Overview of Dark Sector physics

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Feebly-Interacting Particles:
FIPs 2020 Workshop Report

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Plan for 3 lectures

1. Introduction. The need for new physics. Types of particle dark matter. Portals to new Physics. Phenomenology of particle dark matter in broad strokes.

2. Freeze-in dark matter. Light dark sectors. Axions.

3. Search for ~~DM~~ DS in laboratory experiments. Beam experiments (colliders, beam dumps, intensity frontier). Direct detection efforts underground. Blind spots for direct detection.

SM as an Effective Field Theory

Typical BSM model-independent approach is to include all possible BSM operators + light new states explicitly.

$\mathcal{L}_{SM}$

$$\mathcal{L}_{2020s} = -\underbrace{m_H^2\,(H^{+}_{SM}H_{SM}) + \text{all dim 4 terms}\,(A_{SM},\ \psi_{SM},\ H_{SM})} +$$

Neutrino mass operators (e.g. effective Dim=5)

+(Wilson coeff. /Λ^2) × Dim 6 etc ($A_{SM},\ \psi_{SM},\ H_{SM}$) + …

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

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

SM -- Standard Model

DS – Dark Sector

vh

Neutral “portals” to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ “Kinetic mixing” with additional U(1)’ group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}^{(k)}_{\text{med}}\, \mathcal{O}^{(l)}_{\text{SM}}}{\Lambda^n},$$

How to look for New Physics ?

1. High energy colliders.

$$\frac{(\text{small coupling})^2 ?}{(\text{small scale})^2} \qquad \frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q) \;\rightarrow\; \sigma \propto \frac{E^2}{\Lambda^4} \;\rightarrow\; \Lambda > 10\,\text{TeV}$$

2. Precision measurements, especially when a symmetry is broken

$$\frac{1}{\Lambda_{\text{CP}}^2}(\bar{e}i\gamma_5 e)(\bar{q}q) \;\rightarrow\; \text{EDM},\ \frac{1}{\Lambda_{\text{CP}}^2} < 10^{-10}G_F \;\rightarrow\; \Lambda_{\text{CP}} > 10^7\,\text{GeV}$$

3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA64) can be searched.

$$pp \;\rightarrow\; \pi, K, B \;\rightarrow\; HNL + X \;\rightarrow\; HNL \text{ decay to SM}$$

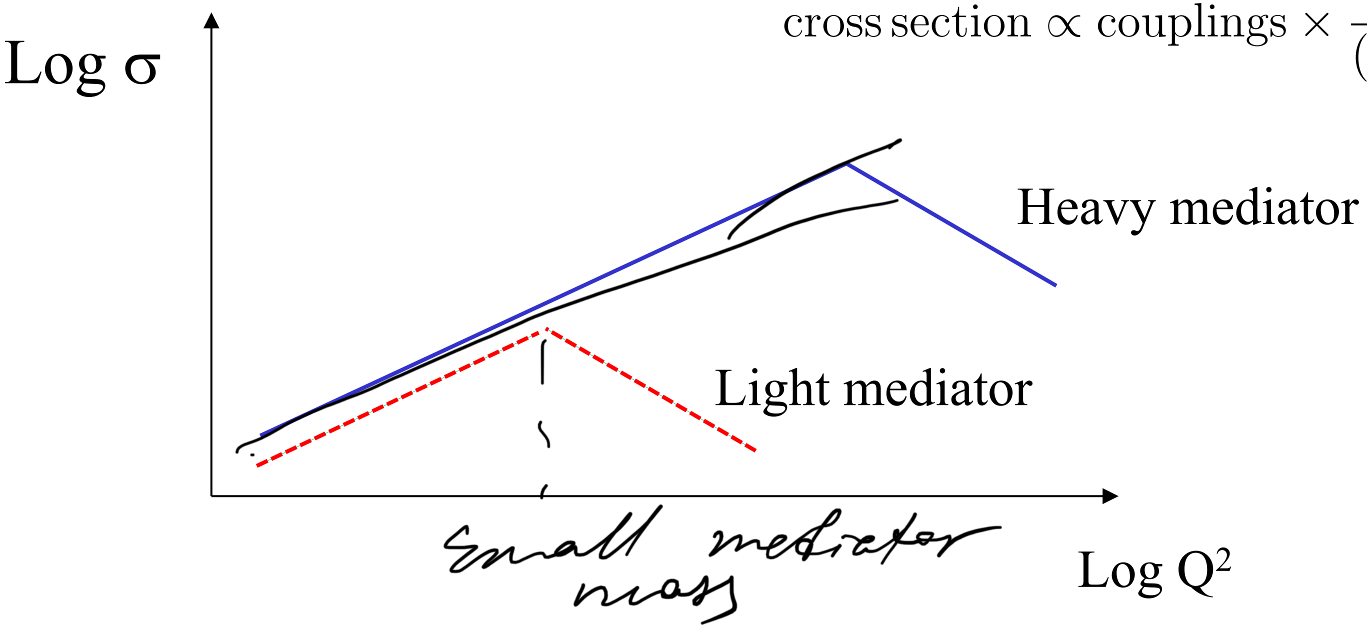
4. DM searches: *Atom + DM → visible energy*
   DM + DM → visible energy

All these methods are employed to look for Dark Sector, and associated particles, such as Dark Matter and mediators.

Light particles change σ(E)

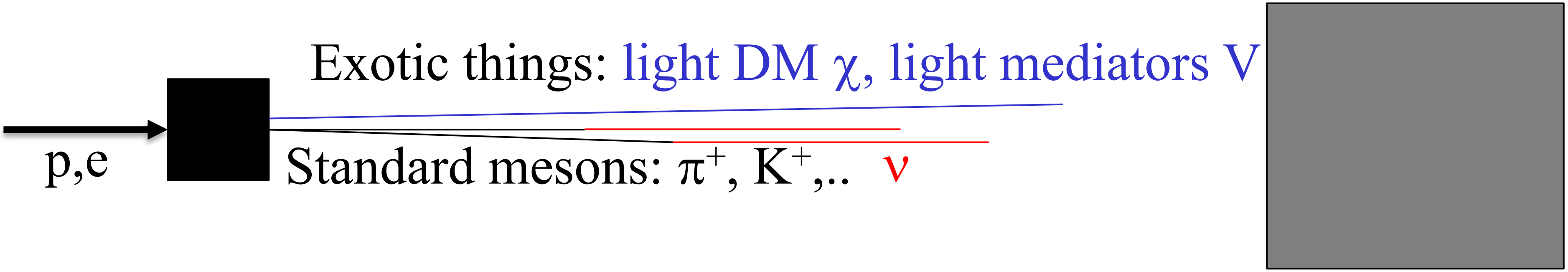
Light particles induced interactions do not benefit from going to large energies the same way as e.g. interactions from heavy particles

$$\text{cross section} \propto \text{couplings} \times \frac{Q^2}{(Q^2+M^2)^2}$$



High intensity is a key to probe light particles with small couplings (feebly interacting particles or FIPs)

How to explore Dark sectors in beam experiments?



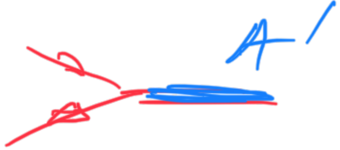
Exotic things: light DM χ, light mediators V

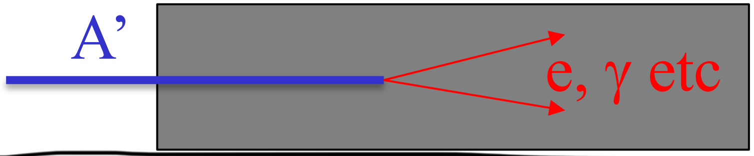
Standard mesons: π^+, K^+,.. ν

Neutrino detector

Options:

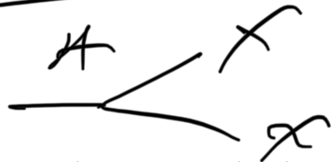
1. Exotic particles are "metastable", decay to SM inside the detector

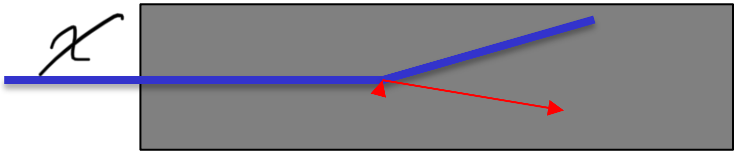




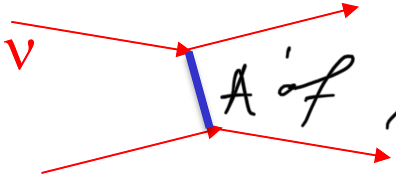
excluded original PQ axion model $f_a = v_{EW}$

2. Exotic particles are "stable", but can scatter on SM particles



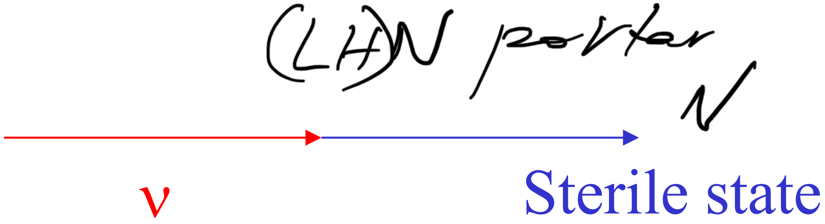


3. Exotic particles exchange can modify neutrino scattering.



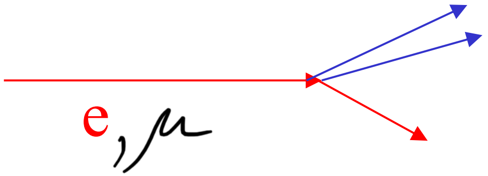
A' of $L_\mu - L_e$

4. There is of course also a possibility of *disappearance* of known particles



5. Missing energy/momentum. (In a collision where particles are sent on target 1-by-1, one can detect abnormal energy/momentum loss. Same for e.g. particle colliders.)

NA64
LDMX



6. Combination of all of the above: e.g. Sterile neutrinos can have ”secret interactions”, and also scatter off SM particles, or the oscillation pattern can change.

Models vs Experiments in "Physics Beyond Colliders" exercise at CERN

Benchmark Cases (MP and PBC, 2018)

1. *Dark photon*
2. *Dark photon + light dark matter*
3. *Millicharged particles*
4. *Singlet scalar mixed with Higgs*
5. *Quartic-dominated singlet scalar*
6. *HNL, e-flavour dominance*
7. *HNL, μ-flavour dominance*
8. *HNL, τ-flavour dominance*
9. *ALPs, coupling to photons*
10. *ALPs, coupling to fermion*
11. *ALPs, coupling to gluons*

Vector

scalar

HNL

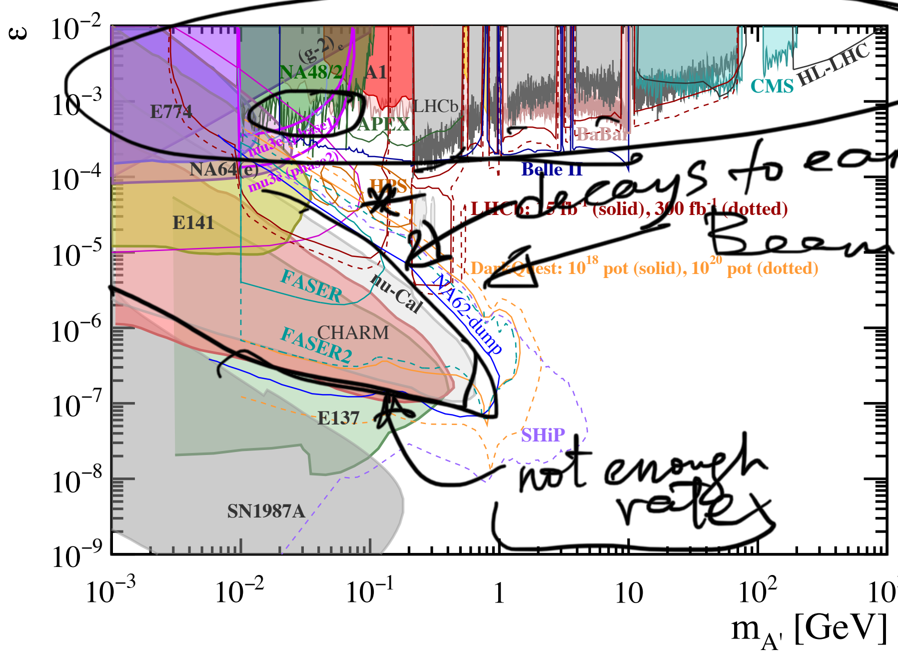
ALPs

Experimental proposals, mostly CERN

SHiP	*Beam Dump*
NA62+	*Flavour, possible BD*
FASER	*LHC add-on*
MATHUSLA	*large LHC add-on*
Codex-B	*LHC add-on*
MilliQan	*LHC add-on*
NA64	*missing momentum*
KLEVER	*flavour*
REDTOP	*fixed target*
IAXO	*axion exp*
ALPs-II	*axion exp*
………	

