Searching for Dark Matter with Paleo-Detectors

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1806.05991, 1811.06844 with **Baum**, Drukier, Freese and Górski
1811.10549, 1906.xxxxx + **Edwards**, Kavanagh and Weniger

Outline

1. Dark matter scattering off nuclei
2. Tracks in ancient minerals
   - Solid state track detectors
   - Problematic backgrounds
3. Projected sensitivity and outlook

Different ways to look for DM-induced nuclear recoils

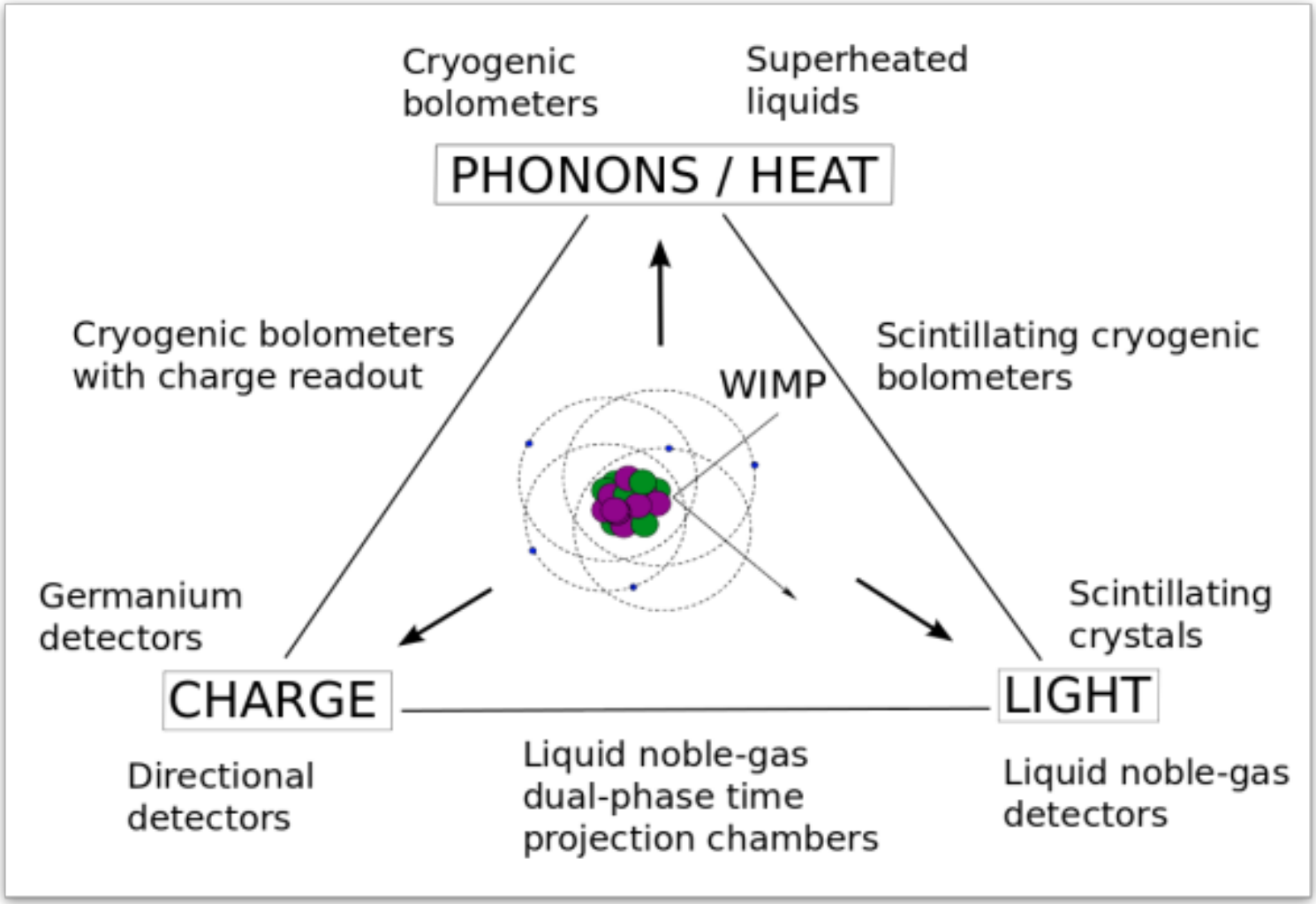
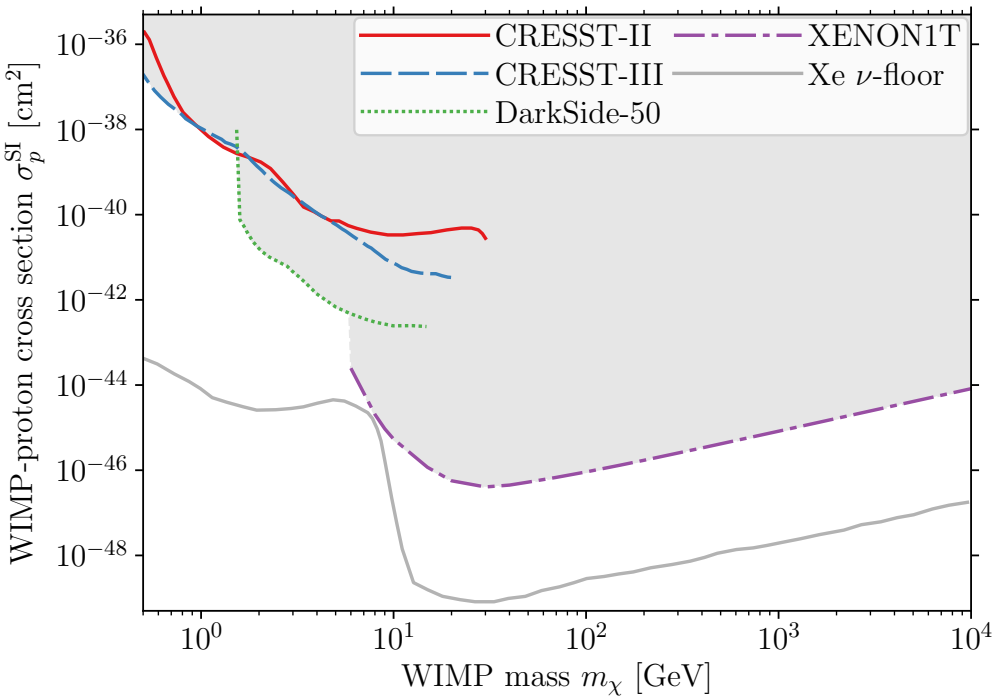


Figure: 1509.08767

Current limits on $\sigma^{SI}_{\chi p}$ from direct detection experiments



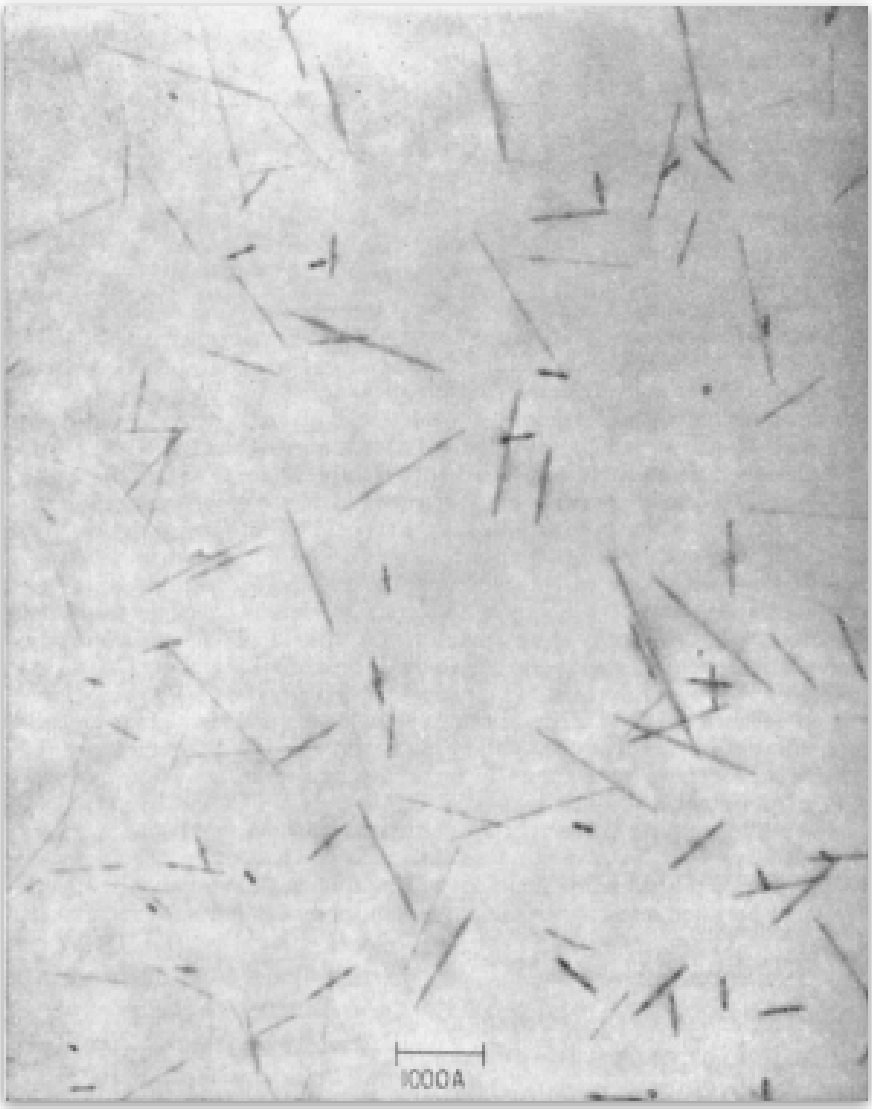
General WIMP mass regimes

- Sensitivity to low m_X limited by threshold
- At higher m_X, depends more on exposure, $\epsilon = \text{time} \times \text{mass}$

Future DD experiments

- $\sim 5\,\text{kg}$ solid state bolometers with $\sim 50\,\text{eV}$ recoil energy thresholds
- $\sim 50\,\text{t}$ of liquid noble gas with $\sim 2\,\text{keV}$ thresholds

Fission fragments can be seen by TEM/optical microscopes



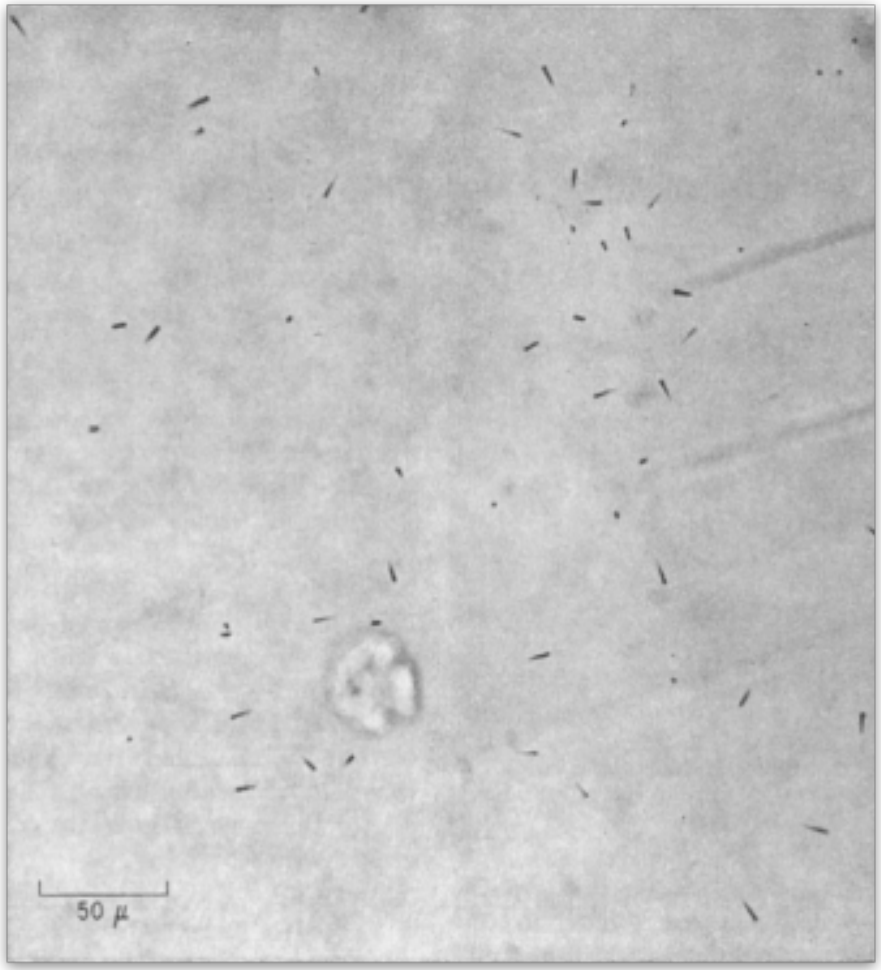
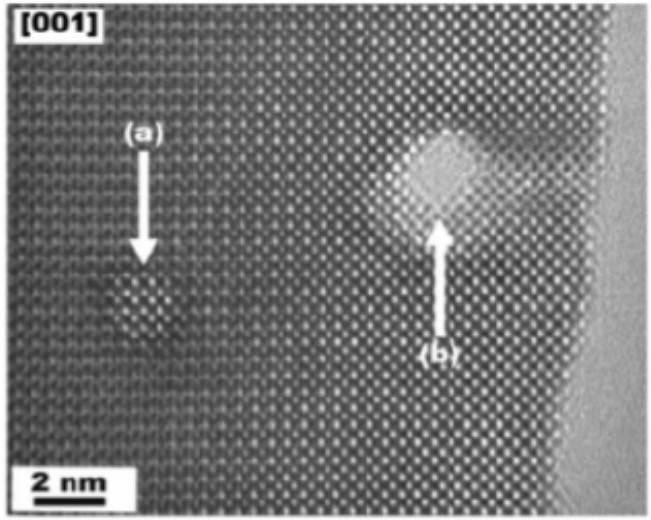


