

Sub-GeV Dark Matter Under Pressure from Direct Detection

Based on: arXiv 2507.15956

Pablo Figueroa

In collaboration with: Andrew Cheek (SJTU), Gonzalo Herrera (MIT), and Ian M. Shoemaker (VT)



Or... Light Dark Matter Interpretation of the PandaX-4T CEvNS Results

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There has been a great (maybe too much 😊) interest in this during TeVPA 2025

Experimental

- XENON Collaboration
(Latest WIMPs and CEvNS result)
- PandaX Collaboration
(PandaX-4T Progress)

Theory

- Pablo Blanco-Mas
(CEvNS Light mediators)
- Anirban Majumdar
(CEvNS Generalized mediators)

Buut, let's do something a bit different...

Overview

1. PandaX-4T CEvNS (2024)
2. DM-e scattering at PandaX-4T
3. Implications for (some) DM Models
4. Conclusion and Outlook

PandaX-4T CEvNS (2024)

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PHYSICAL REVIEW LETTERS **133**, 191001 (2024)

Editors' Suggestion

Featured in Physics

First Indication of Solar ^8B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

“... A total exposure of 1.20 and **1.04 tonne · year** are collected for the paired and **US2**, respectively. After unblinding, 3 and **332 events are observed** with an expectation of 2.8 ± 0.5 and **251 ± 32 background events**, for the paired and **US2 data**, respectively ...”

S2-Only

PandaX-4T **S2 channel** event rate expectations and observations in their ROI.

PandaX-4T S2 Only	Run0	Run1
Cathode	100 ± 24	104 ± 21
MD	25 ± 3	20 ± 4
ERs	1.3 ± 0.1	0.9 ± 0.2
Total bkg.	126 ± 24	125 ± 21
$^8\text{B CE}_{\nu\text{NS}}$	18 ± 4	25 ± 6
Expected	144 ± 25	150 ± 22
Observed	158	174
Combined (Run0 + Run1)		
Expected	294 ± 33	
Observed	332	



← **New Avenues for
Sub-GeV DM Detection**

[For generalized mediators
see Anirban's talk]

DM-e scattering at PandaX-4T

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Dark matter - electron

Dark matter-electron scatterings at liquid Xenon detectors induce a differential event rate in electron ionization energy E_e [Essig et al. (2012)]:

$$\frac{dR}{d \ln E_e} = N_T \sum_{n,l} \mathcal{A}(E_e) \int d^3v \mathcal{F}(\vec{v} + \vec{v}_e) \frac{d\sigma(v, E_e)}{d \ln E_e}$$



Efficiency Function
PANDAX-4T



Dark Matter
Flux



Differential
Cross Section

Dark Matter - electron

The differential ionization cross section is given by [Herrera and Ibarra (2021)]:

$$\frac{d\sigma(v, E_e)}{d \ln E_e} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2 v^2} \int_{q_{\min}^{nl}}^{q_{\max}^{nl}} dq q |f_{\text{ion}}^{nl}(\vec{k}, q)|^2 |F_{\text{DM}}(q)|^2$$

Atomic ionization form factor
 [See Riccardo's talk]

DM form factor

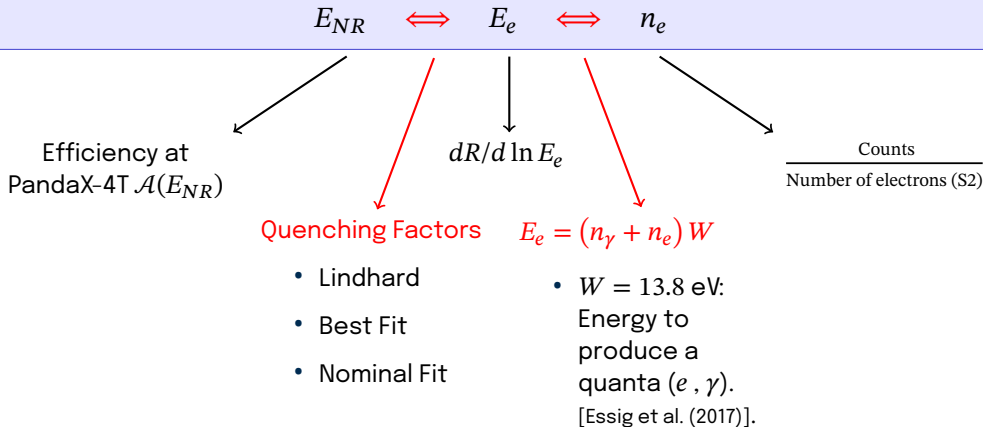
Cross section @ $q = \alpha m_e$

Just $\mathcal{O}_1$ NR operator
 PF, Herrera, Ochoa (2024)

