Millicharged Particle Direct Detection Using Ion Traps

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Based on work in prep with

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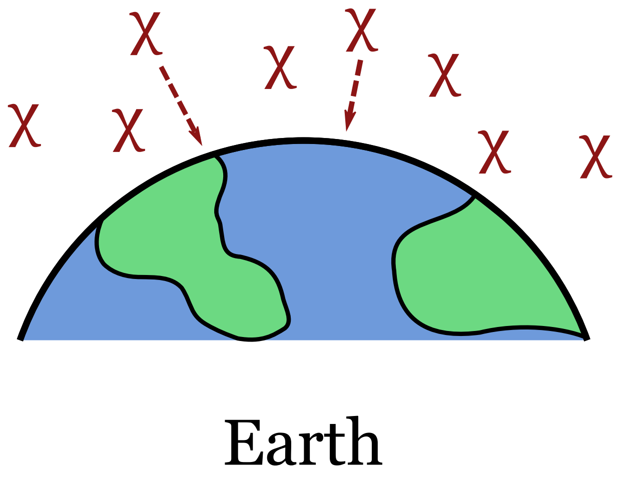
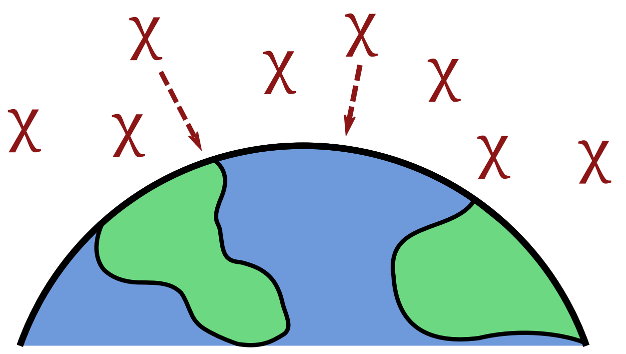
Millicharged Particles (mCP's)

- Anything with electric charge much less than 1
- Could be directly charged or through kinetic mixing
- Can be a dark matter subcomponent
- Produced in some amount by cosmic rays
- Density on Earth can build up through variety of mechanisms

