Paleo-detectors for Galactic Supernovae and Atmospheric Neutrinos

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1906.05800 [galactic SN ν's] with S. Baum, T.D.P. Edwards, B.J. Kavanagh, A.K. Drukier, K. Freese, M. Górski and C. Weniger
2004.08394 [atmospheric ν's] with J.R. Jordan, S. Baum, A. Ferrari, M.C. Marone, P. Sala and J. Spitz

Outline

1. Supernovae, cosmic rays, neutrinos and their interactions
2. Tracks in ancient minerals
   - Solid state track detectors
   - Problematic backgrounds
3. Projected sensitivity of paleo-detectors
   - Galactic CC SN ν's
   - Atmospheric ν's
4. Summary and outlook

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

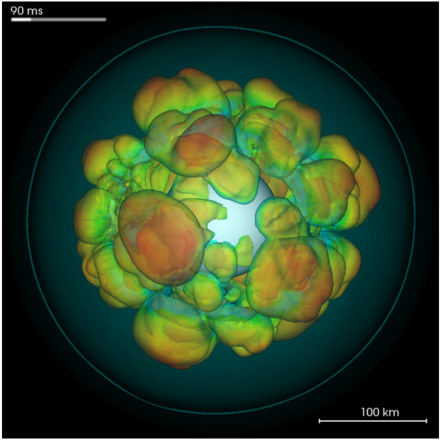


Figure: Supernova simulation after CC

CC SNe primarily in stellar disk

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

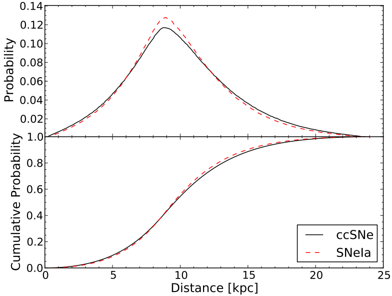


Figure: Distribution of galactic SNe at distance from Earth $f(R_E)$, 1306.0559

Galactic contribution to ν flux over geological timescales

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

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

- Measure galactic CC SN rate
- Traces star formation history

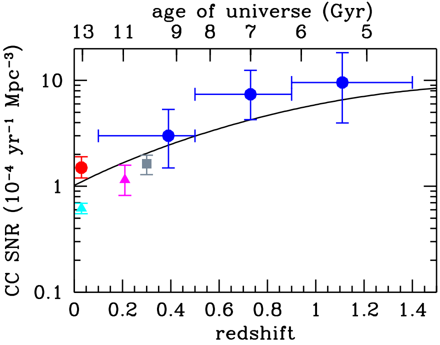
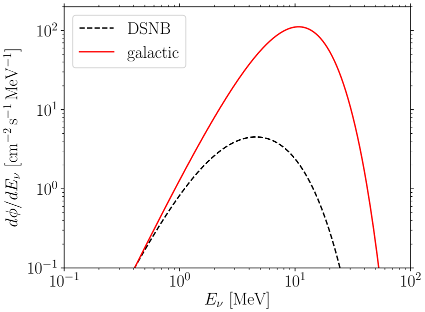
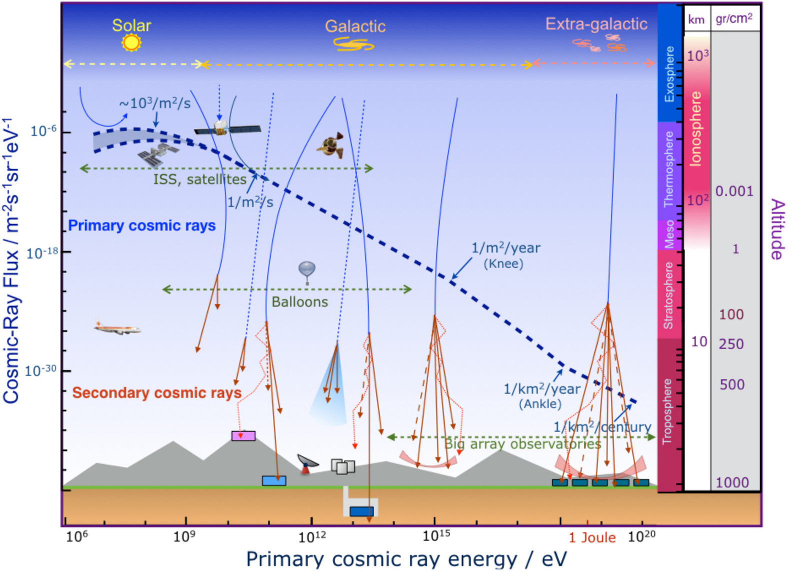


