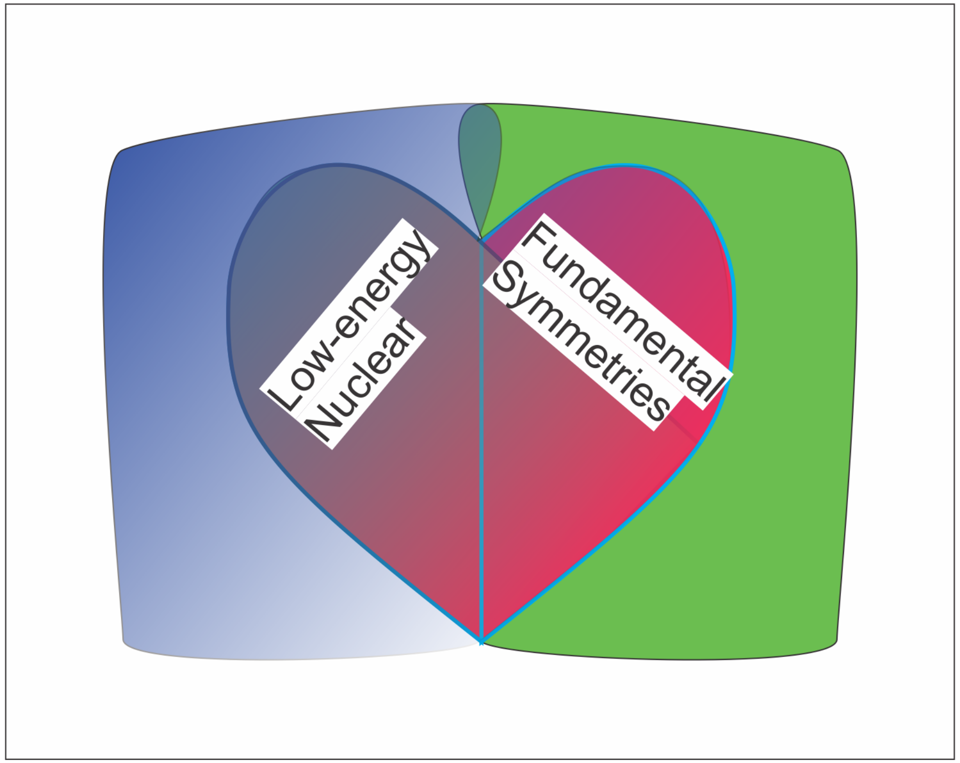
# At the intersection of low-energy nuclear physics and fundamental symmetries




Outline

- CKM unitarity tests
- Double beta decays
- Violation of $P$ and $T$ in nuclei
- Searches for chirality-flipping interactions
- New technologies

# CKM: $V_{\mathrm{ud}}$ → Precision beta decay

J. C. HARDY AND I. S. TOWNER C **102**, 045501 (2020)

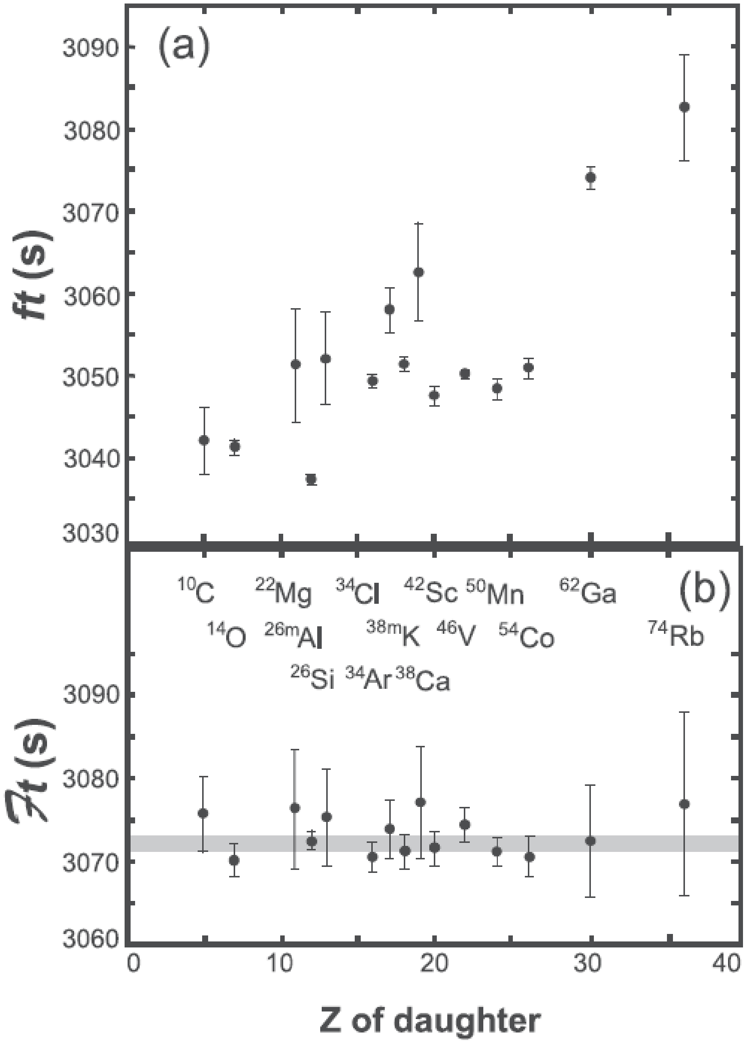
Work make us proud:
very fruitful, yielding $\sim 0.1\%$ precision constraint.

Apparent CKM-non-unitarity prompted new determinations of $V_{\mathrm{us}}$ in 2000's.

Corrections to 0+ → 0+ recently re-examined:
*Radiative*: Seng, Gorchtein, Ramsey-Musolf, Patel, Czarnecki, Marciano
*Isospin-breaking*: Satula, Dobaczewski, Nazarewicz, Konieczka, Werner, Xayavong, Smirnova, Miller

$ft$ values

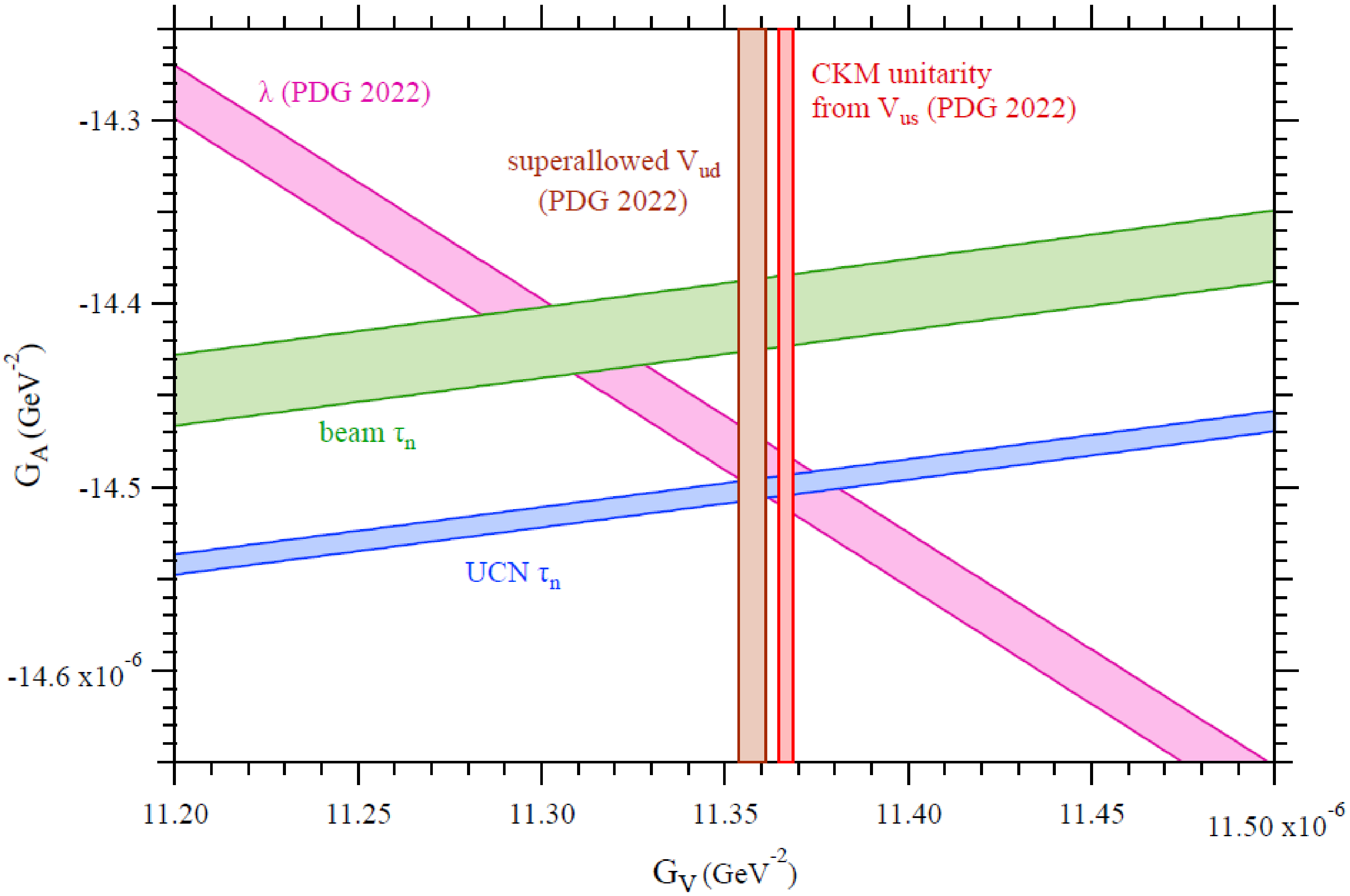
$ft$ values with radiative and isospin-breaking corrections



# CKM and neutron decay

Ignoring "beam $\tau_n$" precision from neutron decay still a factor of $\sim 3$ short of $0^+ \rightarrow 0^+$.

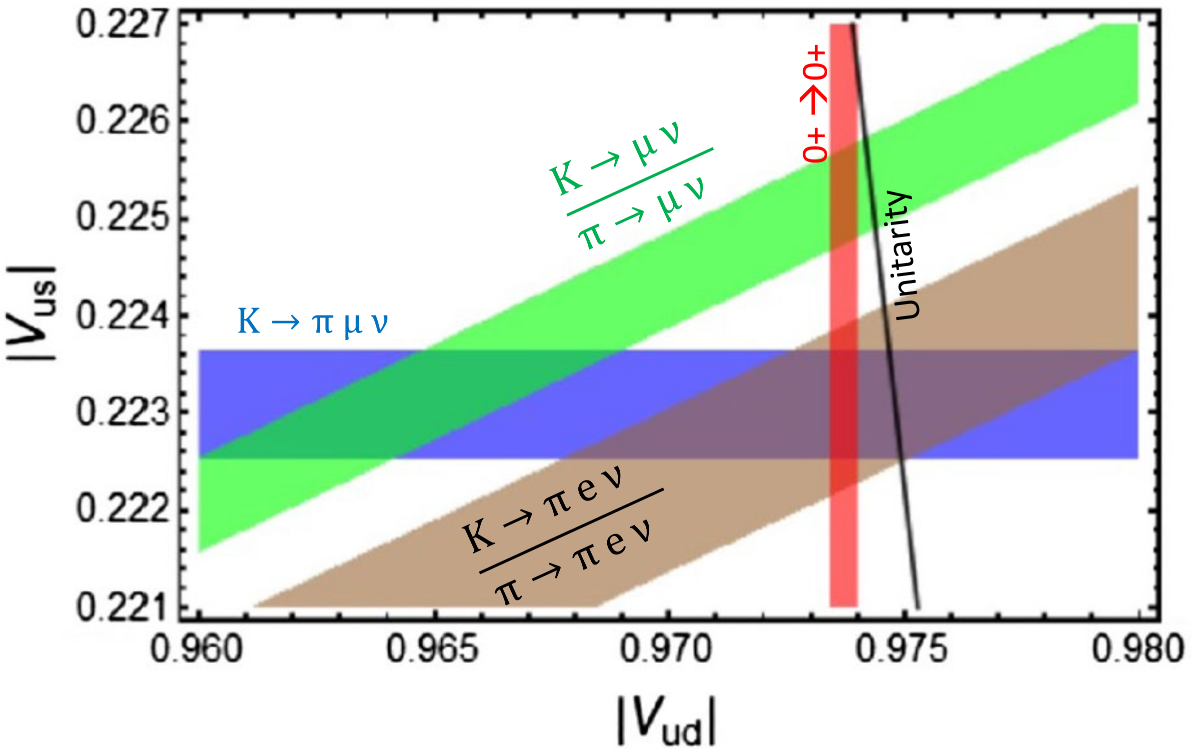
Upcoming experiments could resolve the "$\tau_n$ discrepancy" and reach that level.



