Underground production of electromagnetic dark states by MeV-scale electron beams and detection with CCDs

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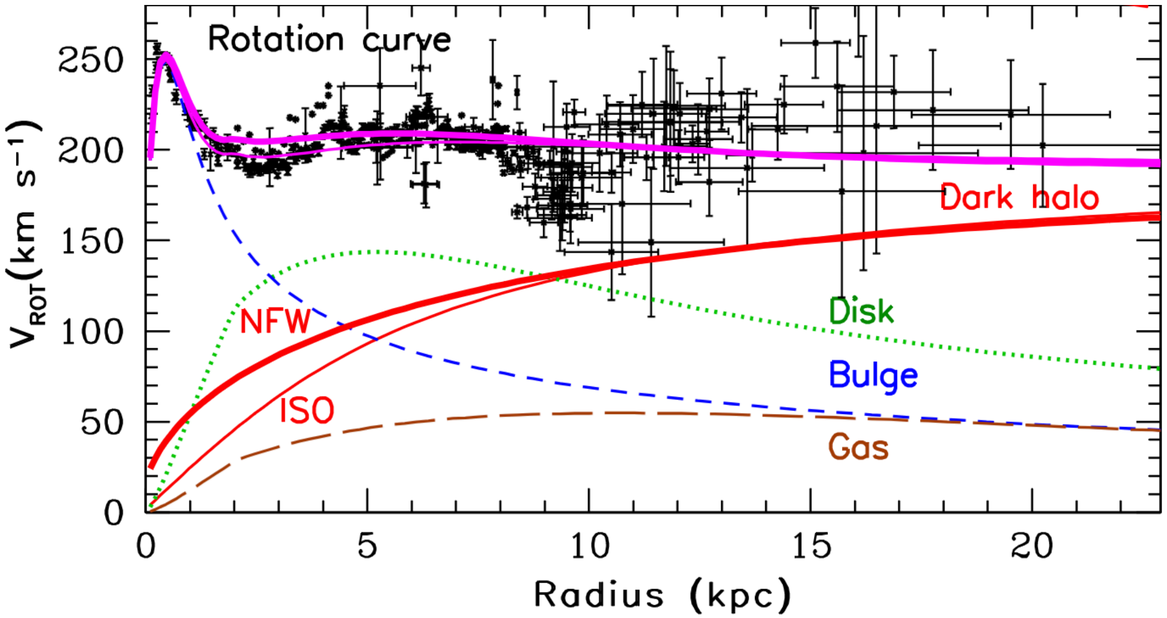
DISCRETE 2026 Bratislava
14th of November 2026

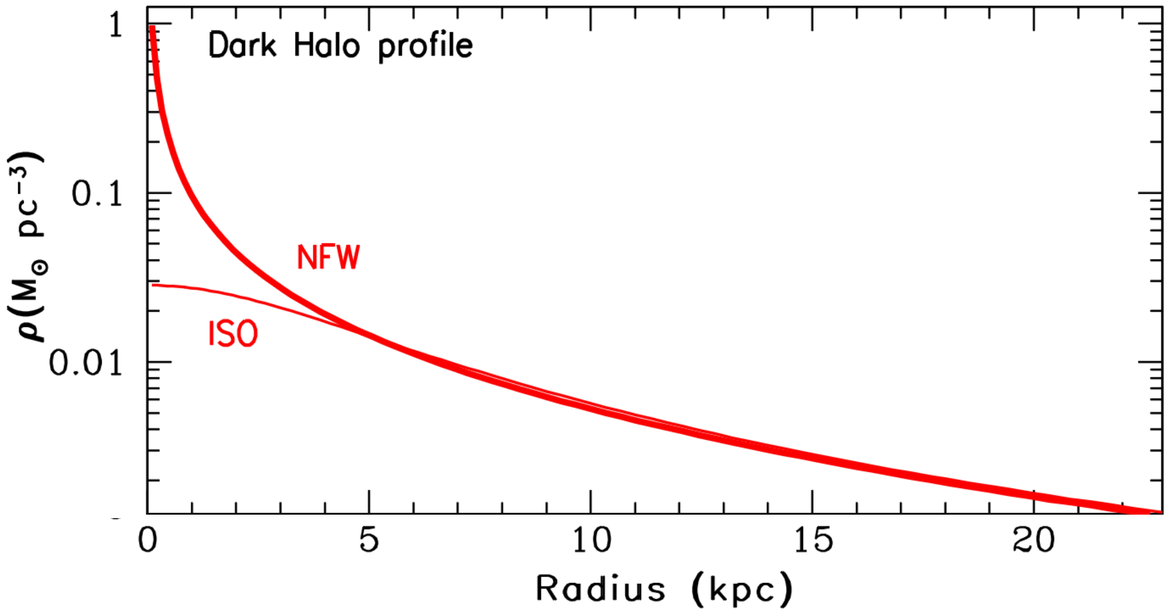
JHEP 05 (2026) 066 [arXiv:2511.02023]

Dark Matter Halos

Dark matter (DM) binds together to form halos surrounding galaxies and clusters

➡ *DM particles broadly follow Maxwell-Boltzmann velocity distribution*



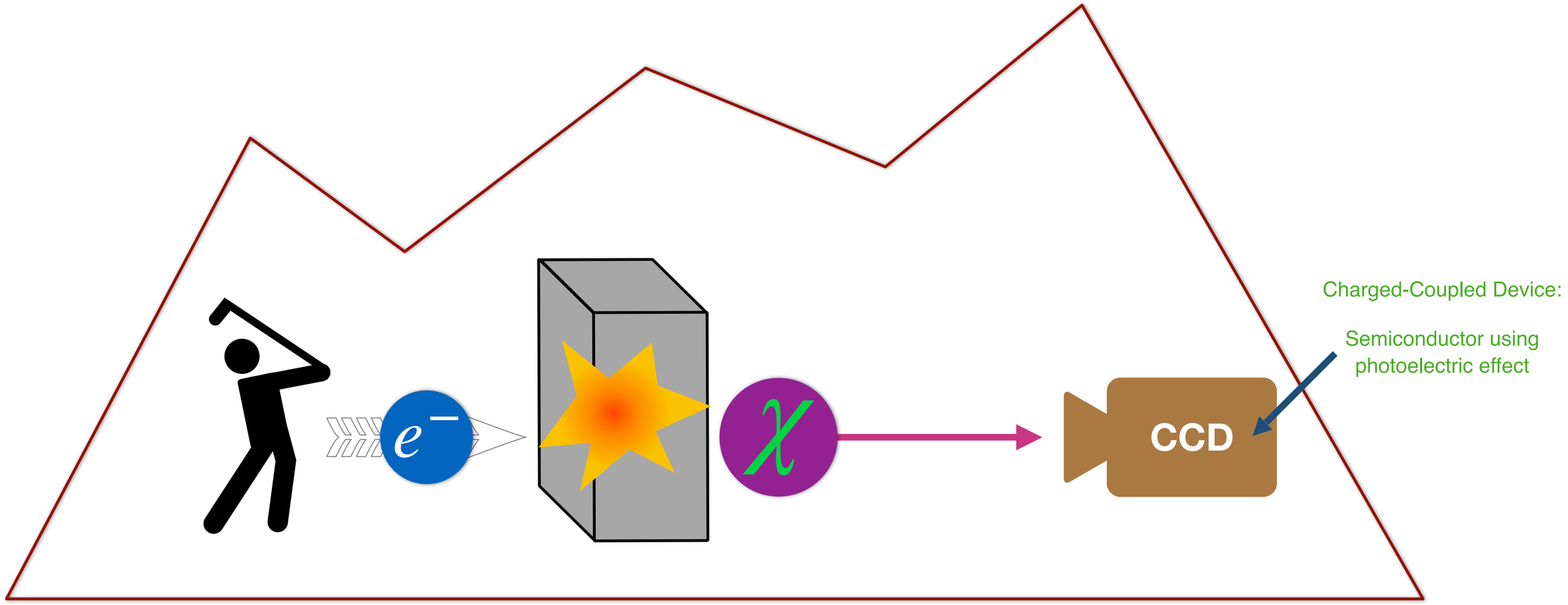


From: Prantzos et al., 2011, arXiv:1009.4620, https://doi.org/10.1103/RevModPhys.83.1001; Sofue et al., arXiv:0811.0859

Dark State Pair-Production in Underground Accelerators

Light Dark matter (DM) in the Galactic halo has low kinetic energy

➡ *Difficult to detect with ordinary direct detection experiments*



Solution: Produce relativistic particles in accelerator

Dark State Pair-Production in Underground Accelerators

Light Dark matter (DM) in the Galactic halo has low kinetic energy

➡ *Difficult to detect with ordinary direct detection experiments*

Goal: model production/detection of relativistic DM

Parameters:

