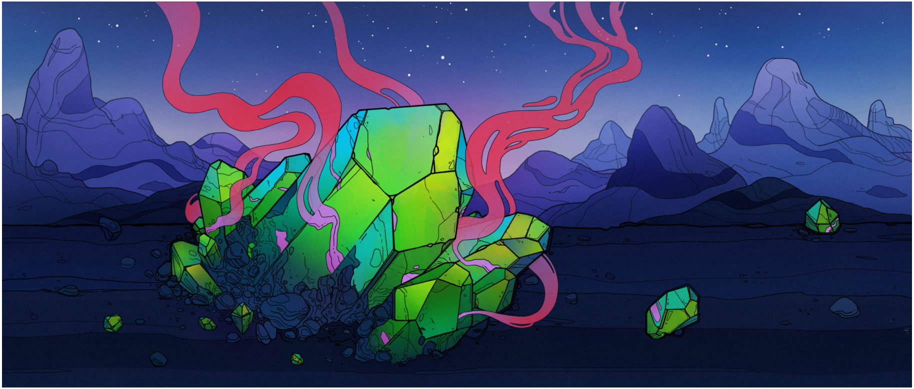
Mineral Detectors for Dark Matter

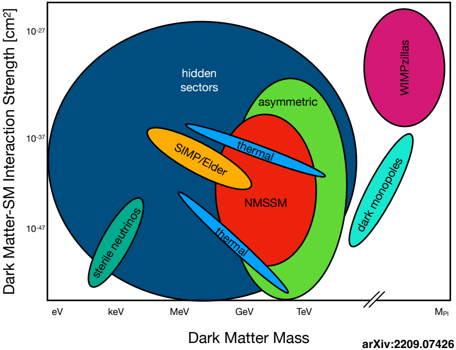


Minerals such as olivine could hold evidence of long-ago collisions between atomic nuclei and dark matter (Olena Shmahalo/Quanta Magazine).

What do we (not) know about Dark Matter?

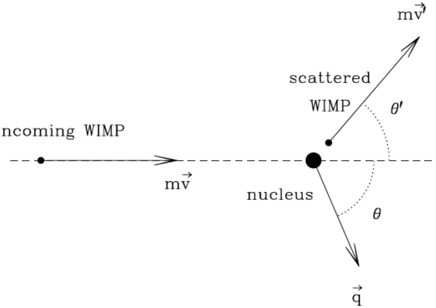
What we (typically) assume

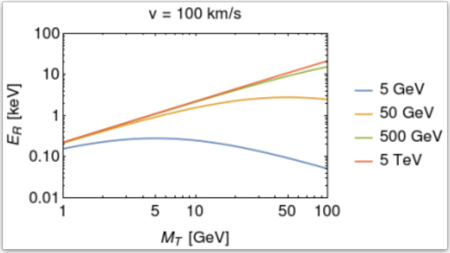
- No E&M interactions
- Must be cold and stable
- Not in the Standard Model



