Mineral Detection of CEνNS

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

arXiv > astro-ph > arXiv:2301.07118

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Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

Sebastian Baum, Patrick Stengel, Natsue Abe, Javier F. Acevedo, Gabriela R. Araujo, Yoshihiro Asahara, Frank Avignone, Levente Balogh, Laura Baudis, Yilda Boukhtouchen, Joseph Bramante, Pieter Alexander Breur, Lorenzo Caccianiga, Francesco Capozzi, Juan I. Collar, Reza Ebadi, Thomas Edwards, Klaus Eitel, Alexey Elykov, Rodney C. Ewing, Katherine Freese, Audrey Fung, Claudio Galelli, Ulrich A. Glasmacher, Arianna Gleason, Noriko Hasebe, Shigenobu Hirose, Shunsaku Horiuchi, Yasushi Hoshino, Patrick Huber, Yuki Ido, Yohei Igami, Yoshitaka Itow, Takenori Kato, Bradley J. Kavanagh, Yoji Kawamura, Shingo Kazama, Christopher J. Kenney, Ben Kilminster, Yui Kouketsu, Yukiko Kozaka, Noah A. Kurinsky, Matthew Leybourne, Thalles Lucas, William F. McDonough, Mason C. Marshall, Jose Maria Mateos, Anubhav Mathur, Katsuyoshi Michibayashi, Sharlotte Mkhonto, Kohta Murase, Tatsuhiro Naka, Kenji Oguni, Surjeet Rajendran, Hitoshi Sakane, Paola Sala, Kate Scholberg, Ingrida Semenec, Takuya Shiraishi, Joshua Spitz, Kai Sun, Katsuhiko Suzuki, Erwin H. Tanin, Aaron Vincent, Nikita Vladimirov, Ronald L. Walsworth, Hiroko Watanabe

MDνDM community

- Groups across Europe, North America and Japan
- Astroparticle theorists, experimentalists, geologists, and materials scientists
- First meeting last October at IFPU in Trieste

Check out our whitepaper!

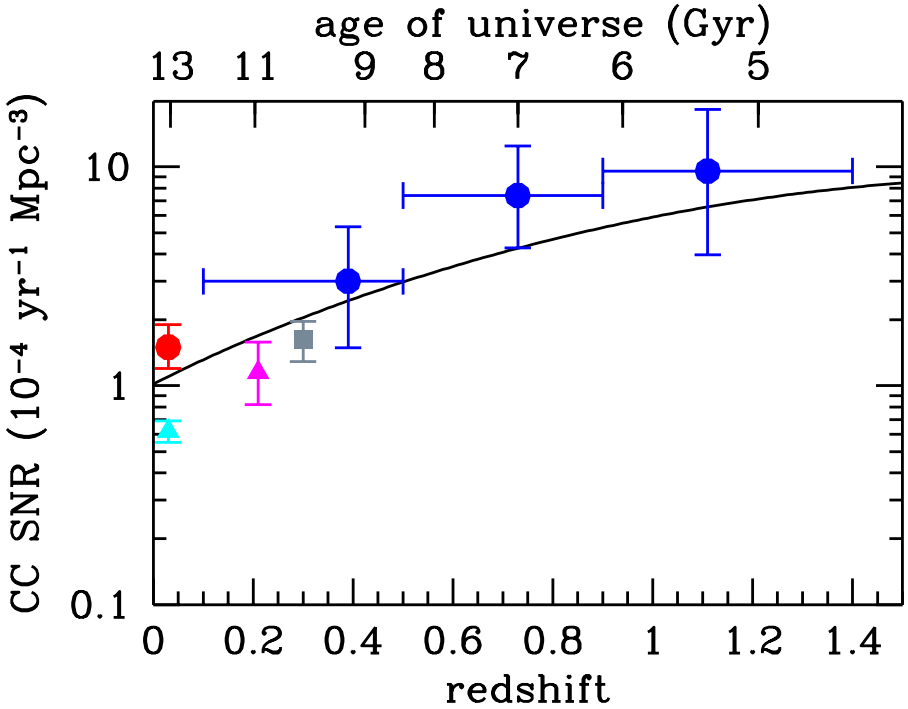
- History of mineral detectors
- Review scientific potential for astroparticle physics, reactor neutrinos and geoscience
- Summary of active and planned experimental efforts

Galactic SN contribution to 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



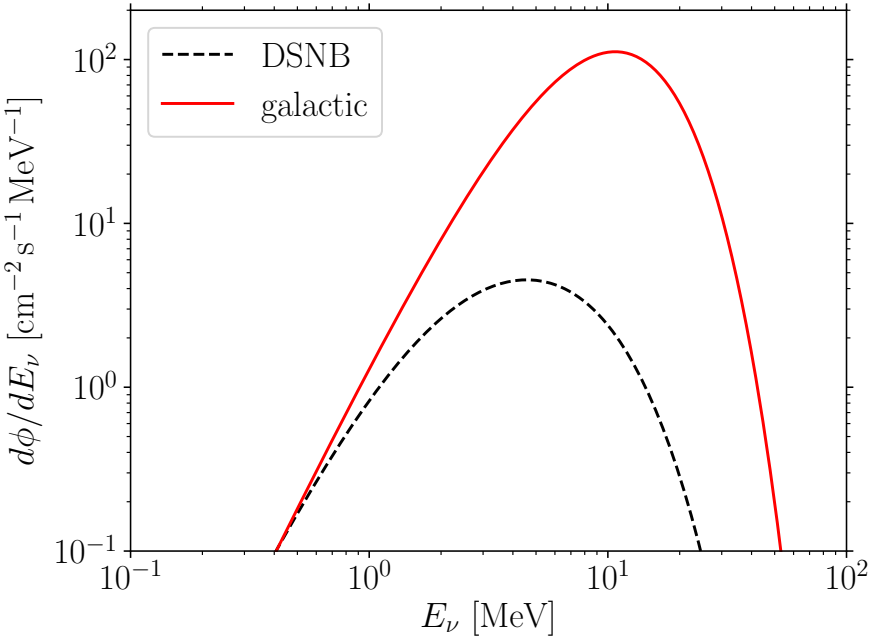
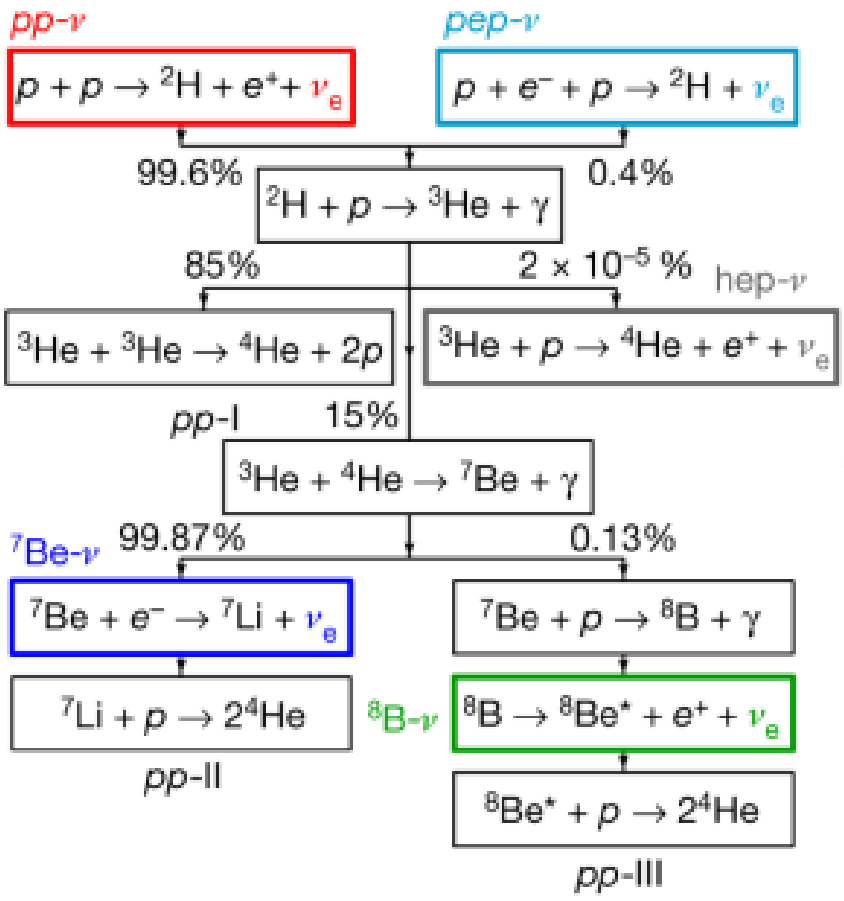
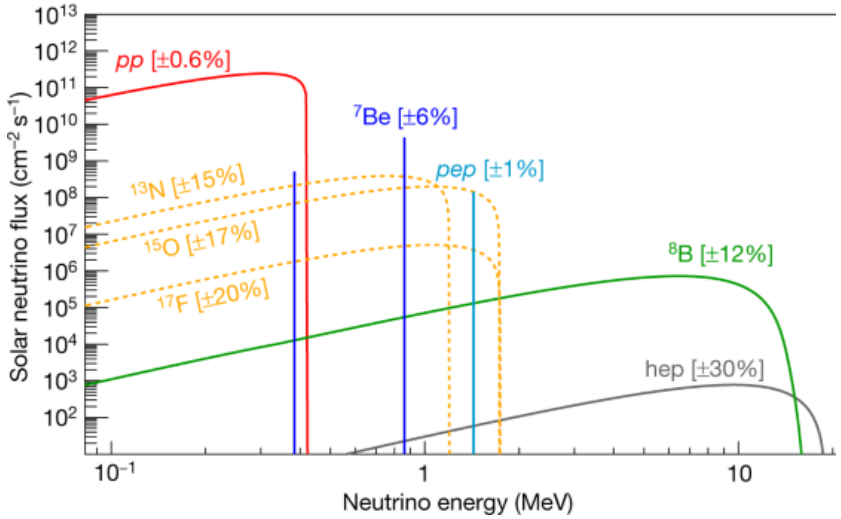


Figure: Cosmic CC SNR, 1403.0007

Probe evolution of standard solar model over time





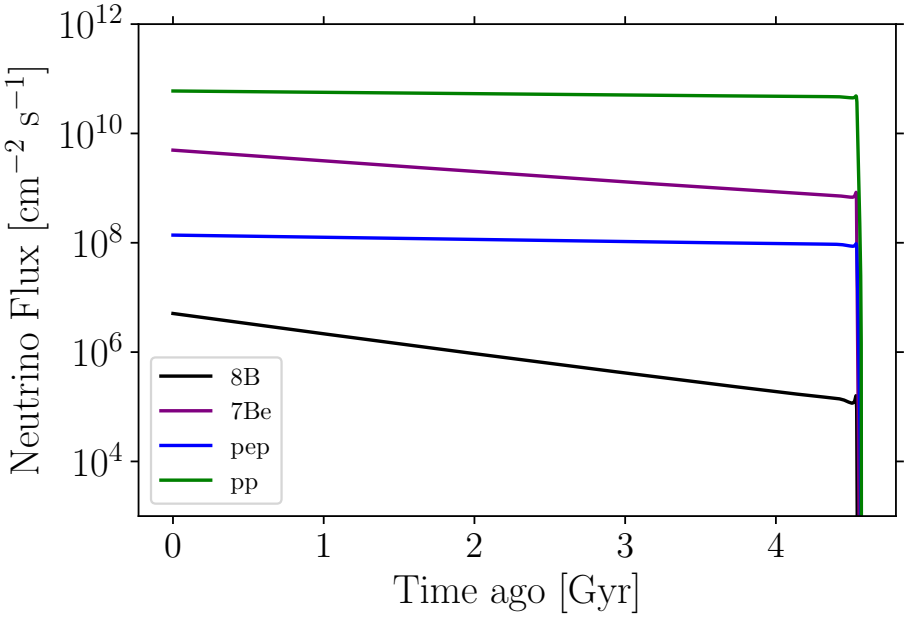
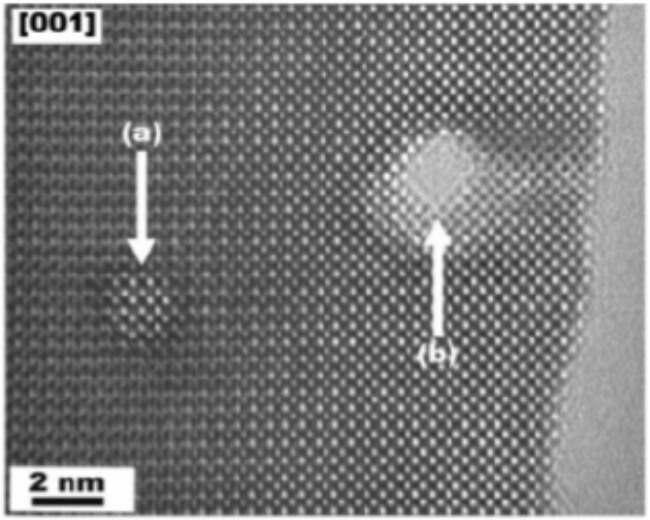