Electron beam in the ~100 MeV range hitting beam dump

DM-mass of ~1 keV – 1 MeV

EM Form Factor Interactions

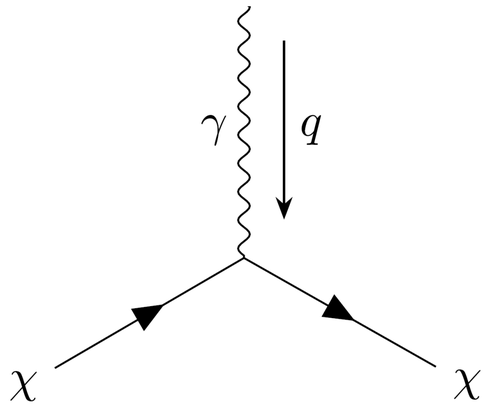
We assume DM interacts weakly with photons

➡ *Millicharge and electromagnetic (EM) form factor interactions*

Introduce new DM as Dirac fermion χ

Millicharge: from QED-like vertex

EM Form Factor: EFT Wilson coefficients



Millicharge: $\mathcal{L}_{\varepsilon e} = \varepsilon e\, \bar{\chi}\gamma^{\mu}\chi A_{\mu}$

Magnetic dipole: $\mathcal{L}_{\mathrm{MDM}} = \frac{1}{2}\mu_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$

Electric dipole: $\mathcal{L}_{\mathrm{EDM}} = \frac{i}{2}d_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu}$

Anapole: $\mathcal{L}_{\mathrm{AM}} = -\, a_{\chi}\, \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$

Charge radius: $\mathcal{L}_{\mathrm{CR}} = b_{\chi}\, \bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu}$

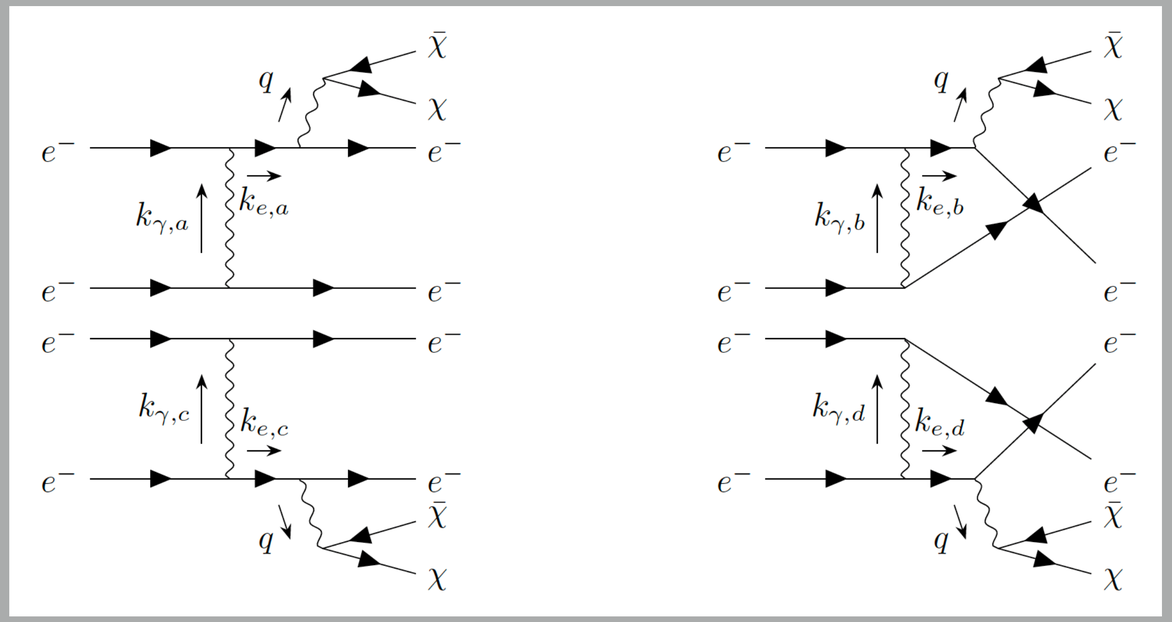
Based on: Chu, Pradler and Semmelrock, 2018, arXiv:1811.04095

Pair Production via Bremsstrahlung

The fermion χ is produced via 2→4 scattering in a beam dump

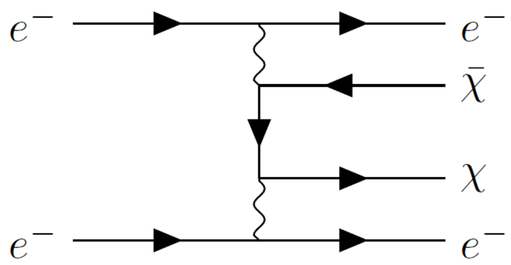
➡ *Focus on e-e scattering; for beam energy ~100 MeV, nuclear interactions are suppressed*

Bremsstrahlung production



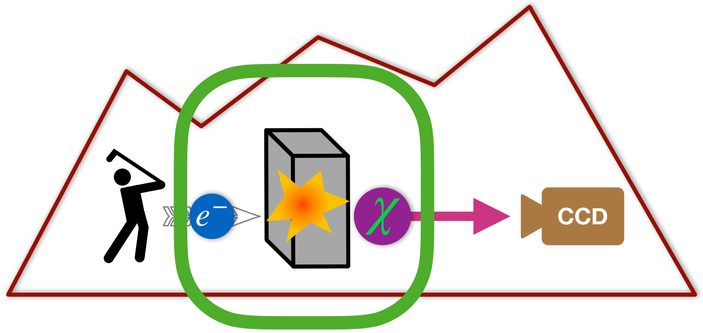
Production cross section

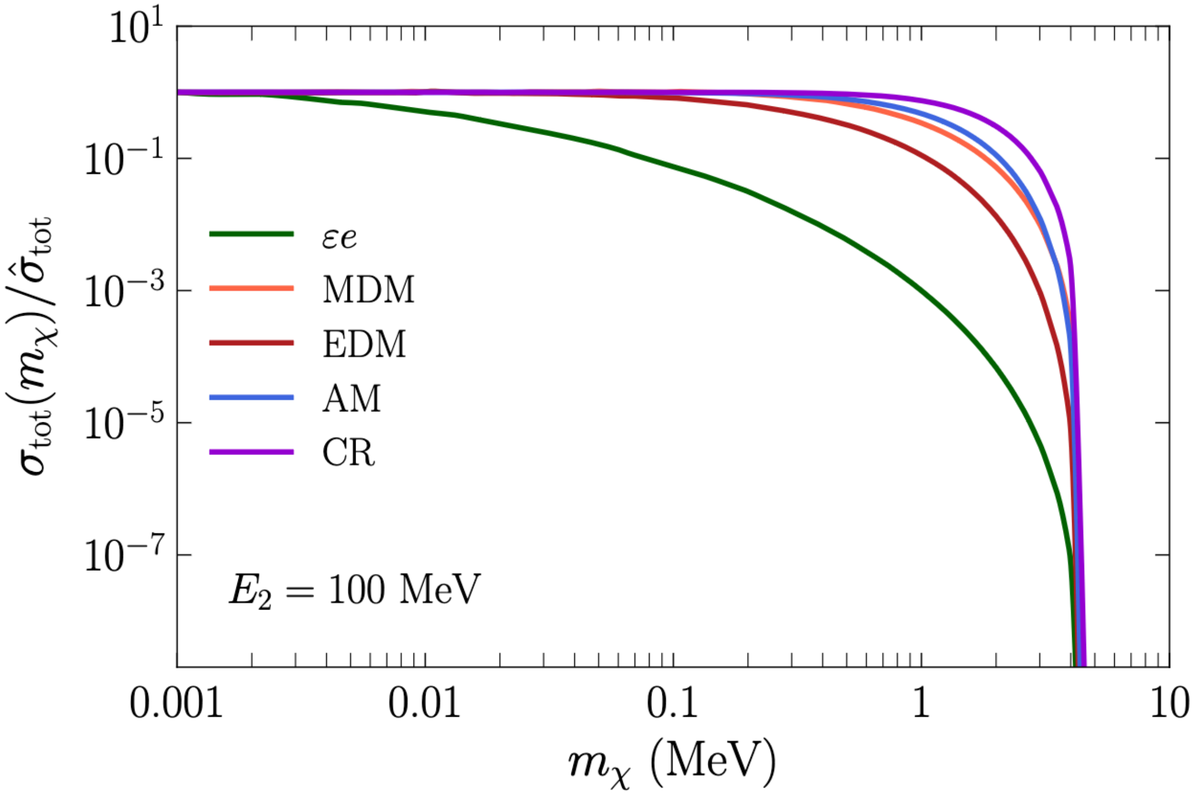
$$\frac{d^2\sigma_{\text{prod}}}{dE_\chi d\cos\theta_\chi} = \frac{|\vec{p}_\chi|}{4m_e|\vec{p}_2|}\int \frac{d\Pi_{2\to4}}{ds_{34\bar{\chi}}dt_{2\chi}}\frac{1}{|J|}|\mathcal{M}_{2\to4}|^2$$

