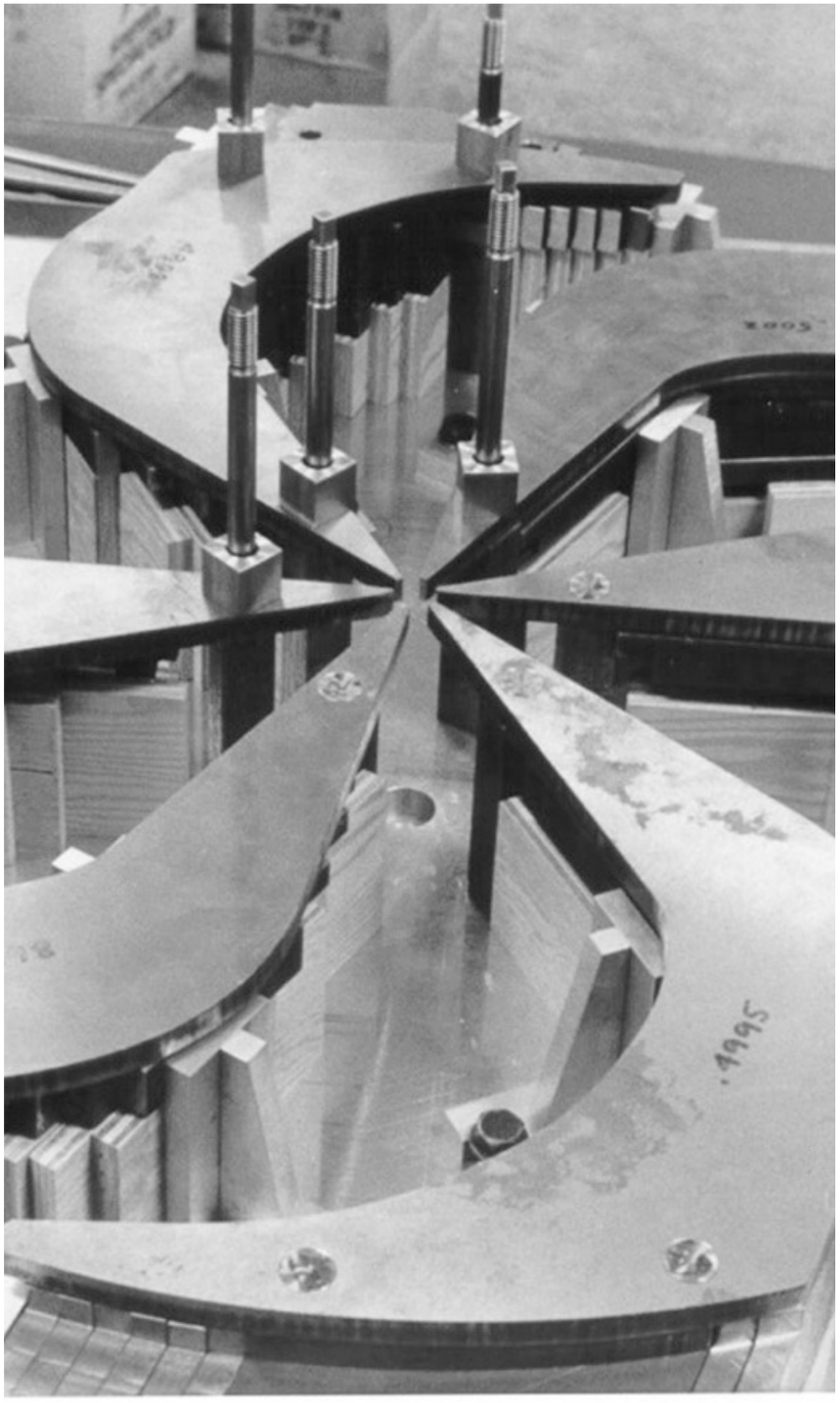
# Radioactive Molecules




Stephan Malbrunot-Ettenauer
TRIUMF, University of Toronto

PSD BAE Retreat 2024

Discovery, accelerated

# ‘Designer Molecules’

**probes for new physics**
- EDM searches
- P violation

**radioactive molecules**

**Applied science**
- nuclear engineering
- medicine

**Astrophysics**

**Quantum Chemistry**

**Atomic, molecular, optical physics**

**Nuclear physics**

*R. F. Garcia Ruiz et al., Nature 581, 396 (2020)*
*S. M. Udrescu, et al. Phys. Rev. Lett. 127, 033001 (2021)*
*Fan et al., Phys. Rev. Lett. 126, 023002 (2021)*

*White Paper arXiv:2302.02165*

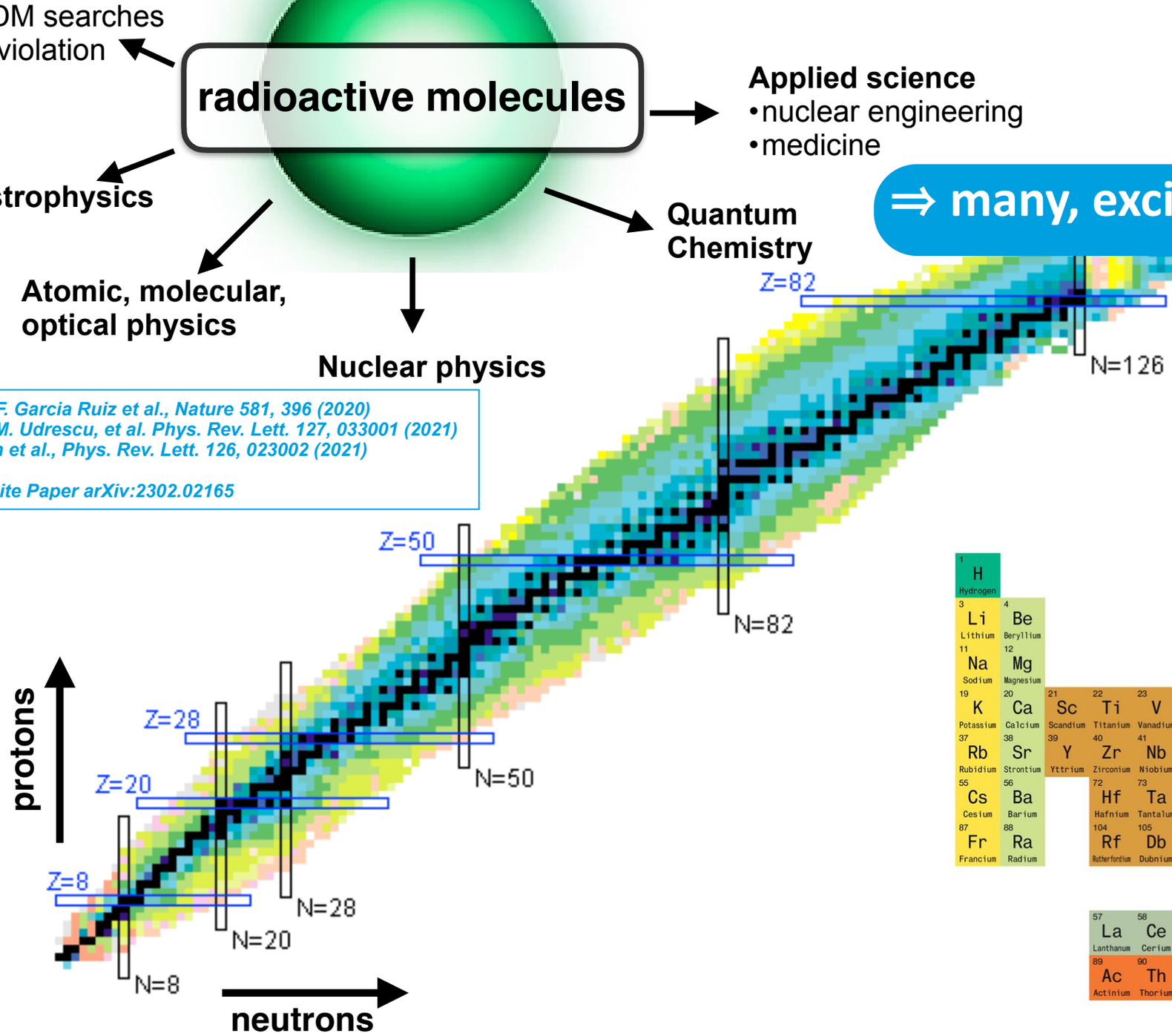



**Table of Isotopes**

**252 stable**

**≈90 naturally occurring radioisotopes**

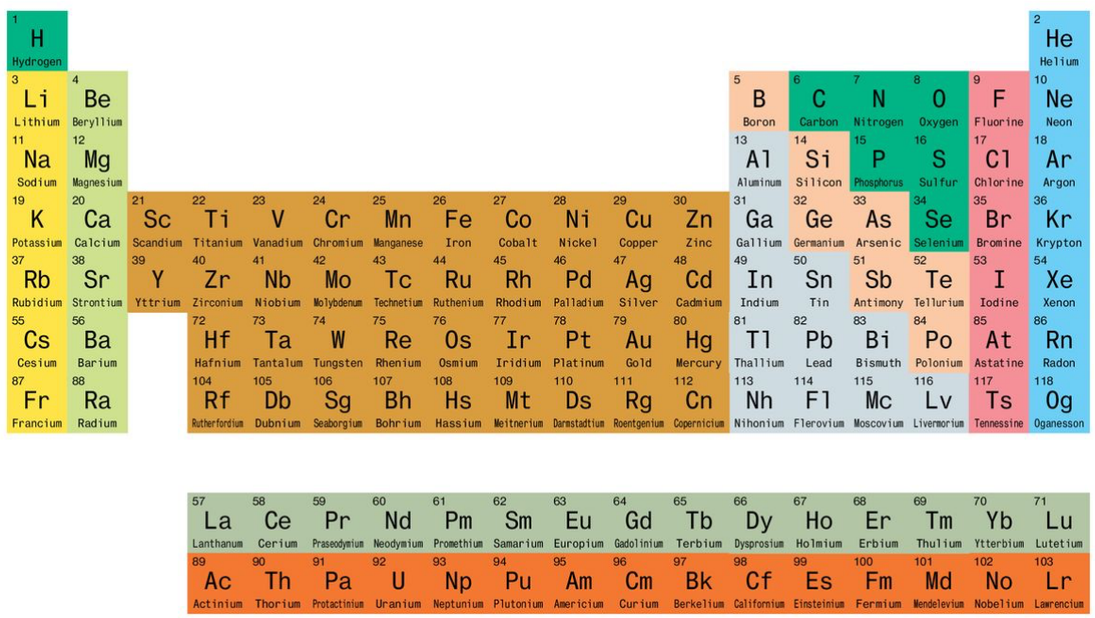
**≈3000 short-lived radionuclides discovered**



