# Precision $\beta$ spectroscopy & Beyond the Standard Model

Leendert Hayen

MORA workshop, March 3 2022

NC State & TUNL, USA

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Theory status: Radiative corrections

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# Introduction: Weak interaction & CKM matrix

Cabibbo-Kobayashi-Maskawa matrix currently exciting topic

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

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Unitarity requires

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

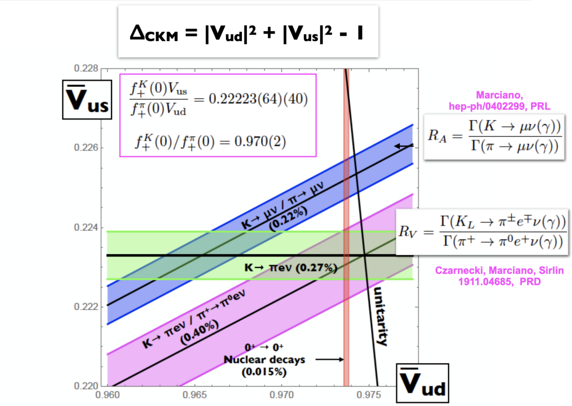
(nuclear) $\beta$ decay, meson decay ($\pi$, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

# CKM unitarity: Current status

Signs of non-unitarity at few $\sigma$ level...

**Disagreement** between $Kl2$ and $Kl3$ $|V_{us}|$ ‘Cabibbo angle anomaly’



$$\Delta_{\mathrm{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1$$

$$\frac{f_+^K(0) V_{us}}{f_+^\pi(0) V_{ud}} = 0.22223(64)(40)$$

$$f_+^K(0)/f_+^\pi(0) = 0.970(2)$$

Marciano, hep-ph/0402299, PRL

$$R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

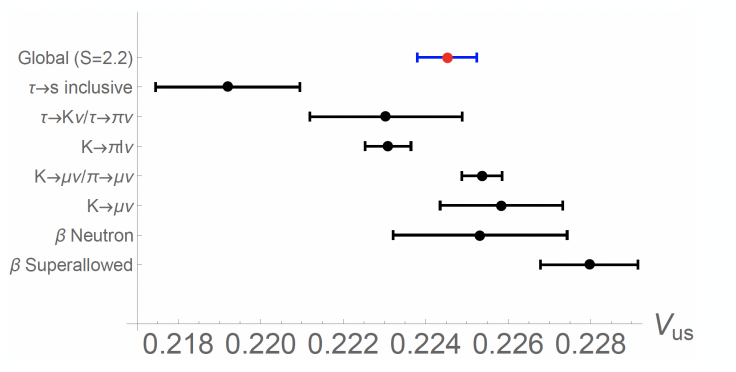
$$R_V = \frac{\Gamma(K_L \to \pi^\pm e^\mp \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))}$$

Czarnecki, Marciano, Sirlin 1911.04685, PRD

Early signs of new physics? Lattice QCD artifacts?

# CKM unitarity: Cabibbo Angle Anomaly

Things get even more interesting… (Falkowski CKM2021)



$\tau$ decays now precise enough to play a role

Cirigliano et al., 2112.02087

# Exotic contributions

What would electroweak Beyond Standard Model look like?

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SM has $V$-$A$ structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu[1-(1-2\epsilon_R)\gamma^5]d + \epsilon_S\, \bar{e}\nu_L \cdot \bar{u}d - \epsilon_P\, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T\, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5)d \Big\} + \text{h.c.},$$

at the quark level (only $\nu_L$)

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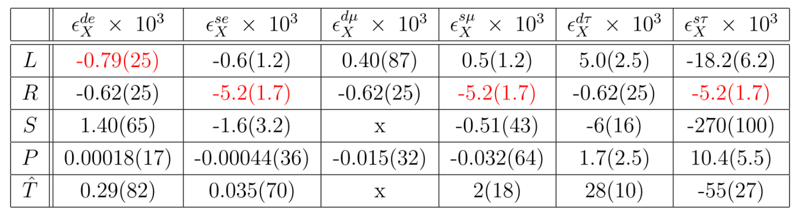
All $\epsilon_i$ are proportional to $(M_W/\Lambda_{BSM})^2$, change kinematics

$\epsilon_i \lesssim 10^{-4} \rightarrow \Lambda_{BSM} \gtrsim 15$ TeV assuming natural couplings

# Exotic contributions

Assume it's single origin new physics



| | $\epsilon_X^{de} \times 10^3$ | $\epsilon_X^{se} \times 10^3$ | $\epsilon_X^{d\mu} \times 10^3$ | $\epsilon_X^{s\mu} \times 10^3$ | $\epsilon_X^{d\tau} \times 10^3$ | $\epsilon_X^{s\tau} \times 10^3$ |
|---|---|---|---|---|---|---|
| $L$ | -0.79(25) | -0.6(1.2) | 0.40(87) | 0.5(1.2) | 5.0(2.5) | -18.2(6.2) |
| $R$ | -0.62(25) | -5.2(1.7) | -0.62(25) | -5.2(1.7) | -0.62(25) | -5.2(1.7) |
| $S$ | 1.40(65) | -1.6(3.2) | x | -0.51(43) | -6(16) | -270(100) |
| $P$ | 0.00018(17) | -0.00044(36) | -0.015(32) | -0.032(64) | 1.7(2.5) | 10.4(5.5) |
| $\hat{T}$ | 0.29(82) | 0.035(70) | x | 2(18) | 28(10) | -55(27) |

