Paleo-Detectors:
Dark Matter and Supernova Neutrinos

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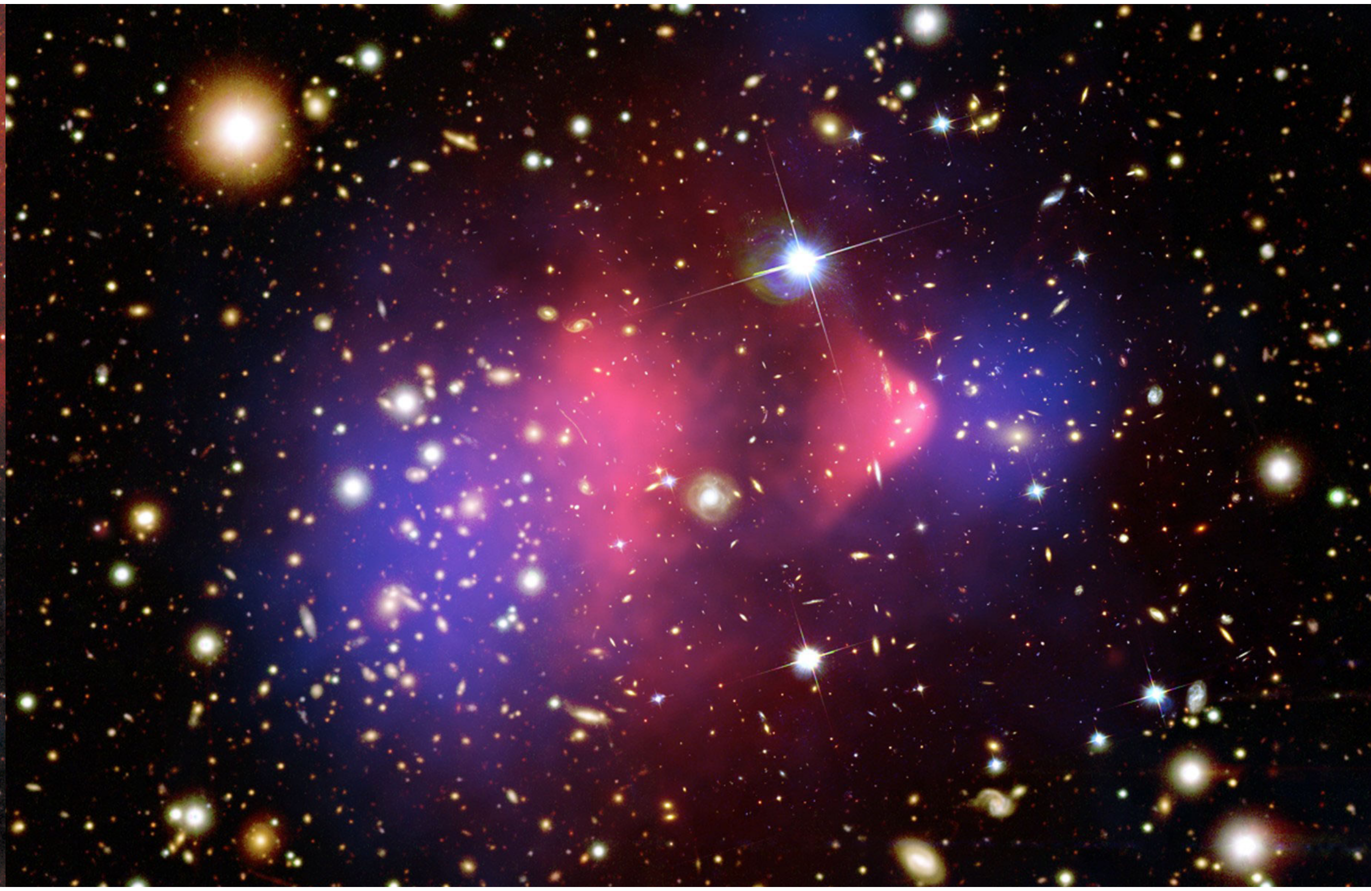
1906.05800, 1811.06844, 1811.10549, 1806.05991

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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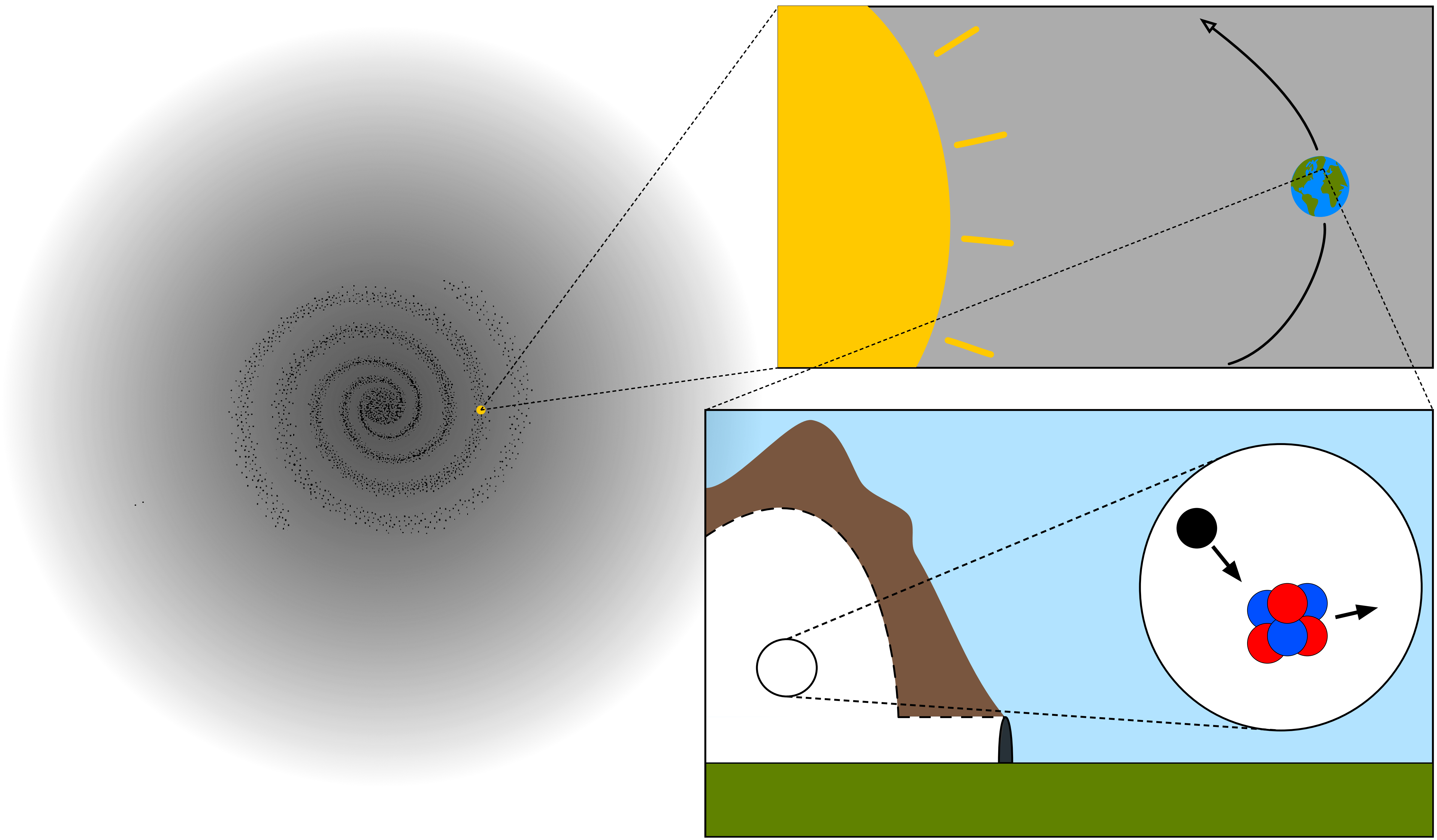
Dark Matter Direct Detection

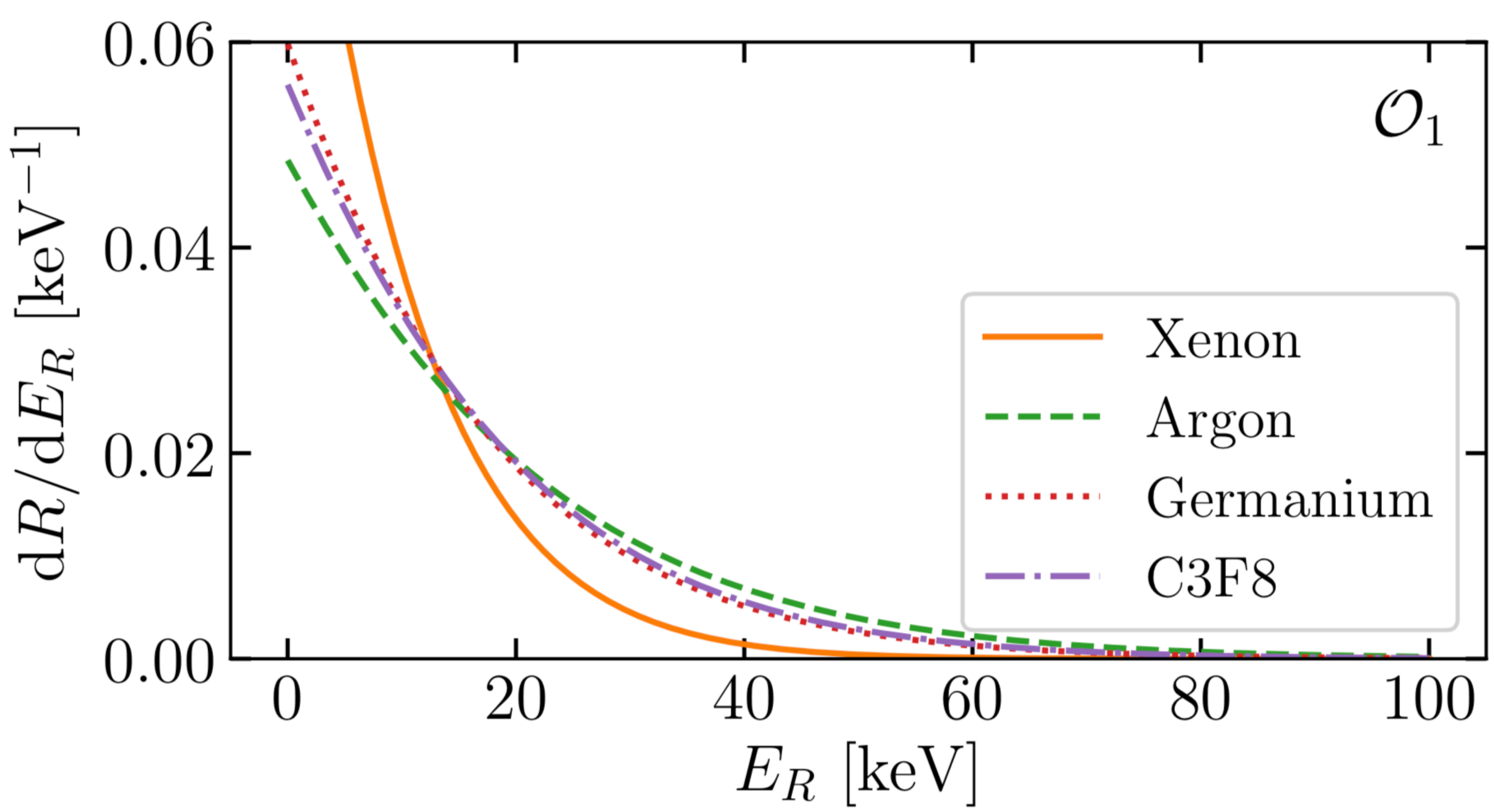


Typical Recoil Energies for Dark Matter and Neutrinos

- Recoil energy of a collision is **O(1) KeV** - very small energy deposit to detect

- Although neutrinos have a small mass, there **increased velocities lead to O(1-10) KeV recoils**

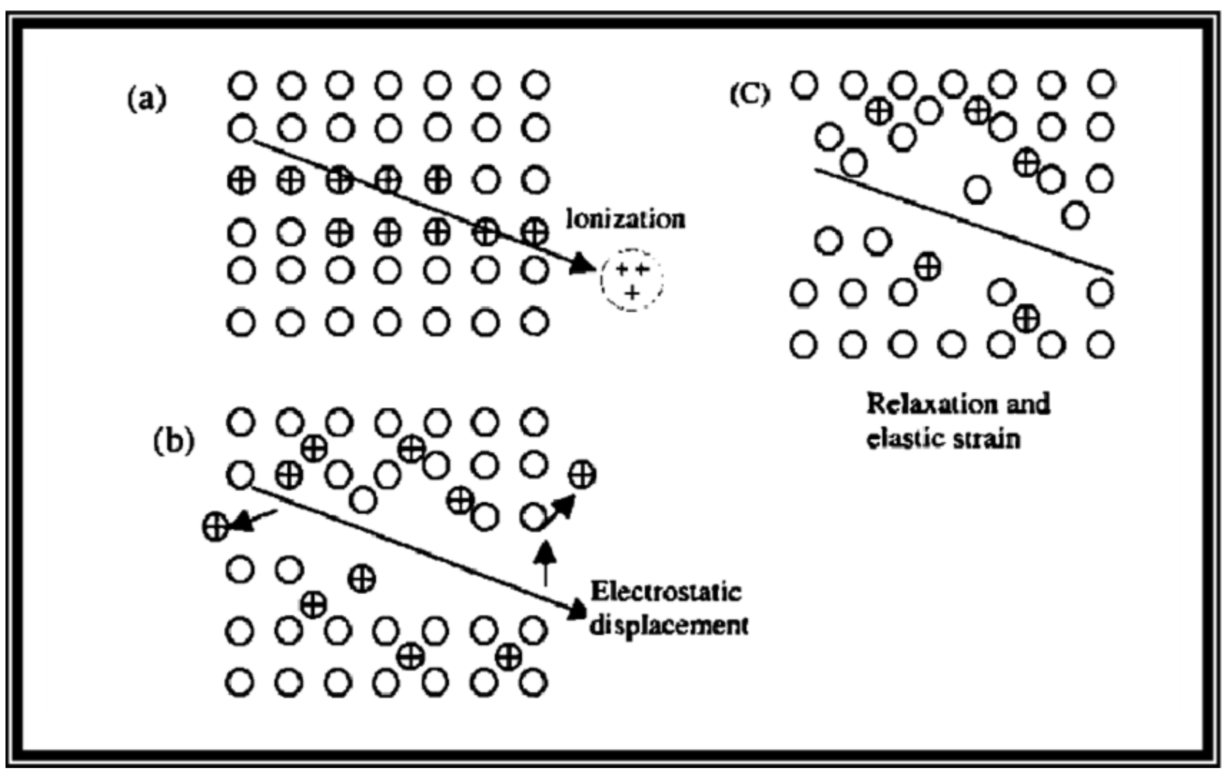
$$E_R \leq 2\frac{m_\chi^2 M_T}{(m_\chi M_T)^2}v^2$$



