Accelerared Dark Matter

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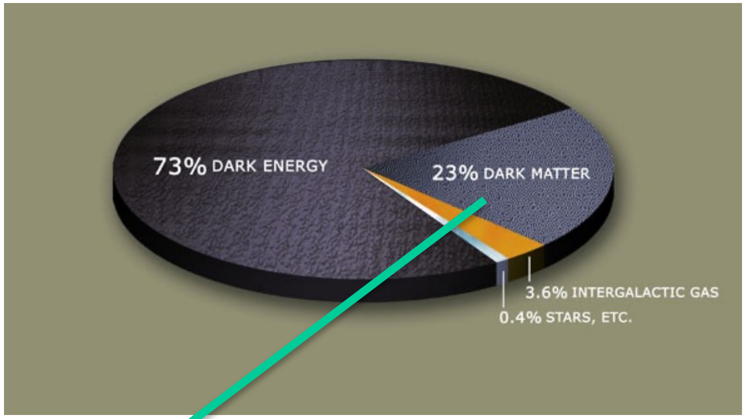
FTPI and U of Minnesota

- Introduction. Dark sectors/feably-interacting particles. Blind spots for direct detection. 2108.10332 [hep-ph]
- New sensitivity to light dark matter via solar reflection (With H. Nie, H. An, J. Pradler, A. Ritz). (2018 PRL, 2021 PRD)
- Acceleration of DM by cosmic rays (With T. Bringmann). 1810.10543 [hep-ph], (2019 PRL)
- Possible use of underground accelerators? (With M. Moore, D. McKeen, D. Morrissey, H. Ramani). 2202.08840 [hep-ph]
- Conclusions

Why identifying dark matter is difficult



Av. Density ~
0.3 GeV/cc – not a lot

$L_{min} \sim 10^{21}$ cm

$L_{exp} \sim \text{few} * 10^2$ cm

We need to extrapolate
19 orders of magnitude!
Theory is the first step!

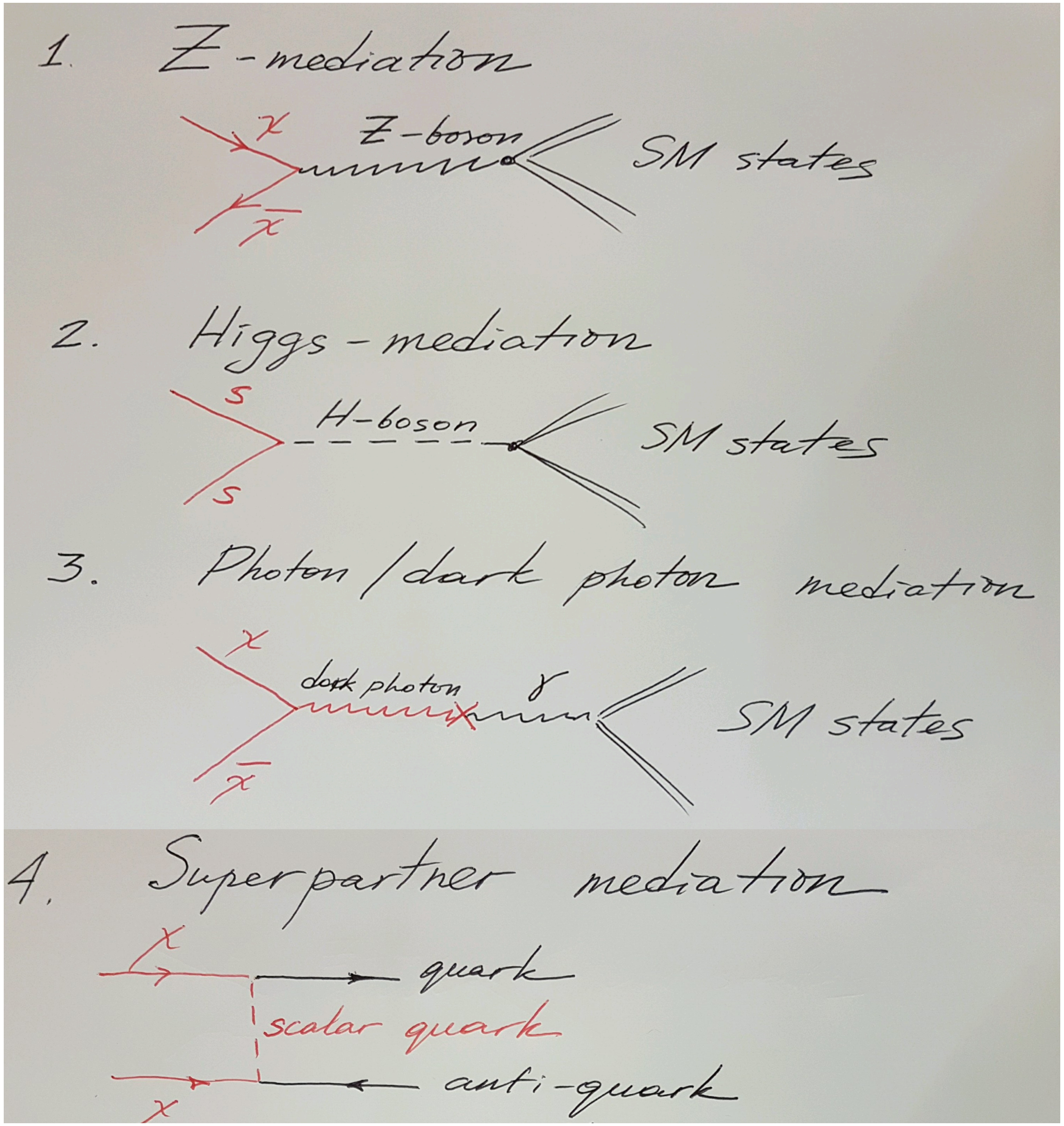
Dark matter could be a new type of particles

Simplicity of the early Universe, makes many of us suspect that the DM might be in the form of unknown (= e.g. beyond-SM particles).

Search for dark matter particles is done at colliders, beam dump experiments, and in low-radiation environments, such as *underground laboratories*.

Goal: explore multiple collisions of DM to fill in “blind spots” to certain types of DM

Examples of DM-SM mediation



- Topic of WIMPs was dominated by SUSY neutralinos for a long time. In the absence of any experimental hints at SUSY at the LHC, the focus shifted to other models.
- Current discussion of DM increasingly shifts away from SUSY to other "minimalistic" options.
- Mass range of possible WIMPs is much larger than originally envisaged by Lee and Weinberg.

Idea of “dark sectors”

Effective field theory with light new degrees of freedom.

$\mathcal{L}_{\text{SM+BSM}} = - m_H^2 \, (H^+_{SM} H_{SM}) +$ all dim 4 terms $(A_{SM},\ \psi_{SM},\ H_{SM}) +$

$+$ (W.coeff. $/\Lambda$) $\times$ Dim 5 $(\psi_{SM},\ H_{SM})$

$+$ (W.coeff. $/\Lambda^2$) $\times$ Dim 6 etc $(A_{SM},\ \psi_{SM},\ H_{SM})\ + \ldots$

all lowest dimension portals $(A_{SM},\ \psi_{SM},\ H,\ A_{DS},\ \psi_{DS},\ H_{DS}) \times$ portal couplings

$+$ dark sector interactions $(A_{DS},\ \psi_{DS},\ H_{DS})$

SM = Standard Model

DS – Dark Sector

Excellent framework for light DM

some WIMP examples

- Scalar dark matter talking to the SM via a “dark photon” (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Fermionic dark matter talking to the SM via a “dark scalar” that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

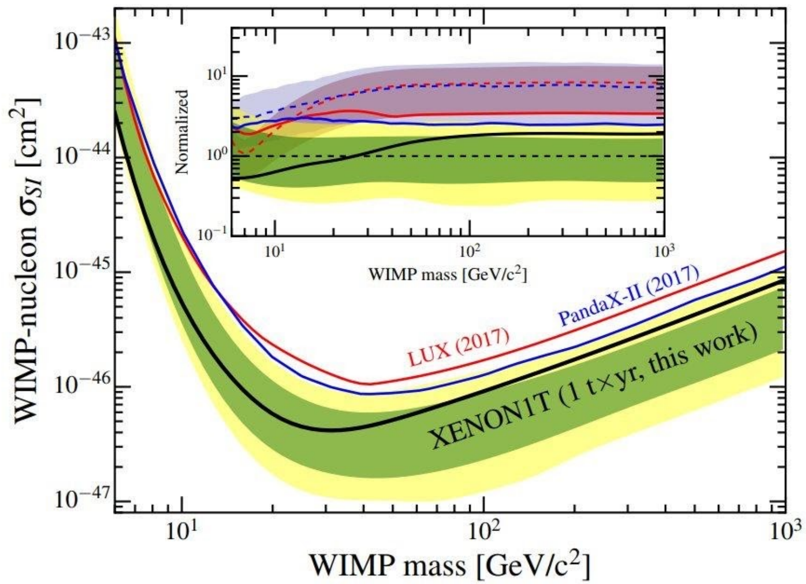
After EW symmetry breaking S (“dark Higgs”) mixes with physical h, and can be light and weakly coupled provided that coupling A is small.

