Mineral Detection of Neutrinos and Dark Matter

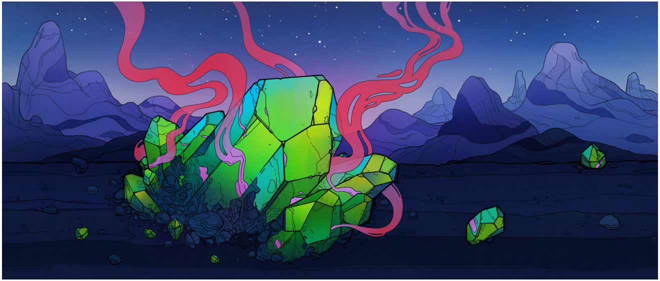

Figure: Olena Shmahalo/Quanta Magazine

Jožef Stefan Institute
Ljubljana, Slovenia

SMASH
machine learning for science and humanities postdoctoral program

I FEEL SLOVENIA

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101081355.

arXiv > astro-ph > arXiv:1806.05991

Sea

Help

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 15 Jun 2018 (v1), last revised 26 Feb 2020 (this version, v3)]

Searching for Dark Matter with Paleo-Detectors

Sebastian Baum, Andrzej K. Drukier, Katherine Freese, Maciej Górski, Patrick Stengel

A large experimental program is underway to extend the sensitivity of direct detection experiments, searching for interaction of Dark Matter with nuclei, down to the neutrino floor. However, such experiments are becoming increasingly difficult and costly due to the large target masses and exquisite background rejection needed for the necessary improvements in sensitivity. We investigate an alternative approach to the detection of Dark Matter-nucleon interactions: Searching for the persistent traces left by Dark Matter scattering in ancient minerals obtained from much deeper than current underground laboratories. We estimate the sensitivity of paleo-detectors, which extends far beyond current upper limits for a wide range of Dark Matter masses. The sensitivity of our proposal also far exceeds the upper limits set by Snowden-Ifft et al. more than three decades ago using ancient Mica in an approach similar to paleo-detectors.





arXiv > astro-ph > arXiv:2405.01626

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[Submitted on 2 May 2024]

Mineral Detection of Neutrinos and Dark Matter 2024. Proceedings

Sebastian Baum, Patrick Huber, Patrick Stengel, Natsue Abe, Daniel G. Ang, Lorenzo Apollonio, Gabriela R. Araujo, Levente Balogh, Pranshu Bhaumik Yilda Boukhtouchen, Joseph Bramante, Lorenzo Caccianiga, Andrew Calabrese-Day, Qing Chang, Juan I. Collar, Reza Ebadi, Alexey Elykov, Katherine Freese, Audrey Fung, Claudio Galelli, Arianna E. Gleason, Mariano Guerrero Perez, Janina Hakenmüller, Takeshi Hanyu, Noriko Hasebe, Shigenobu Hirose, Shunsaku Horiuchi, Yasushi Hoshino, Yuki Ido, Vsevolod Ivanov, Takashi Kamiyama, Takenori Kato, Yoji Kawamura, Chris Kelso, Giti A. Khodaparast, Emilie M. LaVoie-Ingram, Matthew Leybourne, Xingxin Liu, Thalles Lucas, Brenden A. Magill Federico M. Mariani, Sharlotte Mkhonto, Hans Pieter Mumm, Kohta Murase, Tatsuhiro Naka, Kenji Oguni, Kathryn Ream, Kate Scholberg, Maximilian Shen, Joshua Spitz, Katsuhiko Suzuki, Alexander Takla, Jiashen Tang, Natalia Tapia-Arellano, Pieter Vermeesch, Aaron C. Vincent, Nikita Vladimirov, Ronald Walsworth, David Waters, Greg Wurtz, Seiko Yamasaki, Xianyi Zhang

MDνDM community

- Groups across North America, Europe and Japan
- Astroparticle theorists, experimentalists, geologists, and materials scientists

Also check out the whitepaper! arXiv:2301.07118, 2405.01626

- History of mineral detectors
- Review of scientific potential for particle physics, reactor neutrinos and geoscience

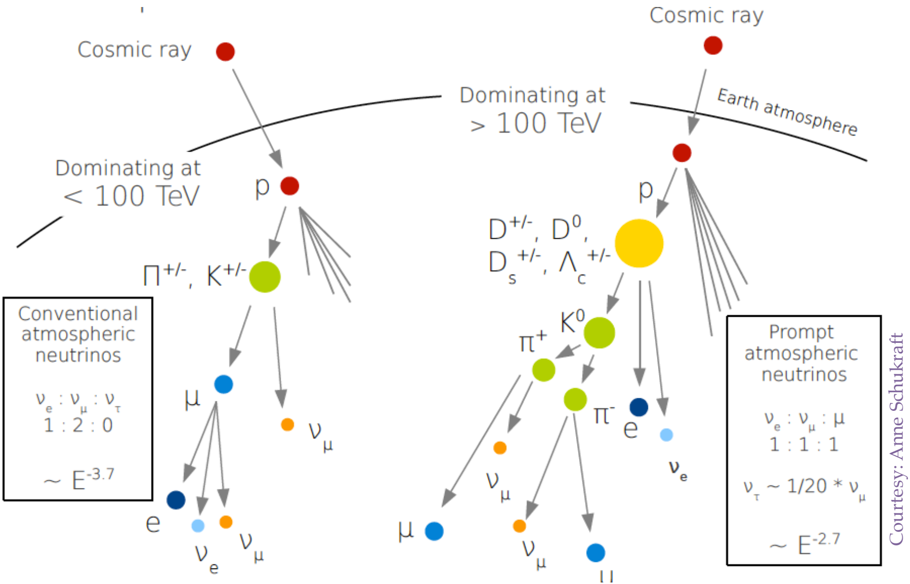
NSF GCR Mineral Detection of Dark Matter

- Syracuse University — Jay Thomas
- Lawrence Livermore National Laboratory — Xianyi Zhang
- SLAC National Accelerator Laboratory — Arianna Gleason, Sulgiye Park, Kazu Terao
- University of Michigan — Igor Jovanovic, Emilie LaVoie-Ingram, Josh Spitz, Kai Sun, Katie Ream, Andrew Calabrese-Day
- Texas, The University of Texas at Austin — Katie Freese, Dionysius Theodosopoulos
- Jožef Stefan Institute — Patrick Stengel
- University of Maryland — William McDonough
- Virginia Tech — Robert Bodnar, Judah DiStefano, Samuel Hedges, Patrick Huber, Vsevolod Ivanov, Giti Khodaparast, Brenden Magill, Maverick Morrison, Thomas O'Donnell, Abigael Parks, Arjun Uppal, Keegan Walkup
- UNF University of North Florida — Chris Kelso, Greg Wurtz
- Universität Zürich UZH — Laura Baudis, Nikita Vladimirov, Christian Wittweg

Outline

1. Applications of mineral detectors
   - Neutrino signals/backgrounds
   - Direct detection of dark matter
2. Tracks in ancient minerals
   - Solid state track detectors
   - More backgrounds
3. Projected sensitivity of mineral detectors
4. Summary and outlook

Atmospheric ν's originating from CR interactions



Galactic contribution to ν flux over geological timescales

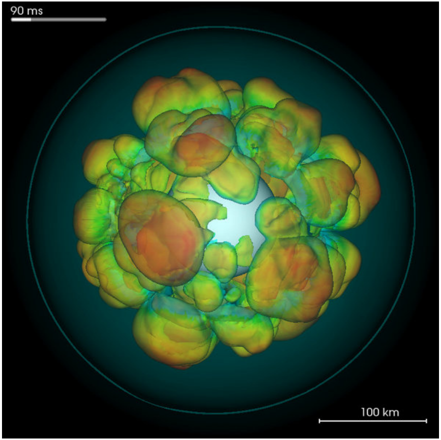


Figure: Supernova simulation after CC

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

- Measure galactic CC SN rate
- Traces star formation history

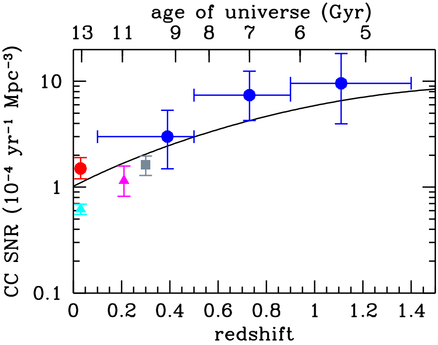
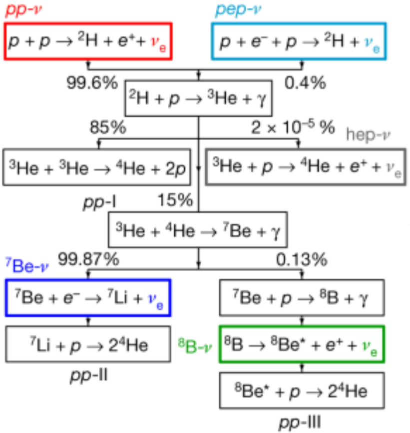
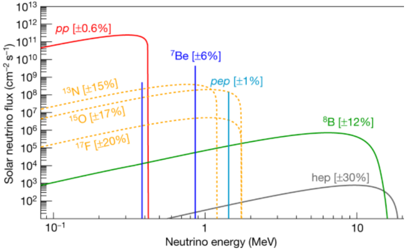


