# Probing new physics from neutrinos at dark matter direct detection experiments

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VIRGINIA TECH™

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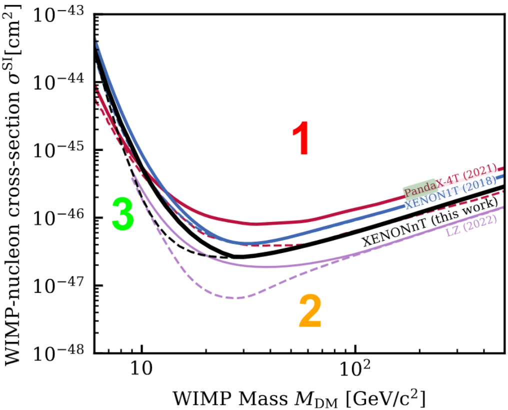
# Direct detection of dark matter

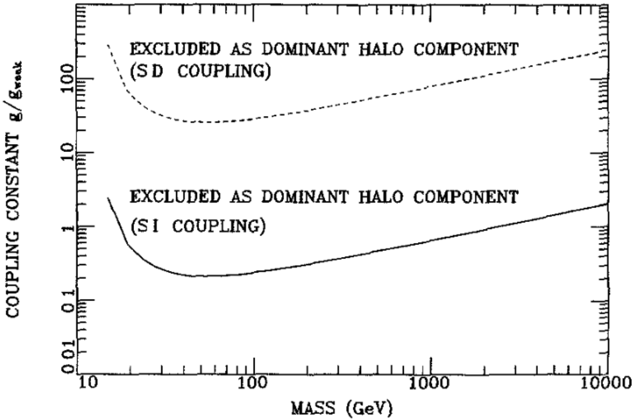



× 1: Ruled out by several experiments

× 2: Dark matter signal masked by solar neutrinos, but reachable in the near future

✓ 3: Unexplored region, hard to reach in the near future

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

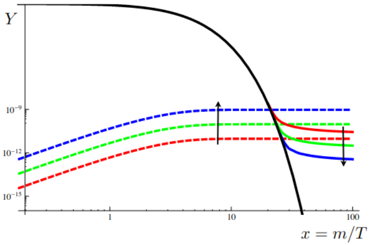



- The first dark matter direct detection experiment was able to constrain a cross section of $\sim 10^{-37}\text{cm}^2$
- Remarkably, in $\sim$ 35 years, experiments have improved their sensitivity by **10 orders of magnitude!**

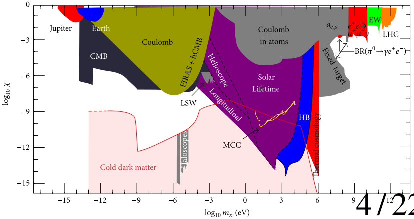
# Light dark matter

- Phenomenologically viable, although neglected in "traditional" WIMP models → **Lee-Weinberg-Hut bound**.
- However, light scalar particles can account for thermal dark matter via exchange of **new fermions and light bosons** (**Boehm, Fayet, 03'**)
- **Asymmetric dark matter**: E.g $3 \to 2$ 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 '19**

