QUANTUM SENSING FOR DARK RELICS

Harikrishnan Ramani
Stanford Institute for Theoretical Physics

Based on:

Forthcoming HR with D. Budker, P. Graham, F. Schmidt-Kaler
arXiv: 2012.03957 HR with M. Pospelov
arXiv: 2010.11190 HR with R. Harnik, M. Pospelov, R. Plestid
arXiv: 1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone

—Banksy

RESEARCH INTERESTS

COLLIDER PHYSICS

- Resummation for jet-vetoed W+W- cross-sections: 1407.4481, 1509.07118, 1606.01034
- Novel Limits on naturalness from Colliders: 1707.03399
- Codex-b: 1911.00481

COSMOLOGICAL PHASE TRANSITIONS

- Electroweak Phase Transition: 1612.00466
- Symmetry non-restoration: 1807.07578
- Novel Phases of confining dark sectors: 2102.11284

DARK MATTER SUBSTRUCTURE

- Pulsar Timing Arrays: 1901.04490, 2005.03030

ULTRALIGHT DM

- Muon g-2 experiments as dark matter detectors 2006.10069

DARK FORCES IN NUCLEAR DECAYS

- GANDHI: 1911.07865

LOW THRESHOLD DETECTORS

- Molecular Excitations and Quantum dots to detect light dark matter: 1907.07682
- Cold Ion Traps: Forthcoming
- Neutron bottle as Dark matter detector: 2008.06061
- Cosmic ray boosted Dark Matter: 2010.11190

NEGATIVE THRESHOLD DETECTORS

- Nuclear Isomers: 1911.07865,1907.00011
- DC Accelerators: 2012.03957

COLLABORATORS OUTSIDE HIGH ENERGY THEORY

Bjoern Lehnert, LBL, KATRIN collaboration

Giovanni Benato
CUORE collaboration
INFN Gran Sasso

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SuperCDMS
UC Berkeley

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IPNL/CNRS

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Theoretical Atomic, Molecular and Optical Physics
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Rupak Mahapatra
MINER collaboration
Texas A&M University

Marivi Fernández-Serra
Condensed Matter Theory
Stony Brook University

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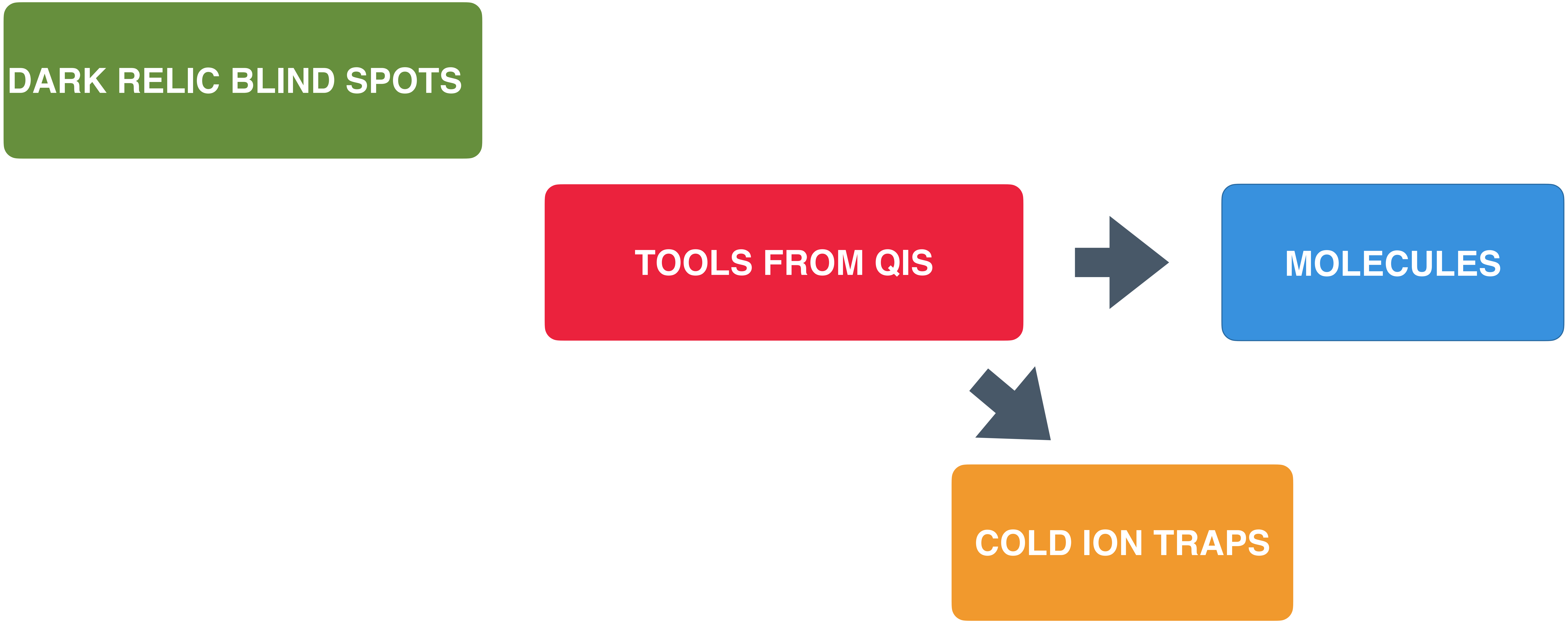
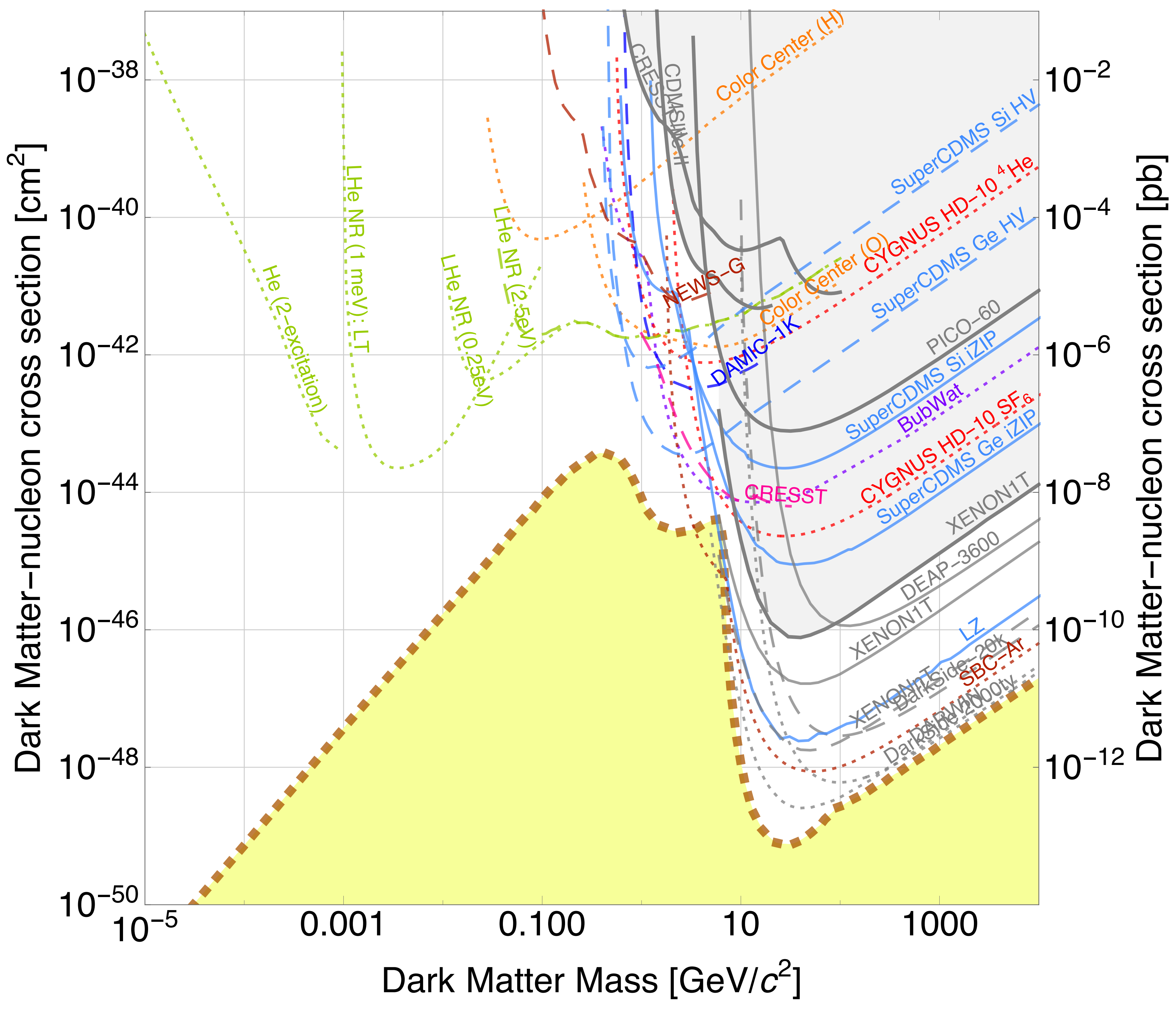
OUTLINE


DARK RELIC BLIND SPOTS
TOOLS FROM QIS
MOLECULES
COLD ION TRAPS

DARK MATTER

DARK MATTER → **STABLE PARTICLE**

- ✦ Ample gravitational evidence for dark matter at early & late times
- ✦ Particle Nature unknown
- ✦ Stable Particle + interactions + thermal history = correct relic density?
- ✦ Stringent Limits in the WIMP mass window - thorough?



DARK RELICS

DARK MATTER → STABLE PARTICLE

DARK RELICS

DARK RELIC ← **STABLE PARTICLE**

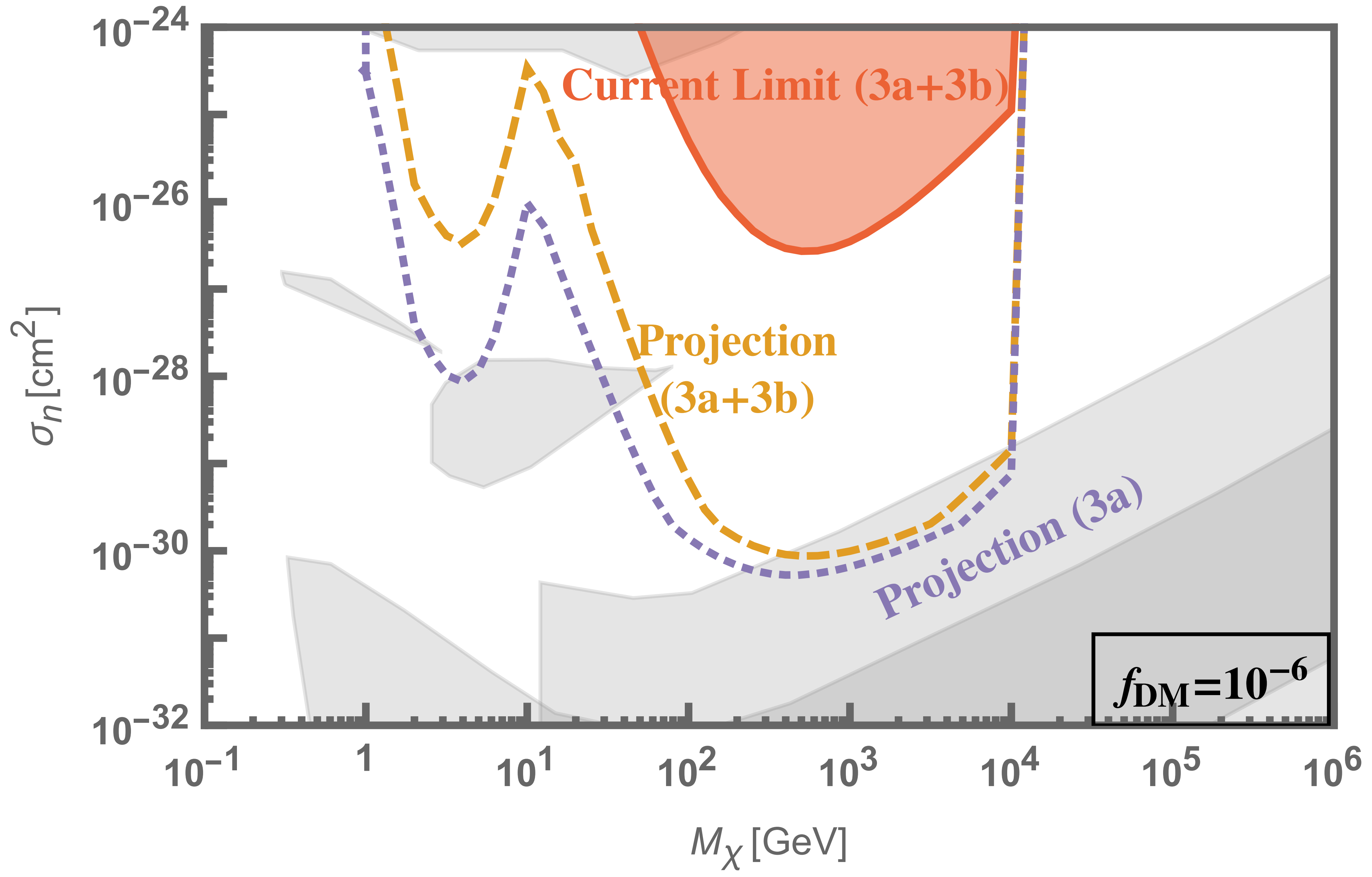
- Well motivated stable particles: Monopoles, axions, squarks, heavy quarks (KSVZ), gluinos (SUSY), Milli-charge Particles (mCPs)

- Robust prediction for relic fractions $f_{\rm DM} \ll 1$

- The only way to access M >> TeV?

- Use same concept for Detection?

1911.07865 (PRL) HR 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

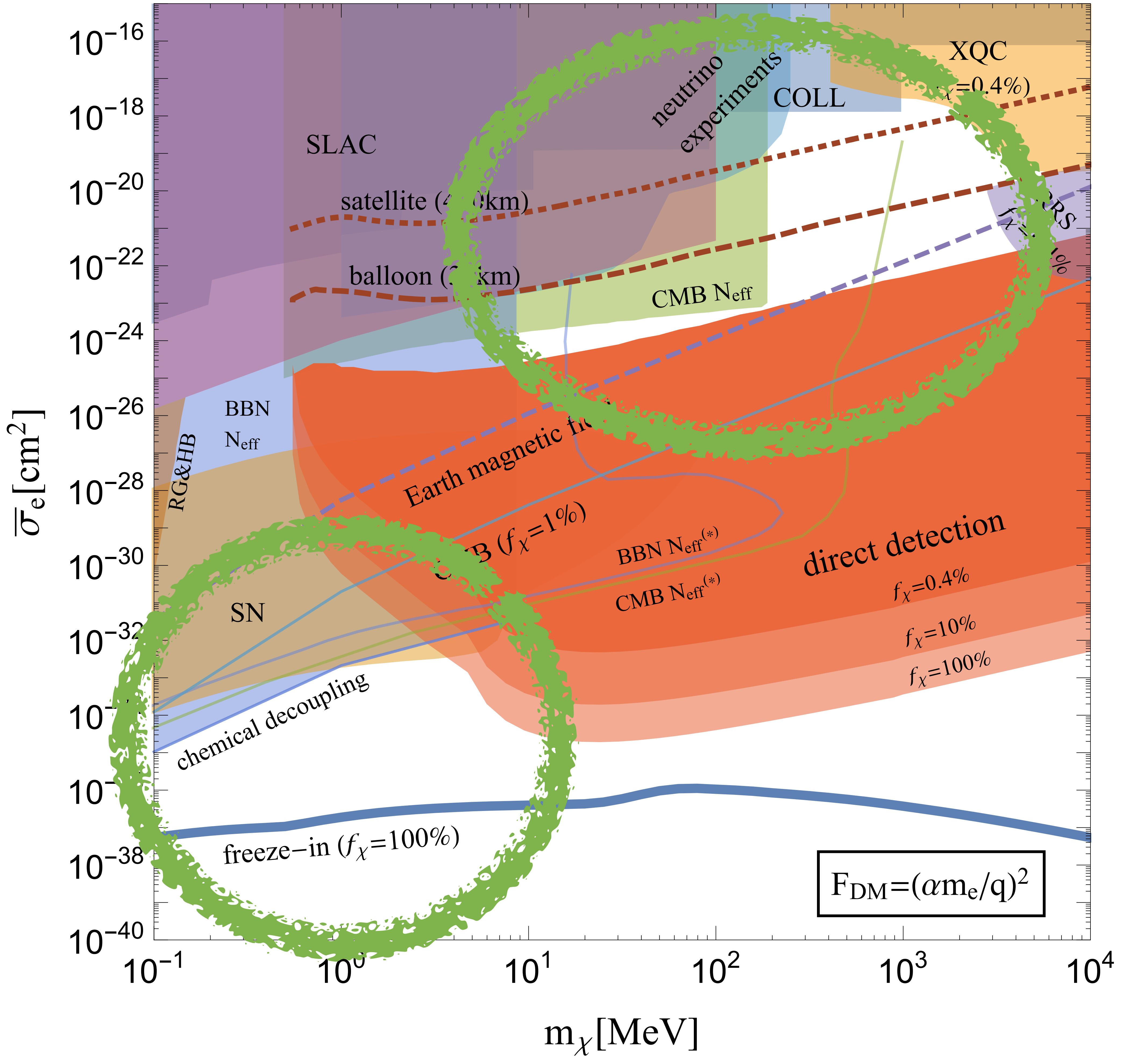
TWO KINDS OF MCPs

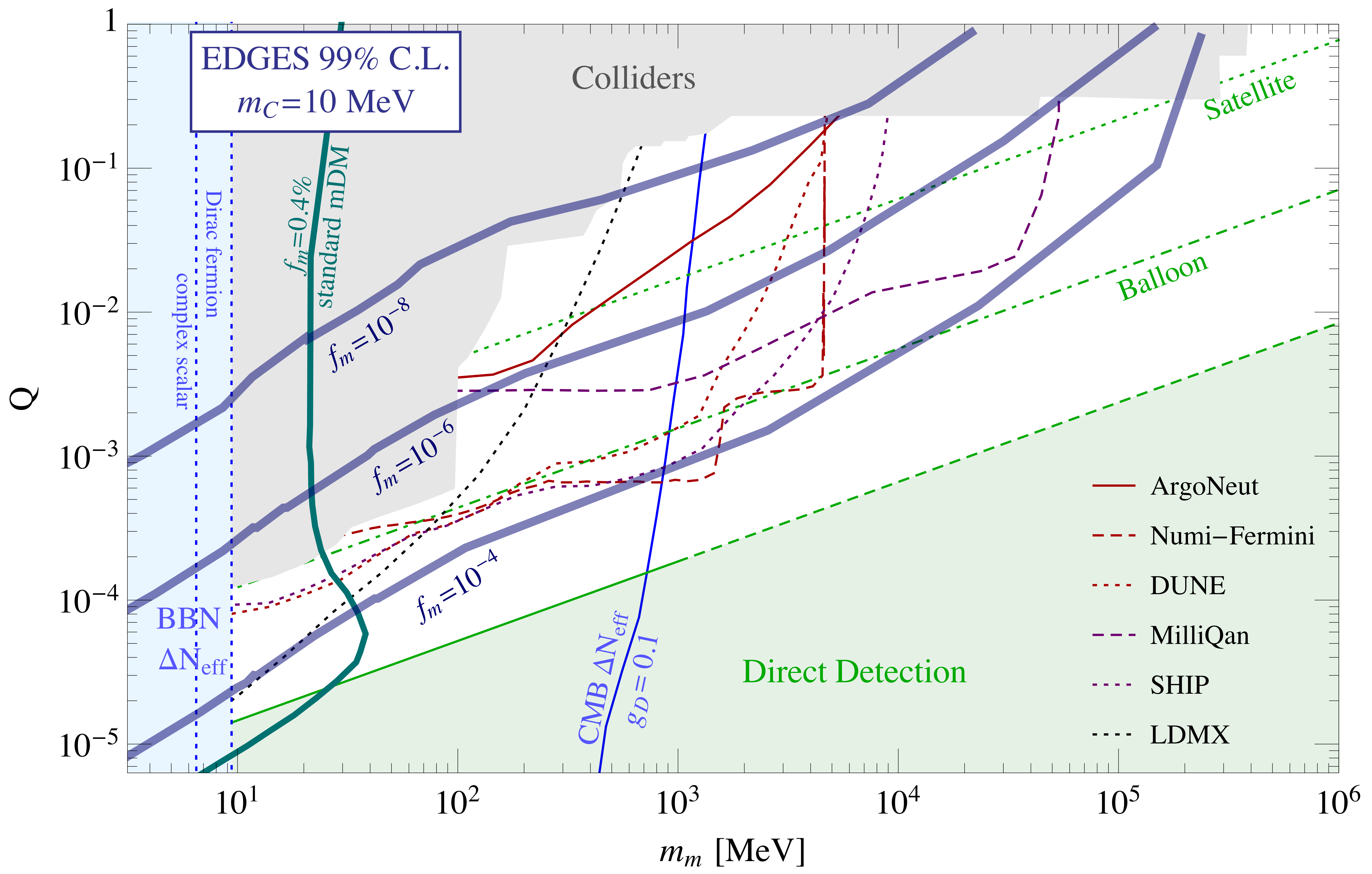
- Dark Photon mediated
- Effectively milli-charged at energies >> $m_{A'}$
- $m_{A'}$ sets the range of interactions with the SM
- For large enough $m_{A'}$, we can ignore long range effects like
  - SN shocks, galactic magnetic fields, solar winds,
  - Electric field due to the ionosphere
- Pure Milli-charge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

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

PARAMETER SPACE

1905.06348 Emken et al , 1908.06986 Liu et al

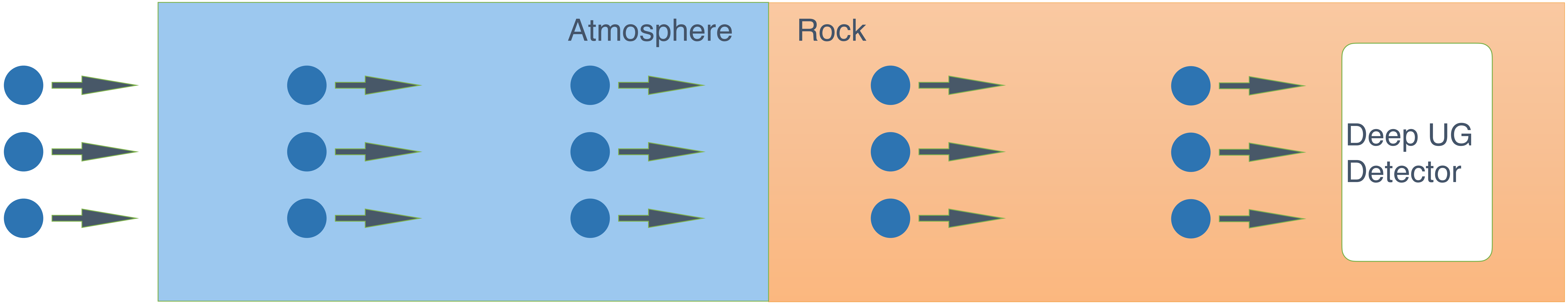




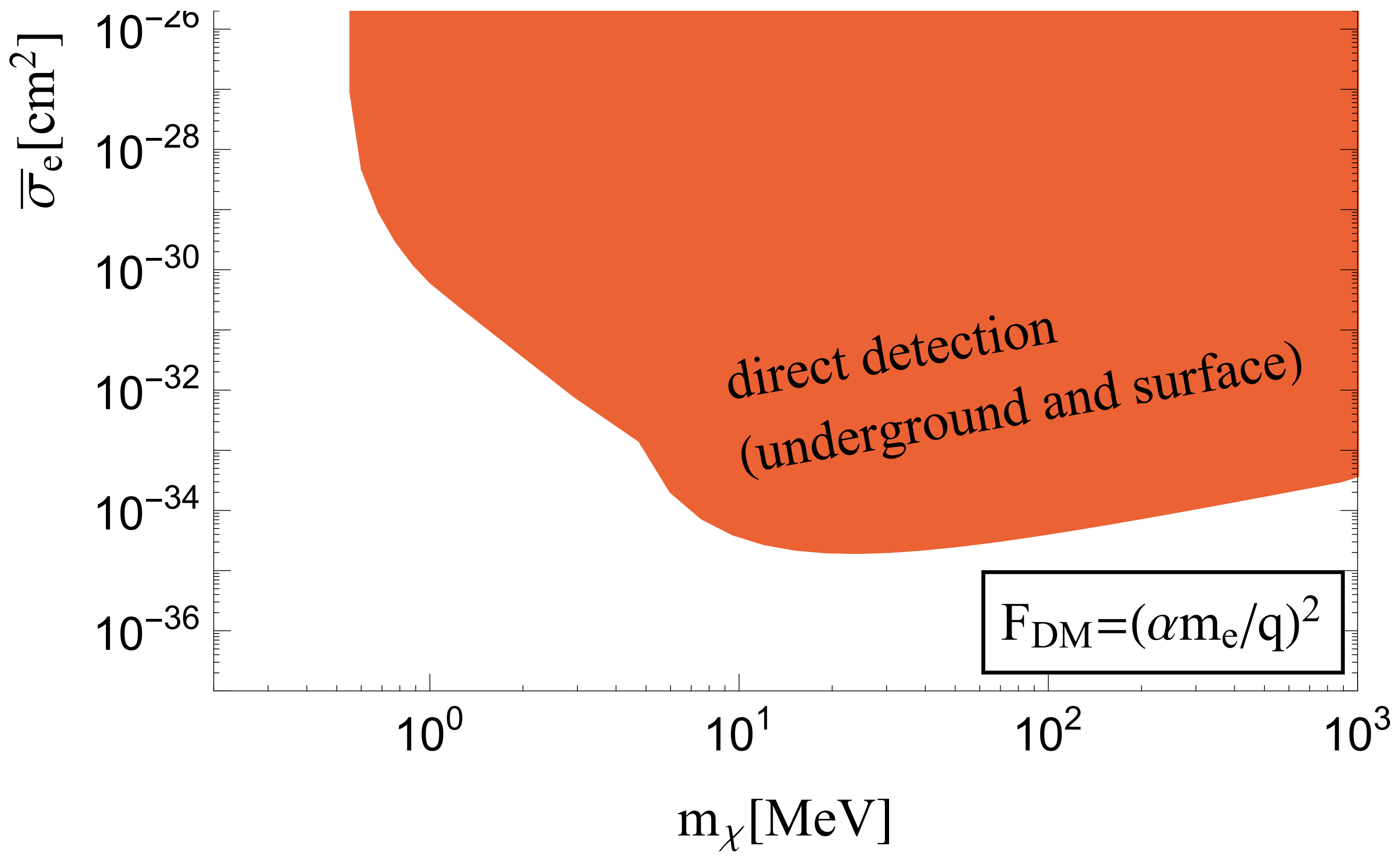
KE smaller than threshold

Colliders/Terrestrial : no reach for small charge
Direct Detection : no reach for large charge (Overburden blocks it)

