Direct Detection with a Solitary Electron

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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Contents

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Dark Photon Dark Matter

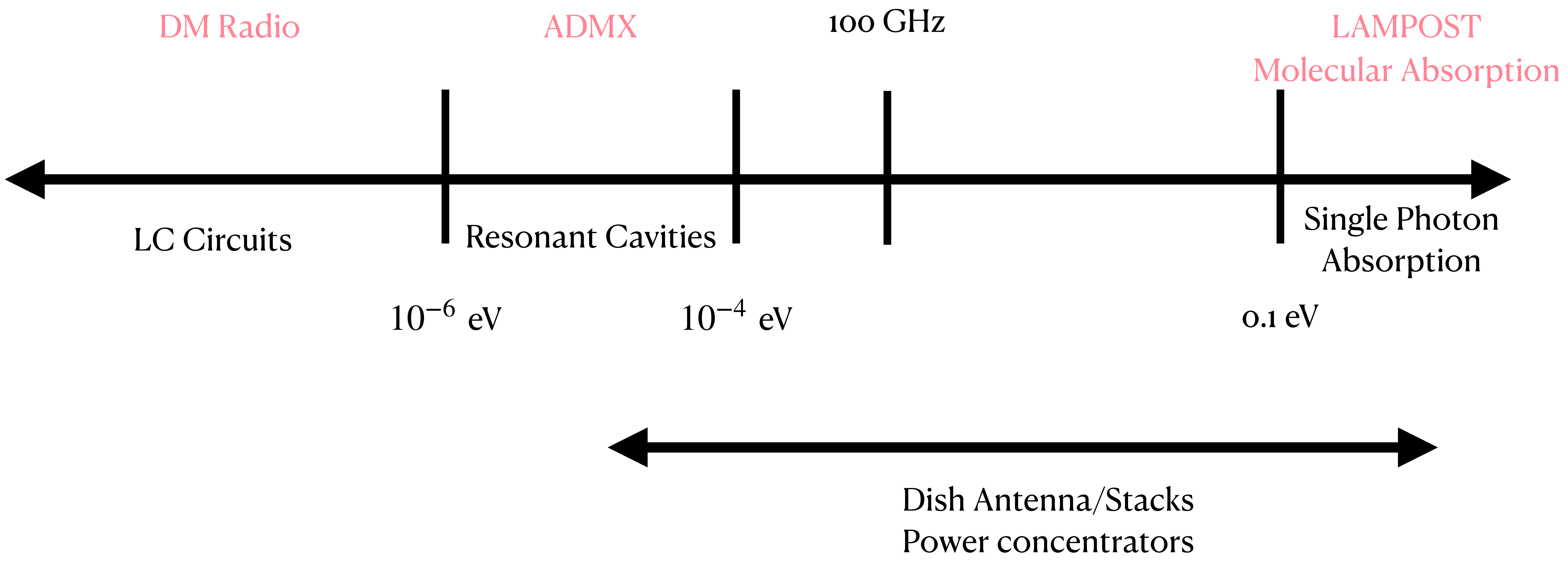
- Simple model: $\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$.
- If $m_{A'} \lesssim 2m_e$, decay too slow: stability
- Several Production mechanisms

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

Detection Strategy

- Kinetic mixing: $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- Produce 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

Blind Spot



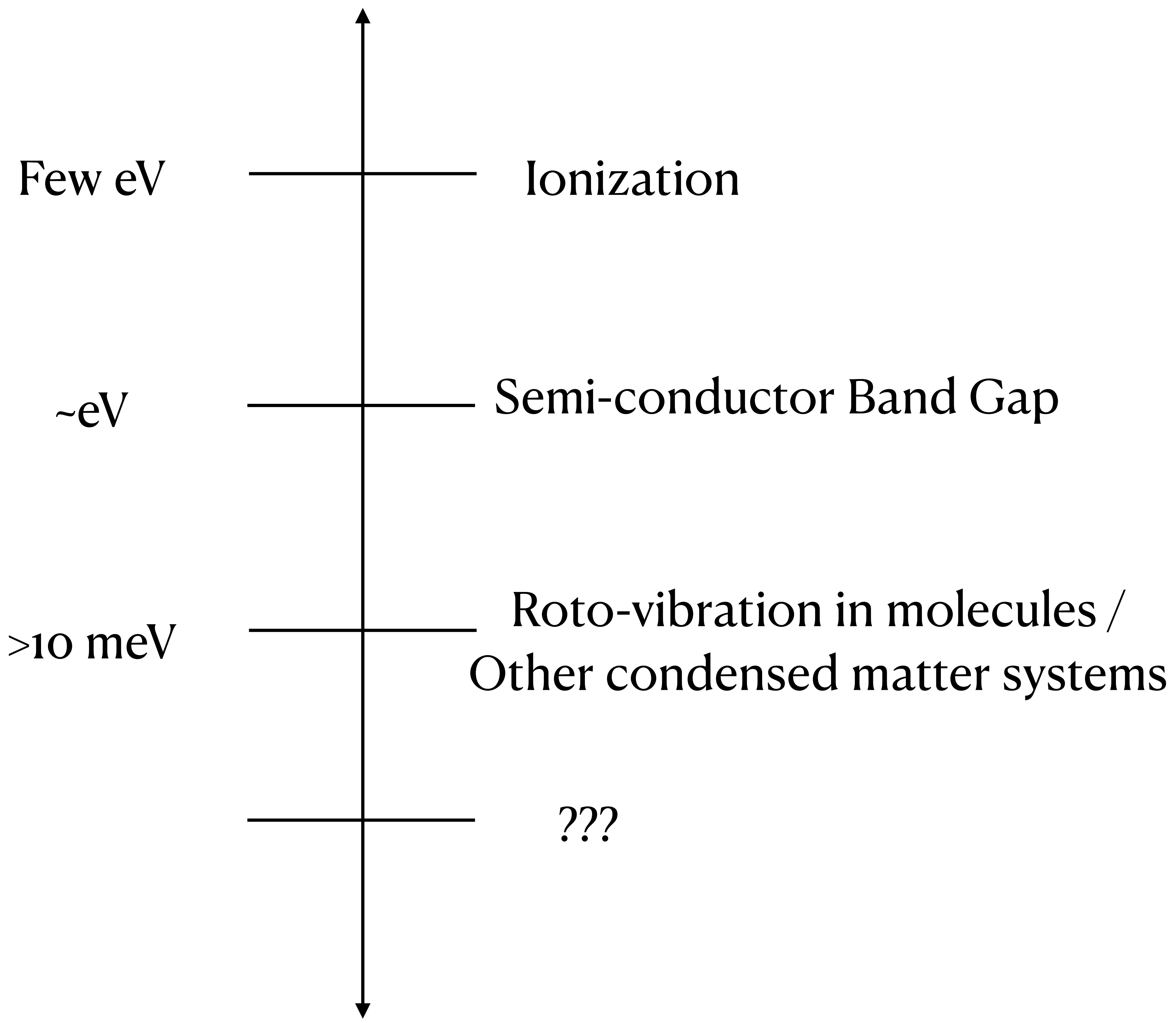
Hard to probe 10^{-4} eV- 0.1 eV

Why?

1) Too high energy for high Q cavities
2) Too low energy for single photon detection
3) Future Detection planned with Dish Antennae
4) Something possible today?

A two level system @ 100 GHz

Energy Gap in two level systems

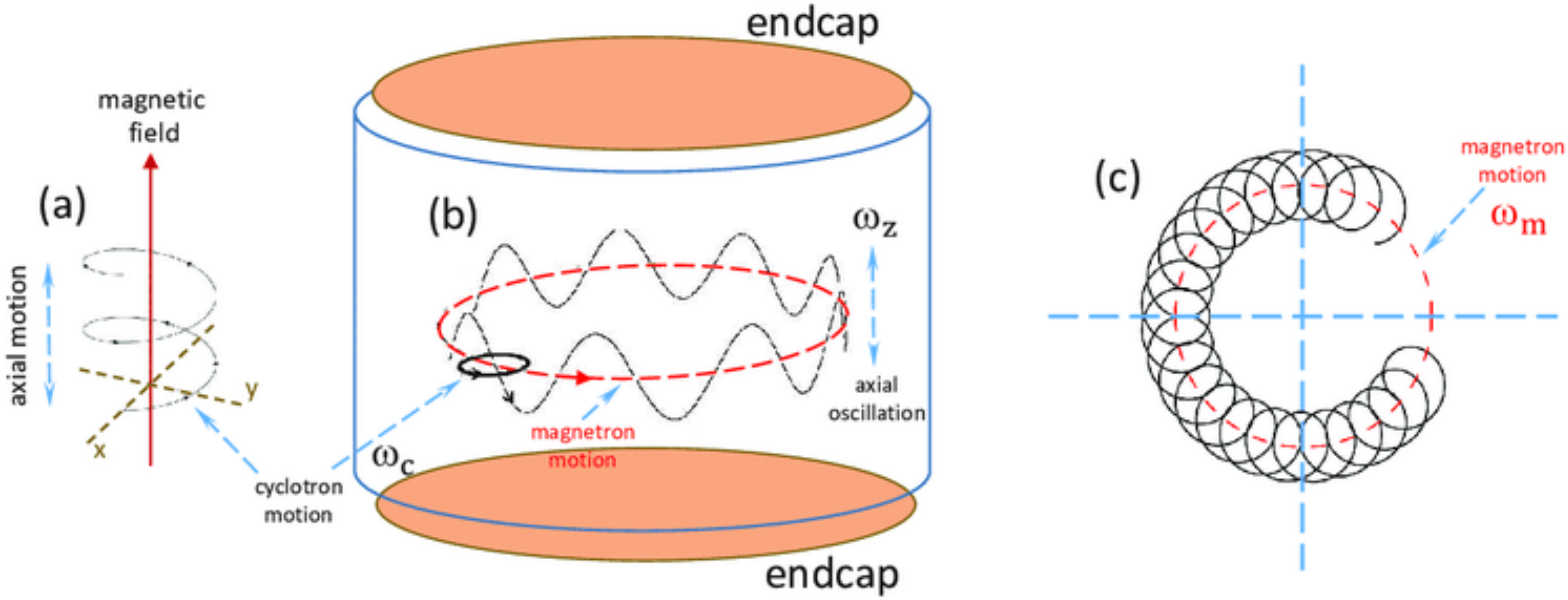


$$\frac{qB}{m_e} \approx 150 \text{ GHz} \frac{B}{5 \text{ T}} \frac{511 \text{ keV}}{m_e}$$

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?

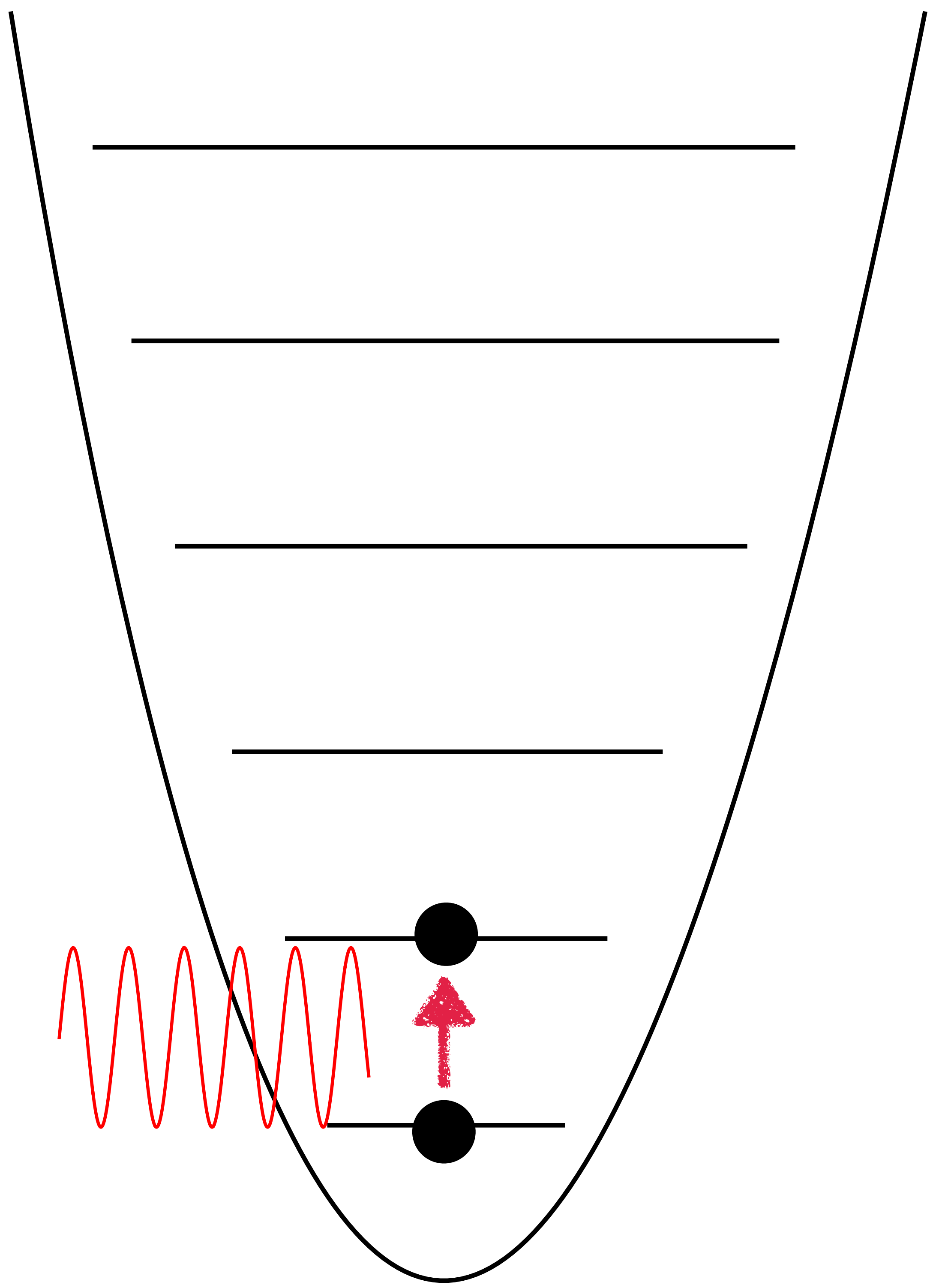
Contents

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

E field causes transition

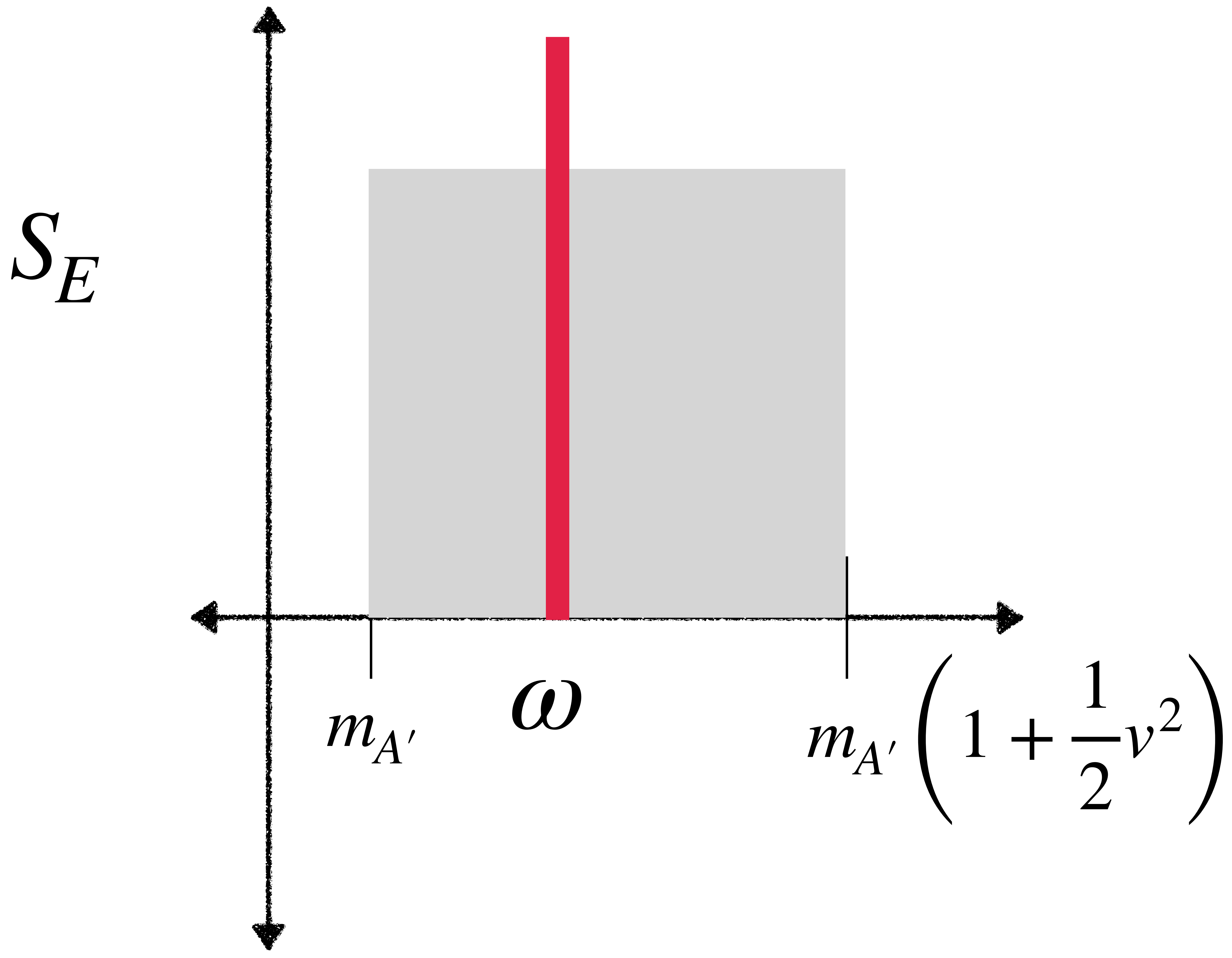


- Only $\Delta n = 1$ transitions allowed (Selection rules)
- Selects very narrow frequency band
- Sensitivity to tiny electric fields

$$\Gamma = \frac{\pi e^2}{2 m_e \omega} S_E(\omega)$$

S_E Power Spectral Density - The amount of power @ frequency ω

Power Spectral Density



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

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

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

Promising!