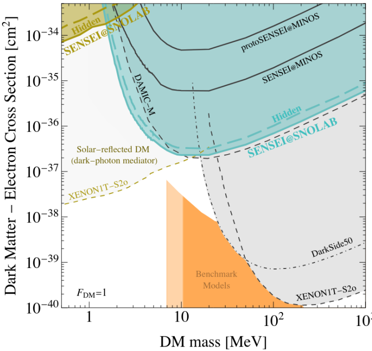



**Jaeckel '13**

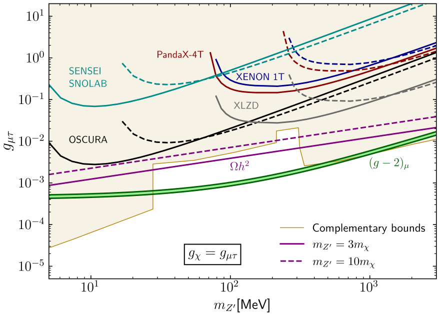


# Direct detection of light dark matter through electron recoils

**SENSEI, 23'**



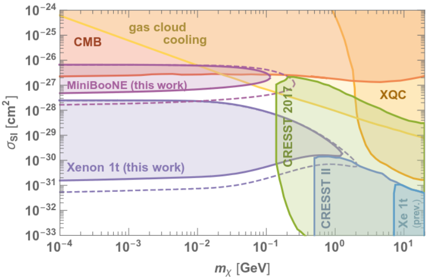

**Figueroa, Herrera, Ochoa, 24'**



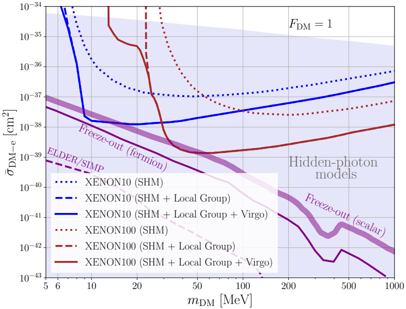

- Light dark matter may scatter off electrons in the atom directly
- Current experiments are orders of magnitude less stringent to electron recoils than to nuclear recoils
- Next generation experiments (**XLZD**, **OSCURA**) will be able to probe motivated models, but we are still far from that

# Direct detection of high-speed light dark matter

**Bringmann, Pospelov, 19'**




**Herrera, Ibarra, 21'**



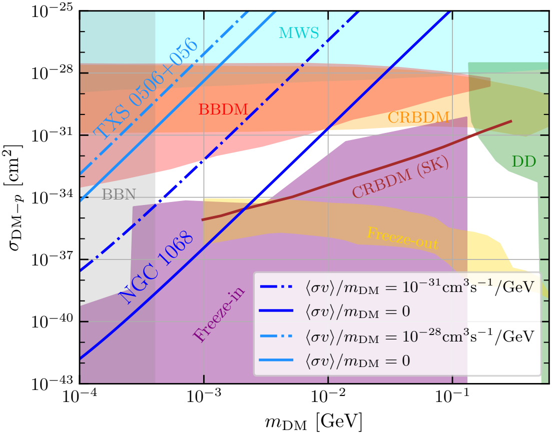

- A fraction of the dark matter flux on Earth may have larger velocities than the escape velocity of the Milky Way

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

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

# Indirect bounds on light dark matter

**Herrera, Murase, 23'**




- Cosmological and astrophysical observables constrain dark matter scattering with baryons
- Strongest bounds arise from **cosmic-ray cooling** in Active Galactic Nuclei, **cosmic-ray boosted dark matter** at Super-Kamiokande, and BBN

All these approaches constrain light dark matter with relatively large cross section, well above the current sensitivity of direct detection experiments at the GeV scale

They are subject to astrophysical/cosmological uncertainties, or probe the coupling to electrons only

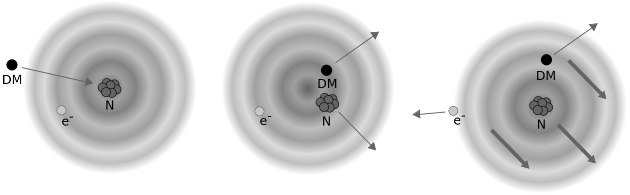
Alternative to constraint light dark matter directly?

**Make use of the Migdal effect**

**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.

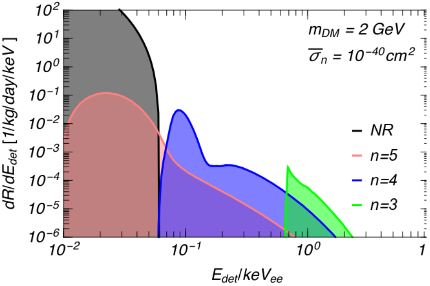
**Dolan, Kahlhoefer, McCabe, 17'**



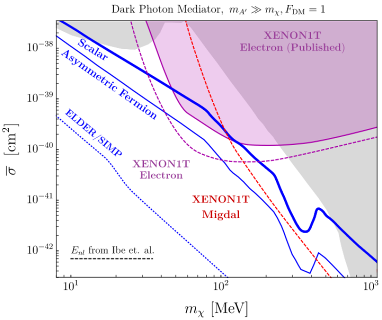

**Light dark matter may induce nuclear recoils below the experimental threshold, but leaving a detectable ionization signal via the Migdal effect**

# 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 via the Migdal effect

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

# Solar neutrinos at direct detection

Low-energy solar neutrinos can interact at Earth-based detectors via three distinctive processes:

- ✓ Neutrino-electron scattering

  **Borexino, 07'**

- ✓ Coherent elastic neutrino-nucleus scattering

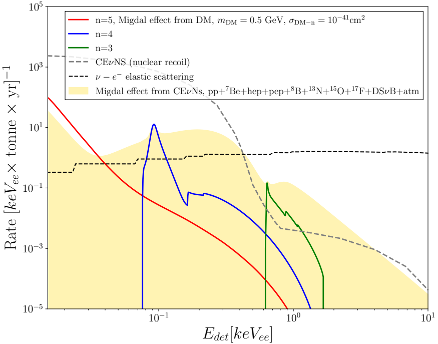
  **PANDAX-4T, XENONnT 24'**

- ? Migdal effect

  **Ignored in the literature**

Which process dominates depending on the deposited energy and detection channel (e.g scintillation vs ionization) ?

