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
1911.maybe with S. Baum, J. Jordan, P. Sala and J. Spitz

Galactic CC SN ν's can induce recoils in paleo-detectors

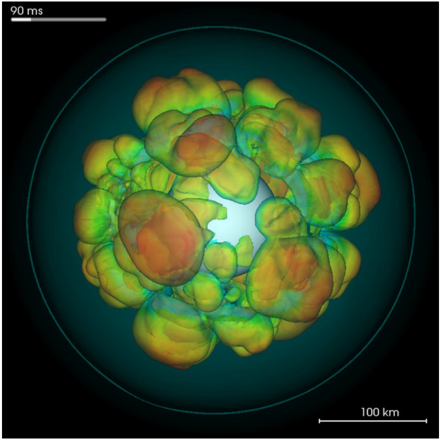
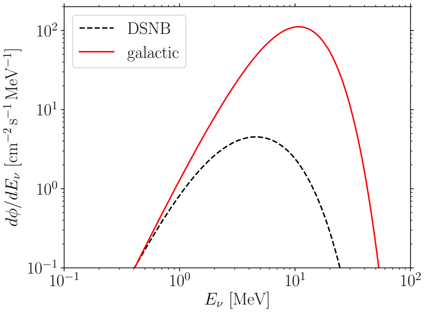


Figure: Supernova simulation after CC

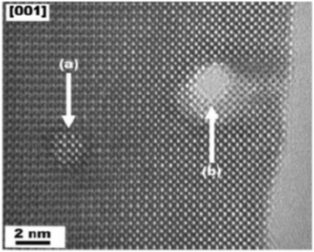
Only $\sim$ 2 SN 1987A events/century

- Measure galactic CC SN rate
- Traces star formation history

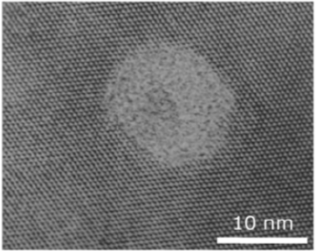


Modern TEM allows for accurate characterization of tracks

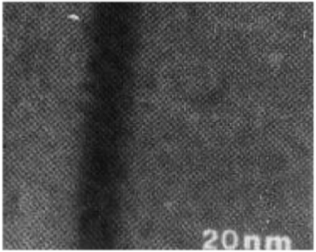
[Toulemonde+, '06]



