Dark Matter Detection with Trapped Ions

Harikrishnan Ramani
Stanford University

2208.06519: X. Fan, G. Gabrielse, P. Graham, R. Harnik, T. Myers, Harikrishnan Ramani, B. Sukra, S. S. Y. Wong and Y. Xiao
Electron Traps for dark photon

PRX Quantum(2022): D. Budker, P. W .Graham, Harikrishnan Ramani, F. Schmidt-Kaler, C. Smorra
Ion Traps for millicharge particles

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- Dark Photon Dark Matter
- Electron Traps
- Results & Projections

- Millicharge Relics
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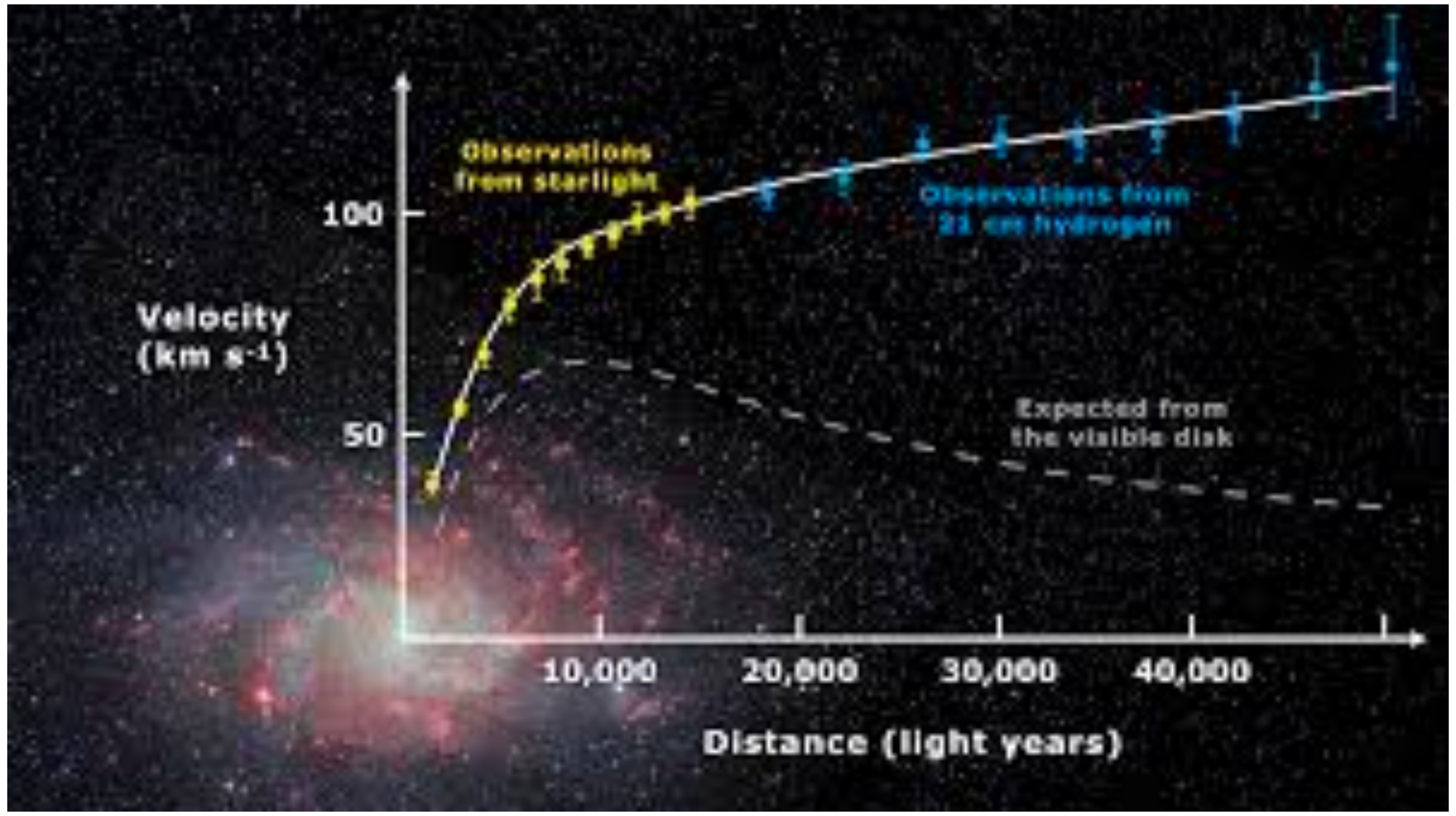
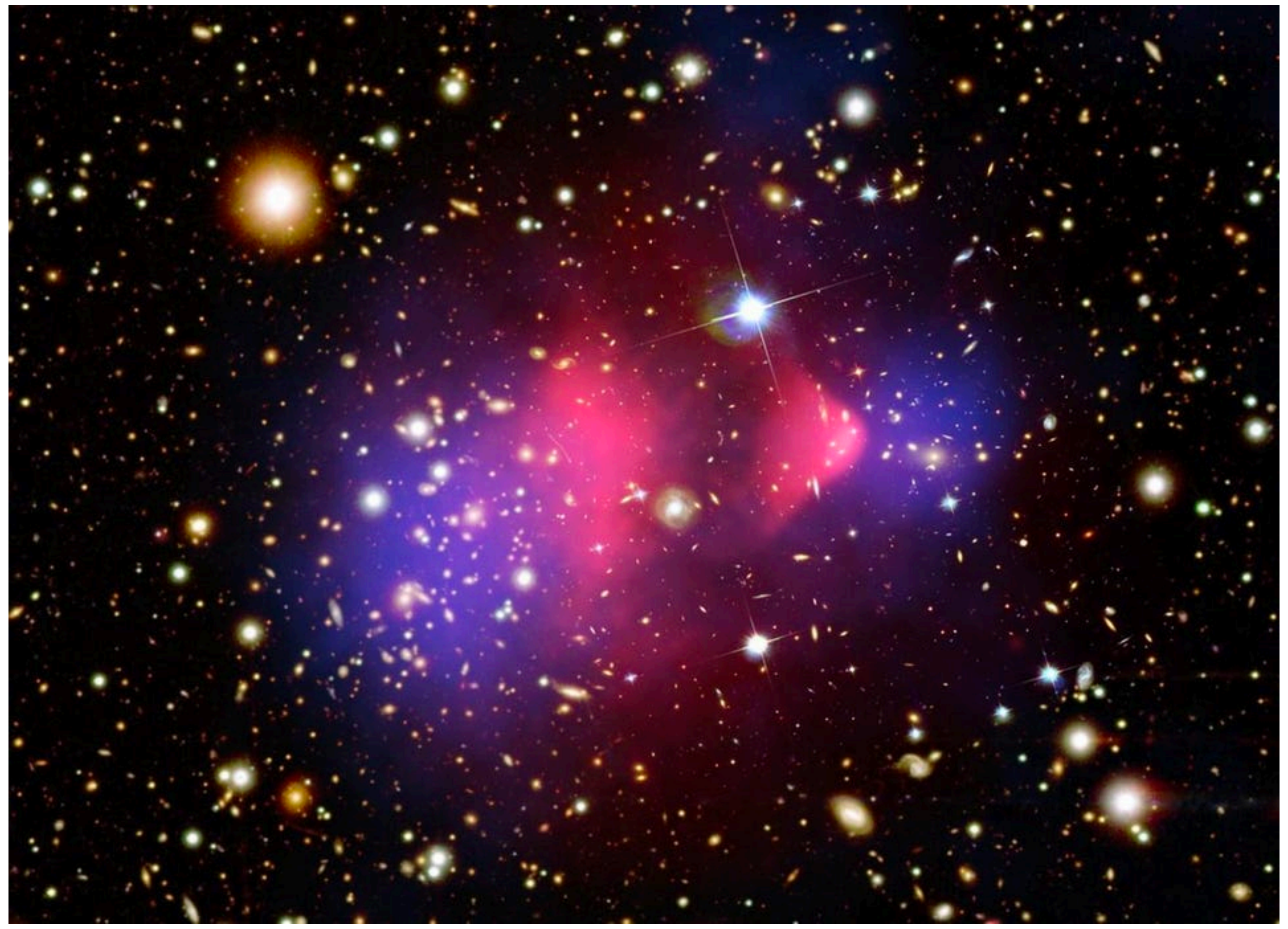
Introduction



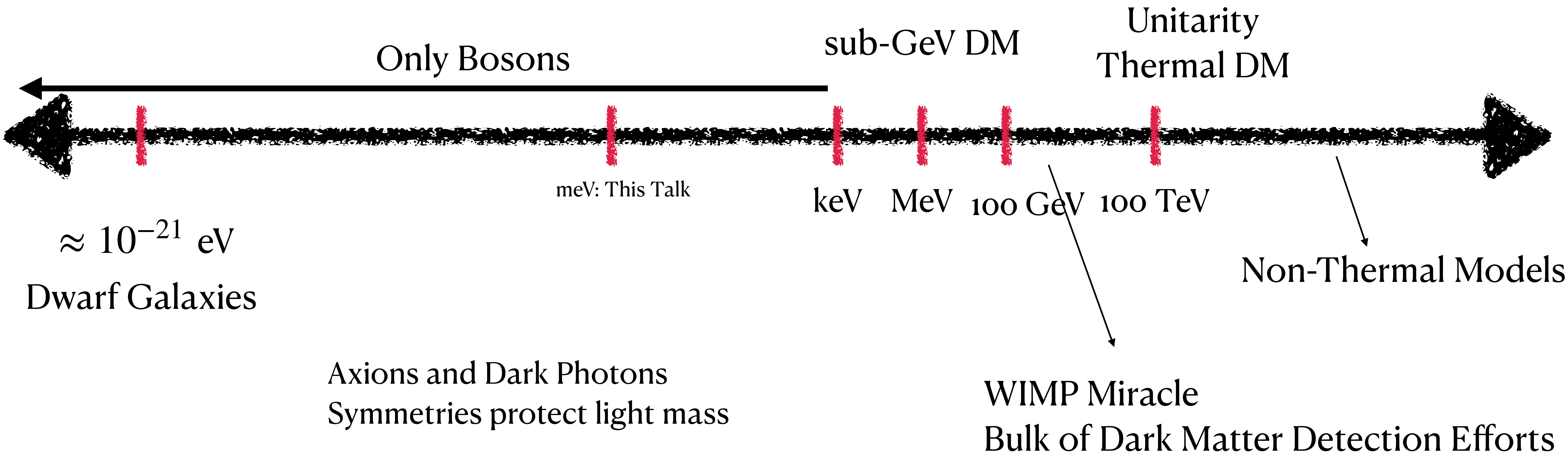


- Overwhelming evidence for Dark Matter (DM)
- Only through Gravitational Interactions
- Cosmic density similar to Standard Model (SM)
- Perhaps other interactions with SM exist?

Dark Matter Mass

Galactic Density: $\rho_{\text{DM}} \approx 0.3 \ \frac{\text{GeV}}{\text{cm}^3}$

What is its Mass?



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Dark Photon Dark Matter

- Simple model: $\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$

Mass of Dark Photon

Dark Photon Dark Matter

- Simple model: $\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$

Mass of Dark Photon   Kinetic Mixing

- Kinetic Mixing allowed by symmetries of the theory
- Only Logarithmically Sensitive to the UV of the theory
- If $m_{A'} \lesssim 2m_e$, decay too slow: stability
- Several Production mechanisms

P. W. Graham, J. Mardon, and S. Rajendran, Phys. Rev. D 93, 103520 (2016).
J. A. Dror, K. Harigaya, and V. Narayan, Phys. Rev. D 99, 035036 (2019).
P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, and F. Takahashi, Phys. Lett. B 801, 135136 (2020).
E. W. Kolb and A. J. Long, Journal of High Energy Physics 2021, 283 (2021)
R.Co, A. Pierce, Z. Zhang, Y. Zhao Phys.Rev.D 99 (2019) 7, 075002
R. Co, K. Harigaya, A. Pierce JHEP 12 (2021) 099

Wave-like @ low masses

$$\rho_{\rm DM} = 0.3\frac{\rm GeV}{\rm cm^3} = (0.04\ \rm eV)^4$$

$m \ll$ eV — eV — TeV

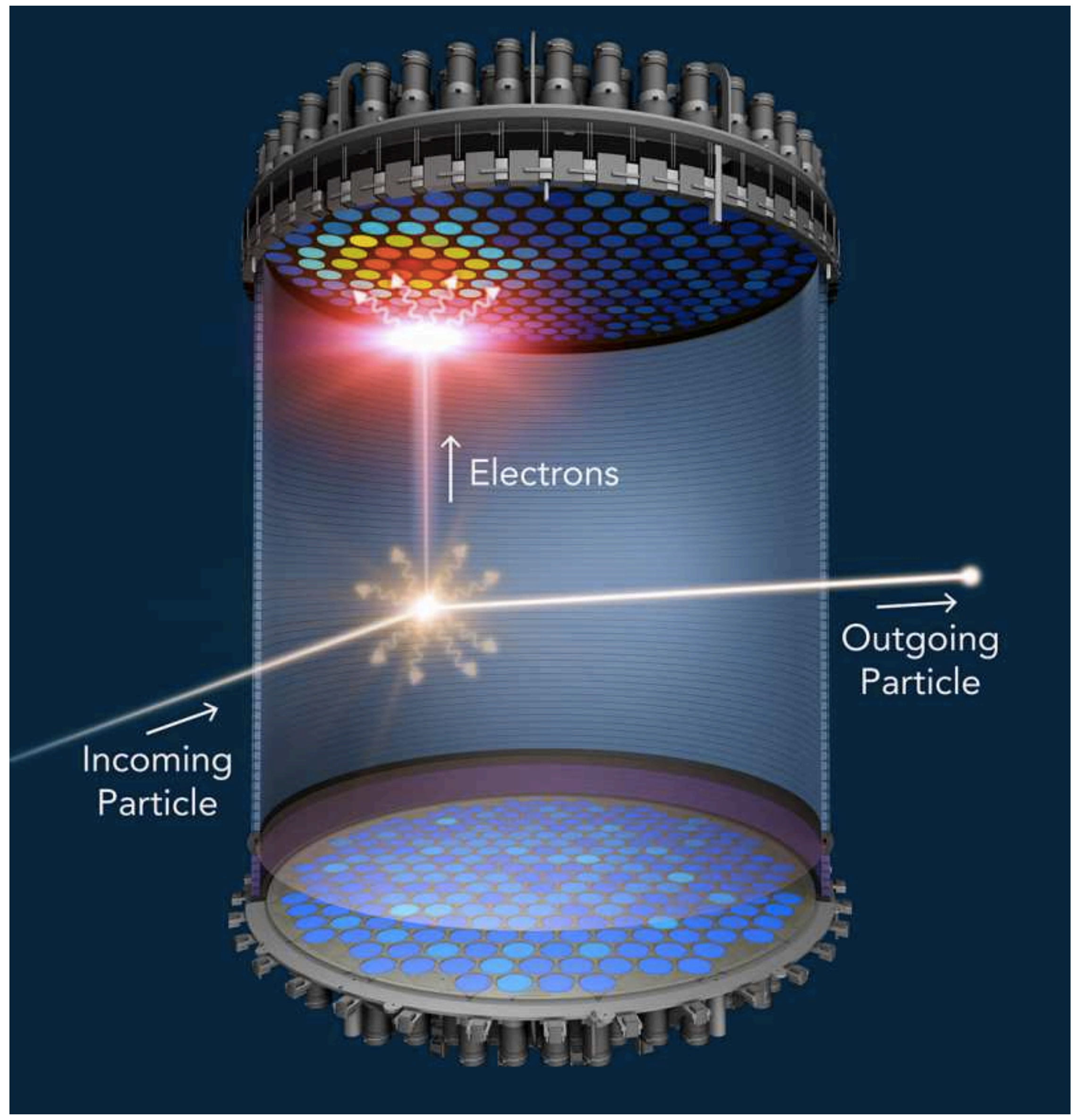
Wave-like:

- Many particles / de-Broglie wavelength
- High Occupation number
- For a vector, the "electric field" is:
- $E = E_0 \cos(\omega t - kx)$

$E_0^2 = 2\rho_{\rm DM} \approx (100\ \rm V/cm)^2$ $\omega \to m_{A'}$ $k \to m_{A'} v_{\rm vir} \ll \omega$

WIMPS

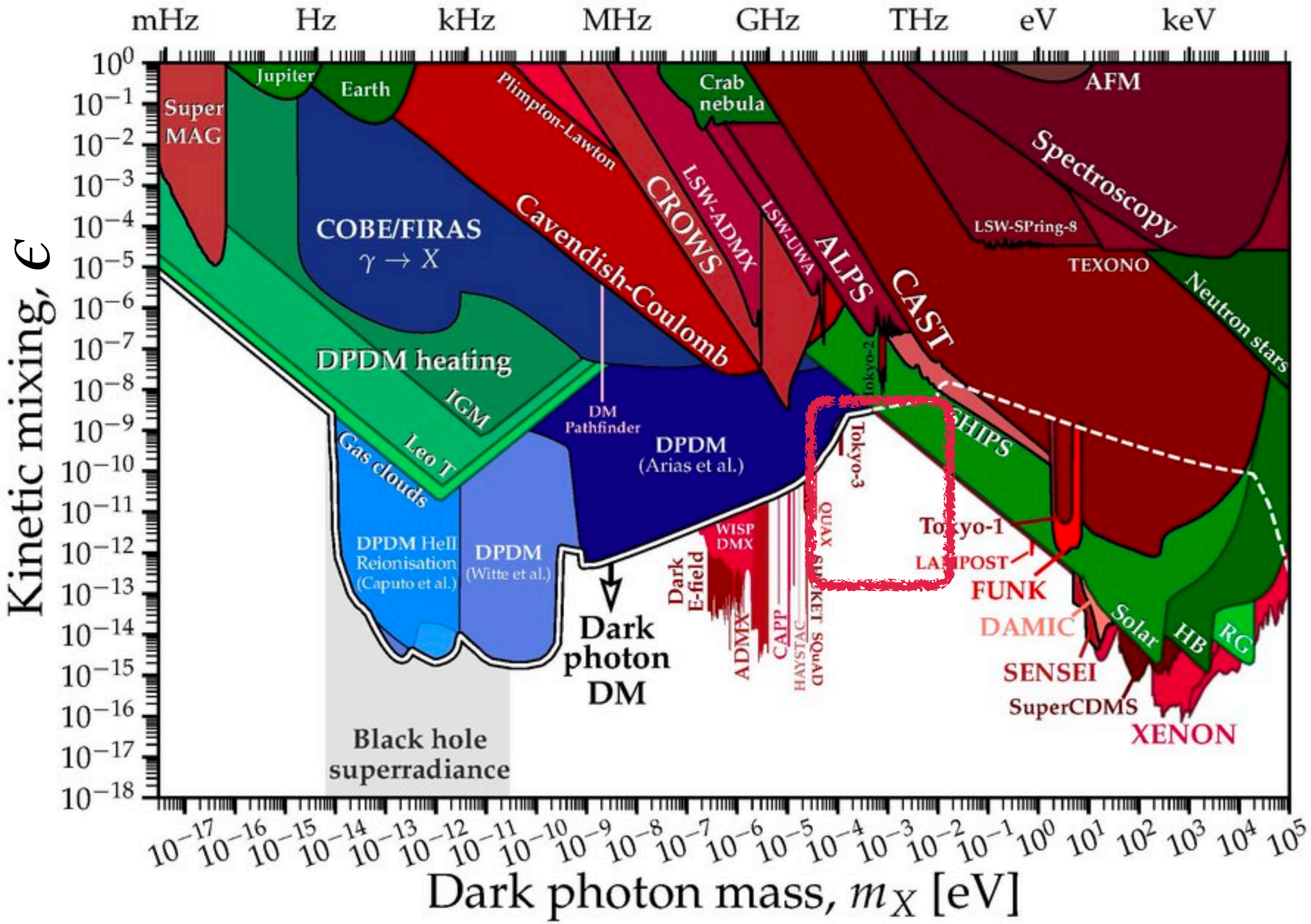
Particle-Like:



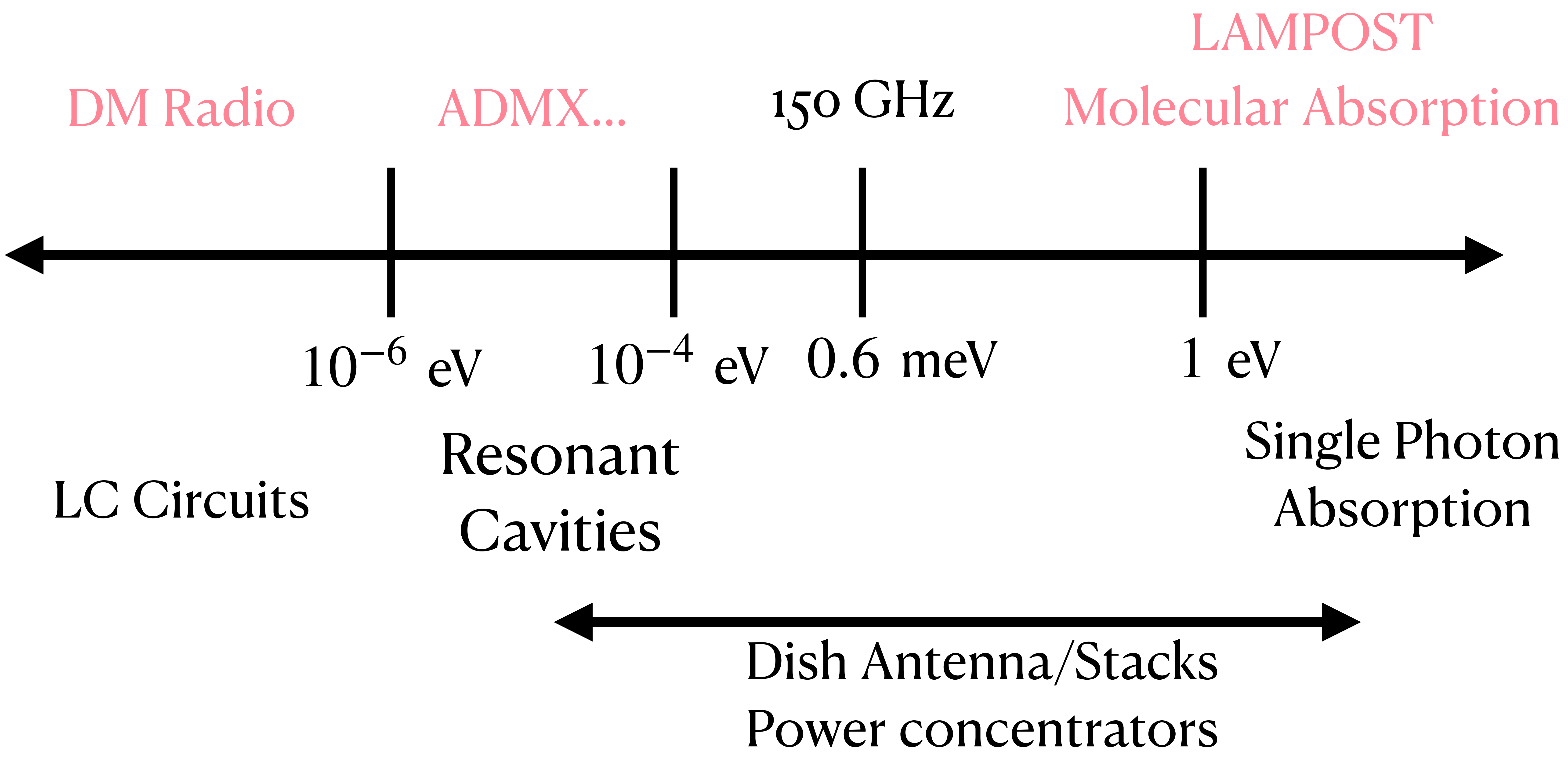
Detection Strategy

- Kinetic mixing: $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$
- Produce SM E&M fields suppressed by ϵ
- Oscillating at frequency $\omega \approx m_{A'}$
- How to detect?
- Devices sensitive to tiny E&B fields at appropriate frequency

Dark Photon Dark Matter



Blind Spot



Hard to probe 10^{-4} eV- 0.1 eV

Why?

1) Too high energy for high Q cavities/resonators
2) Too low energy for single photon detection
3) Existing proposals involve broadband bolometers
4) Resonant detection possible?

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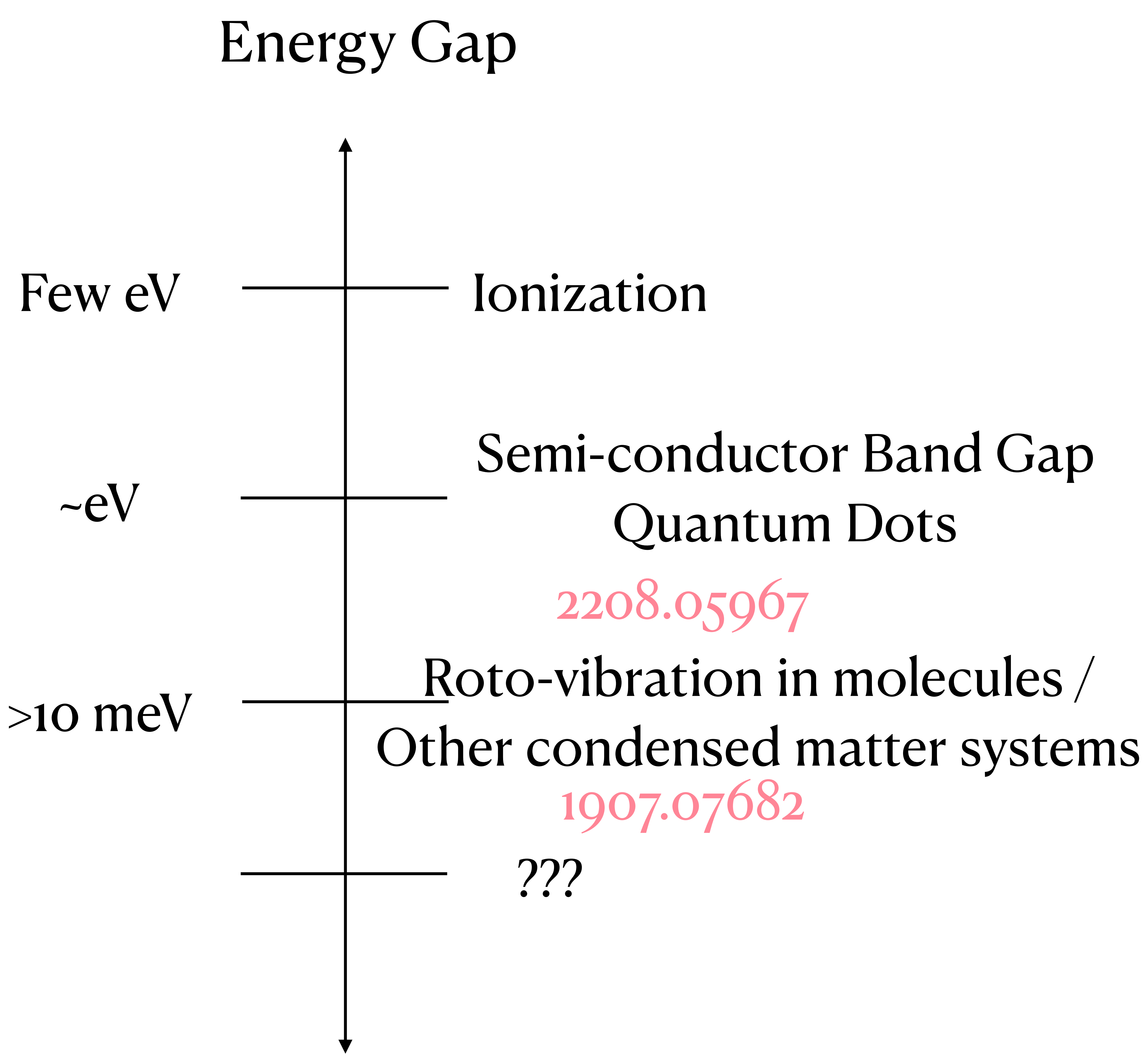
A two level system @100 GHz