**Herrera, 23'**



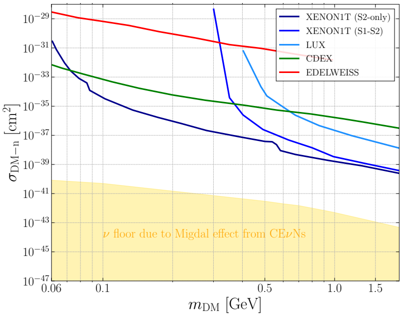

$$\frac{d\sigma_{\nu N-\nu N^* e^-}}{dE_R} = \frac{G_F^2 m_A}{4\pi} Q_V^2 \left(1 - \frac{m_A E_R}{2E_\nu^2}\right) \times \left|Z_{\rm ion} \ (E_{\rm er} \ )\right|^2$$

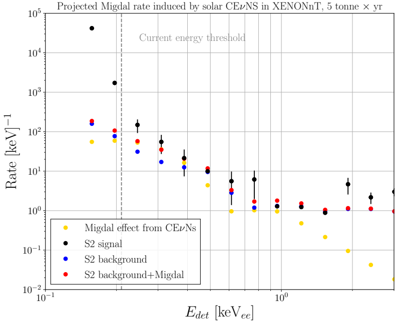
- The Migdal signal from neutrinos can overcome the **nuclear** recoil signal and the **electron** scattering signal at certain energies:

  **S2 (ionization)** → Migdal can dominate for energies below ∼ 0.4 keV

  **S1+S2** → Migdal never dominates, but can induce O(1) corrections in the range ∼ 0.2 – 1 keV

**Herrera, 23'**




- The **neutrino floor** is $\sim$ 4 orders of magnitude away from current sensitivity to the Migdal effect from light dark matter
- The Migdal ionization signal might be **detectable** with 5 tonne $\times$ yr exposures at liquid xenon experiments and S2-like threshold and background
- However, this relies on being able to separate the nuclear recoil and electron ionization signal at energies of 0.1 – 1 keV

# Neutrino electromagnetic interactions

**Lee, Shrock, 77', Petcov, 77'**
Effective interaction vertex between a photon and a neutrino:

$$\mathcal{M}_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\left[f_Q(q^2) + f_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[f_M(q^2) + i f_E(q^2)\gamma_5\right]$$

$f_Q^{fi}(0) = e_{fi}$ charge

$f_M^{fi}(0) = \mu_{fi}$ magnetic moment

$f_E^{fi}(0) = \epsilon_{fi}$ electric moment

$f_A^{fi}(0) = a_{fi}$ anapole moment

Majorana: $e_{ii} = \mu_{ii} = \epsilon_{ii} = 0,\ e_{ij} = 0$

Dirac: $\epsilon_{ii} = 0$

For ultrarelativistic neutrinos ($\gamma_5 \to -1$), the charge and anapole form factors are equivalent:

$$\langle r_\nu^2 \rangle = 6 \left. \frac{d f_Q(q^2)}{dq^2} \right|_{q^2=0} = -6a$$

Cross section:

$$\frac{d\sigma_{\text{anapole}}}{dT} \sim \frac{d\sigma_w}{dT} \text{ after redefinition of } \sin^2\theta_W \to \sin^2\theta_W \left(1 - \frac{1}{2} m_W^2 a_{\nu,\,\text{eff}}\right)$$

$$\frac{d\sigma_{\text{magnetic}}}{dT} \sim \frac{\pi\alpha^2 \mu_{\nu,\text{eff}}^2 Z^2}{m_e^2} \left(\frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2}\right) F_p^2(E_R)$$

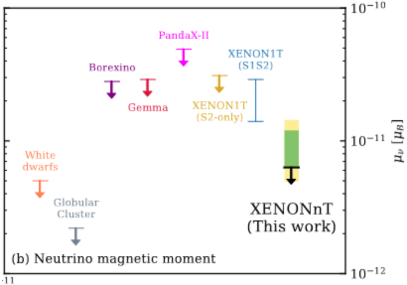
# Expectations and constraints on electromagnetic multipoles

