Mineral detectors on the moon

based on “The Final Frontier for Proton Decay” arXiv:2405.15845
with Sebastian Baum, Cassandra Little, Paola Sala and Joshua Spitz

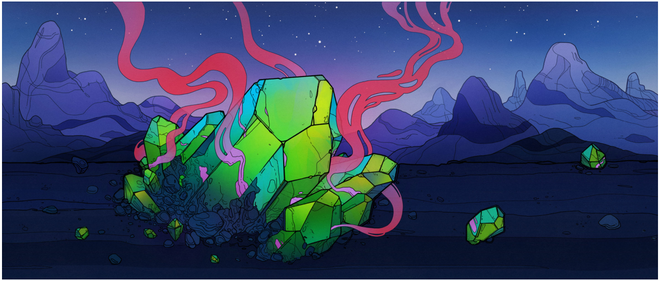

Figure: Olena Shmahalo/Quanta Magazine

Jožef Stefan Institute
Ljubljana, Slovenia

SMASH
machine learning for science and humanities postdoctoral program

I FEEL SLOVENIA

Co-funded by the European Union

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Damage features from recoils in ancient minerals

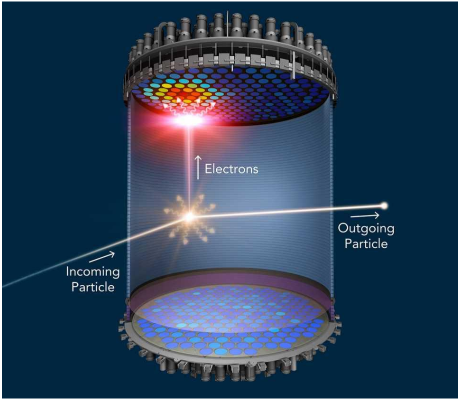


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

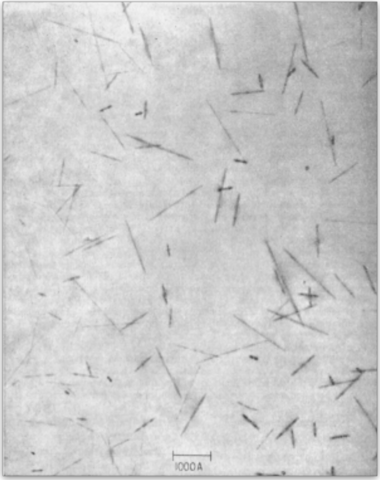


Figure: Price+Walker (1963)

Grand Unified Theories (GUTs)

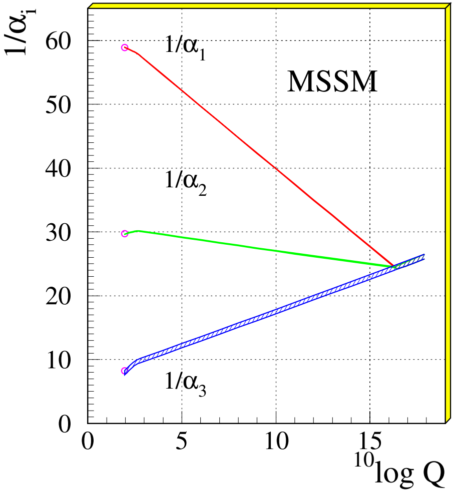


Figure: arXiv:hep-ph/0012288

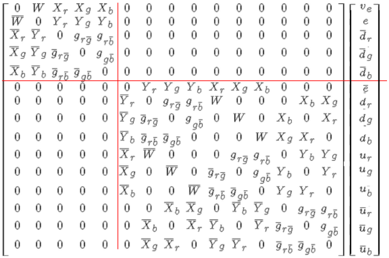


Figure: Paul Bird (2011)

Relevant characteristics of GUTs

- Gauge coupling unification
- SM quarks and leptons in the same **gauge multiplets**

GUTs generically predict proton decay

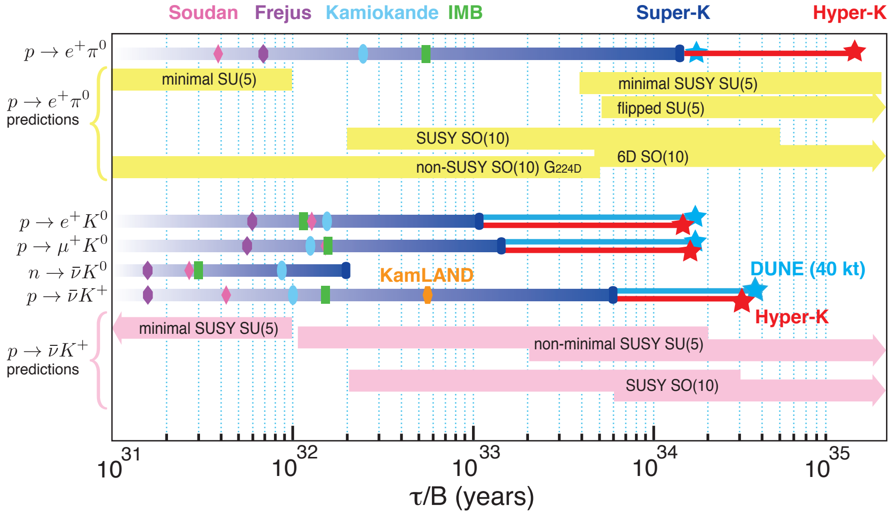
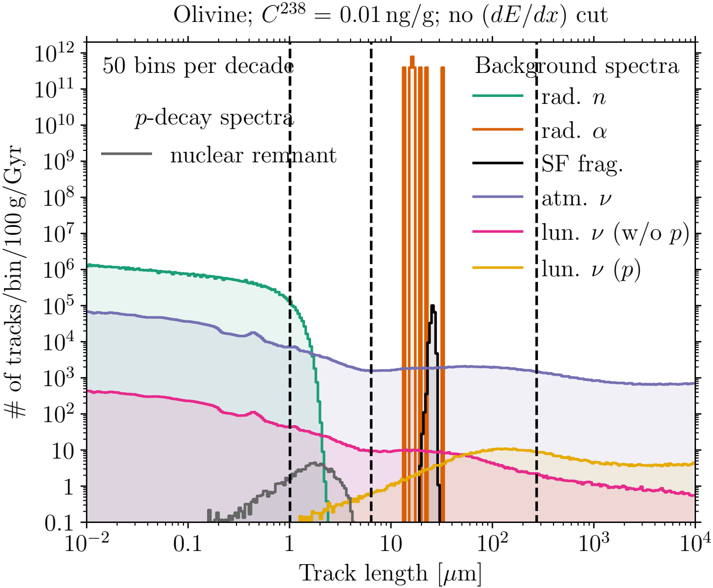
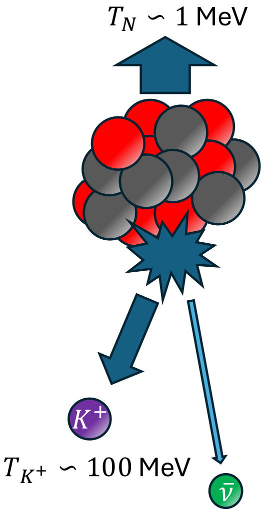


