Paleo-detectors for Dark Matter I

Backgrounds and mineral optimization

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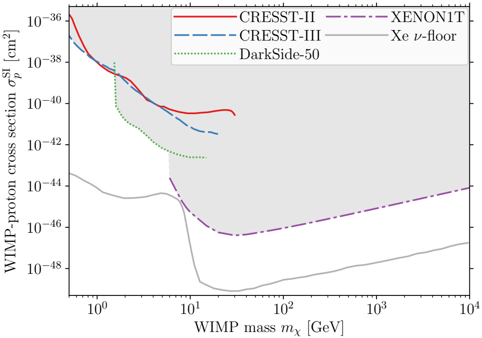
1806.05991, 1811.06844 with **Baum**, Drukier, Freese and Górski
1811.10549 + Edwards, Kavanagh and Weniger

Current limits on σ_{Xp}^{SI} from direct detection experiments



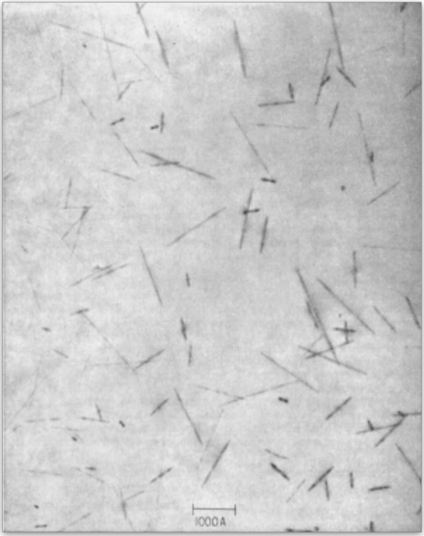
General WIMP mass regimes

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

Future experiments

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

Fission fragments can be seen by TEM/optical microscopes



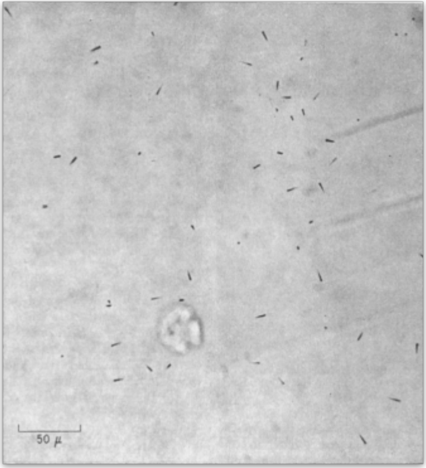
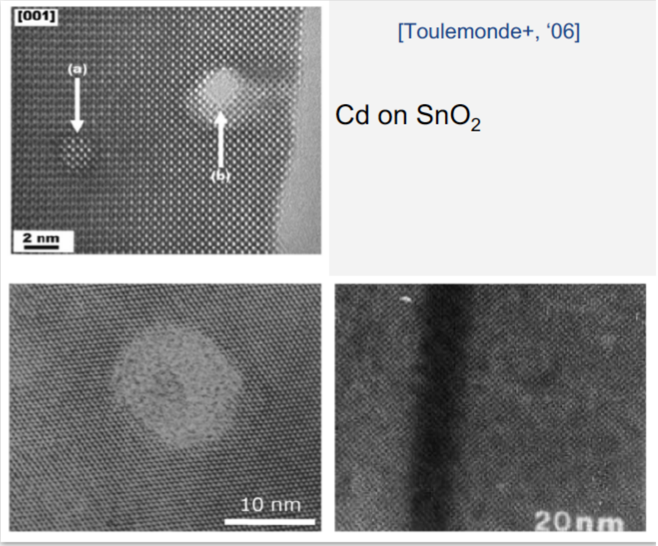


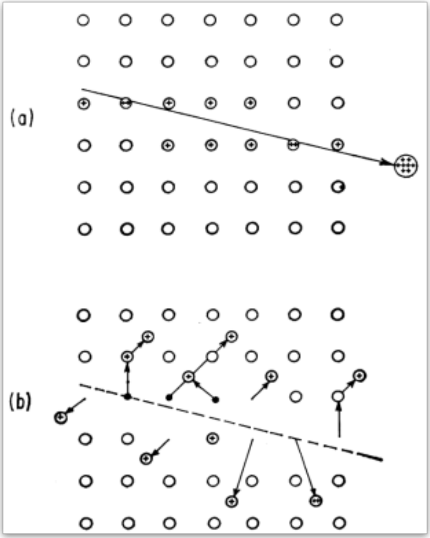
Figure: Price+Walker '63

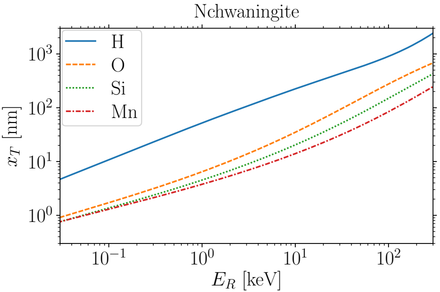
Modern TEM allows for accurate characterization of tracks



Pb on Mica | Xe on $Y_3Fe_5O_{12}$

Ion explosion spike model for damage as recoils are stopped





Track length from stopping power

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

Cosmogenic backgrounds supressed in deep boreholes

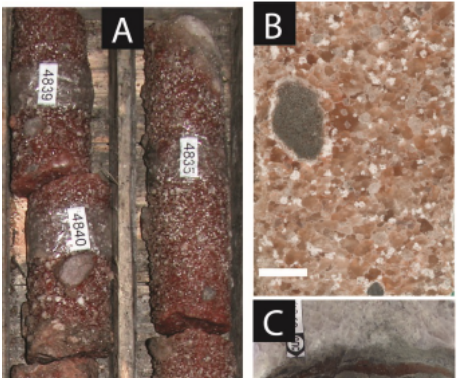


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

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

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

Deep boreholes for geological research and oil exploration

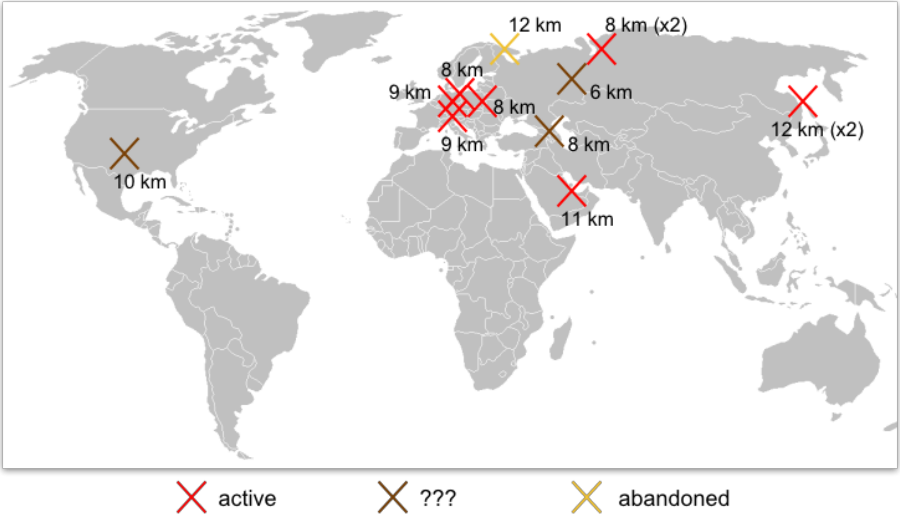
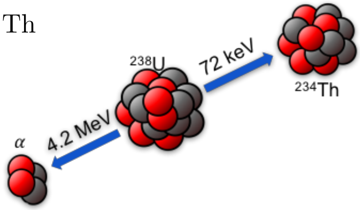


Figure: Credit S. Baum

Radiogenic backgrounds from ^{238}U contmaination

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

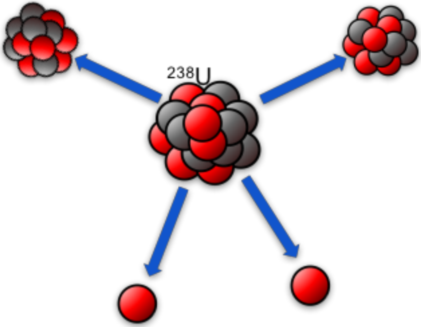


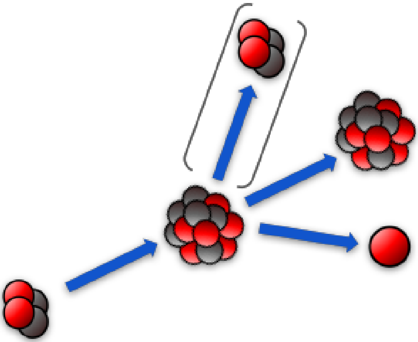
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

"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





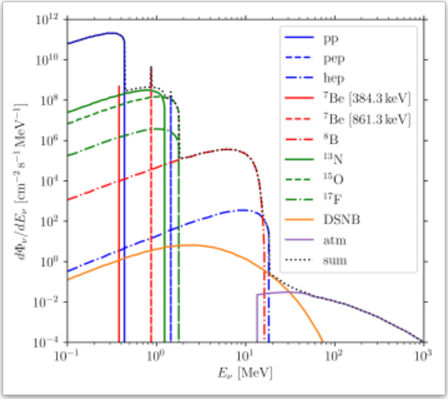
SF yields $\sim$ 2 neutrons with $\sim$MeV

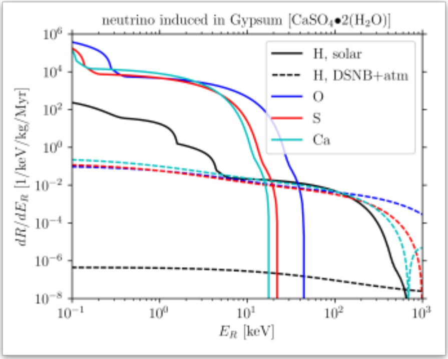
Each neutron will scatter elastically 100-1000 times before moderating