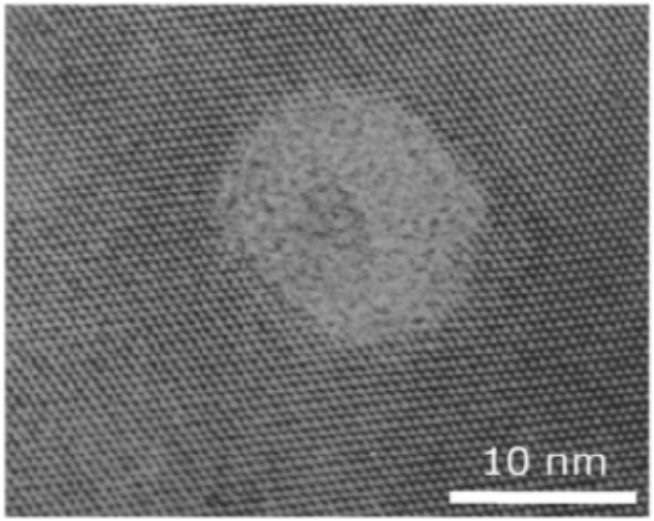
Figure: Price+Walker '63

Modern TEM allows for accurate characterization of tracks

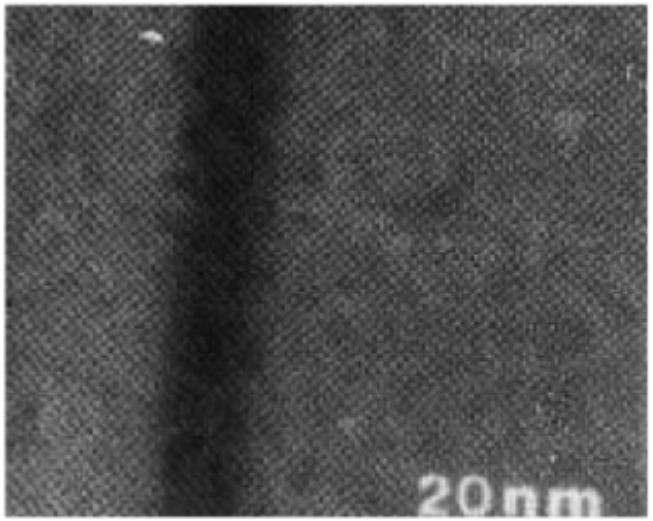


[Toulemonde+, '06]

Cd on SnO_2

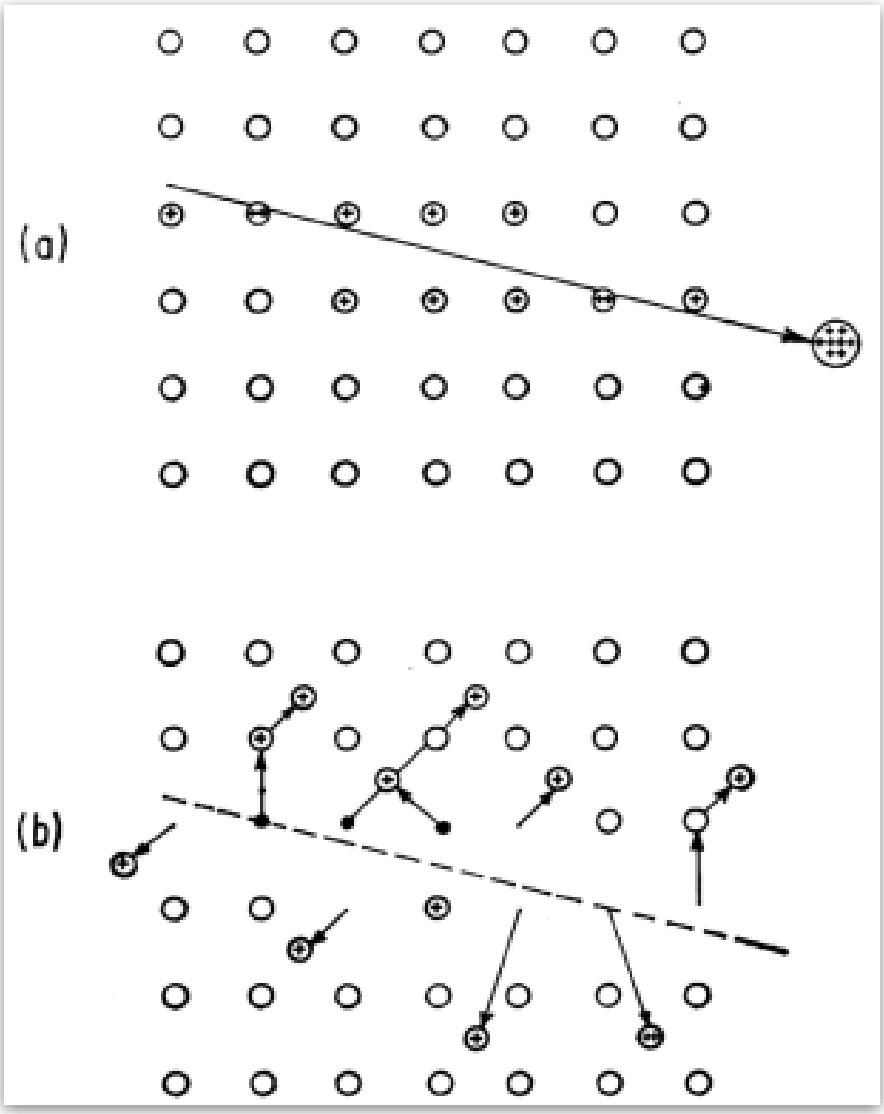


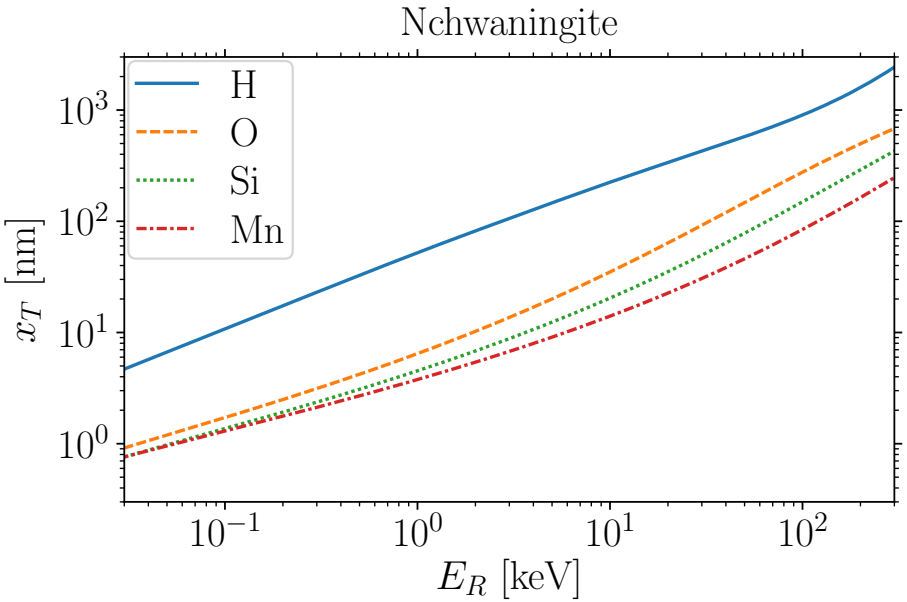
Pb on Mica



Xe on $Y_3Fe_5O_{12}$

Ion explosion spike model for damage as recoils are stopped





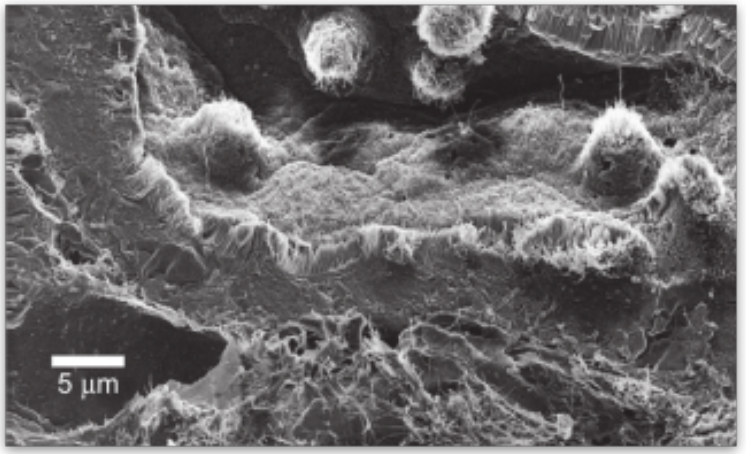
Track length from stopping power

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

Cleaving and etching limits ϵ and can only reconstruct 2D

Readout scenarios for different m_χ

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



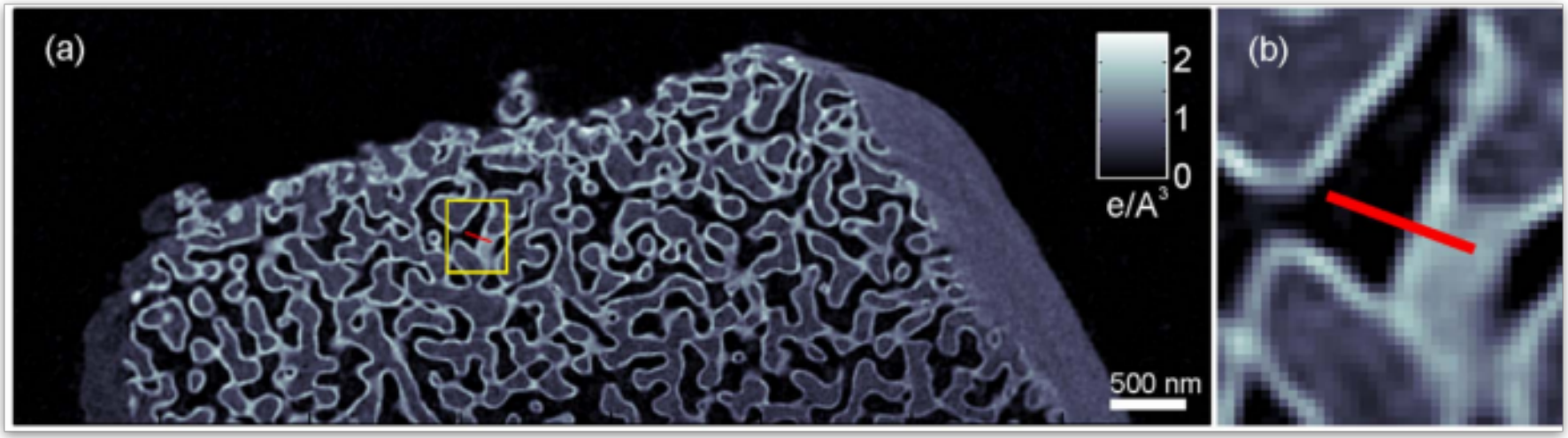


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Cosmogenic backgrounds suppressed in deep boreholes

Depth	Neutron Flux
2 km	$10^6/\mathrm{cm}^2/\mathrm{Gyr}$
5 km	$10^2/\mathrm{cm}^2/\mathrm{Gyr}$
7.5 km	$10^{-1}/\mathrm{cm}^2/\mathrm{Gyr}$
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

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

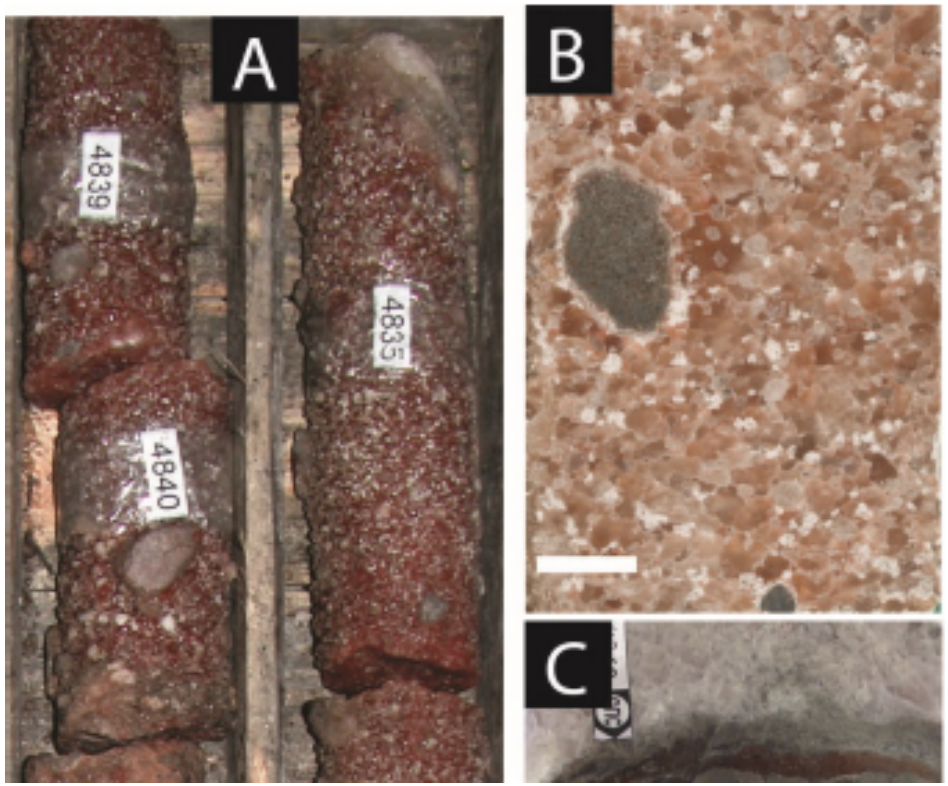
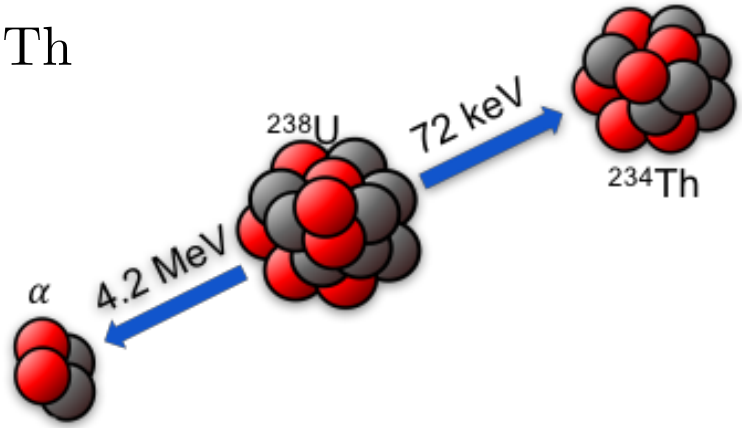