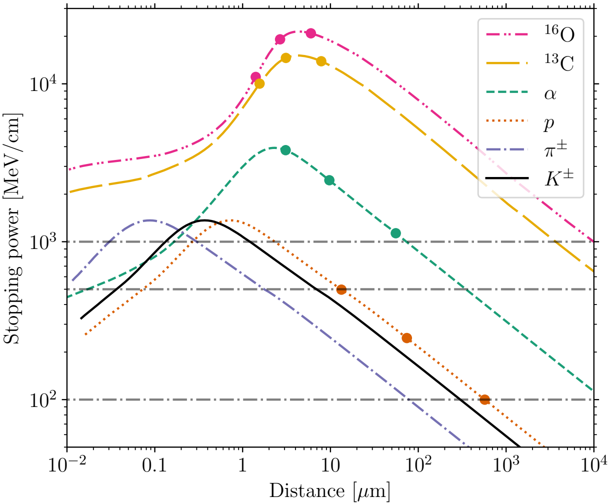
Figure: arXiv:1805.04163

Paleo-detector signatures are needles in a haystack

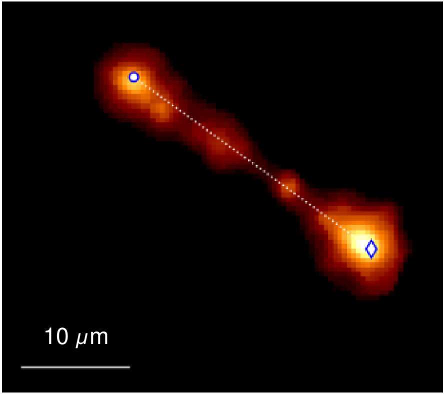


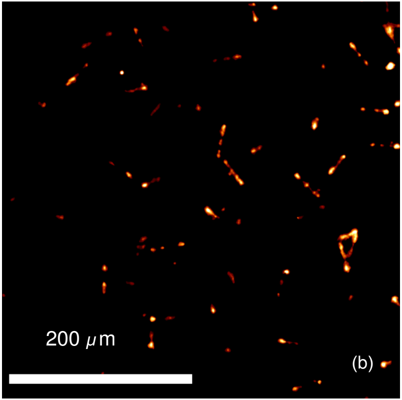
Large exposure from small target $\Rightarrow$ $\mathrm{kg\,Gyr} = 1\,\mathrm{Mton\,yr}$





Proton decay remnants could be detected by color centers





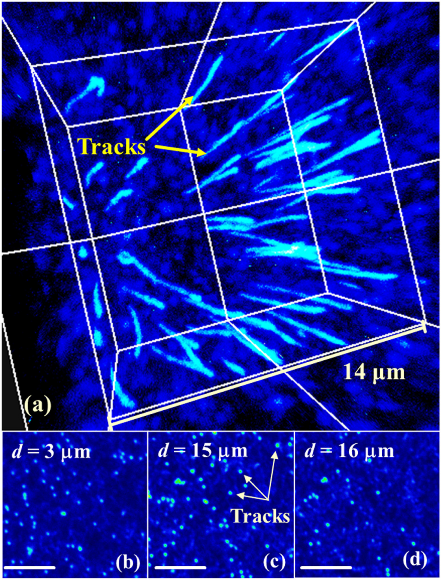
$^{6}\mathrm{Li} + n \to \alpha(2.1\mathrm{MeV}) + \mathrm{T}(2.7\mathrm{MeV})$

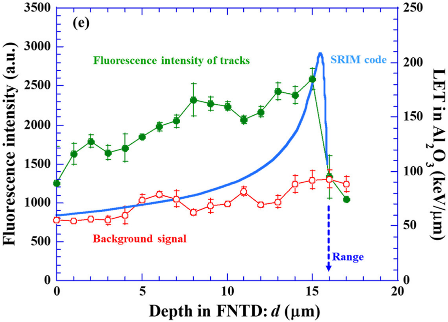
- Ranges of $\alpha \sim 6\mu$m, $\mathrm{T} \sim 33\mu$m
- Sparse CCs along track $\sim 4\mu\mathrm{m}^{-1}$
- Bragg peaks brighter at the ends

PALEOCCENE arXiv:2503.20732

- 3D imaging of CCs in bulk
- **Low ionizing CC tracks**
- Could scan $\sim$cm^3 in hours

Fluorescent nuclear track detectors for K^+ endpoints

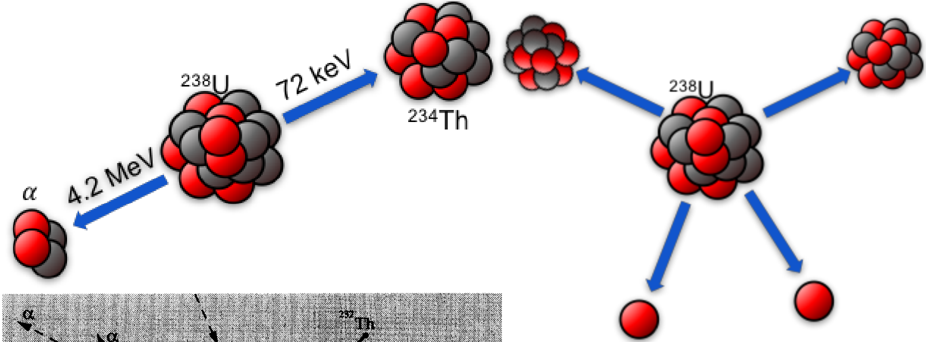


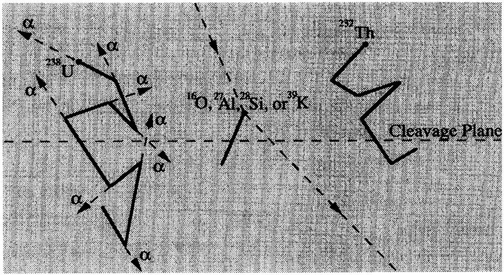


Figures from Kusumoto et al. (2022) show proton tracks in doped sapphire

- Theory of track formation?
- Are tracks robust to annealing?
- Use ***dE/dx* proxy** for tracks

Nuclear recoils from α-decays and spontaneous fission

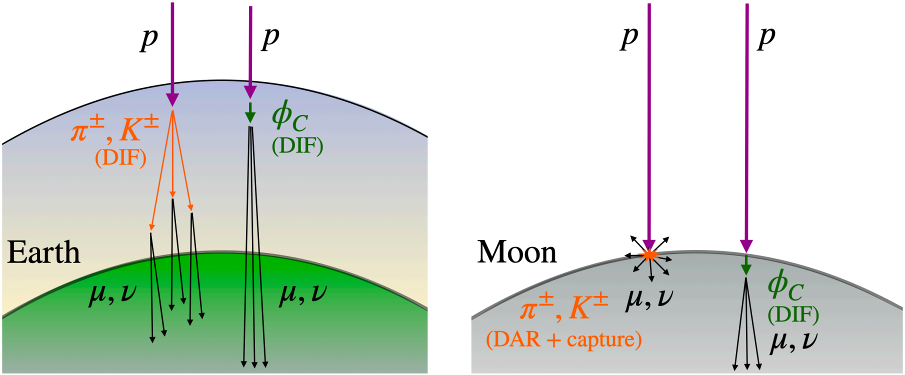




Need very radiopure minerals

Ultra-basic rocks formed in the mantle with $C^{238} \gtrsim 0.01\,\mathrm{ppb}$

Atmospheric neutrinos induce $\mathcal{O}(100)\ K^+/100\,\mathrm{g}/\mathrm{Gyr}$



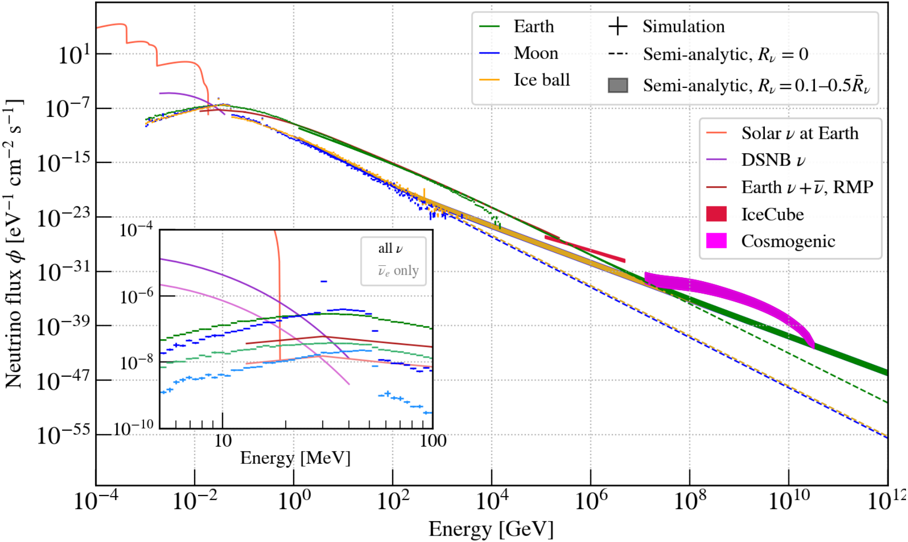
Figures from arXiv:2411.09634

- Conventional secondary mesons **decay in flight** on Earth
- Prompt fluxes from short-lived mesons decaying in flight

