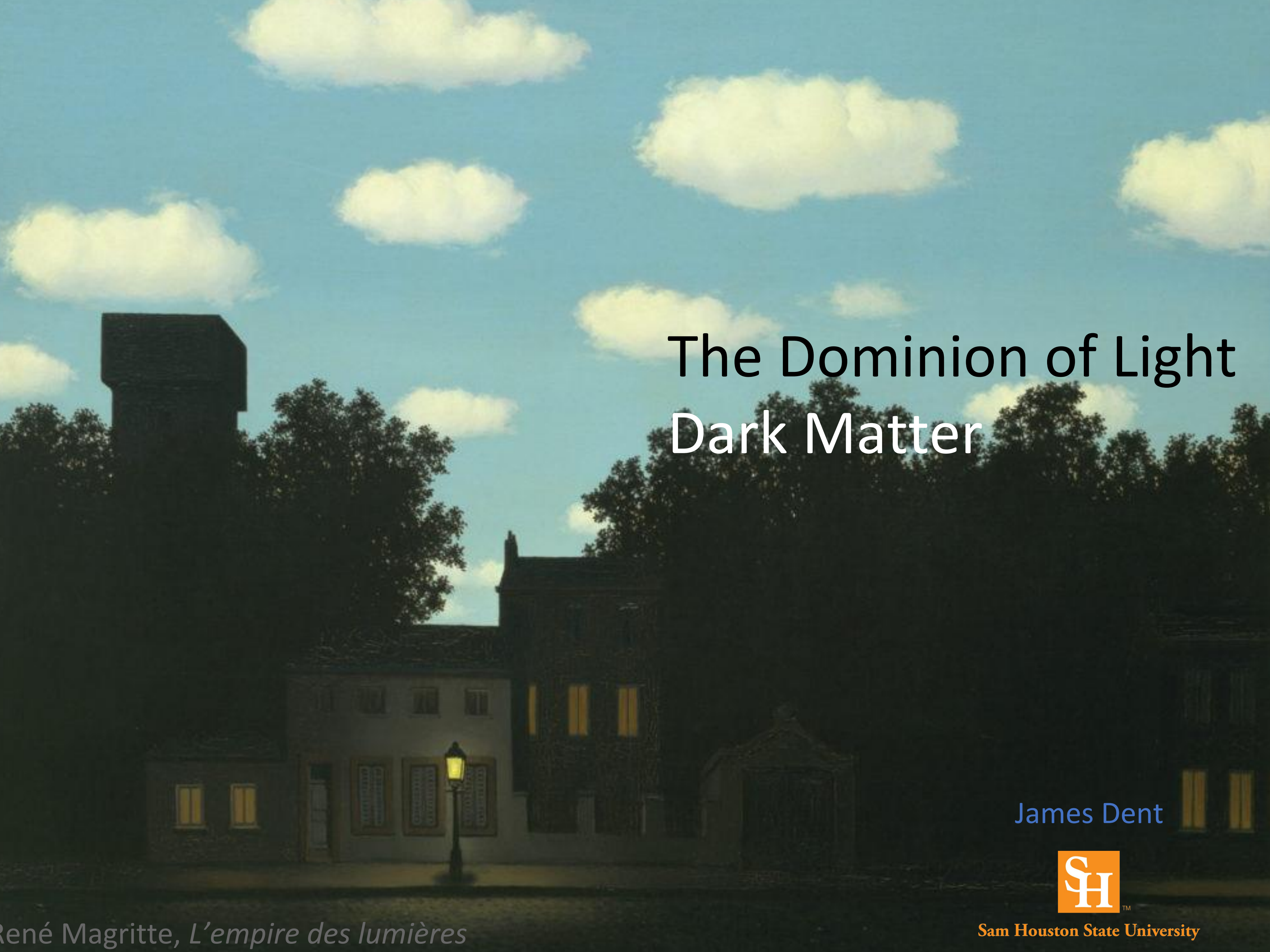
The Dominion of Light
Dark Matter

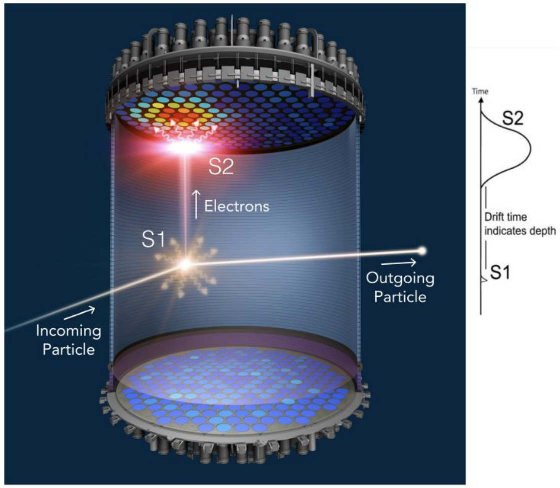


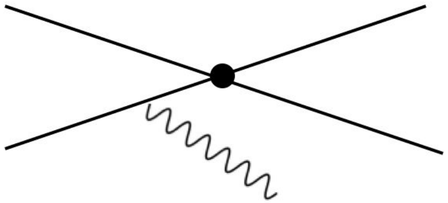
James Dent

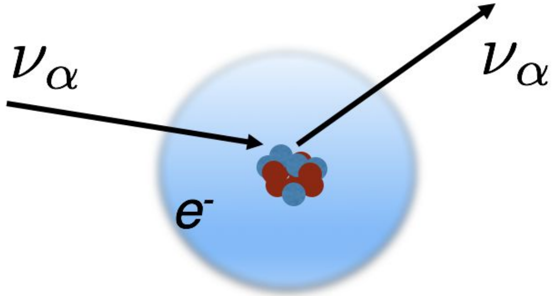
Sam Houston State University

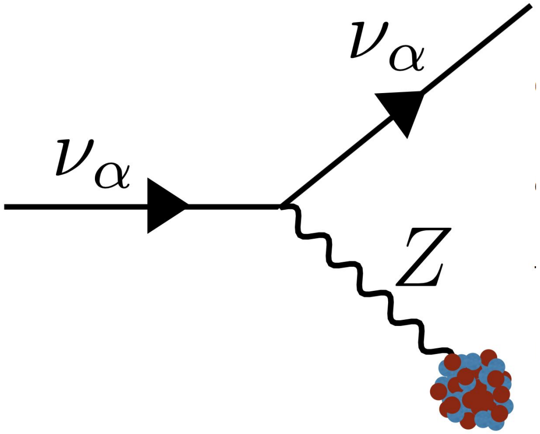
René Magritte, *L'empire des lumières*

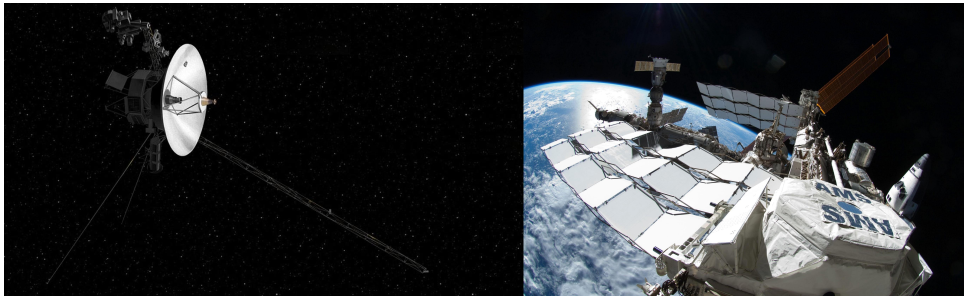
Outline


S2
Electrons
S1
Incoming Particle
Outgoing Particle
Time
S2
Drift time indicates depth
S1




ν_α
ν_α
e^-


ν_α
ν_α
Z



The Migdal Effect and Photon Bremsstrahlung in effective field theories of dark matter direct detection and coherent elastic neutrino-nucleus scattering

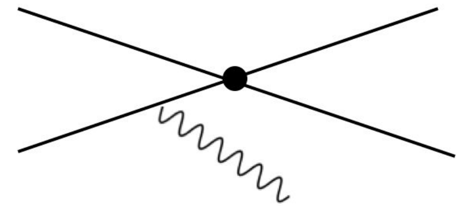
arXiv:1905.00046

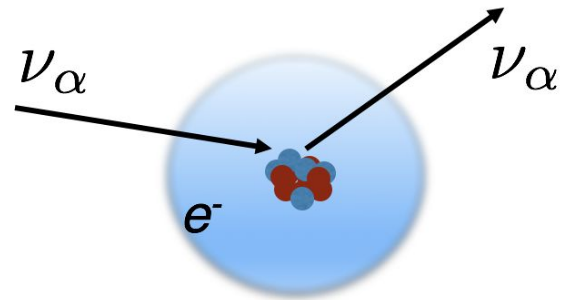
Nicole Bell Jayden Newstead Subir Sabharwal Tom Weiler

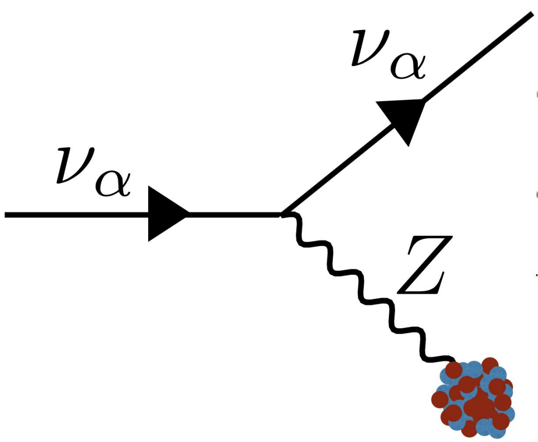
THE UNIVERSITY OF MELBOURNE

ASU

VANDERBILT UNIVERSITY





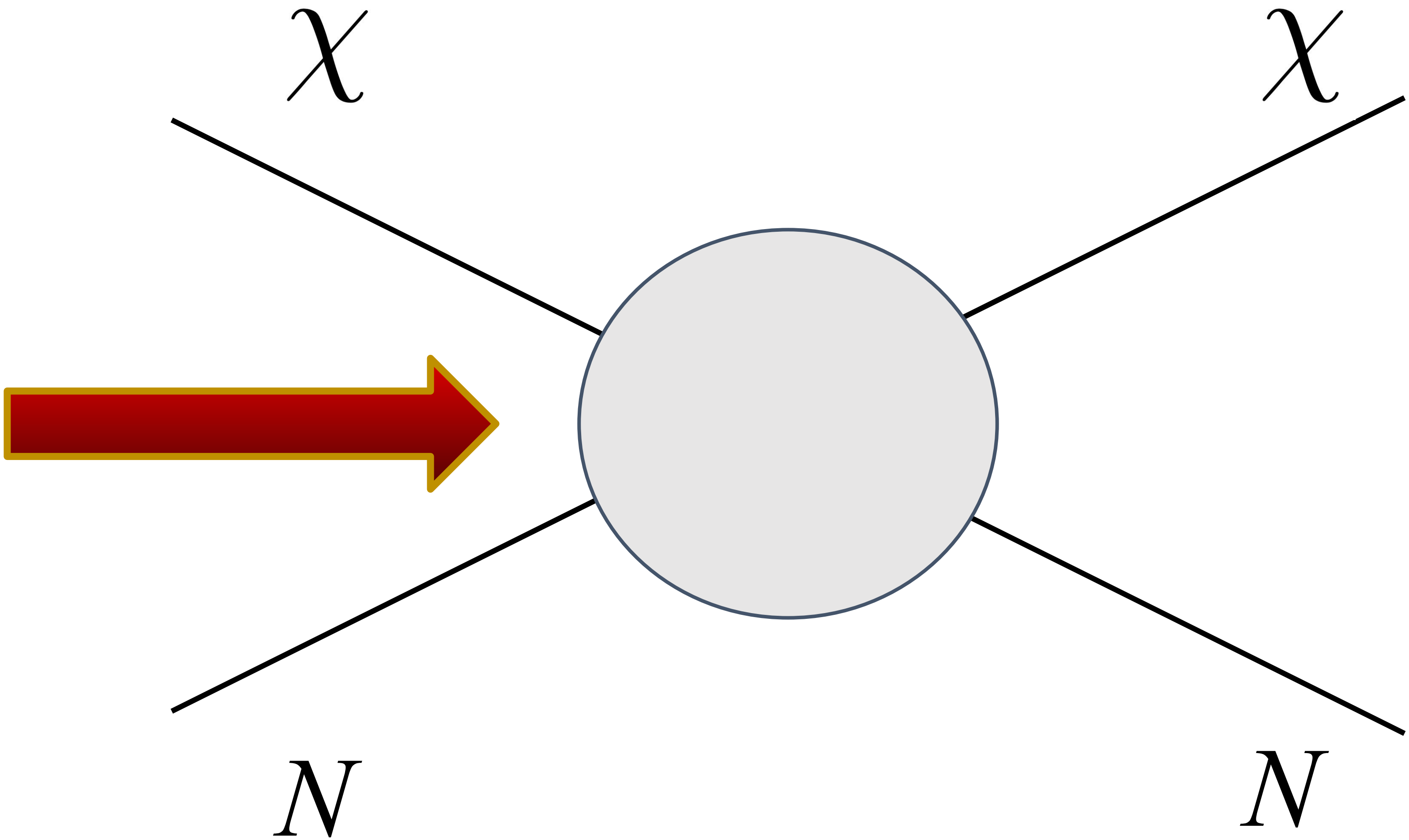


Jayden Newstead

Bhaskar Dutta Ian Shoemaker

ATM

VT


χ
χ
N
N

Direct Detection Review

Momentum Exchanged $\mathcal{O}(<100\text{MeV})$

$$q = \sqrt{2 m_T E_R}$$

Recoil energy $\mathcal{O}(10\text{keV})$

$$E_R = \frac{\mu_{\chi T}^2 v^2}{m_T}(1 - \cos\theta)$$

Incident energy

$$E_i = \frac{m_\chi v^2}{2}$$

$$v \sim \mathcal{O}(10^{-3})$$

$$E_{\mathrm{R,max}} = \frac{2\mu_{\chi \mathrm{T}}^2 v^2}{m_T}$$

Direct Detection Review

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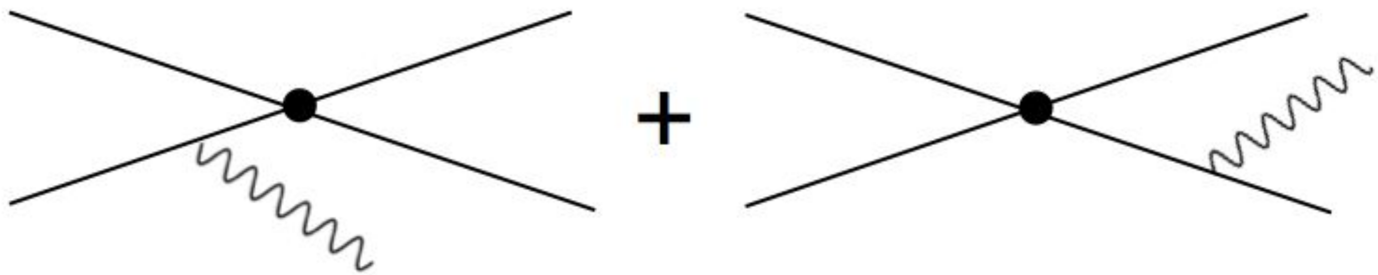
$$E_{\mathrm{R,max}} = \frac{2\mu_{\chi \mathrm{T}}^2 v^2}{m_T}$$

For: $m_\chi = 100\ \mathrm{GeV}\ m_T = 130\ \mathrm{GeV},\ E_{\mathrm{R,max}} \simeq 50\ \mathrm{keV}.$

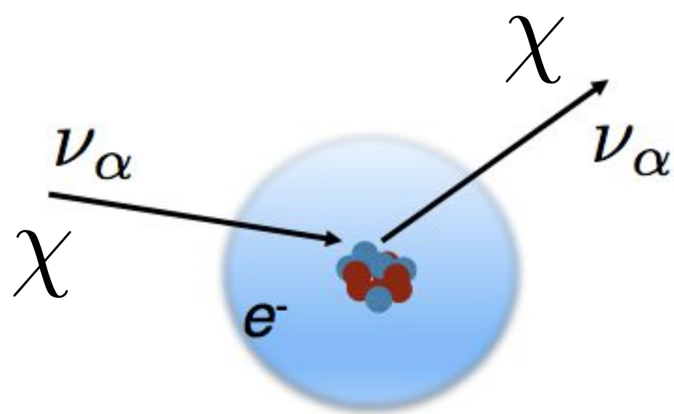
For: $m_\chi = 10\ \mathrm{GeV}\ m_T = 130\ \mathrm{GeV},\ E_{\mathrm{R,max}} \simeq 1.3\ \mathrm{keV}.$

Alternative Signals for sub-GeV Probes

Bremsstrahlung

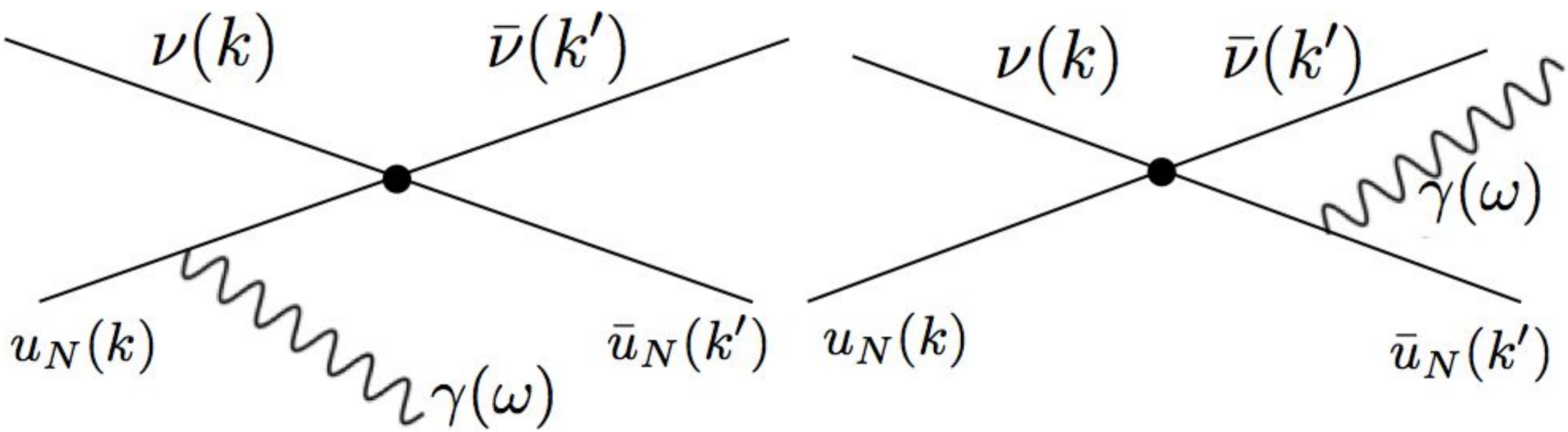


Migdal



Bremsstrahlung in $\chi + N \to \chi + N + \gamma$ DM scattering has been explored as a means of accessing sub-GeV mass DM

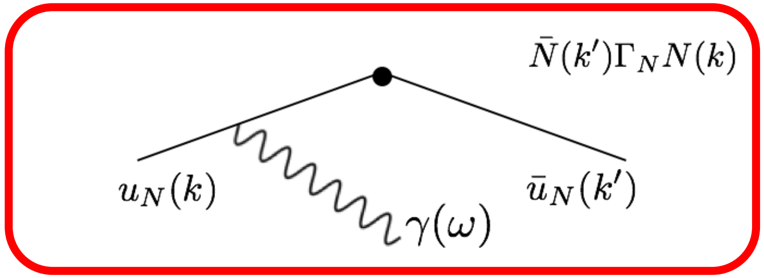
C. Kouvaris and J. Pradler, PRL 2017, 1607.01789
C.McCabe, PhysRevD (2017) 1702.04730



$$\nu + N \to \nu + N + \gamma$$

We want to examine the possibility of brem signals when nuclear recoil energies are below threshold.

