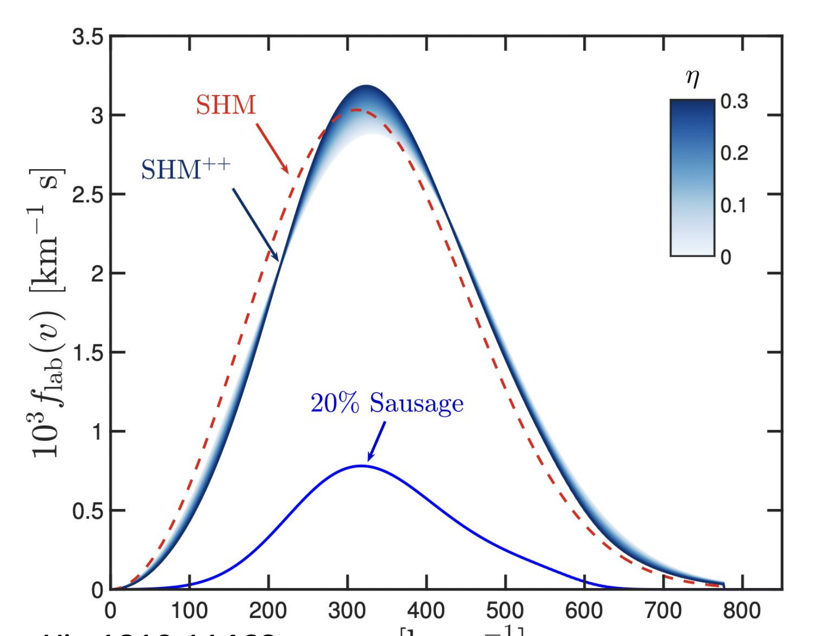
Dark Matter from Monogem

Christopher Cappiello, Neal Avis Kozar,
Aaron Vincent

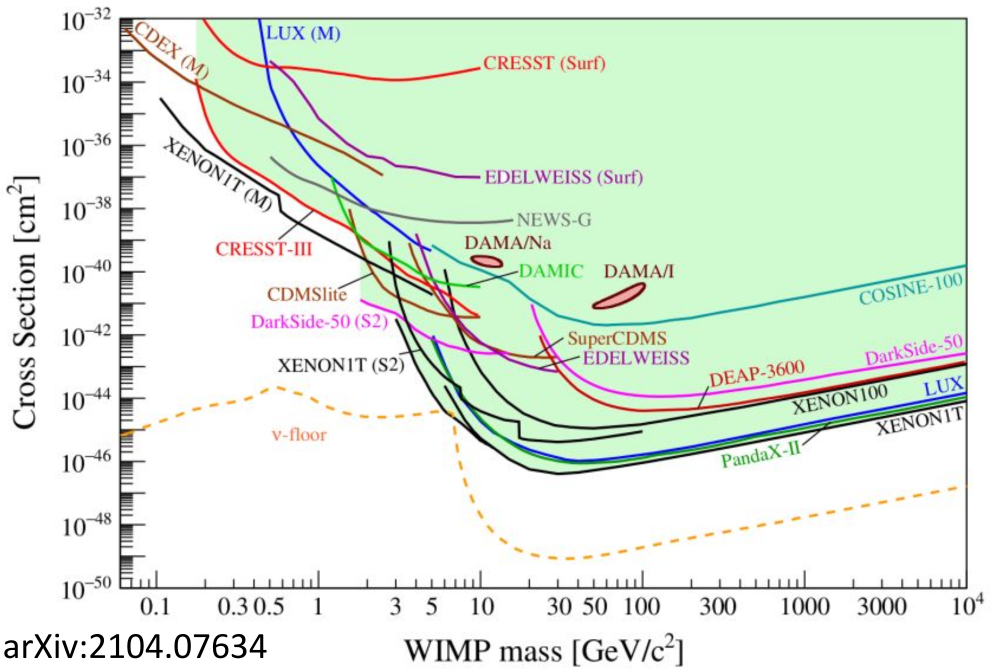
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University

What is Dark Matter's Velocity?



arXiv:1810.11468



arXiv:2104.07634

Boosted Dark Matter

Boosted Dark Matter at Neutrino Experiments

Lina Necib,[1,*] Jarrett Moon,[2] Taritree Wongjirad,[2] and Janet M. Conrad[2]
[1] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2] Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Current and future neutrino experiments can be used to discover dark matter, not only in searches for dark matter annihilating to neutrinos, but also in scenarios where dark matter itself scatters off Standard Model particles in the detector. In this work, we study the sensitivity of different neutrino detectors to a class of models called boosted dark matter, in which a subdominant component of a dark sector acquires a large Lorentz boost today through annihilation of a dominant component in a dark matter-dense region, such as the galactic Center or dwarf spheroidal galaxies. This analysis ... -based Super-K ... s. We study the ... reshold, volume ... -specific features ... ng signatures of

Strong New Limits on Light Dark Matter from Neutrino Experiments

Christopher V. Cappiello[1,2,*] and John F. Beacom[1,2,3,†]
[1] Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210
[2] Department of Physics, Ohio State University, Columbus, OH 43210
[3] Department of Astronomy, Ohio State University, Columbus, OH 43210
(Dated: November 18, 2019)

The non-detection of GeV-scale WIMPs has led to increased interest in more general candidates, including sub-GeV dark matter. Direct-detection experiments, despite their high sensitivity to WIMPs, are largely blind to sub-GeV dark matter. Recent work has shown that cosmic-ray elastic scattering with sub-GeV dark matter would both alter the observed cosmic ray spectra and produce a flux of relativistic dark matter, which would be detectable with traditional dark matter experiments as well as larger, higher-threshold detectors for neutrinos. Using data, detectors, and analysis t... space exc... elastic sca...

The Sun as a sub-GeV Dark Matter Accelerator

Timon Emken,* Chris Kouvaris,† and Niklas Grønlund Nielsen‡
CP^3-Origins, University of Southern Denmark, Campusvej 55, DK-5230 Odense, Denmark

Sub-GeV halo dark matter that enters the Sun can potentially scatter off hot solar nuclei and be ejected much faster than its incoming velocity. We derive an expression for the rate and velocity distribution of these reflected particles taking into account the Sun's temperature and opacity. We further demonstrate that future direct detection experiments could use these energetic reflected particles to probe light dark matter in parameter space that cannot be accessed via ordinary halo dark matter.

