An Attractive Scenario for Light Dark Matter Direct Detection

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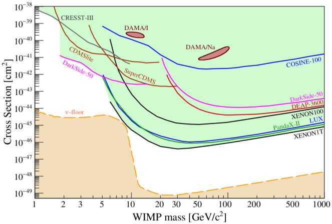
Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**

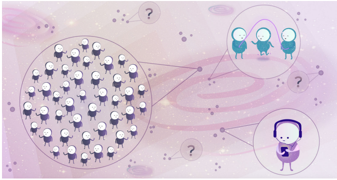
- Need for a **Dark Matter** candidate

- large experimental effort to detect DM [Schumann '19]
- so far DM only observed via its gravitational interactions



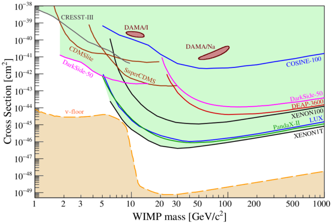
⇒ DM resides within a "dark sector" which only feebly interacts with SM

(Hidden sector review: [Essig et al. 1311.0029])



Dark Matter

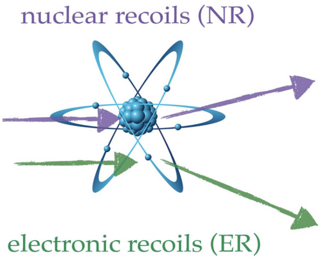
- large experimental effort to detect DM $\leftrightarrow$ theoretical effort for DM phenomenology
- early focus on weak scale $\sim$ 100 GeV
- null results $\rightarrow$ expand experimental and theoretical efforts to **lower** masses



$\Rightarrow$ **new challenges** arise in detecting low mass DM

Low mass DM

- lower mass $\rightarrow$ smaller available energies in collisions of DM with detector target material $\rightarrow$ requires lower detection energy thresholds & controlling backgrounds that could overwhelm the signal
- weak scale DM: nuclear recoil signals $\leftrightarrow$ DM below GeV scale: electron recoil signals



Low mass DM

- rough estimate of recoil energy:

  nucleus mass $m_N \sim 10$ GeV, virial velocity of DM $v_{DM} \sim 10^{-3}$

  recoil energy: $E_R \sim (m_{DM} v)^2/(2m_N)$

  $m_{DM} \sim 100$ GeV $\rightarrow E_R \sim 10$ keV

  $m_{DM} \sim 0.1$ GeV $\rightarrow E_R \sim$ eV $\ll$ keV threshold of experiments!

Low mass DM

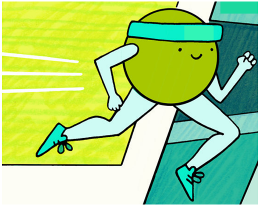
- improvement: look at **electron recoil** signals!
- estimate for recoil energy:
  electrons in atoms are delocalized over length scales of order Bohr radius $a_0 \sim (\alpha m_e)^{-1}$, momentum $q \sim 1/a_0$, electron velocity $v_e \sim \alpha \gg v_{DM}$

  $\rightarrow E_R \sim q^2/(2m_e) \sim 10$ eV$\ll$ keV threshold!
- can only detect electron recoil signal in an experiment with $>$ keV energy threshold when velocities are near $v_{DM} \sim 0.1 \gg v_{esc} \sim$ few $\times 10^3$

  $\rightarrow$ **severe** suppression of the expected abundance of any such DM particles in the halo population

Low mass DM

- ways out:
  - devise experimental technique with **threshold $\ll$ keV** [SENSEI 1804.00088, DAMIC 1105.5191, EDELWEISS 2003.01046, SuperCDMS 1804.10697]
  - new ideas to **increase DM velocity**: boosted DM from decays of a more massive DM states [D'Eramo, Thaler '10, Huang, Zhao '13, Agashe, Cui, Necib, Thaler '14] or due to interactions with energetic particle, such as cosmic rays [Bringmann, Pospelov '18, Ema, Sala, Sato '18]

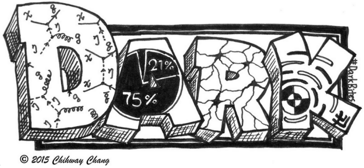


Low mass DM

- ways out:
  - devise experimental technique with threshold $\ll$ keV [DAMIC 1105.5191, SENSEI 1804.00088, EDELWEISS 2003.01046, SuperCDMS 1804.10697]
  - new ideas to increase DM velocity: boosted DM from decays of a more massive DM states [D'Eramo, Thaler '10, Huang, Zhao '13, Agashe, Cui, Necib, Thaler '14] or due to interactions with energetic particle, such as cosmic rays [Bringmann, Pospelov '18, Ema, Sala, Sato '18]
- however with these mechanism only a **small fraction** of DM can be boosted to higher velocities
- propose a novel scenario, where **all** DM reaches the Earth at velocities $v \sim 0.1$!