Take away point: *with lots of investment in searching for DM with masses > GeV, models with sub-GeV DM can be a blind spot.*

Search for WIMP-nucleus scattering
(+latest LUX, XENON 1T and PANDA-X results)

Strongest constraints on nuclear recoil

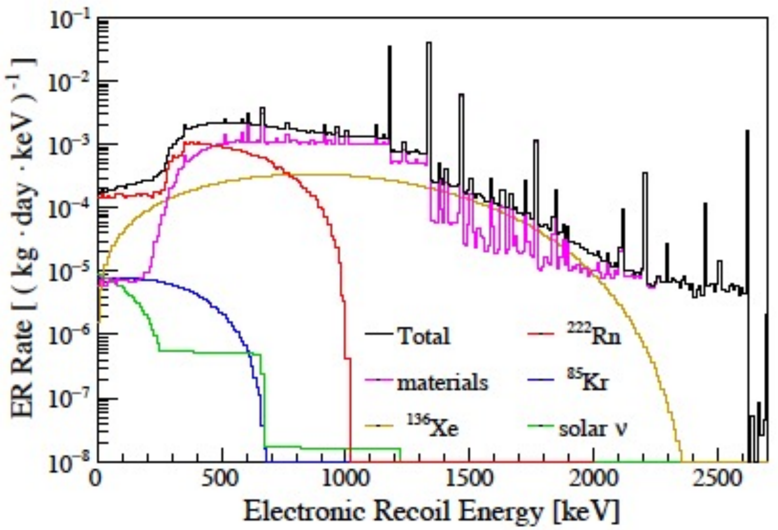
This direction can still be improved at modest cost, by being clever



Requires enormous effort and investment

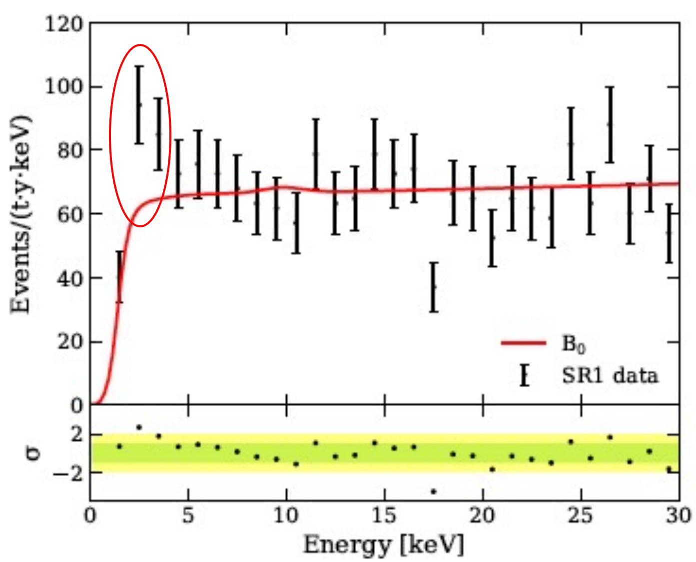
- Optimum sensitivity, $m_{WIMP} \sim m_{Nucleus}$ (a little lighter because of nuclear form factor).
- No sensitivity below $m_{WIMP} \sim$ few GeV, due to exceedingly small recoil that does not give much light or scintillation.
- *Summer 2020 – interesting hint on excess in electron recoil.*

Impressive results by Xenon1T in achieving low backgrounds and high sensitivity



2015 projections, 1512.07501

This is the most sensitive device for rare keV-scale events.

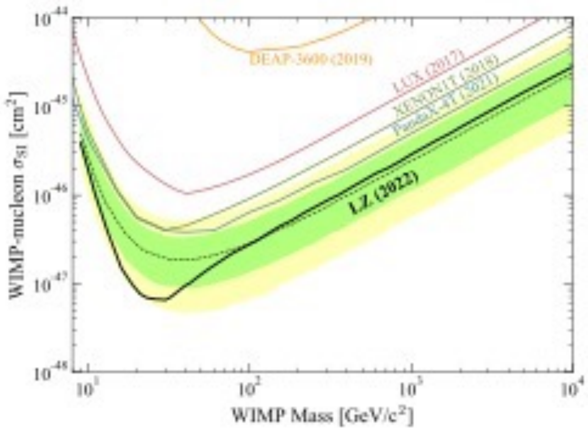


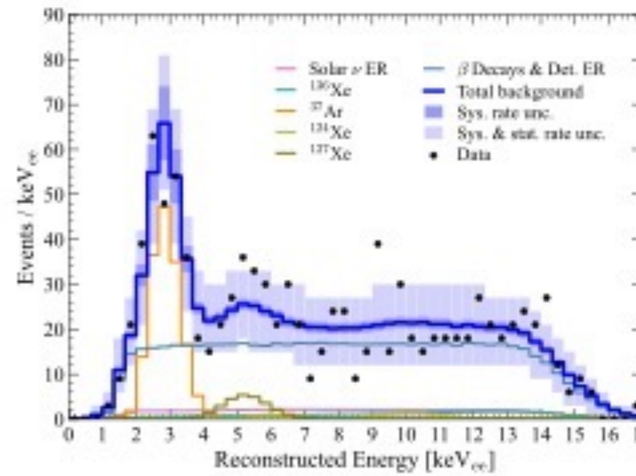
2020 results, 2006.09721

There is a slight excess in low-energy bins → lots of attempts to explain it

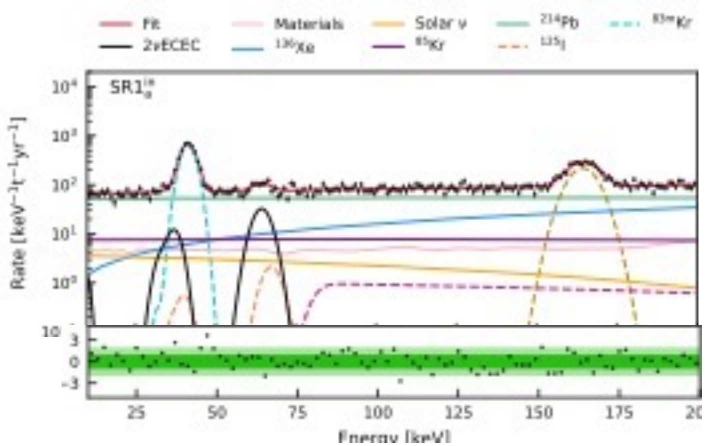
Updates from 2022

- Impressive update from successor of LUX, LZ

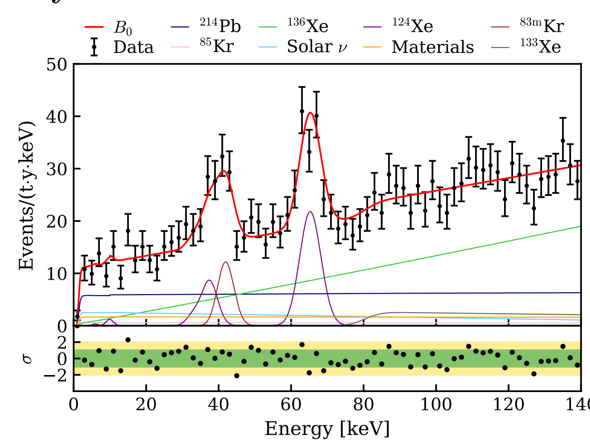




- (+2νECEC decay of ^{124}Xe.)



Search for New Physics in Electronic Recoil Data from XENONnT



(Next frontier - 2νECβ$^+$ decay of ^{124}Xe. Building towards 0νECβ$^+$ search of LNV) $T_{1/2}^{2\nu\mathrm{ECEC}} = (1.1 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{sys}}) \times 10^{22}$ yr. (~3 smaller than theory)

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!

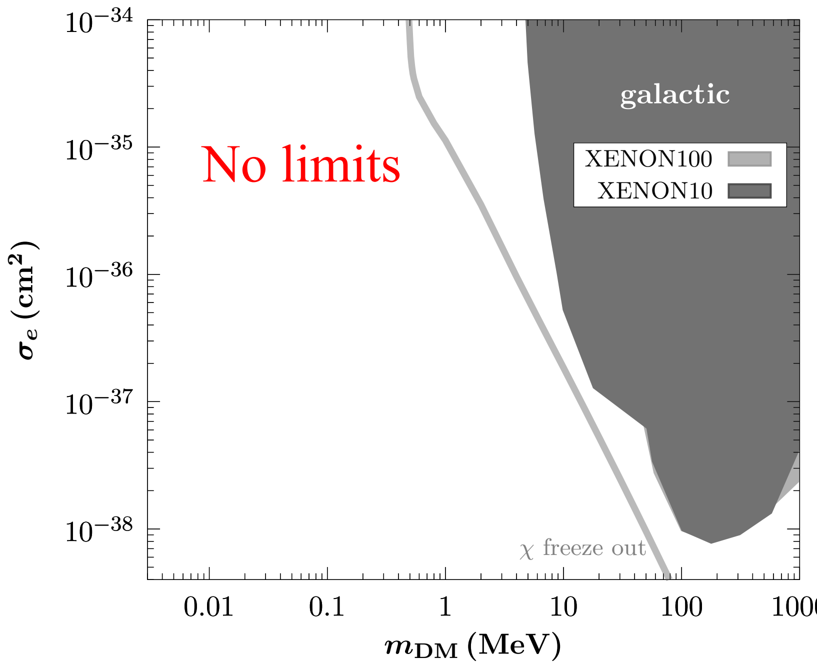
2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,
   Kin energy ~ kT ~0.03 eV

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

   Below the ionization threshold!

