Symmetry-violating properties from single molecular ions in a Penning trap

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New Opportunities for Fundamental Physics Research with Radioactive Molecules Workshop — July 2, 2021

EMA lab

Massachusetts Institute of Technology

Acknowledgements

Caltech
TRIUMF
FRIB
THE UNIVERSITY OF CHICAGO

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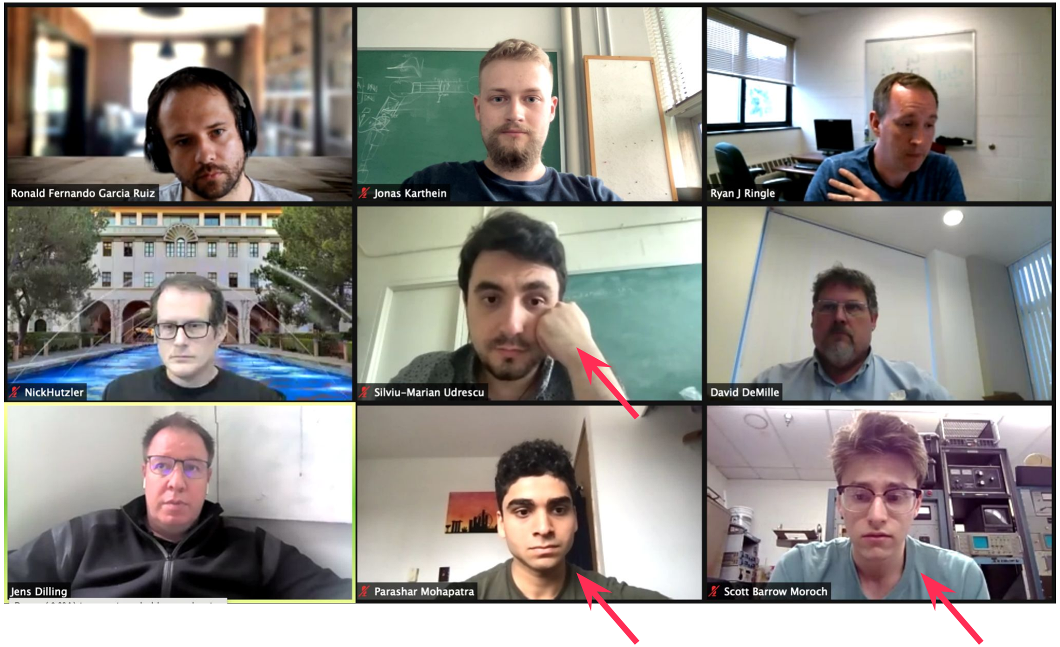
Massachusetts Institute of Technology



