Neutron Lifetime Anomaly and a Composite Solution

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2008.06061 with Surjeet Rajendran

—Banksy

Outline

1 Neutron Lifetime Anomaly

2 Dark Matter Accumulation

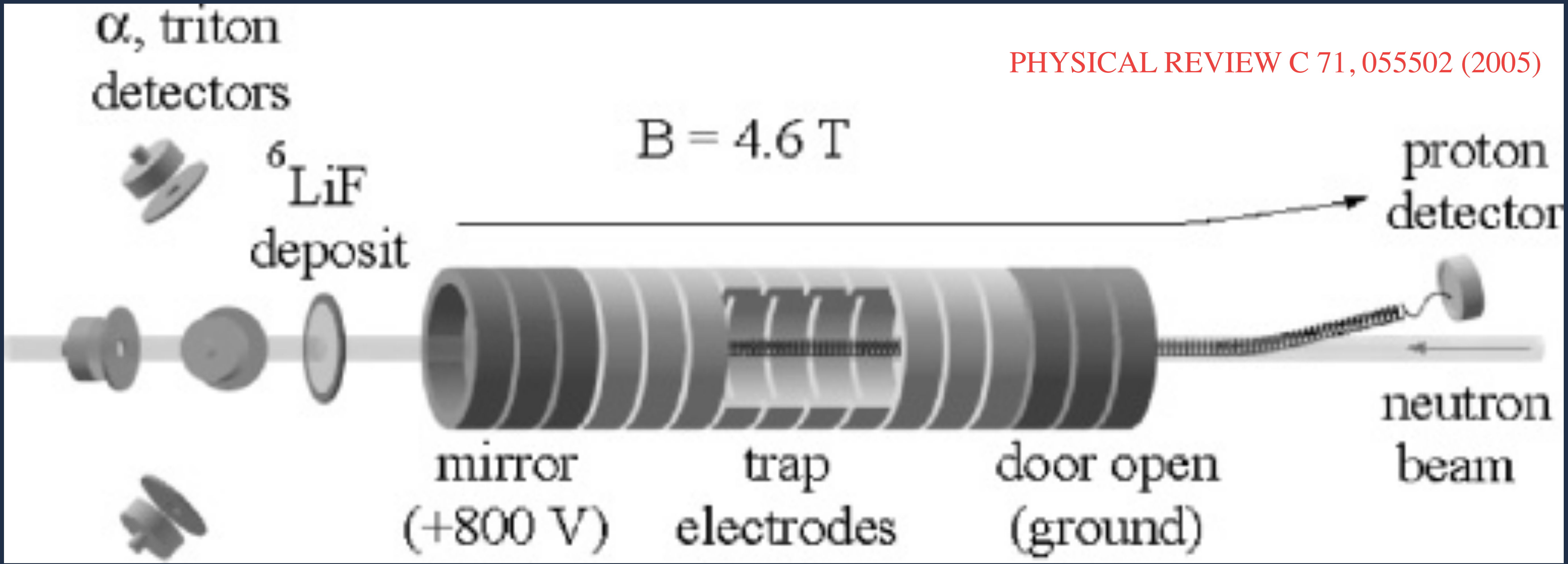
3 Explanation

4 Conclusion

Neutron Lifetime

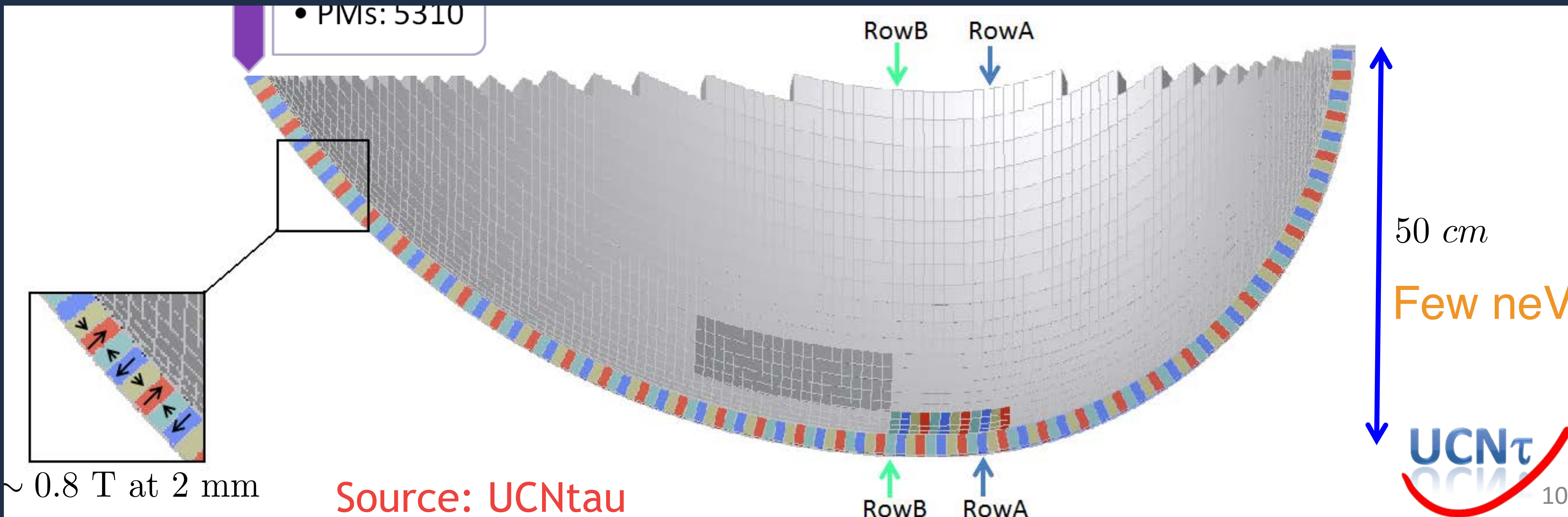
- Neutron discovered almost 90 years ago
- Lifetime roughly half the duration of seminar
- Simplest example of β decay
- Can extract V_{ud} without nuclear matrix elements
- Lifetime uncertainty : uncertainty in Helium abundance predicted by BBN
- How accurately do we know it? - two ways to measure

