

Status update on the next-generation Penning-trap mass spectrometry at TITAN

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TRIUMF, McGill University

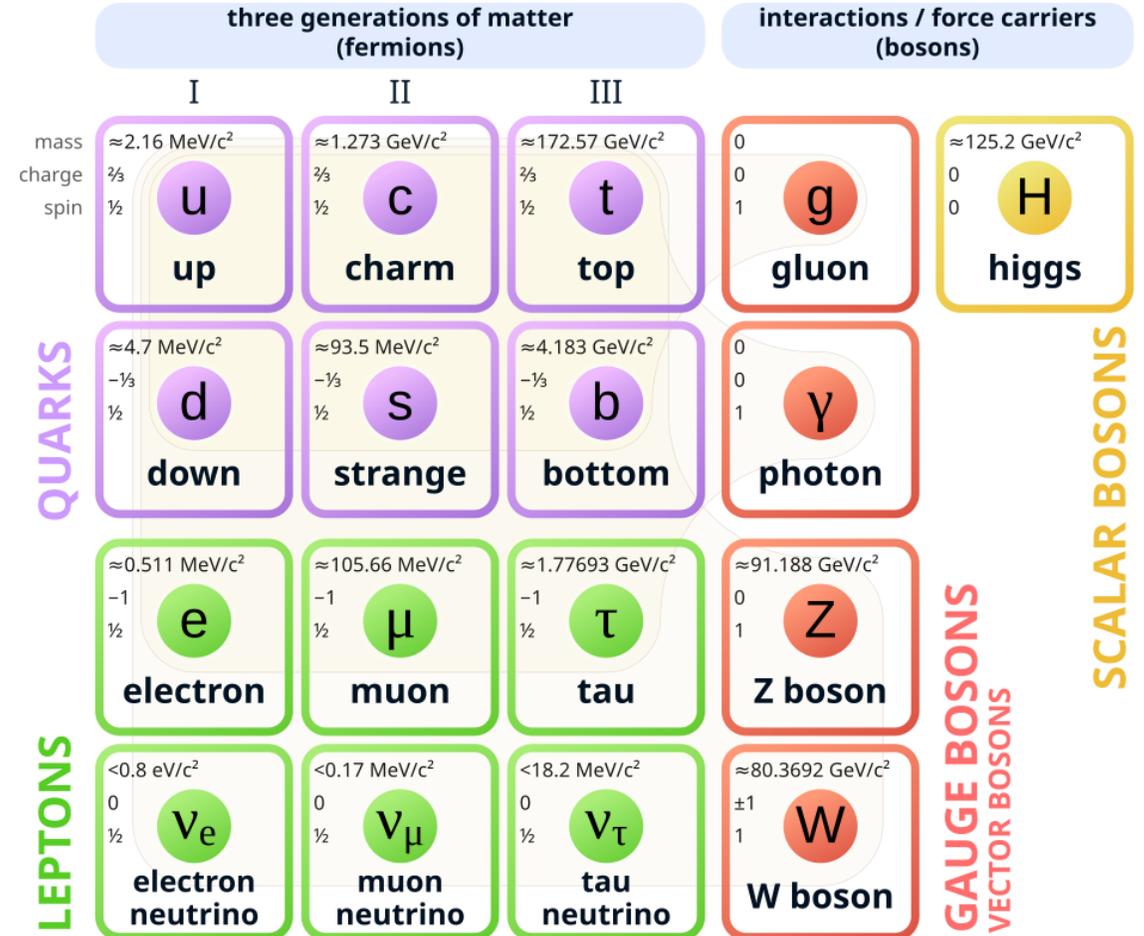
Motivation

- Investigating the Standard Model requires high precision and accurate mass spectrometry

$$\frac{\delta m}{m} < 10^{-8}$$

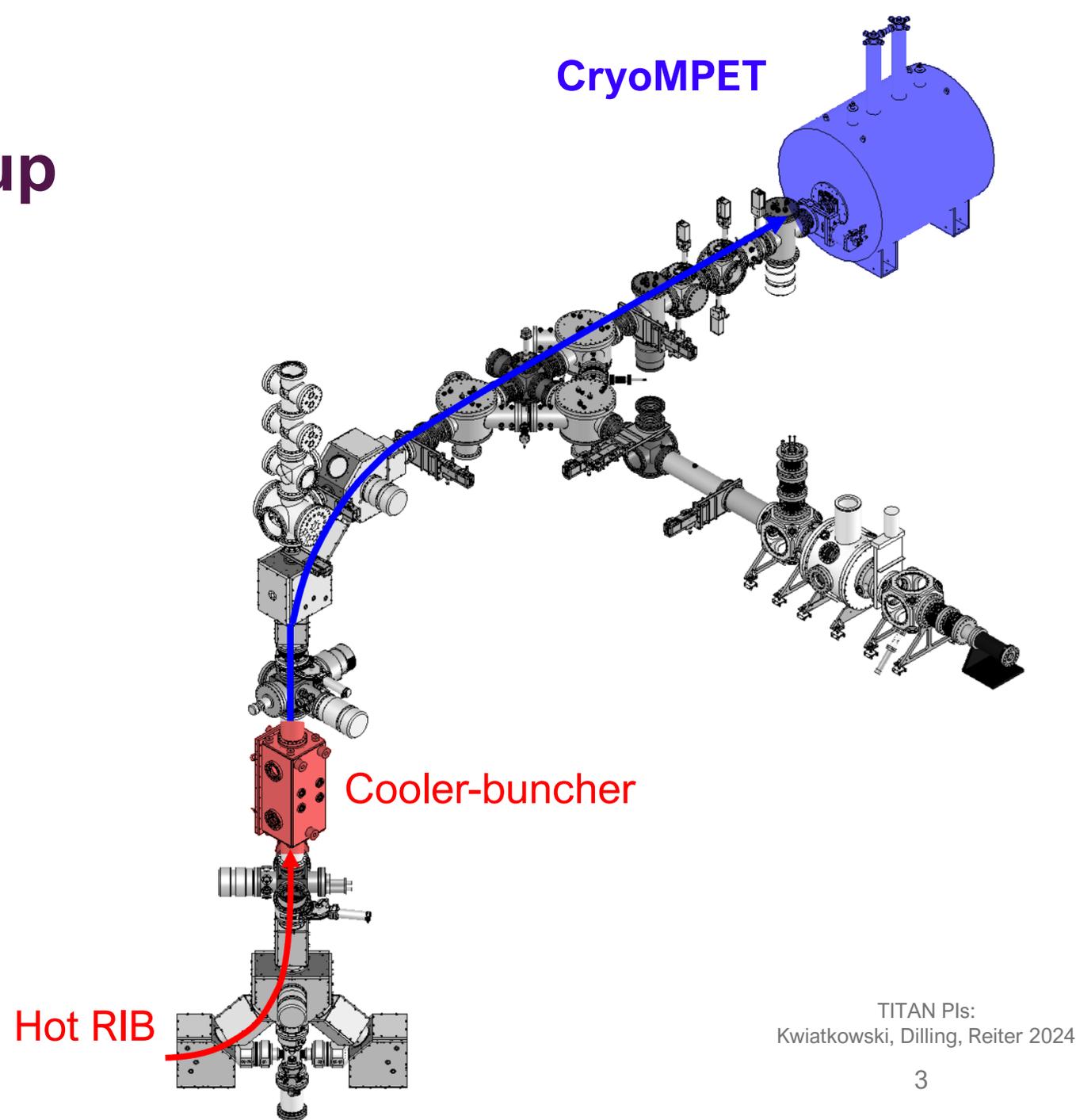
- E.g. Testing the unitarity of quark mixing
- Can only be done with Penning Trap Mass Spectrometry
 - Radioactive ion experiments routinely achieve $\frac{\delta m}{m} \approx 10^{-9}$

