Explorations of pseudo-Dirac dark matter having keV splittings and interacting via transition electric and magnetic dipole moments

Shiuli Chatterjee
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based on

"Explorations of pseudo-Dirac dark matter having keV splittings and interacting via transition electric and magnetic dipole moments"
SC, Ranjan Laha **(arXiv: 2202.13339 [hep-ph])**

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Outline

- Motivation for studying inelastic Dark Matter (DM) at direct detection
- Model: Transition electric and magnetic dipole moments
  - Freeze-in production
  - Direct detection of solar upscattered dark sector particle
  - Complementary constraints
- Summary

Inelastic Dark Matter: Motivation from XENON1T

- XENON1T results motivate the study of inelastic DM:
  - Typical recoil energies for standard WIMP DM

$$E_R \sim \mu_{DM\, e} v_{DM}^2 \sim O(eV)$$

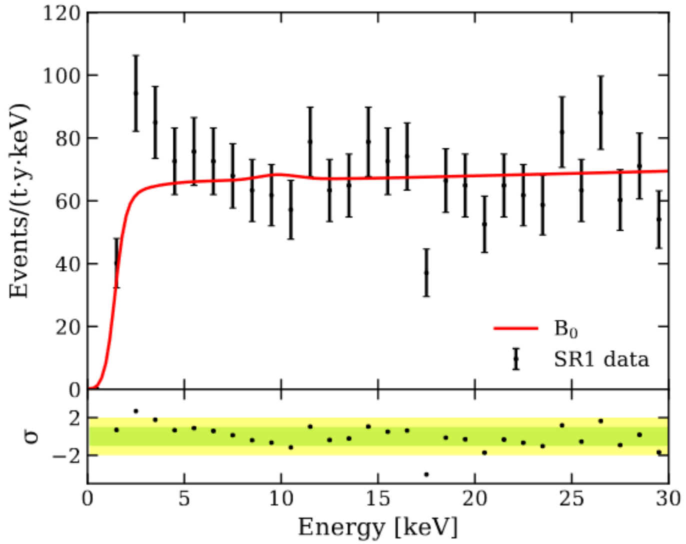
  - While for an inelastic (down) scattering process

$$\chi_2 e \to \chi_1 e,$$

deposited energy is equal to mass difference

$$E_R \sim \delta \equiv m_{\chi_2} - m_{\chi_1}.$$

- Unprecedented low background rate of 76 ± 2 events/(tonne × year× keV) for electronic recoil between recoil energies of 1–30 keV.
- While there has been great excitement over the "excess", it is also the leading measurement for electron recoil with the lowest backgrounds.



Aprile et al (Xenon collaboration) arXiv2006.09721 [hep-ex]

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- We investigate a minimal model of inelastic DM
  - In the absence of any additional gauge symmetry, lowest dimension operator for effective interactions give

$$\mathcal{L}_{int} \supset \frac{1}{2}\mu_\chi(\bar{\chi}_1 \sigma_{\mu\nu}\chi_2)F^{\mu\nu} + \frac{i}{2} d_\chi(\bar{\chi}_1 \sigma_{\mu\nu}\gamma_5 \chi_2)F^{\mu\nu}$$

with transition electric and magnetic dipole moments.

  - Photon mediated searches → significant for Direct Detection

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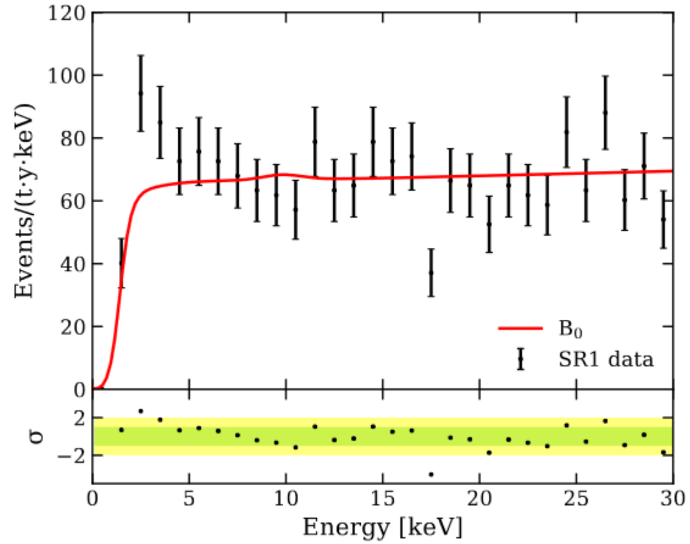

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Inelastic Dark Matter: Constraints

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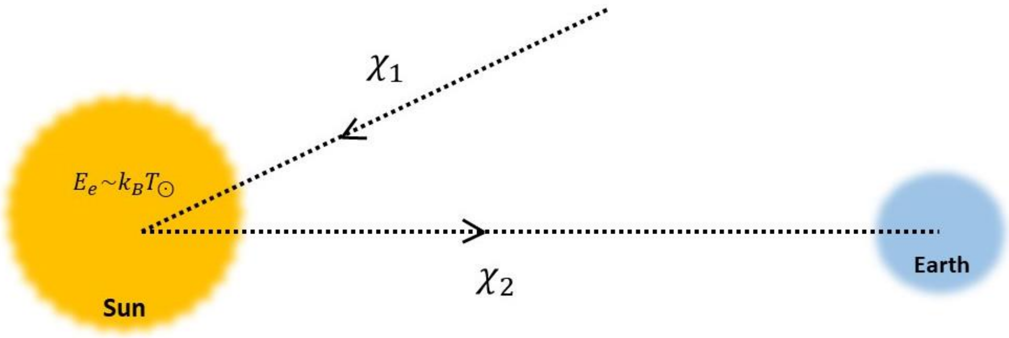
- Freeze-in production: The parameter space that reproduces observed relic density leads to only χ_1 surviving on cosmological scales, with χ_2 decaying away.
- XENON1T threshold energy for electron recoil of 1 keV
- Solar temperature, $T_\odot \simeq 1.1$ keV
- An interesting co-incidence that leads to the interesting scenario of Solar up-scattering of χ_1 to χ_2 by electrons with subsequent down-scattering at direct detection (DD) experiments leading to potentially observable signatures of this model.