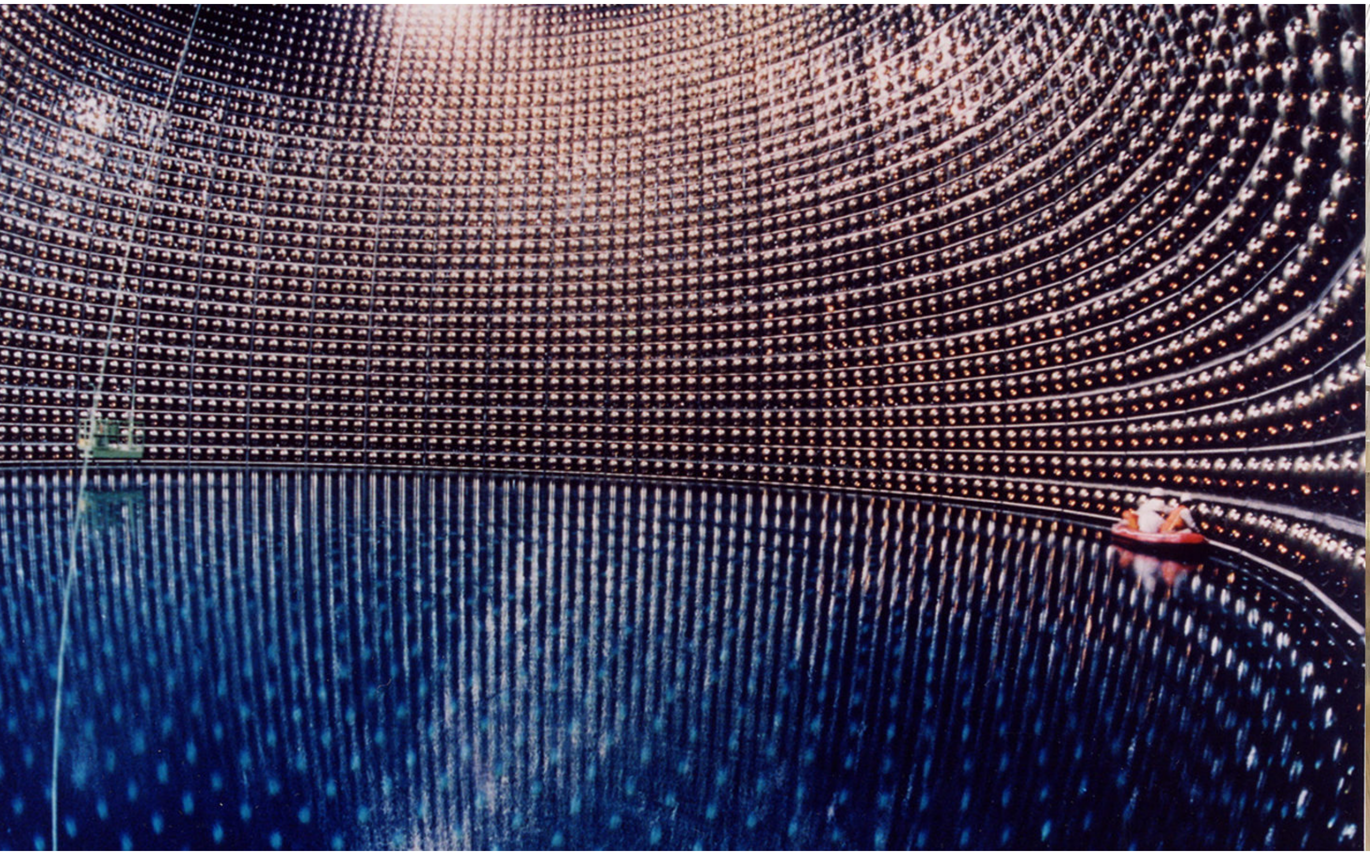
Small Damage Track Features can be Observed in Minerals

- Paleo-detectors are minerals from **far below the Earths surface (5-10 km)**. Importantly they are 1 billion years old

- **Permanent damage track** features in the structure of the mineral.



Basics of Building a Detector: Mass vs Exposure



$$\text{Recoil Rate} \propto \text{Target Mass} \times \text{Observation Time}$$

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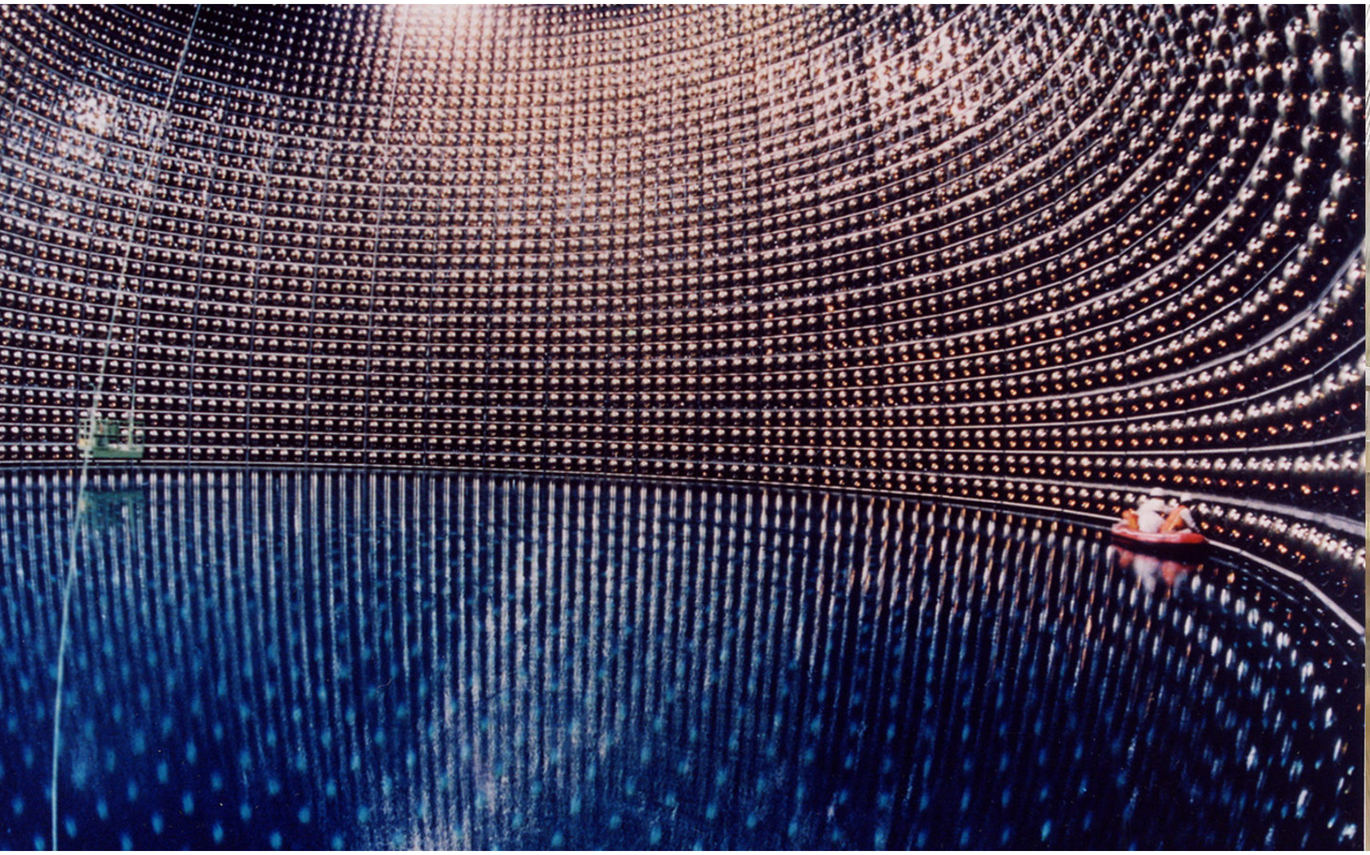

$$\text{Recoil Rate} \propto \text{Target Mass} \times \text{Observation Time}$$

Huge Targets (↑)

Smallish Exposure (↓)

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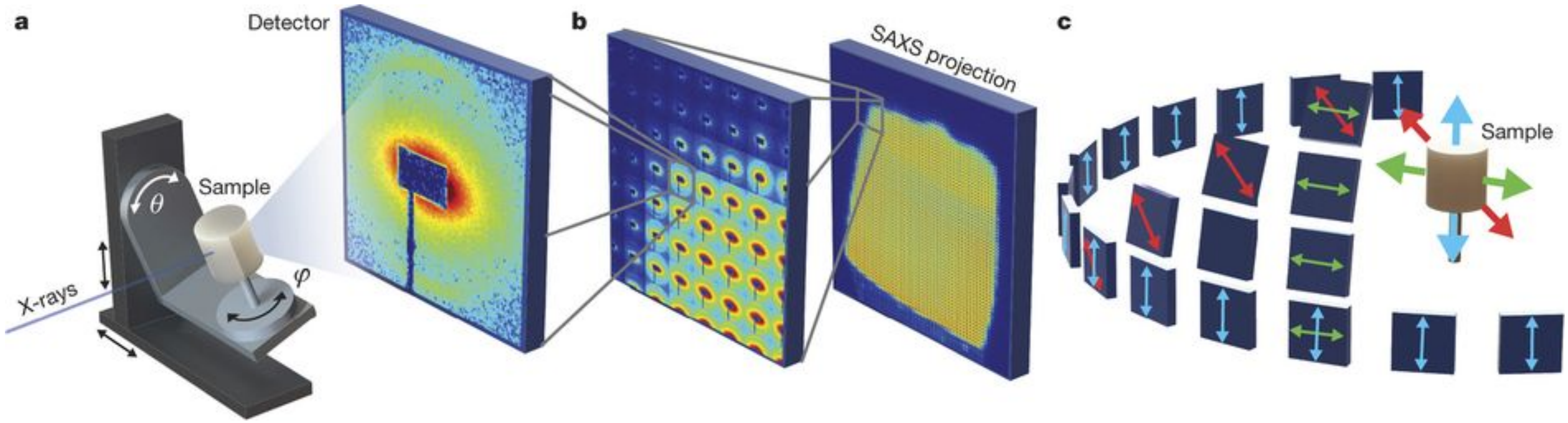
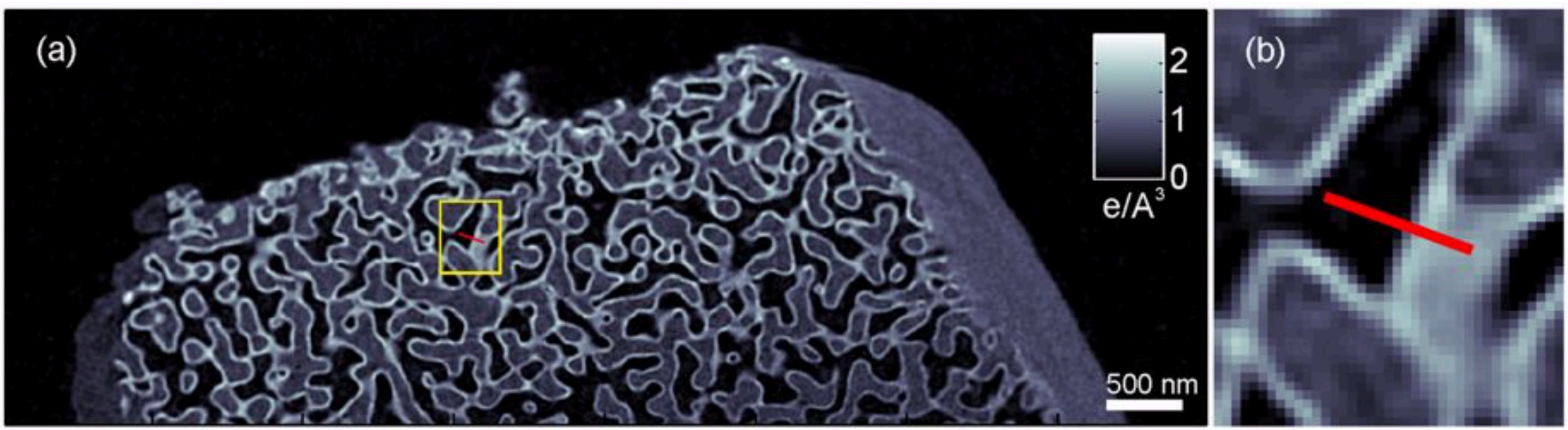
↓ **Small Targets**

↑ **Huge Exposure**

Reading the Tracks: X-ray Tomography

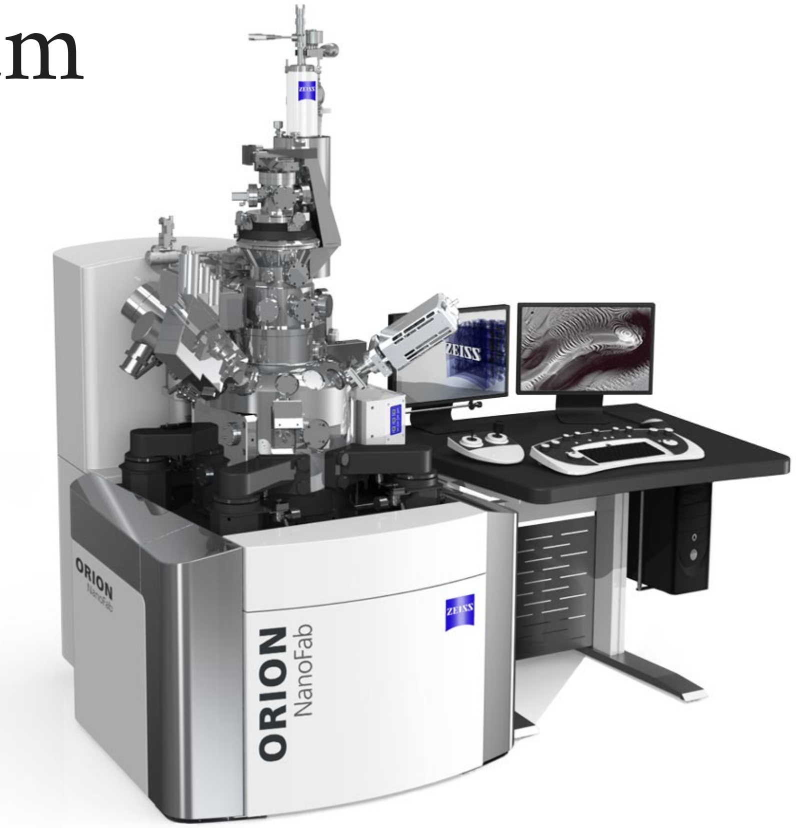


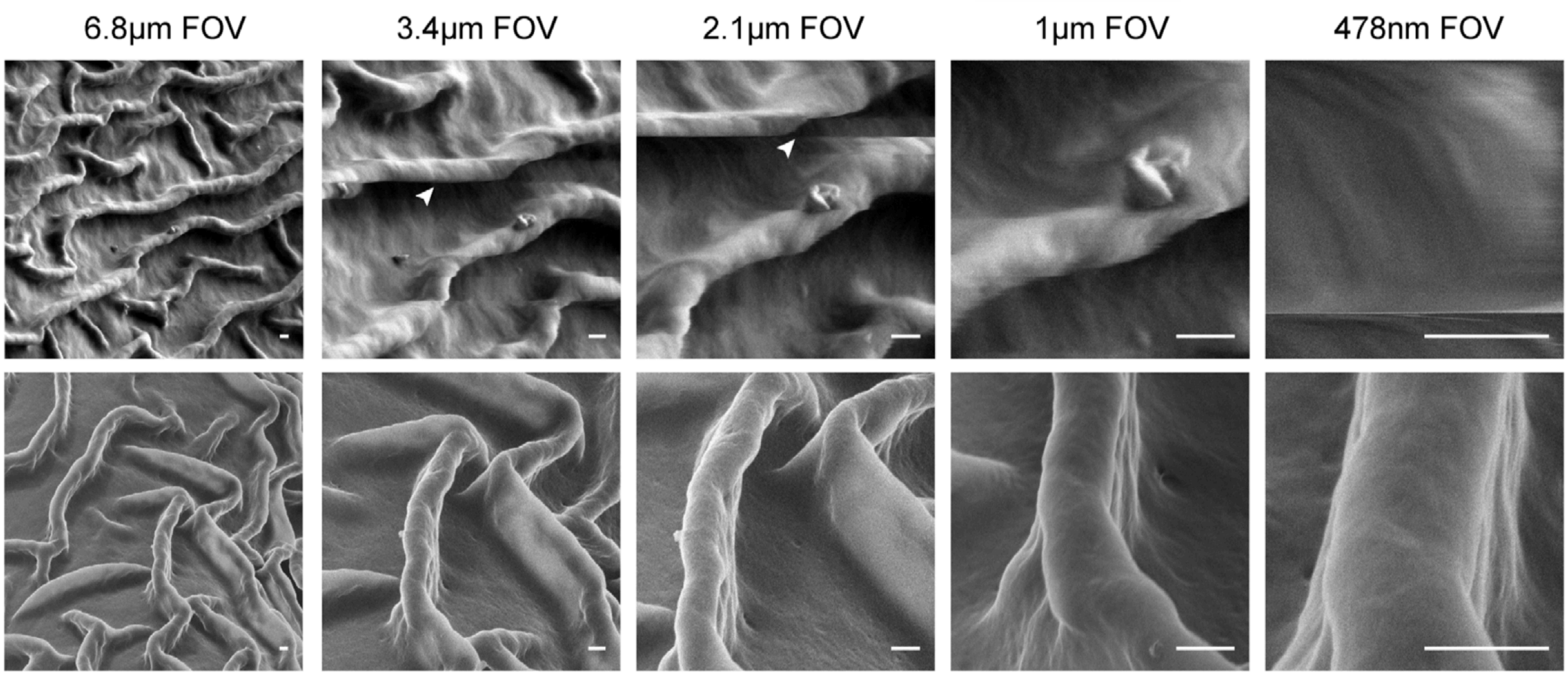


Holler et al. 14

Reading the Tracks: Helium-Ion Beam

- Able to reach **< 1nm resolution**
- To take measurements efficiently, must remove layers and scan at same time