Cirigliano et al., 2112.02087

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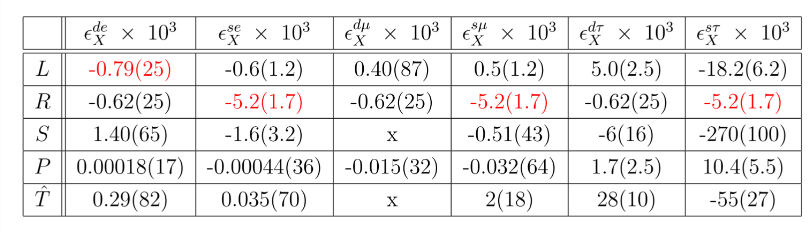

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Takeaways assuming Standard Model physics:

- Most precise $V_{ud}$ & $V_{us}$ not consistent with unitarity
- Significant internal inconsistencies within $V_{us}$
- Taken at face value $\sim 3\sigma$ for new physics

# BSM from $\beta$ spectroscopy

How is $\beta$ spectroscopy relevant? Sensitivity from Fierz

$$\Gamma \propto 1+b_F\frac{m_e}{E}+\boldsymbol{J}\left[A\hat{\boldsymbol{p}}_e+\ldots\right]; \qquad b_F=\frac{2}{1+\rho^2}\left(\frac{g_S\epsilon_S}{\tilde{g}_V}+\rho^2\frac{4g_T\epsilon_T}{\tilde{g}_A}\right)$$

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- Unified description at $\mathcal{O}(0.01\%)$
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Not easy, but **recent progress**

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# General framework

Large number of effects determine $f_i$, but separated into

- Dynamics: Nuclear structure, Coulomb corrections, ...
- Kinematics: Real photon emission (bremsstrahlung), atomic excitations

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- Dynamics: Nuclear structure, Coulomb corrections, ...
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Grosso modo, dynamics depends on nucleus, kinematics depends on expt geometry and detection scheme

Typically some overlap between the two

LH, A Young, 2009.11364

# Form factors

Non-perturbative many-body physics is *hard*, but symmetries are still obeyed

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Non-perturbative many-body physics is *hard*, but symmetries are still obeyed

Conservation of angular momentum

→ spherical harmonic expansion

→ treat initial and final states as ‘elementary’ particles and stuff all unknowns into form factors

$$F_{KL}(q^2)$$

with $q = p_f - p_i$ and continue analysis

# Theory status: Unified approach

Hard work from Behrens-Bühring, Holstein, ...

| Item | Effect | Formula | Magnitude |
|---|---|---|---|
| 1 | Phase space factor | $pW(W_0 - W)^2$ | Unity or larger |
| 2 | Traditional Fermi function | $F_0$ | |
| 3 | Finite size of the nucleus | $L_0$ | $10^{-1}$-$10^{-2}$ |
| 4 | Radiative corrections | $R$ | |
| 5 | Shape factor | $C$ | |
| 6 | Atomic exchange | $X$ | |
| 7 | Atomic mismatch | $r$ | |

LH et al., RMP 90 (2018) 015008

# Analytical $\beta$ spectrum shape

| Item | Effect | Formula | Magnitude |
|---|---|---|---|
| 8 | Atomic screening | $S$ | $10^{-3}$-$10^{-4}$ |
| 9 | Shake-up | See 7 | |
| 10 | Shake-off | See 7 | |
| 11 | Isovector correction | $C_I$ | |
| 12 | Recoil Coulomb correction | $Q$ | |
| 13 | Diffuse nuclear surface | $U$ | |
| 14 | Nuclear deformation | $D_{\mathrm{FS}}$ | |
| 15 | Recoiling nucleus | $R_N$ | |
| 16 | Molecular screening | $\Delta S_{\mathrm{Mol}}$ | |
| 17 | Molecular exchange | Case by case | |

Pretty well understood

LH et al., RMP 90 (2018) 015008

# Theory status: Quantifiable uncertainties

To first order have to deal with 3 extra form factors

$$C(Z,W) \sim 1 \pm \frac{4}{3}\frac{W}{M_N}\frac{\boldsymbol{b}}{Ac} \pm \frac{4\sqrt{2}}{21}\alpha Z W R \boldsymbol{\Lambda} - \frac{1}{3WMc}(\pm 2\boldsymbol{b} + \boldsymbol{d})$$

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Fill in typical numbers to obtain shape factor corrections

| Matrix element | Name | Slope (% $\mathrm{MeV}^{-1}$) |
|---|---|---|
| $b$ | Weak Magnetism | 0.5 |
| $d$ | Induced Tensor | 0.1 |
| $\Lambda$ | Induced Pseudoscalar | 0.1 |

Relative effects larger for cancellations in correlations

# Quantifiable uncertainties: mirror decays?

Traditional shell model: ~~Quantifiable uncertainties~~

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But mirror nuclei are very useful probe ($^3$He & $^3$H, $^{19}$Ne & $^{19}$F, …
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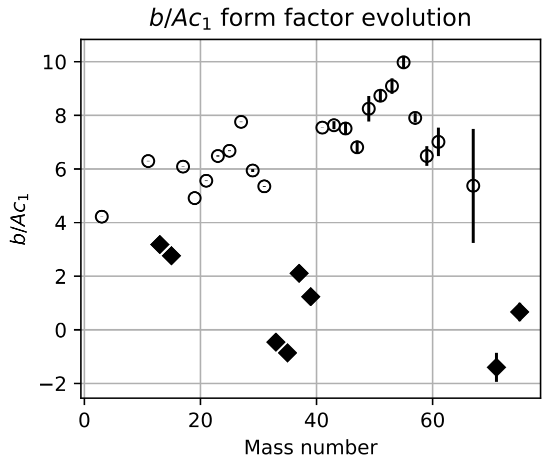
Weak magnetism known from symmetry

$$b_{CVC} = \pm A\sqrt{\frac{J+1}{J}}(\mu_f - \mu_i) \longleftrightarrow b_{SM} = A(g_M\mathcal{M}_{GT} + g_V\mathcal{M}_L)$$