The highest-speed local dark matter particles come from the Large Magellanic Cloud

G. Besla,[a,1] A. H. G. Peter,[b] N. Garavito-Camargo[a]
[a] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
[b] CCAPP, Department of Physics, and Department of Astronomy, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH ...
E-mail: gbesla@email.arizona.edu, pe... jngaravitoc@email.arizona.edu

Abstract. Using N-body simulations of ... the Milky Way (MW), tailored to repro... we show that the high-speed tail of the ... whelmingly of LMC origin. Two popu... were once bound to the LMC, and 2) ... to the response of the halo to the rece... of 700-900 km/s with respect to the E... high-speed particles follow trajectories ... reached in June. For low-mass dark ... signal in direct-detection experiments, ... and elastic scattering cross sections eve... non-disrupt... Neighborho...

Novel direct detection constraints on light dark matter

Torsten Bringmann[1] and Maxim Pospelov[2,3]
[1] Department of Physics, University of Oslo, Box 1048, N-0371 Oslo, Norway
[2] Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada
[3] Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada
(Dated: June 2018)

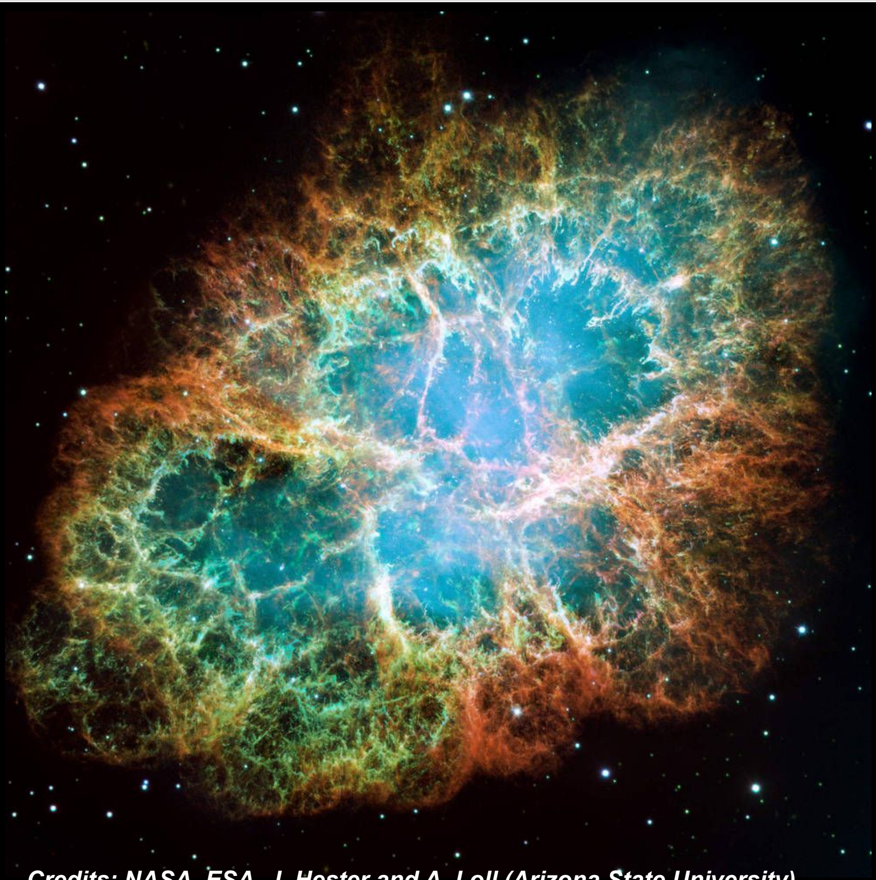
All attempts to directly detect particle dark matter (DM) scattering on nuclei suffer from the partial or total loss of sensitivity for DM masses in the GeV range or below. We derive novel constraints from the inevitable existence of a subdominant, but highly energetic, component of DM generated ... tors, as ... section ... M.

Directly Detecting MeV-scale Dark Matter via Solar Reflection

Haipeng An,[1,2] Maxim Pospelov,[3,4] Josef Pradler,[5] and Adam Ritz[3]
[1] Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA, 91125, USA
[2] Department of Physics, Tsinghua University, Beijing 100084, China
[3] Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada
[4] Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada
[5] Institute of High Energy Physics, Austrian Academy of Sciences, 1050 Vienna, Austria
(Dated: August 2017)

If dark matter (DM) particles are lighter than a few MeV/c^2 and can scatter off electrons, their interaction within the solar interior results in a considerable hardening of the spectrum of galactic dark matter received on Earth. For a large range of the mass vs cross section parameter space, $\{m_e, \sigma_e\}$, the 'reflected' component of the DM flux is far more energetic than the endpoint of the ambient galactic DM energy distribution, making it detectable with existing DM detectors sensitive to an energy deposition of $10-10^3$ eV. After numerically simulating the small reflected component of the DM flux, we calculate its subsequent signal due to scattering on detector electrons, deriving new constraints on σ_e in the MeV and sub-MeV range using existing data from the XENON10/100, LUX, PandaX-II, and XENON1T experiments, as well as making projections for future low threshold direct detection experiments.