arXiv:2209.07426

Nuclear recoils induced by elastic WIMP-nucleus scattering





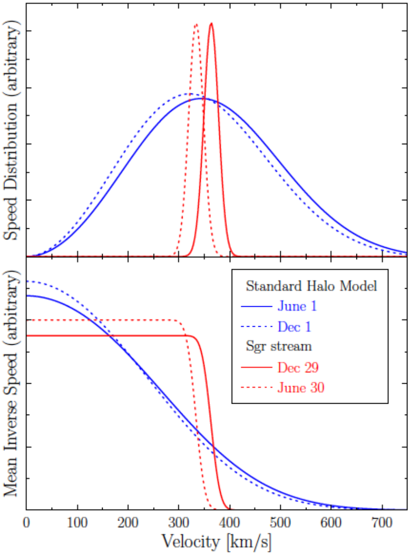
Scattering kinematics ⇒ event rate

- 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

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

WIMP velocity distribution and induced recoil spectra



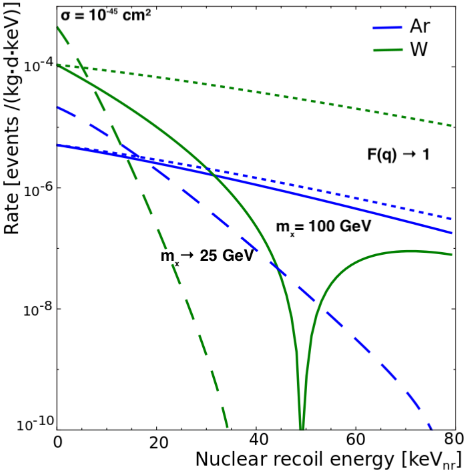
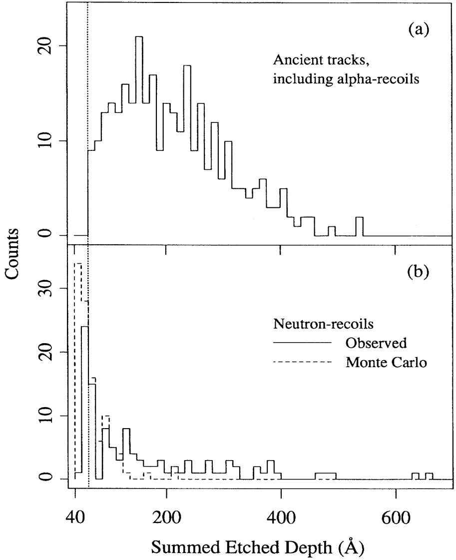


Figure: (left) 1209.3339 (right) 1509.08767

Mineral detectors used to constrain WIMPs before



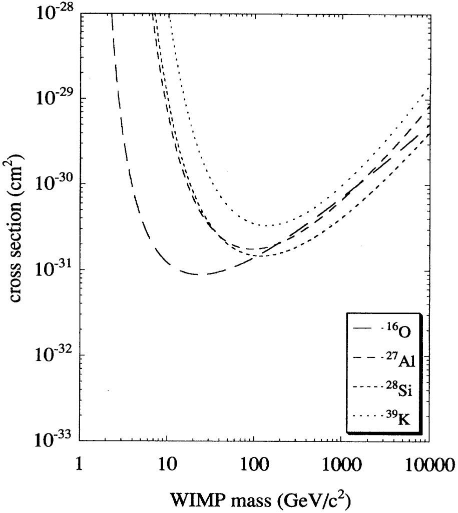
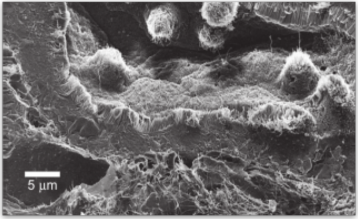


Figure: Snowden-Ifft et al. (1995)

