Signatures of rare species of Dark Matter

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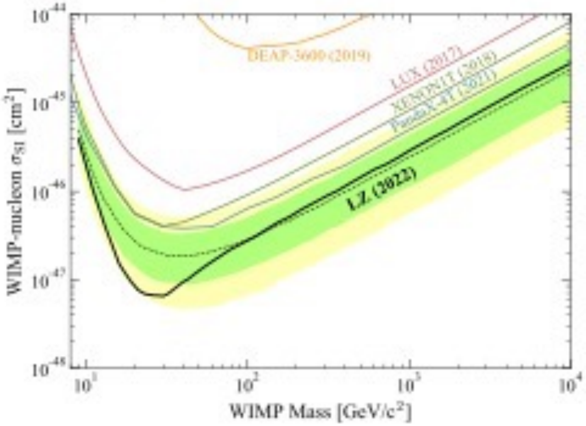
- Introduction. Rare species of dark matter. "Less is more".
- DM flux: "traffic jam" and hydrostatic population
- Signatures:

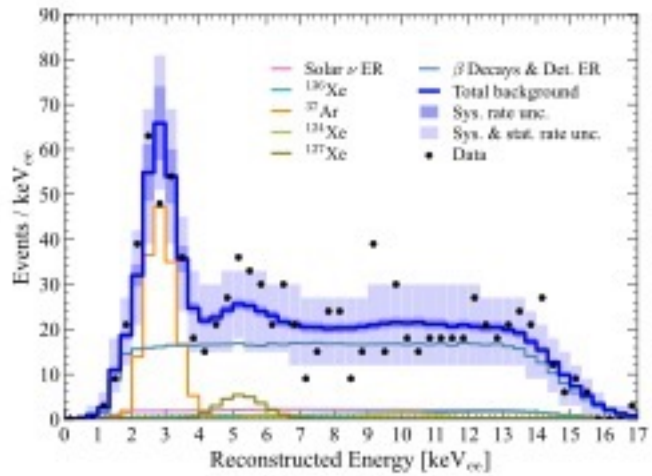
1. Signatures for neutrino detectors: Direct annihilation inside underground neutrino detectors, stopped π/μ source in the center of the Earth.
2. Possible use of underground accelerators: a scheme to search for strongly interacting DM in double collisions.
3. De-excitations of nuclear isomers. ^{180}Ta.
4. Nucleus-DM bound state formation, *in-situ*.

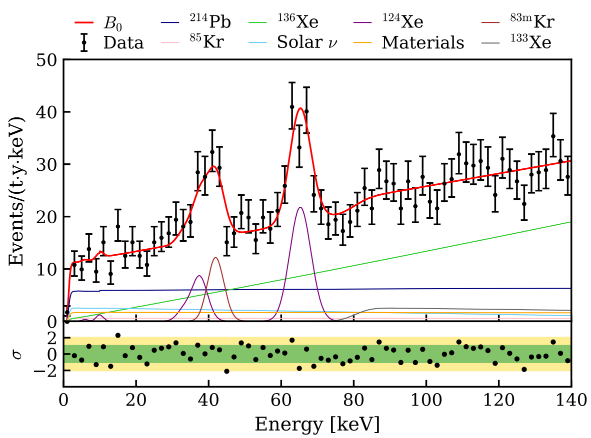
References

- D. McKeen, D. Morrissey, MP, H. Ramani, A. Ray, 2303.03416[hep-ph]
- M. Moore, D. McKeen, D. Morrissey, MP, H. Ramani, 2202.08840 [hep-ph], PRD 2022
- A. Berlin, H. Liu, MP, H. Ramani, 2302.06619 [hep-ph], 2110.06217 [hep-ph], PRD 2022.
- MP and H. Ramani, 2012.03957 [hep-ph], PRD 2022.
- B. Lehnert et al., 1911.07965 [Astro-ph.co], PRL 2020
- MP, S. Rajendran, H. Ramani, 1907.00011 [hep-ph], PRD 2020.

- Impressive 2022 updates of Direct detection limits by LZ, XenonNT.







Search for New Physics in Electronic Recoil Data from XENONnT

Two blind areas for direct detection

1. ~MeV scale dark matter: Kin Energy $= mv^2/2 \sim (10^{-3}c)^2(\mathrm{MeV}/c^2) \sim \mathrm{eV}$.

   Below the ionization threshold!

2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,

   Kin energy ~ kT ~0.03 eV

   (Typically cannot be entire DM, but is limited to fraction $f_\chi < 10^{-3}$)

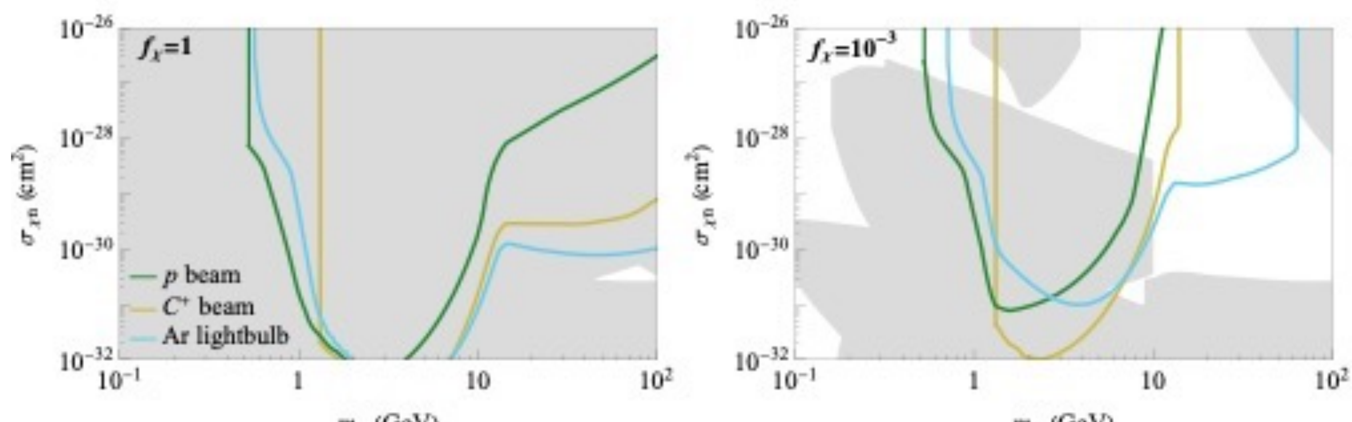
   Below the ionization threshold!

Rare species of dark matter

- Most advanced direct dark matter detection experiments are so far ahead of other probes that we would not be able to distinguish between ($f_\chi = 1$ and $\sigma = 10^{-47}$ cm^2, and e.g. $f_\chi = 10^{-3}$ and $\sigma = 10^{-44}$ cm^2)

- Assuming a wide range of f_χ , 10^{-10} to 1 is reasonable, as it can be broadly consistent with the freeze-out models.

- If $f_\chi << 1$ (e.g. 10^{-5}) significant blind spots exist for large scattering cross section values (e.g. 10^{-28} cm^2) which can easily arise in models with relatively light mediators. The accumulation and distribution of DM inside astrophysical bodies (most importantly, the Earth) will change.

