NEW RESULTS AND OPPORTUNITIES FOR DETECTING TERRESTRIALLY BOUND DARK MATTER

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Based on:

arXiv: 2110.06217 HR with A. Berlin, H. Liu, M. Pospelov
arXiv: 2108.05283 HR with D. Budker, C. Smorra, P. Graham, F. Schmidt-Kaler, S. Ulmer
arXiv: 2012.03957 HR with M. Pospelov

OUTLINE

- ✦ Strongly Interacting Dark Relics & Traffic Jams
- ✦ Milli-charge Particle Detection with Ion Traps
- ✦ Dark-Standard Model bound states for a heavy Dark Photon

DARK RELICS

DARK MATTER → STABLE PARTICLE

DARK RELICS

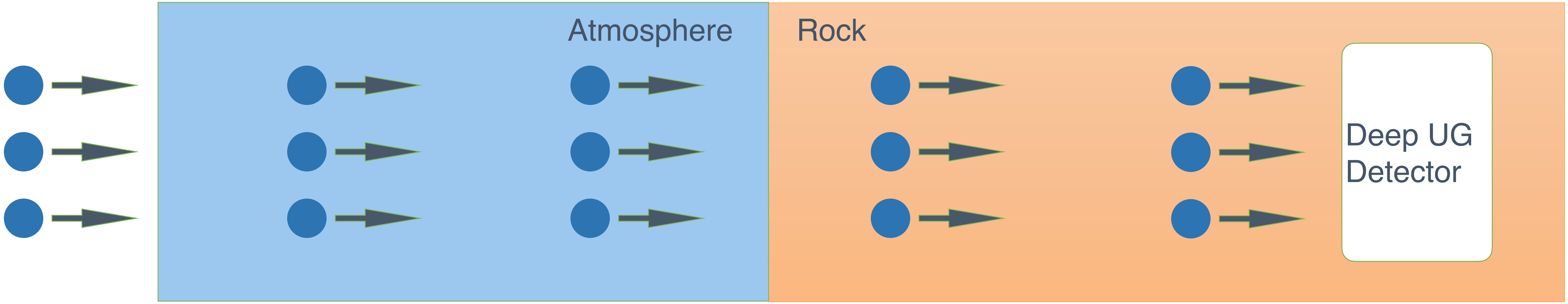
DARK RELIC ← STABLE PARTICLE

- Well motivated stable particles: Monopoles, axions, squarks, heavy quarks (KSVZ), gluinos (SUSY), "Milli-charge" Particles (mCPs)
- Robust prediction for relic fractions $f_\chi = \dfrac{\rho_\chi}{\rho_{\rm DM}} \ll 1$
- The only way to access $M_\chi \gg$ TeV?
- Use same concept for Detection?

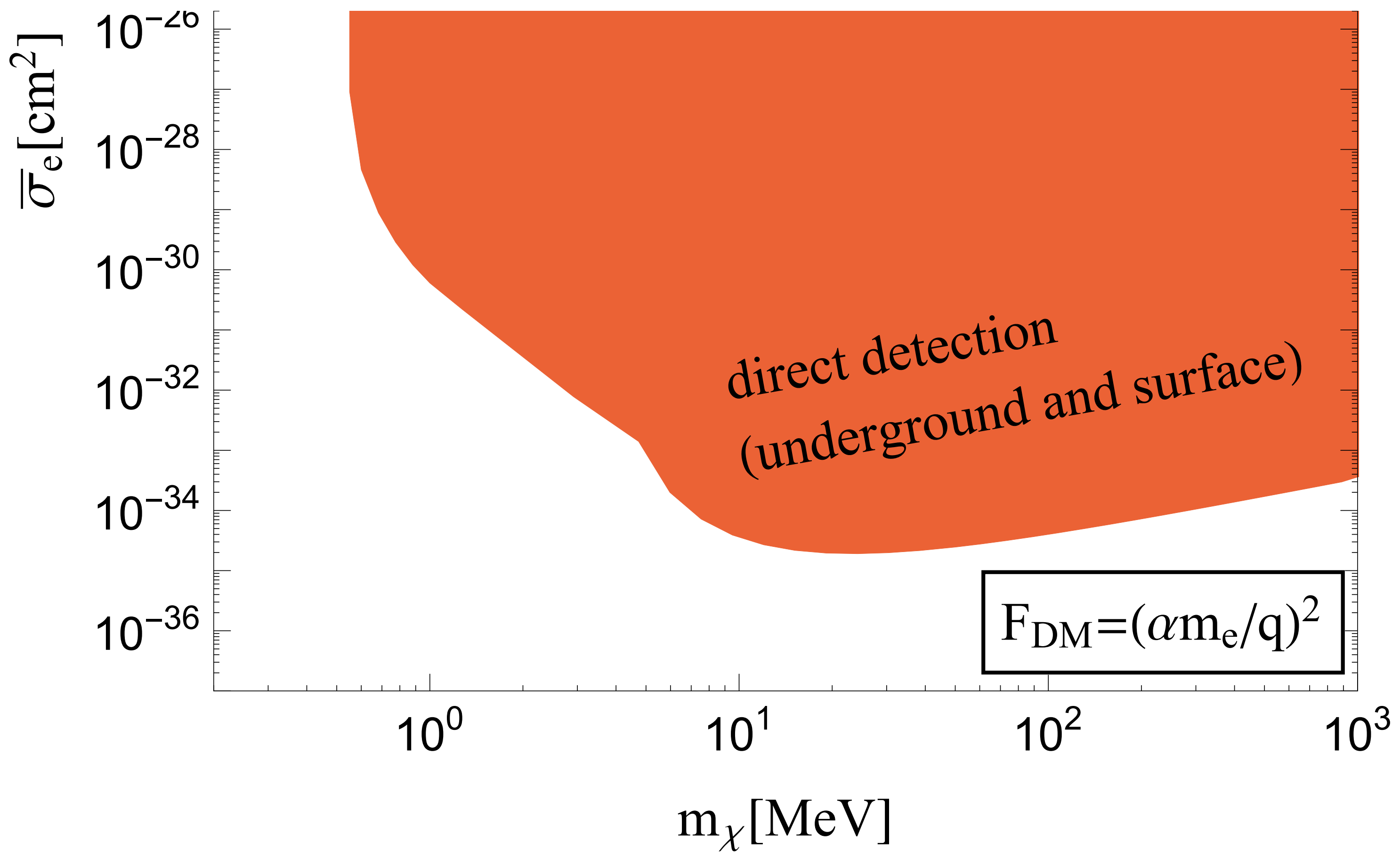
LARGE SM-RELIC INTERACTIONS

- Plethora of example models with large interactions with SM
  - Gluino/KSVZ/Squark Inspired "hybrid hadrons" (Qg or $Qq\bar{q}'$) 1801.01135 Luca, Mitridate, Redi, Smirnov, Strumia
  - Sextaquark DM (uuddss bound state) 2007.10378 Farrar, Wang, Xu
  - Large N Composites 1807.03788 Grabowska, Melia, Rajendran
  - Milli-charges: Recent interest in explaining EDGES anomaly 1905.06348 Emken et al , 1908.06986 Liu et al
  - Heavy Dark Photon Mediated 2110.06217 Berlin, Liu, Pospelov, Ramani
- Some really interesting consequences for Direct Detection

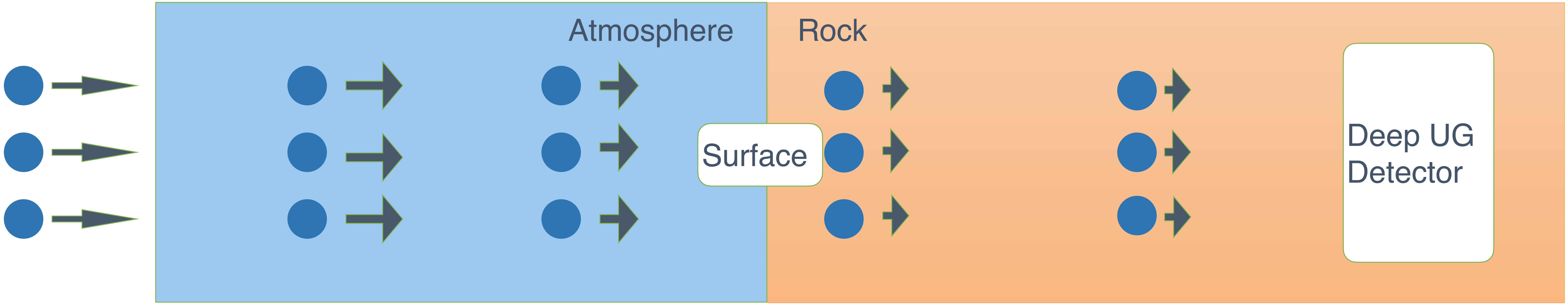
SMALL X-SECTION



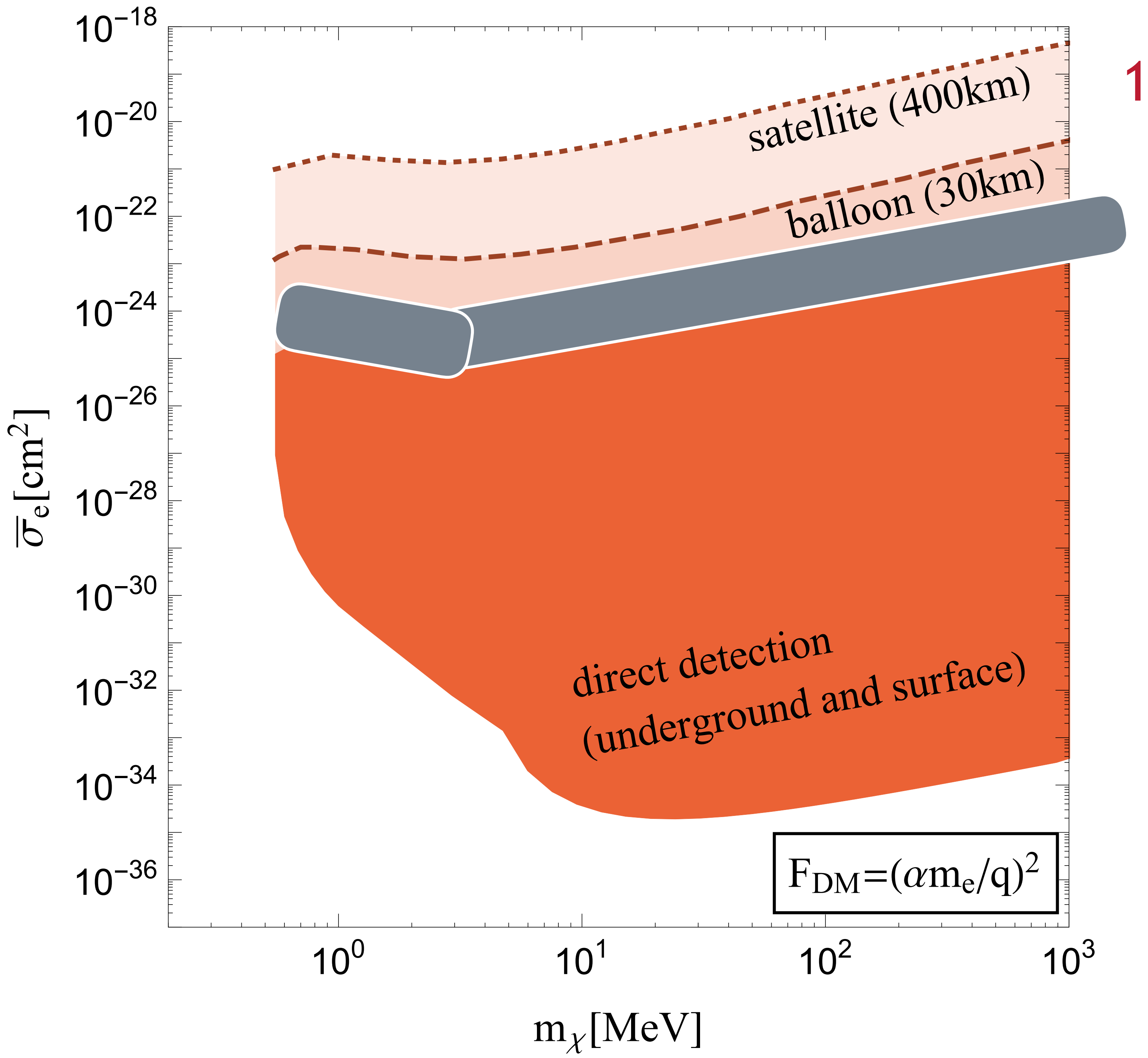
1905.06348 Emken et al



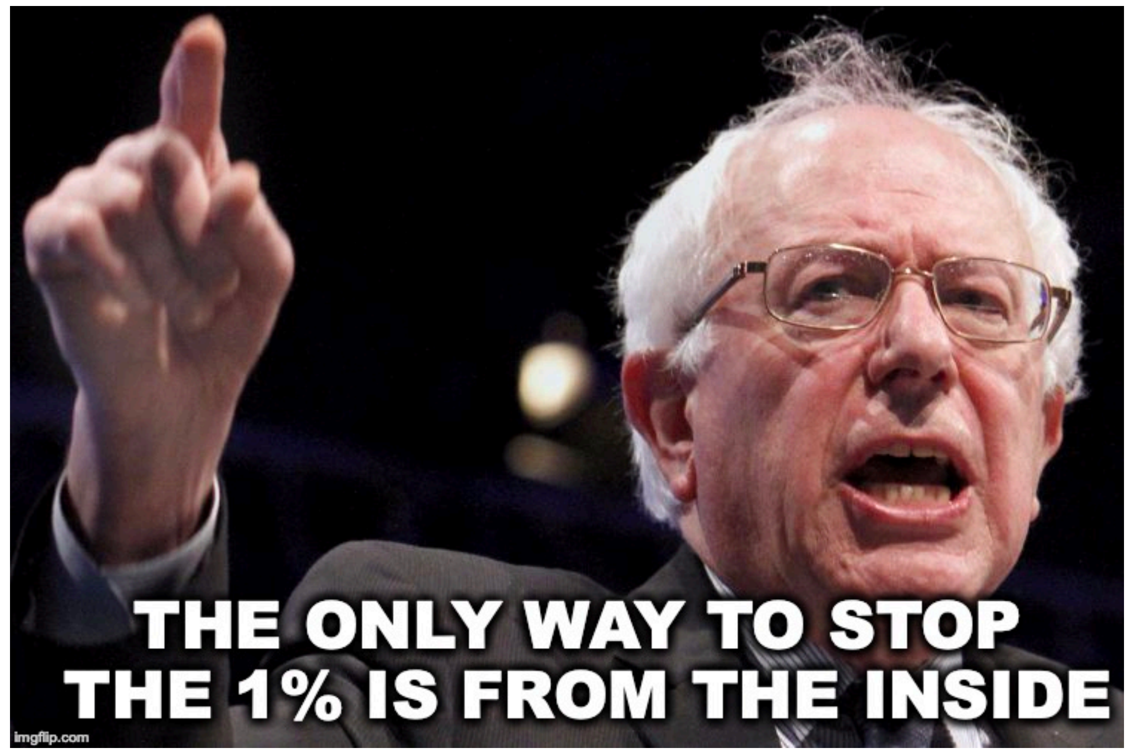
LARGE X-SECTION



- Reaches detector after thermalizing
- KE=300 Kelvin (26 meV)
- Current DD threshold : eV