I hope that in the end, a clear strategy for building up CERN intensity frontier program will emerge, with new sensitivity to sub-EW scales

Visibly and invisibly decaying dark photons



Searches of enhancement

m_{ll}

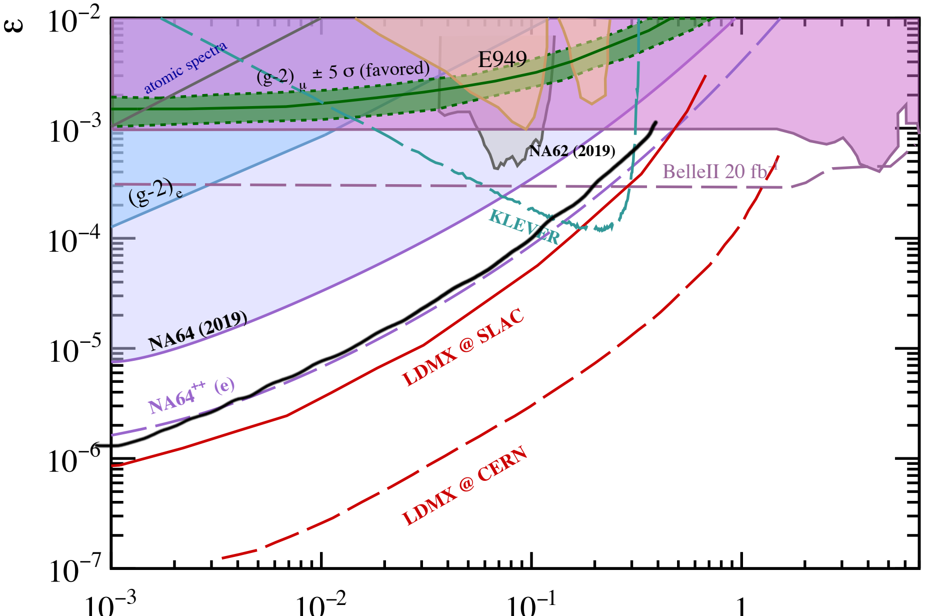
decays to early

Beam dump

not enough rate

$A' \to l^+ l^-$

Benchmark cases 1 and 2, models with visible [top] and invisible [bottom] decays of dark photons



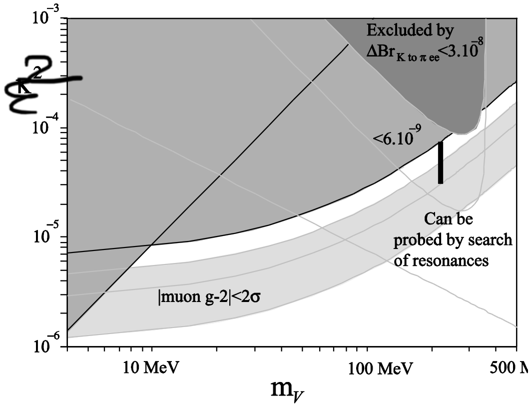
$A' \to \chi \bar{\chi}$

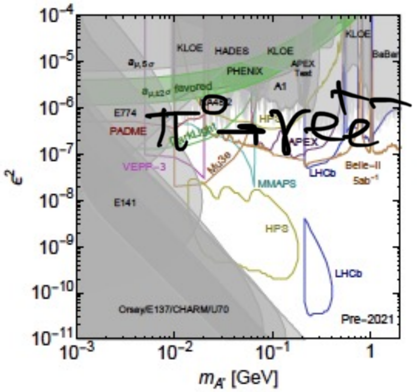
New physics and muon g-2

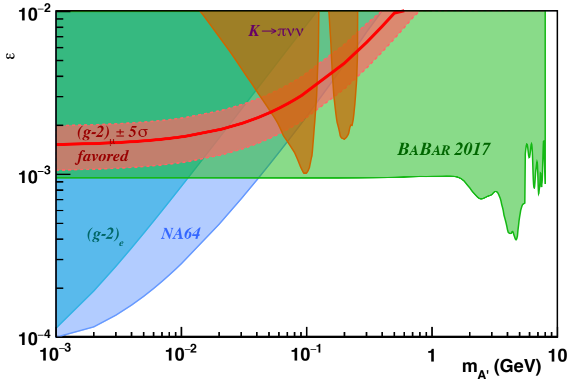
Models with light particles.

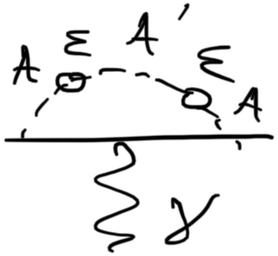
Dark photons (pushes g-2 in the positive direction, reducing disrepancy)

$$\Delta \underline{\mu_{\rm d.ph.}} = \frac{\alpha\varepsilon^2}{2\pi}\times em\int_0^1 dx\,\frac{x^2(1-x)}{m_\mu^2x^2+m_V^2(1-x)} \to \begin{cases} \frac{\alpha\varepsilon^2}{2\pi}\times\frac{e}{2m_\mu} & \text{at } m_V \ll m_\mu \\ \frac{\alpha\varepsilon^2}{2\pi}\times\frac{em_\mu}{3m_V^2} & \text{at } m_V \ll m_\mu \end{cases}$$

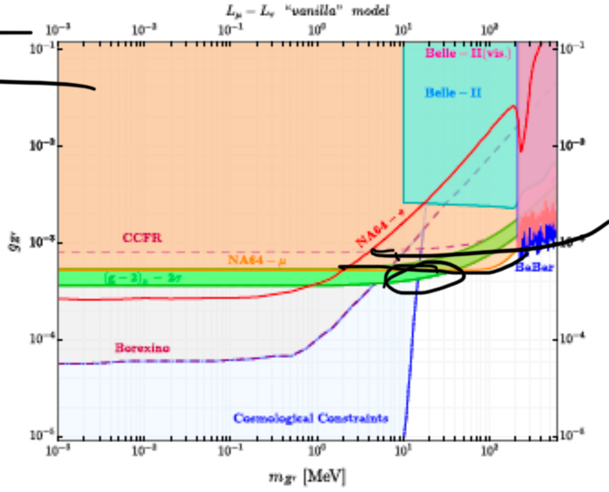






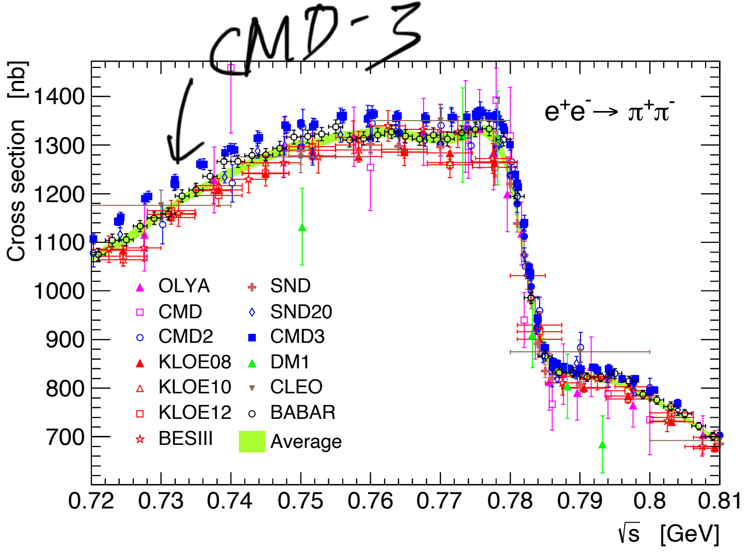


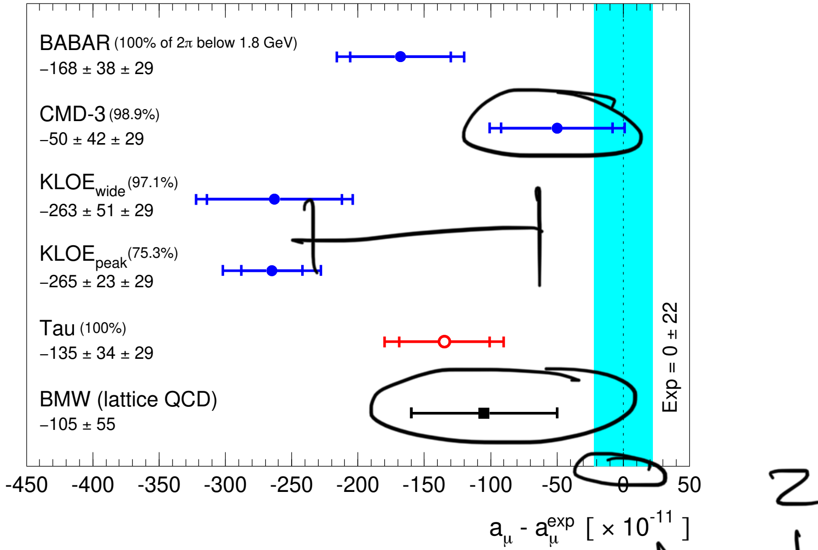
By now both visibly and invisibly decaying dark photons (e.g. to dark matter) are probed much below levels interesting for the muon g-2.



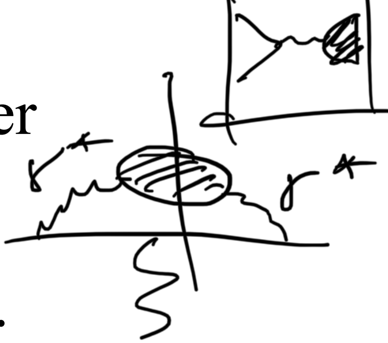
In the “barely alive” category: L_μ-L_τ gauge boson below the dimuon threshold. Invisible decay, hard to produce with e^-.

Doubts grow: is there a muon g-2 problem?



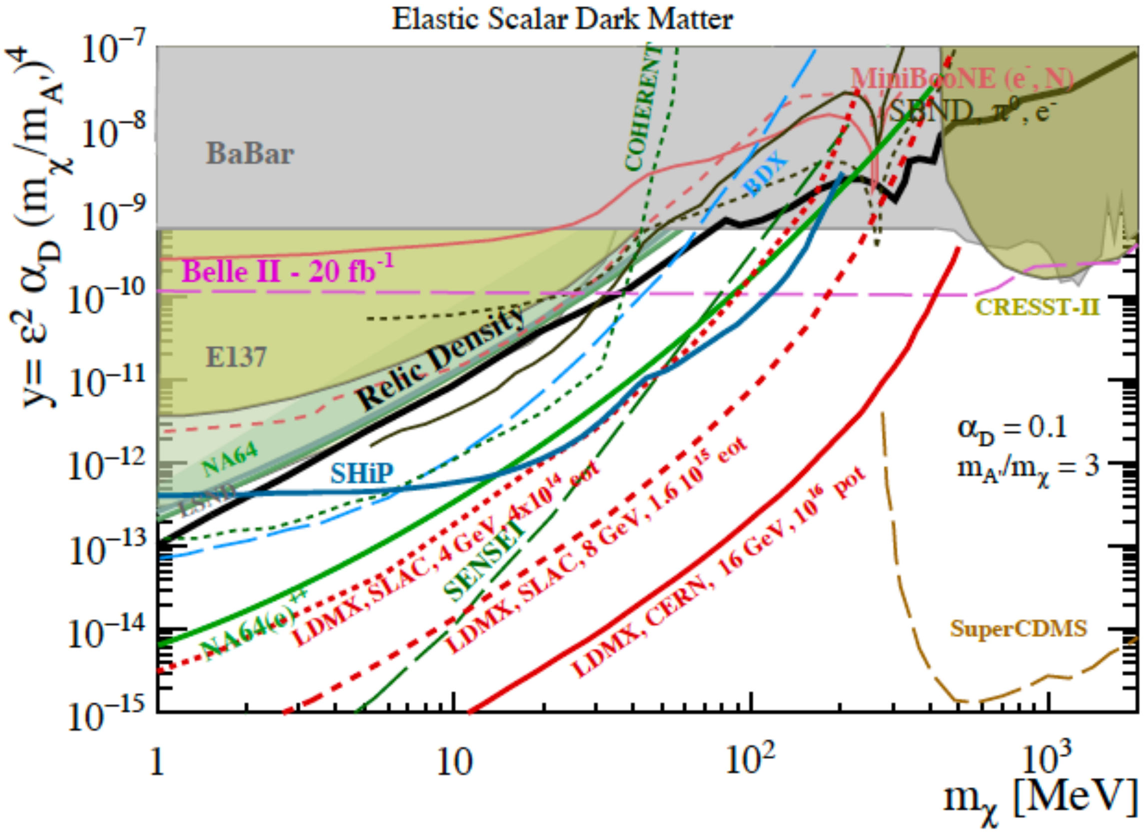


(From M. Davier et al, 2023)



- The reasons why CMD-3 results are considerably larger (compared to global errors) are not entirely clear.
- They (CMD-3) are consistent with BMW lattice result.
- This invites additional scrutiny for the ``radiative return" method of measuring hadron production cross section.
- One can no longer claim ~5σ discrepancy between theory and experiment for muon g-2.