Also see the recent paper: A.Millar, G.Raffelt, L.Stodolsky, and E.Vitagliano, 1810.06584 for very low E_ν with an examination of neutrino mass effects



Bremsstrahlung in the process $\chi + N \rightarrow \chi + N + \gamma$
Can be used to detect scattering processes that produce nuclear recoils below detector thresholds.

The endpoints of the maximum nuclear recoil energy and emitted photon are key to the extended reach

$$v_{\min} = \frac{m_T E_R + \mu_T \delta}{\mu_T \sqrt{2 m_T E_R}}$$

$$E_{R,\max} = \frac{2\mu_T^2 v_{\max}^2}{m_T},$$

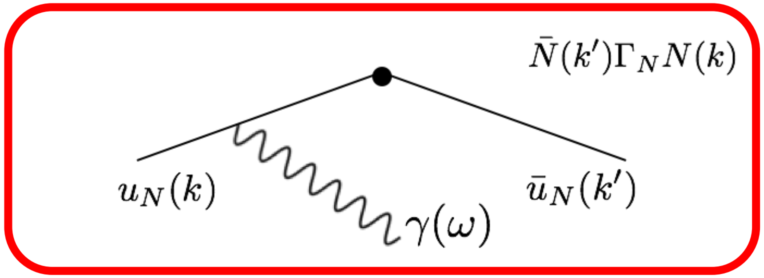
$$\delta_{\max} = \frac{\mu_T v_{\max}^2}{2}.$$

For the case of dark matter much lighter than the target nucleus

$$m_T \gg m_\chi$$

$$E_{R,\max} \approx 2 \left(\frac{m_\chi}{\text{GeV}}\right)^2 \left(\frac{\text{GeV}}{m_T}\right) \left(\frac{v_{\max}^2}{10^{-6}}\right) \text{keV}$$

$$\delta_{\max} \approx \frac{1}{2} \left(\frac{m_\chi}{\text{GeV}}\right) \left(\frac{v_{\max}^2}{10^{-6}}\right) \text{keV},$$



$$E_{R,\mathrm{max}} \approx 2\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_T}\right)\left(\frac{v_{\mathrm{max}}^2}{10^{-6}}\right)\mathrm{keV}$$

$$\delta_{\mathrm{max}} \approx \frac{1}{2}\left(\frac{m_\chi}{\mathrm{GeV}}\right)\left(\frac{v_{\mathrm{max}}^2}{10^{-6}}\right)\mathrm{keV},$$

Typically one finds that sub-GeV dark matter creates

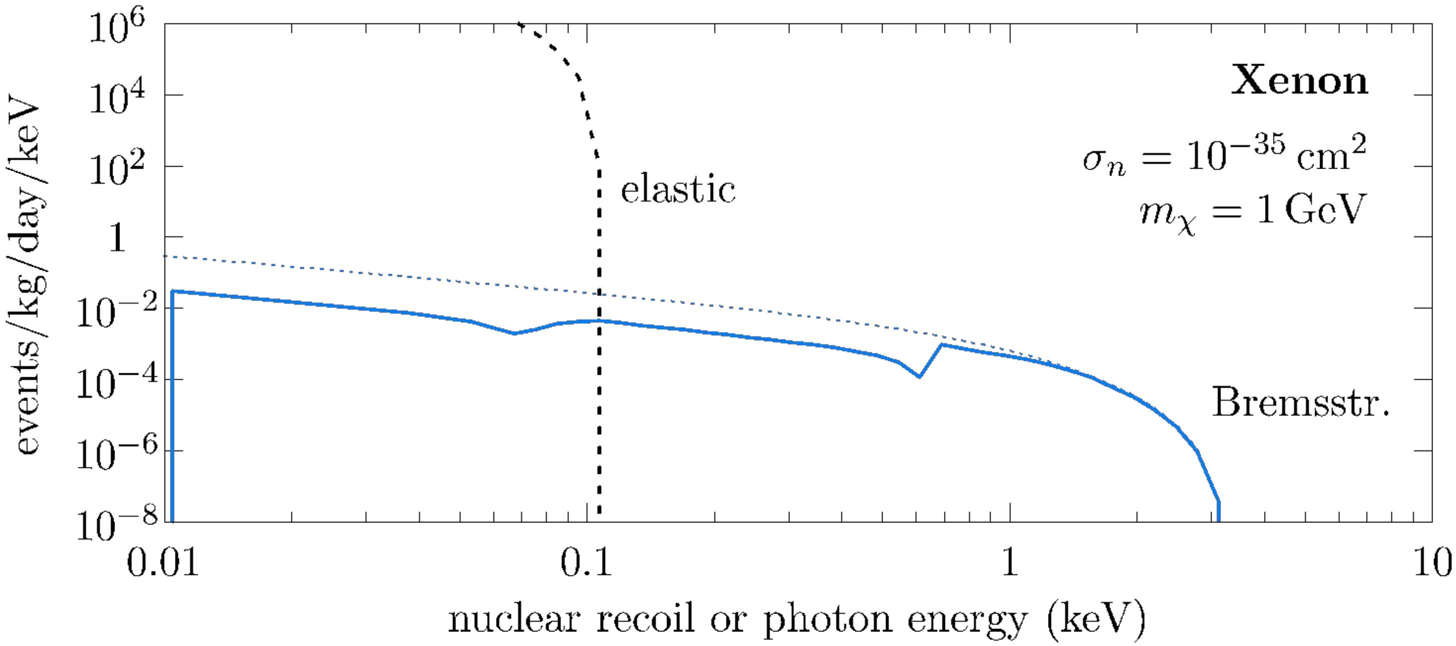
$$\delta_{\mathrm{max}} > E_{R,\mathrm{max}}$$

For example, a 1 GeV particle incident on xenon will produce

$$E_{\mathrm{R,max}} \lesssim 10^{-1}\ \mathrm{keV}\ \text{and}\ \delta_{\mathrm{max}} \sim 3\ \mathrm{keV}$$

The double differential cross-section factorizes into kinematic terms multiplied by the 2-2 elastic differential cross-section

$$\frac{d^2\sigma}{dE_R d\omega} = \frac{4\alpha Z^2}{3\pi}\frac{E_R}{m_T\omega}\left(\frac{d\sigma}{dE_R}\right)_{(2\to 2)}$$



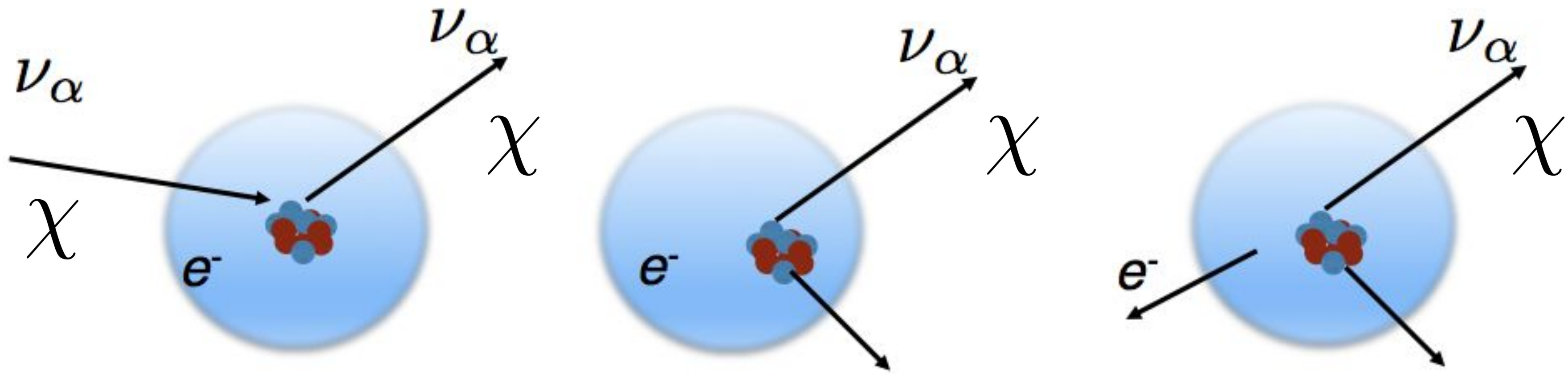
$$\frac{dR}{d\omega} = N_T \frac{\rho_\chi}{m_\chi}\int_{|\mathbf{v}|\geq v_{\min}} d^3\mathbf{v}\, v f_v(\mathbf{v}+\mathbf{v}_e)\frac{d\sigma}{d\omega}$$

C. Kouvaris and J. Pradler, PRL 2017, 1607.01789

The Migdal Effect

A.B.Migdal, J.Phys. USSR (1941), Landau & Lifschitz, QM Sec.41

Ionization and excitation of electron states from the relative momentum arising when the nucleus is given an impulse.



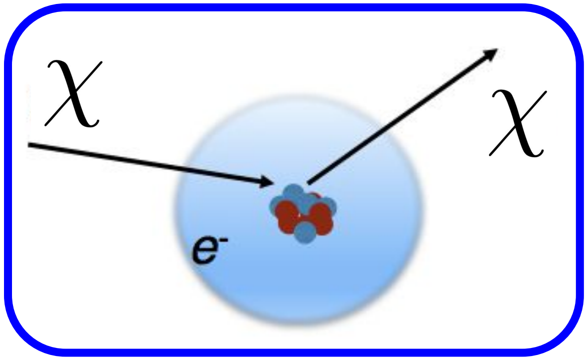
Proposed for dark matter detection years ago, and recently revisited in more detail.

M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, JHEP (2018) 1707.07258

M.Dolan, F.Kahlhoefer, and C.McCabe, PRL(2018) 1711.09906 (above figure adapted from this paper)

Does *not* suffer from the same suppression as brem.

R. Bernabei et al., Int. J. Mod. Phys. A22, 3155 (2007), arXiv:0706.1421
B. M. Roberts, V. V. Flambaum, and G. F. Gribakin, Phys. Rev. Lett. 116, 023201 (2016),arXiv:1509.09044



The double differential cross-section factorizes into the ionization rate multiplied by the 2-2 elastic differential cross-section

$$\frac{d^2R}{dE_R dv} = \frac{d^2R_{\chi T}}{dE_R dv} \times |Z_{\text{ion}}|^2$$

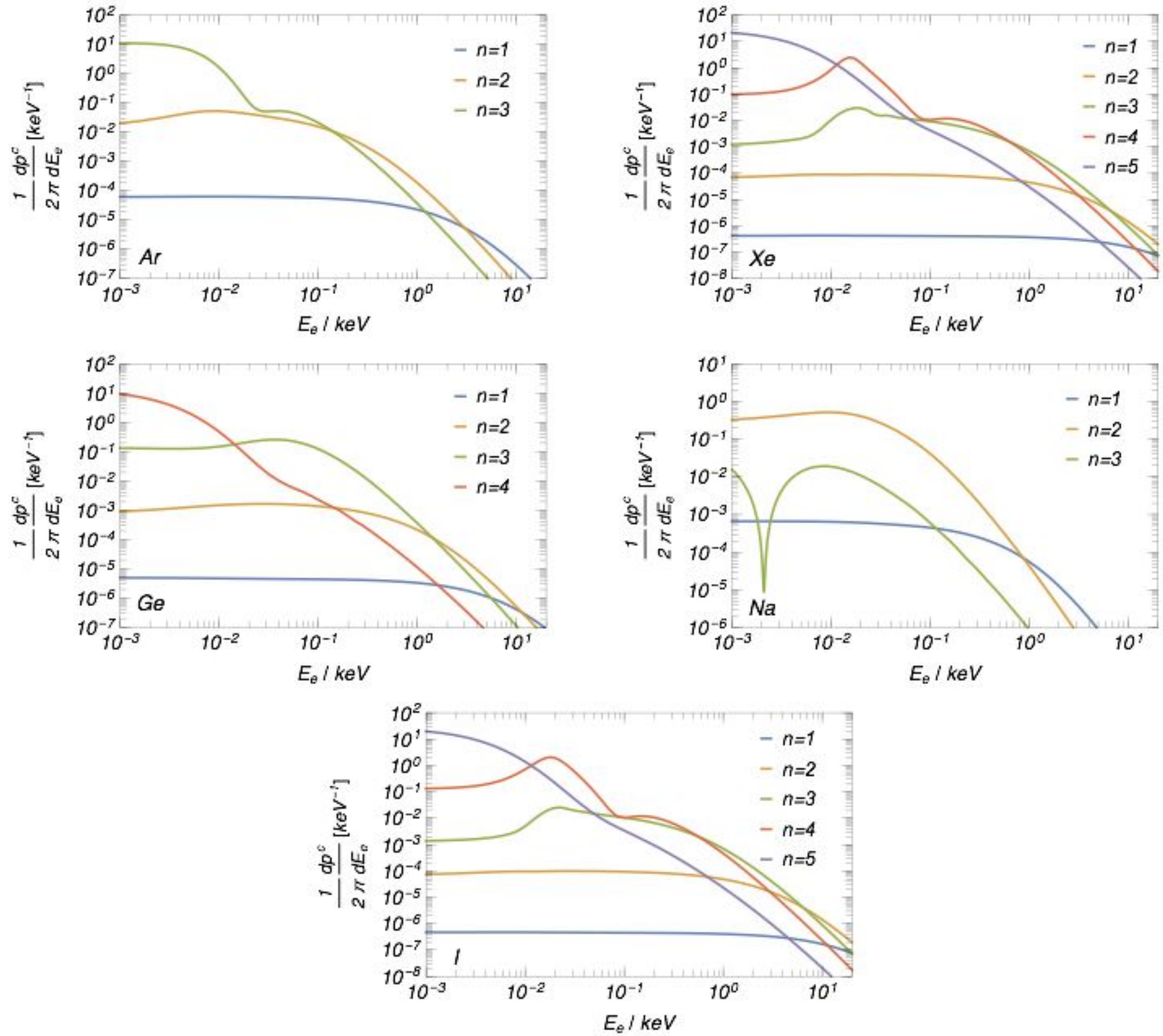
The ionization rate is given in terms of the ionization probability

$$|Z_{\text{ion}}|^2 = \frac{1}{2\pi}\sum_{n,\ell}\int dE_e \frac{d}{dE_e} p^c_{q_e}(n\ell \to (E_e))$$

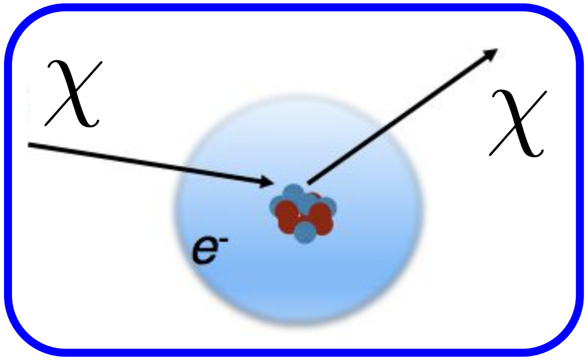
The differential rate is then

$$\frac{d^3R}{dE_R dE_{\text{EM}} dv} = \frac{d^2R_0}{dE_R dv} \times \frac{1}{2\pi}\sum_{n,\ell}\frac{d}{dE_e} p^c_{q_e}(n\ell \to (E_e))$$