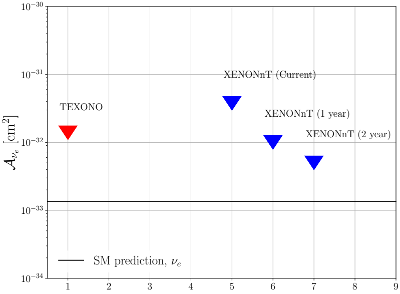
The values of the anapole and magnetic moment in the SM are small

$$a_{ij}^{\rm SM} \simeq \frac{G_F}{12\sqrt{2}\pi^2} \sum_{\alpha=e,\mu,\tau} \left(3 - 2\log\frac{m_\alpha^2}{m_W^2}\right) U_{\alpha j} U_{\alpha i}^* \sim 10^{-34}\ {\rm cm}^2$$

$$\mu_{ij}^{\rm SM} \simeq \frac{3eG_{\rm F}}{16\sqrt{2}\pi^2} (m_i + m_j) \times \left(\delta_{ij} - \frac{1}{2} \sum_{\alpha=e,\mu,\tau} U_{\alpha i}^* U_{\alpha j} \frac{m_\alpha^2}{m_W^2}\right) \lesssim 10^{-18} \mu_B$$

**XENONnT, 22’**

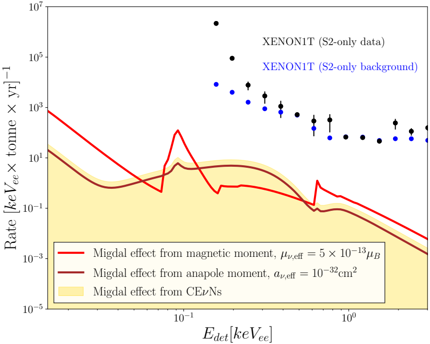



Current constraints lie ~ 7 orders of magnitude away from the magnetic moment prediction, but only ~ 1 order of magnitude away from the anapole moment

# Migdal effect from neutrino electromagnetic interactions

**Herrera, 23'**




- The **anapole moment** scattering rate has the same shape as the weak rate
- The **magnetic moment** interaction has an ionization rate with distinct shape, due to the enhancement of the cross section at small neutrino energy

# Neutrino non-standard interactions: new light mediators

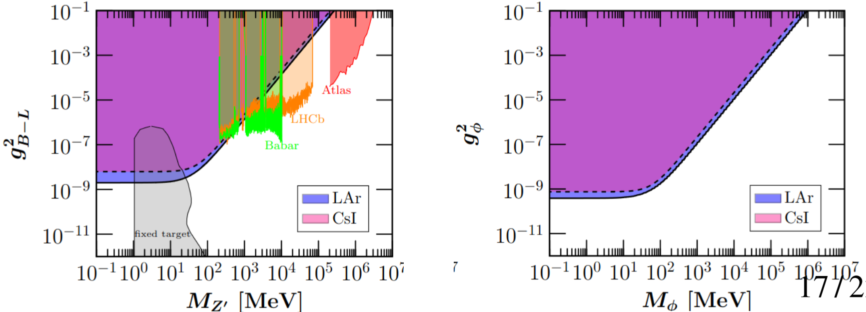
- Scalar mediator:

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2 m_A^2}{4\pi} \frac{g_{\nu\phi} Q_\phi^2 E_R}{E_\nu^2 \left(2m_A E_R + m_\phi^2\right)^2}$$

- Vector mediator → redefinition of weak vector charge:

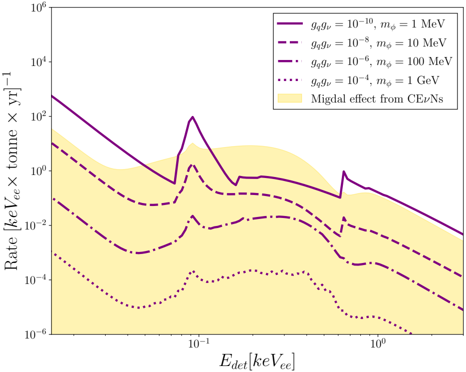
$$Q_V \rightarrow Q_{Z'} = Q_V + \frac{g_{\nu Z'}}{\sqrt{2}G_F} \frac{(2g_{uZ'}+g_{dZ'})ZF_p(E_R)+(g_{uZ'}+2g_{dZ'})NF_n(E_R)}{2m_A E_R + m_{Z'}^2}$$

