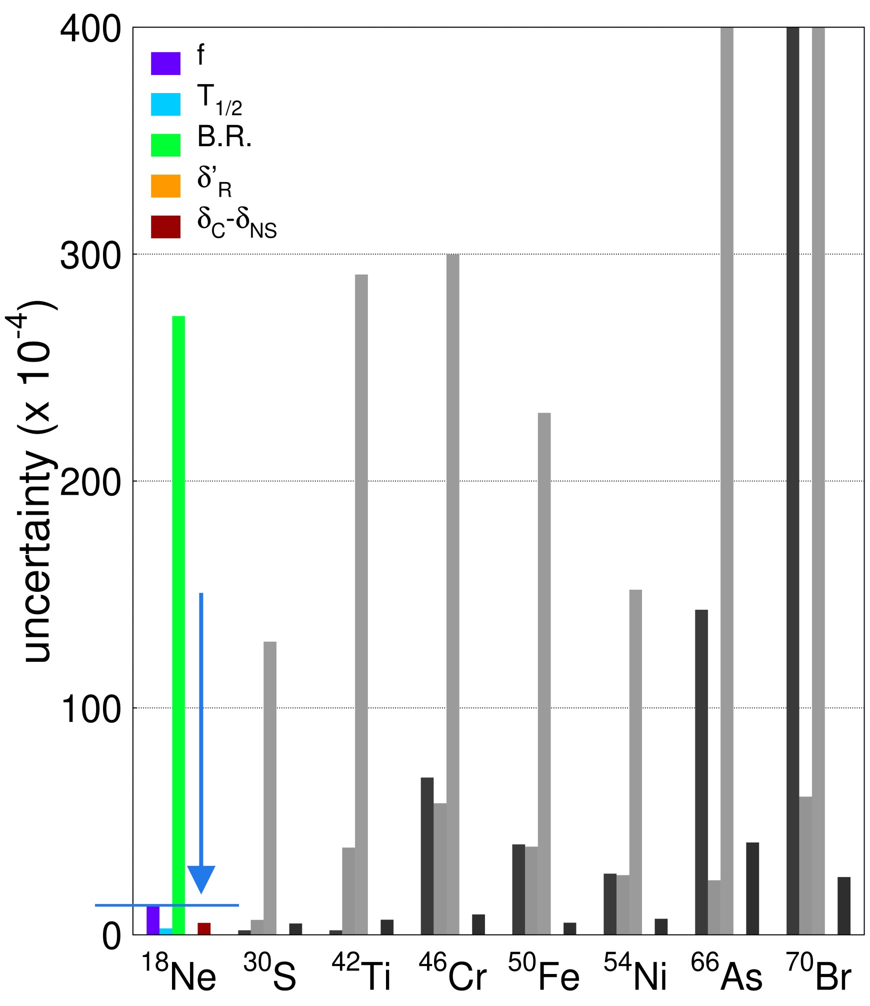


Phase 1: Expts at SPIRAL1 & LISE

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

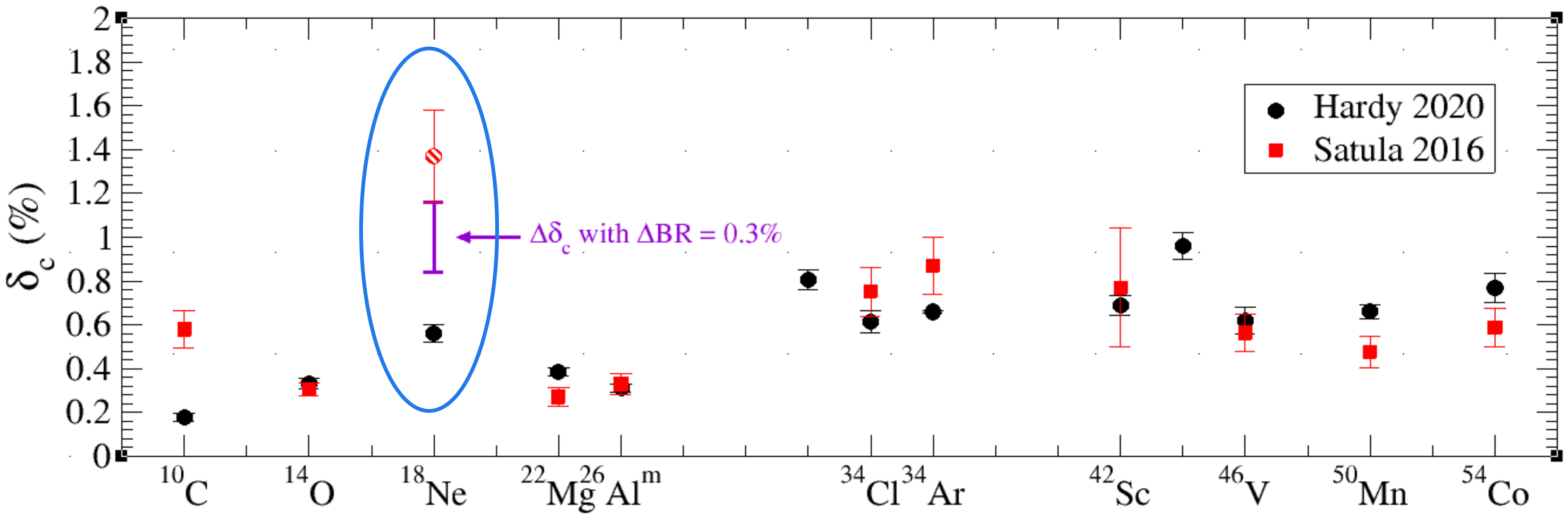
First experiment of Phase 1: ^{18}Ne @ SPIRAL1 (GANIL)



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

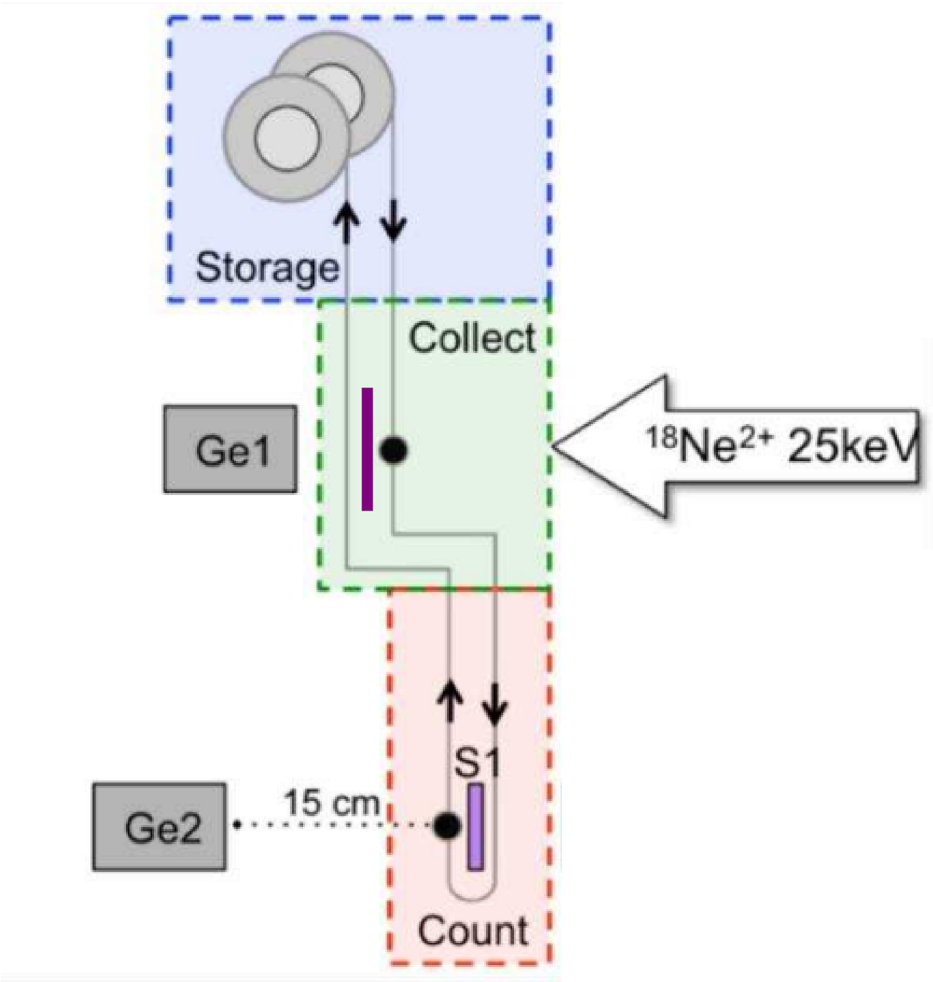
GOAL

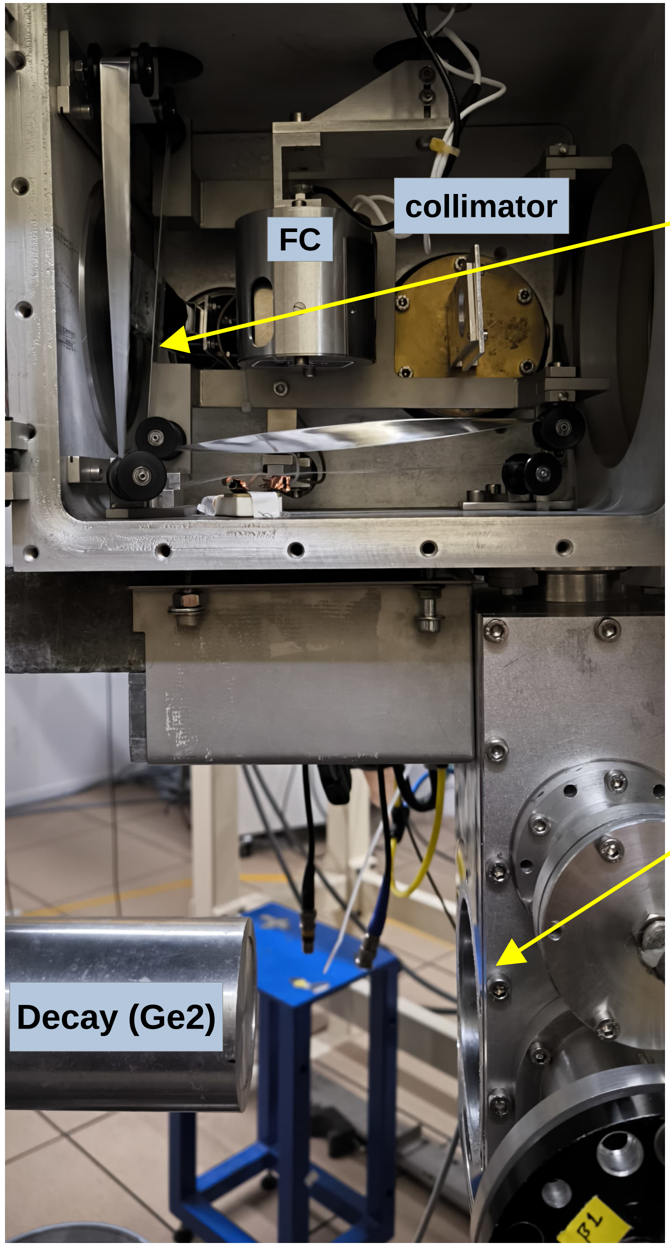
- Reduce uncertainty on SA branching ratio to **0.3%**
- Sensitive to differentiate between models for ISB corrections

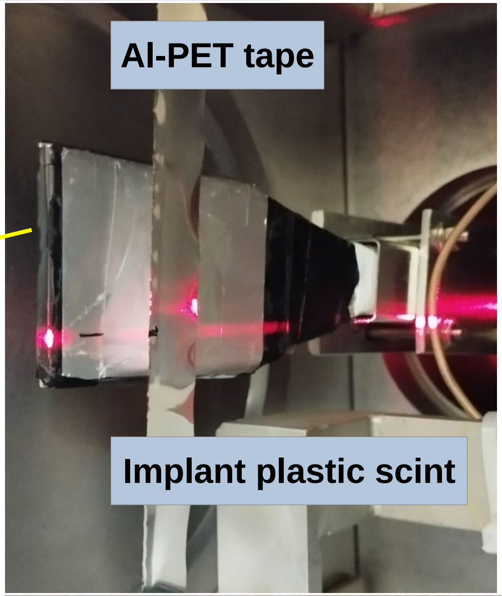


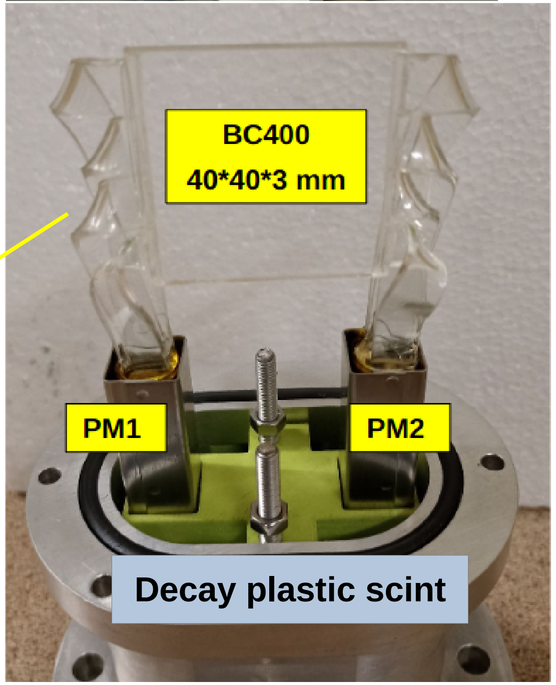
Experiment done in June 2025...

^{18}Ne @ GANIL : experimental setup









Ne-18: hunting for a aluminized tape

Shenzhen Western Hemisphere Technology Co.,Ltd

www.whtape.com

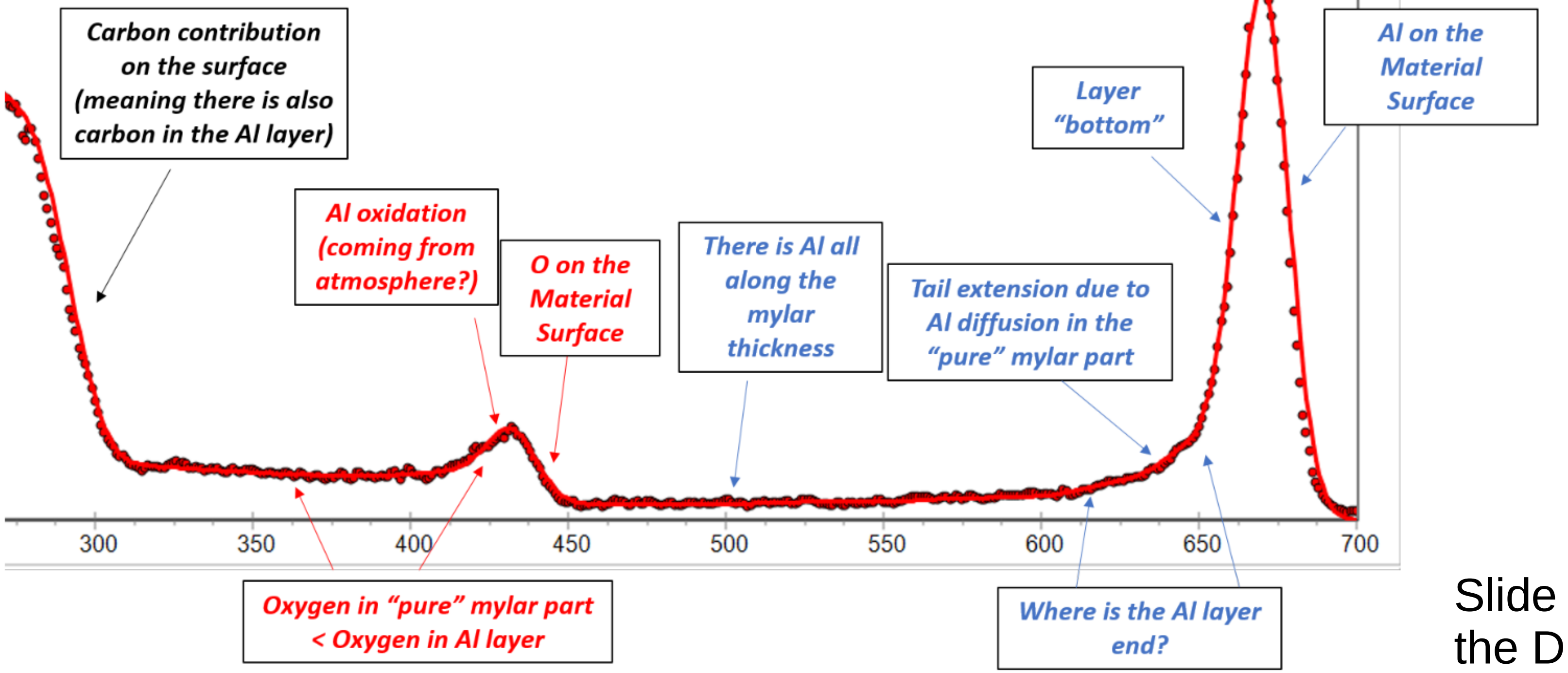
Aluminum Coated Mylar film
(38u Mylar+0.5u Alu)
12mm*2000m