Figure: Cosmic CC SNR, 1403.0007



CRs brought to you by TRAGALDABAS, 1701.07277



Flux of atmospheric ν's originating from CR interactions

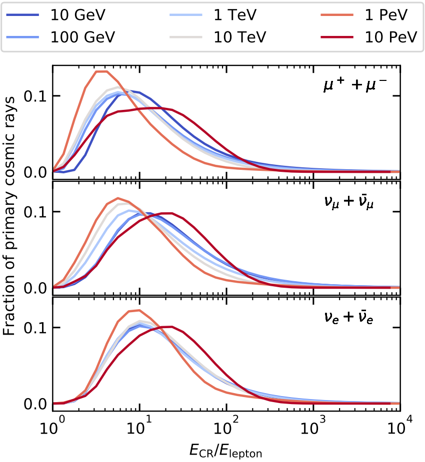


Figure: E_{CR} to leptons, 1806.04140

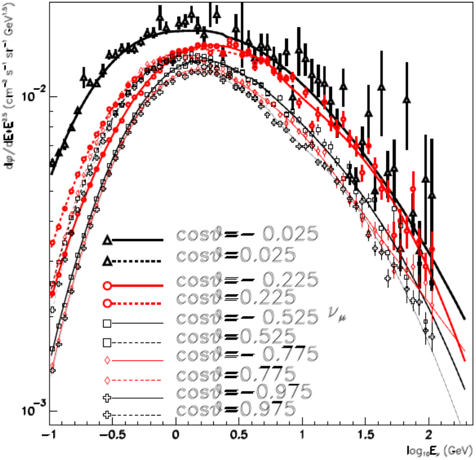


Figure: FLUKA simulation of ν_μ flux at SuperK for solar max, hep-ph/0207035

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

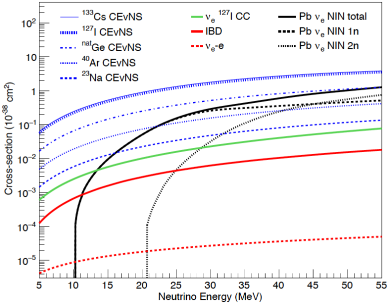


Figure: COHERENT, 1803.09183

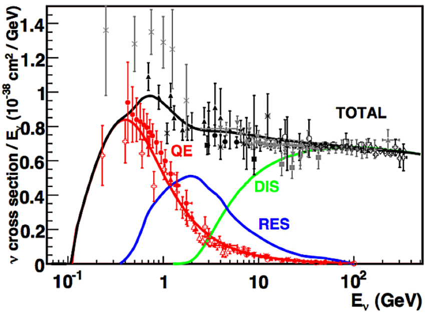
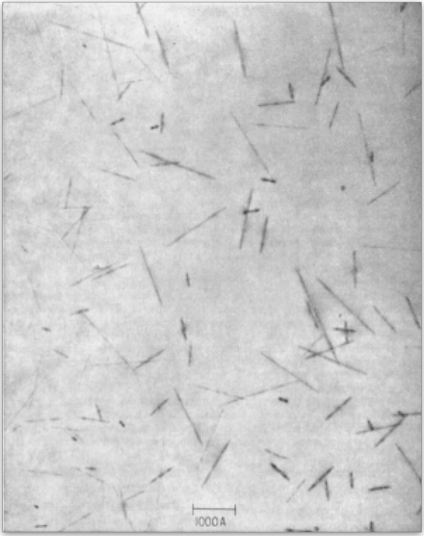