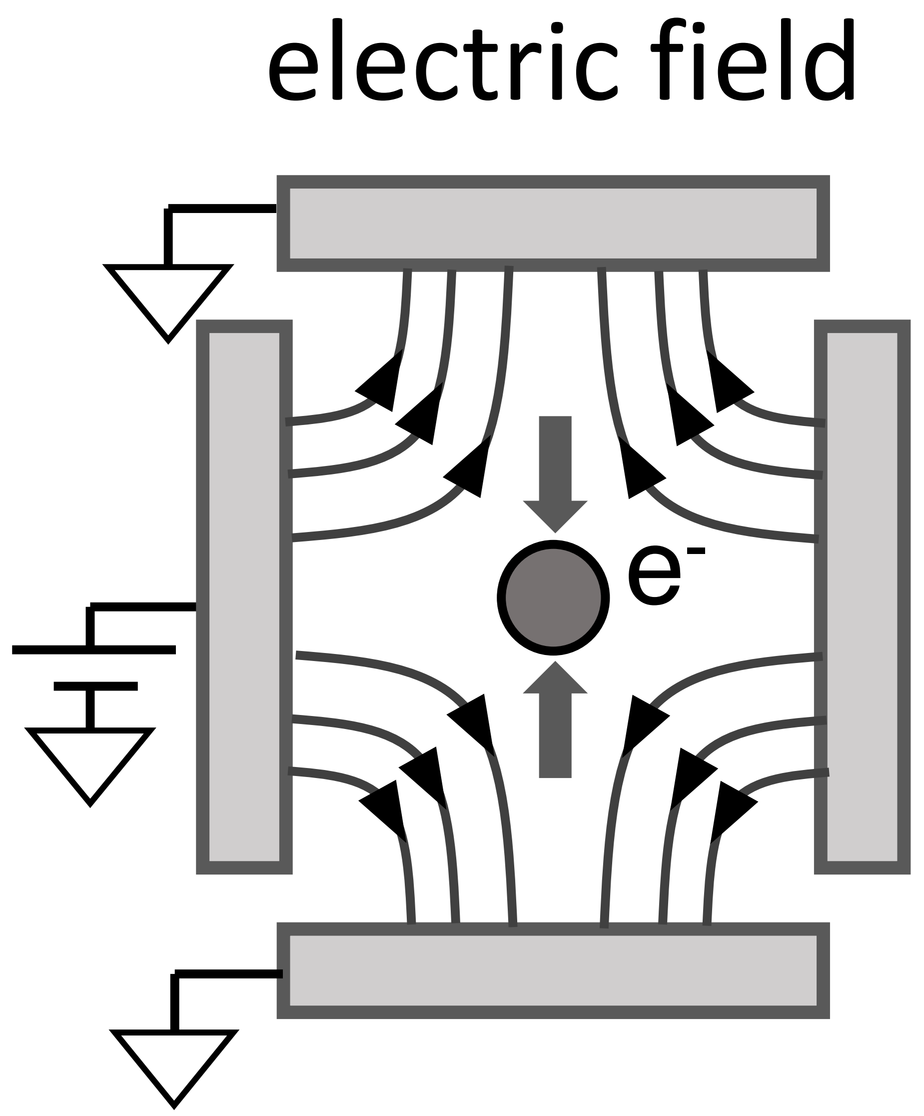


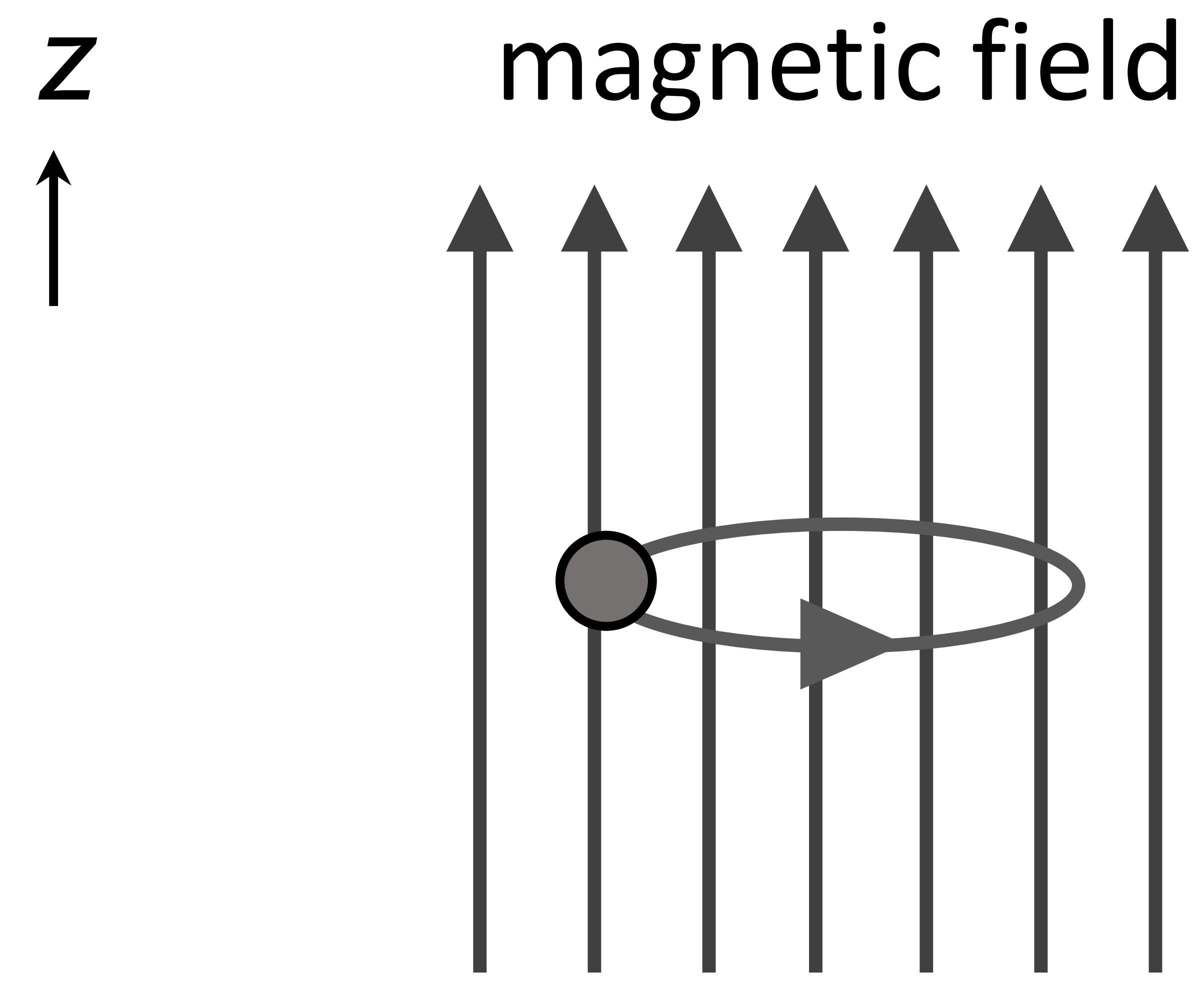
$$\frac{qB}{m_e} \approx 150\ \mathrm{GHz}\frac{B}{5\ \mathrm{T}}\frac{511\ \mathrm{keV}}{m_e}$$

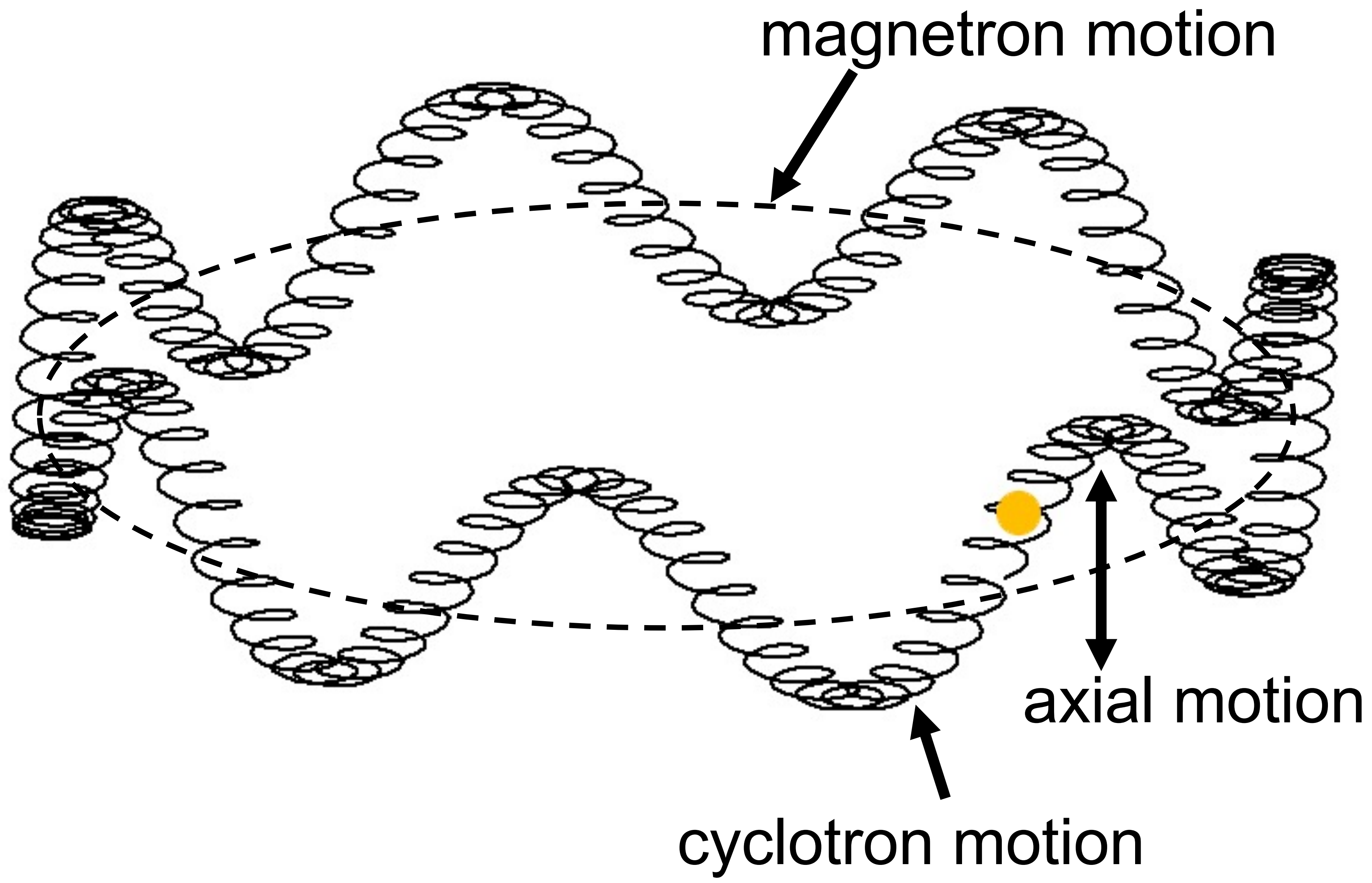
(0.6 meV)

1) Electrons trapped in a strong magnetic field, exhibit cyclotron orbits - Quantized.
2) A resonant detector for a dark photon?
3) Dial magnetic field to scan resonant frequency
4) Possible to detect a single jump?

Electron in a Penning Trap

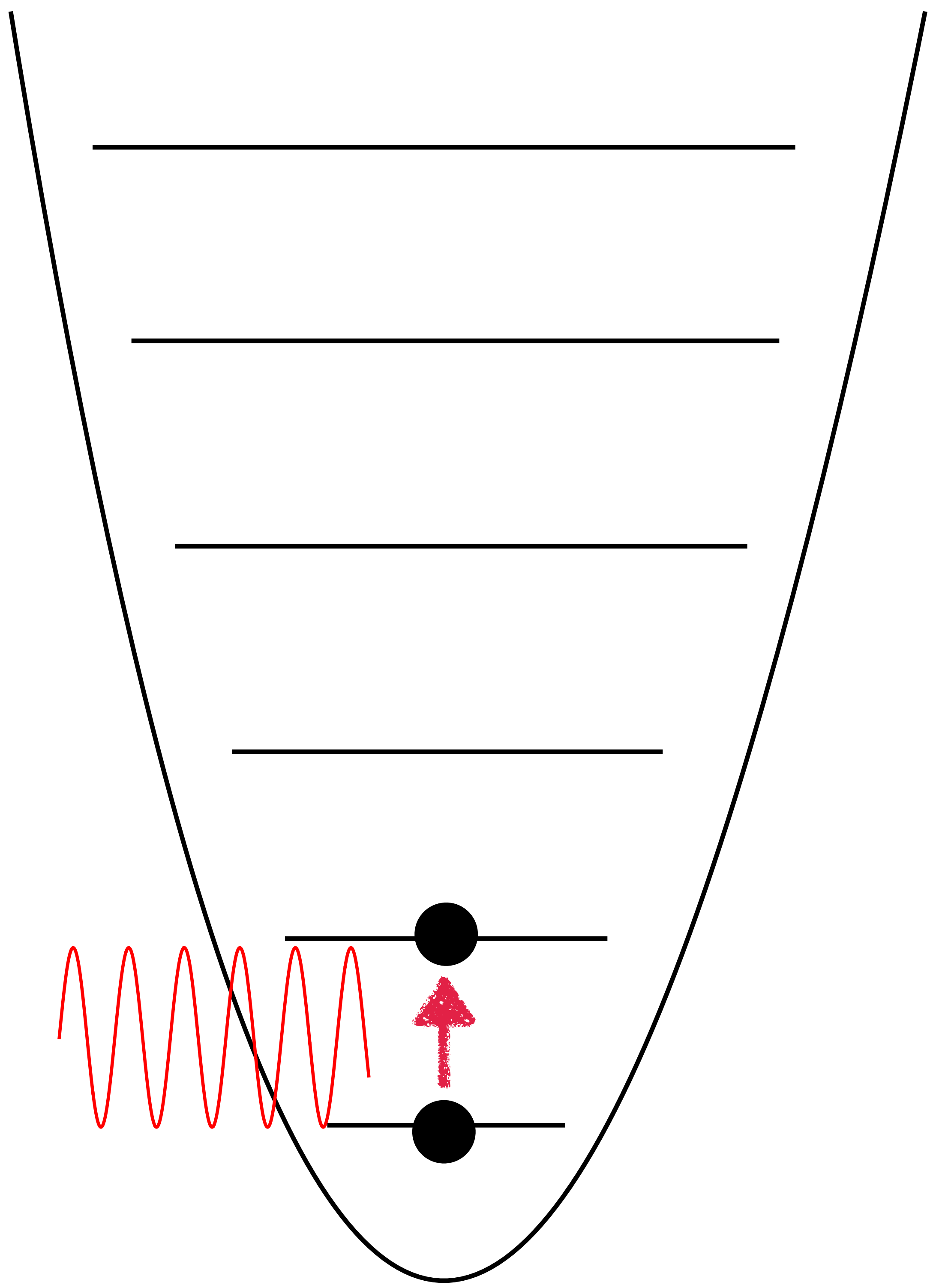






- Local Minimum & trapping from Quadrupole Electric and axial Magnetic fields
- Three Harmonic oscillators for cyclotron/magnetron/axial modes
- Can trap electrons for years - used in metrology and quantum computing

A new way to detect dark photons



- Only $\Delta n = 1$ transitions allowed (Selection rules)
- Sensitivity to tiny electric fields

$$\Gamma \approx \frac{\pi e^2}{2m_e\omega}\frac{\rho_{\rm DM}}{\Delta\omega} \longrightarrow \text{Signal Width}$$

$$\approx \frac{5}{10\text{sec}}\left(\frac{\epsilon}{10^{-8}}\right)^2\left(\frac{2\pi\times 100\text{ GHz}}{\omega}\right)^2$$

For a single electron

Measuring quantum state

Peil & Gabrielse - 1999

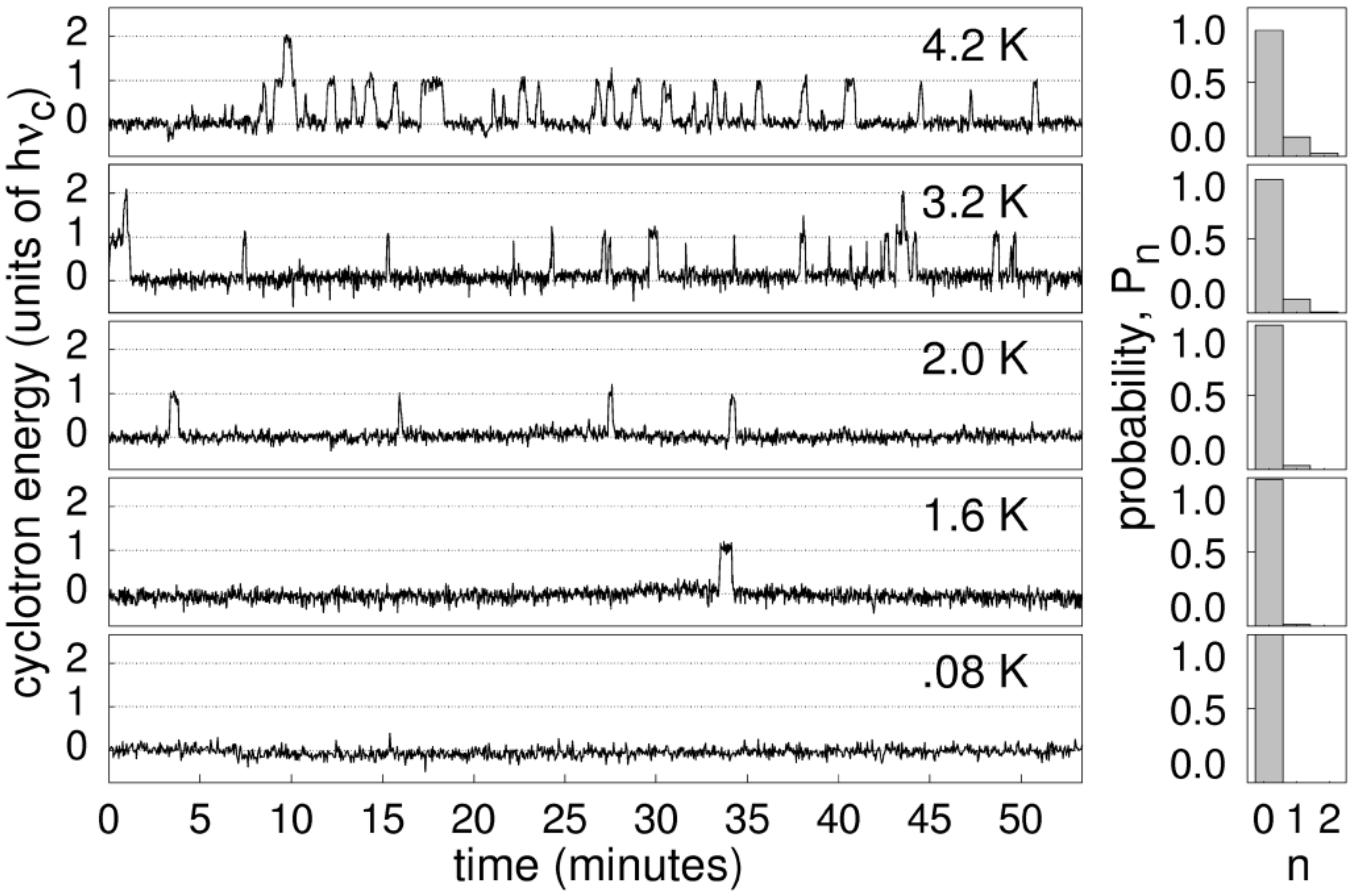
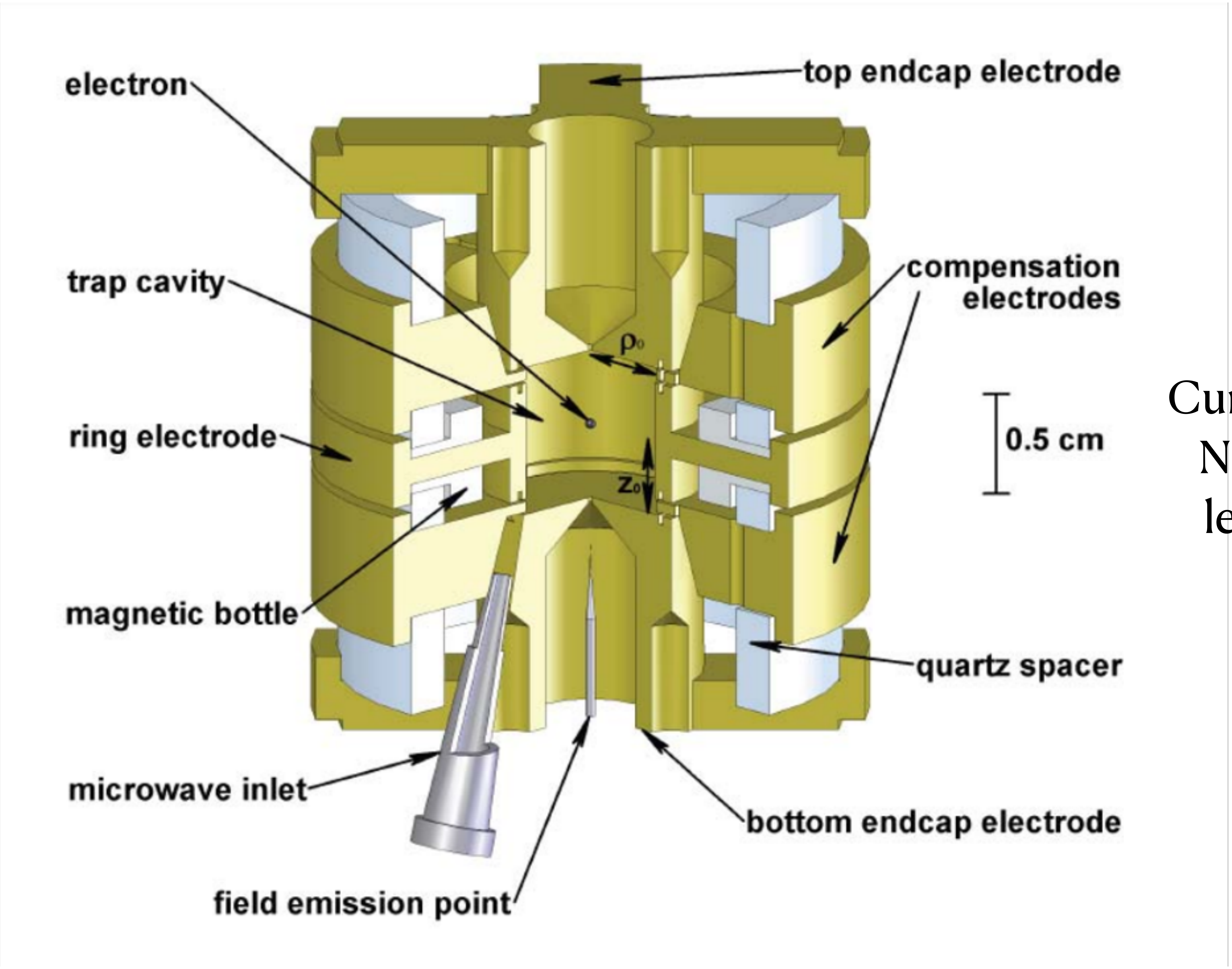


FIG. 2. Quantum jumps between the lowest states of the one-electron cyclotron oscillator decrease in frequency as the cavity temperature is lowered.

- Quantum Non-Demolition measurement of the electron cyclotron state is possible
- 1 sec observation time
- At temperatures below 1K, no first excitation observed

Apparatus

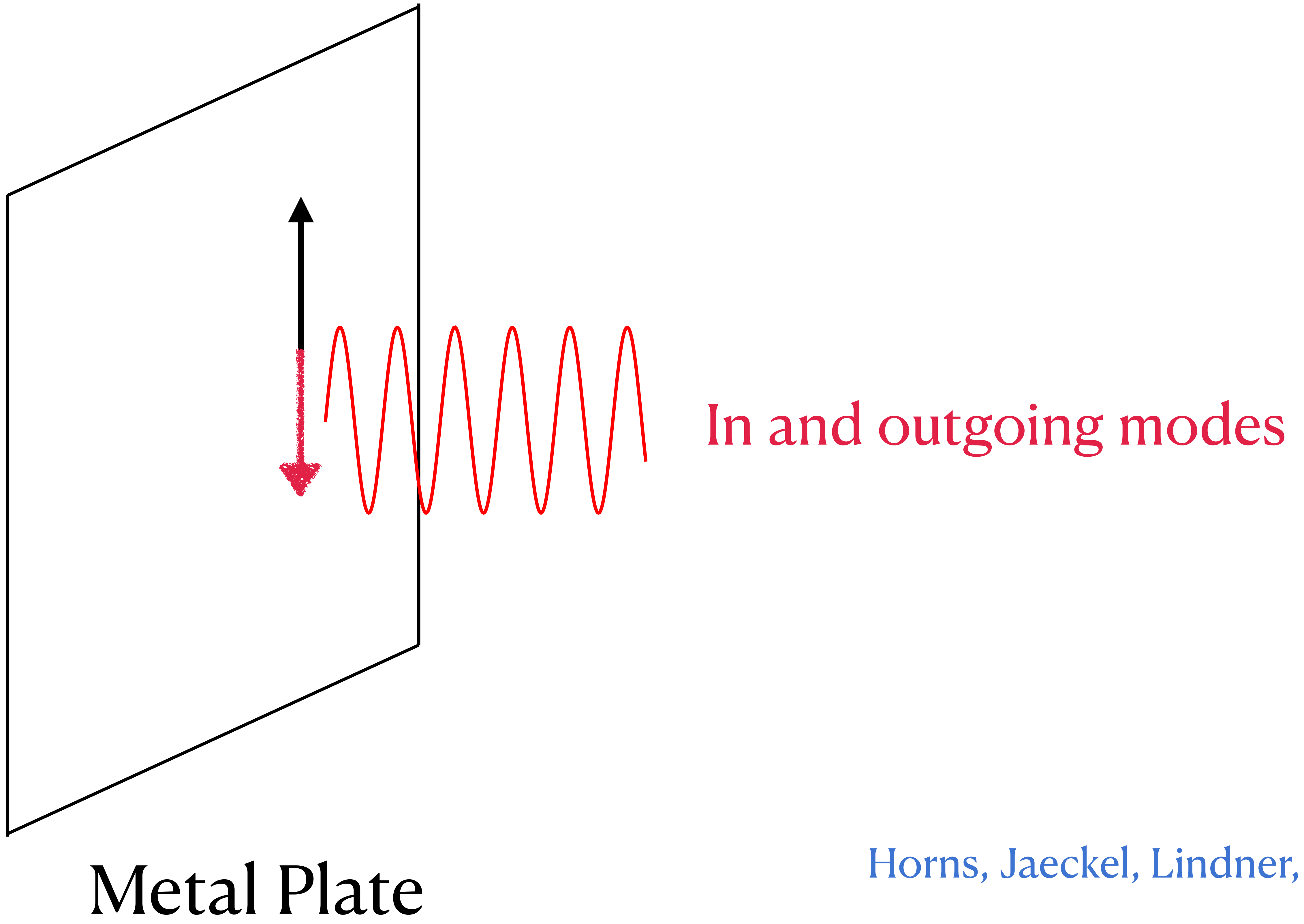


Currently Used by Gabrielse group at Northwestern University for world leading electron g-2 measurement

Effect of a metal plate

$$E_{||}^{\text{Dark}} = \epsilon\sqrt{2\rho_{\text{DM}}}\cos\omega t$$

$$E_{||}^{\text{pw}} = -\epsilon\sqrt{2\rho_{\text{DM}}}\cos\left(\omega t \pm kx\right)$$