Beam Method



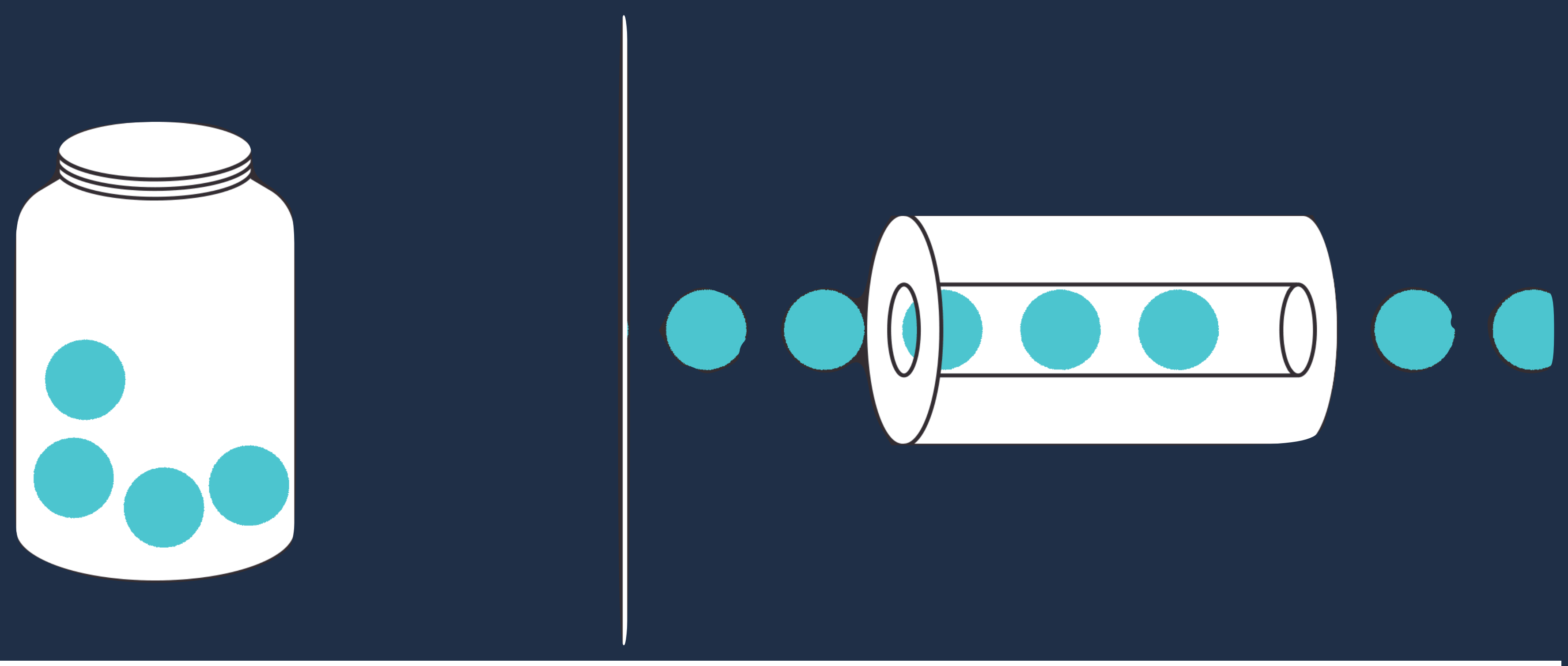
- Lifetime measured by counting protons from ß decay of cold neutrons (40 K)
- # neutrons inside trap, counted by subsequent LiF deposit
- Protons trapped inside through E & B fields
- Subsequently accelerated and counted

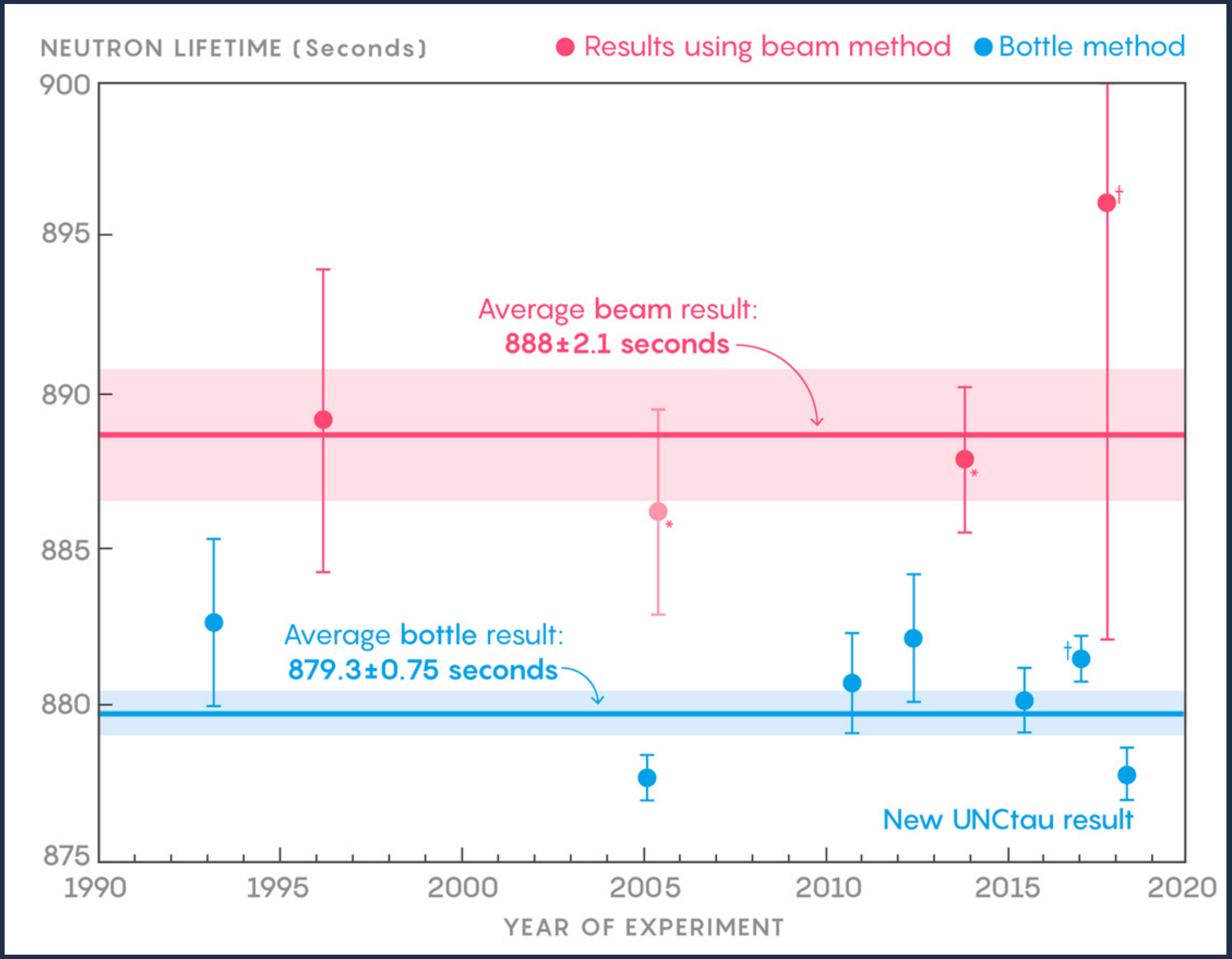
Bottle Method



- ~**50 neV (0.5 mK)** trap for measuring UCN lifetime
- Trapped neutrons measured often

