Paleo-detectors for Galactic SN Neutrinos

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1906.05800 with S. Baum, T. Edwards, B. Kavanagh, A. Drukier, K. Freese, M. Górski and C. Weniger
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Galactic CC SN ν's can induce recoils in paleo-detectors

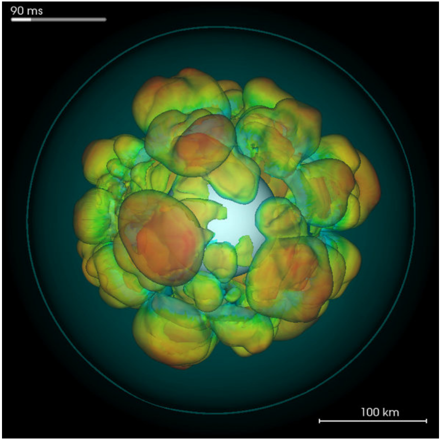
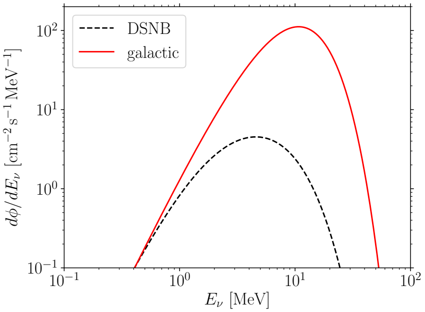


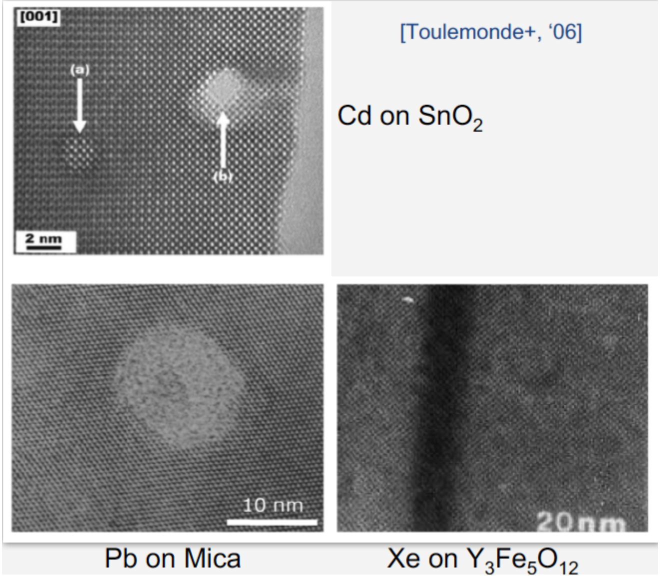
Figure: Supernova simulation after CC

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

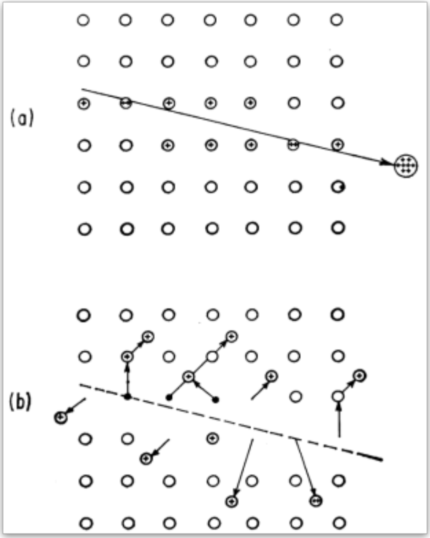
- Measure galactic CC SN rate
- Traces star formation history