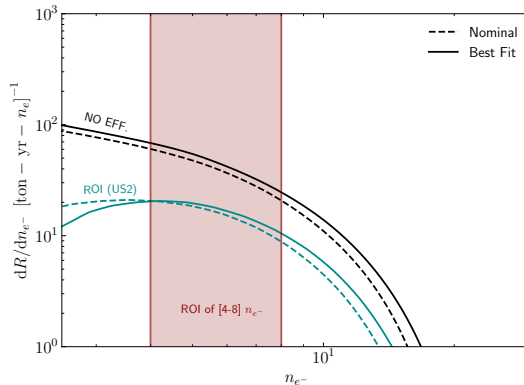
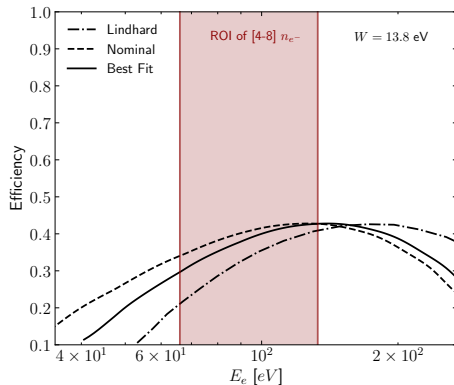
Our particle physics model is encoded in:

$$F_{\text{DM}}(q) = \frac{(m_{A'}^2 + \alpha^2 m_e^2)}{(m_{A'}^2 + q^2)}, \quad \bar{\sigma}_e = \frac{16\pi\alpha\alpha_D\epsilon^2\mu_{\chi e}^2}{(m_{A'}^2 + \alpha^2 m_e^2)^2}$$

So... What can we do?



Efficiency & Quenching Factors



So... What can we do next?

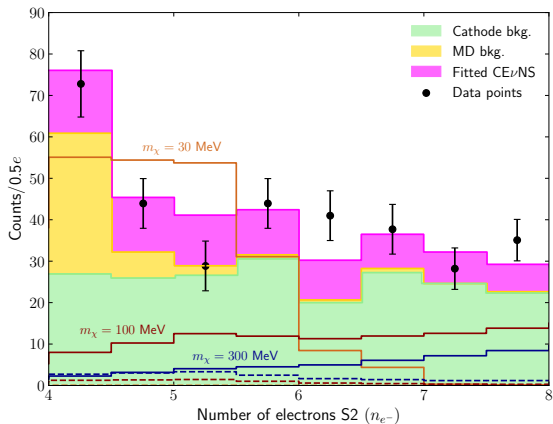
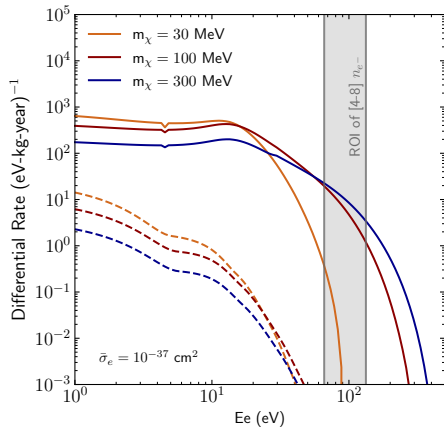
Then, we compute the total rate in each bin i as

$$s_i(\bar{\sigma}_e, m_\chi) = \mathcal{E} \int_{n_{e^-}^{\min,i}}^{n_{e^-}^{\max,i}} \frac{dR}{dn_{e^-}} dn_{e^-}$$



Predicted DM-e scattering signal

DM-e at PandaX-4T



Does it fit any better?

We define a log-likelihood function summing over all bins i as [Brenner et al. (2022)]:

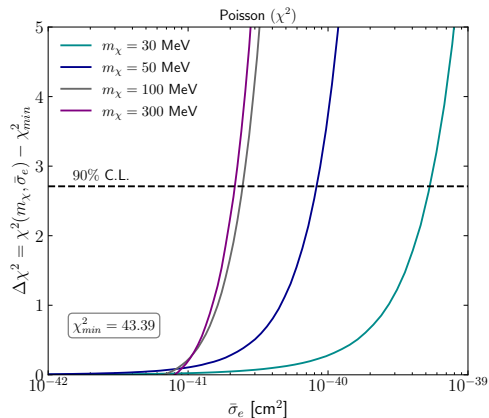
$$\log \mathcal{L}(\bar{\sigma}_e, m_\chi) = \sum_i [n_i \log(s_i + b_i) - (s_i + b_i) - \log(n_i!)]$$

with,

- n_i : Number of **observed** events.
- b_i : Expected **background** events.
- s_i : **Predicted DM-e signal** $s_i(\bar{\sigma}_e, m_\chi)$.