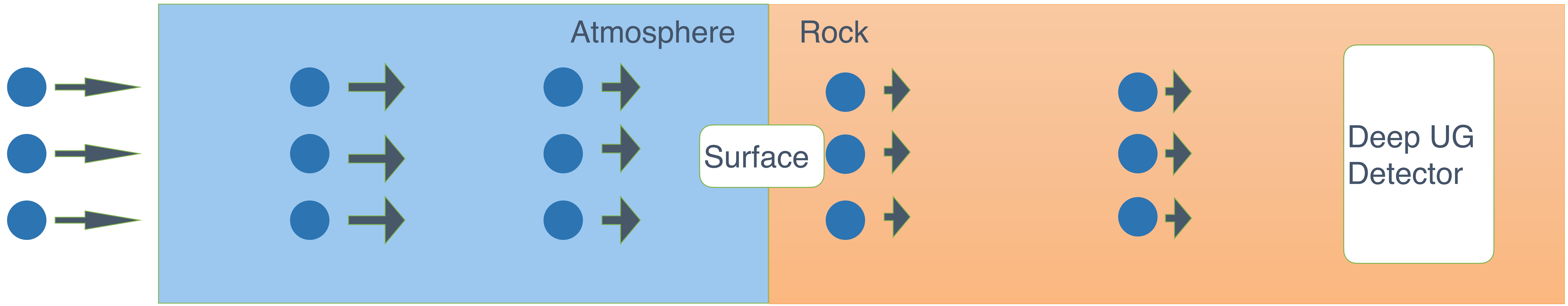
SMALL X-SECTION

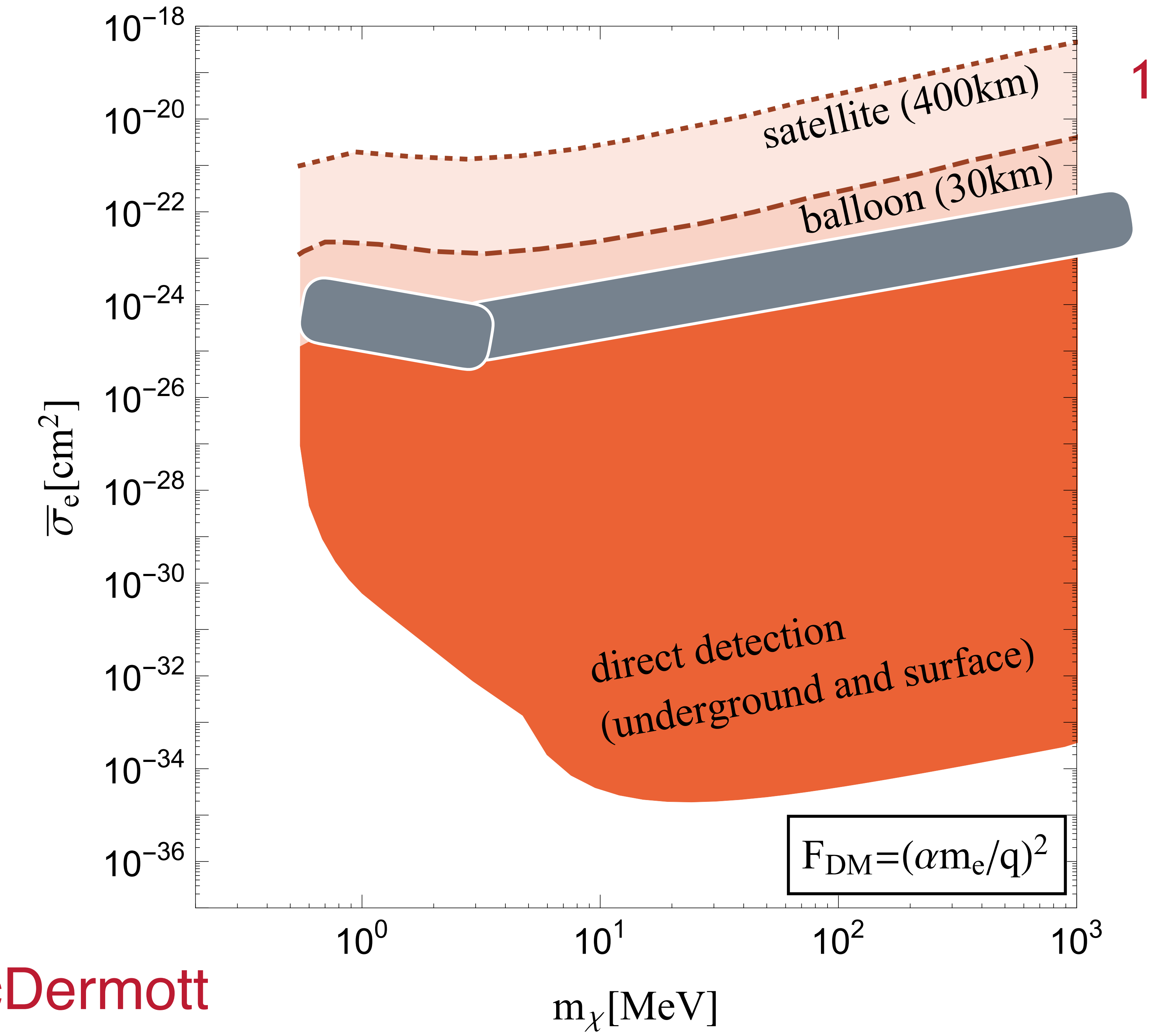


1905.06348 Emken et al



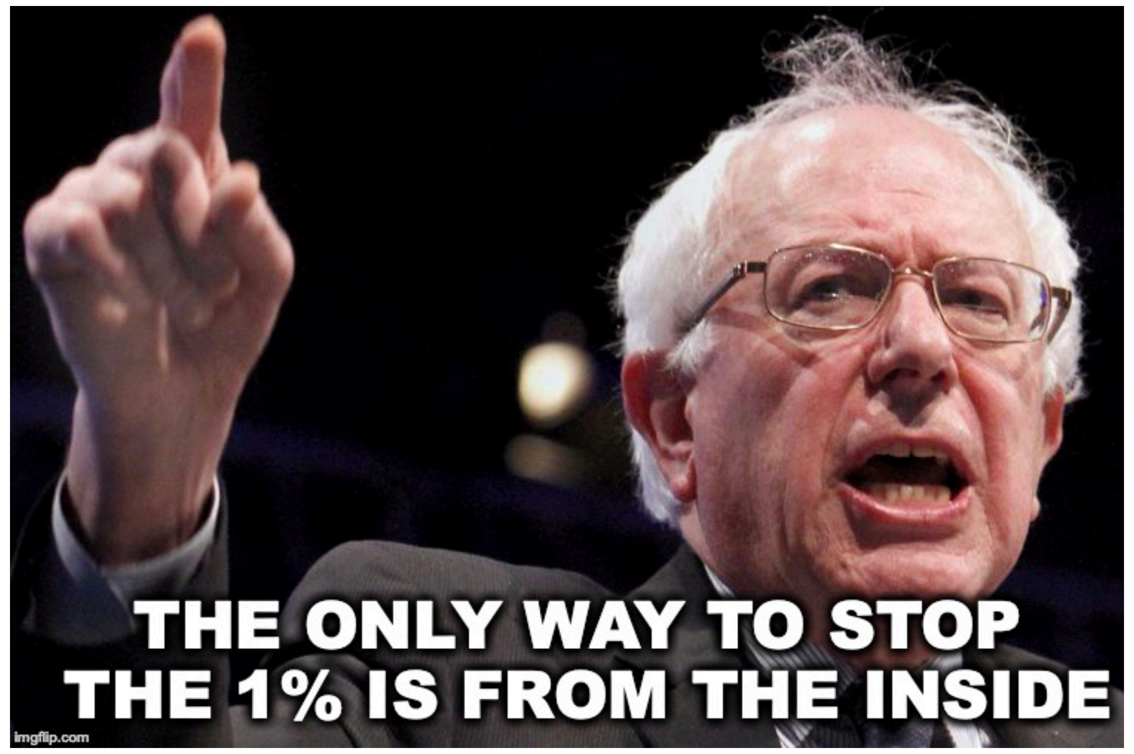
LARGE X-SECTION





1905.06348 Emken et al

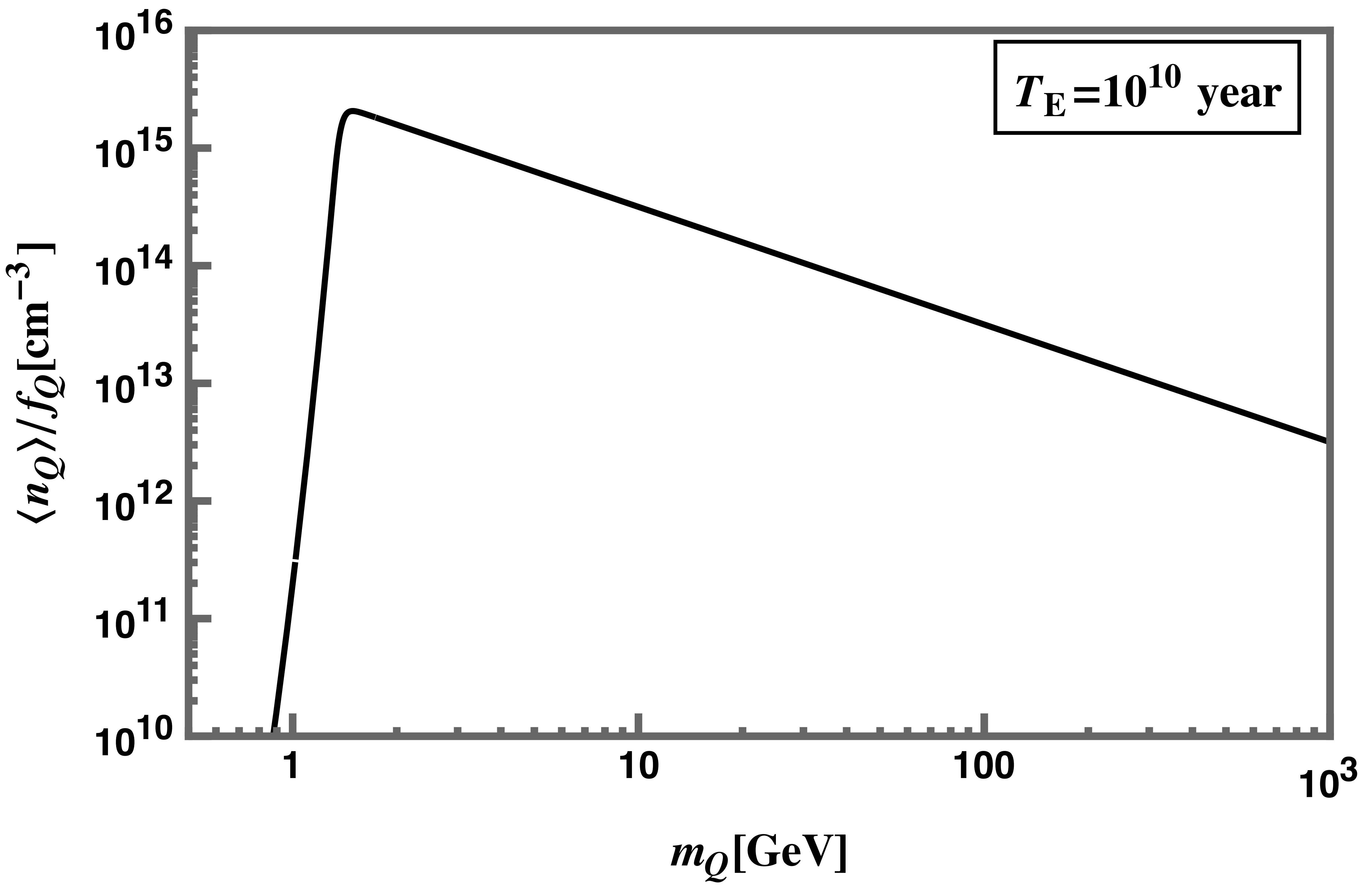
- Reaches detector after thermalizing
- KE=300 Kelvin (26 meV)
- Current DD threshold : eV



For contact interactions: 1802.03025 Hooper, McDermott

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

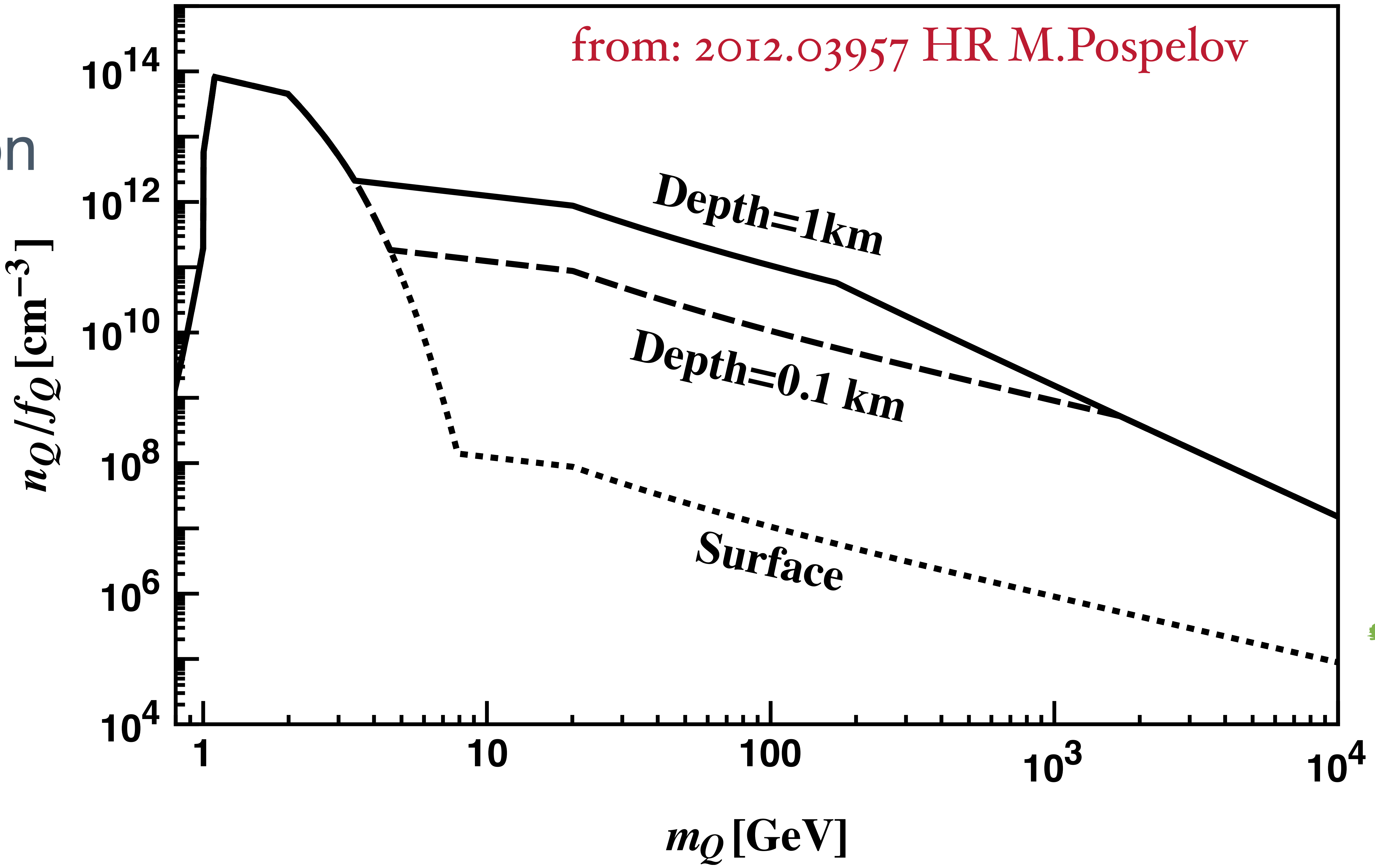
TRAFFIC JAM

- Sinking not immediate.
- Downward drift /diffusion

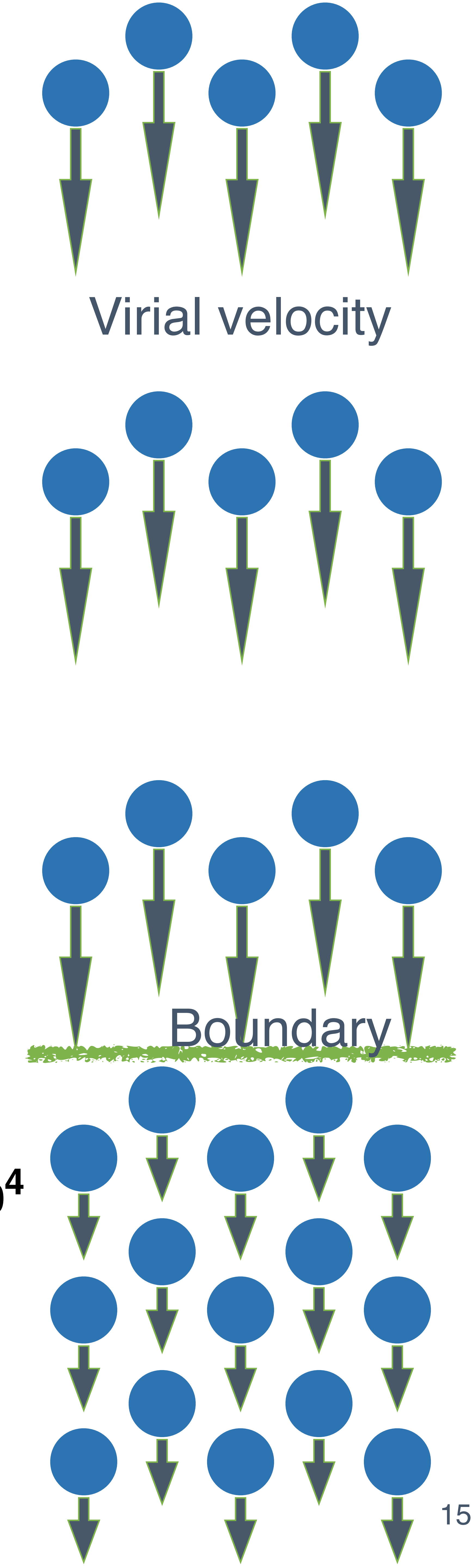
  $v_{term} \ll v_{th} \ll v_{vir}$

- Traffic Jam on the way

  $$\eta_{term} = \frac{n_{lab}}{n_{vir}} = \frac{v_{vir}}{v_{term}}$$



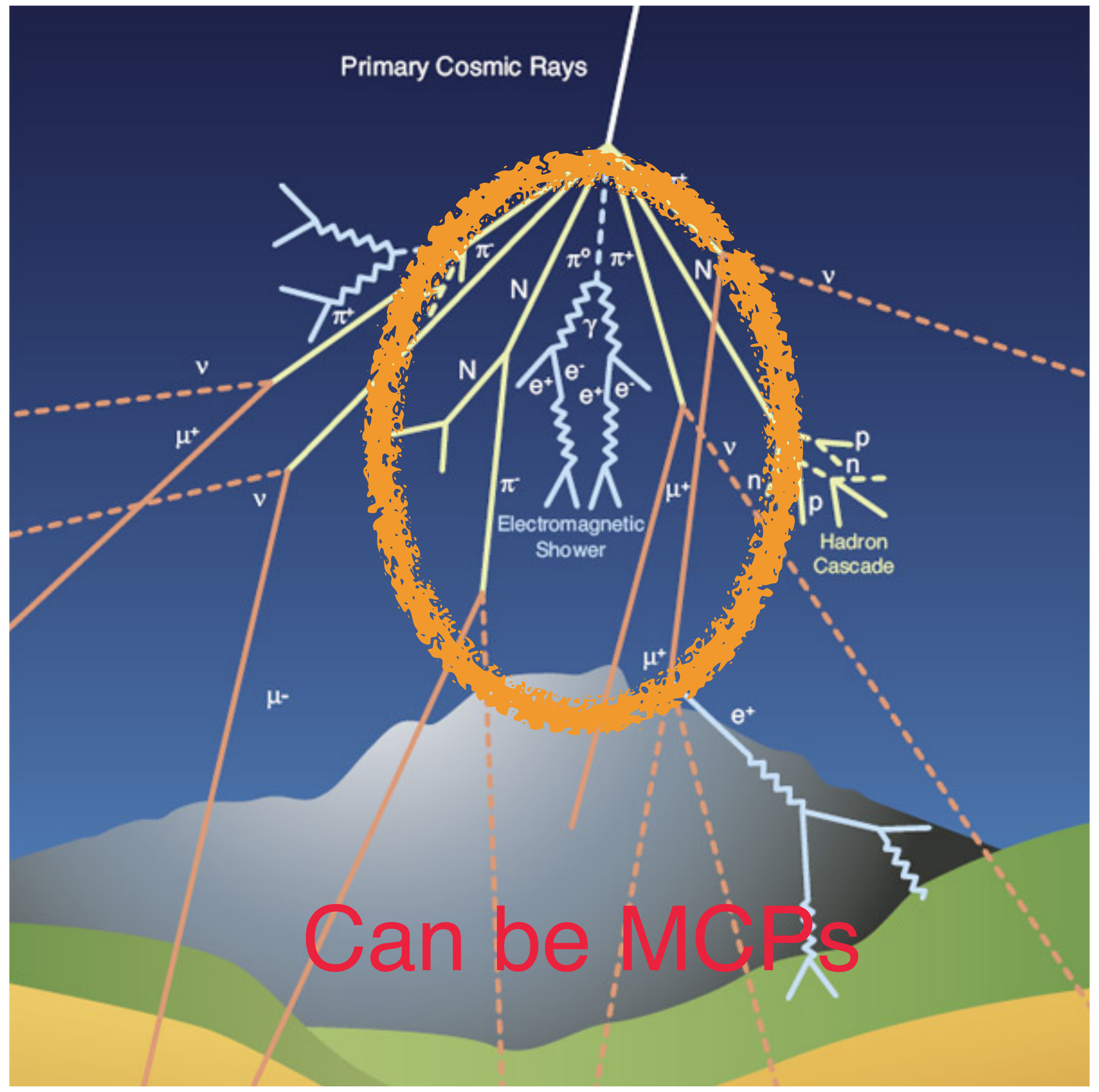
For any $\epsilon > 10^{-6}$

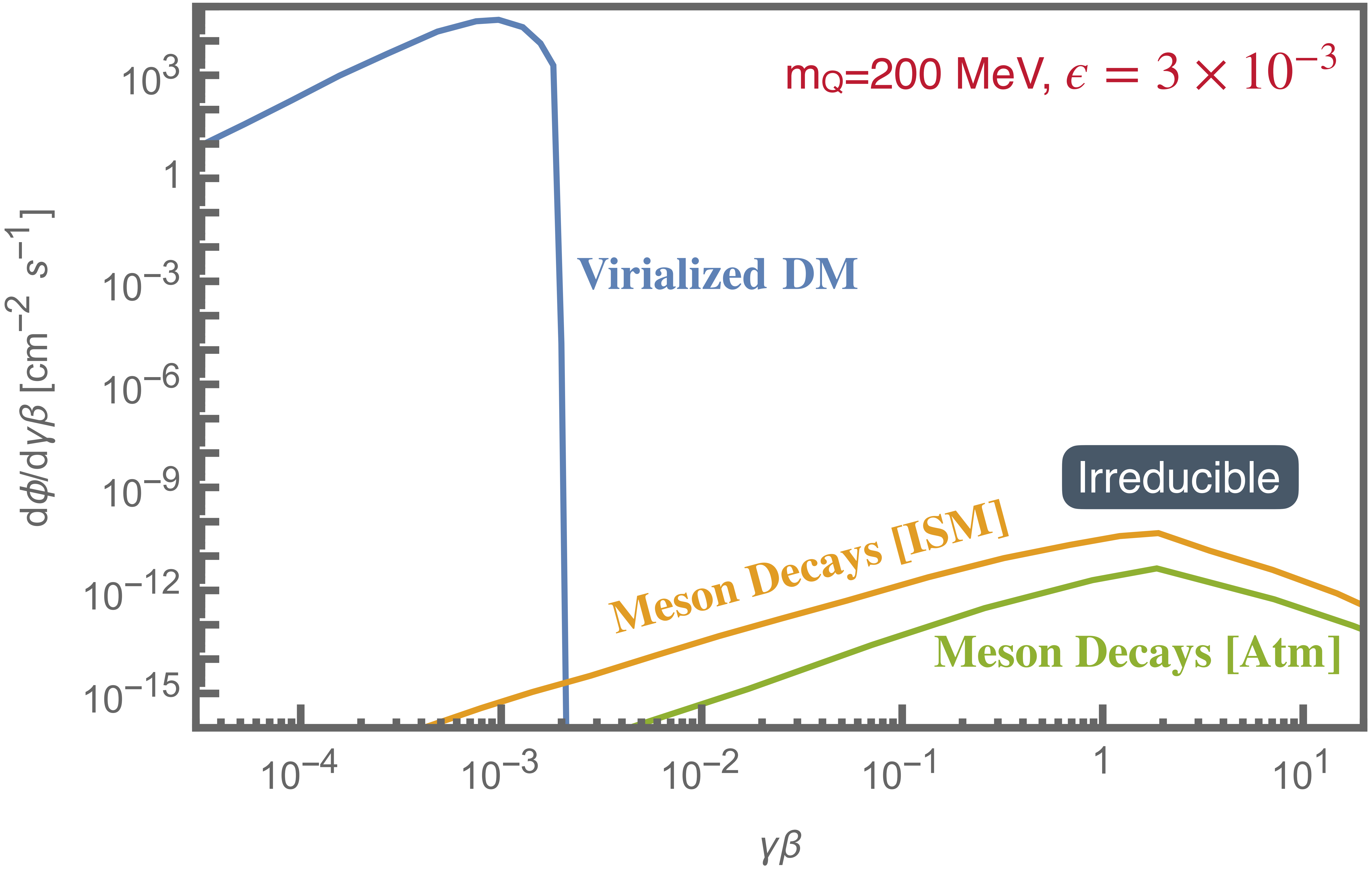


IRREDUCIBLE MCP POPULATION

2010.11190 HR, Roni Harnik, Ryan Plestid and Maxim Pospelov

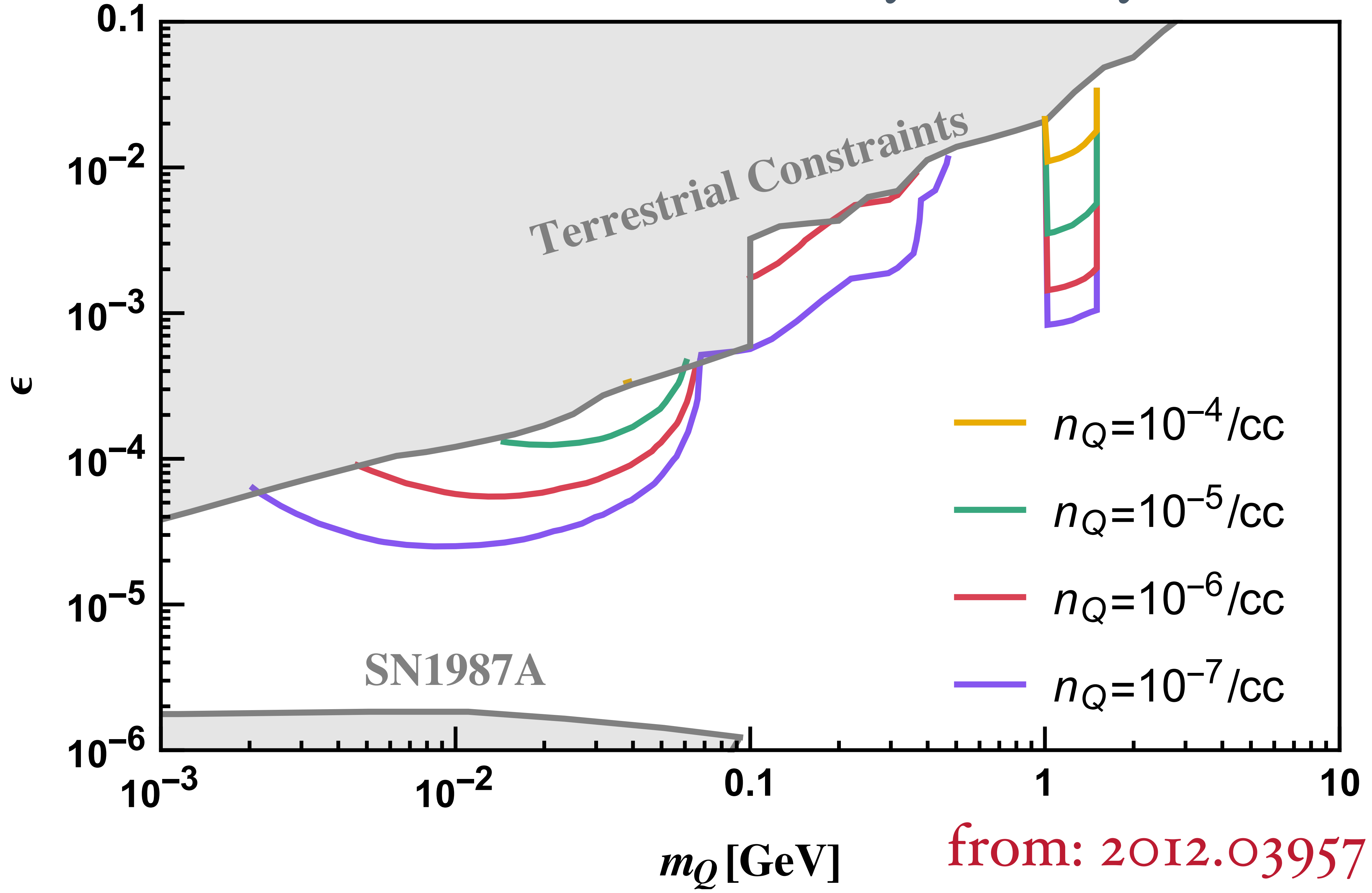
- Mesons produced in Cosmic ray collisions can decay into mCPs
- Contribution to irreducible density on Earth

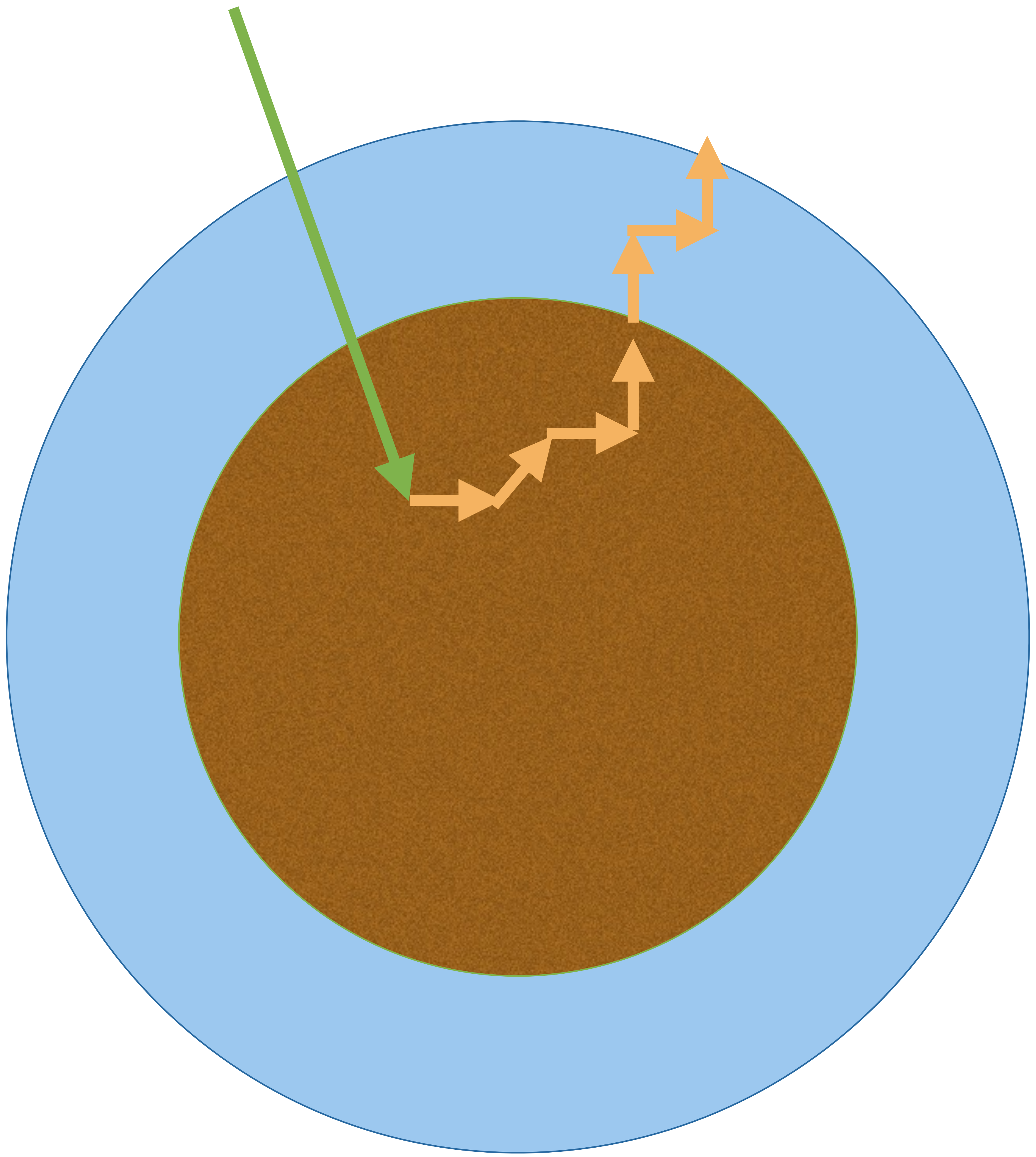




REVERSE TRAFFIC JAM

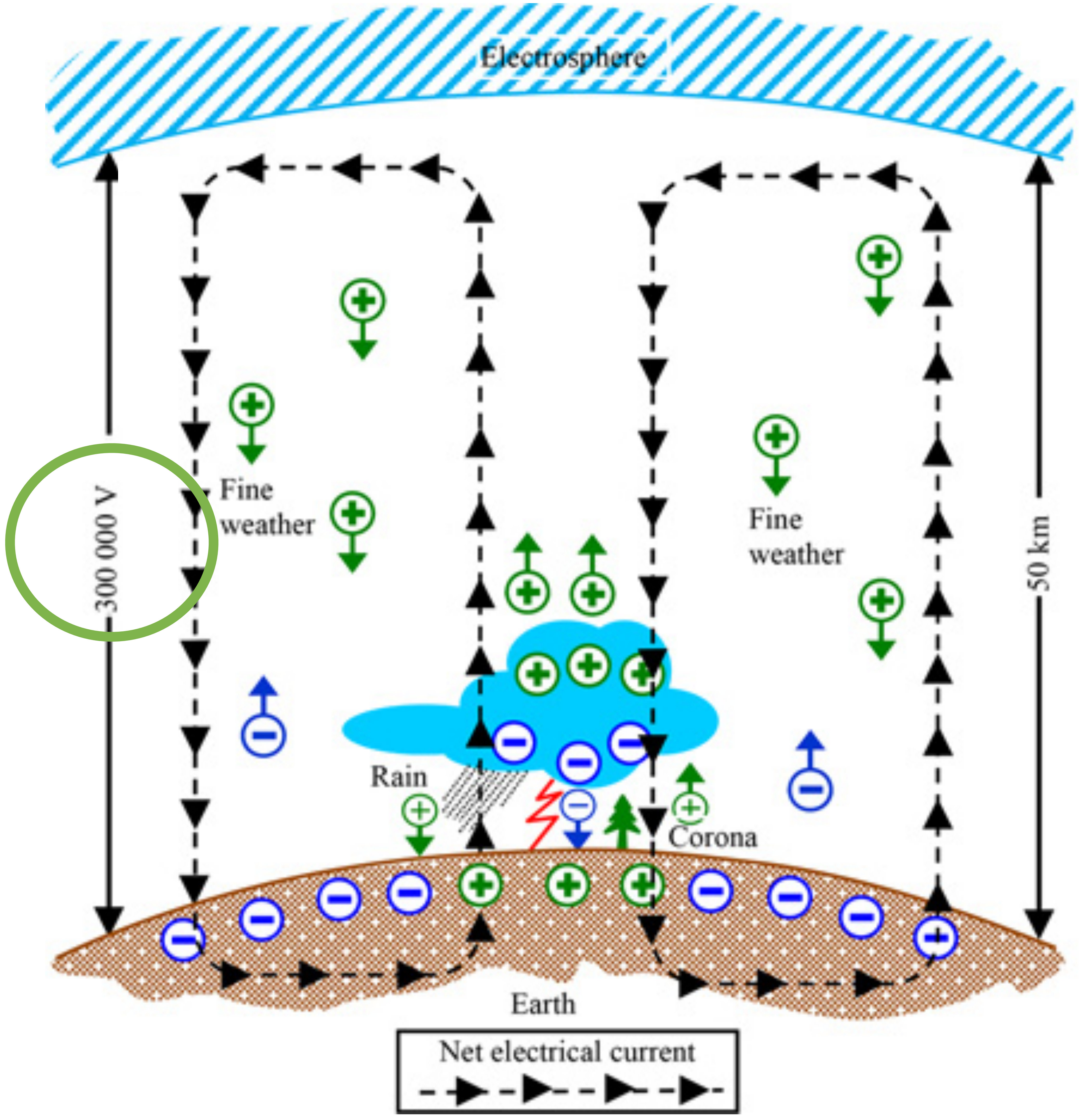
- High boost, hence penetrates deep
- Thermalized mCP, large x-section, (MFP~ micron)
- Evaporates for m_Q < GeV, but very slowly.