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



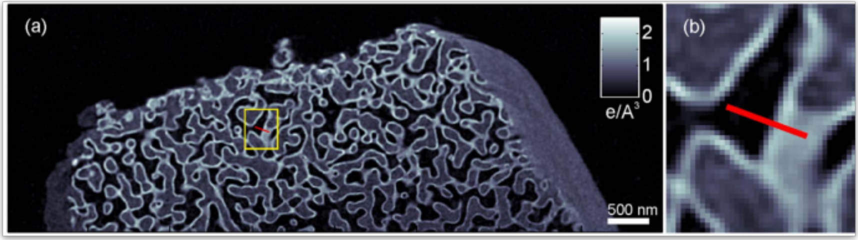
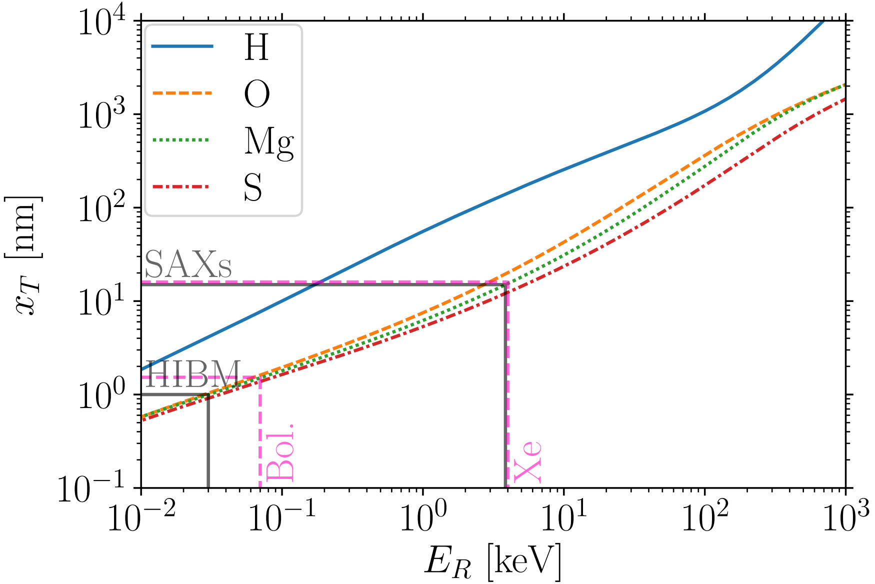


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Integrate stopping power to estimate track length



Cosmogenic backgrounds suppressed in deep boreholes

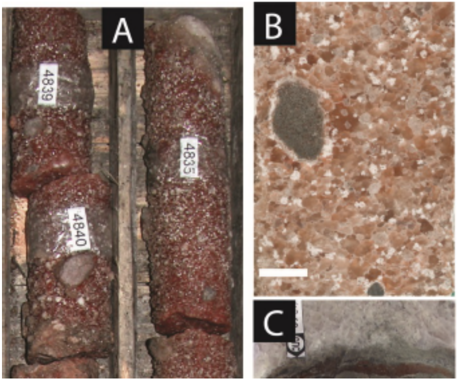


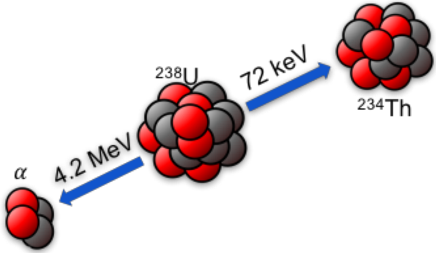
Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

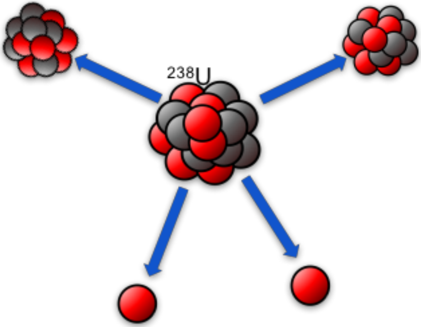
Depth	Neutron Flux
2 km	$10^6/\text{cm}^2/\text{Gyr}$
5 km	$10^2/\text{cm}^2/\text{Gyr}$
6 km	$10/\text{cm}^2/\text{Gyr}$
50 m	$70/\text{cm}^2/\text{yr}$
100 m	$30/\text{cm}^2/\text{yr}$
500 m	$2/\text{cm}^2/\text{yr}$

