Direct detection of light dark matter

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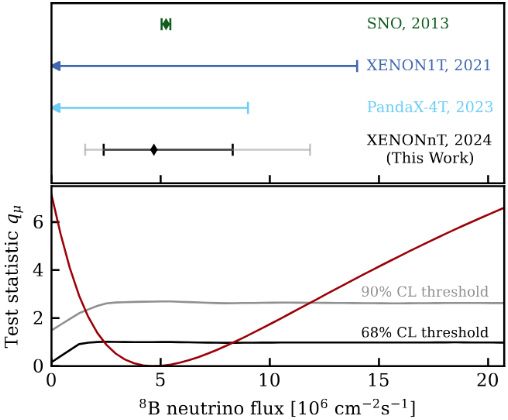
Talk based on works together with Ian M. Shoemaker, Patrick Huber, Pablo Figueroa, Fredy Ochoa, Kohta Murase, James M. Cline and Alejandro Ibarra

Direct detection has reached the neutrino "floor" or "fog"

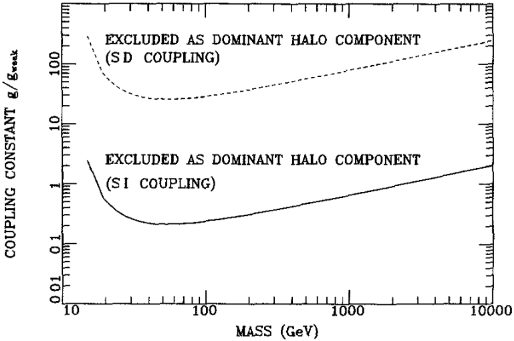
XENONnT, 24'



...via Coherent Elastic Neutrino Nucleus (CEνNS) from ^{8}B solar neutrinos

2.6-2.7 σ at PANDAX-4T and XENONnT

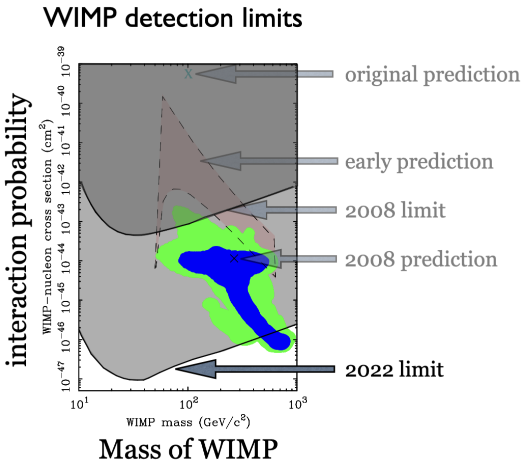
Ahlen, Avignone, Brodzinski, Drukier, Gelmini, Spergel, 1987'



- The first dark matter direct detection experiment was able to constrain a cross section of $\sim 10^{-37}\text{cm}^2$
- Remarkably, in $\sim$ 35 years, experiments have improved their sensitivity by **10 orders of magnitude!**

But still no WIMP

DM tools



Large set of proposed models already excluded: Z and Higgs mediated dark matter, Early ("simple") supersymmetric models...

Schade schokolade!

Light dark matter

- In a holistic view of fine-tuning (going beyond the hierarchy problem) light dark matter is well-motivated → **It only requires a few parameters to reproduce the observed abundance of the Universe**.

- Historically neglected due to **Hut-Lee-Weinberg bound**.

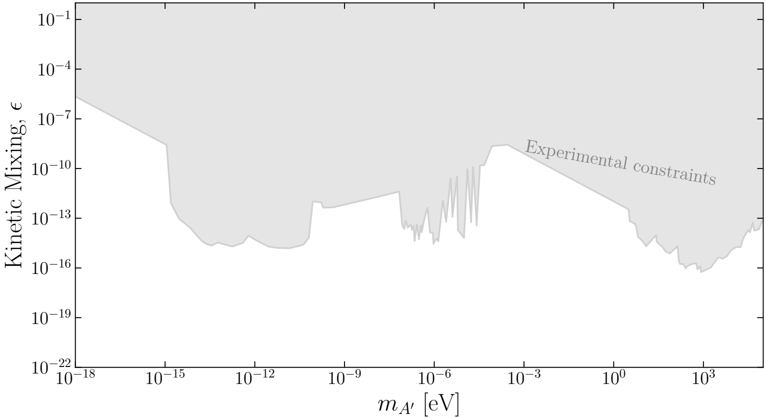
- However, light scalar particles can account for thermal dark matter via exchange of **new fermions F and light bosons A'** (**Boehm, Fayet, 03'**)

$$\sigma v \propto 1/m_F^4 \rightarrow \text{independent on dark matter mass!}$$

$$\sigma v \propto m_{\mathrm{DM}}^2/m_{A'}^4 \rightarrow \text{works if } m_{\mathrm{DM}} \sim m_{A'}$$

