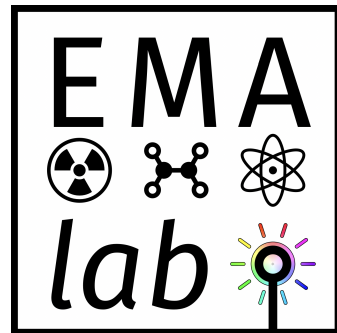


Precision Spectroscopy of Single Molecular Ions in a Penning Trap

Dr. Jonas Karthein – MIT Department of Physics

INT workshop on Parity Non-Conservation II – Jan. 27, 2022

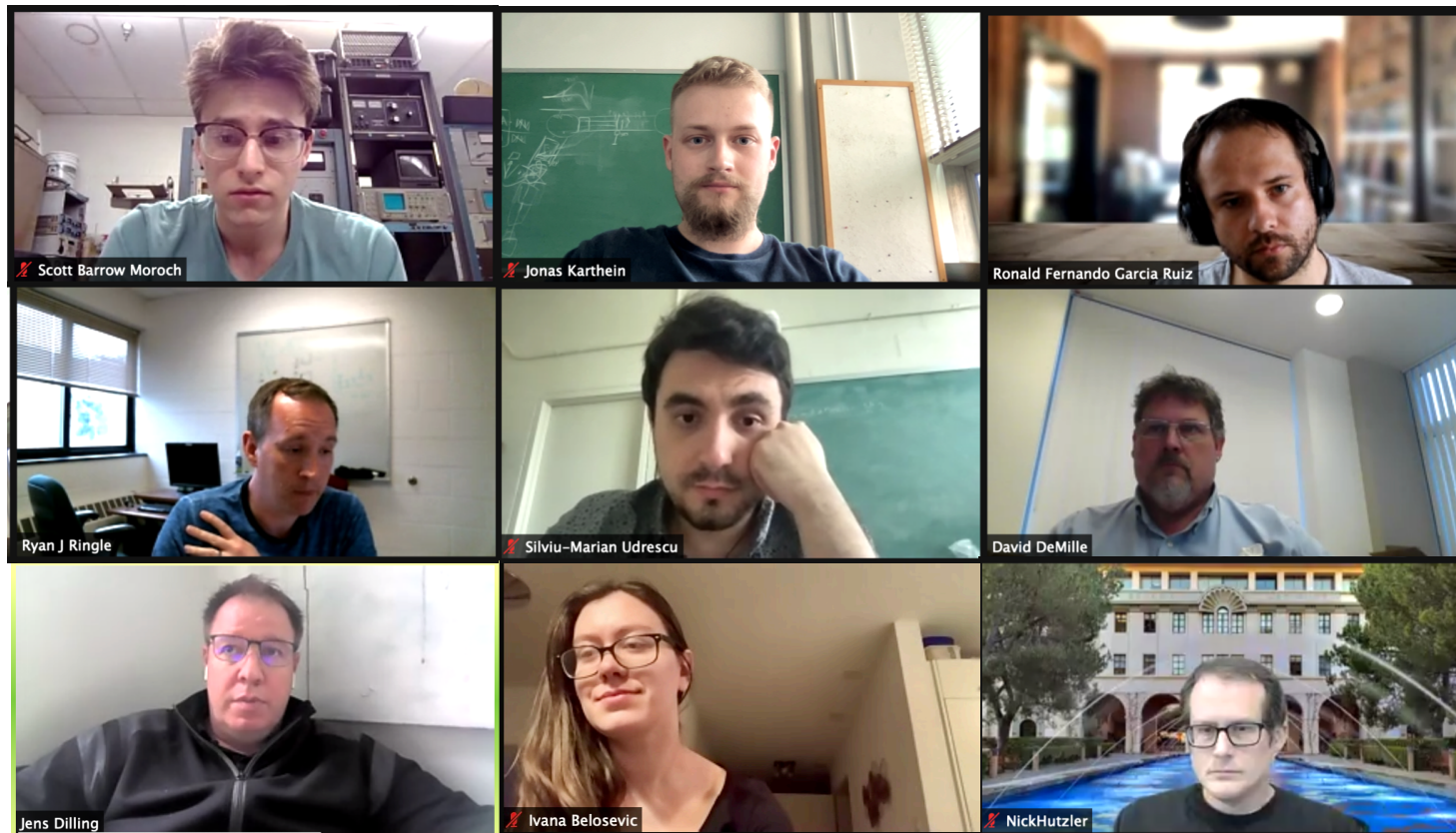
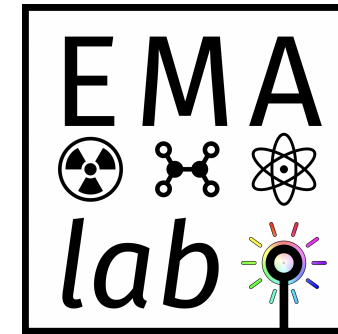


Goal for today

Combining **ion traps** and **laser spectroscopy** will (very soon!) allow us to study hadronic parity violation in **single molecules**.

Our new collaboration

Caltech



Group at MIT:

R.F. Garcia Ruiz, I. Belosevic,
A.J. Brinson, H. Kakioka,
J. Karthein, S. Moroch,
F.C. Pastrana, S.M. Udrescu,
A. Vernon, S. Wilkins

Main collaborators:

D. DeMille, J. Dilling,
N. Hutzler, R. Ringle

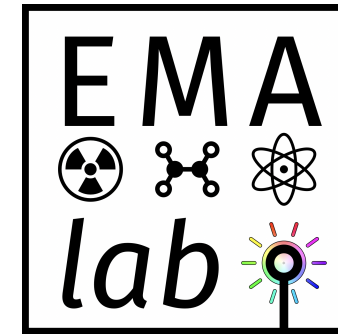
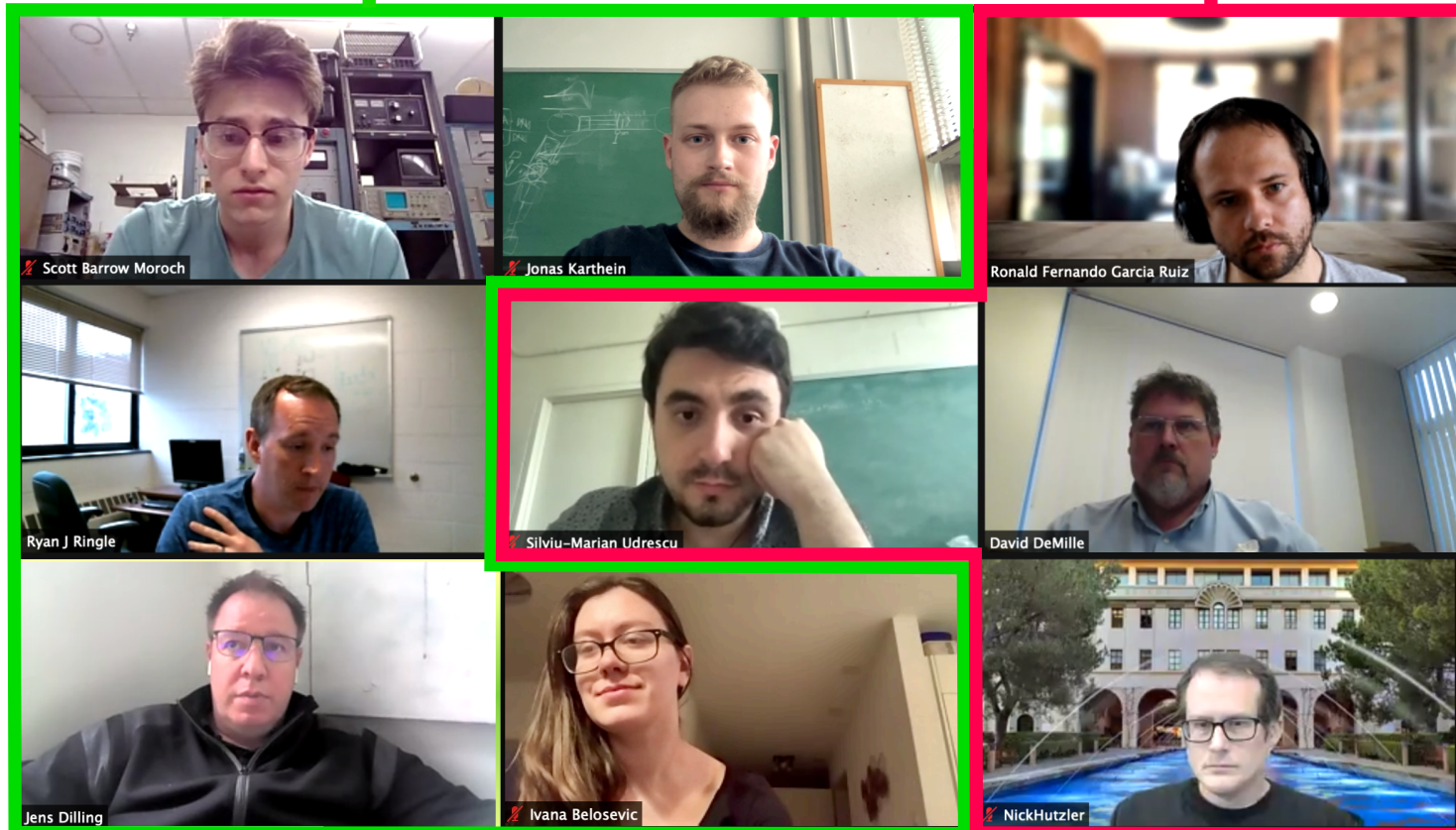
<https://garciaruizlab.com>