Supernova Shocks as Dark Matter Sources



Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

The Good

v > 0.01 c

Ejecta mass ~few $M_\odot$

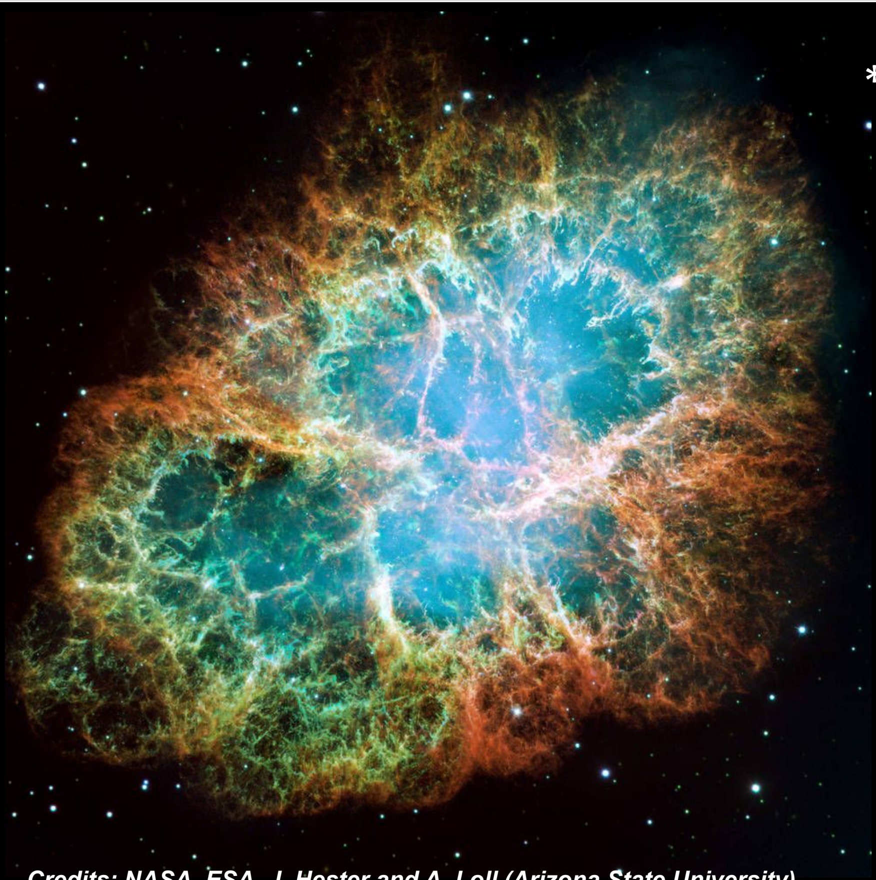
The Bad

Distances > 100 pc

Transient, not constant

Supernova Shocks* as Dark Matter Sources

*NOT Fermi Acceleration



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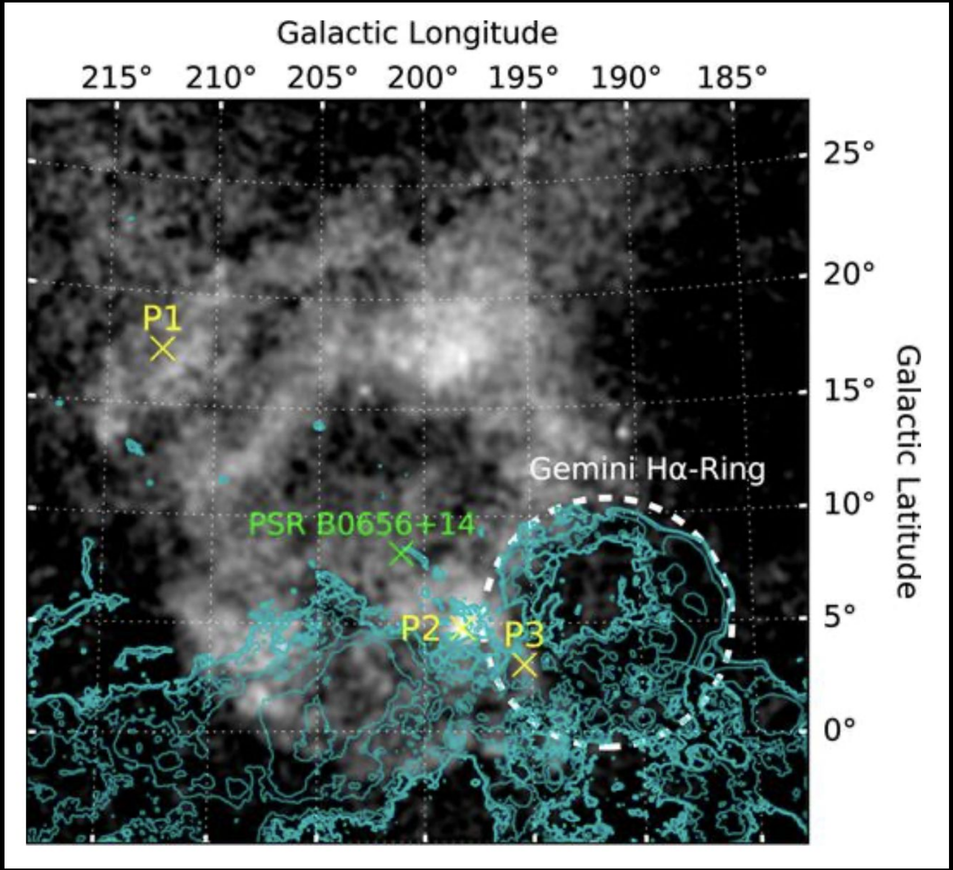
The Monogem Ring



ROSAT image of the Monogem Ring (taken from Knies, Sasaki and Plucinsky 2018)

Age = 68,000 years
Distance = 300 pc
Corresponding velocity: 4,300 km/s

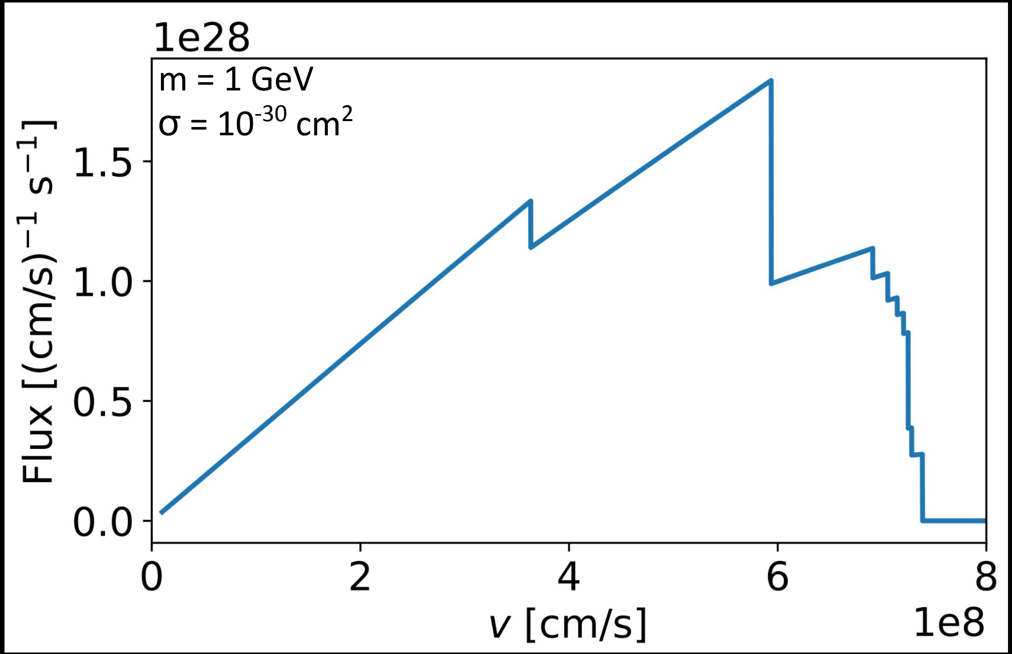
Esn = $8*10^{50}$ erg, assume 5 $M_\odot$

$$R_s(t) = R_0\left(\left(\frac{t}{t_0}\right)^{-5\lambda_{FE}} + \left(\frac{t}{t_0}\right)^{-5\lambda_{ST}}\right)^{-1/5}$$

$$V_s(t) = \frac{R_0}{t_0}\left(\frac{R_s(t)}{R_0}\right)^6\left(\lambda_{FE}\left(\frac{t}{t_0}\right)^{-5\lambda_{FE}-1} + \lambda_{ST}\left(\frac{t}{t_0}\right)^{-5\lambda_{ST}-1}\right)$$