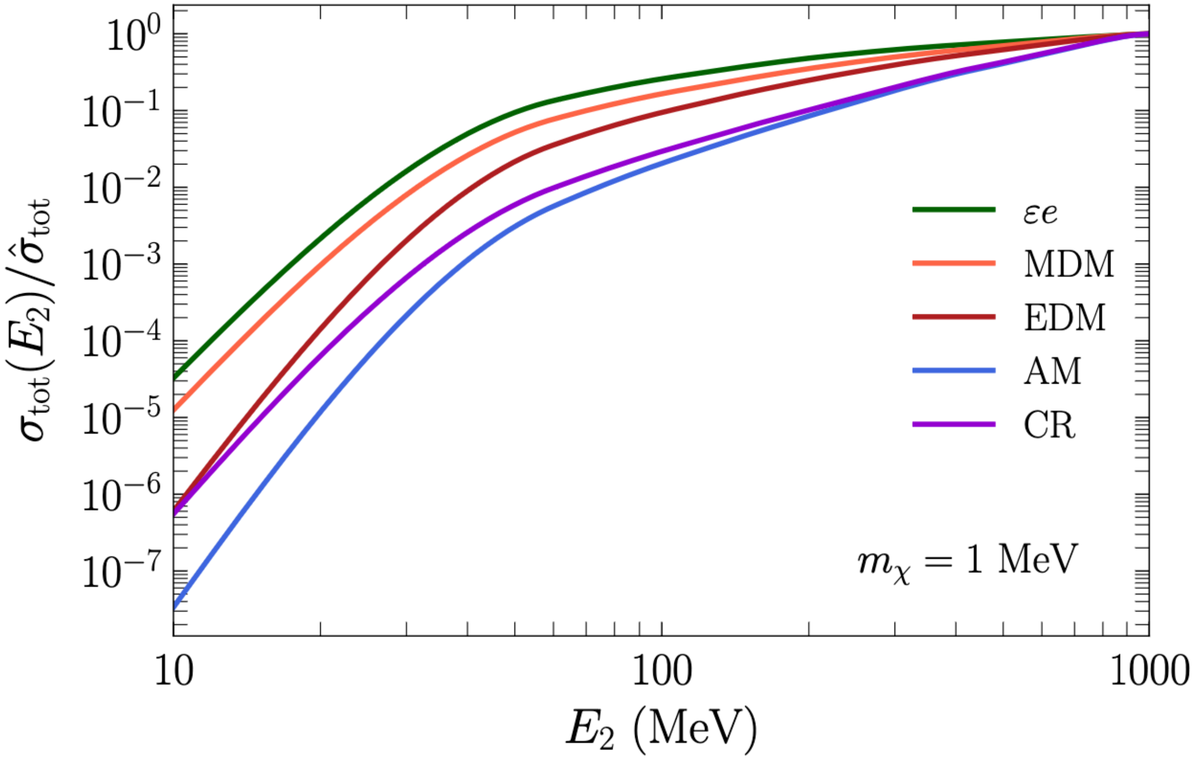


Internal bremsstrahlung is suppressed by small coupling

Pair Production via Bremsstrahlung



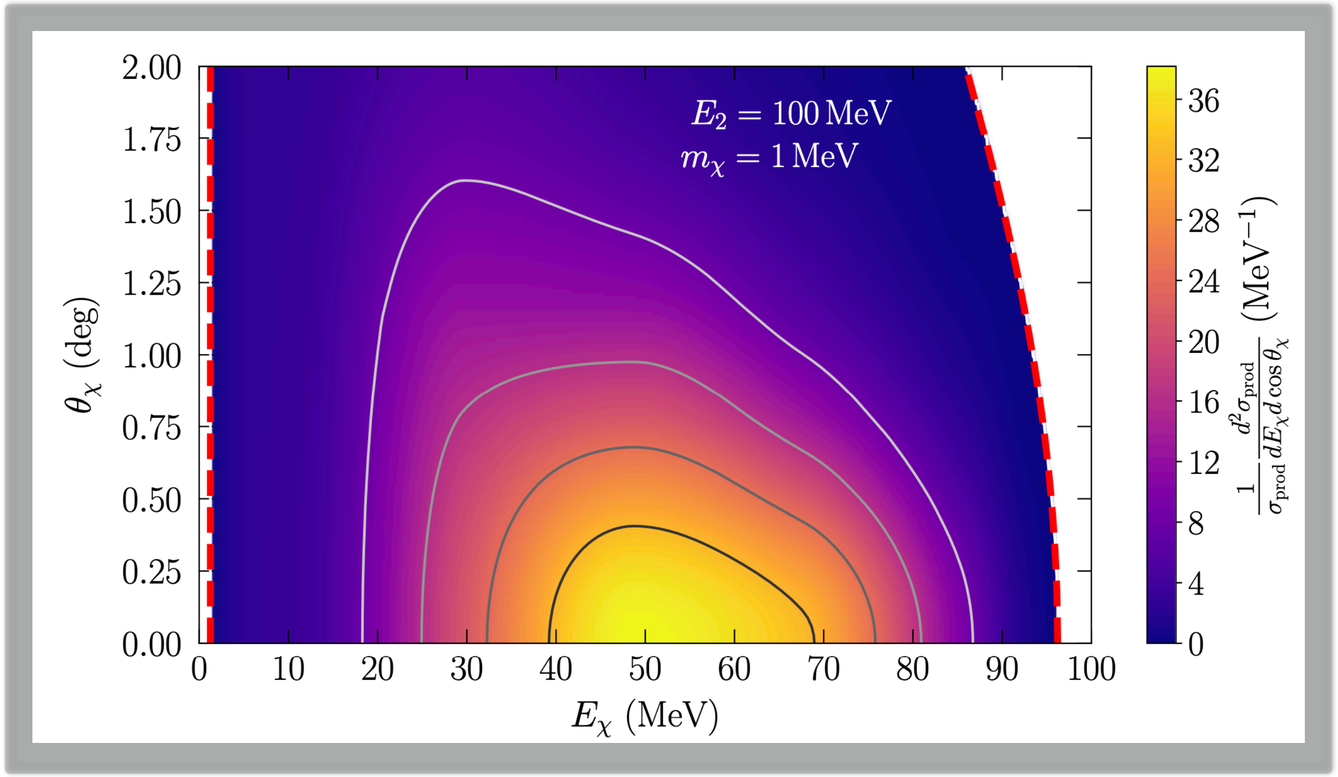


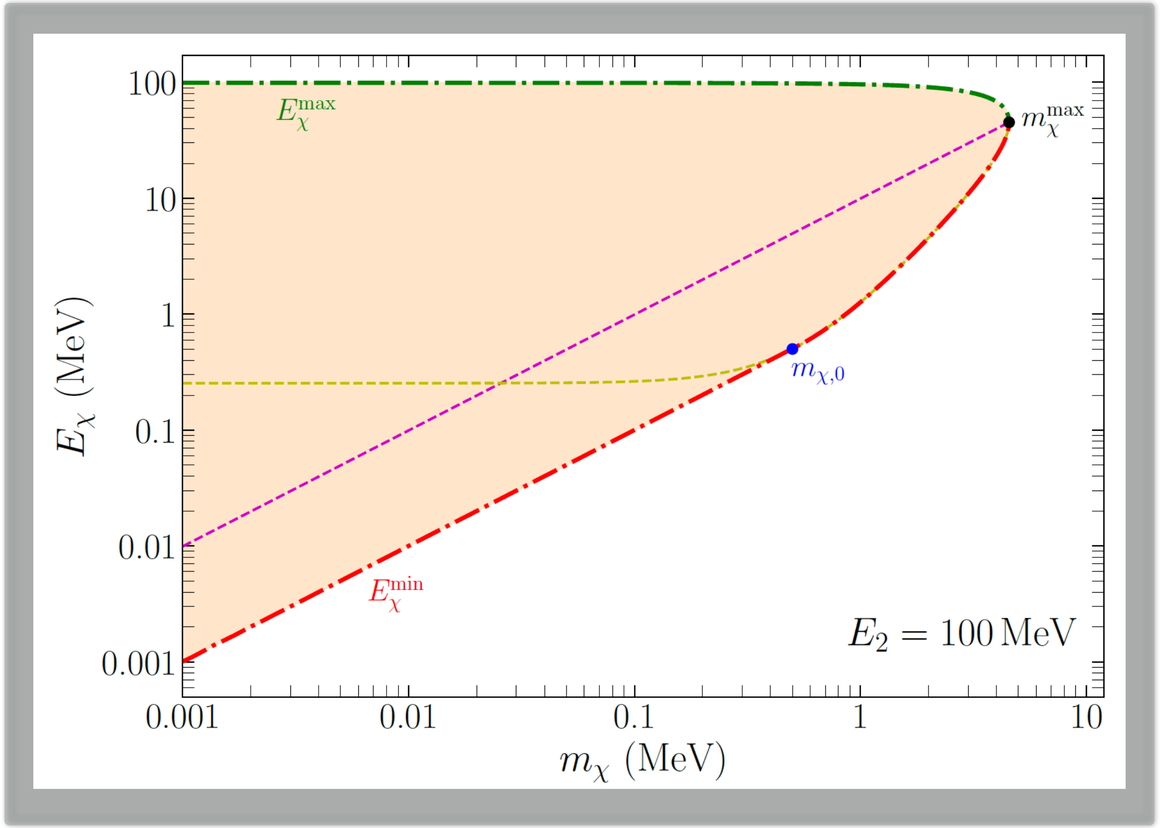


Analytical Four Body Phase Space

A four body phase space highly non-trivial and has 7 independent Lorentz invariants

➡ *Analytic treatment instead of event generators*





Detection via Solid State Effects

Detection happens in semi conductors, e.g. CMOS or CCD

➡ *Solid state effects, such as plasmons, become important*

χ-electron interaction modelled through electron loss function:

$$\frac{d\sigma_{e\chi,\mathrm{bnd}}}{dE_R} = \frac{e^2}{2n\pi^2\beta^2}\int_{E_R/\beta}^{2|\vec{p}_\chi|-E_R/\beta}\frac{dk}{k}F(E_R,k)\left\{\mathrm{Im}\left(\frac{-1}{\epsilon(E_R,k)}\right)+(\beta^2k^2-E_R^2)\mathrm{Im}\left(\frac{-1}{k^2-E_R^2\epsilon(E_R,k)}\right)\right\}$$

The dielectric function $\epsilon(E_R,k)$ is calculated via QCDark and accounts for effects like plasmons.