(α, n) rate low, many decay α's

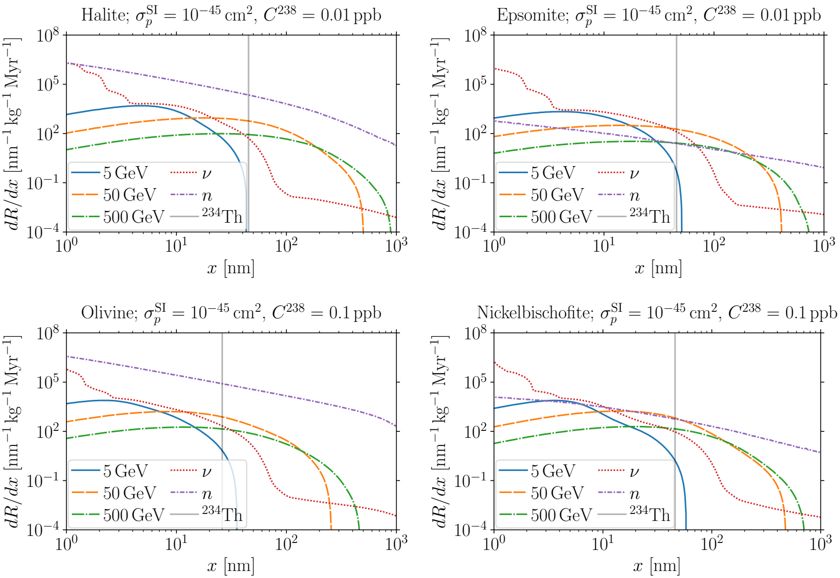
Heavier targets typically better for (α, n) and bad for SF, need H

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





x_T spectra from product of stopping power and recoils



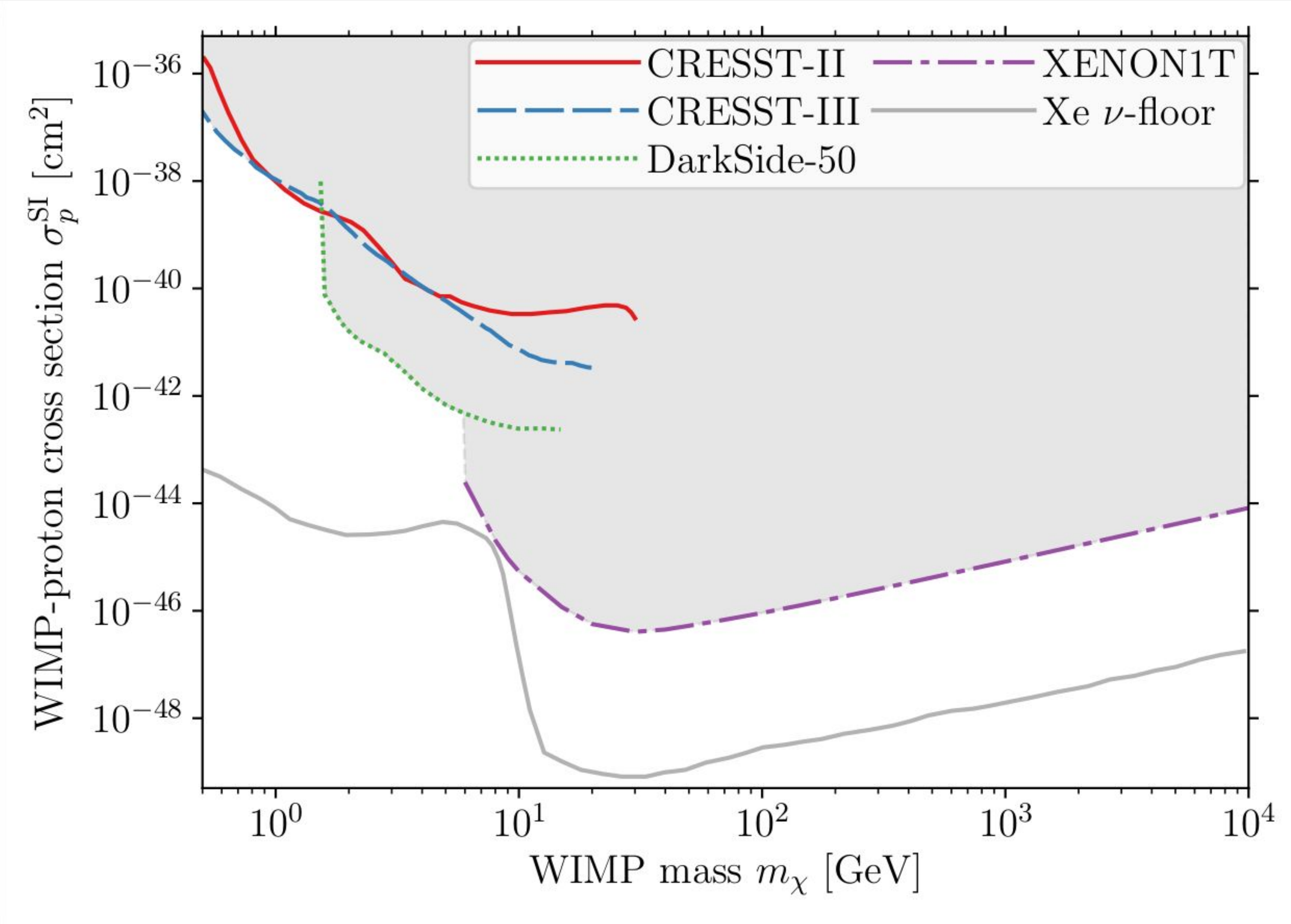
Paleo-Detectors for Dark Matter II
- read out and sensitivity projections -

SB, Drukier, Freese, Gorski, Stengel: 1806.05991, 1811.06844
Edwards, Kavanagh, Weniger, SB+: 1811.10549