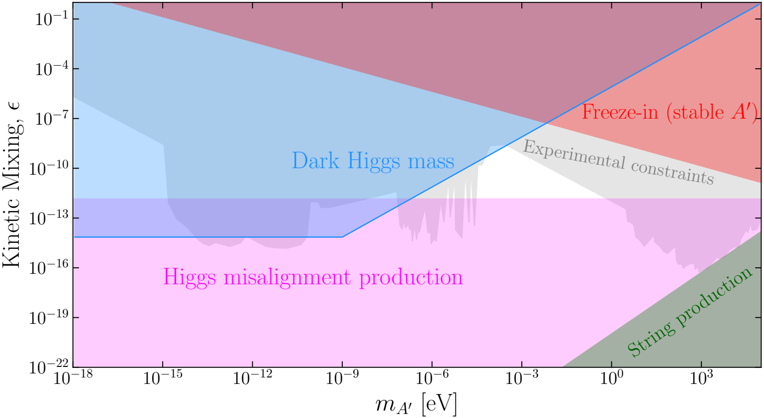
- **Asymmetric dark matter**: E.g $3 \rightarrow 2$ processes in the dark sector yield MeV thermal dark matter (**Hochberg, Kuflik, Volansky, Wacker, 14'**)

- Dark matter may also be produced non-thermally, **freezing-in** instead of freezing-out (**Hall, Jedamzik, March-Russell, West, 09'**)



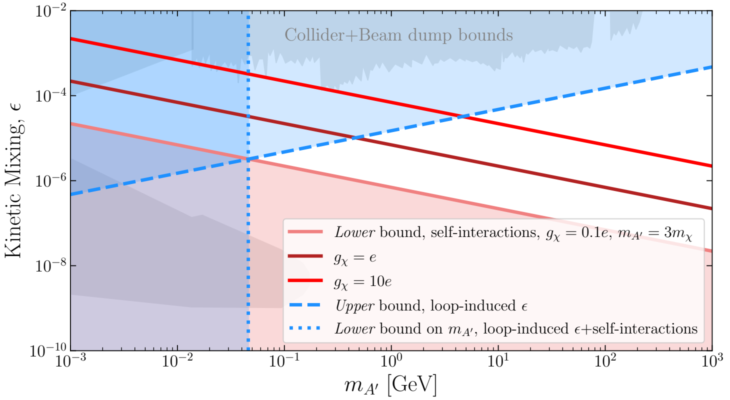
- Ultralight or massless vector mediators (freeze-in) or heavy mediators with masses above a few MeV (freeze-out) still largely allowed

Cline, Herrera, 24'



- Not true if your dark photon is higgsed
- $m_{A'} = gv, m_h = 2\lambda v^2, \lambda \leq 8\pi/3,$
- $\epsilon \sim ge/16\pi^2 \rightarrow \frac{m_h}{m_{A'}} \lesssim \frac{0.01}{\epsilon}$

Cline, Herrera, 24'



- The combination of the bound on self-interactions and thermal abundance restricts the scenario $m_{A'} > m_{\text{DM}}$ significantly.
- But there are alternatives, *E.g* Secluded DM ($m_{A'} < m_{\text{DM}}$) , **Pospelov, Ritz, Voloshin, 07'**
- One can also relax the loop-level relation $\epsilon \sim eg/16\pi^2$

Three ways to directly detect light dark matter

- Dark matter-electron scattering
- The Migdal effect
- High-energy flux of dark matter reaching the Earth

Three ways to directly detect light dark matter

- **Dark matter-electron scattering**
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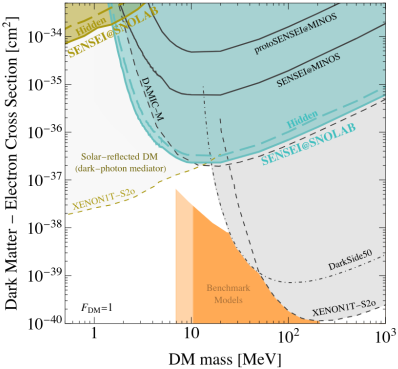
Dark matter-electron scattering