from: 2012.03957 HR M.Pospelov

EARTH E-FIELD

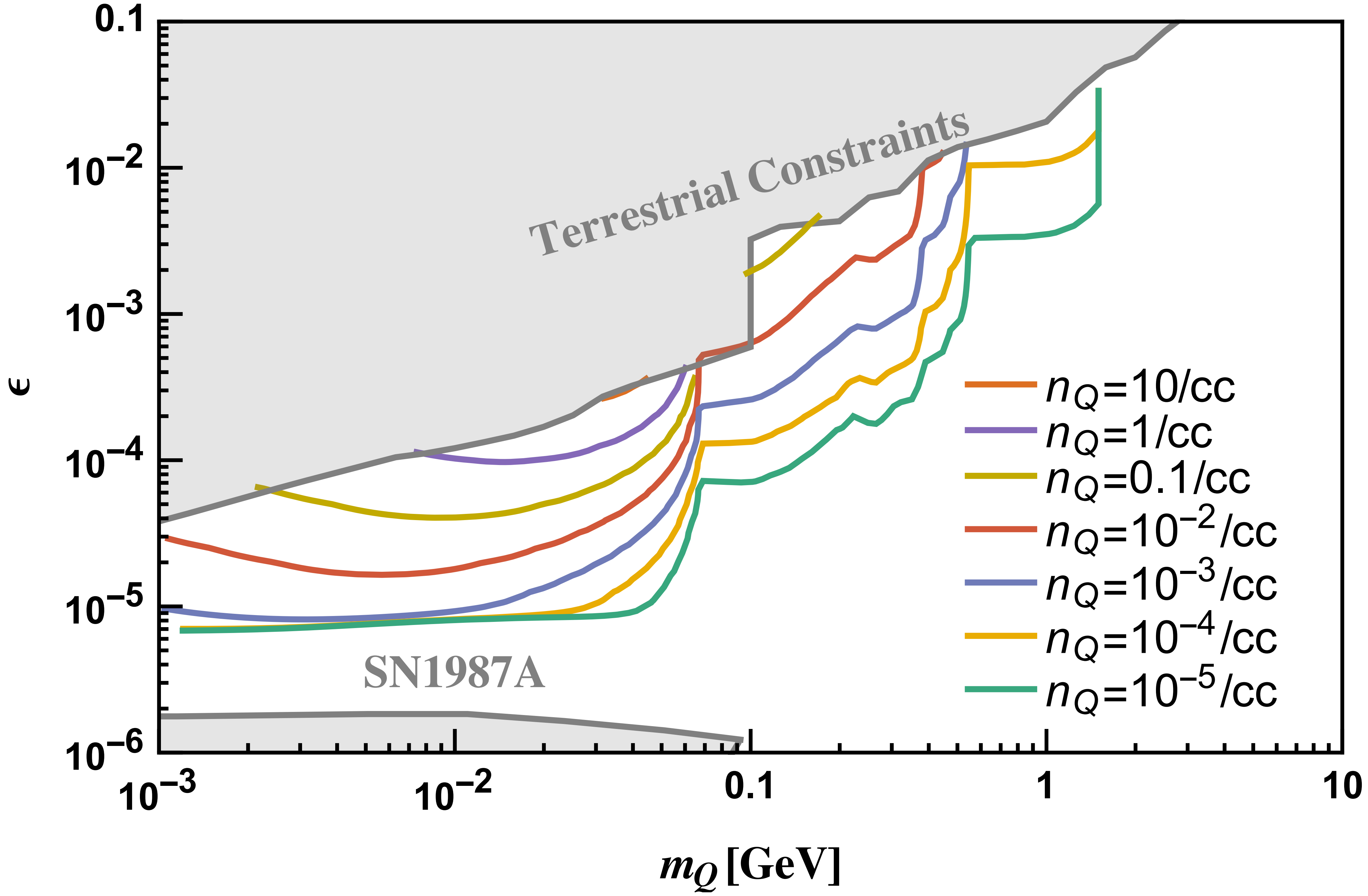


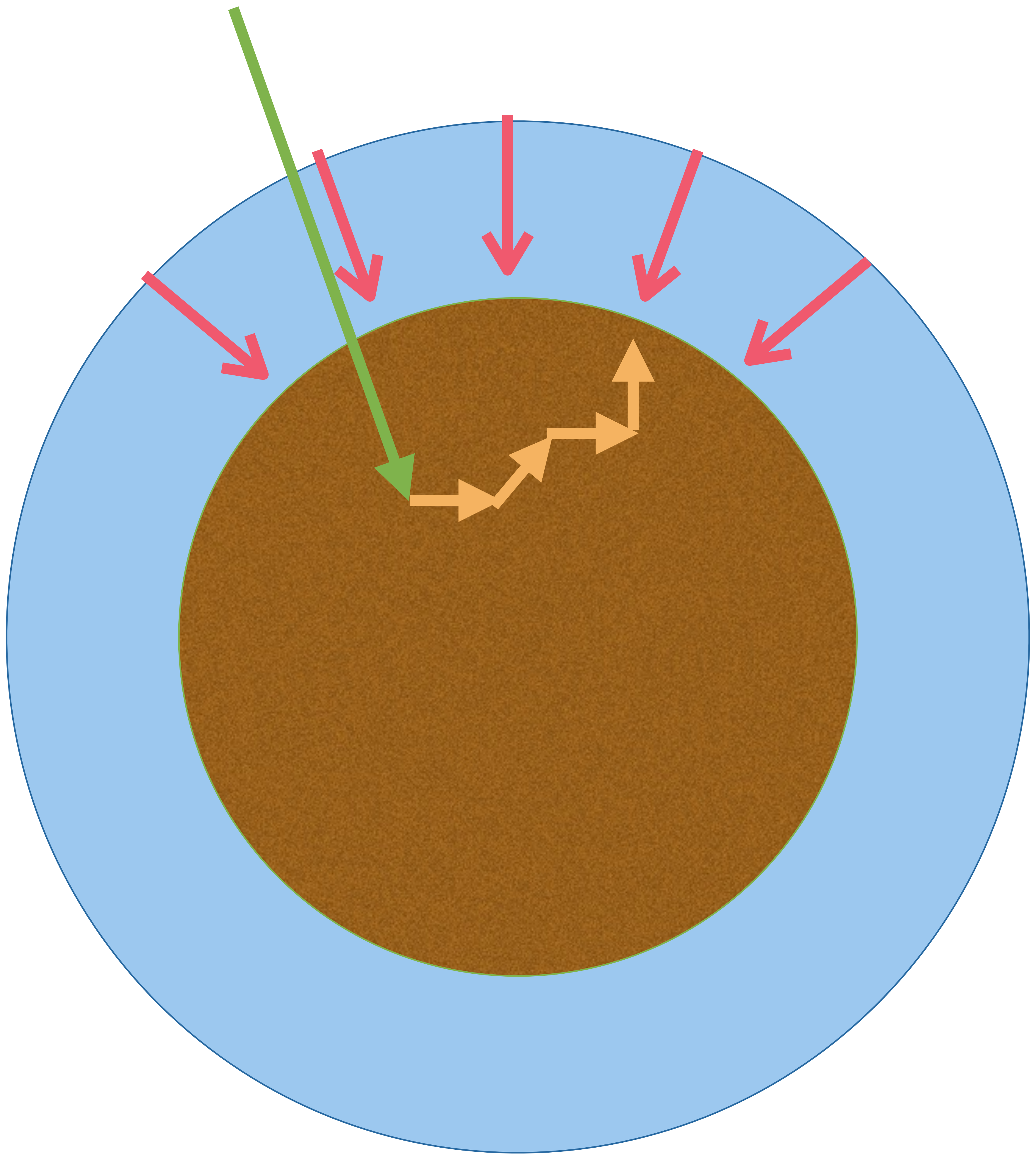
Electric Field ~ 100 V/meter

Lightning discharge
A Beroual and I Fofana

EFFECT OF EARTH E-FIELD

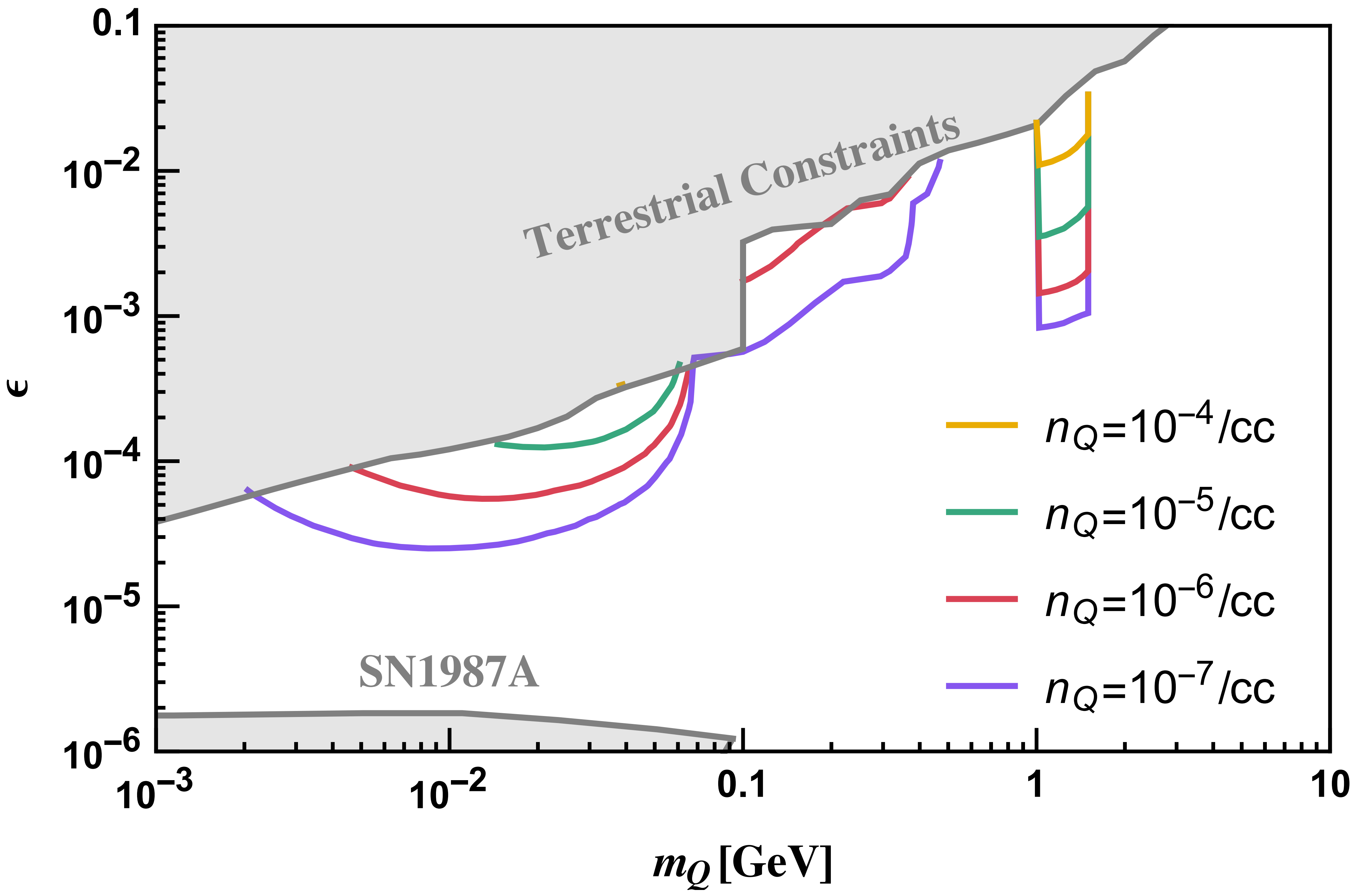
- If pure Milli-charge, it feels earth electric field
- Evaporation turned off for large positive mCP





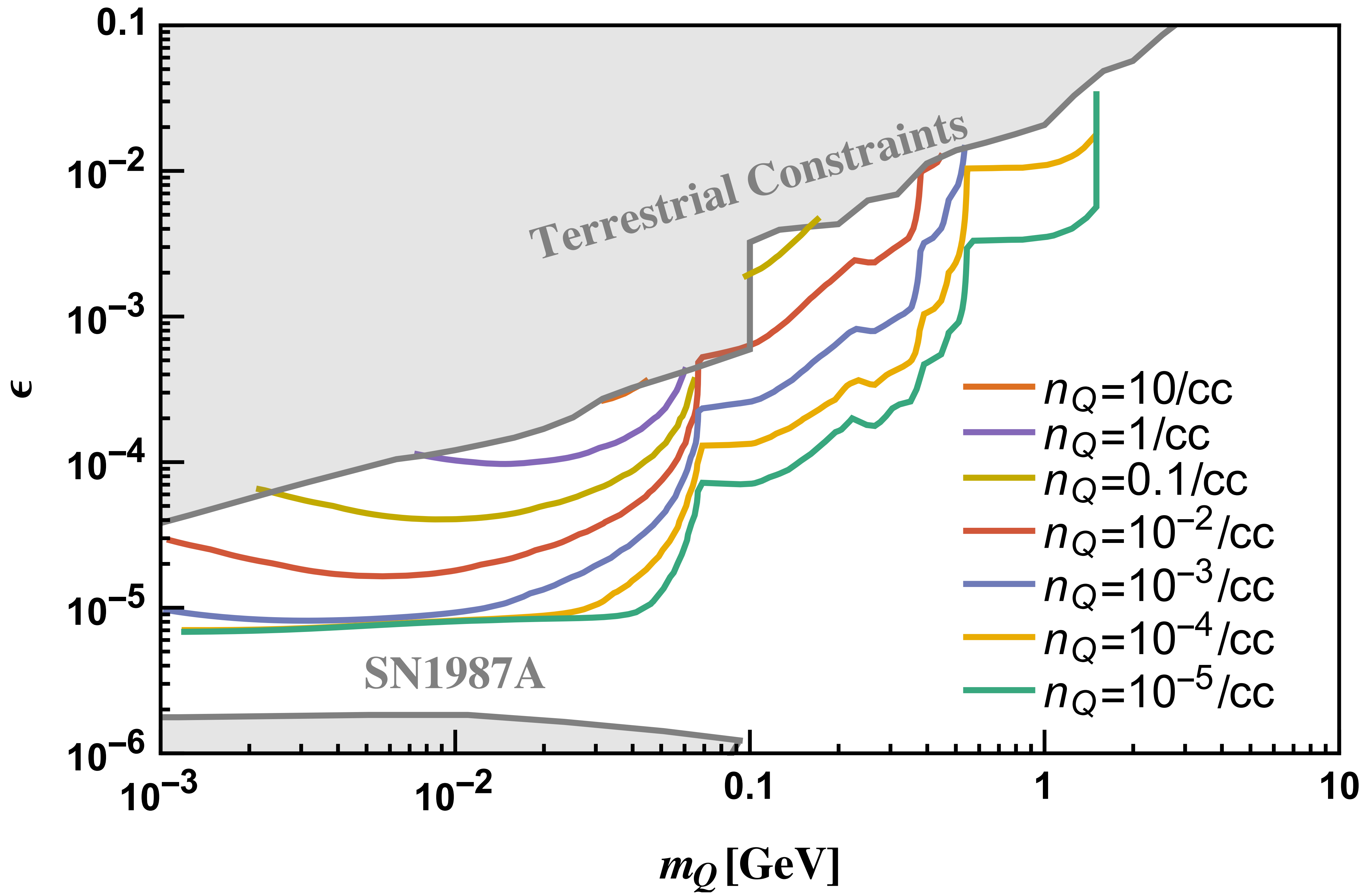
IRREDUCIBLE MCP POPULATION

With evaporation



Dark Photon MCP

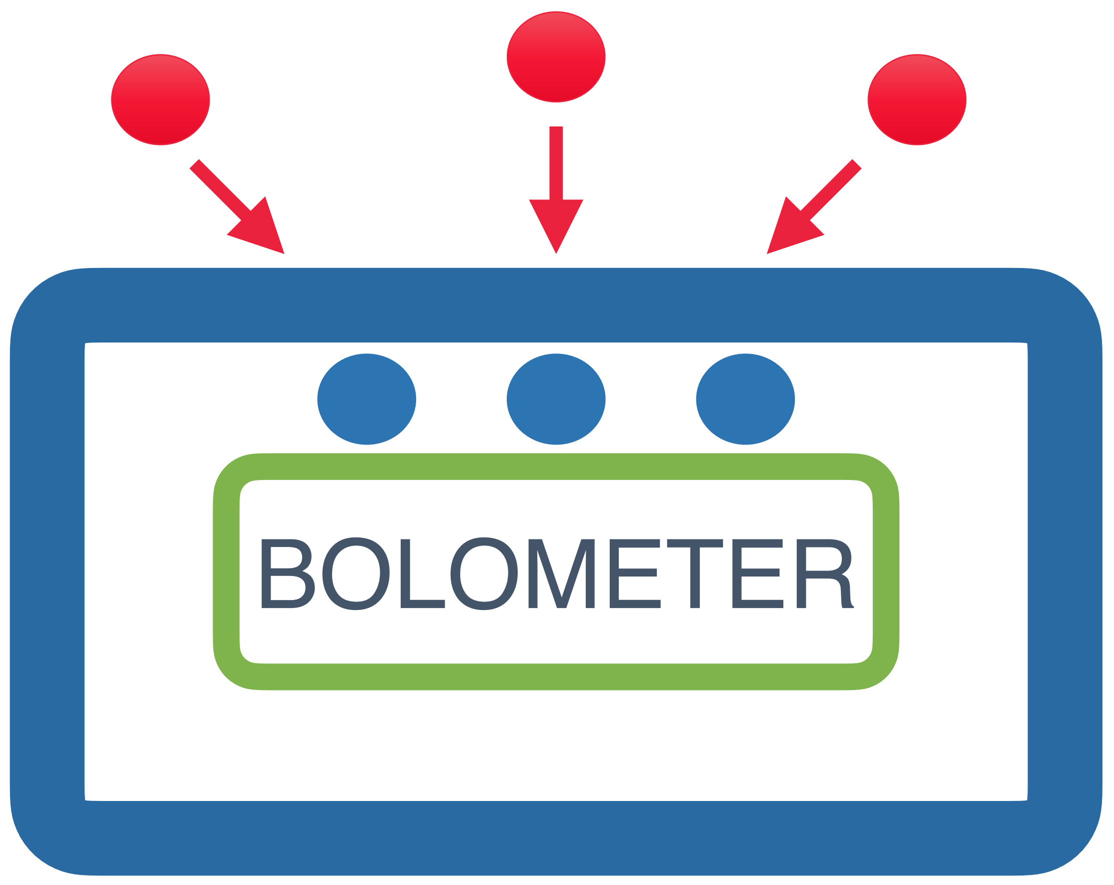
Without evaporation



Pure MCP

from: 2012.03957 HR M.Pospelov

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

EXISTING LIMITS

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

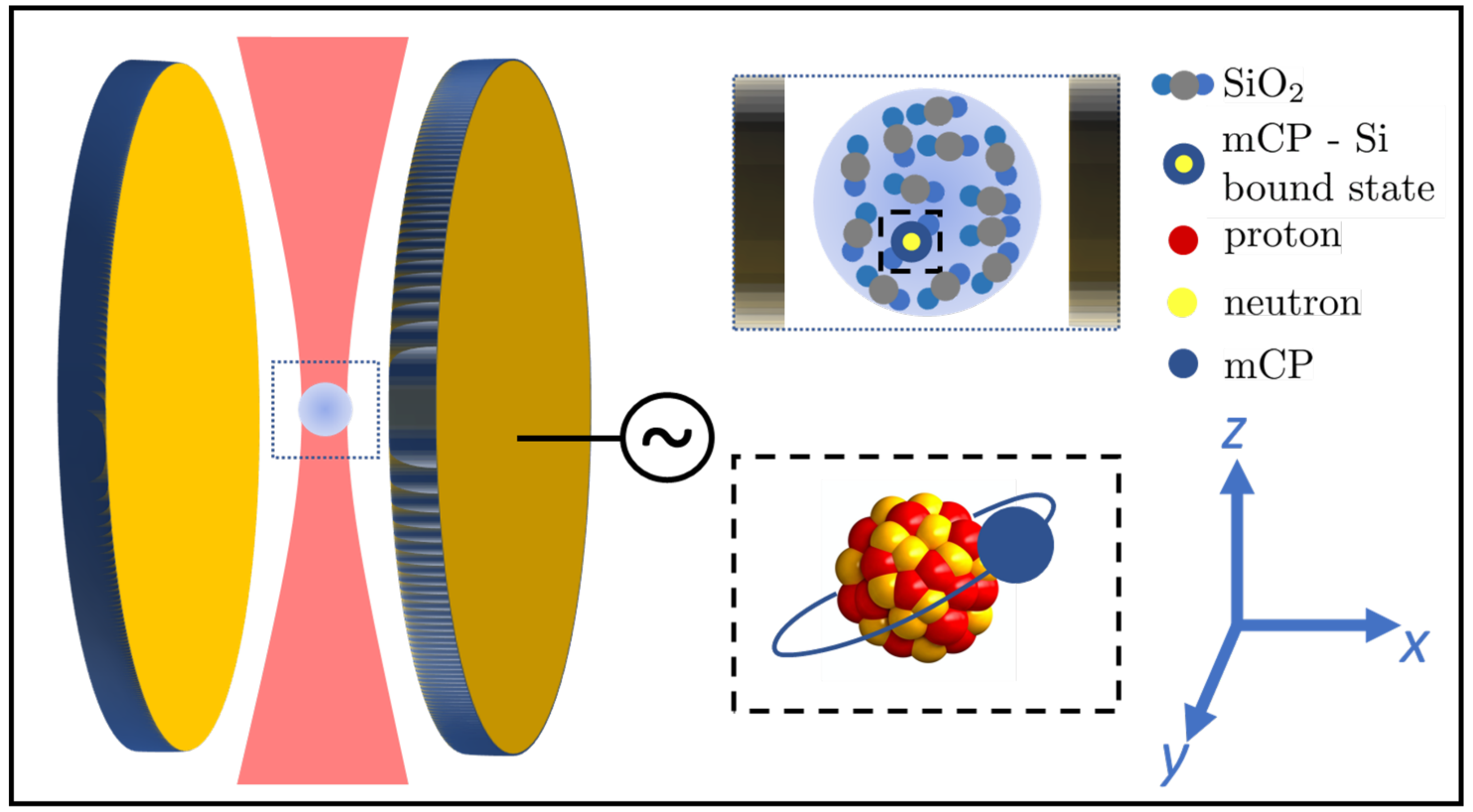
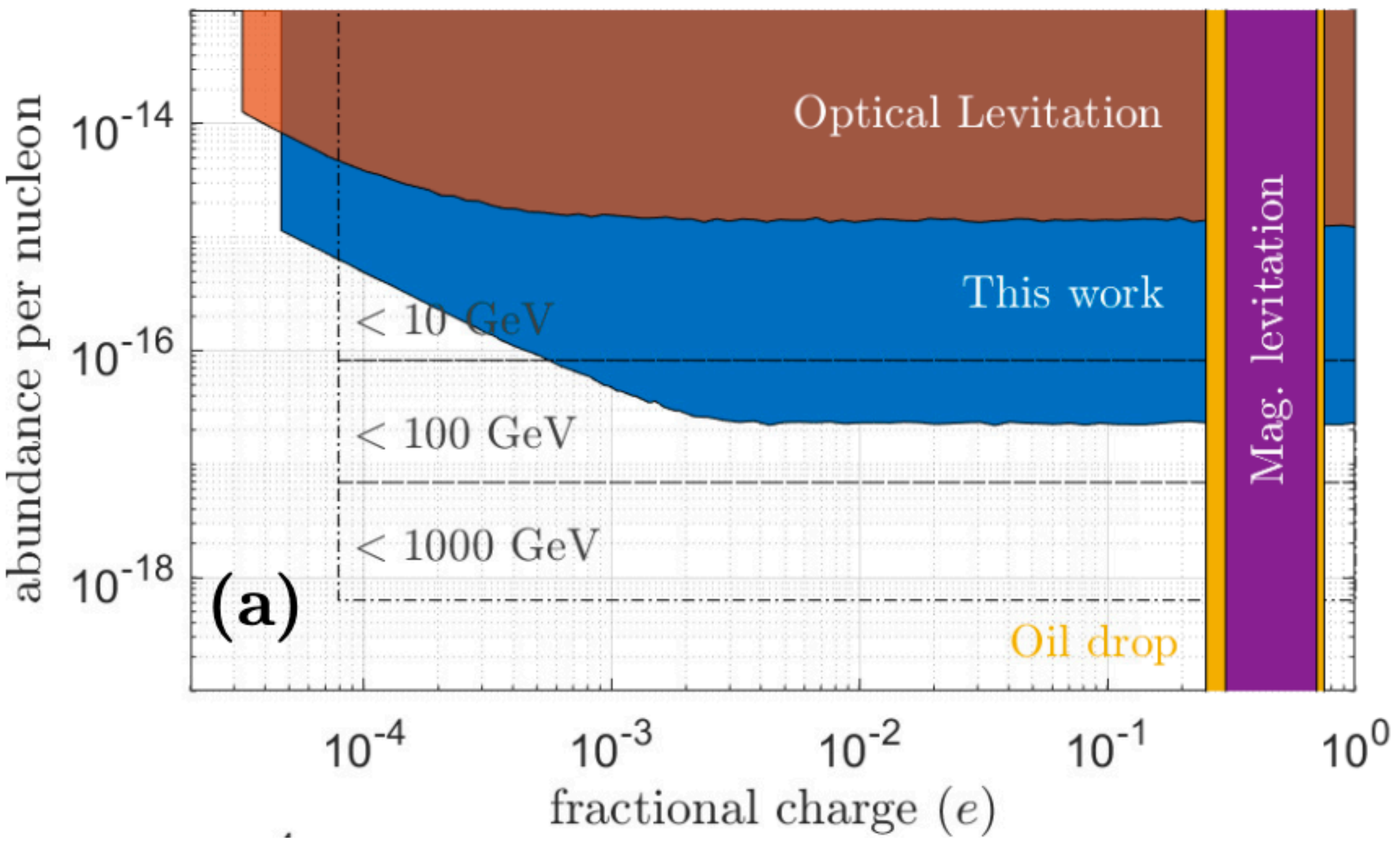
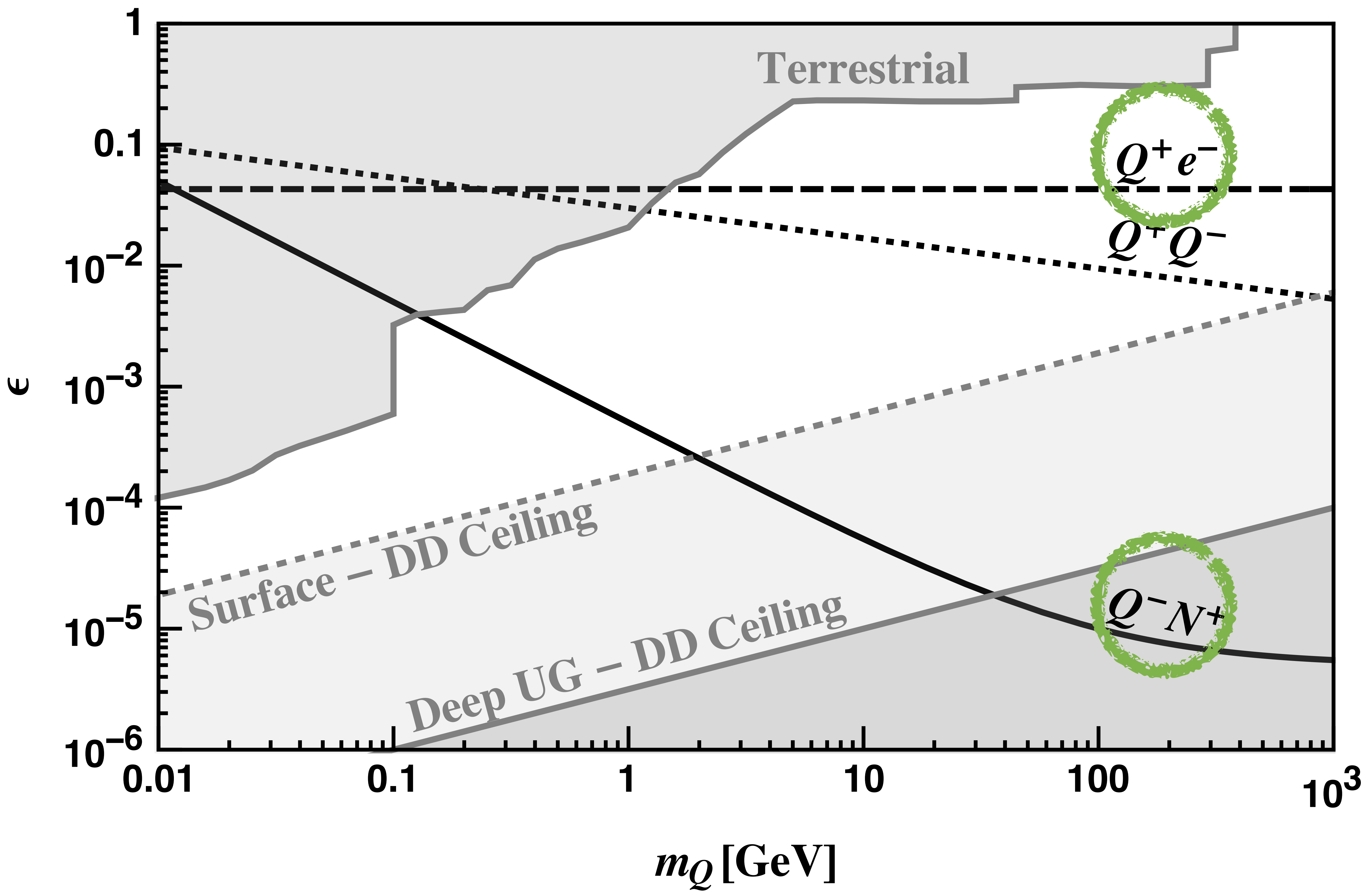


FIG. 1. SiO_2 spheres are levitated in high vacuum between a pair of parallel electrodes to search for a violation of charge neutrality by, *e.g.*, a mCP electrostatically bound to a Si or O nucleus in the sphere.



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

BOUND STATES



from: 2012.03957 HR, M.Pospelov

ENERGY THRESHOLD

Large Charge

Mass < MeV

DM Mass > MeV

WIMPs

0 eV

T_{room}=26 meV

< 1 eV

Few eV

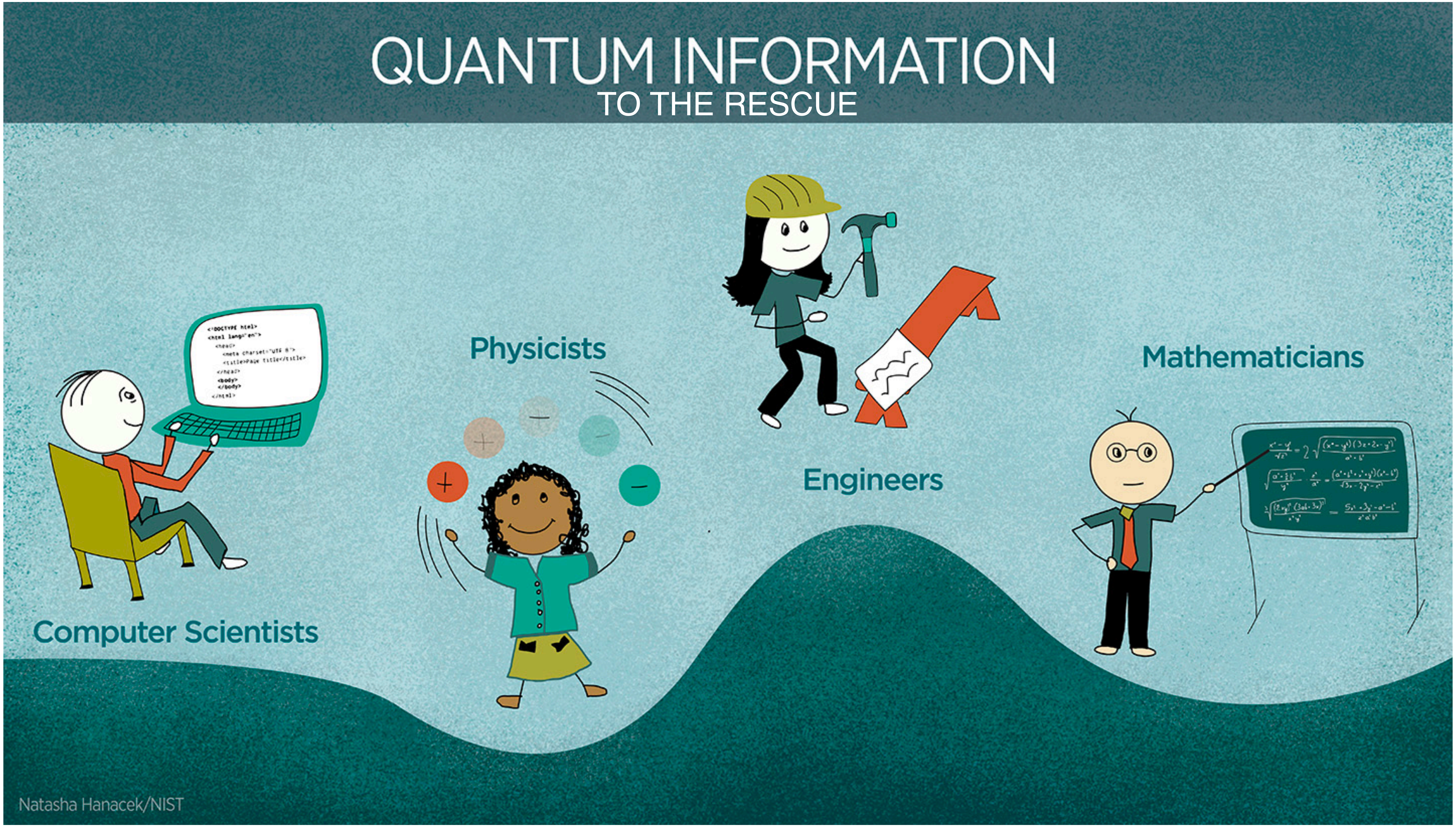
1 keV

Energy Threshold

Xenon e
Migdal
SENSEI
Super-CDMS

LZ
Xenon 1T n
Panda-X

TWIN CHALLENGES


QUANTUM INFORMATION
TO THE RESCUE
Physicists
Mathematicians
Engineers
Computer Scientists
Natasha Hanacek/NIST

