Detecting Terrestrial Dark Matter Traffic Jams

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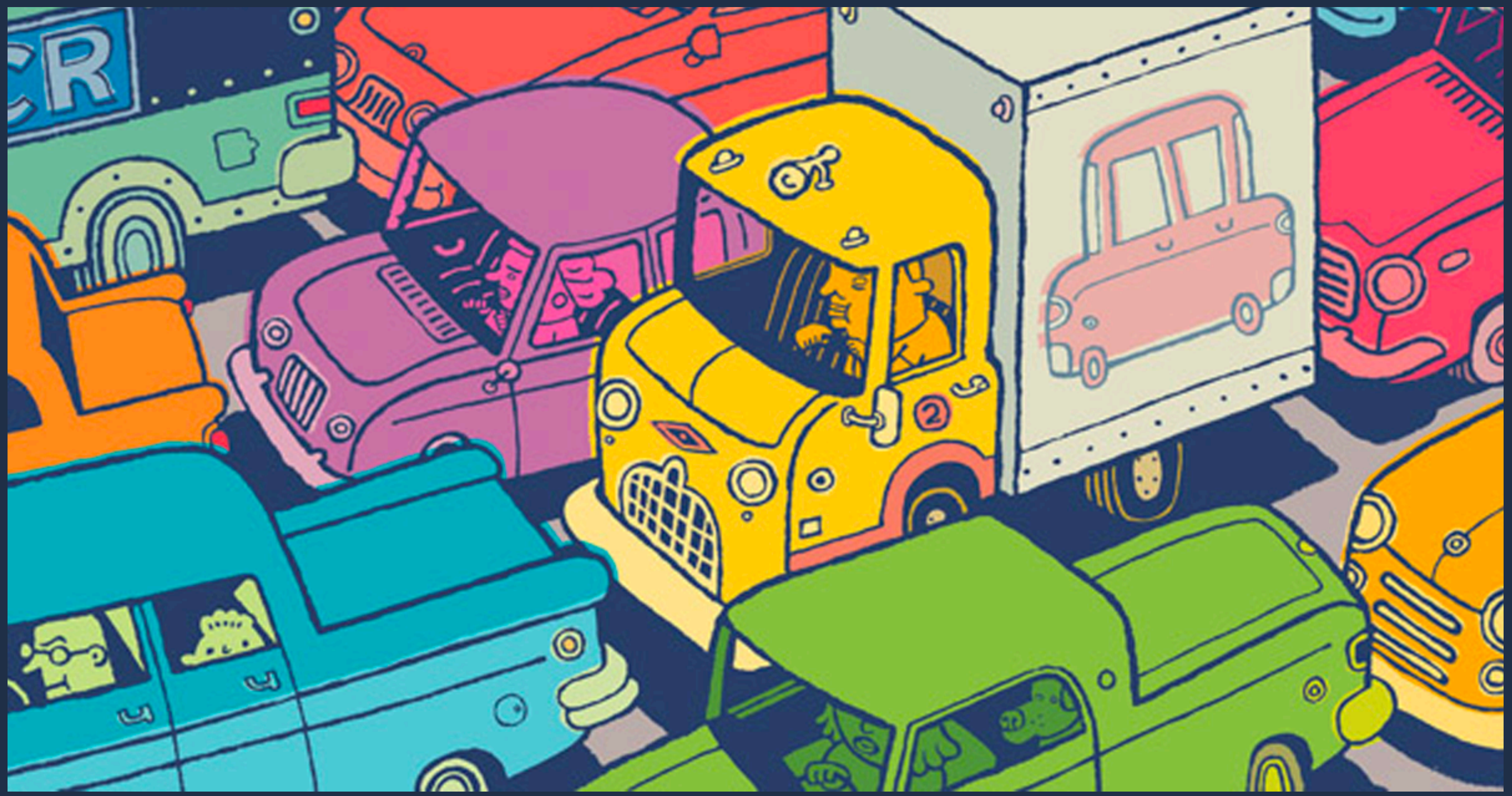
1907.00011 (PRD editor's suggestion)
with Maxim Pospelov and Surjeet Rajendran

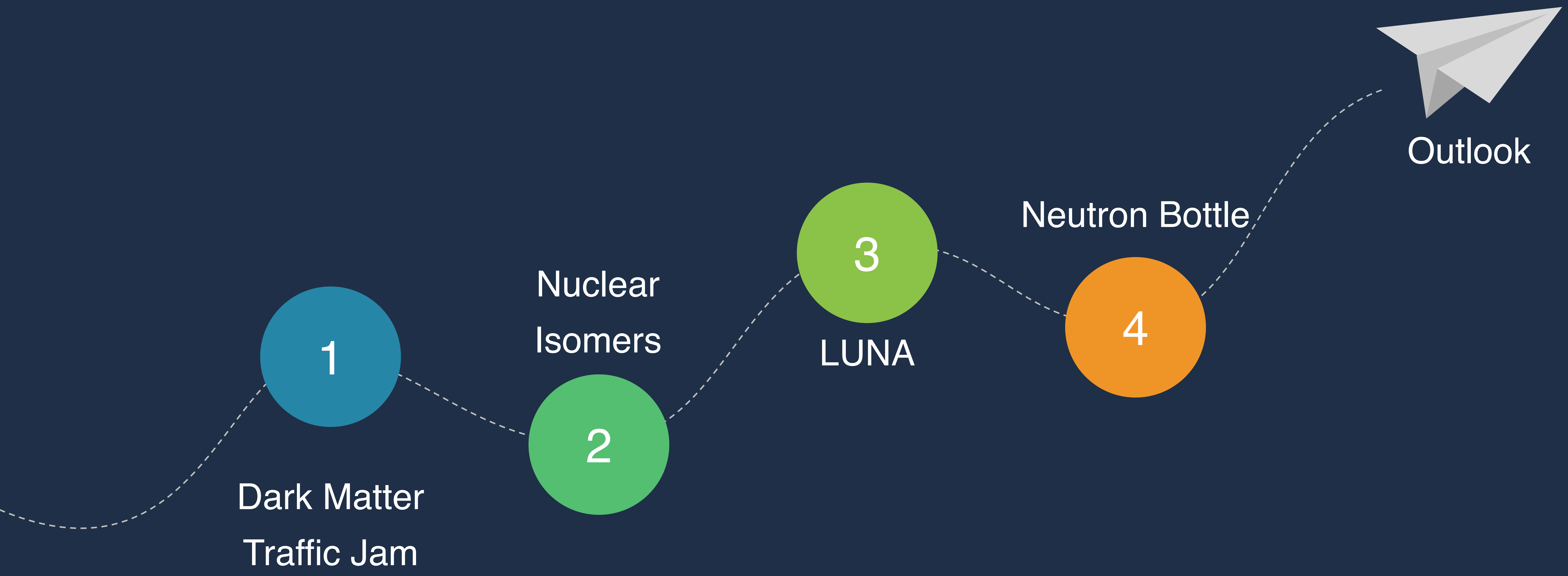
Experimental results arXiv:1911.07865 (PRL)
with M Hult, B Lehnert, G Lutter,
M Pospelov, S Rajendran, and Kai Zuber

2008.06061 with S Rajendran
Forthcoming with M Pospelov
Forthcoming with SR, Matt Pyle and Julien Billard




—Banksy

Outline



1
Dark Matter
Traffic Jam
2
Nuclear
Isomers
3
LUNA
4
Neutron Bottle
Outlook

Stable Dark Relics

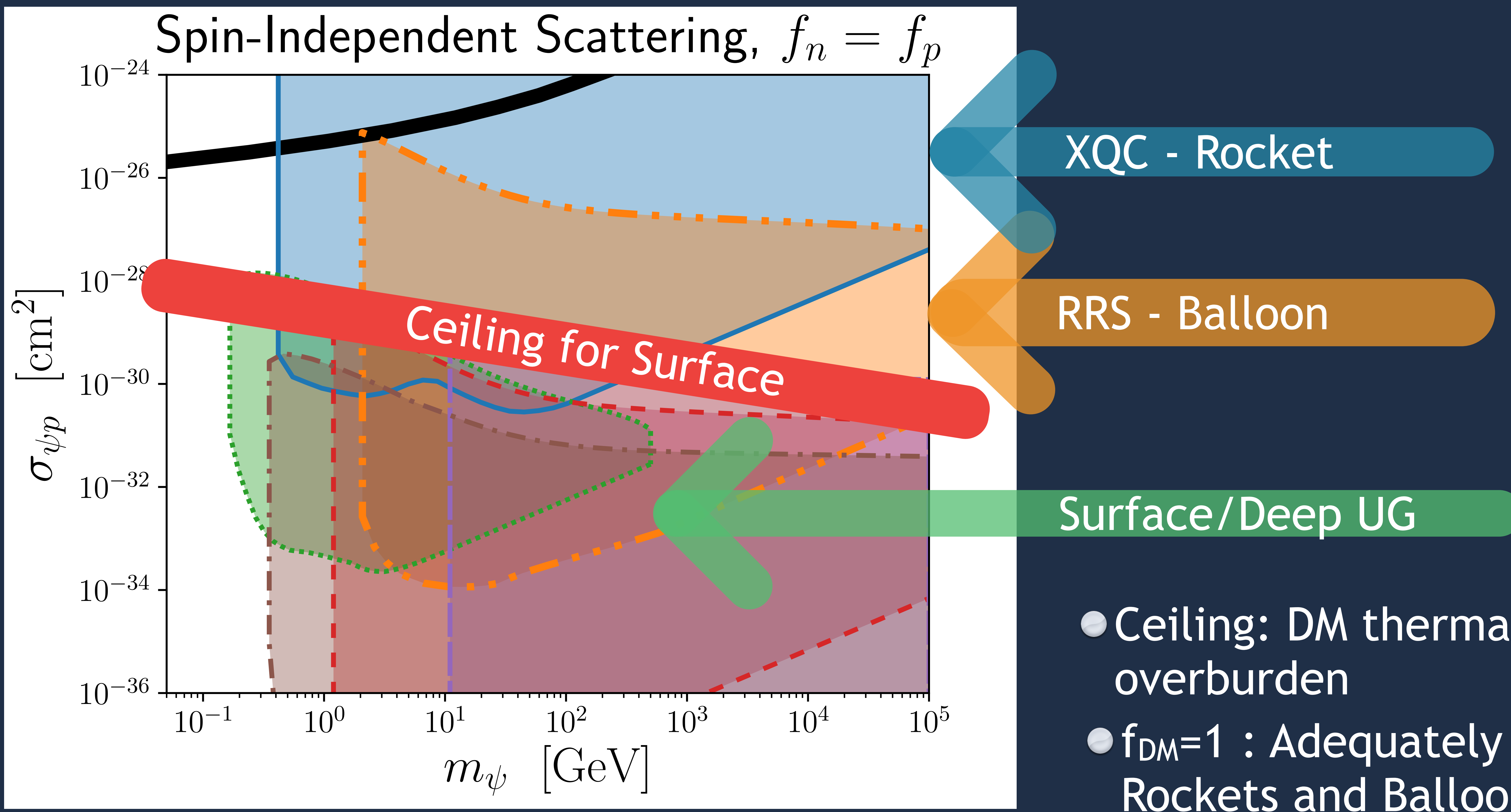
- Well motivated stable particles ubiquitous in literature
- Should expect some cosmic abundance
- DM examples: WIMPs, axions, mCPs
- Might not make up all of DM
- Could Dark Relic accumulate on earth?

Yes for large DM-SM cross-section

Large x-section: Model Variations

- Heavy quark - SM quark hybrid hadrons with strong interactions
    - Inspired by Gluinos - 1801.01135 Luca et al,1811.08418 - Gross et al
- Milli-charged particles 1908.06986 Liu et al, 1905.06348 Emken et al
    - Recent interest due to EDGES anomaly
- Blobs with large long range force 1807.03788 Grabowska et al
- Strong coupling typically predicts subcomponent DM

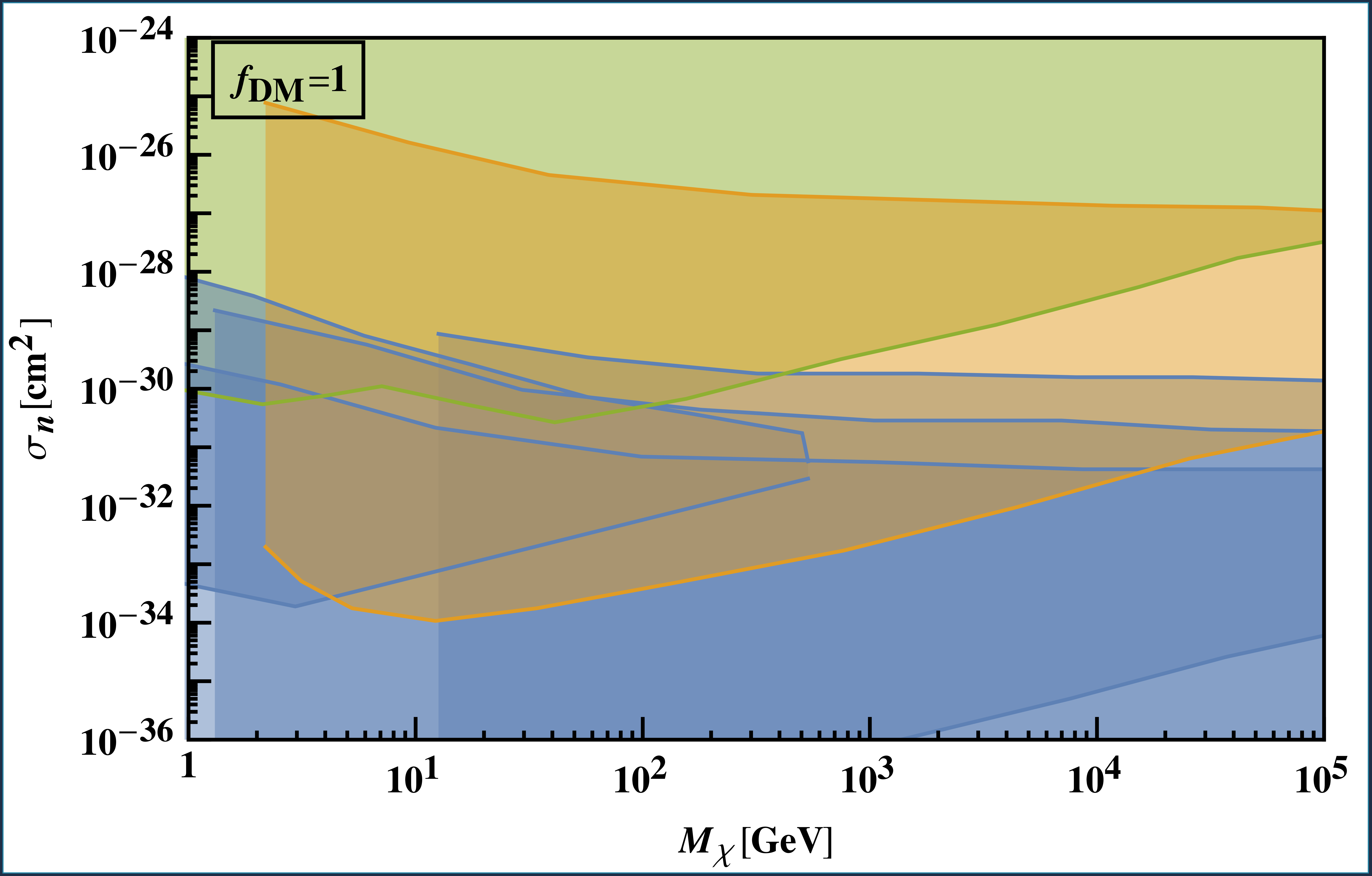
A ceiling for large coupling



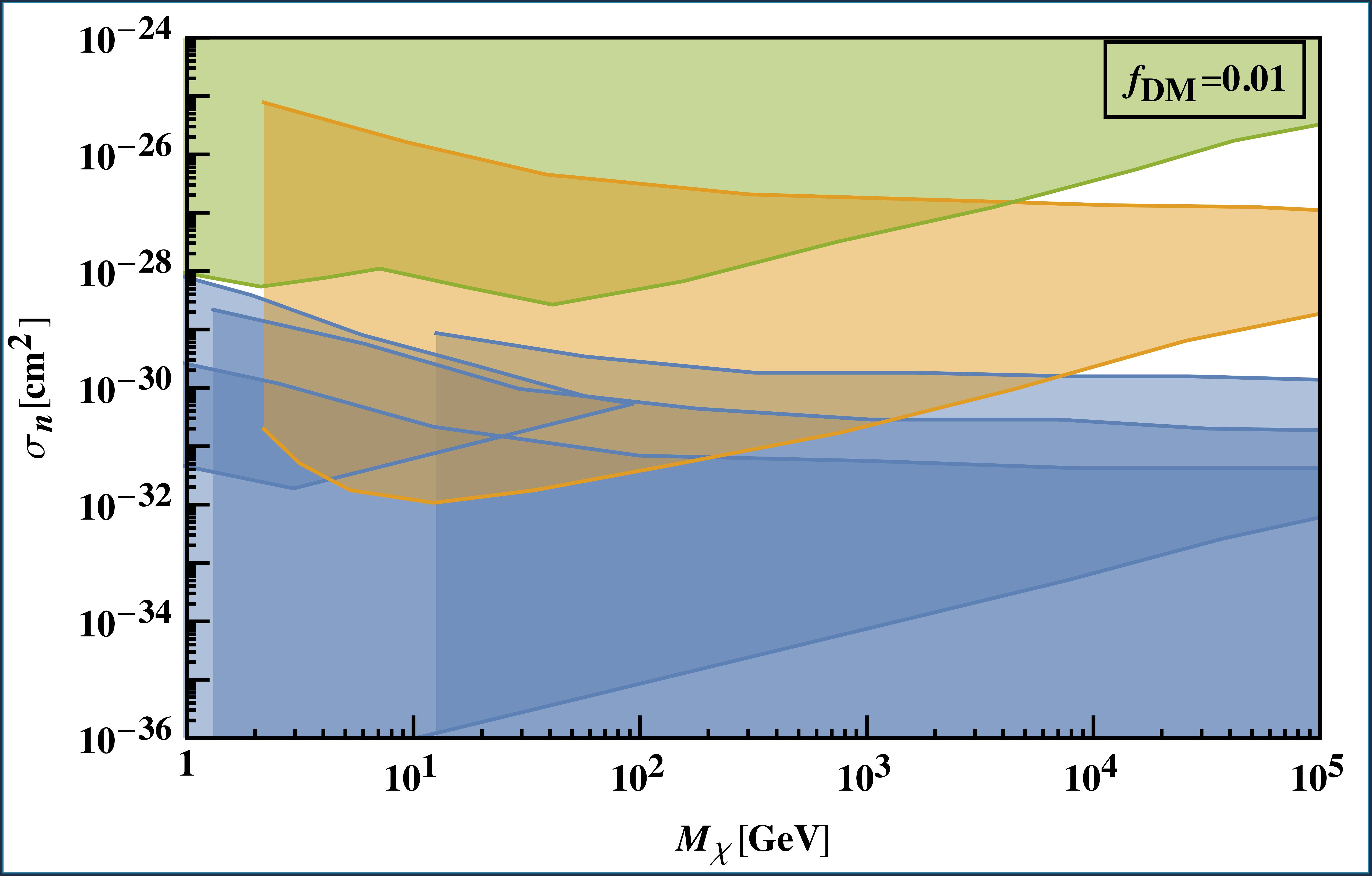
- Ceiling: DM thermalizes in overburden
- f_{DM}=1 : Adequately covered by Rockets and Balloons
- What about subcomponent?