Direct detection, scattering of DM on electrons, 2017 slide

Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program



- For a given DM mass particle, in the MeV and sub-MeV range, the recoil energy of electrons is enhanced compared to nuclear recoil by M_{nucl}/m_e
- Sensitivity to energy depositions as low as 10 eV – reality *now*.
- Near future – O(1eV) sensitivity and below. Many recent works on this topic.
- Huge number of suggestions: *using superconductors, graphene, Weyl semimetals, DNA, to push threshold lower.* Somewhat of science fiction at this point.

Comparing counting rates in large Xe detectors and in low-recoil solid state

- LZ, Xenon NT, the counting rate is as low as ~ 10 events / ton / year / keV, With E > 1 keV

- Typical counting rates at lowest threshold semiconductor detectors are large, currently plagued by unexplained excess:

EXCESS

Collaborative summary paper based on the results reported at EXCESS 2021

https://arxiv.org/abs/2202.05097

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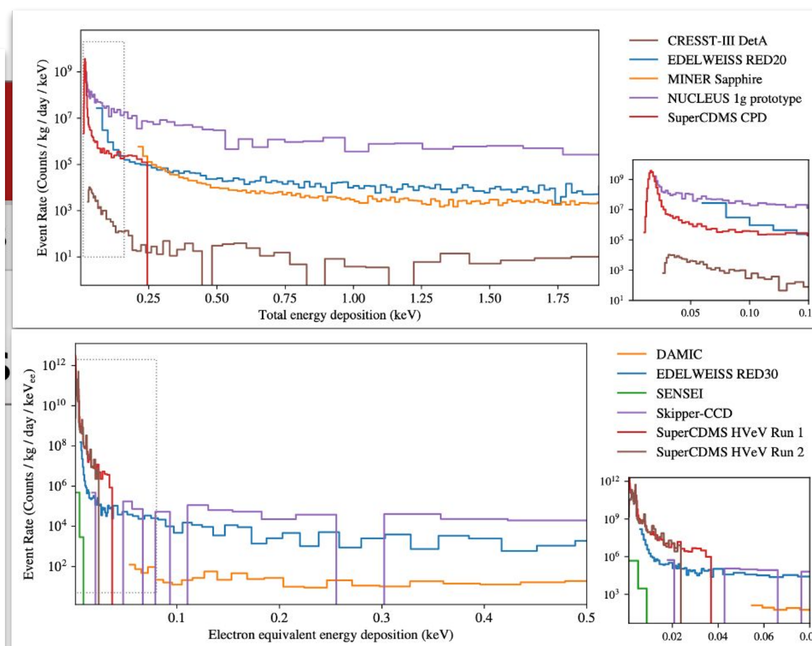
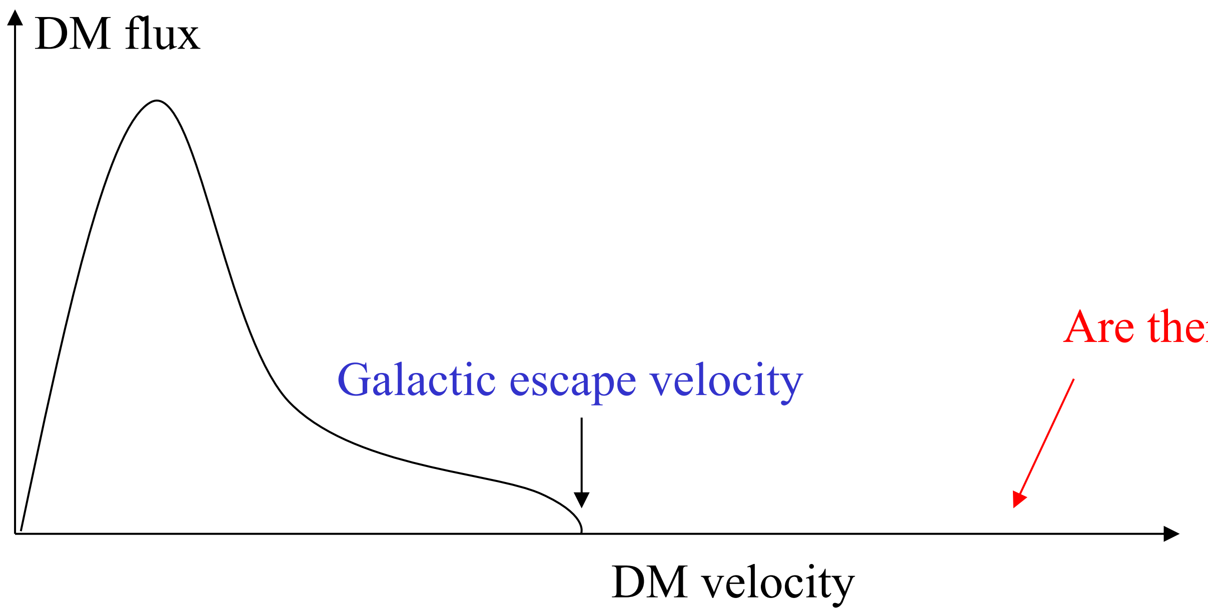


Main limitation of light WIMP searches

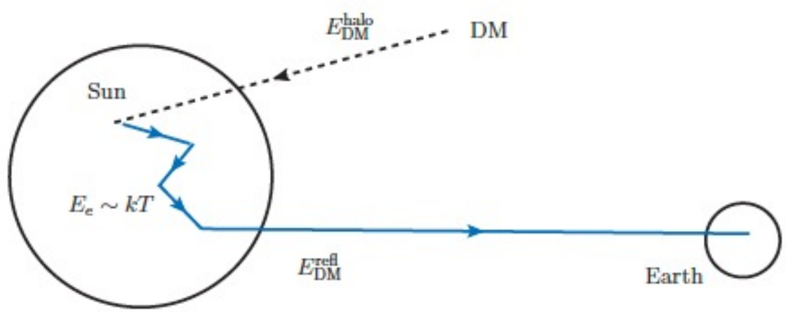
- The kinetic energy of galactic dark matter is limited by
  $E_{gal,\,max} = m_{DM}\,(v_{escape})^2/2.$
- For MeV-range DM, this energy is below the ionization energy of Xe (13 eV). For MeV DM maximum kinetic energy is ~ 1 eV
- Are there processes that bring DM energy above $E_{gal,\,max}$?

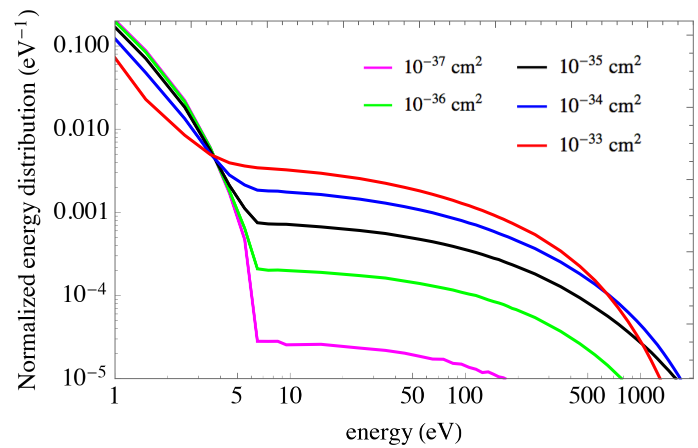


Case 1: DM scattering on electrons. Case 2: DM scattering on nucleons

"Reflected DM": extending the reach of Xe experiments to WIMP scattering on electrons

- (An, MP, Pradler, Ritz, PRL 2018, An, Nie, MP, Pradler, Ritz, 2108.10332, Emken, 2102.12483)
- DM can scatter inside the Sun and get accelerated above the ionization threshold