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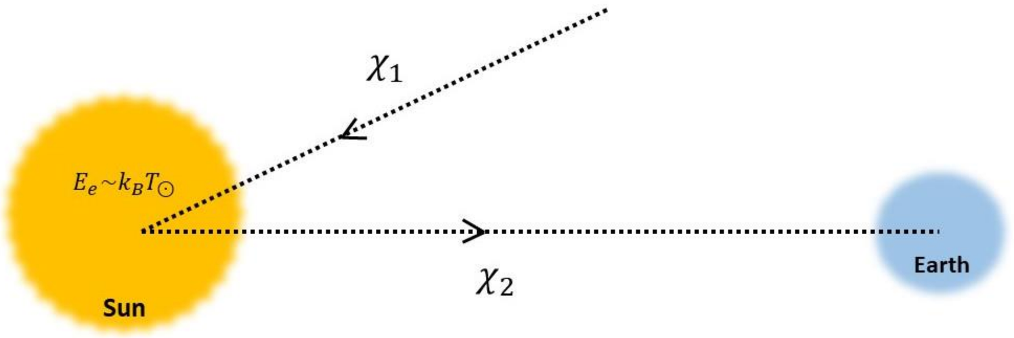
- An interesting co-incidence that leads to the interesting scenario of Solar up-scattering of χ_1 to χ_2 by electrons with subsequent down-scattering at direct detection (DD) experiments leading to potentially observable signatures of this model.
- Also complementary constraints from
  - BaBar, LEP
  - NA64
  - Supernova cooling



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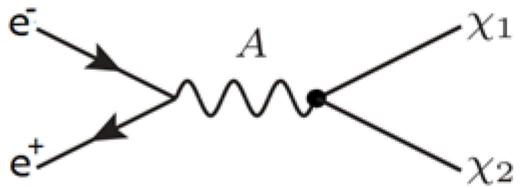
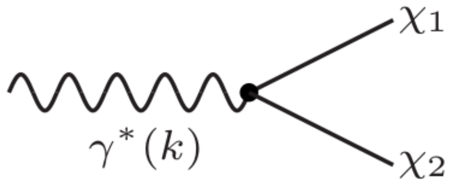
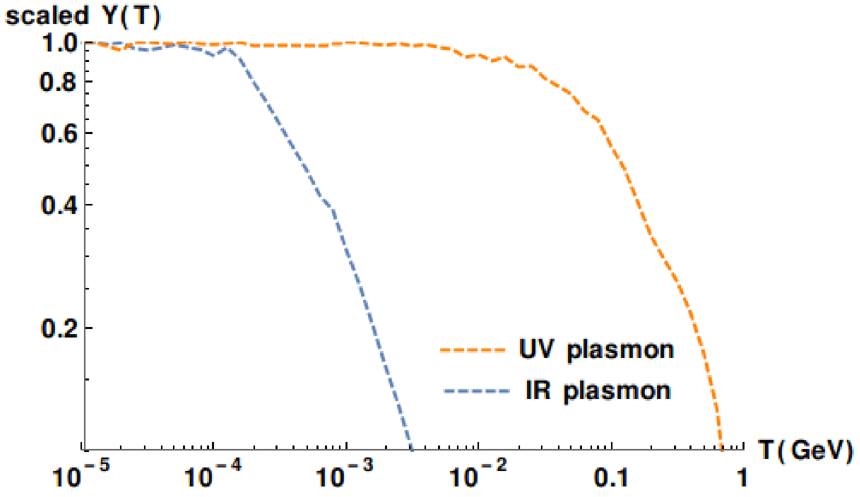
Freeze-in: Annihilation and plasmon decay

- An additional production channel was identified for freeze-in mechanism (Dvorkin et al 2019).
- Decay of photons that acquire an in-medium plasma mass. This was already known in the SN cooling process.
- These plasmon decays were shown to be a dominant channel for DM production for sub-MeV DM masses (lighter than the electron).
- Thus including this channel was shown to lead to significant reduction in the predicted signal strength for DM searches.
- In UV freeze-in the plasmon production is also maximum at largest temperature and there is no competition between the $2 \longrightarrow 2$ process and the decay process

$$\underbrace{\mu_\chi(\bar{\chi}_1\sigma_{\mu\nu}\chi_2)F^{\mu\nu}}_{\text{Magnetic dipole moment }(MDM)} \quad , \quad \underbrace{i\, d_\chi(\bar{\chi}_1\sigma_{\mu\nu}\gamma_5\chi_2)F^{\mu\nu}}_{\text{Electric dipole moment }(EDM)}$$



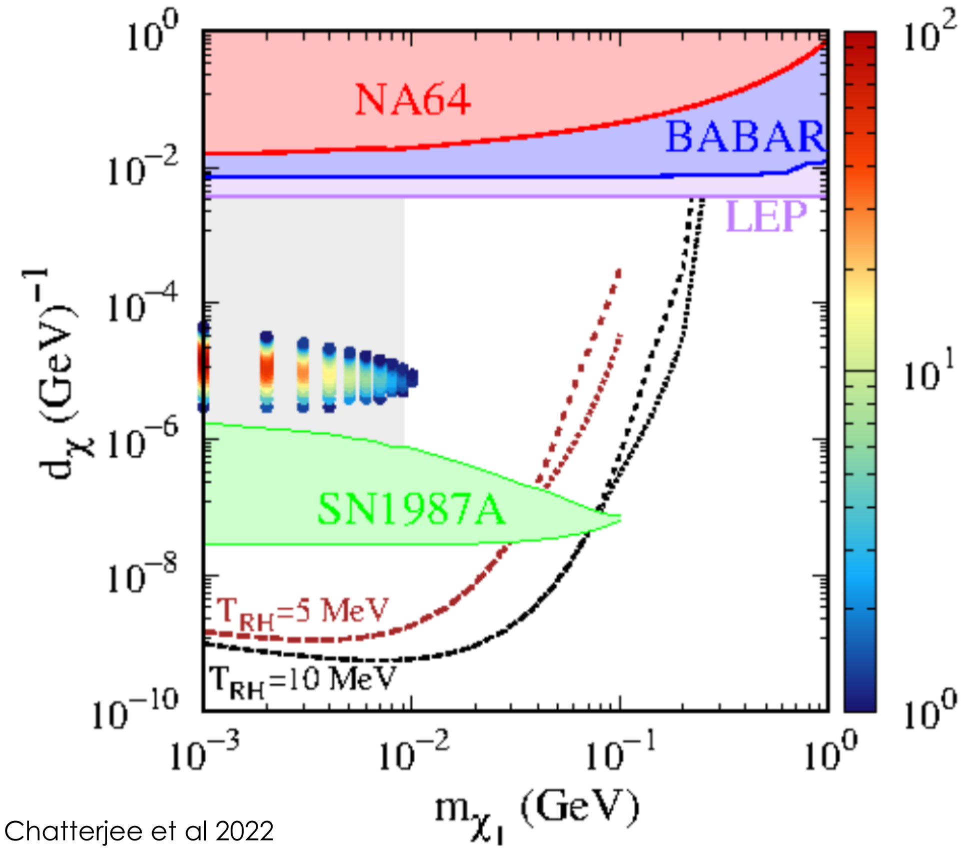




Chatterjee et al 2022

(Chang et al 2019)