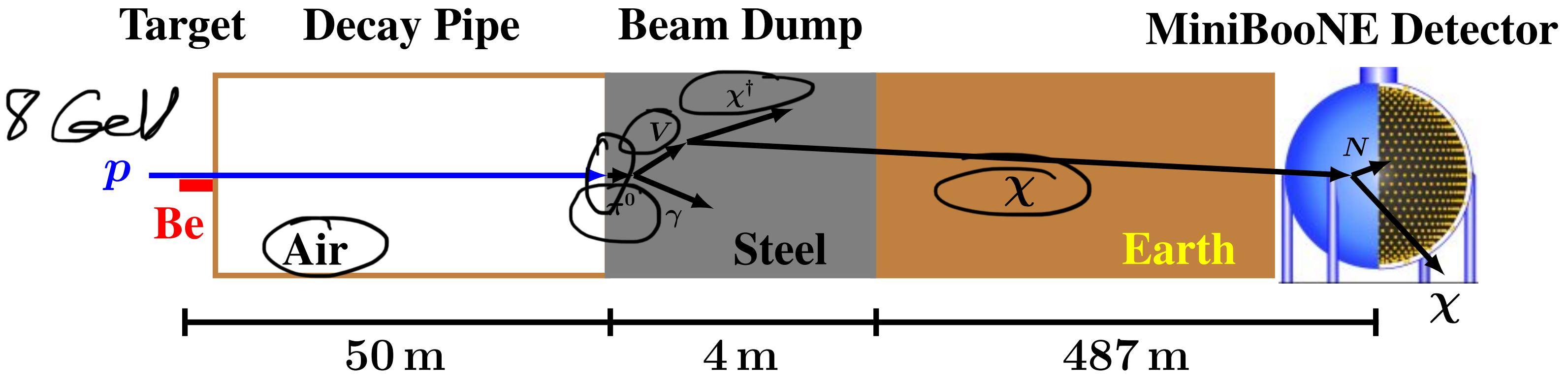
Dark photons decaying to dark matter

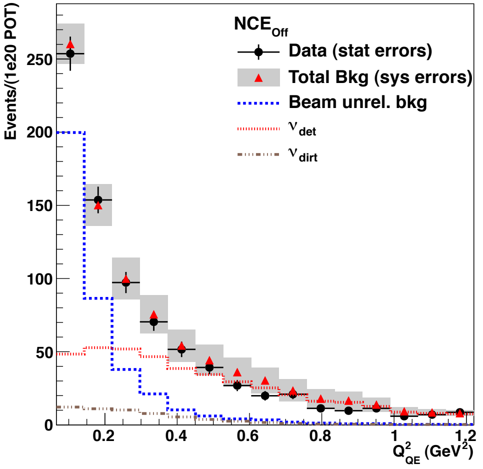


Experiments that look for missing energy/momentum have advantage over experiments looking at production & detection of dark matter: ε^2 vs ε^4 scaling. *However in case of positive signal, it is harder to decide what it could be.*

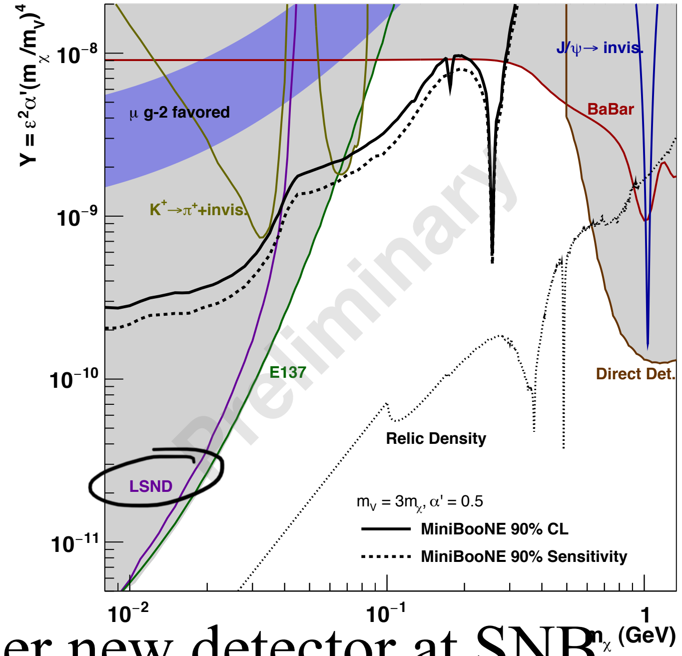
MiniBooNE search for light DM

arXiv:1702.02688, PRL 2017.





	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

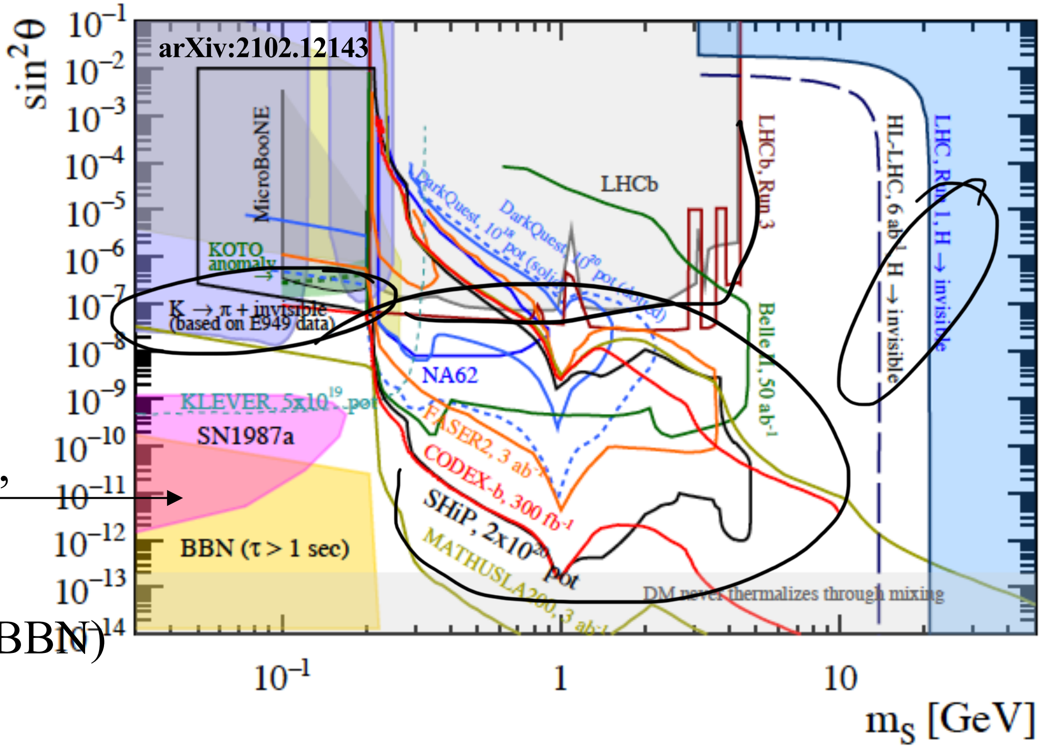


Subject to future improvement with much closer new detector at SNB

Constraints on dark scalar

(„milli-Higgs")

$\text{DM DM} \to S^* S^* \to \text{SM SM SM SM}$



Astroparticle,

Cosmology

(SN 1987A, BBN)

Notice that the constraints on dark scalar are strong in flavour-type experiments

PBC projects:

NA62-Kaon, NA62-dump,

KLEVER, FASER2,

CODEX-b, SHiP, MATHUSLA,…

Worldwide landscape

MicroBooNE, KOTO, DarkQuest,

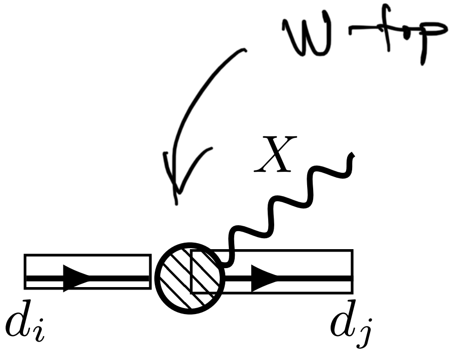
Belle-II, LHCb, ATLAS, CMS

Major LABs involved

CERN, KEK, JPARC, FNAL,…

Non-conserved currents will be sensitive to high-mass scales through loops

- It is well known that there is an enhancement of non-conserved currents inside loops leading to FCNC. The key – access to momenta ~ m_W and m_t.



- For a fully conserved current, like couplings of dark photon,

$$Amplitude \sim \underbrace{G_F\, m^2_{meson}}$$

For a non-conserved current, such as Higgs-mixed scalar

$$Amplitude \sim G_F\, \underline{\underline{m^2_{top}}}$$

Light Higgs-like particle through the super-renormalizable portal

Example: new particle admixed with a Higgs.

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \underbrace{ASH^\dagger H}_{}$$

After (Higgs Field = vev + fluctuation h), the actual Higgs boson mixes with S.

Mixing angle: $$\boxed{\theta} = \frac{Av}{m_h^2}$$

The model is technically natural as long as A not much larger than m_S Low energy: new particle with Higgs couplings multiplied by θ.
Mixing angle and mass can span many orders of magnitude.

New effects in Kaon and B-decays.

Higgs penguin in flavor physics

- Calculations of the “Higgs penguin” are especially neat:

$$\mathcal{M}_S = \frac{S}{v} m_b \bar{s}_L b_R \times \frac{3}{2}\theta \frac{(y_t^{\rm SM})^2 V_{tb} V_{ts}^*}{16\pi^2}$$

- *Notice the absence of any complicated function of* m_t/m_W. The reason being is that the effect is similar to scale anomaly:

$$\underline{m_t \bar{t} t} \to \underbrace{\left(1+\frac{h}{v}\right)}\, m_t \bar{t} t \quad \to \quad \text{H.peng.} \;\sim (\gamma\cdot p)\frac{\partial}{\partial v}\underbrace{\text{SelfEnergy}(m_t/m_W)}$$

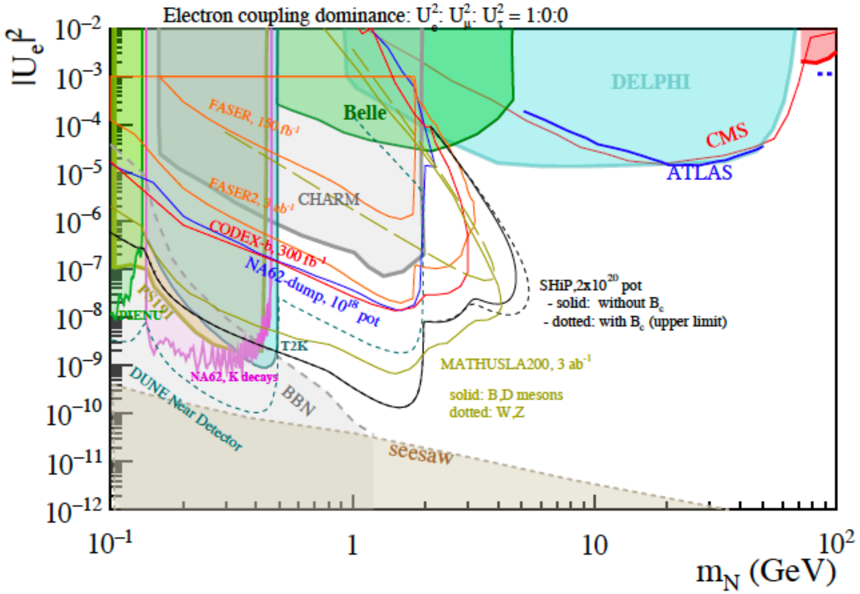
$$\frac{\partial}{\partial v}\text{SelfEnergy}(m_t/m_W) = \frac{\partial}{\partial v}\text{SelfEnergy}\underline{(y_t/g_W) = 0?}$$

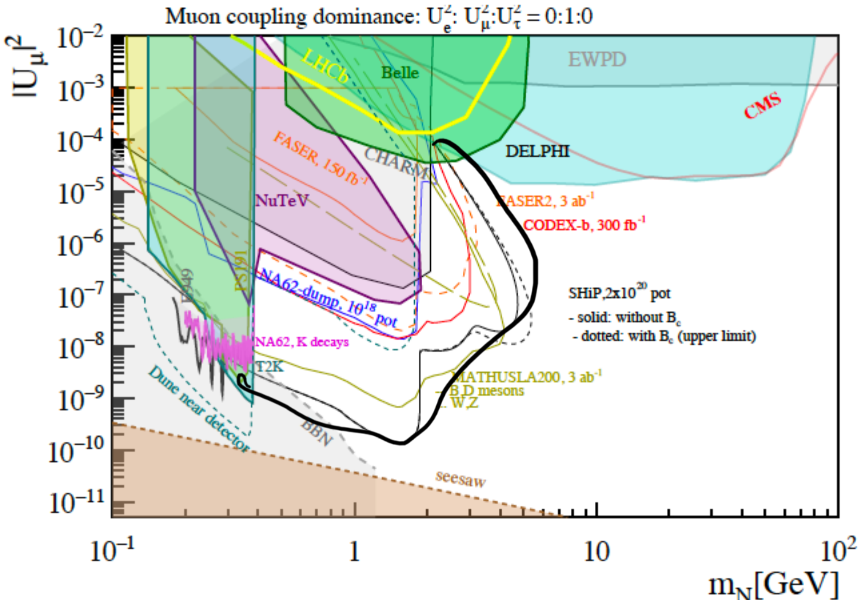
- The result is not 0 because of the scale dependence,

  Self-Energy ~ $\overbrace{\text{Log}(M_{\rm reg}/v)}$

$$\underline{\Gamma_{K\to\pi+\phi-{\rm mediator}}} \simeq \left(\ \theta\ \right)^2 \left(\frac{3m_t^2 V_{td} V_{ts}^*}{16\pi^2 v^2}\right)^2 \frac{m_K^3}{64\pi v^2}.$$

Constraints on HNLs





400 MeV ~ 10^{15} GeV

Exp 100 MeV – weak scale

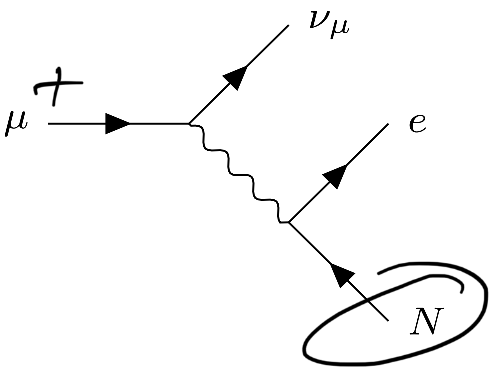
- Charged current production of HNLs followed by displaced decays

- Lower masses are typically disfavored by cosmology.