Spin-Independent Scattering: Upscattered Flux

Nucleus	f_i
^{1}H	0.493
^{4}He	0.35
^{16}O	0.1
^{28}Si	0.02
^{12}C	0.015
^{56}Fe	0.007
^{20}Ne	0.005
^{24}Mg	0.005
^{32}S	0.005



$$\Phi(v) = \int dE\, \delta(E - \frac{1}{2}m_x v^2)\rho_x V_s(t) \sum_i \left(\frac{M_{ej} f_i}{m_i} + \frac{4}{3}\pi R_s(t)^3 n_0 \delta_{i,1} \right) v \frac{d\sigma_{xi}}{dE}$$

Spin-Independent Scattering: Flux at Earth

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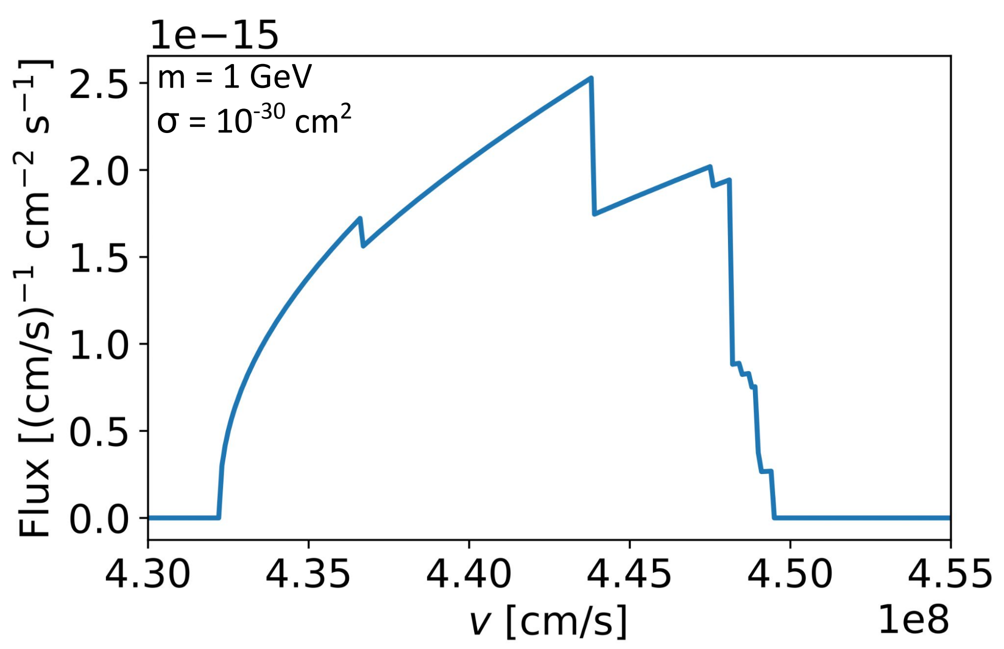
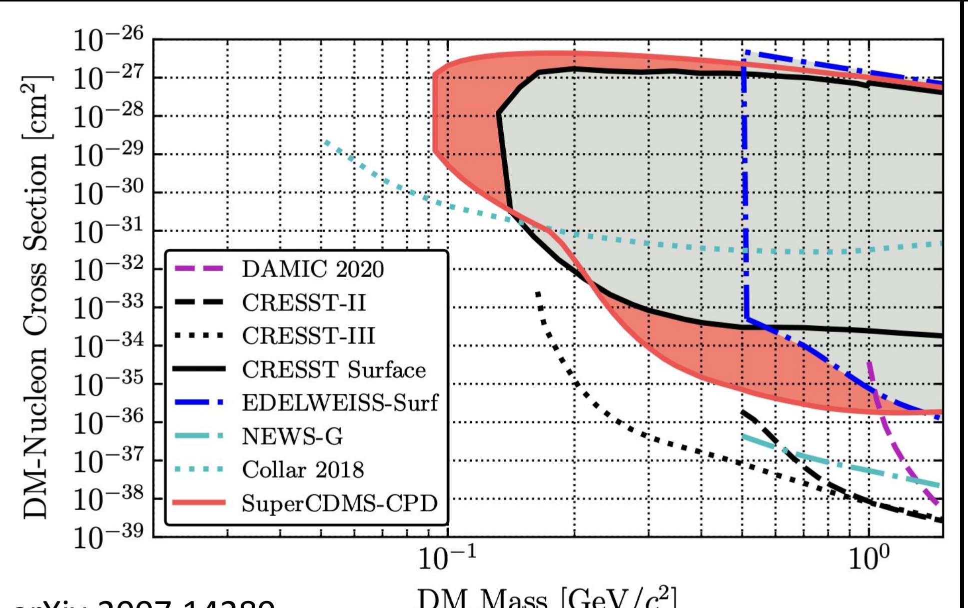
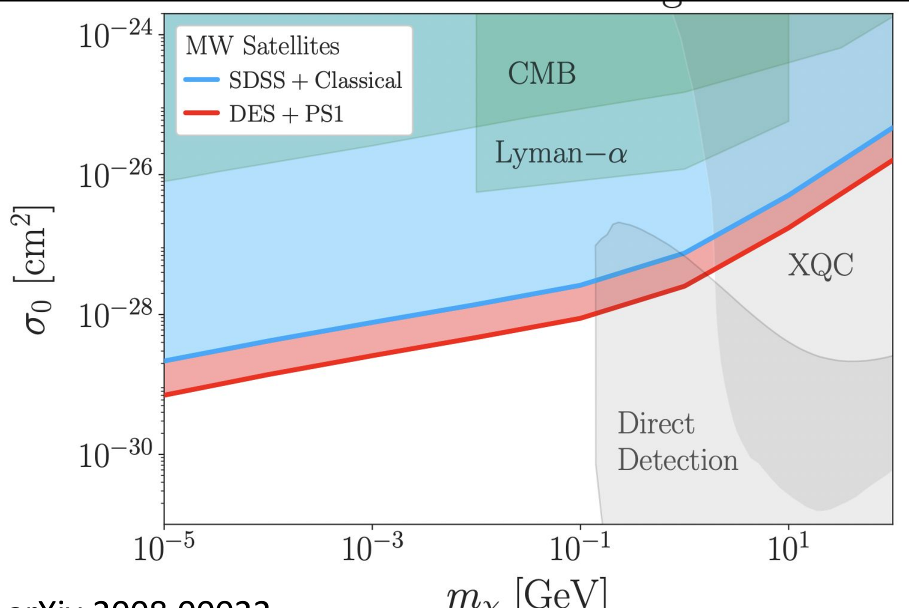