[Hooper, McDermott 1802.03025]

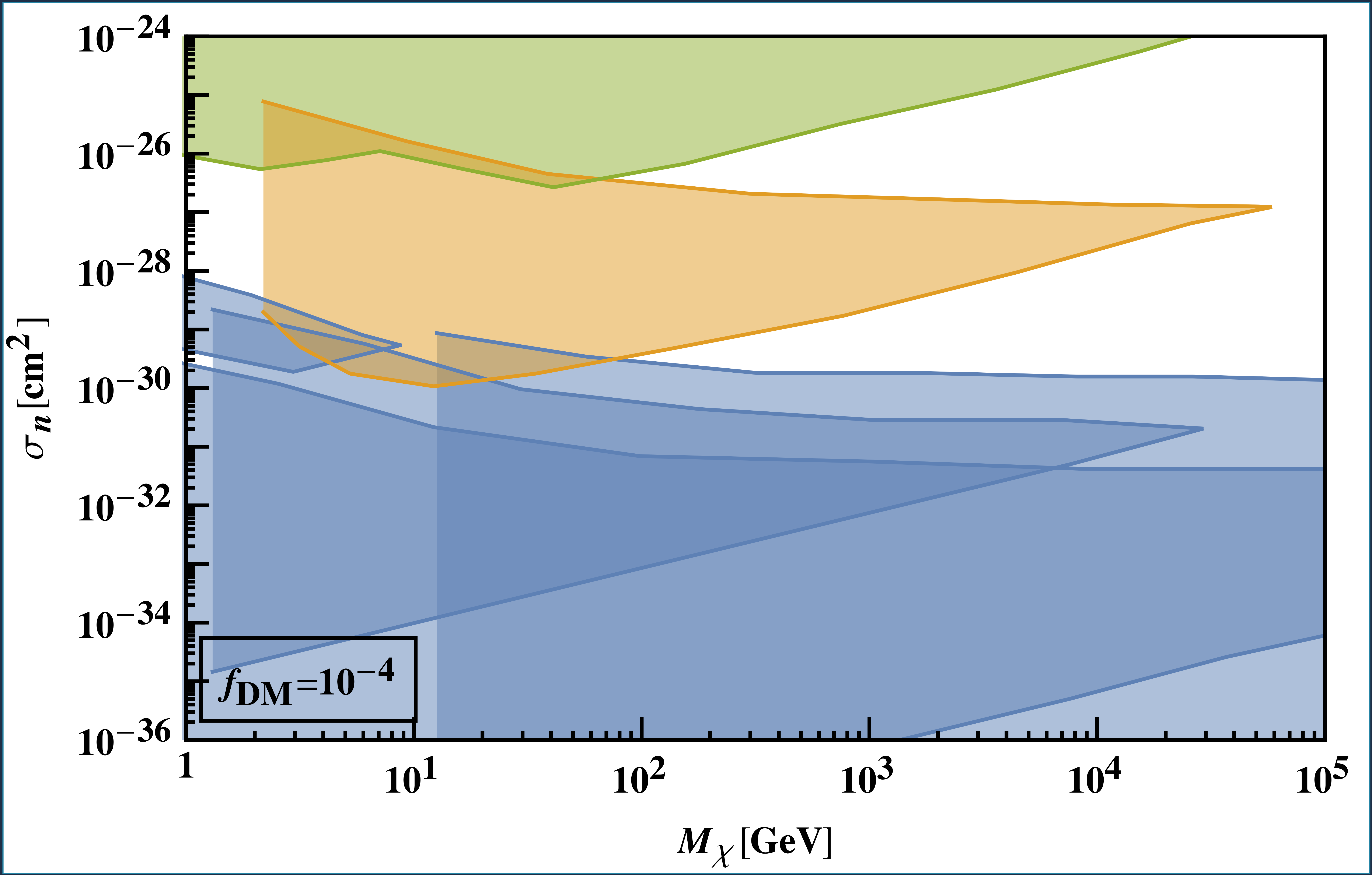
Subcomponent



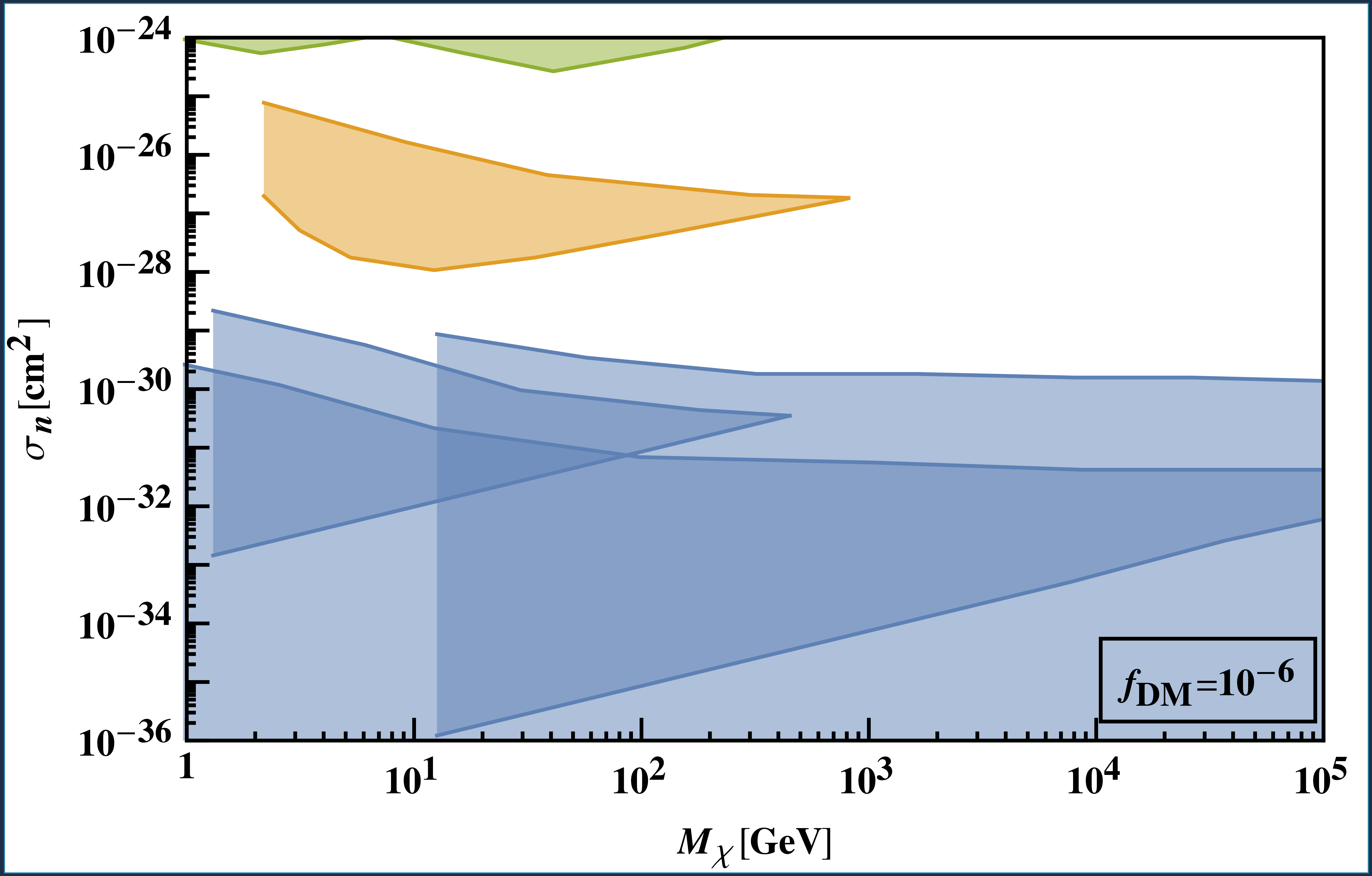
Subcomponent



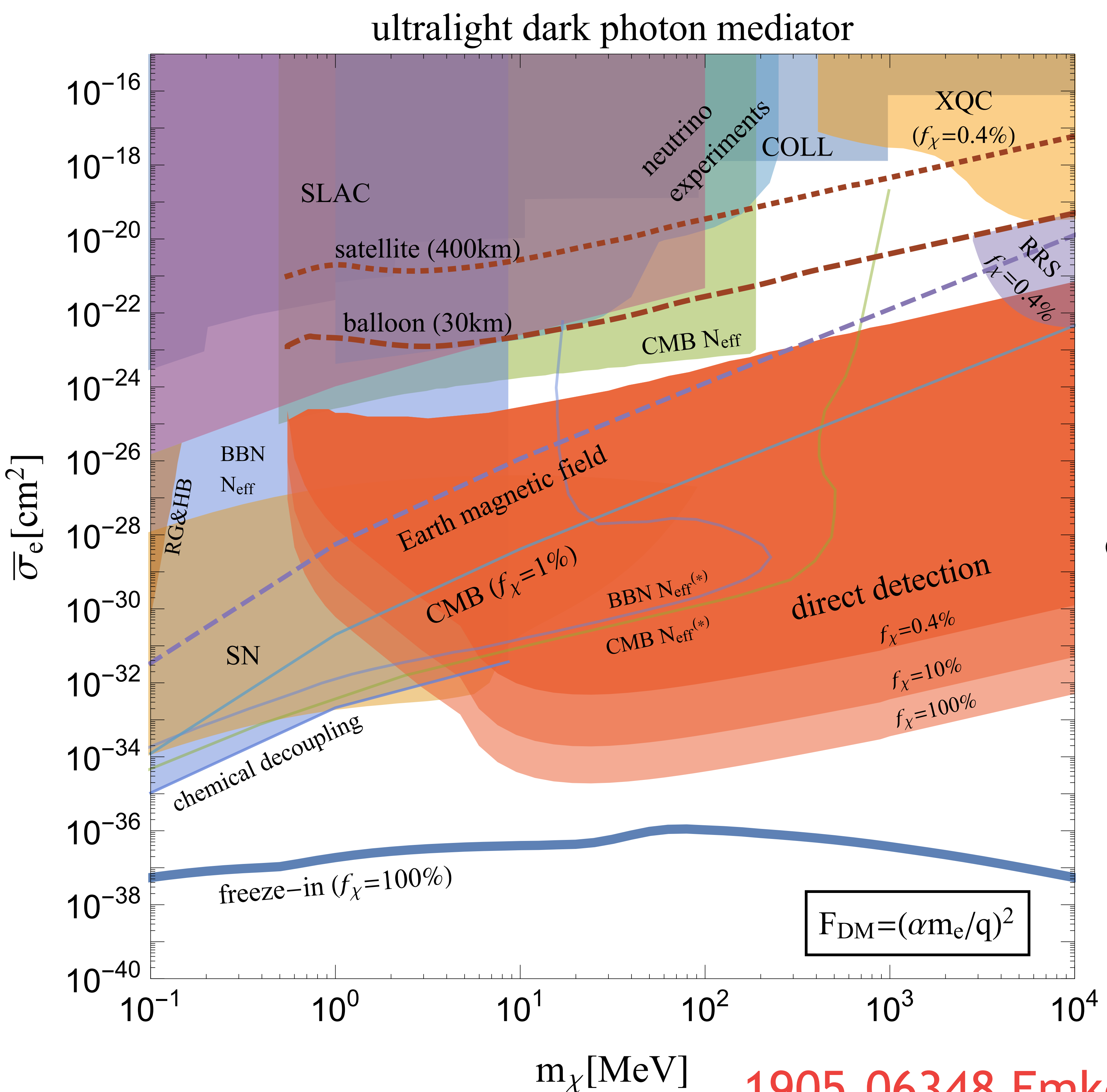
Subcomponent

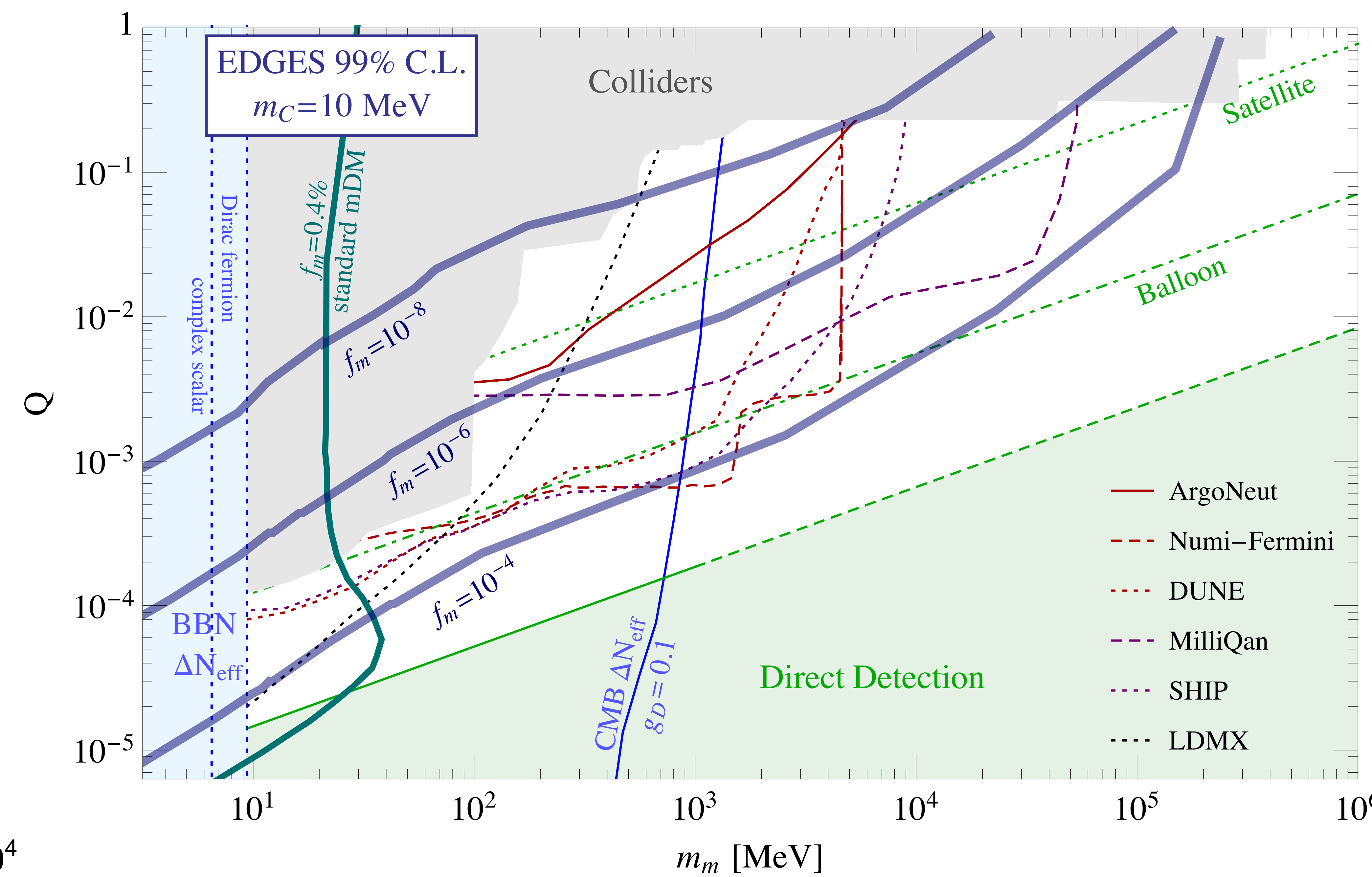


Subcomponent



MCP parameter space





1905.06348 Emken et al , 1908.06986 Liu et al

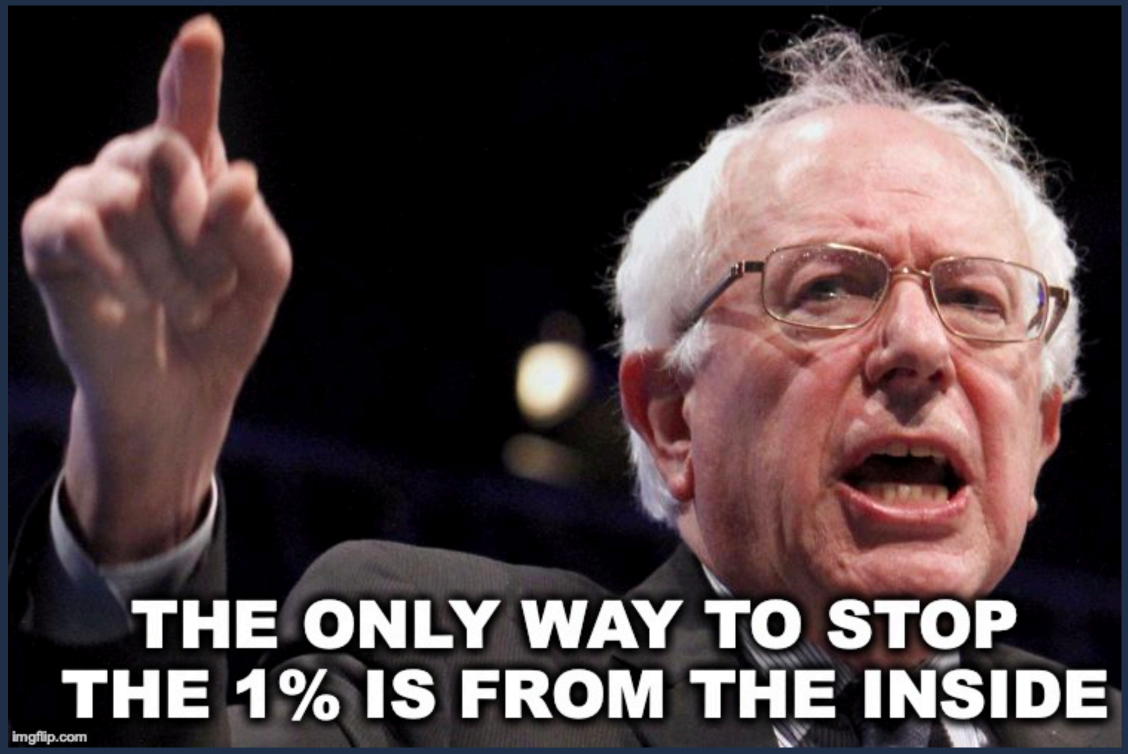
What happens to the shielded DM?

