Studies of Radium containing molecules for Fundamental Physics



Figure modified from https://sphereofinfluence360.com/

Ronald Fernando Garcia Ruiz, ***MIT***

Workshop on Precision Measurements with Radioisotopes
Texas A&M, Aug 2025

Graduate Students



G. Mondel



A. Brinson
NSF Fellowship



H. Kakiota
Ezoe Memorial Fellowship



S. Moroch
Hertz Foundation Fellowship



F. Pastrana
Santo Domingo Fellowship



D. Gonzales
(Harvard)



J. Munoz
MIT Fellowship



M. Fulghieri



F. Shungo

Postdoctoral Researchers



S. Flayol



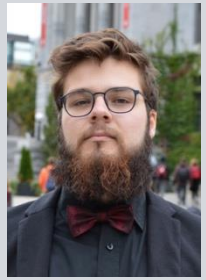
G. Clausen
SNSF Fellowship



S. Ebadi
Pappalardo Fellowship



A. Jadbabaie
NSF MPS Ascend Fellow



A. Belly
NSERC Fellow

Former Members



S. Wilkins
FRIB/MSU



J. Karthein
Texas A&M



S. Udrescu
U. Chicago

Undergraduate Students



N. Ching-Hau



S. Munoz



Y. Lewis



R. Hernandez



S. Becerra

FRIB

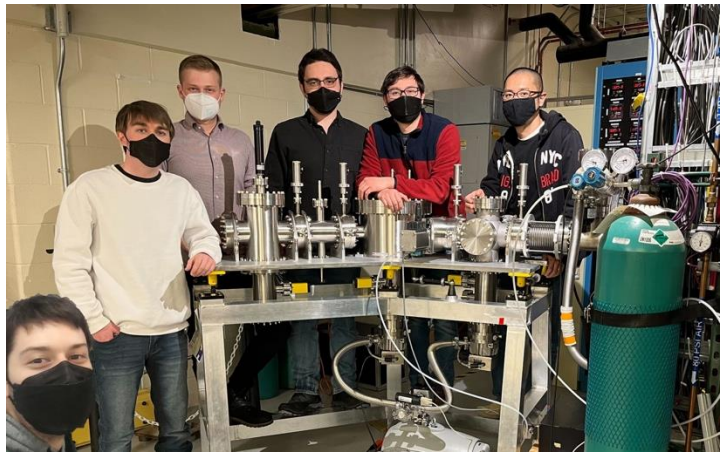
Bates Lab

Thanks to…



MANCHESTER 1824 · KU LEUVEN · CERN · MIT Massachusetts Institute of Technology · PEKING UNIVERSITY · UNIVERSITY OF GOTHENBURG

RISE @ FRIB



FRIB

Particle & Nuclear & Atomic & Molecular

D. Lee (MSU)
W. Nazarewicz (FRIB/MSU)
J. Dobaczewski (York)
J. Holt (TRIUMF)
R. Stroberg (U ND)
…

R. Berger (Malbroune)
A. Borchevsky (Groningen)
L. Skripnikov (Petersburg)
…

RaX Collaboration



Caltech · Harvard · FRIB

Theory

Experimen



NEPTUNE

MIT · Texas A&M · Max-Planck-Institut für Kernphysik · Caltech · FRIB · The University of Chicago

Laser Spectroscopy work at FRIB and CERN

RISE
@ BECOLA/FRIB

Talks: K. Minamisono
B. Rickey @ "Precision measurements working group"

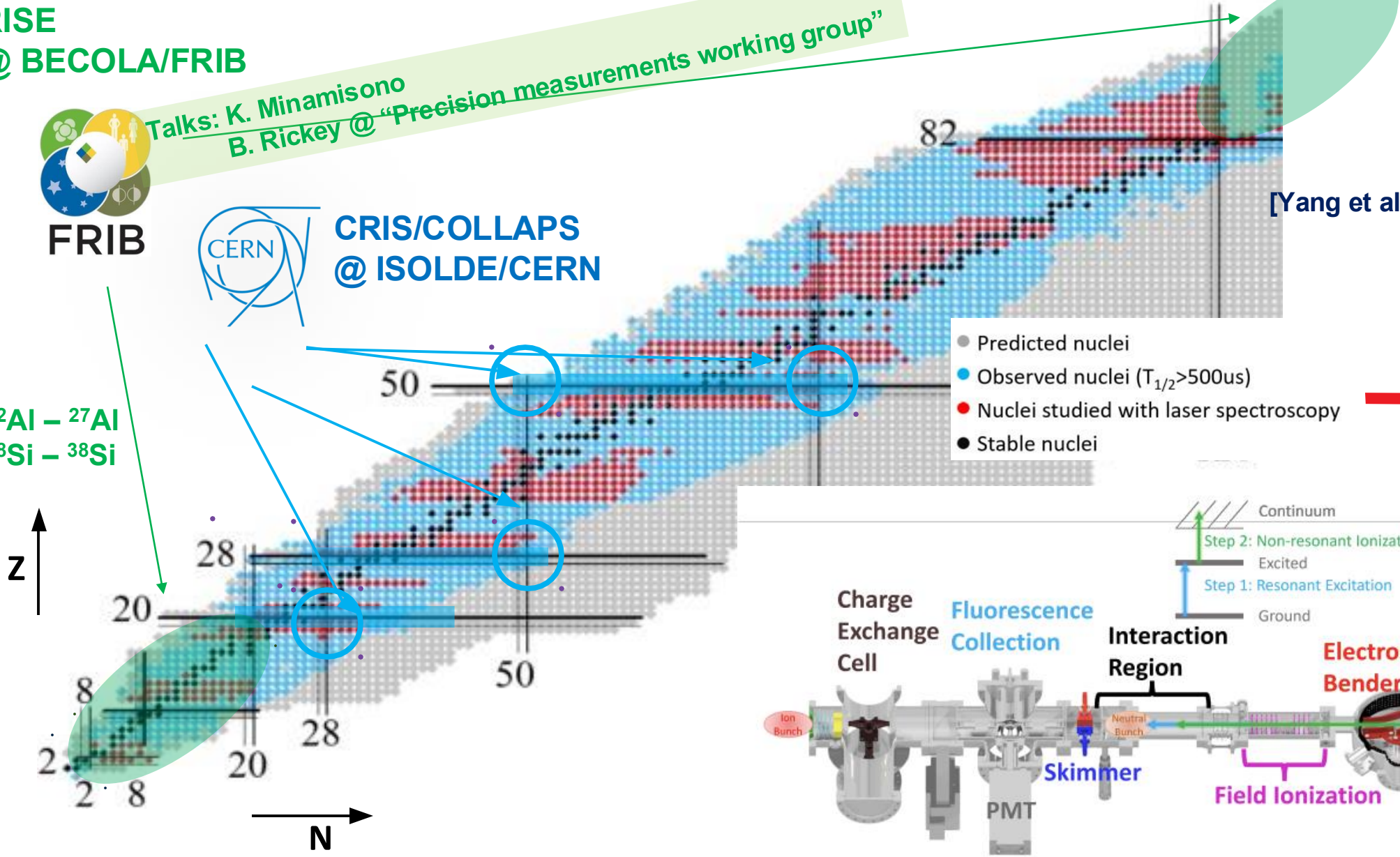
FRIB

CERN

CRIS/COLLAPS
@ ISOLDE/CERN

[Yang et al. PPNP 129, 104005 (2023)]

✔ ^{22}Al – ^{27}Al
✔ ^{28}Si – ^{38}Si



$\langle r^2 \rangle$ I Q μ

Laser Spectroscopy work at FRIB and CERN

RISE
@ BECOLA/FRIB

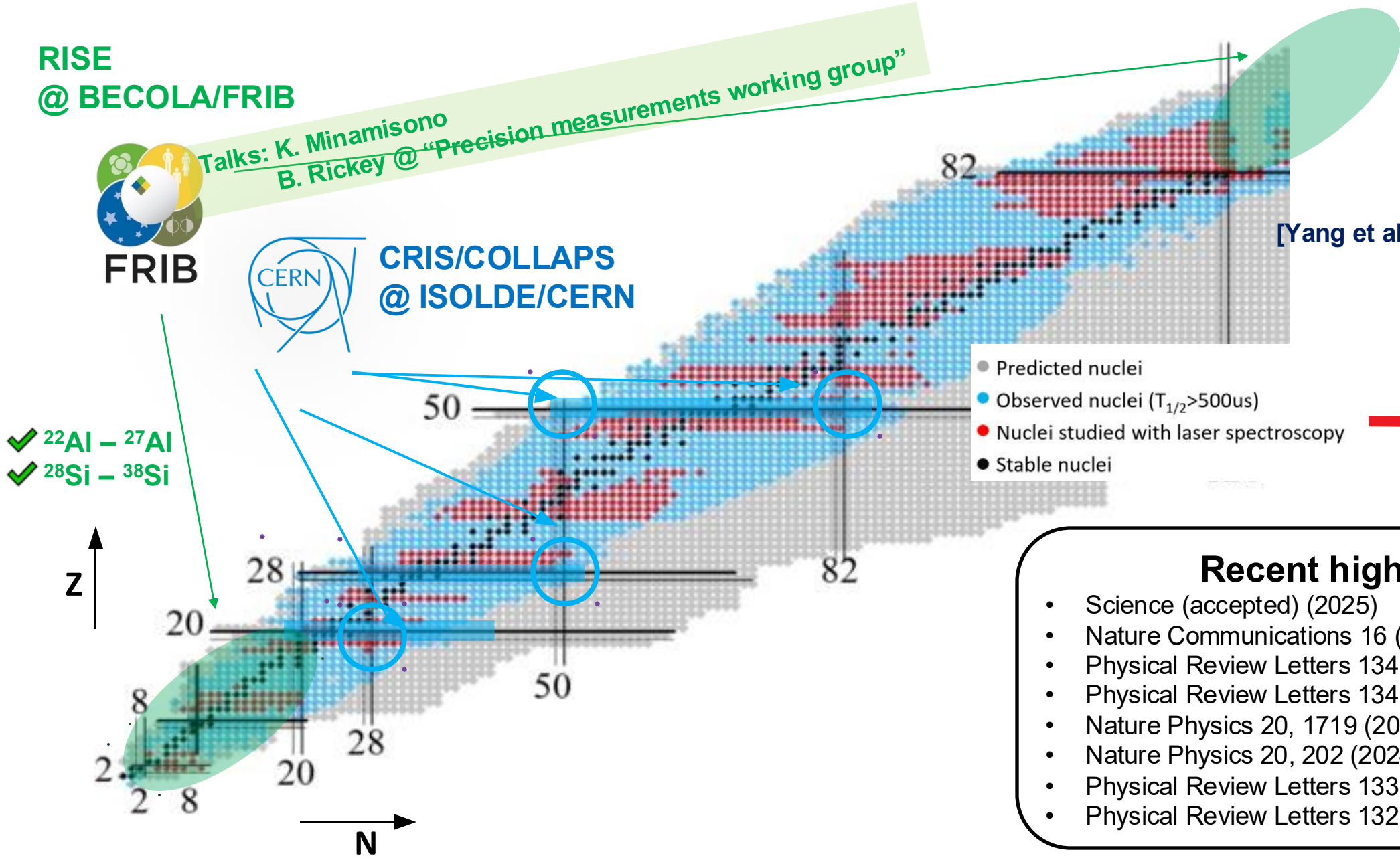
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[Yang et al. PPNP 129, 104005 (2023)]



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Recent highlights:

- Science (accepted) (2025)
- Nature Communications 16 (1), 2139 (2025)
- Physical Review Letters 134 (25), 252501 (2025)
- Physical Review Letters 134 (18), 182501 (2025)
- Nature Physics 20, 1719 (2024)
- Nature Physics 20, 202 (2024)
- Physical Review Letters 133, 033003 (2024)
- Physical Review Letters 132, 162502 (2024)

"Terra incognita"

Sensitivity (ions/s)