1905.06348 Emken et al

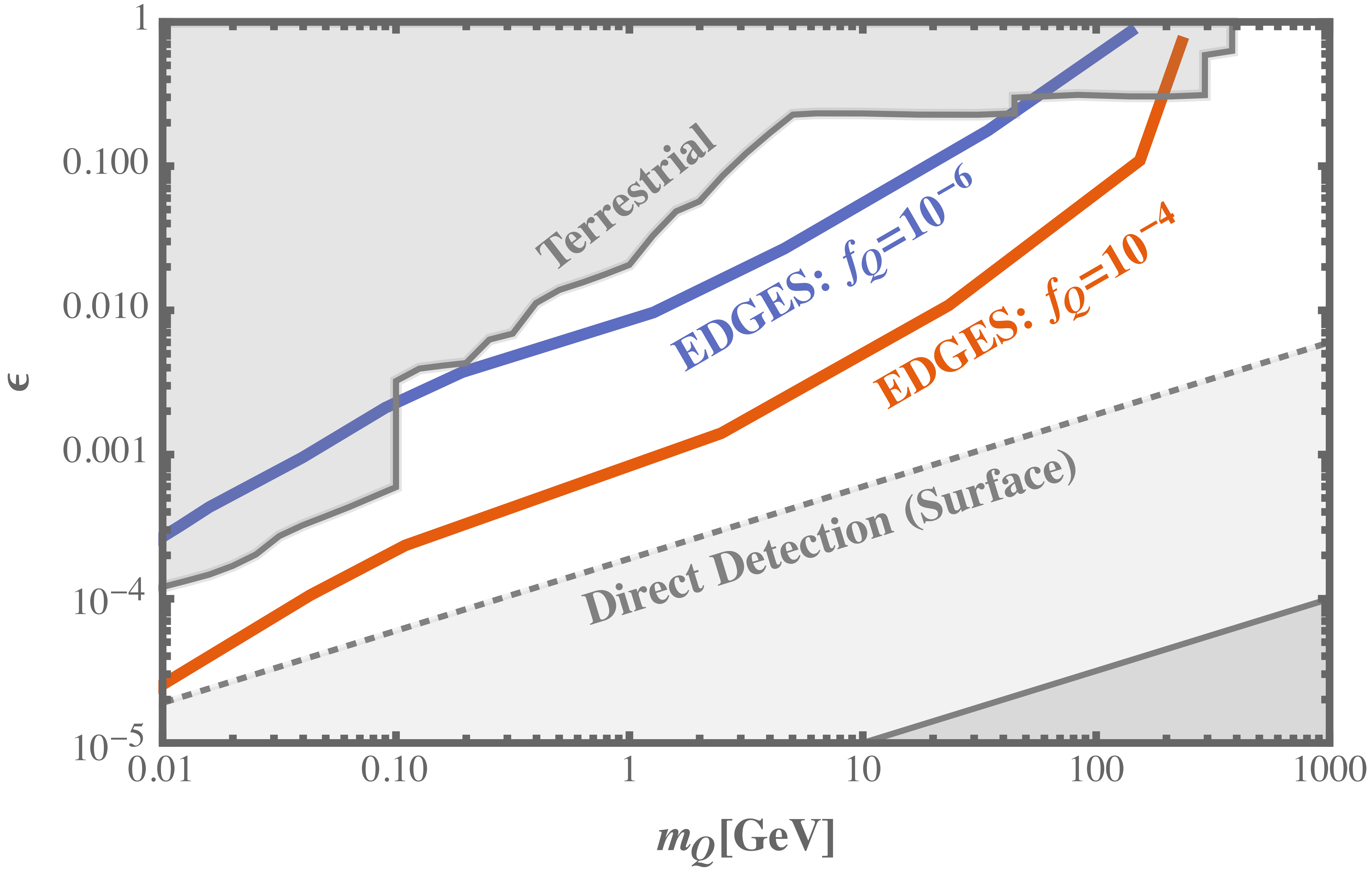


MILLICHARGE PARTICLES

- Particles with tiny electric charges: ϵe
- Simple models to write (with or without a dark photon)
- Charge quantization a century old mystery
- Predictions of explanation: monopoles and/or GUTs not observed yet
- Looked for in various experimental programs
- Recent resurgence due to EDGES anomaly

MCP PARAMETER SPACE

Adapted from: 1908.06986 Liu et al



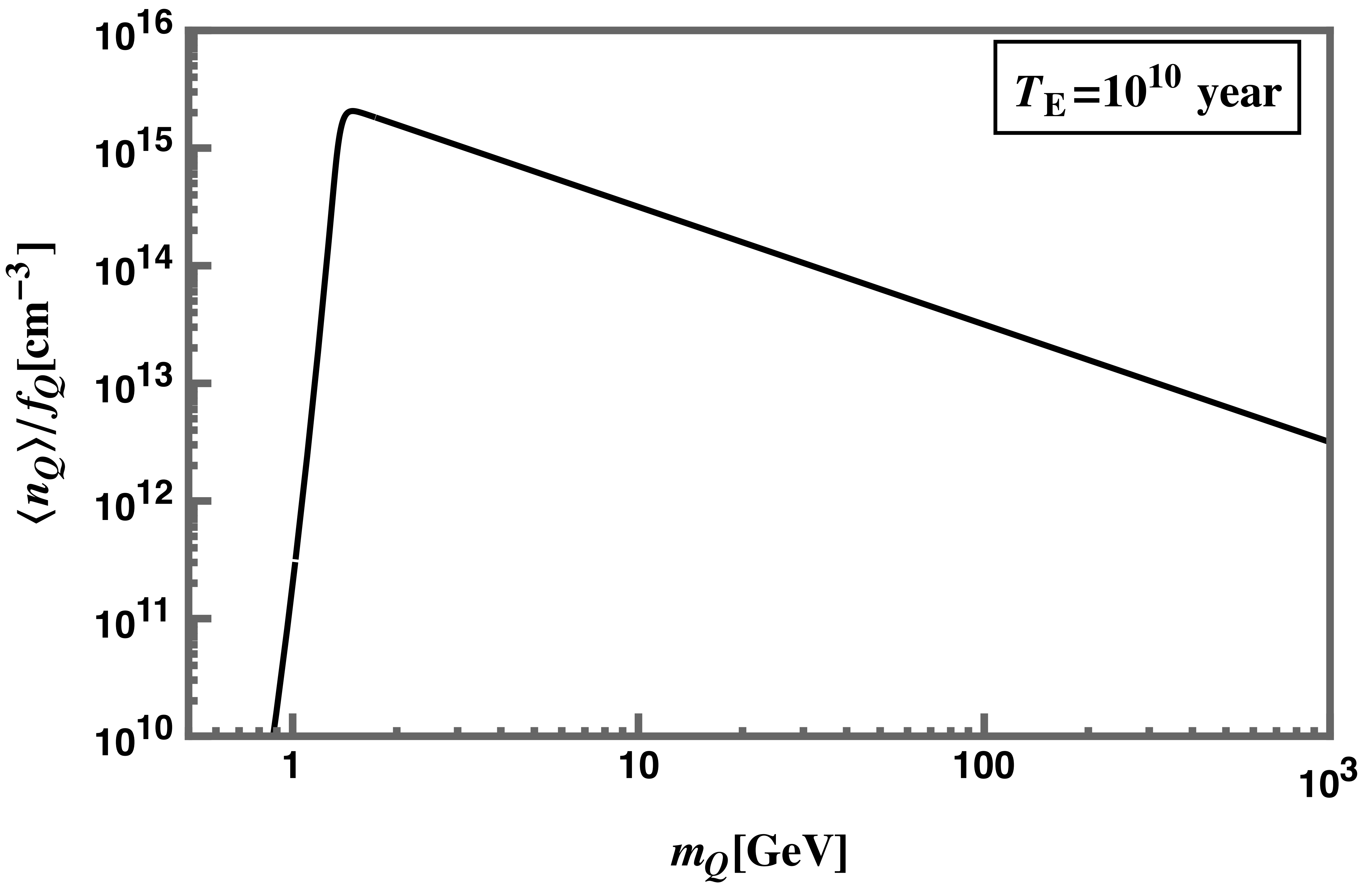
KE smaller than threshold

Colliders/Terrestrial : no reach for small charge

Direct Detection : no reach for large charge (Overburden blocks it)

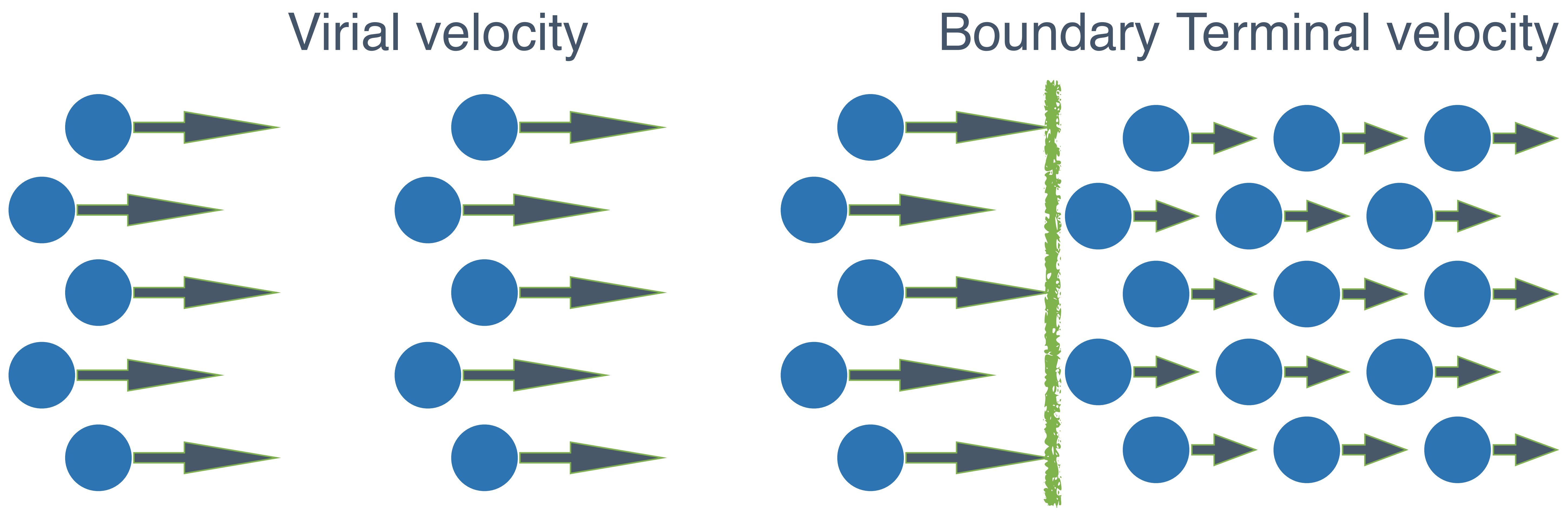
TERRESTRIAL ABUNDANCE

- DM thermalizes, but stuck on Earth if $v_{\rm th} < v_{\rm esc}$
- Accumulation over the age of the Earth causes tremendous enhancement
- $\eta = \frac{\pi R_E^2 \mathrm{v}_{\rm vir}}{\frac{4}{3}\pi R_E^3} T_E \approx 10^{16}$
- DM lighter than GeV evaporates $v_{\rm th} > v_{\rm esc}$
- Heavier than GeV sinks due to gravity



from: 2012.03957 HR M.Pospelov

TRAFFIC JAM



- Sinking not immediate.
- Downward drift

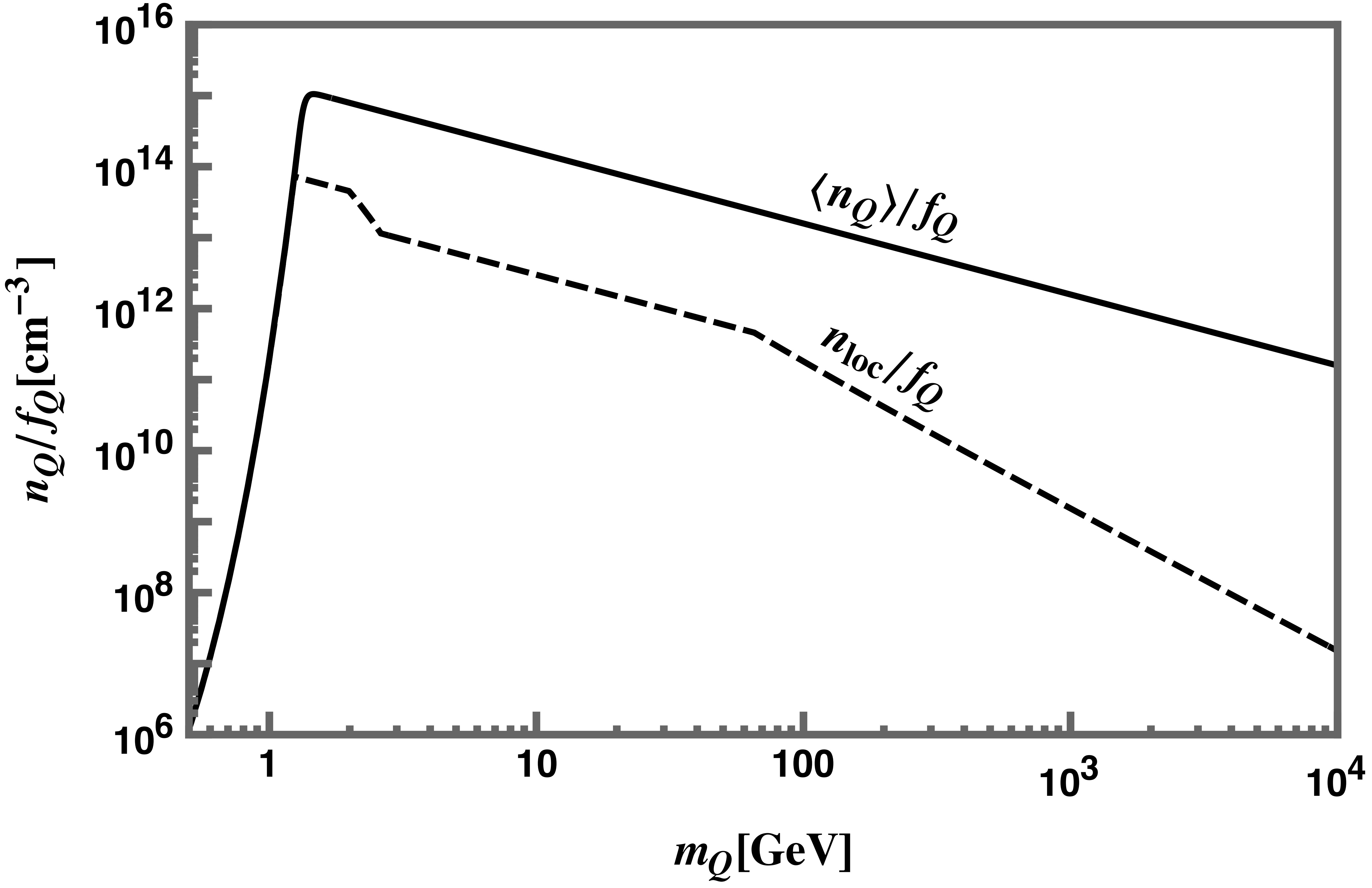
$$\mathrm{v}_{\mathrm{term}} \ll v_{\mathrm{th}} \ll v_{\mathrm{vir}}$$

- Traffic Jam on the way

$$\eta_{\mathrm{term}} = \frac{n_{\mathrm{lab}}}{n_{\mathrm{vir}}} = \frac{\mathrm{v}_{\mathrm{vir}}}{\mathrm{v}_{\mathrm{term}}}$$