Cosmic Rays Induce Large Backgrounds

Depth [km]	2	5	7.5	10
Neutron Flux [1/cm²/Gpc]	10^3	10^1	10^{-4}	10^{-8}

Natural Radioactivity: Single alphas

- **Natural radioactivity**, most importantly **Uranium-238** causes multiple backgrounds

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

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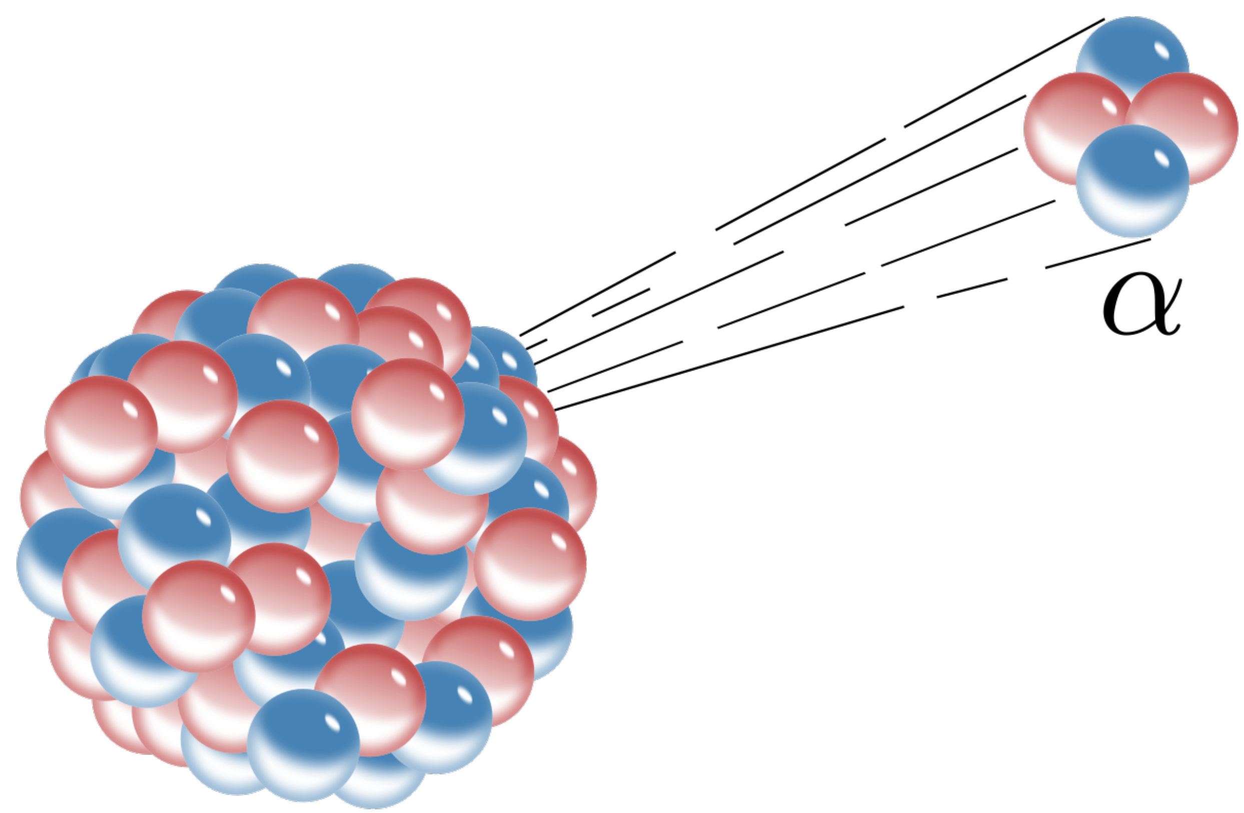
$$\xrightarrow{\alpha} {}^{226}\mathrm{Ra} \xrightarrow{\alpha} {}^{222}\mathrm{Rn} \xrightarrow{\alpha} \ldots \longrightarrow {}^{206}\mathrm{Pb}$$

- Half life of the second **alpha in the decay chain is 10^5 yr**

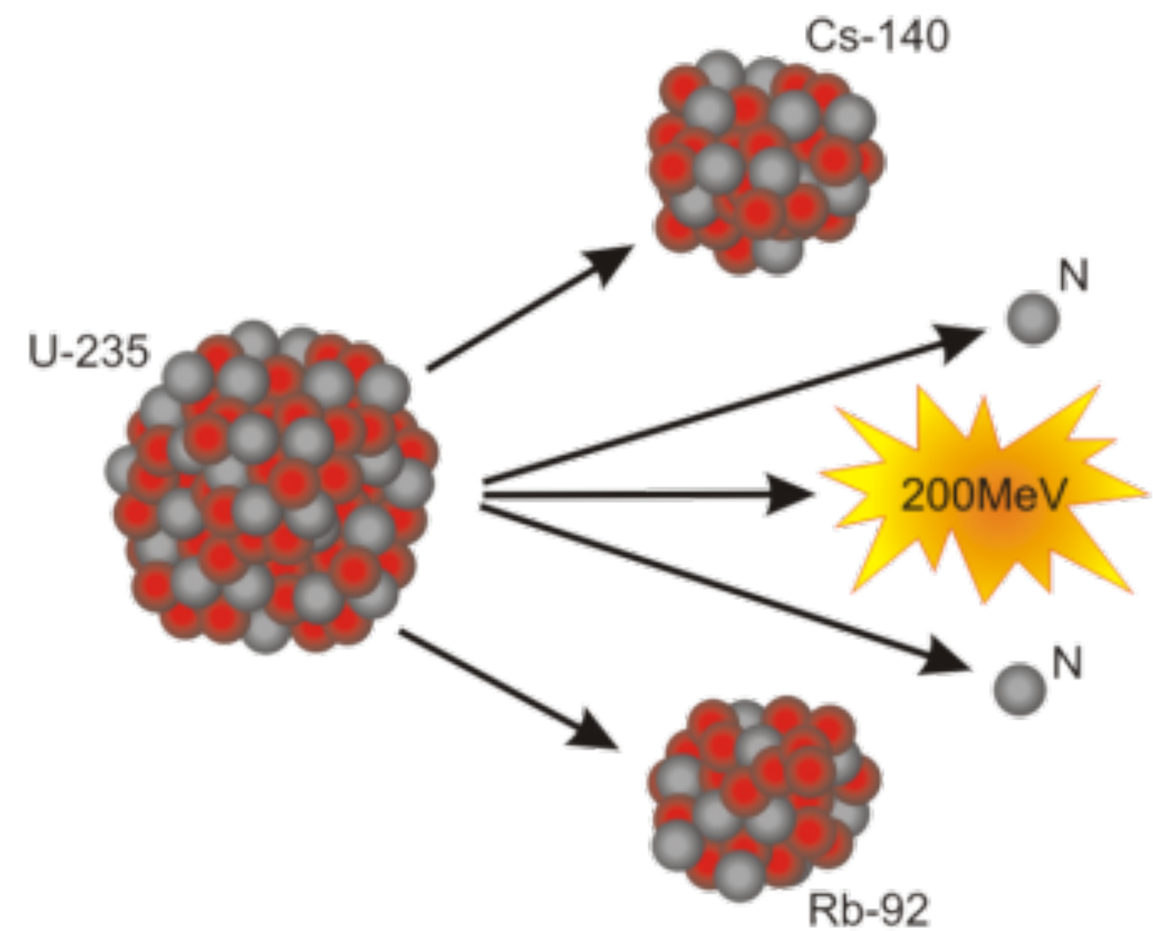
- Alpha does not leave a track, but the **daughter nucleus does**



Natural Radioactivity: Spontaneous Fission

- Sometimes uranium spontaneously splits into two lighter nuclei, whilst emitting fast neutrons

- These neutrons cause many well separated tracks - **huge background**



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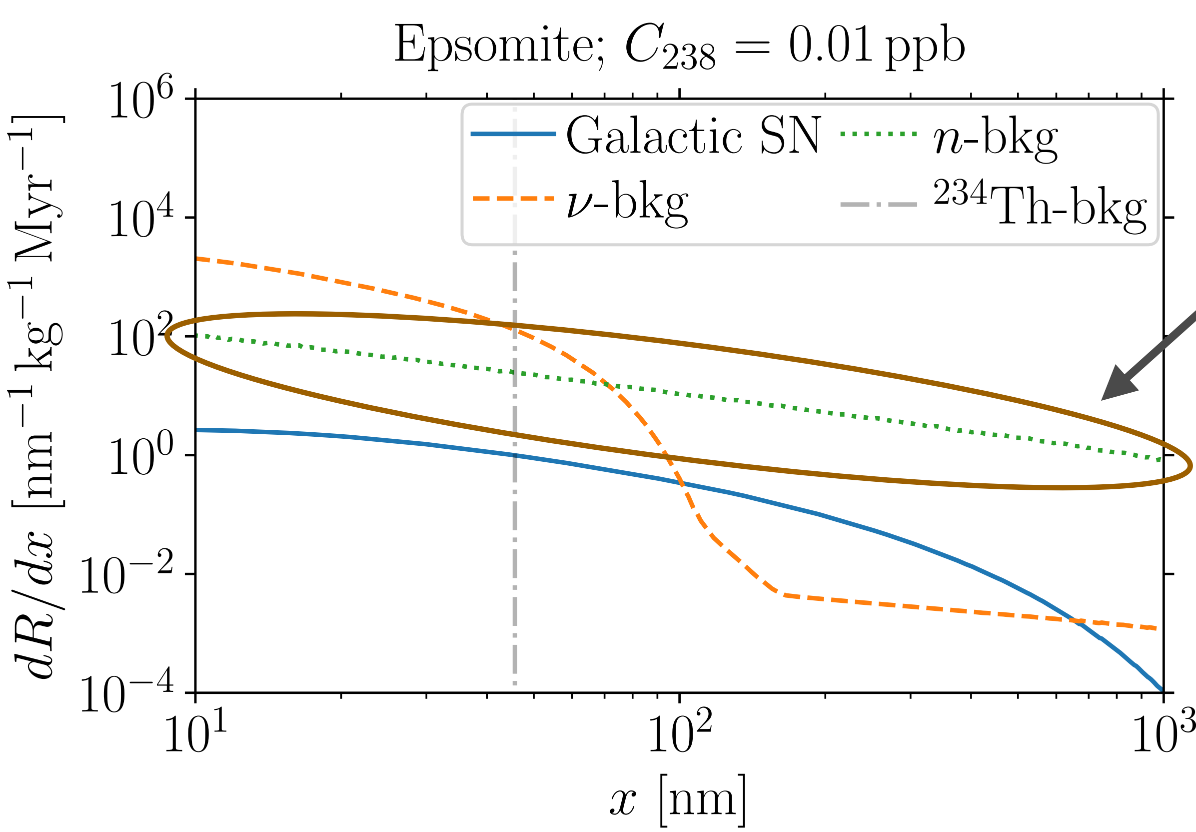

