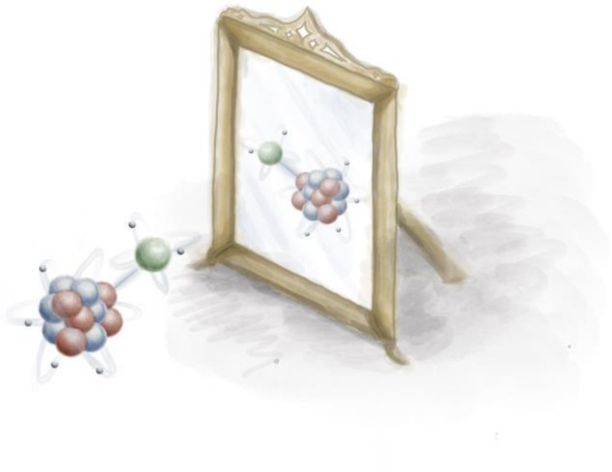
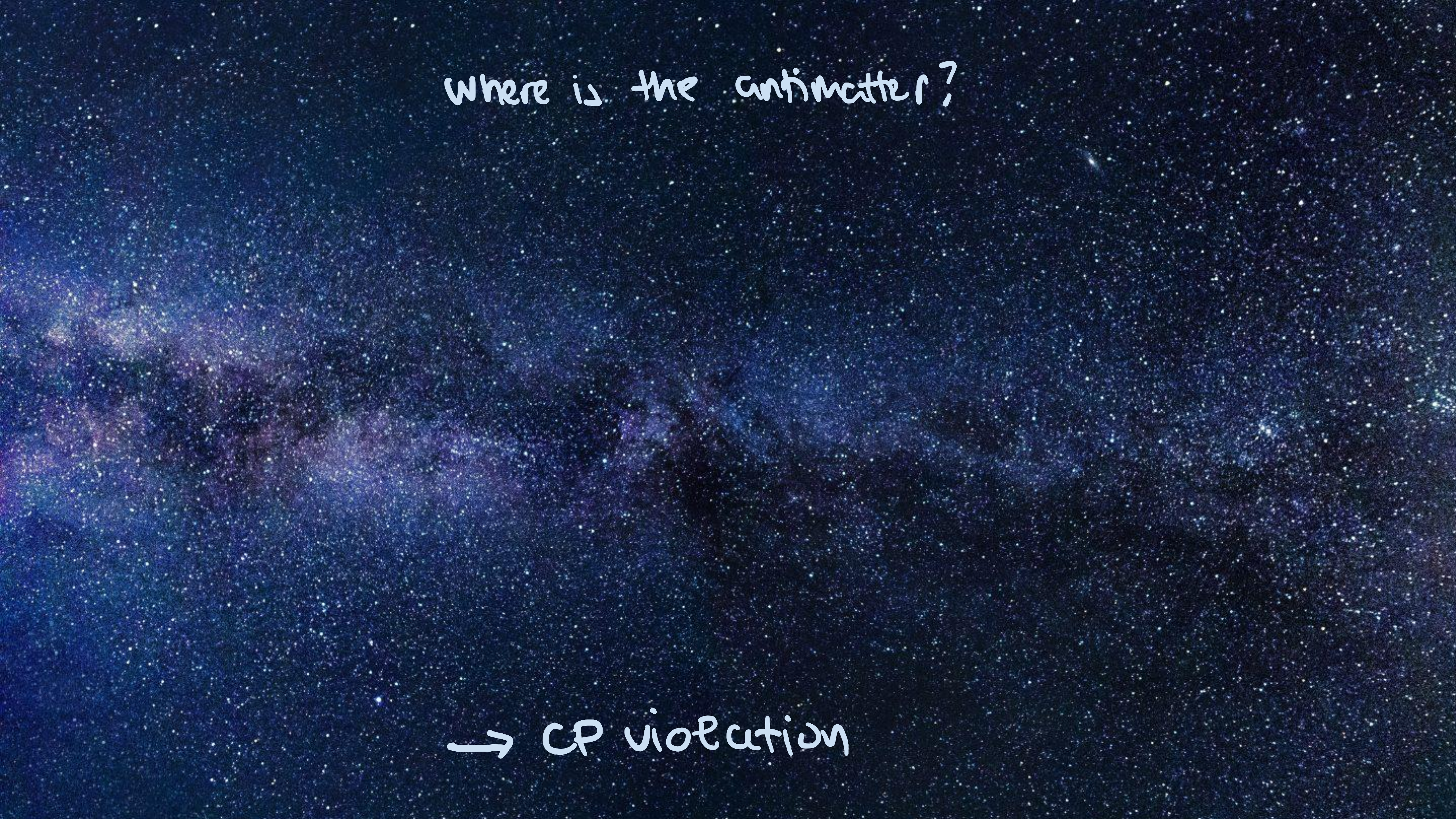
Radioactive molecules for fundamental physics at TRIUMF



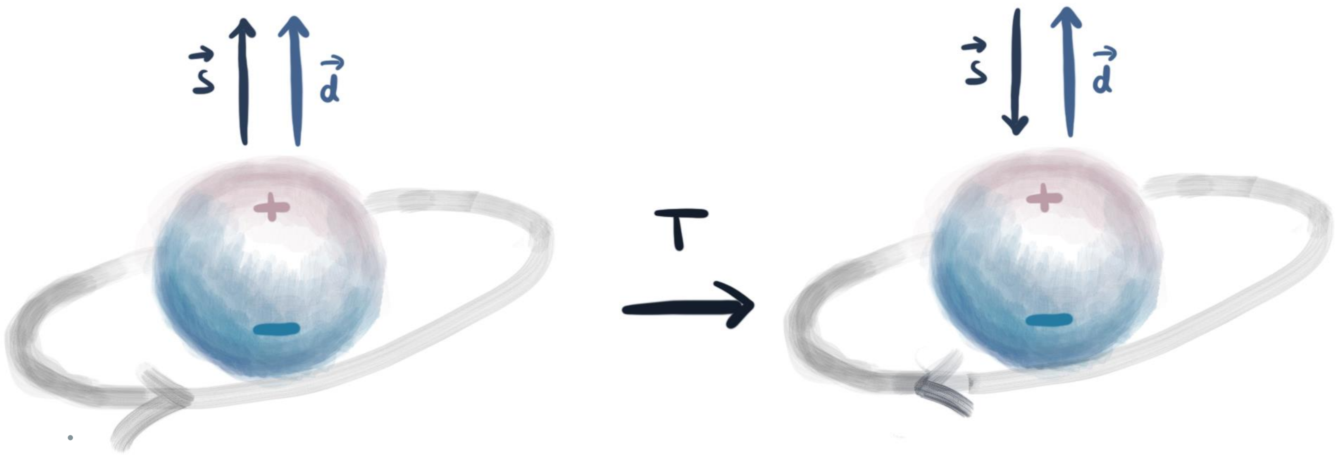
Ivana Belosevic

on behalf of RadMol collaboration


where is the antimatter?


where is the antimatter?
→ CP violation

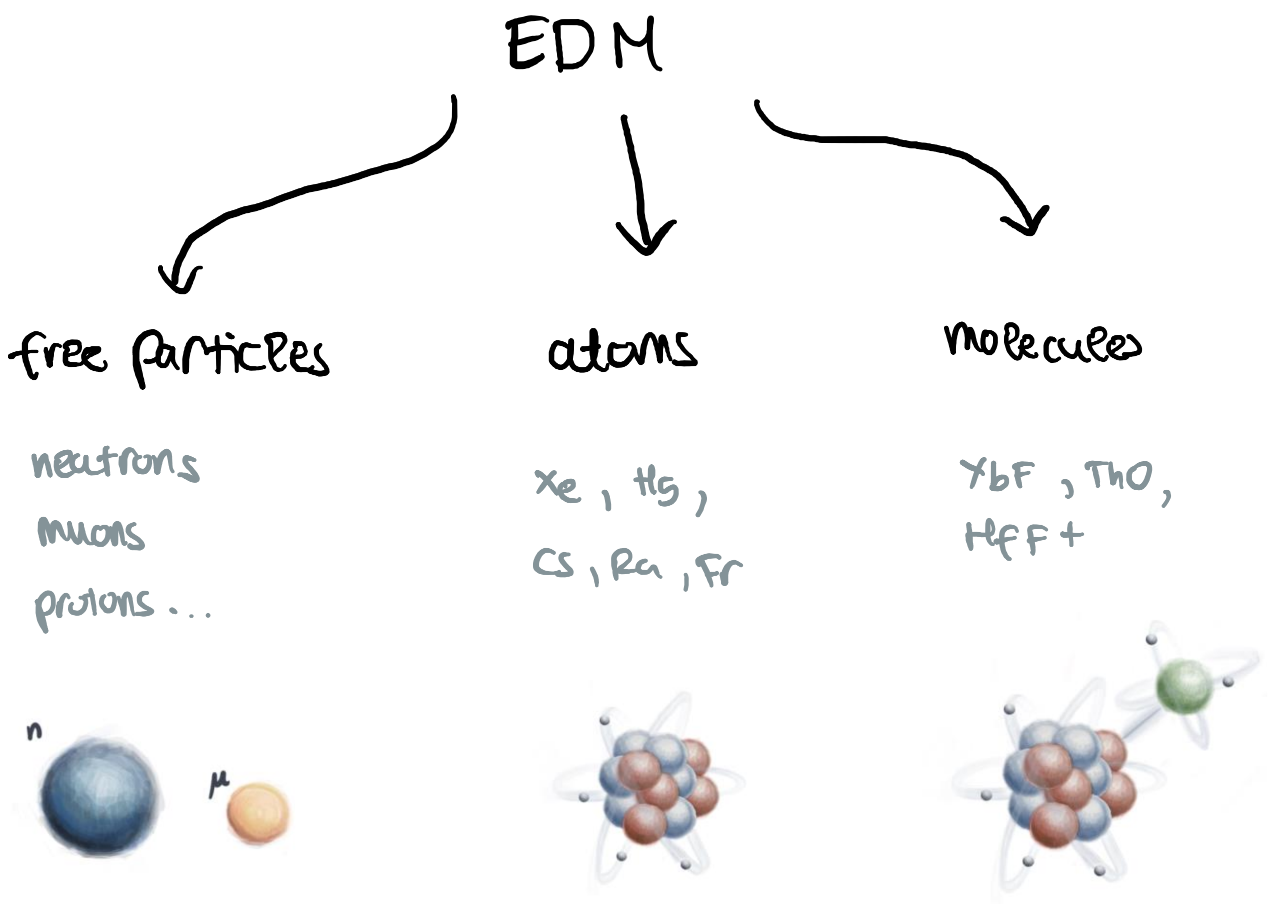
Where does the CP violation come from? -> EDM



