Particle Dark Matter - a theoretical overview

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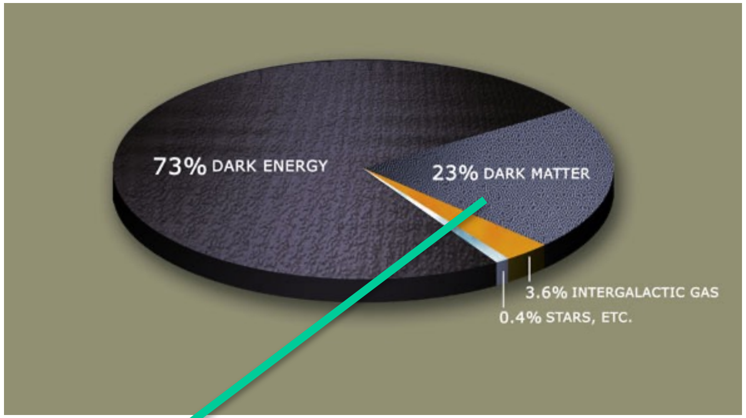
- Introduction.
- Quick implications of the recent LZ results.
- *Models with blind spots for direct detection*: a. very light dark matter, b. strongly interacting dark matter.
- New opportunities in direct dark matter detection.
- Outlook.

Why identifying dark matter is difficult



Av. Density ~

0.3 GeV/cc – not a lot

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

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

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

Current ideas about particle DM genesis

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. (asymmetric WIMPs are a variation.)

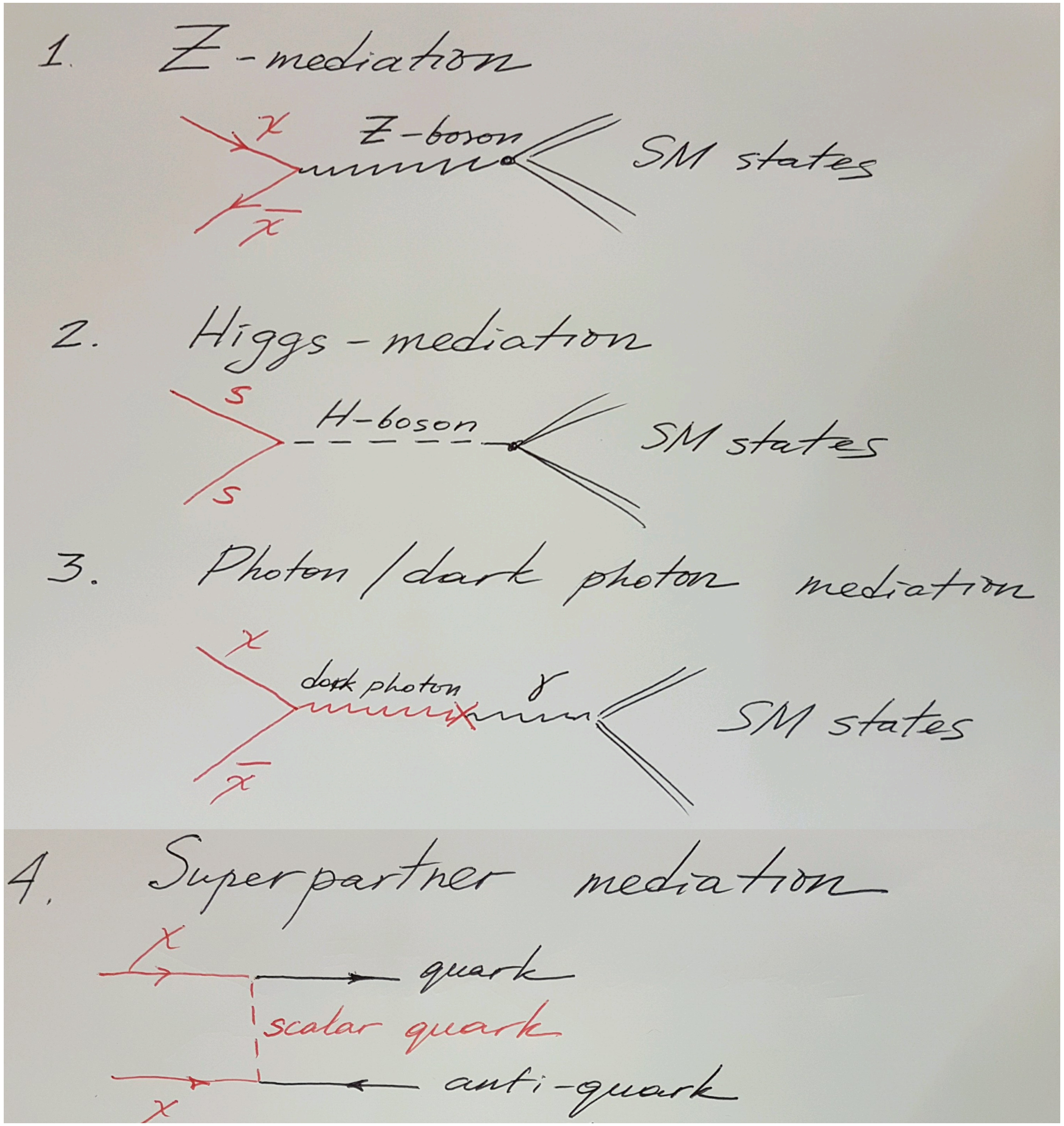
Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Many reasonable options. *Signatures can be completely different.*

Macroscopic DM? Primordial Black holes, of course. But this is not the only possibility. Topological and non-topological solitons, clumps of DM etc.

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.

Implication of the successful stream of Xe-based DM experiments

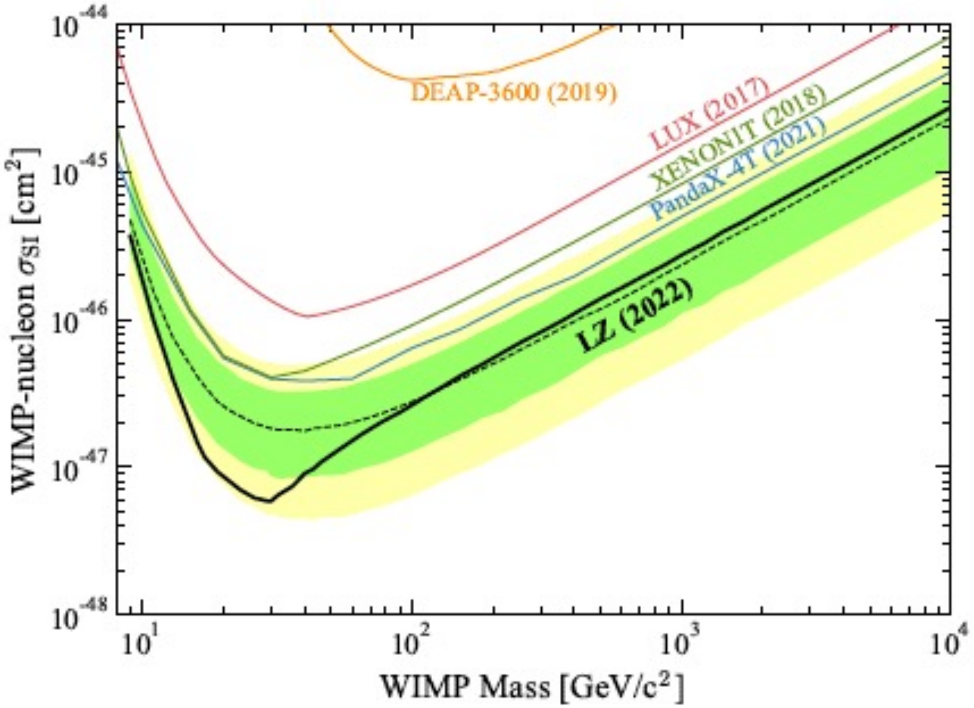
- Series of successful experiments: Xenon-100,1T; LUX, LZ; PandaX's have pushed the limits on the nucleon cross section for weak-scale mediated Dark Matter.

- While Z-exchange based models (a-la Lee and Weinberg) has long been ruled out, new constraints put significant pressure on Higgs-mediated models, pushing them into multi-TeV territory. Loop-induced Higgs/W-box models (e.g. SUSY Higgsino-like) will "soon" be probed.

- Large mass and self-shielding properties also allow for the breakthrough sensitivities for the electron recoil ($E_{recoil} > 200$ eV), providing strong constraints on light DM, and on exotic particle emission from the Sun.