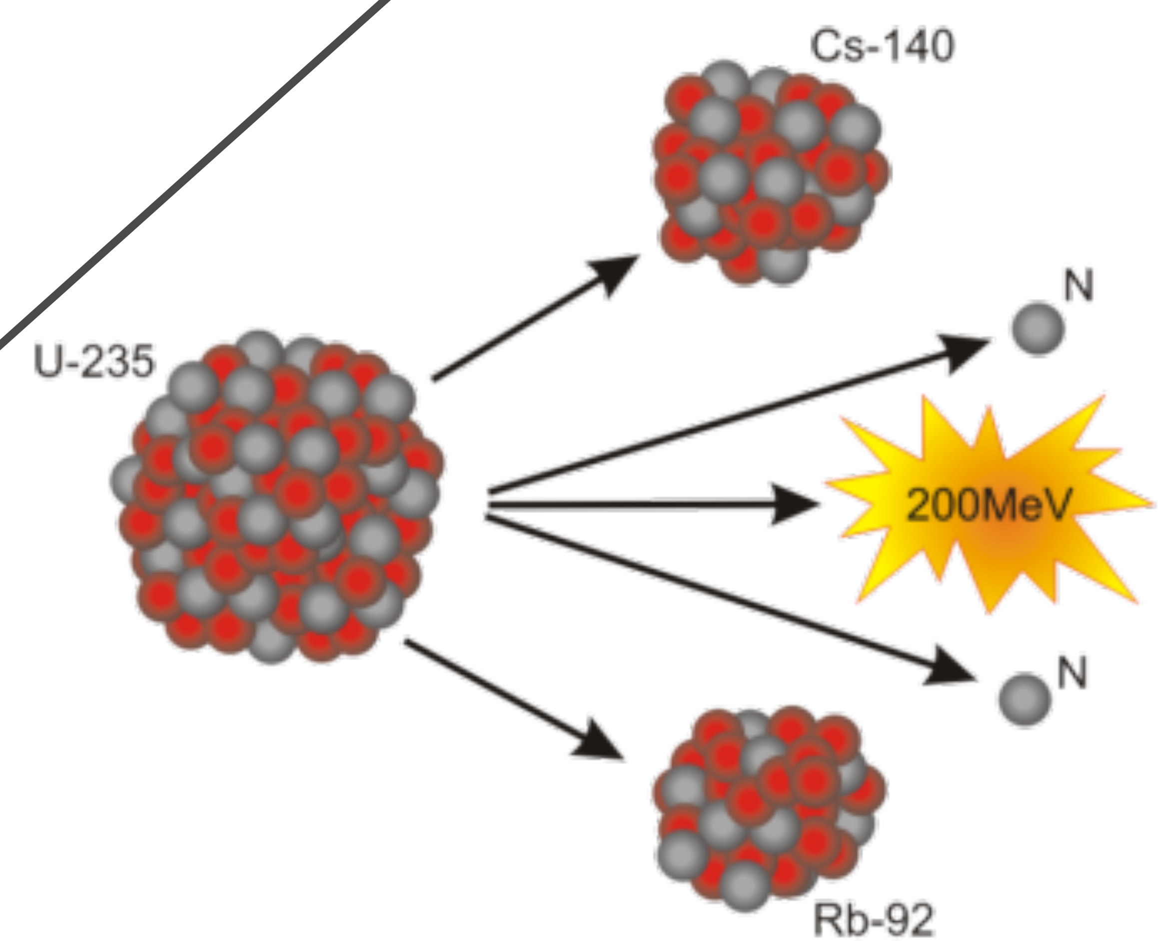

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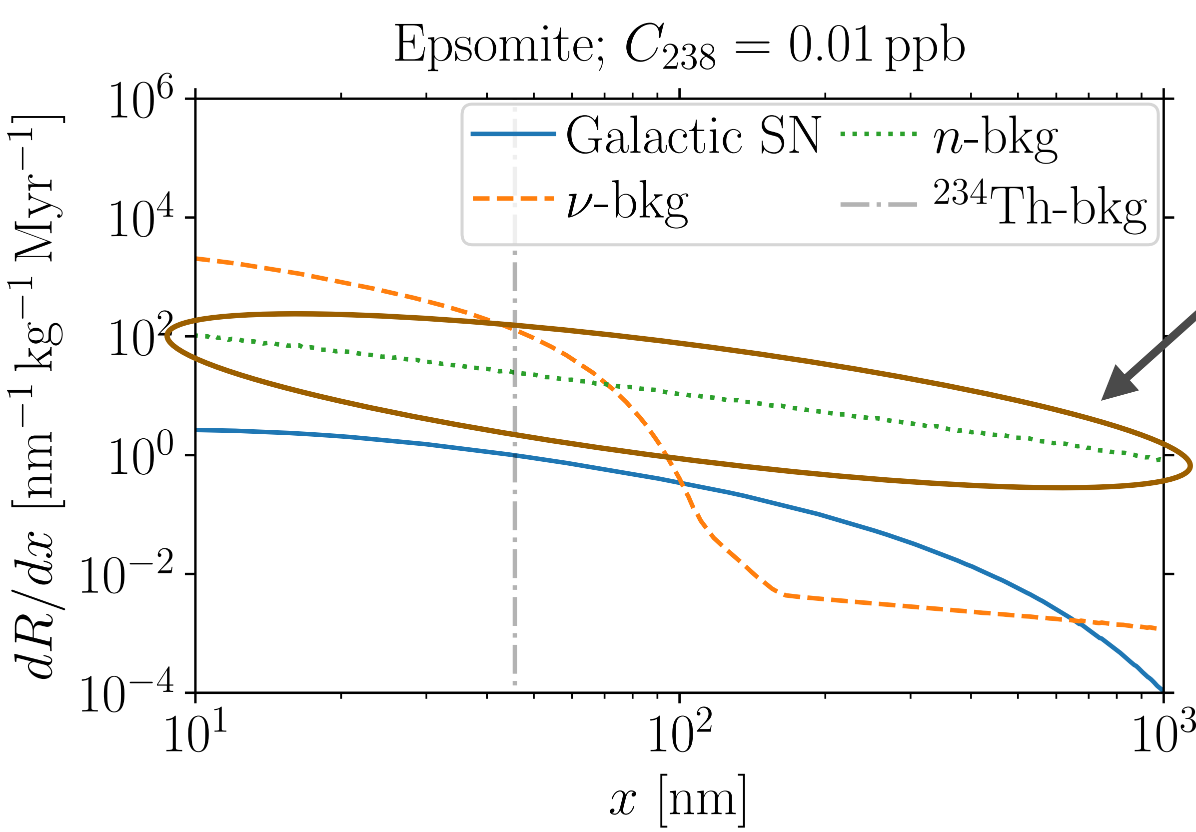
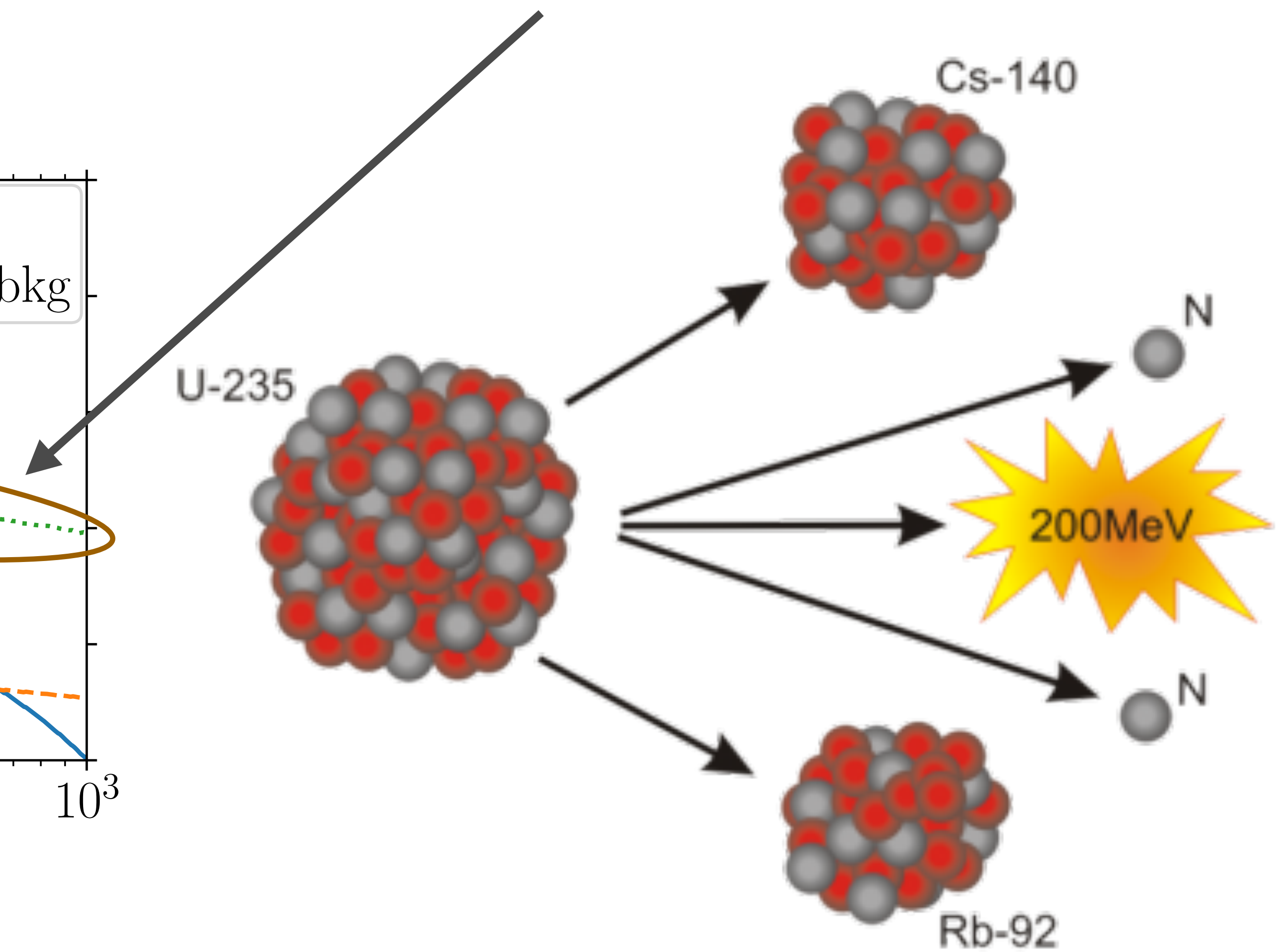
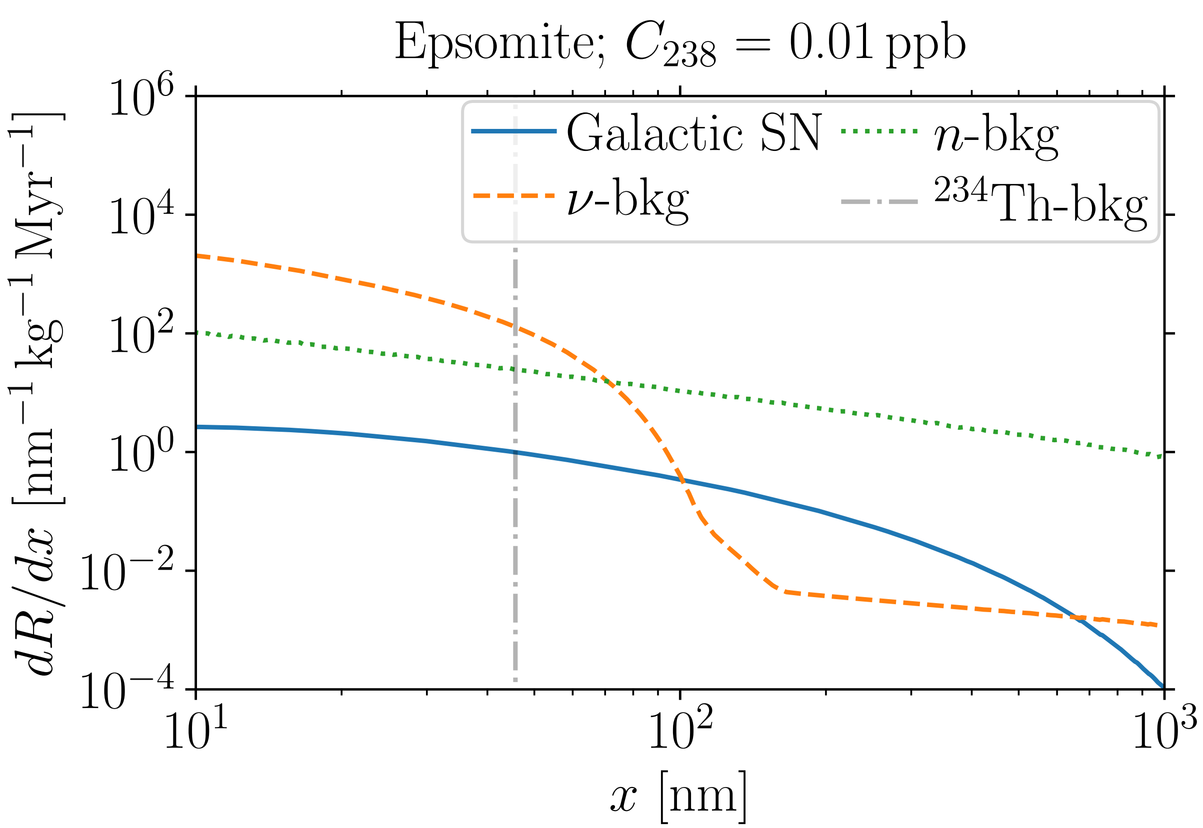




$$\text{Uranium-238 Concentration} \sim 0.01\,\text{ppb}$$

Background Neutrinos: Solar and Atmospheric



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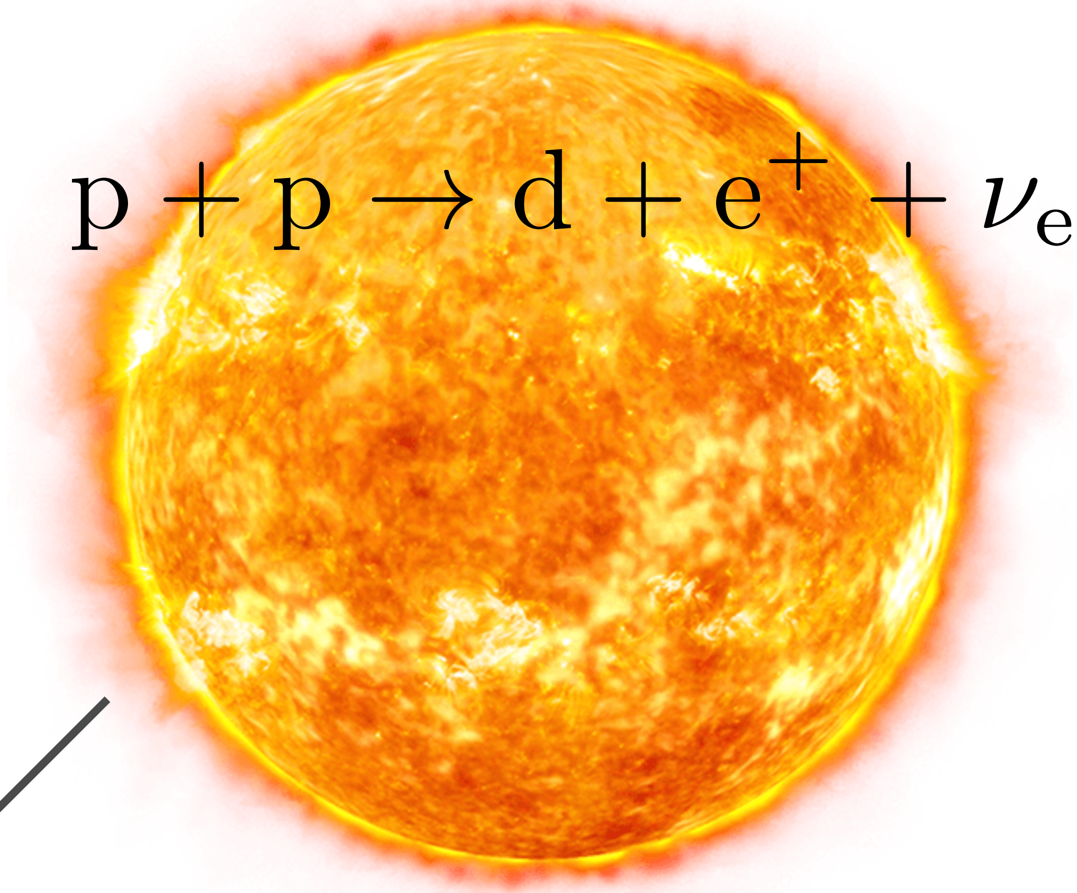