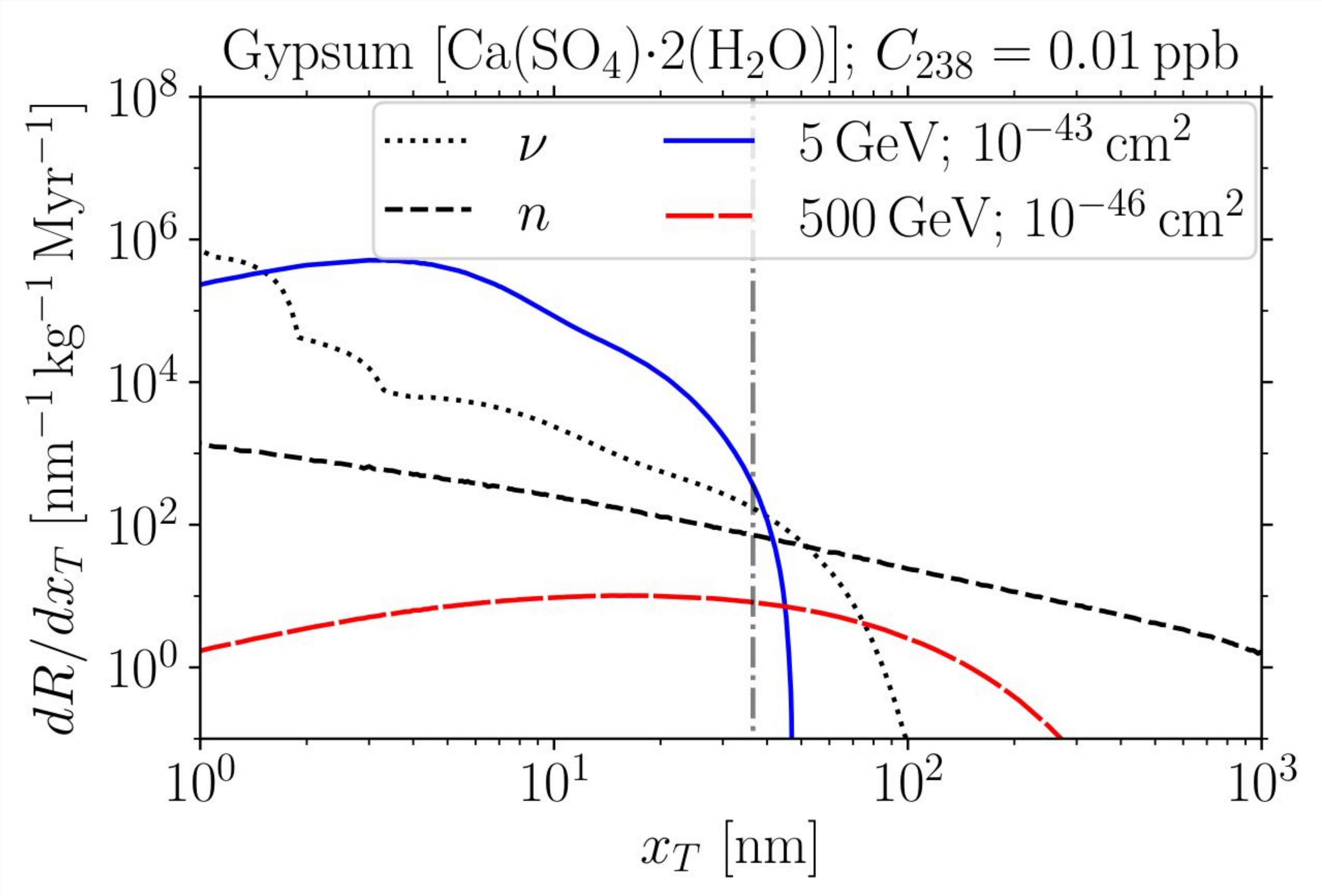
Sebastian Baum

Oskar Klein Centre for Cosmoparticle Physics
Stockholm University

Status of Direct Detection



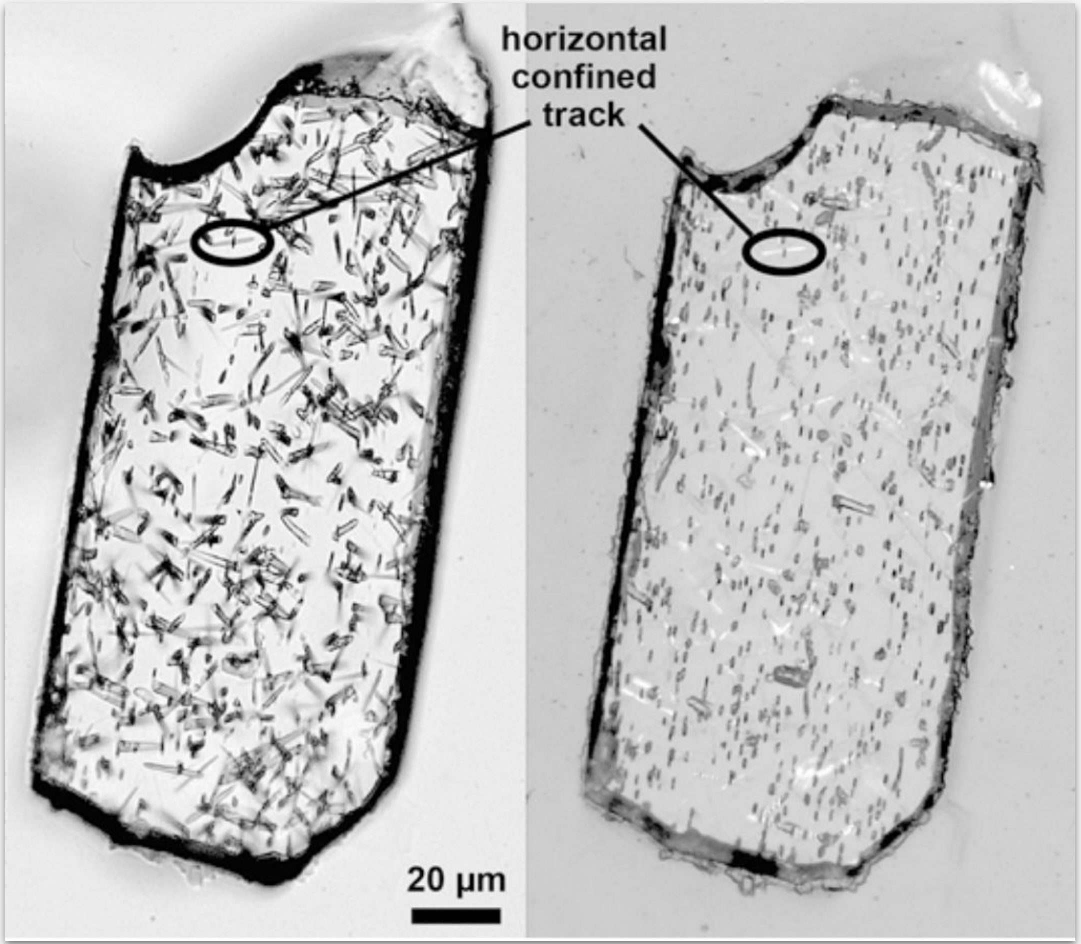
What do we want to do?



Read-out methods: Optical Transmission Microscopy

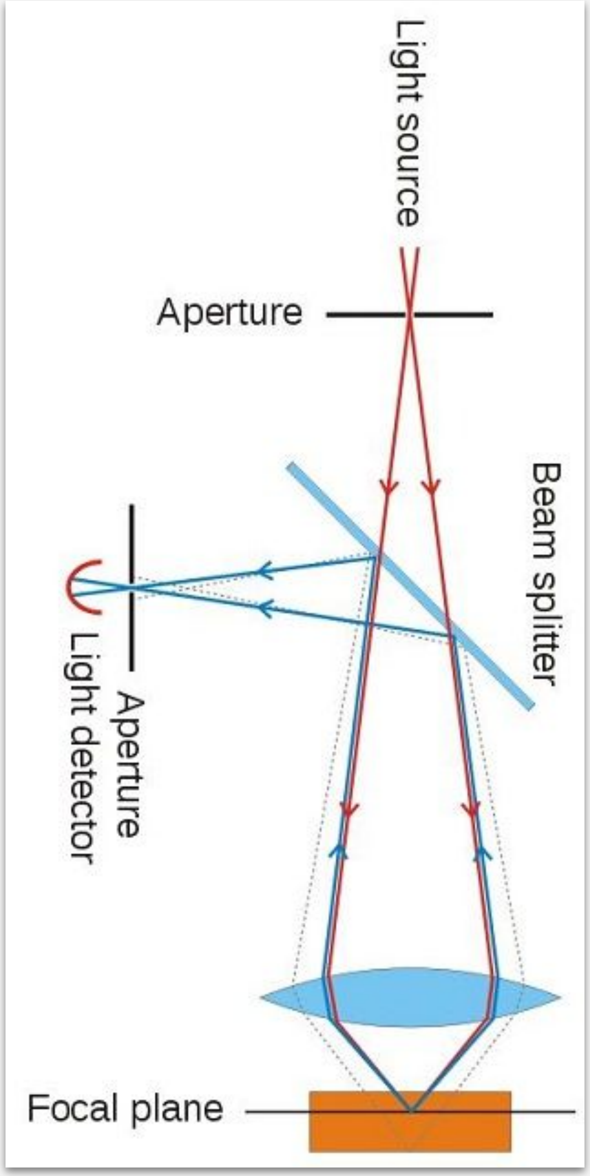
- Widely available
- Cheap
- Resolutions of a few 100 nm
- Requires etching

Etched fission tracks in Apatite



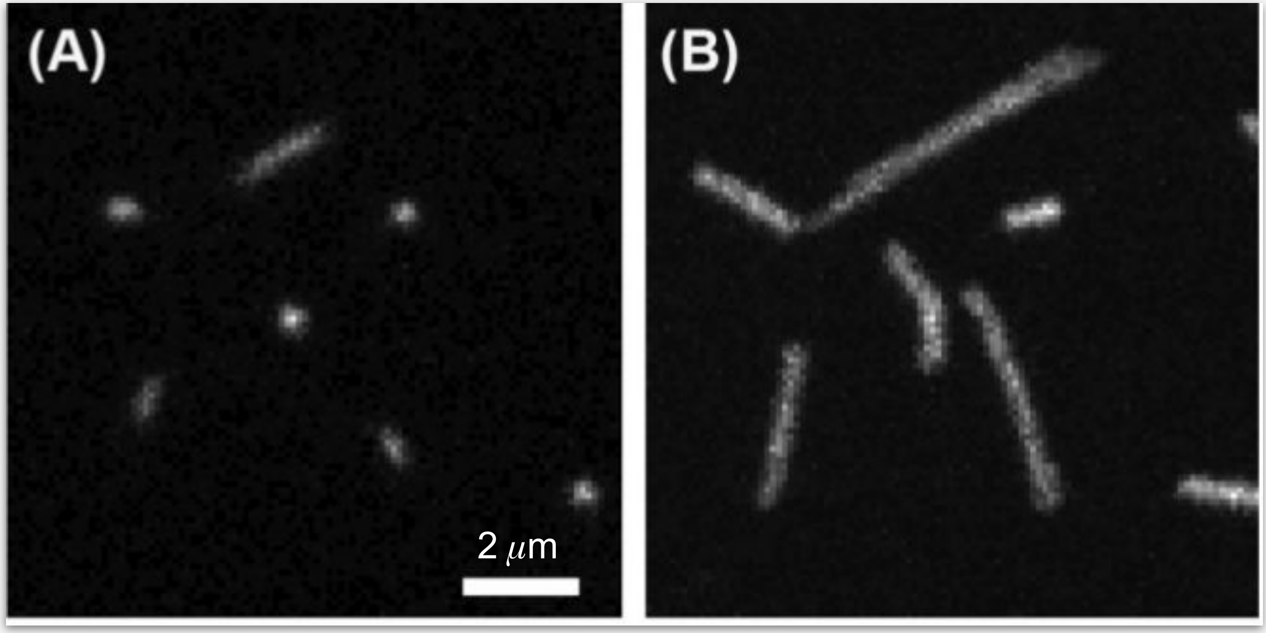
[Thomson, '16]

Read-out methods: Confocal Microscopy



α-tracks in Al_2O_3:C,Mg (without etching!)

Single picture | Longest projection of 3D

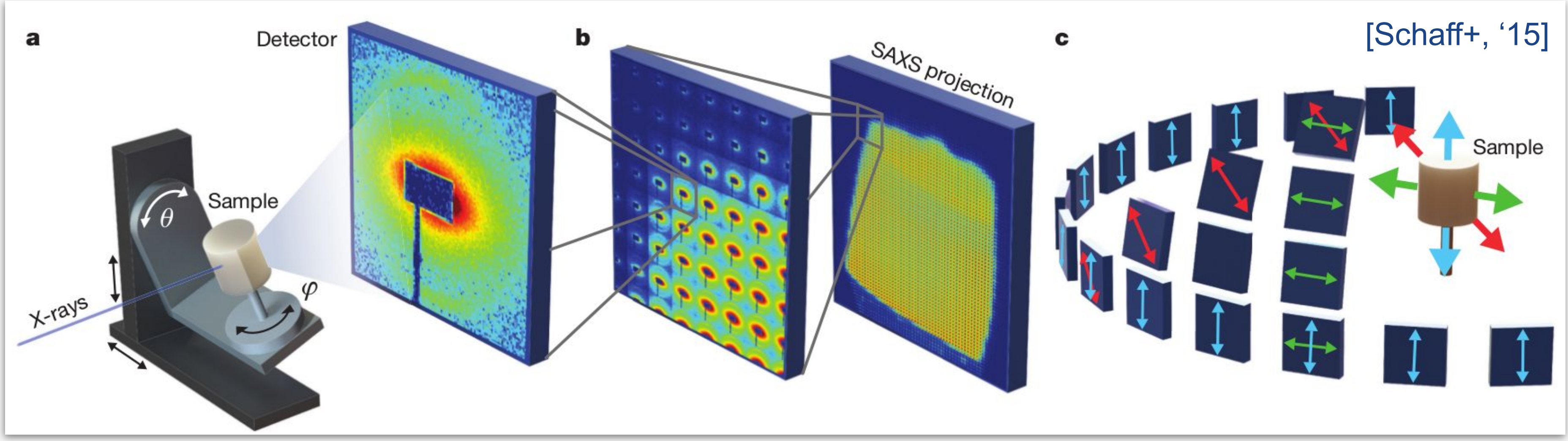


[Kouwenberg+, '18]