Standard Model of Elementary Particles



TITAN Experimental Setup

- Continuous Radioactive Ion Beam (RIB) received from TRIUMF
 - Ions produced by ISOL technique
 - Ions then accelerated to 20keV and sent to TITAN
- Cooler-buncher accumulates, cools ions, and sends bunches to cryogenic Measurement Penning Trap (CryoMPET)



Penning Trap Mass Spectrometry

- Apply a quadrupolar electric field inside a strong magnetic field to trap ions
 - Inside the trap, ions have three eigenmotions:

$$\nu_+ \gg \nu_z \gg \nu_-$$

- Goal is to measure the ion's cyclotron frequency:

$$\nu_c = \frac{1}{2\pi} \frac{qB}{M} \approx \nu_+ + \nu_-$$

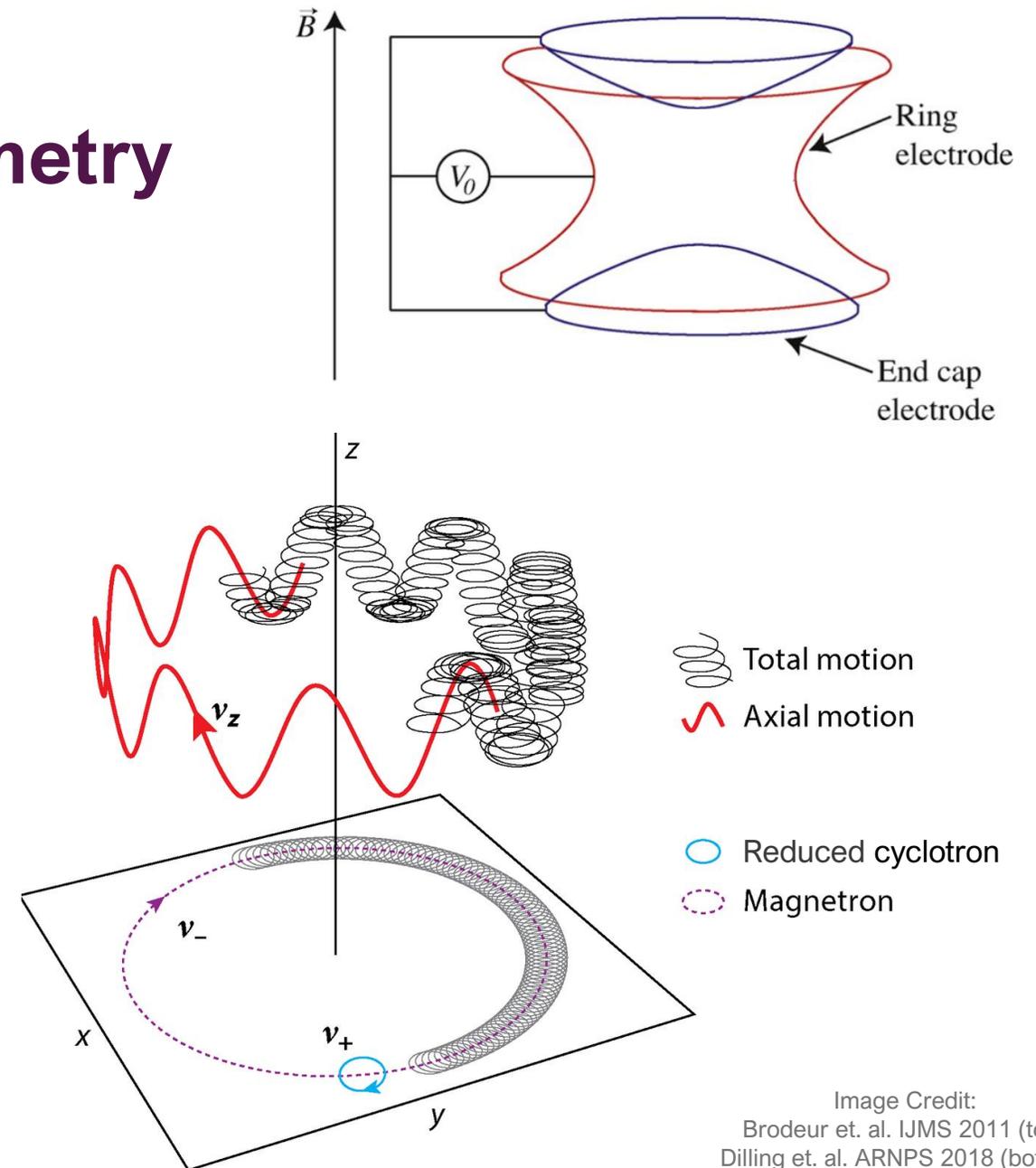
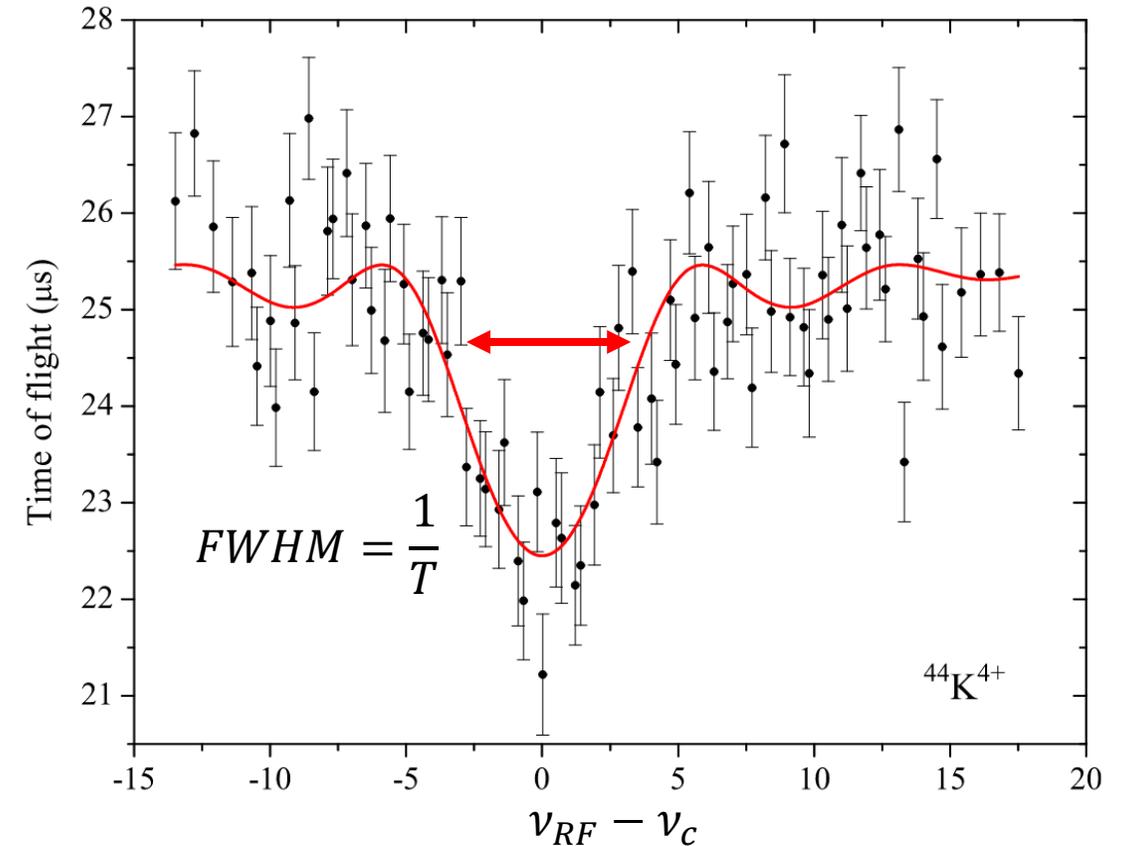