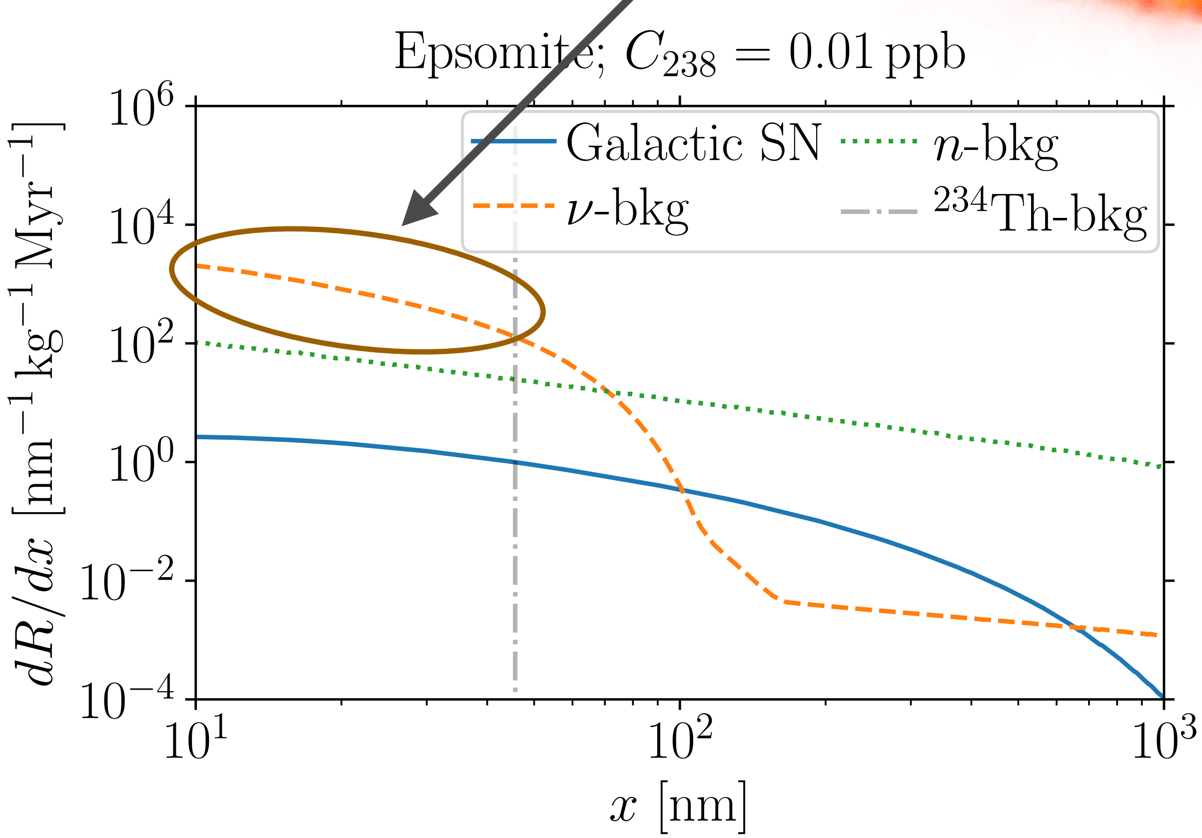

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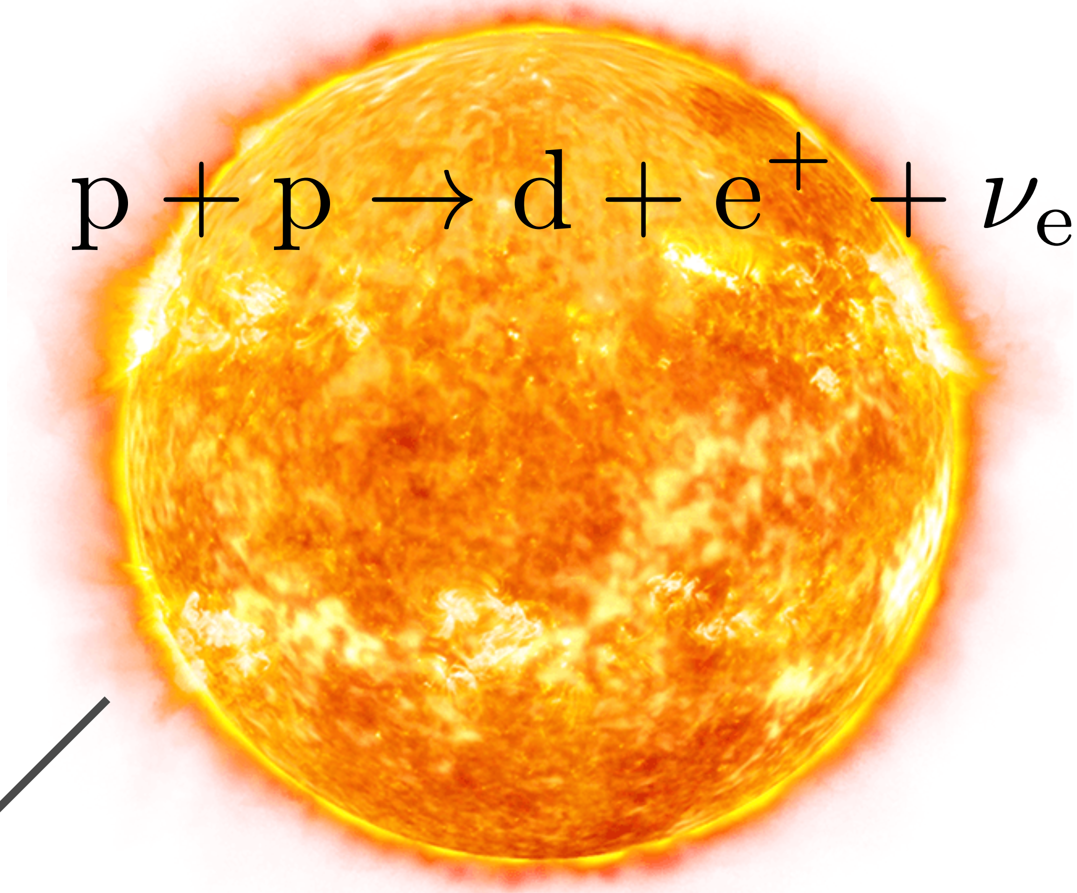
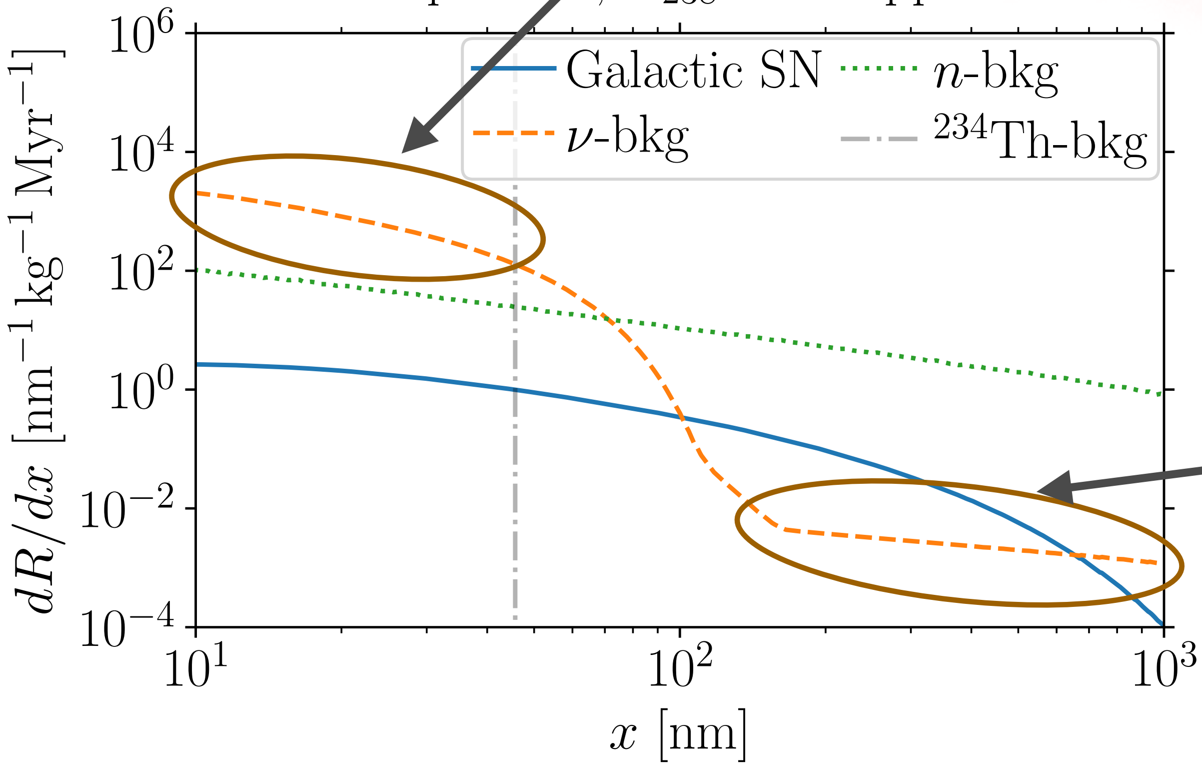


$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

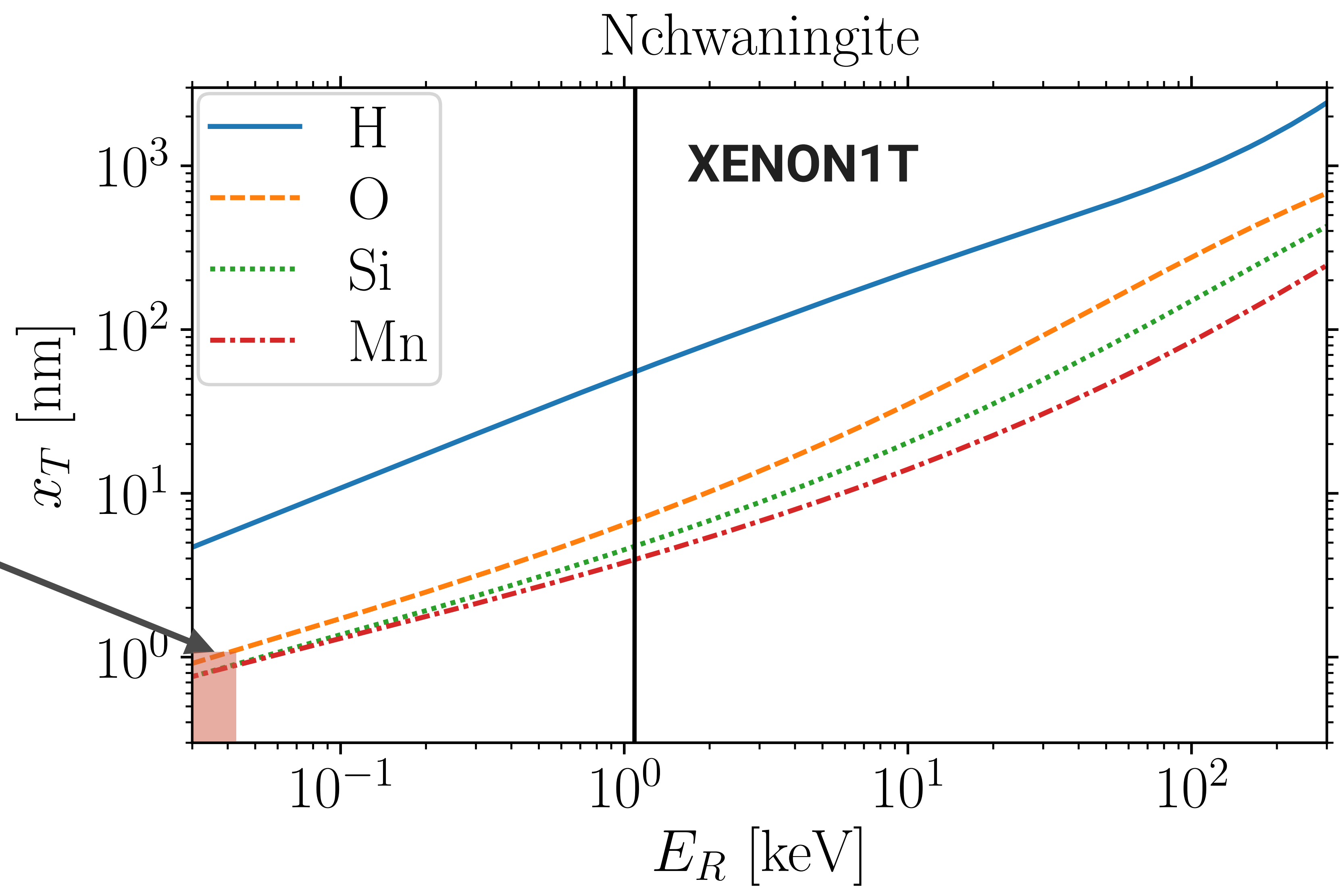


Dark Matter

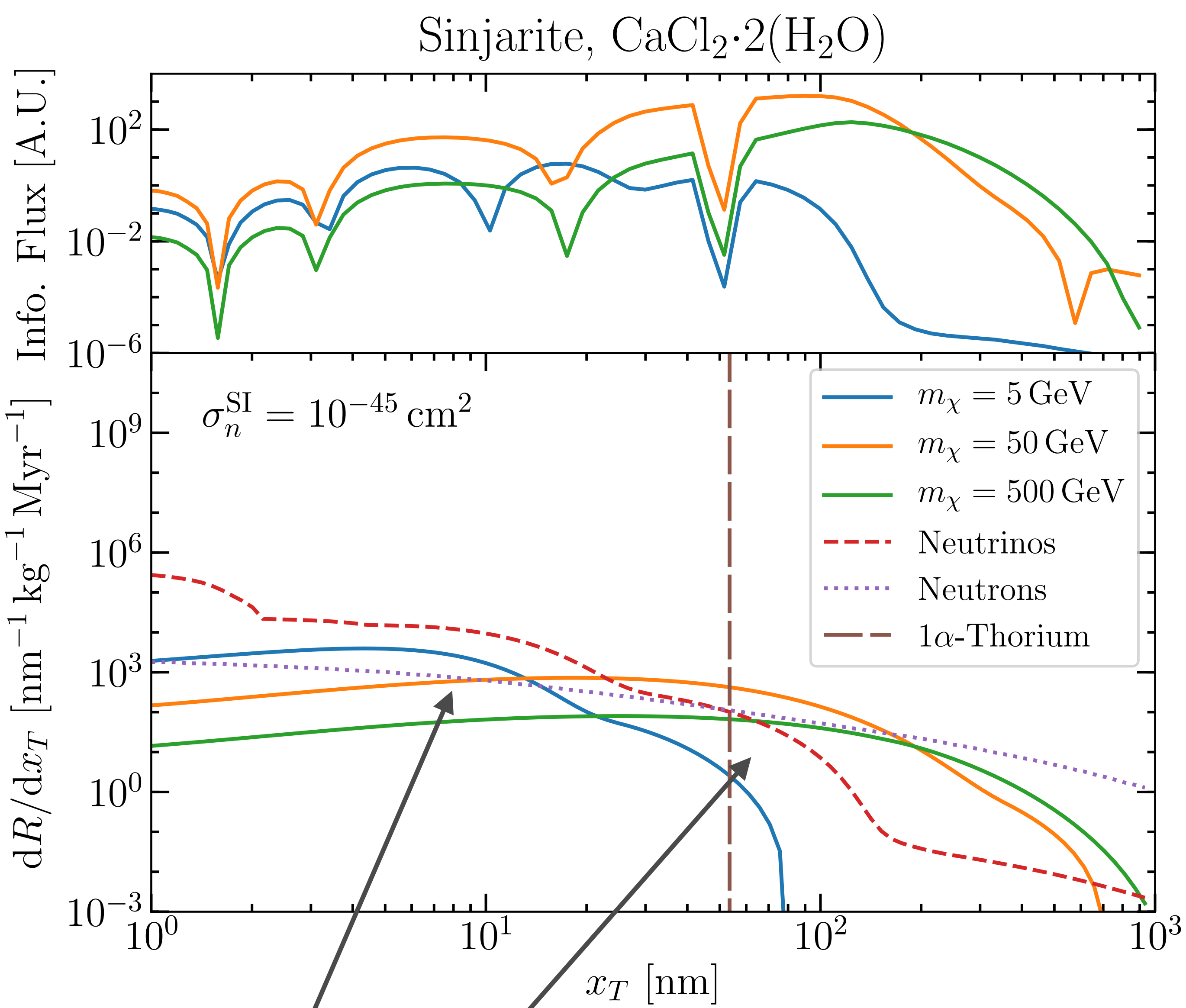
1811.06844, 1811.10549, 1806.05991

Paleo-Detectors Can Probe Low Energy Recoils

High track length resolution allows us to probe **low energy recoils** - We are therefore sensitive to lighter dark matter



Dark Matter Signal



Bumps from different nuclei in mineral

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_N m_\chi} \int_{v_{\min}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \mathrm{d}^3\mathbf{v}$$