TRAFFIC JAM DENSITIES

from: 2012.03957 HR M.Pospelov

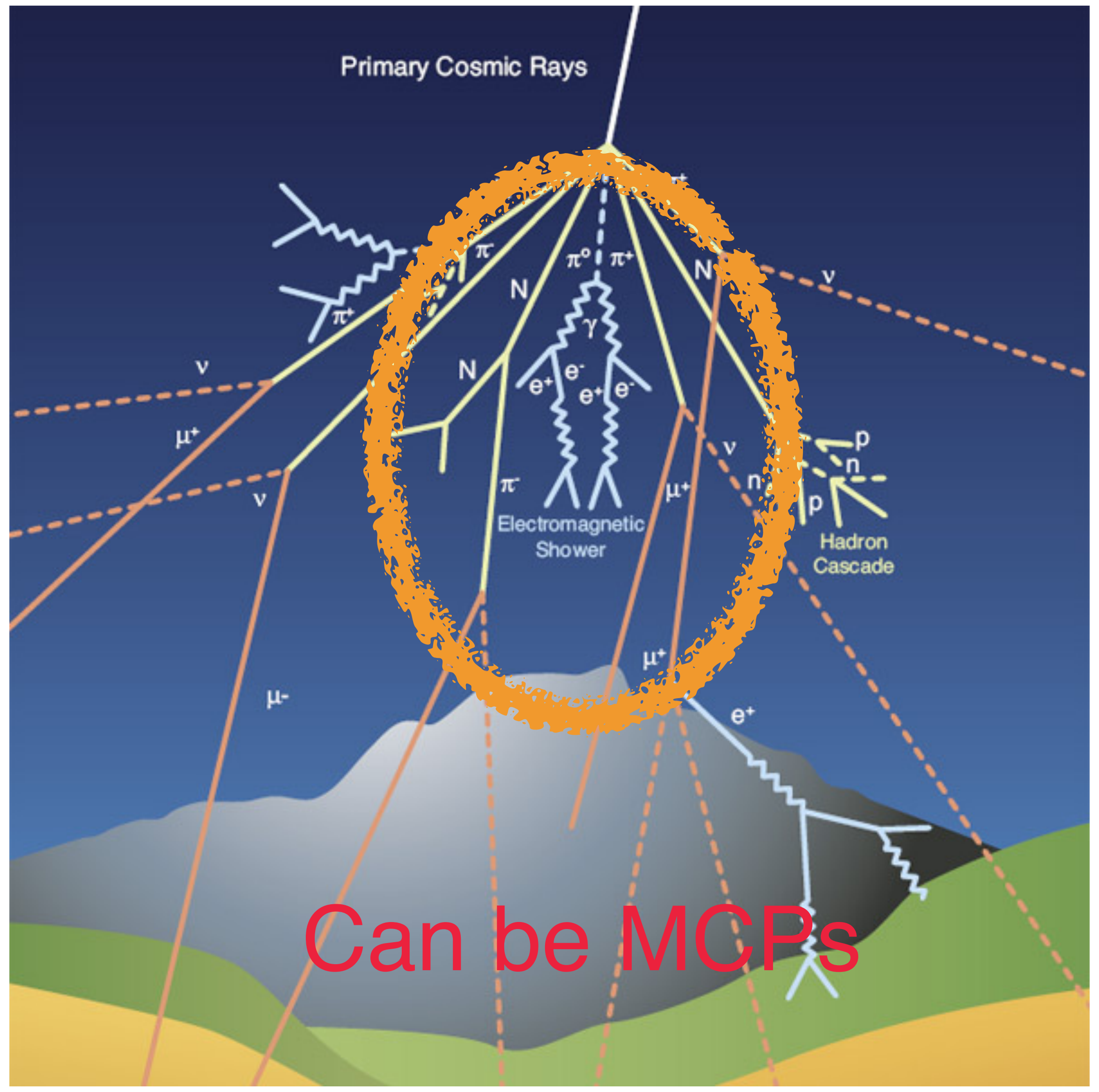


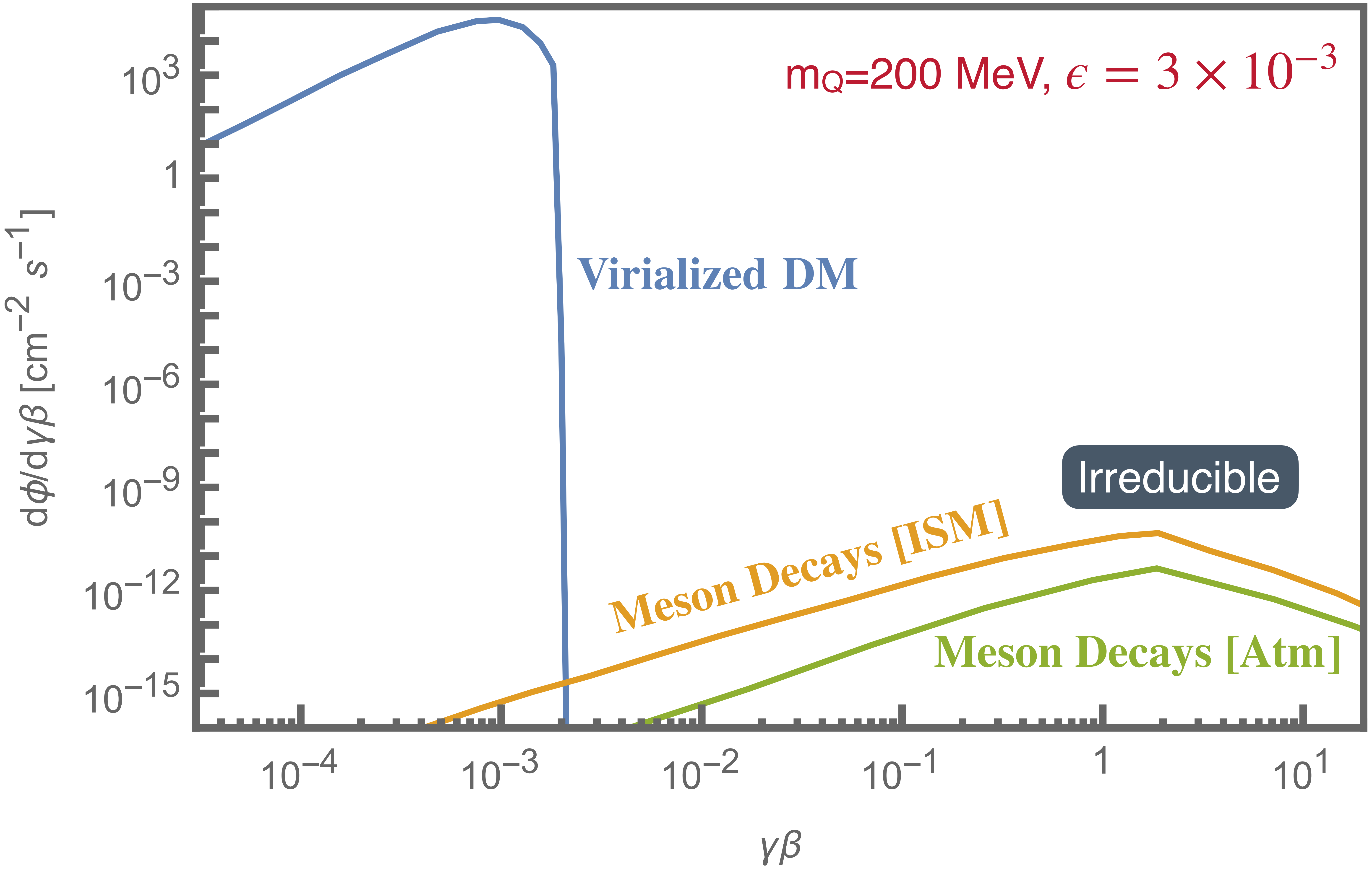
True for charges $\epsilon \gtrsim 10^{-6}$

IRREDUCIBLE MCP POPULATION

2010.11190 HR, Roni Harnik, Ryan Plestid and Maxim Pospelov

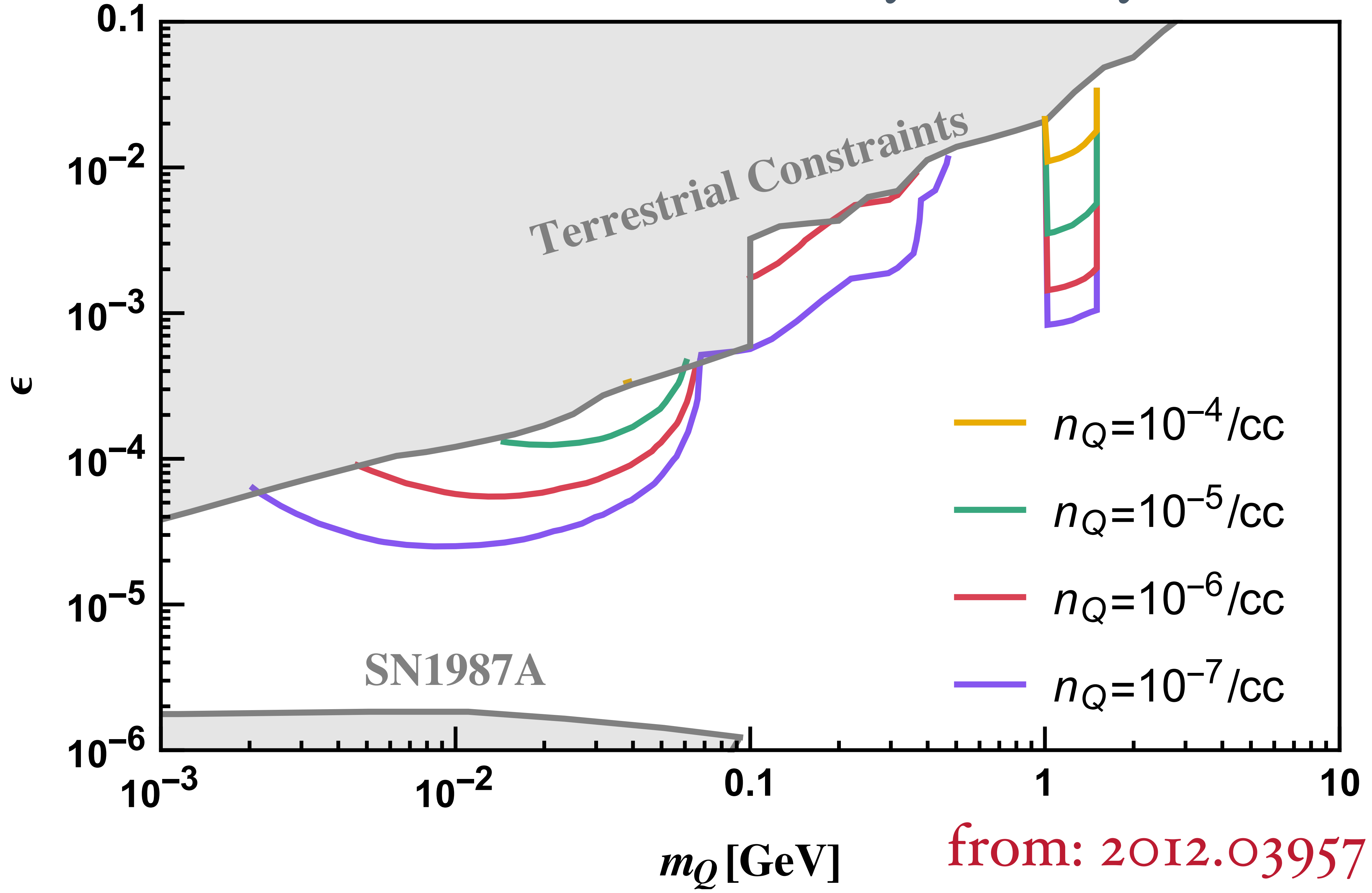
- Mesons produced in Cosmic ray collisions can decay into mCPs
- Contribution to irreducible density on Earth