Figure: Cosmic CC SNR, 1403.0007

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





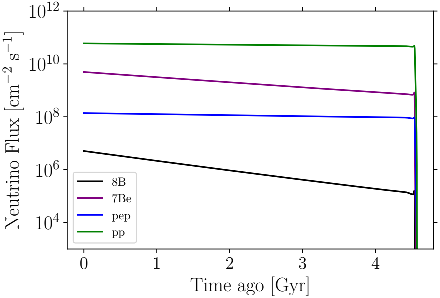


Figure: Today's flux at Borexino (Nature, 2018) and time dependence of GS metallicity model, 2102.01755

Rotation curves of spiral galaxies and the Bullet Cluster

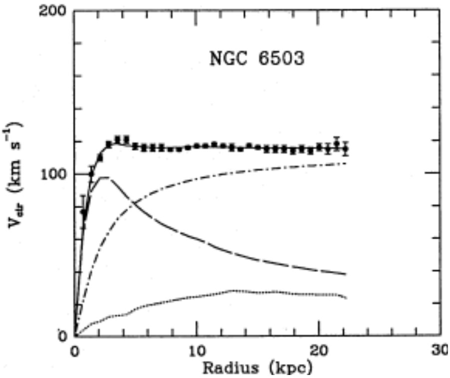


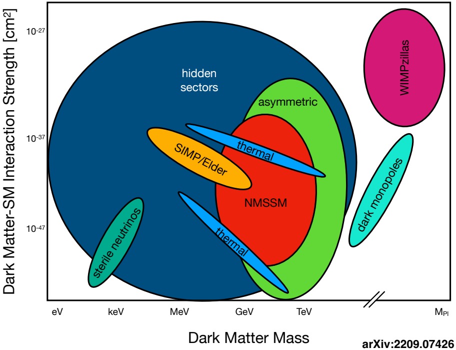
Figure: Begeman et al. (1991)

Figure: Clowe et al. (2006)

What do we (not) know about dark matter?

What we (typically) assume

- No E&M interactions
- Must be cold and stable
- Not in the Standard Model



arXiv:2209.07426

Direct detection experiments

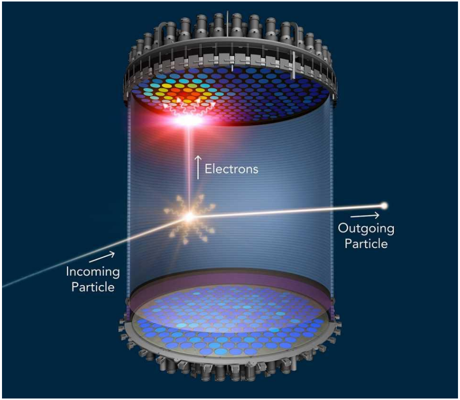
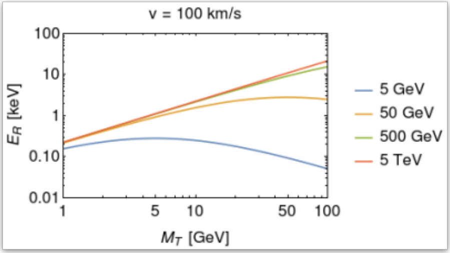


Figure: LUX-ZEPLIN (LZ) Collaboration / SLAC National Accelerator Laboratory

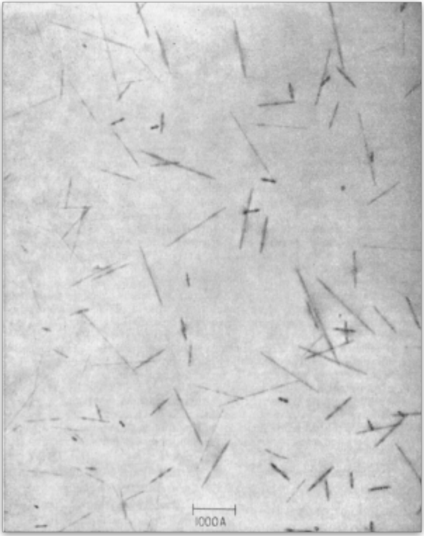


Scattering kinematics ⇒ event rate

- Interactions with quarks, gluons ⇒ with nucleons ⇒ with nuclei
- Convolute with astrophysical WIMP flux from observations
- **Sensitivity** $\propto N_{\rm target} \times T_{\rm exp}$

Outline

Fission fragments can be seen by TEM/optical microscopes



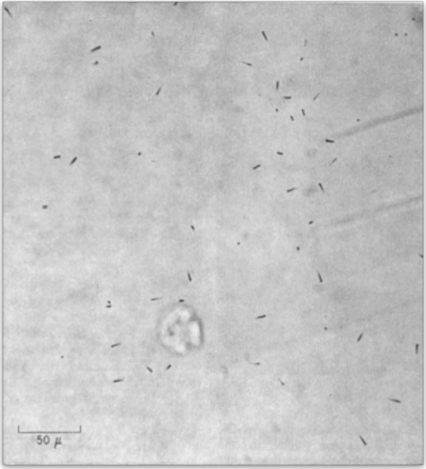
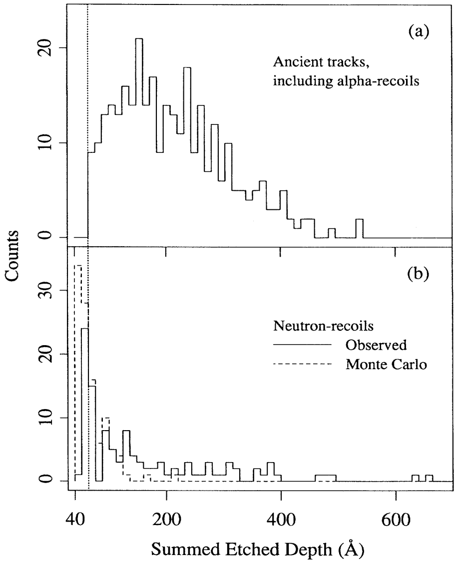


Figure: Price+Walker '63

Mineral detectors used to constrain WIMPs before



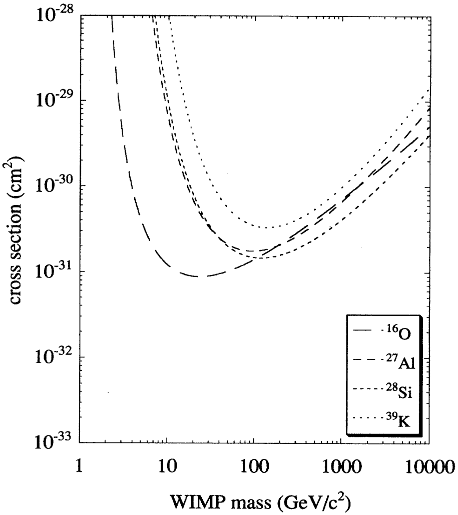
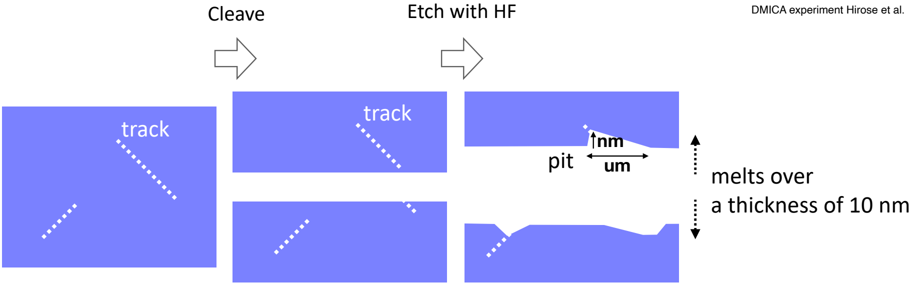
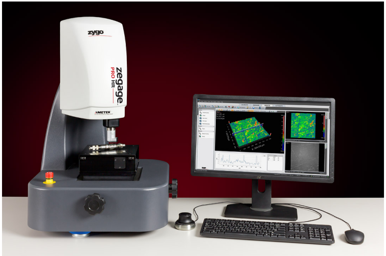


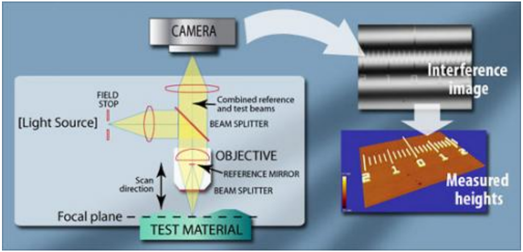
Figure: Snowden-Ifft et al. (1995)

New techniques allow for much larger readout capacity

DMICA experiment Hirose et al.