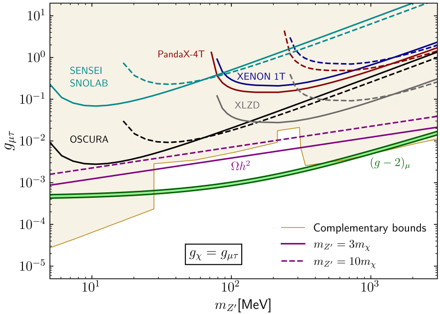
- Discussed in the context of direct detection of GeV scale WIMPS long ago, **Bernabei 07 Kopp, Niro, Schwetz, Zupan, 10'**
- This channel allows to extend sensitivity to light dark matter, $q = \sqrt{2 m_e E_{er}} \simeq \mathrm{keV}$, **Essig, Mardon, Volansky, 10'**
- Current experiments are orders of magnitude less stringent to electron recoils than to nuclear recoils

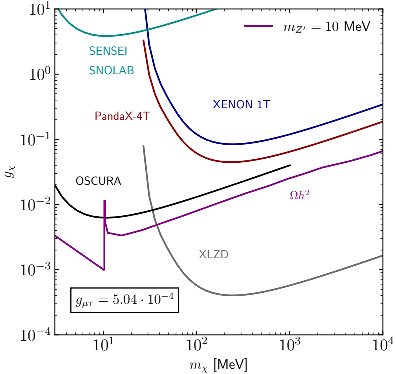
SENSEI, 23'



Dark matter-electron scattering in a concrete model

Figueroa, Herrera, Ochoa, 24'





- Vast majority of works focus on $U(1)$ extension of the SM, worth looking into concrete gauged symmetries to allow for comparison with complementary constraints on new mediators $\rightarrow$ e.g $L_\mu - L_\tau$

- Next generation experiments (**XLZD**, **OSCURA**) will be able to probe such models

Three ways to directly detect light dark matter

- Dark matter-electron scattering
- **The Migdal effect**
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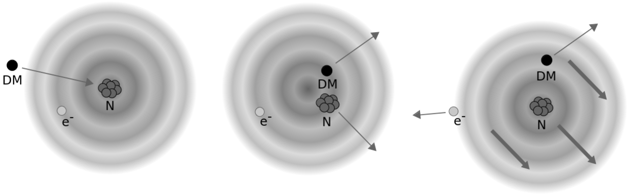
Migdal, 1939

In nuclear collisions involving large energy transfer there must occur ionization of the recoil atoms. If the velocity acquired by the nucleus is not too large, then it can carry its electrons off with it, and ionization takes place only in the outer, weakly bound shells. For large velocities, on the other hand, the nucleus recoils right out of its electronic shells instead of carrying them with it.

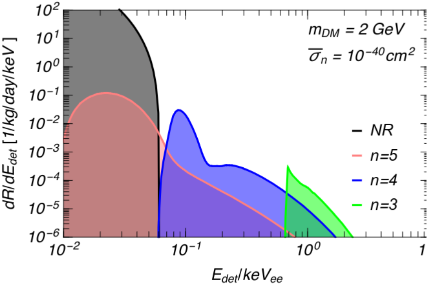
Dolan, Kahlhoefer, McCabe, 17'



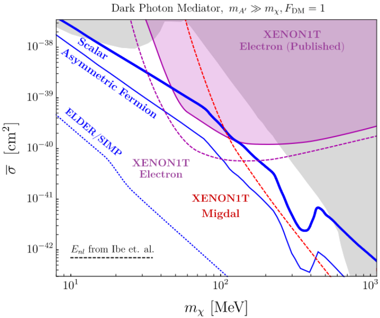
Light dark matter may induce nuclear recoils below the experimental threshold, but leaving a detectable ionization signal via the Migdal effect

The Migdal effect in dark matter direct detection

Ibe, Nakano, Shoji, Suzuki, 17'



Baxter, Kahn, Krnajic, 17'