RBS analysis by Cyril Bachelet, IJCLab: not Ok

Rather 1700 m: Ok

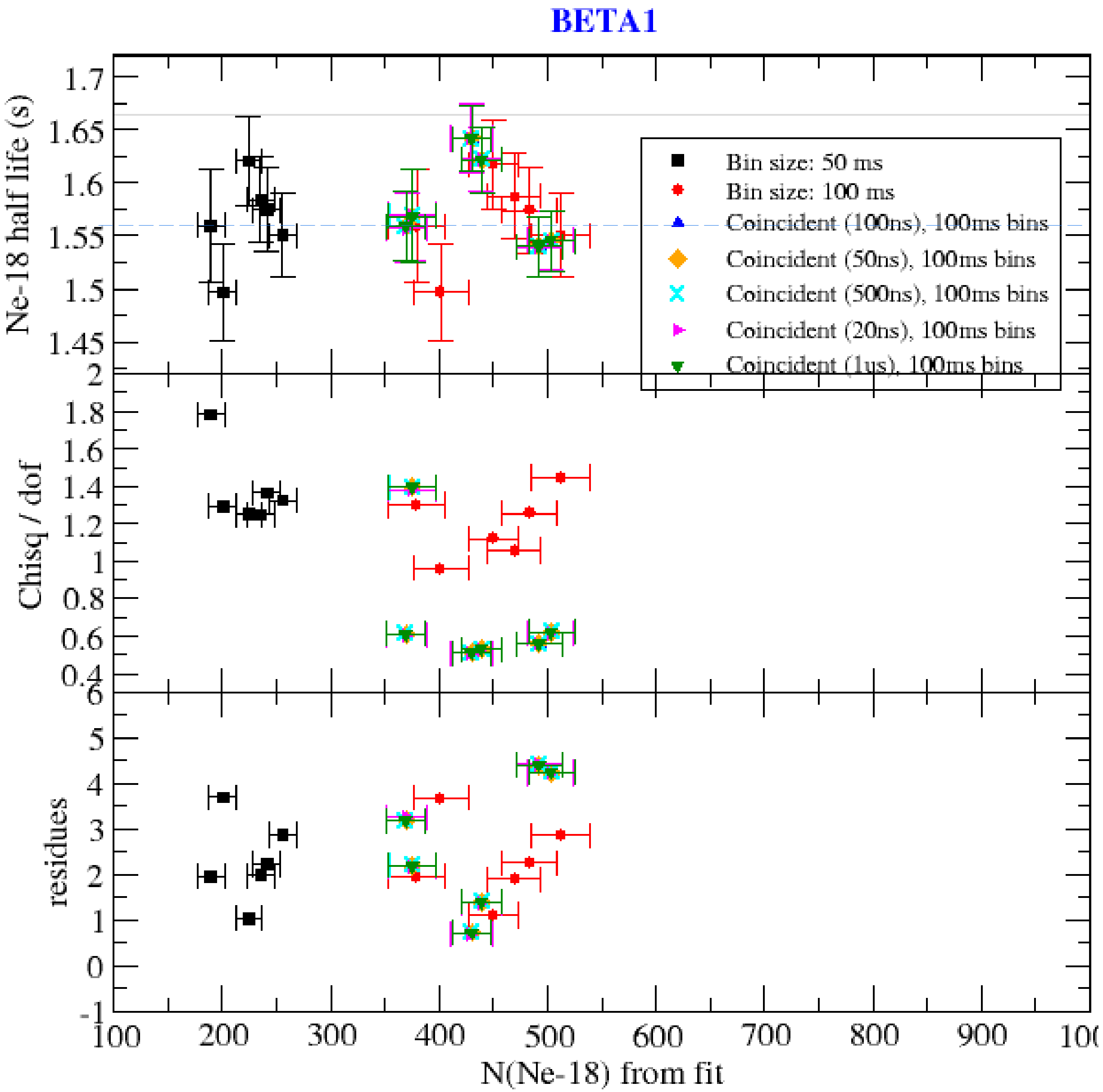
- The Al deposit turns out to be ~14 nm thick (500 nm expected!)
- Migration of Al inside the tape and of C/H in the Al layer!
- Only ~2% Oxygen while 18% are expected (Mylar = $H_8C_{10}O_4$)

-> Does anybody knows a Mylar Aluminized (~100 nm) tape provider?



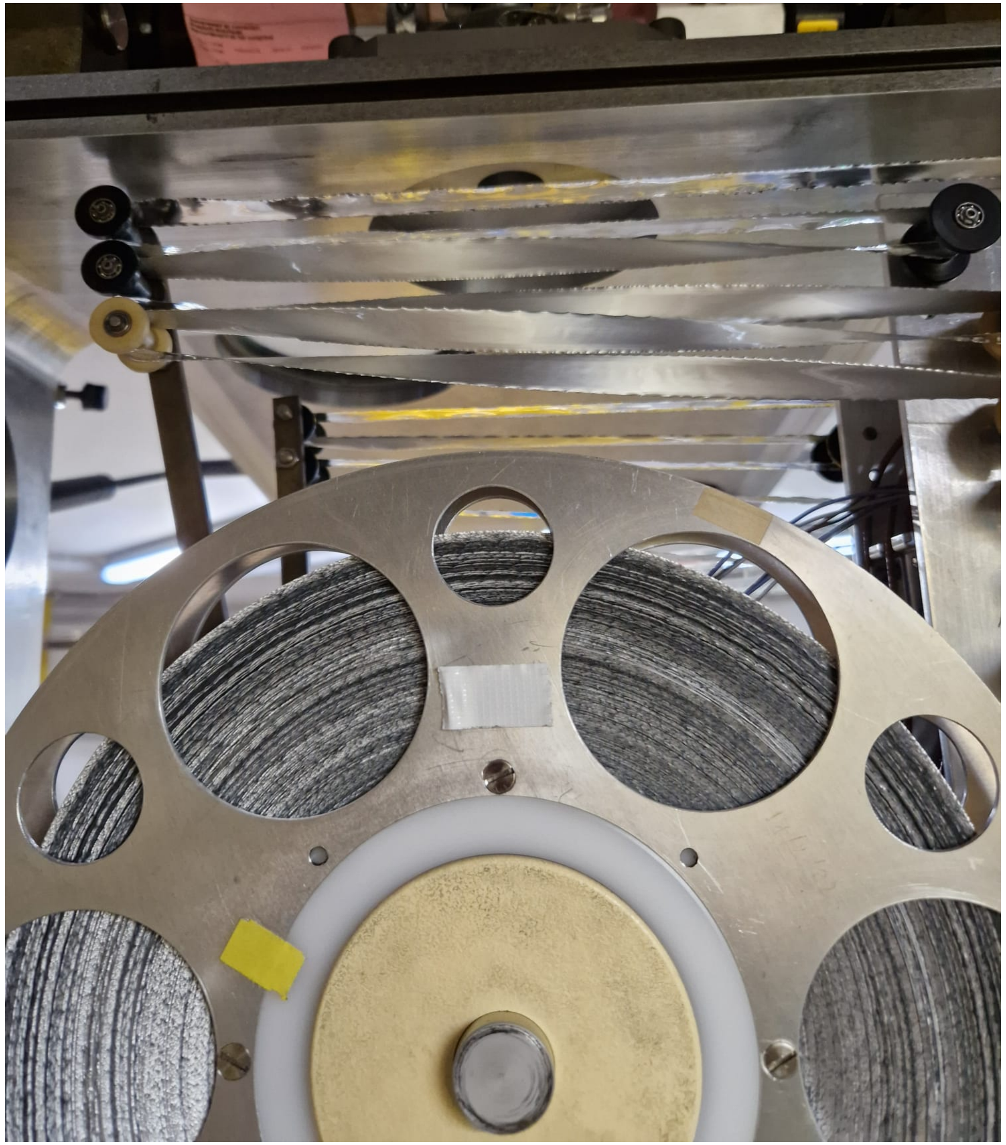
Slide extracted from J.-C. Thomas' talk at the DESIR-BESTIOL Meeting Dec 2024

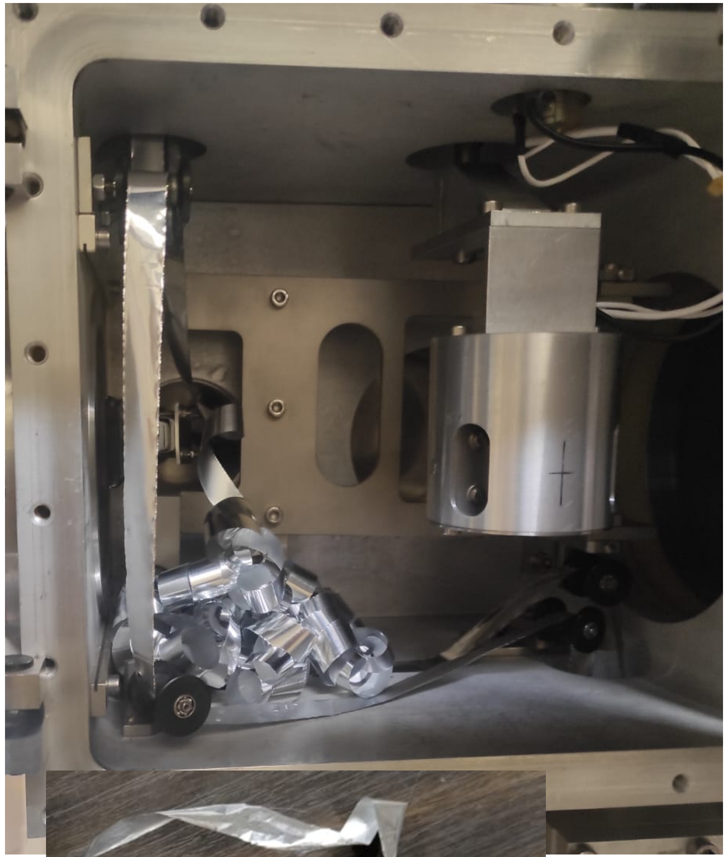
Ne-18: hunting for a aluminized tape

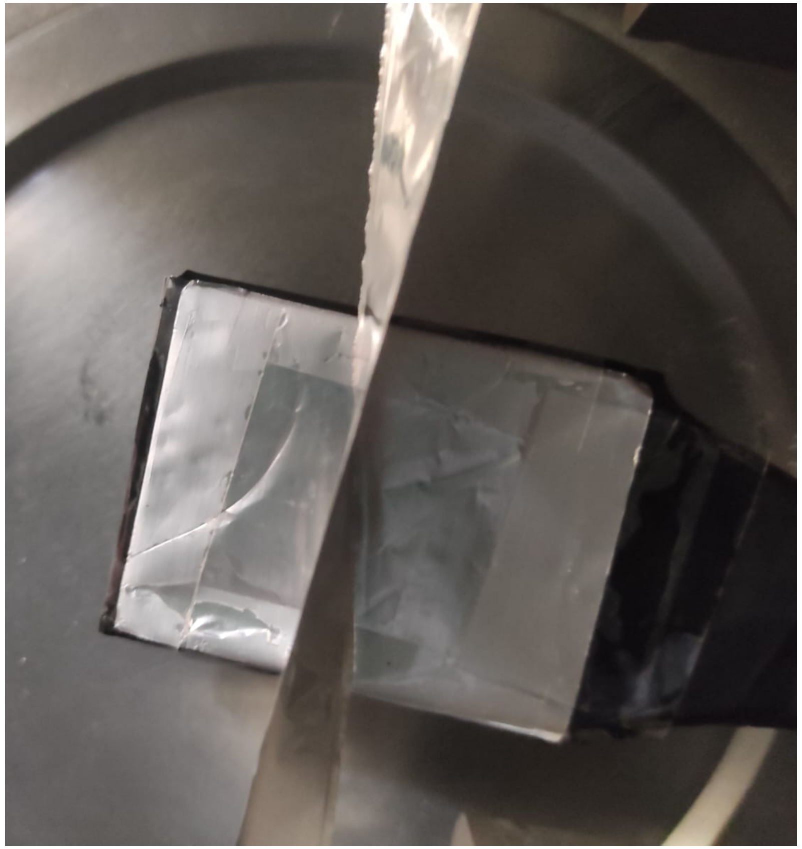


Test run in April 2025 : Ne-18 diffused out of the tape

^{18}Ne @ GANIL : tape woes ...