Figure: Inclusive CC $\sigma_{\nu N}$, 1305.7513

Fission fragments can be seen by TEM/optical microscopes



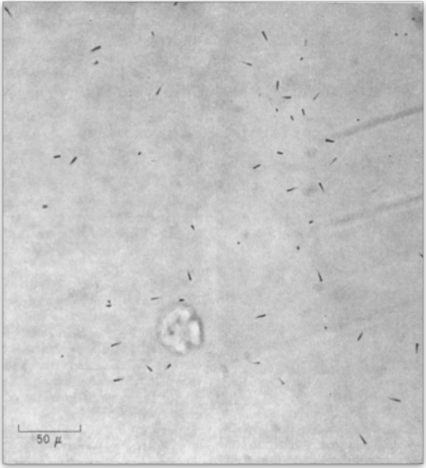
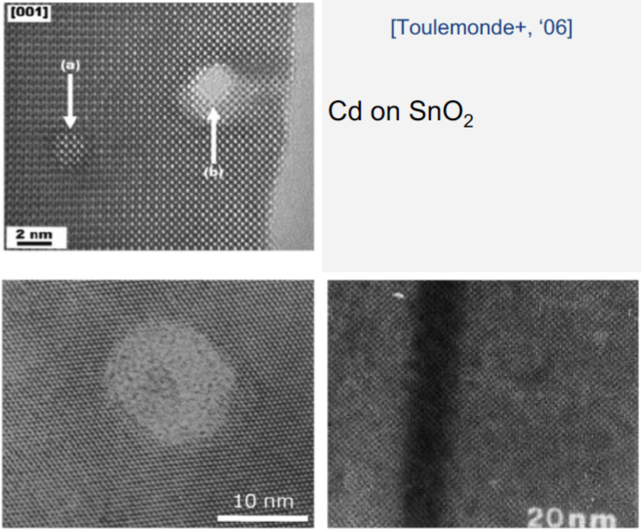


Figure: Price+Walker '63

Modern TEM allows for accurate characterization of tracks

[Toulemonde+, '06]



Cd on SnO_2

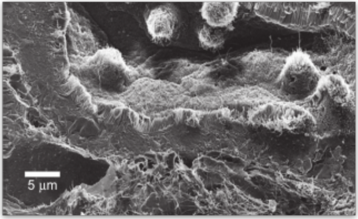
Pb on Mica

Xe on $Y_3Fe_5O_{12}$

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



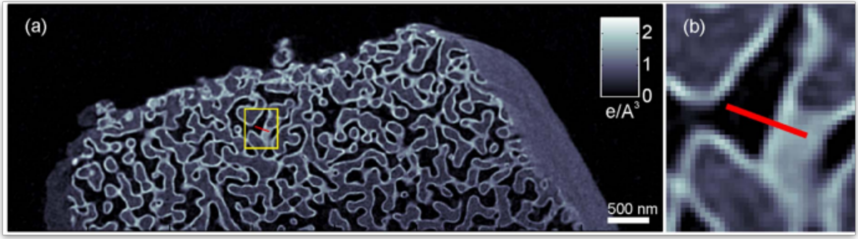
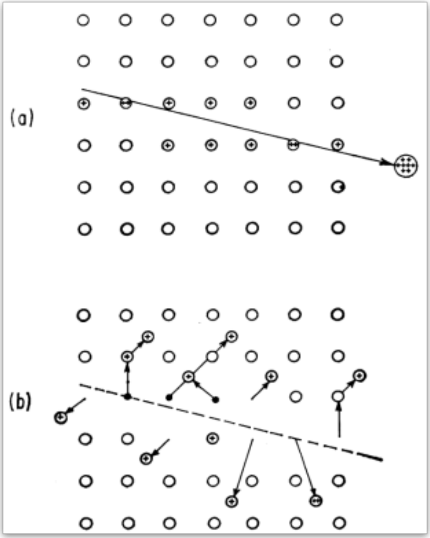