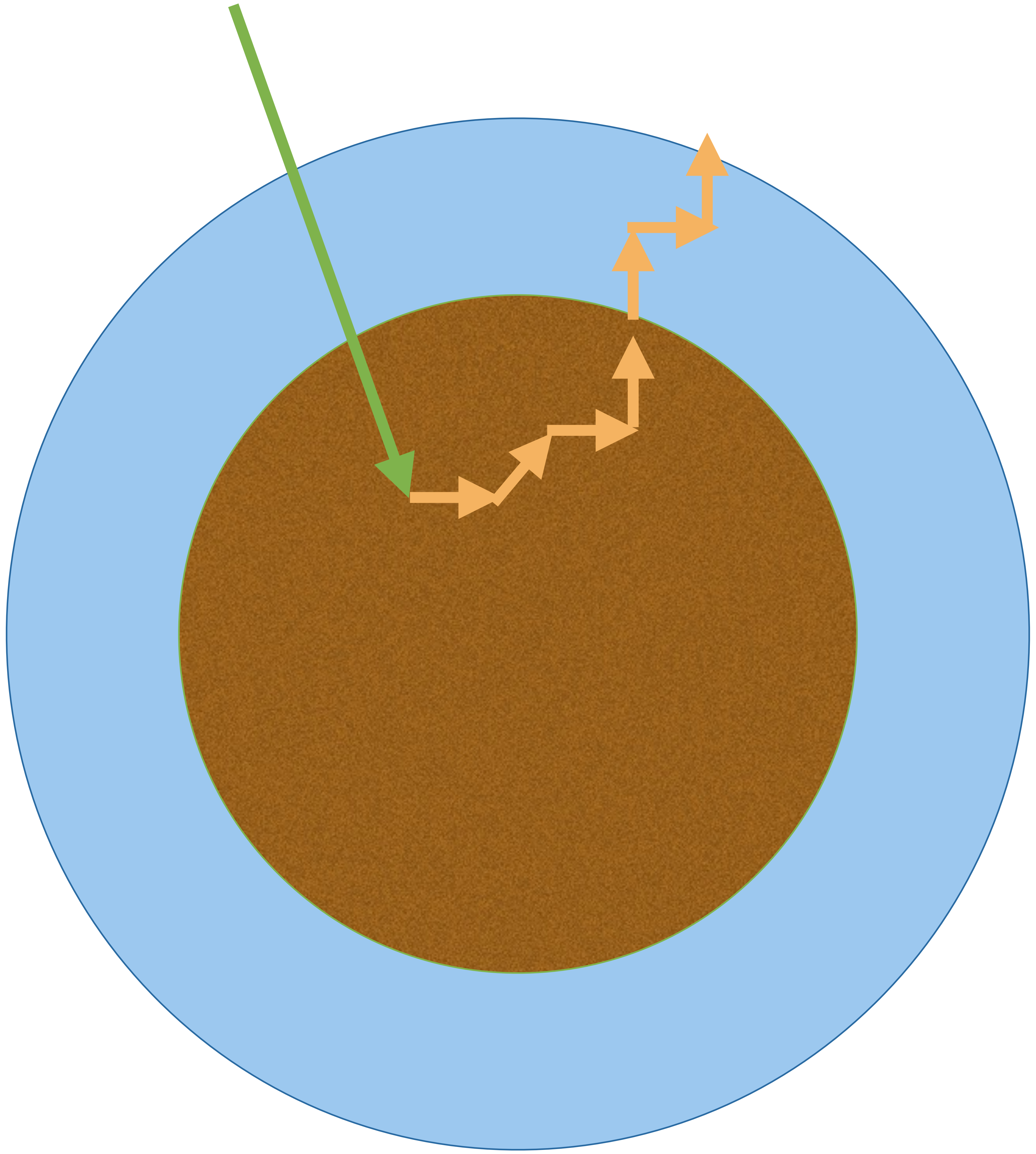




REVERSE TRAFFIC JAM

- 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

EXISTING LIMITS

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

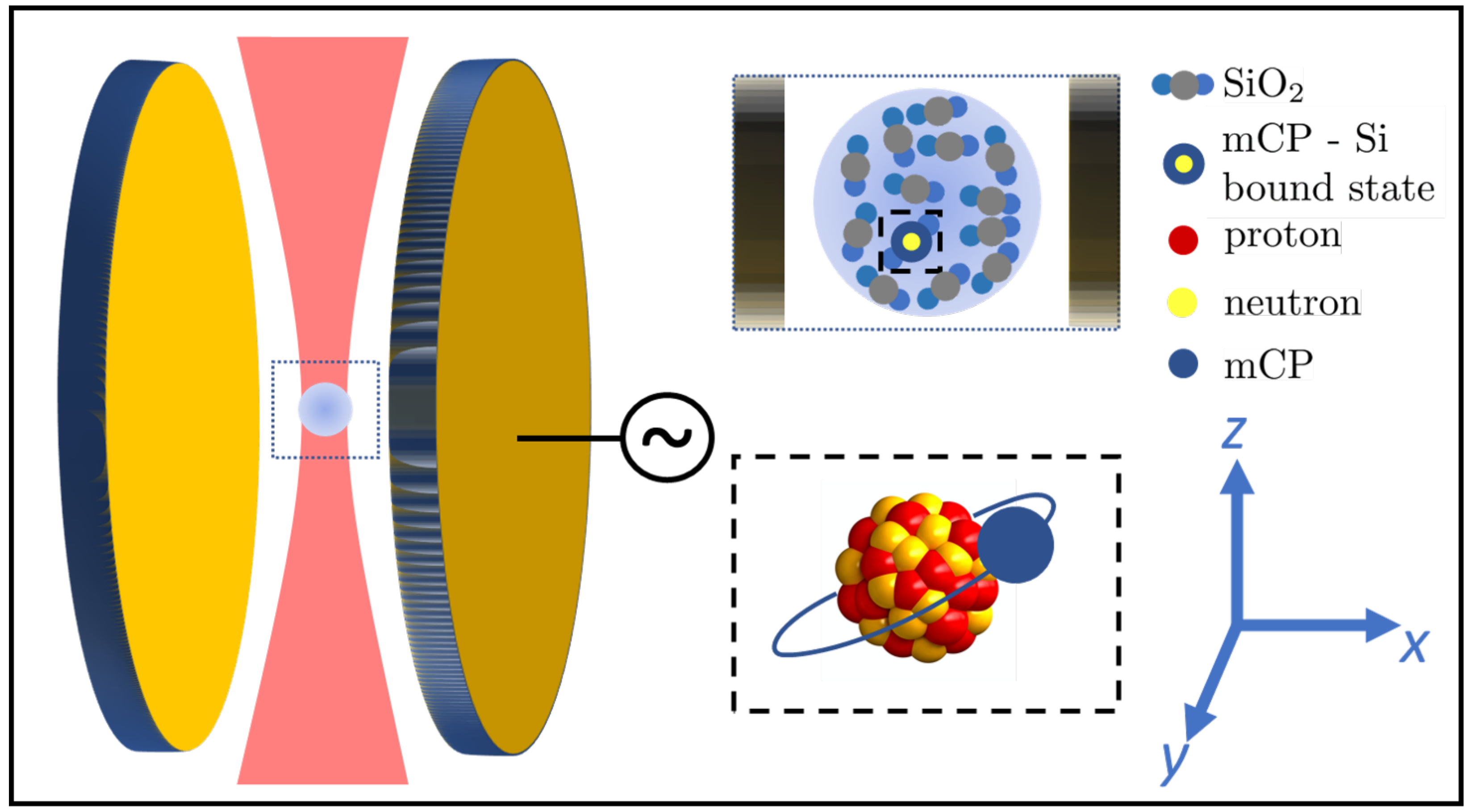
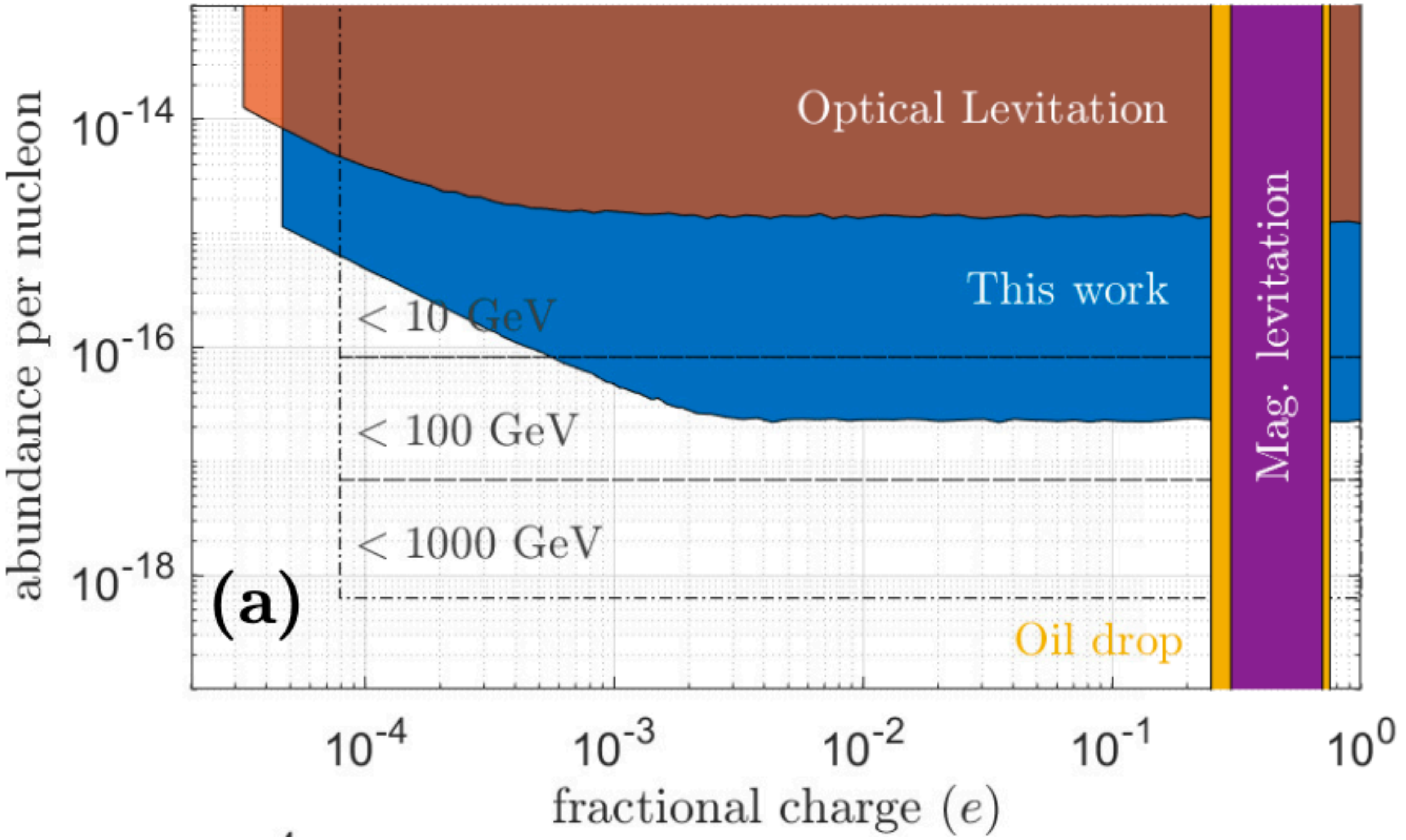
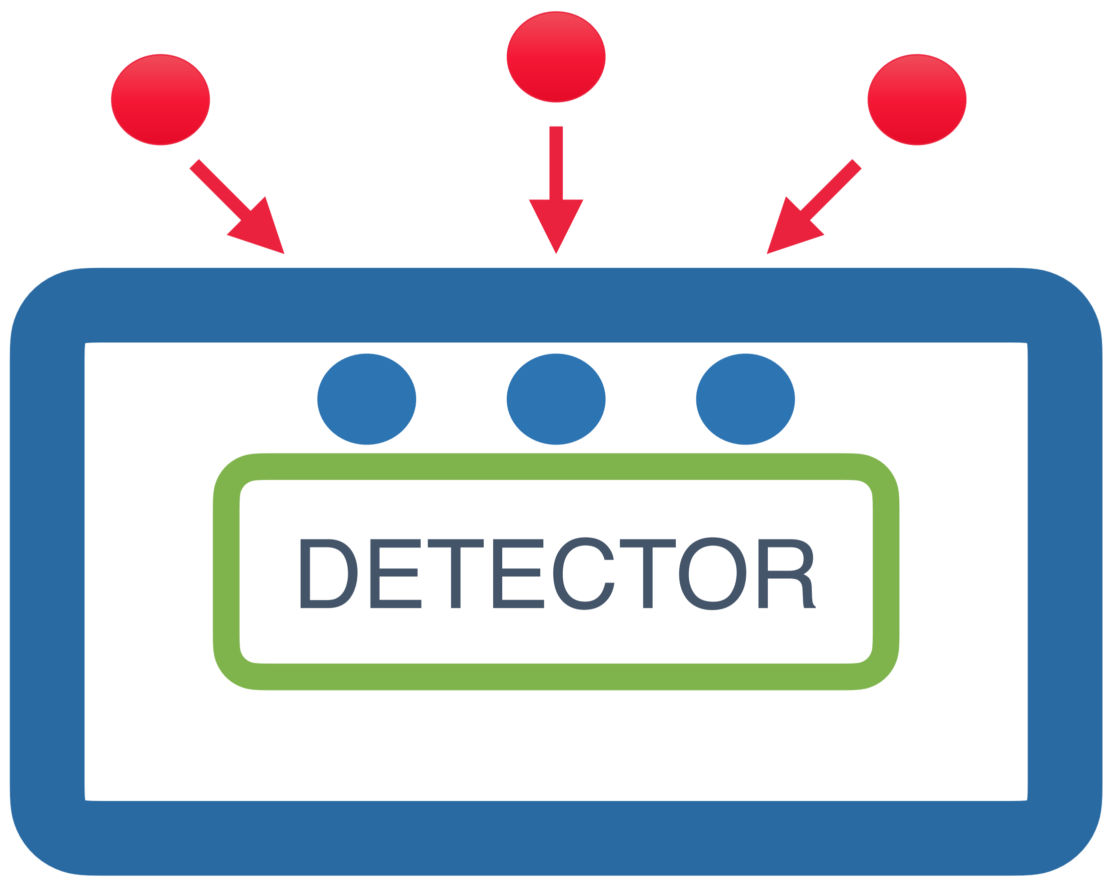


FIG. 1. SiO_2 spheres are levitated in high vacuum between a pair of parallel electrodes to search for a violation of charge neutrality by, *e.g.*, a mCP electrostatically bound to a Si or O nucleus in the sphere.



10^{24} Nucleon cm^{-3}

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

WISHLIST

- Detect Small energy deposit: 300 Kelvin ≈ 26 meV
- If target charged, then huge Rutherford x-sections

$$\frac{d\sigma}{dq^2} \propto \frac{1}{q^4}$$ at small momentum transfer

- $T_{\rm wall} \gg E_{\rm thr}$
- Large number of targets … not required

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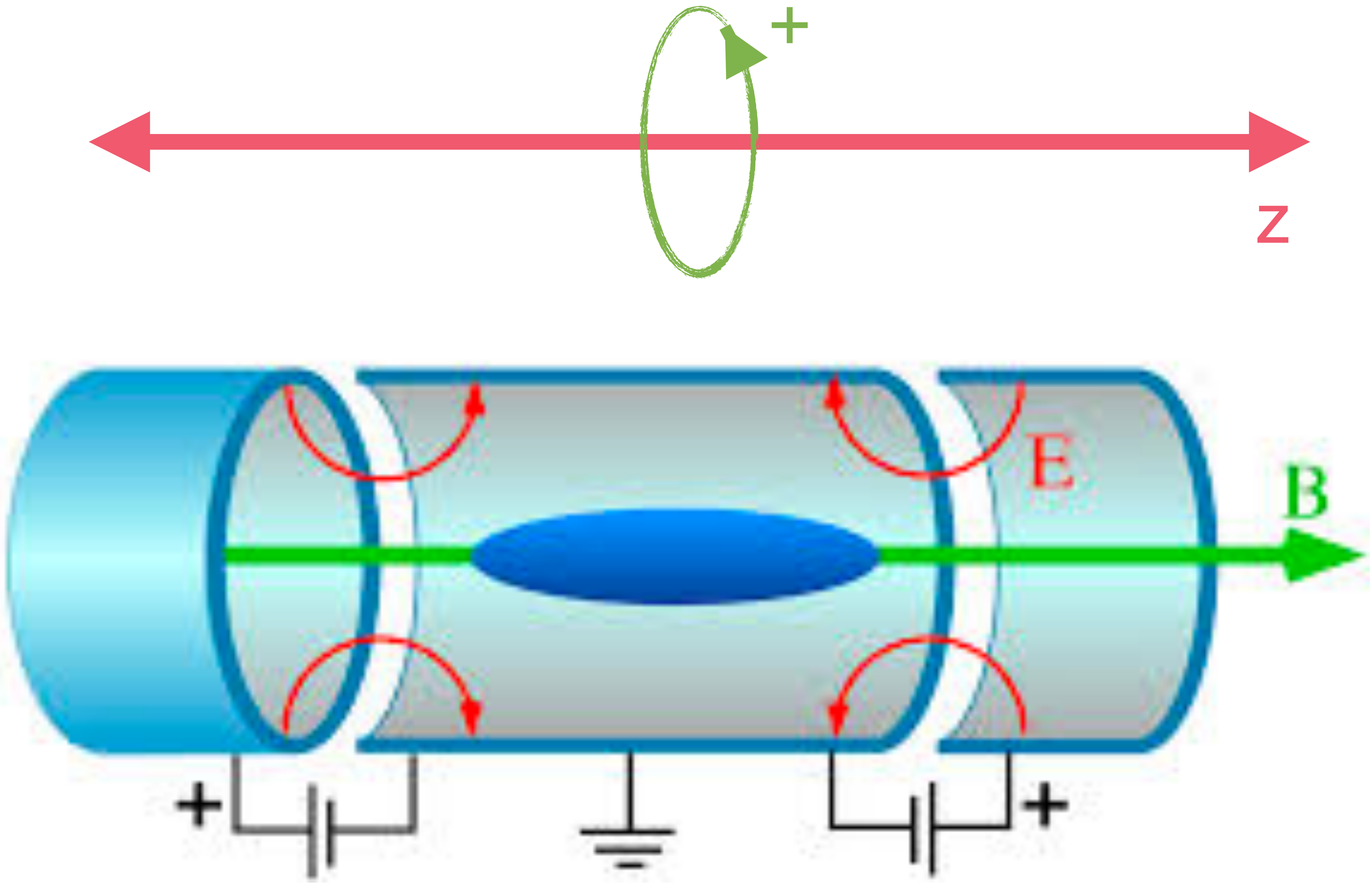
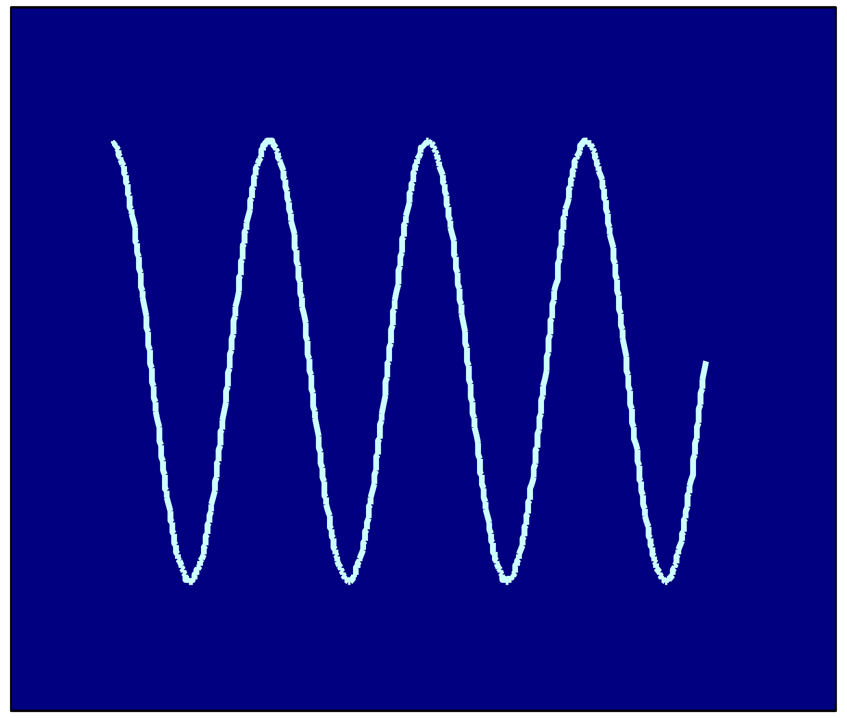
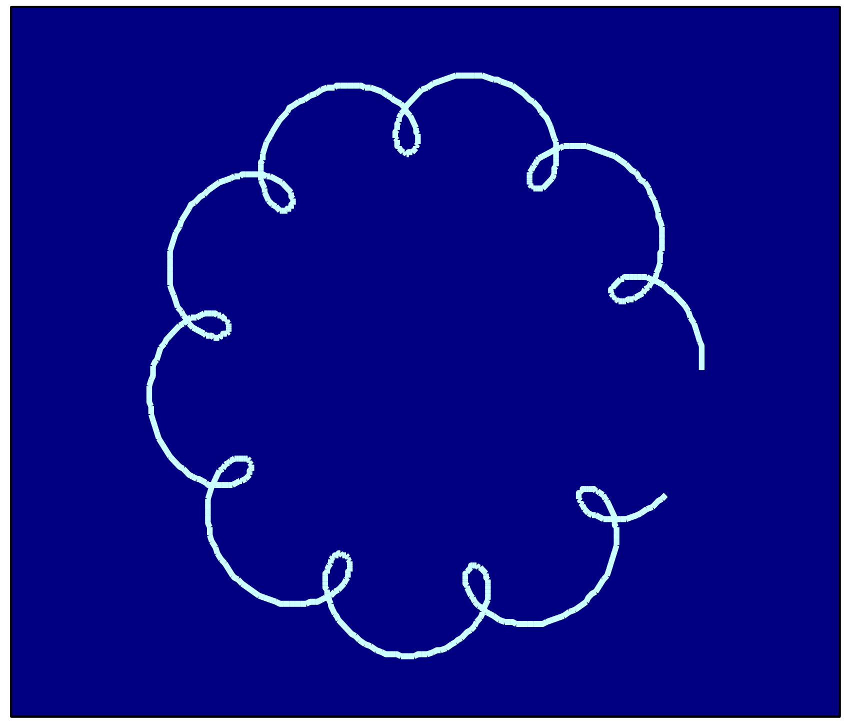
IONS IN COLD TRAPS