Our new collaboration

Ion trapping
experts

+

Laser spectroscopy
experts



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<https://garciaruizlab.com>

Our AMO techniques

nature

Article | [Open Access](#) | [Published: 27 May 2020](#)

Spectroscopy of short-lived radioactive molecules

[R. F. Garcia Ruiz](#) ✉, [R. Berger](#) ✉, ... [X. F. Yang](#) [+ Show authors](#)

[Nature](#) **581**, 396–400 (2020) | [Cite this article](#)

14k Accesses | **31** Citations | **163** Altmetric | [Metrics](#)

nature physics

Letter | [Open Access](#) | [Published: 23 September 2021](#)

Mass measurements of $^{99-101}\text{In}$ challenge ab initio nuclear theory of the nuclide ^{100}Sn

[M. Mougéot](#) ✉, [D. Atanasov](#), [J. Karthein](#) [+ Show authors](#)

[Nature Physics](#) **17**, 1099–1103 (2021) | [Cite this article](#)

3311 Accesses | **2** Citations | **57** Altmetric | [Metrics](#)

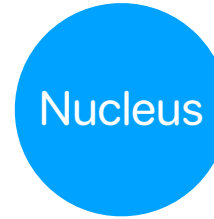
Our group at MIT has successfully applied **atomic physics techniques** (traps, lasers) to study the **nuclear structure**.

We believe that we can use these techniques to study fundamental physics.

Our AMO techniques

Laser spectroscopy

Optical Laser →



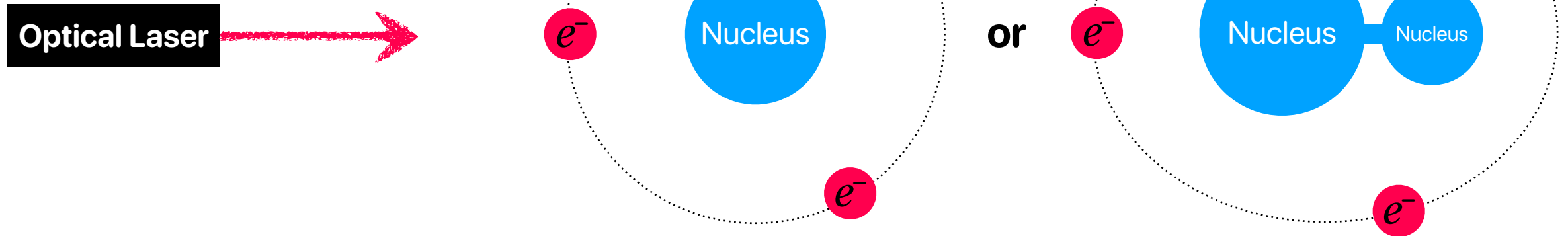
"nothing happens"

→ nuclear excitations $\sim 10^5 - 10^8$ eV

→ (near) optical lasers $\sim 10^{-2} - 10^2$ eV

Our AMO techniques

Laser spectroscopy

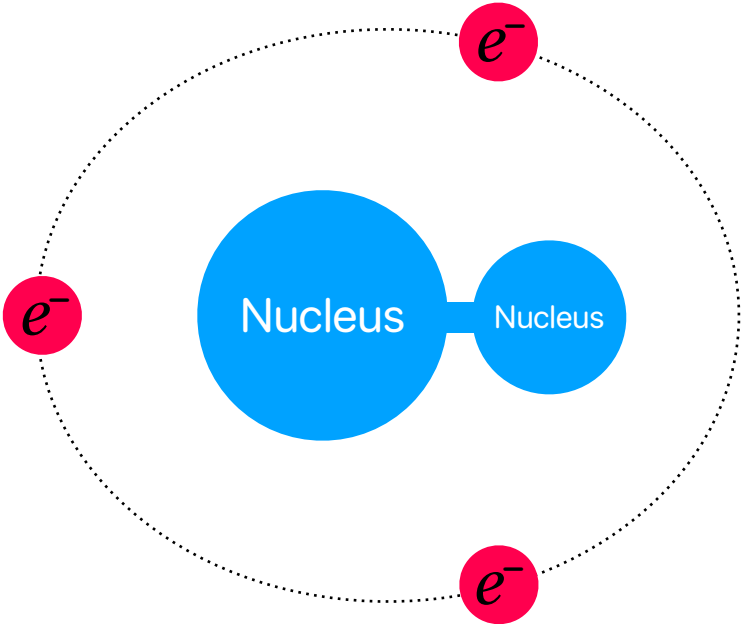


→ Learn about the atomic/
molecular Hamiltonian!

Our AMO techniques

Laser spectroscopy

Optical Laser



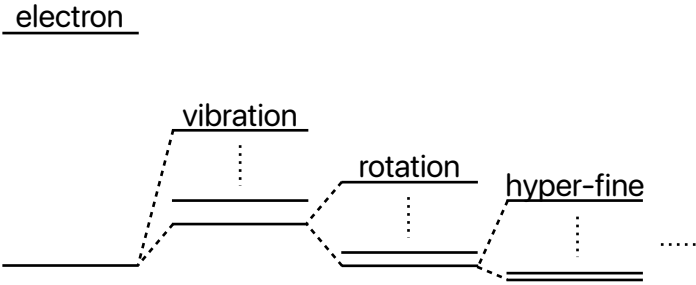
The effective molecular Hamiltonian H_{mol}

$$H_{\text{mol}} = H_e + H_{\text{vib}} + H_{\text{rot}} + H_{\text{sr}} + H_{\text{hfs}} + \dots + H_{\text{pV}} + H_{\text{PTV}}$$

	↓	↓	↓	↓	↓	↓	↓
[eV] ~	2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$\ll 10^{-15}$

experimentally resolvable ←

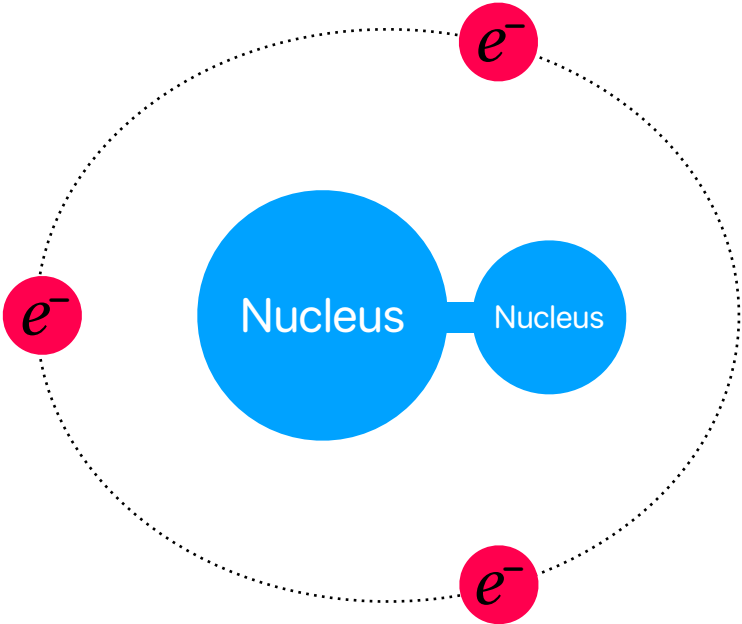
Structure →



Our AMO techniques

Laser spectroscopy

Optical Laser →



The effective molecular Hamiltonian H_{mol}

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

[eV]