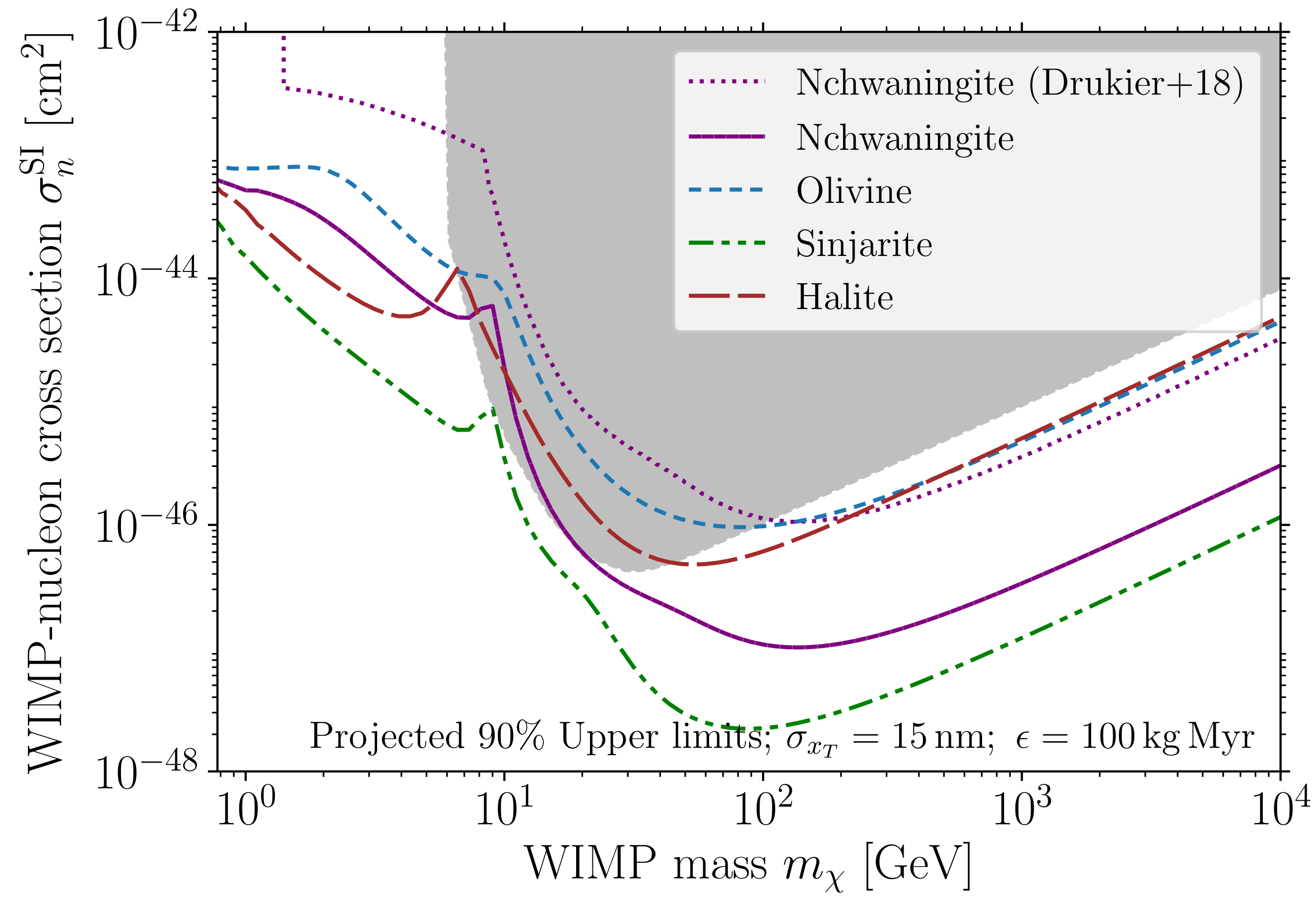
$$+$$

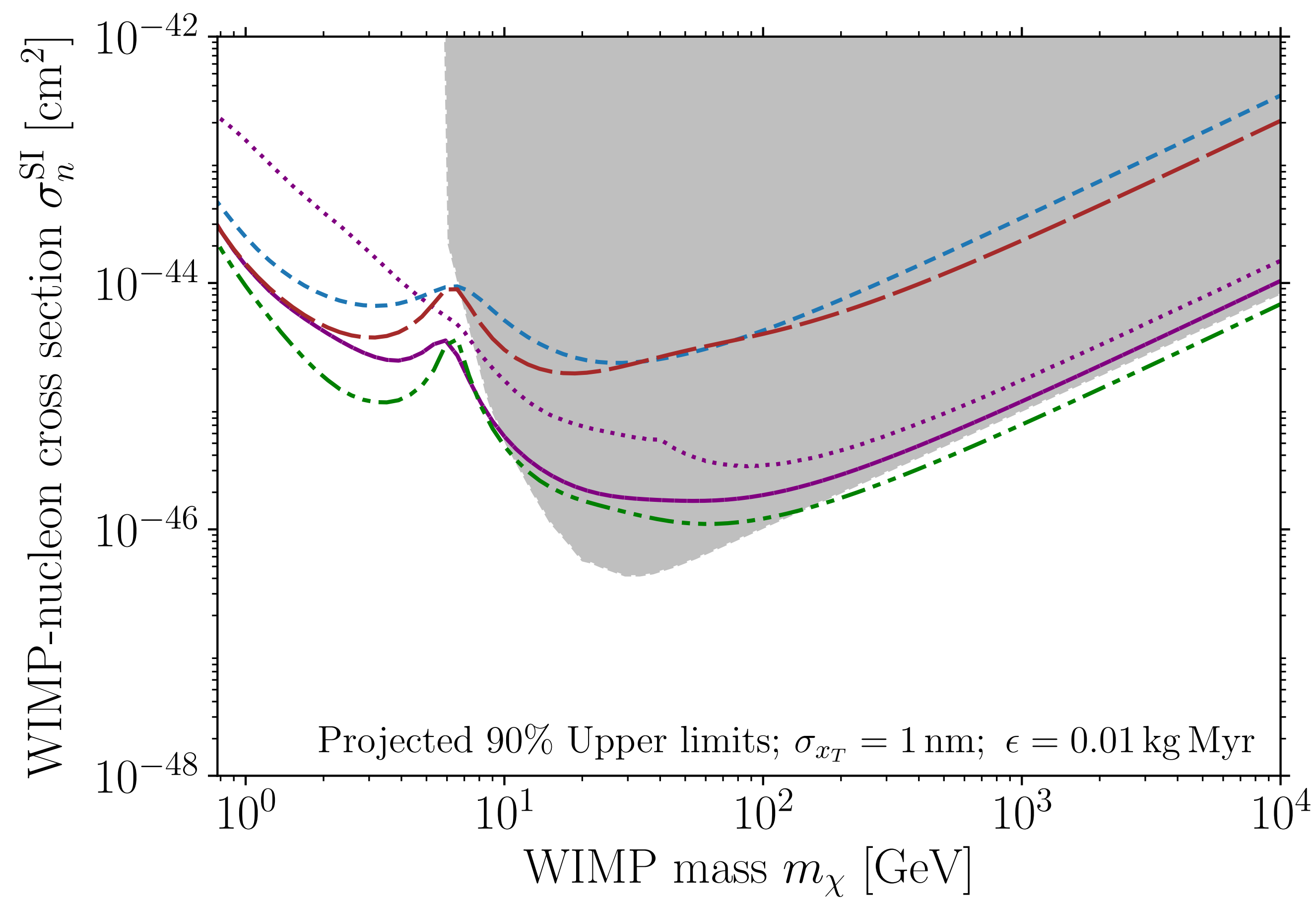
$$\frac{\mathrm{d}R}{\mathrm{d}x_T} = \sum_i^{\text{nuclei}} \xi_i \frac{\mathrm{d}R_i}{\mathrm{d}E_R} \left(\frac{\mathrm{d}E_R}{\mathrm{d}x_T}\right)_i$$

- Density of DM, DM mass, and nucleon mass
- **Velocity distribution** of DM in the galaxy
- Interaction **strength** as a **function of energy**

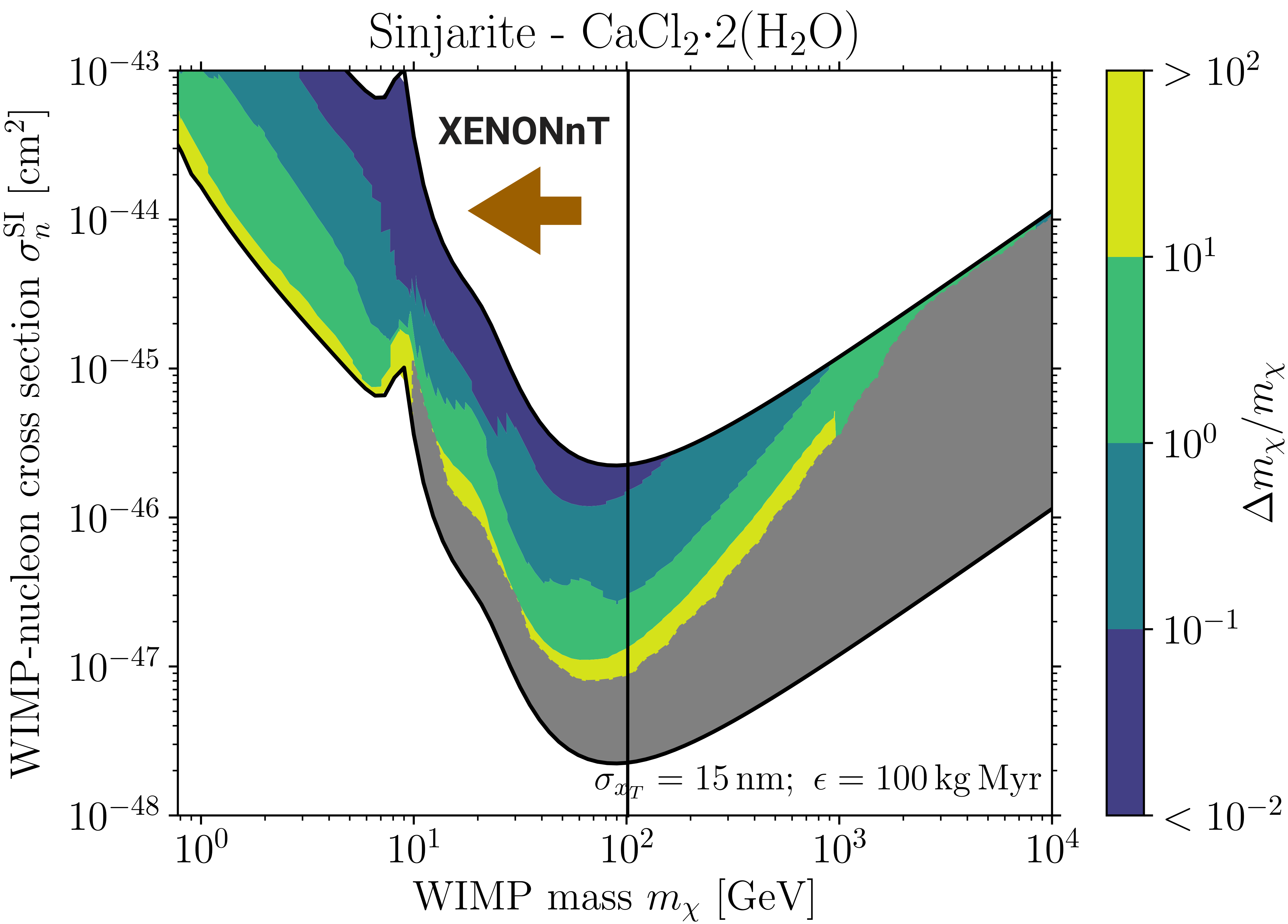
Dark Matter Limits

- Using Helium-Ion beam microscopy we can achieve large gains in sensitivity to **low mass DM**
- Scanning more material allows us to achieve around **many times more sensitivity** than current experiments at higher masses