QIS CHALLENGE

QUBITS

Two Level Systems

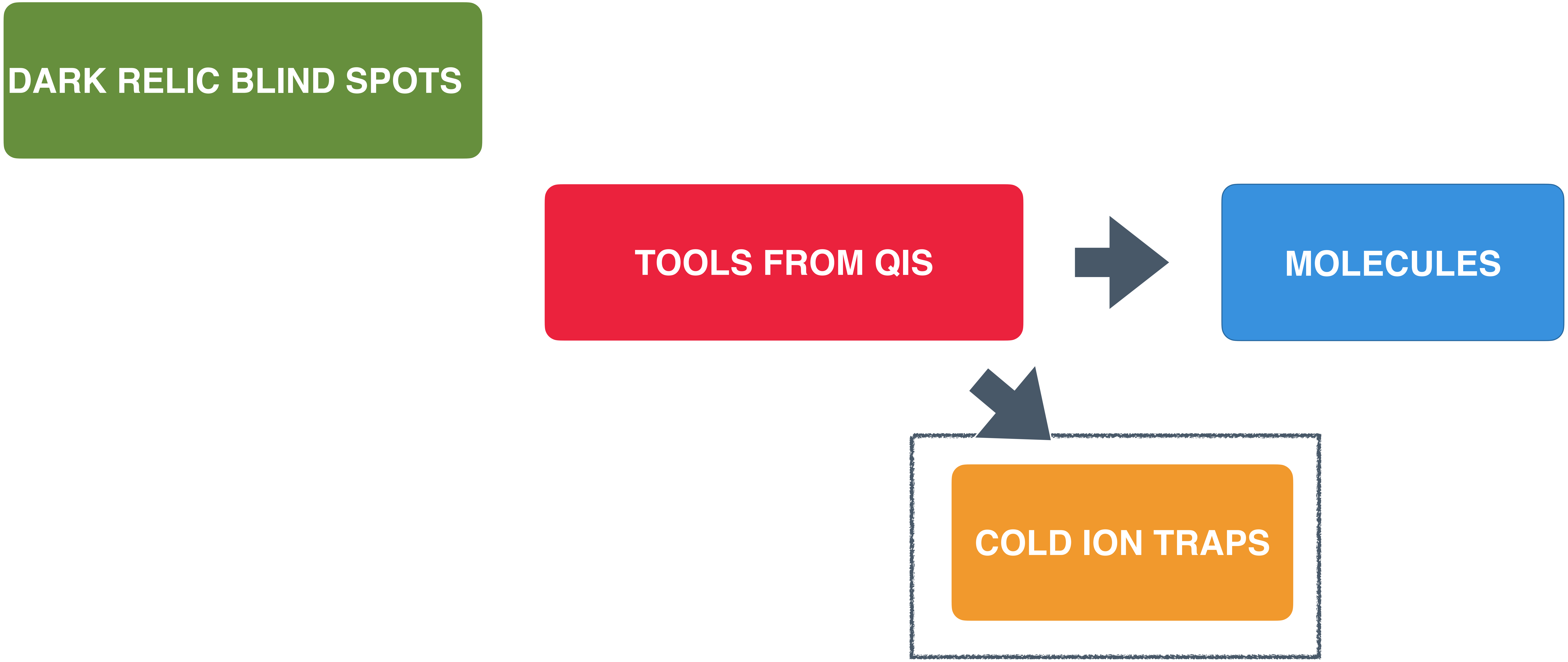
A. Ions
B. Molecules
C. Quantum Dots
D. Superconducting Qubit

READ-OUT

Image Current Detection
Lasers
Photon/Phonon Detectors

DD TARGET

DETECTOR



For Ambient Millicharge Population

Cryogenic silicon surface ion trap

Michael Niedermayr[1], Kirill Lakhmanskiy[1], Muir Kumph[1], Stefan Partel[2], Johannes Edlinger[2], Michael Brownnutt[1] and Rainer Blatt[1,3]

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[2]Forschungszentrum Mikrotechnik, FH Vorarlberg, Hochschulstr. 1, 6850 Dornbirn, Austria
[3]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstr. 21A, 6020 Innsbruck, Austria

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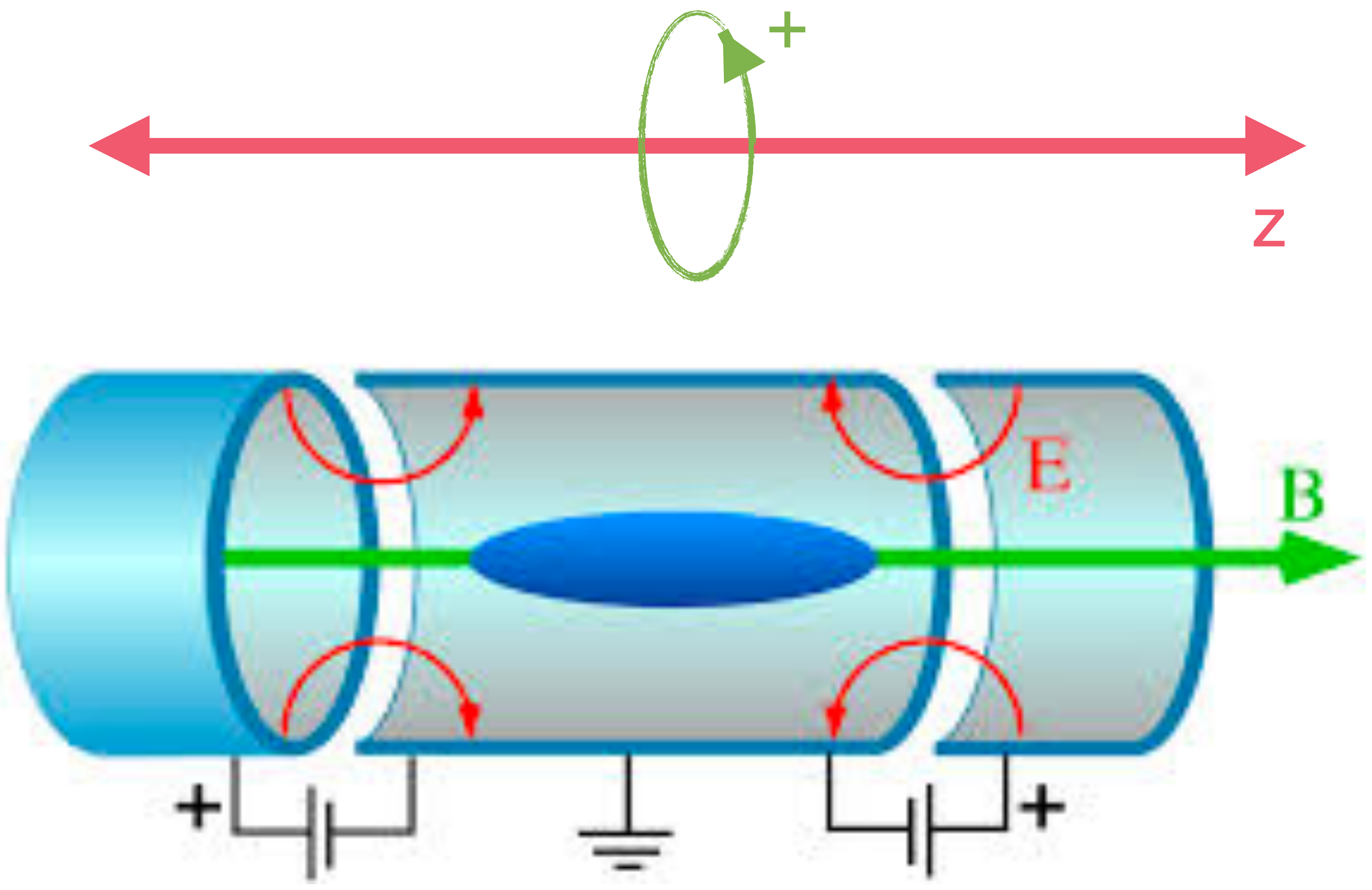
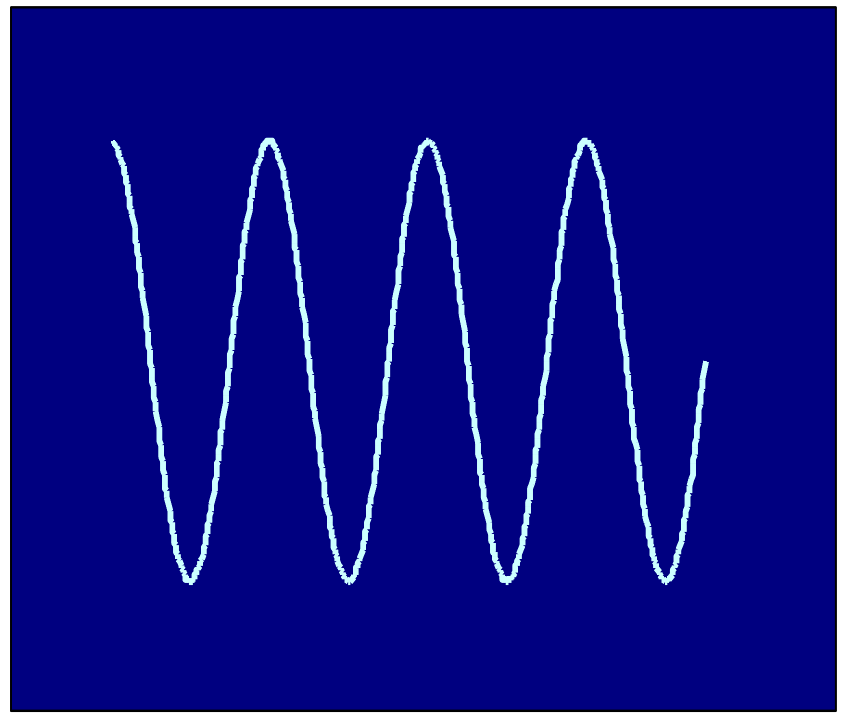
Abstract. Trapped ions are pre-eminent candidates for building quantum information processors and quantum simulators. They have been used to demonstrate quantum gates and algorithms, quantum error correction, and basic quantum simulations. However, to realise the full potential of such systems and make scalable trapped-ion quantum computing a reality, there exist a number of practical problems which must be solved. These include tackling the observed high ion-heating rates and creating scalable trap structures which can be simply and reliably produced. Here, we report on cryogenically operated silicon ion traps which can be rapidly and easily fabricated using standard semiconductor technologies. Single $^{40}Ca^{+}$ ions have been trapped and used to characterize the trap operation. Long ion lifetimes were observed with the traps exhibiting heating rates as low as $\dot{\bar{n}} = 0.33$ phonons/s at an ion-electrode distance of 230 μm. These results open many new avenues to arrays of micro-fabricated ion traps.

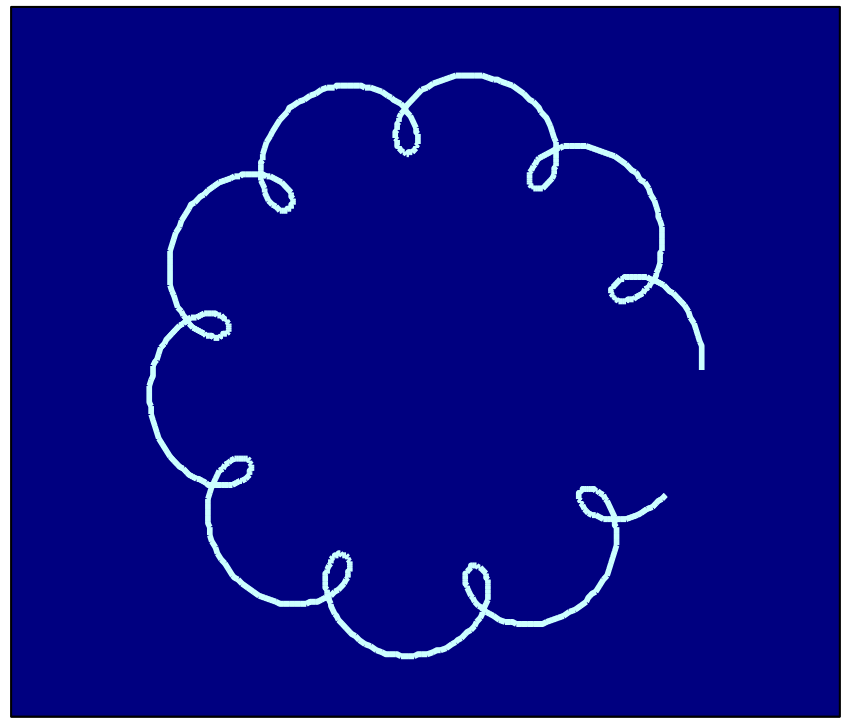
IONS IN COLD TRAPS



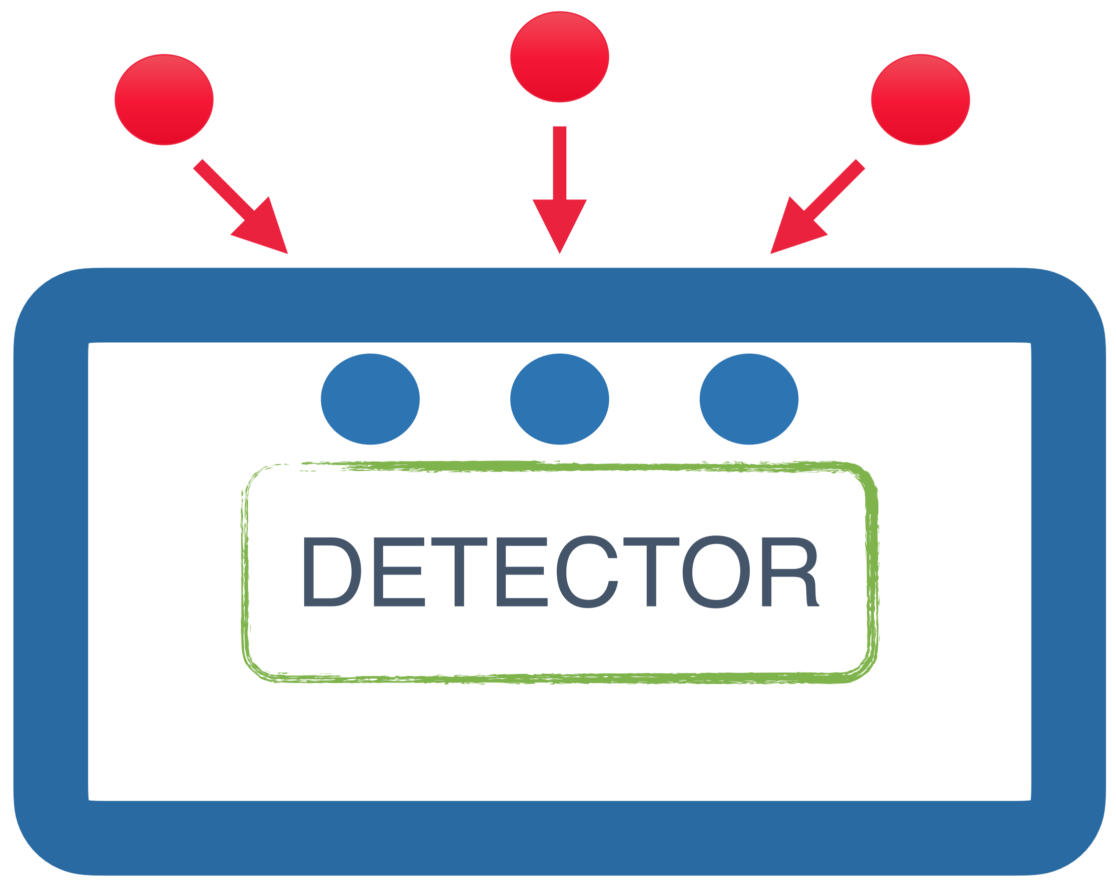
- Ions trapped for Quantum Computing
- Stable in trap for O(year)
- High vacuum to reduce background rate
- $T_{\text{wall}} \gg T_{\text{trap}}$



Axial motion



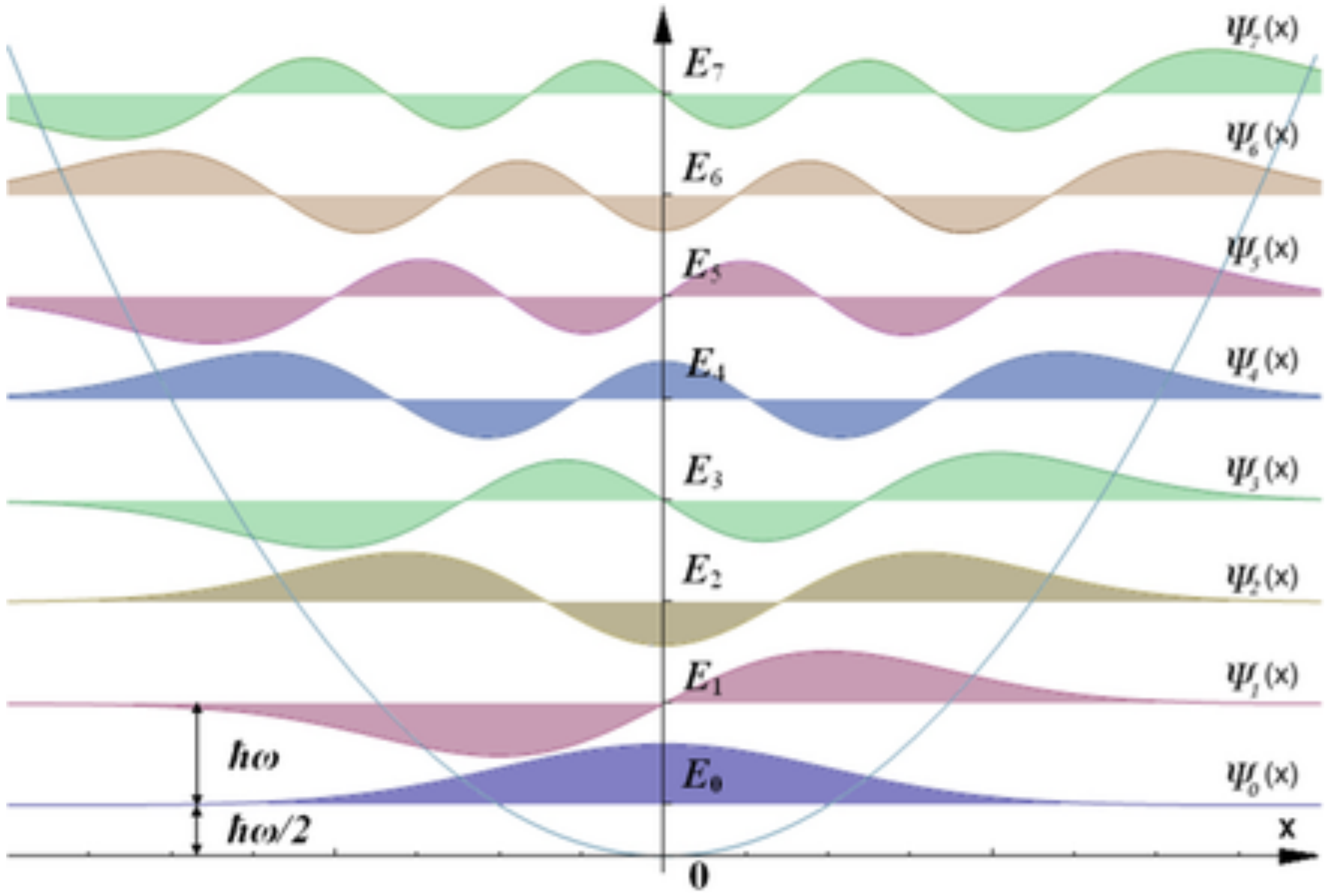
Radial motion

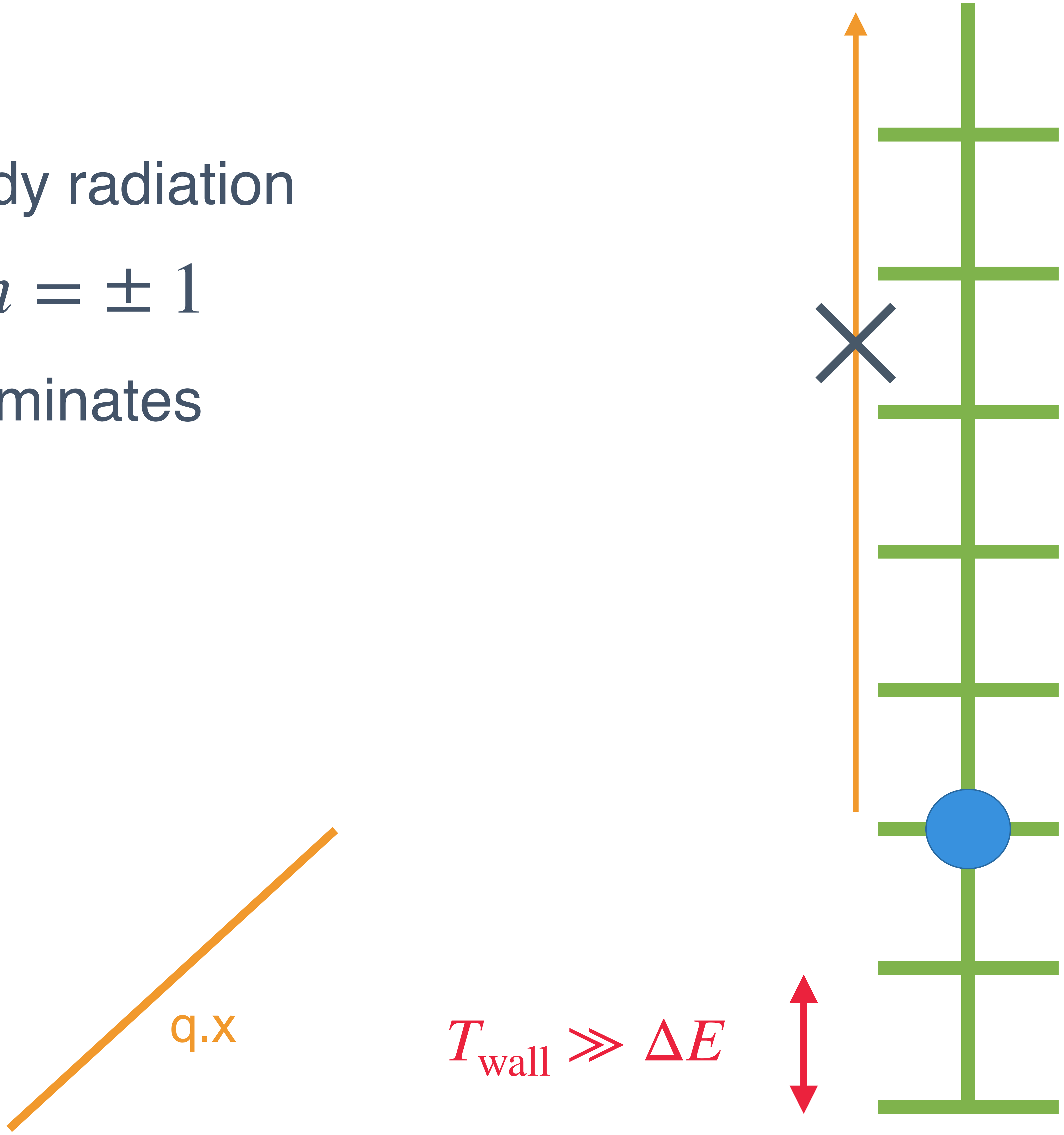



WALL @ 300 K
Negligible heat transfer
TRAP@50μK

SELECTION RULES

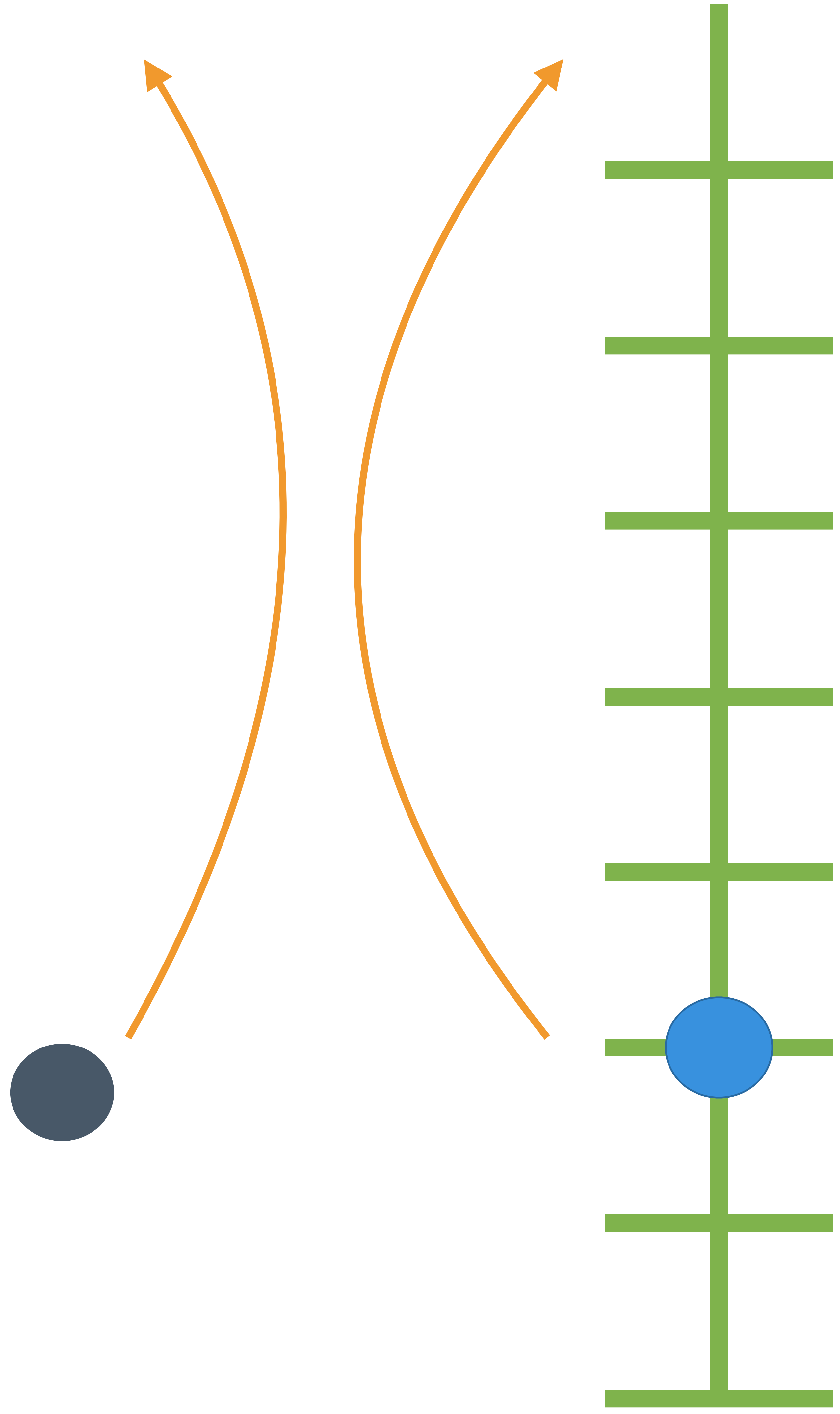
- Approximate Harmonic Oscillator
- Negligible background gas, only blackbody radiation
- Selection rules for photon absorption, $\Delta n = \pm 1$
- Electric Field noise from Penning trap dominates





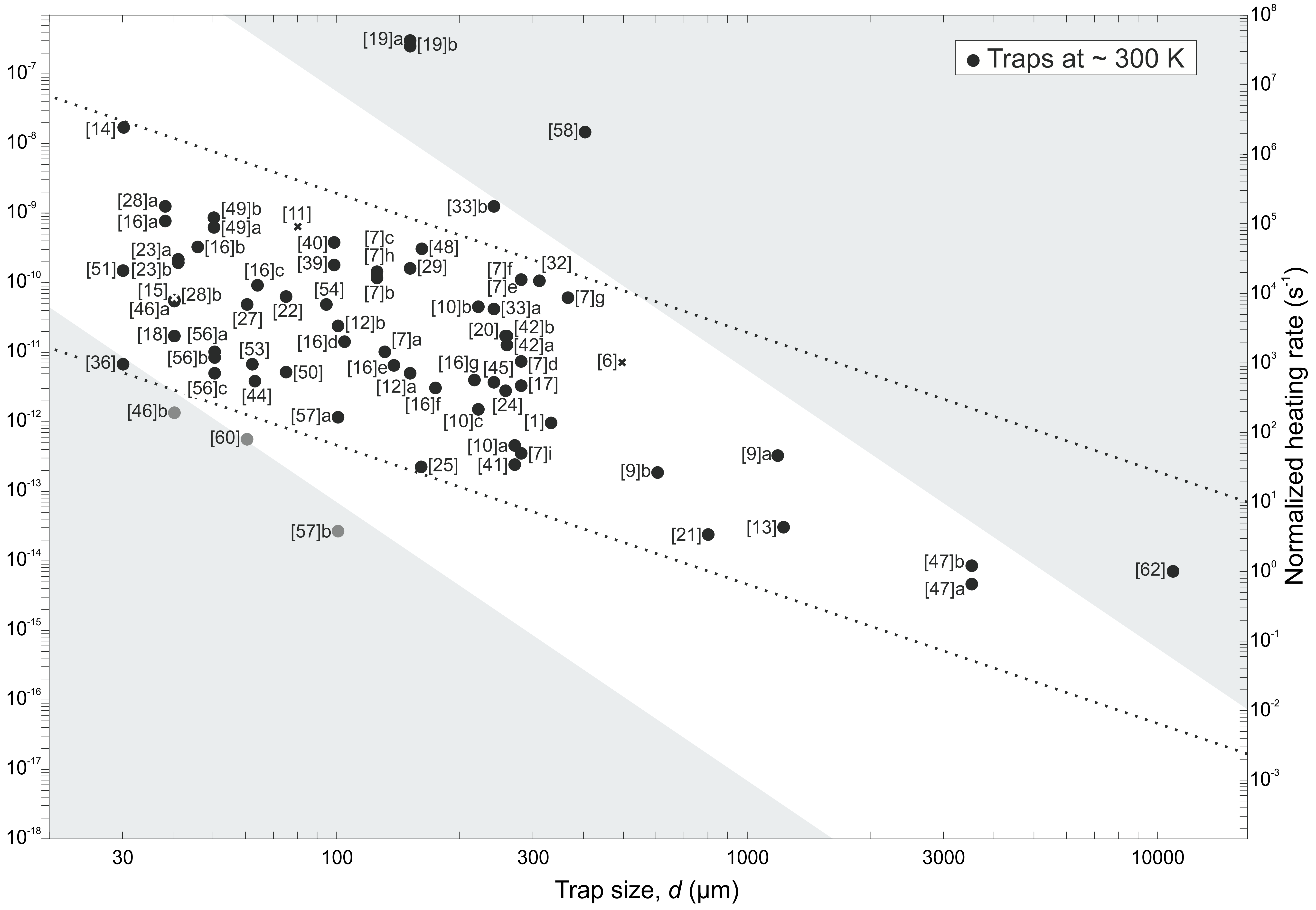
SELECTION RULES

- Scattering breaks selection rules
- Momentum transfer ≫ Energy Transfer



DATA

- ✦ ^{40}Ca ions used
- ✦ $\nu_+, \nu_-, \nu_z \approx$ MHz $\approx$ **4neV** $\approx 50\mu$K
- ✦ Sensitive to single quantum jumps in "+"
- ✦ $\dfrac{dn_+}{dt} \approx \dfrac{1}{\text{sec}}$
- ✦ Heating Rate: $10^{-9}\dfrac{\text{eV}}{\text{sec}}$



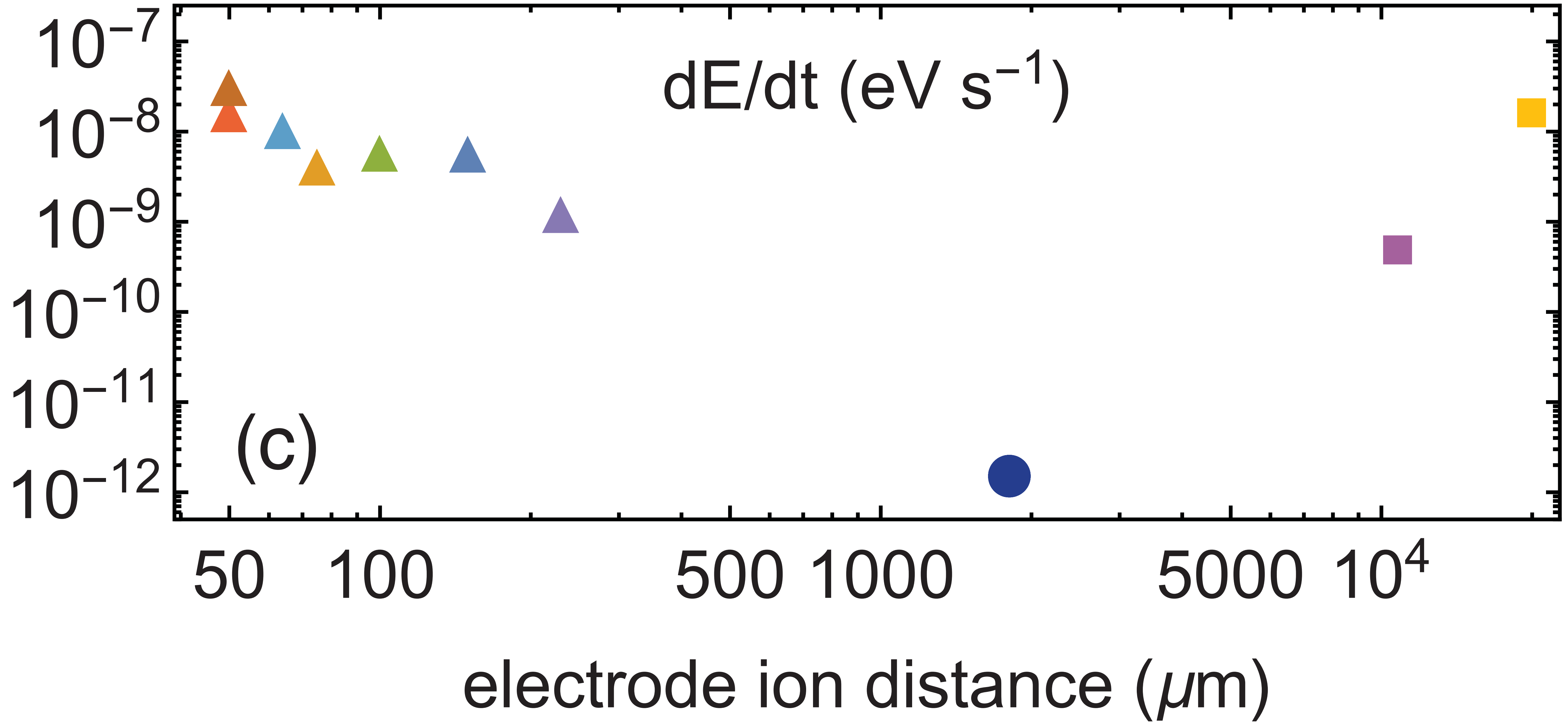
1409.6572 M. Brownnutt, M. Kumph, P. Rabl & R. Blatt