**⇒ many, exciting science opportunities**

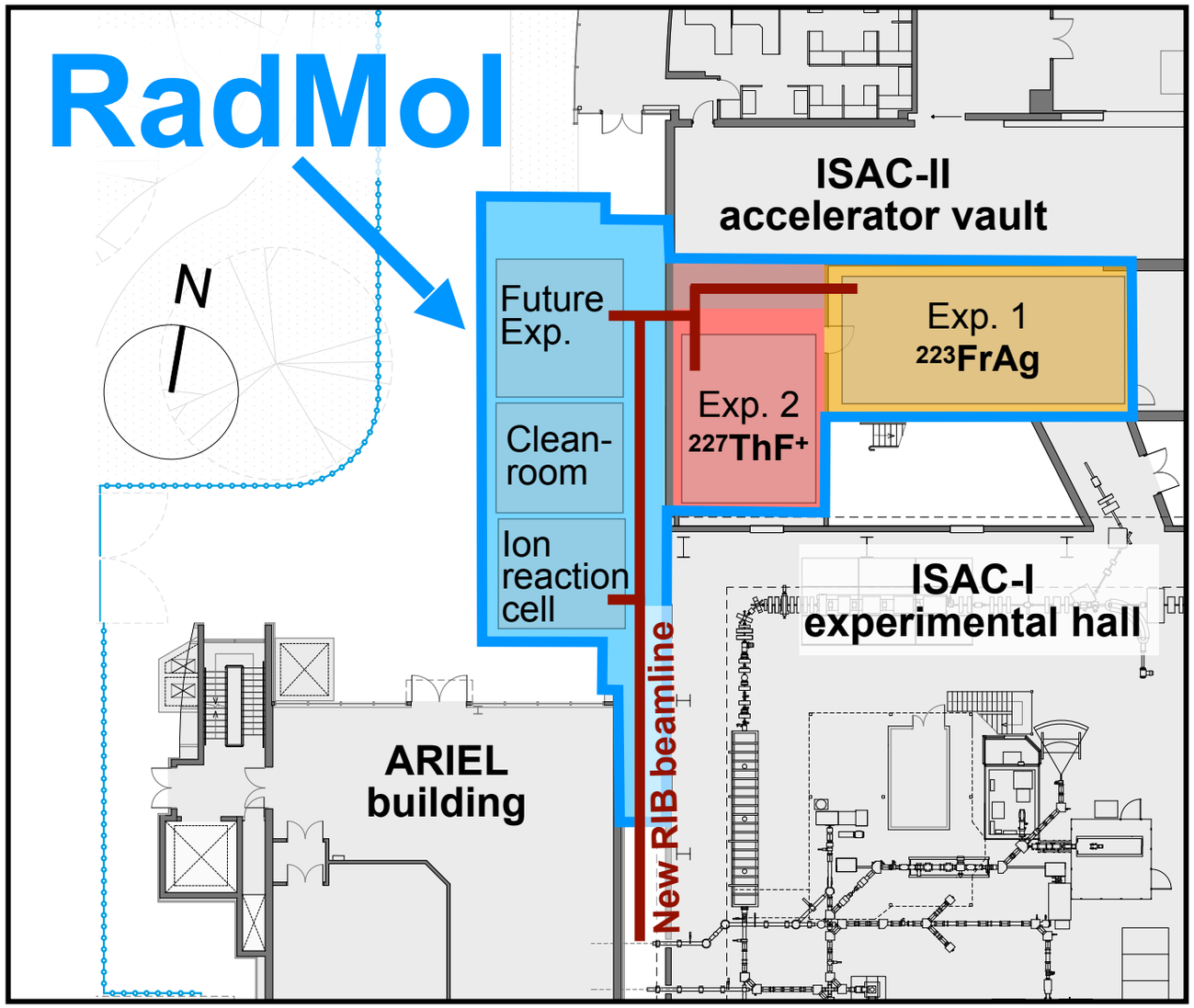
**Table of Elements**

**80 chemical elements (with stable nuclides)**



# RadMol

## *a radioactive molecule lab for fundamental physics*






**Goal:**

- dedicated laboratory to study of radioactive molecules
- to host 3 experimental stations
- precision studies for searches for new physics
- Molecular EDM with unprecedented sensitivity to nuclear T-breaking Schiff moments
- provision for expansions into other fields

**TRIUMF advantages:**

- large variety in radioactive ion beams (RIB)
- high beamtime availability (3 independent RIBs)
- existing laboratory space for large, multi-station program

**Current Canadian Team:**

- 12 faculty and staff physicists

**RadMol Collaboration:**

UBC · University of Manitoba · TRIUMF · McGill · The University of Chicago · University of Colorado Boulder · MIT Massachusetts Institute of Technology · Harvard · University of Waterloo · University of Toronto · uOttawa · Johns Hopkins University · University of Maryland · Philipps Universität Marburg · university of groningen · Temple University · The University of Edinburgh

new official collaborator!

# ‘Designer Molecules’

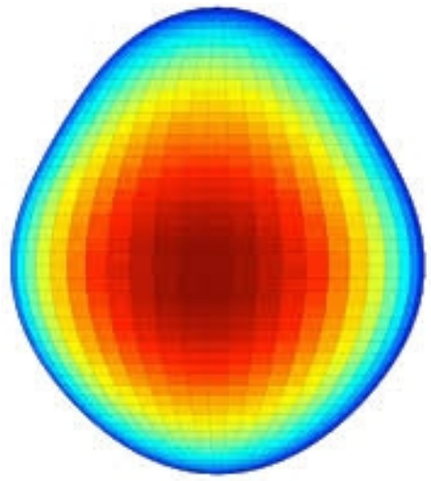
## … for searches for time-reversal violation in atomic nuclei



**$^{199}$Hg present ‘gold standard’ for limit on nuclear Schiff moment**

$|d_{Hg}| < 7.4 \cdot 10^{-30}$ e cm (95% confidence limit)

$|S_{Hg}| < 3.1 \cdot 10^{-13}$ e fm$^3$ *B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016)*



**Enhancement factors in our approach:**

- **octupole** deformed nuclide x 100-1,000
- in polar molecule x 1,000-10,000

} compared to $^{199}$Hg

- in atom or ion trap x 1,000 compared to beam experiments

**all known cases in radionuclides**

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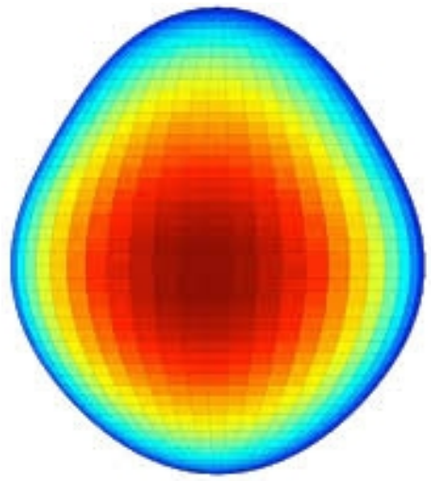

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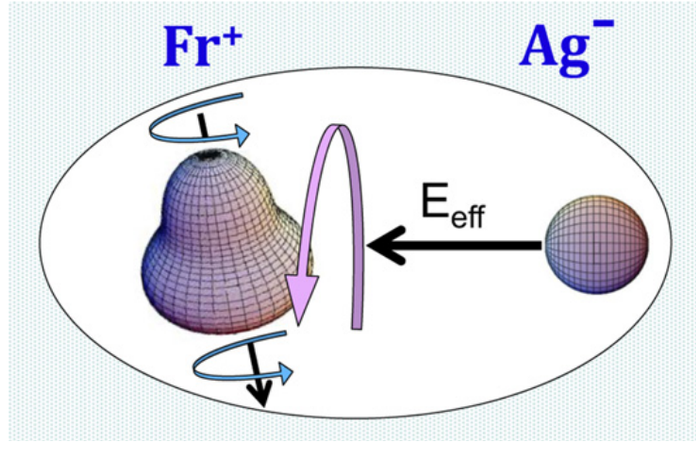
} compared to $^{199}$Hg

**all known cases in radionuclides**

**Example: $^{223}$FrAg**

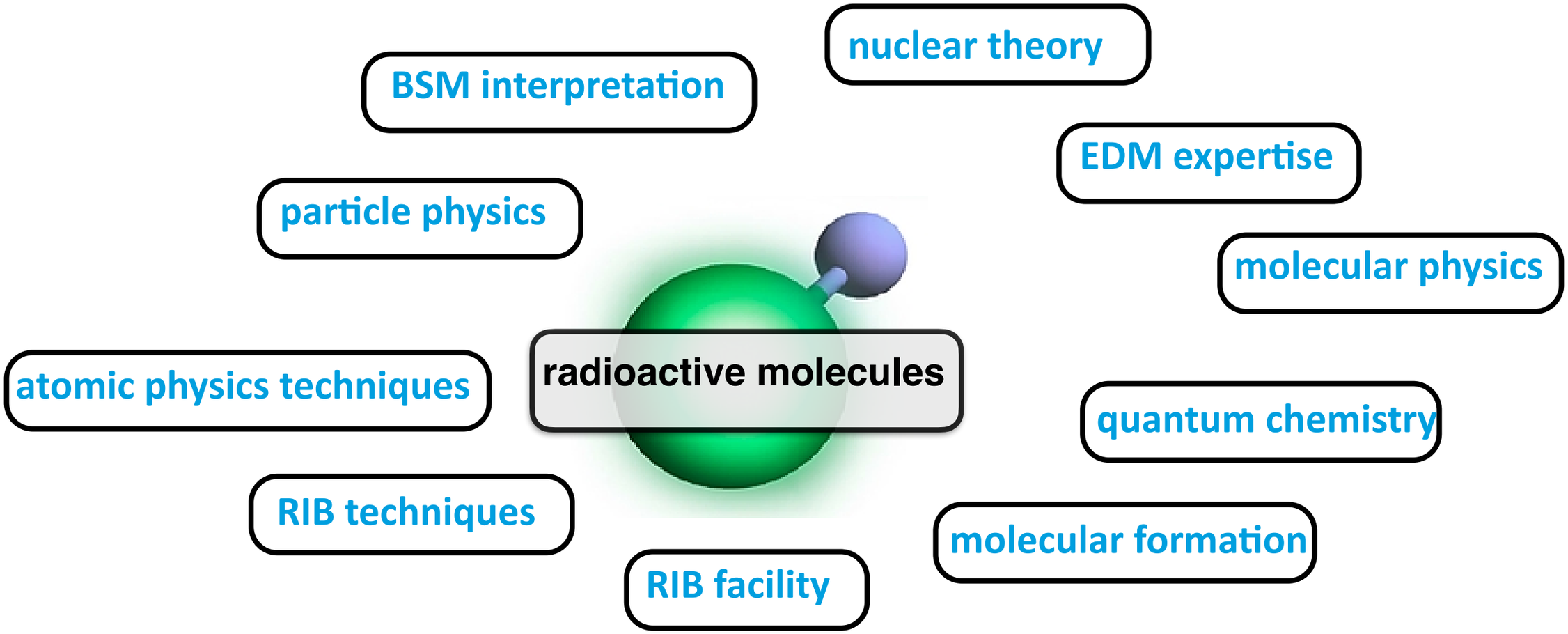
- **intrinsic enhancement of $10^7$ compared to $^{199}$Hg**

*V. V. Flambaum and V. A. Dzuba. Phys. Rev. A 101, 042504 (2020)*
*T. Fleig. private communications with D. DeMille (2022)*




- need to be produced at TRIUMF
  - ➡ challenge: reduced availability
- **anticipated gain: x 1,000 for certain CPV-parameters (comp to $^{199}$Hg)**

# Multidisciplinary






**General theme for experiments:**

translate high-precision AMO techniques into accelerator lab

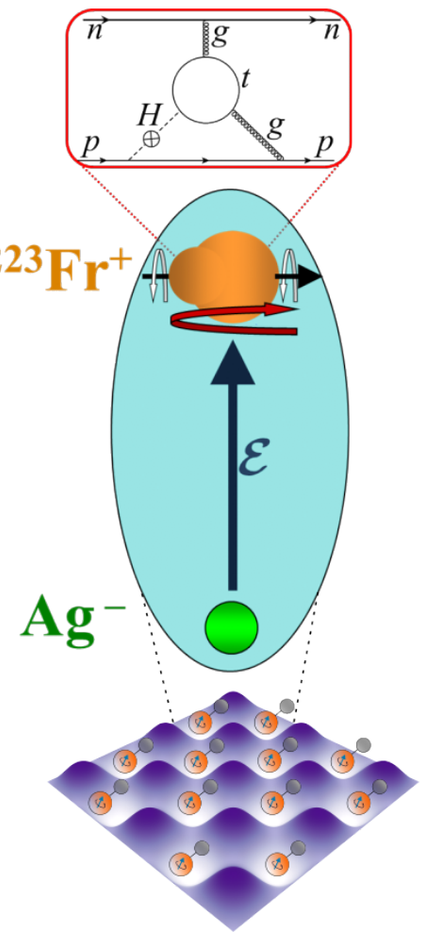
# RadMol collaboration

| Institution | Department | Principal Investigators |
|---|---|---|
| TRIUMF | Physical Sciences | Behr, Holt, Malbrunot-Ettenauer, Kwiatkowski, Teigelhöfer |
| | Accelerator Division | Babcock, Charles |
| | Life Sciences Division | Radchenko |
| University of British Columbia | Physics&Astronomy | Madison |
| | Chemistry | Momose, Krems |
| University of Toronto | Physics | Vutha |
| University of Waterloo | Physics&Astronomy | Jamison |
| University of Manitoba | Physics&Astronomy | Gwinner |
| McGill University | Physics | Buchinger |
| University of Ottawa | Physics | Stolow |
| | | |
| University of Chicago / USA | Physics | DeMille |
| University of Colorado, Boulder / USA | Physics | Cornell |
| University of Edinburgh | Physics&Astronomy | Reiter |
| University of Groningen / NL | Physics | Borschevsky, Hoekstra |
| Harvard University | Physics | Fan |
| Johns Hopkins University/USA | Chemistry | Cheng |
| Massachusetts Institute of Technology / USA | Physics | Garcia Ruiz |
| University of Maryland / USA | Physics | Orozco |
| University of Marburg / GER | Chemistry | Berger |
| Temple University / USA | Physics | Kotochigova |