10^{-8}

10^{-6}

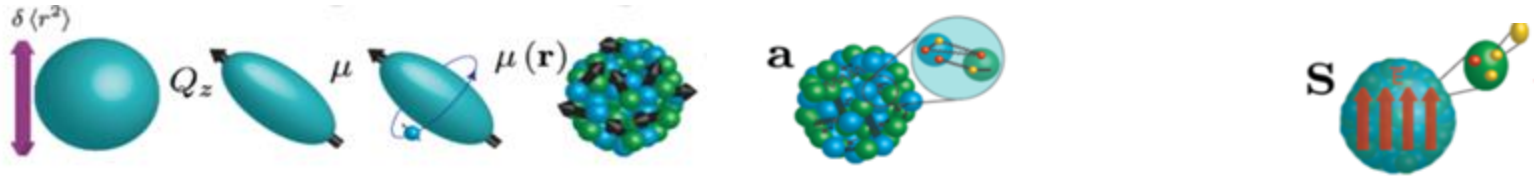
10^{-4} ← *Super Heavy Elements*

10^{-2} ← *Neutron Dripline*

10^{0} ← *Proton Dripline*

10^{2}

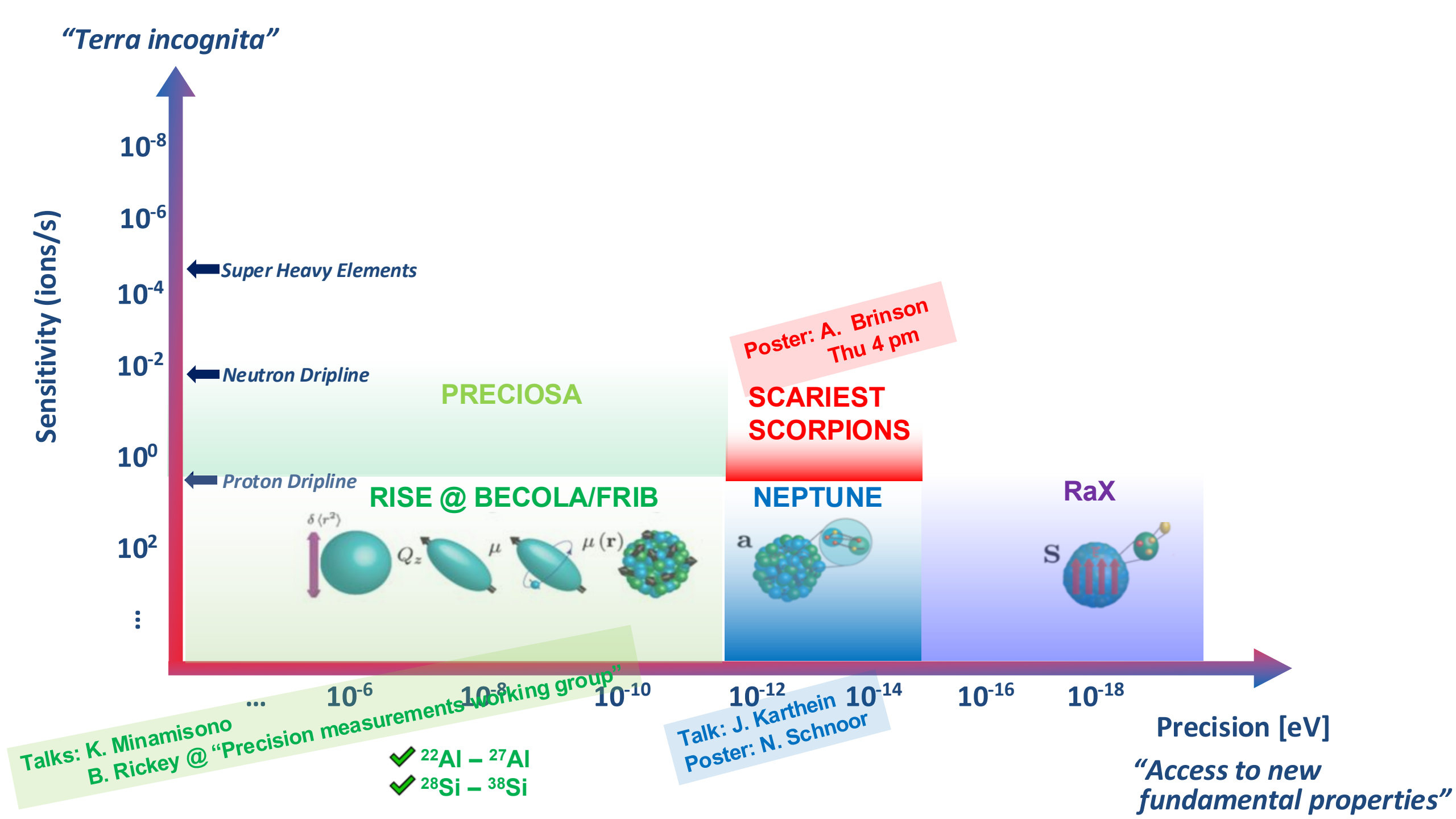
⋮



… 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}

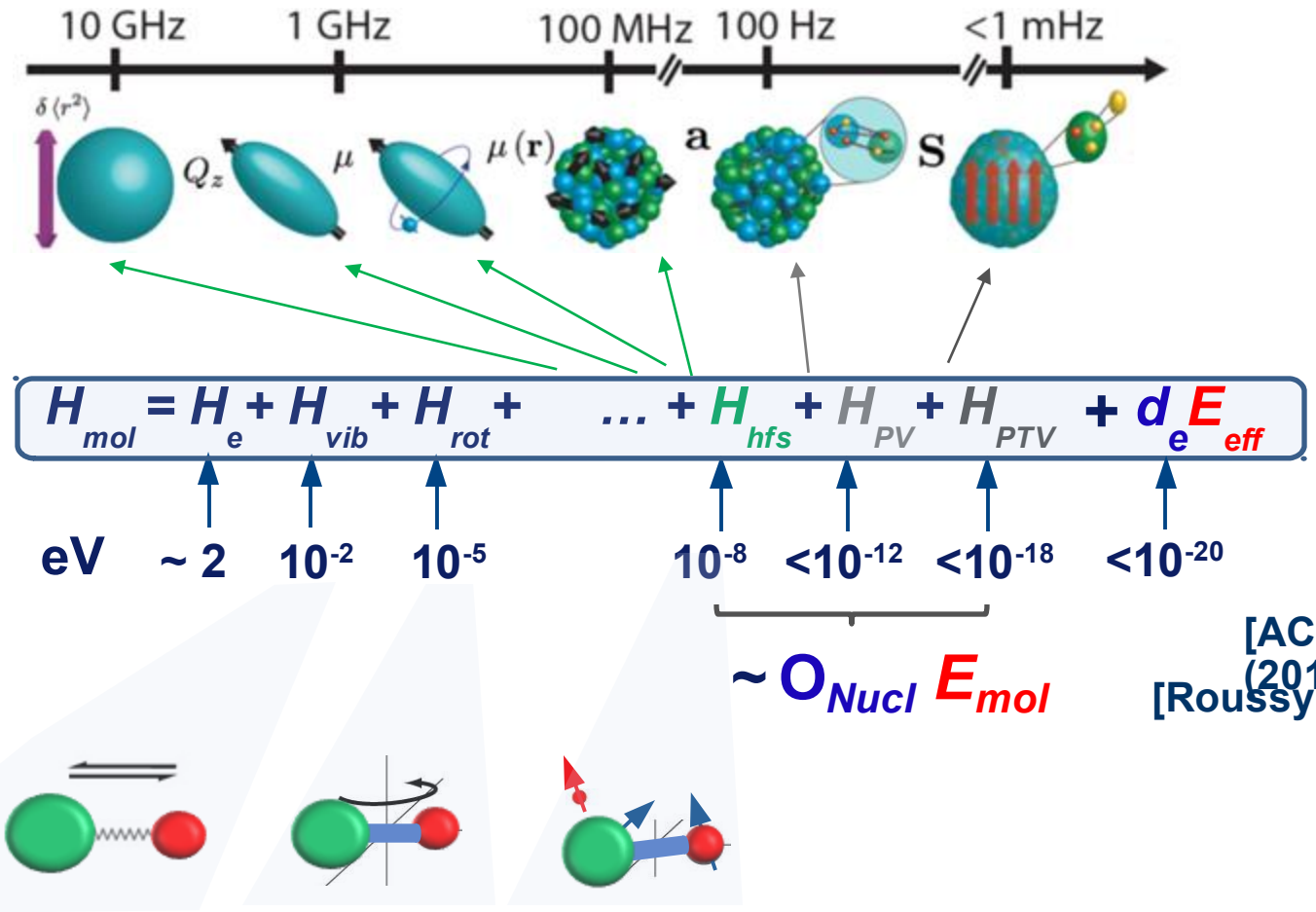
Precision [eV]

"Access to new fundamental properties"


"Terra incognita"
Sensitivity (ions/s)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
...
Super Heavy Elements
Neutron Dripline
Proton Dripline
PRECIOSA
RISE @ BECOLA/FRIB
Poster: A. Brinson
Thu 4 pm
SCARIEST
SCORPIONS
NEPTUNE
RaX
Talks: K. Minamisono
B. Rickey @ "Precision measurements working group"
✓ ^{22}Al – ^{27}Al
✓ ^{28}Si – ^{38}Si
Talk: J. Karthein
Poster: N. Schnoor
... 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}
Precision [eV]
"Access to new fundamental properties"

Why (Radioactive) Molecules?

Nuclear spin > 0



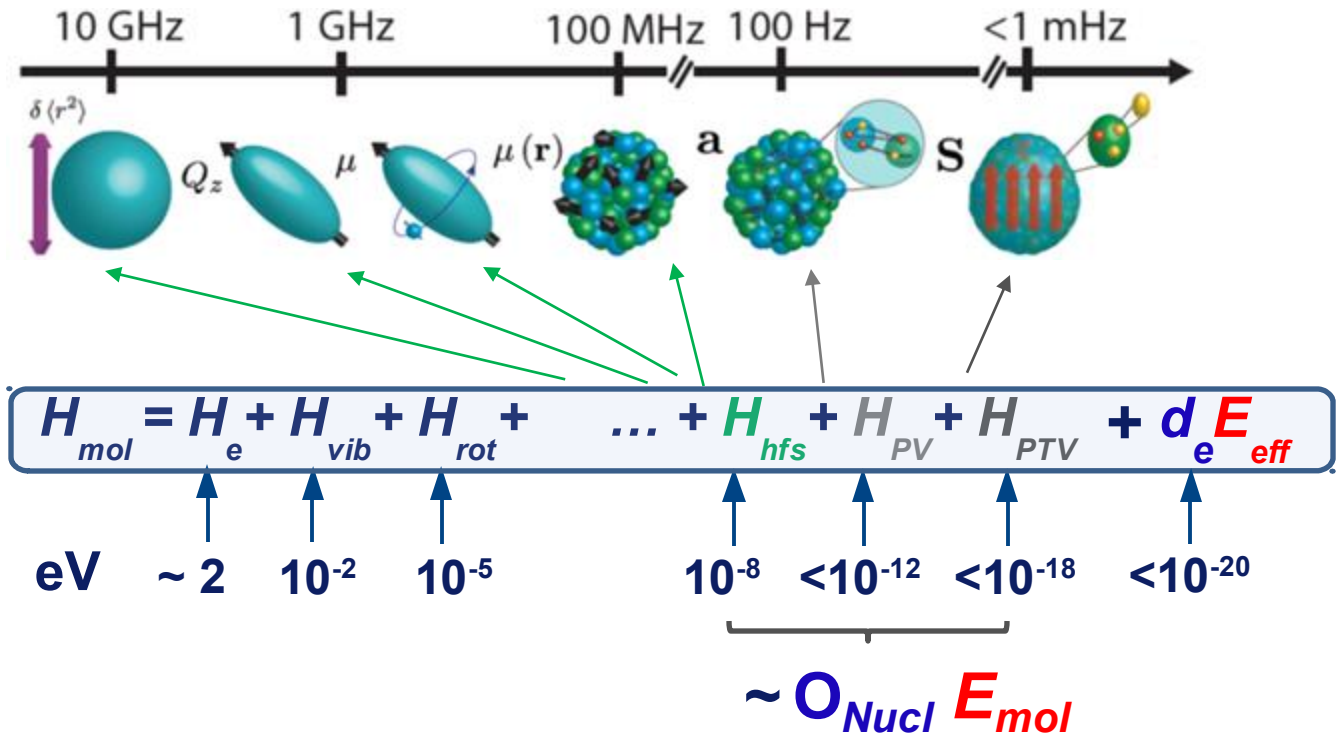
[1 eV=241.8 THz]

[ACME, Nature 562, 355 (2018)]

[Roussy et al. Science 381, 46 (20

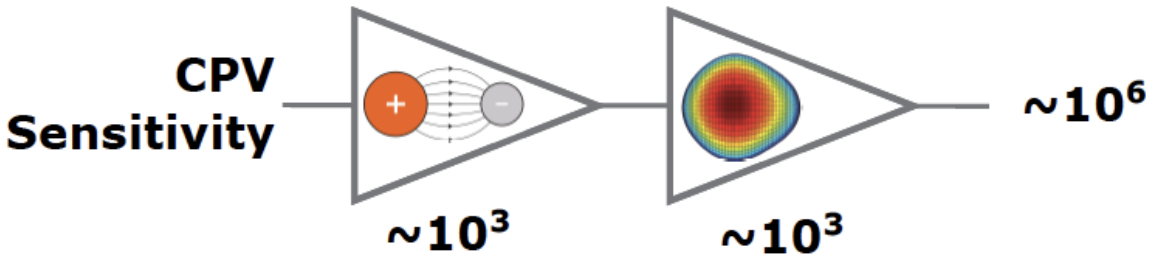
Why (Radioactive) Molecules?

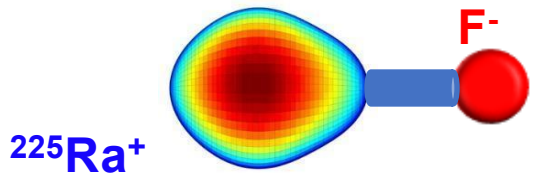
Nuclear spin > 0



[1 eV=241.8 THz]

Molecule X Nuclear

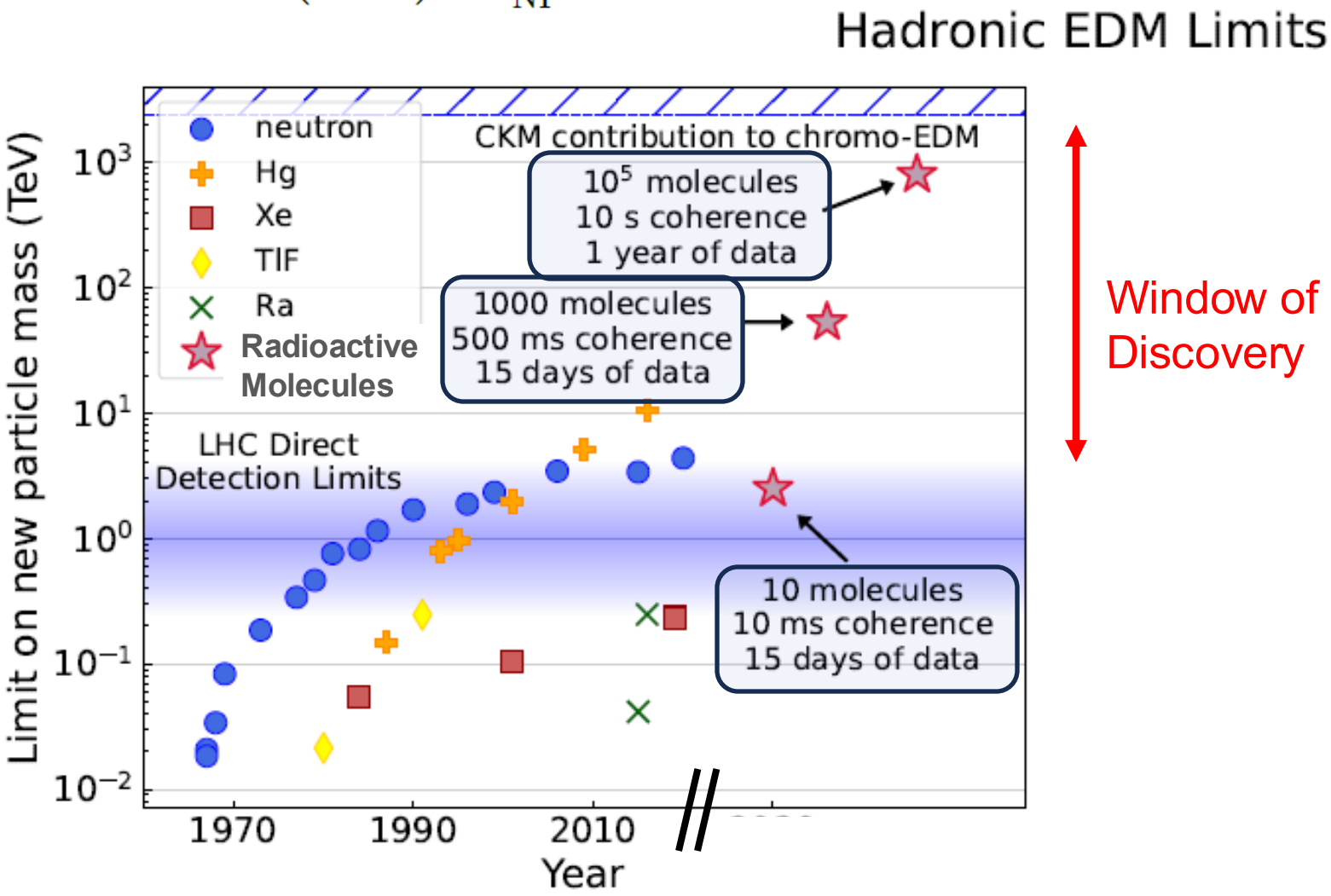




RaF: [Isaev et al. Phys. Rev. A 82, 052521 (2010)]

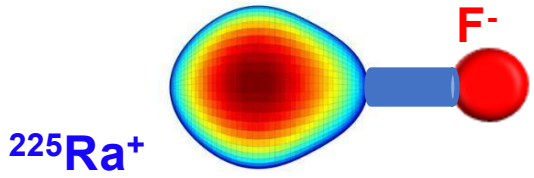
Why (Radioactive) Molecules?

$$d_{\mathrm{f}} \sim q_{\mathrm{f}} \sin\phi_{CP} \left(\frac{g^2}{16\pi^2}\right)^{\ell} \frac{m_f}{E_{\mathrm{NP}}^2}$$



Window of Discovery

Why (Radioactive) Molecules?