Dark matter accumulation

- With large x-sections, O(1) capture on earth
- Can lead to large enhancements

$$\langle \eta \rangle = \frac{\langle n \rangle}{n_{\rm vir}} = \frac{4\pi R_E^2}{4/3\pi R_E^3} v_{\rm vir} T_E \sim 2.2 \times 10^{16}$$

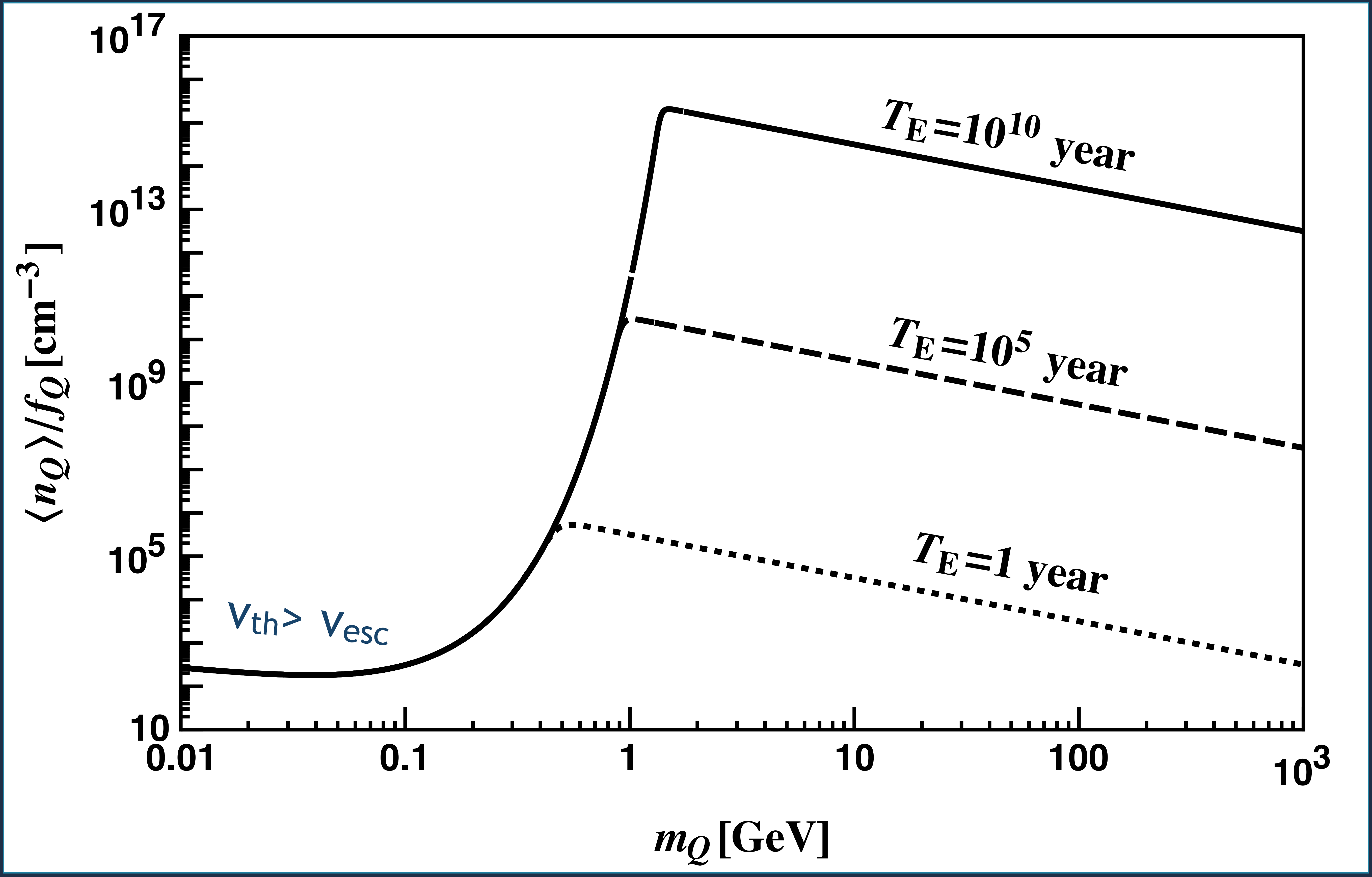
- Thermalized with T_{room}= 0.025 eV
- Does not show up in traditional DD
- But how much collects near the surface?



Evaporation

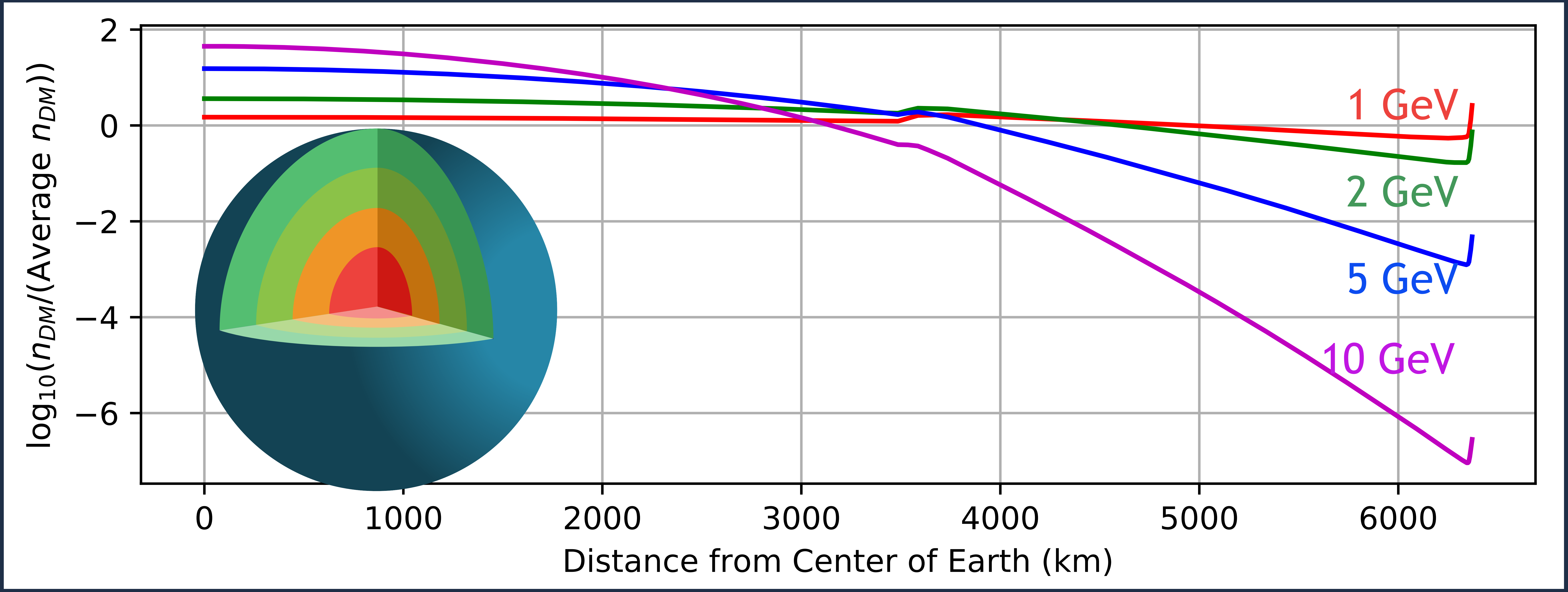
DM below GeV rapidly evacuates since
thermal velocity is larger than escape velocity

Also see: 1805.08794:Neufeld, Farrar, McKee



Equilibrated population

- gravity, temperature, density variations on earth



DM heavier than 1 GeV sinks
DM lighter than 1 GeV evaporates

1805.08794:Neufeld, Farrar, McKee

Heavier population

- Sinking not immediate:
- Diffusion

$$v_{\rm diff} = \frac{v_{\rm th}}{h n_{\rm rock} \sigma_T}$$

- Terminal velocity is set up

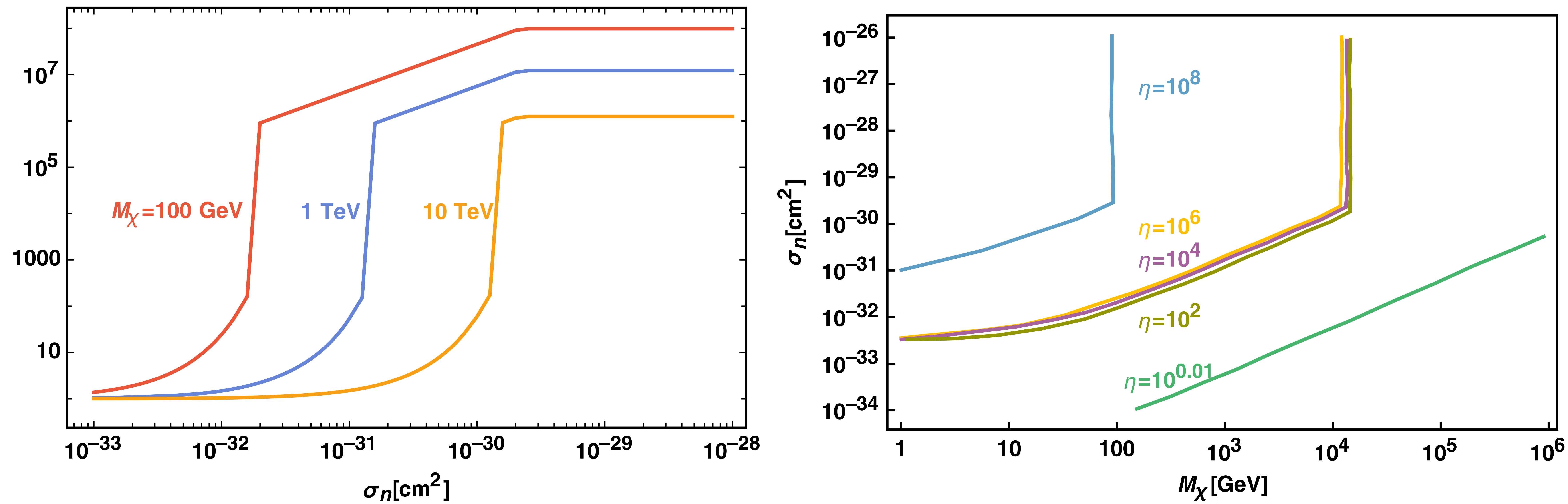
$$v_{\rm term} = \frac{3 m_\chi g T}{m_{\rm gas}^2 n_{\rm gas} \langle \sigma_T v^3 \rangle}$$

- Traffic Jam on the way

$$\eta_{\rm diff(term)} = \frac{n_{\rm diff(term)}}{n_{\rm vir}} = \frac{v_{\rm vir}}{v_{\rm diff(term)}}$$

Heavier population

Contact interactions



ArXiv: 1907.00011

Transfer x-section saturated by size of rock nuclei

How to detect?

- Dark Matter very slow: E~ 0.025 eV
- Large number densities
- Detector with low/no threshold at the expense of exposure?
- Can we accelerate this dark matter?
- After-all, large number densities and cross-sections

Detection Strategies

Nuclear Isomers

Strongly interacting DM

Electrostatic accelerators

Millicharge DM

Neutron Bottle

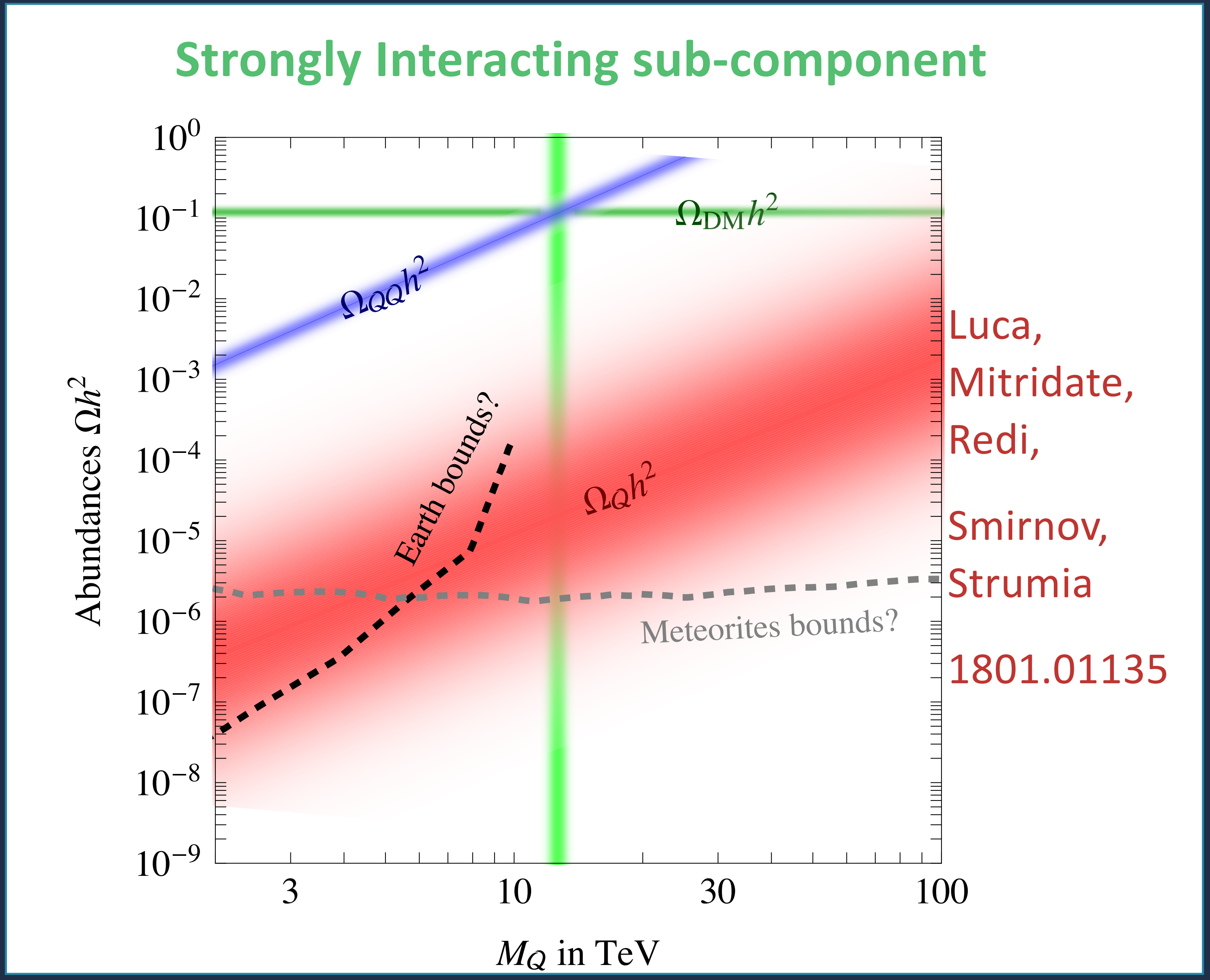
Composite DM

Nuclear Isomers

Contact Interactions and Inelastic DM

Hybrid Hadrons

- Dark matter model with bound state of exotic colored state: QQ if Q ~ 8, and QQQ if Q ~ 3), $E_B \sim (\alpha_3)^2 M_Q$.
- A small subpopulation forms hybrid hadrons with SM quarks: strongly interacting.
- Stable sexaquark dark matter ~ 2 GeV

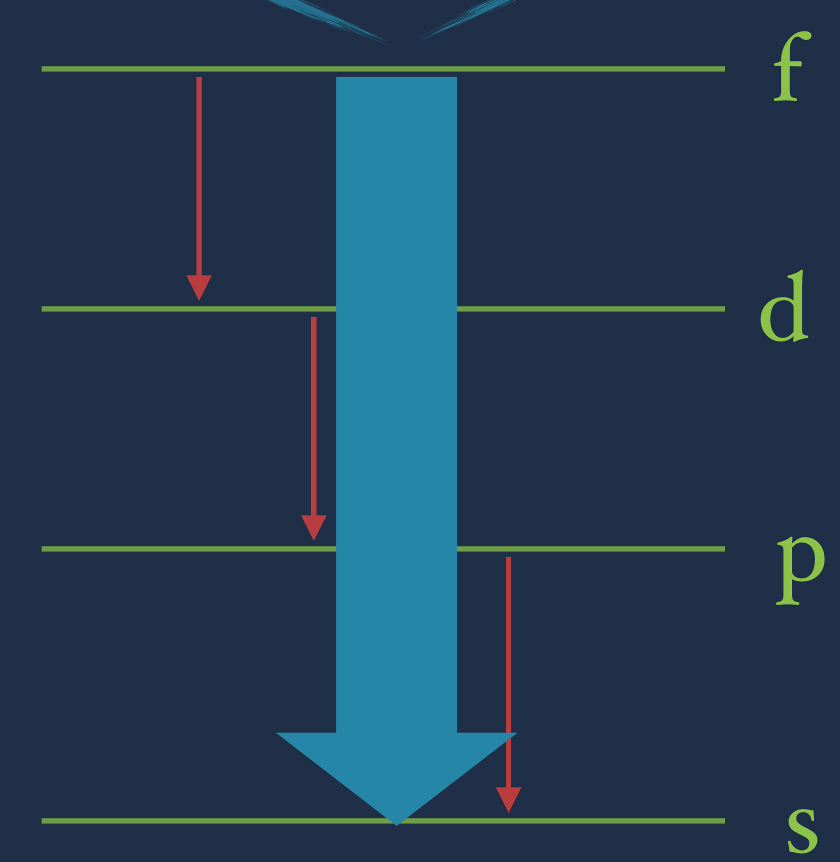


Farrar et al 1708.08951

Thought Experiment

DM with orbital L can cause transition

Hard to shed high L into single photon: Metastable



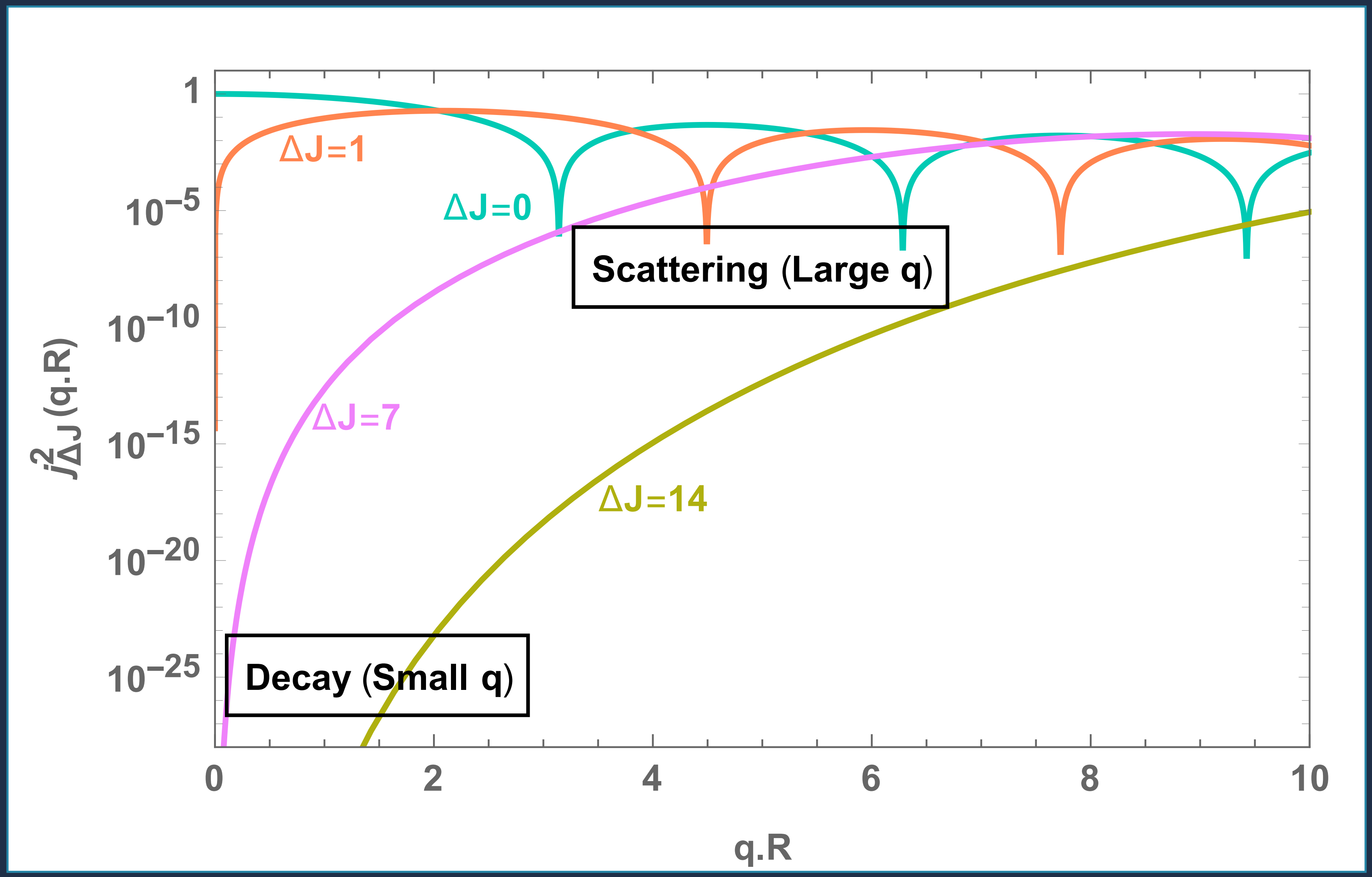
DM can leave with some of the E_f-E_s energy