# CKM: $V_{us}$

C.-Y. Seng et al.
PRD **105**, 013005 (2022)

$K \rightarrow \pi\, \mu\, \nu$ and $\frac{K \rightarrow \pi\, e\, \nu}{\pi \rightarrow \pi\, e\, \nu}$
considered cleaner observables.




$$|V_{ud}|^2_{0^+} + |V_{us}|^2_{K_{e3}} - 1$$
$$= -0.0021(2)_{V_{ud},\mathrm{exp}}(2)_{V_{ud},\mathrm{RC}}(5)_{V_{ud},\mathrm{NS}}(2)_{V_{us},K}(2)_{V_{us},\mathrm{lat}}$$

Unitarity test (PDG):
$\Delta_{\mathrm{CKM}} = -0.0015(7)$

>2σ disagreement with CKM unitarity.

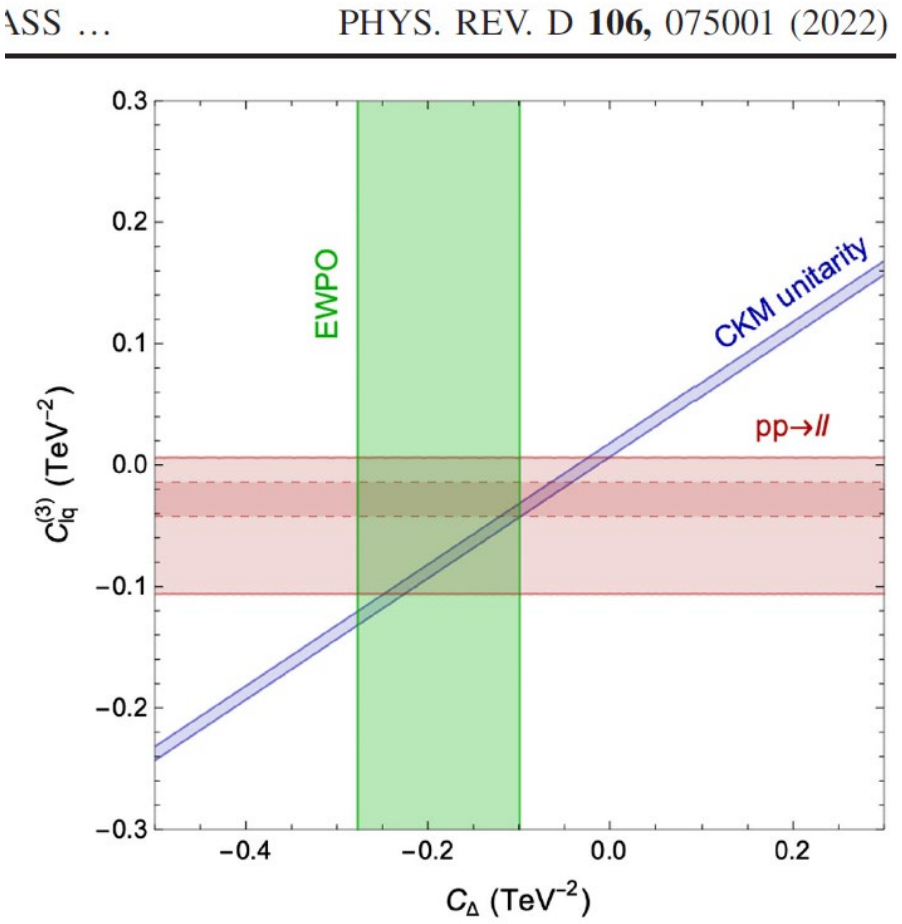
$\Delta_{\mathrm{CKM}}$ varies according to what numbers are used

# CKM and $M_W$

Example of using CKM unitarity constraint:

*Interpreting latest $M_W$ for new physics:* using CKM allows focusing on SM-like effective interaction as source: $(\bar{l}_p \tau^I \gamma_\mu l_r)(\bar{q}_s \tau^I \gamma^\mu q_t)$

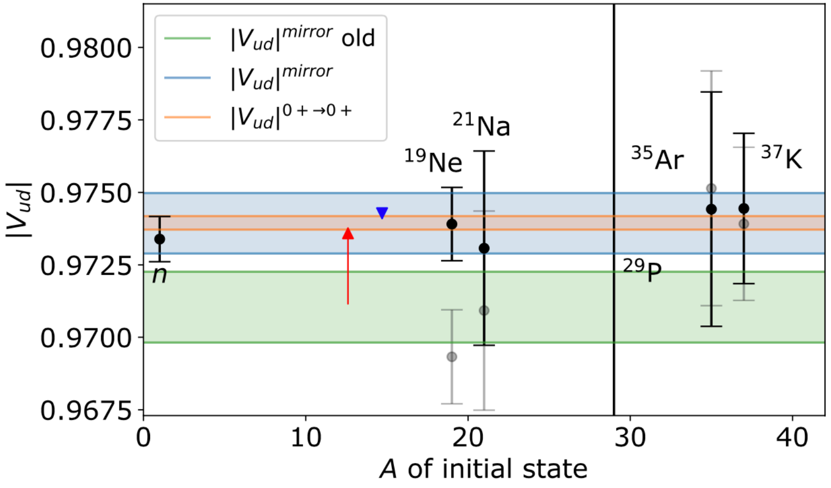
Cirigliano et al.
PRD **106**, 075001 (2022)



# CKM future?

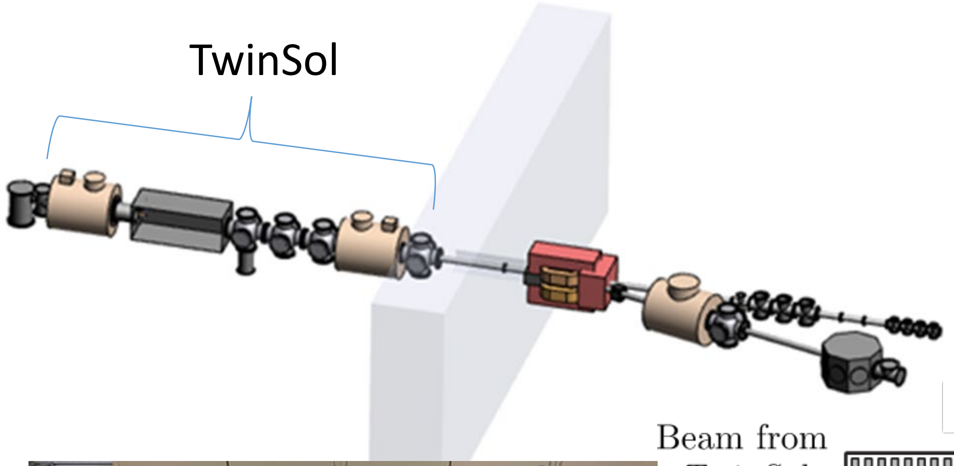
## $V_{\mathrm{ud}}$ from mixed transitions and searches for BSM physics

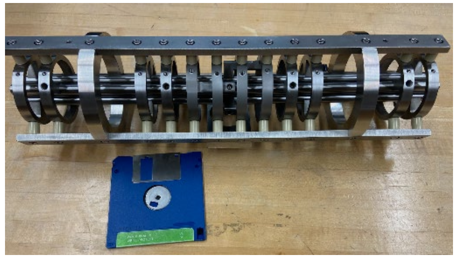
L. Hayen, PRD **103**, 113001 (2021)

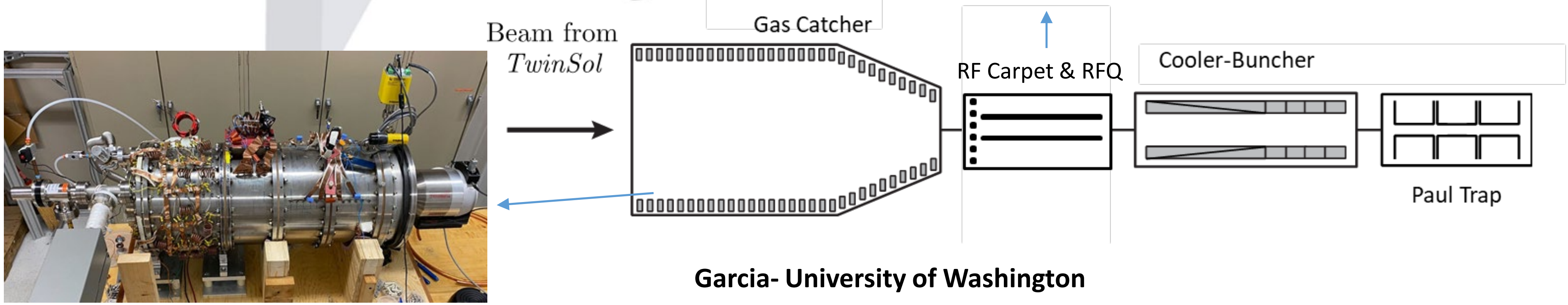



Max Brodeur et al. (Notre Dame)

- Extract $V_{ud}$ from additional mirror transitions
- Use ion traps and ND radioactive beam separator