Image Credit:
 Brodeur et. al. IJMS 2011 (top)
 Dilling et. al. ARNPS 2018 (bottom)

Highly Charged Ions Boost Precision

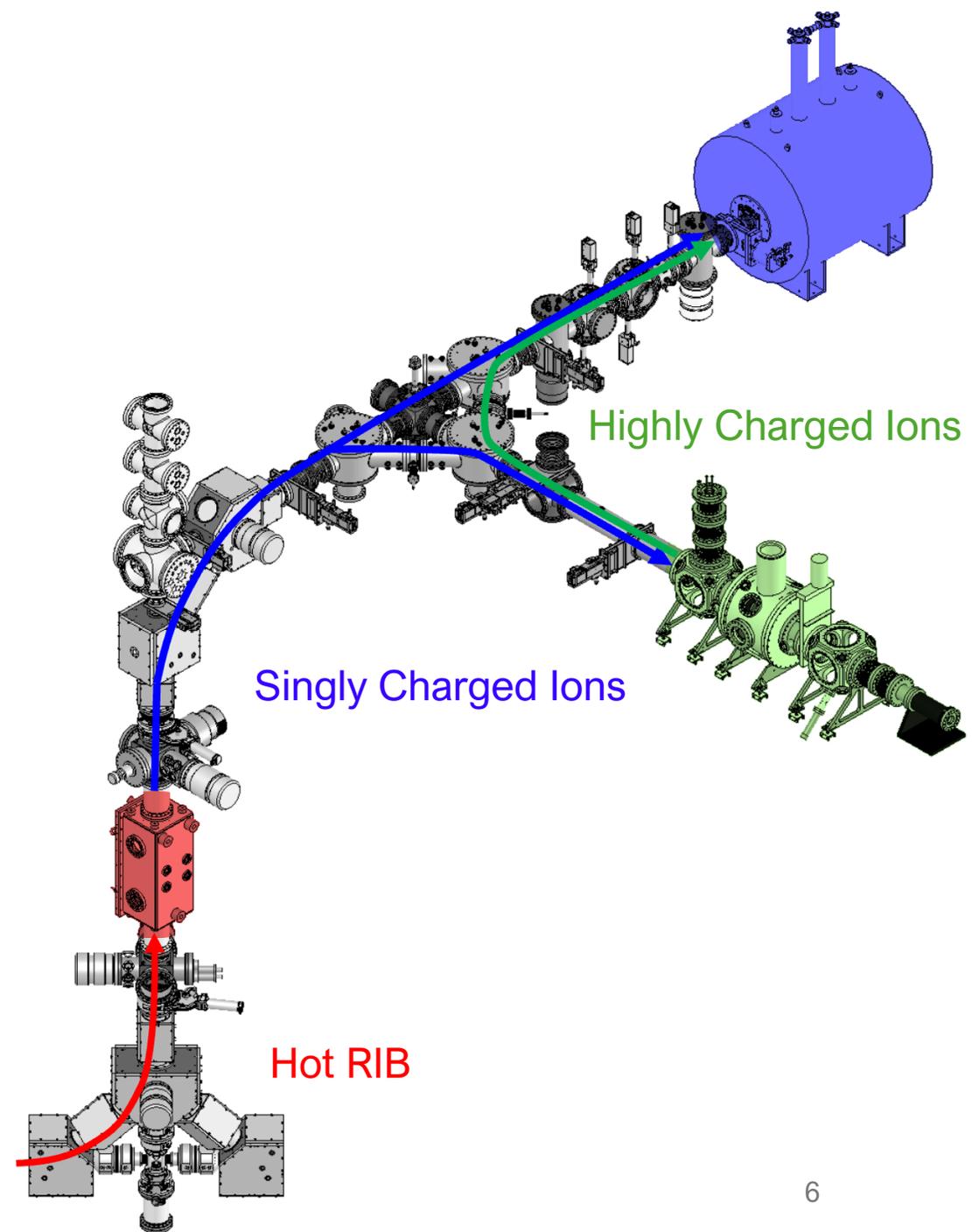
- Precision: $\frac{\delta m}{m} \propto \frac{1}{qTB\sqrt{N}}$
 - Bollen et. al. JAP 1990
- N = statistics ➤ limited by statistics
- B = magnetic field ➤ limited by technology
- T = measurement time ➤ limited by $T_{1/2}$
- q = charge ➤ limited by Z
 - q can improve > 2-3x



- Analytic fit: M. Koenig, et. al. IJMSIP 1995

TITAN's ms Charge Breeder

- ms charge breeder allows for production of higher charge states
 - Bonus: beam purification
- Challenges of Highly Charged Ions:
 - Higher risk of charge exchange ➤ less efficiency
 - Less measurement time due to charge exchange ➤ less precision