Isomers

- Same Z and A different binding energies/nuclear spins.
- Spin difference of ΔJ , lifetime ~ $(k.R_N)^{2\Delta J}$ and $k.R_N << 1$
- Typical nuclear transitions: few ps
- Isomers can have very large timescales
- Store energy in the higher excited state and long-lived
- The army has been interested in metastable isomers as an "energy storage device"

Decay vs Scattering

- Scattering probes at larger momentum, can break the angular momentum barrier



Bessel function estimate, similar to:
Weisskopf estimates for decay

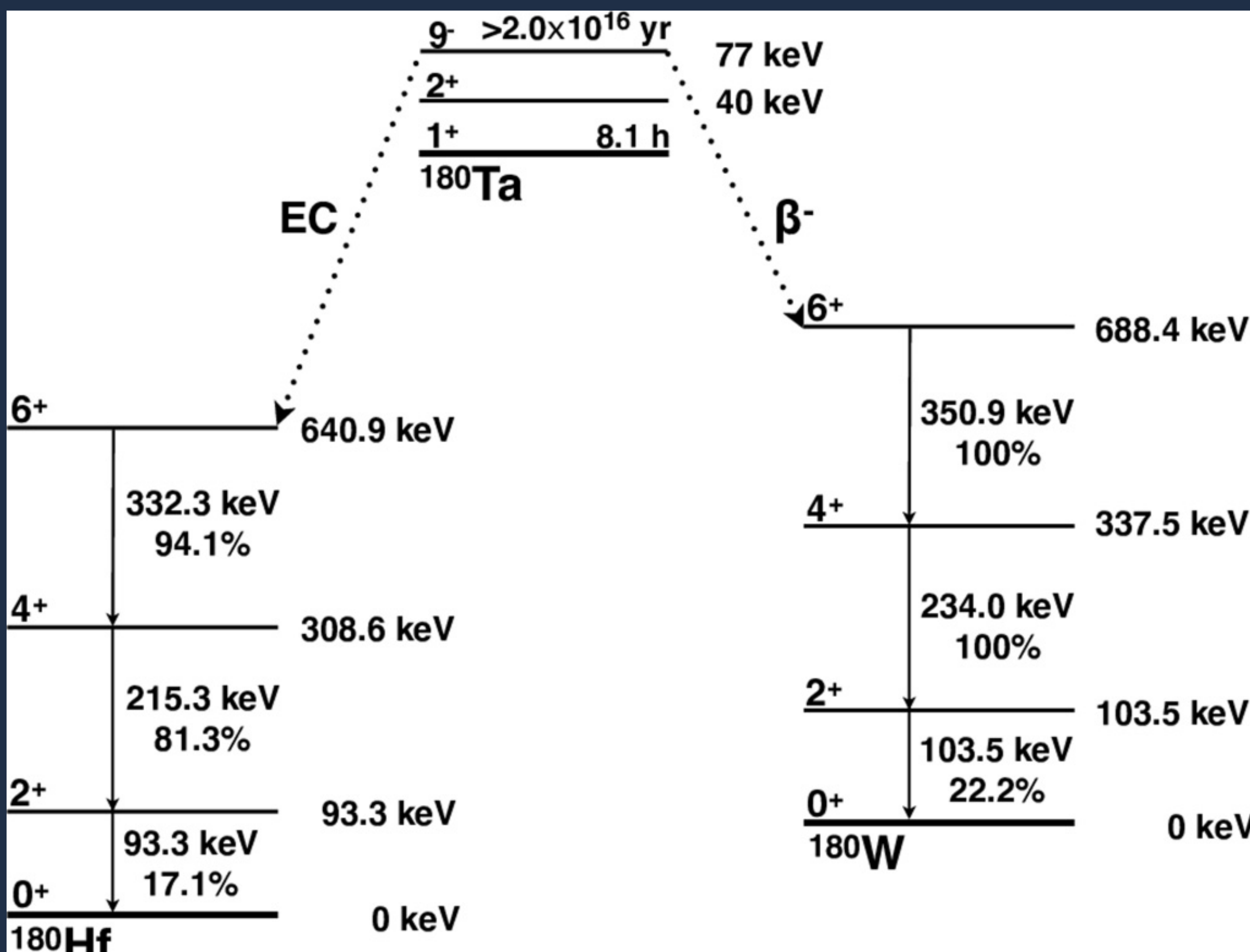
- DM scattering induces transition steals energy in the process…
- An Exothermic Dark Matter Detector

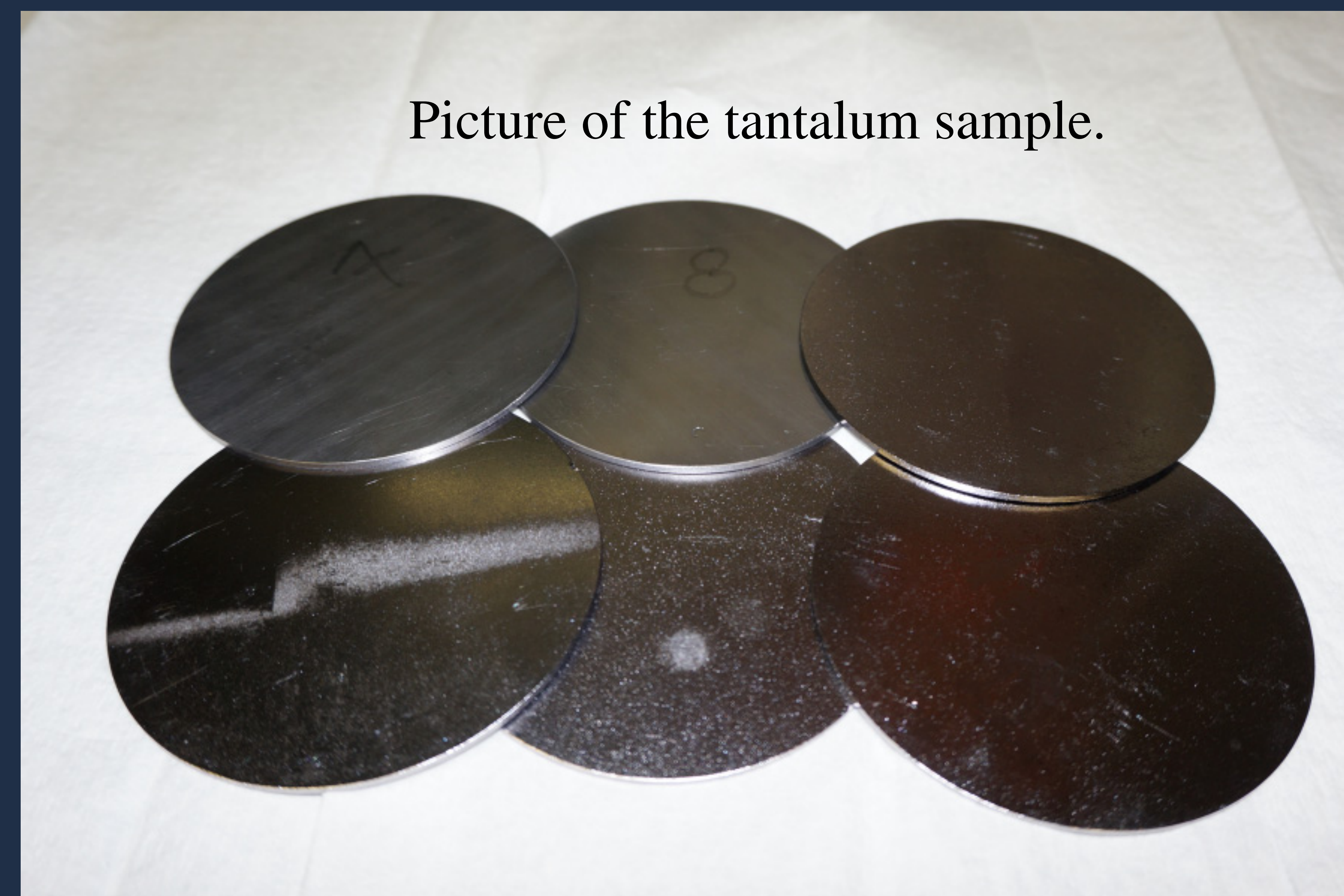
Isomer Candidates

Isomer	$\Delta E_N^{\max}$	levels	Half-life	Source
^{180m}Ta	77 keV	2	$> 10^{16}$ y	Natural
^{137m}Ba	661 keV	2	2.55 min	Nuclear Waste
^{177m}Lu	970 keV	27	160 d	Medical Waste
^{178m}Hf	2.4 MeV	110	31 y	Old experiments

0.01% of all Tantalum mined is ^{180m}Ta

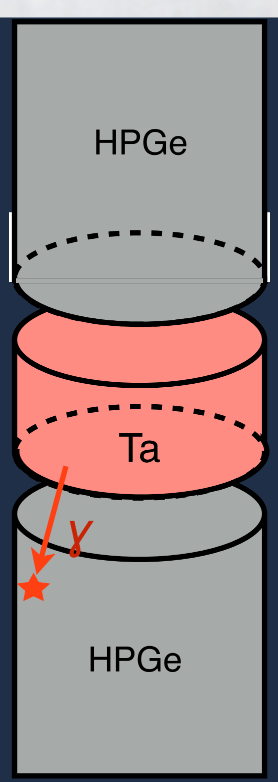
Isomeric Tantalum





Search for the decay of natures rarest isotope ^{180m}Ta

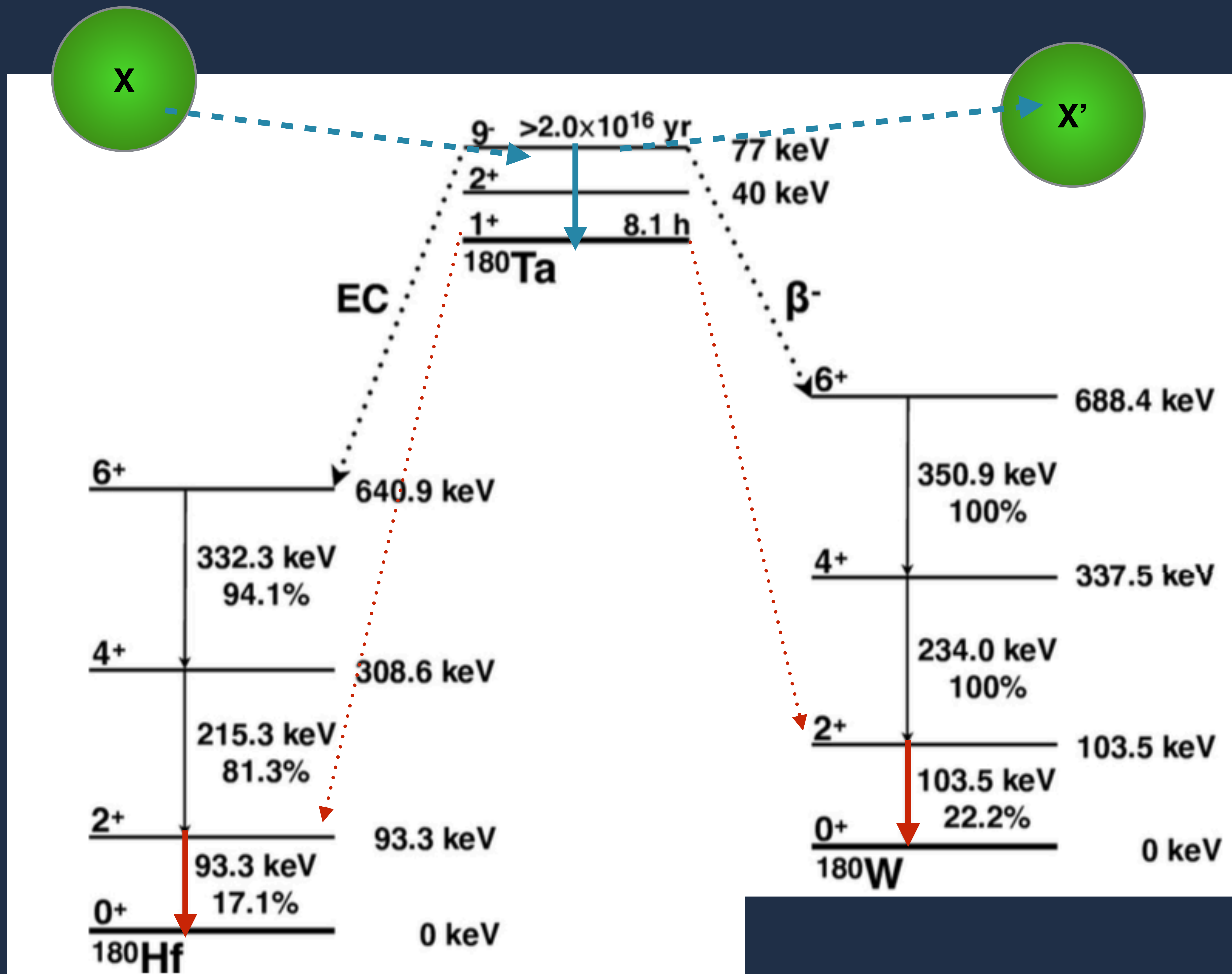
B. Lehnert,[1,2,a] M. Hult,[3,b] G. Lutter,[3,c] and K. Zuber[1,d]



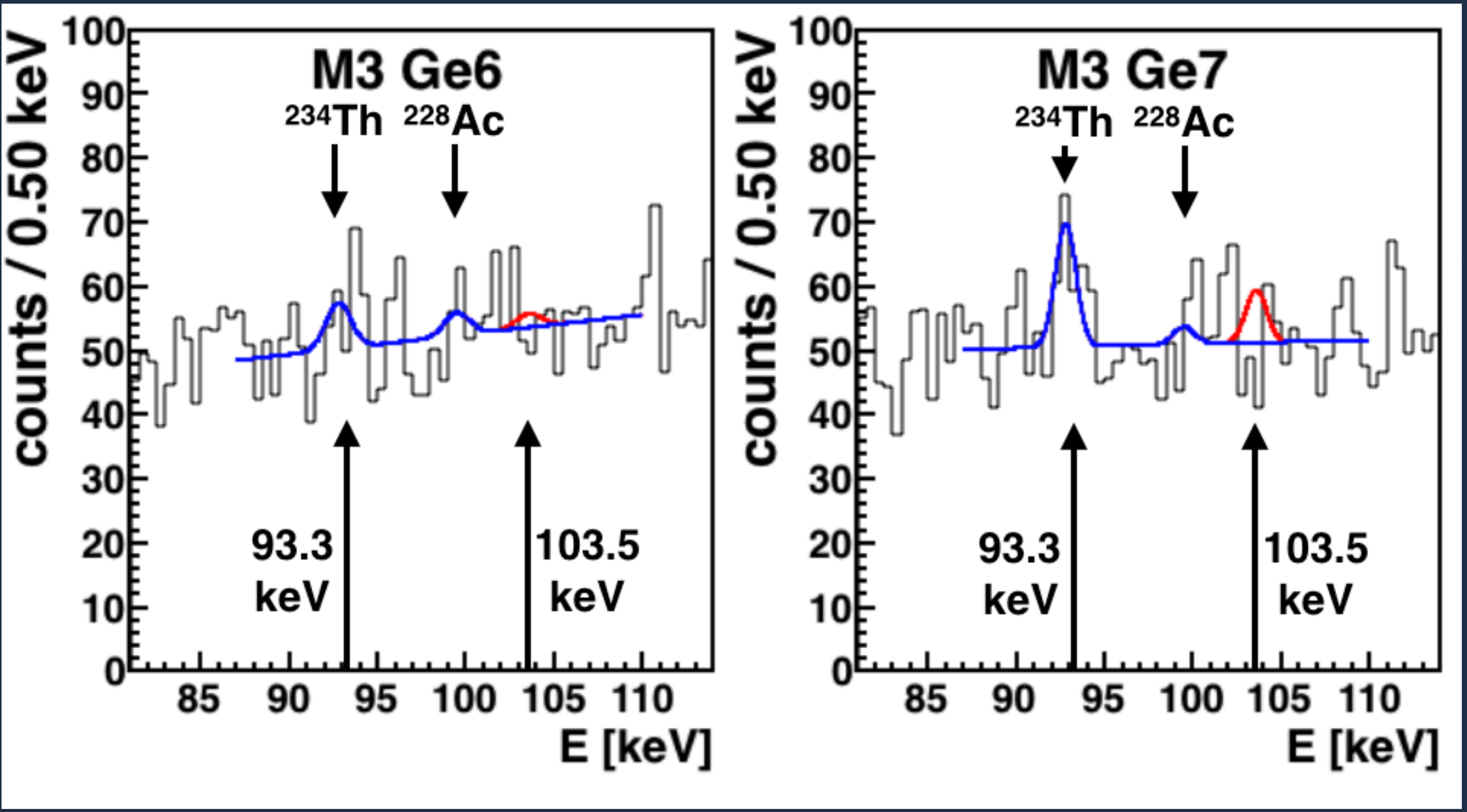
Mode	Half-life 90% CI
β-	>5.8·10^16 yr
EC	>2.0·10^17 yr

