Looking for Dark Matter with Olivine

Sebastian Baum

1806.05991 1811.06844 1811.10549 1906.05800
2004.08394 2106.06559 2107.02812

with Andrzej Drukier, Katie Freese, Maciej Górski & Patrick Stengel
\+ Tom Edwards, Bradley Kavanagh & Christoph Weniger
\+ Johnathon Jordan, Paola Sala, Joshua Spitz
\+ Will DeRocco & Saarik Kalia

Stanford University

Can old rocks teach us about the history of our Galaxy and what makes up our Universe?

100 Myr old mineral samples from the right geological environments

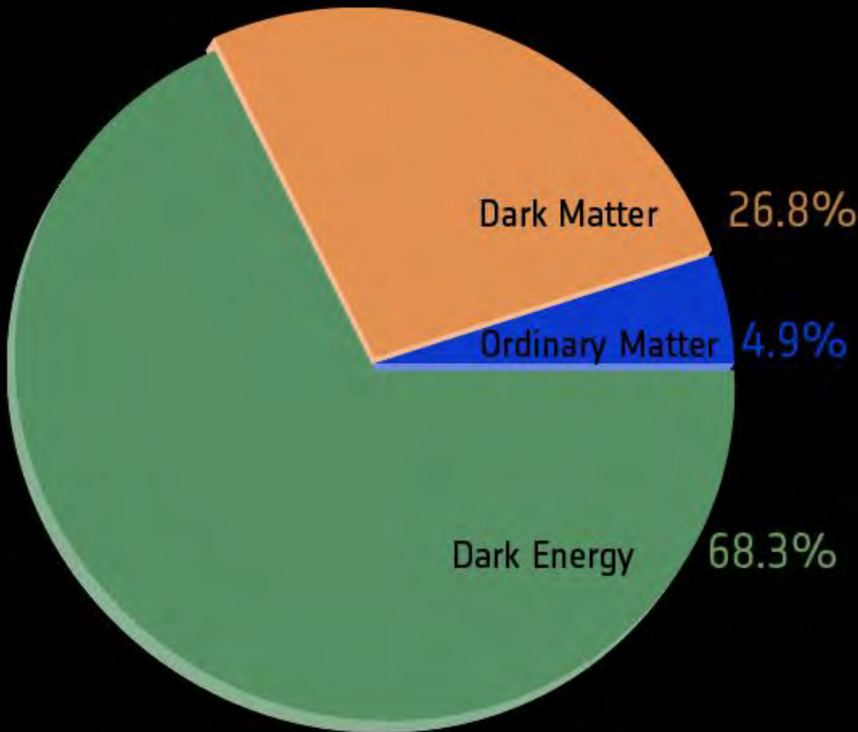
Imaged with modern nanometer-resolution microscopy

Can old rocks teach us about the history of our Galaxy and what makes up our Universe?

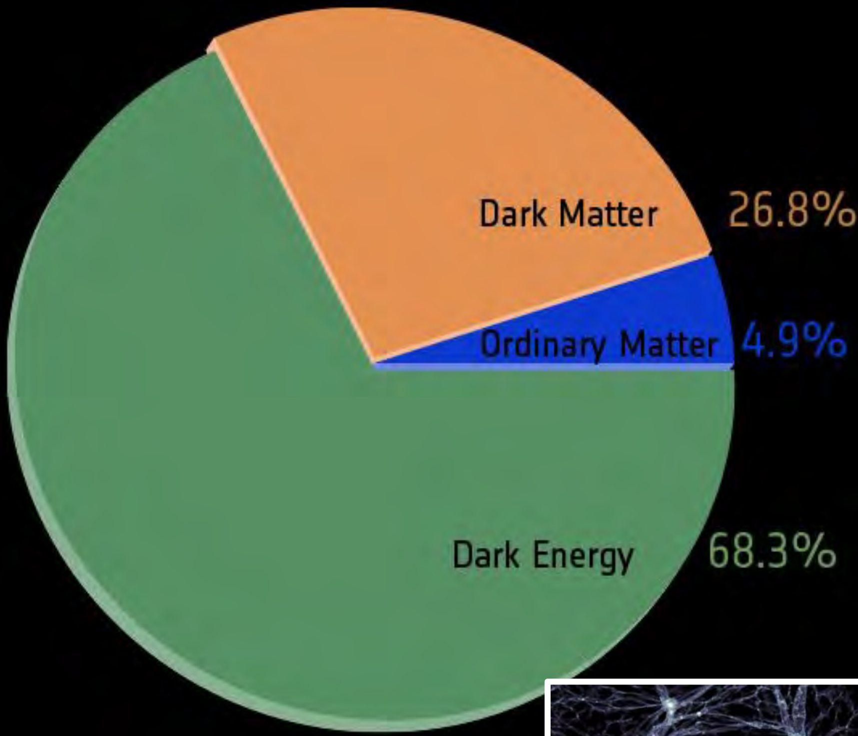
What was the Milky Way’s star formation rate 500 million years ago?

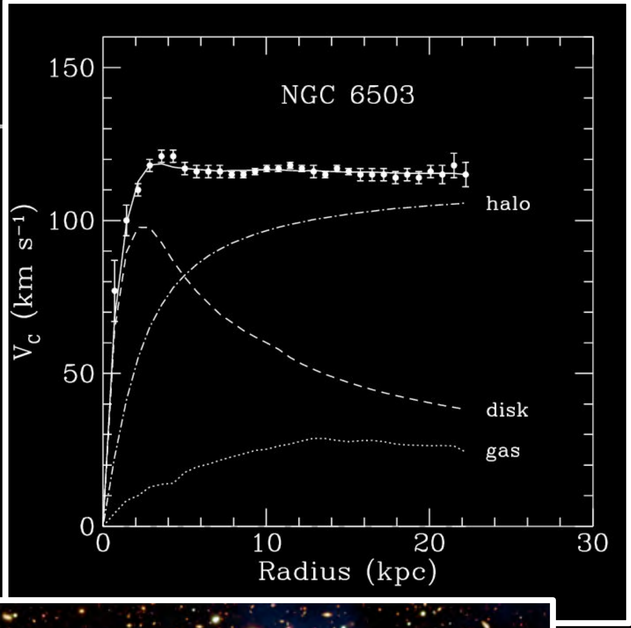
What is Dark Matter?

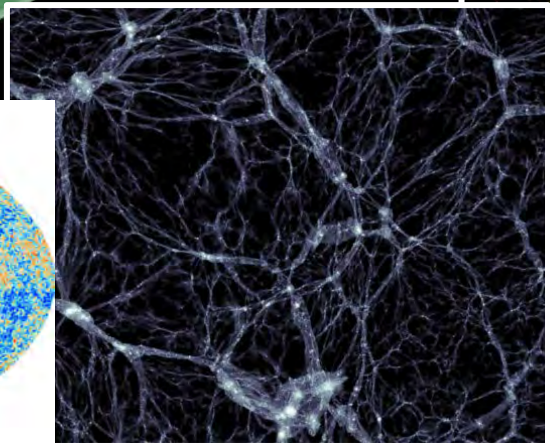
Dark Matter - the missing 85%

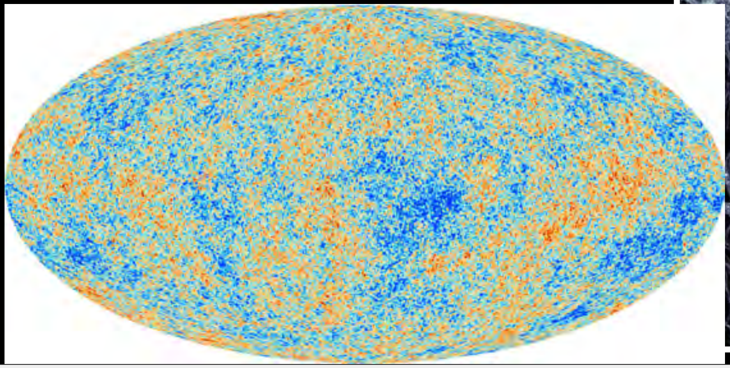


Dark Matter - the missing 85%





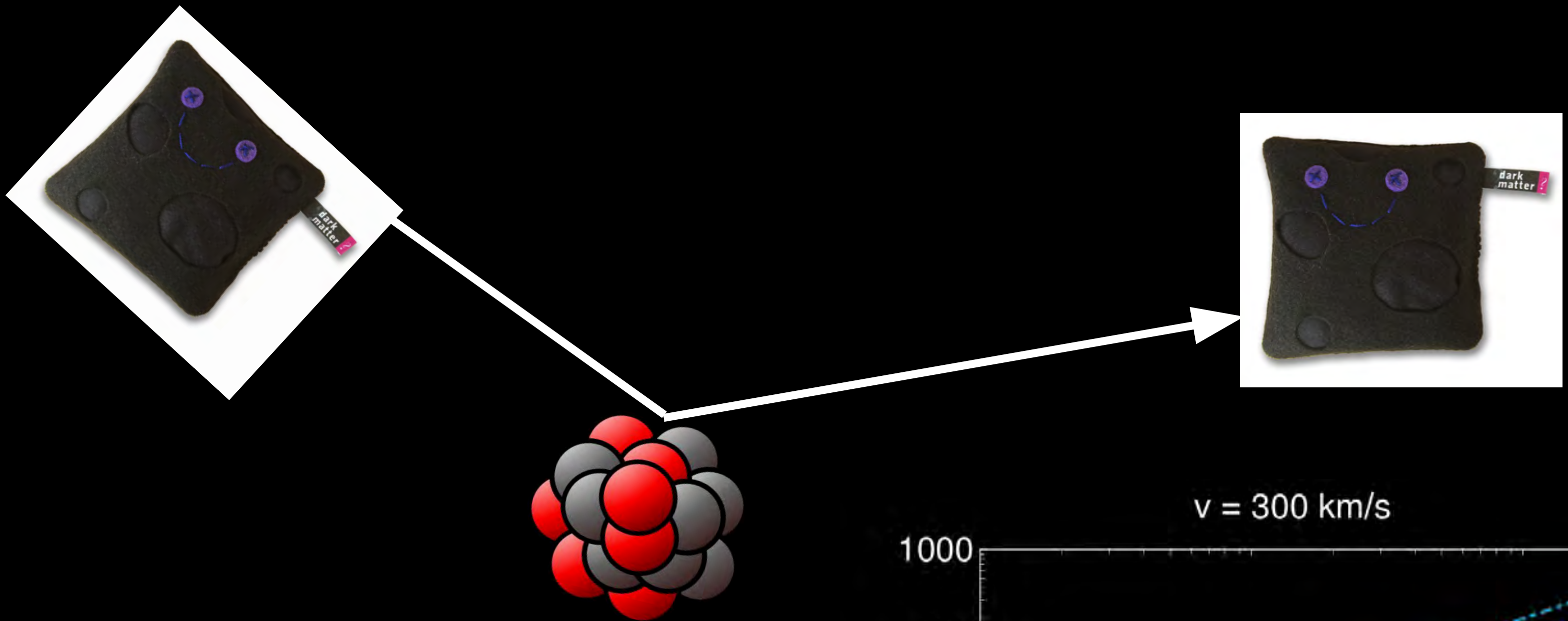


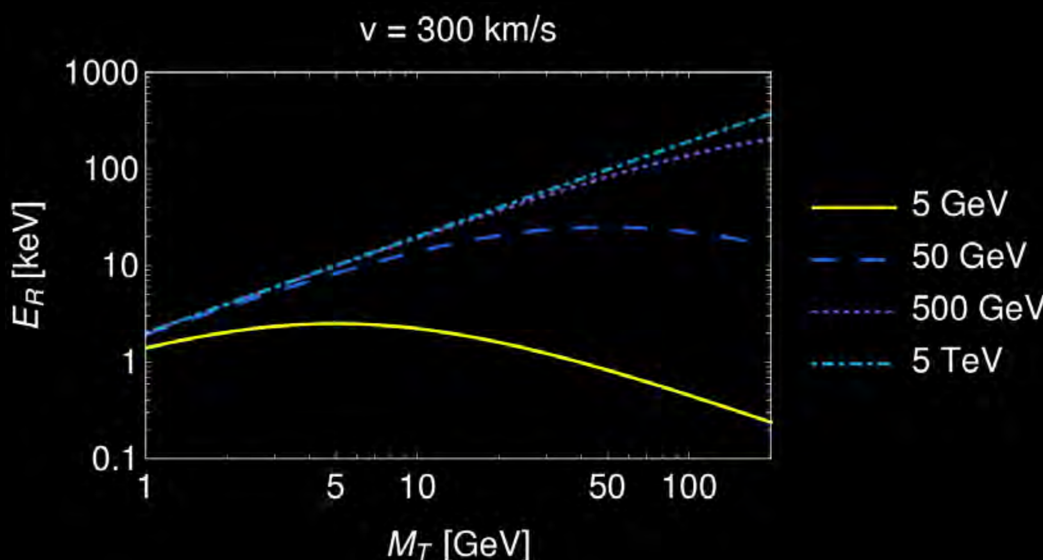


Weakly Interactive Massive Particle (WIMP) DM

Dark Matter could be made up of new particles with mass comparable to ordinary atomic nuclei, and feeble interactions with ordinary matter.

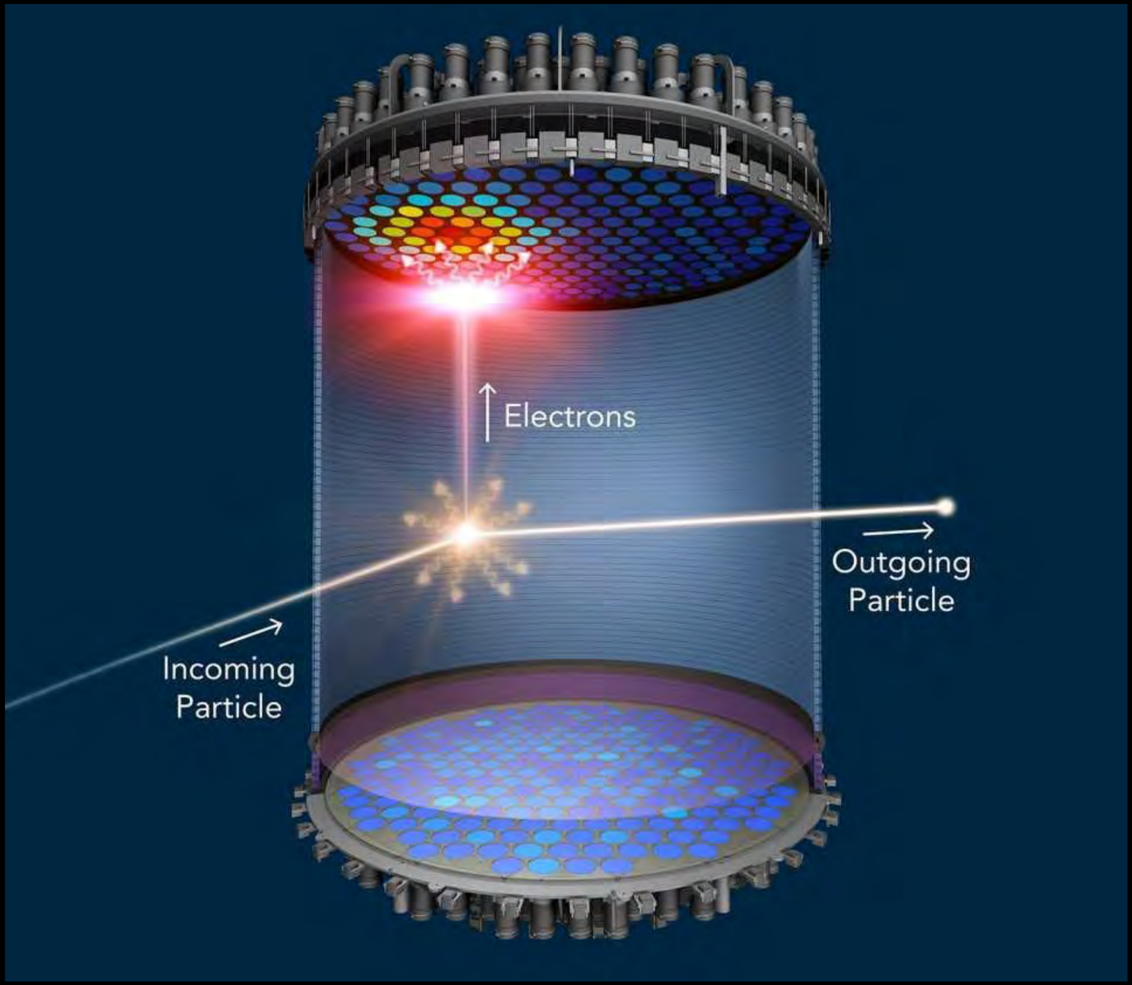
Direct Detection of Dark Matter





Direct Detection of Dark Matter

[LZ collaboration]



# of recoils ∝ exposure = (target mass) × (time)

1987: 750 g of Ge

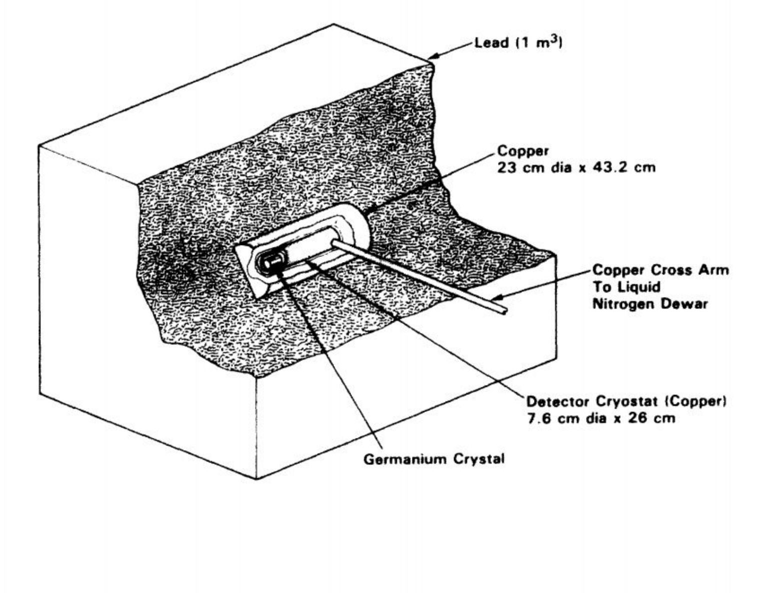
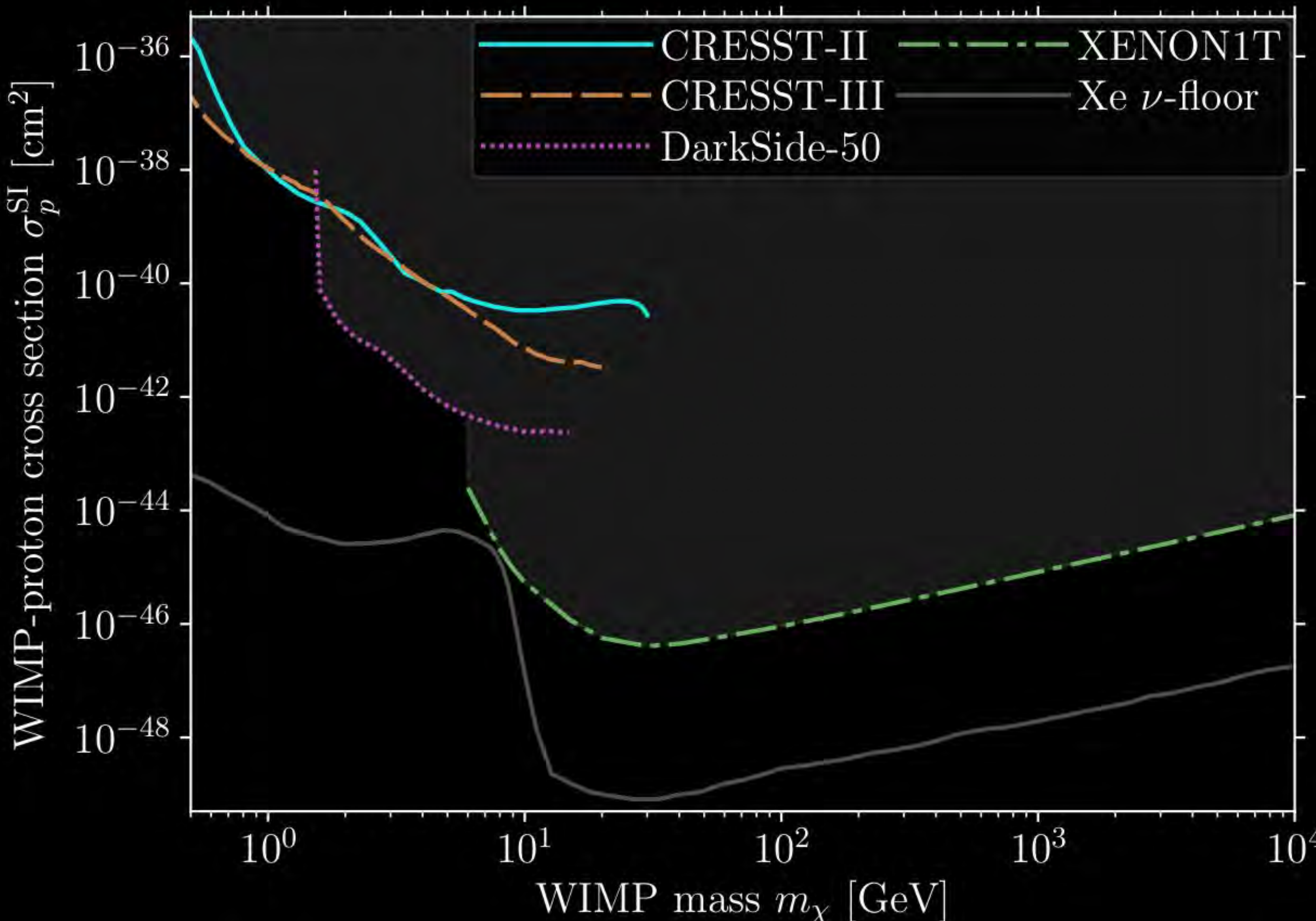


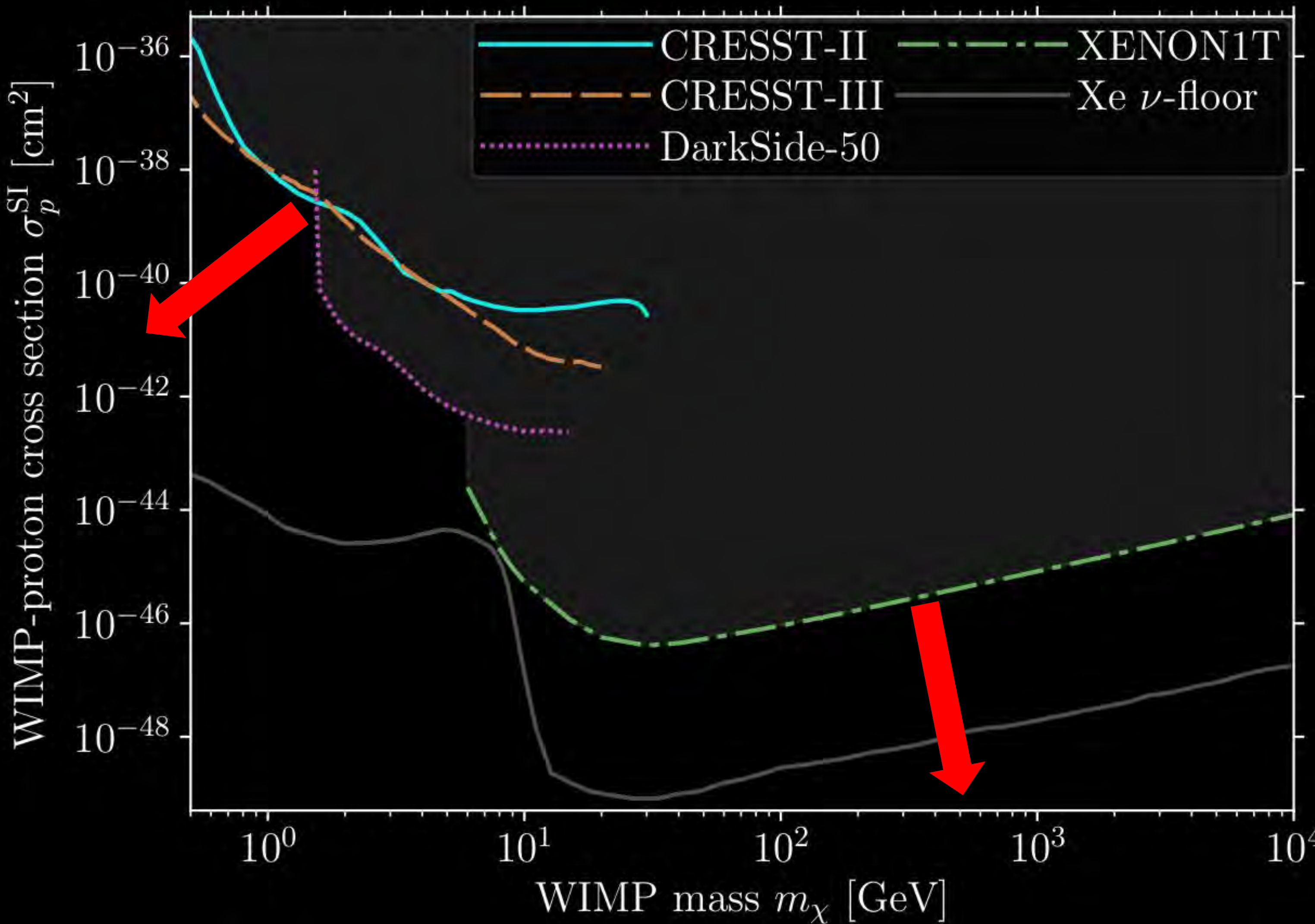
FIG. 1. Ultra-low-background, 135 cm^3 prototype Ge detector with copper inner shield.