Upgrade 1: Cryogenic Trap

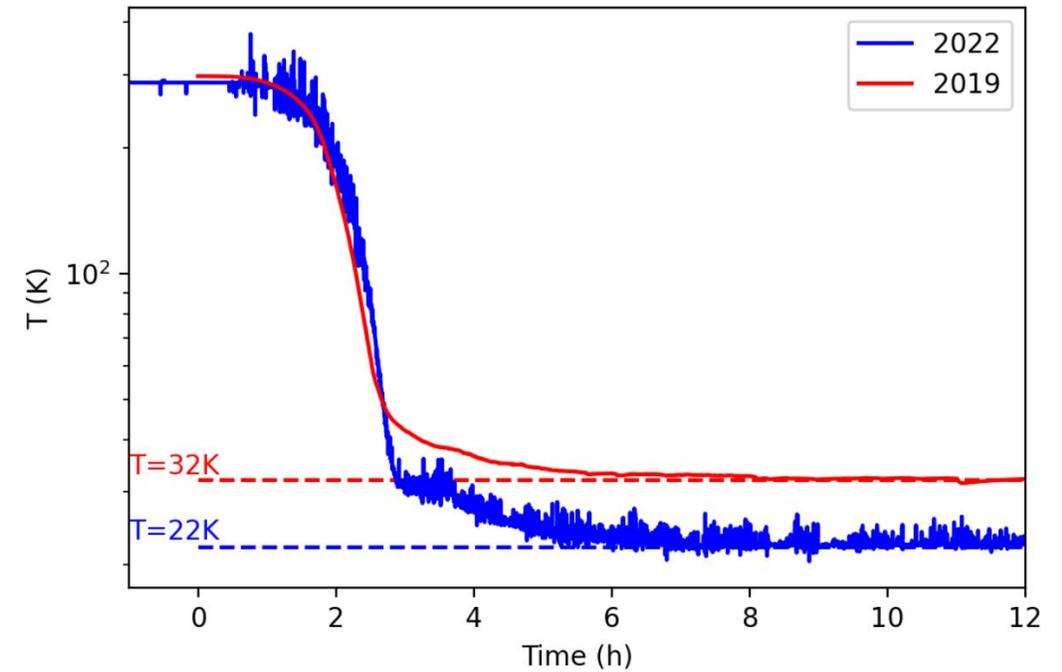
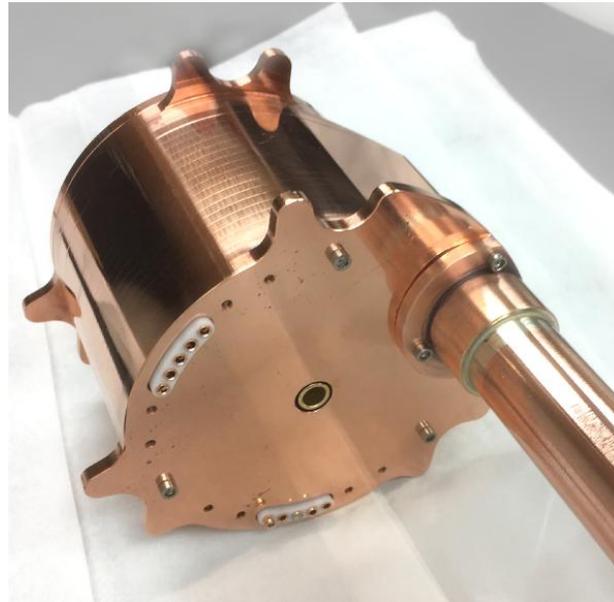
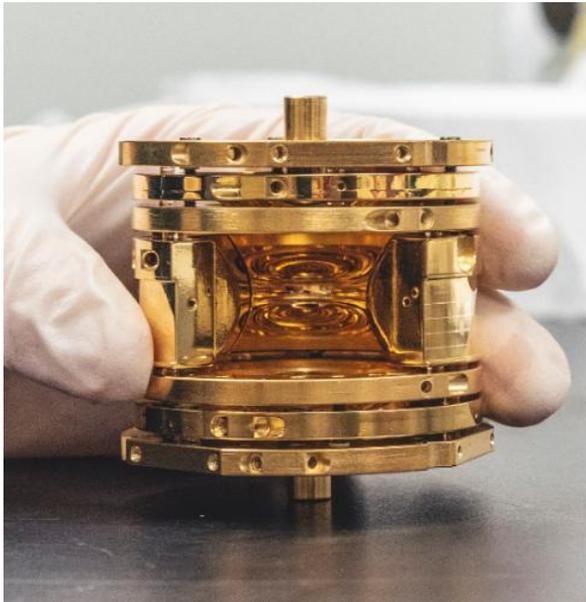


Image Credit:
Leistenschneider PhD thesis 2019 (left two)
Lykiardopoulou PhD thesis 2023 (right)

Vacuum improvements manifest longer measurement times

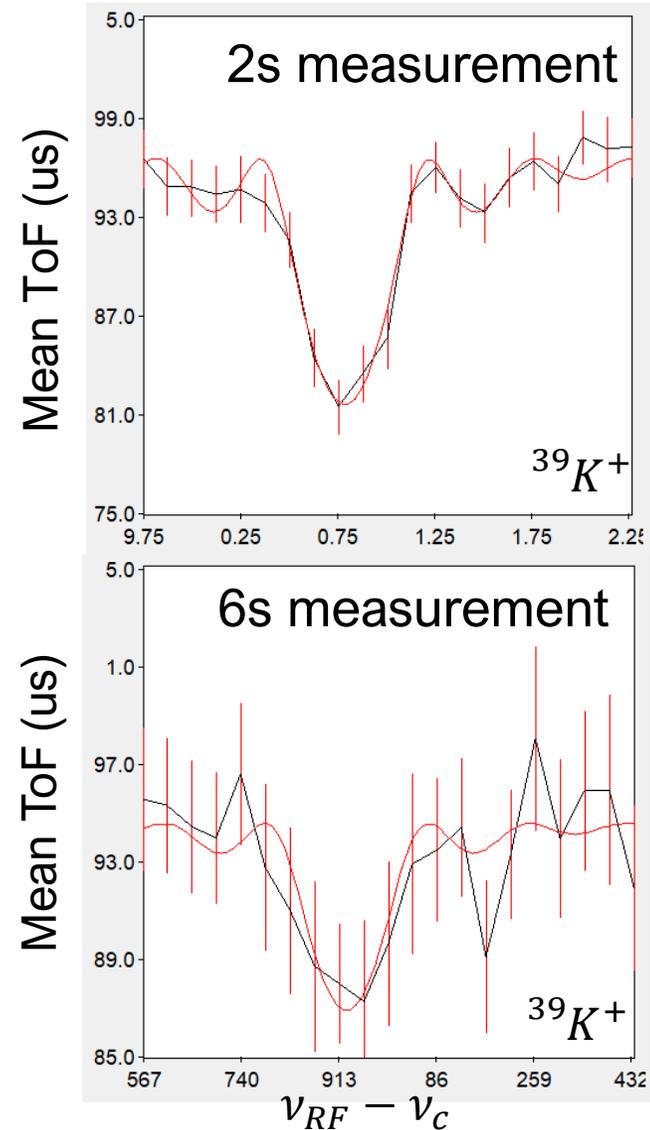
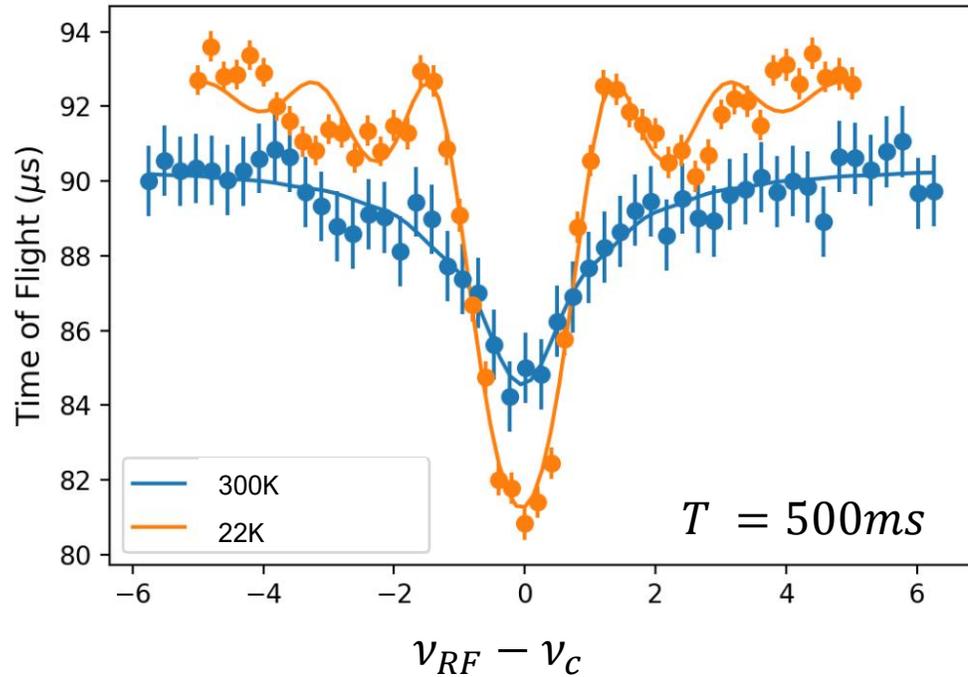
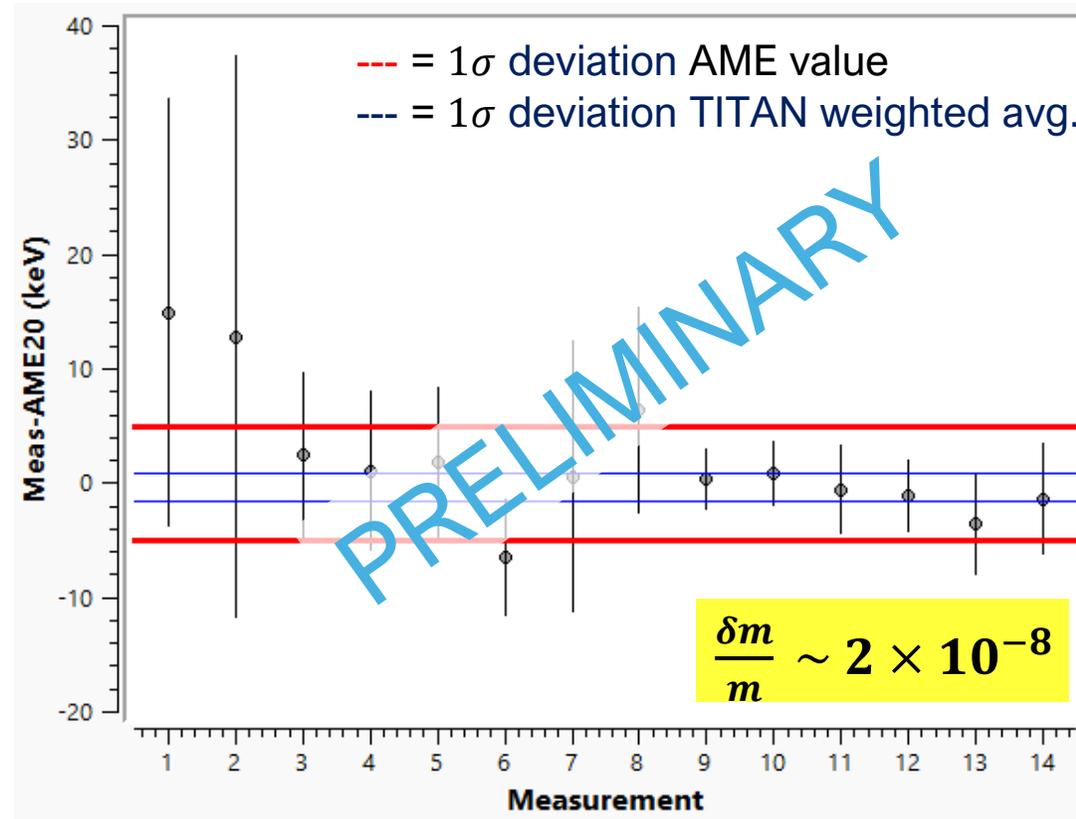