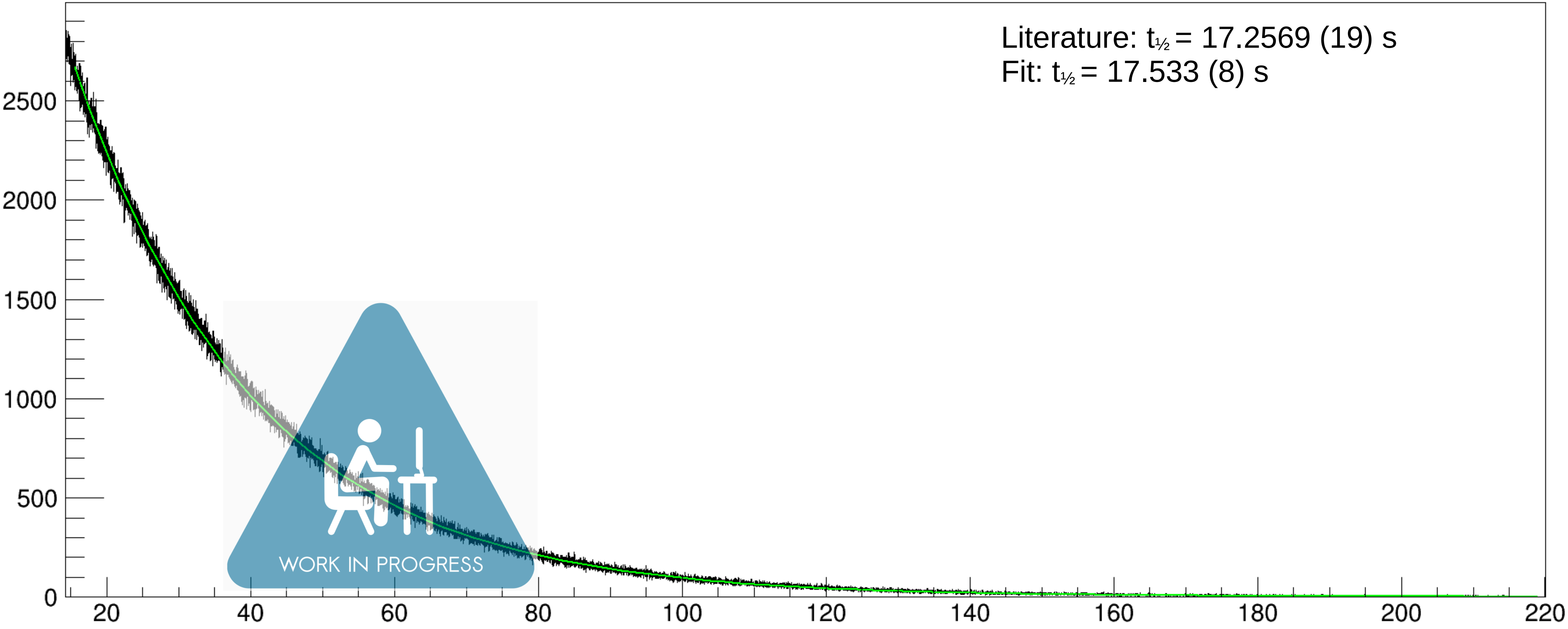




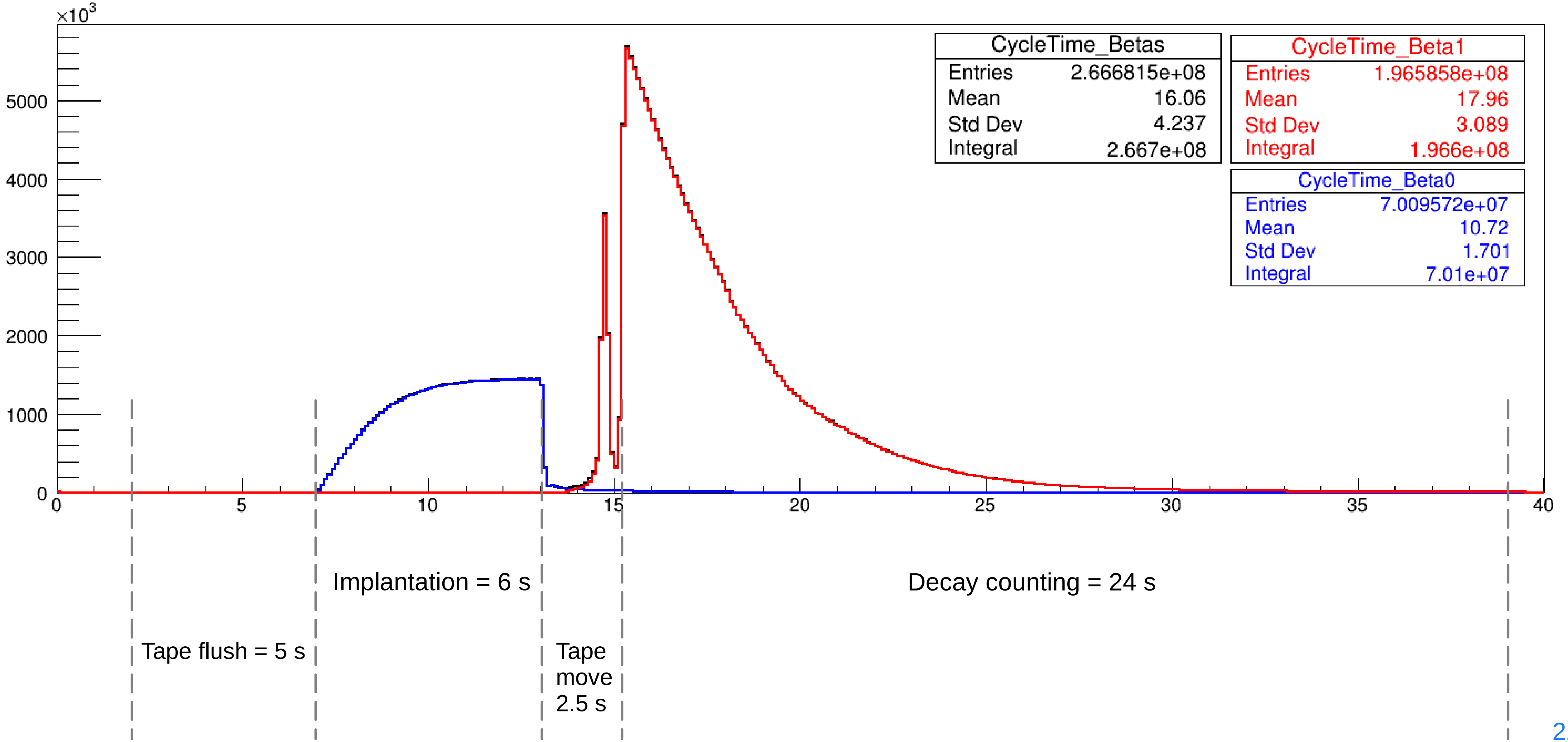
7 μm aluminium glued onto 12 μm PET

AlFiPa
ALUMINIUM FILM PAPER

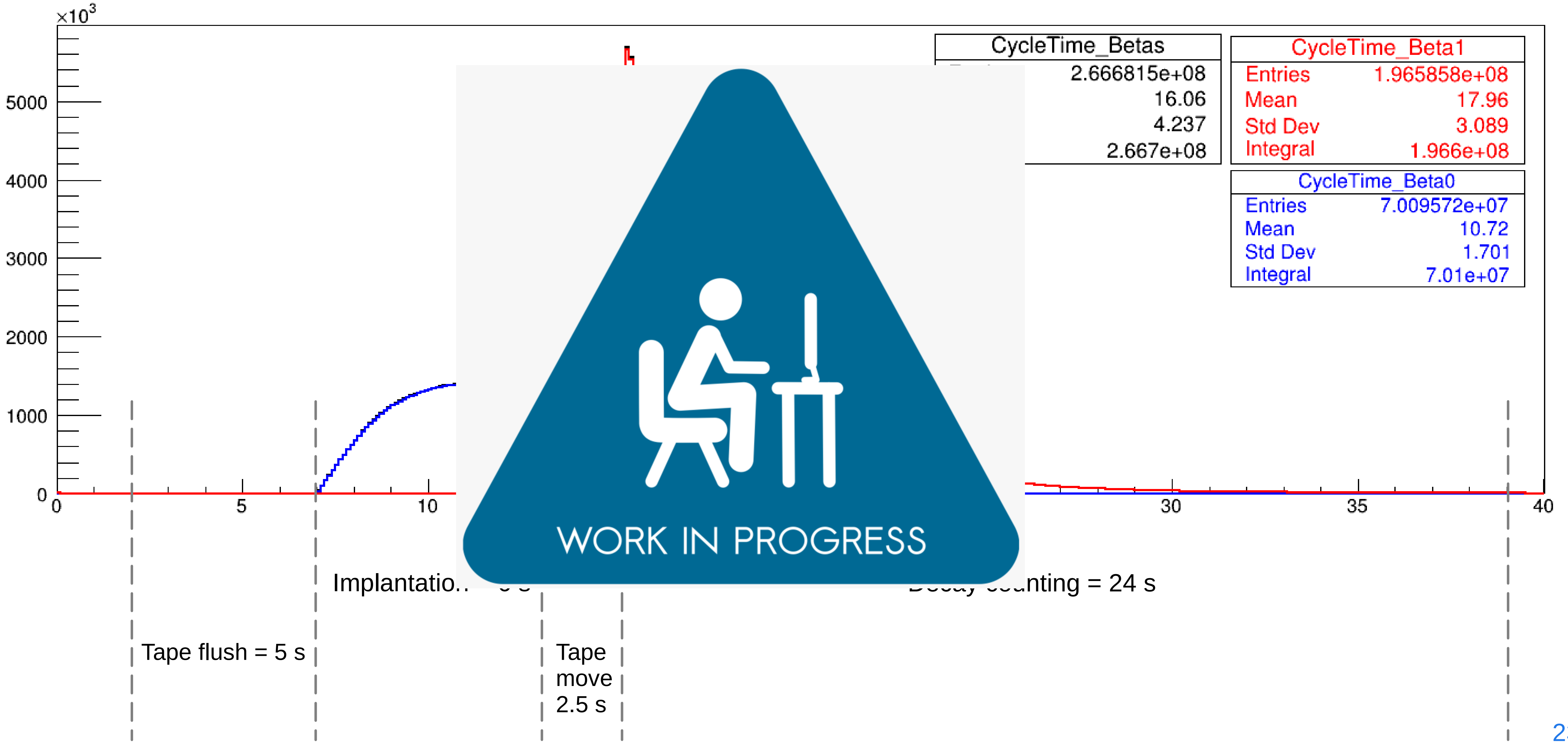
^{19}Ne half-life: did the tape work???



Moving on to our actual experiment but first ^{18}Ne $t_{½}$



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



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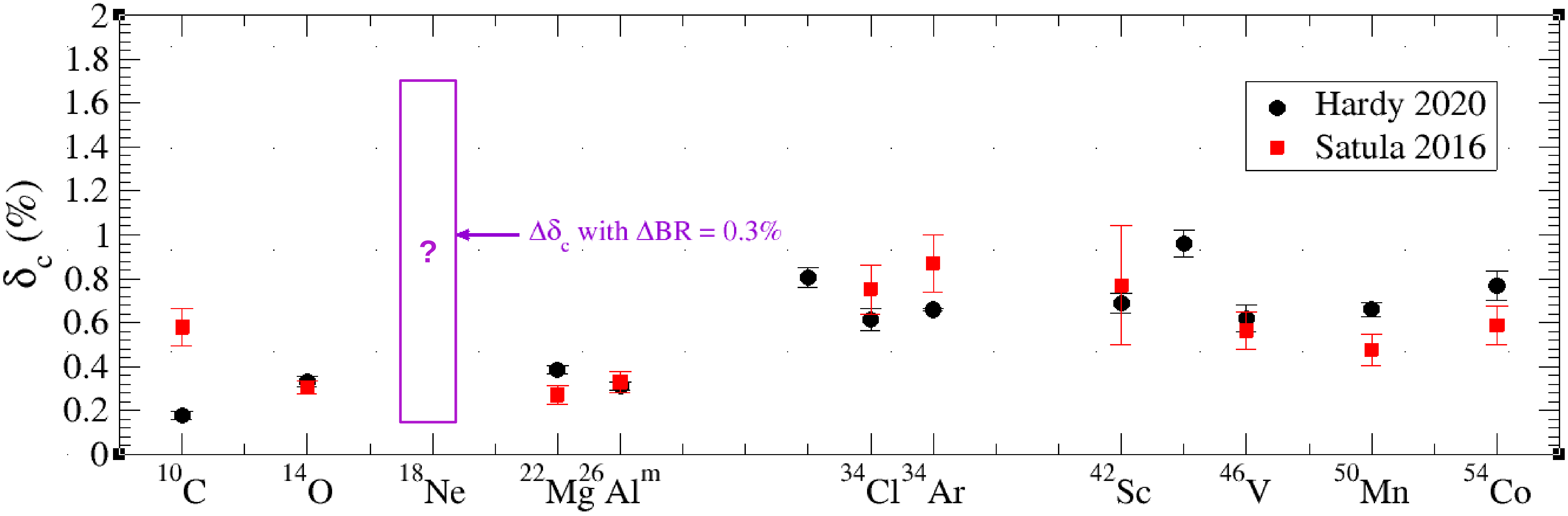
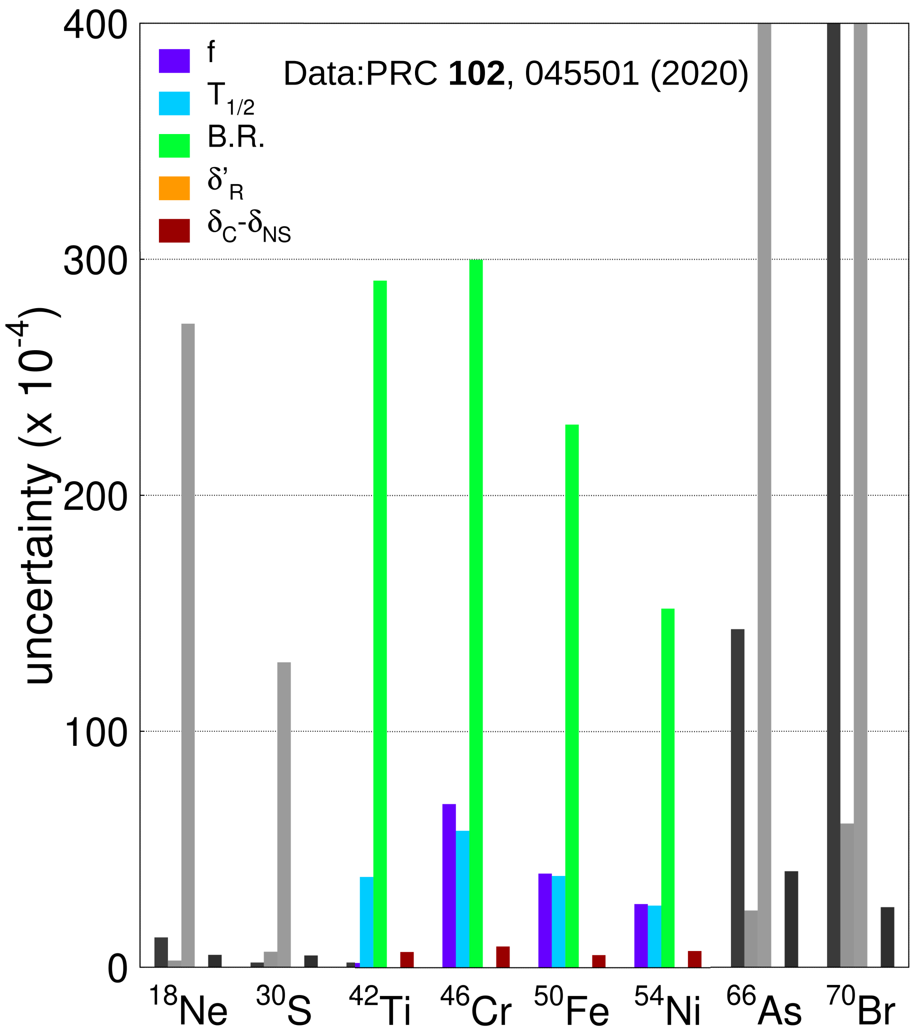
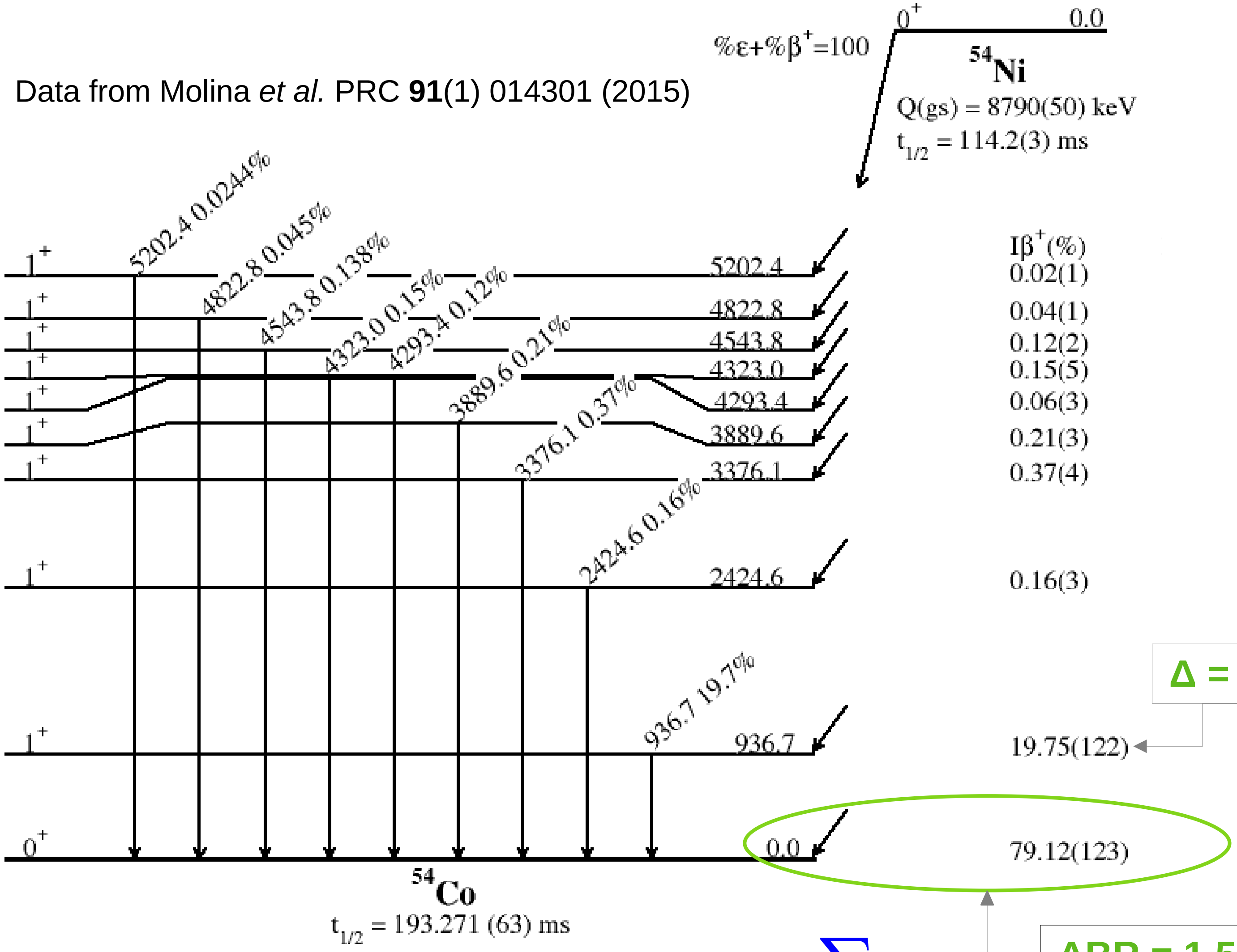