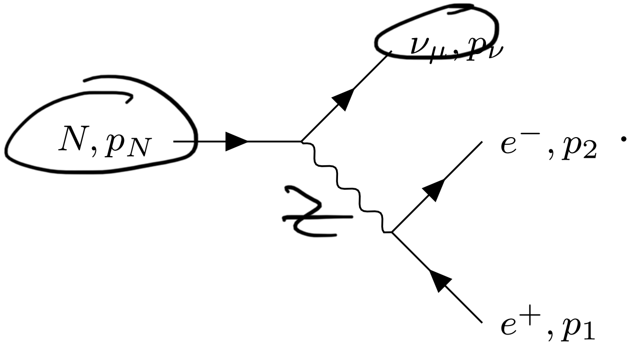
decays of D mesons

New HNL constraints from old LSND

- With Y. Ema, Z. Liu and K. Lyu, e-Print: 2306.07315 [hep-ph]

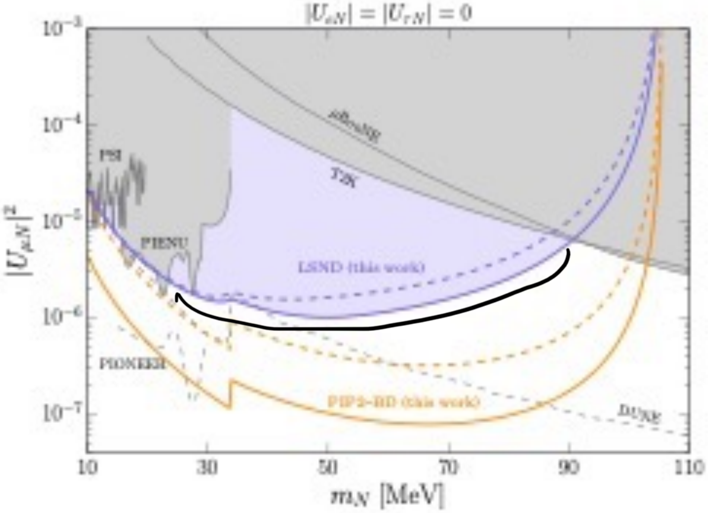


Production



Detection

- Sometimes a pair will look like a single electron → contributes to *ν–e* scattering sample at LSND. Strong acceptance penalty.

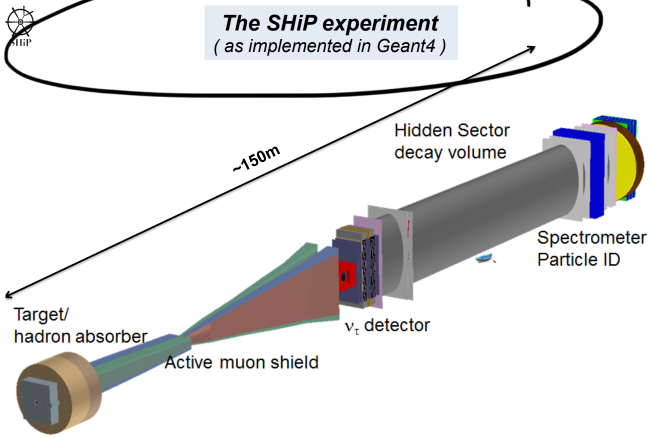


- Even with the penalty, LSND provides novel constraints due to enormous POT.

- Future experiments may improve on these constraints.

Important features of new facilities (e.g. SHiP)

- High intensity O(>10^{20} POT) & High energy, E=400 GeV. (Compare e.g. to 800 GeV CCFR/NuTeV where O(10^{18} POT) was collected.)
- Copious amounts of s, c, b quarks, and tau-mesons can be produced, enabling studies of their very rare decay modes.
- A much shorter baseline than before, 100 m or less (with NuTeV, CHARM~ O(km)). Enables access to much shorter-lived relics.
- Proton-nucleus collision followed by an absorber creates a "beam dump of everything". (Over 10^{21} hard gamma and positrons, over 10^{16} muons going through the absorber). *This is not yet a fully investigated advantage.*



New opportunities at the LHC

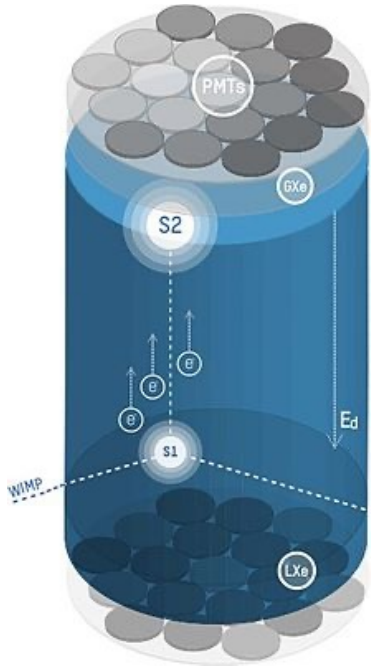
- LHC will continue to take date in the next ~ 15 years, and will become instensity frontier machine.
- Several possibilities of “on-axis” and ”off-axis” detectors exist.
- Among the forward detectors, FASER idea and implementation has been particularly successful.
- First detection of LHC neutrinos in 2023!

Summary

- Efforts to detect Dark Sector are not limited to DM searches.
- A wide variety of models and methods of detection have been investigated in various detection schemes (rare meson decays, displaced decays of light DS states, missing energy/momentum etc.)

Extending the reach of direct detection experiments

Xenon-based dark matter experiments

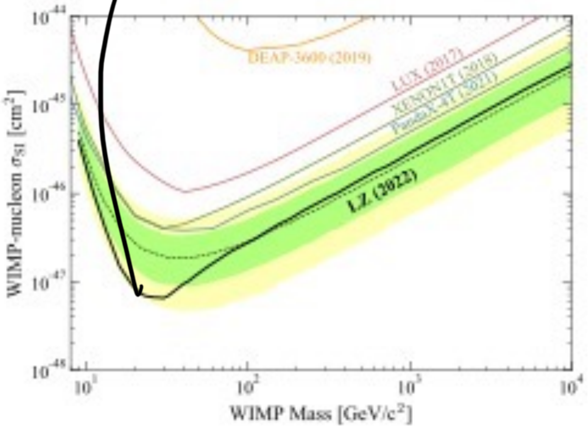


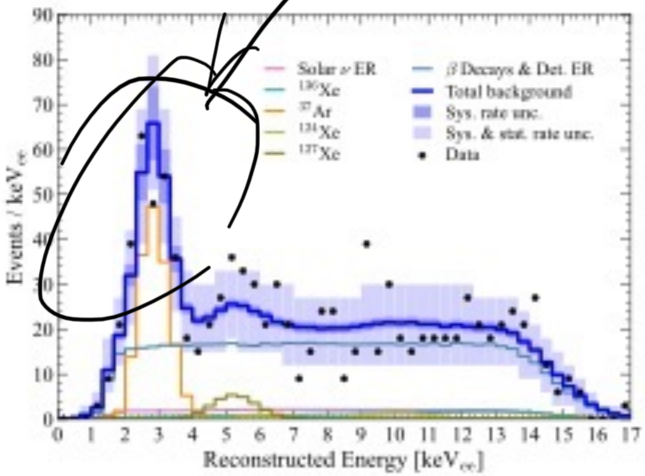
- Based on two signals: initial scintillation "on impact" (S1) and final scintillation (S2) from drift electrons.
- Ratio of S1/S2 is used to discriminate between electron and nuclear recoils
- More or less same technology is used in Xenon10, Xenon100, 1T, nT, LUX, LZ, Panda-X

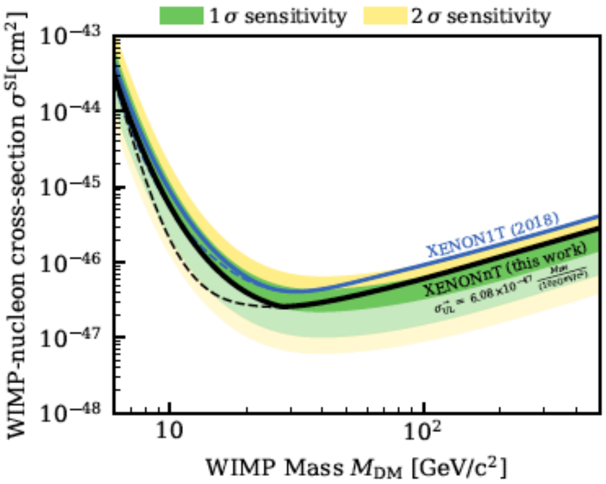
Xenon nT is installed in Gran Sasso, Italy. LZ is the US project.

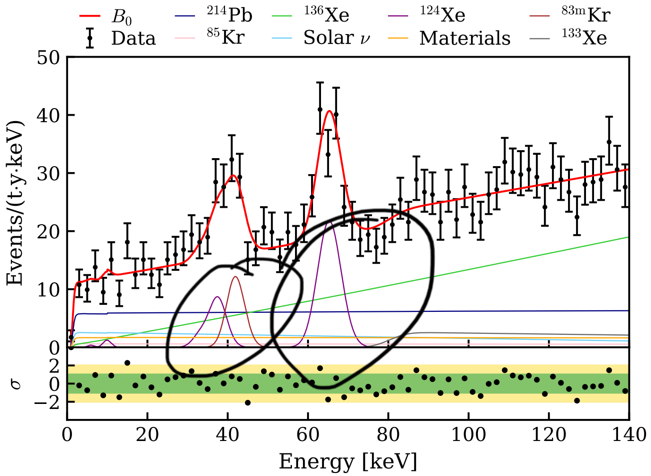
- Impressive 2022-24 updates of Direct detection limits by LZ, XenonNT.

bckgr ^{37}Ar









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

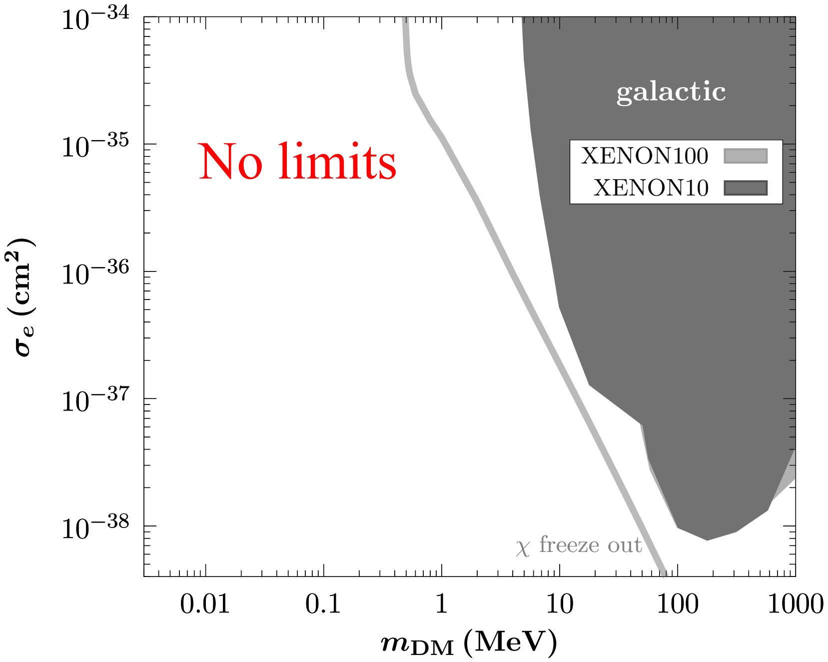
(Typically cannot be entire DM, but is limited to fraction $f<10^{-3}$)

Below the ionization threshold!