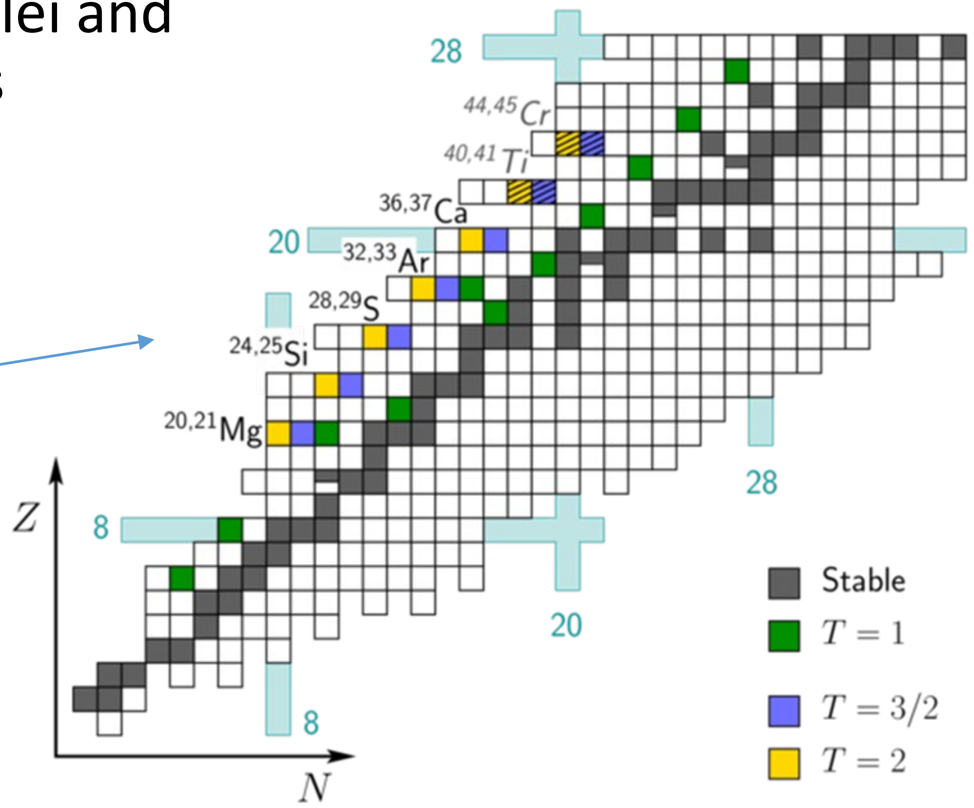


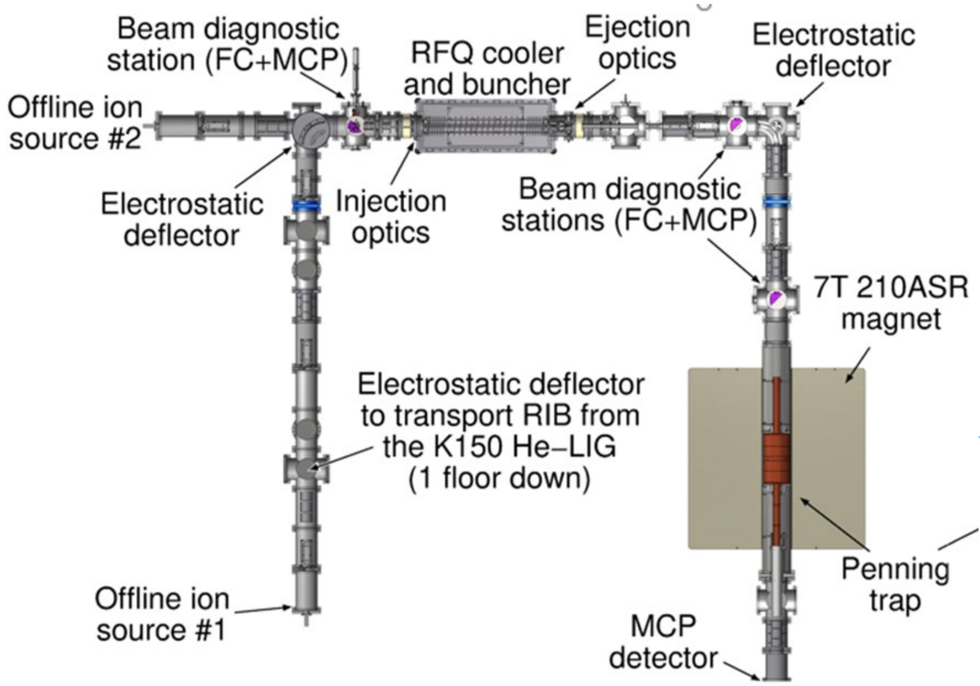
# CKM future?

## $V_{\mathrm{ud}}$ from proton-rich nuclei and searches for BSM physics

Dan Melconian et al. (Texas A&M)

Extend to systematic work including proton-rich nuclei



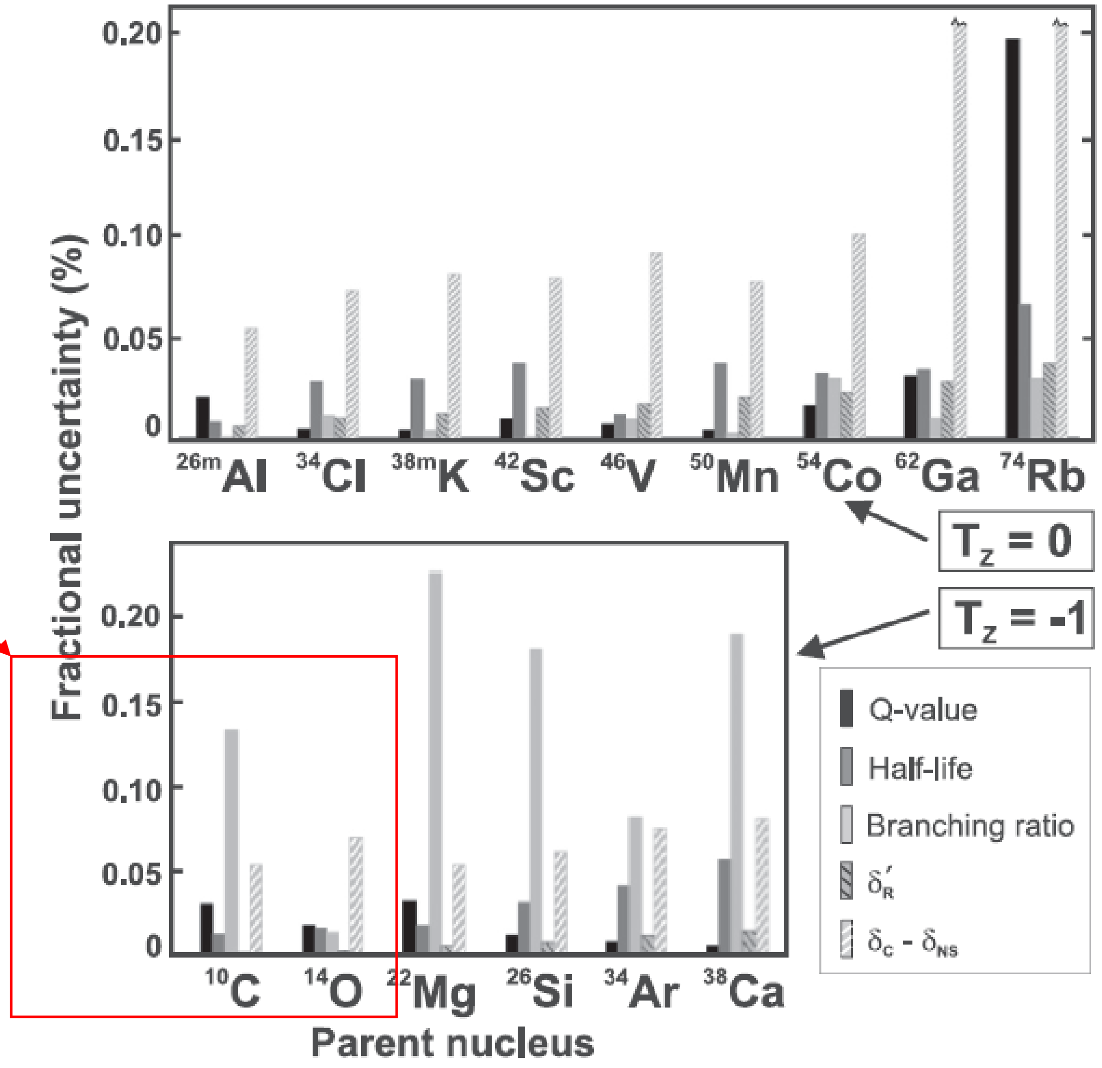




TAMU trap
at Texas A&M

# CKM future?

Improve measurements of $^{10}C$?
Ab-initio theory doable and suggests focusing experimental efforts on it.

New experiments?




From Hardy & Towner,
Phys. Rev. C **102**, 045501 (2020).

# CKM unitarity tests

Needs:
Further improvements in modeling for radiative corrections
New data to help with systematics of isospin breaking
$V_{\mathrm{ud}}$ from $^{10}$C promises to be easiest to interpret

$V_{\mathrm{ud}}$ from neutron should reach similar precision as 0+ → 0+ in next 10 years.

PIONEER experiment ($V_{\mathrm{ud}}$ from pion decay) aimed at similar precision.

# Double beta decays and nuclear structure

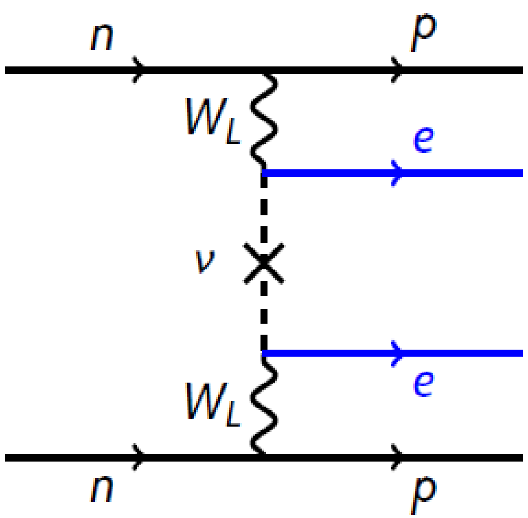



Diagram proportional to effective "Majorana mass" of light neutrinos,

$$\overline{m_\nu} = \sum_{i=1,3} U_{ei}^2 m_i$$

if 0νββ decay is seen → neutrinos are their own antiparticles.

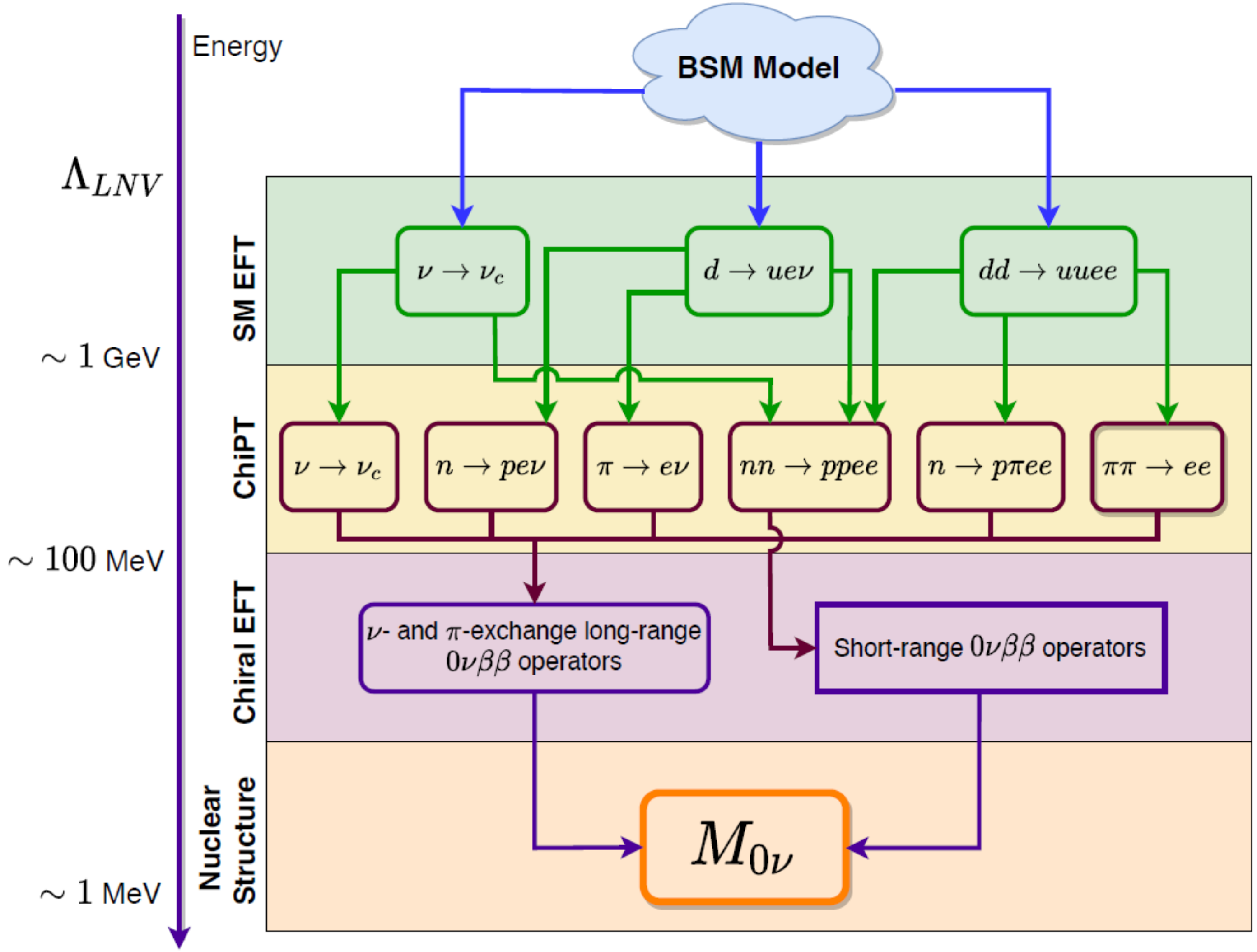
Rates depend on squares of unknown nuclear matrix elements

$$\frac{dN}{dt} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} + M_T^{0\nu} - 2 g_{NN} M_{CT}^{0\nu} \right|^2 \quad |\overline{m_\nu}|^2$$