~ 2

10^{-2}

10^{-5}

10^{-6}

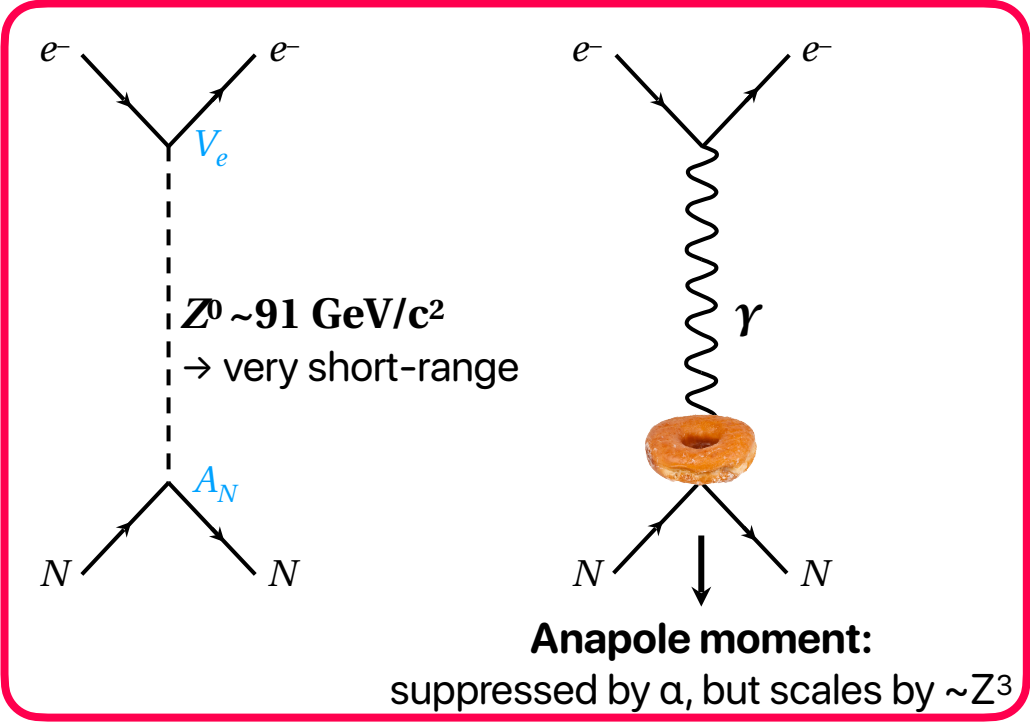
10^{-8}

$< 10^{-12}$

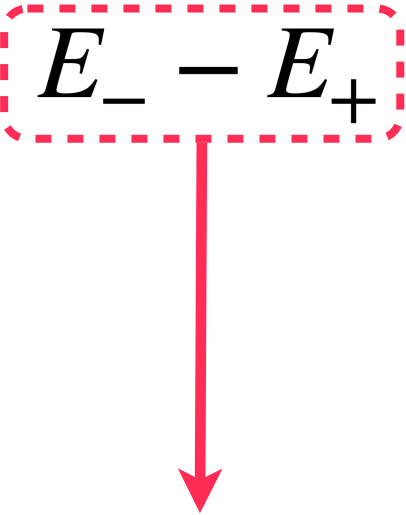
$\ll 10^{-15}$

experimentally resolvable ←

Hadronic Parity Violation



Trick: mixing (electronic) opposite parity states

$$E_{PV} \sim \frac{\langle \psi_{\uparrow}^+ | H_{\pm} | \psi_{\downarrow}^- \rangle}{E_- - E_+}$$


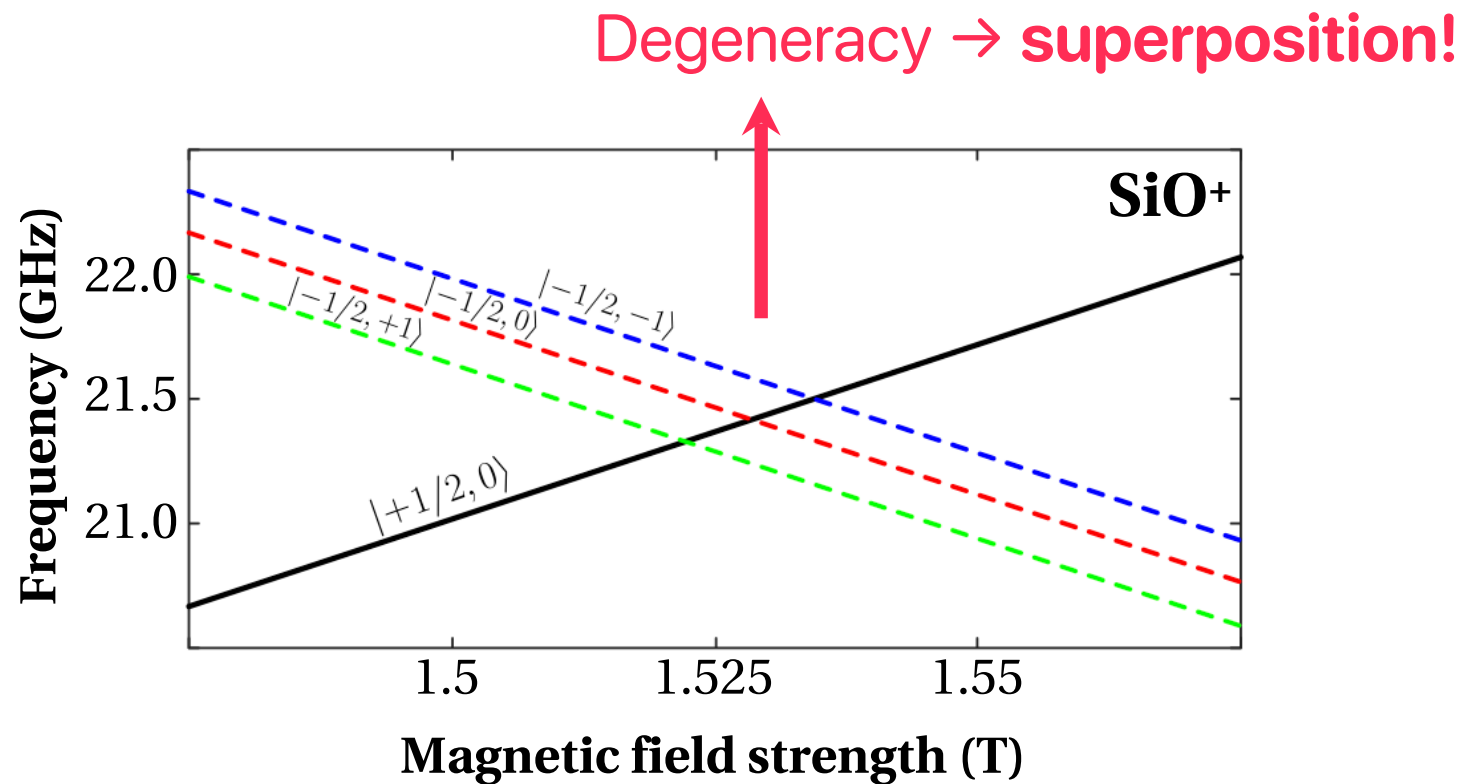
$$P(\text{atom}) \propto (-1)^L \rightarrow (E_- - E_+) \sim 1 \text{ eV}$$

$$P(\text{molecule}) \propto (-1)^N \rightarrow (E_- - E_+) \sim 10 \mu\text{eV}$$

→ **$\sim 10^5$ natural amplification in molecules**

Trick: mixing (electronic) opposite parity states

$$E_{PV} \sim \frac{\langle \psi_{\uparrow}^+ | H_{\pm} | \psi_{\downarrow}^- \rangle}{E_- - E_+} \quad + \quad \vec{B} \neq 0 \quad \rightarrow \text{Zeeman shift!}$$
$$+ \quad \text{RF} \quad \rightarrow \text{Stark mixing!}$$



→ **10^{11} amplification compared to atoms!**

Trick: mixing (electronic) opposite parity states

Superposition of states: $|\psi(t)\rangle = c_+(t) |\psi_{\uparrow}^+\rangle + e^{-i\Delta t} c_-(t) |\psi_{\downarrow}^-\rangle$

1. Prepare: $|\psi(0)\rangle = N |\psi_{\downarrow}^-\rangle \longrightarrow$ laser depletion of $|\psi_{\uparrow}^+\rangle$

Trick: mixing (electronic) opposite parity states

Superposition of states: $|\psi(t)\rangle = c_+(t) |\psi_{\uparrow}^+\rangle + e^{-i\Delta t} c_-(t) |\psi_{\downarrow}^-\rangle$

1. Prepare: $|\psi(0)\rangle = N|\psi_{\downarrow}^{-}\rangle \longrightarrow$ laser depletion of $|\psi_{\uparrow}^{+}\rangle$

2. Measure:

$c_+(t_{\text{end}}) \propto \Delta, d\mathcal{E}, \omega, t_{\text{end}}, iW$

counting experimental parameter physics!

Trick: mixing (electronic) opposite parity states

Superposition of states: $|\psi(t)\rangle = c_+(t) |\psi_{\uparrow}^+\rangle + e^{-i\Delta t} c_-(t) |\psi_{\downarrow}^-\rangle$

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2. Measure:

$c_+(t_{\text{end}}) \propto \Delta, d\mathcal{E}, \omega, t_{\text{end}}, iW$

counting experimental parameter physics!

→ "simple" counting experiment!

→ $>10^{11}$ amplification compared to atoms!

Trick: mixing (electronic) opposite parity states

Superposition of states: $|\psi(t)\rangle = c_+(t) |\psi_{\uparrow}^+\rangle + e^{-i\Delta t} c_-(t) |\psi_{\downarrow}^-\rangle$

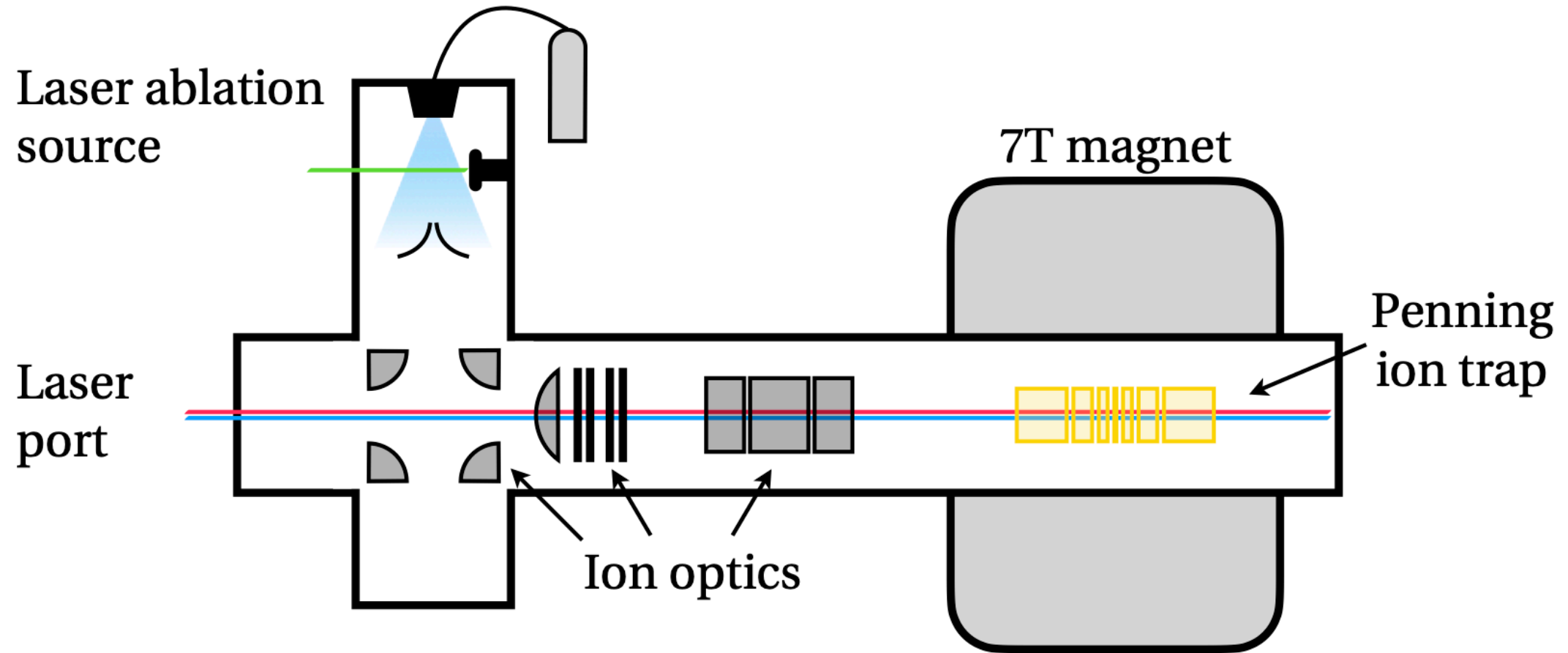
1. Prepare: $|\psi(0)\rangle = N |\psi_{\downarrow}^-\rangle \longrightarrow$ laser depletion of $|\psi_{\uparrow}^+\rangle$