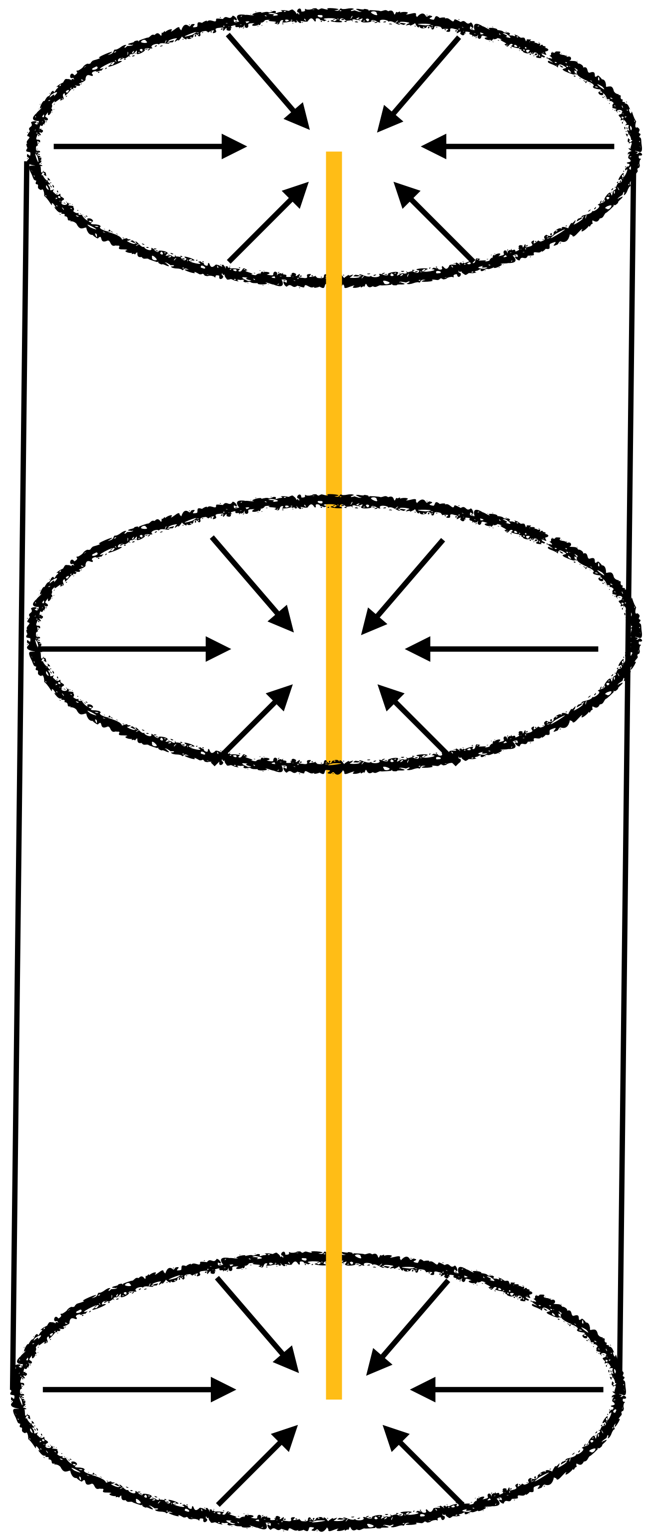


Horns, Jaeckel, Lindner, Redondo 1212.2970

Concentration

$$\kappa(0) = 1 - J_0(0)/J_0(mR) \approx \sqrt{mR}$$

$$\kappa(0) = 1 - j_0(0)/j_0(mR) \approx mR$$

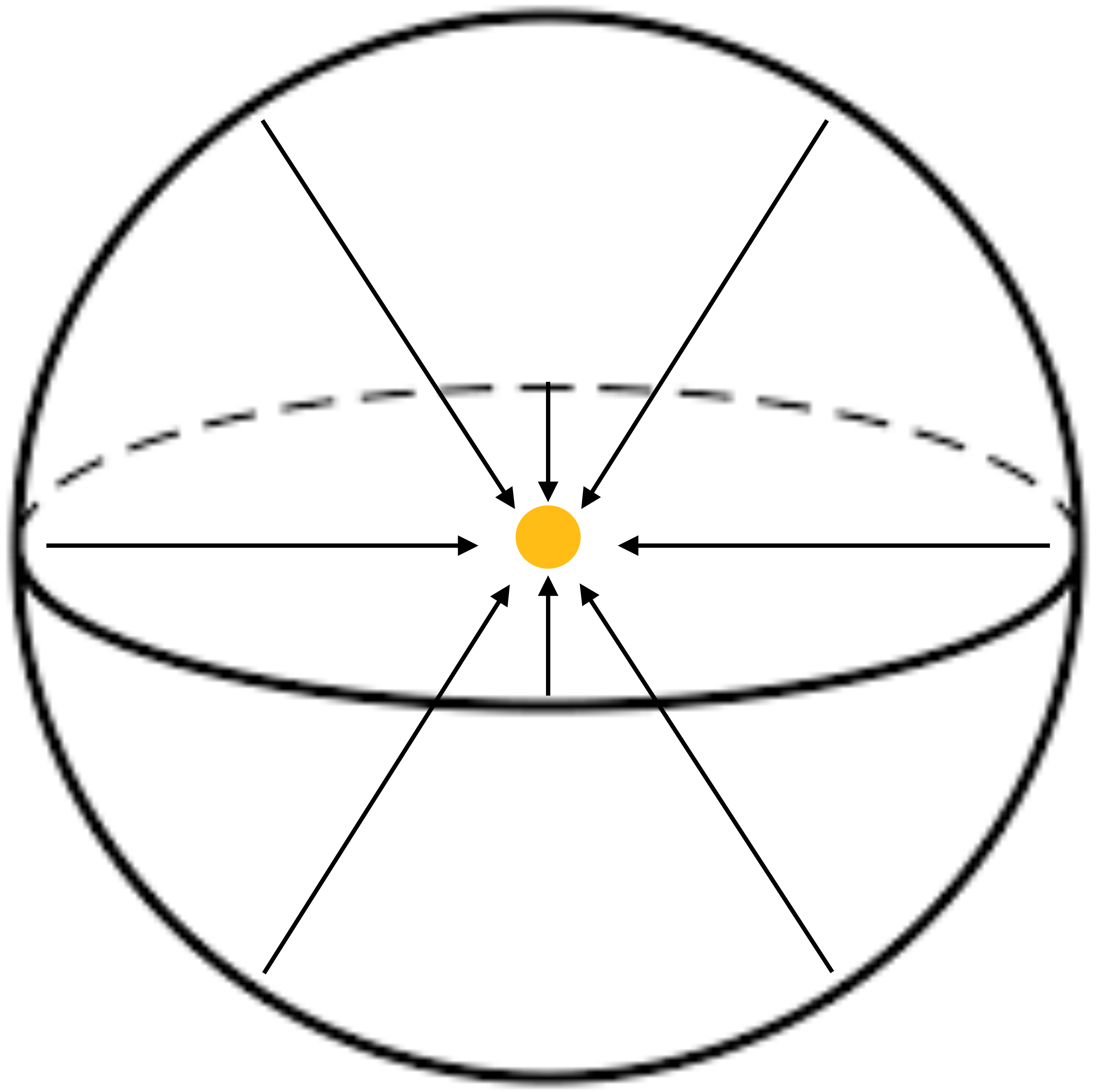


Only linear focussing

- Focussing effect because of Boundary conditions
- Will be practically useful only if we build $mR \gg 1$

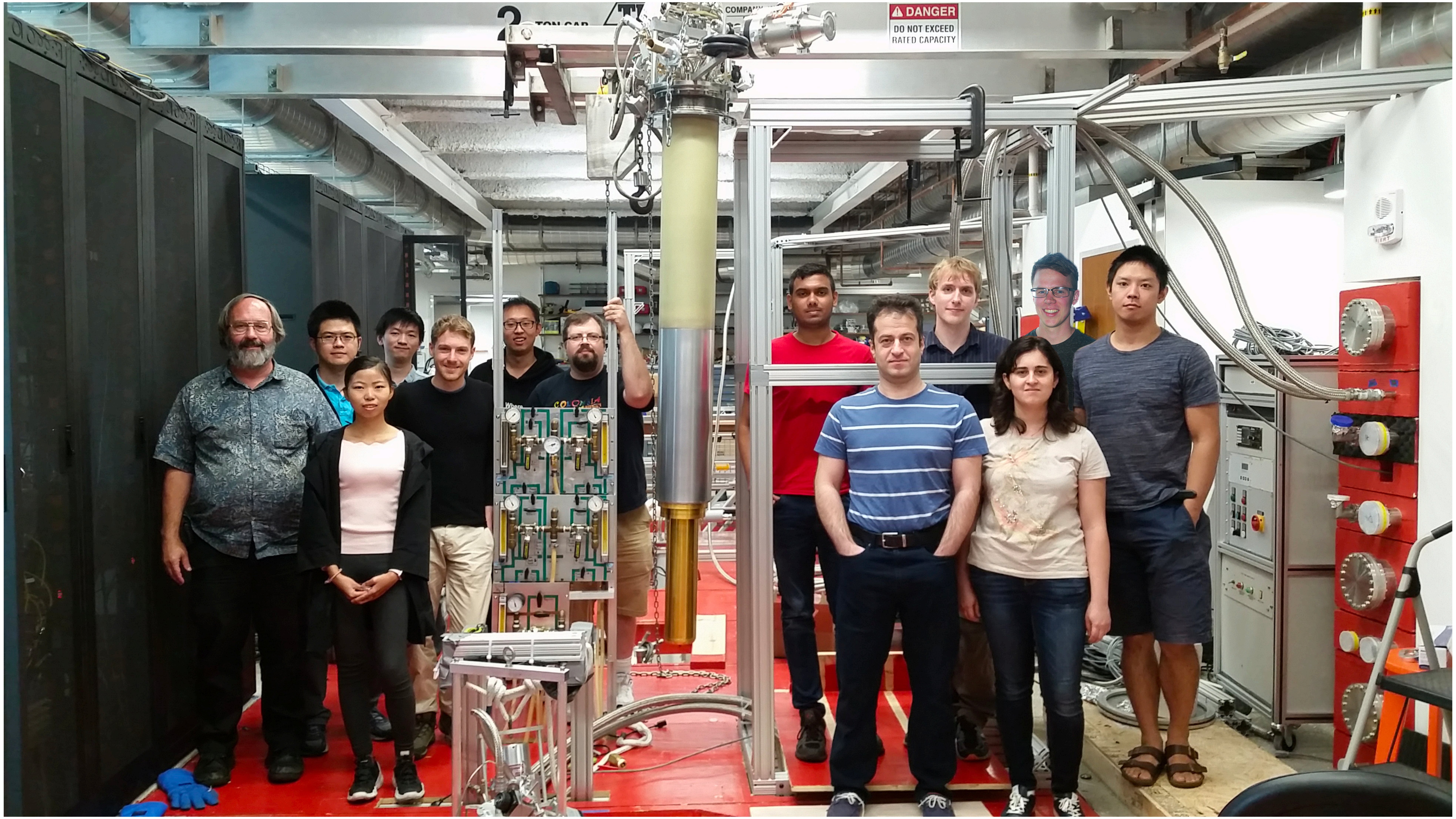
Currently $mR \approx 14$

$\kappa = \dfrac{E_{\text{cav}}}{E_{\text{free}}}$	m :DM mass R :Radius



Quadratic Focussing

Gabrielse Group



Data

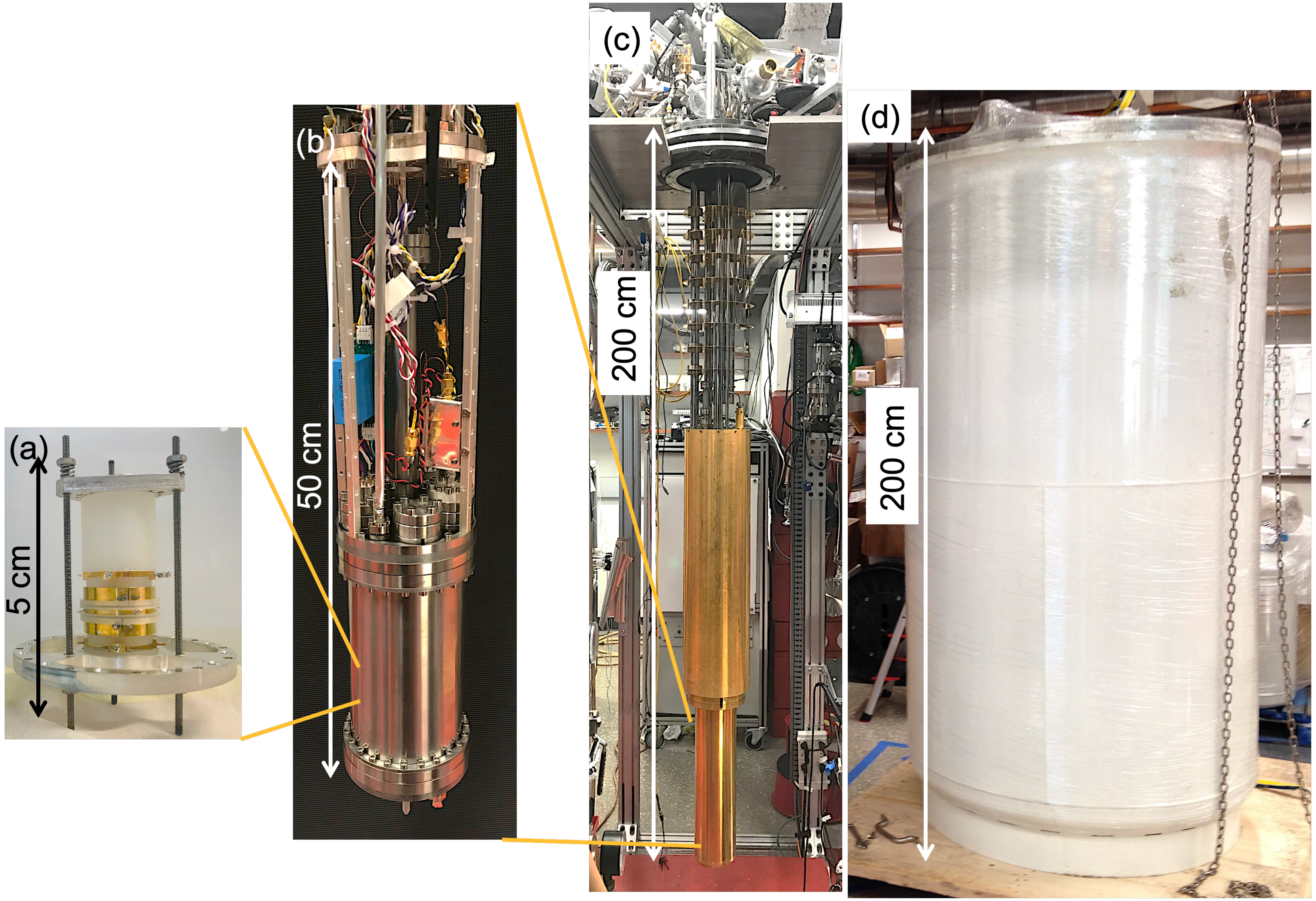


Figure 2.4: The entire setup of the experiment. A Penning trap (a) is housed in a titanium vacuum chamber (b), and the vacuum chamber is suspended at the bottom of a dilution refrigerator (c). The dilution refrigerator is inserted into the dewar (d), which has the superconducting magnet at its bottom. See also Fig. 2.7.

run #	time (date. hour:minute)	observation length (s)
1	11. 12:46 – 13. 13:15	148058
2	14. 18:26 – 15. 11:33	58162
3	15. 11:50 – 17. 17:22	179698
4	17. 18:38 – 18. 18:40	80640
5	19. 12:15 – 21. 15:43	172312
total	—	638870

TABLE I. Datasets for DPDM search in 2022 March. Each run consists of the repeated measurement cycle in fig. 3.

638870 sec = 177.5 hour

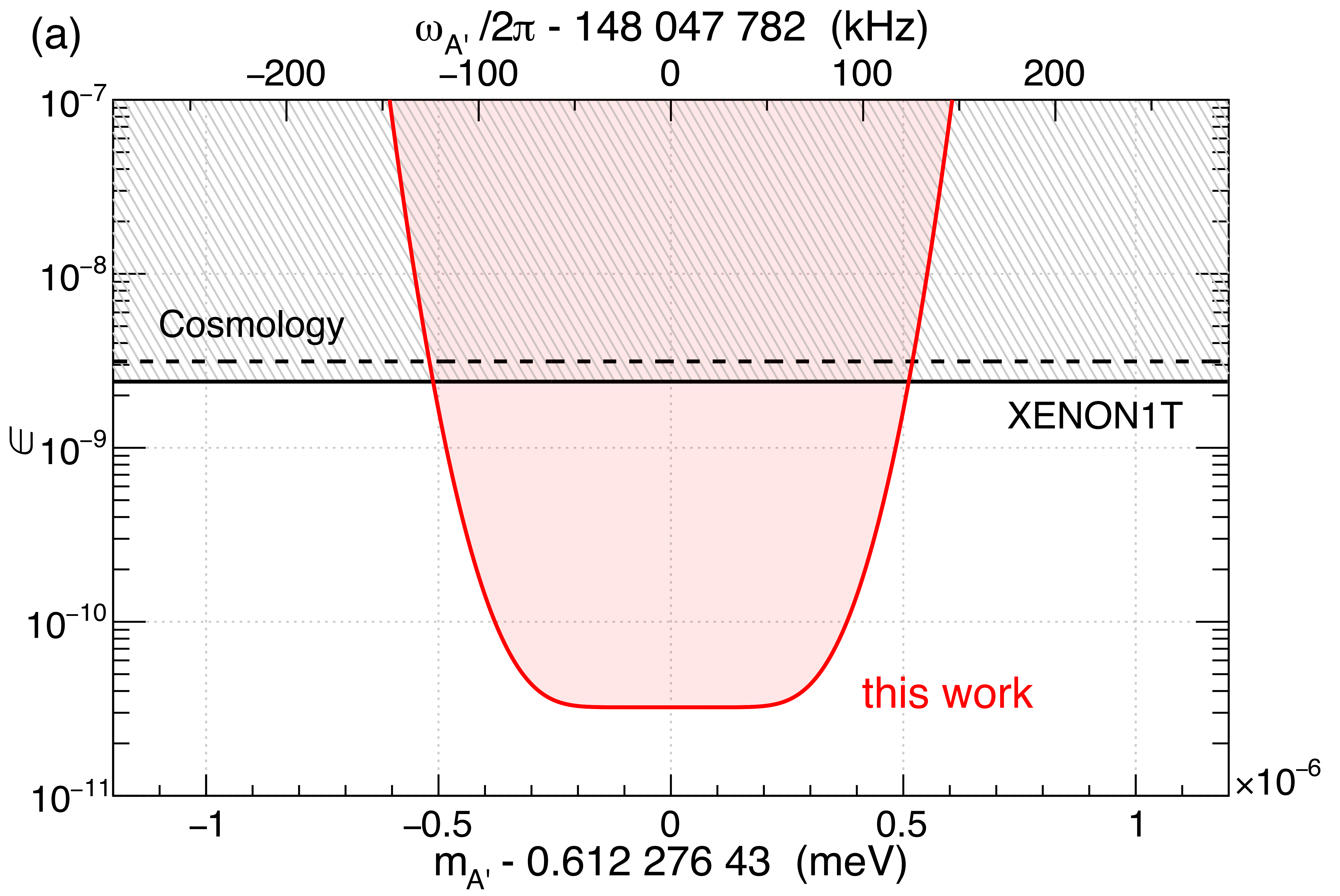
Contents

Current Data

- Non-observation in 177.5 hour data
- 2 σ limits of

$$\Gamma_+ < -\frac{1}{\zeta T_{\rm tot}} \log\left(1 - CL\right) = 4.33 \times 10^{-6}~{\rm s}^{-1}$$

- No scanning - width set by DM $\Delta\omega = 10^{-6}\omega$
- Acts as proof of principle
- Also demonstrates no background



To Do

- Scanning 15 sec/bin

4 Apr 2022 in Politics & Policy

Helium is again in short supply

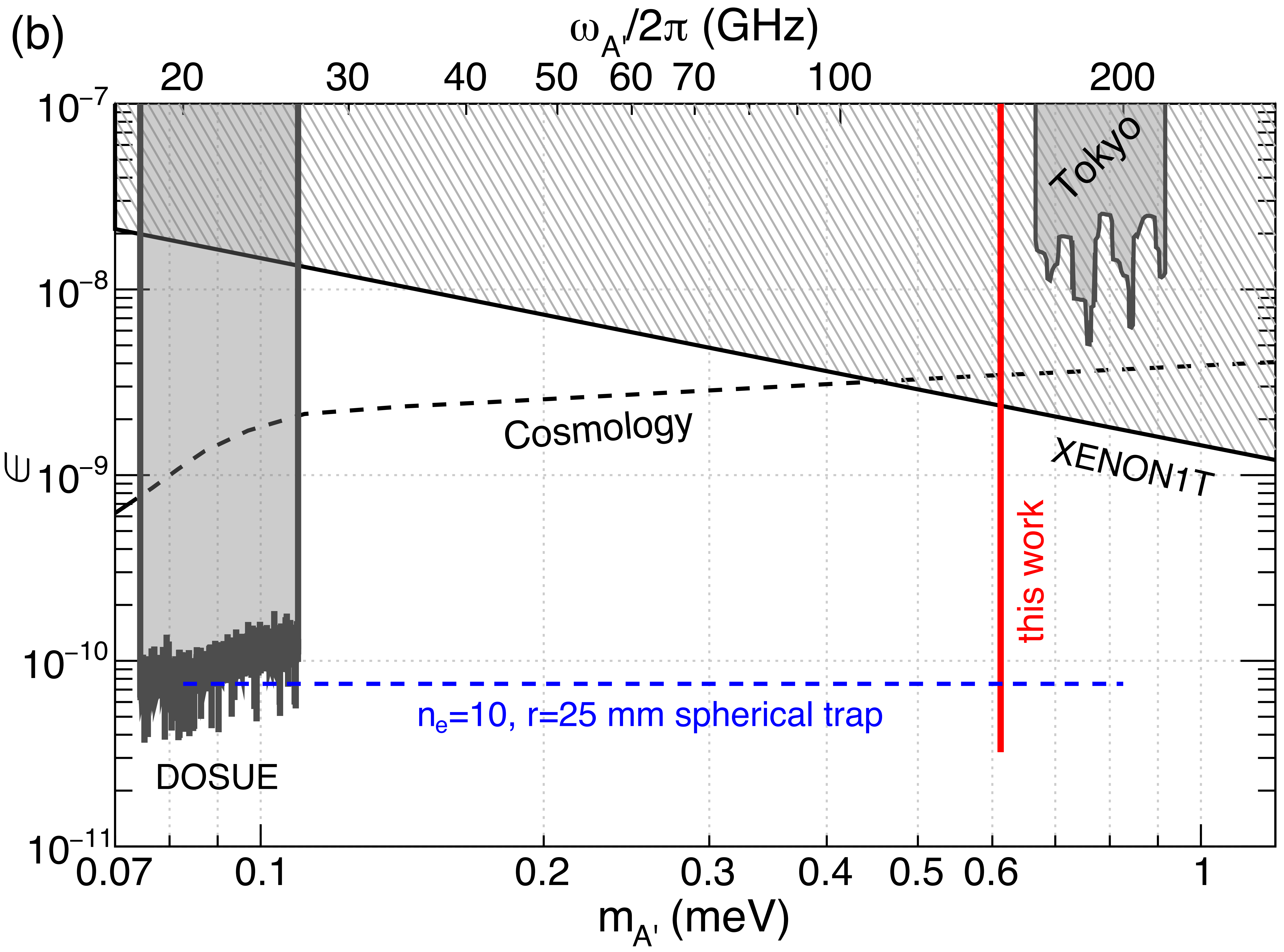
The war in Ukraine isn't much of a factor, yet.

David Kramer

The federally operated Cliffside Helium Plant in

< PREV NEXT >

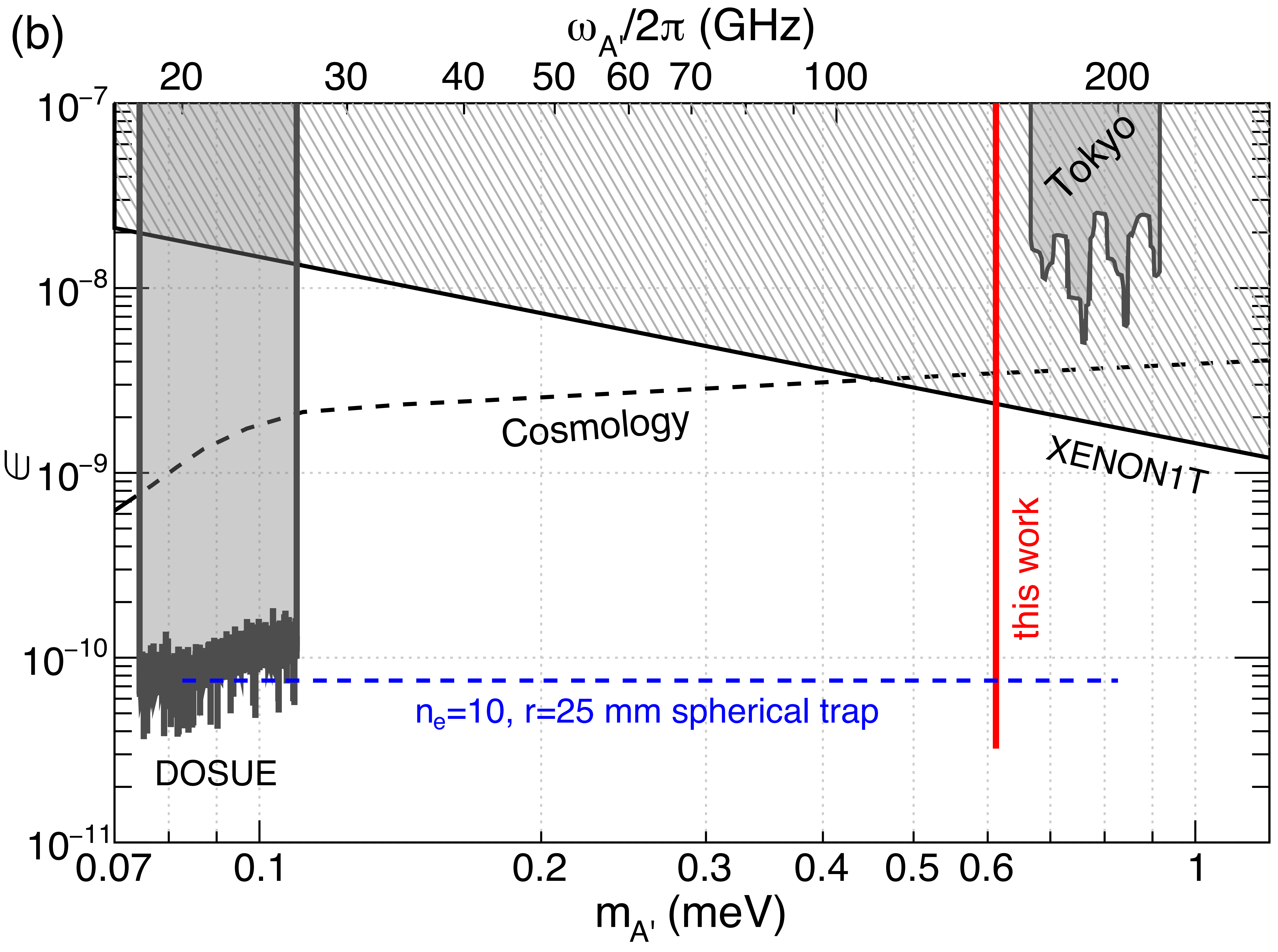
physicstoday.scitation.org



To Do

- Scanning 15 sec/bin
- Future:

A. Bigger Cavities
B. More electrons
C. Higher excited states
D. Other Shapes?



Summary

- Dark Photon Dark Matter: hard to probe in the 100 GHz range
- We proposed a new way to detect this

using existing apparatus built for electron g-2 measurements:

a trapped electron

- Pilot Run @ single frequency observed no events
- Scanning/Other improvements on the anvil

Contents

Introduction

DARK MATTER → STABLE PARTICLE

DARK RELIC ← **STABLE PARTICLE**

- Well motivated stable particles: Monopoles, axions, squarks, heavy quarks (KSVZ), gluinos (SUSY), Milli-charge Particles

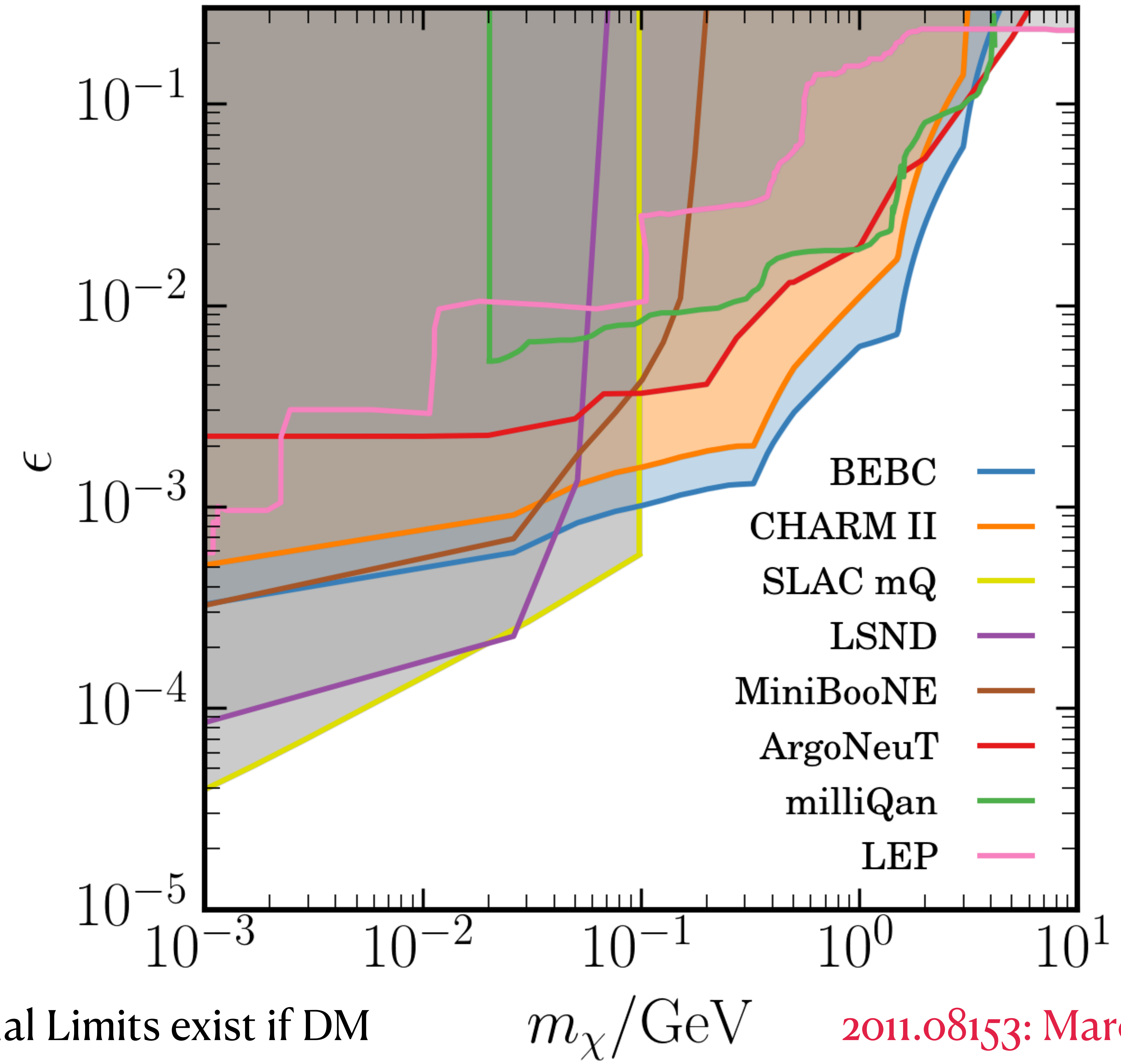
See for e.g. De Luca et al. 1801.01135
And Gross et al. 1811.08418