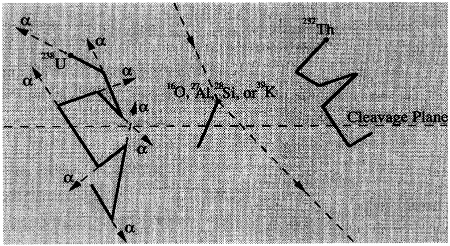
Need minerals with low ^{238}U

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

Find α-recoils and model radiogenic neutron background



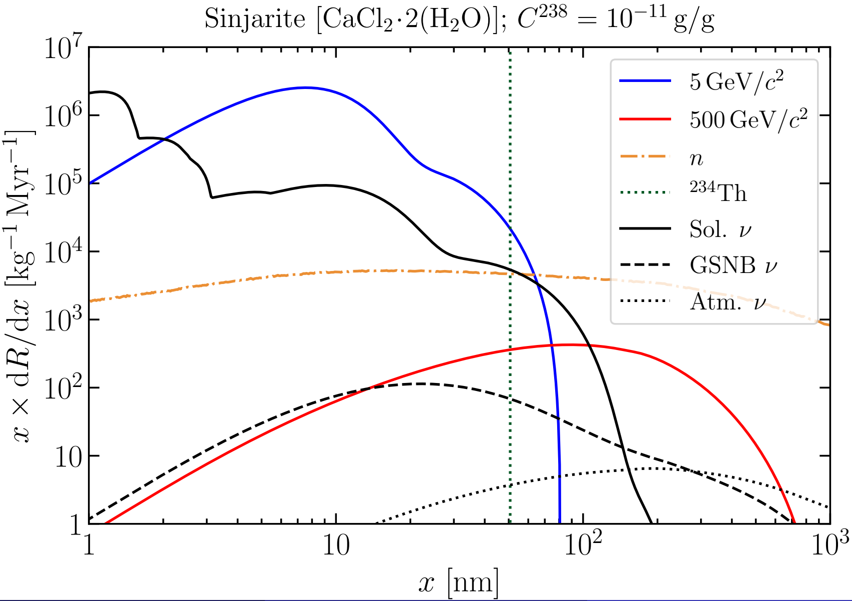




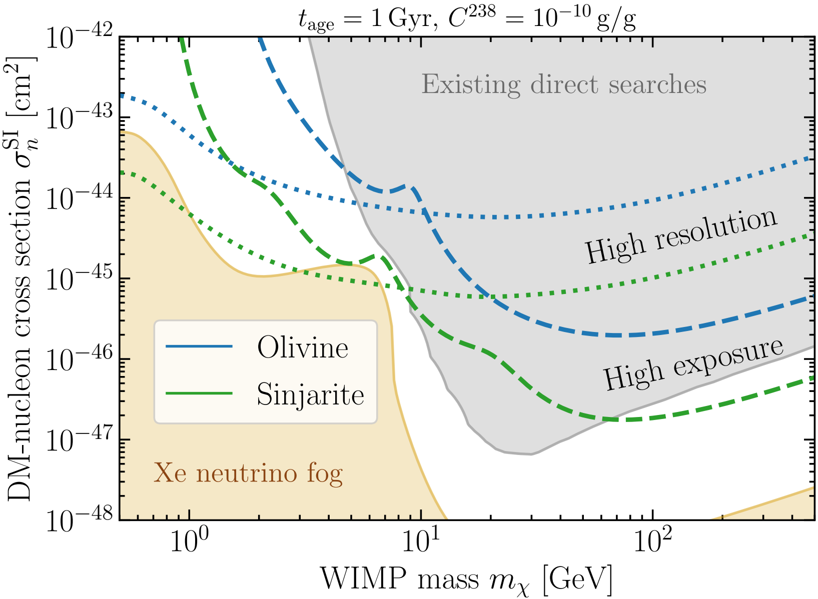
SF yields several ∼ MeV neutrons

Each neutron will scatter elastically 10-1000 times before moderating

Use track length spectra to pick out WIMP signal



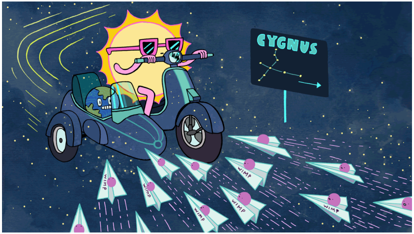
Trade-off between read-out resolution and exposure