where $\mu$ are magnetic moments, $\mathcal{M}_i$ matrix elements

# Weak magnetism

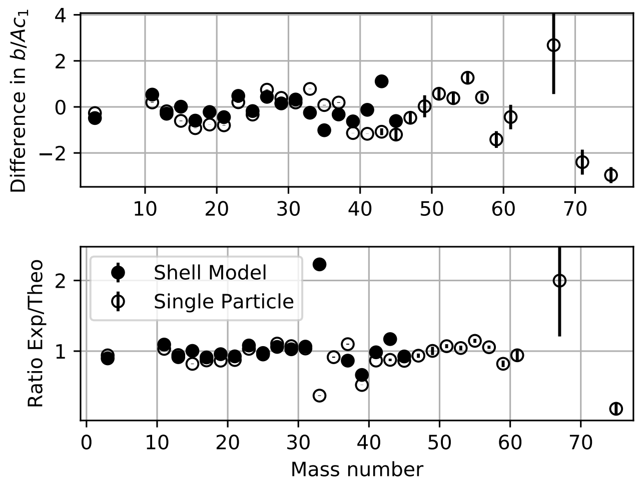
Major compilation effort (Severijns, LH, et al., 2109.08895)



Just part of data set; open: $l + 1/2$, closed: $l - 1/2$

# Weak magnetism

How does shell model perform right now?



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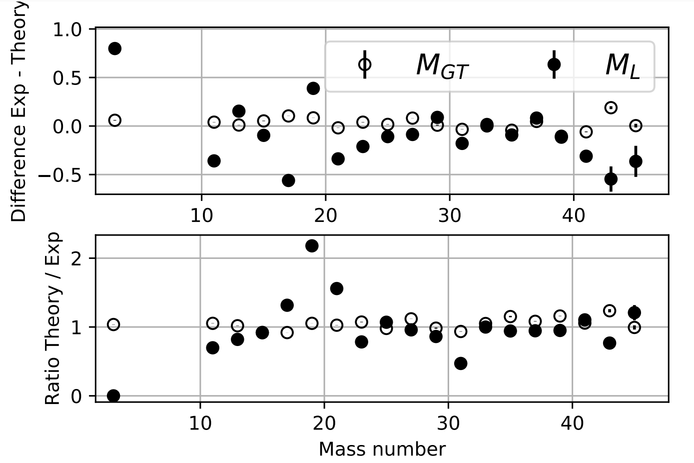
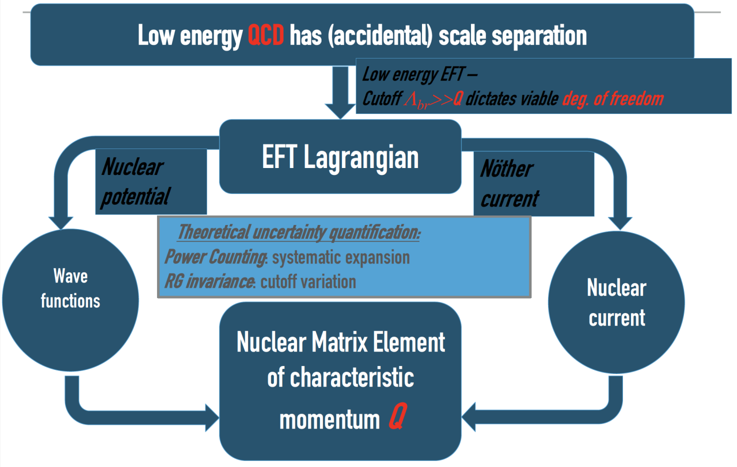


‘Easy’ matrix elements only accurate to 10-20%

# Quantifiable uncertainty: effective field theory

Modern approaches use (chiral) effective field theory



Low energy QCD has (accidental) scale separation

*Low energy EFT –*
*Cutoff $\Lambda_{b\gamma}$>>Q dictates viable deg. of freedom*

EFT Lagrangian

*Nuclear potential*

*Nöther current*

*Theoretical uncertainty quantification:*
*Power Counting*: systematic expansion
*RG invariance*: cutoff variation

Wave functions

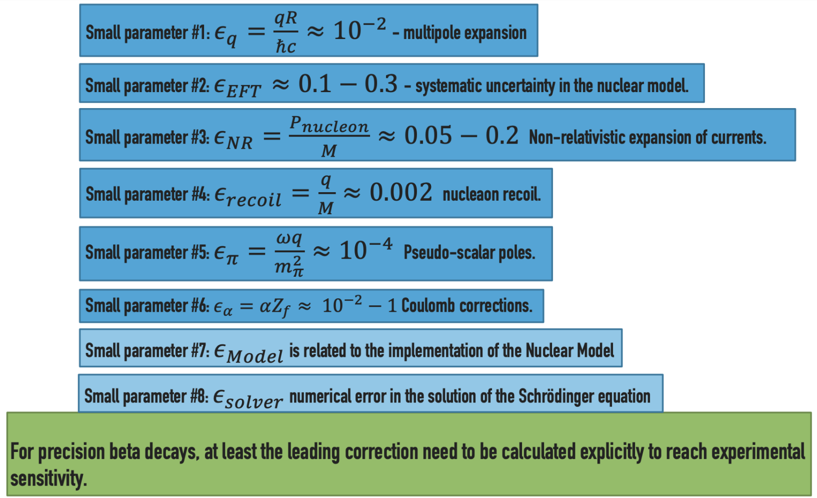
Nuclear current

Nuclear Matrix Element of characteristic momentum *Q*

Slide by Doron Gazit

# Quantifiable uncertainty: expansion parameters

Can define a number of small parameters for expansion



**Small parameter #1:** $\epsilon_q = \frac{qR}{\hbar c} \approx 10^{-2}$ **- multipole expansion**

**Small parameter #2:** $\epsilon_{EFT} \approx 0.1 - 0.3$ **- systematic uncertainty in the nuclear model.**

**Small parameter #3:** $\epsilon_{NR} = \frac{P_{nucleon}}{M} \approx 0.05 - 0.2$ **Non-relativistic expansion of currents.**