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https://garciaruizlab.com

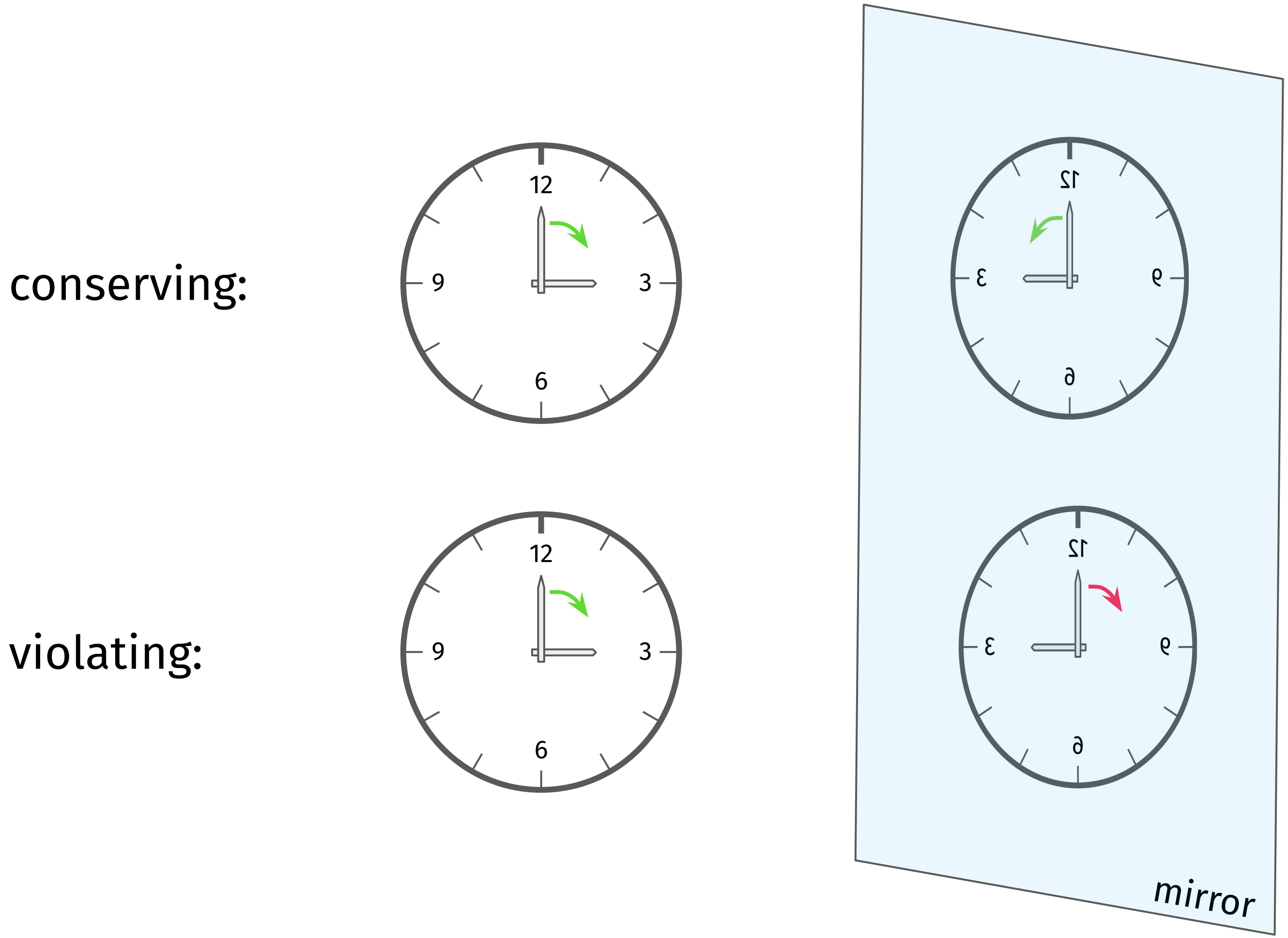
My goal for today

Merging well-established atomic physics techniques,

namely (Penning) ion traps & lasers,

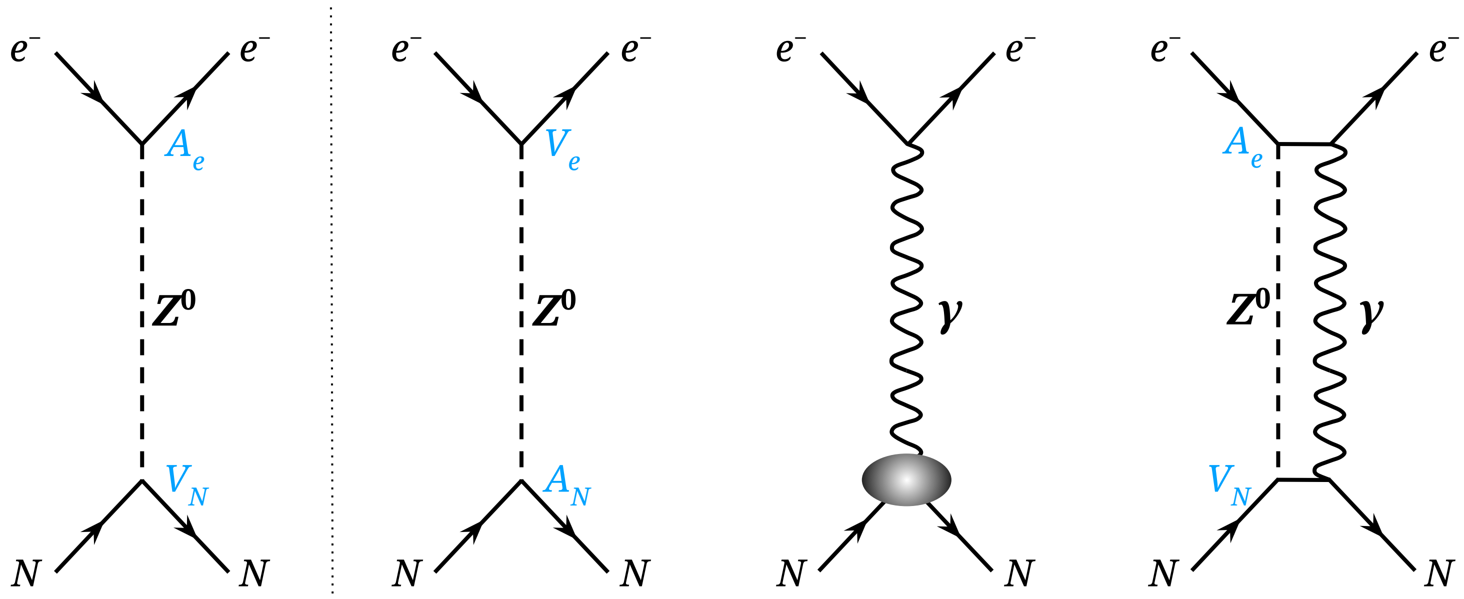
optimally suited to tackle open nuclear physics challenges!

Parity



Parity violation (PV)

→ Flambaum, Safranova, Haxton, DeMille, Ramsey-Musolf, Navratil, Porsev, Borschevsky, Skripnikov, …



↓ suppressed in diatomic molecules

↓ Anapole moment → suppressed by α but scales by ~Z^3

Wood, C. S. *et al. Science* 275, 1759 (1997).
Porsev, S.G. *et al. PRL* 102, 181601 (2009).
Safronova, M.S. *et al. Rev. Mod. Phys.* 90, 025008

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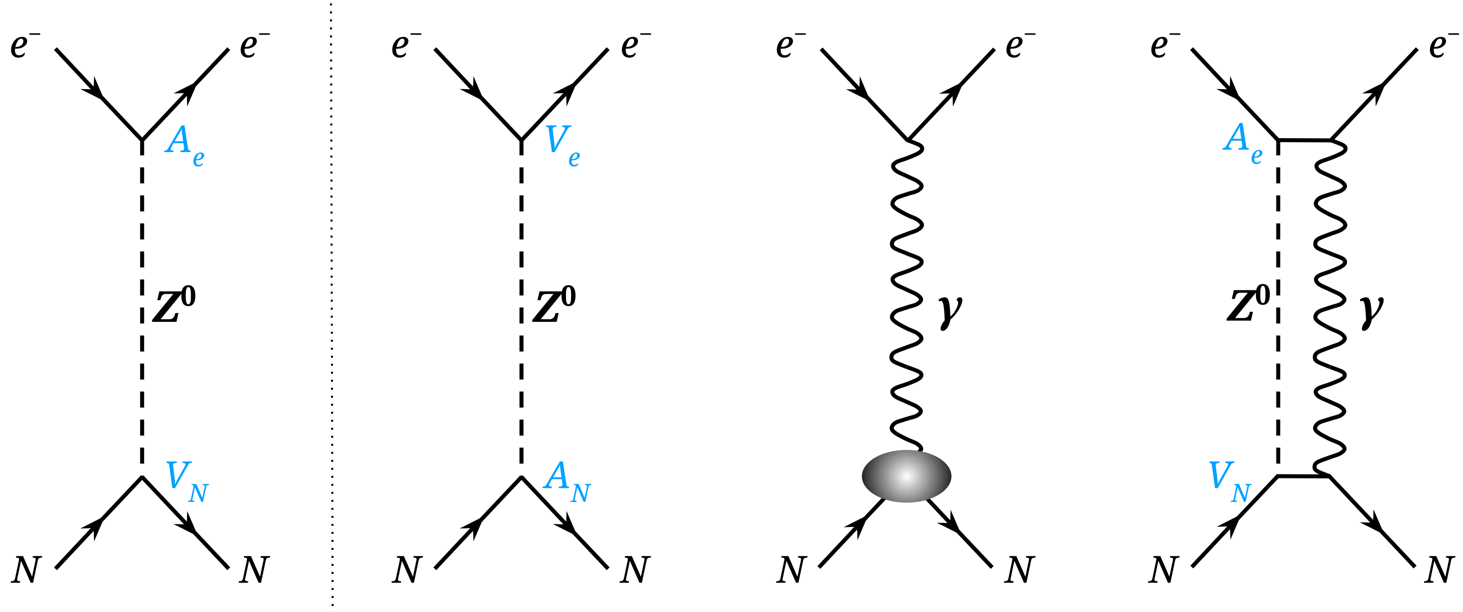

→ give access to electroweak coupling (vs. electron scattering), new bosons (*Z'* → TeV scale; dark), neutron skin distribution, ..?