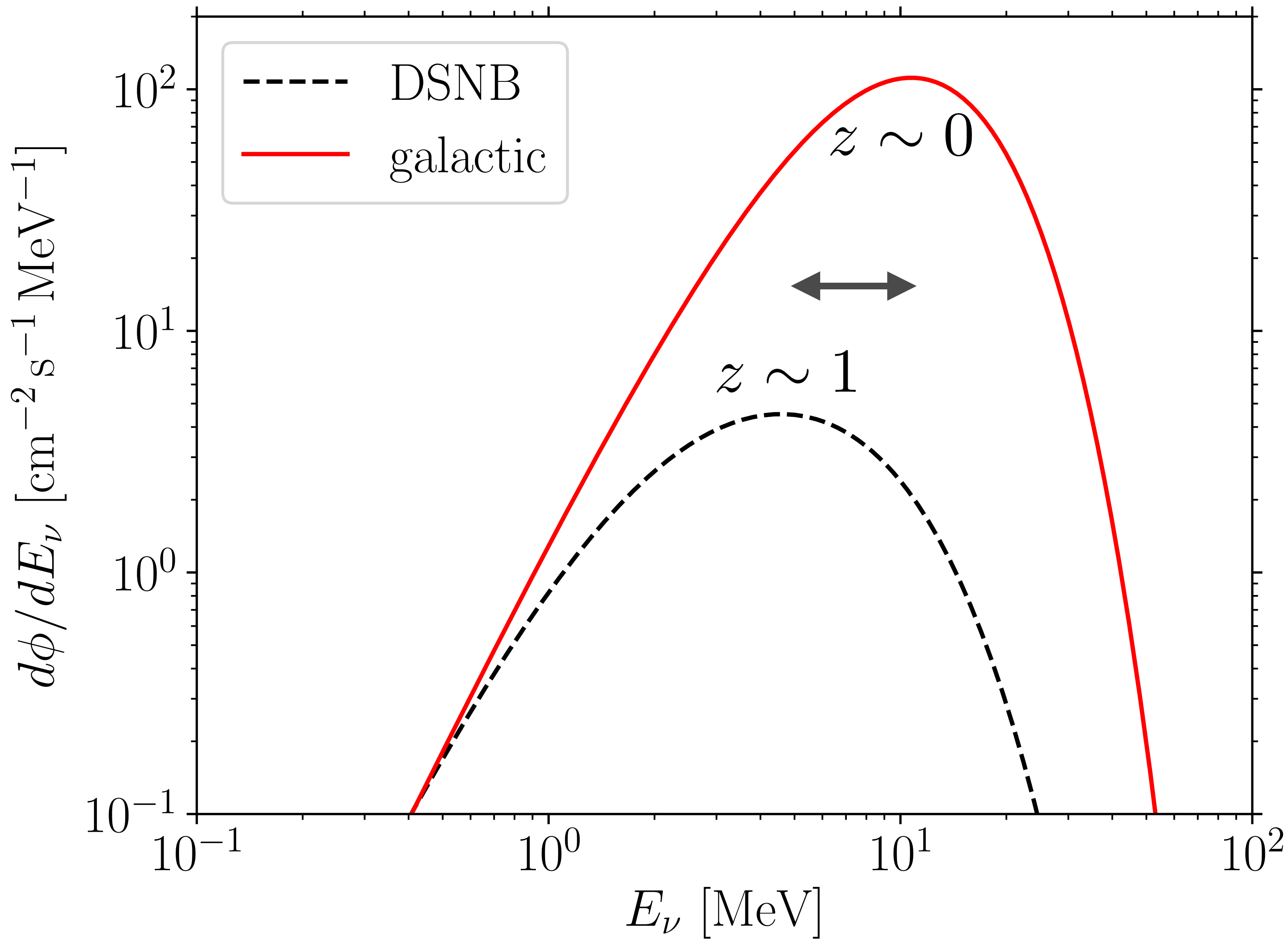
Reconstruction of DM Mass



Galactic Supernova Neutrinos

1906.05800

Galactic Signal much Larger than the Diffuse Background

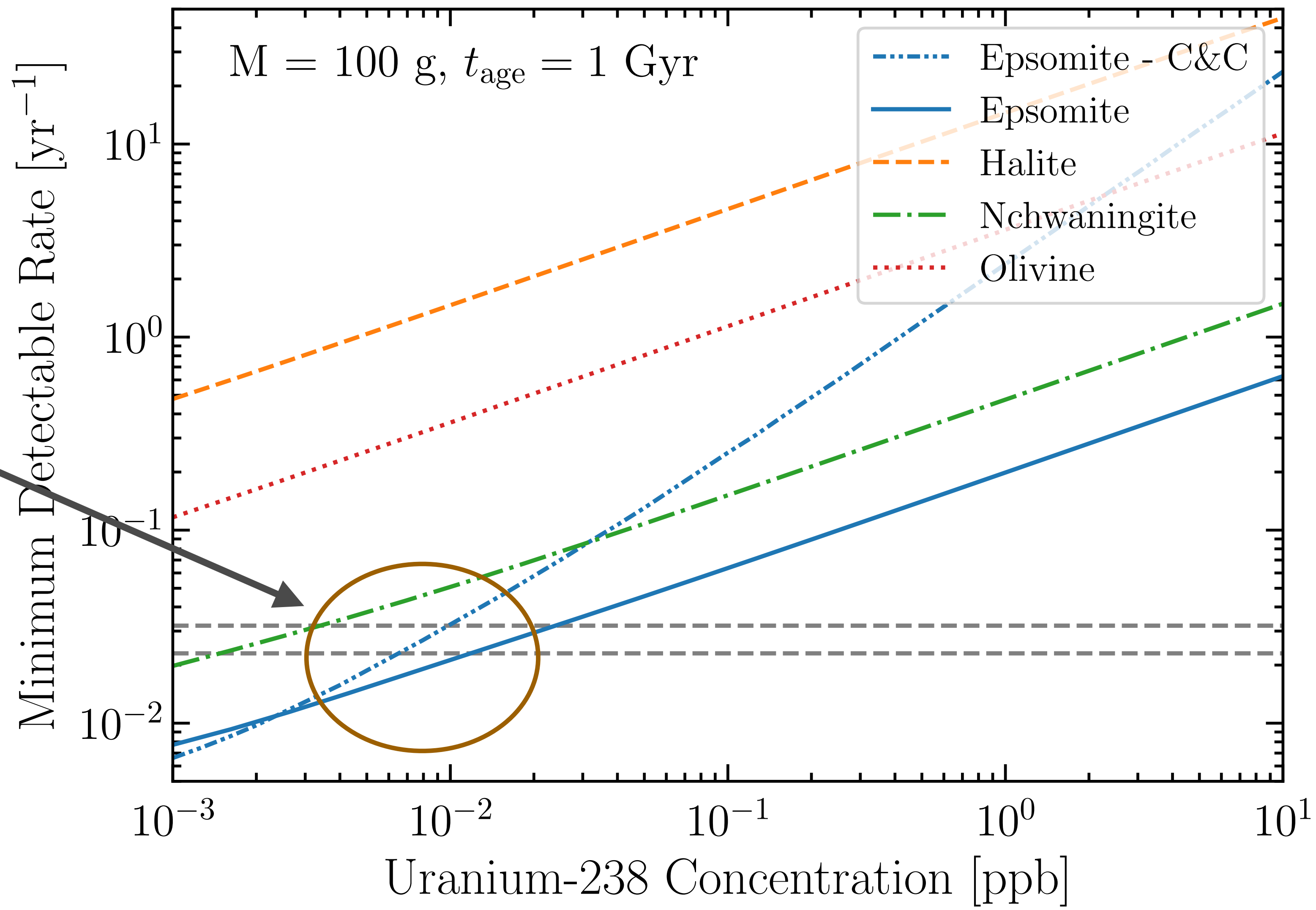


Signal from galactic supernova is **much larger than DSNB**

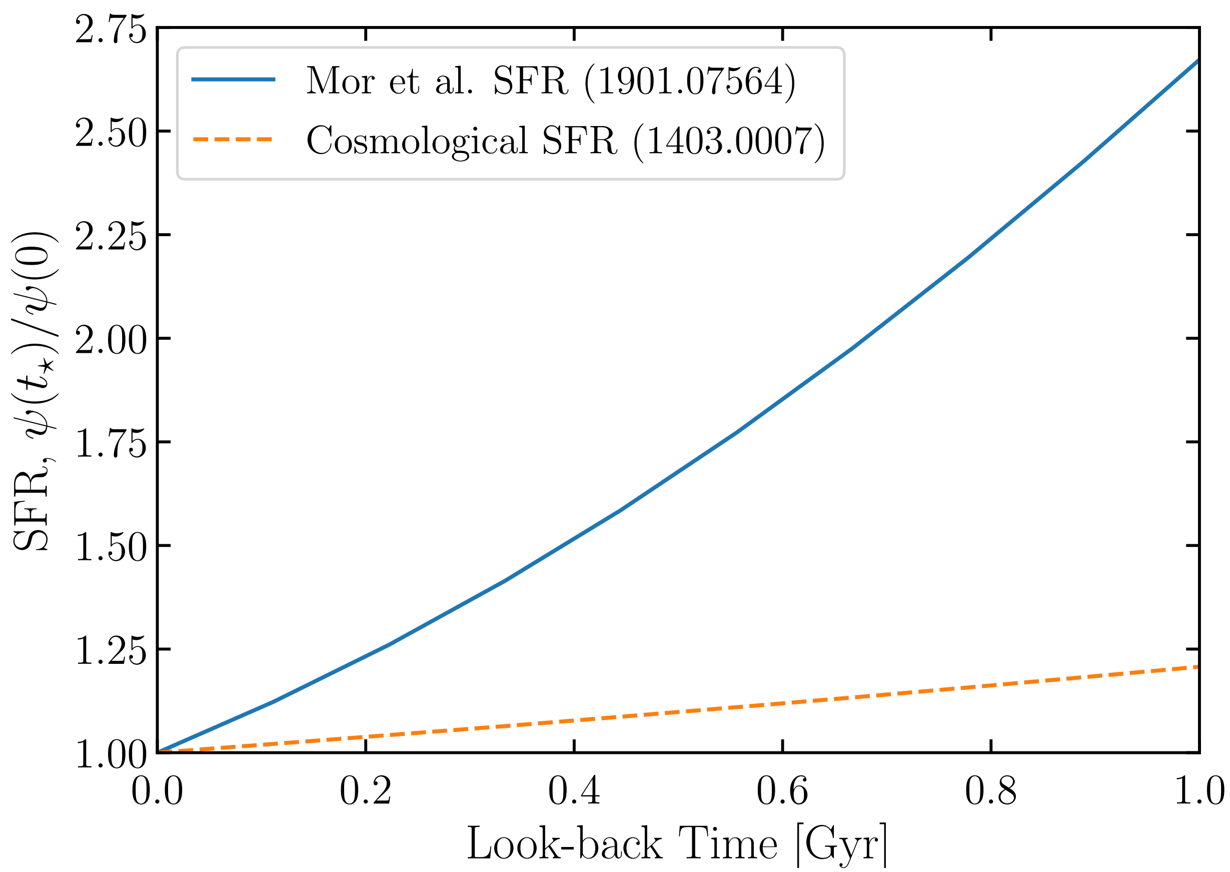
Galactic SN spectrum **peaks at different energy** due to redshift

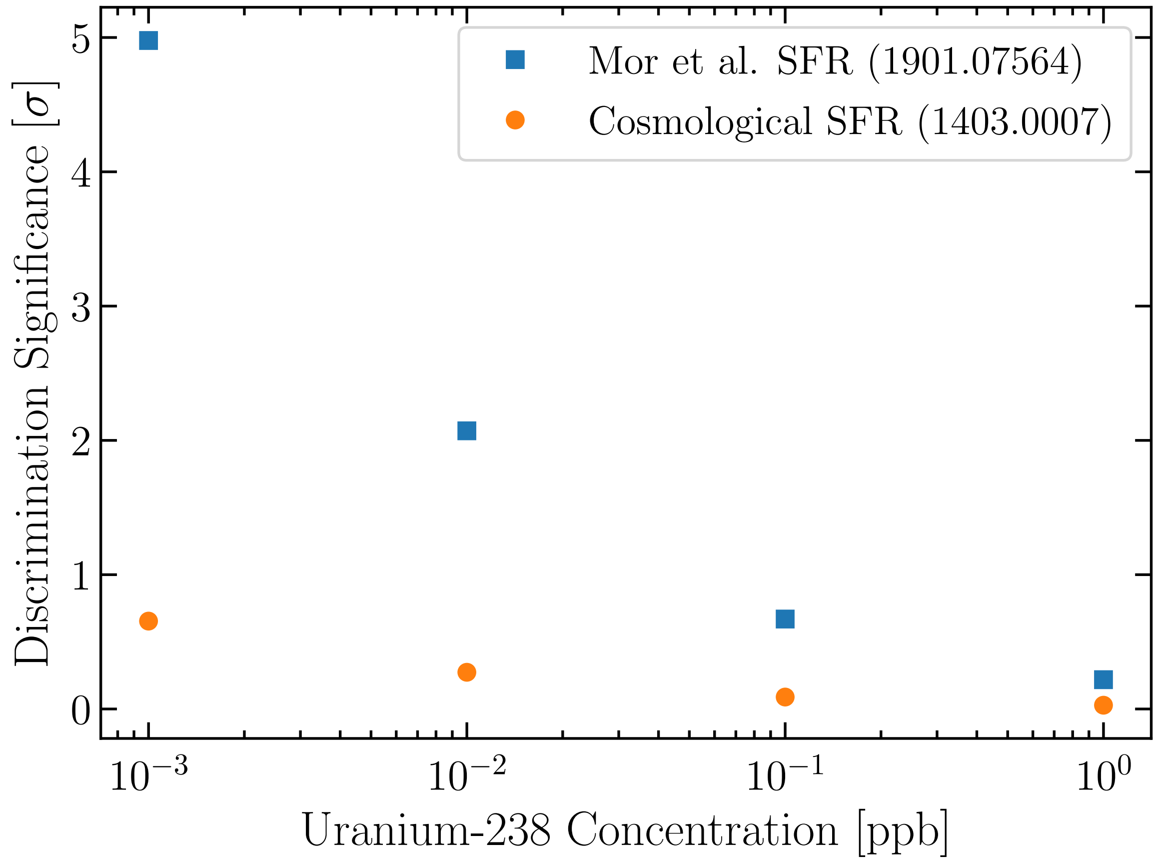
Paleo-detectors can Observe Galactic Supernovae

- **3-sigma detection** if we achieve low enough concentrations of Uranium-238
- Here we assume a constant rate of SNe throughout the history of the galaxy



Star Formation Rates





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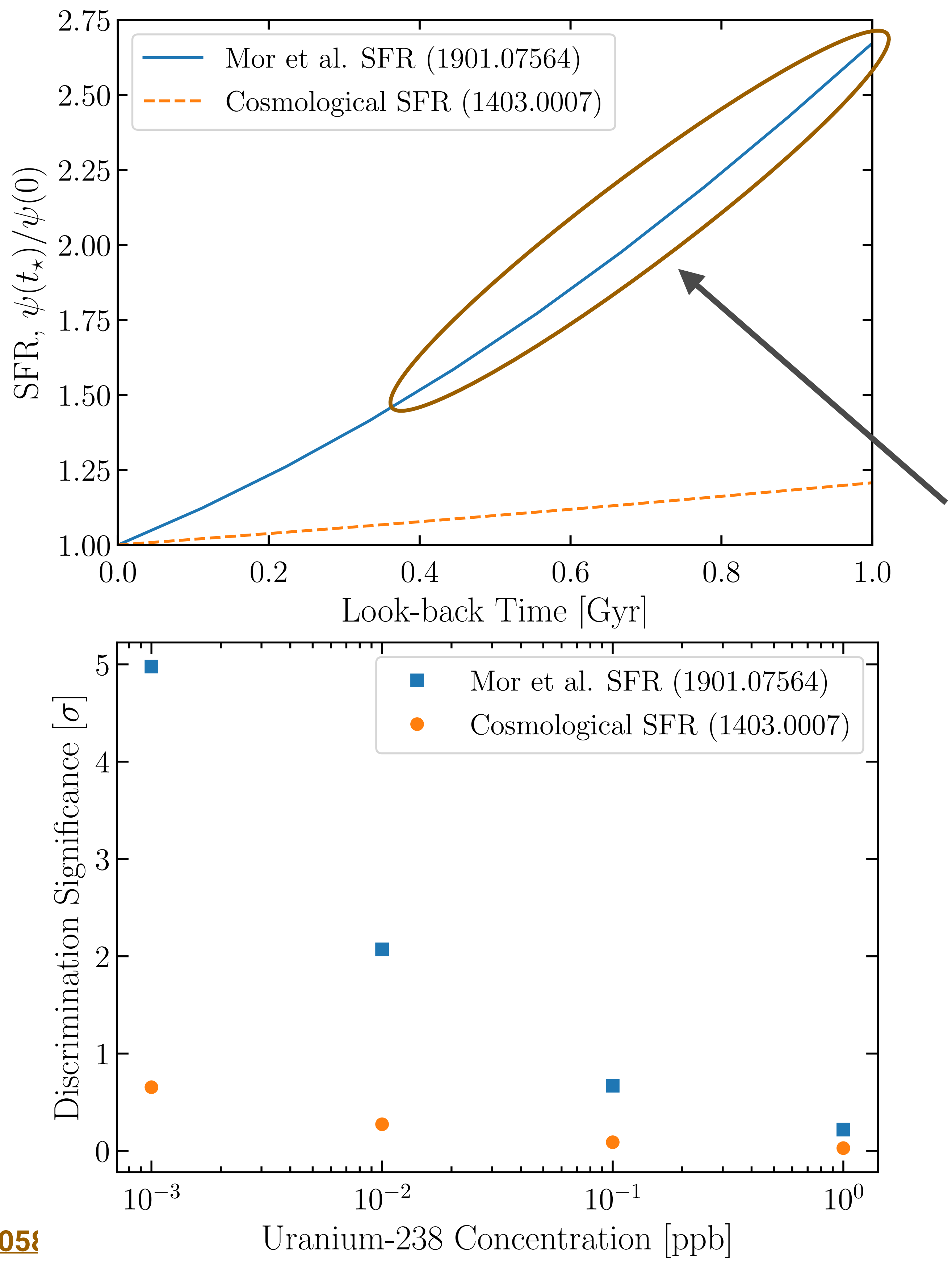
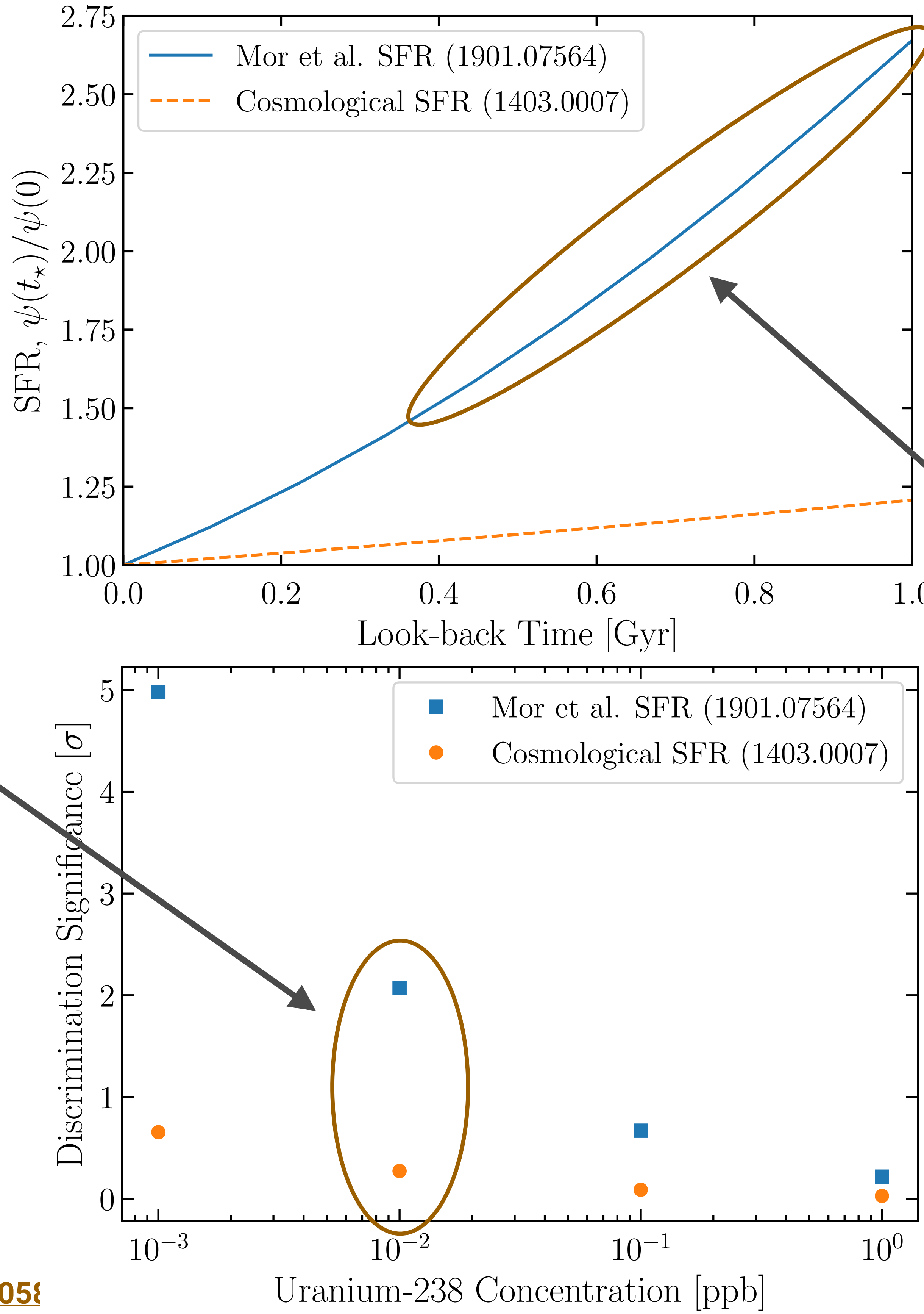