**Small parameter #4:** $\epsilon_{recoil} = \frac{q}{M} \approx 0.002$ **nucleaon recoil.**

**Small parameter #5:** $\epsilon_{\pi} = \frac{\omega q}{m_{\pi}^2} \approx 10^{-4}$ **Pseudo-scalar poles.**

**Small parameter #6:** $\epsilon_{\alpha} = \alpha Z_f \approx 10^{-2} - 1$ **Coulomb corrections.**

**Small parameter #7:** $\epsilon_{Model}$ **is related to the implementation of the Nuclear Model**

**Small parameter #8:** $\epsilon_{solver}$ **numerical error in the solution of the Schrödinger equation**

**For precision beta decays, at least the leading correction need to be calculated explicitly to reach experimental sensitivity.**

Slide by Doron Gazit

# Quantifiable uncertainty: Effective field theory

- EFT expansion parameter $\epsilon_{EFT} \propto \frac{\max(q,Q,\dots)}{M_{br}} \approx \frac{1}{10} - \frac{1}{3}$:
  - Breakdown scale in chiral EFT is about $4\pi f_\pi \approx 1$ GeV/c
  - Order by order expansion of the currents: $J_{SM} = J^{LO} + \epsilon_{EFT} \cdot J^{NLO} + \epsilon_{EFT}^{a} J^{N^aLO}$ *with* $a > 1$
  - LO – single nucleon current
  - NLO – corrections to single nucleon currents
  - NLO or higher orders include 2-body currents (magnetic – $NLO$, weak axial –$N^{7/4\div 3}LO$)

Pavon Valderama, Phillips; PRL (2015)

# Quantifiable uncertainty: Effective field theory

Form factor decomposition remains **exactly same**

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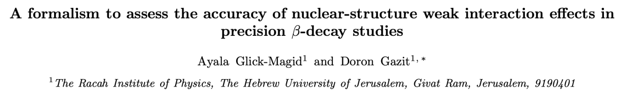
Form factor decomposition remains **exactly same**

To get predictive results, substitute FF for NME at $\mathrm{N}^X\mathrm{LO}$

Strong push by **Jerusalem group**

Beta spectrum of unique first-forbidden decays as a novel test for fundamental symmetries

Ayala Glick-Magid[a], Yonatan Mishnayot[a,b,c], Ish Mukul[b], Michael Hass[b], Sergey Vaintraub[c], Guy Ron[a], Doron Gazit[a,*]

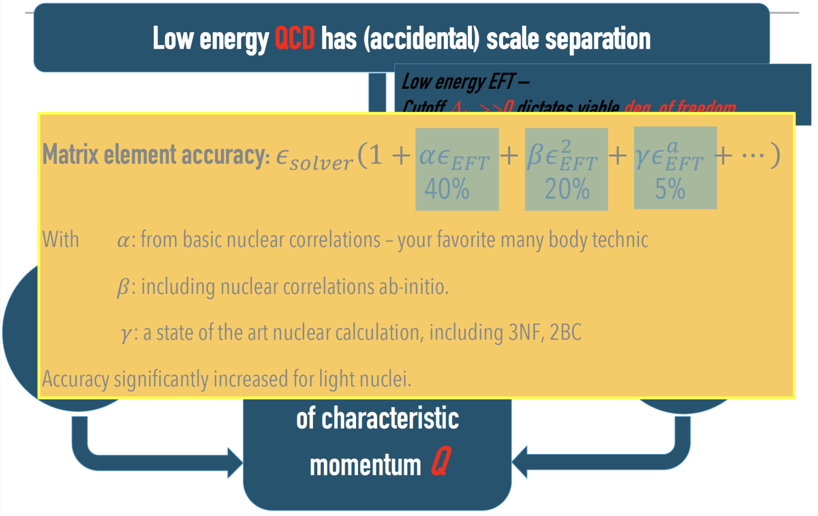


**A formalism to assess the accuracy of nuclear-structure weak interaction effects in precision $\beta$-decay studies**

Ayala Glick-Magid[1] and Doron Gazit[1,*]

[1] *The Racah Institute of Physics, The Hebrew University of Jerusalem, Givat Ram, Jerusalem, 9190401*

# Effective field theory



**Low energy QCD has (accidental) scale separation**

*Low energy EFT –*

*Cutoff $\Lambda_\chi$ >>Q dictates viable deg. of freedom*

**Matrix element accuracy:** $\epsilon_{solver}\left(1+\underset{40\%}{\alpha\epsilon_{EFT}}+\underset{20\%}{\beta\epsilon_{EFT}^2}+\underset{5\%}{\gamma\epsilon_{EFT}^a}+\cdots\right)$

With $\alpha$: from basic nuclear correlations – your favorite many body technic

$\beta$: including nuclear correlations ab-initio.

$\gamma$: a state of the art nuclear calculation, including 3NF, 2BC

Accuracy significantly increased for light nuclei.