- Widely available
- Resolution ~100 nm
- Requires fluorescent targets

Read-out methods: X-ray tomography

= Small-Angle X-ray Scattering (SAXS) pytchography
+ computer tomography



Single "pixel" of sample

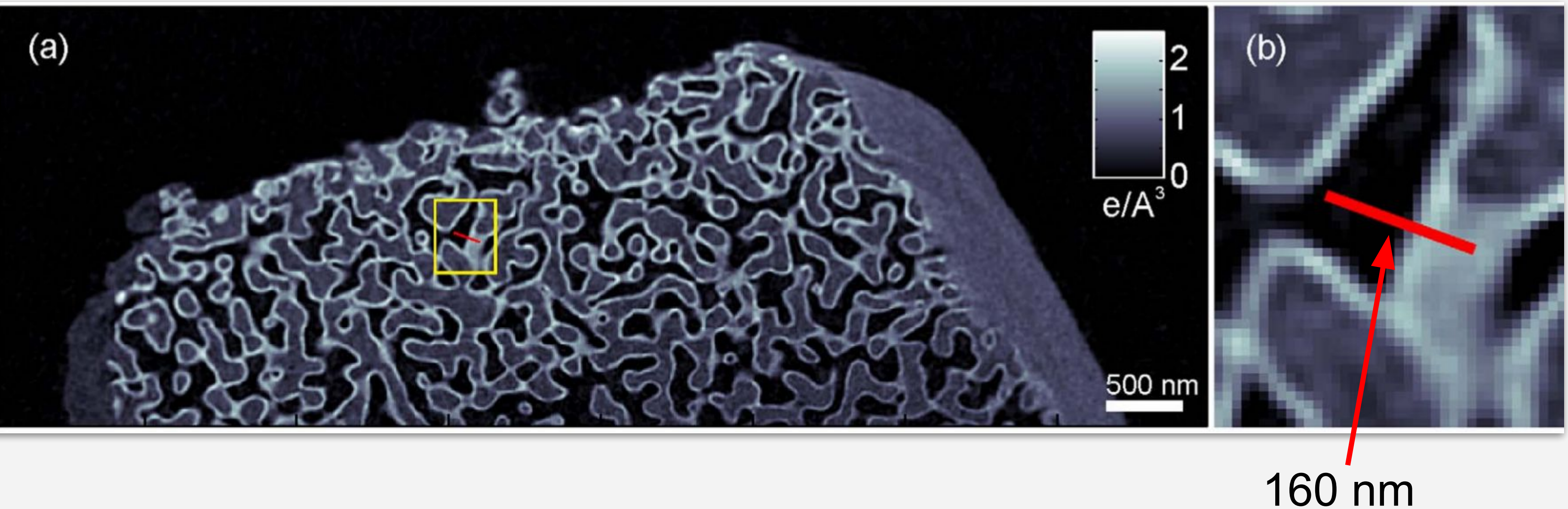
Combine "pixels" into 2D picture

Reconstruct 3D image from 2D pictures

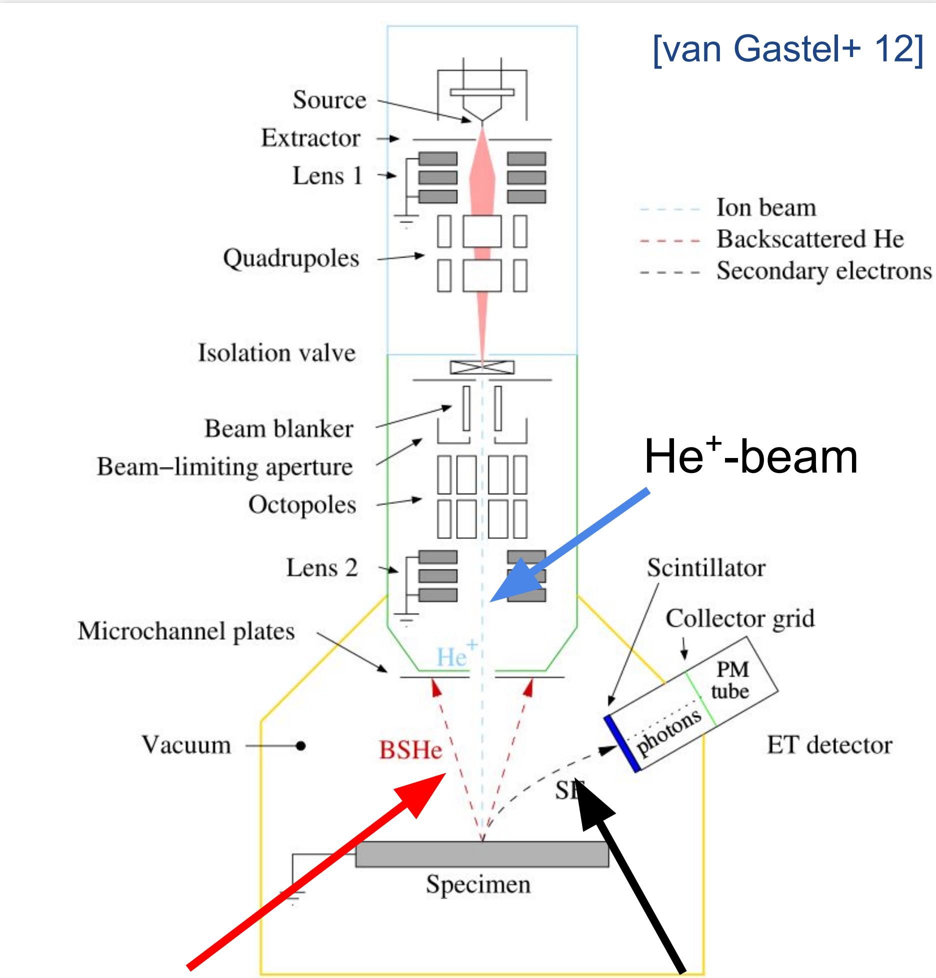
Read-out methods: X-ray tomography

- 16 nm isotropic 3D resolution demonstrated!
- Requires synchrotron light source

[Holler+, ‘14]



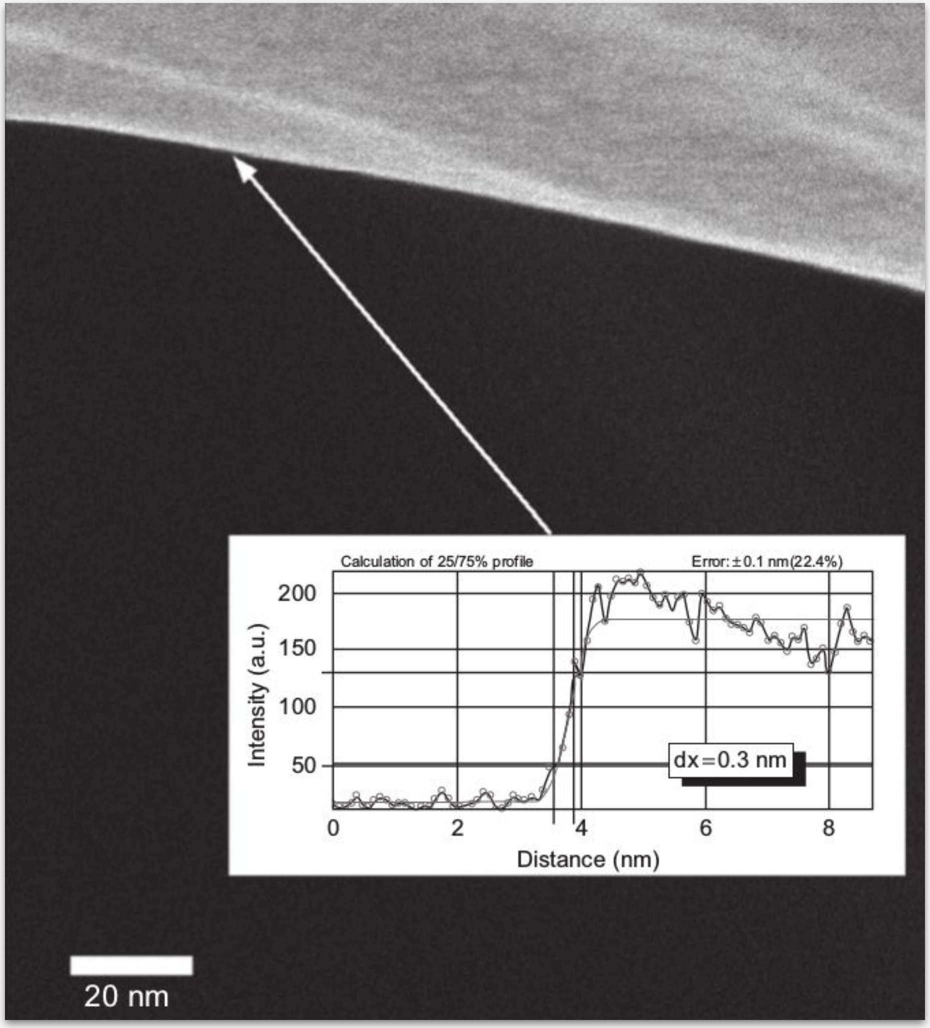
Read-out methods: He-Ion Beam Microscopy