? ? ? ? ? ?

$H_{mol} = H_{e} + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{RV} + H_{PTV}$

	H_e	H_{vib}	H_{rot}	H_{hfs}	H_{RV}	H_{PTV}
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

$\sim O_{Nucl}\, E_{mol}$

Why (Radioactive) Molecules?

RaF Molecules

Talk: S. Wilkins

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

Udrescu et al. PRL 127, 033001 (2021) ✓

Udrescu, Wilkins et al. Nature Phys 20, 202 (2024) ✓

Wilkins, Udrescu et al. Science (2025) ✓

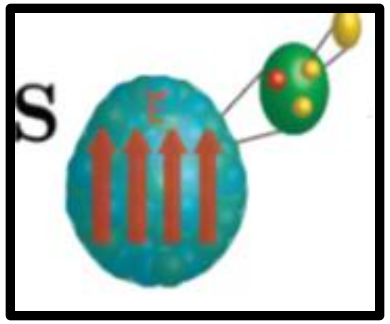
$$\sigma_d \sim \frac{1}{O_N E_{mol} \tau \sqrt{\dot{N} T}}$$

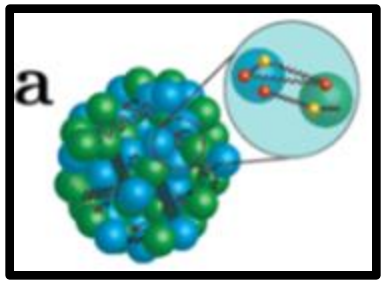


$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

$$\sim O_{Nucl}\, E_{mol}$$

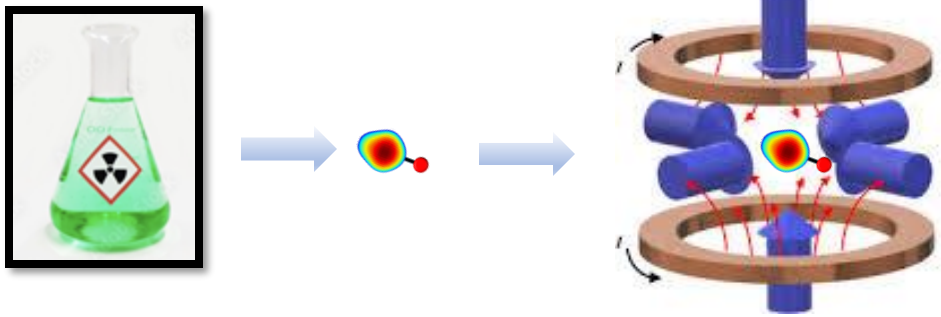




NEPTUNE Project

RaX Collaboration

RaX Collaboration



J. Doyle (Harvard), N. Hutzler (Caltech),
R.F. Garcia Ruiz (MIT) & FRIB

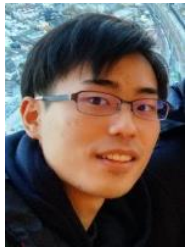
FRIB

Caltech


S. Ebadi


A. Jadbabaie


M. Fulghieri


F. Shungo

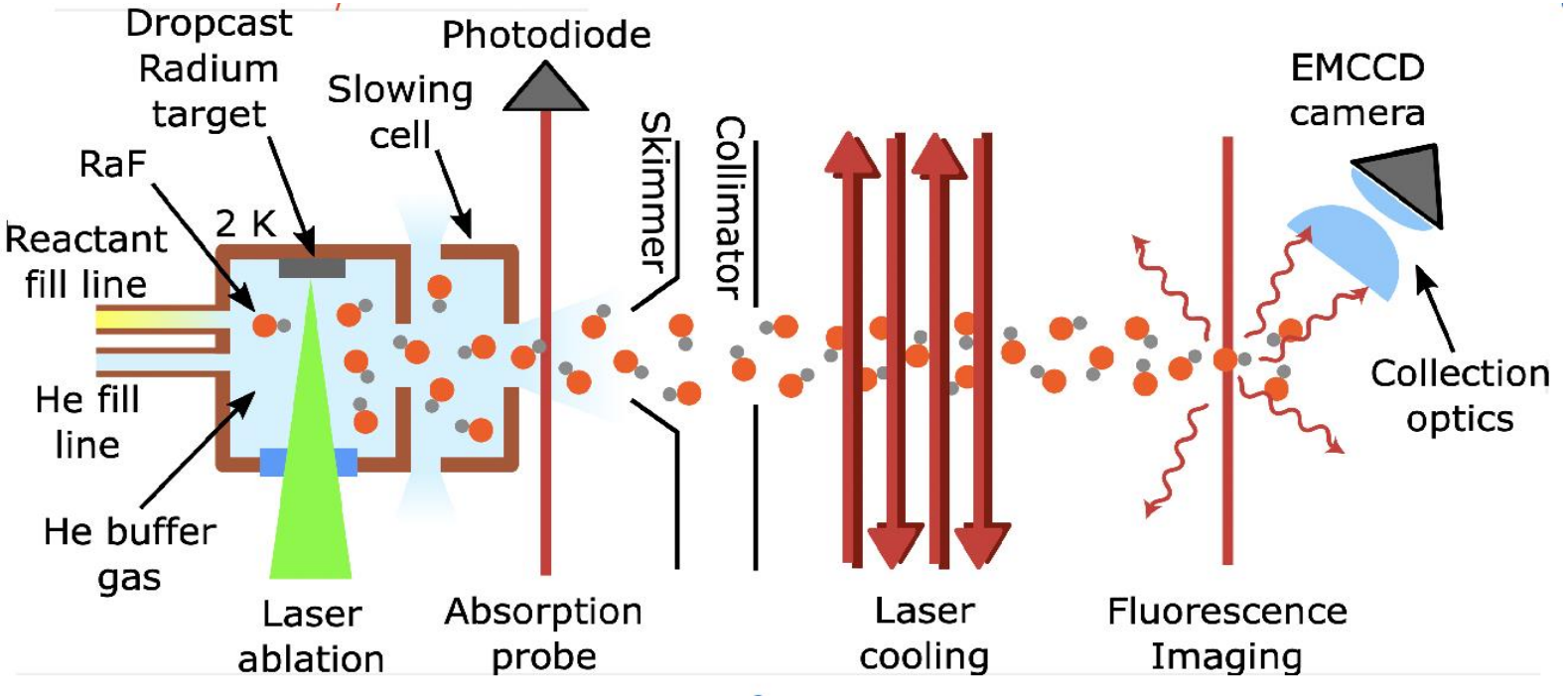

S. Ganguly

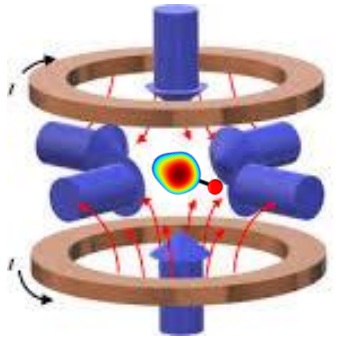

K. Khusainova


S. Munoz

RaX Collaboration



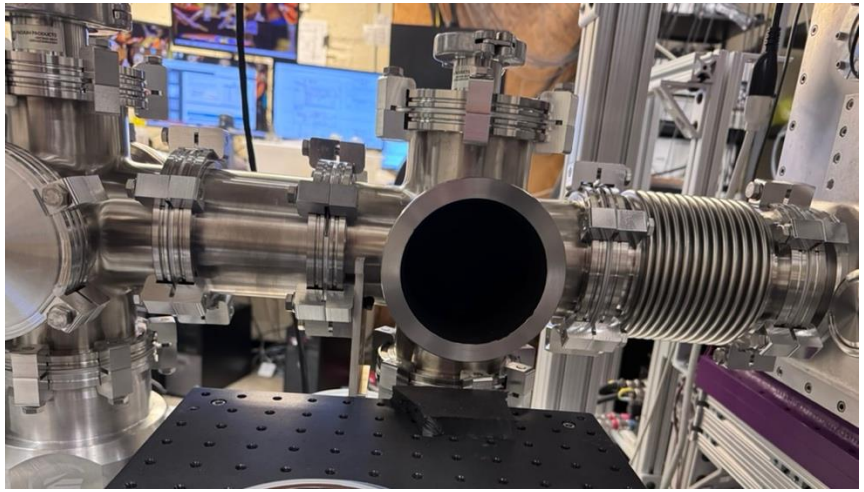




✓ RaX Control DAQ



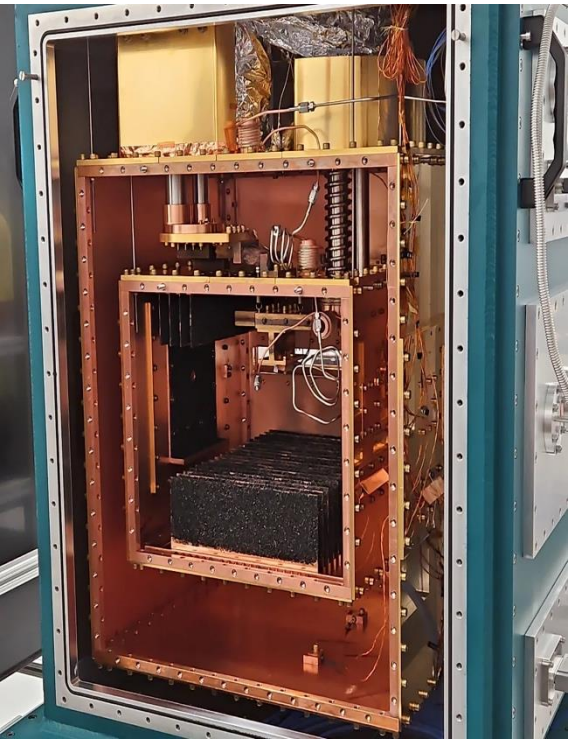
✓ Beamline

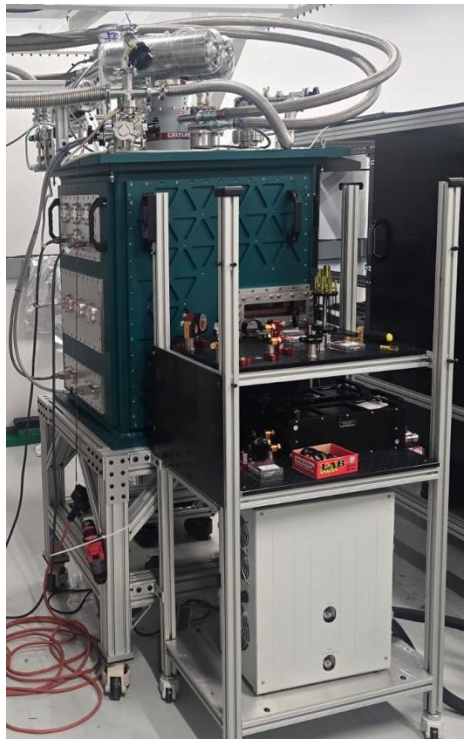


✓ Tests with BaF Molecules



✓ Buffer Gas Cell

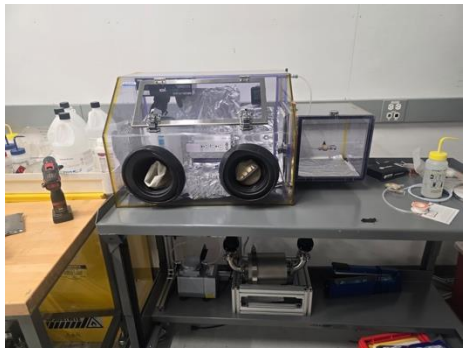




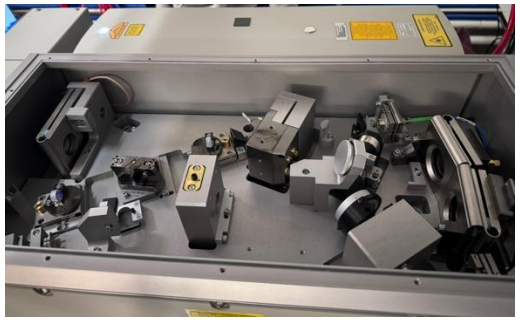
✓ Gas injection System



✓ RaX Drop Casting



✓ Lasers are being installed

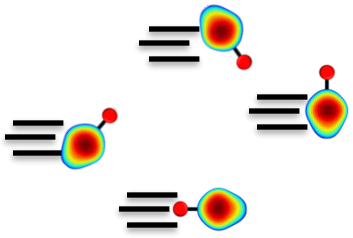


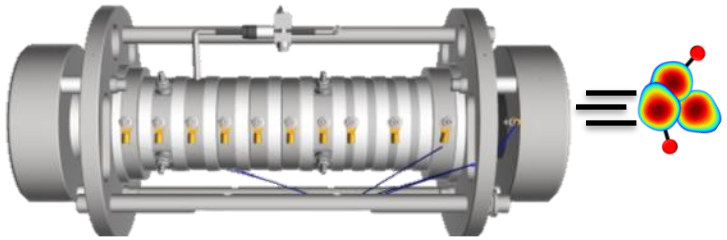
Towards Efficient RaF Trapping Via RaF^-