Need to compute and assign uncertainty so experimentalists can
1. plan experiments
2. draw conclusions from results

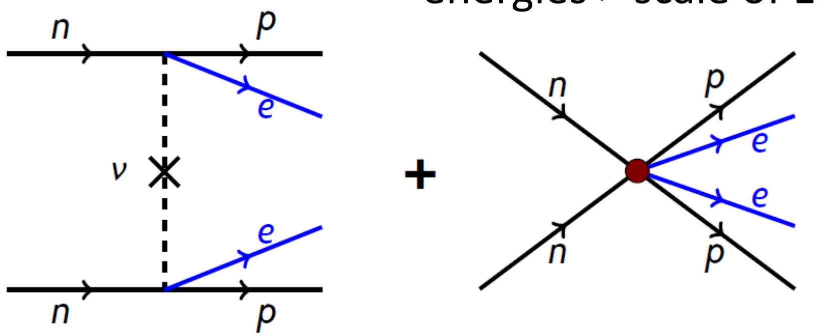
# Double beta decays and nuclear structure

## How We Understand Things: A Tower of EFTs



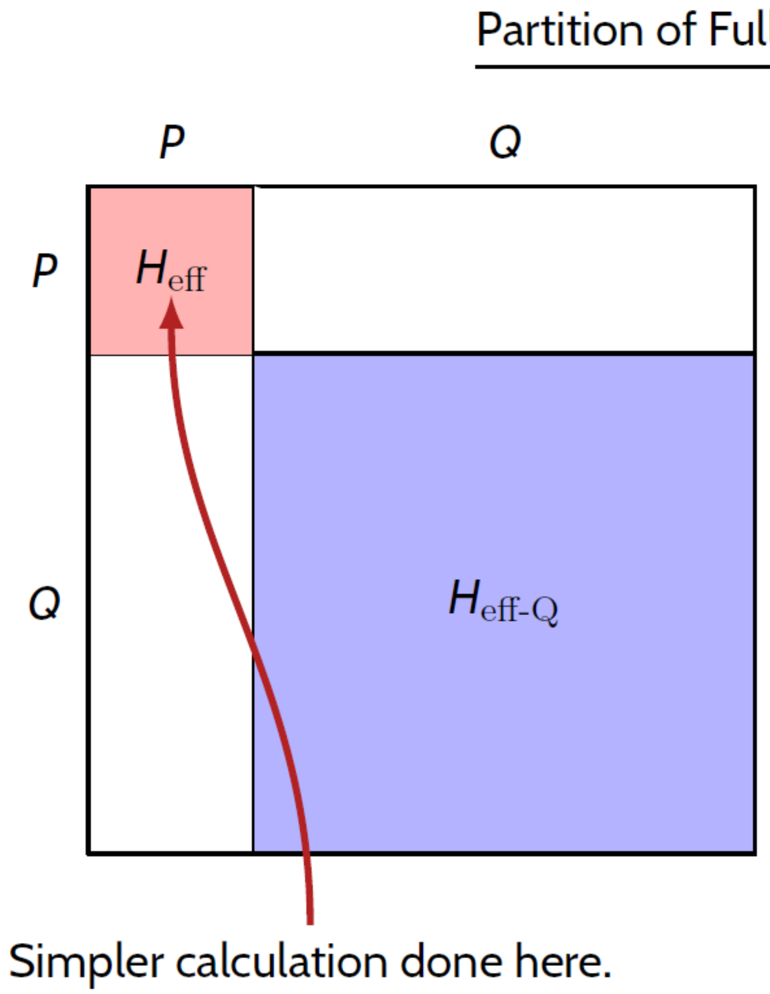

Usual long-range exchange

Contact term from short-range exchange at energies > scale of EFT.



# Double beta decays and nuclear structure

## Ab Initio Nuclear-Structure for Heavy Nuclei




*P* = subspace you want
*Q* = the rest

Task: Find unitary transformation to make *H* block-diagonal in *P* and *Q*, with $H_{\text{eff}}$ in *P* reproducing most important eigenvalues.

Must must apply same unitary transformation to transition operator.

many-body effective operators (beyond 2- or 3-body) can be treated approximately

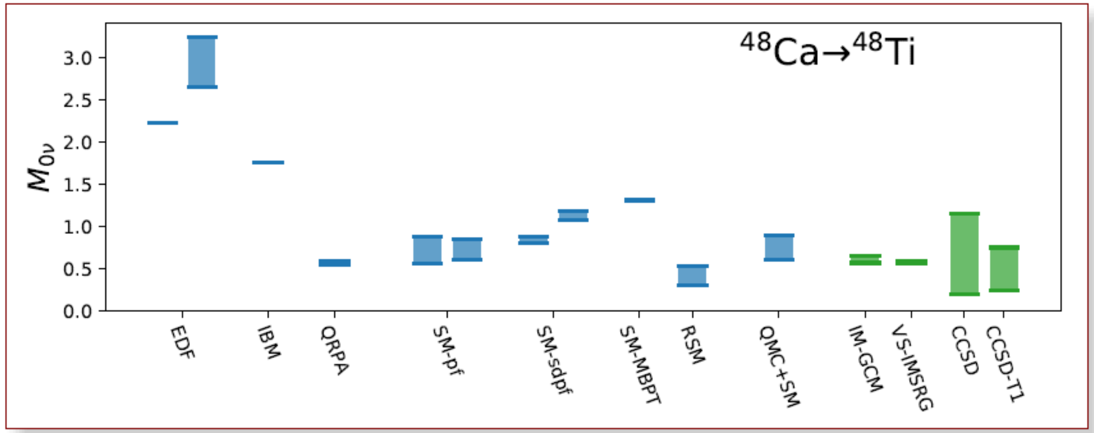
# Double beta decays and nuclear structure

## Ab Initio Light-$\nu$-Exchange Matrix Elements for $^{48}$Ca

### In-Medium Generator Coordinate Method and Coupled Clusters

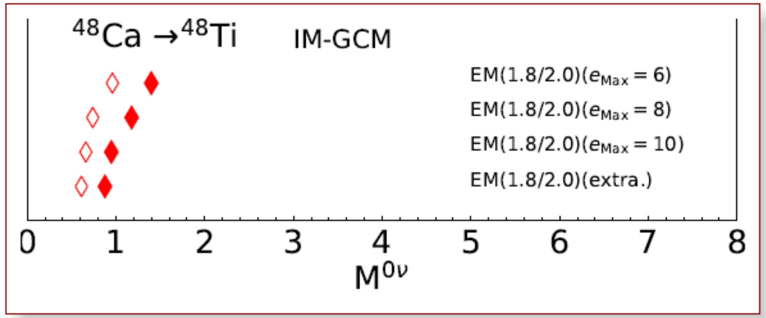
Ab initio results are leading order in $\chi$EFT

Comparison of all methods: no contact




Yao, Bally, Engel, Wirth, Rodríguez, Hergert
PRL **124**, 232501 (2020)

Novario, Gysbers, Engel, Hagen, Jansen, Morris, Navrátil, Papenbrock, Quaglioni
PRL **126**, 182502 (2021)




Effect of contact in “IM-GCM”

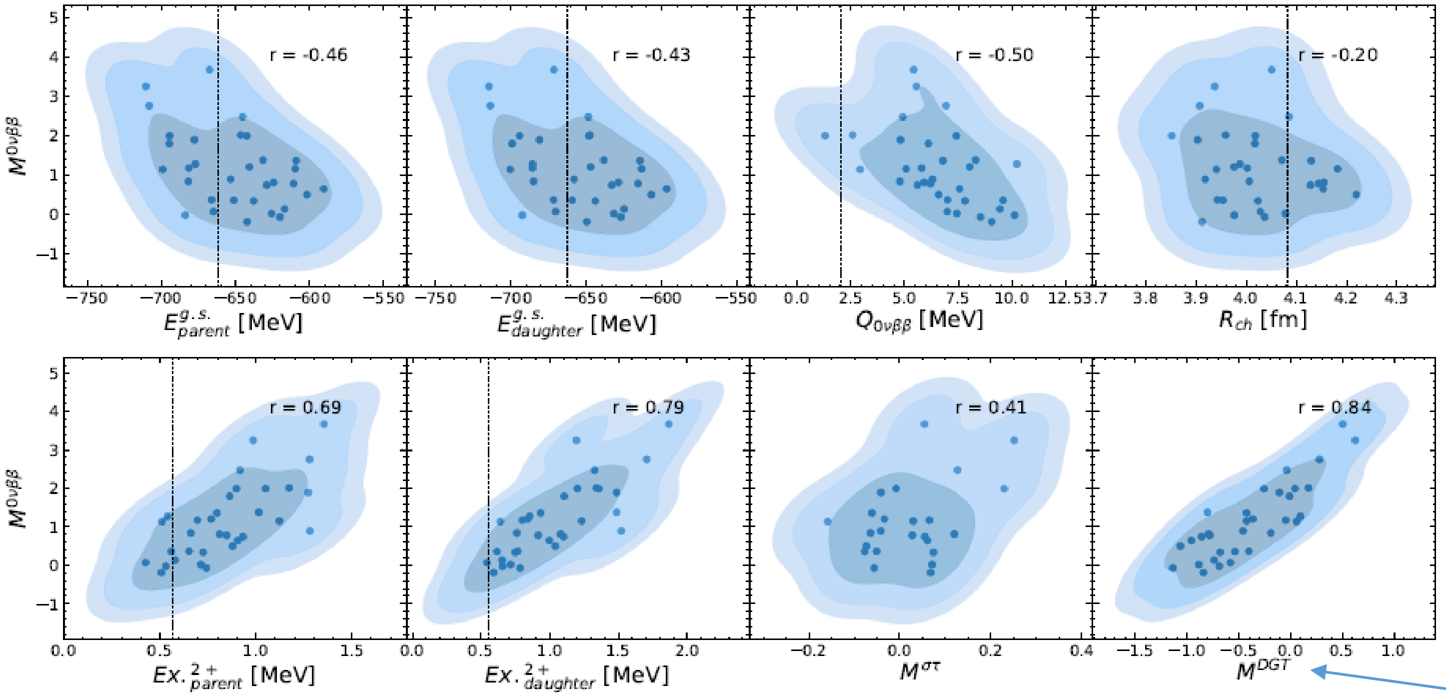
Cirigliano et al.
PRL **120**, 202001 (2018).

# Double beta decays and nuclear structure

## Heavier Elements

Valence-Space In-Medium Similarity Renormalization Group

Results in $^{76}$Ge for lots of different chiral interactions (A. Belley et al., arXiv:2210.05809)




Matrix elements are small compared to phenomenological ones, but still quite uncertain.

In-Medium Generator-Coordinate Method gives similar results with the particular interaction for which it's been tested.

Results for heavier isotopes in the works.