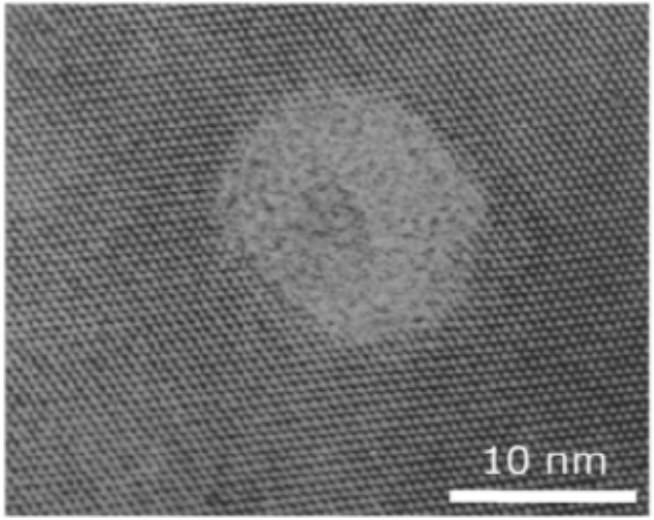
Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Modern TEM allows for accurate characterization of tracks

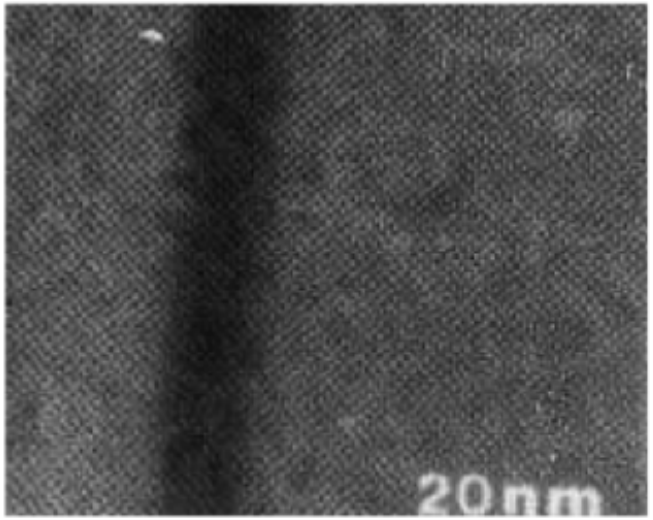


[Toulemonde+, '06]