T > 1000 K

RaF^+





Gas filled ion Cooler and buncher



T~300 K

RaF^+



(Charge exchange)

$RaF^+ + Na \Rightarrow Na^+ + RaF$

RaF

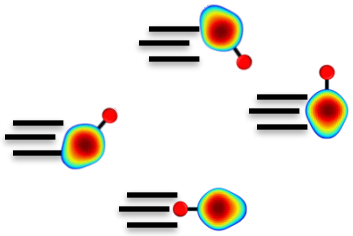


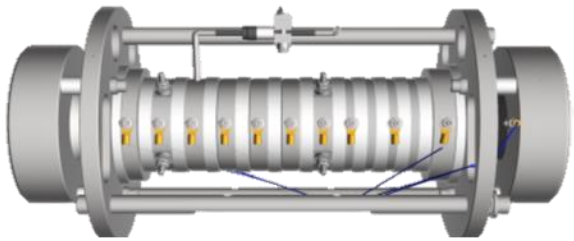
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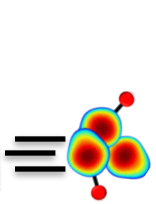
T > 1000 K

RaF^+





Gas filled ion Cooler and buncher





T~300 K

RaF^+



(Charge exchange)

$RaF^+ + 2Na \Rightarrow 2Na^+ + RaF^-$

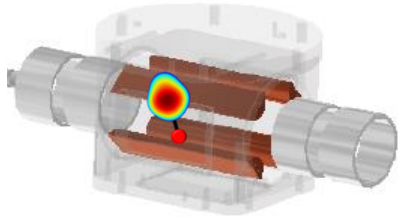
RaF^-





T < 4 K

RaF



$RaF^- + \gamma \Rightarrow RaF + e$

Towards Efficient RaF Trapping Via RaF⁻

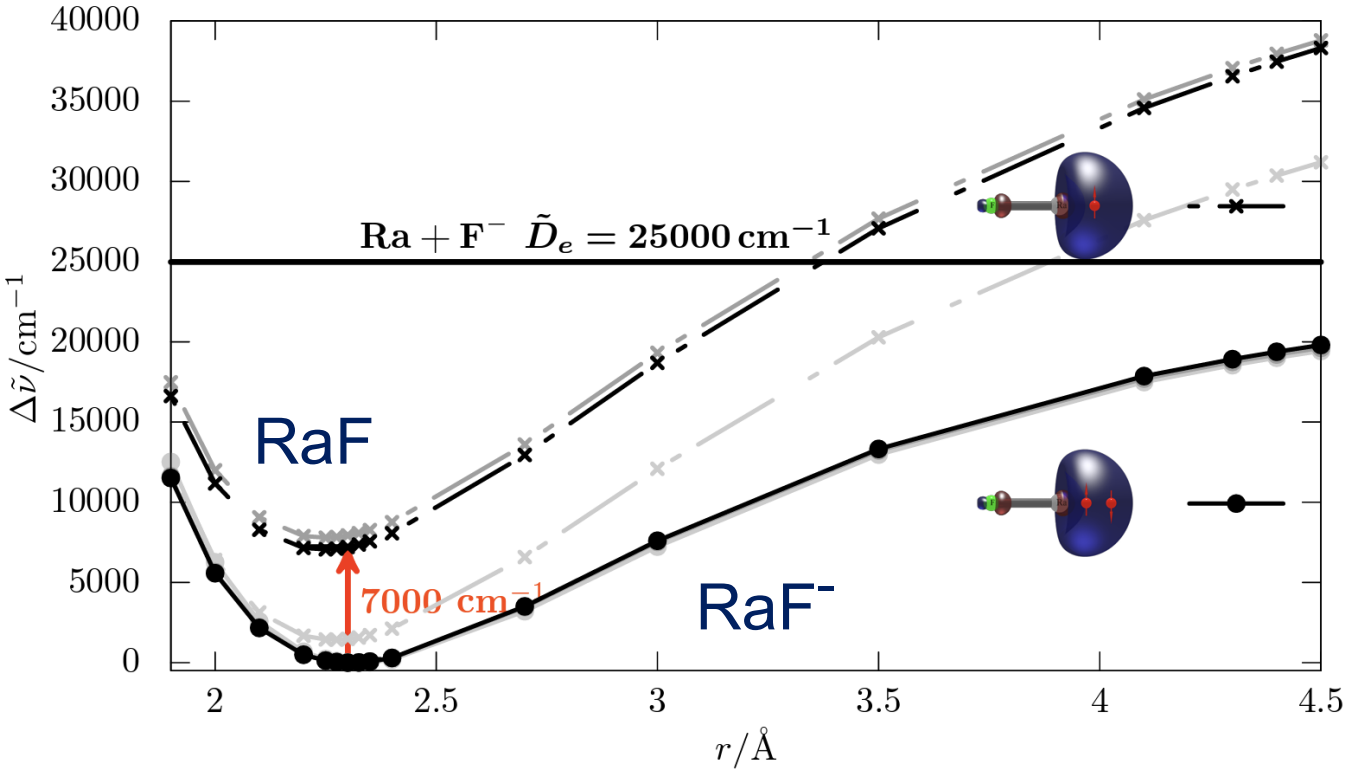
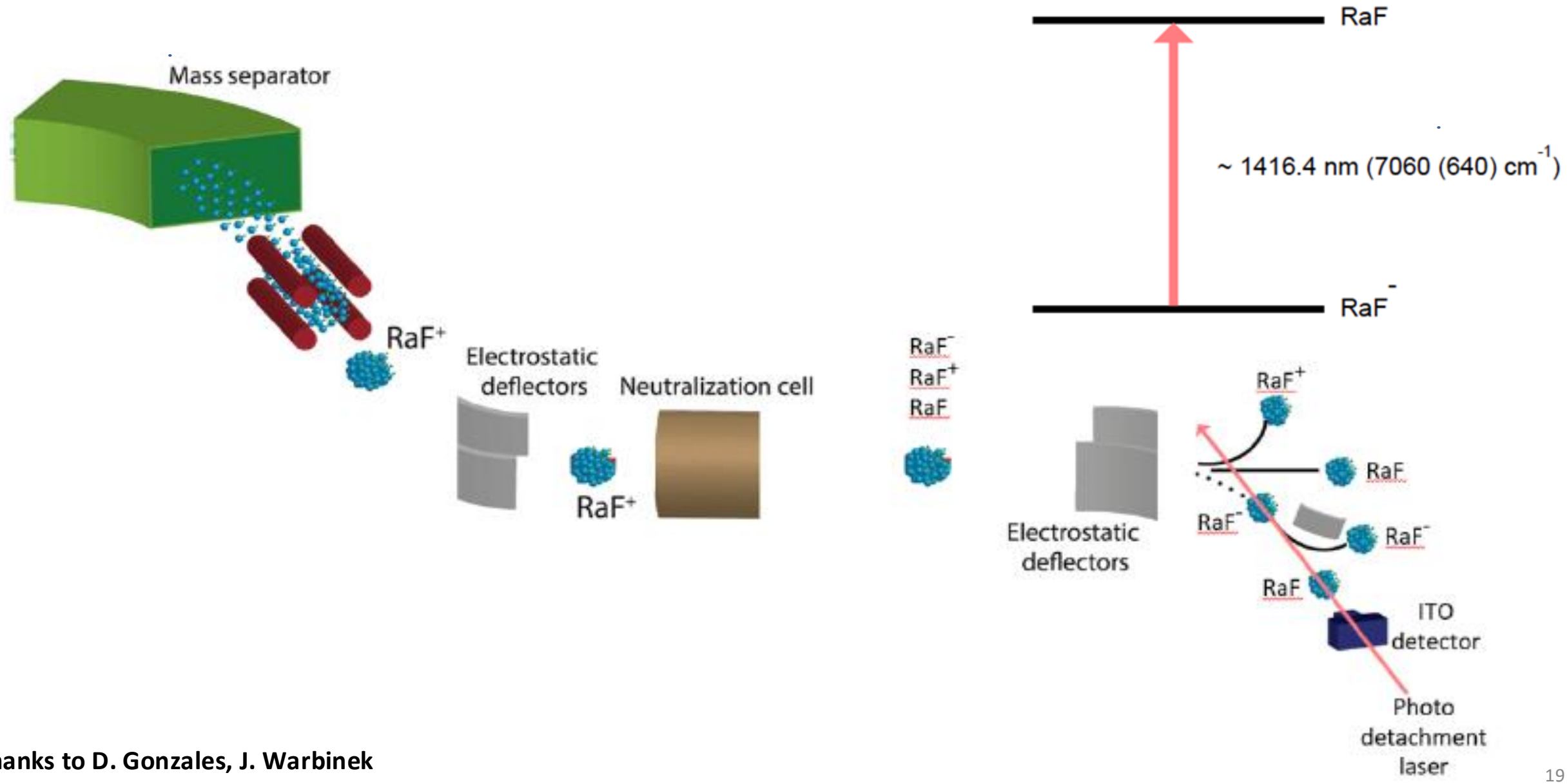


Table I. Dissociation wavenumbers $\tilde{D}_e$, adiabatic photoelectron detachment wavenumbers (ADW), equilibrium bond length r_e and harmonic vibrational wavenumber $\tilde{\omega}_e$ of MF^- computed at the level of RECP-CCSD(T)

Molecule	$\tilde{D}_e/\mathrm{cm}^{-1}$	ADW/cm^{-1}	r_e/Å	$\tilde{\omega}_e/\mathrm{cm}^{-1}$
BeF^-	28 700	8590	1.42	1060
MgF^-	21 600	10 800	1.82	577
CaF^-	26 200	8300	2.01	516
SrF^-	25 000	7950	2.15	434
BaF^-	26 800	6770	2.27	439
RaF^-	23 600	7210	2.36	401

Gaul, Garcia Ruiz, Berger. arXiv:2403.09320 (2024)

Towards Efficient RaF Trapping Via RaF^-



Thanks to D. Gonzales, J. Warbinek

Towards Efficient RaF Trapping Via RaF^-

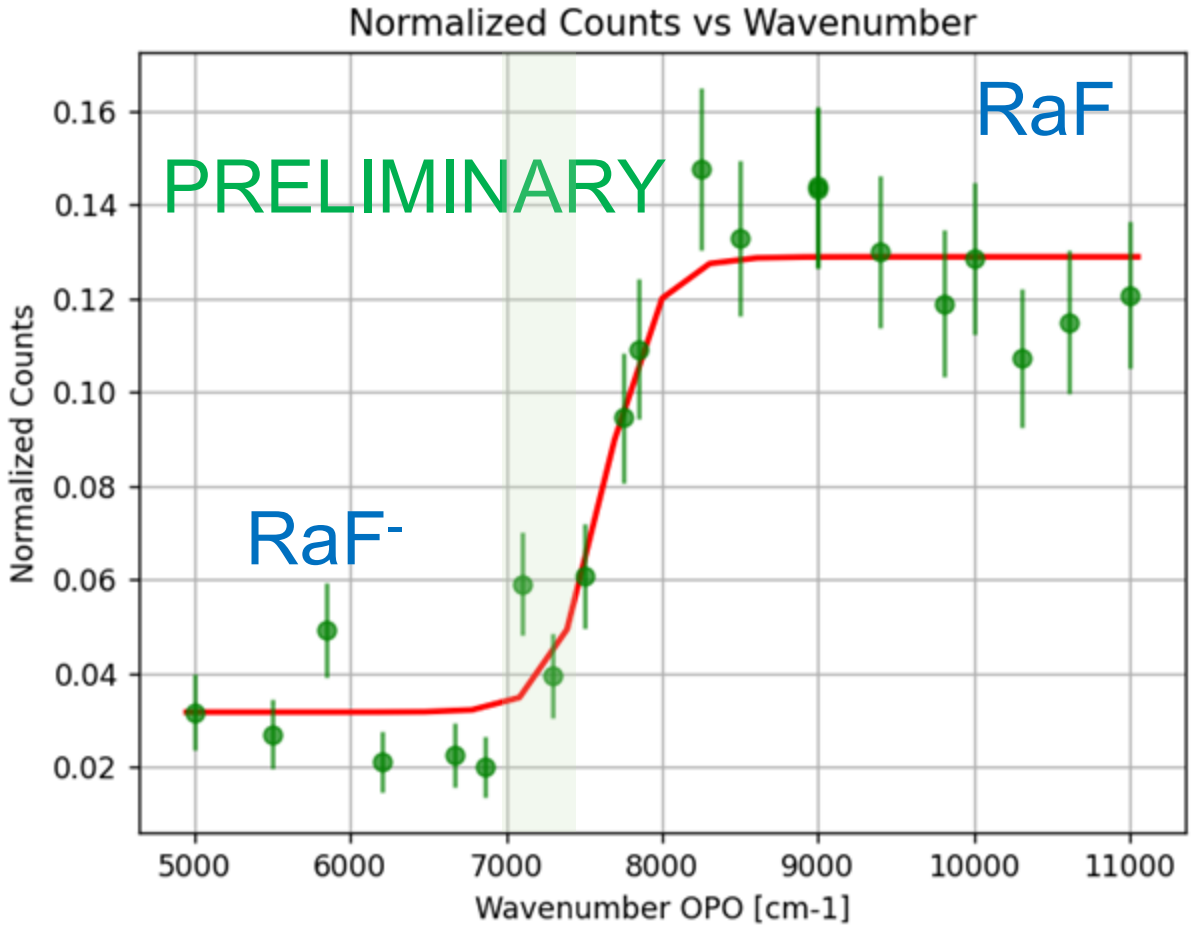
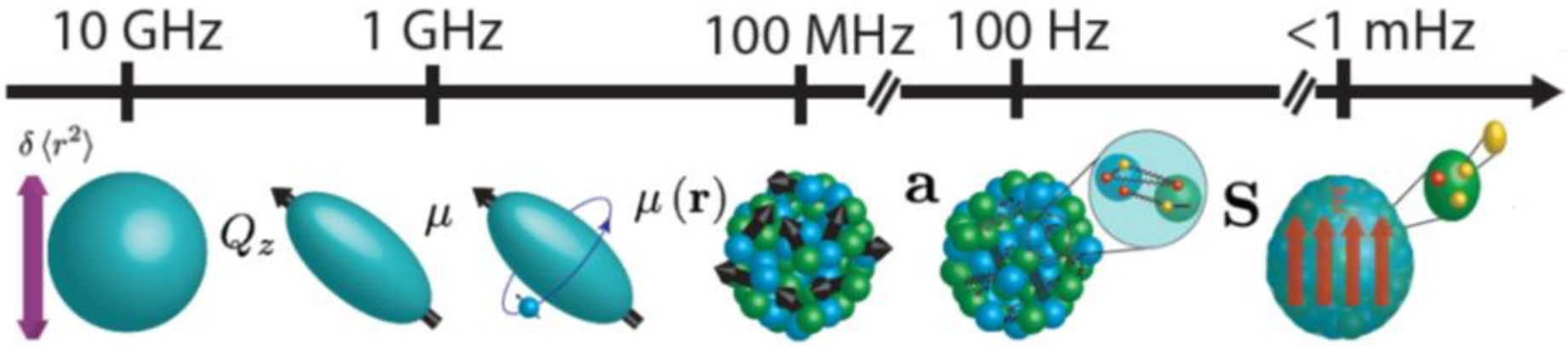


