# Superallowed Fermi β Decay

## The low-energy precision frontier of nuclear physics
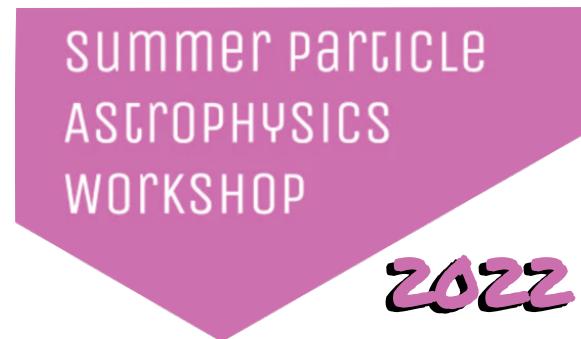
**Dr. Gwen Grinyer** she/her/hers

*Department of Physics, University of Regina, Regina, SK S4S 0A2, Canada*

Gwen.Grinyer@uregina.ca   @gwendoesscience   @gwendoesscience

# Hi! I'm Gwen!

- **My academic journey:**
  - **B.Sc. McMaster University (2002)** 🇨🇦
  - **M.Sc. University of Guelph (2004)** 🇨🇦
  - **Ph.D. University of Guelph (2008)** 🇨🇦
  - **PDF Michigan State (2008-2010)** 🇺🇸
  - **Staff scientist CEA (2010-2017)** 🇫🇷
  - **Professor U Regina (since 2017)** 🇨🇦

- **My lived experience:**
  - **Experimental nuclear physicist**
  - **Mum of 3 kids (ages 6, 13, 15)**
  - **First female physics Prof. at UofR**
  - **Only LGBTQ+ STEM Prof. at UofR**
  - **Passionate about EDI in STEM**

- **More about me:** 📷 **@gwendoesscience**
  🐦 **@gwendoesscience**
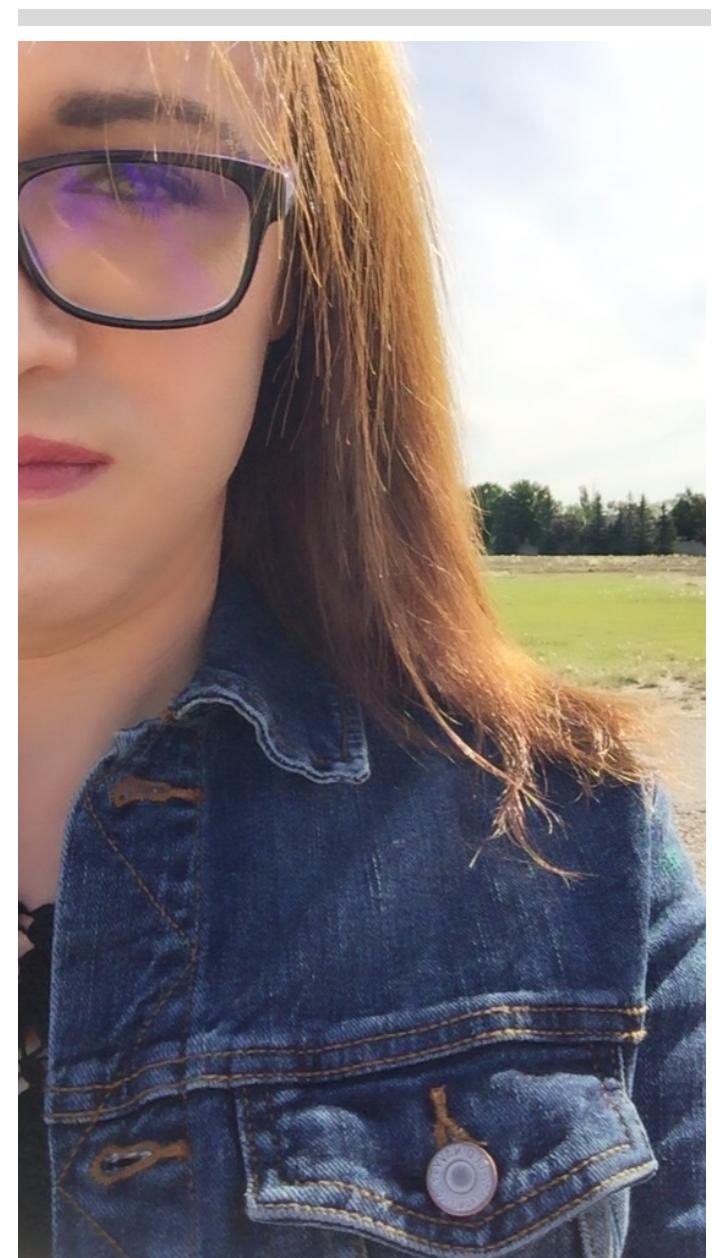
# Nuclear β decay

- **A neutron turns into a proton (or vice versa)**

  **β⁻** $\quad {}^{A}_{Z}X_N \quad \rightarrow \quad {}^{A}_{Z+1}Y_{N-1} + e^- + \overline{\nu_e},$

  neutron $\longrightarrow$ proton

  **β⁺** $\quad {}^{A}_{Z}X_N \quad \rightarrow \quad {}^{A}_{Z-1}W_{N+1} + e^+ + \nu_e.$

  proton $\longrightarrow$ neutron
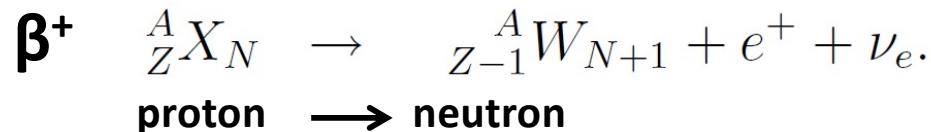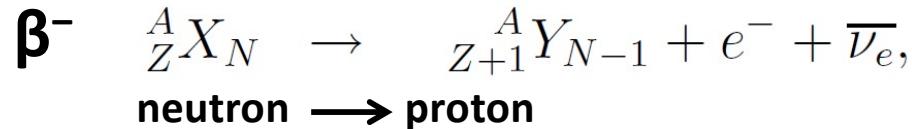
- **Momentum conservation & selection rules:**

  $$\vec{J_P} = \vec{J_D} + \vec{L} + \vec{S} \qquad \pi_P = \pi_D(-1)^L$$

  - **Allowed** decays (L=0)
  - Forbidden decays (L=1,2,3,...)