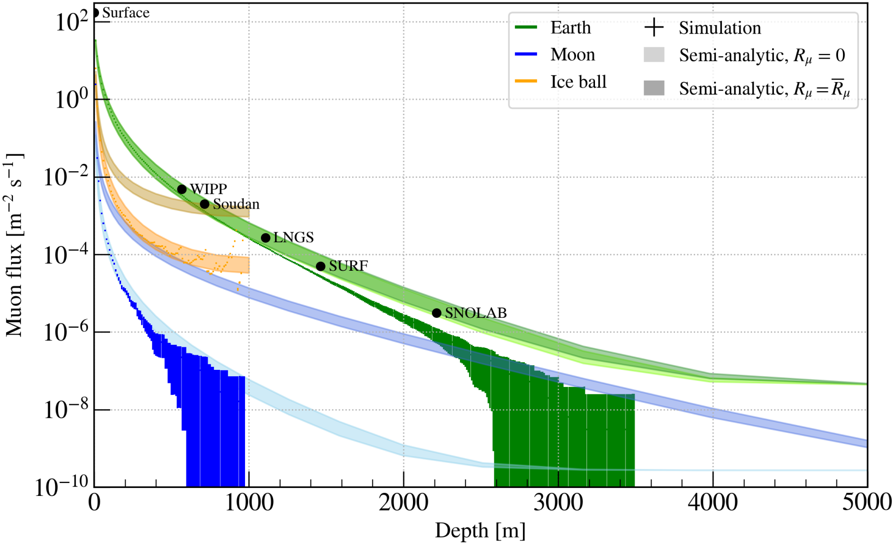
Suppression of lunar μ and ν fluxes

- Conventional secondary mesons **decay at rest** on the Moon
- Less suppression of short-lived mesons decaying in flight

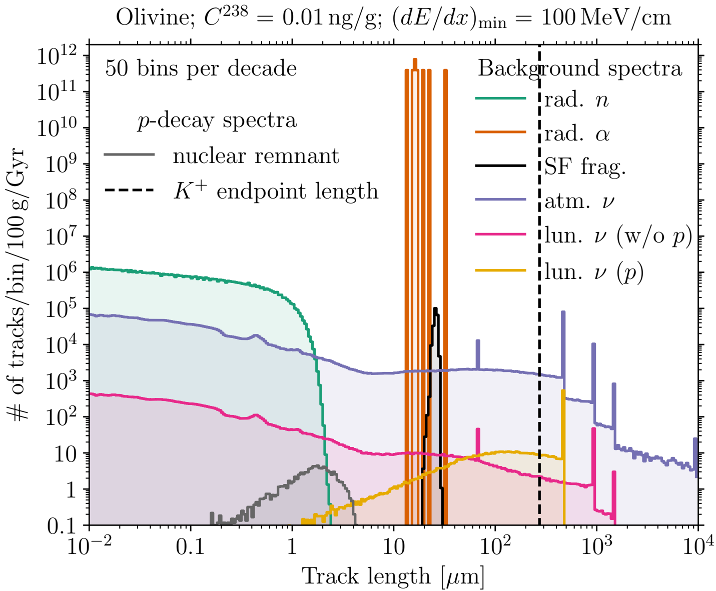
Lunar neutrinos induce $\sim 0.5\,K^+/100\,\mathrm{g}/\mathrm{Gyr}$ in Olivine



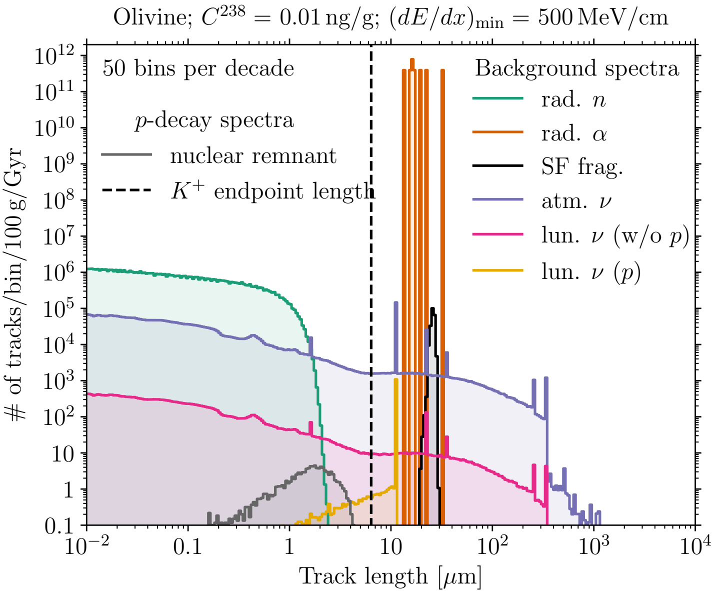
Lunar muons induce $\sim 0.1\, K^+/100\,\mathrm{g}/\mathrm{Gyr}$ at $\sim 5\,\mathrm{km}$ depth



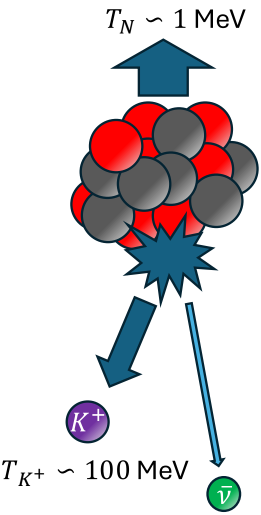
Expect $\lesssim 6\,K^+/100\,\mathrm{g}/\mathrm{Gyr}$ for $\tau(p \to \bar{\nu} K^+) > 5.9 \times 10^{33}$ yr

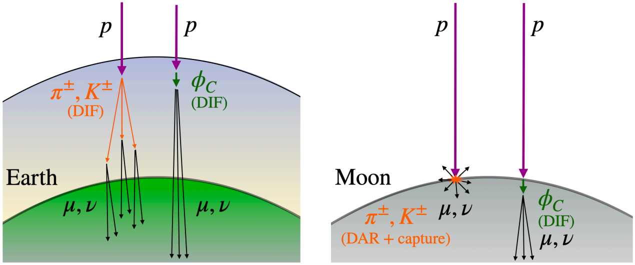


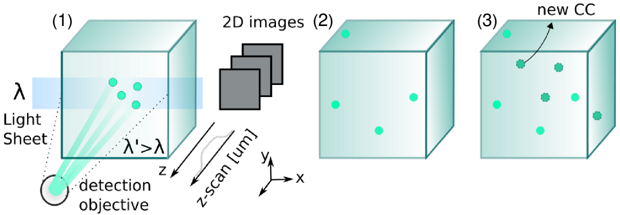
Increase dE/dx threshold from 100 to 500 MeV/cm