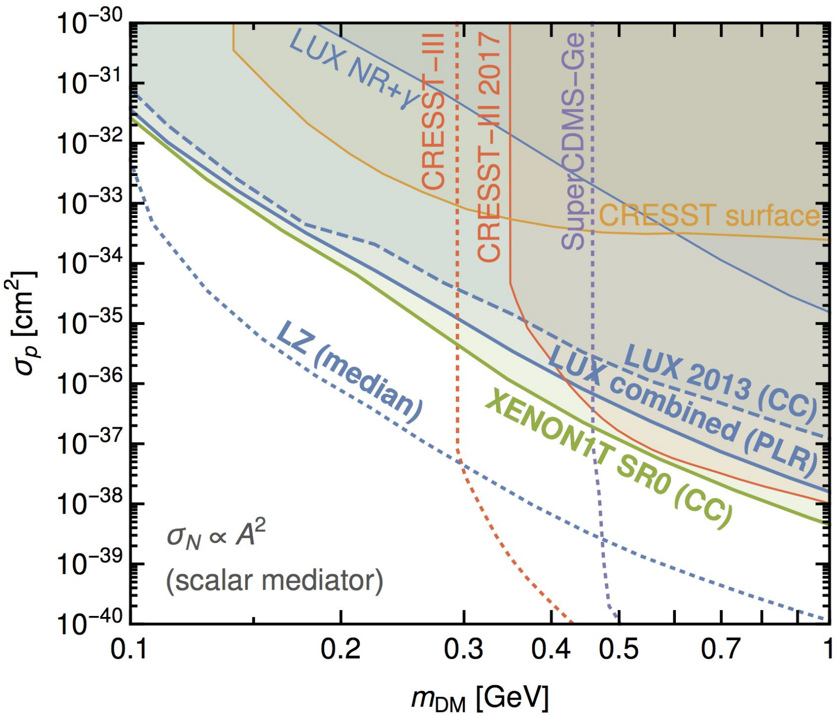
Ionization Probabilities have been calculated: `Flexible Atomic Code`

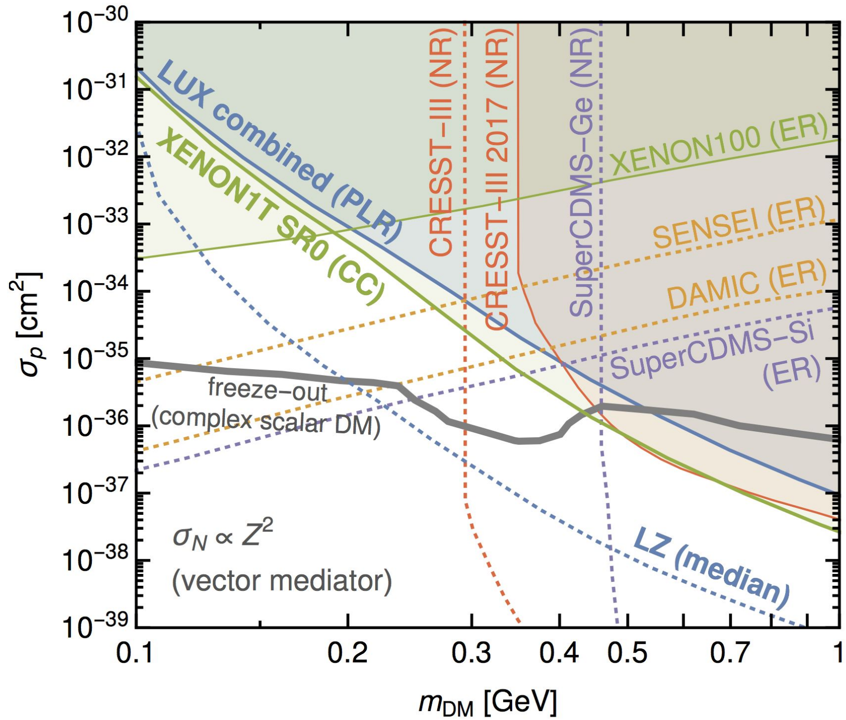


M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, JHEP (2018) 1707.07258



The Migdal effect has been used to place new bounds on sub-GeV dark matter





M.Dolan, F. Kahlhoefer, and C.McCabe, PRL (2018) 1711.09906

The Migdal Effect and Photon Bremsstrahlung in effective field theories of dark matter direct detection and coherent elastic neutrino-nucleus scattering

arXiv:1905.00046

Nicole Bell
THE UNIVERSITY OF MELBOURNE

Jayden Newstead
ASU

Subir Sabharwal

Tom Weiler
VANDERBILT UNIVERSITY

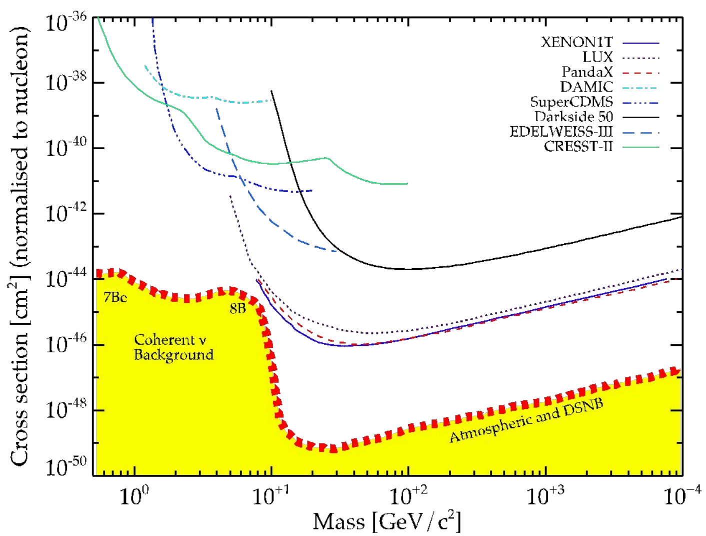
We have examined the Migdal effect and photon brem in the context of the EFT approach, placing new limits on Xe1T

$$\mathcal{O}_1 \quad 1_\chi 1_N$$

$$\mathcal{O}_4 \quad \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_6 \quad \left(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi\right)\left(\frac{\vec{q}}{m_N} \cdot \vec{S}_N\right)$$

$$\mathcal{O}_{10} \quad 1_\chi \left(i\frac{\vec{q}}{m_N} \cdot \vec{S}_N\right)$$

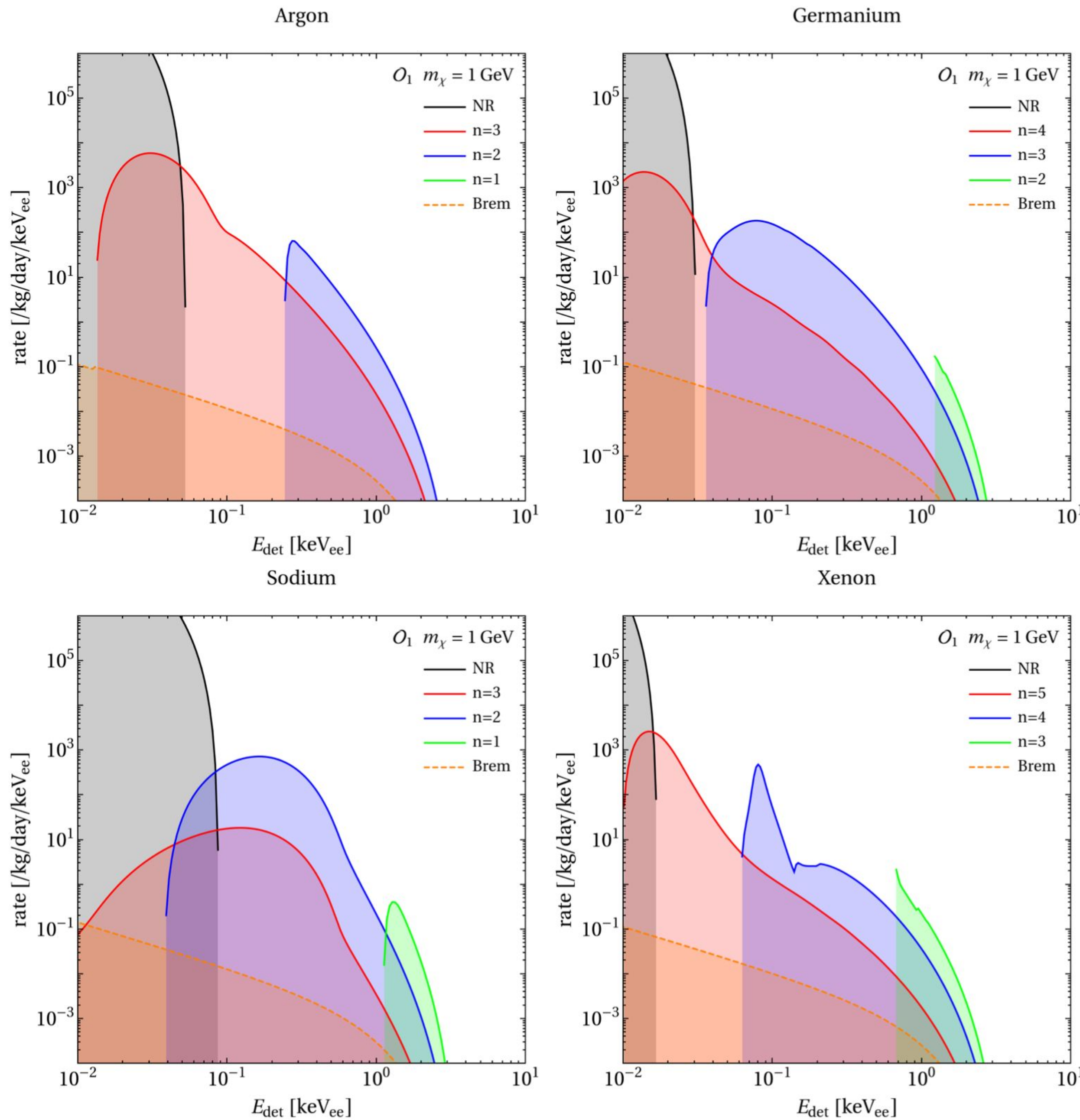


We've also reassessed the neutrino background in the presence of these effects

$$\rho_{\chi,\odot} = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$$

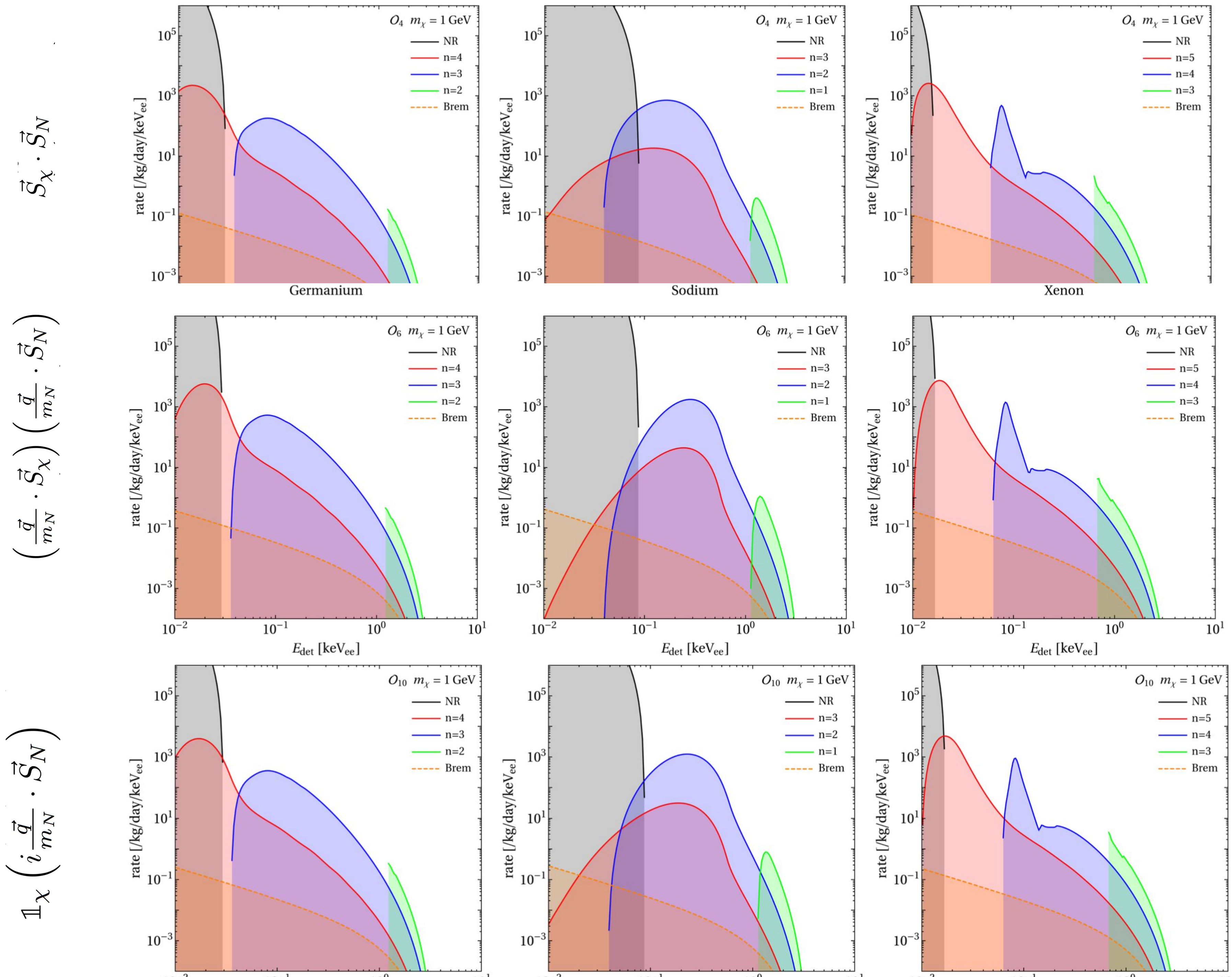
$$v_{\text{esc}} = 544 \text{ km} \cdot \text{s}^{-1}$$

$$v_0 = 220 \text{ km} \cdot \text{s}^{-1}$$

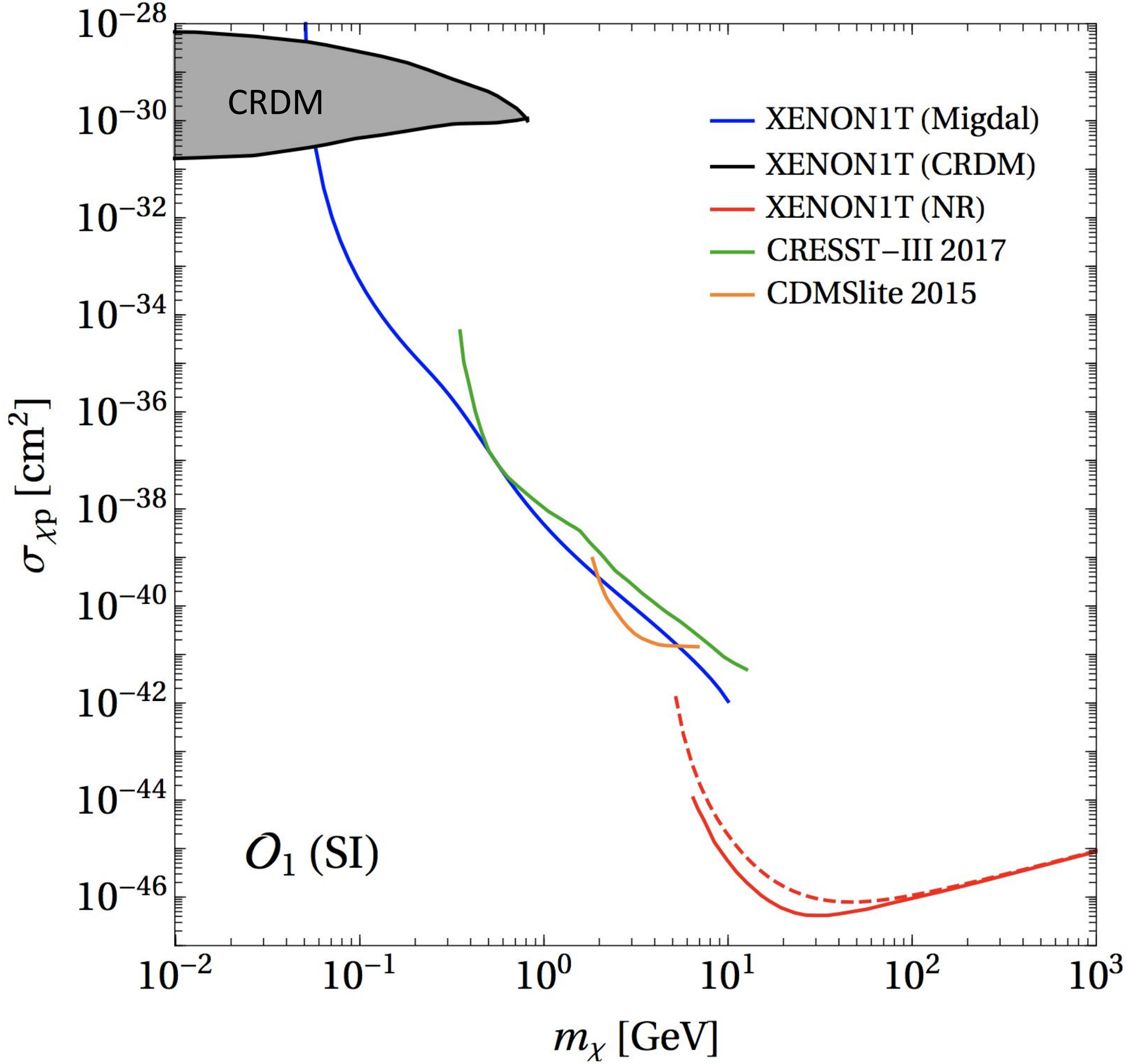


$$\frac{dR}{dE_R} = N_T \frac{\rho_{\chi,\odot}}{m_\chi m_T} \int_{v>v_{\min}} \frac{d\sigma}{dE_R} v f(\vec{v}) d^3 v.$$