Estimate of the Milky Way SFR from Gaia

Star Formation Rates

Baseline case can rule out constant rate at **2 sigma** depending on model



Estimate of the Milky Way SFR from Gaia

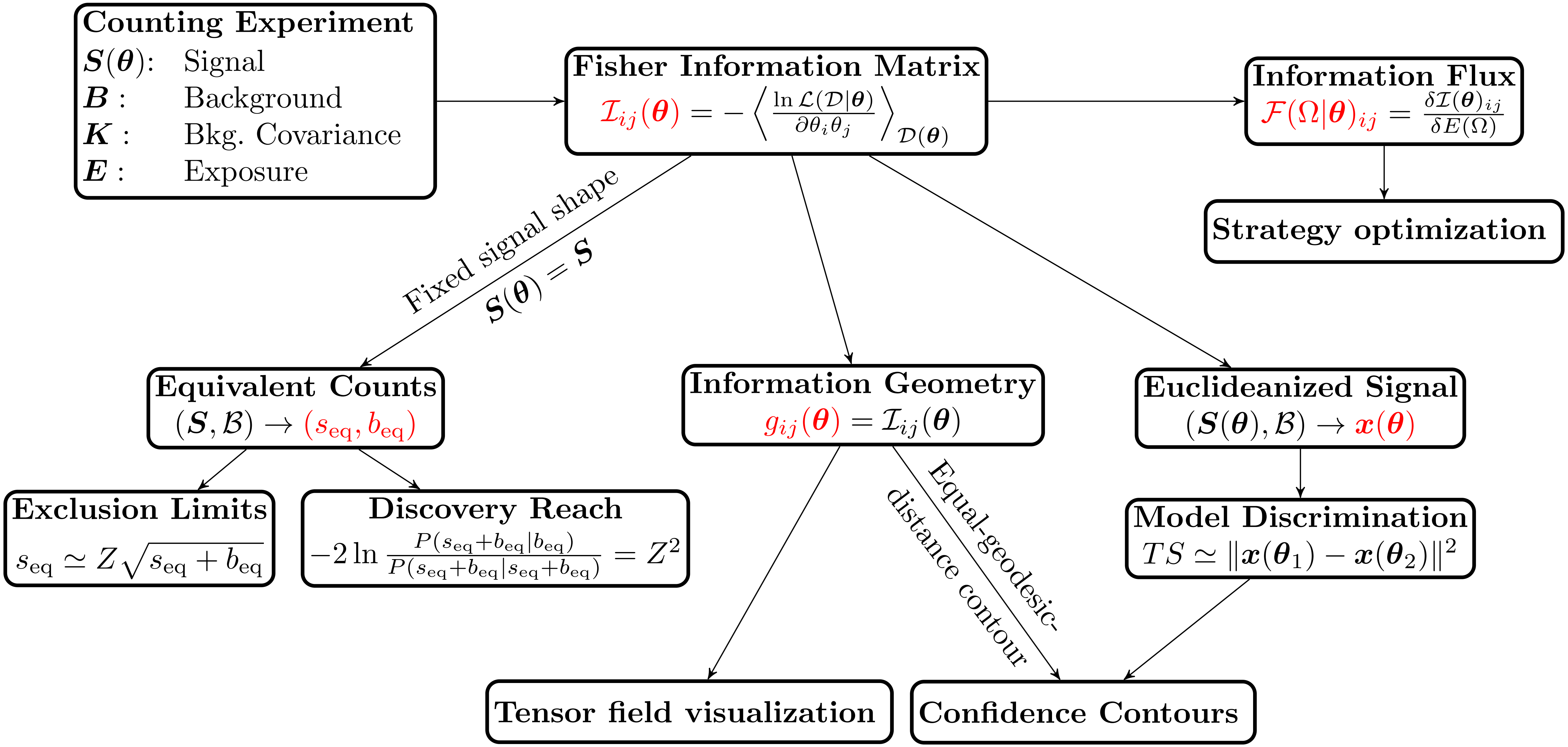
Conclusions

1. **Paleo-Detectors represent a new way to probe keV scale interactions**

2. **They potentially represent the most sensitive dark matter detectors to date**

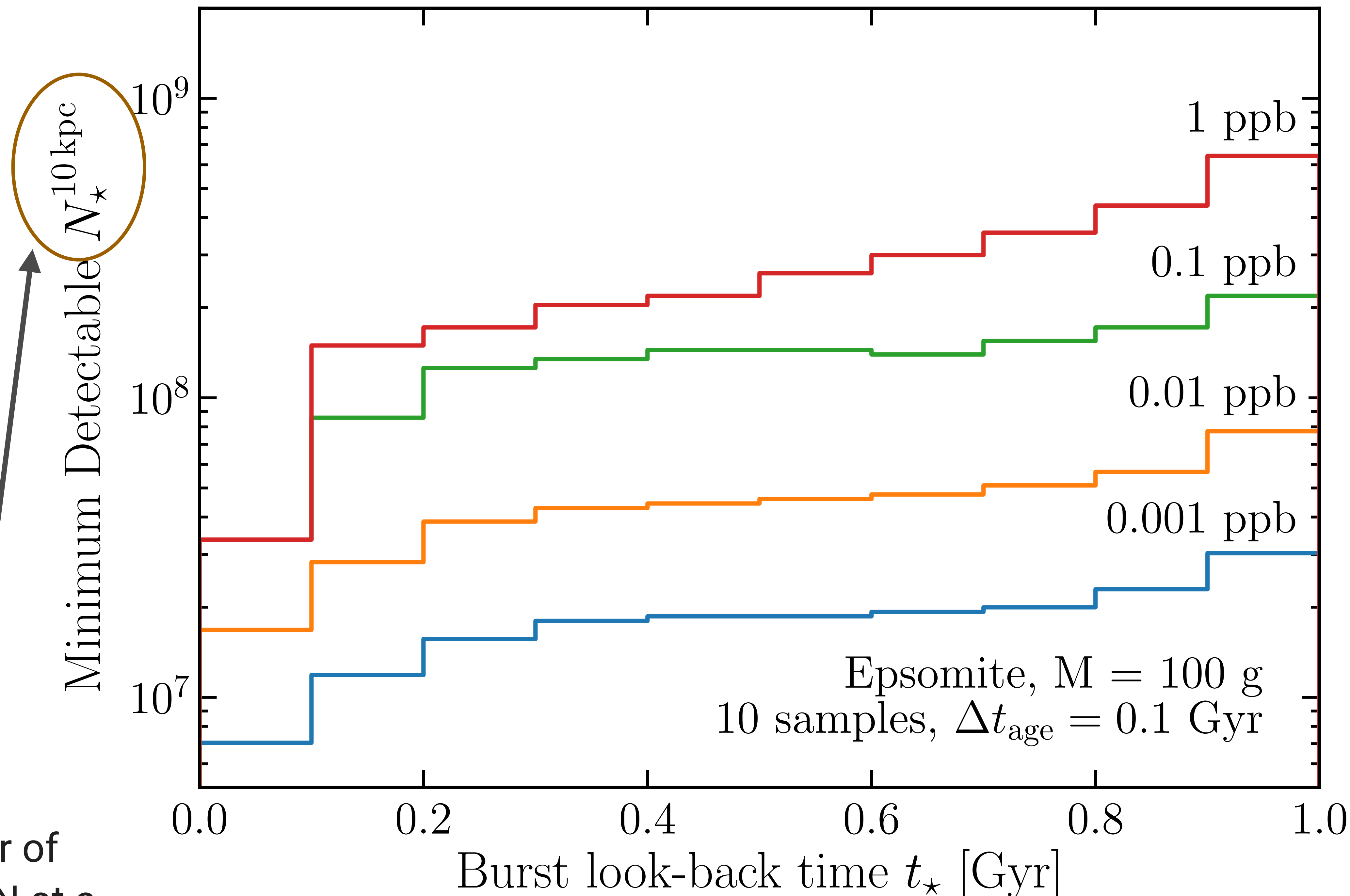
3. **Paleo-Detectors can detect neutrinos from supernovae within our galaxy**

We use swordfish to Analyse the Spectra Easily



1704.05458, 1712.05401
https://github.com/cweniger/swordfish

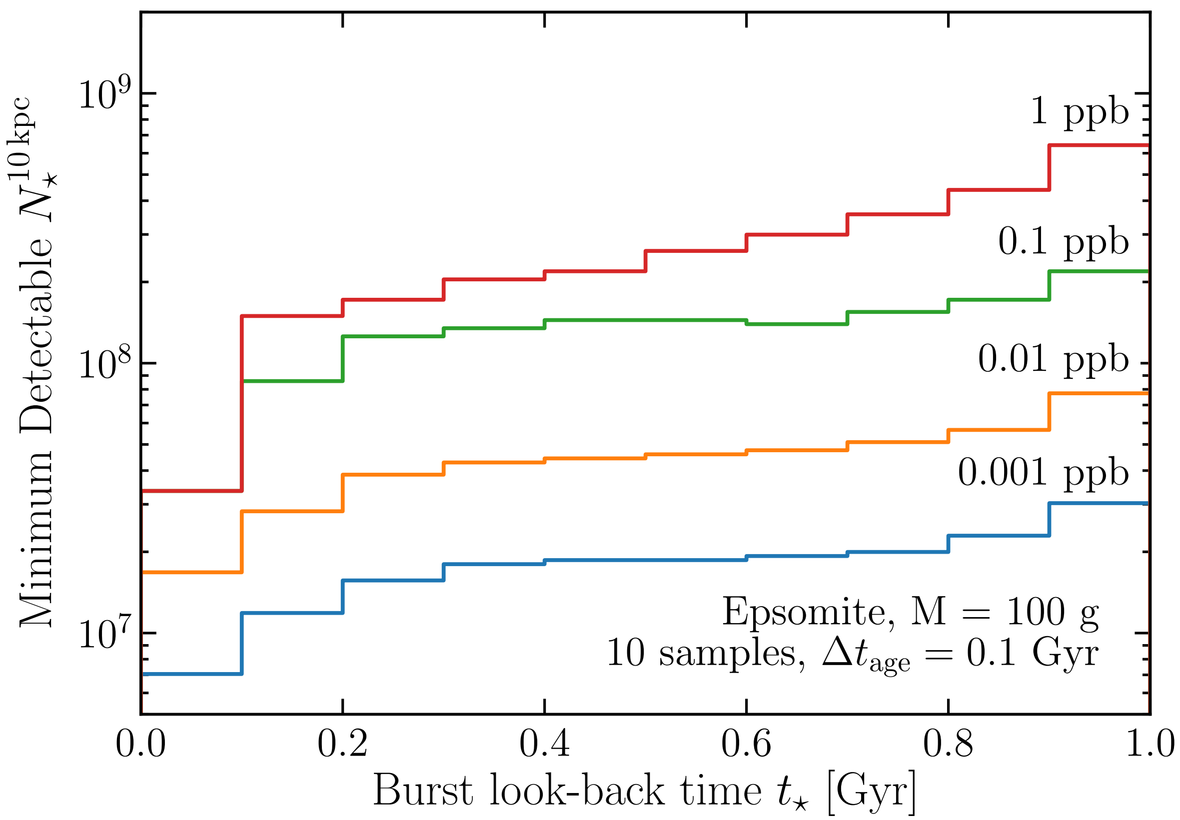
We can Constrain Burst Like Events



Number of normal SN at a distance of 10 kpc

$$F \propto \frac{L}{d^2}$$

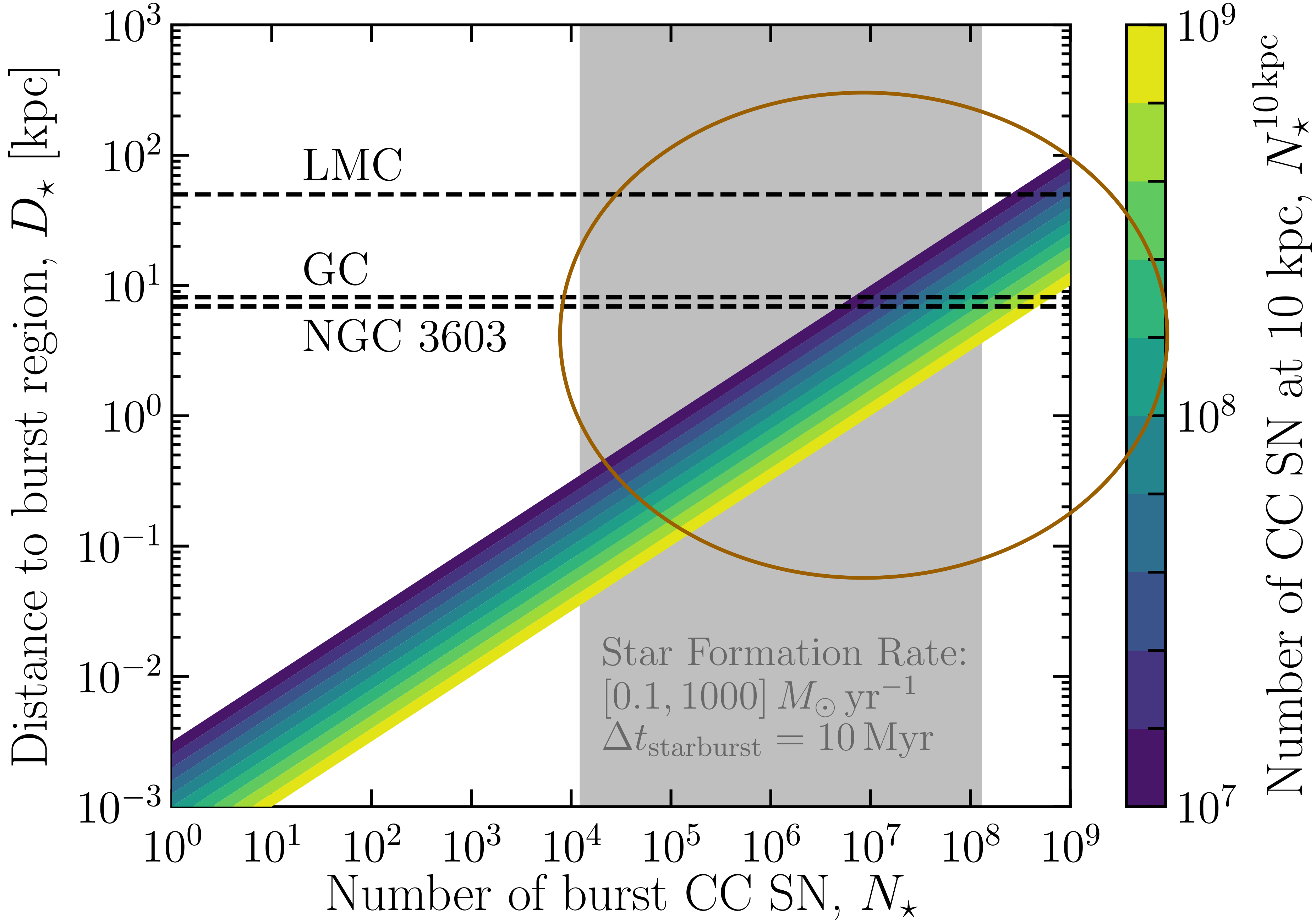
Constraining Burst Like Events



Bursts a long time ago must be brighter

Bursts that happened recently can be detected more easily

Star Burst Scenario



Close by Supernova