T violation ⟷ CP violation

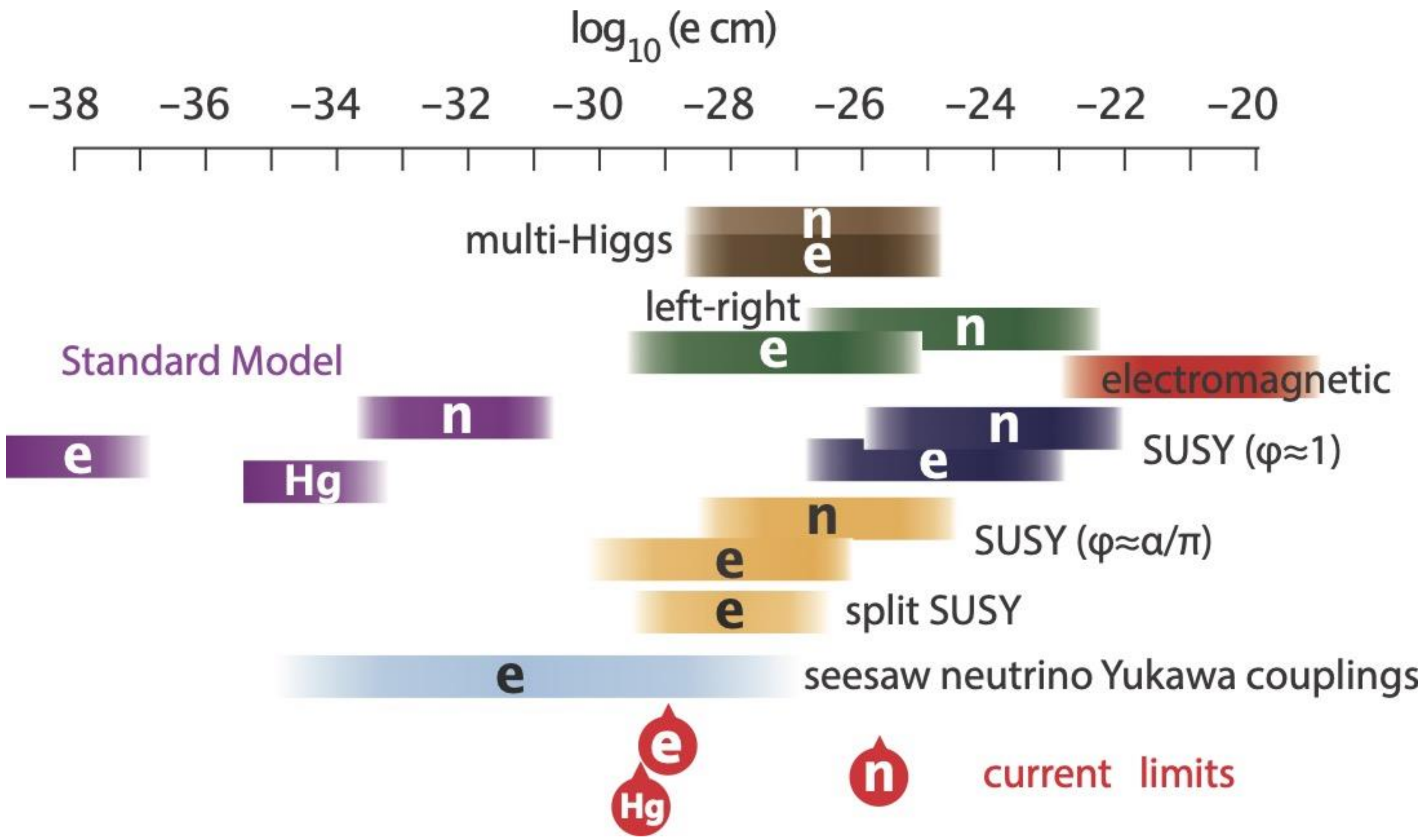
(assuming CPT is conserved)

Where to look for EDM?



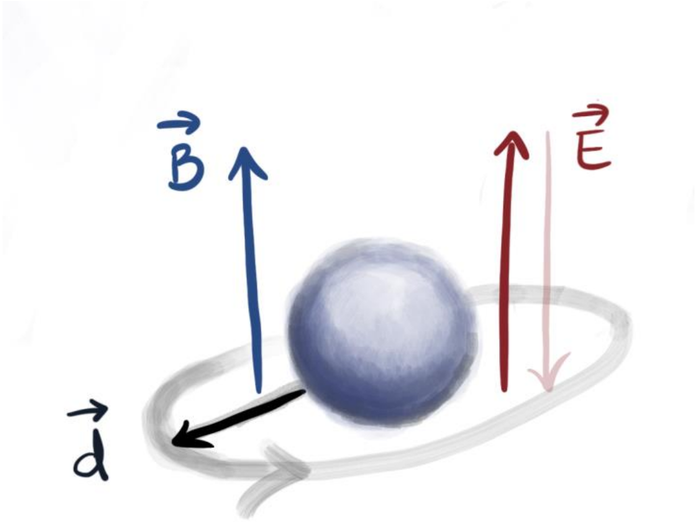
Different systems are sensitive to different sources of CP violation -> complementary

Current EDM limits



Canadian Institute of Nuclear Physics, https://cinp.ca/fundamental-symmetries-homepage

Measuring EDM



$\sim d \cdot E_{eff}$

EDM sensitivity:

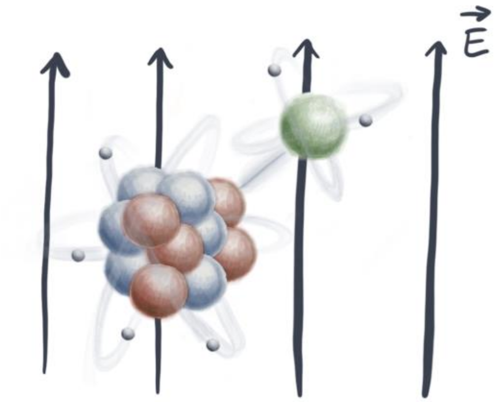
$$\delta_d \sim \frac{1}{E_{eff} \cdot \sqrt{\tau N}}$$

E_{eff}: effective electric field

Why (radioactive) molecules?

Strong effective electric fields:

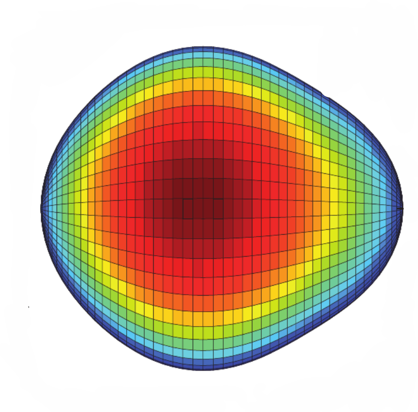
- For heavy, polar molecules



$E_{eff} = 80\,GV/cm$ for $E_{ext} = 1\,V/cm$

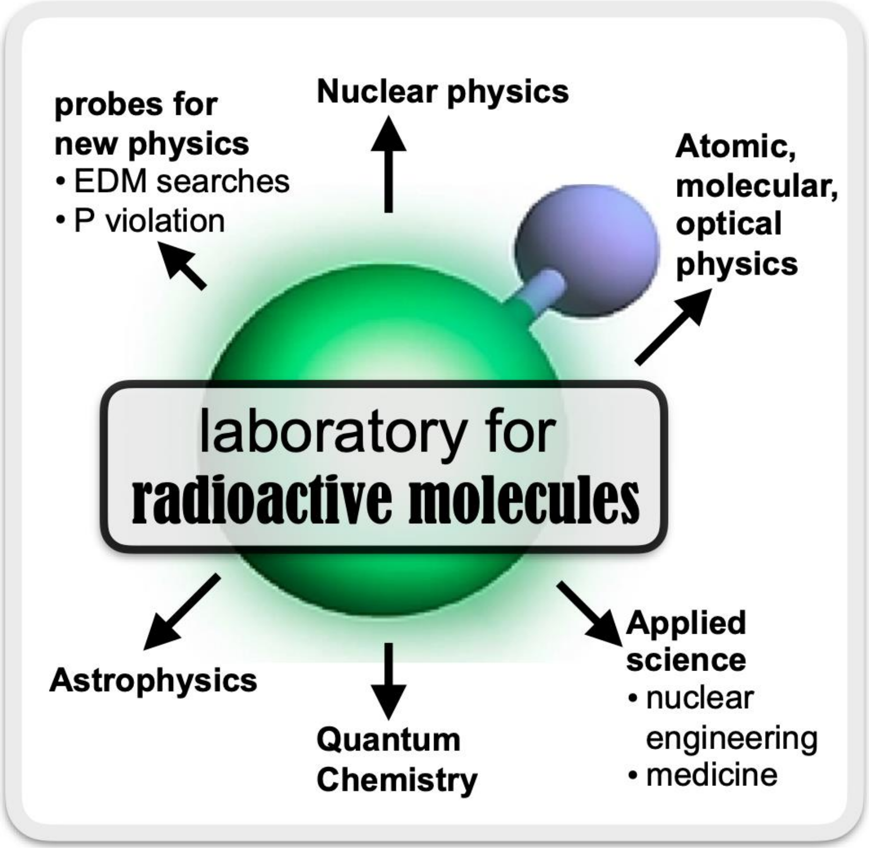
Octupole deformation

- Enhanced sensitivity to T-violating Schiff moments (see talk by J. Singh)



Gaffney et al., Nature 497, 199 (2013)

Radioactive Molecules at TRIUMF



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)