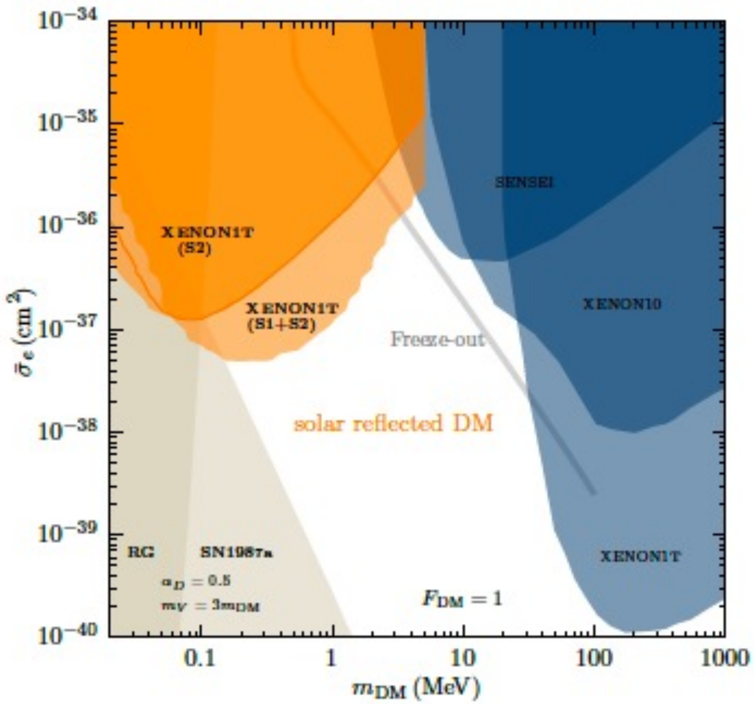




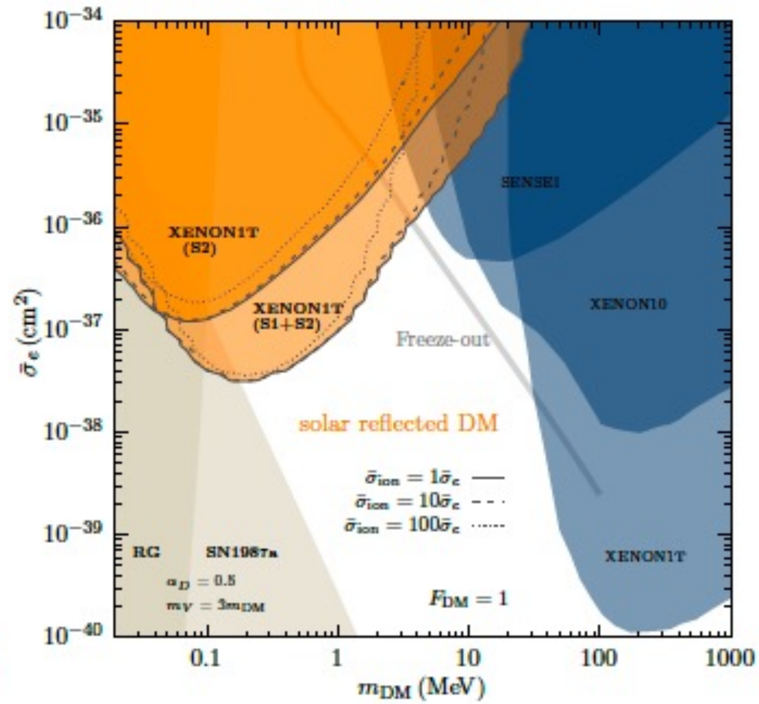
- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with $v_{dm}\sim10^{-3}c$ (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\, T_{core}/m_e)^{1/2} \sim$ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- Huge penalty in the flux of "reflected" DM ~ 10^{-6} ~ solid angle of the Sun

$$\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{1\,{\rm A.U.}}\right)^2 \sigma_e n_e^{\rm core} R_{\rm core}, & \sigma_e \ll 1\,{\rm pb}, \\ S_g\left(\frac{R_{\rm scatt}}{1\,{\rm A.U.}}\right)^2, & \sigma_e \gg 1\,{\rm pb}. \end{cases}$$

Contact mediator, limits on σ_e



only electrons

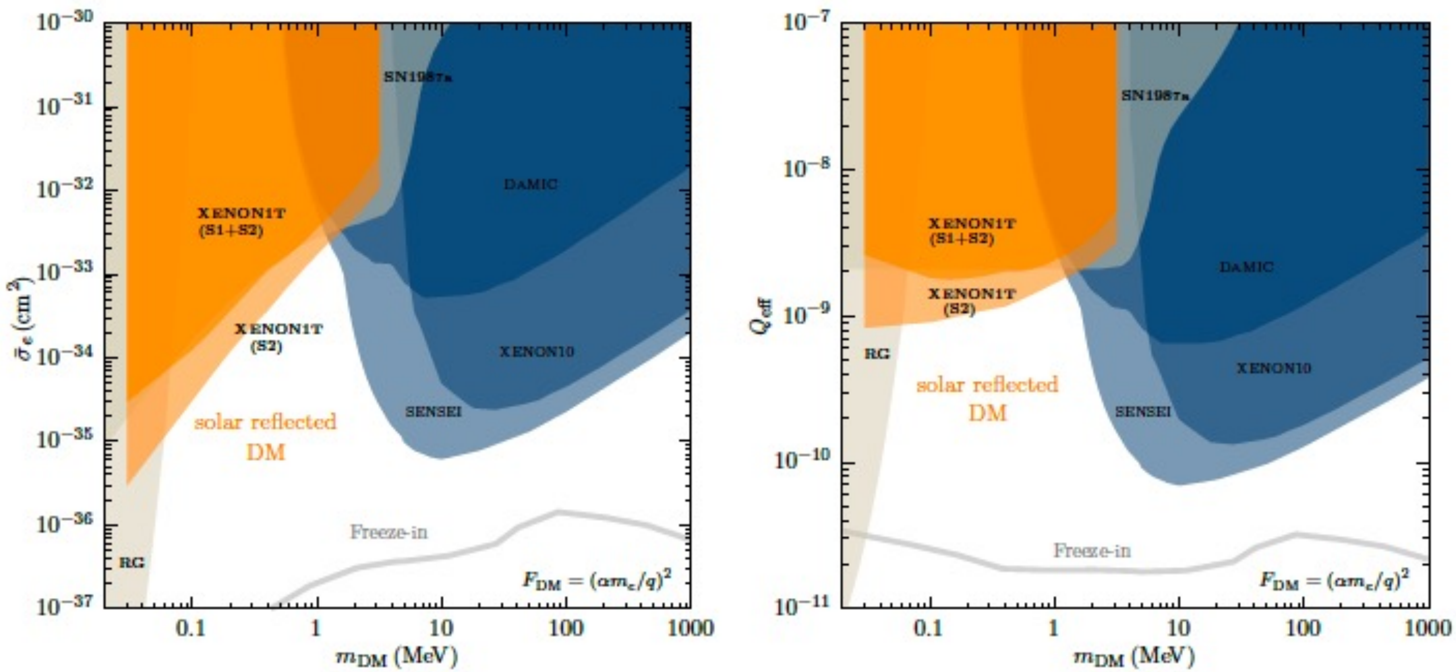


electrons and protons

An, Nie, MP, Pradler, Ritz, 2017, 2021

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux.
- If the scattering on ions is very strong, it can degrade energy of escaping particle and soften the constraining power.
- See also similar work by Emken 2021.

Massless mediators, limits on σ_e

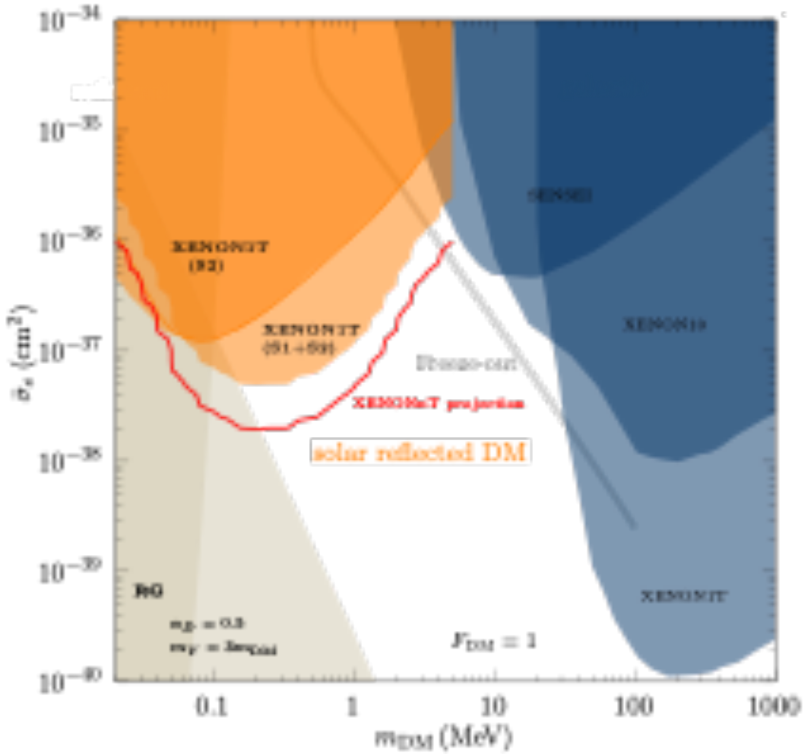


cross section normalized on $q=m_e\alpha$ Effective charge

An, Nie, MP, Pradler, Ritz, 2021

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux.
- Second case, massless mediator = milli-charged dark matter, Xe1T is sensitive to $Q_{eff} \sim 10^{-9}$ e.