Bottle Beam disagreement





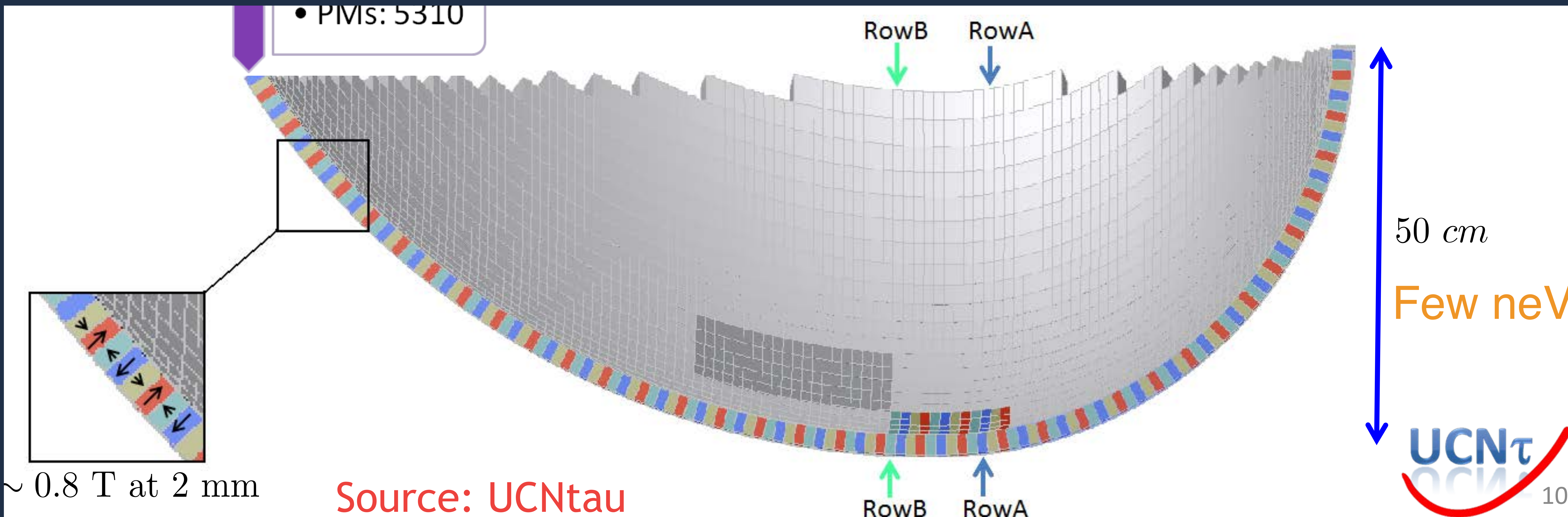
source:
Quanta Magazine

Discrepancy approaching 4 σ

Possible BSM explanation?

- Beam measures protons, hence only β decay
- Bottle measures inclusive
- BSM decay channel? -1801.01124 Fornal & Grinstein
- Highly restricted parameter space: larger nuclei stable
- Can neutrons in trap scatter with DM and disappear?

Scattering with DM



- ~**50 neV** trap for measuring UCN lifetime
- DM can kick neutrons off trap affecting measurement
- ~50 neV DD detector with small exposure
- How much and what cross-section do we need?

Bottle results

Experiment	Description	trap potential [neV]	lifetime
Pattie Jr 18 [2]	grav + magnetic no extrapolation	50	$877.7 \pm 0.7 + 0.4/-0.2$
P. Serebrov 18 [17] UCN	grav +oil	70	$881.5 \pm 0.7 \pm 0.6$
ARZUMANOV 15[18]	double bottle	100	880.2 ± 1.2
STEYERL 12[19]	material bottle	106	$882.5 \pm 1.4 \pm 1.5$
PICHLMAIER 10[20]	material bottle	106	$880.7 \pm 1.3 \pm 1.2$
SEREBROV 05[21]	grav+oil trap	106	$878.5 \pm 0.7 \pm 0.3$

How much DM?

$$\Gamma_{\rm DM} + \Gamma_{\rm beam} = \Gamma_{\rm bottle}$$

$$n\sigma v + \frac{1}{\tau_{\rm beam}} = \frac{1}{\tau_{\rm bottle}}$$

$$\sigma = 5.35 \times 10^{-25}{\rm cm}^2 \sqrt{\frac{m_{\rm DM}}{\rm GeV}} \frac{10^{14}/{\rm cm}^3}{n}$$

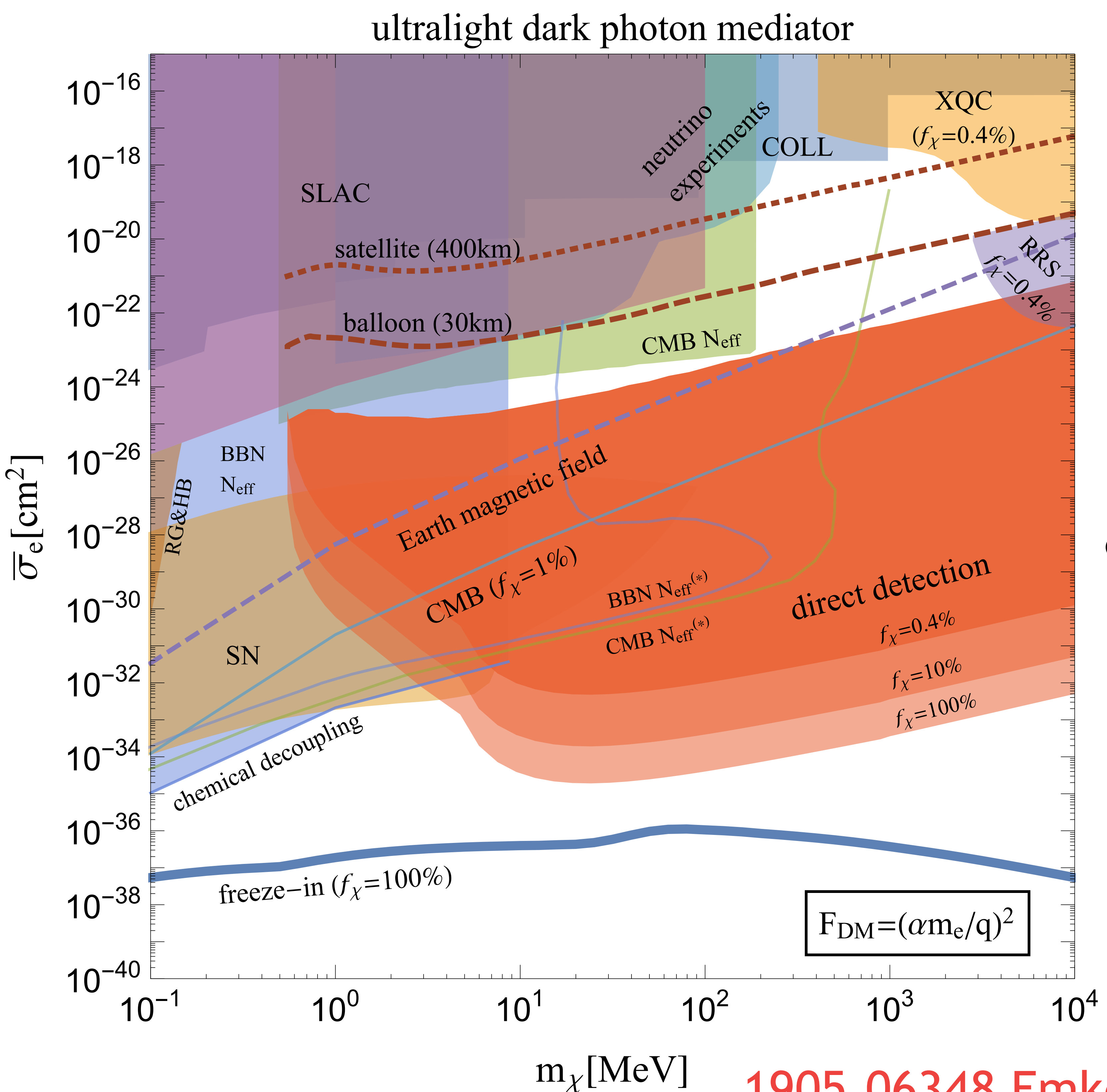
- This is no ordinary virial dark matter
- Where have we seen DM with large x-section and densities?
- May 04 2020 Maxim Pospelov’s talk on metastable isomers