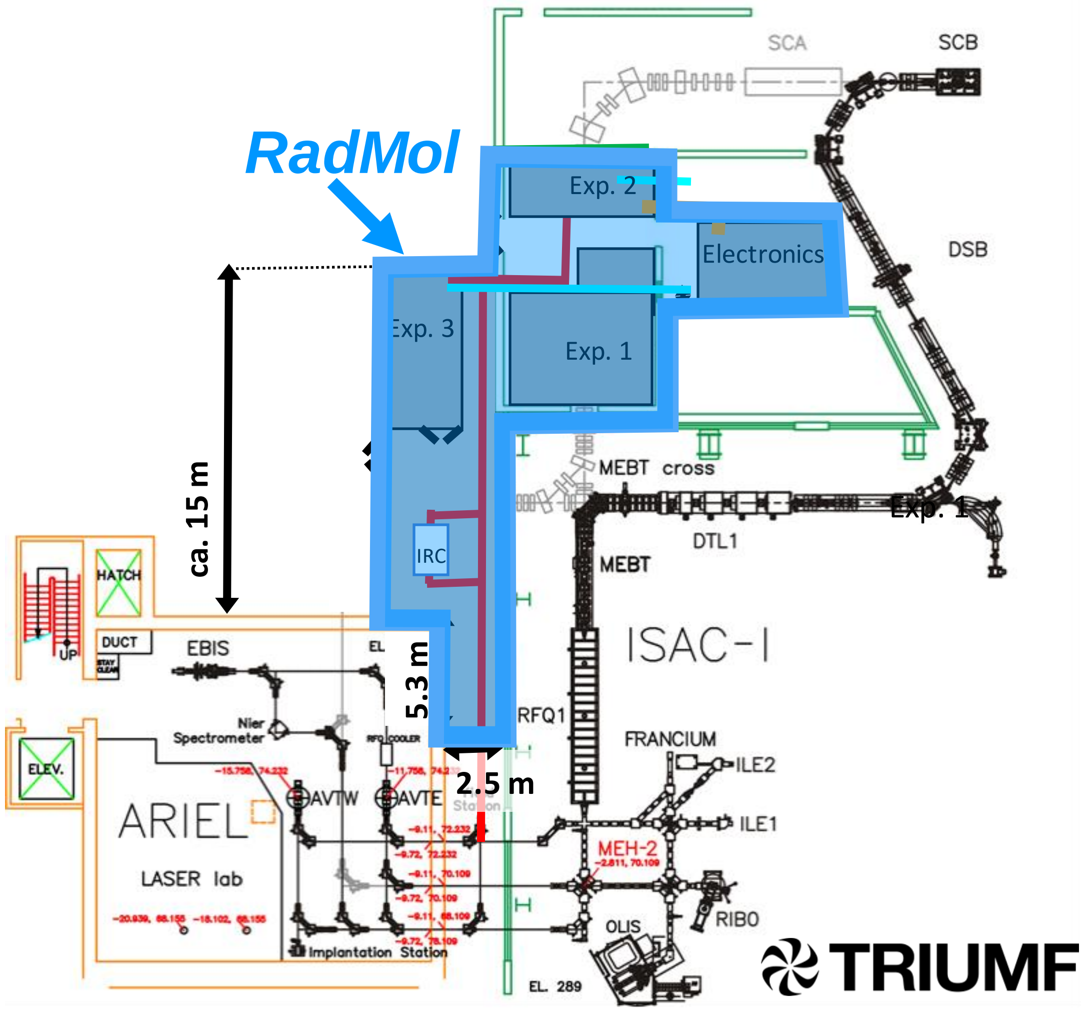
Goals:

- unique laboratory for radioactive molecules
- precision studies for searches for new physics
- Molecular EDM with unprecedented sensitivity to **nuclear T-breaking Schiff moments**

TRIUMF advantages:

- large variety in radioactive ion beams (RIB)
- high beamtime availability
- existing laboratory space for large, multi-station program
- building on existing AMO expertise

RadMol laboratory



New TRIUMF laboratory

- dedicated laboratory to study of radioactive molecules
- to host 3 experimental stations
- provision for expansions into other fields

Current Canadian Team:

- 12 faculty and staff physicists: UofToronto, TRIUMF, UBC, U. Manitoba, McGill, UofOttawa, UofWaterloo

Funding Strategy & Timeline

- NSERC: foundational work towards first science results
- CFI application in 2024 (?) for laboratory infrastructure

Radioactive molecules at TRIUMF

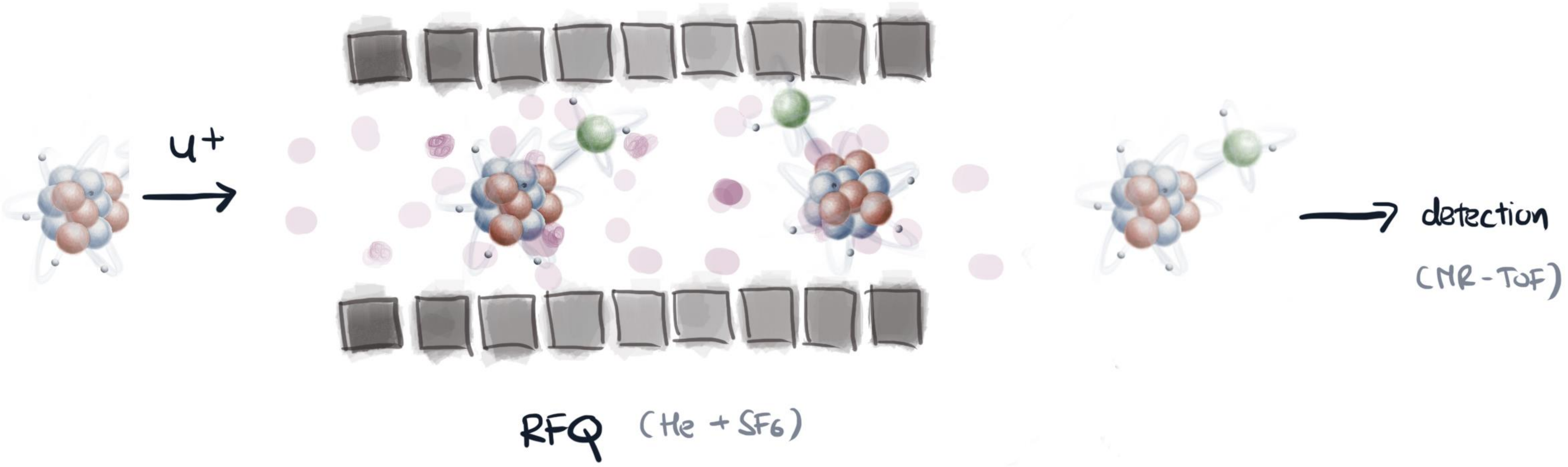
Three parallel approaches:

1. Singly charged molecules: **AcF^{+}**
2. "Highly" charged molecules: **PaF^{3+}**
3. Neutral molecules: **FrAg**

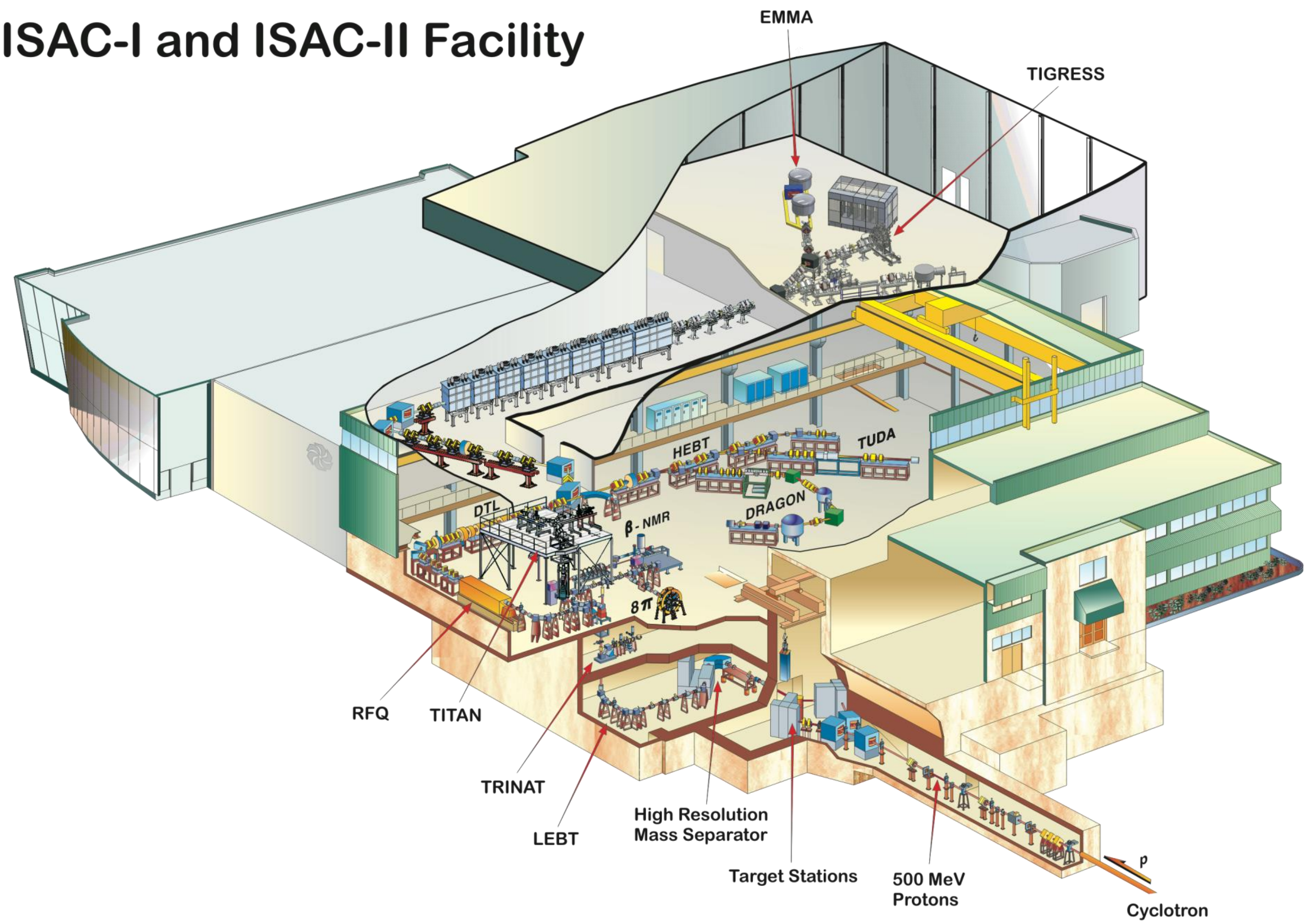
Molecule formation

General Strategy:

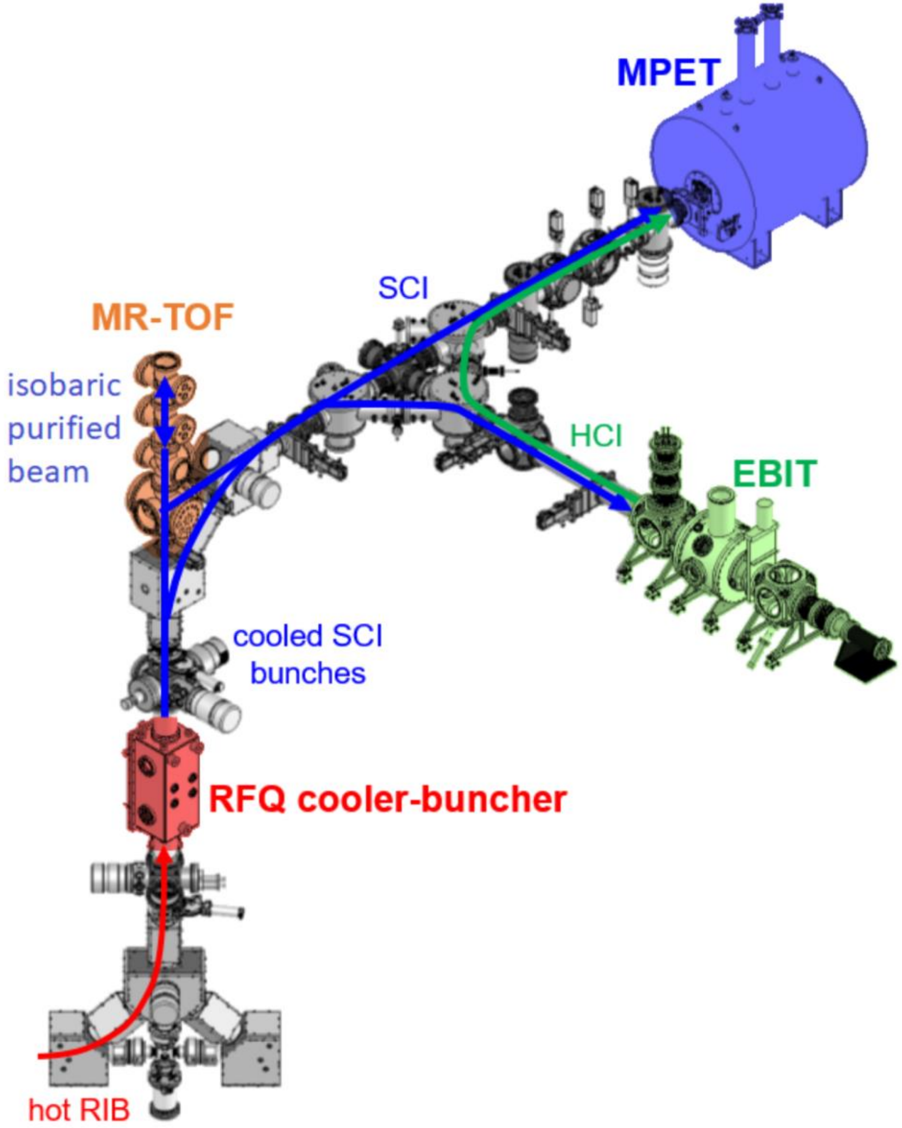
- Goal: formation of radioactive fluorides molecules: AcF^{+}, ThF^{+}, PaF^{+3}, etc.
- start with ('stable'), readily available U or lanthanides
- extend developed techniques to radioactive molecules
- use TITAN MR-ToF system for identification



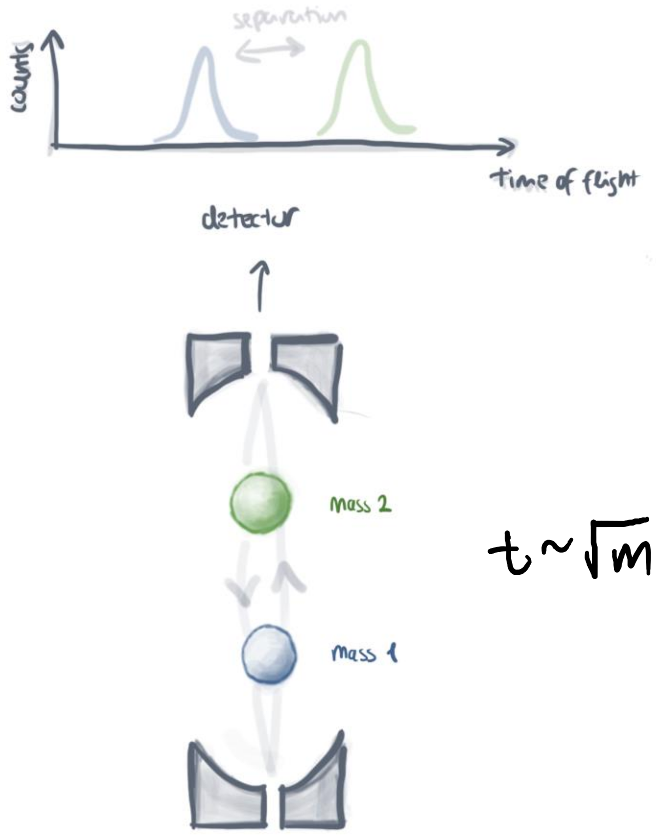
ISAC-I and ISAC-II Facility



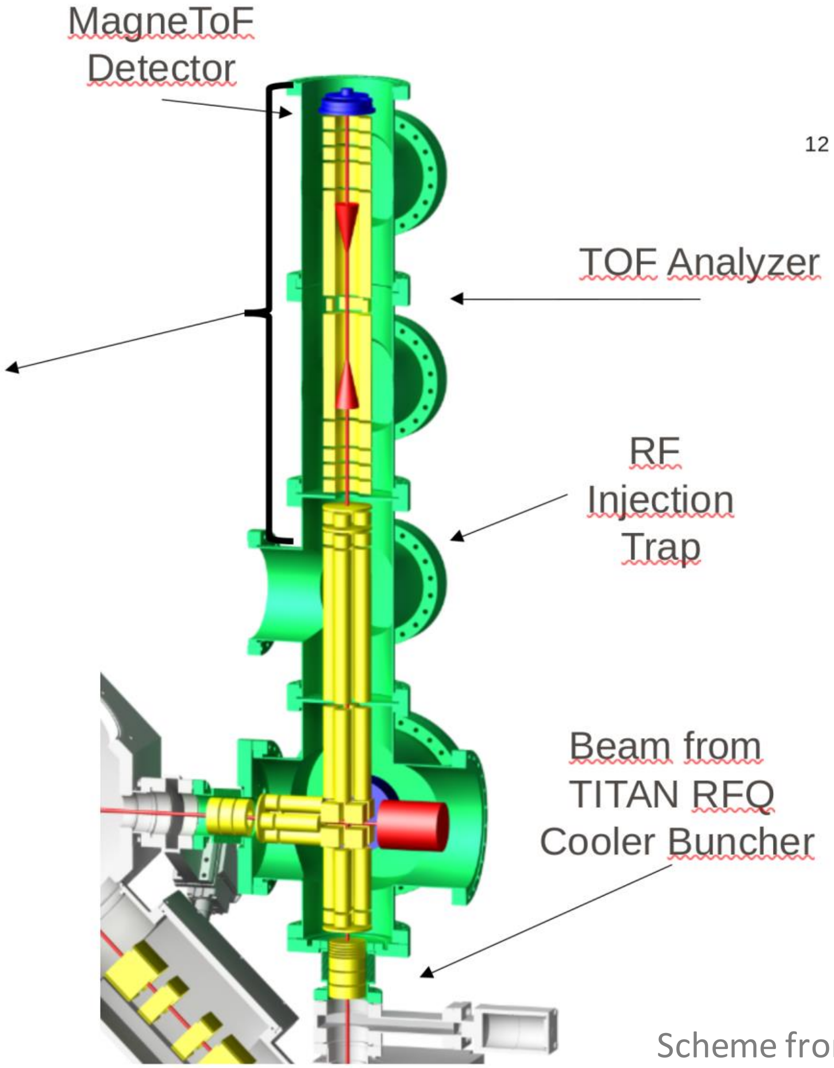
TITAN


MPET
SCI
MR-TOF
isobaric
purified
beam
HCI
EBIT
cooled SCI
bunches
RFQ cooler-buncher
hot RIB

