Mining Heavy Charged Relic

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Preliminary (2025): Reza Ebadi, Peter W. Graham, Erwin H. Tanin, Samuel S. Y. Wong

Stanford University

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- For example, in supersymmetry with R-parity, the lightest supersymmetric particle could be a charged slepton.

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- Attracted much experimental interest in 1980s; most notably, search for heavy hydrogen in sea water achieved concentration limit of 10^{-29}! [Smith et. al., Nucl. Phys. B 206, 333 (1982)]
- **However**, need to assume their distribution is undisturbed by the evolution of the galaxy, solar system, planetary formation, and water current.

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- We also ambitiously aim to extend that experiment's mass sensitivity from 1 TeV to 10^{10} TeV.

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- In both cases, win by the age of the rock.

Distribution in Geological Rocks

Stopping Length

Stopping power of matter due to ionization:

$$\frac{dE}{dx} \approx 1\ \mathrm{GeV/m}; \quad \text{for } v_{\mathrm{DM}} \sim 10^{-3}$$

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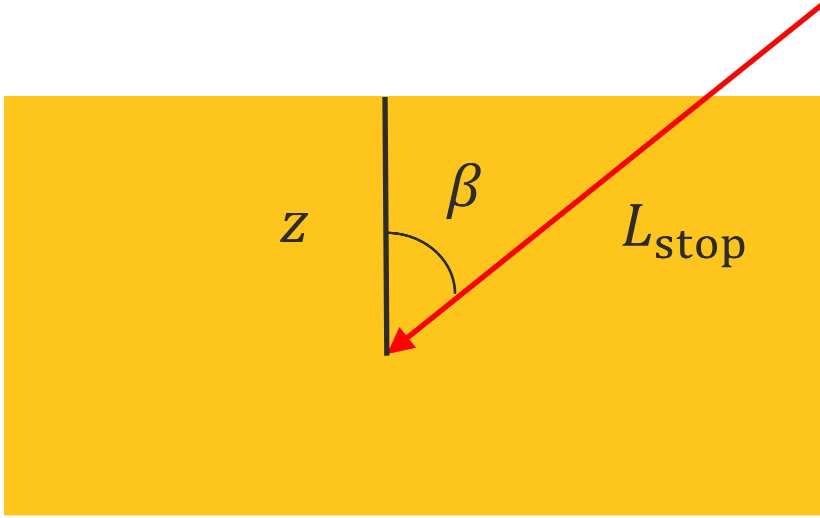
Atmosphere equivalent to 10 m of rock, so $m_X \lesssim 10^4$ TeV thermalized in air and do not penetrate earth.

Distribution in the Earth (Flat Earth Approx)

Number density of a rock at depth z

$$n_X = \Phi_X \Delta t \frac{z}{2L_{\mathrm{stop}}^2} \Theta(L_{\mathrm{stop}} - z)$$



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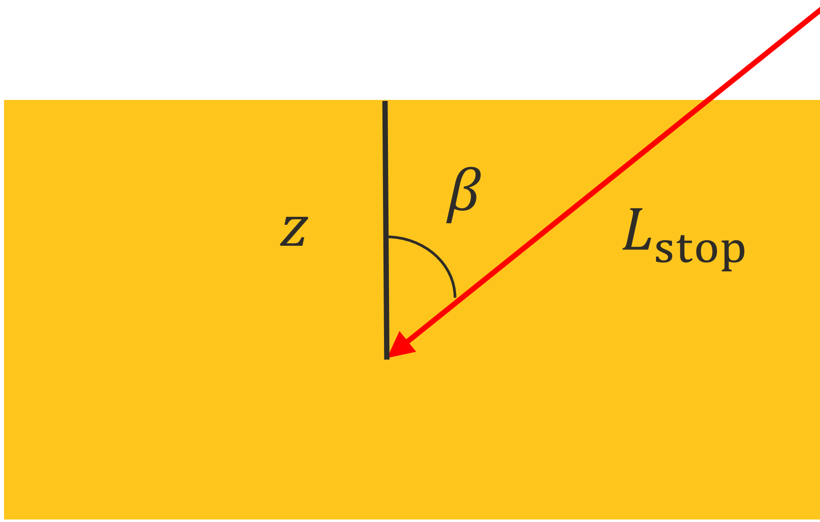