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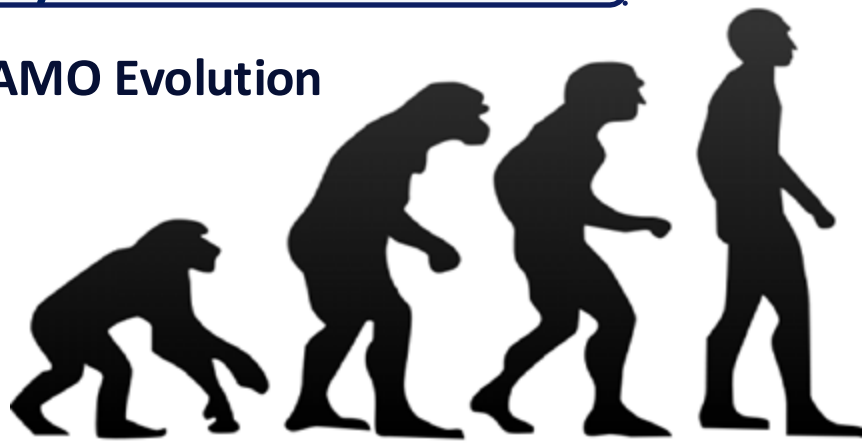
Gaul, Garcia Ruiz, Berger. arXiv:2403.09320 (2024)

Summary and Outlook

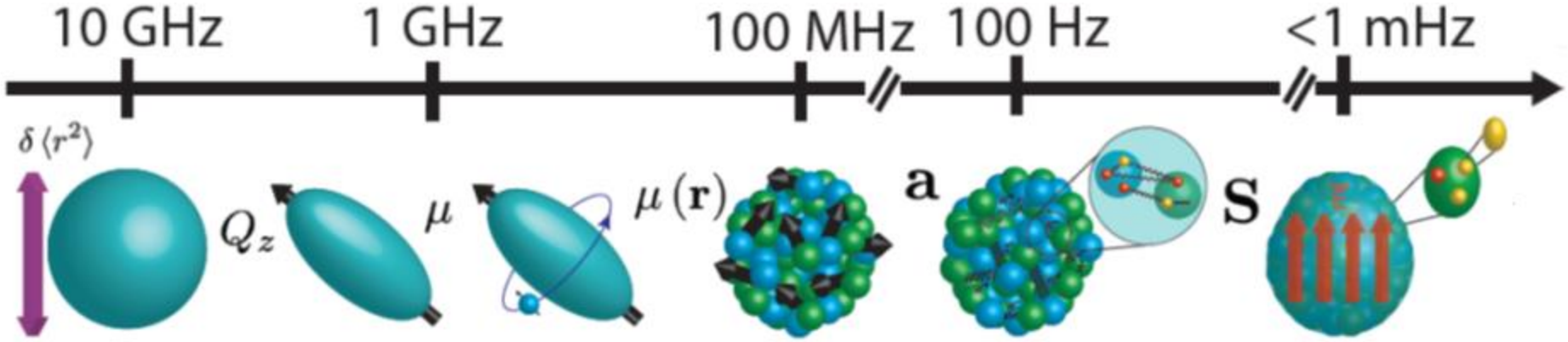


Radioactive molecules offer a new window into our exploration of electroweak nuclear properties

Summary and Outlook



We are here!





$$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$<10^{-15}$

Summary & Outlook

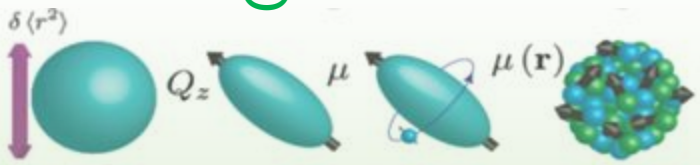
"Terra incognita"

Sensitivity (ions/s)

10^{-8}
10^{-6}
Super Heavy Elements
10^{-4}
10^{-2}
Neutron Dripline
10^{0}
Proton Dripline
10^{2}
⋮

PRECIOSA

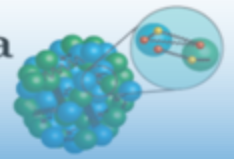
RISE @ BECOLA/FRIB



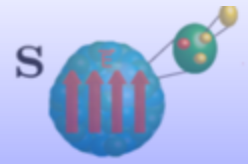
Poster: A. Brinson

SCARIEST
SCORPIONS

NEPTUNE



RaX



… 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}

Precision [eV]

Talks: K. Minamisono
B. Rickey @ "Precision measurements working group"

✔ ^{22}Al – ^{27}Al
✔ ^{28}Si – ^{38}Si

Talk: J. Karthein
Poster: N. Schnoor

"Access to new fundamental properties"

Laser Spectroscopy work at FRIB and CERN

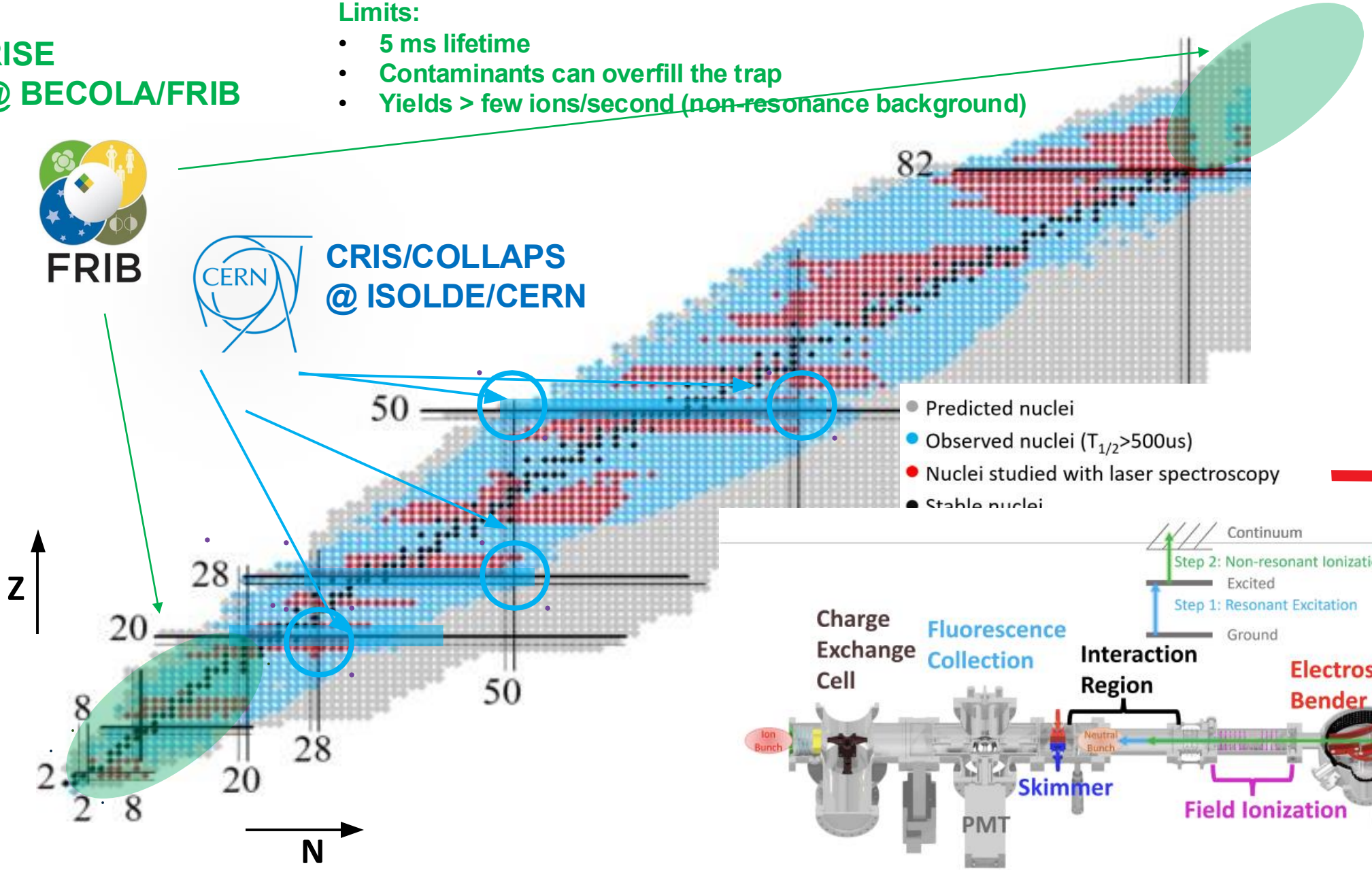
RISE
@ BECOLA/FRIB

Limits:
- 5 ms lifetime
- Contaminants can overfill the trap
- Yields > few ions/second (~~non-resonance background~~)

