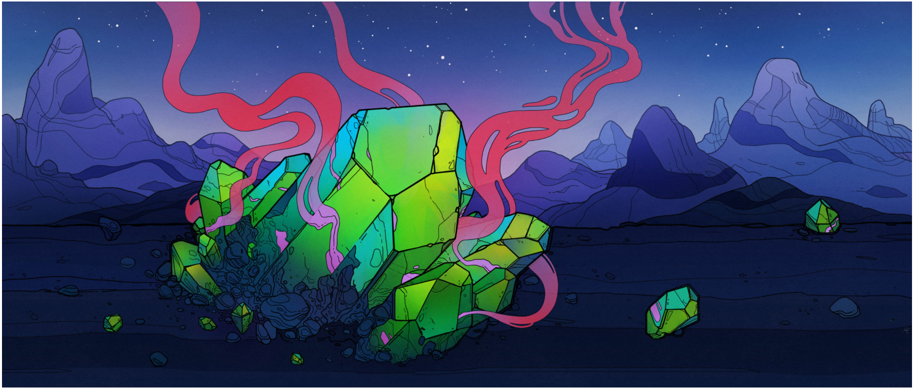
Mineral Detection of Dark Matter



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

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[Submitted on 17 Jan 2023]

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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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

Trade large target mass for long exposure time

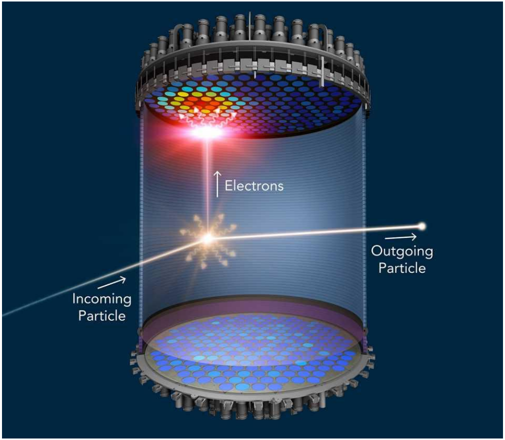


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

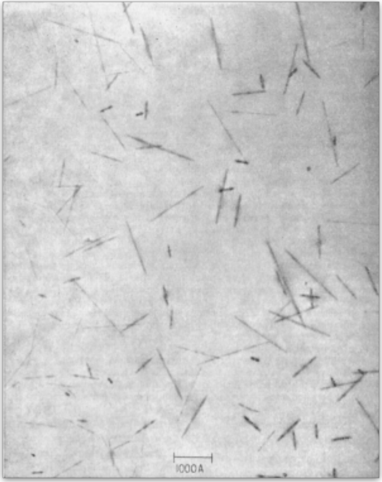


Figure: Price+Walker '63

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

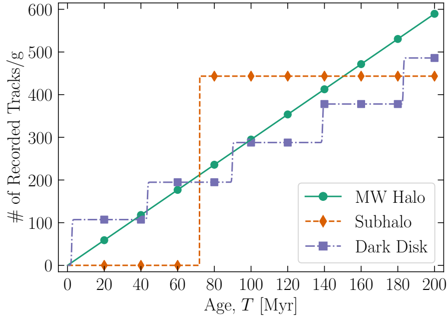


Figure: Time dependent DM signals in series of gypsum detectors for $m_X^{\rm disk} = 100\,{\rm GeV}$, $\sigma_{Xp}^{\rm disk} = 10^{-43}\,{\rm cm}^2$ and $\Sigma^{\rm disk} = 10 M_\odot/{\rm pc}^2$, 2107.02812

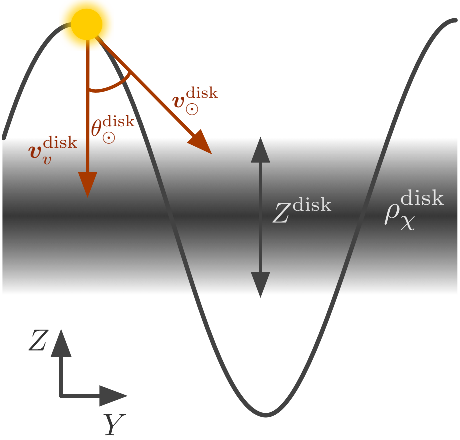
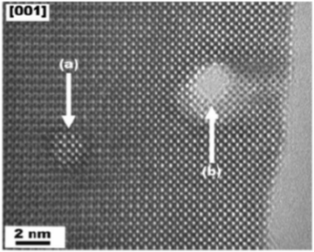