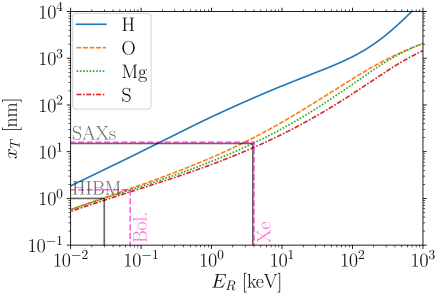
Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

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

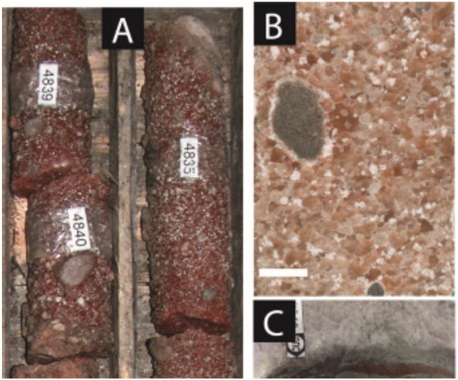


Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

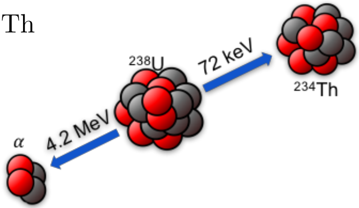
Depth	Neutron Flux
2 km	$10^6/\mathrm{cm}^2/\mathrm{Gyr}$
5 km	$10^2/\mathrm{cm}^2/\mathrm{Gyr}$
6 km	$10/\mathrm{cm}^2/\mathrm{Gyr}$
50 m	$70/\mathrm{cm}^2/\mathrm{yr}$
100 m	$30/\mathrm{cm}^2/\mathrm{yr}$
500 m	$2/\mathrm{cm}^2/\mathrm{yr}$

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

Radiogenic backgrounds from ^{238}U contamination

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

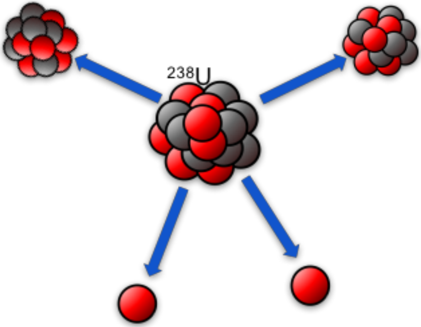


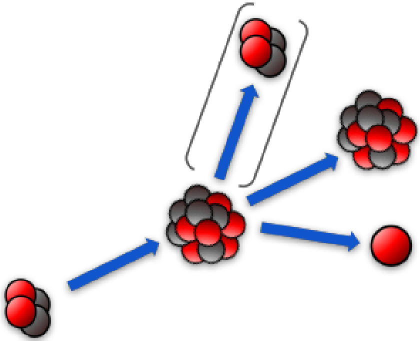
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr

"1α" events difficult to reject without additional decays

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

Neutrons and fragments from SF and (α, n) interactions





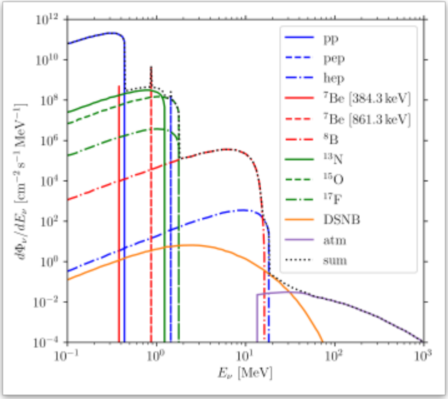
$\sim$MeV n's, $\sim$10 MeV fragments

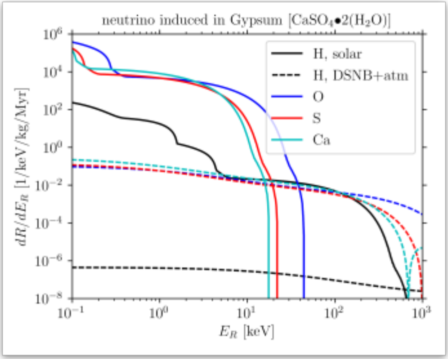
Neutrons scatter $\mathcal{O}(100)$ times, filter monoenergetic fragments

(α, n) rate low, many decay α's

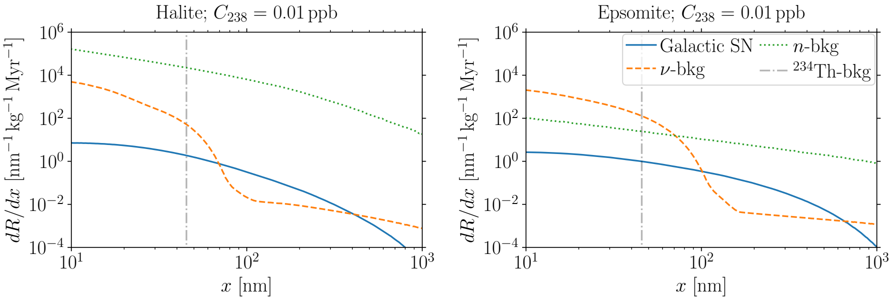
Heavy targets better for (α, n) and bad for neutron moderation, need H

Solar and atmospheric ν's bracket galactic CC SN signal





Track length spectra for detecting galactic CC SN ν's

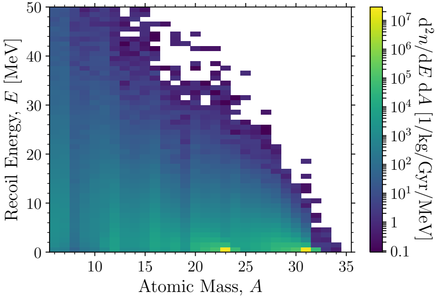


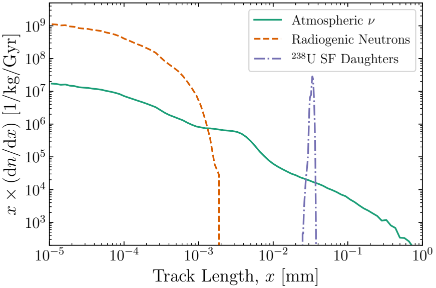
Large exposure probes rare events

- 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

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

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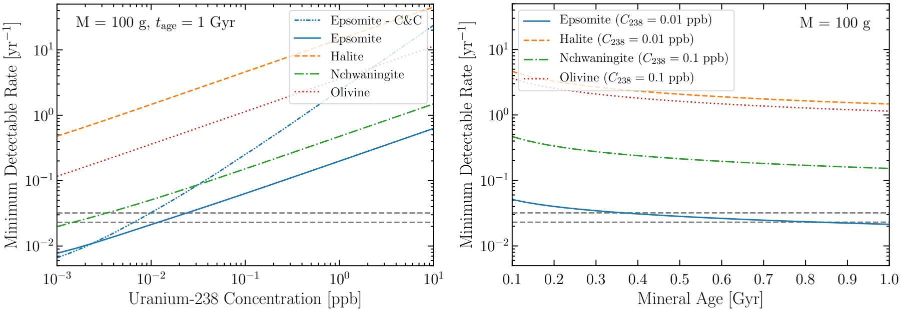
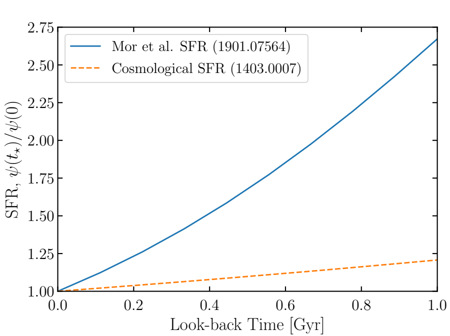
Sensitivity to galactic CC SN rate depends on C^{238}