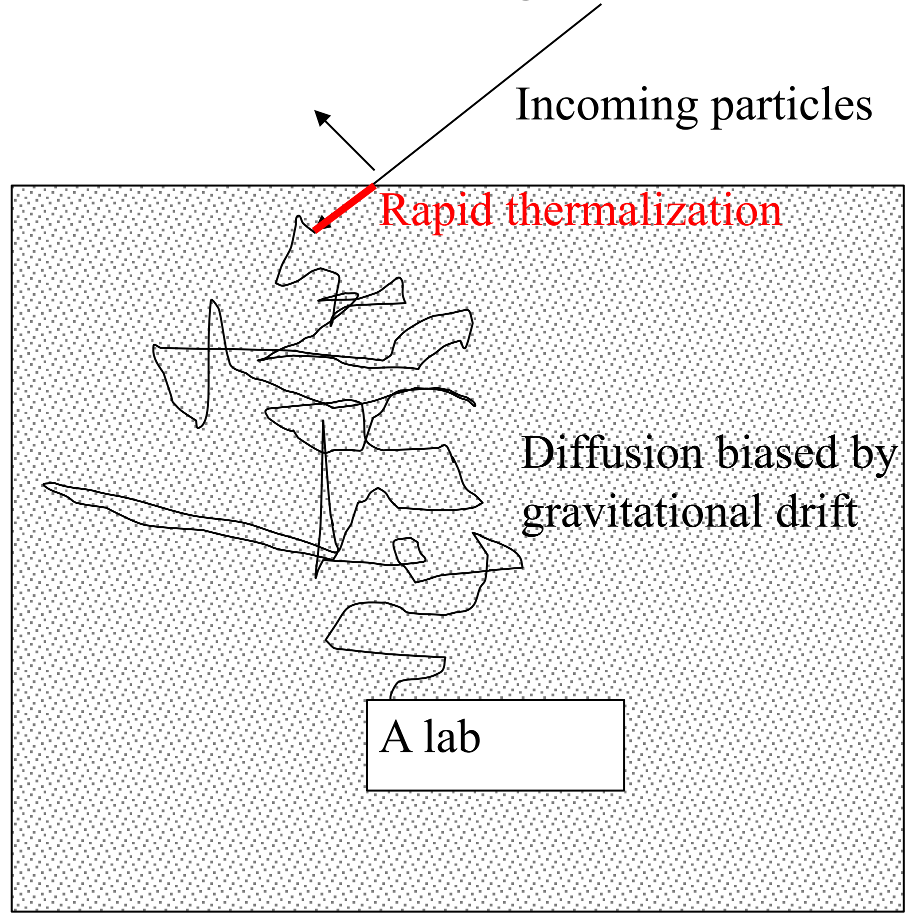


Dark matter traffic jam

- Rapid thermalization
- Flux conservation: $v_{in} n_{halo} = v_{terminal}\, n_{lab}$.
- Terminal sinking velocity is determined by the effective mobility (~ inverse cross section) and gravitational forcing

$$v_{\rm term} = \frac{3 M_\chi g T}{m_{\rm gas}^2 n \langle \sigma_t v_{\rm th}^3 \rangle}$$

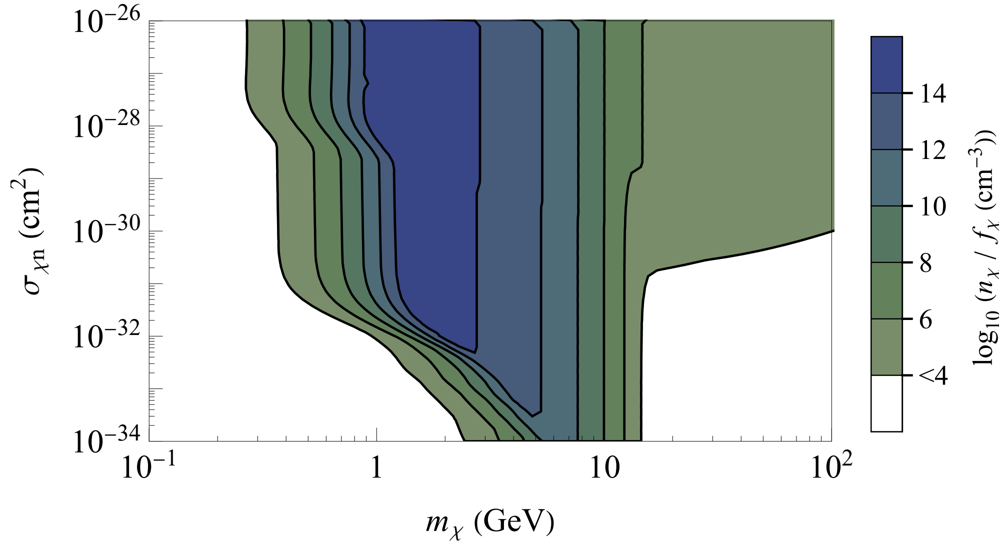
- Change in velocity from incoming ~ 10^7 cm/s to typical sinking velocity of 10 cm/s results in $n_{lab} \sim 10^6\, n_{halo}$. **Not visible to DD**
- At masses < 10 GeV upward flux is important and density goes up.



MP, Rajendran, Ramani 2019 MP, Ramani 2020, Berlin, Liu, MP, Ramani, 2021

Density of trapped particles: best mass range = few GeV.

- Lowest mass – evaporation, Highest mass – traffic jam, intermediate mass – trapping with almost uniform distribution inside Earth's volume.



- Enhancement of the density can be as high as 10^{14}. (First noted by Farrar and collaborators)
- "Less is more". Having 1 GeV particle with $f_\chi = 10^{-5}$ fractional DM abundance may result in ~ 10^9/cm^3 concentrations, not 10^{-5}/cm^3 . This has to be exploited.

Signature #1: annihilation inside the SK volume

- DM is often searched by its annihilation to neutrinos, with subsequent conversion of neutrinos to visible energy inside neutrino telescopes
- We propose that DM can be searched with direct annihilation inside detector volumes in the mass range ~ 1-5 GeV.

- Hydrostatic population is built up by incoming DM until it is counter-balanced by the annihilation (we assume s-wave). The distribution over radius is given by Euler eq. (see our papers, + Leane, Smirnov)

$$\frac{\nabla n_\chi(r)}{n_\chi(r)} + (\kappa+1)\frac{\nabla T(r)}{T(r)} + \frac{m_\chi g(r)}{k_B T(r)} = 0$$

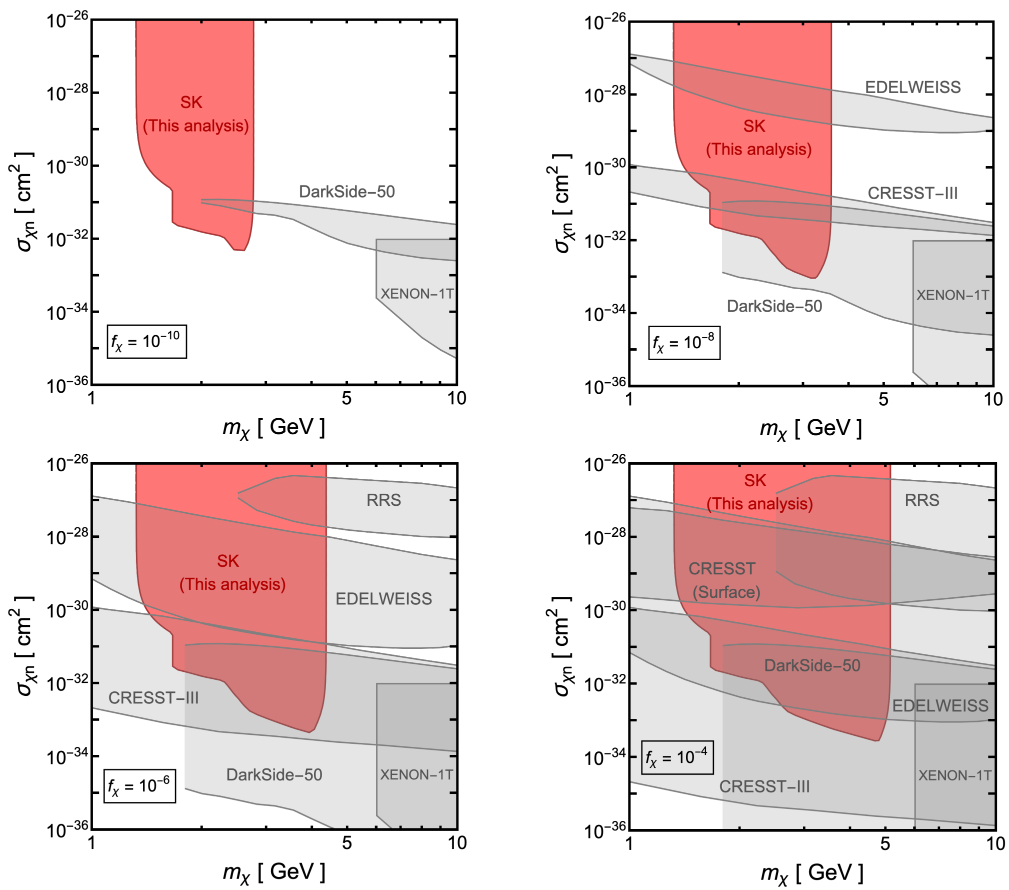
- Annihilation rate inside SK is easily calculable