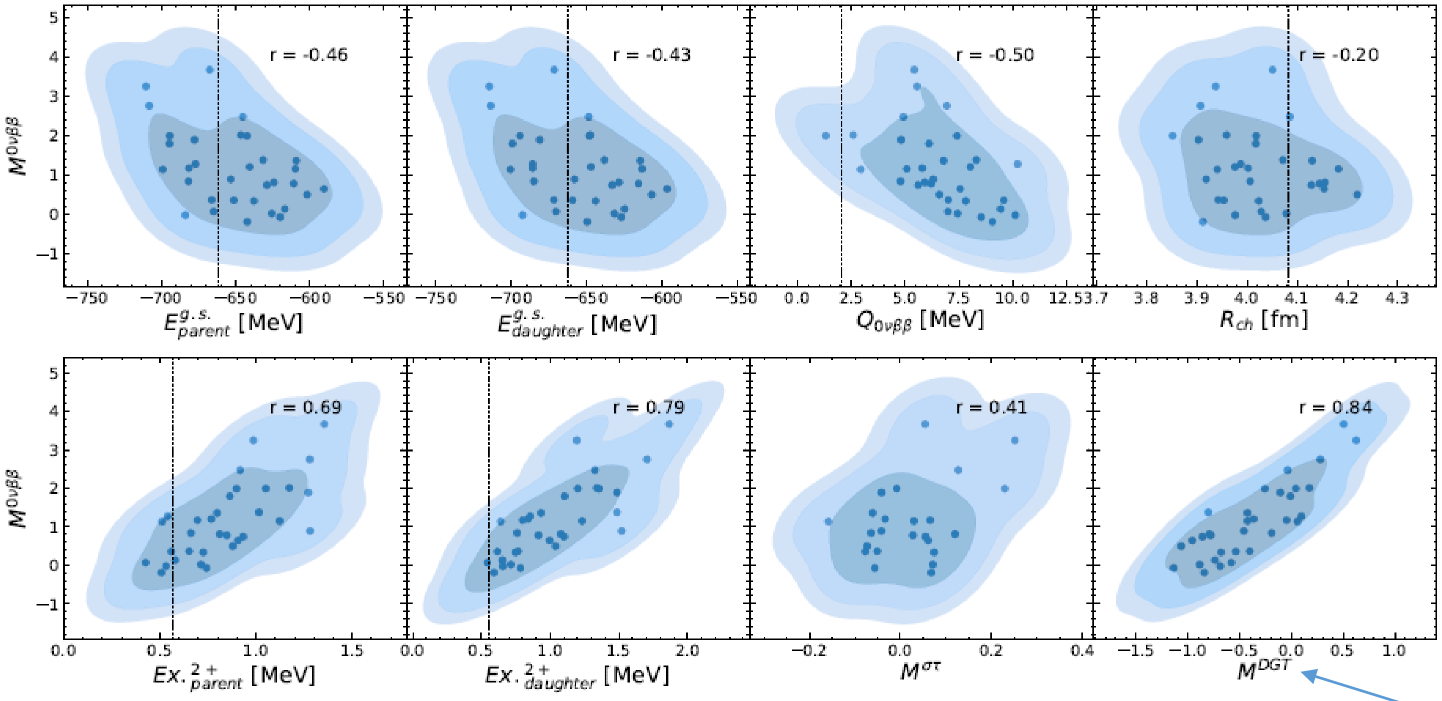
Shimizu, Menendez, Yako
PRL **120**, 142502 (2018)

# Double beta decays and nuclear structure

## Heavier Elements

Valence-Space In-Medium Similarity Renormalization Group

Results in $^{76}$Ge for lots of different chiral interactions (A. Belley et al., arXiv:2210.05809)



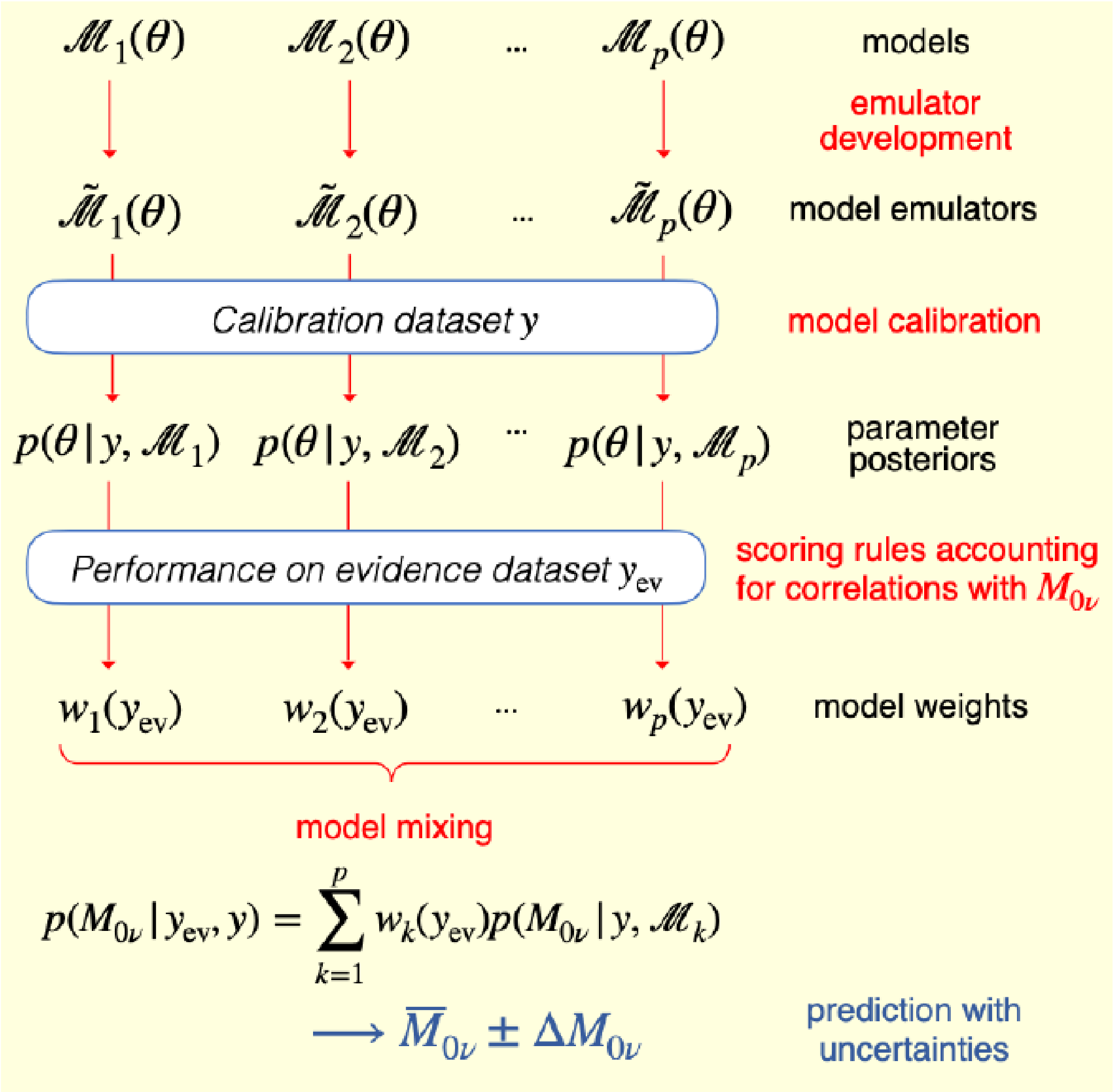

Matrix elements are small compared to phenomenological ones, but still quite uncertain.

In-Medium Generator-Coordinate Method gives similar results with the particular interaction for which it's been tested.

Results for heavier isotopes in the works.

Nice correlation, but difficult to measure

# Double beta decays and nuclear structure




EFT framework allows assessing uncertainties

# Double beta decays and nuclear structure

Modeling has undergone a revolution
EFT allows for a converging scheme
Aiming for determination of uncertainties
Theory developments important for supporting the experimental program

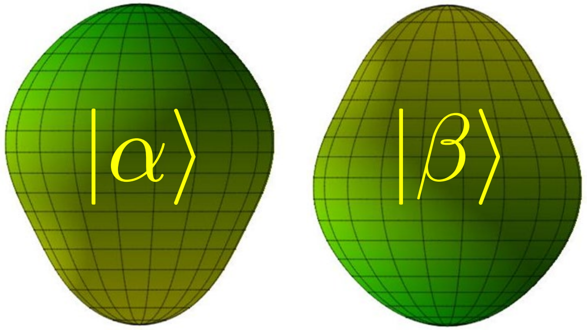
# $P$ and $T$ Violation in Nuclei

$CP$ violation in Standard Model not enough for matter-antimatter asymmetry.
Expect to find new physics responsible for it.

Searches for EDMs a very sensitive probe.
EDMs very small and difficult to measure.

Higher sensitivity via Schiff Nuclear Moments in heavy nuclei→ octupole deformation enhancements

Parity Doublet for high enhancement




Schiff Moment

$$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle \langle ez\rangle}{6}$$

$$S \equiv \langle\Psi_0|\, S_z\, |\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z\, |\Psi_k\rangle \langle\Psi_k|\, V_{PT}\, |\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

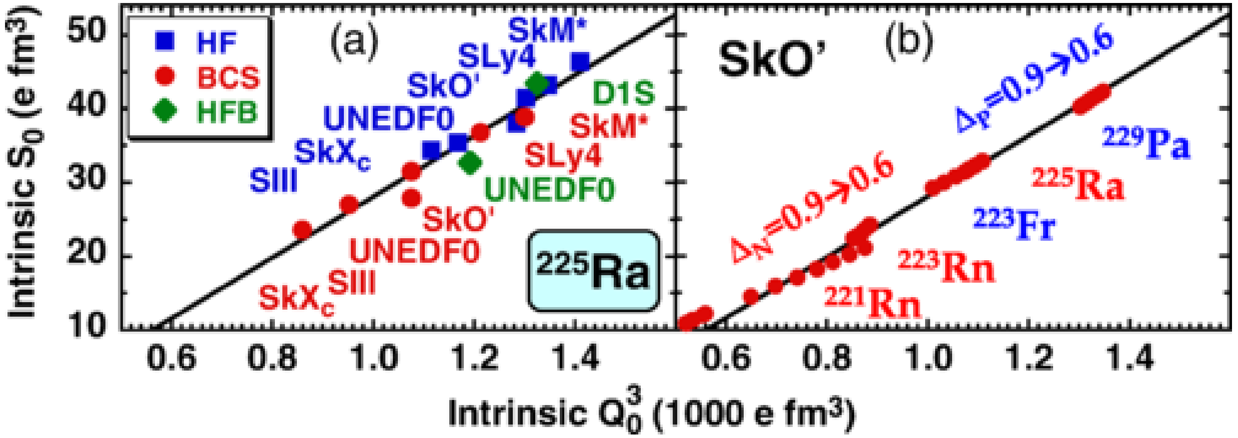
CP-violating physics (unknown)

Nuclear deformation with large Schiff moment

Difference in nuclear energy

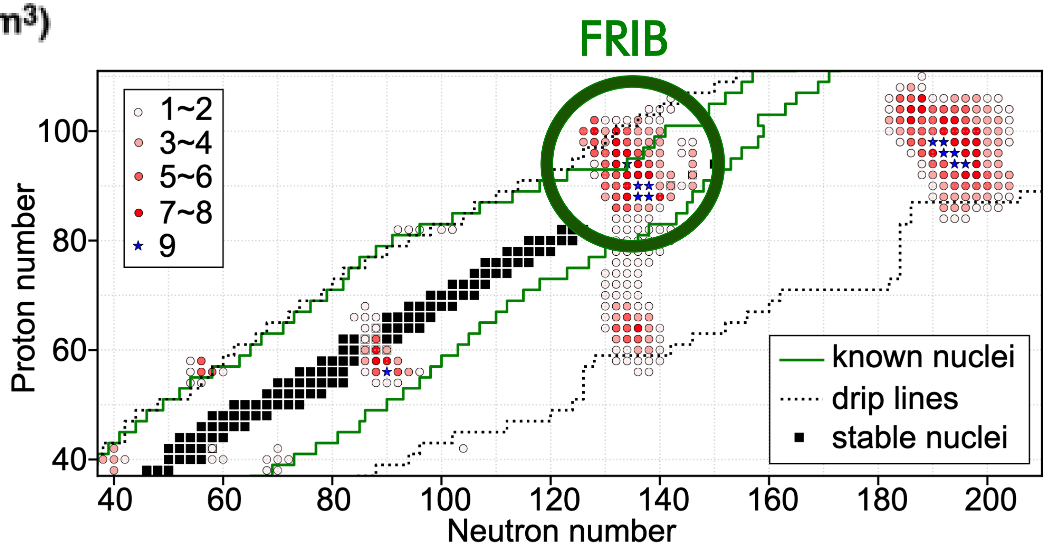
# EDMs: calibrating calculations of Schiff Moments

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$




Dobaczewski, Engel, Kortelainen, Becker
PRL **121**, 232501 (2018)
Cao, Agbemava, Afanasjev, Nazarewicz, Olsen
PRC **102**, 024311 (2020)

Nuclear structure measurements combined with nuclear theory can calibrate the new physics sensitivity of “enhancer” isotopes with uncertainty quantification.