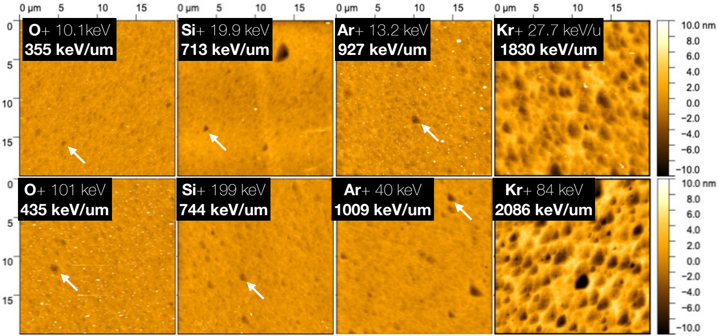






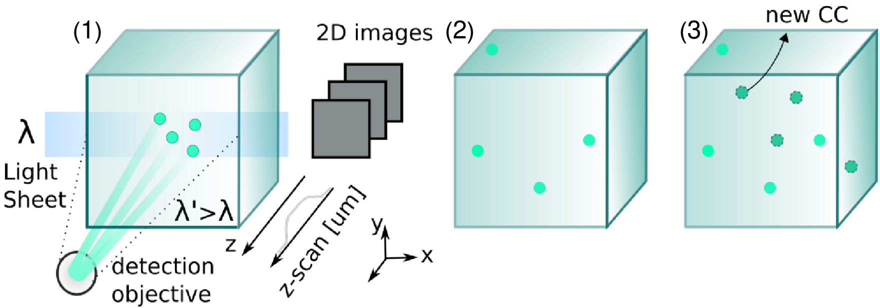
Increase throughput from AFM to optical profilometry

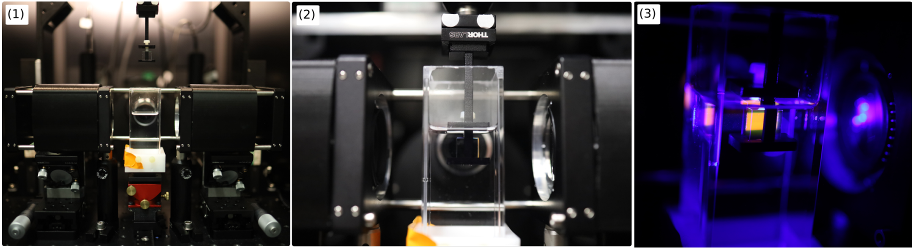
Irradiation dose is 80 ions per field of view (20umx20um).



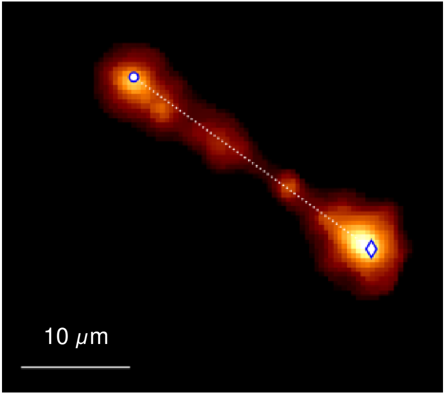
proxy	DM scattering	alpha recoils
pit formation efficiency	several to 10 %	~ 100%

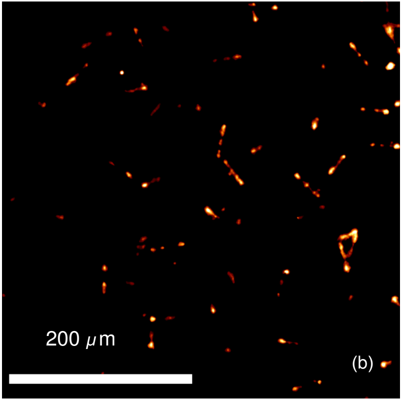
Color centers can be used to probe low energy recoils





Fission tracks from irradiation of LiF with thermal neutrons





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

- 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

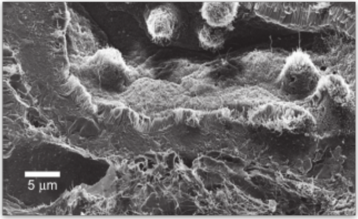
PALEOCCENE arXiv:2503.20732

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

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



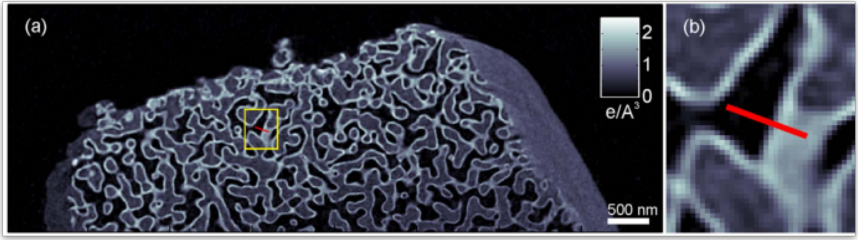
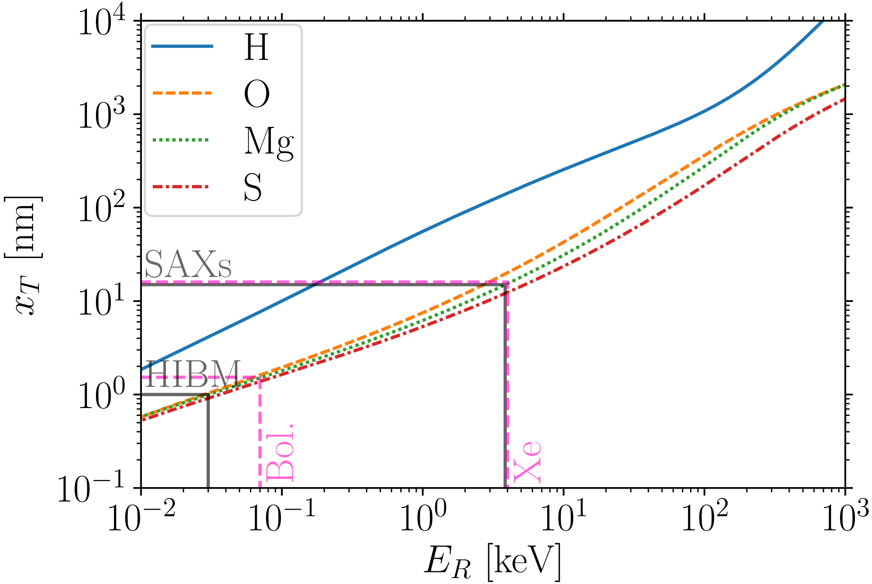


Figure: HIM rodent kidney Hill+ '12, SAXs nanoporous glass Holler+ '14

Integrate stopping power to estimate track length



Cosmogenic backgrounds suppressed in deep boreholes

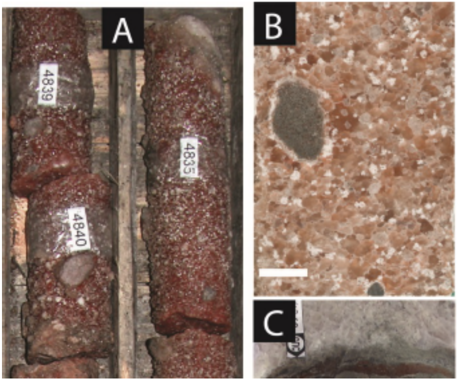


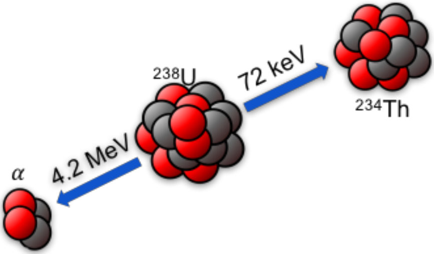
Figure: $\sim$ 2Gyr old Halite cores from $\sim$ 3km, as discussed in Blättler+ '18

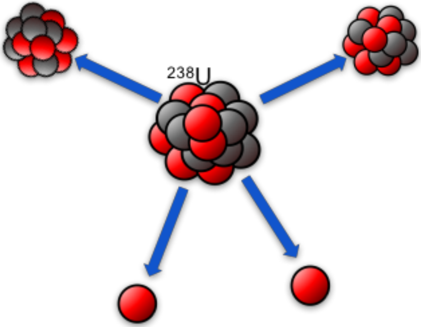
Depth	Neutron Flux
2 km	$10^6/\text{cm}^2/\text{Gyr}$
5 km	$10^2/\text{cm}^2/\text{Gyr}$
6 km	$10/\text{cm}^2/\text{Gyr}$
50 m	$70/\text{cm}^2/\text{yr}$
100 m	$30/\text{cm}^2/\text{yr}$
500 m	$2/\text{cm}^2/\text{yr}$