MR-ToF MS



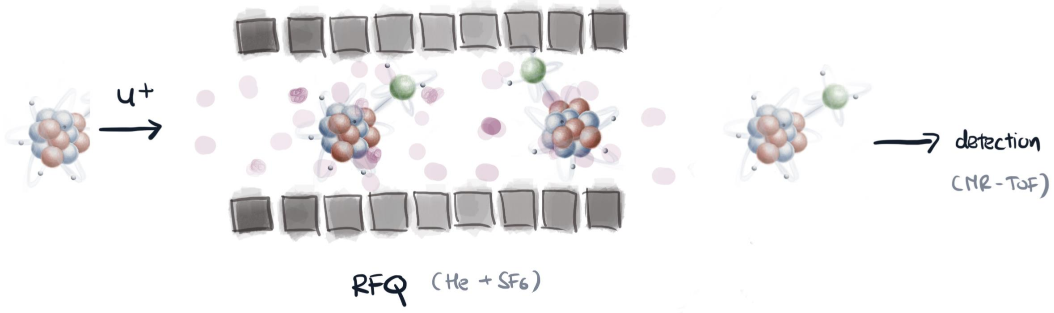
$t \sim \sqrt{m}$

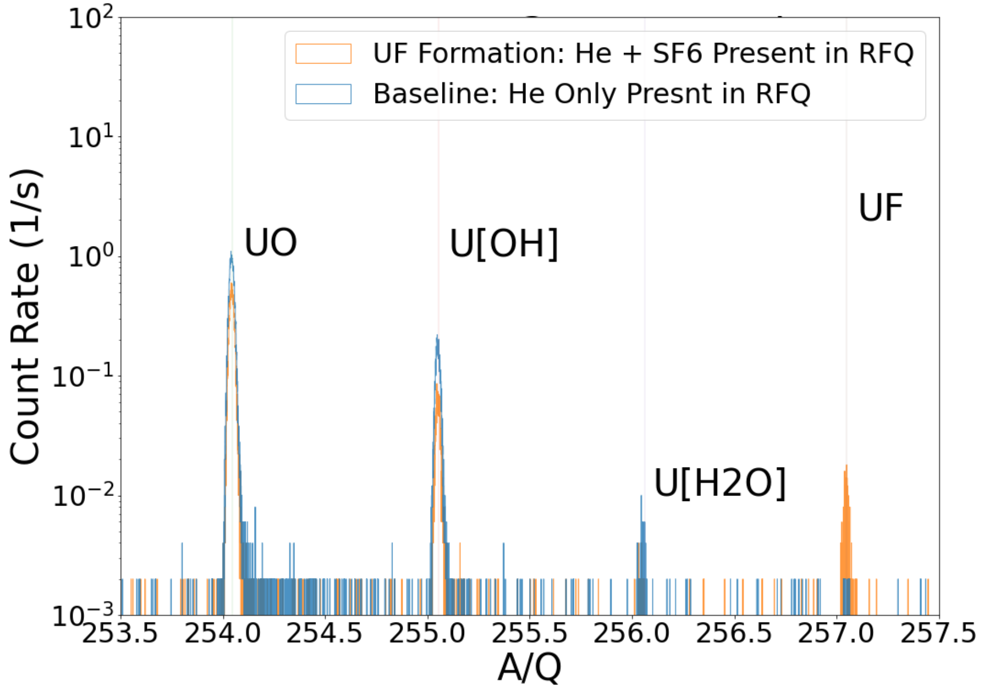


C. Jesch et al., Hyperfine Interact. 235 (2015) 97

Scheme from A. Jacobs, JINA-CEE talk (2022)

UF_x in TITAN cooler-buncher

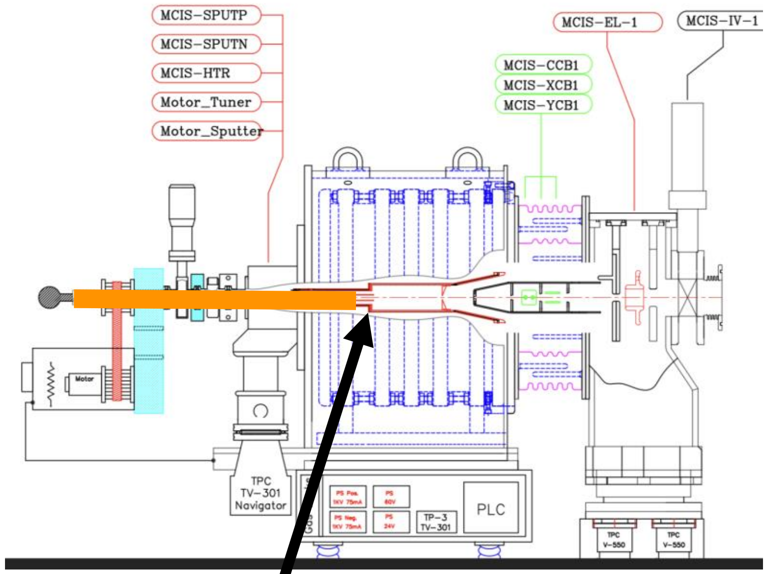




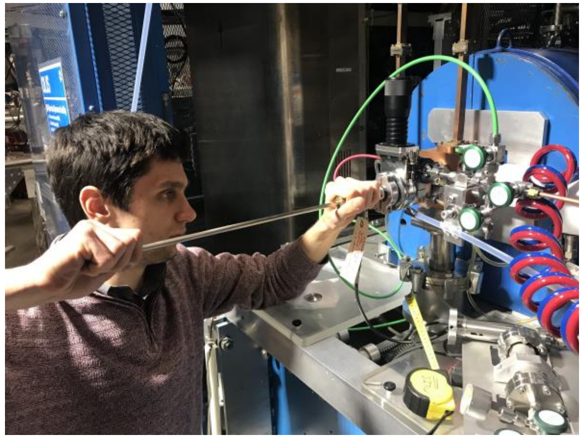
Conclusions:

- UF^+ successfully formed in cooler buncher
- lots of other chemistry with residual gas
- formation of UF_2^+ is generally favored
- UF^+ from target much higher intensity

New OLIS beams



Ce sample



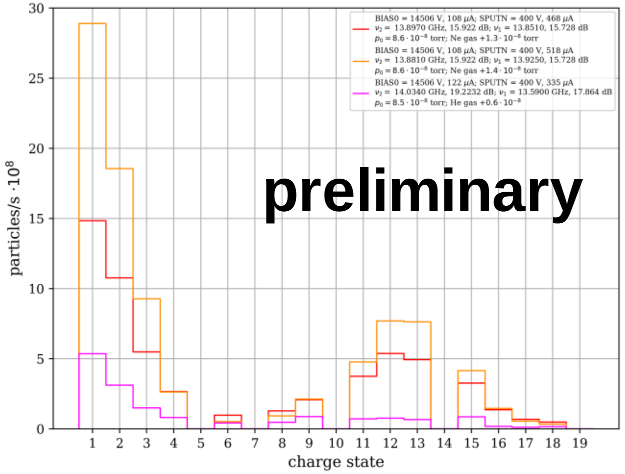
MultiCharge Ion Source (MCIS)

K Jayamanna et al., Rev Sci Instr. 81, 02A331 (2010)

- **New:** sputtering of (Ce) sample
- New opportunities for beams at OLIS
- For RadMol: Ce chemical analog to Th

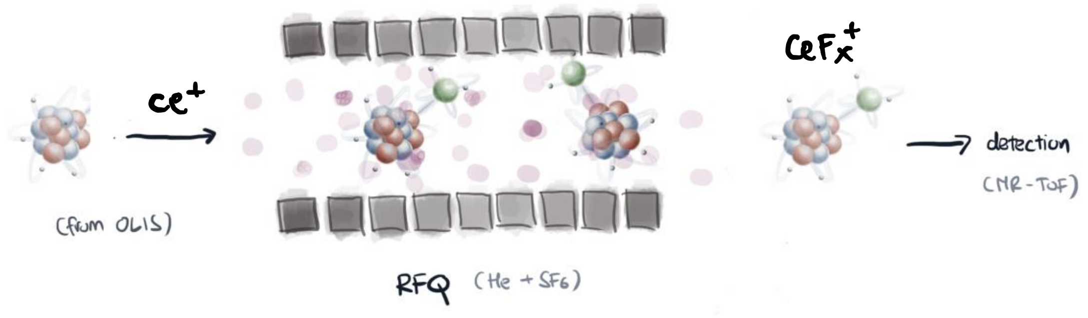
57 La	58 Ce	59 Pr	60 Nd	**lanthanides**
89 Ac	90 Th	91 Pa	92 U	**actinides**

$^{140}Ce^{+q}$: different source config.

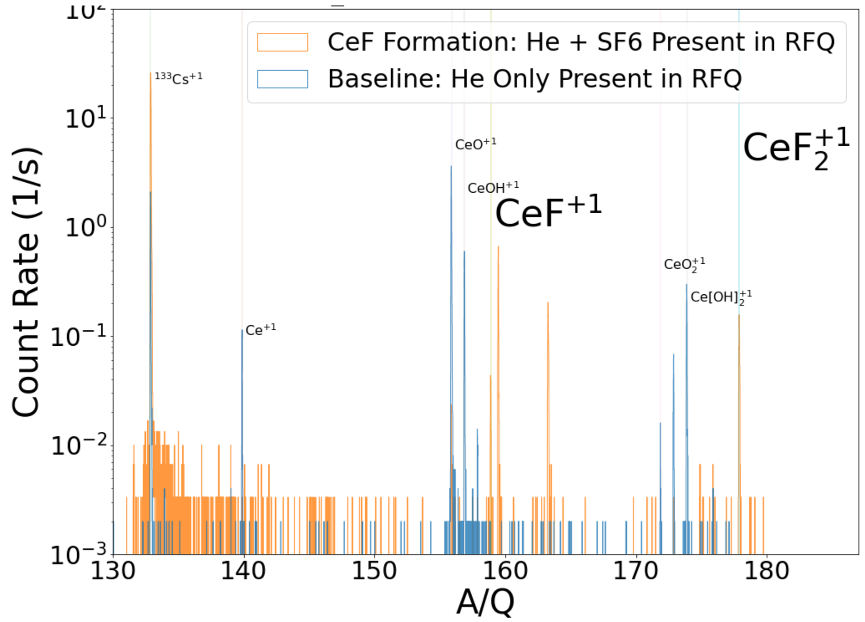


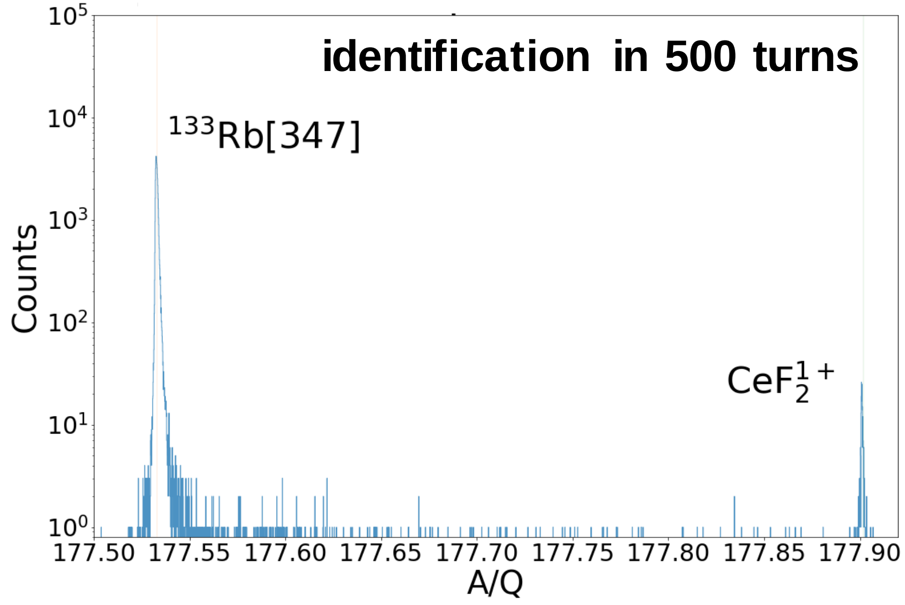
P. Justus, C. Charles, et al., in prep.