Image Credit:
Lykiardopoulou PhD thesis 2023 (left)
Kakkar PhD Work (right two)

Online Commissioning: $^{48}\text{Sc}^+$

- ^{48}Ca is a $0\nu\beta\beta$ candidate
- To understand the nuclear structure, we needed to measure the Q-value of the intermediate nucleus, ^{48}Sc



Atomic Mass Evaluation (AME)

Error Budget Status

Source	Mitigation	Status
Magnetic field inhomogeneities	Manufacturing specifications / Upper limit calculations	Complete
Magnetic field misalignment	Vacuum chamber alignment	Complete
Magnetic field decay	Measurement	Experiment Specific
Trap misalignment	Trap self-aligning holder	Complete
Trap imperfections	Experimental design / Upper limit calculations	Complete
Octopole and Dodecapole characterization	Upper limit calculation	In progress
Compensation	Validate with offline source	In progress

Error Budget Status

Source

Magnetic field inhomogeneities	Magnetic field misalignment	Vacuum chamber alignment
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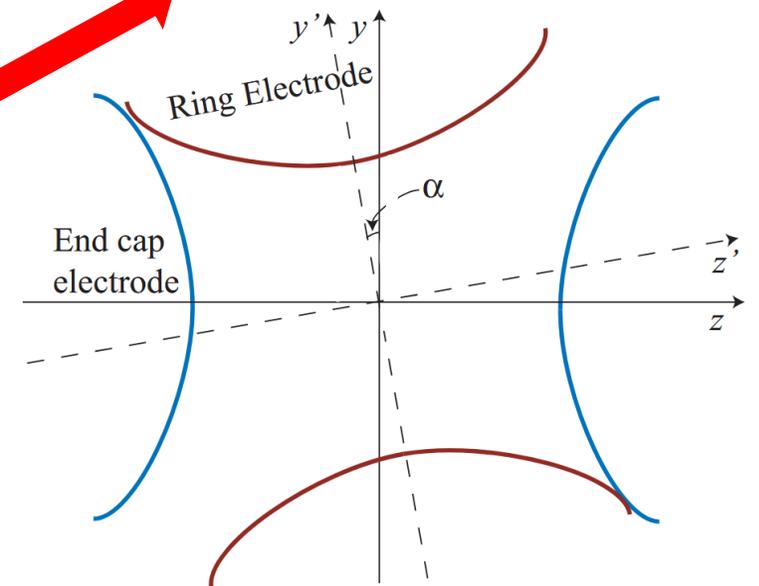
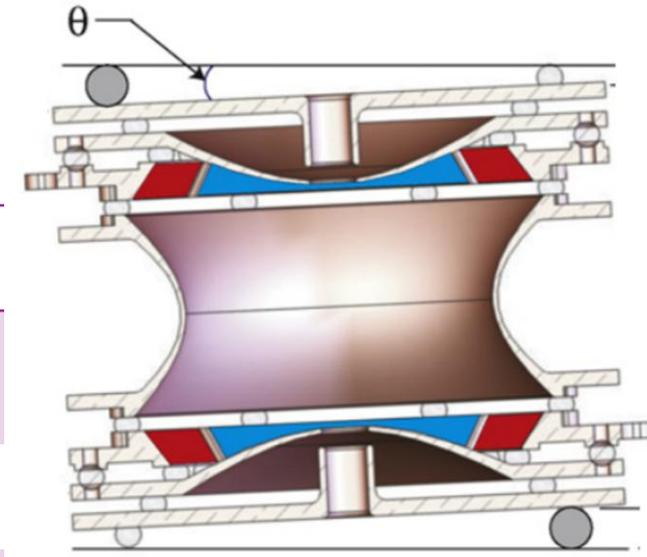
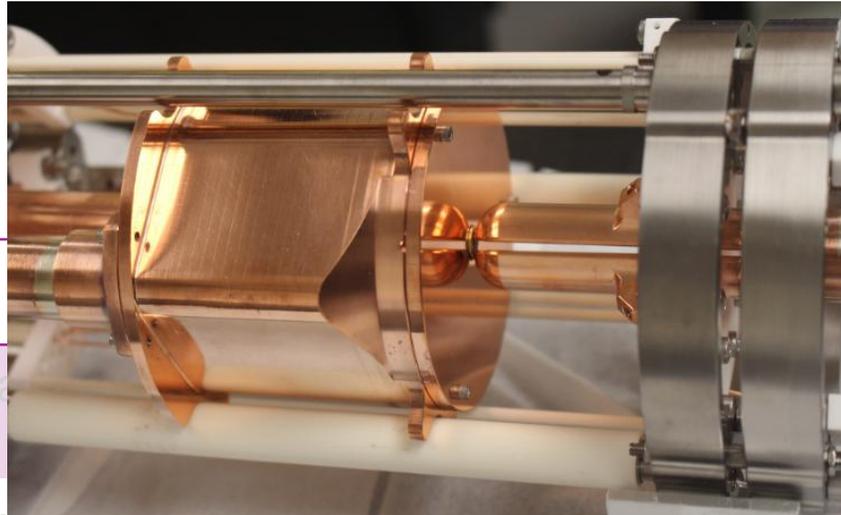
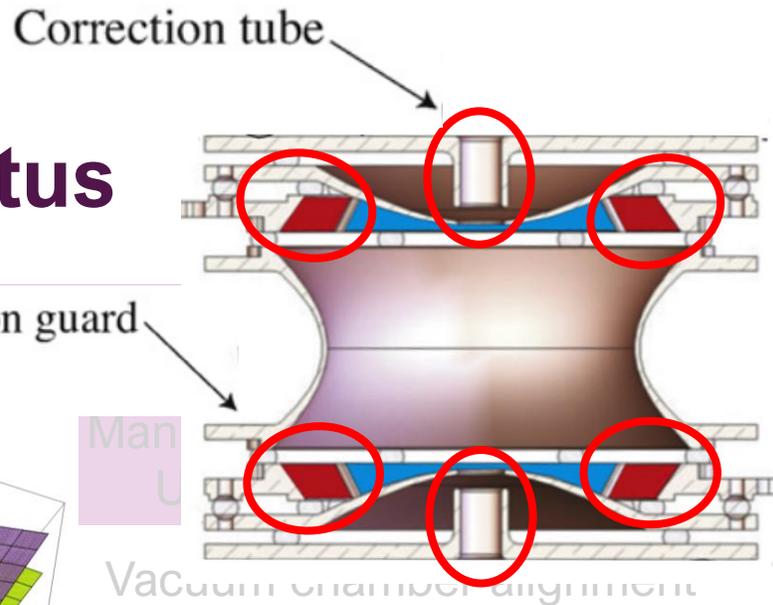
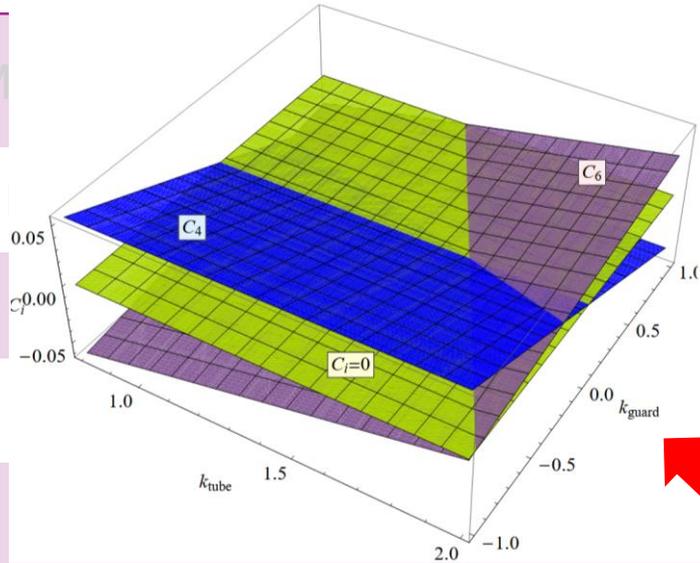