Interpreting recent LZ results for the Higgs-mediated scalar DM model

arXiv:2207.03764v1



- The best sensitivity at $m_{DM} \sim 30$ GeV drops below 10^{-47}cm^2 benchmark

In the scaling regime, $m_{DM} > m_{Xe}$, the limit on the DM-nucleon cross section is $\sigma < 2.5\ 10^{-46}$ cm^2 (m_{DM}/TeV)

This has strong implications for particle physics models of WIMP DM.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - m_0^2 S^2 + \lambda S^2 (H^\dagger H)$$

Interpreting recent LZ results for the Higgs-mediated scalar DM model

Combining together a prior on the dark matter annihilation cross section,

$$\langle \sigma_{ann} v \rangle = \frac{\lambda^2}{4\pi m_S^2} \simeq 10^{-36}\mathrm{cm}^2 \times c$$

with the expression for the Higgs-boson-mediated nucleon-DM scattering cross section

$$\sigma_{pS} = \frac{\lambda^2}{\pi^2 m_S^2} \frac{m_p^2\,(200\,\mathrm{MeV})^2}{m_h^4}$$

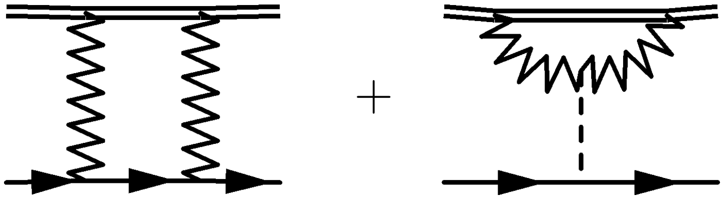
and using LZ limit $\sigma_{pS} < 2.5\ 10^{-46}\ \mathrm{cm}^2\,(m_S/\mathrm{TeV})$ we obtain the limit

$$m_S \gtrsim 1\,\mathrm{TeV}$$

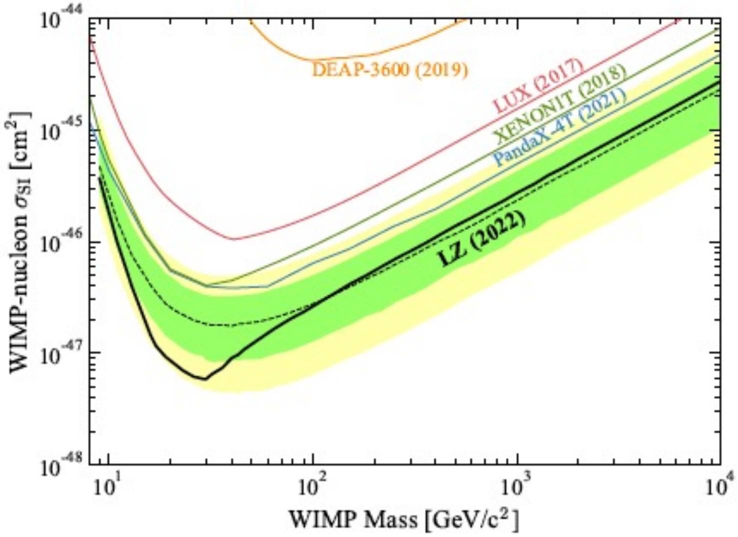
It implies that the coupling constant λ becomes moderately large, $\lambda > 0.15$, making it larger than the Higgs self-interaction coupling. *Subsequent experimental improvements may completely rule out this minimal type of models.*

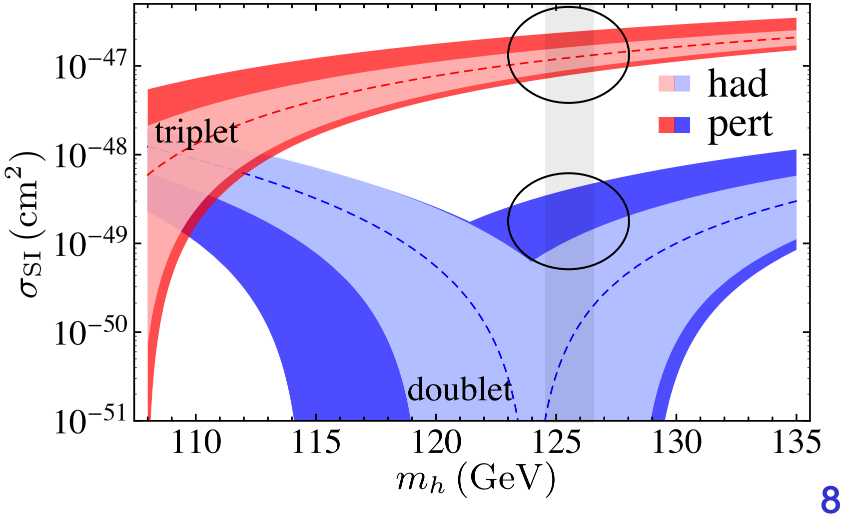
Next frontier – loop-mediated EW interaction

Models of heavy particles that have EW interactions but do not have a direct coupling to the Z-boson (e.g. due to small mass splitting) will interact via EW loops



W-box, and loop-induced Higgs exchange



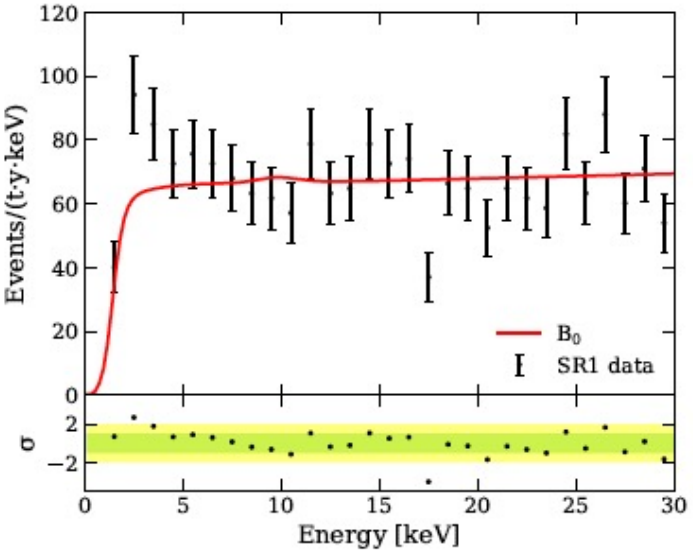


From Hill, Solon, 2013

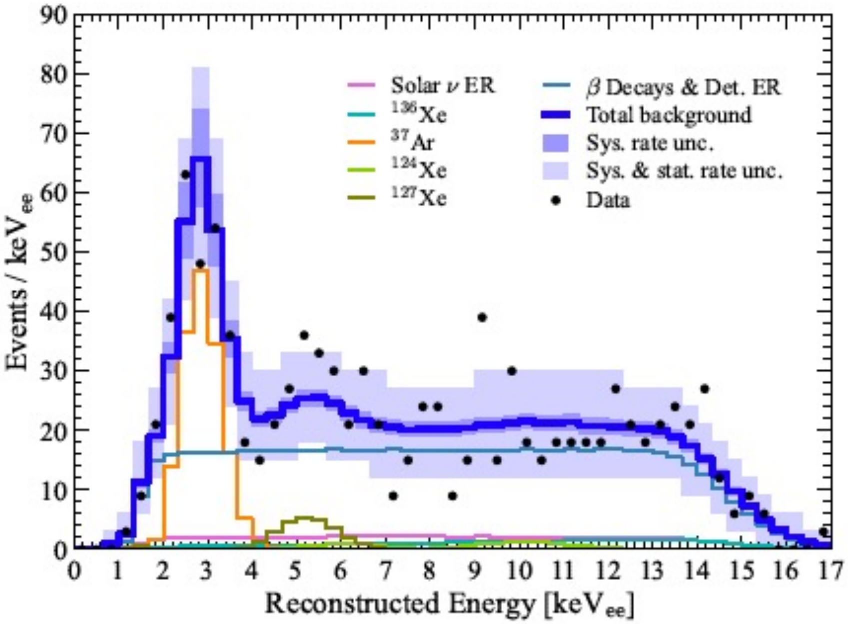
Implication for electron recoil?

Intriguing [excess!] results from the 2020 Xenon-1T study of the electron recoil will soon be tested by the LZ collaboration.