Test statistic:

$$\chi^2(\bar{\sigma}_e, m_\chi) \equiv -2 \log \mathcal{L}(\bar{\sigma}_e, m_\chi).$$



Does it fit any better?

We define a log-likelihood function summing over all bins i

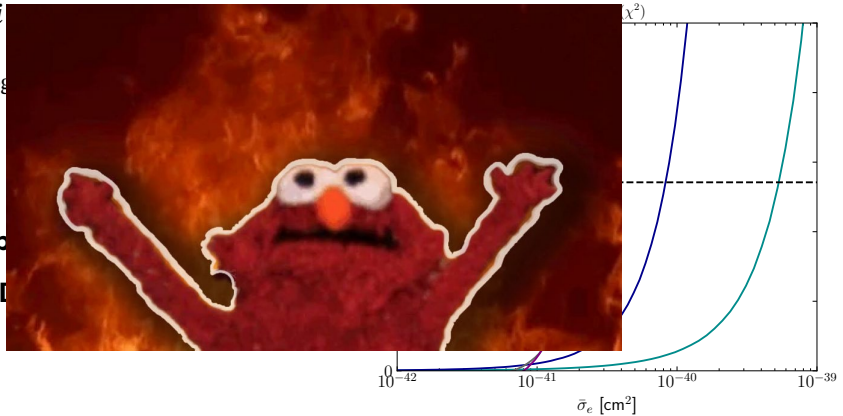
$$\log \mathcal{L}(\bar{\sigma}_e, m_\chi) = \sum_i [n_i \log$$

with,

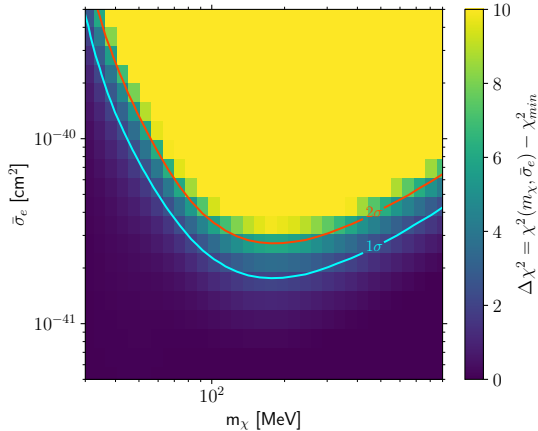
- n_i : Number of
- b_i : Expected b
- s_i : **Predicted**

Test statistic:

$$\chi^2(\bar{\sigma}_e, m_\chi) \equiv -2 \log \mathcal{L}(\bar{\sigma}_e, m_\chi).$$



No Problem



...and find upper bounds on $\bar{\sigma}_e$ from:

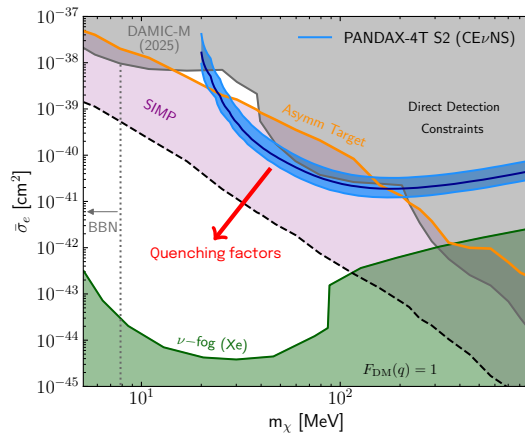
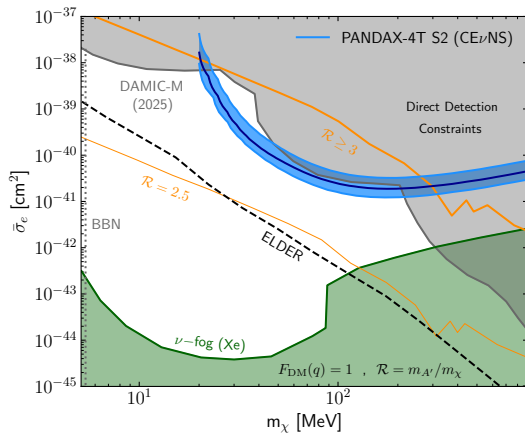
$$\Delta\chi^2 = \chi^2(\bar{\sigma}_e, m_\chi) - \chi_{min}^2 = \chi_\sigma^2$$