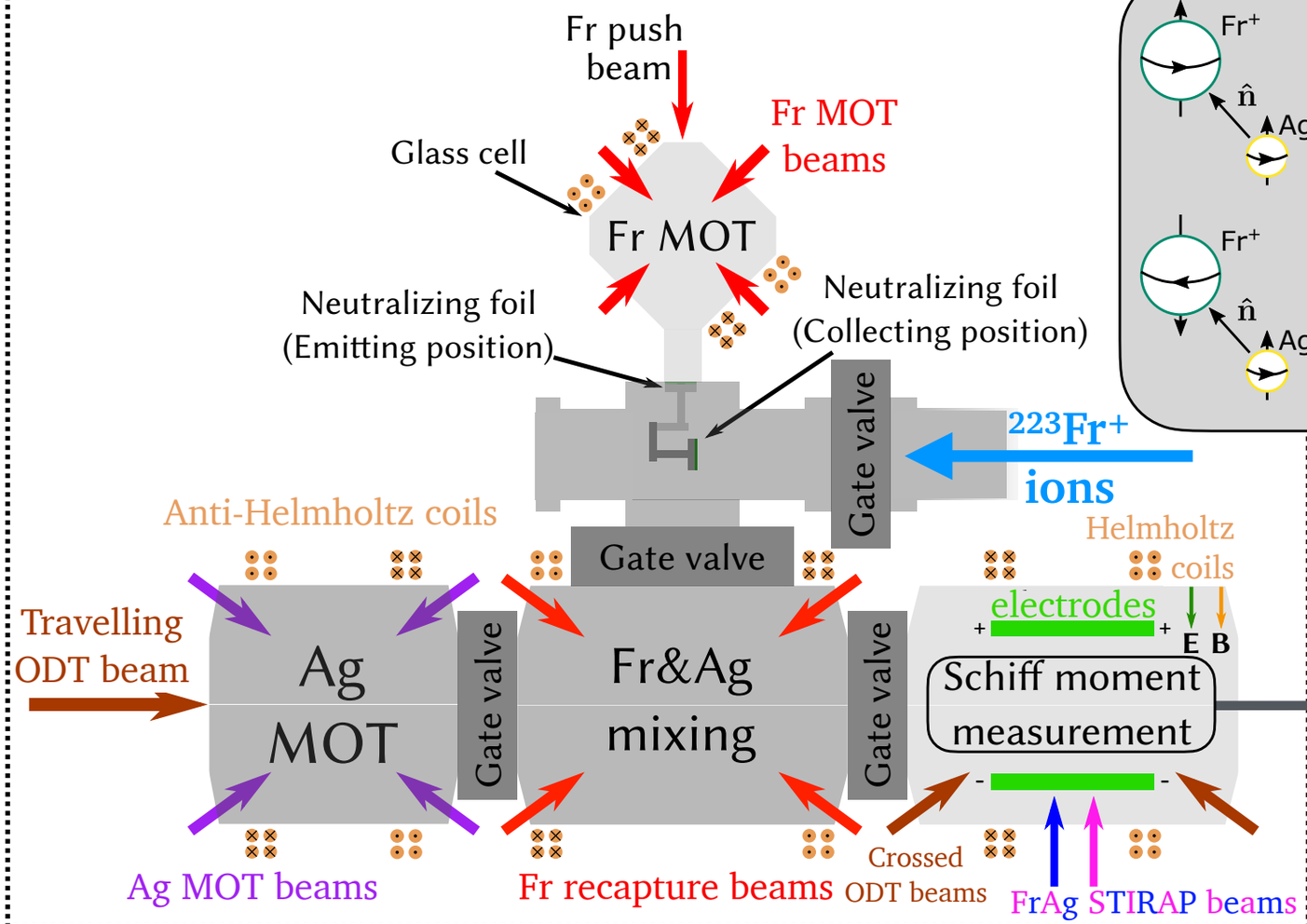
# $^{223}$FrAg experiment



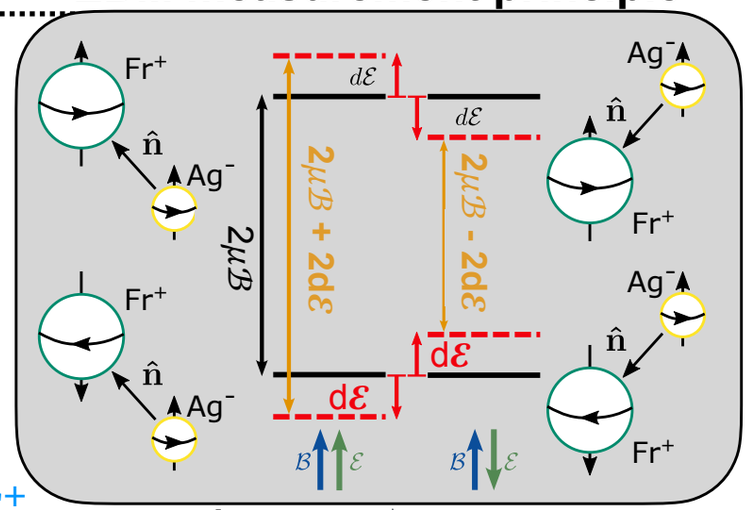
**concept**




**experimental apparatus**

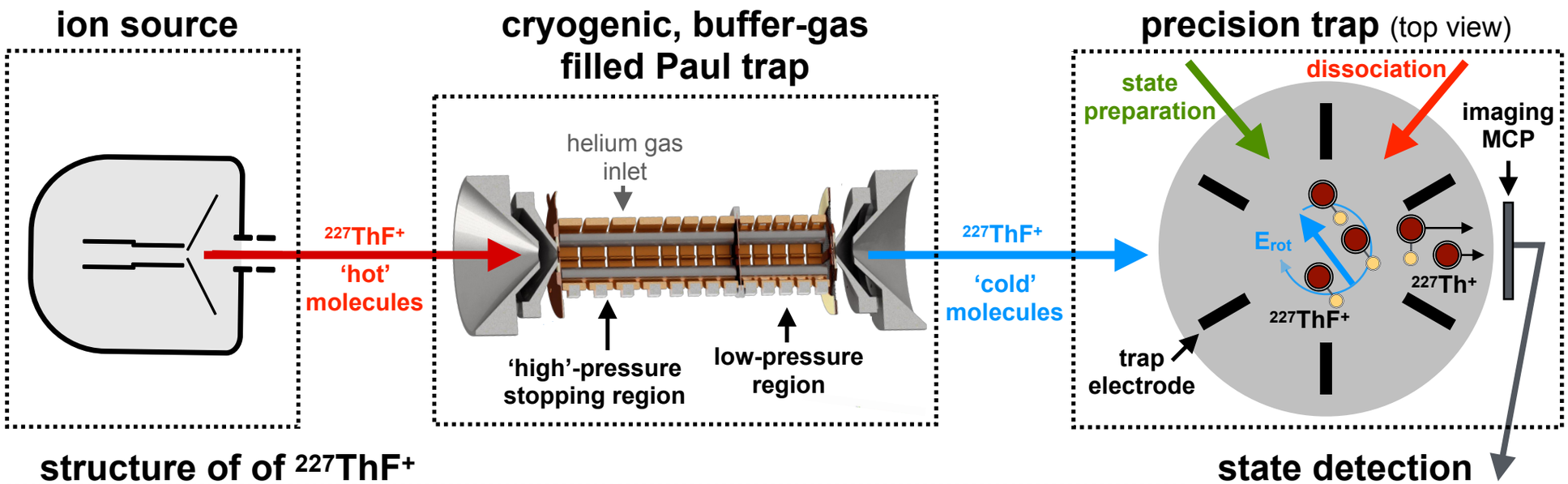


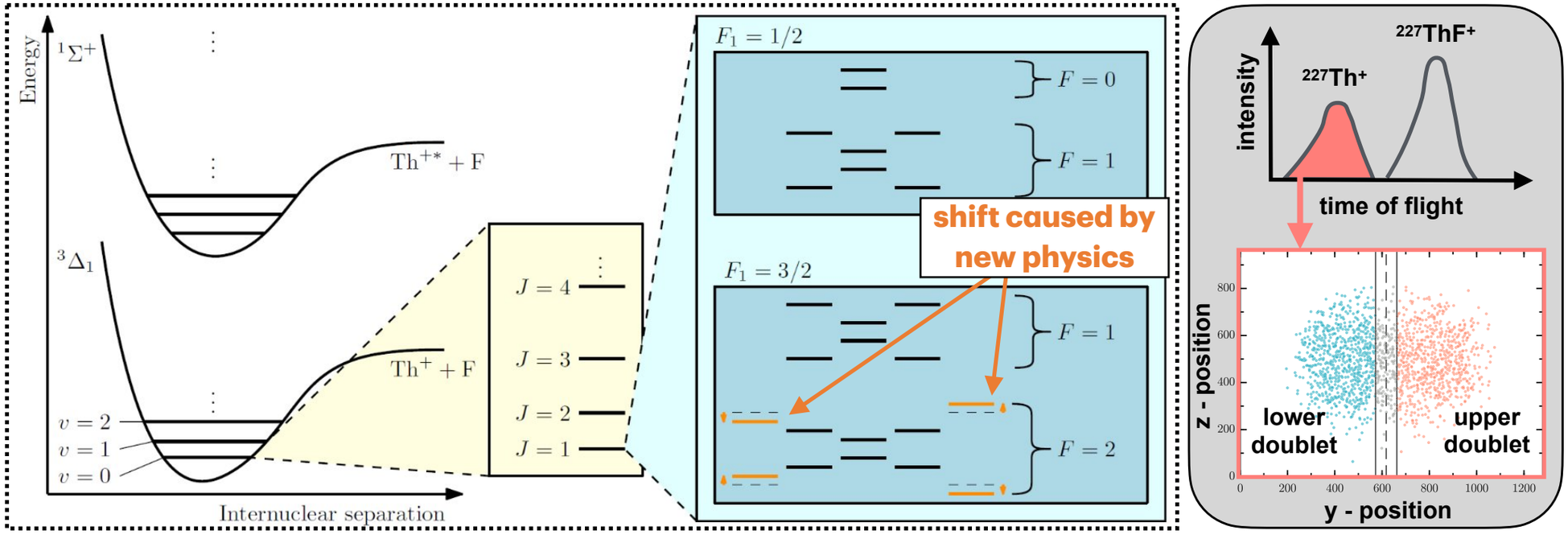

**EDM measurement principle**




- led by Chicago (DeMille)
- benefits from Fr trapping knowhow at TRIUMF/Manitobo
- obtained 2.8 MUSD grant by Moore foundation (ca. 400 kCAD directly to TRIUMF)
- $^{223}$Fr's half-life 23 min: high-intensity online access + low-intensity offline source ($^{227}$Ac)