DATA

- Anti-protons: BASE experiment, CERN
- $\frac{dn_+}{dt} \approx \frac{0.1}{\text{hour}}$
- Lowest measured: $\Delta\omega_+ = 10^{-12}\ \text{eVs}^{-1}$

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]

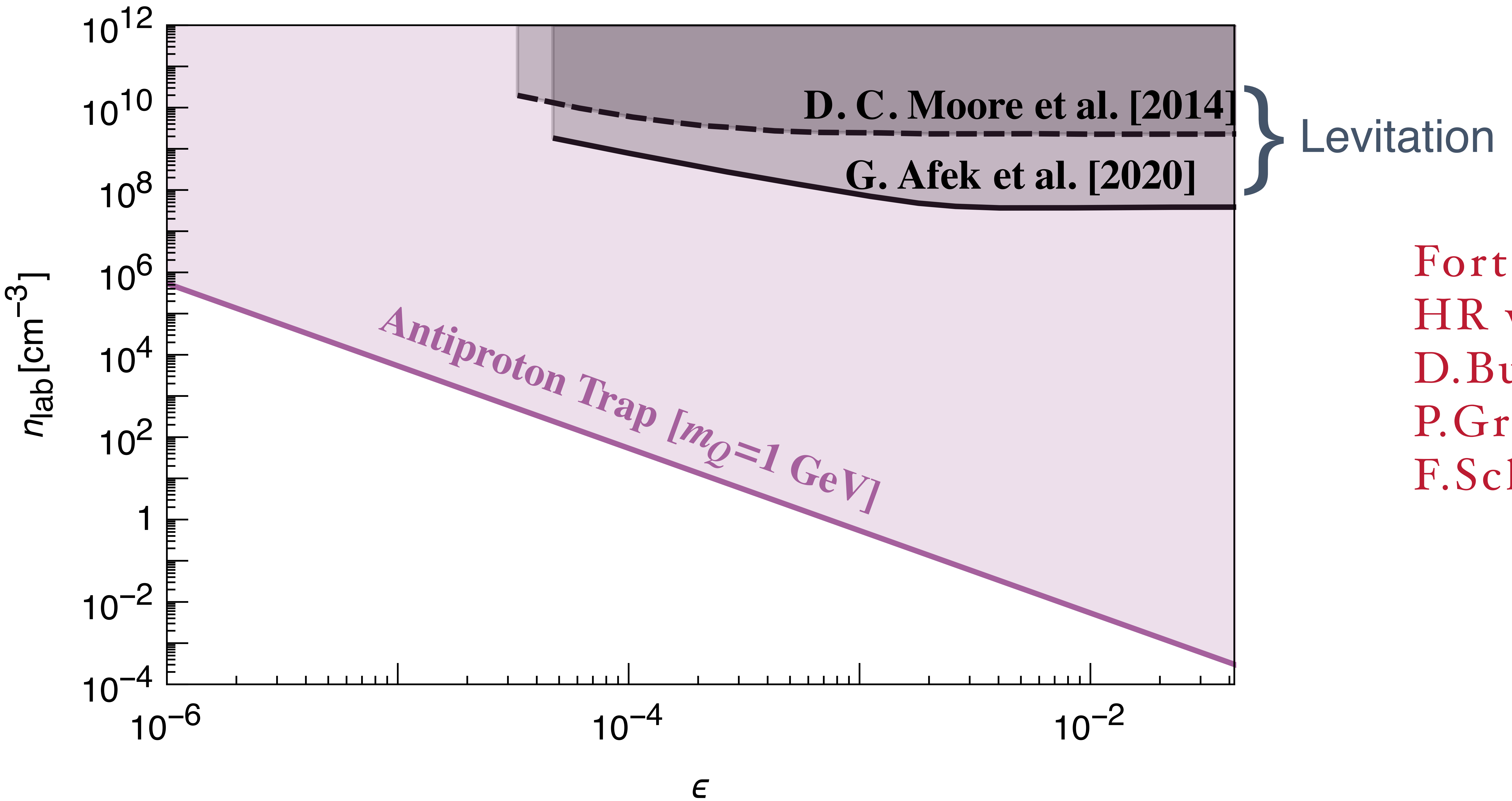


CAPABILITIES

- 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

TERRESTRIAL POPULATION CONSTRAINTS

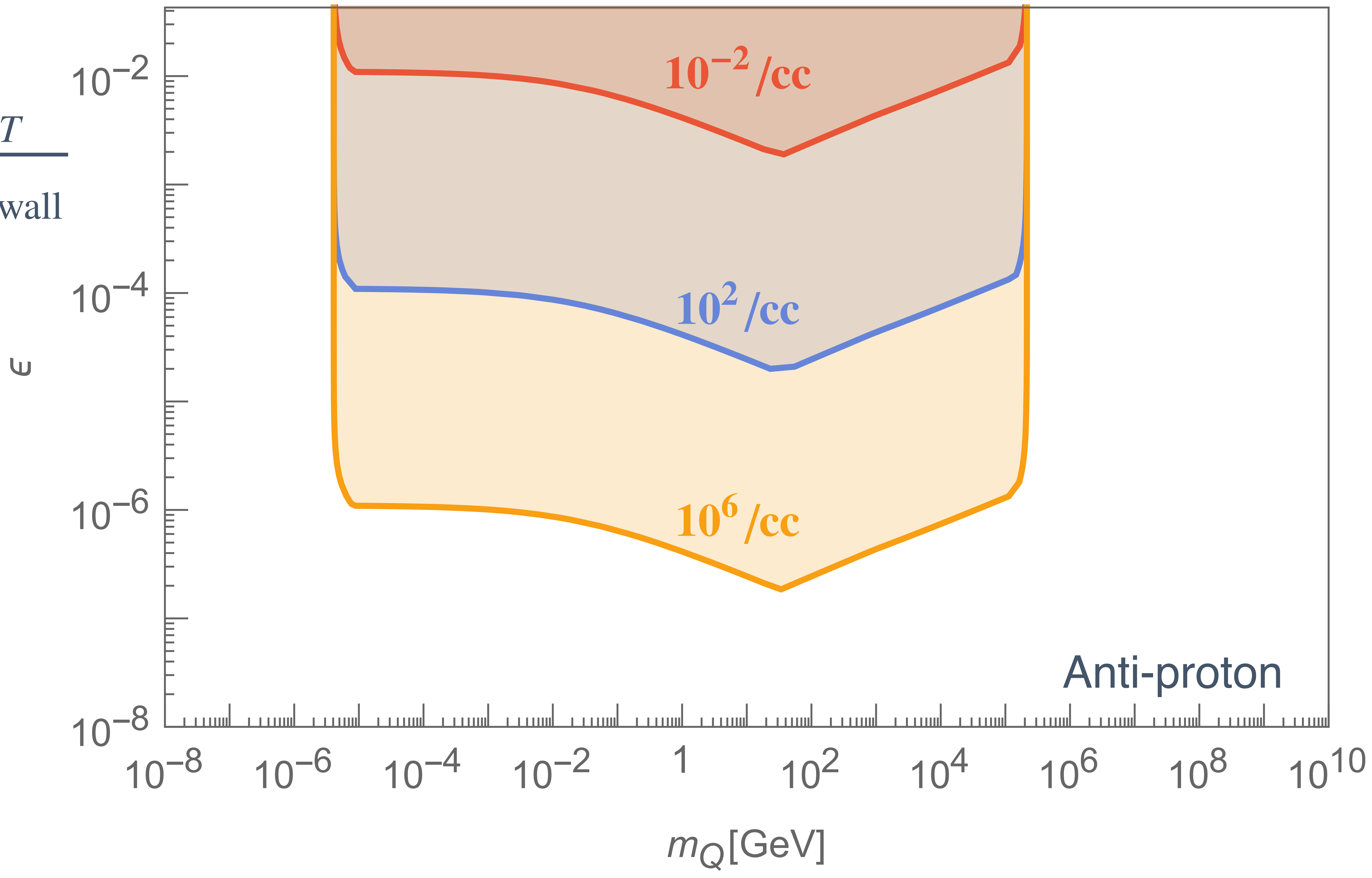
$$\frac{dE_{\rm dep}}{dt} = \int E_{\rm dep}(q^2)\frac{4\pi\alpha^2\epsilon^2}{v^2q^4}dq^2 \quad \approx 10^{-6}\frac{\rm eV}{\rm sec}\epsilon^2\frac{n_{\rm lab}}{1/{\rm cm}^3}\frac{\rm GeV}{m_{\rm ion}}\ldots > 10^{-12}\frac{\rm eV}{\rm sec}$$



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

TERRESTRIAL POPULATION CONSTRAINTS

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

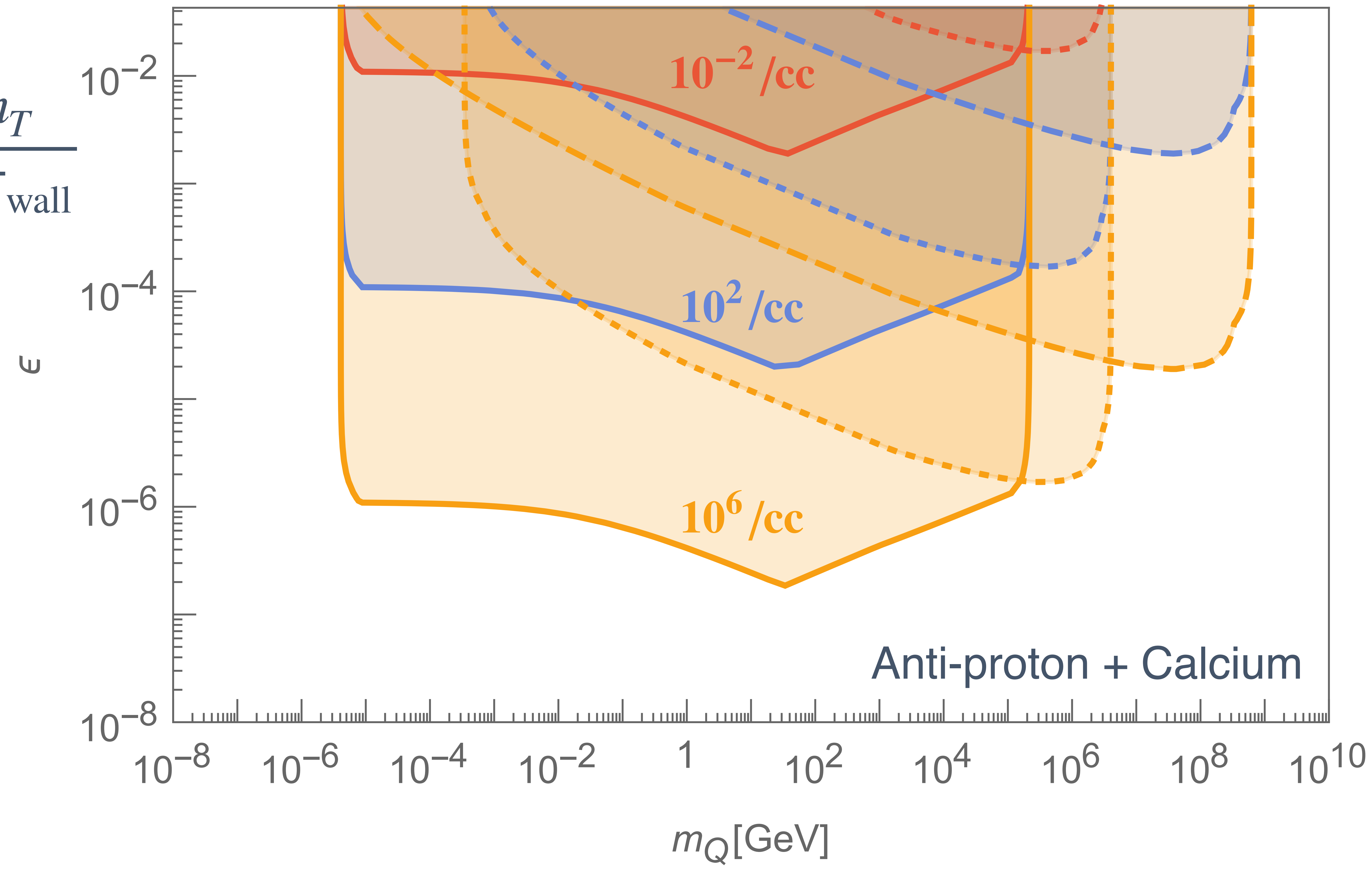


$$m_Q^{max} = \frac{16 m_T T_{trap} T_{wall}}{E_{min}^2}$$

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

TERRESTRIAL POPULATION CONSTRAINTS

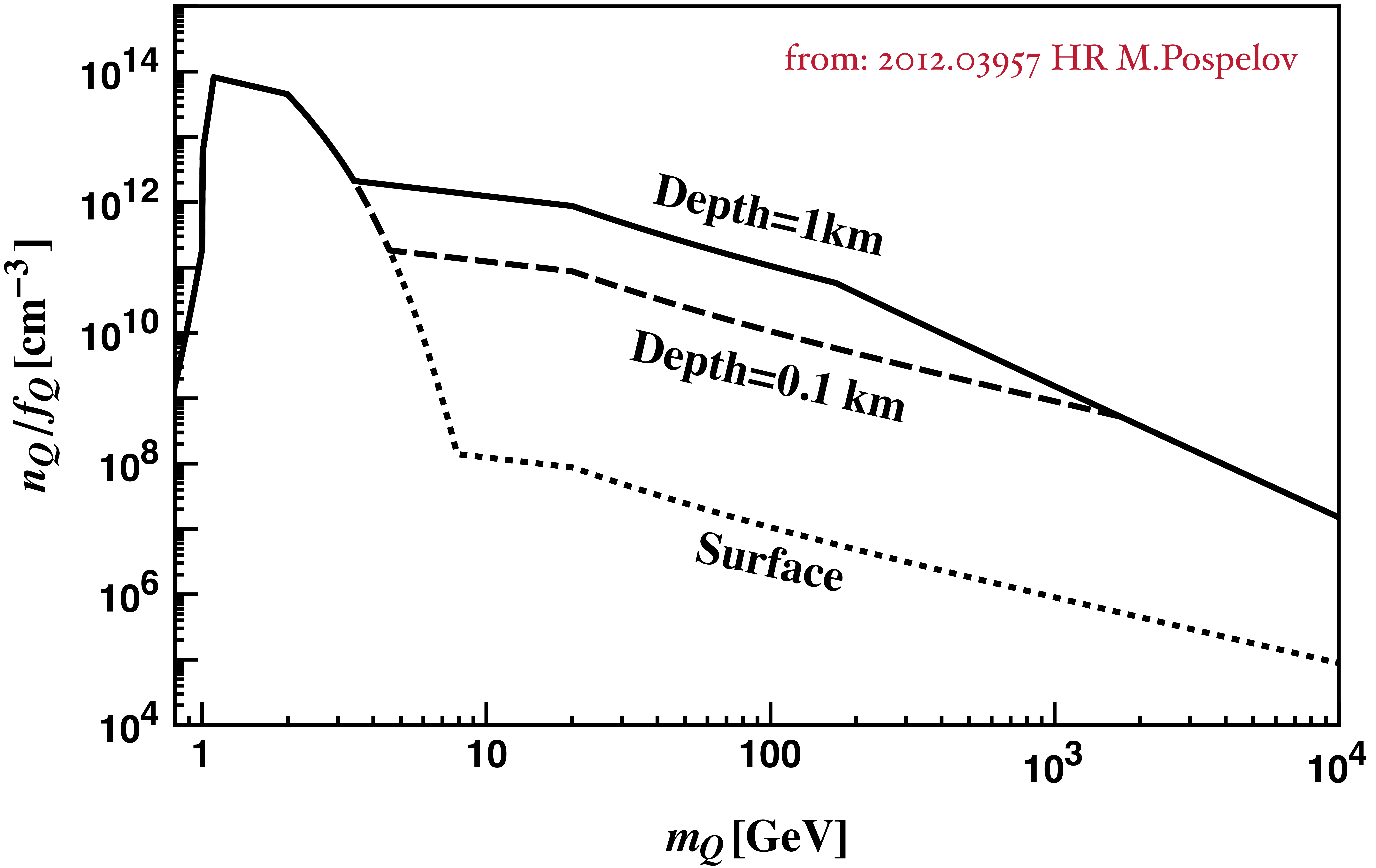
$$m_Q^{\min} = \frac{E_{\min}^2 m_T}{16 T_{\text{trap}} T_{\text{wall}}}$$



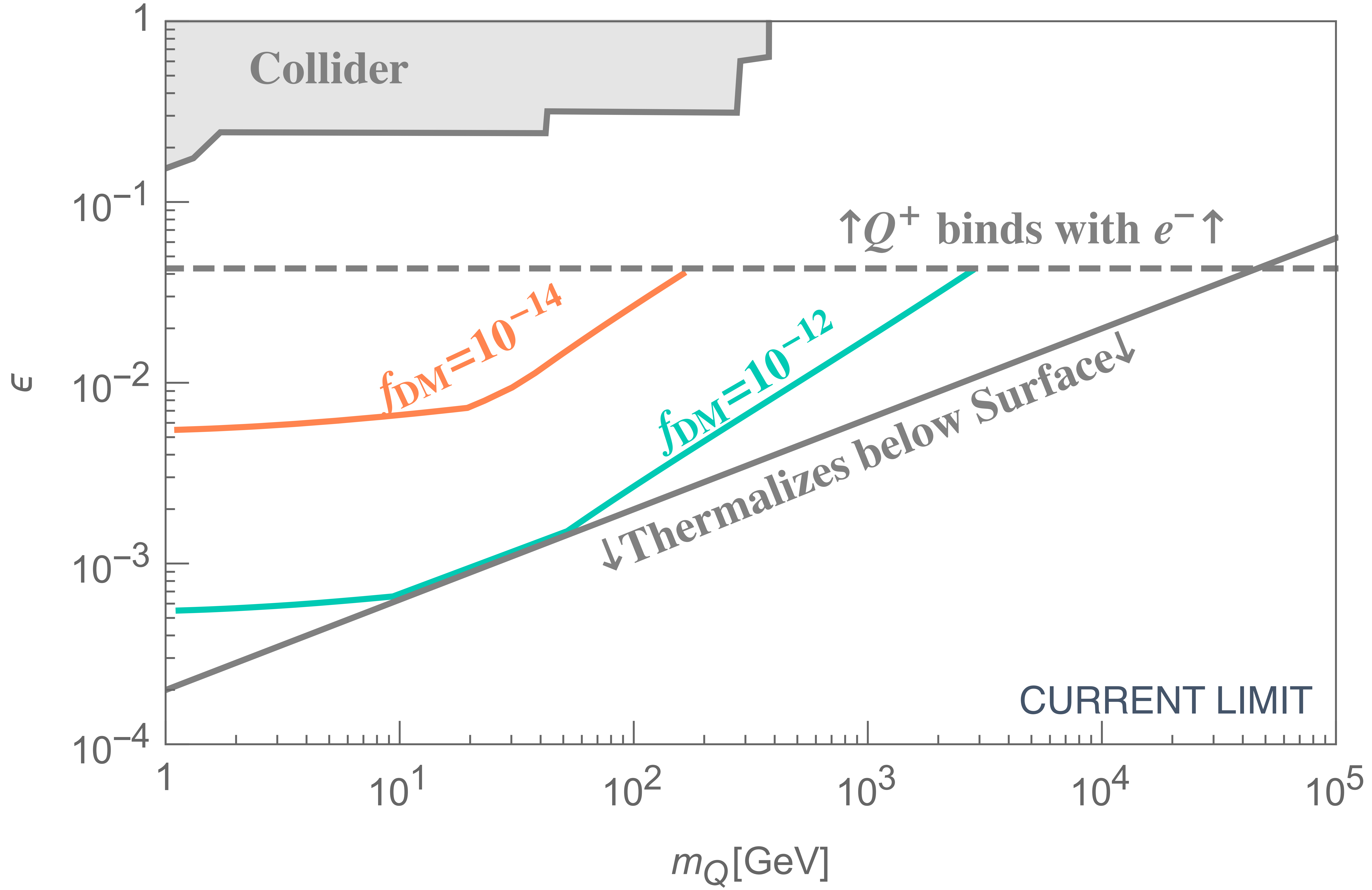
$$m_Q^{\max} = \frac{16 m_T T_{\text{trap}} T_{\text{wall}}}{E_{\min}^2}$$

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

TRAFFIC JAM DENSITY

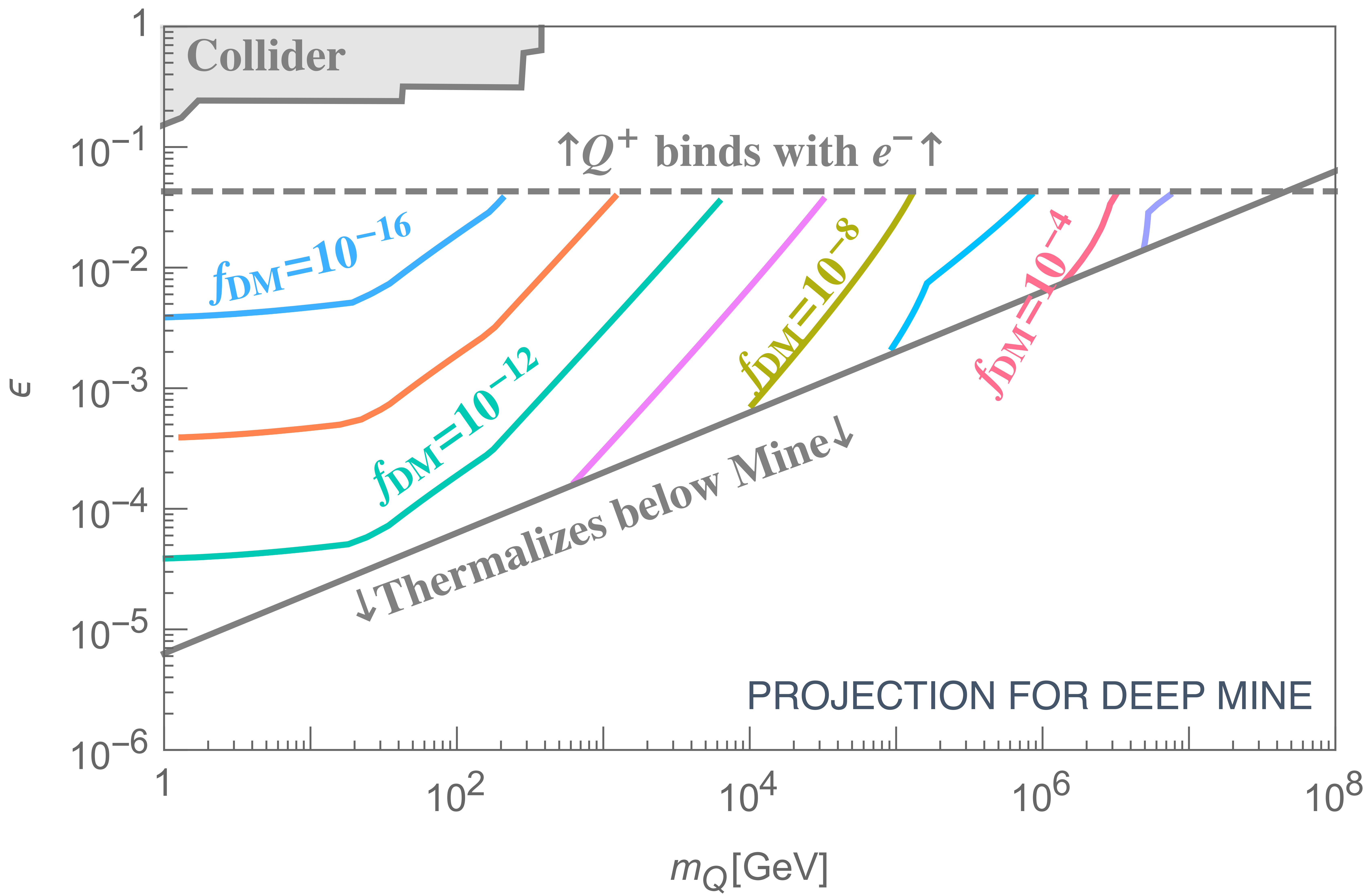


LIMITS ON DARK MATTER



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

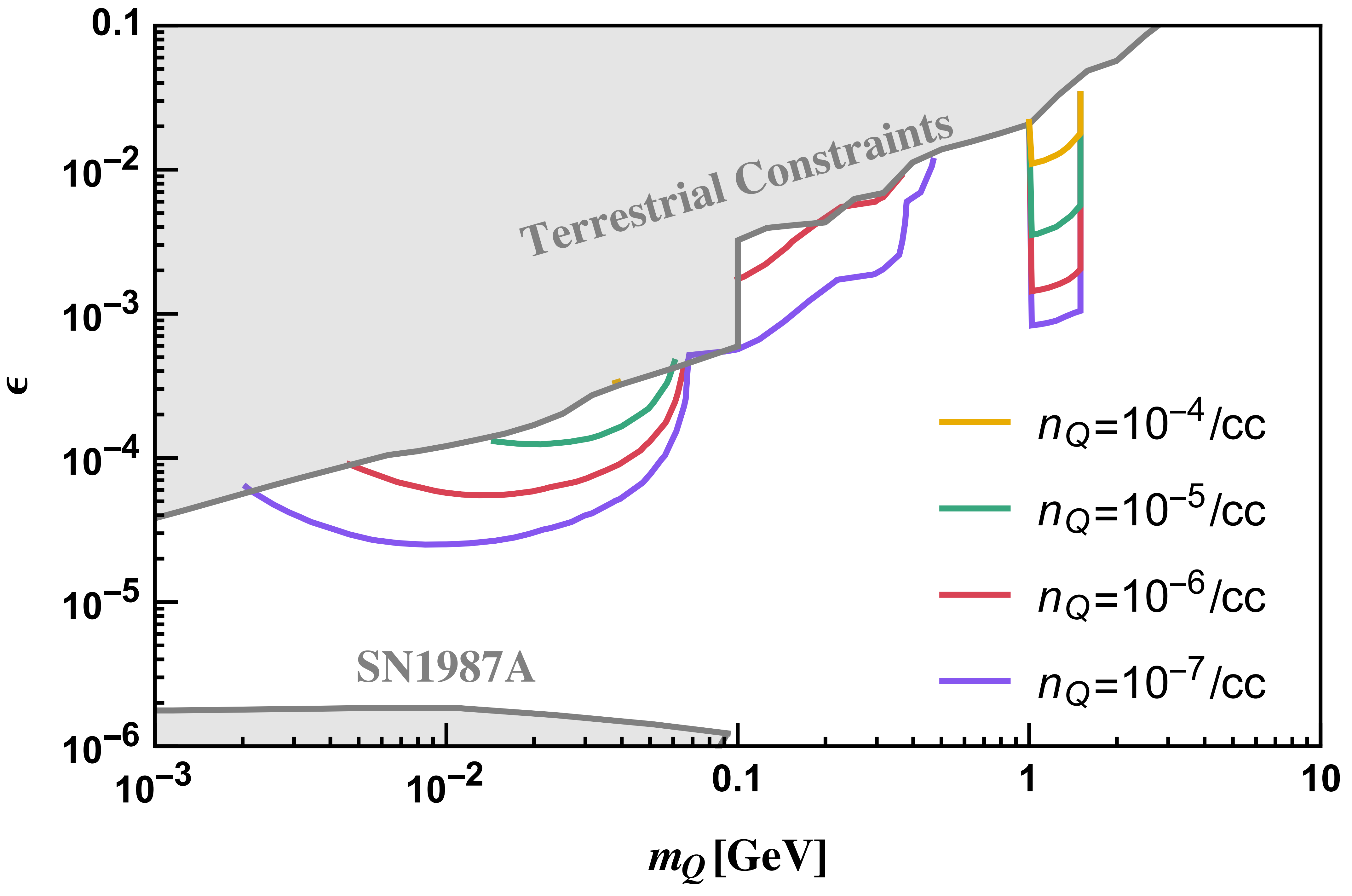
PROJECTION FOR DEEP MINE



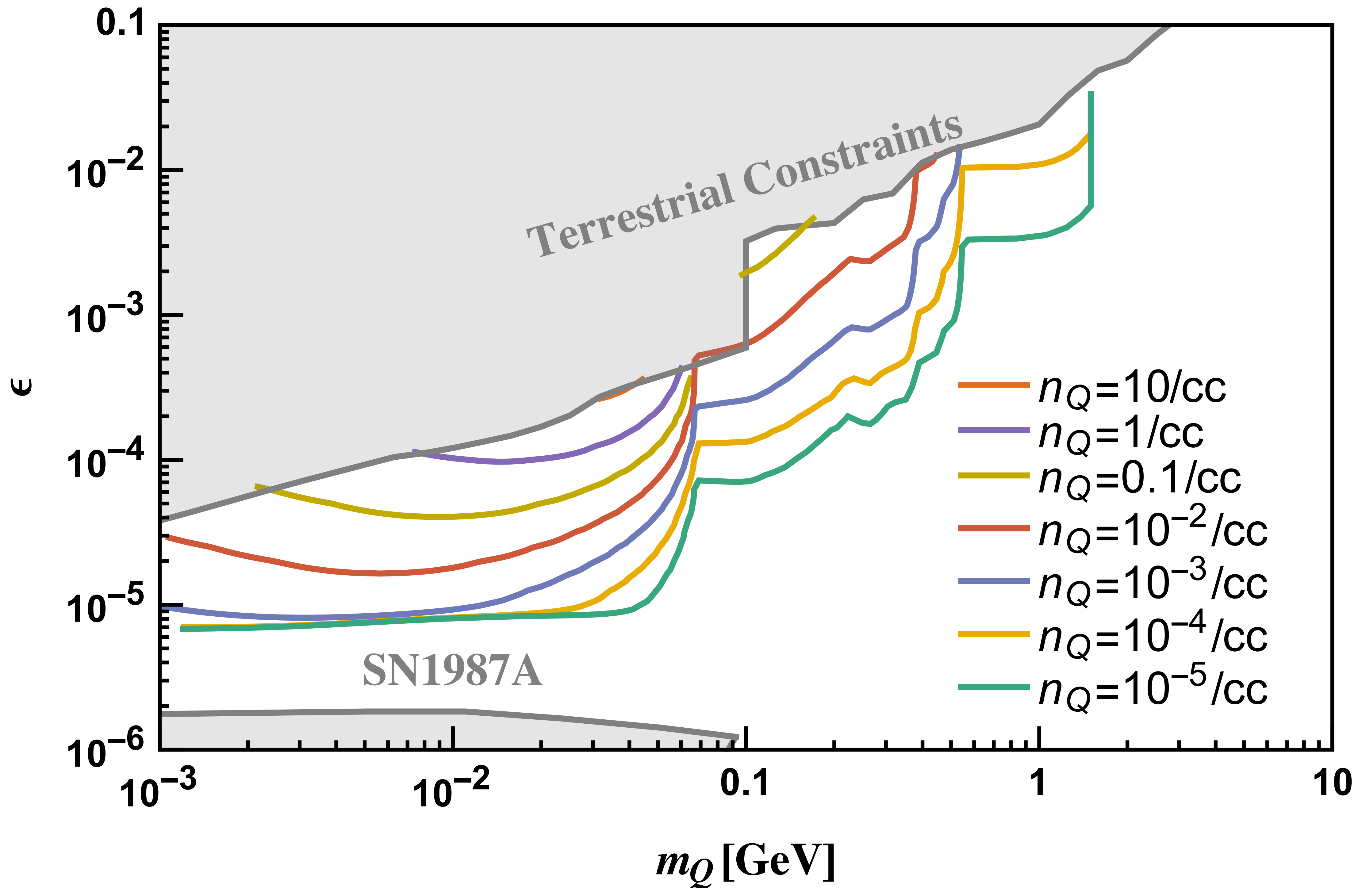
Forthcoming HR with D.Budker, P.Graham, F.Schmidt-Kaler