Modern TEM allows for accurate characterization of tracks

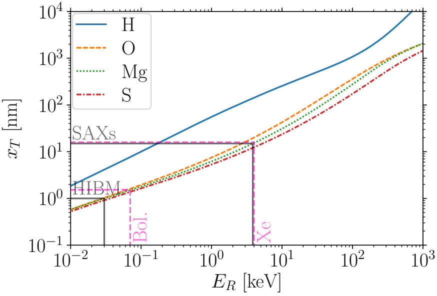


Paleo-detectors look for damage from recoiling nuclei



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

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

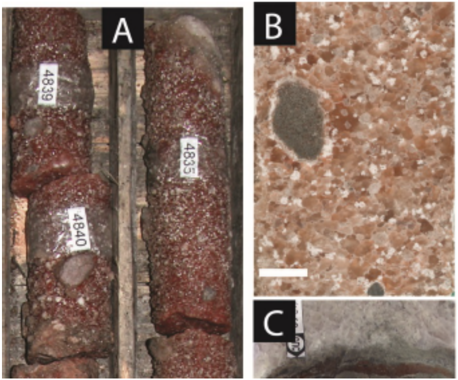
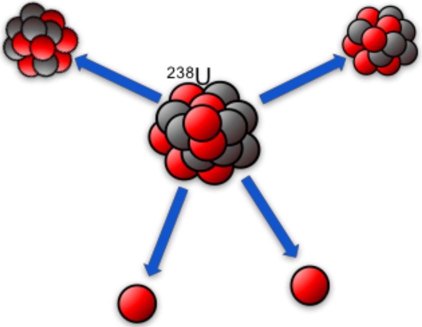
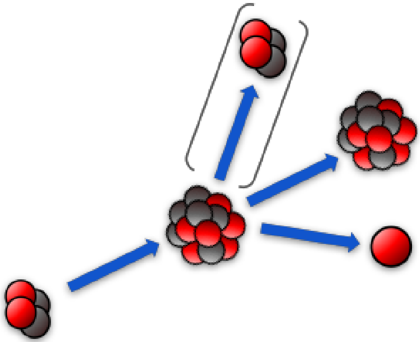


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

Fast neutrons from SF and (α, n) interactions





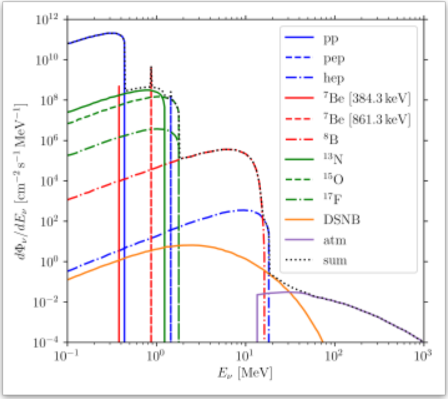
SF yields ~ 2 neutrons with $\sim$MeV

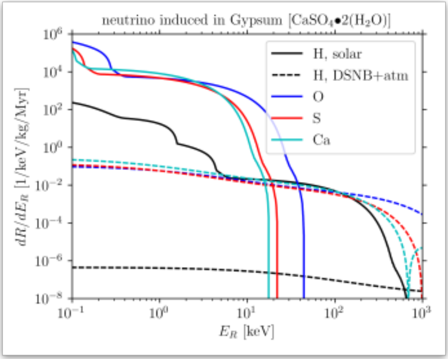
Each neutron will scatter elastically 10-1000 times before moderating

(α, n) rate low, many decay α's

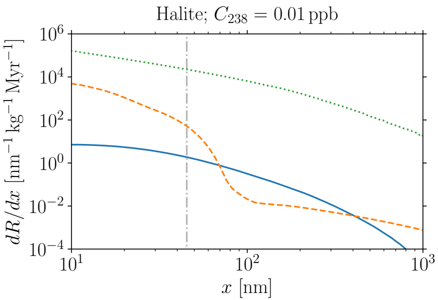
Heavy targets better for (α, n) and bad for neutron moderation, need H

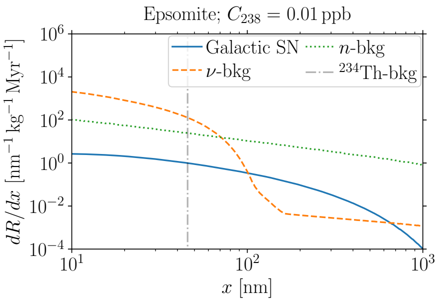
Solar and atmospheric ν background recoils bracket signal