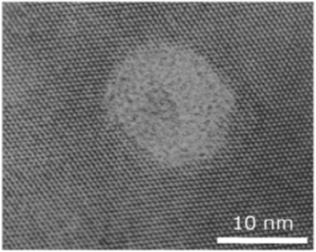
Figure: Dark Disk cartoon, 2107.02812

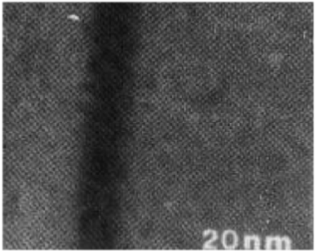
Modern TEM allows for accurate characterization of tracks



[Toulemonde+, '06]

Cd on SnO_2





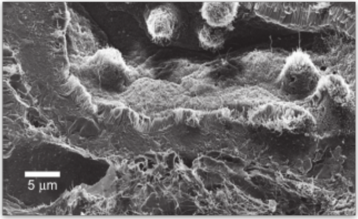
Pb on Mica

Xe on $Y_3Fe_5O_{12}$

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



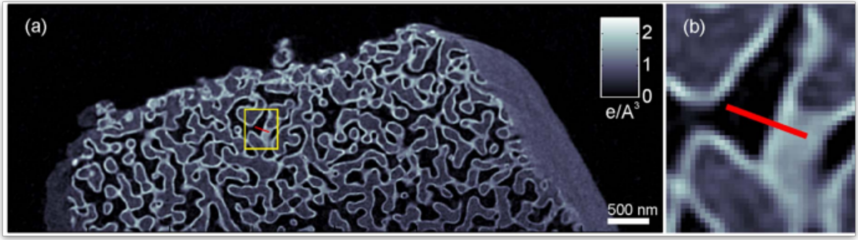
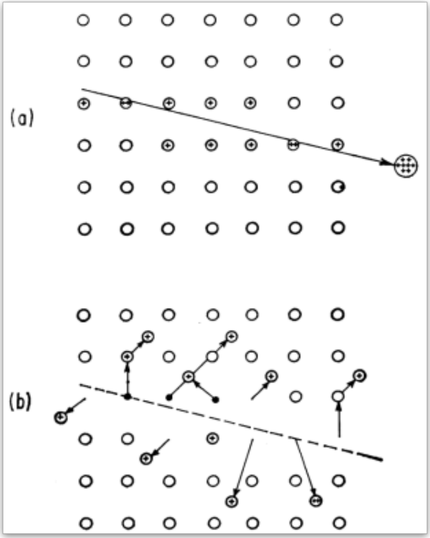


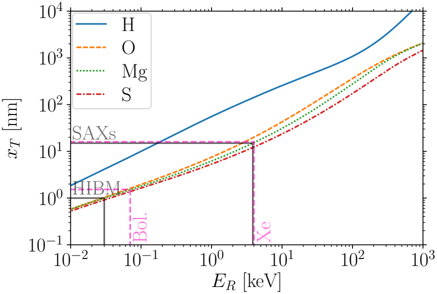
Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Mineral detectors look for damage from recoiling nuclei



Track length from stopping power

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



Cosmogenic backgrounds suppressed in deep boreholes

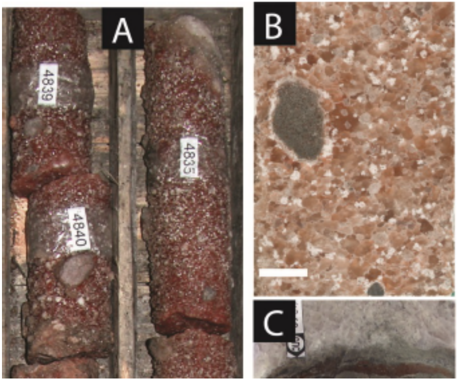


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

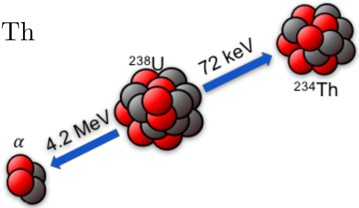
Depth	Neutron Flux
2 km	$10^6/\text{cm}^2/\text{Gyr}$
5 km	$10^2/\text{cm}^2/\text{Gyr}$
6 km	$10/\text{cm}^2/\text{Gyr}$
50 m	$70/\text{cm}^2/\text{yr}$
100 m	$30/\text{cm}^2/\text{yr}$
500 m	$2/\text{cm}^2/\text{yr}$