# $^{227}ThF^{+}$ experiment



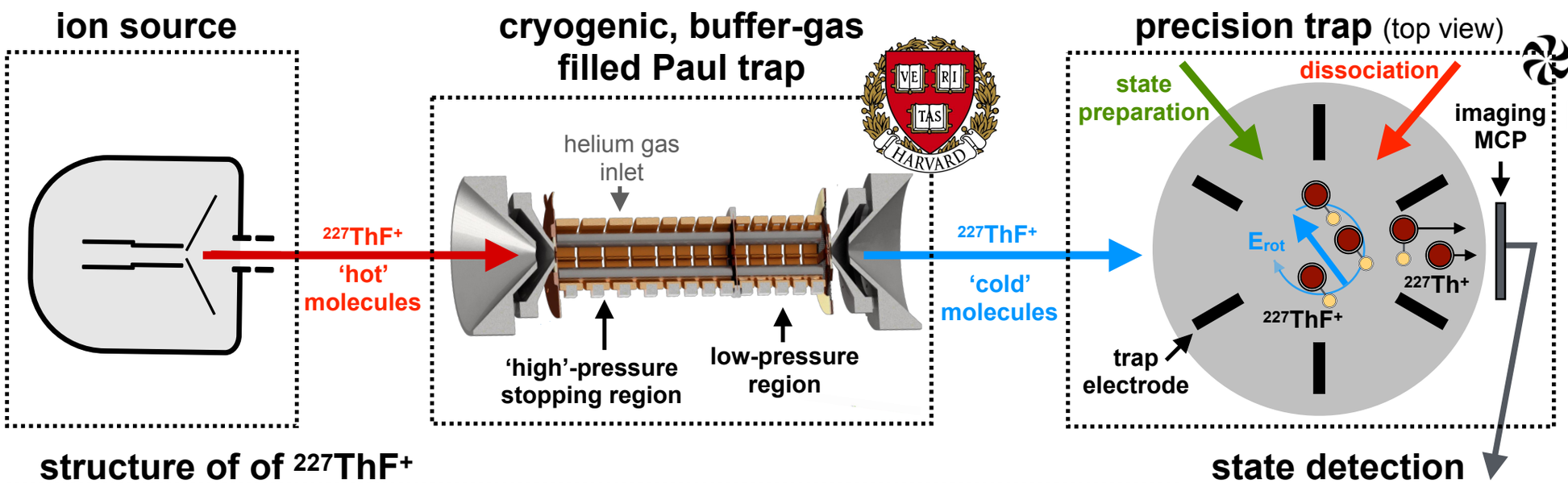




structure of of $^{227}ThF^{+}$

- experimental EDM techniques analogous to JILA electron EDM experiment
- molecular structure of $^{232}ThF^{+}$ known from spectroscopy at JILA
- access to $^{227}Th$ via $^{227}Ac$ sample from life sciences ⇒ strong inter-divisional effort

(Accelerator, Life Sciences, Physical Sciences)

# $^{227}ThF^{+}$ experiment




TRIUMF
University of Colorado Boulder
UNIVERSITY OF TORONTO



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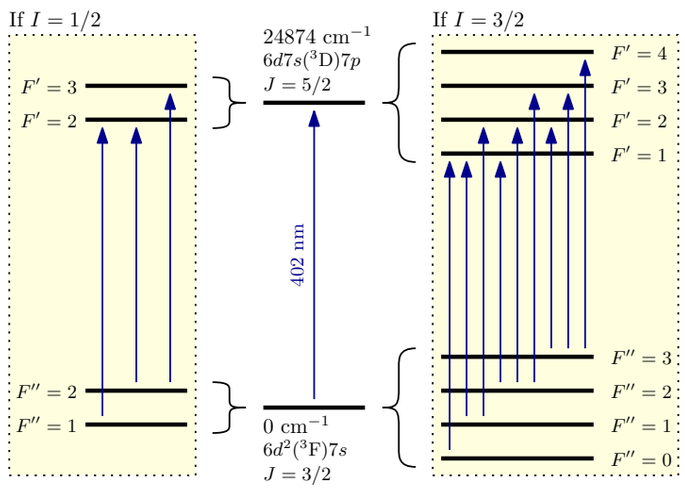
# 1st step: laser spectroscopy of $^{227}Th^{+}$

**Goal:** measure nuclear spin & magnetic moment of $^{227}Th^{+}$






**Challenge:** Th beams at ISAC (and globally)

**Solution:**
- $^{227}Ac$ sample in Life Sciences: generator of $^{227}Th$ via chemical separation
- form ‘offline’ beam in ISAC target
- mass separation in ISAC magnetic mass separator
- laser spectroscopy in polarizer line (using TITAN buncher)

**Competition on $^{227}Th^{+}$:**
- TRIUMF has leading edge
- others will follow, e.g. Pa LOI at ISOLDE on similar concept

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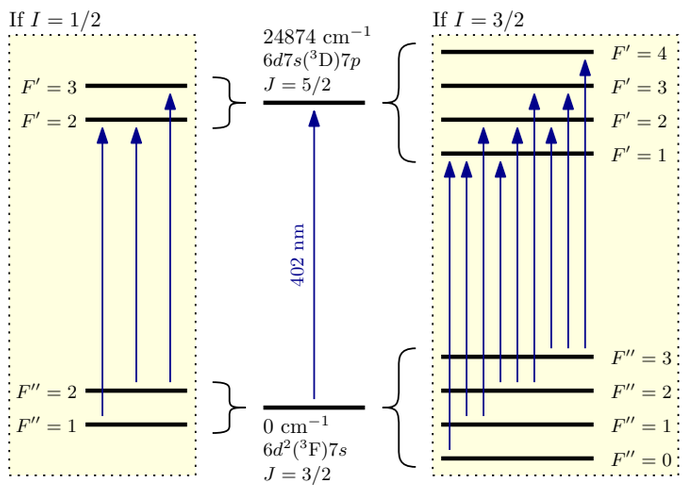




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**Vision for future RadMol laboratory:**
**Infrastructure for chemical and mass separation for fundamental physics and medical isotope research**

**Competition on $^{227}Th^{+}$:**
- TRIUMF has leading edge
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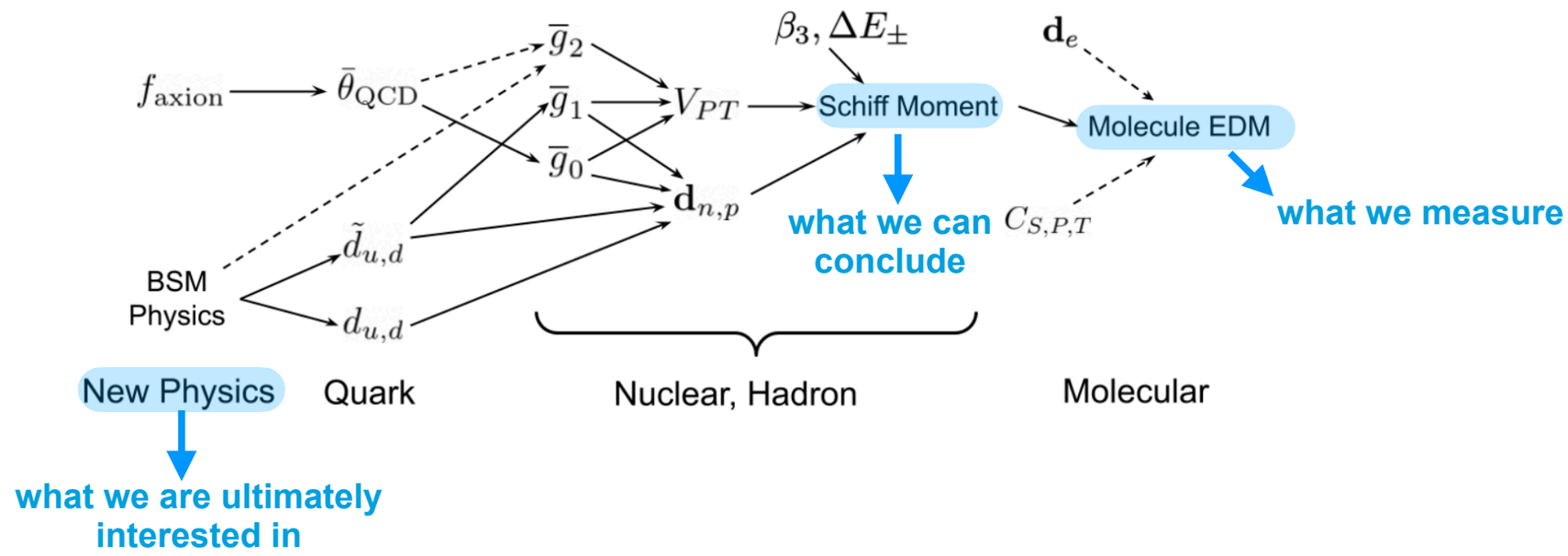
# why 2 experiments?

- 2 complementary techniques: neutral atoms ⇔ singly charged ions
- different systematics
- different sensitivity to underlying physics






- TRIUMF's attractiveness to this new, emerging field
  - ➡ beam availability & strong beams (for Fr) or unique sample (for Th)
  - ➡ in-house expertise in sample and beam preparations
  - ➡ existing expertise (FrPNC, TRINAT, TITAN, laser, target and ion sources)
  - ➡ existing laboratory space ⇒ experimental work has already started

S2068LOI - S2171LOI S2279LOI - S2309 -

- FrAg apparatus: unique approach ⇔ $ThF^+$ apparatus: 'universal' spectroscopy setup

# spectroscopy of other ionic molecules

## Examples for other radioactive molecules:

$RaOCH_3^+$ *Fan et al., Phys. Rev. Lett. 126, 023002 (2021)*
*Yu and Hutzler, Phys. Rev. Lett. 126, 023003 (2021)*

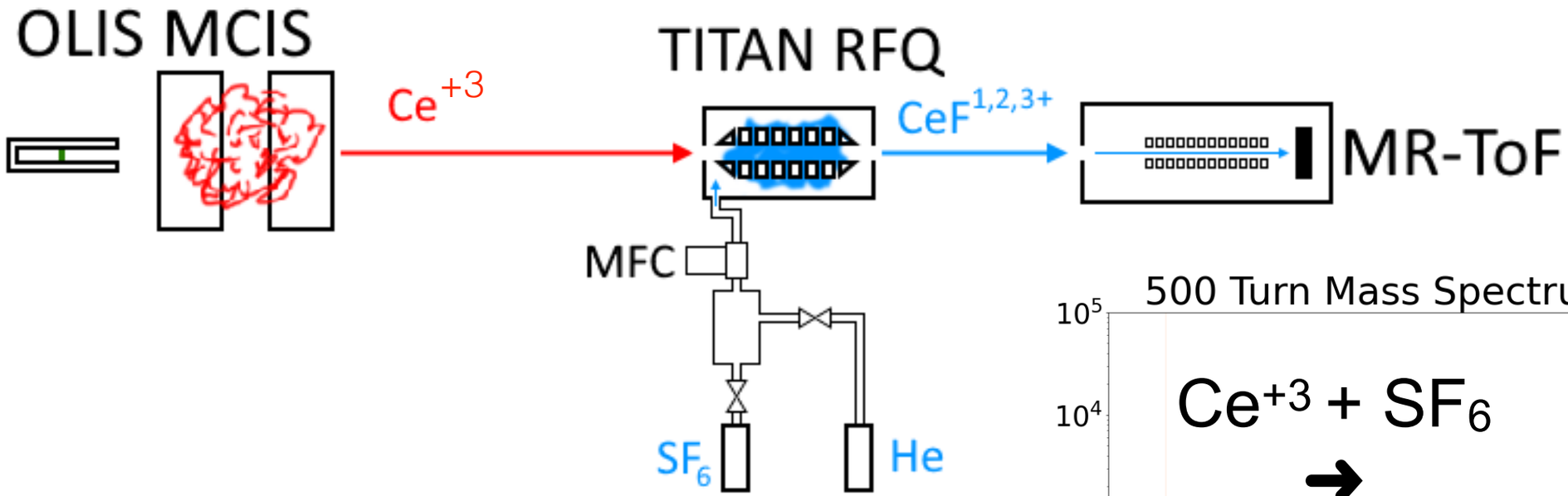
$PaF^{3+}$ *C. Zülch et al., arXiv:2203.10333 (2022)*