Track length spectra for detecting galactic CC SN ν's





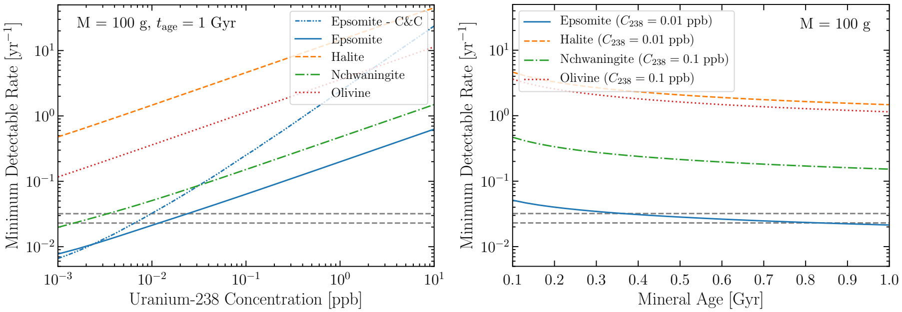
Backgrounds in hydrated MEs

- Relatively flat n-bkg extends out to longer track lengths
- Shorter track lengths dominated by solar ν's

Background systematics

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

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

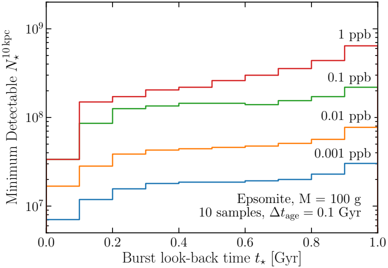


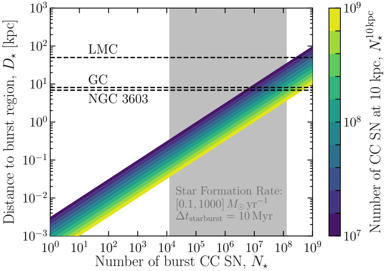
Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]
Nchwaningite [$Mn_2^{2+}SiO_3(OH)_2\cdot(H_2O)$]
Olivine [$Mg_{1.6}Fe_{0.4}^{2+}(SiO_4)$]

Large ϵ probes rare events

- NOT background free
- Spectral information $\Rightarrow$ reduction of systematics

Probe time averaged or localized star formation history





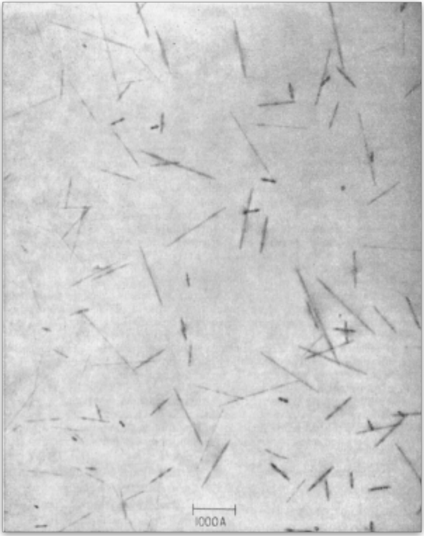
Searches for WIMPs and other ν's

- Sensitivity to DM potentially competitive with next generation DD experiments
- Could measure evolution of solar/atmospheric ν flux and probe history of sun/cosmic rays

Feasability of paleo-detectors

- Need model of geological history
- Preliminary mass spec indicates MEs with $C^{238} \lesssim 0.1$ ppb
- Determine efficiency of effective 3D recoil track reconstruction