The interaction type enters through a form factor:

$$F_{\varepsilon e} = \varepsilon^2$$
$$F_{\mathrm{MDM}}/\mu_\chi^2 = F_{\mathrm{EDM}}/d_\chi^2 = (k^2-E_R^2)/e^2$$
$$F_{\mathrm{AM}}/a_\chi^2 = F_{\mathrm{CR}}/b_\chi^2 = (k^2-E_R^2)^2/e^2$$

[Dreyer et al., 2023, arXiv:2306.14944], [Essig et al., 2024, arXiv:2403.00123]

Detection Event Rate

The detection cross section is binned into n-electron events

➡ *We consider 2-7 electron events due to detector properties*

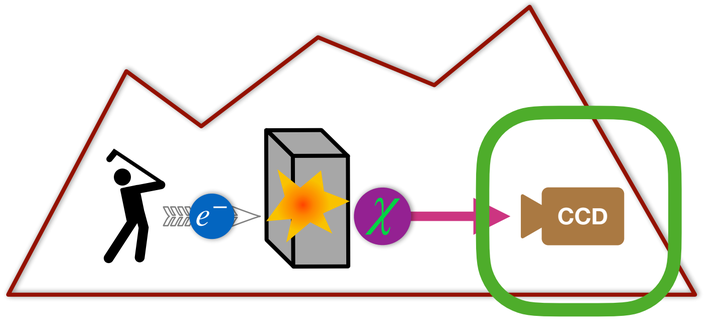
$$\sigma_n = \int_{E_R^{\min}}^{E_R^{\max}} dE\, p_n(E) \frac{d\sigma_{e\chi}}{dE_R} \longrightarrow \sigma_{\rm det} = \sum_{n=2}^{7} \sigma_n$$

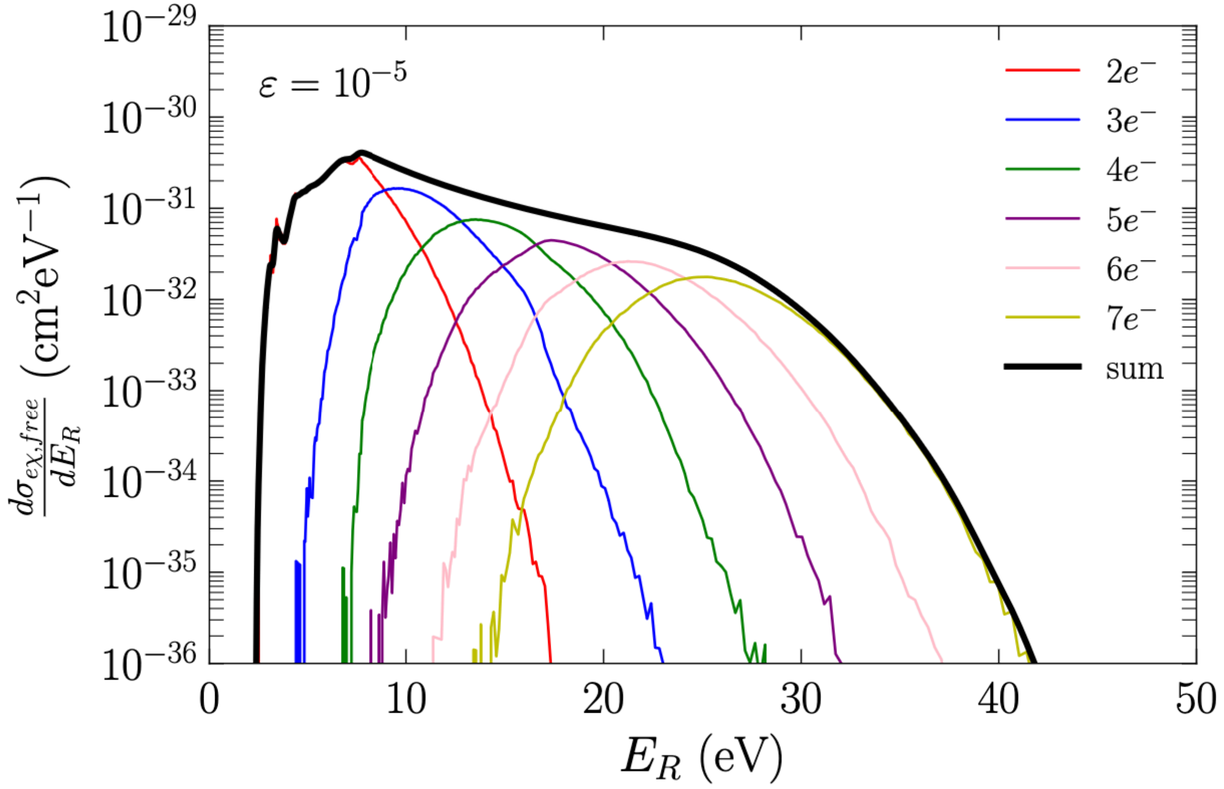
$$\frac{dN_{\rm event}}{dE_R} = N_{\rm EOT} n_T X_T n_{\rm det} L_{\rm det} \int dE_\chi d\cos\theta_\chi \frac{d^2\sigma_{\rm prod}}{dE_\chi d\cos\theta_\chi} \frac{d\sigma_{\rm det}}{dE_R}$$

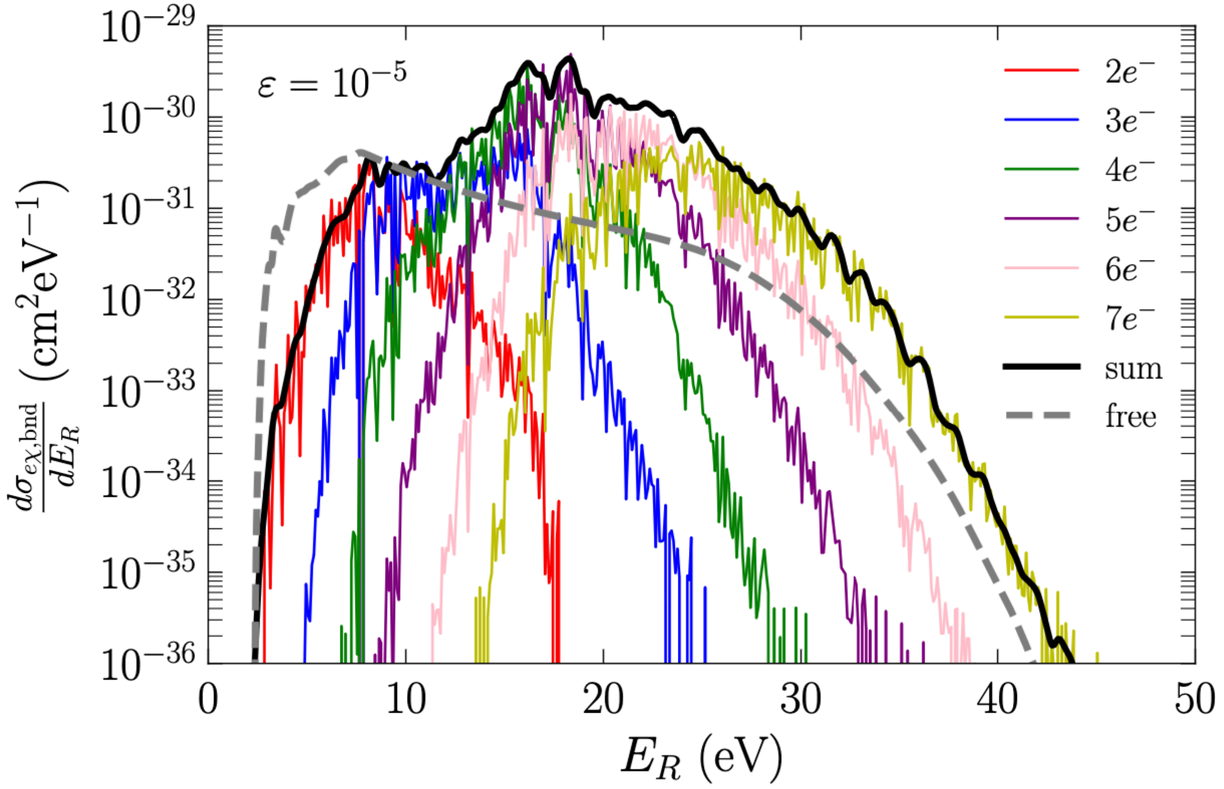
- $N_{\rm EOT}$: electrons on target
- n_T: beam dump electron density
- X_T: beam dump radiation length
- $n_{\rm det}$: detector electron density
- $L_{\rm det}$: detector length