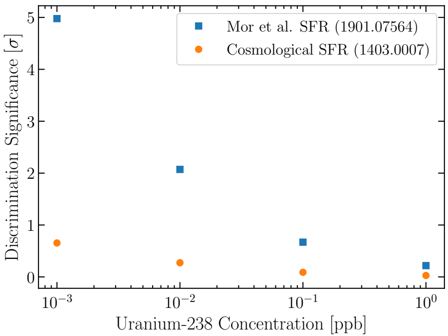


Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]

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





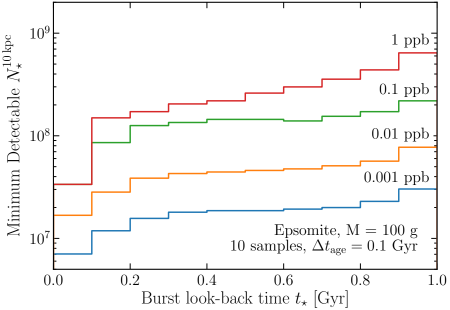
Coarse grained cumulative time bins

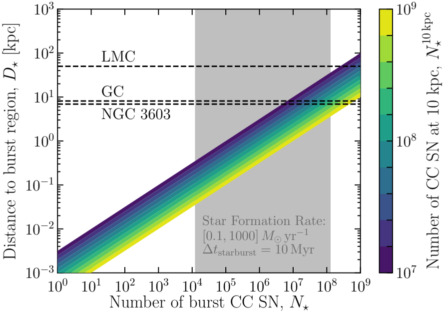
- 10 Epsomite paleo-detectors
- 100 g each, $\Delta t_{\rm age} \simeq 100$ Myr

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

Probe time- and space-localized enhancements to CC SNR





Starburst increases SFR by $\sim 10^3$

- Short duration $\Delta t \lesssim 10$ 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 $D_* \lesssim 10$ pc

Geomagnetic field deflects lower energy CR primaries

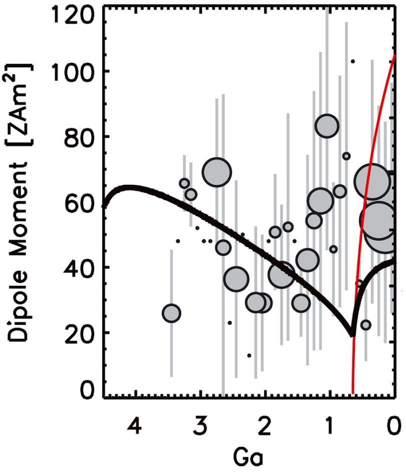
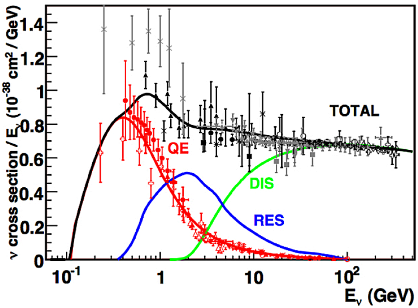


