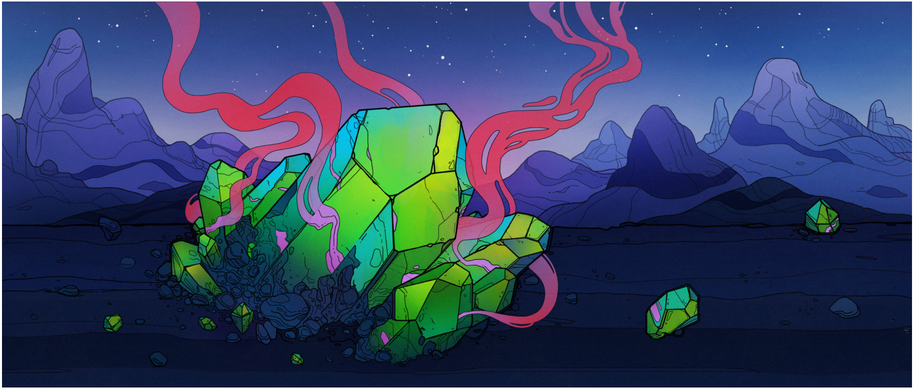
Mineral Detection of Dark Matter



Minerals such as olivine could hold evidence of long-ago collisions between atomic nuclei and dark matter (Olena Shmahalo/Quanta Magazine).

Trade large target mass for long exposure time

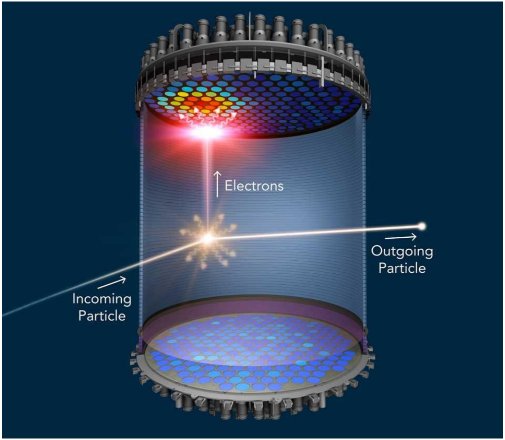


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

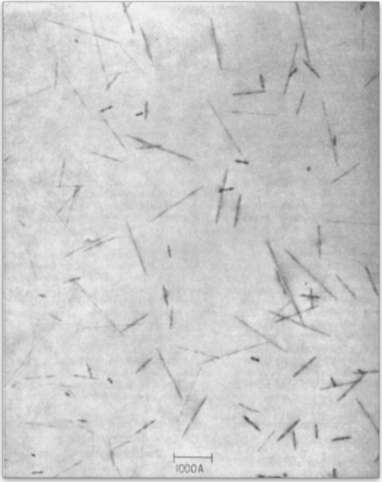
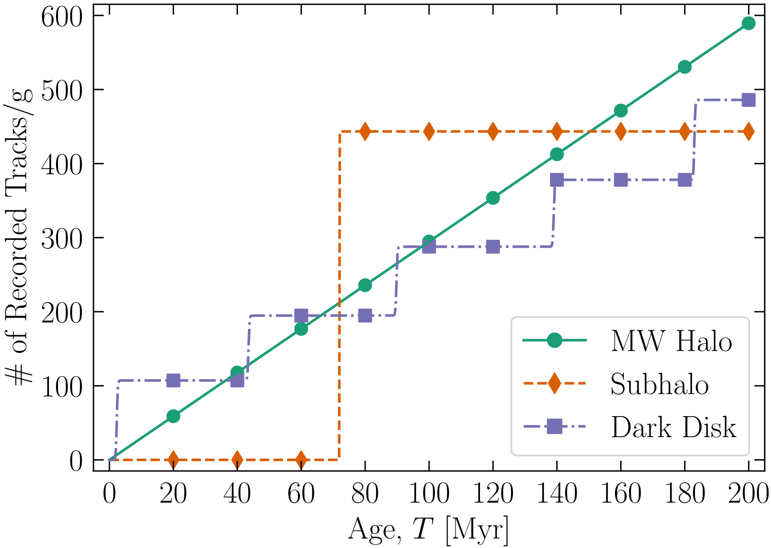
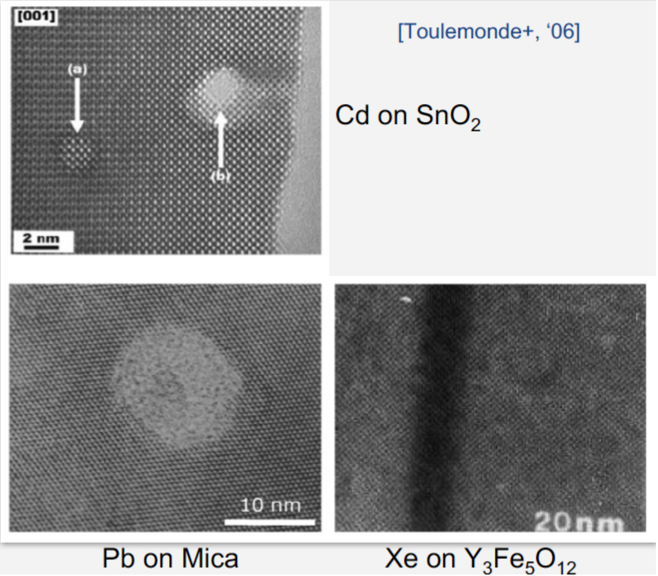


Figure: Price+Walker ’63

Mineral detectors can look for signals “averaged” over geological timescales or for time-varying signals