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

Radiogenic backgrounds from ^{238}U contamination

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

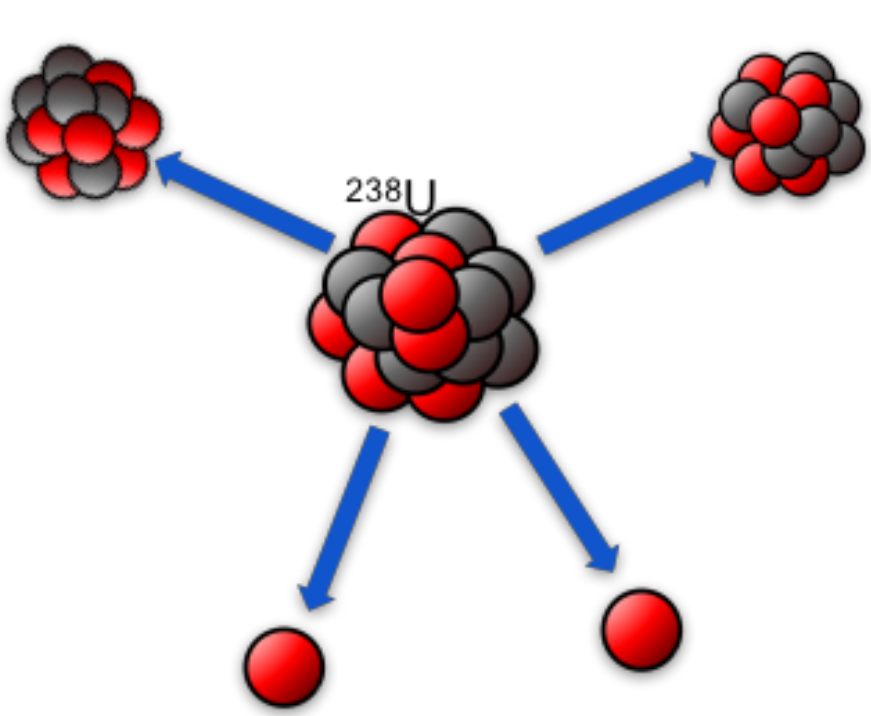


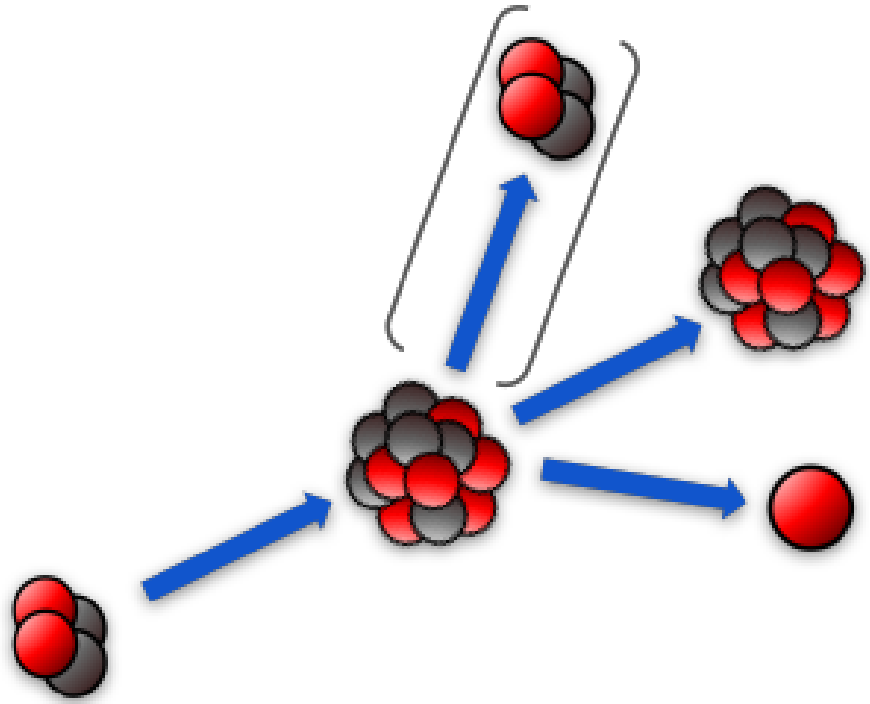
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %)	1.159 min
	IT (0.16 %)	
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

"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





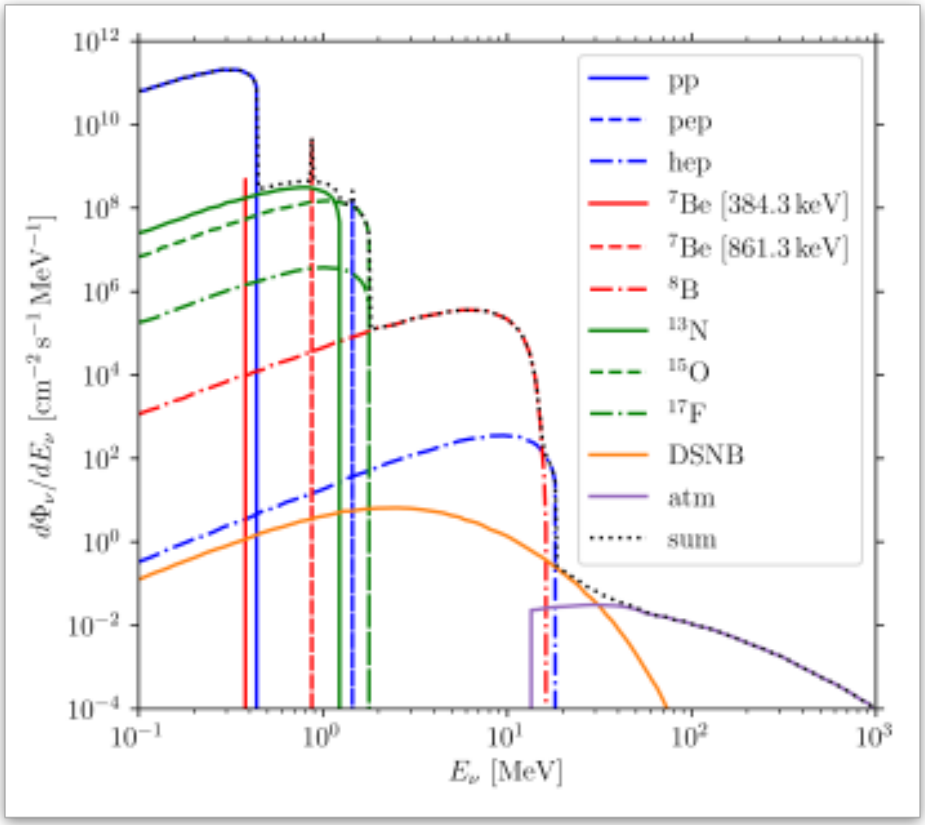
SF yields $\sim$ 2 neutrons with $\sim$MeV

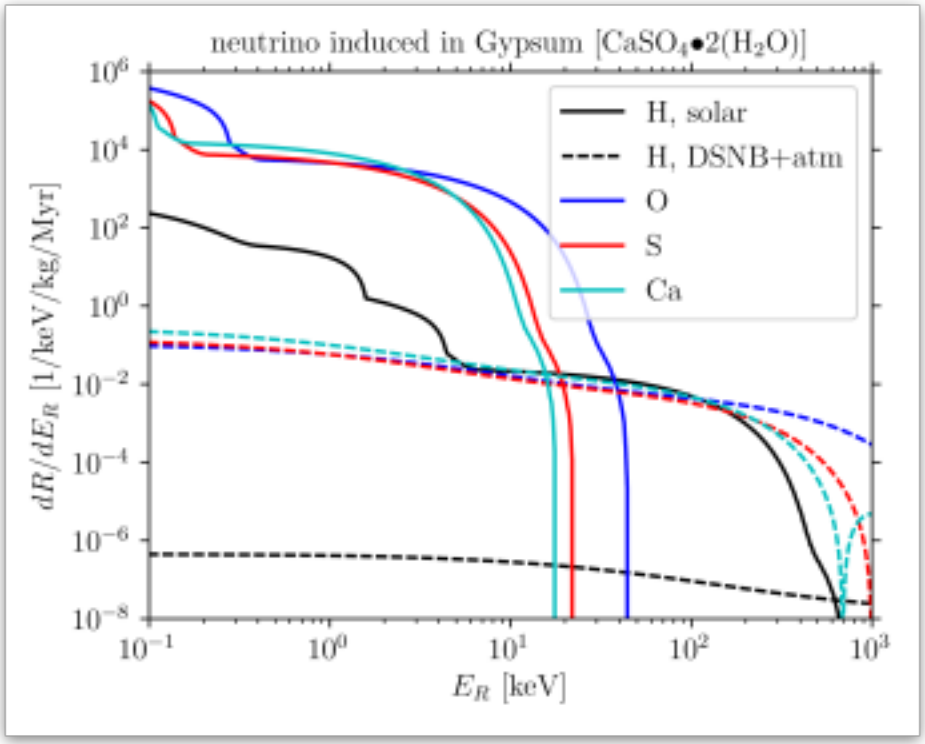
Each neutron will scatter elastically 100-1000 times before moderating

(α, n) rate low, many decay α's

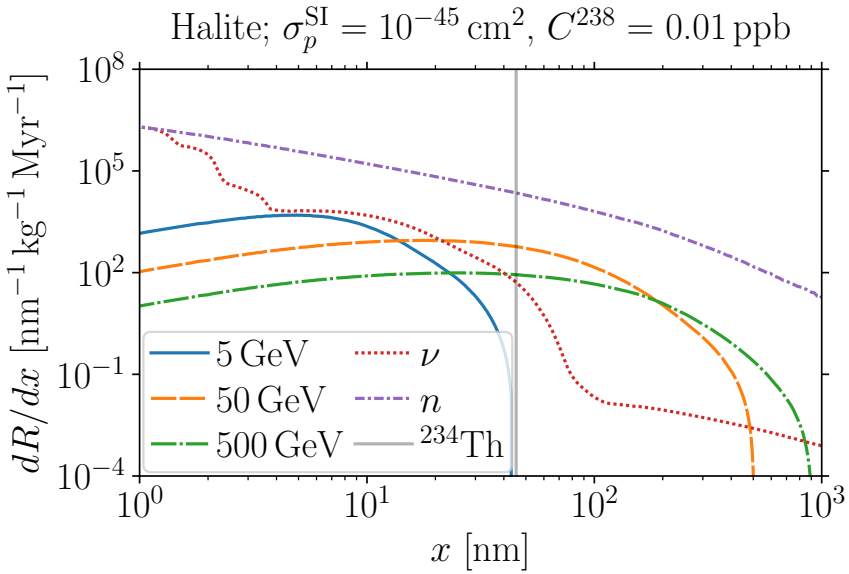
Heavy targets better for (α, n) and bad for neutron moderation, need H

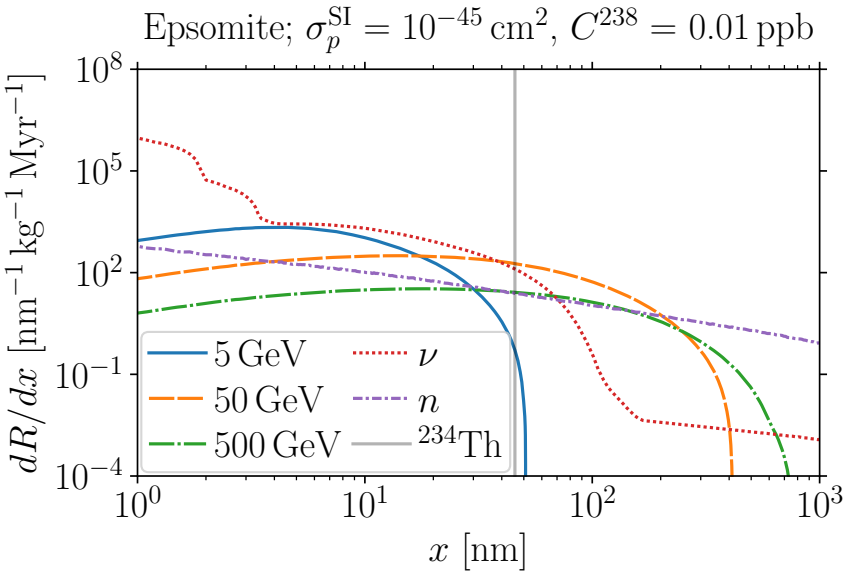
Coherent elastic ν-nucleus scattering yields DD "ν floor"