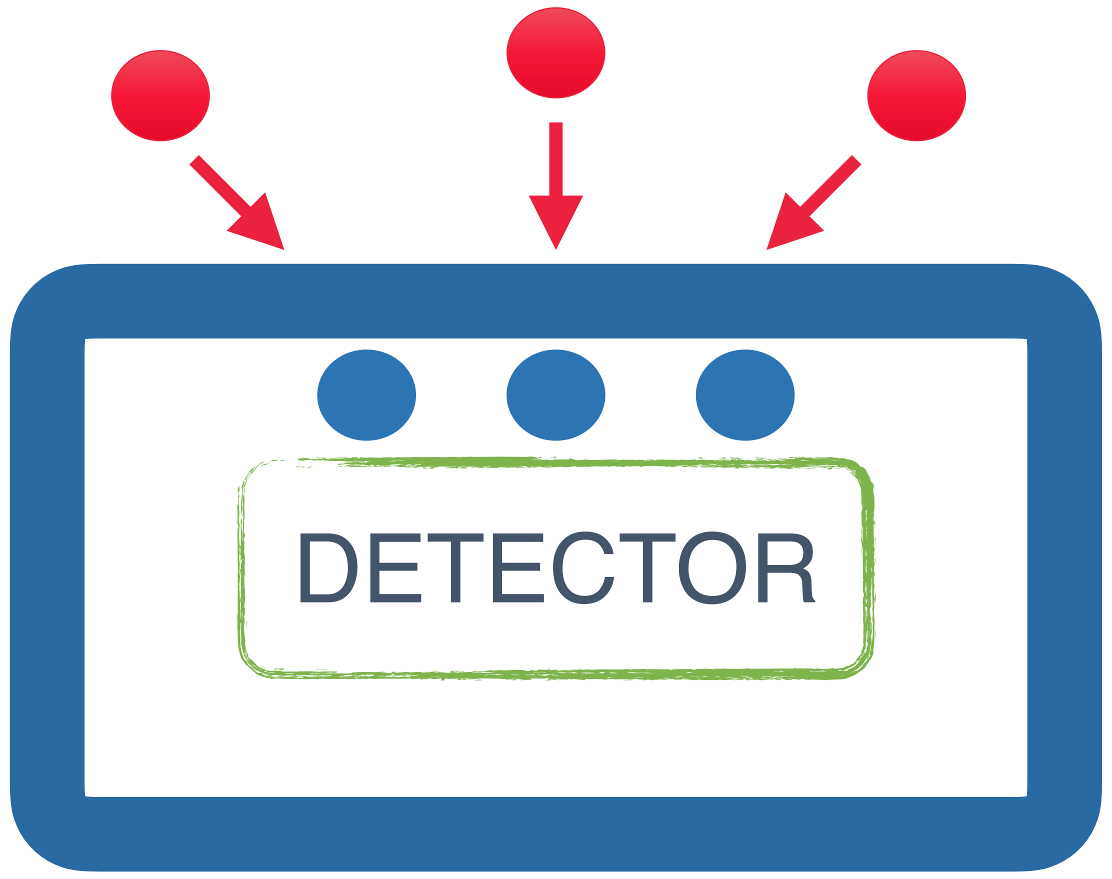
- Single Ion trapped in Electromagnetic fields
- Used in Quantum Metrology/ Quantum Computing
- Stable in trap for O(year)
- $T_{\text{wall}} \gg T_{\text{trap}}$



Axial motion



Radial motion



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	$^9\mathrm{Be}^+$	0.1 V	300 K	$\omega_z = 14.8$	14.8	640
Goodwin et al, 2016 [43]	Penning	$^{40}\mathrm{Ca}^+$	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
					$\omega_- = 0.050$		

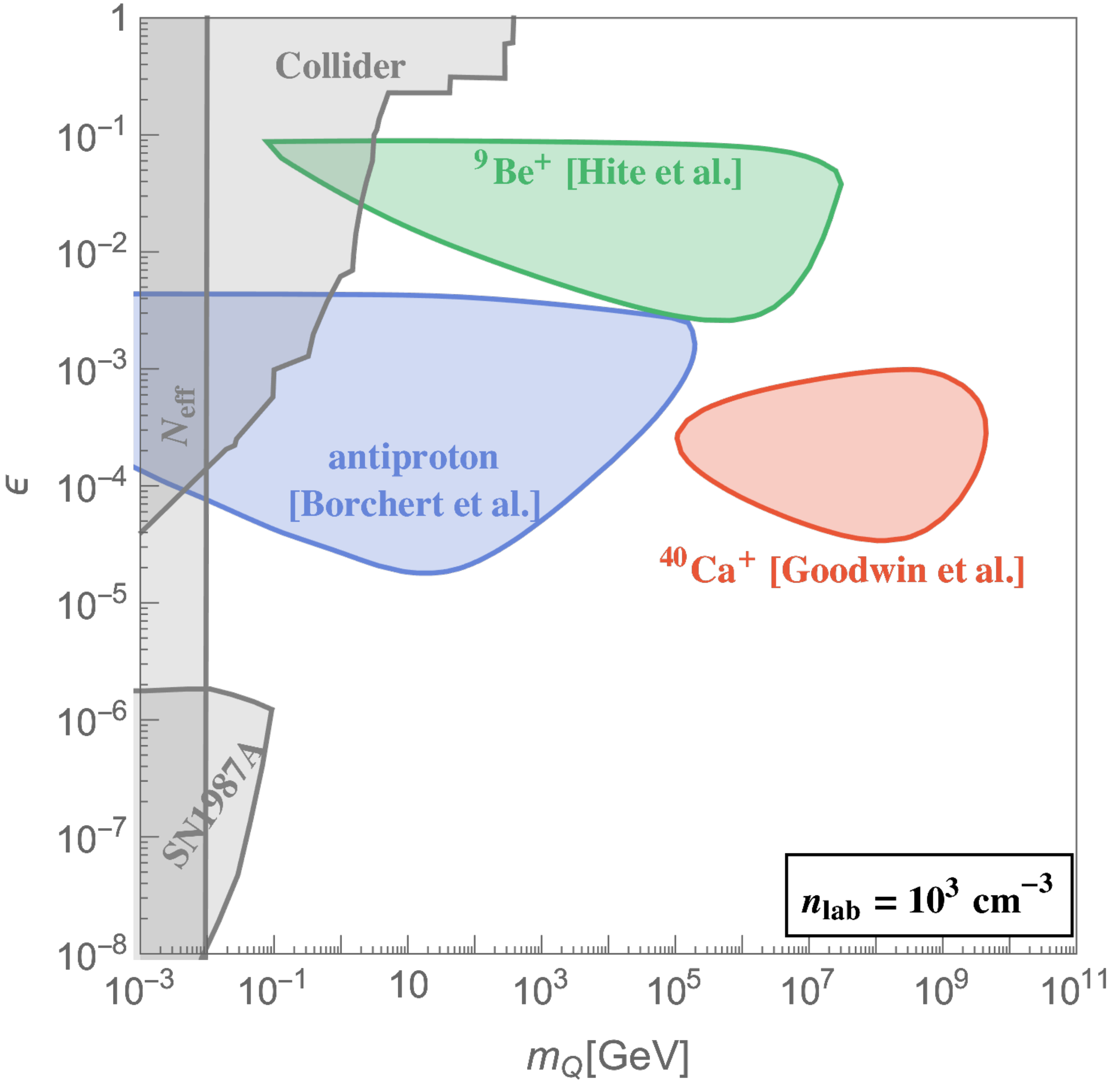
No reach for $\epsilon \gtrsim \dfrac{T_{\mathrm{wall}}}{V_z}$

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

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



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

arXiv: 2108.05283
HR with
D. Budker,
C. Smorra,
P. Graham,
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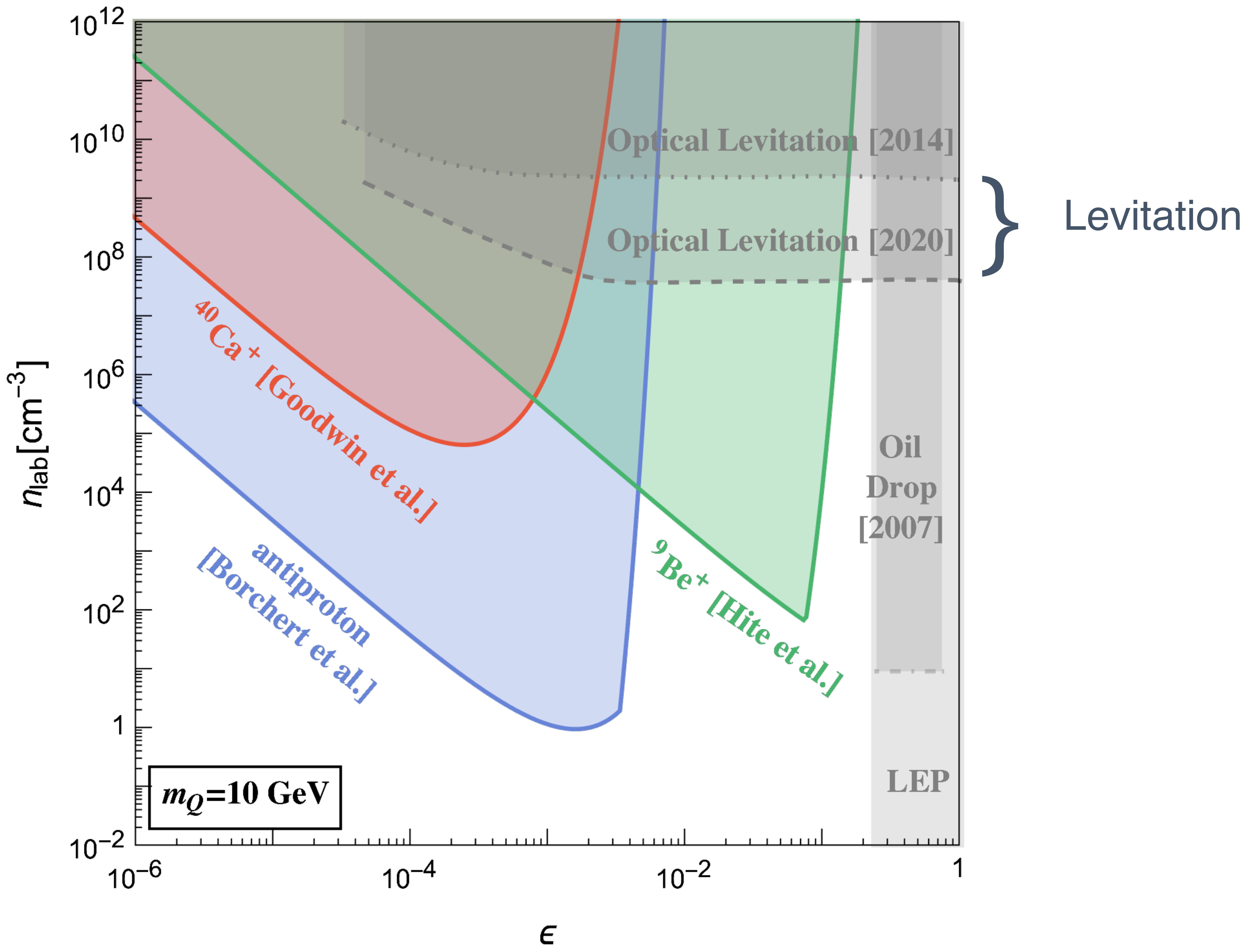
TERRESTRIAL POPULATION CONSTRAINTS



arXiv: 2108.05283
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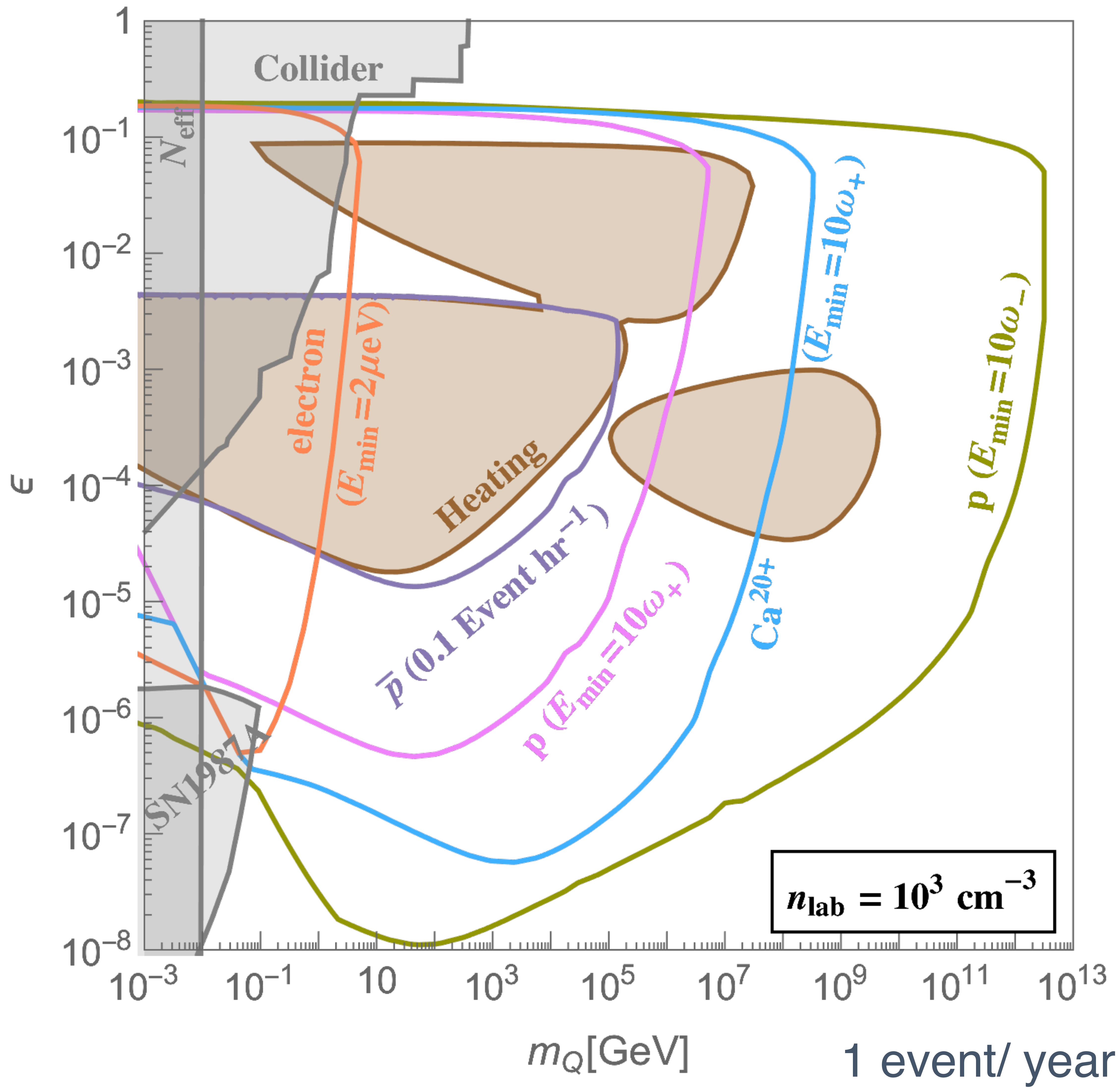
POSSIBLE IMPROVEMENTS