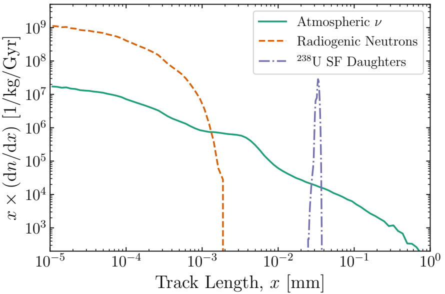
Figure: Driscoll, P. E. (2016), *Geophys. Res. Lett.*, 43, 5680-5687

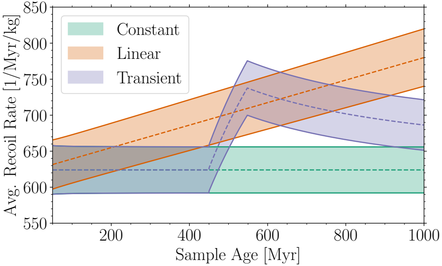
Rigidity $p_{CR}/Z_{CR} \simeq E_{CR}$ for CR protons

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



Could use large exposure to differentiate between scenarios





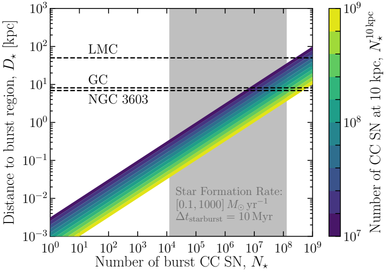
$N \sim 6 \times 10^4$ tracks in $100\,\mathrm{g} \times 1\,\mathrm{Gyr}$

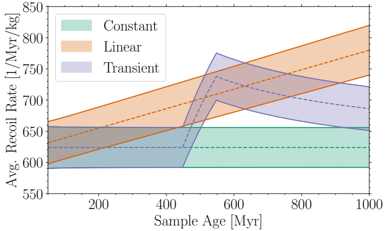
- $2\,\mu\mathrm{m} \lesssim x \lesssim 20\,\mu\mathrm{m}$ potentially sensitive to geomagnetic effects
- $50\,\mu\mathrm{m} \lesssim x \lesssim 1\,\mathrm{mm}$ from DIS associated with $E_{CR} \gtrsim 100$ GeV

Series of halite targets with (M_i, t_i)

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

Paleo-detectors use ν's to probe the evolution of our galaxy





Feasability of paleo-detectors

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

Searches for WIMPs and other ν's

- Sensitivity to DM potentially competitive with next generation DD experiments
- Could probe DM substructure
- Solar ν flux over last $\sim$Gyr

Semi-analytic range calculations and SRIM agree with data

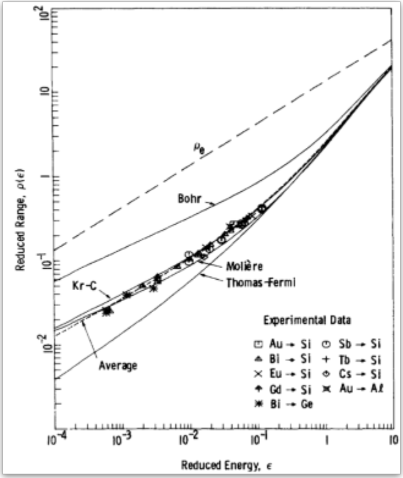
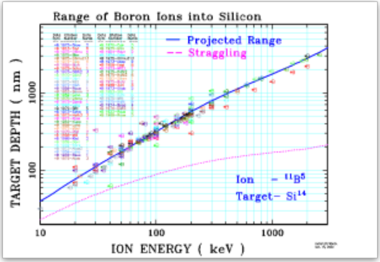
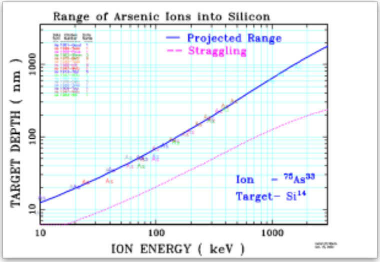


Figure: Wilson, Haggmark+ '76





Simulation chain for calculation of atmospheric ν's