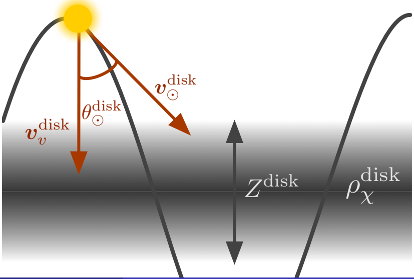


Mineral detectors could probe the nature of Dark Matter

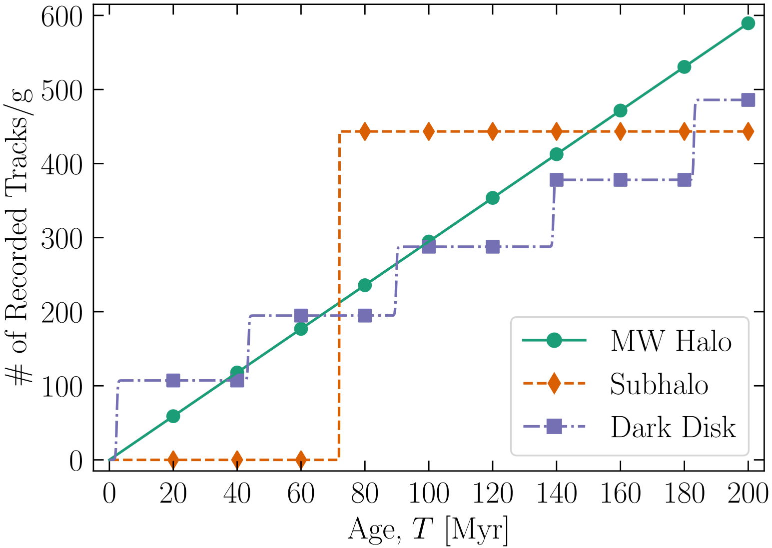
Conventional and novel signatures

- Competitive for heavier WIMPs
- Go to ν floor at smaller m_X
- Composite DM $\Rightarrow$ macro tracks
- Directional WIMP signals today
- Time-varying signals over Gyr

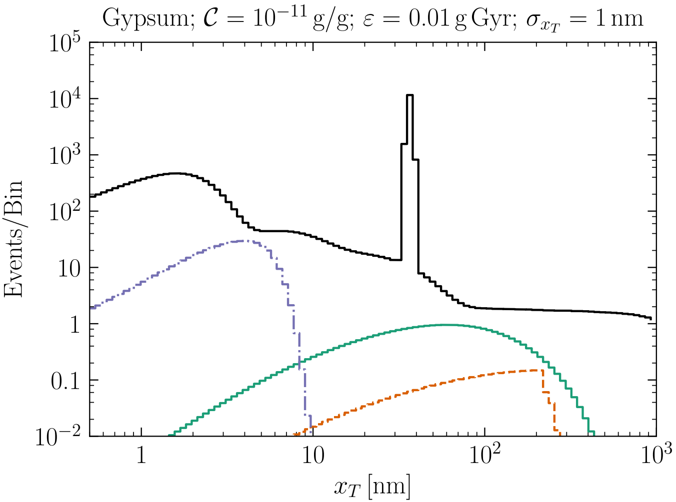




Mineral detectors can look for signals “averaged” over geological timescales or for time-varying signals