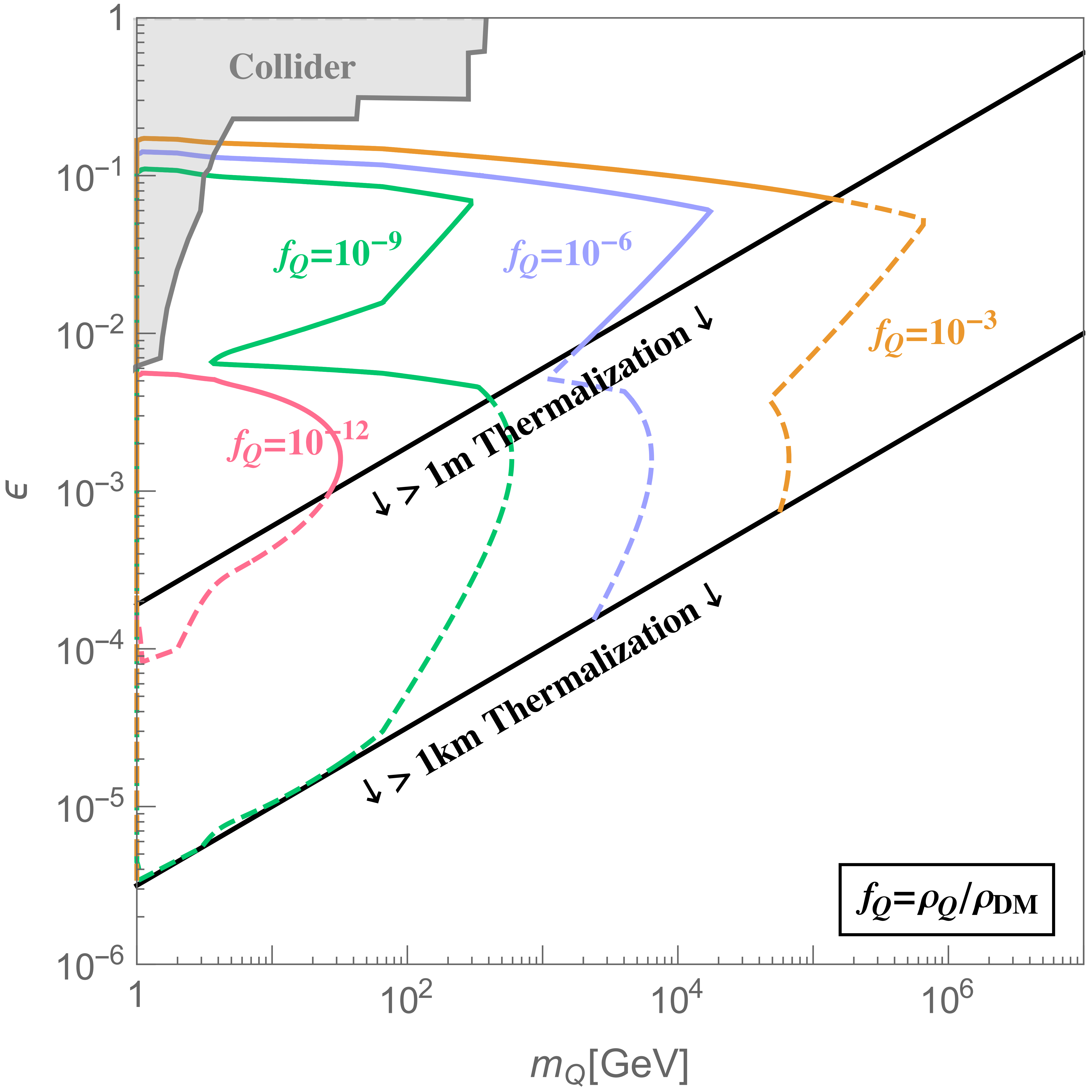
- Single Event Measurement instead of cumulative heating rate
- Requires high cadence data and energy resolution
- Highly Charged Ions
- Using electron targets - less momentum transfer for same energy transfer

PROJECTIONS

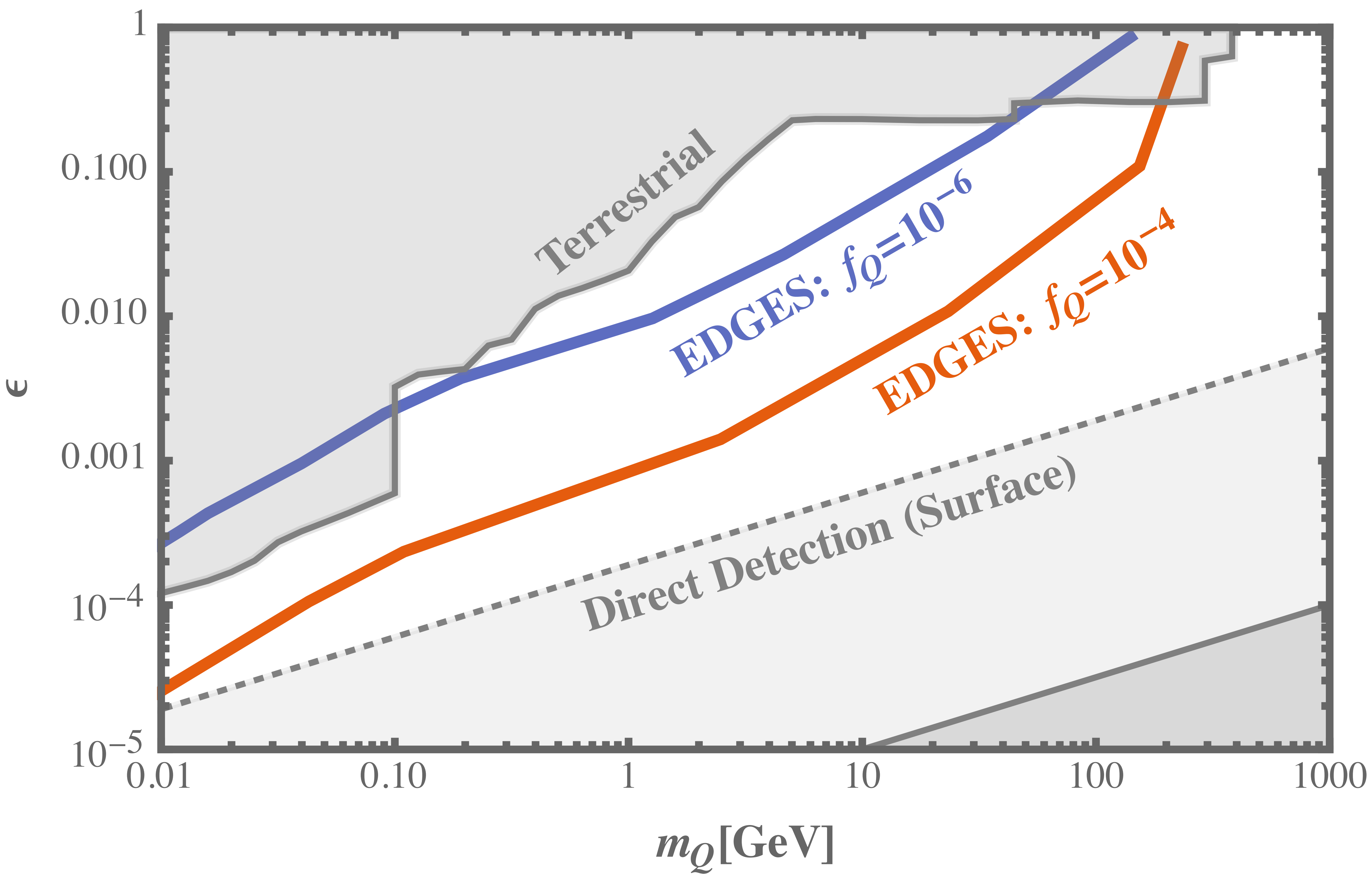


1 event/ year unless otherwise stated

LIMITS ON DARK MATTER



Adapted from: 1908.06986 Liu et al



OUTLOOK

- ✦ Repeating experiment in deep mine
- ✦ Collective excitations in Ion lattices
- ✦ Accumulating mCPs in an electric field bottle

OUTLINE

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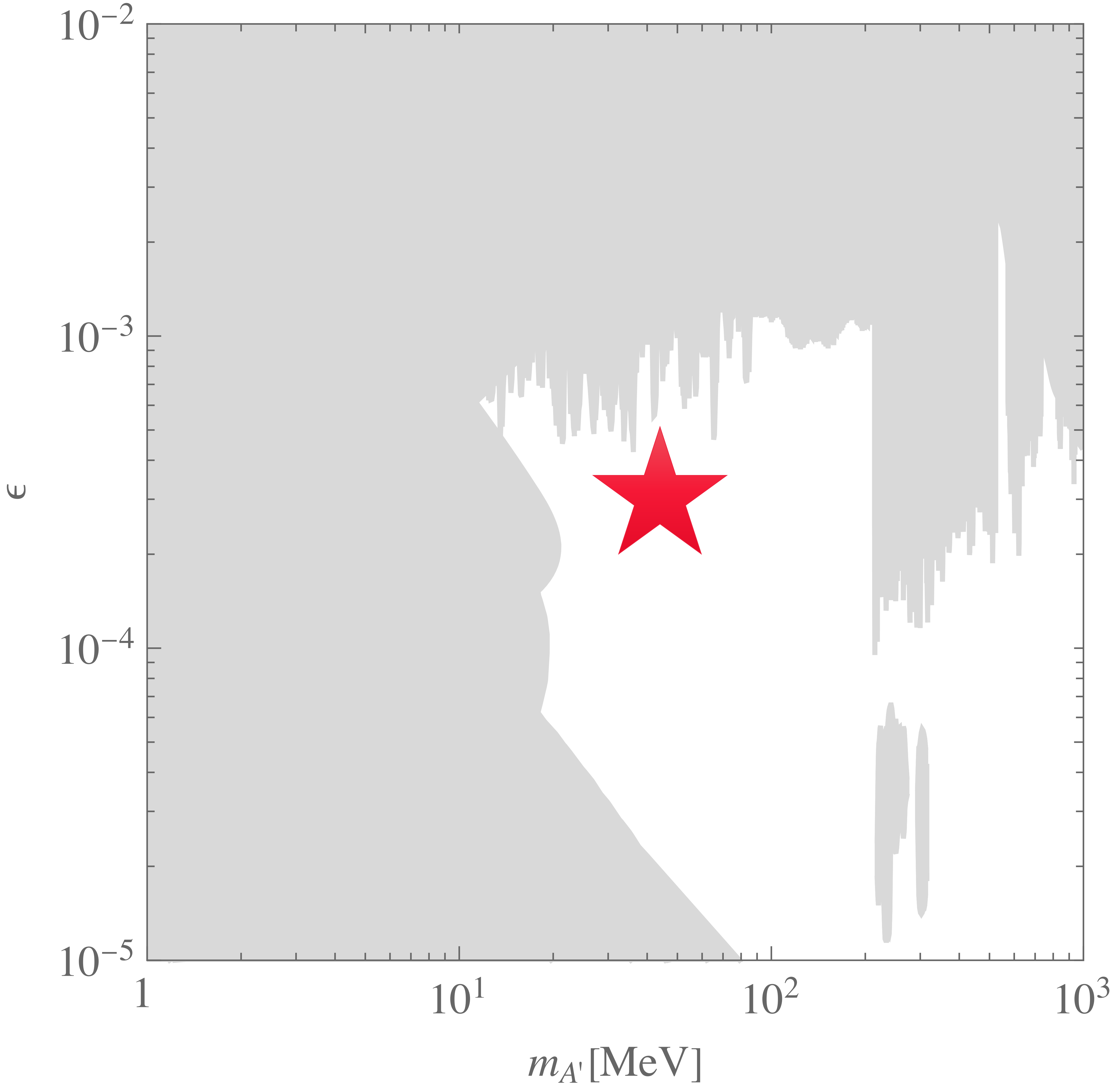
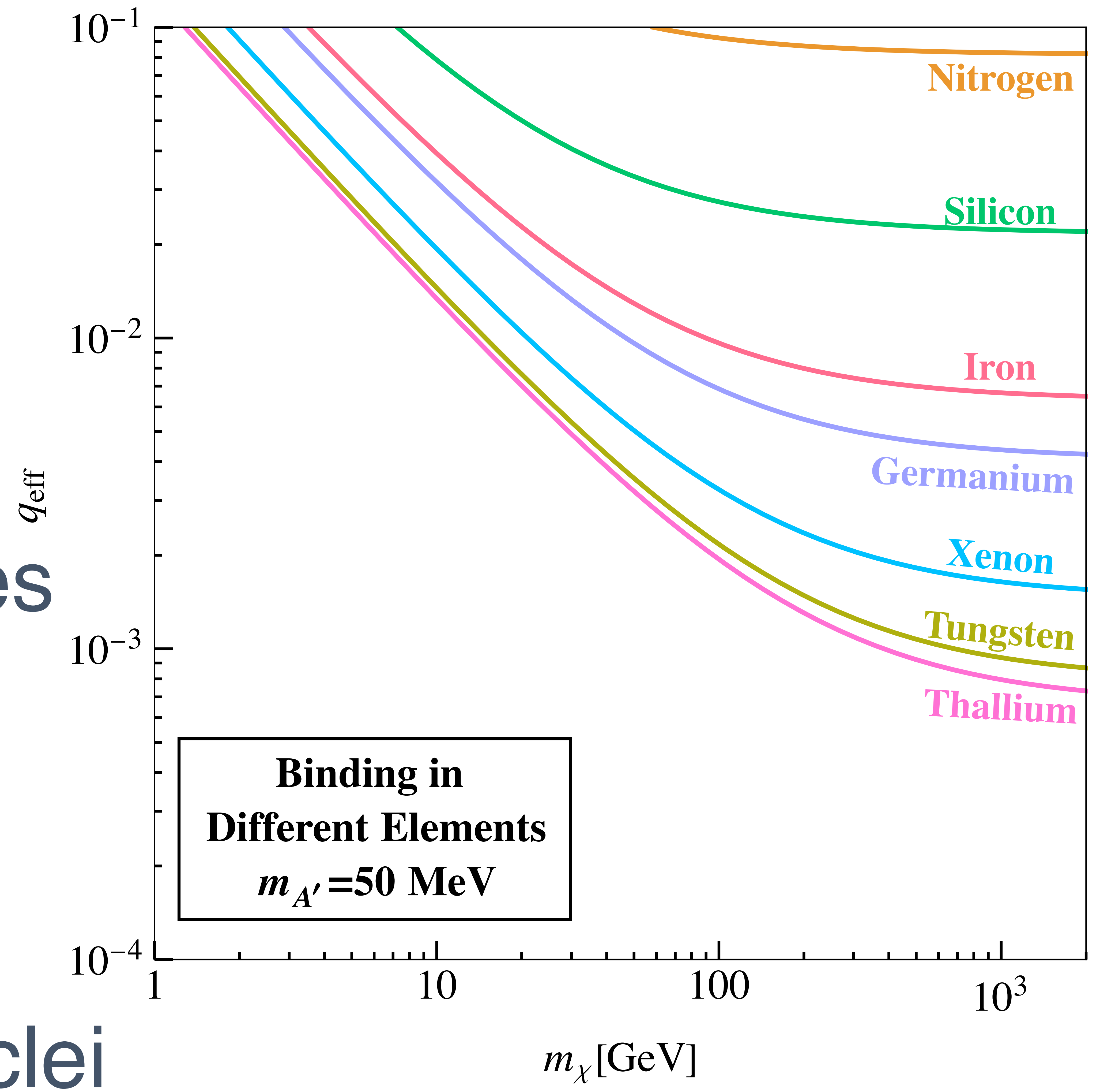
HEAVY DARK PHOTON MEDIATOR



MEDIATOR FOR BOUND STATES?

