ASGARD: A novel probe for new physics

61st International Winter Meeting on Nuclear Physics

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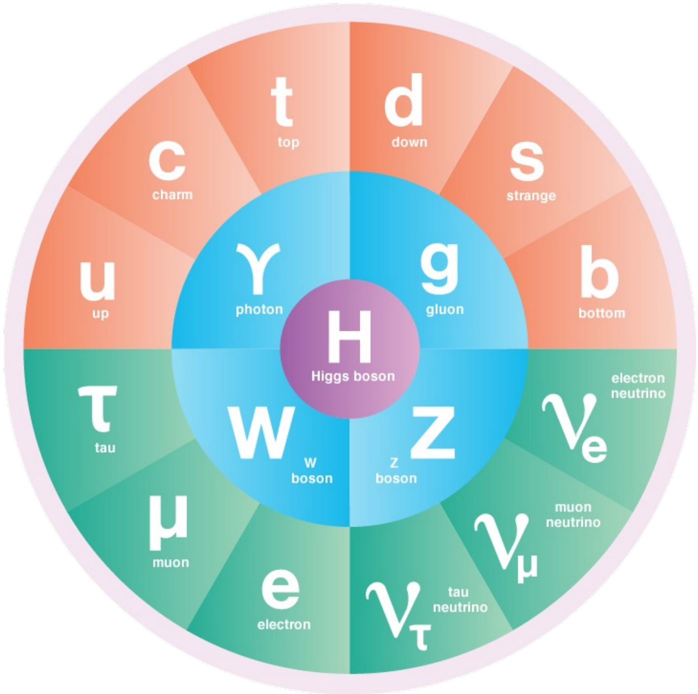
To the Standard Model… and beyond!



Many shortcomings in the Standard Model:

- Does not account for gravity
- No answer for the matter-antimatter asymmetry
- ~95% of the universe (dark matter and dark energy)
- …

What to do?

Precision measurements in beta decay -> sensitive to new physics beyond **10 TeV** for precisions at the **10^{-4}** level

- CKM unitarity
- Exotic currents

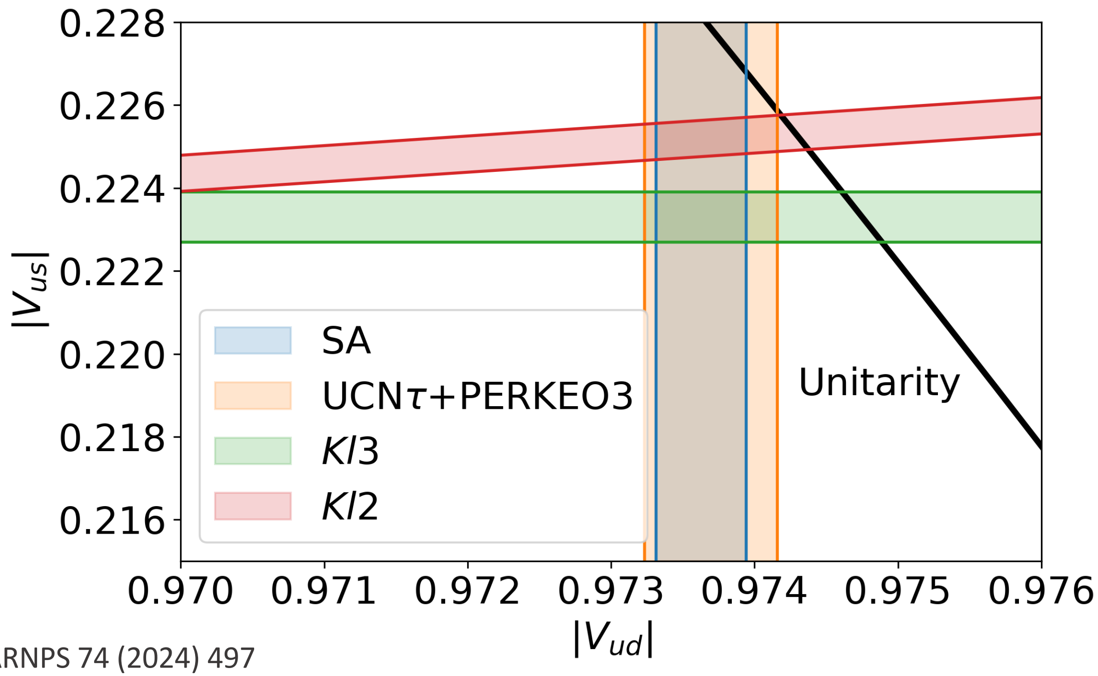
CKM Matrix

Cabbibo-Kobayashi-Maskawa matrix:

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

Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + \underbrace{|V_{ub}|^2}_{\sim 10^{-5}} = 1$

Nuclear β decay Meson decay

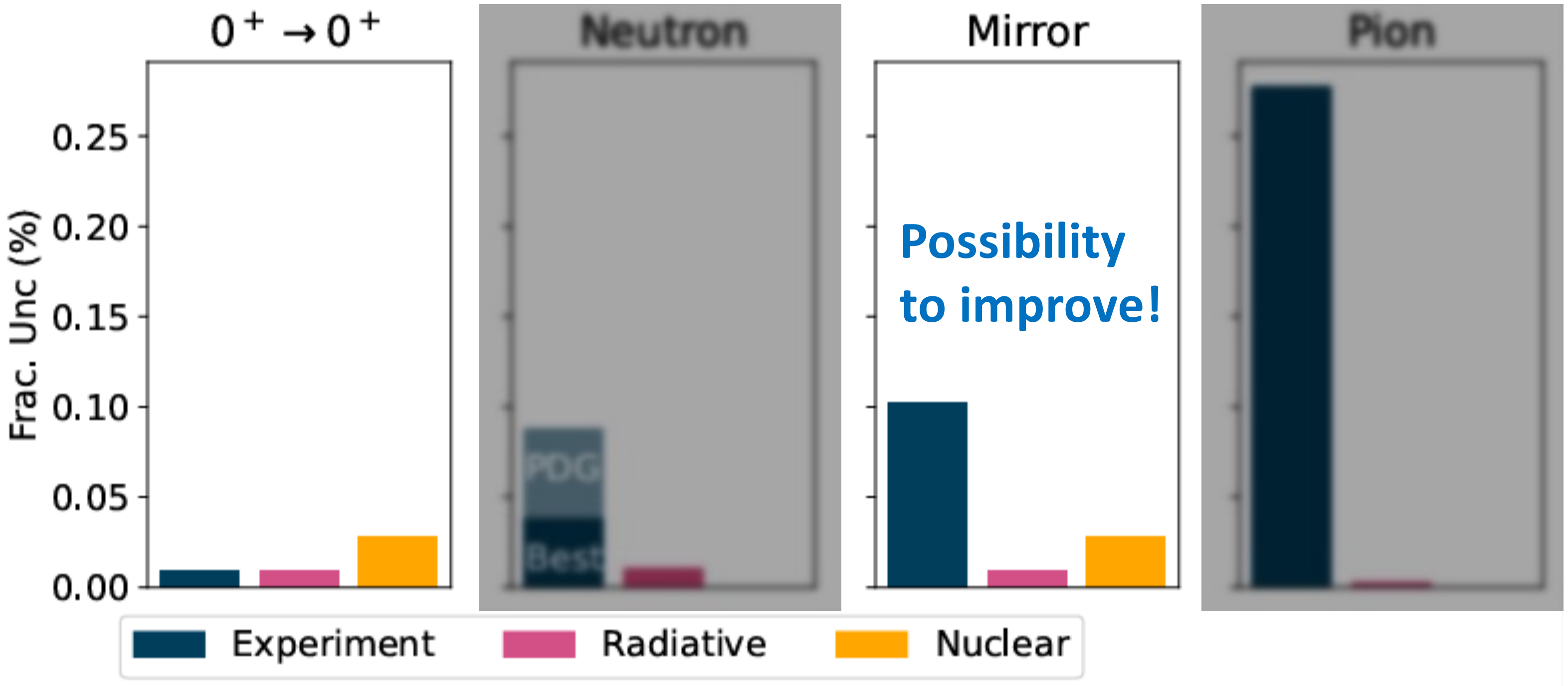


Non unitarity:

- New generation of fermions
- Non V-A contributions in the weak interaction

*L. Hayen, ARNPS 74 (2024) 497

Status of V_{ud}



0^+ -> 0^+: very difficult to do any better!
New opportunities lie in mirror transitions

*L. Hayen, ARNPS 74 (2024) 497

How to improve V_{ud} ?