$AcO^+$ *Flambaum and V. A. Dzuba, Phys. Rev. A 101, 042504 (2020).*

$CeF^{+2}$, $AcF^+$ *R. Berger, private communications*

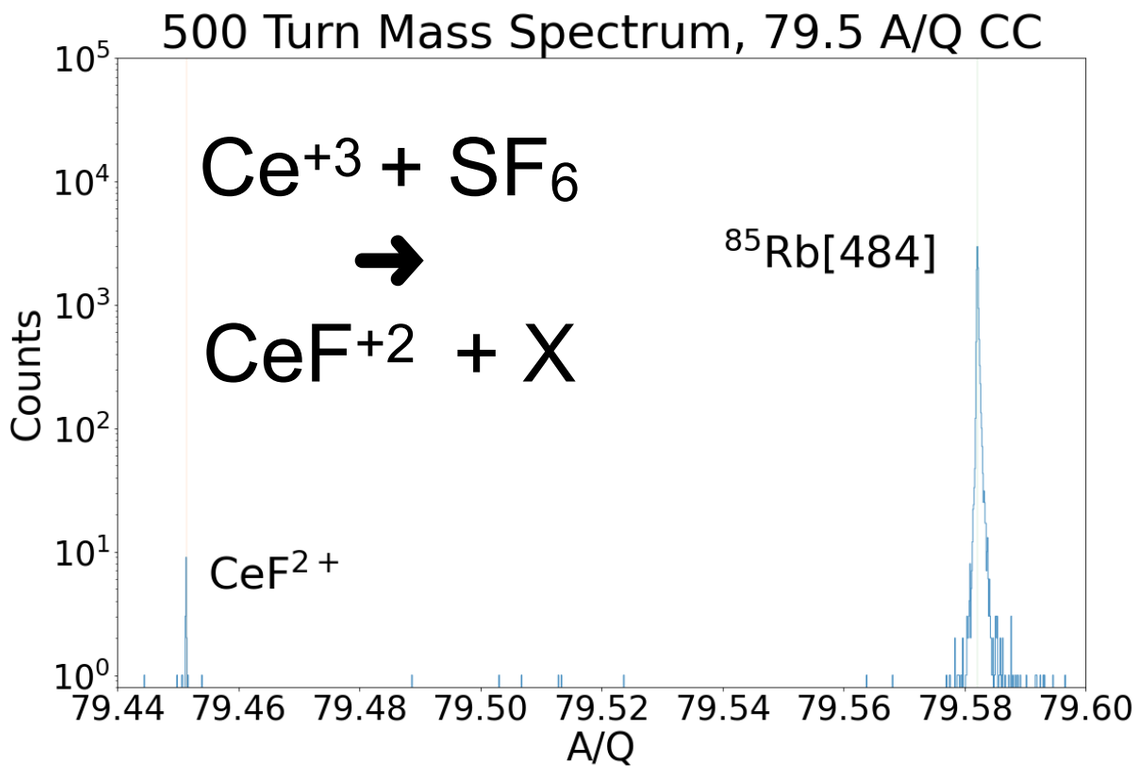


## First step to spectroscopy: Molecular Formation / Present




*Manuscript (almost) completed*

Successful collaboration between Accelerator, Life Sciences, Physical Sciences Divisions



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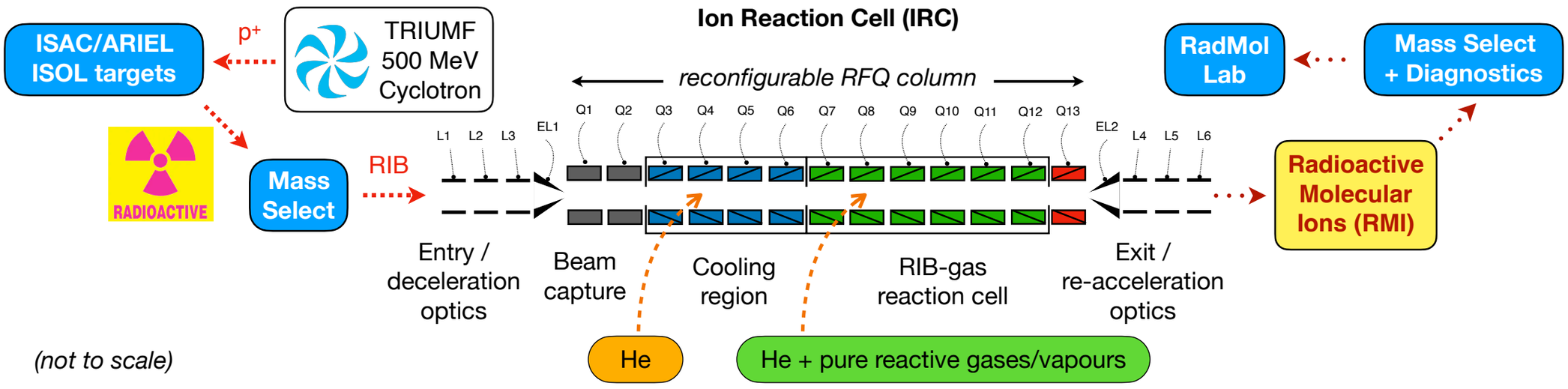
## First step to spectroscopy: Molecular Formation / Future

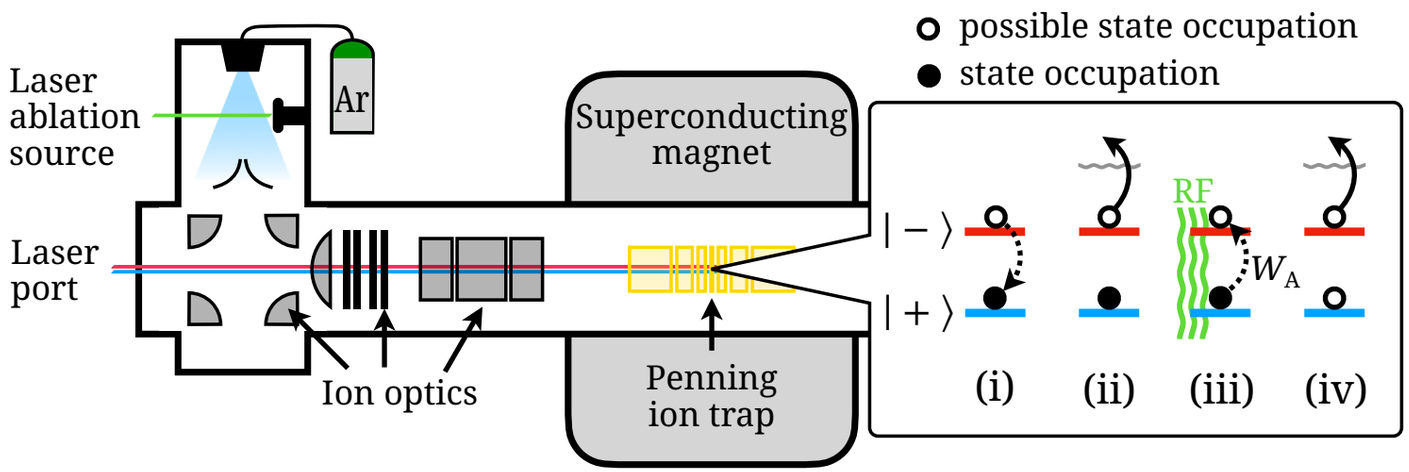
Dedicated Ion Reaction Cell (led by C. Charles)