[Ahlen+ ‘87, Avignone+ ‘86]

2022: 8 tonnes of Xe

[XENON collaboration]

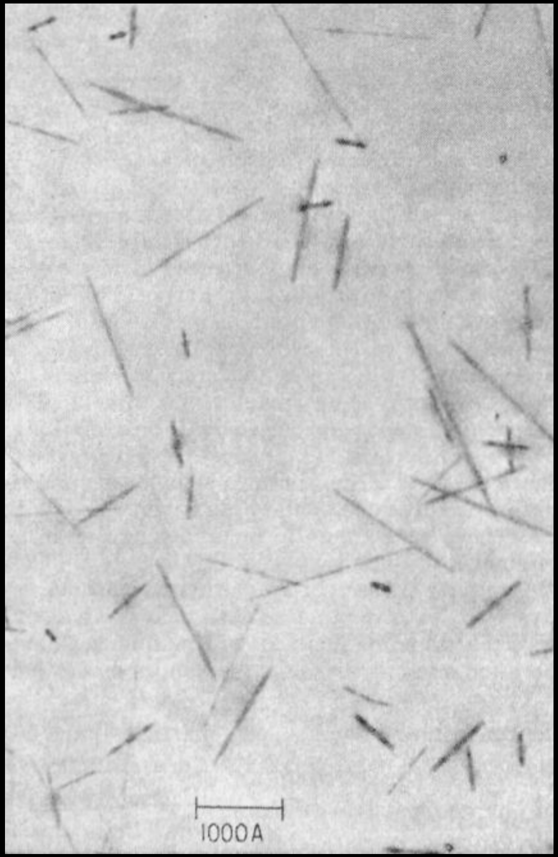

CRESST-II
CRESST-III
DarkSide-50
XENON1T
Xe ν-floor
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
WIMP-proton cross section σ_p^{SI} [cm^2]
10^0
10^1
10^2
10^3
10^4
WIMP mass m_χ [GeV]



CRESST-II
CRESST-III
DarkSide-50
XENON1T
Xe ν-floor
WIMP-proton cross section σ_p^{SI} [cm^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
WIMP mass m_χ [GeV]

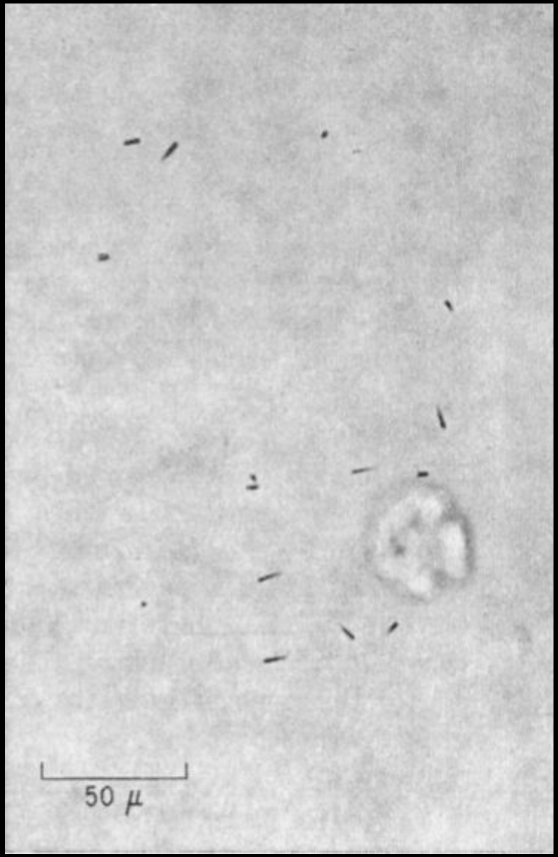
Solid State (Nuclear) Track Detectors (SSTDs)

Fission fragment tracks in synthetic Mica, TEM



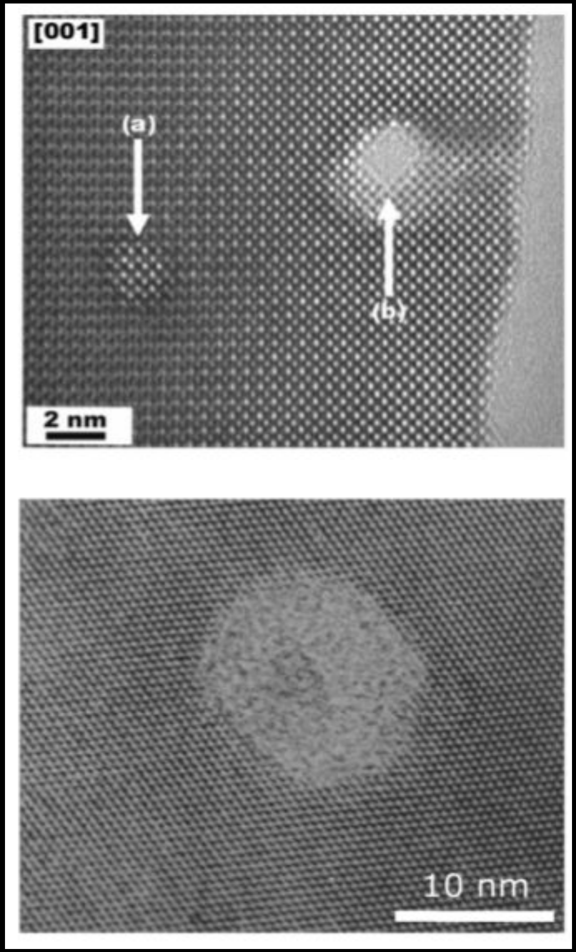
[Price&Walker '63]

Fossil Tracks in Madagascar Phlogopite; optical microscopy after chemical etching.



[Price&Walker '63]

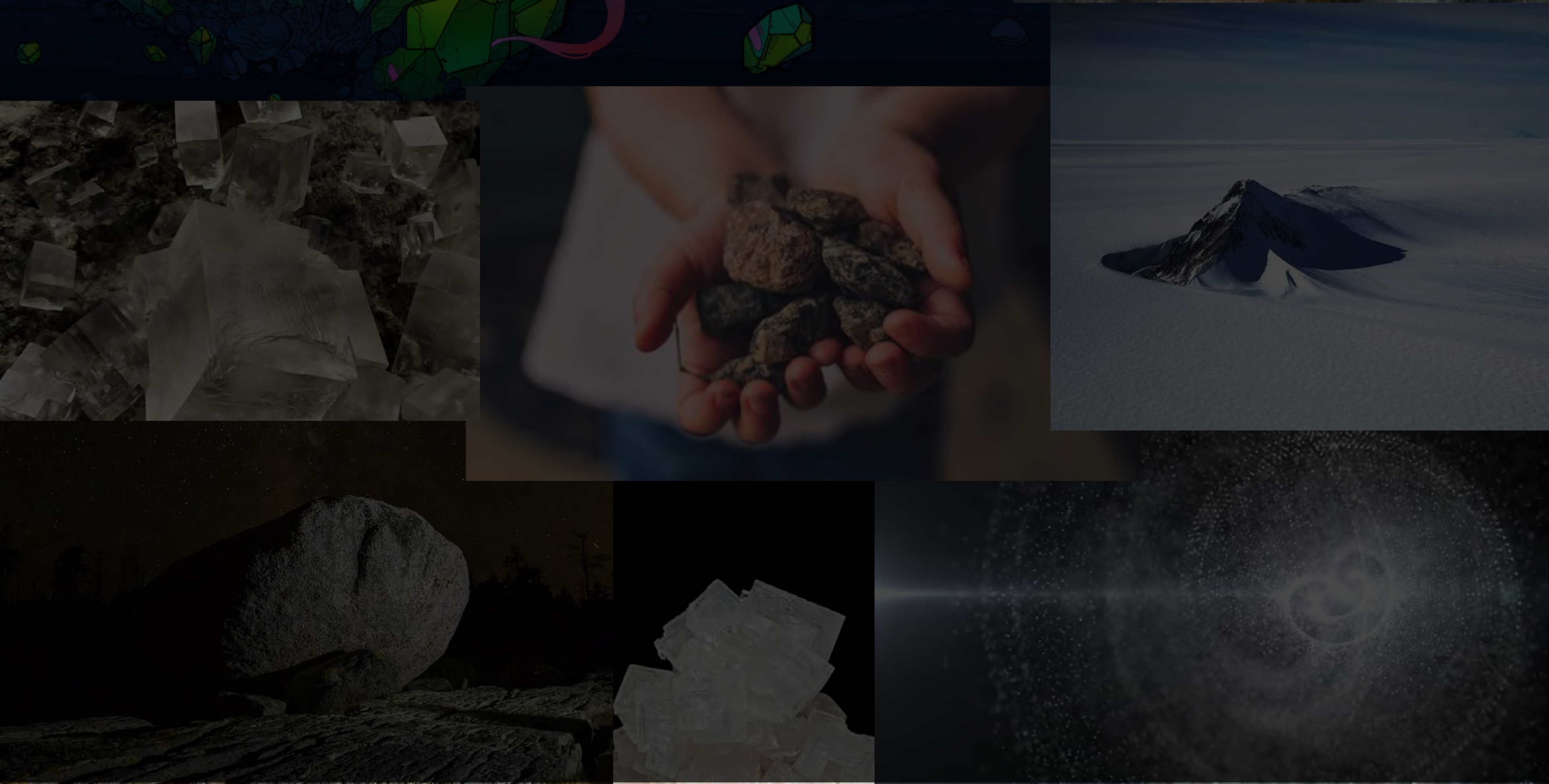
High-resolution TEM



[Toulemonde+ '06]

Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)

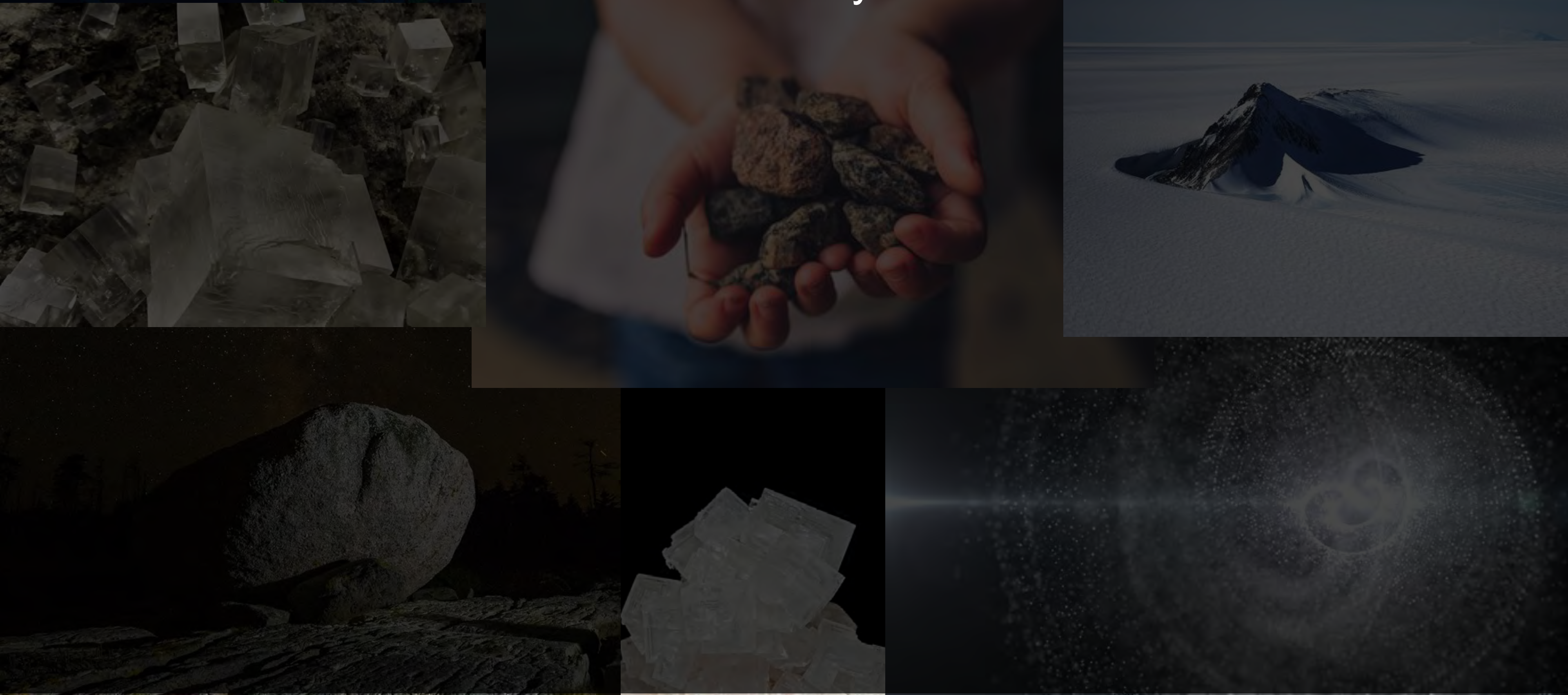


Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years

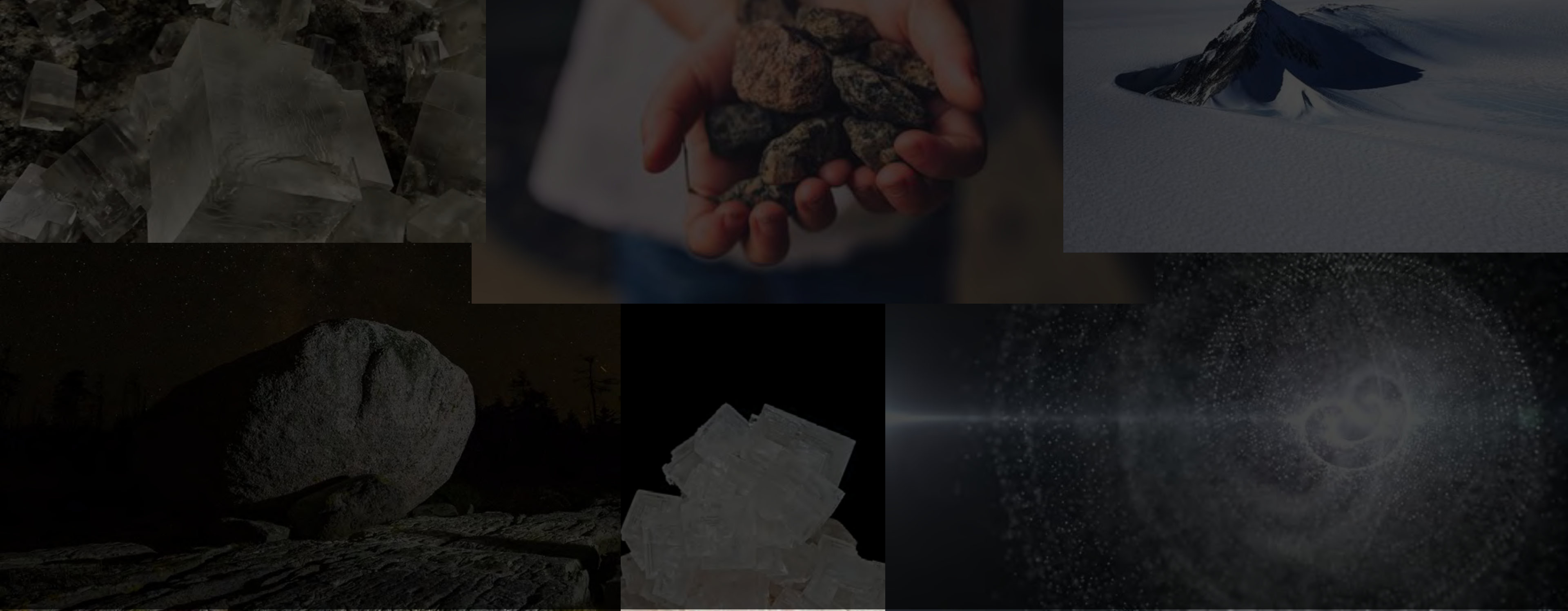
Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years
- Natural minerals are as old as $\sim 10^9$ years



Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years
- Natural minerals are as old as $\sim 10^9$ years
- Modern microscopy technology allows for nanometer-scale resolution!

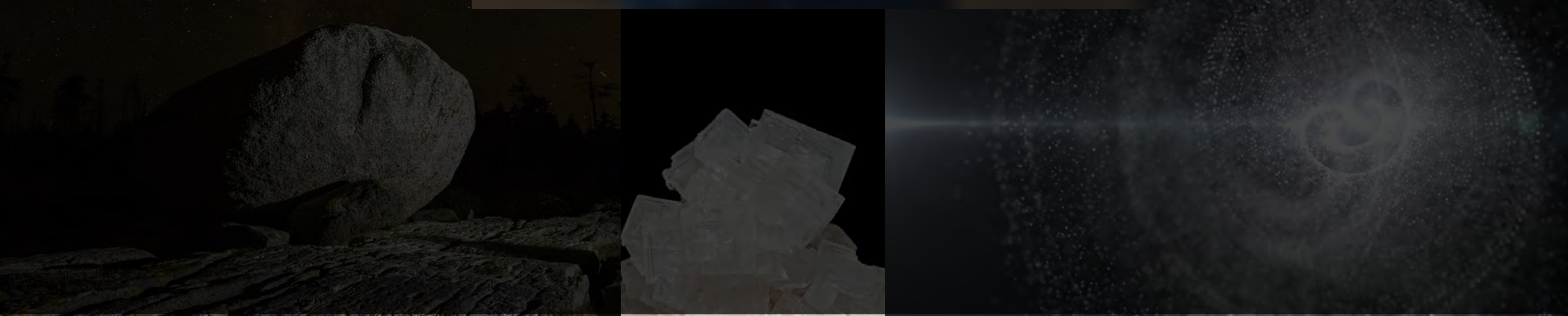


Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years
  Natural minerals are as old as $\sim 10^9$ years
- Modern microscopy technology allows for nanometer-scale resolution!

Exposure through time

$100\ \text{g} \times 1\ \text{Gyr} = 10\ \text{kilotonne} \times 10\ \text{yr}$



Paleo-Detectors

- Many (natural) minerals are good SSTDs
  (need to be insulator or poor semiconductor)
- Once created, damage tracks can be preserved for $\gg 10^9$ years
  Natural minerals are as old as $\sim 10^9$ years
- Modern microscopy technology allows for nanometer-scale resolution!

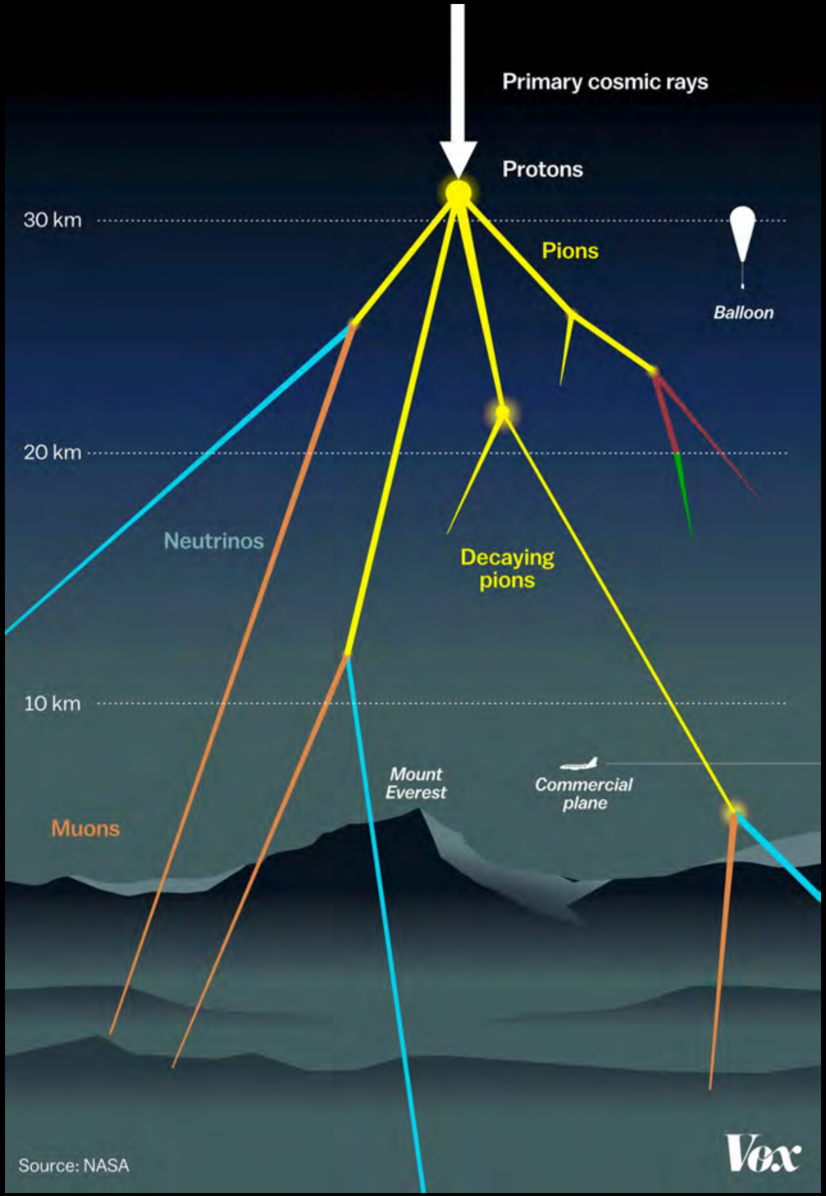
Exposure through time

$100\text{ g} \times 1\text{ Gyr} = 10\text{ kilotonne} \times 10\text{ yr}$

$\lesssim$ keV recoil thresholds

Backgrounds, Backgrounds, Backgrounds

- Cosmogenic



Backgrounds, Backgrounds, Backgrounds

- Cosmogenic

Exponentially suppressed with depth*:

Depth [km]	2	5	6	7
Neutron flux [1/cm^2/Gyr]	10^6	100	10	0.1

Note, that storage close to the surface until read-out is ok:

Depth [m]	100	250	500
Neutron flux [1/cm^2/yr]	30	8	2

*Neutron production from atmospheric neutrinos becomes relevant at depths larger than ~ 6 km

Backgrounds, Backgrounds, Backgrounds

- Cosmogenic → use target samples from deep underground

Backgrounds, Backgrounds, Backgrounds

- Cosmogenic → use target samples from deep underground
- Radioactivity

Backgrounds, Backgrounds, Backgrounds

- Cosmogenic → use target samples from deep underground
- Radioactivity
  - Get radiopure samples

Type	Rock forming minerals		Marine Evaporites
	Formed from Crust	Formed from Mantle	
Examples	Quartz, Feldspar, Mica	Olivine, Nchwaningite	Gypsum, Halite
^{238}U level (in weight)	10^{-6} (ppm)	10^{-10} (0.1 ppb)	10^{-11} (0.01 ppb)

[SB+ 1906.05800]

Backgrounds, Backgrounds, Backgrounds

- Cosmogenic → use target samples from deep underground
- Radioactivity → get radiopure samples (containing hydrogen)

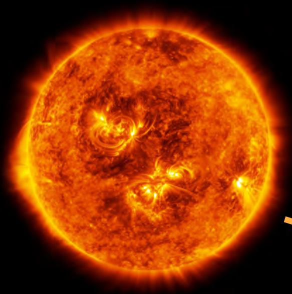
Backgrounds, Backgrounds, Backgrounds

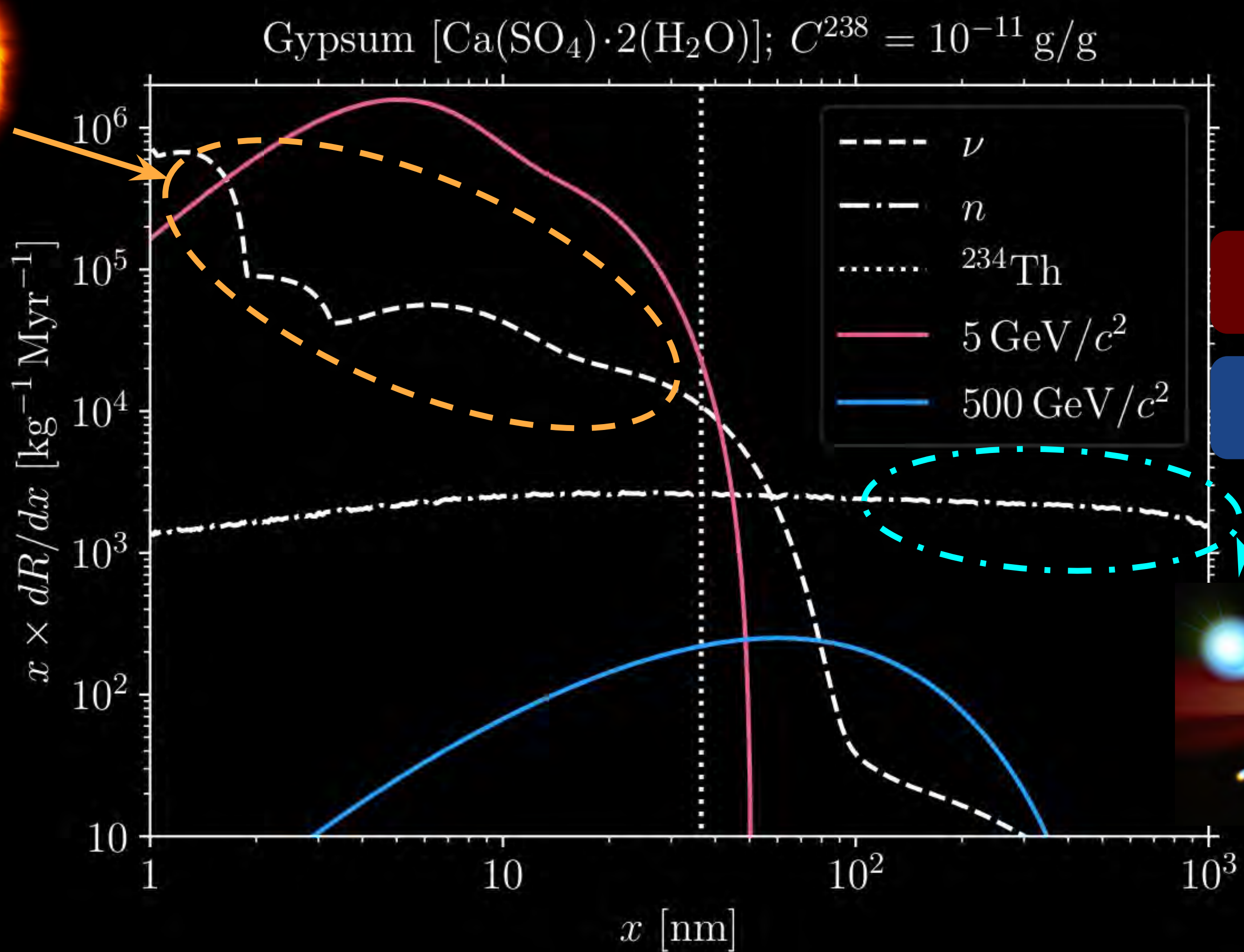
- Cosmogenic → use target samples from deep underground
- Radioactivity → get radiopure samples (containing hydrogen)
- Neutrinos → background or signal?