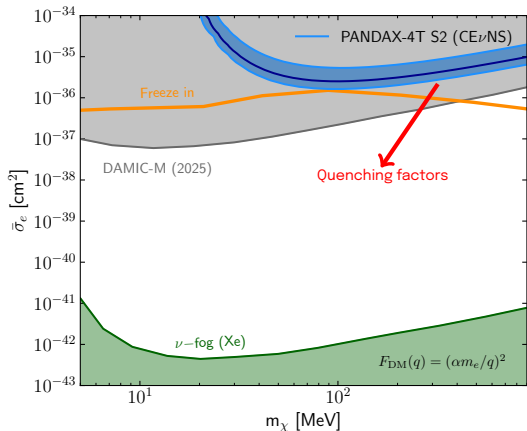
Implications for (some) DM Models

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Heavy Mediator



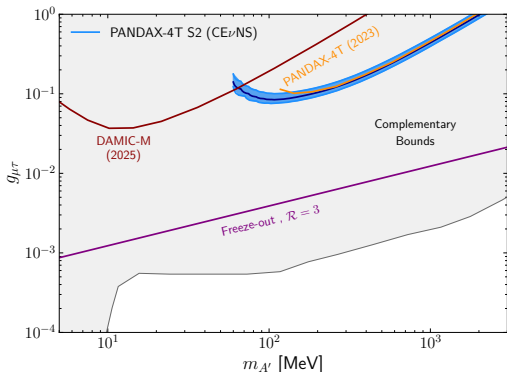
Massless Mediator



NOTE ADDED

While this work was being completed, the PandaX-4T collaboration released an analysis of sub-GeV DM from their ionization S2-only data [Zhang et al. (2025)]. Our limits for heavy mediators agree well with theirs, but our limits for light mediators are less stringent by a factor of ~ 2 . The collaboration explicitly mentions that their limits for light mediators rely on a different treatment on the expected signal than the prescription we described here.

$L_\mu - L_\tau$ symmetry



In this model, the muon and tau lepton doublets also possess a current

[Foldenauer (2019); Hapitas et al. (2022)]:

$$\mathcal{L} \supset g_{\mu\tau} (\bar{\mu} \gamma_\mu \mu - \bar{\tau} \gamma_\mu \tau + \bar{\nu}_\mu \gamma_\mu P_L \nu_\mu - \bar{\nu}_\tau \gamma_\mu P_L \nu_\tau) A'^\mu$$

while the dark current is given by:

$$J_\mu = g_\chi Q_\chi \bar{\chi} \gamma_\mu \chi$$

The dark gauge coupling is $g_\chi = g_{\mu\tau} Q_\chi$, and Q_χ is the DM charge under $L_\mu - L_\tau$.

Conclusion and Outlook

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Conclusions

We have derived novel bounds from the PandaX-4T S2-only ionization search for CE ν NS, finding that these are world-leading for heavy mediators in the range $m_\chi \sim 20 - 200$ MeV, but weaker than DAMIC-M for light or massless mediators.

The recent data from DAMIC-M and PandaX-4T also dives well into other models such as SIMPs/ELDERs, and approaches benchmarks for freeze-in, and concrete gauged symmetries such as the $U(1)_{L_\mu-L_\tau}$.

We have assessed the uncertainty in the PandaX-4T models arising from different choices of the charge-yield and quenching factors.

Thank you for your attention

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In collaboration with: Andrew Cheek (SJTU), Gonzalo Herrera (MIT), and Ian M. Shoemaker (VT)