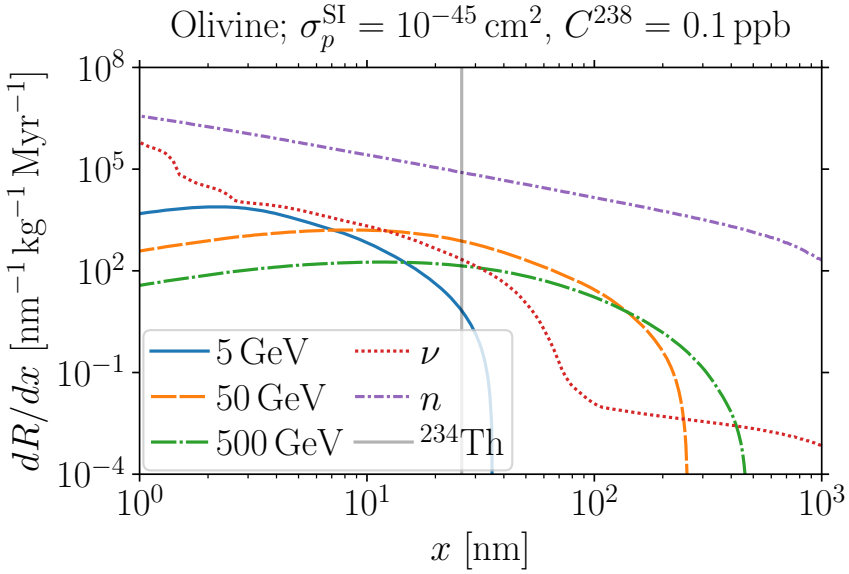


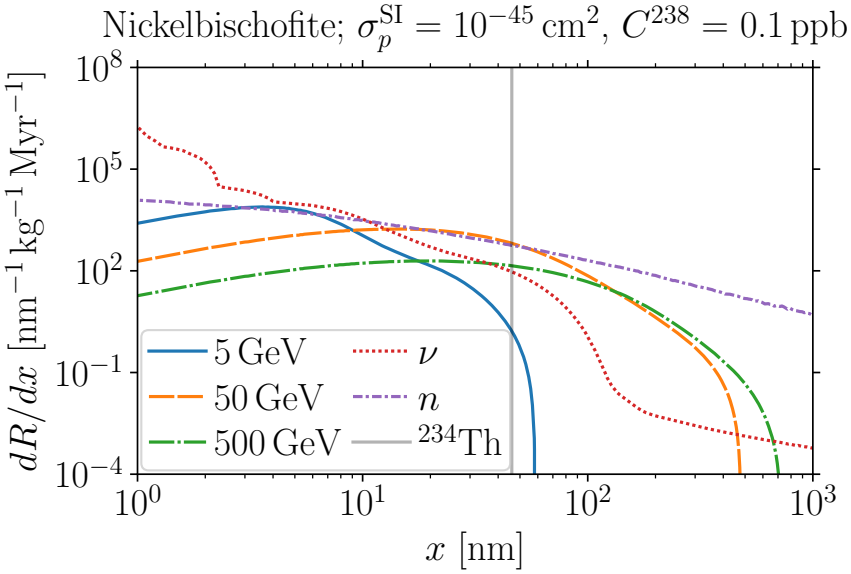


x_T spectra from product of stopping power and recoils

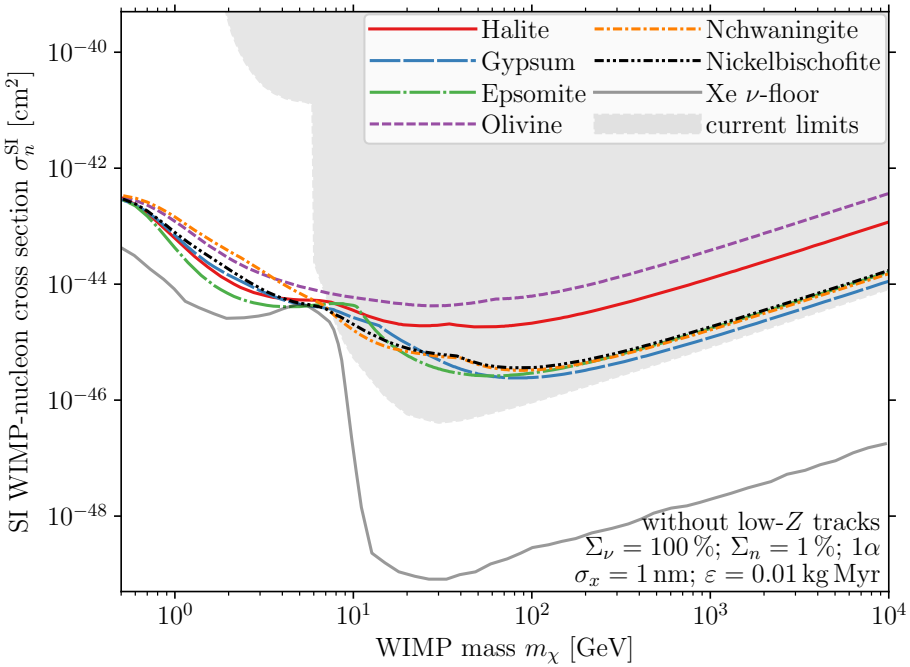


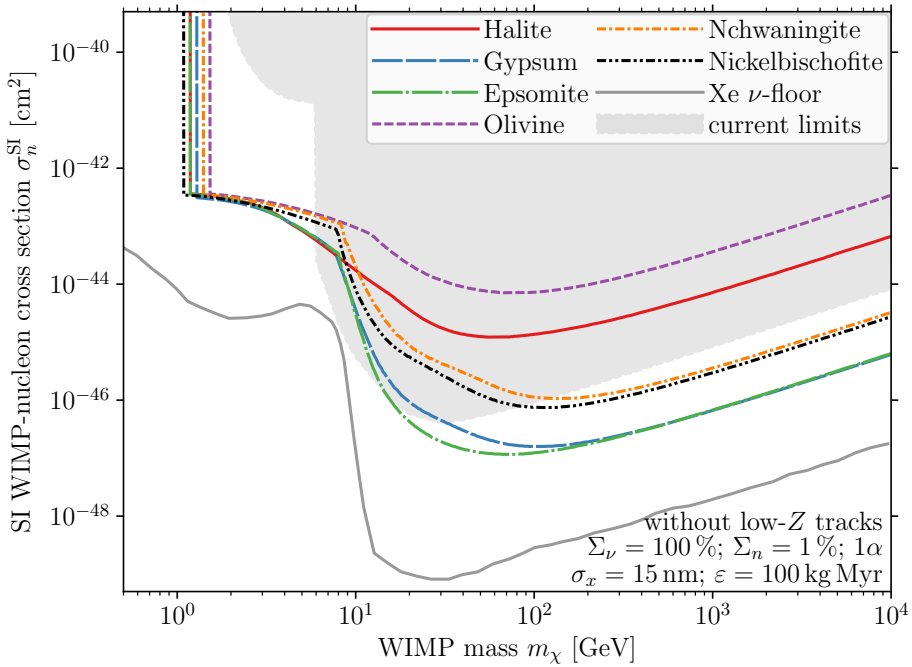






Larger exposure and radiopure targets probe smaller σ^{SI}_{Xp}





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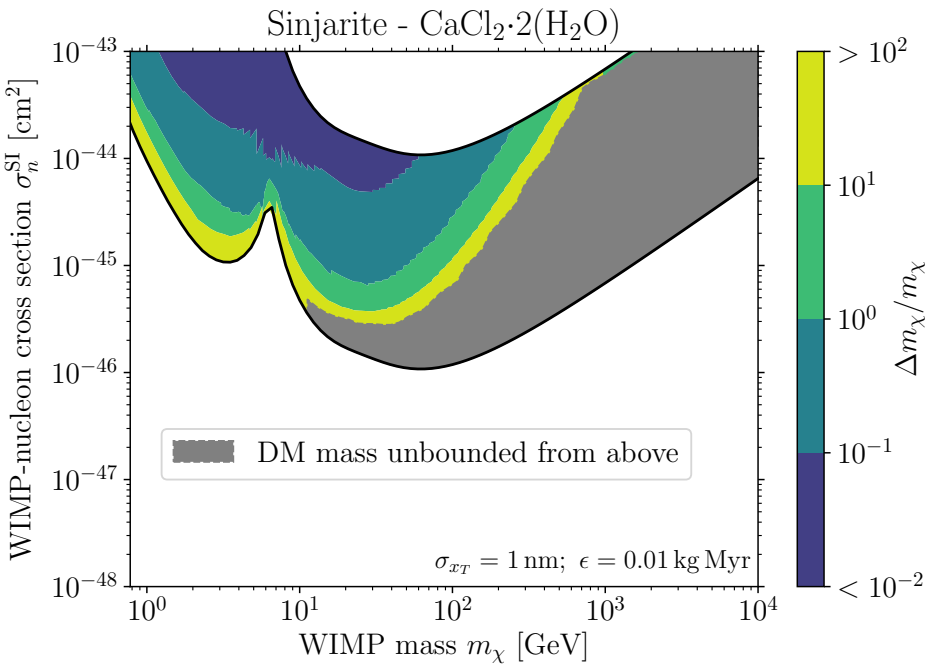
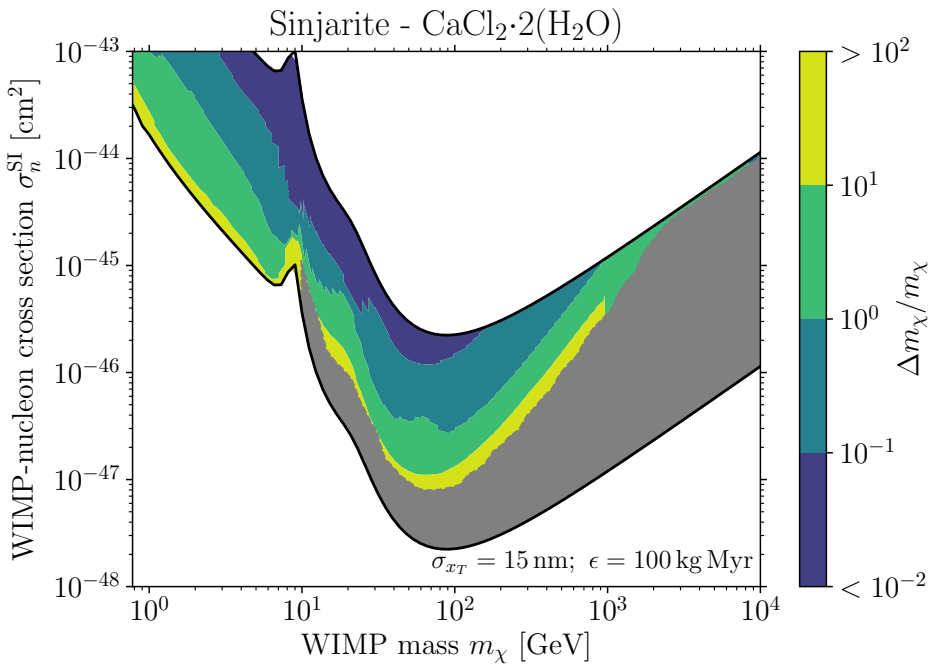
Gypsum [$Ca(SO_4)\cdot 2(H_2O)$]
Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Olivine [$Mg_{1.6}Fe^{2+}_{0.4}(SiO_4)$]

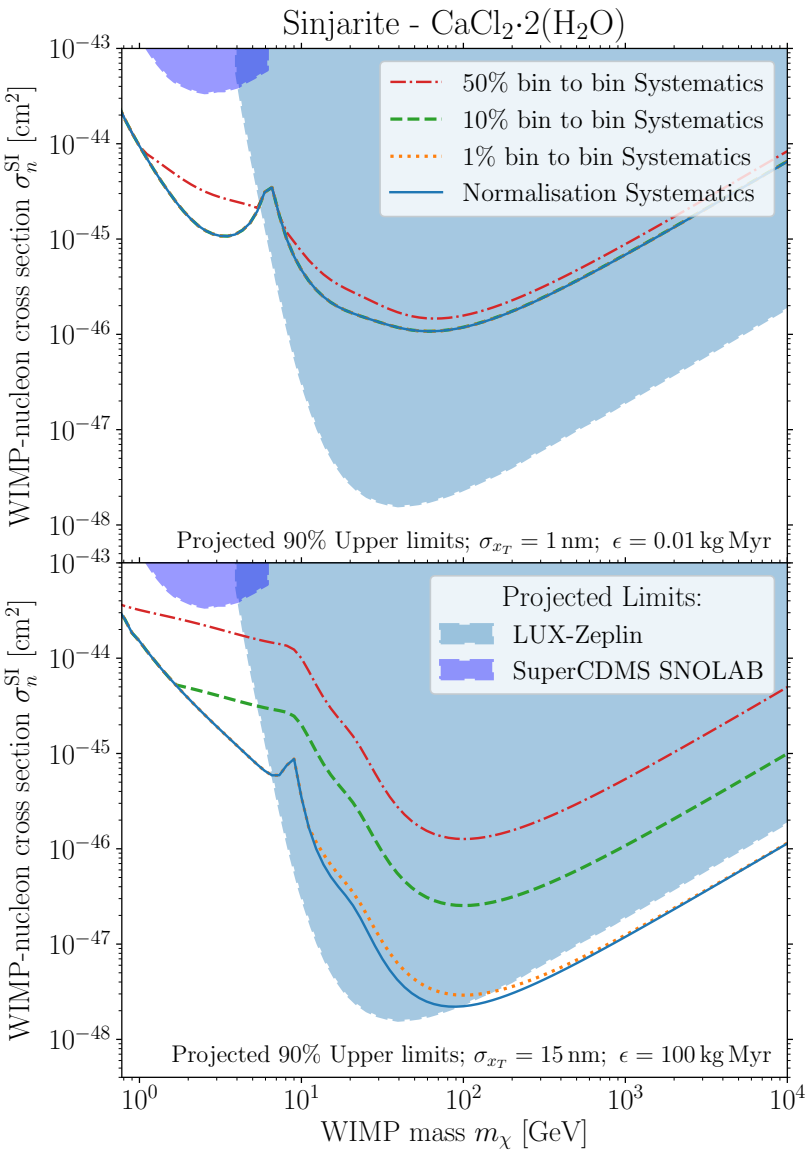
Nchwaningite [$Mn^{2+}_2SiO_3(OH)_2\cdot(H_2O)$]
Nickelbischofite [$NiCl_2\cdot 6(H_2O)$]