Cd on SnO_2

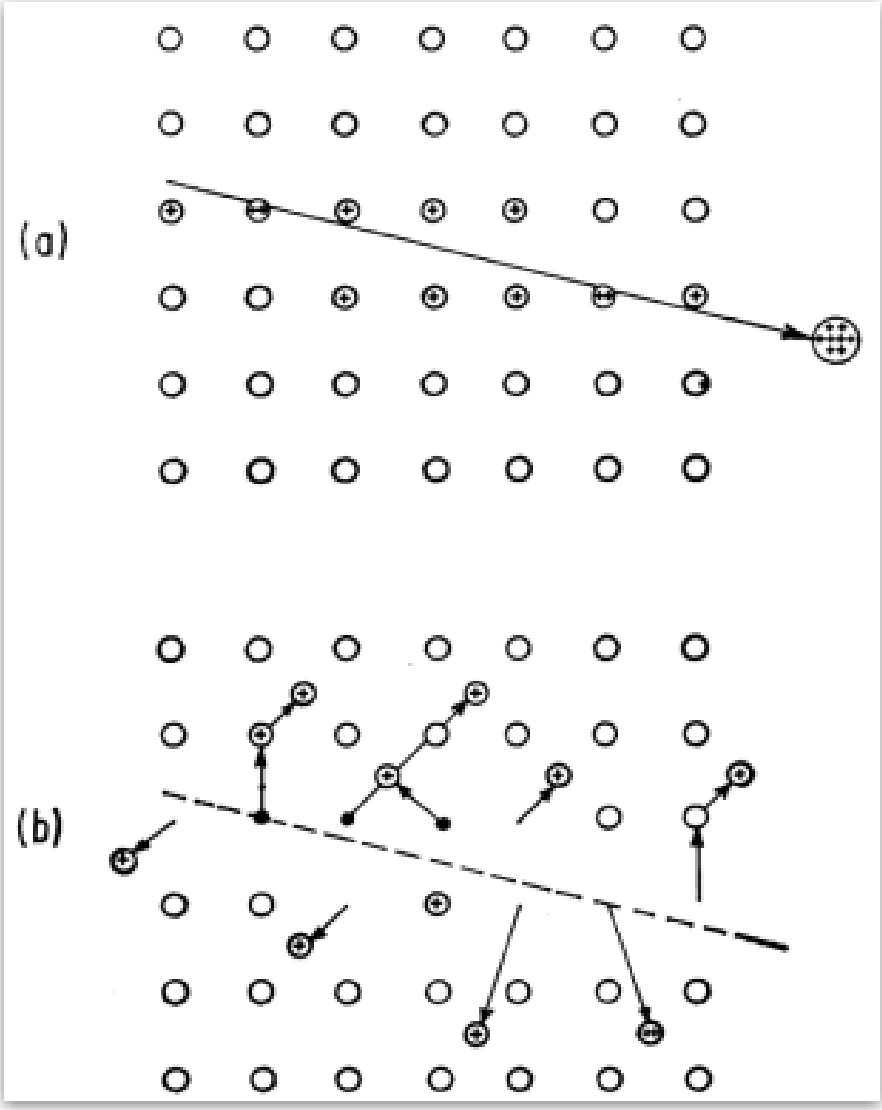


Pb on Mica



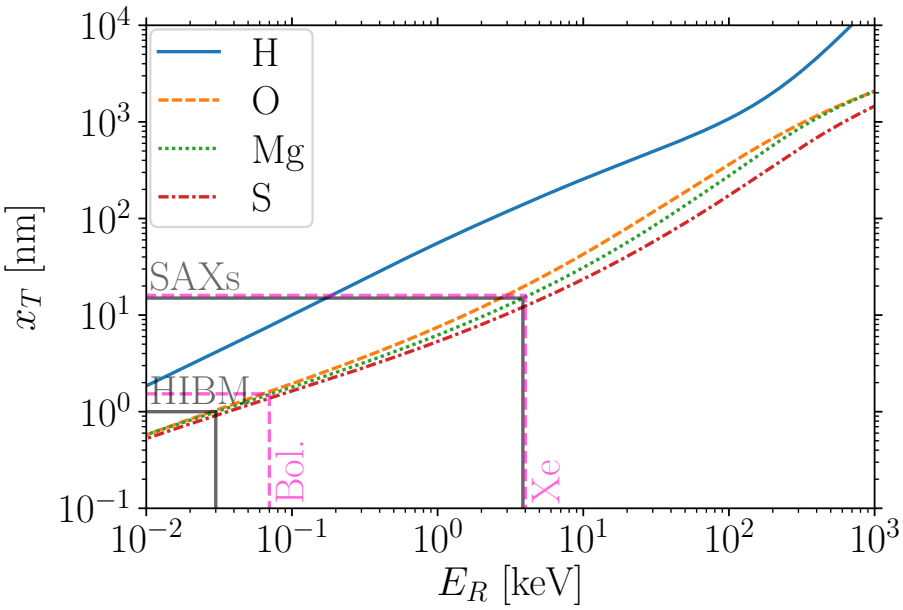
Xe on $Y_3Fe_5O_{12}$

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

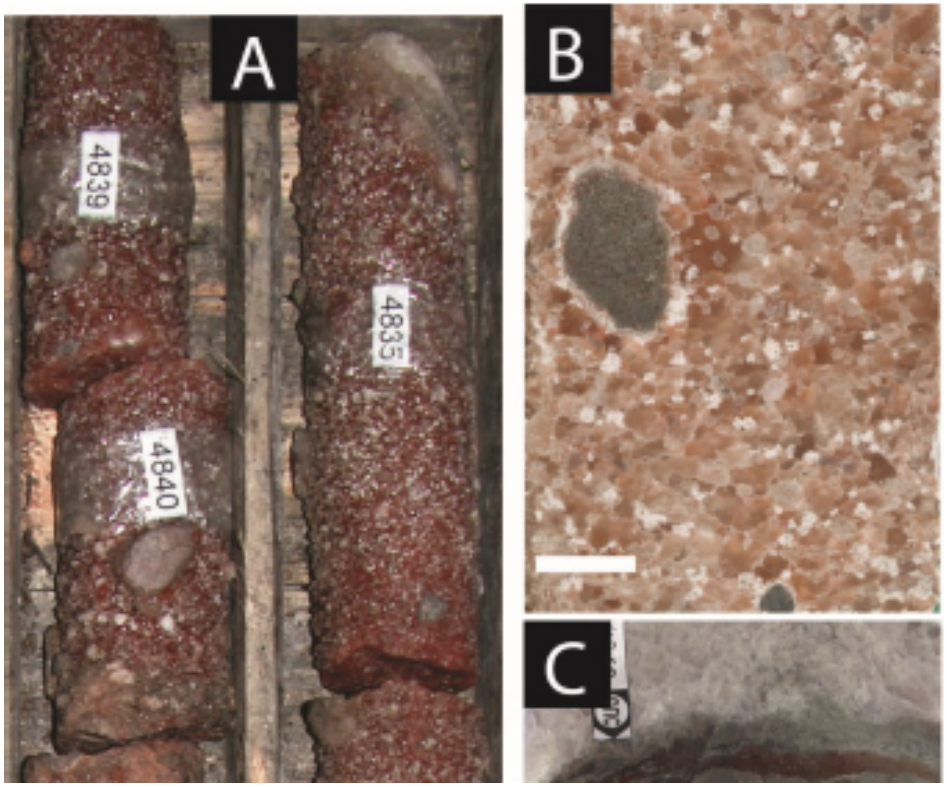


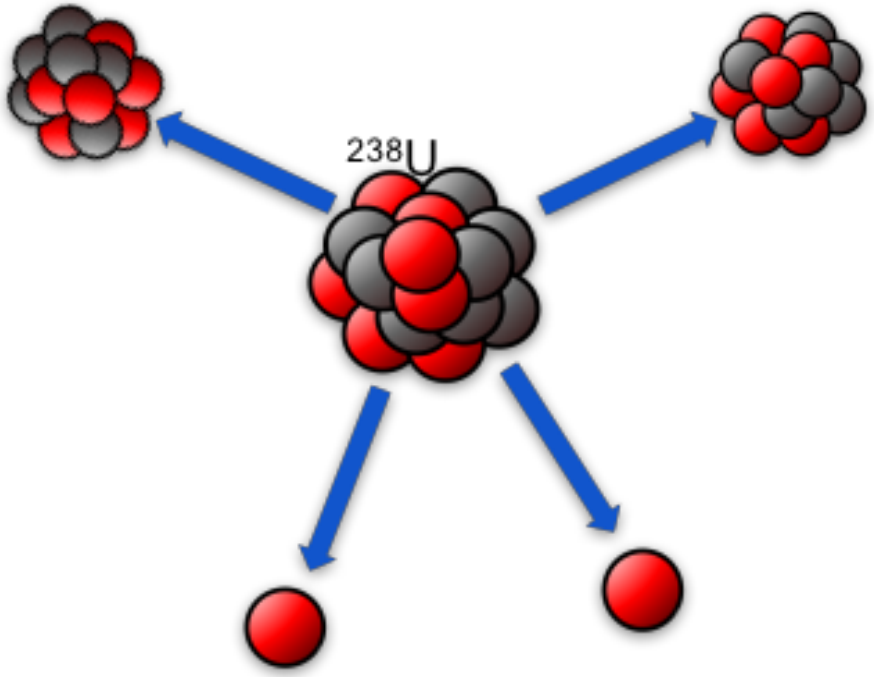
Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

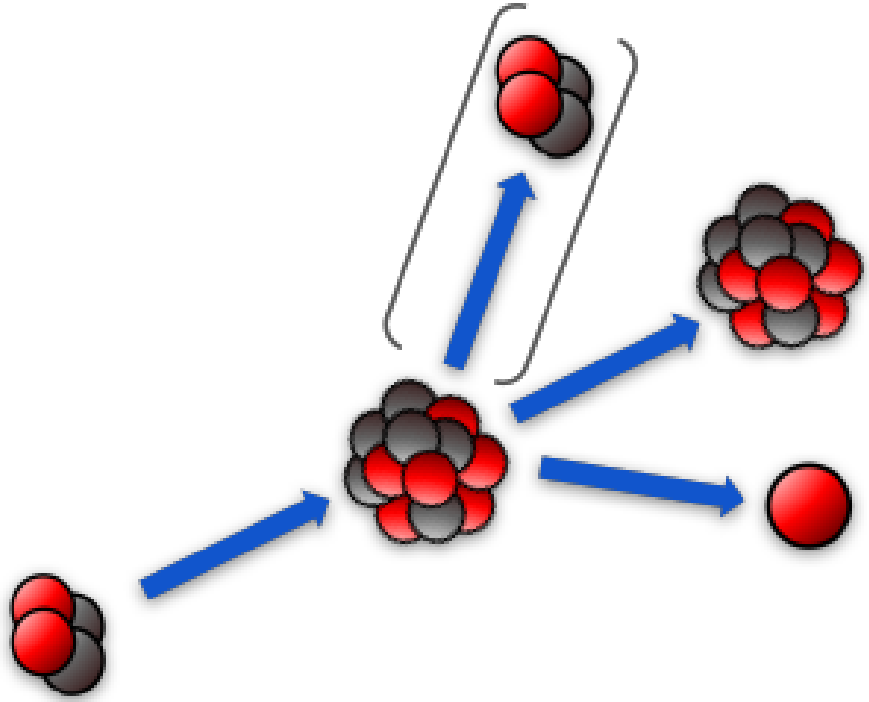
Depth	Neutron Flux
2 km	$10^6/\mathrm{cm}^2/\mathrm{Gyr}$
5 km	$10^2/\mathrm{cm}^2/\mathrm{Gyr}$
6 km	$10/\mathrm{cm}^2/\mathrm{Gyr}$
50 m	$70/\mathrm{cm}^2/\mathrm{yr}$
100 m	$30/\mathrm{cm}^2/\mathrm{yr}$
500 m	$2/\mathrm{cm}^2/\mathrm{yr}$

Need minerals with low ^{238}U

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

Fast neutrons from SF and (α, n) interactions





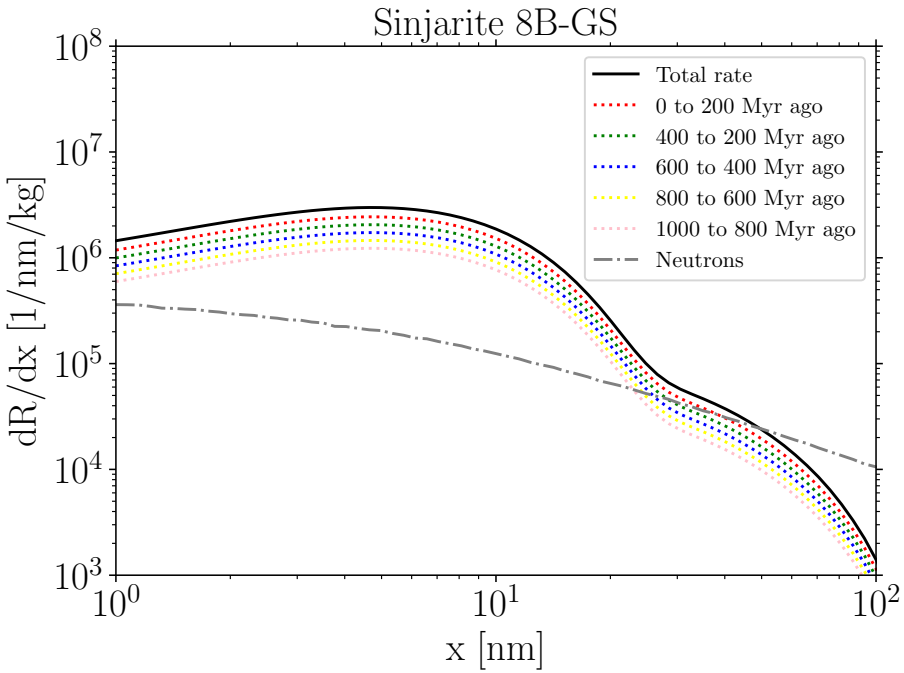
SF yields $\sim$ 2 neutrons with $\sim$MeV

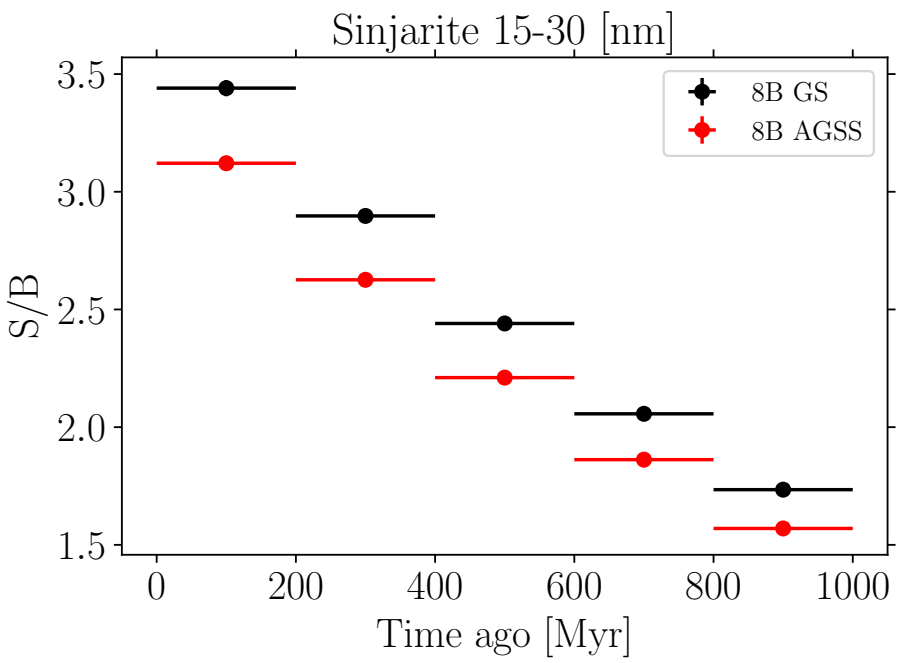
Each neutron will scatter elastically 10-1000 times before moderating

(α, n) rate low, many decay α's

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

Could use large exposure to differentiate between scenarios





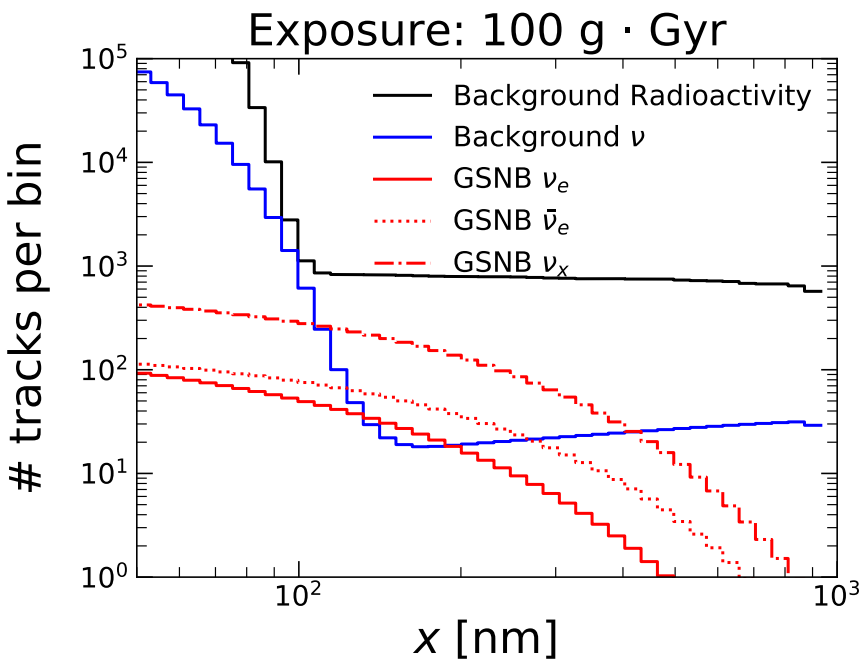
Could measure ^8B flux over time

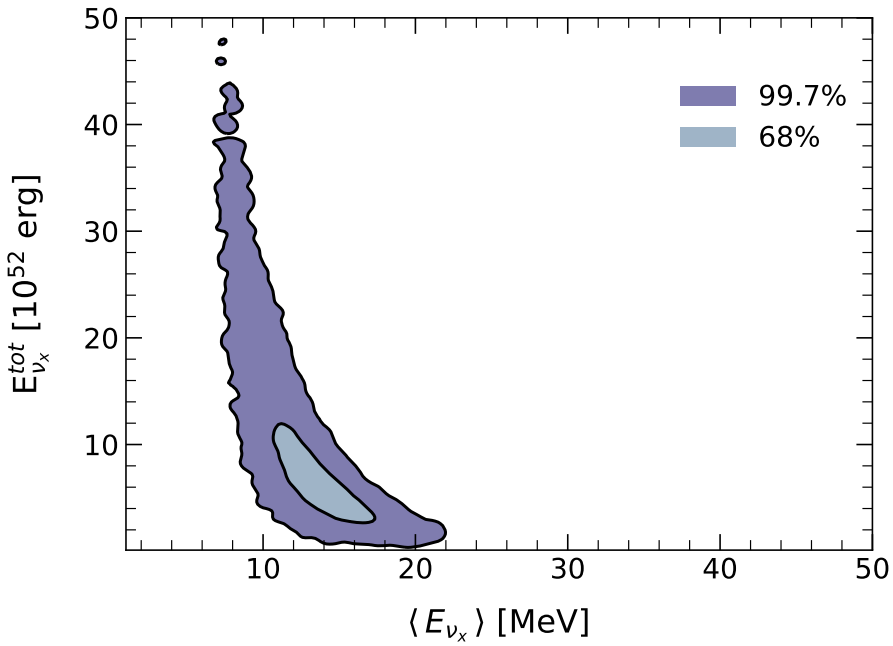
- Higher $E_\nu \Rightarrow$ longer tracks
- Highly dependent on solar core temperature with flux $\propto T^{24}$
- Sensitive to metallicity model

