Charged particles for dark matter detection

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Stanford

Topics

1. Millicharged particle detection with trapped ions
2. Axion detection with storage rings

Millicharged Particle Detection with Trapped Ions

with

Dmitry Budker

Harikrishnan Ramani

Ferdinand Schmidt-Kaler

Christian Smorra

Stefan Ulmer

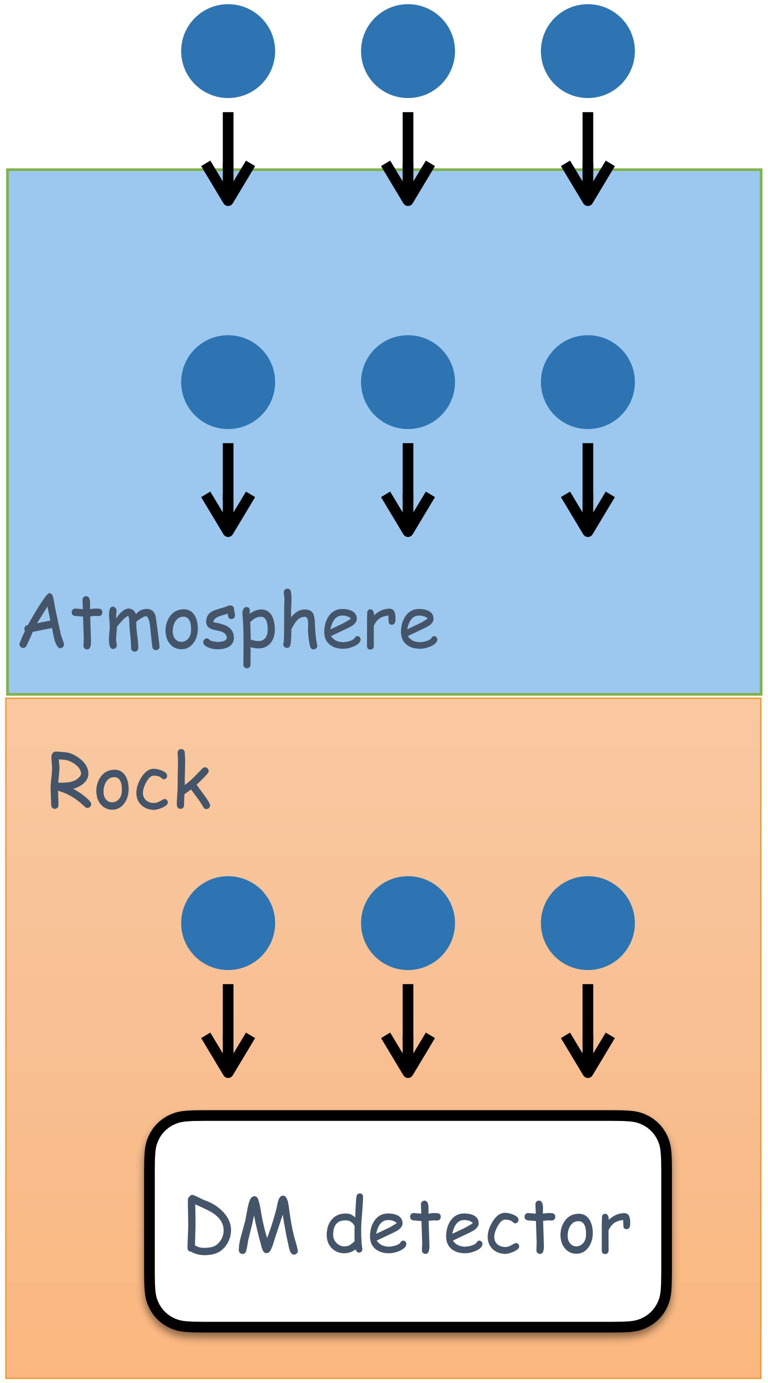
to appear

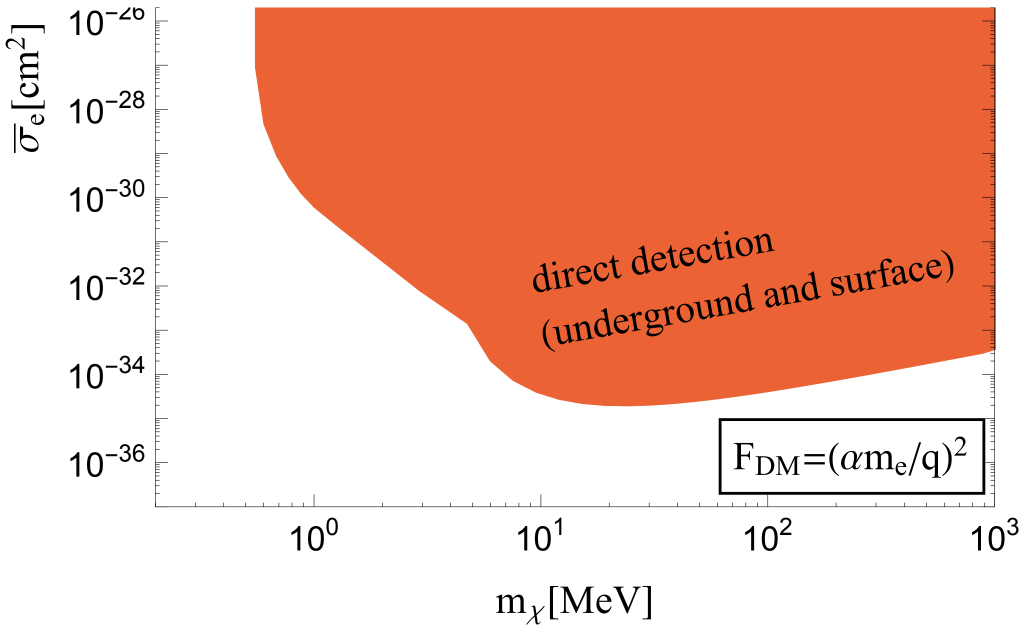
Detection of Millicharged Particles

significant interest recently in “millicharged” particles (charge = εe)

- mystery of charge quantization, dark matter candidate, EDGES anomaly…

weakly coupled particles penetrate Earth





1905.06348 Emken et al

Detection of Millicharged Particles

significant interest recently in "millicharged" particles (charge = εe)

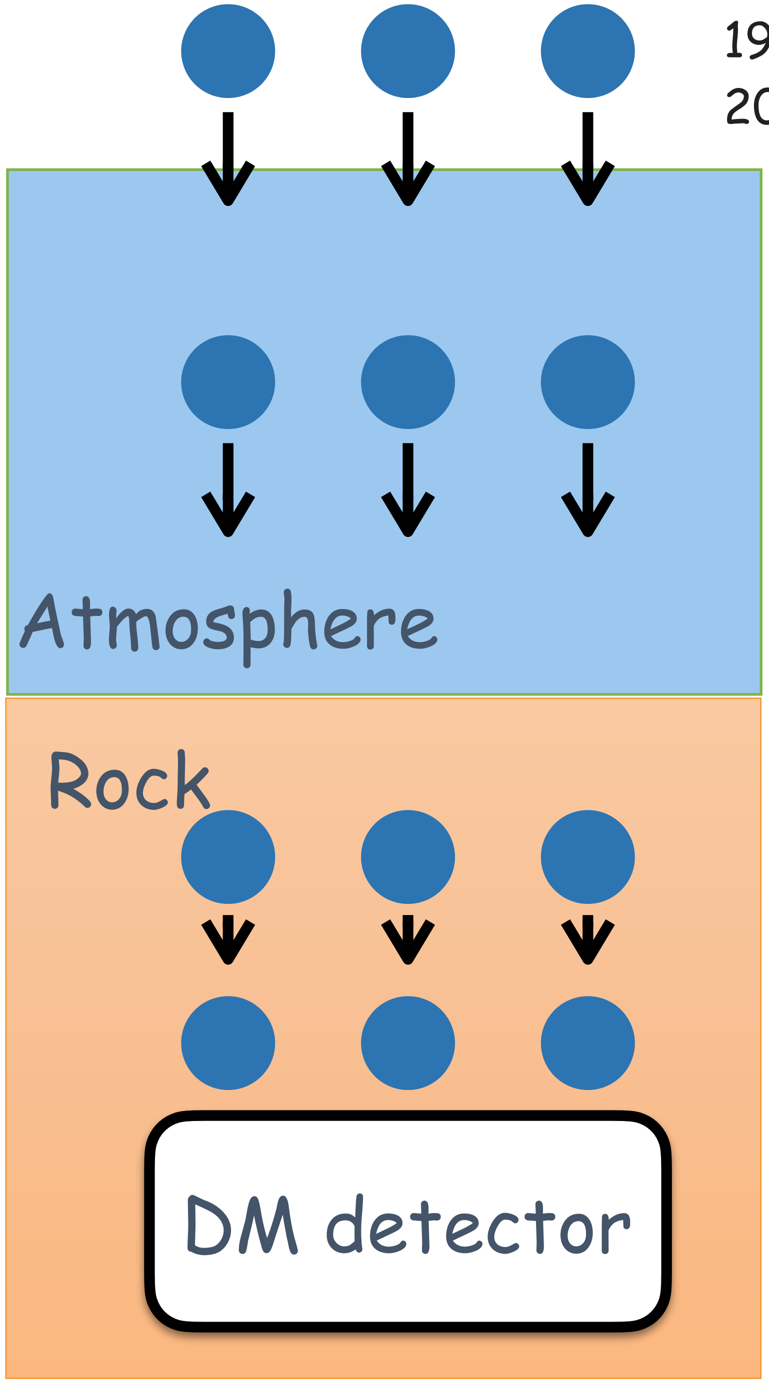
- mystery of charge quantization, dark matter candidate, EDGES anomaly…