Large exposures in MDs could probe DM and proton decay



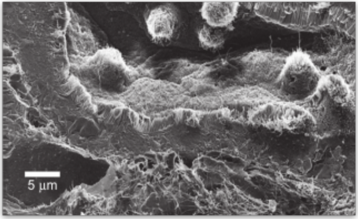




Cleaving and etching limits ϵ and can only reconstruct 2D

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



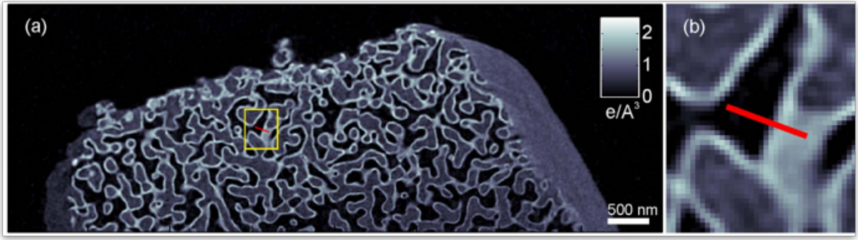
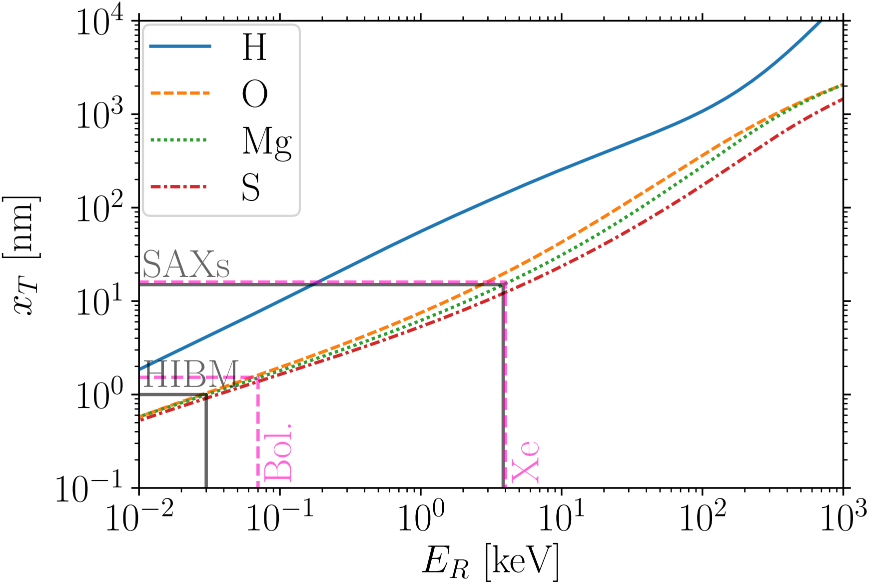
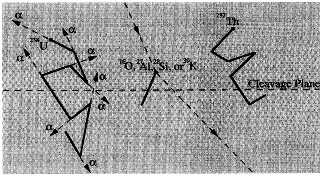


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

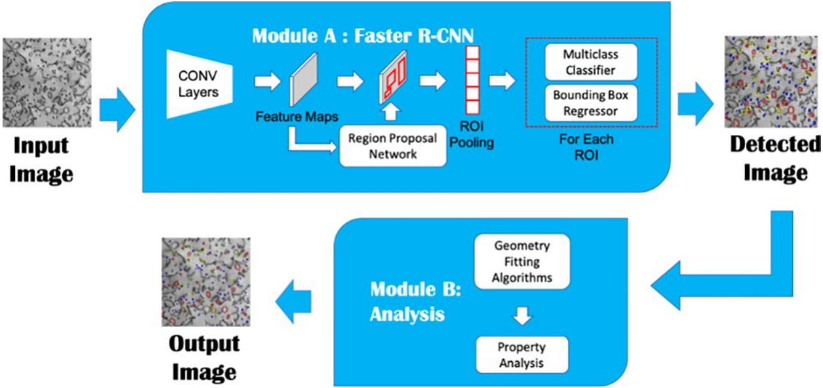
Integrate stopping power to estimate track length



Recognition of sparse tracks is a data analysis challenge



- 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



Scattering cross sections ⇒ scattering rates

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

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

Differential cross section

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

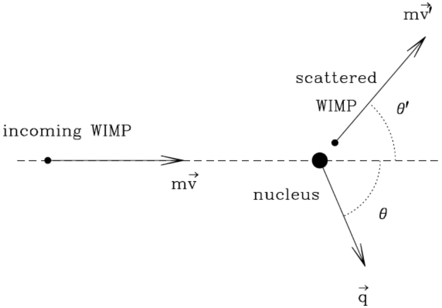
$$F(q) \simeq \frac{9\,[\sin(qR) - qR\cos(qR)]^2}{(qR)^6}$$

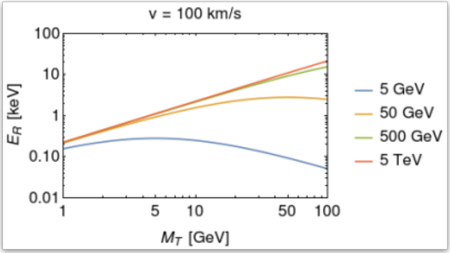
Differential scattering rate

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

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

Nuclear recoils induced by elastic WIMP-nucleus scattering





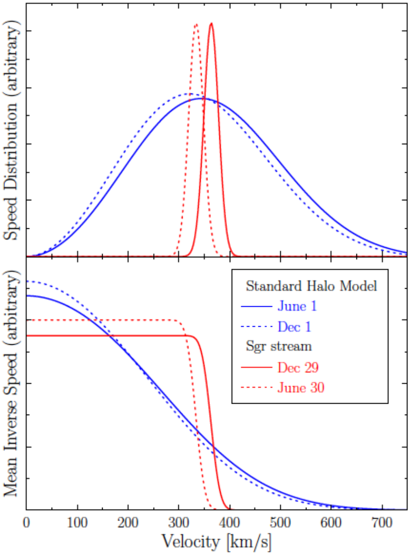
Rate per unit time per unit mass

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

Scattering kinematics ⇒ event rate

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

WIMP velocity distribution and induced recoil spectra



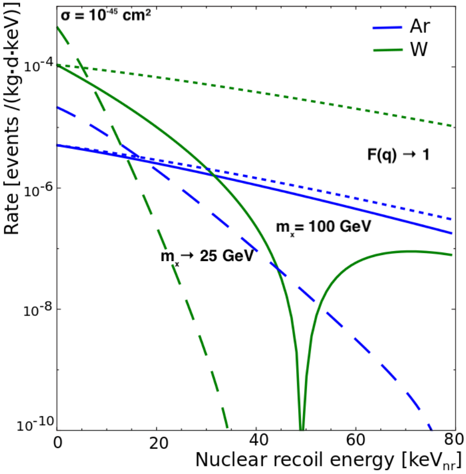
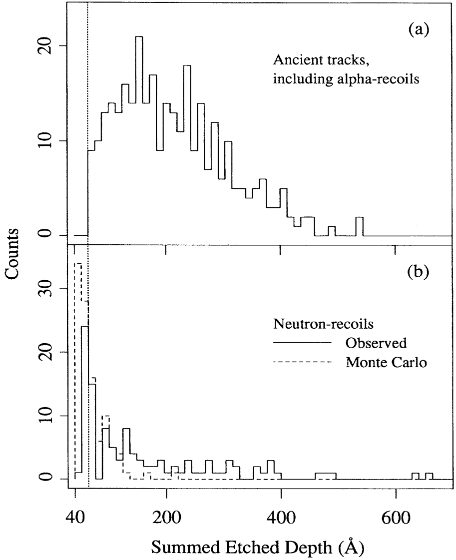