Modern TEM allows for accurate characterization of tracks



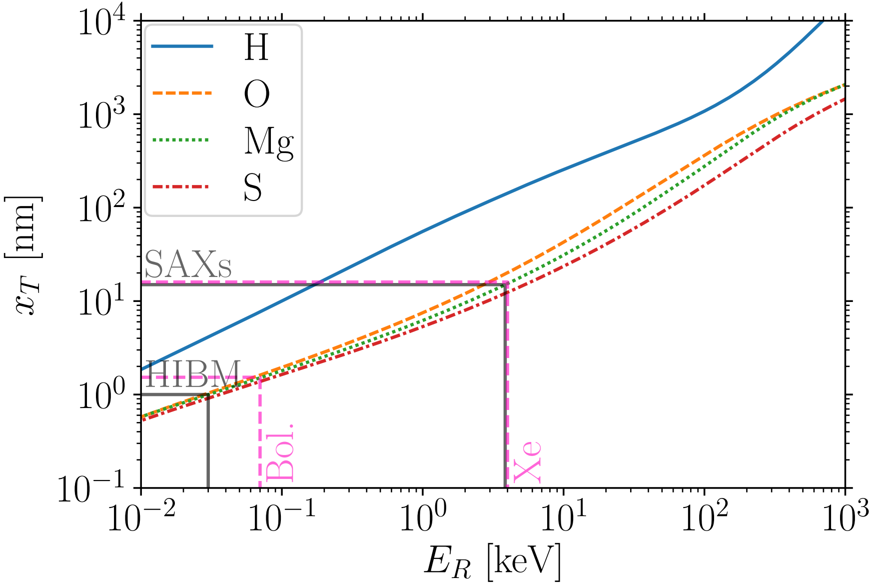
[Toulemonde+, '06]

Cd on SnO_2

Pb on Mica

Xe on $Y_3Fe_5O_{12}$

Integrate stopping power to estimate track length



Cosmogenic backgrounds suppressed in deep boreholes

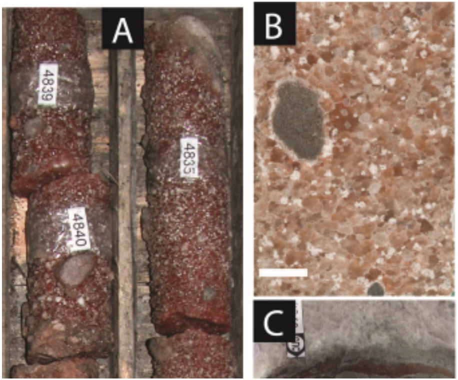


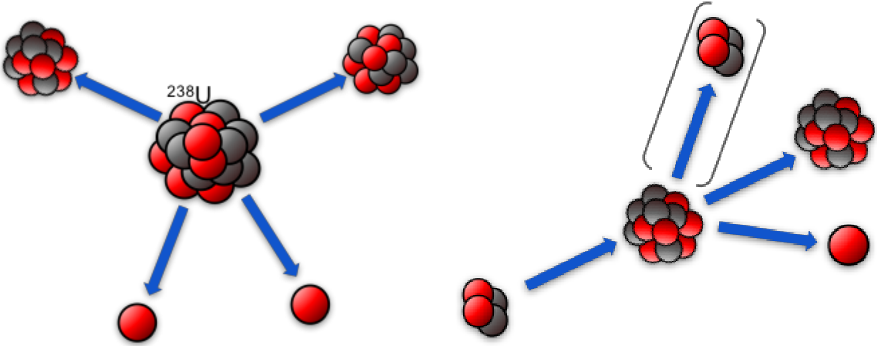
Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

Depth	Neutron Flux
2 km	$10^6/\mathrm{cm}^2/\mathrm{Gyr}$
5 km	$10^2/\mathrm{cm}^2/\mathrm{Gyr}$
6 km	$10/\mathrm{cm}^2/\mathrm{Gyr}$
50 m	$70/\mathrm{cm}^2/\mathrm{yr}$
100 m	$30/\mathrm{cm}^2/\mathrm{yr}$
500 m	$2/\mathrm{cm}^2/\mathrm{yr}$

Need minerals with low ^{238}U

- Marine evaporites with $C^{238} \gtrsim 0.01\,\mathrm{ppb}$
- Ultra-basic rocks from mantle, $C^{238} \gtrsim 0.1\,\mathrm{ppb}$