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Error Budget Status



Source



Status

Complete

Complete

Measurement

Trap self-aligning holder

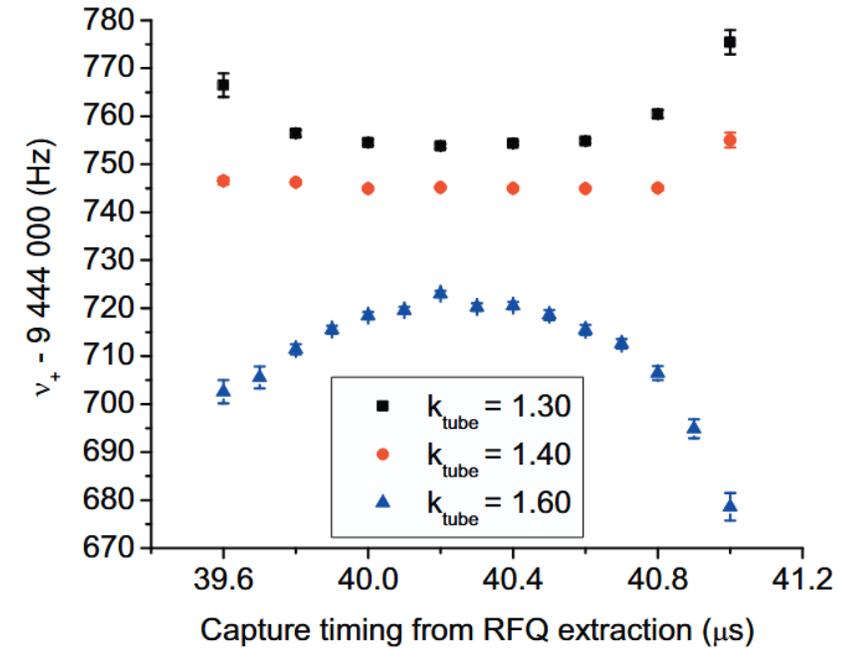
Experimental design / Upper limit calculations