For mirror transitions:

$$\boxed{\mathcal{F}t \equiv f_V t_{1/2}(1+\delta)\left(1+\rho^2\frac{f_A}{f_V}\right) = \frac{K}{V_{ud}^2}}$$

Things you need to know to get V_{ud} :

- Q-values (f_V)
- $t_{1/2}$
- Theoretical corrections (δ)

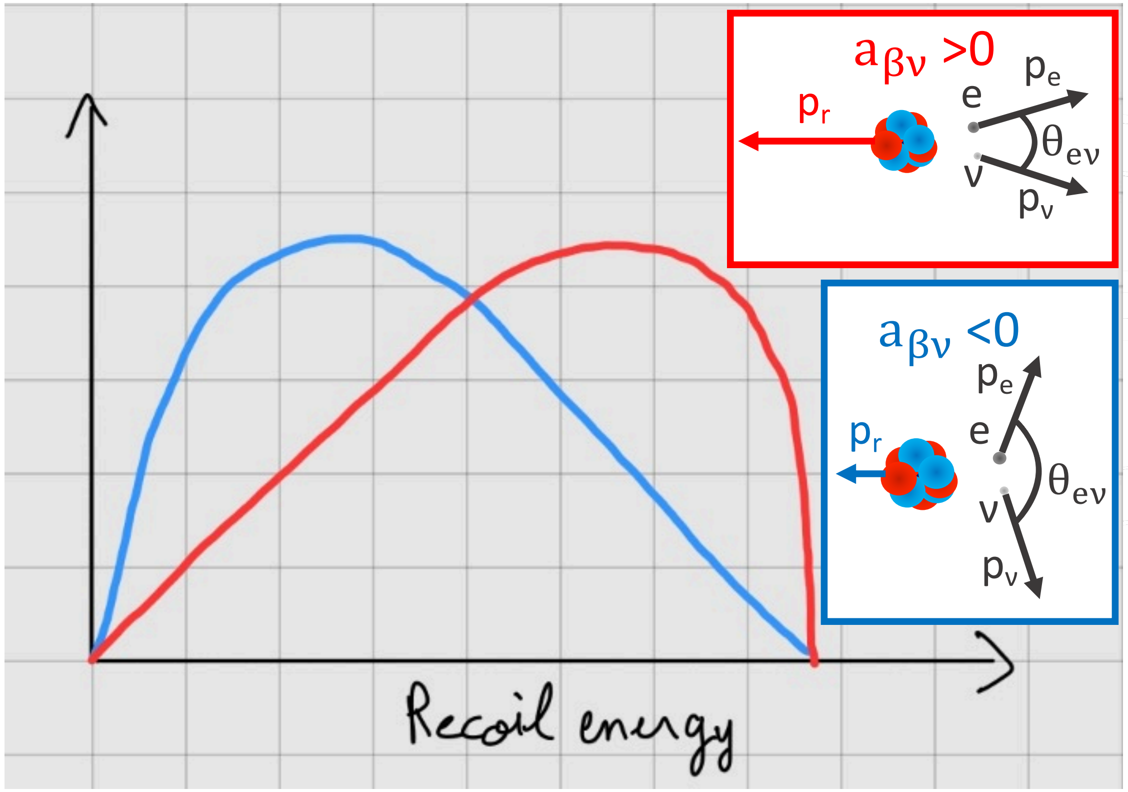
Known with high precision for many mirror transitions

- $\rho = \frac{g_A M_{GT}}{g_V M_F}$: GT/Fermi mixing ratio

The question becomes: how to obtain ρ ?

Recoil energy spectrum

Recoil spectrum: directly sensitive to $a_{\beta\nu}$



Beta-neutrino angular correlation:

$$a_{\beta\nu} \approx \frac{1 - \rho^2/3}{1 + \rho^2}$$

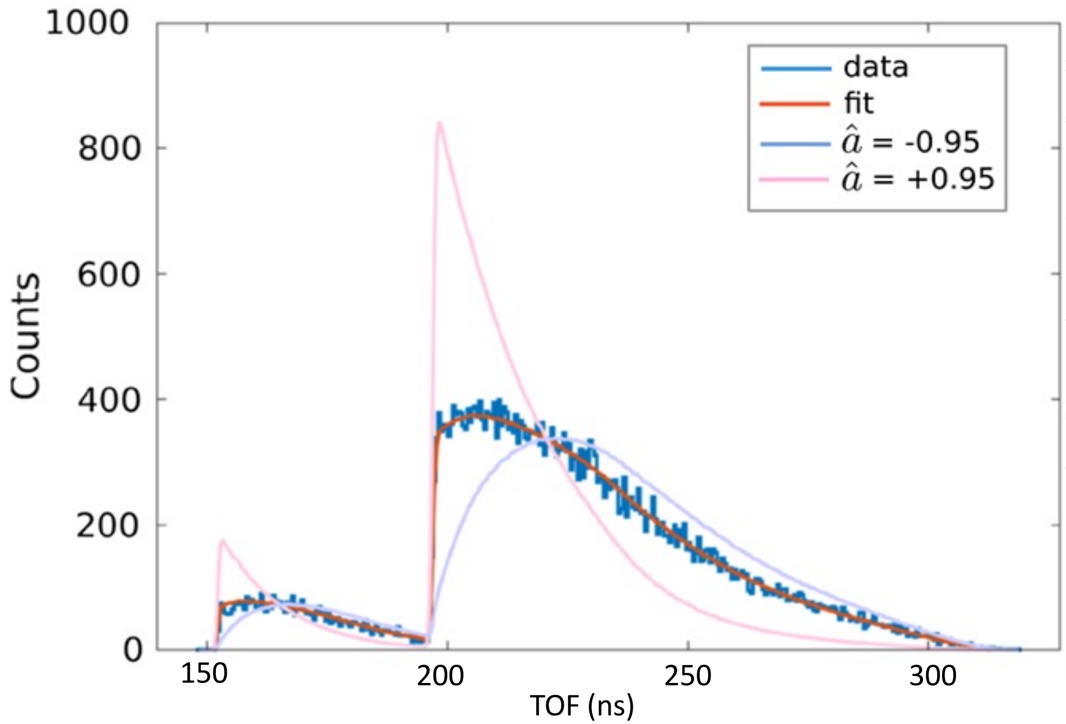
Strategy:

- Measure recoil spectrum
- Obtain $a_{\beta\nu}$
- Calculate ρ
- Obtain V_{ud}

Very simple right ?!

Recoil spectroscopy: Not a simple task!

Recoil measurements using optical and electromagnetic traps



Provides **indirect measurement** of the **longitudinal momentum** through **TOF** and position rather than the kinetic energy

Measurements reported @ **1%** level for ^{6}He, ^{21}Na and ^{38m}K

⇒ **Very difficult to go for higher precisions** due to technical limitations

Need for new solutions!

*P. Müller et al., PRL 129, 182502 (2022)

Novel technology for recoil spectroscopy

Meet the Superconducting tunneling junctions **STJ:**

Energy threshold of **1.5 eV**

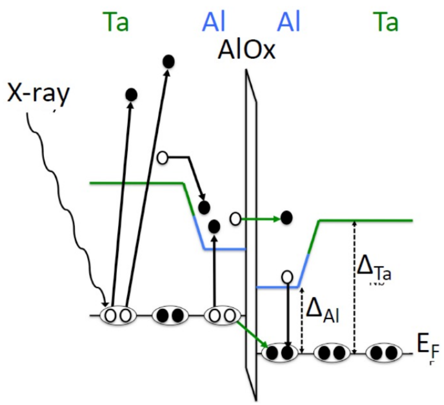
-> Perfect for recoil spectroscopy

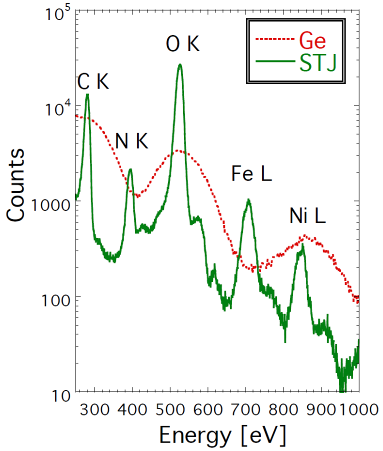
Superconducting energy gap Δ~1 meV (breaking Cooper pairs)

-> Resolution in the order of **1 eV** (significantly better than HPGe or Si(Li))

Count rate ~10^4 counts/sec per chip (significantly higher than TES)

-> Ideal for experiments with **radioactive ion beams** (RIB)



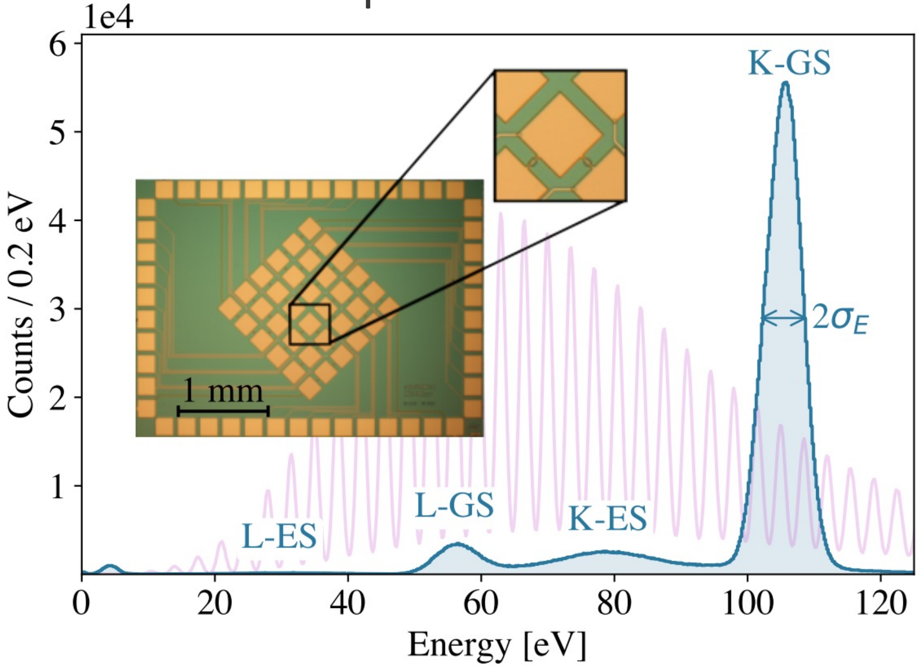


Novel technology for recoil spectroscopy

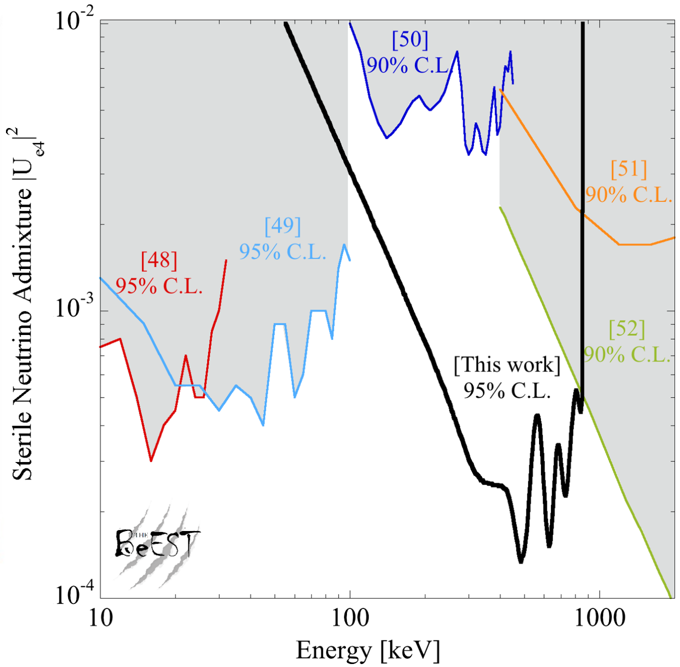
^{7}Be L/K capture ratio in Ta based **STJ**