Fast neutrons from SF and (α, n) interactions



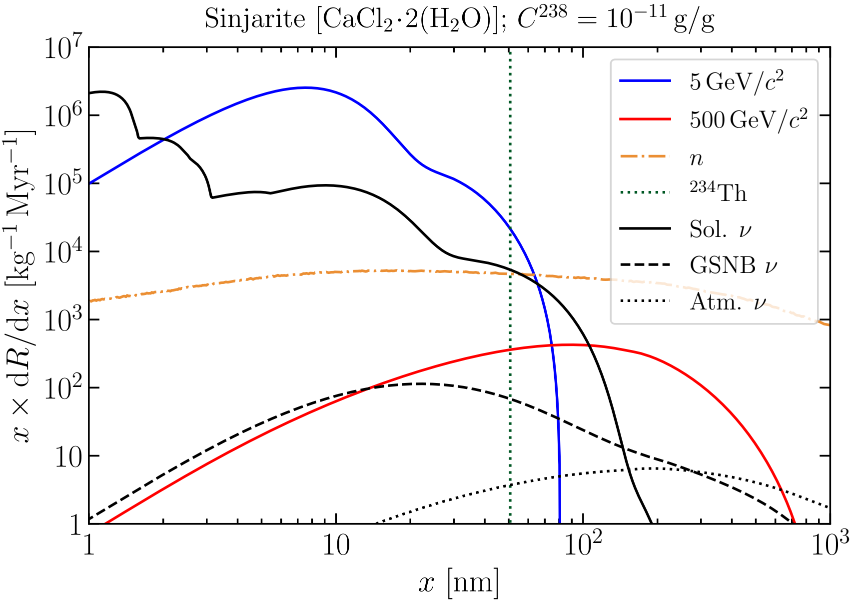
SF yields ∼ 2 neutrons with ∼MeV

Each neutron will scatter elastically 10-1000 times before moderating

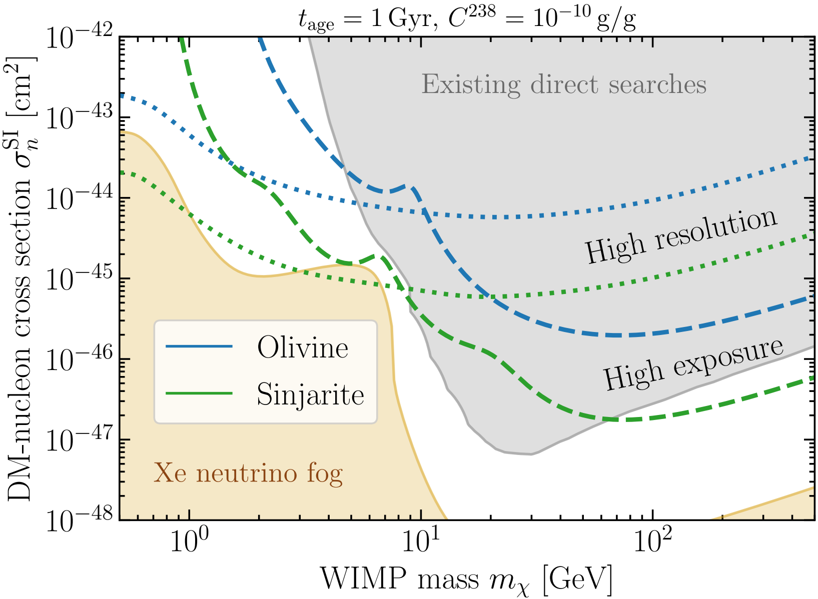
(α, n) rate low, many decay α's

Heavy targets better for (α, n) and bad for neutron moderation, need H

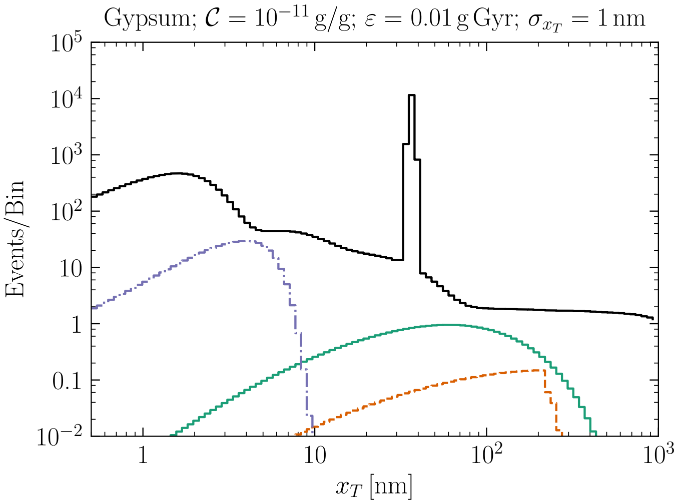
Use track length spectra to pick out WIMP signal



Read-out threshold vs exposure

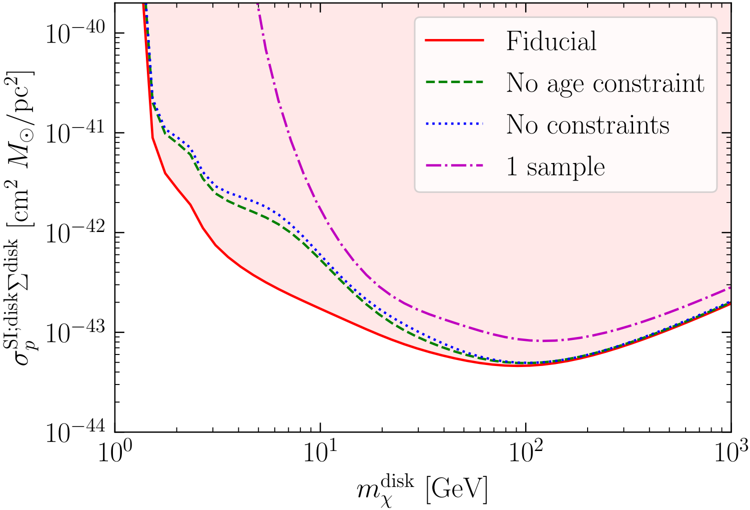


Dark disk transit every $\sim 45\,\mathrm{Myr}$



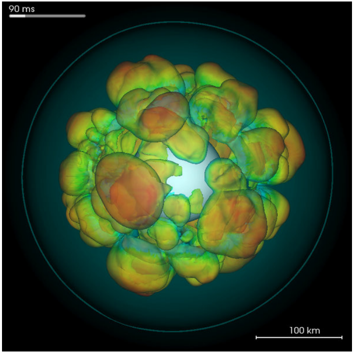
$m_X^{\mathrm{disk}} = 100\,\mathrm{GeV}$ $\sigma_{Xp}^{\mathrm{disk}} = 10^{-43}\,\mathrm{cm}^2$ $m_X = 500\,\mathrm{GeV}$ $\sigma_{Xp} = 5 \times 10^{-46}\,\mathrm{cm}^2$