Cd on SnO_2

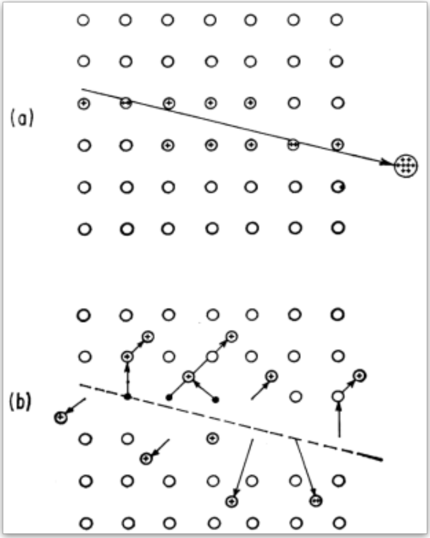


Pb on Mica



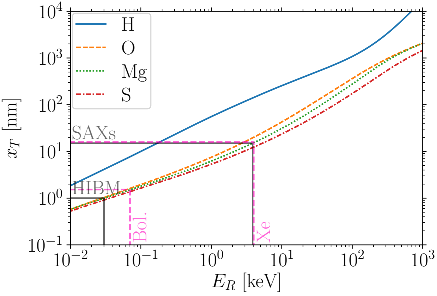
Xe on $Y_3Fe_5O_{12}$

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

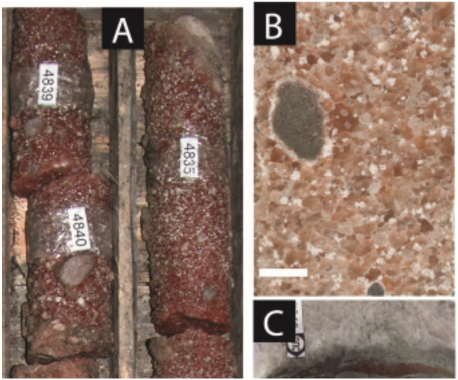
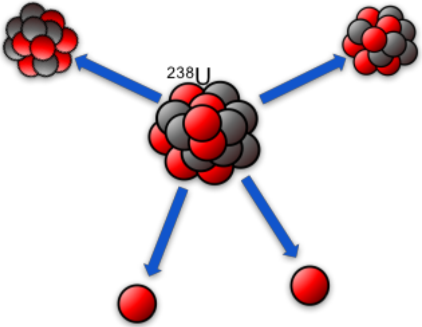
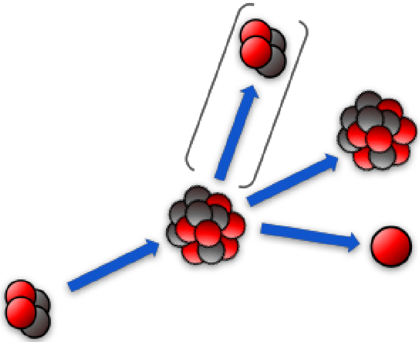


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

Fast neutrons from SF and (α, n) interactions





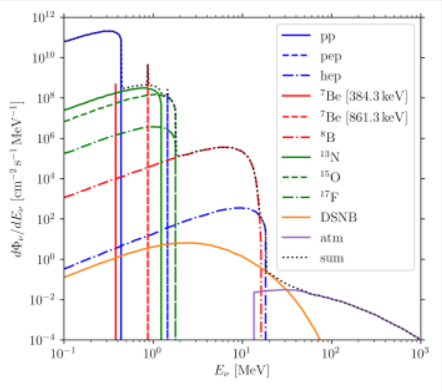
SF yields ~ 2 neutrons with $\sim$MeV

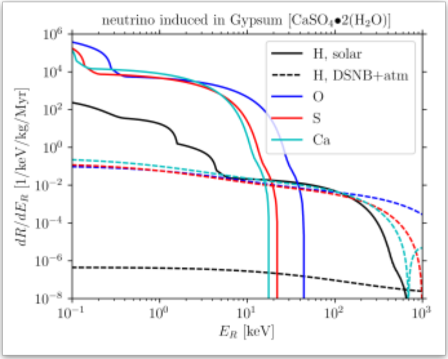
Each neutron will scatter elastically 10-1000 times before moderating

(α, n) rate low, many decay α's

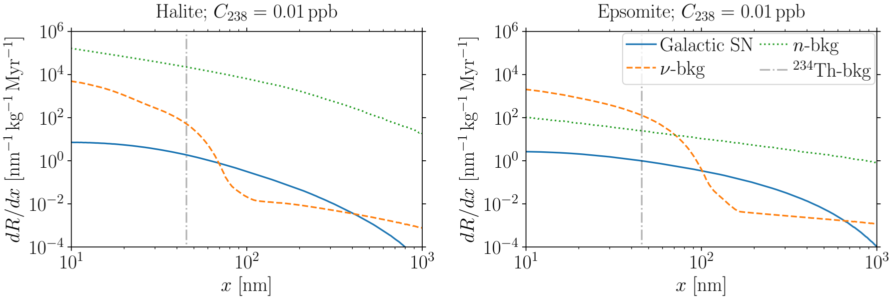
Heavy targets better for (α, n) and bad for neutron moderation, need H