2. Measure: $c_+(t_{\text{end}}) \propto \Delta, d\mathcal{E}, \omega, t_{\text{end}}, iW$

$\downarrow$ counting $\downarrow$ experimental parameter $\downarrow$ physics!

3. Uncertainty: $\delta W \propto \frac{1}{\sqrt{N_{\text{rate}} \cdot T_{\text{total}} \cdot t_{\text{coh}}}} \longrightarrow$ Single ions, but long coherence times!

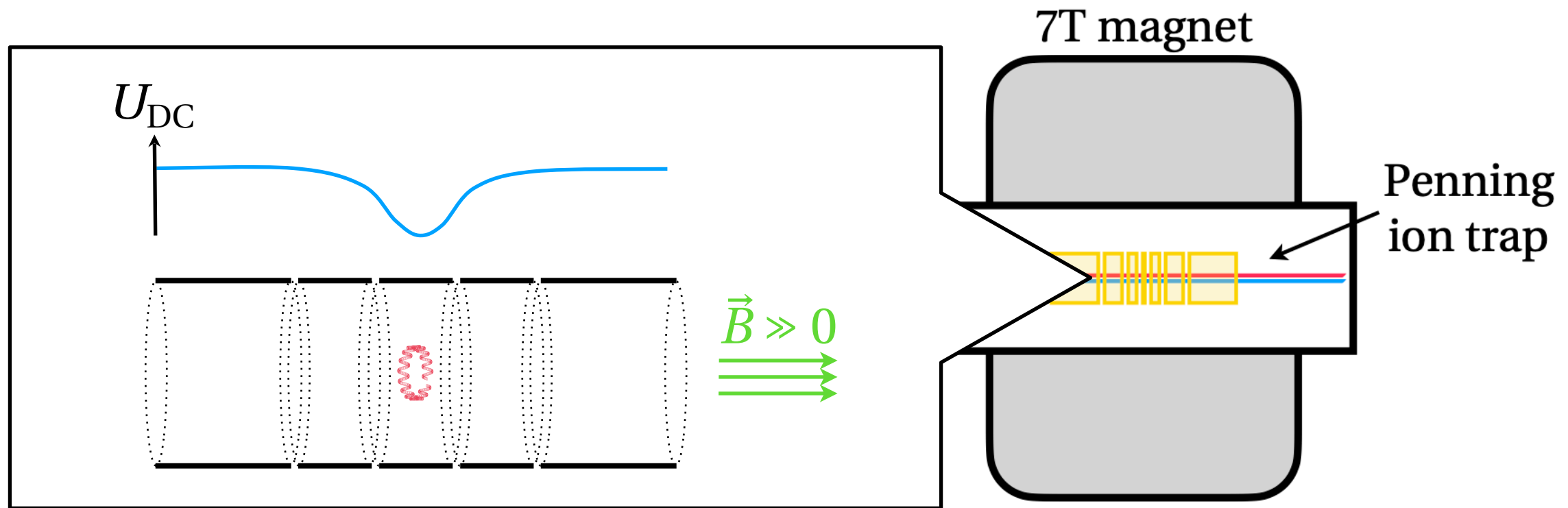
New setup: PV studies in a Penning trap



New setup: PV studies in a Penning trap

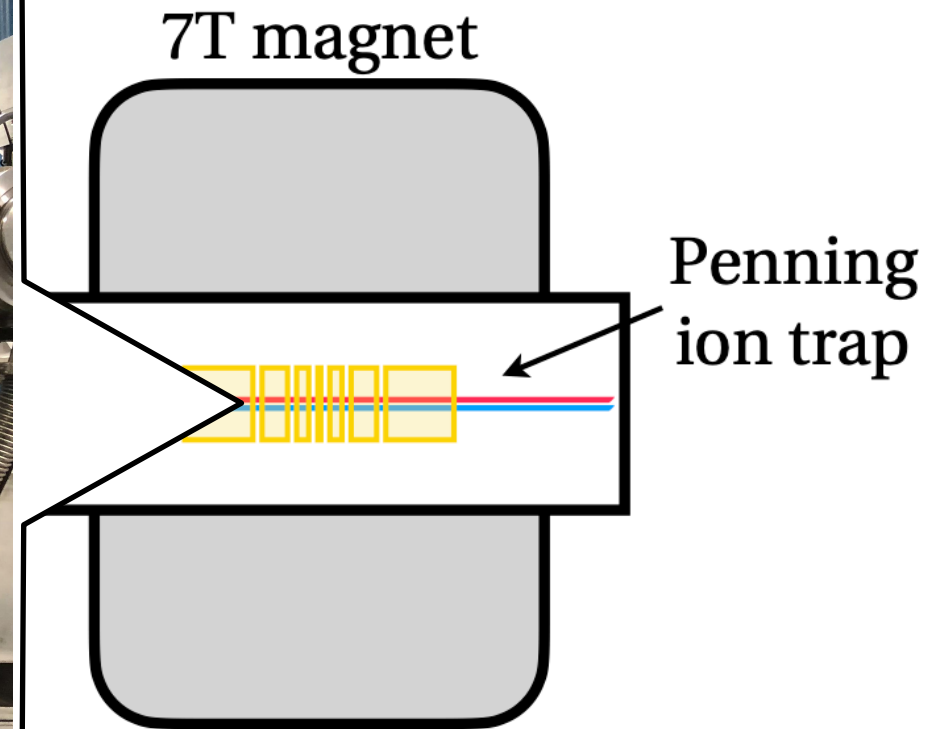
Penning ion trap =

electrostatic potential + strong magnetic field



- Full control over eigenmotions through resonant RF-excitation
- Long ($\gg 1$ s) trapping times for single ions
- Large mass range: [e^- ... >1000 u]
- Easy laser access