Only long-lived radioactivity

Laser calibration:
linear response down to few eVs



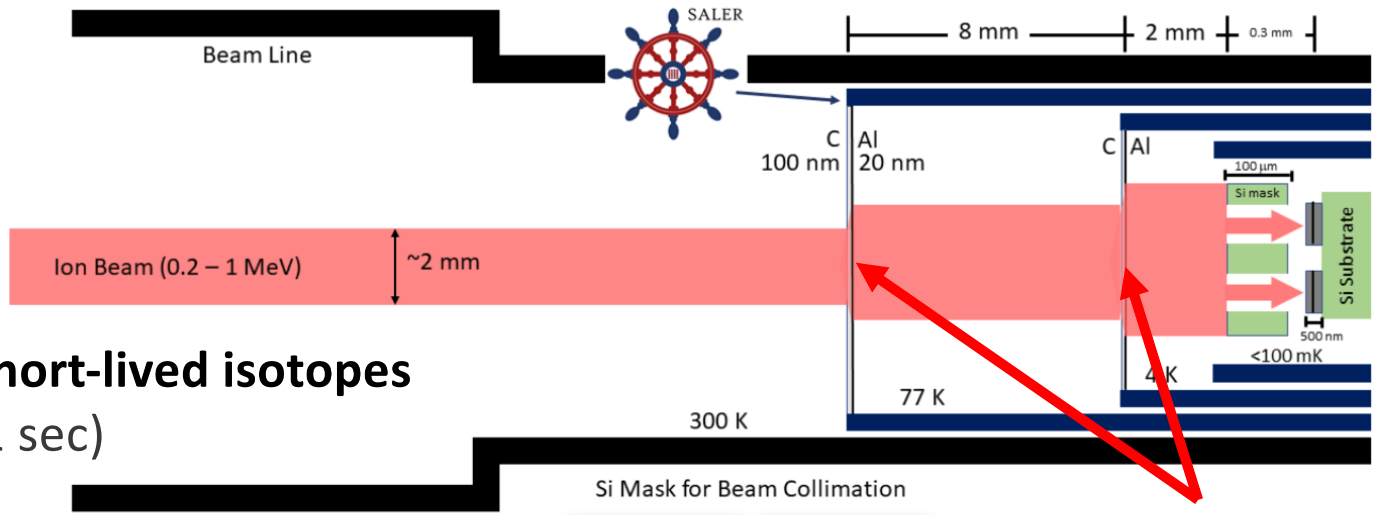
*J. Smolsky et al, accepted In review at **Nature**



*S. Fretwell et al., PRL 125, 032701 (2020)
*S. Friedrich et al., PRL 126, 021803 (2021)

SALER prototype experiment – Proof of principle at RIB facility

SALER

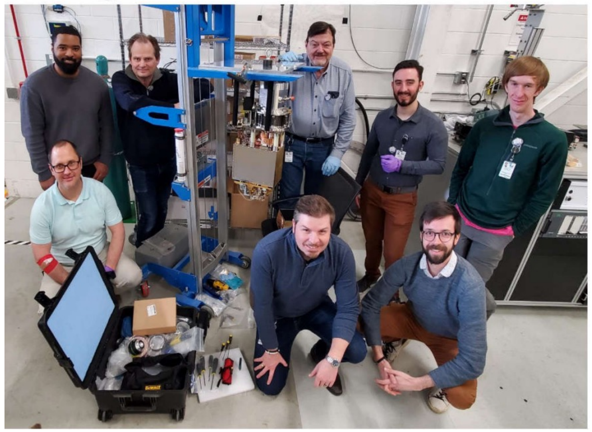


Same setup as BeEst!

BeEST -> SALER: **short-lived isotopes** ($t_{1/2} > 0.1$ sec)

Thermal windows:
limited isotopes and limited control of systematics

- Acceptance testing complete
- Commissioning started
- Will continue through 2024



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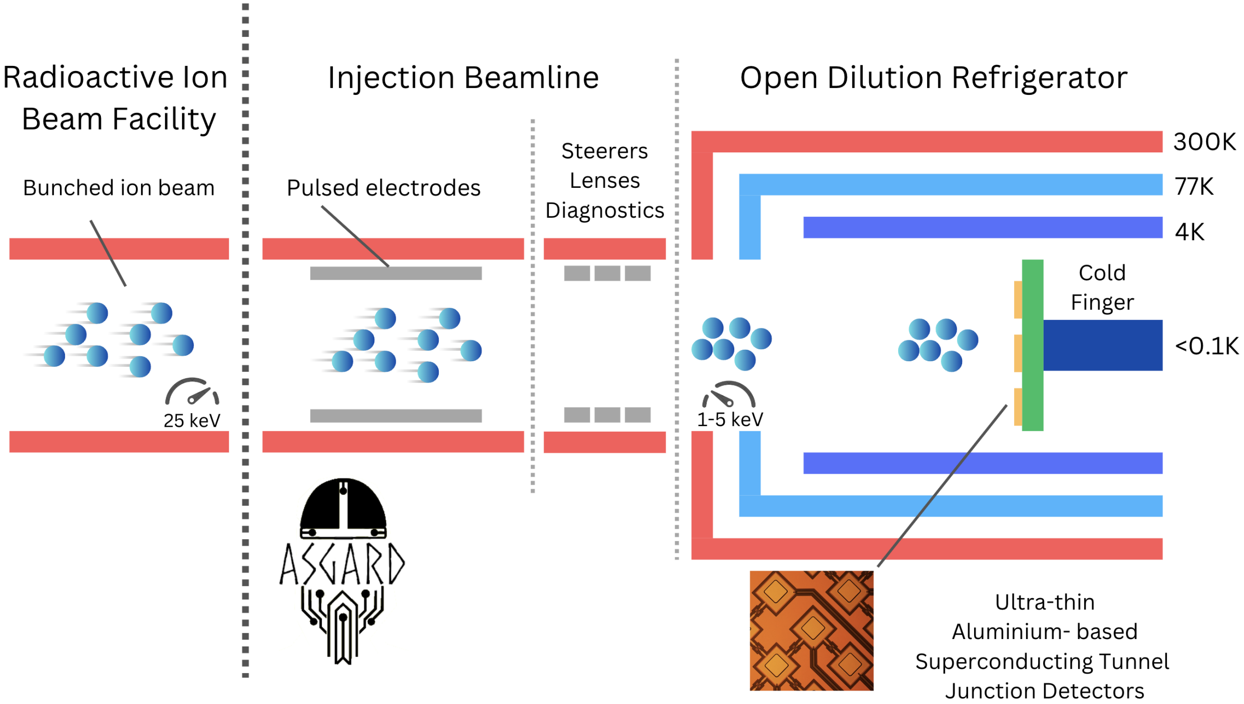
ASGARD project

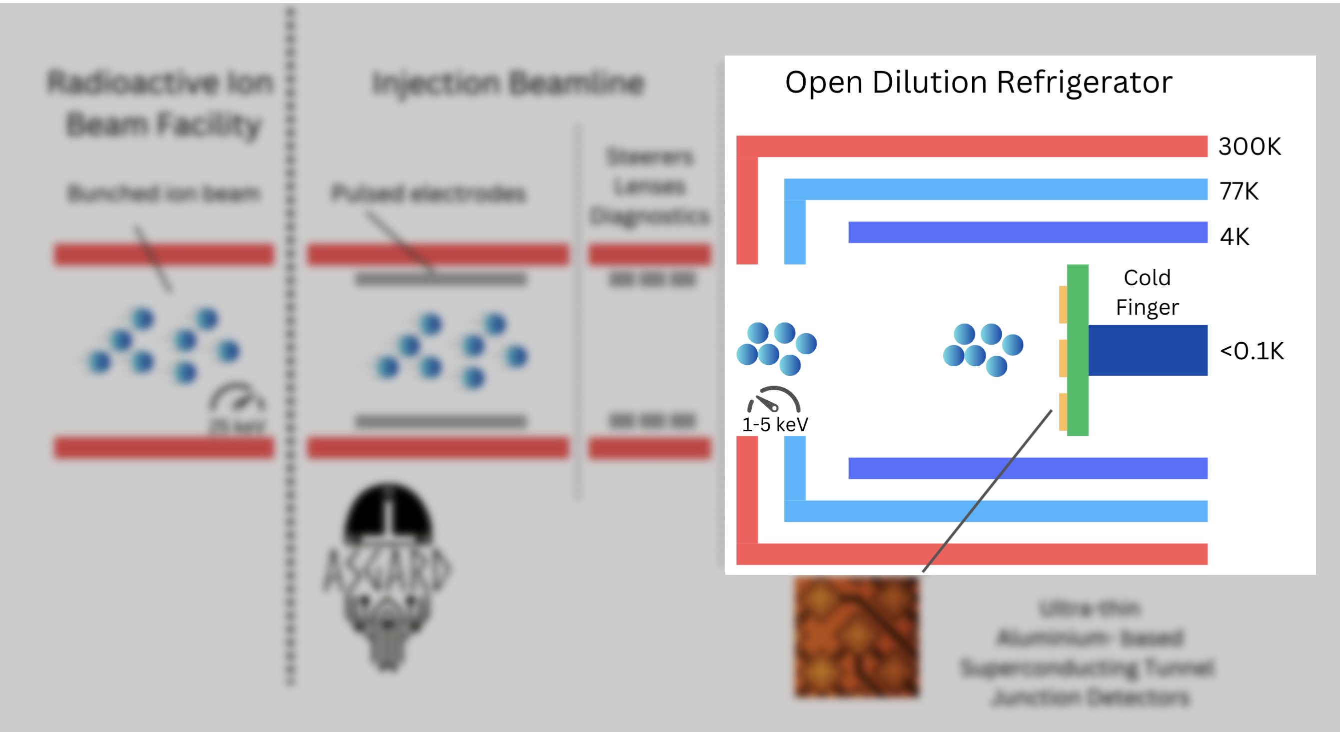
ASGARD: **A**luminium **S**uperconducting **G**rid **A**ssembly for **R**adiation **D**etection

Open cryogenic detection for **recoil spectroscopy** at **ISOL** facilities using **STJ**!