Update using Xenon NT, limits on σ_e



only electrons

An, Nie, MP, Pradler, Ritz, 2017, 2021

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux.
- If the scattering on ions is very strong, it can degrade energy of escaping particle and soften the constraining power.
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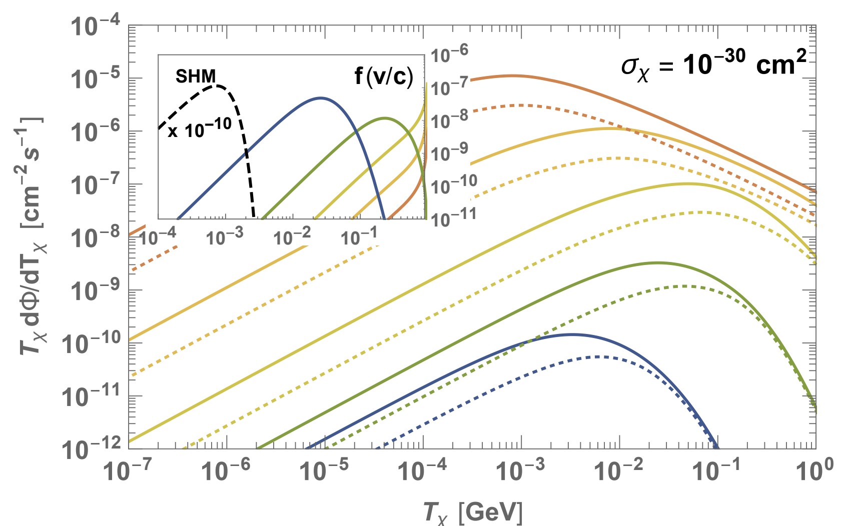
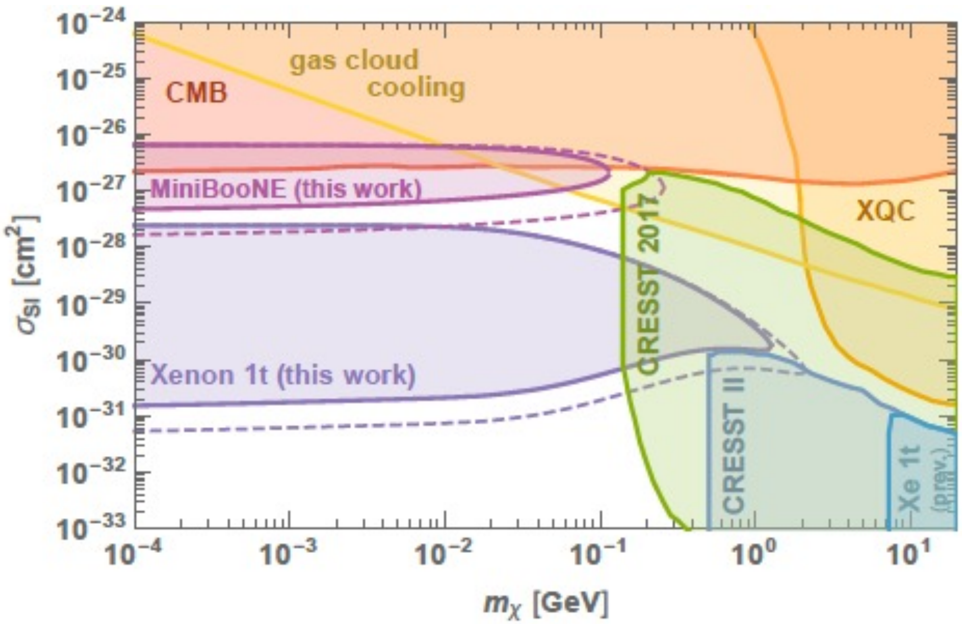
Light DM accelerated by cosmic rays

- There is always a small energetic component to DM flux (Bringmann, Pospelov, PRL 2019, others) due to interaction with cosmic rays.
- Typically: MeV DM mass → eV kinetic energy → sub-eV nuclear recoils. No limits for $\sigma_{\text{nucleon-DM}}$ for DM in the MeV range.
- This is not quite true because there is always an energetic component for DM, not bound to the galaxy. Generated through the very same interaction cross section: σ_χ

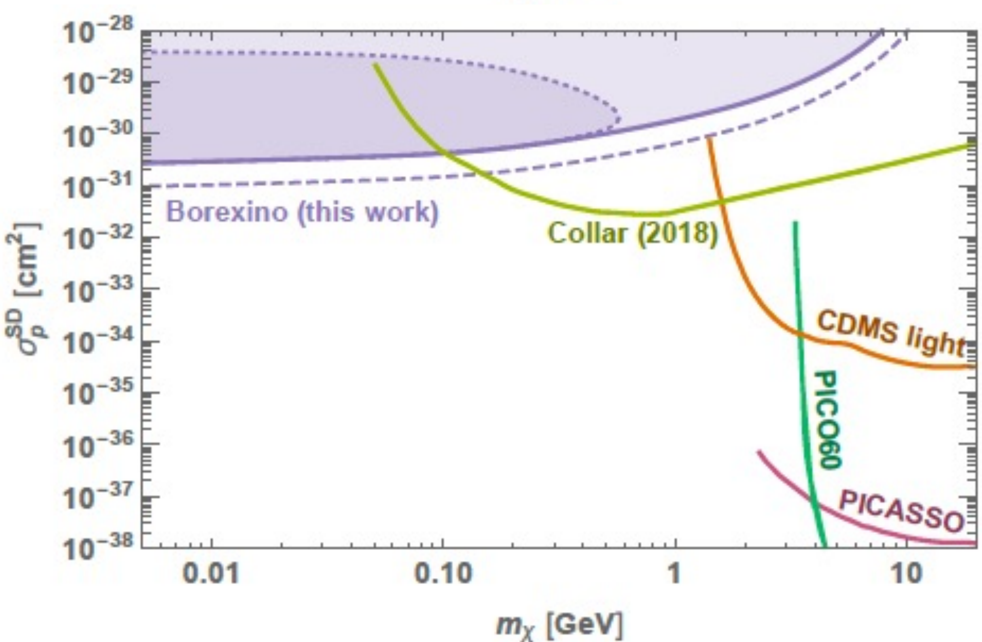
Main idea: Collisions of DM with cosmic rays generate sub-dominant DM flux with ~ 100 MeV momentum – perfect for direct detection type recoil.



Resulting limits on WIMP-nucleon scattering

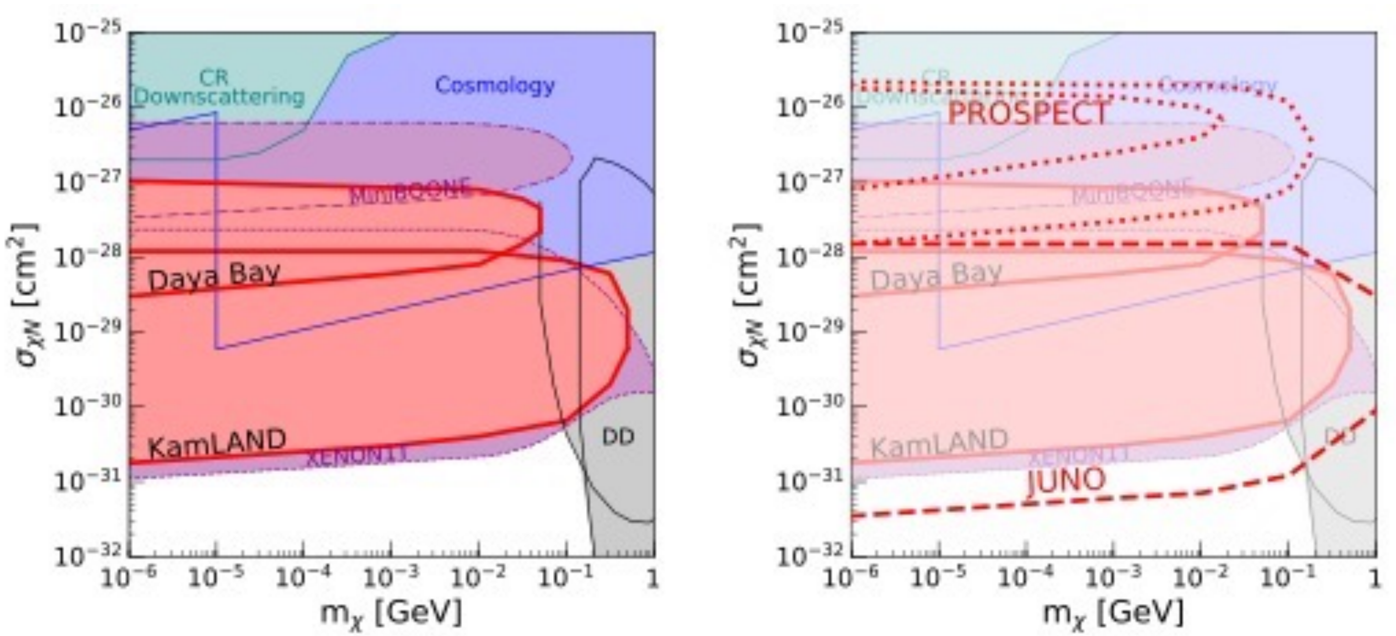


- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of $\sigma = 10^{-29}$-10^{-31}cm^2 !



- Scattering on free protons in e.g. Borexino, SNO, SK sre also very constraining e.g. for the spin-dependent scattering.
- (Ema, Sala, Sato had an independent work along the same lines for σ_e)

Updated limits on WIMP-nucleon scattering



- More neutrino experiments can be used to "fill the gaps", Beacom and Cappiello, 1906.11283
- If the DM cross section is large, an interesting spin-off can be considered in an underground laboratory environment where one could use accelerators (LUNA, JUNA) to "speed up" DM in a first collision and detect it using DM detectors in a second collision (in collaboration with Douglas, McKeen, Morrissey, Ramani, 2022)

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 $\sim kT \sim 0.03$ eV

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

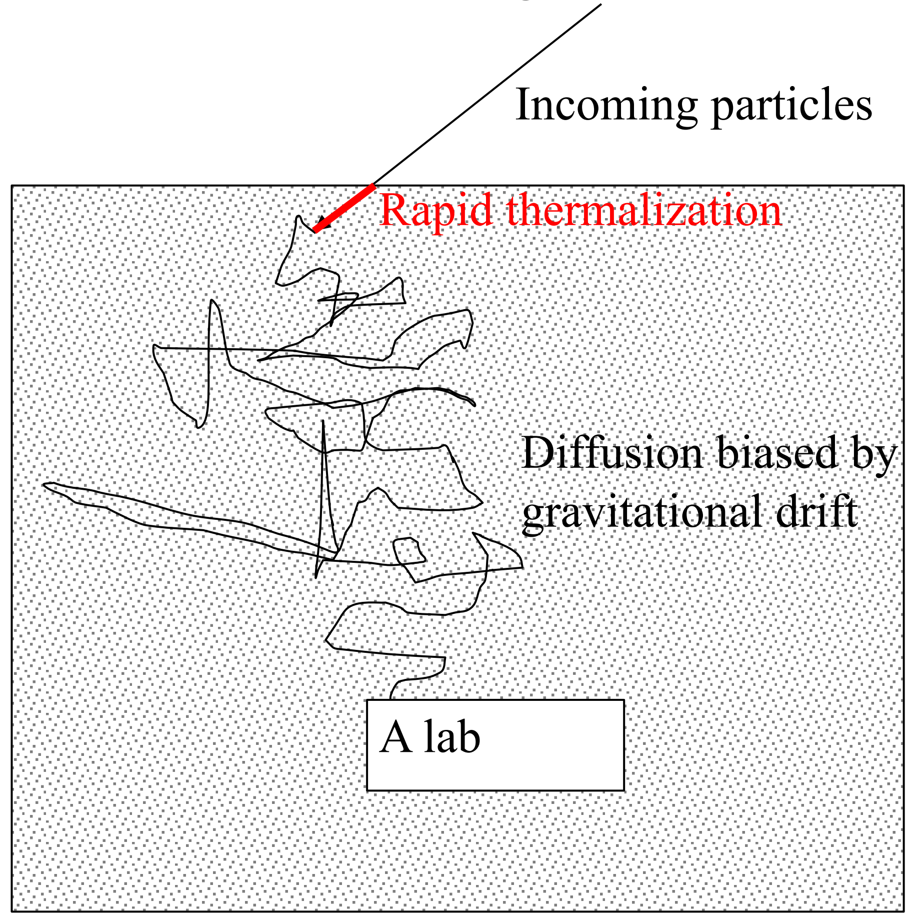
   Below the ionization threshold!