**Miranda et al, 20'**



# Dependence of the ionization rate with mediator mass

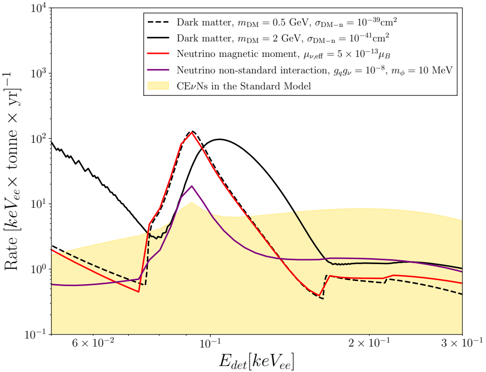
**Herrera, 23'**




- The **ratio of momentum transfer and mediator mass** determines the shape of the spectrum $q^2/m_\phi^2$
- For light mediators, the dominant rate arises from the $pp$ neutrino flux, while for heavy mediators the $8B$ contribution dominates, which smoothes out the peaks in the spectrum

# A peak in the spectrum at ~ 0.1 keV

**Herrera, 23'**

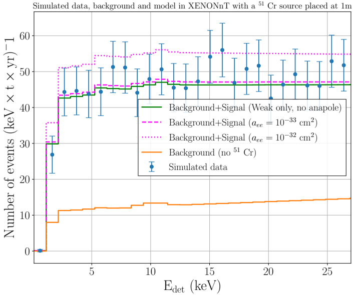


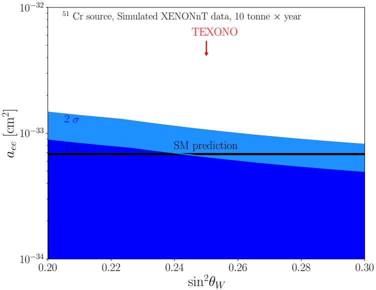

- New physics can induce a **distinct peak** in the ionization spectrum around 0.1 keV, arising from the ionization of $n = 4$ electrons by $pp$ neutrinos, which is absent in the weak interaction spectrum

- It can be hard to discriminate among different models in most cases

# Detecting the neutrino anapole moment with $^{51}$Cr

**Herrera, Huber, 24'**

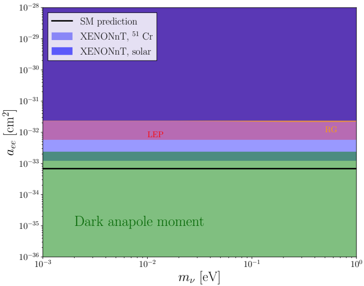


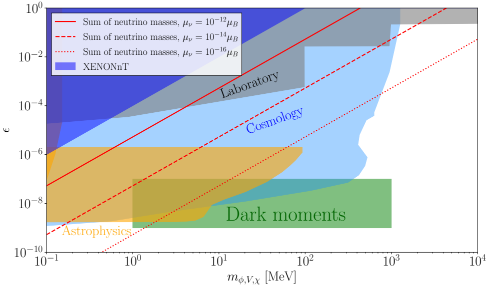




- The neutrino flux from a $^{51}$**Cr** source placed at 1m from the detector is $\sim$ 20 times larger than the pp neutrino flux
- In absence of systematics, signal events grow linearly with exposure as $\mathcal{E}$, while statistical uncertainty grows as $\sqrt{\mathcal{E}}$
- 1-2$\sigma$ level sensitivity with **exposures of $\sim$ 10 tonne $\times$ years**, robust against uncertainties on weak mixing angle

# Electromagnetic moments as a window to light new physics

**Babu, Jana, Lindner, 20'**
**Herrera, Shoemaker, *In progress*, Herrera, Huber, 24'**




- **Light millicharged sectors** can enhance or suppress the neutrino electromagnetic moments

$$\mathcal{L}_\phi \supset \bar{\nu}_\alpha \phi^* \chi_\alpha$$
$$\mathcal{L}_\mathrm{V} \supset \bar{\nu}_\alpha \gamma^\mu V_\mu \chi_\alpha + \bar{\nu}_\alpha G \chi_\alpha$$

- A measurement of the anapole moment, or a stronger constraint on the magnetic moment of the neutrino thus allows to constrain millicharged dark sectors that couple to neutrinos.

# Conclusions

- There is a neutrino floor for light dark matter searches induced by the Migdal effect from solar neutrinos
- The Migdal ionization signal from neutrinos can dominate over the nuclear recoil and electron scattering signal at certain energies
- We propose to search for peaks in the ionization spectrum of liquid xenon experiments around $\sim 0.1$ keV, a clean signature that can provide hints of new physics from both dark matter and neutrinos
- We propose to place a radioactive source near a liquid xenon detector may allow to detect the neutrino anapole moment for the first time
  $\rightarrow$ 10 tonne $\times$ years required to achieve 1-2$\sigma$ sensitivity

# Thanks for your attention

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