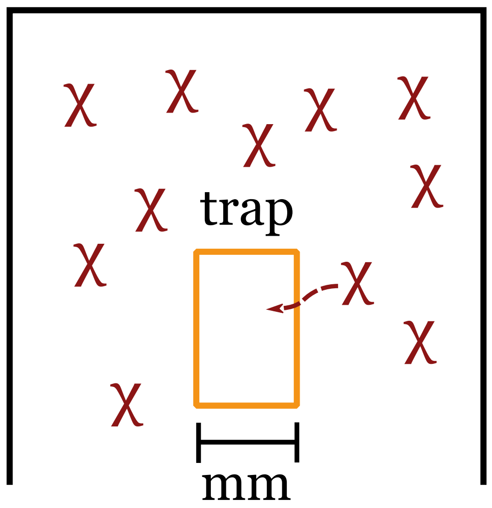
Direct Detection Setup



Direct Detection Setup

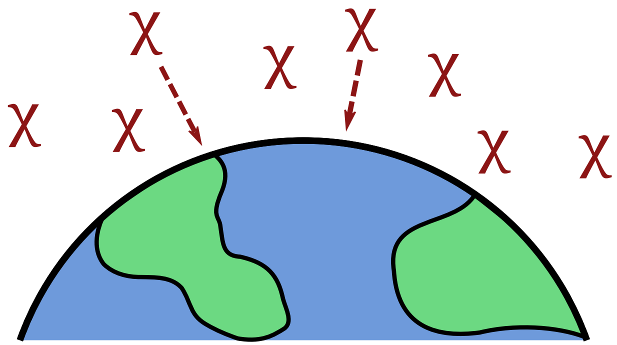


Earth

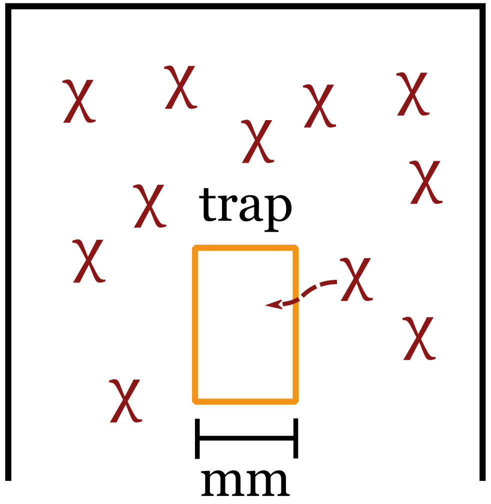


Lab

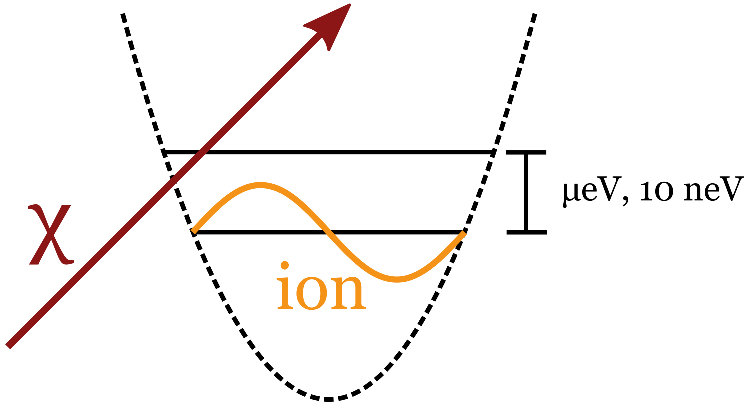
Direct Detection Setup



Earth



Lab



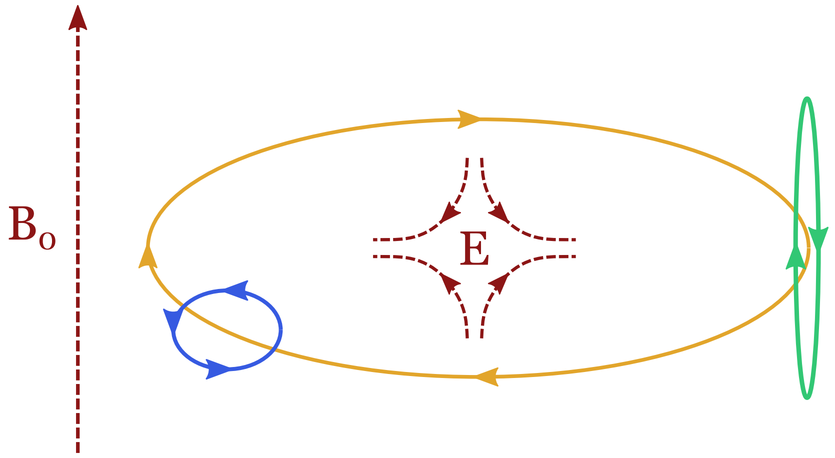
Penning Trap

Direct detection with very low energy thresholds

Ion Traps (Penning Traps)

- 3 different Harmonic States: cyclotron, axial and magnetron

$$\vec{B} = B_0 \hat{z} \qquad V(\vec{r}) = \frac{1}{2} m_{\text{ion}} \omega_z^2 \left(z^2 - \rho^2/2\right)$$



- Extra "magnetic bottle" field introduces anharmonicities
- Can read out individual changes in cyclotron numbers, using axial frequency

$$\Delta\omega_z \approx \frac{q_{\text{ion}} B_2}{m_{\text{ion}}^2 \omega_z} \left[\left(n_c + \frac{1}{2}\right) + \frac{\omega_m}{\omega_c} \left(n_m + \frac{1}{2}\right) \right]$$