FRIB

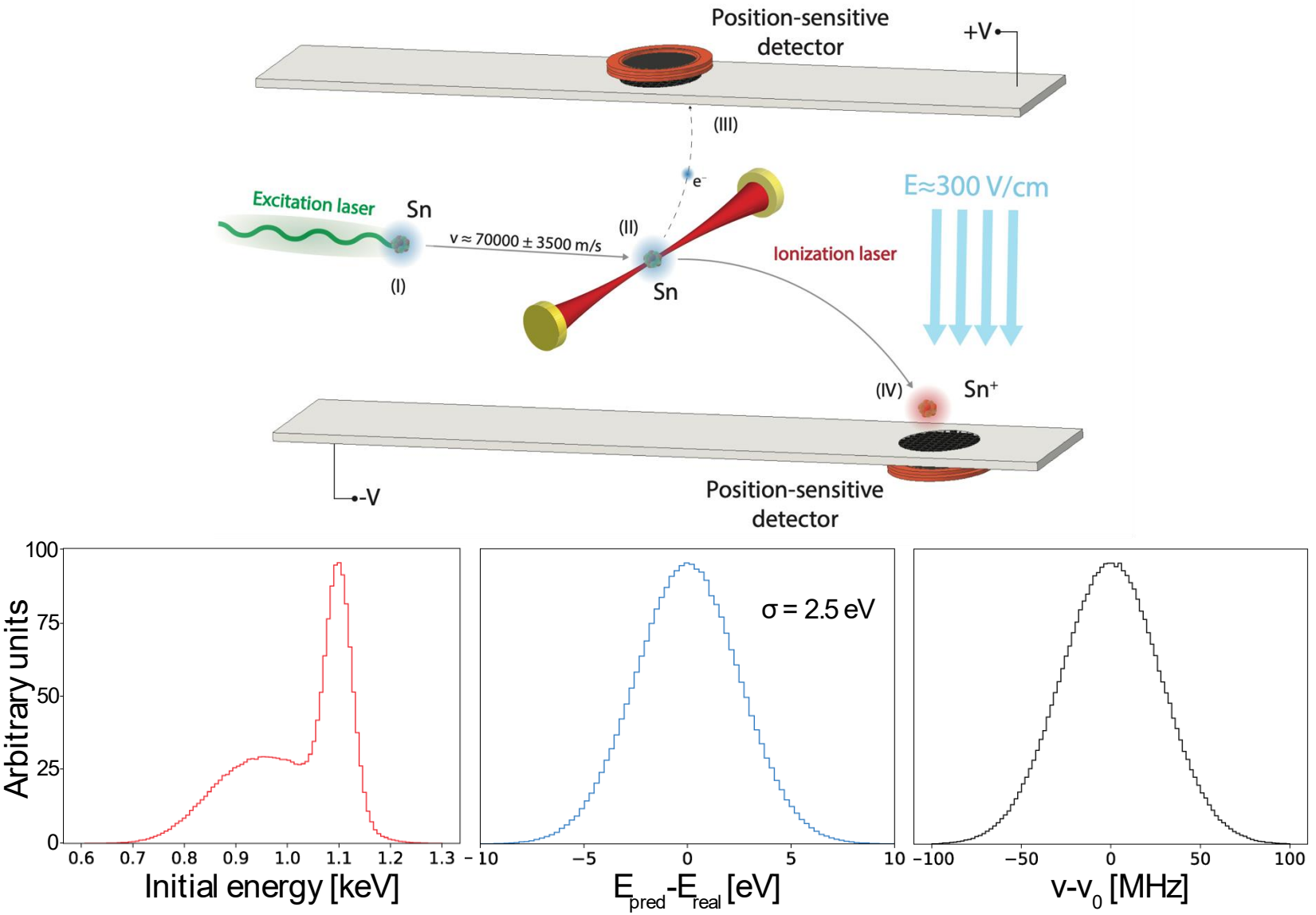
CERN

CRIS/COLLAPS
@ ISOLDE/CERN



$\langle r^2 \rangle$ I Q μ

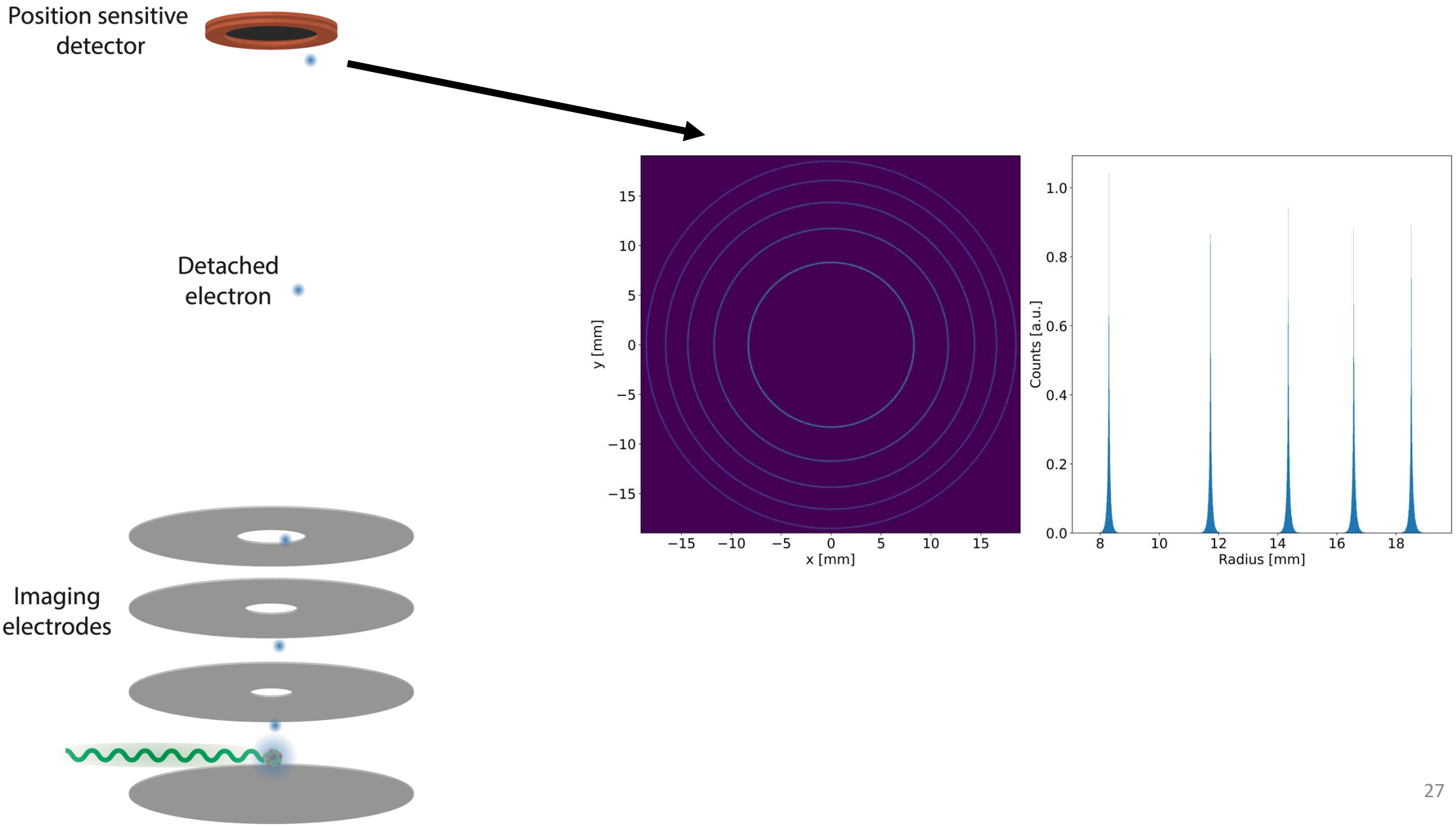
Photo-**R**esonance **E**xcitation and **C**avity **Io**nization **S**pectroscopy **A**pparatus (PRECIOSA)



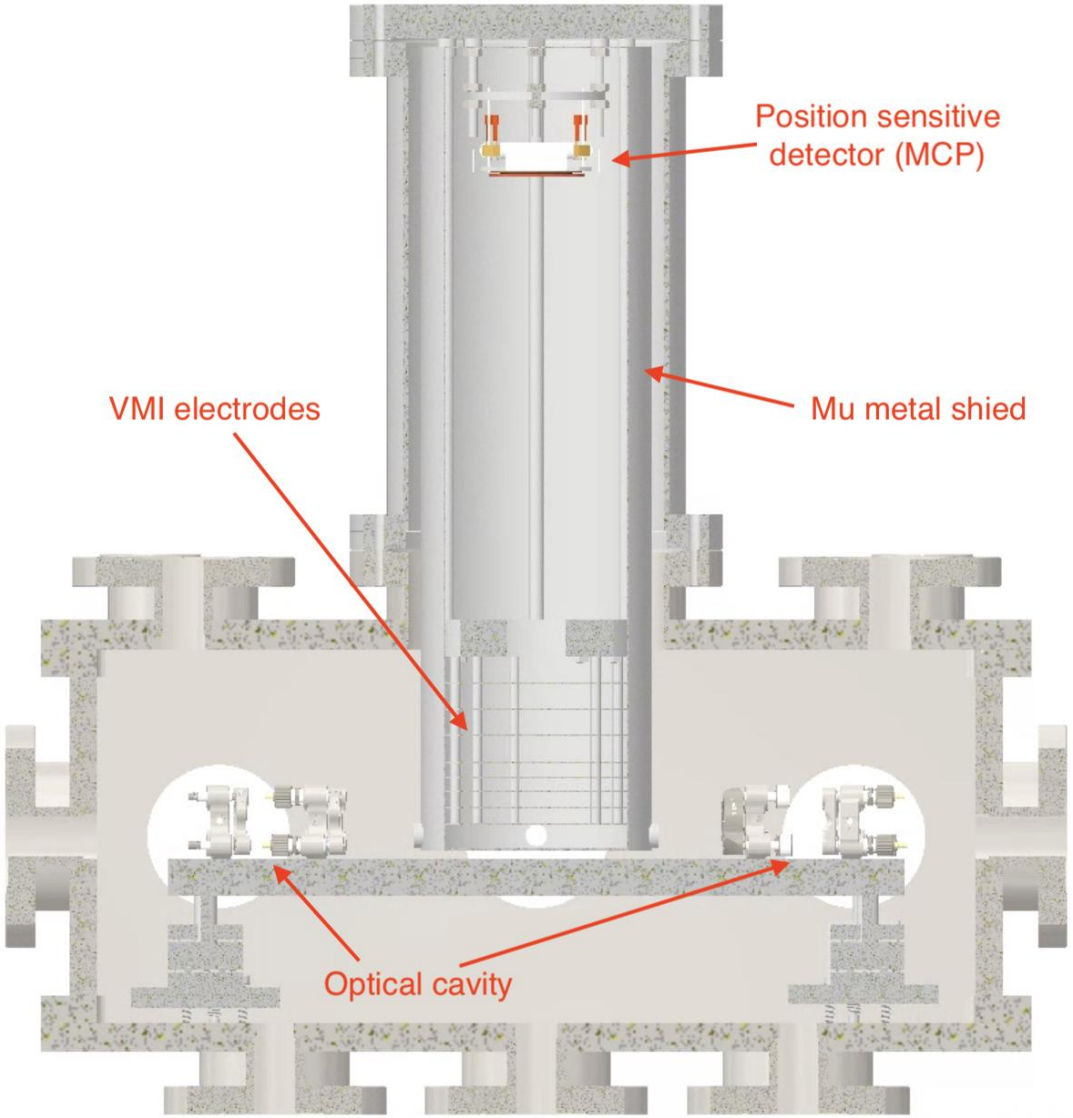
Udrescu et al., Phys. Rev. Research 6, 013128 (2024)