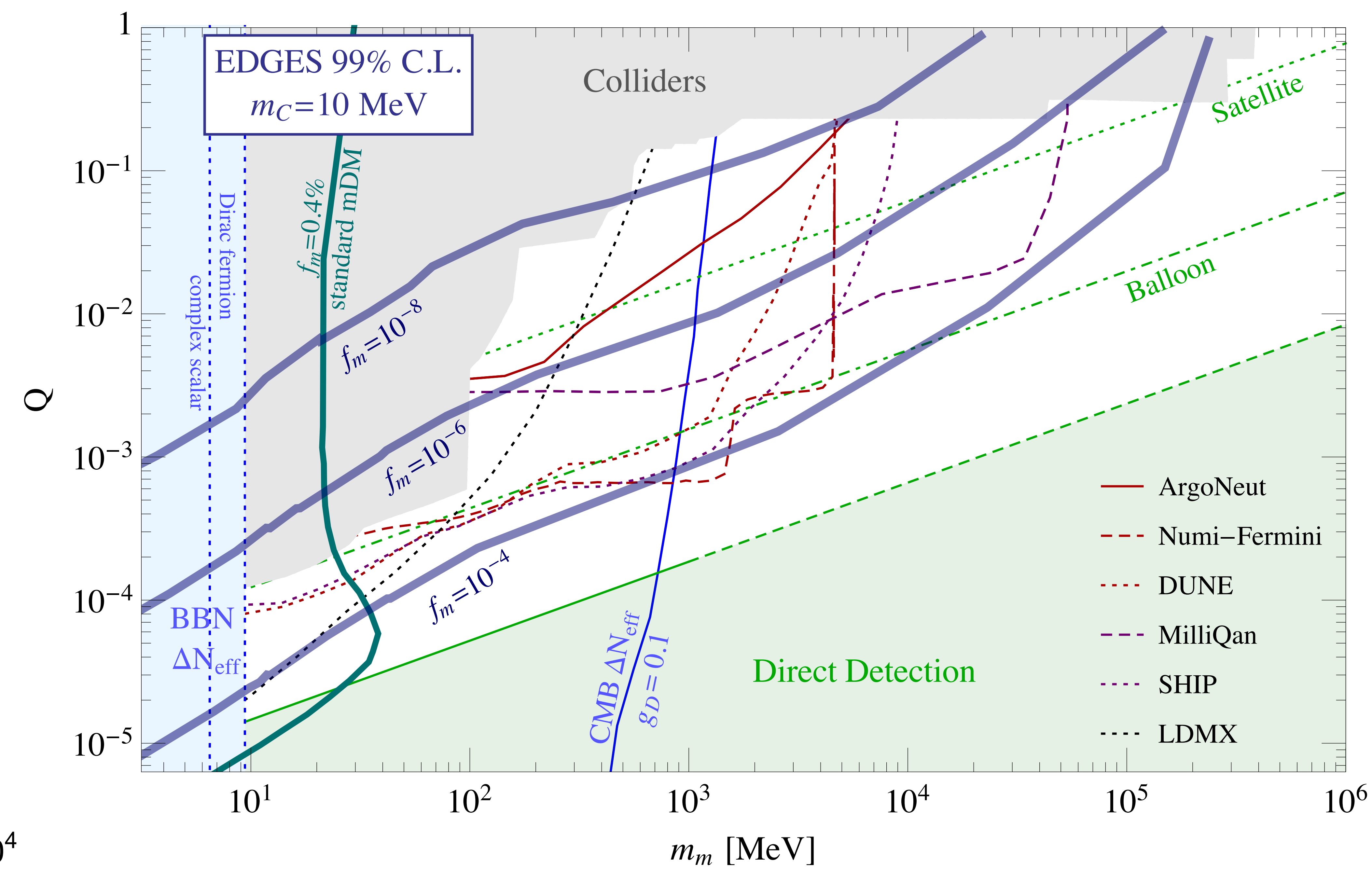
Models with large cross-sections

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
- Why are these models alive?

Millicharge parameter space





1905.06348 Emken et al , 1908.06986 Liu et al

Atmospheric/Rock overburden stops DM from reaching experiment with enough kinetic energy

What happens to the shielded DM?

Dark matter accumulation

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

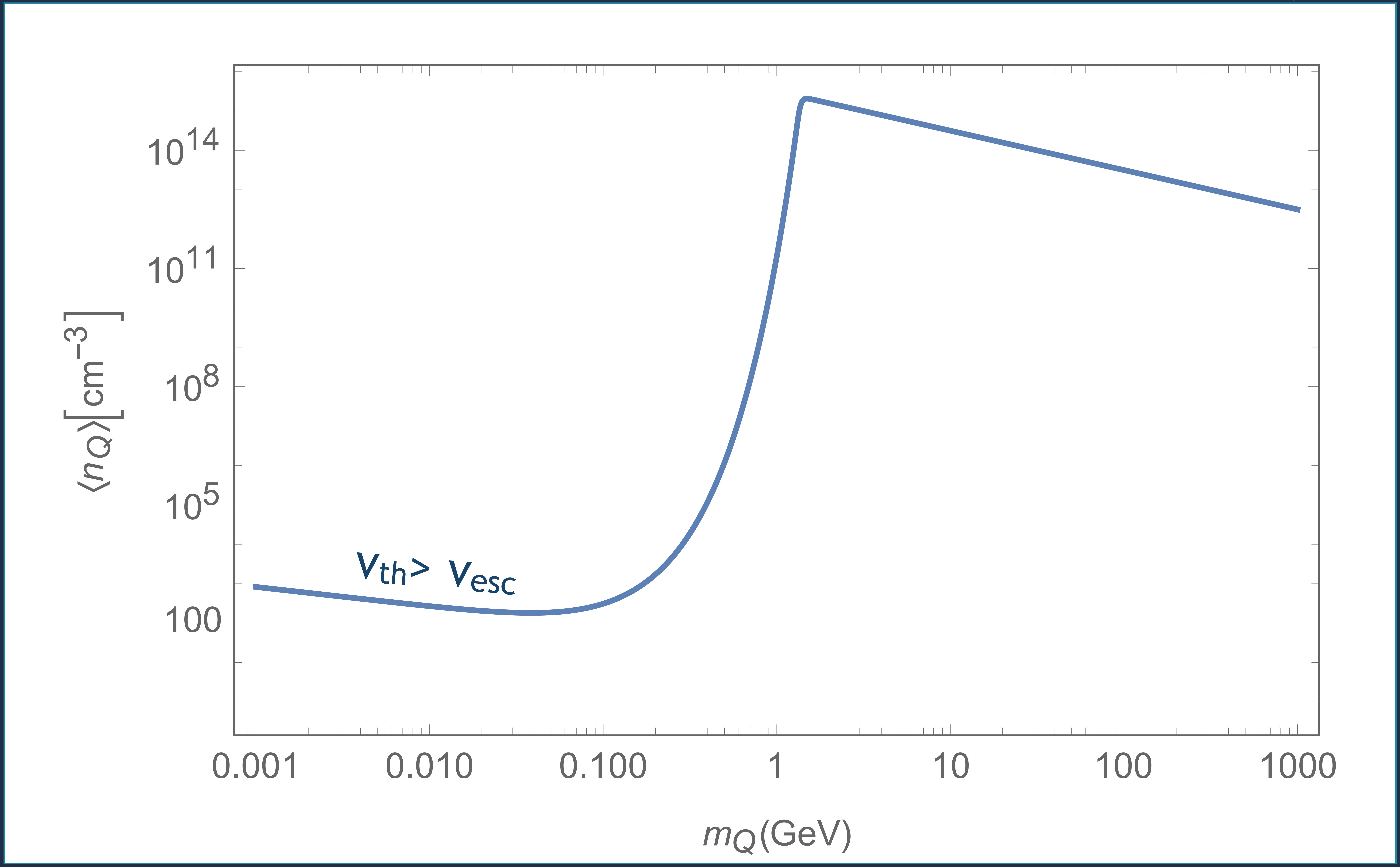
$$\langle \eta \rangle = \frac{\langle n \rangle}{n_{\rm vir}} = \frac{4\pi R_E^2}{4/3\pi R_E^3} v_{\rm vir} T_E \sim 2.2 \times 10^{16}$$