Need minerals with low ^{238}U

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

Find α-recoils and model radiogenic neutron background





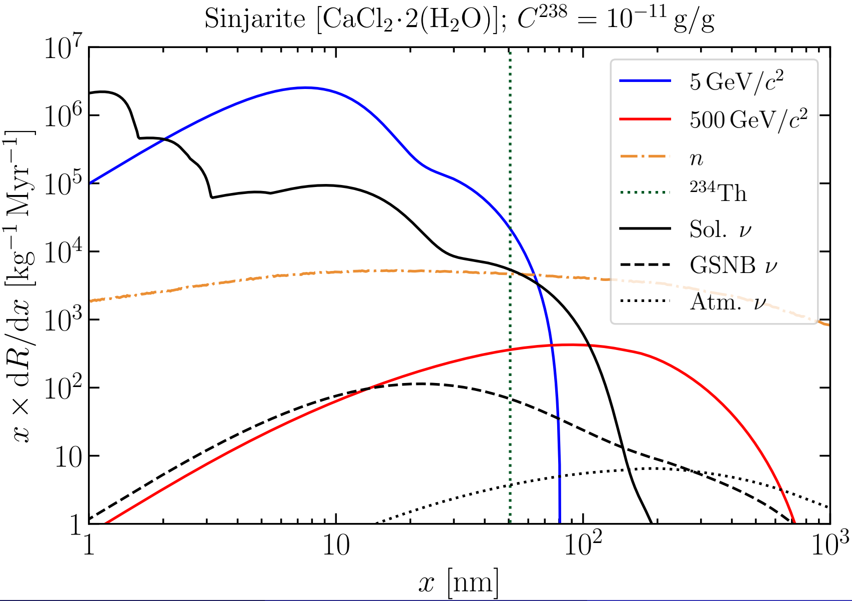
Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^{9} yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %) IT (0.16 %)	1.159 min
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^{5} yr

SF yields several $\sim$MeV neutrons

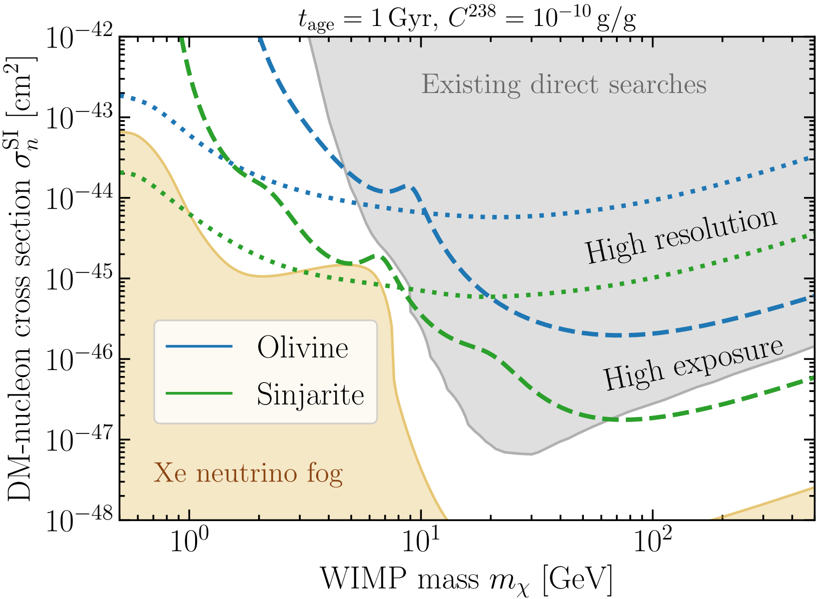
Each neutron will scatter elastically 10-1000 times before moderating

Outline

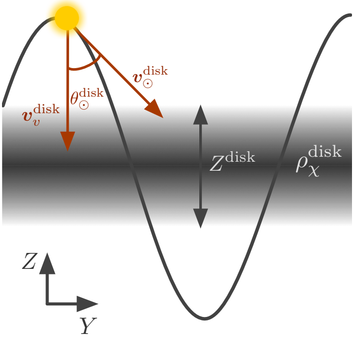
Use track length spectra to pick out WIMP signal

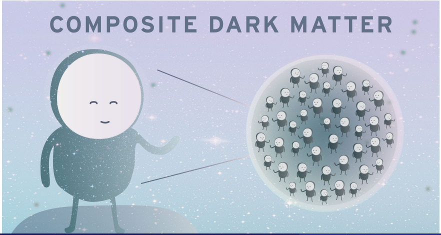


Trade-off between read-out resolution and exposure



Mineral detectors could probe rare and/or previous events





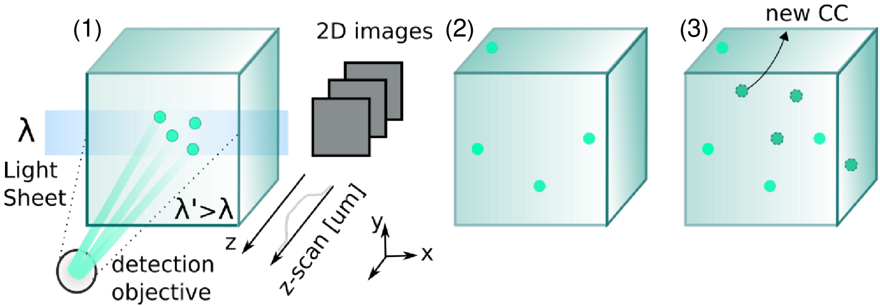
Look for DM and astrophysical ν's

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

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**

The PALEOCCENE Collaboration



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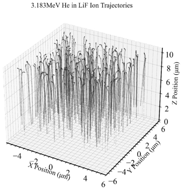
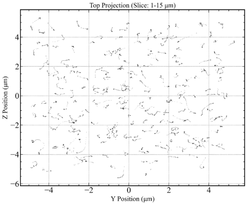
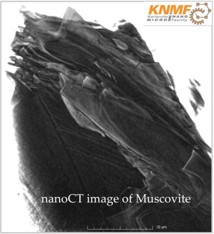
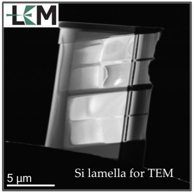


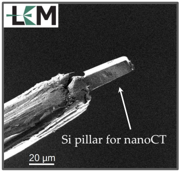


Track simulation & analysis

Sample preparation & imaging





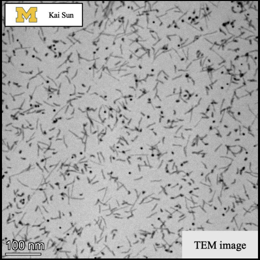


- **Collaborative project** - **KIT institutes** (astroparticle, microscopy) & **Uni. Heidelberg** (geology)
- **Experimental studies** of natural & artificial samples (irradiated & blank), accompanied by simulations
- **Establish** the techniques for **imaging** & **analysis** of **particle-induced tracks** in minerals

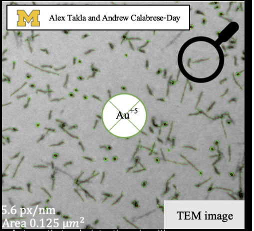
Atmospheric Neutrino and Dark Matter Detection at the University of Michigan

PI: Josh Spitz, spitzj@umich.edu
RA: Emilie LaVoie-Ingram, emlavoie@umich.edu

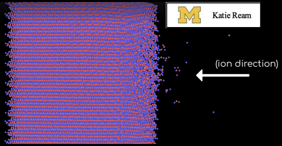
- Ion irradiation of various minerals to study morphology of nuclear recoil damage tracks
- TEM imaging for high resolution measurements
  - Currently testing x-rays for high throughput, high resolution track imaging at U-M and SLAC
- Automatic track detection algorithm
- LAMMPS molecular dynamics simulations to study track formation
- GEANT4 simulations to study cosmogenic neutron background in ancient minerals as a function of rock overburden



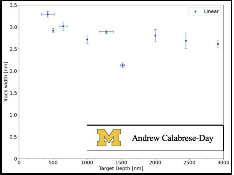
Gold ion tracks in olivine



Automatic track detection algorithm



LAMMPS simulation of gold ion penetrating quartz



Track width v. depth data for gold irradiated olivine

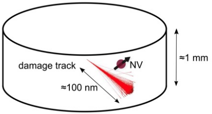

EURECApd project
Toho U., Nagoya U., Kyoto U. Kanagawa U. JAMSTEC
JAMSTEC
Ultra Heavy Dark Matter
・composite dark matter
e.g., Q-ball, quark, nugget, nuclearite・・
・Magnetic Monopole
・(Primordinal Black Hole : PBH)
Sun
Mica
50μm
50μm
Ultra Heavy Element
→ meteorite analysis
Transuranium element
• r-process in Neutron star merger (NSM)
• Accelerator mechanism
• Solar flare
The deepest search for ultra heavy dark matter
Over dark matter density
SKYLAB (1978)
MACRO (2000)
MICA (monopole search 1986)
Flux [/cm²/sec/sr]
Q-ball (SECS) mass [GeV]
Automatic scanning system for Paleo Detector
High speed scanning and imaging processing
system based on the nuclear emulsion technology
Au 350 MeV
Olivine
100 μm

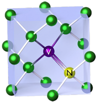
[qtc.umd.edu](qtc.umd.edu)

Mineral detection at the University of Maryland:

Directional detection of neutrinos and dark matter with quantum diamond sensors

Lead personnel: Prof. Ronald Walsworth, Dr. Daniel Ang (dga@umd.edu)