[Ramanathan and Kurinsky, 2020, arXiv:2004.10709]

Detection via Solid State Effects

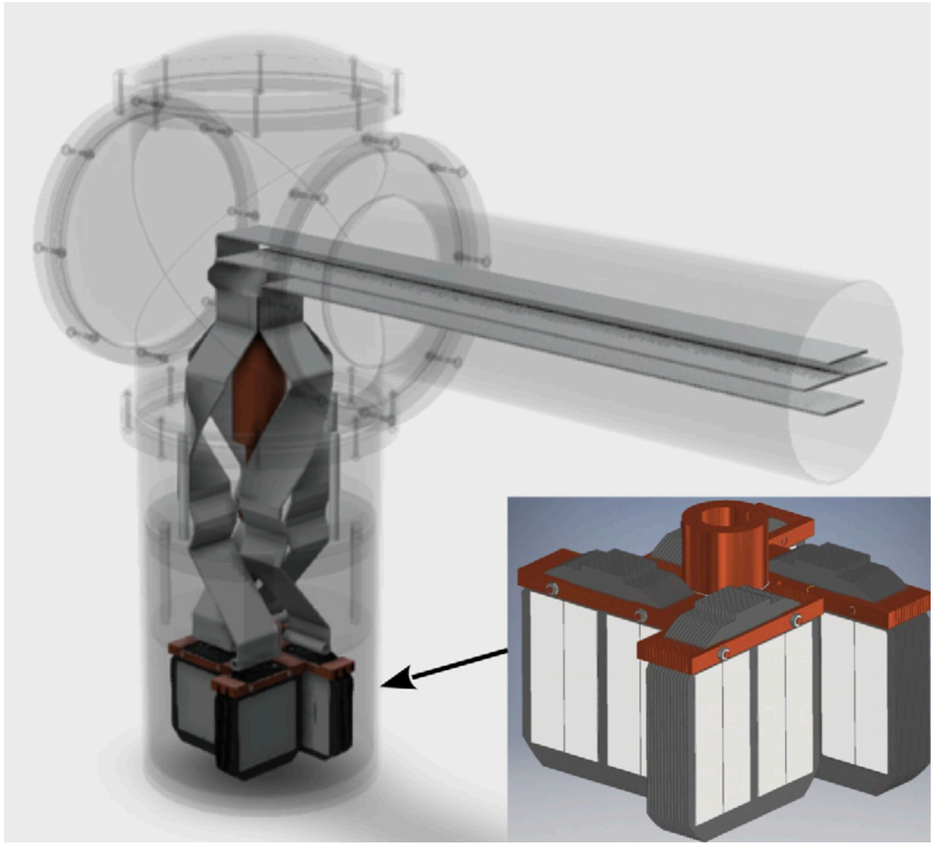






DAMIC-M as an Example

- DArk Matter In CCDs at Modane
- Successor to DAMIC at SNOLAB, Canada
- DM Direct detection using silicon CCDs with Skipper-CCD
- Single electron resolution → few eV energy resolution



Skipper-CCD:

Method to repeatedly measure the same charge packet in a CCD to reduce noise.

the Spokesperson for DAMIC-M is Paolo Privitera from U Chicago

[Papadopoulos for DAMIC-M collab., 2022, https://doi.org/10.1016/j.nima.2022.167184]