  - **Fermi** decays (S=0)
  - Gamow-Teller decays (S=1)
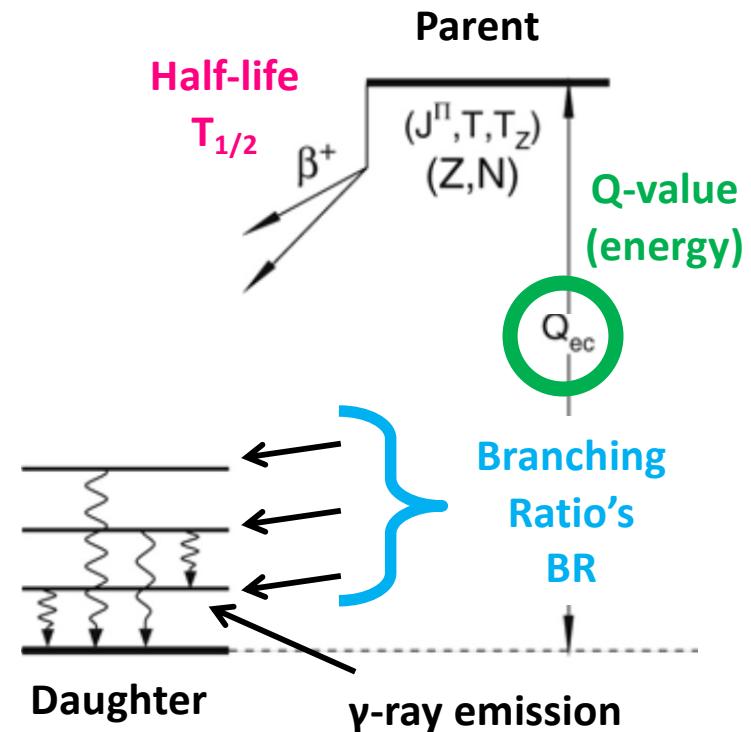
# Half-lives and *ft* values

| Case | $J^\pi$ (P→D) | Classification | $T_{1/2}$ | Fraction |
|:---:|:---:|:---:|:---:|:---:|
| $^{18}N \to {}^{18}C$ | $1^- \to 1^-$ | Allowed (GT&F) | 624 ms | 64% "Superallowed" |
| $^{6}He \to {}^{6}Li$ | $0^+ \to 1^+$ | Allowed (GT only) | 807 ms | |
| $^{10}C \to {}^{10}B$ | $0^+ \to 0^+$ | Allowed (F only) | 19 s | 1% |
| $^{38}Cl \to {}^{38}Ar$ | $2^- \to 2^+$ | 1st Forbidden | 37 min | 33% |
| $^{36}Cl \to {}^{36}Ar$ | $2^+ \to 0^+$ | 2nd Forbidden | $3 \times 10^5$ years | 1% |
| $^{40}K \to {}^{40}Ca$ | $4^- \to 0^+$ | 3rd Forbidden | $1 \times 10^9$ years | 0.1% |
| $^{50}V \to {}^{50}Cr$ | $6^+ \to 2^+$ | 4th Forbidden | $1 \times 10^{17}$ years | 0.1% |

- **The *ft* value is a convenient way to characterize nuclear β decay**

Q-value  Half-life  Constants

$$ ft = \frac{f T_{1/2}}{BR} = \frac{K}{g^2 |M_{fi}|^2} $$

Branching Ratio

Strength  Matrix element

# Nuclear Isotopic Spin (Isospin)

- **Introduced by Heisenberg in 1932**
  - Protons and neutrons – (iso)spin projections of the "nucleon"
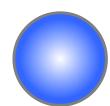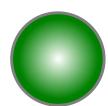
$$t_z(p) = -\frac{1}{2} \qquad t_z(n) = +\frac{1}{2}$$

- **Total isospin (T) and isospin projection $T_z$ of the nucleus**
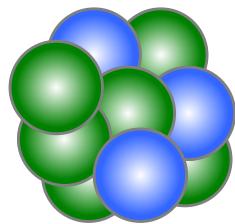
$$T_z = \frac{1}{2}(N - Z) \qquad \mathbf{T} = |T_z|, |T_z| + 1, \cdots, \frac{N+Z}{2}$$

- **Nuclear β decay is a neutron changing into a proton (or vice versa)**
  - Fermi decay between "isobaric analogue states" is a ladder operator

$$|M_F|^2 = (T \mp T_z)(T \pm T_z + 1)$$

For T = 1 decays $\longrightarrow$ $|M_F|^2 = 2$    **Exact!**
(to extent that isospin valid)

# Conserved Vector Current Hypothesis (CVC)

- **The *ft* values for superallowed Fermi decays…**

$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{g^2|M_{fi}|^2}$$

constants ✓

**strength?**

isospin ✓

- **CVC hypothesis (based on analogy to electrodynamics)**
  - **A universal coupling constant – the electric charge "e"**

**e = 1.602 176 487 x 10⁻¹⁹ C**

  - **The weak interaction is also thought to have a universal coupling constant!**

**$G_V$ = 1.13621 x 10⁻⁵ GeV⁻²**

$G_V$
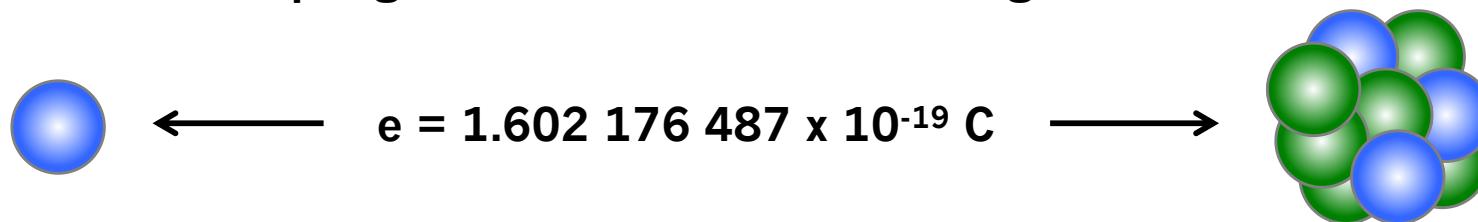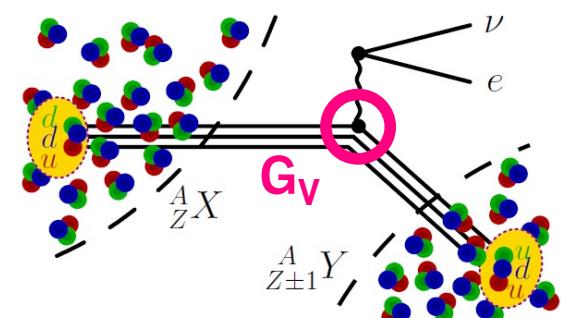
**R.P.Feynman and M.Gell-Man PR 109, 193 (1958)**

# Conserved Vector Current Hypothesis (CVC)

- **The *ft* values for superallowed Fermi decays... should be constant!**

$$ft = \frac{fT_{1/2}}{BR} = \frac{K}{2G_V{}^2} = \text{constant} \; \text{?}$$

- **CVC hypothesis (based on analogy to electrodynamics)**
  - **A universal coupling constant – the electric charge "e"**

**e = 1.602 176 487 x 10$^{-19}$ C**

  - **The weak interaction is also thought to have a universal coupling constant!**