100 g samples with 15 nm resolution

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

Measure heavy-lepton flavor ν_x's with mineral detectors





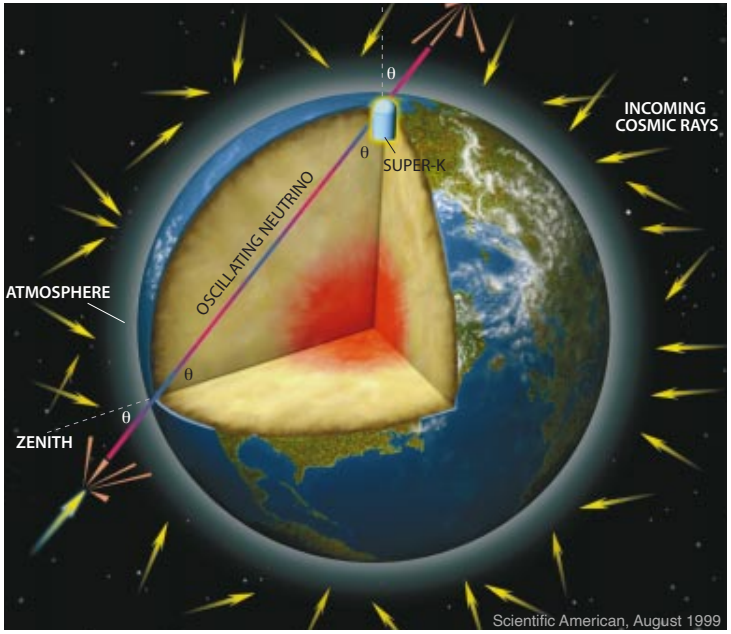
Complement future measurements of DNSB $\nu_e/\bar{\nu}_e$ at DUNE/Hyper-K

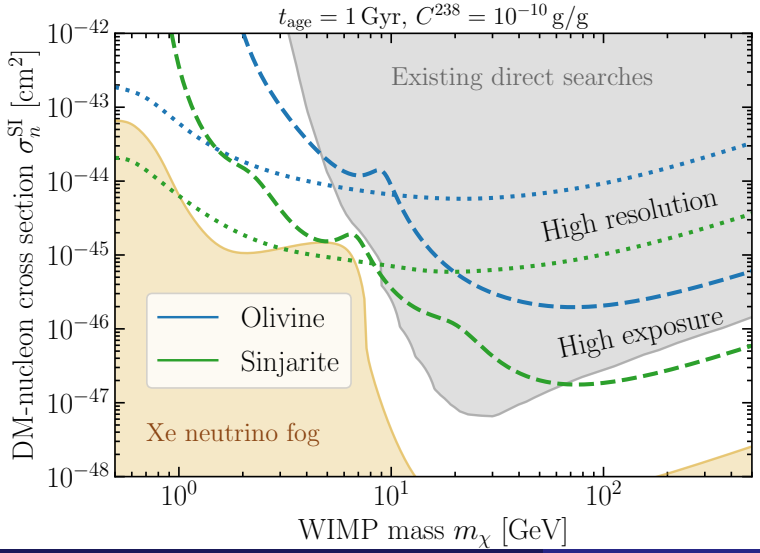
- $C^{238} \lesssim 0.1\,\mathrm{ppb} \Rightarrow S_x/\sqrt{B} \gtrsim 3\sigma$
- MCMC analysis for ν spectra with $\Delta_{SN}^{\nu_e,\nu_x} \sim 10\%$, $\Delta_B^{\nu_e} \sim 20\%$

Pinched Fermi-Dirac distribution

$$\frac{\mathrm{d}n}{\mathrm{d}E_\nu} \propto \frac{E_\nu^{\mathrm{tot}}}{\langle E_\nu \rangle^2} \left(\frac{E_\nu}{\langle E_\nu \rangle} \right)^3 e^{-\frac{4E_\nu}{\langle E_\nu \rangle}}$$

Mineral detectors could probe rare and/or previous events





Look for astrophysical ν's and DM

- Measure solar (2102.01755), CC SN (**1906.05800**, 2203.12696), atmospheric (**2004.08394**) ν's
- WIMP DM (**2106.06559**), substructure (2107.02812), composite DM (2105.06473)

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**

Galactic CC SN ν's can induce recoils in mineral detectors

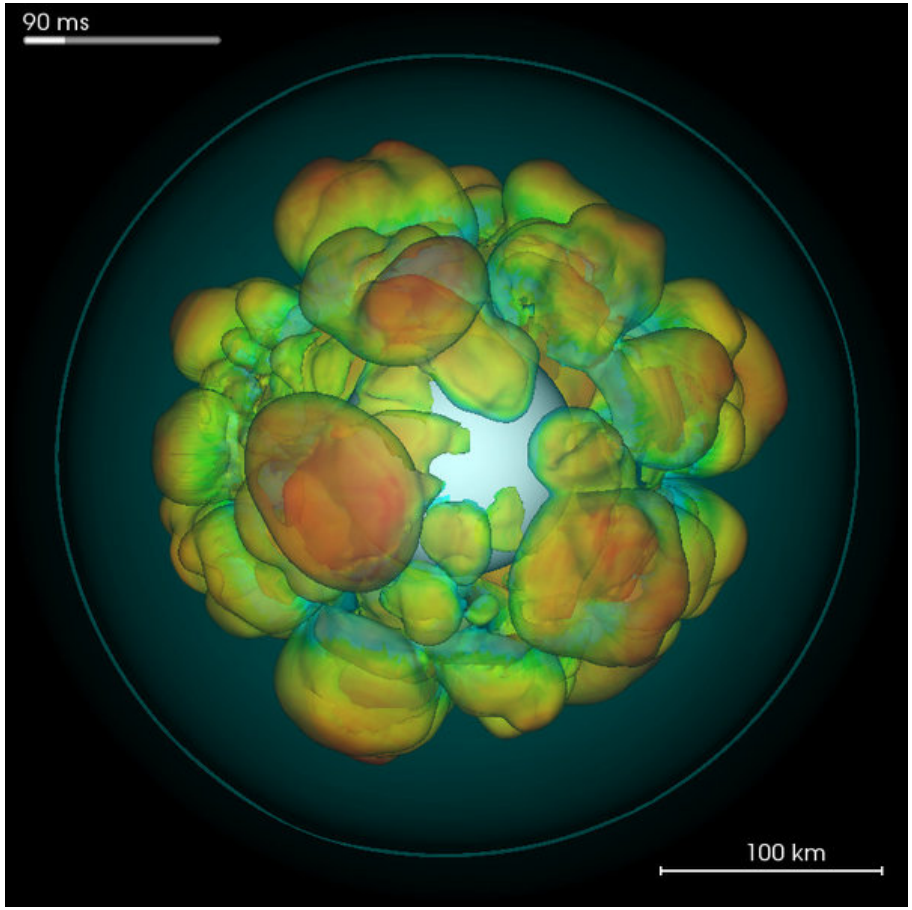


Figure: Supernova simulation after CC

CC SNe primarily in stellar disk

$$\rho_{SN} \propto e^{-R/R_d} e^{-|z|/H_d}$$

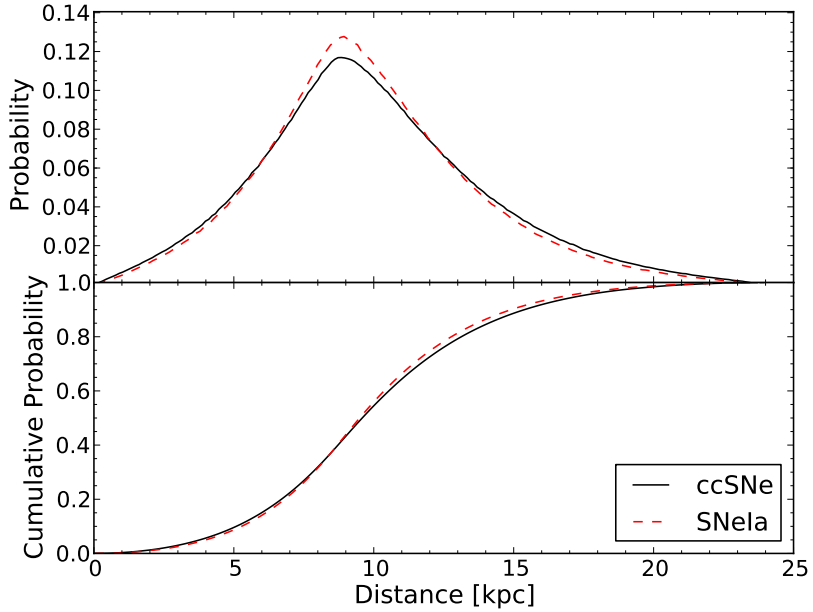
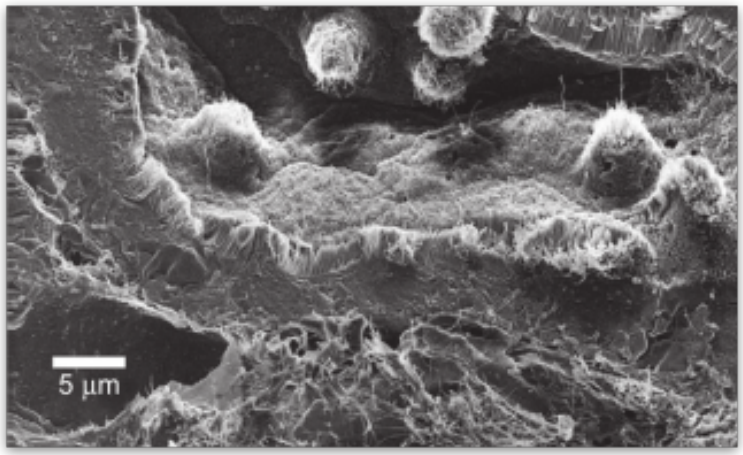