Computation of Interaction Rate

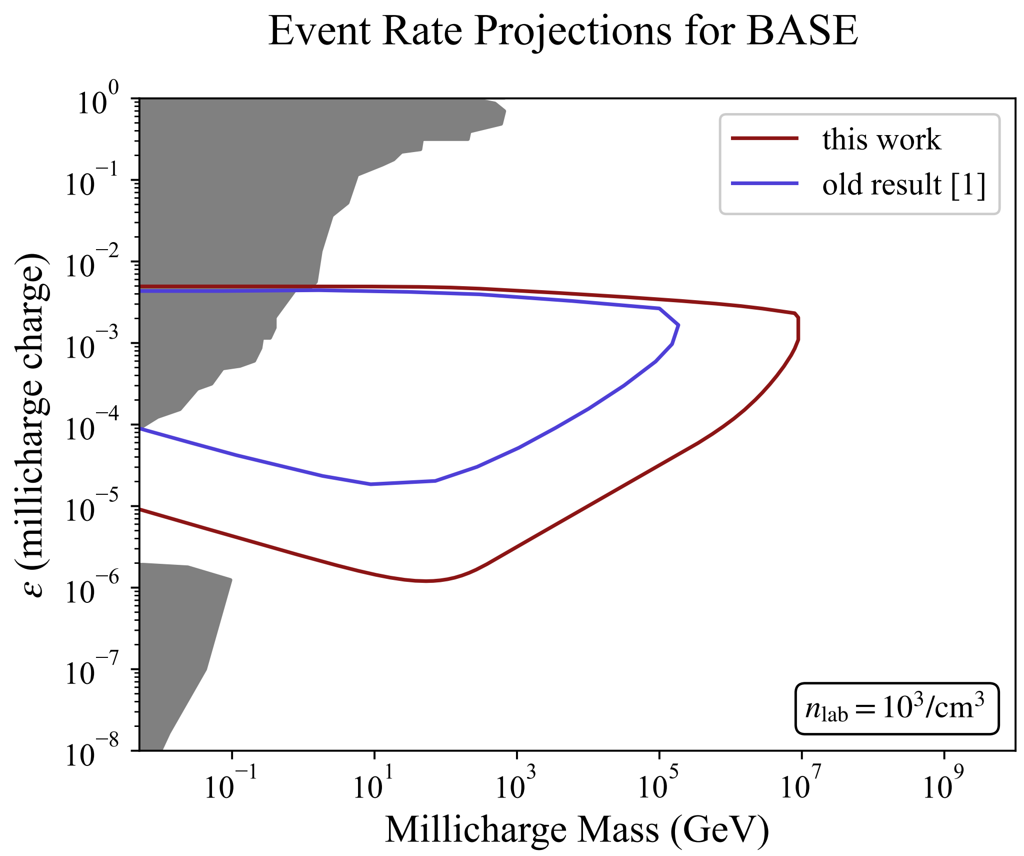
- First proposed in 2108.05283 [1] (used classical computation)
- Quantum calculation of mCP scattering off trapped ion:

$$\Gamma_{if} = \int dv_Q f(v_Q) \frac{2(\epsilon\alpha)^2 n_Q}{v_Q} \int d^3\vec{q}\, \frac{|S_{fi}(\vec{q})|^2}{|\vec{q}|^5} \Theta(p_i + p_f - q)\Theta(q - |p_i - p_f|)$$