**G$_V$ = 1.13621 x 10$^{-5}$ GeV$^{-2}$**

**G$_V$**
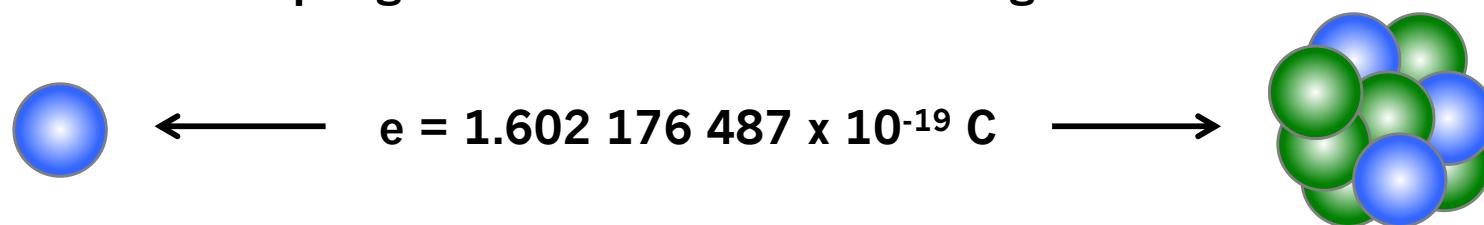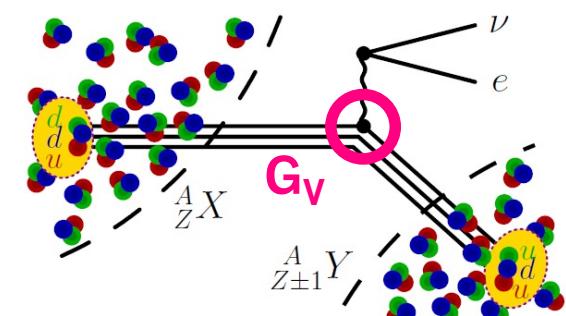
**R.P.Feynman and M.Gell-Man PR 109, 193 (1958)**

# Superallowed *ft* values

- **World survey of superallowed decays**
  - **> 220 independent measurements**

- **Superallowed *ft* values**
  - **Range from 3040 s to 3100 s (2%)**
  - **Higher-order effects (theory)**



x 100
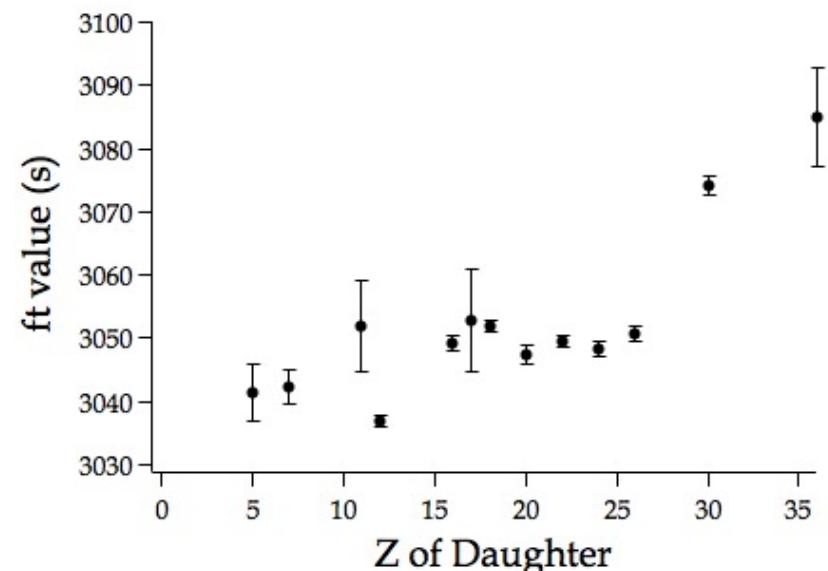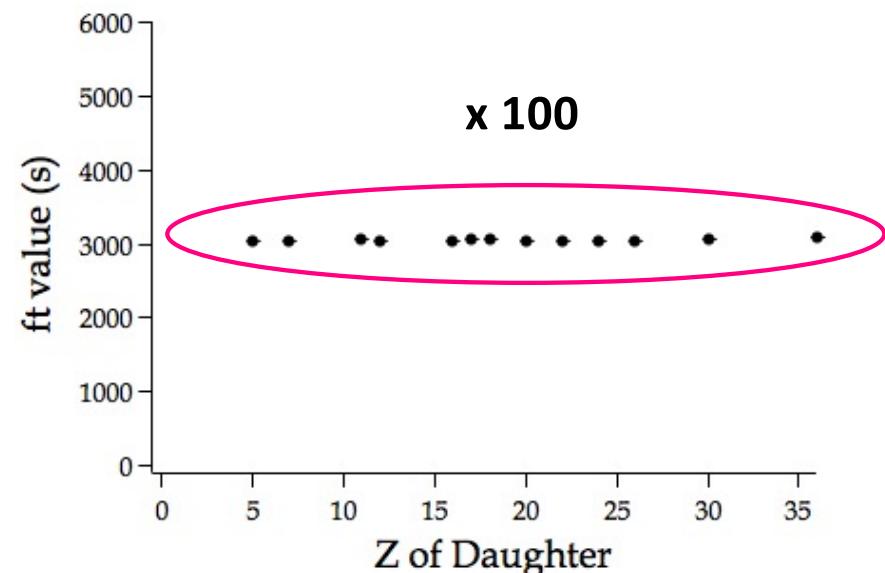
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  - **Broken by charge dependent forces**

$$|M_F|^2 = 2(1 - \delta_C)$$

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$$|M_F|^2 = 2(1 - \delta_C)$$

- **Corrected Ft values**
  - **Constant at the level of $9 \times 10^{-5}$**
  - **Validation of the CVC hypothesis**
  - **Strong constraint on "new physics"**



$Ft_{avg} = 3072.24 \pm 1.85$ s    $\chi^2/\nu = 0.47$
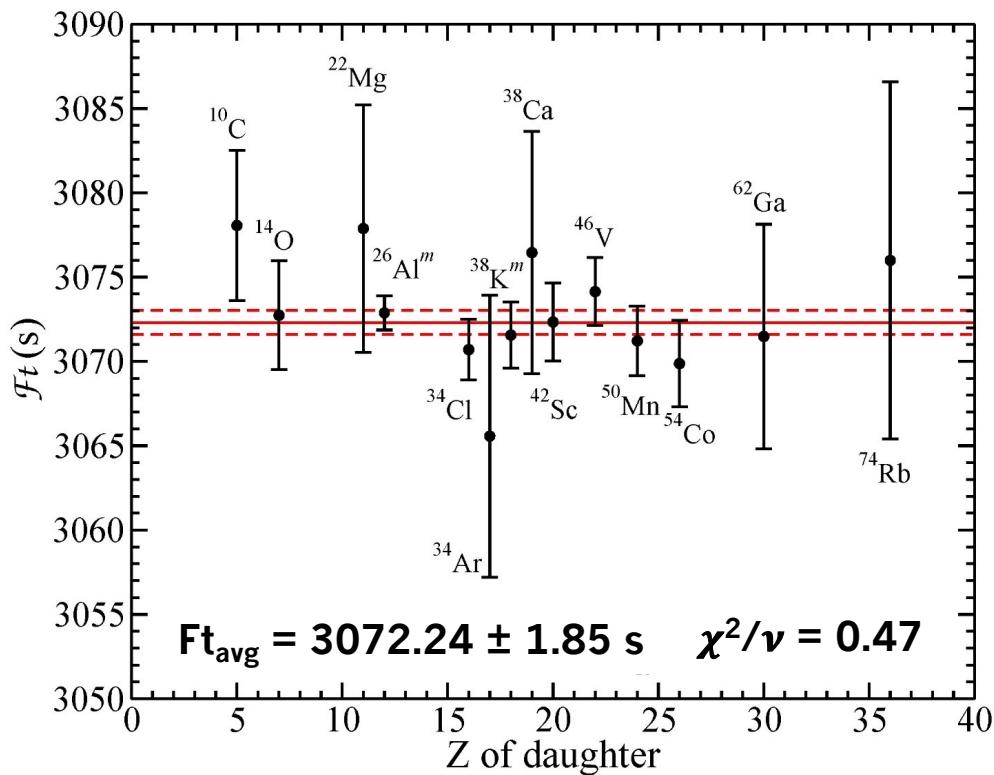
# Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- **The CKM matrix plays a central role in the Standard Model**
  - It describes *all* quark flavour changing interactions (including β decay)
  - Given that there are 3 quark generations, CKM is a 3x3 matrix