[NASA / SDO / Seán Doran]

[NASA/CXC/SAO]

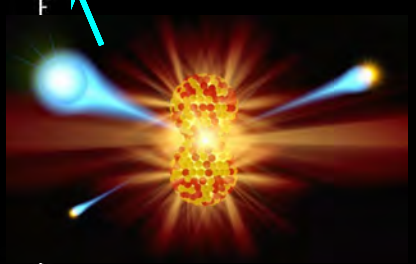
Backgrounds vs Dark Matter



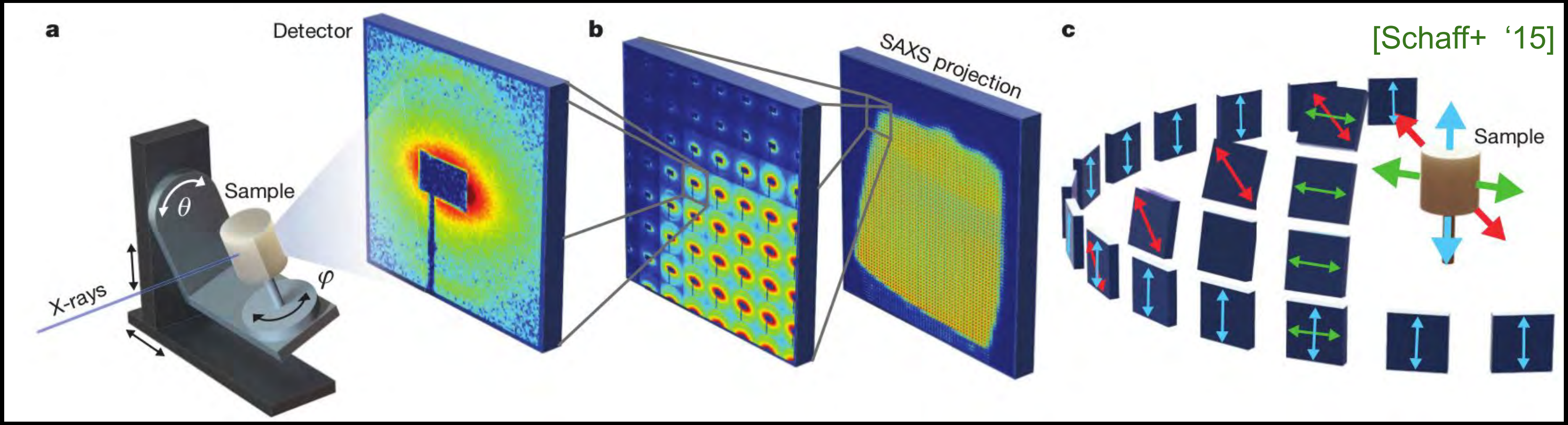


$\sigma_p^{SI} = 10^{-43}$ cm^2

$\sigma_p^{SI} = 10^{-46}$ cm^2



Read-Out Methods (i): X-ray Ptychography



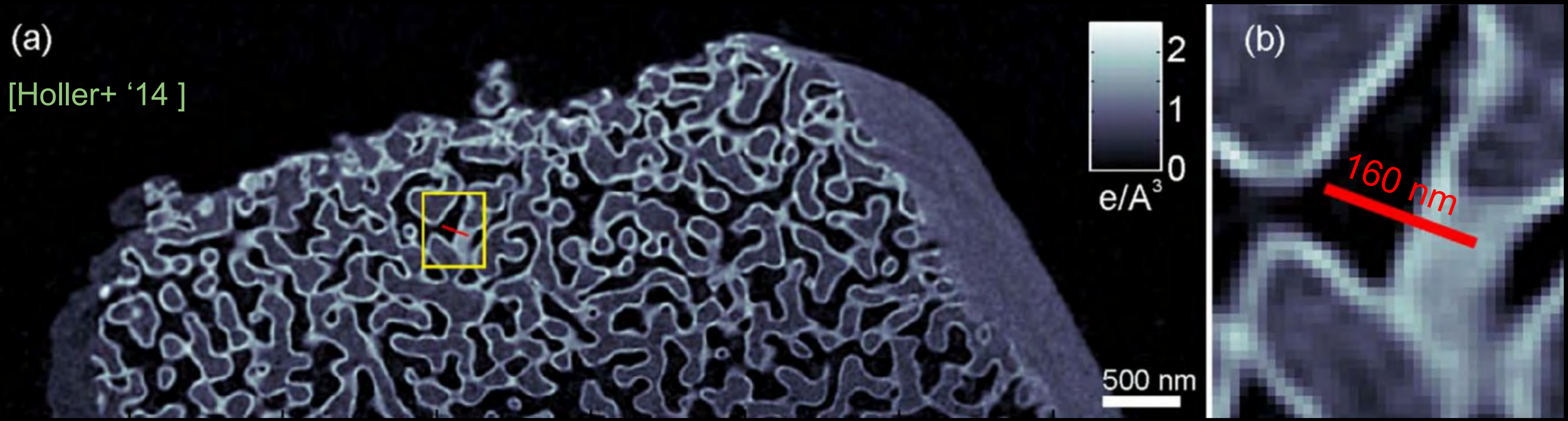
Single "pixel" of sample

Combine "pixels" into 2D picture

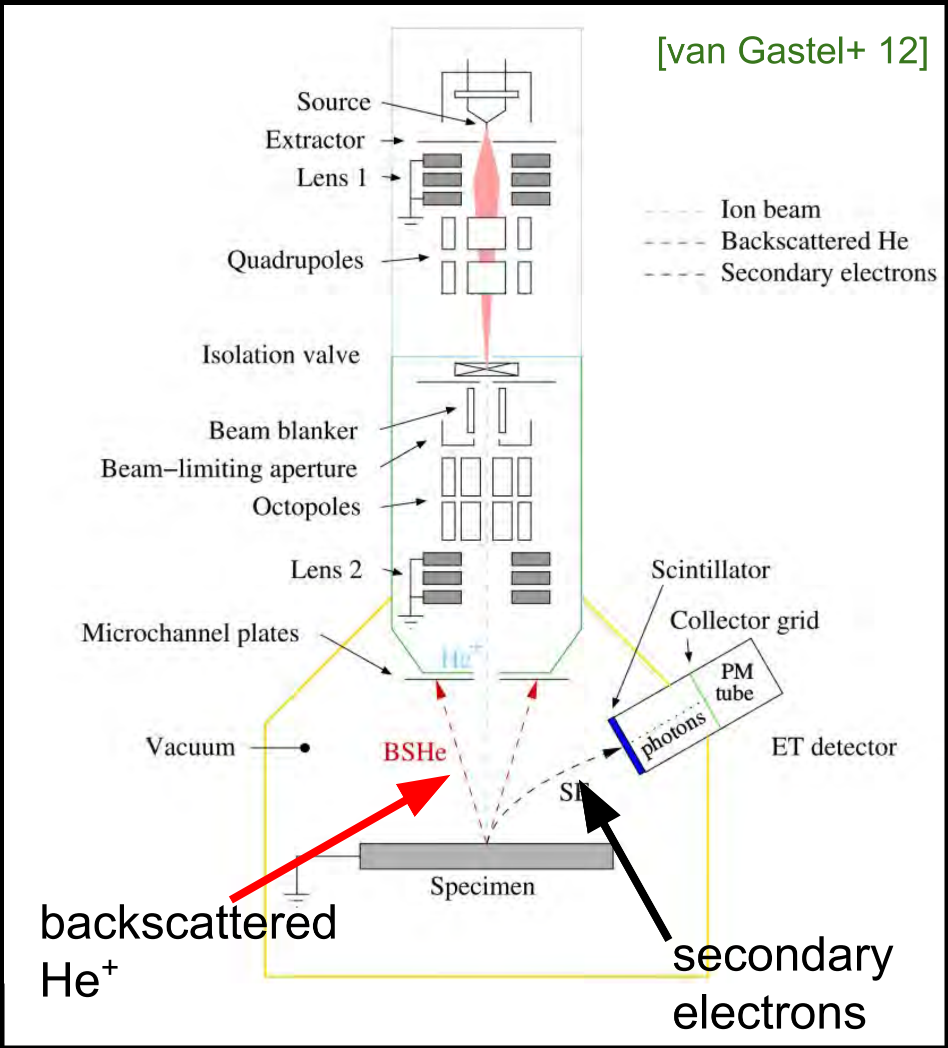
Reconstruct 3D image from 2D pictures

Read-Out Methods (i): X-ray Ptychography

- 16 nm isotropic 3D resolution demonstrated!
- Requires synchrotron light source

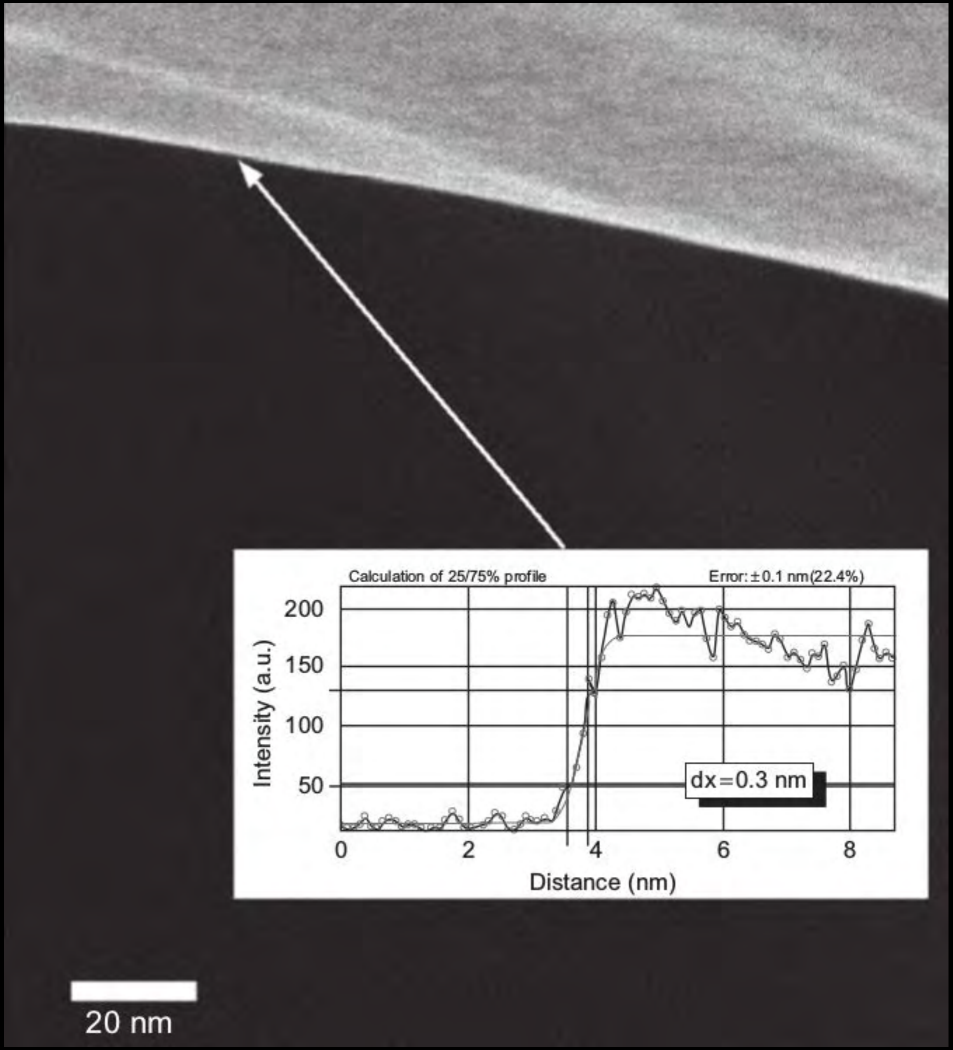


Read-Out Methods (ii): He-Ion Beam Microscopy



Read-Out Methods (ii): He-Ion Beam Microscopy

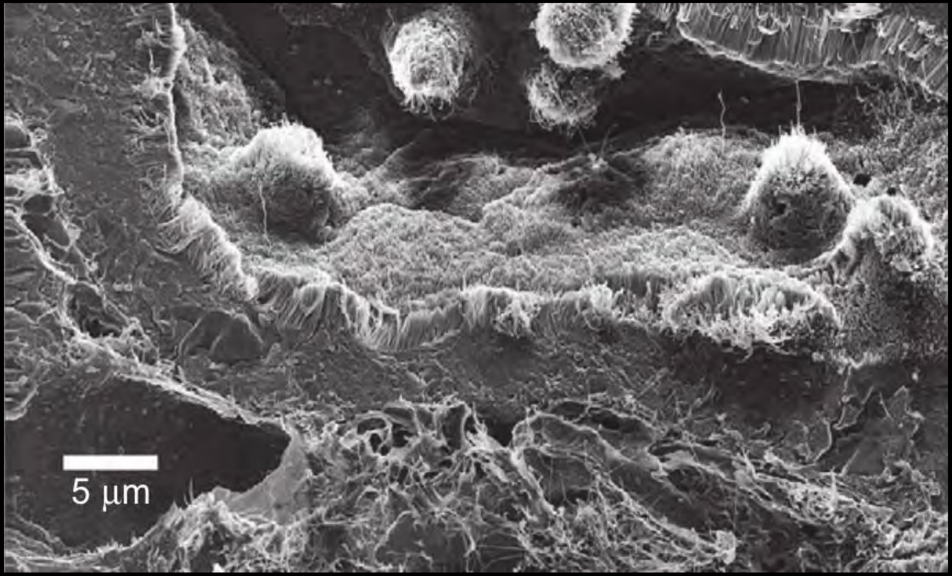
Edge of graphite flake [Hill+ ‘12]

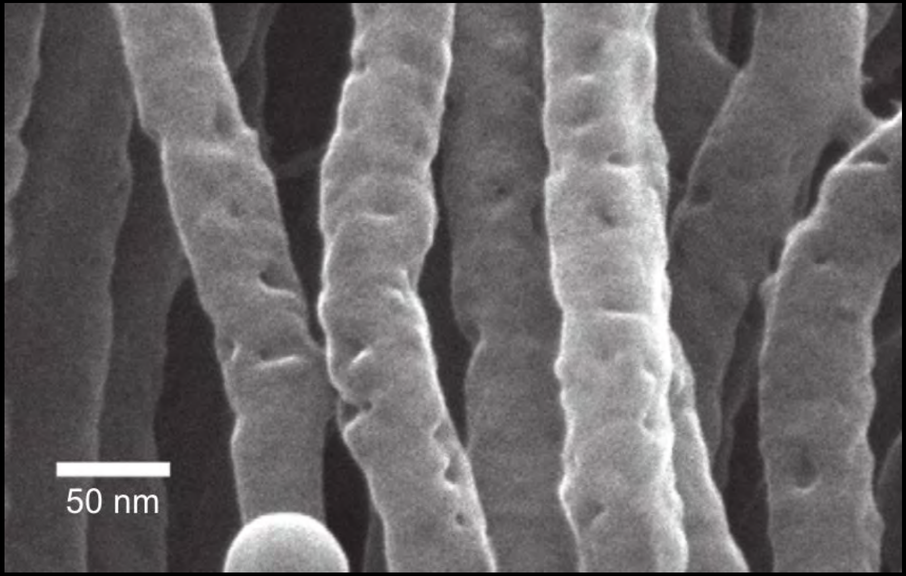


Read-Out Methods (ii): He-Ion Beam Microscopy

Overview & Zoom-in of rodent kidney

[Hill+ ‘12]

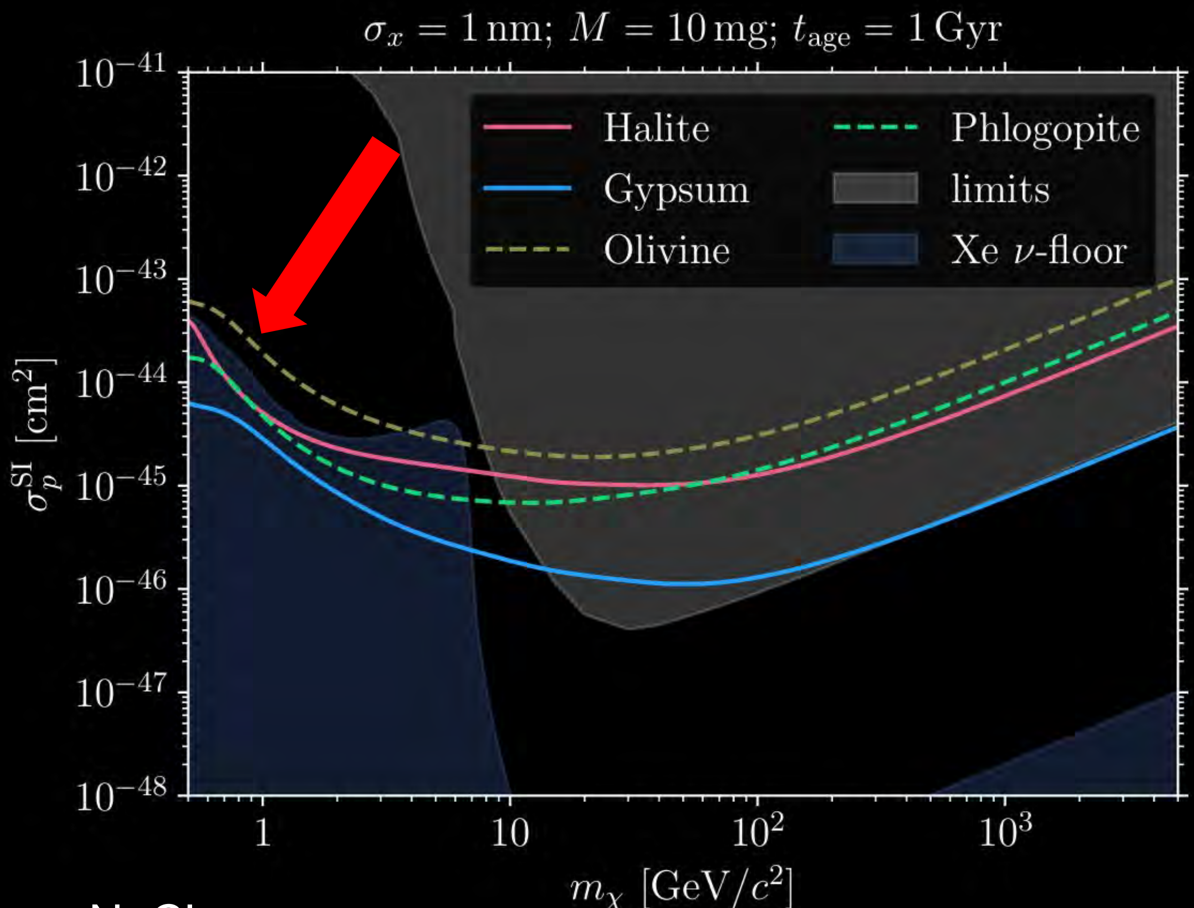




Dark Matter Sensitivity Projections

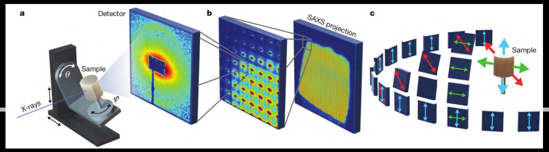
"High-Resolution" read-out:

- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)



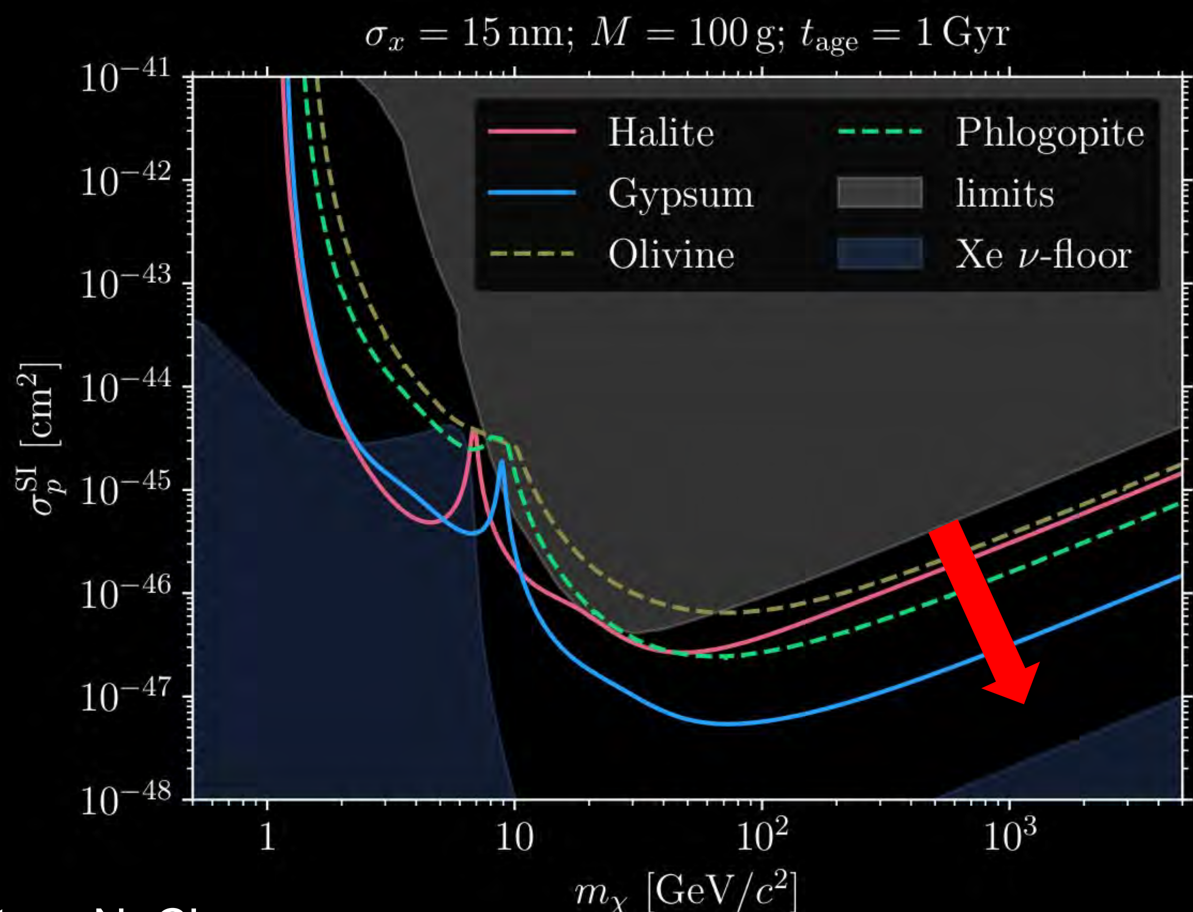
- Halite -- NaCl
- Gypsum -- $Ca(SO_4)\cdot 2(H_2O)$
- Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
- Phologopite --$KMg_3AlSi_3O_{10}F(OH)$