Read-out methods: He-Ion Beam Microscopy

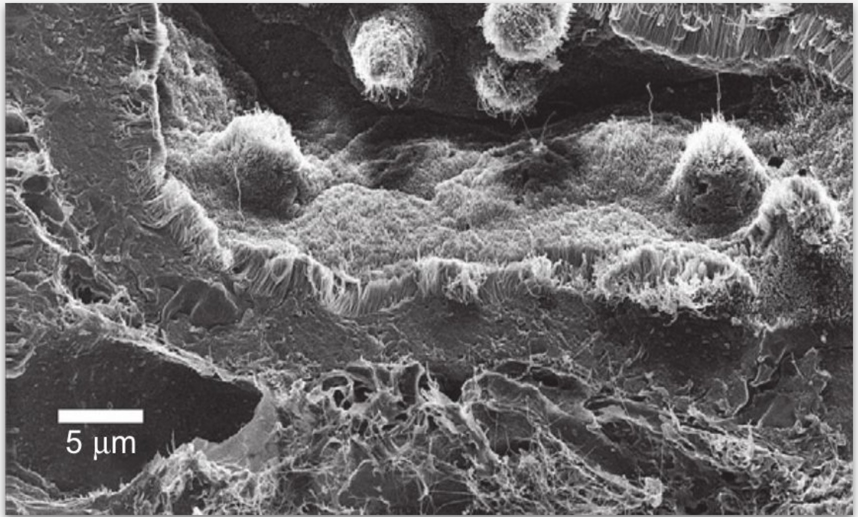
Edge of graphite flake

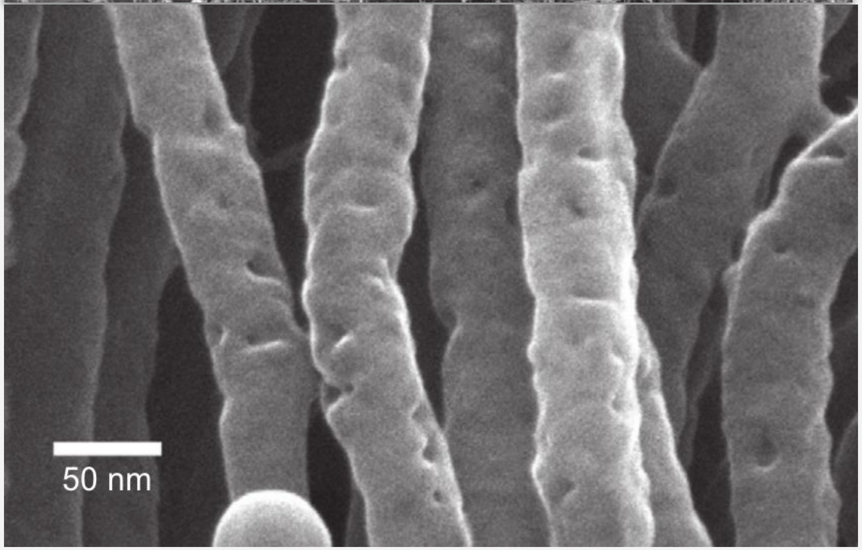
[Hill+ 12]



Overview & Zoom-in of rodent kidney

[Hill+ 12]



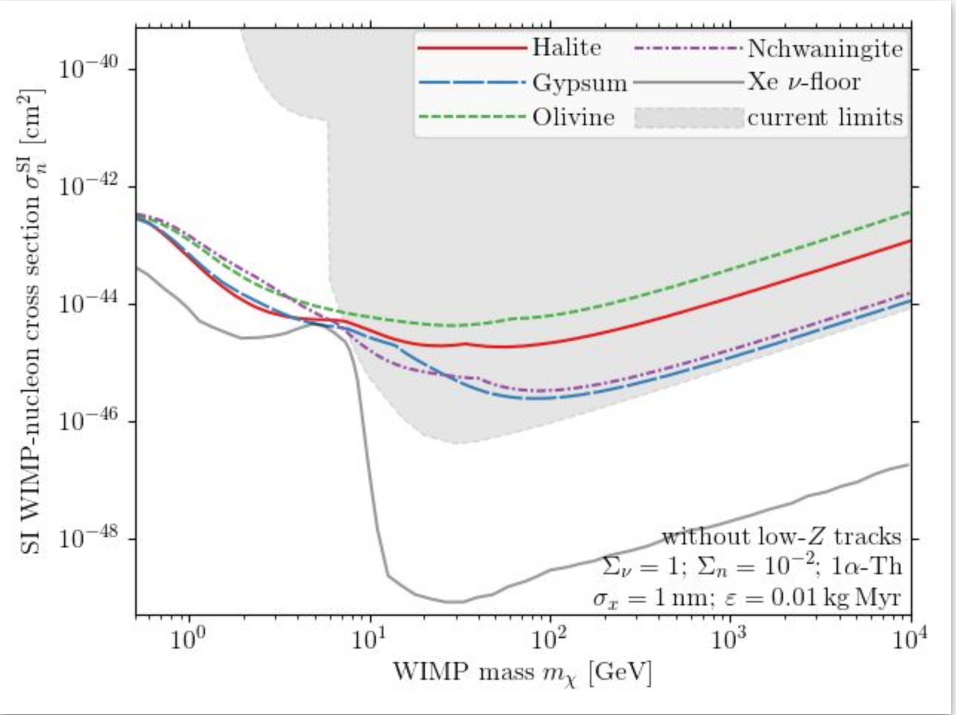


Dark Matter Sensitivity Projections

[Drukier, SB+ 1811.06844]

Good resolution, small target mass

- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)

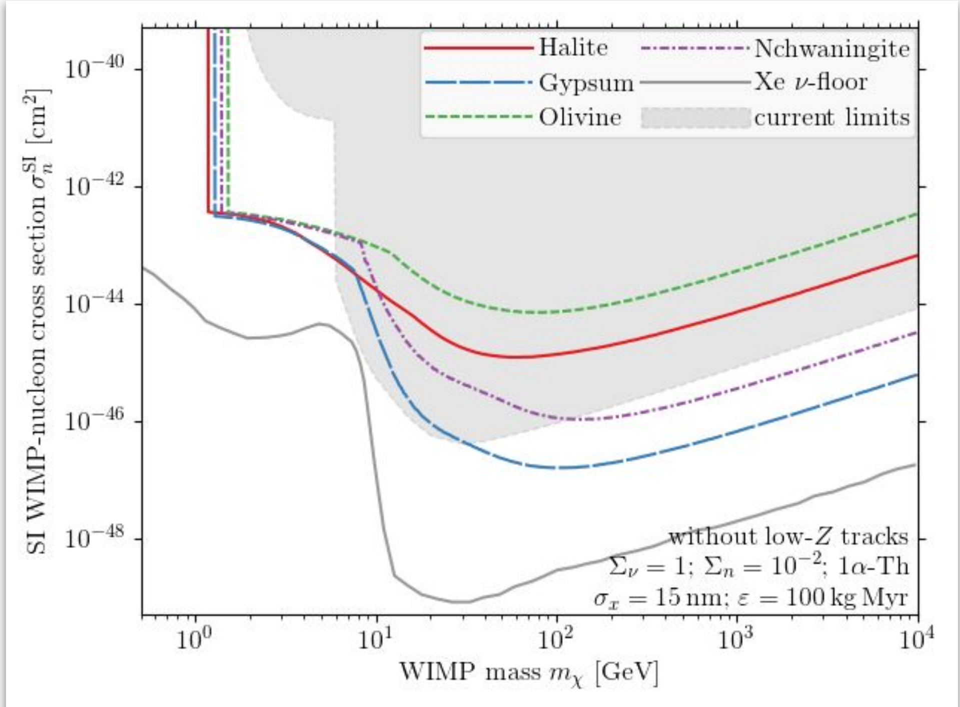


Halite: NaCl

Gypsum: $CaSO_4 \cdot 2(H_2O)$

Larger target mass, worse resolution

- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)



Olivine: $Mg_{1.6}Fe_{0.4}(SiO_4)$

Nchwaningite: $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

SD proton-only interactions

[Drukier, SB+ 1811.06844]

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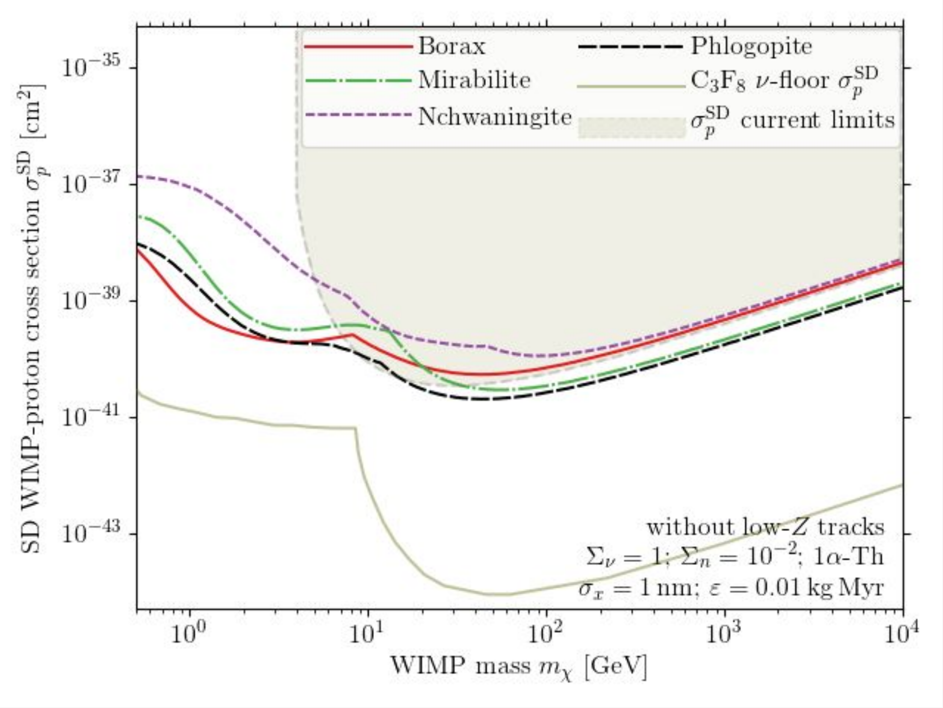
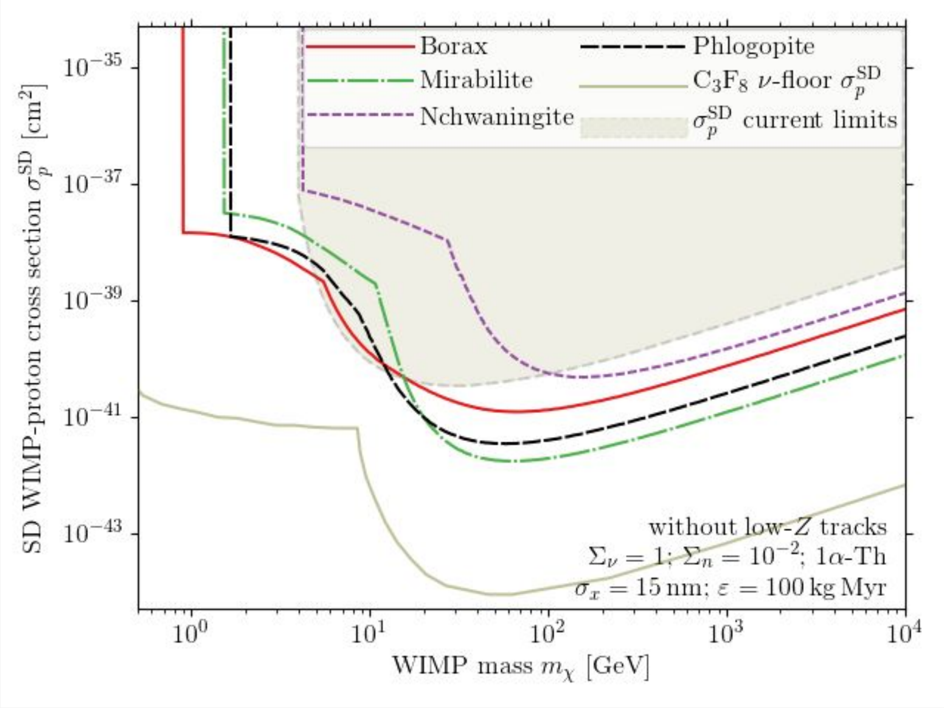