**of characteristic momentum $Q$**

Slide by Doron Gazit

# Example: Ab initio $^{6}$He study

Gamow-Teller $\beta$ decay of $^{6}$He experimentally very popular, part of isotriplet

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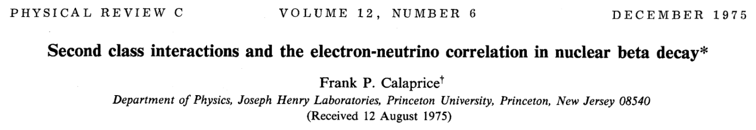


PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

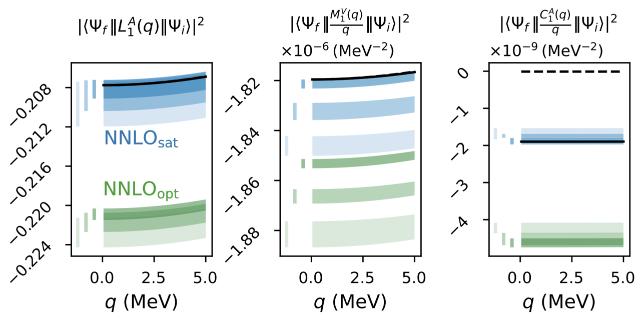
**Second class interactions and the electron-neutrino correlation in nuclear beta decay***

Frank P. Calaprice[†]
*Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540*
(Received 12 August 1975)

Theory: $d = 2.4(?) \leftrightarrow$ Experiment $d = 33(25) \ldots$

# Example: Ab initio $^6$He study

Recent work led by Jerusalem group (2107.10212)



using no-core shell model

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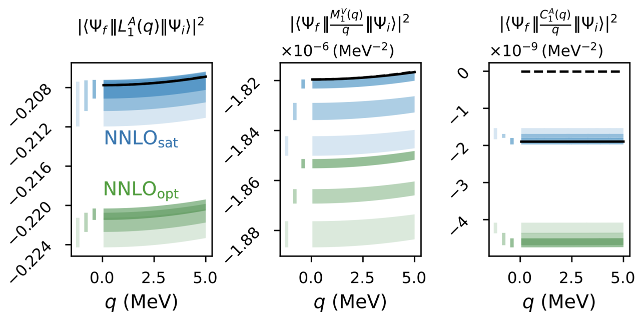
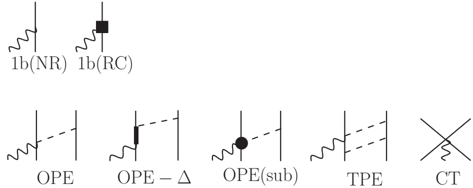


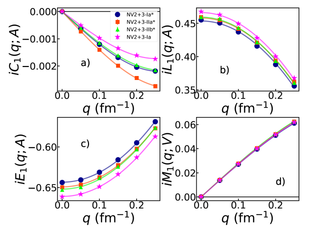
using no-core shell model

Promising, but **but no 2 body currents**

# Example: Ab initio $^6$He study

Variational & Green's function Monte Carlo study **with 2 body currents** (with King, Pastore, et al.)

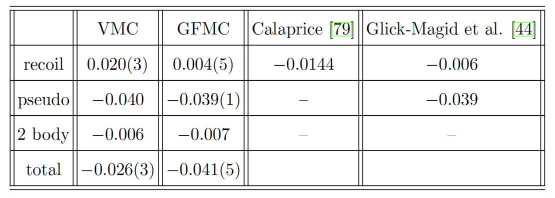




4 different models, very good agreement with CVC for weak magnetism ($\lesssim 1\%$)

# Monte Carlo Ab initio $^6$He study

## Importance of 2BC



| | VMC | GFMC | Calaprice [79] | Glick-Magid et al. [44] |
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| recoil | 0.020(3) | 0.004(5) | −0.0144 | −0.006 |
| pseudo | −0.040 | −0.039(1) | – | −0.039 |
| 2 body | −0.006 | −0.007 | – | – |
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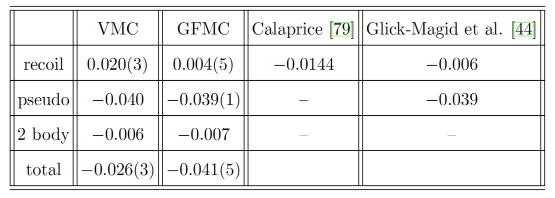

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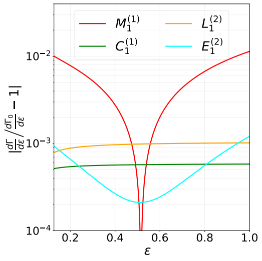
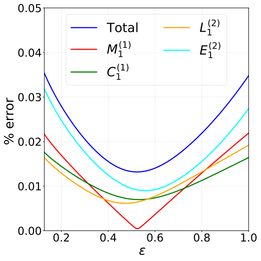
## Resulting spectral uncertainty





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# Unresolved radiative corrections

Past years have seen a lot of activity on RC

- Dispersion treatment of neutron $\Delta_R^V$
- First calculations of $\Delta_R^A$
- Current algebra with EFT

Seng, Gorchtein [PRL 2018, PRD 2019], Hayen [PRD 2021], Shiells [PRD 2021], CMS [PRD 2020], . . .

# Unresolved radiative corrections

Past years have seen a lot of activity on RC

- Dispersion treatment of neutron $\Delta_R^V$
- First calculations of $\Delta_R^A$
- Current algebra with EFT

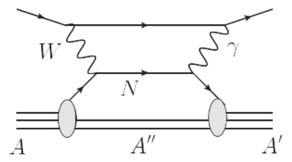
Seng, Gorchtein [PRL 2018, PRD 2019], Hayen [PRD 2021], Shiells [PRD 2021], CMS [PRD 2020], . . .