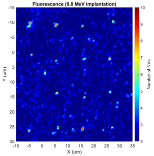


Nitrogen-vacancy center

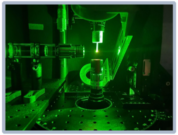
- WIMP dark matter particles and neutrinos can induce nuclear recoils that leave 10-100 nm damage tracks in diamond
- **Goal:** locate and characterize damage track with nitrogen-vacancy (NV) quantum sensors embedded in the diamond to deduce energy and direction of initial particle
- Directionality allows distinguishing WIMPs from the solar neutrino background
- Requires state-of-the-art quantum diamond microscopy techniques at the micro- and nanoscales
- See Ebadi et al., *AVS Quantum Sci.* 4 (4): 044701 (2022)

Current research activities

- Experiments creating and detecting artificial ion-induced damage tracks (at Sandia National Lab)
- Developing light-sheet quantum diamond microscope (LS-QDM) for high-speed, high-resolution diamond scanning
- Developing NV super-resolution imaging techniques to resolve and characterize individual damage tracks at the nanoscale

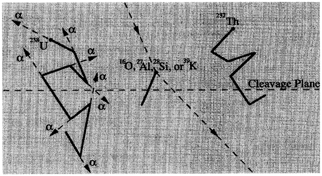


Single ion impact damage sites

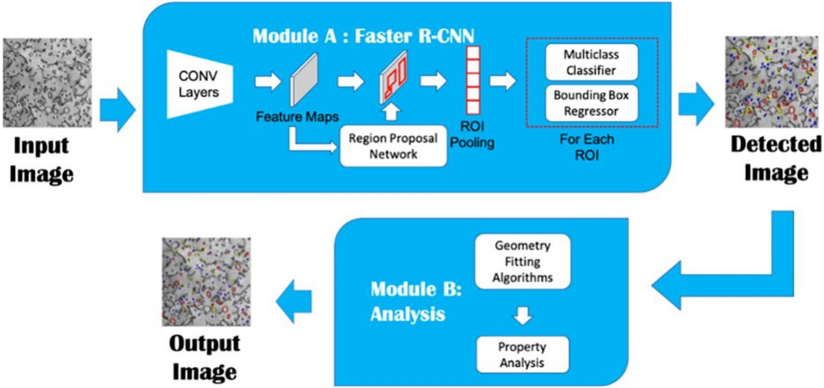


LS-QDM @ UMD

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



Scattering cross sections ⇒ scattering rates

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

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

Differential cross section

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

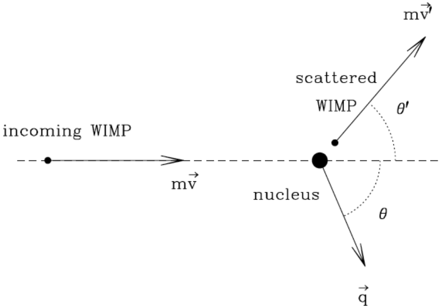
$$F(q) \simeq \frac{9\left[\sin(qR) - qR\cos(qR)\right]^2}{(qR)^6}$$

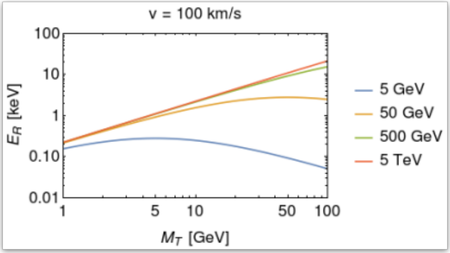
Differential scattering rate

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

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

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

Dark matter density in the galaxy

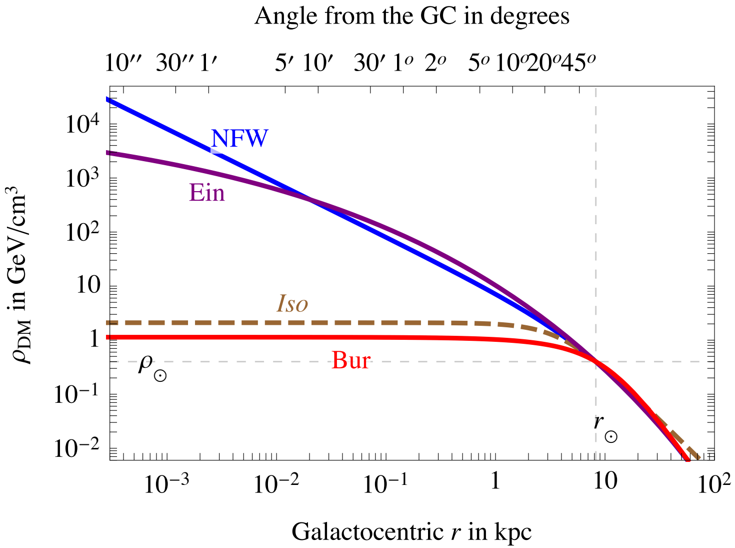
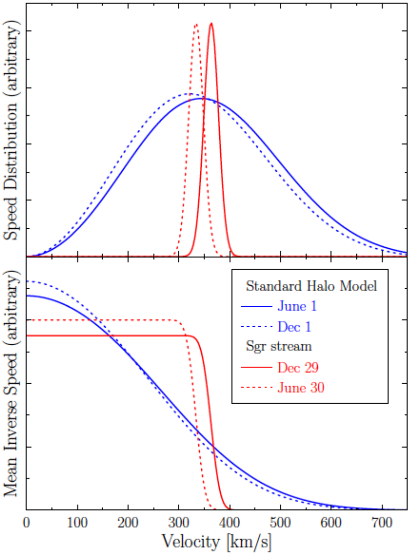


Figure: 2406.01705

WIMP velocity distribution and induced recoil spectra



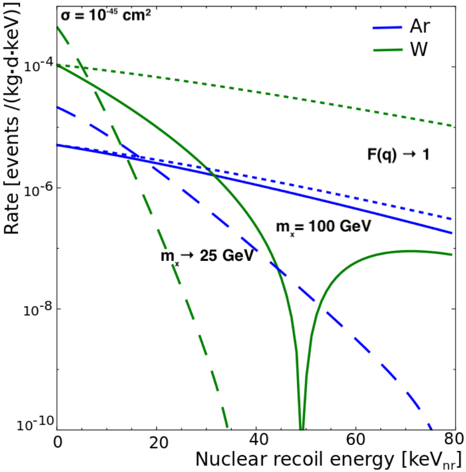
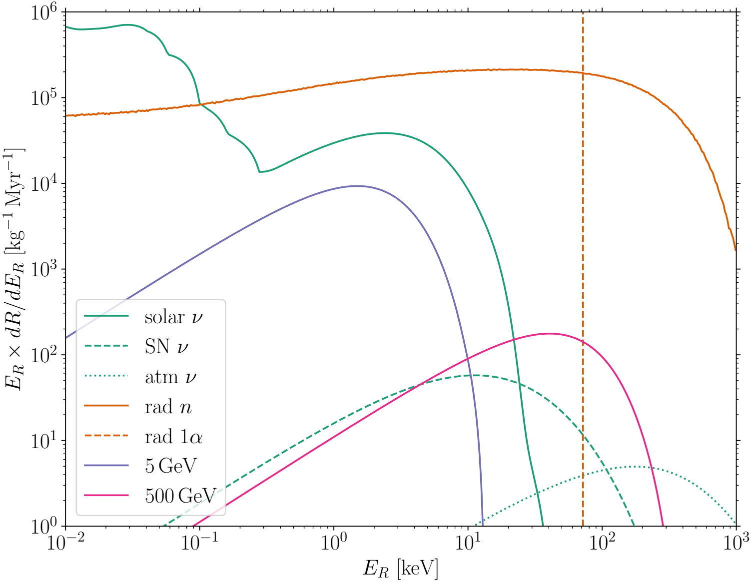
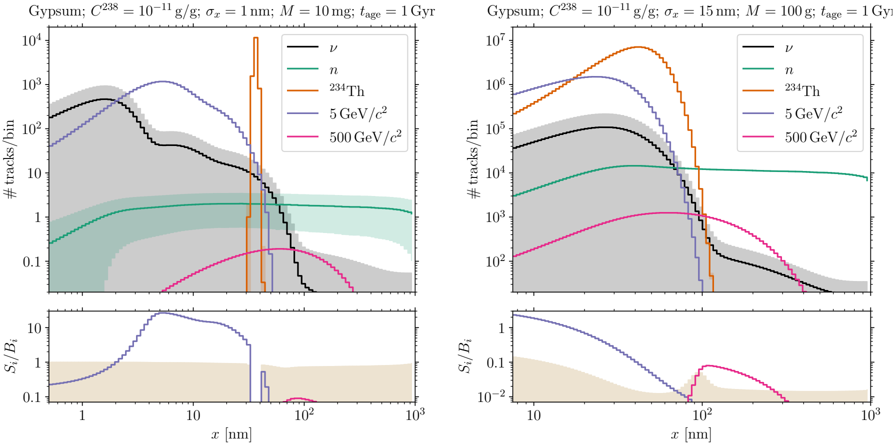