- Robust prediction for relic fractions $f_{\rm DM} \ll 1$
- The only way to access $M_\chi \gg$ TeV or coupling $\ll 1$?
- Cosmic Neutrino Background
- Relics invoked to explain recent anomalies
- Same Direct Detection Concept

Millicharge Particles

- Particles with tiny electric charges: ϵe
- Simple models to write (with or without a dark photon)
- Charge Quantization?!?
- Stable Particles : Relic Density Exists?
- Looked for in various experimental programs
- Recent resurgence due to EDGES anomaly

Existing Limits



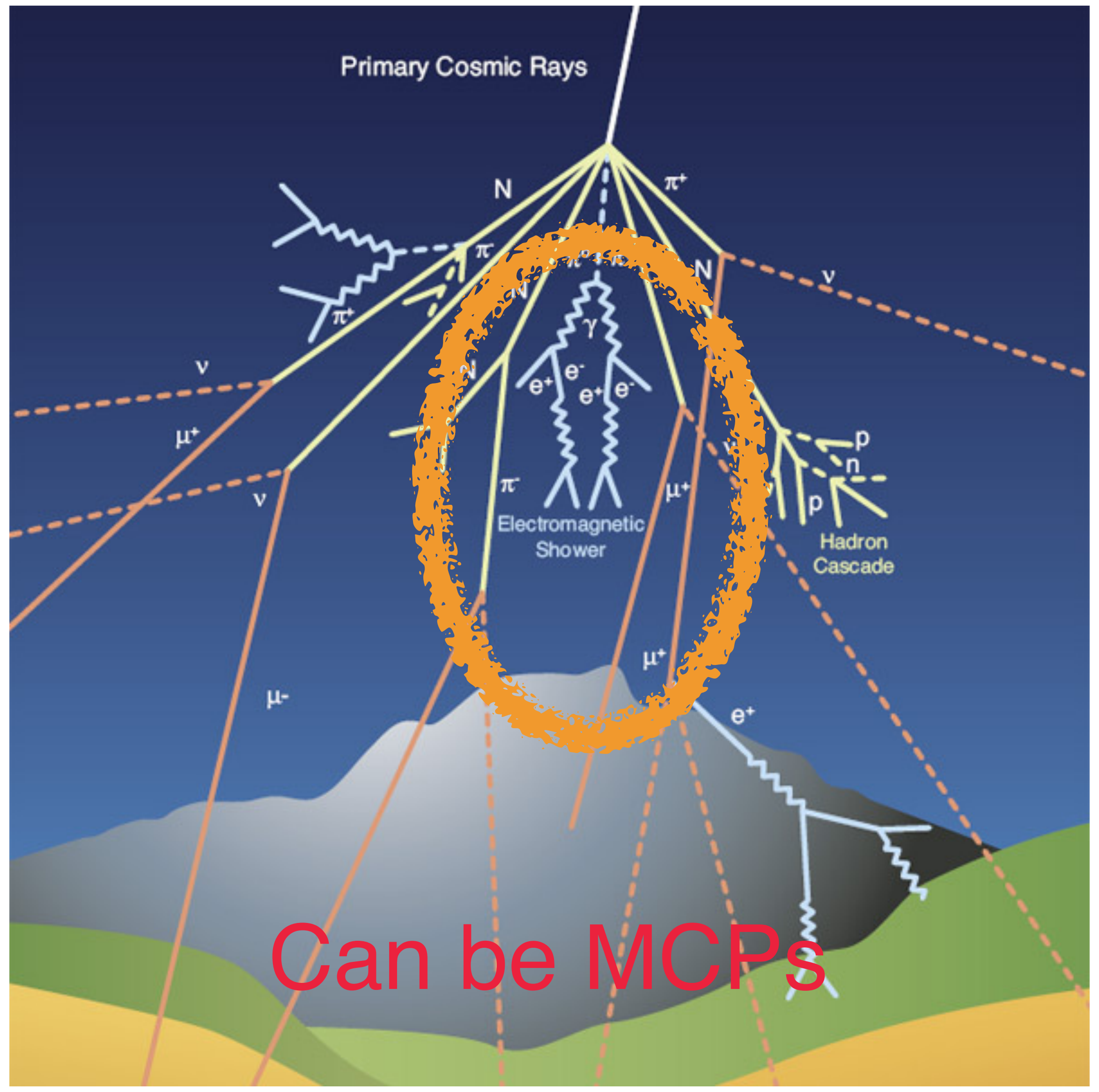
*Additional Limits exist if DM

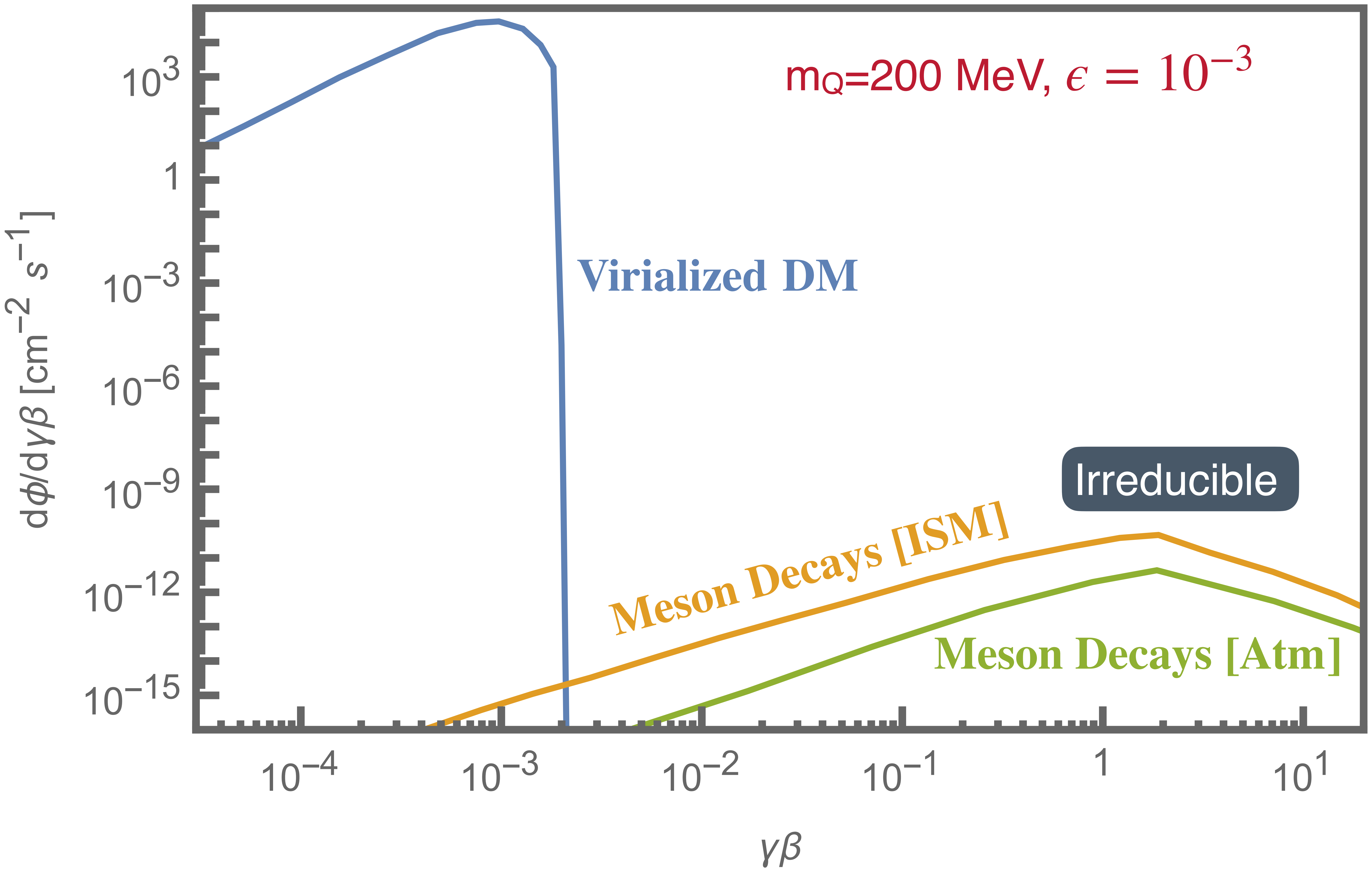
2011.08153: Marocco & Sarkar

An Irreducible mCP source

2010.11190 HR, Roni Harnik, Ryan Plestid and Maxim Pospelov

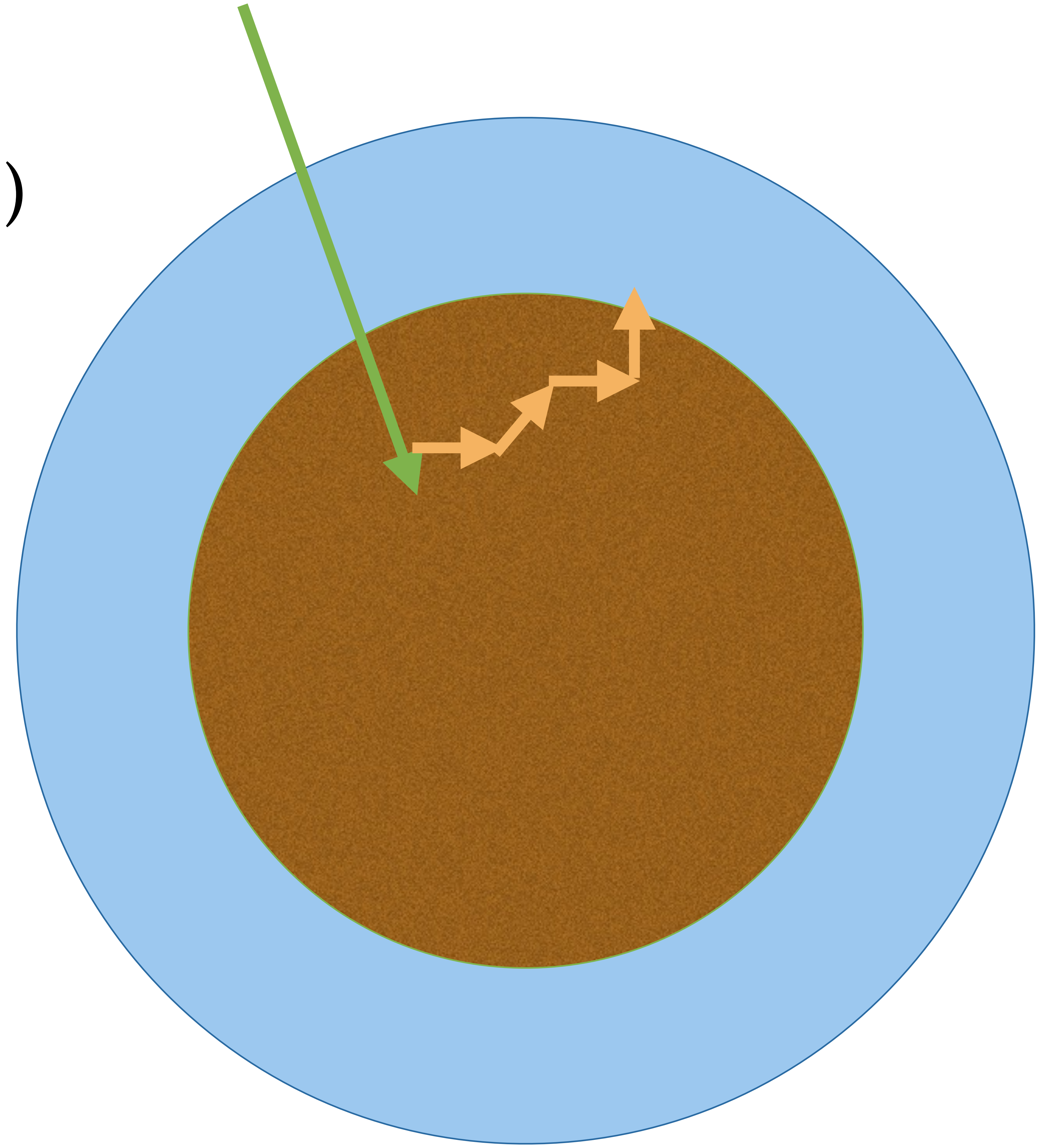
- Mesons produced in Cosmic ray collisions can decay into mCPs
- Contribution to irreducible flux on Earth





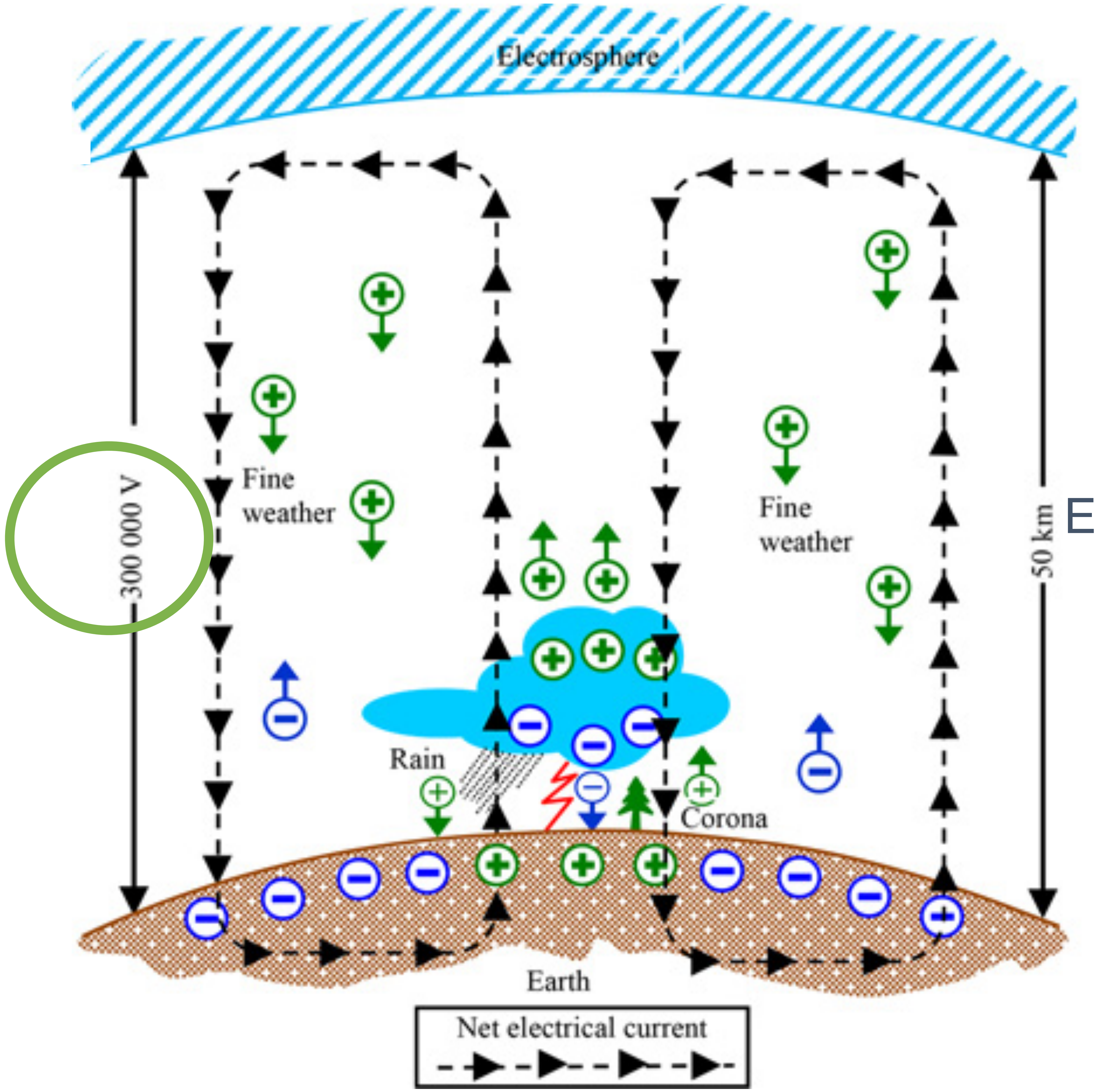
Temporary accumulation

- High boost, hence penetrates deep
- Thermalized mCP, large x-section, (MFP~ micron)



from: 2012.03957 H. Ramani, M.Pospelov

Earth E-field

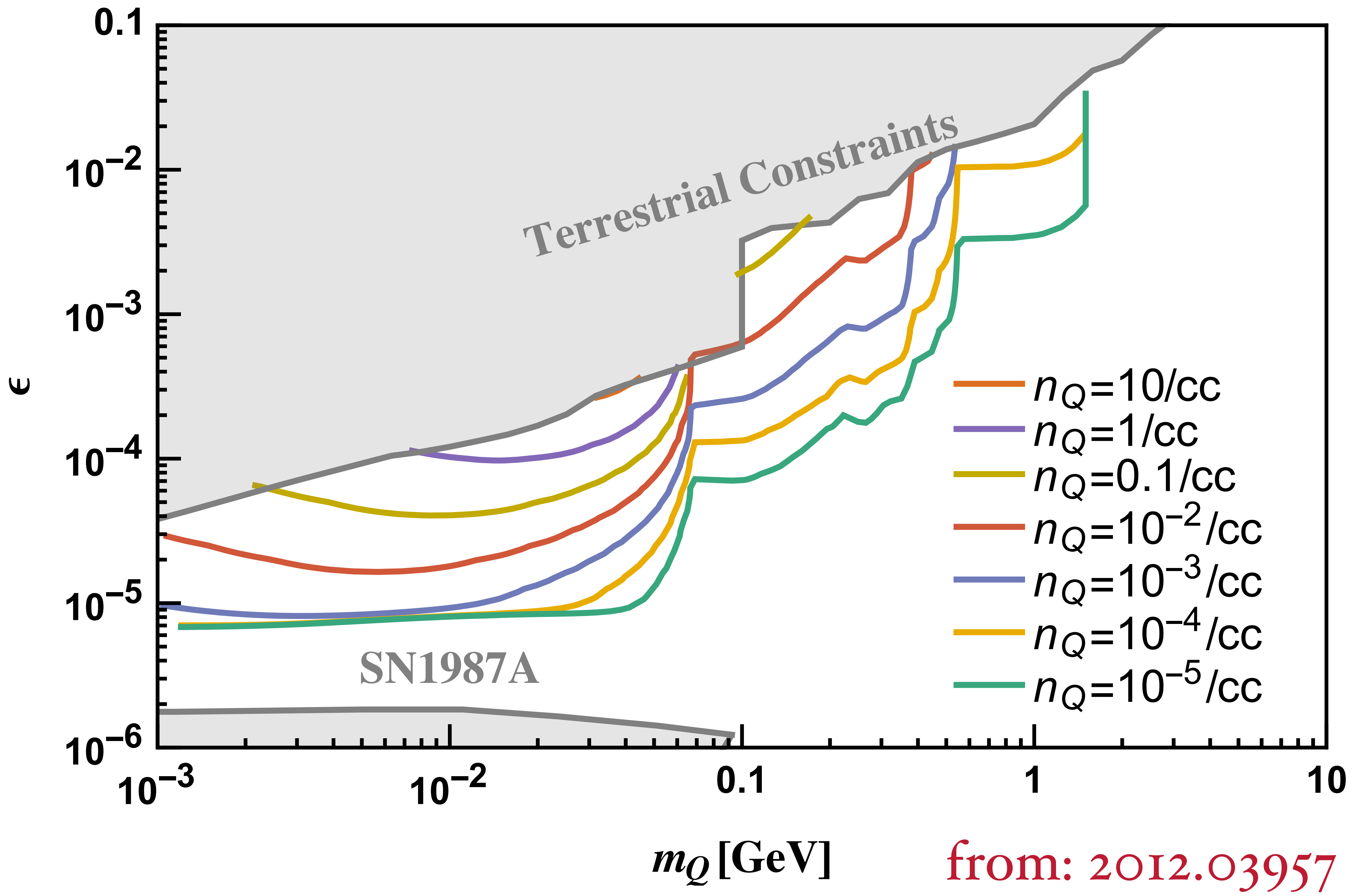


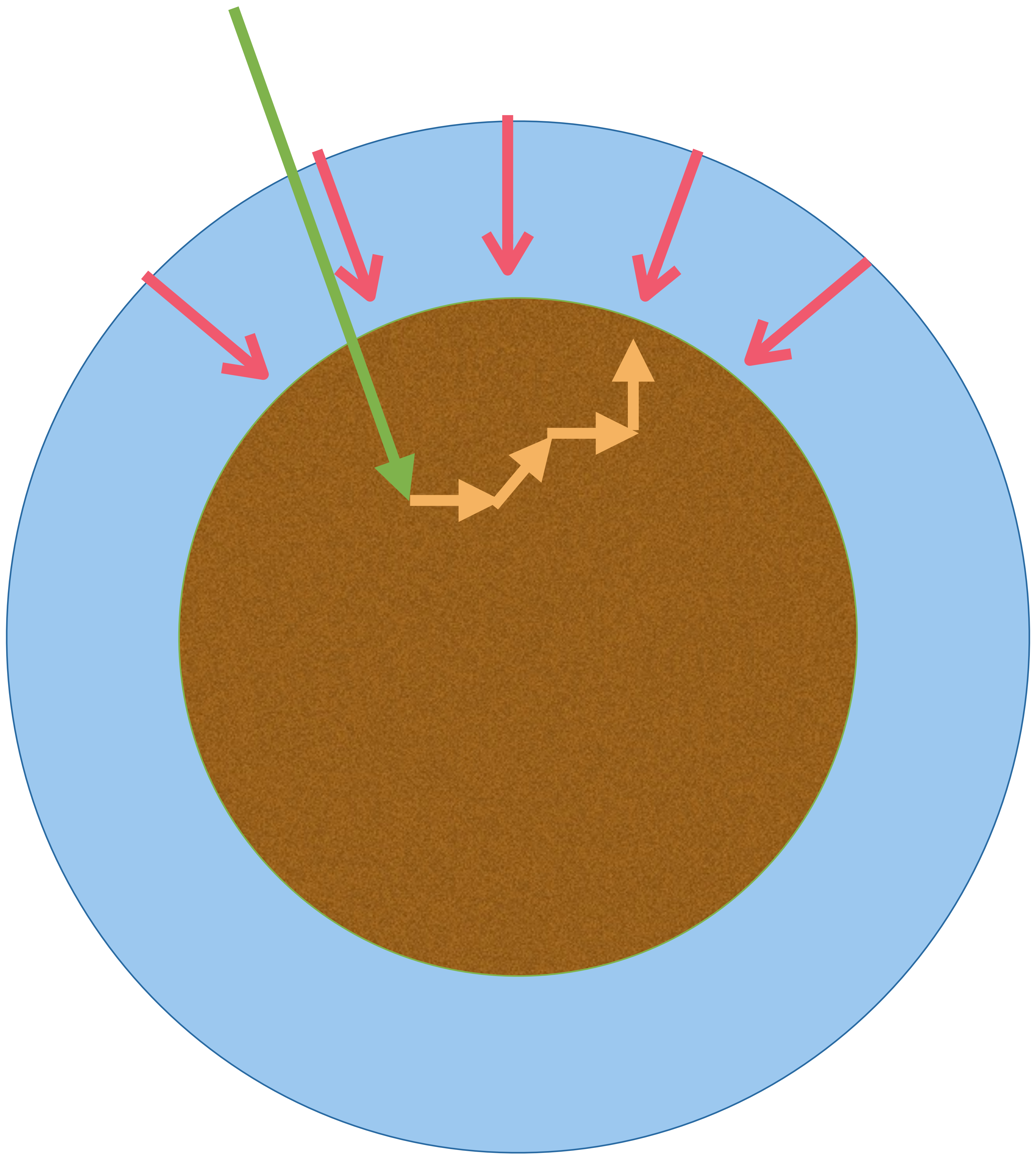
Electric Field ~ 100 V/meter

Lightning discharge
A Beroual and I Fofana

Permanent Accumulation

- If pure Milli-charge, it feels earth electric field
- Evaporation turned off for large positive mCP
- Accumulation over 5 Billion years

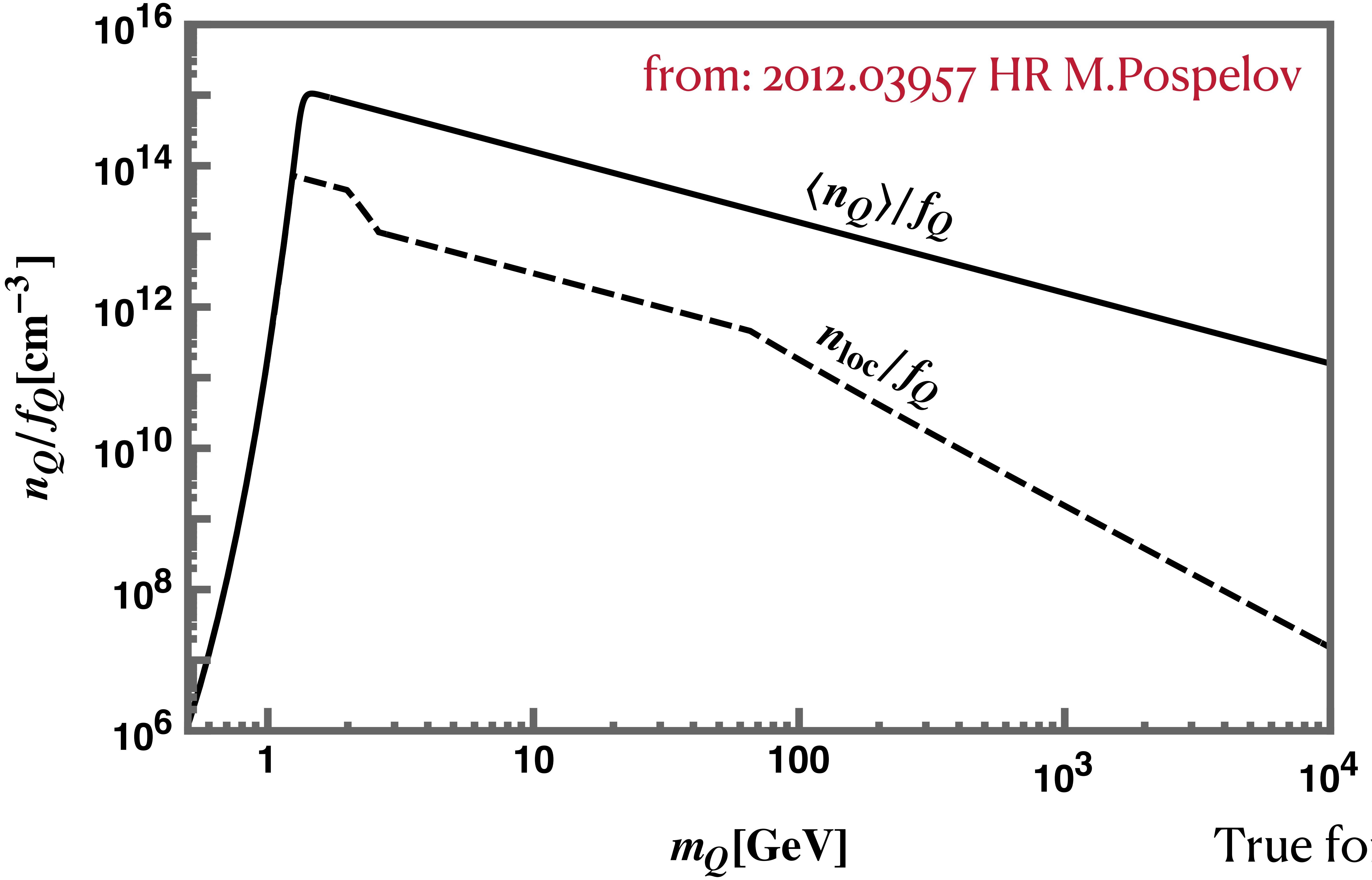




from: 2012.03957 H. Ramani, M.Pospelov

Dark Matter

Enhancement:
$$\frac{\text{Area} \times \text{DM flux}}{\text{Volume} \times \text{DM density}} \times \text{Age of Earth} = \frac{\pi R_E^2 v_{\rm vir}}{\frac{4}{3}\pi R_E^3} T_E \approx 10^{16}$$

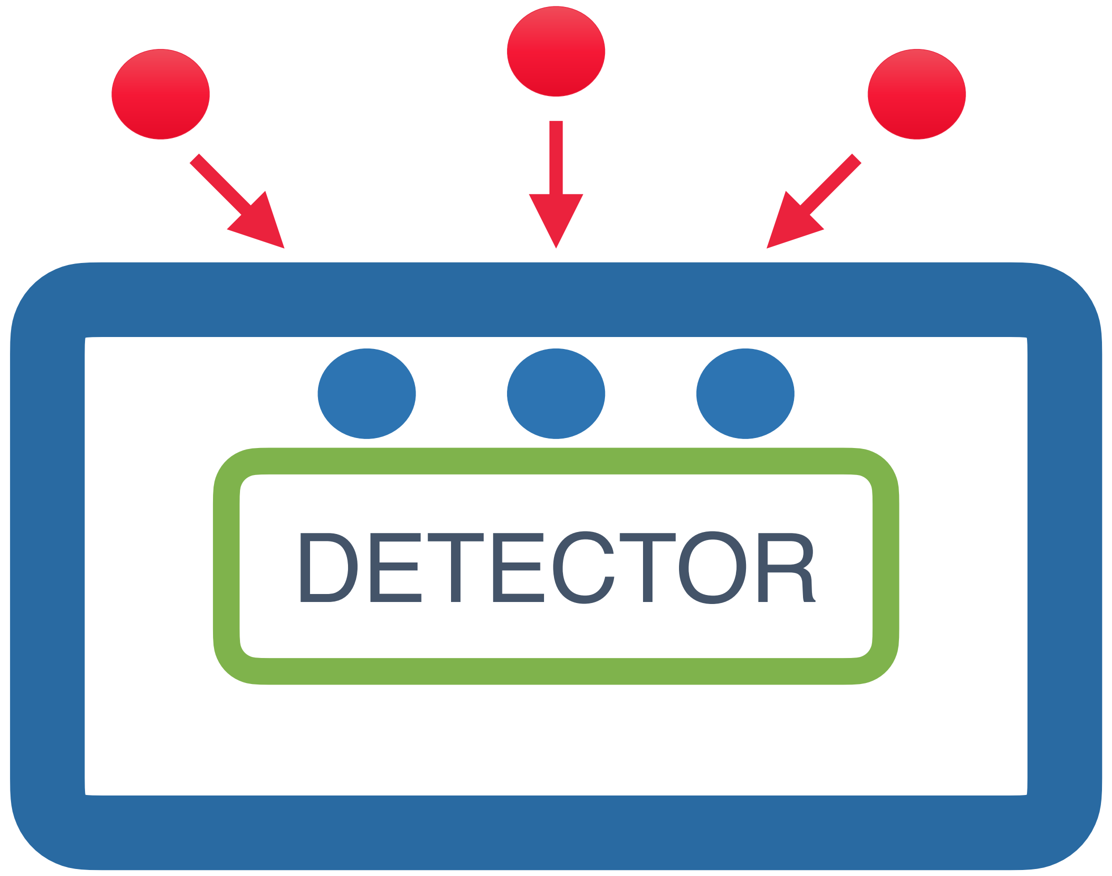


True for charges $\epsilon \gtrsim 10^{-6}$

Detection Nightmare

- Despite large number density & cross-section

- Small energy deposit: $300 \ \text{Kelvin} \approx 26 \ \text{meV}$



- Low threshold detectors have low temperature walls to reduce background

- Small MFP~ micron, rapidly thermalize with walls

Sisyphean Task?