$$\Gamma_{\rm ann}^{\rm SK} = \langle \sigma v \rangle_{\rm ann} n_\chi^2(R_\oplus) V_{\rm SK}$$

$$\Gamma_{\rm ann}^{\rm SK} = \Gamma_{\rm cap} \times \frac{V_{\rm SK} G_\chi^2(R_\oplus)}{4\pi \int_0^{R_\oplus} r^2 dr G_\chi^2(r)} \xrightarrow{G_\chi \to 1} \Gamma_{\rm cap} \times \frac{V_{\rm SK}}{V_\oplus},$$

Similar to di-nucleon decay signatures

- Constraints from a possible background-free search
- Lower masses evaporate, heavier masses sink too much.

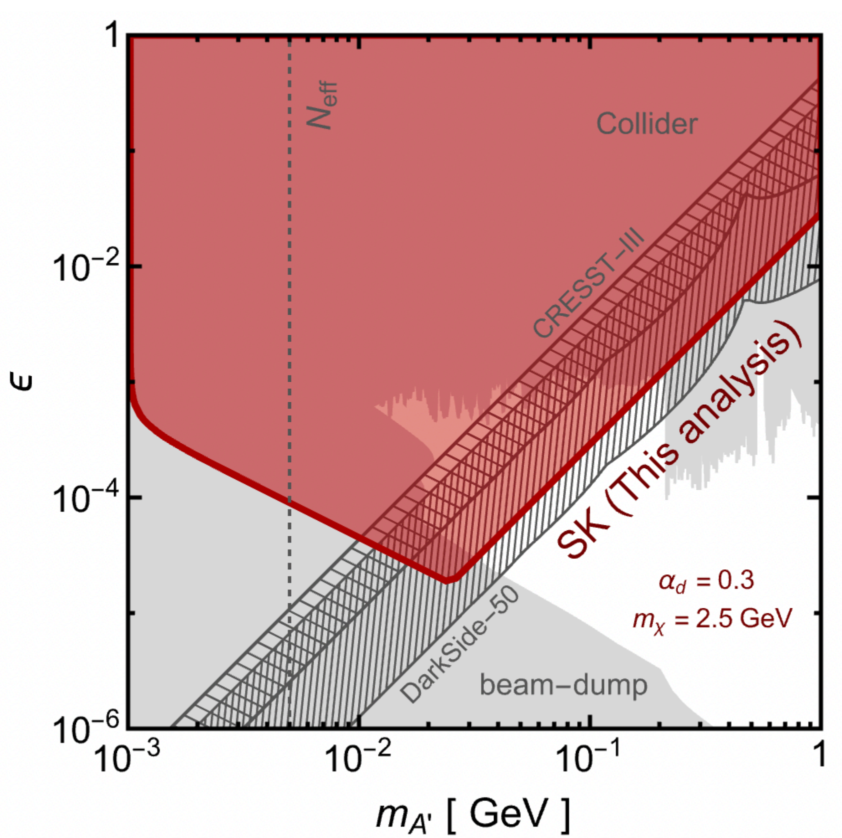


Assuming a background free search with $2m_\chi$ invariant mass energy release. In many models: strong similarity to nn→$\pi^0\pi^0$ search by SK (background free, ~0.1 signal efficiency).

Constraints on dark photon mediated DM

- Dark photon mediate DM with $m_{A'} < m_\chi$.

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}\right)^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}\left(A'_\mu\right)^2 + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi\,,$$



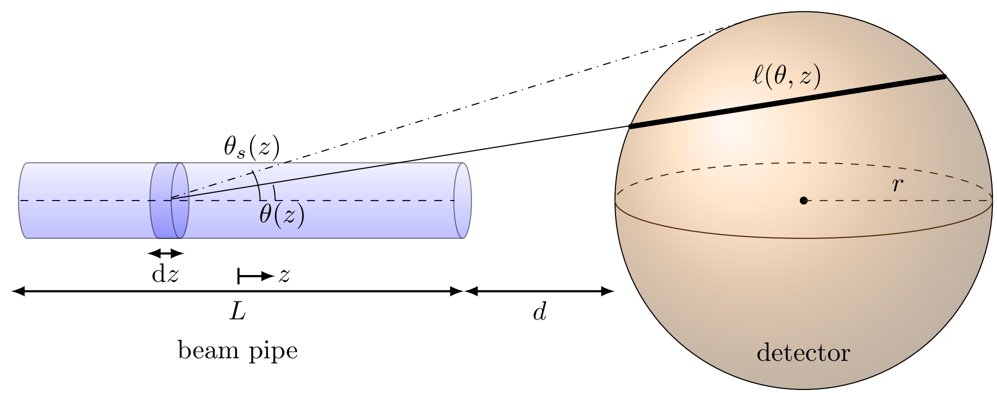
$\chi\bar{\chi} \rightarrow A'A'$ with $A' \rightarrow$ SM

Dark coupling constant of 0.3 and dark matter mass of 2.5 GeV results in the fractional abundance ~ 3 10^{-9}. New parameter space covered.

For heavier than 5 GeV masses main signature are neutrinos from Earth's center.

Signature # 2: Using underground accelerators to "accelerate" dark matter

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators (LUNA, JUNA) for a completely different purpose: studies of nuclear reactions.
- We propose to couple nuclear accelerators and dark matter detectors: accelerated protons (or other nuclei) can strike DM particles that can subsequently be detected with a nearby detector.



- This is going to be relevant for models with large DM-nuclear cross section where A. interaction is enhanced, B. density is enhanced.

Spectrum of recoil

- Energy of nuclei in the detector after experiencing collision with the accelerated DM.