Dark Matter Sensitivity Projections



"High-Exposure" read-out:

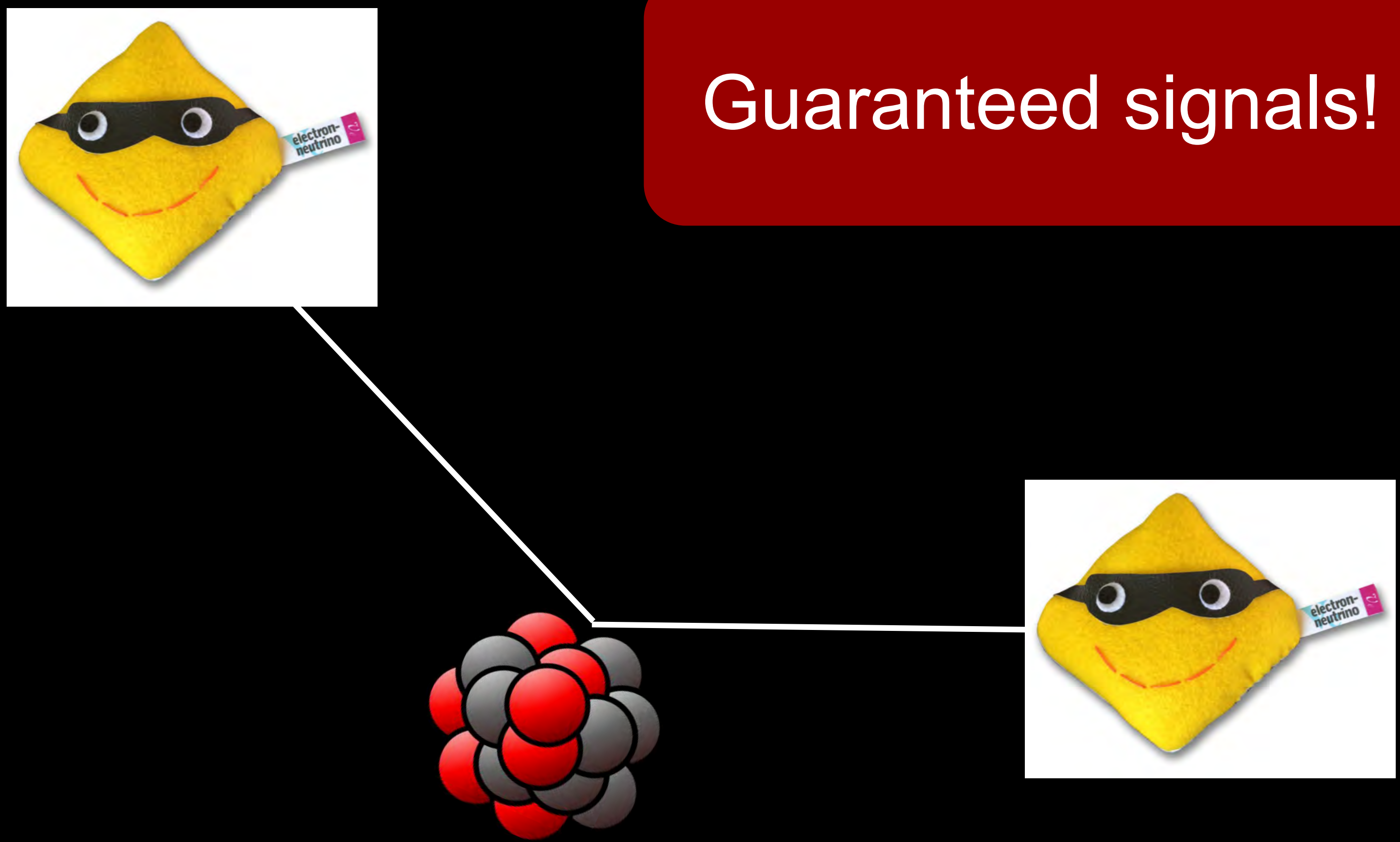
- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)



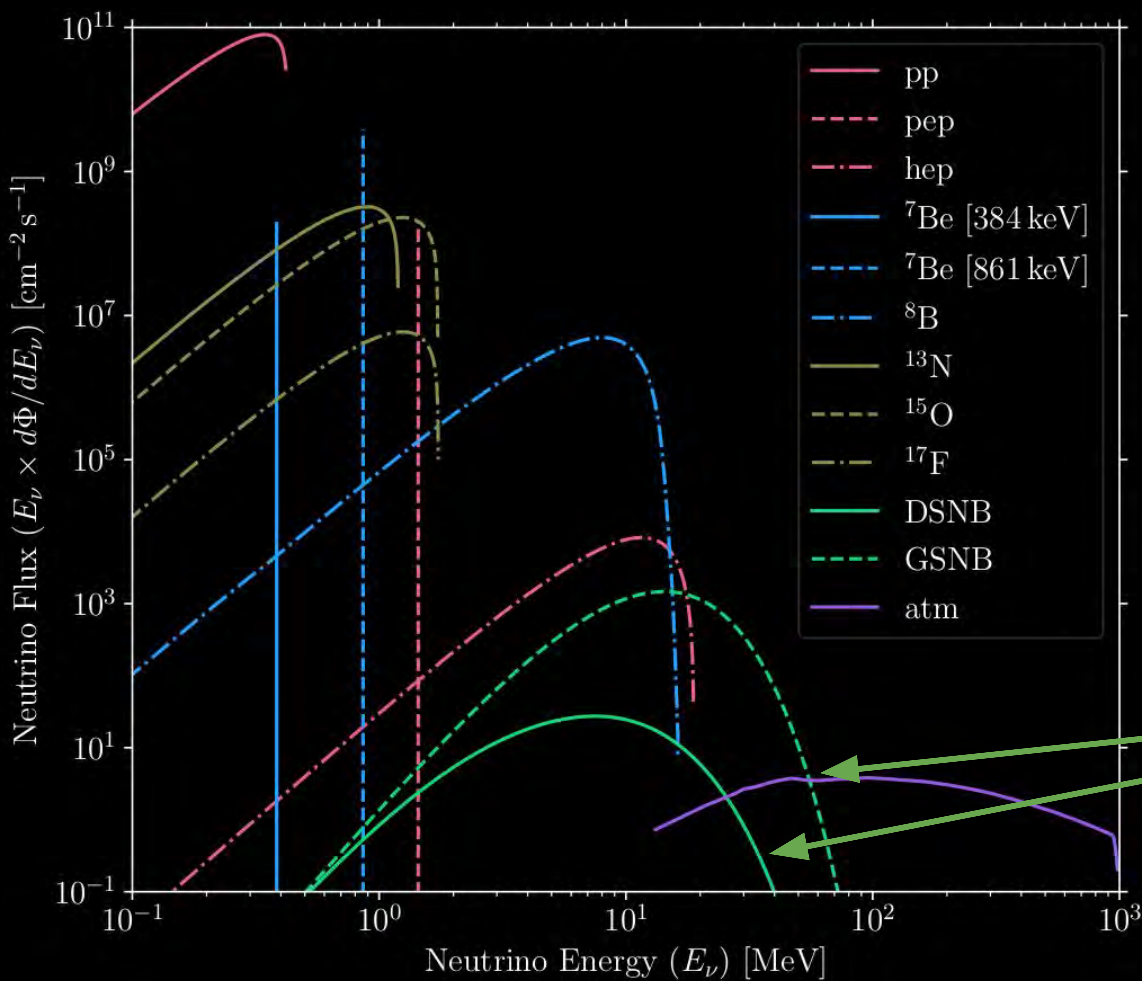
- Halite -- NaCl
- Gypsum -- $Ca(SO_4)$•$2(H_2O)$
- Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
- Phologopite --$KMg_3AlSi_3O_{10}F(OH)$

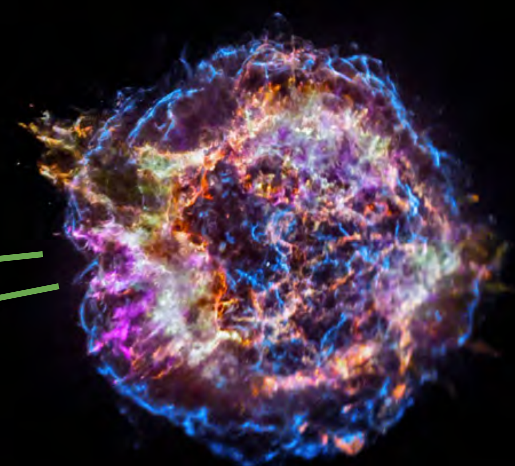
Switching gears...

Guaranteed signals!



Paleo-Detectors for Galactic Supernovae

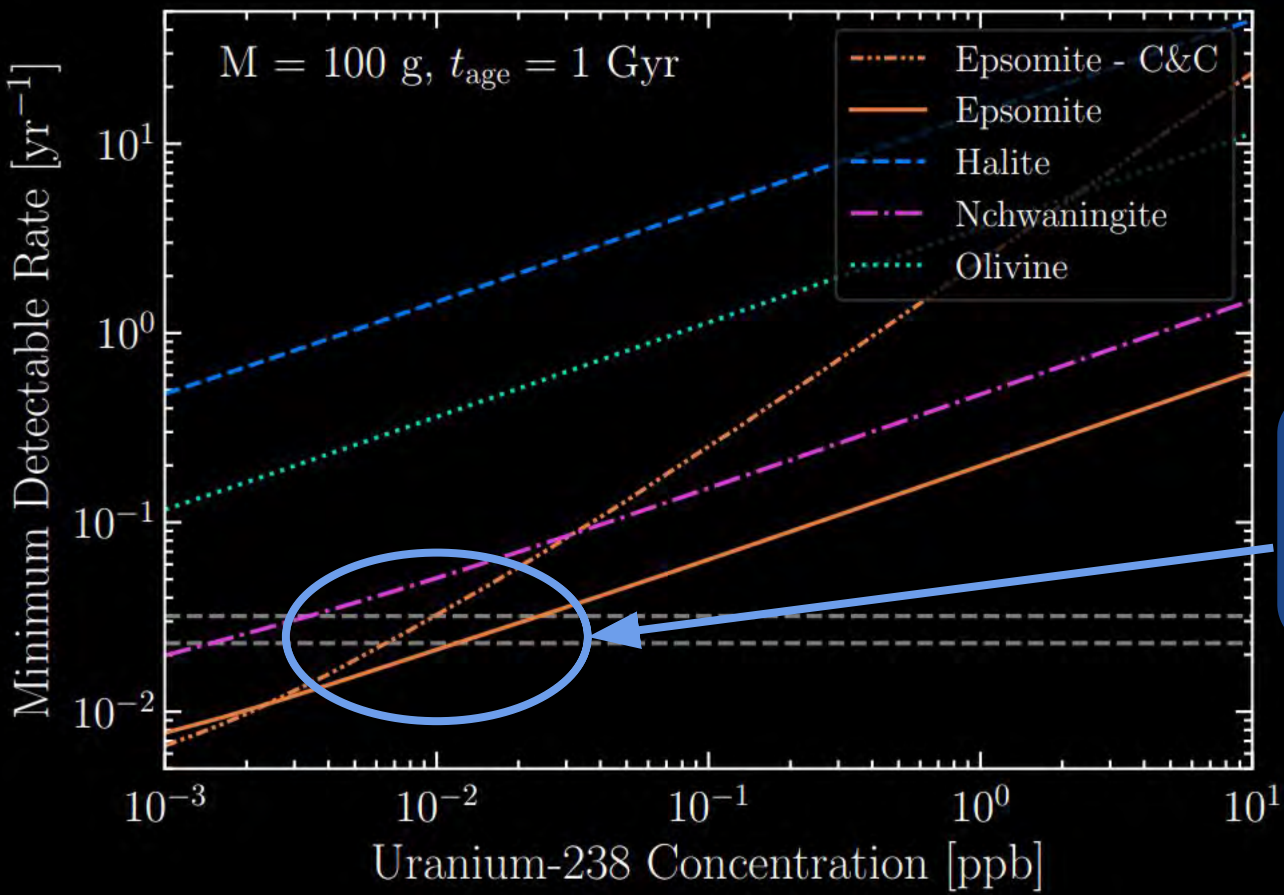




[NASA/CXC/SAO]

Measuring the Galactic Supernova Rate?

[SB+ 1906.05800]

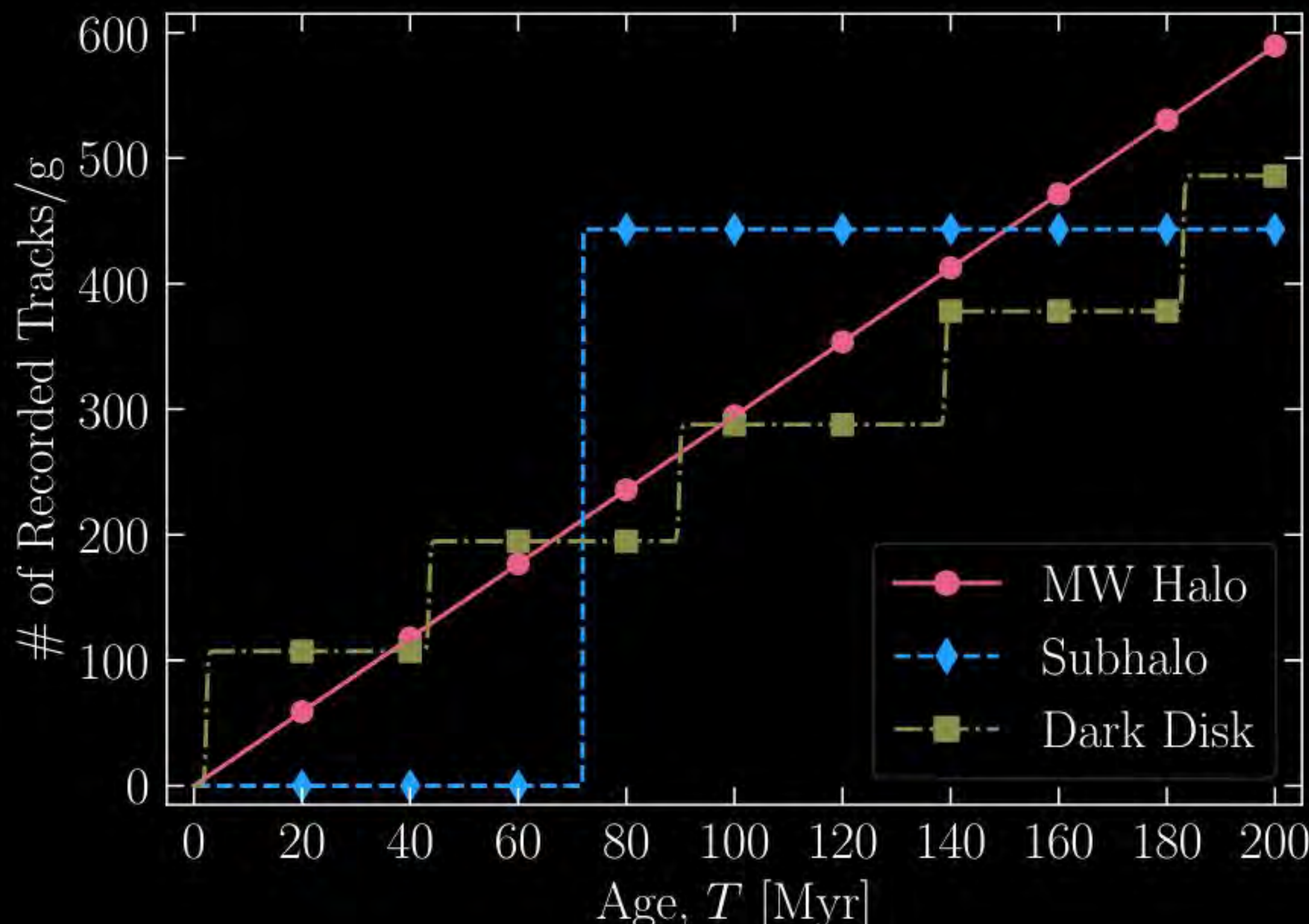


Detectable with sufficiently radiopure minerals!

- Halite -- NaCl
- Epsomite -- $MgSO_4 \cdot 7(H_2O)$
- Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
- Nchwaningite -- $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

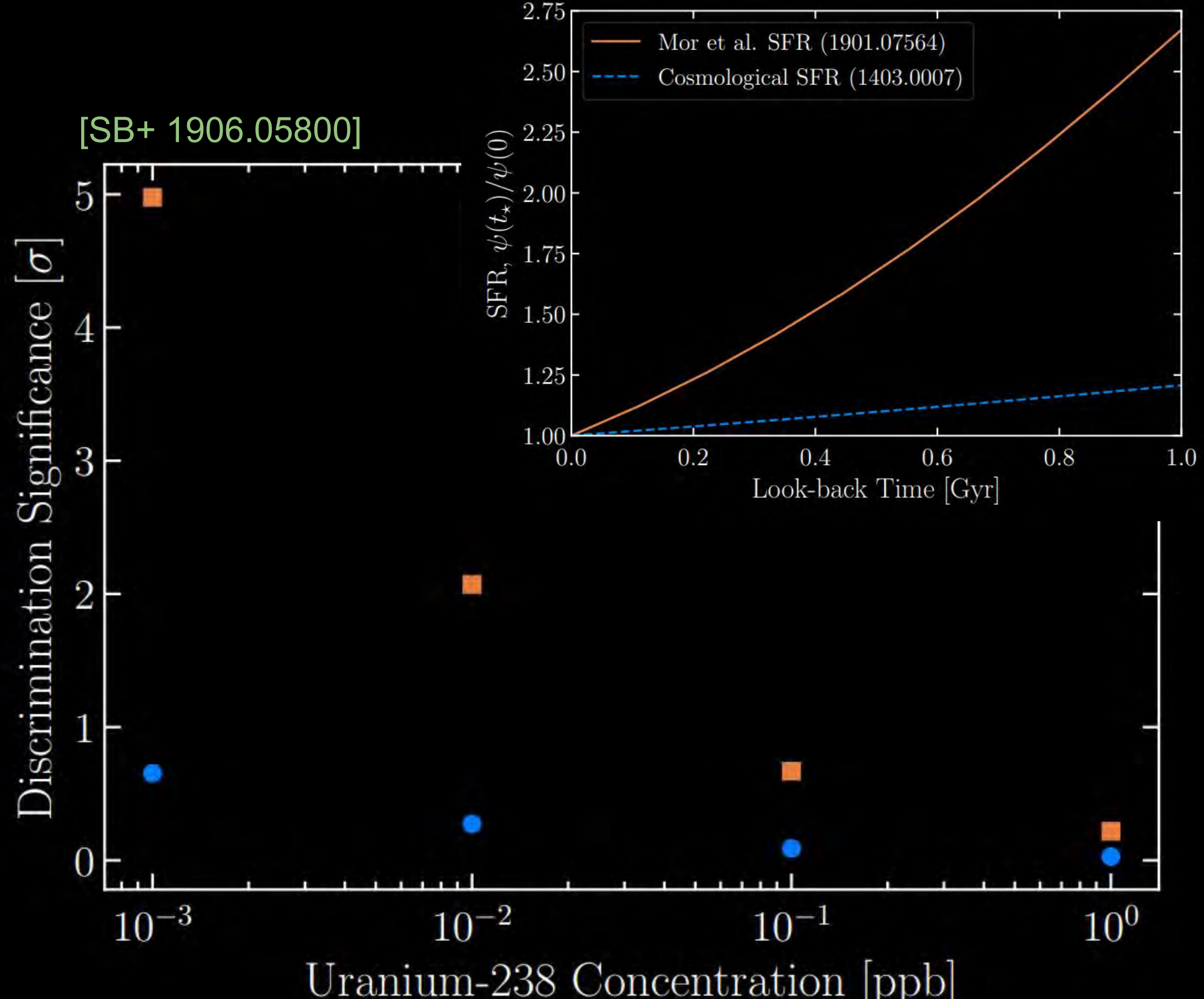
Beyond the rate: Time-varying Signals

[SB, DeRocco, Edwards, Kalia, 2107.02812]



Learning about the Time-Dependence of the SN rate?

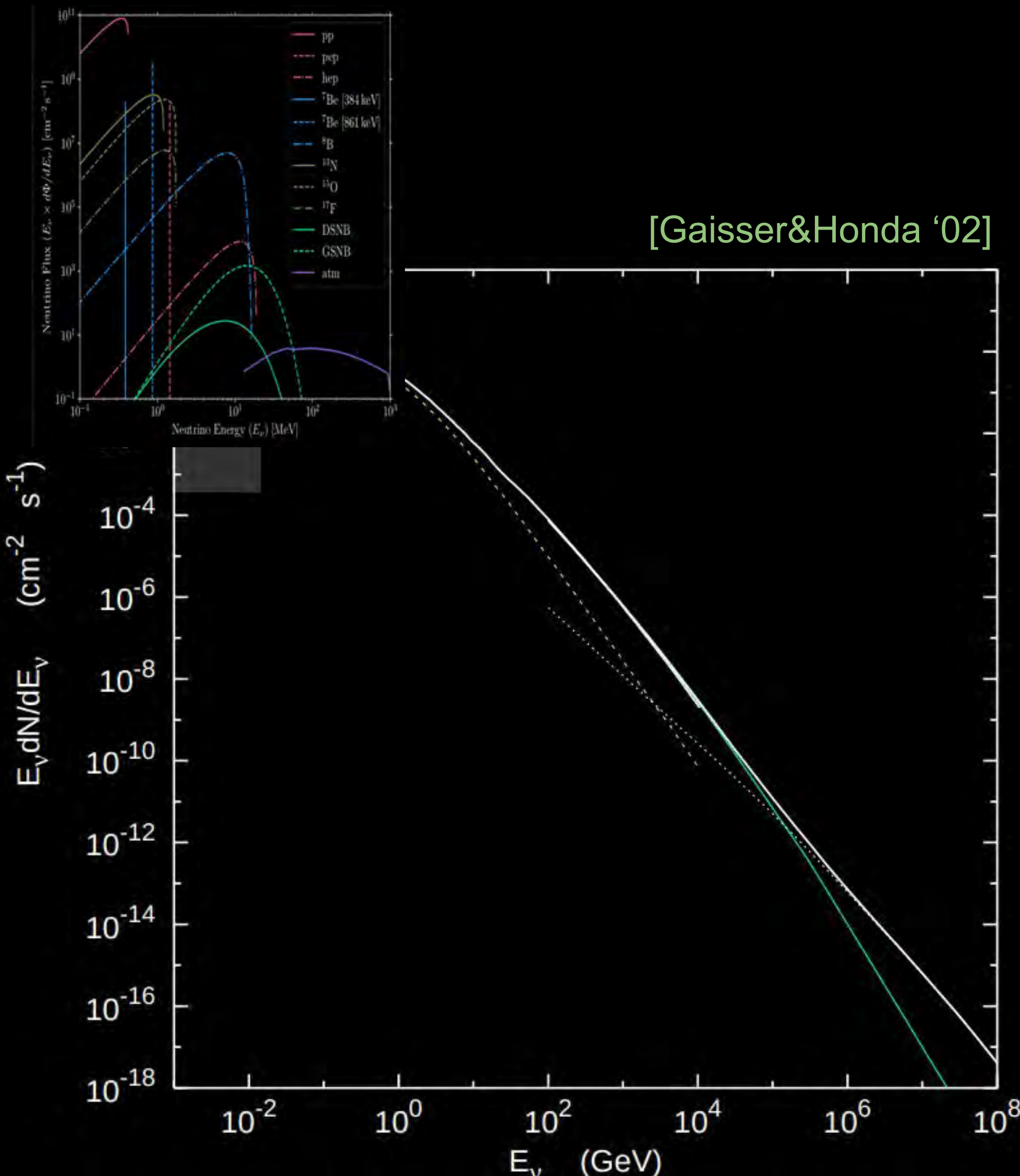
[SB+ 1906.05800]

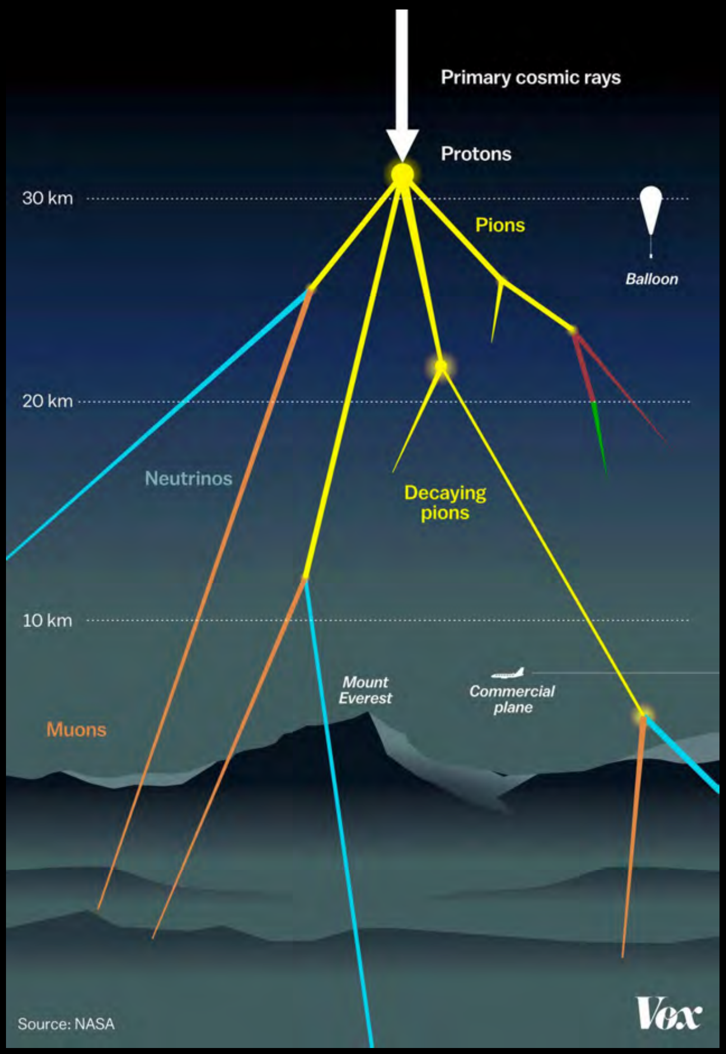


Epsomite -- $MgSO_4 \cdot 7(H_2O)$

What About a Little More Energetic Neutrinos?