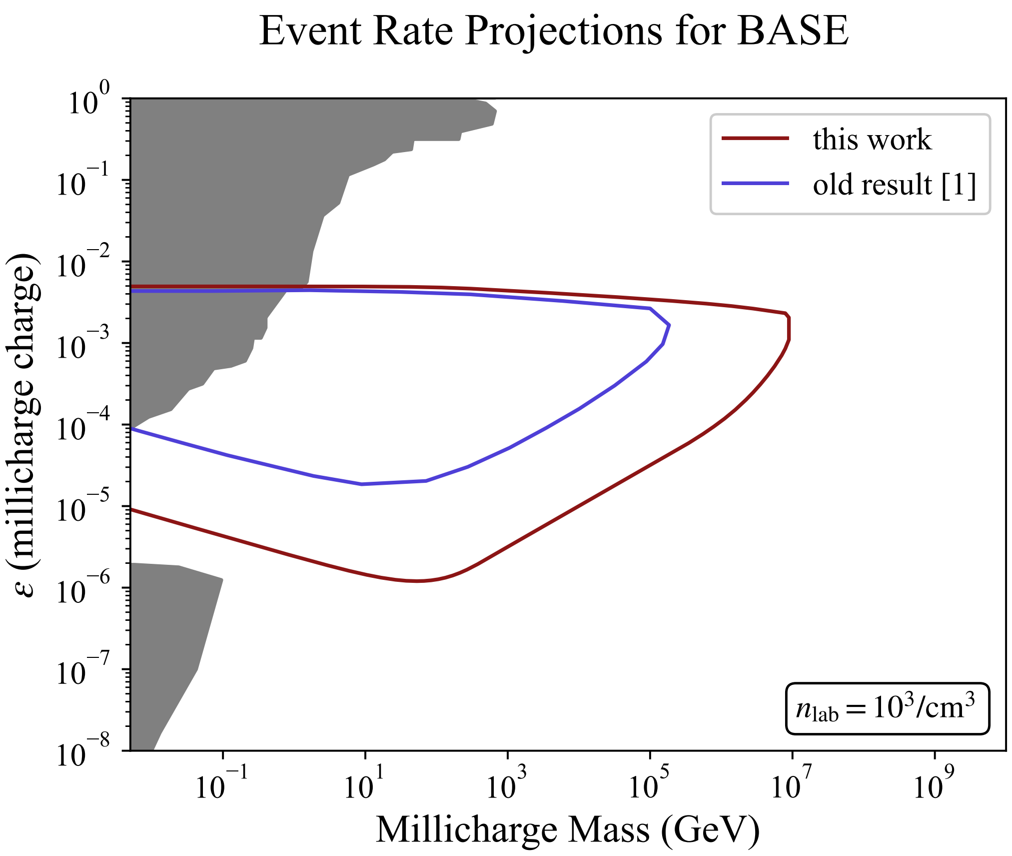
- Penning trap form factor is 3 harmonic oscillator form factors:

$$\begin{aligned} S_{fi}(\vec{q}) = &\langle n_c' | D_c(i\rho_0(q_x - iq_y)/2) | n_c \rangle \\ &\times \langle n_m' | D_m(i\rho_0(q_x + iq_y)/2) | n_m \rangle \\ &\times \langle n_z' | D_z(iz_0 q_z/\sqrt{2}) | n_z \rangle \end{aligned}$$

Improved Trap Sensitivity



Improved Trap Sensitivity



This gives a nice improvement in sensitivity; can do even better

Background Reduction with Fast Readout

- Turn up B_2 2410.05549 $$\Delta\omega_z \approx \frac{q_{\text{ion}} B_2}{m_{\text{ion}}^2 \omega_z}\left[\left(n_c + \frac{1}{2}\right) + \frac{\omega_m}{\omega_c}\left(n_m + \frac{1}{2}\right)\right]$$
- Individual changes to cyclotron number can be read
- Background photon jumps have a selection rule, making large jumps exponentially suppressed:

$$P(n \text{ excitations in } \Delta t) = \frac{\lambda^n e^{-\lambda}}{n!} \qquad \lambda = \Delta t\, \bar{n}_\gamma n_c \gamma_{c,0}$$

- Readout happens on micro-second timescales

Signal Enhancement with Lower Gap

- Decreasing the cyclotron frequency increases signal rate
  - For many millicharge parameters $\Gamma \propto (\Delta E)^{-2}$ ~ Coulomb divergence
  - Can decrease the energy threshold by ~3 orders of magnitude