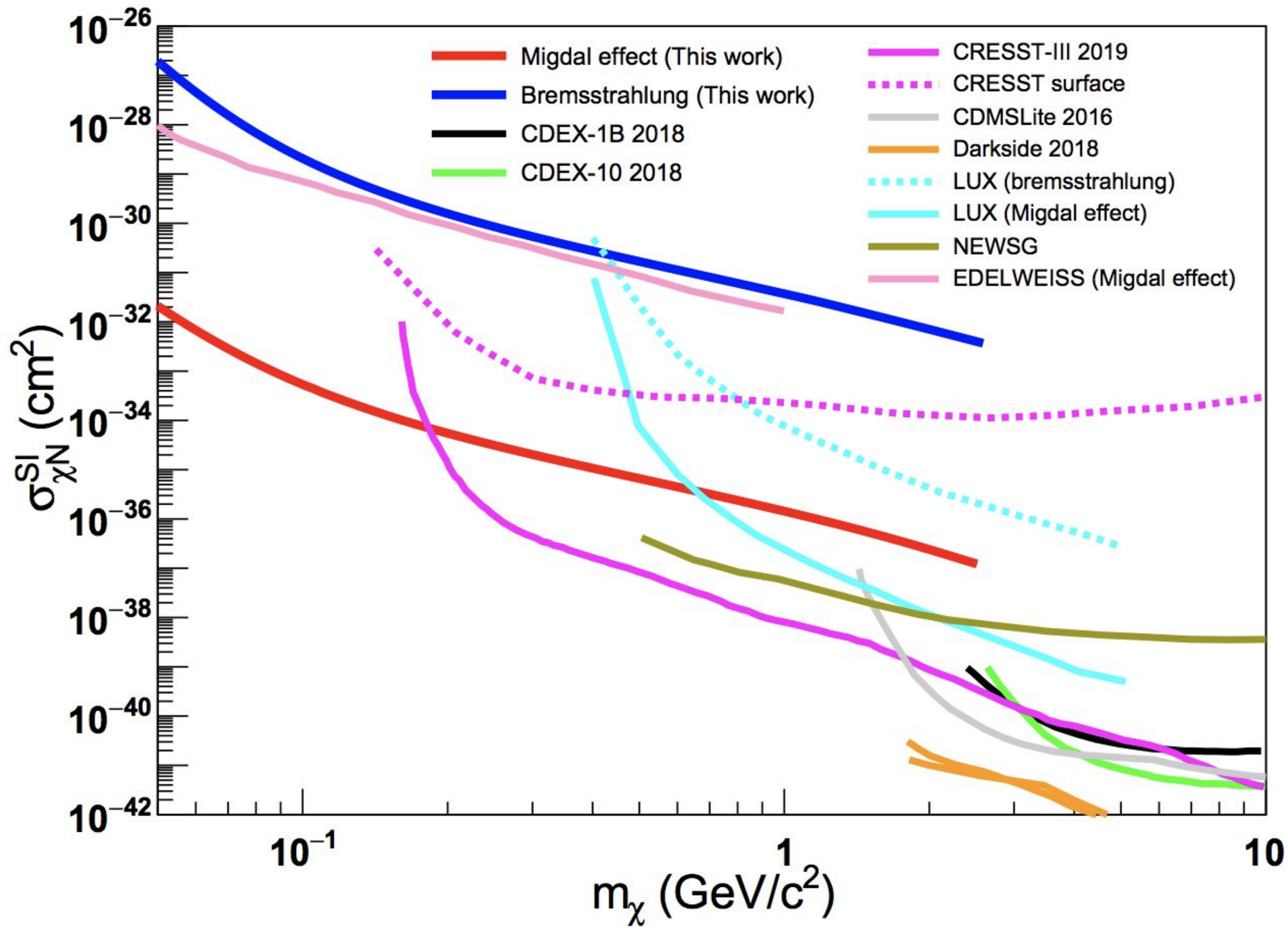
$\mathcal{O}_1$ $\mathbb{1}_\chi \mathbb{1}_N$



$\vec{S}_\chi \cdot \vec{S}_N$
$\left(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi\right)\left(\frac{\vec{q}}{m_N} \cdot \vec{S}_N\right)$
$\mathbb{1}_\chi \left(i \frac{\vec{q}}{m_N} \cdot \vec{S}_N\right)$
$\mathcal{O}_4$ $m_\chi = 1$ GeV
$\mathcal{O}_6$ $m_\chi = 1$ GeV
$\mathcal{O}_{10}$ $m_\chi = 1$ GeV
NR
n=5
n=4
n=3
n=2
n=1
Brem
rate [/kg/day/keV$_{ee}$]
E_{det} [keV$_{ee}$]
Germanium
Sodium
Xenon

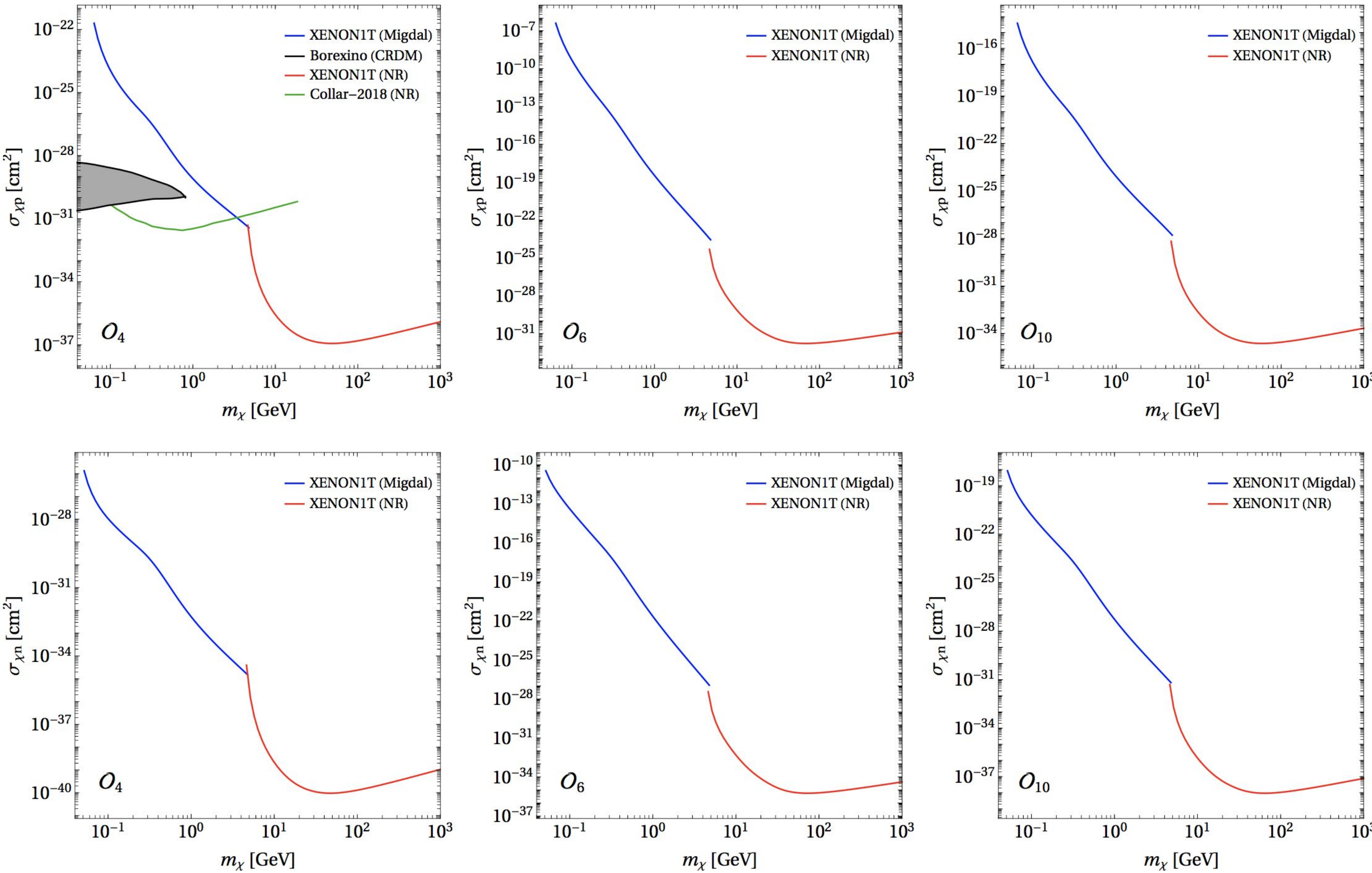


CRDM
XENON1T (Migdal)
XENON1T (CRDM)
XENON1T (NR)
CRESST−III 2017
CDMSlite 2015
$\mathcal{O}_1$ (SI)
$\sigma_{\chi p}$ [cm^2]
m_χ [GeV]
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

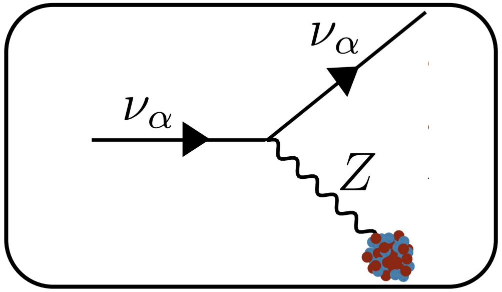


939 g Germanium detector at CJPL
737.1 kg·day exposure and 160 eVee threshold

Constraints on spin-independent nucleus scattering with sub-GeV WIMP dark matter from the CDEX-1B Experiment at CJPL
CDEX Collaboration (Z.Z. Liu (Tsinghua U., Beijing) *et al.*). May 1, 2019. 5 pp.
e-Print: **arXiv:1905.00354 [hep-ex]**



XENON1T (Migdal)
Borexino (CRDM)
XENON1T (NR)
Collar–2018 (NR)
$\mathcal{O}_4$
$\sigma_{\chi p}$ [cm^2]
m_χ [GeV]
10^{-22} 10^{-25} 10^{-28} 10^{-31} 10^{-34} 10^{-37}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
XENON1T (Migdal)
XENON1T (NR)
$\mathcal{O}_6$
$\sigma_{\chi p}$ [cm^2]
m_χ [GeV]
10^{-7} 10^{-10} 10^{-13} 10^{-16} 10^{-19} 10^{-22} 10^{-25} 10^{-28} 10^{-31}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
XENON1T (Migdal)
XENON1T (NR)
$\mathcal{O}_{10}$
$\sigma_{\chi p}$ [cm^2]
m_χ [GeV]
10^{-16} 10^{-19} 10^{-22} 10^{-25} 10^{-28} 10^{-31} 10^{-34}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
XENON1T (Migdal)
XENON1T (NR)
$\mathcal{O}_4$
$\sigma_{\chi n}$ [cm^2]
m_χ [GeV]
10^{-28} 10^{-31} 10^{-34} 10^{-37} 10^{-40}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
XENON1T (Migdal)
XENON1T (NR)
$\mathcal{O}_6$
$\sigma_{\chi n}$ [cm^2]
m_χ [GeV]
10^{-10} 10^{-13} 10^{-16} 10^{-19} 10^{-22} 10^{-25} 10^{-28} 10^{-31} 10^{-34} 10^{-37}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
XENON1T (Migdal)
XENON1T (NR)
$\mathcal{O}_{10}$
$\sigma_{\chi n}$ [cm^2]
m_χ [GeV]
10^{-19} 10^{-22} 10^{-25} 10^{-28} 10^{-31} 10^{-34} 10^{-37}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}



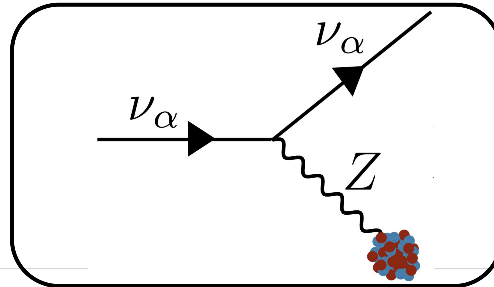
To include the Migdal effect for coherent neutrino-nucleus scattering, we include the ionization rate

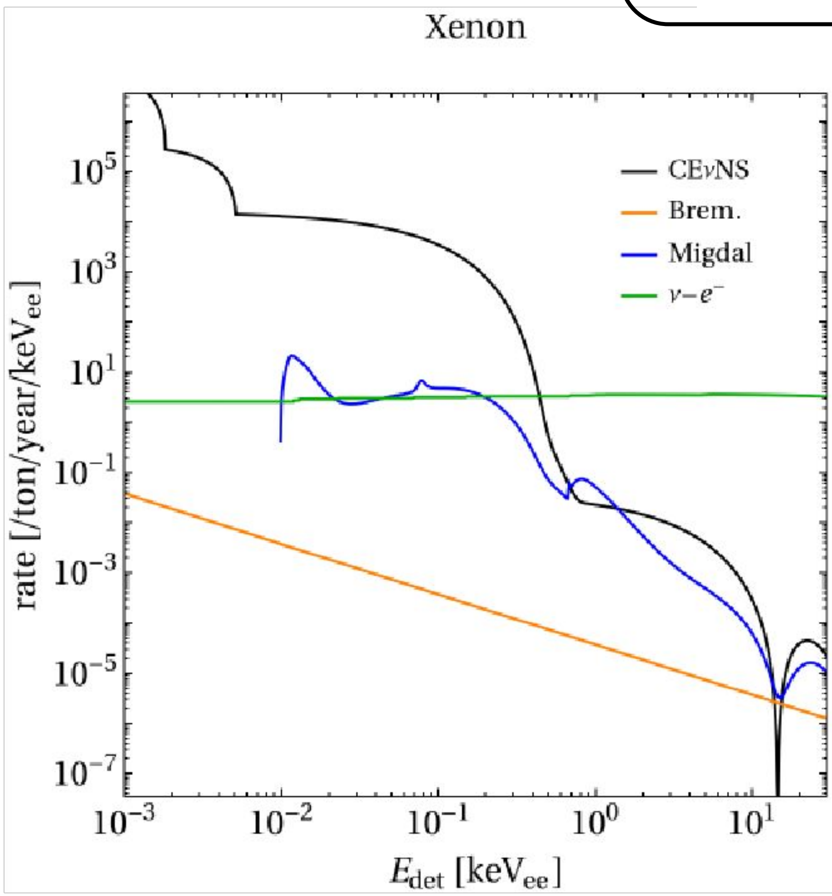
$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi} Q_V^2 m_T \left(1 - \frac{m_T E_R - E_{\rm EM}^2}{2E_\nu^2}\right) F(q)^2 \times |Z_{FI}|^2$$

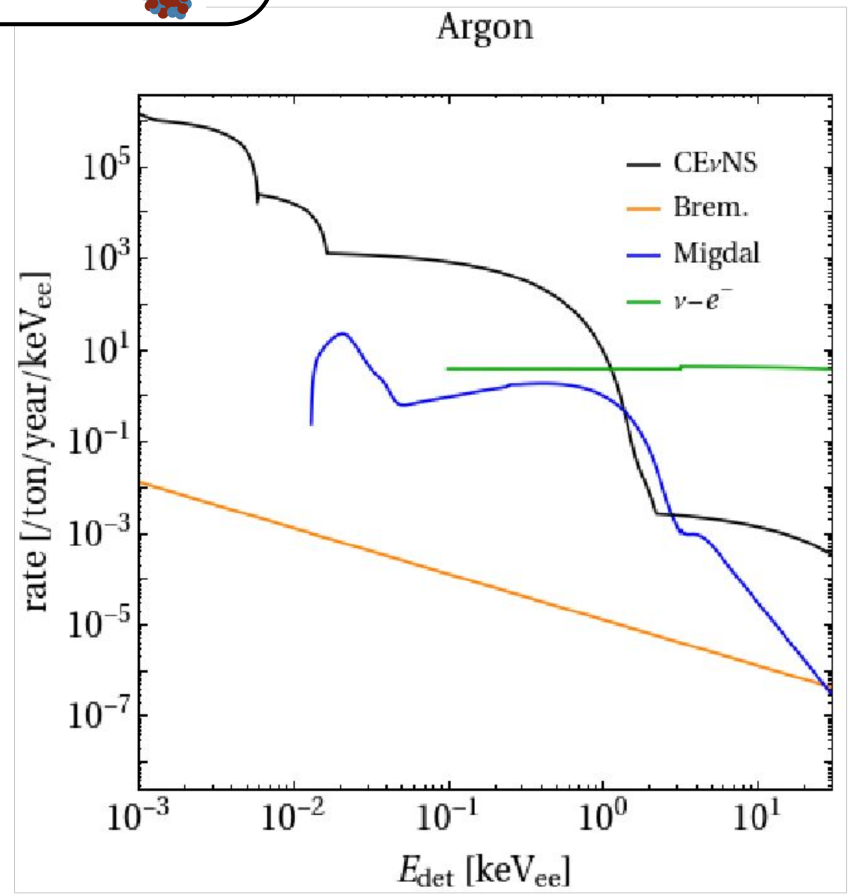
The kinematic endpoints are

$$\frac{(E_e + E_{n\ell})^2}{2m_T} < E_R < \frac{(2E_\nu - (E_e + E_{n\ell}))^2}{2(m_T + 2E_\nu)}$$

Including the incident fluxes from solar and atmospheric neutrinos, we have calculated the new rates as a function of detected energy







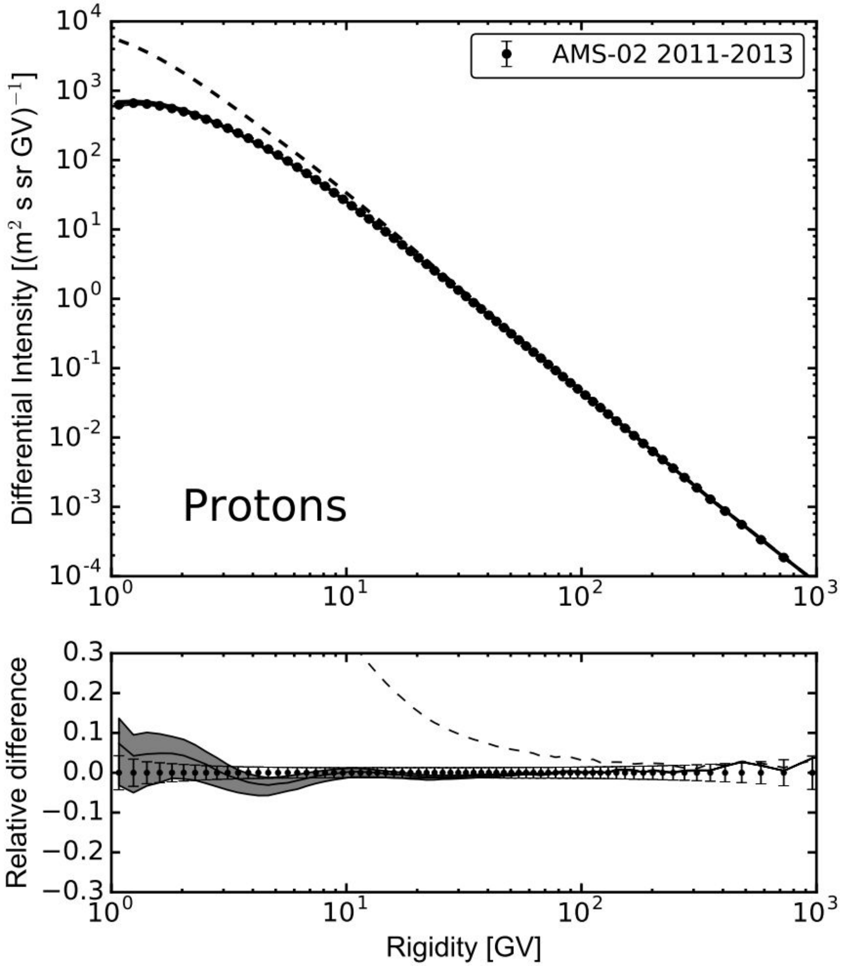
There is a small window where the Migdal effect induced signal is comparable in rate to the nuclear recoil signal.