Figure: Distribution of galactic SNe at distance from Earth $f(R_E)$, 1306.0559

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



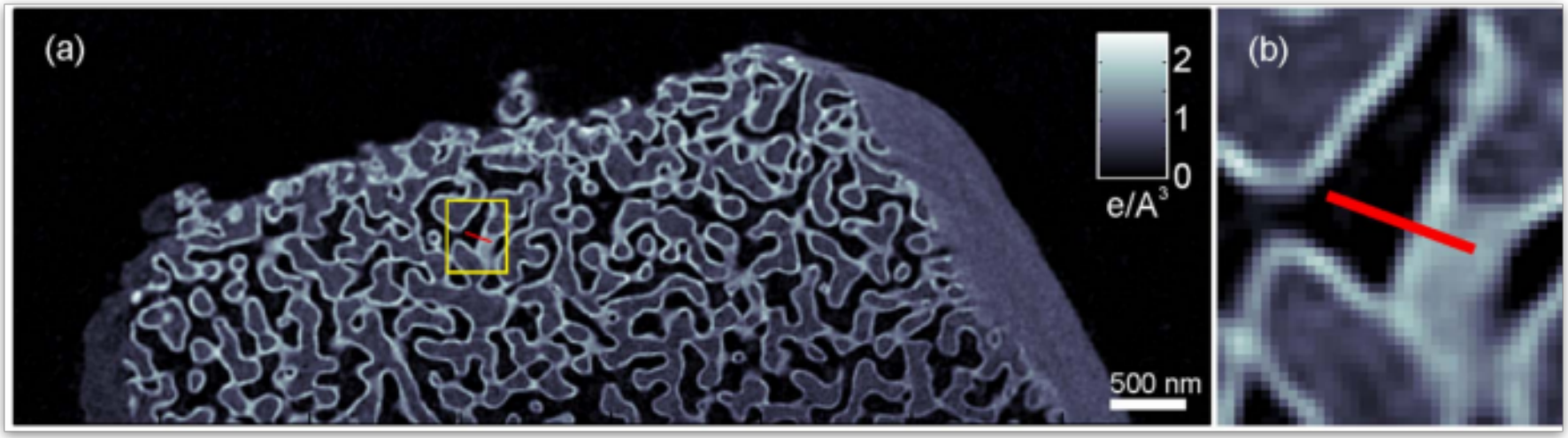
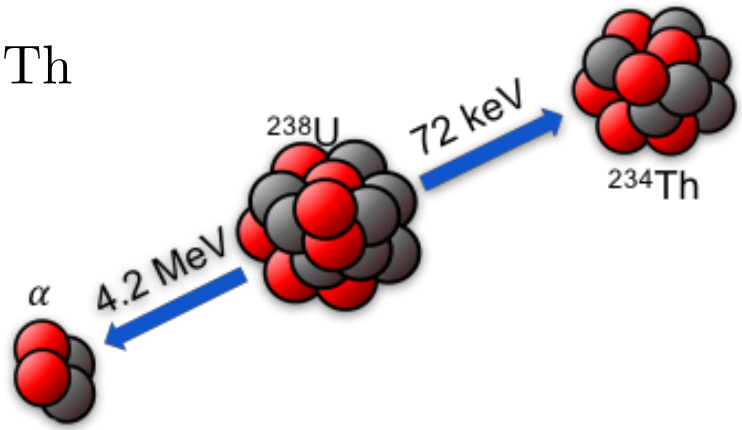


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Radiogenic backgrounds from ^{238}U contamination

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



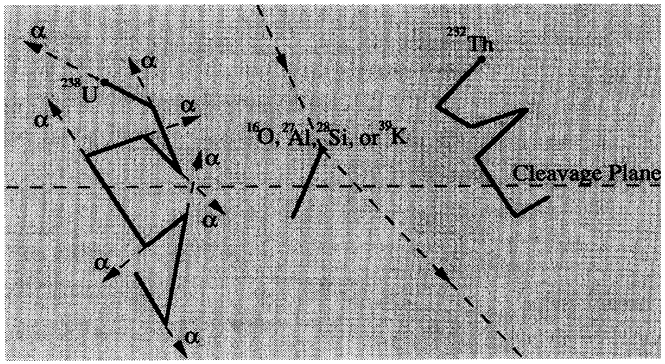
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %)	1.159 min
	IT (0.16 %)	
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

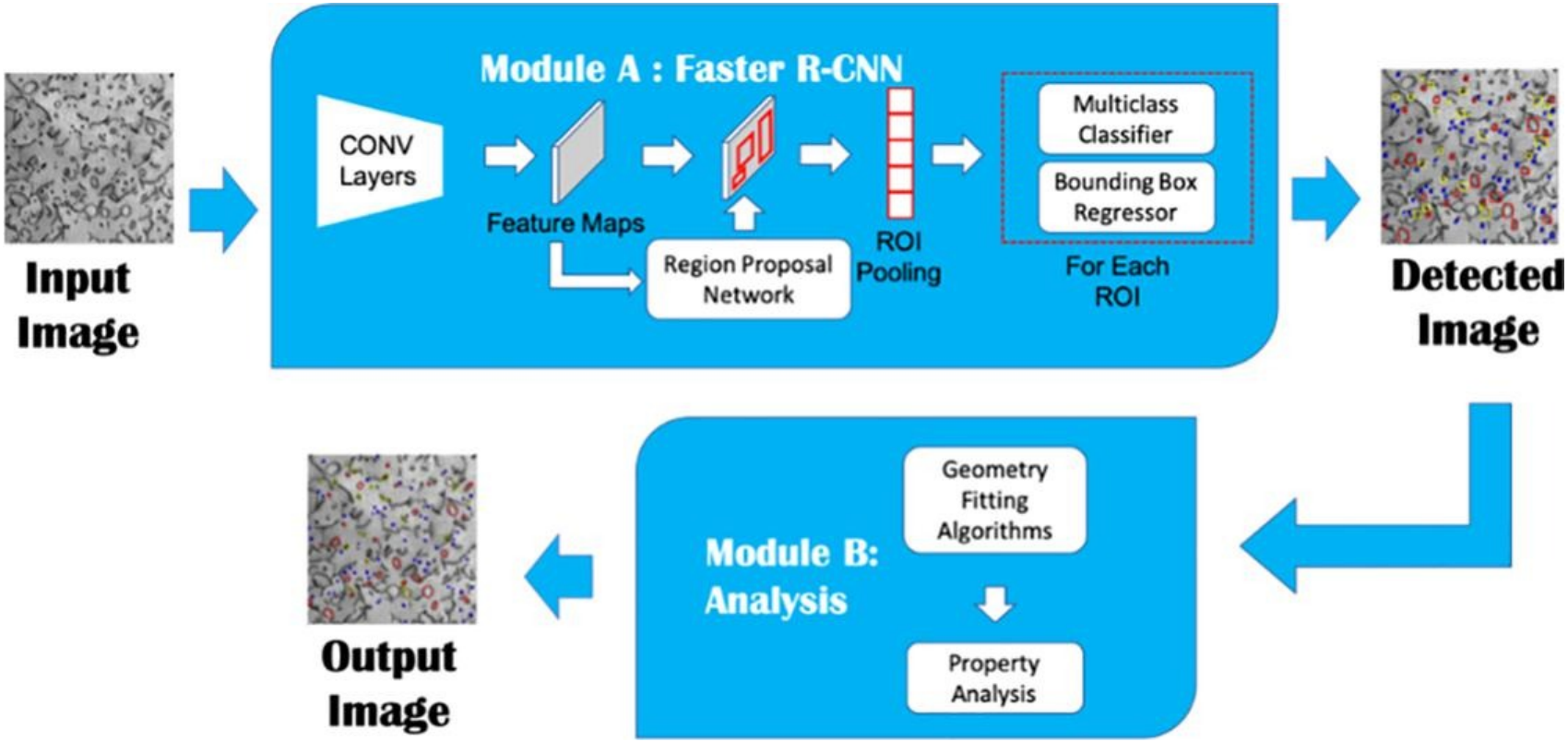
"1α" events difficult to reject without additional decays

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

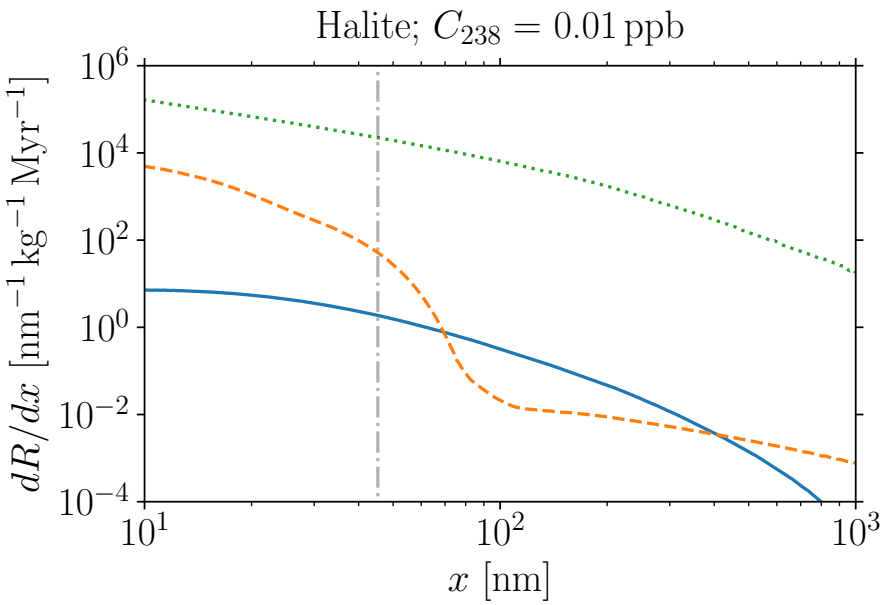
Quick aside on data analysis and α-recoil background

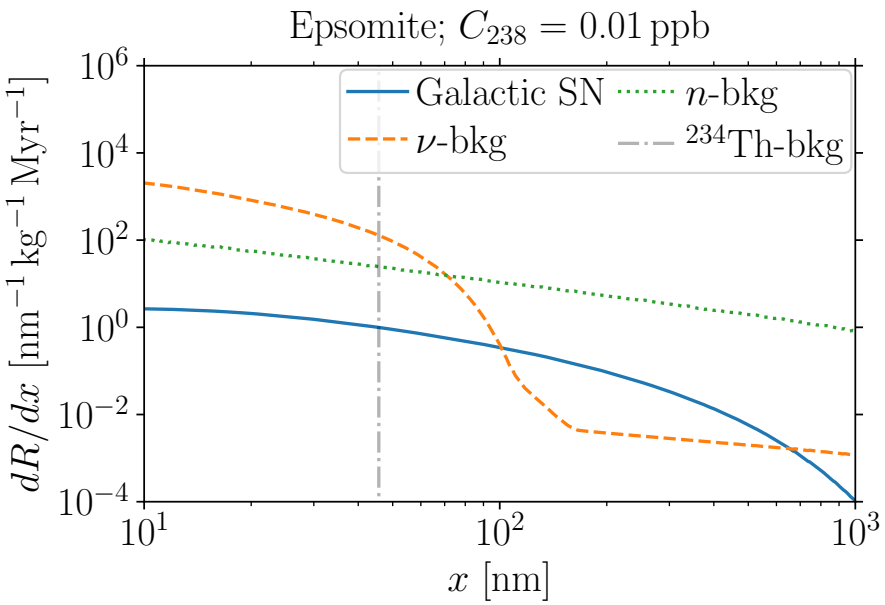
- 15 nm resolution of 100 g sample $\Rightarrow 10^{19}$ mostly empty voxels
- 1 Gyr old with $C^{238} = 0.01$ ppb $\Rightarrow 10^{13}$ voxels for α-recoil tracks