Measuring quantum state

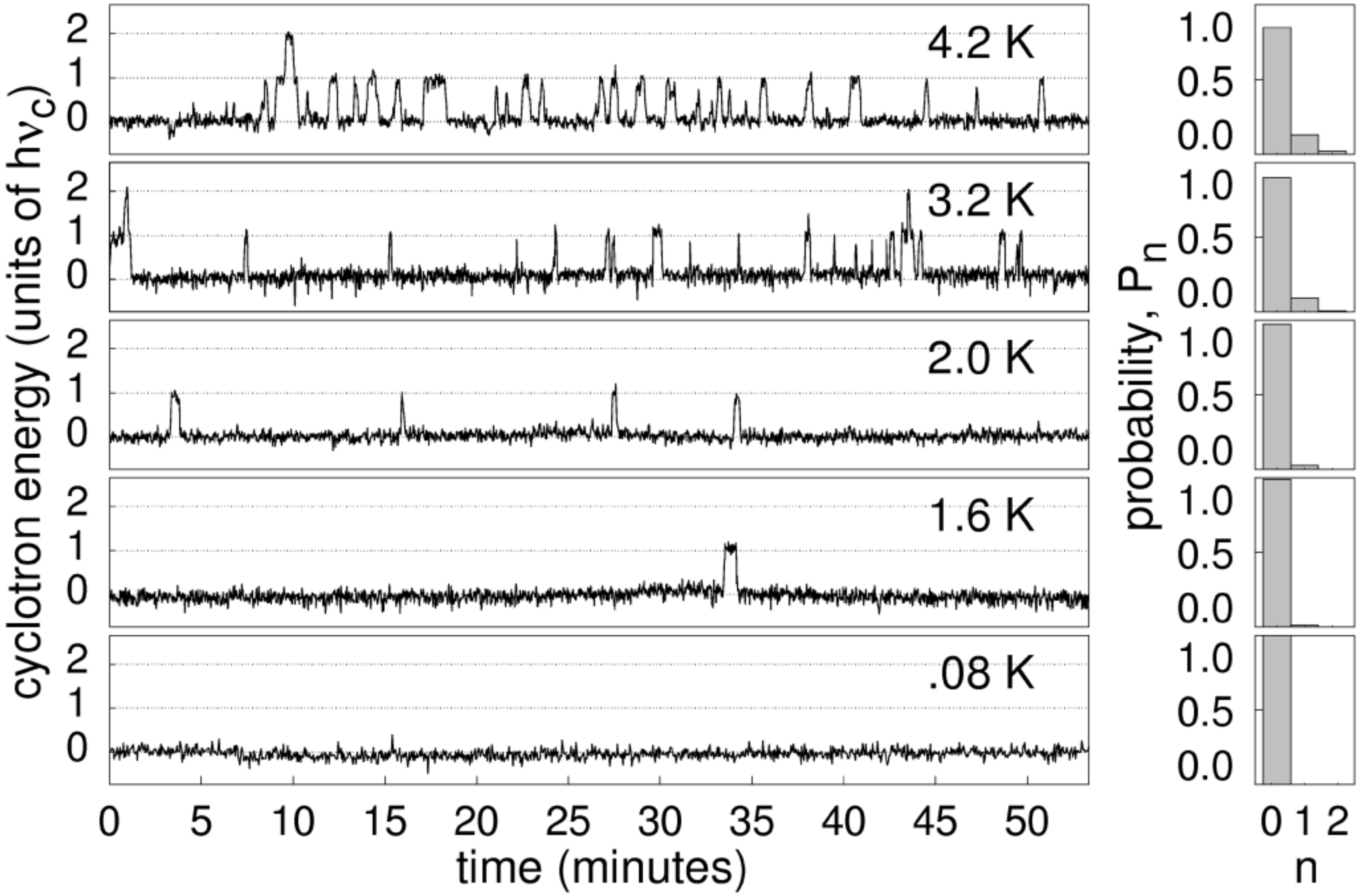
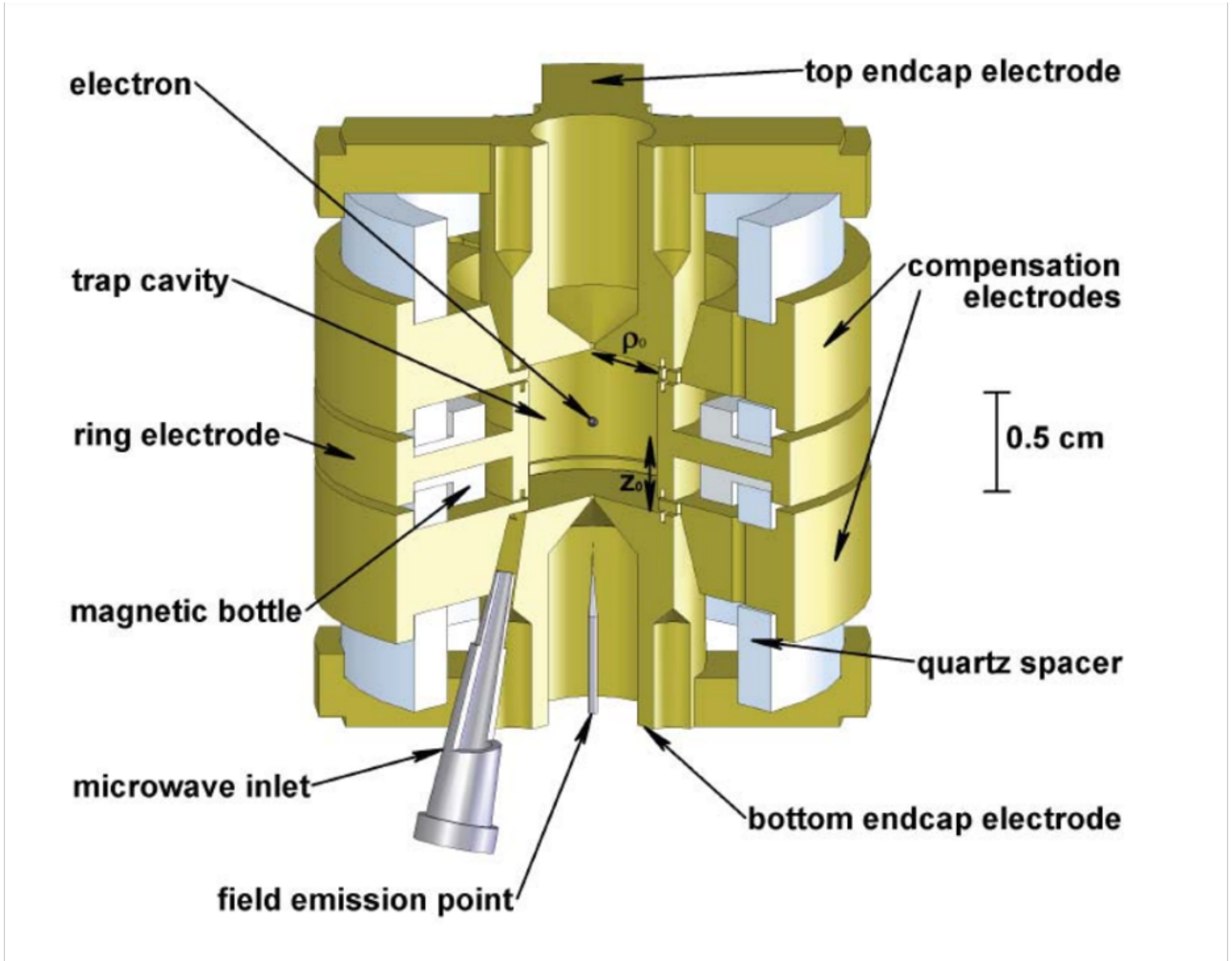


FIG. 2. Quantum jumps between the lowest states of the one-electron cyclotron oscillator decrease in frequency as the cavity temperature is lowered.

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

Peil & Gabrielse - 1999

Apparatus



electron
top endcap electrode
trap cavity
compensation electrodes
ρ₀
ring electrode
0.5 cm
z₀
magnetic bottle
quartz spacer
microwave inlet
bottom endcap electrode
field emission point

Contents

- Dark Photon Dark Matter
- Electron Traps
- Cavities as Electric Field Concentrators

- Millicharge Relics
- Ion Traps

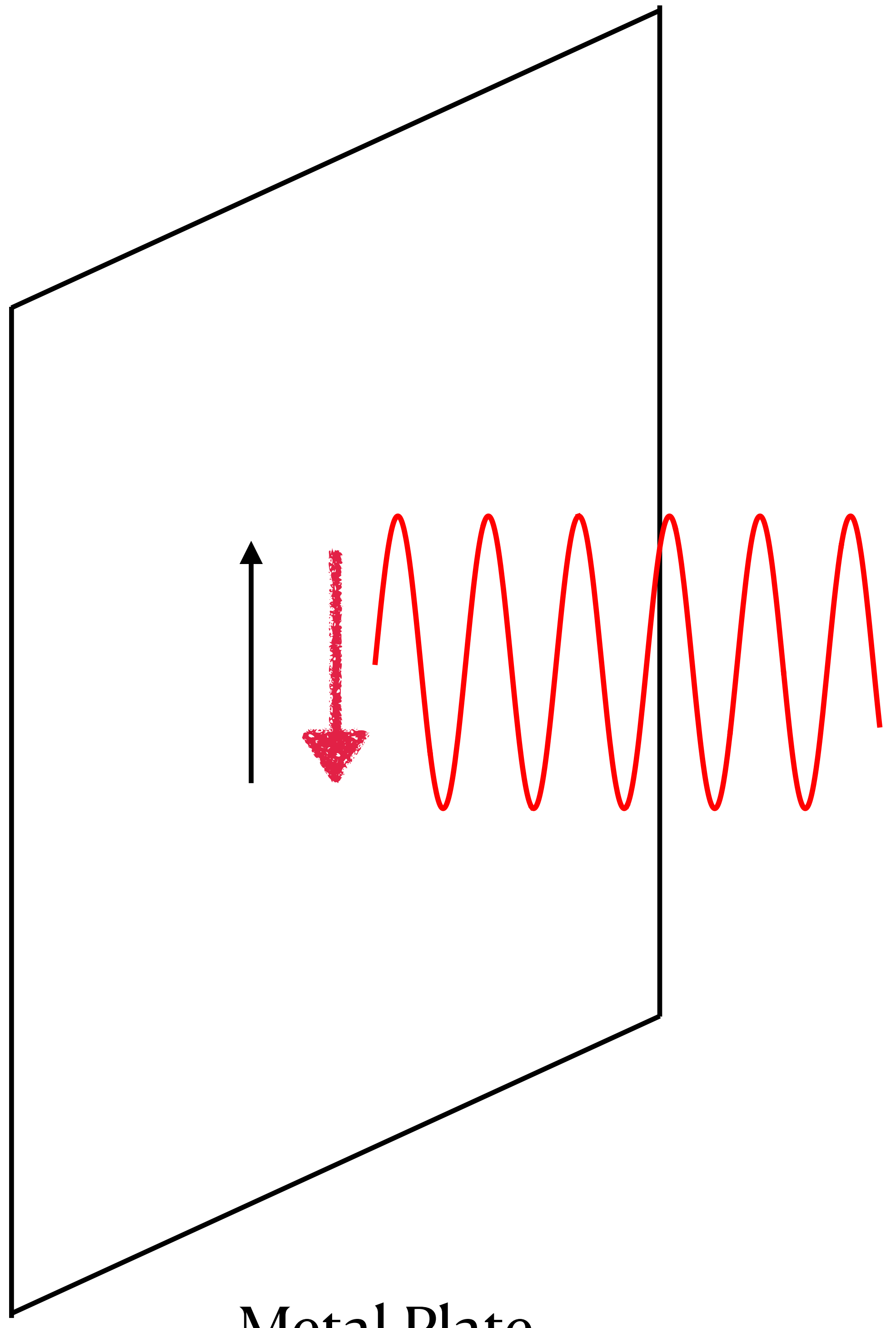
Effect of Cavity

- Work in Interaction Basis: E^{active} that couples to SM and E^{dark}
- Metal boundaries destroy $E_{||}^{\text{active}}$
- When $mR \ll 1$,
- $E_{||}^{\text{dark}}$ oscillates back to $E_{||}^{\text{active}} \Longrightarrow (mR)^2$ suppression
- For $mR \gg 1$ what happens?

Effect of a metal plate

$$E_{1||}^{\rm obs} = \epsilon\sqrt{2\rho_{\rm DM}}\cos\omega t$$

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



In and outgoing modes

Metal Plate

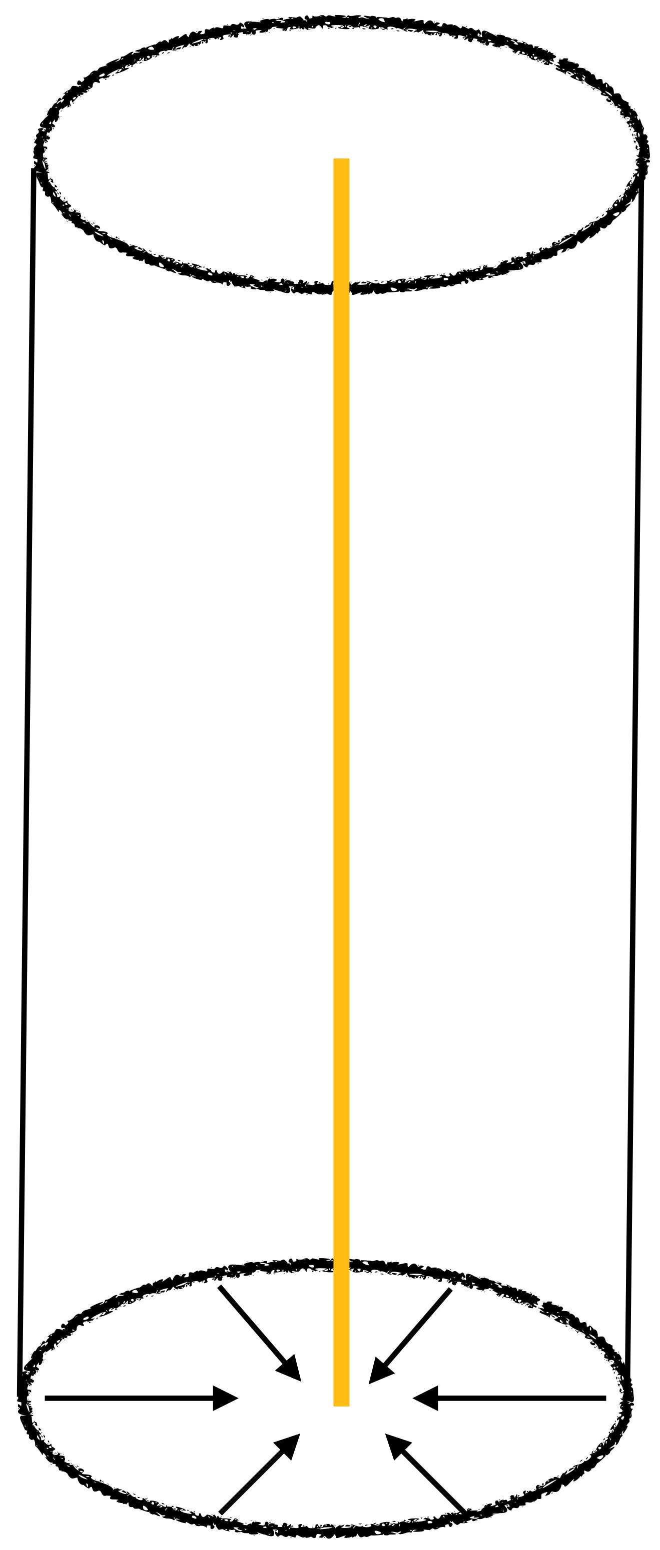
Horns, Jaeckel, Lindner, Redondo 1212.2970

Consequence: Dish antenna focus!