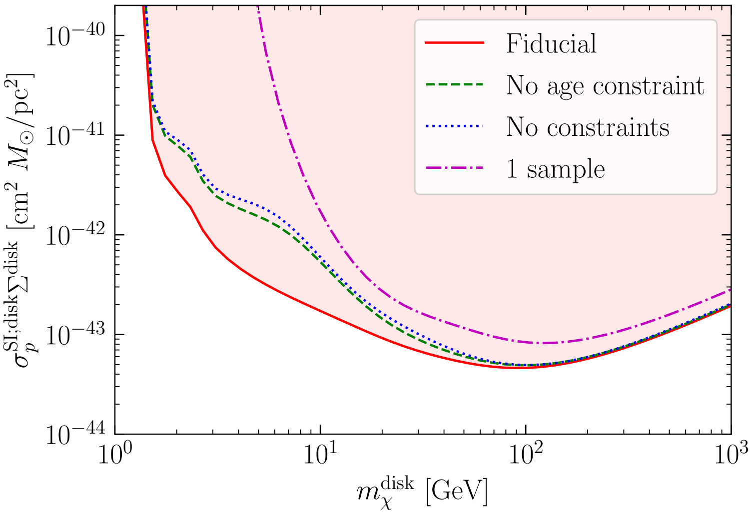


Multiple samples to detect dark disk transit every $\sim 45\,\mathrm{Myr}$



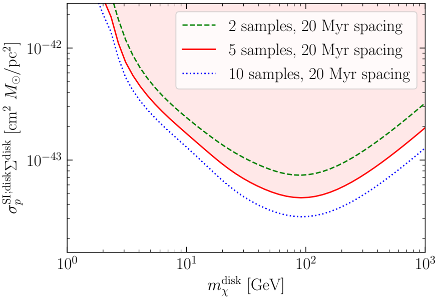
$m_X^{\rm disk} = 100\,\mathrm{GeV}$ $\sigma_{Xp}^{\rm disk} = 10^{-43}\,\mathrm{cm}^2$ $m_X = 500\,\mathrm{GeV}$ $\sigma_{Xp} = 5 \times 10^{-46}\,\mathrm{cm}^2$

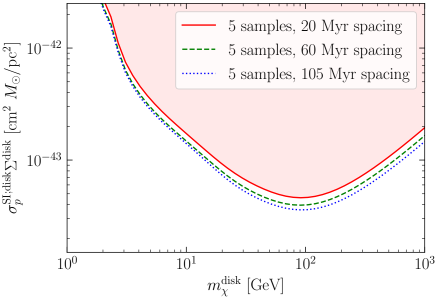
Distinguish from halo with 20, 40, 60, 80, 100 Myr samples



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

Change number of samples and sample spacing in time





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

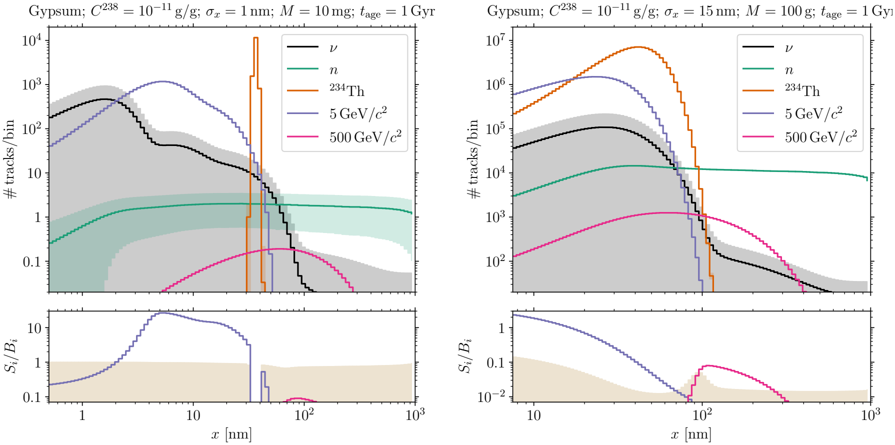
$$F(q) \simeq \frac{9\left[\sin(qR) - qR\cos(qR)\right]^2}{(qR)^6}$$

Differential scattering rate

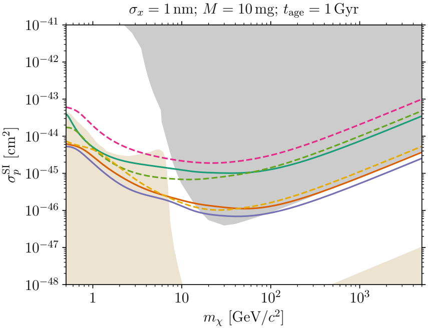
- Rate per unit time per unit detector mass for all nuclei
- Convolute cross section with astrophysical WIMP flux