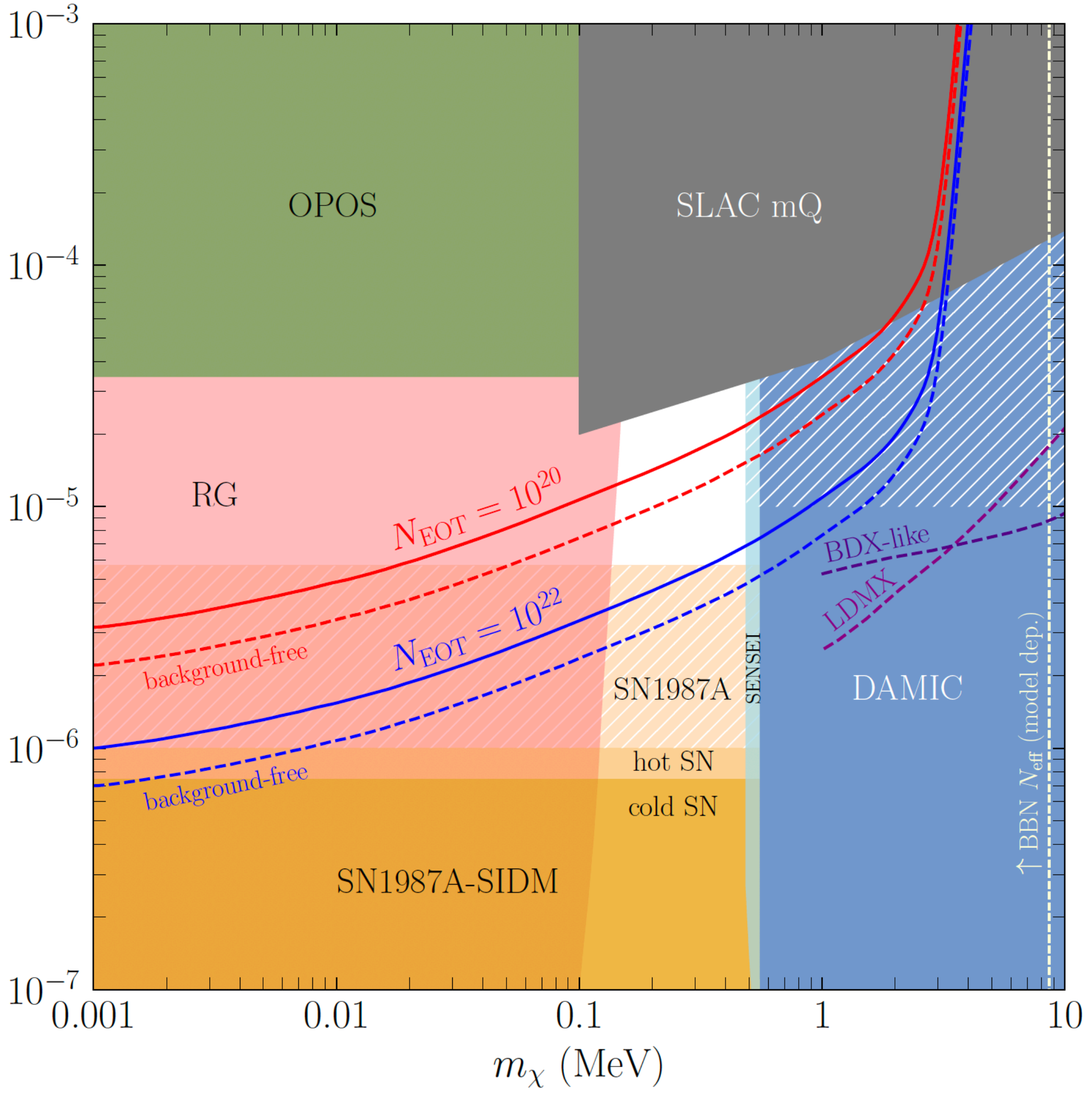
Millicharged Particles — Prediction

Results for an electron beam of 100 MeV

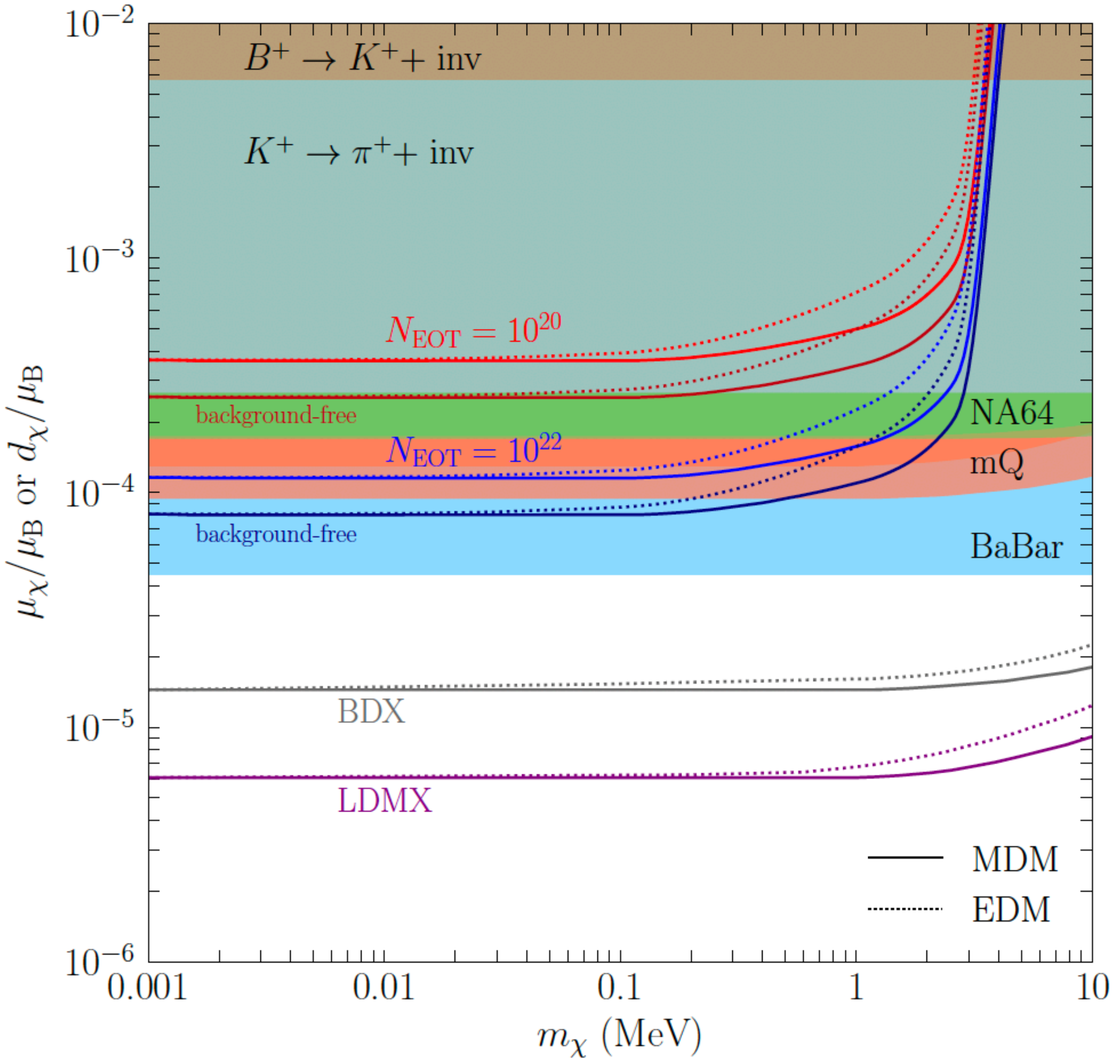
➡ *Useful for experimental proposals*

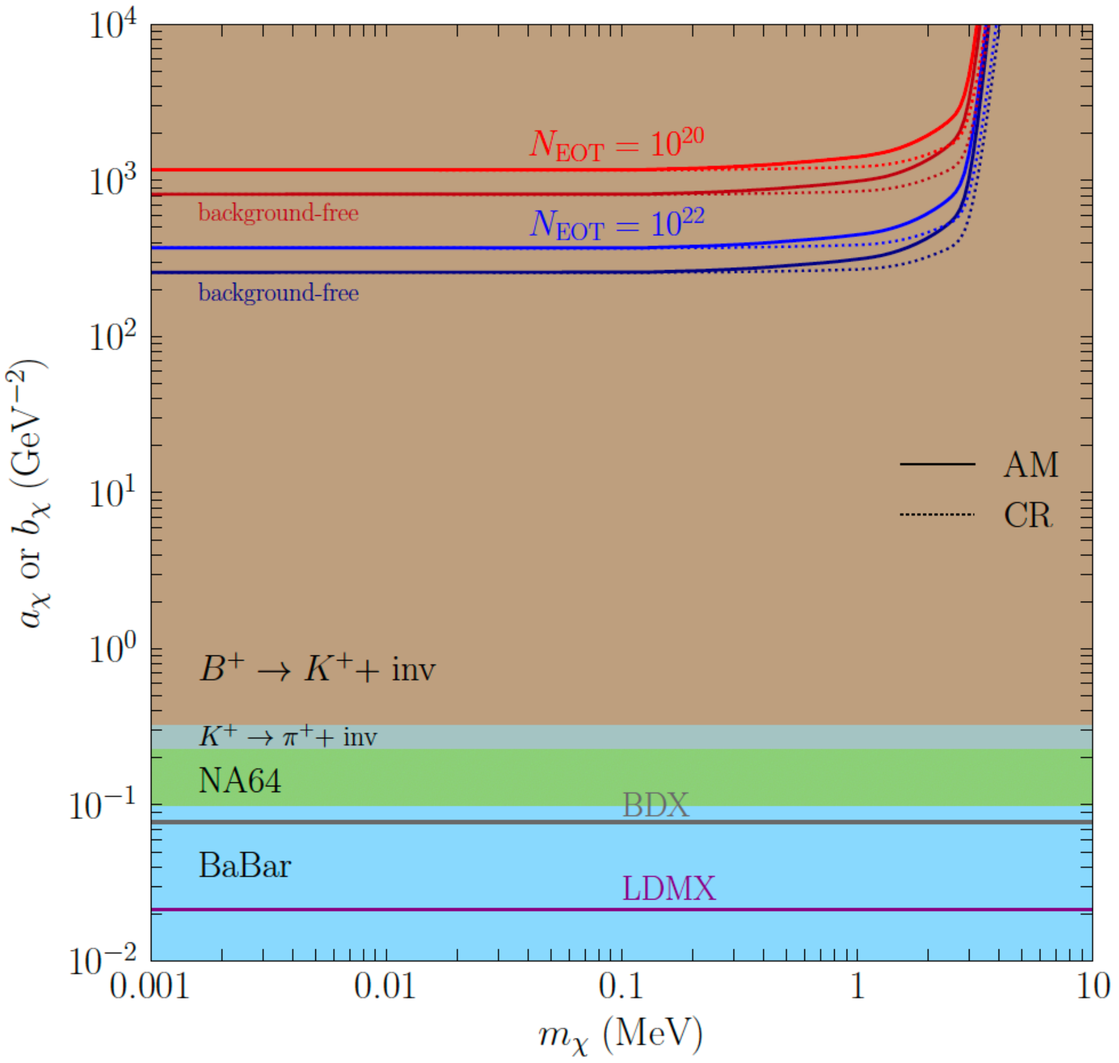
$n_{\rm det} = 4.7 \times 10^{22}\ {\rm cm}^{-3}$, $L_T = 52 \times 670\ \mu{\rm m}$, $N_{\rm EOT} = 10^{20}$,
$X_T = 0.56\ {\rm cm}$, $n_T = 2.7 \times 10^{24}\ {\rm cm}^{-3}$,
$\theta_\chi^{\rm max} = 1^\circ$, $\sqrt{s} \approx 10\ {\rm MeV}$

A millicharged particle of keV-MeV mass could be detected by this set-up.



Dipole & Dim-6 Dark Matter — Prediction





[Ramanathan and Kurinsky, 2020, arXiv:2004.10709]

Thank you for your attention!

Additional Slides

Dim-7 Operators

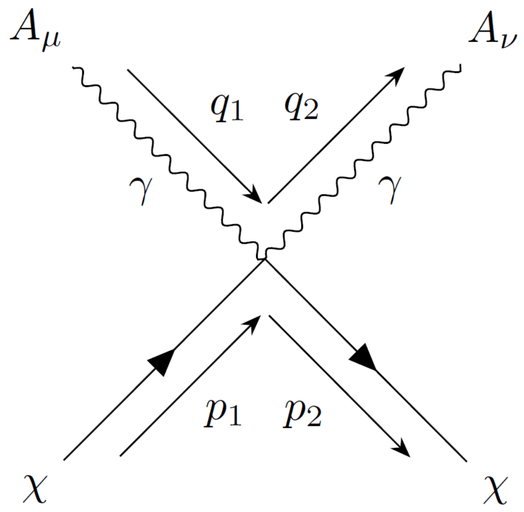
Additionally, we can consider 7-dimensional operators, called (pseudo)-Rayleigh or susceptibility operators:

$$\text{scalar Rayleigh interaction - SR } (r_\chi): \qquad \mathcal{L}_{Rs} = \frac{1}{4} r_\chi \, \bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$$

$$\text{pseudoscalar Rayleigh interaction - PR } (\tilde{r}_\chi): \qquad \mathcal{L}_{Rp} = \frac{i}{4} \tilde{r}_\chi \, \bar{\chi}\gamma^5\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

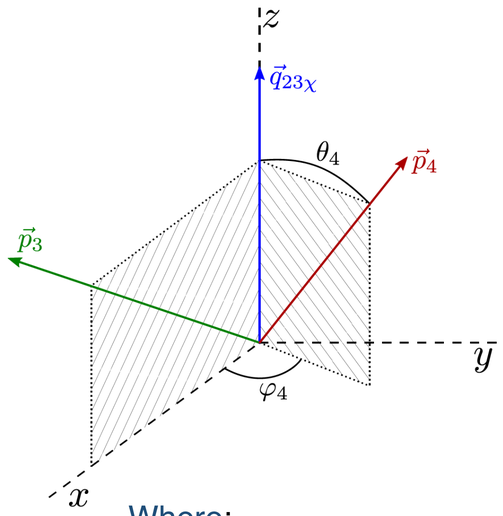
These give rise to the Feynman rules:

$$\text{SR:} \quad i\Gamma^{\mu\nu}_{Rs}(q_1, q_2) = i r_\chi (q_2^\mu q_1^\nu - q_1 \cdot q_2 \eta^{\mu\nu}),$$
$$\text{PR:} \quad i\Gamma^{\mu\nu}_{Rp}(q_1, q_2) = -\tilde{r}_\chi \gamma^5 \varepsilon^{\mu\nu\sigma\rho} q_{1\sigma} q_{2\rho}.$$