Concentration

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

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

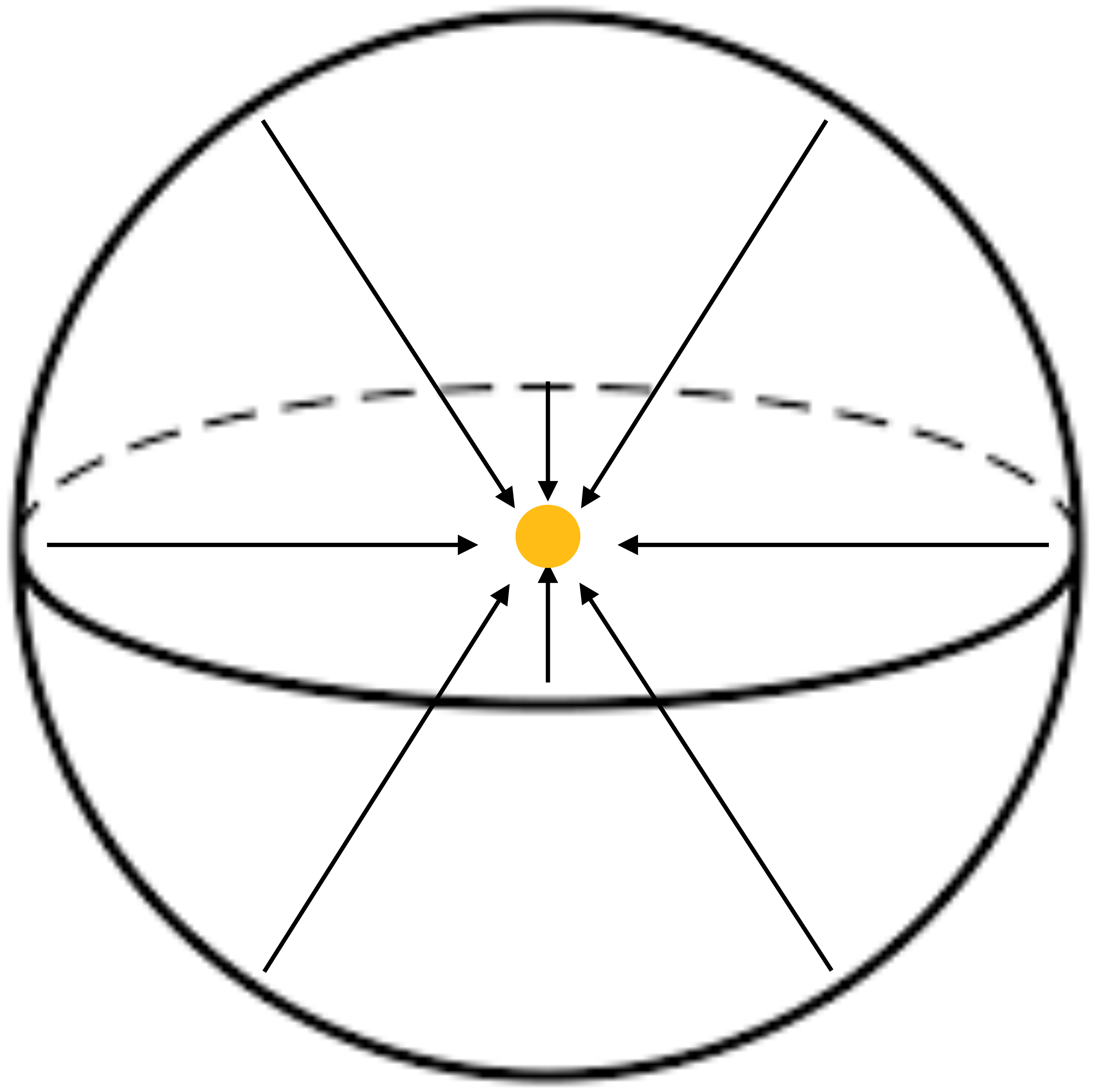


Only linear focussing

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

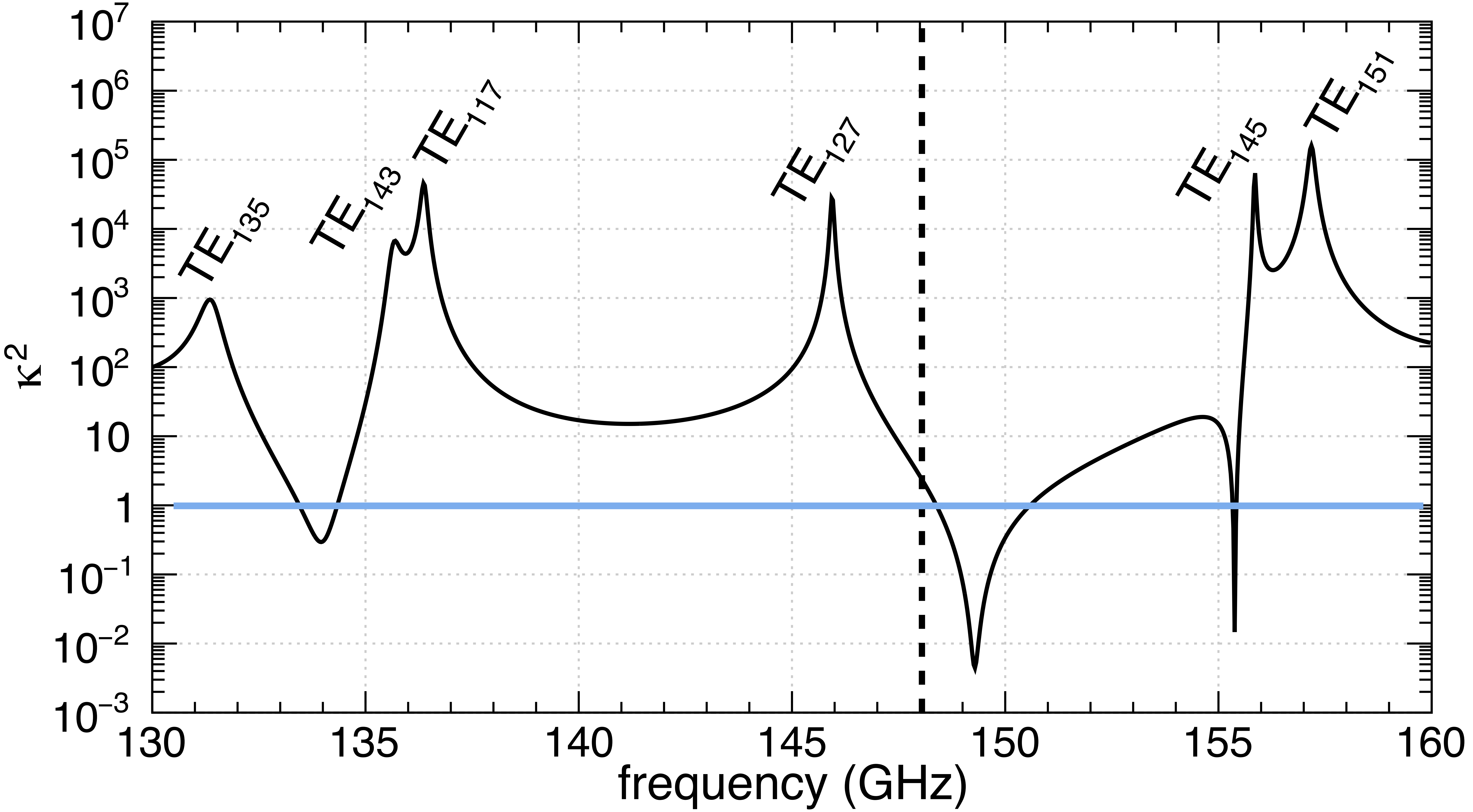
Currently $mR \approx 14$

$$\kappa = \frac{E_{\text{cav}}}{E_{\text{free}}}$$



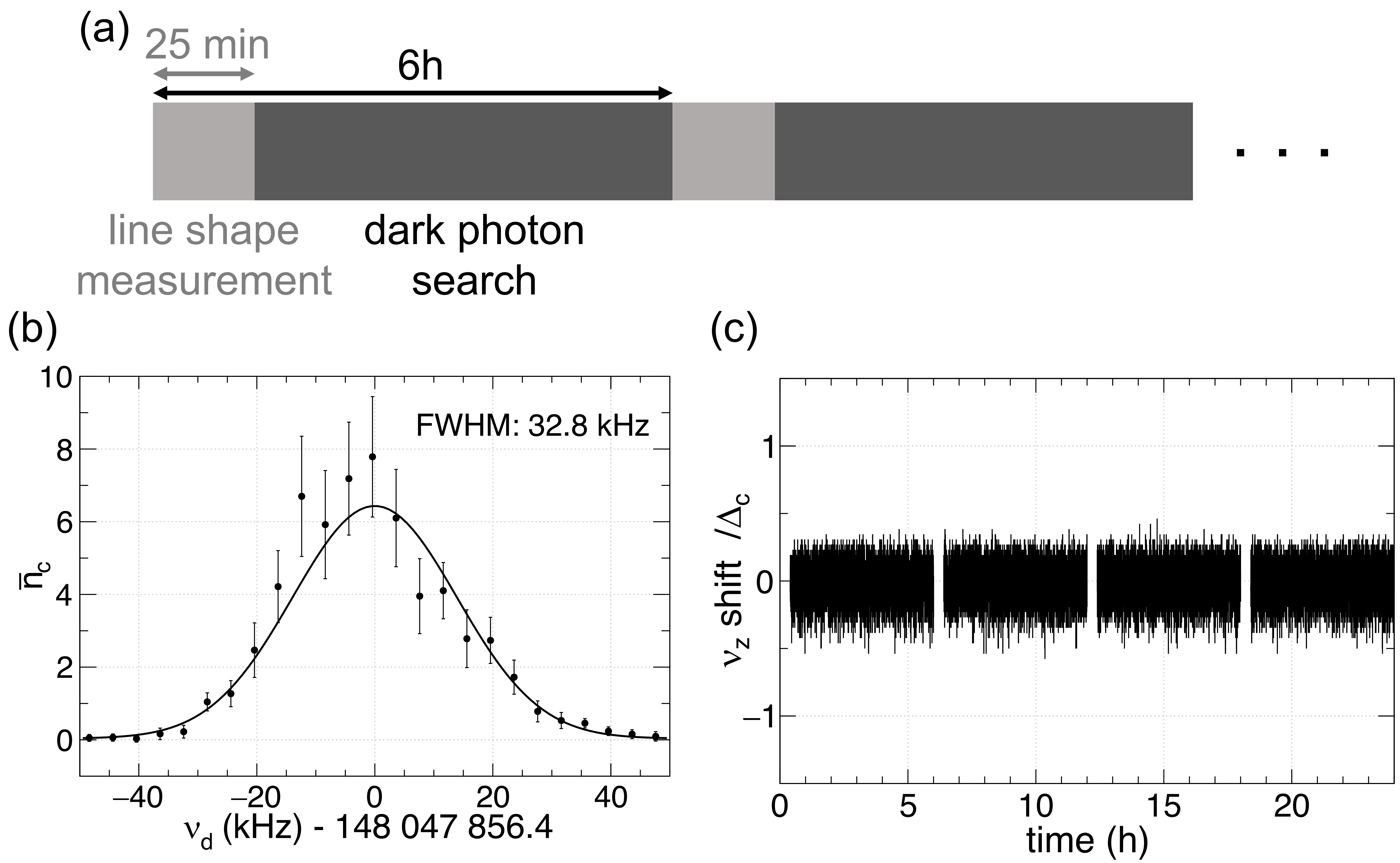
Quadratic Focussing

Kappa Today



R=0.5 cm

Data



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.

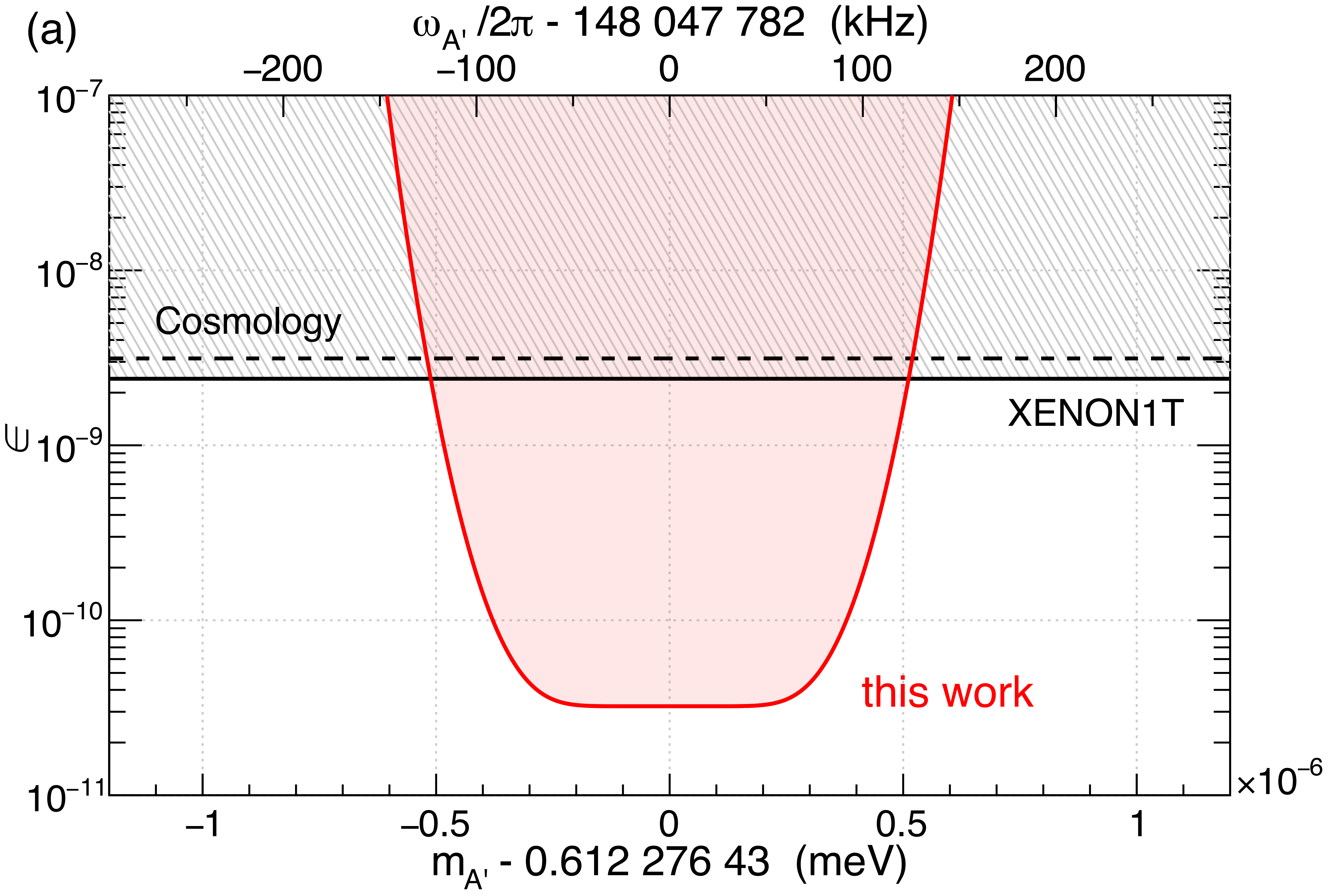
638870 sec = 177.5 hour

Current Data

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

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

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



To Do

- Scanning 15 sec/bin

4 Apr 2022 in Politics & Policy

Helium is again in short supply

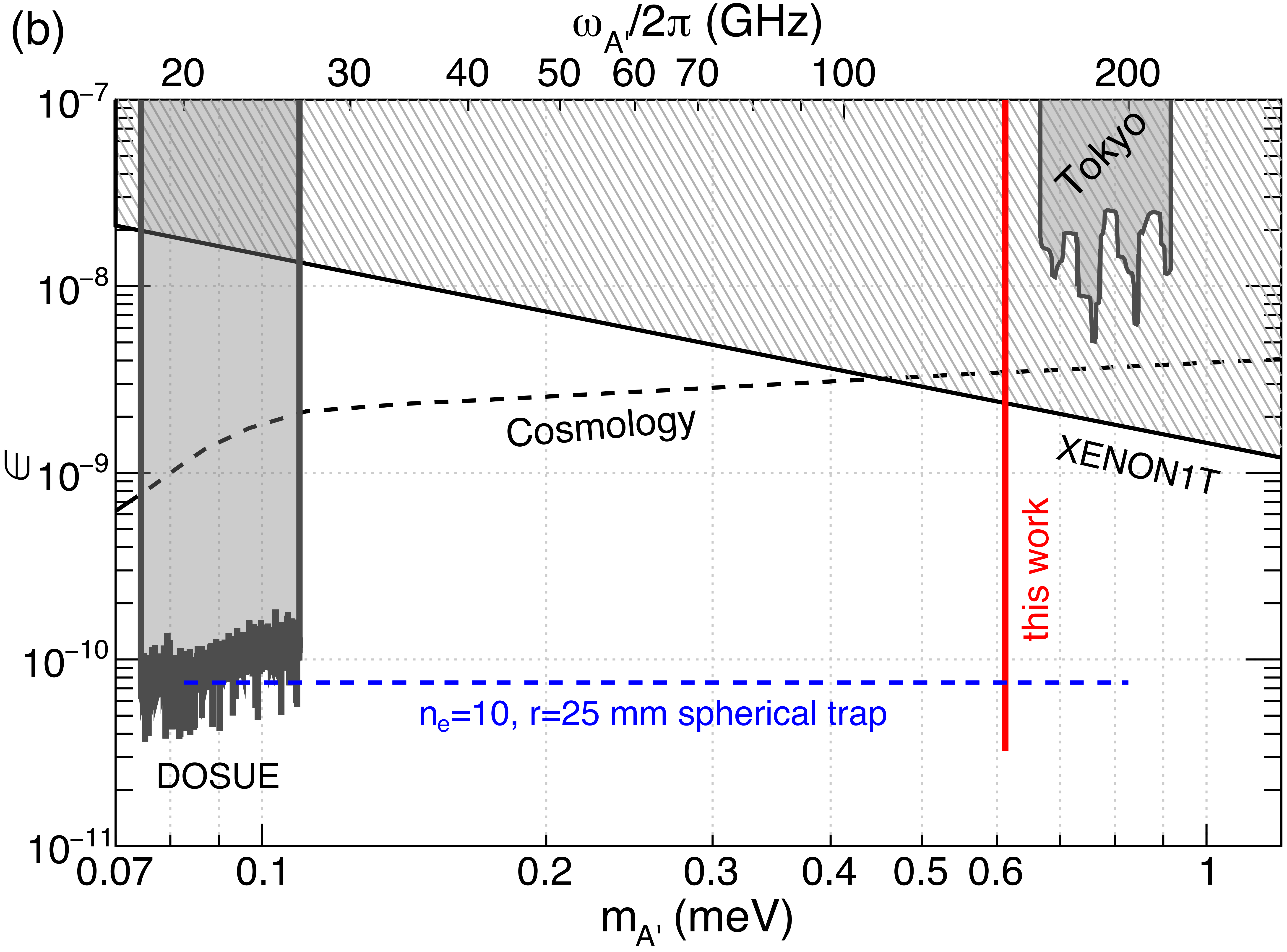
The war in Ukraine isn't much of a factor, yet.

David Kramer

The federally operated Cliffside Helium Plant in

‹ PREV NEXT ›

physicstoday.scitation.org

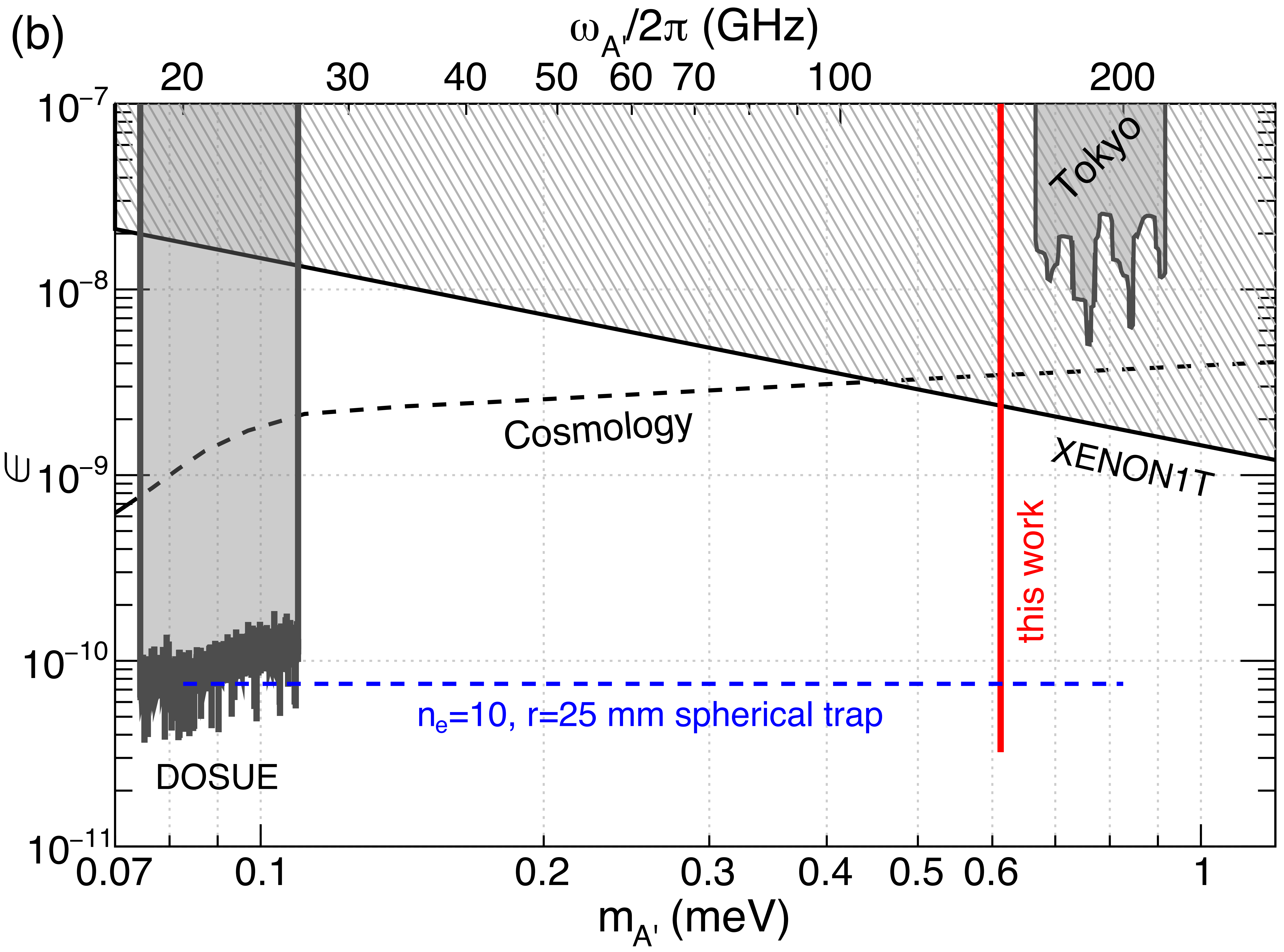


To Do

- Scanning 15 sec/bin

- Future:

A. Bigger Cavities
B. More electrons
C. Higher excited states



Summary

- Dark Photons hard to probe in the 0.1 meV to 1 meV range
- A single electron's cyclotron jump, picks out this frequency
- Pilot Run @ single frequency shows no background
- Scanning/Other improvements on the anvil