**β decay**

up     down

**Proton**     **Neutron**

- U  up quark    $q = +2/3e$
- D  down quark  $q = -1/3e$

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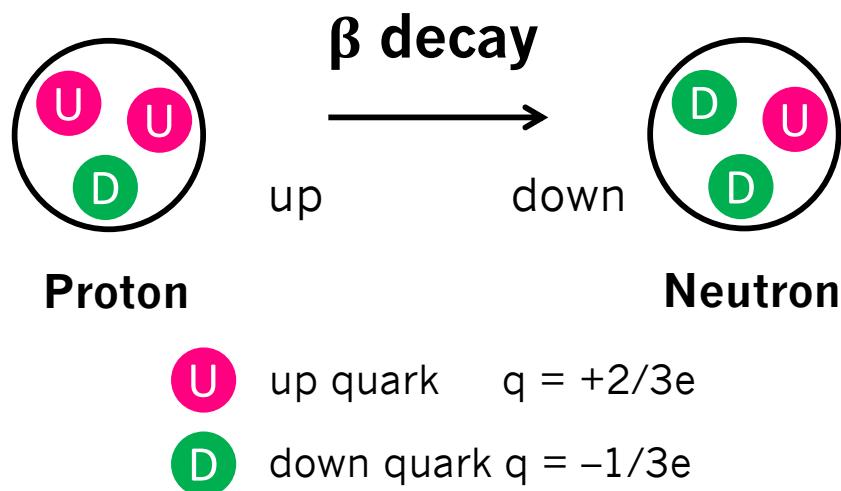
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- **In the Standard Model the CKM matrix describes a *unitary* transformation**

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

# CKM Unitarity Test

- **The most precise test of CKM unitarity comes from the *top row***
  - **$V_{ud}$ is by far the largest and is obtained precisely from superallowed decays**

Constants

$$|V_{ud}|^2 = \frac{2912.95 \pm 0.54}{\overline{\mathcal{F}t}}$$

*Average Ft value* **from 15 superallowed Fermi transitions between $^{10}$C and $^{74}$Rb**

**CKM**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
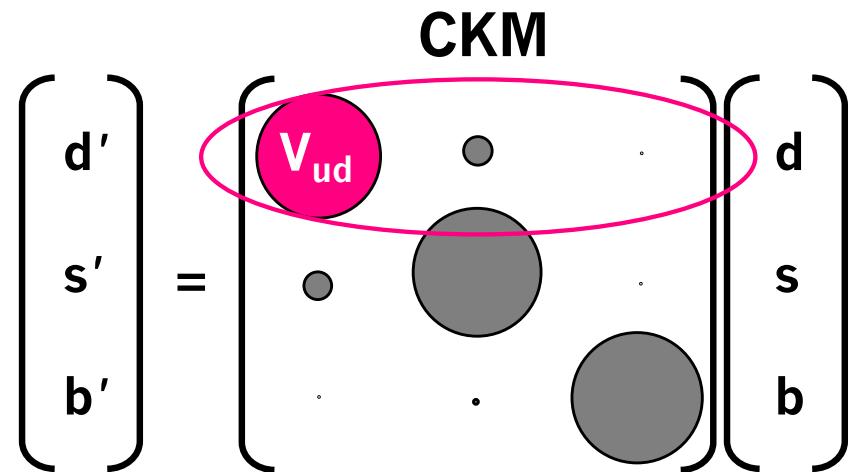
$|V_{ud}| = 0.97373(31)$
$|V_{us}| = 0.2243(5)$
$|V_{ub}| = 0.00394(36)$

- **Present status of the test of CKM unitarity:**

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)$$

**2.5σ deviation from unity!!!**

# TRIUMF's ISAC Facility

**☀ TRIUMF**

- **Canada's National Laboratory for Nuclear and Particle Physics**
  - **Isotope Separator and Accelerator (ISAC)**