Looking for theory collaborations for ISB corrections

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





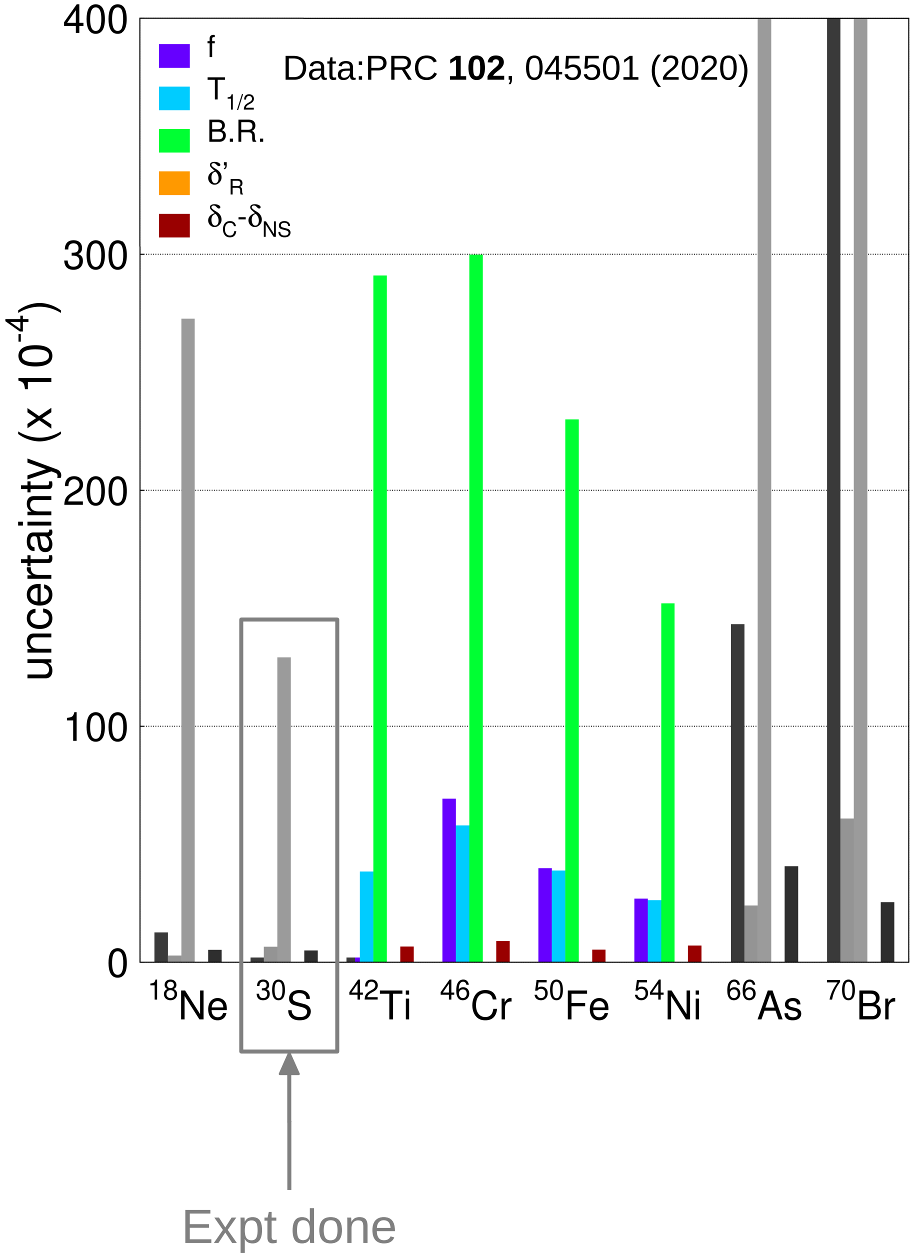
Δ = 6%

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

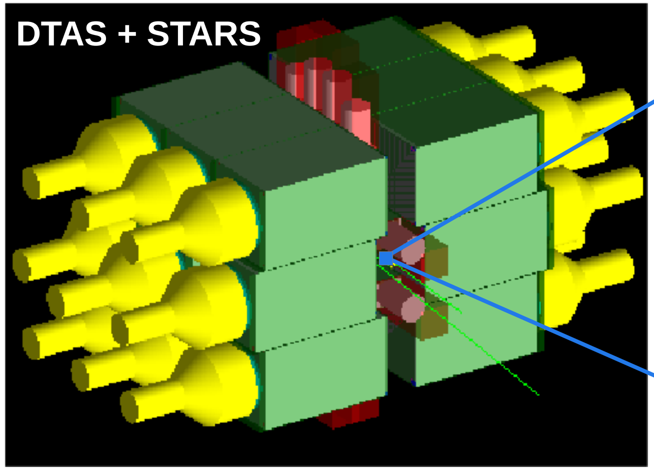
ΔBR = 1.5%,
Reqd Δ = 0.3%

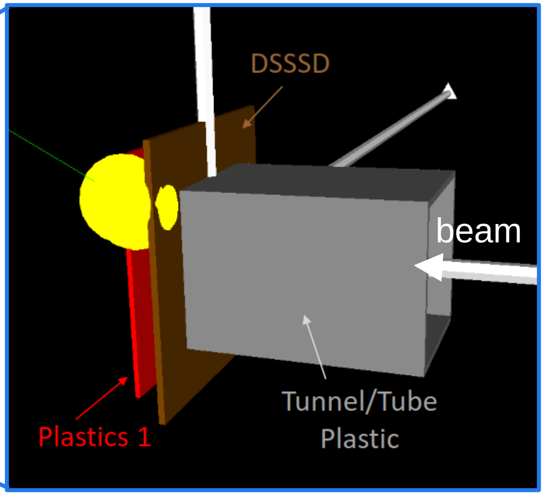
- Largest uncertainty: SA branching ratio
- Several competing $0^+ \rightarrow 1^+$ transitions that need to be measured with high precision
- High energy, low intensity γ transitions => Possibly suffering from Pandemonium effect

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) crystals) + **STARS** (16 $LaBr_3$:Ce)
  - High efficiency + high segmentation + good energy resolution + sub ns timing resolution
- **TAGS @ LISE scheduled for 2026**





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

Muriel FALLOT (Subatech)
25 September 2025 14:20
VIP 2 (MoHo)

Julien PEPIN (Subatech/IFIC)
22 September 2025 14:45
Inspire 2 (MoHo)

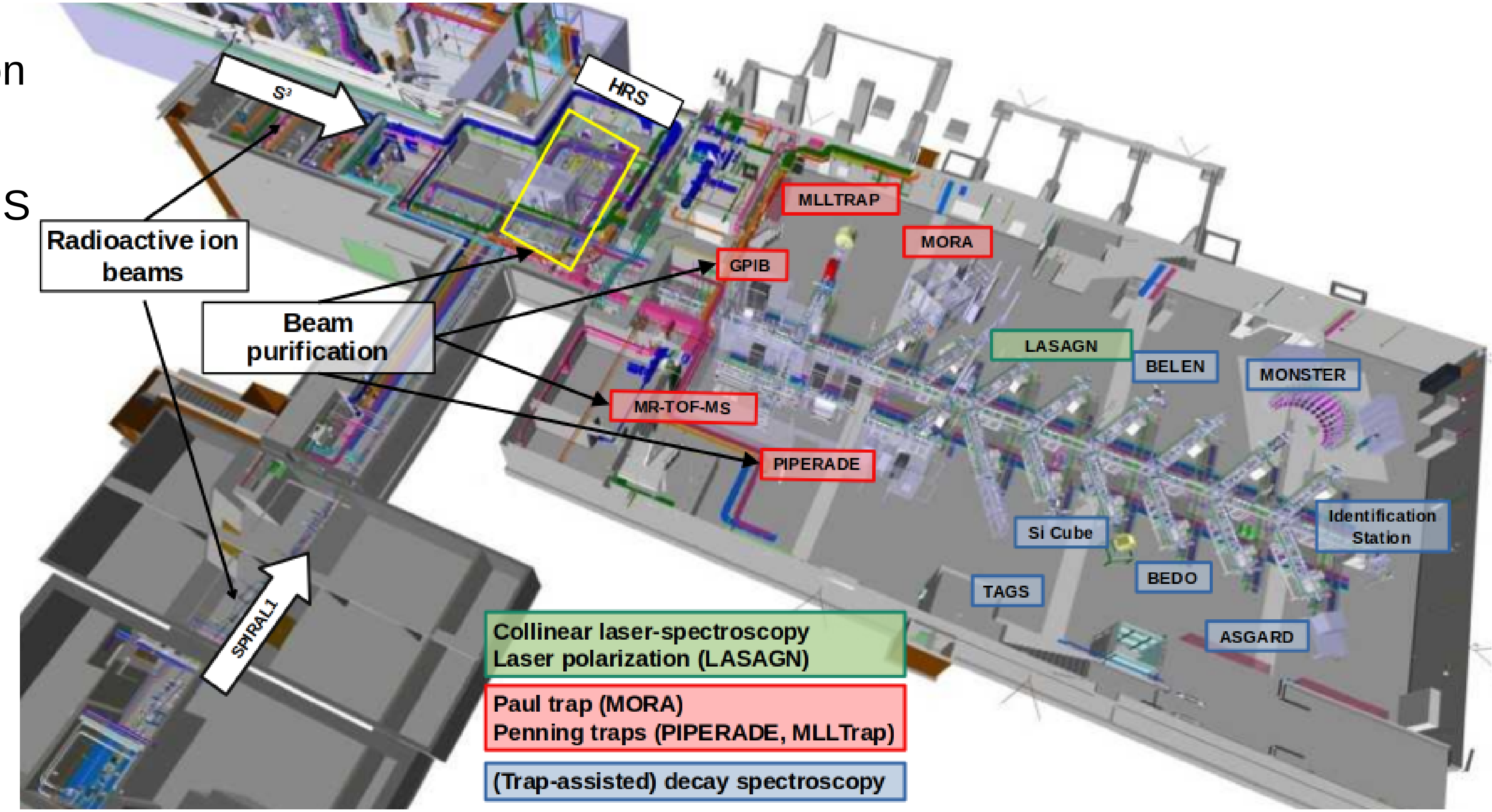
Amanda Porta (Subatech laboratory)
23 September 2025 15:05
Inspire 2 (MoHo)

Phase 2.01 with DESIR: Beyond ^{54}Ni towards ^{98}In

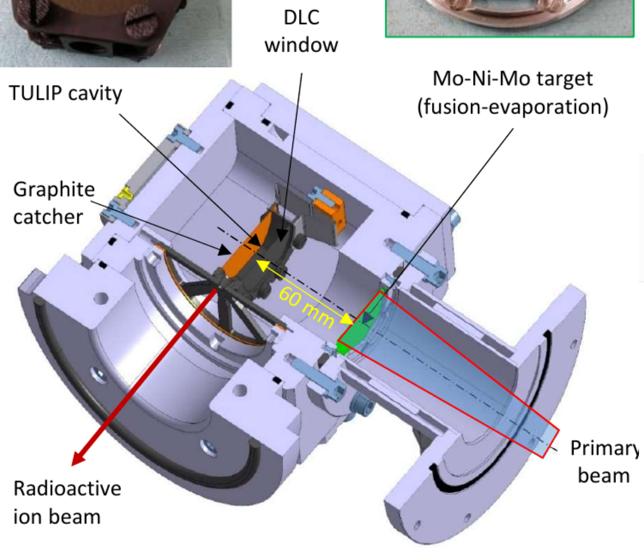
Tests δ_c models where most sensitive, i.e large Z

- **RIB from SPIRAL1 & SPIRAL2 (via S^3-LEB)**
  - Charge state: 1^+, Energy < 60 keV
  - Fusion evaporation for RIB production
- **Multiple purification devices**
  - HRS, GPIB, PIPERADE, MR-TOF-MS
  - Expectation: $m/\Delta m \sim 10^6$
- **Multiple experimental programs**
  - BESTIOL: decay spectroscopy
  - DETRAP: trapped ion studies
  - LUMIERE: laser spectroscopy

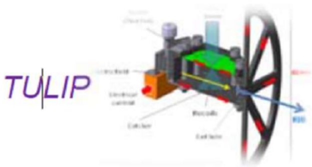
First stable beams in 2027



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

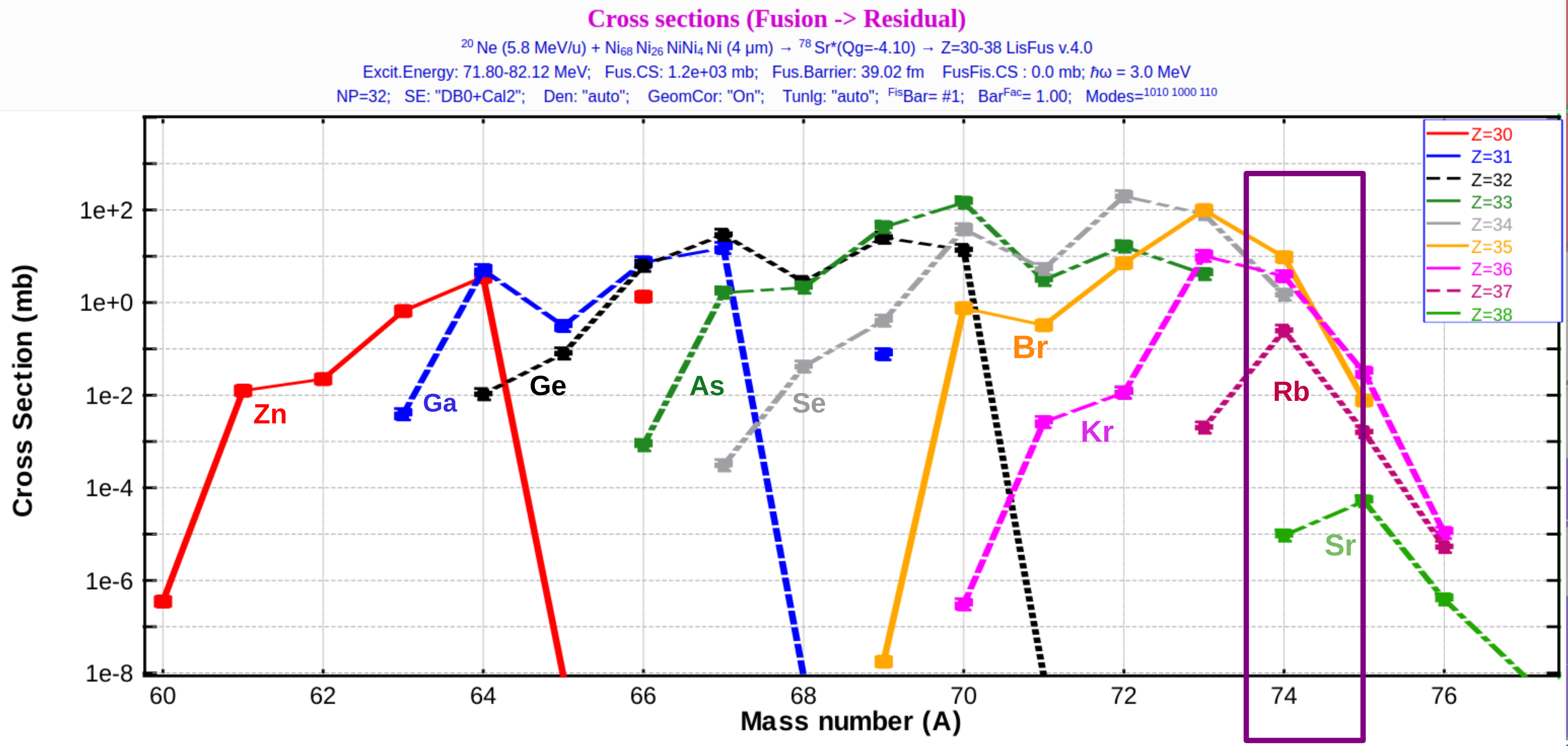


anr

CES 31: Physique Subatomique (PRC)