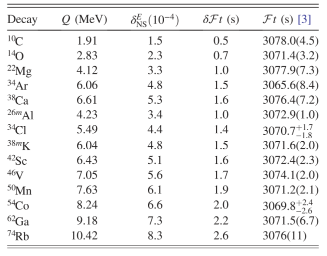
But in last years, two problems have shown up

1. Quasielastic contributions in nuclear $\gamma W$ box
2. Unexpected large isospin breaking corrections

# Quasielastic $\gamma W$ contributions

In 2018, Gorchtein [PRL 123 042503] found $\mathcal{O}(0.01\%)$/MeV effects due to quasielastic effects in $\gamma W$ box





| Decay | $Q$ (MeV) | $\delta^E_{\mathrm{NS}}(10^{-4})$ | $\delta\mathcal{F}t$ (s) | $\mathcal{F}t$ (s) [3] |
|---|---|---|---|---|
| $^{10}$C | 1.91 | 1.5 | 0.5 | 3078.0(4.5) |
| $^{14}$O | 2.83 | 2.3 | 0.7 | 3071.4(3.2) |
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| $^{34}$Cl | 5.49 | 4.4 | 1.4 | $3070.7^{+1.7}_{-1.8}$ |
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| $^{42}$Sc | 6.43 | 5.1 | 1.6 | 3072.4(2.3) |
| $^{46}$V | 7.05 | 5.6 | 1.7 | 3074.1(2.0) |
| $^{50}$Mn | 7.63 | 6.1 | 1.9 | 3071.2(2.1) |
| $^{54}$Co | 8.24 | 6.6 | 2.0 | $3069.8^{+2.4}_{-2.6}$ |
| $^{62}$Ga | 9.18 | 7.3 | 2.2 | 3071.5(6.7) |
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Substantial increase in $\mathcal{F}t^{0+\to 0^+}$ uncertainty!

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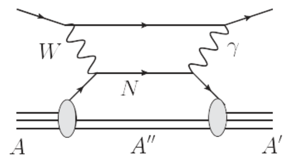

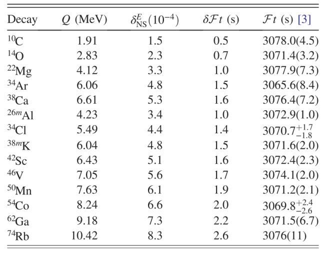

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Substantial increase in $\mathcal{F}t^{0+\to 0^+}$ uncertainty!

Potential target for future experiments, needs theory attention

Hardy & Towner PRC 2020

# Isospin breaking corrections

With $\Delta_R^A$ seemingly settled, can we compare to lattice?

$$g_A^{exp}[1+\Delta_R^A/2]^{-1} \overset{?}{\approx} g_A^{LQCD}(1-2\epsilon_R)$$

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Previous calculations were performed assuming isospin symmetry

V. Cirigliano, J. De Vries, LH, E. Mereghetti, A. Walker-loud, 2202.10439

# Isospin breaking corrections

**New**: Using chiral EFT

$$g_A = g_A^{(0)} \left( 1 + \sum_{n=2}^{\infty} \Delta_\chi^{(n)} + \frac{\alpha_{\mathrm{em}}}{2\pi} \sum_{n=0}^{\infty} \Delta_{\mathrm{em}}^{(n)} + \frac{(m_u - m_d)^x}{\Lambda_\chi^x} \sum_n \Delta_{\delta m}^{(n)} \right)$$

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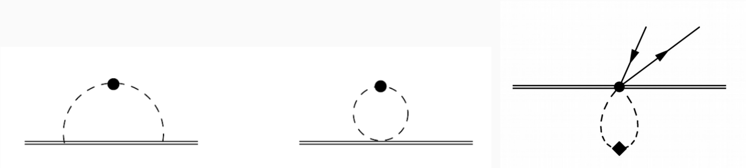
calculate strong isospin breaking corrections

Dominant diagrams at LO (in chiral $\mathcal{L}$)



$$\Delta_{\mathrm{em}}^{(0)} = Z_{\pi} \left[ \frac{1 + 3 g_A^{(0)\,2}}{2} \log \frac{\mu^2}{m_{\pi}^2} - g_A^2 + \hat{C}_{\pi}(\mu) \right] \approx 0.6\% + \mathrm{LEC}$$

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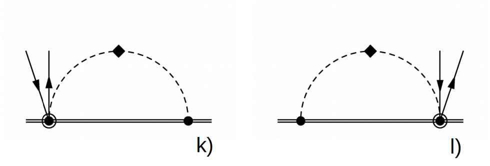
calculate strong isospin breaking corrections

Dominant diagrams at NLO (in chiral $\mathcal{L}$)



$$\Delta_{\rm em}^{(1)} = Z_\pi \frac{4\pi m_\pi}{m_N} \left[ c_4 - c_3 + \frac{3}{8} + \frac{9}{16} g_A^2 \right] \approx 1.8\%$$

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Total corrections are $>2\%$ $+$ LEC of unknown size! (precision of LQCD is now $<1\%$)

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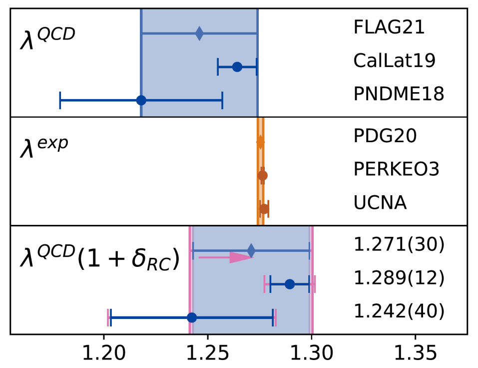

2.7$\sigma$ shift in CalLat $\lambda$ value! (2202.10439v1)

# Isospin breaking corrections

Additionally found ISB in weak magnetism & tensor interaction

$$\mu_{\text{weak}} - (\mu_p - \mu_n) = -\frac{\alpha Z_\pi}{2\pi} \frac{g_A^2 m_N \pi}{m_\pi} \sim 10^{-2}$$

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$\beta$ spectrum changes of $10^{-5}$, not to worry(?)

Due to cancellation in correlations, $\mathcal{O}(0.01\%)$ for neutron, anticipated $\mathcal{O}(0.1\%)$ for $^{19}$Ne!

Nuclear effects with EFT are on the schedule, say tuned!

# Theory summary

Theory for precision $\beta$ decay is looking pretty good, but work remains on quantifiable uncertainties (but formalism carries over)

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$^6$He is excellent test case, path forward is conceptually clear

Bigger questions due to isospin-breaking & nuclear corrections in radiative corrections

- Needs more theory attention
- Spectral (& correlation) measurements can be sensitive to RC changes in $V_{ud}$!