IRREDUCIBLE MCP POPULATION

With evaporation

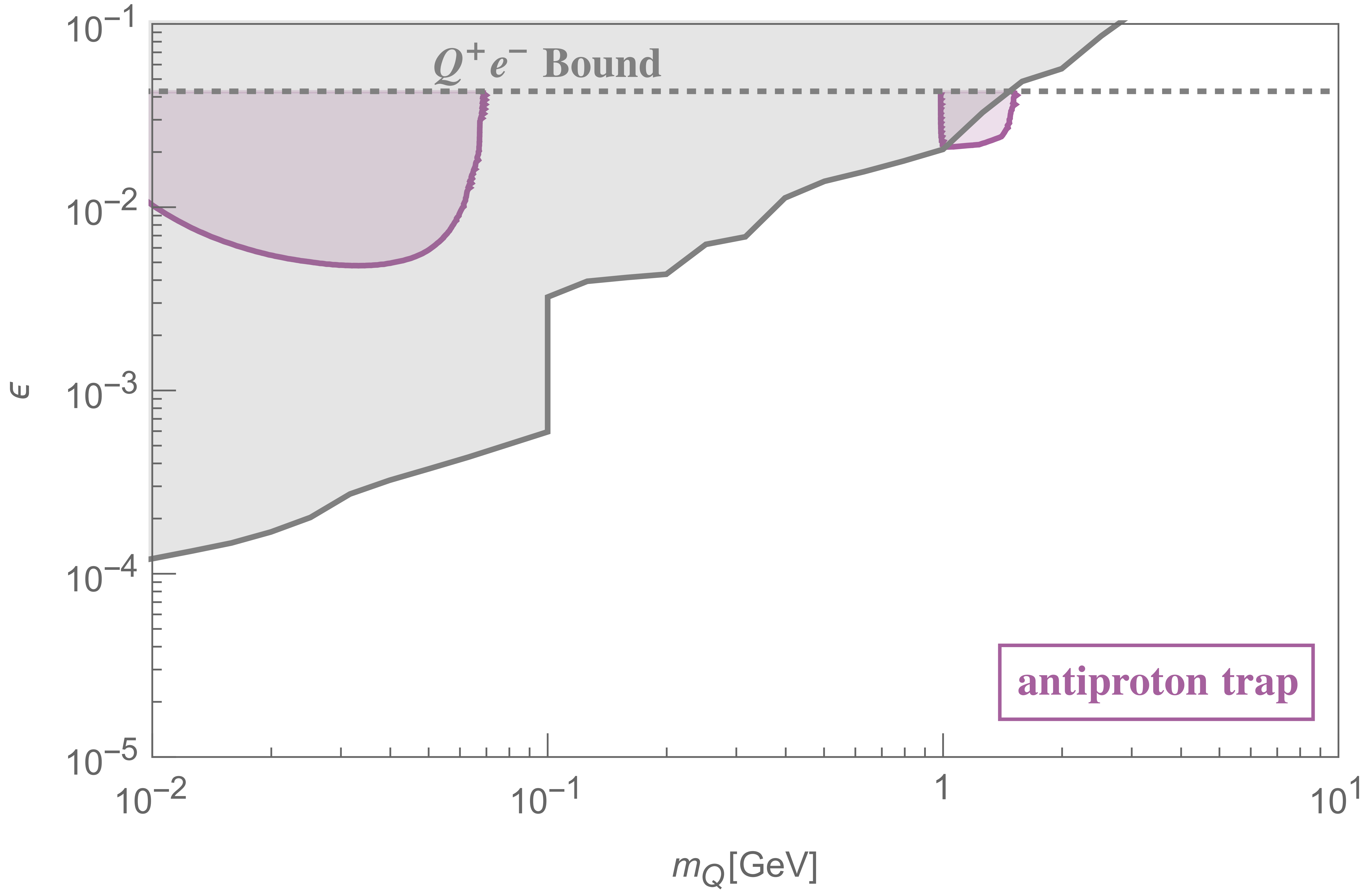


Without evaporation



from: 2012.03957 HR M.Pospelov

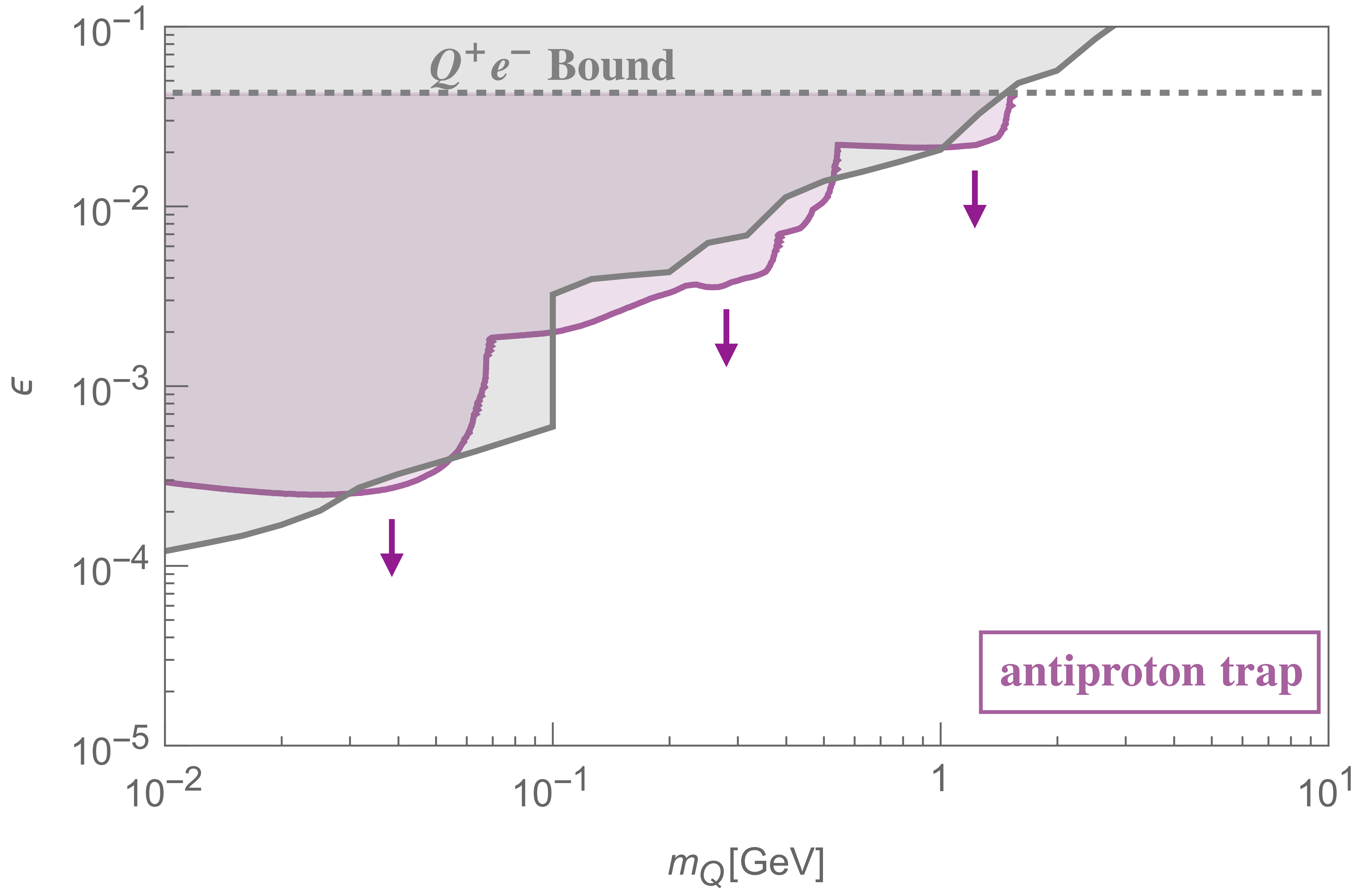
IRREDUCIBLE LIMIT (COSMIC RAY)



Evaporation on - non-trivial DP mass

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

IRREDUCIBLE LIMIT (COSMIC RAY)



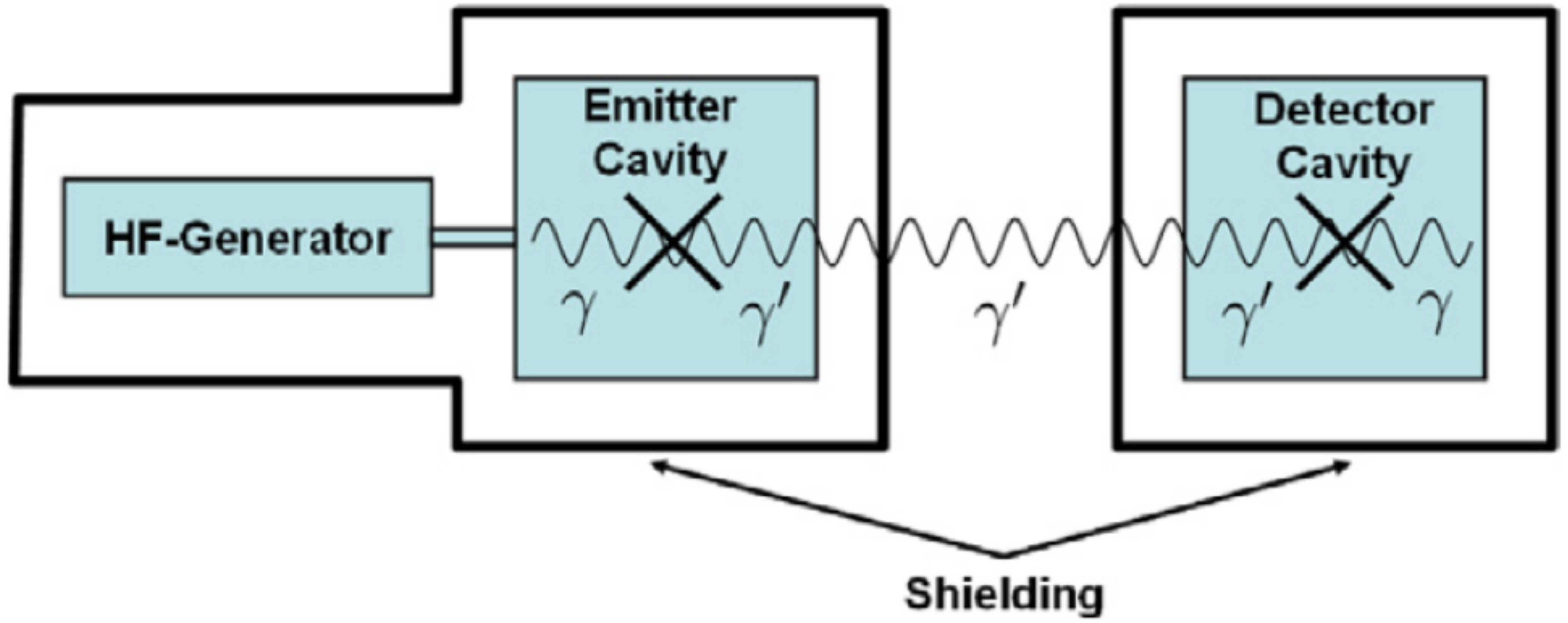
Evaporation off - pure millicharge

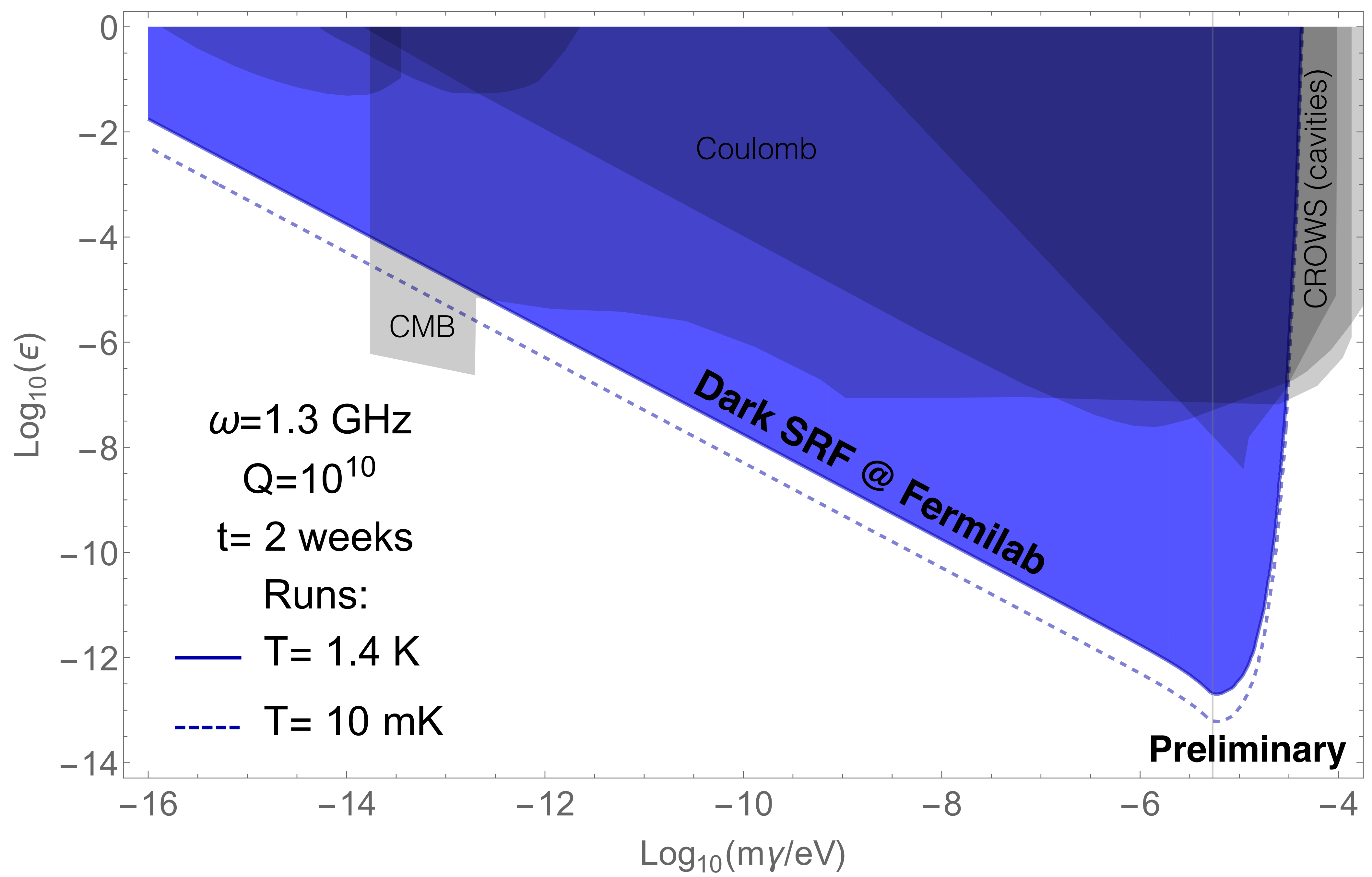
Forthcoming HR with D.Budker, P.Graham, F.Schmidt-Kaler

OUTLOOK

- ✦ Heating due to “-“ and “z” modes
- ✦ Electron traps to extract more energy at same q
- ✦ Repeating experiment in deep mine
- ✦ Collective excitations in Ion lattices
- ✦ Accumulating mCPs in an electric field bottle

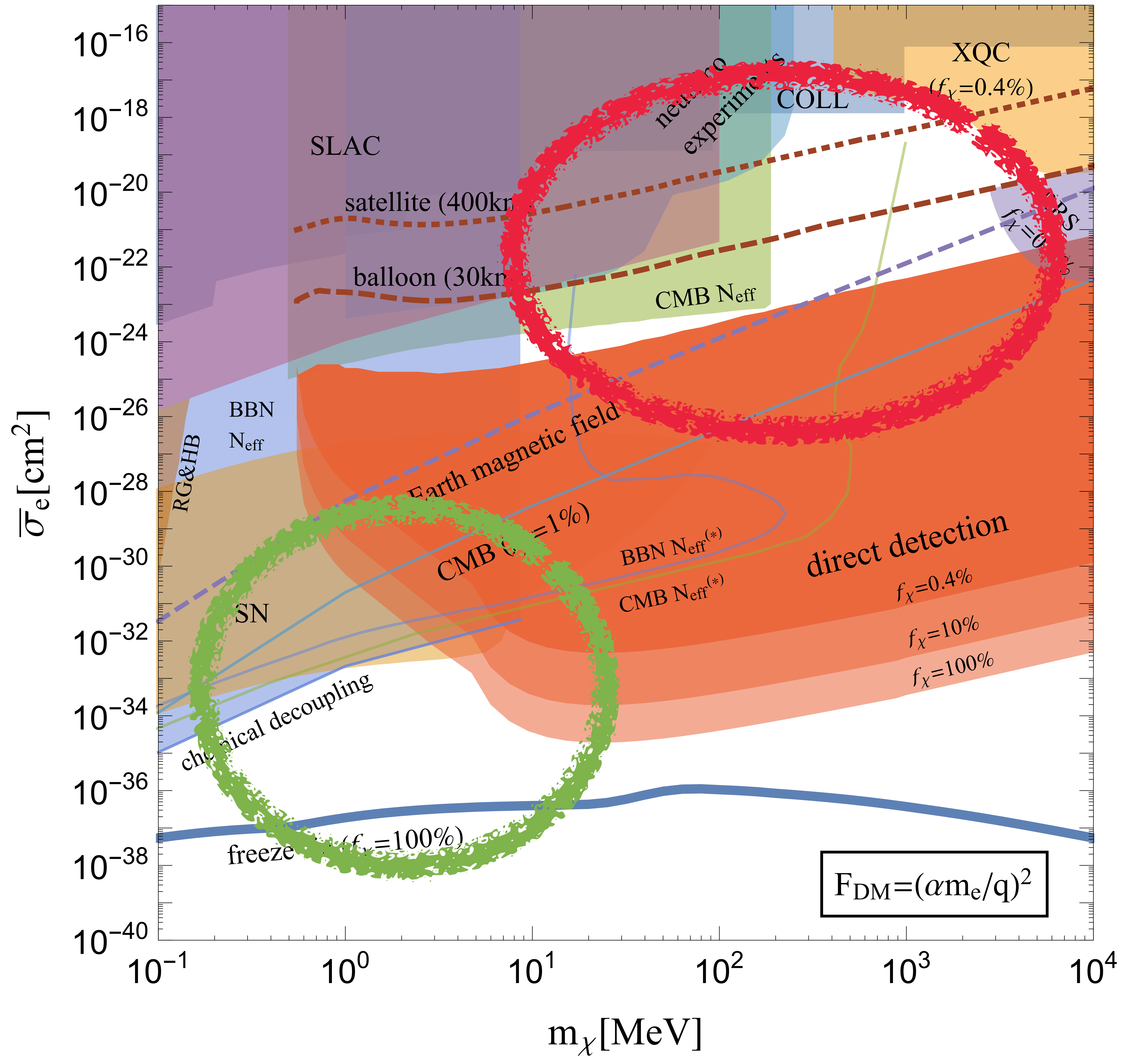
DARK SRF for TRAFFIC JAM?





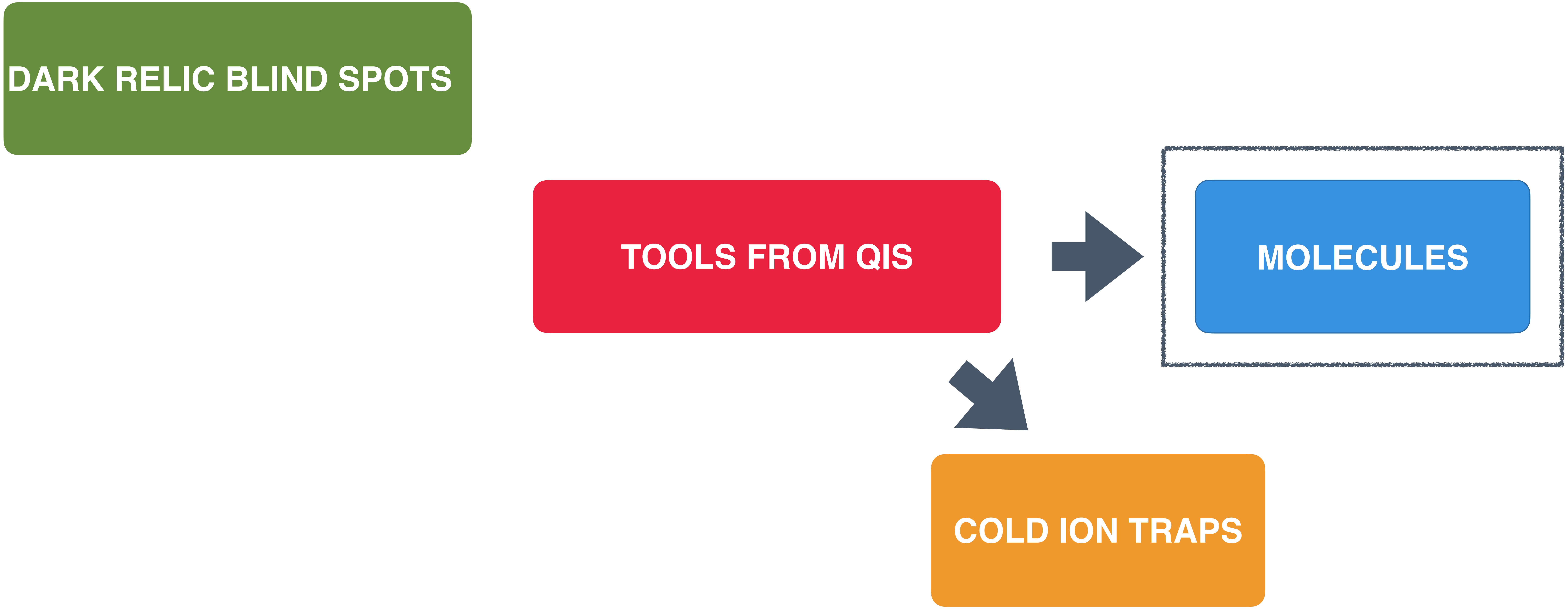
- LSW experiment Dark SRF@ Fermilab
- Constraints decouple for small $m_{A'}$
- Ambient mCP traffic jam: thermal mass $\Pi_{A'} \propto \alpha_D n_Q \gg m_{A'}$
- Novel effect, milli-charges oscillations produce A'
- New constraints in Transverse mode?
- Ongoing with A. Berlin, H. Liu, M. Pospelov,

ultralight dark photon mediator



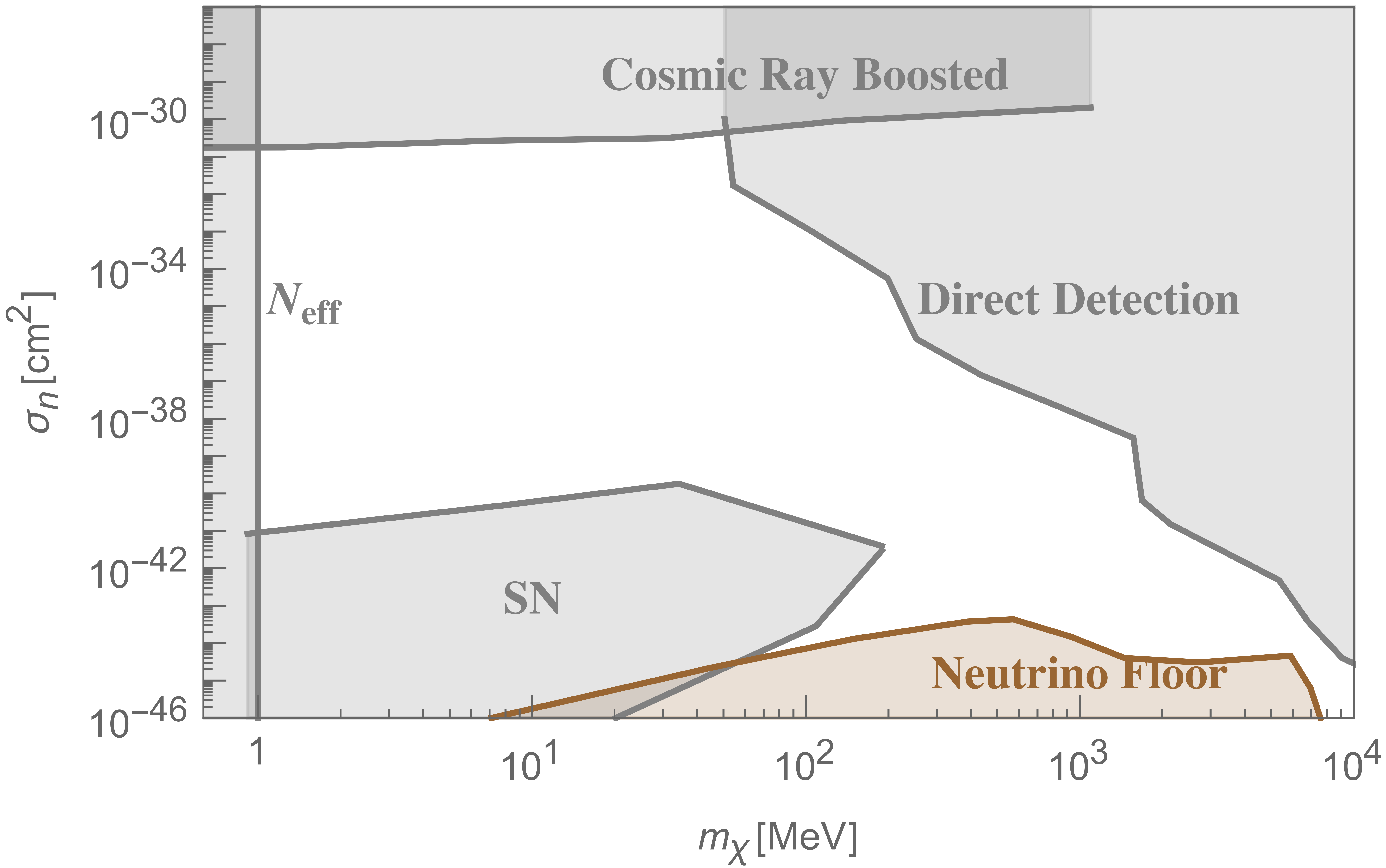
26 meV

eV


DARK RELIC BLIND SPOTS
TOOLS FROM QIS
MOLECULES
COLD ION TRAPS

NUCLEOPHILIC

Adapted from: 1908.00007 Krnjaic & Mcdermott

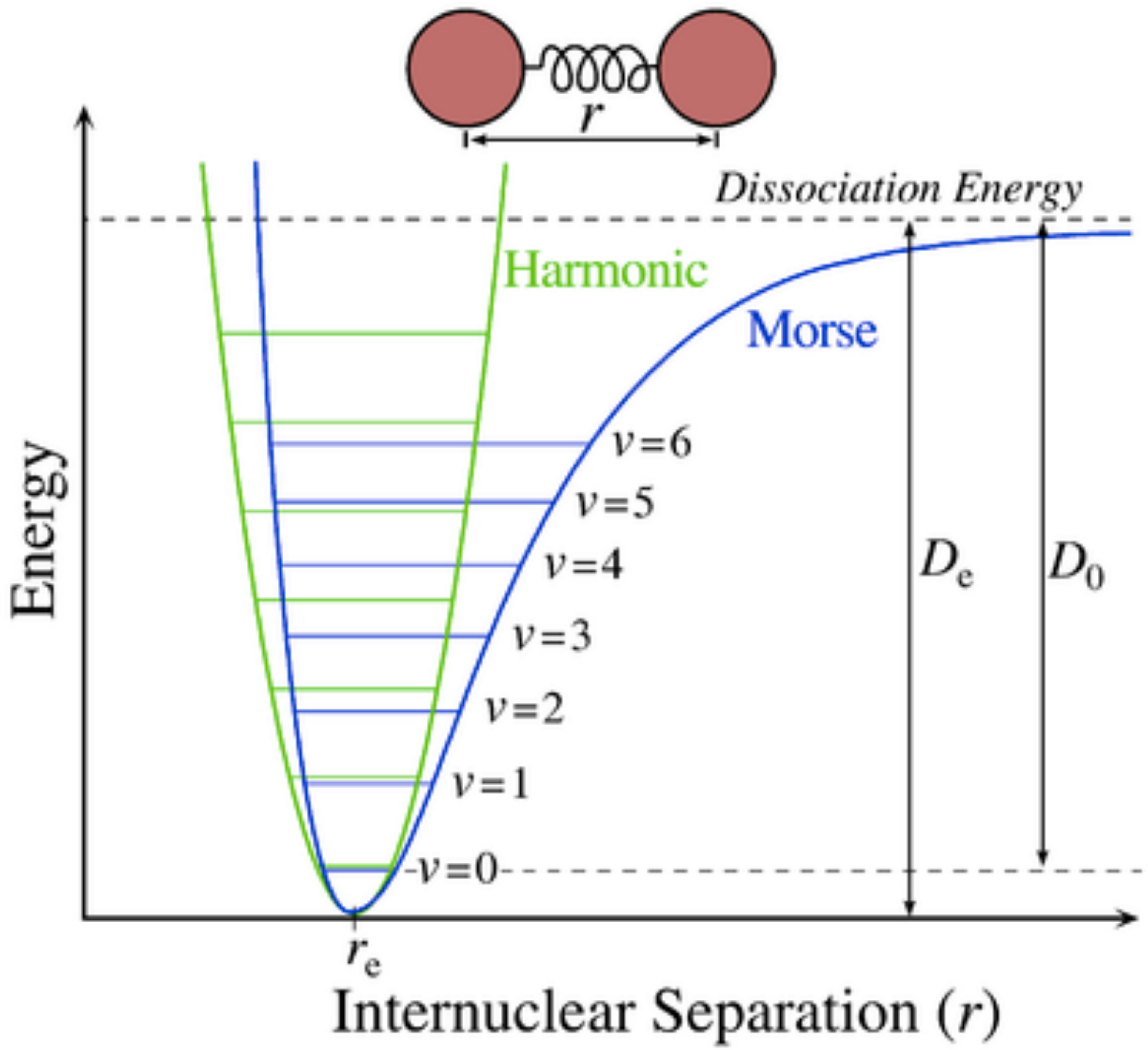


KINEMATICS

- The total energy deposited in elastic scatter:
- $$E_{\text{tot}} = \frac{q^2}{2m_N} = \left[\frac{m_\chi}{m_N}\right]\frac{1}{2}m_\chi v_\chi^2$$
- Extra m_χ/m_N suppression compared to KE available.
- Inelastic scatter with target, extract more energy

MOLECULES

1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone

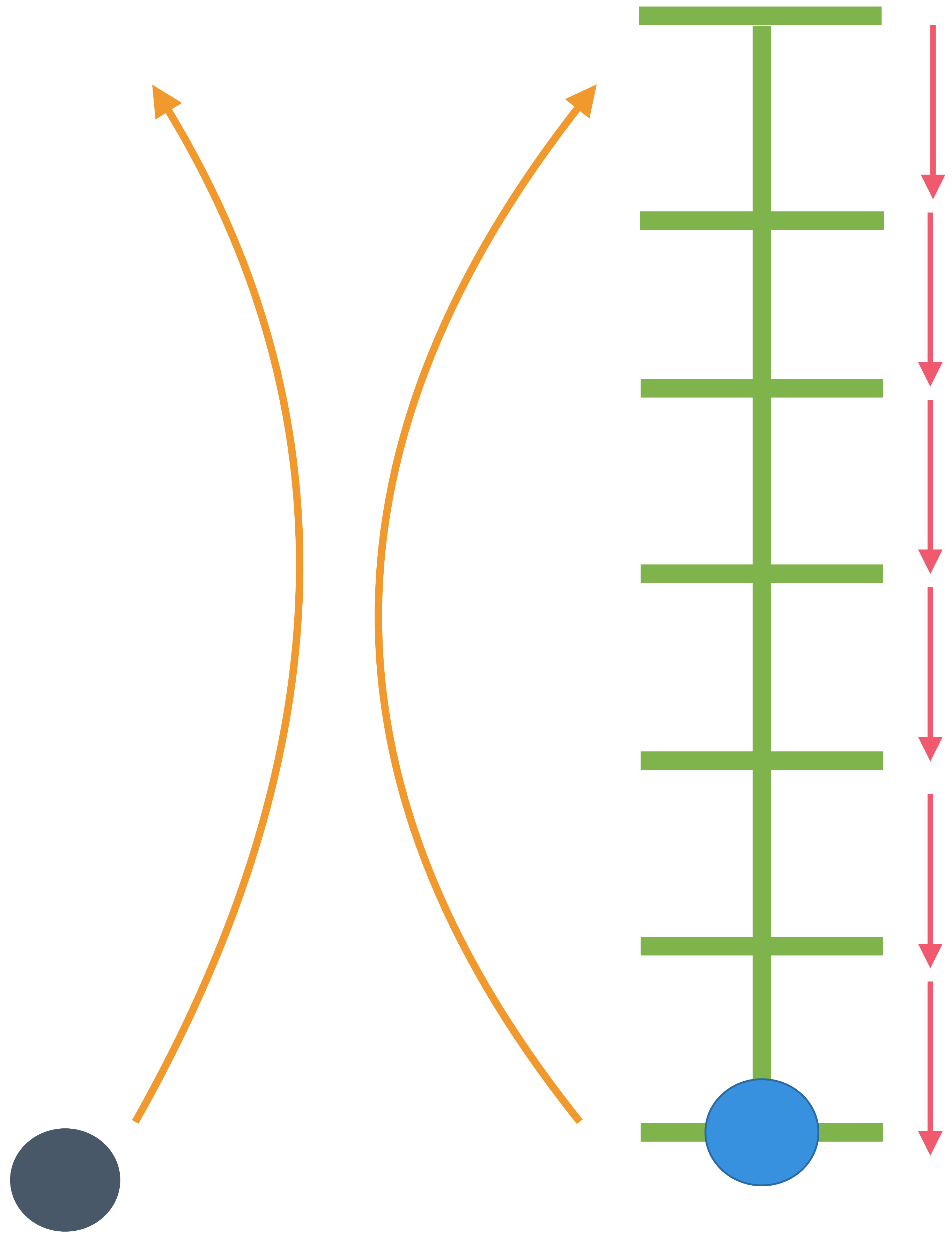


- Described by a Morse Potential.
- Approximately a Harmonic Oscillator potential.
- v levels approximately equally spaced.