Figure: (left) 1209.3339 (right) 1509.08767

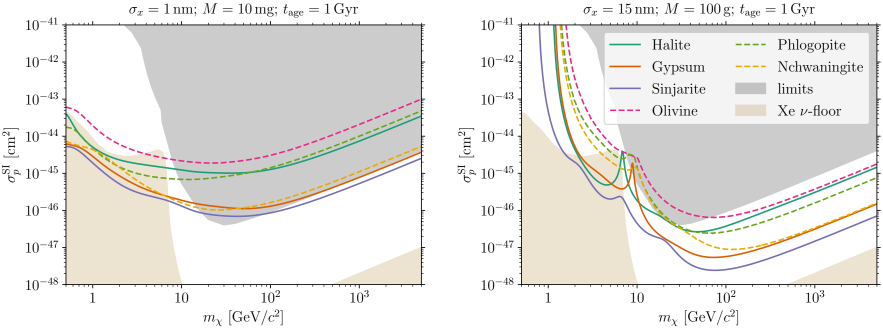
Putting together all of the signals and backgrounds



Track length spectra after smearing by readout resolution

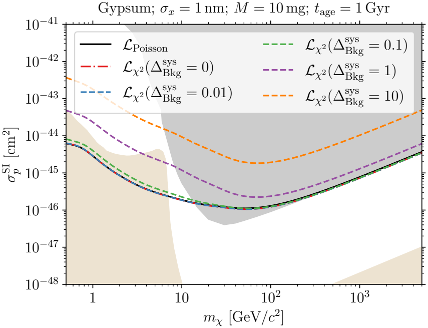


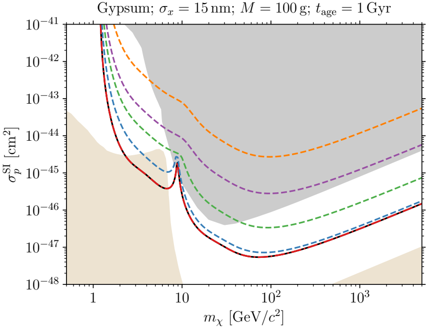
Sensitivity for different targets



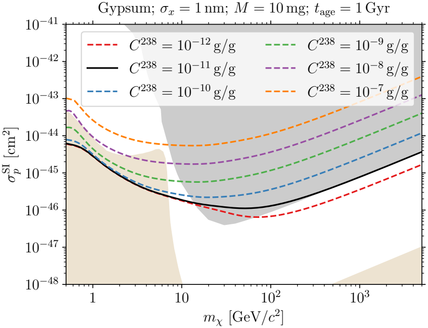
Halite	NaCl	$C^{238} = 10^{-11}$ g/g
Gypsum	$Ca(SO_4){\cdot}2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Sinjarite	$CaCl_2{\cdot}2(H_2O)$	$C^{238} = 10^{-11}$ g/g
Olivine	$Mg_{1.6}Fe^{2+}_{0.4}(SiO_4)$	$C^{238} = 10^{-10}$ g/g
Phlogopite	$KMg_3AlSi_3O_{10}F(OH)$	$C^{238} = 10^{-10}$ g/g
Nchwaningite	$Mn^{2+}_2SiO_3(OH)_2{\cdot}(H_2O)$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

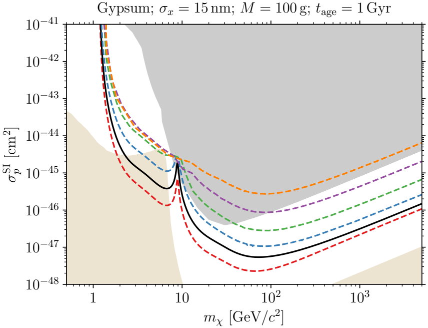
Effects of background shape systematics





Sensitivity for different ^{238}U concentrations





Stochastic nuclear stopping reduces sensitivity to low m_χ

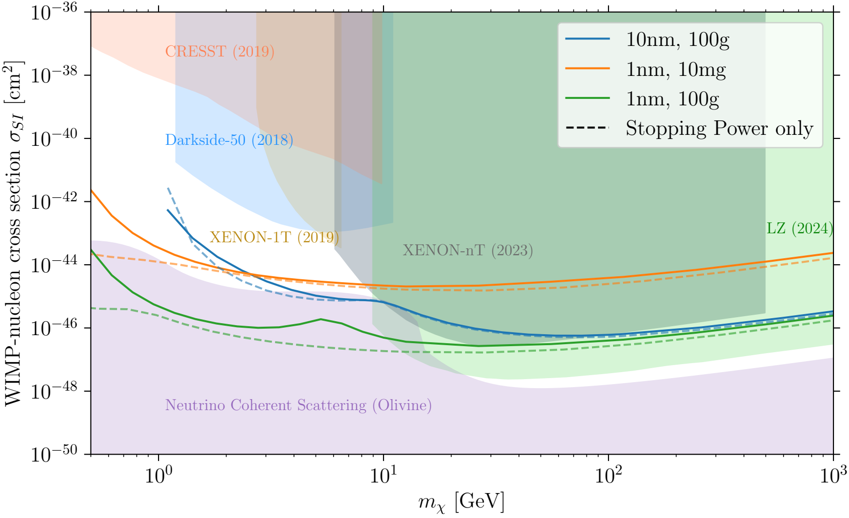
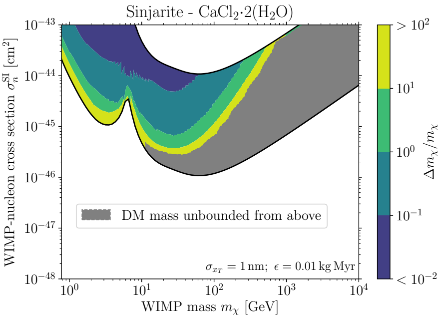
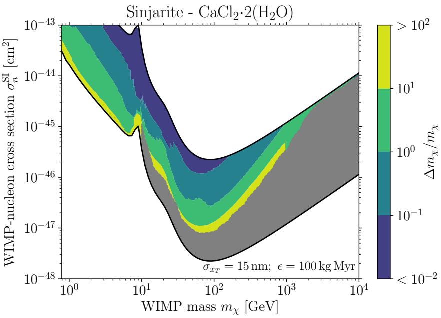


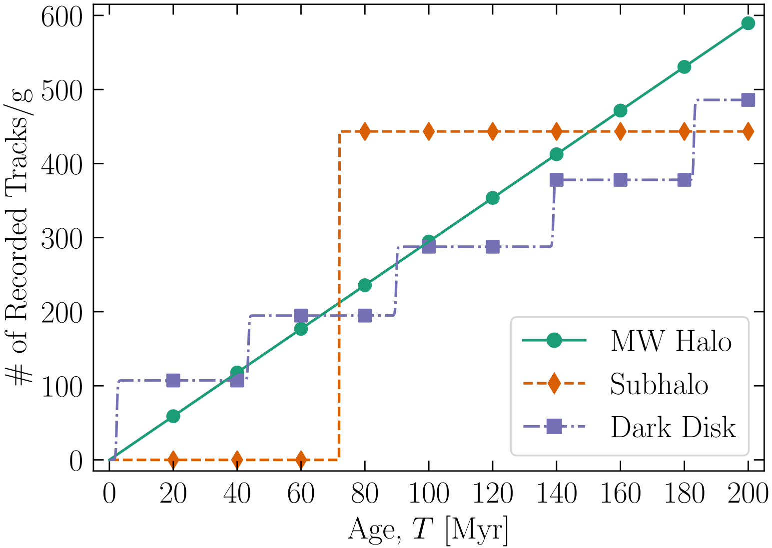
Figure: 2504.08885

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



Subhalos sufficiently close give $\mathcal{O}(1)$ enhancement to ρ_χ

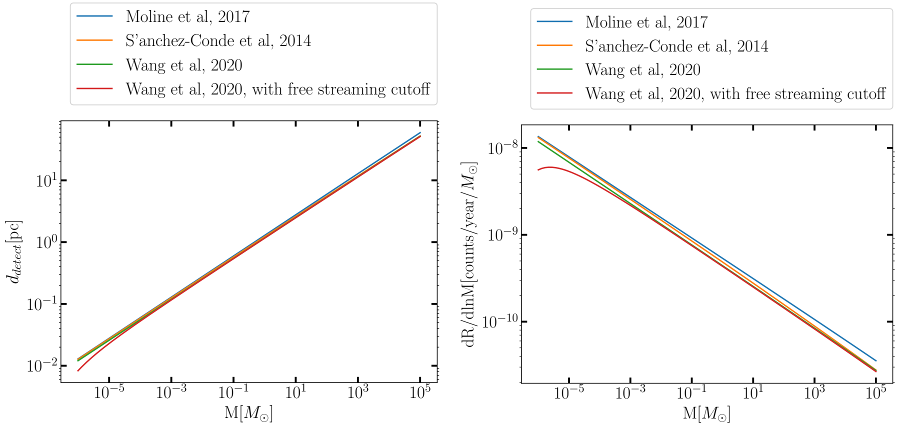
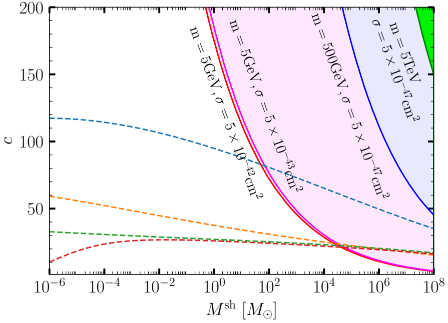