Octopole and Dodecapole characterization

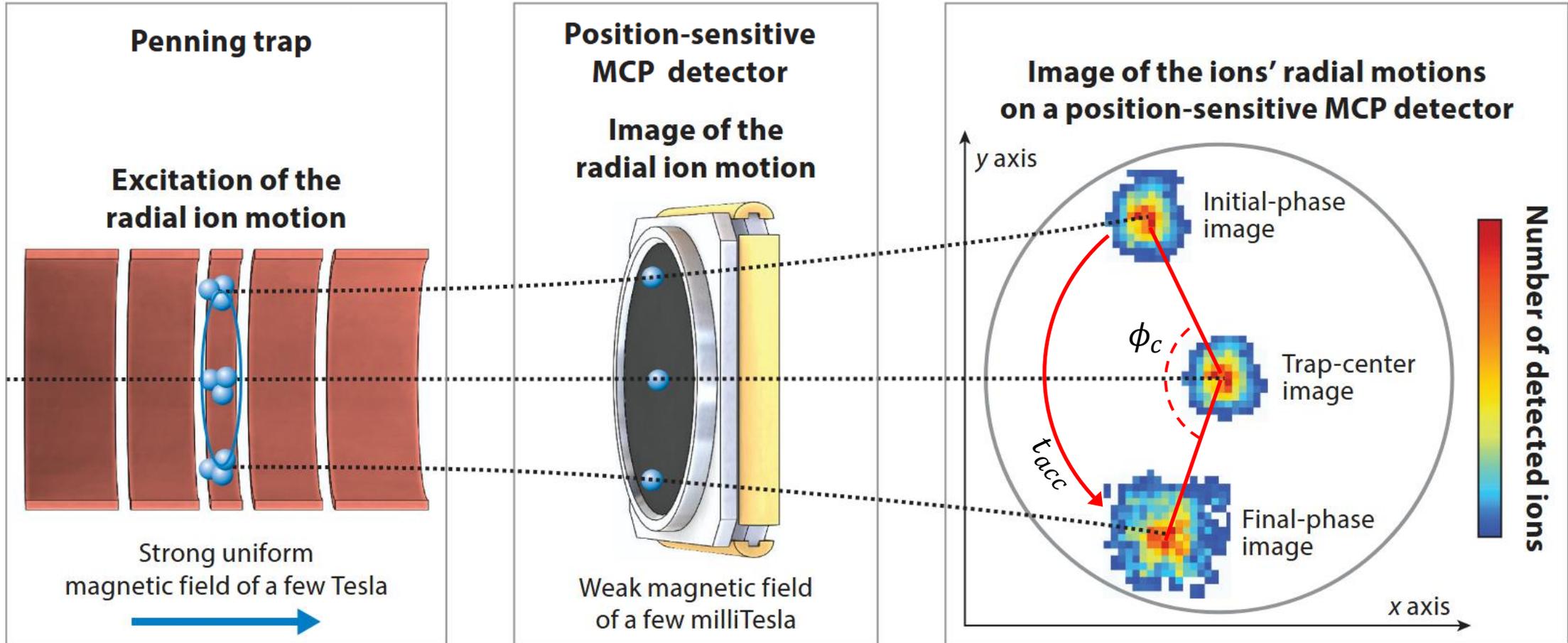
Upper limit calculation

Compensation

Validate with offline source



Upgrade 2: Phase-Imaging technique boosts precision



$$\nu_c \approx \nu_+ + \nu_- = \frac{1}{2\pi} \frac{qB}{M} = \frac{\phi_{total}}{2\pi t_{acc}} = \frac{\phi_c + 2\pi N}{2\pi t_{acc}}$$

$$\frac{\delta m}{m} \propto \frac{1}{qt_{acc}} \frac{\delta r}{r}$$

Phase Imaging Upgrades

Upgrade	Status
Install upgraded position sensitive detector	Done
Implement DAQ changes for Phase Imaging	In progress
Develop online analysis tool	Done
Phase Imaging specific compensation	To-do
Test offline with singly charged ions	To-do
Upgrade power supplies for higher stability	To-do
Test with highly charged ions	To-do
Test online with RIB	To-do

Phase Imaging Upgrades

Upgrade

Install upgraded position sensitive detector

Implement DAQ changes for Phase Imaging

Develop online analysis tool

Phase Imaging specific compensation

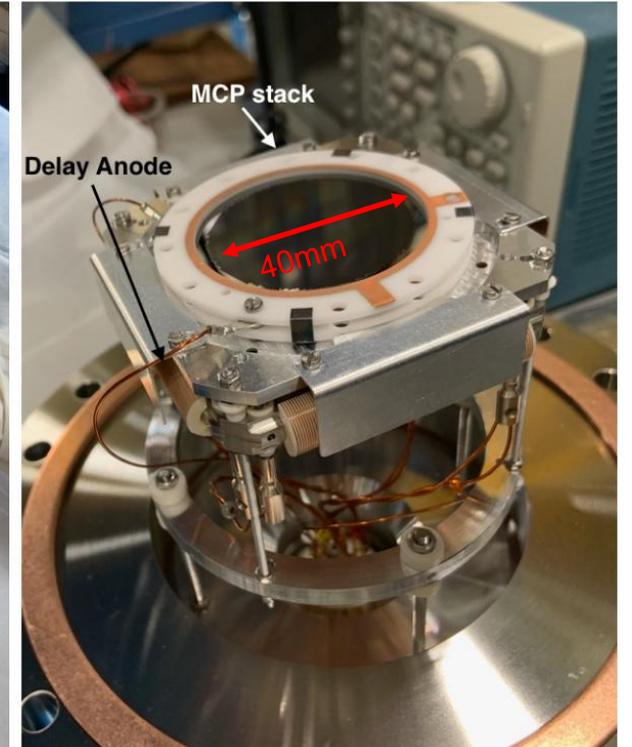
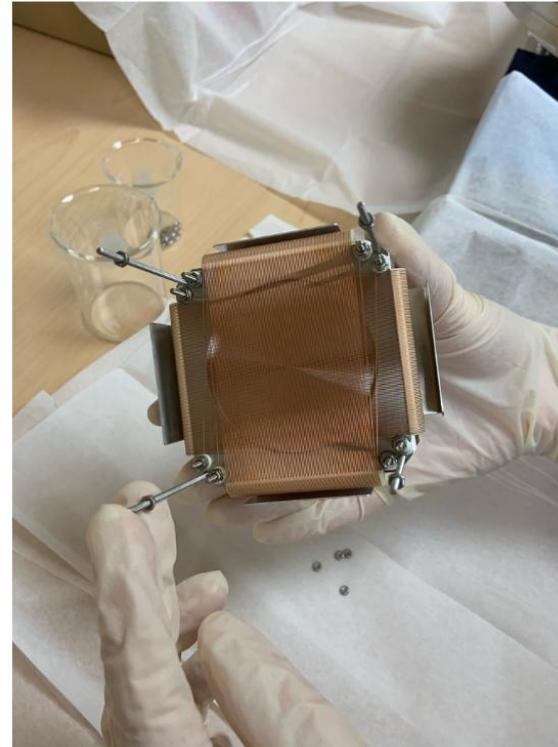
Test offline with singly charged ions