CeF_x in TITAN cooler-buncher

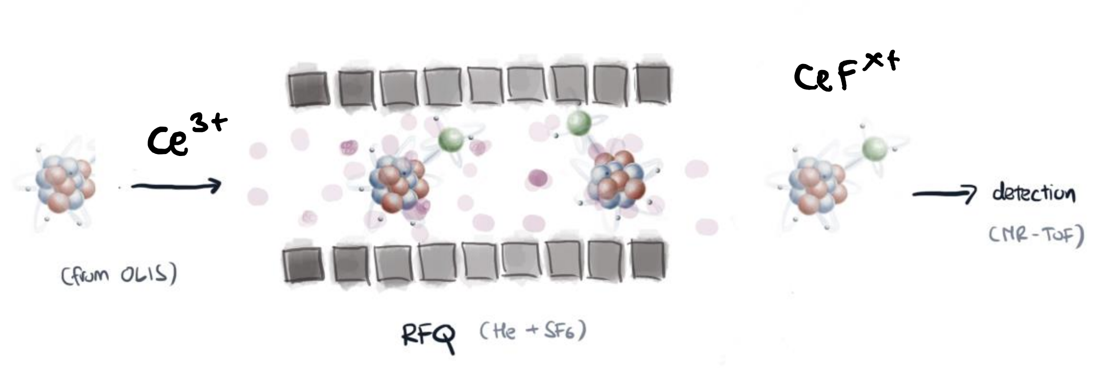


Conclusions:
- less reactive
- CeF^+ successfully formed
- excellent prospect for ThF^+



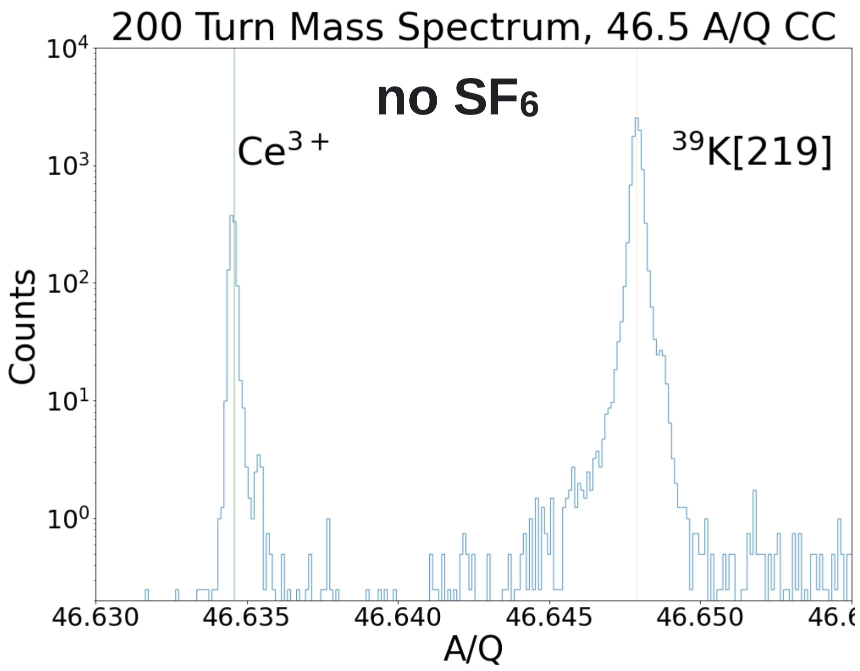


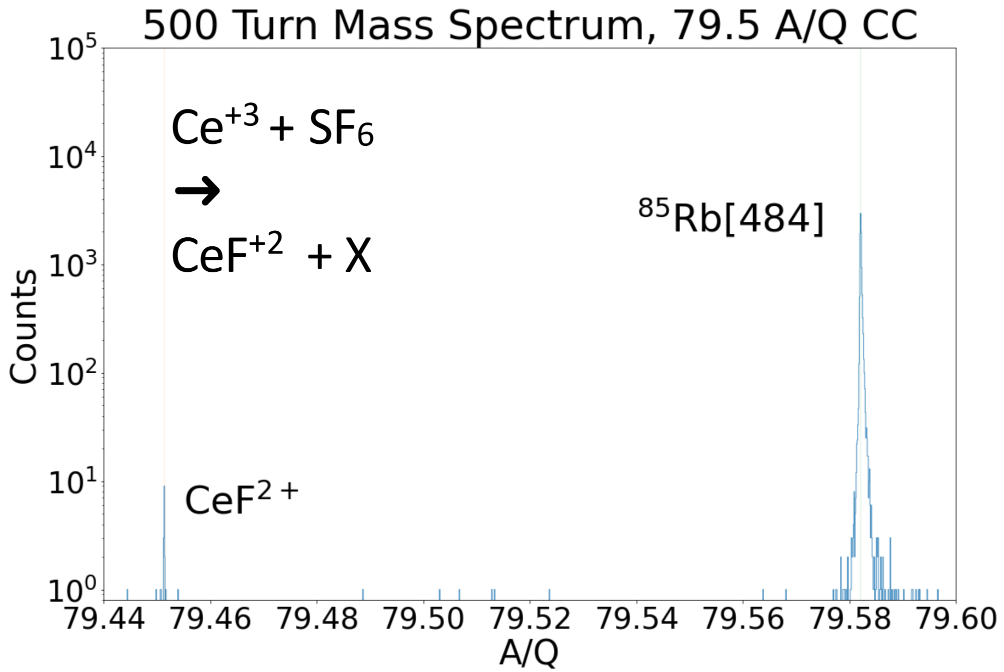
CeF^{2+} in TITAN cooler-buncher



Conclusions:

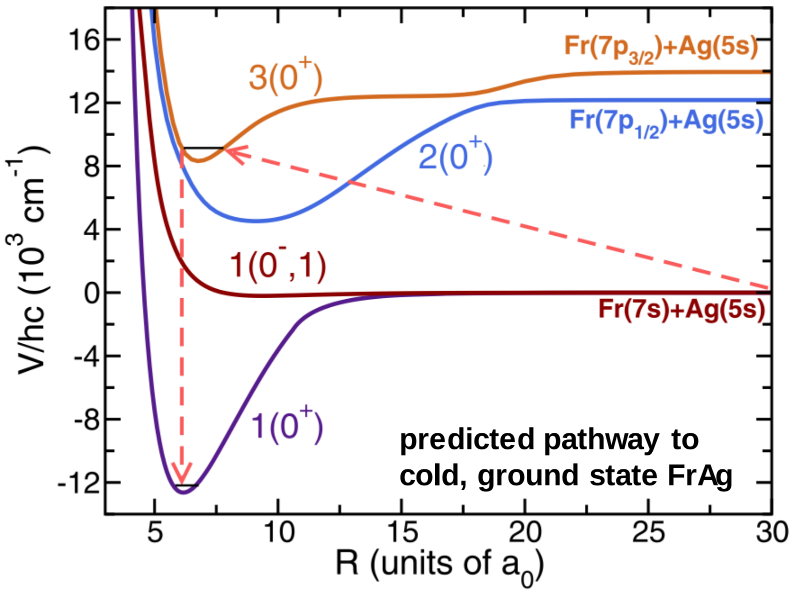
- CeF^{+2} successfully formed
- Excellent prospect for ThF^{+2}



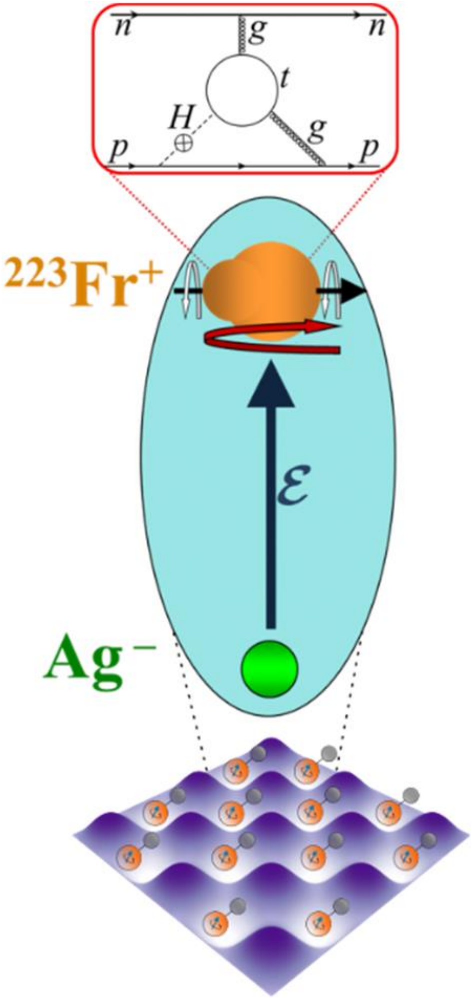


The Case of ^{223}FrAg

- **Schiff moment: intrinsic enhancement of 10^7 compared to ^{199}Hg**
- ultracold molecule assembled from laser-cooled Fr and Ag atoms
- ^{223}Fr ($T_{1/2}$=22 min) at ISAC: $1.3 \cdot 10^7$ ions/sec
- infrastructure and expertise at TRIUMF's Fr trapping facility
- first exp. goal: measurement of Fr s-wave scattering length
  (input for formation of Bose Einstein Condensate with Fr atoms)



J Kłos et al., New J. Phys. 24, 025005 (2022)



What's next?