But as higher dimensional coupling are even more suppressed as well as these vertices only contributing to our processes starting at one loop, we can safely neglect them

4-body Phase Space: Derivation



The first sub-system consists of:

$$\{q_{4\bar{\chi}} = p_4 + p_{\bar{\chi}}, q_{23\chi}, p_3, p_4\}$$

In the frame where:

$$\vec{q}_{4\bar{\chi}} = 0,\ \vec{q}_{23\chi} \parallel z\text{-axis},\ \ \vec{p}_3 \parallel xz\text{-plane}$$

Insert into full integral

$$1 = \int \frac{ds_{4\bar{\chi}}}{2\pi} \frac{d^3q_{4\bar{\chi}}}{(2\pi)^3 2E_{4\bar{\chi}}} (2\pi)^4 \delta^{(4)}(q_{4\bar{\chi}} - p_4 - p_{\bar{\chi}})$$

Integrate over $p_3, q_{4\bar{\chi}}$ yielding

Where:

$$q_{23\chi}^2 = (p_2 - p_3 - p_\chi)^2 = 2m_e^2 + s_{4\bar{\chi}} + t_{2\chi} - s_{34\bar{\chi}} - t_{13}$$

$$\int \frac{d^3q_{4\bar{\chi}}}{(2\pi)^3 2E_{4\bar{\chi}}} \frac{d^3p_3}{(2\pi)^3 2E_3} (2\pi)^4 \delta^{(4)}(q_{34\bar{\chi}} - q_{4\bar{\chi}} - p_3) = \int \frac{d\cos\theta_3}{2\pi} \frac{d\varphi_3}{2\pi} \frac{P_3}{4\sqrt{s_{34\bar{\chi}}}}$$

Integrated sub-system is

$$d\Phi(q_{4\bar{\chi}}) = -\int \frac{dt_{14}}{2\pi} \frac{d\varphi_4}{2\pi} \frac{1}{4} \lambda^{-1/2}(s_{4\bar{\chi}}, m_e^2, q_{23\chi}^2)$$

$$\lambda(a,b,c) = (a-b-c)^2 - 4bc$$

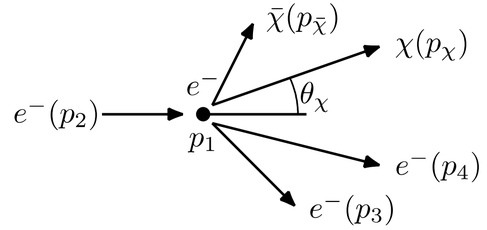
$$dt_{14} = -2P_4\sqrt{\vec{q}_{23\chi}^2}\, d\cos\theta_4$$

We have the pair-production process

$$e^-(p_1) + e^-(p_2) \to e^-(p_3) + e^-(p_4) + \chi(p_\chi) + \bar{\chi}(p_{\bar{\chi}})$$

The input parameters are

$$\{p_1 \cdot p_2, m_e, m_\chi\}$$



Good choice of Lorentz invariants for our problem:

$$s_{4\bar{\chi}} = (p_4 + p_{\bar{\chi}})^2,\ s_{34\bar{\chi}} = (p_3 + p_4 + p_{\bar{\chi}})^2,\ t_{14} = (p_1 - p_4)^2$$
$$t_{13} = (p_1 - p_3)^2,\ t_{2\chi} = (p_2 - p_\chi)^2,\ p_2 \cdot p_3,\ p_3 \cdot p_4$$

Focussing on χ, and integrating yields

$$\frac{d\Pi_{2\to4}}{ds_{34\bar{\chi}} dt_{2\chi}} = \frac{1}{2} \int ds_{4\bar{\chi}} dt_{13} dt_{14} \frac{d\varphi_3}{2\pi} \frac{d\varphi_4}{2\pi} \frac{|J|}{(4\pi)^5} \lambda^{-1/2}(s_{4\bar{\chi}}, m_e^2, q_{23\chi}^2) \lambda^{-1/2}(s_{34\bar{\chi}}, m_e^2, t_{2\chi})$$

The $|J|$ is related to the variable transform:

$$\frac{dE_\chi d\cos\theta_\chi}{ds_{34\bar{\chi}} dt_{2\chi}} = \frac{|J|}{|\vec{p}_\chi|} = \frac{1}{4|\vec{p}_2||\vec{p}_\chi| m_e}$$

4-body Phase Space: Limits

Physical integration limits of Lorentz invariants:

$$\varphi_3 \in [0, 2\pi), \;\; \varphi_4 \in [0, 2\pi)$$

$$(2m_e + m_\chi)^2 \leq s_{34\bar{\chi}} \leq (\sqrt{s} - m_\chi)^2$$

$$(m_e + m_\chi)^2 \leq s_{4\bar{\chi}} \leq (\sqrt{s_{34\bar{\chi}}} - m_e)^2$$

$$[t_{2\chi}]^{\pm} = m_e^2 + m_\chi^2 - \frac{1}{2}(s + m_\chi^2 - s_{34\bar{\chi}}) \pm \frac{1}{2s}\lambda^{1/2}(s, m_e^2, m_e^2)\lambda^{1/2}(s, s_{34\bar{\chi}}, m_\chi^2)$$

$$[t_{14}]^{\pm} = 2m_e^2 - \frac{1}{2s_{4\bar{\chi}}}(s_{4\bar{\chi}} + m_e^2 - q_{23\chi})(s_{4\bar{\chi}} + m_e^2 - m_\chi^2) \pm \frac{1}{2s_{4\bar{\chi}}}\lambda^{1/2}(s_{4\bar{\chi}}, q_{23\chi}, m_e^2)\lambda^{1/2}(s_{4\bar{\chi}}, m_\chi^2, m_e^2)$$

$$[t_{13}]^{\pm} = 2m_2^2 - \frac{1}{2s_{34\bar{\chi}}}(s_{34\bar{\chi}} + m_e^2 - t_{2\chi})(s_{34\bar{\chi}} + m_e^2 - s_{4\bar{\chi}}) \pm \frac{1}{2s_{34\bar{\chi}}}\lambda^{1/2}(s_{34\bar{\chi}}, t_{2\chi}, m_e^2)\lambda^{1/2}(s_{34\bar{\chi}}, s_{4\bar{\chi}}, m_e^2)$$

- While a Lorentz invariant phase space is very general, it is more convent to work with variables tailored to the problem
- In our case, we want to use the energy and angle of the produced particles, so we transform

$$E_\chi = \tfrac{1}{2}m_e + E_2 - \tfrac{1}{2m_e}(s_{34\bar{\chi}} - t_{2\chi}), \;\; \cos\theta_\chi = \frac{s_{34\bar{\chi}} - 2me^2 - m_\chi^2 + 2E_2E_\chi + 2m_eE_\chi - 2m_eE_2}{2\sqrt{E_\chi^2 - m_\chi^2}\sqrt{E_2^2 - m_e^2}}$$

- We get the limits:

$$E_\chi \geq \frac{m_\chi(2m_e + E_2)}{\sqrt{2me(m_e + E_2)}}$$

$$E_\chi \leq \frac{E_2}{2} + \frac{2m_e + E_2}{2m_e(m_e + E_2)}\left(m_\chi^2 - (2m_e + m_\chi)^2\right) + \frac{\sqrt{E_2^2 - m_e^2}}{4m_e(m_e + E_2)}\sqrt{2m_eE_2 - 3m_e^2}\sqrt{2m_eE_2 - 2(m_e^2 + 2m_\chi^2 + 4m_em_\chi)}$$

$$1 \leq \cos\theta_\chi \leq \max\left(-1, \frac{E_2(E_\chi - m_e) + m_e(E_\chi + 2m_\chi + m_e)}{\sqrt{E_\chi^2 - m_\chi^2}\sqrt{E_2^2 - m_e^2}}\right)$$

Angle accounts for relativistic boosting

UV Complete Examples

Millicharged DM arises in massless Dark Photon theories:

Introduce two U(1) gauge fields $\hat{A}_\mu$ and $\bar{A}_\mu$.

These couple to the SM current J_μ and a dark current J'_μ.

The interaction Lagrangian with the kinetic mixing ε is:

$$\mathcal{L} = -\frac{\varepsilon}{2}\hat{F}^{\mu\nu}\bar{F}_{\mu\nu} + \hat{g}J'^{\mu}\hat{A}_\mu + \bar{g}J^\mu\bar{A}_\mu$$

Introduce A_μ and A'_μ by diagonalising the kinetic term:

$$\mathcal{L}' = \hat{g}J'^{\mu}A'_\mu + \left(-\frac{\hat{g}\varepsilon}{\sqrt{1-\varepsilon^2}}J'^{\mu} + \frac{\bar{g}}{\sqrt{1-\varepsilon^2}}J^\mu\right)A_\mu$$

A_μ is the usual photon field and A'_μ is the dark photon field.