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

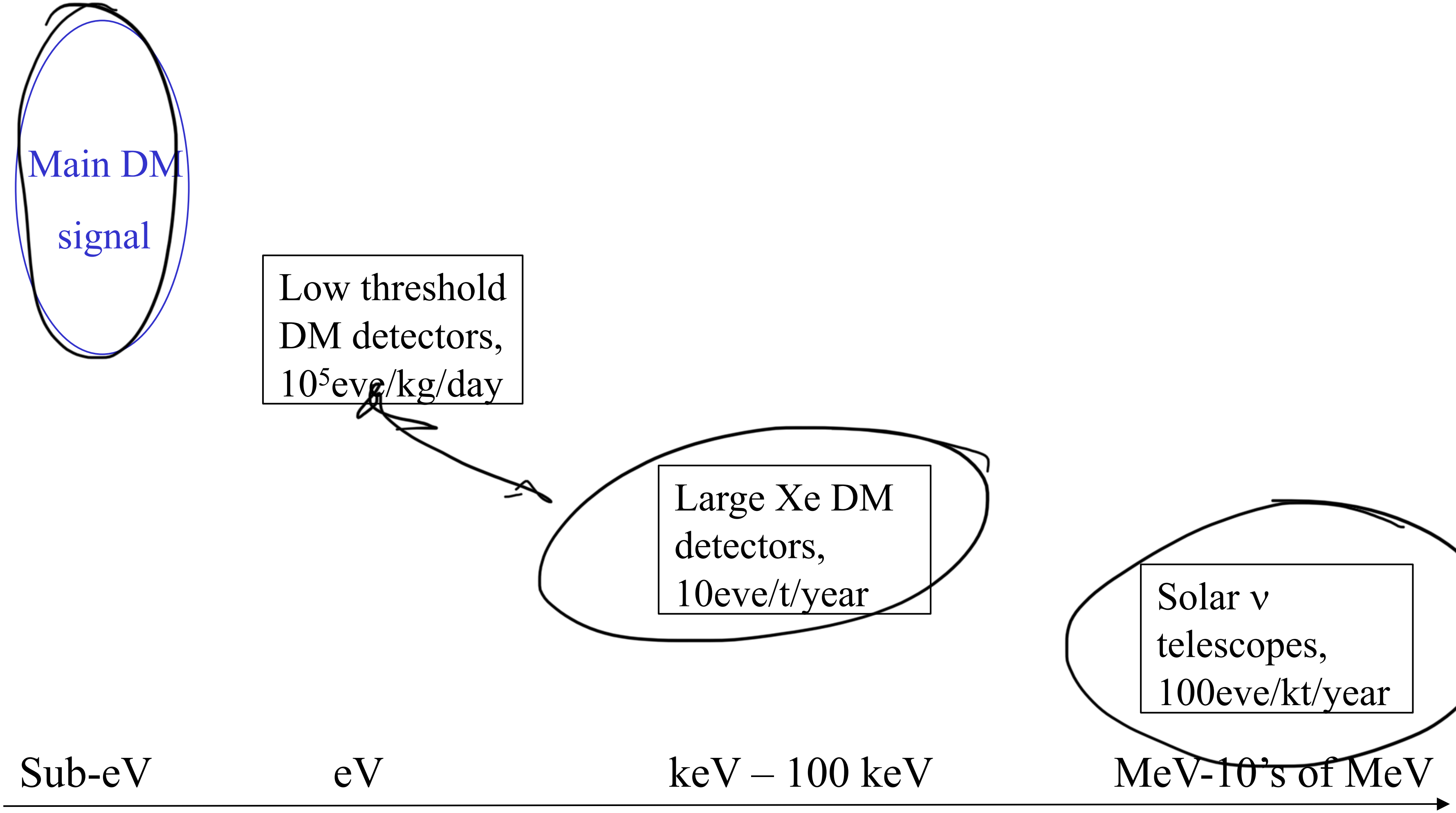
Direct detection, scattering of DM on electrons, 2017 slide

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. Continuing work in this direction.
- Huge number of suggestions: *using superconductors, graphene, Weyl semimetals, DNA, to push threshold lower.* Somewhat of science fiction at this point.

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



Main DM signal

Low threshold DM detectors, 10^5eve/kg/day

Large Xe DM detectors, 10eve/t/year

Solar ν telescopes, 100eve/kt/year

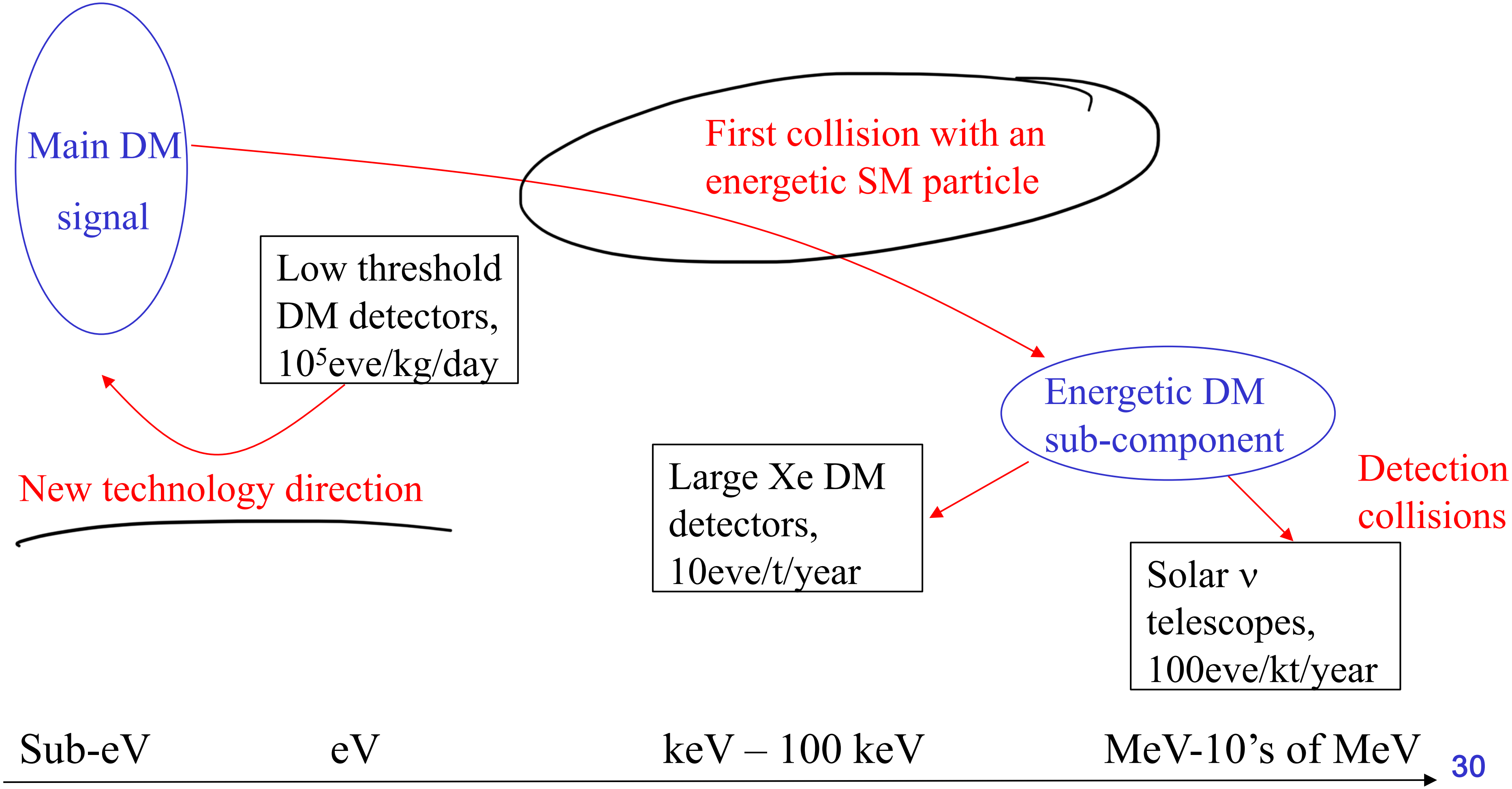
Sub-eV

eV

keV – 100 keV

MeV-10’s of MeV

Goal: explore multiple collisions of DM to fill in "blind spots" to light DM



Main DM signal

Low threshold DM detectors, 10^5eve/kg/day

New technology direction

First collision with an energetic SM particle

Energetic DM sub-component

Large Xe DM detectors, 10eve/t/year

Detection collisions

Solar ν telescopes, 100eve/kt/year

Sub-eV

eV

keV – 100 keV

MeV-10's of MeV

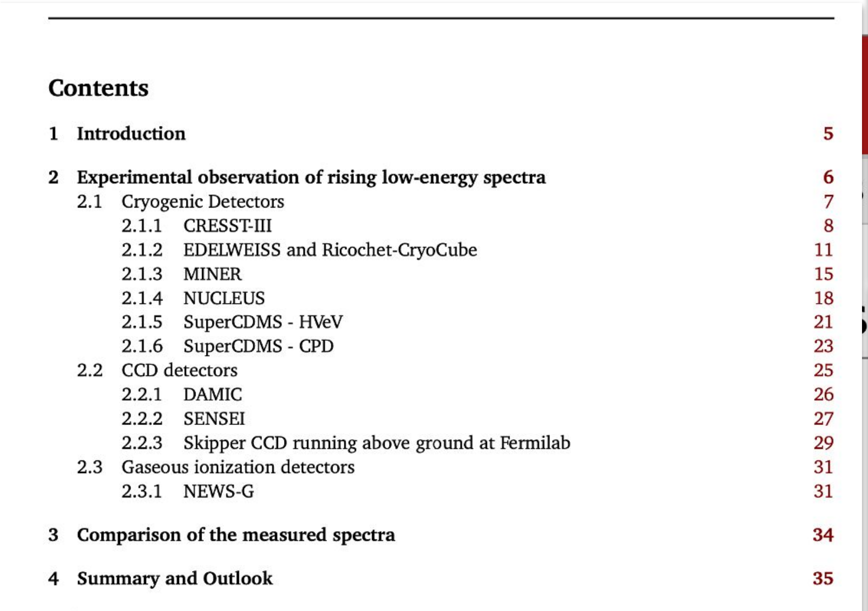
Comparing counting rates in large Xe detectors and in low-recoil solid state

- 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:

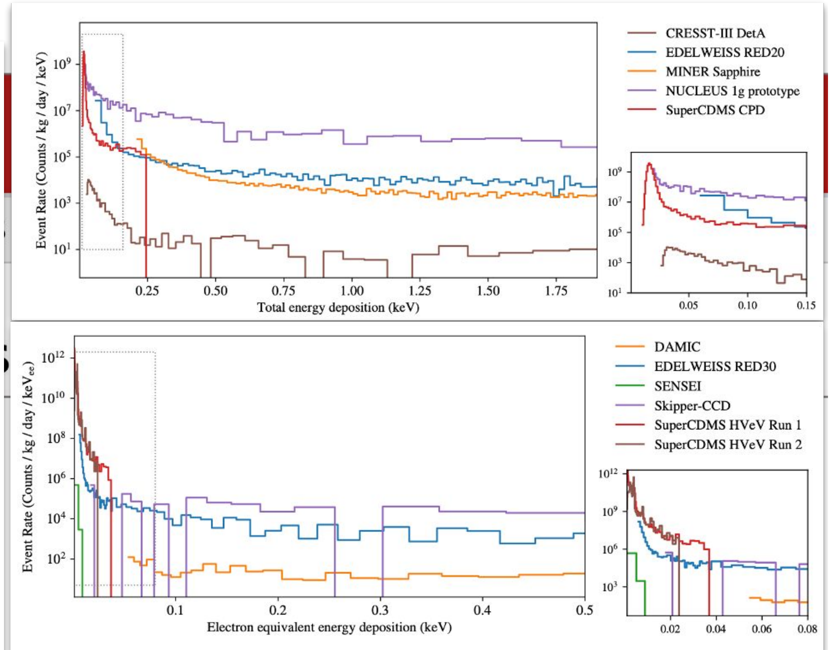
EXCESS

Collaborative summary paper based on the results reported at EXCESS 2021

https://arxiv.org/abs/2202.05097



Contents



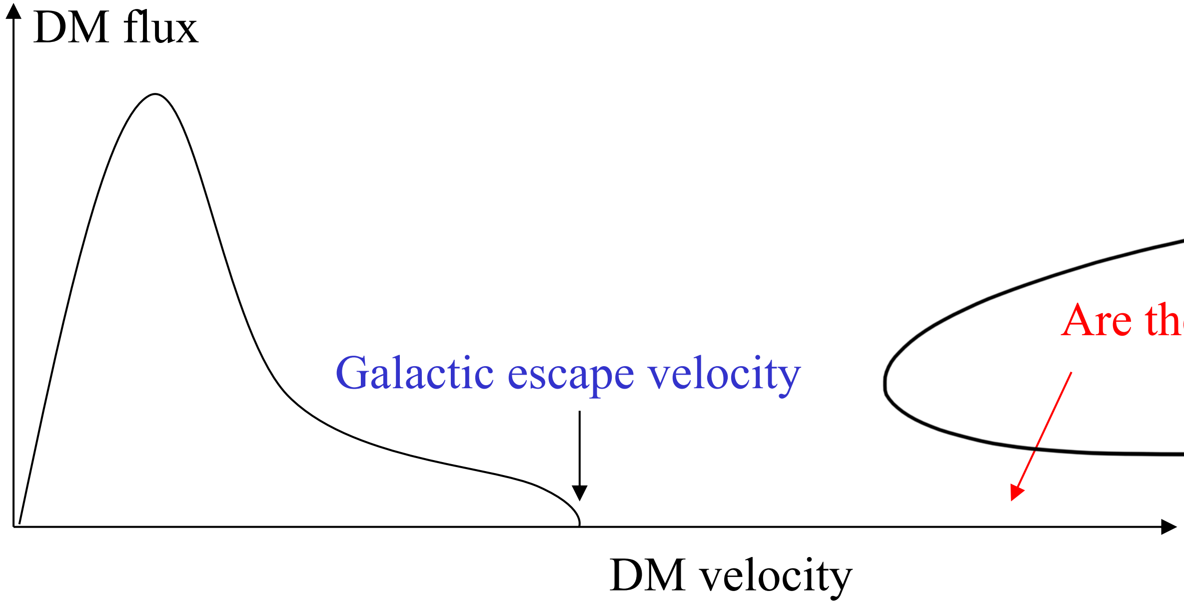
Main limitation of light WIMP searches

- The kinetic energy of galactic dark matter is limited by

  $E_{\text{gal, max}} = m_{DM} (v_{\text{escape}})^2/2.$

- For MeV-range DM, this energy is below the ionization energy of Xe (13 eV). For MeV DM maximum kinetic energy is ~ 1 eV