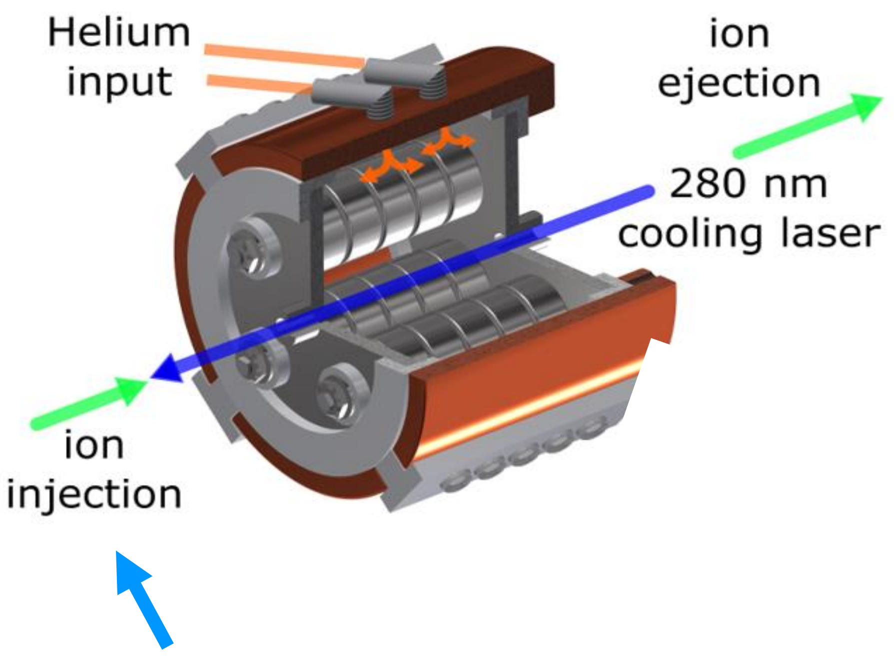
- Further molecular beam development
- Molecule cooling/preparation
- Spectroscopy setup

$$\delta_d \sim \frac{1}{E_{eff} \cdot \sqrt{\tau N}}$$

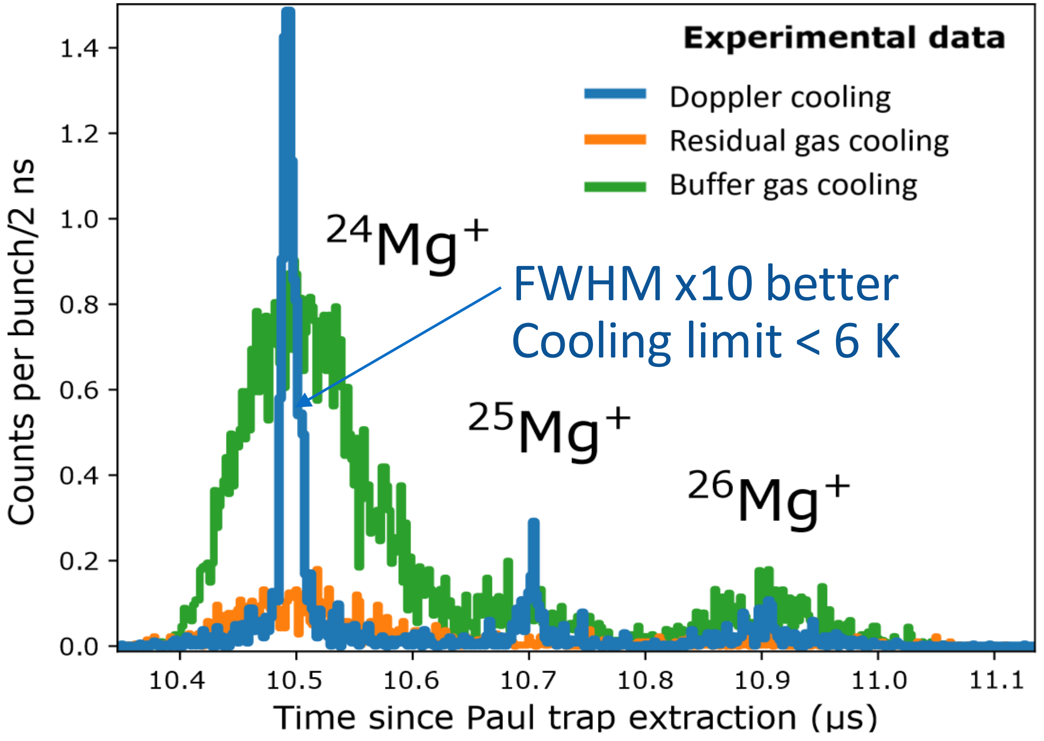
E_{eff}: effective electric field

Doppler cooling at MIRACLS

Paul trap:

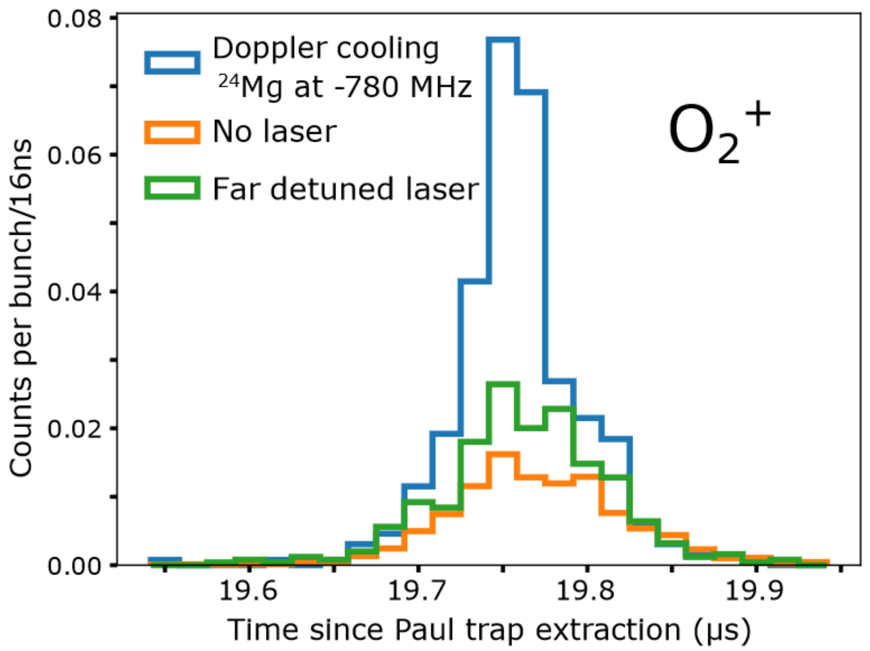


externally produced, fast and 'hot' Mg^+ ion beam



Sympathetic cooling at MIRACLS

- ‘universal’ availability of cold ion ensembles
- including ionic systems which cannot be directly laser-cooled



opportunity for cold molecular RIBs

Issues with our O_2^+ source

can be done better analogous to existing work, e.g. [1],[2]

	O_2^+
Peak width residual-gas or buffer-gas cooling	113(5) ns
Sympathetic cooling	58(4) ns
Improvement in countrate	Factor 2.6

J. Wuebbena et al, Phys. Rev. A 85, 043412 (2012)
[2] M. Guggemos. New Journal of Physics 17, 103001 (2015)
K. Groot-Berning et al. Phys. Rev. A 99, 023420 (2019)

S. Sels, F. Maier et al., Phys. Rev. Res. 4, 033229 (2022)

Summary

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

- **RadMol**
  - dedicated laboratory for radioactive molecules & precision studies at TRIUMF
  - designed to master experimental challenges

- **Cold radioactive, molecular beams**
  - Molecular formation in a radiofreqeuncy cooler-buncher (at TITAN)
  - Doppler + sympathetic cooling (at MIRACLS)