New setup: PV studies in a Penning trap



Working Penning trap setup from TRIUMF
→ currently being shipped to MIT

New setup: PV studies in a Penning trap

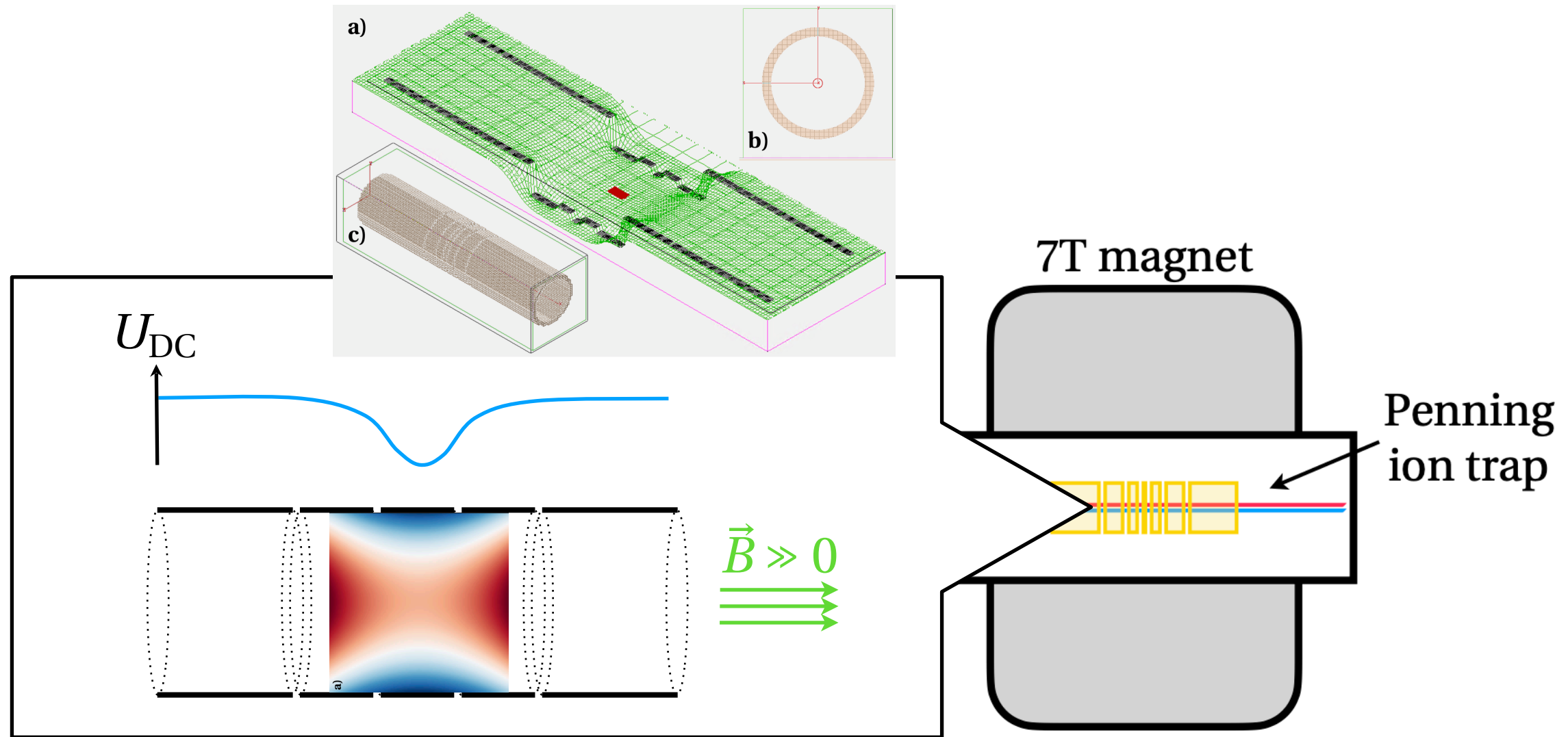


Our colleagues at TRIUMF



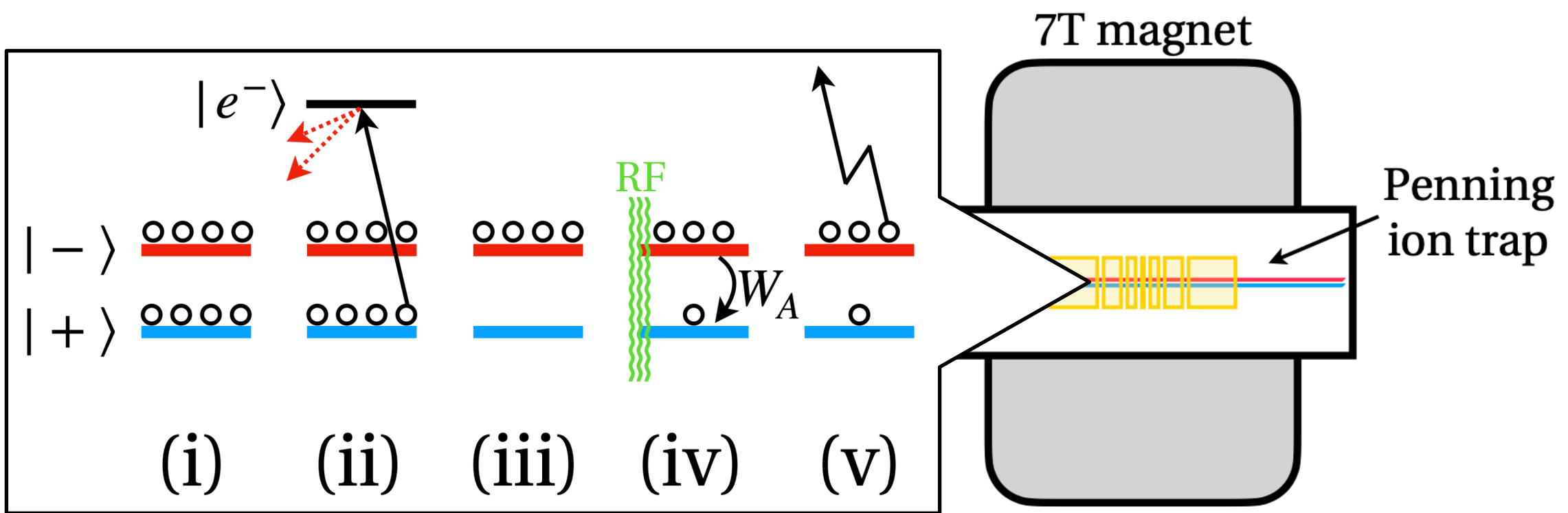
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New setup: PV studies in a Penning trap



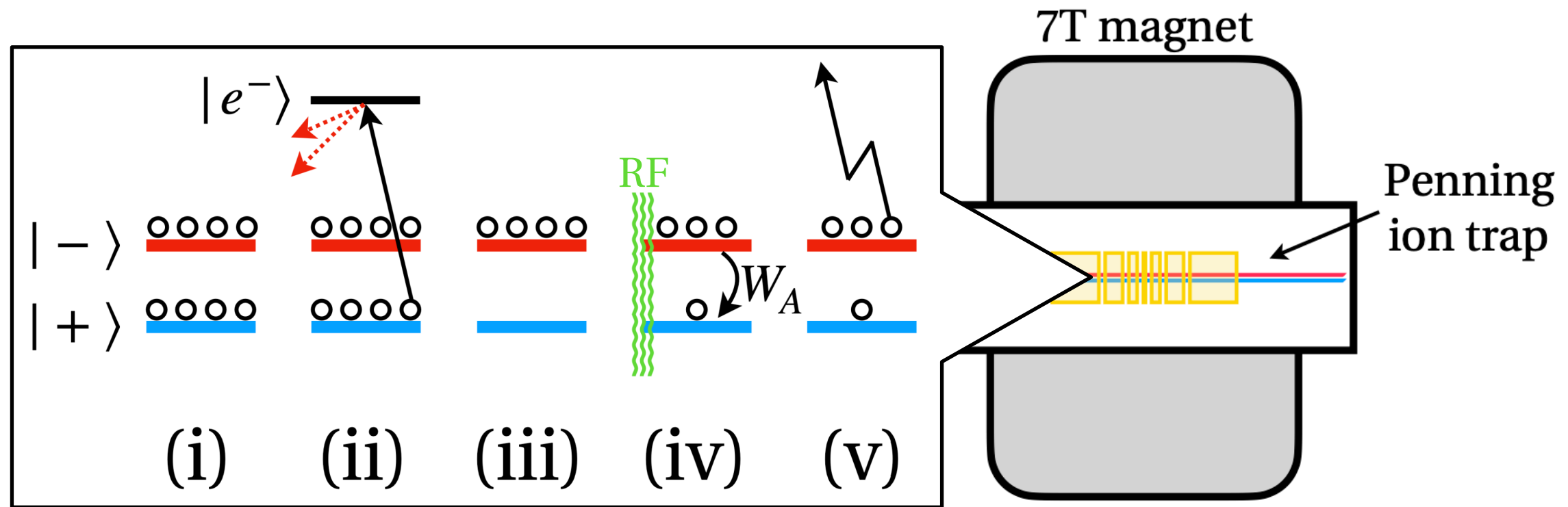
- Numerous simulations (injection, trapping, cooling, detection)
- Optimized electric field ($C_{4,6,8,10} < 10^{-10}$)
- ν_z shifts: $< 10^{-5}$ Hz ($\nu_z \sim 10^5$ Hz)