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

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

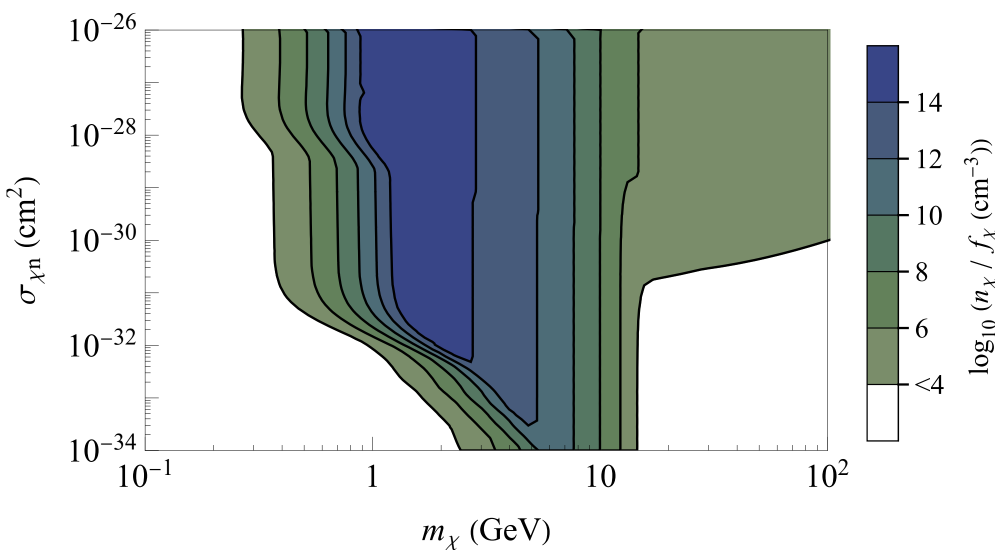
- Change in velocity from incoming ~ 10^7 cm/s to typical sinking velocity of 10 cm/s results in $n_{lab} \sim 10^6\, n_{halo}$. **Not visible to DD**
- At masses < 10 GeV upward flux is important and density goes up.



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

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

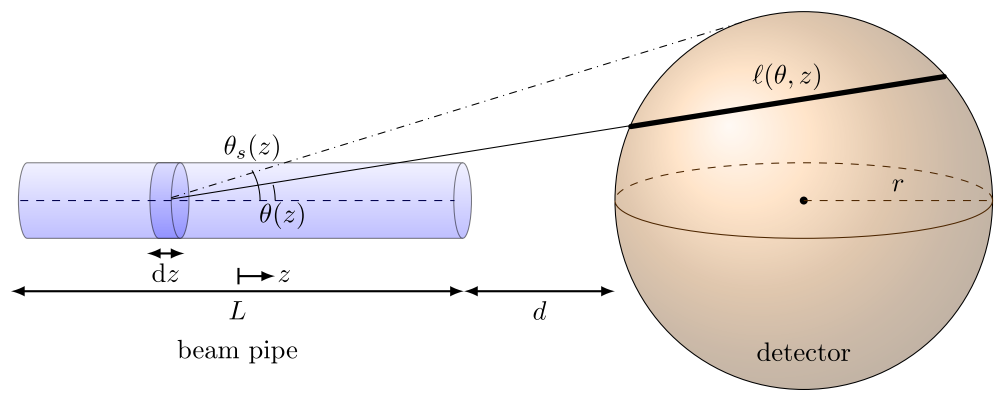
- Lowest mass – evaporation, Highest mass – traffic jam, intermediate mass – trapping with almost uniform distribution inside Earth's volume.



- Enhancement of the density can be as high as 10^{14}.

Using underground accelerators to "accelerate" dark matter

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators in a completely different setting: 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 (blind spot #2), 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.

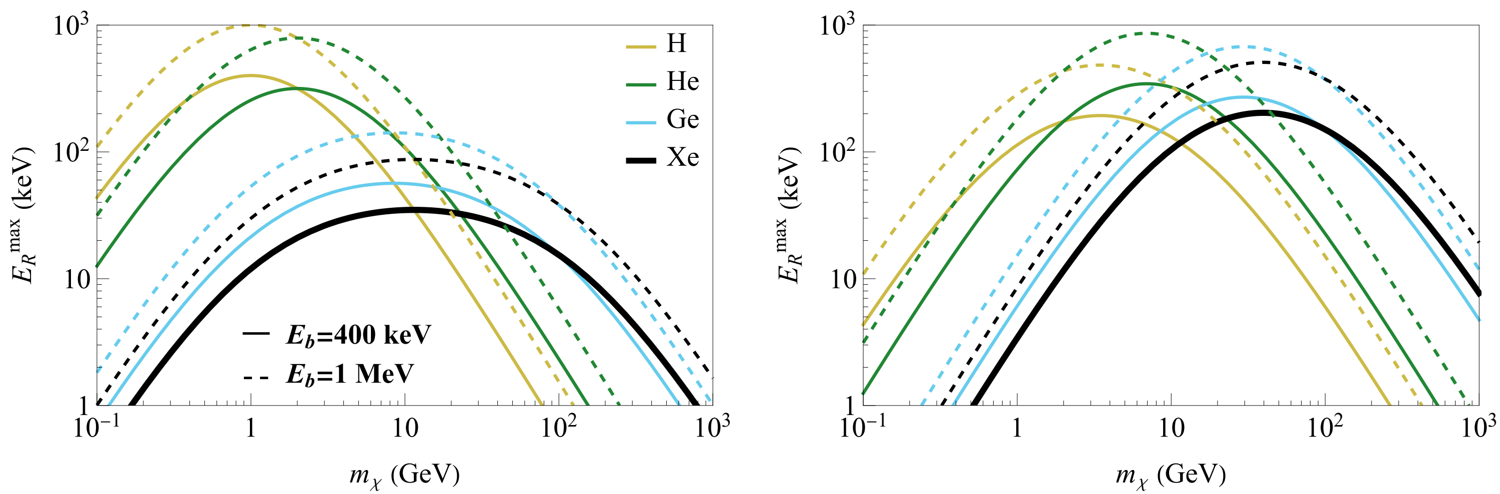
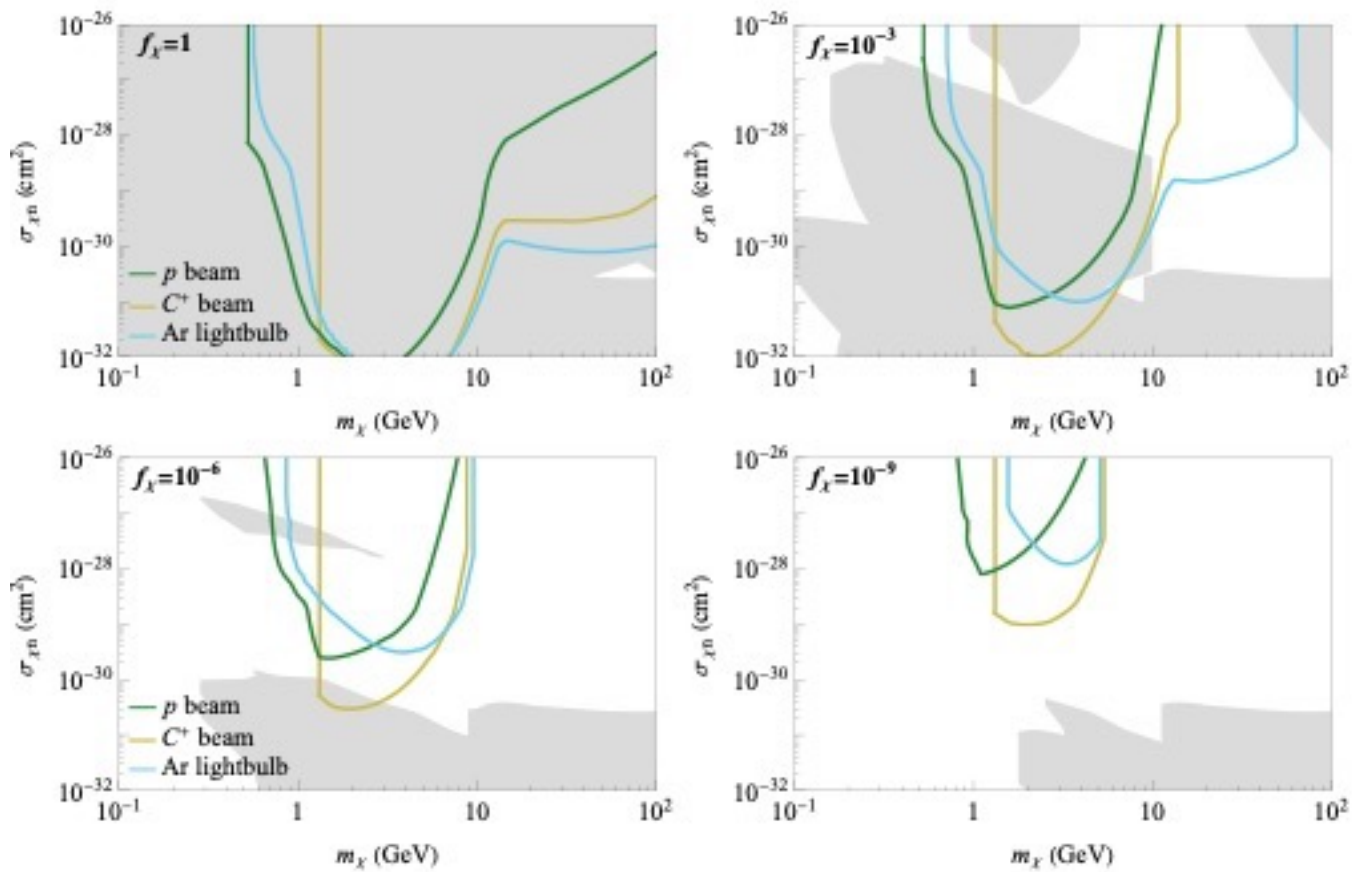