millicharged particles can have large couplings

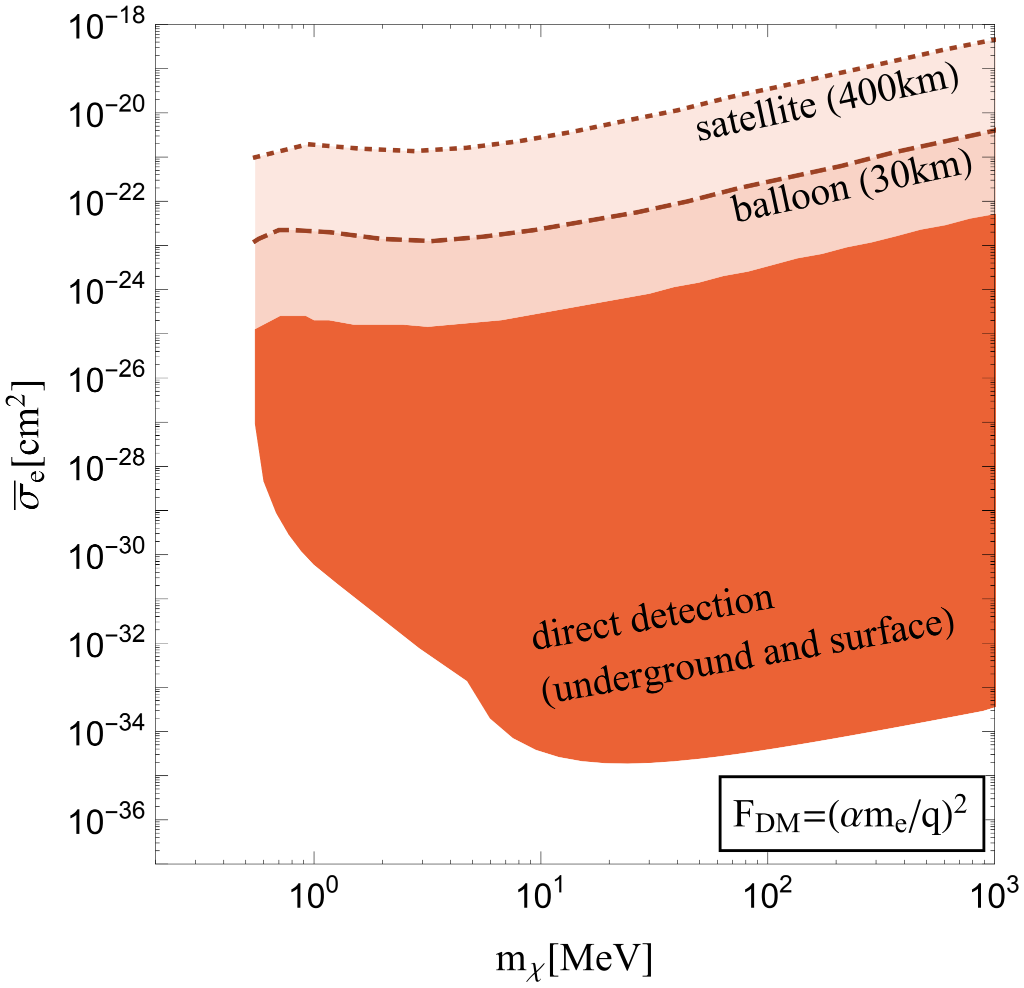
can get stuck + thermalize to 300 K ~ 25 meV

most direct detection expts have thresholds ~ keV maybe down to ~ eV

still diffuse downwards "traffic jam" ➜ very large number densities!



1907.00011 M. Pospelov, S. Rajendran, H. Ramani
2012.03957 M.Pospelov & H. Ramani



1905.06348 Emken et al

A New Kind of Dark Matter Detector

So have low energy millicharged particles, but with large density and large cross section!

How can we detect this?

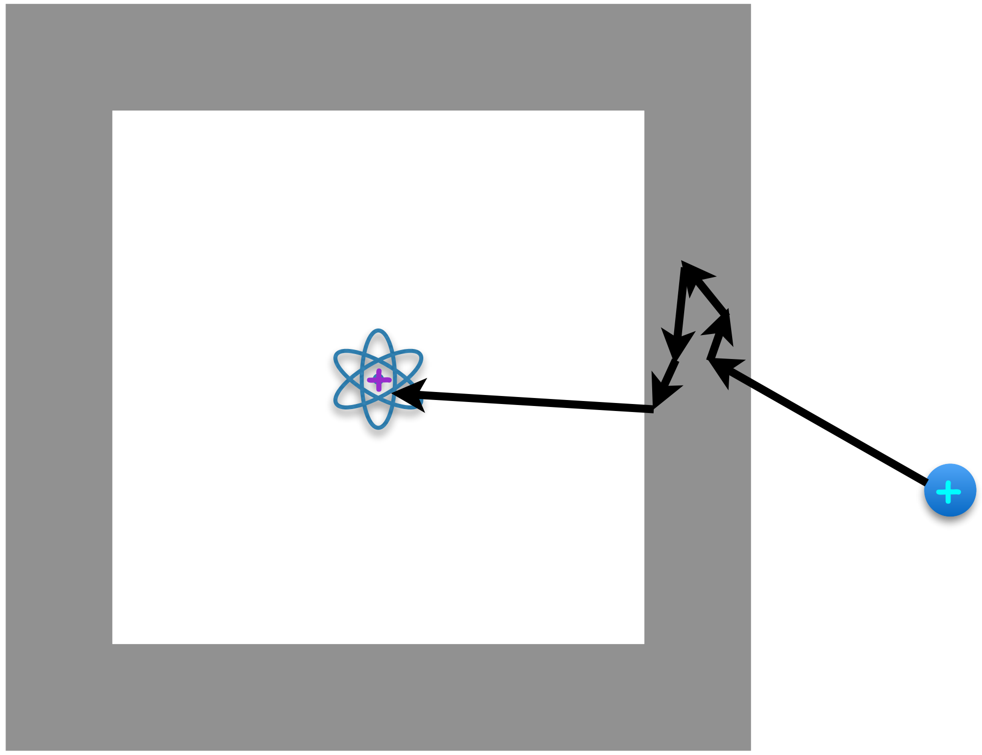
Need a sensitive low threshold detector

Low target mass acceptable

Maximize charged particle scattering

➜ Trapped ion

Ambient millicharged particles scatter off trapped ion, heating it



$$\dot{H} = \sqrt{\frac{2}{\pi}} \frac{n_{\rm mcp} m_{\rm mcp} m_{\rm ion} (T_{\rm mcp} - T_{\rm ion})}{(m_{\rm ion} + m_{\rm mcp})^2} \frac{\sigma_0}{u_{\rm th}^3}$$

$$u_{\rm th}^2 = \frac{T_{\rm ion}}{m_{\rm ion}} + \frac{T_{\rm mcp}}{m_{\rm mcp}}$$

only the ion needs to be cooled

if whole trap is cryogenic the millicharges cool in walls

➜ enhances number density inside trap

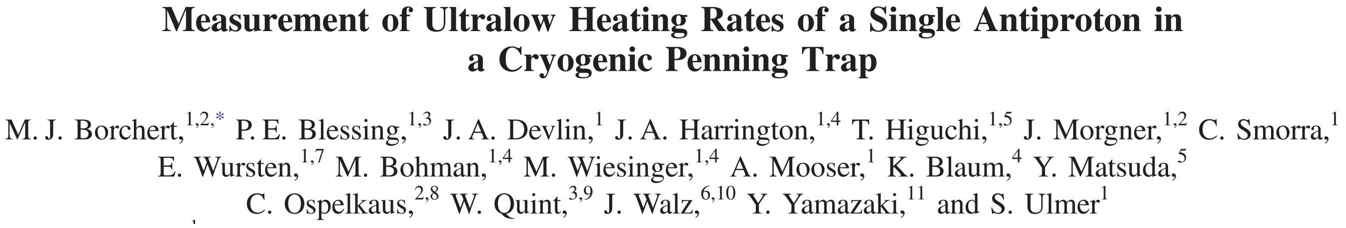
long-range Coulomb scattering ➜ larger cross section at lower velocities

Ion Traps as Detectors

Ion traps excellent at isolation, can detect very low energy depositions!