Figure: (left) 1209.3339 (right) 1509.08767

Mineral detectors used to constrain WIMPs before



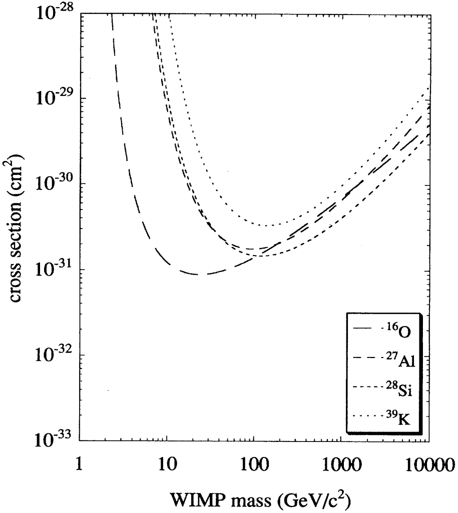
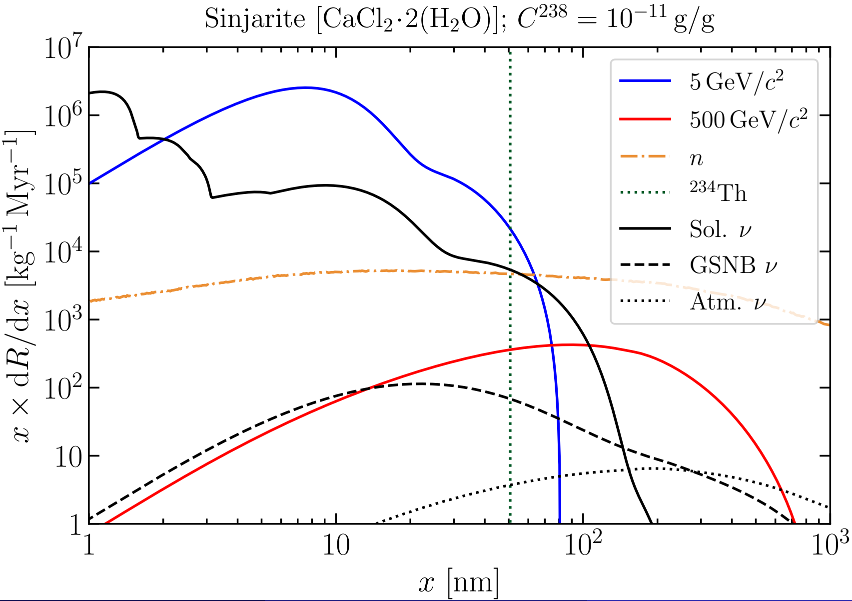
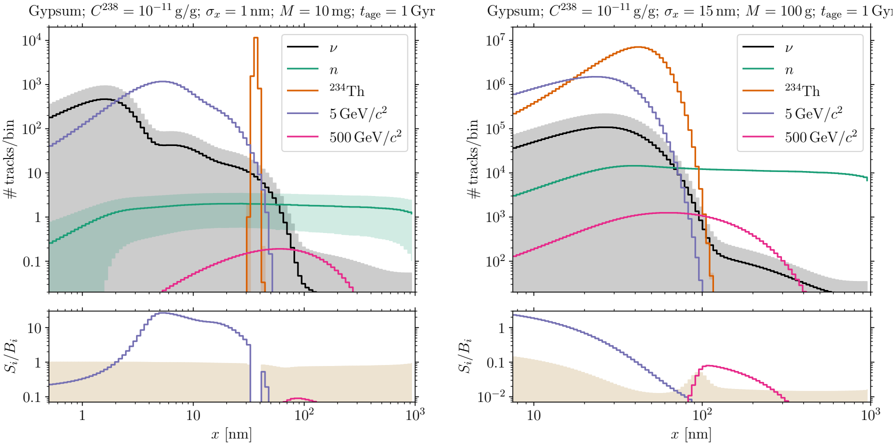


Figure: Snowden-Ifft et al. (1995)

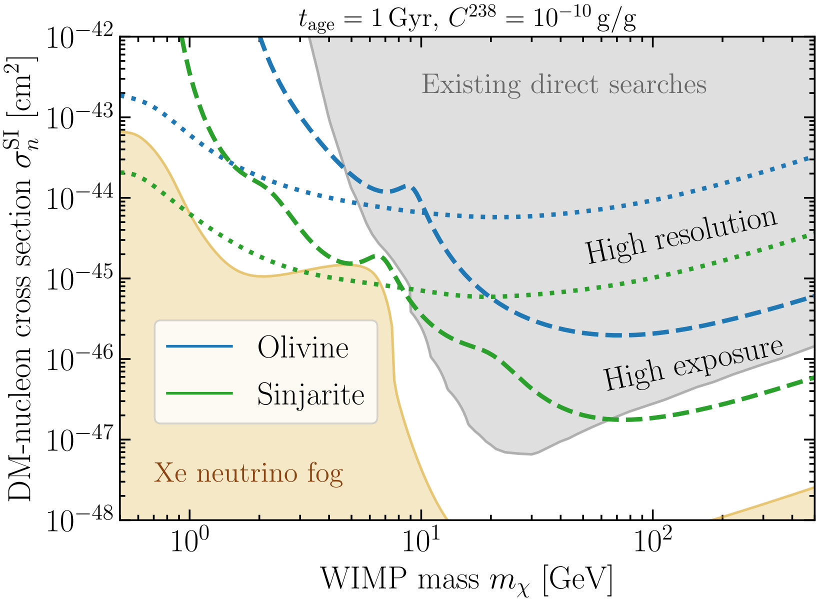
Use track length spectra to pick out WIMP signal



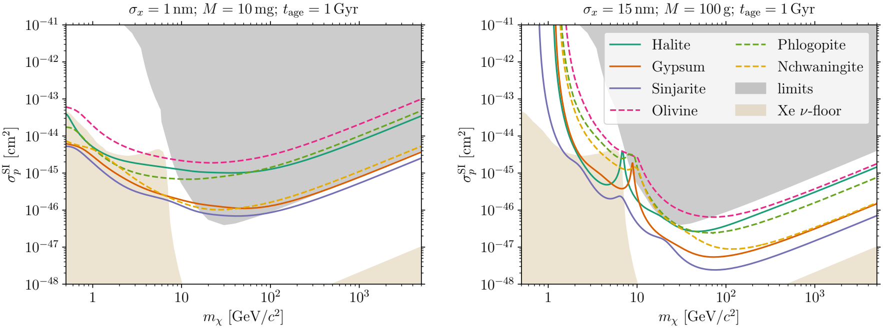
Track length spectra after smearing by readout resolution



Trade-off between read-out resolution and exposure

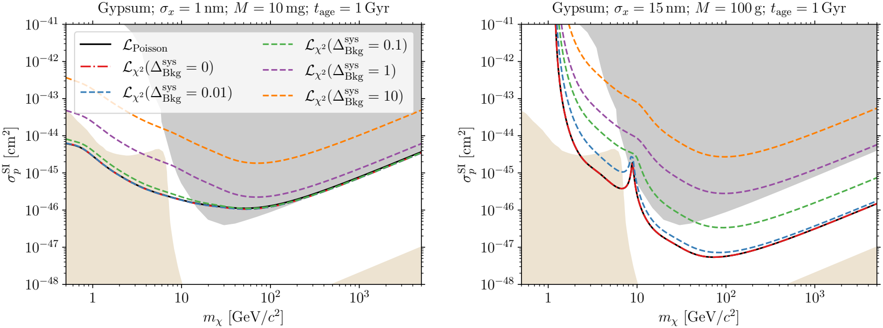


Sensitivity for different targets

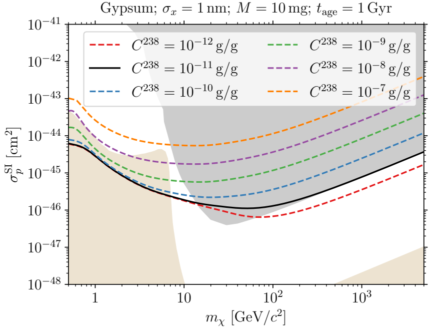


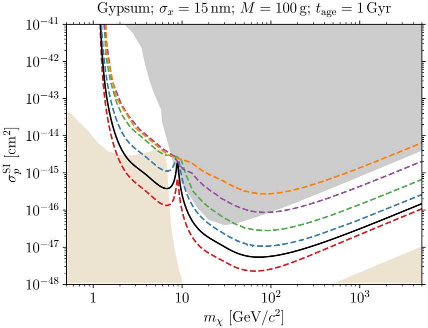
Halite	NaCl	$C^{238} = 10^{-11}$ g/g
Gypsum	$Ca(SO_4)\cdot 2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Sinjarite	$CaCl_2\cdot 2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Olivine	$Mg_{1.6}Fe^{2+}_{0.4}(SiO_4)$	$C^{238} = 10^{-10}$ g/g
Phlogopite	$KMg_3AlSi_3O_{10}F(OH)$	$C^{238} = 10^{-10}$ g/g
Nchwaningite	$Mn^{2+}_2SiO_3(OH)_2\cdot(H_2O)$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