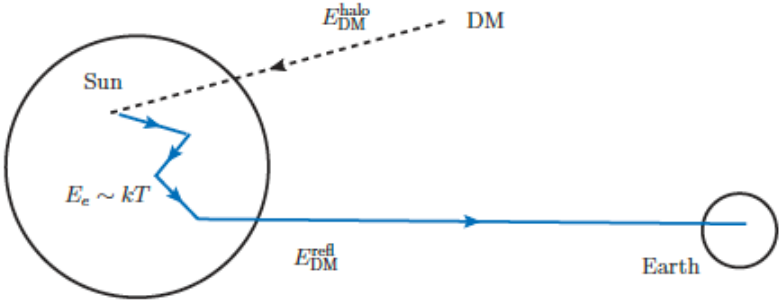
- Are there processes that bring DM energy above $E_{\text{gal, max}}$?

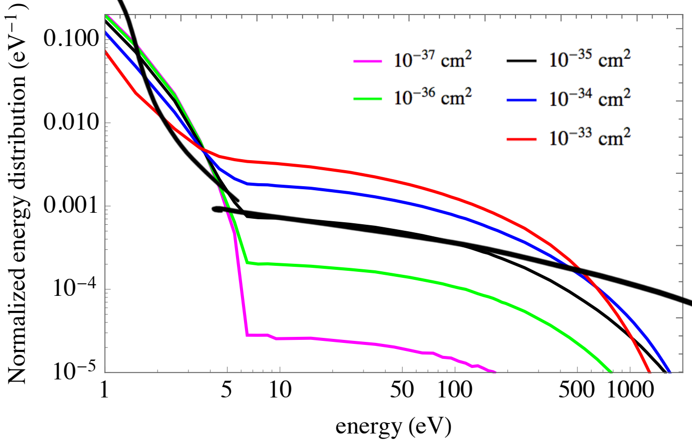


Case 1: DM scattering on electrons. Case 2: DM scattering on nucleons

“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, Essig et al, to appear)
- DM can scatter inside the Sun and get accelerated above the ionization threshold

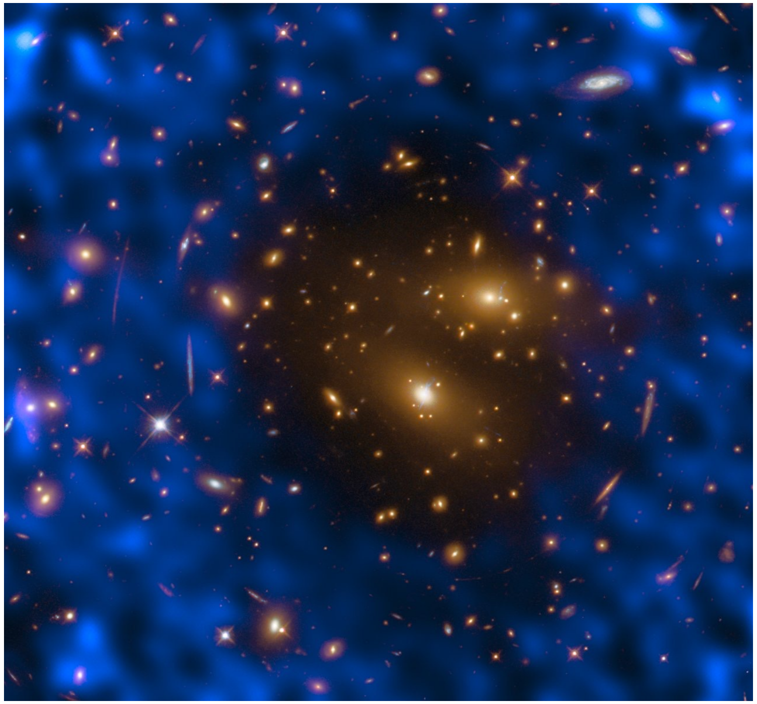




- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with $v_{dm} \sim 10^{-3}c$ (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\, T_{core}/m_e)^{1/2}$ ~ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- Huge penalty in the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

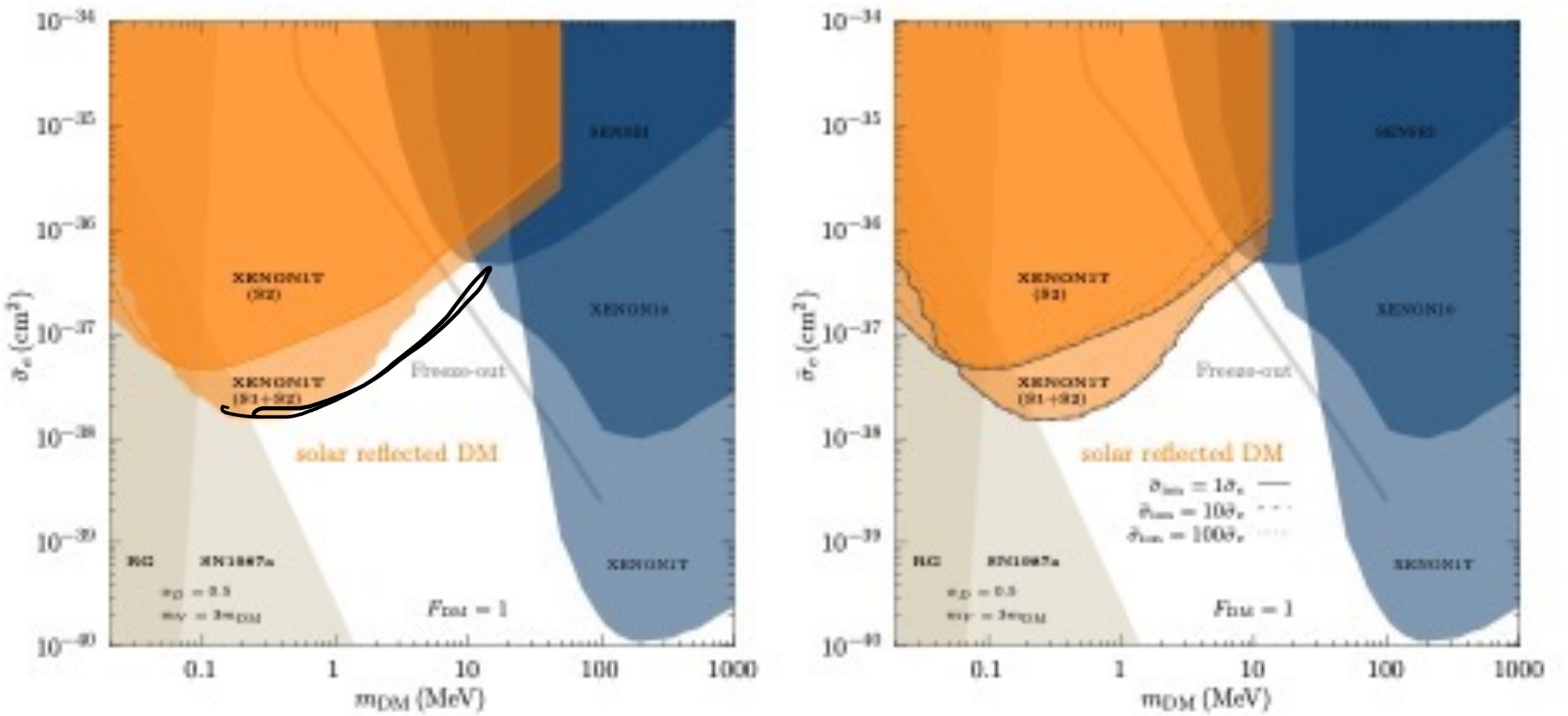
$$\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{1\,{\rm A.U.}}\right)^2 \sigma_e n_e^{\rm core} R_{\rm core}, & \sigma_e \ll 1\,{\rm pb}, \\ S_g \left(\frac{R_{\rm scatt}}{1\,{\rm A.U.}}\right)^2, & \sigma_e \gg 1\,{\rm pb}. \end{cases}$$

Analogy with Sunyaev-Zeldovich effect



- CMB photons are upscattered by hot gas in clusters of galaxies. Decrement at low frequency and increase at higher frequency.
- Solar electrons will do the same to light dark matter. Sun will be seen as a “hot spot” in dark matter.

Contact mediator, limits on σ_e



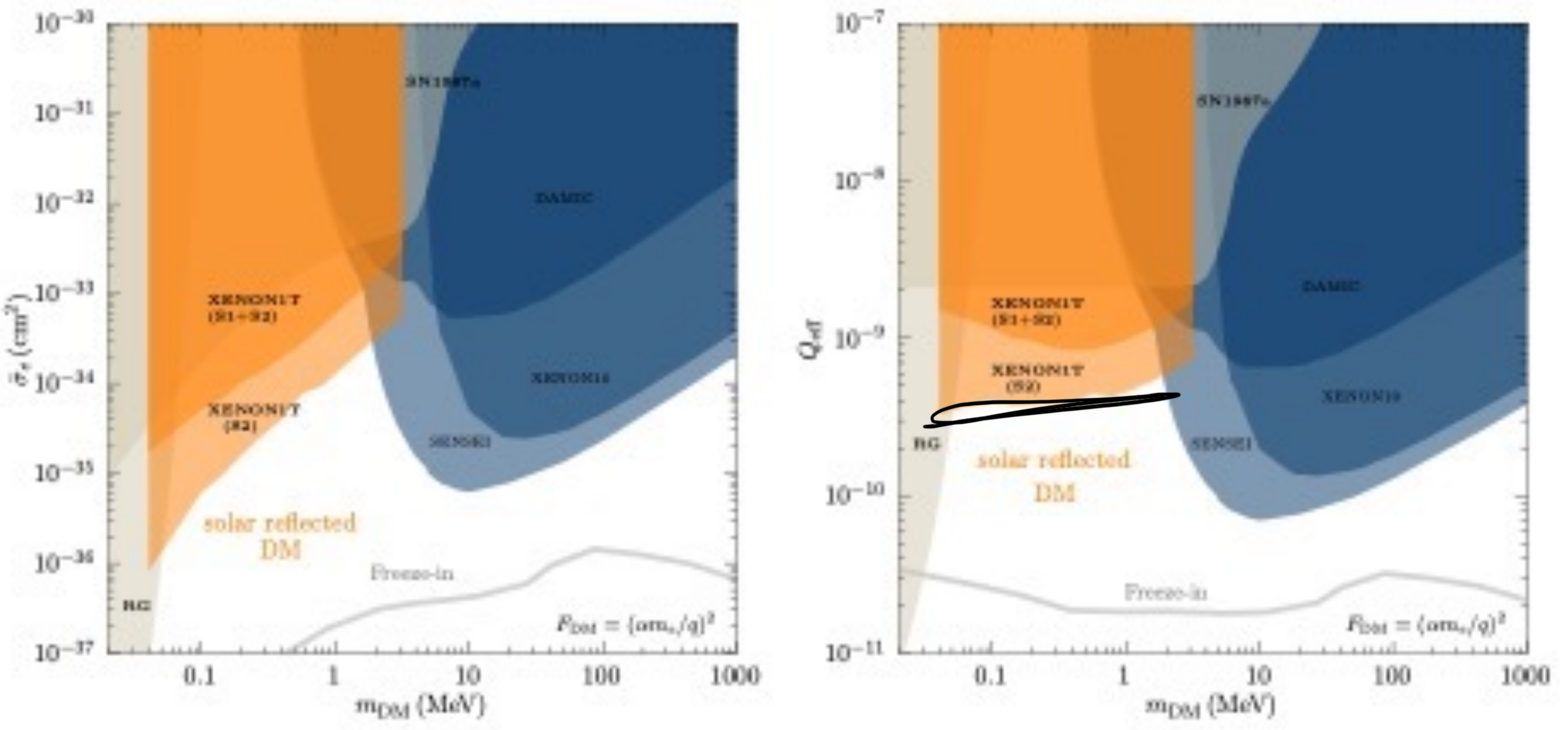
only electrons

electrons and protons

An, Nie, MP, Pradler, Ritz, 2017, 2022

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux. Sensitivity to cross section on electrons down to 10^{-38} cm^2.
- Significant fraction of "freeze-out" line for DM abundance is excluded in a simple WIMP model.