Contents

- Dark Photon Dark Matter
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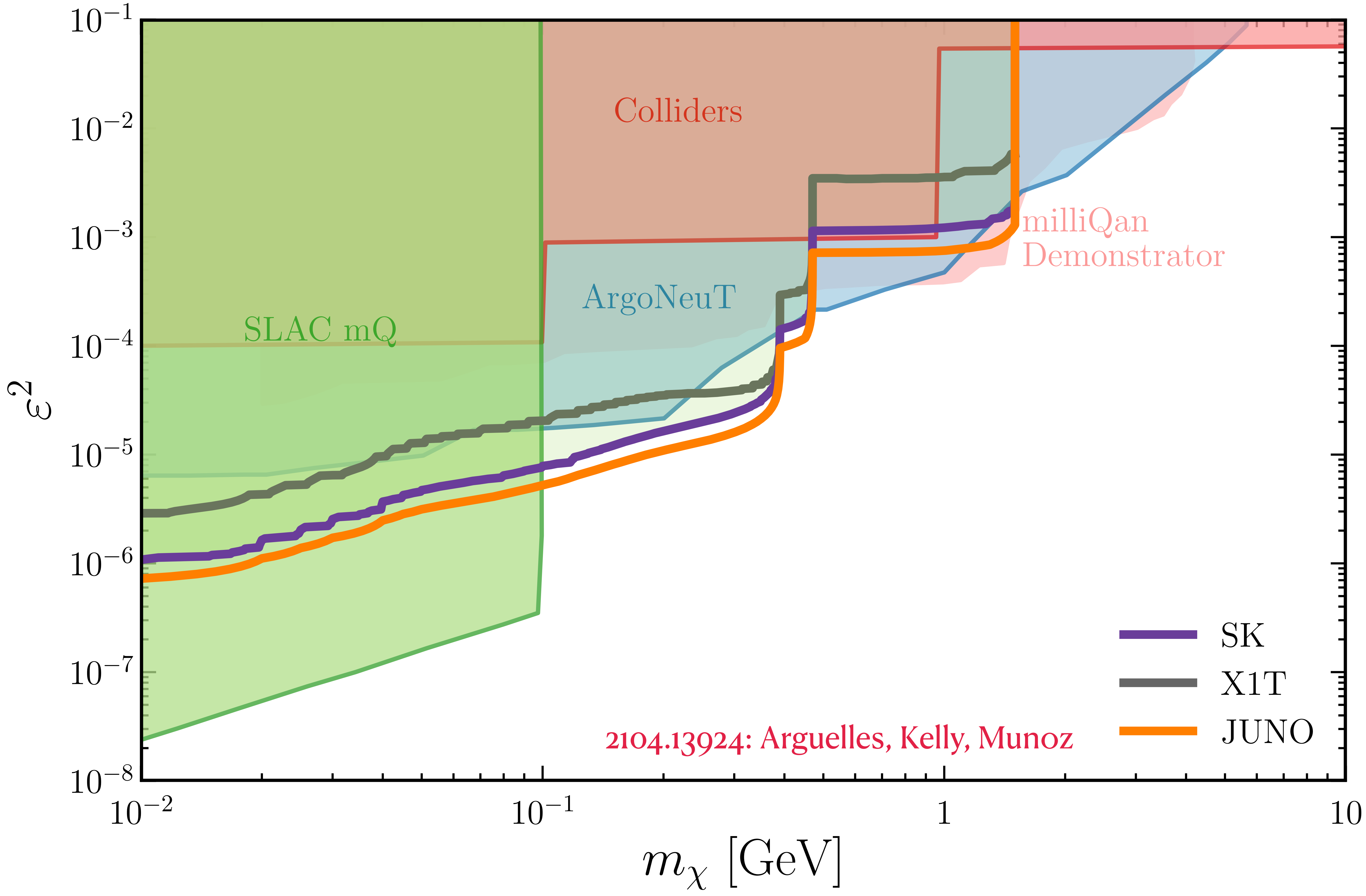
- Millicharge Relics
- Ion Traps

Millicharge Particles

- ✦ Particles with tiny electric charges: ϵe
- ✦ Simple models to write (with or without a dark photon)
- ✦ Looked for in various experimental programs
- ✦ Recent resurgence due to EDGES anomaly

Existing Limits

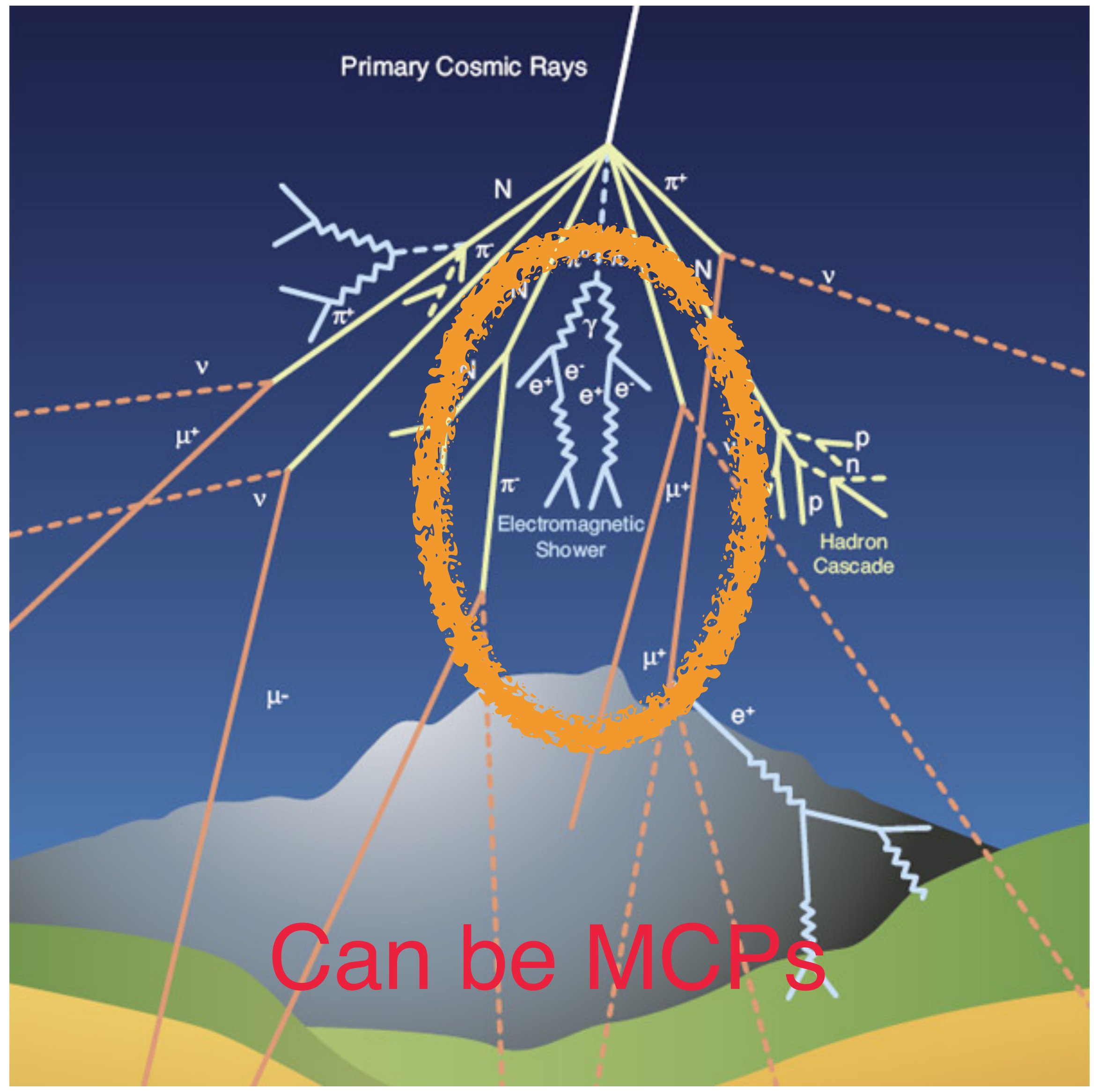


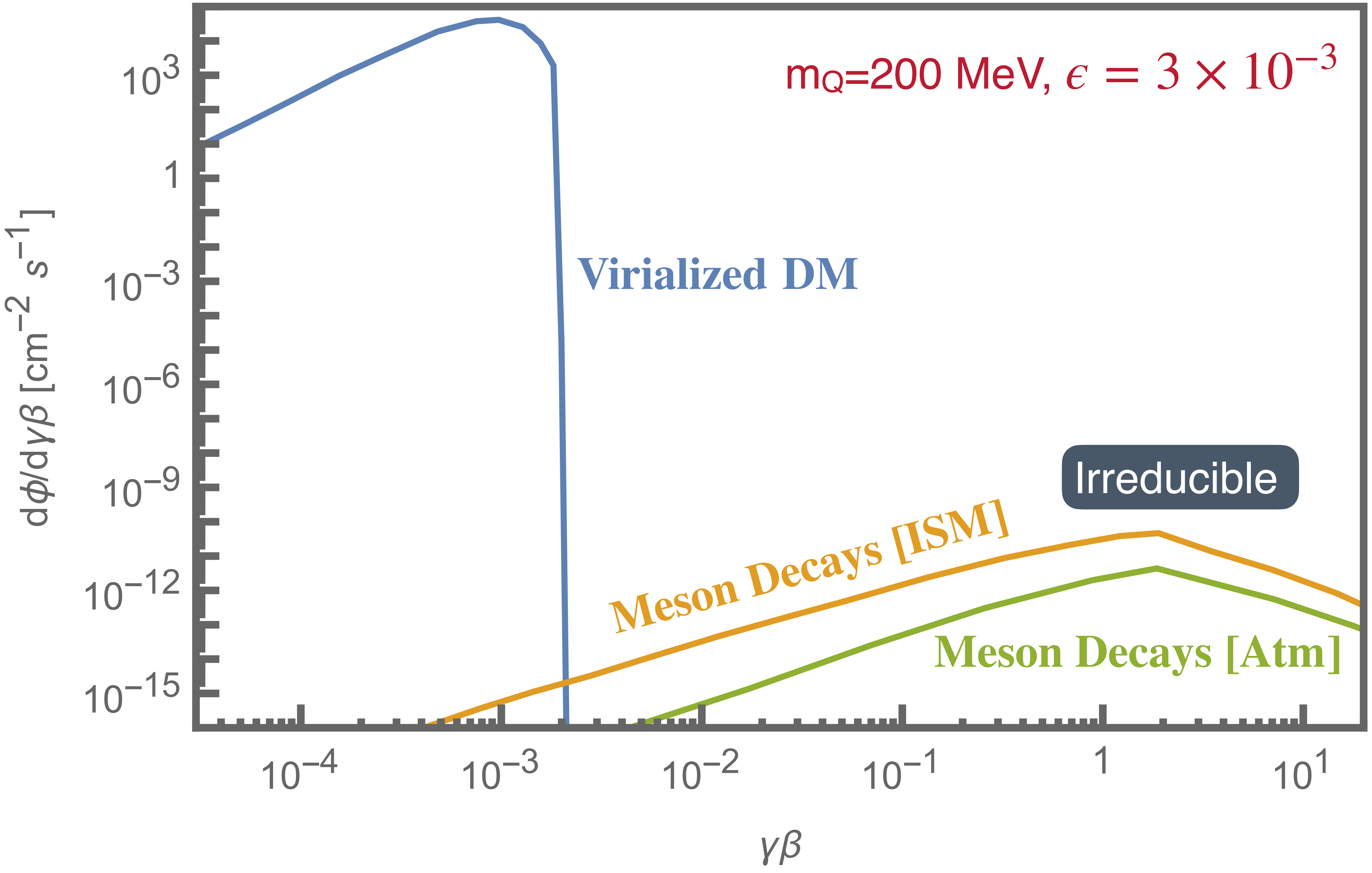
*Additional Limits exist if DM component

An Irreducible mCP source

2010.11190 HR, Roni Harnik, Ryan Plestid and Maxim Pospelov

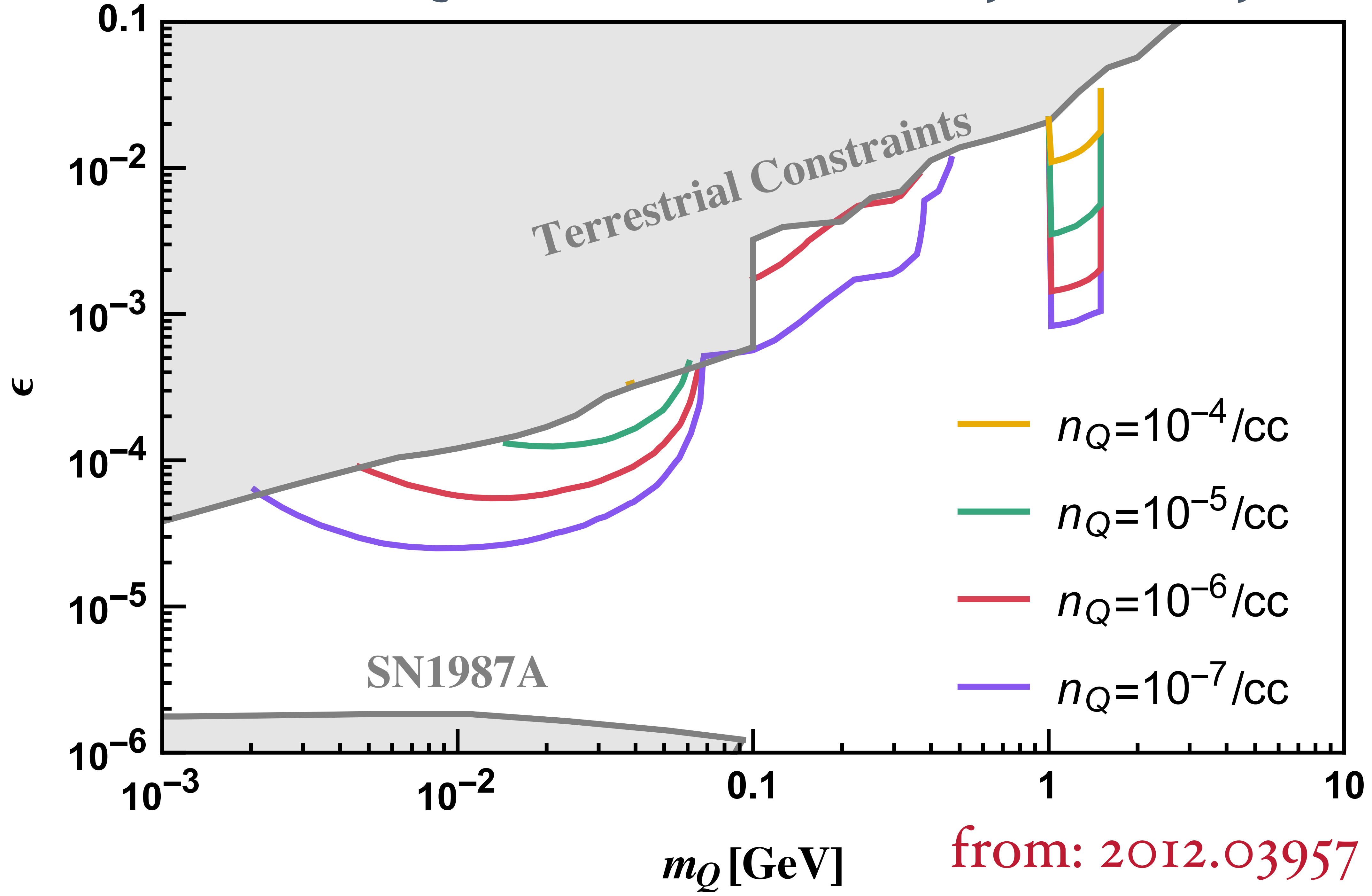
- ✦ Mesons produced in Cosmic ray collisions can decay into mCPs
- ✦ Contribution to irreducible density on Earth