Much recent progress motivated by quantum computing

BASE experiment, CERN

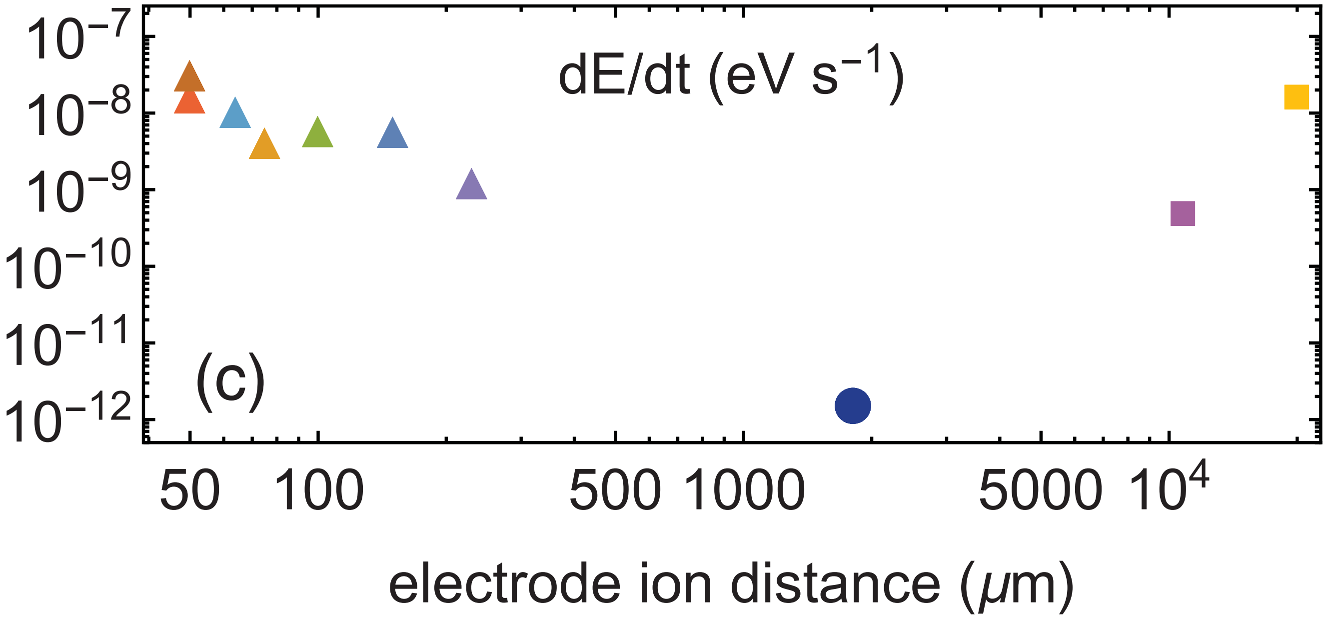


Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap

M. J. Borchert,[1,2,*] P. E. Blessing,[1,3] J. A. Devlin,[1] J. A. Harrington,[1,4] T. Higuchi,[1,5] J. Morgner,[1,2] C. Smorra,[1]
E. Wursten,[1,7] M. Bohman,[1,4] M. Wiesinger,[1,4] A. Mooser,[1] K. Blaum,[4] Y. Matsuda,[5]
C. Ospelkaus,[2,8] W. Quint,[3,9] J. Walz,[6,10] Y. Yamazaki,[11] and S. Ulmer[1]

sensitive to collisions depositing ~ neV

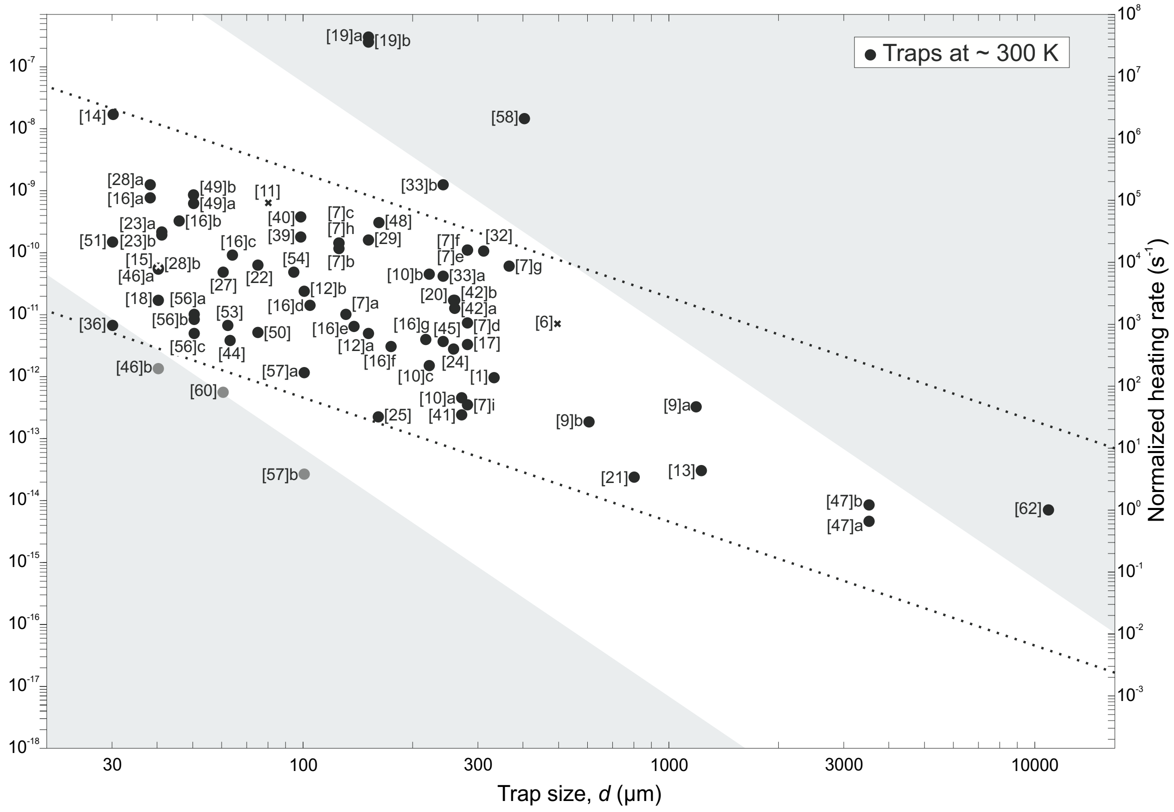
in overall heating rate



Ion Traps

e.g. ^{40}Ca ions sensitive to ~ $10^{-9}\frac{\text{eV}}{\text{sec}}$

with individual collisions ~ few neV



1409.6572 M. Brownnutt, M. Kumph, P. Rabl & R. Blatt

New Limits From Ion Traps

We choose 3 experiments to set new limits

but many more ion trap experiments have achieved low noise and could extend reach

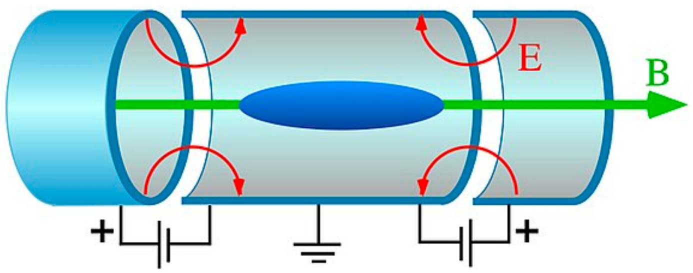
Experiment	Type	Ion	V_z	T_{wall}	ω_p [neV]	T_{trap}[neV]	Heat Rate(neV/sec)
Hite et al, 2012[3]	Paul	^{9}Be	0.1 V	300 K	$\omega_z = 14.8$	14.8	640
Goodwin et al, 2016 [4]	Penning	^{40}Ca	175 V	300 K	$\omega_z = 1.24$	1.24	0.37
Borchert et al, 2019 [5]	Penning	p^-	0.6 V	5.6 K	$\omega_+ = 73.8$ $\omega_- = 0.041$	7380	0.002