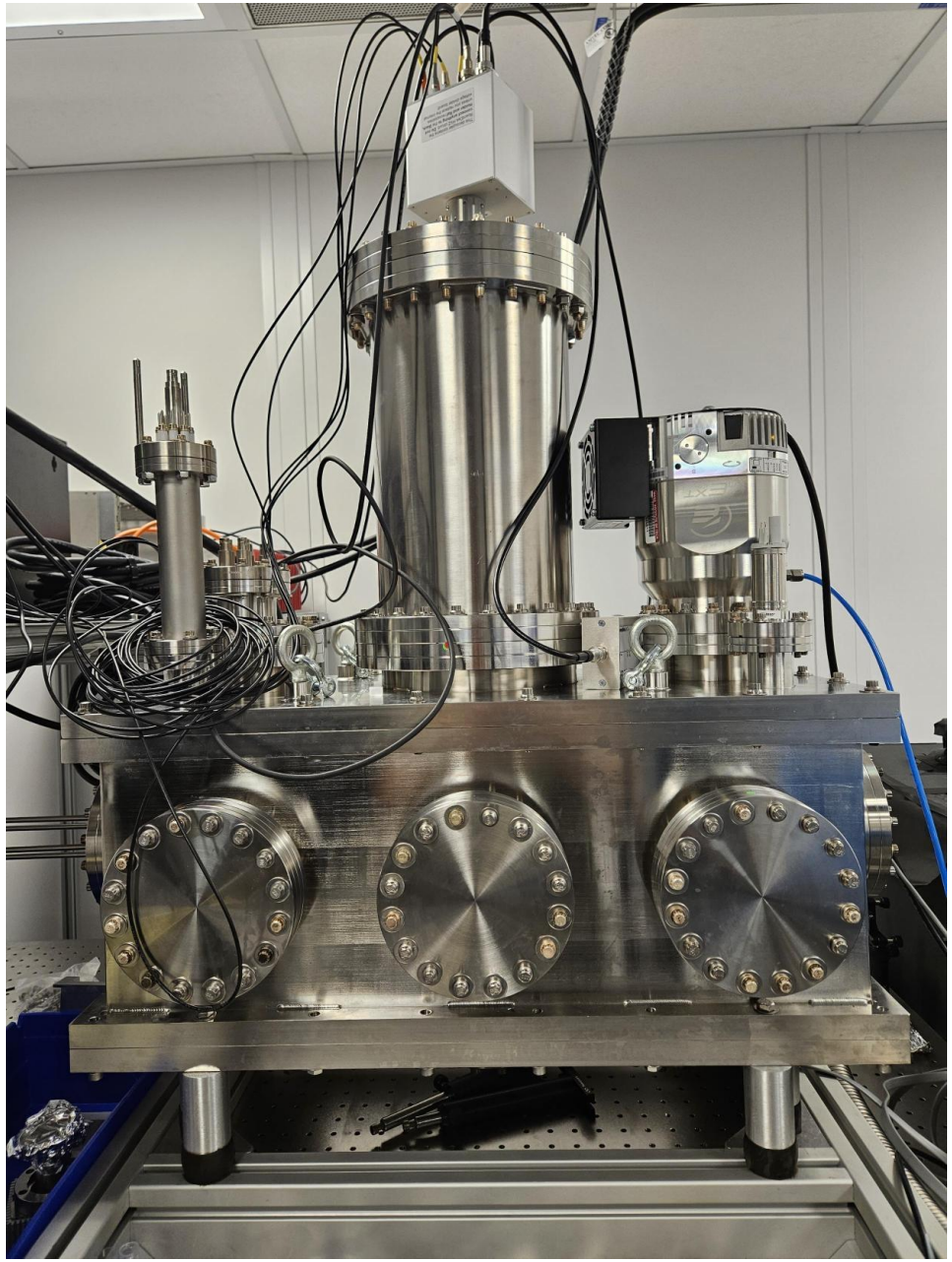
Velocity Map Imagining

Significantly reduced background AND initial electron energy reconstruction

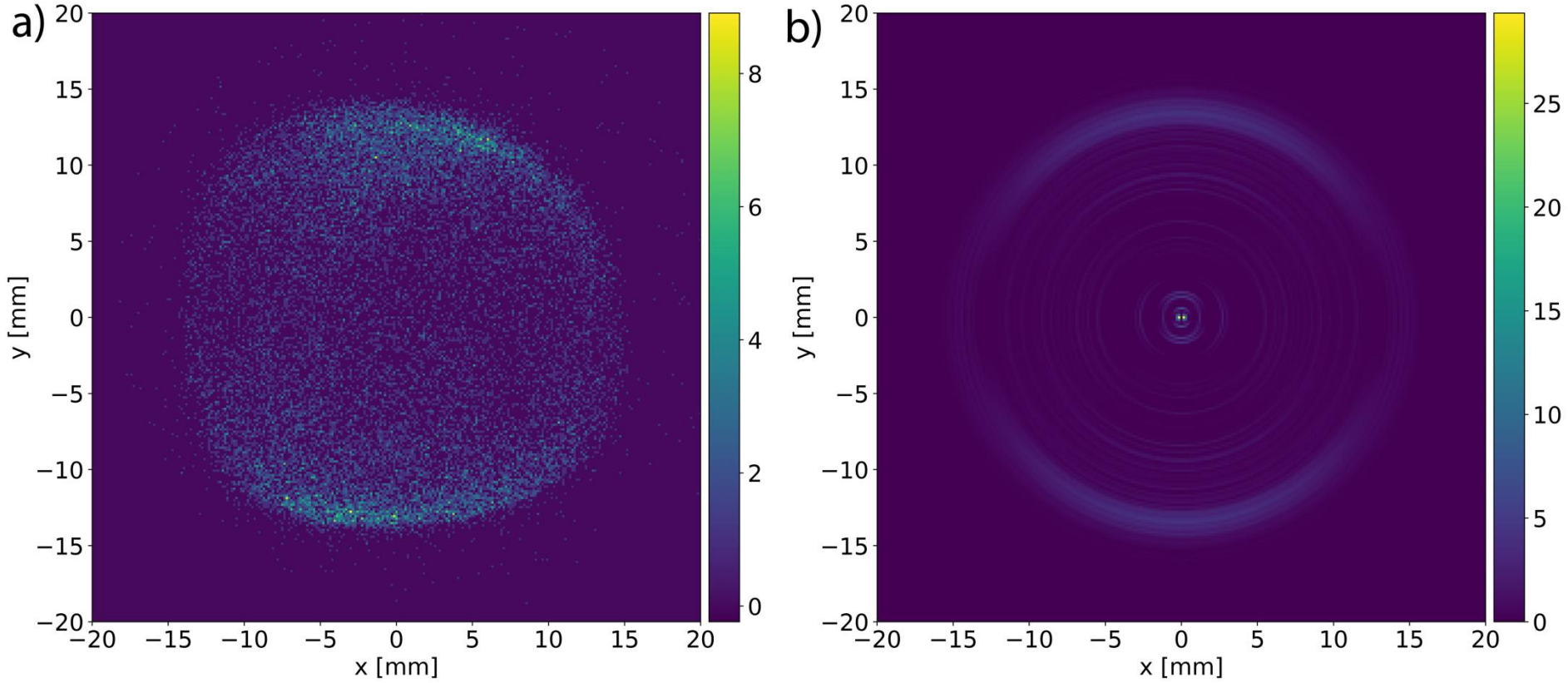


PRECIOSA – Design Vs Experiment



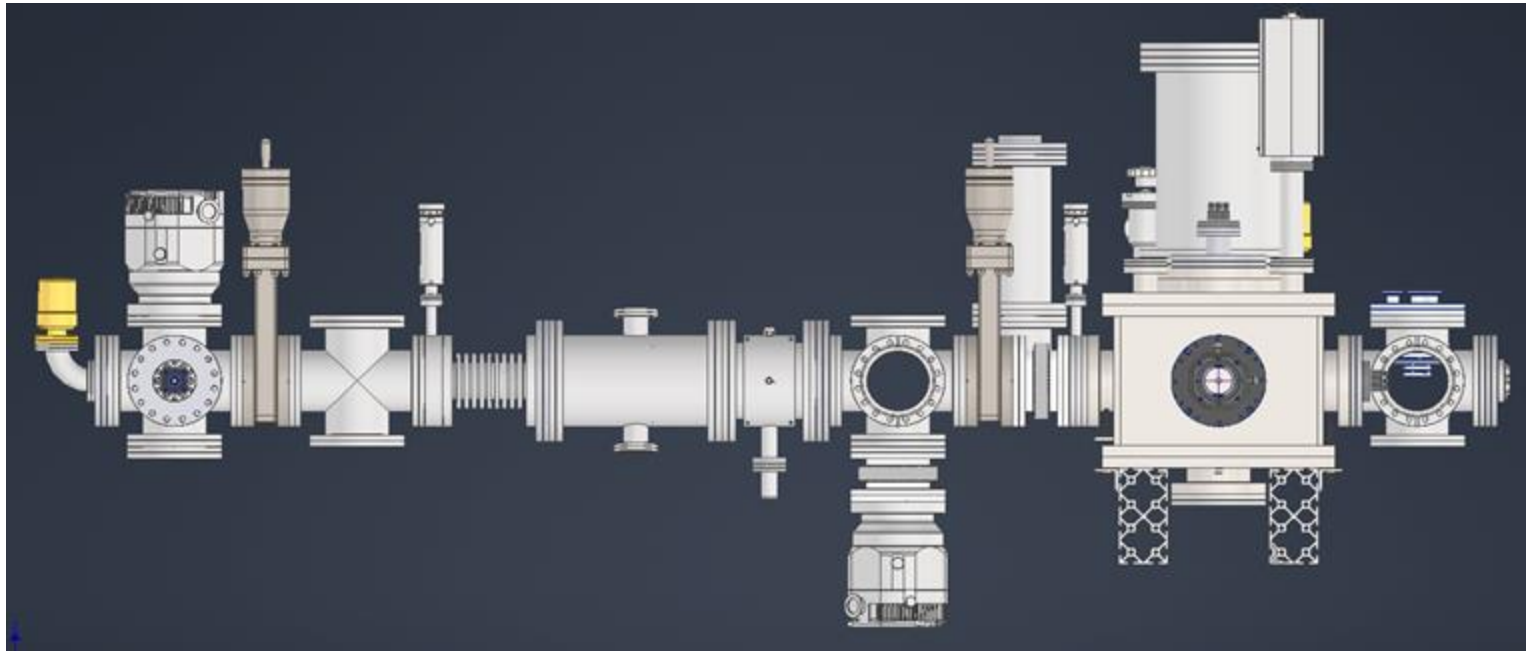


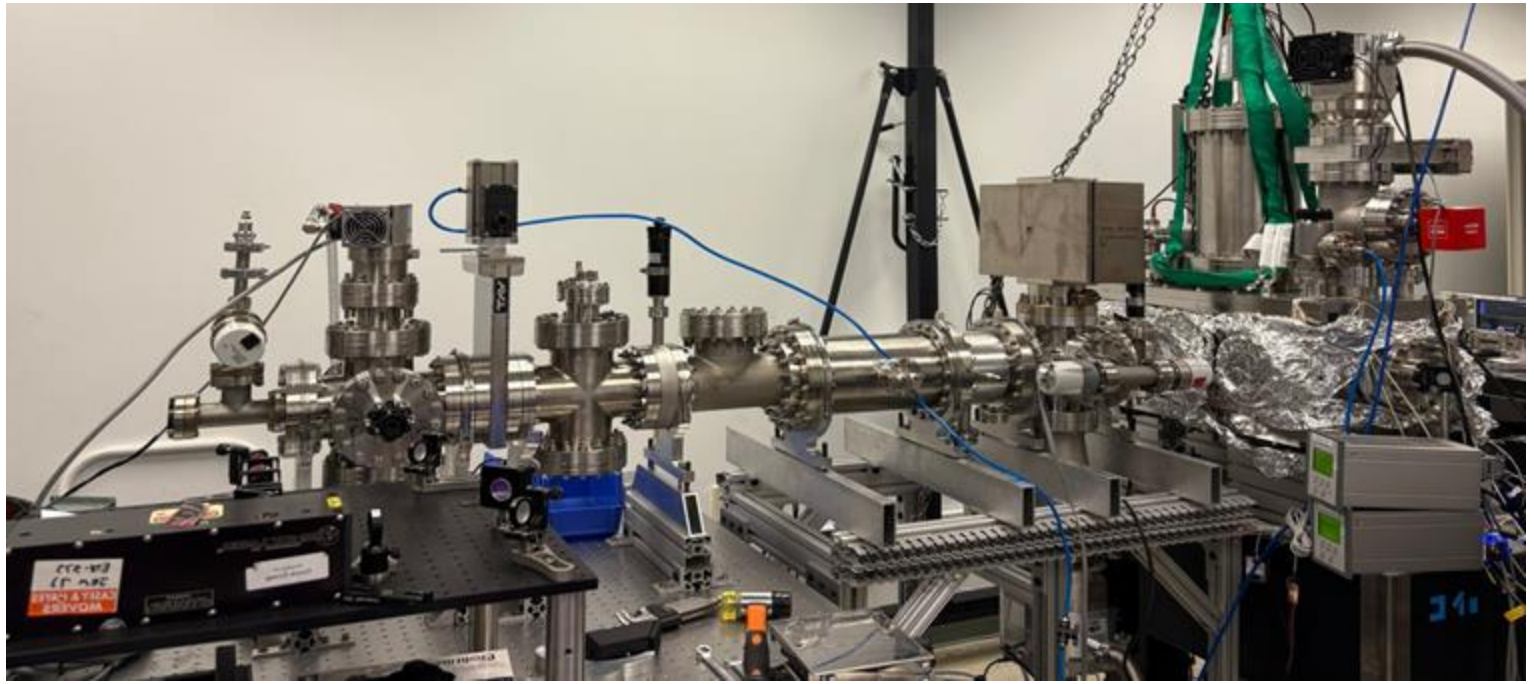
PRECIOSA – Experimental results



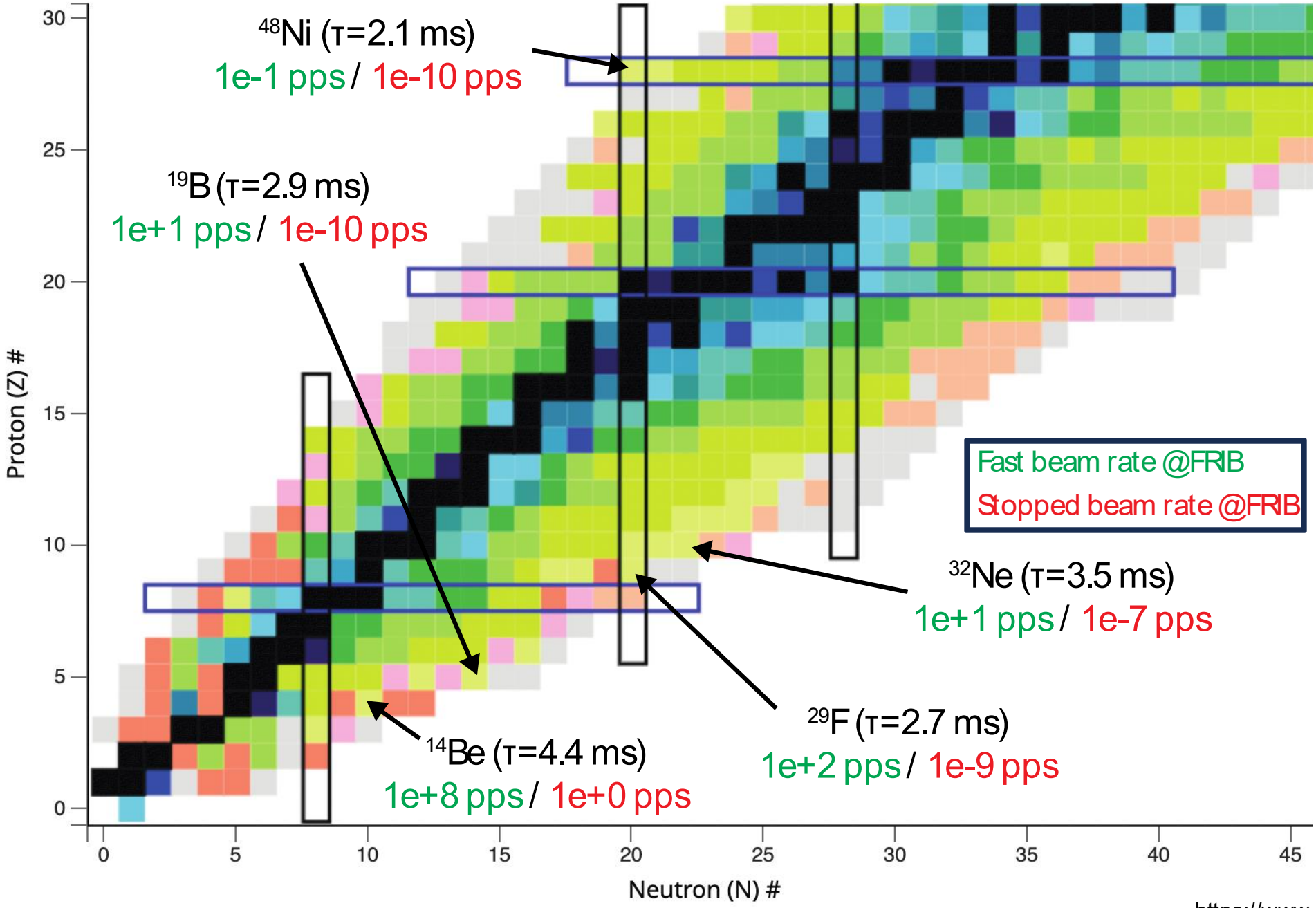
- Yb transition @ 262 nm - $^1S_0(4f^{14}6s^2) \rightarrow^3 P_1(4f^{14}6s7p)$
- Fully tested VMI setup
- < 100 meV resolution
- < 1/min background events