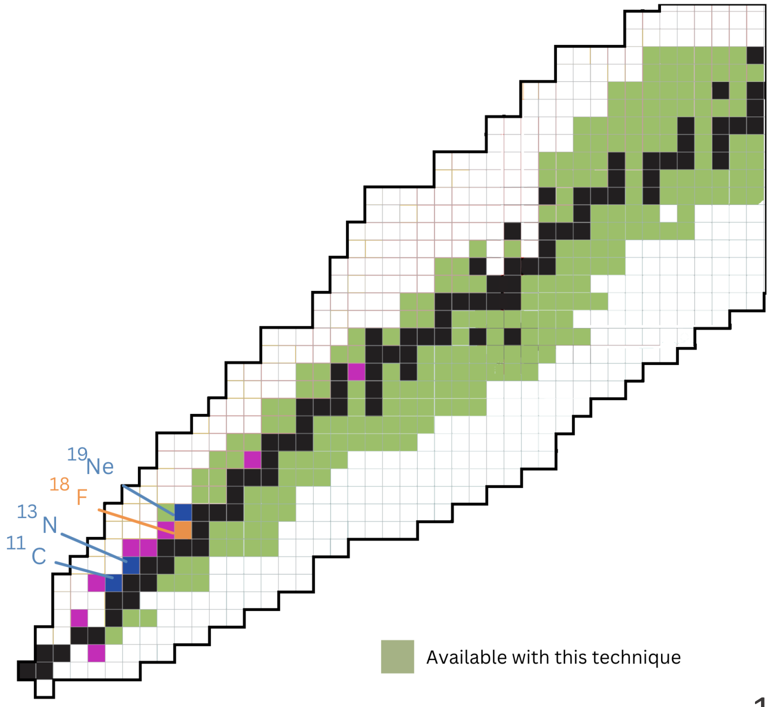


ASGARD project

Key aspect 1: Open dilution Fridge

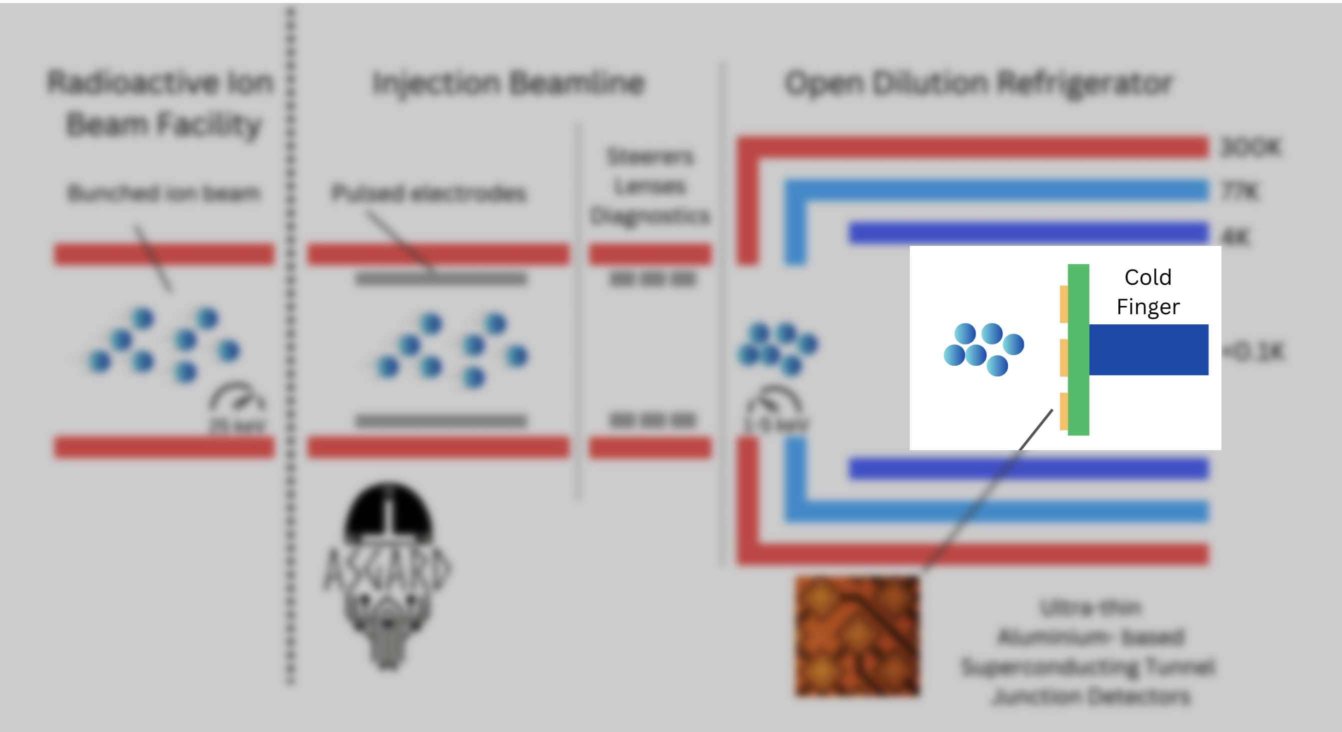


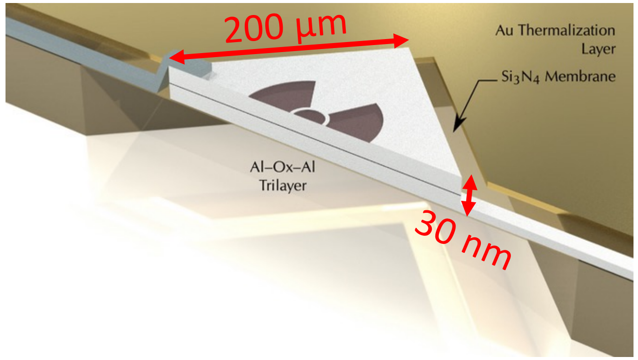
Upgrade from SALER:
Windowless Fridge



ASGARD project

Key aspect 2: Ultra-thin STJ



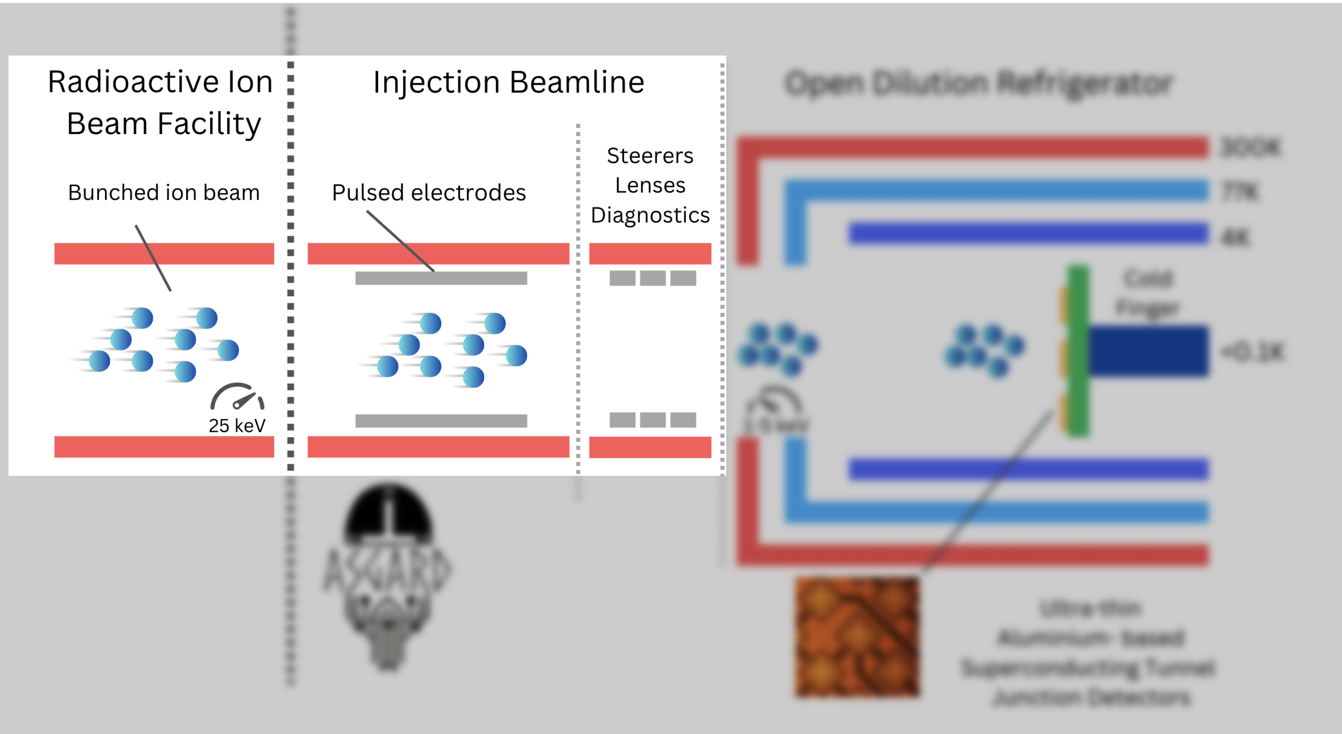


30 nm thick Al based chips (vs 300 nm Ta in SALER)