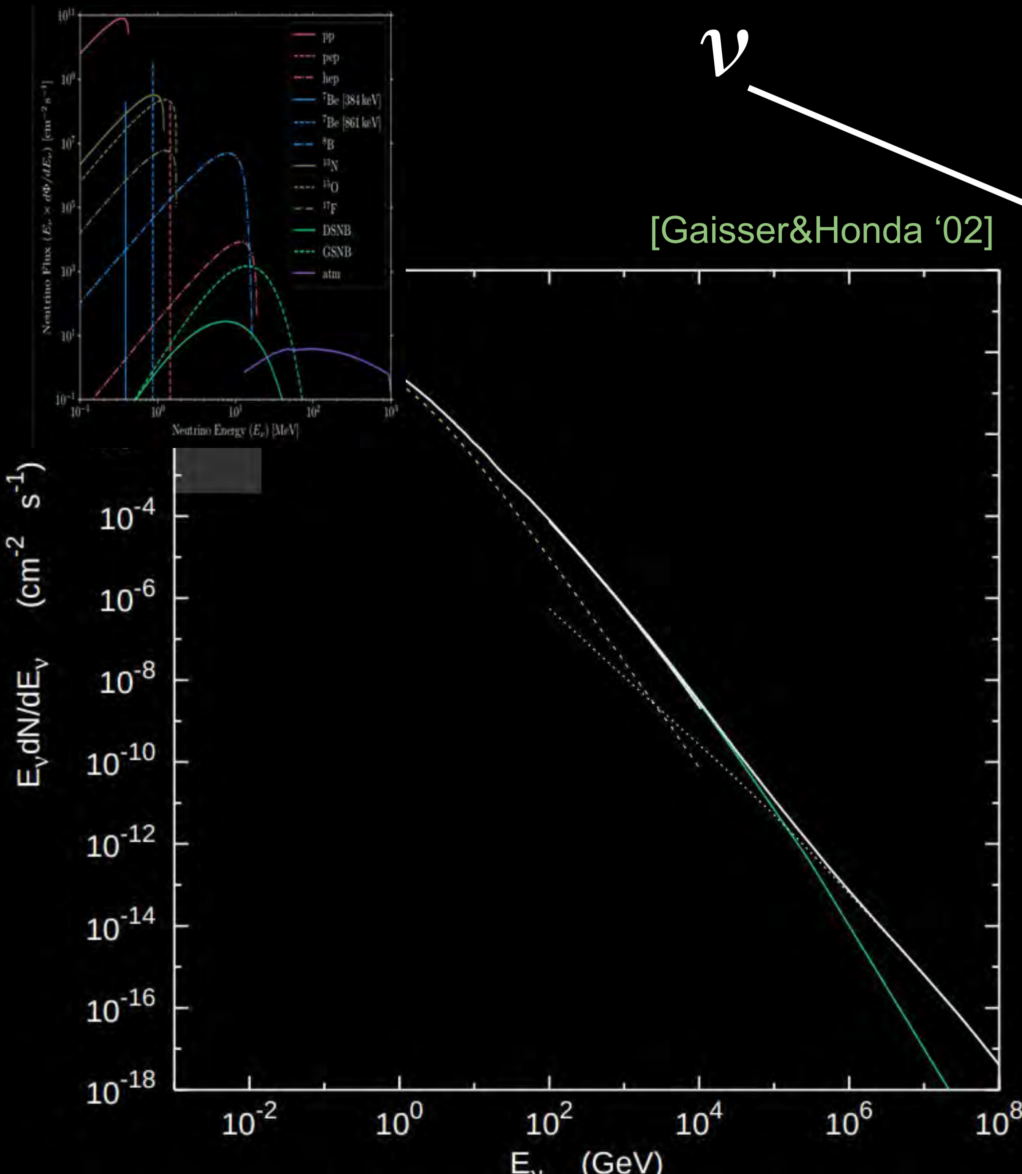
[Gaisser&Honda '02]

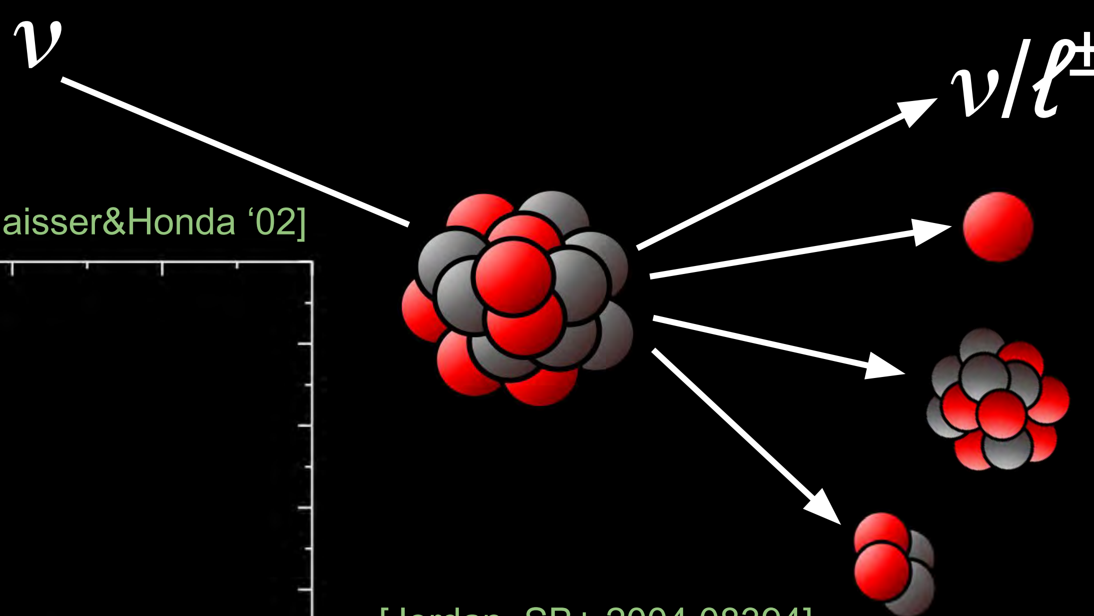




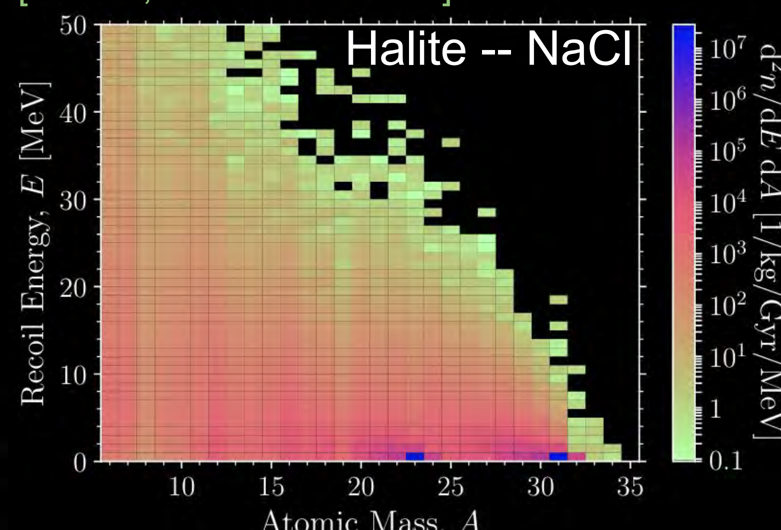
What About a Little More Energetic Neutrinos?

[Gaisser&Honda '02]





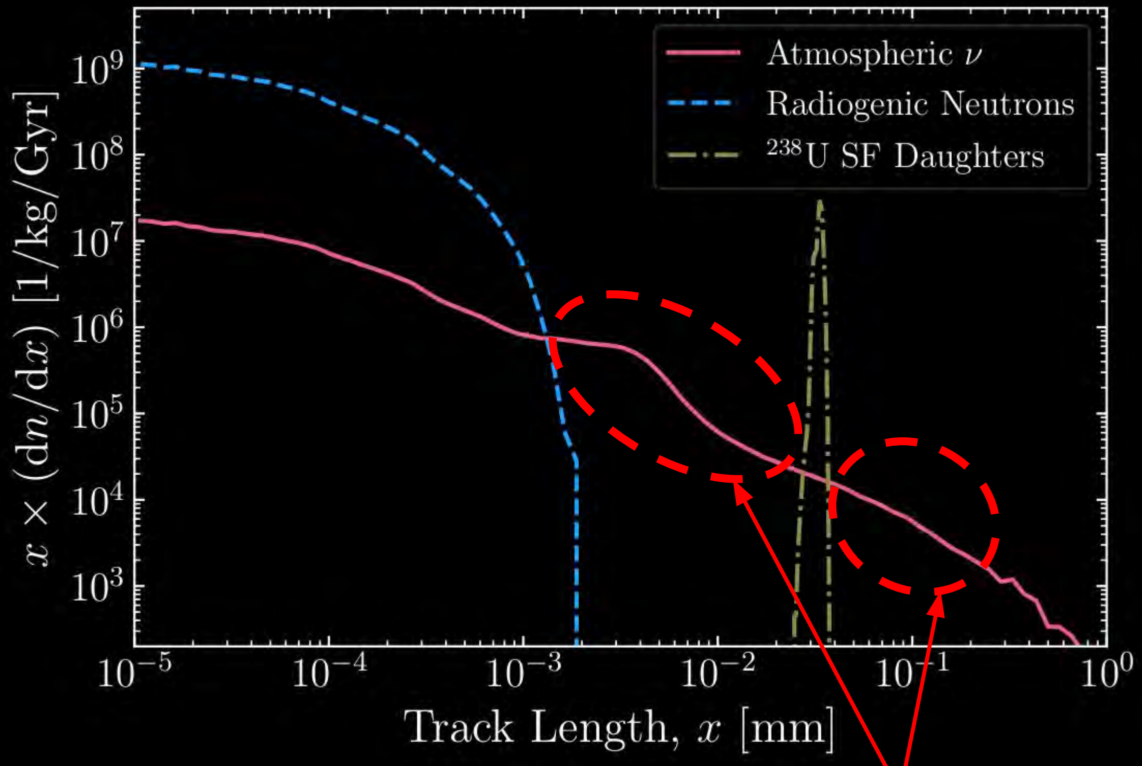
[Jordan, SB+ 2004.08394]



Cosmic Rays & Atmospheric Neutrinos

Halite -- NaCl

[Jordan, SB+ 2004.08394]



Background Free Signal Regions!

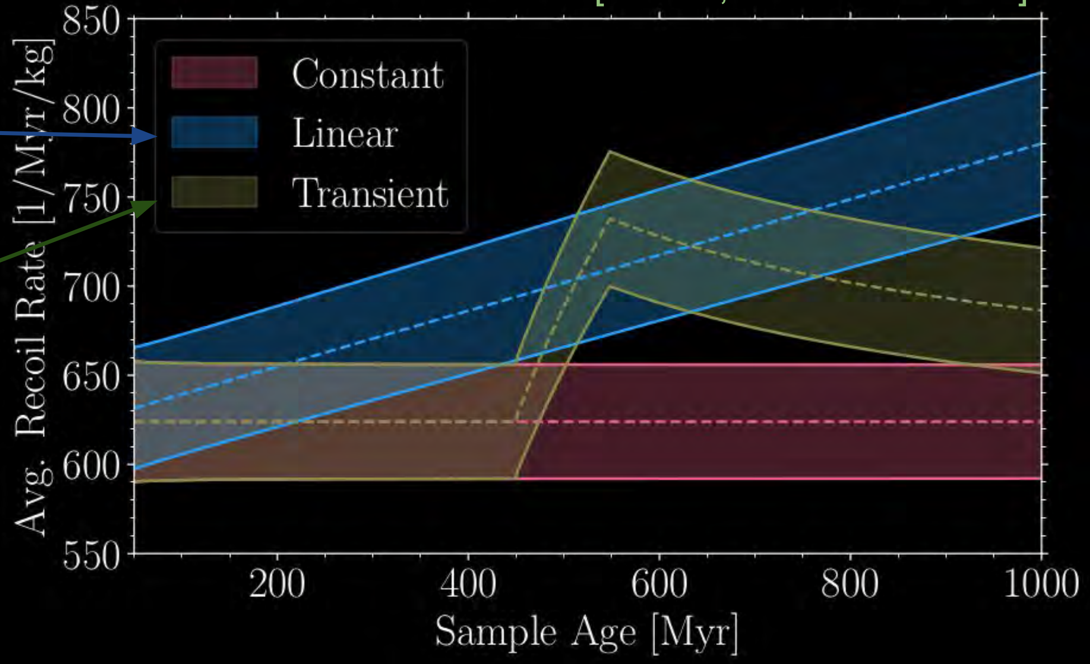
Cosmic Rays & Atmospheric Neutrinos

Could we learn about the rate of cosmic rays hitting Earth going back one billion years?

50% drop over 1 Gyr

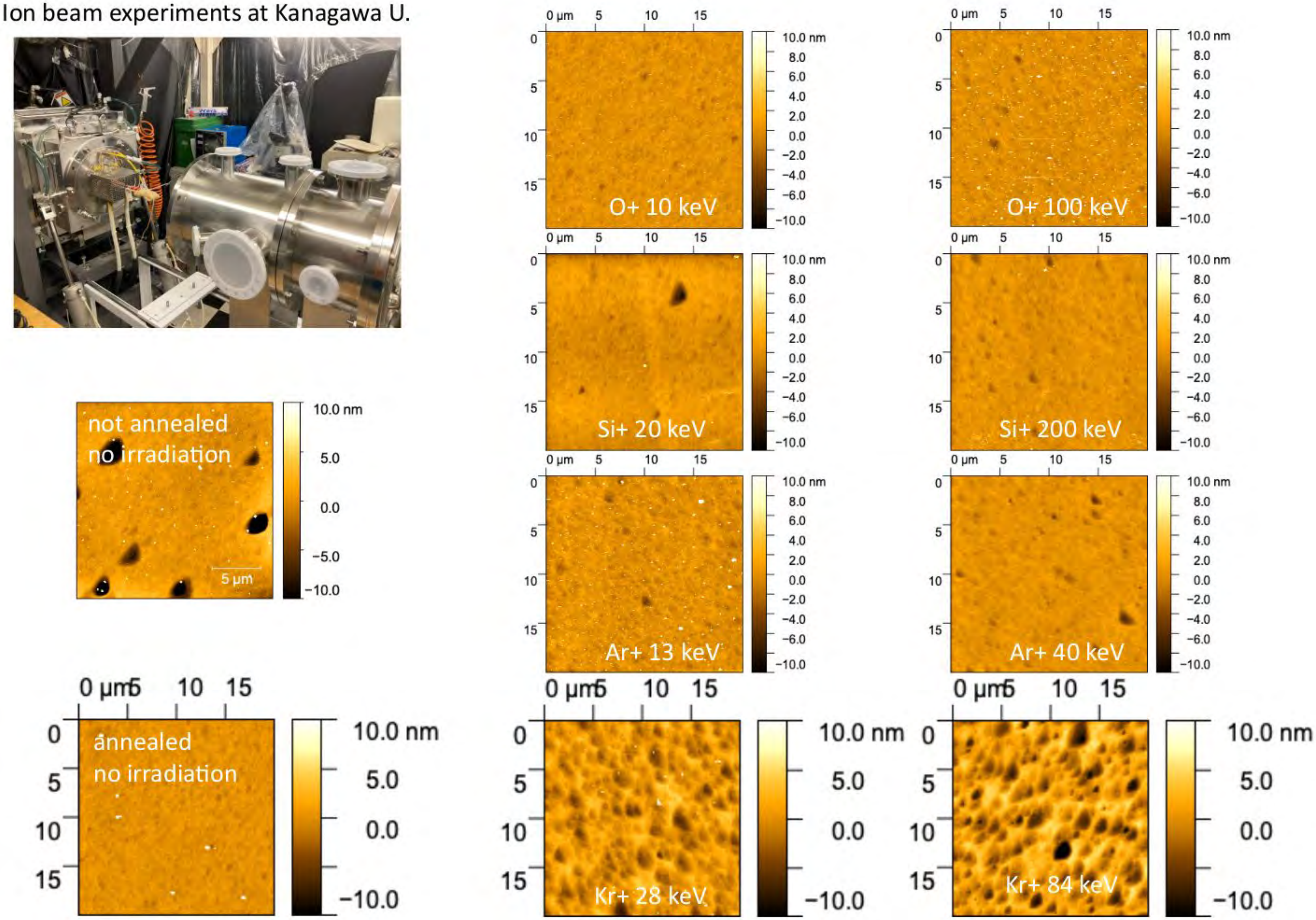
100% enhancement for 100 Myr

[Jordan, SB+ 2004.08394]

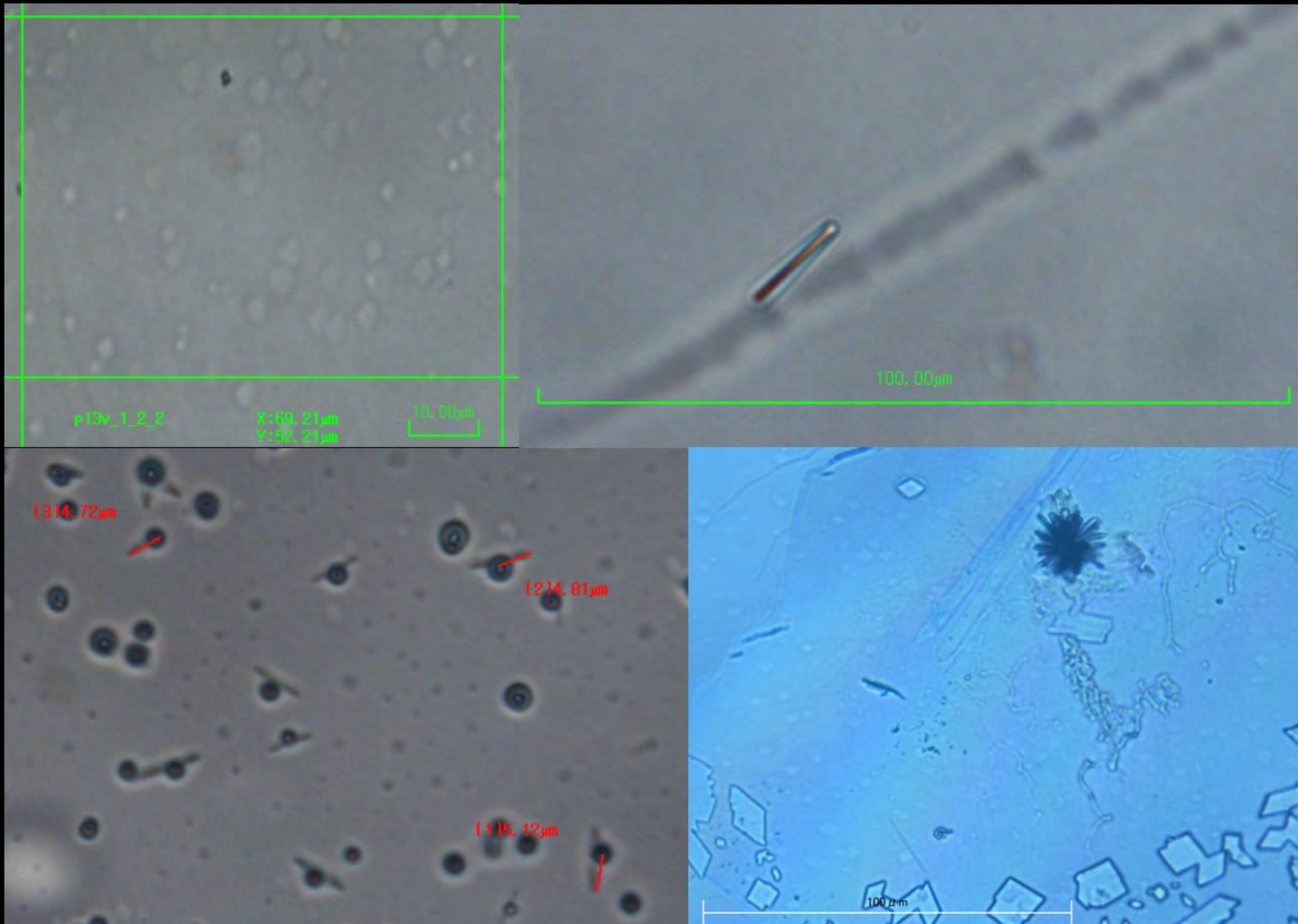


Feasibility studies by Shigenobu Hirose @ JAMSTEC

Ion beam experiments at Kanagawa U.

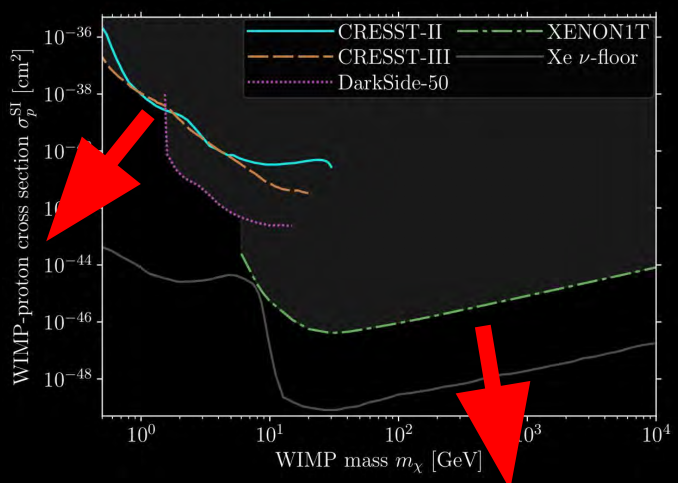


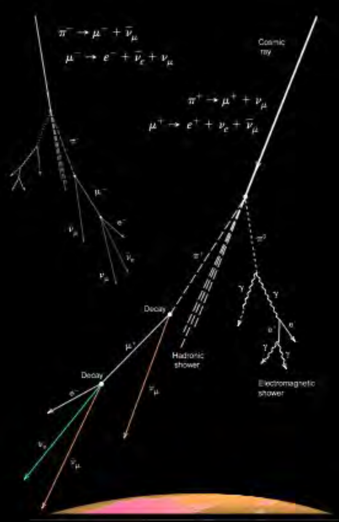
Feasibility studies by Tatsuhiro Naka @ Toho U



Learning about this Universe from Rocks

- Old (10 Myr – 1 Gyr) rocks store information about nuclear recoils
  - Large age brings large exposure: 100 g x 1 Gyr = 100 kt yr!
  - Read-Out promising thanks to modern nano-technology
    - nuclear recoil energy thresholds of 0.1 – 1 keV?
- Reading out a time-series of rocks, one could measure the time-dependence of signals over 10 Myr – 1 Gyr scales!