**TRIUMF 500 MeV Cyclotron 100 μA**

proton beam

**production target**

**ion source**

ions + ionized molecules

**mass separator**

~40 keV beam

experimental area
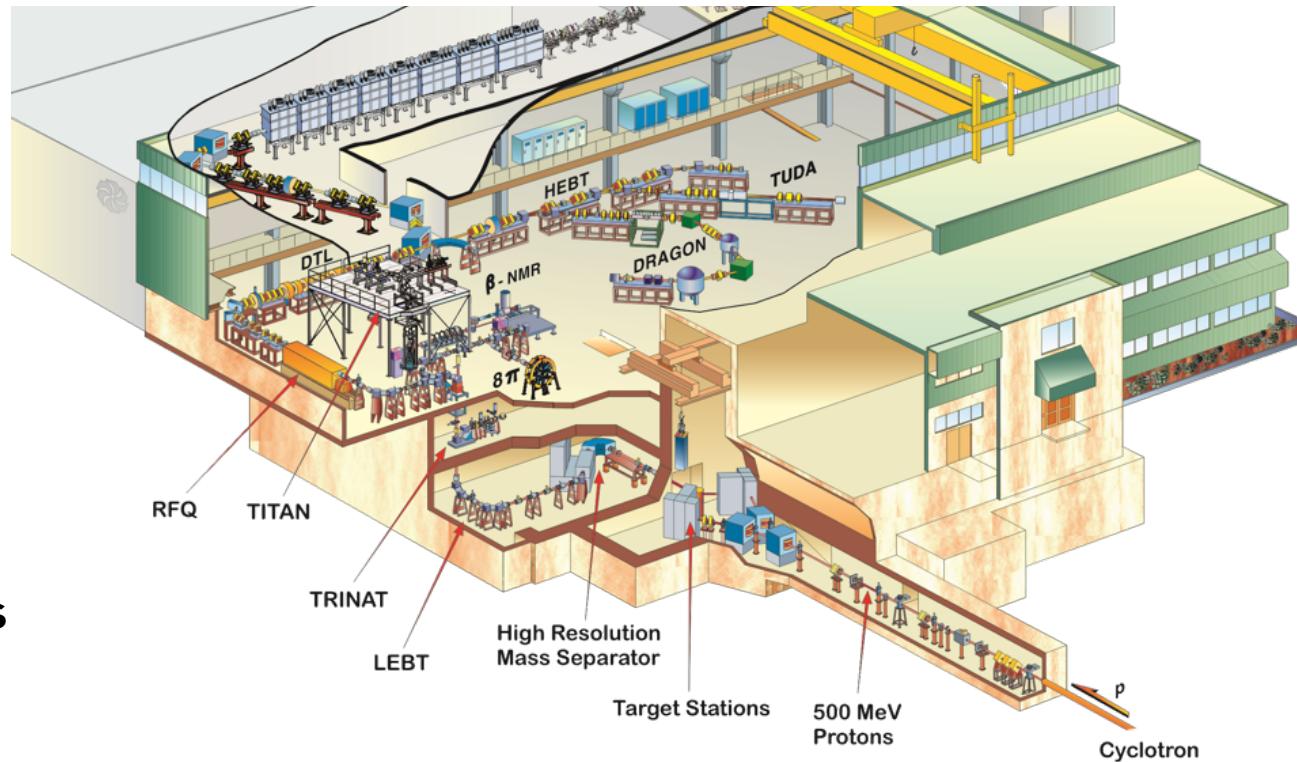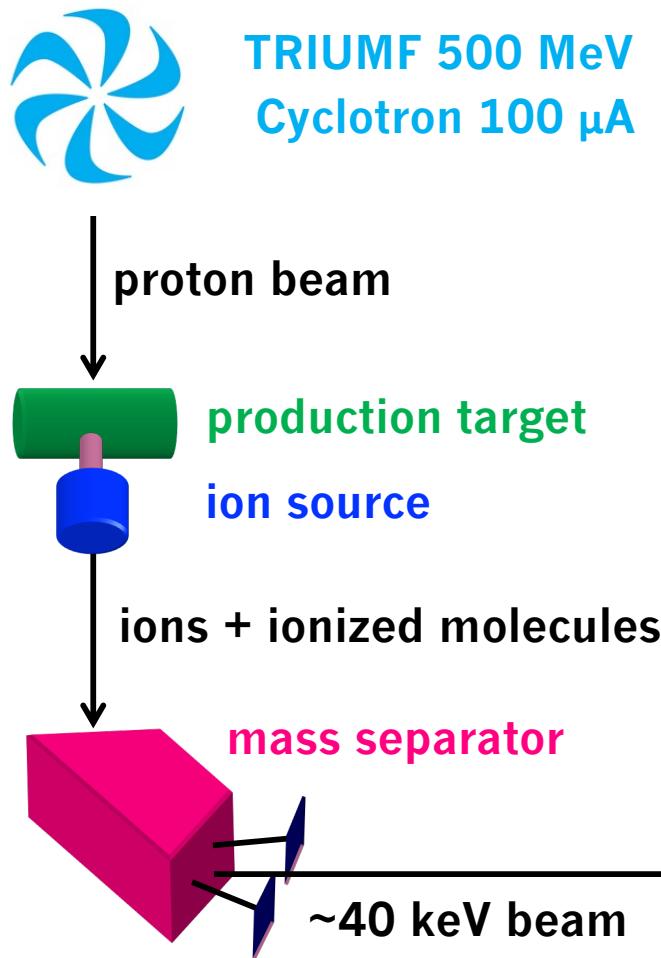
# High-Precision Half-Life Measurements

- **We use a gas proportional counter and a fast tape transport system**
  - **Implant radioactive isotopes from ISAC onto a tape (collection period)**
  - **Rapidly move the sample into a gas counter (beta particles ionize the gas)**
  - **Record the radioactive decay of the sample (exponential decay law)**
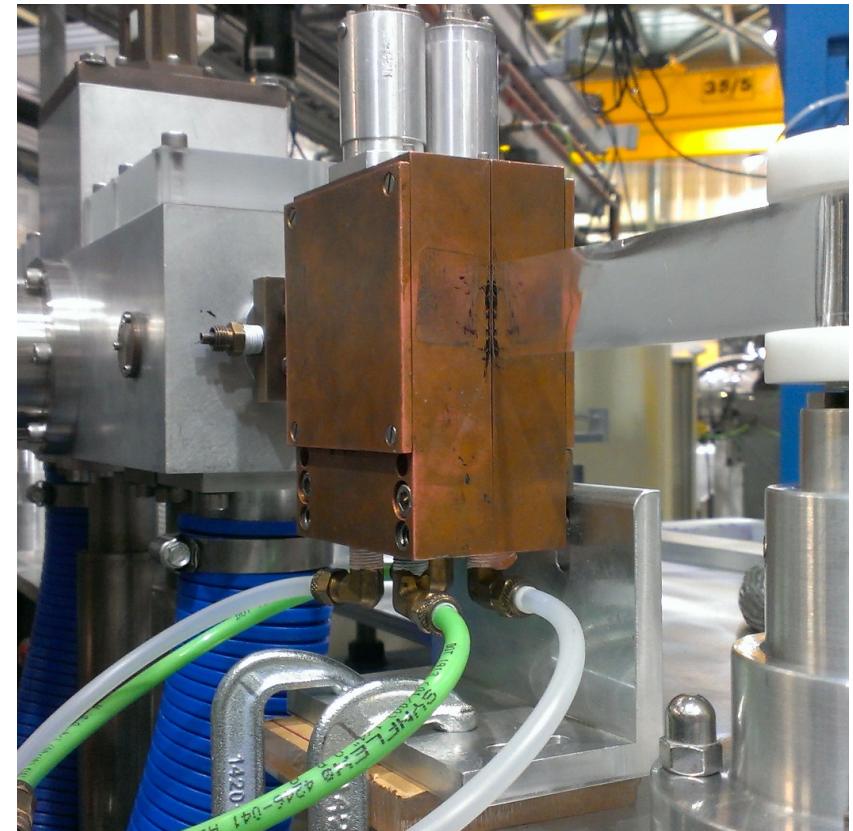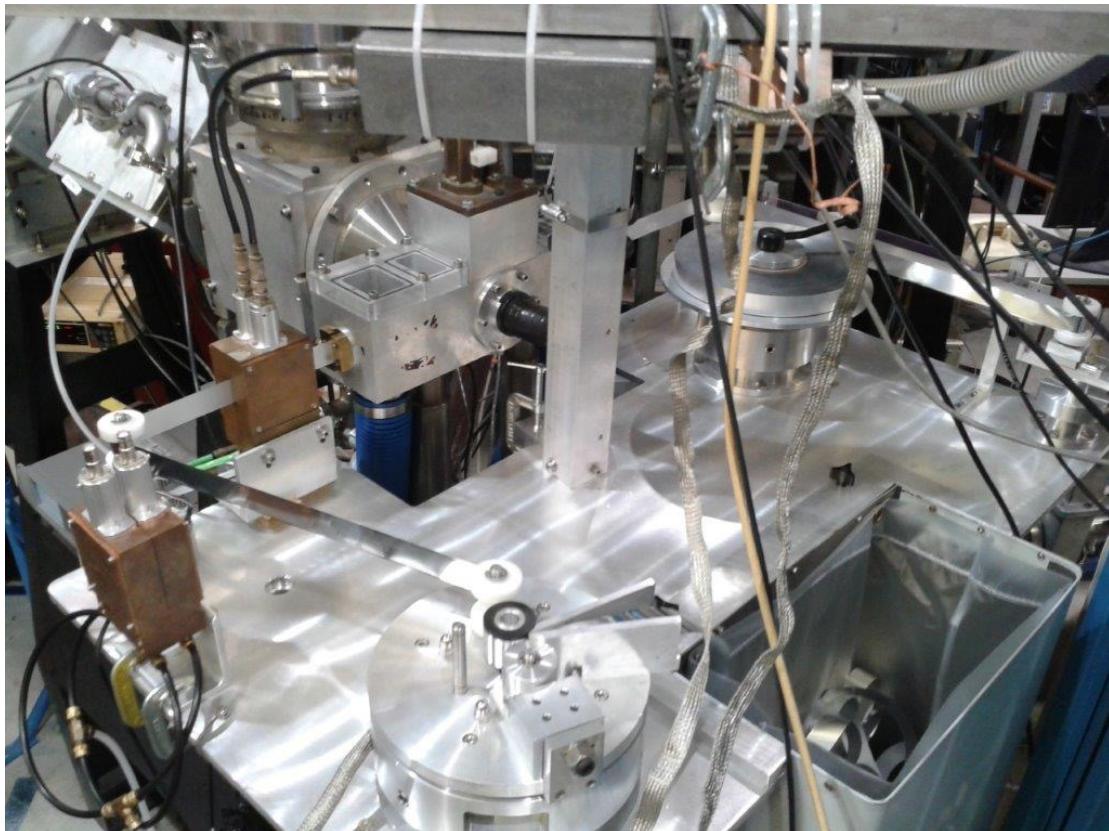
Gwen Grinyer, SP(A)PW, 6 May 2022