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

Evaporation

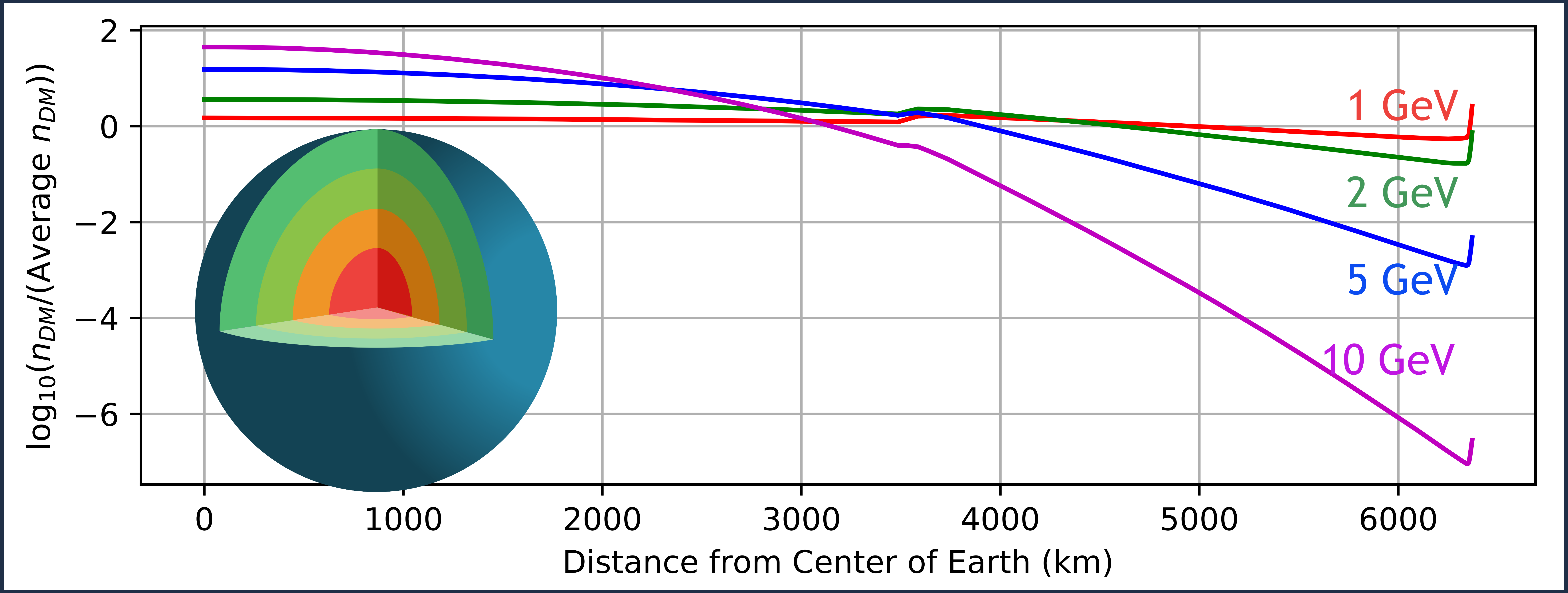
DM below GeV rapidly evacuates since
thermal velocity is larger than escape velocity

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

Detection Strategies

Cryogenic Detectors (ongoing)

Nuclear Isomers	Electrostatic accelerators	Neutron Bottle
Strongly interacting DM	Millicharge DM	Composite DM

Maxim’s talk
1907.00011 (PRD editor’s suggestion)
with MP and SR

Ongoing

This talk

Experimental results 1911.07865
with M Hult, B Lehnert, G Lutter,
MP, SR, and Kai Zuber

Candidate for neutron bottle

- Dark Matter very slow: 300 kelvin or KE~ 0.025 eV
- Higher than neutron bottle trap ~ 50 neV
- Huge Number densities and x-sections
- Perfect for explaining neutron bottle
- Couple to SM with long range force
- Increased x-section at low momentum transfer

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 ~ 10 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
- Coupling large enough - incoming DM trapped
- Intermediate regime - some trapping

subsequent ejection due to self-interactions with virial population

- Invoke blobs of different sizes

heavier population traps lighter population

- Seed population effective at trapping subsequent virial DM

Large self-interactions

- Masses > GeV sink
- Self interactions can arrest this
- Repulsive PE ~ Temperature

$$\frac{g_{\rm blob}^2}{4\pi}\frac{e^{-m_A r_{\rm int}}}{r_{\rm int}} = T_{\rm room}$$

- Maximum density anywhere

$$n_{\rm max} \approx \frac{2\times 10^{13}}{\rm cm^3}\left(\frac{m_A}{10\ \rm eV}\right)^3\left(\frac{\log 10^4}{\log g_D}\right)^{3.4}$$

- Can prevent sinking and cause uniform density

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

Parametrics

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

Cross-section to scatter the neutron from the trap is given by,

$$\sigma_{\rm neut} = \int dq^2 \frac{d\sigma}{dq^2}$$

Integrated between

$$q_{\rm min} = \sqrt{2E_{\rm trap} m_n} \approx 9{\rm eV}.$$

And

$$q_{\rm max} = {\rm Min}\left(R_{\rm blob}^{-1}, \mu v_{\rm th}\right)$$

To obtain,

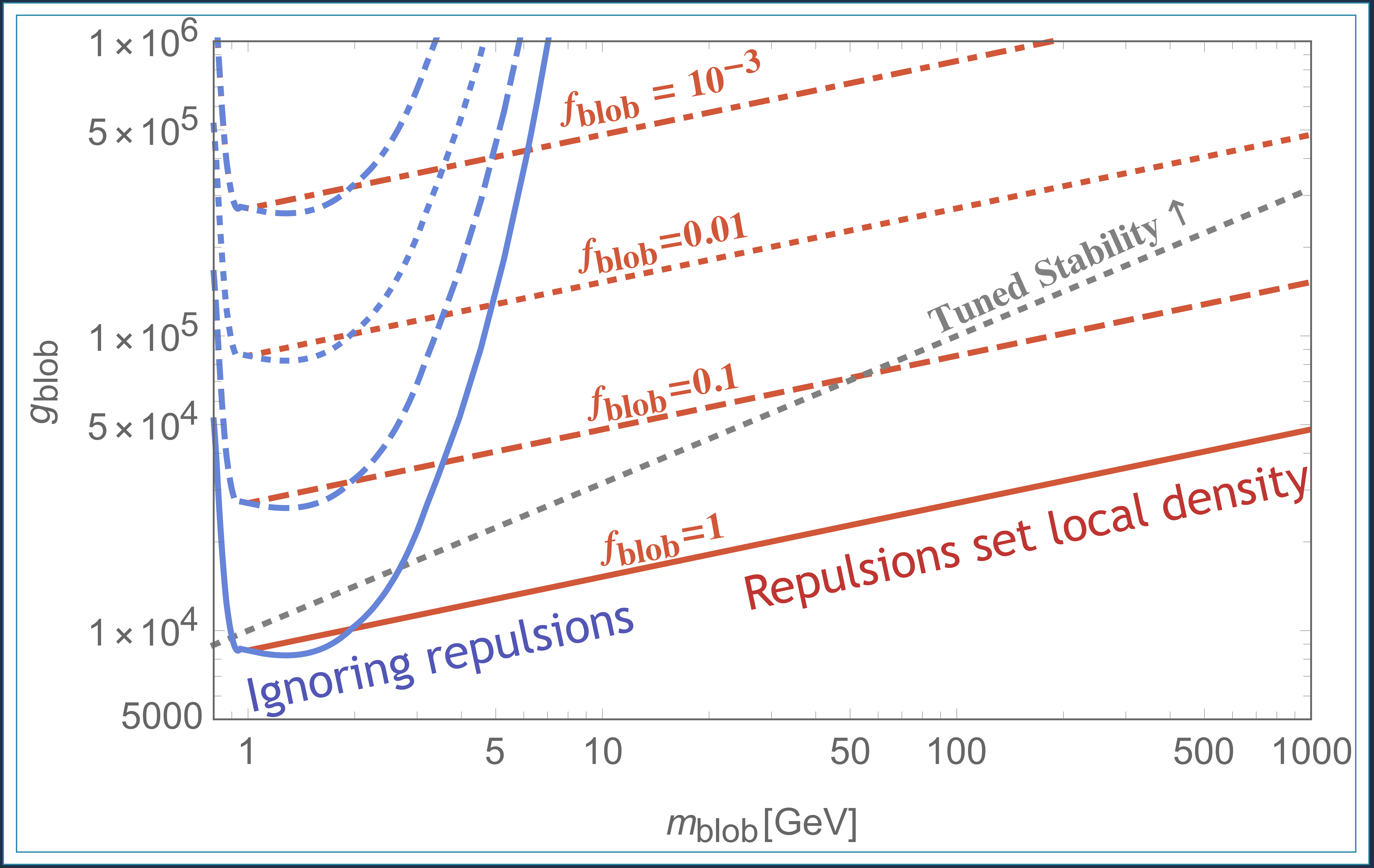
$$\sigma_{\rm neut} = \frac{4g_{\rm blob}^2}{\pi\Lambda^2 v_{\rm th}^2}\frac{\log\left(m_A^2 + q_{\rm max}^2\right)}{\log\left(m_A^2 + q_{\rm min}^2\right)} \approx 10^{-34}{\rm cm}^2 g_{\rm blob}^2 \frac{m_{\rm blob}}{\rm GeV} L_R(q_{\rm min})$$