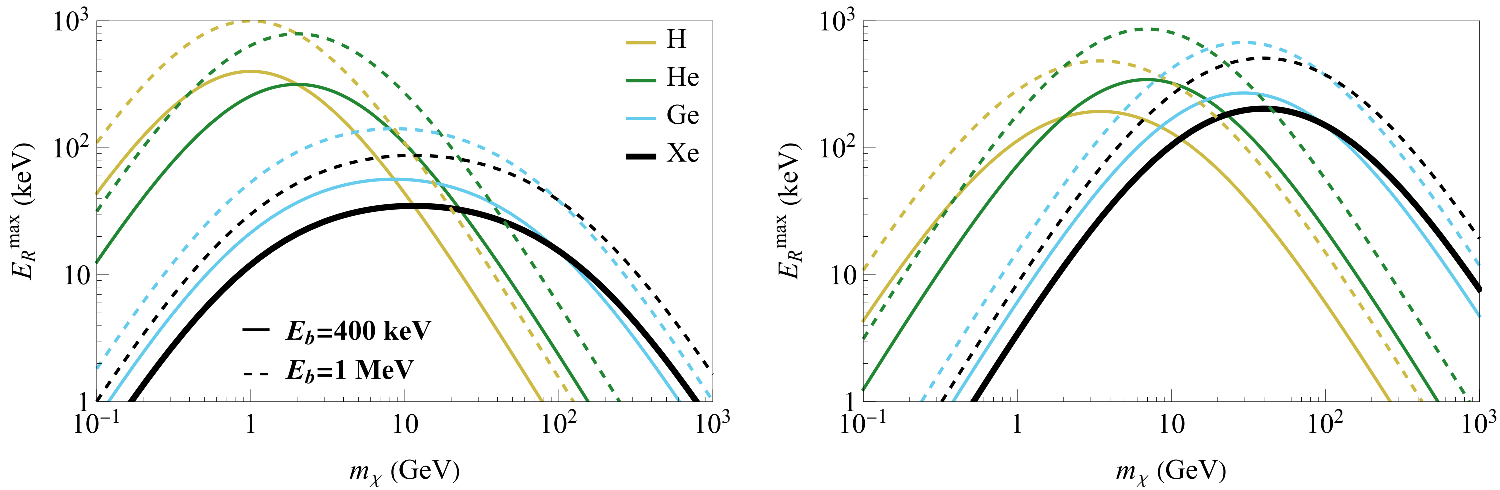
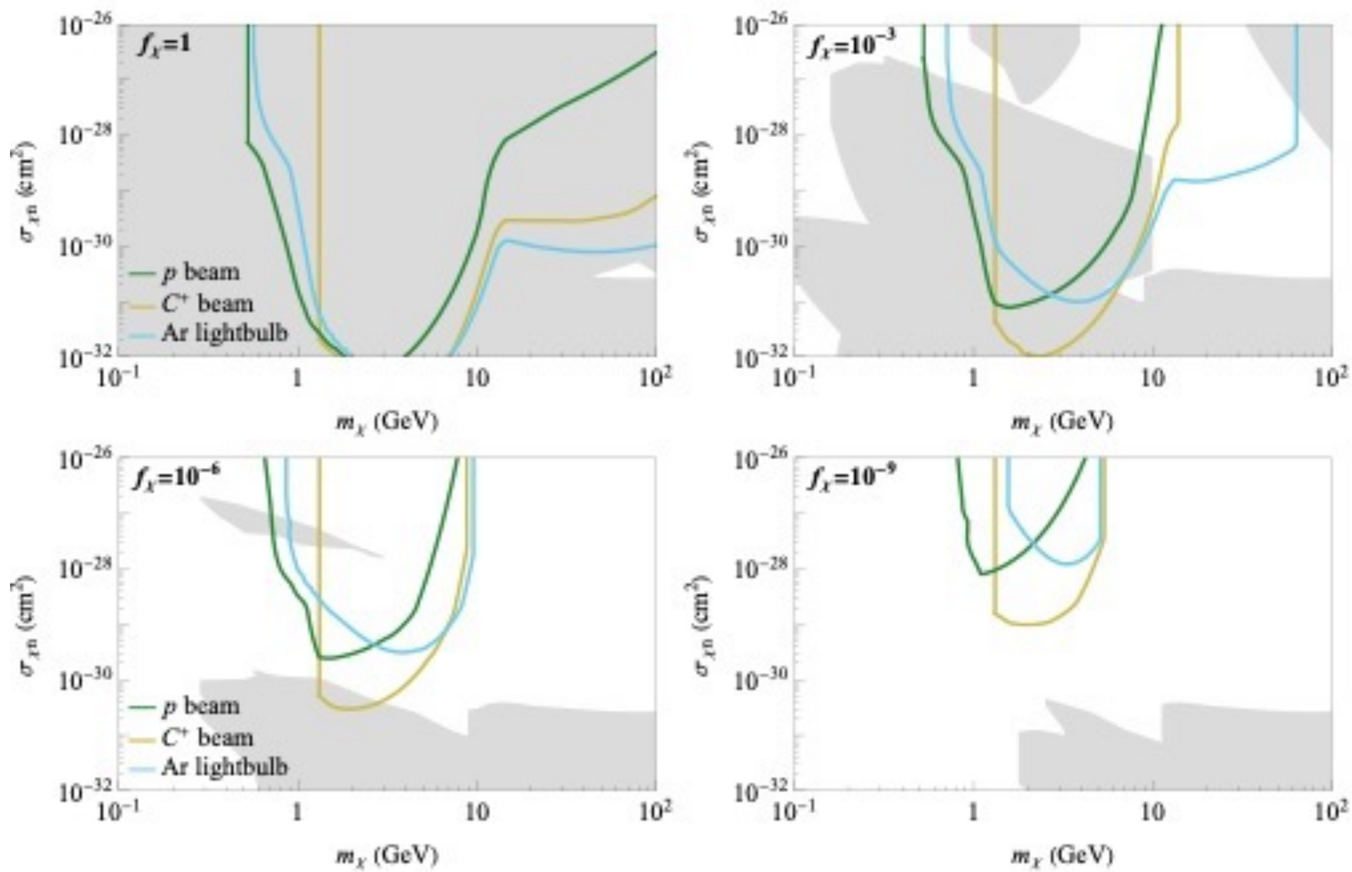


FIG. 3. Maximum nuclear target recoil energies E_R^{max} for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies $E_b = 0.4$ MeV (solid) and $E_b = 1.0$ MeV (dashed) for a selection of target nuclei.

Energy of accelerator is ~ MeV, and given that the thresholds in many detectors are keV and lower, this detection scheme is realistic.

New reach in the parameter space

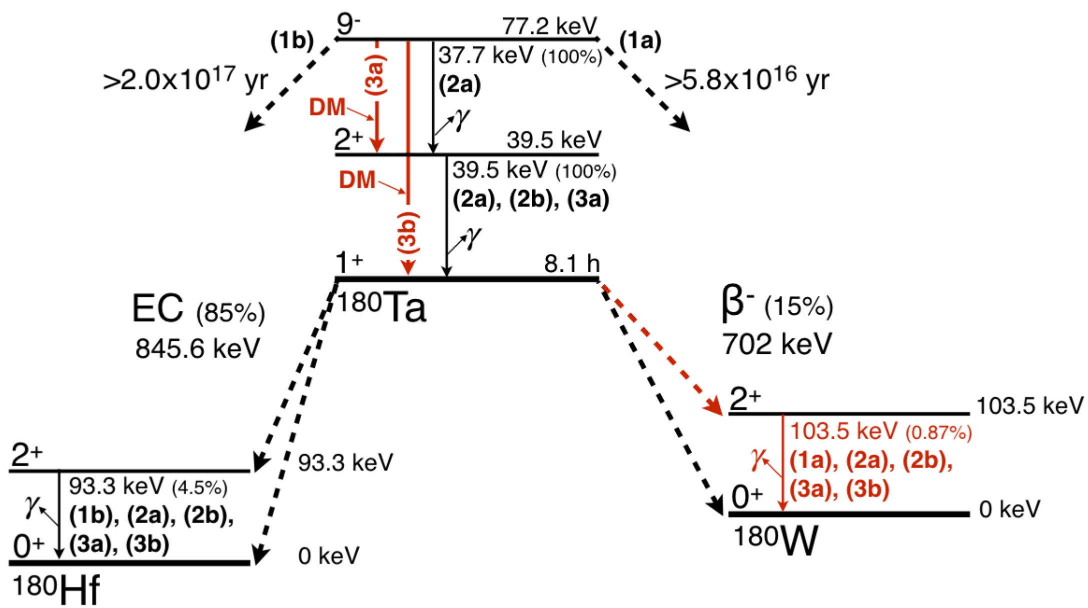
- While 100% fraction of these DM particles is excluded by combination of ballon + underground experiments (gray area), the accelerator+detector scheme is sensitive to small f_χ.