$$H_{PV} \propto G_F \, (\sim 10^{-14}\ \mathrm{J}^{-2})$$

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Mixing of states with opposite parity

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

P(atom) $\propto$ $(-1)^L$ → $(E_- - E_+)$ ~1 eV

P(molecule) $\propto$ $(-1)^N$ → $(E_- - E_+)$ ~10 μeV

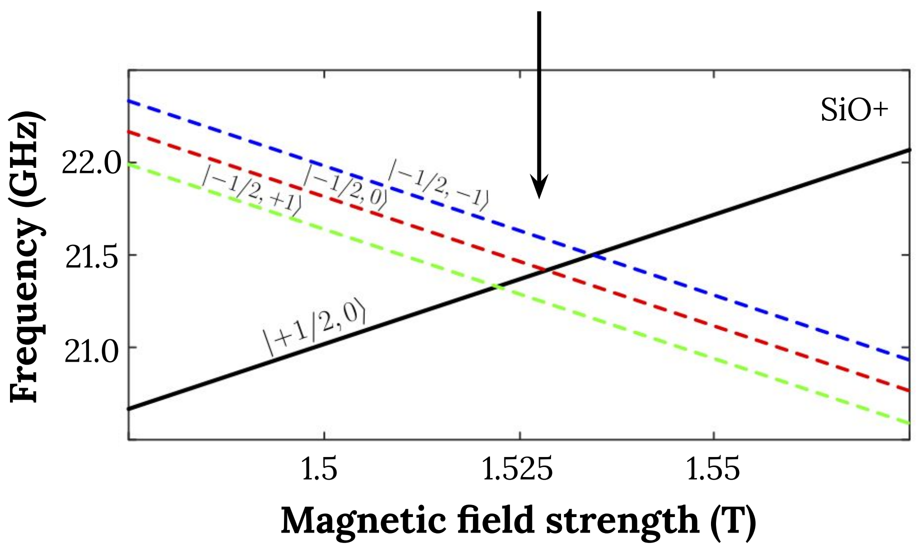
→ ~10^5 natural amplification in molecules

Mixing of states with opposite parity

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

$+ \quad \vec{B} \neq 0 \rightarrow$ Zeeman shift

degeneracy!



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- $\vec{B} \neq 0$ → Zeeman shift
- RF → Stark mixing

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

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Let's prepare: $c_+(0) = 0$ and $c_-(0) = 1$

Let's measure: $c_+(t_{\text{measurement}})$ = ...(math)... $\propto$ iW, Δ, $d\mathcal{E}_0$, ω, $t_{\text{measurement}}$

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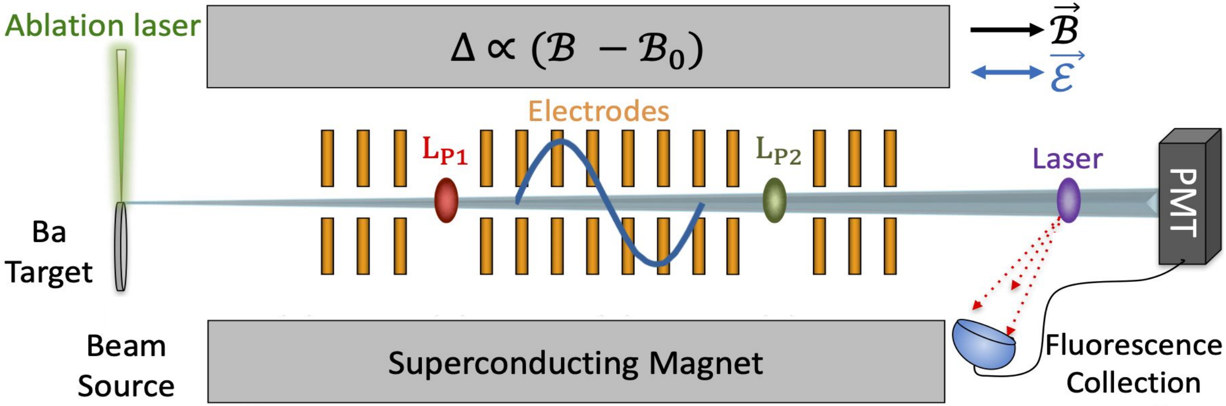
→ "simple" state counting experiment!

→ 10^{11} amplification compared to atoms!

DeMille: proof of principle



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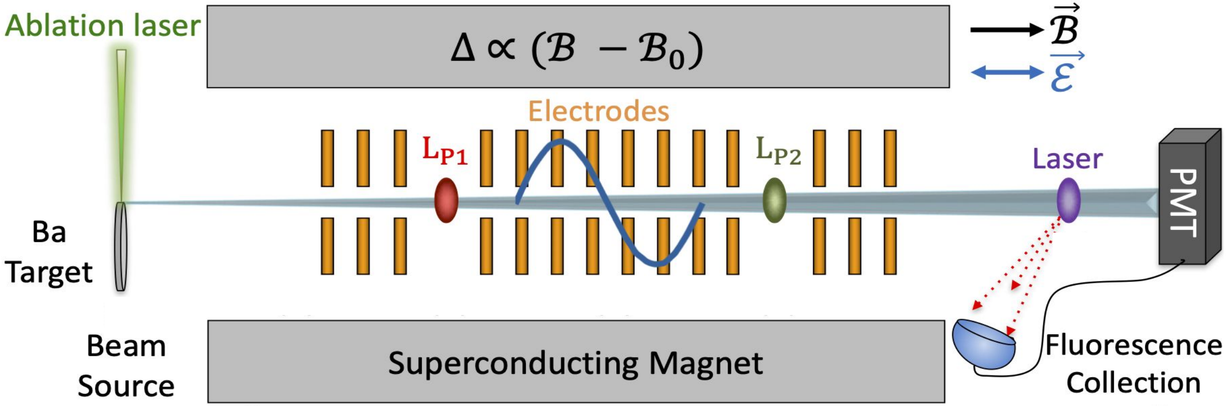
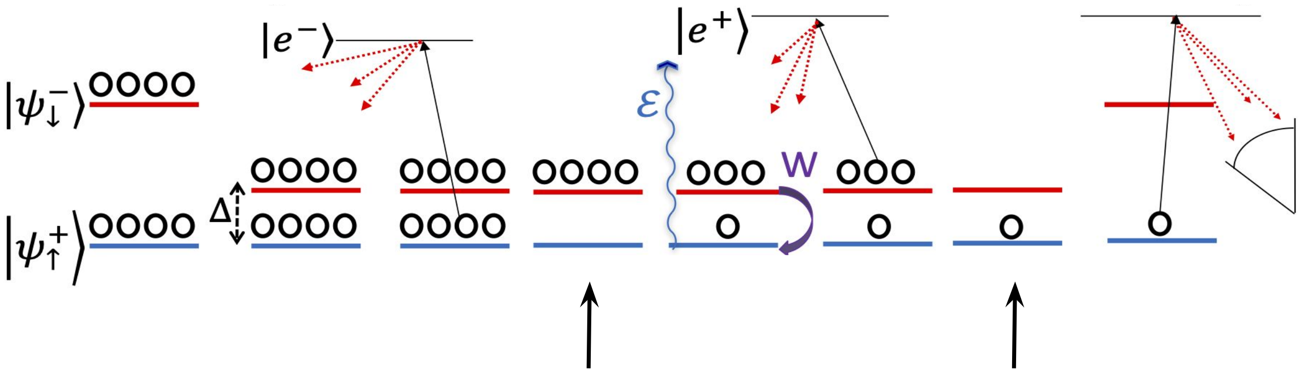