AAPG ANR 2018 GANIL

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



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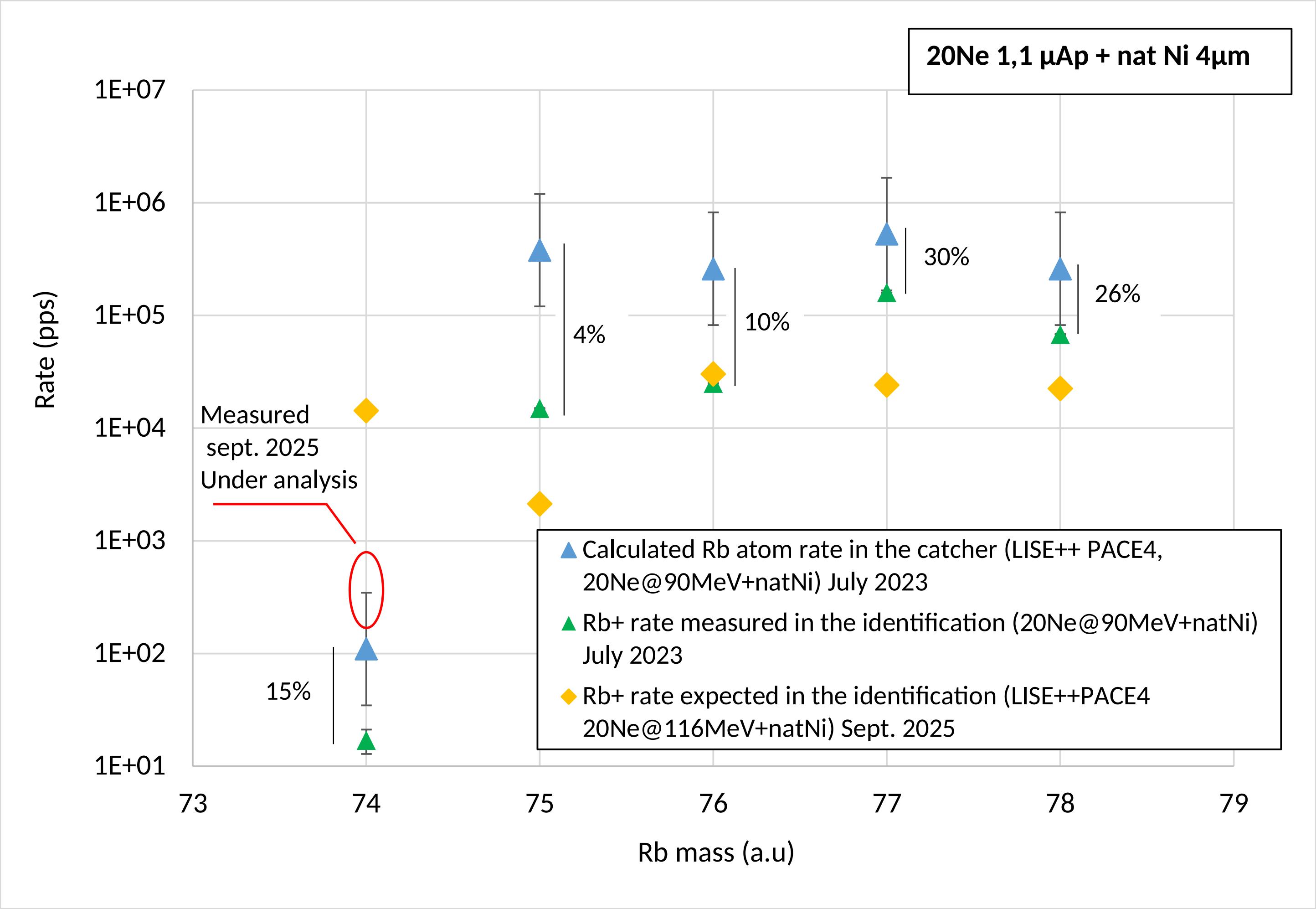

- Expected ion rate of $^{74}Rb^{+}$: ~10^4 pps
- Obtained : few hundreds per second for 1 pµA of ^{20}Ne (under analysis)
  - Cause: entrance window probably broken. No confinment of atoms or ions in the cavity.
- Next test run next week

Test run done 3-7 Sept 205

Summary

- V_{ud} from SA $0^+ \rightarrow 0^+$ currently the most precise, but tensions with CKM unitarity
- Theoretical corrections currently the challenge
- High precision ft data required to constrain models, esp ISB corrections
- At GANIL program underway to improve SA branching ratio for the 8 least precise with plans to move beyond Rb-74
  - Experiment to measure Ne-18 branching ratio done in June 2025, analysis on-going
- Next measurements will be challenged by beam purity and intensity requirements
- Upcoming facilities DESIR and S3-LEB offer promising avenes
- TULIP project underway to produce neutron-deficit short-lived RIBs. First tests of Rb-74 promising

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- High precision ft data required to constrain models, esp ISB corrections
- At GANIL program underway to improve SA branching ratio for the 8 least precise with plans to move beyond Rb-74
  - Experiment to measure Ne-18 branching ratio done in June 2025, analysis on-going
- Next measurements will be challenged by beam purity and intensity requirements
- Upcoming facilities DESIR and S3-LEB offer promising avenes
- TULIP project underway to produce neutron-deficit short-lived RIBs. First tests of Rb-74 promising

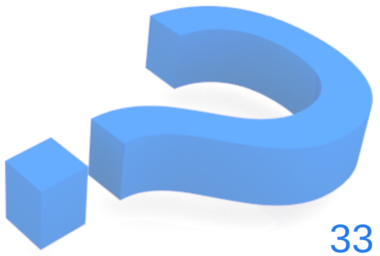
Exciting

times

ahead

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

ANY

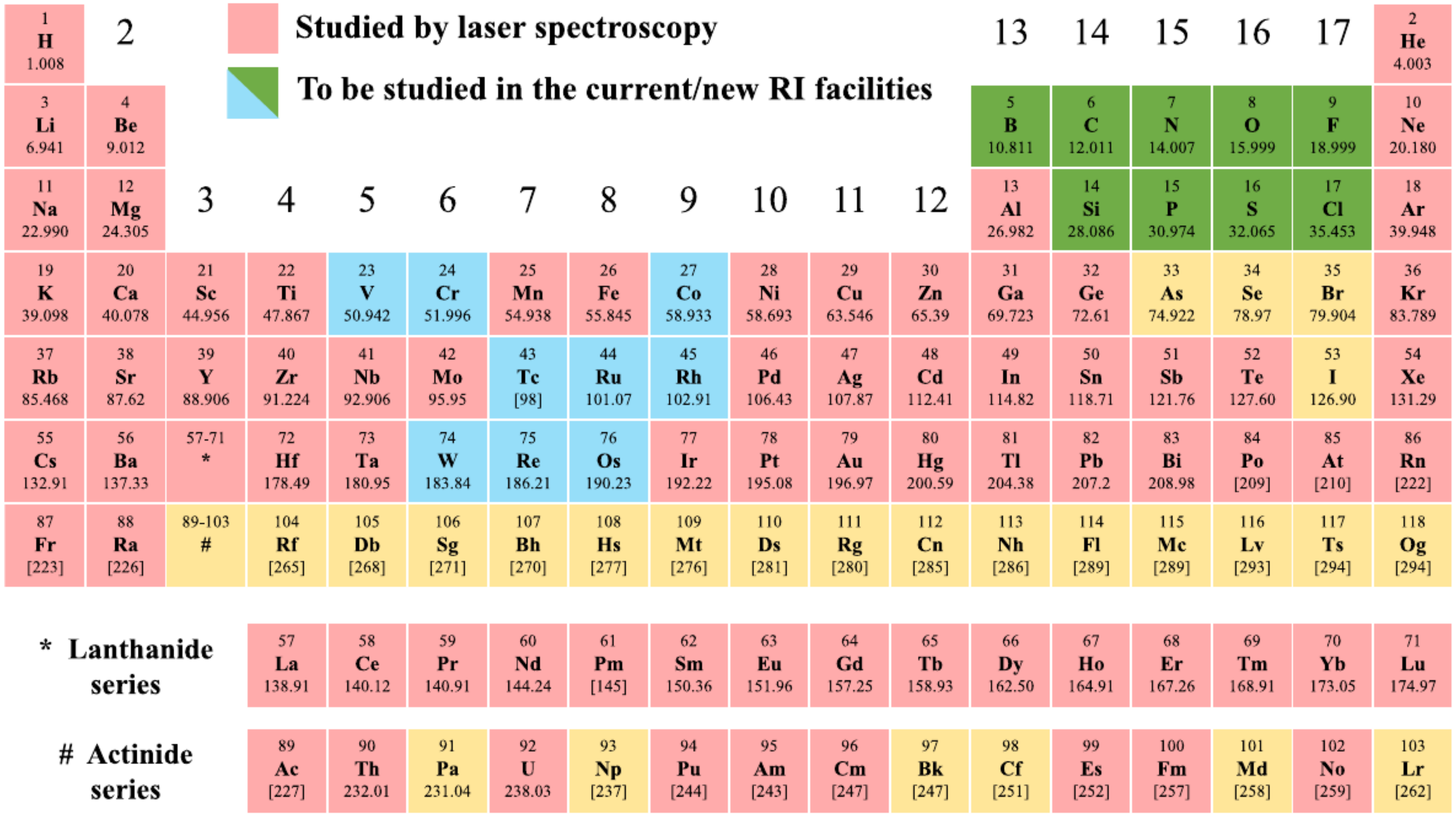


S^3-LEB at a future time

DESIR beams via S^3-LEB

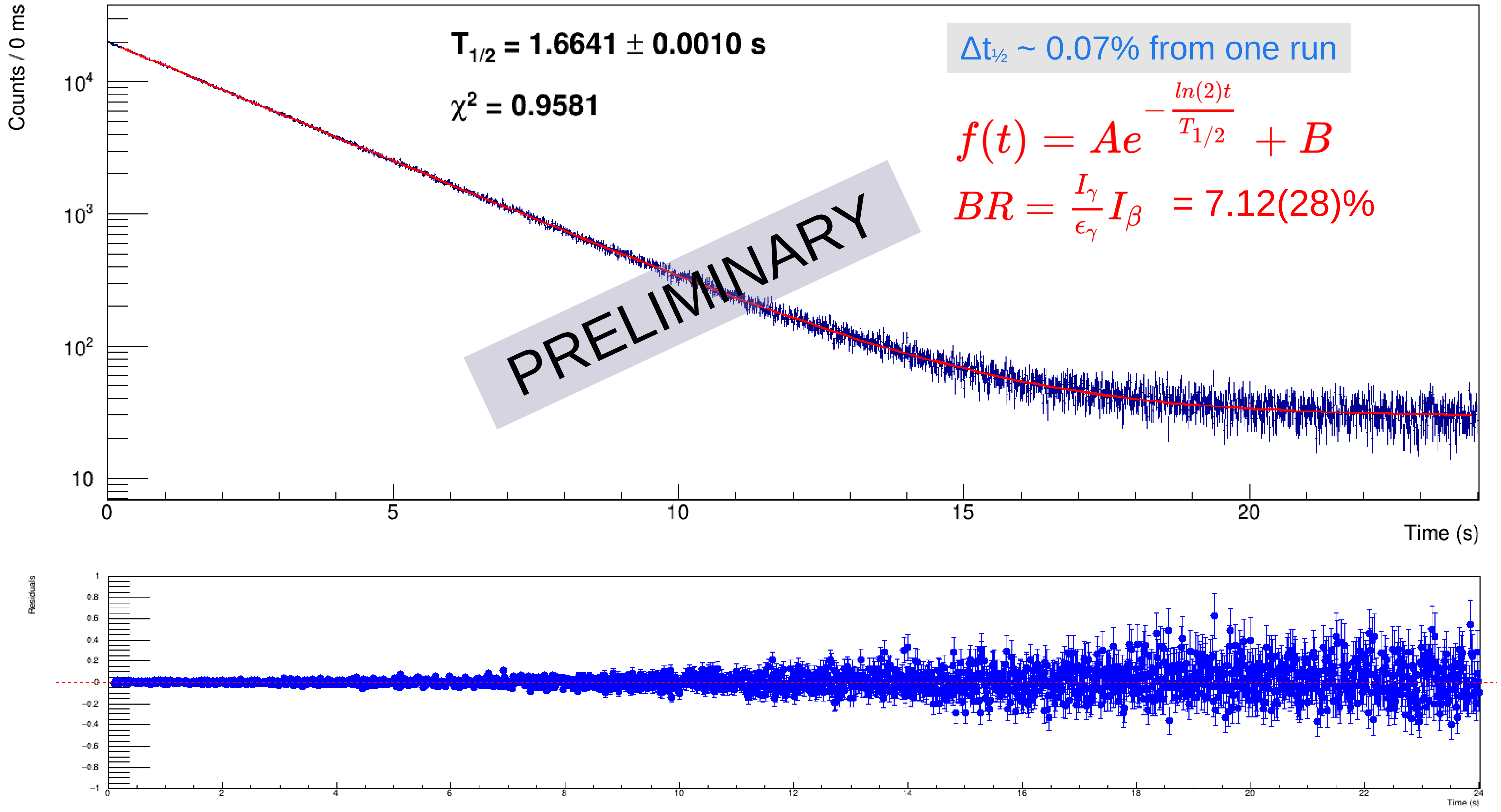
1. $t_{½}$ for know (heavier) SA emitters ^{54}Ni - ^{70}Br : **115 ms and less**
   - Current gas cell extraction time 300-600 ms (projected to 50 ms)
   - Could be a major bottleneck
2. LASER ionization schemes currently not available for all SA emitters
   - Need to collaborate with LASER community to develop efficient laser ionization schemes

SA pair	$t_{½}$ (ms)	Laser spectroscopy ?	S^3 beam yield
^{42}Ti → ^{42}Sc	208.65	Yes	1.6E05
^{46}Cr → ^{46}V	260	Not yet	2.6E03
^{50}Fe → ^{50}Mn	155	Yes	1.2E02
^{54}Ni → ^{54}Co	114.2	Yes	8.0E02
^{66}As → ^{66}Ge	95.77	No	2.2E03
^{70}Br → ^{70}Se	79.1	No	6.5E02