- This is a promising scheme that can be tried without additional enormous investment, with existing accelerators (LUNA, JUNA)

Signature # 3: DM catalyzed de-excitation of nuclear isomers

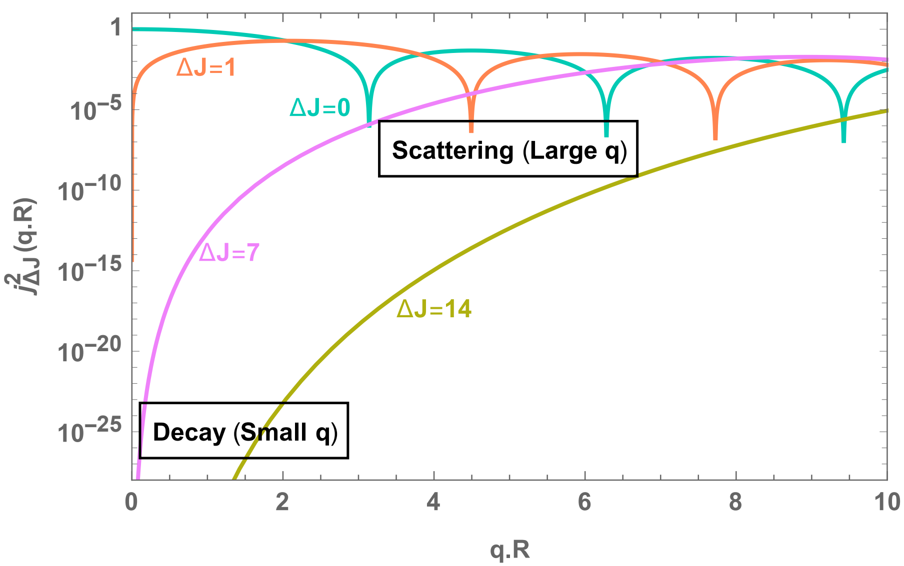
Tantalum180m level structure



- Lifetime of the 9- level exceeds 10^{17} years
- Natural abundance is not all that small, 0.01%.

DM is a source of large recoil momentum → Enhancement

- Momentum transfer k mediated in the γ,β transitions is small: on the order of decaying energy, e.g. 100 keV.
- $(R_{nuclear}\ k) \sim 10^{-3}$. Enters in the HUGE power in the rate, $(R_{nuclear}\ k)^{2\Delta L} \sim (10^{-3})^{14}$.
- Dark matter is rare etc etc – but it carries large k! k ~ / $R_{nuclear}$ easily. Kinematic suppression by $(R_{nuclear} / \lambda)^{2\Delta L}$ is gone.



k_{DM}=(2 ΔE 100 GeV)$^{1/2}$ = 120 MeV

Interesting candidates

Isomer	ΔE_N^{max}	levels	Half-life	Source	Amount	Signal	Hindrance (F_γ)
^{180m}Ta	77 keV	2	$> 10^{16}$ y	Natural	0.3 gram year	Ground State Decay / Secondary	0.16[14]
^{137m}Ba	661 keV	2	2.55 min	Nuclear Waste	0.5 gram year	Secondary	1
^{177m}Lu	970 keV	27	160 d	Medical Waste	1 mg year	Secondary	0.17[a]
^{178m}Hf	2.4 MeV	110	31 y	Old experiments	1 μg year	γ end-point / Secondary	0.29[a]

[a] Hindrance factors for Lu and Hf derived from the observed half-lifes.

- Tantalum 180m is naturally occurring. Non-radioactive. Provides the safest opportunity.
- First searches have been performed, but there is a sustained interest to this element from the nuclear physics community.

Strongly-Interacting DM, potential reach

- Strongly-interacting DM can be detected this way. Here is a possible reach based on 10 kg of Tantalum, and 1 event/yr sensitivity.

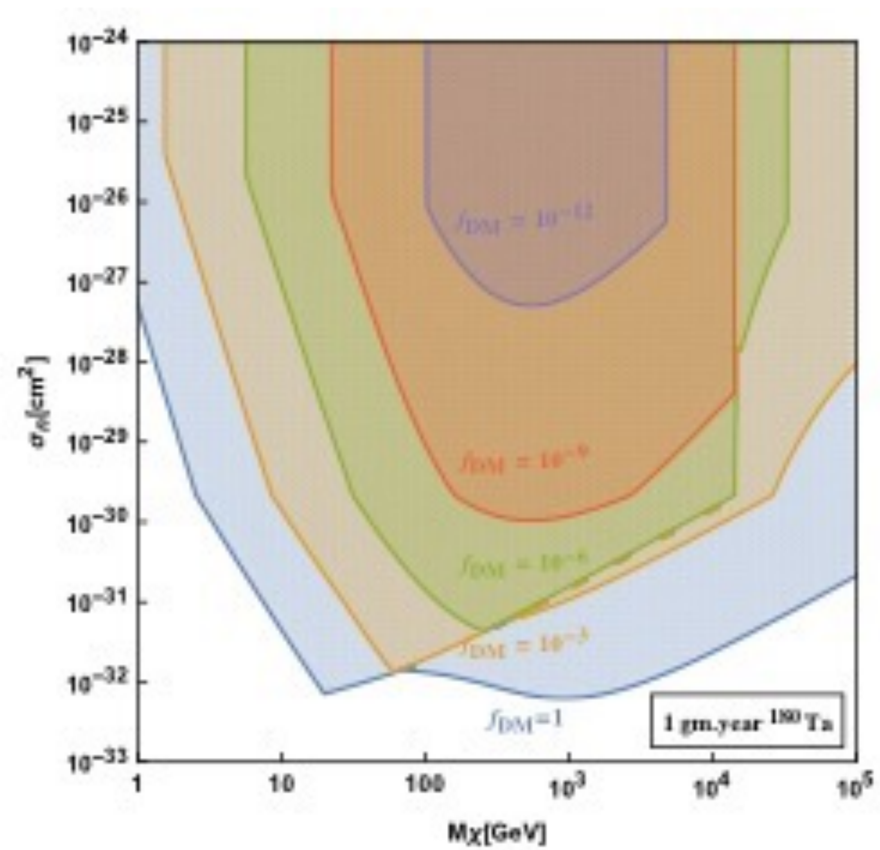
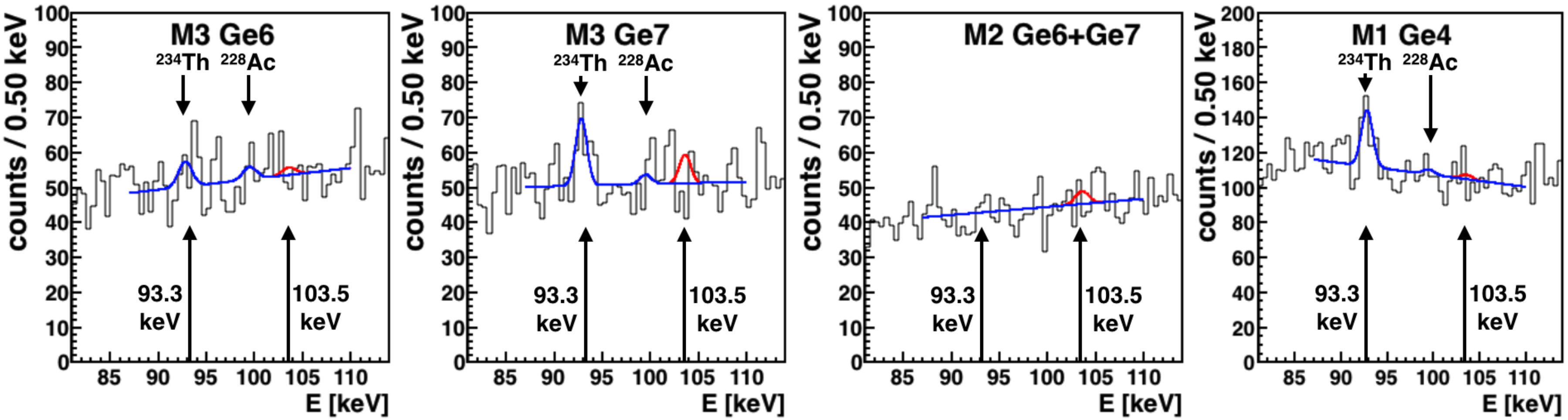