# Table of Contents

# $\beta$ recoil spectroscopy

Spectroscopy experiments currently focused on $\beta$ ($e^-/e^+$), but recoil has interesting features

- Compressed energy range ($<$keV instead of $\sim$ MeV)
- Electron capture gives single recoil peak
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Also, some tricky things...

- Accurate energy reconstruction for $< 1$ keV
- Final state effects (Auger, X-rays, ...)

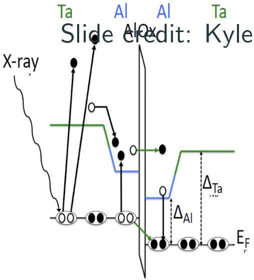
# Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV

  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 µs, making it among the fastest high-resolution quantum sensors available

  → "High" Rate ($10^4$ $s^{-1}$ per pixel)

↖ *Ideal for RIB experiments at ISAC*



Slide credit: Kyle Leach

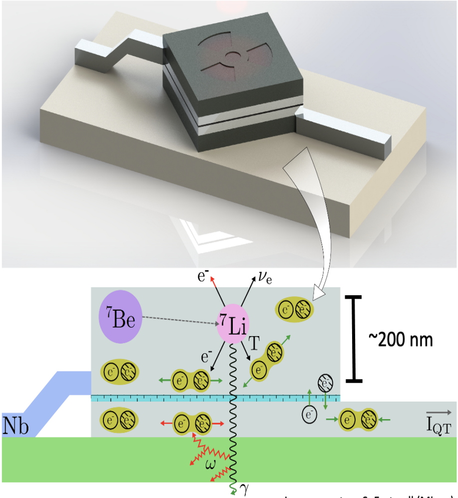
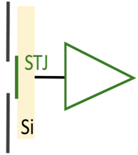


Image courtesy S. Fretwell (Mines)

# Superconducting tunnel junctions

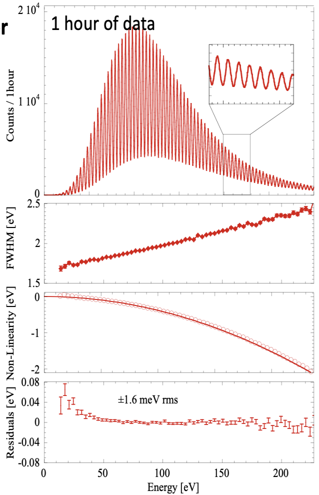


- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage

Slide credit: Kyle Leach

- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity ($10^{-4}$ per eV)

**Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK**



S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

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Slide credit: Kyle Leach

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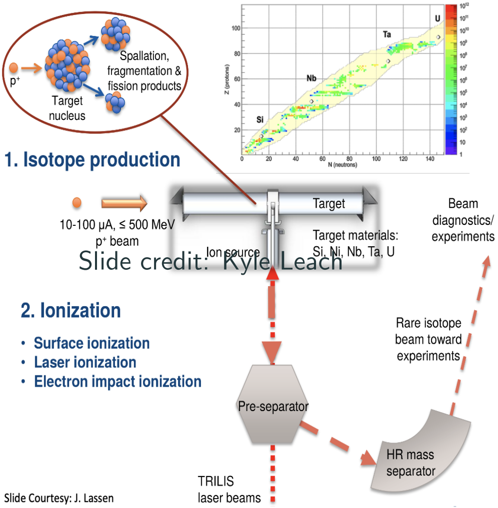


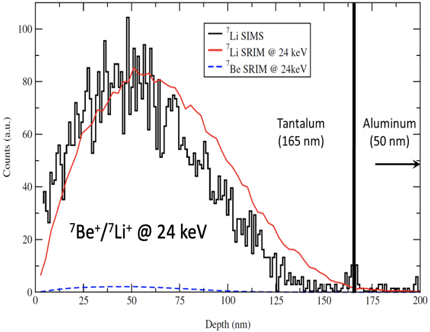
**1. Isotope production**

**2. Ionization**

- **Surface ionization**
- **Laser ionization**
- **Electron impact ionization**

Slide Courtesy: J. Lassen

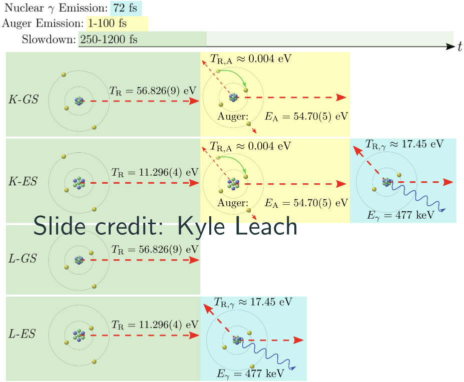
Slide credit: Kyle Leach



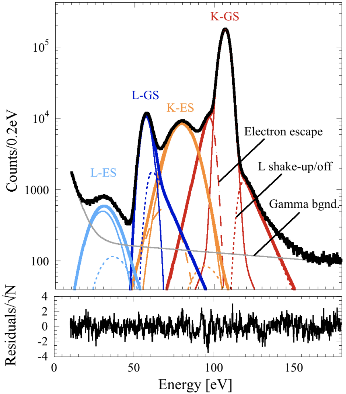
Our current method with $^7$Be for the BeEST:

- Done at the ISAC Implantation Station
- Inactive (room temperature) sensor array
- Clear and ship sensor to lab (LLNL)
- Receive, handle, and cool to < 100 mK

# Superconducting tunnel junctions



Slide credit: Kyle Leach

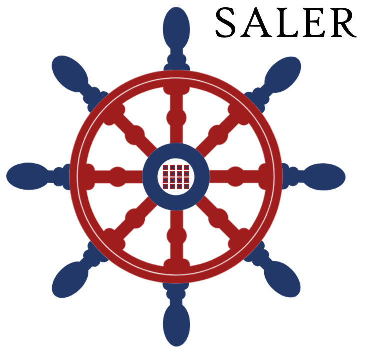


S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

# STJ at RIBs

Can we do the same thing at radioactive ion beam facilities?