room temp,
cryogenic

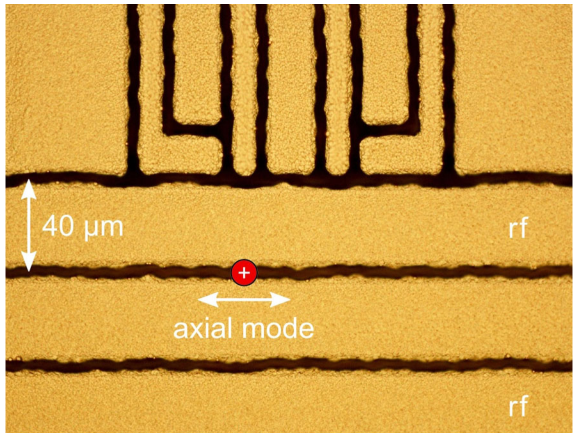
detector
threshold

cooled
ions

sensitivity



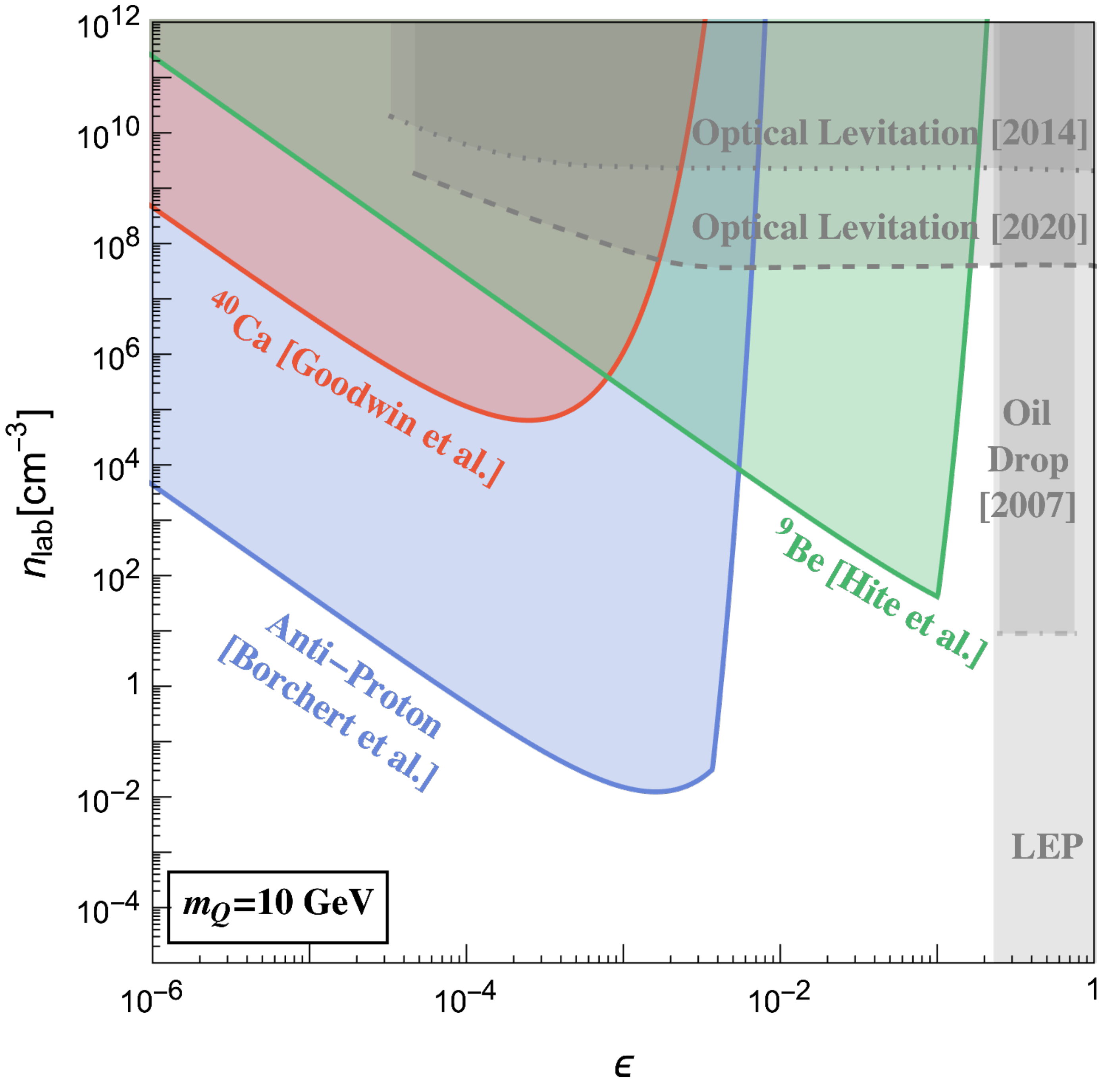
Penning Trap



Paul Trap
(Hite et al)

New Limits From Ion Traps

existing ion traps already reach well past previous bounds



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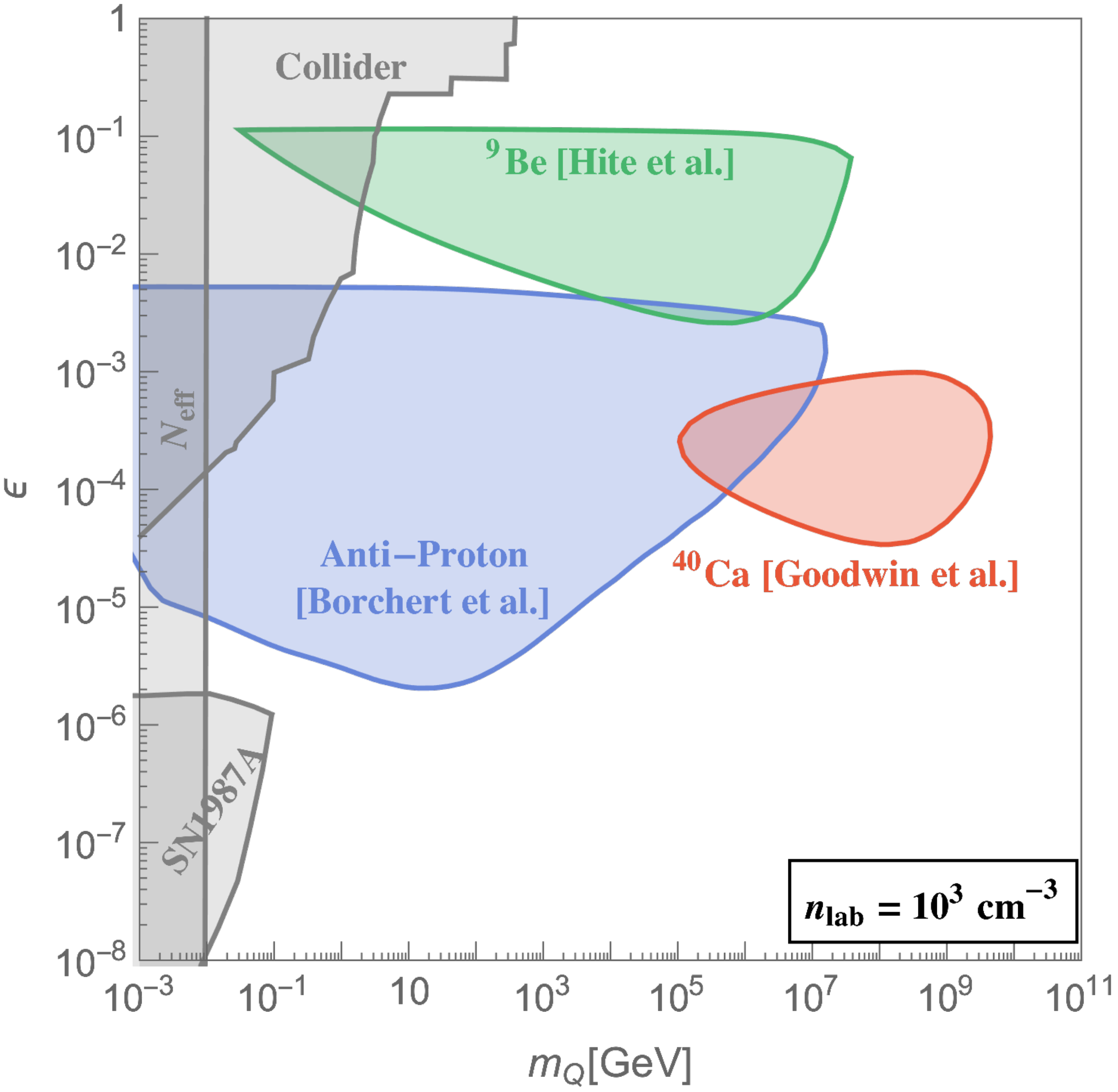
New Limits From Ion Traps

Different experiments have very complementary reach!

Significant differences between traps

- threshold
- target mass
- heating rate
- temperature



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Future Prospects

past measurements not made for dark matter detection already place strong constraints

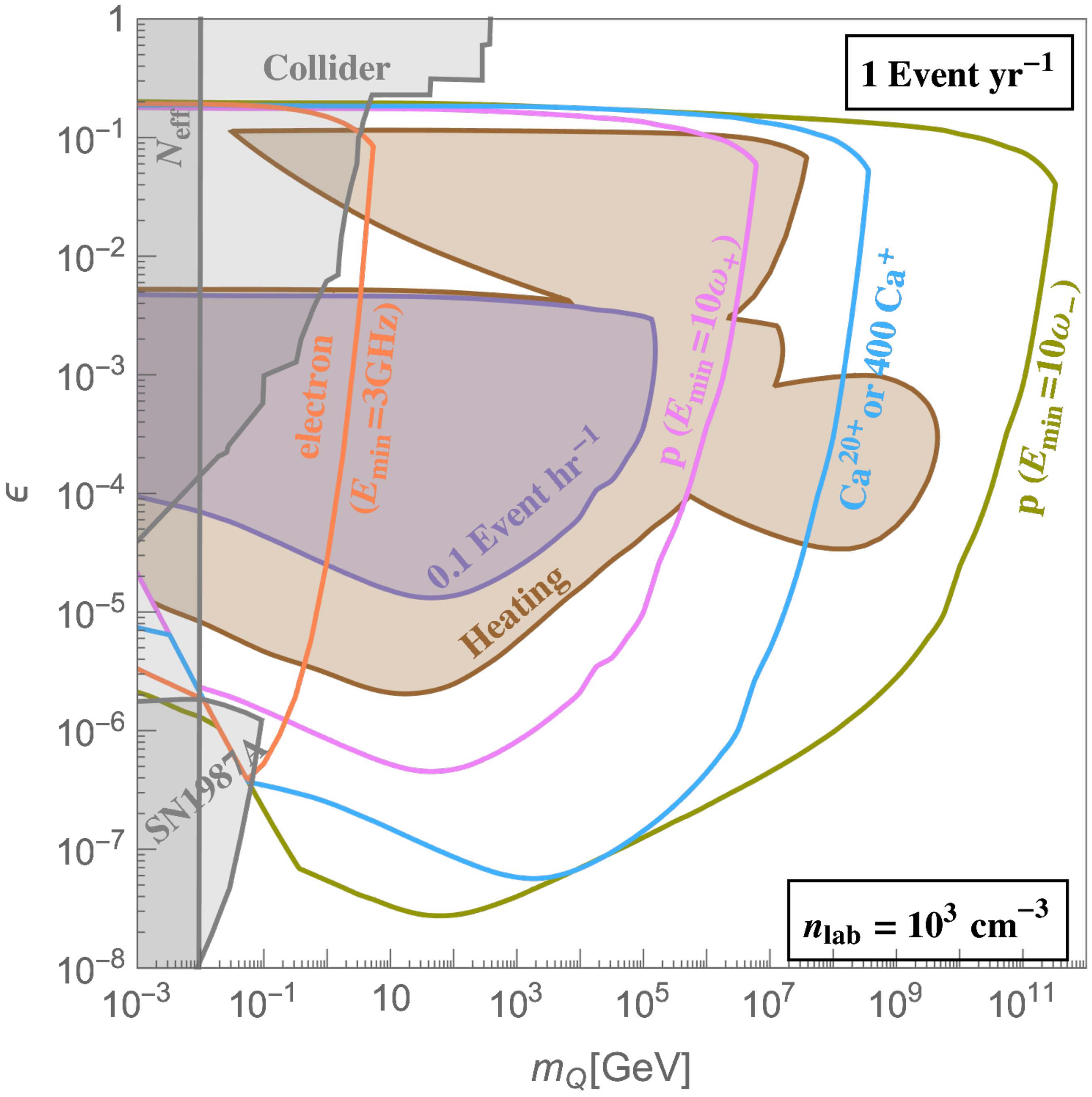
significant improvement possible in future with experiments designed to search for millicharges