$$\Phi_{Earth}(v) = \int dE\,\delta(E - \frac{1}{2}m_x v^2) \int \frac{1}{4\pi D^2}\rho_x V_s(t) \times \sum_i \left(\frac{M_{ej} f_i}{m_i} + \frac{4}{3}\pi R_s(t)^3 n_0 \delta_{i,1} \right) v \frac{d\sigma_{xi}}{dE} \delta(t - (Age - D/v)) dt$$

Spin-Independent Scattering: Flux at Earth



arXiv:2007.14289



arXiv:2008.00022

Velocity-Dependent Scattering: Effective Operators

Operator	Form	v-scaling of σ
$\mathcal{O}_1$	$1_\chi 1_N$	v^0
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	v^4
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	v^4
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	v^0
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	v^4
$\mathcal{O}_6$	$(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	v^4
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	v^2
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$	v^2
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$	v^2
$\mathcal{O}_{10}$	$i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$	v^2
$\mathcal{O}_{11}$	$i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$	v^2
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$	v^2
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	v^4
$\mathcal{O}_{14}$	$i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$	v^4
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$	v^6

Describe general DM-nucleon interactions using a combination of Hermitian, Galilean-invariant quantities

O1 and O4 are spin-independent and spin-dependent, respectively

Limits on other effective operators come from LUX, XENON100, PandaX-II, DEAP-3600,DarkSide-50, CRESST-II, CDMS-II, SuperCDMS, plus cosmology

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$\mathcal{O}_6$	$(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	v^4
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	v^2
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$	v^2
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$	v^2
$\mathcal{O}_{10}$	$i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$	v^2
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Numerical Implementation of NREO Formalism

Capt'n General: A generalized stellar dark matter capture and heat transport code

Neal Avis Kozar,[a,b] **Ashlee Caddell,**[c] **Luke Fraser-Leach,**[d,a,b]
Pat Scott[c] **and Aaron C. Vincent**[*,a,b,e]

[a] *Department of Physics, Enigneering Physics and Astronomy, Queen's University, Kingston, ON, K7L 3N6, Canada*

[b] *Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston ON K7L 3N6, Canada*

[c] *School of Mathematics and Physics, The University of Queensland, St. Lucia, Brisbane, QLD 4072, Australia*

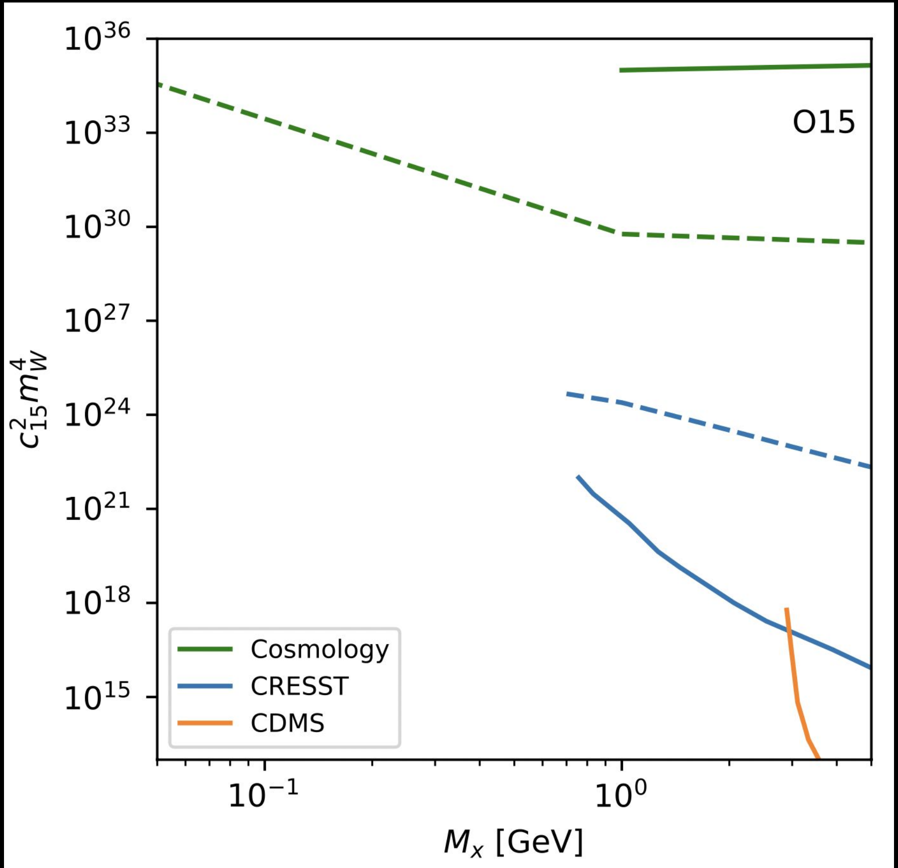
[d] *Department of Physics and Atmospheric Science, Dalhousie University, Coburg Road Halifax, B3H1A6, Canada*