Figure: 2504.13247

Constrain mass-concentration relation for low m_χ



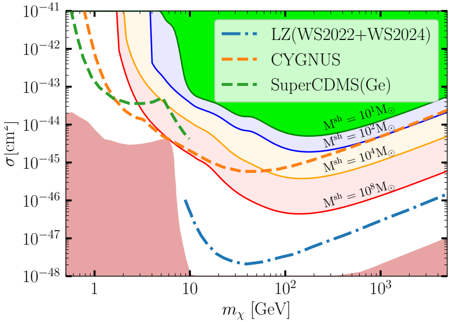
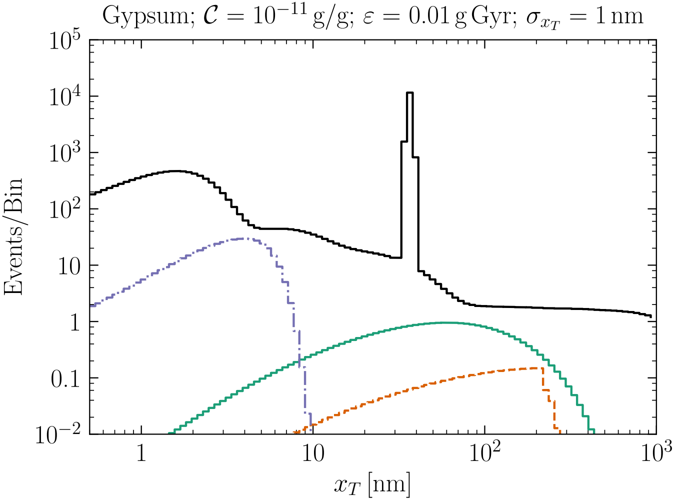


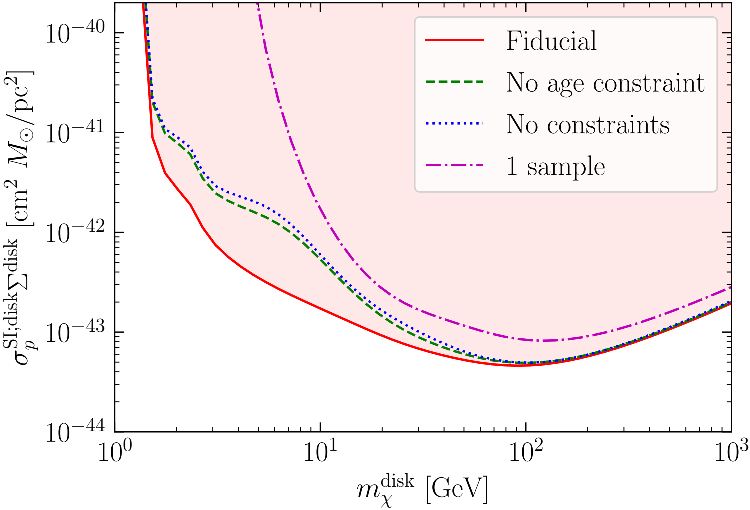
Figure: 2504.13247

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



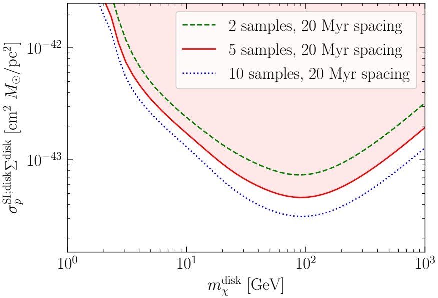
$m_X^{\text{disk}} = 100\,\text{GeV}$ $\sigma_{Xp}^{\text{disk}} = 10^{-43}\,\text{cm}^2$ $m_X = 500\,\text{GeV}$ $\sigma_{Xp} = 5 \times 10^{-46}\,\text{cm}^2$

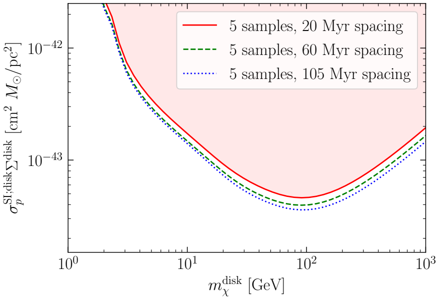
Distinguish from halo with 20, 40, 60, 80, 100 Myr samples



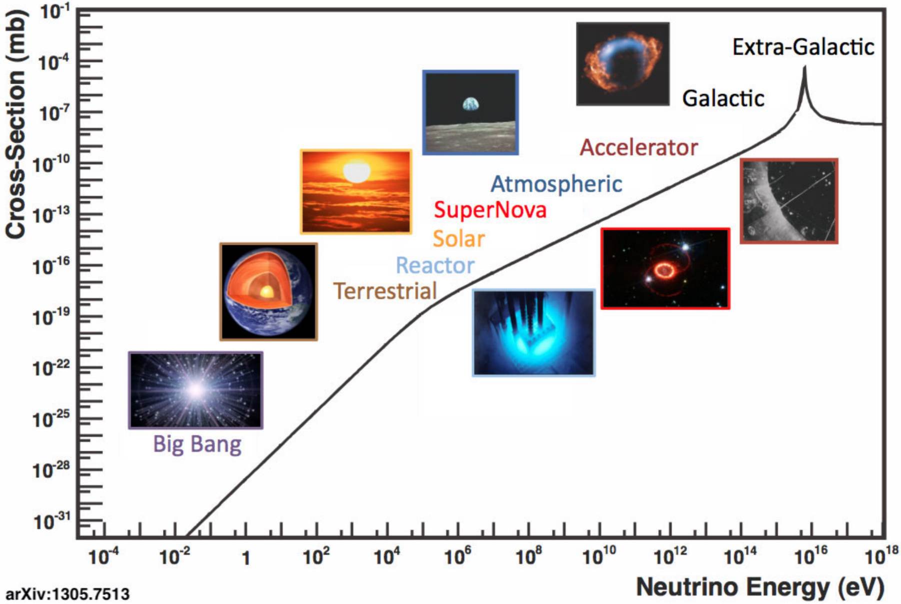
Systematic uncertainties $\Delta_t = 5\%$ $\Delta_M = 0.1\%$ $\Delta_C = 10\%$ $\Delta_\Phi = 100\%$

Change number of samples and sample spacing in time





Neutrinos come from a variety of sources



arXiv:1305.7513

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 $E_\nu \gtrsim 10\,\text{GeV}$

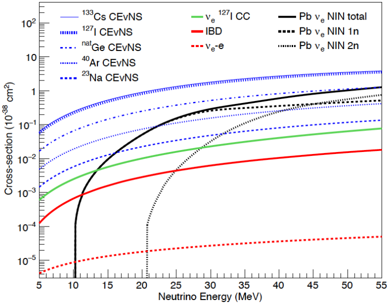


Figure: COHERENT, 1803.09183

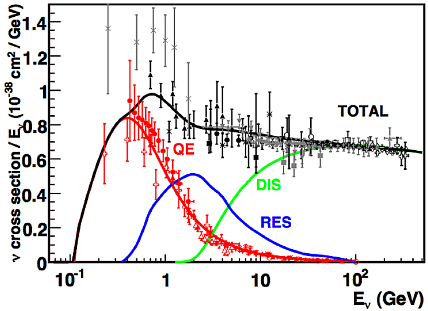


Figure: Inclusive CC $\sigma_{\nu N}$, 1305.7513

Atmospheric ν's originating from CR interactions

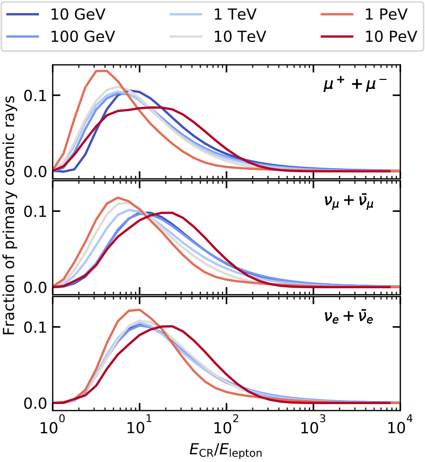


Figure: E_{CR} to leptons, 1806.04140

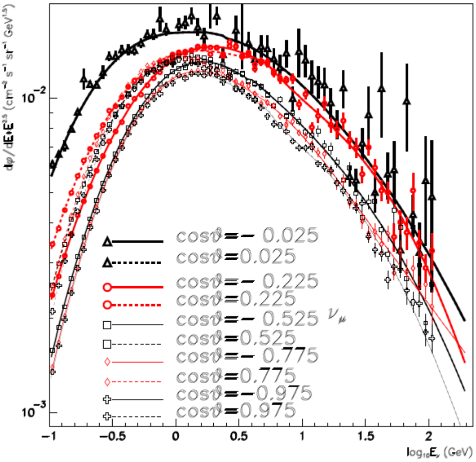


Figure: FLUKA simulation of ν_μ flux at SuperK for solar max, hep-ph/0207035

Geomagnetic field deflects lower energy CR primaries

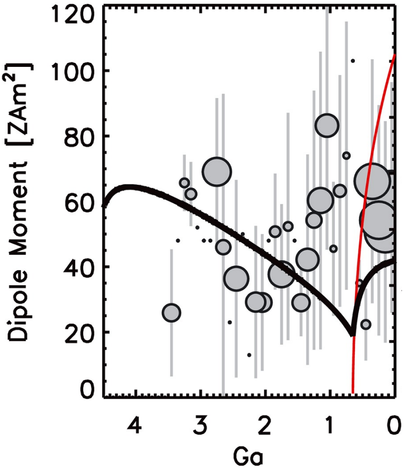
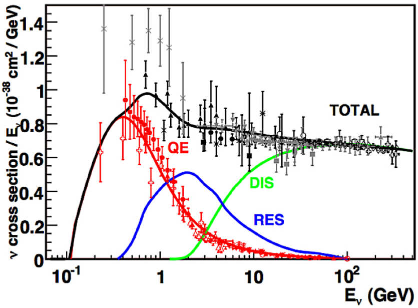