# Provisions for future experiments



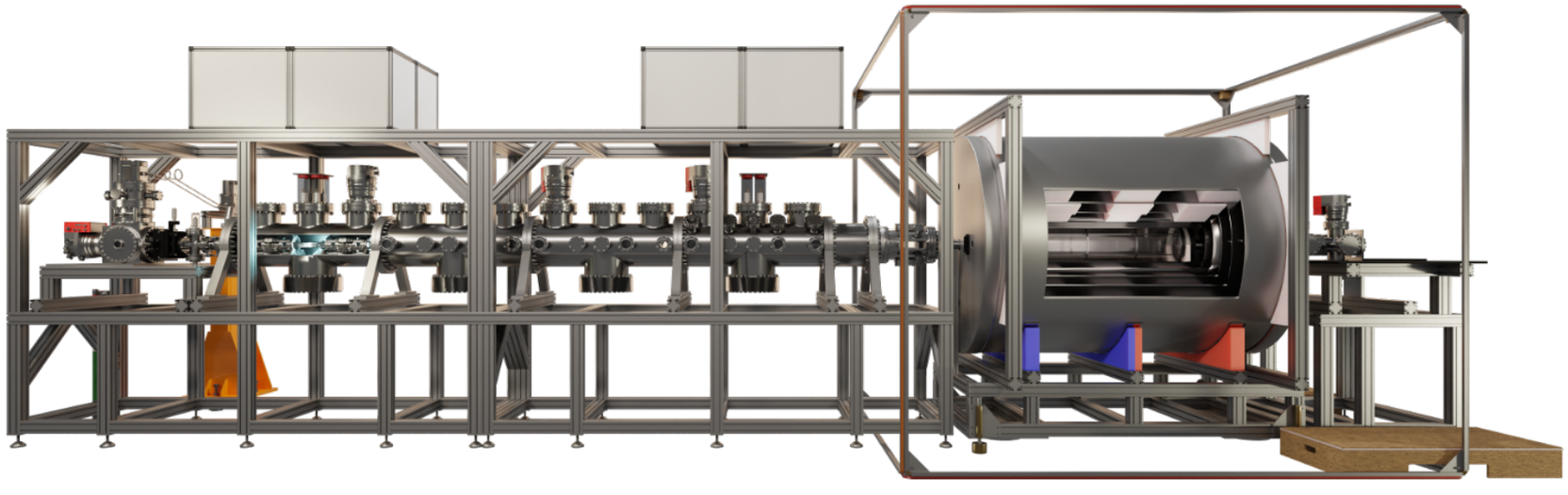
## Nuclear Anapole Moments




Massachusetts Institute of Technology

*Karthein et al., accepted in Phys. Rev. Lett.*

## Spectroscopy of ultra-cold radioactive molecules

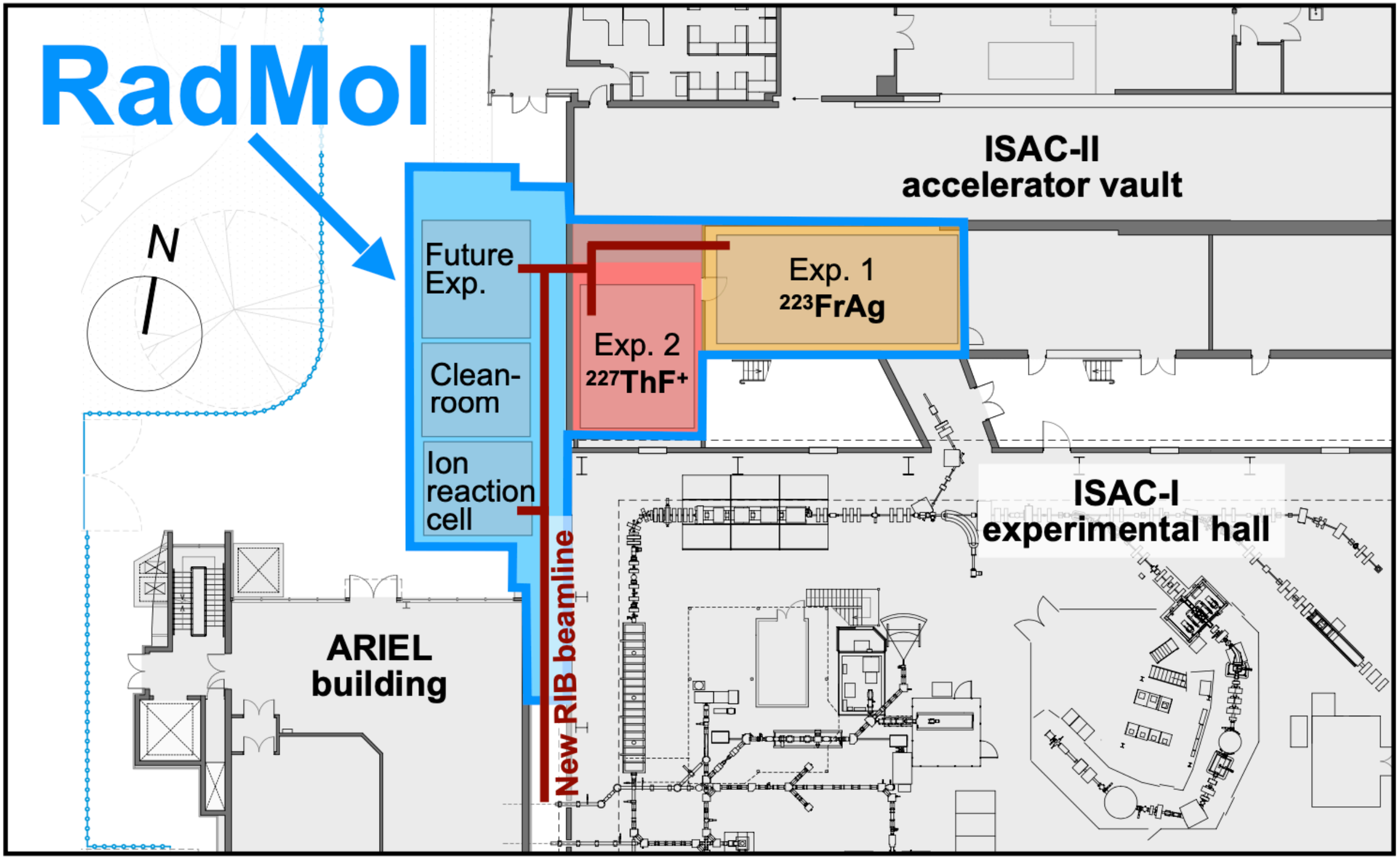


- Quantum chemistry
- Astrophysics
- BSM physics

Steven Hoekstra for BaF

university of groningen

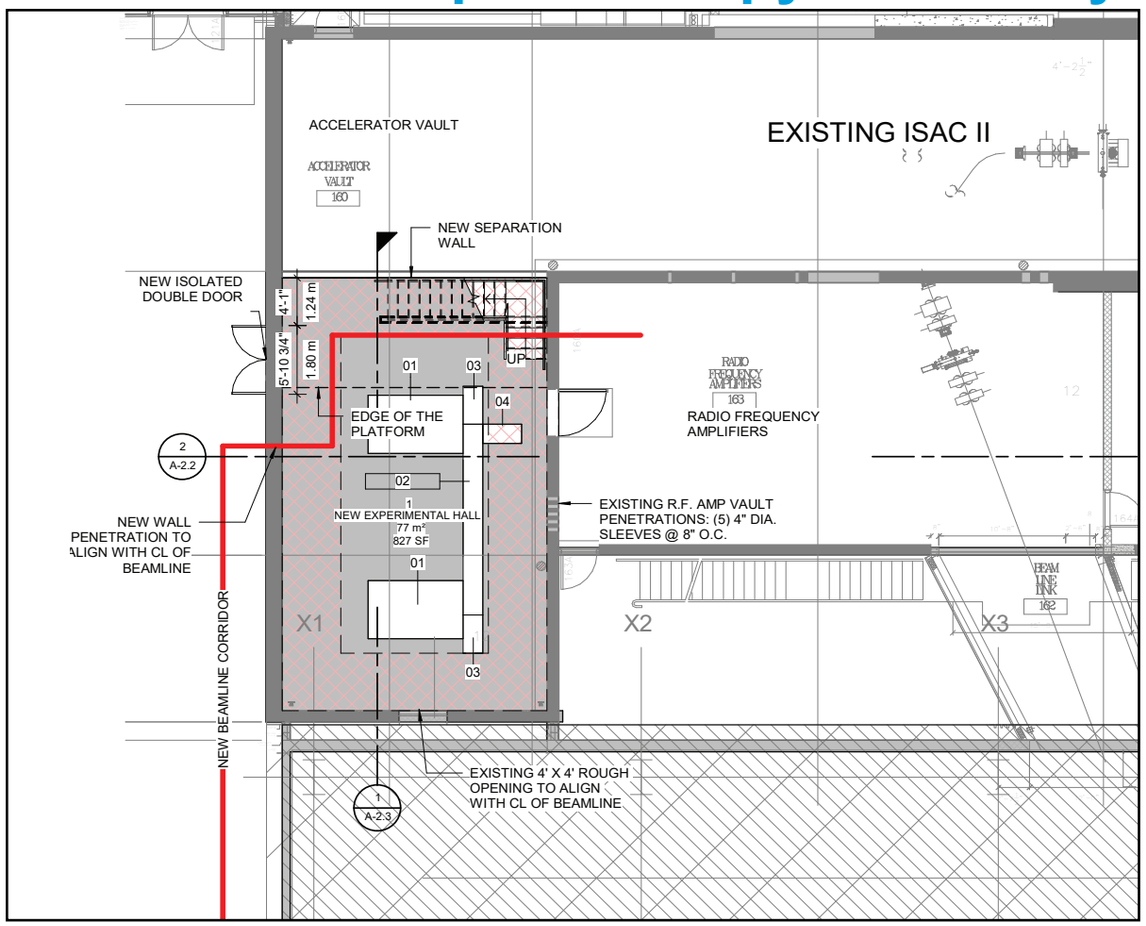