- $q_{\text{eff}} = \epsilon\sqrt{\frac{\alpha_D}{\alpha}}$
- Bohr Radius $R_B^{-1} \approx Z_N \alpha q_{\text{eff}} \mu$
- If $R_B \gtrsim m_{A'}^{-1}$ then no bound states
- For some q_{eff} binding only with heavy SM nuclei
- WIMP DM Detectors = heavy nuclei



TRACKING THRU OVERBURDEN

- Large $q_{\text{eff}} \implies$ Large local overabundances
- No binding in atmosphere with Nitrogen/Oxygen
- No binding in crust upto Iron
- Makes its way into Xenon tank
- Binds with Xenon - releasing E_B

BINDING IN XENON

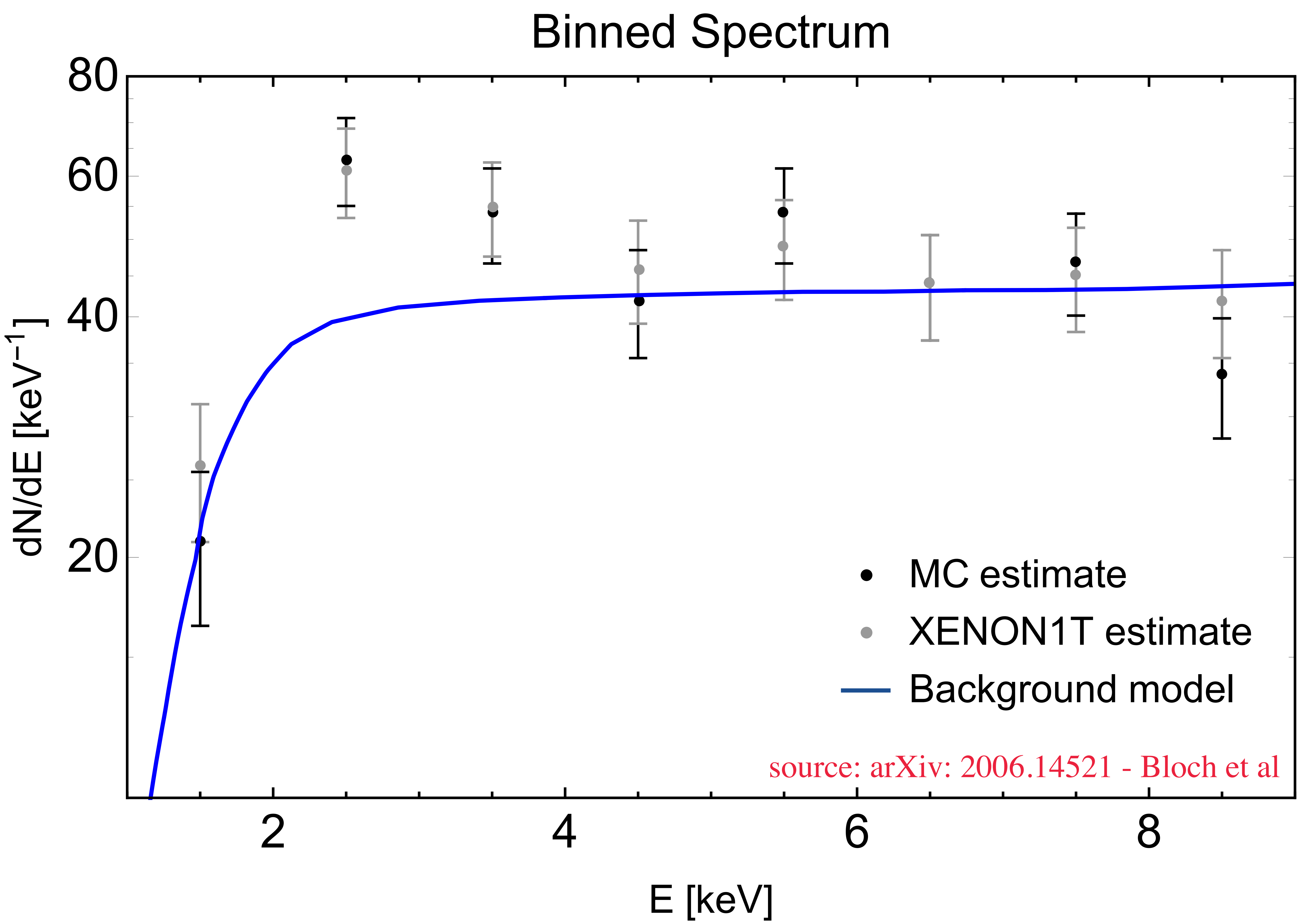
- Binds with Xenon - releasing E_B

$$E_B \sim \boxed{10\ \text{keV}} \times \left(\frac{q_{\text{eff}}}{10^{-3}}\right)^2 \left(\frac{Z}{54}\right)^2 \left(\frac{\mu}{122\text{GeV}}\right)$$

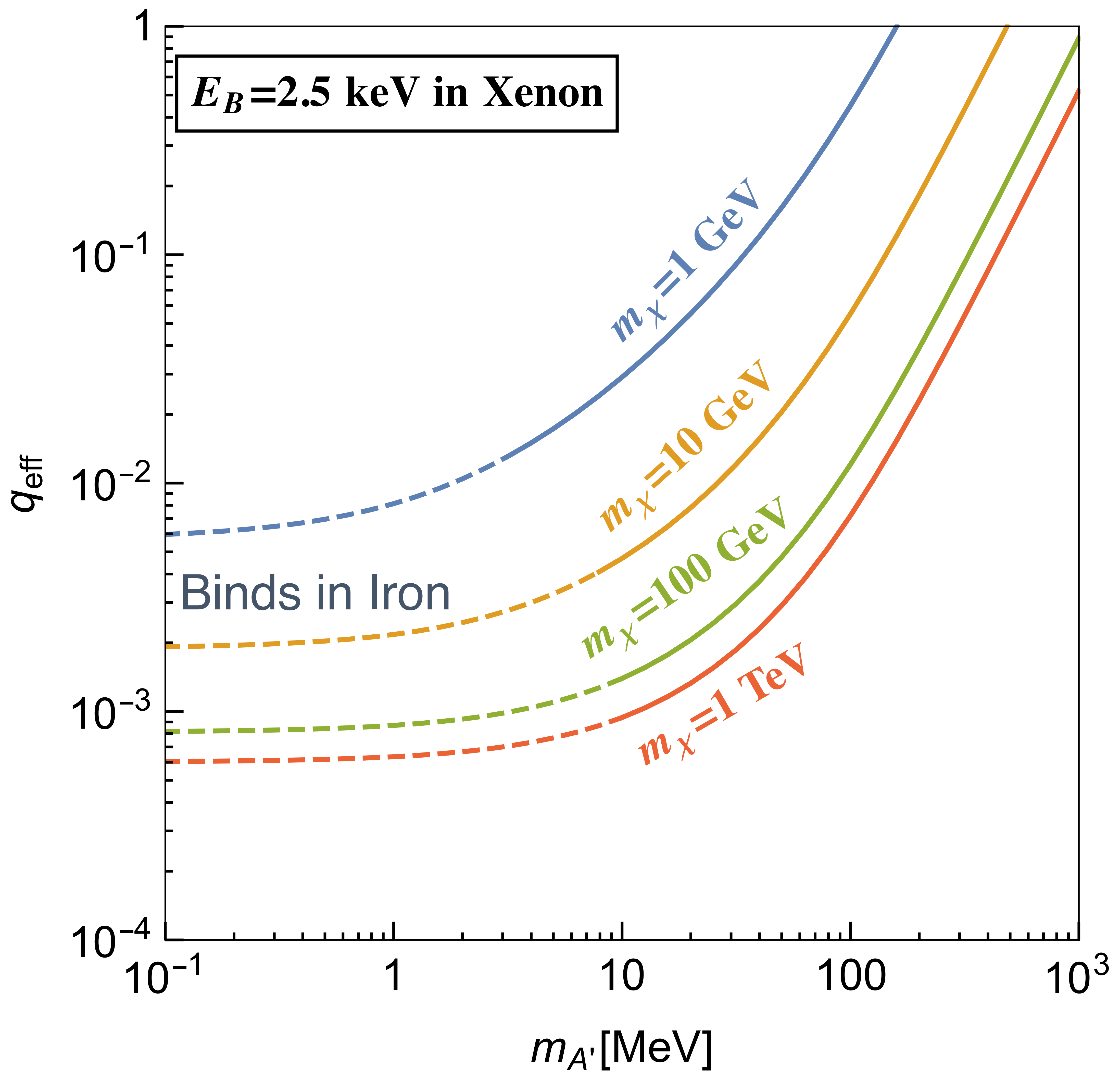
- Usually KE (scattering) / Mass (absorption)
- New source of energy
- Monochromatic electron ejection

XENON S1-S2 SIGNAL

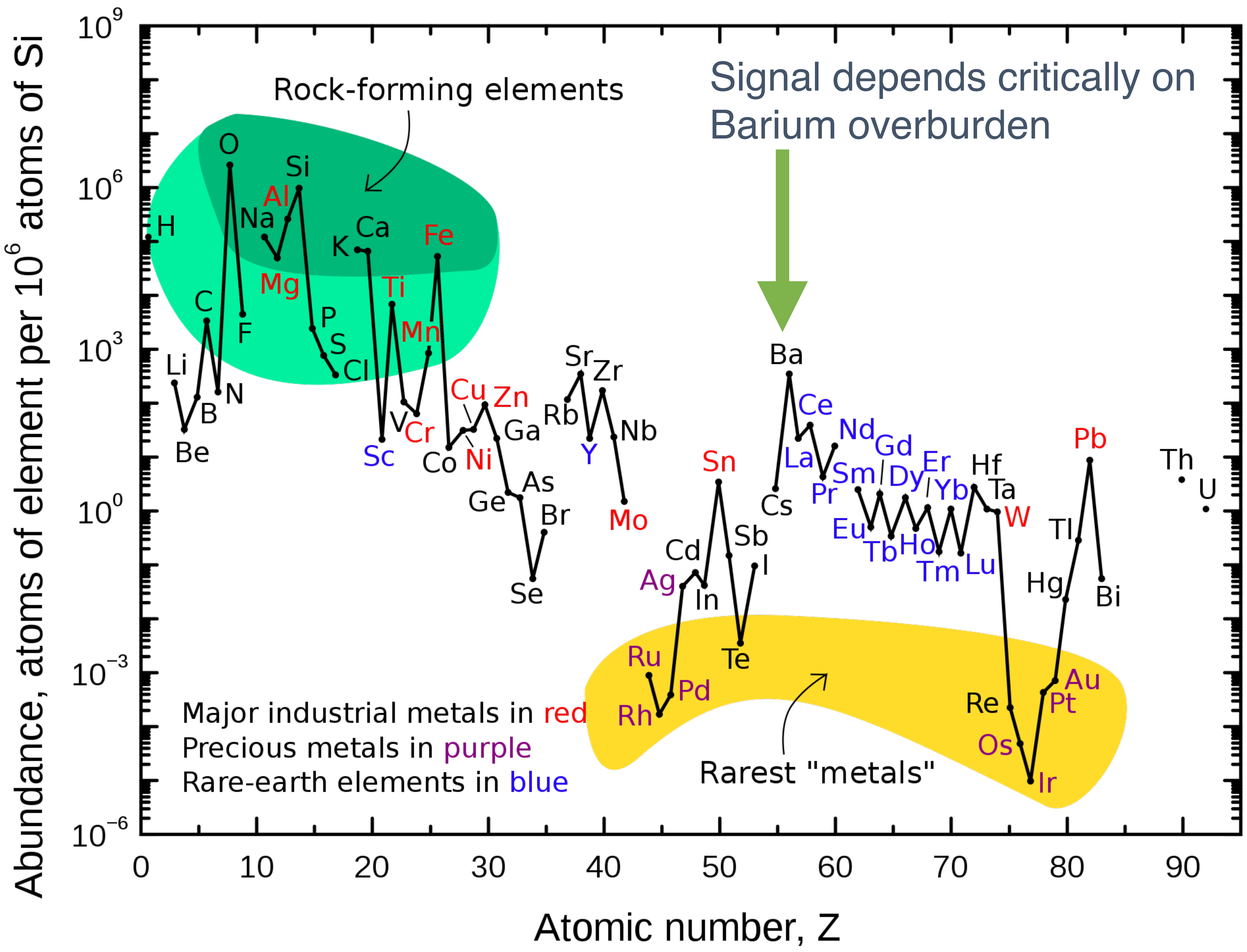
arXiv: 2006.09721v3 - Xenon1T collaboration