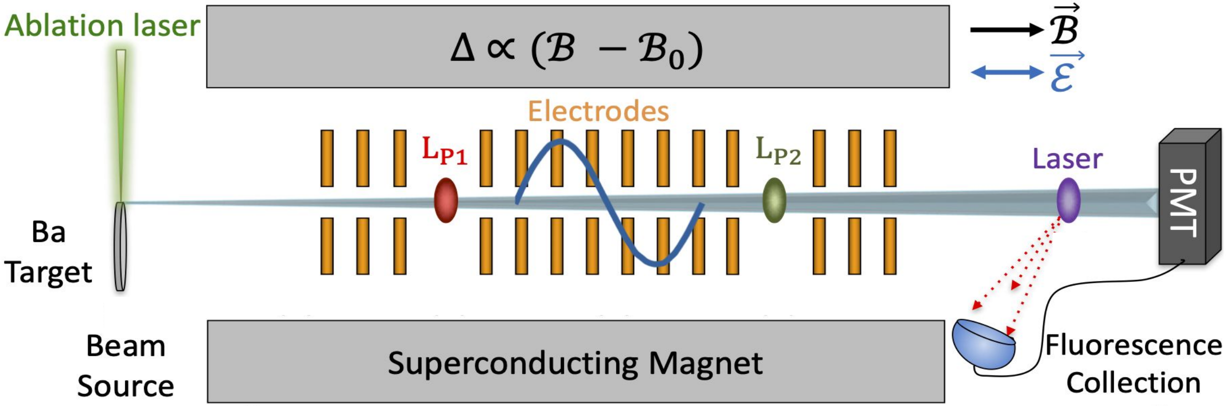
$c_+(0) = 0$ and $c_-(0) = 1$

$c_+(t_{measurement})$

$\propto iW, \Delta, d\mathcal{E}_0, \omega,$

$t_{measurement}$

DeMille: proof of principle



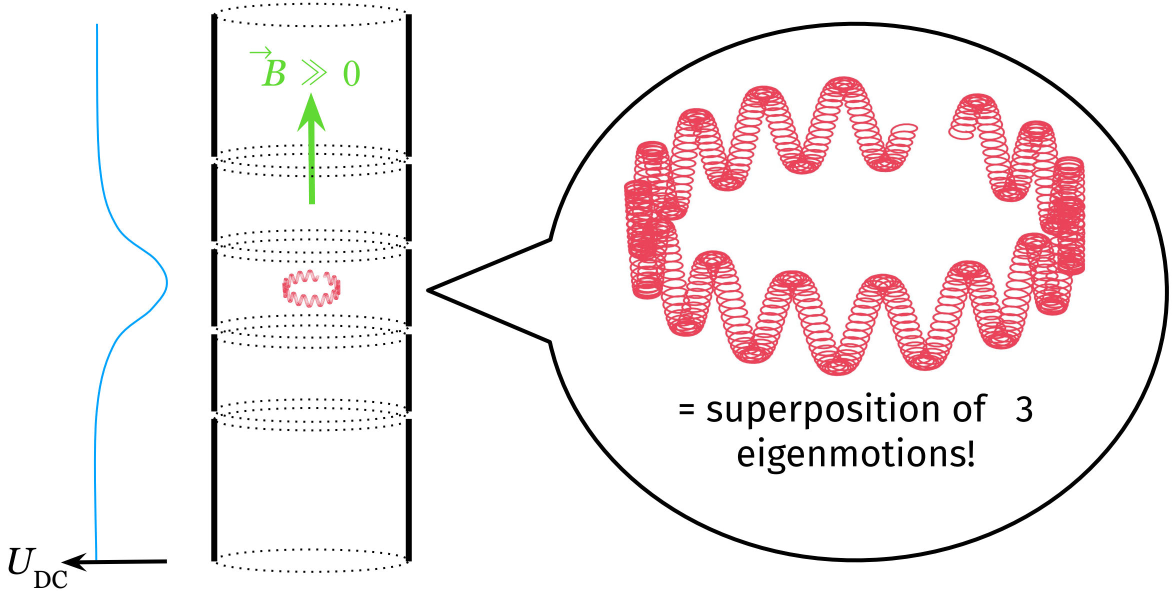
→ 10^{11} amplification compared to atoms!

- Fast beam of neutral molecules → very short laser interaction times (<µs)
- Requires lots of particles → insufficient for radioactive beams
- Final state detection: fluorescence → relatively inefficient

→ Penning trap

Altuntas, E., DeMille, D. *et al.* PRL 120, 142501 (2018).