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

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

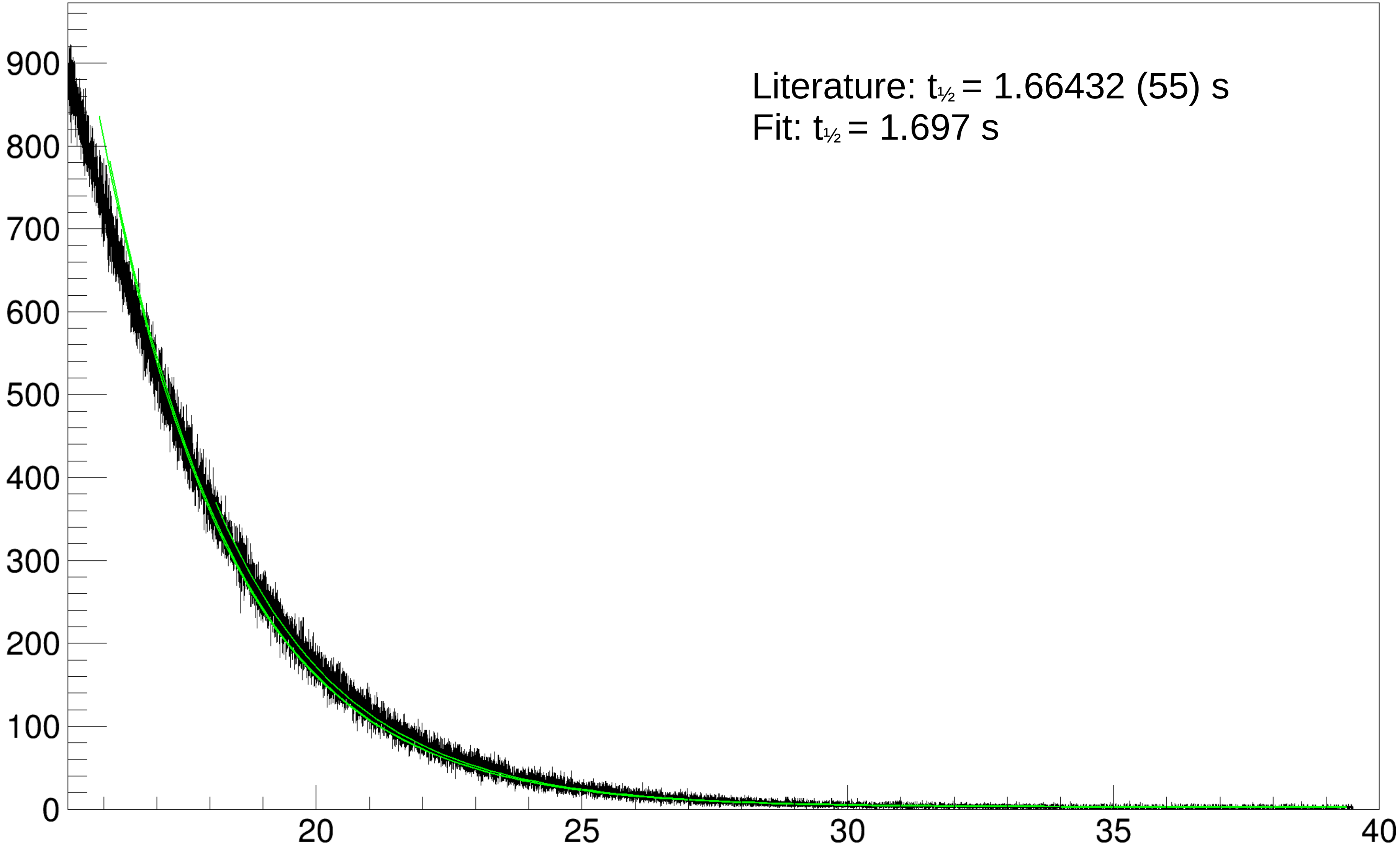


$$f(t) = Ae^{-\frac{ln(2)t}{T_{1/2}}} + B$$

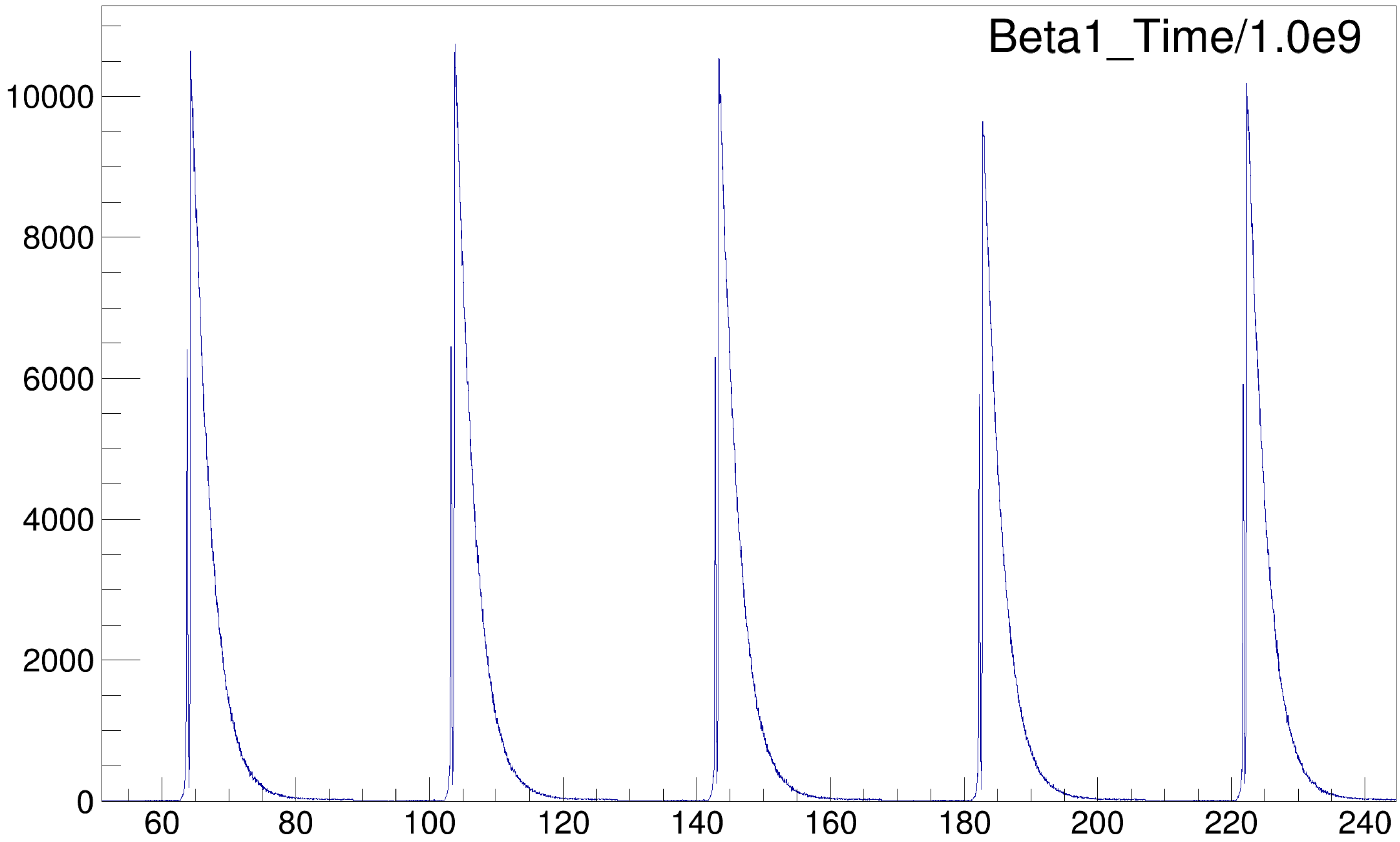
$$BR = \frac{I_\gamma}{\epsilon_\gamma} I_\beta = 7.12(28)\%$$