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





Paleo-detectors are a potentially very sensitive DD method



Large ϵ probes low cross sections

- Need radiopure target minerals
- Sensitivity to $E_R \sim 100\,\mathrm{eV}$ allows probe of low m_X
- Can reconstruct $m_X \lesssim 1\,\mathrm{TeV}$

Experiments and other applications

- Funding available for preliminary demonstration of feasibility
- Investigate ν's from galactic CC SNe over geological timescales
- Use large exposure to study ~~proton decay~~ atmospheric ν's

Semi-analytic range calculations and SRIM agree with data

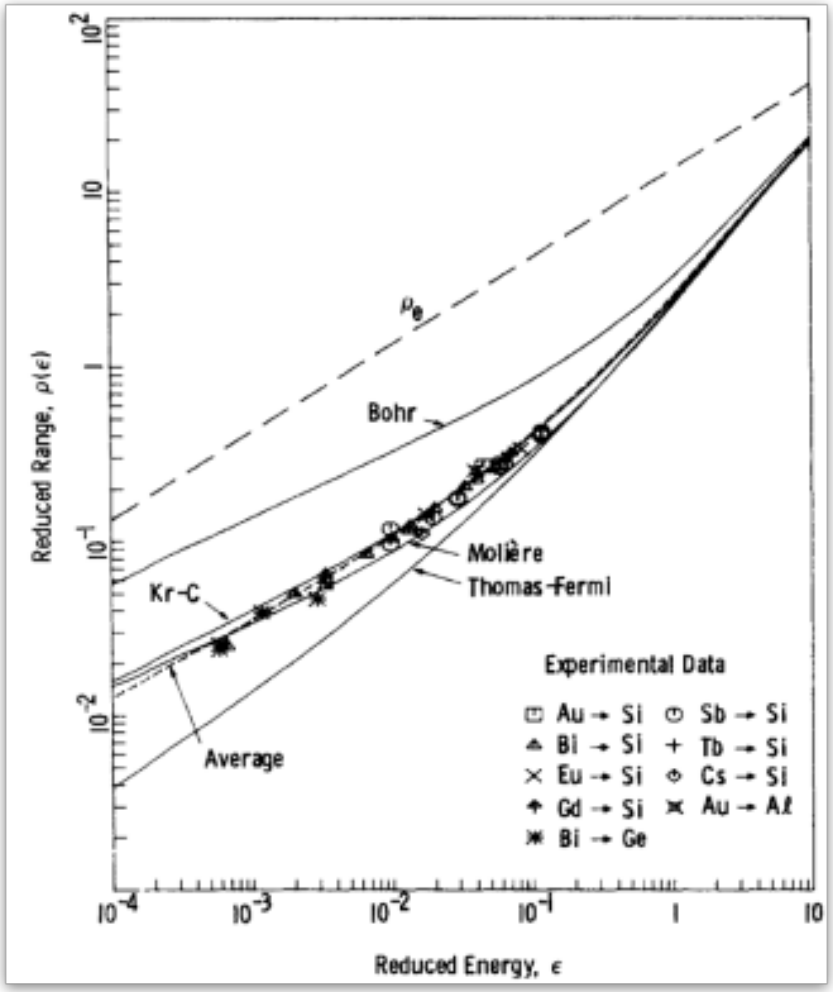
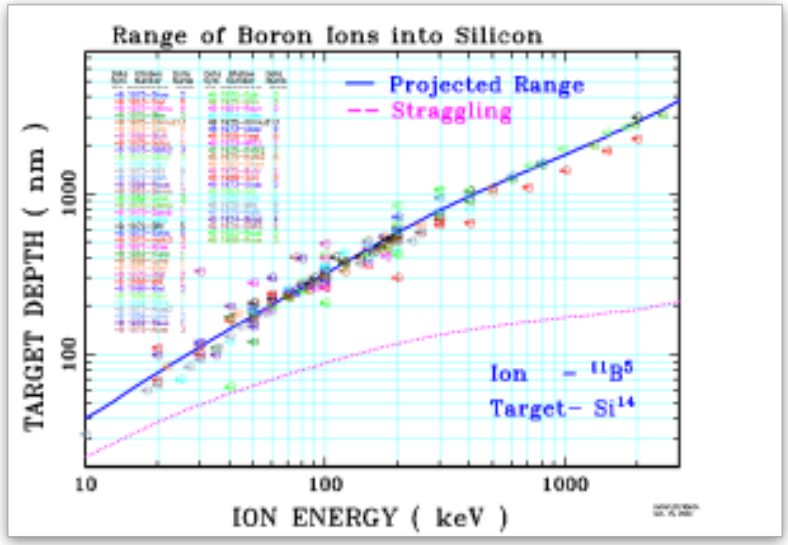
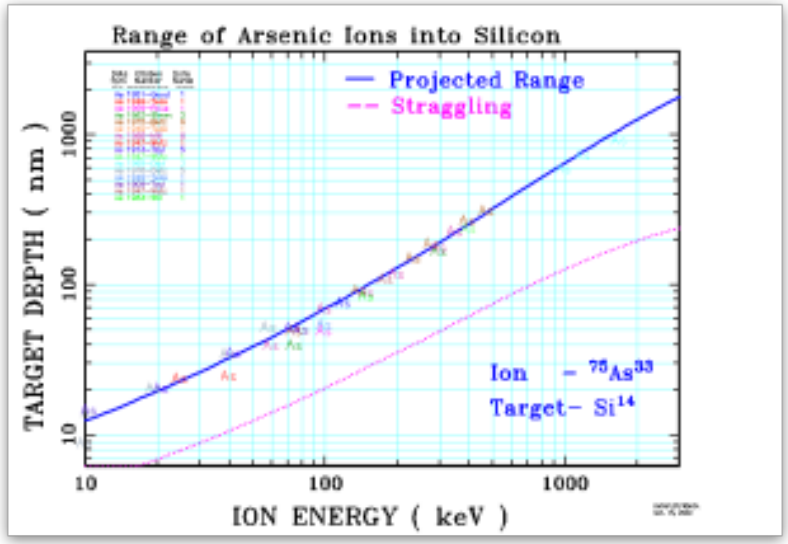
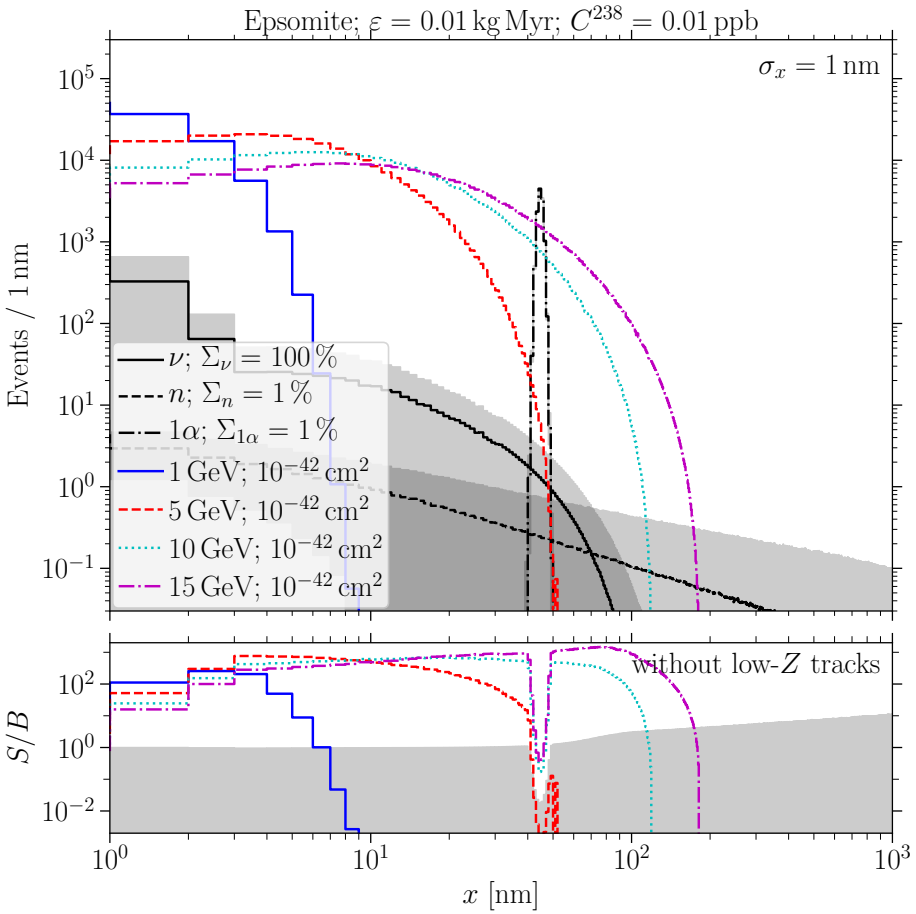