→ Reduce systematic uncertainties (**by 2 orders of magnitude!**)

ASGARD project

Key aspect 3: Precise and flexible implantation



Injection beamline:

Precise implantation energy control

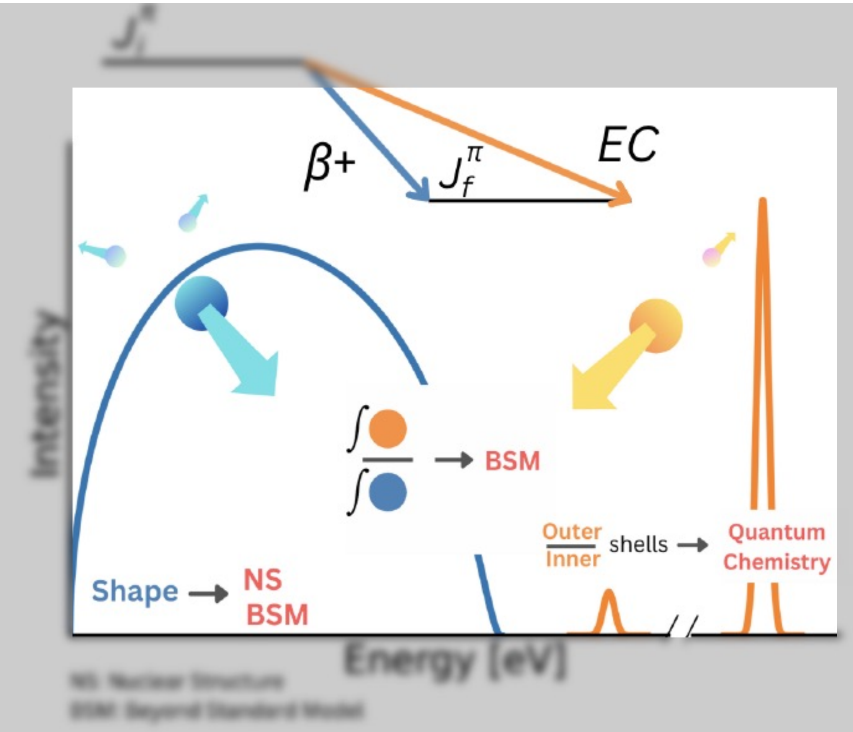
↓

Capability of very shallow implantation

↓

Better control over systematics

ASGARD: Novel BSM windows



ASGARD setup is also sensitive to EC peaks!

V_{ud} measurements: Recoil spectrum shape

Nuclear structure: Branching ratio studies across the nuclear chart

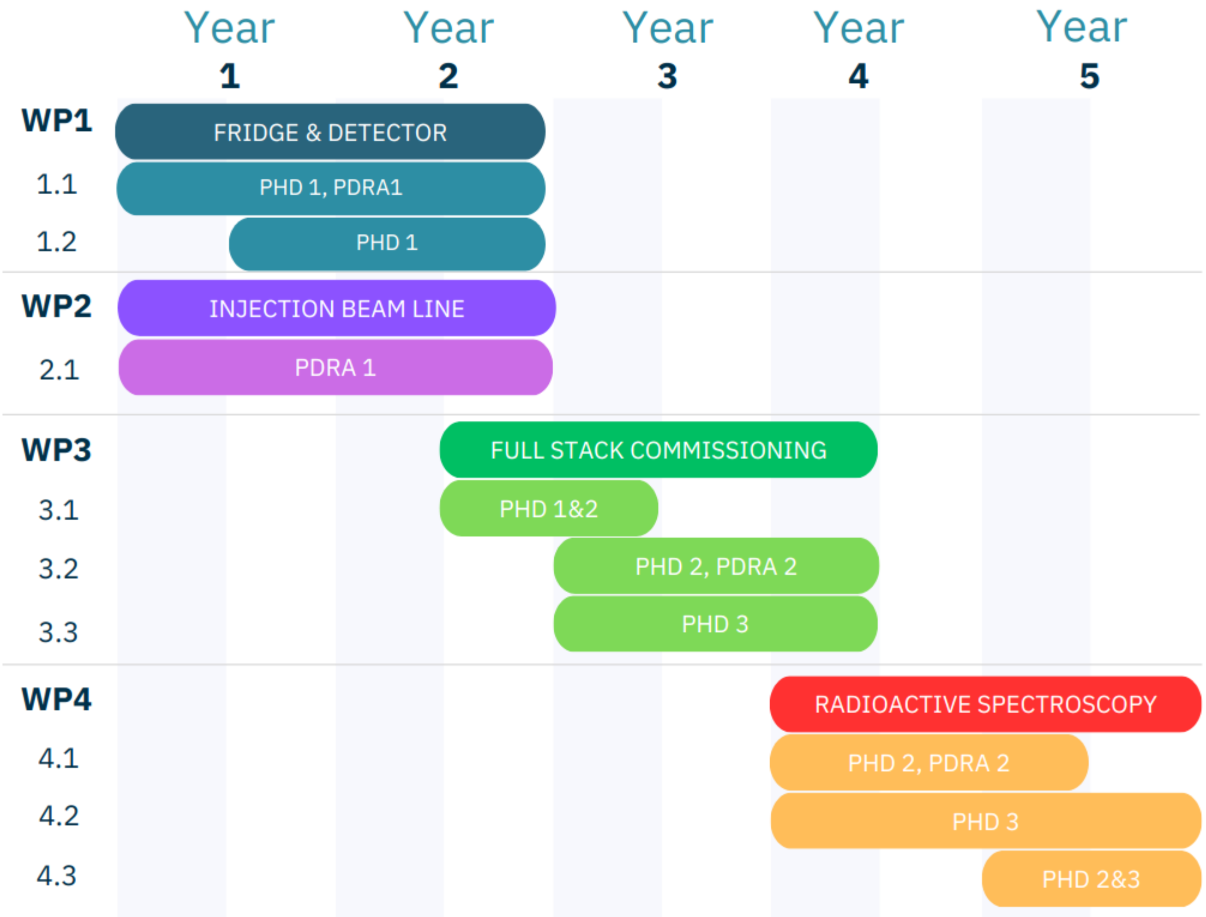
→ In contrast with traditional γ ray spectroscopy, BR can be losslessly reconstructed with total absorption recoil spectroscopy

Auger spectroscopy for medical purposes

Novel measurement for exotic currents:

Counting $\frac{\lambda_{EC}}{\lambda_{\beta+}}$ => Tensor and Scalar currents (through b_F)

ASGARD timeline



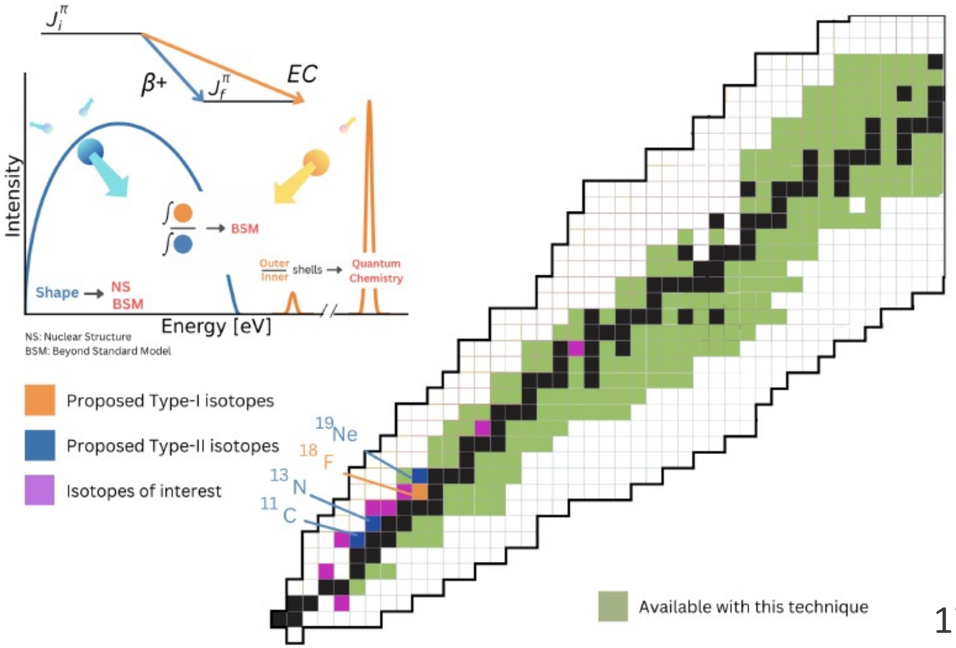
Conclusions and outlook

ASGARD can pioneer **precision** recoil spectroscopy for BSM measurements **across the nuclear chart**

Study of systematic effects on $\mathrm{V_{ud}}$ are conservatively below 0.01%, at least **two orders of magnitude better** than state of the art

ASGARD can open window into

- Novel exotic currents searches
- Precise branching ratio measurements
- Auger spectroscopy for medical applications