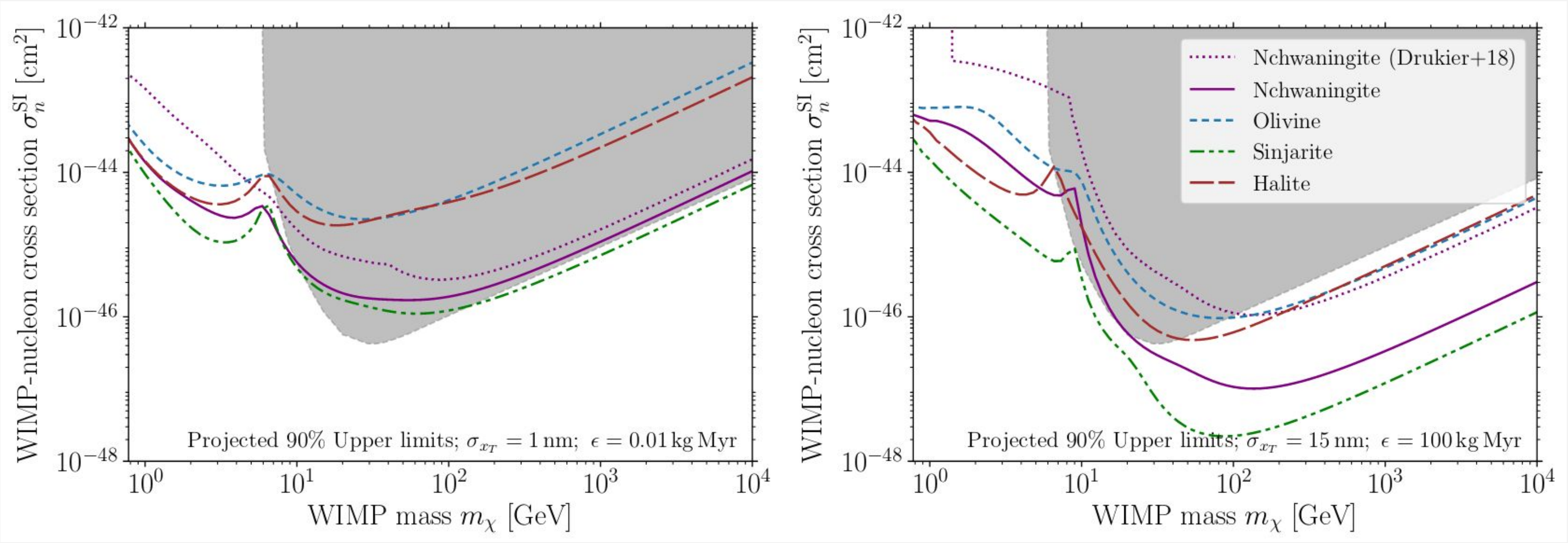


Borax: $\mathbf{Na_2}(\mathbf{B_4}O_5)(OH)_2 \bullet 8(H_2O)$
Mirabilite: $\mathbf{Na_2}SO_4 \bullet 10(H_2O)$

Nchwaningite: $\mathbf{Mn_2}SiO_3(OH)_2 \bullet (H_2O)$
Phlogopite: $\mathbf{K}Mg_3\mathbf{Al}Si_3O_{10}\mathbf{F}(OH)$

Improved sensitivity with spectral analysis

[Edwards, SB+ 1811.10549]

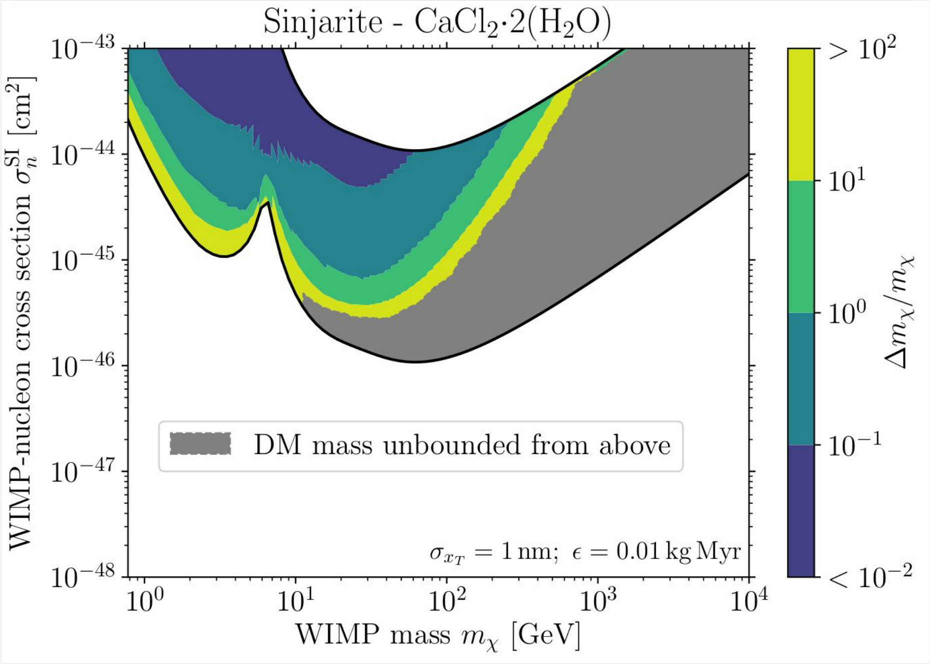


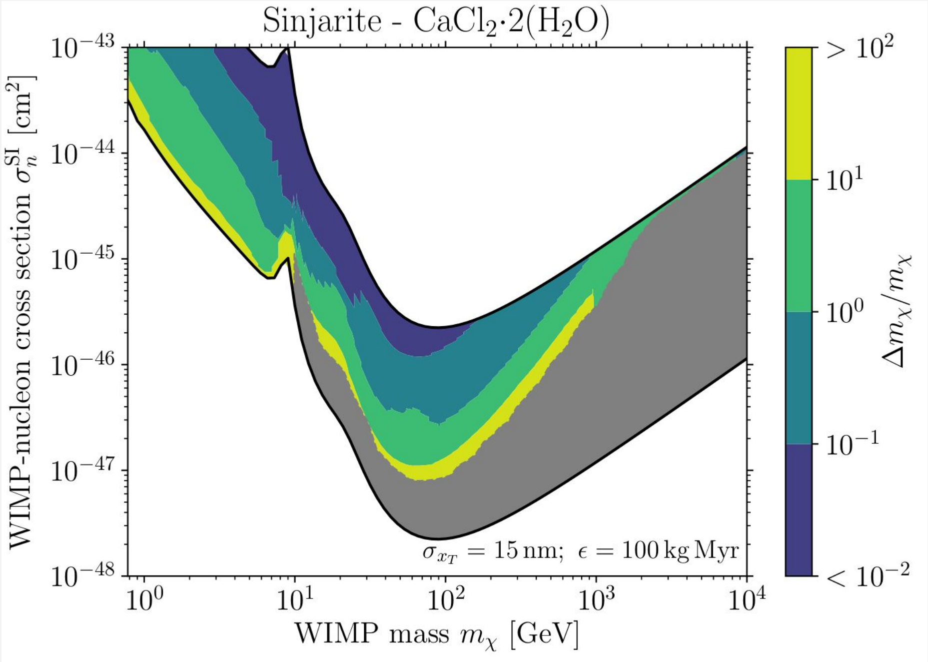
Halite: NaCl
Sinjarite: $CaCl_2 \cdot 2(H_2O)$