New setup: PV studies in a Penning trap



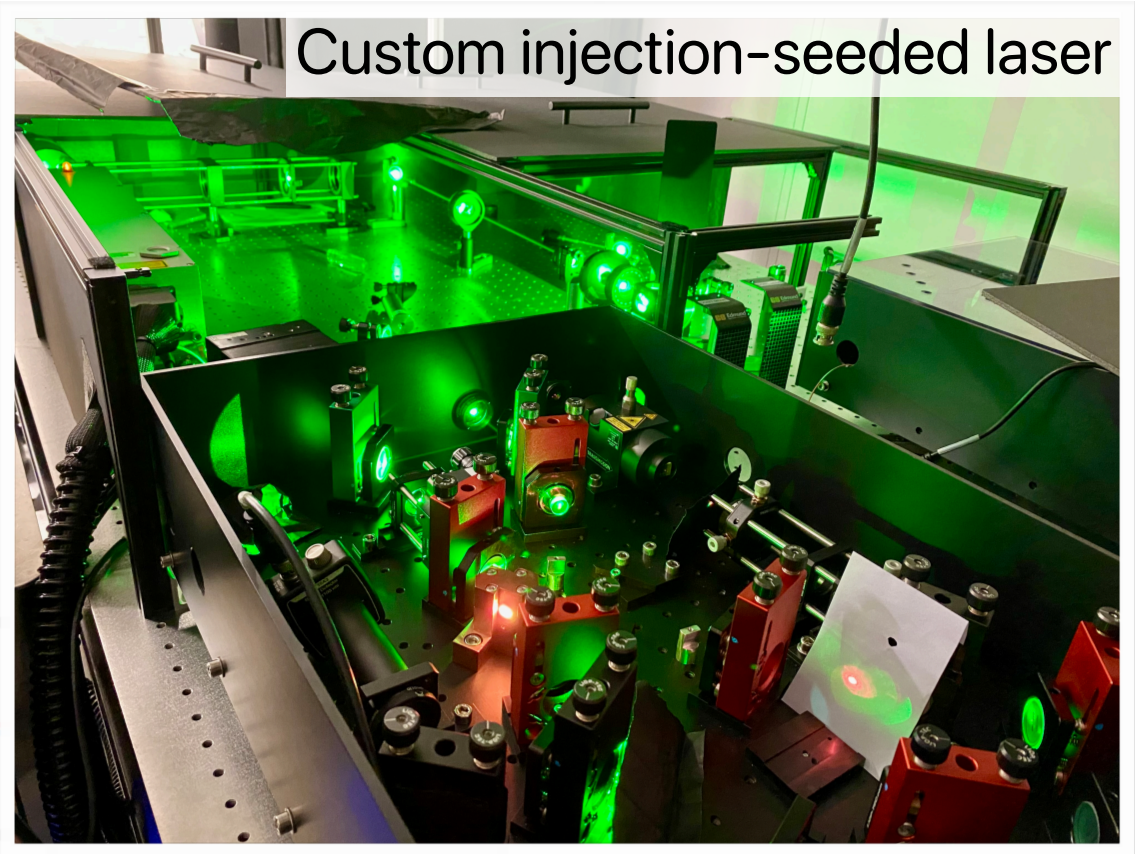
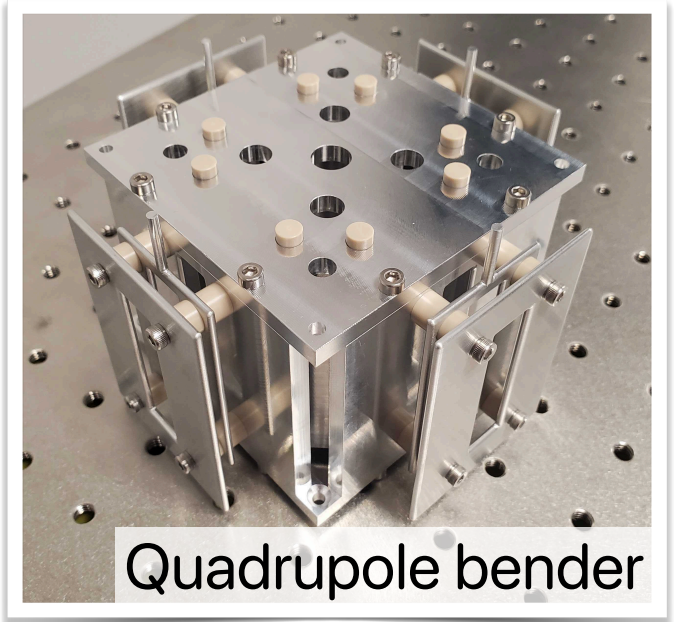
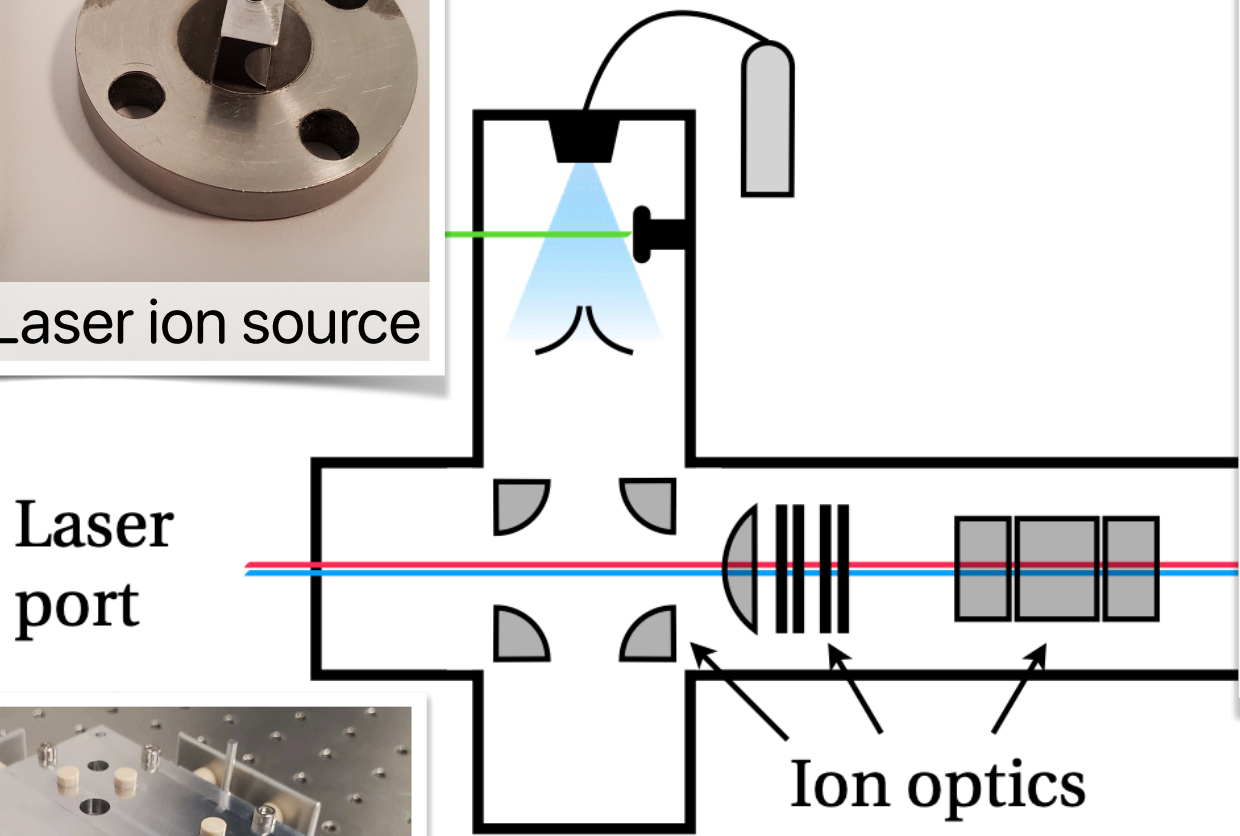
Stable **electrostatic trapping potential** =
oscillating electric field in the ion's restframe!