Massless mediators, limits on σ_e



cross section normalized on $q=m_e\alpha$

Effective charge

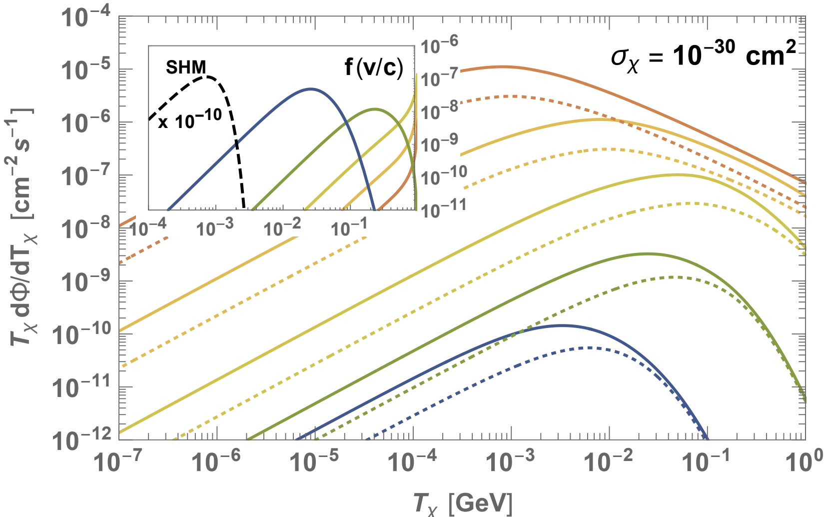
An, Nie, MP, Pradler, Ritz, 2021

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux.
- Second case, massless mediator = milli-charged dark matter, Xe1T is sensitive to $Q_{eff} \sim$ few 10^{-10} e.
- The results are corrected/extended by the Stony Brook group (H. Xu poster)

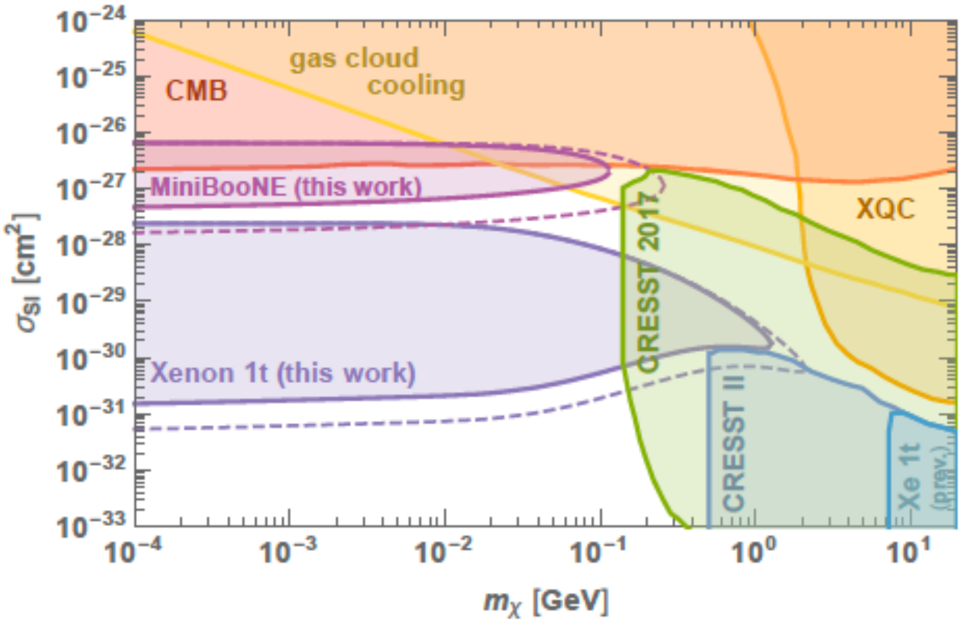
Light DM accelerated by cosmic rays

- 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

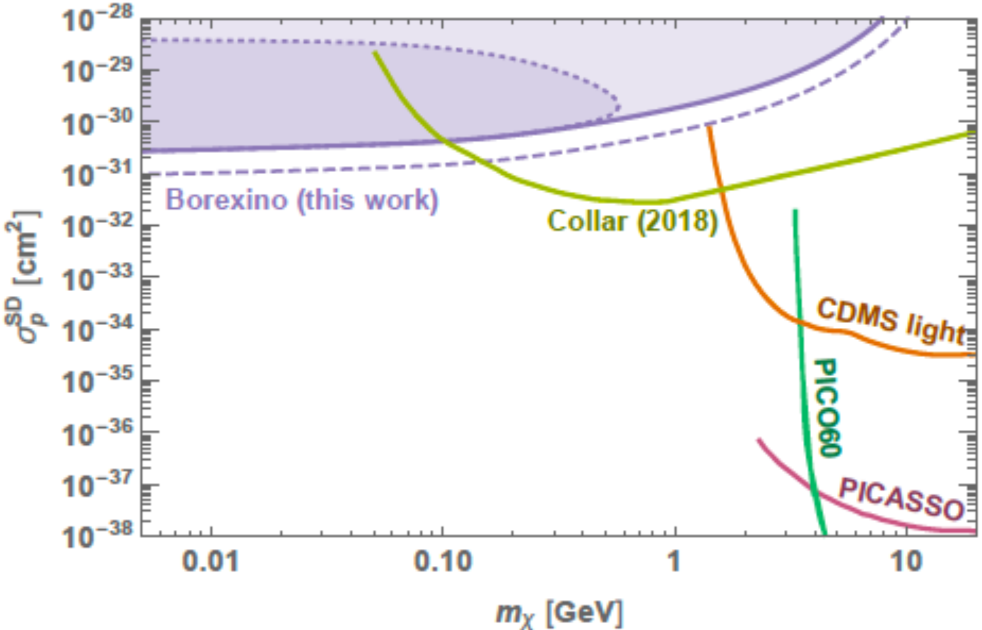
Main idea: Collisions of DM with cosmic rays generate sub-dominant DM flux with ~ 100 MeV momentum – perfect for direct detection type recoil.



Resulting limits on WIMP-nucleon scattering

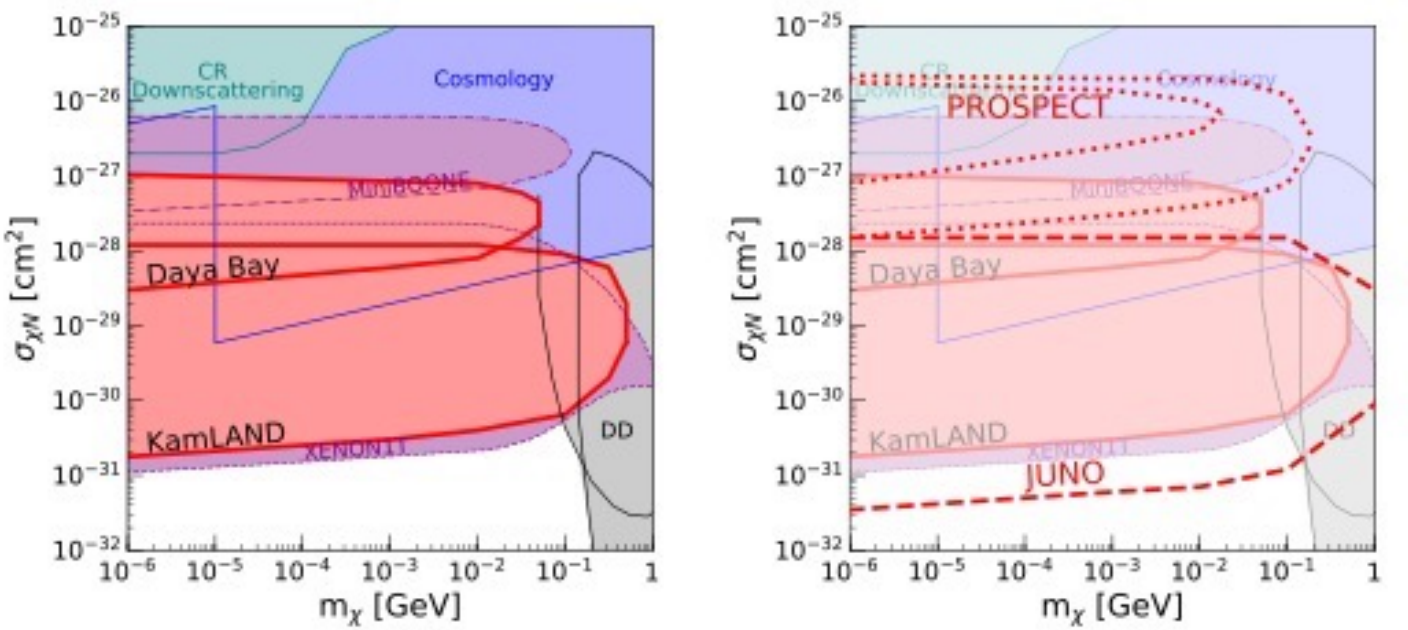


- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of $\sigma = 10^{-29}$-10^{-31}cm^2 !



- 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

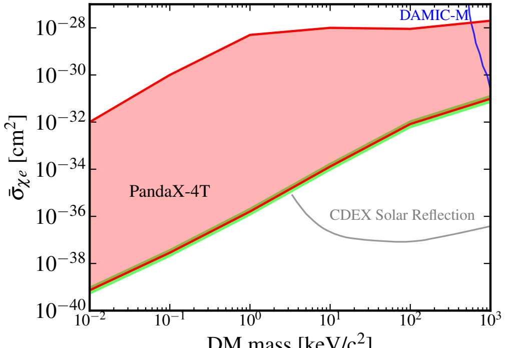


- More neutrino experiments can be used to "fill the gaps", Beacom and Cappiello, 1906.11283
- DM collaborations began to investigate solar & CR reflection idea.

2403.08361

Search for cosmic-ray boosted sub-MeV dark matter-electron scatterings in PandaX-4T

$$\mathcal{L}_{\rm int} = G\bar{\chi}\gamma^\mu\chi\bar{e}\gamma_\mu e,$$



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

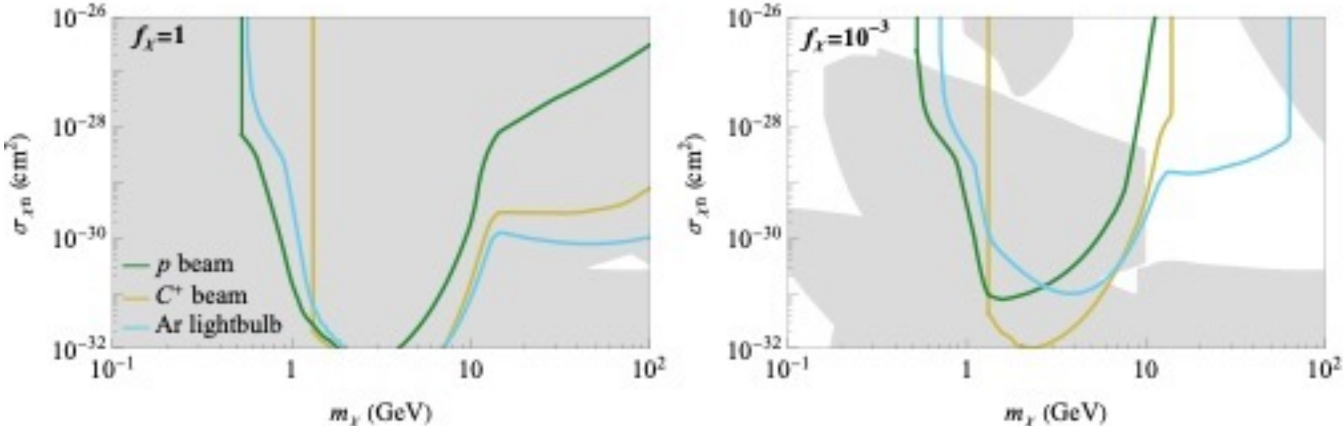
   (Typically cannot be entire DM, but is limited to fraction $f<10^{-3}$)

   Below the ionization threshold!