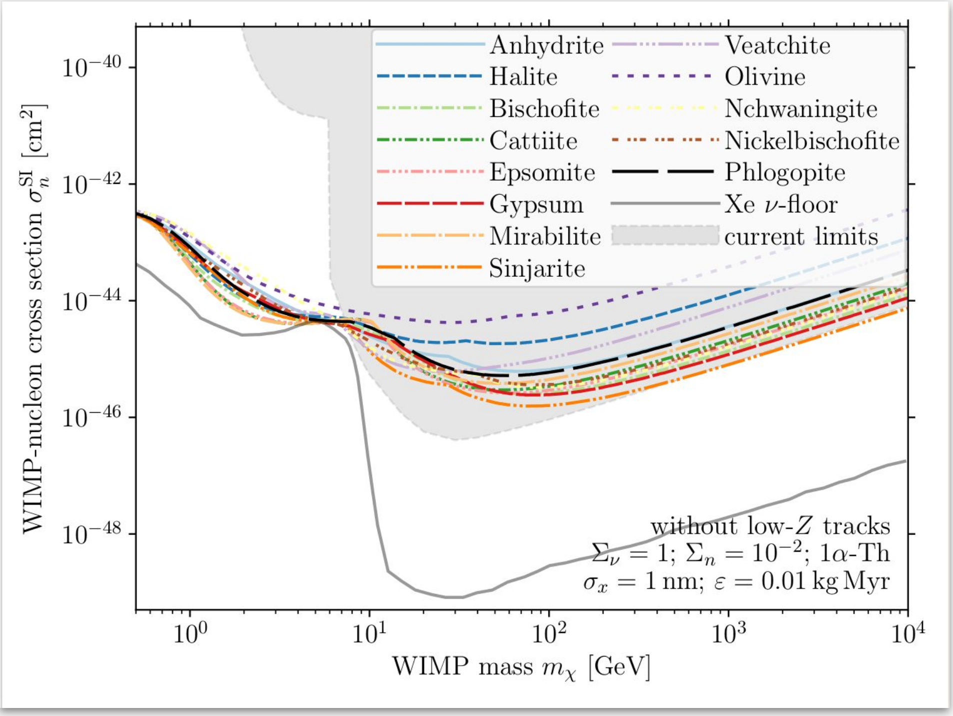
Olivine: $Mg_{1.6}Fe_{0.4}(SiO_4)$
Nchwaningite: $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

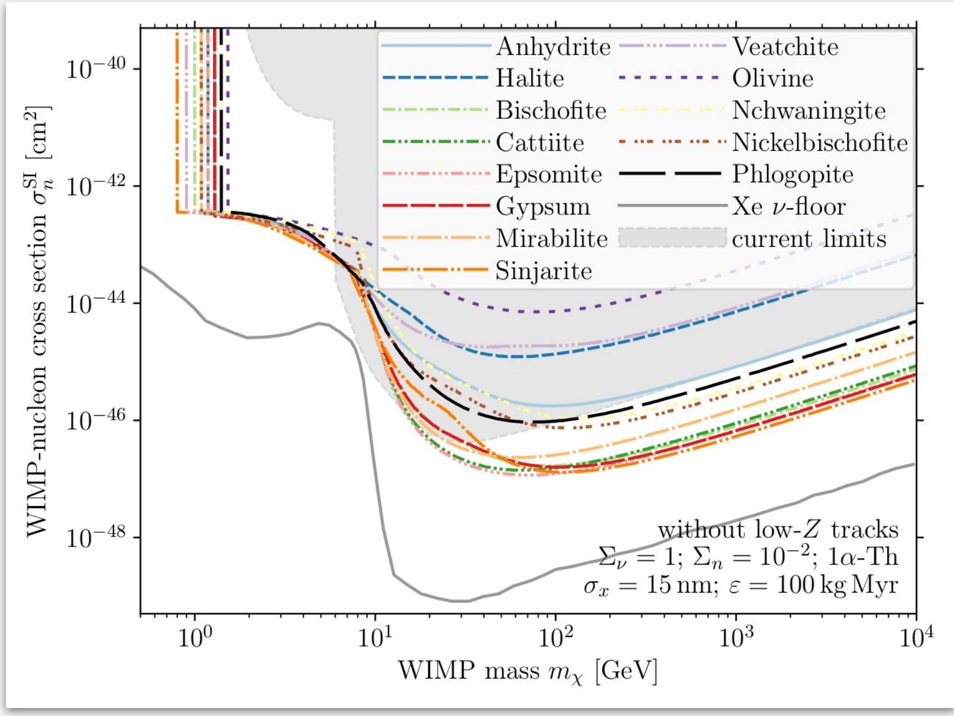
What could you do if you see something?

[Edwards, SB+ 1811.10549]






WIMP-nucleon cross section σ_n^{SI} [cm^2]
WIMP mass m_χ [GeV]
Anhydrite
Halite
Bischofite
Cattiite
Epsomite
Gypsum
Mirabilite
Sinjarite
Veatchite
Olivine
Nchwaningite
Nickelbischofite
Phlogopite
Xe ν-floor
current limits
without low-Z tracks
$\Sigma_\nu = 1$; $\Sigma_n = 10^{-2}$; 1α-Th
$\sigma_x = 1$ nm; $\varepsilon = 0.01$ kg Myr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$\Sigma_\nu = 1$; $\Sigma_n = 10^{-2}$; 1α-Th
$\sigma_x = 15$ nm; $\varepsilon = 100$ kg Myr

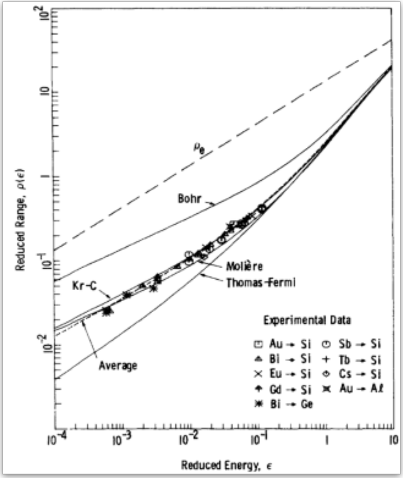
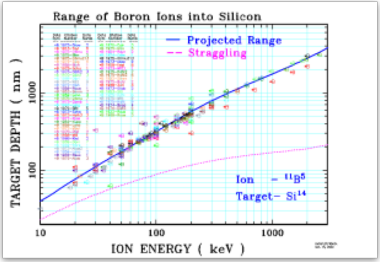
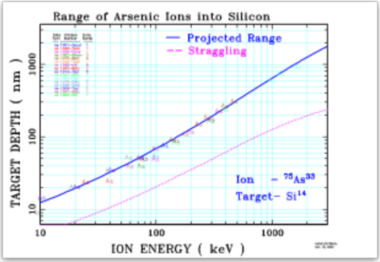