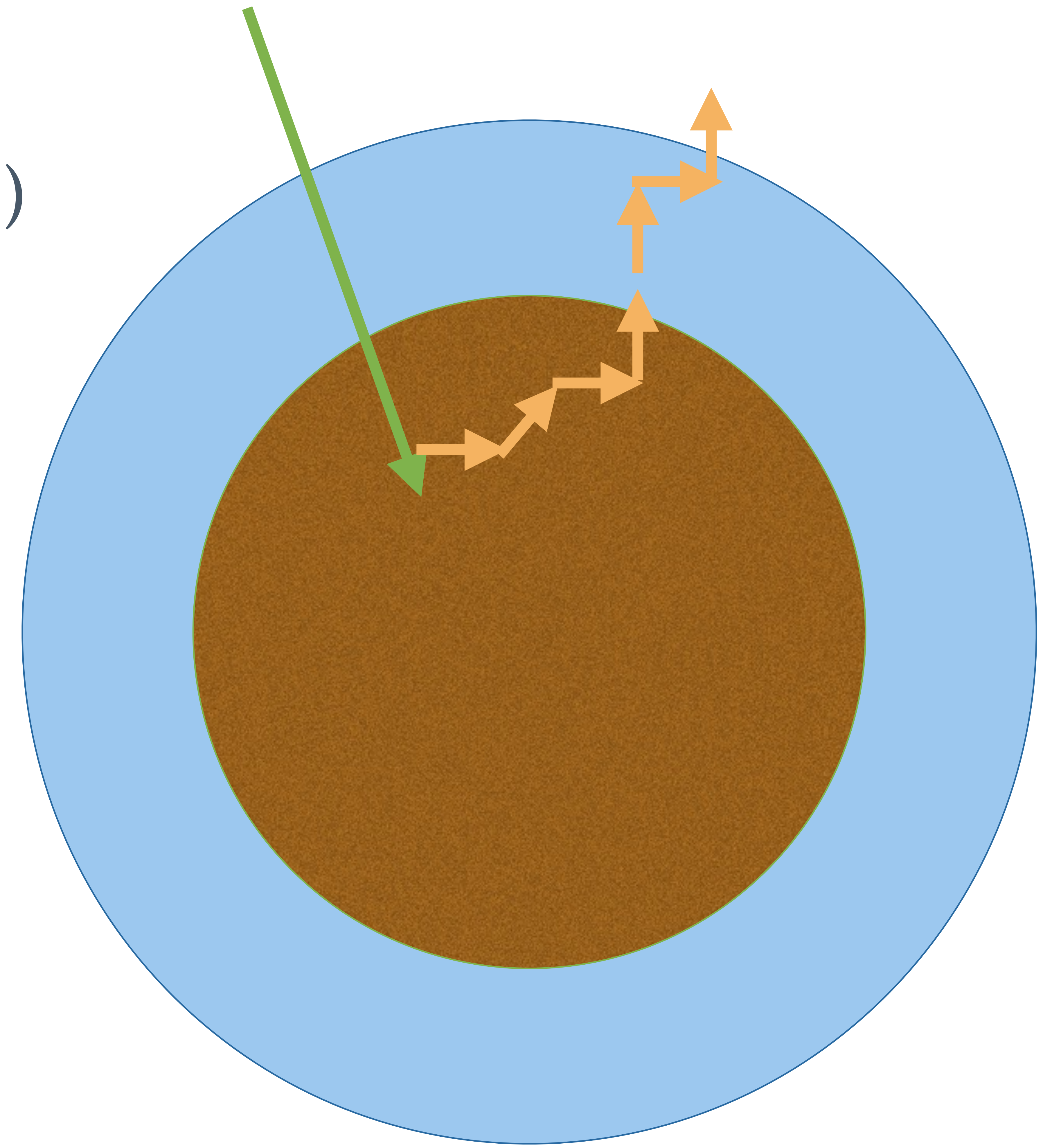




Temporary accumulation

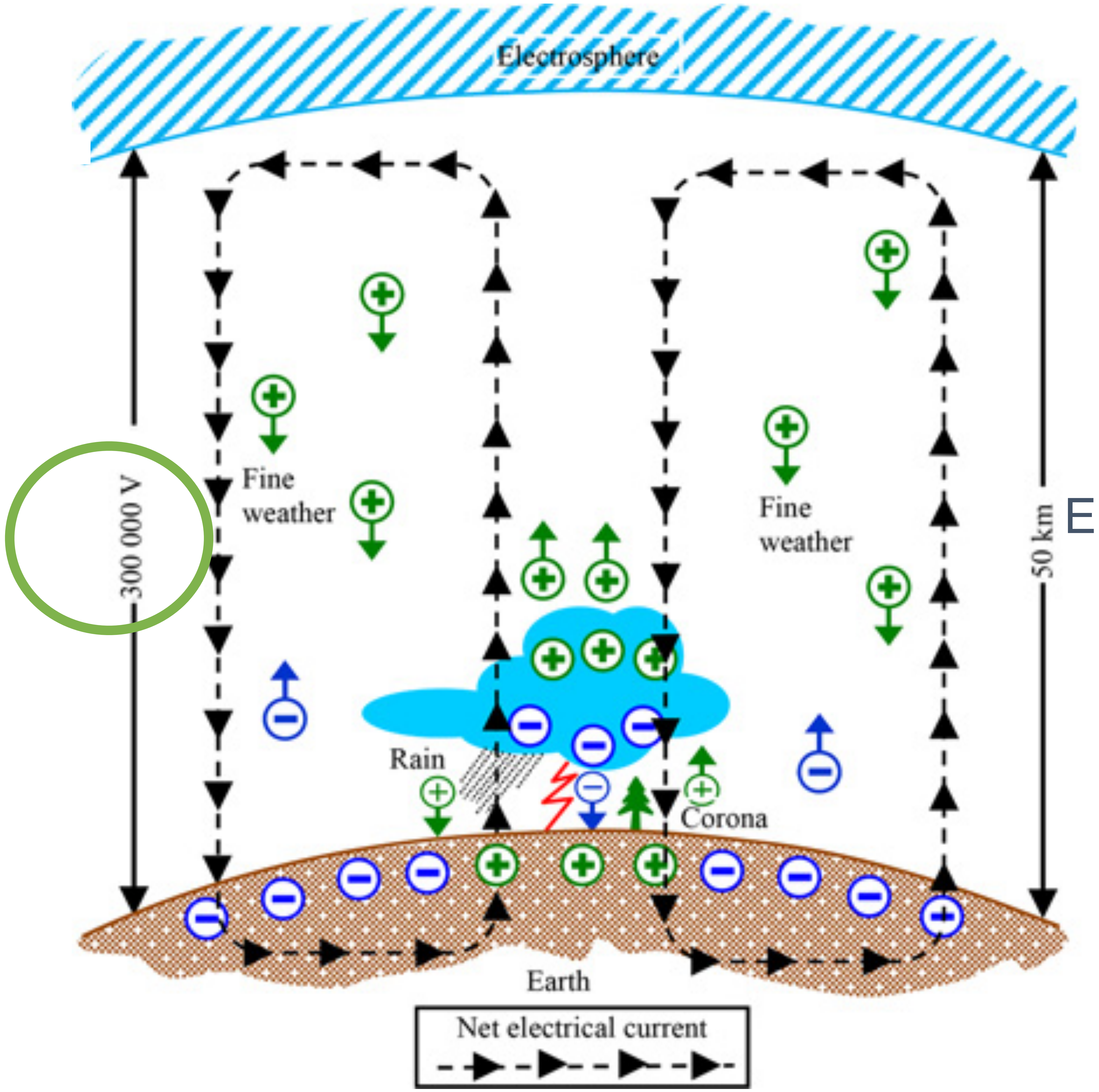
- ✦ High boost, hence penetrates deep
- ✦ Thermalized mCP, large x-section, (MFP~ micron)
- ✦ Evaporates for m_Q < GeV, but very slowly.





from: 2012.03957 HR M.Pospelov

Earth E-field

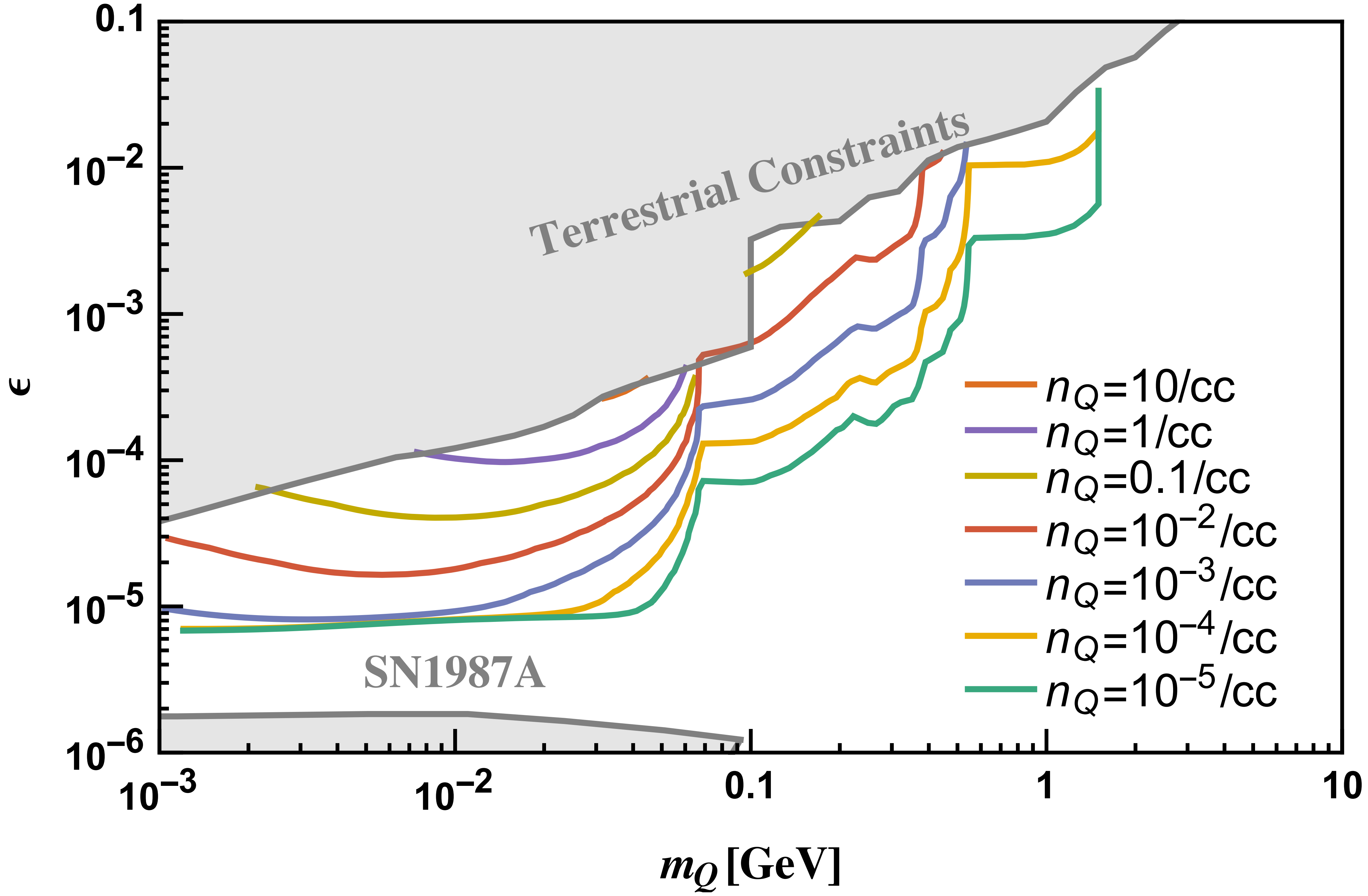


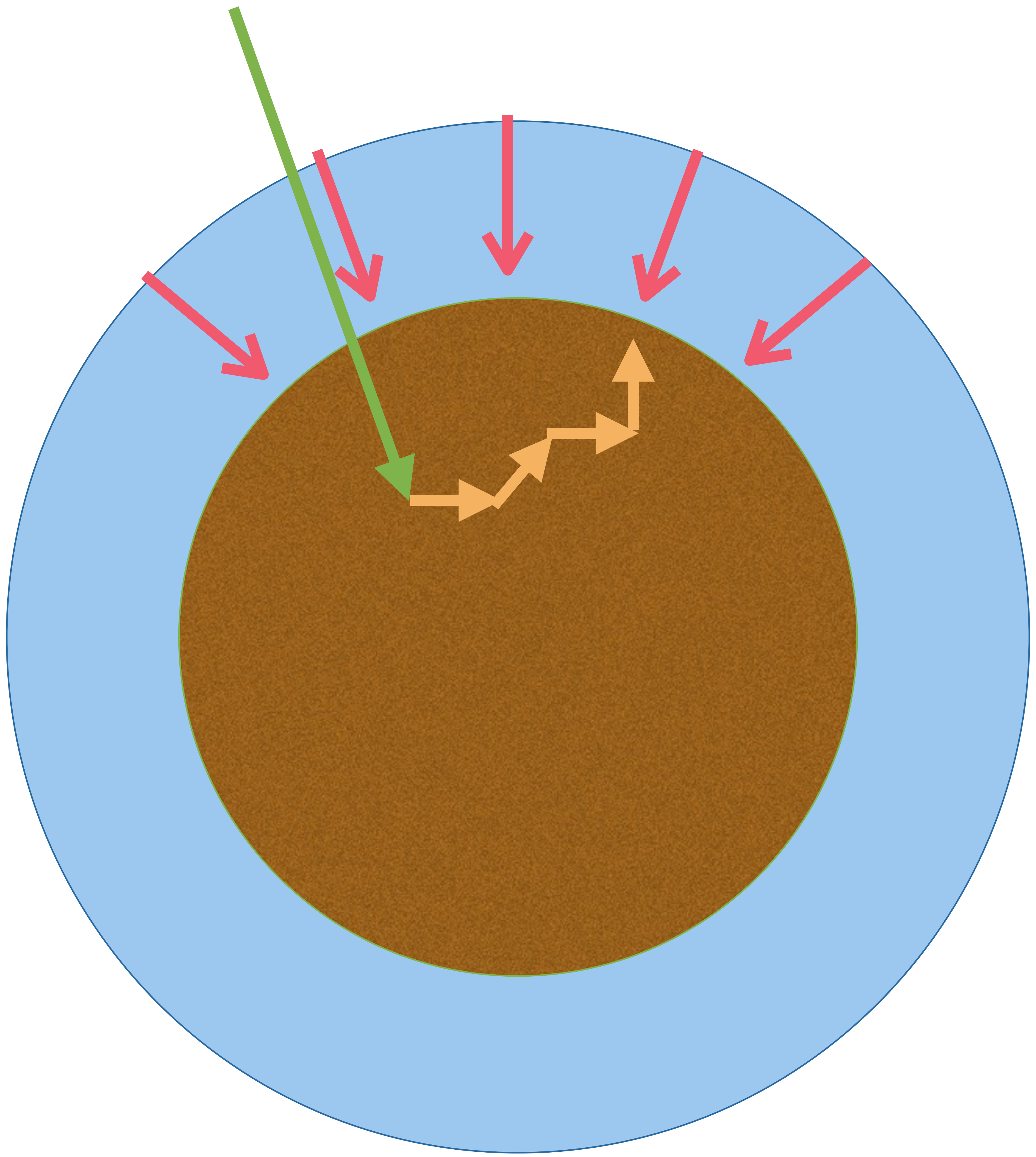
Electric Field ~ 100 V/meter

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





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

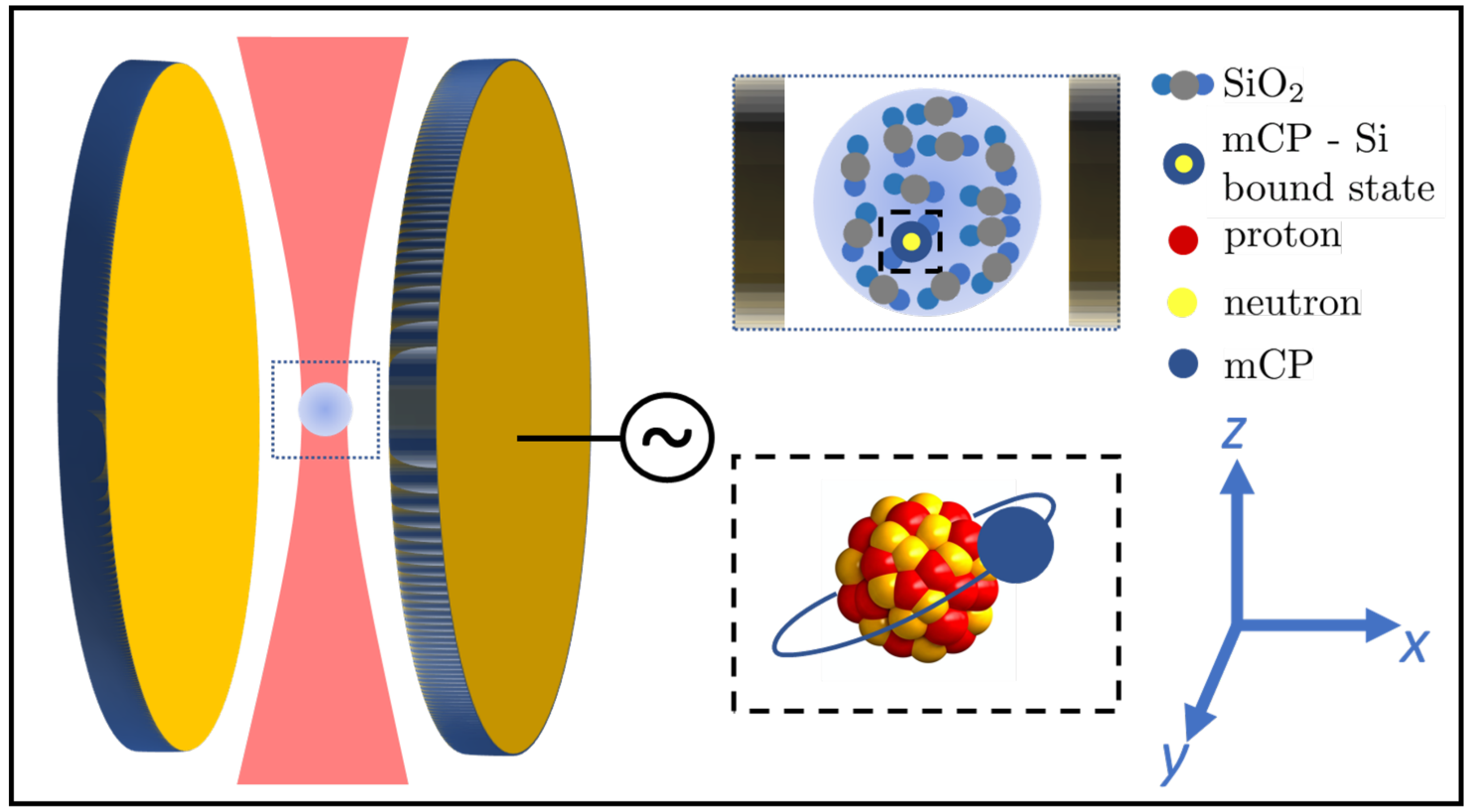
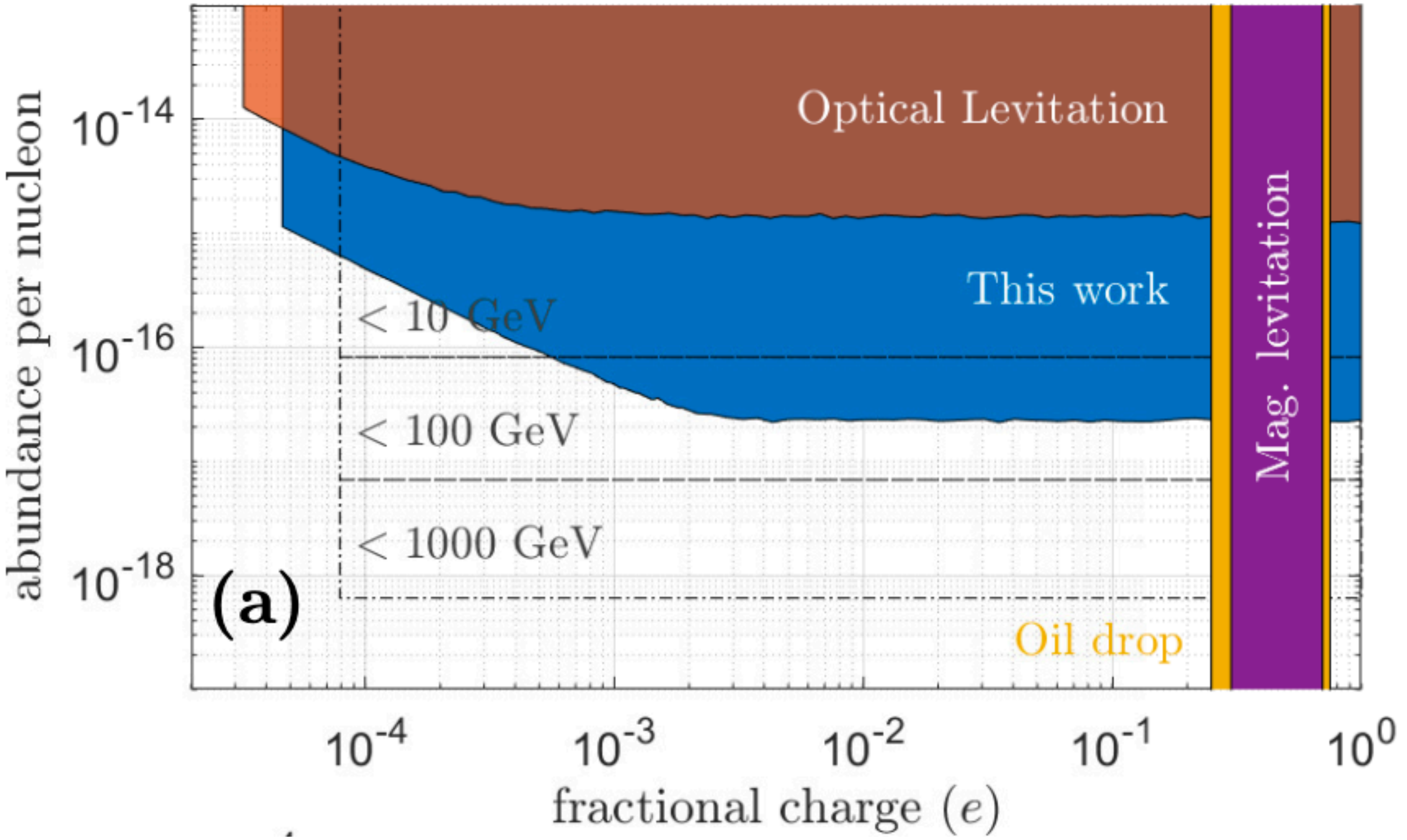


FIG. 1. SiO_2 spheres are levitated in high vacuum between a pair of parallel electrodes to search for a violation of charge neutrality by, *e.g.*, a mCP electrostatically bound to a Si or O nucleus in the sphere.