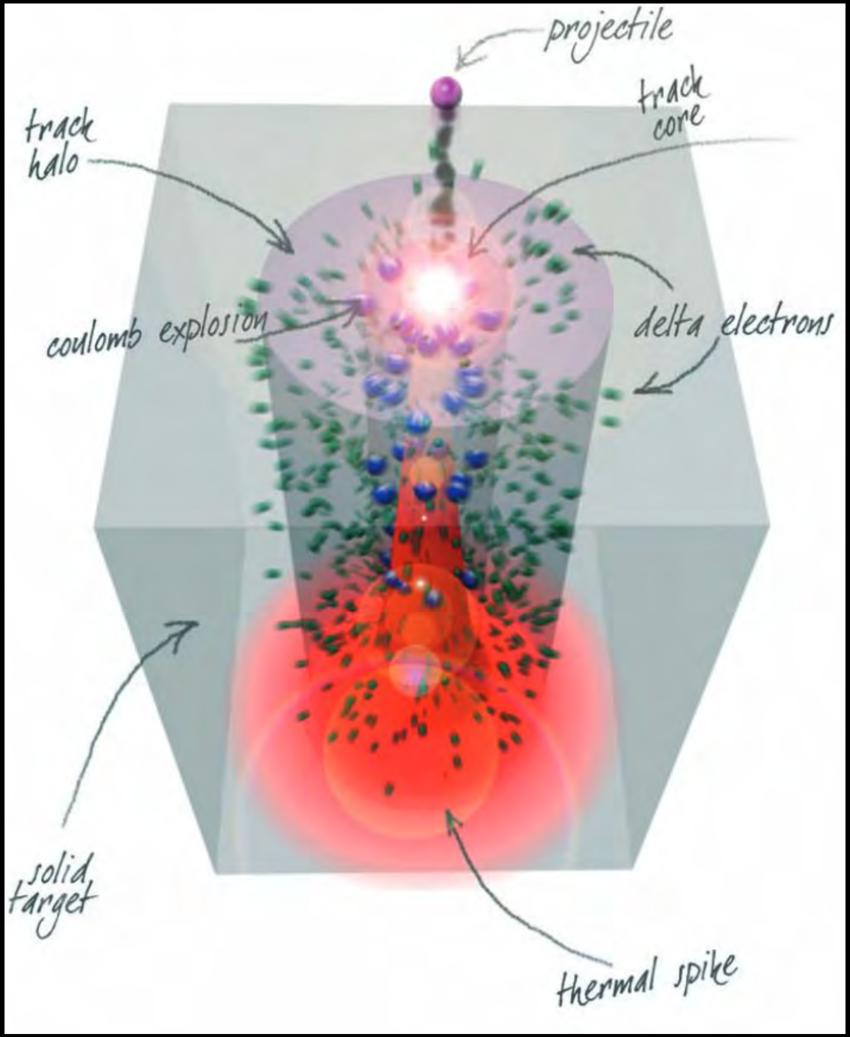




?

Track Formation

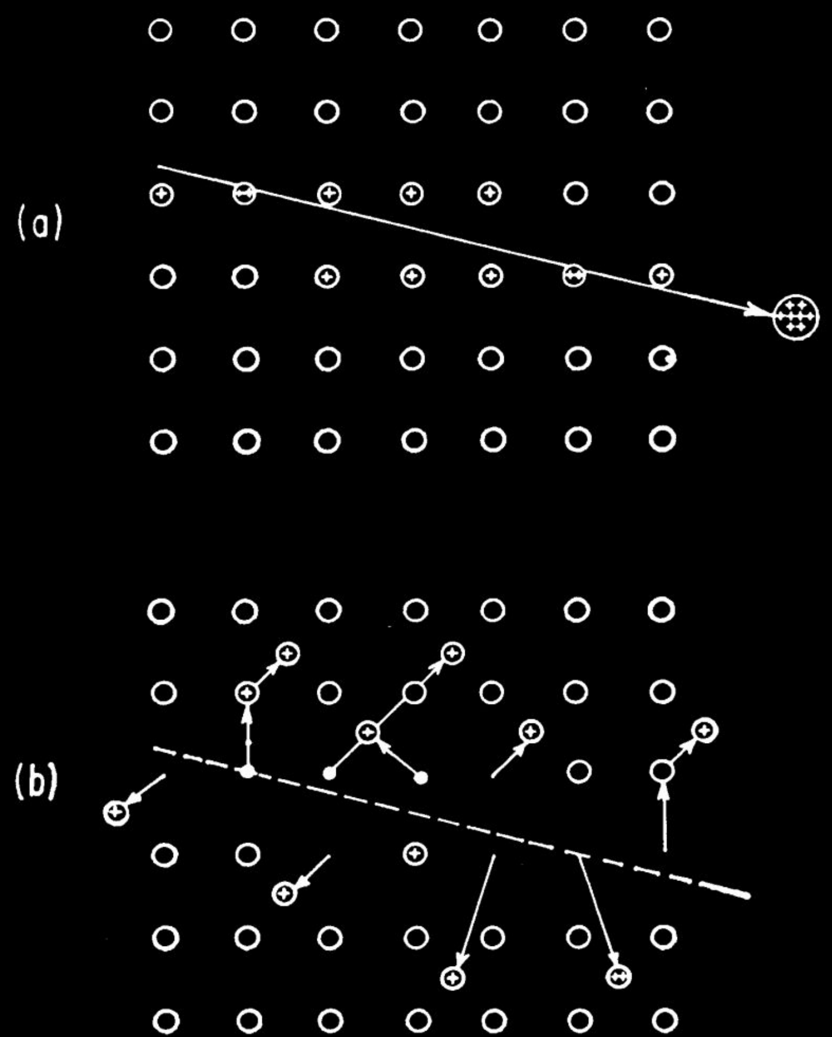
Thermal Spike [Seitz '49]



[Skupiński, '06]

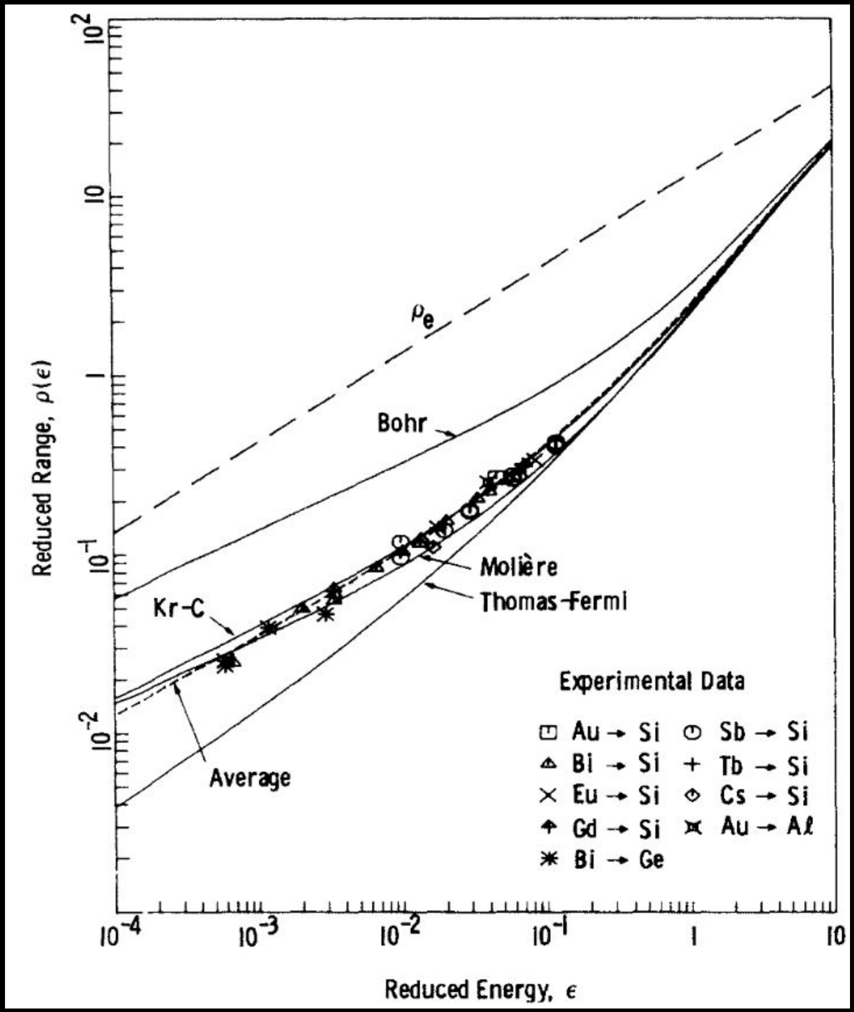
Track Formation

Ion Explosion Spike [Fleischer,Price,Walker ‘65]



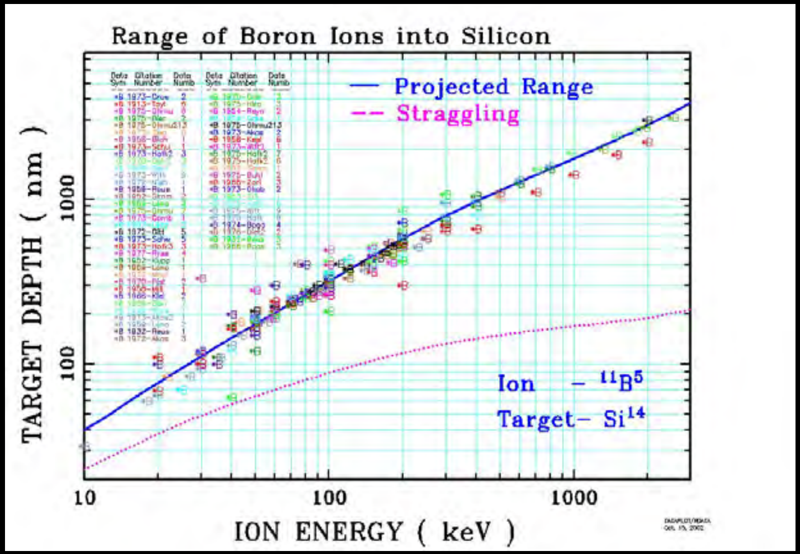
Ion Range Calculations

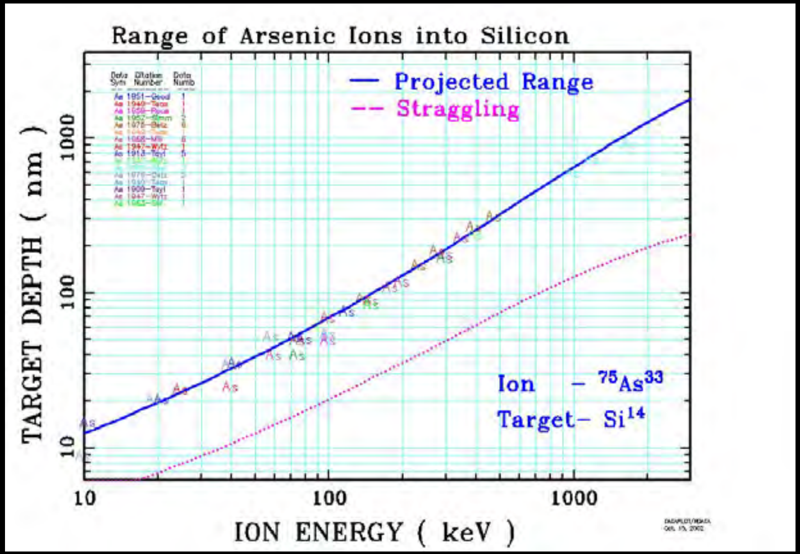
Semi-analytic treatment



[Wilson,Haggmark,Biersack +76]

SRIM



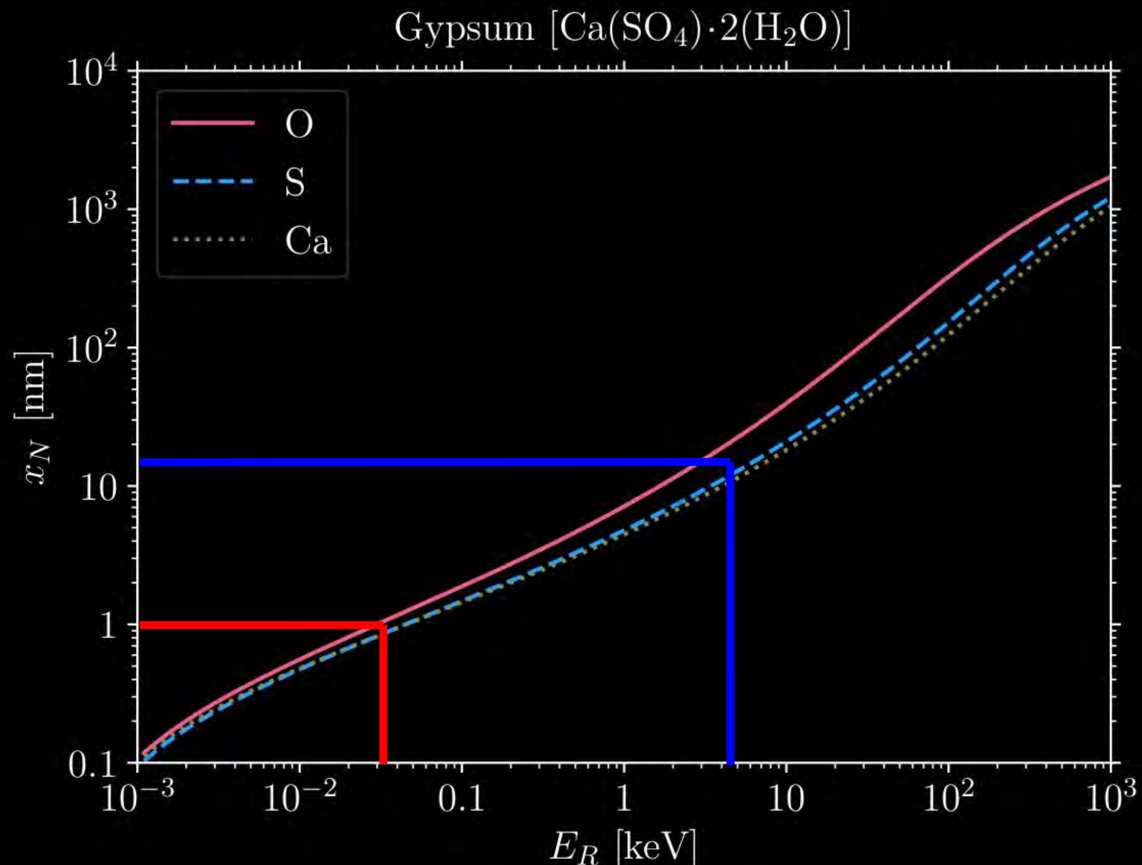


From Recoil Energies to Track Length

$$x_T(E_R) = \int_0^{E_R} dE \left| \frac{dE}{dx_T}(E) \right|^{-1}$$

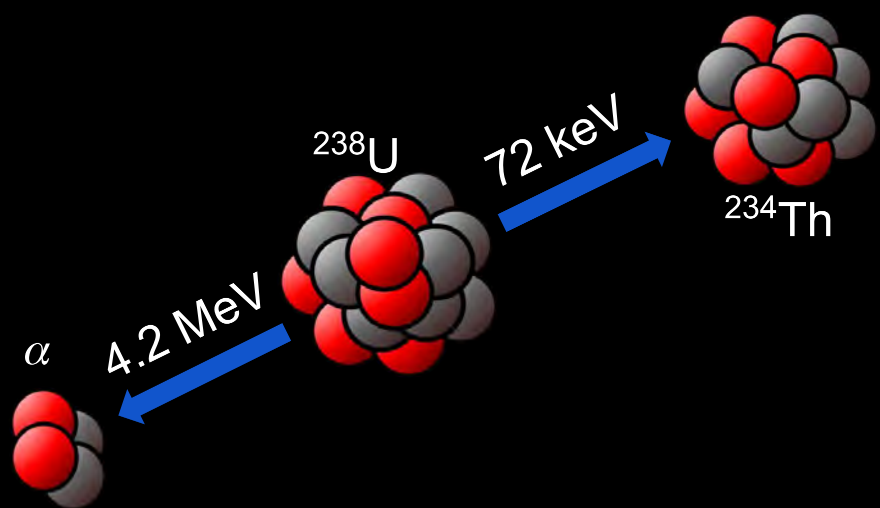
Energy loss due to

- Electronic stopping (off electron clouds)
- Nuclear stopping (off other nuclei)



Radioactive Backgrounds: Single-α

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

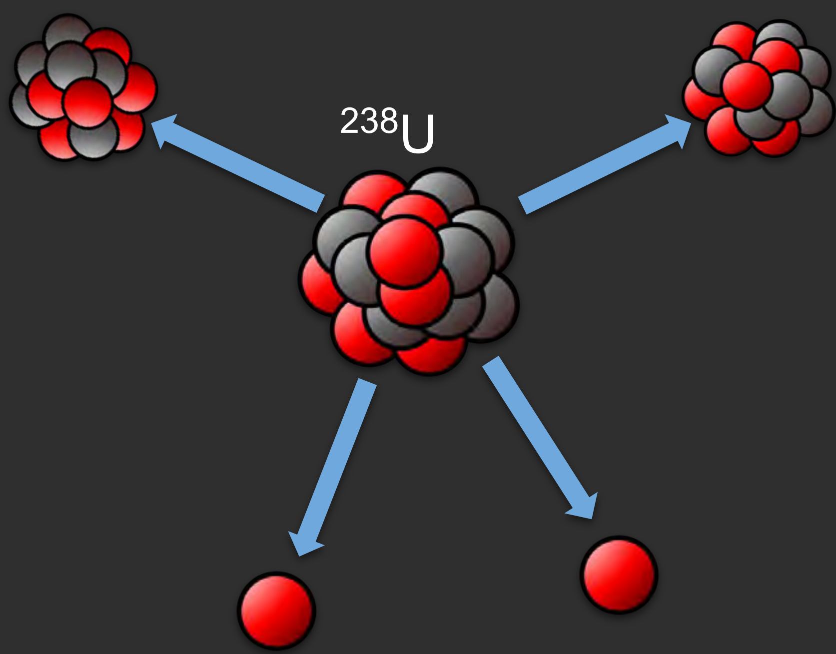


Nucleus	Decay mode	$T_{1/2}$
^{238}U	α	4.468×10^9 yr
	SF	8.2×10^{15} yr
^{234}Th	β^-	24.10 d
$^{234\mathrm{m}}$Pa	β^- (99.84 %)	1.159 min
	IT (0.16 %)	
^{234}Pa	β^-	6.70 d
^{234}U	α	2.455×10^5 yr
^{230}Th	α	7.54×10^4 yr
^{226}Ra	α	1600 yr
^{222}Rn	α	3.8325 d

$$n^{238}_{1\alpha} = n^0_{238}\frac{T^{234}_{1/2}}{T^{238}_{1/2}} = 1.4 \times 10^9\,\mathrm{kg}^{-1}\left(\frac{C^{238}}{0.01\,\mathrm{ppb}}\right)$$

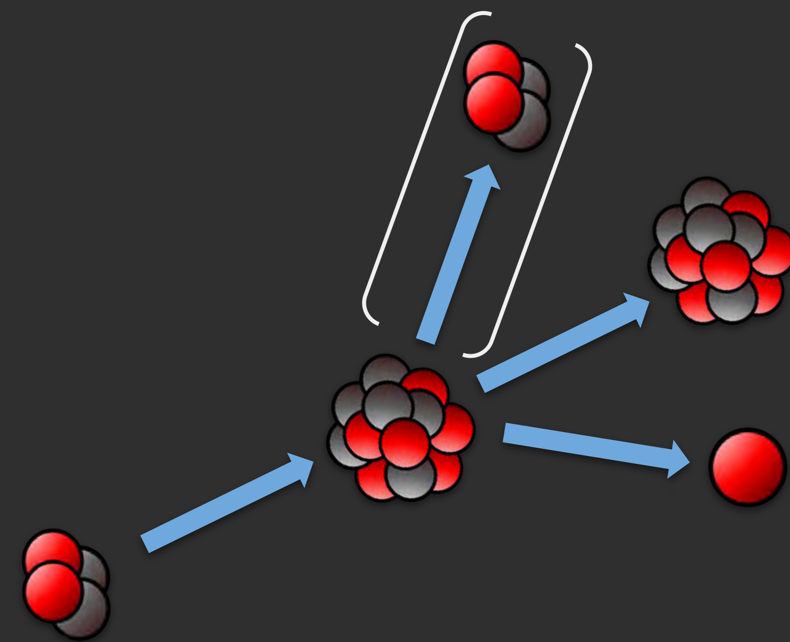
Background Interlude: Neutrons

Spontaneous Fission



~2 neutrons with ~ MeV energies

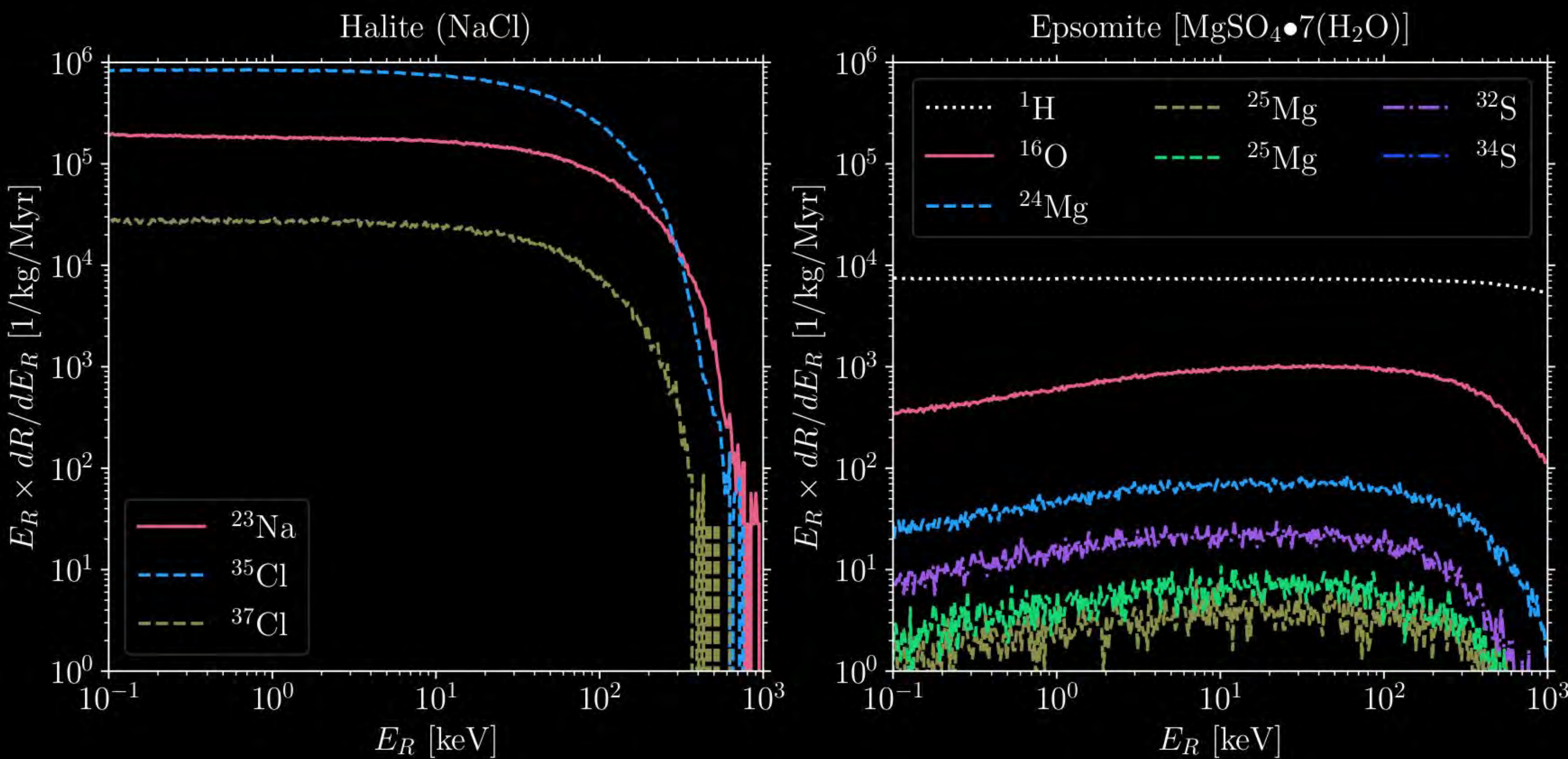
(α, n)-reactions



Rare process, but the number of α-particles is about 10^7 times larger than the number of SF events

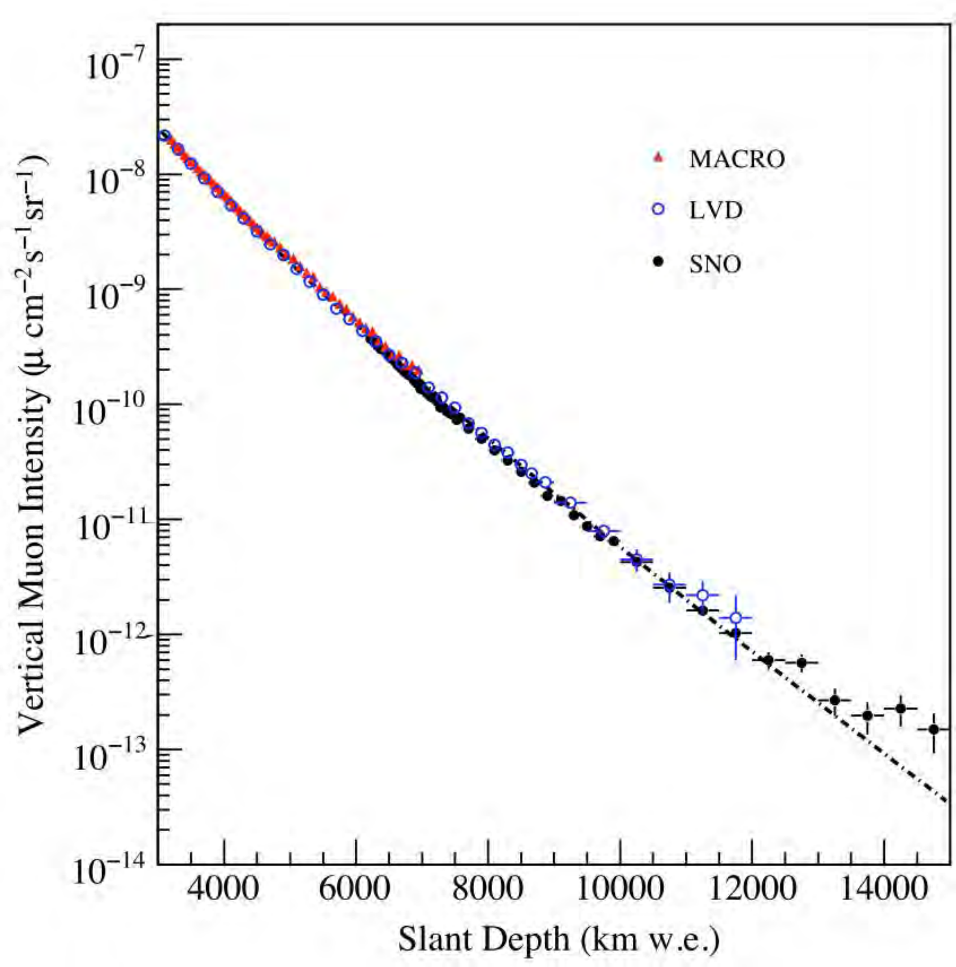
[Drukier, SB+ 1811.06844]