Solution for next-generation experiment: Penning ion trap



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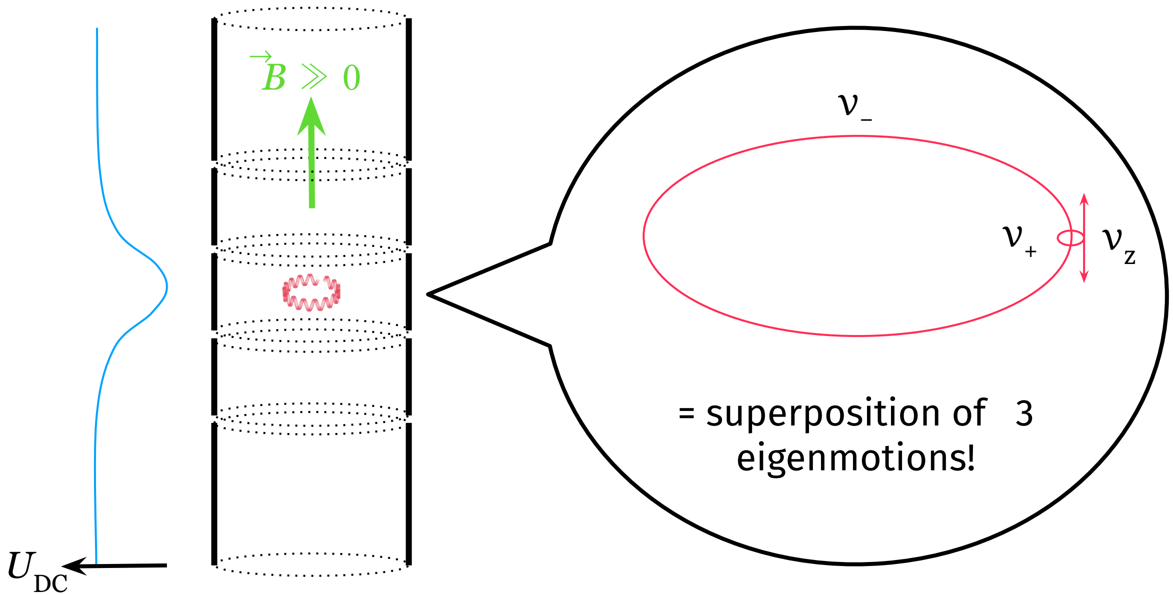

$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} = \frac{B}{2\pi}\frac{q}{m}$$

Brown, L.S. & Gabrielse, G. *Rev. Mod. Phys.* **58**, 223 (1986).

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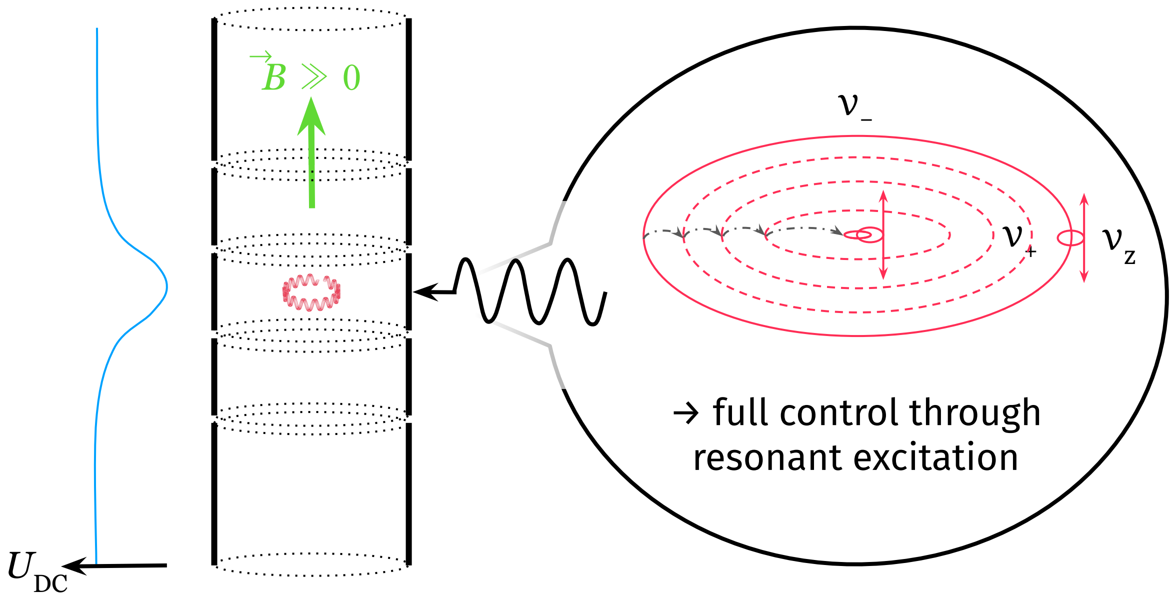
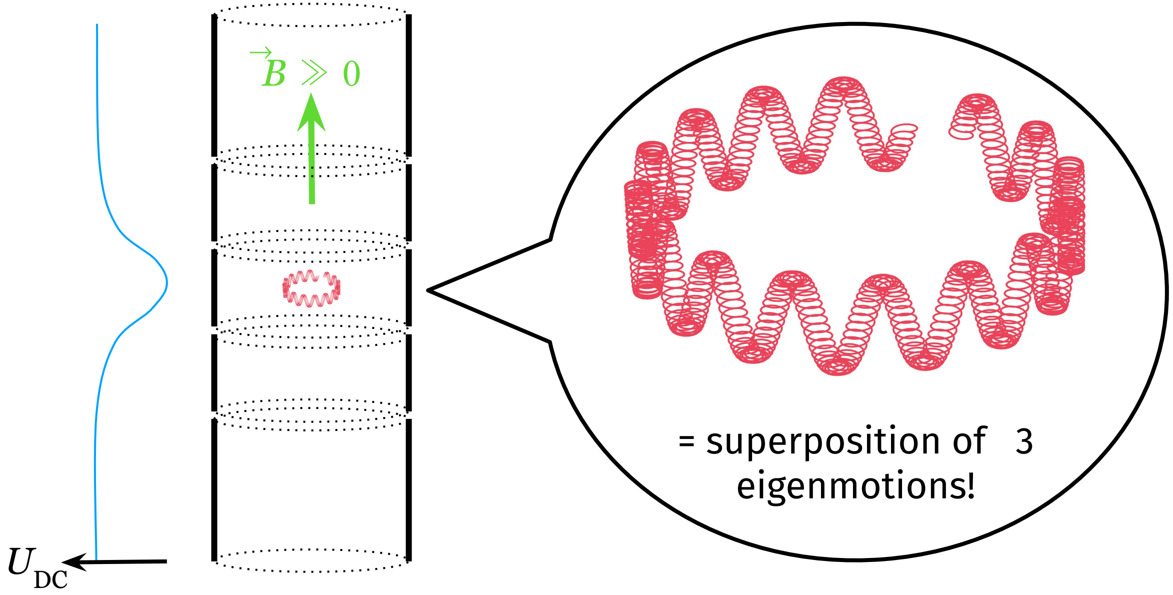