Effects of background shape systematics

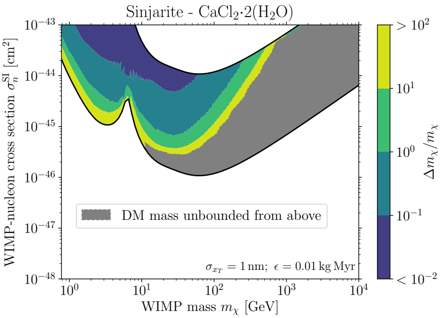


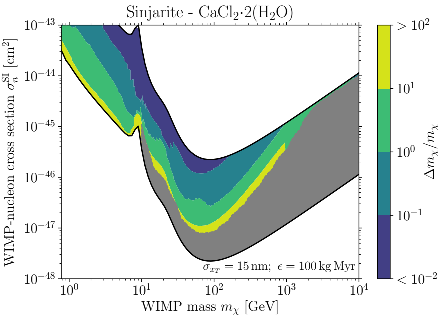
Sensitivity for different ^{238}U concentrations



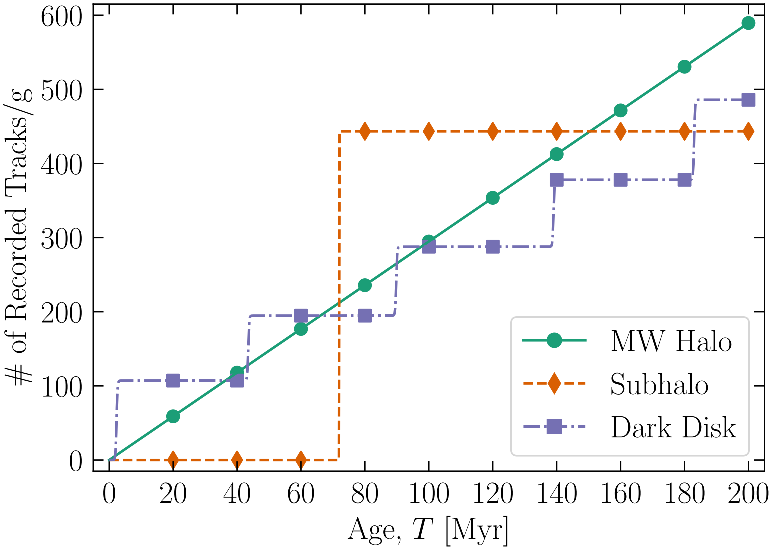


Multiple nuclei and large ϵ allow for optimal $\Delta m_X / m_X$

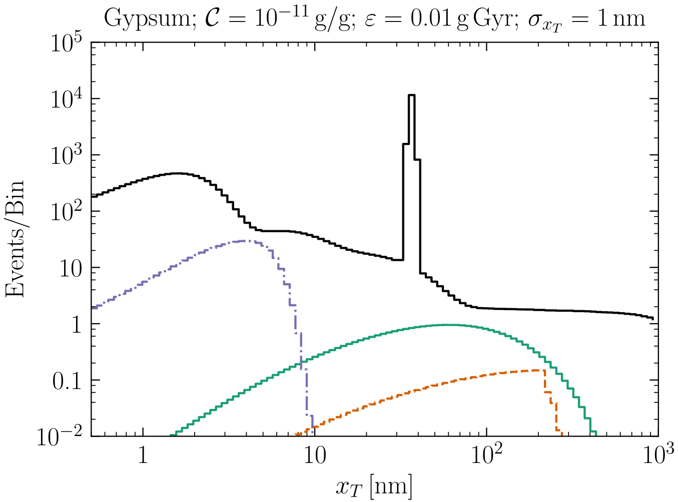




Mineral detectors can look for signals “averaged” over geological timescales or for time-varying signals

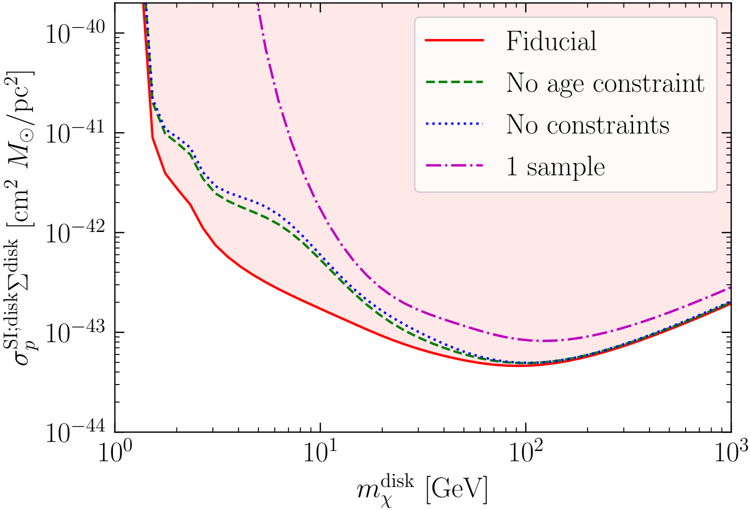


Multiple samples to detect dark disk transit every $\sim 45\,\mathrm{Myr}$



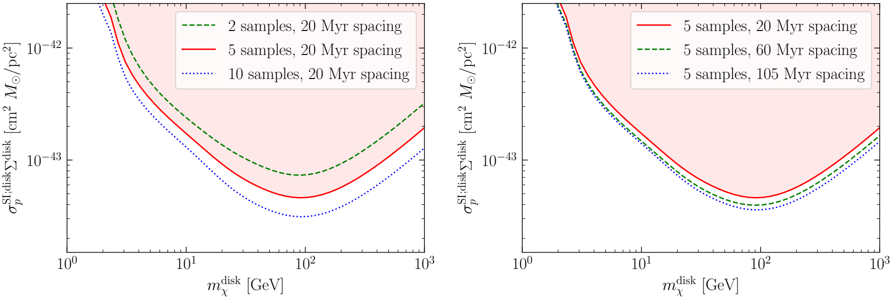
$m_X^{\rm disk} = 100\,\mathrm{GeV}$ $\sigma_{Xp}^{\rm disk} = 10^{-43}\,\mathrm{cm}^2$ $m_X = 500\,\mathrm{GeV}$ $\sigma_{Xp} = 5 \times 10^{-46}\,\mathrm{cm}^2$