$\mathrm{Exposure}_{\mathrm{Xenon1T}}$ = 240 day-ton



$\mathrm{Exposure}_{\mathrm{LZ}}$ = 330 day-ton



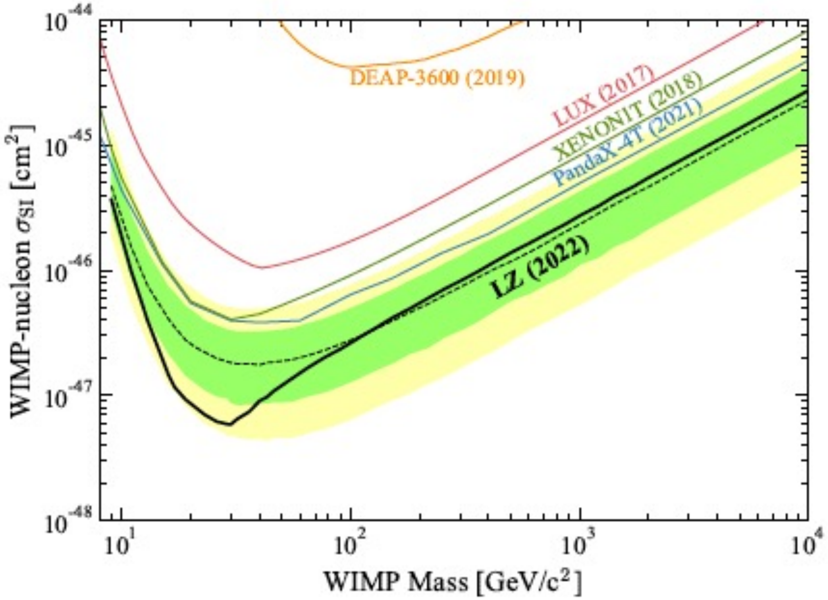
Xenon1T collaboration's model for the background is flat. Excess/signal is consistent with a peak at ~2.5 keV. LZ has a peak identified as the background (^{37}Ar). Main intrigue: is it $^{37}\mathrm{Ar} \propto 2^{-t/(35\,\mathrm{day})}$?

Blind spots for WIMP scattering

(latest LZ, XENON 1T and PANDA-X results)

Strongest constraint 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. But there is sensitivity due to scattering on electrons
- There is no sensitivity to strongly-interacting particles that thermalize on the way to an underground lab.

Two blind areas for direct detection

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

   Below the ionization threshold!

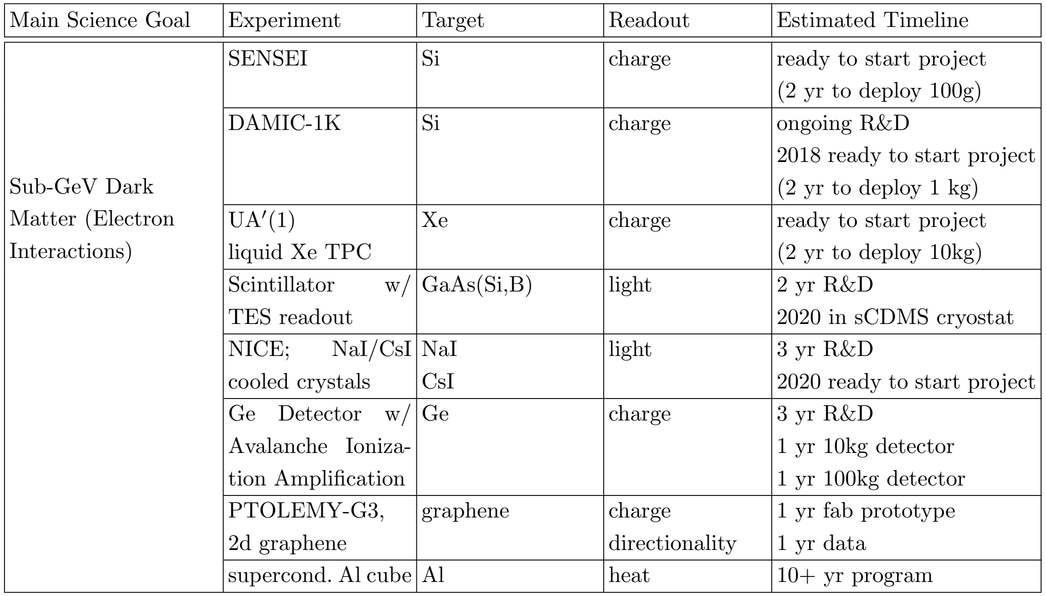
2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,

   Kinetic energy ~ kT ~0.03 eV

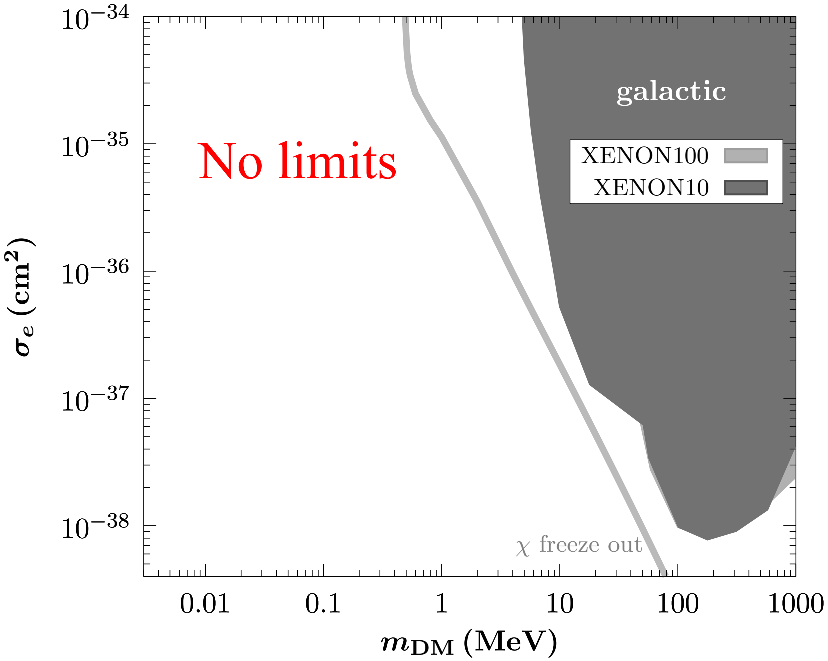
   (Typically cannot be entire DM, but is limited to fraction $f<10^{-3}$)

   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



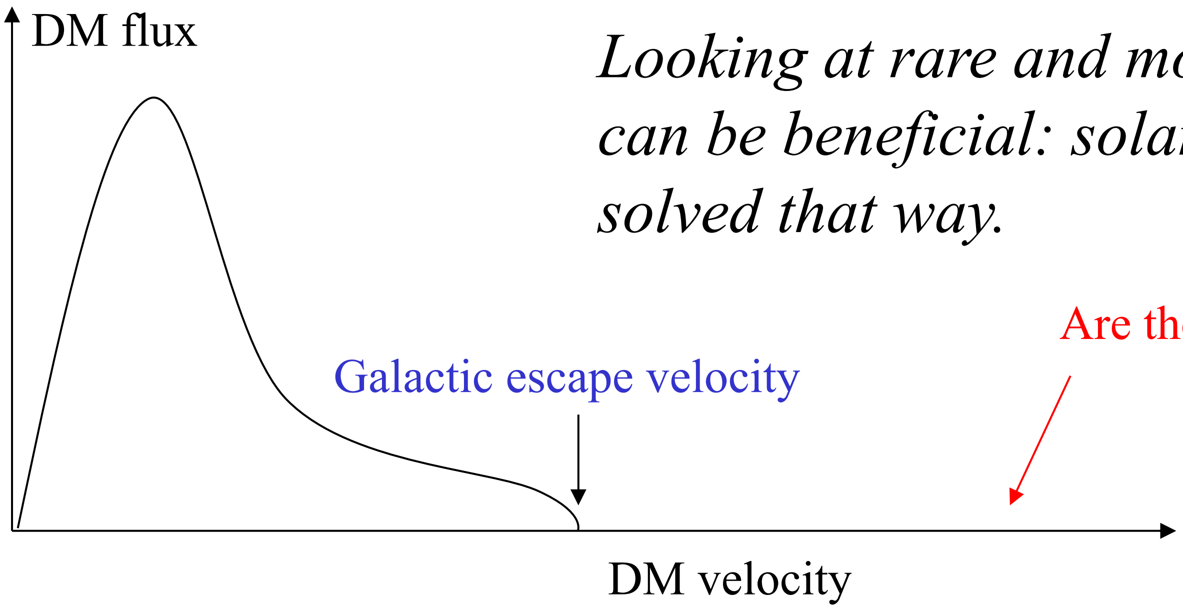
- For a given DM mass particle, in the MeV and sub-MeV range, the recoil energy of electrons is enhanced compared to nuclear recoil by $M_{\rm nucl}/m_e$
- Sensitivity to energy depositions as low as 10 eV – reality *now*.
- Near future – O(1eV) sensitivity and below. Impressive SENSEI results in 2020.
- Huge number of proposals: *using superconductors, graphene, Weyl semimetals, DNA, to push threshold lower.*

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 $E_{gal,\ max}$?



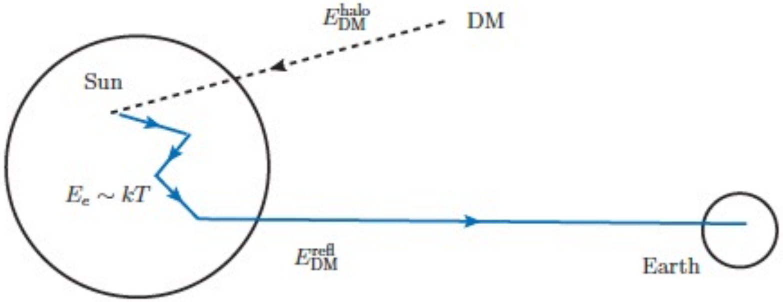
Looking at rare and more energetic fraction can be beneficial: solar ν problem was solved that way.