Need minerals with low ^{238}U

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

Radiogenic backgrounds from ^{238}U contamination

$$^{238}\mathrm{U} \xrightarrow{\alpha} {}^{234}\mathrm{Th} \xrightarrow{\beta^-} {}^{234\mathrm{m}}\mathrm{Pa} \xrightarrow{\beta^-} {}^{234}\mathrm{U} \xrightarrow{\alpha} {}^{230}\mathrm{Th} \xrightarrow{\alpha} {}^{226}\mathrm{Ra} \xrightarrow{\alpha} {}^{222}\mathrm{Rn} \xrightarrow{\alpha} \ldots \longrightarrow {}^{206}\mathrm{Pb}$$

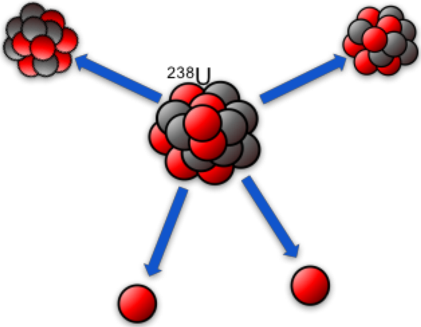


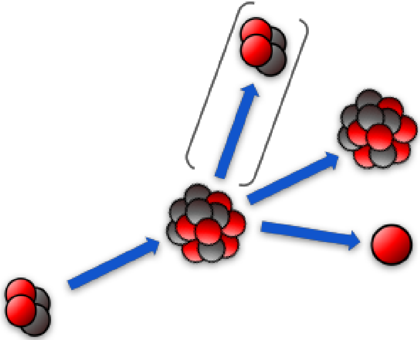
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^{9} yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^{5} yr

"1α" events difficult to reject without additional decays

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

Fast neutrons from SF and (α, n) interactions





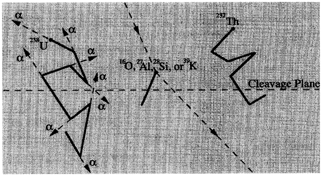
SF yields $\sim$ 2 neutrons with $\sim$MeV

Each neutron will scatter elastically 10-1000 times before moderating

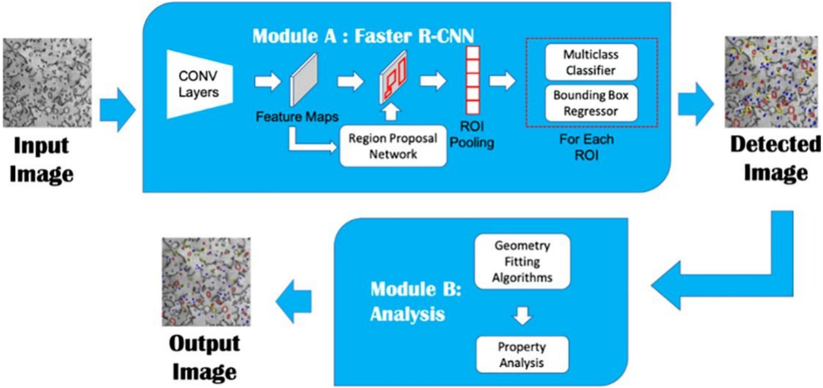
(α, n) rate low, many decay α's

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

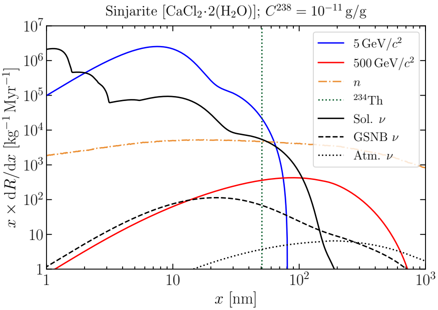
Quick aside on data analysis and α-recoil background