# Nuclear Schiff Moment (NSM) and Magnetic Quadrupole Moment (MQM)

$$S = \underbrace{\kappa_p d_p + \kappa_n d_n}_{\text{short range single nucleon EDMs}} + \underbrace{a_1 g_1 + a_2 g_2}_{\text{long range CPV pion-nucleon couplings}}$$

↓

$$\kappa_p, \kappa_n, a_1, a_2 = \text{from nuclear structure}$$

↑

$$\mathtt{MQM} = \underbrace{\kappa'_p d_p + \kappa'_n d_n}_{\text{short range single nucleon EDMs}} + \underbrace{a'_1 g_1 + a'_2 g_2}_{\text{long range CPV pion-nucleon couplings}}$$

# EDMs: Current Status of Nuclear Structure for CPV Searches

| isotope | $k_p$ | $k_n$ | $a_0$ | $a_1$ | most recent NSM search | experimental status for NSM search |
|---|---|---|---|---|---|---|
| Xe-129 | | X | X | X | 2019 | brand new effort being planned |
| Yb-171 | | | | | 2022 | upgrades underway |
| Hg-199 | X | X | X | X | 2016 | 30-yr–old with another factor of 3 improvement possible |
| Tl-205 | X | | X | X | 1991 | new effort with modern techniques under development |
| Ra-225 | | | X | X | 2016 | upgrades underway |
| Pa-229 | | | X | X | - | some proposals exist |

X = looks okay    X = more work needed

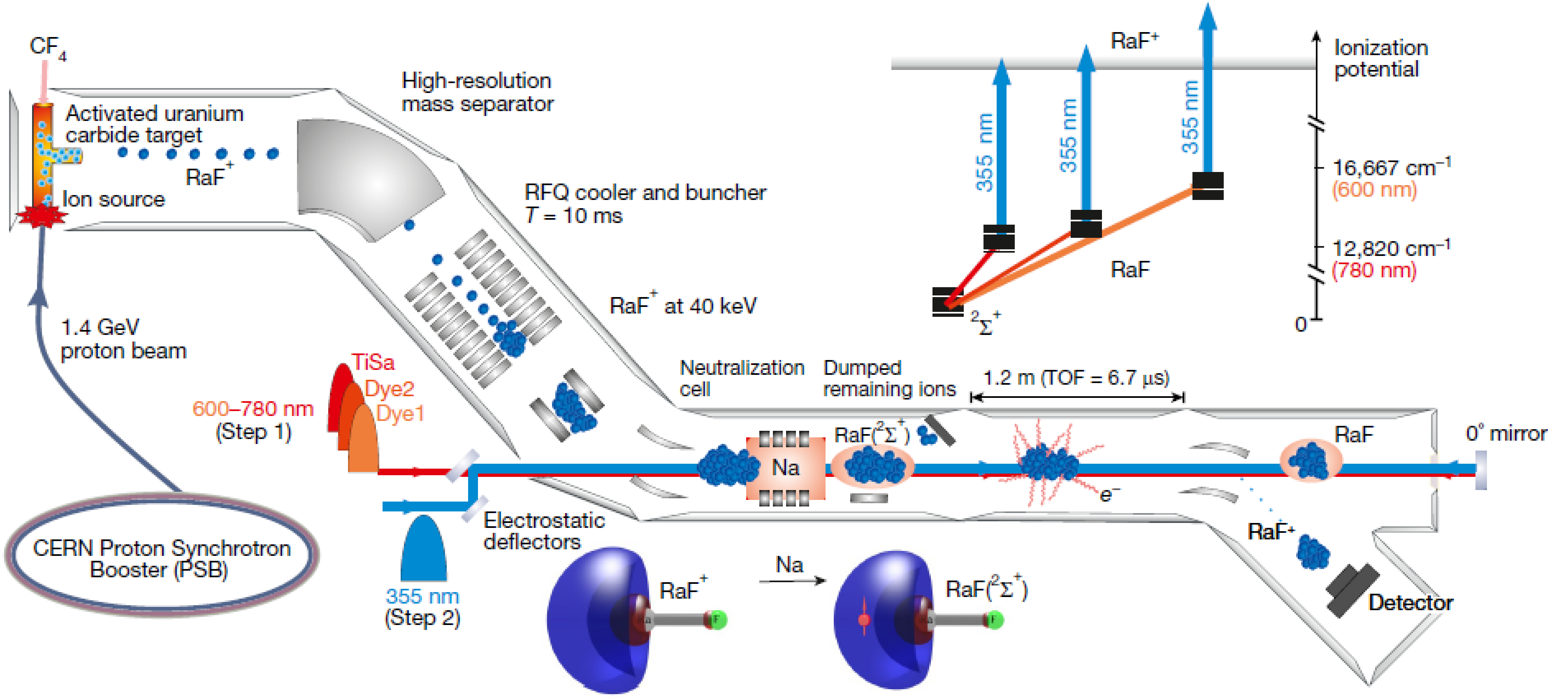
$a_0$ and $a_1$ (NSM) needs joint nuclear structure theory/experiment effort via Coulomb excitation experiments and low energy gamma ray spectroscopy ($^{229}$Pa)

MQM searches planned in $^{173}$Yb and $^{181}$Ta – needs nuclear theory support

# $P$ and $T$ Violation in Nuclei

In addition to shape enhancements →
huge electric field enhancements using dipolar molecules

Garcia-Ruiz et al.
Nature **581**, 396 (2020)






Thanks: Ronald Garcia-Ruiz

# $P$ and $T$ Violation in Nuclei

**$P$-even/$T$-odd observables**

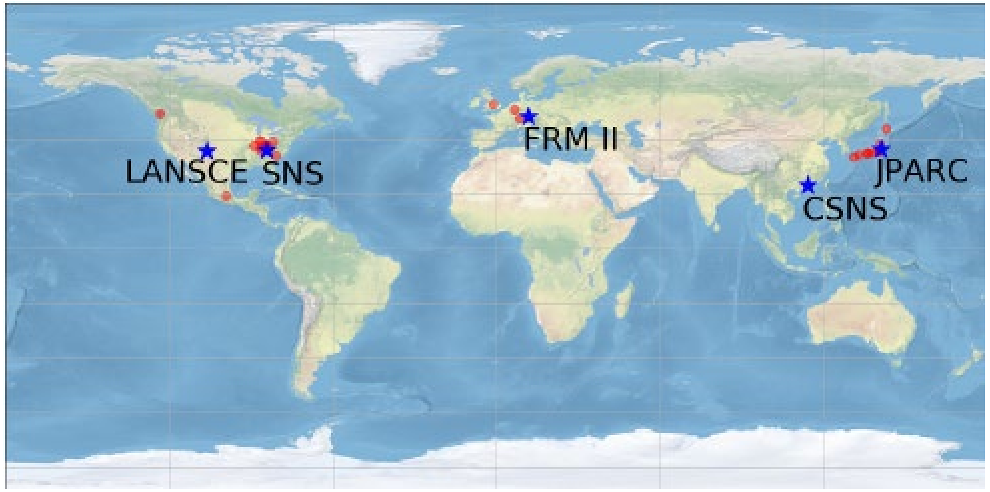
Neutron scattering on tensor-aligned nuclei.
$P$-even/$T$-odd interactions can mix pairs of different $L = 1$ resonances.
Search for contribution to scattering of the form

$$(\vec{k}.\vec{I})\left(\vec{s}.(\vec{k} \times \vec{I})\right)$$

$^{121}Sb$, $^{123}Sb$, $^{127}I$ have large electric quadrupole moments → can be aligned by electric field gradients in crystals at low temps.
Next: get resonance widths, look for enhancements

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

One experiment:
Five neutron sources



# $P$ and $T$ Violation in Nuclei

Many opening opportunities
Enhancement factors can be huge, but experiments are difficult
Selection process needs nuclear structure theory help

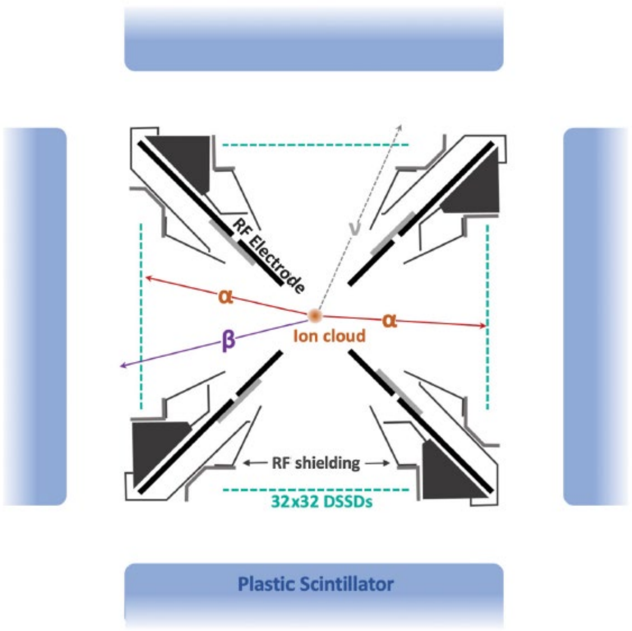
# Searches for Chirality-flipping interactions

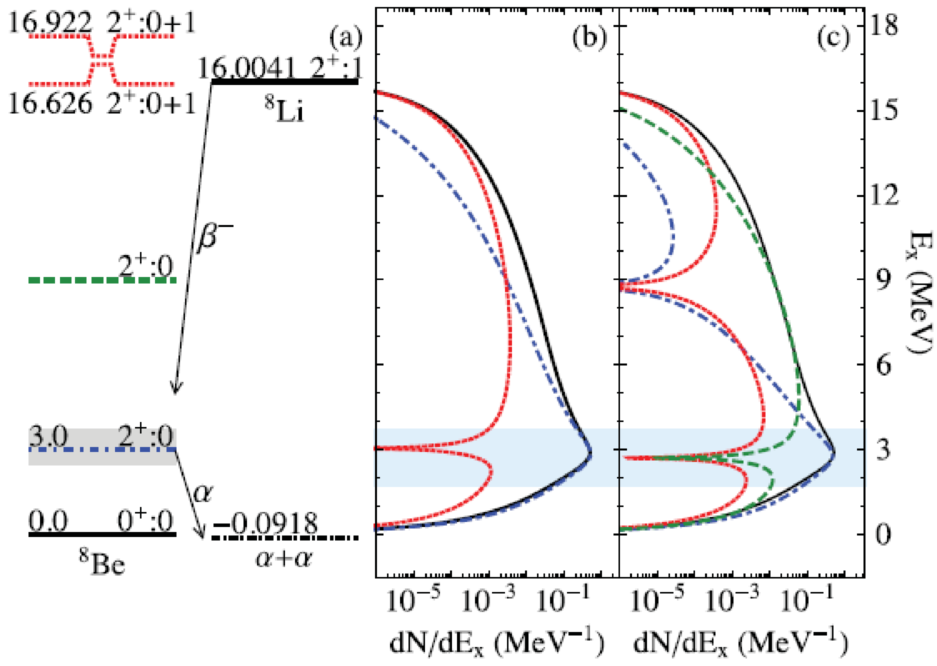
Precise measurements of correlations in beta decays now undergoing a revolution with atom and ion traps