Finally,

$$g_{\rm blob} \approx \frac{7.1\times 10^4}{\sqrt{L_R(9{\rm eV})}}\left(\frac{\rm GeV}{m_{\rm blob}}\right)^{\frac{1}{4}}\sqrt{\frac{10^{14}/{\rm cm}^3}{n_{\rm surf}}}$$

An explanation?

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

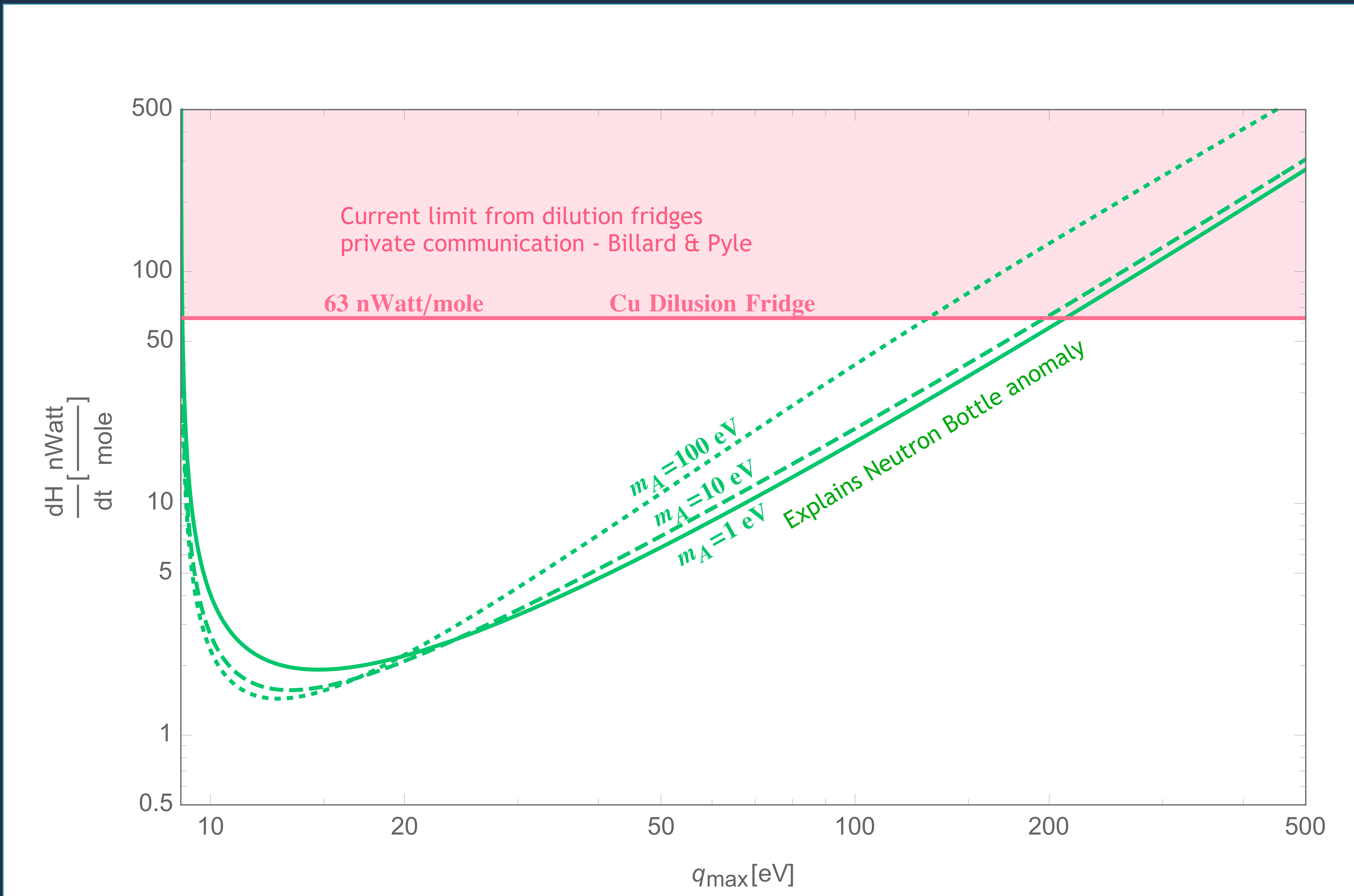


$$\mathcal{L} \supset \frac{1}{\Lambda}\bar{n}\sigma_{\mu\nu}\gamma_5 F_A^{\mu\nu} n + \bar{f}(m_f + D_A^{\mu}\gamma_\mu)f + m_A^2 A^2$$

Measuring DC heating

- Dilution refrigerators ubiquitous in (ultra)cold experiments
- Local DM deposits energy on component kept cold
- Stability of cold component can set limits on DC heating
- Current Limit: 63 nW/mole in copper - private communication - Billard & Pyle