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

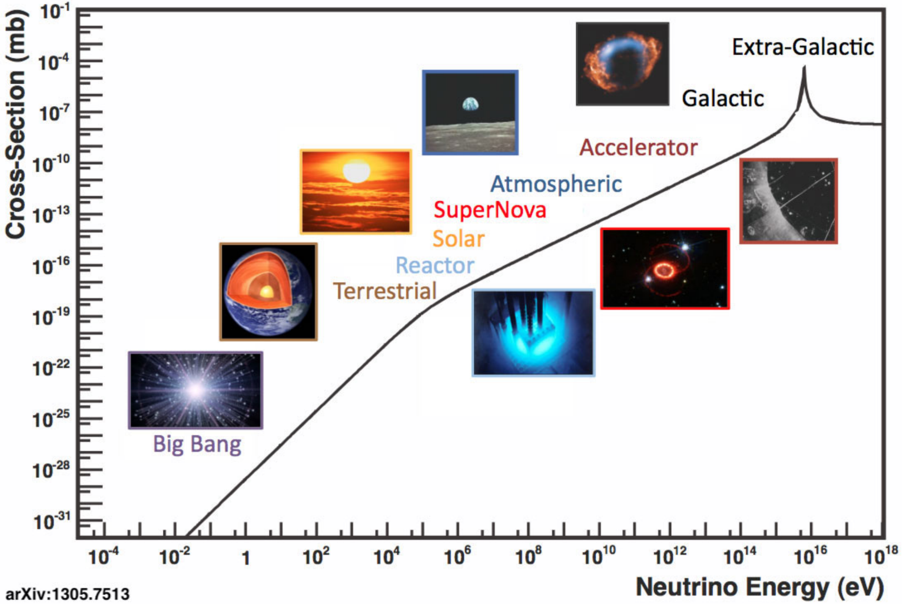


Systematic uncertainties $\Delta_t = 5\%$ $\Delta_M = 0.1\%$ $\Delta_C = 10\%$ $\Delta_\Phi = 100\%$

Change number of samples and sample spacing in time



Neutrinos come from a variety of sources



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

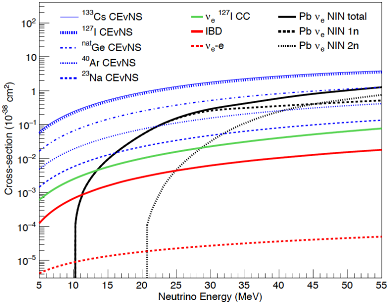


Figure: COHERENT, 1803.09183

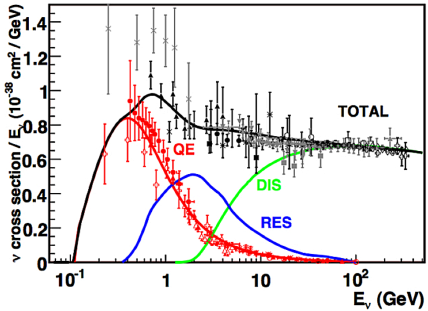
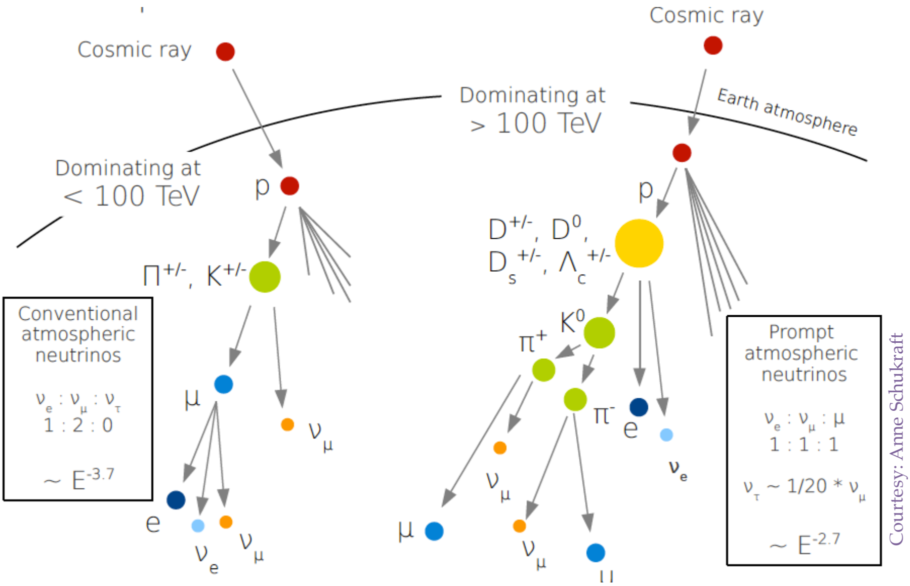


Figure: Inclusive CC $\sigma_{\nu N}$, 1305.7513

Atmospheric ν's originating from CR interactions



Atmospheric ν's originating from CR interactions

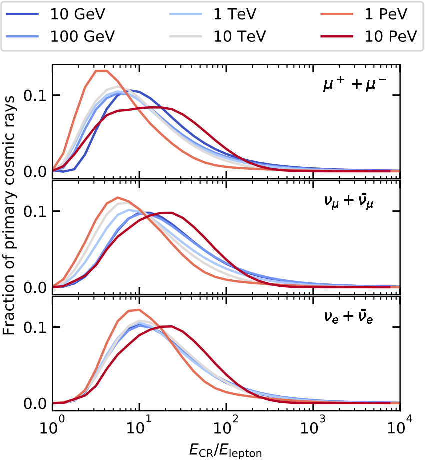


Figure: E_{CR} to leptons, 1806.04140

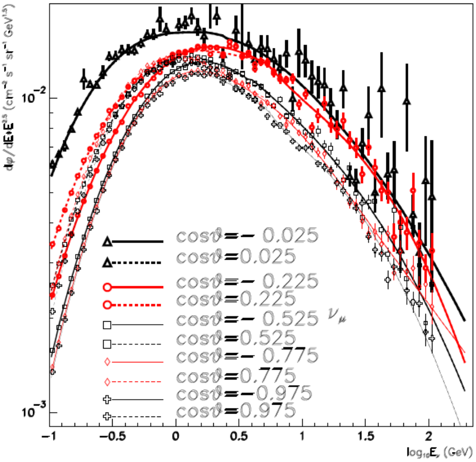


Figure: FLUKA simulation of ν_μ flux at SuperK for solar max, hep-ph/0207035

Geomagnetic field deflects lower energy CR primaries

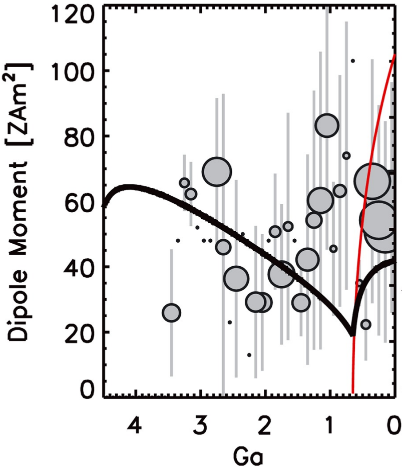
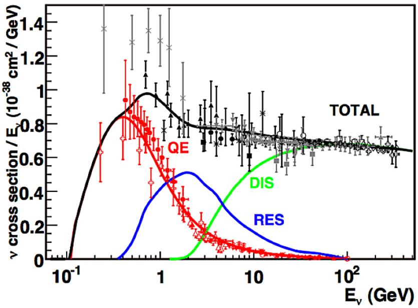


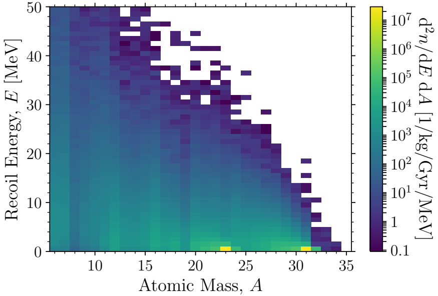
Figure: Driscoll, P. E. (2016), *Geophys. Res. Lett.*, 43, 5680-5687

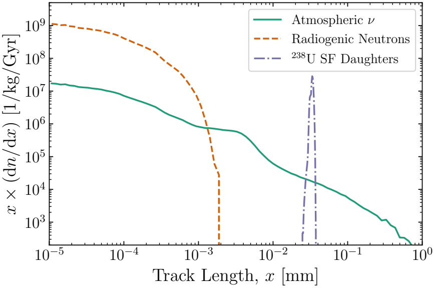
Rigidity $p_{CR}/Z_{CR} \simeq E_{CR}$ for CR protons

- Rigidity cutoff $\propto M_{dip}$ truncates atmospheric ν spectrum at low E_ν
- Maximum cutoff today $\sim 50\,\mathrm{GV}$
- Recall CR primary $E_{CR} \gtrsim 10\, E_\nu$