Solar and atmospheric ν background recoils bracket signal





Track length spectra for detecting galactic CC SN ν's



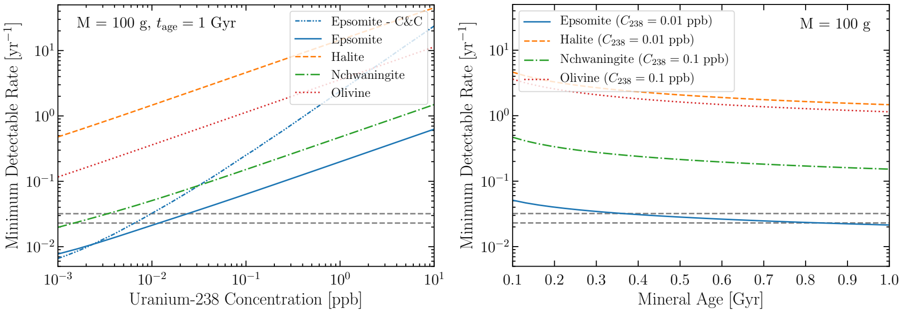
Backgrounds in hydrated MEs

- 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}

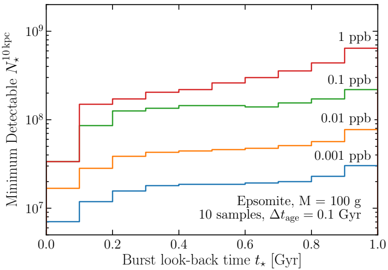


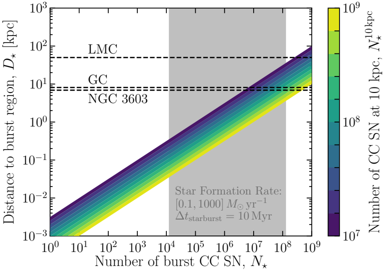
Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]
Nchwaningite [$Mn_2^{2+}SiO_3(OH)_2\cdot(H_2O)$]
Olivine [$Mg_{1.6}Fe_{0.4}^{2+}(SiO_4)$]

Large ϵ probes rare events

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

Probe time averaged or localized star formation history





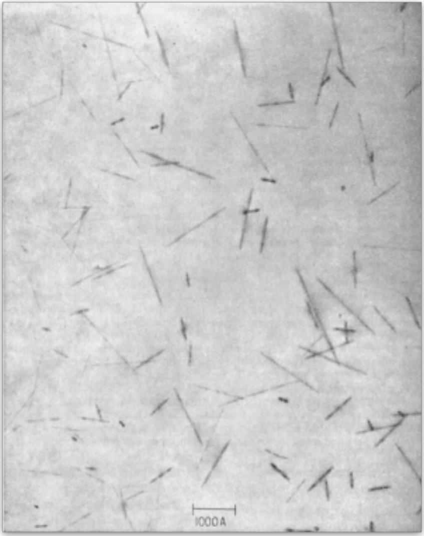
Searches for WIMPs and other ν's

- 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 $C^{238} \lesssim 0.1\,\text{ppb}$
- Determine efficiency of effective 3D recoil track reconstruction