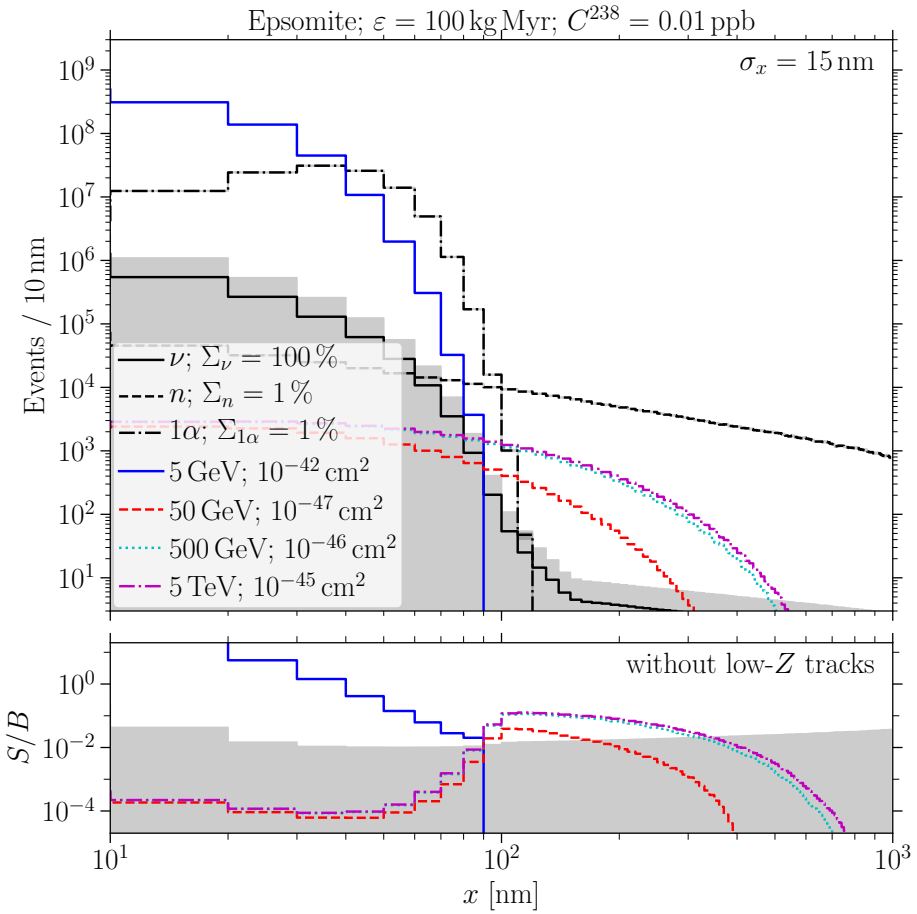
Figure: Wilson, Haggmark+ '76



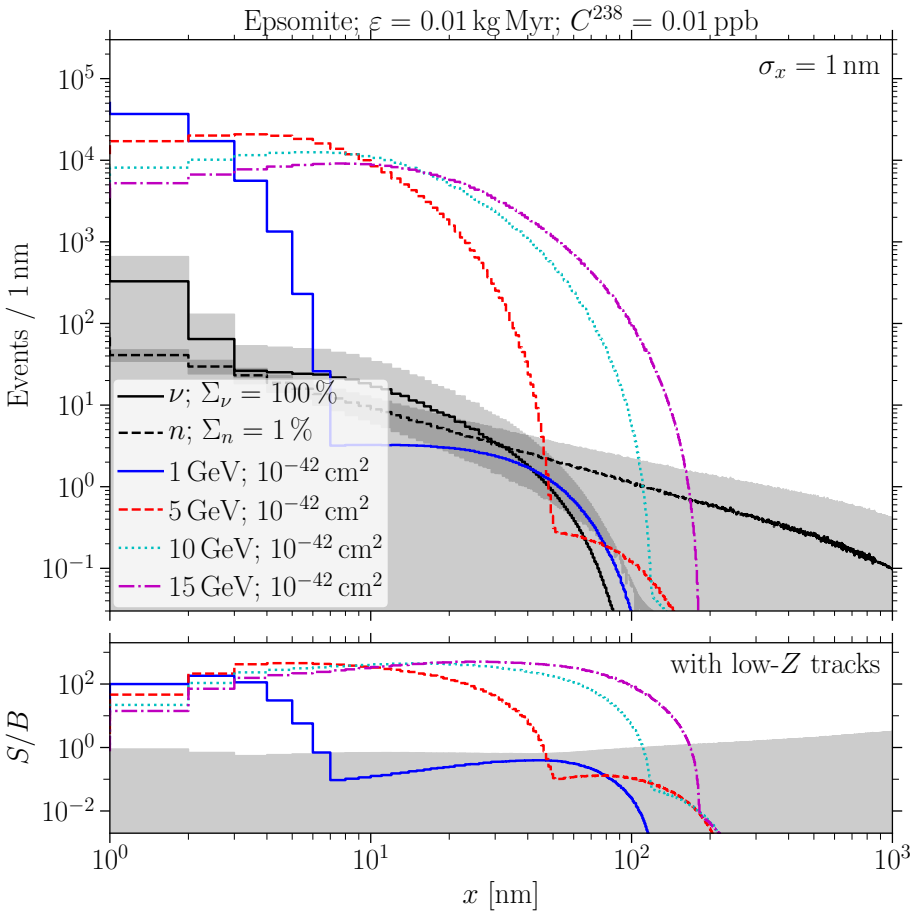


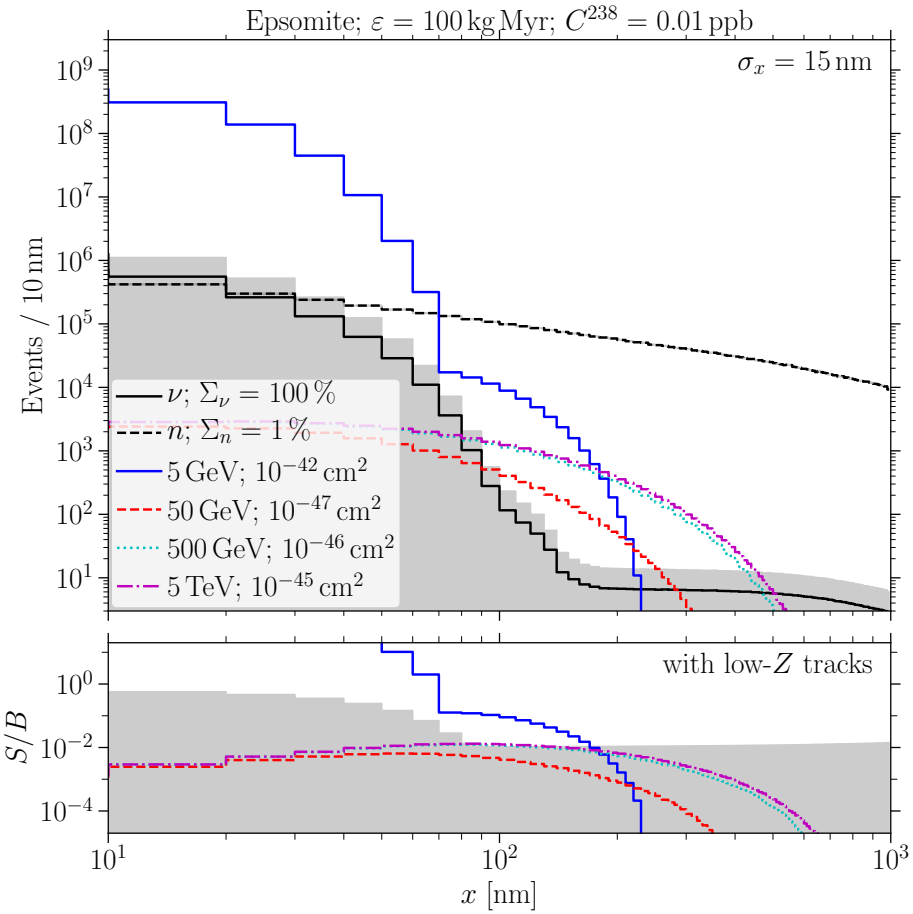
Radiogenic neutron background dominant for higher m_X



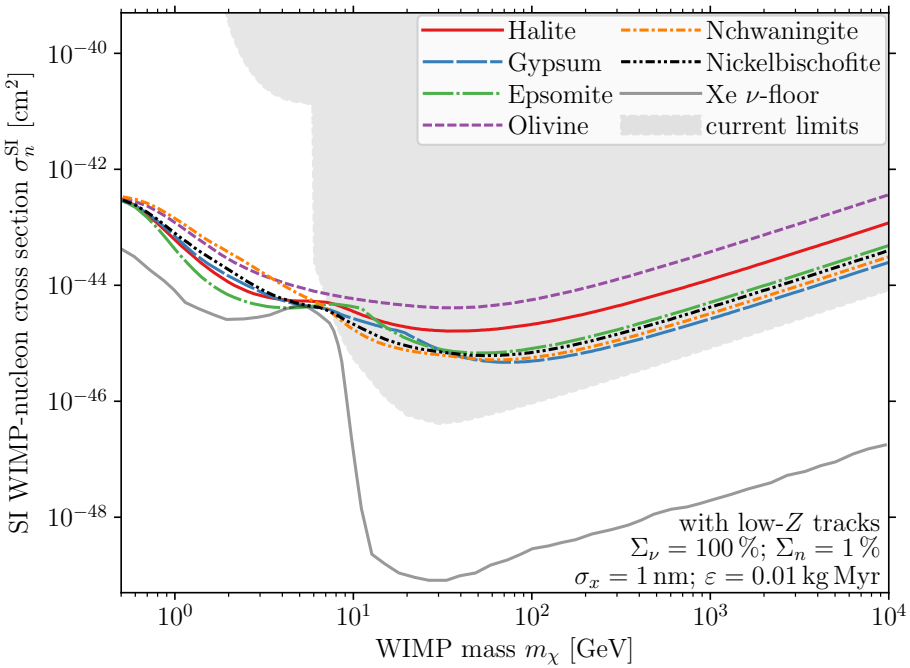


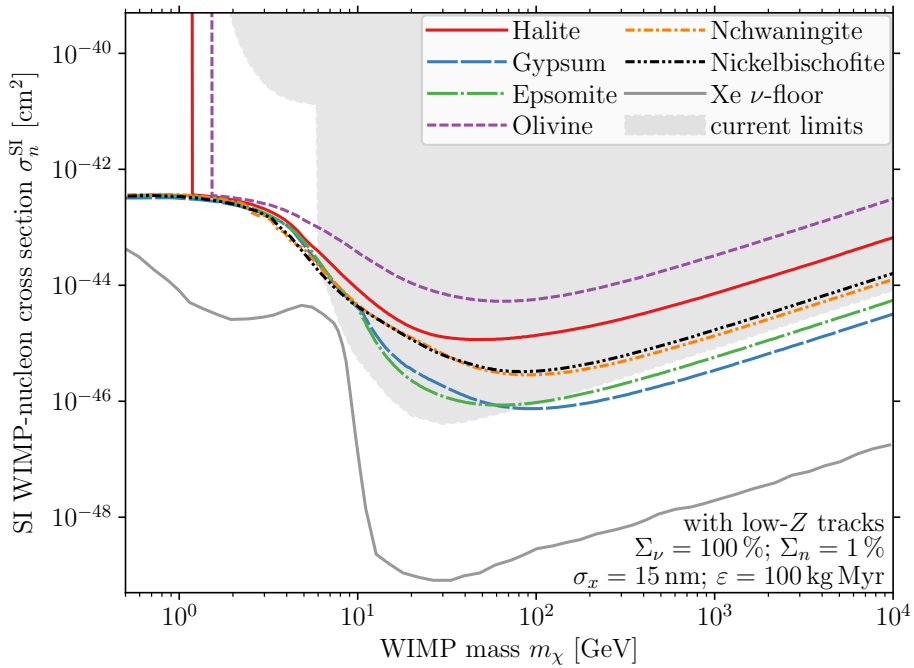
Low-Z tracks eliminate "1α" events, enhance neutrons





Even low resolution with low-Z tracks can probe small m_χ

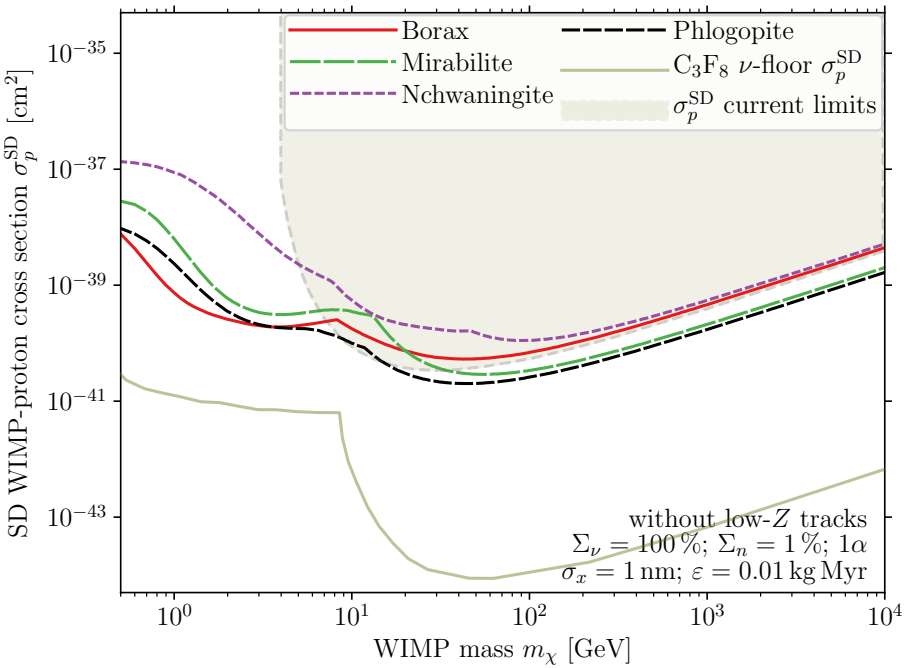


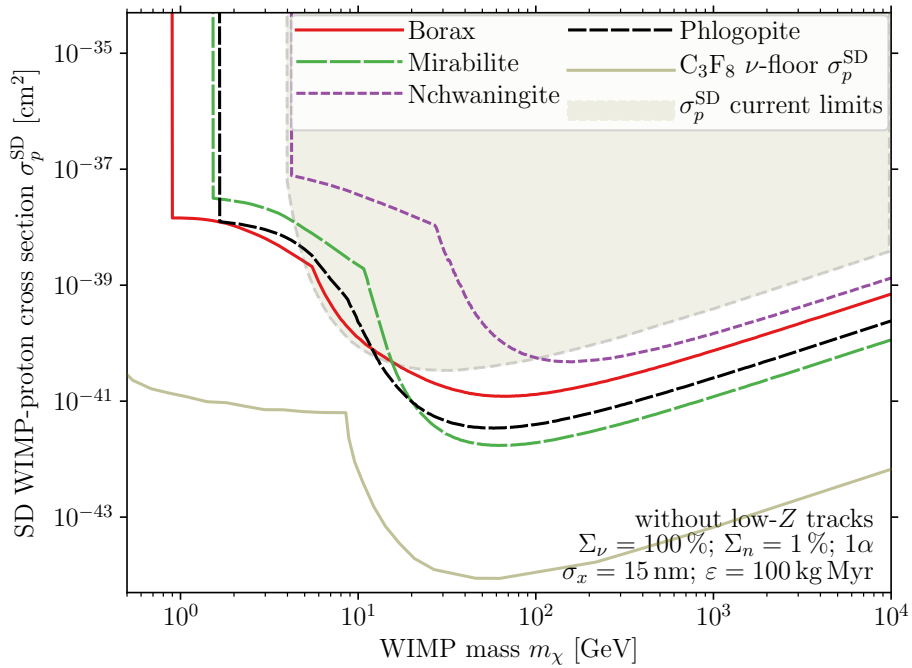


Halite [NaCl]
Gypsum [$Ca(SO_4)\cdot 2(H_2O)$]
Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Olivine [$Mg_{1.6}Fe^{2+}_{0.4}(SiO_4)$]

Nchwaningite [$Mn^{2+}_2SiO_3(OH)_2\cdot(H_2O)$]
Nickelbischofite [$NiCl_2\cdot 6(H_2O)$]