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

Galactic contribution to ν flux over geological timescales

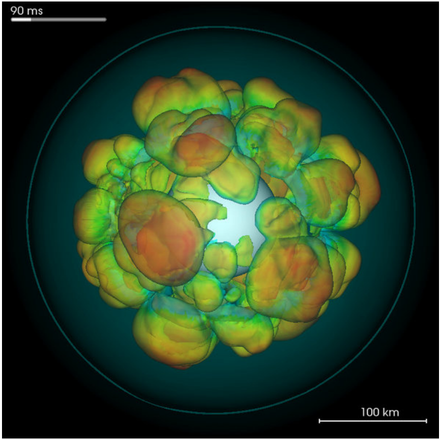


Figure: Supernova simulation after CC

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

- Measure galactic CC SN rate
- Traces star formation history

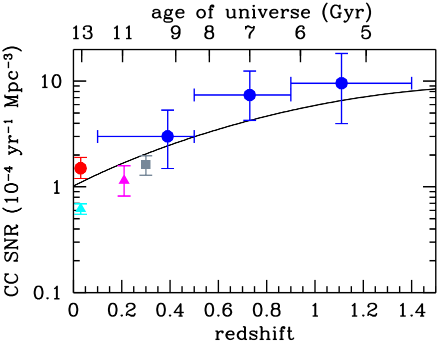


Figure: Cosmic CC SNR, 1403.0007

Galactic contribution to ν flux over geological timescales

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

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

- Measure galactic CC SN rate
- Traces star formation history

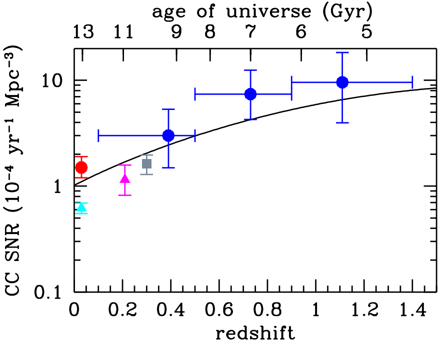
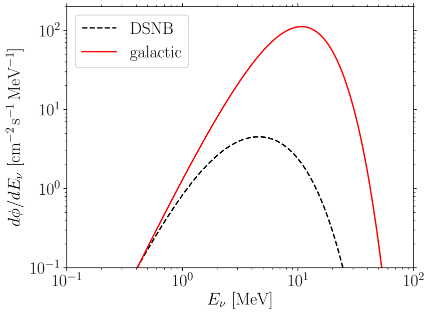
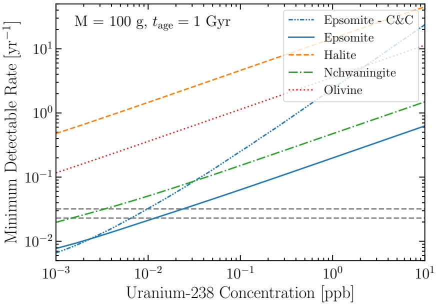
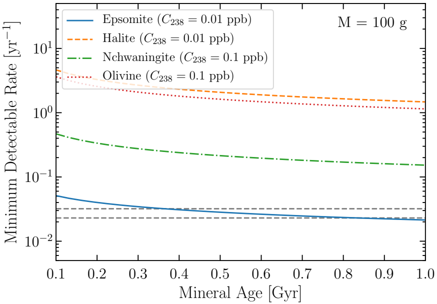


Figure: Cosmic CC SNR, 1403.0007



Sensitivity to galactic CC SN rate depends on C^{238}

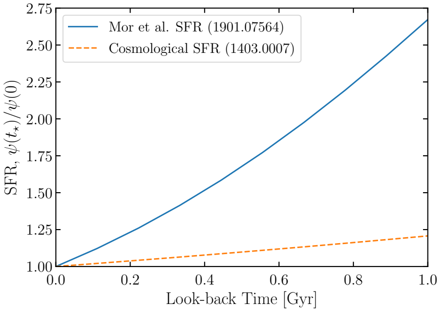


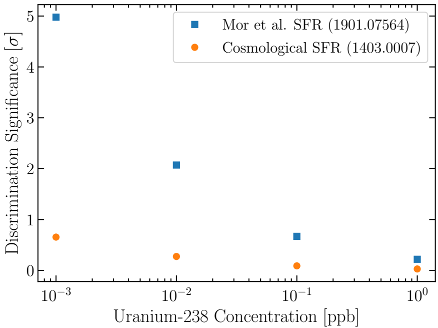


Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]

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

Difficult to pick out time evolution of galactic CC SN rate





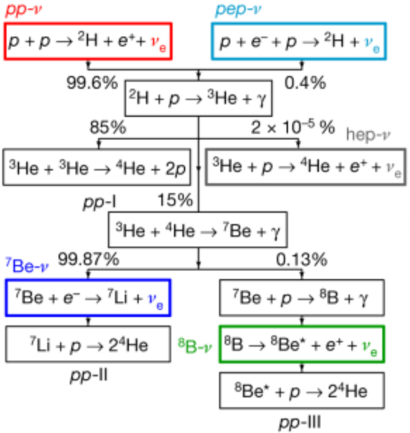
Coarse grained cumulative time bins

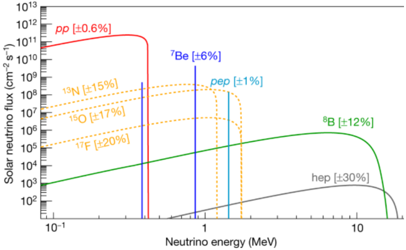
- 10 Epsomite paleo-detectors
- 100 g each, $\Delta t_{\rm age} \simeq 100$ Myr

Determine σ rejecting constant rate

Could only make discrimination at 3σ for $\mathcal{O}(1)$ increase in star formation rate with $C^{238} \lesssim 5$ ppt

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





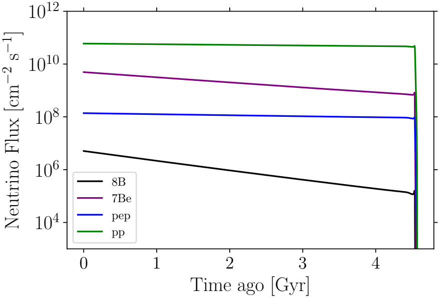
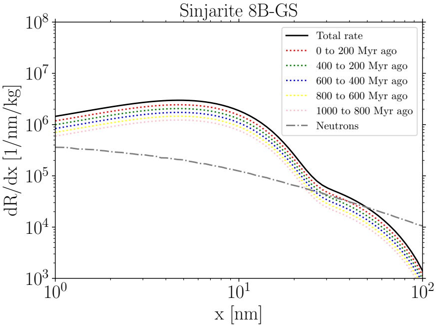
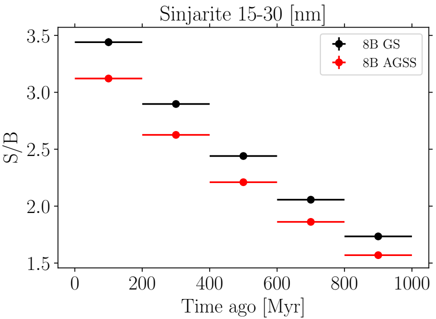


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Could use large exposure to differentiate between scenarios





Could measure ^8B flux over time

- Higher $E_\nu \Rightarrow$ longer tracks
- Highly dependent on solar core temperature with flux $\propto T^{24}$
- Sensitive to metallicity model

100 g samples with 15 nm resolution

- Look in single bin $15 - 30$ nm
- Assume $\Delta_t \sim 10\%$, $\Delta_C = 10\%$
- $N_{\rm tot}^{\rm GS} \sim (1.63 \pm 0.05) \times 10^6$
  $N_{\rm tot}^{\rm AGSS} \sim (1.52 \pm 0.05) \times 10^6$