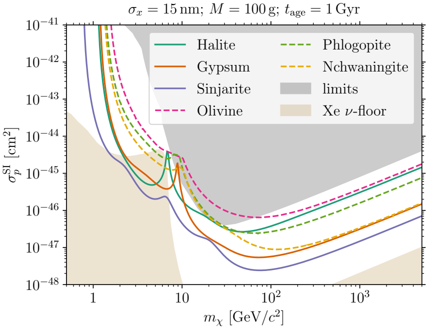
$$\sigma_0^{SI} = \frac{4}{\pi}\mu_{XT}^2\left[Z f_s^p + (A-Z) f_s^n\right]^2$$

Track length spectra after smearing by readout resolution



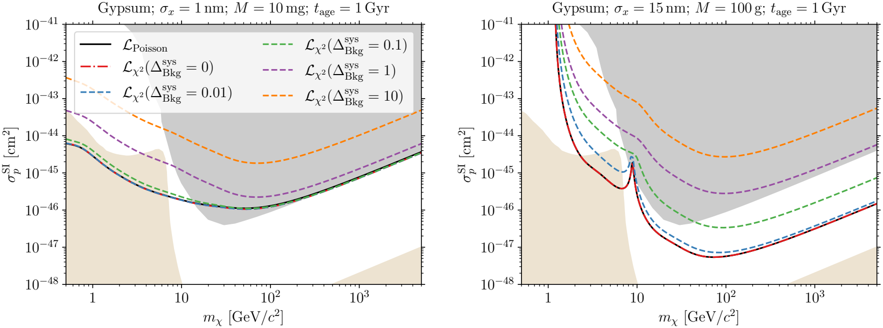
Sensitivity for different targets



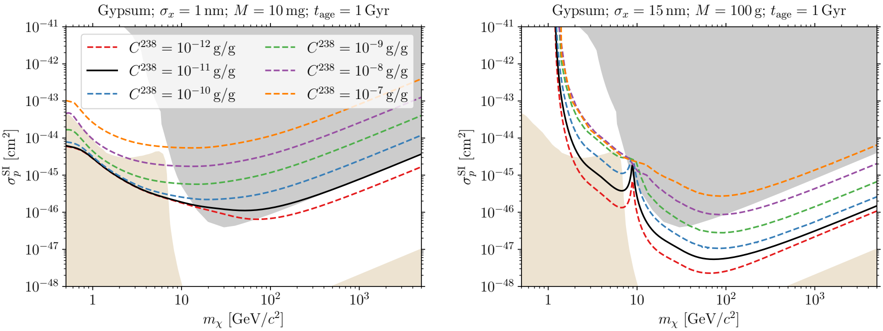


Halite	NaCl	$C^{238} = 10^{-11}$ g/g
Gypsum	$Ca(SO_4)\cdot 2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Sinjarite	$CaCl_2\cdot 2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Olivine	$Mg_{1.6}Fe^{2+}_{0.4}(SiO_4)$	$C^{238} = 10^{-10}$ g/g
Phlogopite	$KMg_3AlSi_3O_{10}F(OH)$	$C^{238} = 10^{-10}$ g/g
Nchwaningite	$Mn^{2+}_2SiO_3(OH)_2\cdot(H_2O)$	$C^{238} = 10^{-10}$ g/g

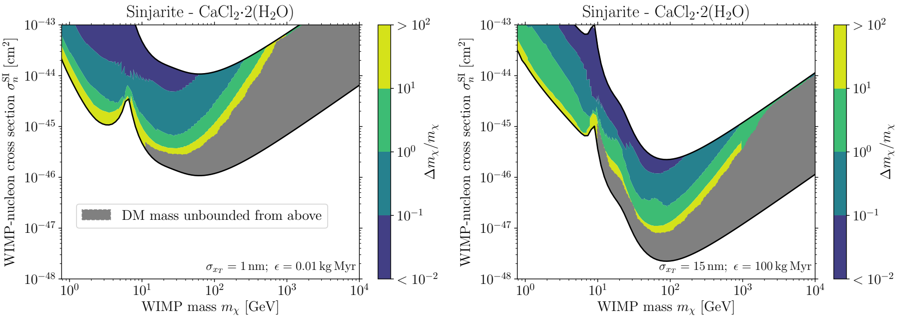
Effects of background shape systematics



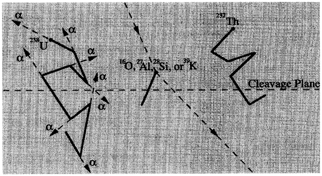
Sensitivity for different ^{238}U concentrations