[e] *Perimeter Institute for Theoretical Physics, Waterloo ON N2L 2Y5, Canada*

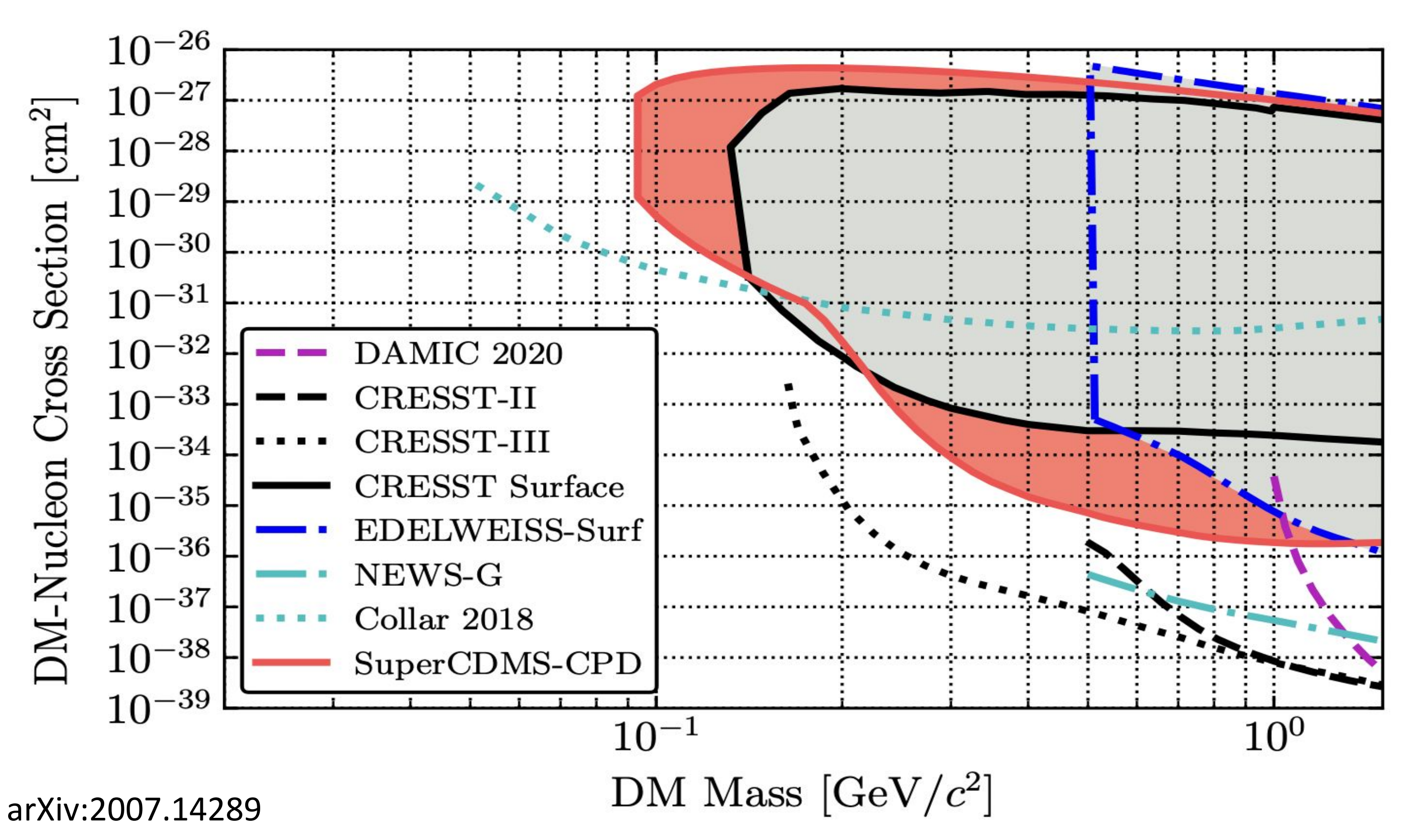
E-mail: *aaron.vincent@queensu.ca

`Capt'n General` is a FORTRAN90 standalone package that can be used to compute the capture and heat transport of dark matter in stars. It can compute capture rates for constant, velocity and momentum-dependent DM-nucleon elastic scattering cross sections, as well as non-relativistic effective operator interactions. `Capt'n General` can be interfaced with the GAMBIT global fitting codebase as well as stellar evolution simulation codes such as `MESA`.