Thank you for your attention
LPC
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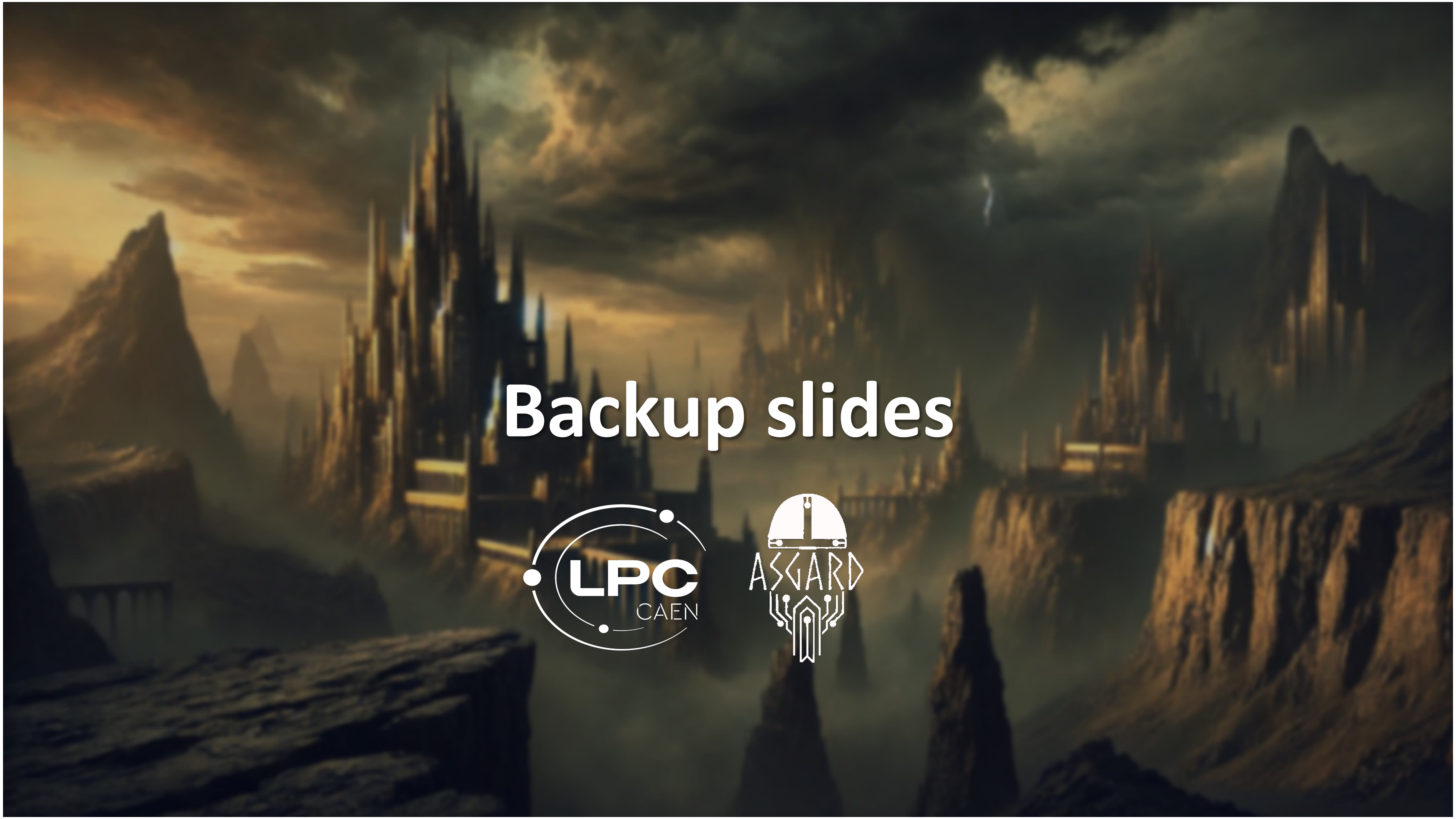
ASGARD

Backup slides



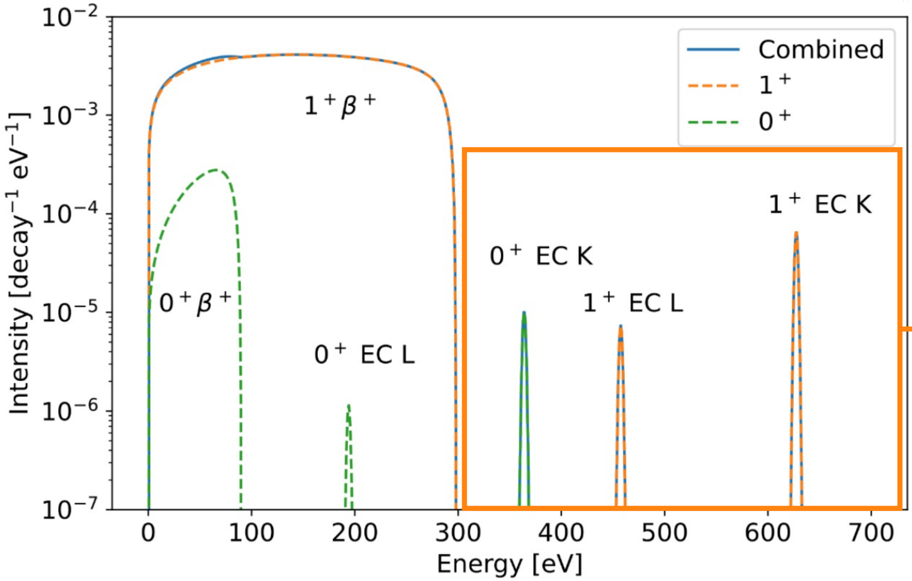
Branching ratio measurement: Novel method for V_{ud} input!

For superallowed $0^+ \rightarrow 0^+$ transitions: ^{10}C

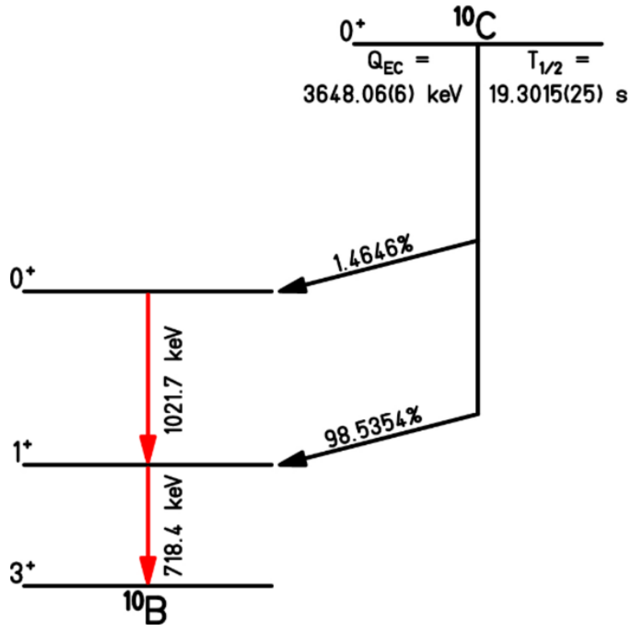
$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

$$t = \frac{t_{1/2}}{BR}(1+P_{EC}) \qquad V_{ud} = \frac{G_V}{G_F}$$

Branching ratio of the transition



Get BR from EC peak ratio!!



$E_\gamma = 2m_e$
Experimentally very difficult to measure BR!

ASGARD: Exotic currents

Lorentz invariance => 5 forms of currents:

$$H_\beta = g_F \sum_i (\bar{\psi}_p \mathcal{O}_i \psi_n)(\bar{\psi}_e \mathcal{O}_i (C_i + C_i' \gamma_5)\psi_\nu) + h.c.$$

Standard Model:

- $C_S = C_S' = C_T = C_T' = 0$

Fierz interference term: $b_F \propto C_{S,T} = 0$ Obtained from beta spectrum => very difficult

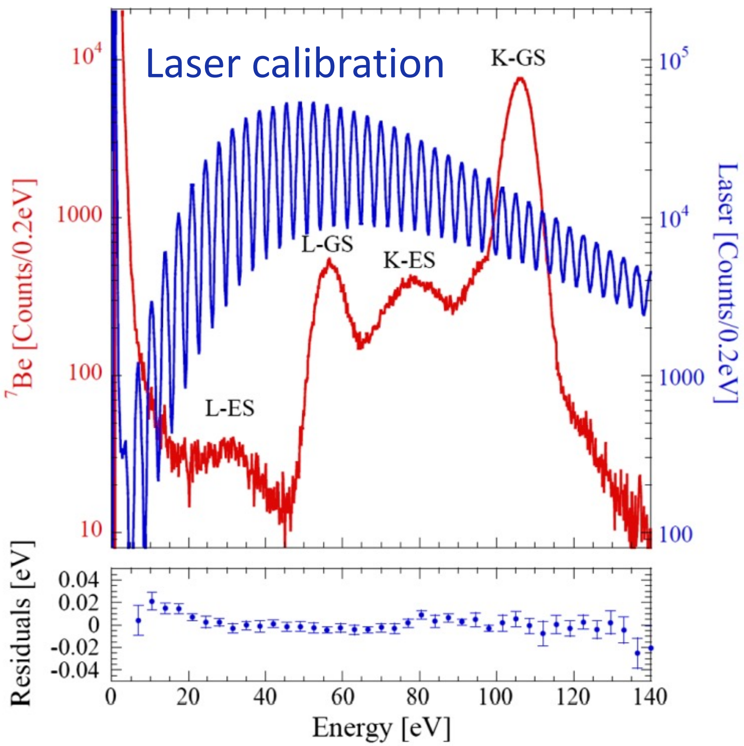
Instead: ratio measurement -> Counting EC/β^+ decays

$$\frac{\lambda_{EC}}{\lambda_{\beta^+}} = \sum_{x=K,L,\ldots} \frac{f_x}{f_{\beta^+}} \left[\frac{1 + b_F m_e/E_x}{1 - b_F m_e/\bar{E}}\right] (1 + 0.001 \times \delta_{theory})$$