✦Crucial assumption: Negative mCPs bind with Silicon nuclei

✦10^{24} Nucleons cm^{-3} translates to 10^{7} mCPs cm^{-3}

Energy Thresholds

Large Charge

DM Mass > MeV

WIMPs

0 eV

T_{room}=26 meV

Few eV

1 keV

Energy Threshold

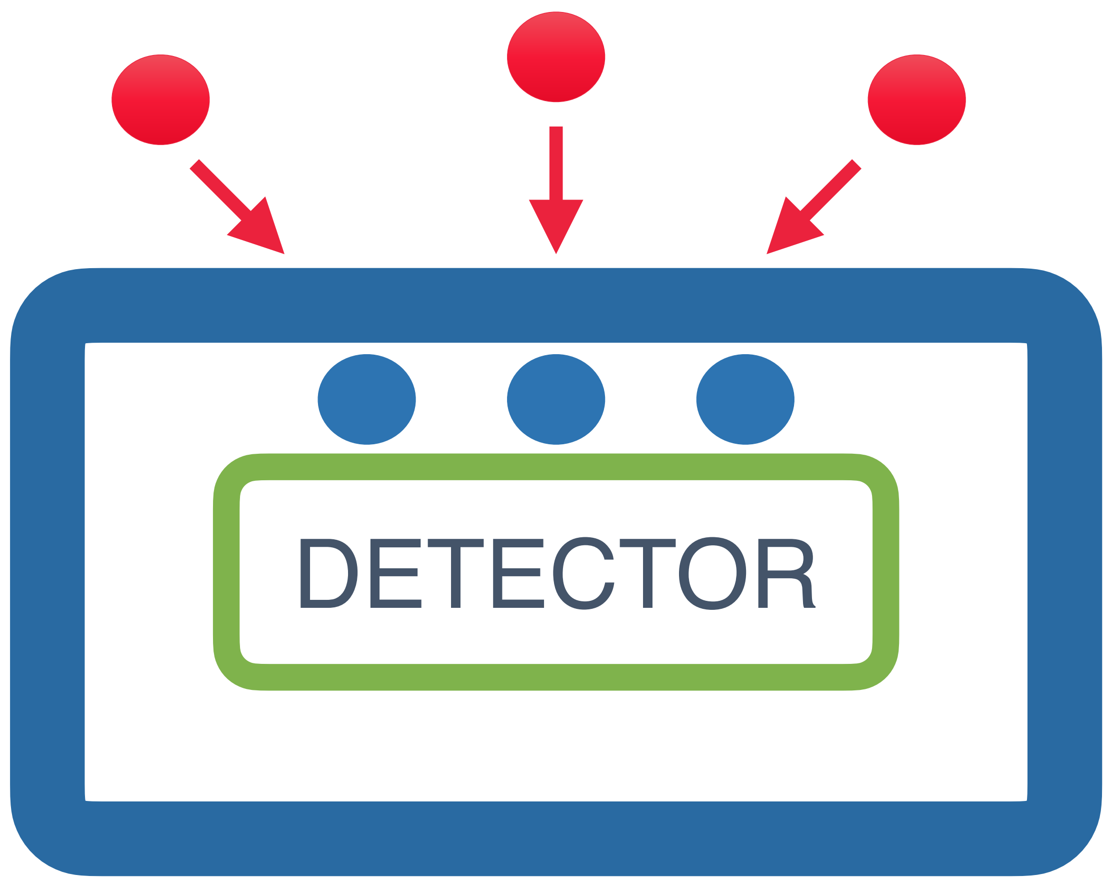
Xenon e

SENSEI
Super-CDMS

LZ
Xenon 1T n
Panda-X

Detection Nightmare

- ✦ Despite large number density & cross-section
- ✦ Small energy deposit: 300 Kelvin ≈ 26 meV
- ✦ Small momentum transfers: See neutral atom



- ✦ Low threshold detectors have low temperature walls to reduce background
- ✦ Small MFP~ micron, rapidly thermalize with walls
- ✦ Electron trap $500\ \mu$eV threshold, $10\ \mu$eV walls.

Sisyphean Task?

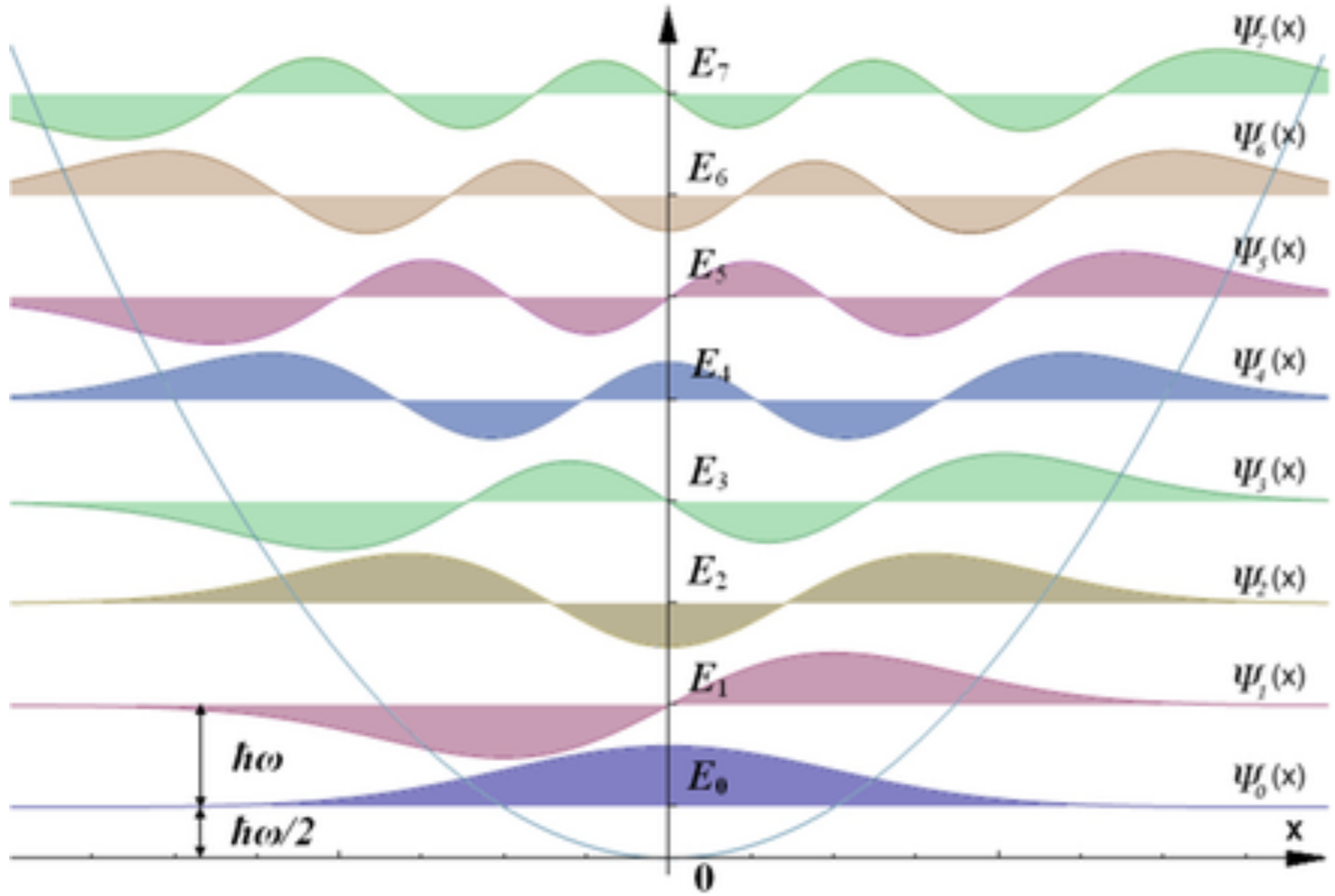
Ion Traps to the rescue!

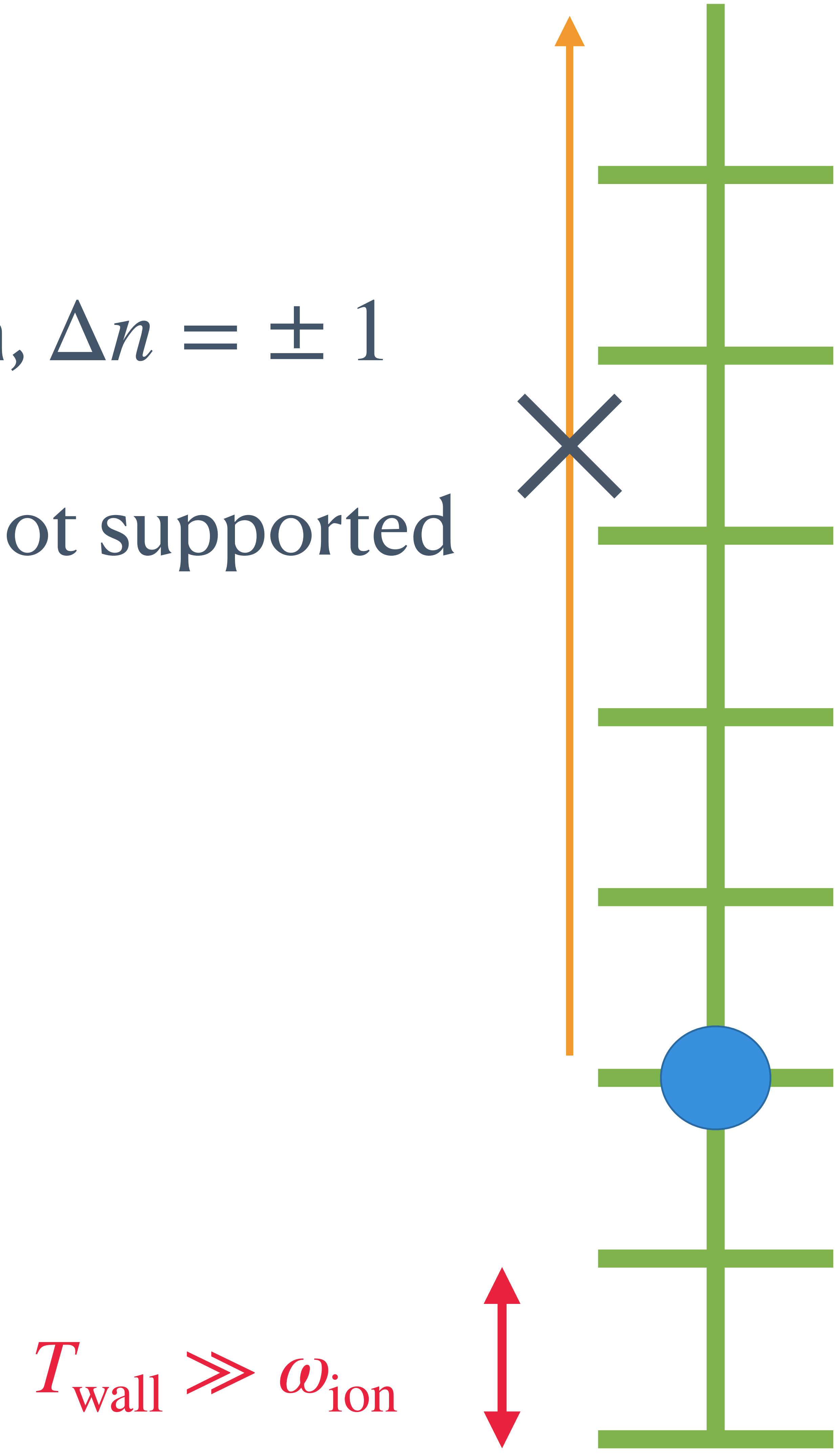
$$\frac{qB}{m_p} \approx 60 \text{ neV} \frac{B}{1\text{T}} \frac{1 \text{ GeV}}{m_p}$$

Dont we have to cool to $T_{\text{wall}} \ll \text{mK}$?

Selection Rules

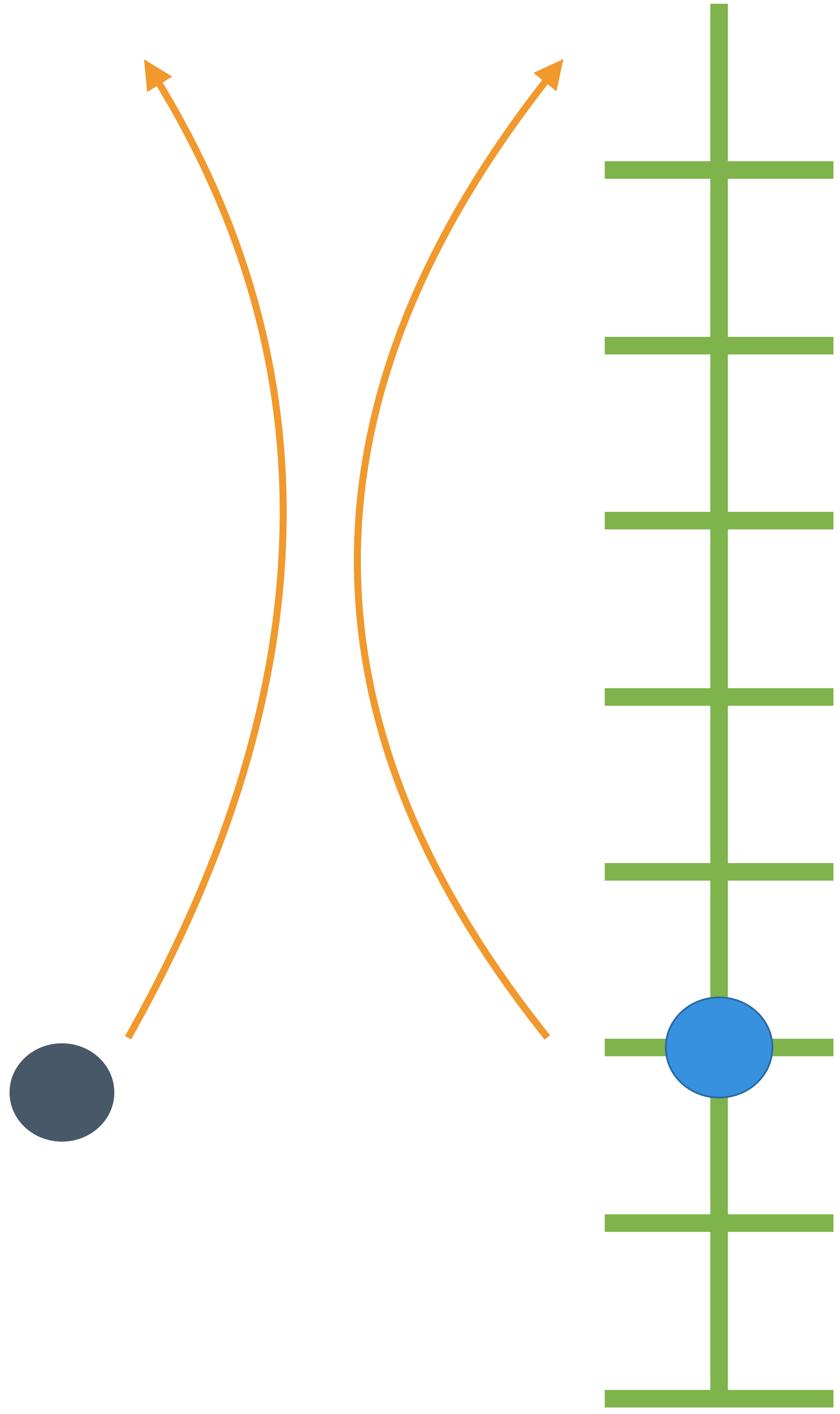
- Approximate Harmonic Oscillator
- Blackbody radiation : Selection rules for photon absorption, $\Delta n = \pm 1$
- Number of photons with energy $\omega_{\text{ion}} \ll T_{\text{wall}}$ is negligible, not supported





Selection Rules

- ✦ Scattering breaks selection rules
- ✦ Momentum transfer $\gg$ Energy Transfer