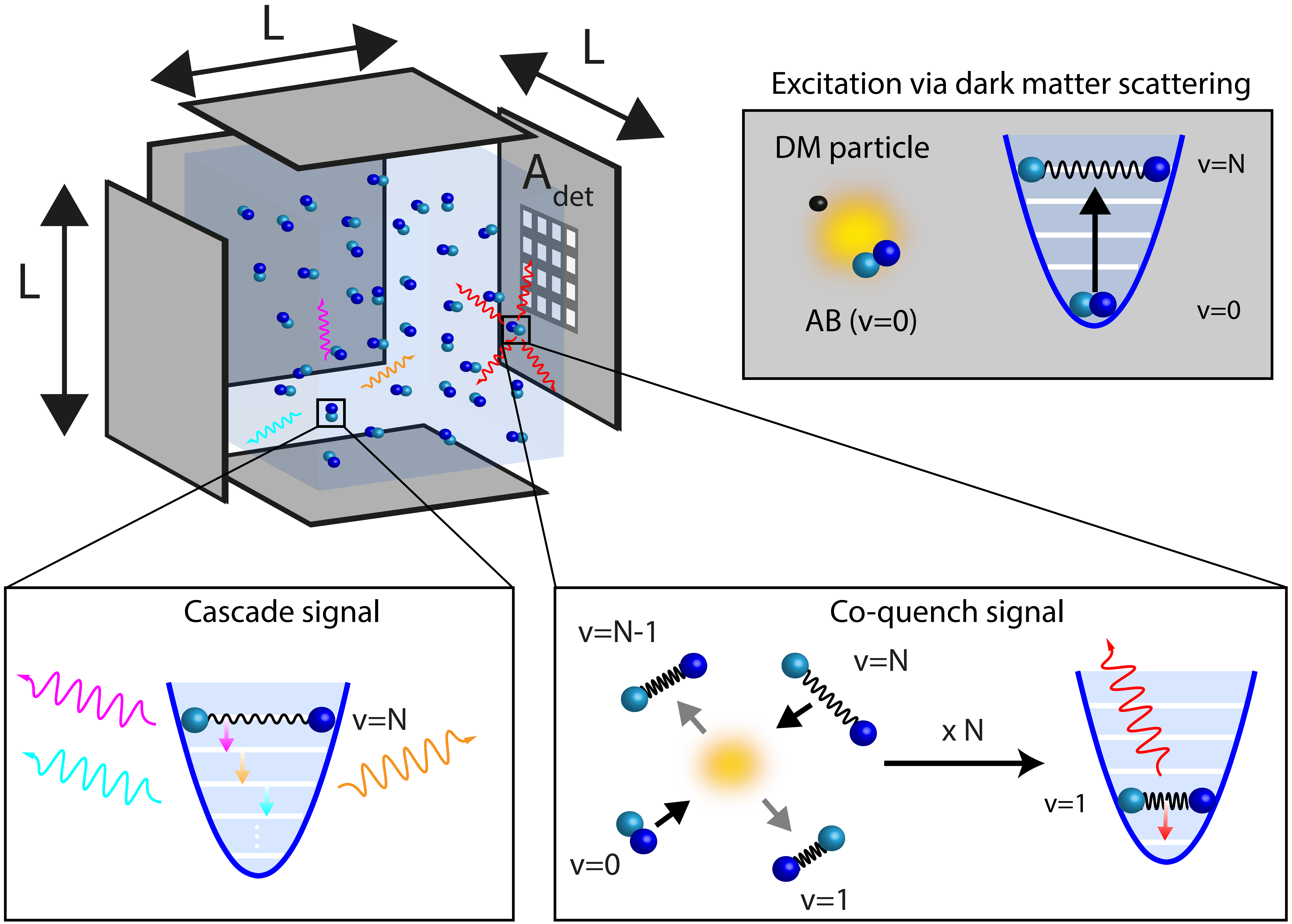
$$E_{vJ} \approx \omega_e \left(v + \frac{1}{2}\right) - \omega_e x_e \left(v + \frac{1}{2}\right)^2$$
$$+ B_e J(J+1) - \alpha_e (v + 1/2) J(J+1) \,.$$

- Level splitting typically 500 meV.
- Corresponds to DM mass 500 keV and above.

SELECTION RULES



CONCEPT

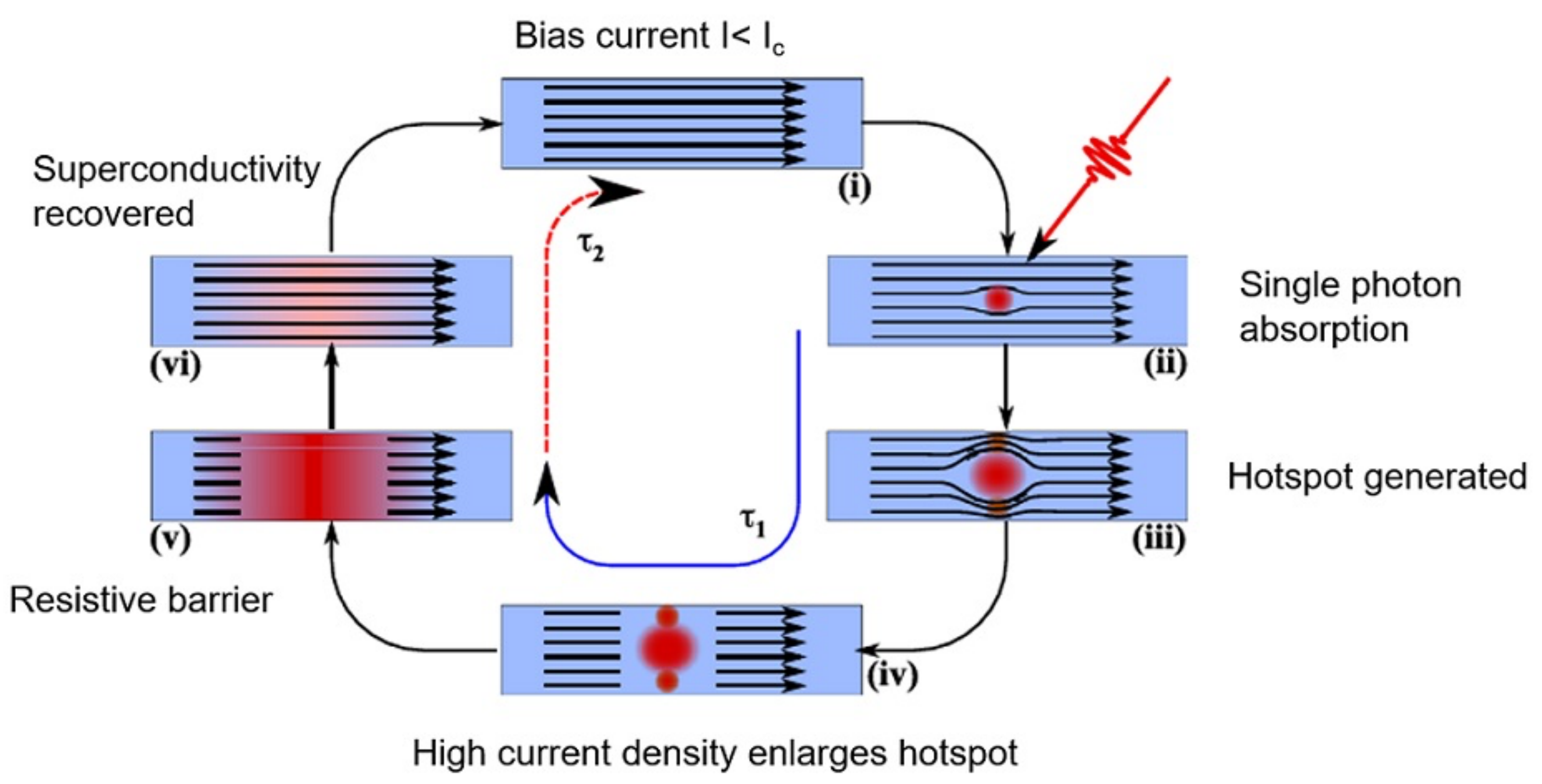


1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone

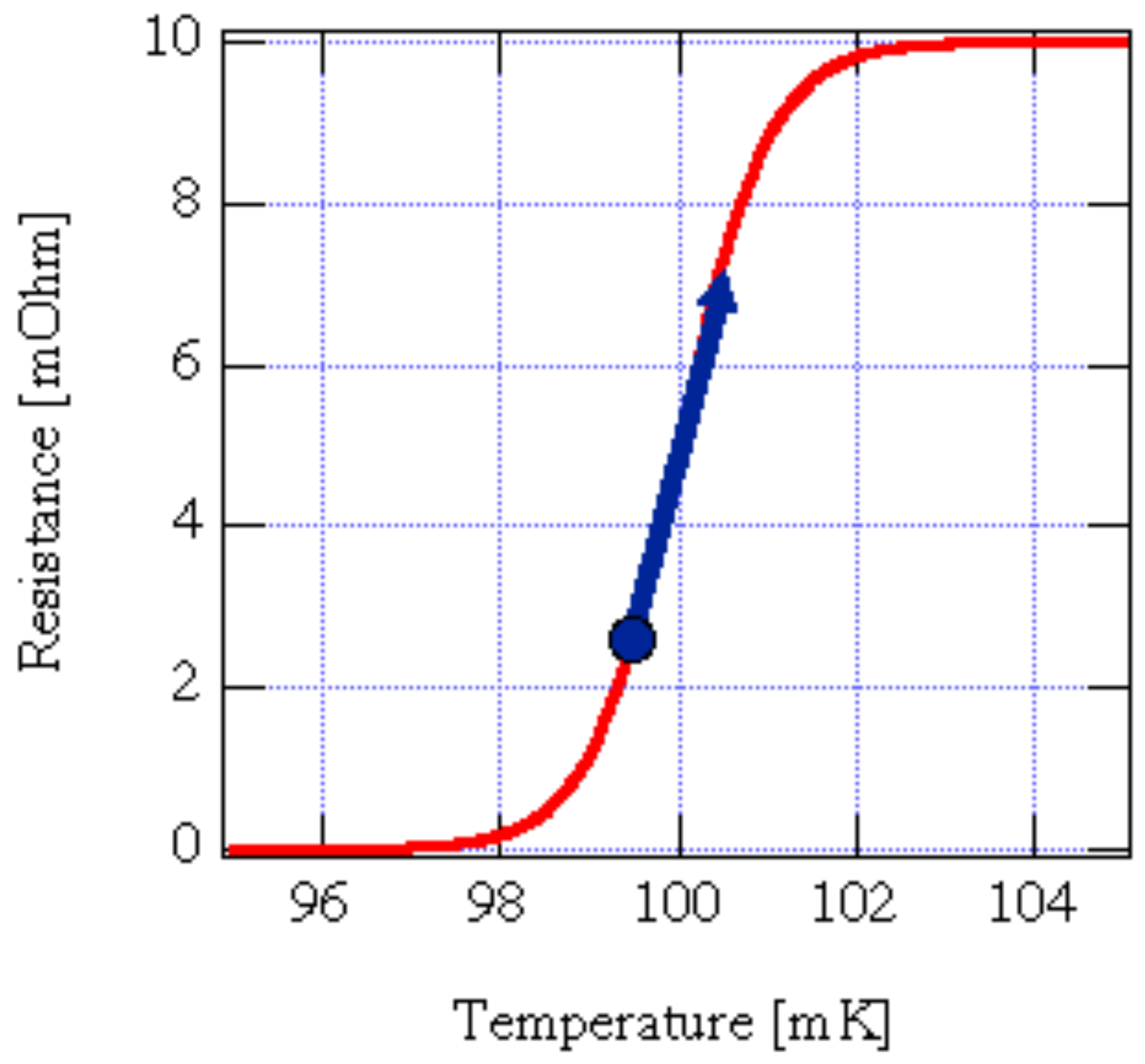
SINGLE PHOTON DETECTORS

- Significant R&D effort for near IR single photon detection
- QIS applications, and also relevant to astronomy
- Three leading candidates: SNSPD, TES, MKID,
- Detect single photons down to 100 meV, small Area ~ 1mm²

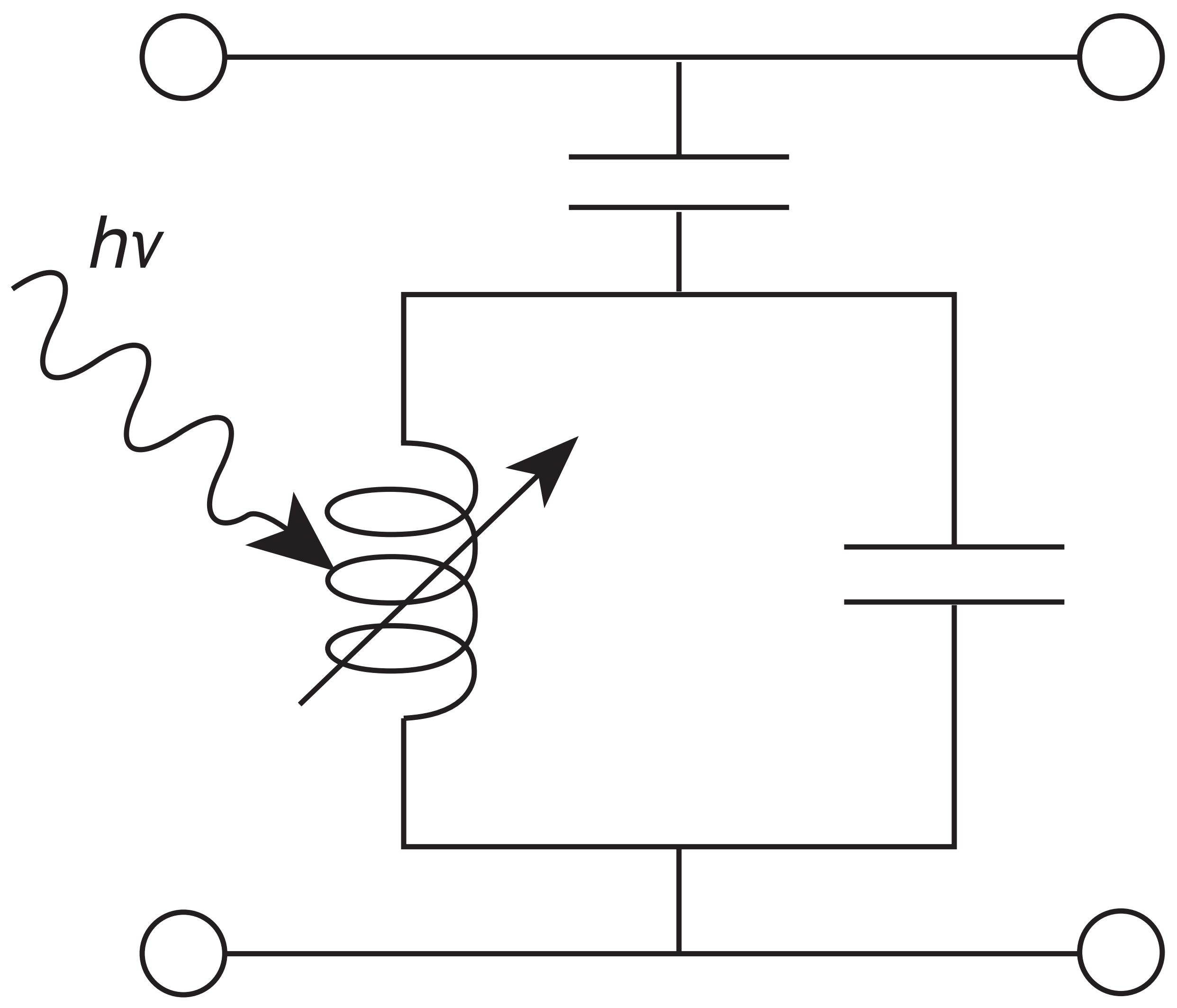
superconducting nanowire single photon detector



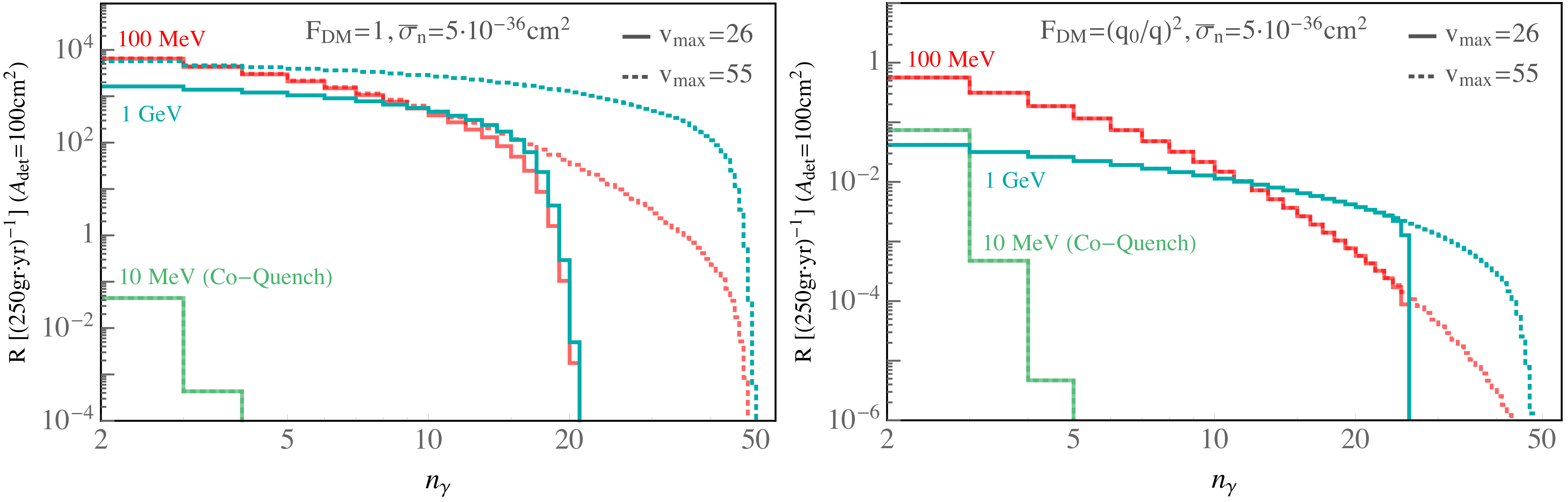
Transition Edge Sensor



Microwave Kinetic Inductance Detector



PHOTON SPECTRUM



1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone

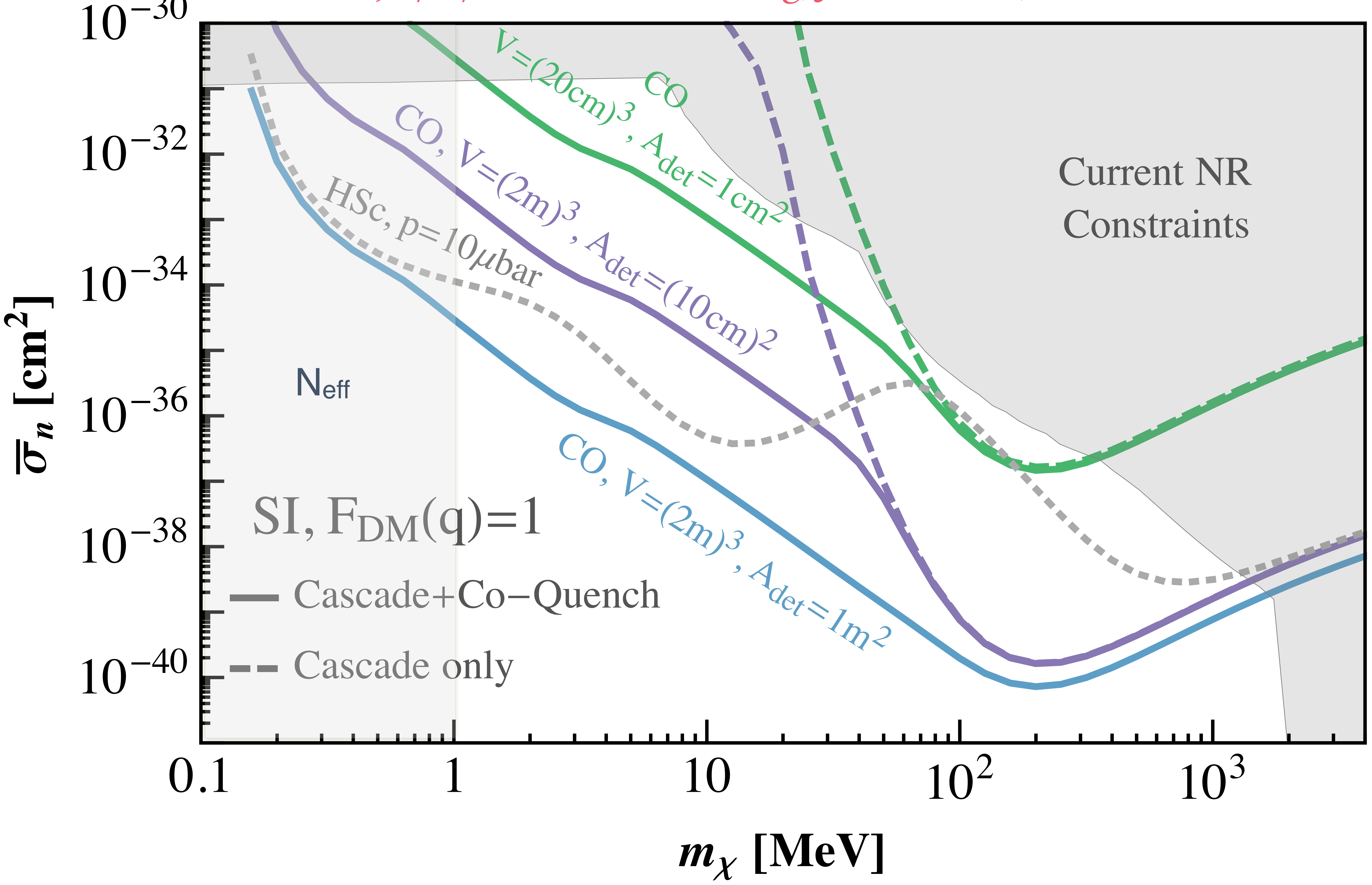
BACKGROUNDS

- Thermal excitations: Cool gas, less than 1/year
- Cosmo/Radiogenics: Active veto, radio-purity & Shielding
- Dark Counts of Detector
- Black Body Radiation

} Time coincidence with large photon yield

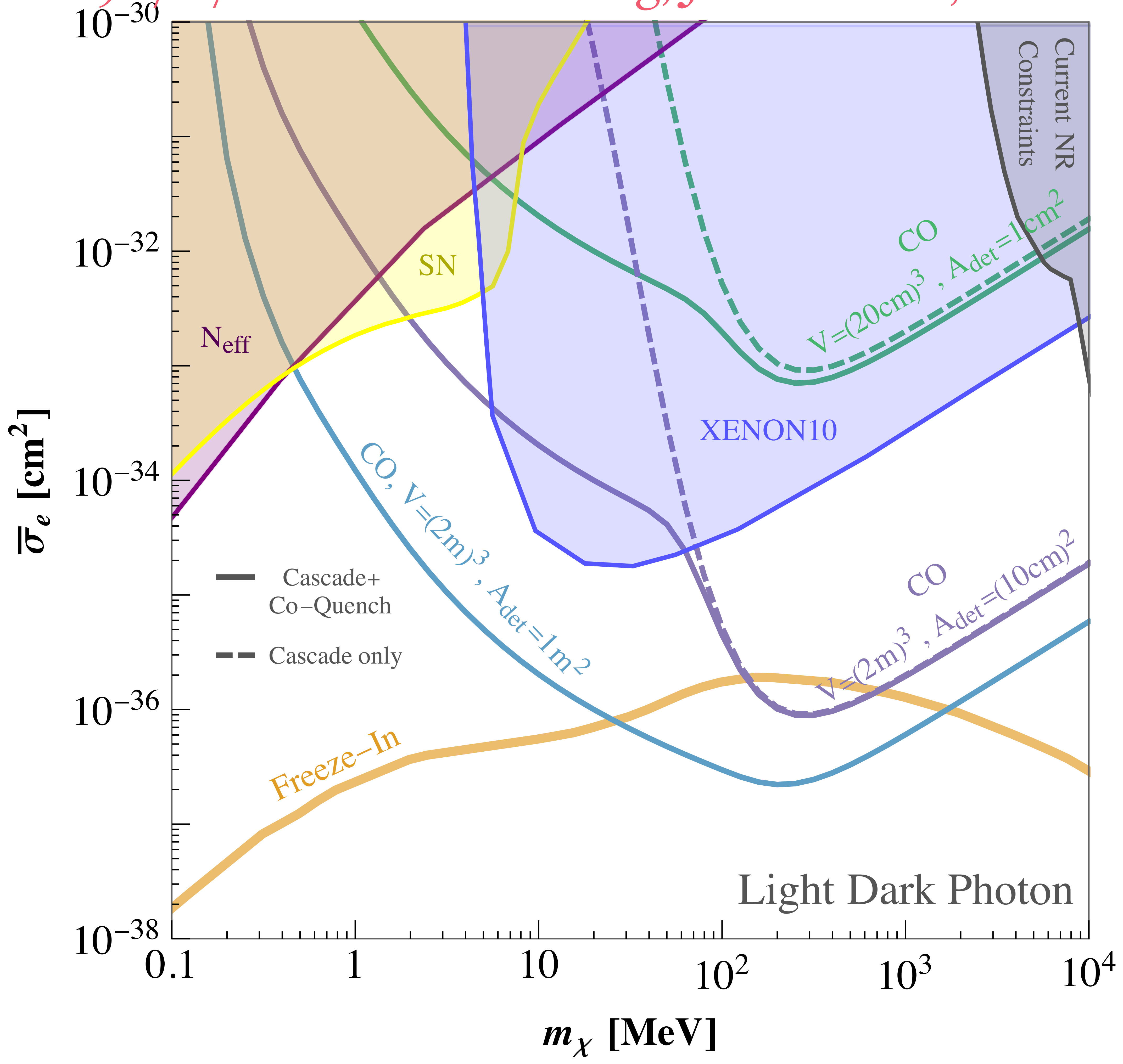
REACH

1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone



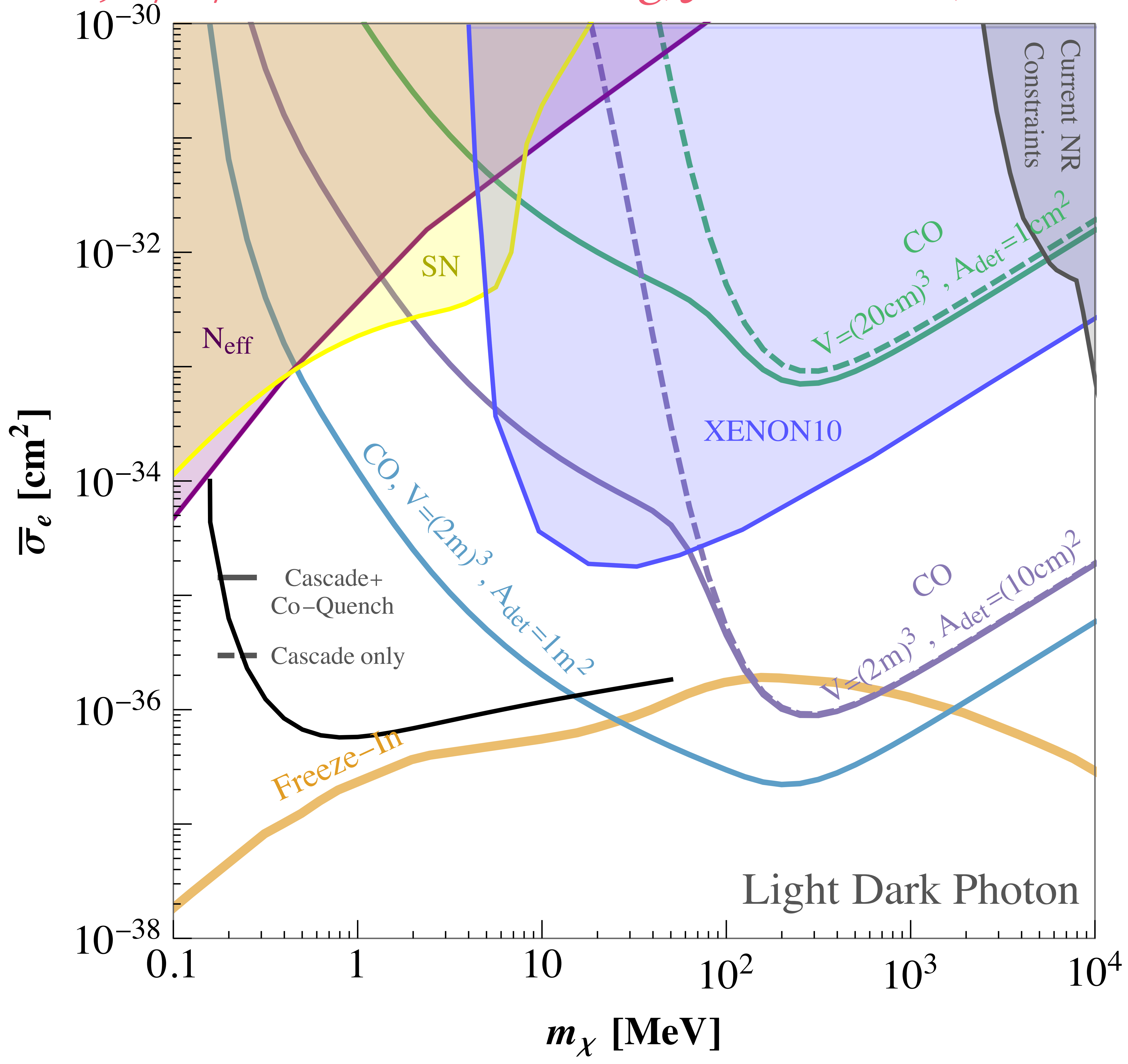
MILLI-CHARGE PARTICLES

1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone



MILLI-CHARGE PARTICLES

1907.07682 HR with R.Essig, J. Perez-Rios, O. Slone



OUTLOOK

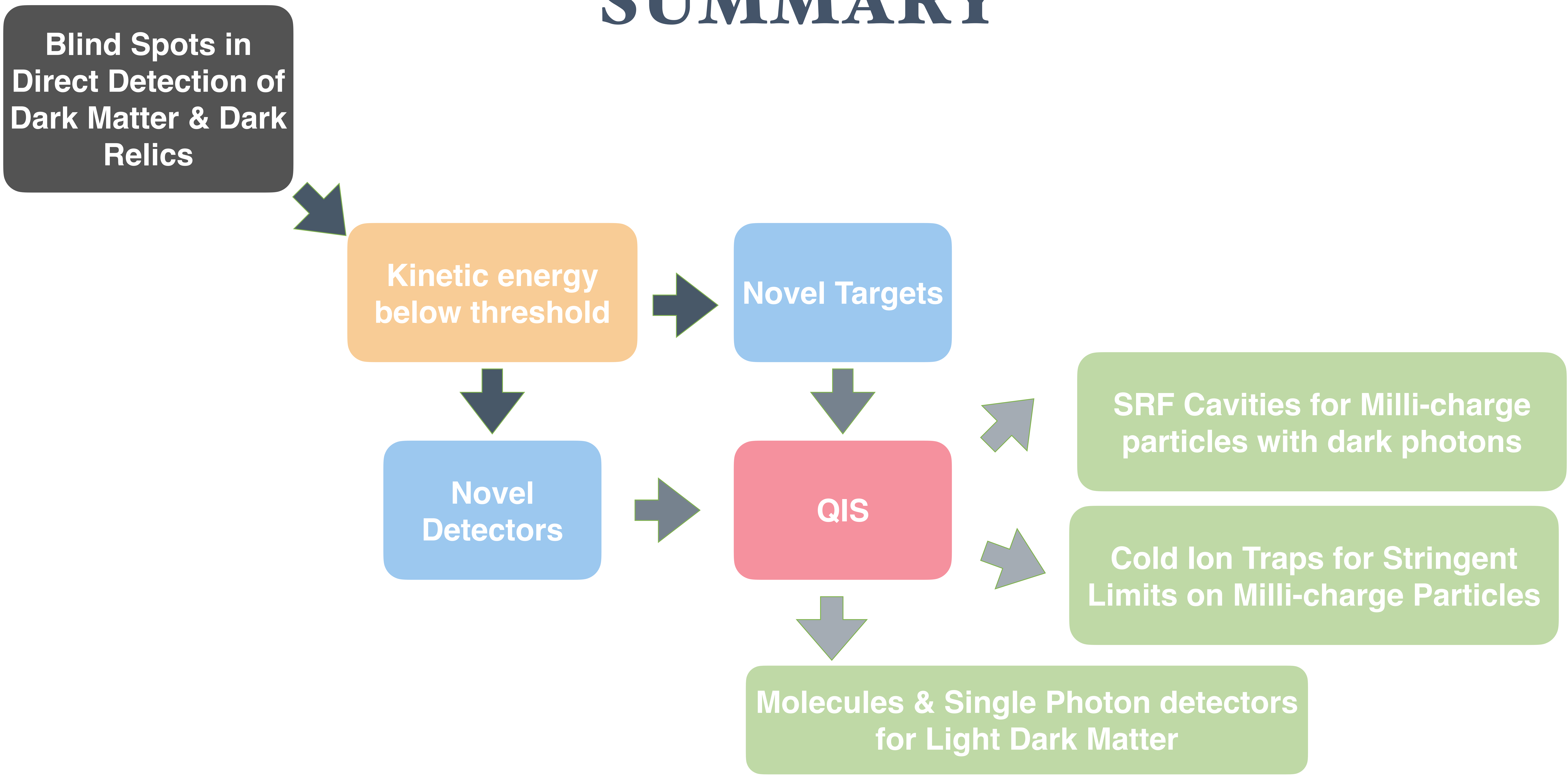
- Quantum Dots - “0-dimensional” semi-conductors - artificial atoms

Forthcoming with C. Blanco, R. Essig, O. Slone, Fernandes-Serra,

- In Solid, measure heat with Transition Edge Sensor, most sensitive bolometer?