Attractive Scenario for Light DM Direct Detection

Based on *"An Attractive Scenario for Light Dark Matter Direct Detection"*
in collaboration with Hooman Davoudiasl and Peter B. Denton
arXiv: 2007.04989



Attractive Scenario for Light DM Direct Detection

[Davoudiasl, Denton, JG ’20]

- **acceleration** of DM: long range attractive force that acts on DM and ordinary matter, but with unequal strengths [Davoudiasl ’17]
- **detection** of DM: short range force which mediates DM-electron scattering in direct detection experiments

Long range force [Davoudiasl, Denton, JG '20]

- long range **attractive** force mediated by ultralight boson with $m_\phi \sim 10^{-14}$ eV and range $3R_\oplus$ [Davoudiasl '17]
- potential of ϕ sourced by Earth

$$V(r) \approx -g_n g_\chi \frac{N_\oplus}{4\pi r}$$

- searches for new long range forces $g_n \lesssim 10^{-24}$ [Schlamminger' 07 ,Fayet' 17]
- no severe constraints on interactions of ϕ with DM [Davoudiasl '17]

$$g_\chi \lesssim 10^{-4} \left(\frac{m_\chi}{100\text{ MeV}}\right)^{3/4}$$

Long range force [Davoudiasl, Denton, JG '20]

- potential of ϕ sourced by Earth

$$V(r) \approx -g_n g_\chi \frac{N_\oplus}{4\pi r}$$

- with $g_n \lesssim 10^{-24}$ [Schlamminger' 07 ,Fayet' 17] and $g_\chi \lesssim 10^{-4} \left(\frac{m_\chi}{100\ \text{MeV}}\right)^{3/4}$ [Davoudiasl '17]
- potential at Earth radius

$$V(R_\oplus) \sim -0.1\ \text{MeV} \left(\frac{g_n}{10^{-24}}\right)\left(\frac{g_\chi}{10^{-7}}\right)$$

- velocity

$$v(R_\oplus) \sim \sqrt{\frac{-V(R_\oplus)}{2\,m_\chi}}$$

for $m_\chi = 10$ MeV $\rightarrow v \sim 0.07$

Short range interaction [Davoudiasl, Denton, JG '20]

- long range force does not mediate DM-electron scattering $\rightarrow$ introduce short range interaction

- light dark photon mediator A_D, with mass m_D, which mixes kinetically with the photon [Holdom '86]

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F_{D\mu\nu} - \frac{m_D^2}{2} A_{D\mu} A_D^\mu + i\, e_D A_{D\mu} \overline{\chi} \gamma^\mu \chi$$

Short range interaction [Davoudiasl, Denton, JG '20]

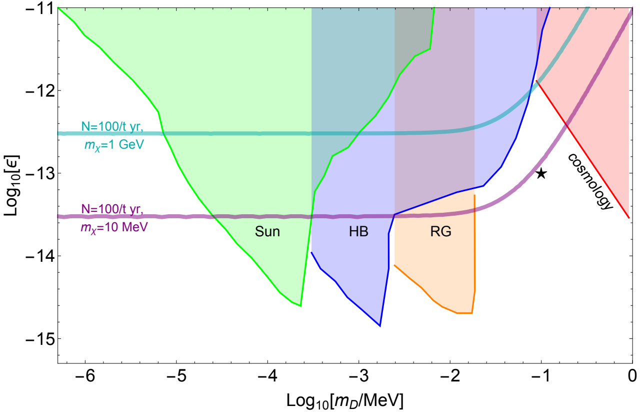
- for cross section use free electron approximation due to large velocity of DM (ignore binding energies and consider outer shell electrons)

- next generation large DM experiments use Xenon (n=4, 5, $Z_{eff} = 26$) (for formalism see [Essig '15])

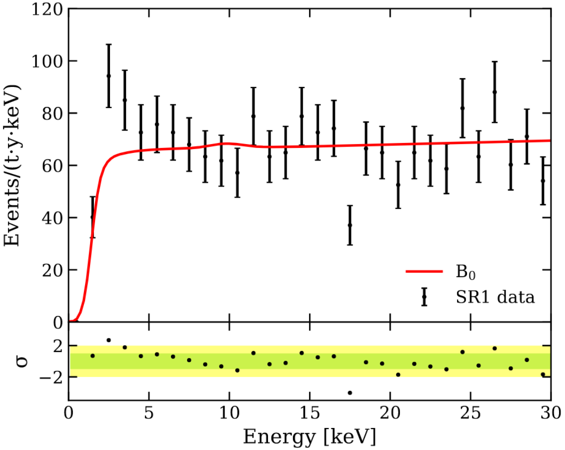
$$(\sigma_e v) = \frac{16\pi\,\alpha\,\alpha_D \epsilon^2 Z_{eff}(\mu_{\chi e}^2 v^2 - m_e E_{th}/2)}{v\,(2m_e E_{th} + m_D^2)(4\mu_{\chi e}^2 v^2 + m_D^2)}$$

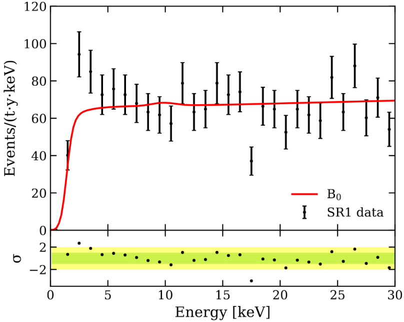
Short range interaction [Davoudiasl, Denton, JG '20]

constraints on mediator [Essig et al'13]