- Electron trap 500 μeV threshold, 10 μeV walls.

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Ion Traps

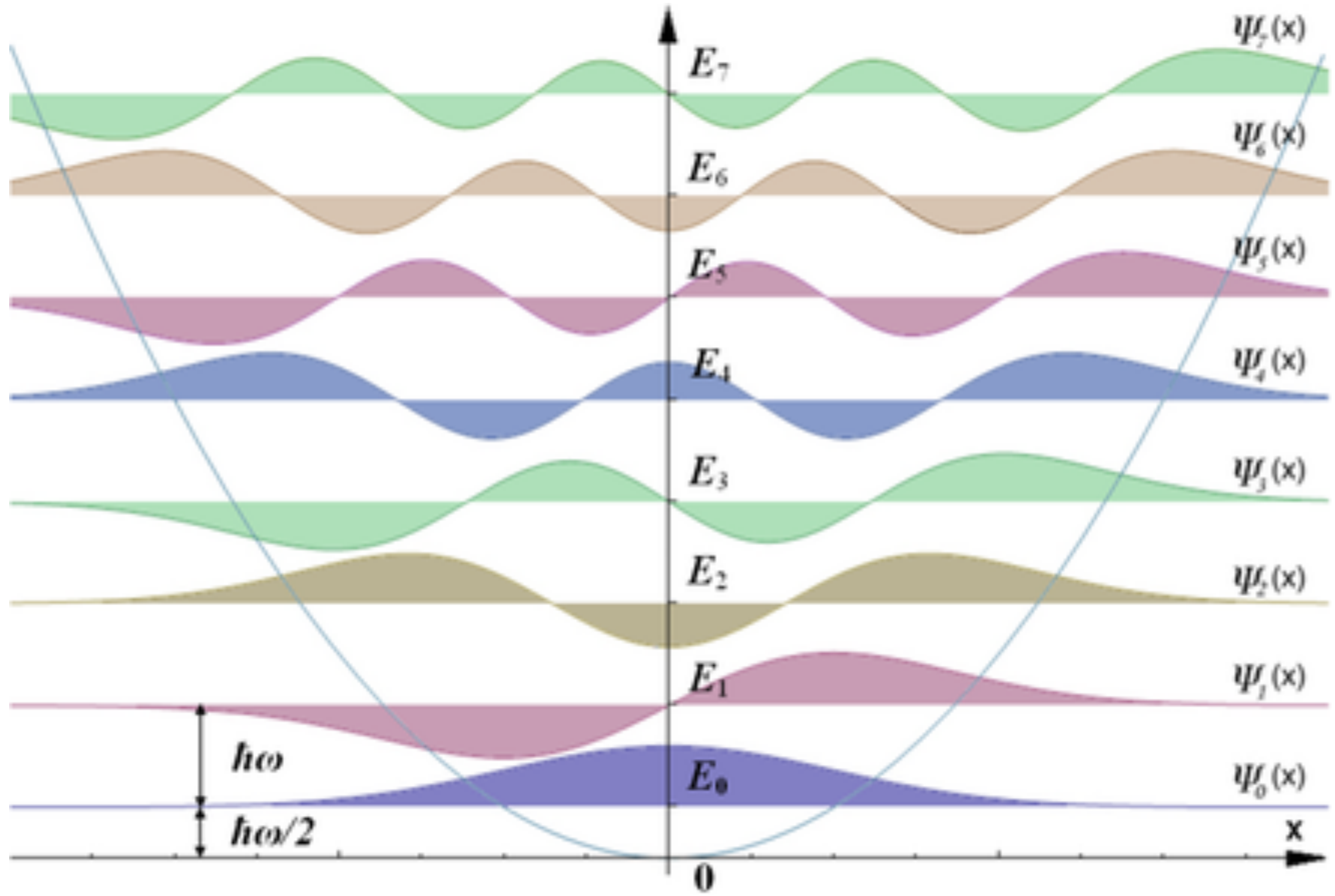
$$\frac{qB}{m_p} \approx 60 \text{ neV} \frac{B}{1\text{T}} \frac{1 \text{ GeV}}{m_p}$$

$$\approx 1\text{mK}$$

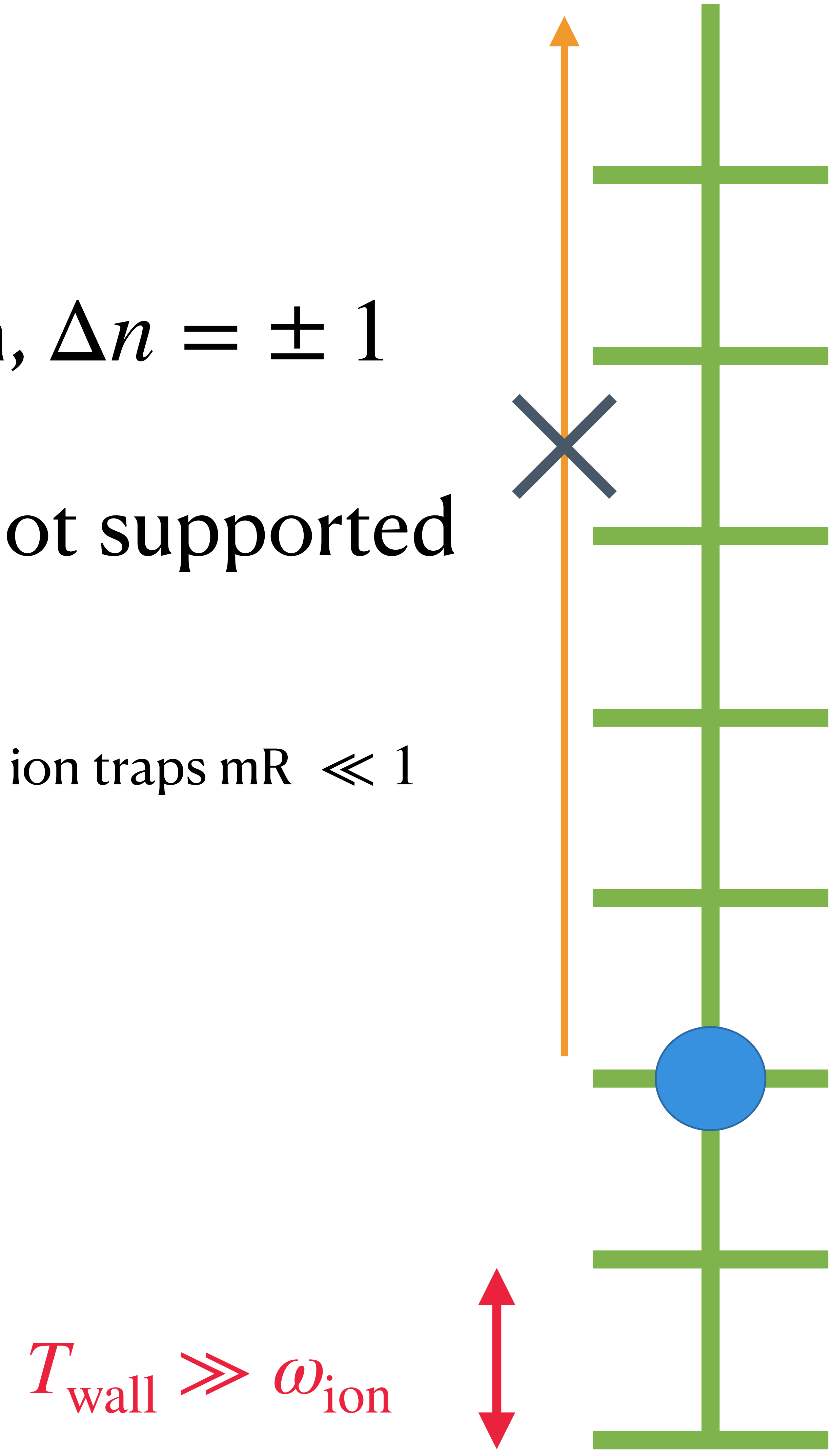
Don't we have to cool to $T_{\text{wall}} \ll$ mK?

Selection Rules

- Approximate Harmonic Oscillator
- Blackbody radiation : Selection rules for photon absorption, $\Delta n = \pm 1$
- Number of photons with energy $\omega_{\text{ion}} \ll T_{\text{wall}}$ is negligible, not supported

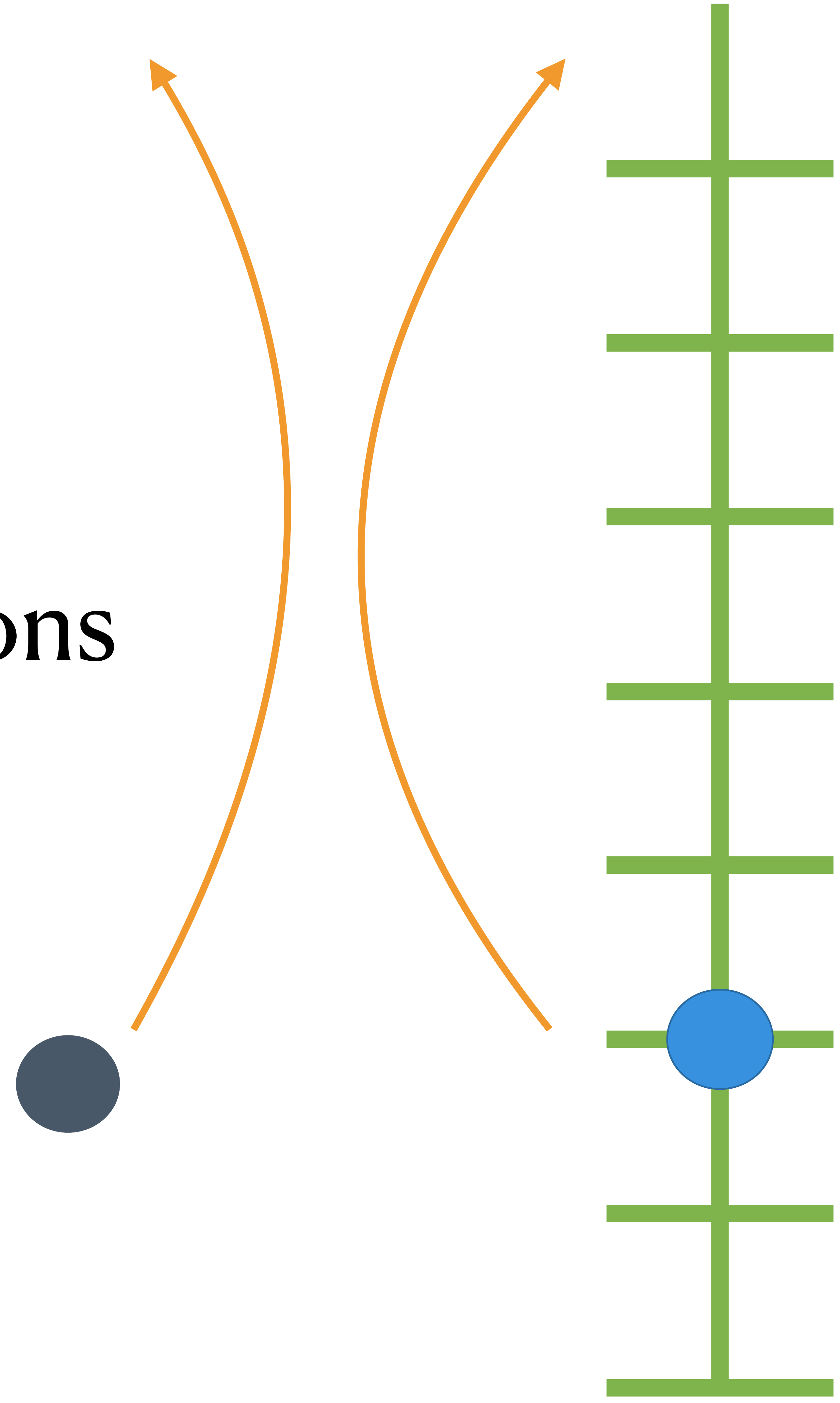


Important Difference: For ion traps mR $\ll 1$



Selection Rules Contd.

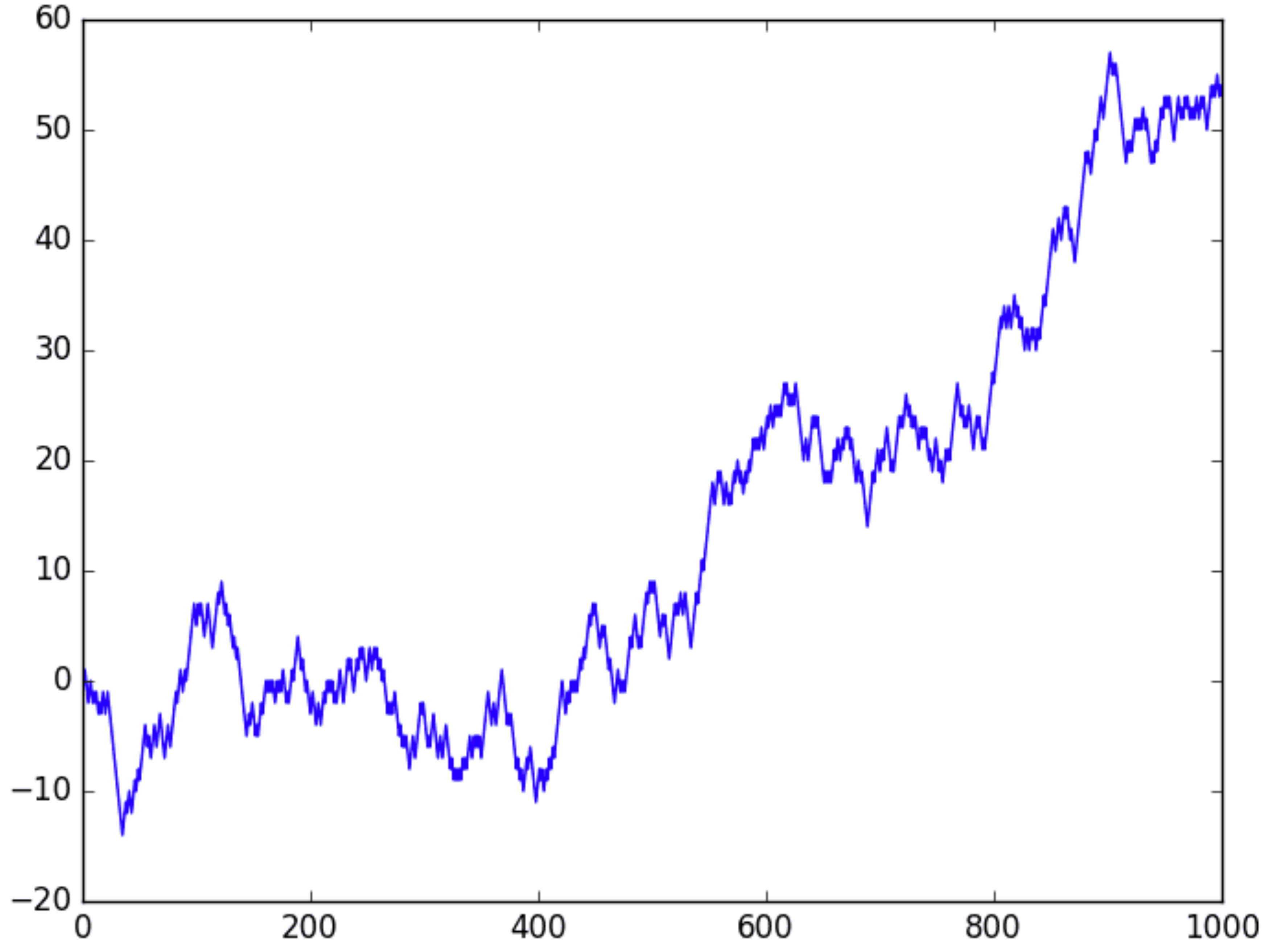
- Scattering breaks selection rules
- Momentum transfer $\gg$ Energy Transfer
- New source of heat transfer from walls to ions



Two Observables

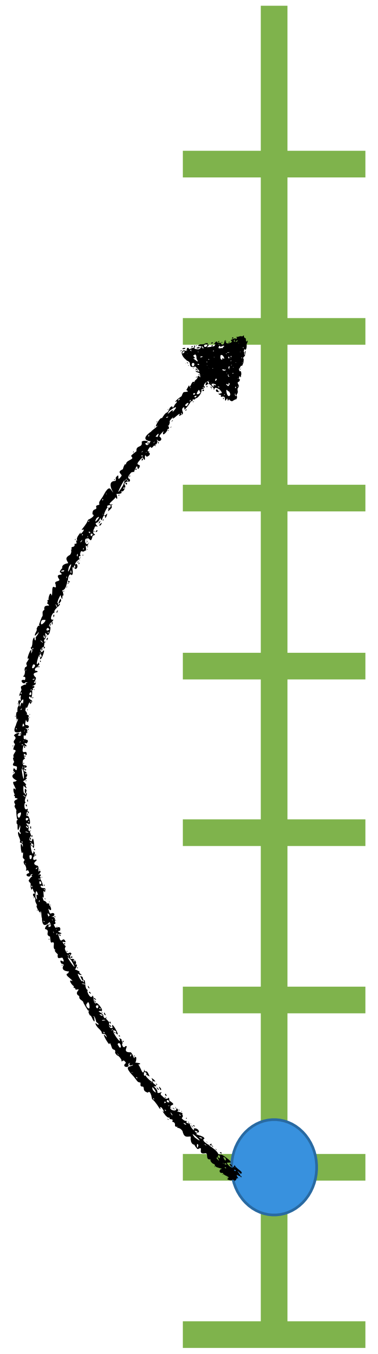
Heating Rate

- Accumulation of tiny magnetron/cyclotron jumps
- Limited by observed Heating
- Existing Data



Event Rate

- Observation of a single jump $\Delta n \gg 1$
- Only gas collisions can cause this
- Planned for future



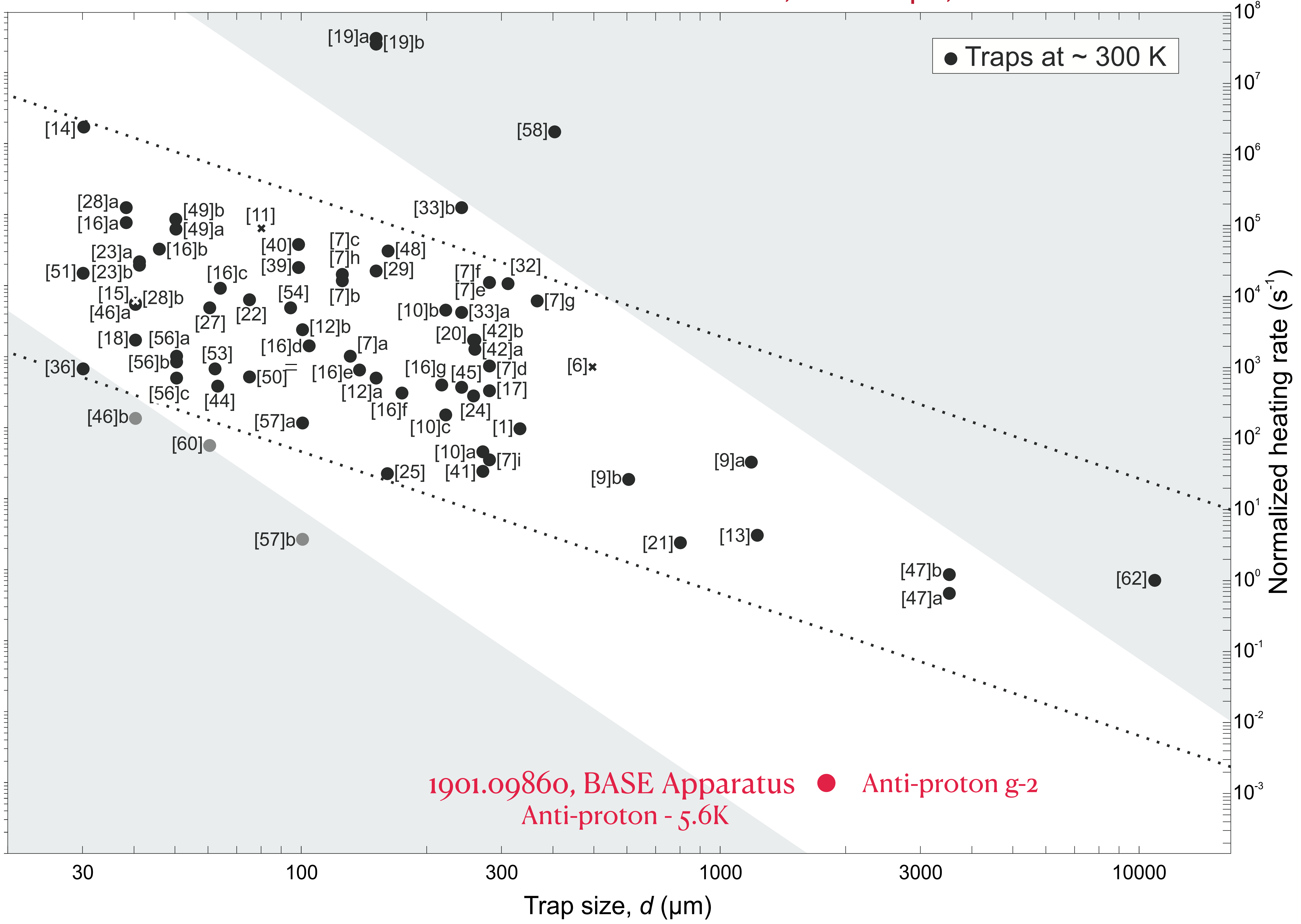
Standard Model Heating

- Cryopumping (cold surfaces trap SM particles) to pressures $< 3 \times 10^{-21}$ bar
- Work Function of metals prevents electron evaporation (Does not stop mCPs)
- Lowest measured: $\dot{\omega} \approx 10^{-12}\ \mathrm{eVs}^{-1}$
- Blackbody Radiation estimate: $\dot{\omega} \approx 10^{-14}\ \mathrm{eVs}^{-1}$
- Background gas estimate: $\dot{\omega} \approx 10^{-16}\ \mathrm{eVs}^{-1}$
- Expected to be from electrode noise

Heating Rate in Ions

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

- ^{40}Ca / ^{9}Be / p ions used
- $\nu_+ \approx$ MHz $\approx$ **4** neV $\approx 50\mu$K
- $\dfrac{dn}{dt} \approx \dfrac{10^{-3}}{\text{sec}}$
- Heating Rate: $\dfrac{\text{peV}}{\text{sec}}$
- Active area of research: Trapped Ion Quantum Computing



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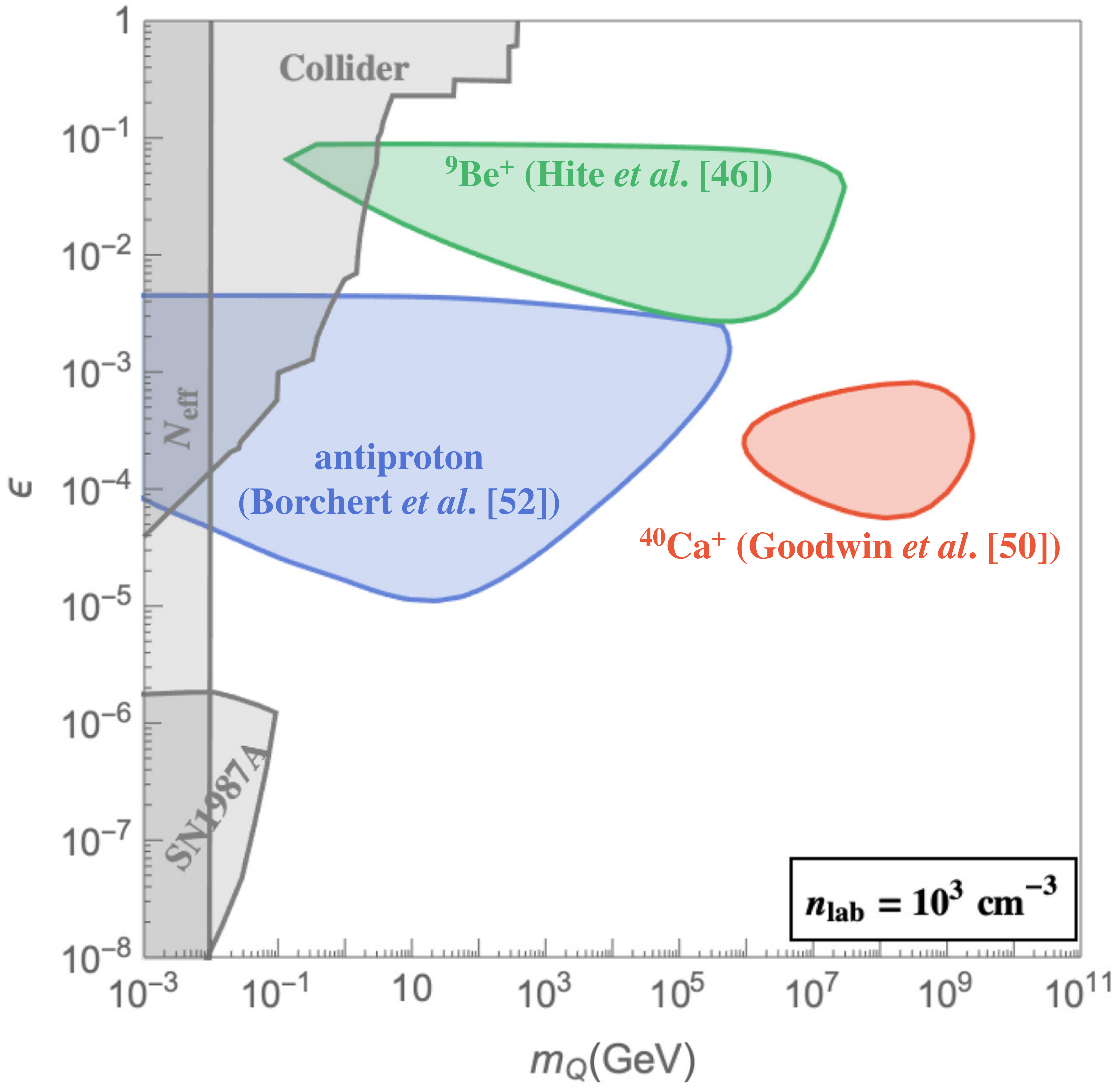
Results