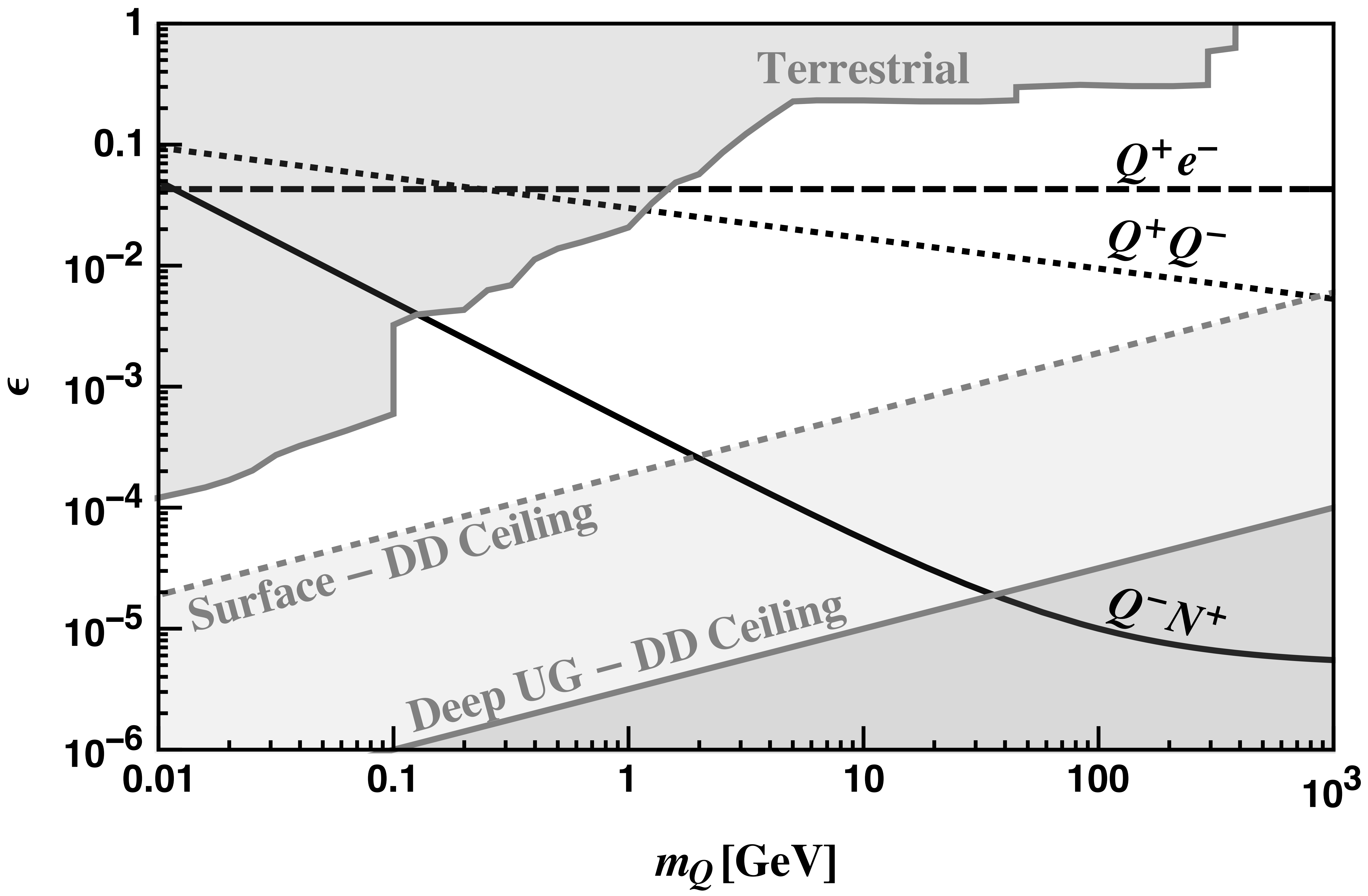
Forthcoming with M. Pyle(super-CDMS), J. Billard (EDELWEISS), and S. Rajendran

SUMMARY


Blind Spots in Direct Detection of Dark Matter & Dark Relics
Kinetic energy below threshold
Novel Targets
Novel Detectors
QIS
SRF Cavities for Milli-charge particles with dark photons
Cold Ion Traps for Stringent Limits on Milli-charge Particles
Molecules & Single Photon detectors for Light Dark Matter

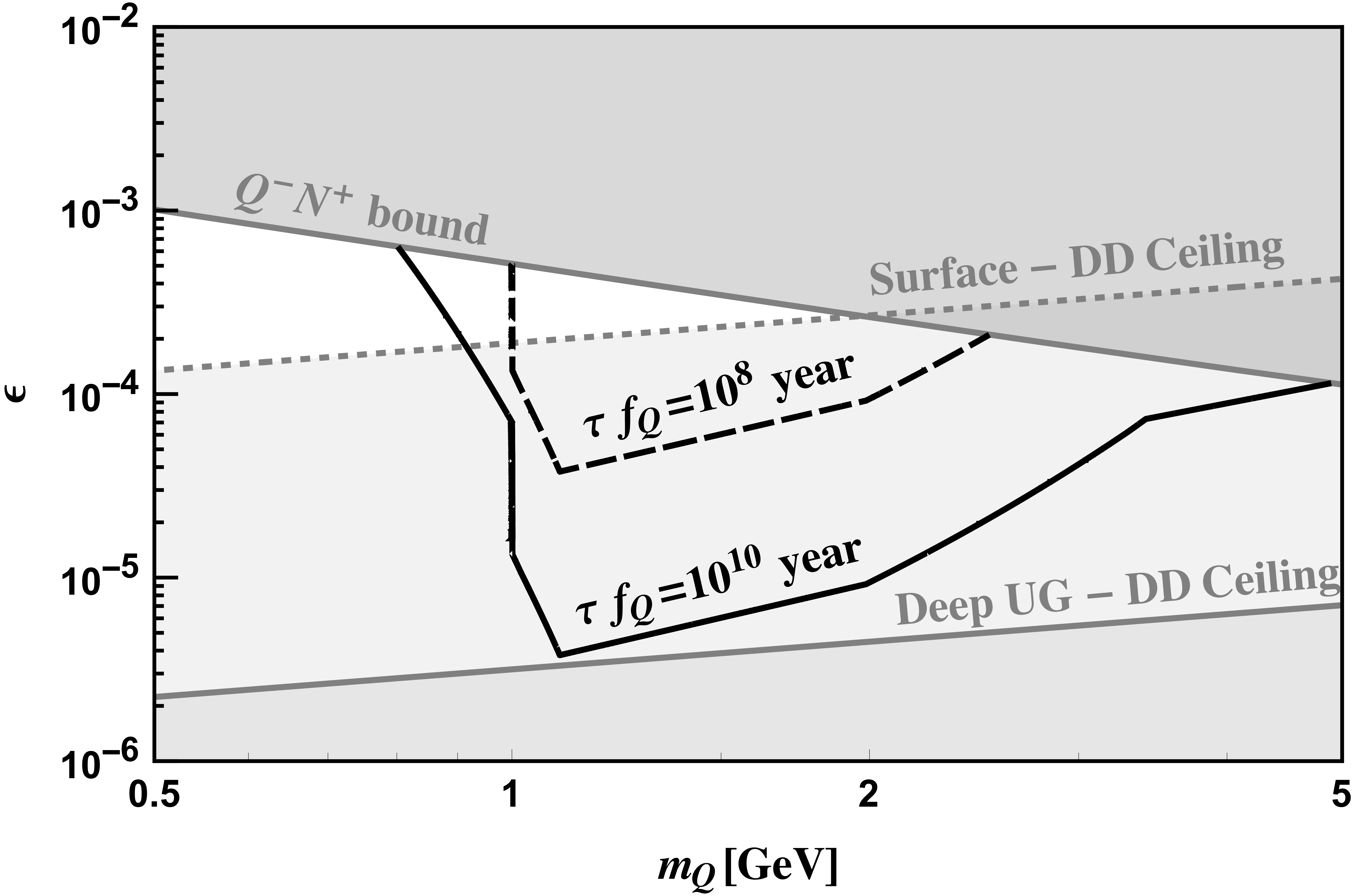
BACKUP

BOUND STATE FORMATION



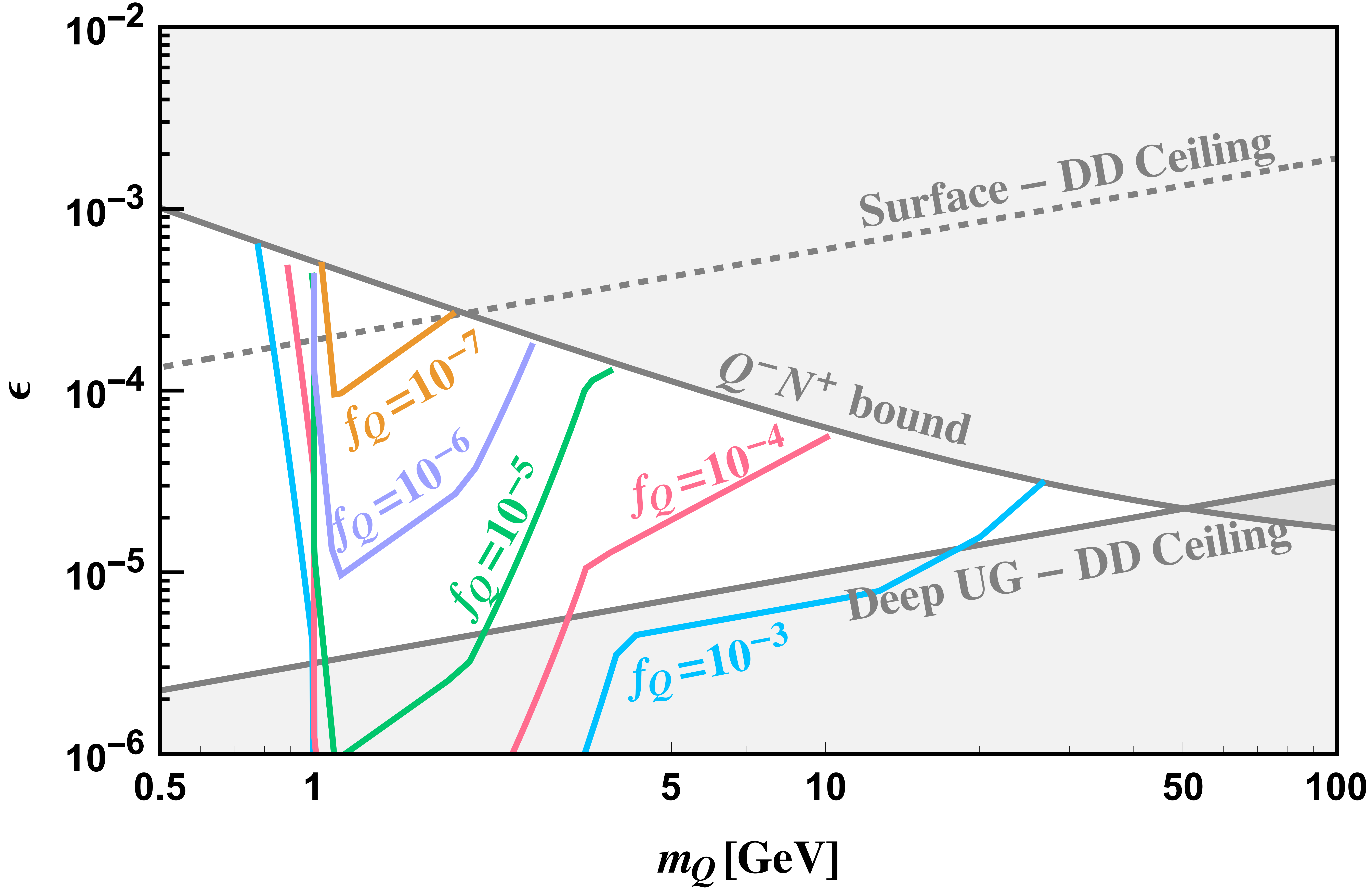
from: 2012.03957 HR, M.Pospelov

LIFETIME



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ϵ
$Q^{-}N^{+}$ bound
Surface – DD Ceiling
$\tau\ f_Q=10^8$ year
$\tau\ f_Q=10^{10}$ year
Deep UG – DD Ceiling
0.5
1
2
5
m_Q [GeV]

ANNIHILATIONS IN SUPER-K



MEASUREMENT

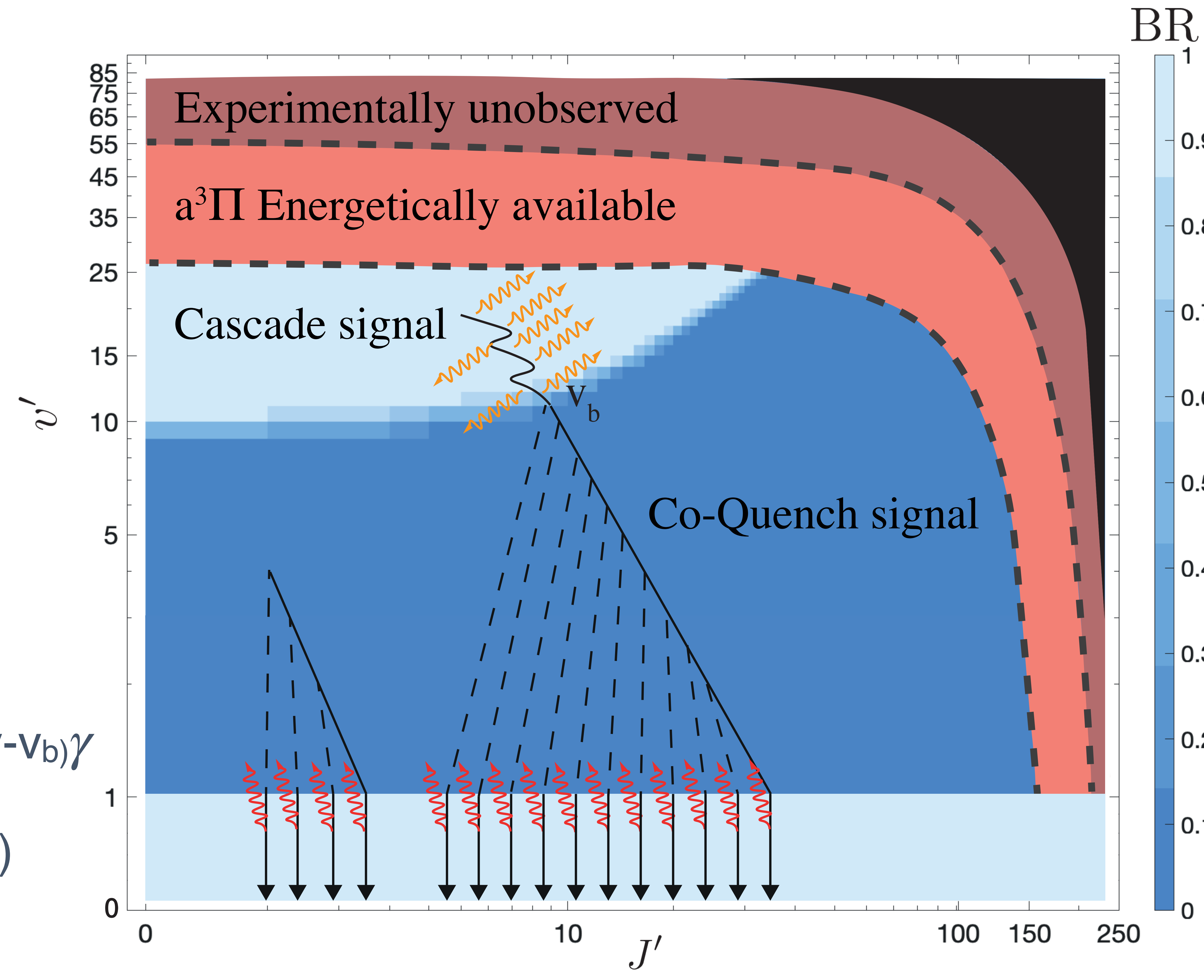
- $\nu_+, \nu_-, \nu_z \approx$ MHz $\approx$ **4neV** $\approx 50\mu$K
- Strong inhomogeneous magnetic field B_2
- $$\Delta\nu_z(n_+, n_-, m_s) = \frac{h\nu_+}{4\pi^2 m_p \nu_z}\frac{B_2}{B_0}\left[\left(n_+ + \frac{1}{2}\right) + \frac{\nu_-}{\nu_+}\left(n_- + \frac{1}{2}\right) + \frac{g_p m_s}{2}\right]$$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

CASCADE VS CO-QUENCH

- Two Types of signal: Cascade & Collisionally Quenched
- Resonant collisional quenching:

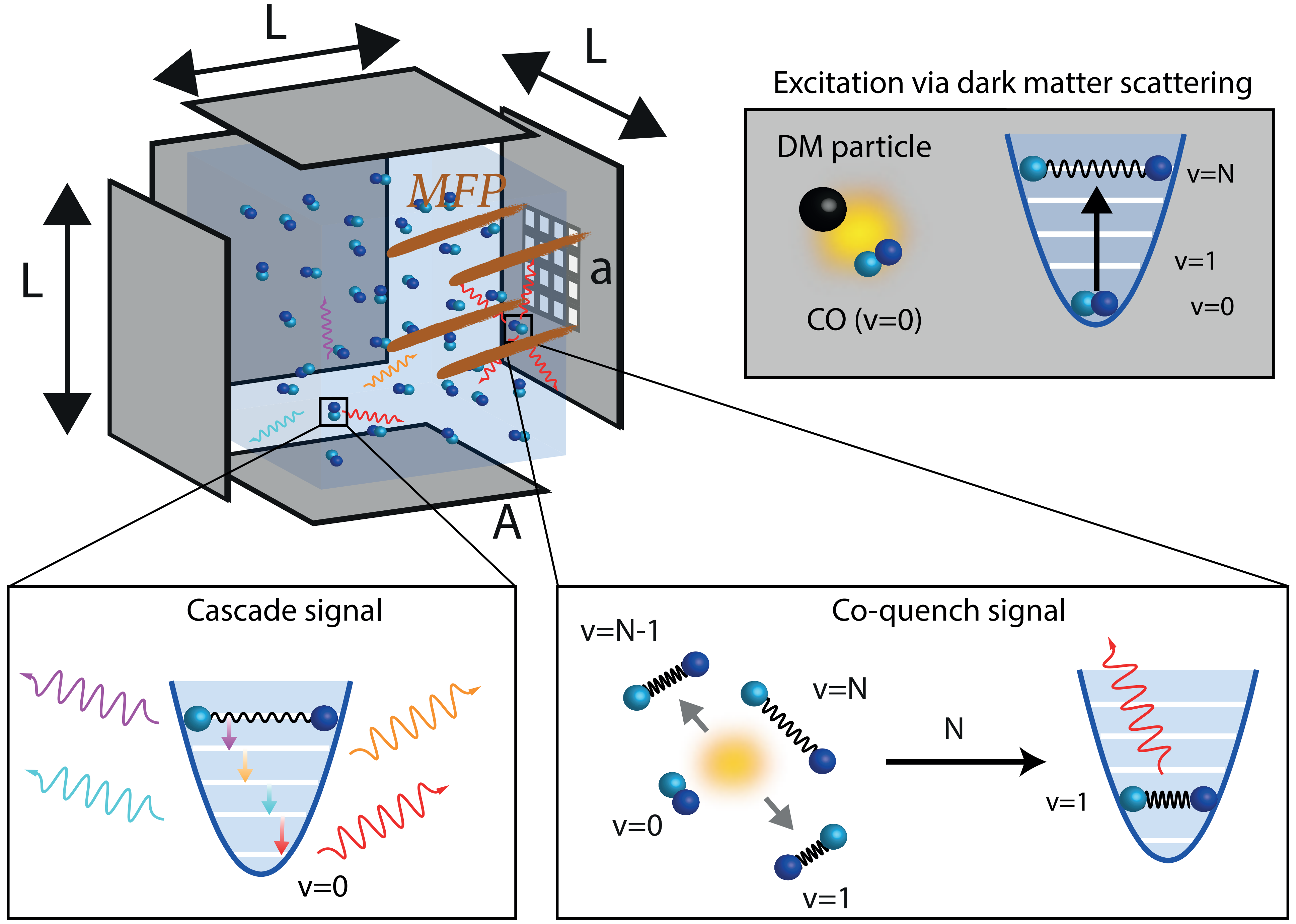
  $AB(v)+AB(0) \rightarrow AB(v-1)+AB(1)$

- Less efficient at high v: Harmonic approximation breaks down.
- Cascades down above some v_b
- Cascade: $AB(v) \rightarrow AB(v-1)+\gamma \rightarrow AB(v-2)+2\gamma \ldots \rightarrow AB(v_b)+(v-v_b)\gamma$
- Co-quench: $AB(v_b)+AB(0) \rightarrow AB(v_b-1)+AB(1) \ldots \rightarrow v_b\, AB(1)$
- $v_b AB(1) \rightarrow v_b\, AB(0) + v_b\, \gamma$



EXTRACTING CO-QUENCH

- ✦ Collisions with Helium buffer gas, broadens line spectrum, increasing MFP
- ✦ Different isotopes of CO, other gases, mutually transparent
- ✦ Can Increase MFP to 20 cm
- ✦ Open mirror box around detector for co-quench
- ✦ Sensitive to cascade signal from rest of the volume



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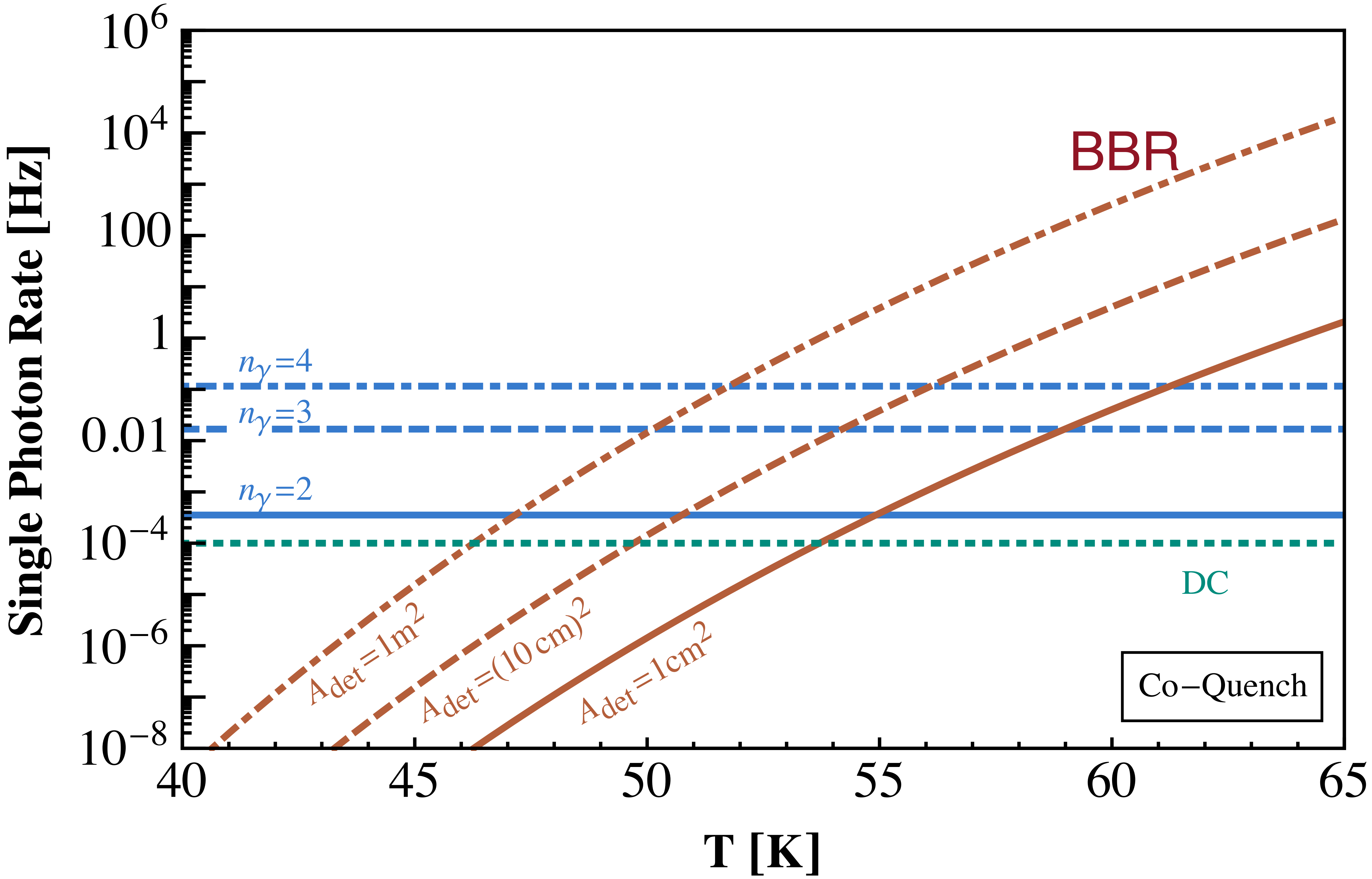
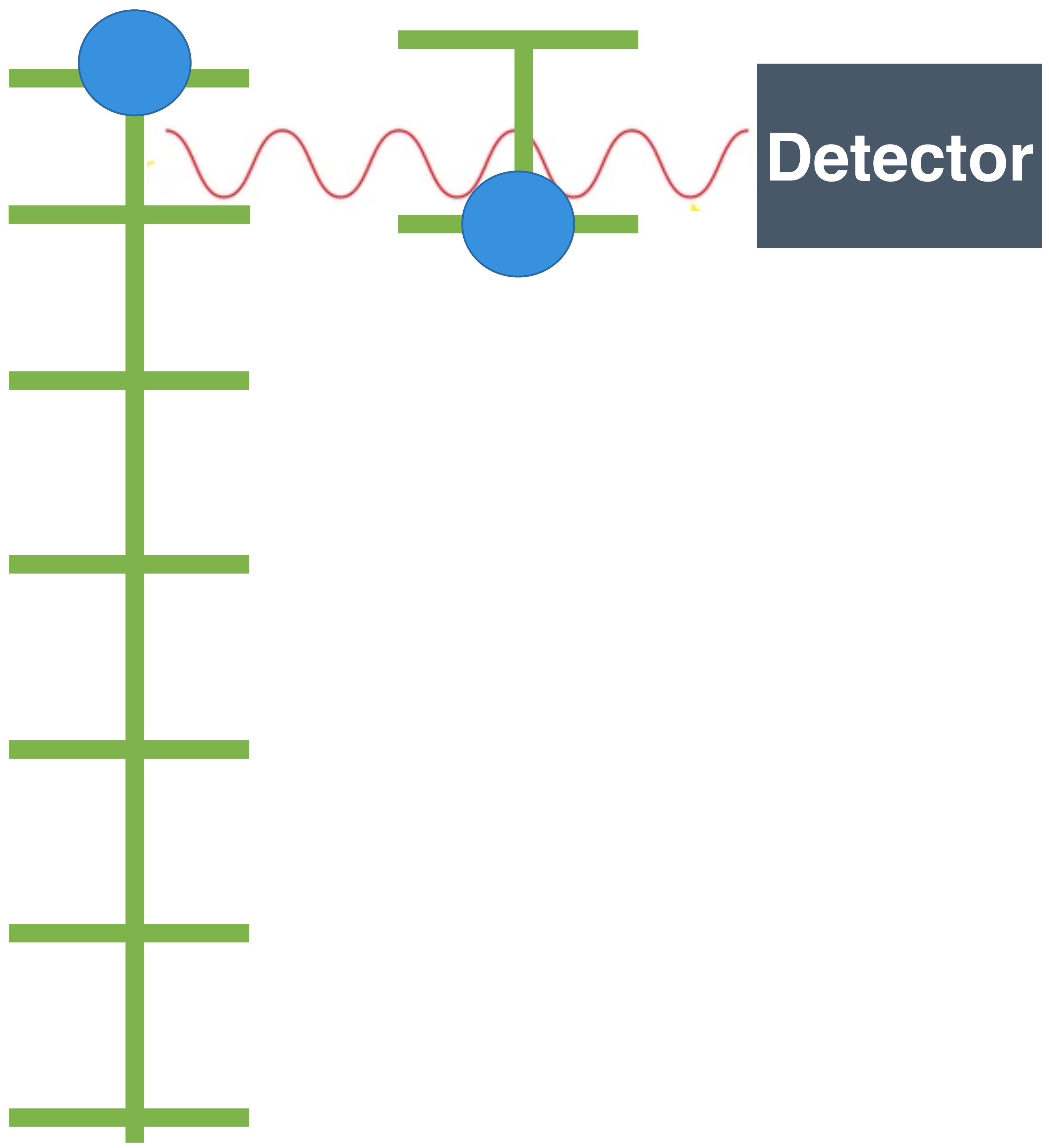


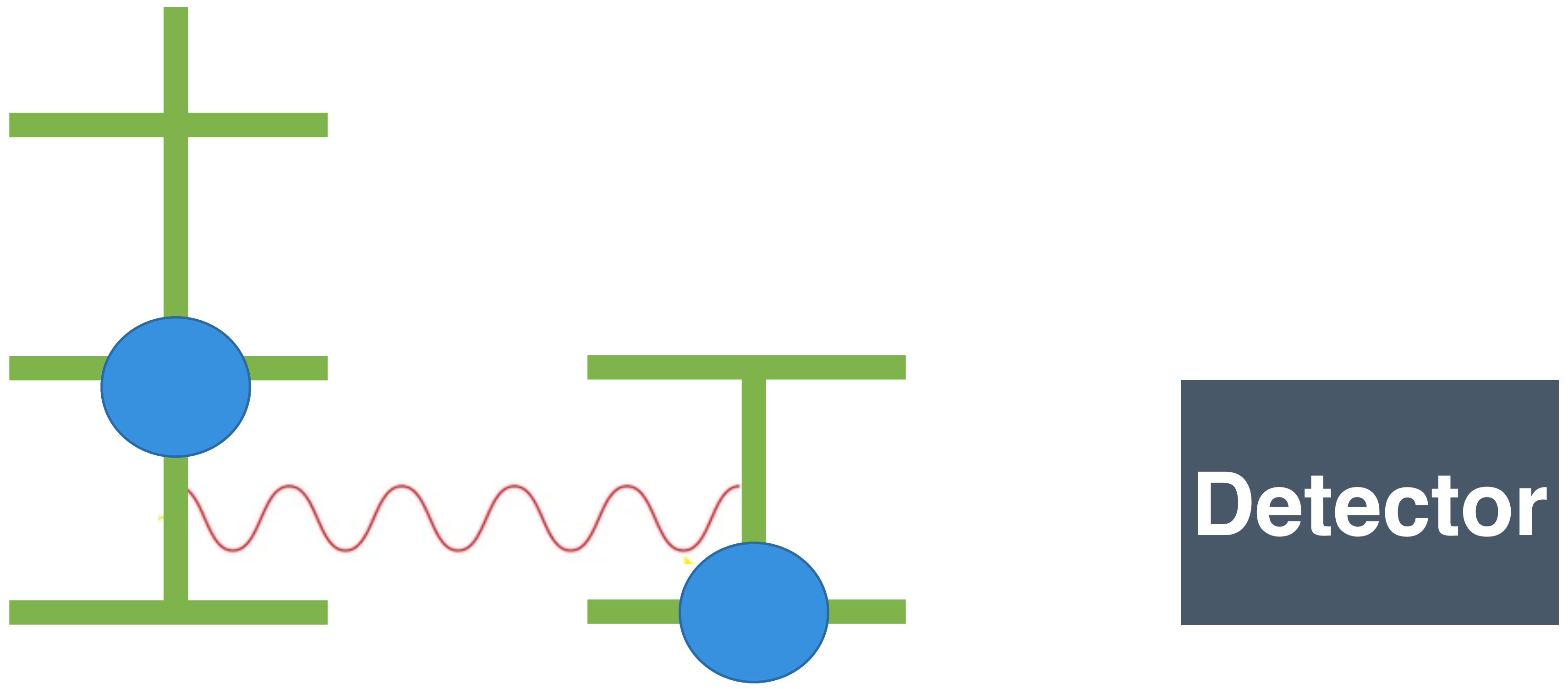
CASCADE VS CO-QUENCH

CASCADE



Off-Resonant

CO-QUENCH



- On-Resonance
- Absorption spoils time-coincidence
- Various methods

MEASUREMENT

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