Freeze-in production



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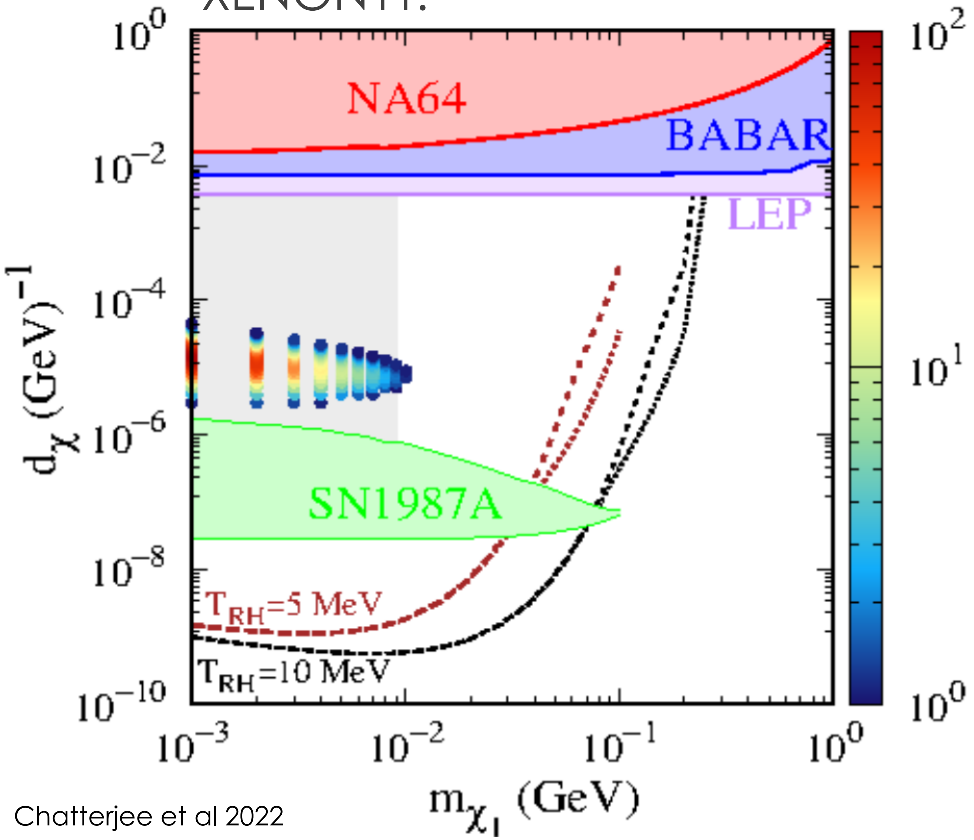
- UV freeze-in: relic density is T_{RH} dependent.
- For a given DM mass, d_χ increases as T_{RH} decreases, to reproduce observed relic density.
- $T_{RH} \geq 4$ MeV (Hannestad 2004)

Transition dipole moment: Direct Detection

XENON1T:



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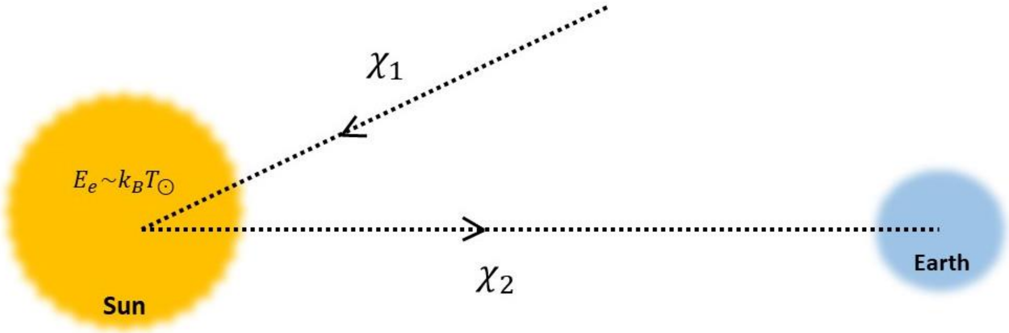


Modified from arXiv:1708.03642 (hep-ph)

Event rate $\propto$ Up-scattering rate $\times\, e^{-\Gamma_{\chi_2} t_{Sun-Earth}} \times \bar{\sigma}_e \times$ electron ionization probability

$\delta \simeq T_\odot$

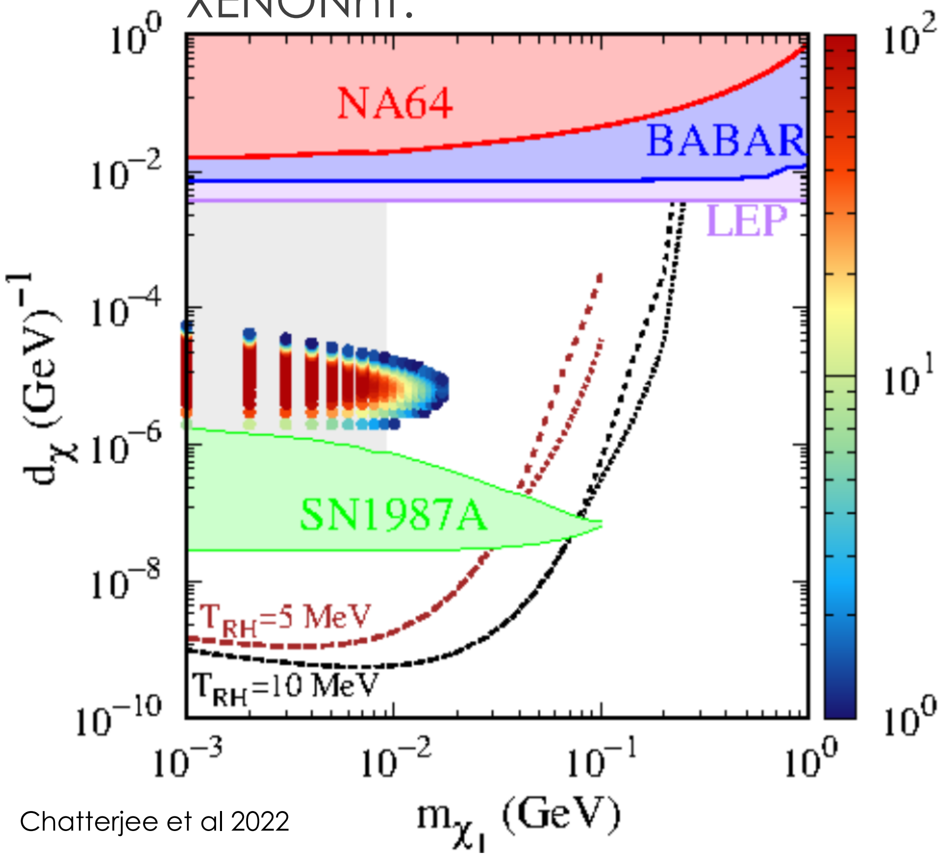
$\Gamma_{\chi_2} \propto d_\chi^2 \delta^3$

$t_{Sun-Earth} \propto 1/m_{\chi_2}$

$\bar{\sigma}_e \propto d_\chi^2$

Transition dipole moment: Direct Detection

XENONnT:



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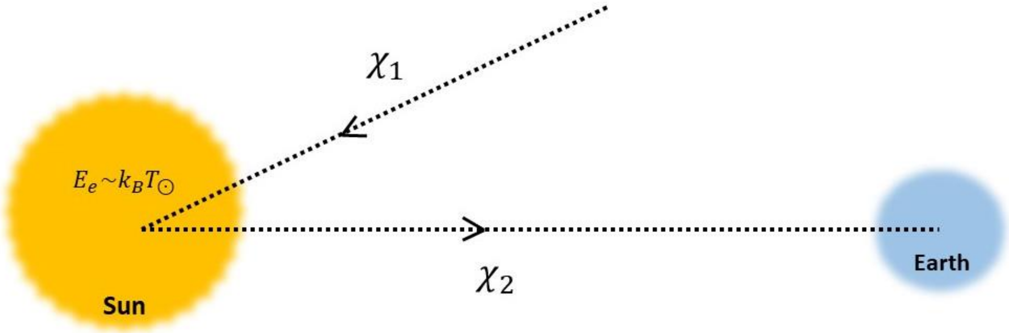

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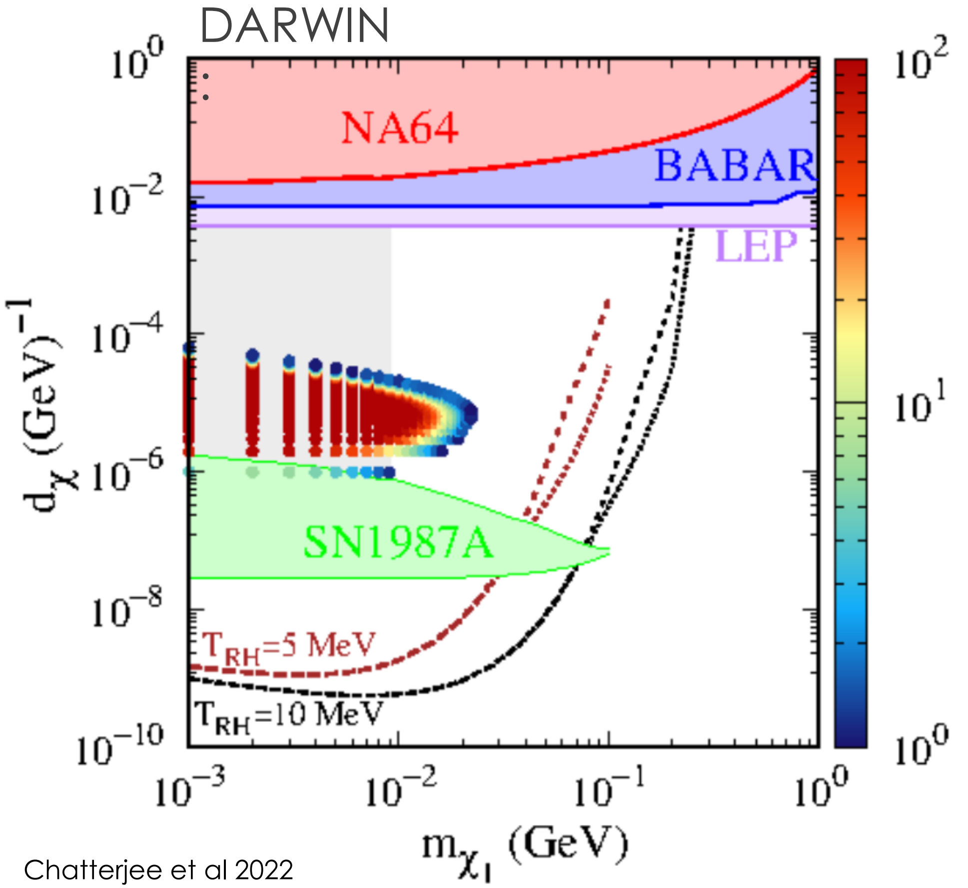
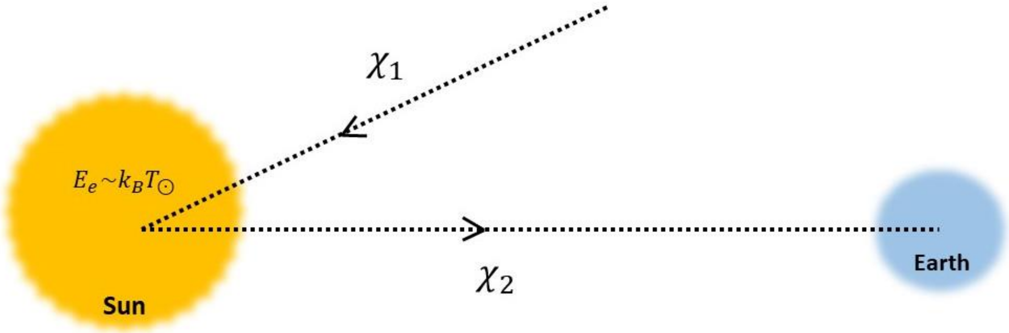


Chatterjee et al 2022



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Event rate ∝ Up-scattering rate× $e^{-\Gamma_{\chi_2} t_{Sun-Earth}}$ × $\bar{\sigma}_e$ × electron ionization probability

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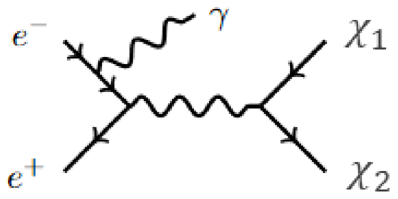
$\bar{\sigma}_e \propto d_\chi^2$

Transition EDM Results:

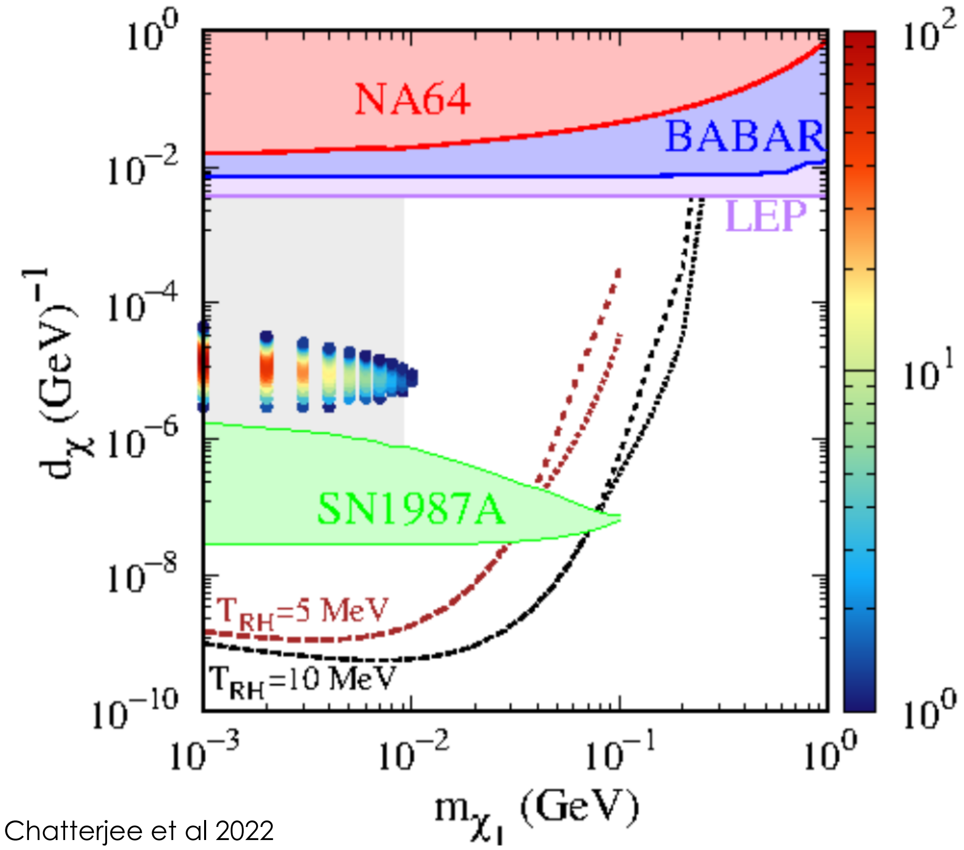
- Complementary constraints on the same parameter space
  1. BaBar, LEP:

     Pair production of DM appearing as missing energy in final state.

$$e^+e^- \to \gamma \chi_1 \chi_2$$



Chu et al (1811.04095)



Chatterjee et al 2022

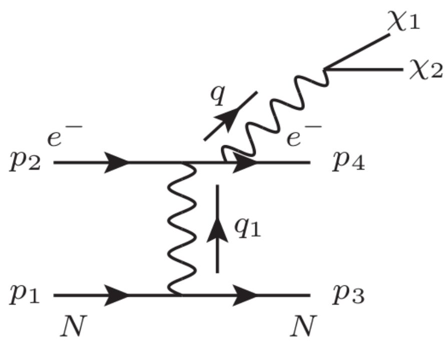
T. B. Collaboration and B. Aubert (2008)
Fortin and Tait (2012)

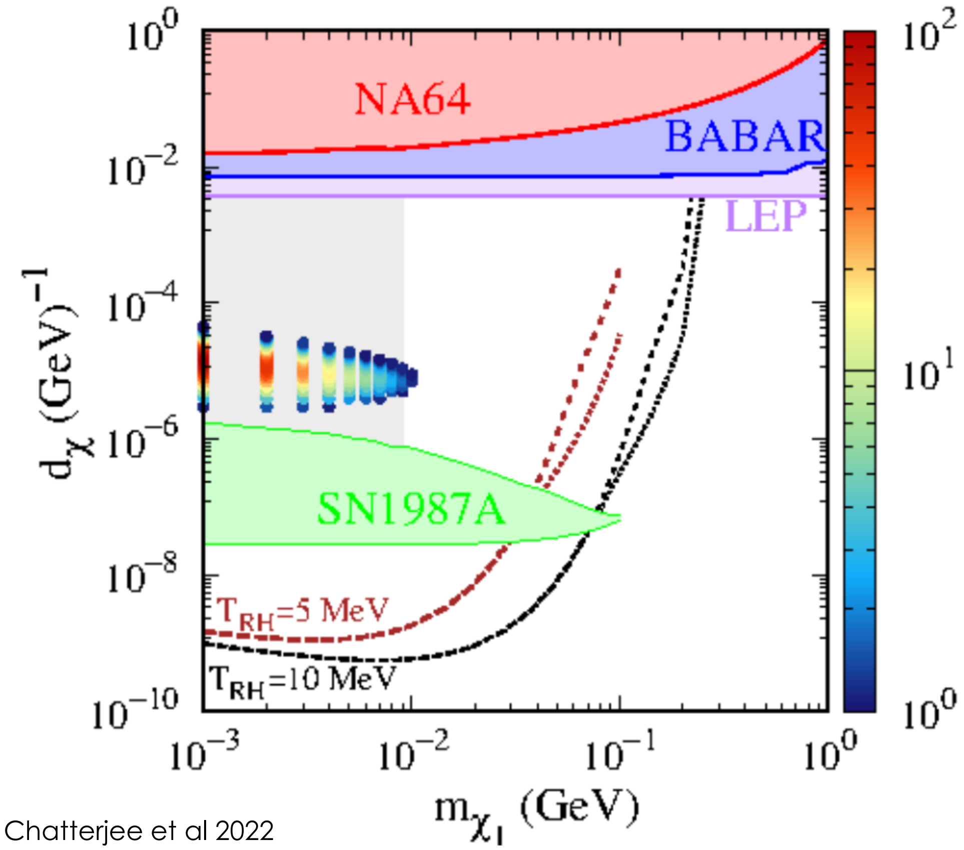
Transition EDM Results:

- Complementary constraints on the same parameter space
  - NA64:

    Beam dump with e^- beam incident upon a fixed target leading to scattering against nucleons.

$$e^- N \rightarrow e^- N\gamma^* \rightarrow e^- N\chi_1\chi_2$$





Chatterjee et al 2022

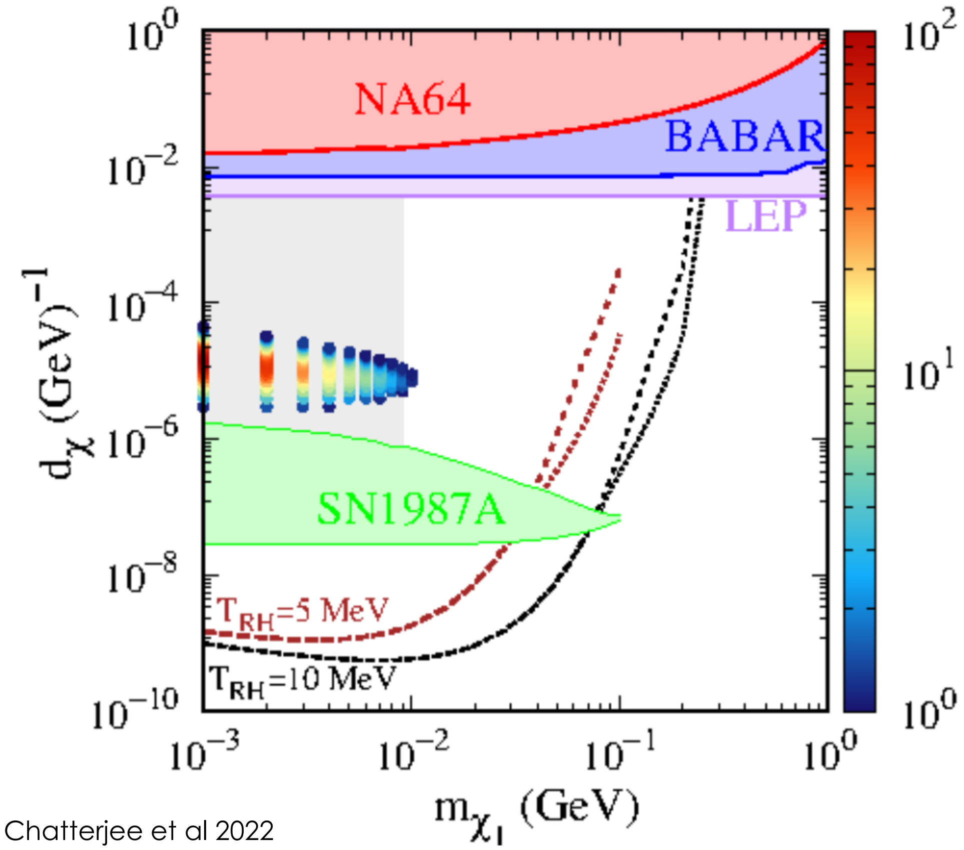
Banerjee et al 2019

Transition EDM Results:

- Complementary constraints on the same parameter space
  - Supernova cooling
    - Light particles can be produced in Supernovae and their subsequent escape can cause extra cooling.

$$e^+e^- \to \chi_1\chi_2$$

    - For too large couplings though they can get trapped within the SN



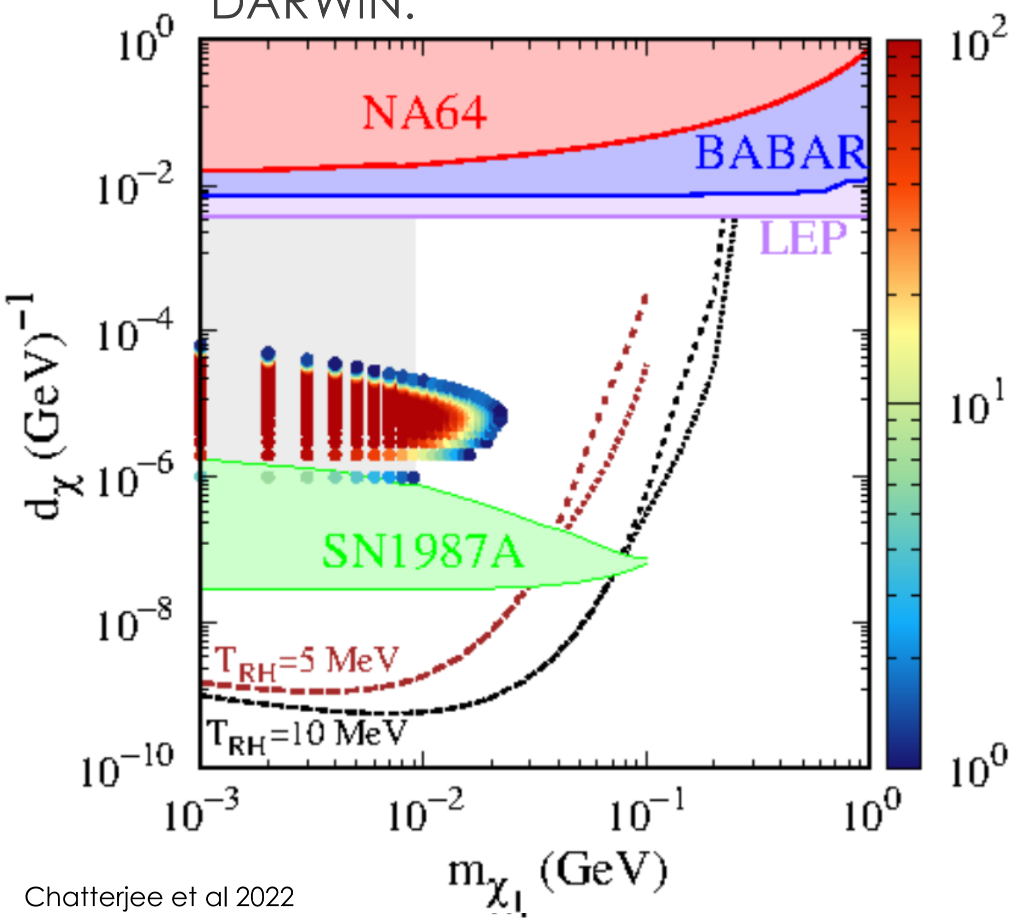
Chatterjee et al 2022

Chu et al 2019

Summary

- We constrain a hitherto unconstrained part of the parameter space for transition electric dipolar DM
    - XENONnt experiment with exposure goal of $20\ tonne \times year$ and projected ER background rates of $12.3 \pm 0.6/(tonne \times keV \times year)$ (Aprile et al 2020)
    - DARWIN experiment with exposure goal of $200\ tonne \times year$ (Aalbers et al 2016)
    - Next generation xenon experiments can either discover this well motivated and minimal dark matter candidate, or constrain how strongly inelastic dark matter can interact via the dipole moment operators.
- Complementary constraints:
    - BaBar, LEP
    - NA64
    - Supernova cooling
- We also showed that production from photon in a dense medium due to thermal effects, plasmon production, is suppressed for DM interacting with SM via higher dimension operators.

DARWIN:



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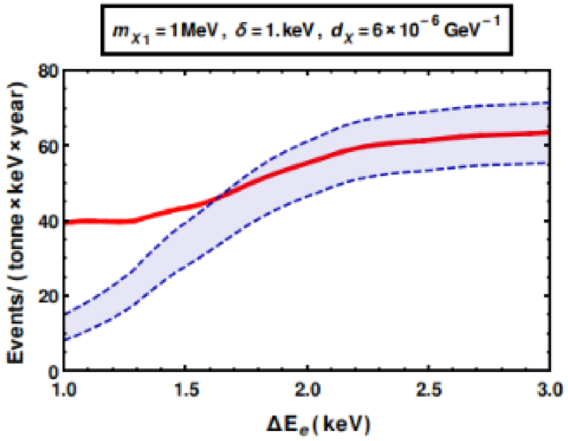
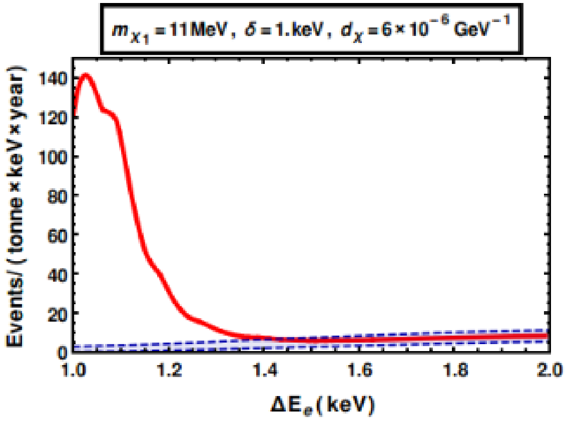
Thank You