Strongly reduced nuclear theory uncertainty

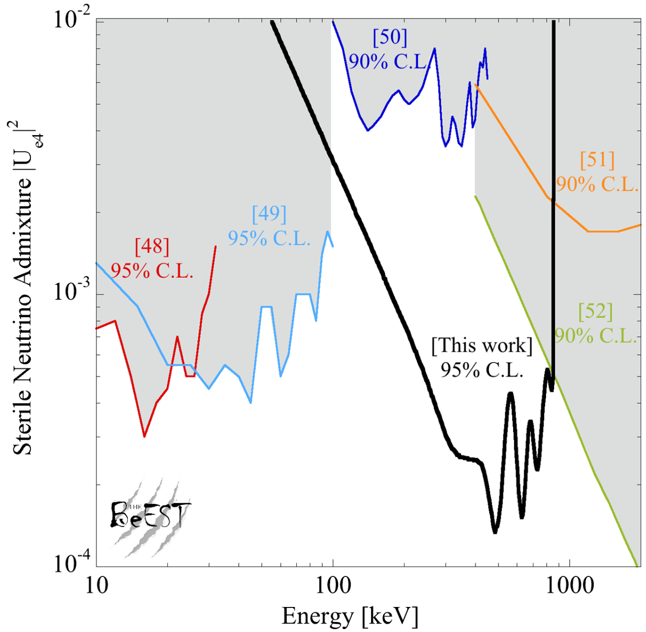
ONLY with direct recoil spectroscopy

Novel technology for recoil spectroscopy



^{7}Be L/K capture ratio in Ta based STJ

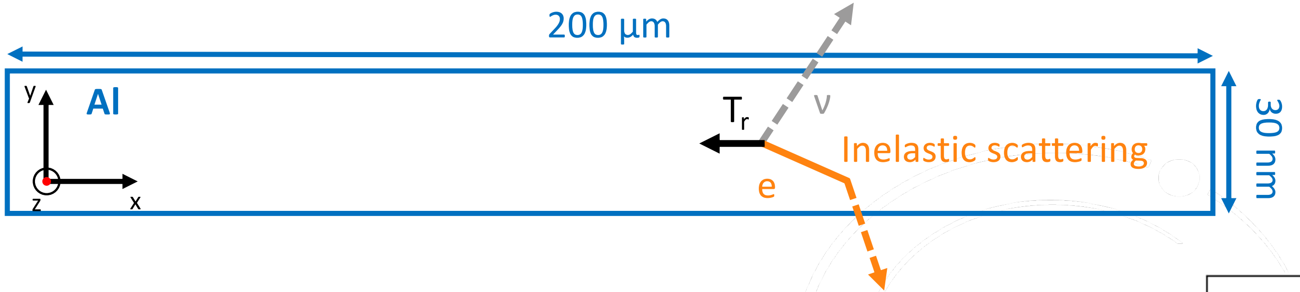
Only long-lived radioactivity



*J. Smolsky et al, arXiv:2404.03102, In review at **Nature**
*S. Fretwell et al., PRL 125, 032701 (2020)
*S. Friedrich et al., PRL 126, 021803 (2021)

Study of systematics

Betas interactions within the STJ:



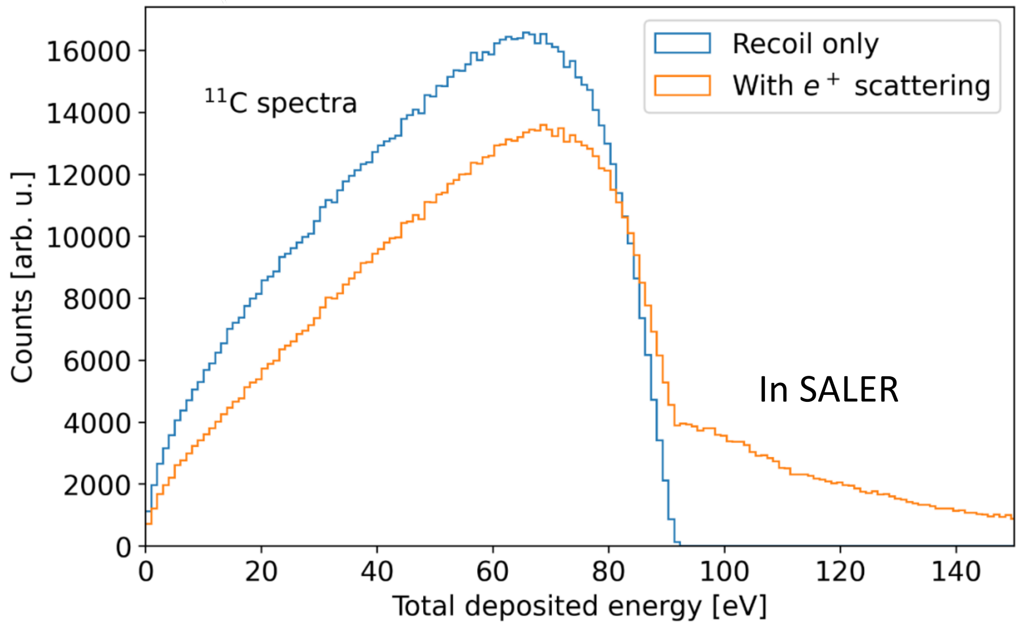
Beta decay energy deposited in STJ:

Full recoil energy deposition

+ Partial beta energy deposition

→ Distortion in the obtained recoil spectrum (influence on extracted $a_{\beta\nu}$)

→ Induced background beyond the recoil spectrum endpoint

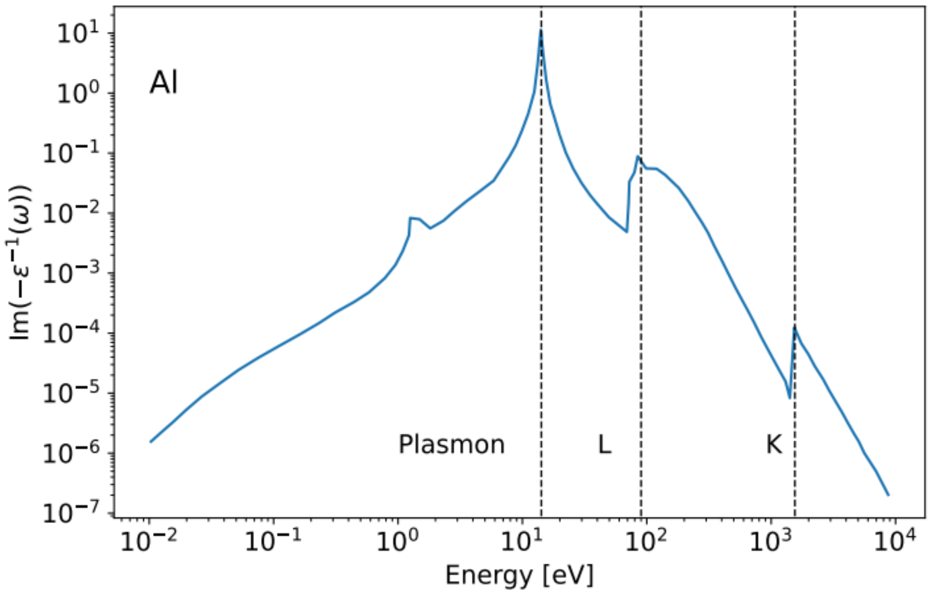


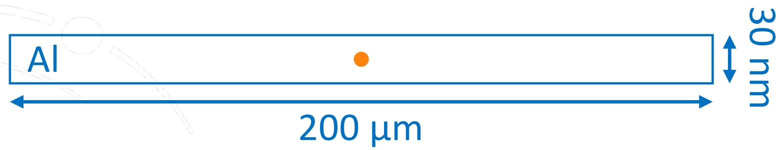
Study of systematics

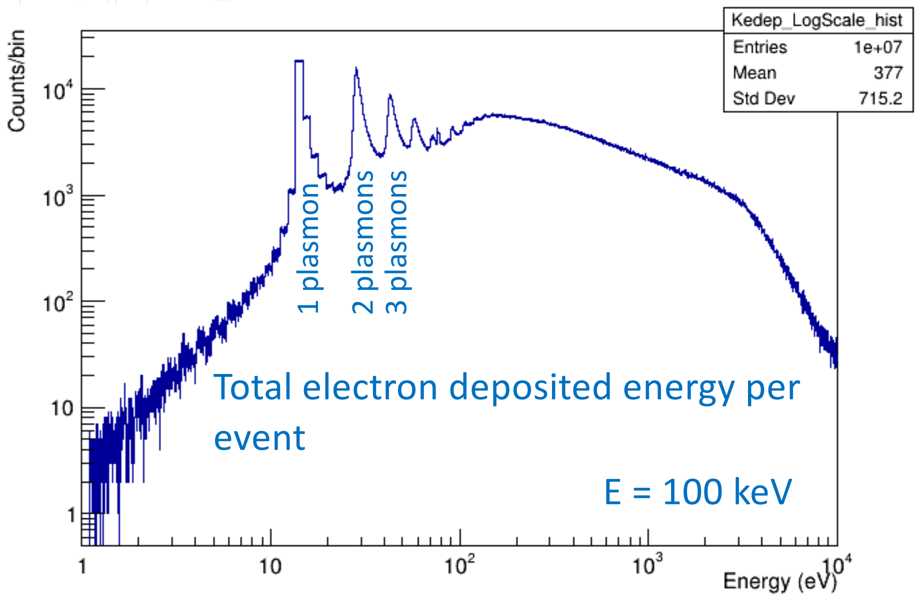
Geant4 standard low energy physics doesn't account for these interactions