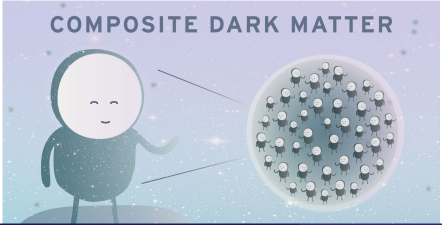
Multiple detectors with ages $t = 20, 40, 60, 80, 100\,\mathrm{Myr}$



Systematic uncertainties $\Delta_t = 5\%$ $\Delta_M = 0.1\%$ $\Delta_C = 10\%$ $\Delta_\Phi = 100\%$

Mineral detectors could probe rare and/or previous events



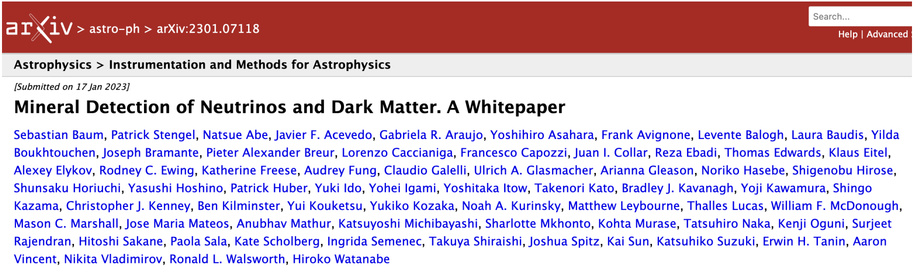


Look for DM and astrophysical ν's

- WIMP DM (**2106.06559**), substructure (**2107.02812**), composite DM (2105.06473)
- Measure solar (2102.01755), galactic CC SN (1906.05800), atmospheric (2004.08394) ν's

Feasibility of mineral detectors

- **Need efficient reconstruction of nuclear recoil tracks**
- Need model of geological history
- Radiopure samples from depth
- **Find a way to handle the data**



Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 17 Jan 2023]

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

Sebastian Baum, Patrick Stengel, Natsue Abe, Javier F. Acevedo, Gabriela R. Araujo, Yoshihiro Asahara, Frank Avignone, Levente Balogh, Laura Baudis, Yilda Boukhtouchen, Joseph Bramante, Pieter Alexander Breur, Lorenzo Caccianiga, Francesco Capozzi, Juan I. Collar, Reza Ebadi, Thomas Edwards, Klaus Eitel, Alexey Elykov, Rodney C. Ewing, Katherine Freese, Audrey Fung, Claudio Galelli, Ulrich A. Glasmacher, Arianna Gleason, Noriko Hasebe, Shigenobu Hirose, Shunsaku Horiuchi, Yasushi Hoshino, Patrick Huber, Yuki Ido, Yohei Igami, Yoshitaka Itow, Takenori Kato, Bradley J. Kavanagh, Yoji Kawamura, Shingo Kazama, Christopher J. Kenney, Ben Kilminster, Yui Kouketsu, Yukiko Kozaka, Noah A. Kurinsky, Matthew Leybourne, Thalles Lucas, William F. McDonough, Mason C. Marshall, Jose Maria Mateos, Anubhav Mathur, Katsuyoshi Michibayashi, Sharlotte Mkhonto, Kohta Murase, Tatsuhiro Naka, Kenji Oguni, Surjeet Rajendran, Hitoshi Sakane, Paola Sala, Kate Scholberg, Ingrida Semenec, Takuya Shiraishi, Joshua Spitz, Kai Sun, Katsuhiko Suzuki, Erwin H. Tanin, Aaron Vincent, Nikita Vladimirov, Ronald L. Walsworth, Hiroko Watanabe

MDνDM community

- Groups across Europe, North America and Japan
- Astroparticle theorists, experimentalists, geologists, and materials scientists
- Next **MDνDM workshop** in Washington DC January 2024

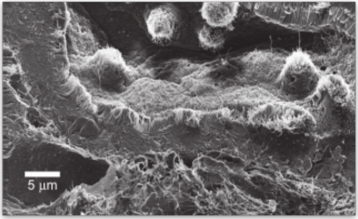
Check out our whitepaper!

- History of mineral detectors
- Review of scientific potential for particle physics, reactor neutrinos and geoscience
- Summary of active and planned experimental efforts

Cleaving and etching limits ϵ and can only reconstruct 2D

Readout scenarios for different x_T

- HIBM+pulsed laser could read out 10 mg with nm resolution
- SAXs at a synchrotron could resolve 15 nm in 3D for 100 g



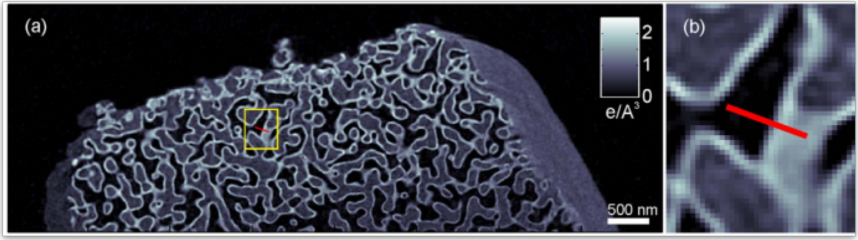
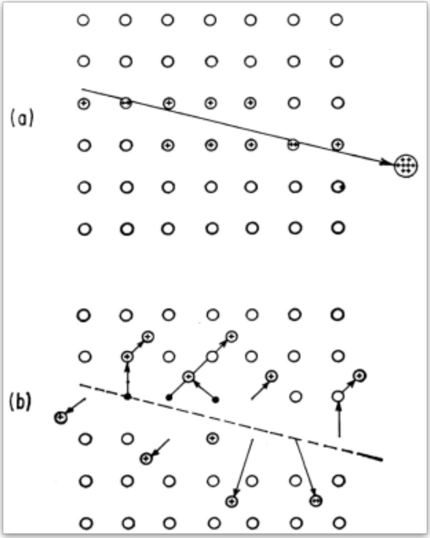