# Laboratory Layout



# Renovation of existing laboratory space

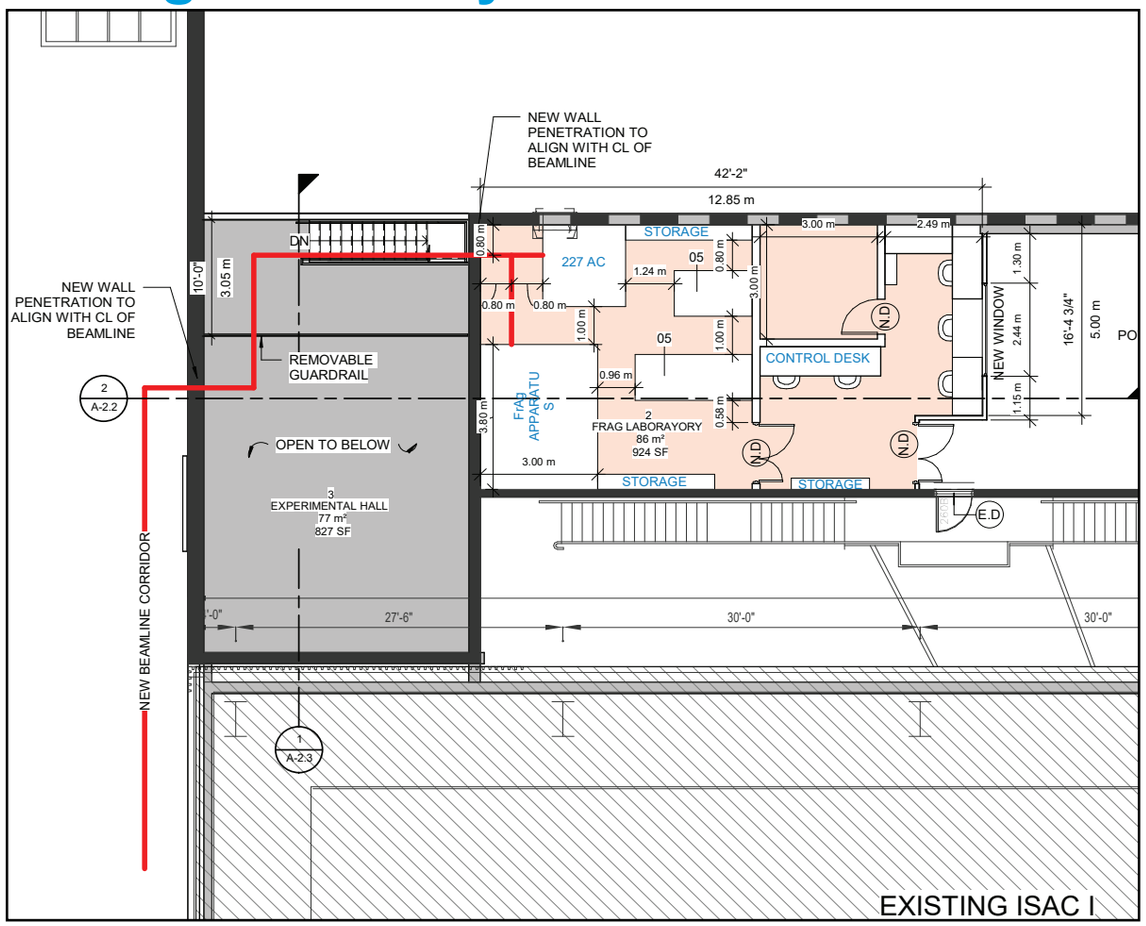


## $ThF^+$ and ion spectroscopy laboratory



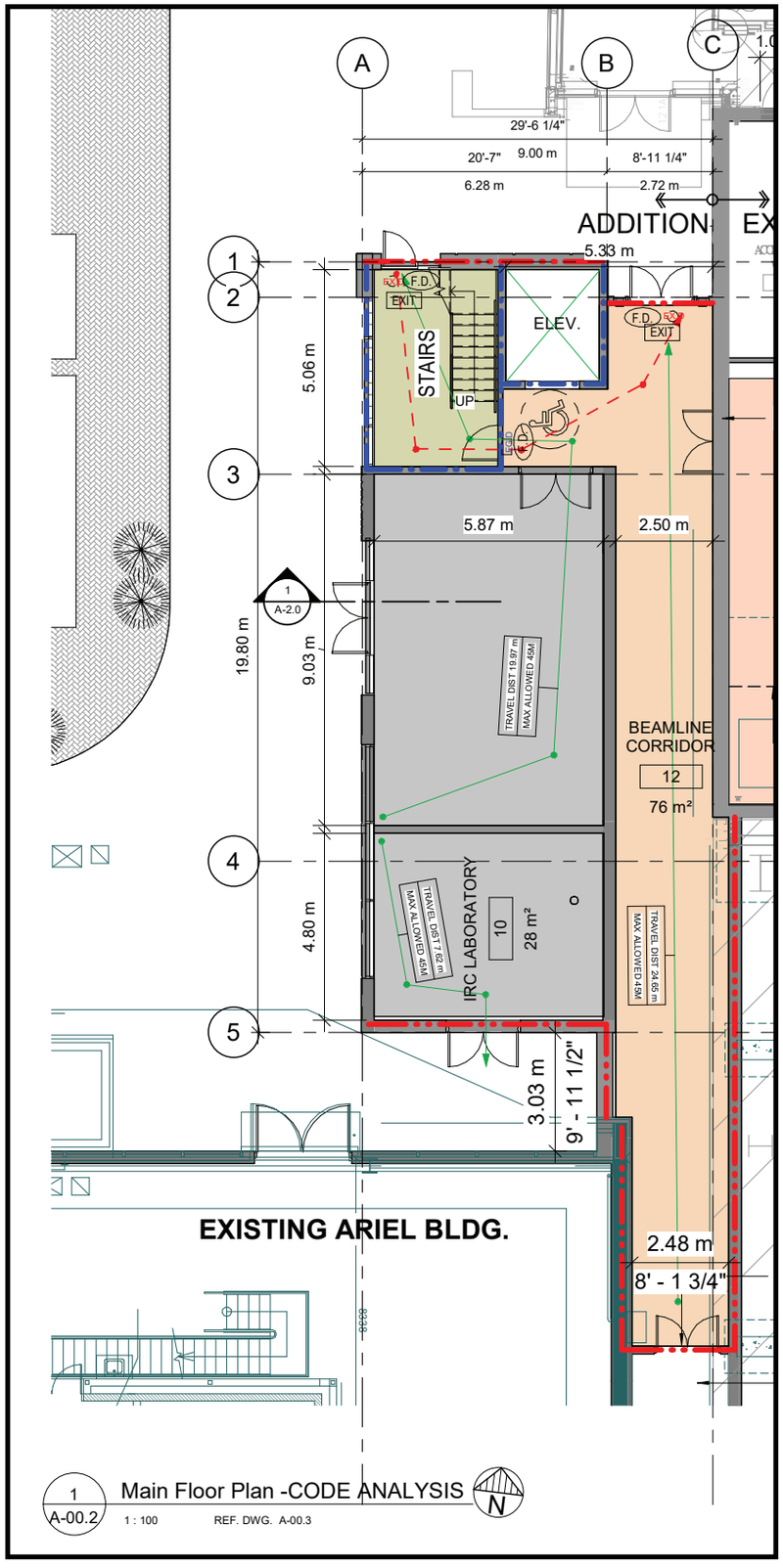

**Ground floor**

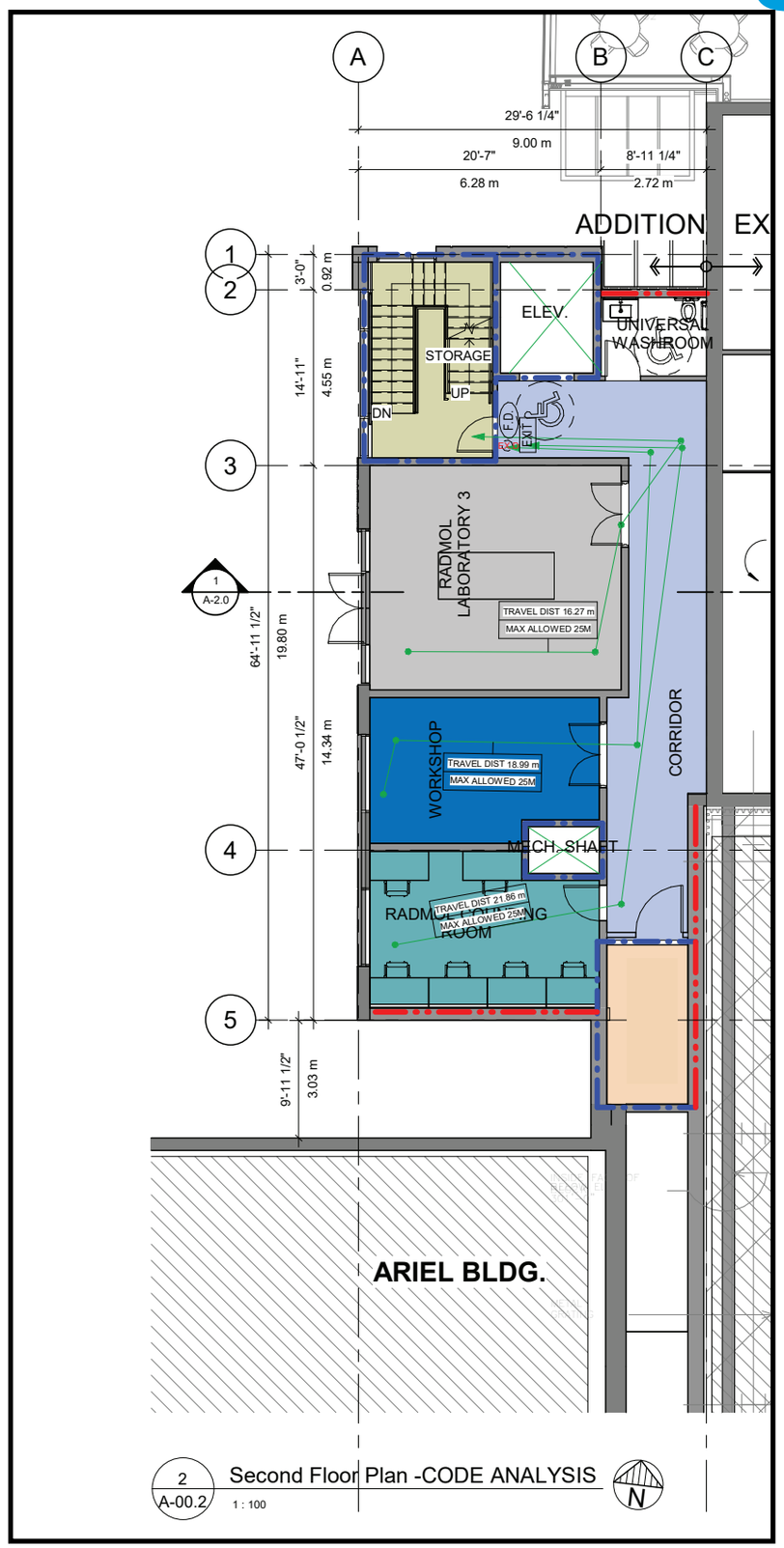
## FrAg laboratory




**Second Floor**

# New ISAC II extension building



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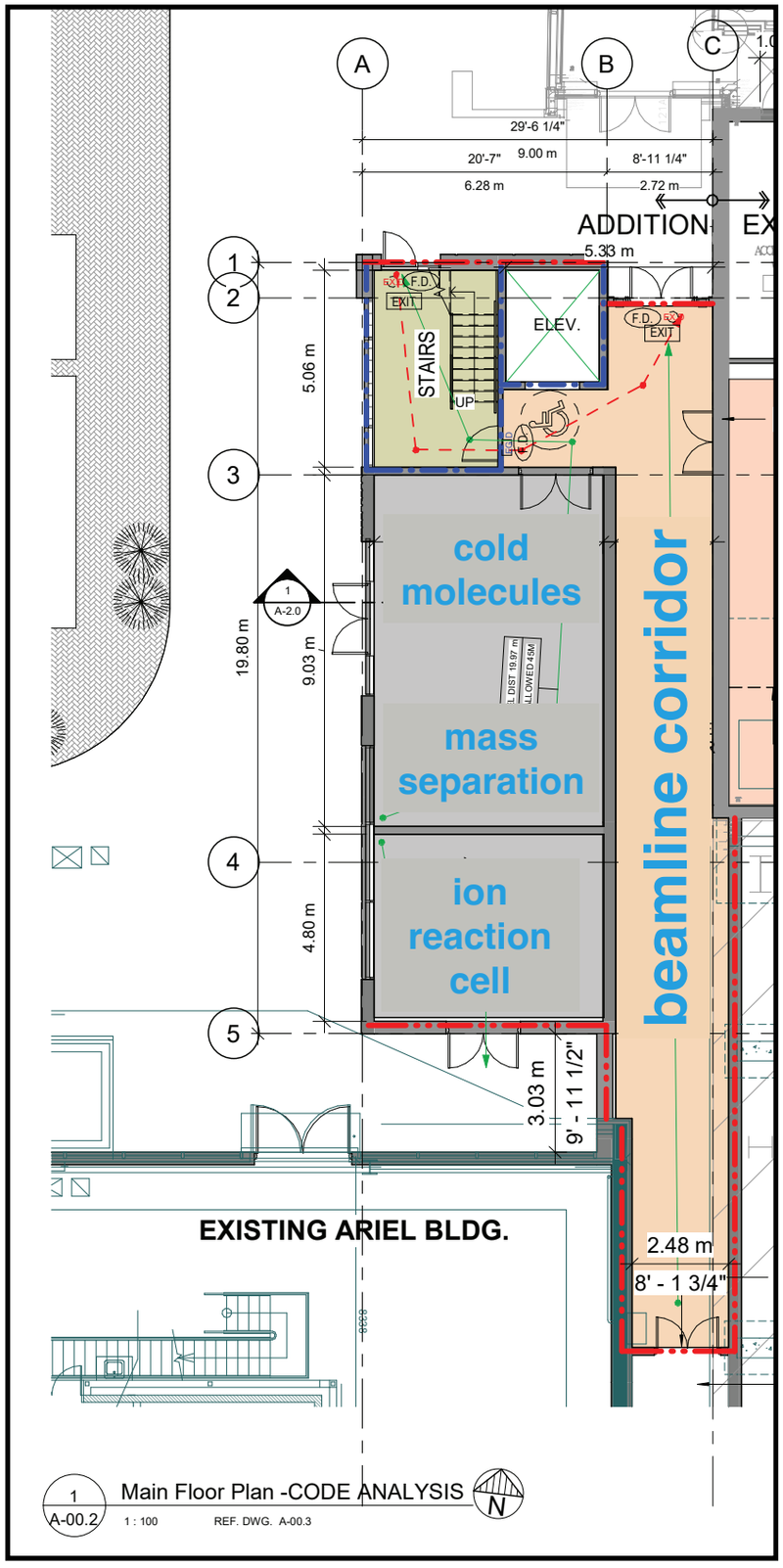