Figure: Wilson, Haggmark+ '76

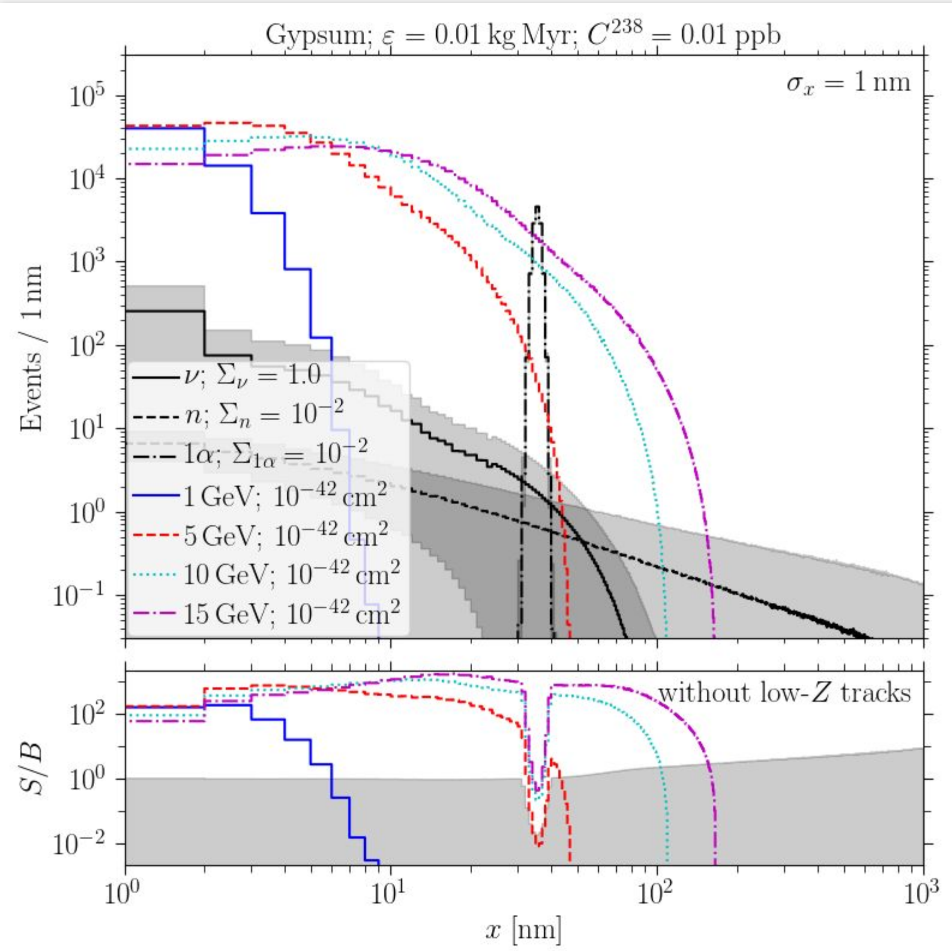


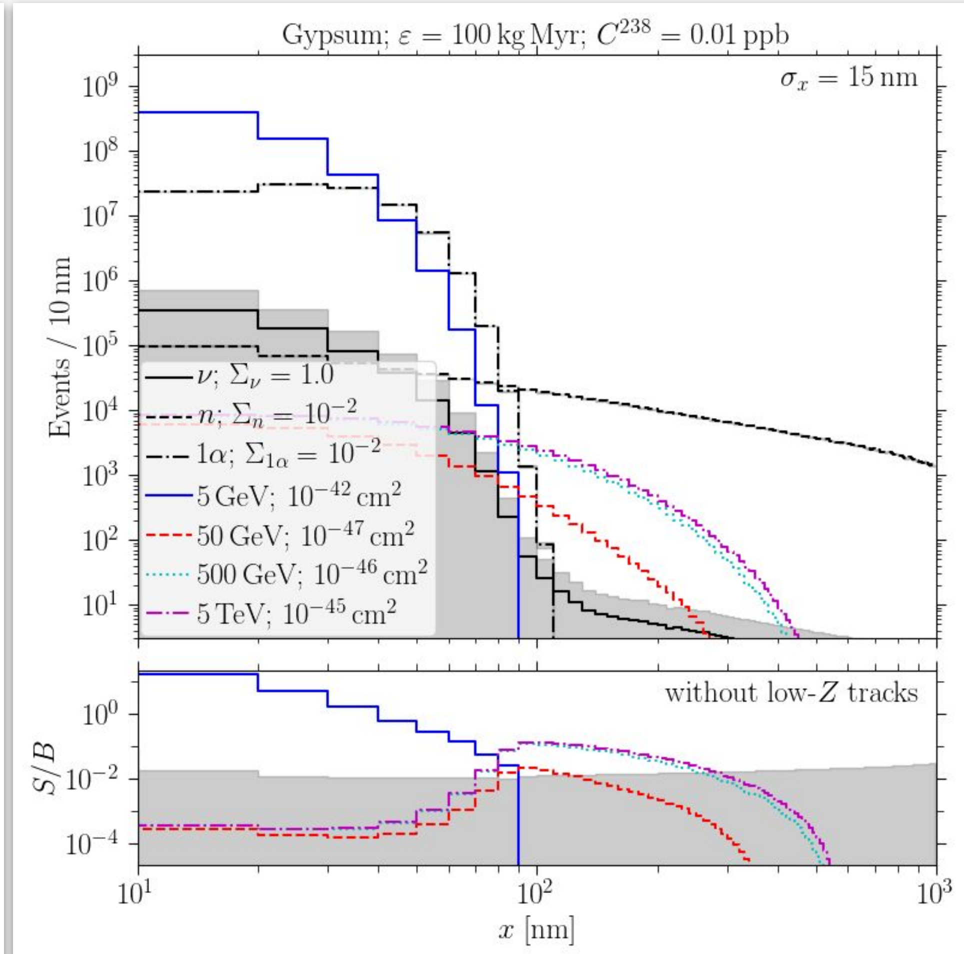


DM against the rest

High-Resolution read-out
- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)

Low-Resolution read-out
- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)



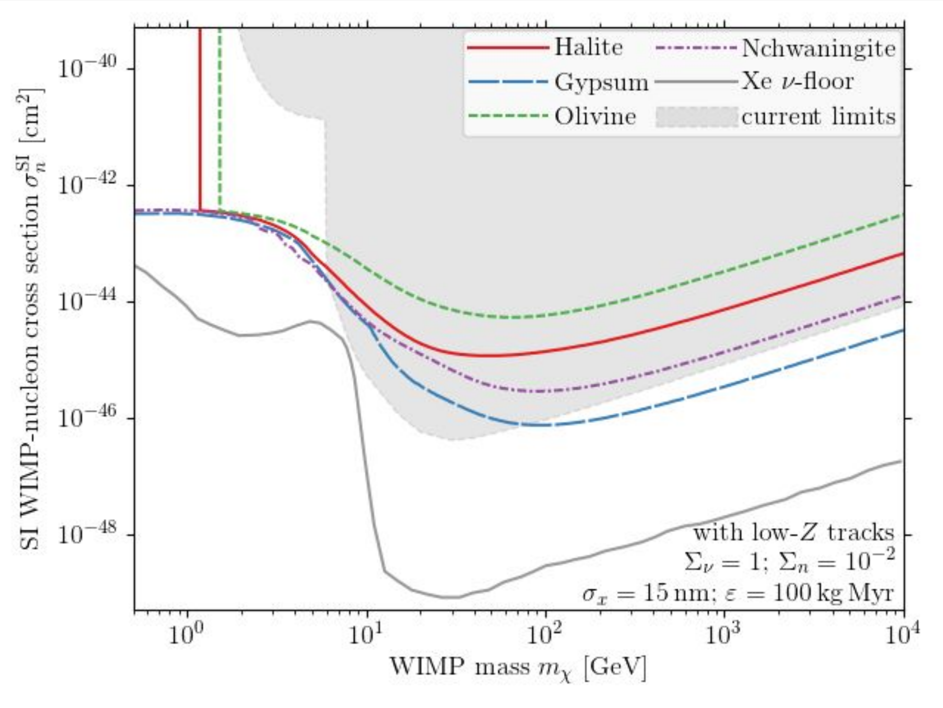


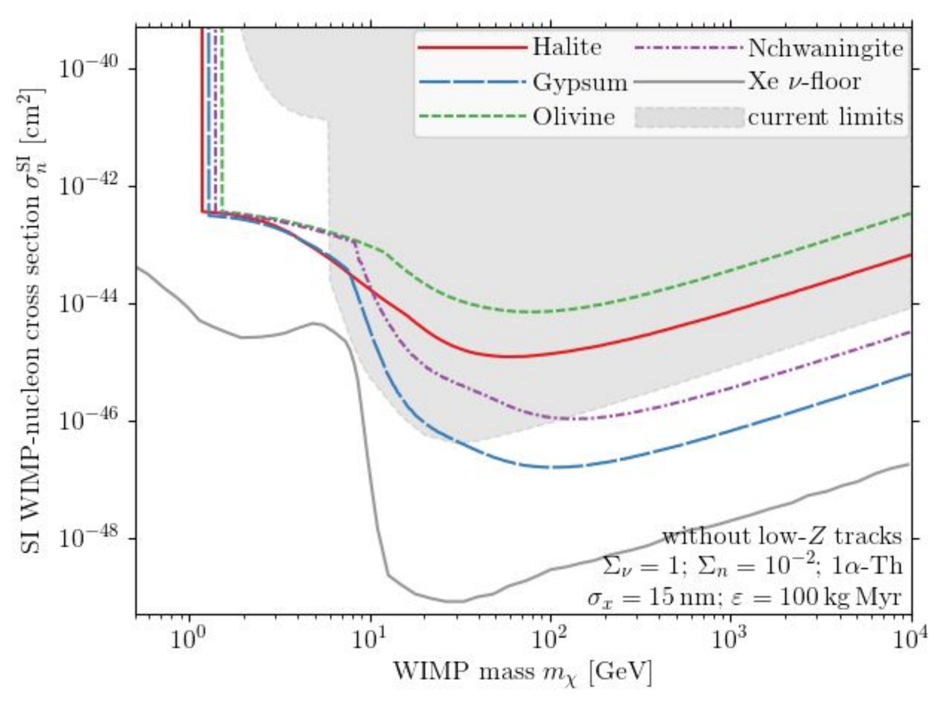
Sensitivity Projections

[Drukier, SB+ 1811.06844]

with low-Z tracks

without low-Z tracks

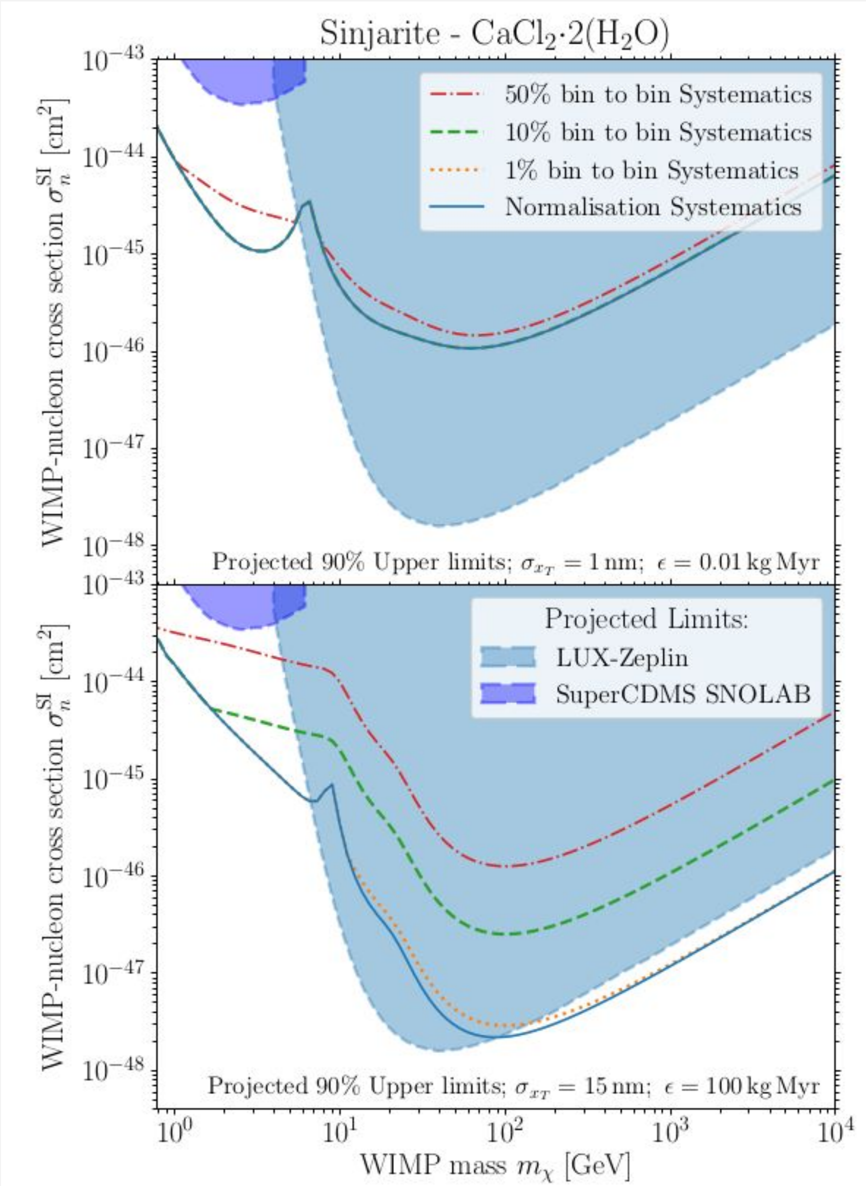




Halite: $NaCl$
Gypsum: $CaSO_4 \cdot 2(H_2O)$

Olivine: $Mg_{1.6}Fe_{0.4}(SiO_4)$
Nchwaningite: $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

Robustness against errors in background spectra



Optimistic systematics assumtions

- 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

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Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*