Searched for subsequent gamma emission from decays

Isomeric Tantalum as a DM detector



Results



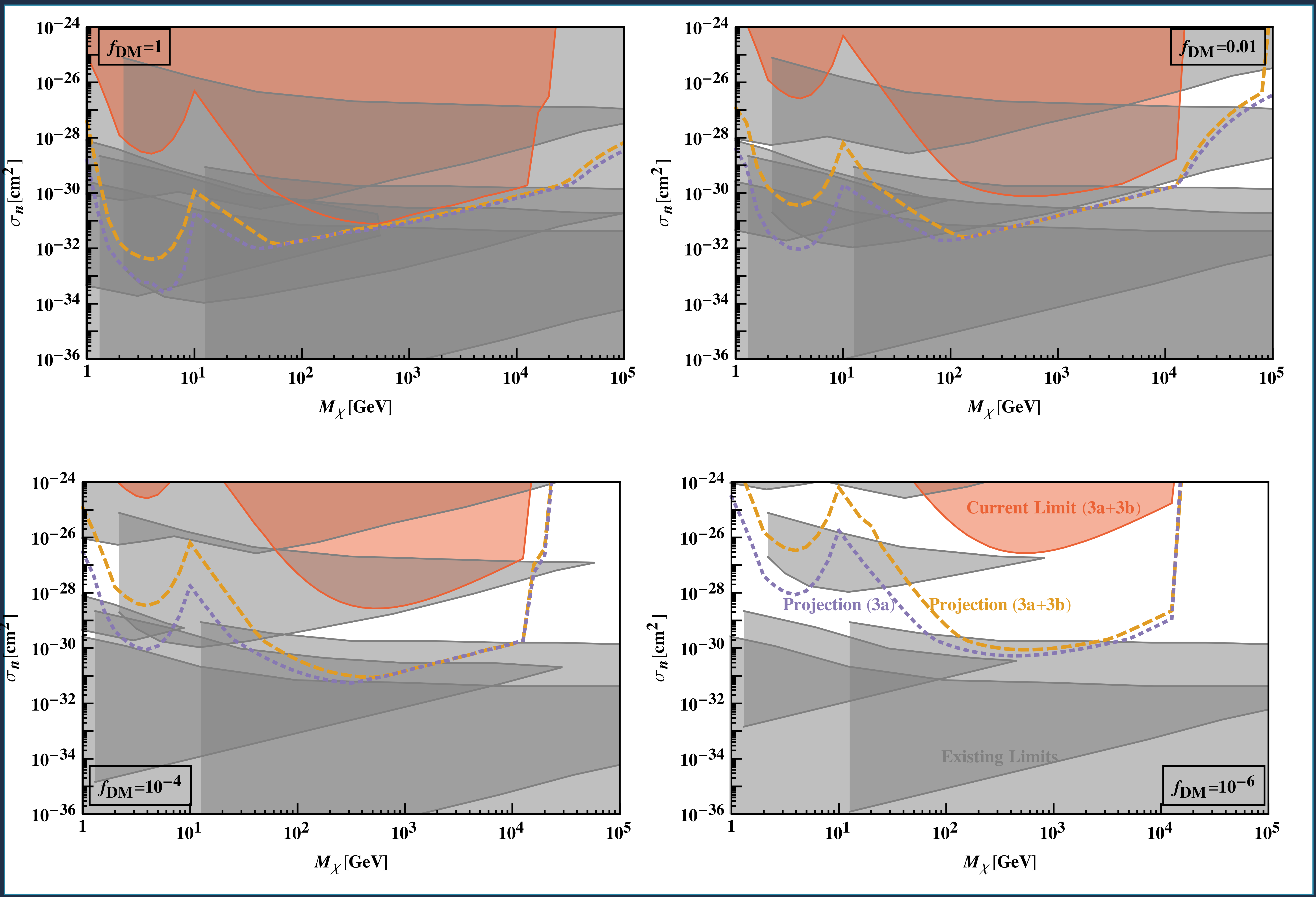
- 93.3 keV line has background contamination
- 103.5 keV used to set limits

$$T_{\frac{1}{2}} > 1.3 \cdot 10^{14}\,\mathrm{yr}\ (90\%\ \mathrm{C.I.})$$

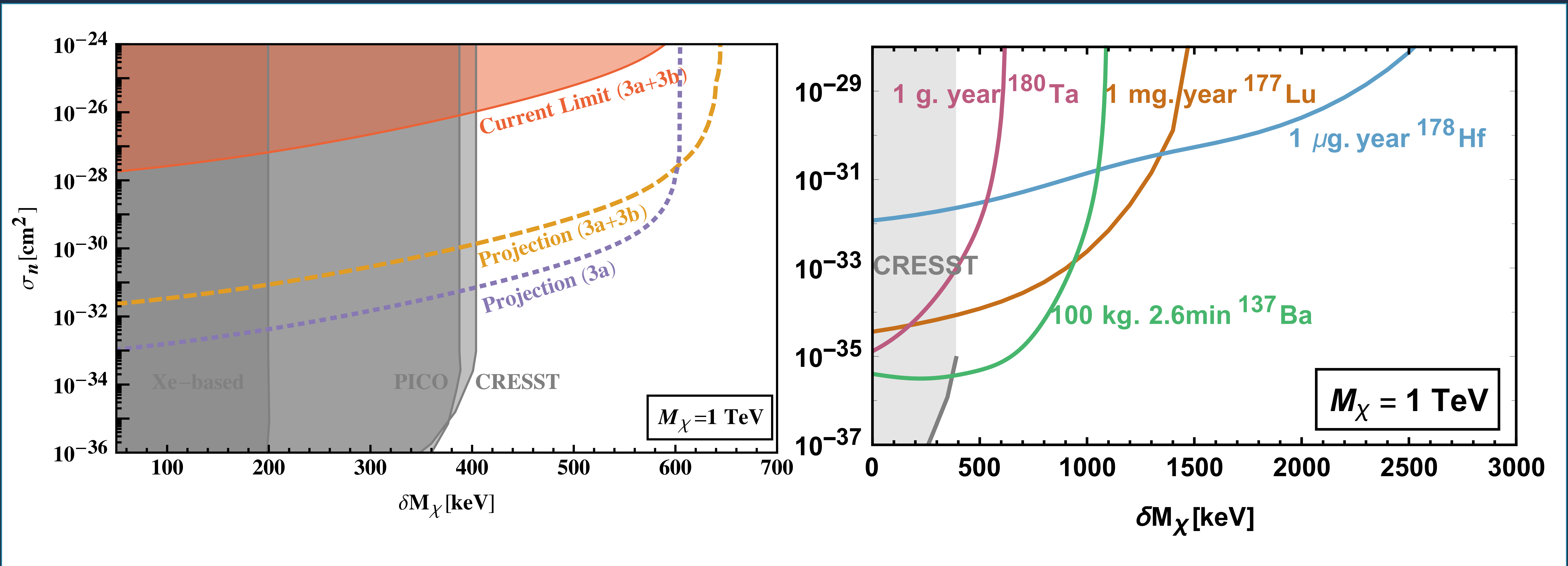
$$\langle \sigma_{\chi \mathrm{Ta}} v_\chi \rangle \leq \frac{M_\chi \log(2)}{T_{\frac{1}{2}}\, \rho_{\mathrm{lab}}}$$

Limits and Projections

Current: $3 \cdot 10^{14}$ a Future: 3(a)+3(b) $1 \cdot 10^{18}$ a 3(a) $4 \cdot 10^{19}$ a

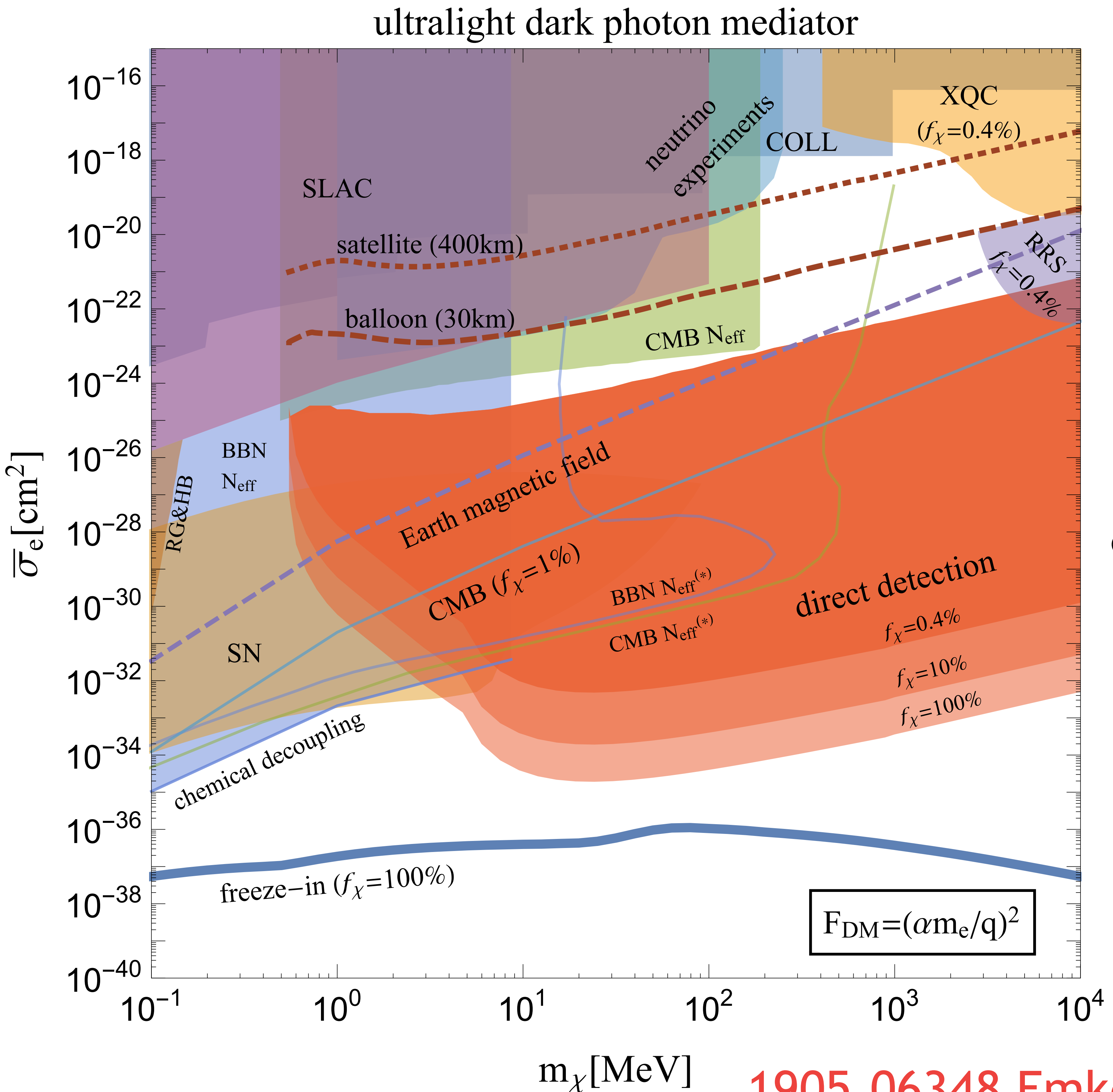


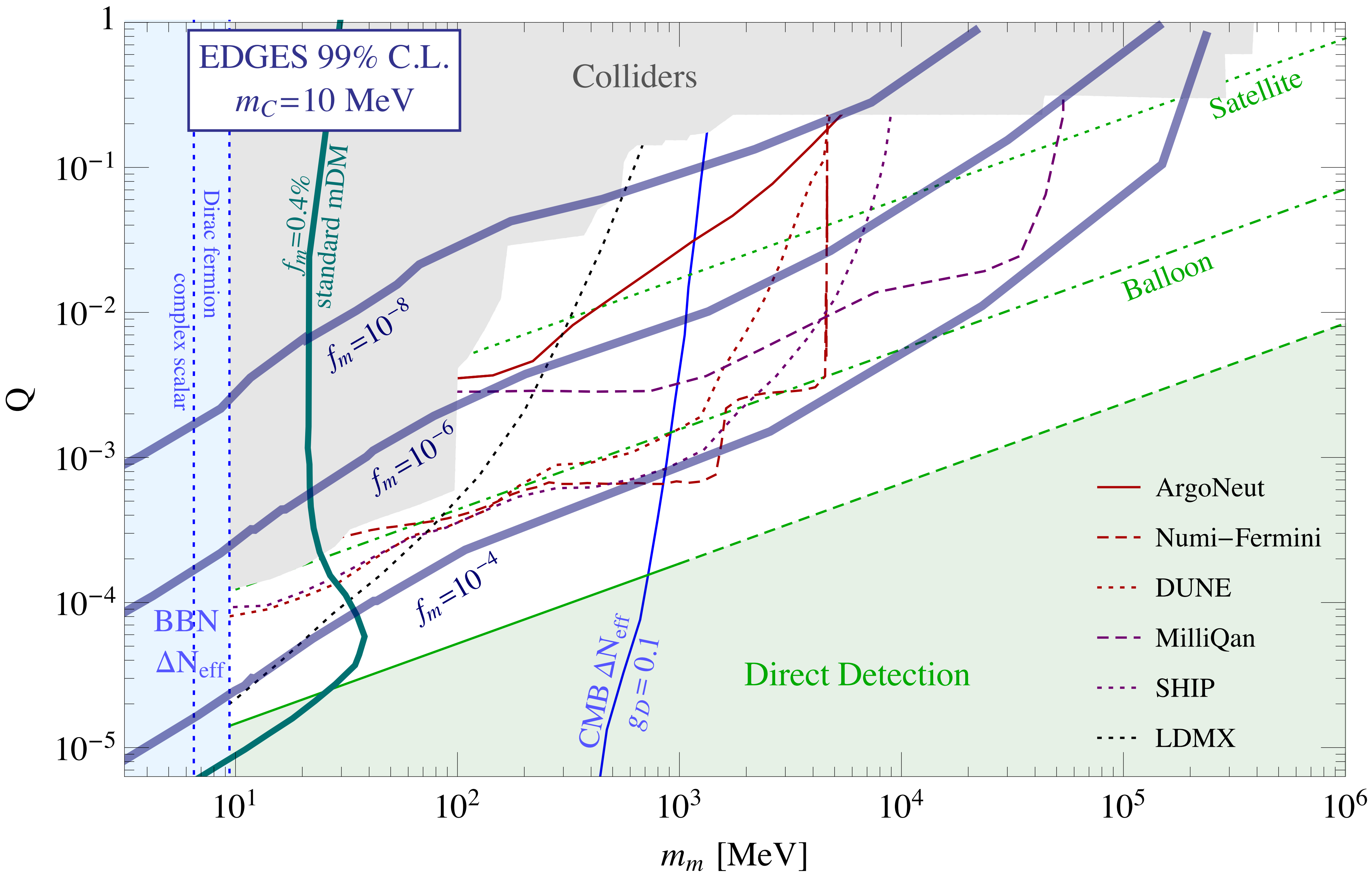
Inelastic Dark Matter



Millicharge Particles

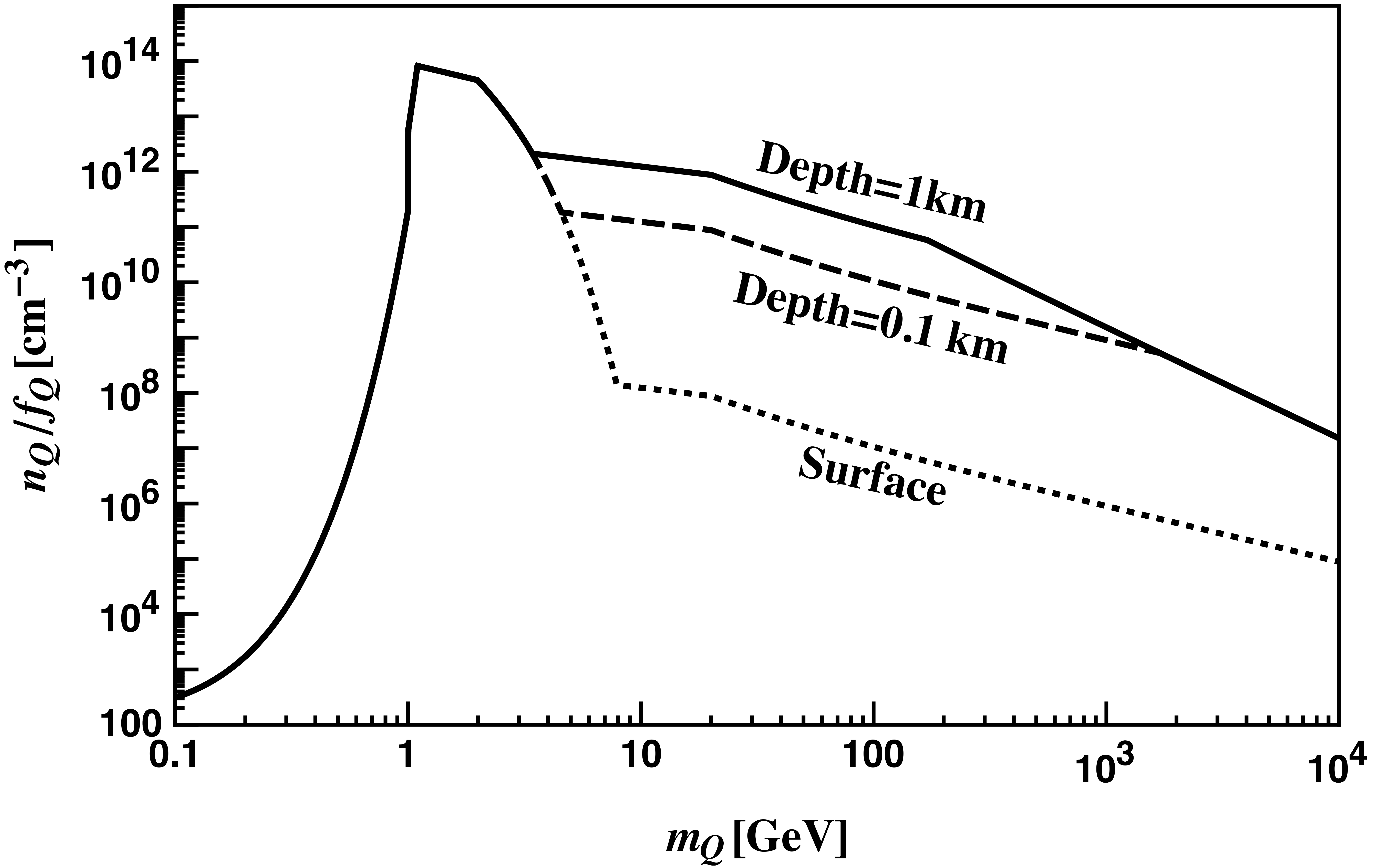
mCP parameter space





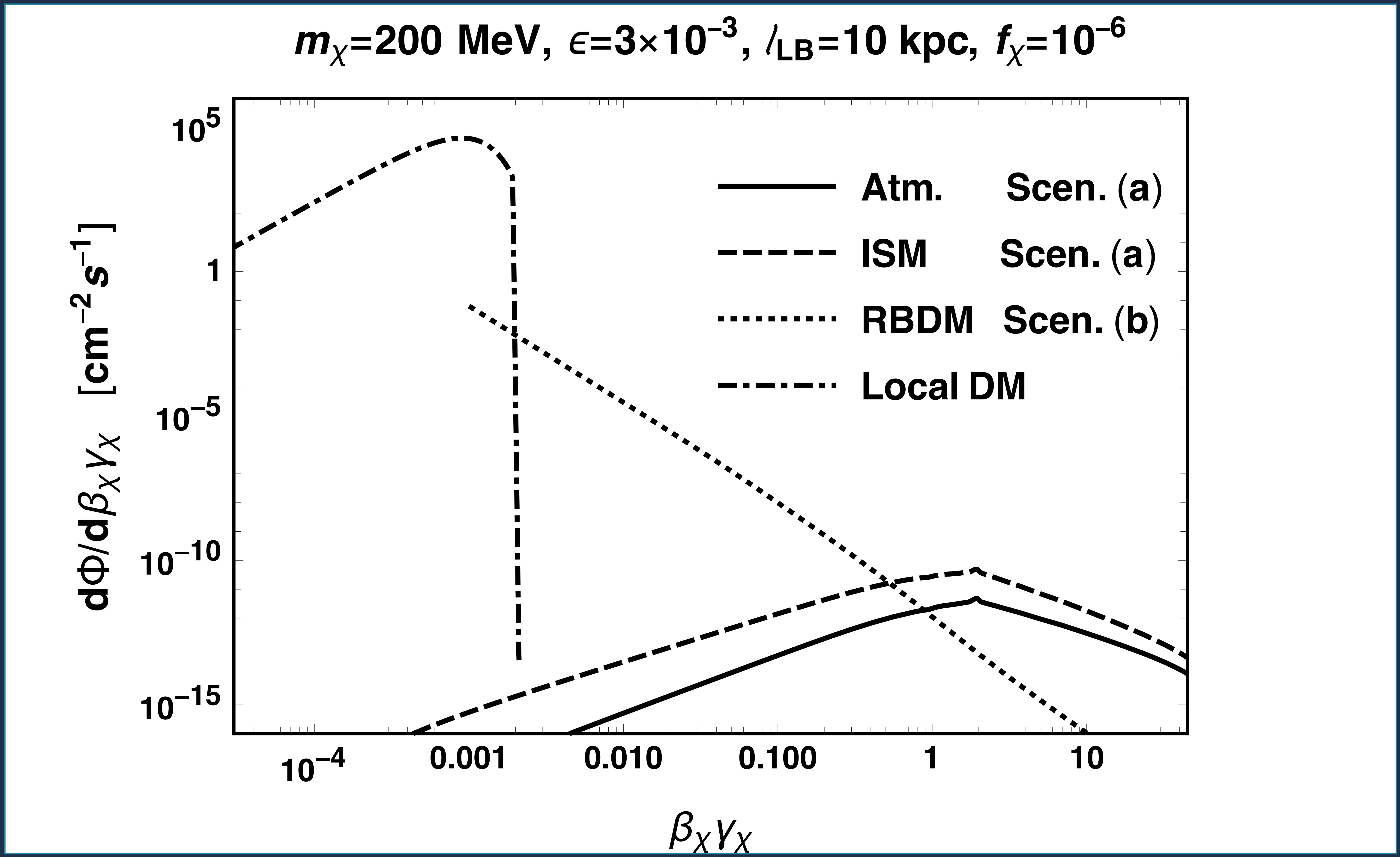
1905.06348 Emken et al , 1908.06986 Liu et al