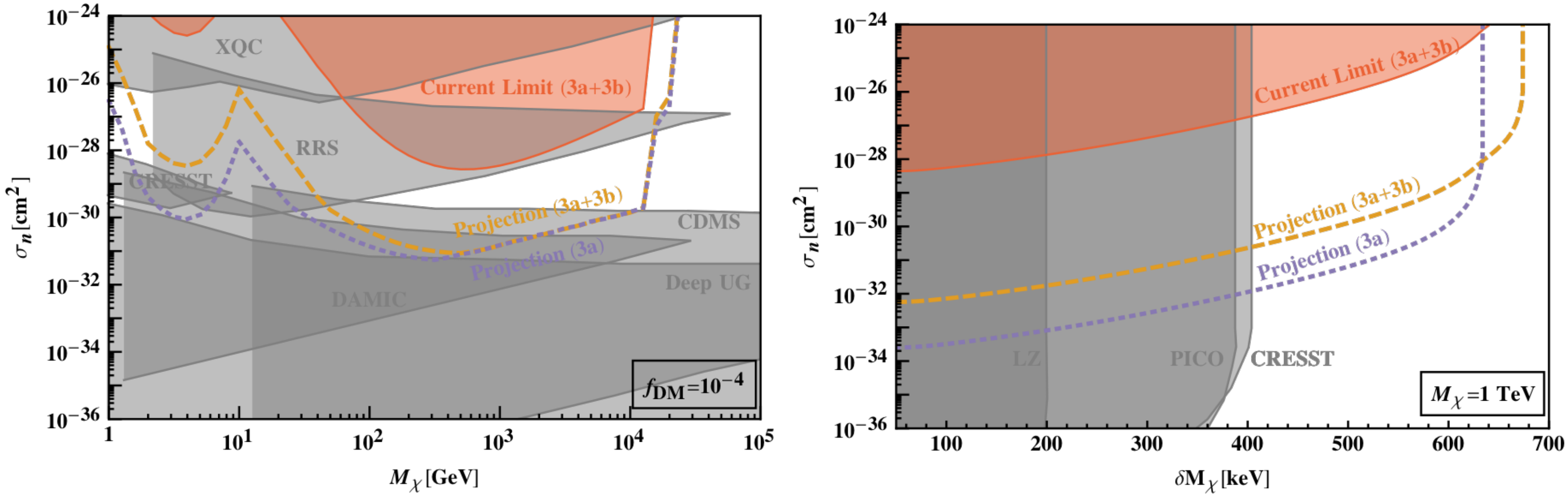
FIG. 3. Projections for limits on per-nucleon cross-section for DM that interacts strongly with nuclei that correspond to 1 gram year exposure for ^{180m}Ta

Experimental search



- DM induces de-excitation of Ta180m down to the ground state.
- Ta180gs decays within a few hours to W and Hf. These decays produce 103.5 and 93.3 keV gammas.
- Search of these gammas above the background in the old data from HADES lab produced upper limits on DM-induced de-excitation of Ta180m. $T_{1/2}>1.3\ 10^{14}$ yr

Experimental constraints



- Left: constraints on strongly-interacting DM, that constitutes a 10^{-4} fraction of the total DM abundance. New parameters relative to XQC are covered.

- Right: constraints on inelastic dark matter. New mass splittings are covered.

- Last comment: bulk Ta can be used to “accelerate” DM.

Signature #4: dark photon mediated interaction may lead to Dark Matter – Nucleus bound state

- Consider a stable elementary particle charged under U(1)'.

$$\mathcal{L} = -\frac{1}{4}(F'_{\mu\nu})^2 - \frac{\varepsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{m_{A'}^2}{2}(A'_\mu)^2 + \bar{\chi}(iD_\mu\gamma_\mu - m_\chi)\chi,$$

- The choice of parameters of interest: $\varepsilon \sim$ up to 10^{-3}; $m_{A'} \sim$ 10-100 MeV, $m_\chi \sim$ 10 - 1000s GeV or larger, $\alpha_{dark} \sim 10^{-2} - 1$.
- Given the choice of parameters abundance can be calculated, assuming the standard cosmological history. However, I am going to treat fraction f_χ as a free parameter taking it small.
- Thus, the standard *visible dark photon* constraints apply.

Nucleus-DM potential

$$V(\mathbf{r}_\chi) = -\varepsilon\sqrt{\alpha\alpha_d}\sum_{i=e,p} Q_i \frac{\exp(-m_{A'}|\mathbf{r}_\chi - \mathbf{r}_i|)}{|\mathbf{r}_\chi - \mathbf{r}_i|}$$

$$\to \varepsilon_{\text{eff}}\alpha \sum_e \frac{\exp(-m_{A'}|\mathbf{r}_\chi - \mathbf{r}_e|)}{|\mathbf{r}_\chi - \mathbf{r}_e|} - Z\alpha\varepsilon_{\text{eff}} V(\mathbf{r}_\chi, R_N)$$

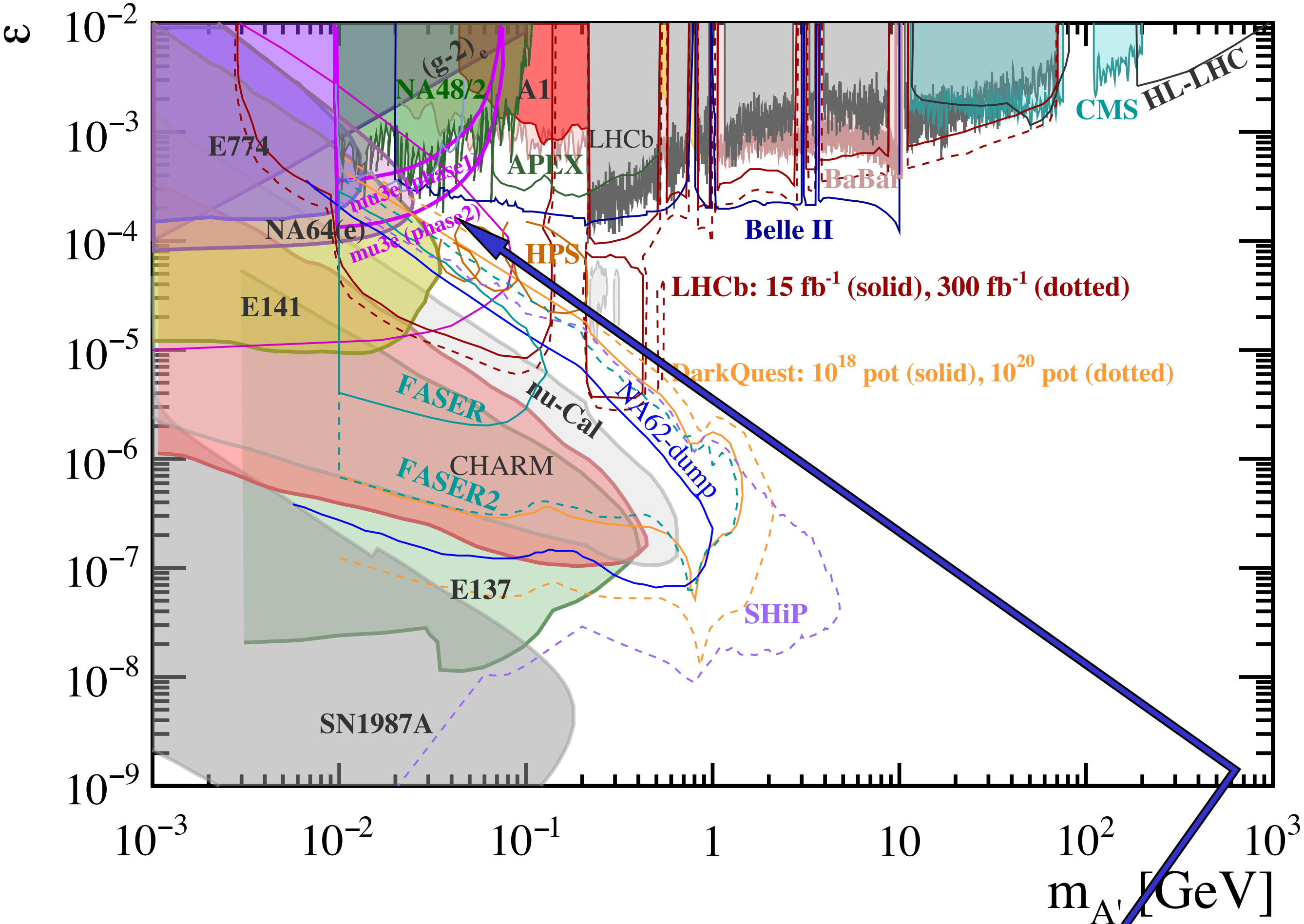
$$V(\mathbf{r}_\chi, 0) = \exp(-m_{A'}|\mathbf{r}_\chi - \mathbf{r}_N|)/|\mathbf{r}_\chi - \mathbf{r}_N|.$$