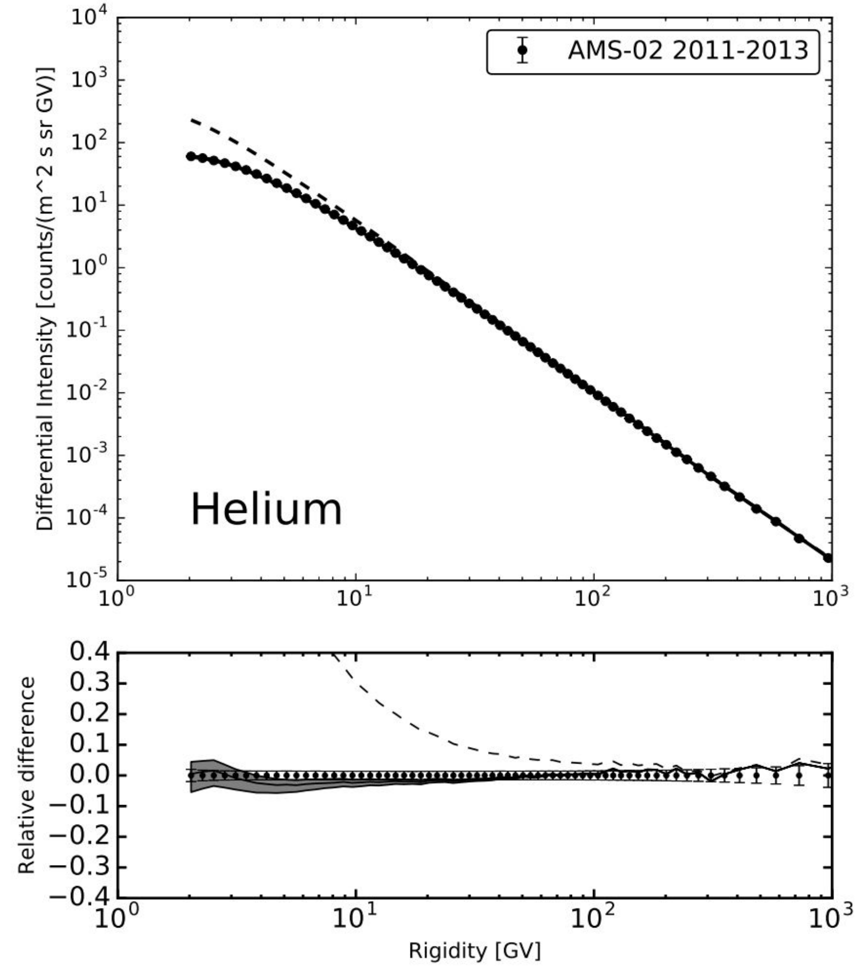
Cosmic ray induced dark matter scattering

C.V. Cappiello, K.C.Y. Ng, and J.F. Beacom PRD 2019, 1810.07705

Bringmann and Pospelov PRL 2019, 1810.10543

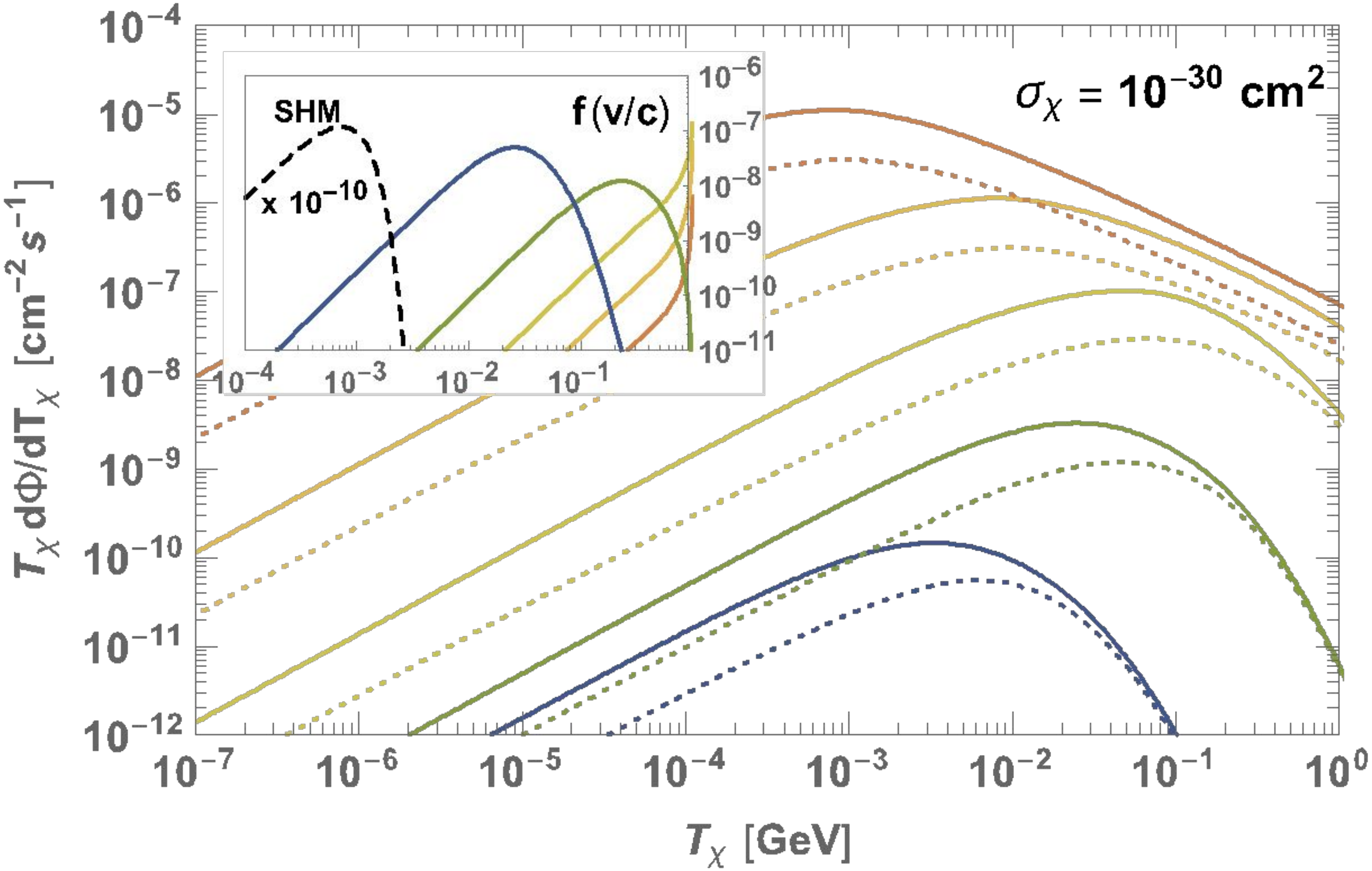
JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon



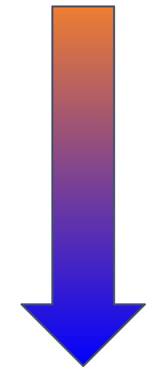


From Observations near the Earth to the Local Interstellar Spectra

S. Della Torre (INFN, Milan Bicocca) *et al.*. Dec 29, 2016.
Conference: C16-09-04.3



$m_\chi = 1$ MeV

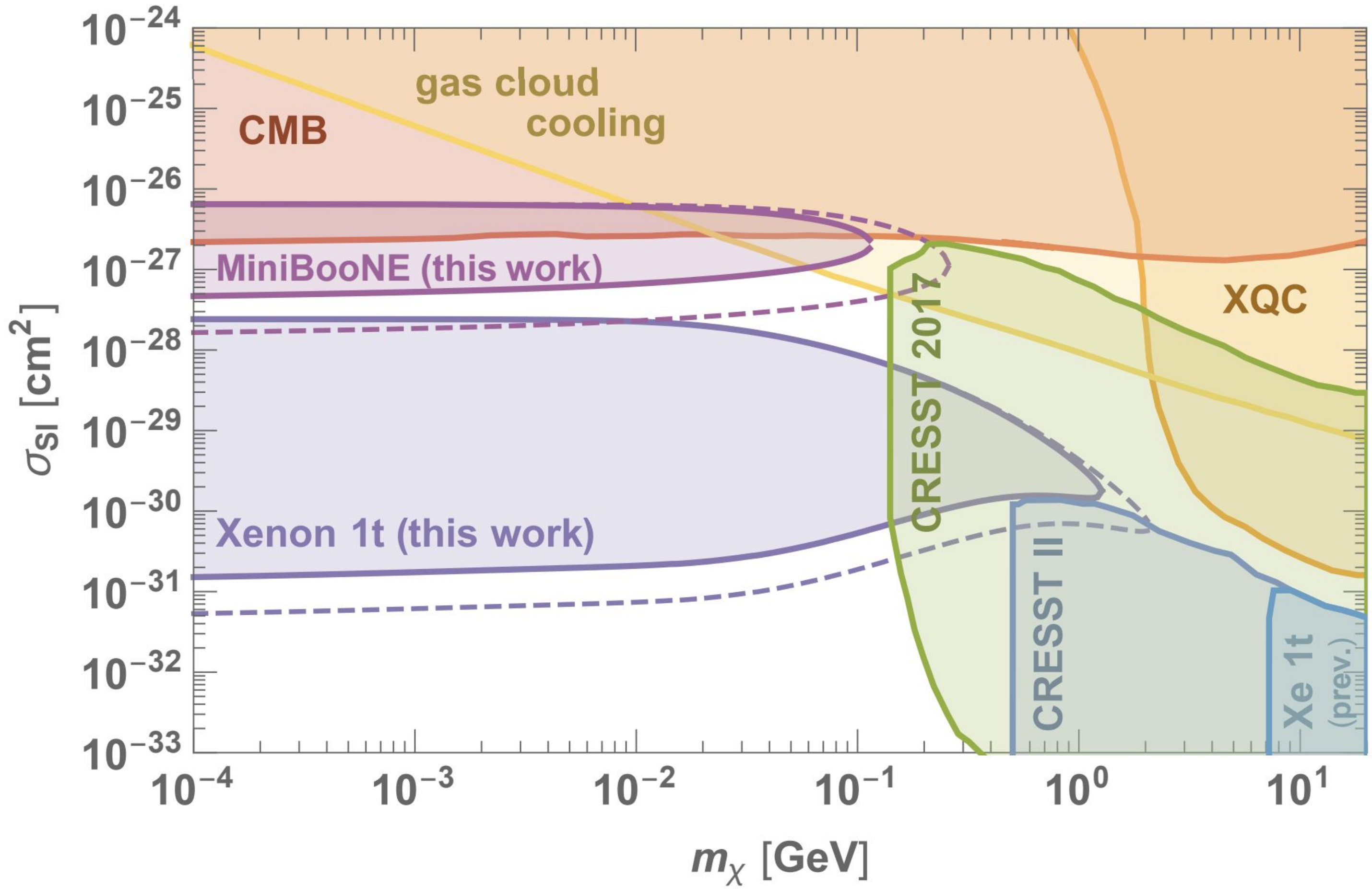


$m_\chi = 10$ GeV

$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{l.o.s.} d\ell\, \sigma_{\chi i} \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_\chi^{\rm local}}{m_\chi} \frac{d\Phi_i^{LIS}}{dT_i} D_{\rm eff}$$

$$\frac{d\Phi_\chi}{dT_\chi} = \int_0^\infty dT_i \frac{d\Phi_\chi}{dT_i} \frac{1}{T_\chi^{\rm max}(T_i)} \Theta\left[T_\chi^{\rm max}(T_i) - T_\chi\right]$$

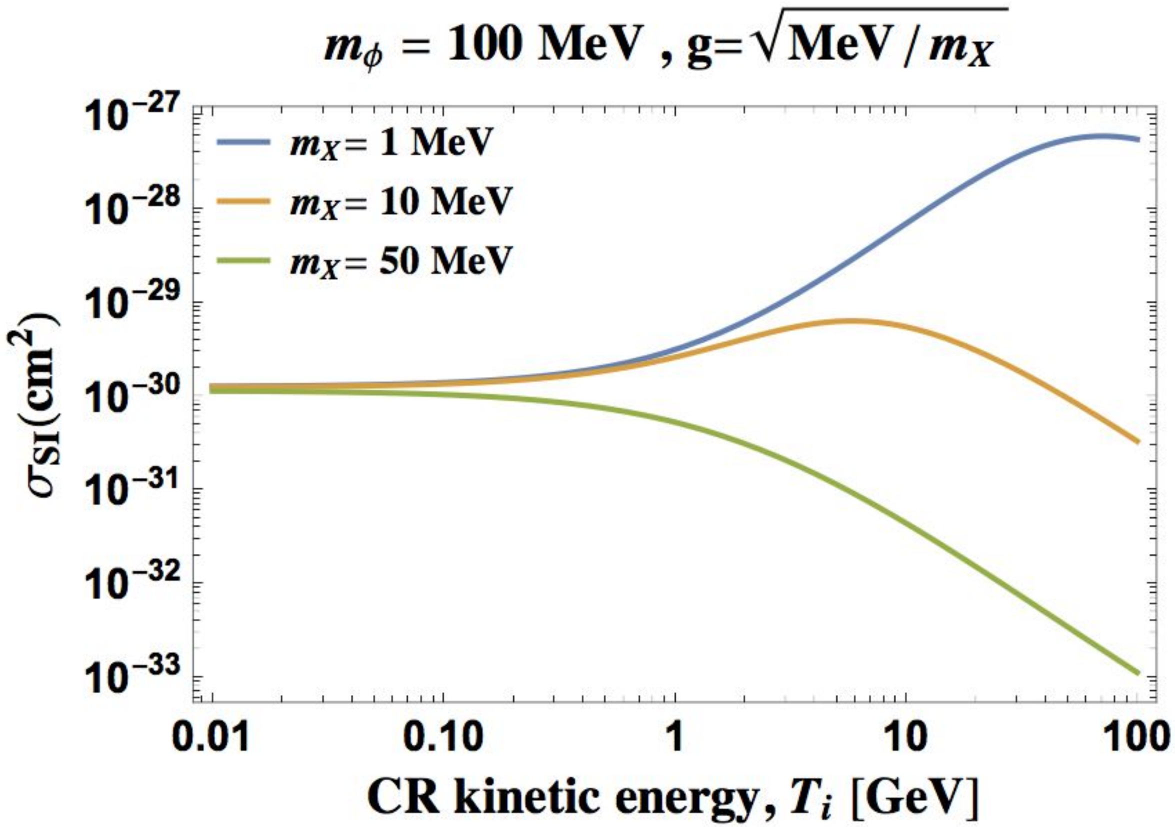
Bringmann and Pospelov PRL 2019, 1810.10543



Bringmann and Pospelov PRL 2019, 1810.10543

$$\mathscr{L} \supset g_\chi \phi \bar{\chi}\chi + g_n \phi \bar{n} n$$

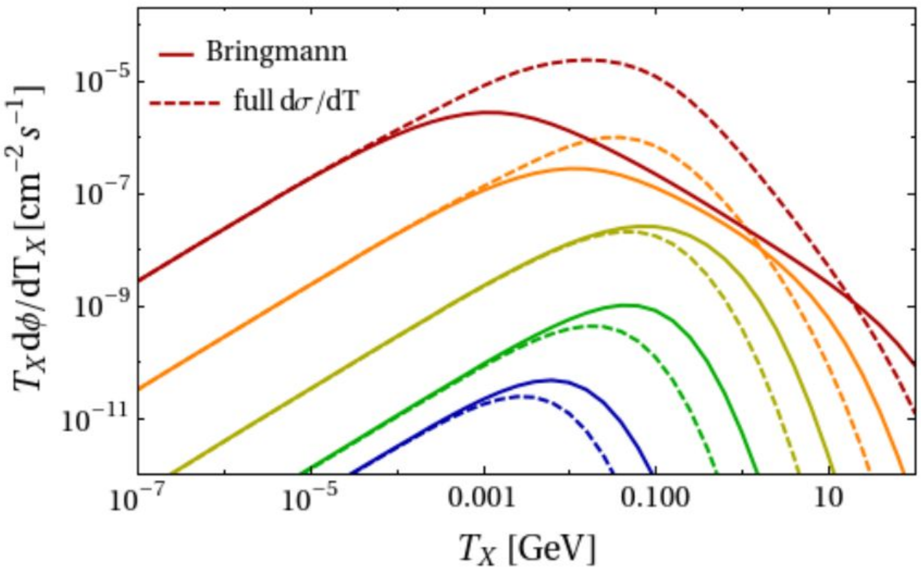
CRDM Preliminary Results

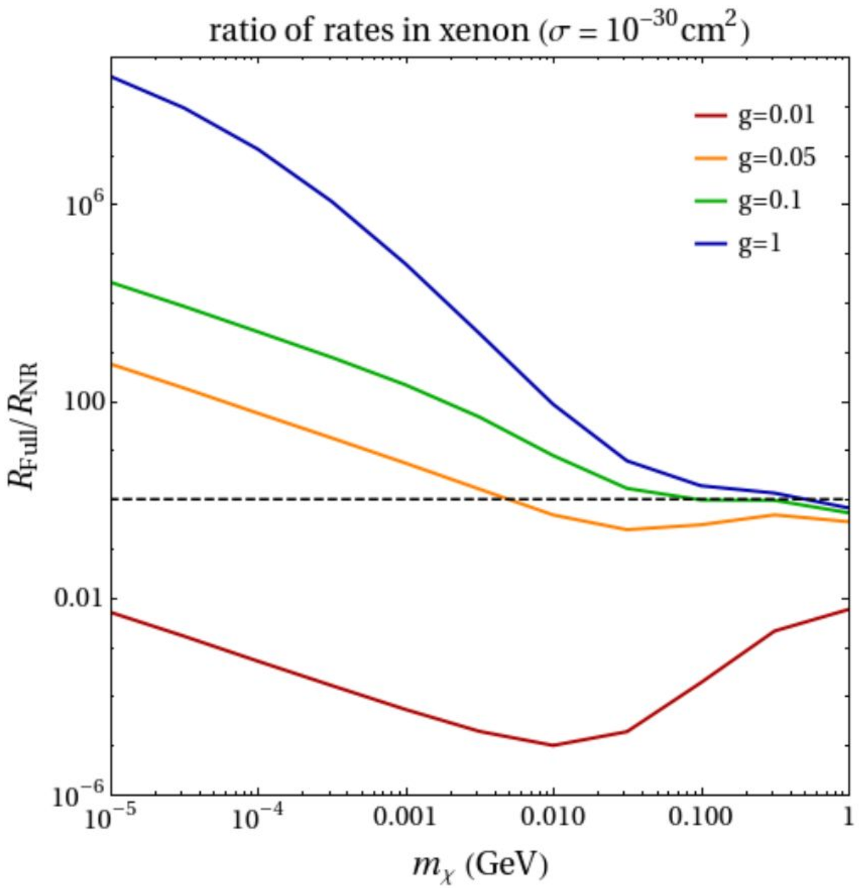


$$\left(\frac{d\sigma}{dT_\chi}\right)_{\text{scalar,CR}} = g_{s\chi}^2 g_{s\text{CR}}^2 \frac{(4m_\chi m^2 + 2T_\chi(m_\chi^2 + m^2) + m_\chi T_\chi^2)}{8\pi(2m_\chi T_\chi + m_\phi^2)^2(T_i^2 + 2mT_i)}$$

JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon

CRDM Preliminary Results

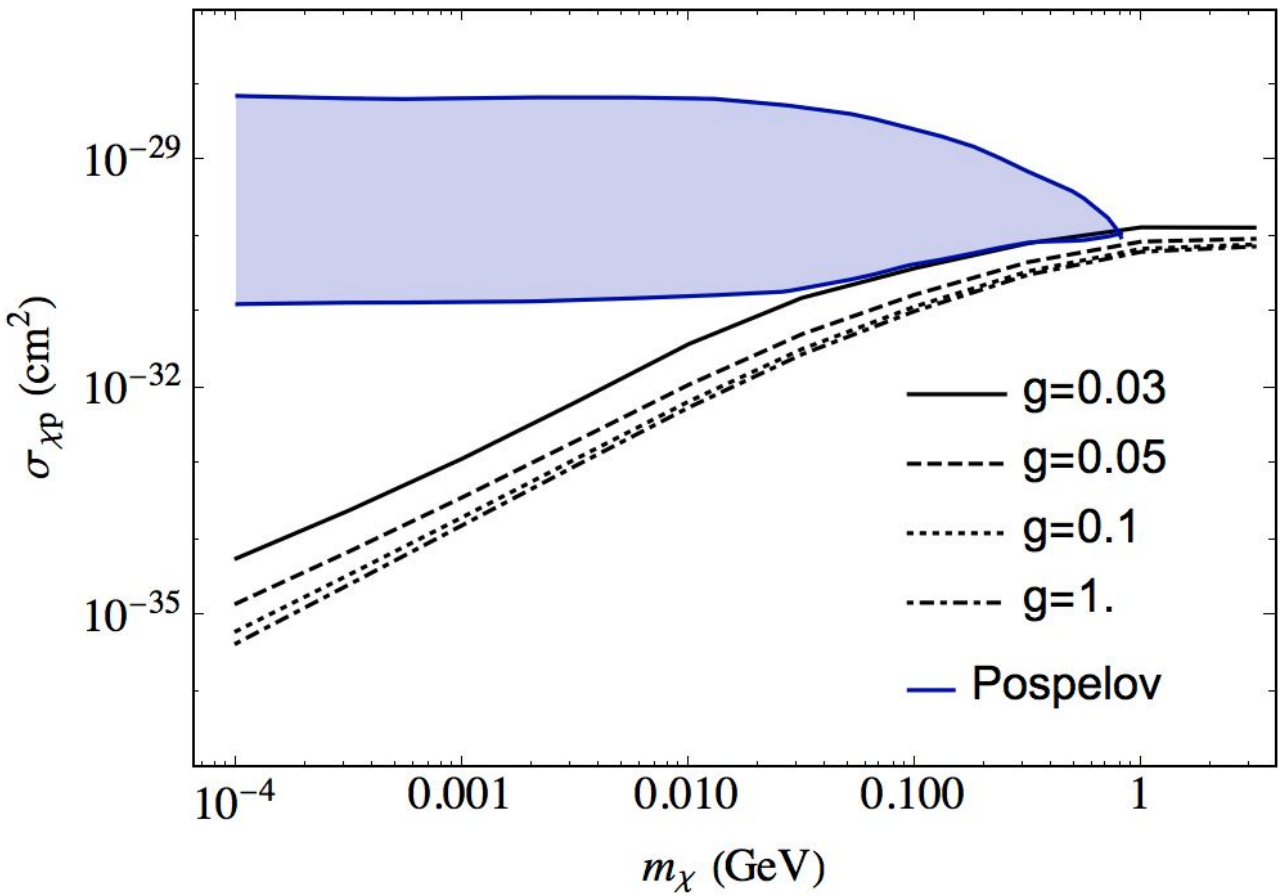




$$\frac{dR}{dE_T} = \frac{1}{m_N}\int_{T_\chi^{\min}}^{\infty} dT_\chi\ \frac{d\Phi_\chi}{dT_\chi}\ \frac{d\sigma_{\chi-n}}{dE_T}$$

Energy dependence must be accounted for on the direct detection side as well

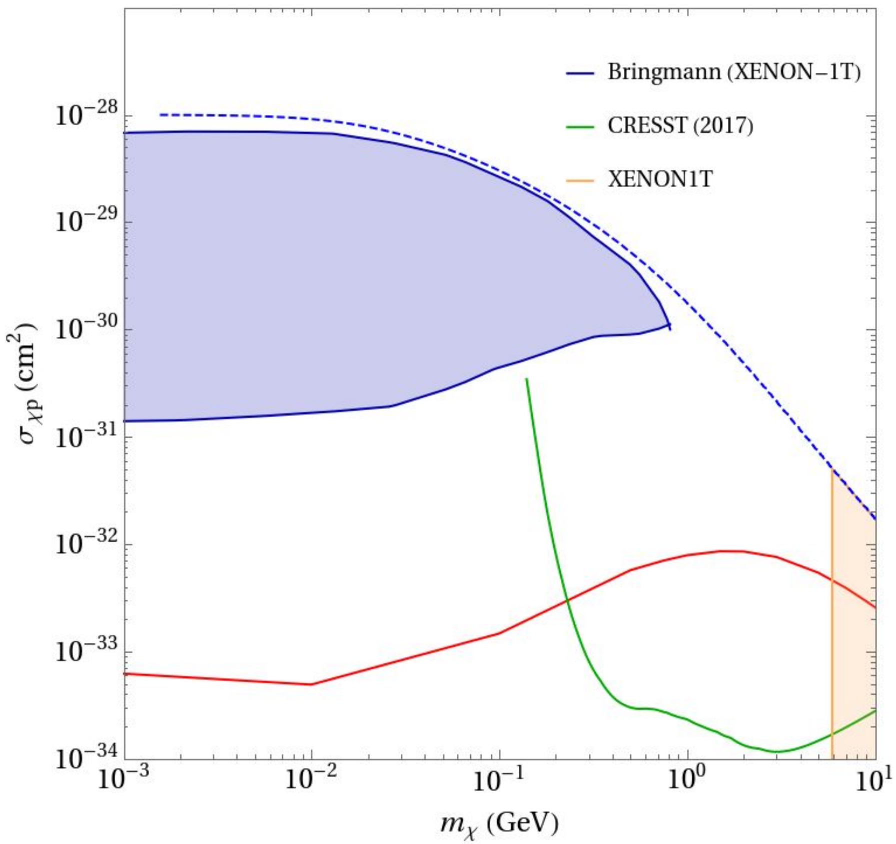
CRDM Preliminary Results

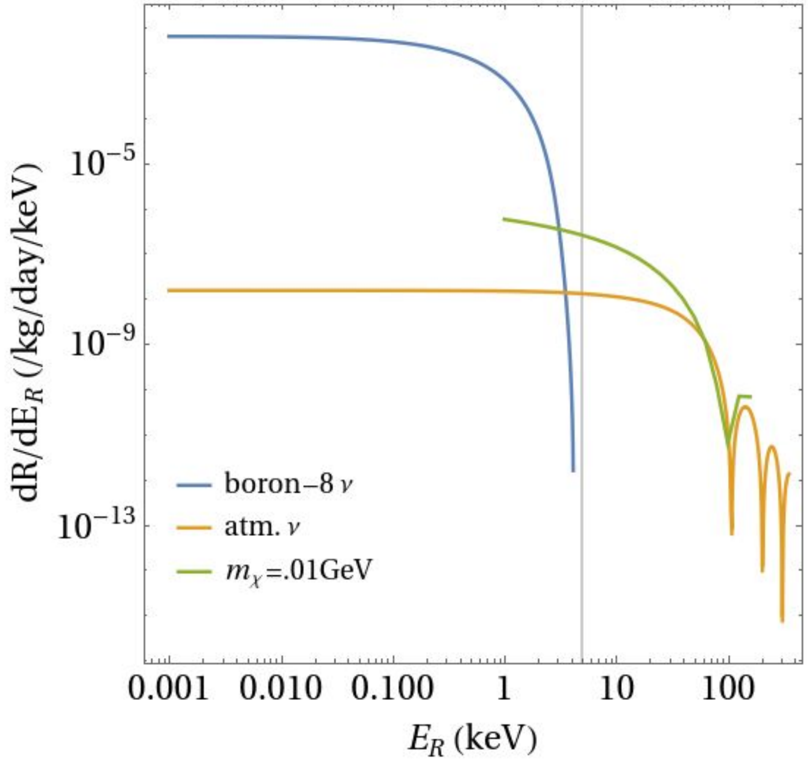


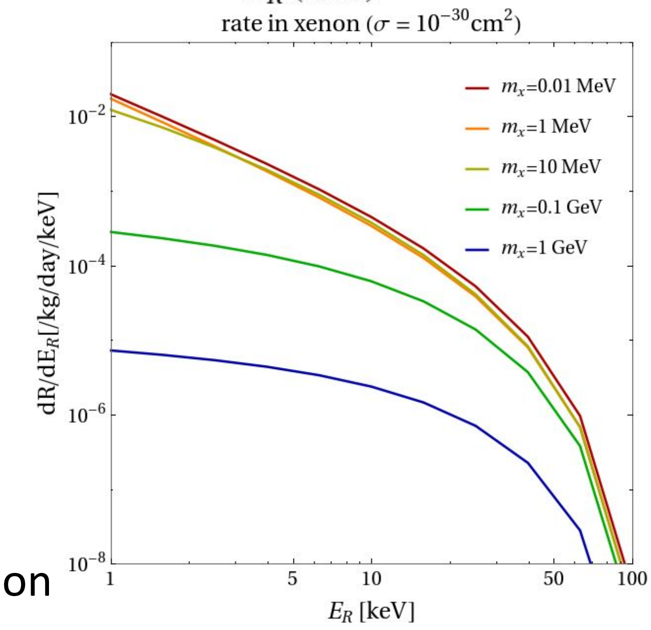
Extension of the constraints for a scalar mediated interaction

JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon

CRDM Preliminary Results







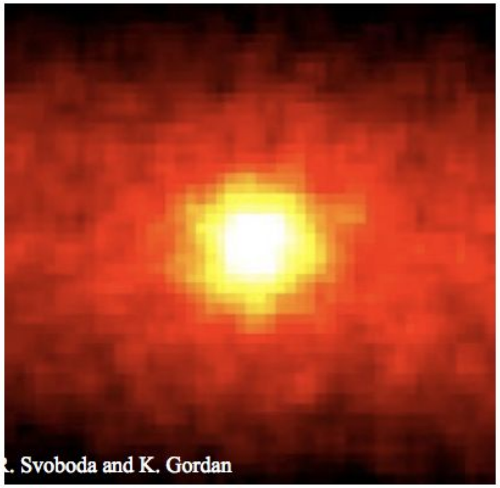
JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon

Summary

A tremendous variety of searches are being carried out for sub-GeV mass dark matter.

Utilizing complementary approaches from experiment and theory in astrophysics, cosmology, and particle physics, we expect a continued coverage of unexplored regions of parameter space.

Neutrino Floor



Solar neutrinos

$$^{8}\mathrm{B} \rightarrow \, ^{7}\mathrm{Be}^{*} + e^{+} + \nu_e$$

$$^{3}\mathrm{He} + \mathrm{p} \rightarrow \, ^{4}\mathrm{He} + e^{+} + \nu_e$$

hep

pp

$$p + p \rightarrow \, ^{2}\mathrm{H} + e^{+} + \nu_e$$

$$p + e^{-} + p \rightarrow \, ^{2}\mathrm{H} + \nu_e$$

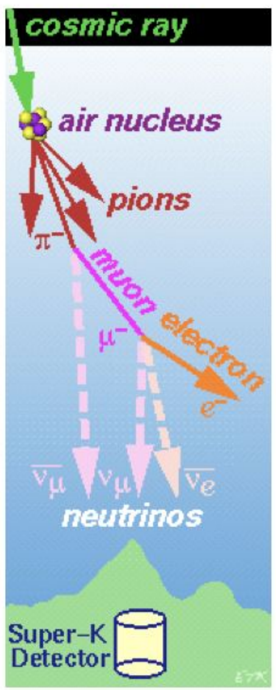
pep

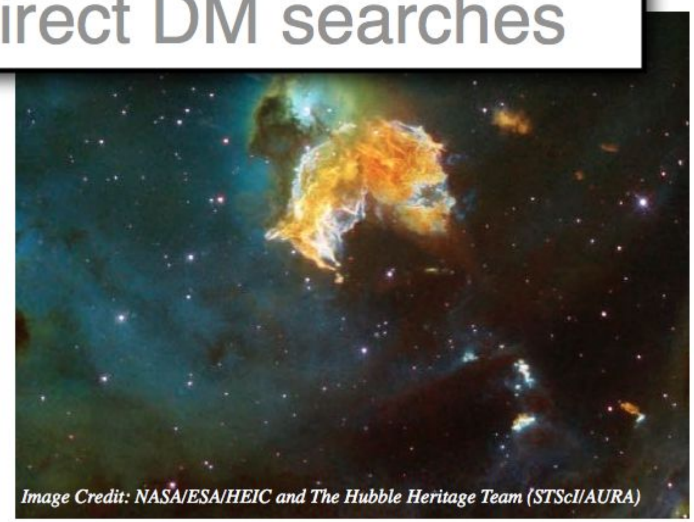
electron capture on $^{7}\mathrm{Be}$

neutrinos from the CNO cycle

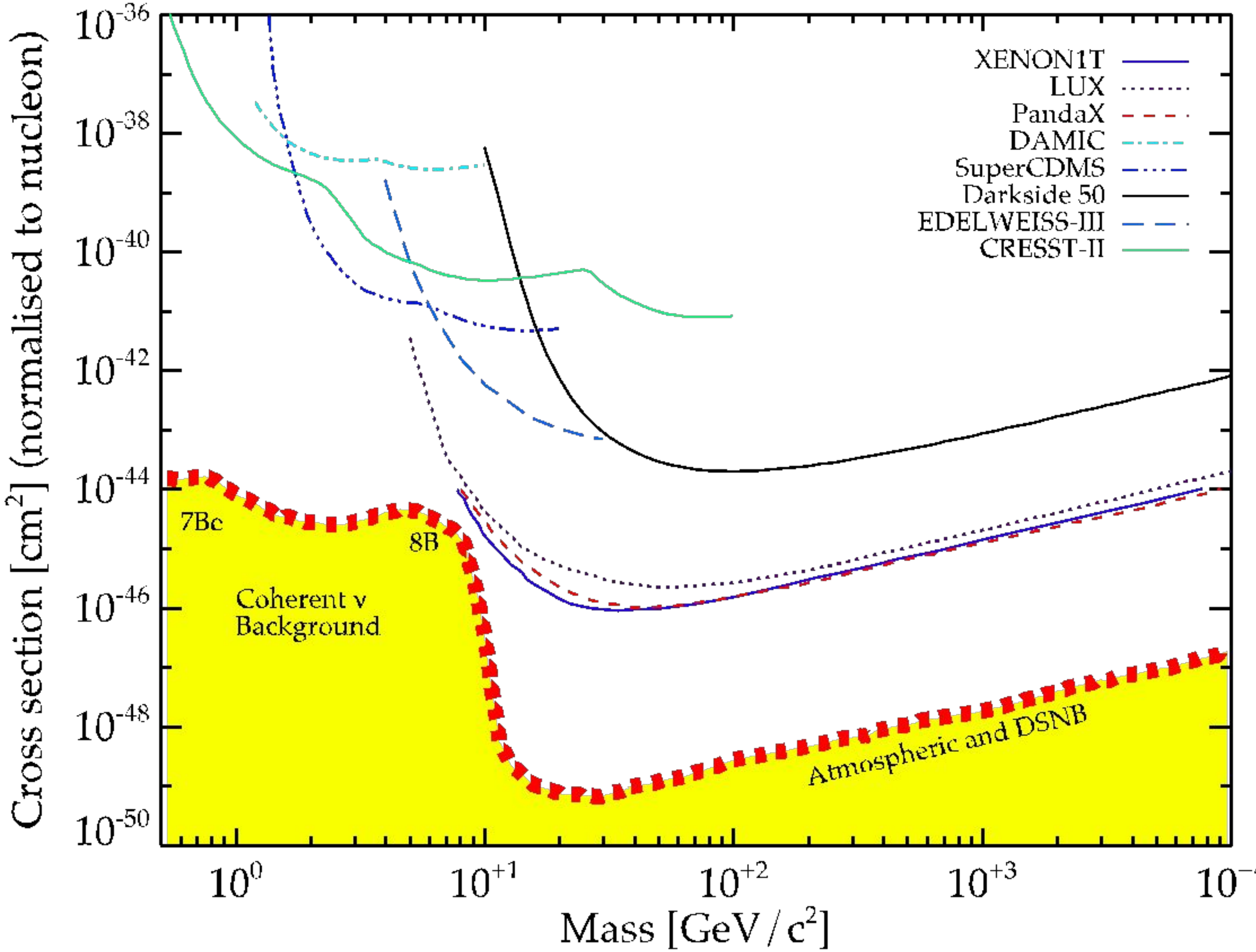
An irreducible background for direct DM searches