FIG. 3. Maximum nuclear target recoil energies E_R^{max} for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies $E_b = 0.4$ MeV (solid) and $E_b = 1.0$ MeV (dashed) for a selection of target nuclei.

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_chi.



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

Seond idea: 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.
- With Berlin, Liu, Ramani

Nucleus-DM potential

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

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

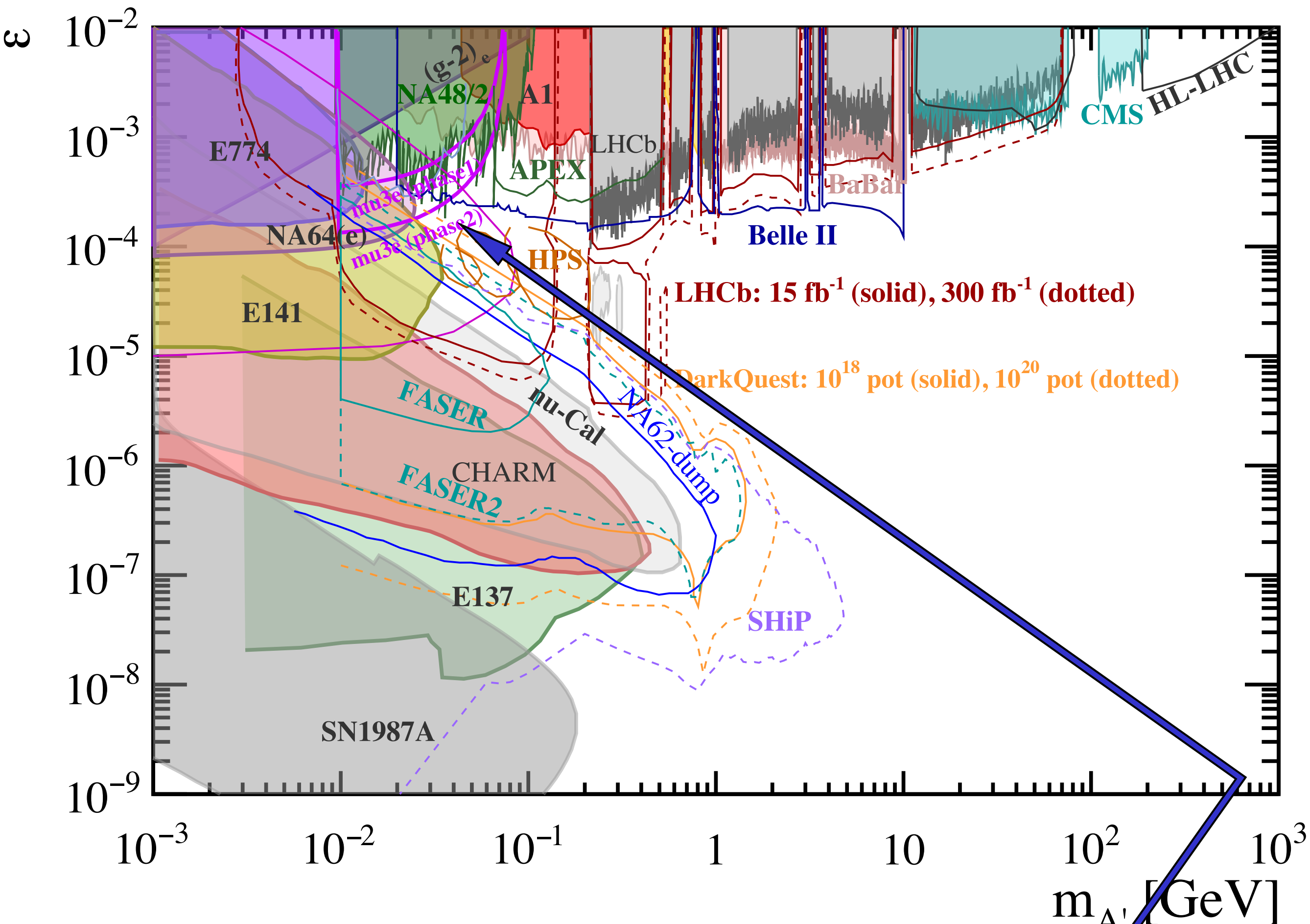
$$V(\mathbf{r}_\chi, 0) = \exp(-m_{A'}|\mathbf{r}_\chi - \mathbf{r}_N|)/|\mathbf{r}_\chi - \mathbf{r}_N|.$$

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

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



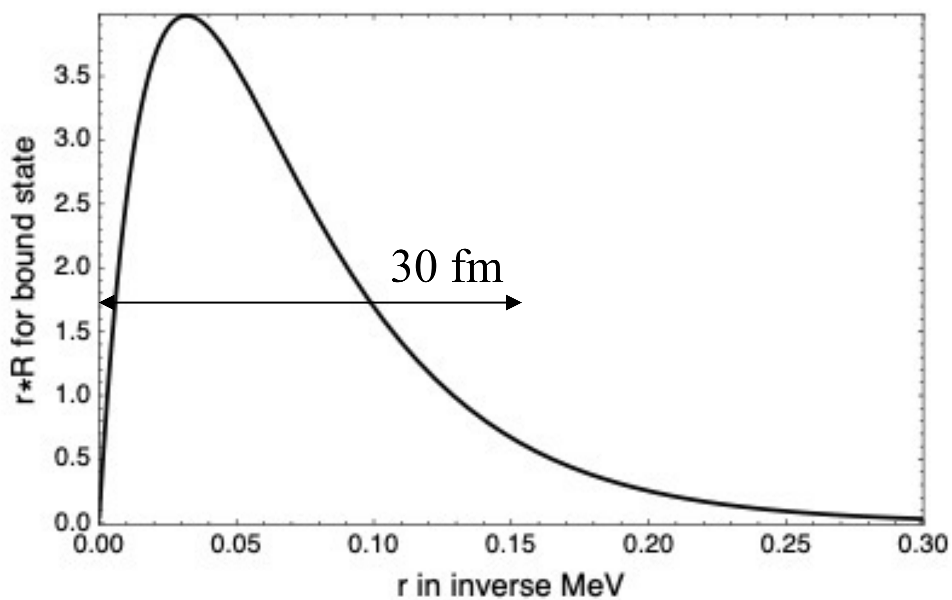
Bound state formation is possible in this corner

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.



$$E_{b.s.} = 2\,{\rm keV},\ \varepsilon_{eff} = 0.85 \times 10^{-3},\ m_V = 15\,{\rm MeV},\ \mu = 100{\rm GeV}.$$

A possible scenario for direct detection (including Xenon excess)

- Small enough f_χ so that surface and balloon experiments are not sensitive.
- Density enhancement after thermalization (traffic jam). Becomes **invisible** to elastic scattering.
- No bound states with light elements – no efficient capture during the sinking
- Efficient capture in an experiment containing heavy enough elements (Xenon, of course. Also, Iodine, Tl etc…).

$$Z + \chi \rightarrow (Z\,\chi) + \text{Energy}$$

- Main feature of the signal: electron-like mono-energetic energy release.
- Possibly non-trivial time structure (i.e. daily and seasonal modulation)