Best limits on DC heating



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

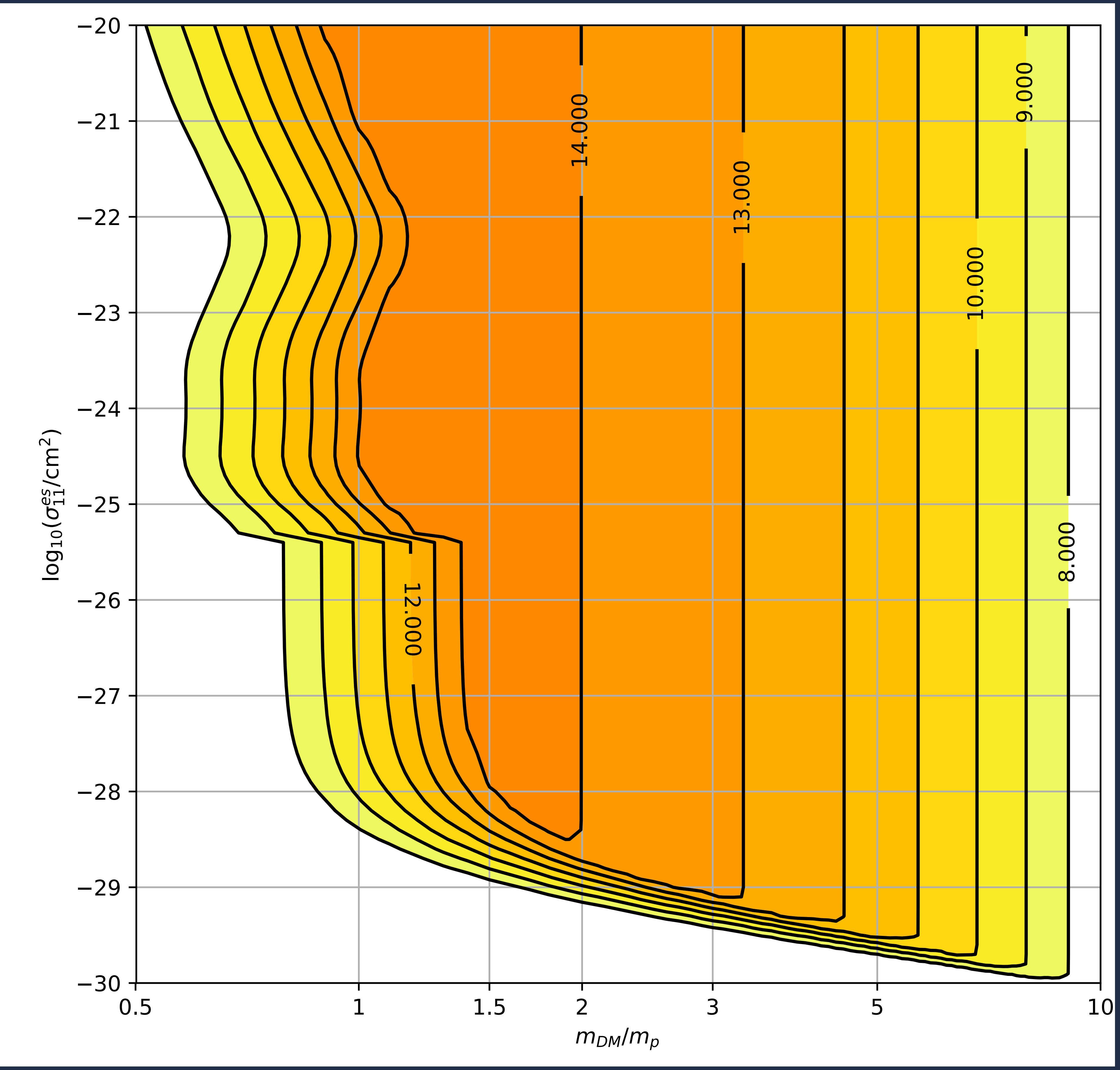
Conclusions

- Persistent discrepancy in neutron lifetime between bottle and beam methods
- Large accumulation of DM blobs possible due to large interactions / self interactions
- Thermalized Blobs can kick neutrons out of bottle explaining the anomaly
- Future cryogenic detectors can test parameter space

Thank you

Backup

Equilibrated population



DM heavier than 10 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

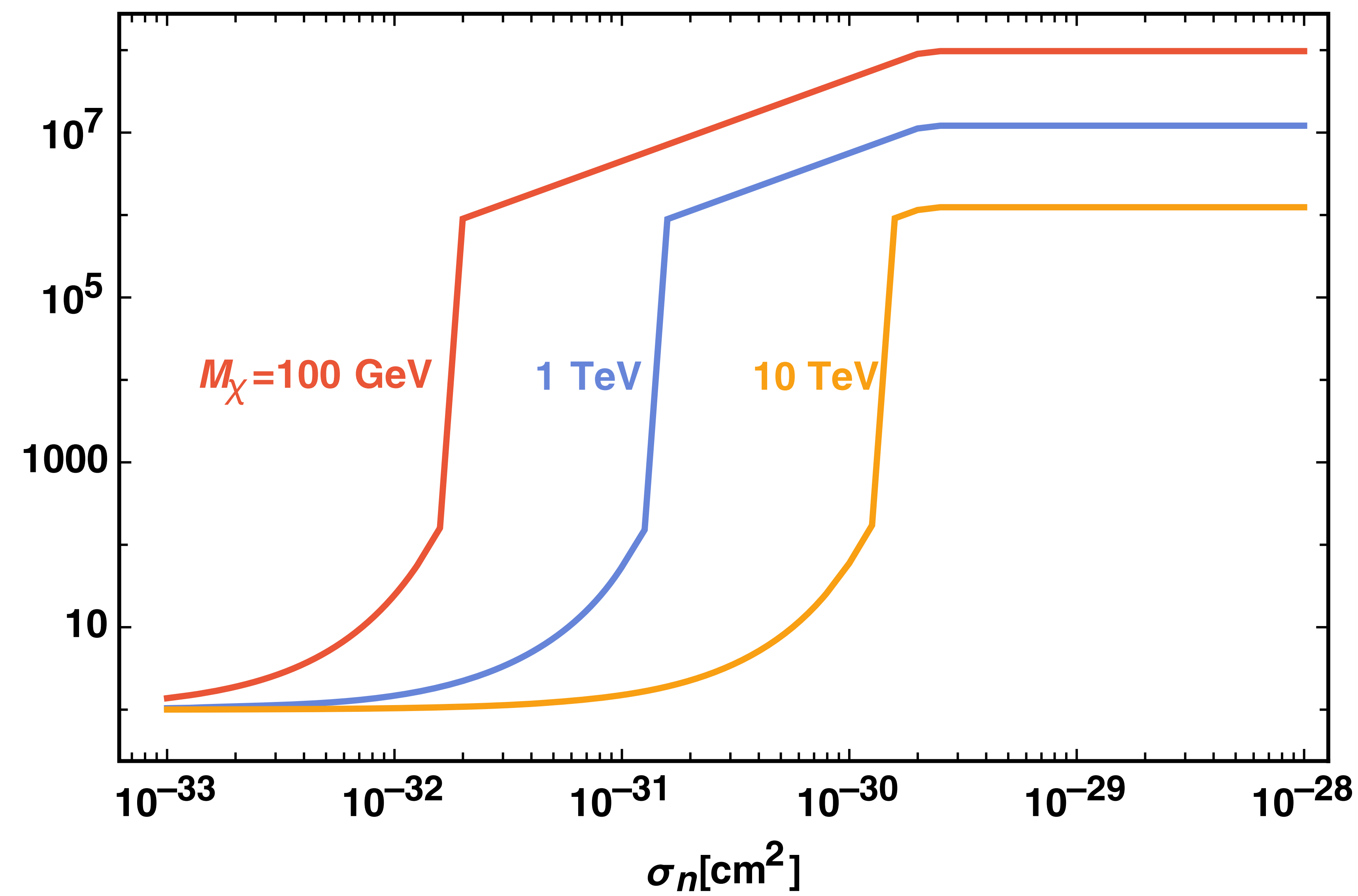
$$v_{\rm term} = \frac{3 m_\chi g T}{m_{\rm gas}^2 n_{\rm gas} \langle \sigma_T v^3 \rangle}$$