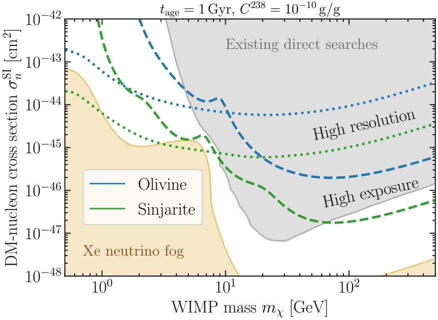


- 15 nm resolution of 100 g sample $\Rightarrow 10^{19}$ mostly empty voxels
- 1 Gyr old with $C^{238} = 0.01$ ppb $\Rightarrow 10^{13}$ voxels for α-recoil tracks



Use track length spectra to pick out WIMP signal





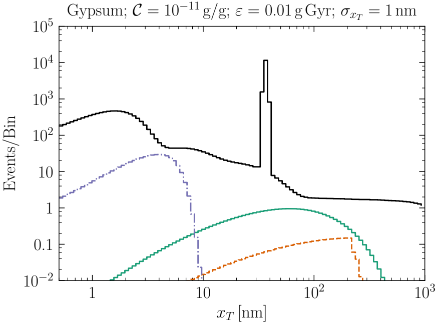
Different background regimes

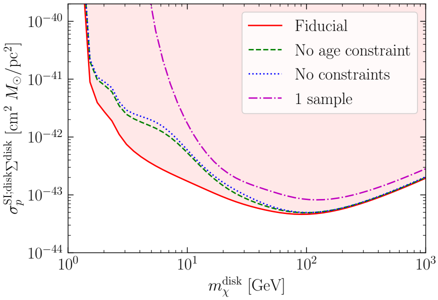
- Solar ν's peak at short track lengths relevant for lighter DM
- Flat spectrum of radiogenic neutrons limits heavier WIMPs

Read-out threshold vs exposure

- Need larger samples to be competitive at heavier masses
- Can potentially go into the neutrino fog at low masses

Measure time-varying signals with a series of samples





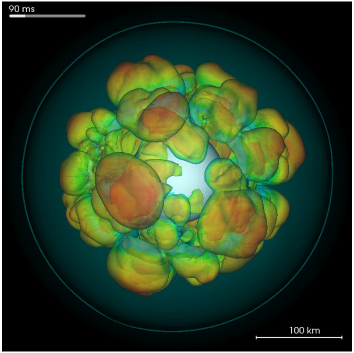
Dark disk transit every ~ 45 Myr

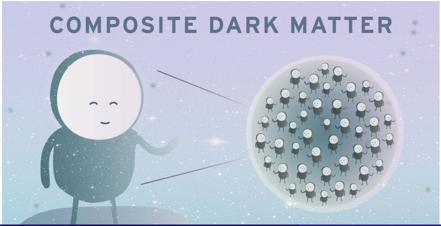
Spectra from dark disk crossing, MW halo, **combined backgrounds**
$m_X^{\mathrm{disk}} = 100$ GeV $\sigma_{Xp}^{\mathrm{disk}} = 10^{-43}\,\mathrm{cm}^2$
$m_X = 500$ GeV $\sigma_{Xp} = 5 \times 10^{-46}\,\mathrm{cm}^2$

Ages $t = 20, 40, 60, 80, 100$ Myr

- Systematic uncertainty $\Delta_t = 5\%$, $\Delta_M = 0.1\%$, $\Delta_C = 10\%$, $\Delta_\Phi = 100\%$
- > 1 samples more important

Mineral detectors could probe rare and/or previous events





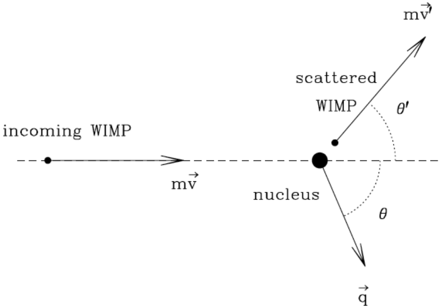
Look for DM and astrophysical ν's

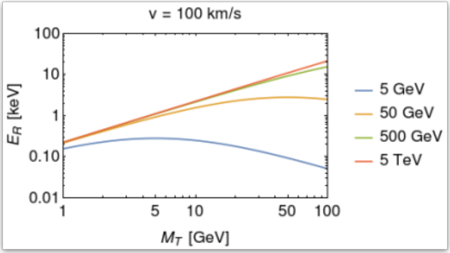
- WIMP DM (**2106.06559**), substructure (2107.02812), composite DM (2105.06473)
- Measure solar (2102.01755), galactic CC SN (**1906.05800**), atmospheric (**2004.08394**) ν's