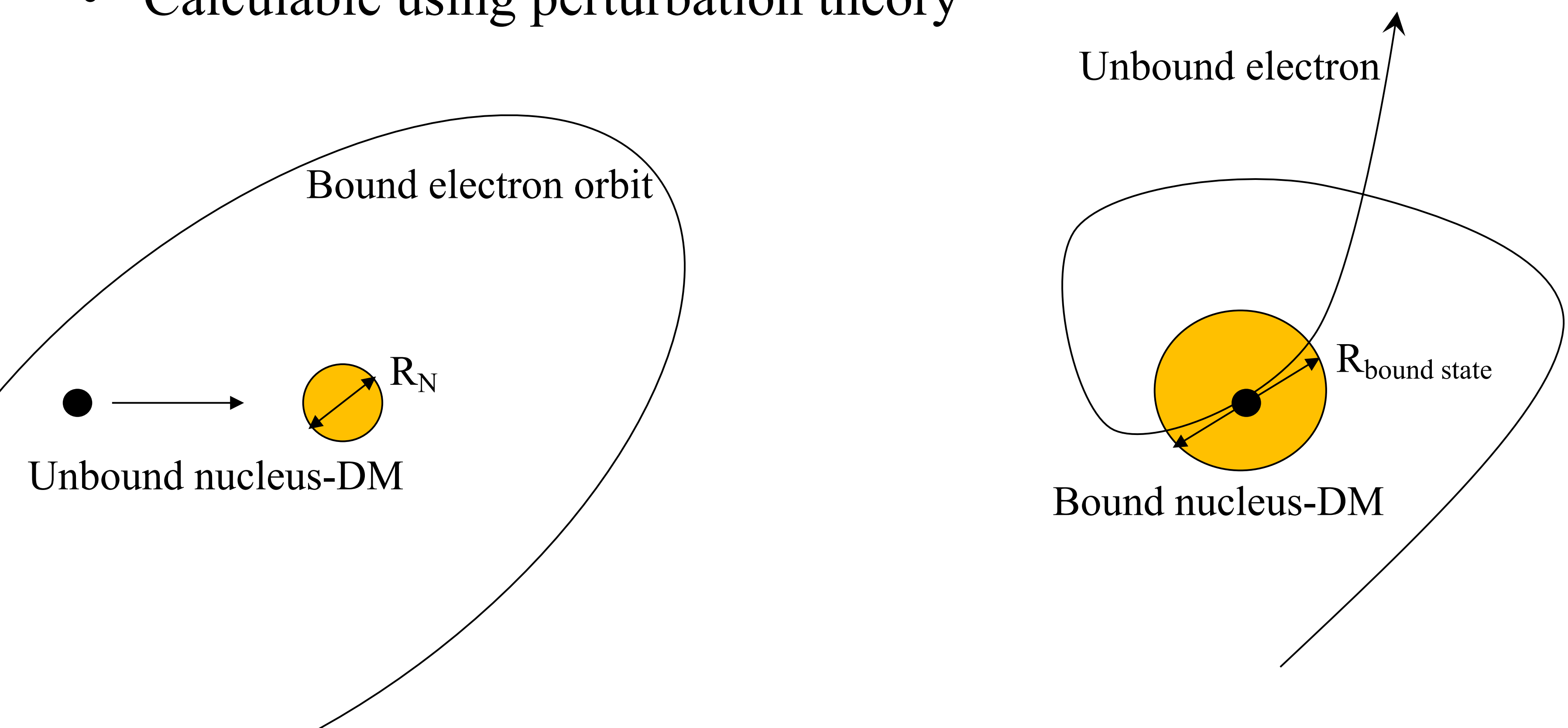
Capture process

- 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

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

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

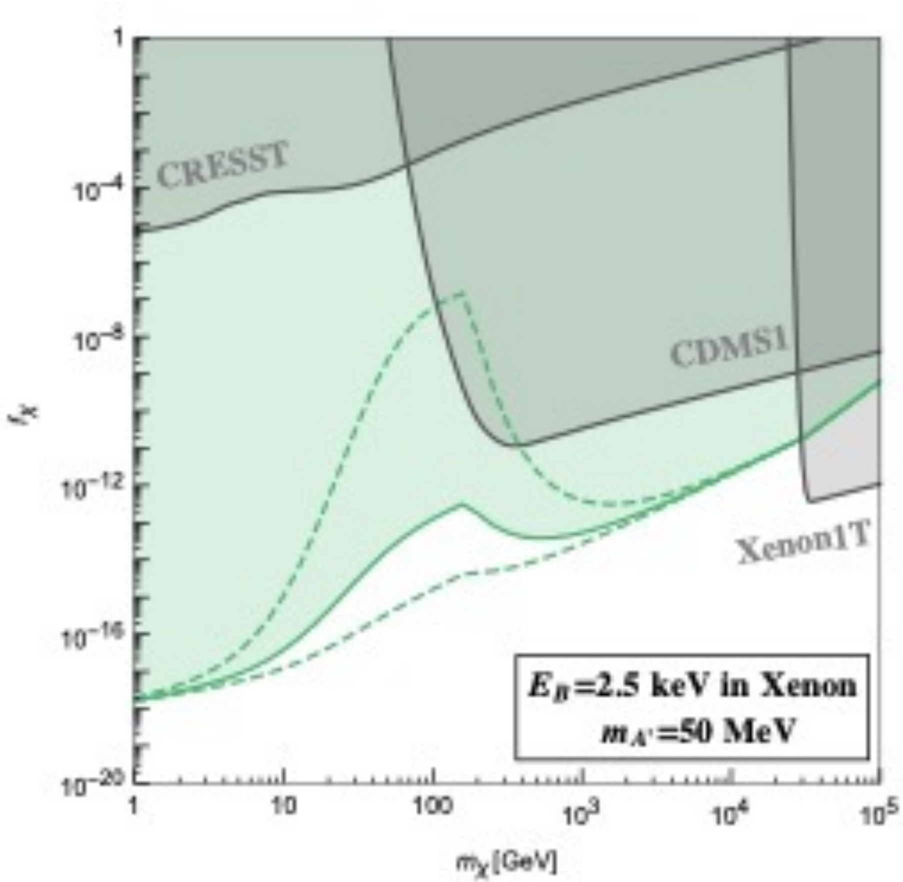
that can be evaluated numerically.

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

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

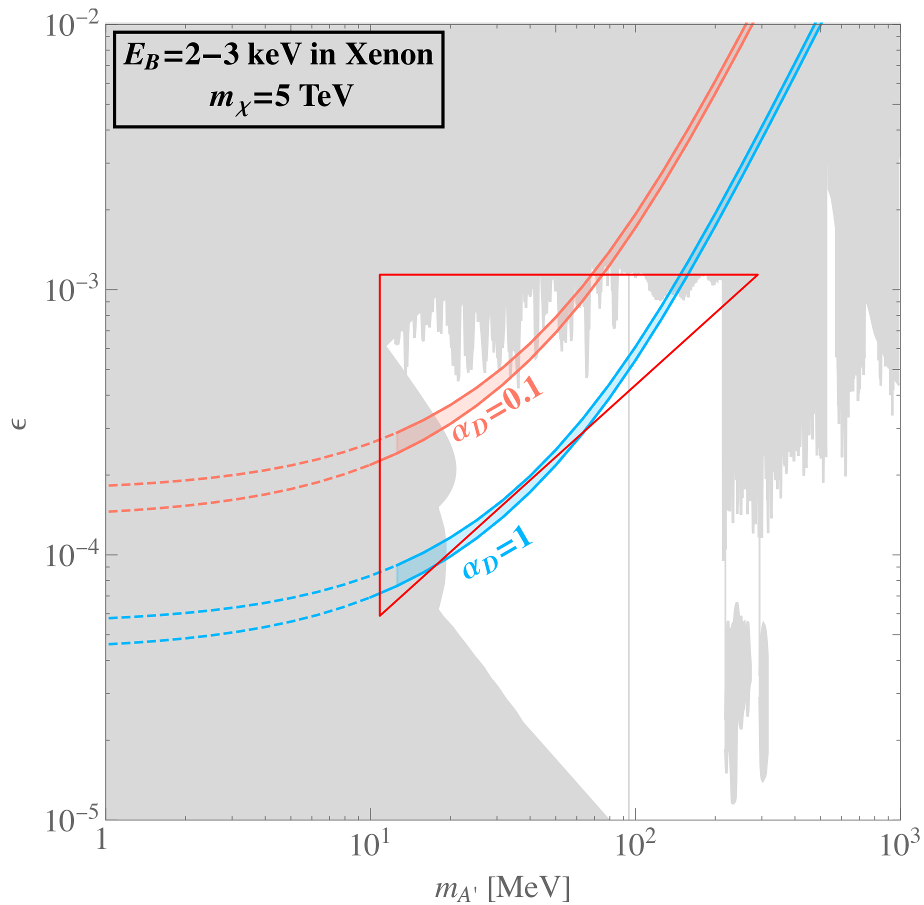
- Since actual c/v ~ 10^6, the actual cross section ~ 10^{-27} cm^2. Not tiny

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



- Anywhere along the boundary of green, Xenon1T excess can be explained.
- If the *unknown* α_{dark}, we do not know "exact" ε parameter that can explain the excess.

Zooming in onto dark photon target parameter space



- A roughly triangular shape of the parameter space, ~ one decade long on each side can explain the Xenon1T excess at small f_χ.
- This parameter space is [hopefully] going to be explored by the LHCb and HPS experiments.

Conclusions

- *Dark sectors/feably interacting particles – that give a wider range of DM masses and possibilities – are being actively explored at the moment.*
- Strong limits can be imposed even in "blind spot" areas – using subdominant components of the flux. *Dark matter "reflected" from solar electrons, Dark Matter "accelerated" by cosmic rays*. So far limits from Xenon on σ_e in 0.1-5 MeV mass range from solar reflection are much better than those from "novel detectors".
- One can use underground accelerators + dark matter detectors to bring DM to higher velocity via first collision, and detect it using the second collision. New parameter space for strongly int DM can be explored.
- 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.