Minerals containing Na, Mn, Al, F... probe SD scattering

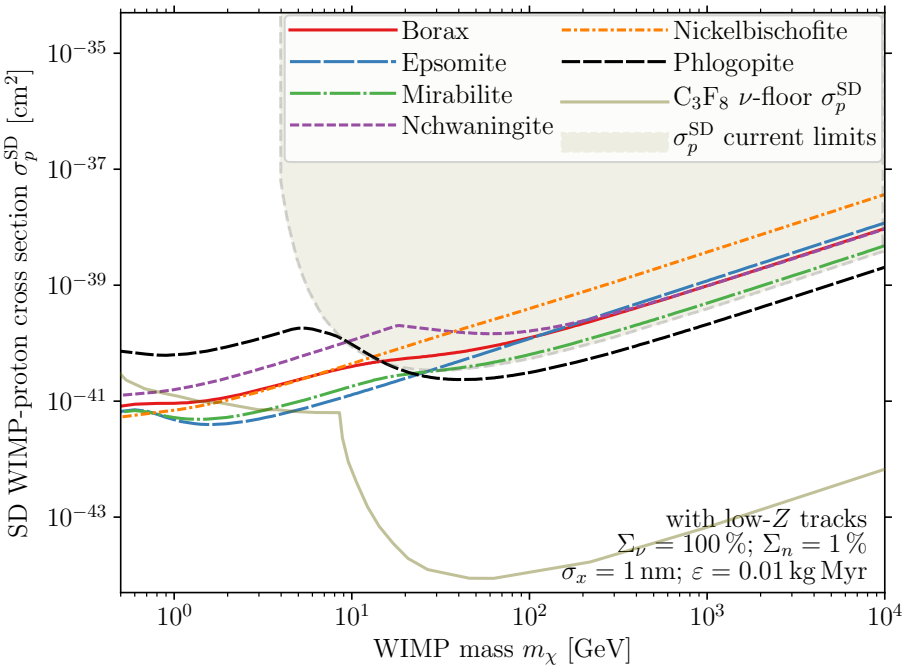


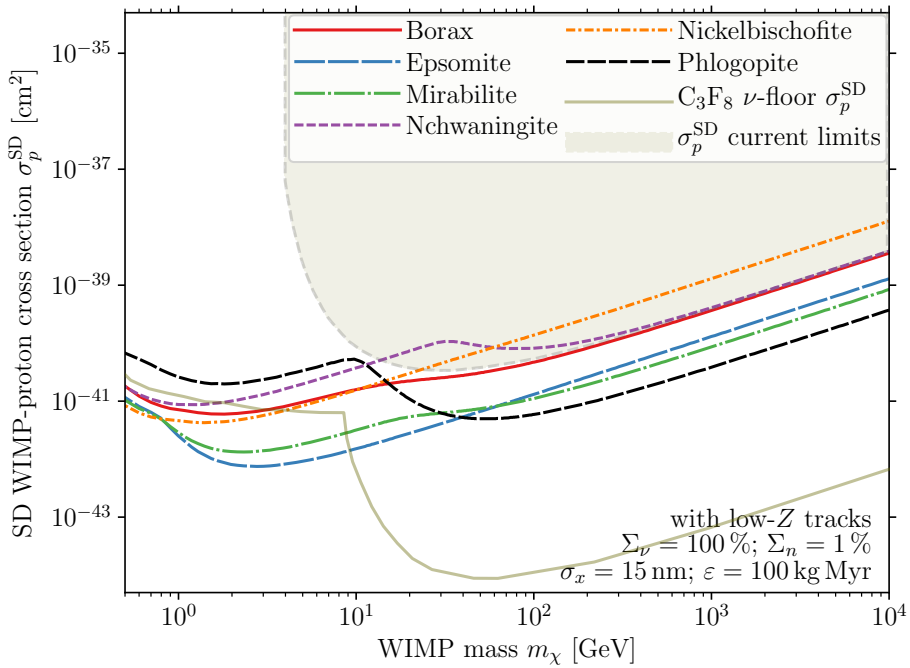


Borax [$Na_2(B_4O_5)(OH)_4 \cdot 8(H_2O)$]
Mirabilite [$Na_2(SO_4) \cdot 10(H_2O)$]
Nchwaningite [$Mn_2^{2+}SiO_3(OH)_2 \cdot (H_2O)$]

Phlogopite [$KMg_3AlSi_3O_{10}F(OH)$]

H can dominate SD signal when low-Z tracks are visible





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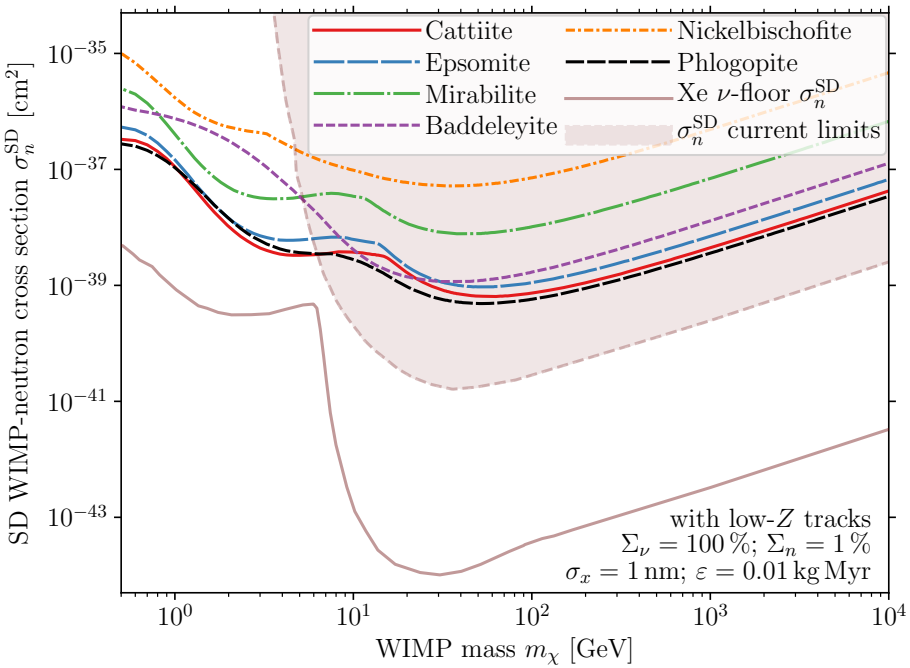
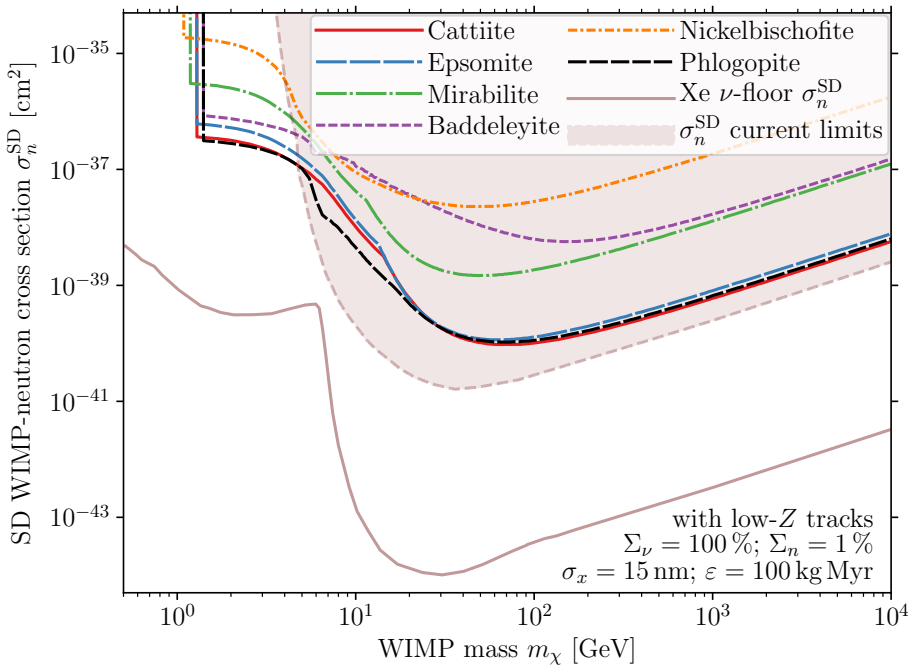
SD scattering with WIMP-neutron coupling





Cattiite [$Mg_{2.92}Fe_{0.01}(PO_4)_{2.01}\cdot 22.05(H_2O)$]

Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]

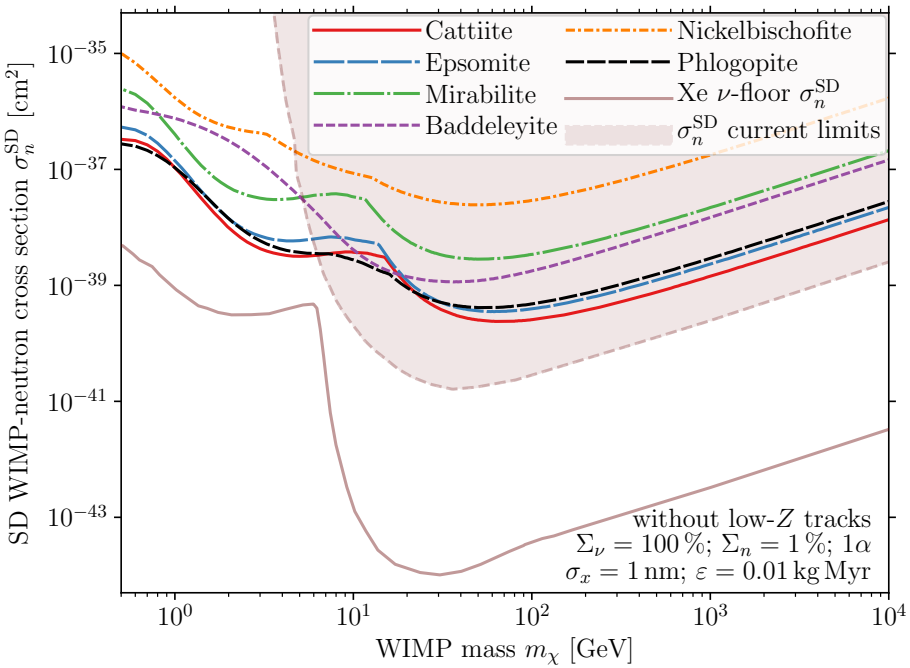
Mirabilite [$Na_2(SO_4)\cdot 10(H_2O)$]

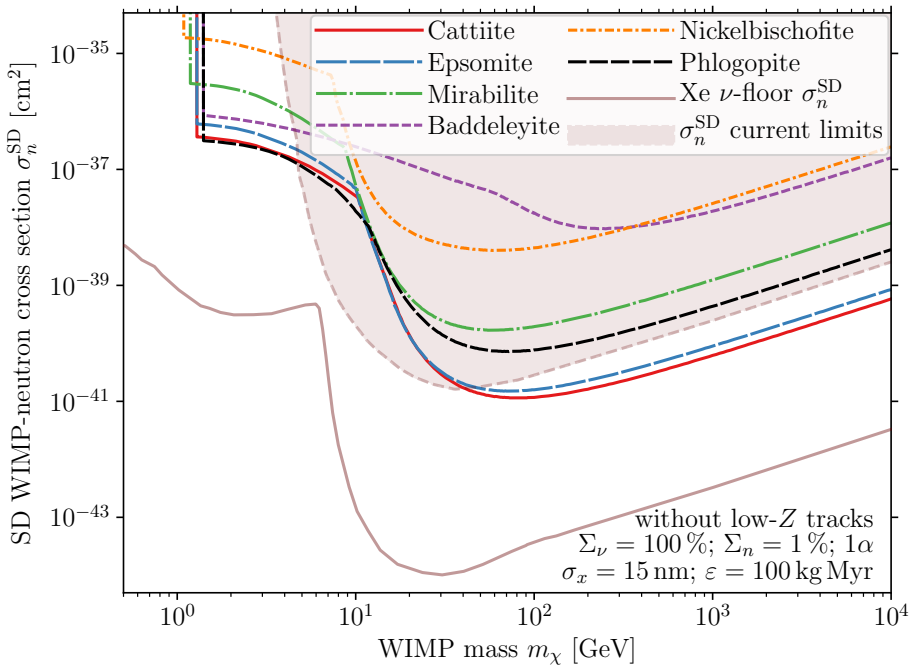
Baddeleyite [ZrO_2]

Nickelbiscofite [$NiCl_2\cdot 6(H_2O)$]

Phlogopite [$KMg_3AlSi_3O_{10}F(OH)$]