- For a point-like nucleus = Yukawa potential.
- Since α_{dark} can be large, $\varepsilon_{\text{eff}} \equiv \varepsilon \times \sqrt{\alpha_d/\alpha} \lesssim O(10)\varepsilon$

Two important consequences of sizeable couplings:

1. Elastic scattering cross section on nuclei is large
2. Strong enough attractive force affords bound states

Constraints on visibly decaying dark photons



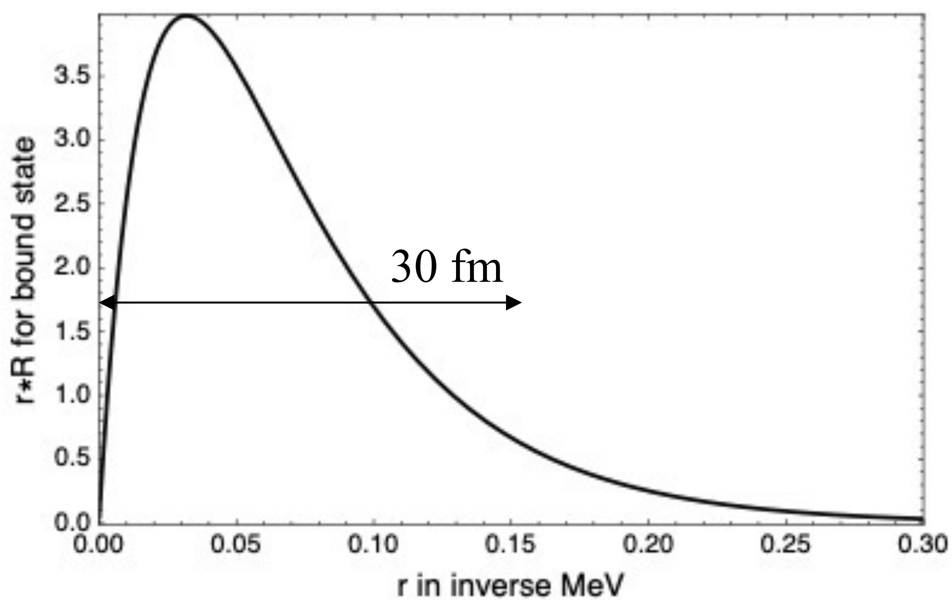
Bound state formation is possible in this corner

Example of the bound state profile

Naïve Bohr-style formula for the bound state with massless mediator:

$$E_{\rm b.s.} \simeq 7.8\,{\rm keV} \times \left(\frac{\varepsilon_{\rm eff}}{10^{-3}}\right)^2 \left(\frac{Z}{54}\right)^2 \left(\frac{\mu}{100\,{\rm GeV}}\right)$$

Actual binding for $m_{A'}$ of 10 MeV in Xenon = 2.6 keV.



$$E_{b.s.} = 2\,{\rm keV},\ \varepsilon_{eff} = 0.85\times10^{-3},\ m_V = 15\,{\rm MeV},\ \mu = 100{\rm GeV}.$$

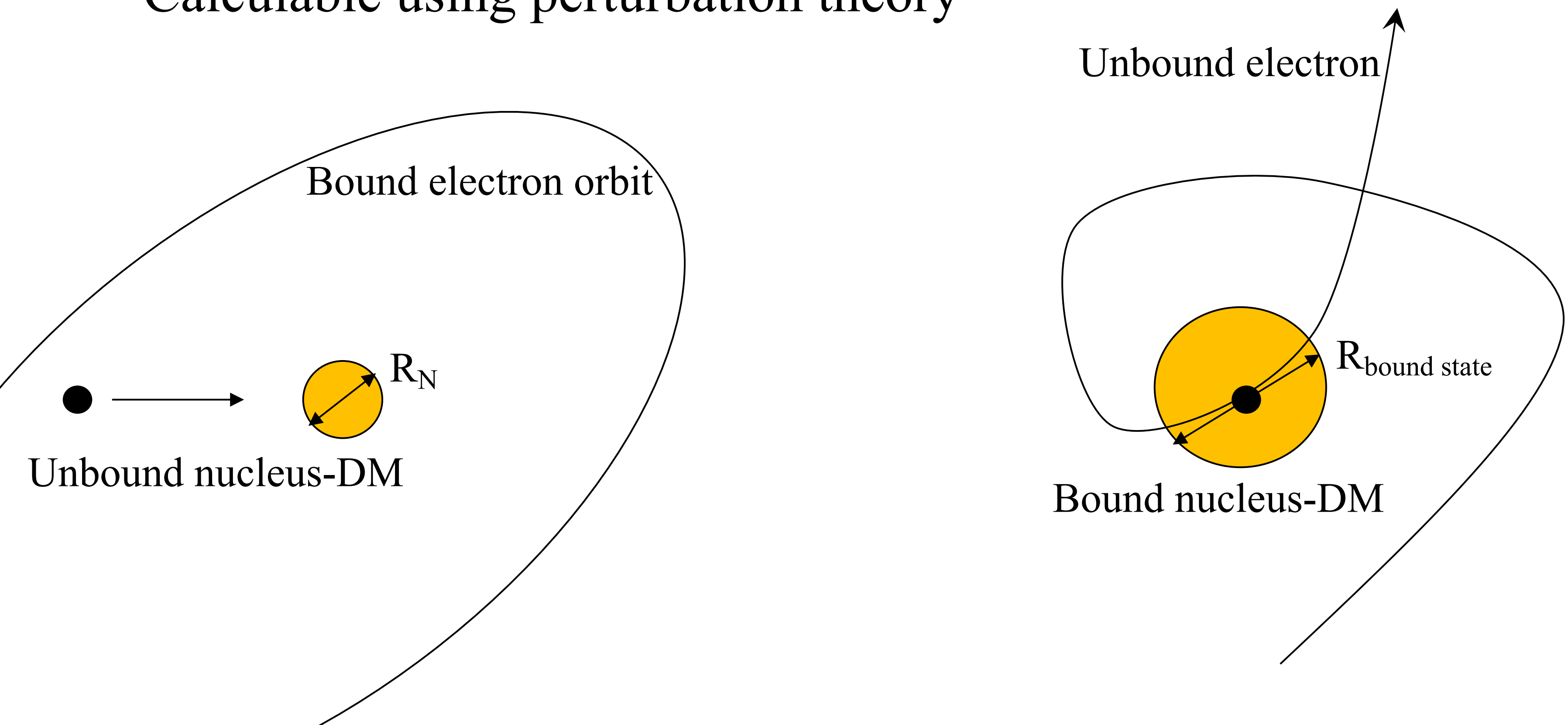
Capture process

- Auger-style process with the ejection of an atomic electron.

$$A + \chi \rightarrow (A^{+}\text{-ion}\ \ \chi) + \text{electron}$$

Dominates over photon emission.