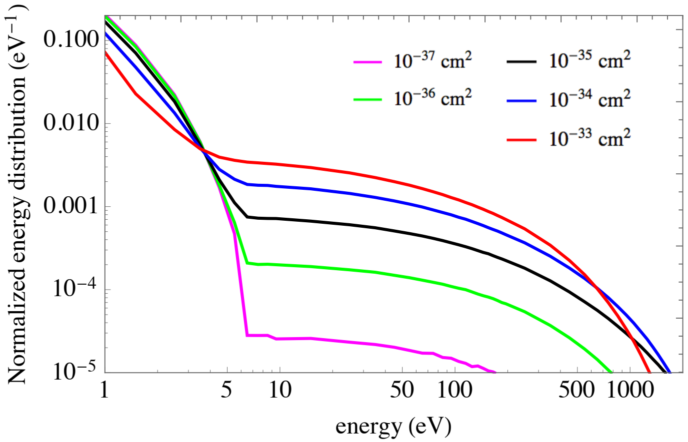
Are there any "fast" DM particles?

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

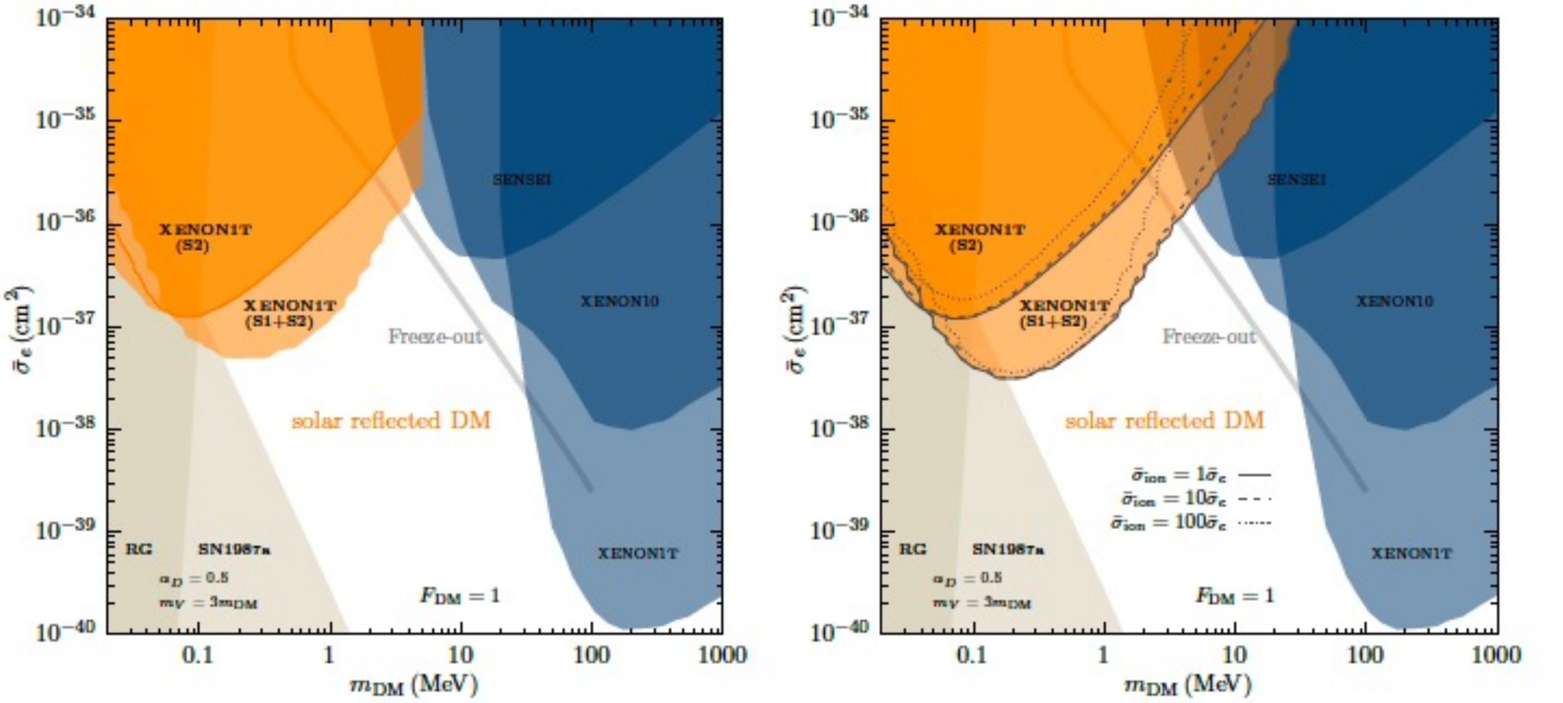




- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with $v_{dm} \sim 10^{-3}c$ (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\ T_{core}/m_e)^{1/2} \sim$ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- Huge penalty in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

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

Contact mediator, limits on σ_e



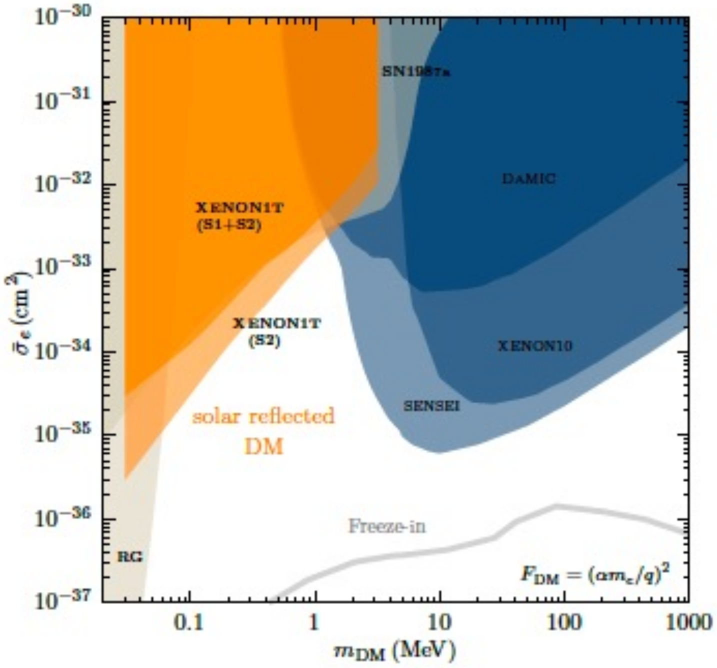
only electrons

electrons and protons

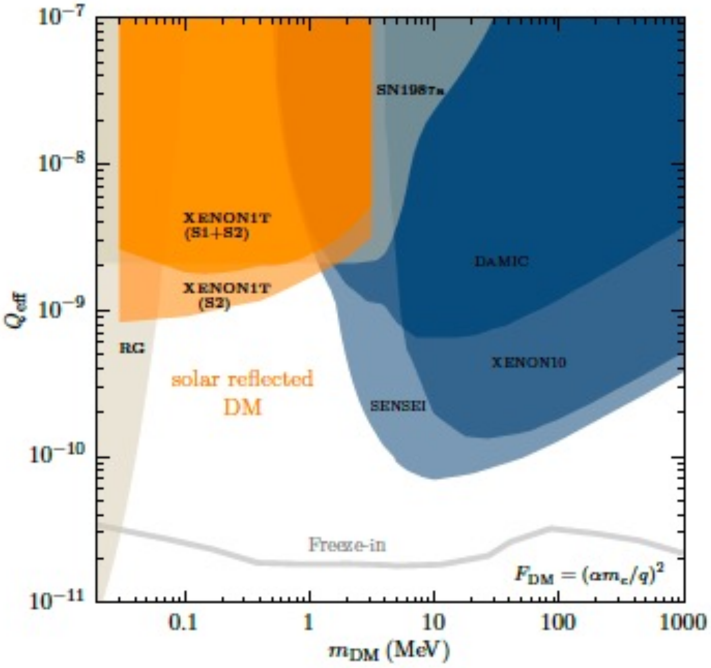
An, Nie, MP, Pradler, Ritz, 2017, 2021

- 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 investigation by Emken 2021.