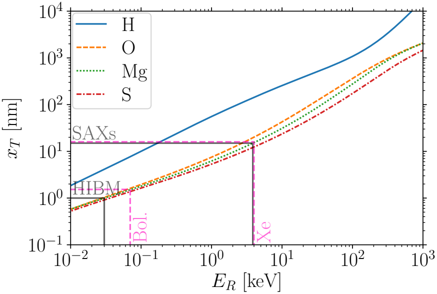
Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Mineral detectors look for damage from recoiling nuclei



Track length from stopping power

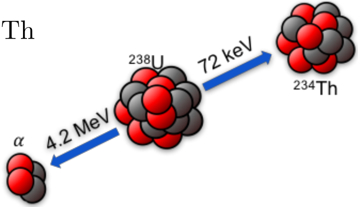
$$x_T(E_R) = \int_0^{E_R} dE \left| \frac{dE}{dx_T}(E) \right|^{-1}$$



Radiogenic backgrounds from ^{238}U contamination

$$^{238}\mathrm{U} \xrightarrow{\alpha} {}^{234}\mathrm{Th} \xrightarrow{\beta^-} {}^{234\mathrm{m}}\mathrm{Pa} \xrightarrow{\beta^-} {}^{234}\mathrm{U} \xrightarrow{\alpha} {}^{230}\mathrm{Th}$$

$$\xrightarrow{\alpha} {}^{226}\mathrm{Ra} \xrightarrow{\alpha} {}^{222}\mathrm{Rn} \xrightarrow{\alpha} \ldots \longrightarrow {}^{206}\mathrm{Pb}$$

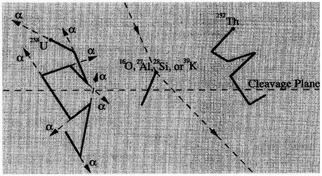


Nucleus	Decay mode	$T_{1/2}$
^{238}U	α SF	4.468×10^9 yr 8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

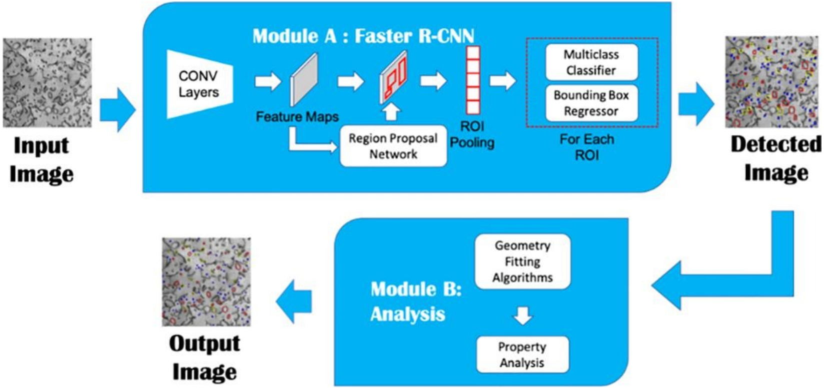
"1α" events difficult to reject without additional decays

- Reject $\sim 10\,\mu$m α tracks
- Without α tracks, filter out monoenergetic ^{234}Th

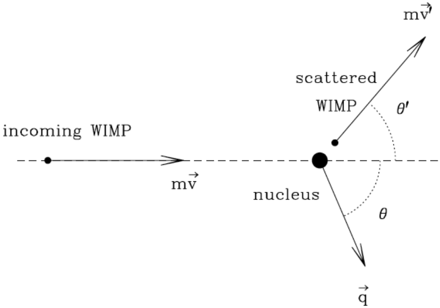
Quick aside on data analysis and α-recoil background

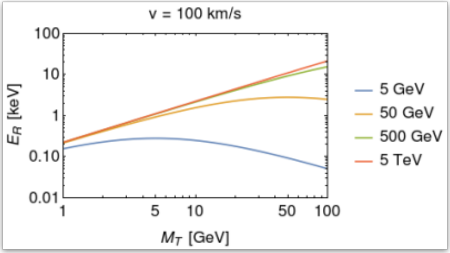


- 15 nm resolution of 100 g sample $\Rightarrow 10^{19}$ mostly empty voxels
- 1 Gyr old with $C^{238} = 0.01$ ppb $\Rightarrow 10^{13}$ voxels for α-recoil tracks



Spin- and velocity-independent WIMP-nucleus scattering





Scattering kinematics ⇒ event rate

- Account for finite size of nucleus
- Convolute with WIMP flux
- Write cross section in terms of WIMP-nucleon interaction

Rate per unit time per unit mass

$$\frac{dR}{dE_R} = \frac{n_X}{2}\frac{\sigma^{SI}_{Xp}}{\mu^2_{Xp}} A^2 F(q)^2 \eta(v_q)$$