mCDM population on Earth



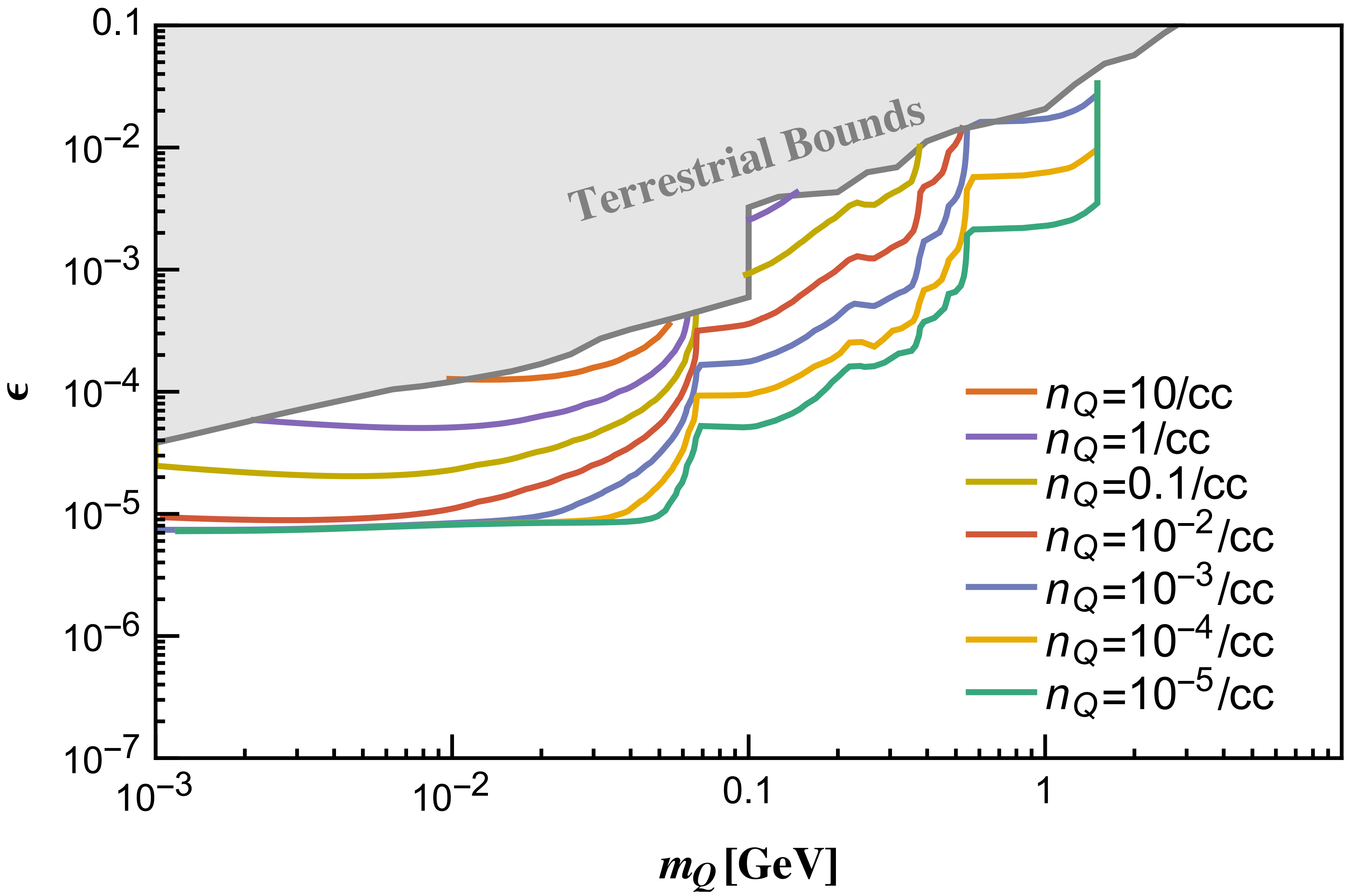
Irreducible mCP population

2010.11190 - Harnik, Plestid, Pospelov, HR



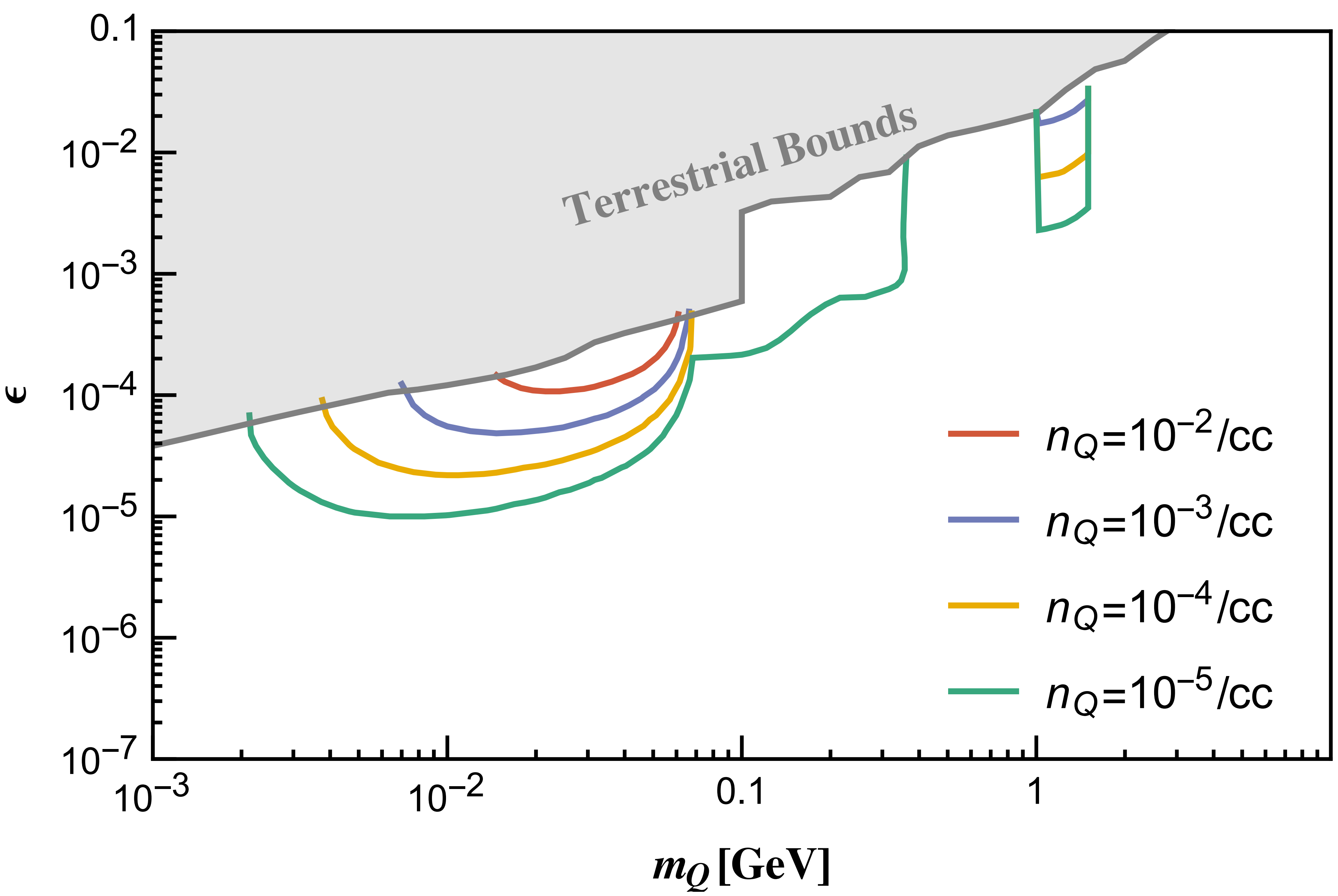
- SM cosmic rays produced mesons can decay into mCPs
- mCPs in the ISM and in the atmosphere can accumulate on Earth
- Stability => Irreducible population