Massless mediators, limits on σ_e



cross section normalized on q=$m_e\alpha$



Effective charge

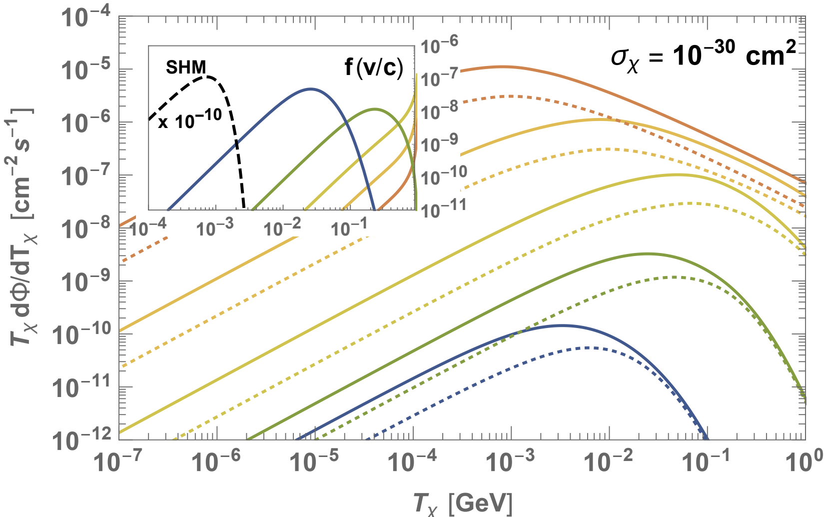
An, Nie, MP, Pradler, Ritz, 2108.10332

- 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}~10^{-9} e.

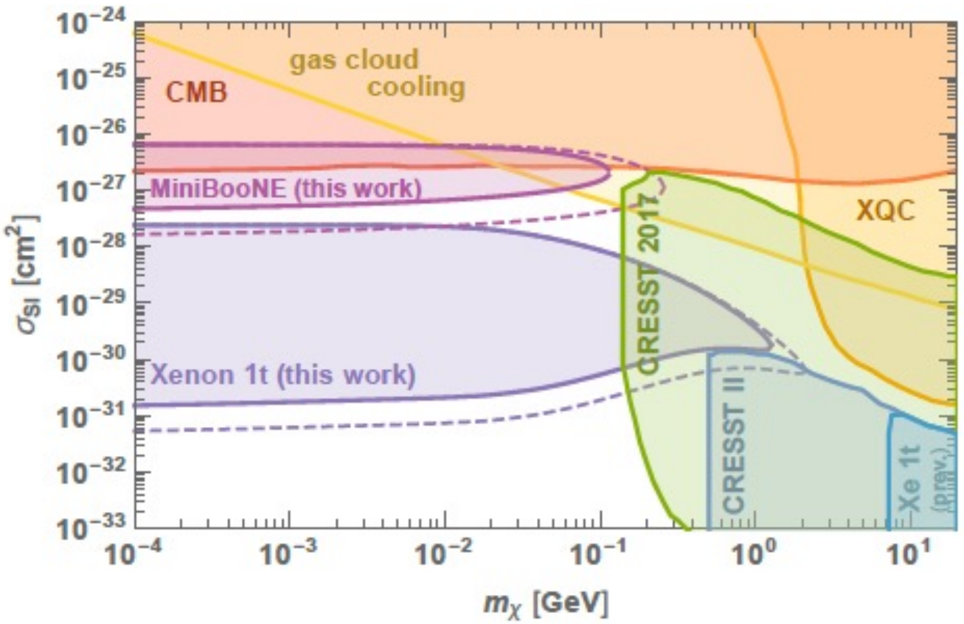
Light DM accelerated by cosmic rays

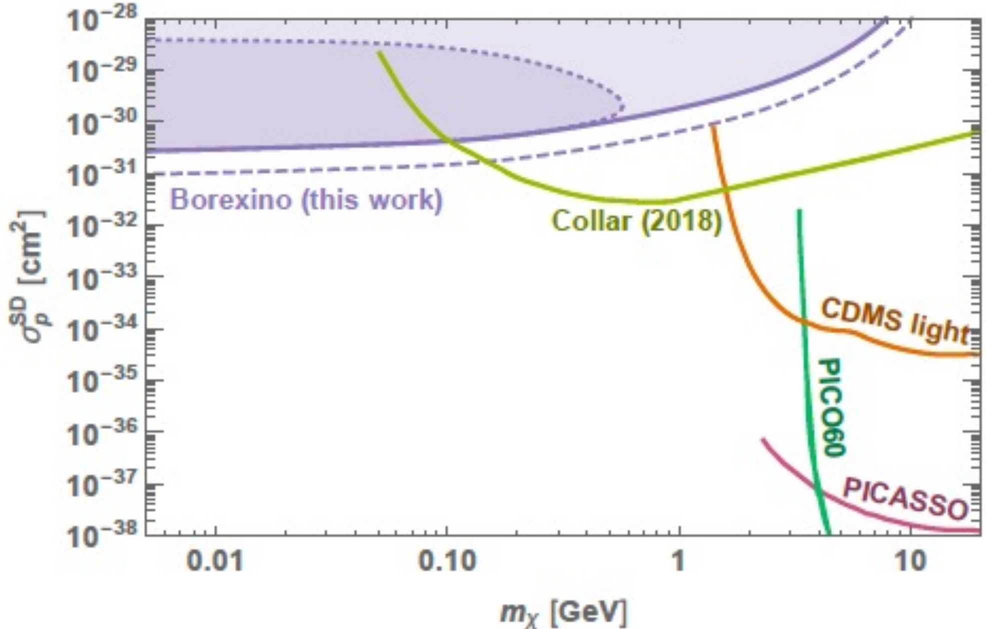
- There is always a small energetic component to DM flux (Bringmann, Pospelov, PRL 2019, others) due to interaction with cosmic rays.
- Typically: MeV DM mass → eV kinetic energy → sub-eV nuclear recoils. No limits for $\sigma_{\text{nucleon-DM}}$ for DM in the MeV range.
- This is not quite true because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

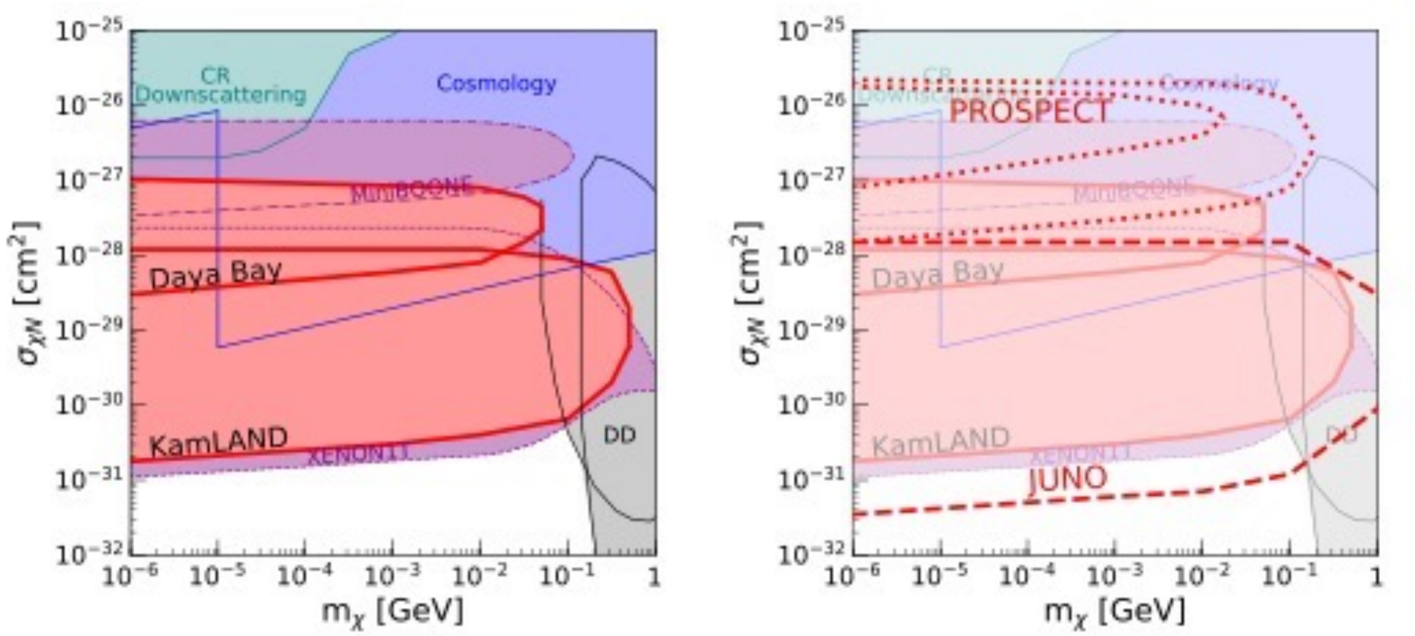




- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of σ = 10^{-29}-10^{-31}cm^2 !

- Scattering on free protons in e.g. Borexino is also very constraining for the spin-dependent scattering.