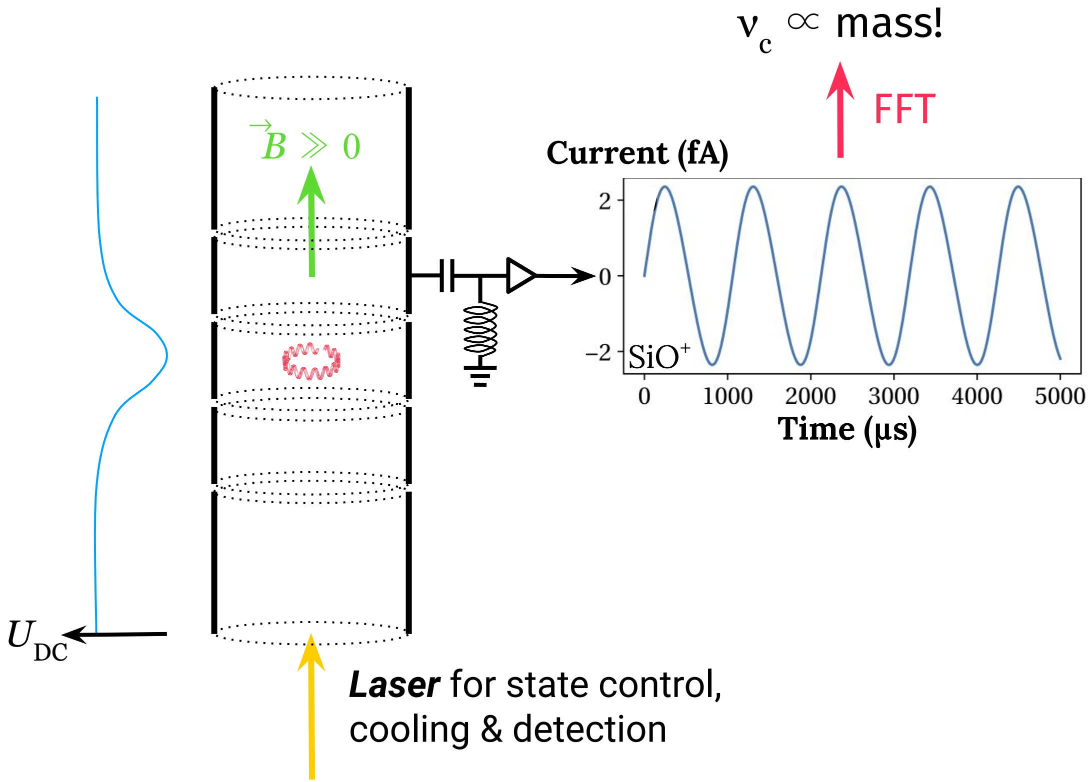
Solution for next-generation experiment: Penning ion trap

- Stable + homogeneous electric & magnetic fields
- Full control over eigenmotions through resonant RF-excitation
- Long ($\gg$ 1 s) trapping times for single ions
- Large mass range: [e⁻ … >1000 u]



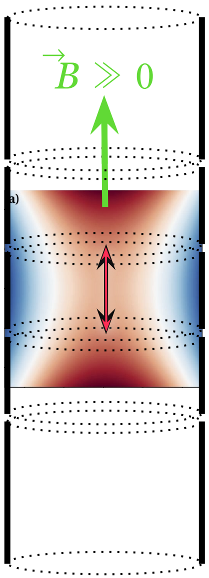
Solution for next-generation experiment: Penning ion trap

- Stable + homogeneous electric & magnetic fields
- Full control over eigenmotions through resonant RF-excitation
- Long (≫ 1 s) trapping times for single ions
- Large mass range: [e⁻ ... >1000 u]
- Easy laser access
- Live-monitoring of motion



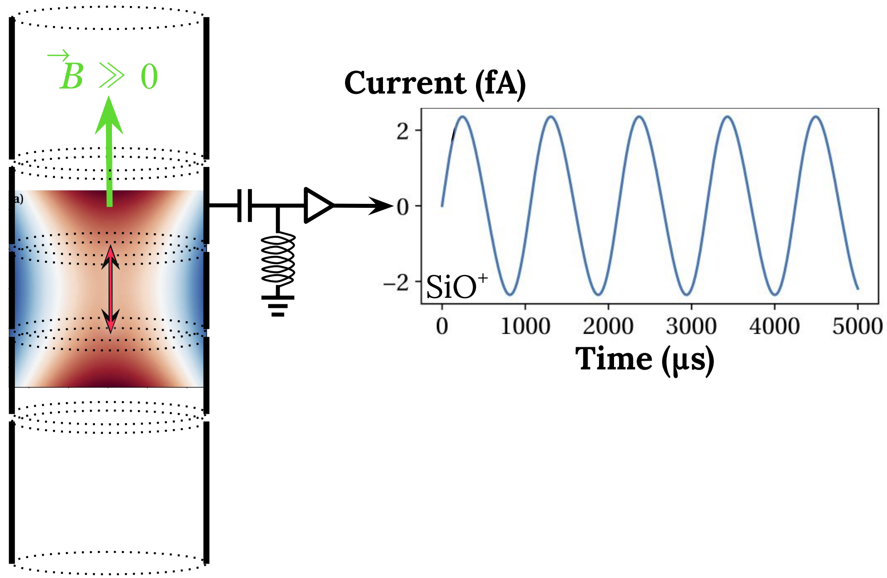
Optimization of harmonic DC potential

- Optimized electric field ($C_{4,6,8,10}$ < 10^{-10})
- ν_z shifts: <10^{-5} Hz (ν_z~ 10^5 Hz)



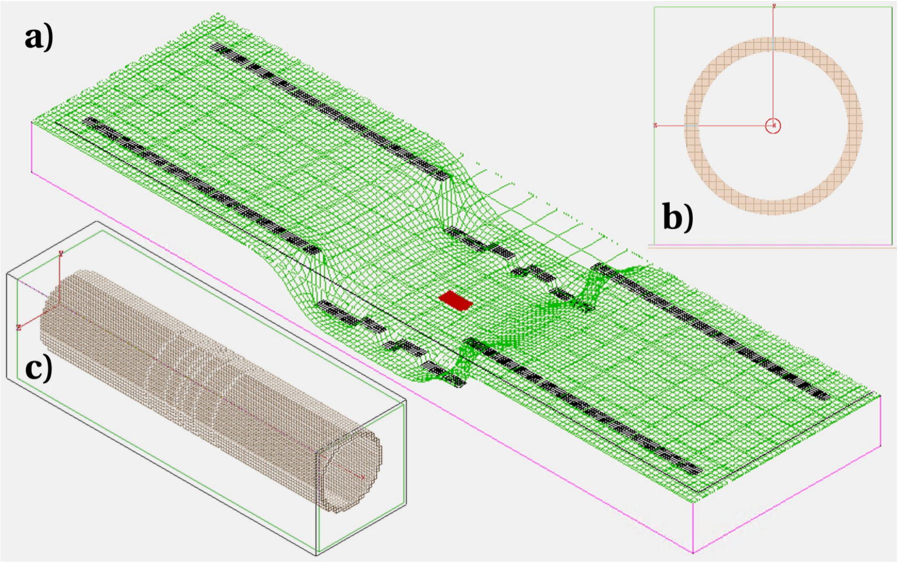
Optimization of harmonic DC potential

- Optimized electric field ($C_{4,6,8,10} < 10^{-10}$)
- ν_z shifts: $<10^{-5}$ Hz ($\nu_z \sim 10^5$ Hz)
- Retrieve information about the RF-field in the rest frame of the ion (DC=AC!)
- Cooling the resonance circuit (goal: 4K)