Scattering cross sections ⇒ scattering rates

$$\frac{d^2\sigma}{dq^2 d\Omega_q} = \frac{d\sigma}{dq^2}\frac{1}{2\pi}\delta\left(\cos\theta - \frac{q}{2\mu_{XT} v}\right) \simeq \frac{\sigma_0 F(q)^2}{8\pi\mu_{XT}^2 v}\delta\left(v\cos\theta - \frac{q}{2\mu_{XT}}\right)$$

$$\frac{d^2 R}{dE_R d\Omega_q} = 2M_T \frac{N_T}{M_T N_T}\int \frac{d^2\sigma}{dq^2 d\Omega_q} n_X\, v\, f(\boldsymbol{v}) d^3 v \simeq \frac{\sigma_0 F(q)^2}{4\pi\mu_{XT}} n_X \hat{f}(v_q, \hat{\boldsymbol{q}})$$

Differential cross section

- δ-function imposes kinematics
- σ_0 is velocity and momentum independent cross section for scattering off pointlike nucleus

$$F(q) \simeq \frac{9\left[\sin(qR) - qR\cos(qR)\right]^2}{(qR)^6}$$

Differential scattering rate

- Rate per unit time per unit detector mass for all nuclei
- Convolute cross section with astrophysical WIMP flux

$$\sigma_0^{SI} = \frac{4}{\pi}\mu_{XT}^2\left[Zf_s^p + (A-Z)f_s^n\right]^2$$

Velocity distribution in the Standard Halo Model (SHM)

Integrate Radon transform

$$\int \hat{f}(v_q, \hat{\boldsymbol{q}})d\Omega_q = 2\pi\eta(v_q)$$

Mean inverse speed

$$\eta(v_q) = \int_{v>v_q} \frac{f(\boldsymbol{v})}{v} d^3v$$

Maxwellian in halo frame

$$\tilde{f}(\boldsymbol{v}) \sim \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3v^2/2\sigma_v^2}$$

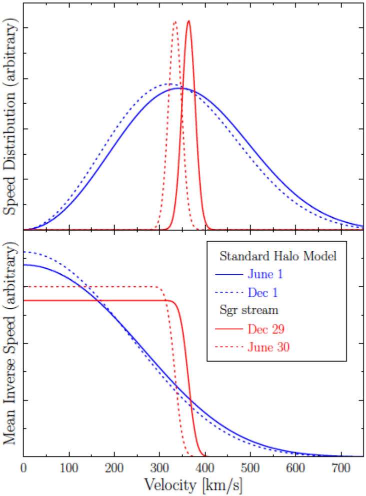


Figure: 1209.3339

Conventional direct detection searches for WIMPs

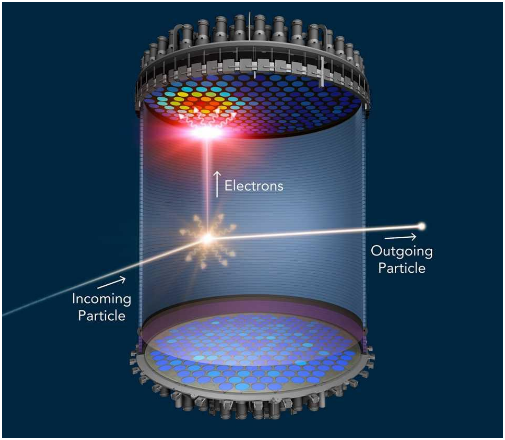


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

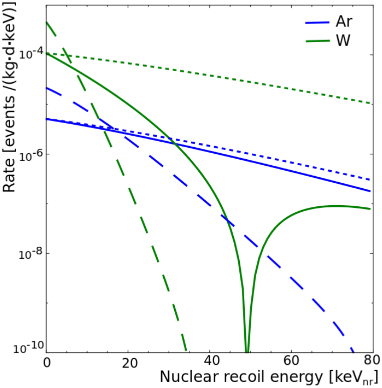


Figure: Event rate for $m_X = 100\,\mathrm{GeV}$ and $\sigma^{SI}_{Xp} = 10^{-45}\,\mathrm{cm}^2$ (solid), $m_X \to 25\,\mathrm{GeV}$ (dashed) and $F(q) \to 1$ (dotted), 1509.08767

Different ways to look for DM-induced nuclear recoils

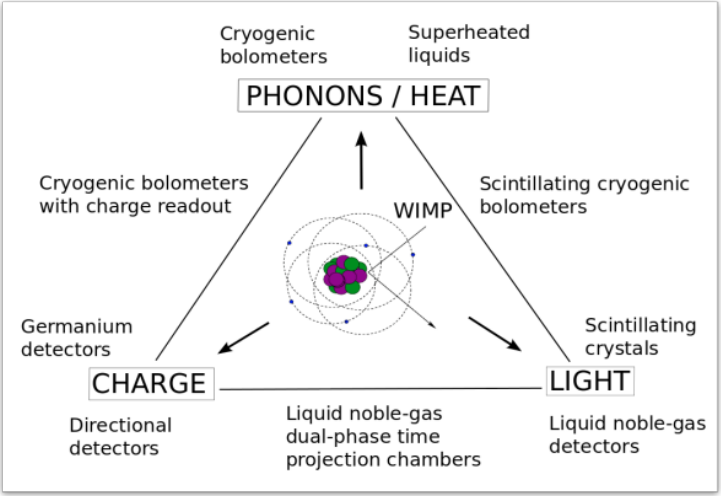
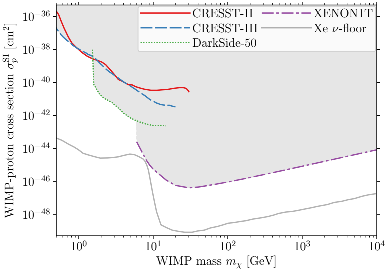