# Half-life of $^{10}$C

- **Beam of radioactive $^{10}$C**
  - **Intensity ~$10^5$ ions/s**

- **Data from 1 cycle (~ 8 mins)**
  - **Precision ± 0.07%**

- **Total of 550 cycles (4 days)**
  - **$T_{1/2}$ = 19.3009(17) s**

$A_0$ = initial activity

$\lambda$ = slope
= ln(2)/$T_{1/2}$

B = background

$T_{1/2}$ = 19.3000(38) s
$\chi^2/\nu$ = 1.07

$\mu = 0.007; \sigma = 1.02$
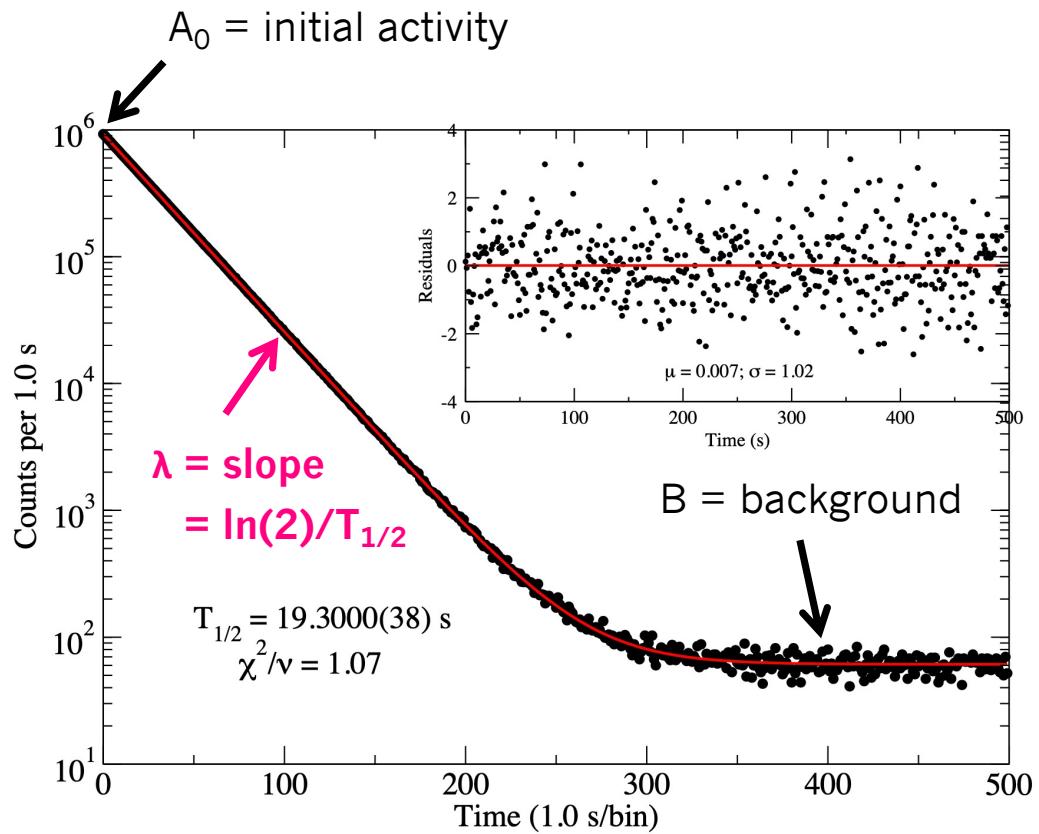
$$A(t) = A_0 e^{-\lambda t} + B$$