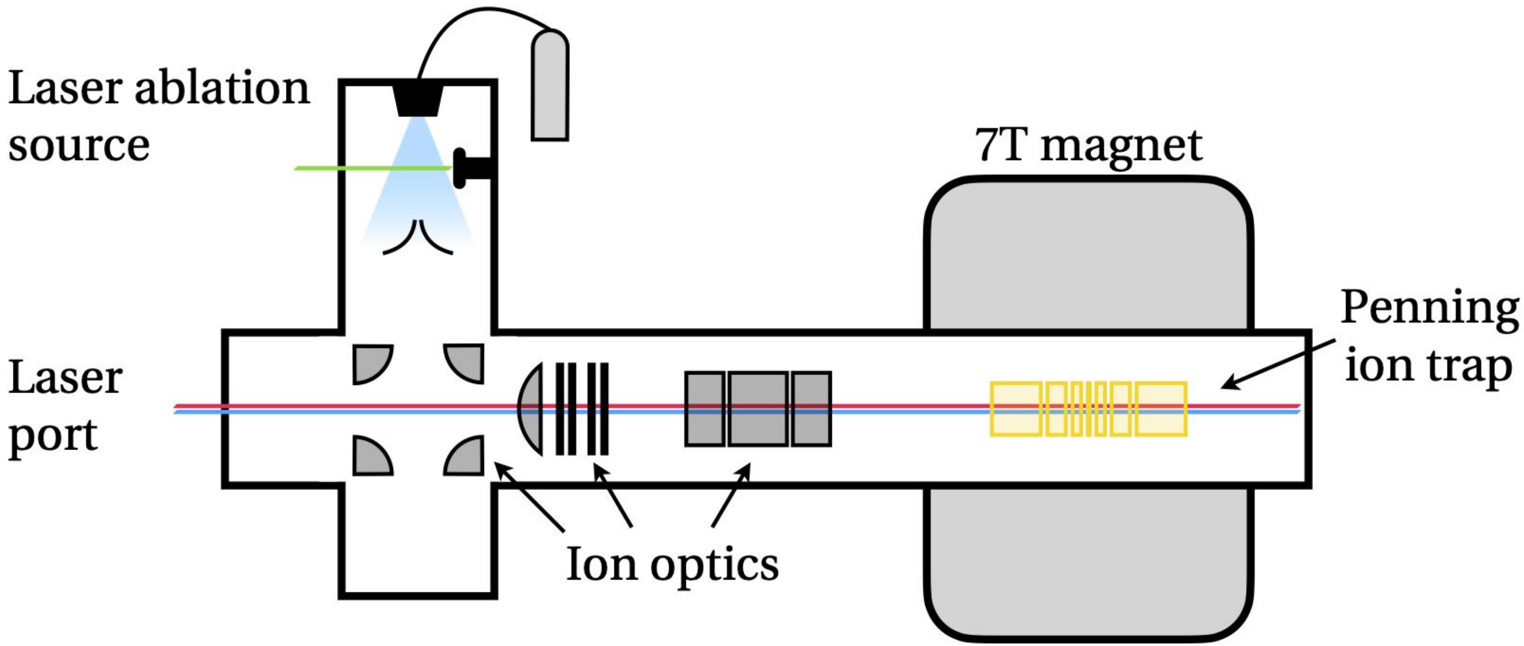
Ion dynamics simulations

- Ion dynamic simulations with SimIon:
  - Transport
  - Trap injection
  - Resonant RF-excitation (= cooling)
  - Image-charge (Shockley-Ramo theorem)



→ Penning trap overcome all downsides through highly stable *E*,*B*-fields, long coherence times and single-ion sensitivity!

New setup: PV studies in a Penning trap



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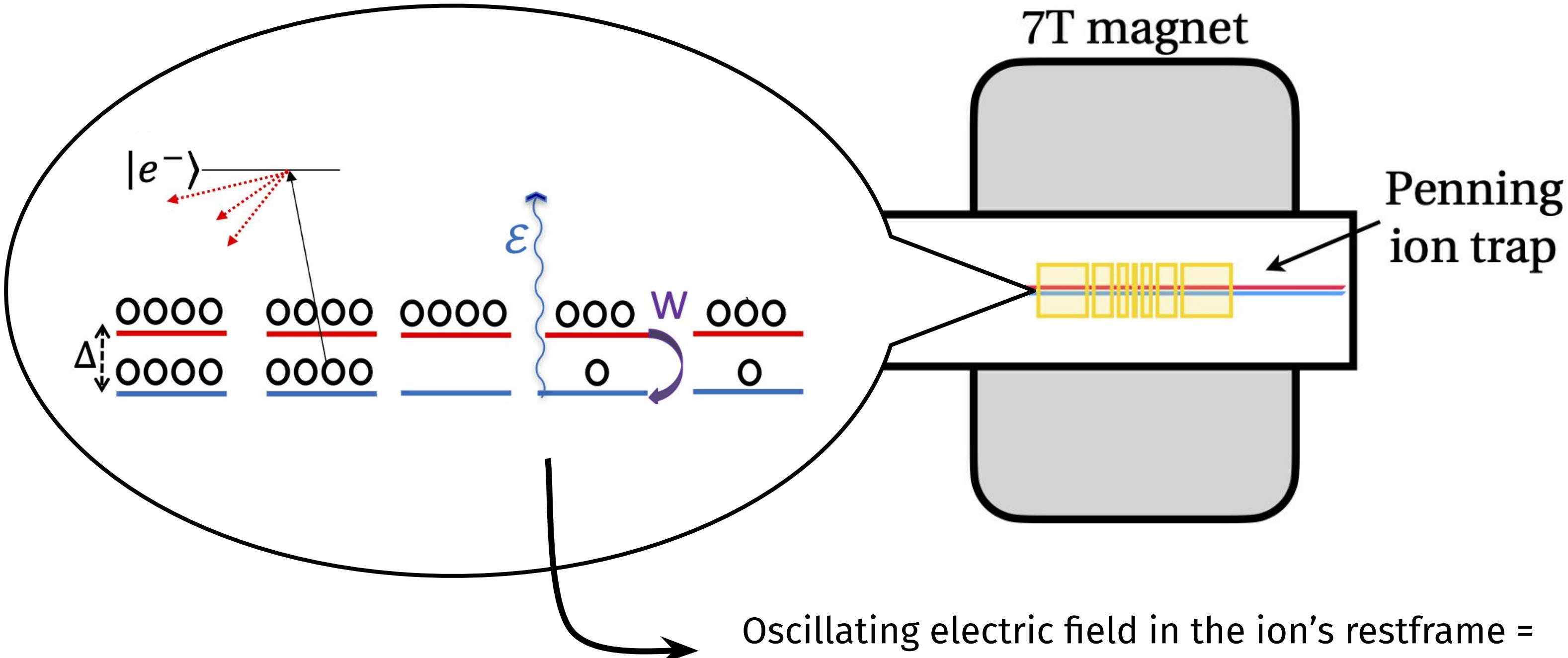

Oscillating electric field in the ion's restframe = stable DC trapping potential!