Irreducible mCP population

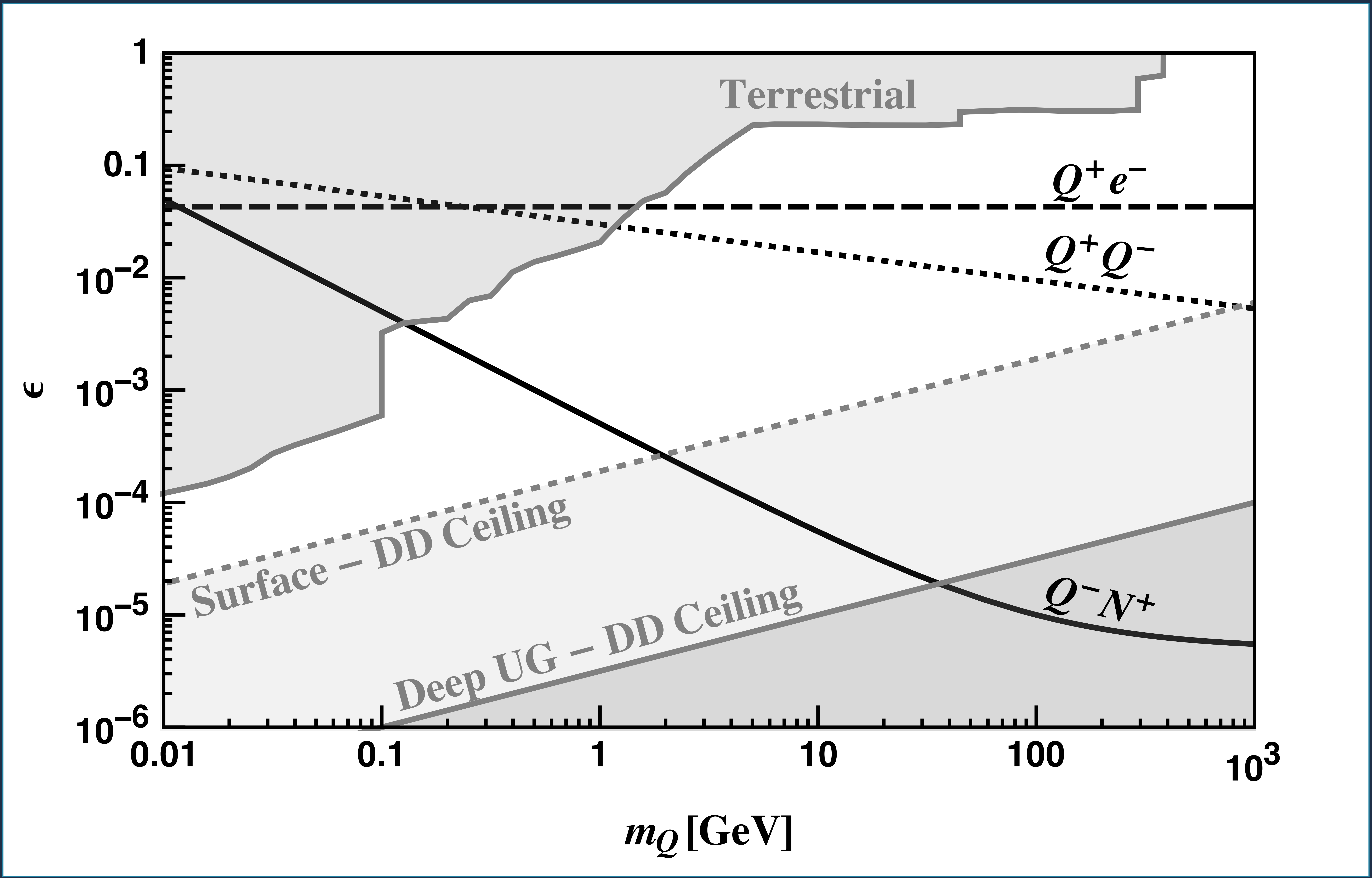


All accumulation with evaporation turned off

Including evaporation

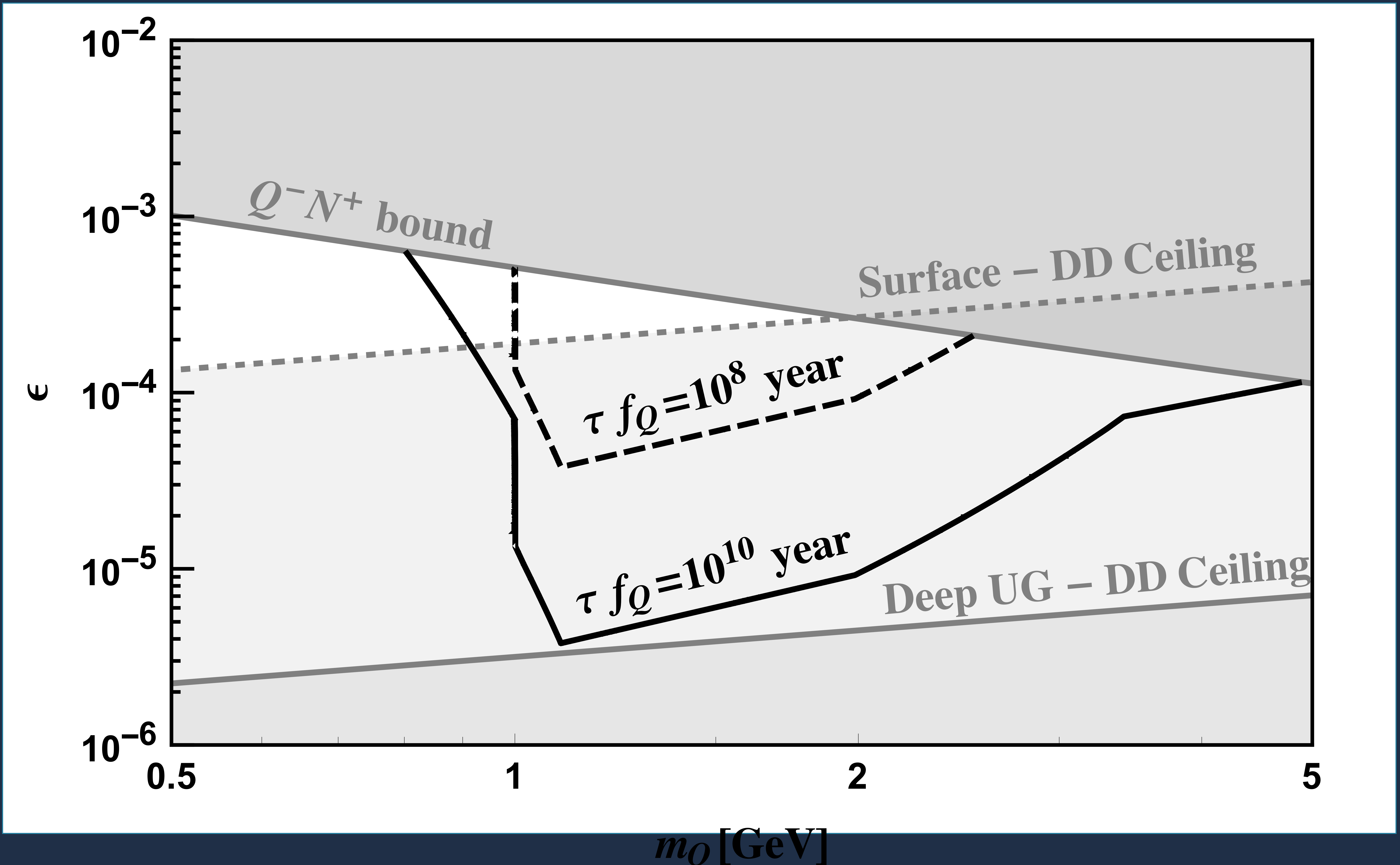


Bound States

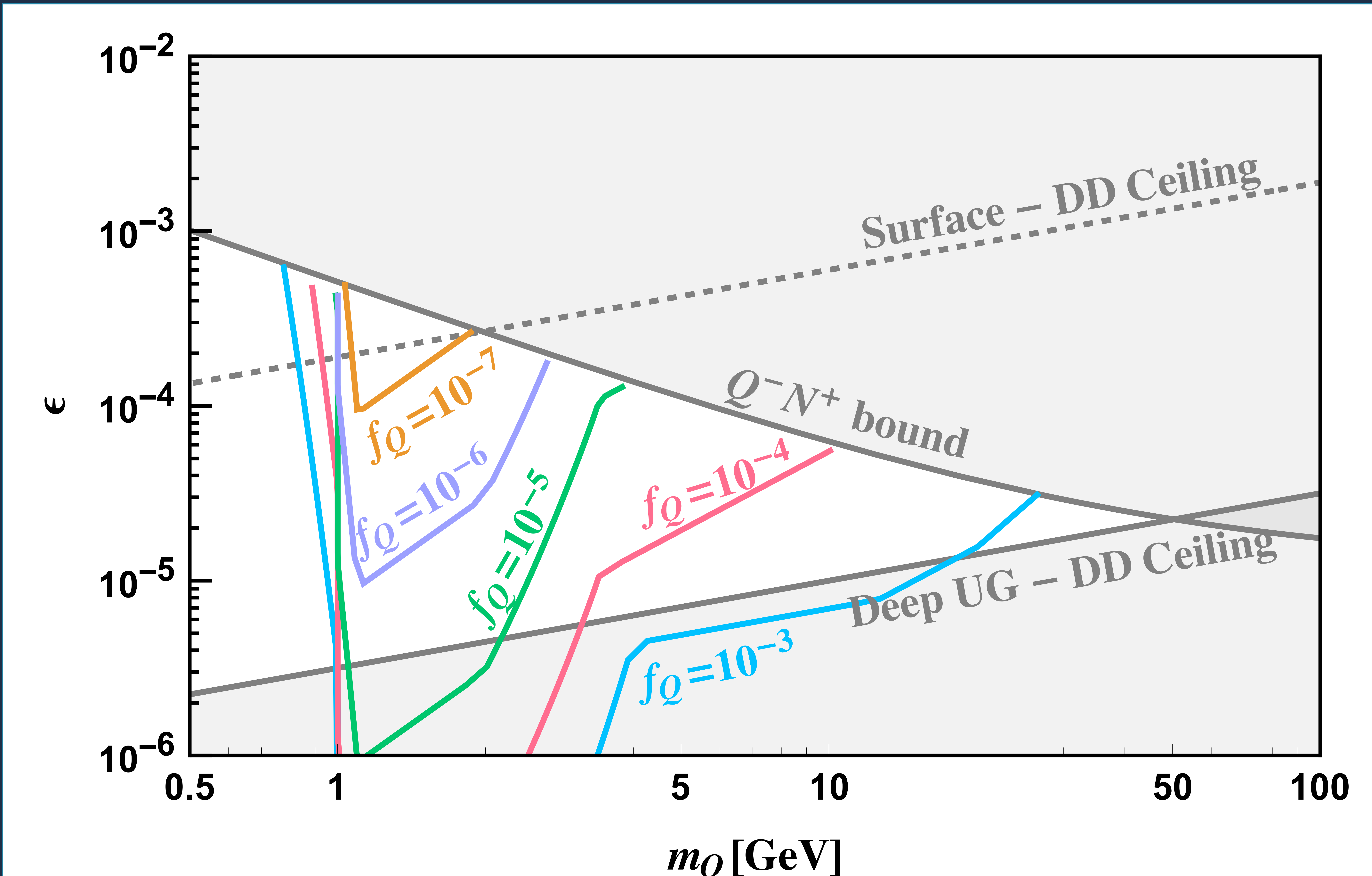


Particle-Anti particle mCDM

Annihilations

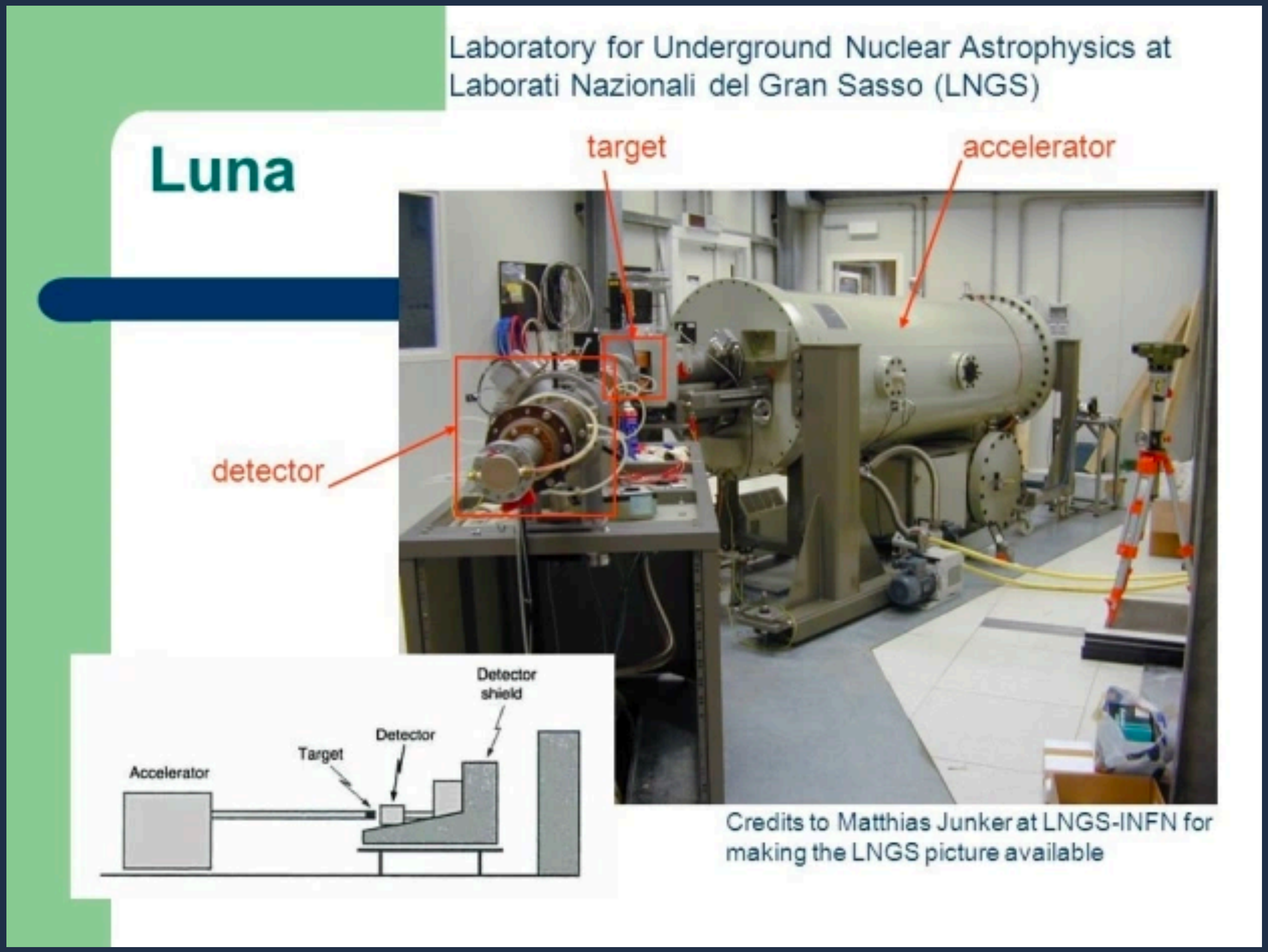


Annihilations in superK



ELECTROSTATIC ACCELERATORS

- Electrostatic accelerators used for nuclear physics



- 400 keV to 3.5 MeV
- LUNA, JUNA, CASPAR

Accelerate MCP traffic jam?

- Operate without loading projectiles
- Accelerated to E= ε x ΔV
    - ε - millicharge
    - ΔV - Voltage

- Can detect with low threshold DM detector

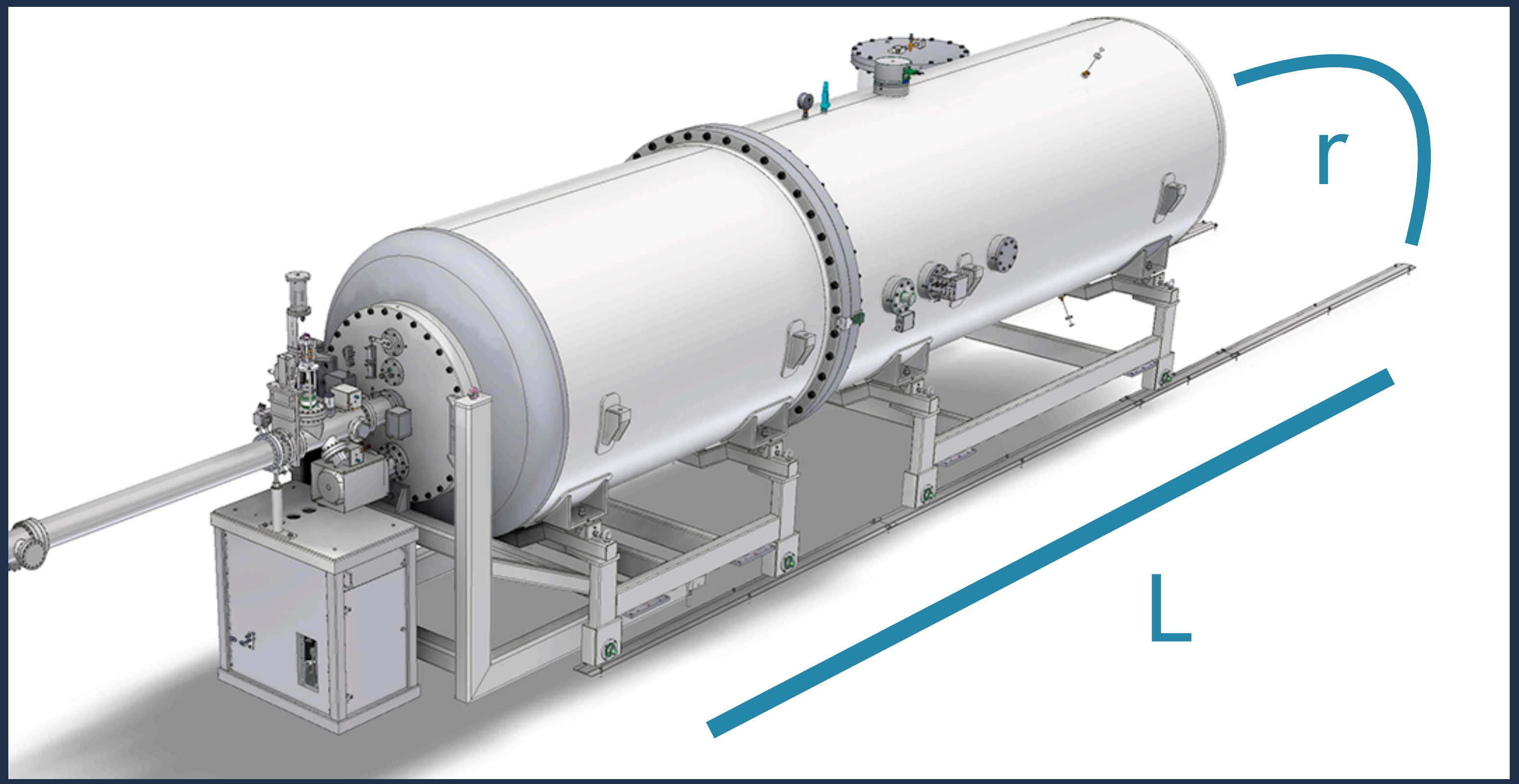
Estimate

- MCP seeps into tube and gets accelerated

$$\Phi[E > E_{\rm thr}] = 2\pi r L \left(1 - \frac{E_{\rm thr}}{\epsilon e \Delta V}\right) \frac{f_Q \eta \rho_Q}{m_Q} v_{\rm th} {\rm Min}[1, \frac{r \epsilon e \Delta V}{L\sqrt{T E_{\rm thr}}}]$$

Area — Energy Threshold — Flux

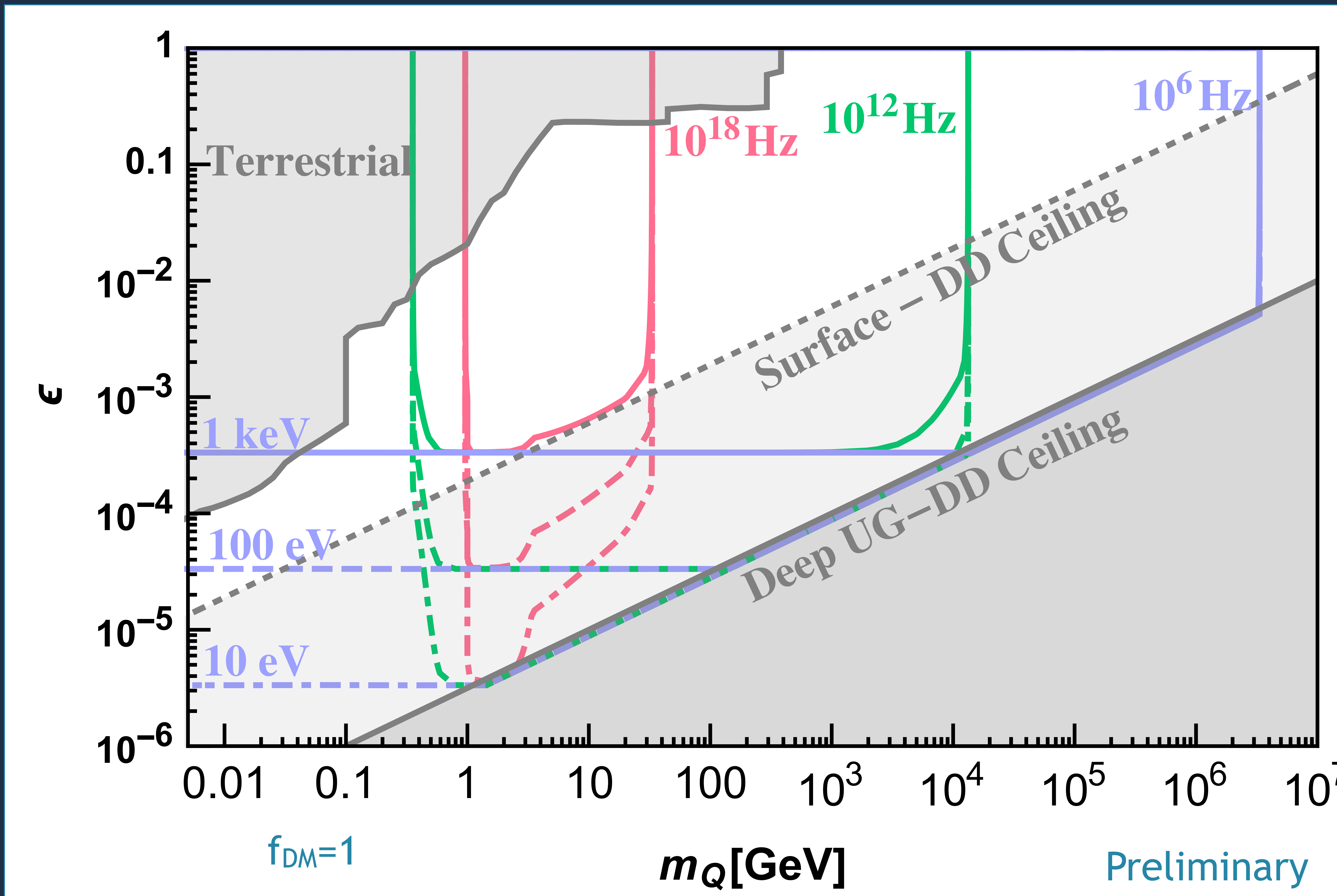
- Energy Threshold: $\epsilon > \frac{E_{\rm thr}}{\Delta V}$



- Accelerated Flux:

$$2\pi r L n_Q v_{\rm th} \approx 10^{20}{\rm Hz} \frac{r}{1{\rm mm}} \frac{L}{1{\rm meter}} \frac{n_Q}{10^{13}/{\rm cm}^3} \sqrt{\frac{\rm GeV}{m_Q}}$$

Accelerated flux



Very High Rate: Promising

Irreducible MCP population

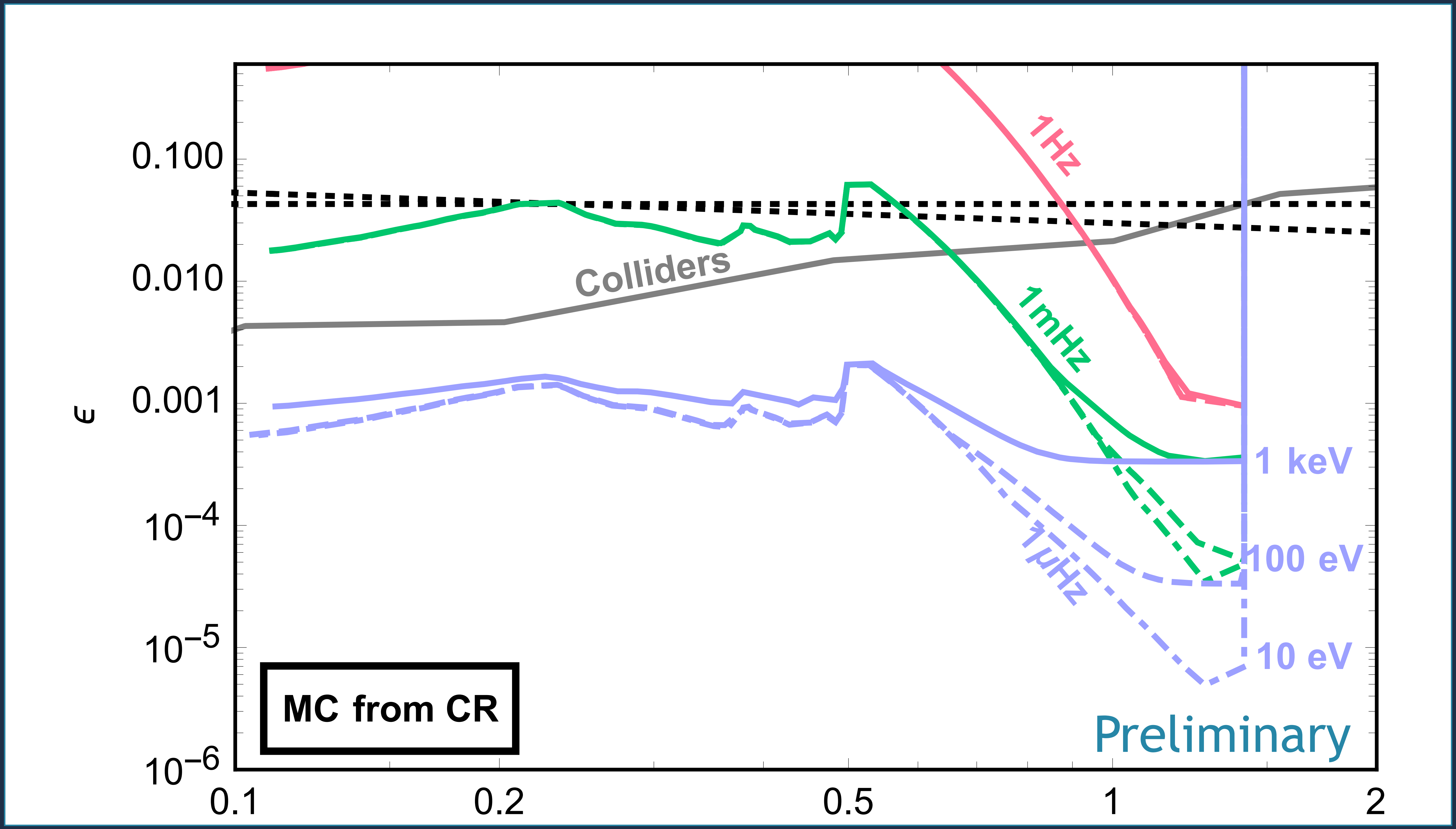
- Cosmic rays produce mesons that decay into MCPs :

  2002.11732 R. Plestid, V. Takhistov Y. Tsai, T. Bringmann, A. Kusenko, M. Pospelov

- Cosmic rays in ISM produce MCPs with magnetic retention

  Roni Harnik, Ryan Plestid, Maxim Pospelov, HR, in preparation

- An Irreducible source of MCPs on Earth



Neutron Bottle

Composite DM

Composite DM

- Confined dark sector forming blobs with large N_f fermions f
- Easily have large charge g_{blob} >>1 under a long range force A (m_A ~ eV)
- Couple A to SM through neutron dipole moment

$$\mathcal{L} \supset \frac{1}{\Lambda}\bar{n}\sigma_{\mu\nu}\gamma_5 F_A^{\mu\nu} n + \bar{f}(m_f + D_A^{\mu}\gamma_\mu)f + m_A^2 A^2$$

Large self-interactions

- Large DM-DM interactions
- More efficient at trapping DM.
- Short-range repulsions can prevent sinking
- Even distribution on earth even for m > 1 GeV

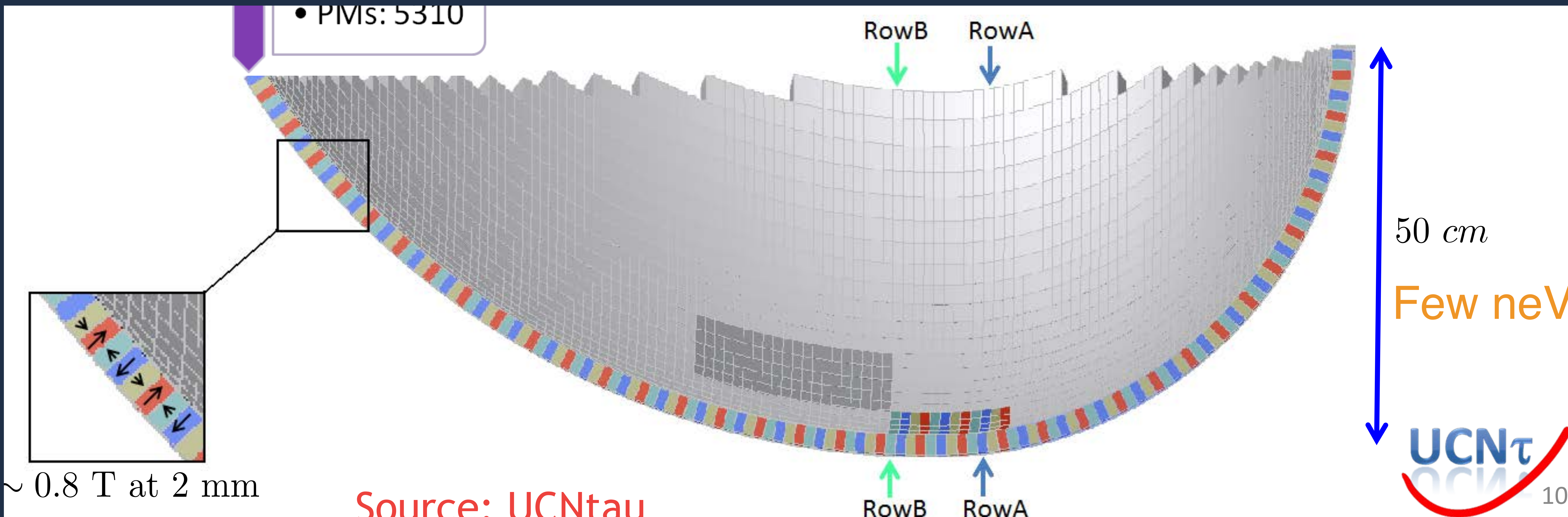
Blobs and Long Range

- Blobs have non-zero radius

$$R_{\text{blob}} = \frac{N_f^{\frac{1}{3}}}{\Lambda_D} = \frac{\chi^{\frac{4}{3}} g_{\text{blob}}^2}{m_{\text{blob}}}$$