Upgrade power supplies for higher stability

Test with highly charged ions

Test online with RIB

Status



To-do

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Phase Imaging Upgrades

Upgrade

Install upgraded position sensitive detector

Implement DAQ changes for Phase Imaging

Develop online analysis tool ←

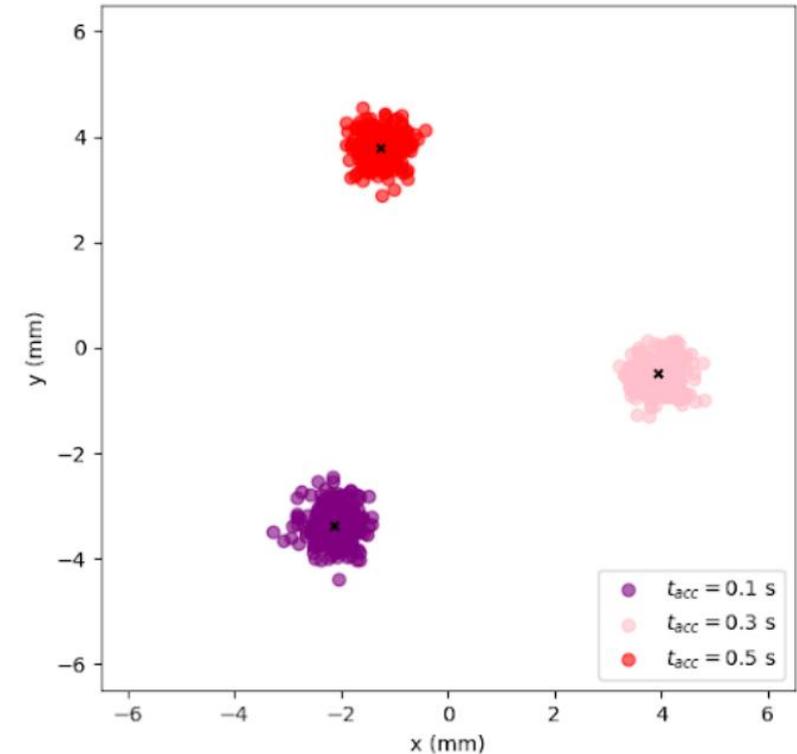
Phase Imaging specific compensation

Test offline with singly charged ions

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To-do

Phase Imaging Upgrades

Upgrade

Install upgraded position sensitive detector

Implement DAQ changes for Phase Imaging

Develop online analysis tool

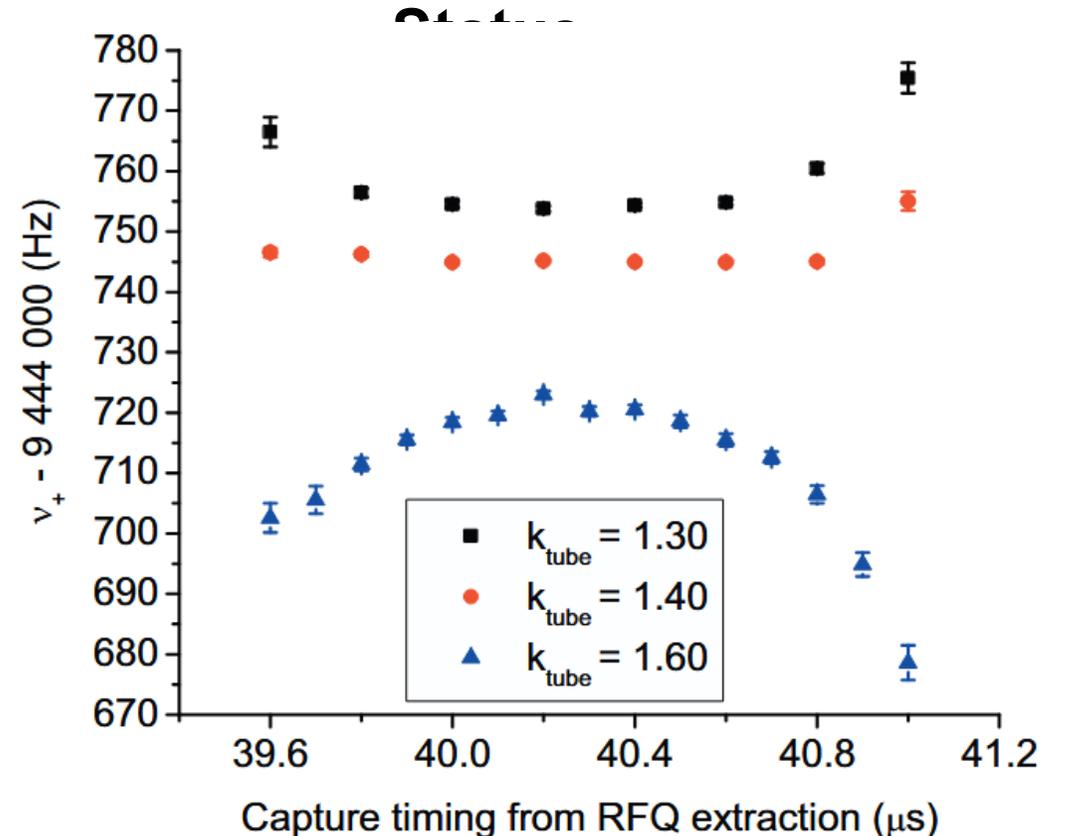
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To-do

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Conclusion

- TITAN has implemented two massive upgrades
 - Cryogenic
 - Phase Imaging
- New Error Budget – publish in 2026
- Developments for Phase Imaging are on the way
 - Online measurements in 2027
 - Routinely achieve $\sim 10^{-10}$ precision for tests of standard model

Precision improvements: $\frac{1}{q} \rightarrow \frac{1}{q^{3/2}}$

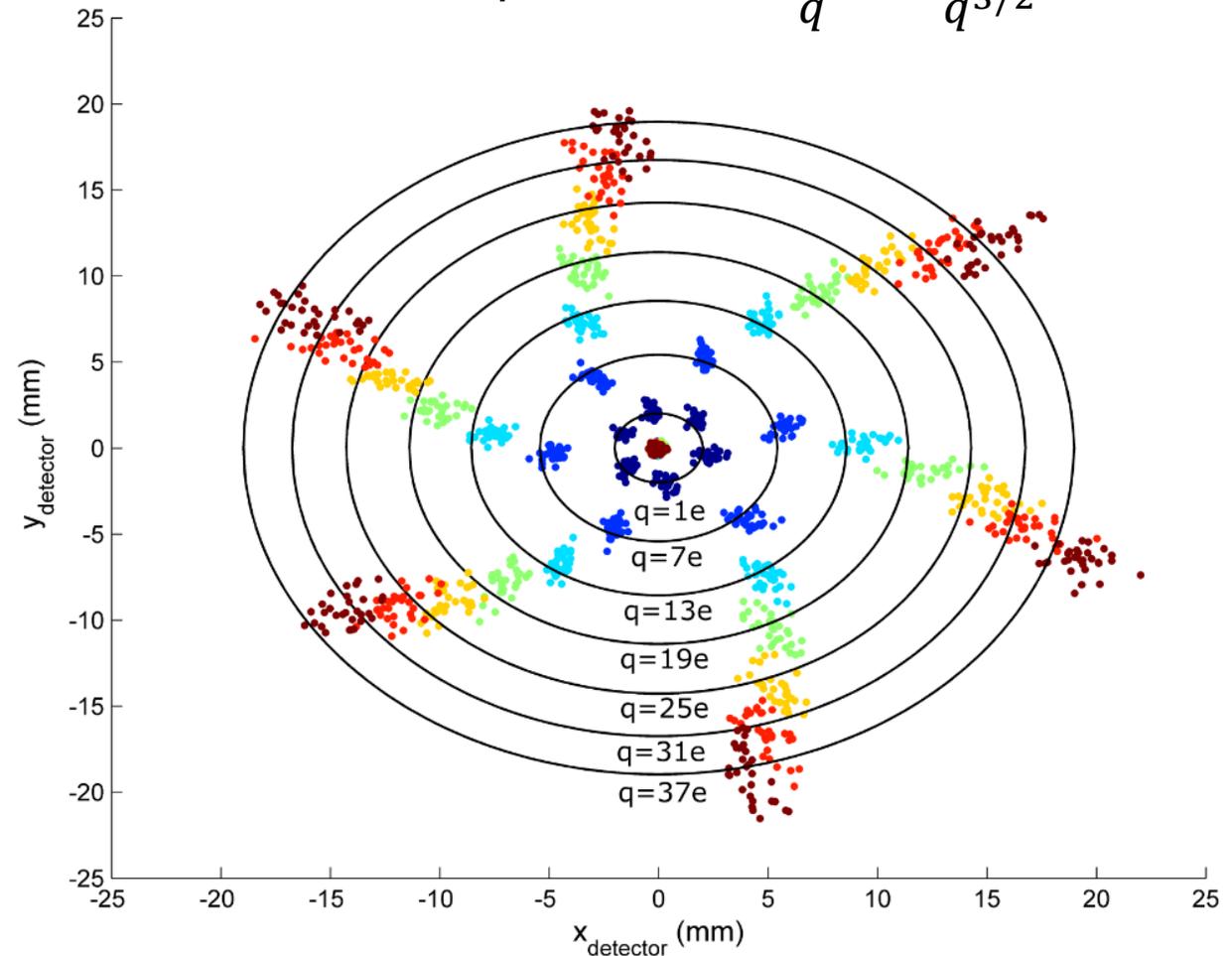


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Lykiardopoulou PhD thesis 2023

TRIUMF is located on the traditional, ancestral, and unceded territory of the x^wməθk^wəyəm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.

TRIUMF's home has always been a seat of learning.



University of Victoria



Time of Flight - Ion Cyclotron Resonance

- Ion starts in the magnetron motion
- Apply a RF pulse over a range of frequencies
- At the cyclotron frequency the ion will convert the magnetron motion into reduced cyclotron motion
- Resonant / higher-energy ions have a shorter travel time to the detector
- The centroid is the cyclotron frequency