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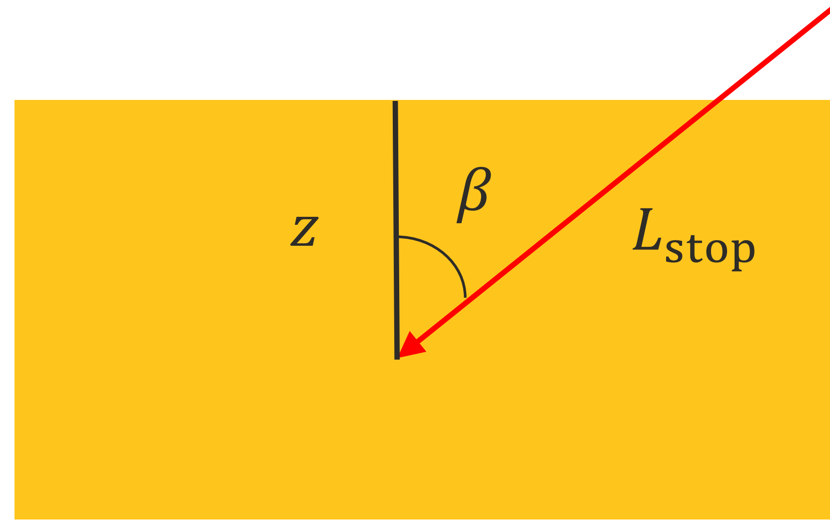

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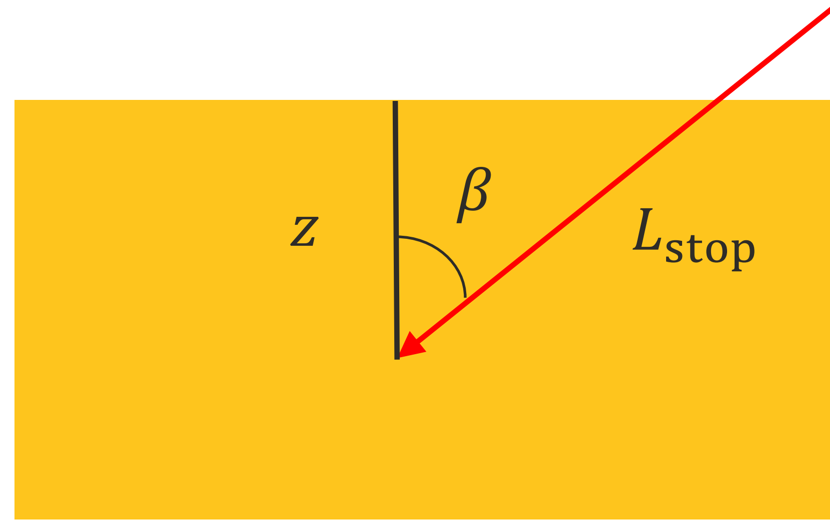