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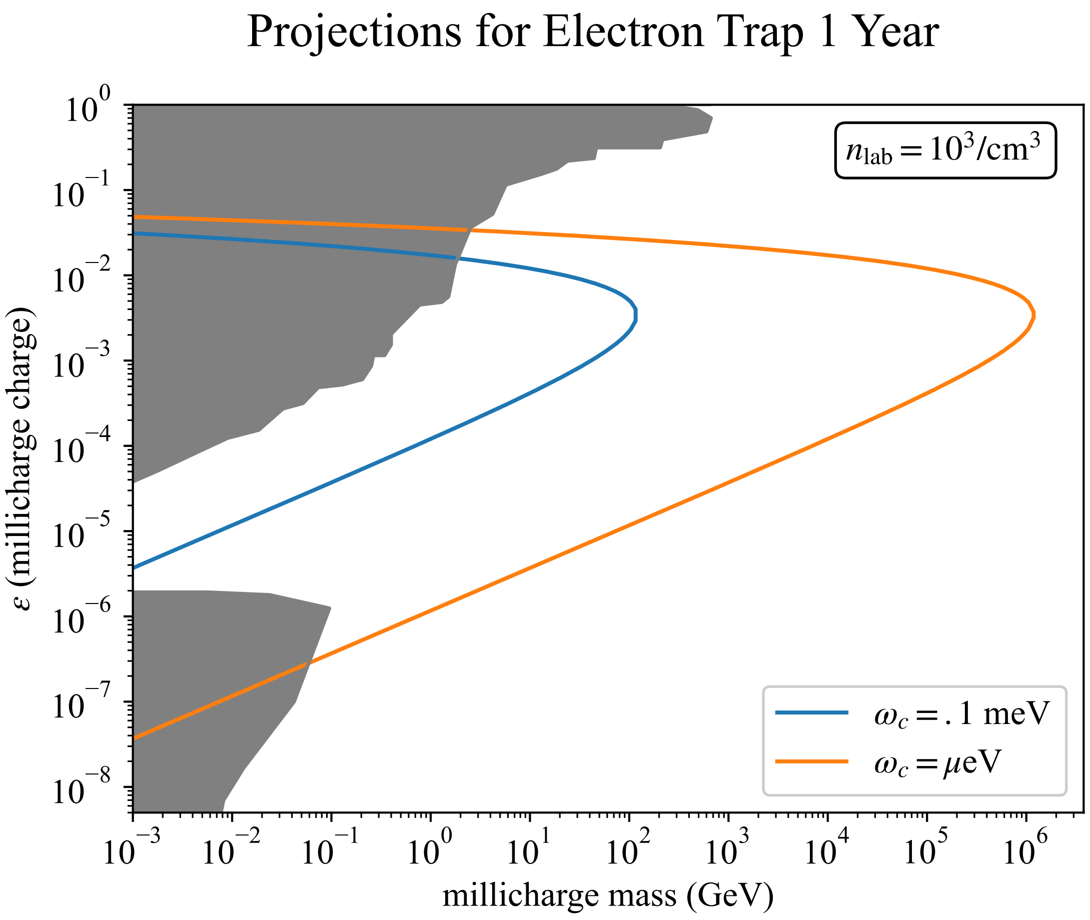
- Decreasing the cyclotron frequency increases signal rate
  - For many millicharge parameters $\Gamma \propto (\Delta E)^{-2}$ ~ Coulomb divergence
  - Can decrease the energy threshold by ~3 orders of magnitude
- Readout is nearly insensitive to the gap
  - Signal goes through angular momentum, not energy
  - $\Delta\omega_z \approx \frac{q_{\text{ion}} B_2}{m_{\text{ion}}^2 \omega_z} \left[\left(n_c + \frac{1}{2} \right) + \frac{\omega_m}{\omega_c} \left(n_m + \frac{1}{2} \right) \right]$
- Background from photon absorption stays about the same
  - $T_\gamma \gg \omega_c$

Projections for Improved Traps



Conclusions

- Ion Traps can be used as effective Millicharge Direct Detectors
- Can explore lots of new parameter space
- Sensitivity can be improved by changing parameters:
  - Decrease readout time to suppress background
  - Decrease energy threshold (by ~ 3 orders of magnitude)

Cosmic Ray Sensitivity