G4Microelec package in Geant4 does for several materials including Al

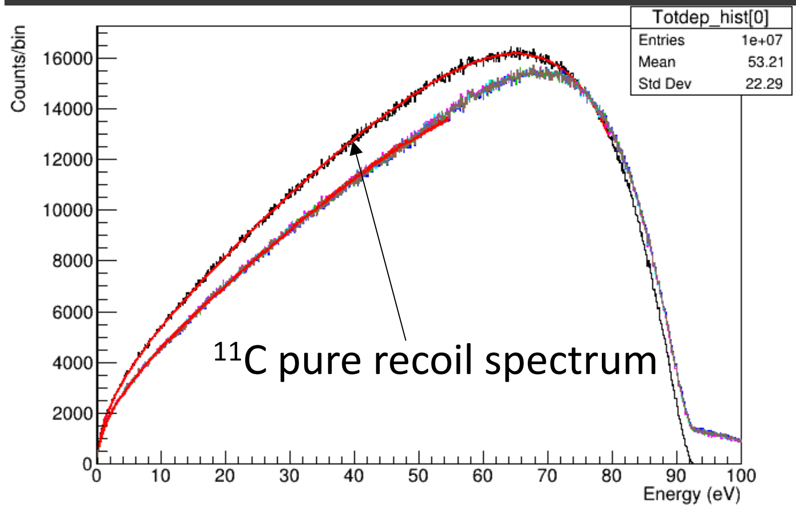
Energy loss function (ELF)

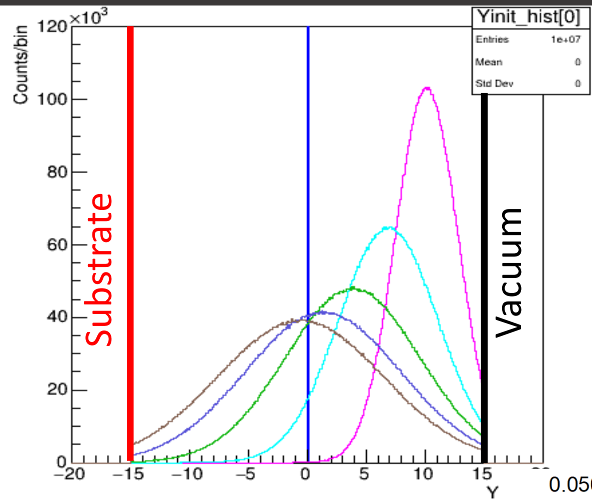




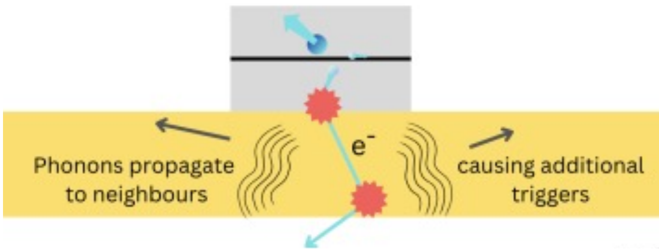


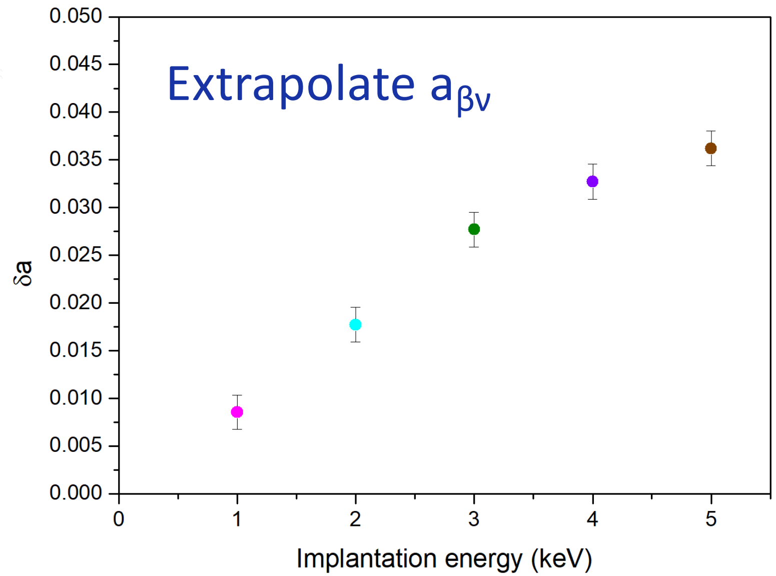
Study of systematics





Anti-coincidence events selection

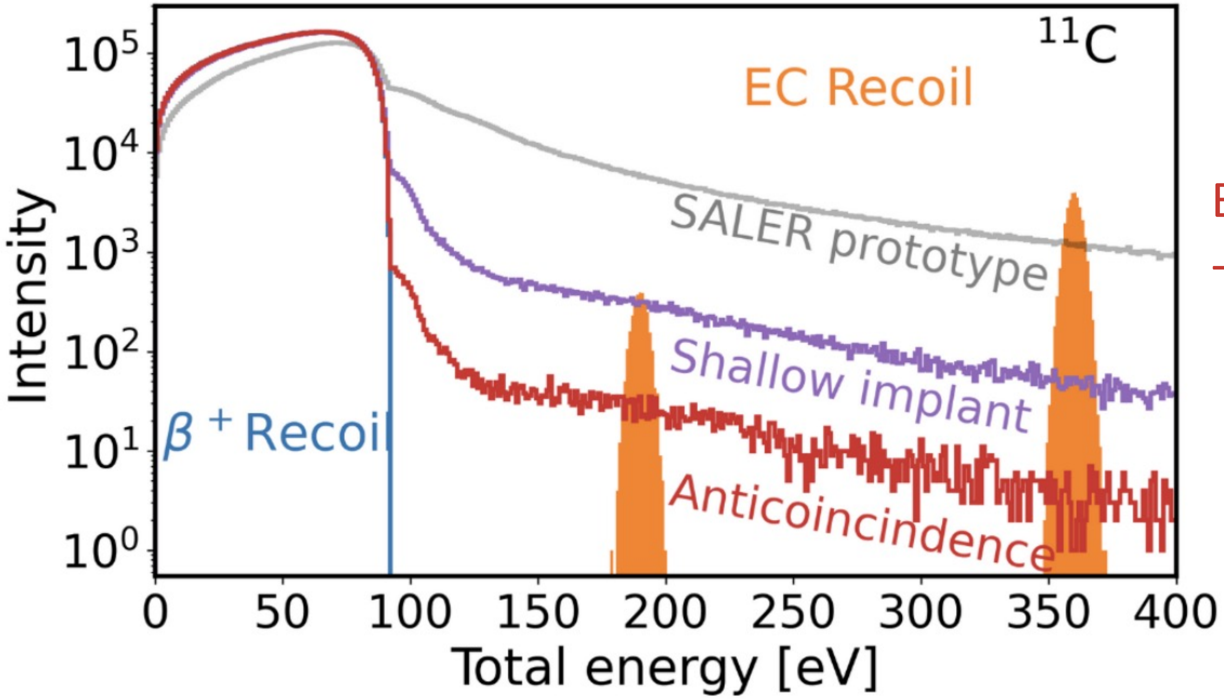




All electrons that goes into the substrate are excluded

Shallow implantation => reduction of electrons interactions inside the STJ

Study of systematics

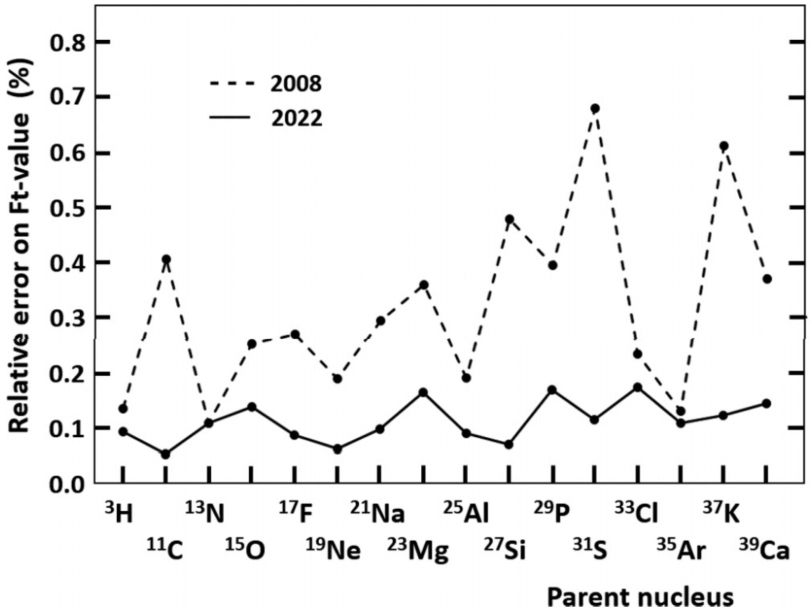


Bias in $a_{\beta\nu}$ ~0.1%
-> Bias in V_{ud} in the order 0.01%

3 orders of magnitude better than SALER!

Systematic uncertainties due to beta scattering inside the STJ is smaller than 0.01%

Uncertainties for mirror transitions



Parent nucleus	$f_V t$ (s)	f_A/f_V	δ'_R (%)	$\delta_C^V - \delta_{NS}^V$ (%)	$\mathcal{F}t^{\text{mirror}}$ (s)	$\delta(\mathcal{F}t^{\text{mirror}})$ %	$\rho = c$ [Eq. (12)]
n	1028.25 ± 0.66	1.0000	1.4902(2)[a]	N/A	1043.58 ± 0.67	0.06	+2.21086(118)
^{3}H	1113.0 ± 1.0	1.0003	1.767(1)	0.16(2)	1130.9 ± 1.0	0.09	−2.1053(14)[b]
^{11}C	3893.4 ± 1.4	0.9992	1.660(4)	1.04(3)	3916.9 ± 1.9	0.05	−0.75442(79)
^{13}N	4621.3 ± 4.7	0.9980	1.635(6)	0.33(3)	4681.3 ± 4.9	0.11	−0.5596(14)
^{15}O	4344.3 ± 5.7	0.9964	1.555(8)	0.22(3)	4402.3 ± 5.9	0.13	+0.6302(16)
^{17}F	2269.5 ± 1.7	1.0020	1.587(10)	0.62(3)	2291.2 ± 1.9	0.08	+1.2955(11)
^{19}Ne	1704.34 ± 0.63	1.0011	1.533(12)	0.52(4)	1721.5 ± 1.0	0.06	−1.60203(92)