Track length spectra for detecting galactic CC SN ν's



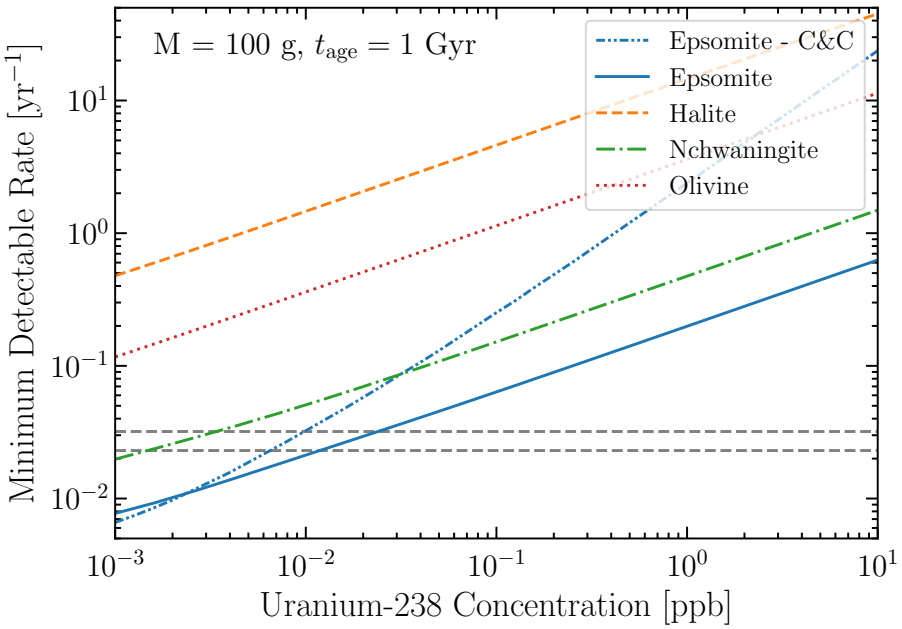


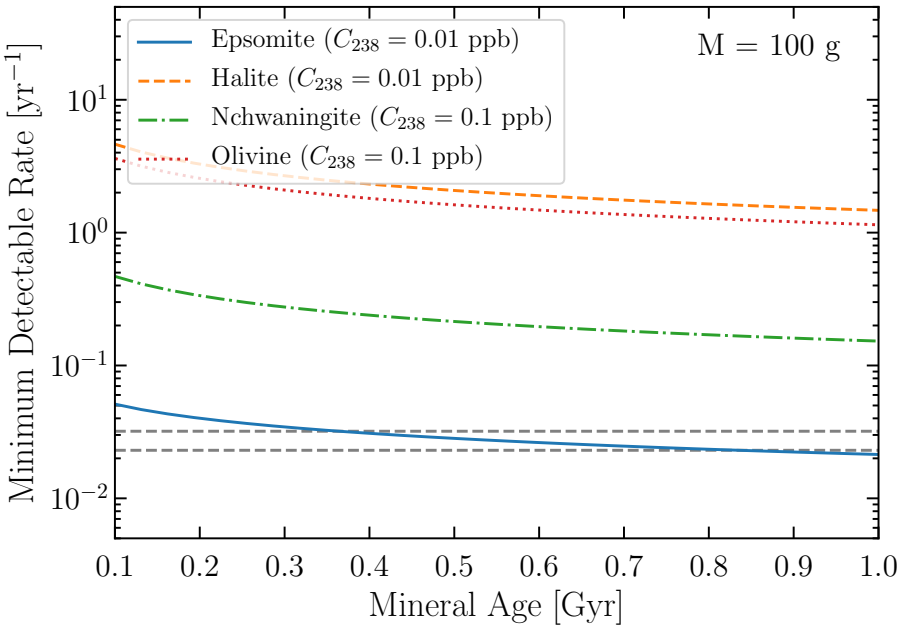
Large exposure probes rare events

- NOT background free, but can calibrate radiogenics in the lab
- Spectral information allows for reduction of bkg systematics

- Assume relative uncertainty 1% for normalization of n-bkg
- Solar and atmospheric ν-bkg assume 100% to account for time variation of fluxes

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

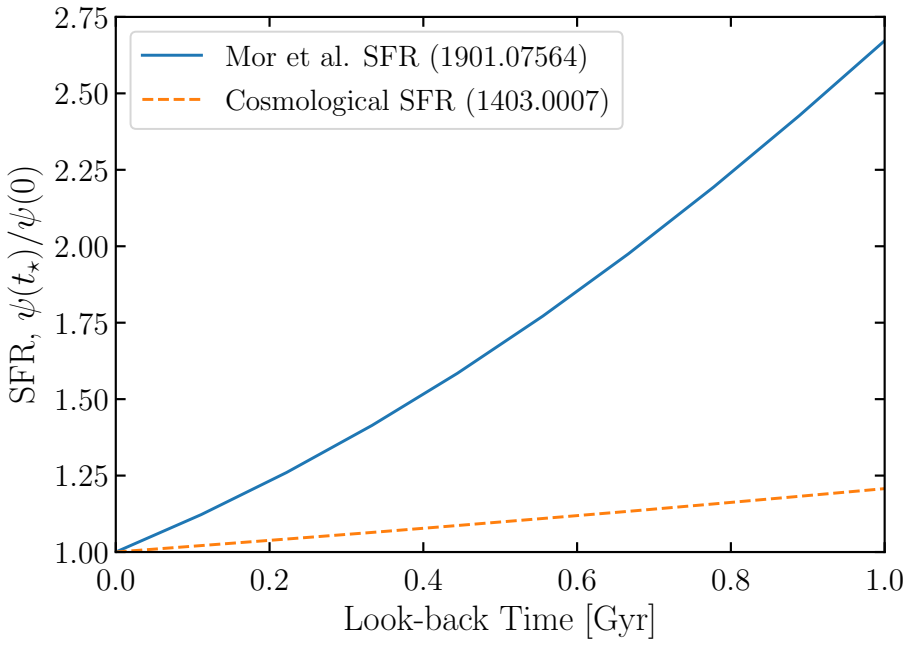


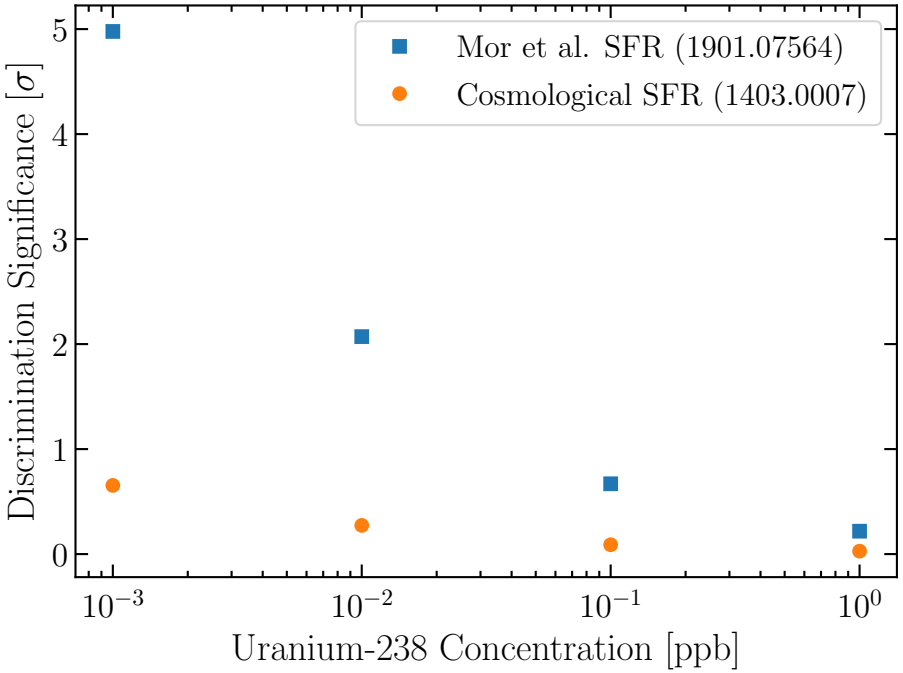


Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]

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





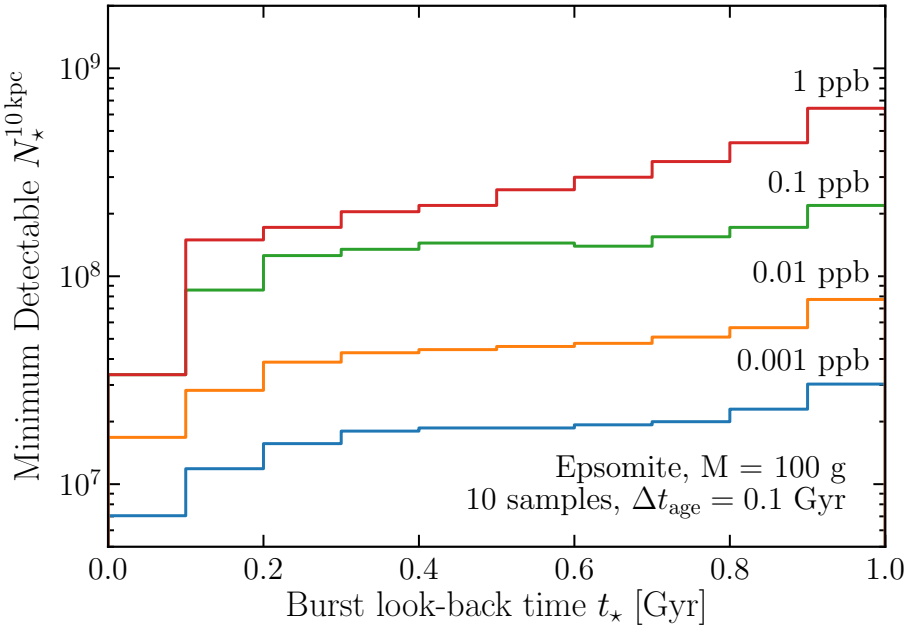
Coarse grained cumulative time bins

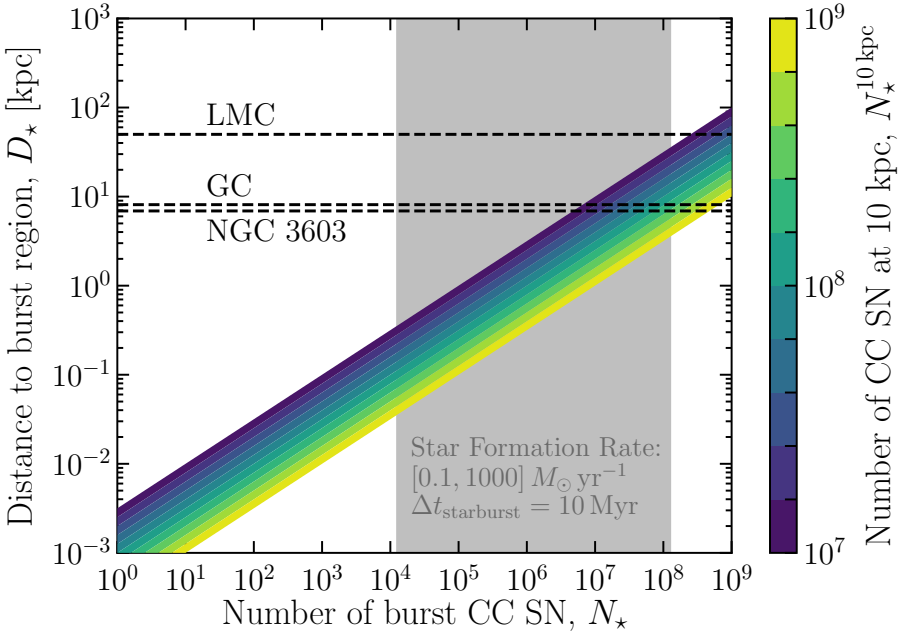
- 10 Epsomite mineral detectors
- 100 g each, $\Delta t_{\rm age} \simeq 100\,{\rm Myr}$