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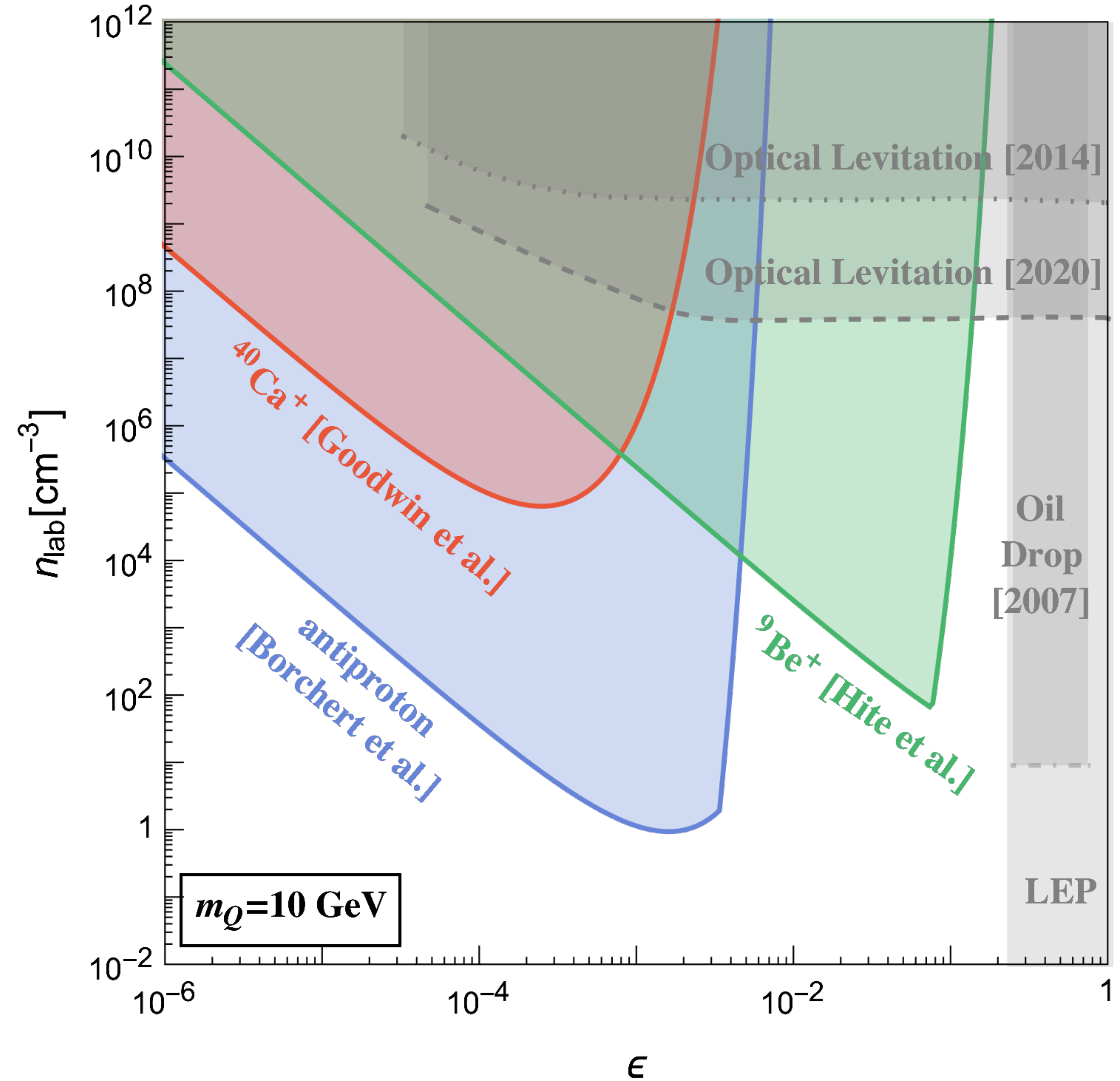
Results



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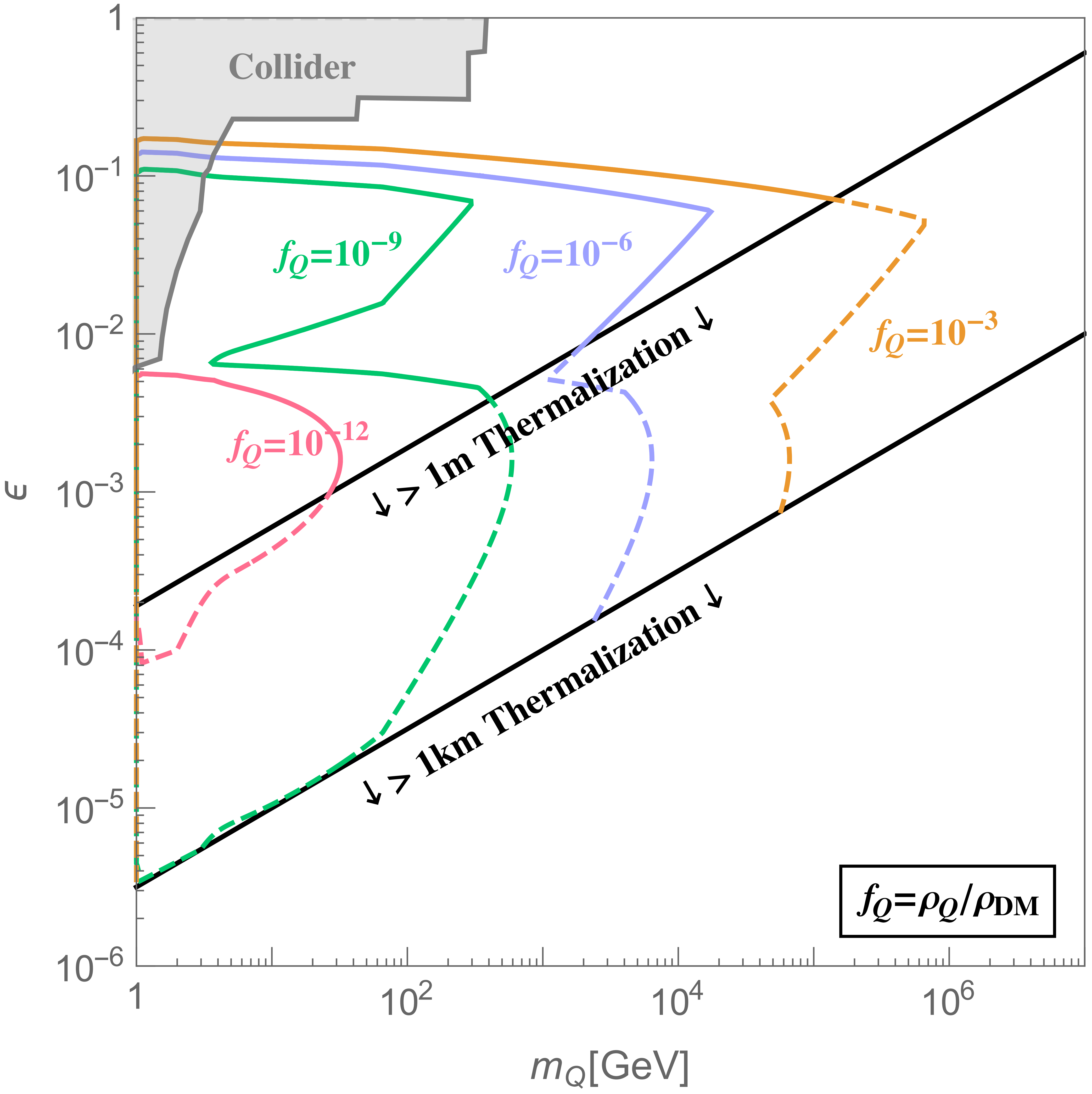
LIMITS ON DARK MATTER FRACTION



PRX Quantum(2022): D. Budker, P. W .Graham, Harikrishnan Ramani, F. Schmidt-Kaler, C. Smorra

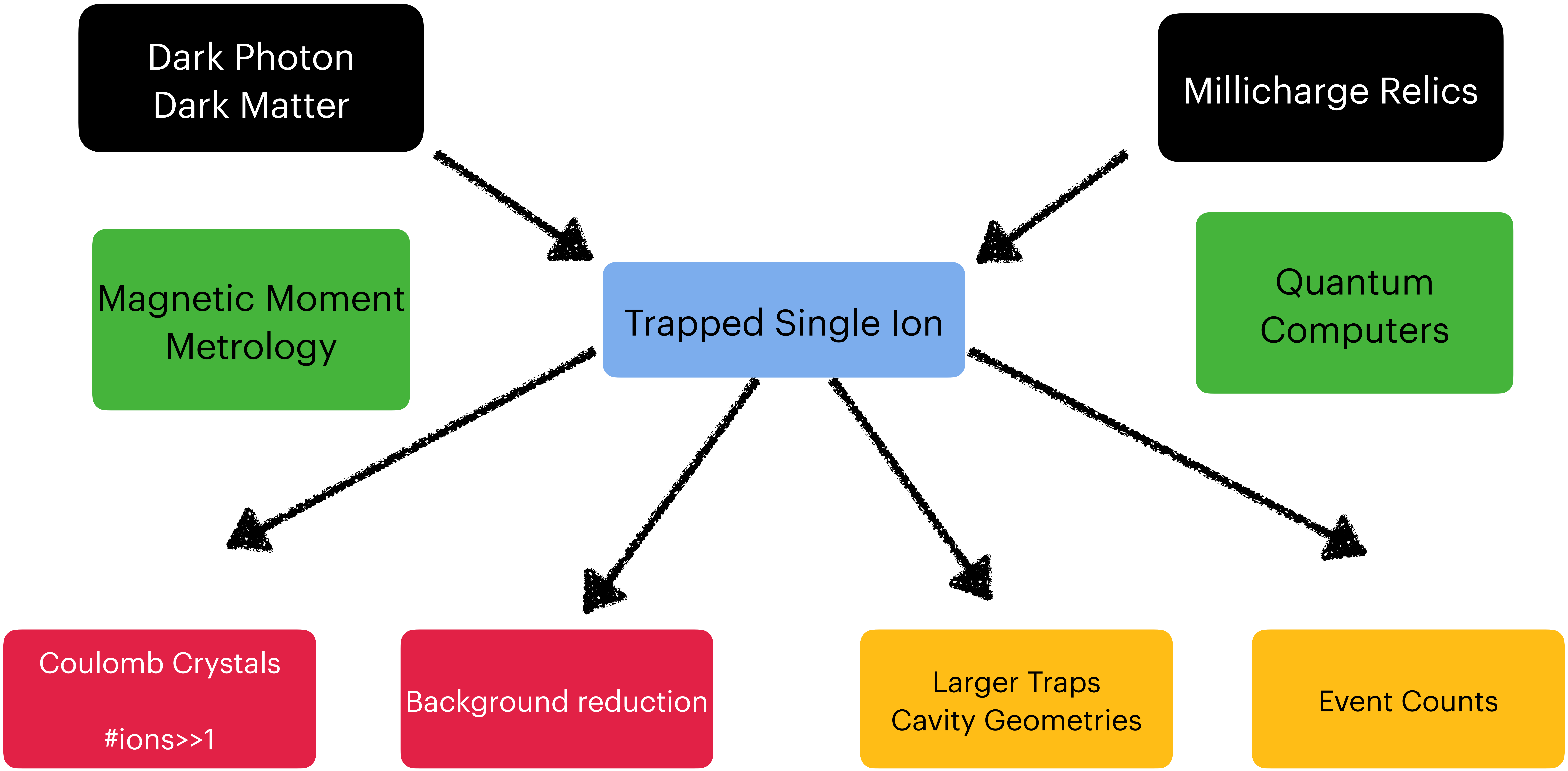
Outlook

- Implementing single event rates
- Excitations in Ion lattices
- Accumulating mCPs in an electric field bottle

Summary - Ion Traps

- Thermal terrestrial millicharge population
  - Irreducible population from Cosmic rays
  - Or $f_{\text{DM}} \ll 1$
- Heating limits on ion traps studied to realize qubits improve existing limits by upto 8 orders of magnitude
- Future dark matter specific studies planned.

Talk Summary



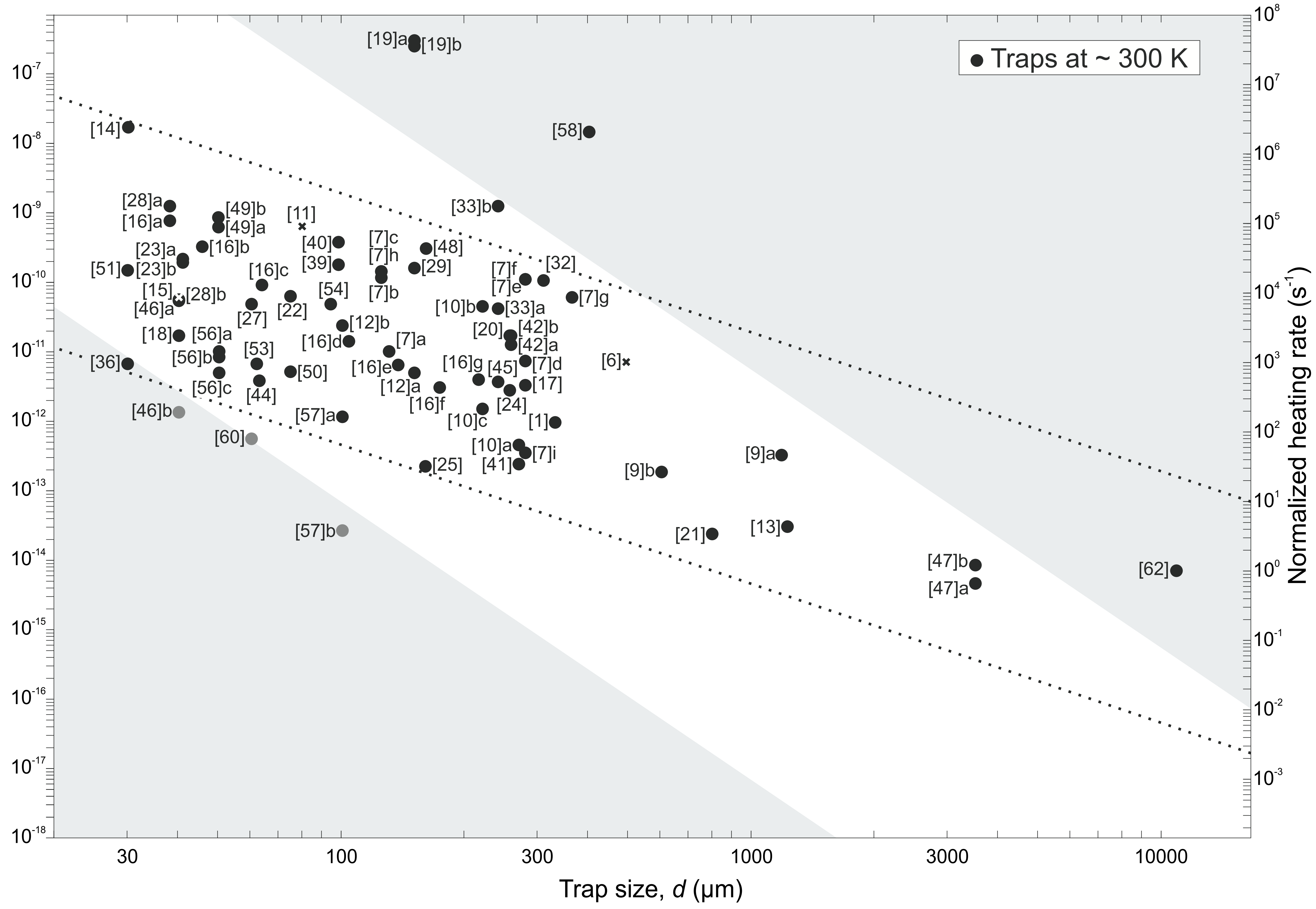
BACKUP

WHAT ABOUT SM IONS

- Mechanical & Ion Pumping to low pressure $\lesssim 10^{-12}$ bar
- Cryopumping (cold surfaces trap SM particles) to pressures $< 3 \times 10^{-21}$ bar
- Work Function of metals prevents electron evaporation
- WF ~ few eV
- $\implies \epsilon \leq \frac{T_{\text{wall}}}{\text{WF}}$ does not feel the effect of the Work function
- Provides a natural sieve for mCPs
- Effects of the trapping potential can also be important

DATA

- $^{40}Ca/^{9}Be$ ions used
- $\nu_+, \nu_-, \nu_z \approx$ MHz $\approx$ **4neV** $\approx 50\mu$K
- $\frac{dn}{dt} \approx \frac{1}{\text{sec}}$
- Heating Rate: $\frac{\text{neV}}{\text{sec}}$



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

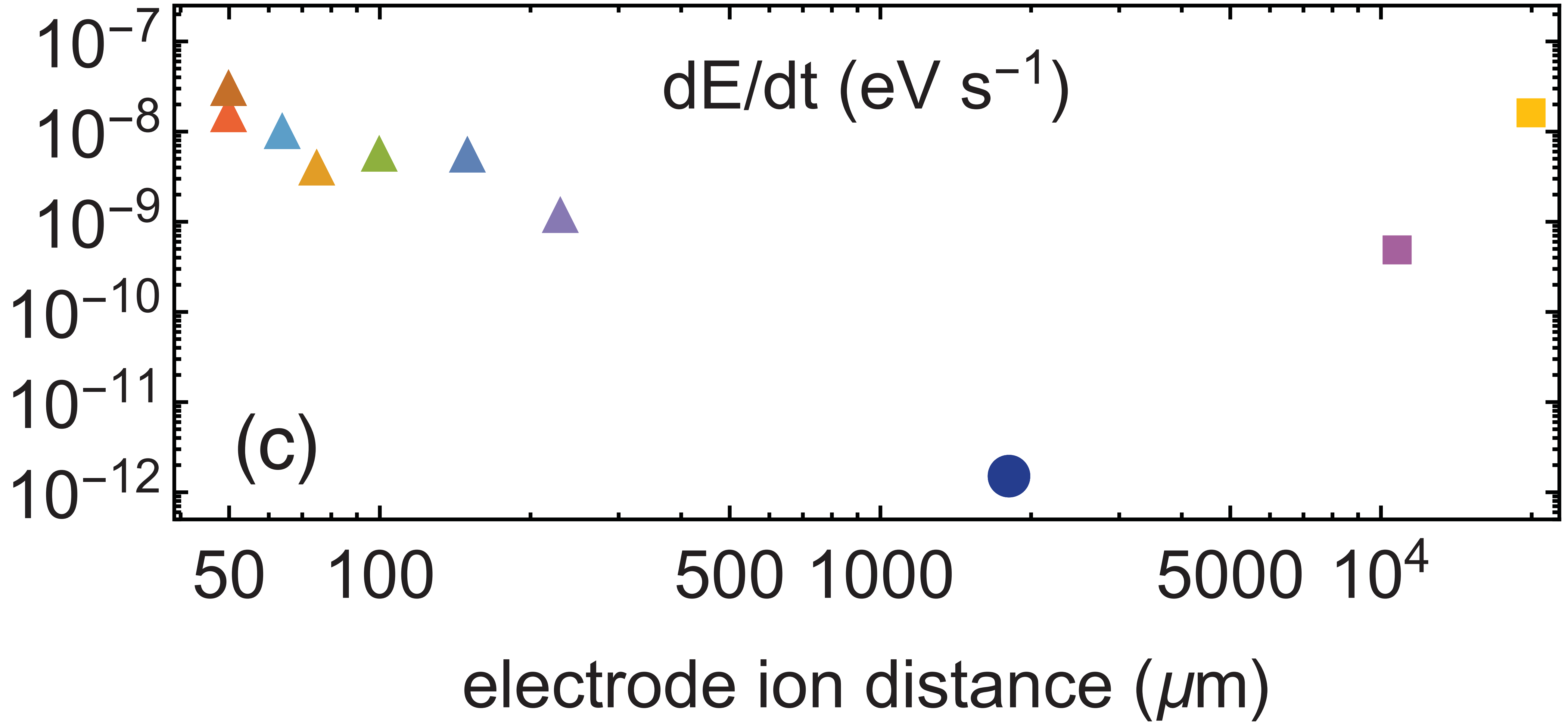
DATA

- Anti-protons: BASE experiment, CERN
- $\frac{dn_+}{dt} \approx \frac{6}{\text{hour}}$
- Lowest measured: $\dot{\omega} \approx 10^{-12}\ \text{eVs}^{-1}$
- BBR estimate: $\dot{\omega} \approx 10^{-14}\ \text{eVs}^{-1}$
- Background gas estimate:

  $\dot{\omega} \approx 10^{-17}\ \text{eVs}^{-1}$
- Expected to be from Electrode noise

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]



DATA SUMMARY

Experiment	Type	Ion	V_z	$T_{\rm wall}$	ω_p [neV]	$T_{\rm ion}$[neV]	Heating Rate (neV/s)
Hite et al, 2012 [40]	Paul	^{9}Be$^+$	0.1 V	300 K	$\omega_z = 14.8$	14.8	640
Goodwin et al, 2016 [43]	Penning	^{40}Ca$^+$	175 V	300 K	$\omega_z = 1.24$	1.24	0.37
Borchert et al, 2019 [44]	Penning	$\bar{p}$	0.633 V	5.6 K	$\omega_+ = 77.4$	7240	0.13
					$\omega_- = 0.050$		

No reach for $\epsilon \gtrsim \frac{T_{\rm wall}}{V_z}$

CAPABILITIES

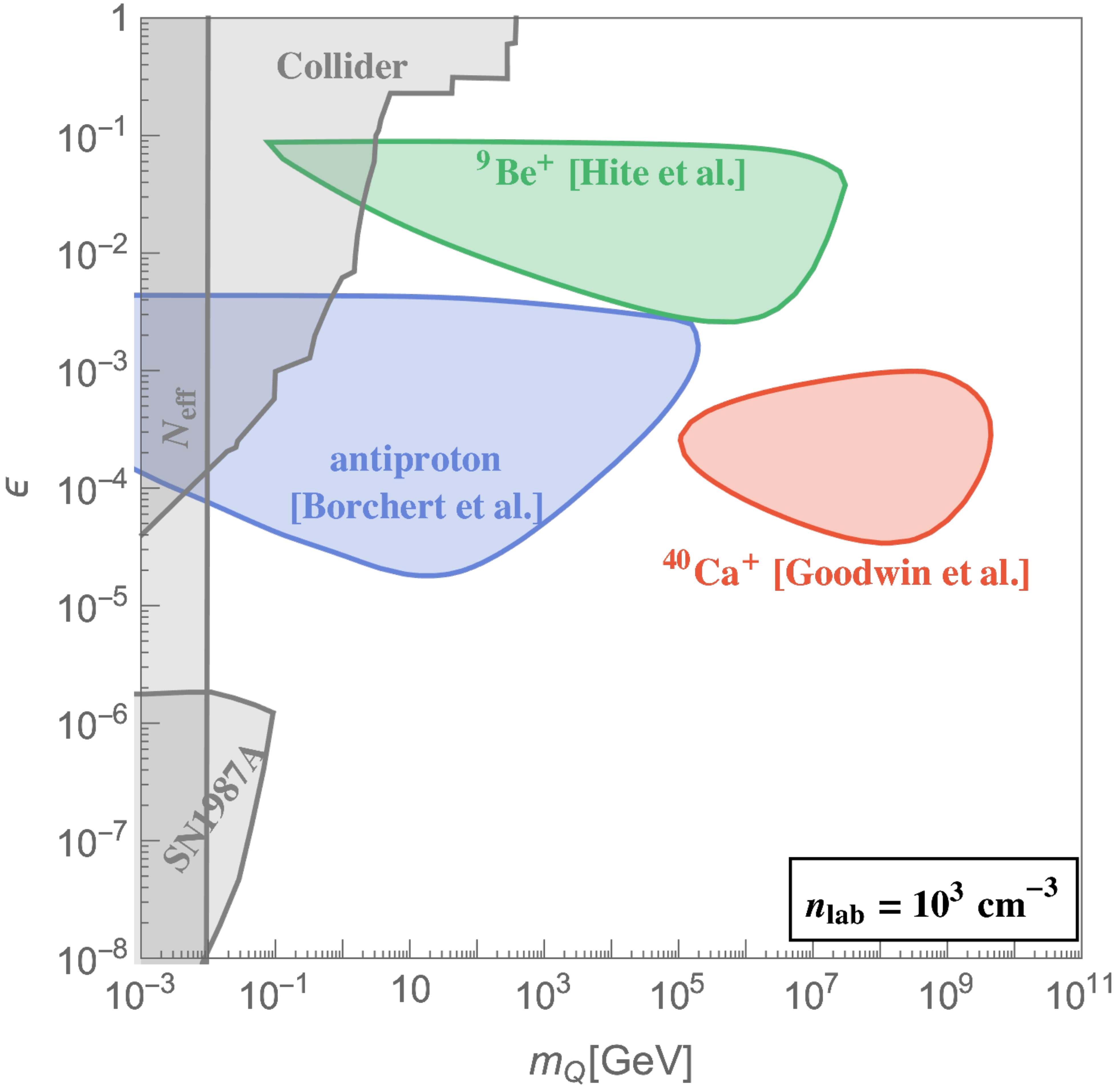
- Low exposure (Single ion x few hours)
- neV direct detection.
- Ultra-low heating rate
- Tiny momentum transfer $q \approx \sqrt{2\text{neV} \times m_T} \approx$ eV
- Still scatter with ion: Enormous Rutherford x-sections for small q
- Perfect for Traffic Jam: Large number densities and cross-sections, KE~26 meV

HEATING RATE

$$\frac{dE_{\text{dep}}}{dt} = \int E_{\text{dep}}(q^2)\frac{4\pi\alpha^2\epsilon^2}{v^2q^4}dq^2 \quad \approx 10^{-6}\frac{\text{eV}}{\text{sec}}\epsilon^2\frac{n_{\text{lab}}}{1/\text{cm}^3}\frac{\text{GeV}}{m_{\text{ion}}}\ldots \gtrsim 10^{-10}\frac{\text{eV}}{\text{sec}}$$

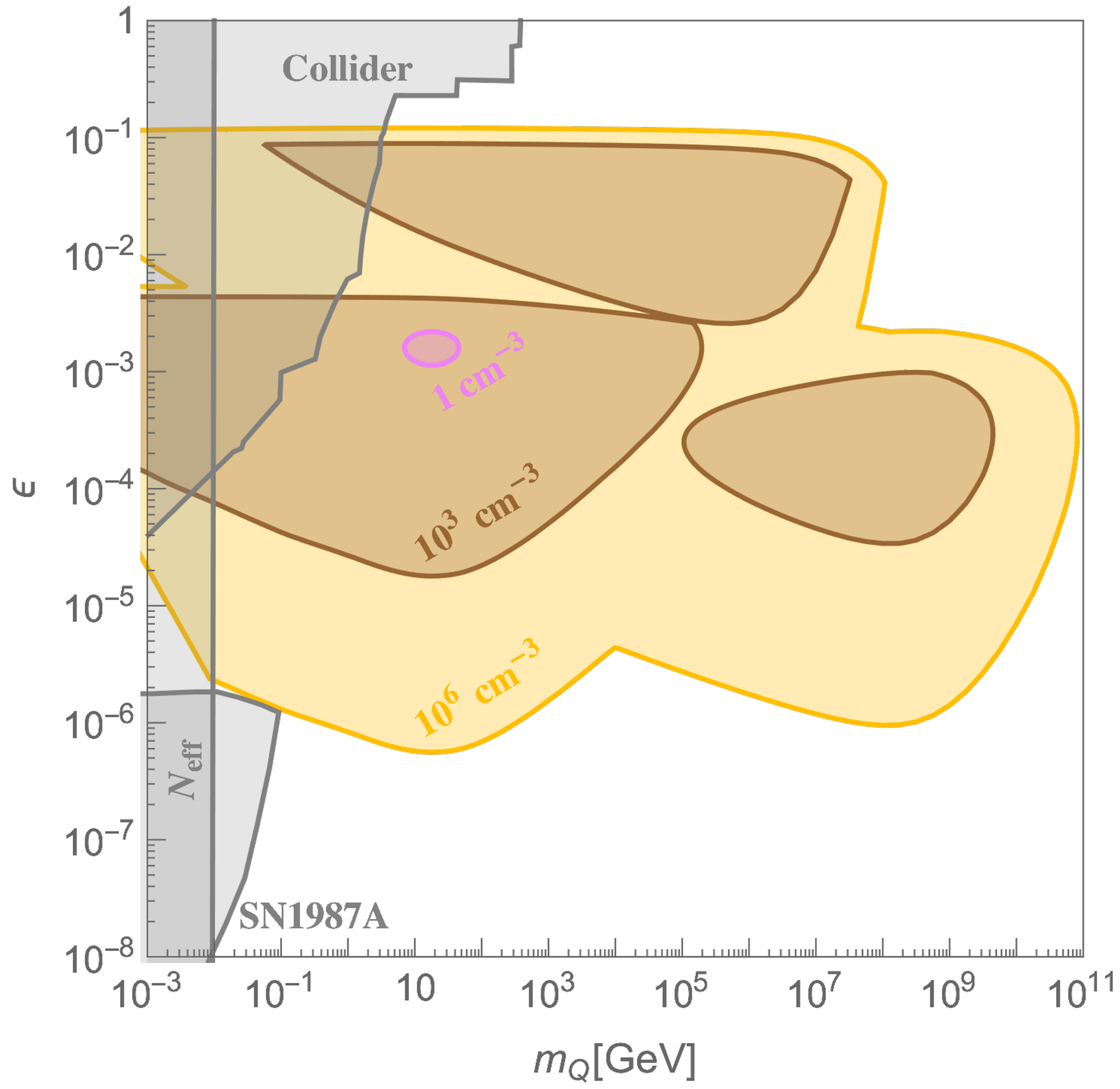
TERRESTRIAL POPULATION CONSTRAINTS

$$m_Q^{\mathrm{min}} = \frac{E_{\mathrm{min}}^2 m_T}{16 \mathrm{T}_{\mathrm{trap}} \mathrm{T}_{\mathrm{wall}}}$$