Figure: 1509.08767

Current limits on σ_{Xp}^{SI} and astrophysical uncertainties



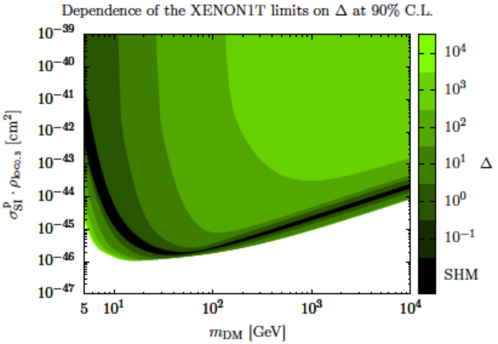
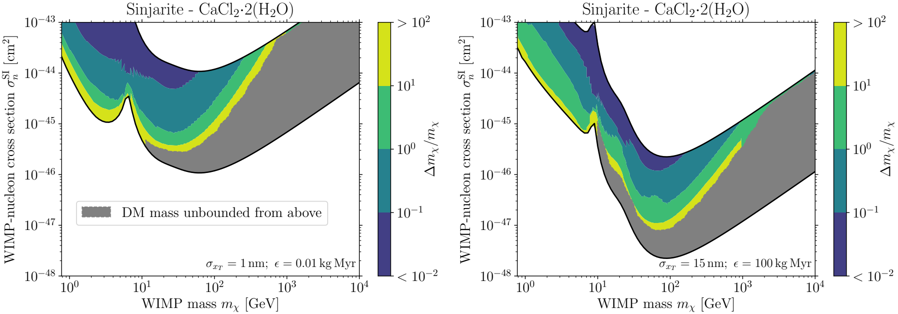


Figure: 1806.08714, variations of σ_v and v_{esc} in SHM and variations away from MB in SHM $\Delta \leq |f(\boldsymbol{v}) - f_{MB}(\boldsymbol{v})|/f_{MB}(\boldsymbol{v})$ for $f(\boldsymbol{v})$ composed of a large number of streams.

When the smoke clears, we have

$$\frac{dR}{dE_R} = \frac{n_X}{2}\frac{\sigma_{Xp}^{SI}}{\mu_{Xp}^2} A^2 F(q)^2 \eta(v_q)$$

Multiple nuclei and large ϵ allow for optimal $\Delta m_X / m_X$



Nuclear recoil spectrum depends on neutrino energy

$$\frac{dR}{dE_R} = \frac{1}{m_T}\int dE_\nu \, \frac{d\sigma}{dE_R}\,\frac{d\phi}{dE_\nu}$$

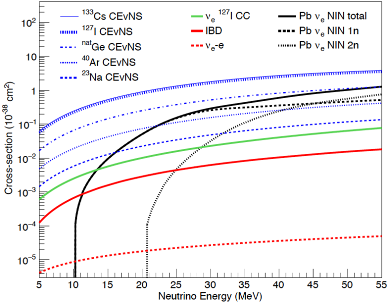


Figure: COHERENT, 1803.09183

- Quasi-elastic for $E_\nu \gtrsim 100\,\mathrm{MeV}$
- Resonant π production at $E_\nu \sim \mathrm{GeV}$
- Deep inelastic for $E_\nu \gtrsim 10\,\mathrm{GeV}$

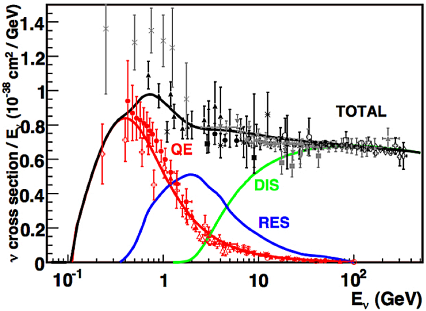
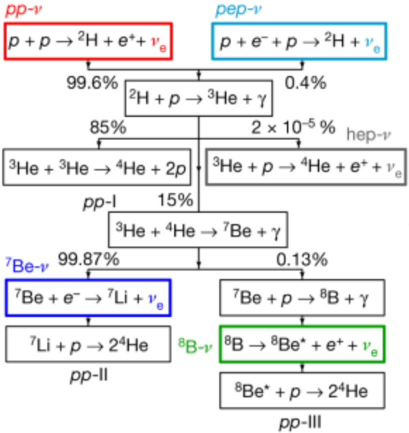


Figure: Inclusive CC $\sigma_{\nu N}$, 1305.7513

Solar ν's produced in fusion chains from H to He



pp-ν

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

pep-ν

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

99.6% 0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85% 2×10^{-5} % hep-ν

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

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

pp-I 15%

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

^{7}Be-ν 99.87% 0.13%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

^{8}B-ν

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

pp-II

${}^8\mathrm{Be}^* + p \rightarrow 2\,{}^4\mathrm{He}$

pp-III

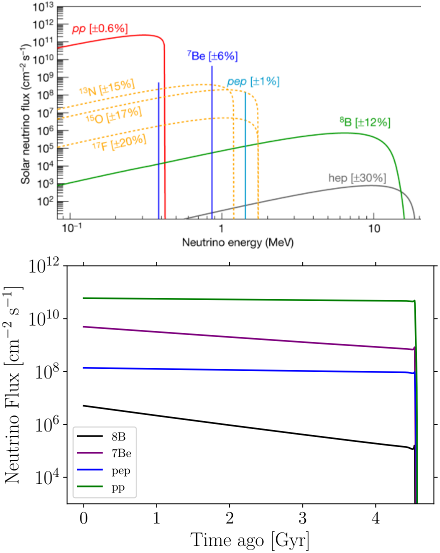


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Galactic contribution to ν flux over geological timescales

$$\frac{\mathrm{d}\phi}{\mathrm{d}E_\nu} = \dot{N}_{\mathrm{CC}}^{\mathrm{gal}} \frac{\mathrm{d}n}{\mathrm{d}E_\nu} \int_0^\infty \mathrm{d}R_E \frac{f(R_E)}{4\pi {R_E}^2}$$