Determine σ rejecting constant rate

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

Probe time- and space-localized enhancements to CC SNR





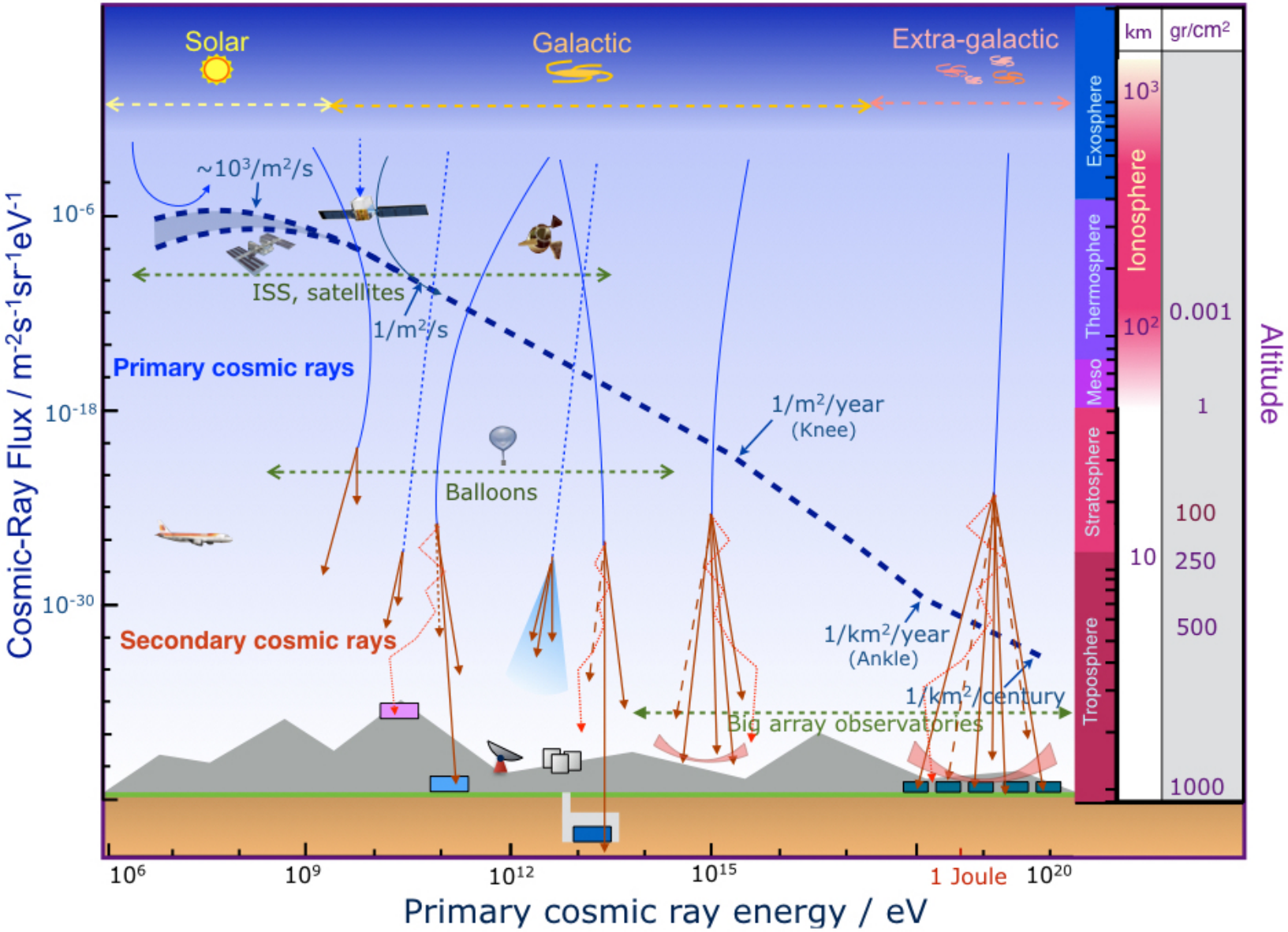
Starburst increases SFR by $\sim 10^3$

- Short duration $\Delta t \lesssim 10\,\mathrm{Myr}$
- Parameterized by N_* CC SNe, D_* to burst region, t_* ago

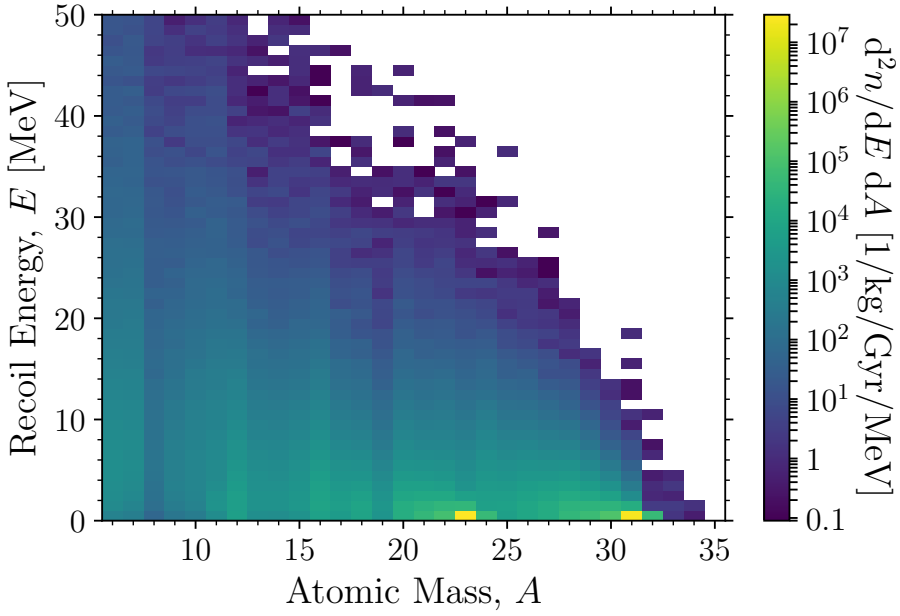
Discriminate against constant rate

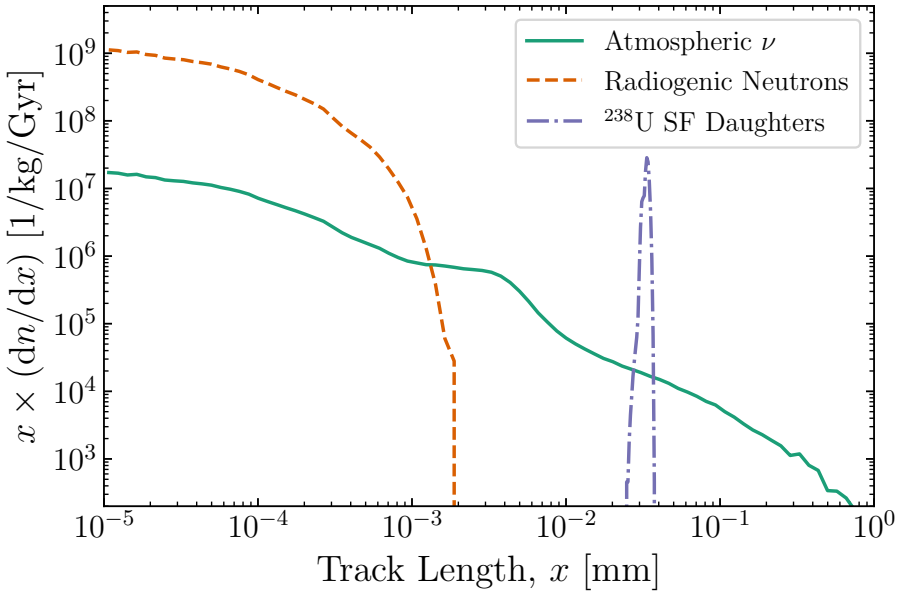
- Sensitive to starburst near GC
- Could detect $N_* = 1$ CC SN within last $\sim$Gyr if $D_* \lesssim 10\,\mathrm{pc}$

CRs brought to you by TRAGALDABAS, 1701.07277



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

Geomagnetic field deflects lower energy CR primaries

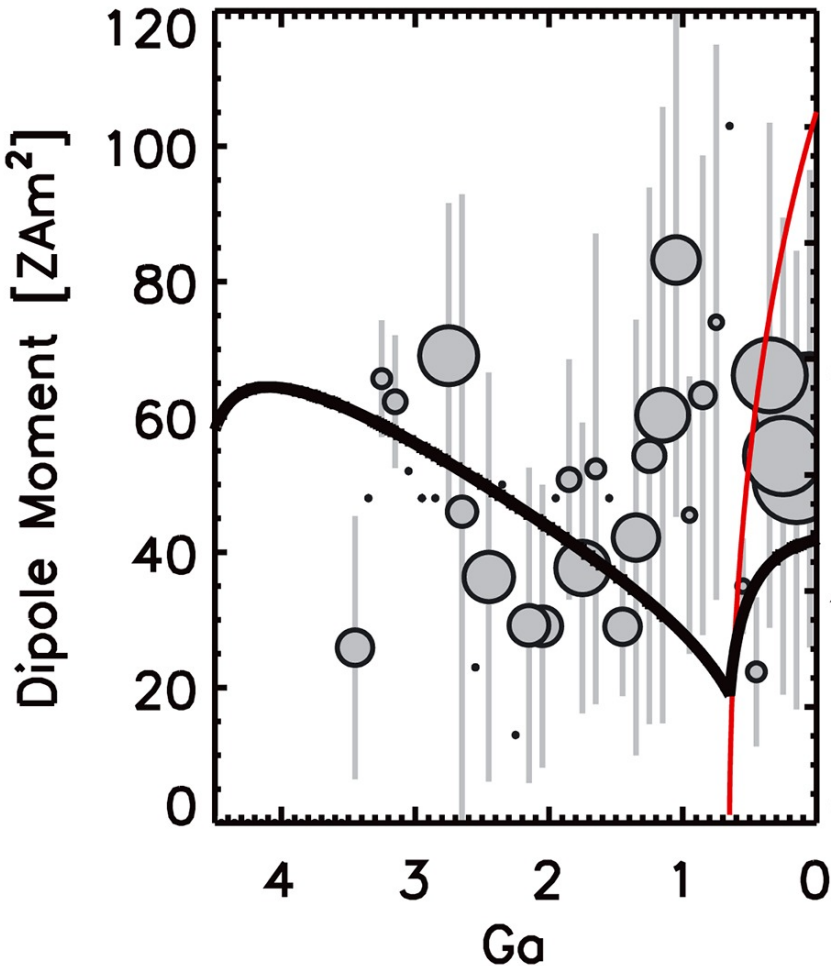
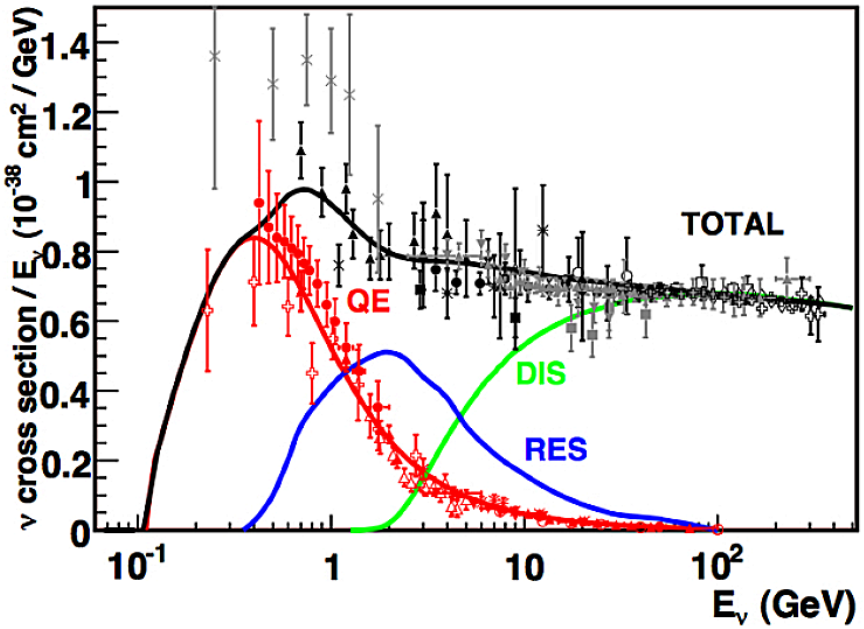