Fission fragments can be seen by TEM/optical microscopes



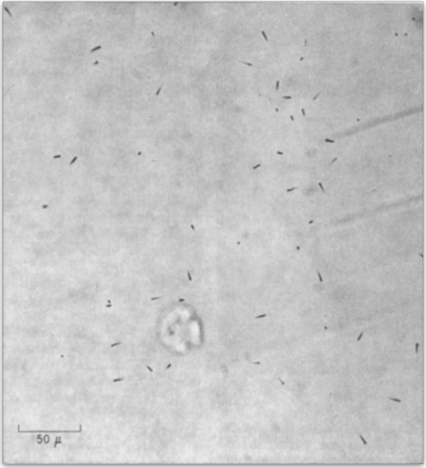


Figure: Price+Walker '63

Semi-analytic range calculations and SRIM agree with data

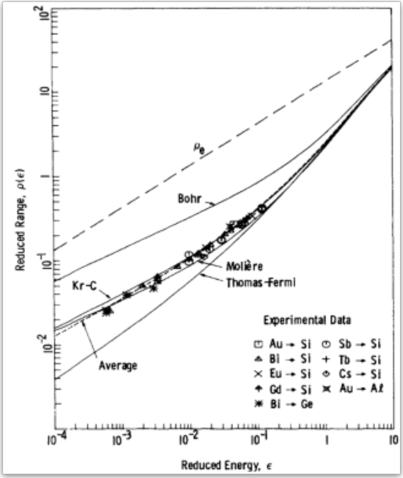
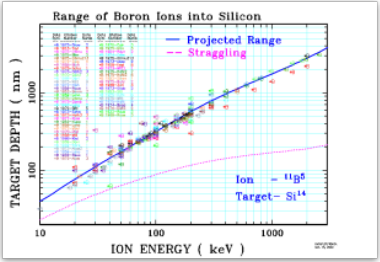
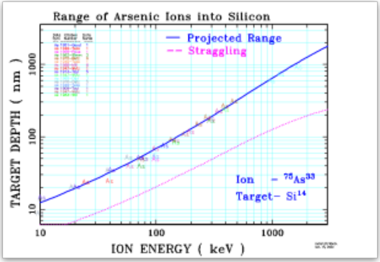


Figure: Wilson, Haggmark+ '76

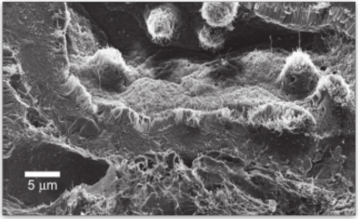




Cleaving and etching limits ϵ and can only reconstruct 2D

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



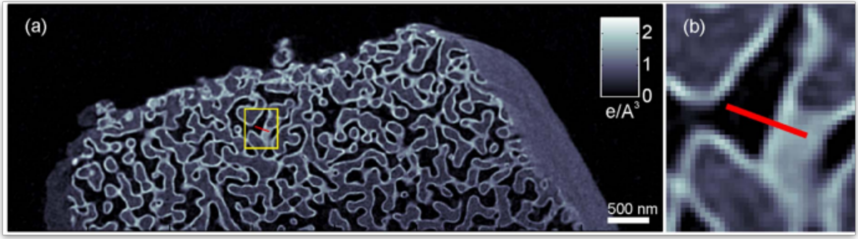
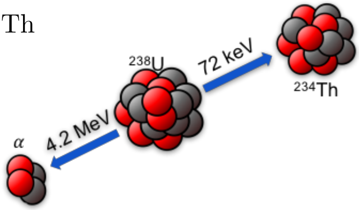


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Radiogenic backgrounds from ^{238}U contamination

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

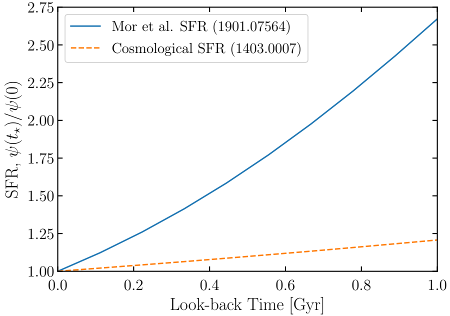


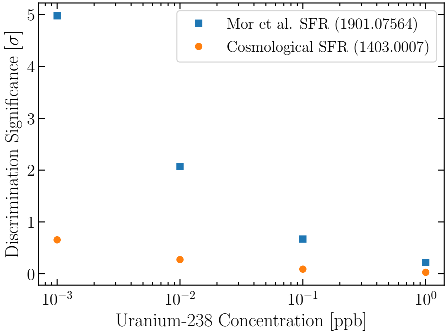
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %)	1.159 min
	IT (0.16 %)	
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

"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, $\Delta t_{\mathrm{age}} \simeq 100$ 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