# Half-life of $^{10}C$

- **Beam of radioactive $^{10}C$**
  - **Intensity ~$10^5$ ions/s**

- **Data from 1 cycle (~ 8 mins)**
  - **Precision ± 0.07%**

- **Total of 550 cycles (4 days)**
  - **$T_{1/2}$ = 19.3009(17) s**

- **Systematic uncertainties**
  - **The most important part!**

- **Half-life of $^{10}C$ @ TRIUMF**
  - **Overall precision ± 0.009%**
  - **Most precise $T_{1/2}$ ever reported!**
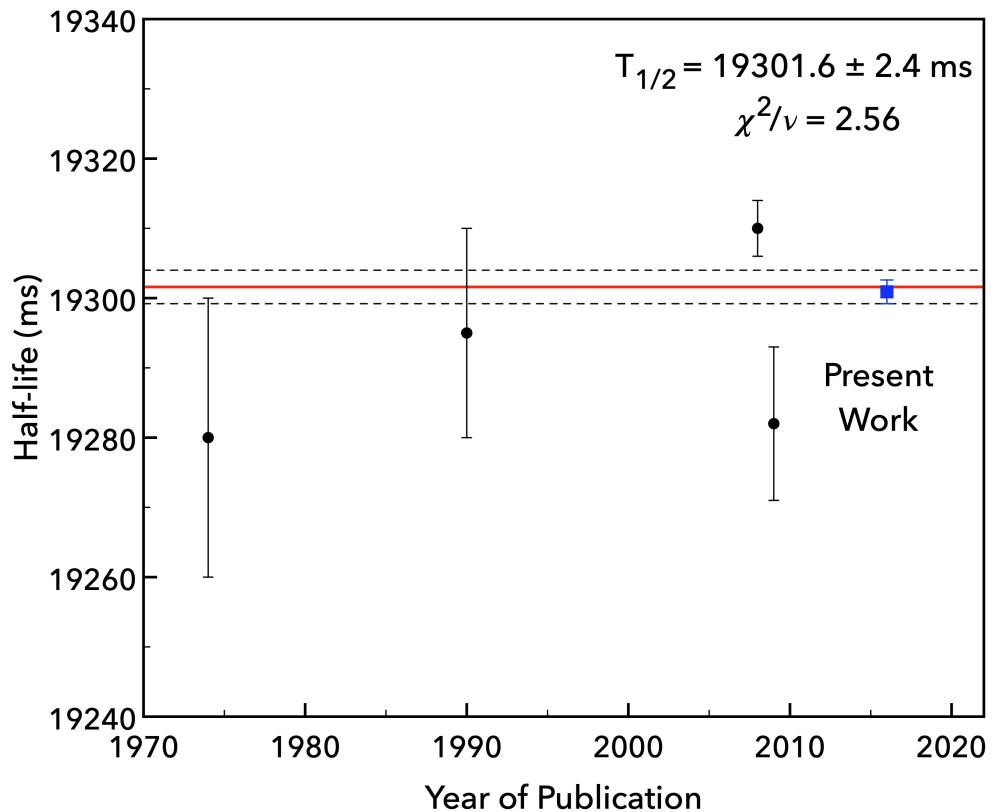


$T_{1/2}$ = 19301.6 ± 2.4 ms
$\chi^2/\nu$ = 2.56

Present Work

# Half-life of $^{14}O$

- **Beam of radioactive $^{14}O$**
  - **Intensity ~$10^5$ ions/s**

- **Data from 1 cycle (~ 25 mins)**
  - **Precision ± 0.10%**

- **Total of 124 cycles (3 days)**
  - **$T_{1/2}$ = 70.6192(70) s**



a)
$T_{1/2}$ = 70627 ± 79 ms
$\chi^2/\nu$ = 0.92

**Half-life = 70.6 s**
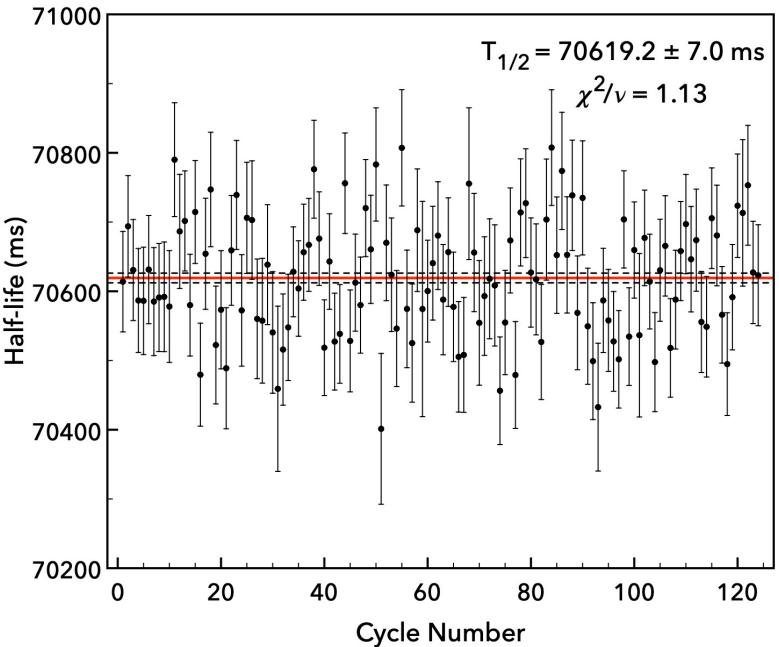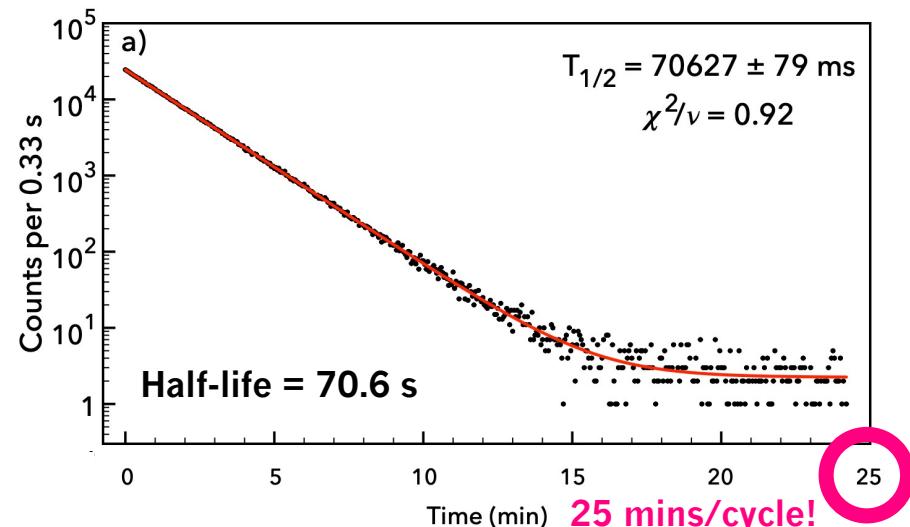
25 mins/cycle!

$T_{1/2}$ = 70619.2 ± 7.0 ms
$\chi^2/\nu$ = 1.13

# Half-life of $^{14}$O

- **Beam of radioactive $^{14}$O**
  - **Intensity ~$10^5$ ions/s**

- **Data from 1 cycle (~ 25 mins)**
  - **Precision ± 0.10%**

- **Total of 124 cycles (3 days)**
  - **$T_{1/2}$ = 70.6192(70) s**

- **Half-life of $^{14}$O @ TRIUMF**
  - **Overall precision ± 0.010%**
  - **Comparable precision to $^{10}$C!**