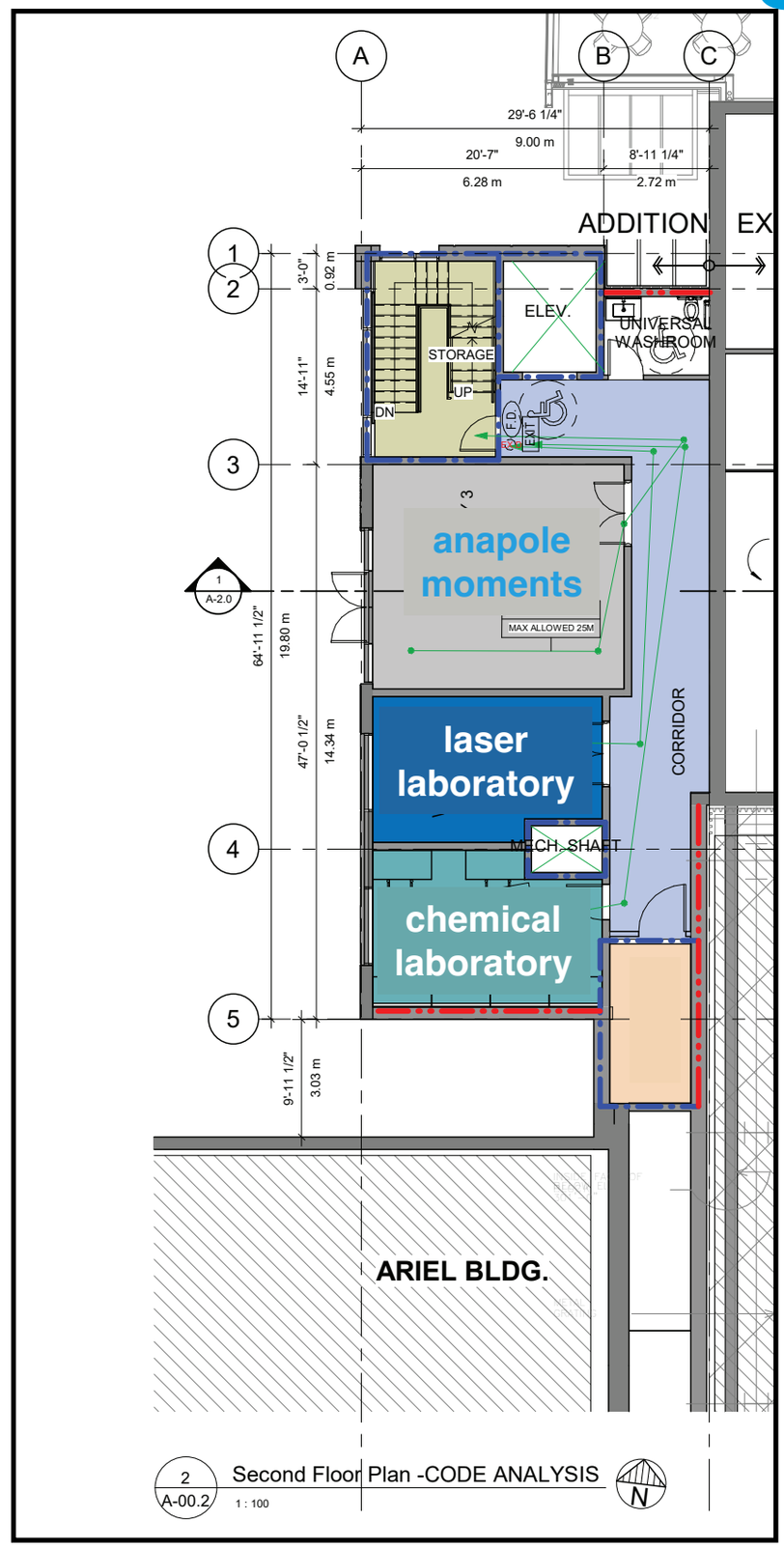

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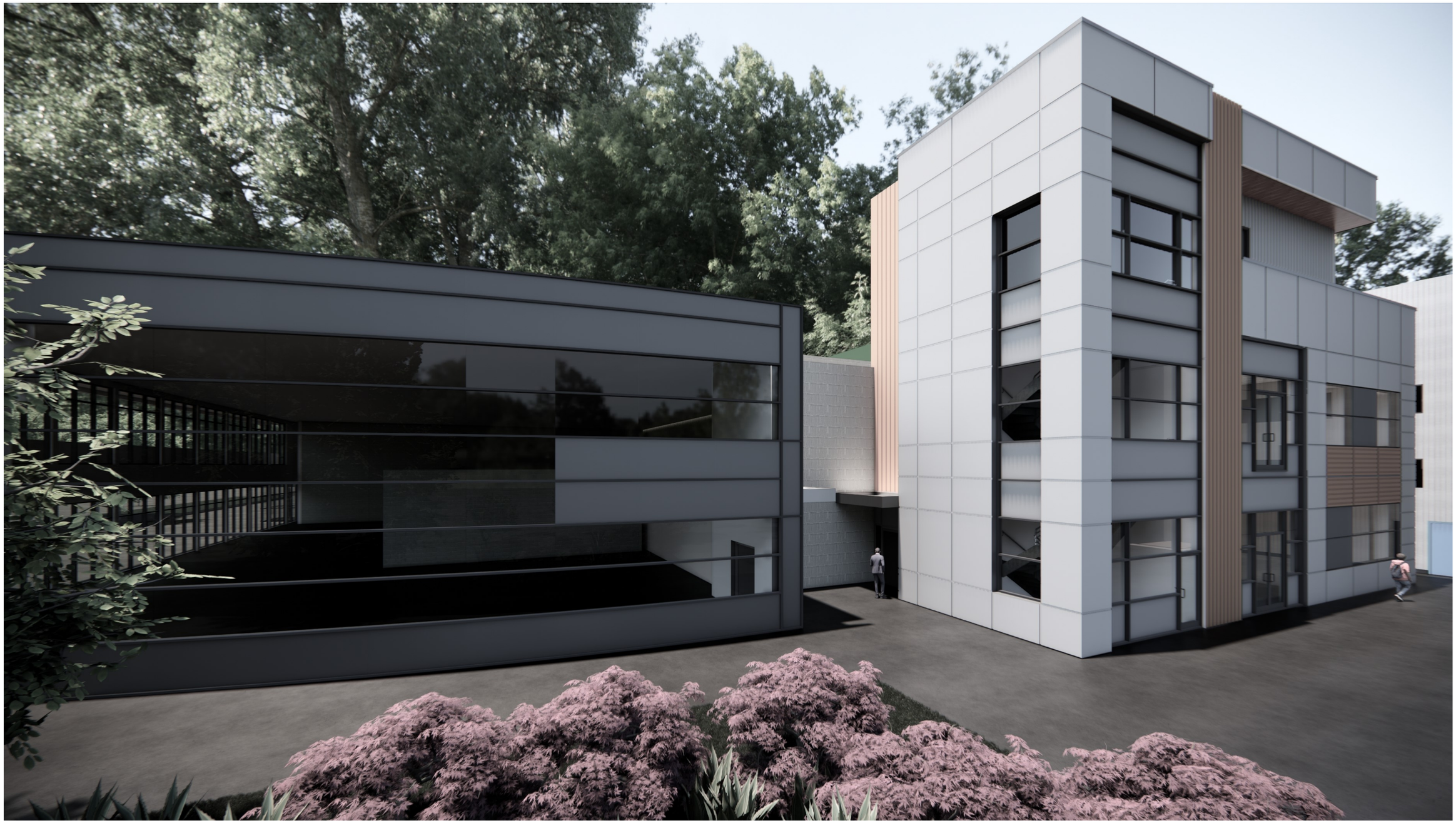


# budget

| Infrastructure or equipment requested | Costs [$MCAD] |
|---|---|
| renovation of laboratory space | 1.2 |
| building extension | 10.8 |
| RIB beam-lines | 2.5 |
| Ion Reaction Cell & integration | 0.5 |
| Experimental Apparatus - $^{223}FrAg$ | 3.2 |
| Experimental Apparatus - $^{227}ThF^{+}$ | 2.8 |
| **TOTAL** | **21.0** |

**12 MCAD**

have to come from BC institutions



| Funding | Amount [$MCAD] |
|---|---|
| CFI envelope | |
| UBC | 4.0 |
| University of Toronto | 3.5 |
| University of Waterloo | 0.4 |
| University of Manitoba | 0.5 |
| Provincial contributions | |
| BC | 4.0 |
| Ontario | 3.9 |
| Manitoba | 0.5 |
| Other | |
| TRIUMF | 4.0 |
| Vendor Discounts | 0.2 |
| **TOTAL** | **21.0** |

**$\sum$ = 12 MCAD**

# Consequences of staging CFI proposal

## Scenario A: full proposal

- leading Schiff moment experiments at TRIUMF
- attract leading AMO scientists in EDM searches
- allows exploitation across TRIUMF divisions
  - ion reaction cell
  - Mass separation capabilities for medical isotopes
  - beamline for new RFQ accelerator in ISAC-II
- clear vision for expansion into wider program
- cement TRIUMF as **the** place for radioactive molecules
- required TRIUMF investment: 4 MCAD



## Scenario B: renovation + $ThF^+$ + FrAg

- required TRIUMF investment: 1.2 MCAD
- Synergy in source development between $ThF^+$ and FrAg (both $^{227}Ac$ based)
- $ThF^+$ in full science program, but no general spectroscopy program
- FrAg only with offline source: why at TRIUMF?
- prospect for later online beam: earliest in 2032 ⇒ not compatible with AMO schedules
- Limited mutual benefits across divisions (while collaboration remains essential)

## Scenario C: 1/2 renovation + $ThF^+$

- required TRIUMF investment: 0.6 MCAD (?)
- only $ThF^+$ in full science program, but no general spectroscopy program
- loss of major collaborators - including UBC
- difficult to argue why UBC is CFI lead

# Summary



- **Radioactive Molecules**
  - ➡ entirely new science path
  - ➡ intriguing & unexplored **probes for New Physics**

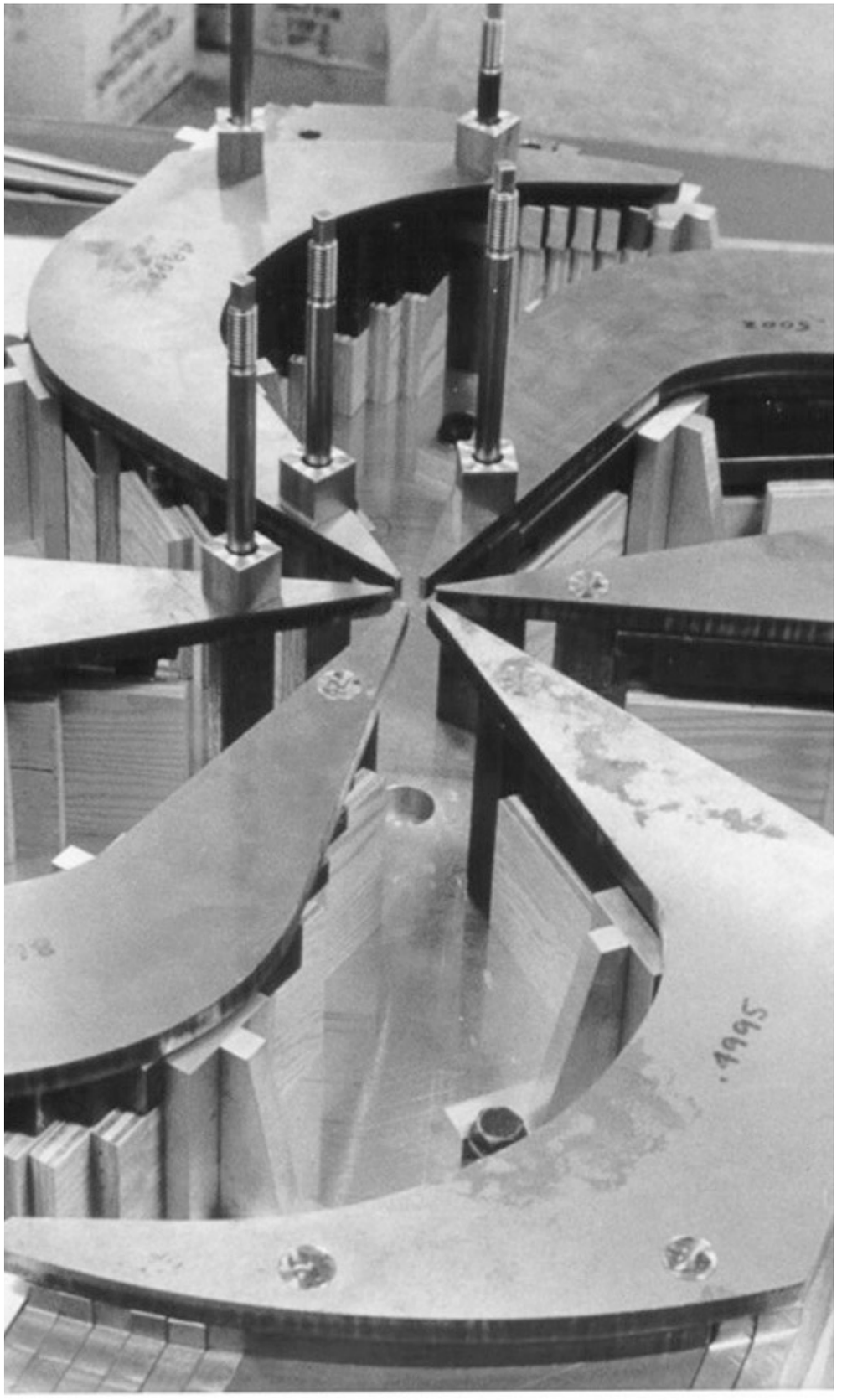
- **RadMol**
  - ➡ dedicated laboratory for radioactive molecules & precision studies at TRIUMF
  - ➡ initial focus: **CP-violating nuclear Schiff moments**
  - ➡ requires multidisciplinary approach & technical developments
  - ➡ strong benefits for collaboration across divisions
  - ➡ attract leading AMO scientists to TRIUMF
  - ➡ TRIUMF is place of choice (if we proceed full scale now)

# RadMol Collaboration:

# Thank you
# Merci

www.triumf.ca

Follow us **@TRIUMFLab**



Discovery, accelerated