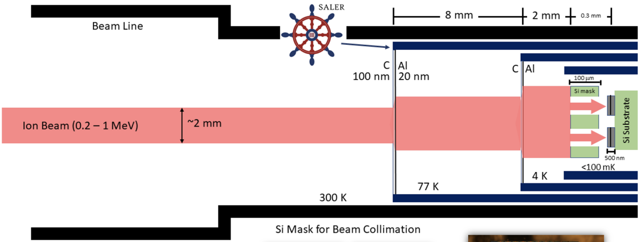
Introducing



Superconducting Array for Low Energy Radiation

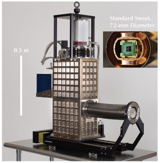
# Superconducting tunnel junctions

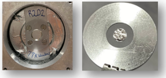
## Concept to couple to beam line



Short-Lived Rare Isotopes ($T_{1/2} > 0.1$ s)

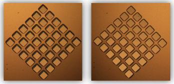
- Beam 0.2 – 1 MeV
- Measurements performed *in-situ* with beamline coupled ADR



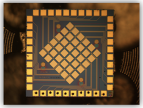


Ultra-Thin (120 nm) Thermal windows

Si Mask for Beam Collimation



Before Alignment After Alignment

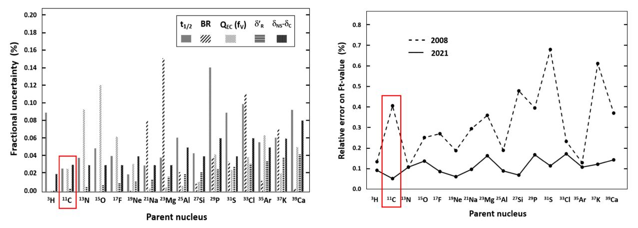


Mounted 36-Pixel Nb STJ Array

Slide credit: Kyle Leach

# SALER plans

$^{11}$C first physics target (long $t_{1/2}$, unreachable with traps!)



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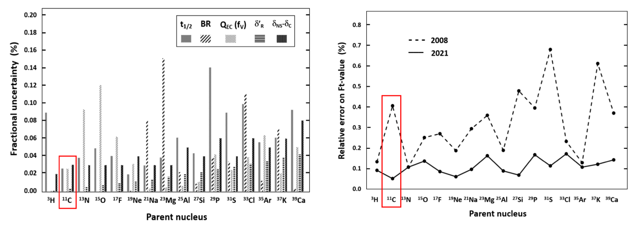
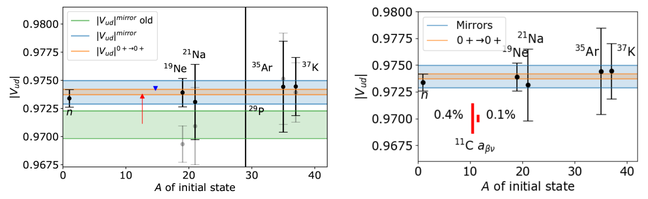
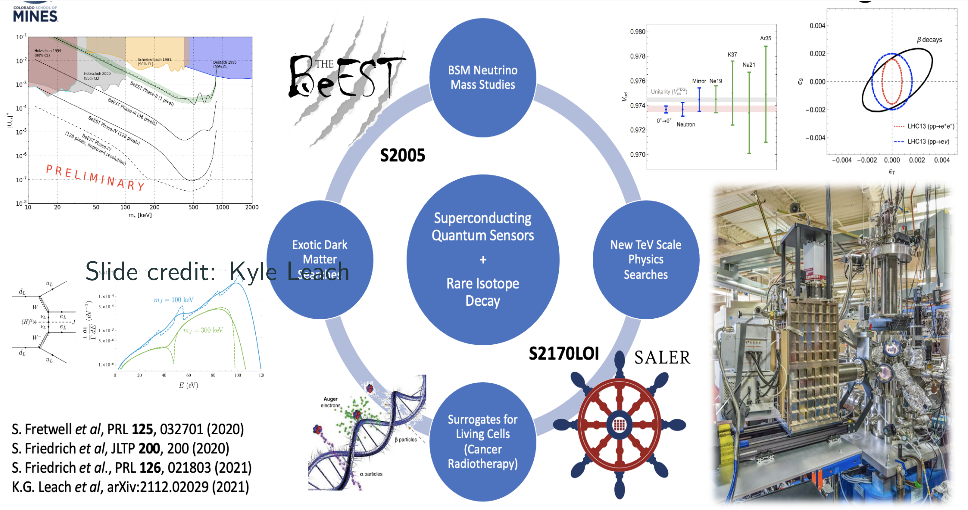


## Excellent $V_{ud}$ sensitivity



**TRIUMF LIO endorsed** with highest priority

# Superconducting tunnel junctions



BSM Neutrino Mass Studies

S2005

Exotic Dark Matter Searches

Superconducting Quantum Sensors + Rare Isotope Decay

New TeV Scale Physics Searches

S2170LOI

Surrogates for Living Cells (Cancer Radiotherapy)

S. Fretwell *et al*, PRL **125**, 032701 (2020)
S. Friedrich *et al*, JLTP **200**, 200 (2020)
S. Friedrich *et al.*, PRL **126**, 021803 (2021)
K.G. Leach *et al*, arXiv:2112.02029 (2021)

Slide credit: Kyle Leach

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Superconducting tunnel junctions promising BSM physics potential via complementary methods, part of $\beta$ spectroscopy without semiconductors

# Thank you

Thank you!

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