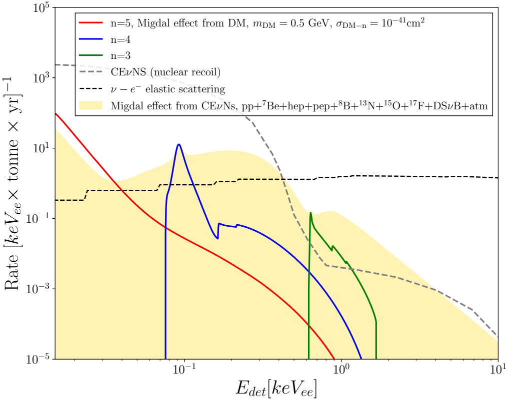


- The **electromagnetic** signal occurs at larger energy than the **nuclear** recoil signal

- Current experiments probe some **thermal** light dark matter models

Where is the neutrino floor in the parameter space of the Migdal (or electron recoil) dark matter signal?

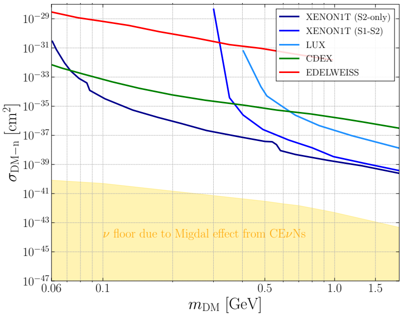
Herrera, 23'

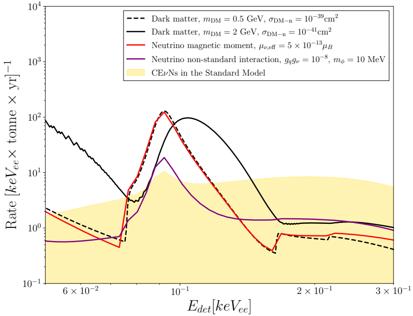


$$\frac{d\sigma_{\nu N-\nu N^* e^-}}{dE_R} = \frac{G_F^2 m_A}{4\pi} Q_V^2 \left(1 - \frac{m_A E_R}{2E_\nu^2}\right) \times \left|Z_{\rm ion}\ (E_{\rm er}\ )\right|^2$$

- The **Migdal** signal from neutrinos can overcome the **nuclear** recoil signal and the **electron** scattering signal at certain energies
- Migdal signal from dark matter is masked by neutrinos for $\sigma_{\rm DM-n} \lesssim 10^{-41}{\rm cm}^2$

Herrera, 23'





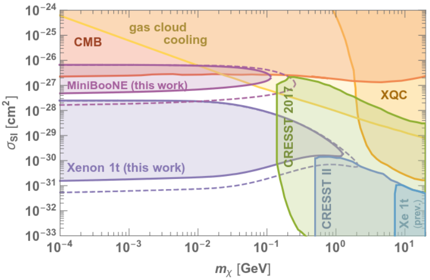
- The **neutrino floor** is ~ 4 orders of magnitude away from current sensitivity to the Migdal effect from light dark matter
- Dark matter induces a distinct peak in the ionization spectrum of Xenon, unlike solar neutrinos via weak interactions
- However, BSM interactions of neutrinos may induce a peak that resembles the dark matter signal

Three ways to directly detect light dark matter

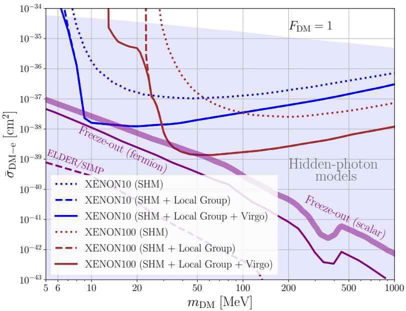
- Dark matter-electron scattering
- The Migdal effect
- **High-energy flux of dark matter reaching the Earth**

Direct detection of high-speed light dark matter

Bringmann, Pospelov, 19'



Herrera, Ibarra, 21'



- A fraction of the dark matter flux on Earth may have larger energies than the gravitationally bound particles from the halo

  $\rightarrow$ Extended sensitivity to low-mass dark matter

- E.g: **Cosmic-ray boosted dark matter**, **non-galactic dark matter**, Boosted dark matter from annihilations/decays...

The sensitivity of direct detection experiments to light dark matter is still orders of magnitude weaker than for GeV scale dark matter

Alternatives to probe light dark matter scatterings indirectly?