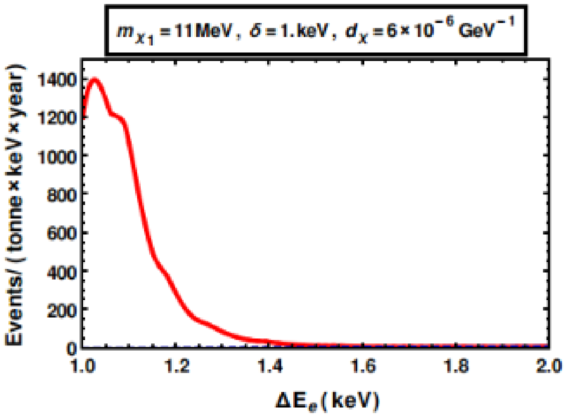
Back-up: EDM results Inelastic



(a) $m_{\chi_1} = 1\,\mathrm{MeV}$, $\delta = 1\,\mathrm{keV}$ at XENON1T



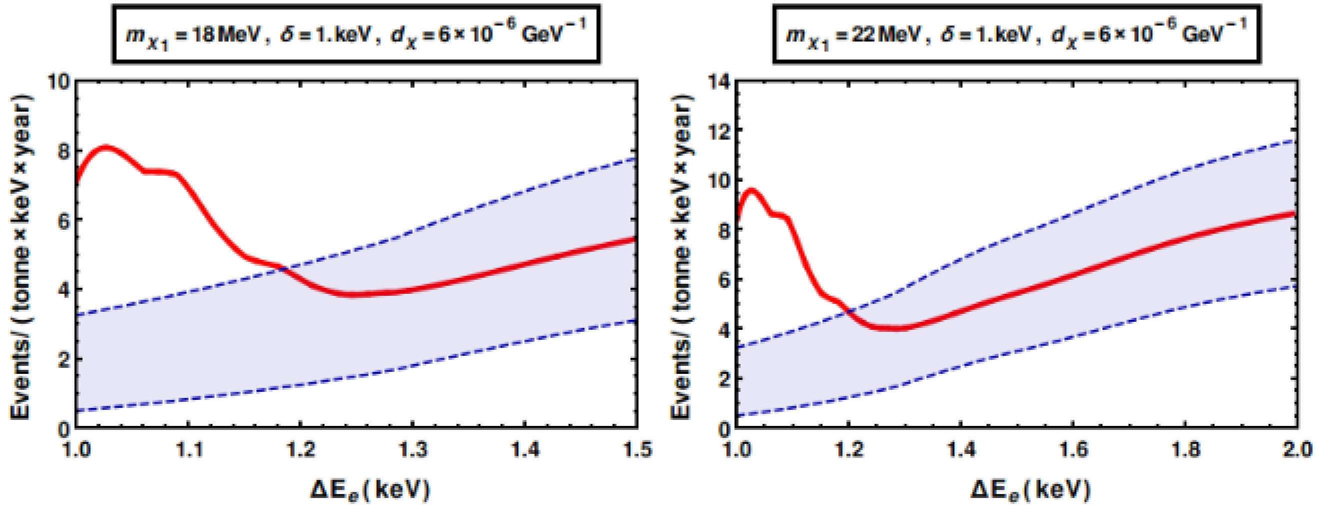
(b) $m_{\chi_1} = 11\,\mathrm{MeV}$, $\delta = 1\,\mathrm{keV}$ at XENONnT



(c) $m_{\chi_1} = 11\,\mathrm{MeV}$, $\delta = 1\,\mathrm{keV}$ at DARWIN

FIG. 8: Differential event rates for EDM DM with $\delta = 1.0\,\mathrm{keV}$. Shown in blue are the background rates with the band representing Poissonian ($\pm\sqrt{N}$) uncertainties and in red are the signal+background rates.

Back-up: EDM results Inelastic



(a) $m_{\chi_1} = 18\,\mathrm{MeV}$, $\delta = 1\,\mathrm{keV}$ at XENONnT

(b) $m_{\chi_1} = 22\,\mathrm{MeV}$, $\delta = 1\,\mathrm{keV}$ at DARWIN

FIG. 9: Differential event rates for EDM DM with $\delta = 1.0\,\mathrm{keV}$. Shown in blue are the background rates with the band representing Poissonian ($\pm\sqrt{N}$) uncertainties and in red are the signal+background rates.

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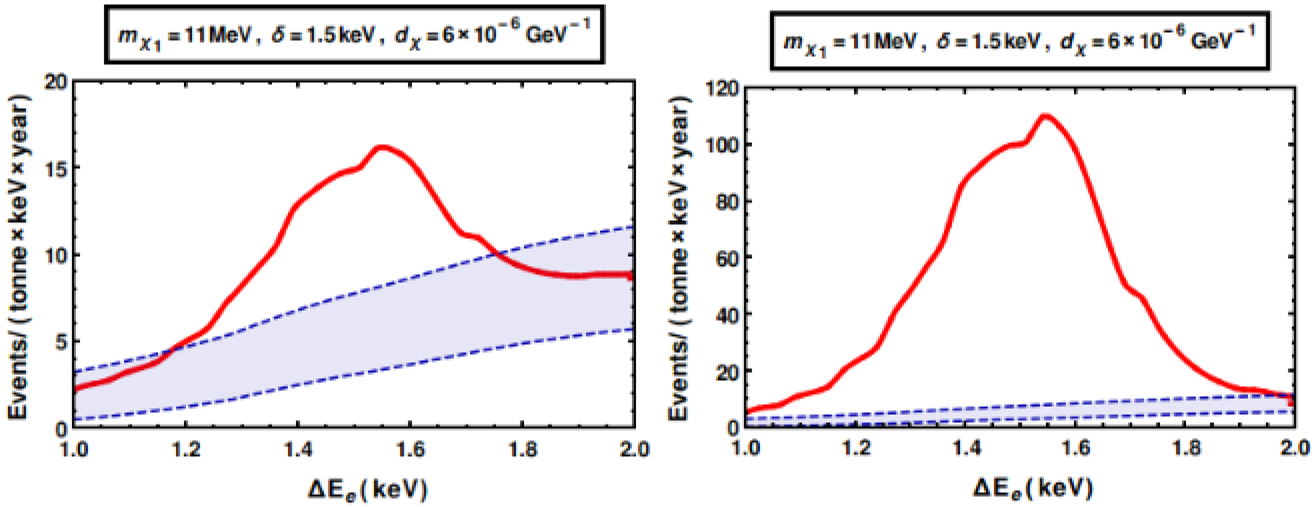
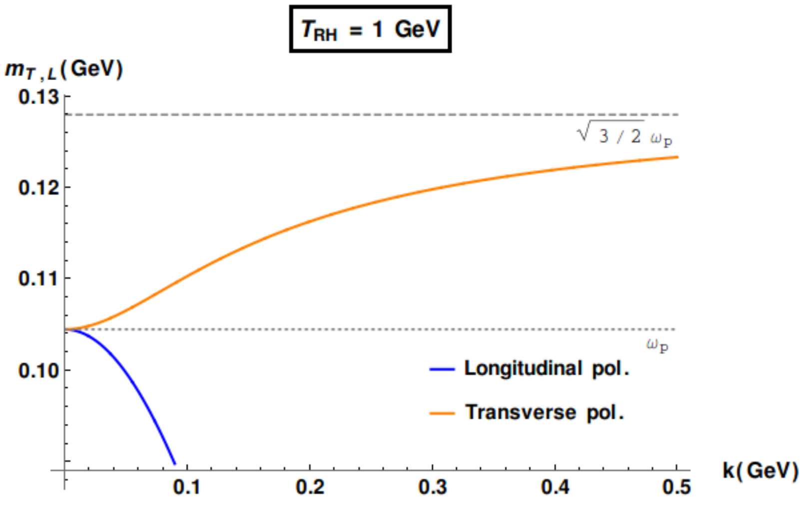


(a) $m_{\chi_1} = 11\,\mathrm{MeV}$, $\delta = 1.5\,\mathrm{keV}$ at XENONnT (b) $m_{\chi_1} = 11\,\mathrm{MeV}$, $\delta = 1.5\,\mathrm{keV}$ at DARWIN

FIG. 10: Differential event rates for EDM DM with $\delta = 1.5\,\mathrm{keV}$. Shown in blue are the background rates with the band representing Poissonian ($\pm\sqrt{N}$) uncertainties and shown in red are the signal+background rates.