New setup: PV studies in a Penning trap



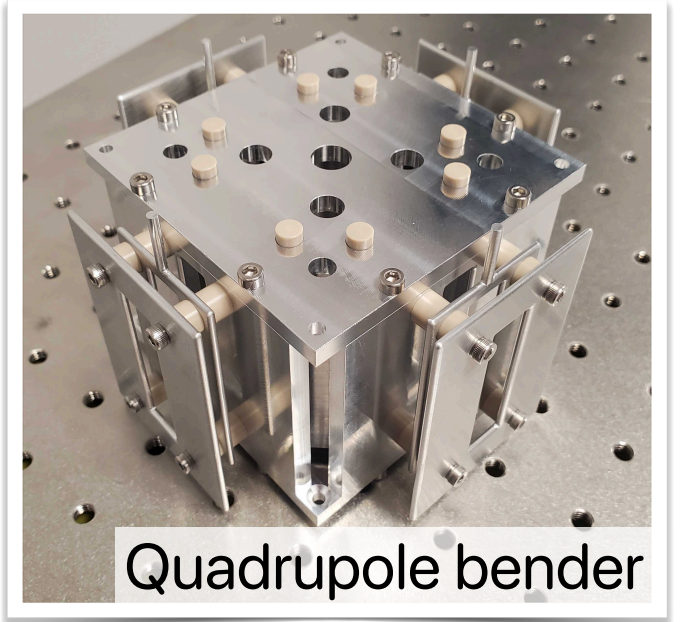
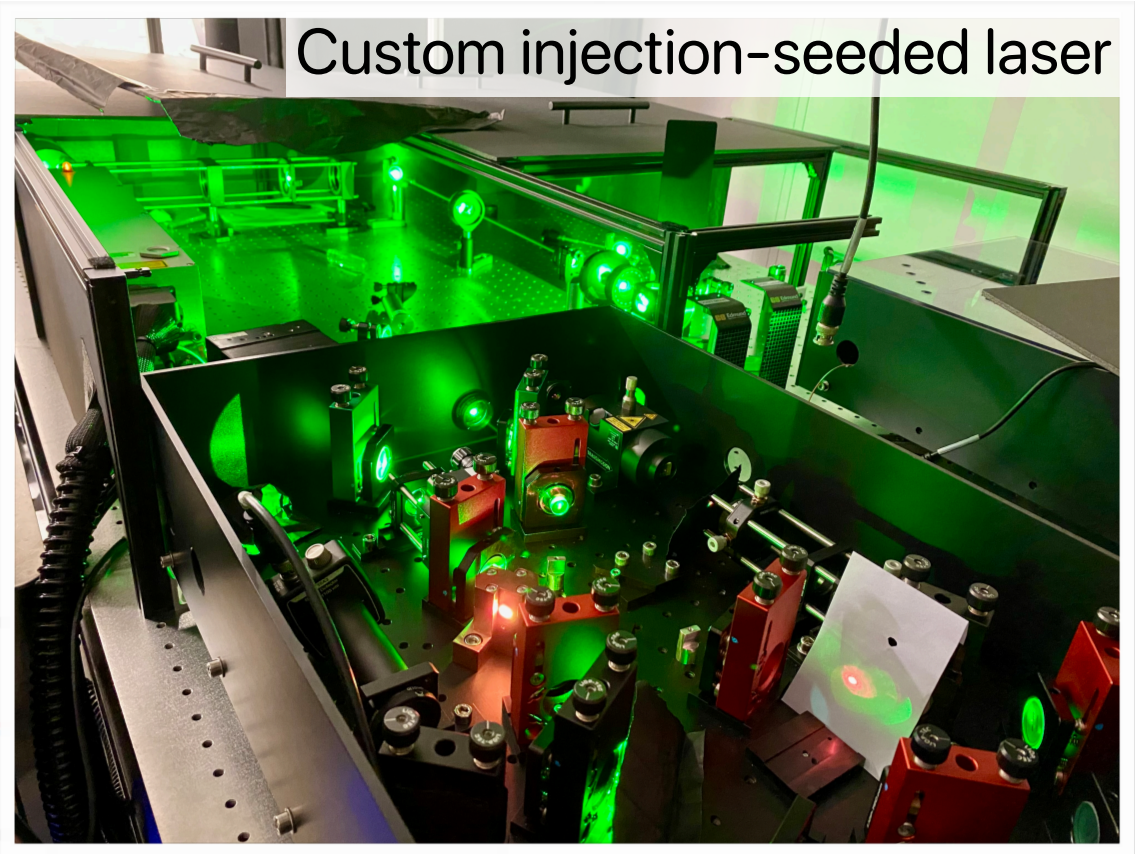
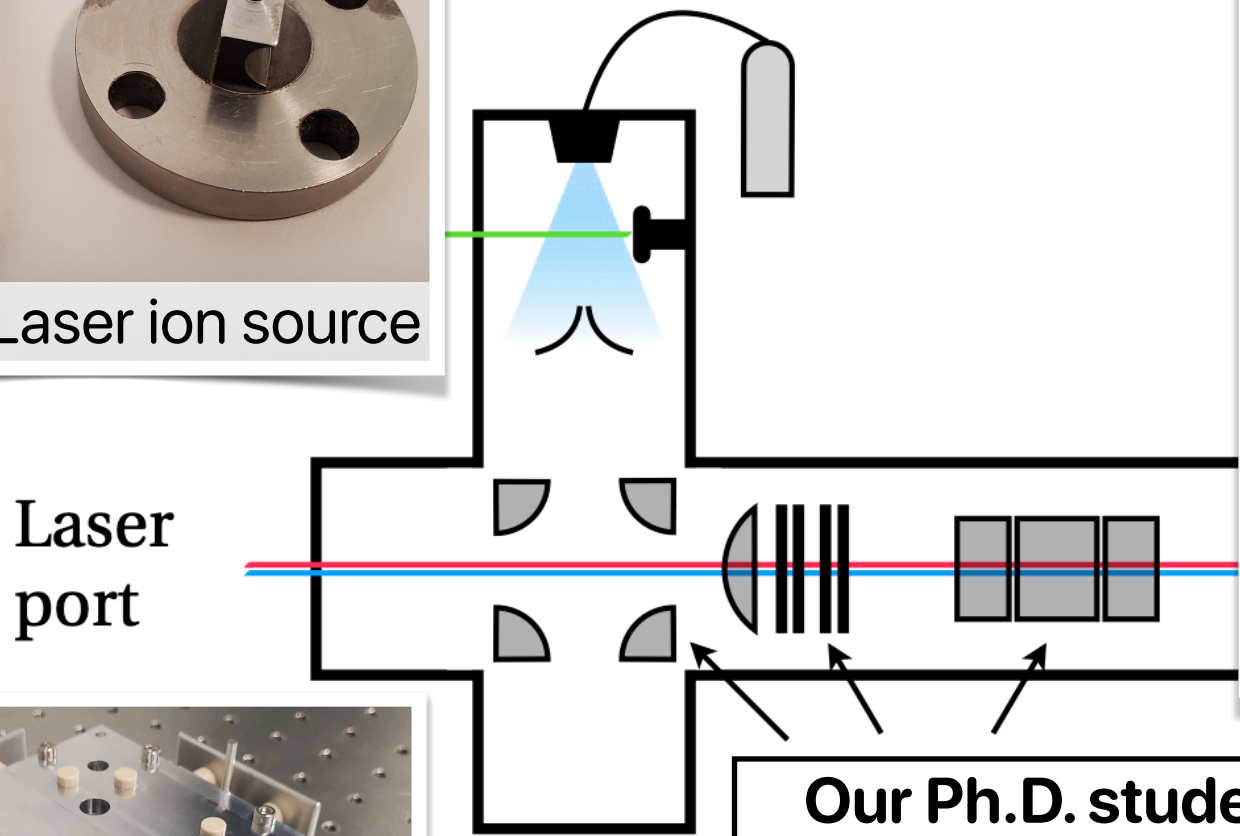
Detection through **mass measurement** after
molecular photodissociation of $| - \rangle$

New setup: PV studies in a Penning trap



+ pump lasers, OPOs, ... ✓

New setup: PV studies in a Penning trap



Our Ph.D. students at MIT



Silviu Udrescu



Scott Moroch

+ pump lasers, OPOs, ... ✓

Project outline and outlook

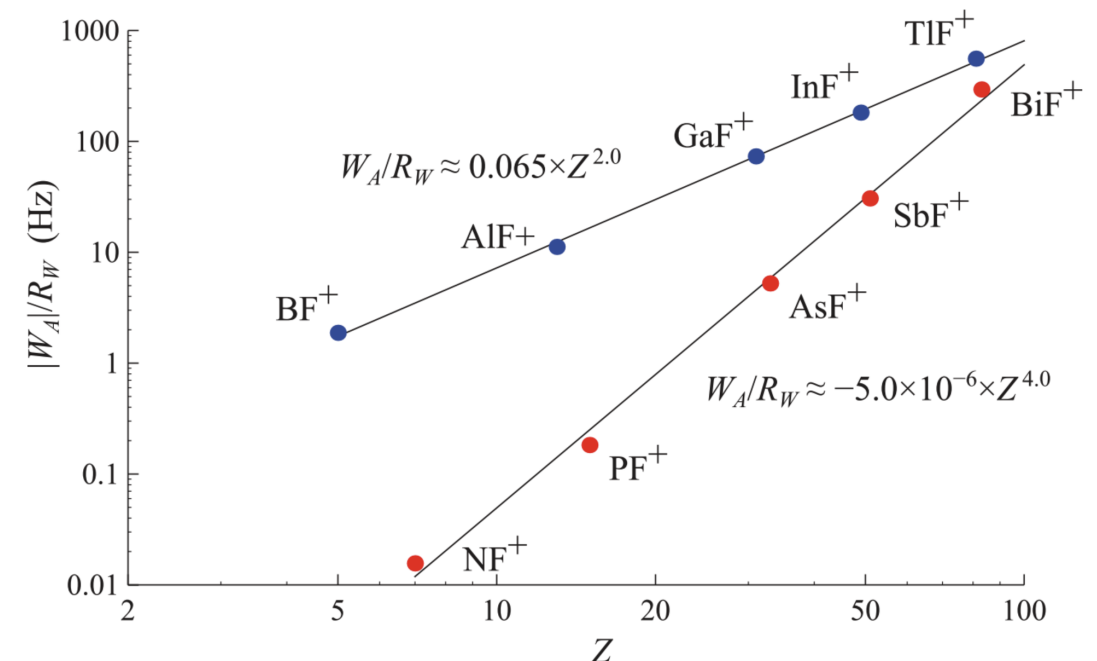
- Simulations for existing magnet + room-temperature Penning trap from TRIUMF
- Simulations + design of a new cryogenic Penning trap
- Laser-ion source, electrode & beamline support procurement
- Magnet + Penning trap transport from TRIUMF to MIT (Q1 2022)
- Parity-violating measurements of diatomic molecules SiO⁺ (2022/2023)
- Production and systematic studies of cryogenic Penning trap (2022/2023)

Day 1 sensitivity for SiO⁺ (W ~ 16 Hz):

$N_{\text{rate}} = 1/\text{s}$, $t_{\text{coh}} = 15 \text{ ms}$, $T_{\text{total}} = 1 \text{ day} \rightarrow \delta W/W \sim 15\%$

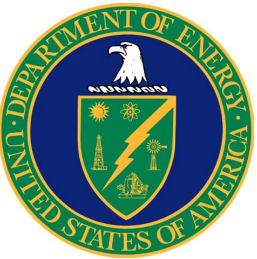
Sensitivities for O, F, and B about factor 5-10 lower

$$\delta W \propto \frac{1}{\sqrt{N_{\text{rate}} \cdot T_{\text{total}} \cdot t_{\text{coh}}}}$$



Project outline and outlook

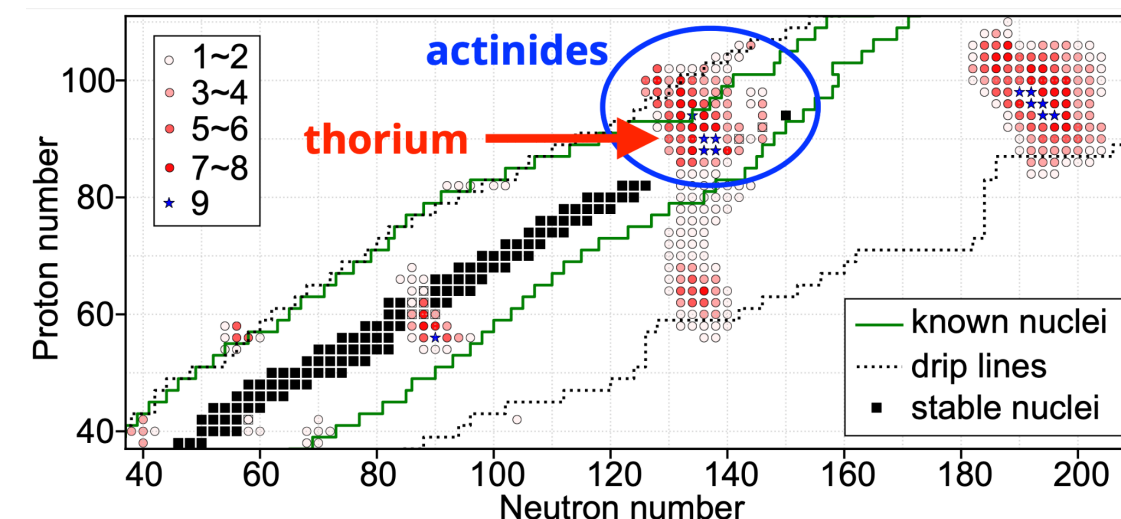
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- Parity-violating measurements of diatomic molecules SiO^+ (2022/2023)
- Production and systematic studies of cryogenic Penning trap (2022/2023)
- Long-term goal: experiments at radioactive ion beam facilities (FRIB/TRIUMF; ~2025)