Atmospheric neutrinos

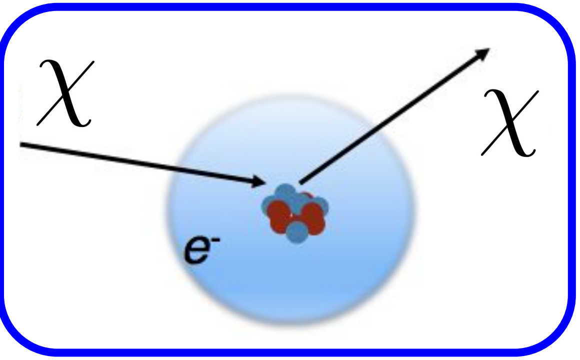


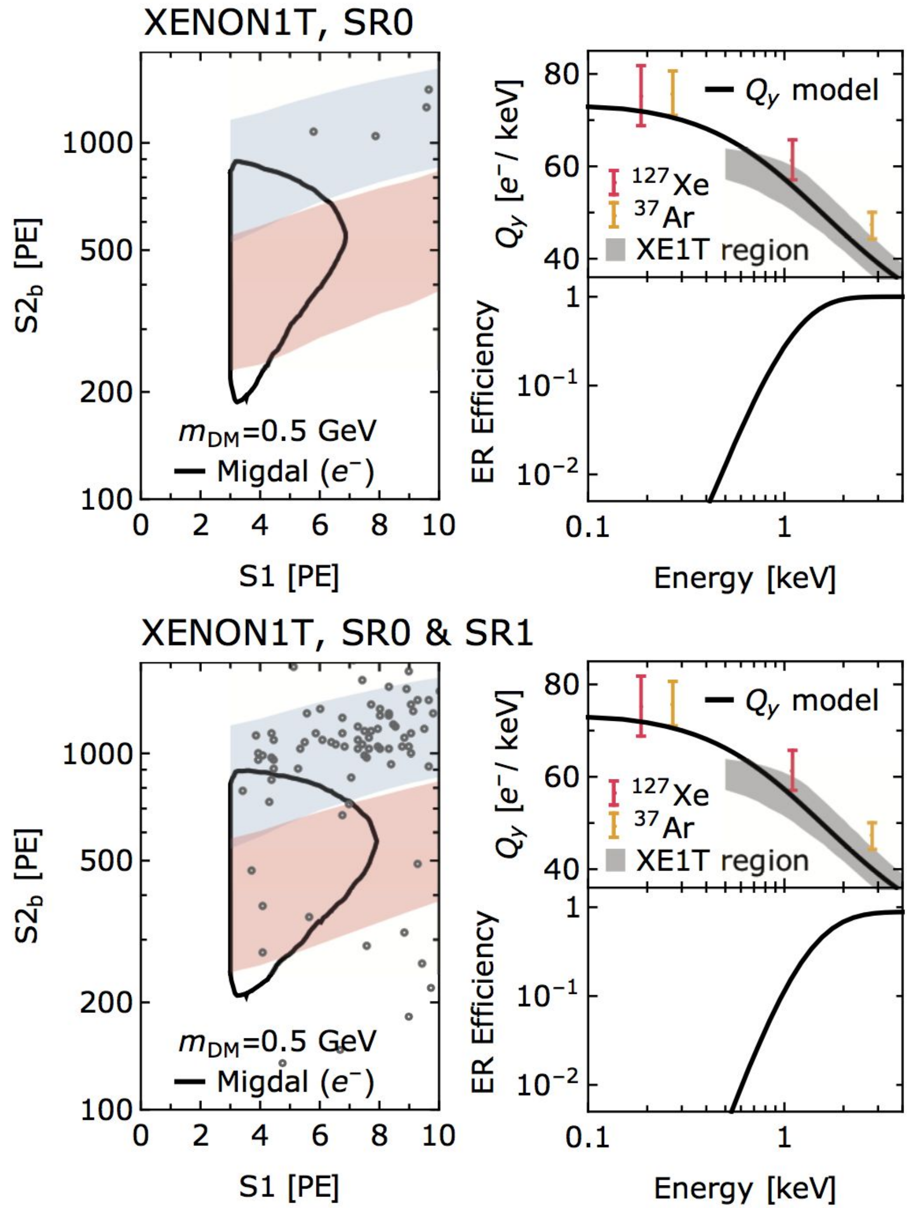


Diffuse SN background



Akimov *et al*. 1803.09183, Figure by L. Strigari





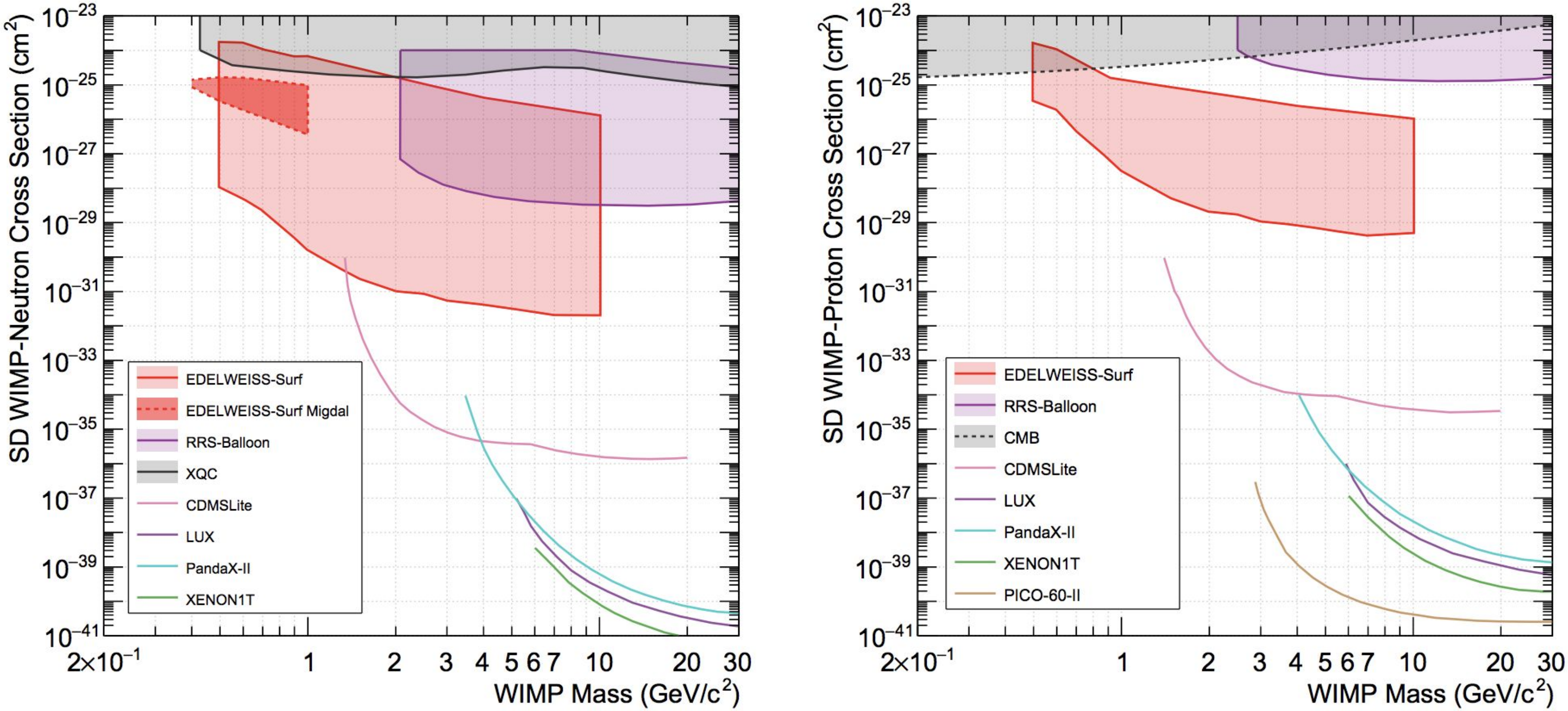
$$\mathrm{S1} = g_1\, L_y\, E_{\mathrm{EM}}$$

$$\mathrm{S2} = g_2\, Q_y\, E_{\mathrm{EM}}$$

$$\frac{1}{W} = L_y + Q_y$$

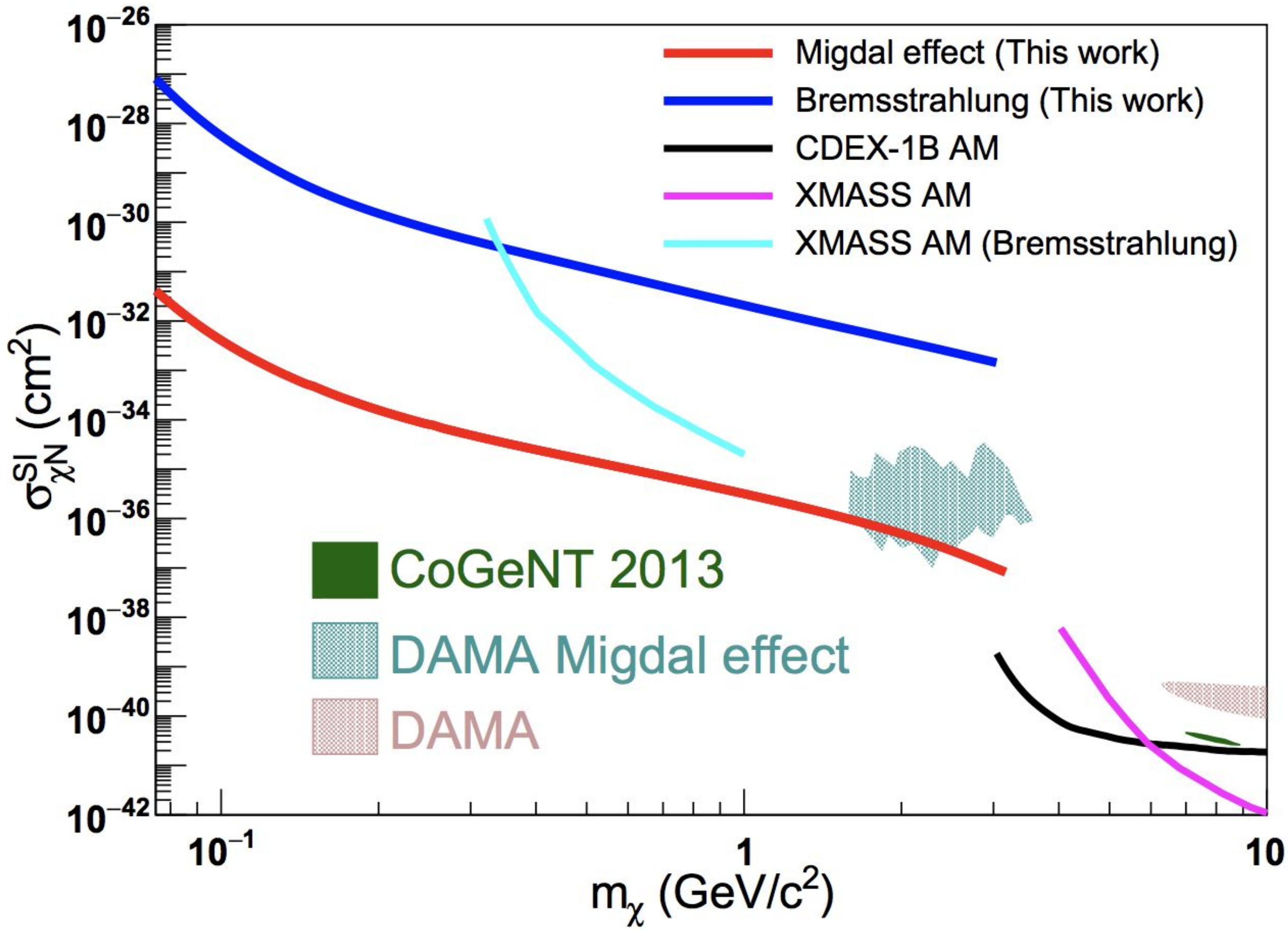
M.Dolan, F. Kahlhoefer, and C.McCabe, PRL (2018) 1711.09906

Migdal and Brem limits and experimental results



33.4 g Ge, 60 eV threshold

EDELWEISS Collaboration (E. Armengaud (IRFU, Saclay) *et al.*). Jan 11, 2019. 15 pp.
Published in **Phys.Rev. D99 (2019) no.8, 082003**

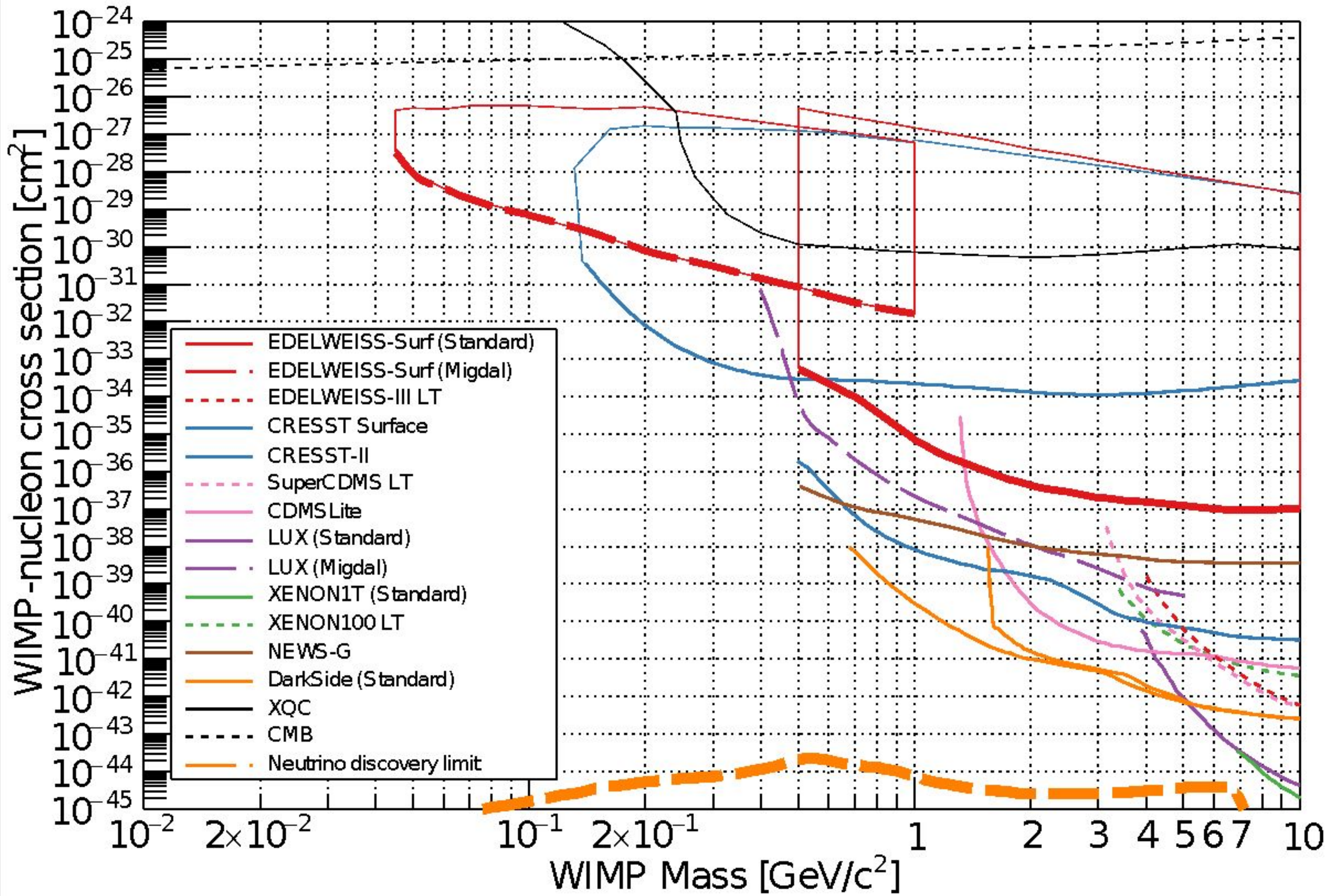


939 g Germanium detector at CJPL
1107.5 kg·day exposure and 250 eVee threshold for annual modulation search

Constraints on spin-independent nucleus scattering with sub-GeV WIMP dark matter from the CDEX-1B Experiment at CJPL

CDEX Collaboration (Z.Z. Liu (Tsinghua U., Beijing) *et al.*). May 1, 2019. 5 pp.