Acknowledgement

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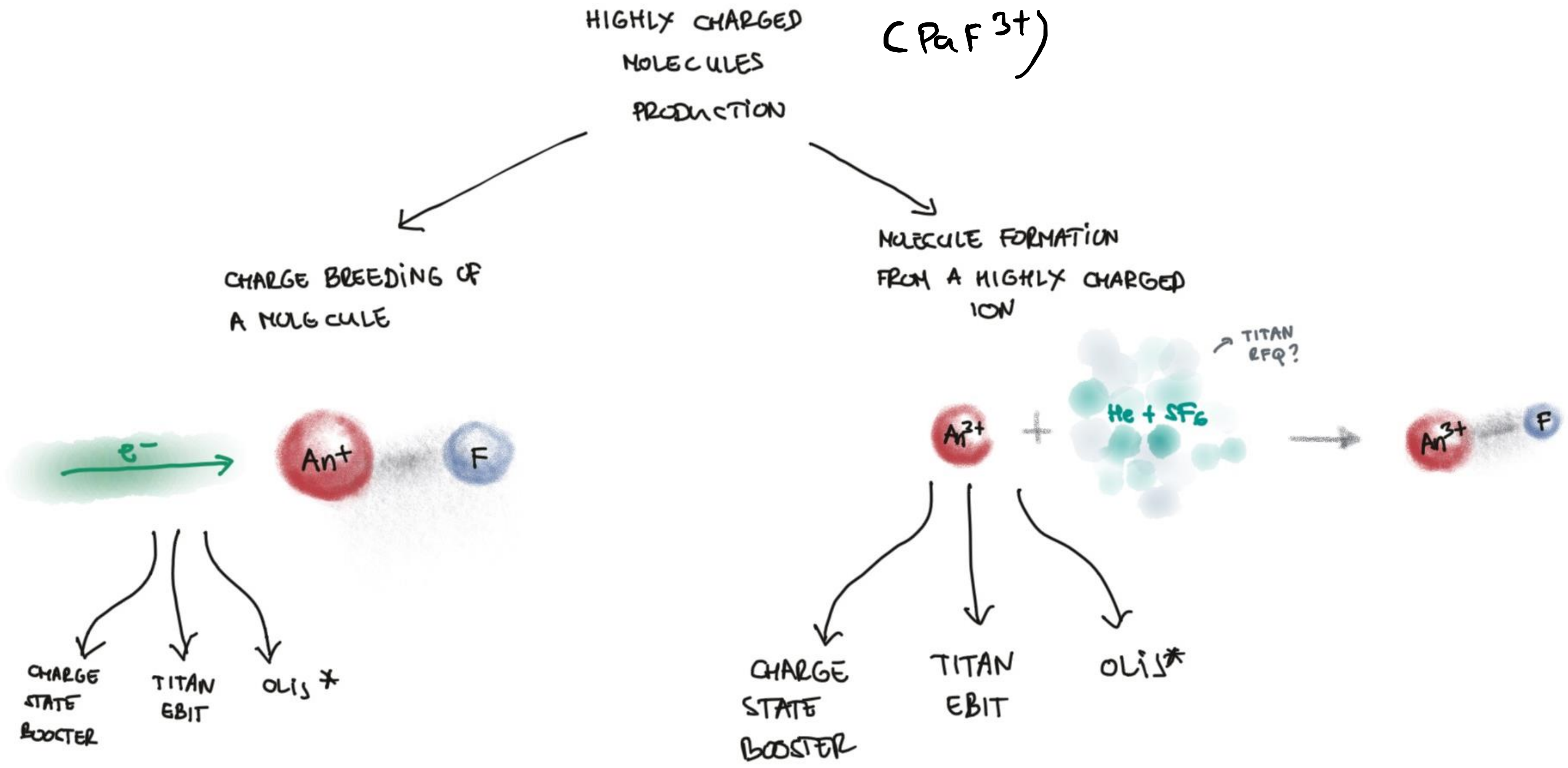
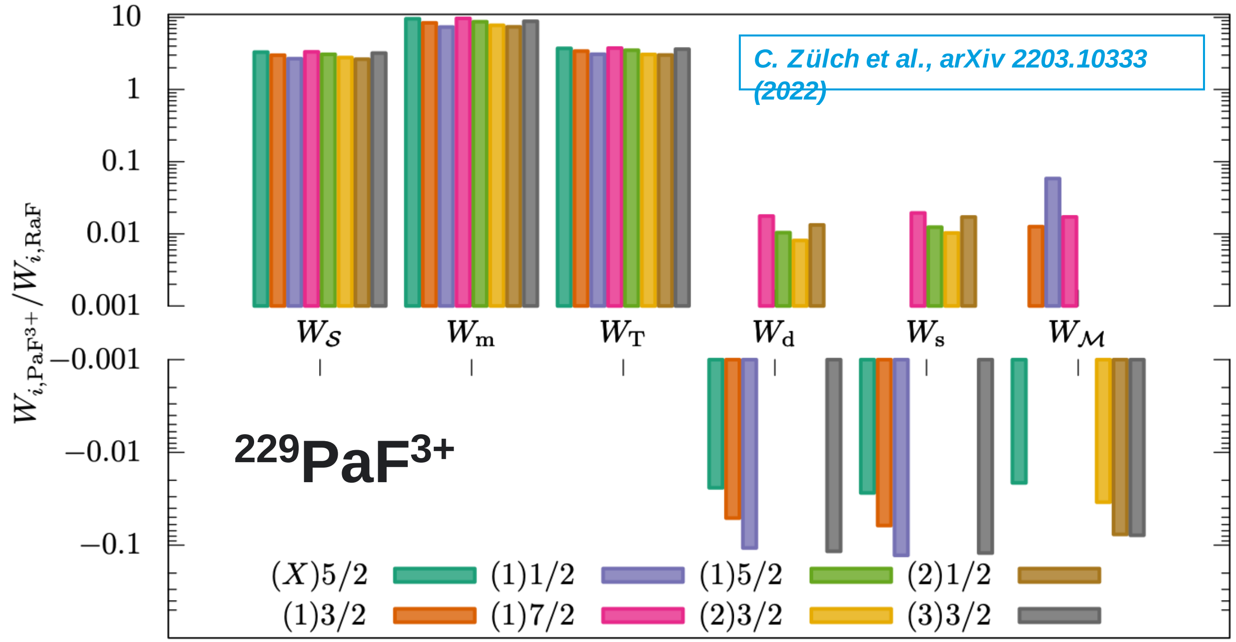
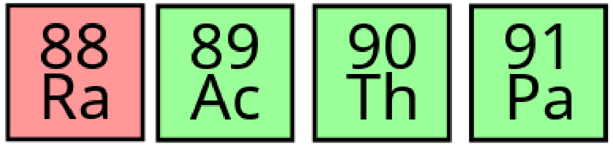
I. Belosevic, **L. Croquette**, P. Fischer, **C. Kanitz, F. Hummer, E. Leistenschneider,**
S. Lechner, F. Maier, P. Plattner, A. Roitman, M. Rosenbusch, **S. Sels**, **R. Simpson,** F. Wienholtz,
M. Vilen, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, S. Malbrunot-Ettenauer

Backup slides


HIGHLY CHARGED MOLECULES PRODUCTION
(PaF 3+)
CHARGE BREEDING OF A MOLECULE
e⁻
An+
F
CHARGE STATE BOOSTER
TITAN EBIT
OLIS *
MOLECULE FORMATION FROM A HIGHLY CHARGED ION
TITAN RFQ?
An2+
He + SF6
An3+
F
CHARGE STATE BOOSTER
TITAN EBIT
OLIS*

‘Highly’ charged radioactive molecules

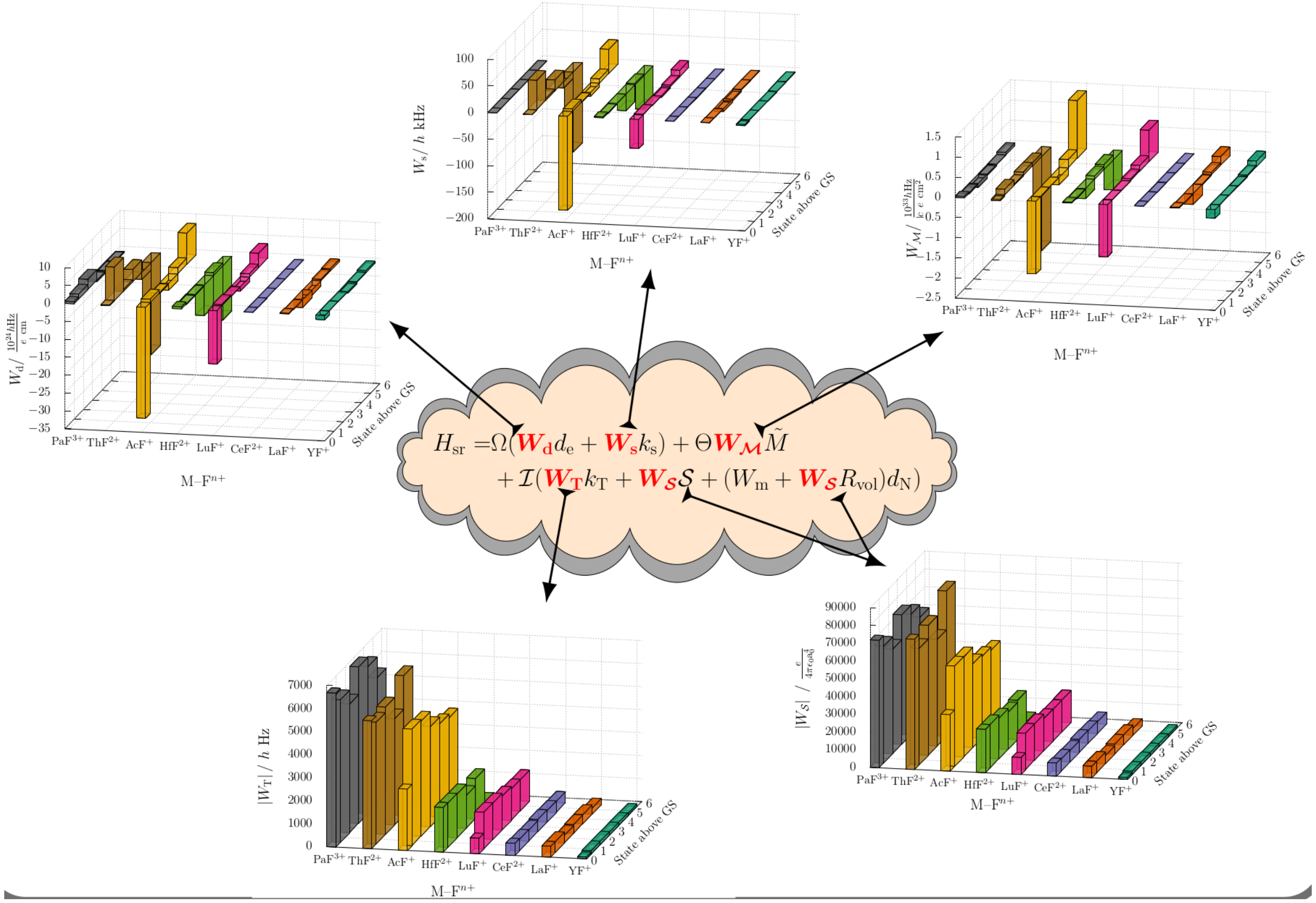




- iso-electronic to (neutral) RaF
- notable sensitivity increase for new physics
- easily trap-able
- potential for direct laser cooling?

other iso-electronic molecules: AcF^{+}, ThF^{+2}

P,T – violating Hamiltonian



where W_i are electron structure parameters enhancing different P,T violating parameters. These are

- d_e - the electron electric dipole moment
- k_s - the scalar-pseudoscalar nucleon-electron current interaction
- $\mathcal{M}$ - the nuclear magnetic quadrupole moment
- k_T - the tensor-pseudotensor nucleon-electron current interaction
- $\mathcal{S}$ - the nuclear Schiff moment
- d_p - the proton electric dipole moment, and
- R_{vol} - a nuclear structure factor that enhances d_p

In this context, Ω is the projection of the total electronic angular momentum on the molecular axis, $\mathcal{I}$ is the projection of the nuclear spin on the molecular axis, and Θ describes the electron and nuclear spin interaction along molecular axis [6, 7].

‘Designer Molecules’

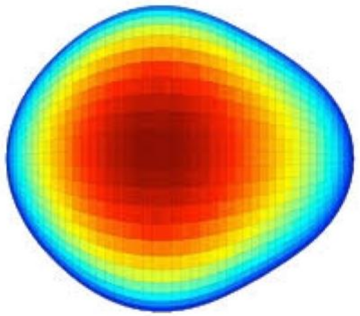
… for searches for nuclear Schiff moment

^{199}Hg present ‘gold standard’

$|d_{Hg}| < 7.4 \cdot 10^{-30}$ 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 $\times 10^2$-10^3 } compared to ^{199}Hg
- in polar molecule $\times 10^3$-10^4 } compared to ^{199}Hg
- in atom or ion trap $\times 10^3$ compared to beam experiments

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)