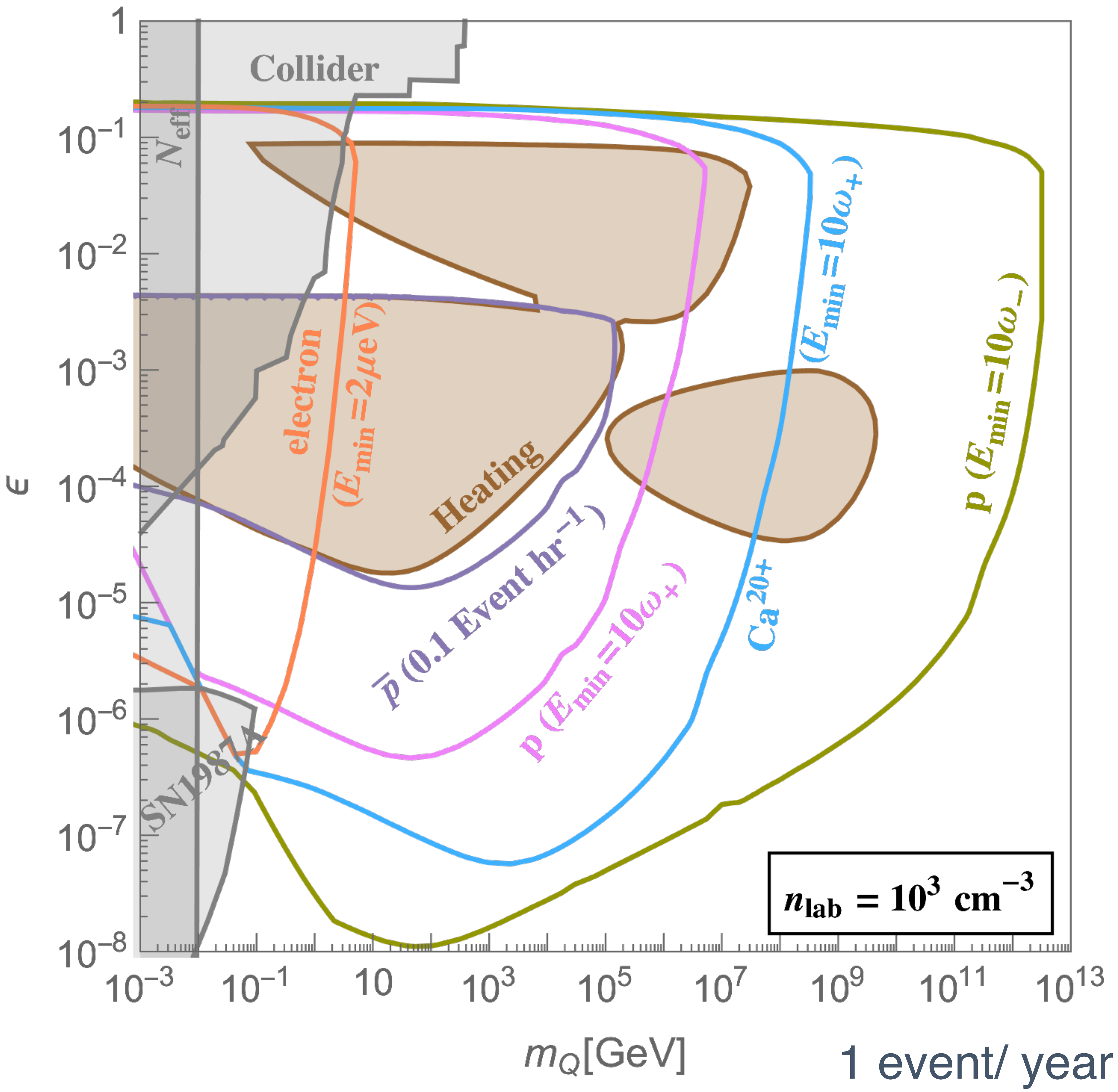


$$m_Q^{\mathrm{max}} = \frac{16 m_T T_{\mathrm{trap}} T_{\mathrm{wall}}}{E_{\mathrm{min}}^2}$$

TERRESTRIAL POPULATION CONSTRAINTS



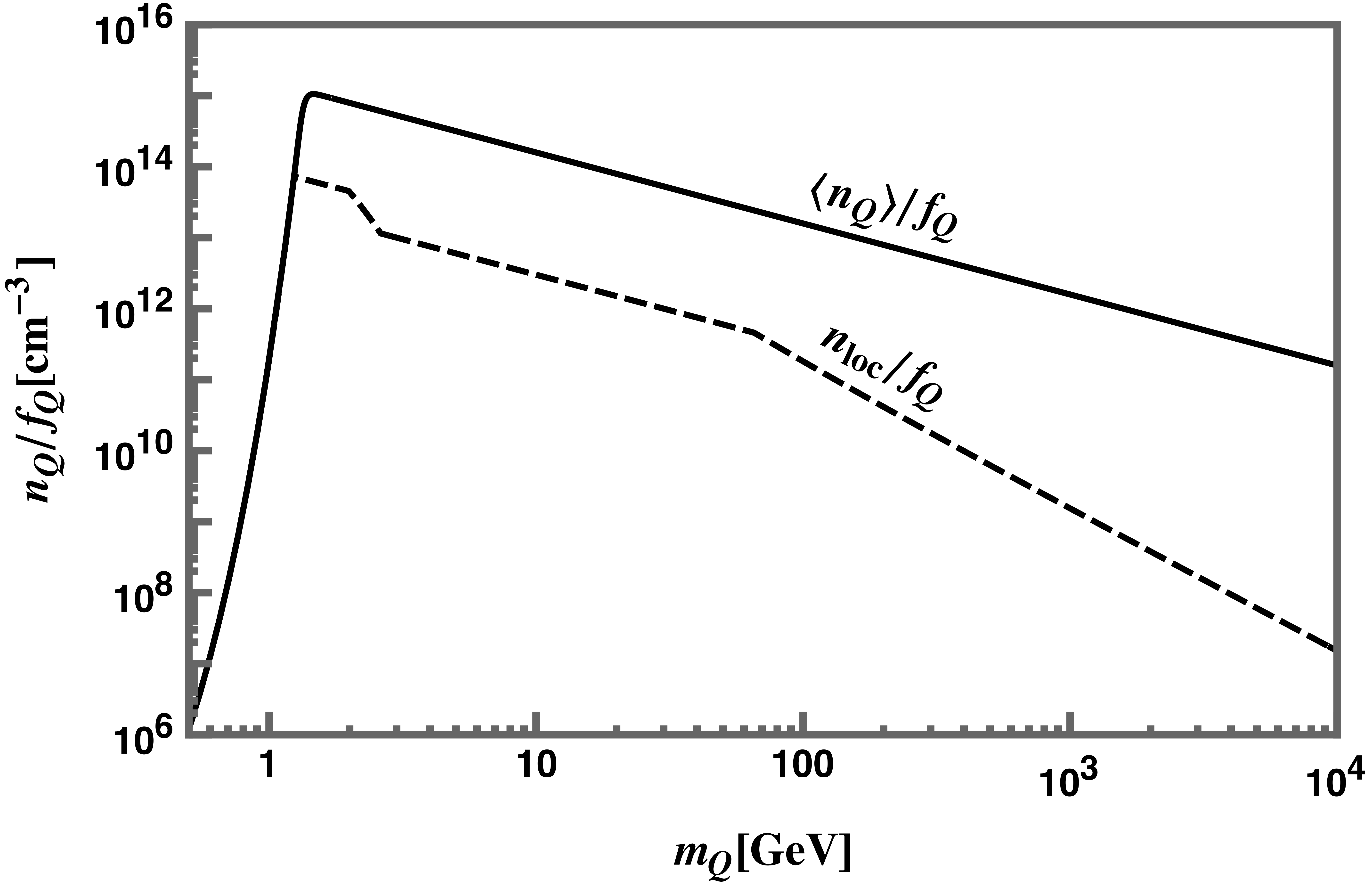
PROJECTIONS



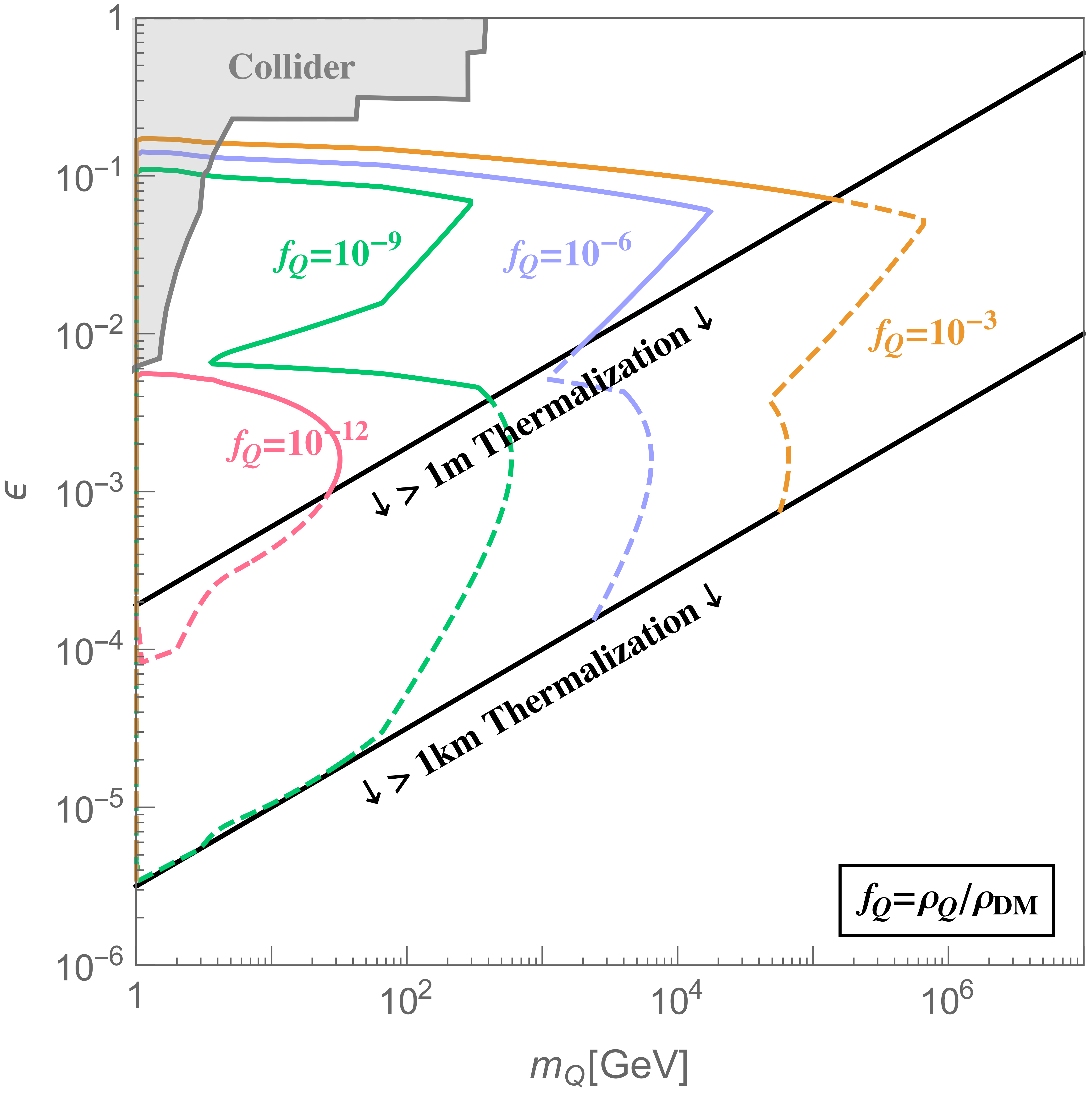
1 event/ year unless otherwise stated

TRAFFIC JAM DENSITIES

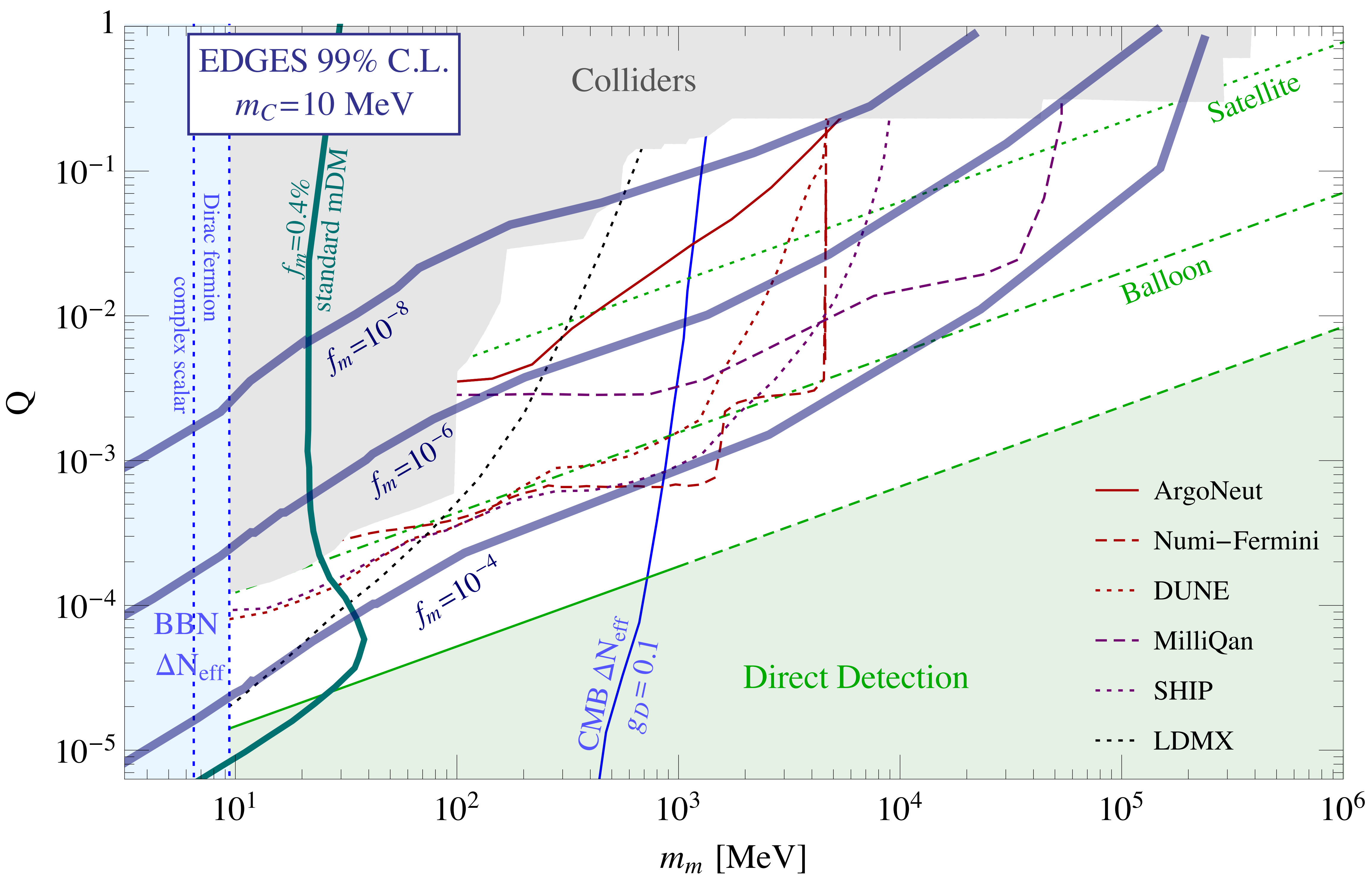
from: 2012.03957 HR M.Pospelov



LIMITS ON DARK MATTER



1908.06986 Liu et al

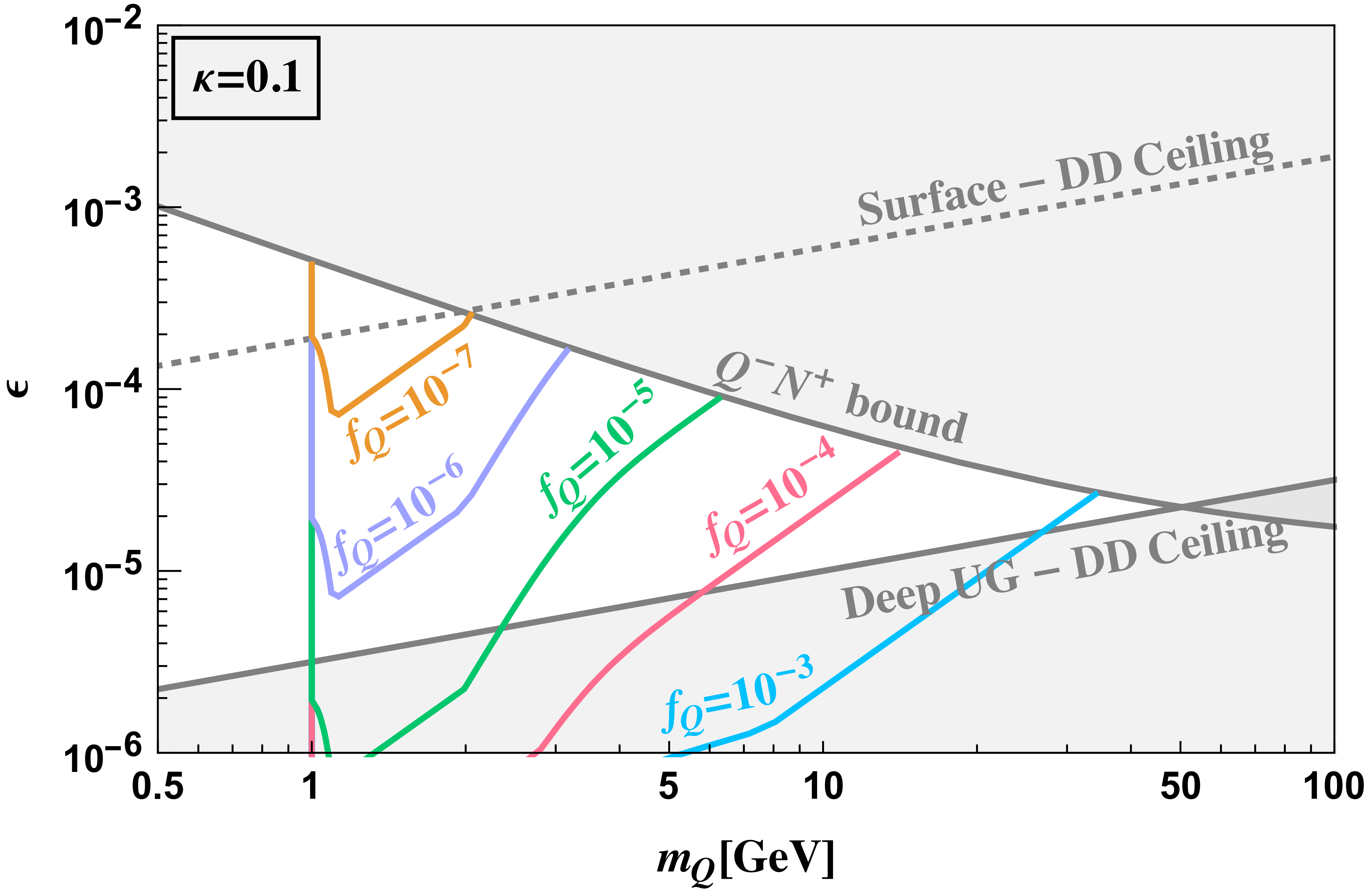


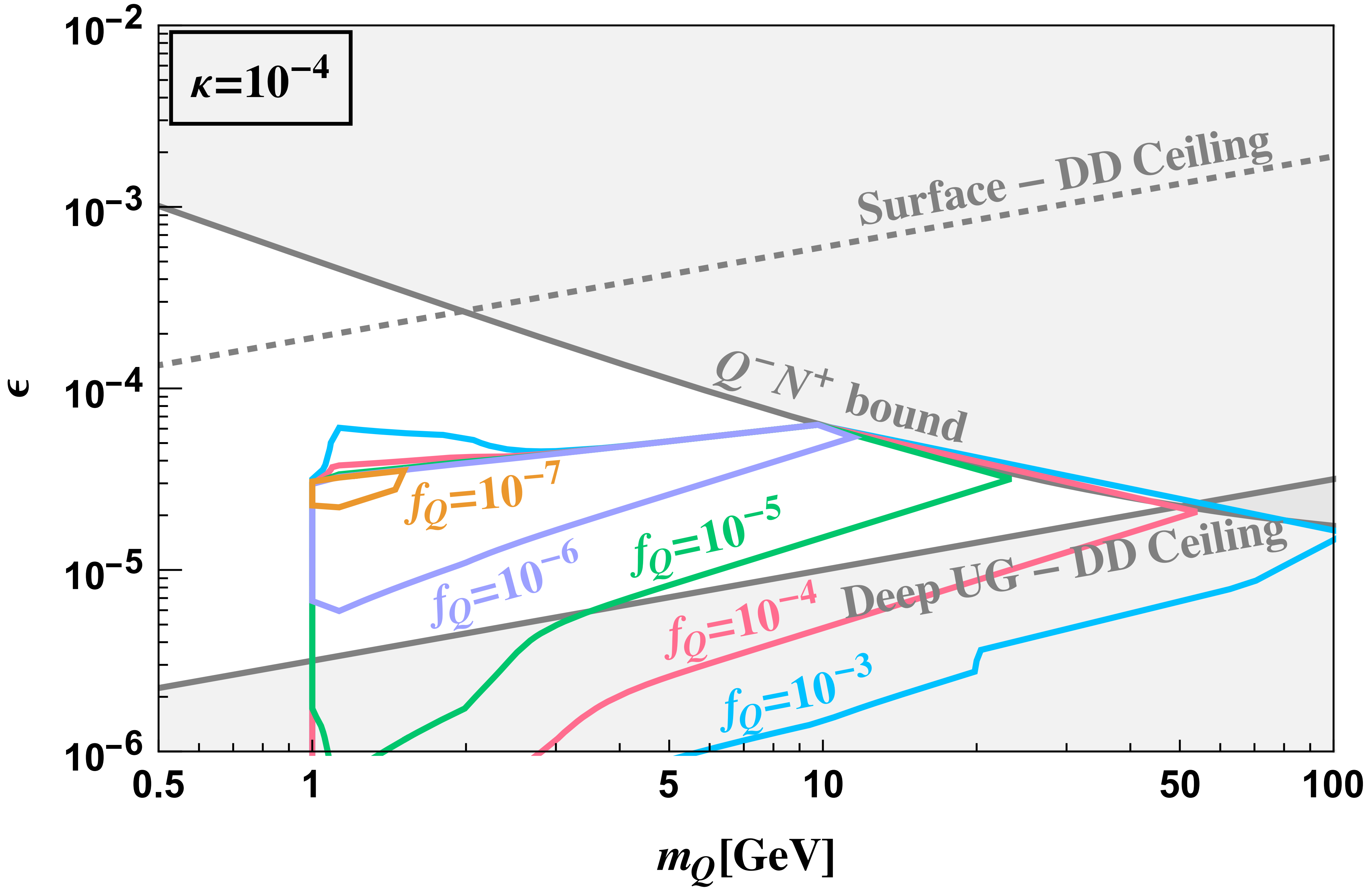
TWO KINDS OF MCPs

- Dark Photon mediated
- Effectively milli-charged at energies >> $m_{A'}$
- $m_{A'}$ sets the range of interactions with the SM
- For large enough $m_{A'}$, we can ignore long range effects like
  - SN shocks, galactic magnetic fields, solar winds,
  - Electric field due to the ionosphere
- Pure Milli-charge or tiny Dark Photon mass, these effects important:

see for e.g. A.Stebbins & G. Krnjaic 1908.05275

ANNIHILATIONS IN SUPER-K





Existing Limits

1408.4396 D.C. Moore, A.D. Rider, G. Gratta

2012.08169 G. Afek, F. Monteiro, J. Wang, B. Siegel, S. Ghosh, D.C. Moore

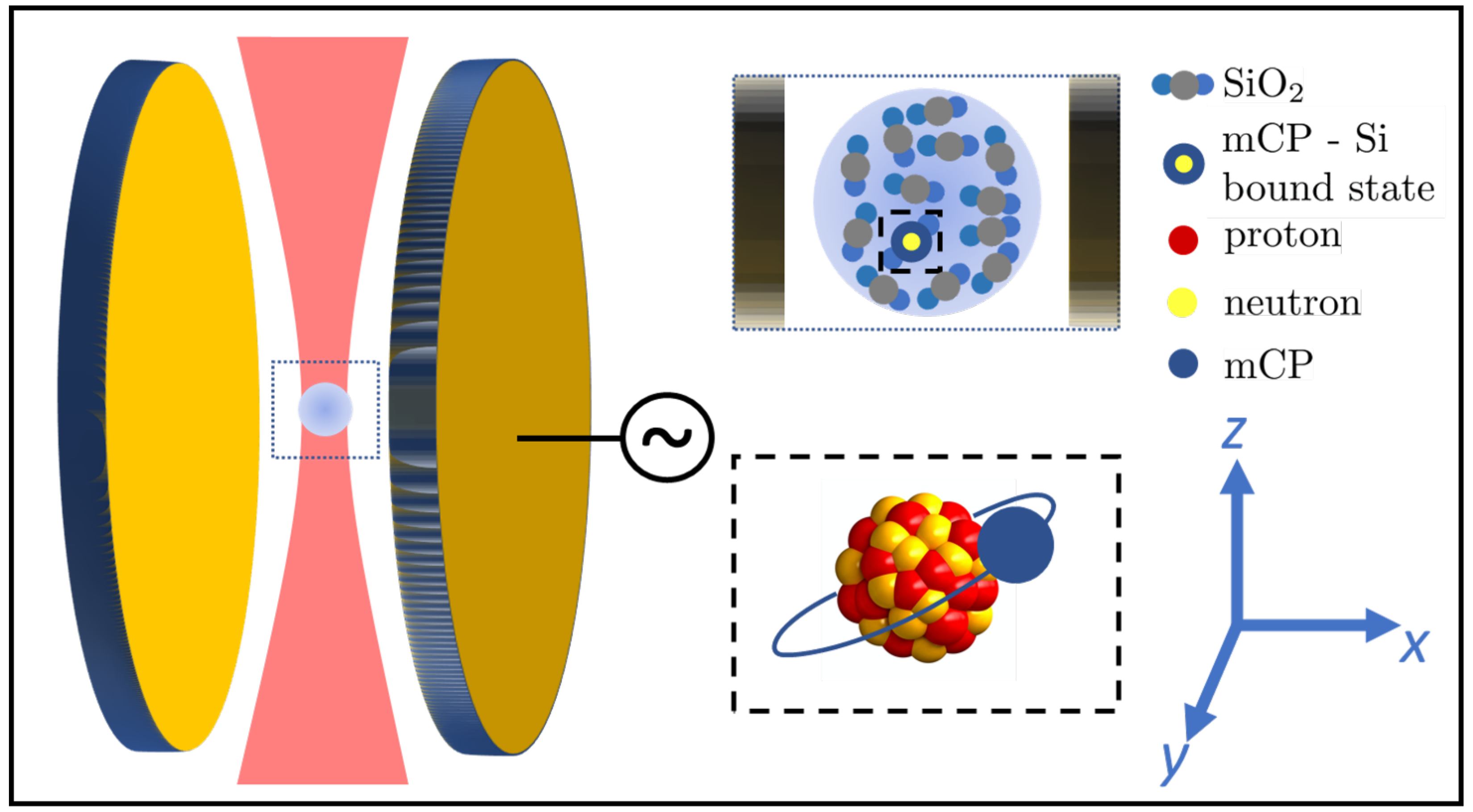
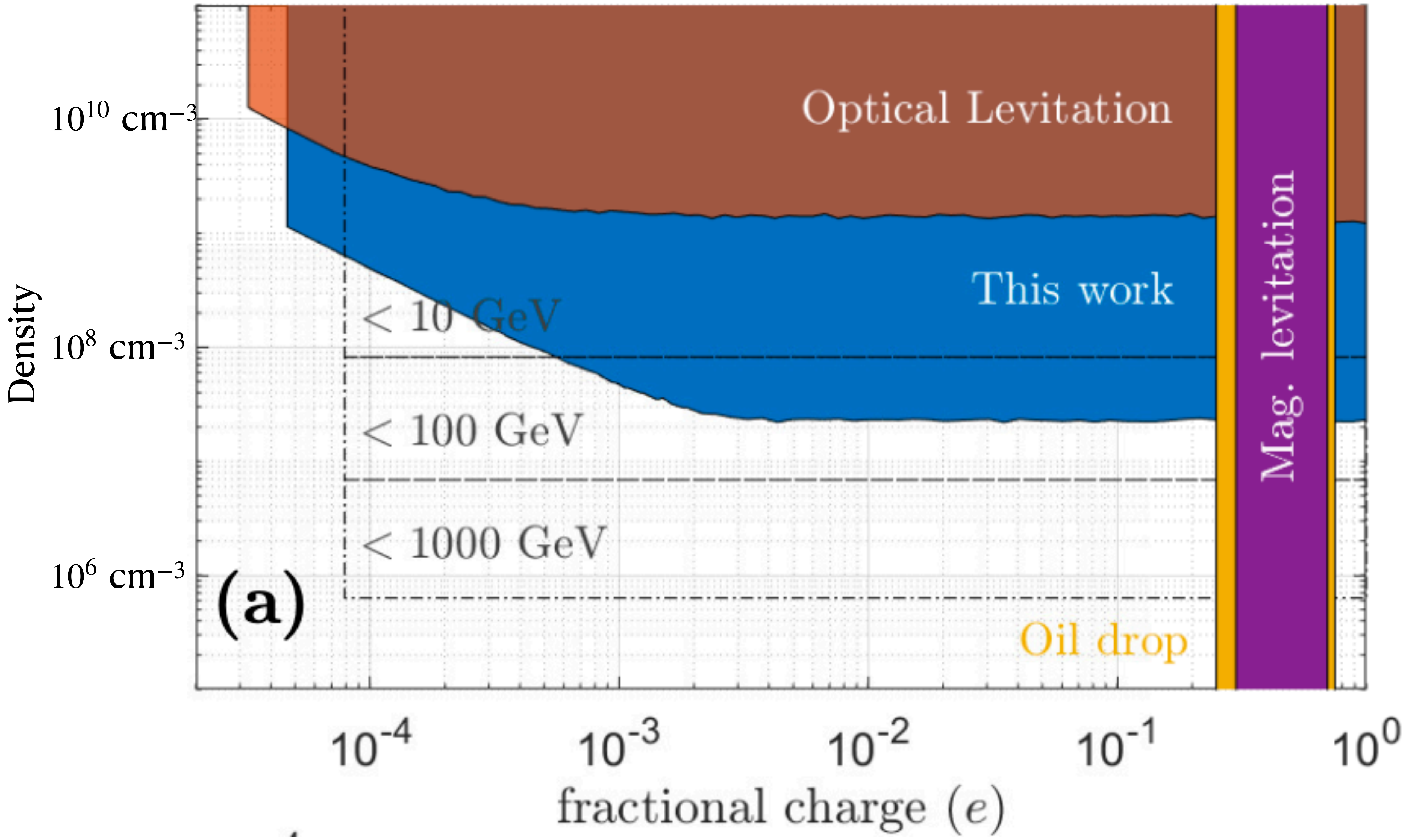
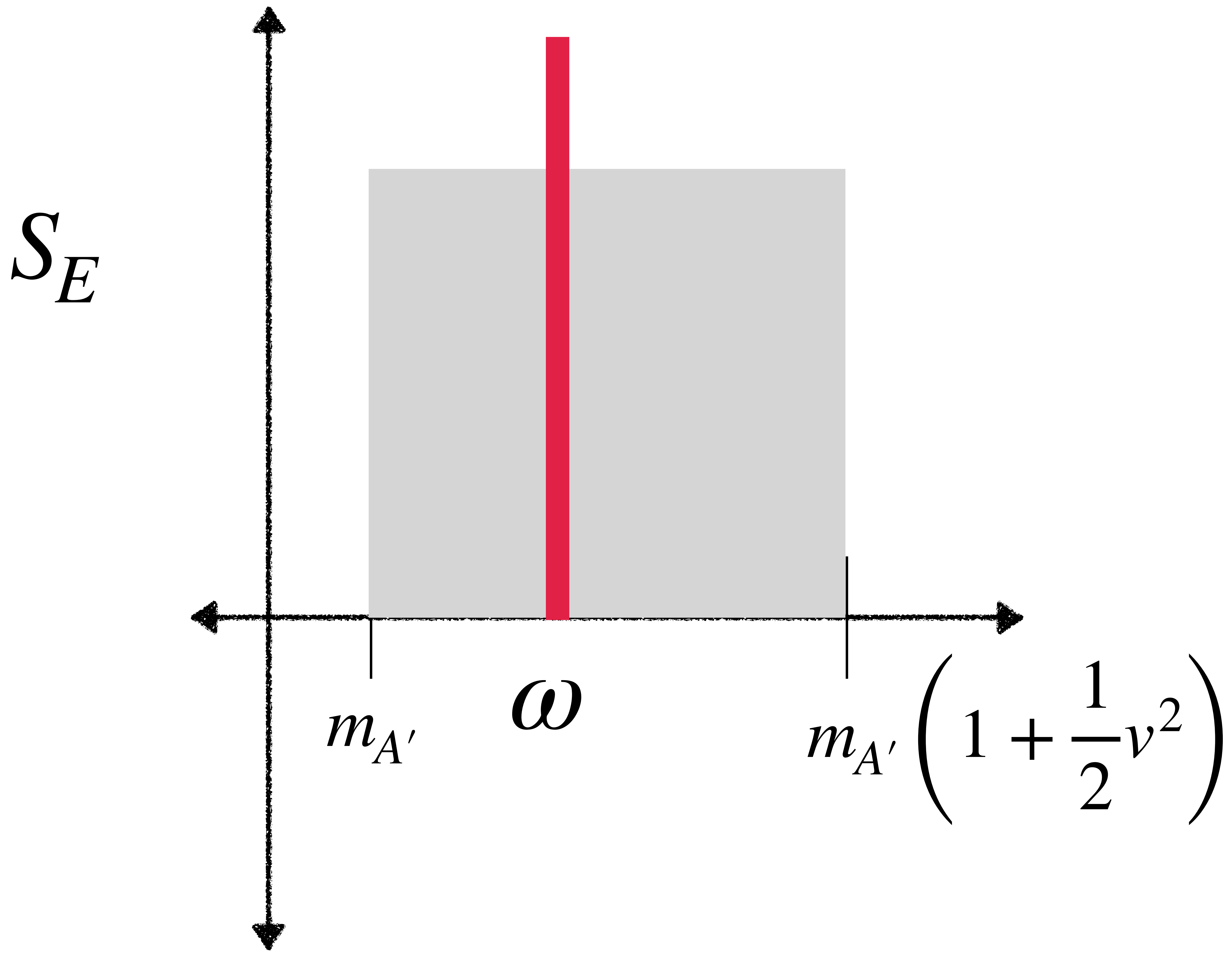