Heating Rate in Ions

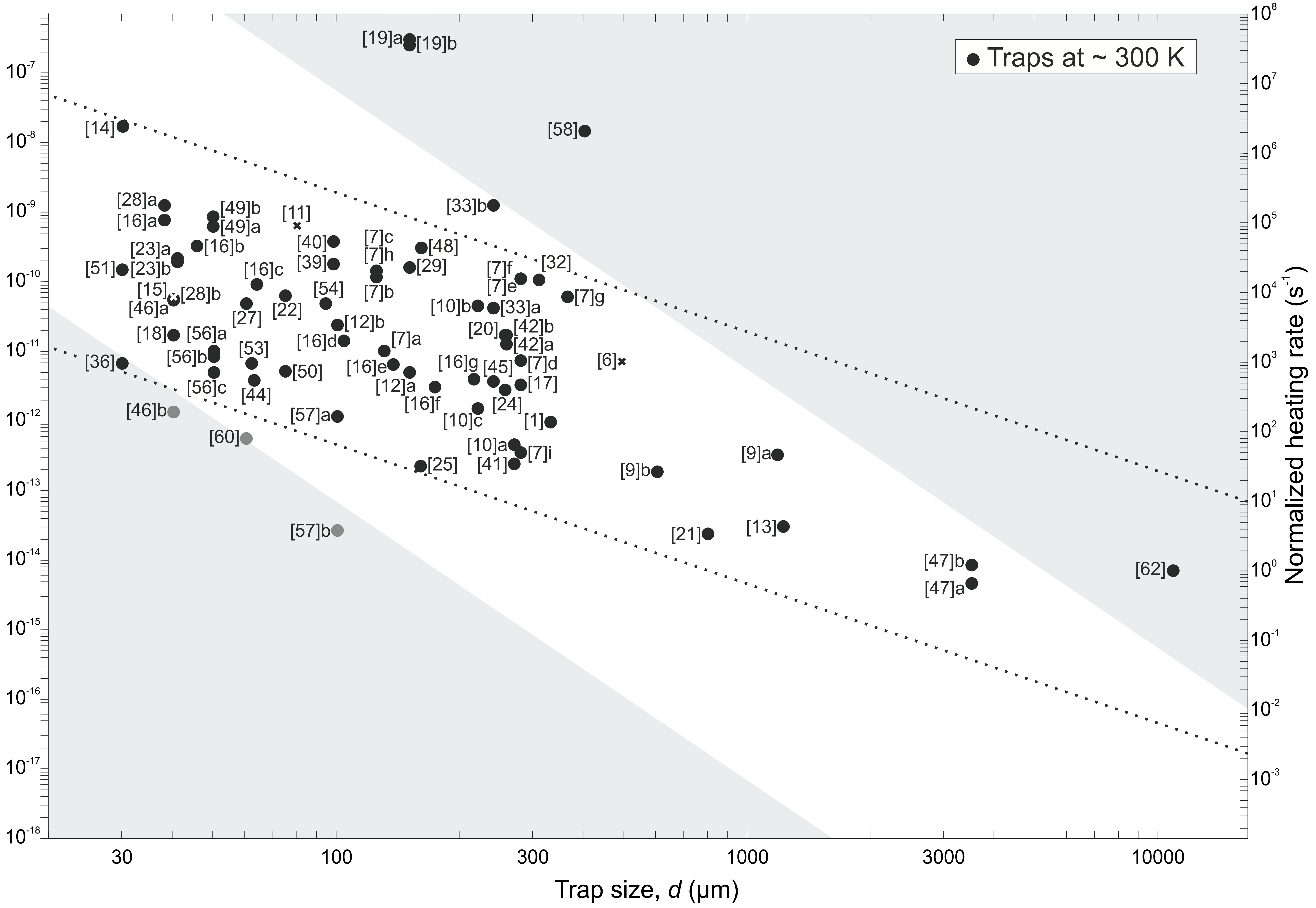
^{40}Ca / ^{9}Be / p ions used

✦ $\nu_+, \nu_-, \nu_z \approx$ MHz $\approx$ **4** neV

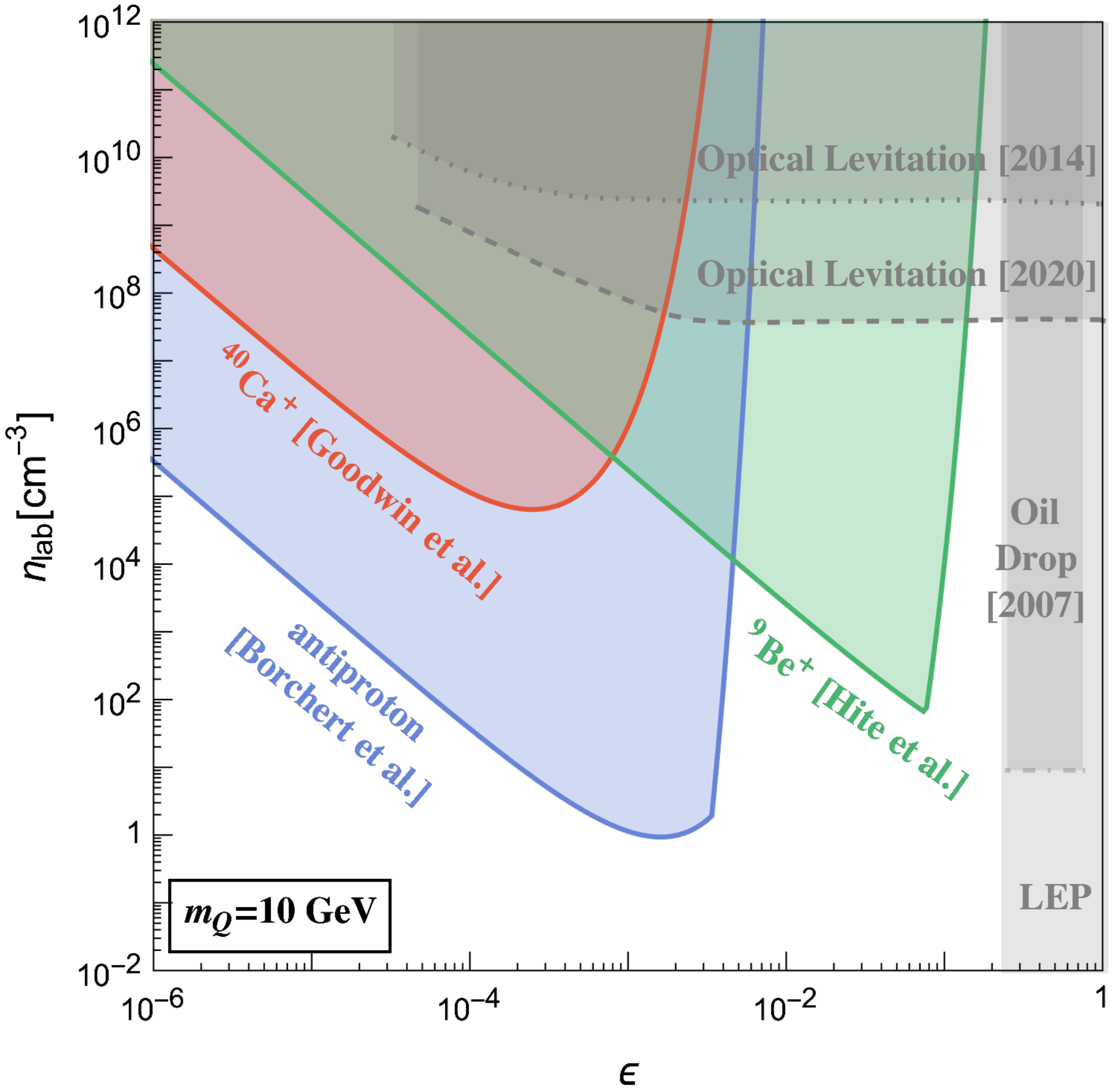
$\approx 50\mu$K

✦ $\dfrac{dn}{dt} \approx \dfrac{1}{\text{sec}}$

✦ Heating Rate: $\dfrac{\text{neV}}{\text{sec}}$

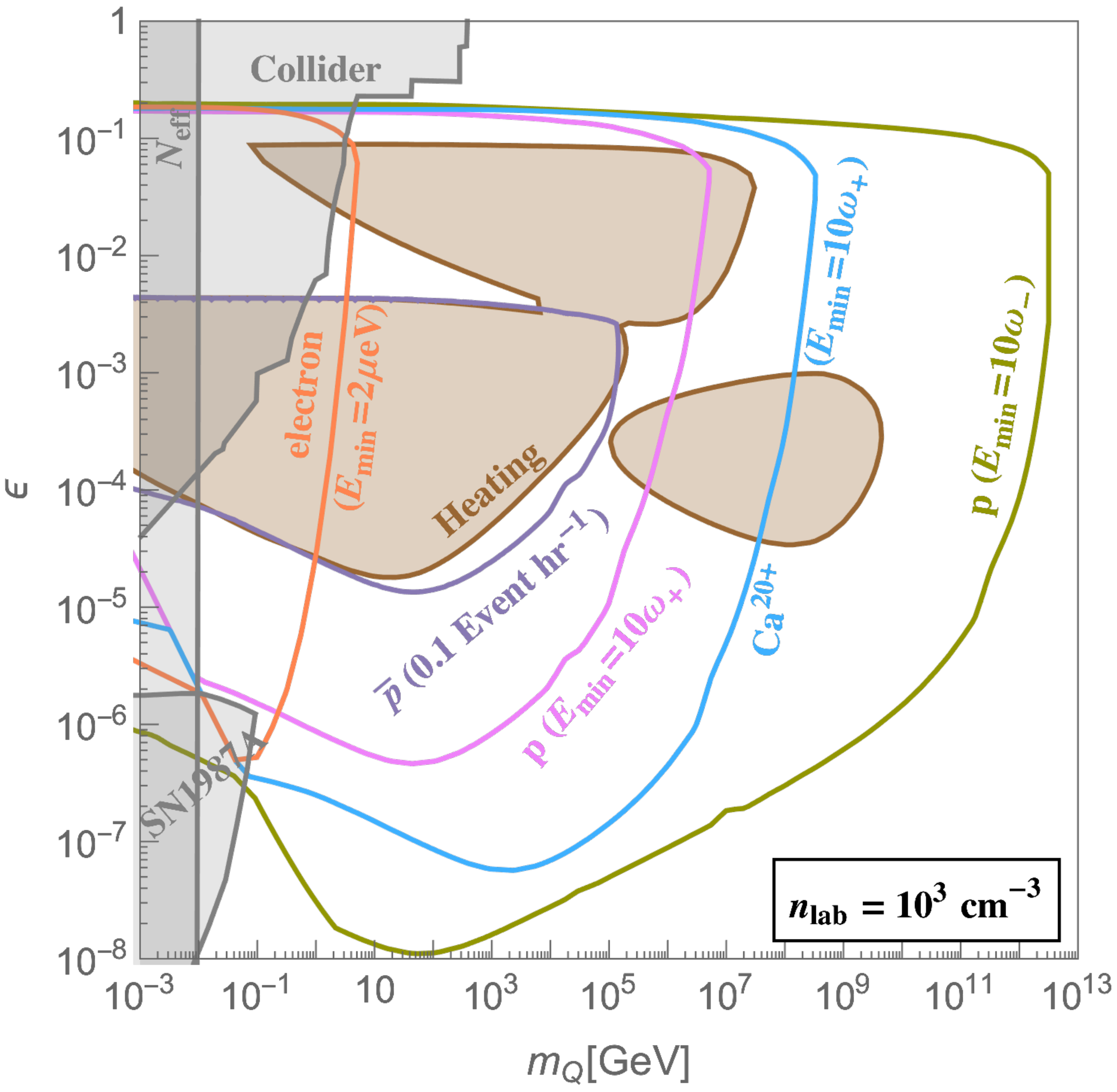


Results



Optical Levitation [2014]
Optical Levitation [2020]
Oil Drop [2007]
LEP
$^{40}Ca^+$ [Goodwin et al.]
antiproton [Borchert et al.]
$^{9}Be^+$ [Hite et al.]
m_Q=10 GeV
$n_{lab}[cm^{-3}]$
ϵ
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-6}
10^{-4}
10^{-2}
1

Projections



Outlook

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

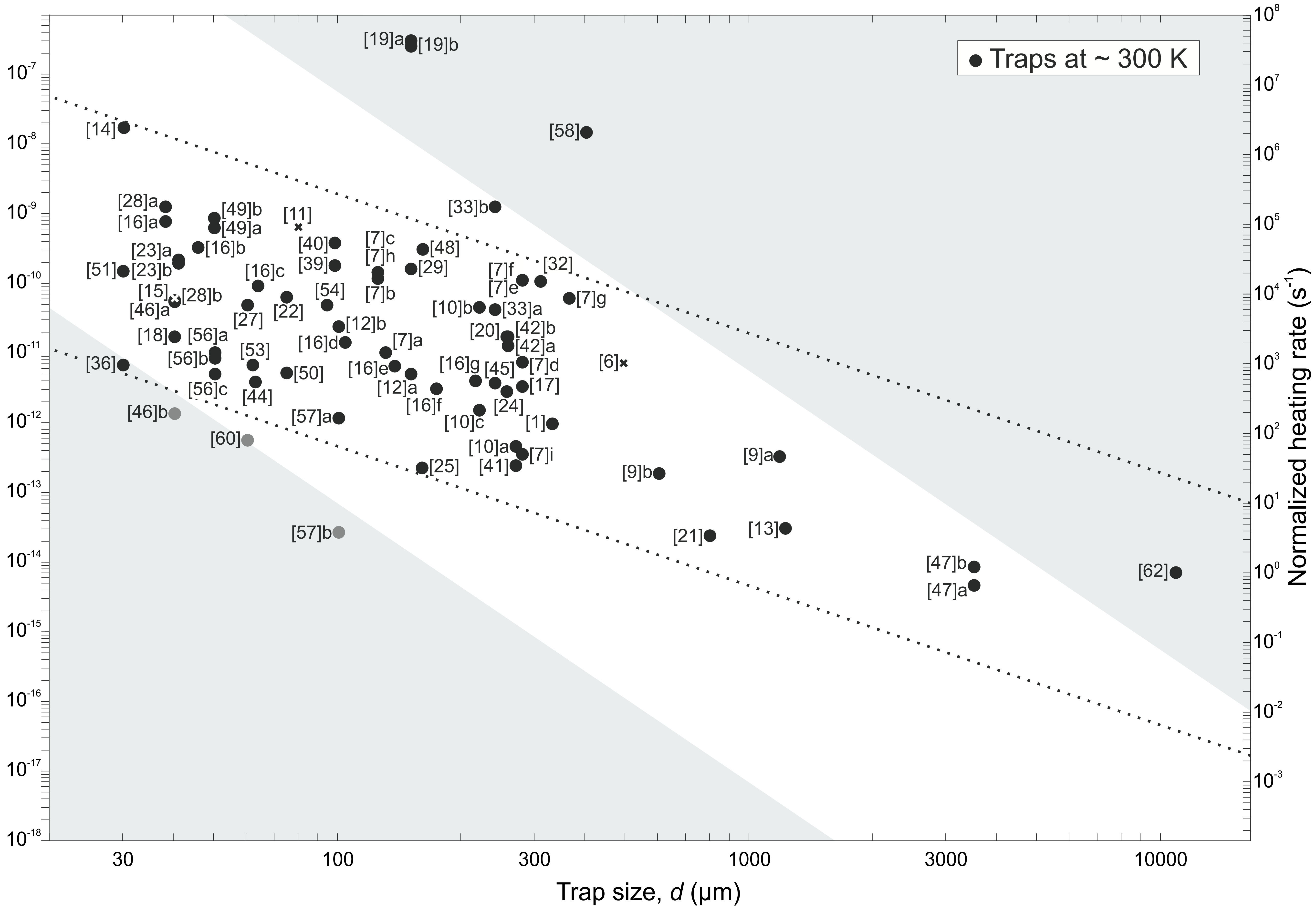
BACKUP

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
- $\dfrac{dn}{dt} \approx \dfrac{1}{\text{sec}}$
- Heating Rate: $\dfrac{\text{neV}}{\text{sec}}$



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

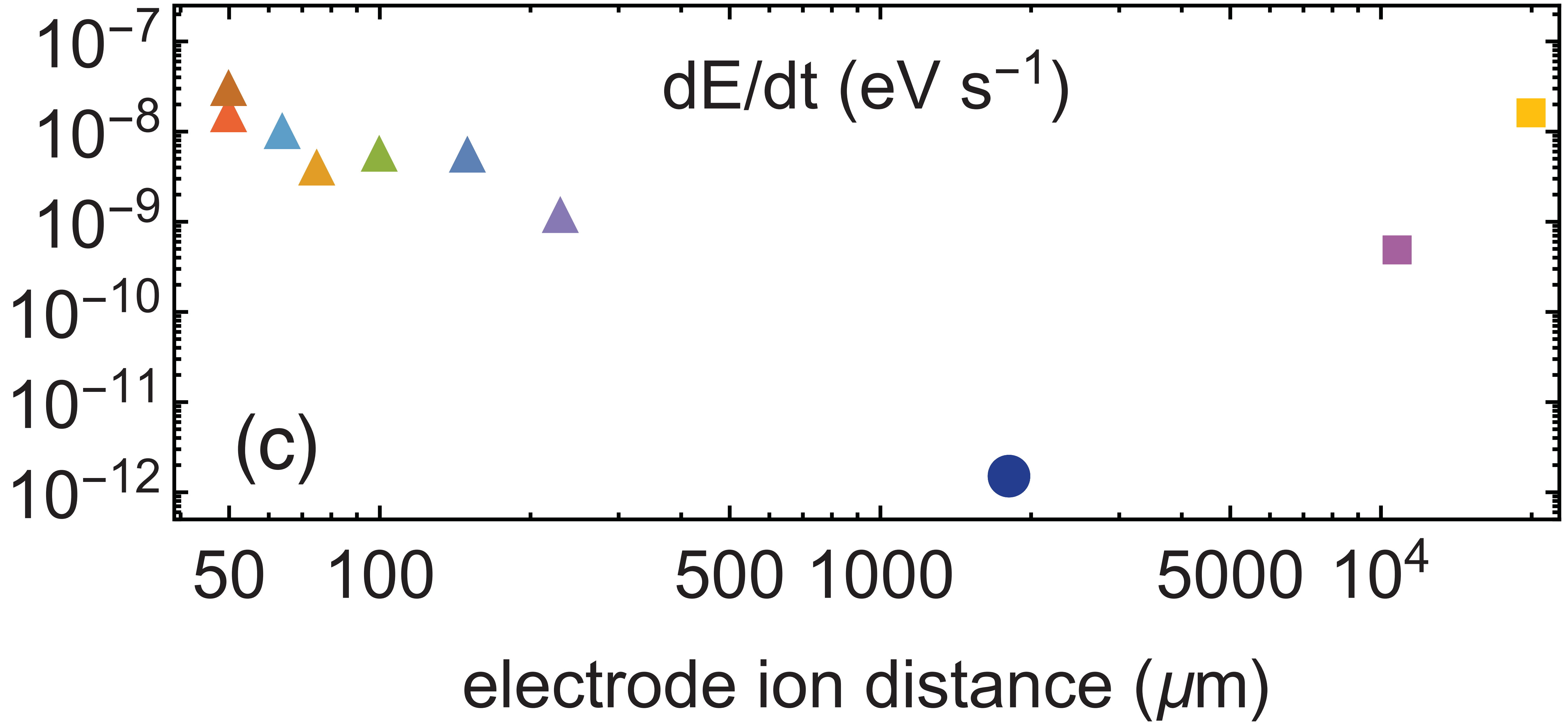
DATA

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

  $\Delta\omega \approx 10^{-16}\ \text{eVs}^{-1}$
- 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_{wall}	ω_p [neV]	T_{ion}[neV]	Heating Rate (neV/s)
Hite et al, 2012 [40]	Paul	$^9Be^+$	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	$\omega_+ = 77.4$ $\omega_- = 0.050$	7240	0.13

No reach for $\epsilon \gtrsim \dfrac{T_{\text{wall}}}{V_z}$

CAPABILITIES

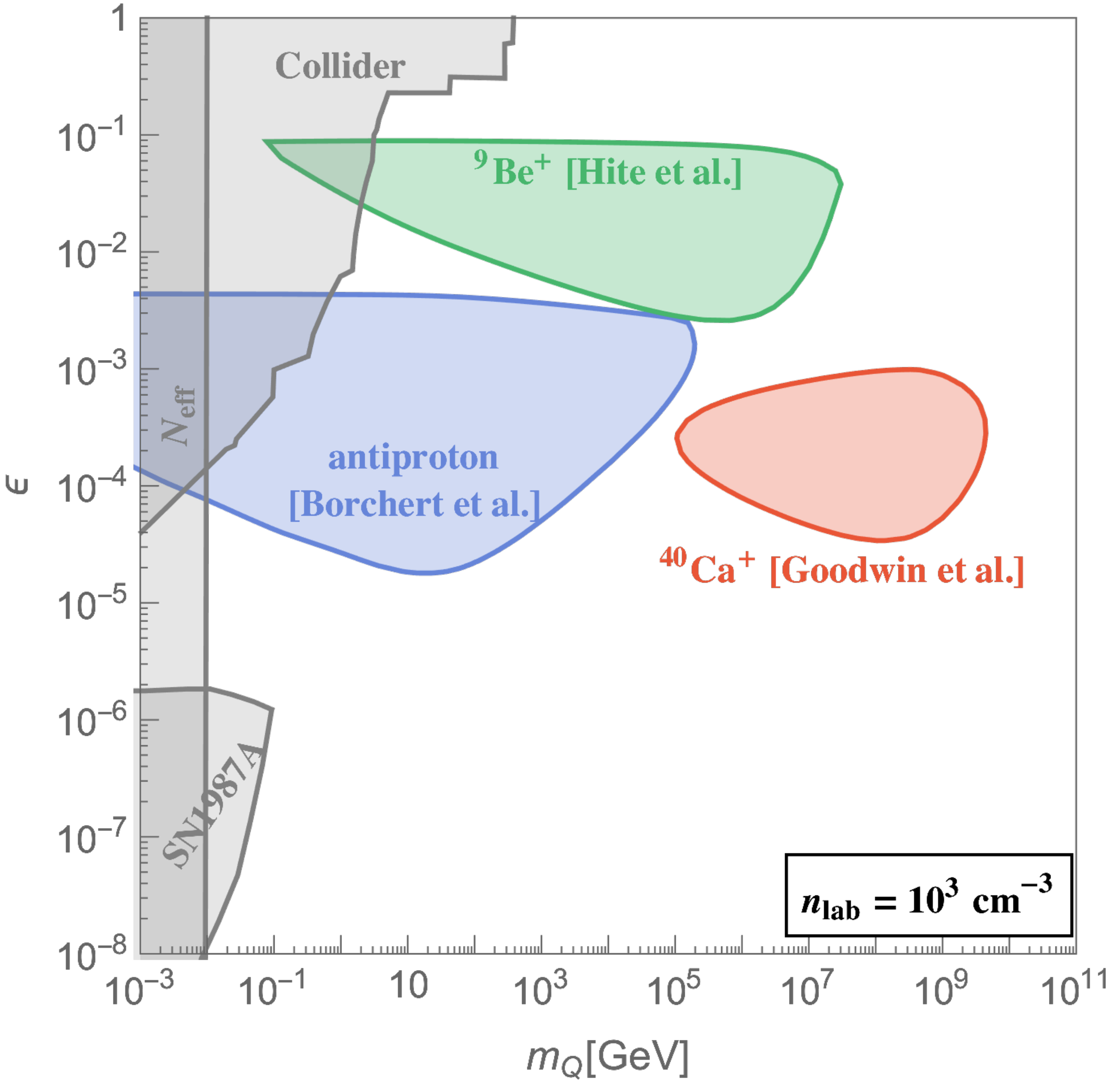
- Low exposure (Single ion x few hours)
- neV direct detection.
- Ultra-low heating rate
- Tiny momentum transfer $q \approx \sqrt{2\text{neV} \times m_T} \approx$ eV
- Still scatter with ion: Enormous Rutherford x-sections for small q
- Perfect for Traffic Jam: Large number densities and cross-sections,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