- **Article published 3 days ago!**
  - **Shivani Sharma, U of R**
  - **Now at Sunnybrook Hospital**
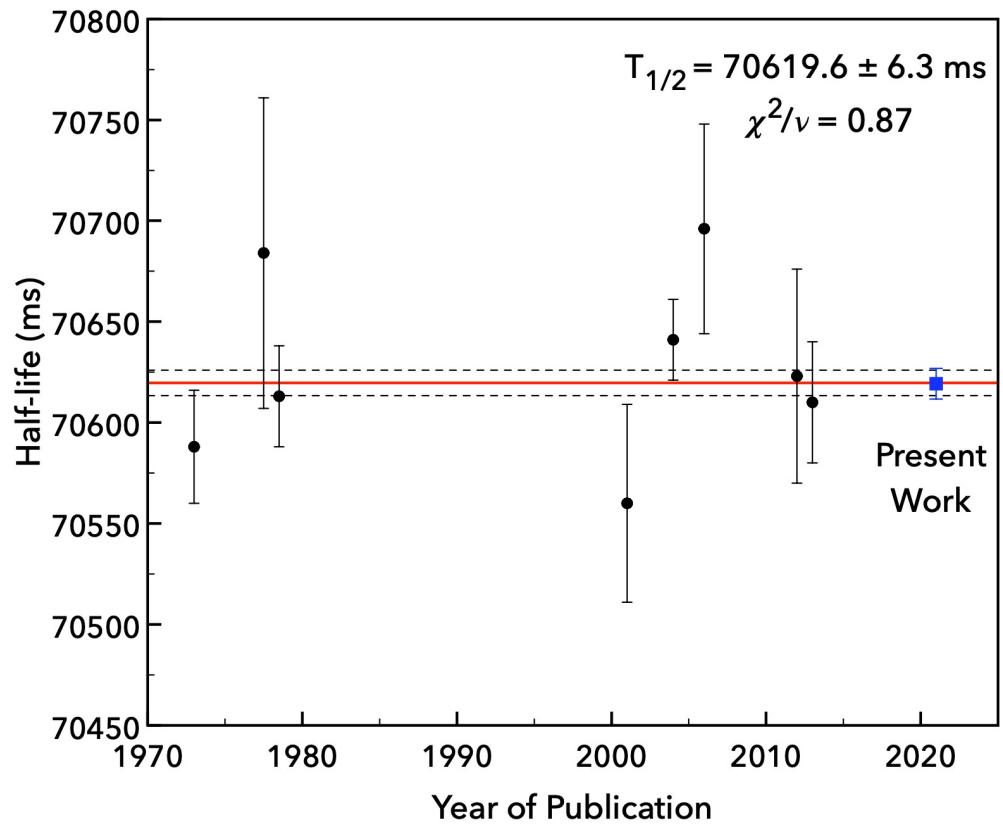
# Next generation: GRIFFIN

**TRIUMF**

- **New HPGe γ-ray spectrometer**
  - **16 large volume "clover" detectors**
  - **Fully operational since 2015**

- **Experiment S1140: Half-life of $^{14}O$**
  - **Statistical precision ± 0.03%**

- **Regina students lead the analysis!**
  - **M.Sc. Nastaran Saei**
  - **Ph.D. Eric Gyabeng Fuakye**

- **Experiment S1848: BR of $^{34}Ar$**
  - **New experiment at ISAC!**
  - **To be scheduled in 2023**
  - **Looking for interested students!**

  https://griffin.triumf.ca
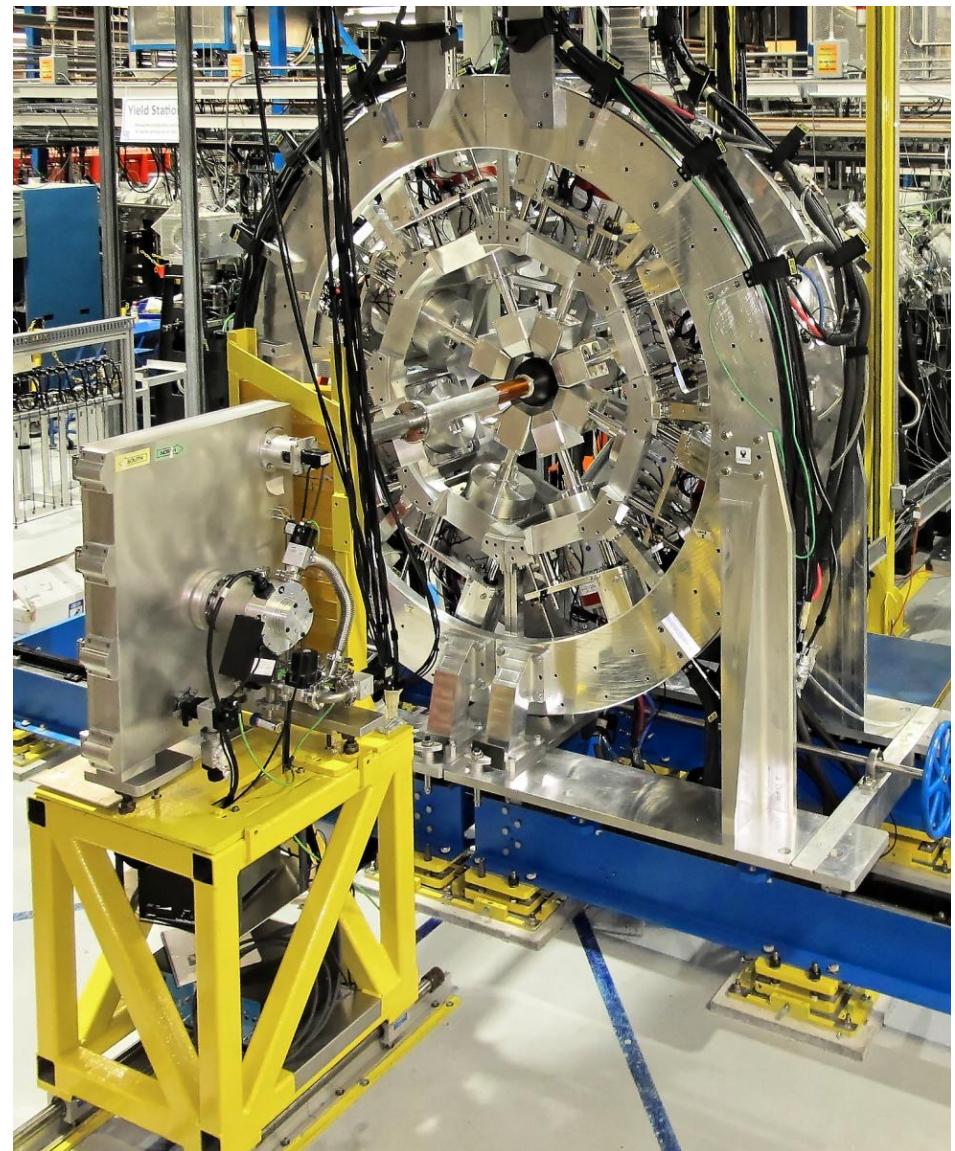
# Thank you so much!

- **Superallowed Fermi β Decay**
    - The precision frontier of NP
    - Crucial constraints on the SM
    - Demanding test of CKM unitarity

- **Experiments at TRIUMF-ISAC**
    - Best place for these studies
    - World-leading detectors/expertise

- **Many other projects in my group!**
    - I am always looking for students!
    - Please contact me if interested!!

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 @gwendoesscience

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