Background Interlude: Moderating Neutrons with H

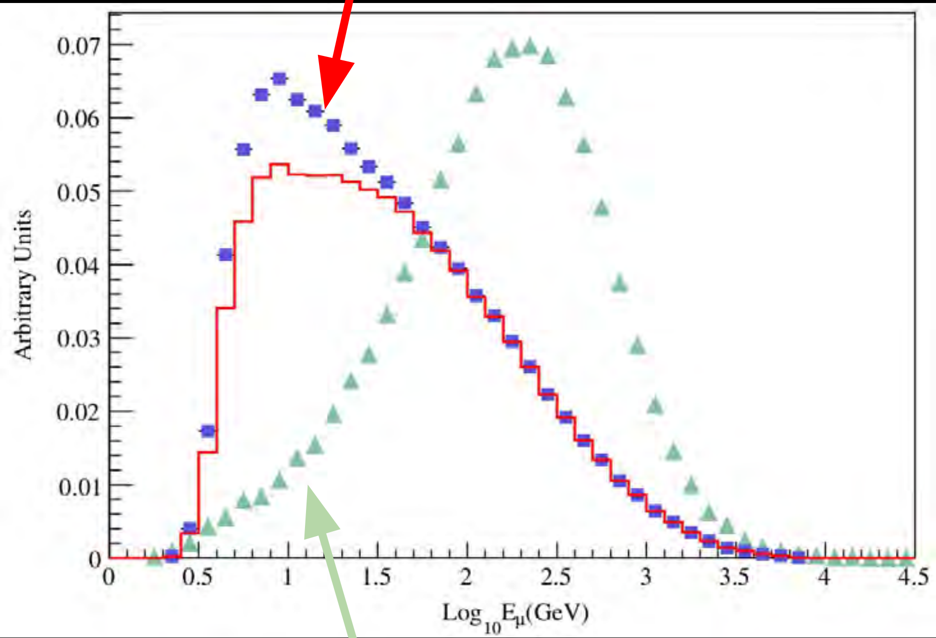


Neutrons from Atmospheric Neutrinos

[Aharmim+ '09]



muons from atmospheric neutrinos
w/o (w) neutrino oscillations



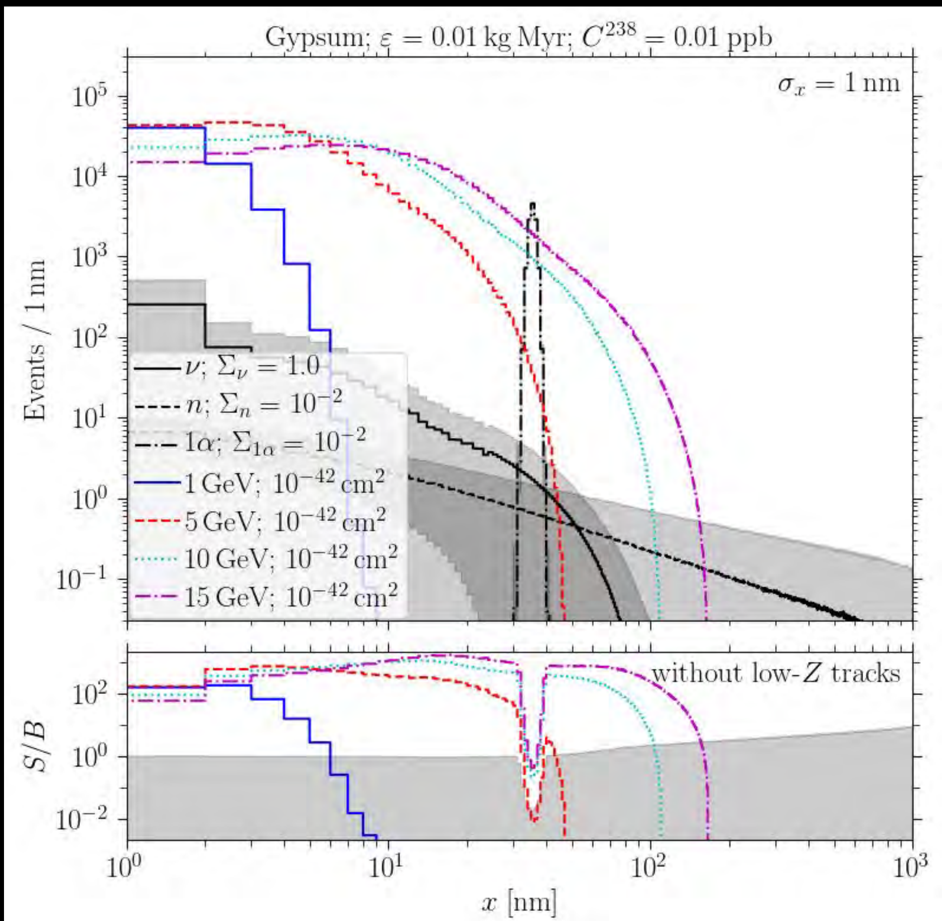
cosmic-ray muons
(@ 6 km w.e)

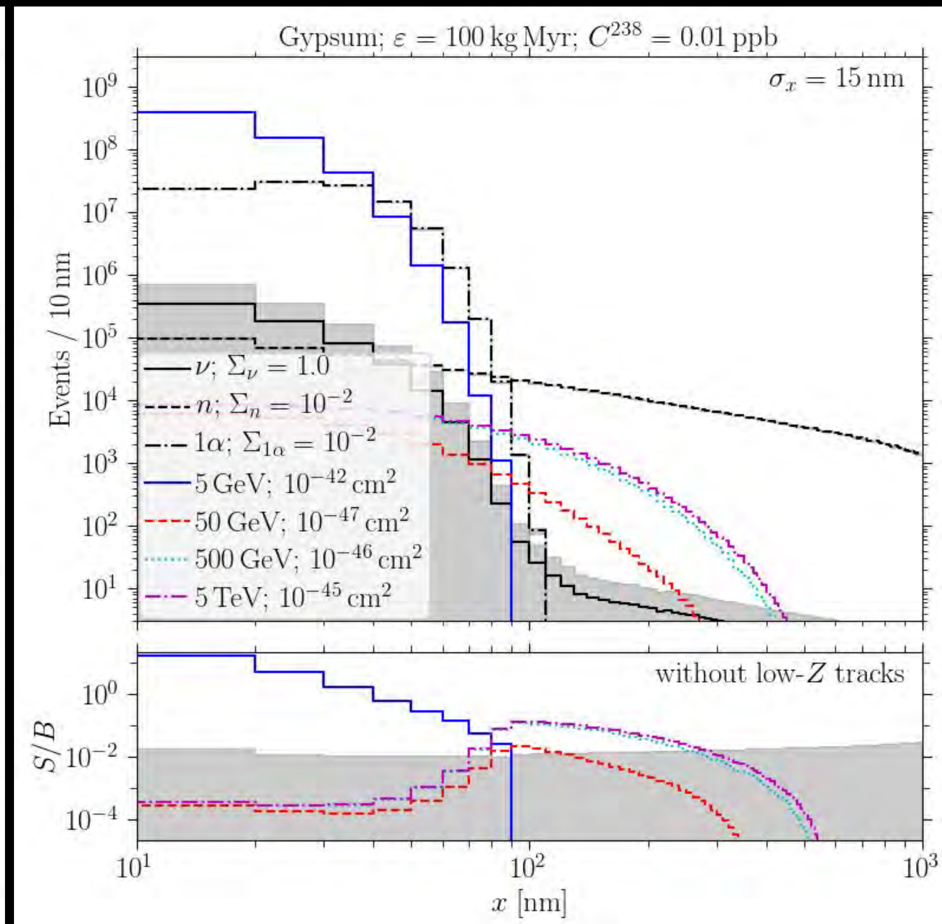
Dark Matter Against The Rest

[SB+ ‘19 (1811.06844)]

High-Resolution read-out
- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)

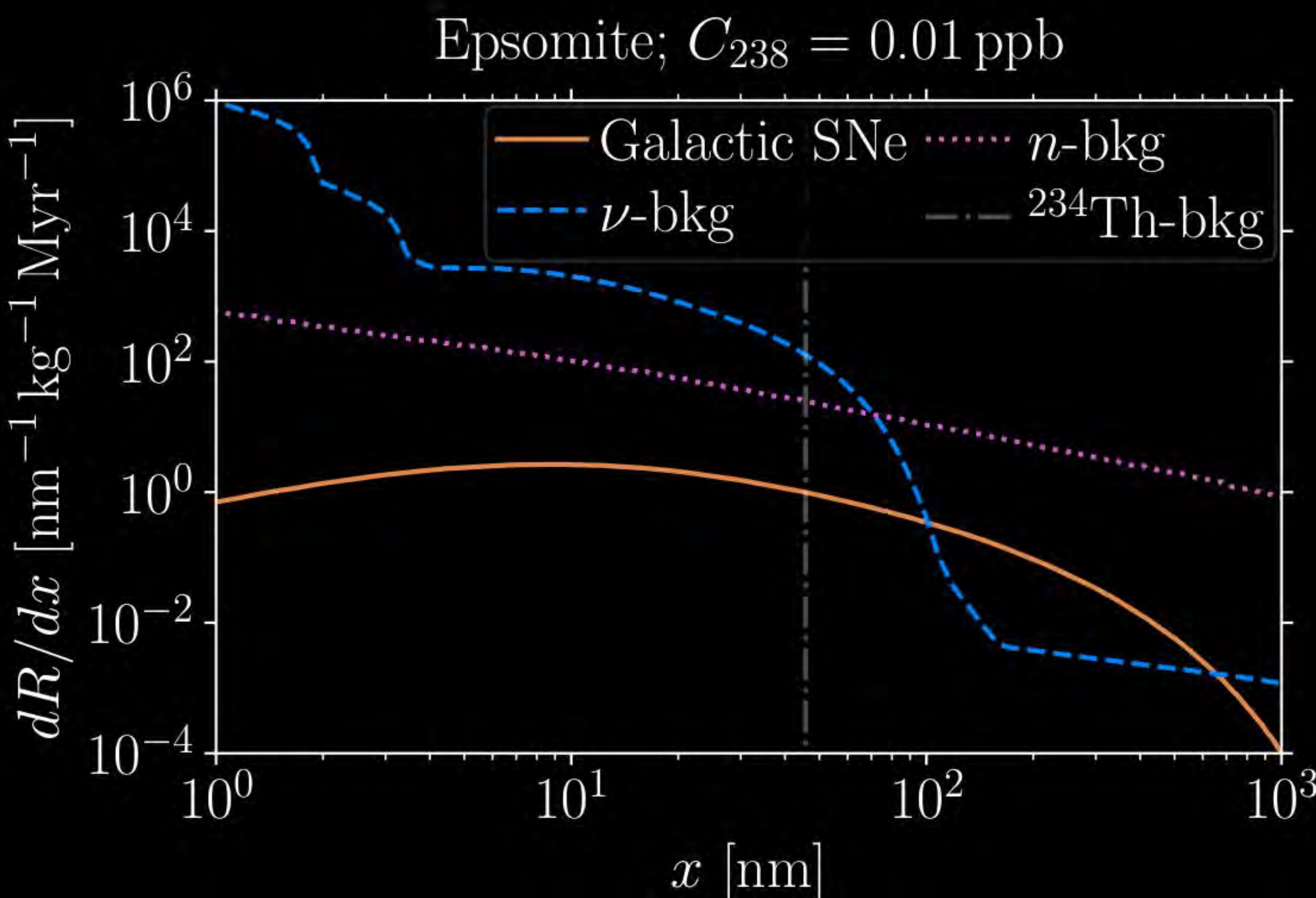
Low-Resolution read-out
- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)





Backgrounds vs Supernova Neutrinos

Epsomite -- $MgSO_4 \cdot 7(H_2O)$

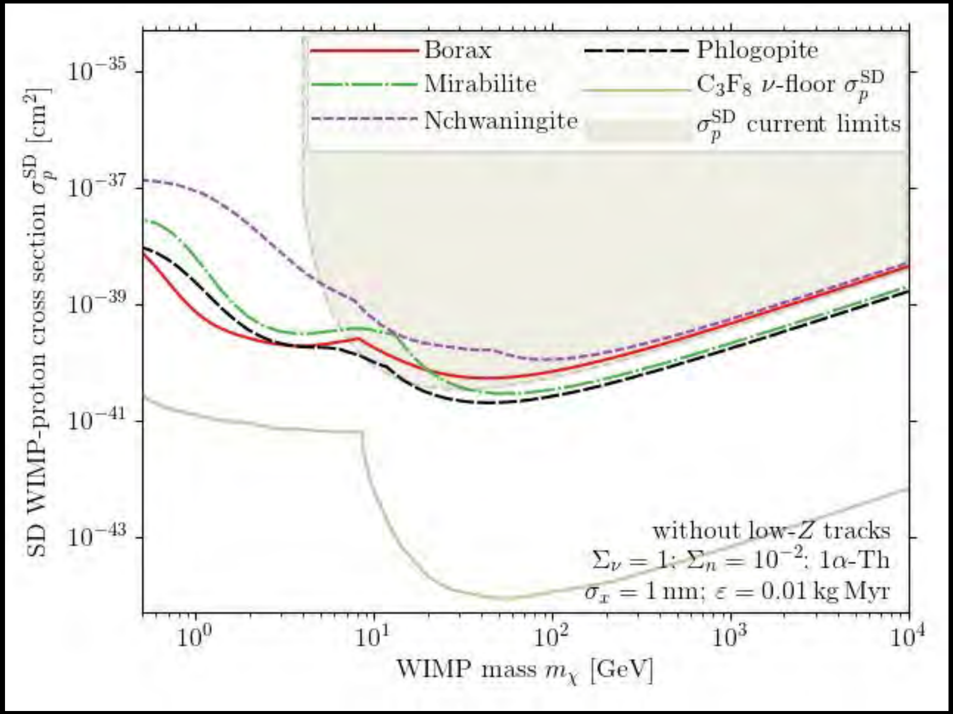


Sensitivity Projections: SD Proton-Only

[SB+ ‘19 (1811.06844)]

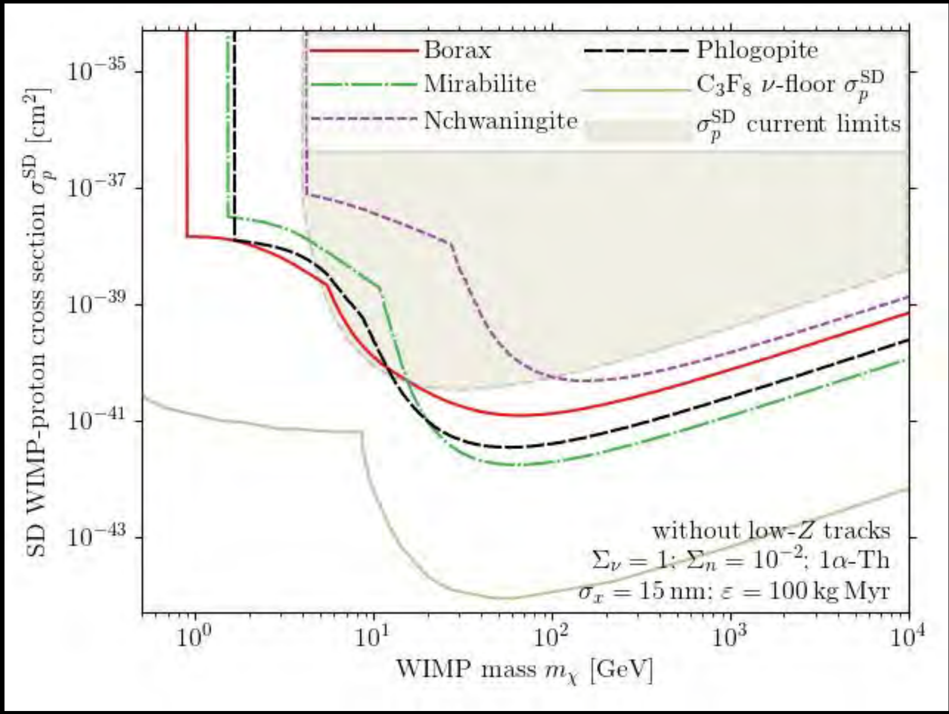
Good resolution, small target mass

- 1 nm spatial resolution
- Exposure: (10 mg) x (1 Gyr)



Larger target mass, worse resolution

- 15 nm spatial resolution
- Exposure: (100 g) x (1 Gyr)

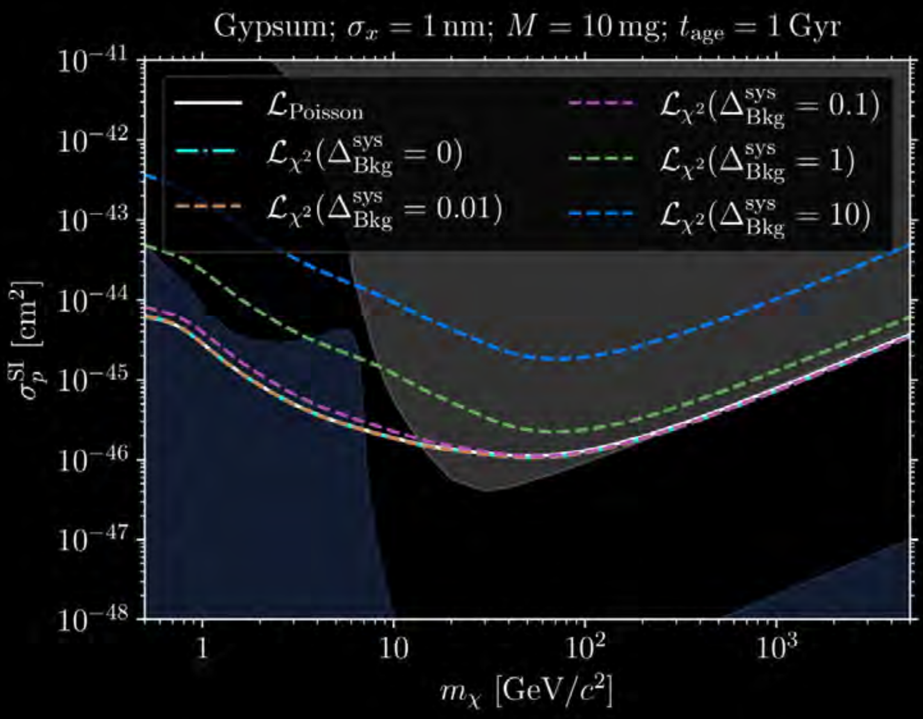


Borax -- $\mathbf{Na_2}(\mathbf{B_4}O_5)(OH)_2 \cdot 8(H_2O)$
Mirabilite -- $\mathbf{Na_2}SO_4 \cdot 10(H_2O)$

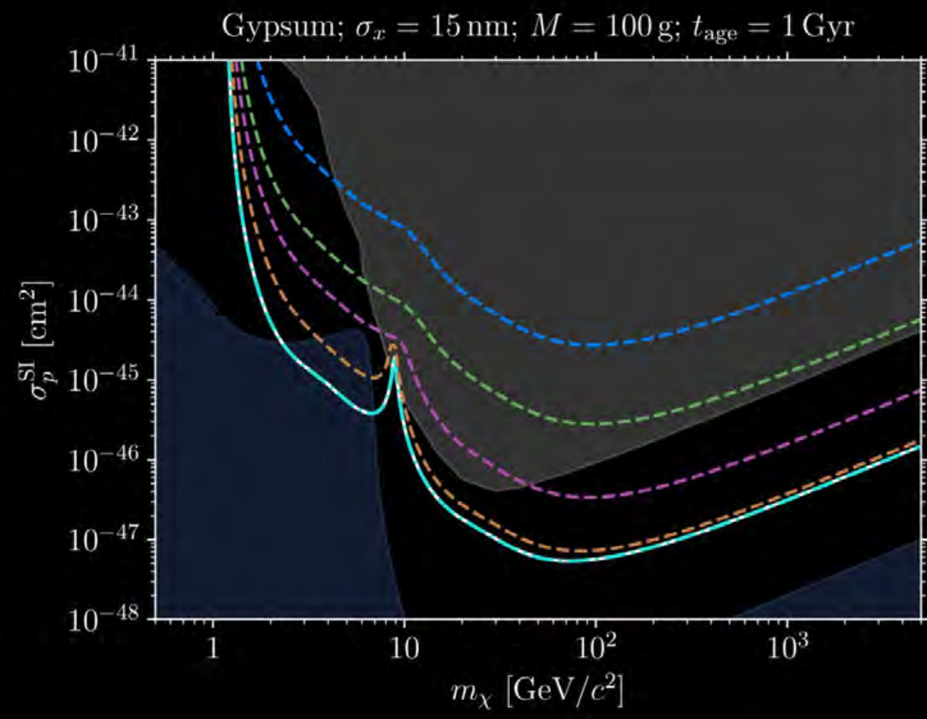
Nchwaningite -- $\mathbf{Mn_2}SiO_3(OH)_2 \cdot (H_2O)$
Phlogopite -- $\mathbf{K}Mg_3\mathbf{Al}Si_3O_{10}\mathbf{F}(OH)$

Robustness Against Errors in Background Shape

"High Resolution"

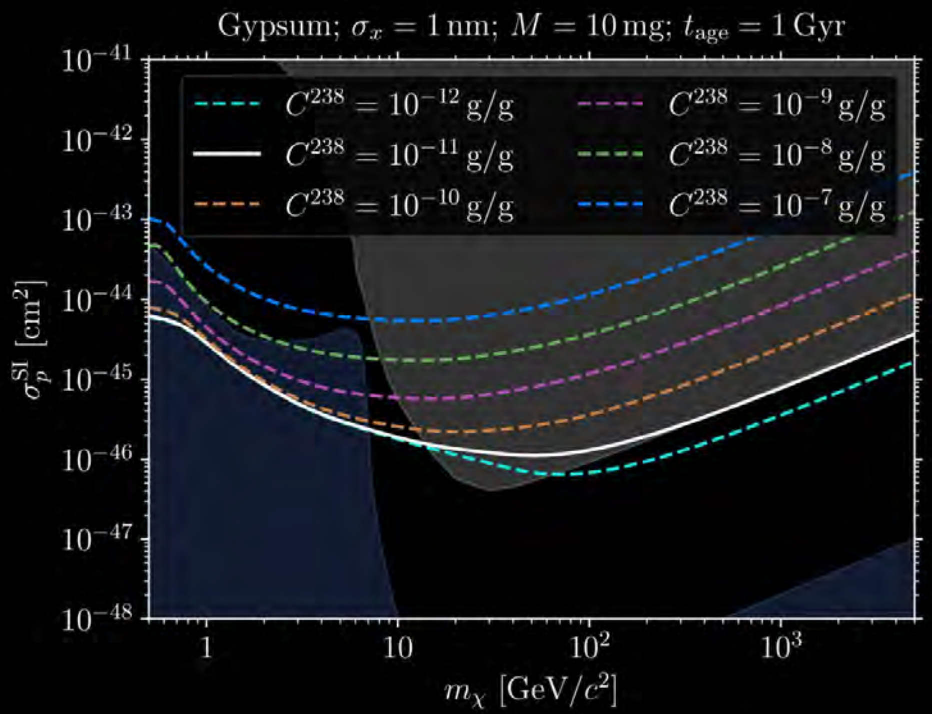


"High Exposure"