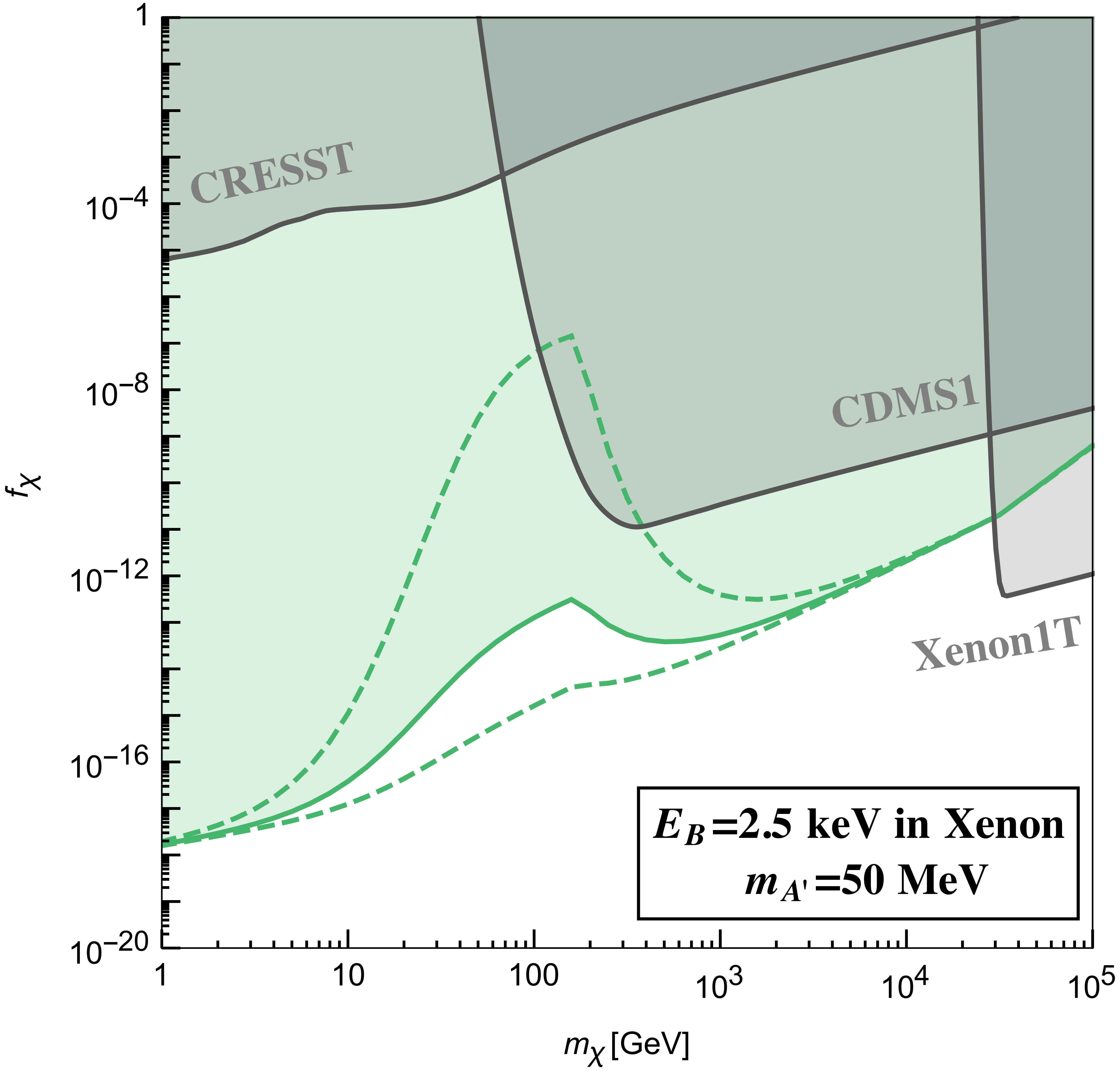
$E_B = 2.5$ keV in Xenon



HEAVY ELEMENTS IN OVERBURDEN

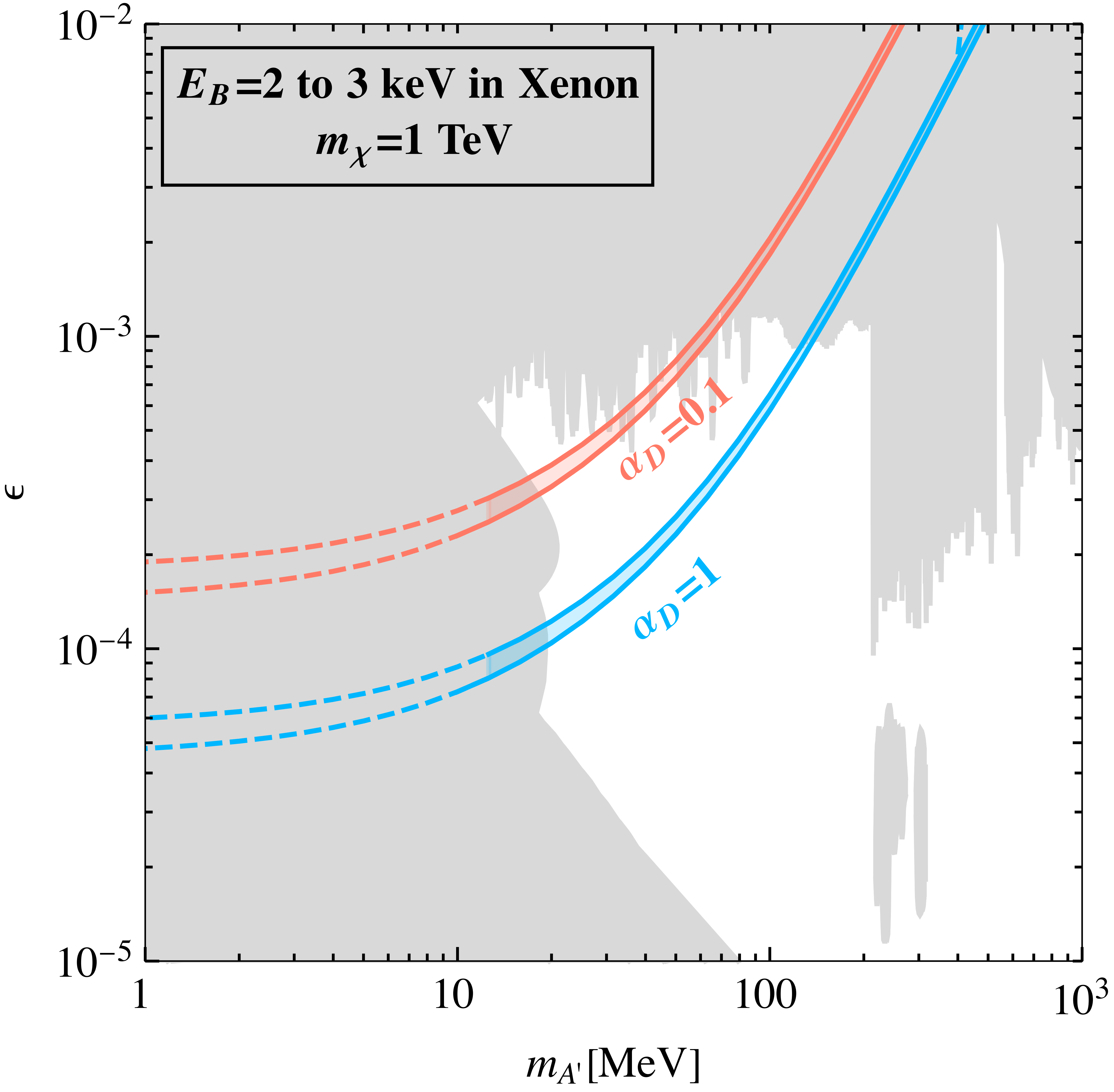


PARAMETER SPACE



- $n_{\mathrm{Ba}} \in (0.7 - 6) \times 10^{18} \mathrm{cm}^{-3}$
- Extremely small DM fractions explain anomaly
- Limits set everywhere above

DARK PHOTON PARAMETER SPACE



TRAFFIC JAM DETECTION

MODEL	DETECTION STRATEGY	arXiv
Contact Interactions/ QCD	1) Isomeric Tantalum 2) Uncollider 3) Bolometers	1911.07865 Forthcoming Forthcoming
Dark Photon Mediated	Bound states in Xenon	2110.06217
Millicharge Particles	1) Electrostatic Accelerator 2) Ion Traps	2012.03957 2108.05283
B-L mediated blobs	1) Neutron Bottle	2008.06061

SUMMARY

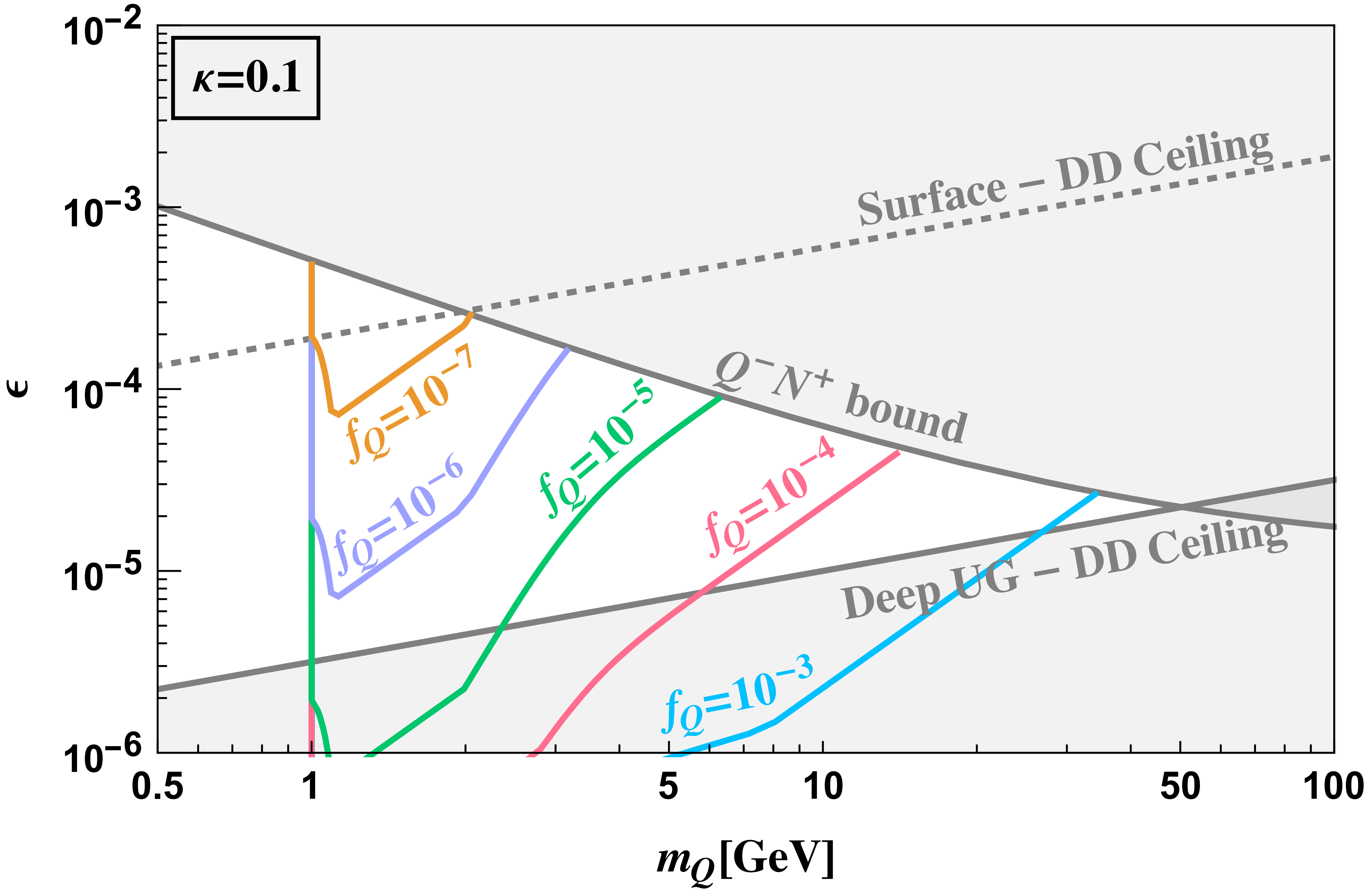
- ✦ Small abundances of stable dark relics are natural
- ✦ Large SM couplings $\Longrightarrow$ captured on earth
- ✦ Huge terrestrial densities due to traffic jam
- ✦ Model 1: mCPs can be detected with ion traps
- ✦ Model 2: heavy dark photon mediated, form bound states in heavy element detectors.

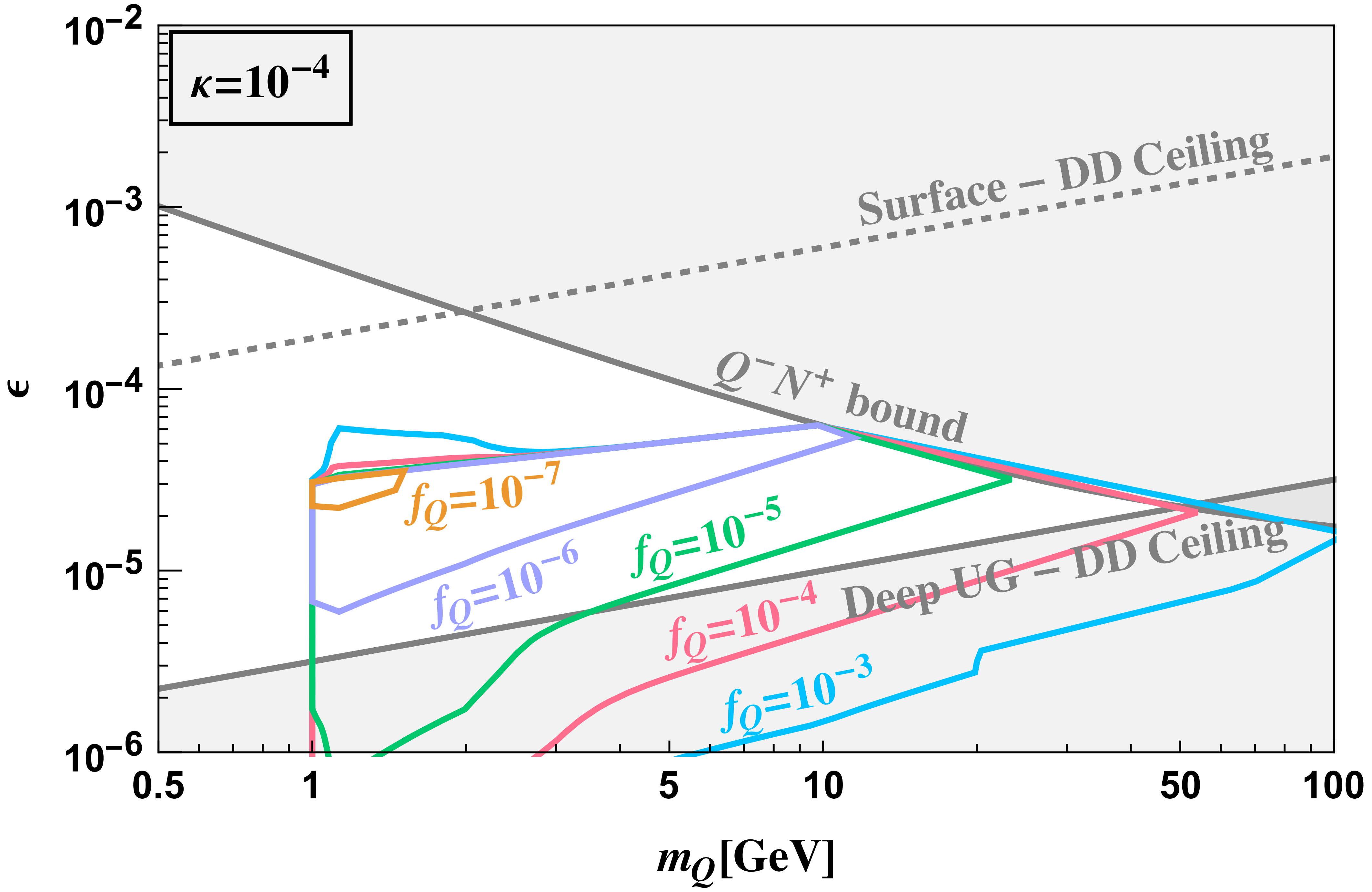
BACKUP

SIGNALS

SYMMETRIC POPULATION

ANNIHILATIONS IN SUPER-K





CAPTURE CROSS-SECTION

$$\sigma_B v_{\mathrm{rel}} \approx \frac{4\pi}{9}\frac{(Z\alpha m_e)^5}{(2\mu E_B)^{7/2}}(\frac{\mu}{m_N})^4 F_\chi^2 F_e^2\,.$$

$$\sigma_B v_{\mathrm{rel}} \simeq 5\times 10^{-35}\mathrm{cm}^2 \times \left(\frac{\mu}{\mathrm{GeV}}\right)^{0.55}$$

MEASUREMENT

- $\nu_+, \nu_-, \nu_z \approx$ MHz $\approx$ **4neV** $\approx 50\mu$K
- Strong inhomogeneous magnetic field B_2
- $$\Delta\nu_z(n_+, n_-, m_s) = \frac{h\nu_+}{4\pi^2 m_p \nu_z}\frac{B_2}{B_0}\left[\left(n_+ + \frac{1}{2}\right) + \frac{\nu_-}{\nu_+}\left(n_- + \frac{1}{2}\right) + \frac{g_p m_s}{2}\right]$$
- $\Delta\nu_z$ measured with image current detection to detect Δn_+