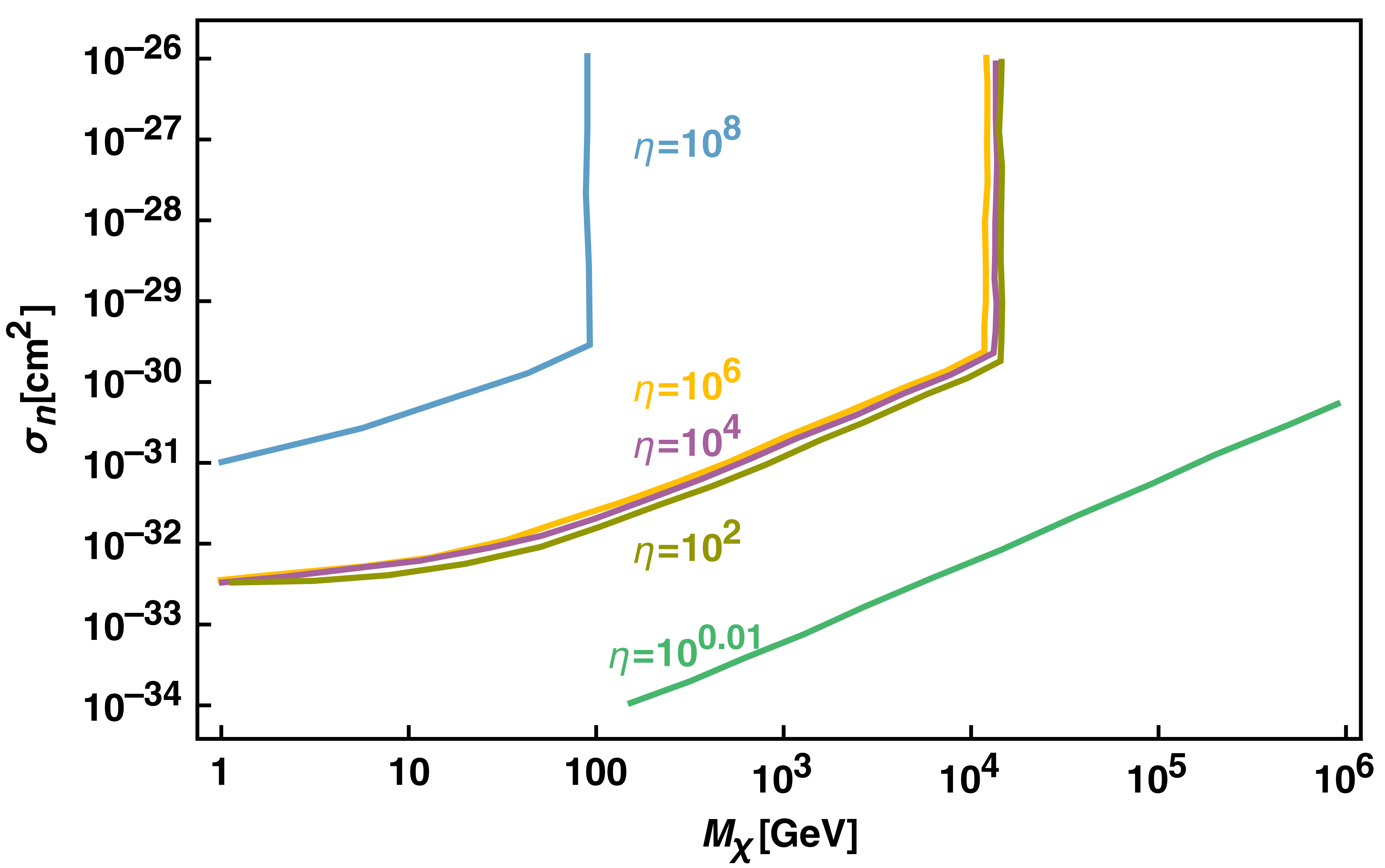
- Traffic Jam on the way

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

Heavier population

Contact interactions

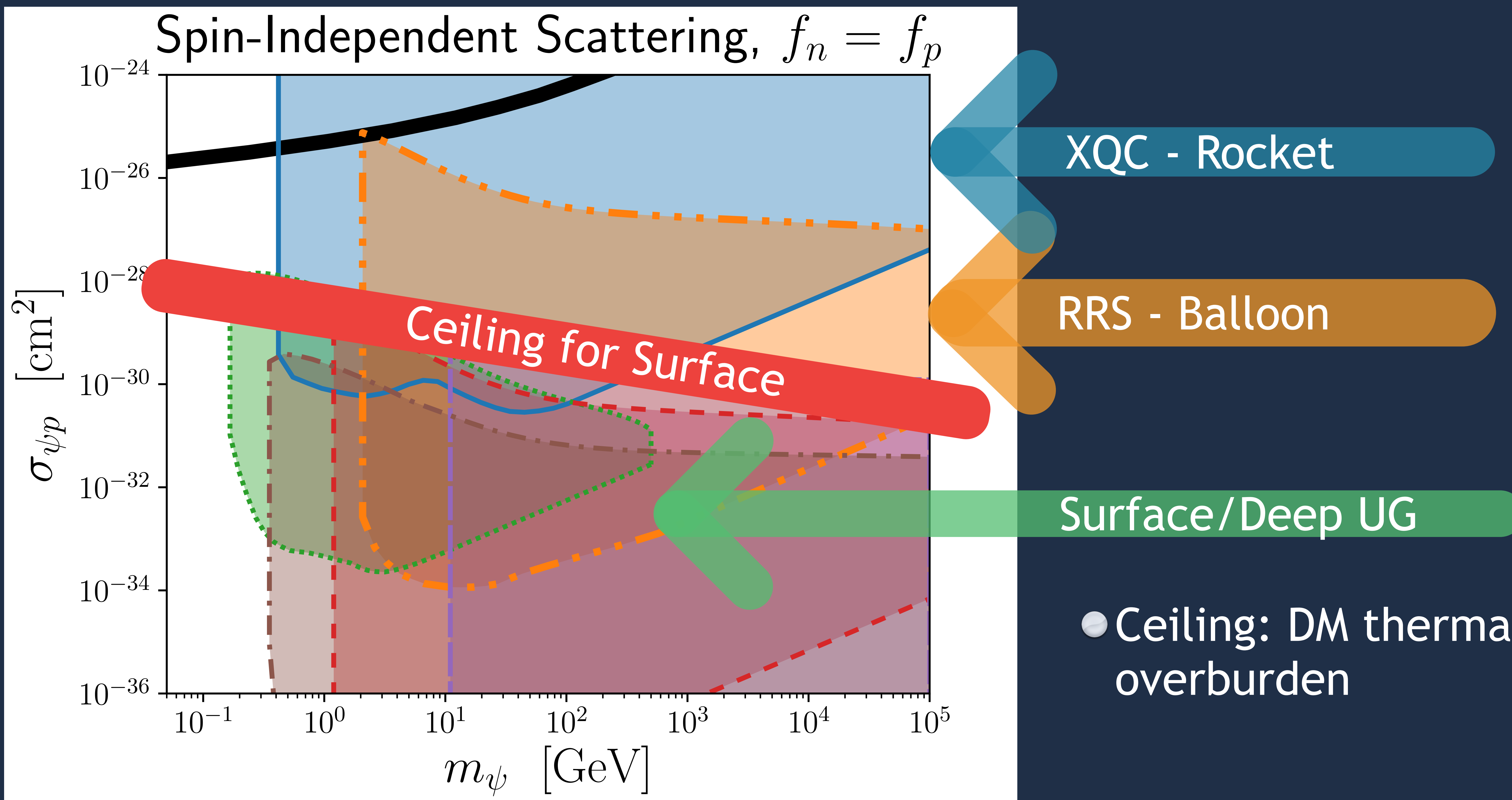




ArXiv: 1907.00011

Transfer x-section saturated by size of rock nuclei

A ceiling for large coupling



- Ceiling: DM thermalizes in overburden

[Hooper, McDermott 1802.03025]