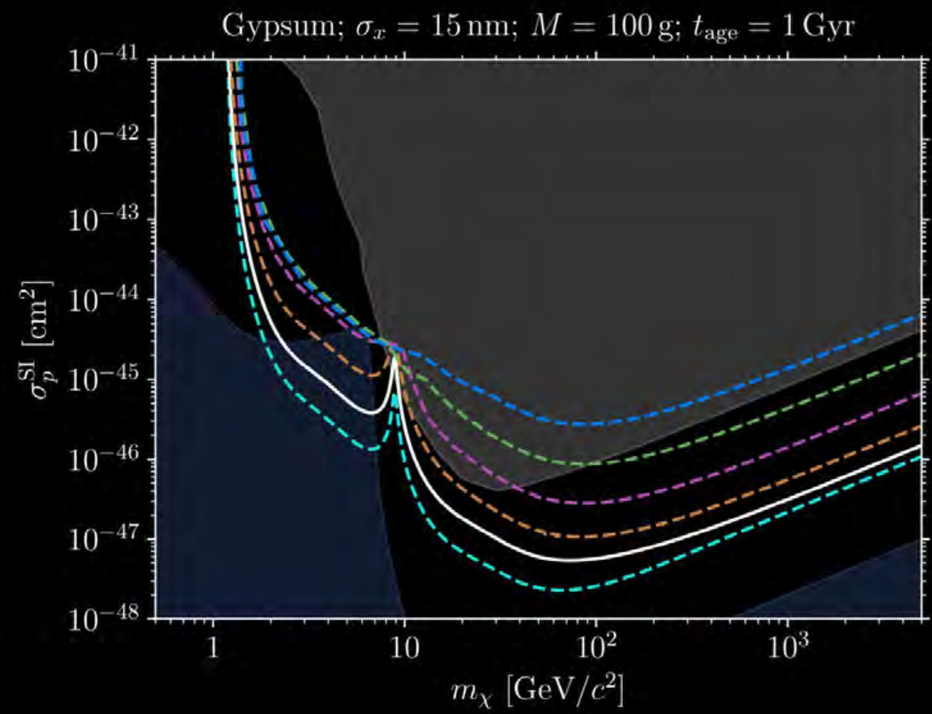


DM sensitivity for different radiopurities

“High Resolution”

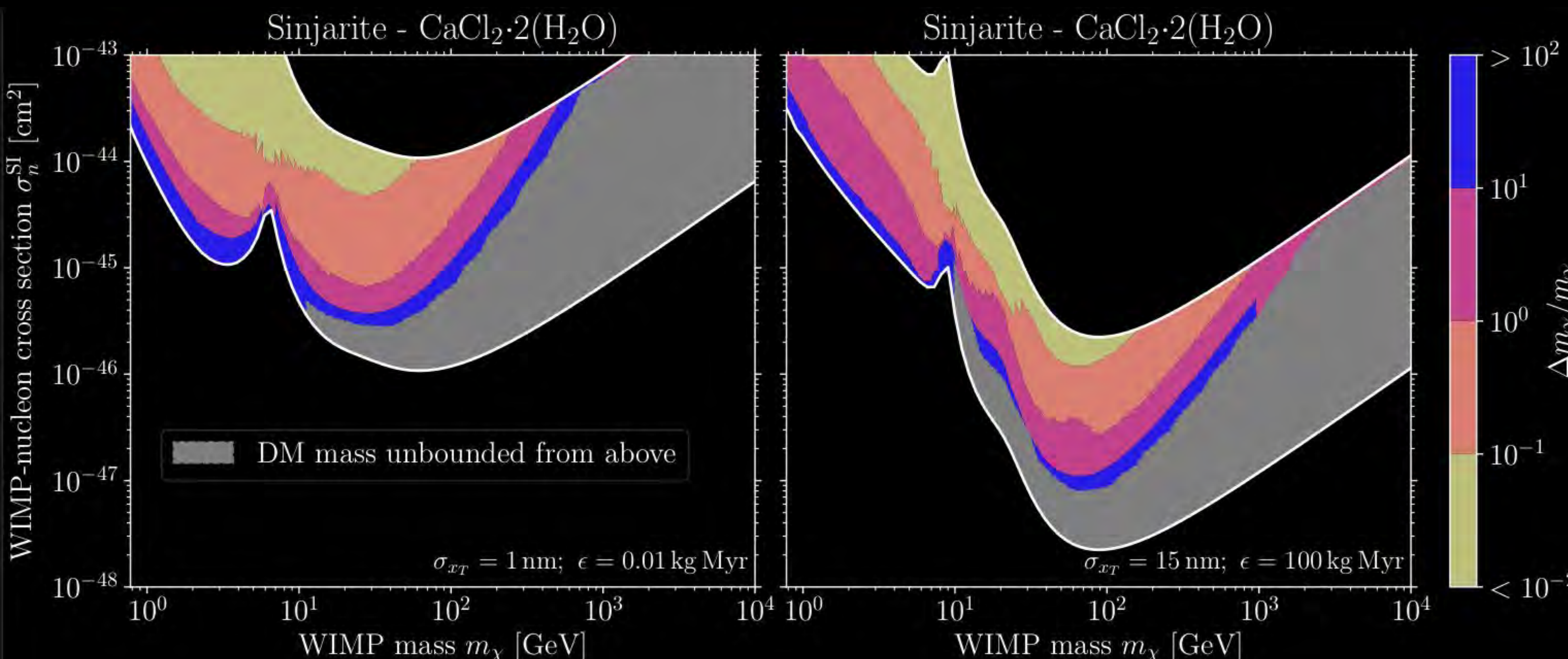


“High Exposure”



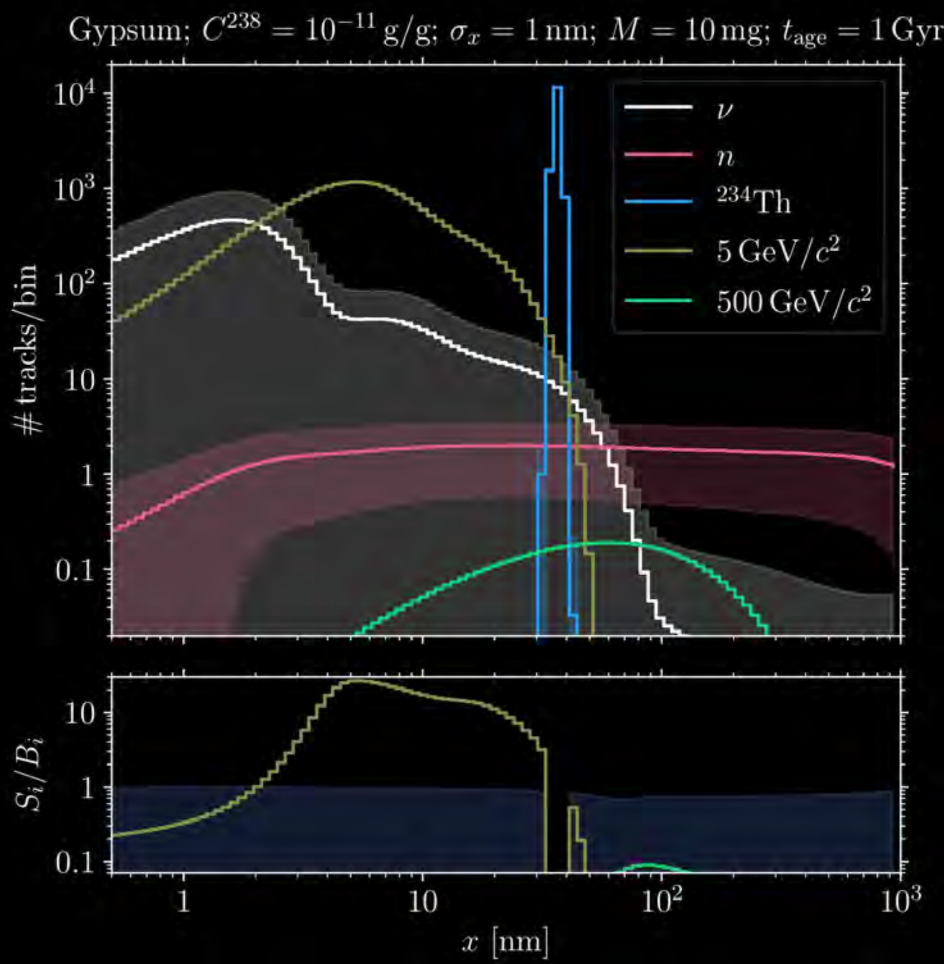
Measuring the Dark Matter mass

[Edwards, SB+ 1811.10549]

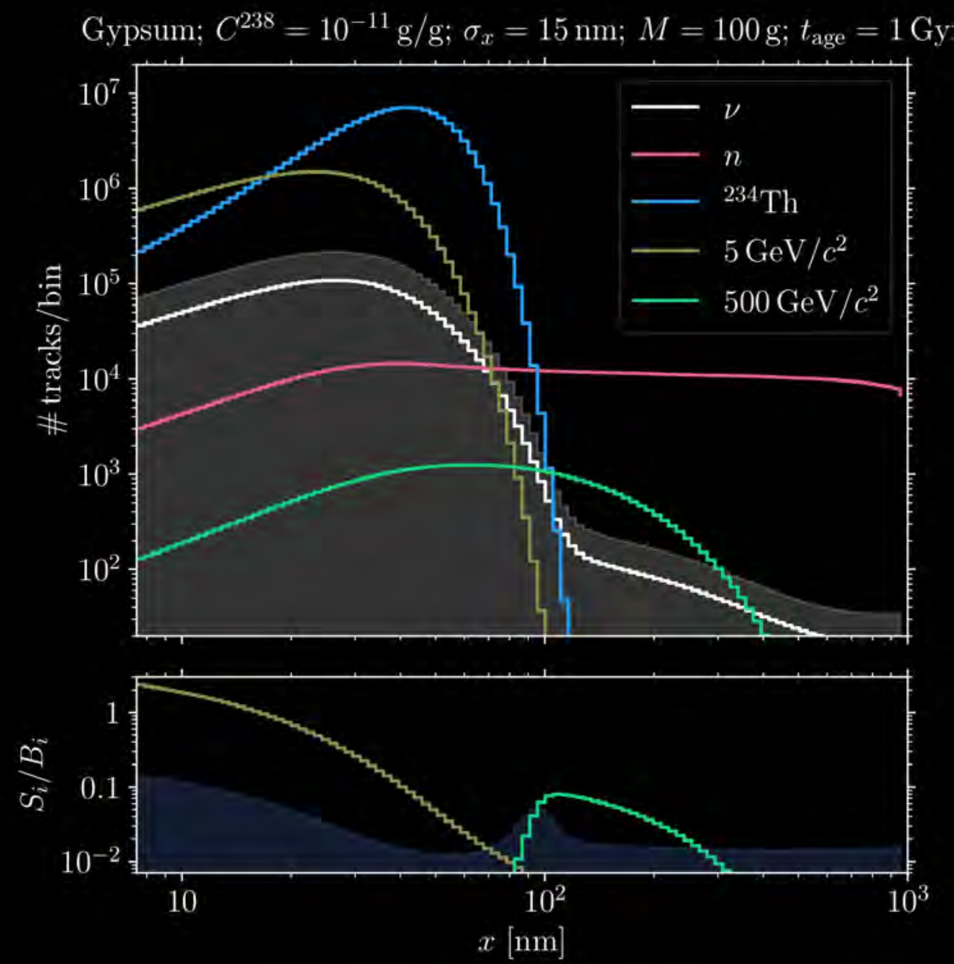


Digging a Signal out of the Background

"High Resolution"



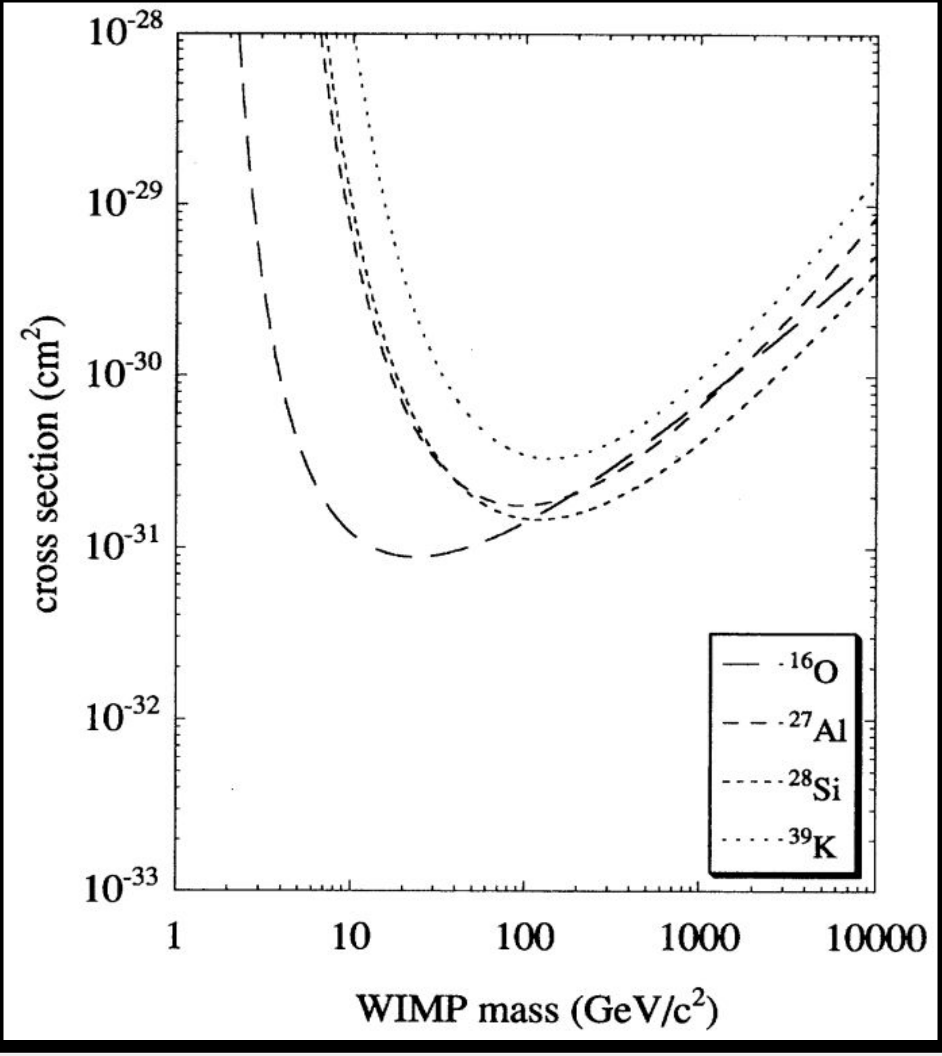
"High Exposure"



VOLUME 74, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1995

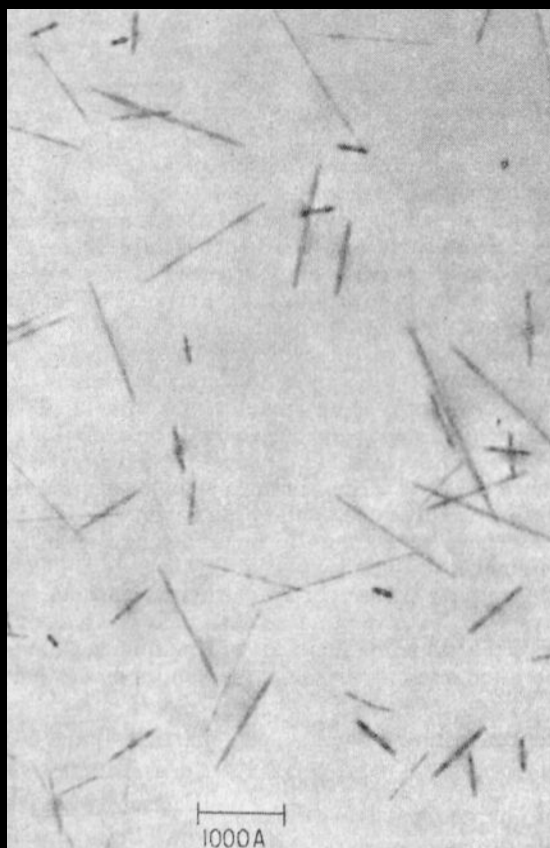
Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*



What has changed?

Fission fragment tracks
in synthetic Mica, TEM

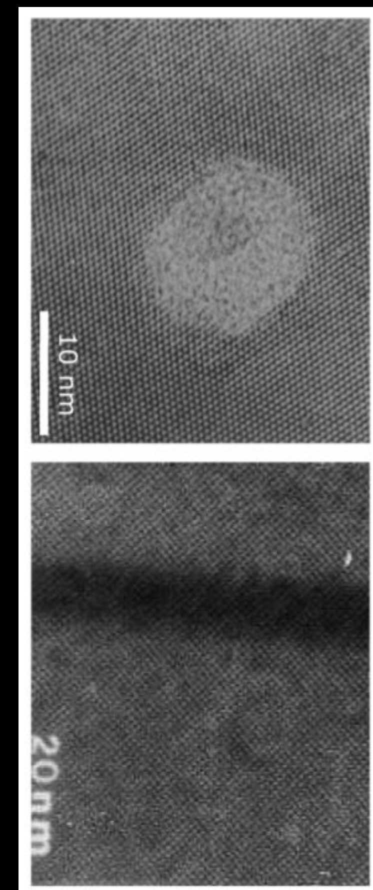


[Price&Walker '63]

High-resolution TEM
pictures of ion tracks

Pb on Mica

Xe on $Y_3Fe_5O_{12}$

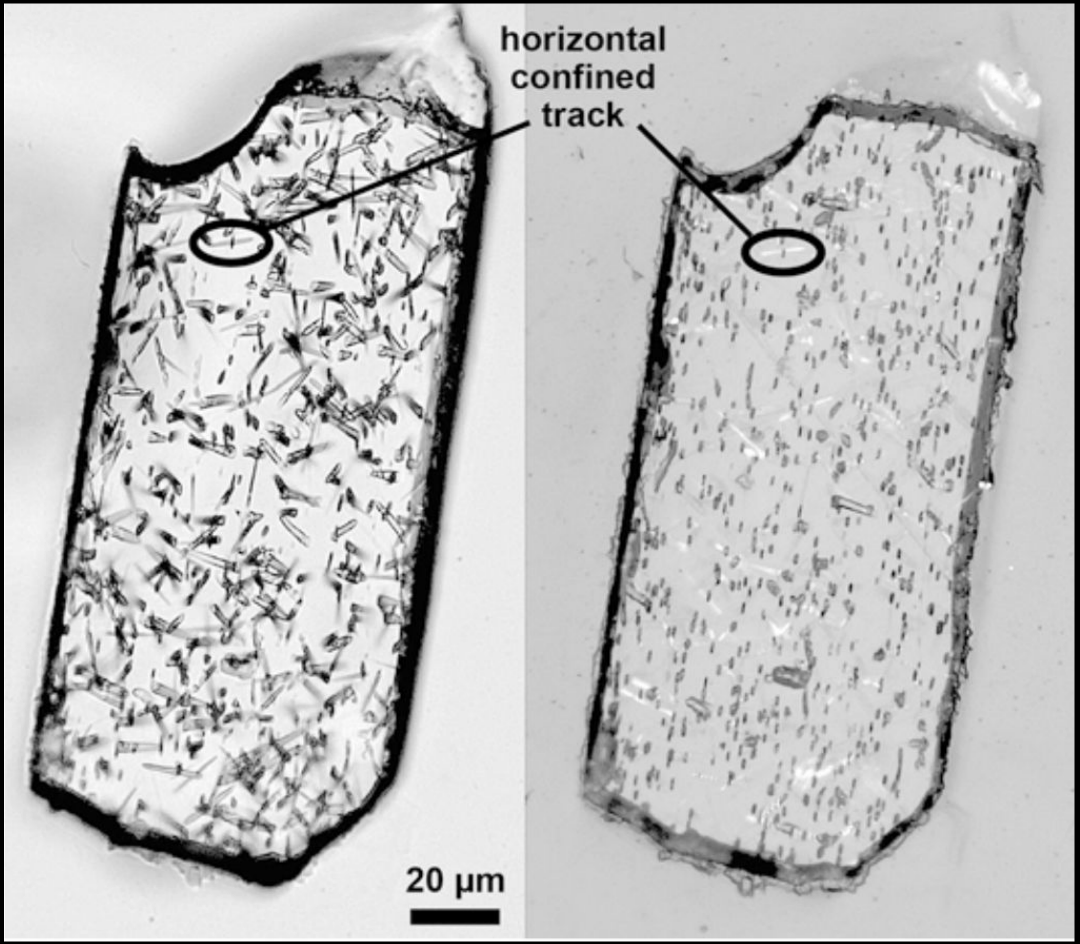


[Toulemonde+ '06]

Read-Out Methods: Optical Microscopy

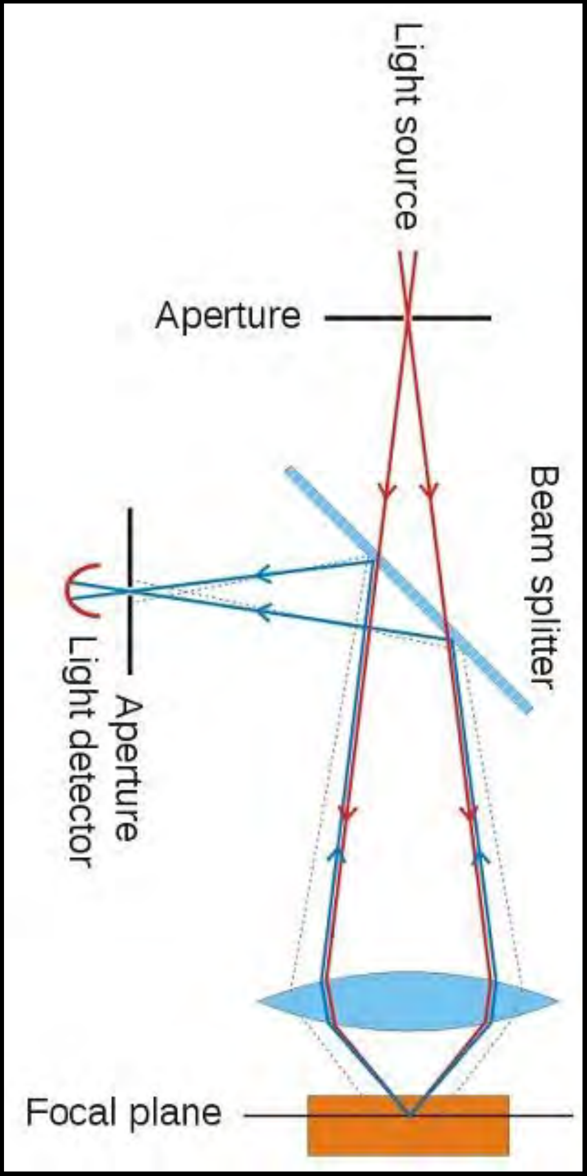
- Widely available
- Cheap
- Resolutions of a few 100 nm
- Requires etching

Etched fission tracks in Apatite



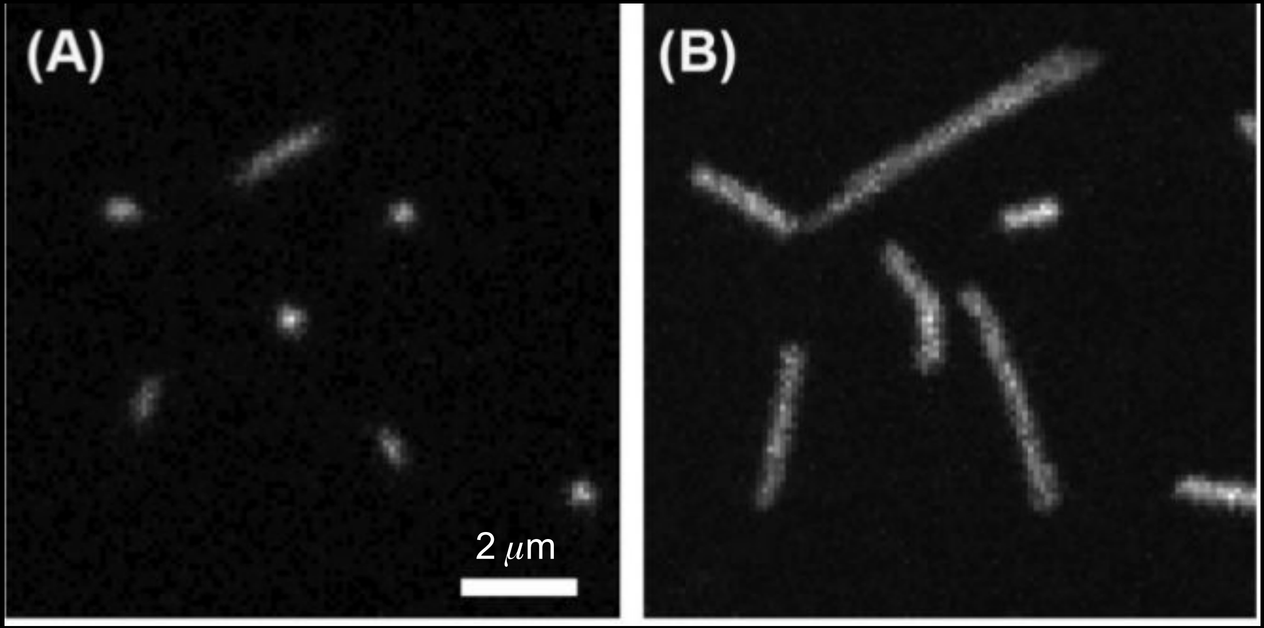
[Thomson '16]

Read-Out Methods: Confocal Microscopy



α-tracks in Al_2O_3:C,Mg (without etching!)

Single picture | Longest projection of 3D



[Kouwenberg+ '18]

- Widely available
- Resolution ~100 nm
- Requires fluorescent targets