~~Nightmare~~ embarrassing scenario

Rare species of strongly interacting DM

- 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 (talk to Juan) 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.

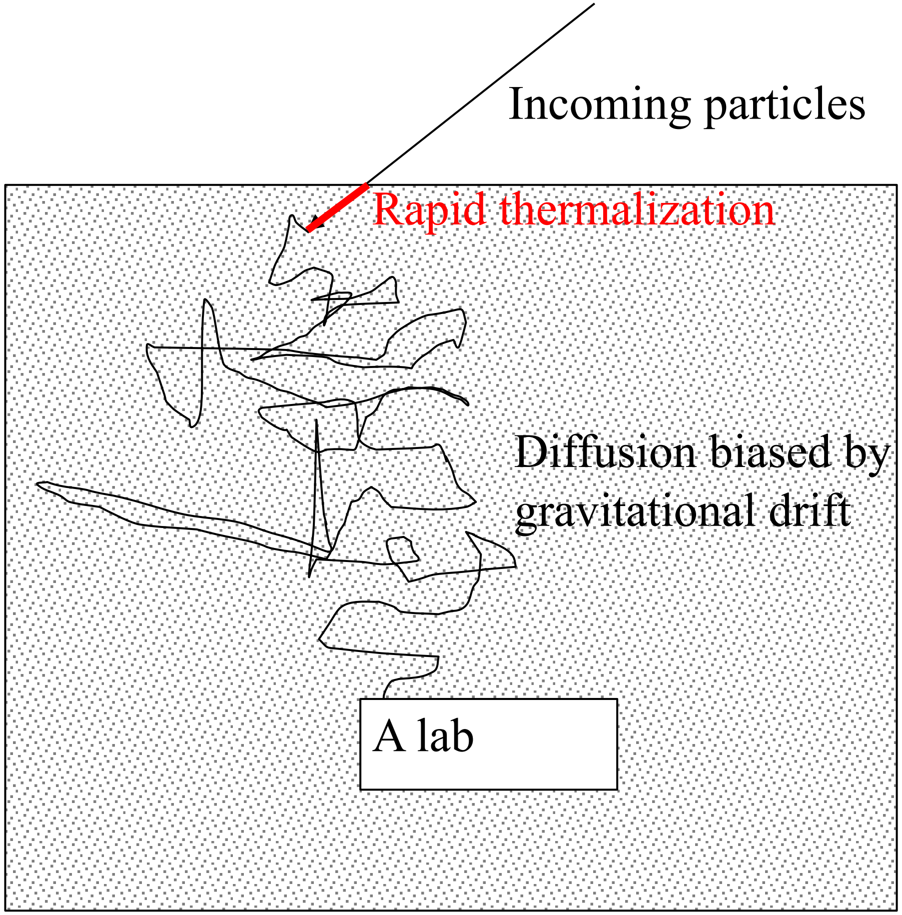


Dark matter traffic jam

- 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

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

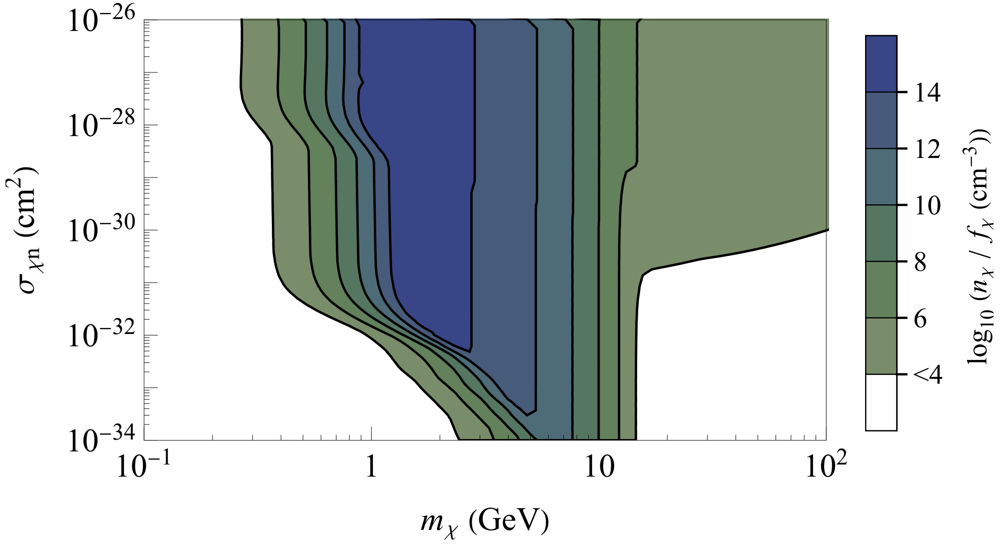
- Change in velocity from incoming ~ 10^7 cm/s to typical sinking velocity of 10 cm/s results in $n_{lab} \sim 10^6\, n_{halo}$. **Not visible to DD**
- At masses < 10 GeV upward flux is important and density goes up.



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

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

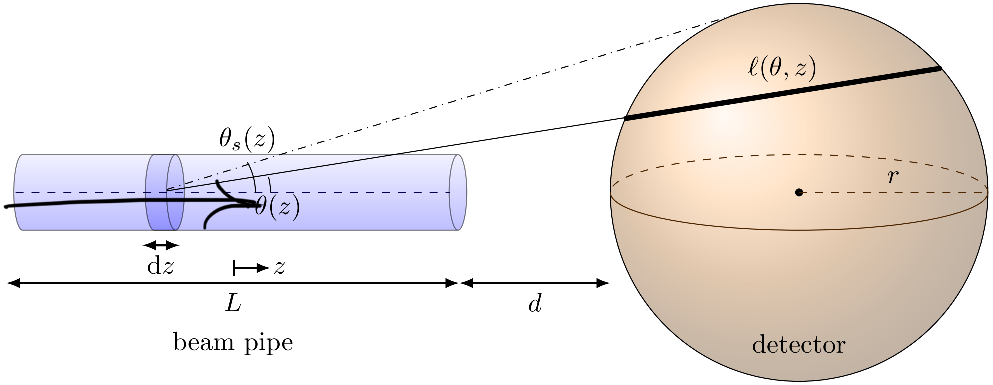
- Lowest mass – evaporation, Highest mass – traffic jam, intermediate mass – trapping with almost uniform distribution inside Earth's volume.



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

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.
- $\chi+p \rightarrow \chi_E+p$



$Z+\chi \rightarrow Z_E+ \chi$

- 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.

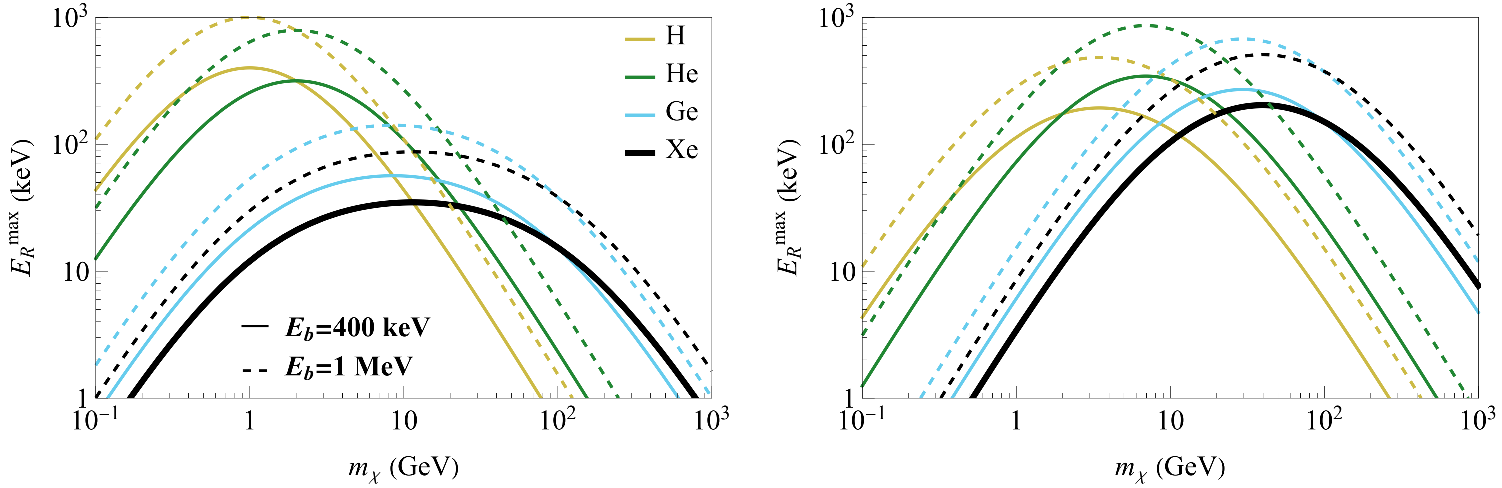
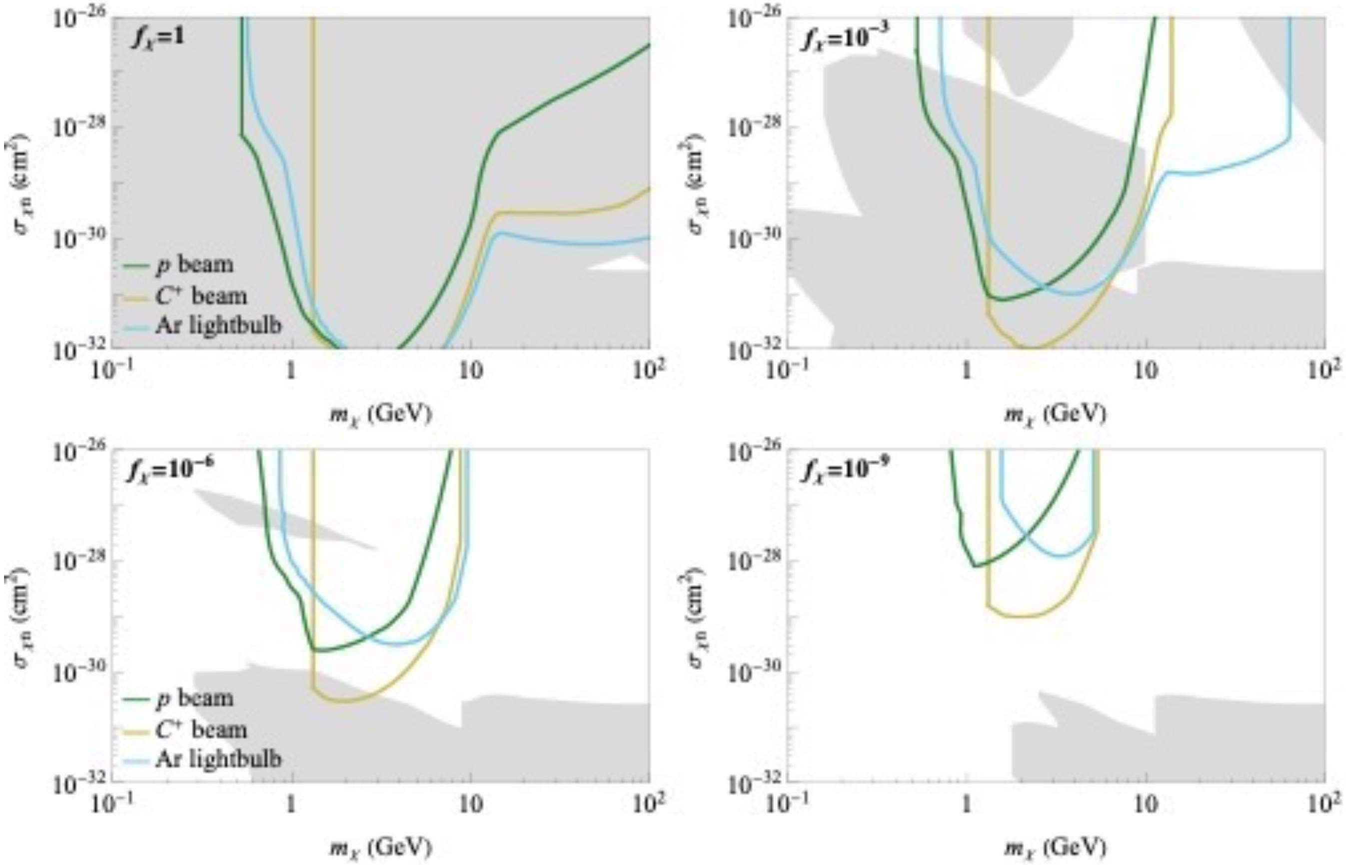


FIG. 3. Maximum nuclear target recoil energies $E_R^{\max}$ for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies $E_b = 0.4$ MeV (solid) and $E_b = 1.0$ MeV (dashed) for a selection of target nuclei.

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)

Conclusions (part III)

- Dark sectors/feebly interacting particles – that give a wider range of DM masses and possibilities – are being actively explored at the moment.
- Beam dump opportunities (from a few MeV to 400 GeV range, and LHC high intensity run, 13.6 TeV) provide ample opportunities to explore the parameter space of most reasonable (benchmark) dark sector models.
- The diversity of dark sector 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.
- 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".