References

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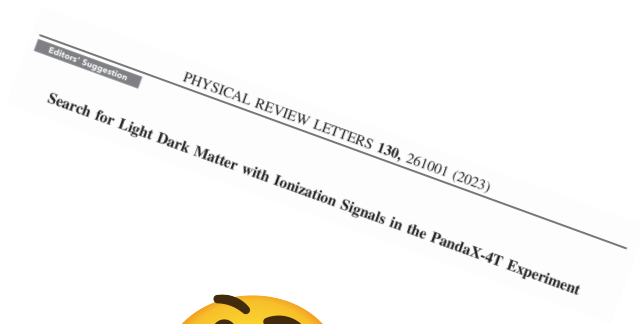
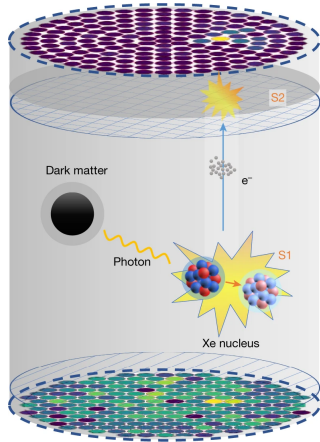
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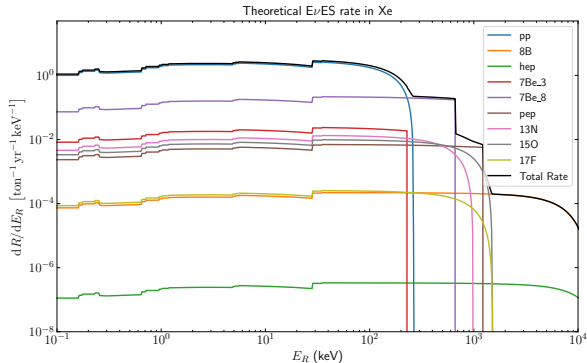
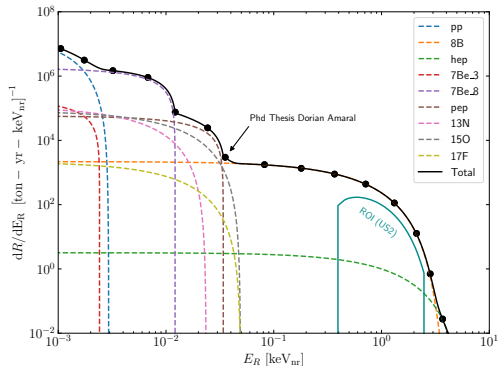
Back Up

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S2-Only (In a nutshell)



CEvNS and EvES spectrum



Theoretical SvDD

We compute the CE ν NS scattering rate as

$$\frac{dR}{dE_R} = \mathcal{A}(E_R) \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_{\nu N}}{dE_R}$$

where $\frac{d\sigma_{\nu N}}{dE_R}$ refers to the SM $\nu - N$ cross section.

- $\mathcal{A}(E_R)$ is the experiment-dependent efficiency, which we discussed previously.
- We make use of the best-fit charge yield.
- We take the default flux of ^8B solar neutrinos, $d\phi/dE_\nu$, with normalization $5.46 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ from SvDD Amaral et al. (2023).

Theoretical SvDD

The data in [Collaboration (2024)] is presented in bins of S2 n_{e^-} . The translation between E_{NR} and n_{e^-} is carried out through the charge yield $Q_y(E_R)$ as [De Romeri et al. (2025)]:

$$n_{e^-} = E_R Q_y(E_R).$$

The differential event rate as a function of n_{e^-} is then expressed through:

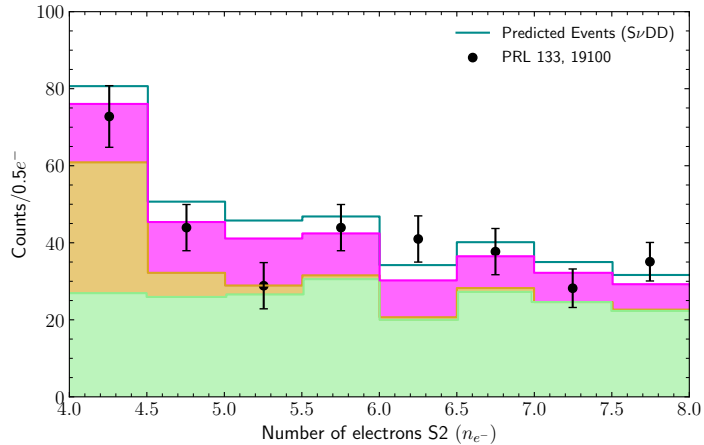
$$\frac{dR}{dn_{e^-}} = \frac{dR}{dE_R} \frac{dE_R}{dn_{e^-}}$$

and the events per bin are

$$R_i = \mathcal{E} \int_i \frac{dR}{dn_{e^-}} dn_{e^-},$$

where the integral is performed over the size of each bin i .

Theoretical SvDD



Majorana DM

In this model, the DM is a Majorana fermion with current

$$J'_\mu = \frac{1}{2} \bar{\chi} \gamma_\mu \gamma_5 \chi.$$

This model is poorly tested by direct detection due to the suppression of the scattering cross section with relative velocity as $\sigma \sim v^2$, since the typical DM velocity in the galactic halo is $v \sim 10^{-3}c$.