- observing individual events reduces heating background, requires continuous monitoring of ion (already employed in some experiments)

- highly charged ion boosts signal

- lower threshold boosts event rate

- collective excitations in ion crystals could also reduce backgrounds



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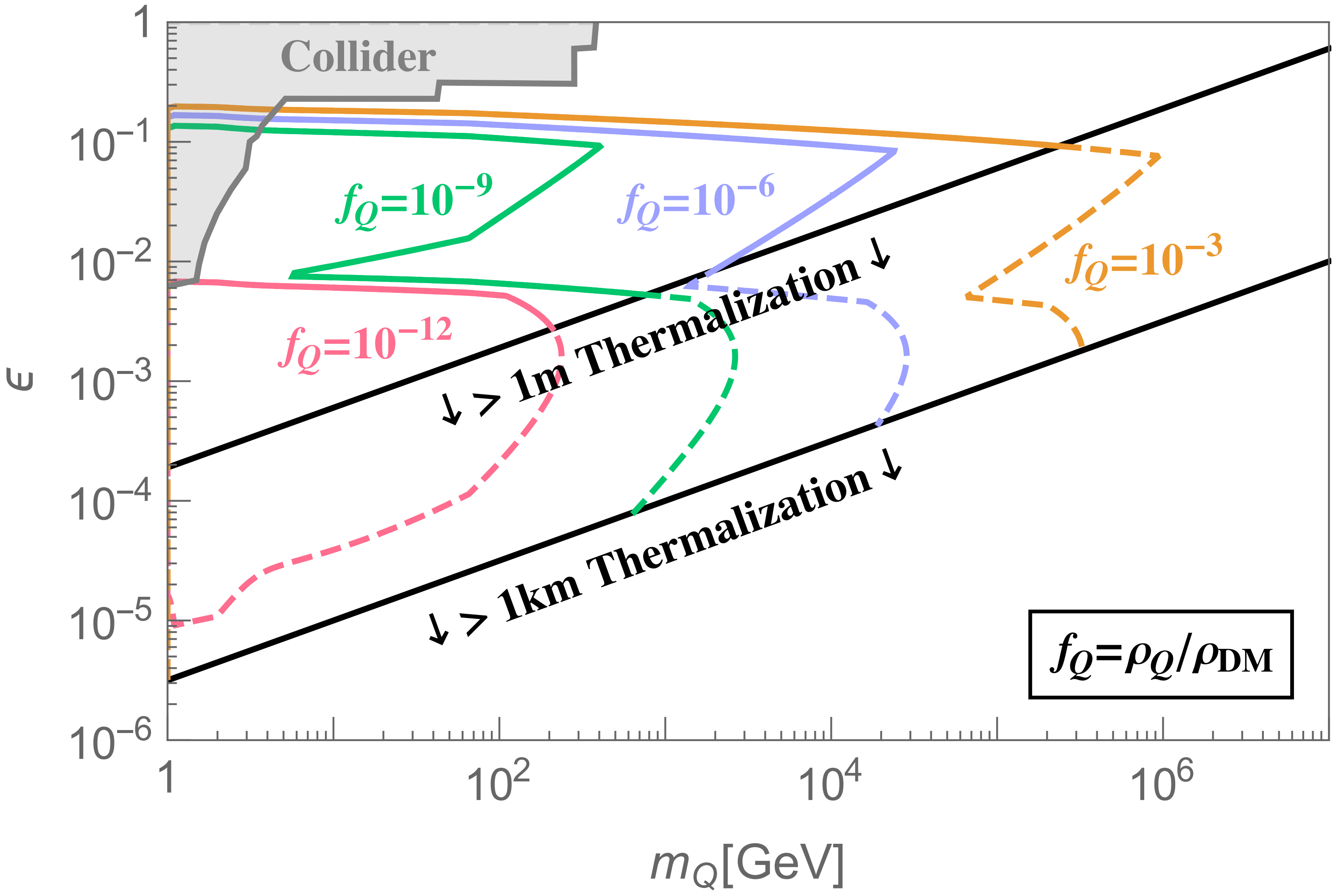
Dark Matter Detection

Bounds as a fraction of dark matter:



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Storage Ring Detection of Dark Matter and Dark Energy

with

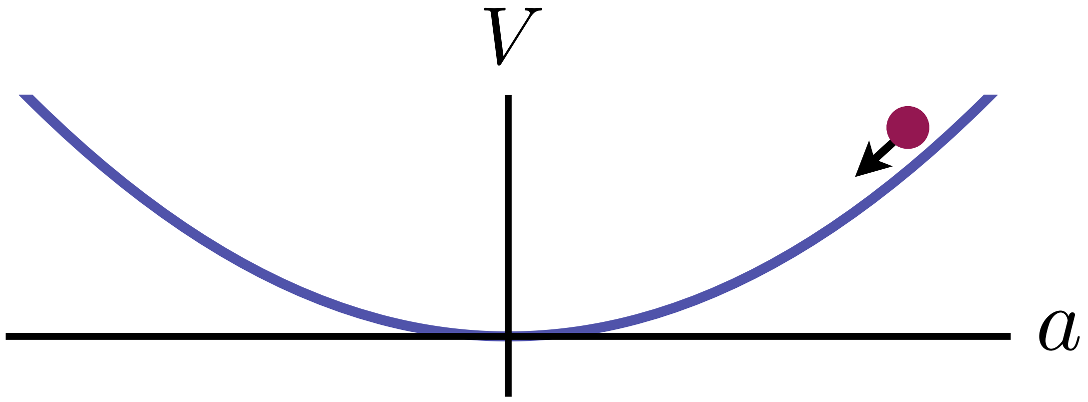
Selcuk Haciomeroglu
David E. Kaplan
Zhanibek Omarov
Surjeet Rajendran
Yannis K. Semertzidis

PRD (2021)

Axion Dark Matter or Dark Energy Field

axion dark matter has high phase space occupancy,
looks like homogeneous, slowly oscillating scalar field in galaxy

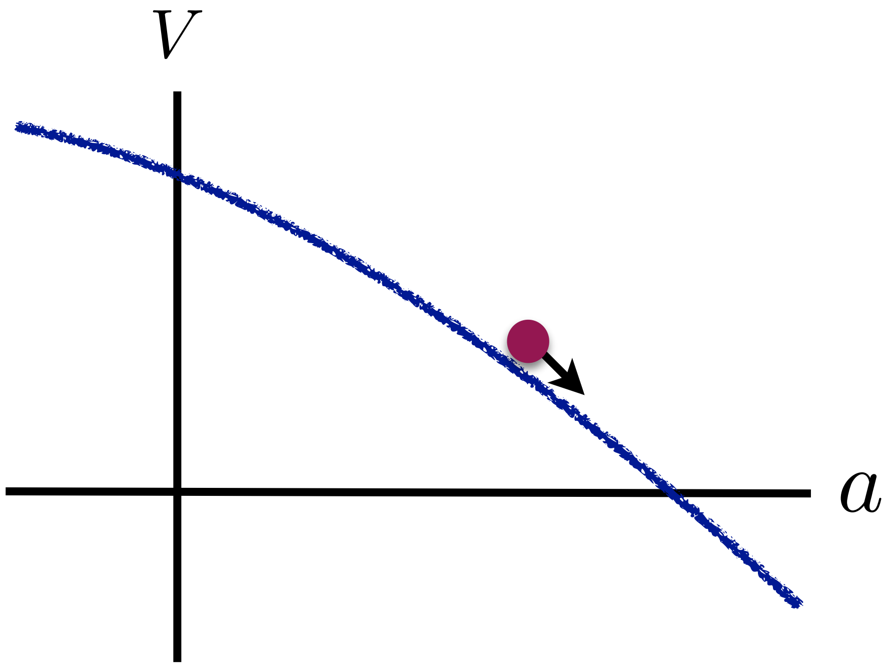
Dark Matter:



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

if dark energy is anything other than a constant, it too must be a scalar field

Dark Energy:



very homogeneous, slowly rolling scalar
field across entire universe

$$a(t) \sim a_0 + a_1 t$$

detecting dynamical dark energy similar to ultralight dark matter!