Limits on Effective Operators

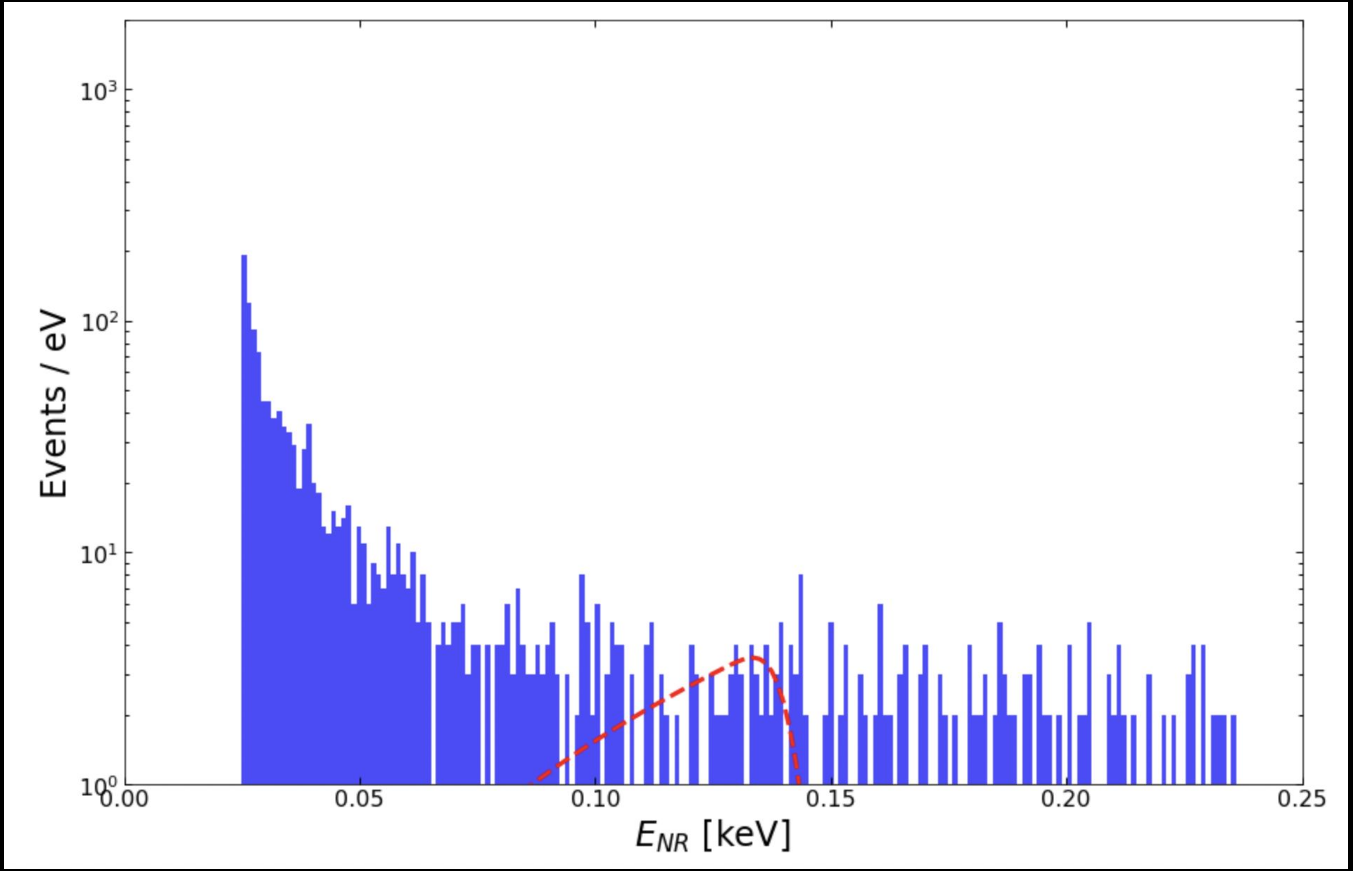


SuperCDMS Surface Athermal Phonon Detector

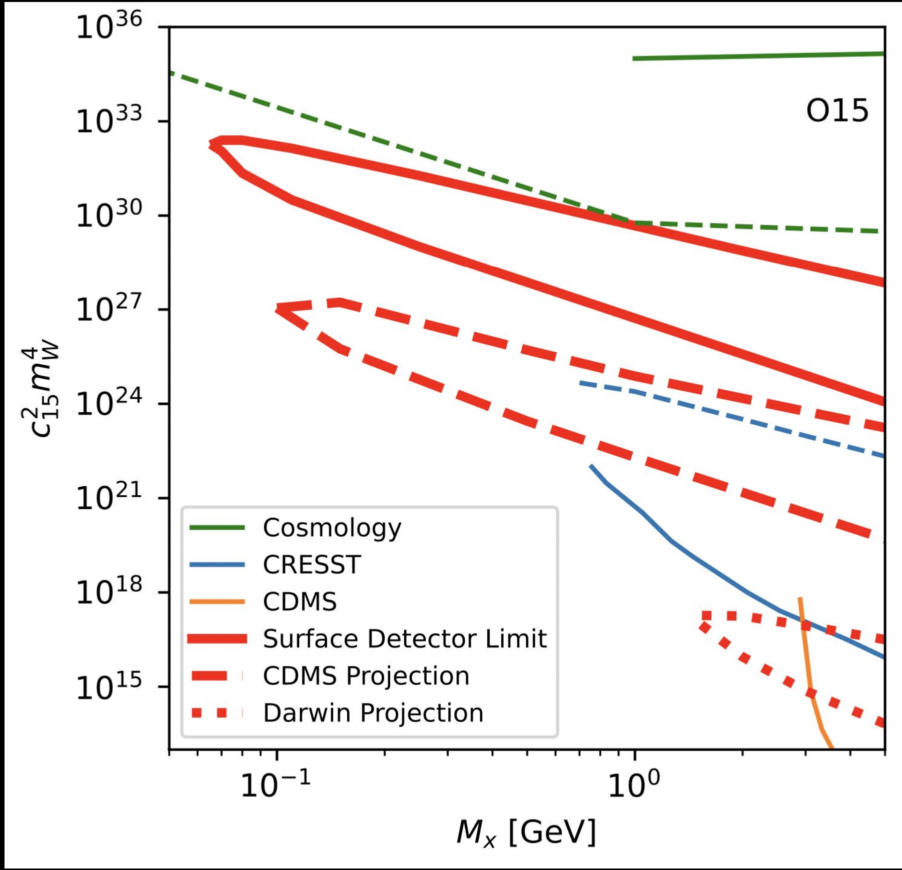


arXiv:2007.14289

SuperCDMS Surface Athermal Phonon Detector



Limits on Effective Operators

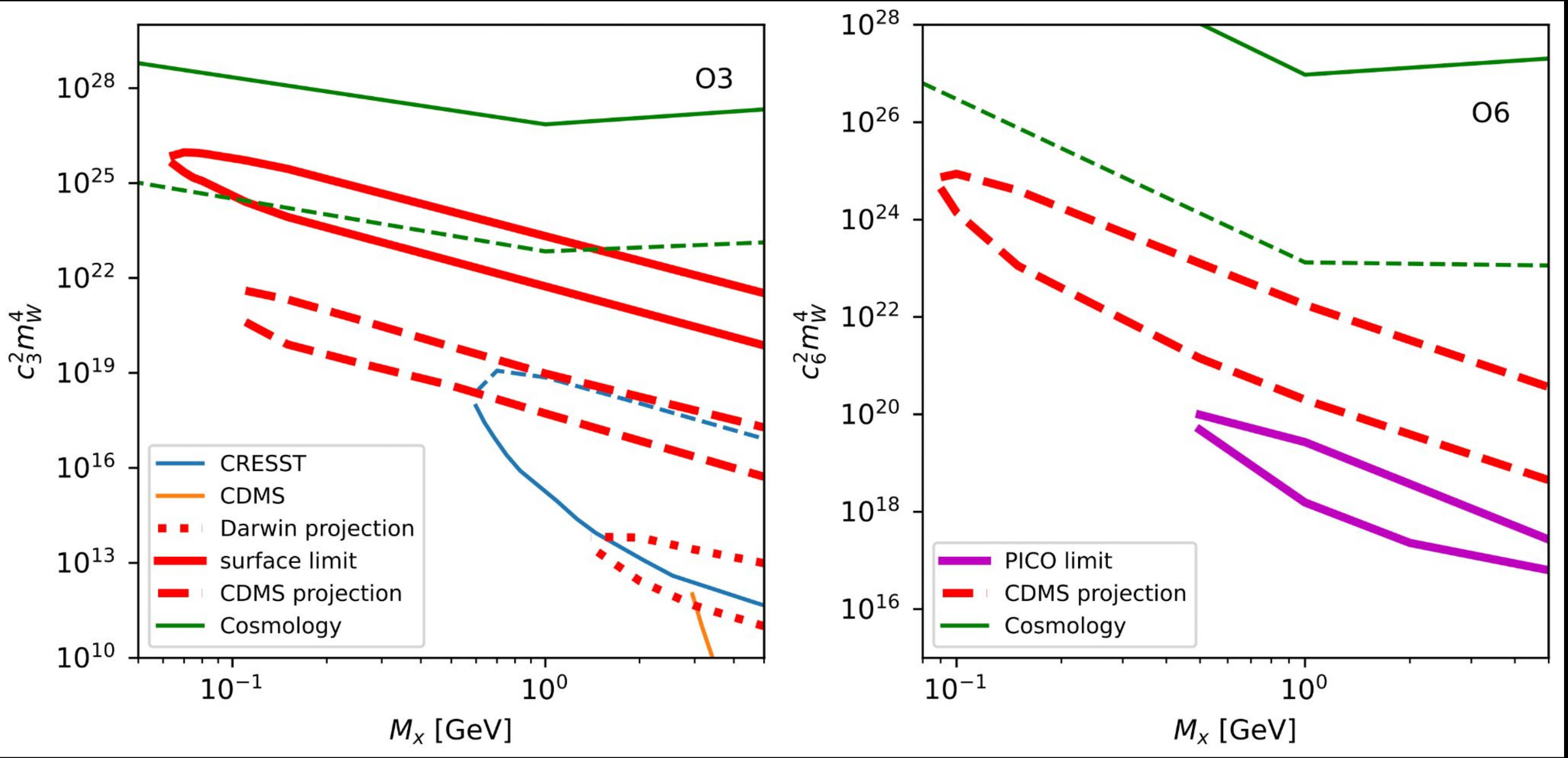


Solid: Surface Phonon Detector

Dashed: SuperCDMS SNOLAB Projection

Dotted: DARWIN Projection

Limits on Effective Operators



Thank you!

Neal Avis Kozar: Global fit of Non-relativistic Effective Operator Dark Matter using Solar Neutrinos, Thursday at 14:40 (Dark Matter XI)

Thank you to Bradley Kavanagh for modifications to WIMpy_NREFT code!

Nonrelativistic Reduction of Lagrangian Terms

j	$\mathcal{L}^j_{\text{int}}$	Nonrelativistic Reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar\chi\chi\bar N N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i\bar\chi\chi\bar N\gamma^5 N$	$i\frac{\vec q}{m_N}\cdot\vec S_N$	$\mathcal{O}_{10}$	O/O
3	$i\bar\chi\gamma^5\chi\bar N N$	$-i\frac{\vec q}{m_\chi}\cdot\vec S_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$	O/O
4	$\bar\chi\gamma^5\chi\bar N\gamma^5 N$	$-\frac{\vec q}{m_\chi}\cdot\vec S_\chi\frac{\vec q}{m_N}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$	E/E
5	$\frac{P^\mu}{m_\mathrm{M}}\bar\chi\chi\frac{K_\mu}{m_\mathrm{M}}\bar N N$	$4\frac{m_\chi m_N}{m_\mathrm{M}^2}1_\chi 1_N$	$4\frac{m_\chi m_N}{m_\mathrm{M}^2}\mathcal{O}_1$	E/E
6	$\frac{P^\mu}{m_\mathrm{M}}\bar\chi\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_\mathrm{M}}N$	$-\frac{m_\chi}{m_N}\frac{\vec q^2}{m_\mathrm{M}^2}1_\chi 1_N - 4i\frac{m_\chi}{m_\mathrm{M}}\vec v^\perp\cdot\left(\frac{\vec q}{m_\mathrm{M}}\times\vec S_N\right)$	$-\frac{m_\chi}{m_N}\frac{\vec q^2}{m_\mathrm{M}^2}\mathcal{O}_1 + 4\frac{m_\chi m_N}{m_\mathrm{M}^2}\mathcal{O}_3$	E/E
7	$\frac{P^\mu}{m_\mathrm{M}}\bar\chi\chi\bar N\gamma_\mu\gamma^5 N$	$-4\frac{m_\chi}{m_\mathrm{M}}\vec v^\perp\cdot\vec S_N$	$-4\frac{m_\chi}{m_\mathrm{M}}\mathcal{O}_7$	O/E
8	$i\frac{P^\mu}{m_\mathrm{M}}\bar\chi\chi\frac{K_\mu}{m_\mathrm{M}}\bar N\gamma^5 N$	$4i\frac{m_\chi}{m_\mathrm{M}}\frac{\vec q}{m_\mathrm{M}}\cdot\vec S_N$	$4\frac{m_\chi m_N}{m_\mathrm{M}^2}\mathcal{O}_{10}$	O/O
9	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_\mathrm{M}}\chi\frac{K_\mu}{m_\mathrm{M}}\bar N N$	$\frac{m_N}{m_\chi}\frac{\vec q^2}{m_\mathrm{M}^2}1_\chi 1_N + 4i\frac{m_N}{m_\mathrm{M}}\vec v^\perp\cdot\left(\frac{\vec q}{m_\mathrm{M}}\times\vec S_\chi\right)$	$\frac{m_N}{m_\chi}\frac{\vec q^2}{m_\mathrm{M}^2}\mathcal{O}_1 - 4\frac{m_N^2}{m_\mathrm{M}^2}\mathcal{O}_5$	E/E