Only $\sim$ 2 SN 1987A events/century

- Measure galactic CC SN rate
- Traces star formation history

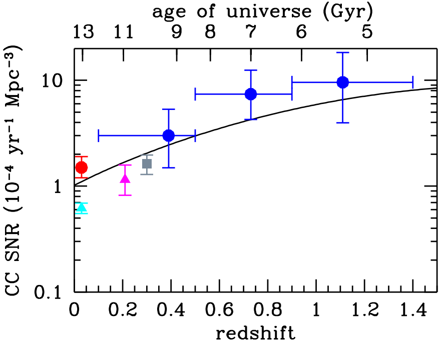
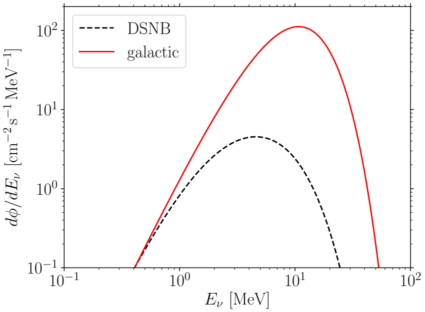


Figure: Cosmic CC SNR, 1403.0007



Atmospheric ν's originating from CR interactions

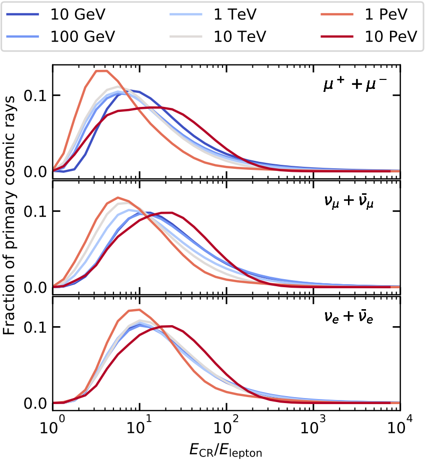


Figure: E_{CR} to leptons, 1806.04140

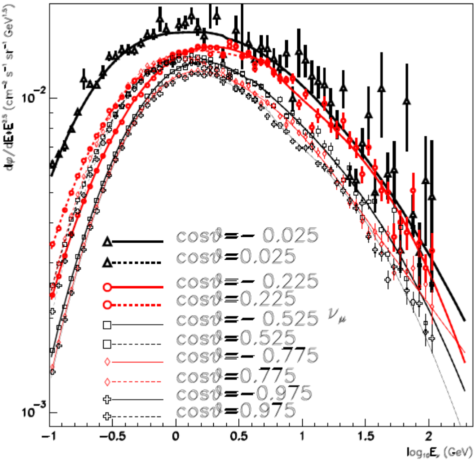
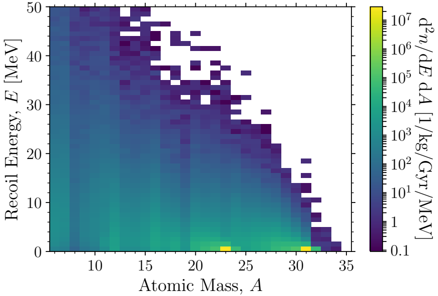
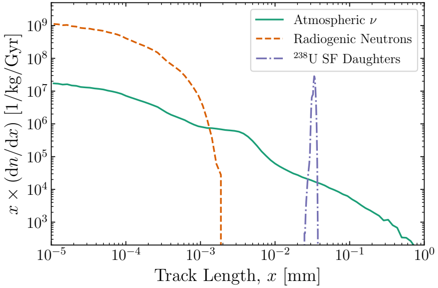


Figure: FLUKA simulation of ν_μ flux at SuperK for solar max, hep-ph/0207035

Recoil spectra from atmospheric ν's incident on NaCl(P)





Recoils of many different nuclei

- Low energy peak from QE neutrons scattering ^{23}Na, ^{31}P
- High energy tail of lighter nuclei produced by DIS

Background free regions for $\gtrsim 1\,\mu$m

- Radiogenic n-bkg confined to low x, regardless of target
- Subdominant systematics from atmosphere, heliomagnetic field

Semi-analytic range calculations and SRIM agree with data

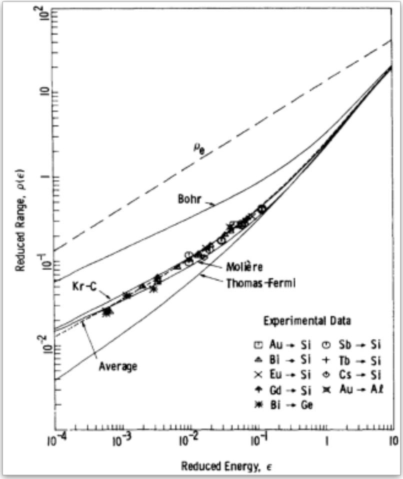


Figure: Wilson, Haggmark+ '76