"Axion Wind"

How detect such a dark matter or dark energy field?

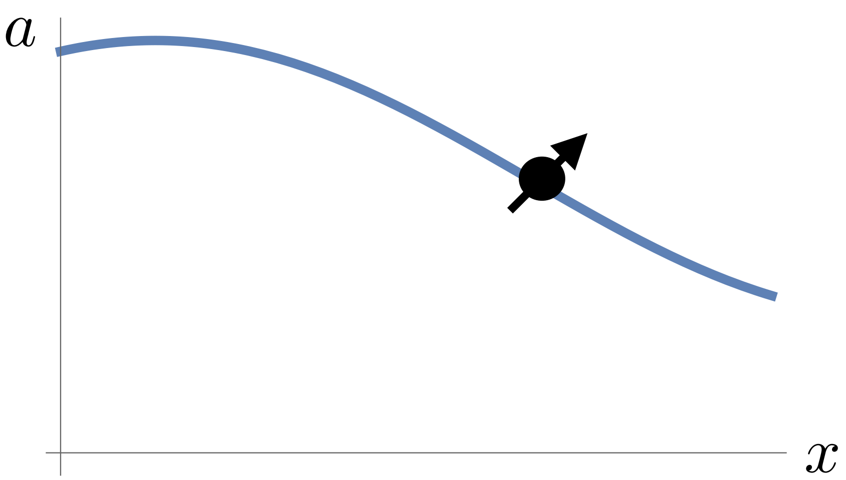
It will generically have several (axion-like) couplings to us

I will focus on nucleon coupling: $H \ni -g_{\mathrm{aNN}} \vec{\nabla} a \cdot \vec{\sigma}$ ← proton's spin

coupling constant

like an effective "magnetic field"

$\vec{\nabla} a \propto$ spatial momentum of axion



a proton's spin precesses in DM axion field

around the axion momentum ("wind")

if DM, axion wind signal oscillates in time

'axion wind' effect ➜ low-mass axion DM searched for by high precision lab experiments
e.g. atomic magnetometry, NMR, spin-polarized torsion balances, UCN…

The Effect

axion-nucleon coupling: $H \ni -g_{\rm aNN}\, \vec{\nabla} a \cdot \vec{\sigma}$ ← proton's spin

coupling constant

like an effective "magnetic field"

$\vec{\nabla} a \propto$ spatial momentum of axion $\vec{\nabla} a \sim \vec{v}_a \sqrt{\rho_a}$

for dark matter: $v_a \sim 10^{-3}$ $\rho_a = \rho_{\rm DM}$ large velocity suppression!

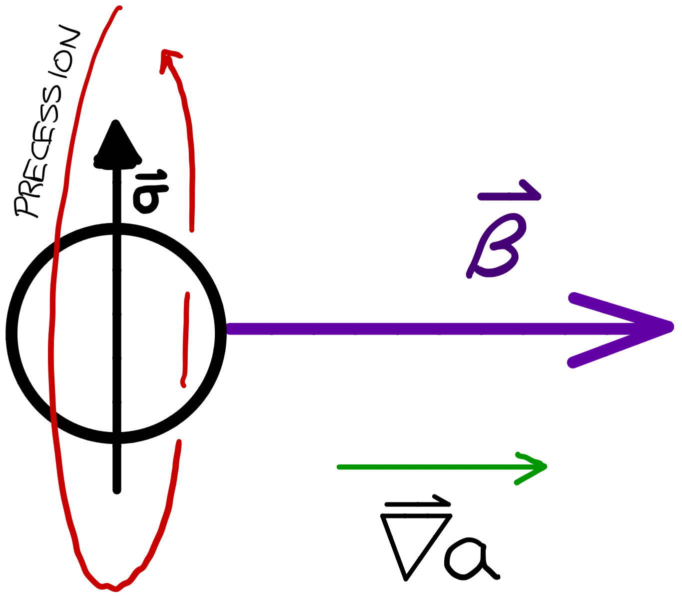
for dark energy: $v_a \sim 0$ in cosmic rest frame, but in lab frame $v_a \sim 10^{-3}$

large velocity suppression in the lab

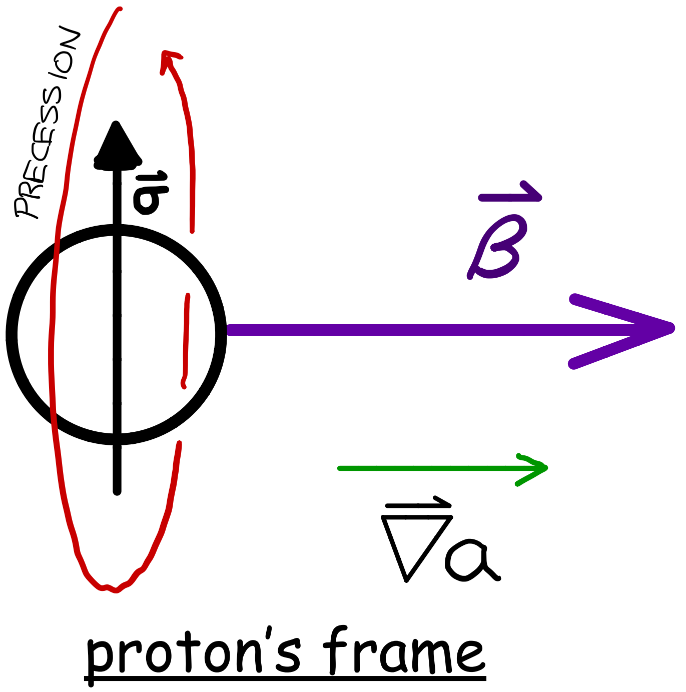
generally hard to boost a precision lab experiment to relativistic speeds...

Can accelerate individual particles to relativistic speeds

then precisely measure spin precession



Storage Rings

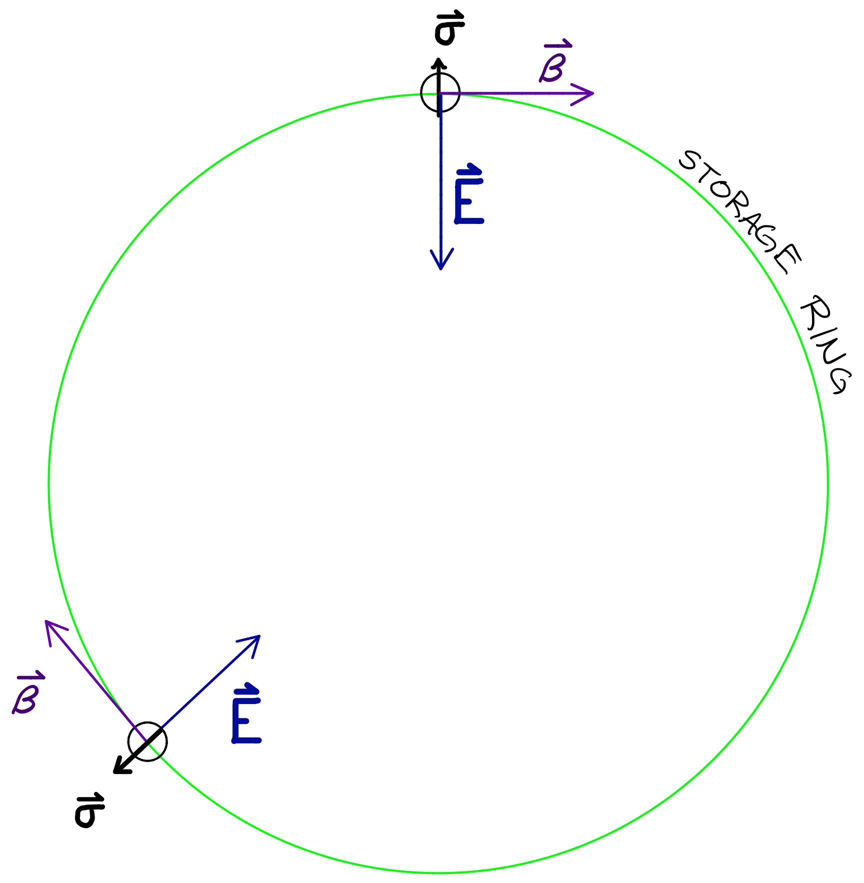


$H \ni -g_{\mathrm{aNN}}\, \vec{\nabla} a \cdot \vec{\sigma}$ spin precession signal $\sim H \times (\mathrm{time})$

want long integration times ➜ go in a circle instead of a straight line

then even a constant dark energy wind keeps changing direction (as seen by proton)

➜ effect averages to zero



need proton's spin to precess along with axion wind

➜ 'frozen spin' method!