Ion traps with special designs at **Notre Dame and Texas A&M (see above, under CKM)**

Classic $A = 8$ experiment at ANL: recent results

M. T. Burkey *et al.*
PRL **128**, 202502 (2022)
Sargsyan et al.
PRL **128**, 202503 (2022)

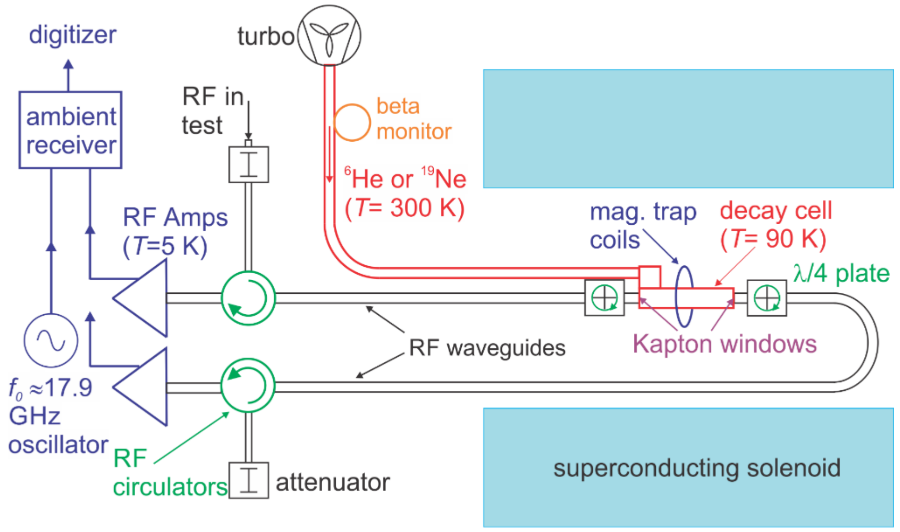


# Searches for Chirality-flipping interactions

New technique for beta spectra measurements → Cyclotron Radiation Emission Spectroscopy (CRES).
Get energy from $\omega = qBc^2/E$
Following Project 8 developments for $^3$H (~18 keV).
Applied to higher endpoints of $^6$He, $^{19}$Ne (~few MeV).

Hope to reach beyond part-per-mille precision to surpass LHC sensitivity.



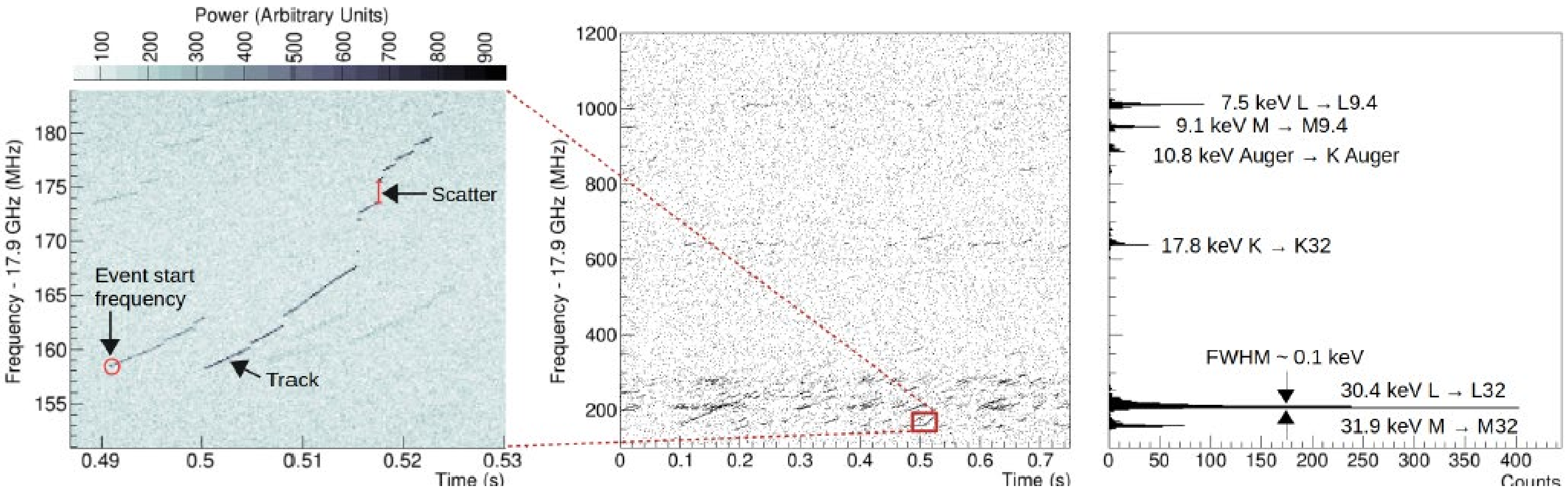

$^6$He-CRES


W. Byron[1], N. Buzinsky[1], W. DeGraw[1], M. Fertl[2], A. Garcia[1], H. Harrington[1], L. Hayen[3], D. McClain[5], D. Melconian[5], P. Mueller[6], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[6], D. Stancil[3], D.W. Storm[1], H.E. Swanson[1], R.J. Taylor[3], B.A. VanDevender[4], F. Wietfeldt[7], A. Young[3]

University of Washington, Johannes Gutenberg Universitat Mainz, North Carolina State University, Texas A&M University, Argonne National Laboratory, Pacific Northwest National Laboratory

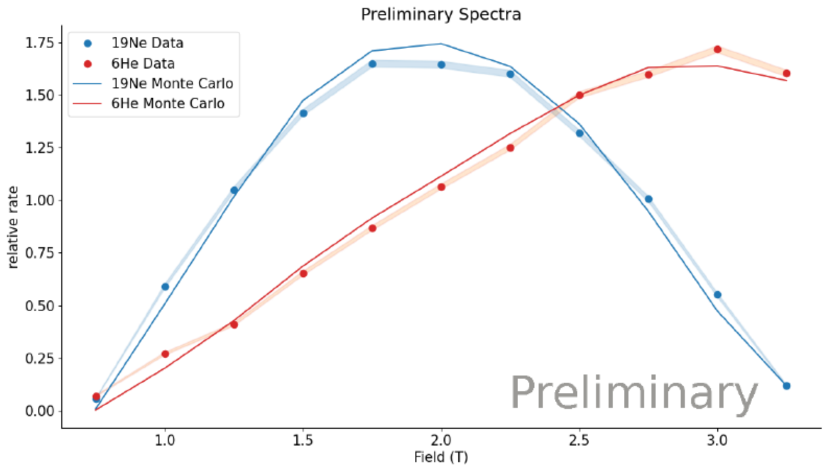
# Searches for Chirality-flipping interactions: CRES

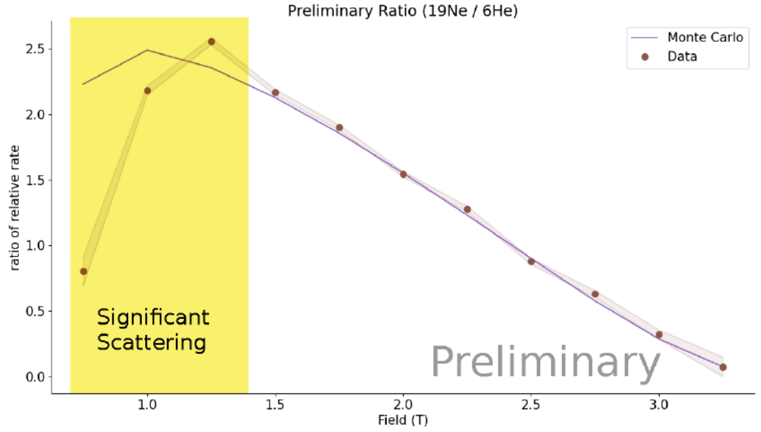
$\omega = qBc^2/E$




https://arxiv.org/abs/2209.02870

$^{83m}$Kr source



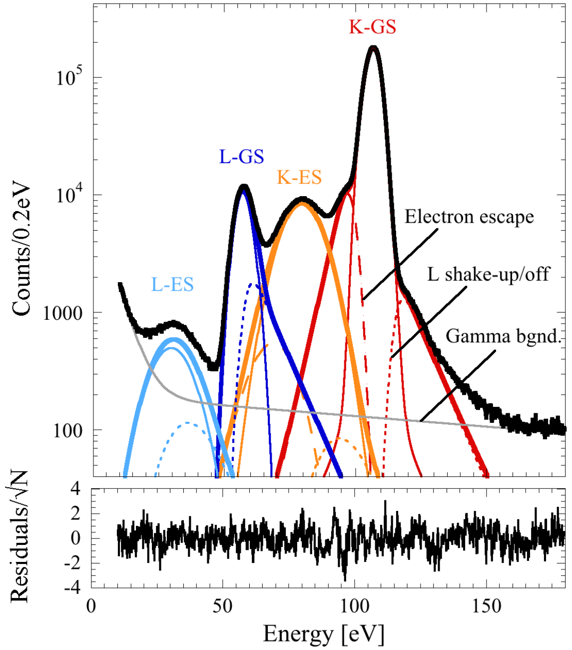

$^{6}$He and $^{19}$Ne preliminary

# Searches for Chirality-flipping interactions

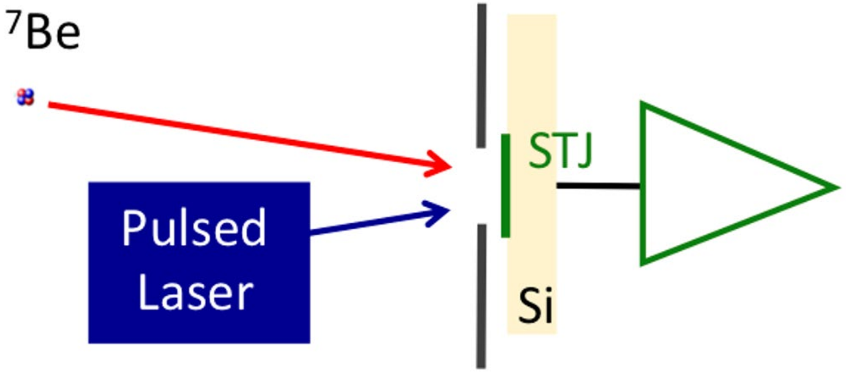
Can reach sensitivities beyond LHC only with nuclear theory, including uncertainties.
→ Recoil-order and radiative corrections that affect the observables.
→ Needed for $^{6}$He, $^{8}$B, $^{14}$O, $^{19}$Ne…

# New Technologies: $^7$Be Decay in Superconducting Tunnel Junctions

Rare-isotope implantation at TRIUMF-ISAC


A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.,* J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, J. Low Temp. Phys. **200**, 200 (2020)

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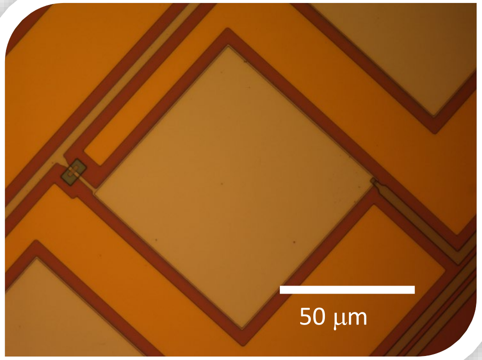
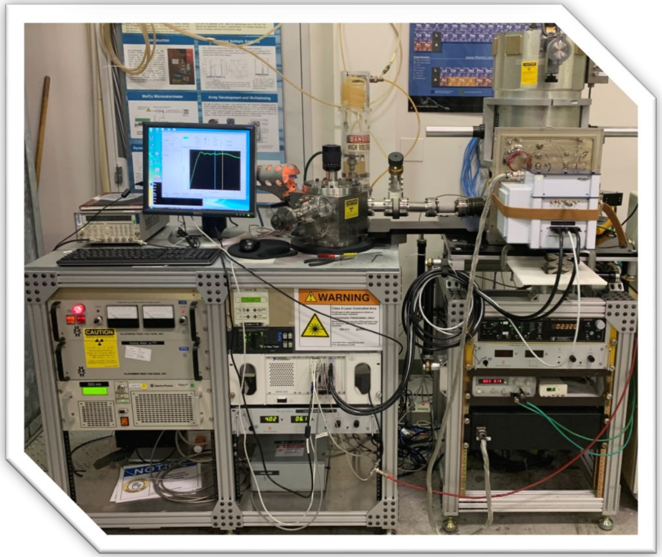
STAR CRYOELECTRONICS