e-Print: **arXiv:1905.00354** **[hep-ex]**



33.4 g Ge, 60 eV threshold

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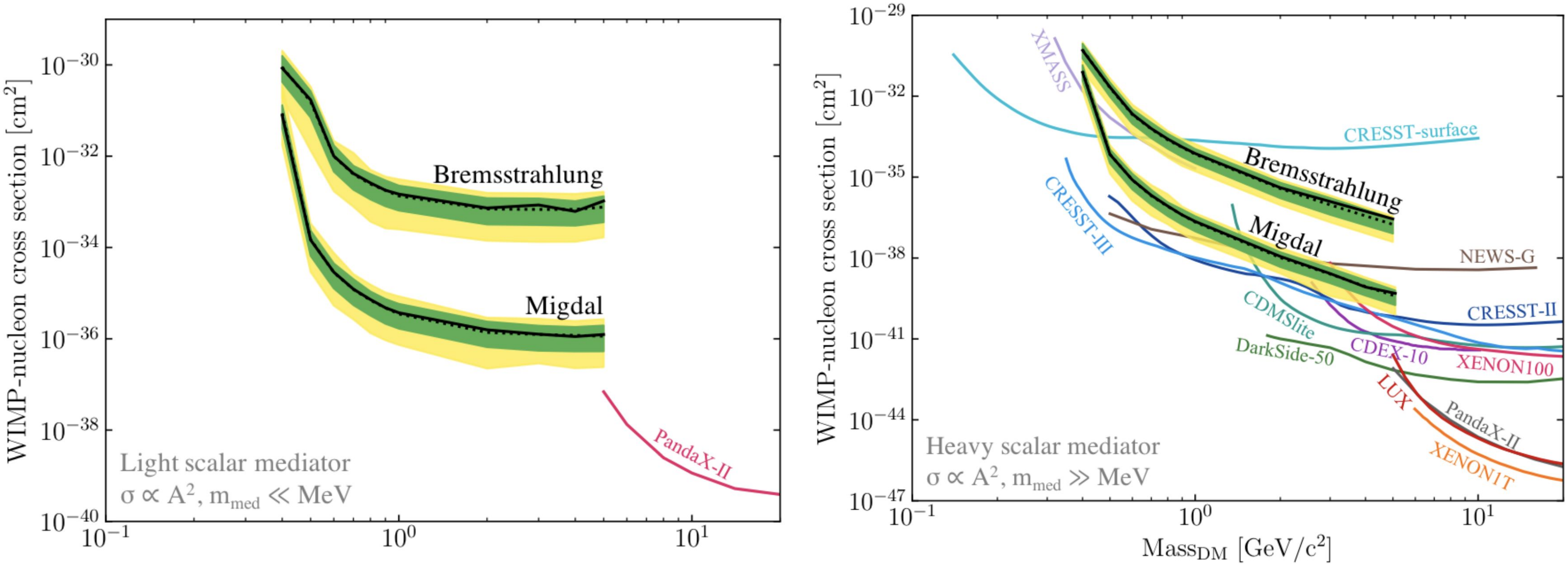
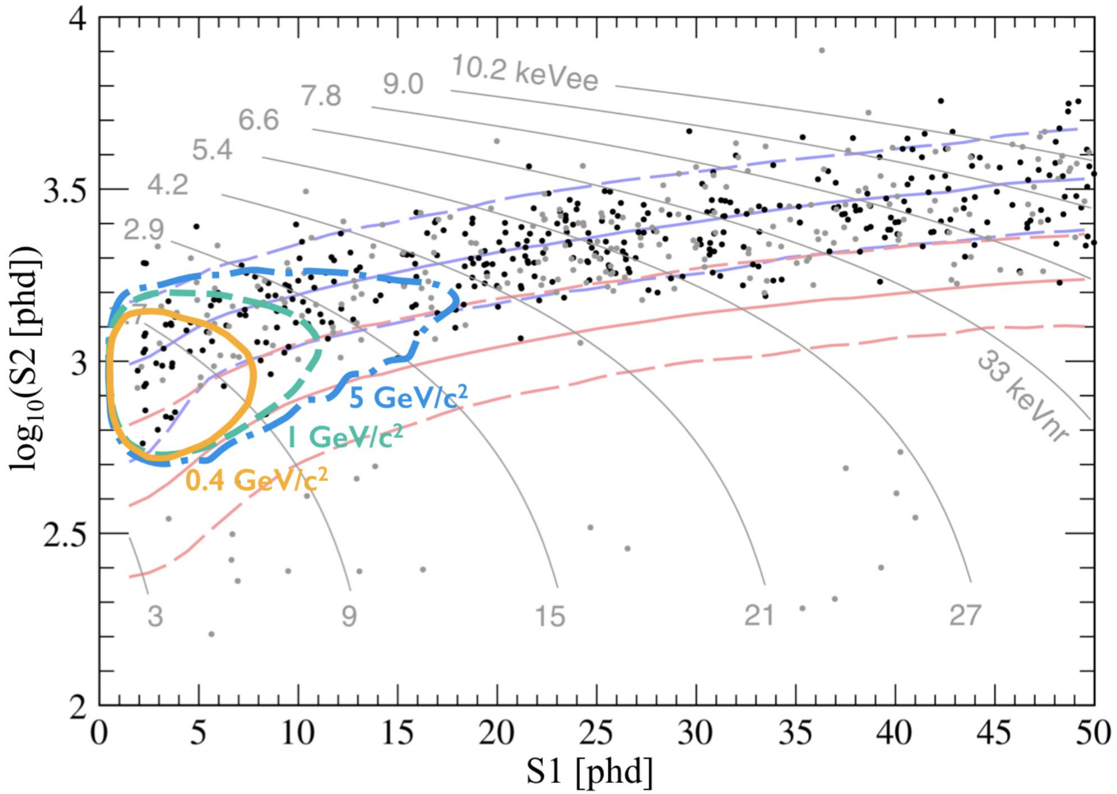
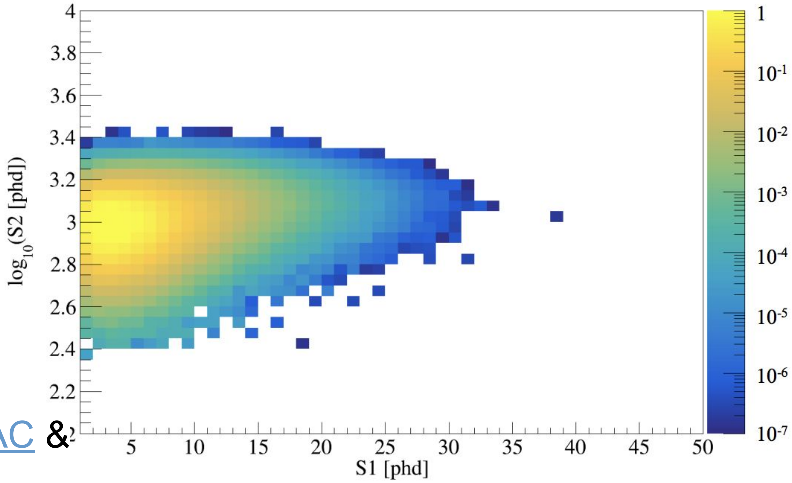


LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Nov 27, 2018. 7 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.13, 131301**

e-Print: **arXiv:1811.11241** **[astro-ph.CO]**



$$E = W\left(n_\gamma + n_e\right) = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$



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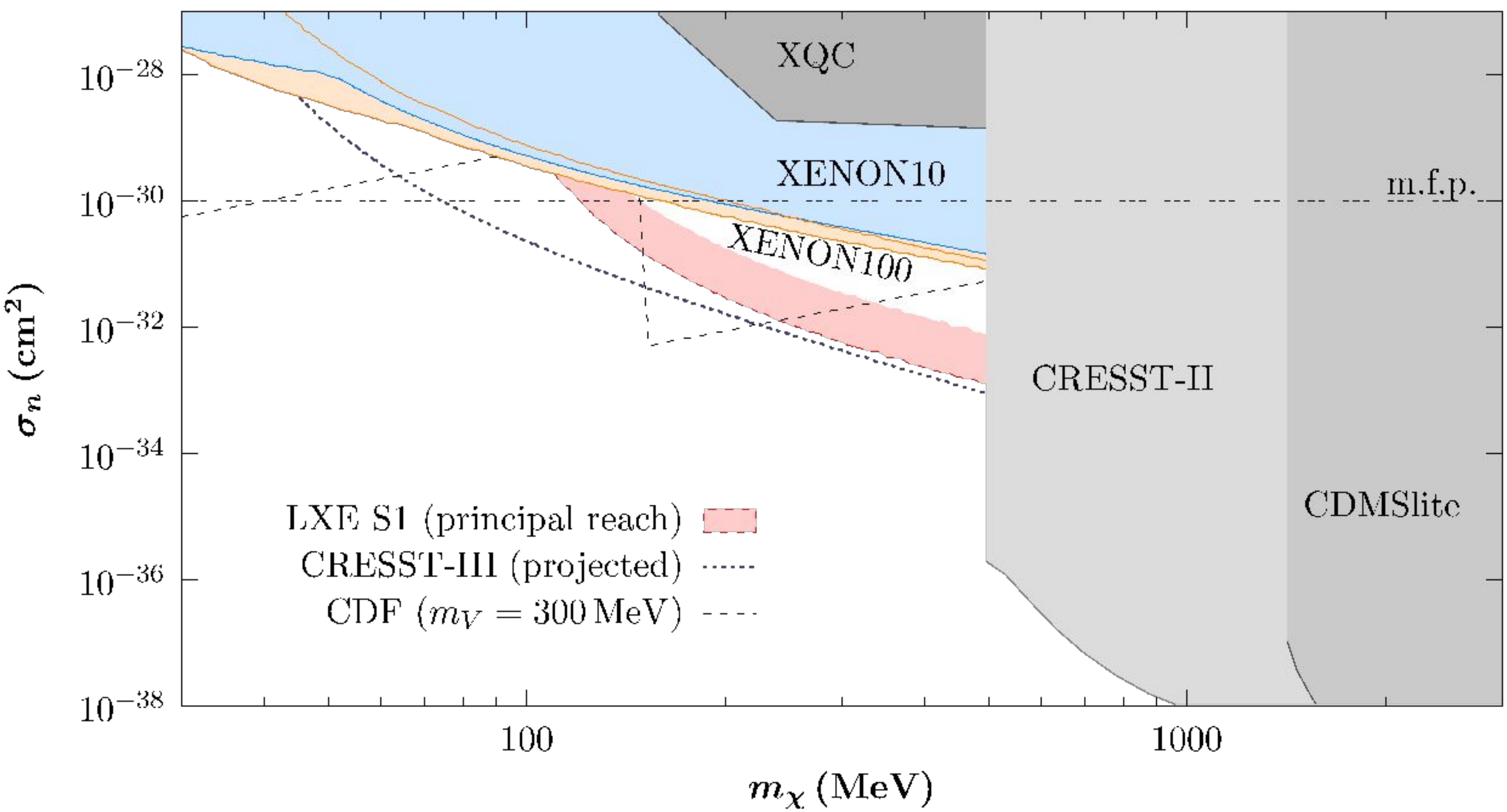


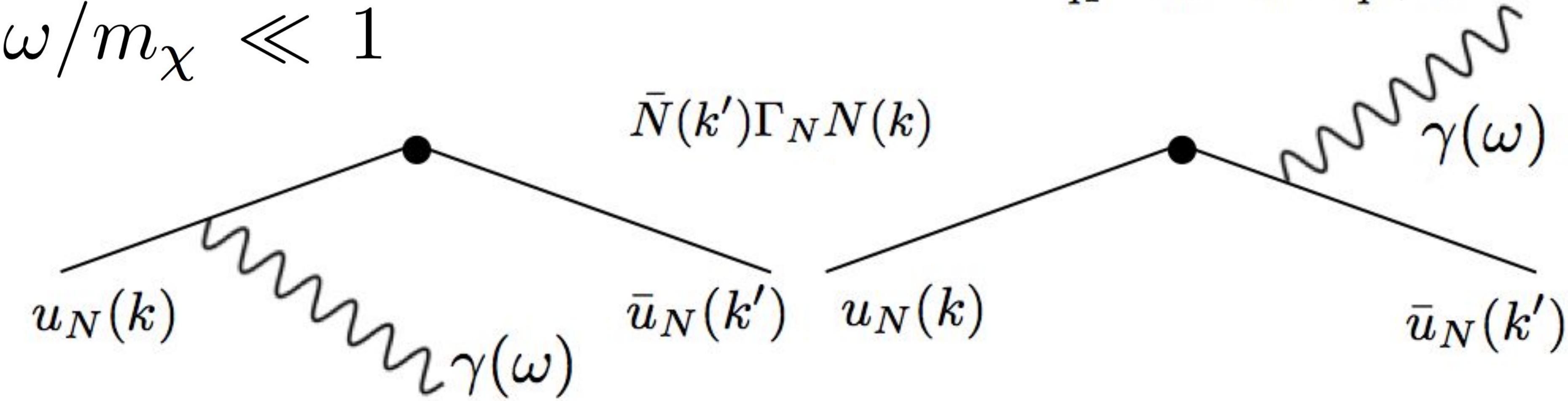
C. Kouvaris and J. Pradler, PRL 2017, 1607.01789

Matrix element factorization for 2-to-3 into 2-2+ kinematic factors

$$\vec{q} \equiv \vec{p'} - \vec{p}$$

$$\vec{q}_T \equiv \vec{k} - \vec{k'} = \vec{q} + \vec{\omega}$$

$$\omega / m_\chi \ll 1$$

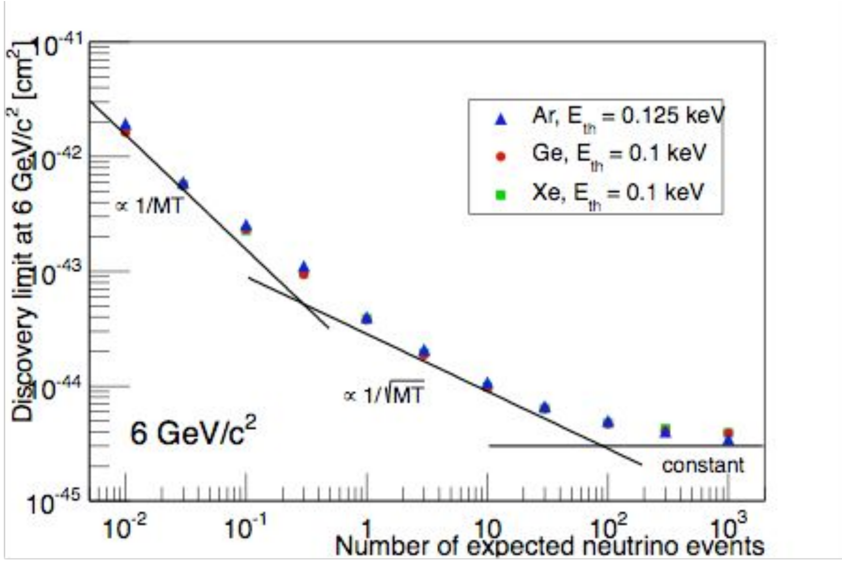


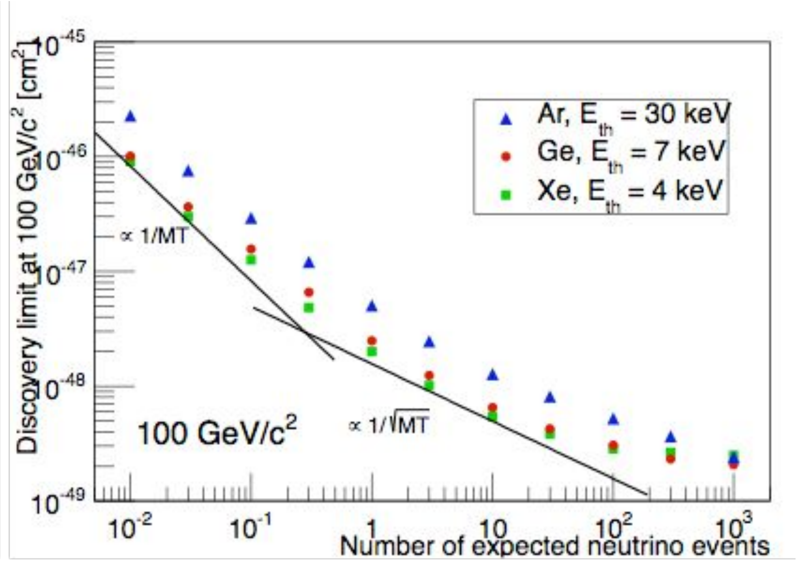
$$\bar{u}_N(k')\left[\Gamma_N\left(\frac{\not{k}+m_N}{(k-\omega)^2-m_N^2}-\frac{\not{\omega}}{(k-\omega)^2-m_N^2}\right)\not{\epsilon}+\not{\epsilon}\left(\frac{\not{k}'+m_N}{(k+\omega')^2-m_N^2}+\frac{\not{\omega}}{(k+\omega)^2-m_N^2}\right)\Gamma_N\right]u_N(k)$$

$$\bar{u}(k')\Gamma_N u(k)\left(-\frac{k\cdot\epsilon}{k\cdot\omega}+\frac{k'\cdot\epsilon}{k'\cdot\omega}\right)$$

$$\rightarrow |\mathcal{M}|^2_{2-2}(Ze)^2\left(\frac{\vec{q}\cdot\vec{\epsilon}}{m_T\omega}\right)^2$$

Discovery Evolution





Discovery limits as a function of background neutrino events for Argon, Germanium, and Xenon.

A given experiment has a 90% probability to obtain at least a 3σ detection

6GeV WIMP: Ge 240 kg-yr, Xe 130 kg-year

100GeV WIMP: Ge 32.5 ton-yr, Xe 21.5 ton-year

The issue is that the spin-independent (and spin-dependent) WIMP-Nucleus scattering is practically indistinguishable from the coherent neutrino-nucleus scattering.

Direct Detection Review

Momentum Exchanged $O(<100\text{MeV})$

$$q = \sqrt{2 m_T E_R}$$

Incident energy

$$E_i = \frac{m_\chi v^2}{2}$$

Recoil energy $O(10\text{keV})$

$$v \sim \mathcal{O}(10^{-3})$$

$$E_R = \frac{\mu_{\chi T}^2 v^2}{m_T}(1 - \cos\theta)$$

$$E_{\rm R,max} = \frac{2\mu_{\chi \rm T}^2 v^2}{m_T}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_{\chi,\odot}}{m_\chi m_T} \int_{v>v_{\rm min}} \frac{d\sigma}{dE_R} v f(\vec{v}) d^3v$$