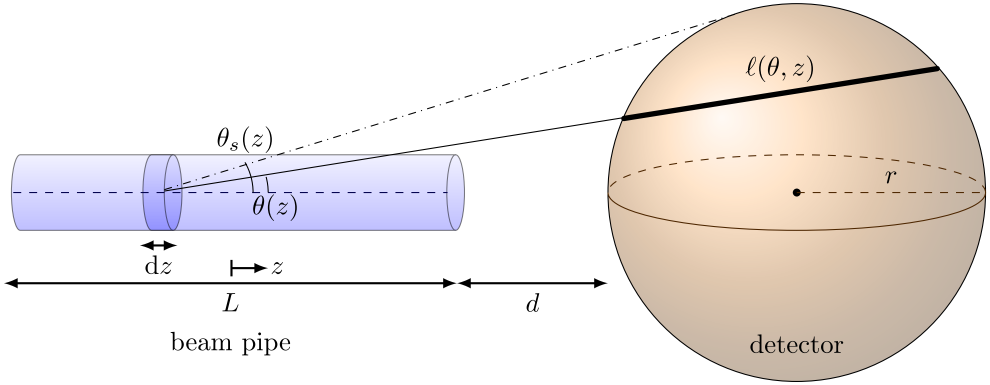
Updated limits on WIMP-nucleon scattering



- More neutrino experiments can be used to “fill the gaps”, Beacom and Cappiello, 1906.11283
- If the DM cross section is large-ish, an interesting spin-off can be considered in an underground laboratory environment where one could use existing particle beams to “accelerate” DM in a first collision and detect it using DM detectors in a second collision (in collaboration with Moore, McKeen, Morrissey, Ramani, 2202.08840)

Using underground accelerators to "accelerate" dark matter

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators (e.g. LUNA, JUNA etc) 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.



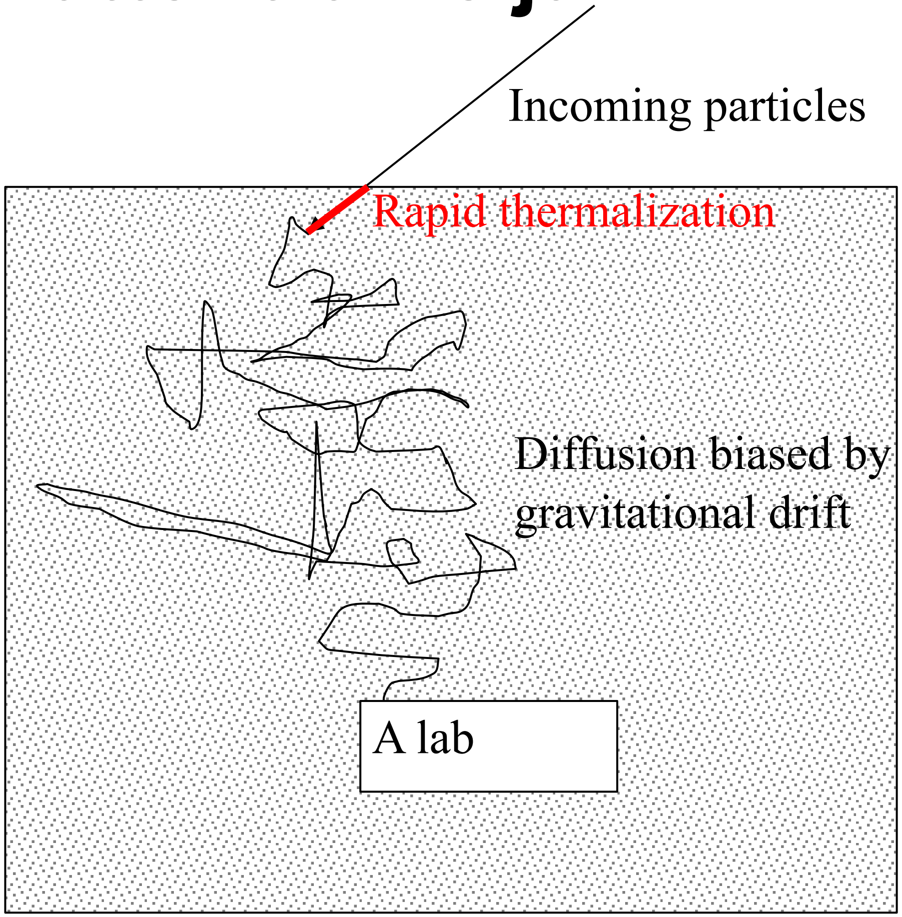
- This is going to be relevant for models with large DM-nuclear cross section (blind spot #2), where A. interaction is enhanced, B. density is enhanced.

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 and gravitational forcing

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

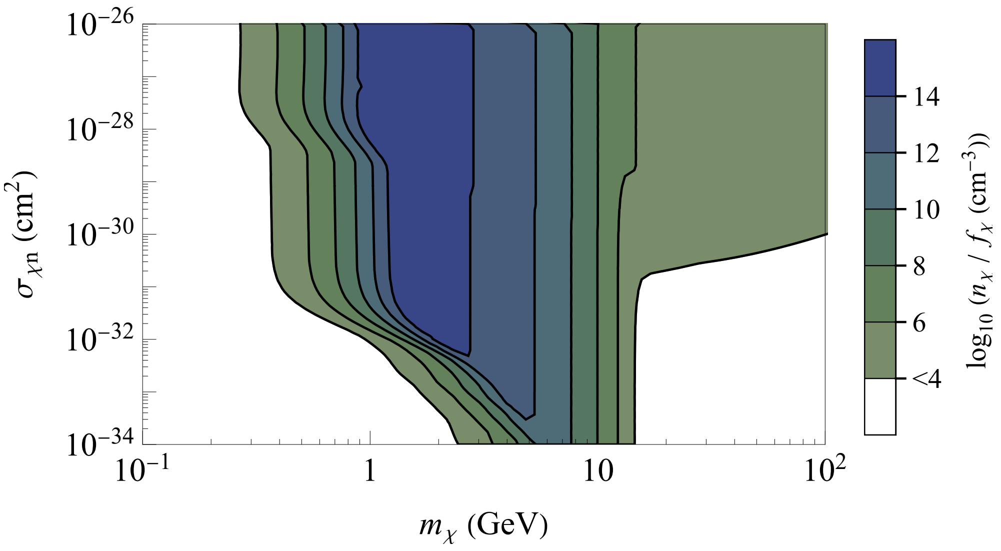
- Change in velocity from incoming $\sim 10^7$ cm/s to typical sinking velocity of 10 cm/s (for a 100 mbn σ) results in $n_{lab} \sim 10^6\, n_{halo}$. **Not visible to direct detection.**
- At masses < 10 GeV upward flux is important and density goes up.



MP, Rajendran, Ramani 2019 MP, Ramani 2020, Berlin, Liu, MP, Ramani, in prep

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}.