Plasmon production



$$\Gamma_{T,L} = \int \frac{d^3 p_{\chi 2}}{(2\pi)^3 (2E_{\chi 2})} \frac{d^3 p_{\chi 1}}{(2\pi)^3 (2E_{\chi 1})} (2\pi)^4 \delta^4 (k - p_{\chi 1} - p_{\chi 2}) \frac{1}{2\omega_{T,L}} \sum_{\text{spins}} |\mathcal{M}|^2_{\gamma^* \to \chi_1, \chi_2}$$

$$\omega_p^2 = \sum_{\psi \in SM} \frac{4\alpha}{\pi} \int_0^\infty dp \frac{p^2}{E} \left(1 - \frac{1}{3} v^2\right) (f_\psi + f_{\bar\psi})$$

$$\omega_1^2 = \sum_{\psi \in SM} \frac{4\alpha}{\pi} \int_0^\infty dp \frac{p^2}{E} \left(\frac{5}{3} v^2 - v^4\right) (f_\psi + f_{\bar\psi})$$

$$\omega_T^2 = |\vec{k}|^2 + \omega_p^2 \frac{3\omega_T^2}{2v_\star^2 |\vec{k}|^2} \left(1 - \frac{\omega_T^2 - v_\star^2 |\vec{k}|^2}{2\omega_T v_\star |\vec{k}|} \ln \frac{\omega_T + v_\star |\vec{k}|}{\omega_T - v_\star |\vec{k}|}\right), \quad 0 \le |\vec{k}| < \infty$$

$$\omega_L^2 = \omega_p^2 \frac{3\omega_L^2}{v_\star^2 |\vec{k}|^2} \left(\frac{\omega_L}{2v_\star |\vec{k}|} \ln \frac{\omega_L + v_\star |\vec{k}|}{\omega_L - v_\star |\vec{k}|} - 1\right), \quad 0 \le |\vec{k}| \le k_{max}$$

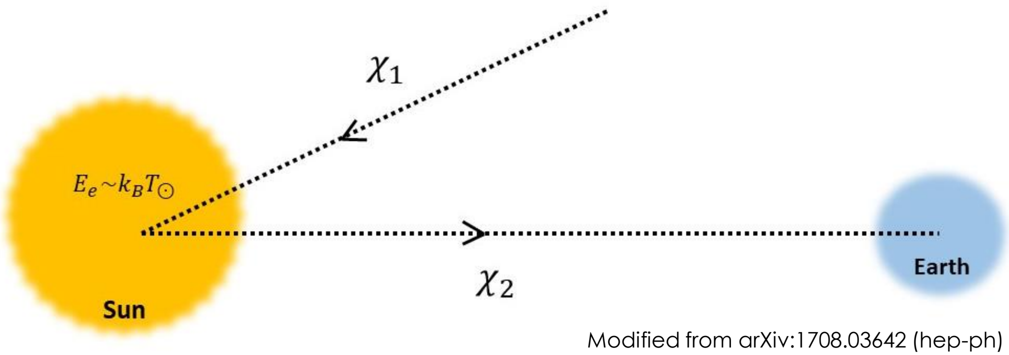
$$Z_T(k) = \frac{2\omega_T^2 (\omega_T^2 - v_\star^2 |\vec{k}|^2)}{3\omega_p^2 \omega_T^2 + (\omega_T^2 + |\vec{k}|^2)(\omega_T^2 - v_\star^2 |\vec{k}|^2) - 2\omega_T^2 (\omega_T^2 - |\vec{k}|^2)},$$

$$Z_L(k) = \frac{2(\omega_L^2 - v_\star^2 |\vec{k}|^2)}{3\omega_p^2 - (\omega_L^2 - v_\star^2 |\vec{k}|^2)} \frac{\omega_L^2}{\omega_L^2 - |\vec{k}|^2}.$$

Inelastic Dark Matter at XENON1T

$$\mathcal{L}_{int} \supset \frac{1}{2}\mu_\chi(\bar{\chi}_1\sigma_{\mu\nu}\chi_2)F^{\mu\nu} + \frac{i}{2}d_\chi(\bar{\chi}_1\sigma_{\mu\nu}\gamma_5\chi_2)F^{\mu\nu}$$

- The parameter space that reproduces observed relic density for freeze-in production leads to only χ_1 surviving on cosmological scales, χ_2 decays away
- The coincidence of the XENON1T threshold energy for electron recoil (1 keV) and the Sun's temperature ($T_\odot \simeq 1.1$ keV) leads to the interesting scenario of Solar up-scattering of χ_1 to χ_2 by electrons.
- The rates are given as:



Modified from arXiv:1708.03642 (hep-ph)

$$\frac{dR_{ion}}{d\Delta E_e} = n_T\, \epsilon(\Delta E_e) \sum_{n,l} \frac{1}{\Delta E_e - E_{nl}} \frac{\bar{\sigma}_e}{64\mu^2_{\chi_2,e}} \int dK_{\chi_2} \frac{d\Phi}{dK_{\chi_2}} \frac{m_{\chi_2}}{K_{\chi_2}} e^{-t(K_{\chi_2})\times\Gamma_{\chi_2}} \times \int_{q^-}^{q^+} dq\, q\, |F_{DM}(q)|^2 \left|f_{nl\to\Delta E_e - E_{nl}}(q)\right|^2$$

with Solar upscattering rate: $\frac{d\Phi}{dK_{\chi_2}} = n_e \langle \frac{d\sigma_{\chi_1\to\chi_2}}{dK_{\chi_2}} v_e \rangle \frac{n_{\chi_1,\odot} V_\odot}{4\pi(1AU)^2}$

atomic form factor: $\left|f_{nl\to\Delta E_e - E_{nl}}(q)\right|^2$

DM-electron reference cross section: $\bar{\sigma}_e$

An et al arXiv:1708.03642 (hep-ph)
Baryakhtar et al arXiv: 2006.13918 (hep-ph)

Back-up: Solar parameters for Inelastic DM