Feasibility of mineral detectors

- Determine efficiency of effective 3D recoil track reconstruction
- Need model of geological history
- Radiopure samples from depth
- **Find a way to handle the data**

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

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

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

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

Maxwellian in halo frame

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

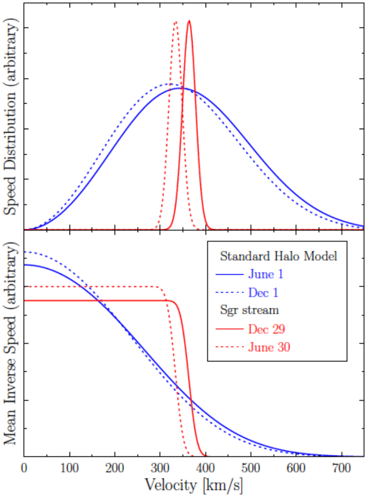


Figure: 1209.3339

Conventional direct detection searches for WIMPs

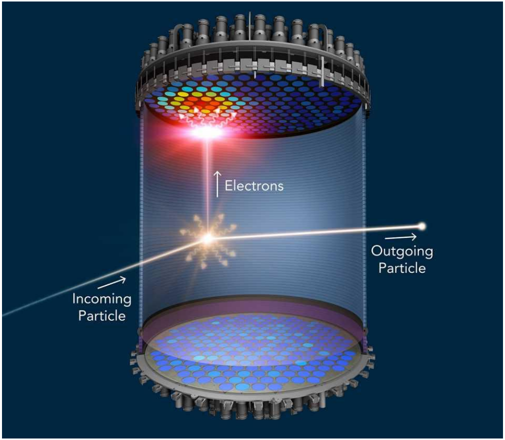


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

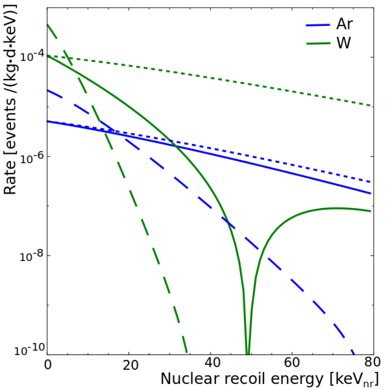


Figure: Event rate for $m_X = 100\,\mathrm{GeV}$ and $\sigma^{SI}_{Xp} = 10^{-45}\,\mathrm{cm}^2$ (solid), $m_X \to 25\,\mathrm{GeV}$ (dashed) and $F(q) \to 1$ (dotted), 1509.08767

Different ways to look for DM-induced nuclear recoils

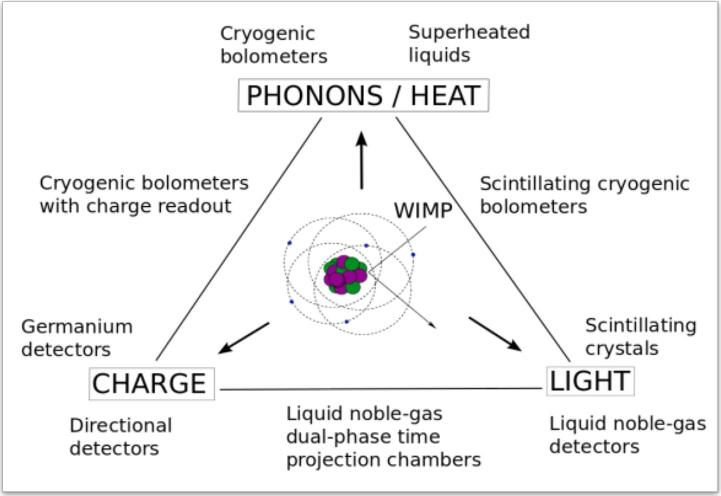
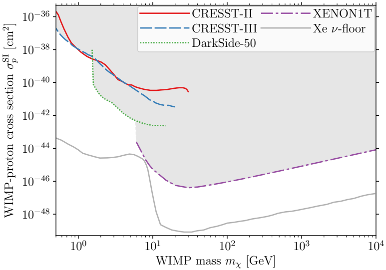
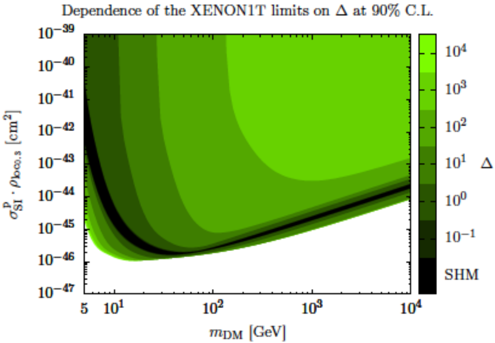