SD scattering with WIMP-neutron coupling





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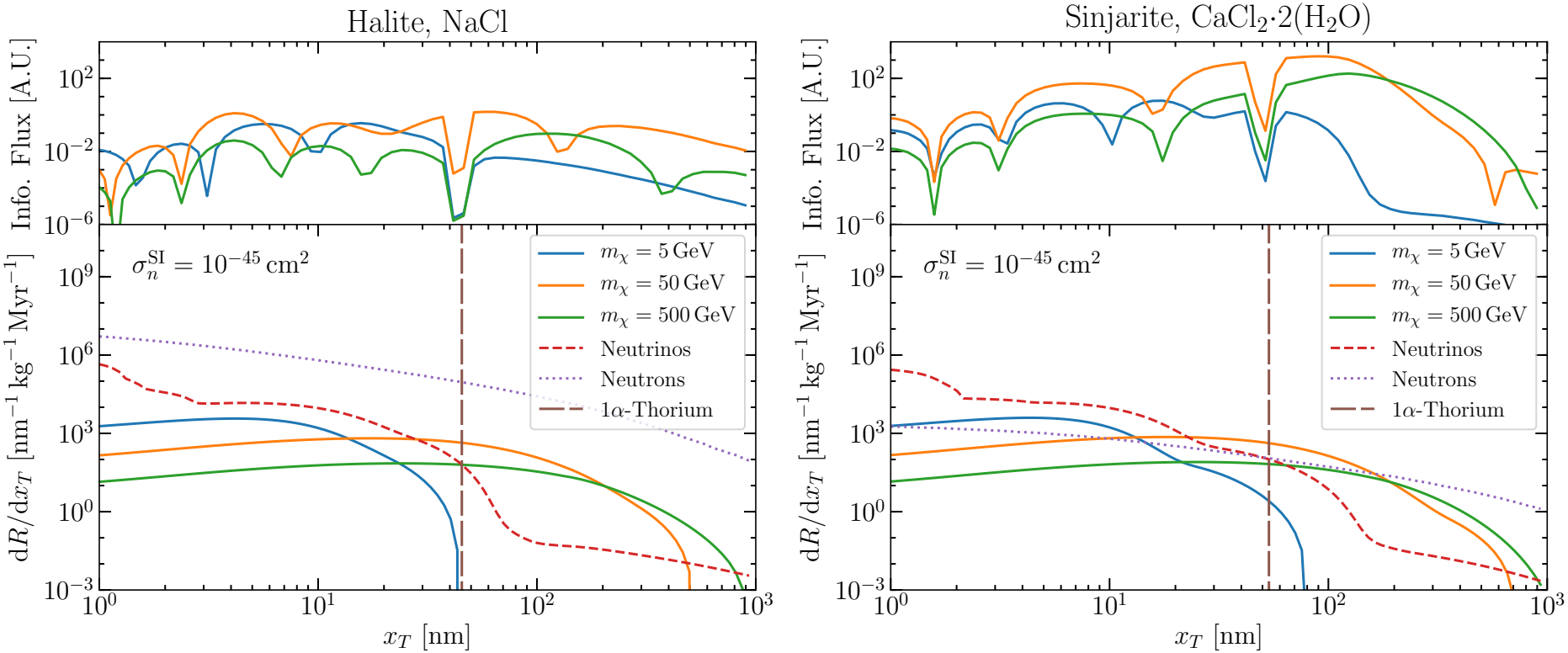
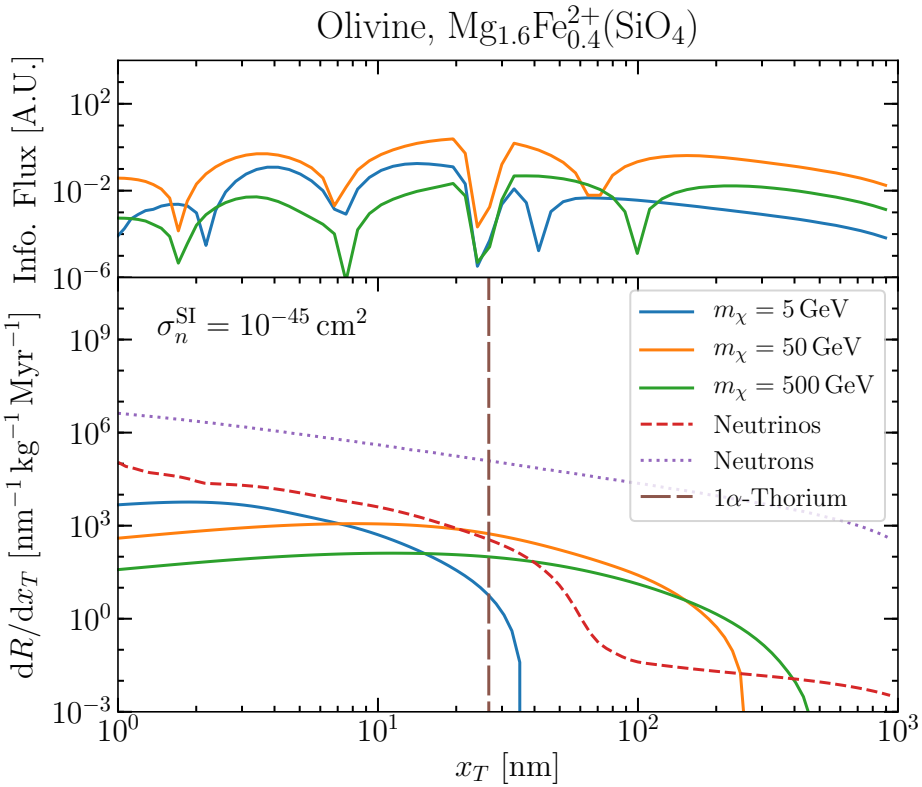
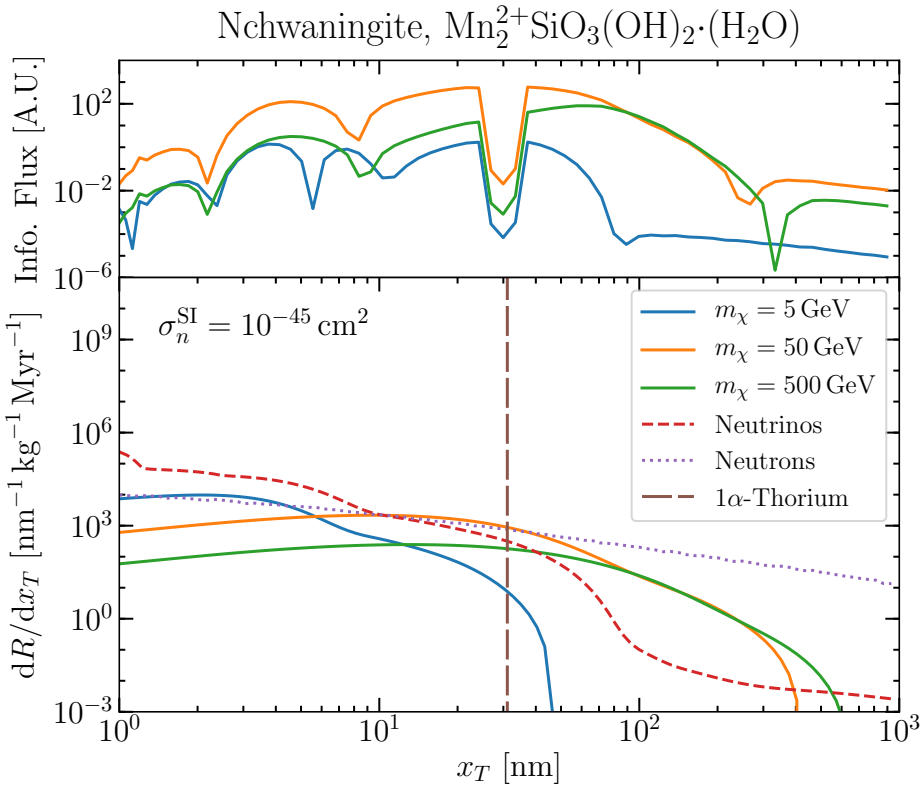
Use control regions to improve control of backgrounds

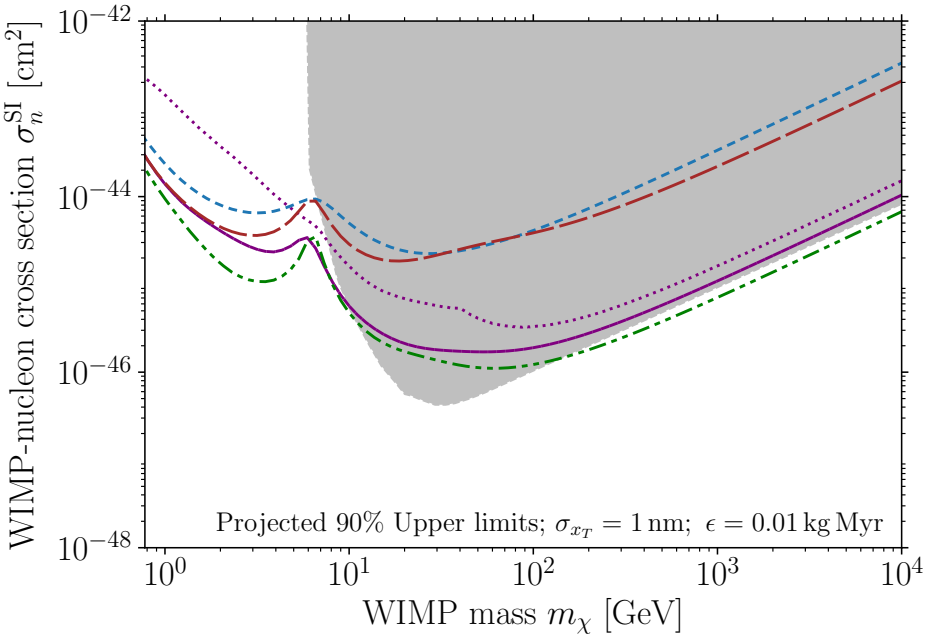


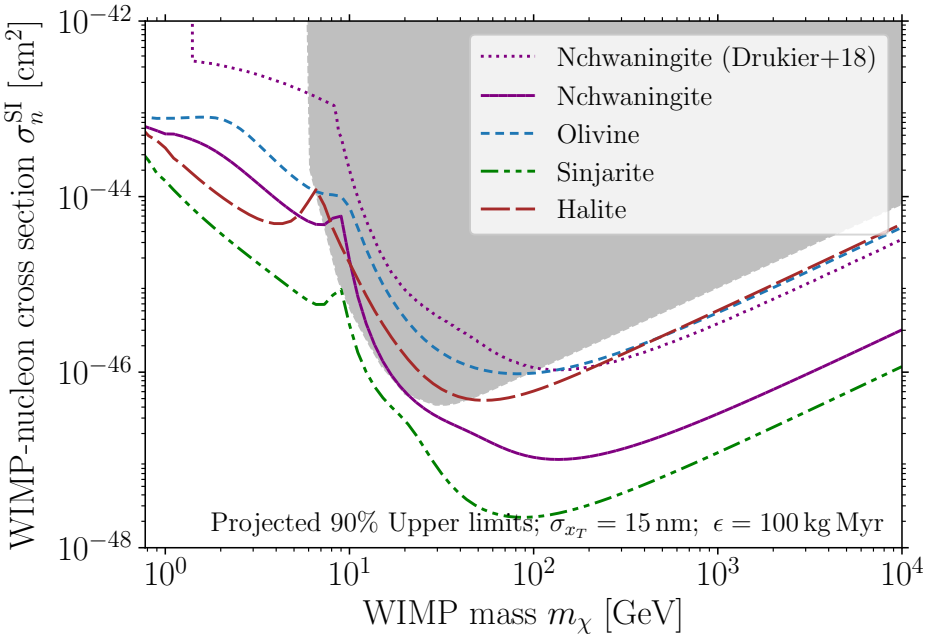
Use control regions to improve control of backgrounds





Can gain up to an order of magnitude in sensitivity

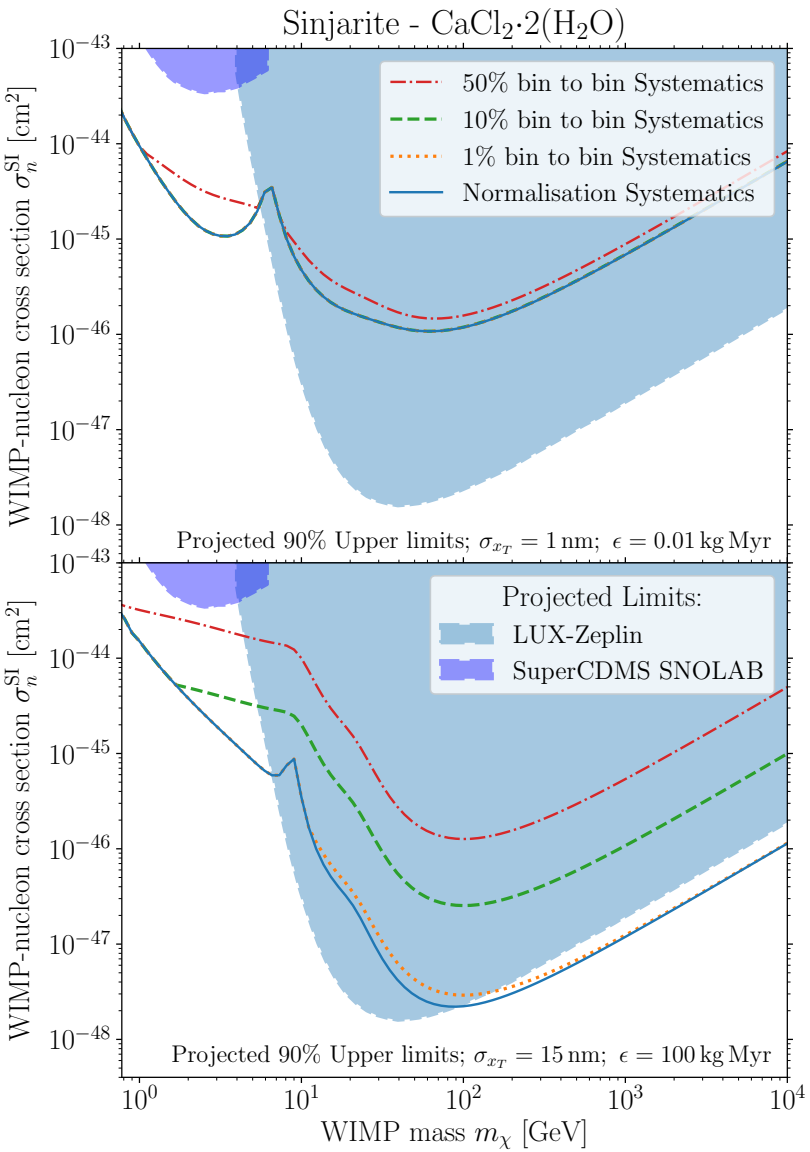




Nchwaningite[$Mn_2^{2+}SiO_3(OH)_2\cdot(H_2O)$]
Olivine[$Mg_{1.6}Fe_{0.4}^{2+}(SiO_4)$]

Sinjarite[$CaCl_2\cdot 2(H_2O)$]
Halite[NaCl]

How robust is sensitivity to background shape systematics?



Optimistic systematics assumptions

- Assume 1% normalization systematics for "constant" radiogenic backgrounds
- Neutrino fluxes could have varied substantially over ∼Gyr, assume more conservative 100%

Allow systematic to vary bin to bin

- High resolution benchmark robust to bin to bin systematics
- Background shape systematics can significantly reduce sensitivity at high exposure