Fission fragments can be seen by TEM/optical microscopes



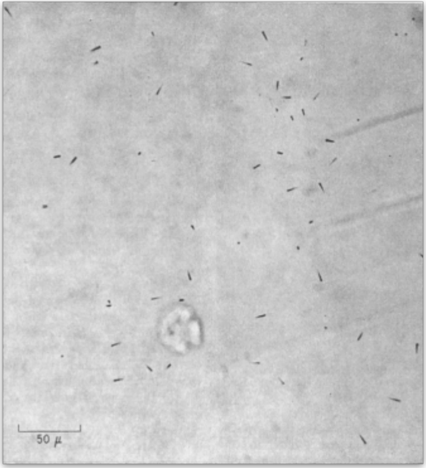


Figure: Price+Walker '63

Semi-analytic range calculations and SRIM agree with data

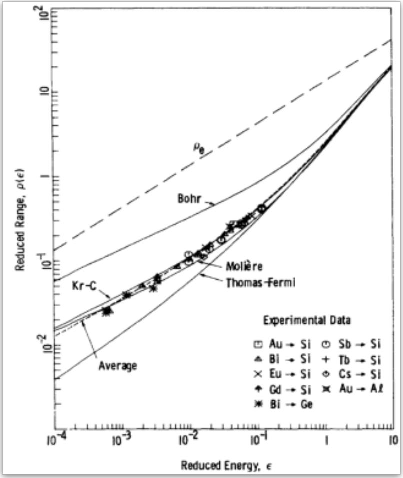
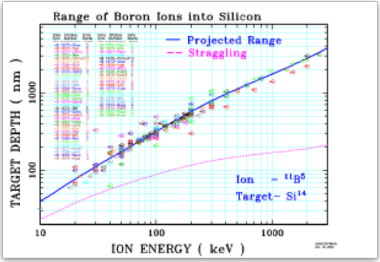
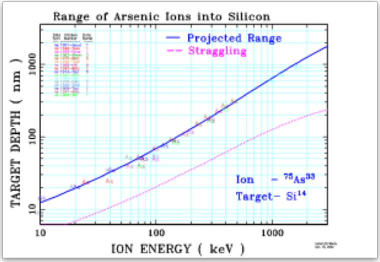


Figure: Wilson, Haggmark+ '76

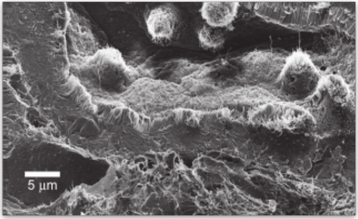




Cleaving and etching limits ϵ and can only reconstruct 2D

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



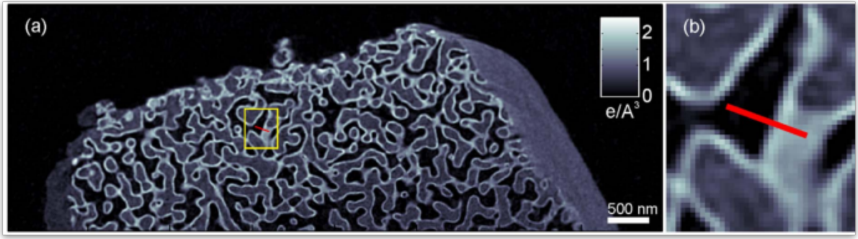
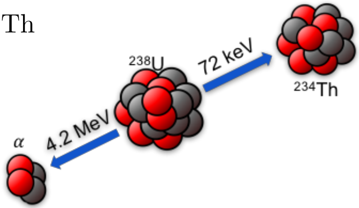


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Radiogenic backgrounds from ^{238}U contamination

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

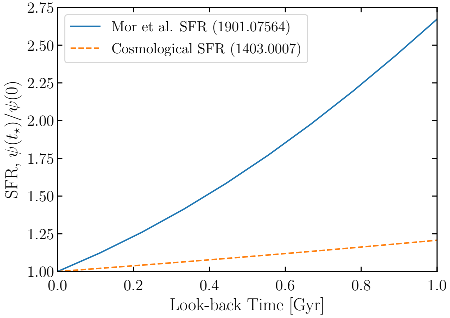


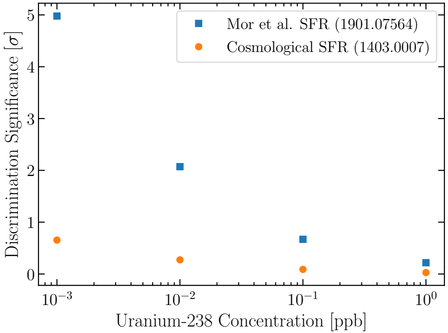
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %)	1.159 min
	IT (0.16 %)	
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

"1α" events difficult to reject without additional decays

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

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