Figure modified from: [Altuntas, E., DeMille, D. *et al.* PRL 120, 142501 (2018).]

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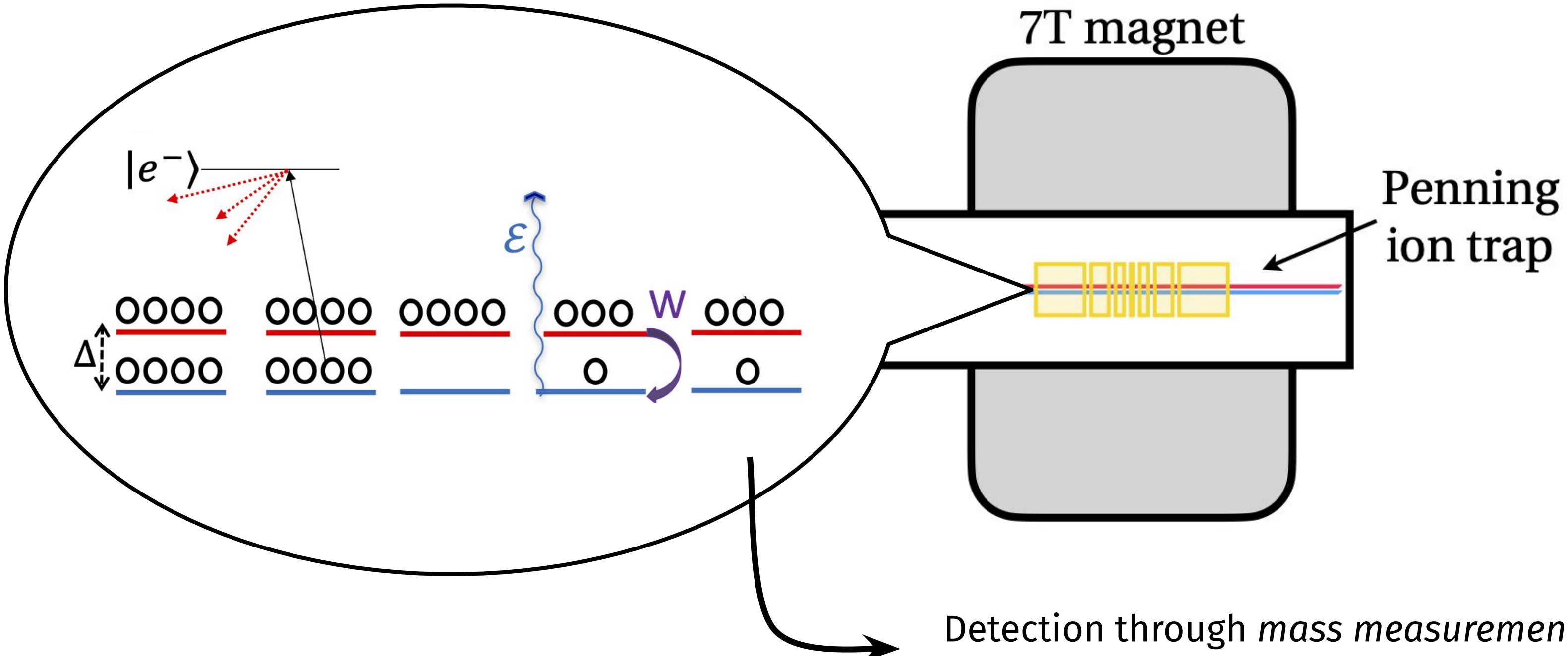

Detection through *mass measurement* after laser-induced molecular break-up

Next steps

- Simulations for TRIUMF magnet + room-temperature Penning trap
- Simulations + design of a new cryogenic Penning trap
- Magnet + Penning trap transport from TRIUMF to MIT (summer 2021)
- Systematic studies of existing magnet and Penning trap (2022)
- Production and systematic studies of cryogenic Penning trap (2022/2023)
- Parity-violating measurements of diatomic molecules (SiO^+, InF^+, ...)

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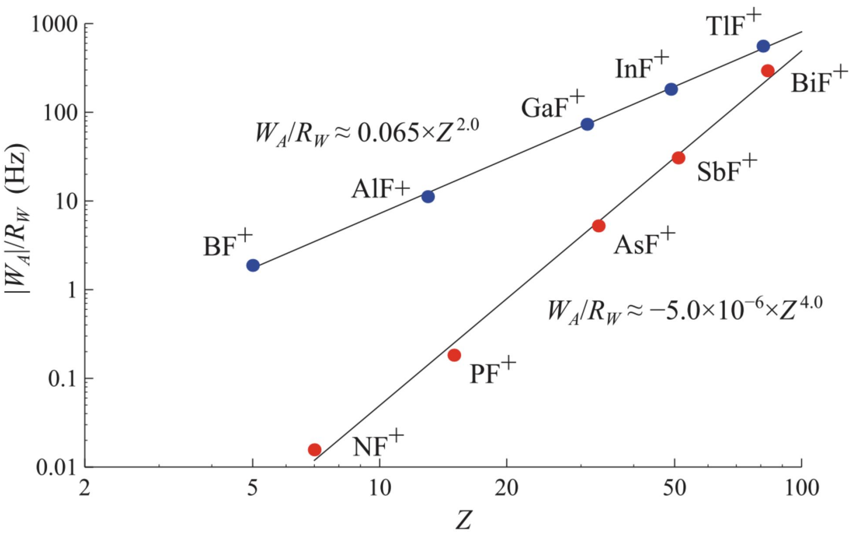

Borschevsky, A. *et al.* PRA 86, 050501(R) (2012).

Stollenwerk, P.R. et al. PRL 125, 113201 (2020).