Thanks to:
Silviu Udrescu
Fabian Pastrana
Tatiana Lamprea





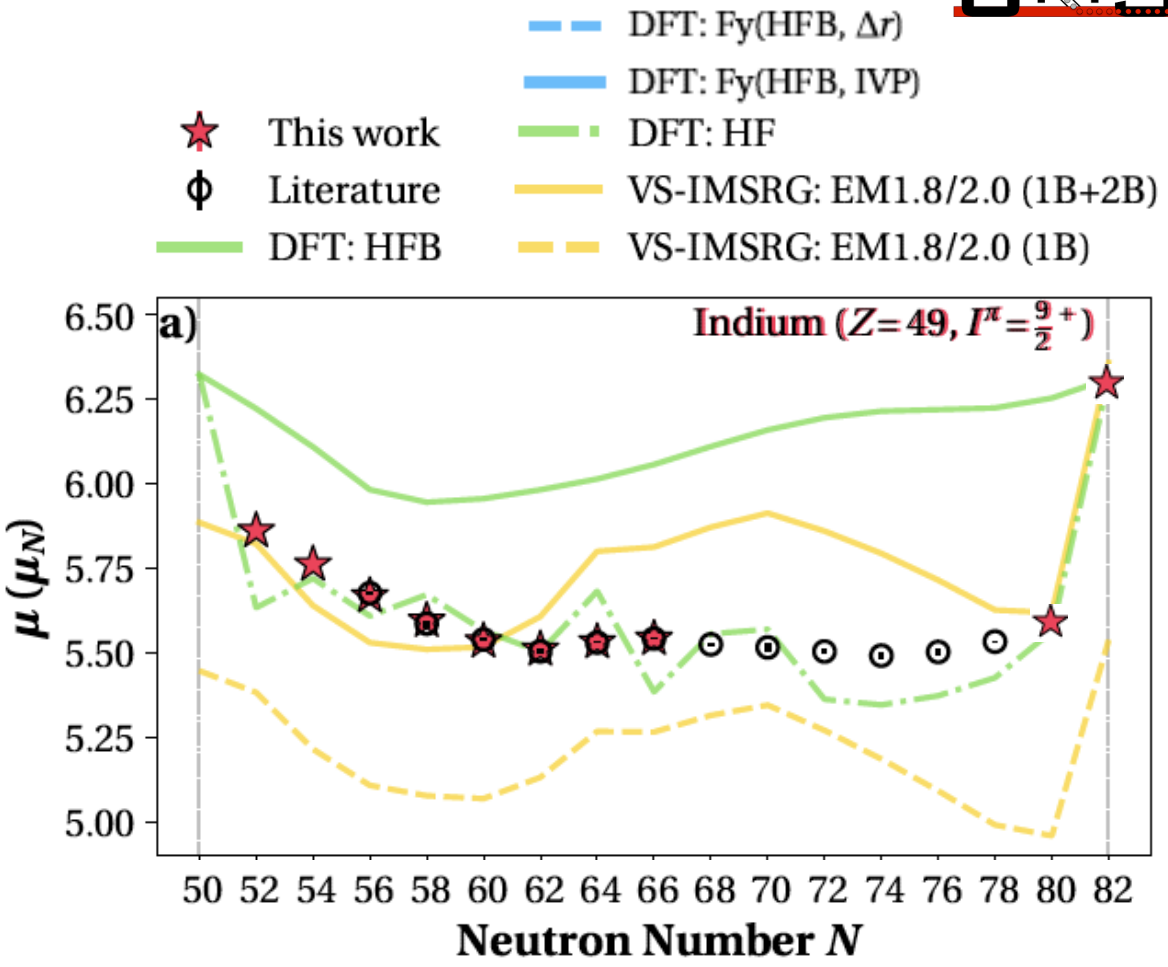
Access to new key nuclear systems

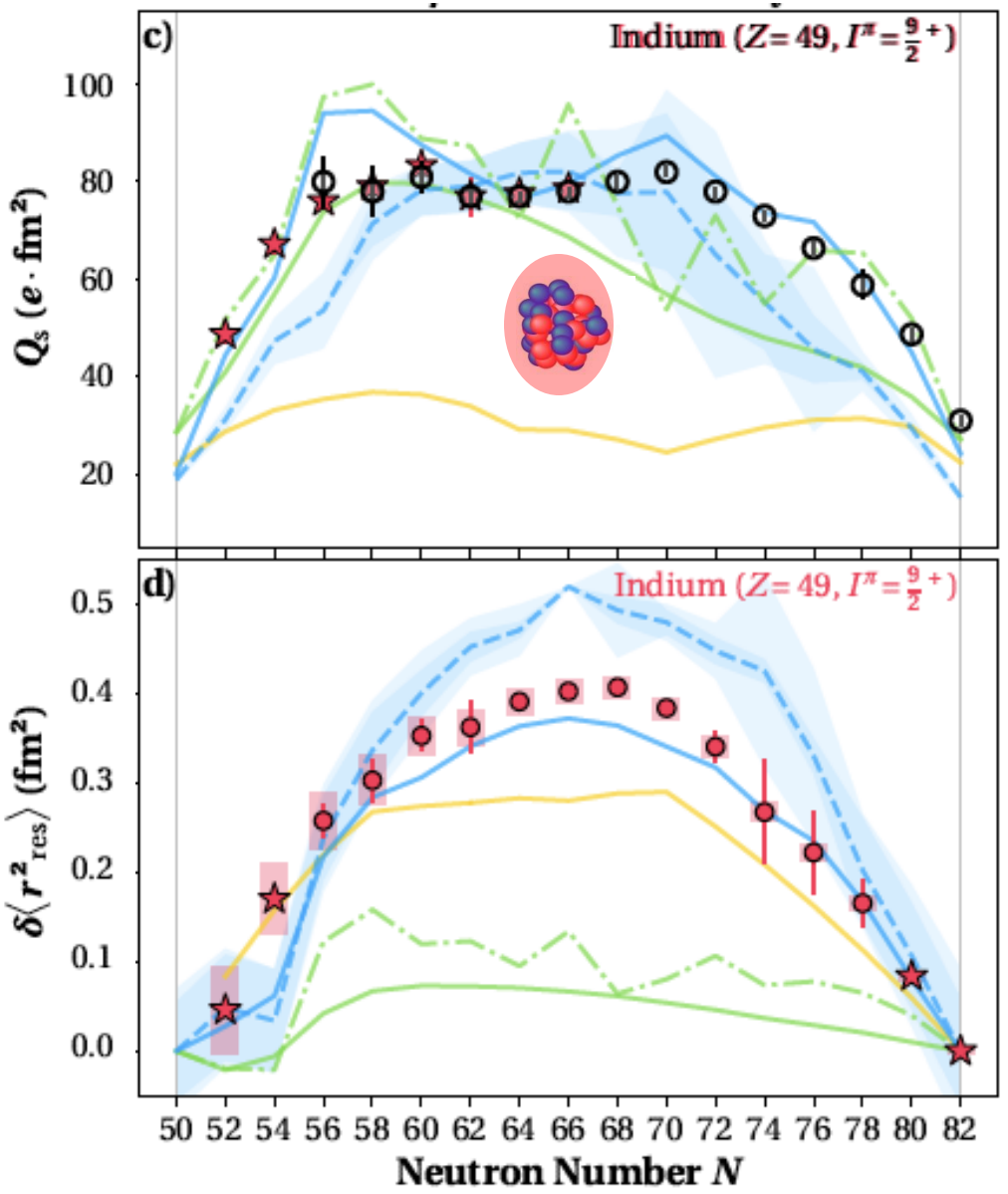


https://www.nndc.bnl.gov/nudat3/

Laser Spectroscopy Around ^{100}Sn and ^{132}Sn

CRIS @ISOLDE/CERN



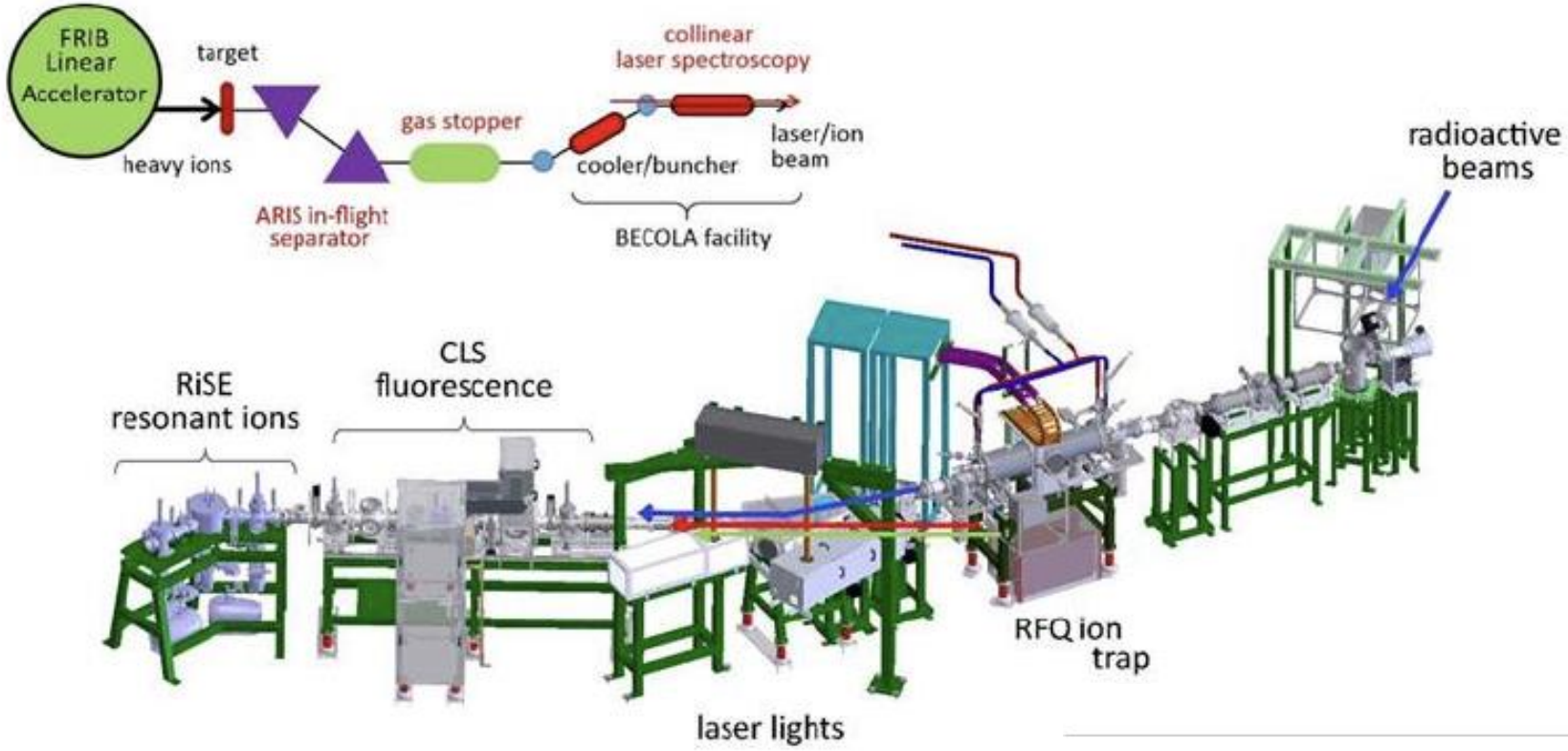


$^{115-131}$In: [Karthein et al. Nature Phys 20, 1719 (2024)]

$^{104-132}$Sn: [Gustafsson et al. Submitted (2024)]

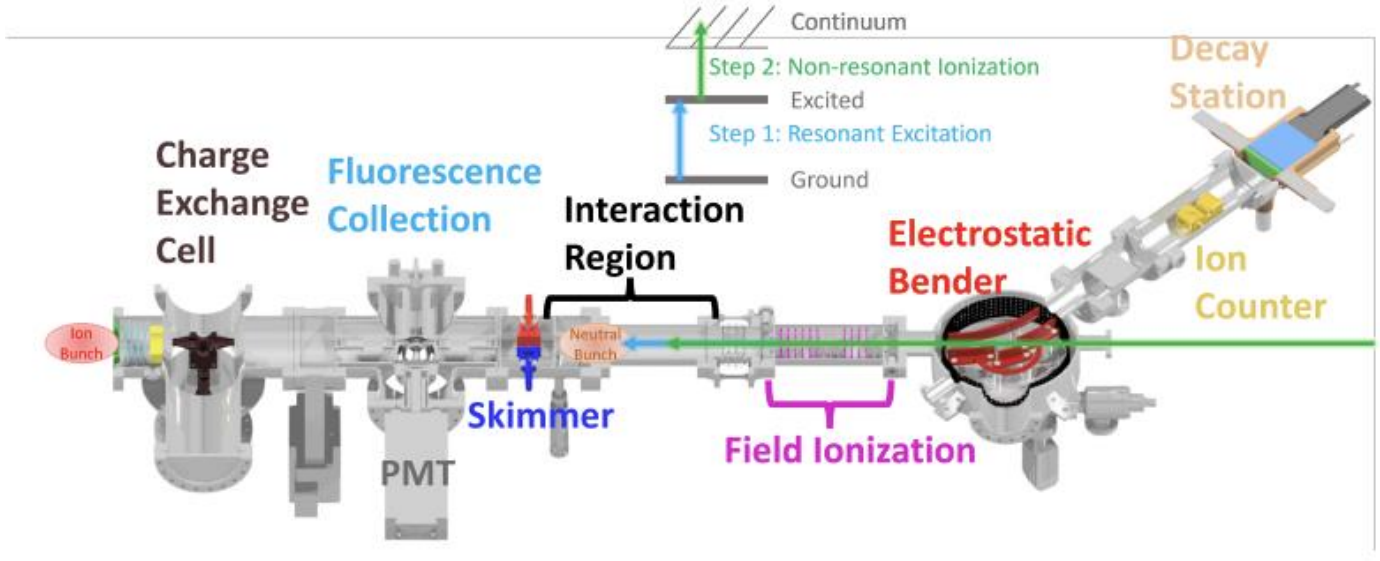
$^{101-114}$In: [Vernon et al. Nature 607, 260 (2022)]

RISE @ BECOLA/FRIB



RISE @ BECOLA/FRIB:

- ✔ ^{22}Al – ^{27}Al
- ✔ ^{28}Si – ^{38}Si



Talks: K. Minamisono
B. Rickey @ "Precision measurements working group"

Radioactive Molecules for Fundamental-Symmetry Tests

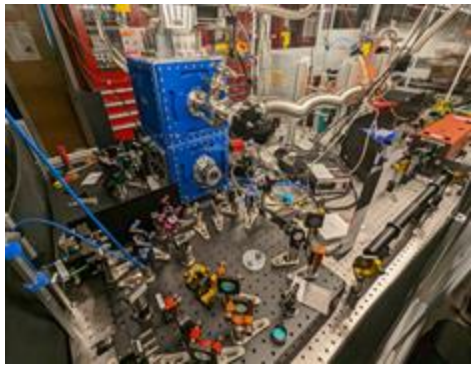
→ RaOH, $RaOH^+$ and $RaOCH_3^+$

[Hutzler, Jayich, …]

[Fan et al. Phys. Rev. Lett. 126, 023002 (2021)]

[Yu & Hutzler Phys. Rev. Lett. 126, 023003 (2021)]

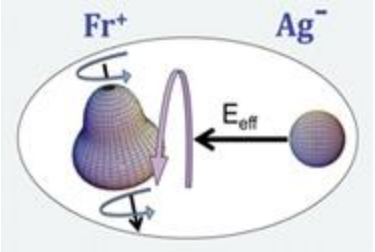
Hutzler's group: RaOH @ Caltech



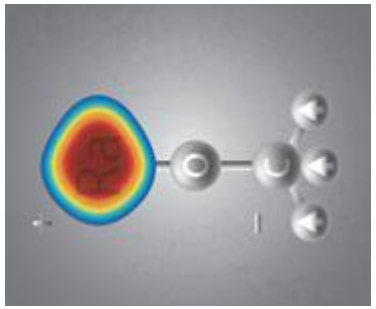
→ Assembling molecules from cold atoms [Demille]

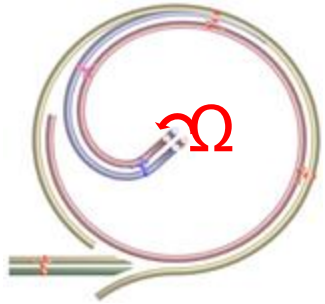
- RaAg
- FrAg

[New J. Phys. 23, 113039 (2021)]



→ Centrifuge Deceleration



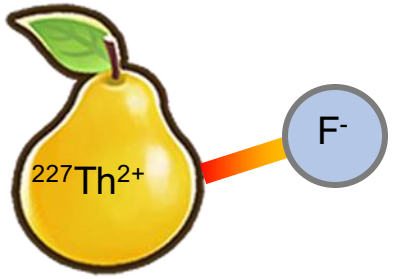


Xing Wu

$RaOCH_3$ @ FRIB/MSU

→ $^{227}ThF^+$

[Boon Ng, Cornell, Fang, Malbrunot …]



→ Molecules in Noble Gas Solids (York/Toronto/MSU)

[Singh, Vutha,…]

[Vutha et al. PRA 98:032513 (2018)]