FIG. 1. SiO_2 spheres are levitated in high vacuum between a pair of parallel electrodes to search for a violation of charge neutrality by, *e.g.*, a mCP electrostatically bound to a Si or O nucleus in the sphere.



- Crucial assumption: Negative mCPs bind with Silicon nuclei
- Relax assumption and look for Positive mCPs?

Power Spectral Density



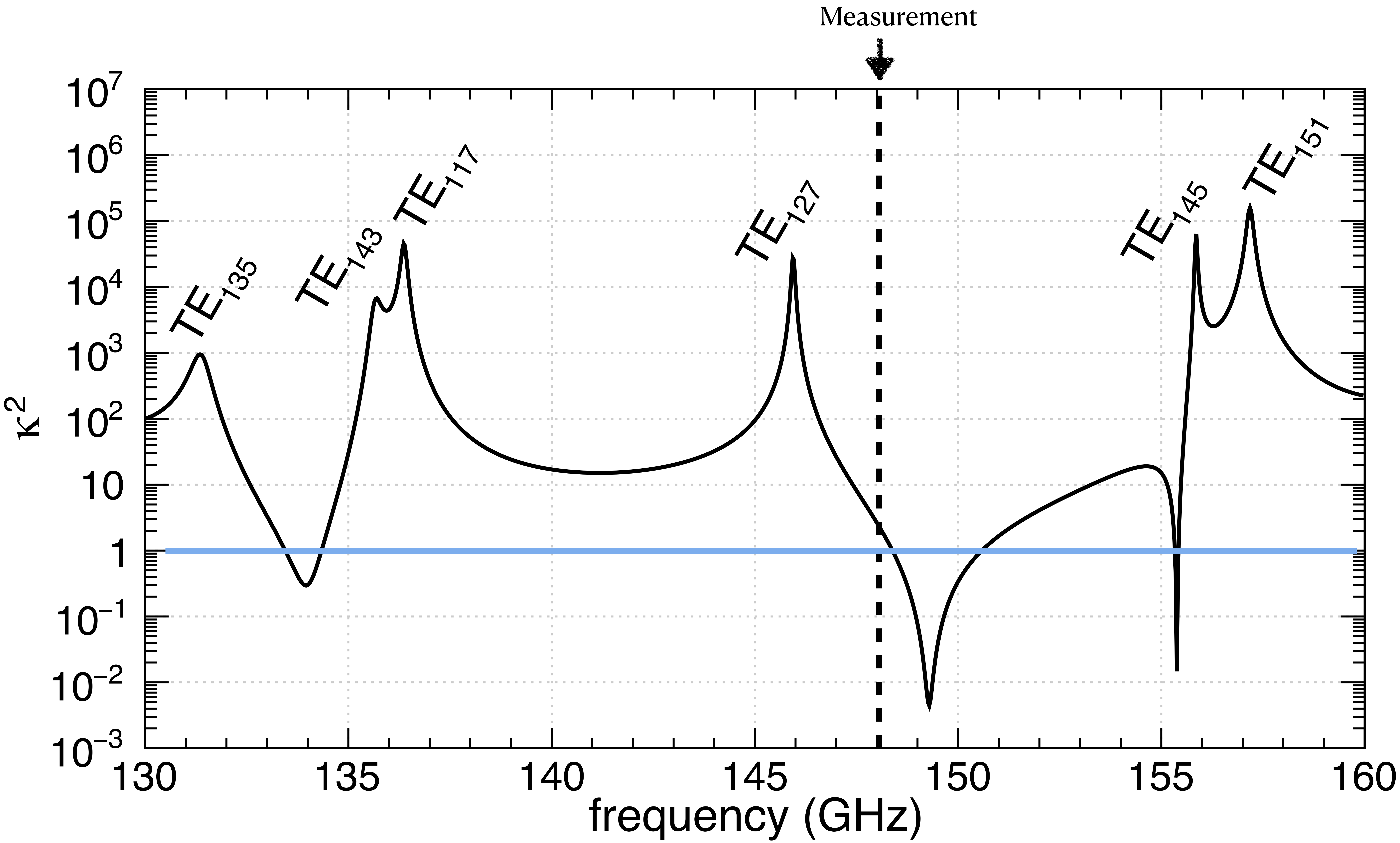
$$S_E = \epsilon^2 \frac{\rho_{\rm DM}}{\mathrm{v}_{\rm vir}^2 m_{A'}}$$

$$\Gamma \approx \frac{\pi e^2}{2 m_e \omega} \frac{\rho_{\rm DM}}{10^{-6}\omega}$$

$$\approx \frac{5}{10\mathrm{sec}} \left(\frac{\epsilon}{10^{-8}}\right)^2 \left(\frac{2\pi \times 100\ \mathrm{GHz}}{\omega}\right)^2$$

Promising!

Existing Setup

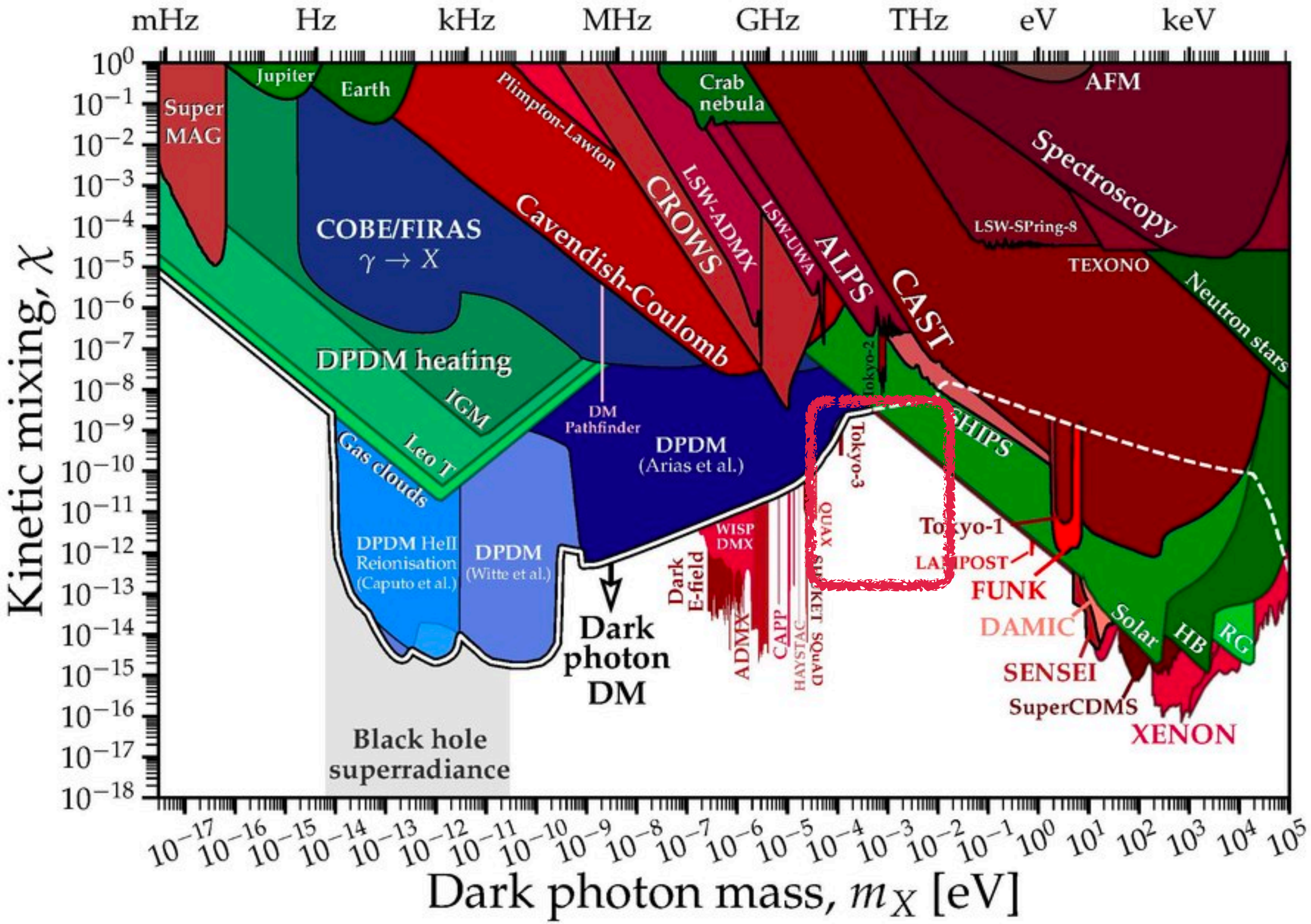


R=0.5 cm

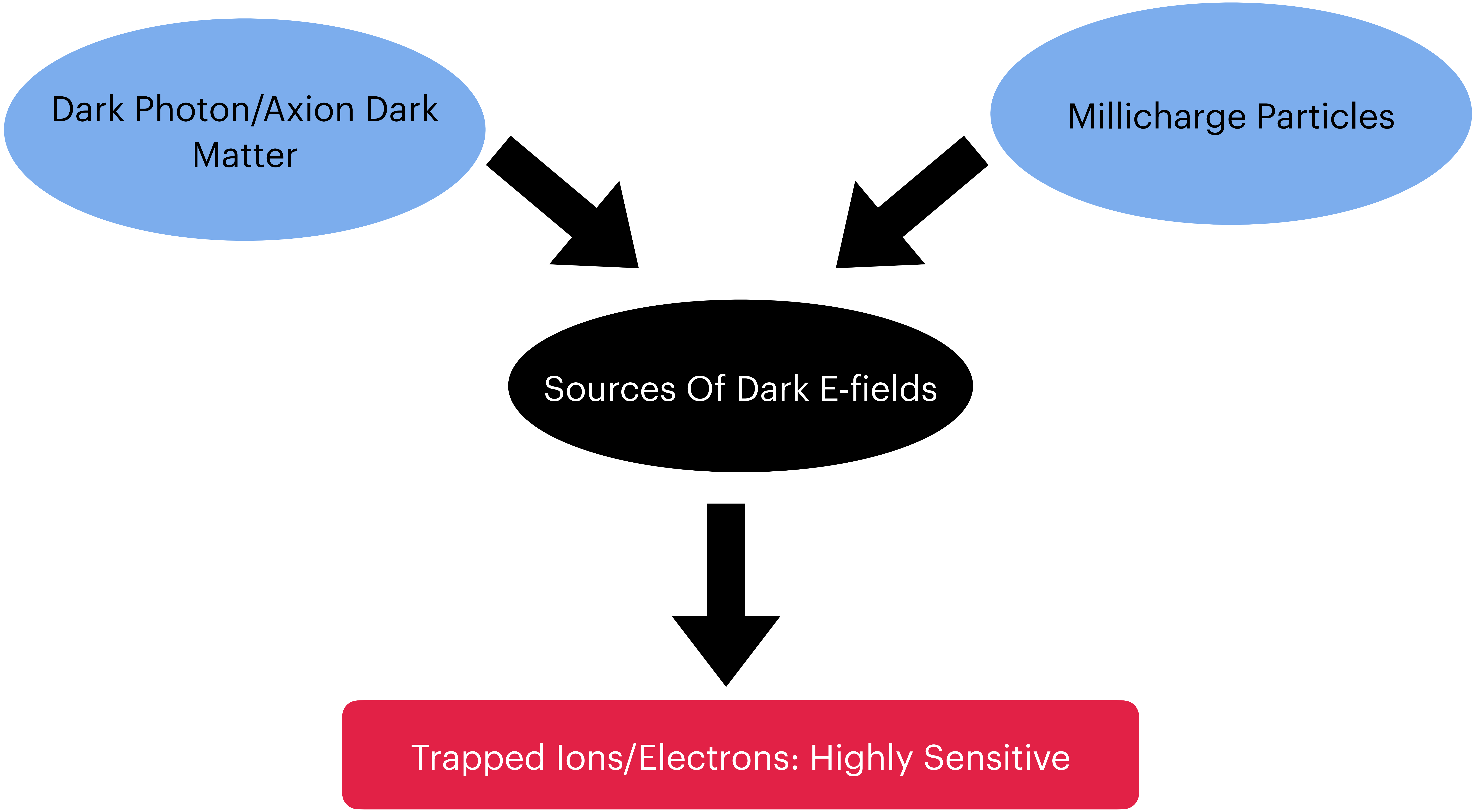
Effect of Cavity

- Work in Interaction Basis: E^{a} (active) that couples to SM and E^{s} (Sterile)
- $\mathscr{L} \supset -\frac{1}{4}\left(F_{\mathrm{a}}F^{\mathrm{a}} + F_{\mathrm{s}}F^{\mathrm{s}}\right) - eJ_{\mu}^{\mathrm{em}}A_{a}^{\mu} + \epsilon m_{A'}A_{a}A_{s}$
- Metal boundaries destroy $E_{||}^{\mathrm{a}}$

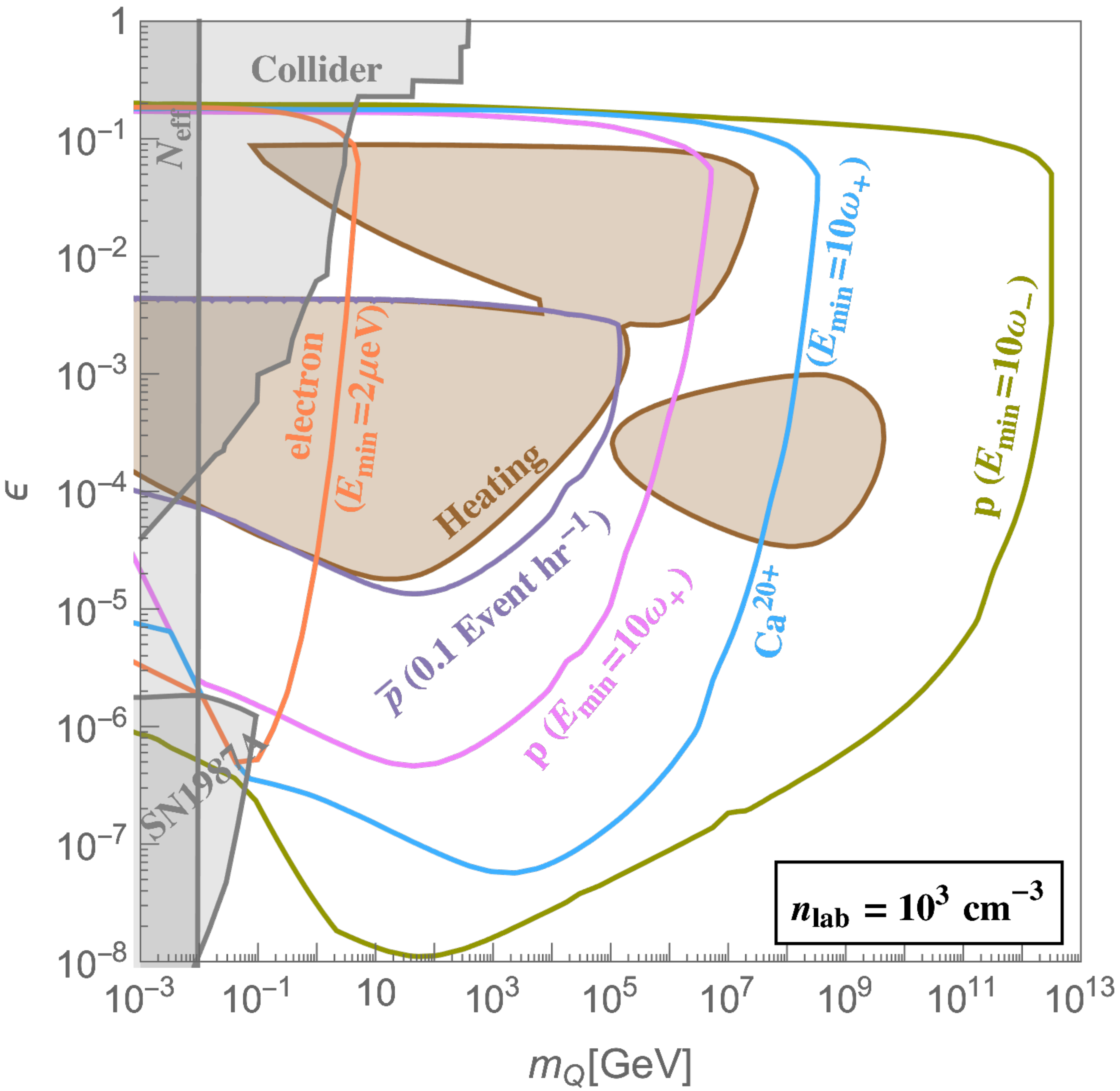
Dark Photon Dark Matter



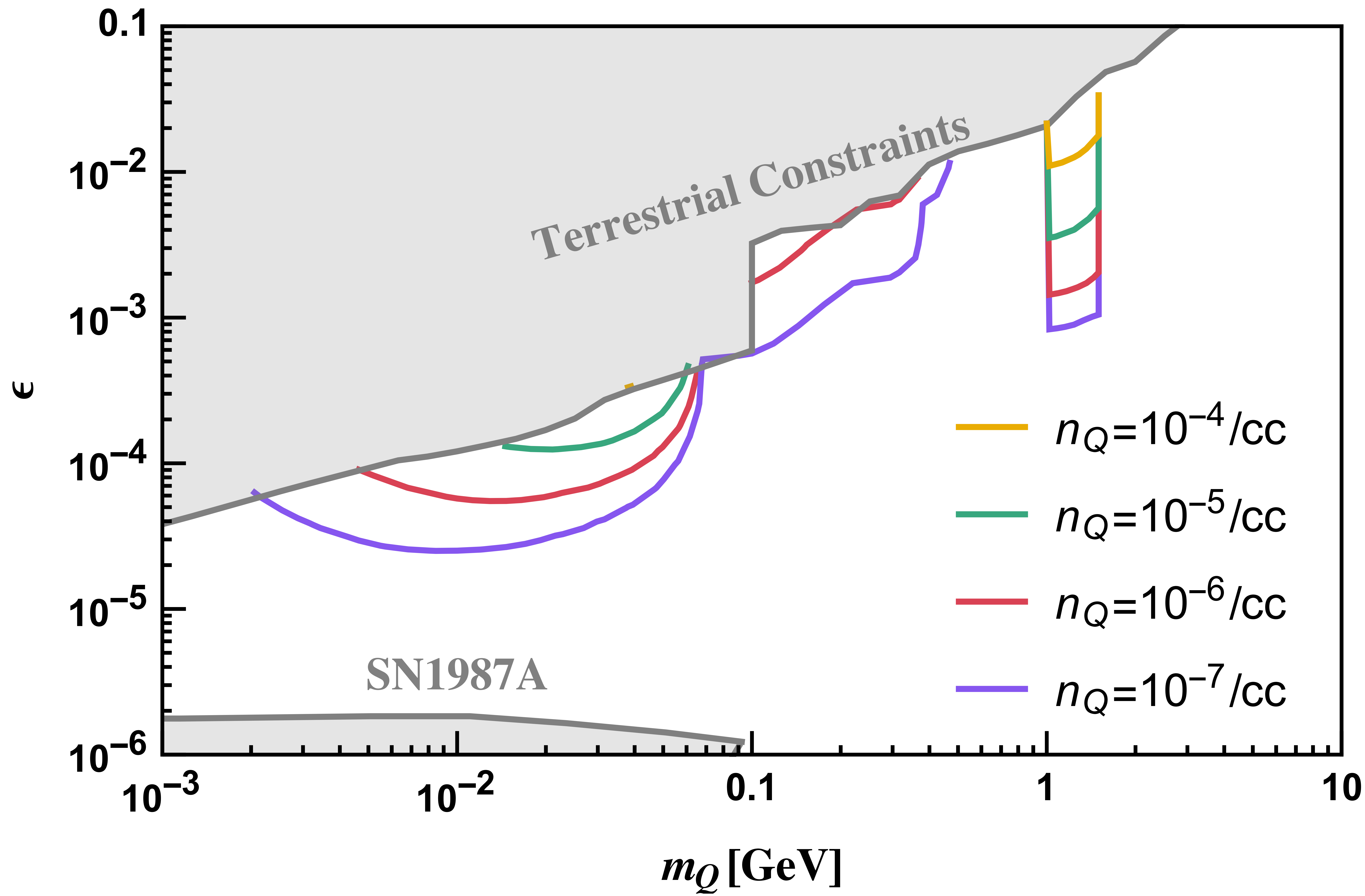
Sources of Dark E-Fields

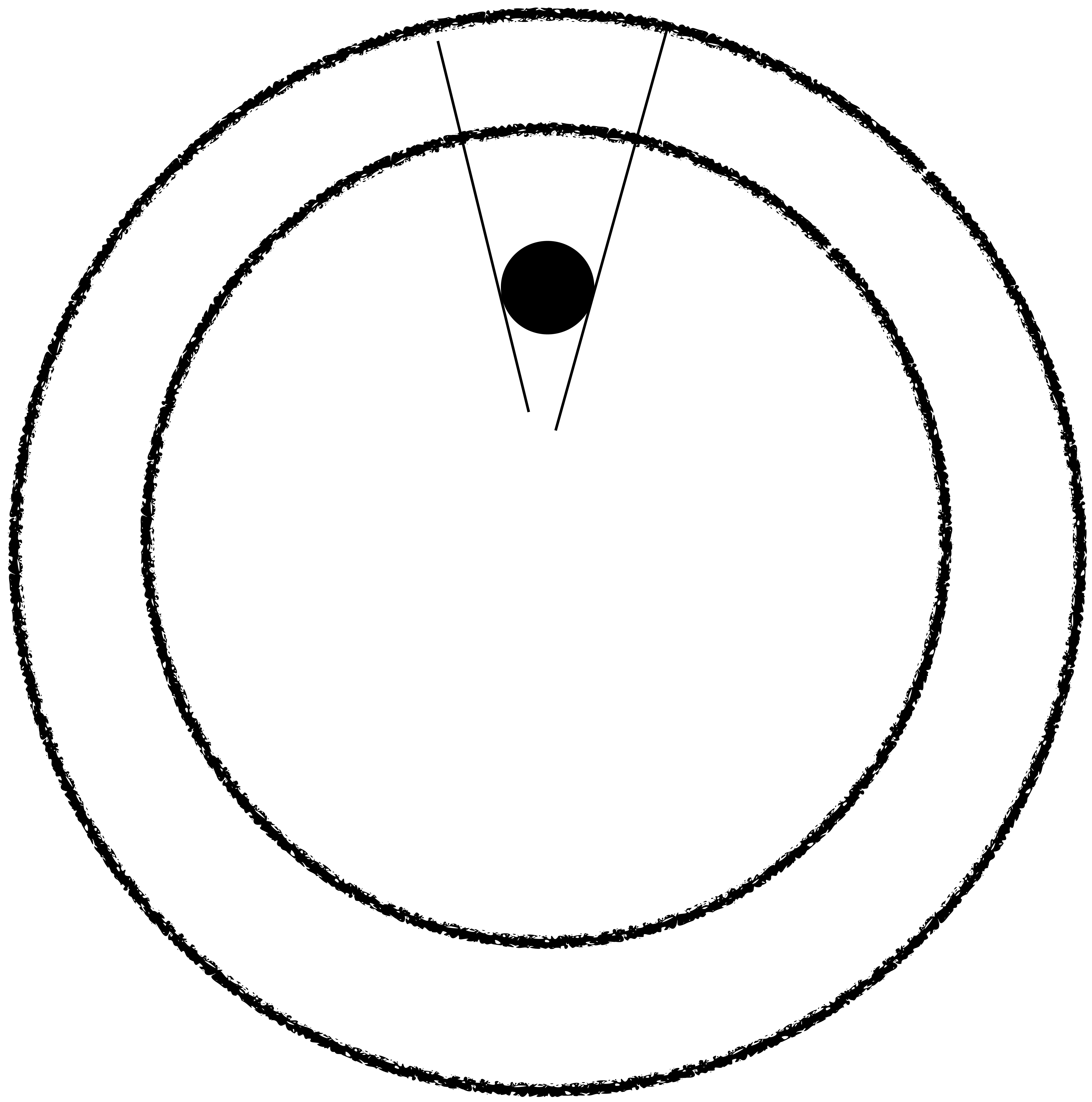


Projections



Dark Photon Mediated





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