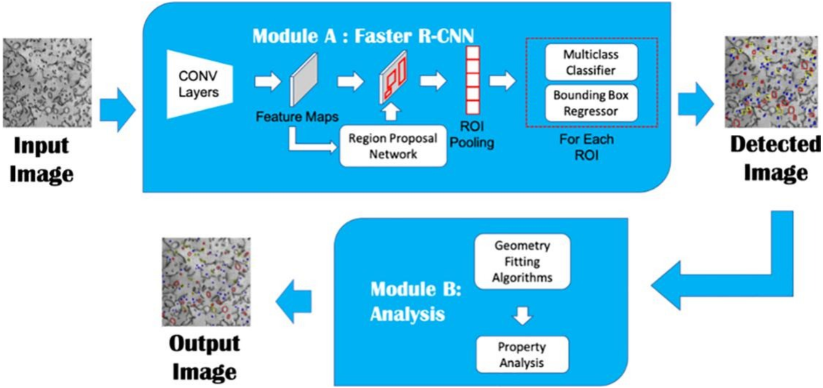
Multiple nuclei and large ϵ allow for optimal $\Delta m_X / m_X$



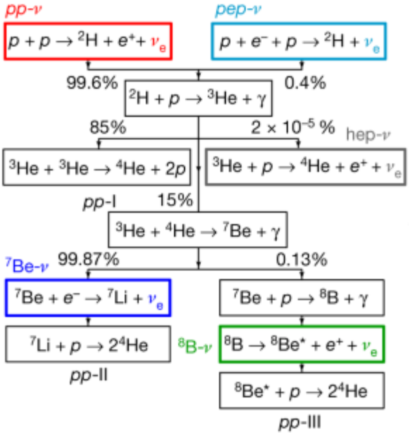
Quick aside on data analysis and α-recoil background

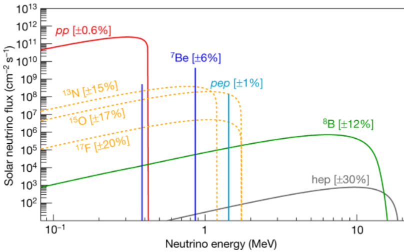


- 15 nm resolution of 100 g sample $\Rightarrow 10^{19}$ mostly empty voxels
- 1 Gyr old with $C^{238} = 0.01$ ppb $\Rightarrow 10^{13}$ voxels for α-recoil tracks



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





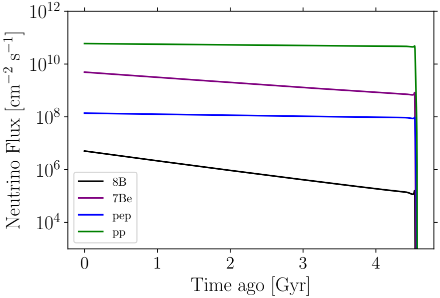


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Galactic contribution to ν flux over geological timescales

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

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

- Measure galactic CC SN rate
- Traces star formation history

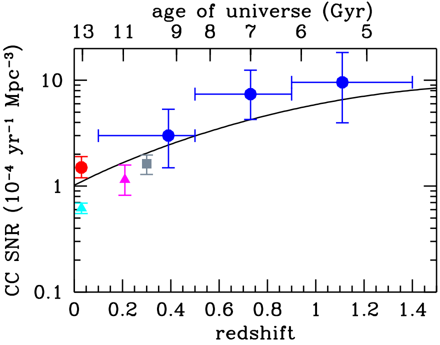


Figure: Cosmic CC SNR, 1403.0007