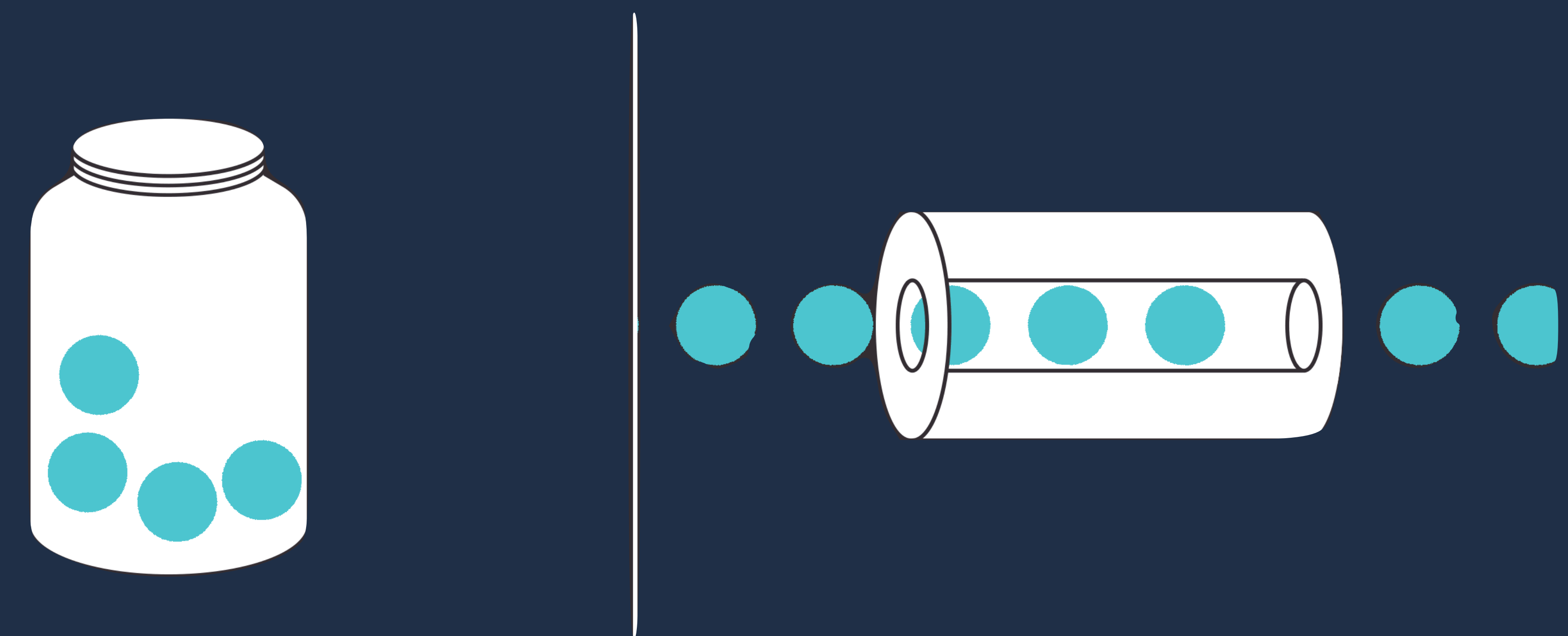
- Coherence at low momentum
- Long range force further prefers smaller momentum transfers
- What are the lowest momentum probes known?

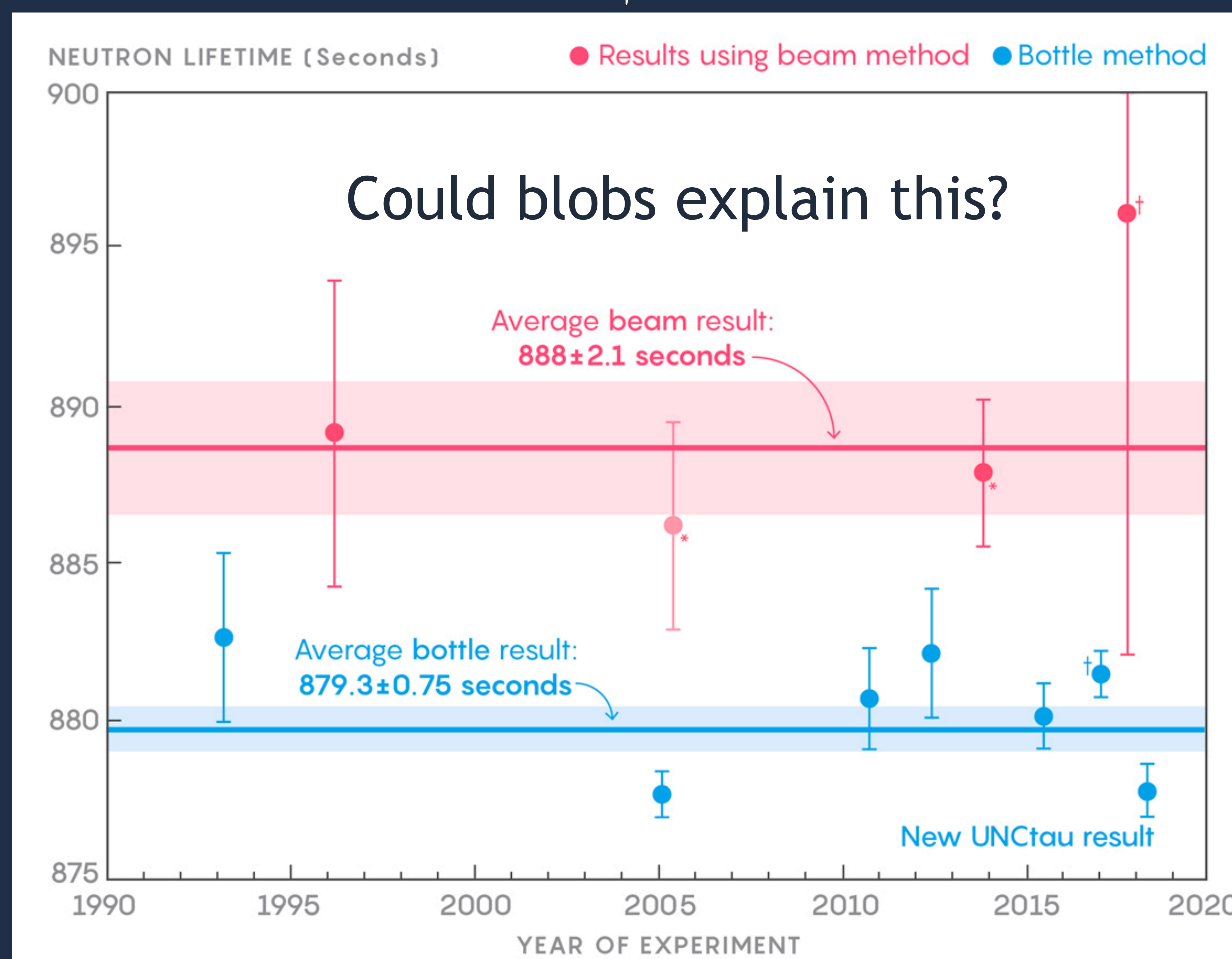
Neutron Bottle



- ~**50 neV** trap for measuring UCN lifetime
- DM can kick neutrons off trap affecting measurement
- ~50 neV DD detector with small exposure
- Useful for Traffic jam composite dark matter?

Bottle Beam disagreement

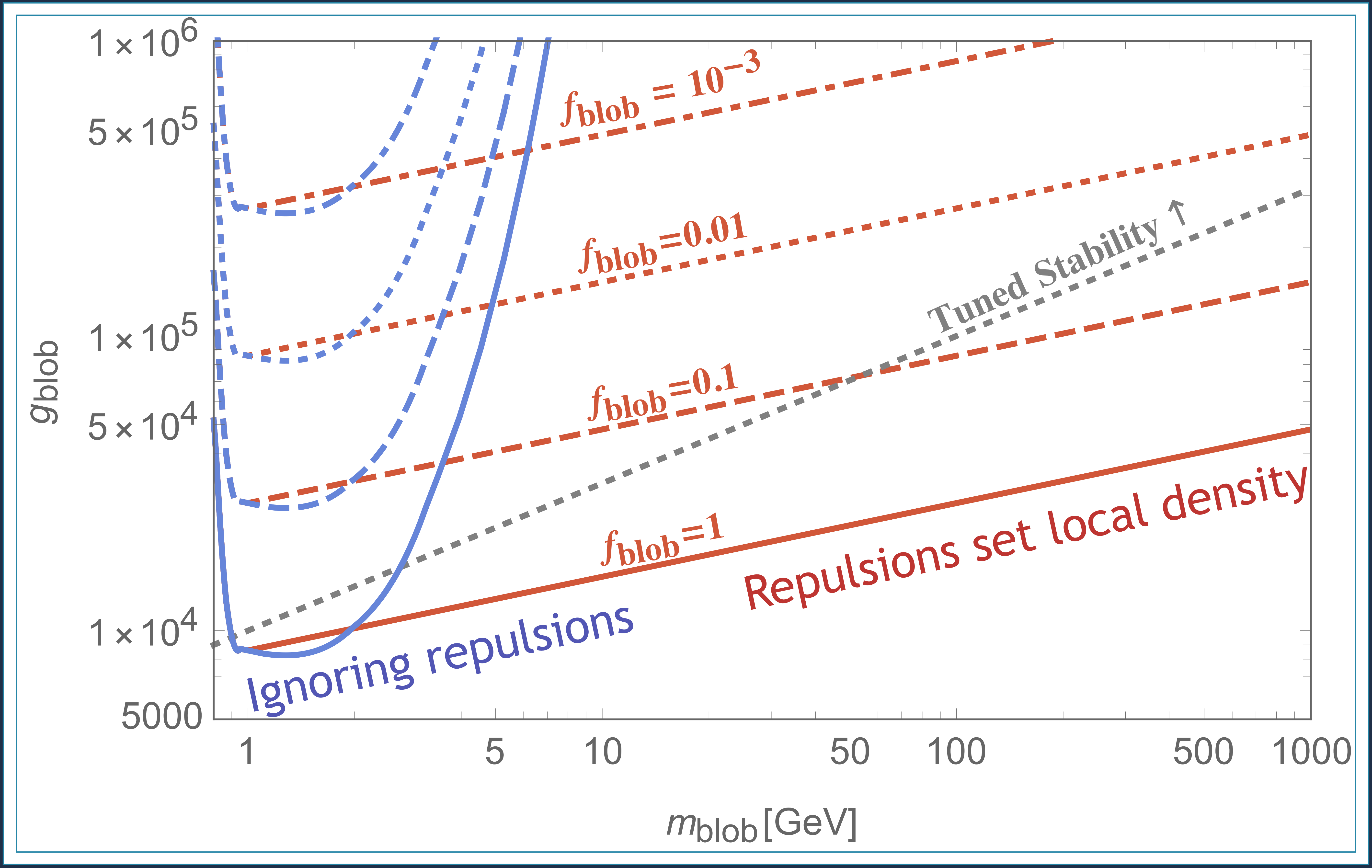




source:
Quanta Magazine

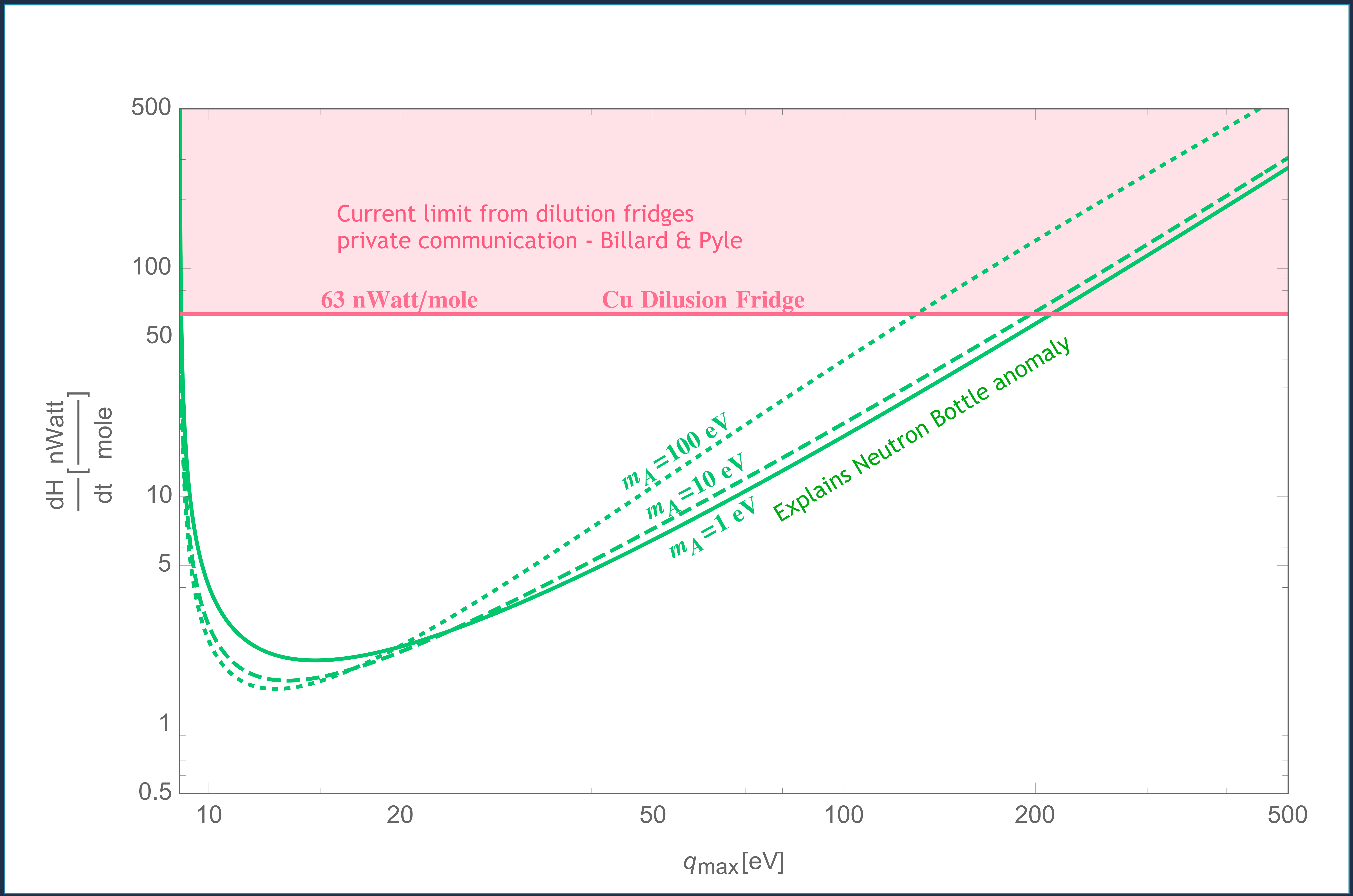
An explanation?

DM blobs made of DM fermions
Blob charge: g_{blob}
Neutron dipole moment: below SN bounds



$$\mathcal{L} \supset \frac{1}{\Lambda}\bar{n}\sigma_{\mu\nu}\gamma_5 F_A^{\mu\nu} n + \bar{f}(m_f + D_A^{\mu}\gamma_\mu)f + m_A^2 A^2$$

Best limits on DC heating



Ongoing work, 10^{-12} Watt (surface), 10^{-16} Watt (deep UG)
with J.Billard, M.Pyle, SR

OUTLOOK

- Repeating Tantalum experiment with more exposure
- Using Tantalum shielding as a springboard onto traditional DD experiment
- LUNA as an “uncollider”
- Exploring theory space for motivated f_{DM} vs coupling

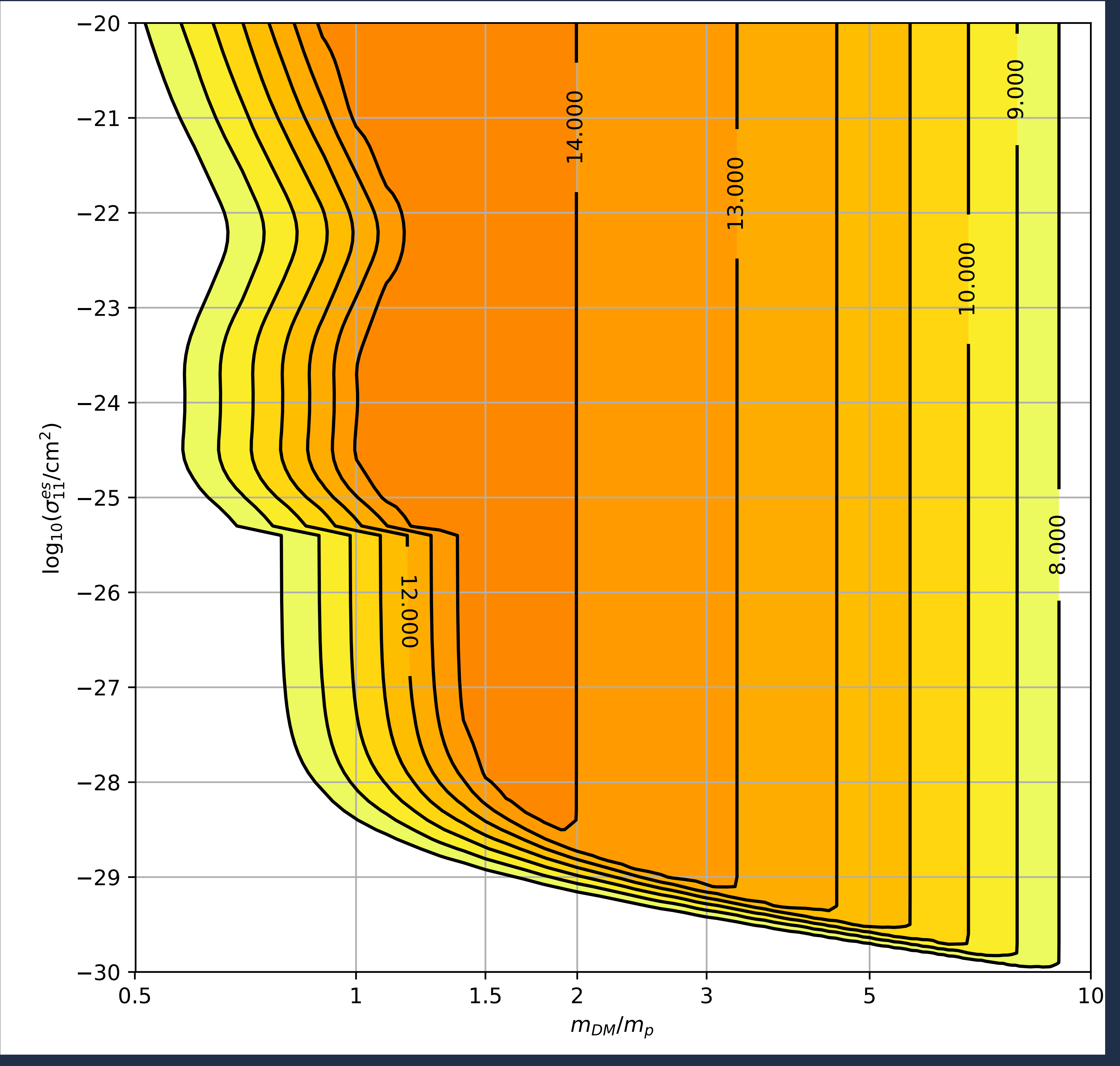
Conclusions

- Large coupling to SM results in large terrestrial build up
- Nuclear isomers for contact interactions
- Electrostatic accelerators for milli-charge
- Neutron bottle anomaly could be explained by dark blobs
- Future: DC heat deposit in cryogenics

Thank you

Backup

Equilibrated population



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1805.08794:Neufeld, Farrar, McKee