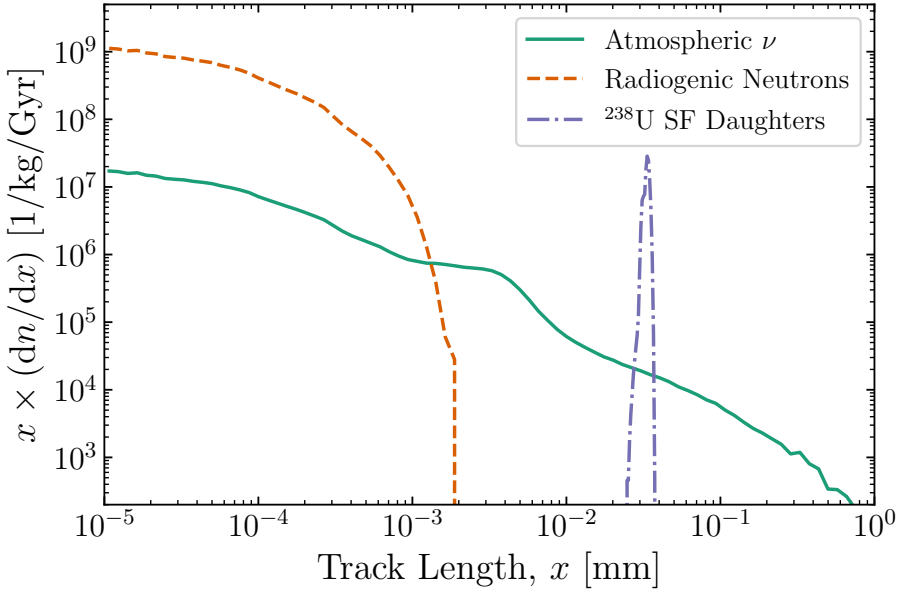
Figure: Driscoll, P. E. (2016), *Geophys. Res. Lett.*, 43, 5680-5687

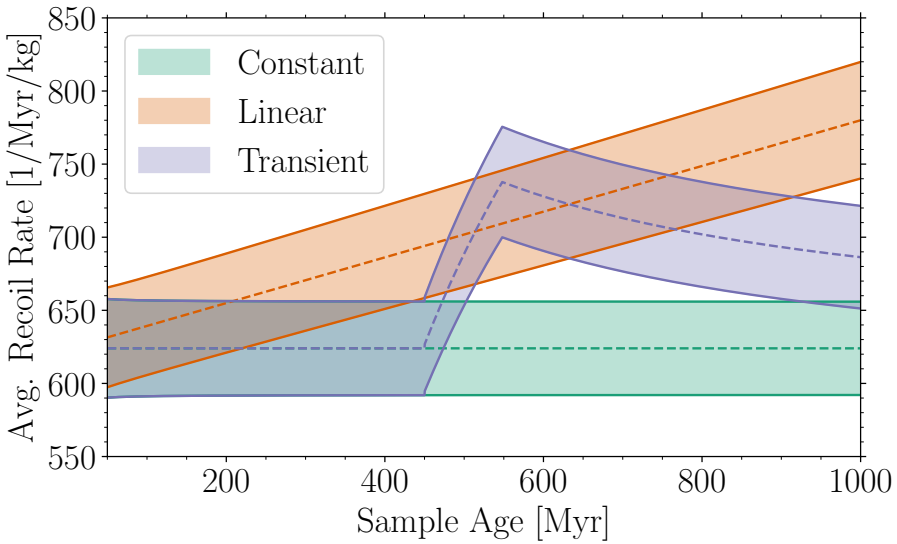
Rigidity $p_{CR}/Z_{CR} \simeq E_{CR}$ for CR protons

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



Atmospheric ν's yield recoils in background free regions





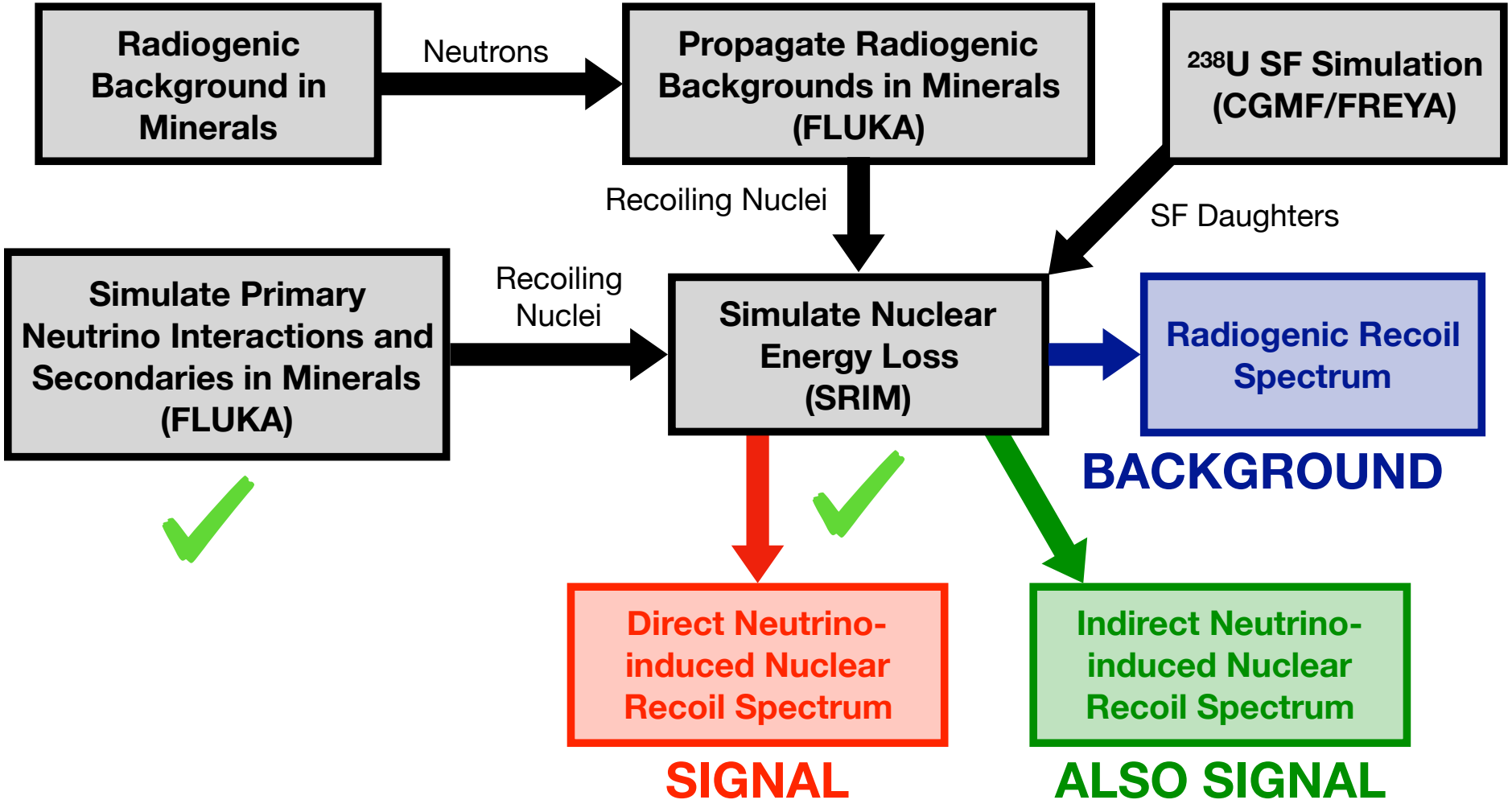
$N \sim 6 \times 10^4$ tracks in $100\,\mathrm{g} \times 1\,\mathrm{Gyr}$

- $2\,\mu\mathrm{m} \lesssim x \lesssim 20\,\mu\mathrm{m}$ potentially sensitive to geomagnetic effects
- $50\,\mu\mathrm{m} \lesssim x \lesssim 1\,\mathrm{mm}$ from DIS associated with $E_{CR} \gtrsim 100\,\mathrm{GeV}$

Series of halite targets with (M_i, t_i)

- Averaged recoil rate $N_i/t_i M_i$
- Sensitivity limited by geological history, read-out systematics
- Assume $\Delta_t = 5\%$, $\Delta_M = 1\%$

Simulation chain for calculation of atmospheric ν's



Semi-analytic range calculations and SRIM agree with data

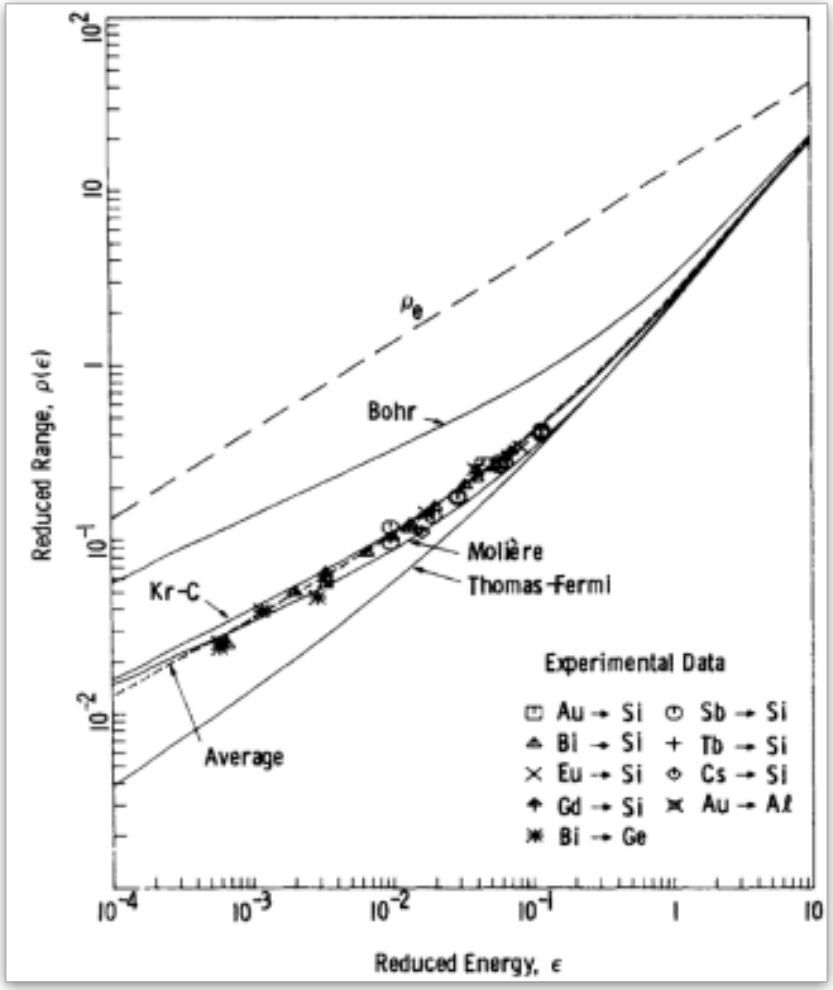


Figure: Wilson, Haggmark+ '76