- slight excess of electron recoils in the few keV range reported by XENON1T! [XENON, 2006.09721]

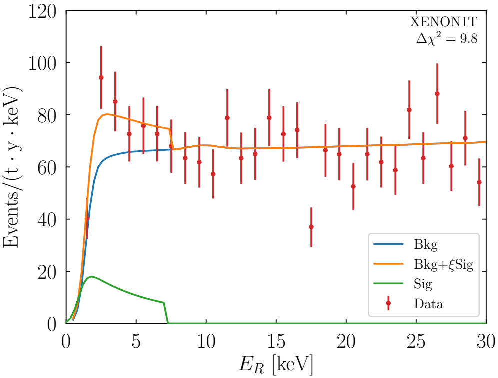




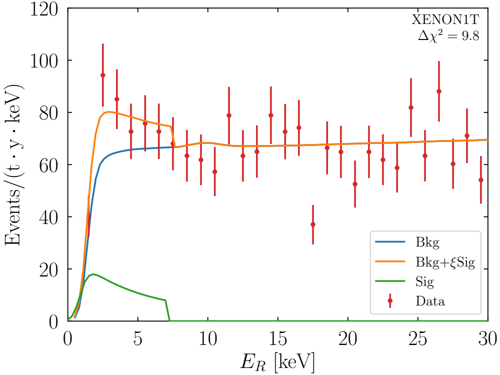
- excess between 1-7 keV, 285 events observed, 232 ($\pm$15) expected [XENON, 2006.09721]
- DM interpretation? (many other explanations in the literature)

XENON1T [Davoudiasl, Denton, JG '20]

- DM particle with $v_{DM} \sim 10^{-3}$ leads to $E_R \ll$ keV $\rightarrow$ DM with virial velocity not an explanation!
- **need to increase DM velocity** [Kannike '20, Alhazmi et al '20, Fornal' 20]
- test our scenario for the XENON1T excess



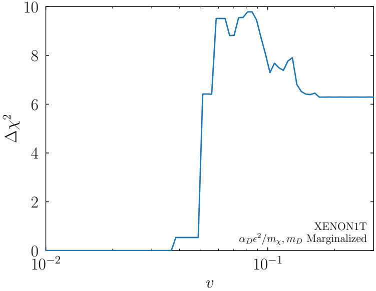
- best fit: $\alpha_D \epsilon^2 / m_\chi = 1.2 \cdot 10^{-28}$ MeV^{-1}, $m_D = 0.081$ MeV, and $v = 0.085$
- test statistic $\chi^2 = 36.6$ compared to background only hypothesis with $\chi^2 = 46.4$



- key feature of the model: not only a suppression of events at low energy due to dark photon mass, also at high energy due to sharp velocity distribution → anticipate that the spectrum would fall off fairly sharply at higher recoil energies

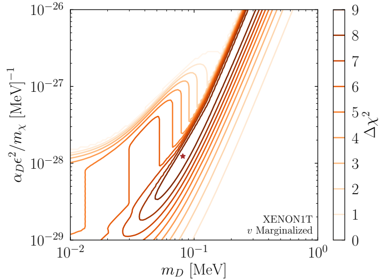
XENON1T [Davoudiasl, Denton, JG '20]

- velocity projection where the other parameters are marginalized over



- $v \sim 0.1$ is preferred

- for smaller velocities the DM doesn't have enough kinetic energy to have an effect above XENON1T's threshold, at high velocities an improved fit is found, but it slightly overestimates the signal at larger recoil energies



- best fit point: $m_D \sim 0.1$ MeV, $\alpha_D \epsilon^2/m_\chi \sim 10^{-28}$ MeV^{-1}, for example satisfied for $\alpha_D = 0.1$, $\epsilon = 10^{-13}$, $m_\chi = 10$ MeV
- center is maximally preferred at $\Delta\chi^2 > 9$, top left is significantly disfavored as it over-predicts the signal, bottom right returns to the SM

Additional predictions [Davoudiasl, Denton, JG '20]

- **"dark matter rain"**: attractive nature of the potential in our scenario would provide a nearly radial flux, both up-going and down-going $\rightarrow$ significant anisotropy of the signal $\rightarrow$ test in experiments that have directional sensitivity

- **altitude dependent detection rate**: velocity gain as DM falls into the Earth $\rightarrow$ expect a very slightly higher rate at detectors in underground mines than those at the surface

Summary and Conclusions

- unique model of DM wherein the Earth provides an attractive force on it due to an ultralight mediator
- large effect on the velocity distribution near the Earth, accelerate 100% of the DM and yielding a nearly radial flux, velocity distribution is highly peaked
- introduce short range mediator to allow for DM-electron scattering, model is consistent with known astro-physical, cosmological, and laboratory experiments
- found a good fit to the XENON1T excess
- future tests of scenario with XENON1T, XENONnT, “dark matter rain"

Thank you for your attention!