Analysis by Samuel Lecanuet, LP2i Bordeaux

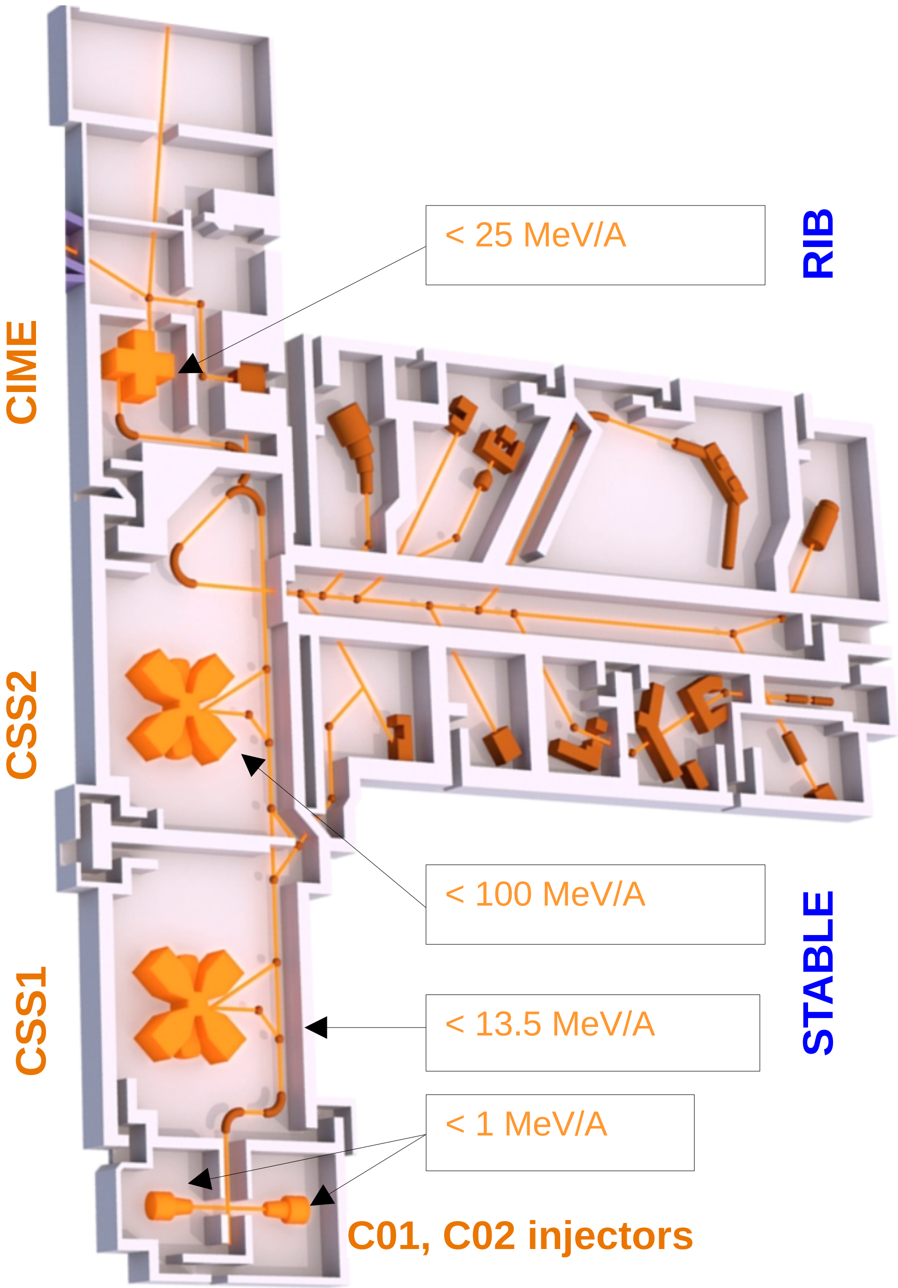
Backup: Ne18 half-life



Backup: Ne18 events in plastic scintillator per run



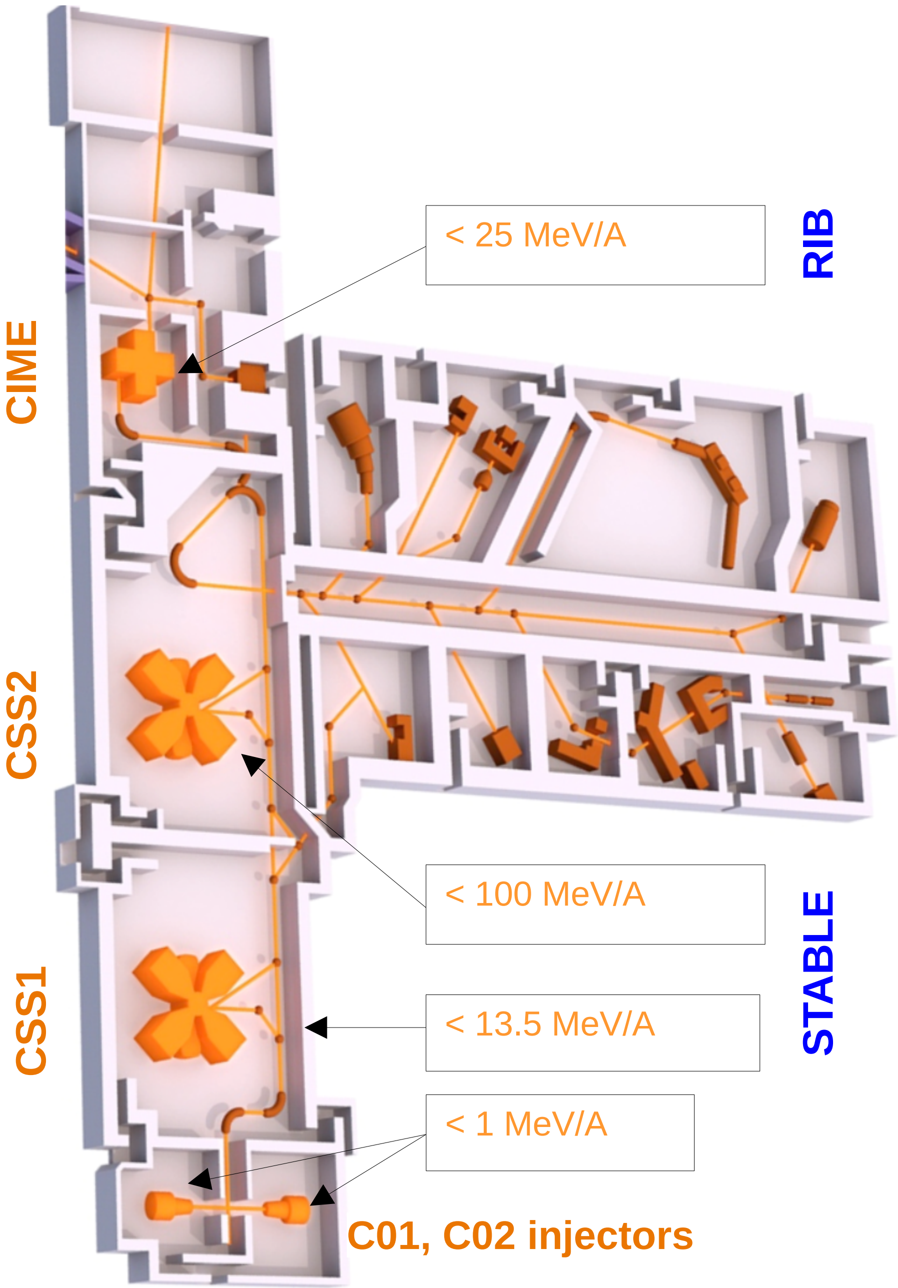
Superallowed program at GANIL: Phase 1

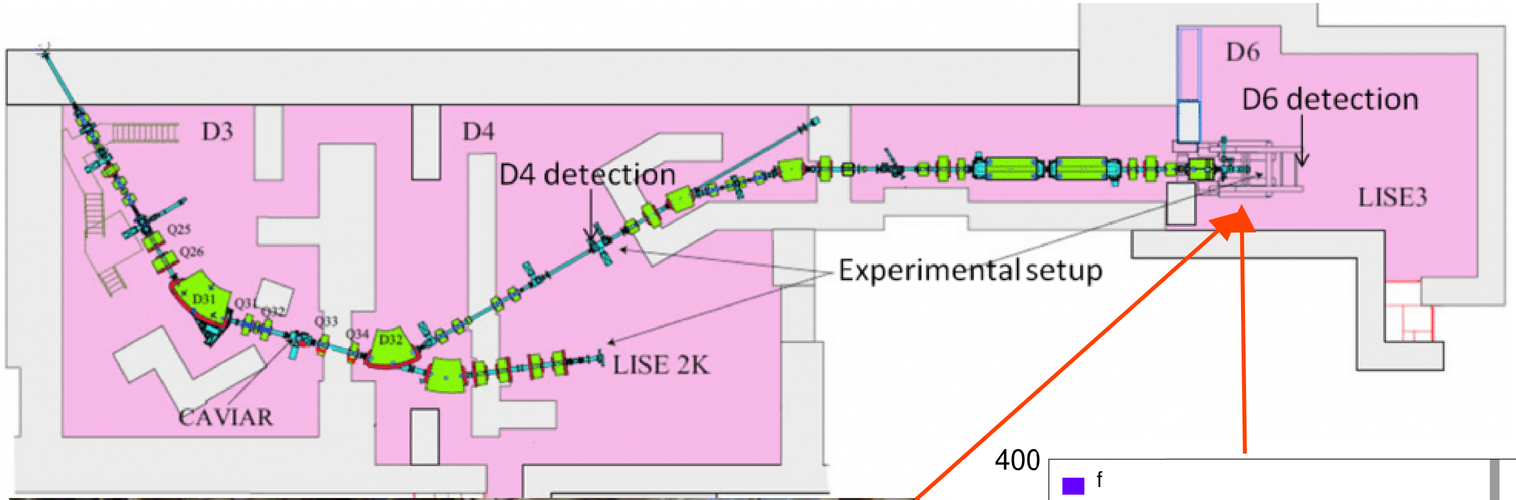


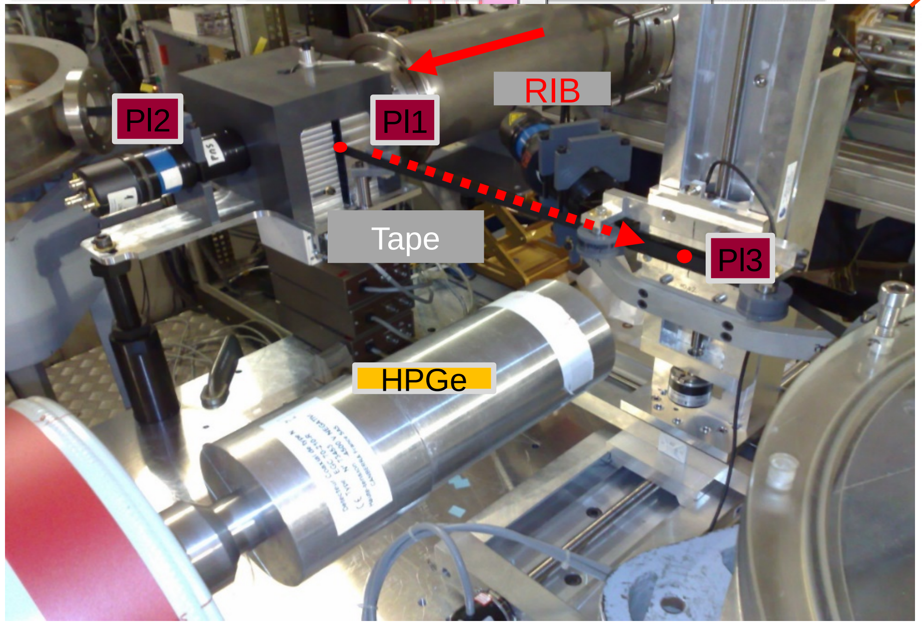
Superallowed radioactive ion beams

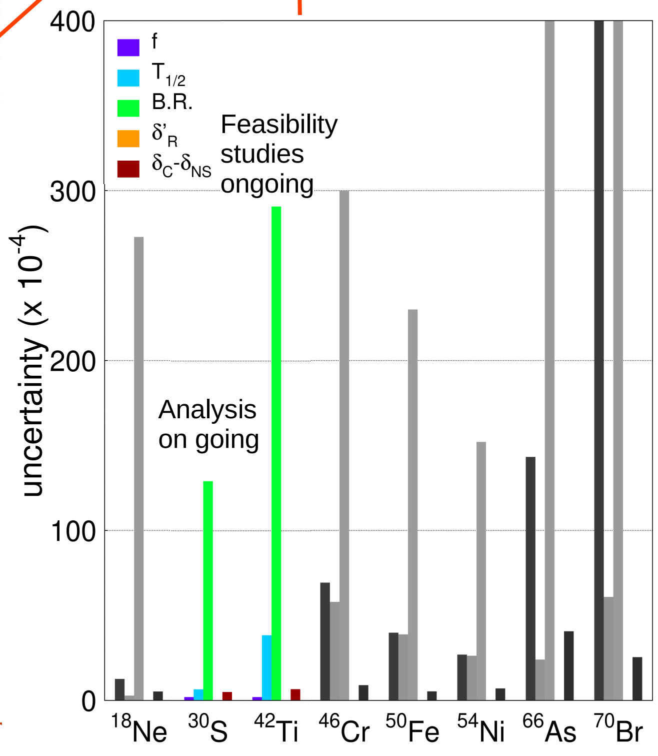
- In-flight fragmentation at LISE
- ISOL technique at SPIRAL1

Superallowed program at GANIL: Phase 1



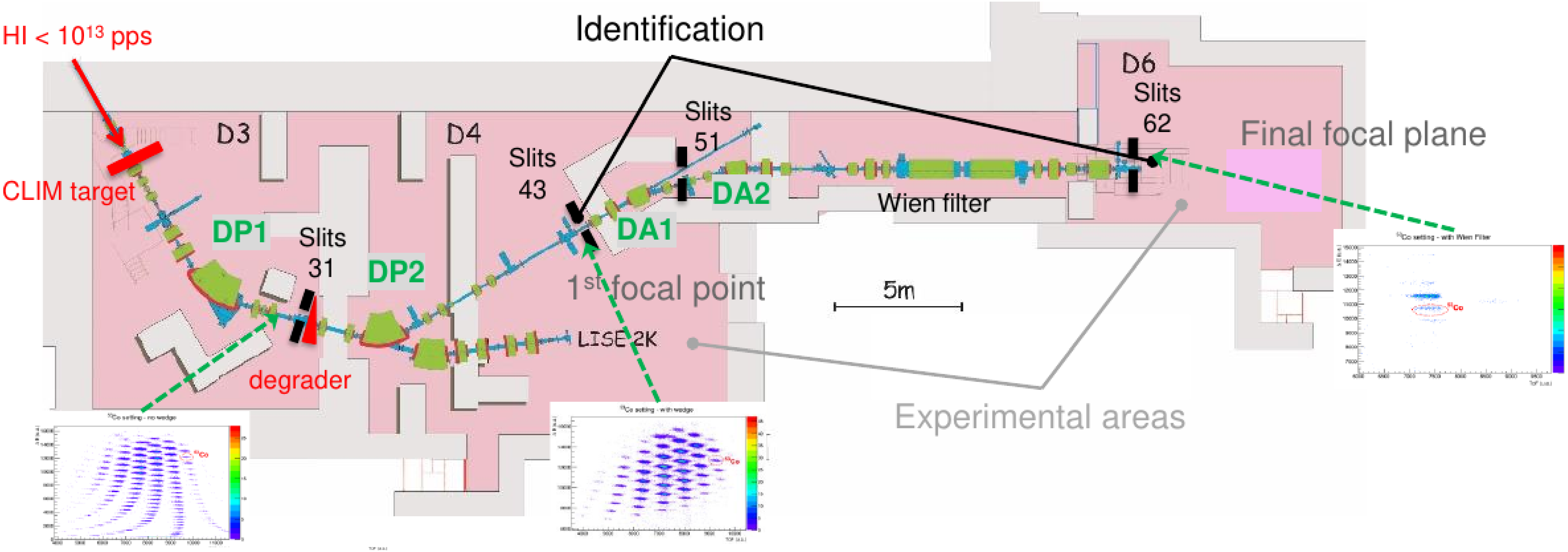






https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimer

SA decays @ GANIL:LISE (^{38}Ca, ^{30}S, ^{42}Ti)

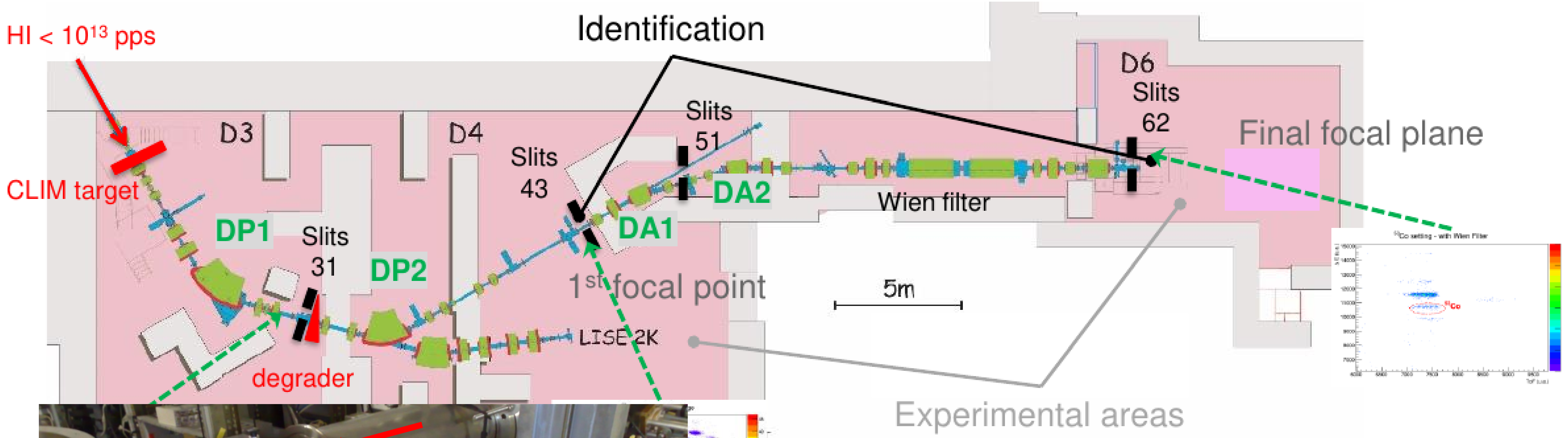


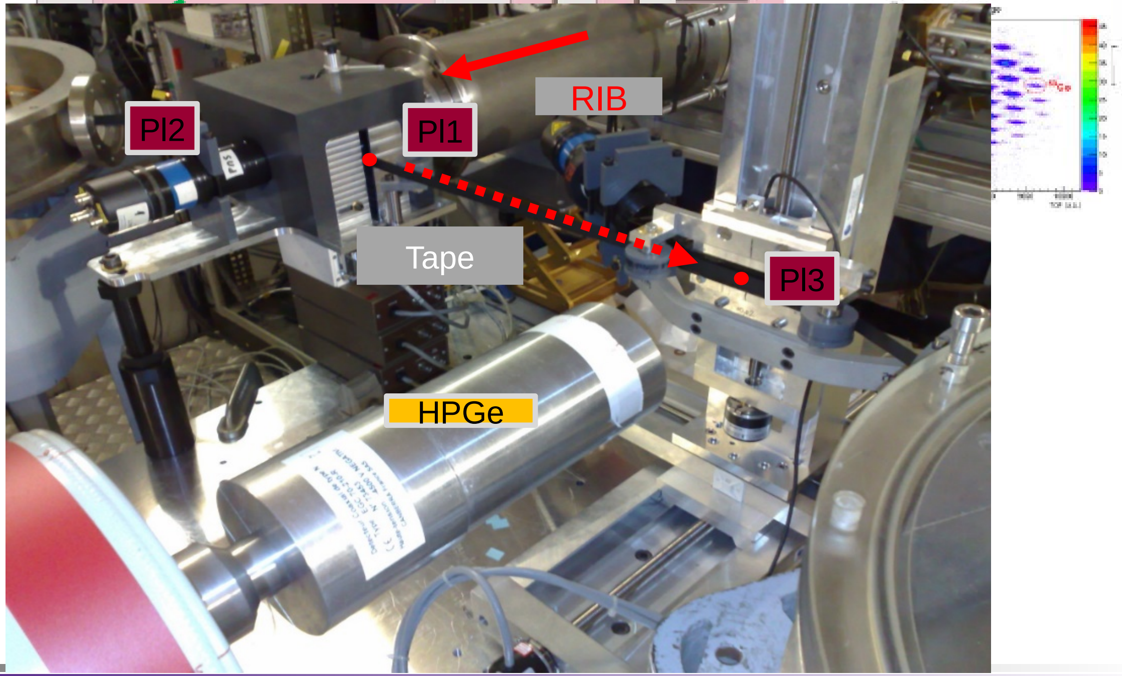
- 3 stages selection: $B_{\rho1}$ ~p/Z (DP1); degrader + $B_{\rho2}$ ~A^3/Z^2 (DP2); velocity filter (v) ++ a number of slits
- Identification: ΔE, ToF (+XY)
- Experimental areas: D4 (+ LISE2K), D6

- $B_{\rho2}$ ≤ 3.2 T.m (4.3 T.m on LISE 2K)
- Δp/p ≤ ±2.5 %
- Angular acceptance: 1 msr (3.5 on LISE2K)

Slide credit: J.-C. Thomas

SA decays @ GANIL:LISE (^{38}Ca, ^{30}S, ^{42}Ti)

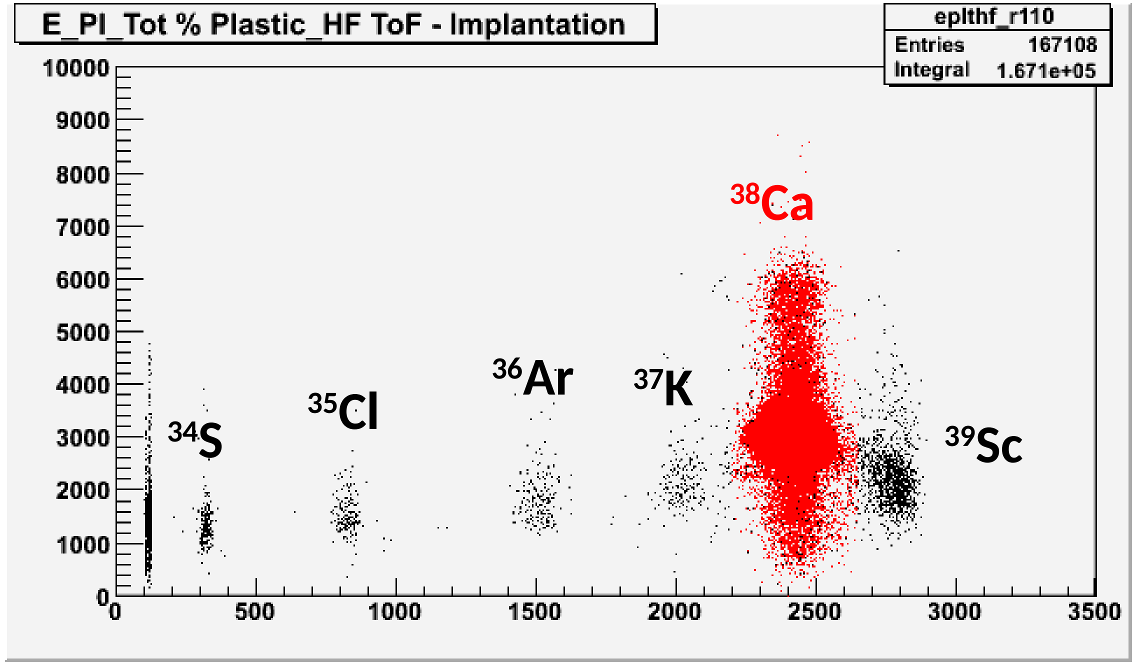


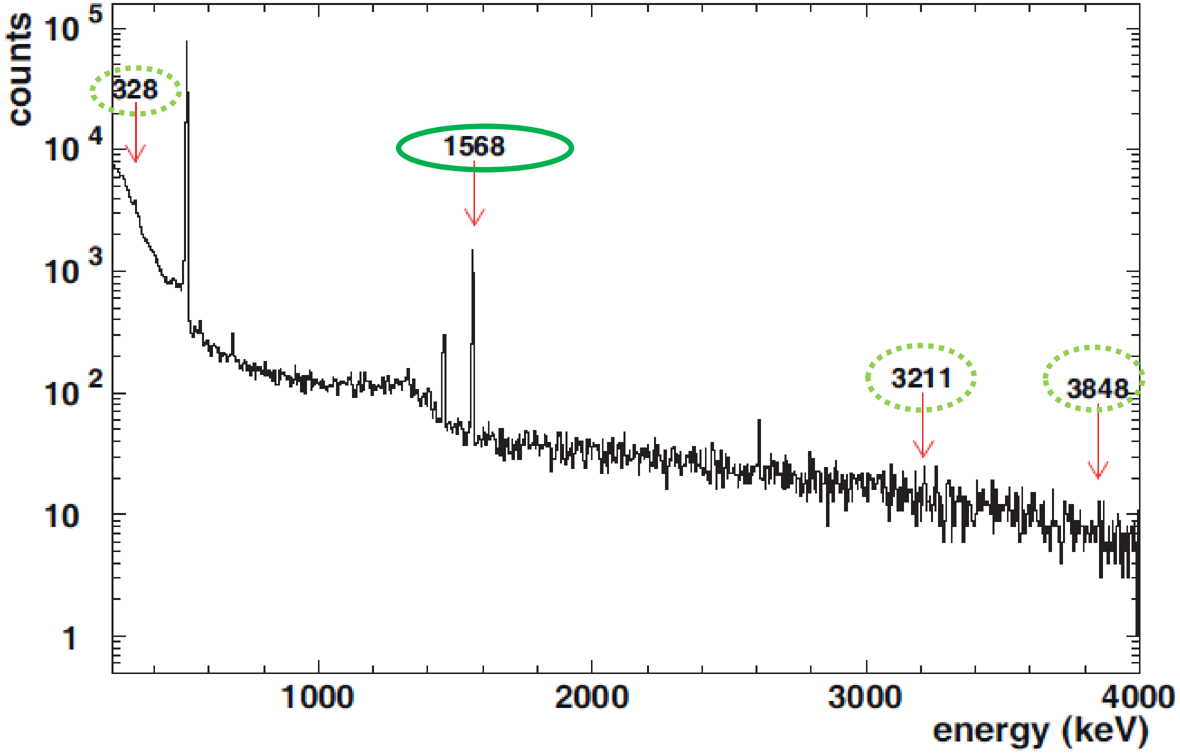


Experimental Setup for SA β decay studies

- PI1, PI2: implantation monitoring
- PI3: $t_{1/2}$ measurement
- HPGe: BR measurement
- Movable tape drive system