10	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_\mathrm{M}}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_\mathrm{M}}N$	$4\left(\frac{\vec q}{m_\mathrm{M}}\times\vec S_\chi\right)\cdot\left(\frac{\vec q}{m_\mathrm{M}}\times\vec S_N\right)$	$4\left(\frac{\vec q^2}{m_\mathrm{M}^2}\mathcal{O}_4 - \frac{m_N^2}{m_\mathrm{M}^2}\mathcal{O}_6\right)$	E/E

arXiv:1308.6288

Nonrelativistic Reduction of Lagrangian Terms

10	$\bar{\chi} i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$4\left(\frac{\vec{q}^2}{m_M^2}\mathcal{O}_4-\frac{m_N^2}{m_M^2}\mathcal{O}_6\right)$	E/E
11	$\bar{\chi} i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4i\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\cdot\vec{S}_N$	$-4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
12	$i\bar{\chi} i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5 N$	$\left[i\frac{\vec{q}^2}{m_\chi m_M}-4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\right]\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{10}+4\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{12}+4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
13	$\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$4\frac{m_N}{m_M}\vec{v}^\perp\cdot\vec{S}_\chi$	$4\frac{m_N}{m_M}\mathcal{O}_8$	O/E
14	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$-4i\vec{S}_\chi\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
15	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4\vec{S}_\chi\cdot\vec{S}_N$	$-4\mathcal{O}_4$	E/E
16	$i\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K^\mu}{m_M}\bar{N}\gamma^5 N$	$4i\vec{v}^\perp\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_{13}$	E/O
17	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$-4i\frac{m_N}{m_M}\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi$	$-4\frac{m_N^2}{m_M^2}\mathcal{O}_{11}$	O/O
18	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\left[i\frac{\vec{q}^2}{m_N m_M}-4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)\right]$	$\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{11}+4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
19	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$	$4i\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\vec{v}_\perp\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_{14}$	E/O
20	$\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5 N$	$-4\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$-4\frac{m_N^2}{m_M^2}\mathcal{O}_6$	E/E

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