Figure: 1509.08767

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



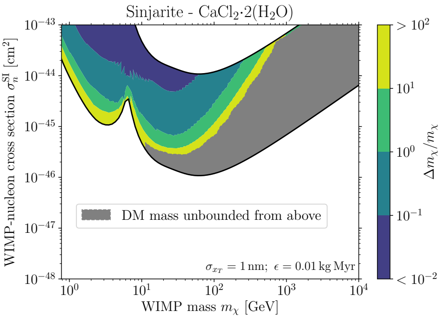


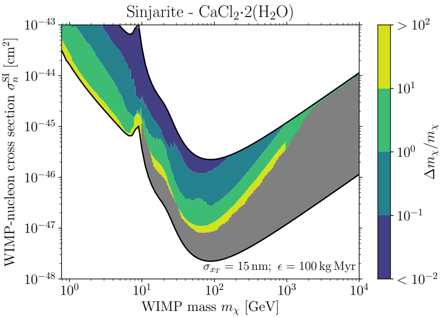
When the smoke clears, we have

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

Figure: 1806.08714, variations of σ_v and $v_{\rm esc}$ 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.

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





Nuclear recoil spectrum depends on neutrino energy

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

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

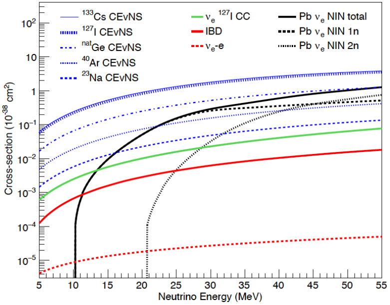


Figure: COHERENT, 1803.09183

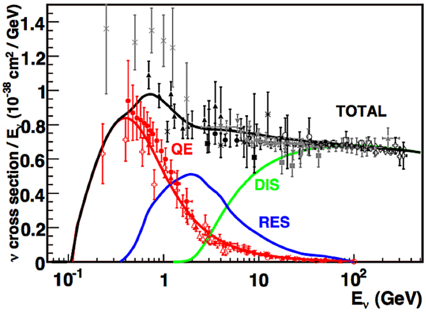
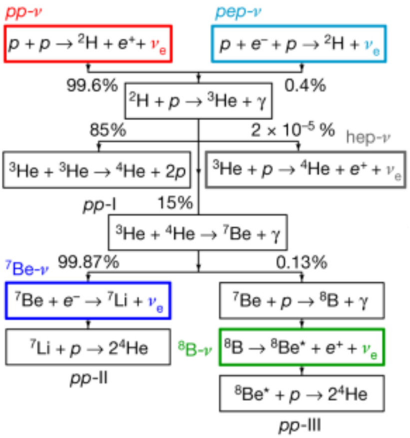


Figure: Inclusive CC $\sigma_{\nu N}$, 1305.7513

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



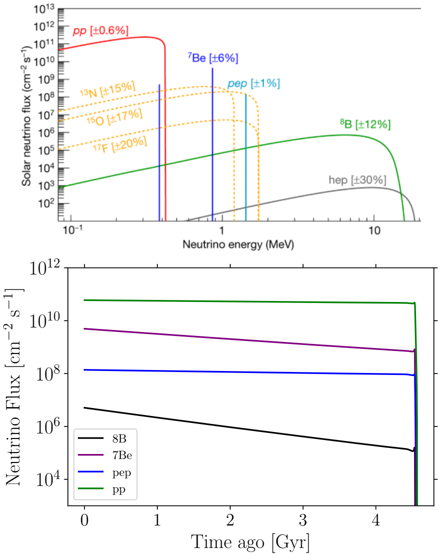


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Galactic contribution to ν flux over geological timescales

$$\frac{d\phi}{dE_\nu} = \dot{N}_{\rm CC}^{\rm gal} \frac{dn}{dE_\nu} \int_0^\infty dR_E \frac{f(R_E)}{4\pi R_E{}^2}$$