Redefine charges to get the electric charge e and the dark charge e':

$$\mathcal{L}' = -e'\sqrt{1-\varepsilon^2}J'^{\mu}A'_\mu + (\varepsilon e J'^{\mu} + eJ^\mu)A_\mu$$

Photon now couples to the dark current with a millicharge

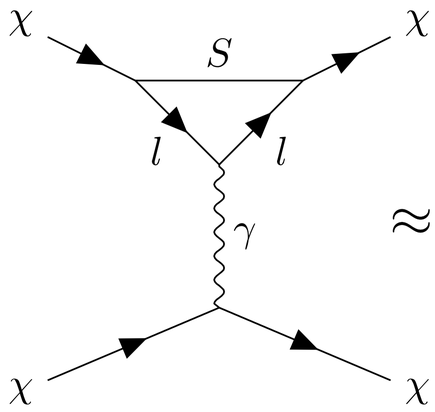
EM form factors can arise from loop effects in a UV-complete theory:

Consider a massive scalar S charged under $\mathrm{U}_Y(1)$ with hypercharge $Y = 1$.

Introduce a Yukawa interaction of a singlet Dirac fermion χ with leptons ψ_l

$$\mathcal{L}_S = -y_l S\bar{\chi}P_R\psi_l + \text{h.c.}, \quad y_l ... \text{Yukawa coupling.}$$

Take the following diagram and match it to the MDM effective operator:



$$\approx -\mu_\chi\sigma^{\mu\nu}q_\nu \Rightarrow \mu_\chi \sim \frac{y_l^2 Q}{M}\frac{m_l}{M}$$

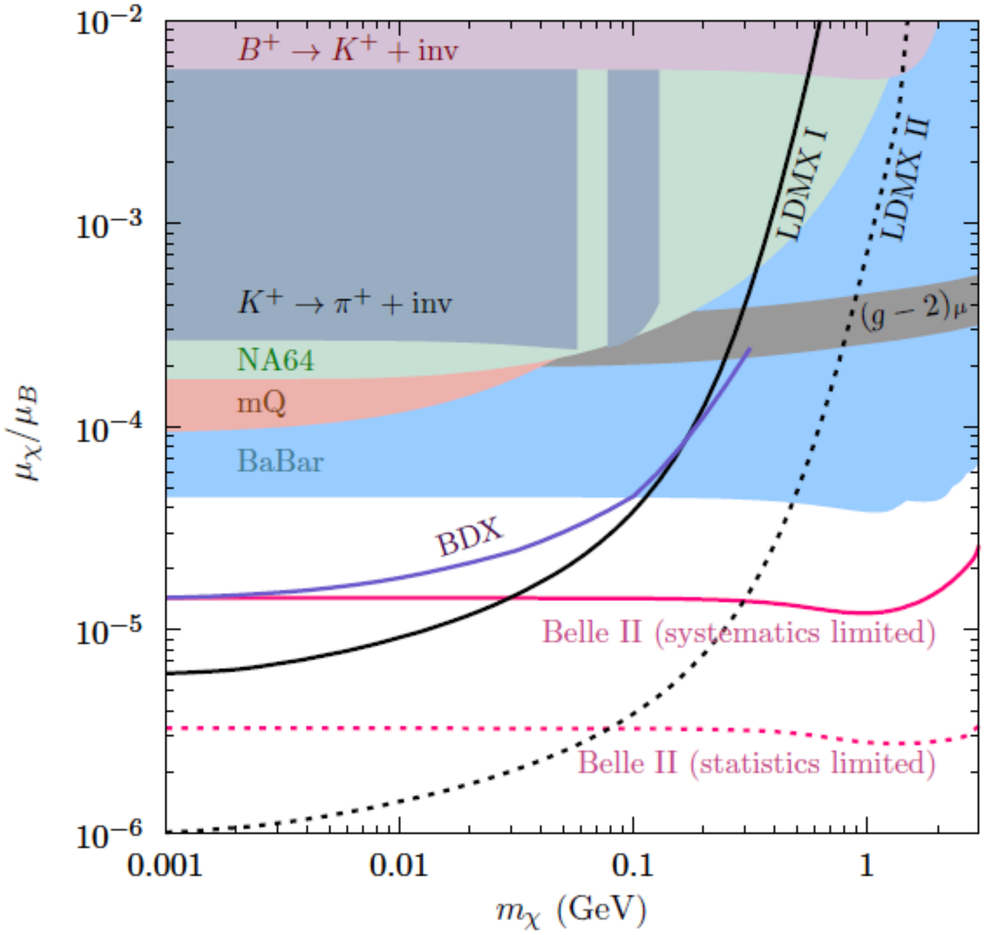
Electric charge of lepton

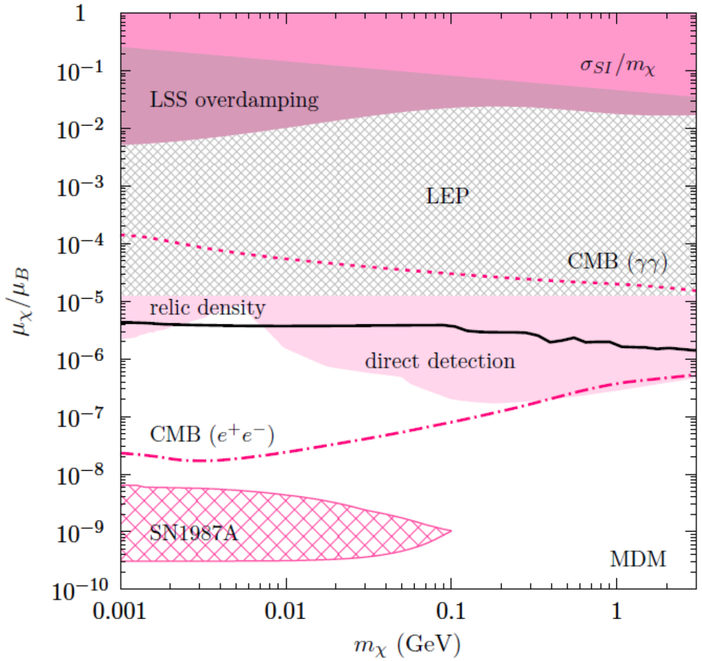
Lepton mass

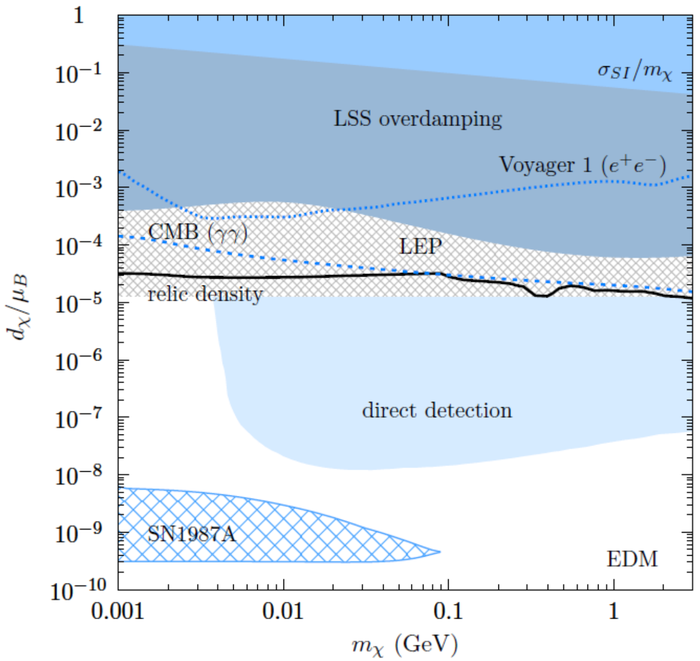
Mass of scalar

[Fabbrichesi et al., 2020, arXiv:2005.01515], [Kavanagh et al., 2018, arXiv:1810.00033]

Existing Bounds







[Chu, Pradler, Semmelrock, 2018, arXiv:1811.04095]

Potential Corrections

- Because of sensitivity of the detector, we need to consider low energy corrections to the detection cross section
- Possible bound state corrections are $\frac{d\sigma_1 - d\sigma_0}{d\sigma_0} = 10^{-3}$ approximately, which is negligible in our case
- The solid state effects inside the CCD effects can come from phonons and plasmons
- The corrections due to phonons would be of the order of phonon energies of ~0.1-100meV, additionally suppressed by the DM being relativistic and light
- Corrections from plasmon were considered through the electron loss function

[Plestid, Wise, 2024, arXiv:2403.12184]

Backgrounds

- Main background (BG) for CCD is dark current: avoided by discarding single charge events

- Beam induced BGs: low energy BG avoided by shielding between beam dump and detector
  high energy BG (e.g. muons) can be tagged by Skipper-CCD and excluded

- Simulations indicate that beam-induced neutrons are subdominant BGs

- Beam electrons (100 MeV) are stopped by having a dump and shielding of a few cm

- Meson BG are a non-issue due to beam energy below the pion production threshold