SA decays @ GANIL:LISE (^{38}Ca, ^{30}S, ^{42}Ti)





- Fragmentation of ^{40}Ca@50MeV/A
- ~99.5 % purity, ~10^4 pps @ 2 eμA

$t_{1/2}$ = 443.63(35) ms => 0.08 % precision
BR = 77.14(35)% => 0.4% precision

First SA beta decay studied at GANIL

B. Blank et al., Eur. Phys. J. A **51**, 8 (2015)

SA decays @ GANIL:LISE (^{38}Ca, ^{30}S, ^{42}Ti)

- Fragmentation of ^{32}S @ 50MeV/A => few 10^4 pps ^{30}S
- Wein filter issues
  - ~99% purity when operating
  - ~ 60% otherwise
- Analysis ongoing

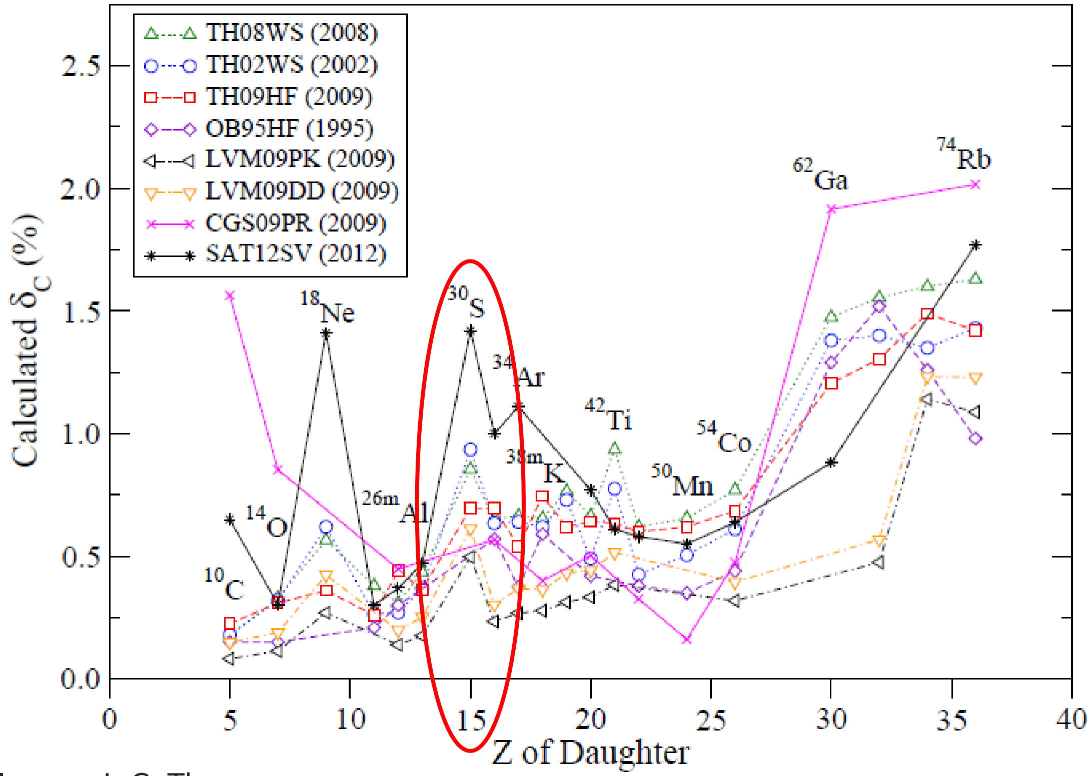
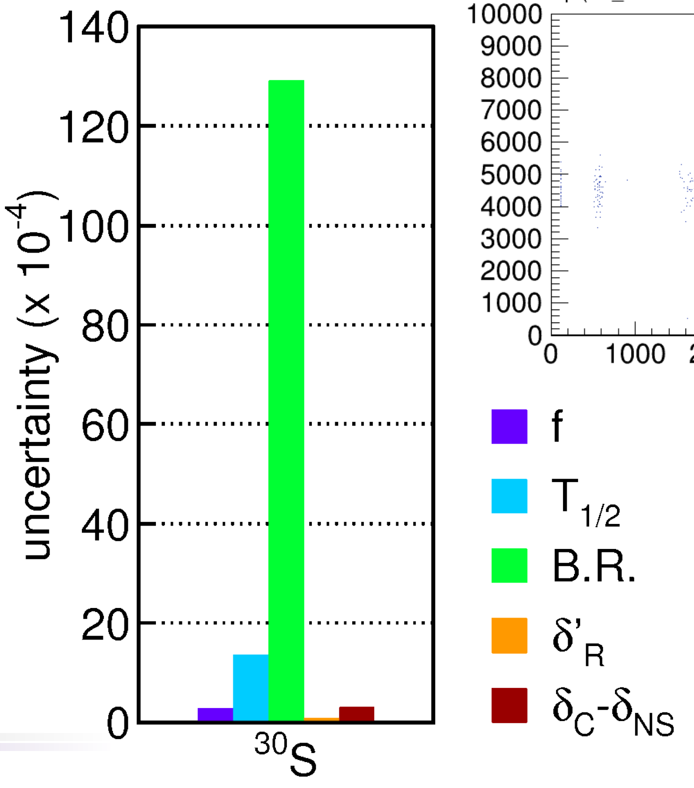
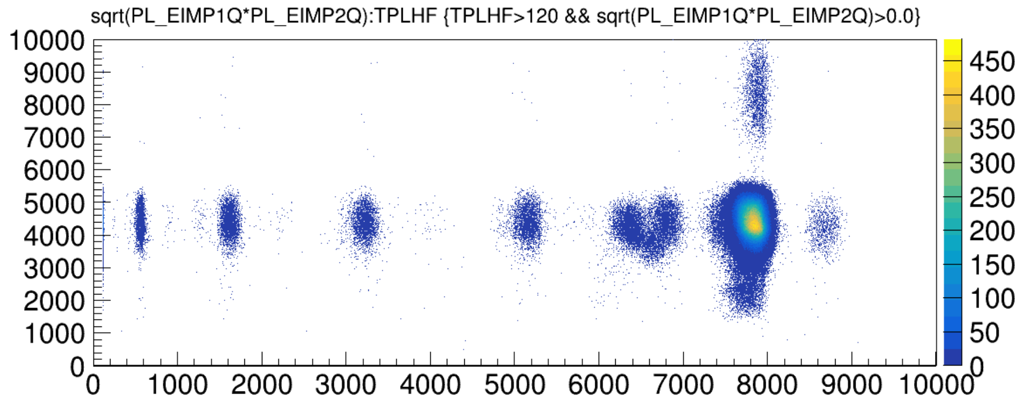
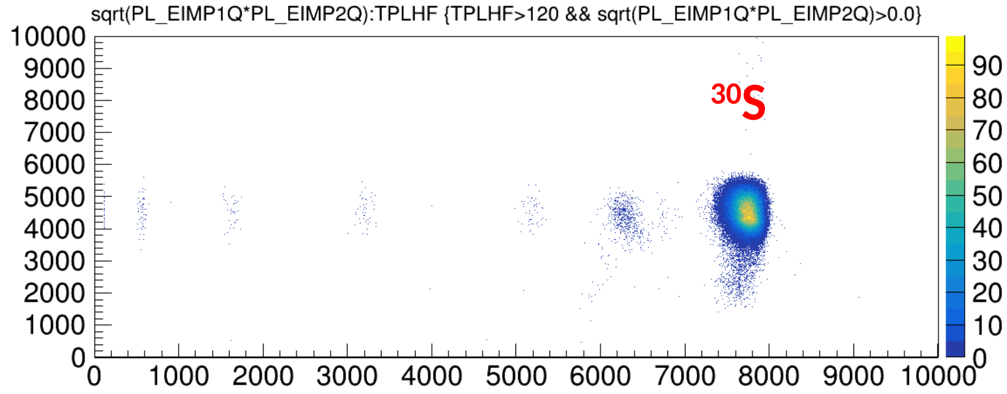


Image: J.-C. Thomas







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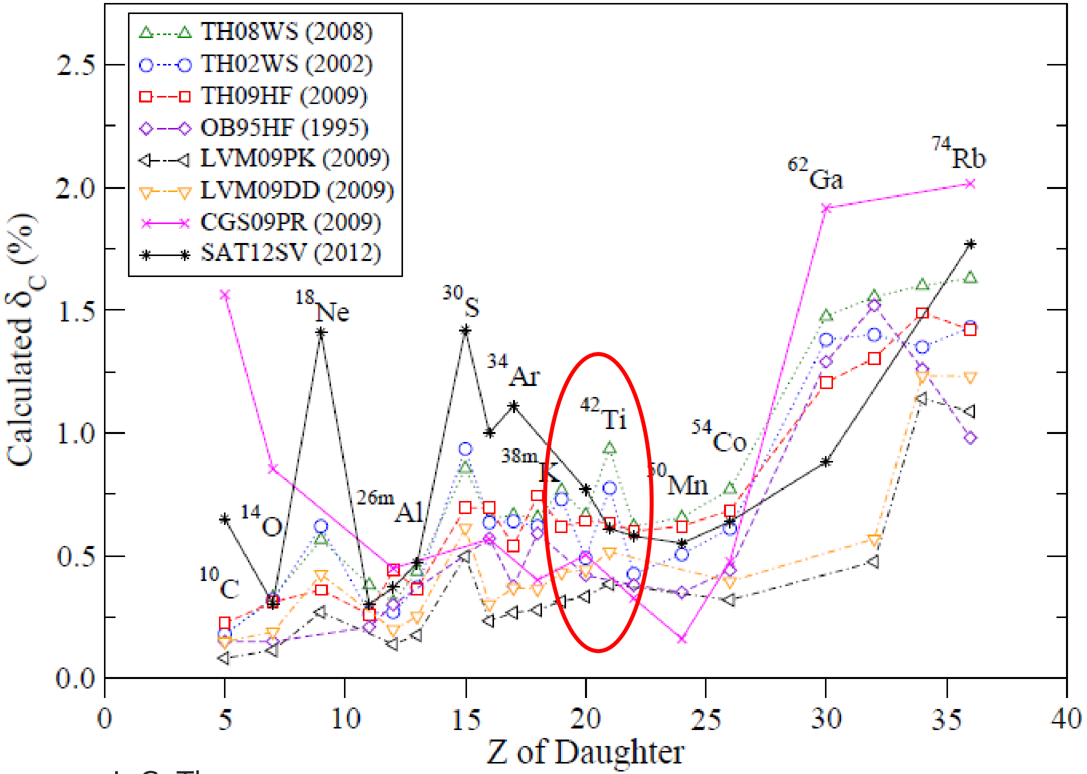
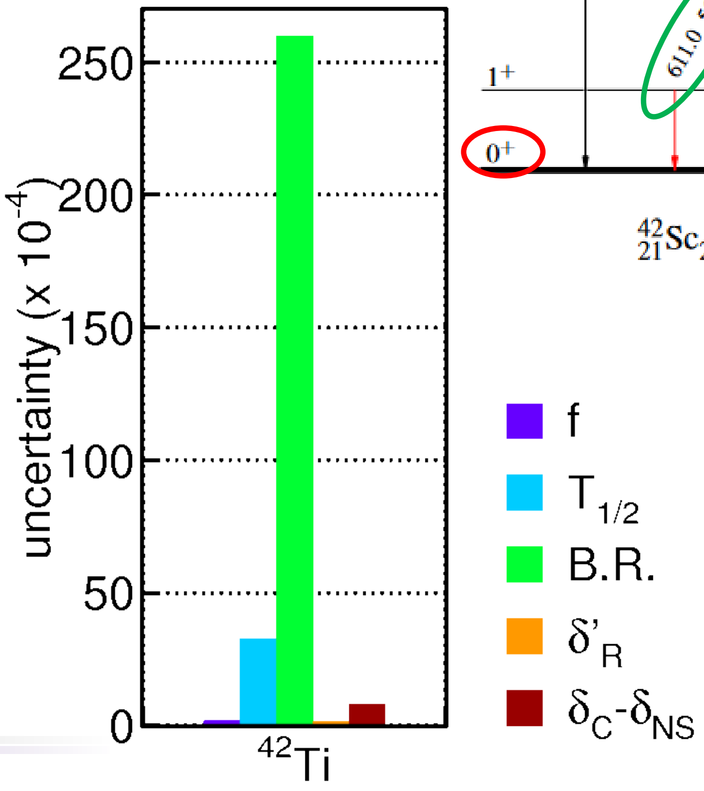
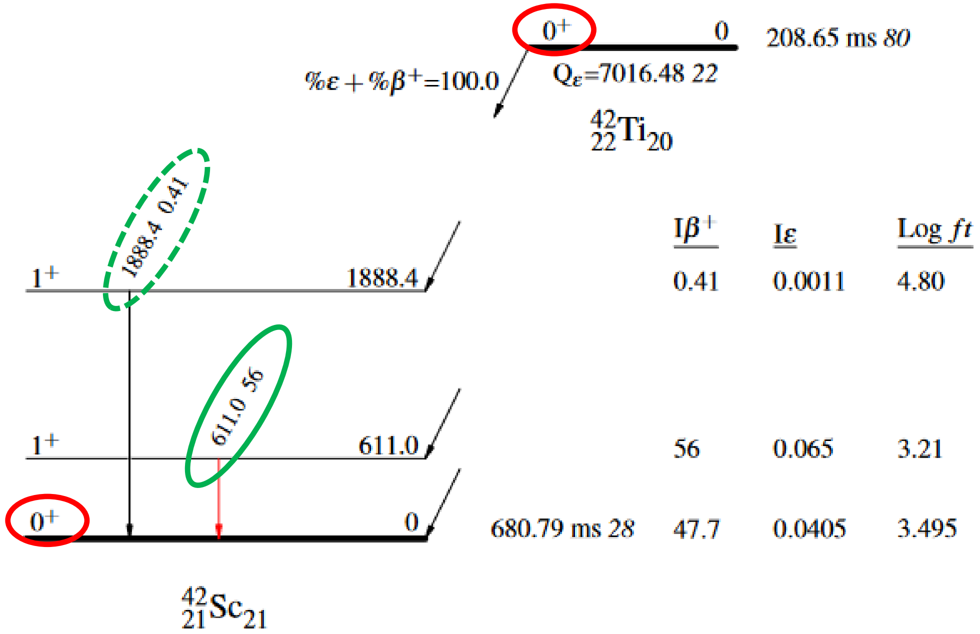
SA decays @ GANIL:LISE (^{38}Ca, ^{30}S, ^{42}Ti)

- Fragmentation ^{46}Ti@70 MeV/A -> ^{42}Ti@35 MeV/A
  - 4.10^4 pps ~99 % purity expected
- Concern about the LISE++ reliability
  - Scan of momentum distributions with CAVIAR
- Future proposal at LISE with Fast Tape System







Images: J.-C. Thomas

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