Spectrum of recoil

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

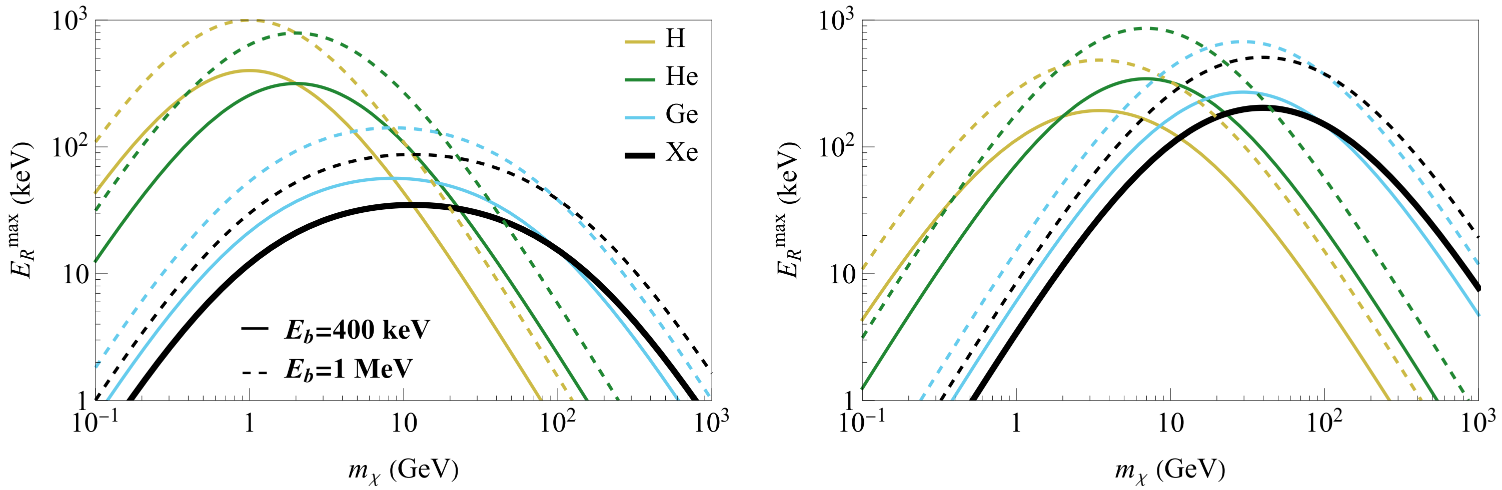
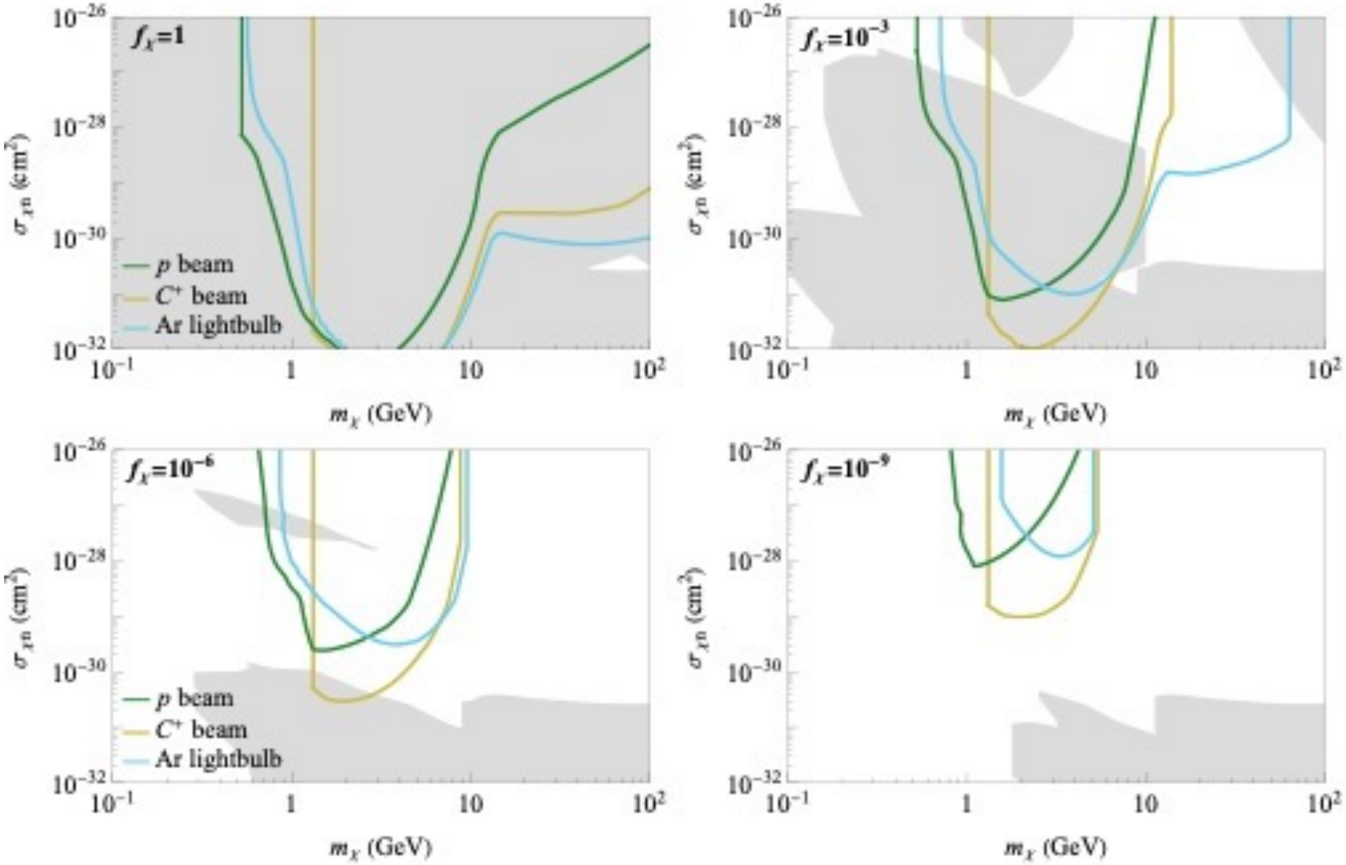


FIG. 3. Maximum nuclear target recoil energies $E_R^{\max}$ for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies $E_b = 0.4$ MeV (solid) and $E_b = 1.0$ MeV (dashed) for a selection of target nuclei.

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)

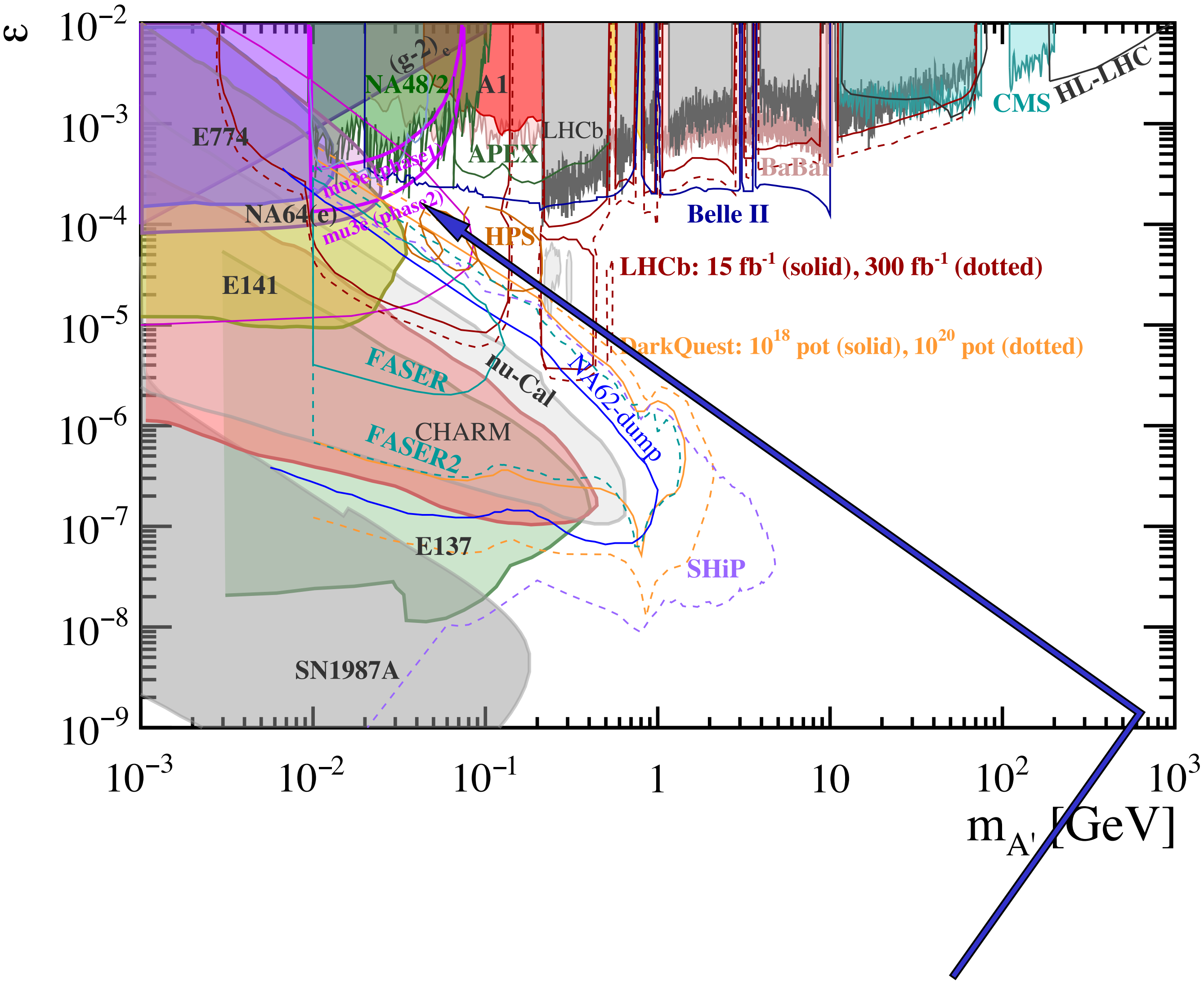
Final idea: dark photon mediated interaction may lead to Dark Matter – Nucleus bound state

- 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, 2110.06217

Constraints on visibly decaying dark photons



Bound state formation is possible in this corner

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

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)