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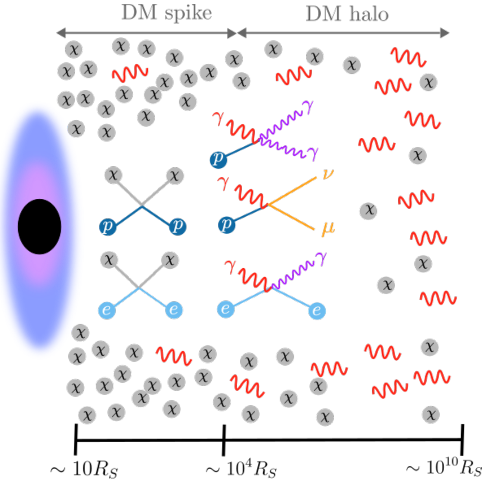
Alternatives to probe light dark matter scatterings indirectly?

Look at observable regions of the Universe with high density of both dark matter particles and Standard Model particles

$\rightarrow$ **The vicinity of supermassive black holes!**

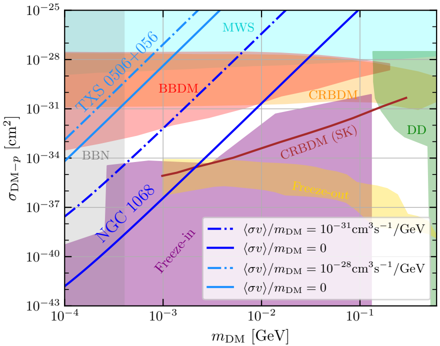


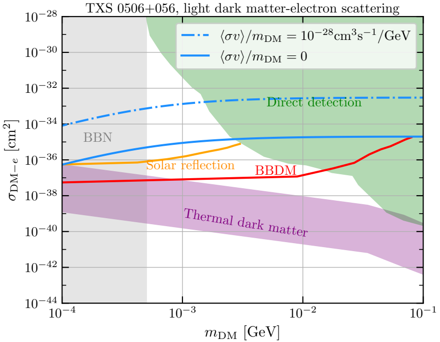
- High-energy protons and electrons can cool efficiently via interactions with ambient photons and gas in the AGN

- May they also cool via scatterings with the ambient dark matter particles ?

Cosmic ray cooling in the dark matter spike

Herrera, Murase, 23'





- Strongest constraint to date on light dark matter coupling to protons for $m_{\rm DM} \lesssim 10^{-3} - 10^{-2}$ GeV

- Limits are more robust than those from boosted dark matter, since they don't rely on assumptions on the cosmic ray spectrum

- **Probes the favored region by freeze-out and freeze-in at some dark matter masses**

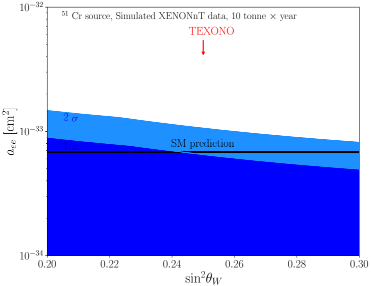
Neutrino physics with direct detection experiments

- The anapole moment of neutrinos in the SM is detectable with near-future exposures if we place a ^{51}Cr source near a liquid xenon tank → **Best chance to detect an electromagnetic interaction of the neutrino**

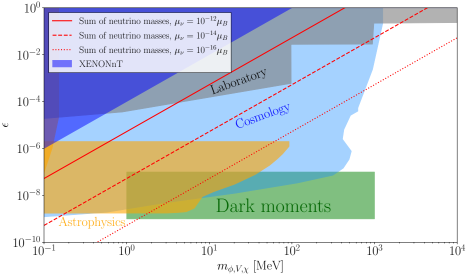
- Neutrino electromagnetic properties are windows to new physics, *E.g* **light neutrinophilic U(1) dark matter sectors**

- Other possibilities: Migdal effect, light mediators, sterile neutrinos...

Herrera, Huber, 24'



Herrera, Shoemaker, *In progress*



Conclusions

- Light dark matter is a well motivated candidate yet poorly tested by direct detection experiments, but one must be careful since there are strong theoretical/experimental constraints on new mediators to the dark sector.
- Dark matter-electron scattering, the Migdal effect and boosted dark matter searches are a promising avenue to test light dark matter, yet indirect probes such as cosmic ray cooling in Active Galactic Nuclei can provide stronger sensitivity at the moment.
- Direct detection experiments are excellent probes of neutrino scattering, and may allow to measure the neutrino anapole moment in the near future.