Accepted Th-isomer and molecules proposal at FRIB:

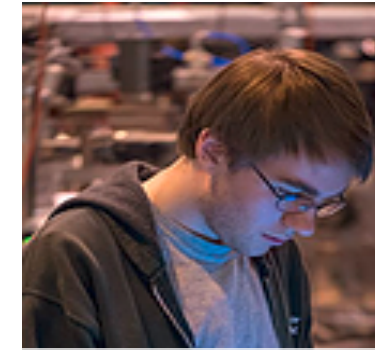
J. Karthein et al. PAC1#21023:

- Actinide molecules $W_A \sim 2000$ Hz (additional 10^3 amplification!)
- Nuclear clock ($\alpha = \text{const.?$, dark matter, ...)
- Octupole deformation

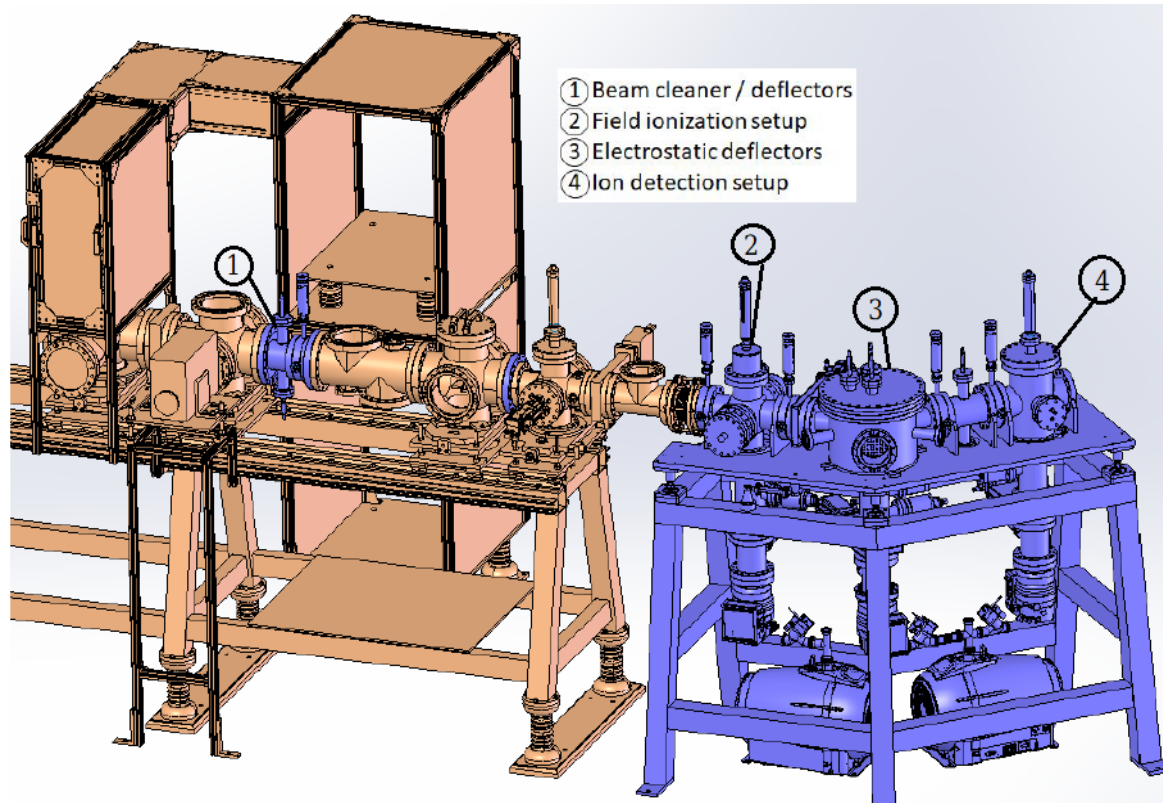


FRIB: next-gen precision laser spectroscopy

- RISE project started (Dec. 2020)
- Beamline Design completed (Apr. 2021)
- Experimental parts ordered (May 2021)
- Commissioning at MIT Bates (Jan. 2022)
- Installation at FRIB completed (Mar. 2022)
- First experimental campaigns (Summer 2022)



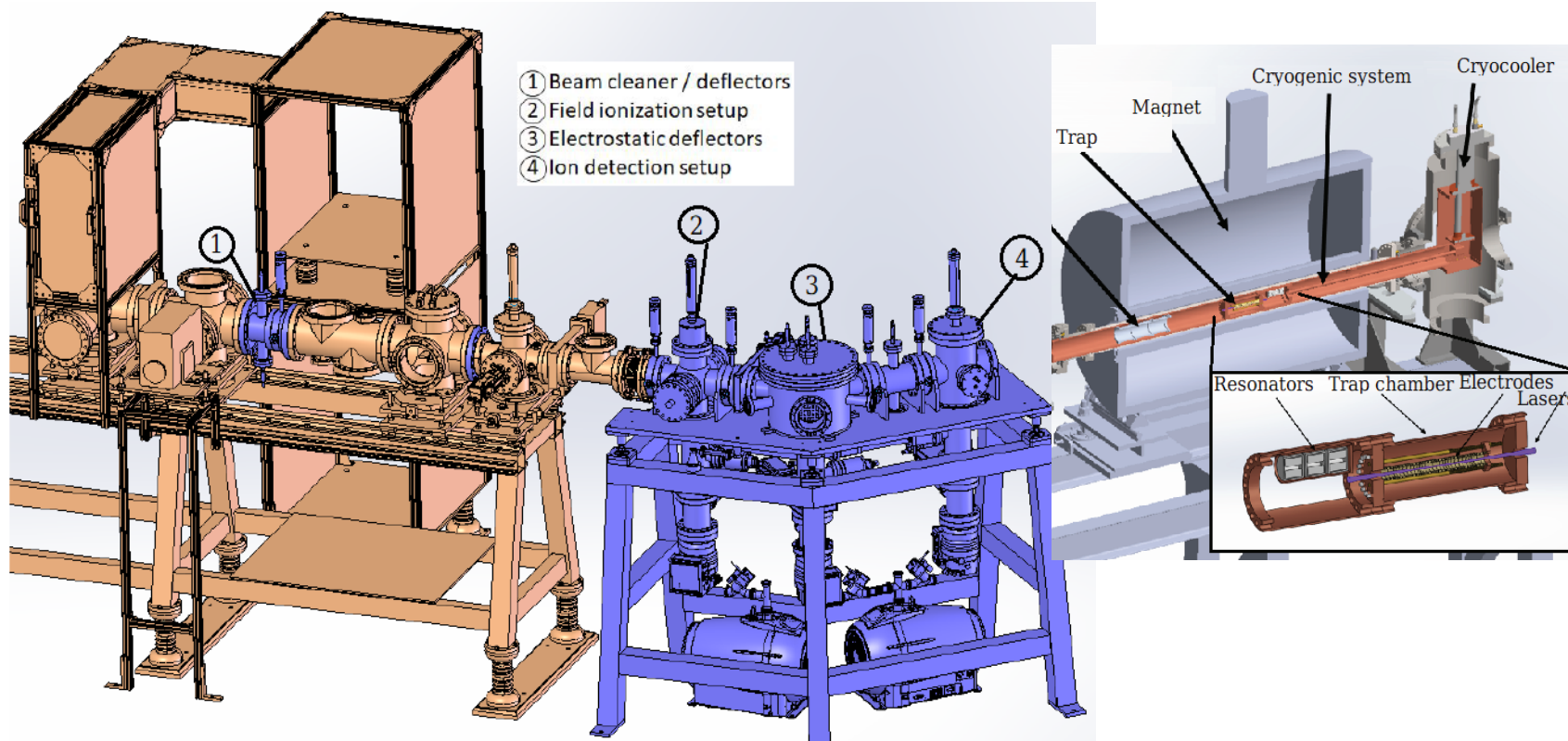
Dr. Adam Vernon



RISE@BECOLA ready to ship to FRIB next week!

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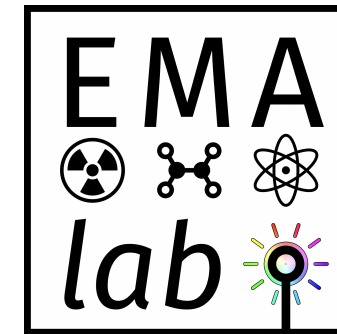


Optimally suited to attach
a Penning trap setup!

Acknowledgement



<https://garciaruiizlab.com>



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Main collaborators:

D. DeMille, J. Dilling, N. Hutzler, R. Ringle

Technical/administrative support:

A. Convertino, E. Ihloff, D. Petterson, C. Vidal