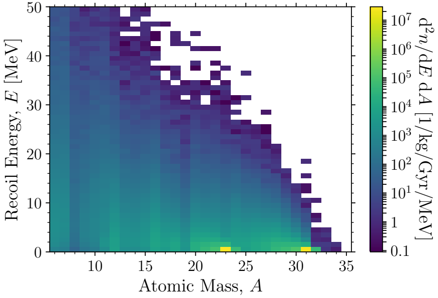
Figure: Driscoll, P. E. (2016), *Geophys. Res. Lett.*, 43, 5680-5687

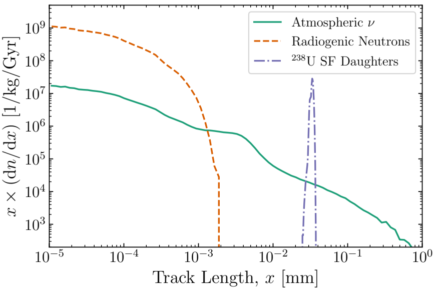
Rigidity $p_{CR}/Z_{CR} \simeq E_{CR}$ for CR protons

- 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

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

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

- Measure galactic CC SN rate
- Traces star formation history

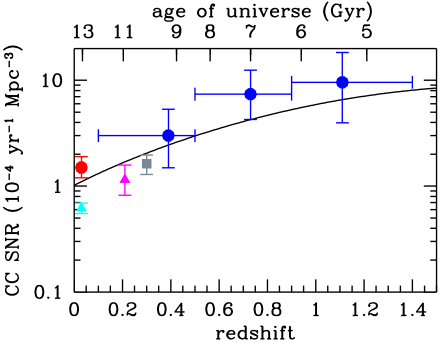
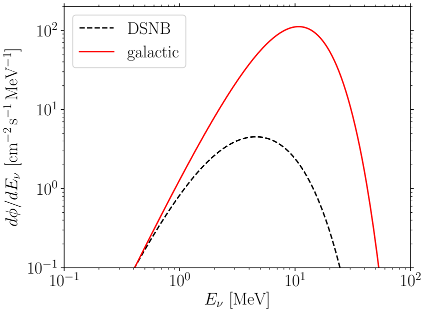
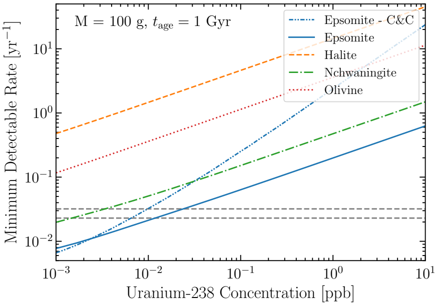
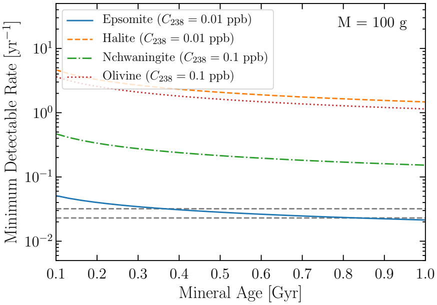


Figure: Cosmic CC SNR, 1403.0007



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

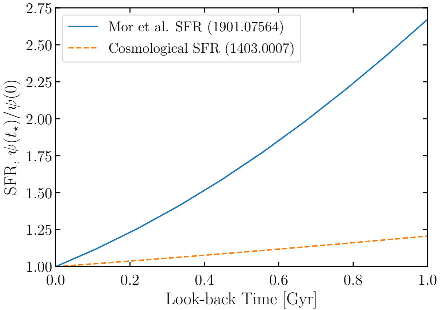


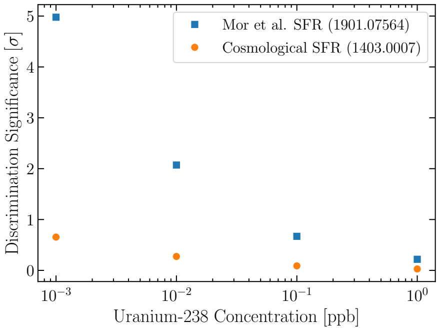


Epsomite [$Mg(SO_4)\cdot 7(H_2O)$]
Halite [NaCl]

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





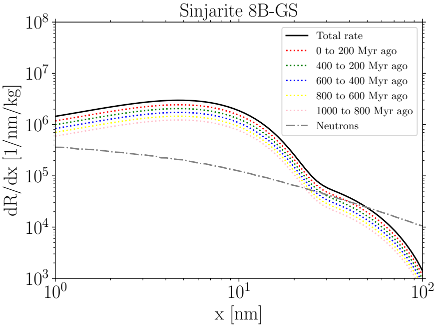
Coarse grained cumulative time bins

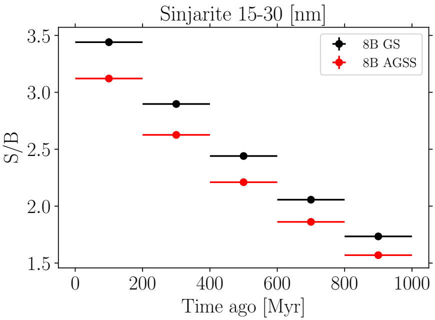
- 10 Epsomite paleo-detectors
- 100 g each, $\Delta t_{\rm age} \simeq 100$ Myr

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

Could use large exposure to differentiate between scenarios





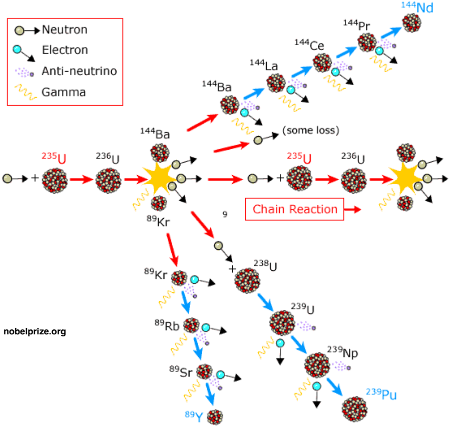
Could measure ^8B flux over time

- 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 $\Delta_t \sim 10\%$, $\Delta_C = 10\%$
- $N_{\rm tot}^{\rm GS} \sim (1.63 \pm 0.05) \times 10^6$
  $N_{\rm tot}^{\rm AGSS} \sim (1.52 \pm 0.05) \times 10^6$

Reactor ν's produced in β decays of fission fragments



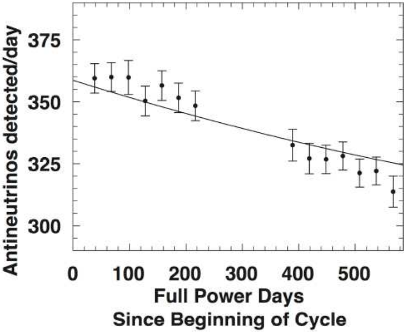


Figure: Processes yielding reactor ν's and time dependence over the course of reactor fuel cycle for $^{239}\mathrm{Pu}$ (1605.02047)

Nuclear non-proliferation safeguards

- Measure soft nuclear recoils
- Passive and robust detectors operable at room temperature

Semi-analytic range calculations and SRIM agree with data

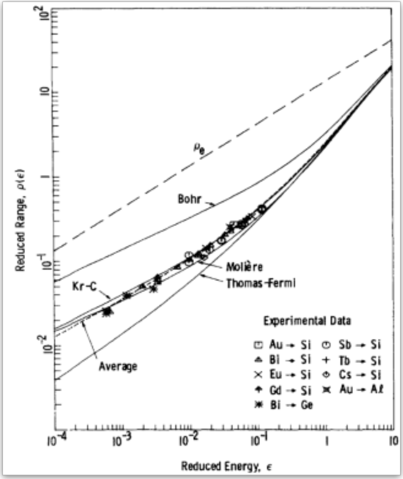


Figure: Wilson, Haggmark+ '76