**Ta, Al, and Nb-based STJ Sensors**

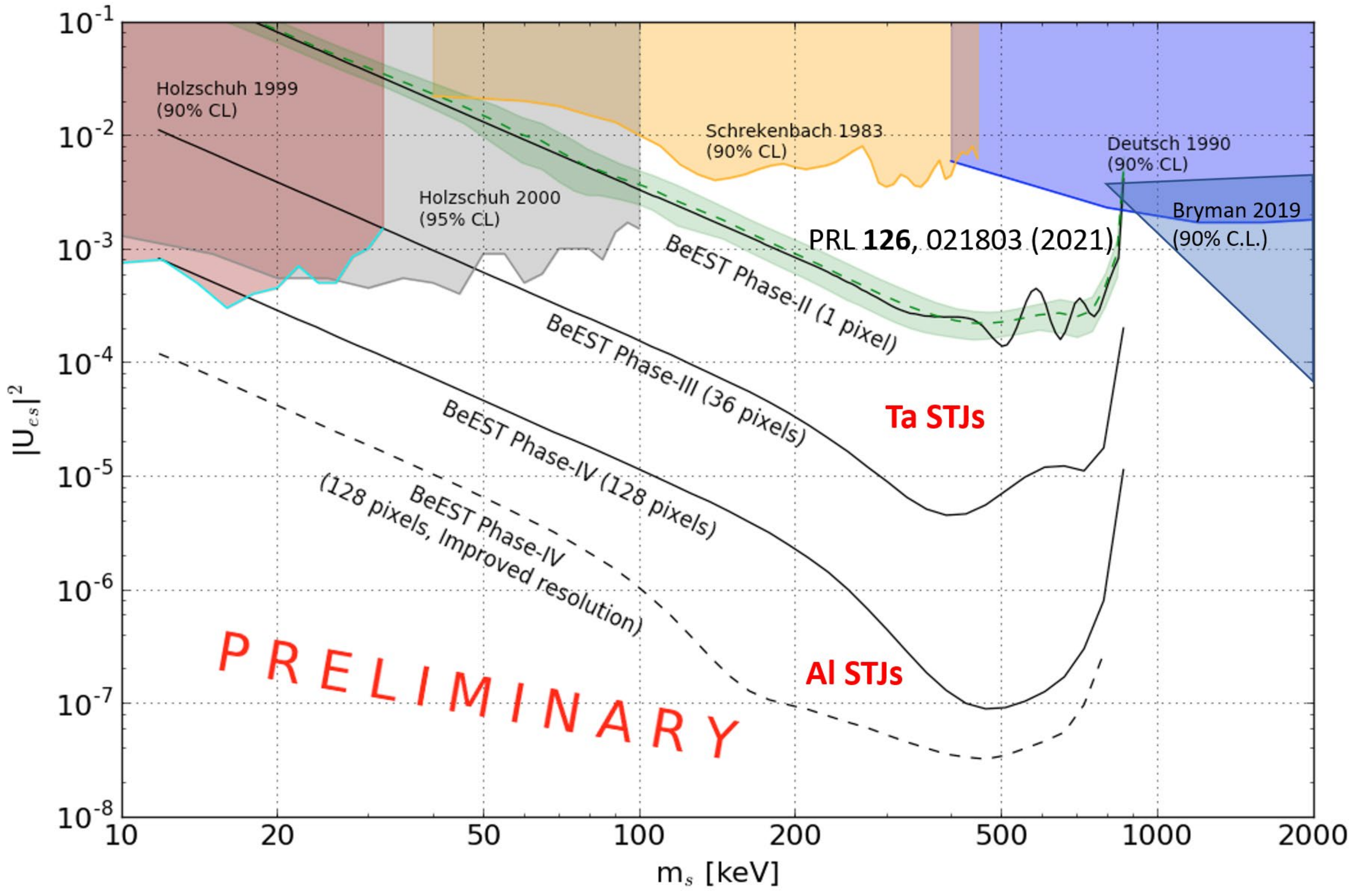


**Garcia- University of Washington**

**Thanks: Kyle Leach**

# New technologies: BeEST limits and projections for future phases




Garcia- University of Washington

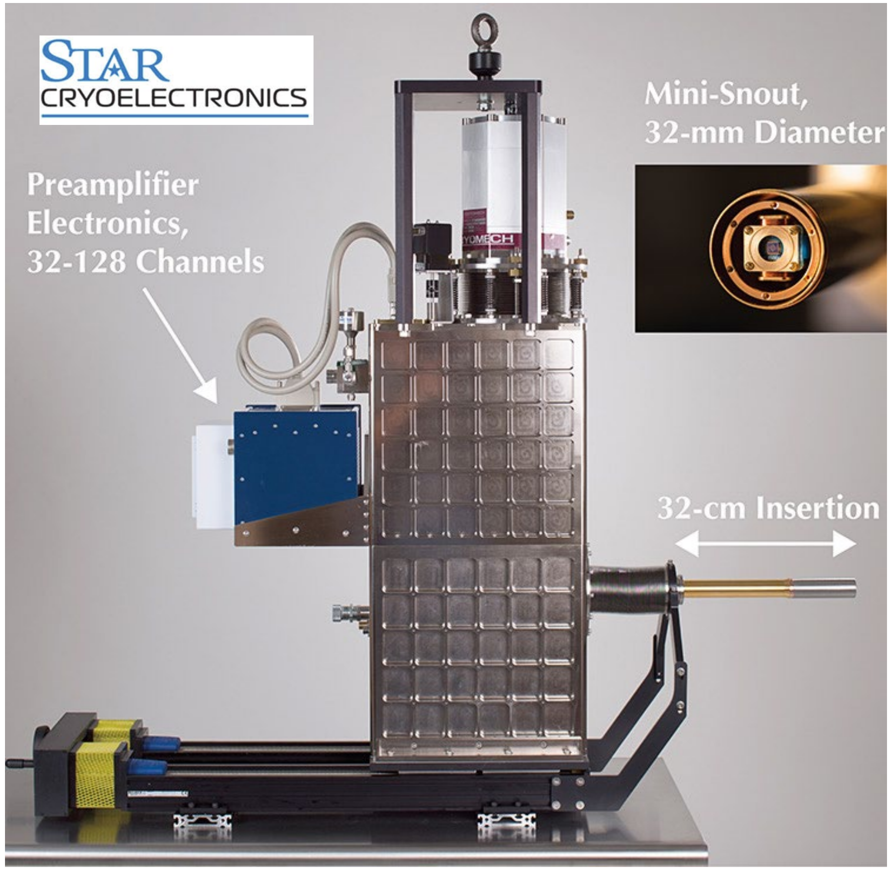
Thanks: Kyle Leach

# New Technologies: implantations at FRIB open up opportunities

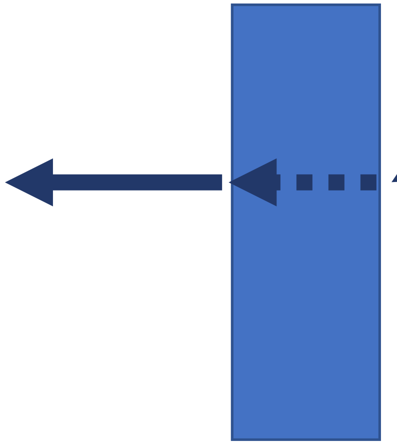
Measure eV-scale nuclear recoil with high precision

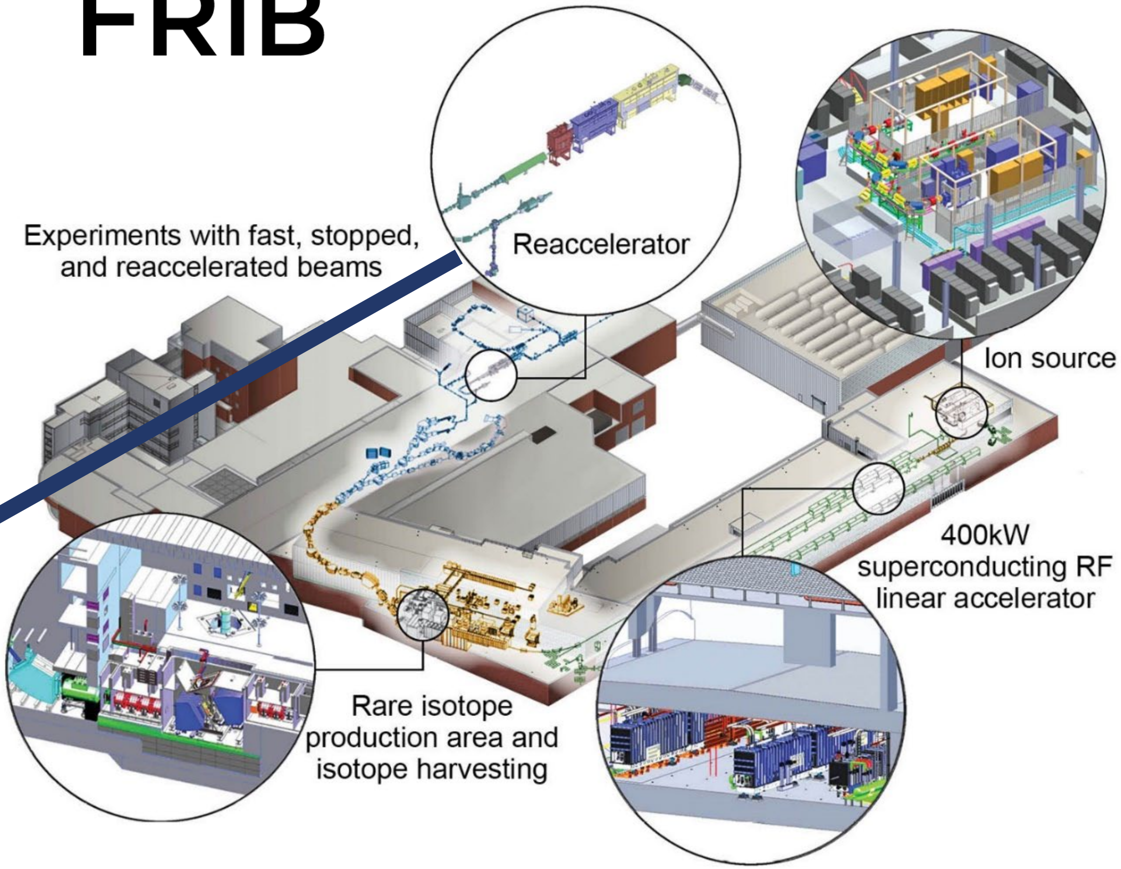
**"Low" Energy ReA beam (~1 MeV/u)**

FRIB




~ 8 μm Al degrading foil






**Garcia- University of Washington**

**Thanks: Kyle Leach**

# Summary

Experiencing a revolution in our field brought by:

1. New technologies
   → ion and atom traps combined with RIBs
   → completely new ways of detection imported from other fields (RF astronomy, Superconducting Tunnel Junction…
2. Improved theory allowing for optimizing opportunities and calculating SM expectations, including uncertainties.