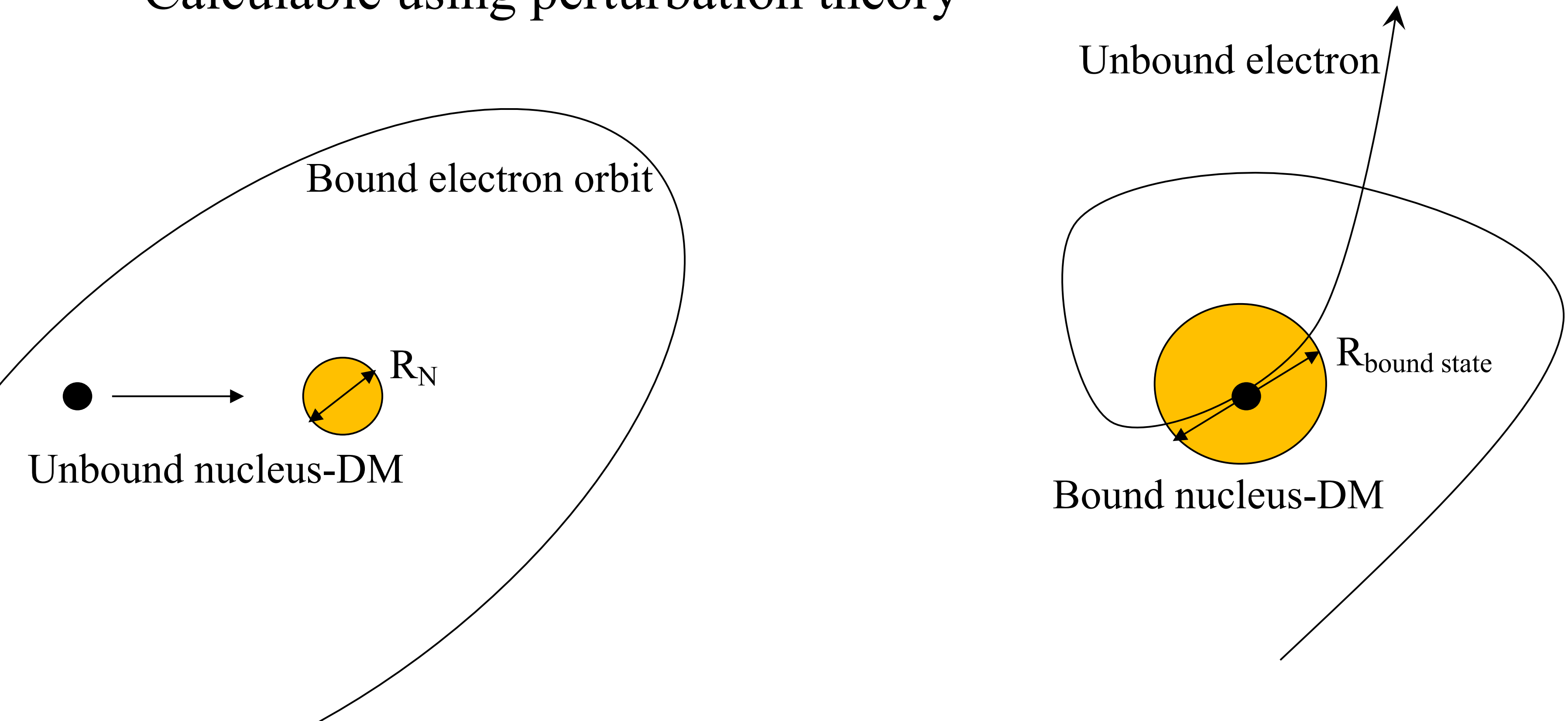
Capture process

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

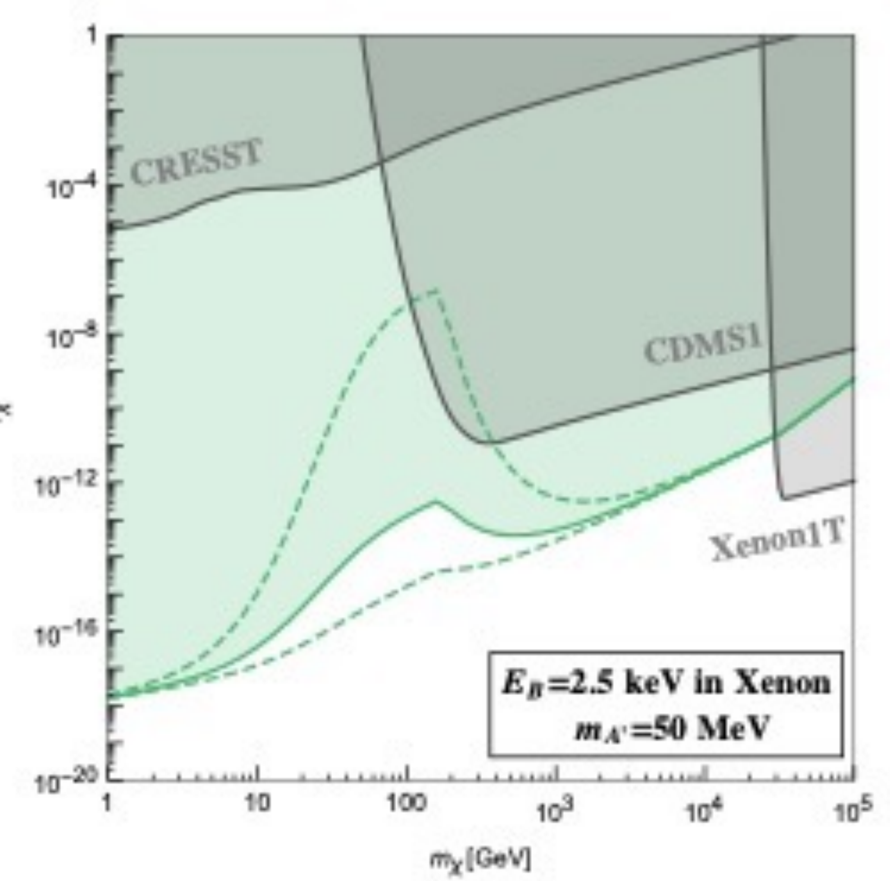
$$A + \chi \rightarrow (A^{+}\text{-ion}\ \ \chi) + \text{electron}$$

Dominates over photon emission.

- Calculable using perturbation theory

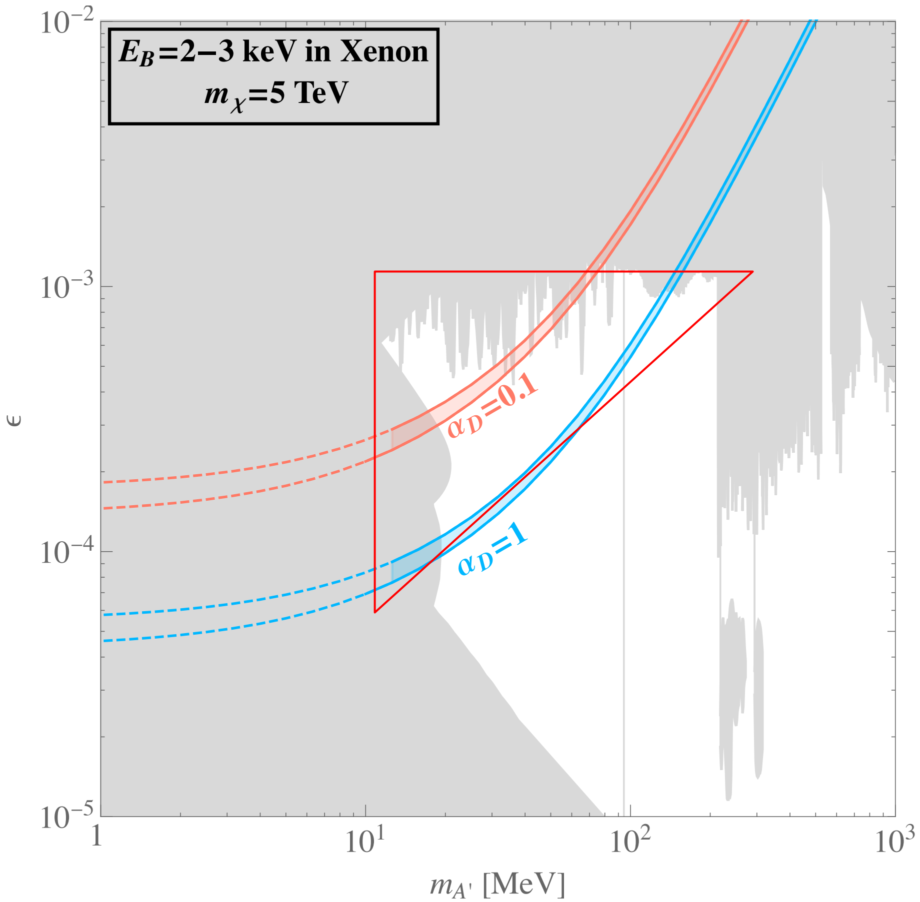


One can probe exceedingly small admixtures of DM particles that can bind to Xe nucleus



- 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

- Considerable investment goes into attempts to directly detect dark matter – it is a distinct possibility, especially if DM is a WIMP.
- *LZ experiment is another milestone in the WIMP searches, toping the competitors at the moment, for the search of* m_{DM} *> few GeV. Has a huge potential of improving limits on electron recoil.*
- 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.*
- Coupling of underground accelerators with dark matter detectors will allow probing strongly-interacting sub-component of dark matter. If the coupling is strong enough and force is attractive, bound states with heavy elements can form, providing exquisite sensitivity in DD exp.
- 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.