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

- Measure galactic CC SN rate
- Traces star formation history

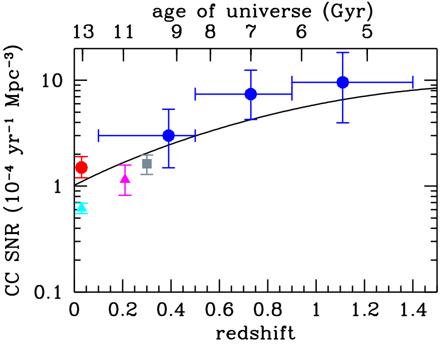
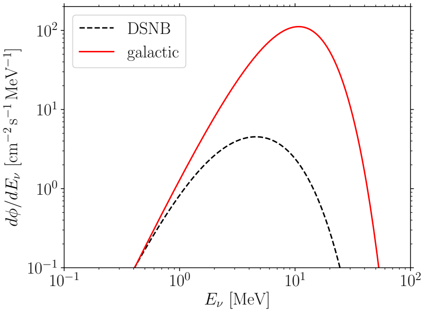


Figure: Cosmic CC SNR, 1403.0007



Atmospheric ν's originating from CR interactions

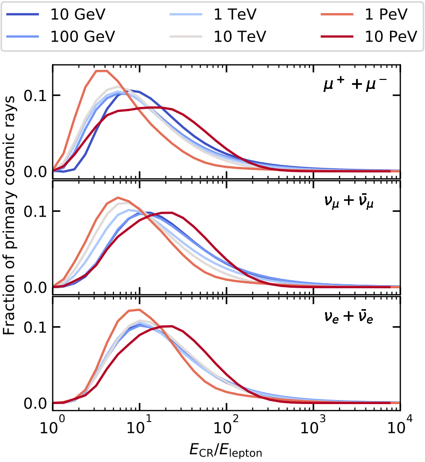


Figure: E_{CR} to leptons, 1806.04140

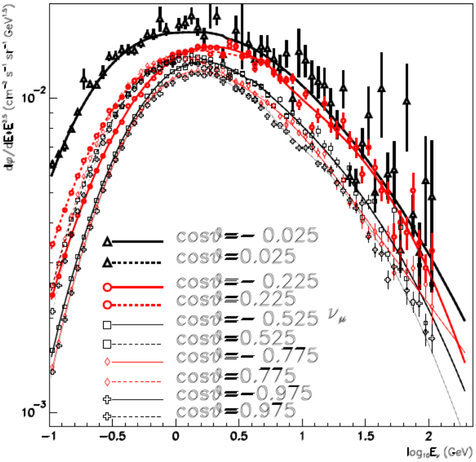
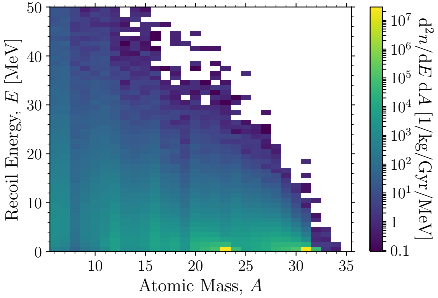
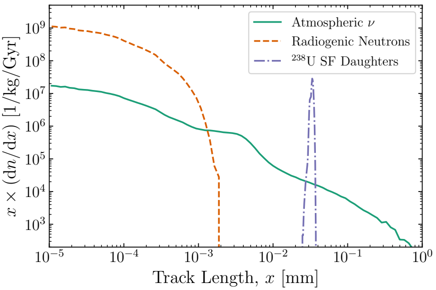


Figure: FLUKA simulation of ν_μ flux at SuperK for solar max, hep-ph/0207035

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

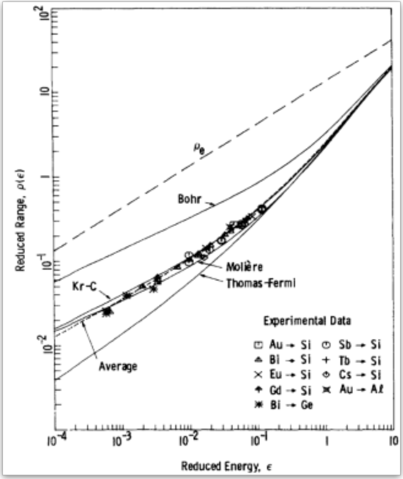


Figure: Wilson, Haggmark+ '76