HEATING RATE

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

TERRESTRIAL POPULATION CONSTRAINTS

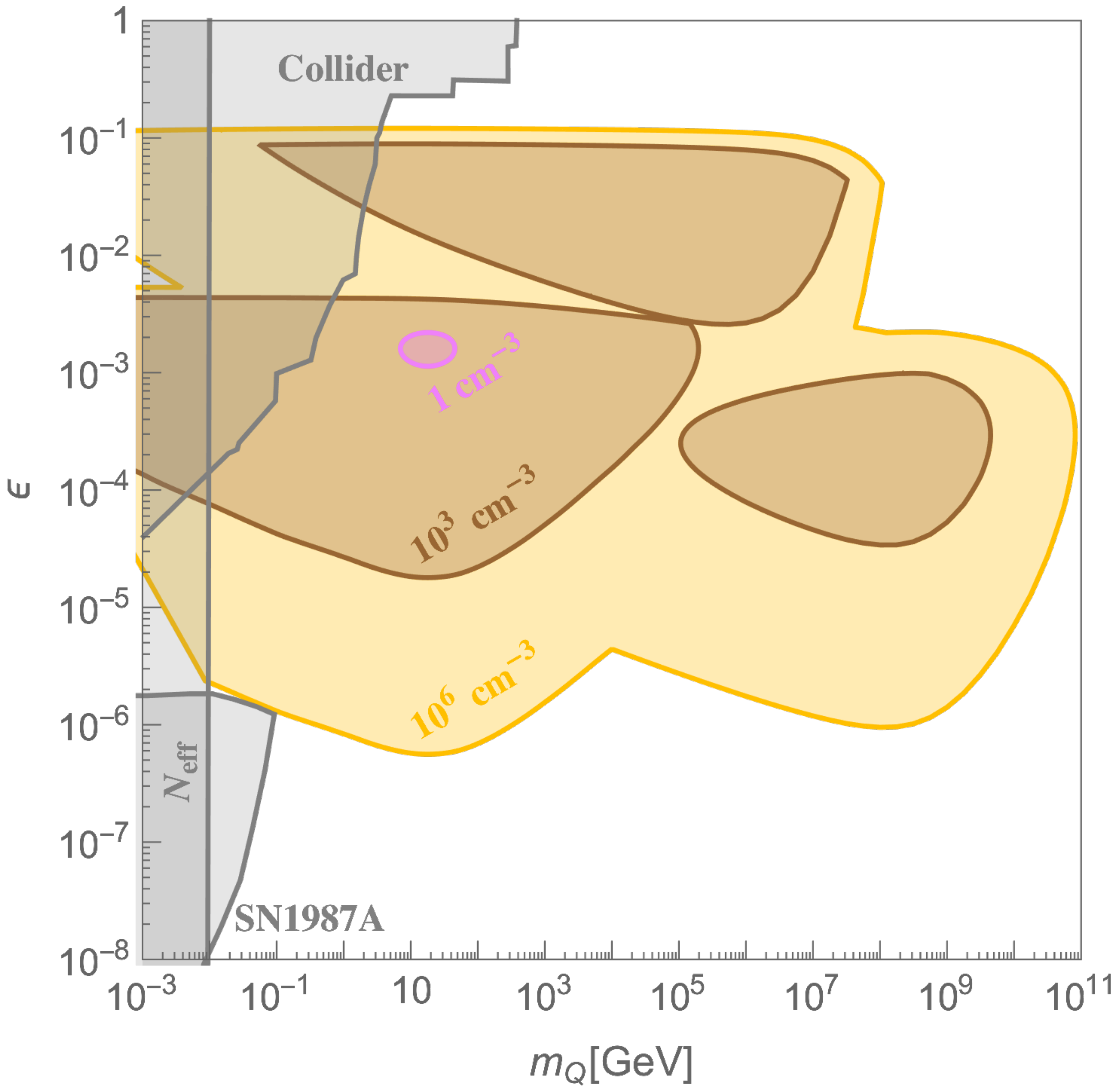
$$m_Q^{\min} = \frac{E_{\min}^2 m_T}{16 T_{\mathrm{trap}} T_{\mathrm{wall}}}$$



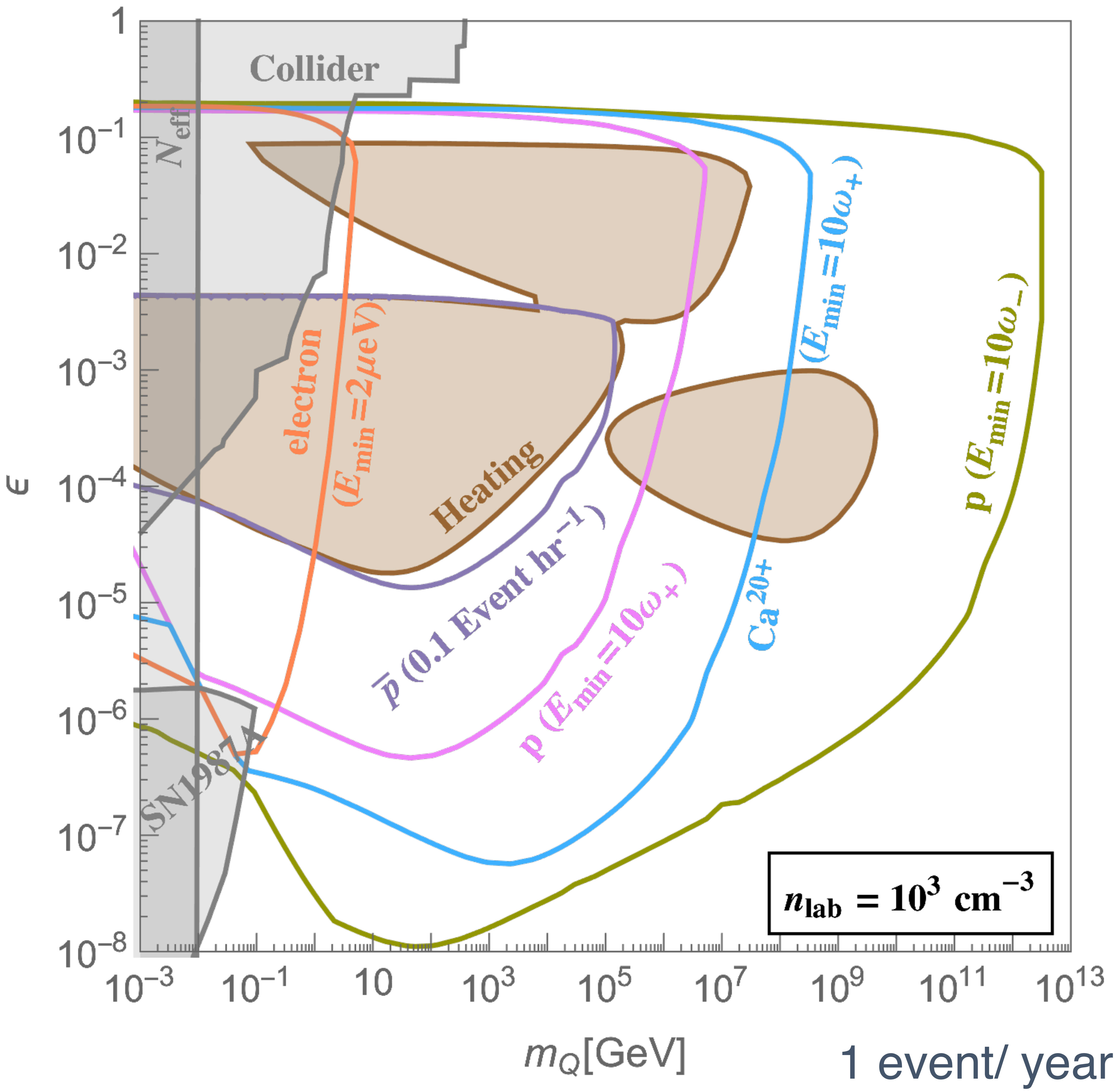
$$m_Q^{\max} = \frac{16 m_T T_{\mathrm{trap}} T_{\mathrm{wall}}}{E_{\min}^2}$$

Forthcoming HR with D.Budker, P.Graham, F.Schmidt-Kaler

TERRESTRIAL POPULATION CONSTRAINTS



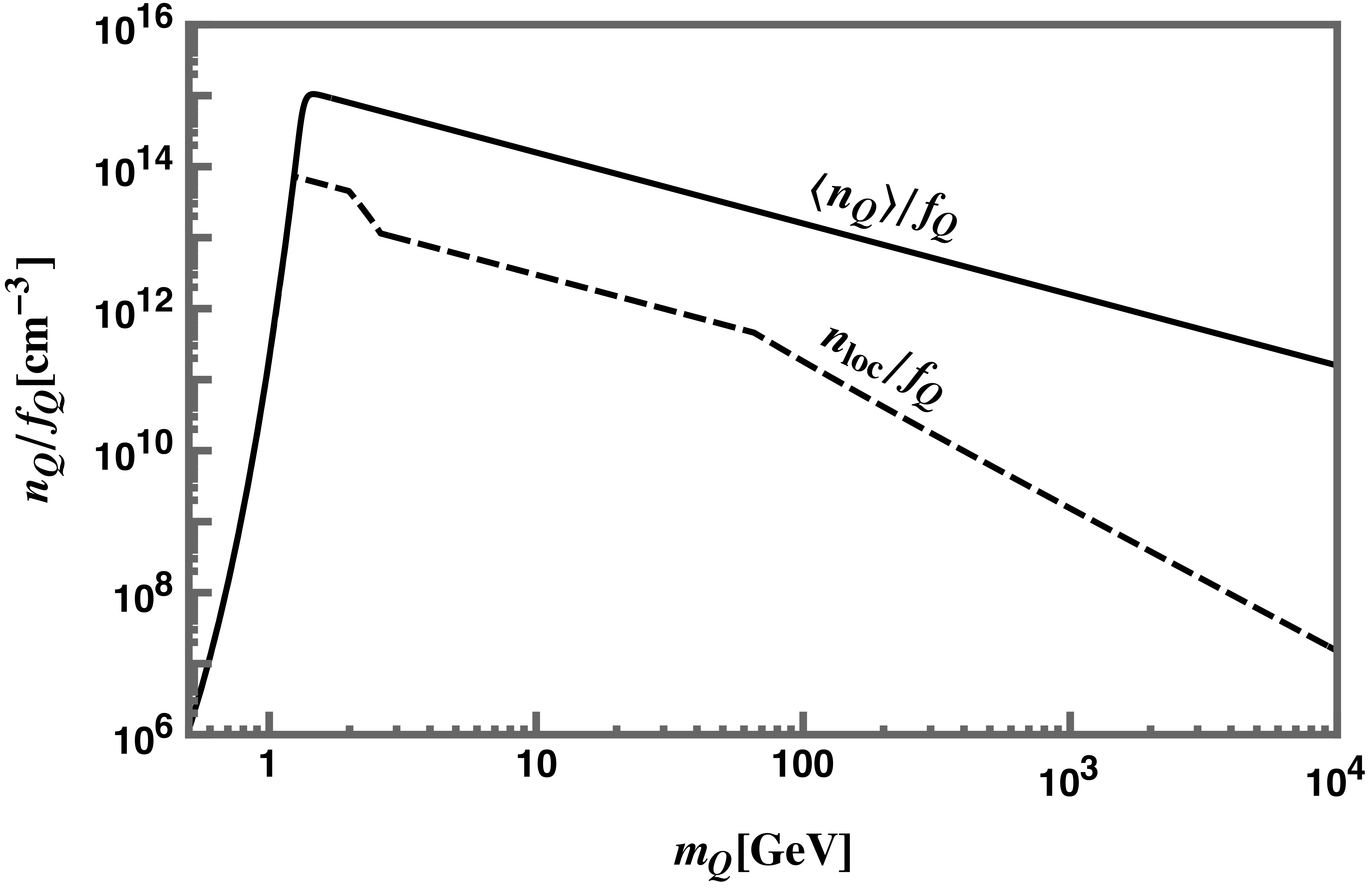
PROJECTIONS



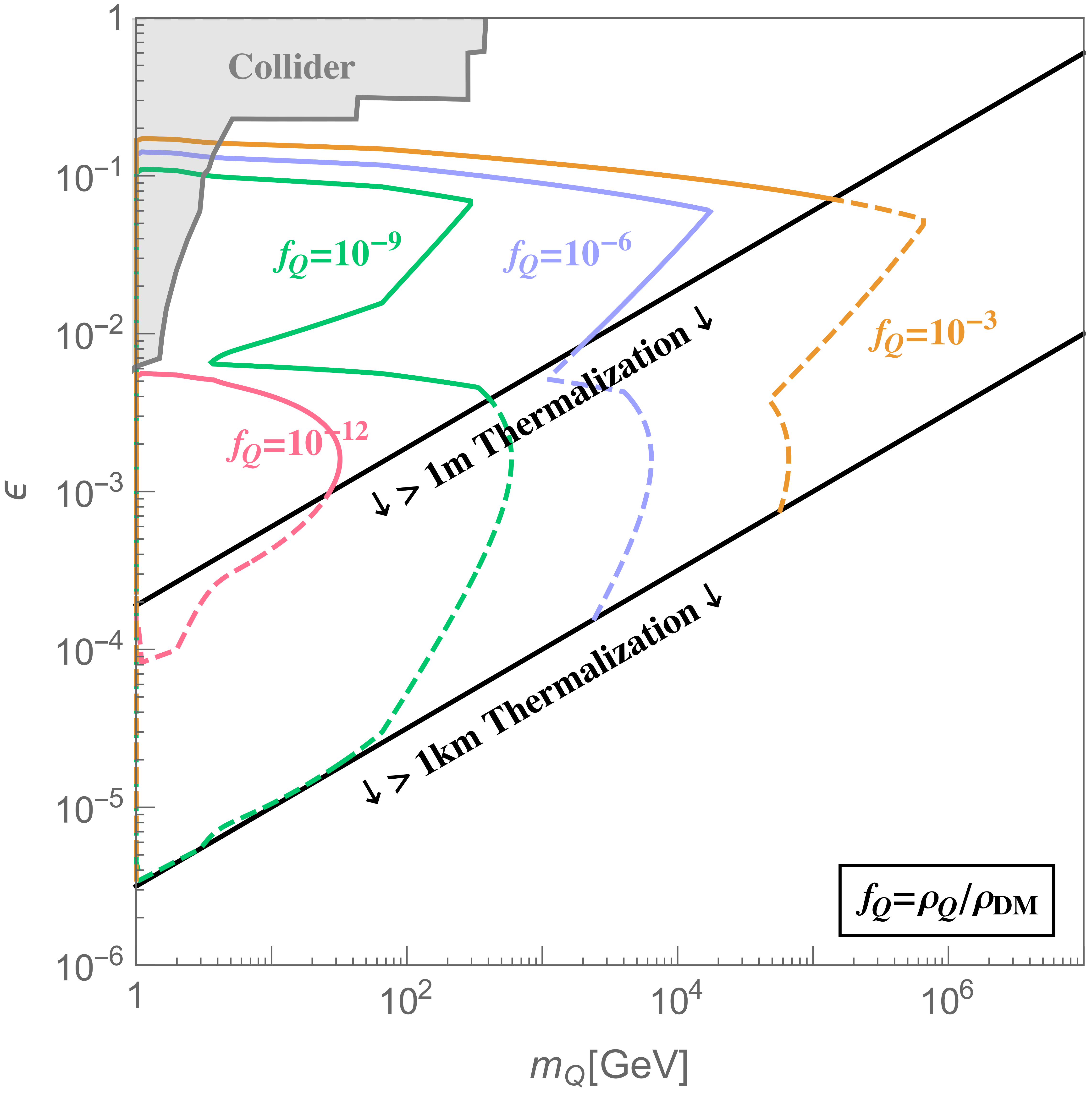
1 event/ year unless otherwise stated

TRAFFIC JAM DENSITIES

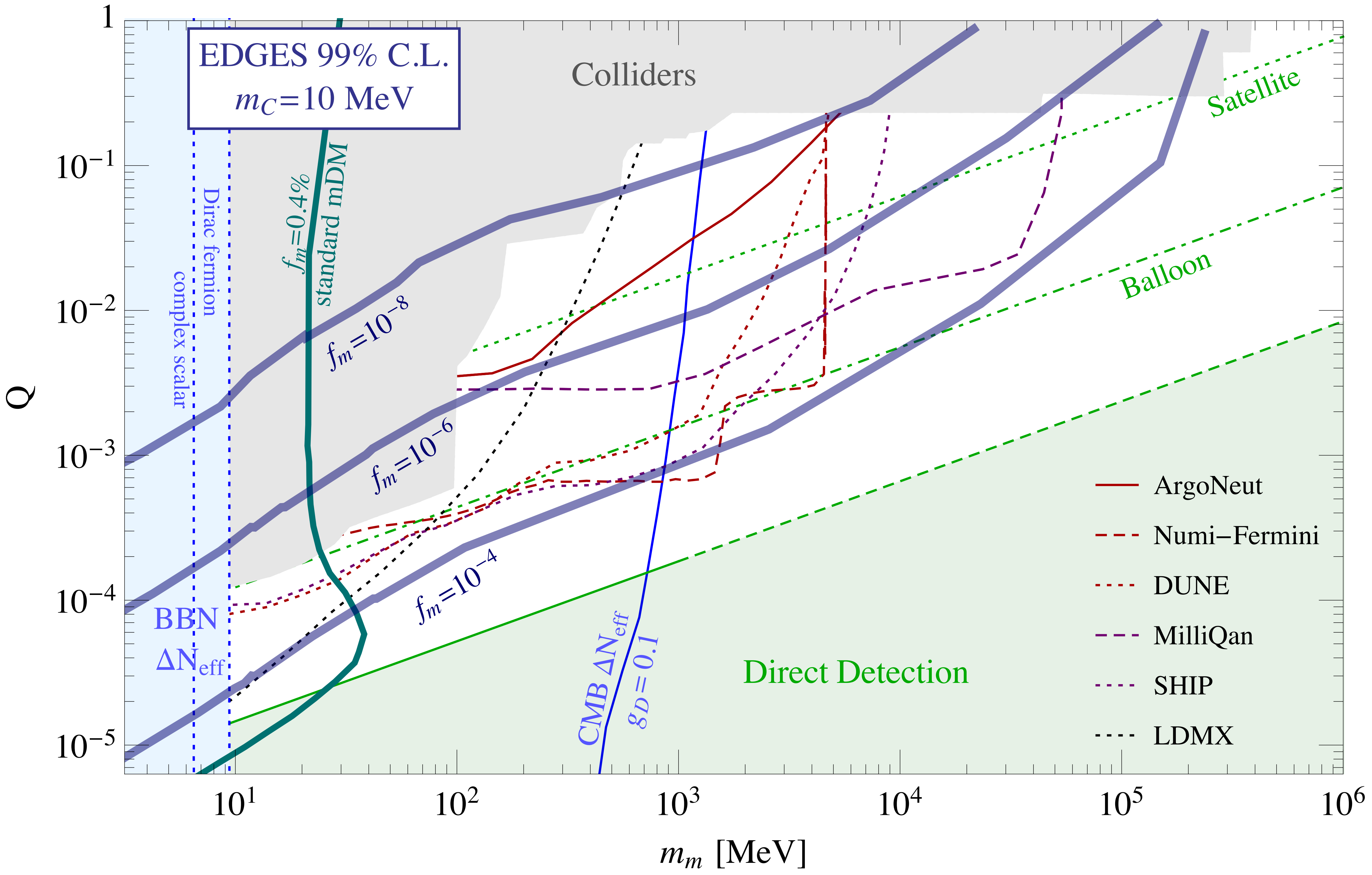
from: 2012.03957 HR M.Pospelov



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