- Calculable using perturbation theory



Calculation/estimate of the capture rate

S-wave (DM-nucleus) to outgoing electron s-wave capture rate:

$$\sigma_{s-s} v = \frac{(4\pi)^3}{9} \left(\frac{\mu}{m_N}\right)^4 \frac{(Z\alpha m_e)^2 (\alpha m_e)^3}{m_V^7} \rho_N^2 \rho_e^2$$

where radial integrals are given by

$$\rho_N = m_V^{7/2} \int_0^\infty dr \times r^4 G(r) R_{b.s.}(r)$$

$$(\rho_e)^2 = 2(\alpha m_e)^{-3} \sum_n \left(R_{n0}(0) \frac{R_{p_e 0}(0)}{2p_e} \sqrt{v_e} \right)^2$$

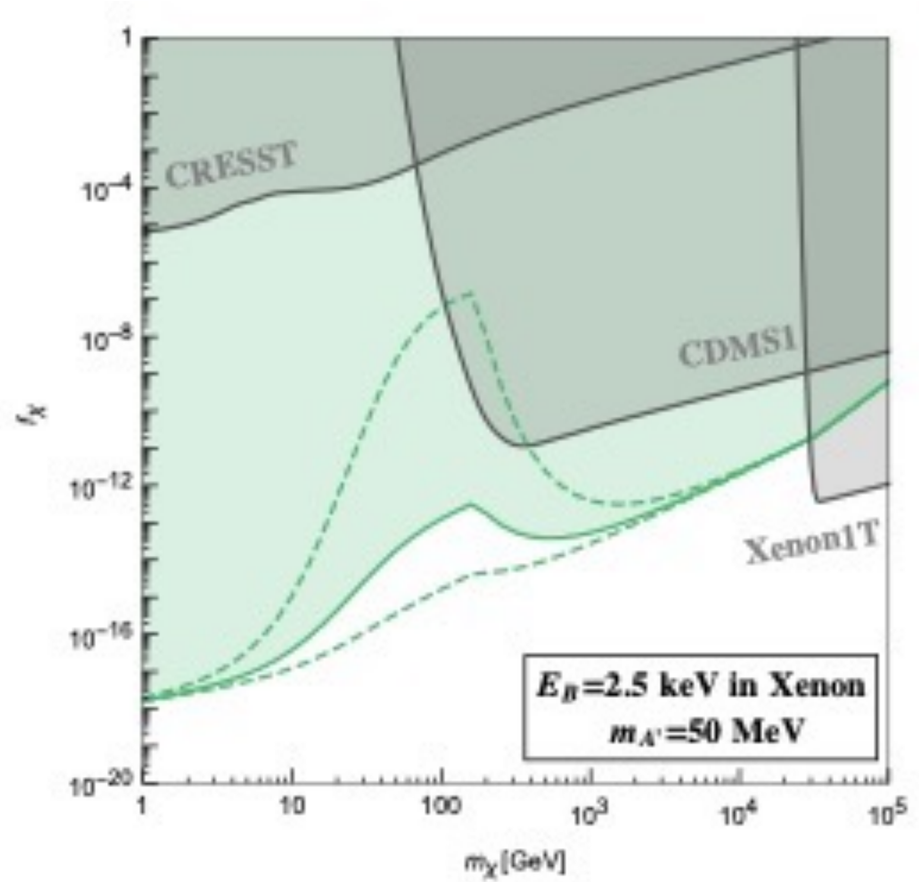
that can be evaluated numerically.

At fiducial choice of parameters, (Xenon, mediator mass = 15 MeV, m = 100 GeV, effective ε giving 2 keV binding) the estimate is

$$\sigma_{s-s} v \simeq 10^{-33} \mathrm{cm}^2$$

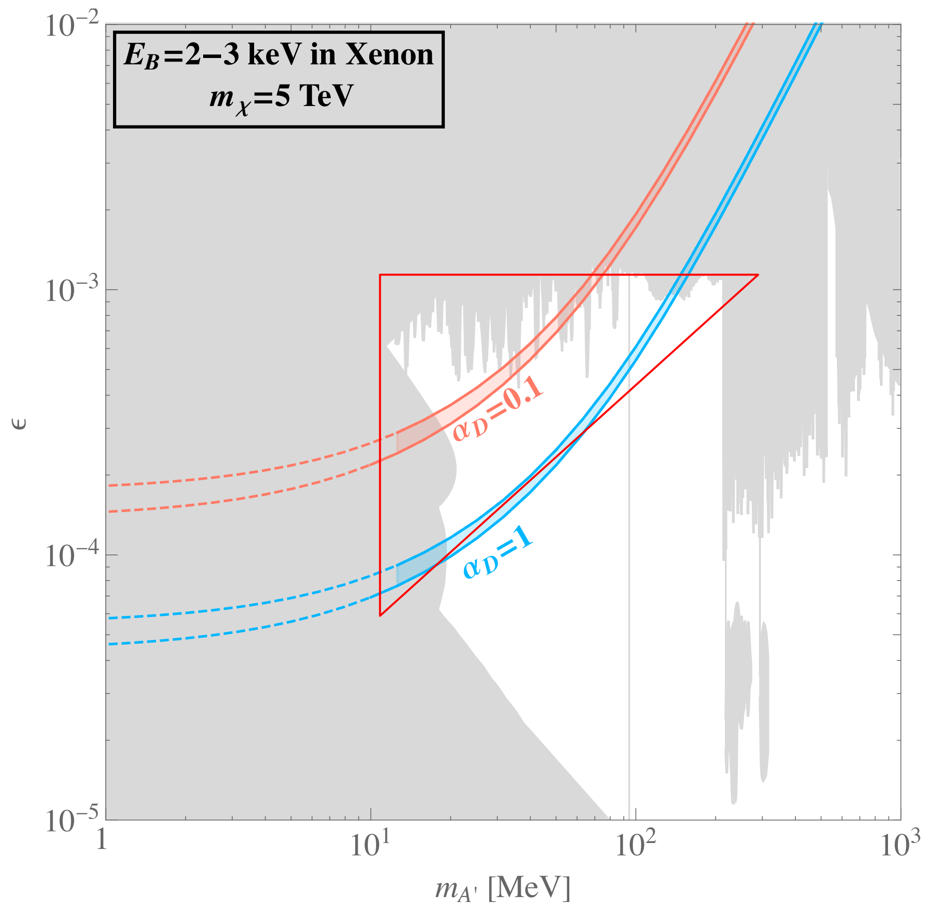
- Since actual c/v ~ 10^6, the actual cross section ~ 10^{-27} cm^2. Not tiny

One can probe exceedingly small admixtures of DM particles that can bind to Xe nucleus



- Strong sensitivity to very small abundance, down to 10^{-17} level.
- Main uncertainty due to rock composition (e.g. how much Barium Gran Sasso mountain has).

Zooming in onto dark photon target parameter space



- A roughly triangular shape of the parameter space, ~ one decade long on each side supports DM-nucleus bound states.
- This parameter space is [hopefully] going to be explored by the LHCb and HPS experiments.

Conclusions

- *The assumption that we search for 100% of DM is just an assumption.*
- Interesting physics can result from rare species of DM, as their elastic cross sections can be very sizeable resulting in enhanced population inside the Earth (traffic jam and hydrostatic population).
- The diversity of DM models creates a diversity of experimental signatures – now it is the right time to explore them, as much investment is made into direct detection of dark matter.
- Signature 1: direct annihilation inside the neutrino detectors (strong constraints from SK).
- Signature 2: nuclear accelerators to upscatter DM and detect recoil.
- Signature 3: nuclear isomer de-excitation is catalyzed. Ta180 is a very attractive candidate.
- Signature 4: DM and heavy atoms can form bound states leading to O(keV) scale energy deposition inside DM detectors. Can explore the rarest species of DM, down to 10^{-18}.