avoids velocity suppression, improves signal by $\sim 10^3$

(don't get γ since time dilation reduces time in proton's frame)

inject protons

spin precession signal grows linearly in time

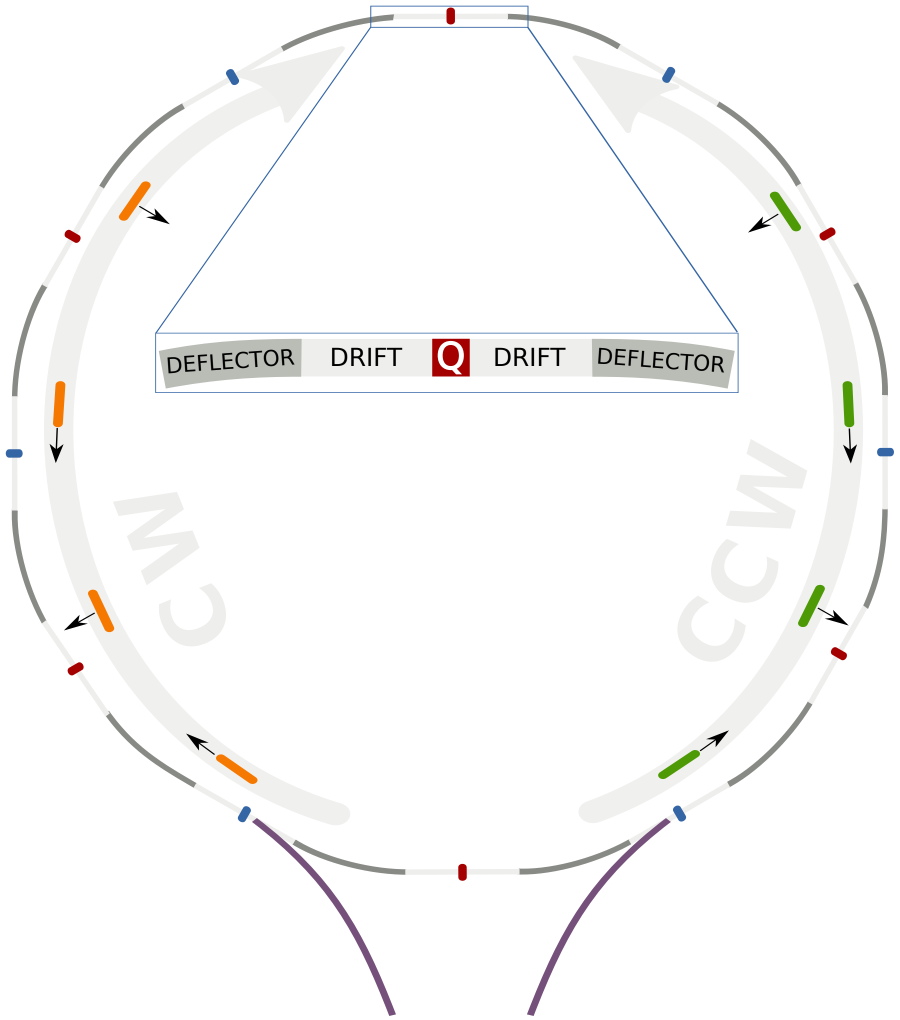
measure spin precession rate

Storage Ring Schematic

same hardware as proton storage ring EDM proposal

(see e.g. Storage Ring EDM Collaboration 1502.04317)
we relied on built up knowlege, simulation machinery:

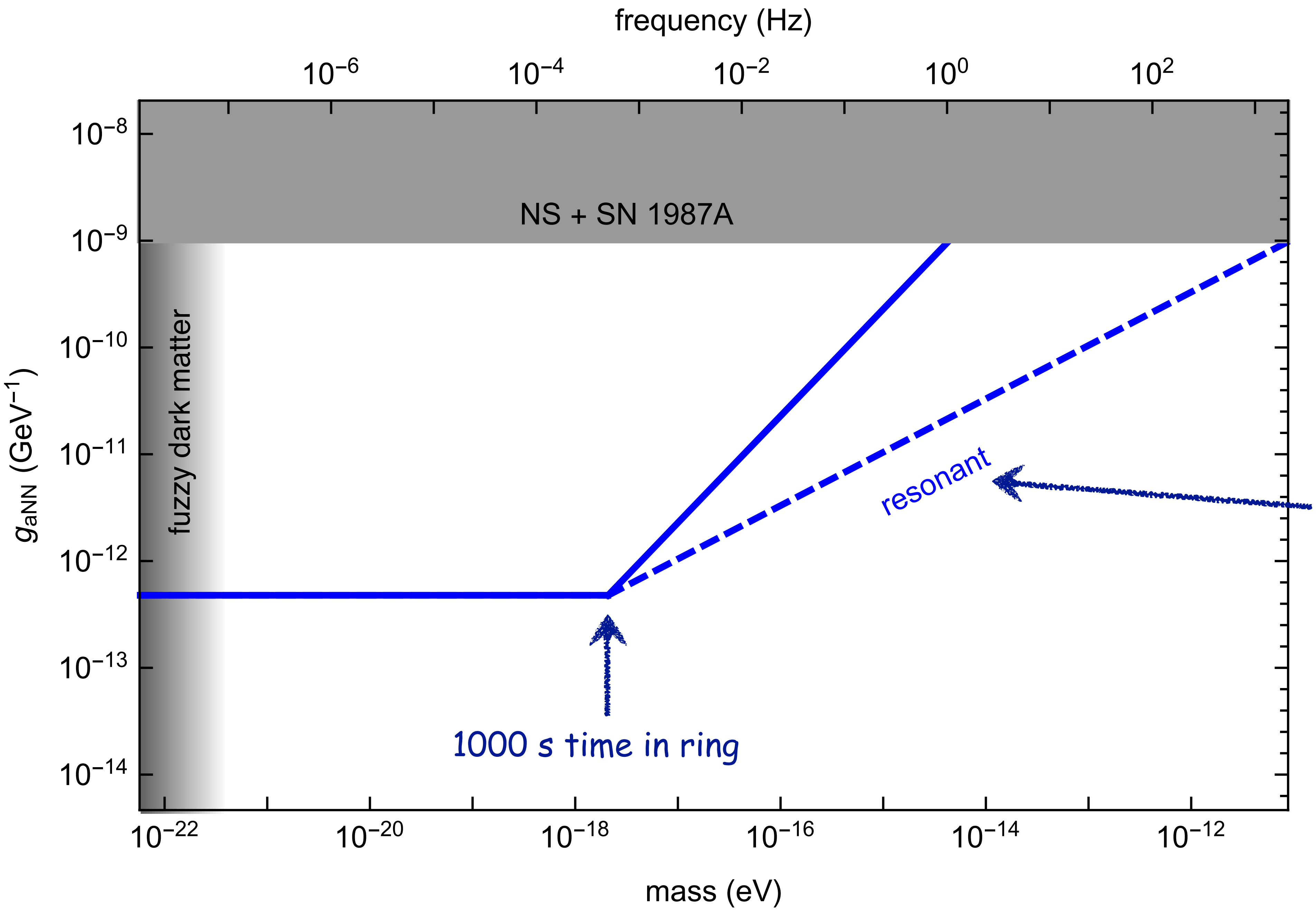
counter-propagating beams
cancel backgrounds



Effect	**Remediation**
Radial B-field.	Small effect.
Unwanted vertical forces when other than magnetic focusing is present.	Small effect.
Dipole vertical E-fields.	Small effect.
Quadrupole E-field in the electric bending sections.	Small effect.
Corrugated (non-planar) orbit.	Minimize effect with symmetric lattice design. Finally, keep the stored beams at zero average vertical angle when integrating over the electric field bending sections.
Longitudinal B-field.	The CW and CCW stored proton spins rotate in *same* direction, while the (pseudo-)scalar fields rotate them in opposite directions.
Geometrical phase effect due to lattice elements imperfections.	Equivalent to a spin resonance due to lattice elements imperfections. Cancel with magnetic quadrupole polarity switching.
Geometrical phase effect due to external magnetic fields.	Equivalent to a spin resonance due to external magnetic interference coupled with electric field bending section misplacement.[24, 26] When the local spin effects are kept below 1nT B-field equivalent, the effect is negligible even for one directional (CW or CCW only) storage. In this polarization case, the relevant fields and lattice misplacements may be in a different direction than the previous table.
RF cavity vertical and horizontal misalignment.	Small effect.

need beam position (splitting between CW and CCW) measured to ~ 100 nm in 1000 s fill
easily achieved with SQUID-based Beam Position Monitors (SBPMs) shown to have 10 nm/Hz$^{1/2}$

Storage Ring Sensitivity to Axion Dark Matter



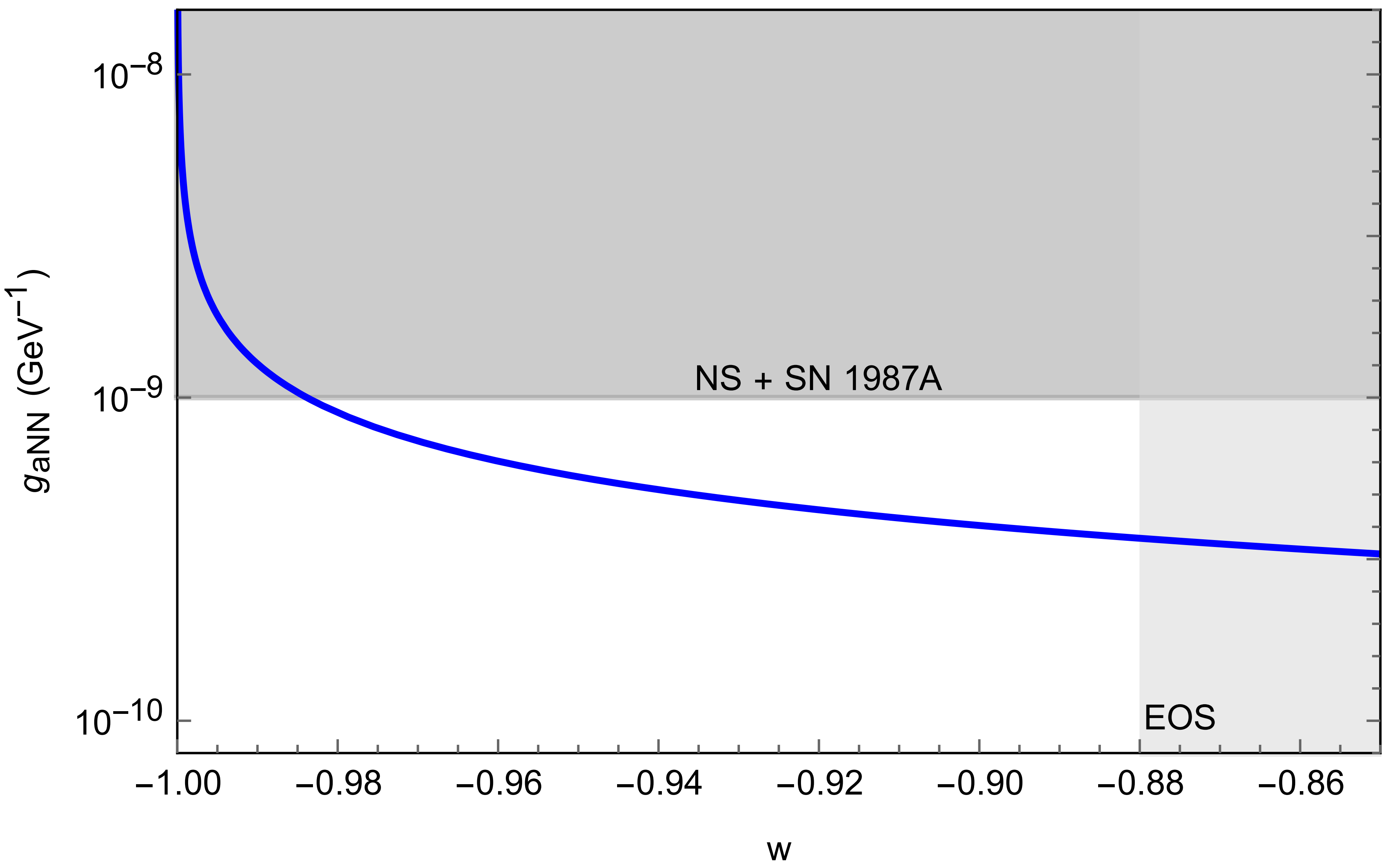
1000 s time in ring

axion oscillates faster than 1000 s, signal averages down.

choose slight ‘detuning’ from magic momentum so proton spin precesses relative to velocity at axion frequency

one of the most sensitive searches for axion dark matter in this mass range

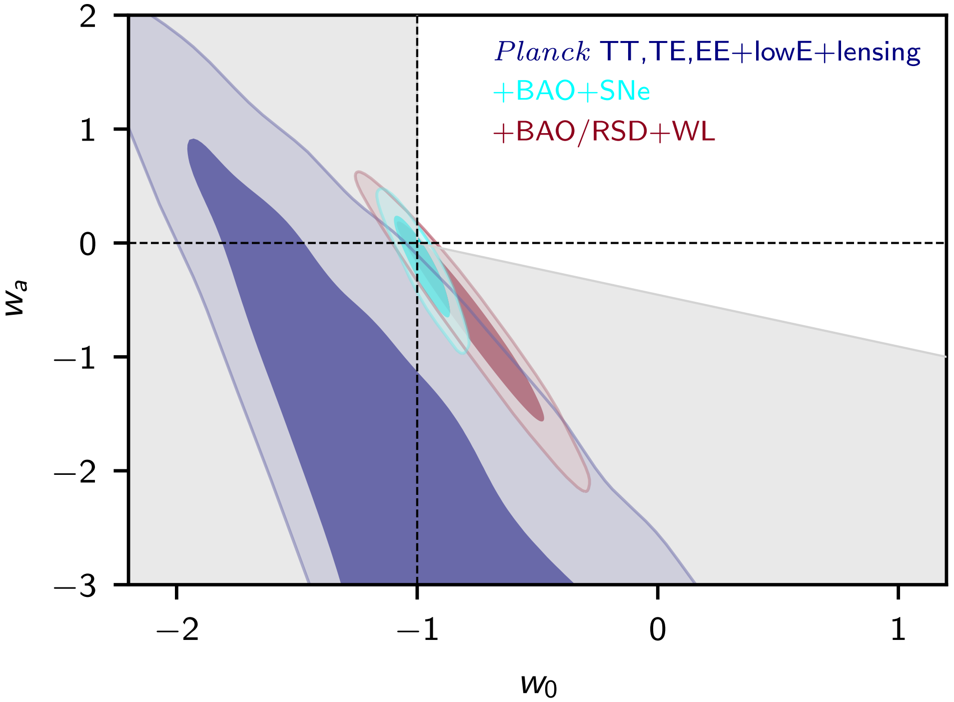
Storage Ring Sensitivity to Dark Energy



less sensitive to dark energy than dark matter since energy density is ~10^5 smaller

only known technique to reach sensitivity to dark energy past current bounds in this coupling

hopefully inspires improvements!



Conclusions

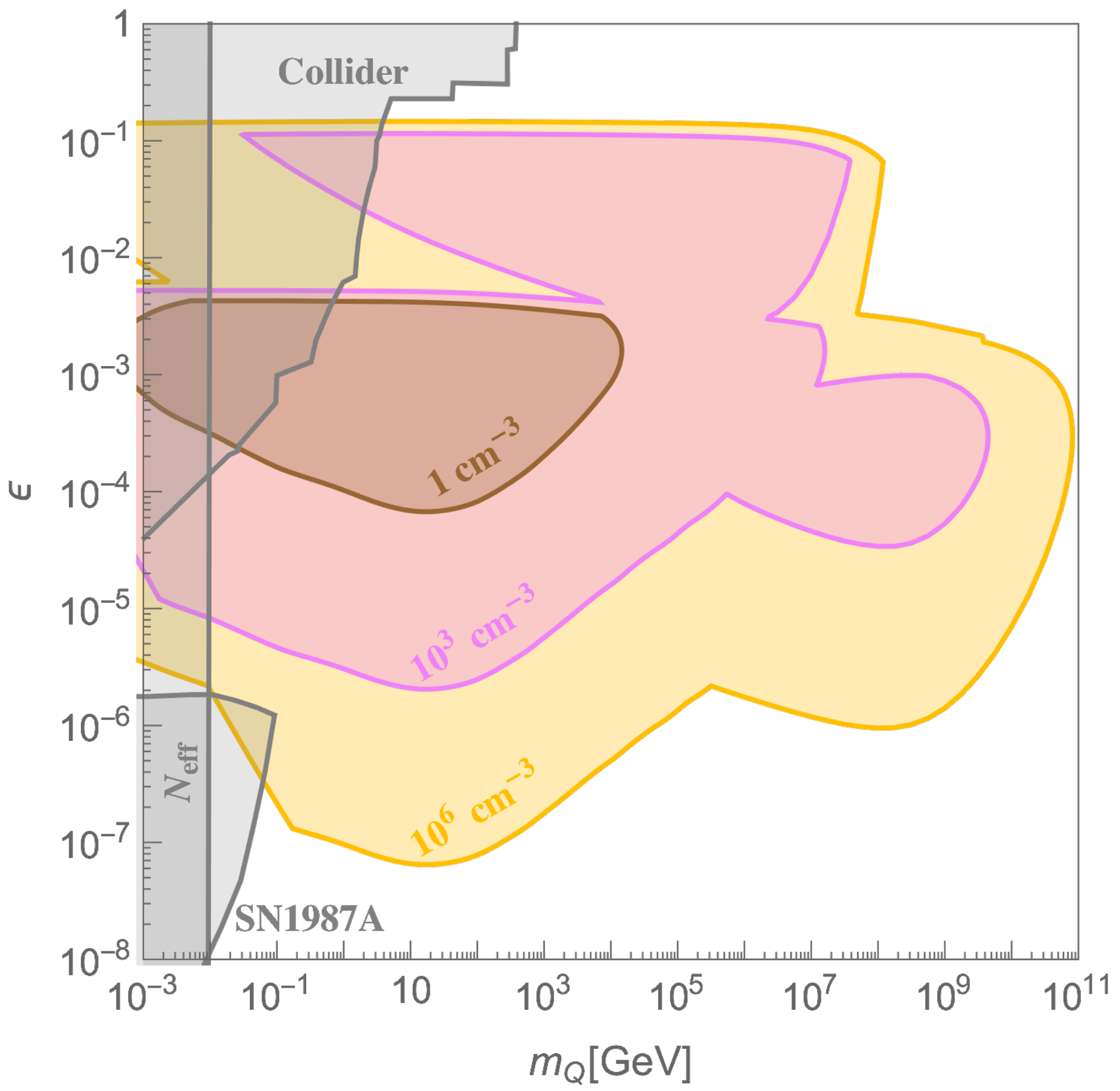
1. Trapped ions are excellent detectors for millicharged particles with large cross sections. Already set new limits, large improvements possible.

2. Storage rings can detect axion dark matter (and even dark energy) in the lightest mass range

Backup

Ion Traps as Detectors

if millicharged particles exist, existing ion traps already reach well past previous bounds



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significant improvements possible (e.g. highly charged ions, single events, ion crystals…)