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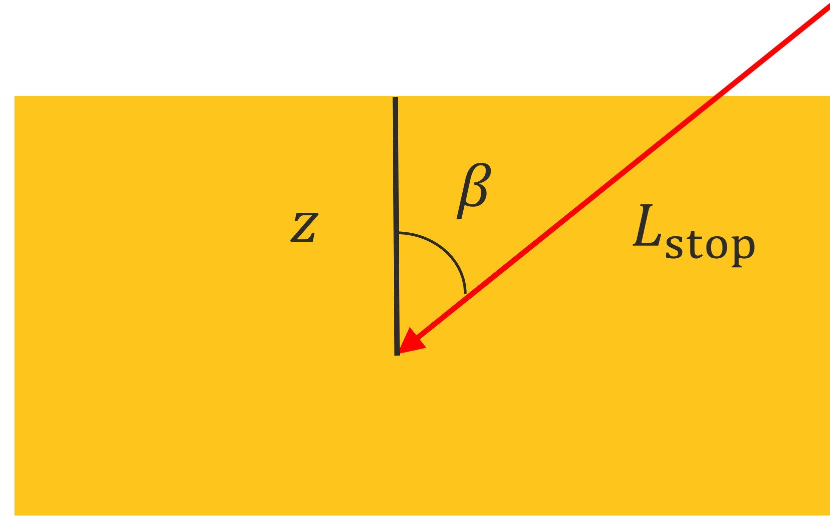

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More dark matter at larger z due to the effective area of the surface relative to the flux:

$$\cos\beta = \frac{z}{L_{\text{stop}}}$$

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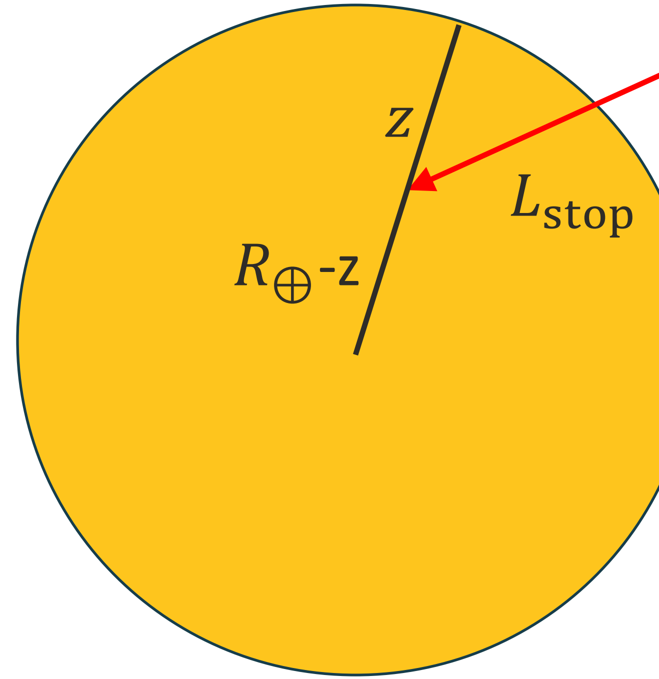

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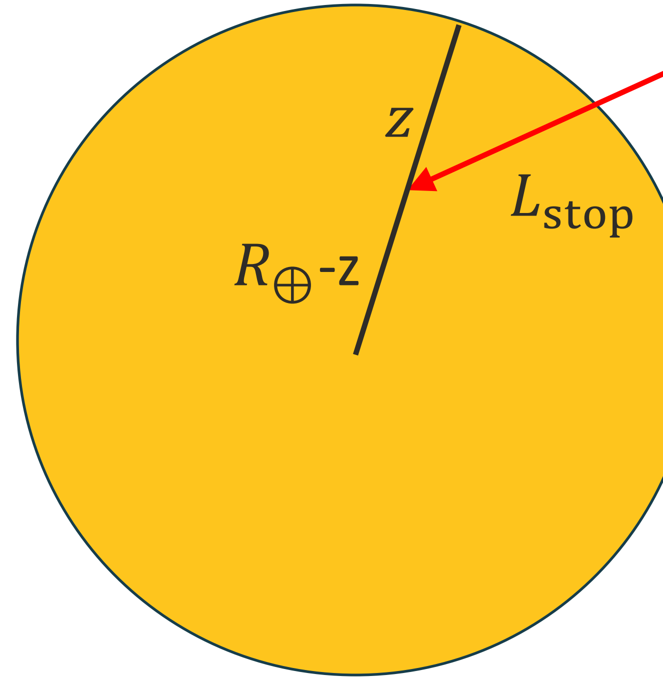

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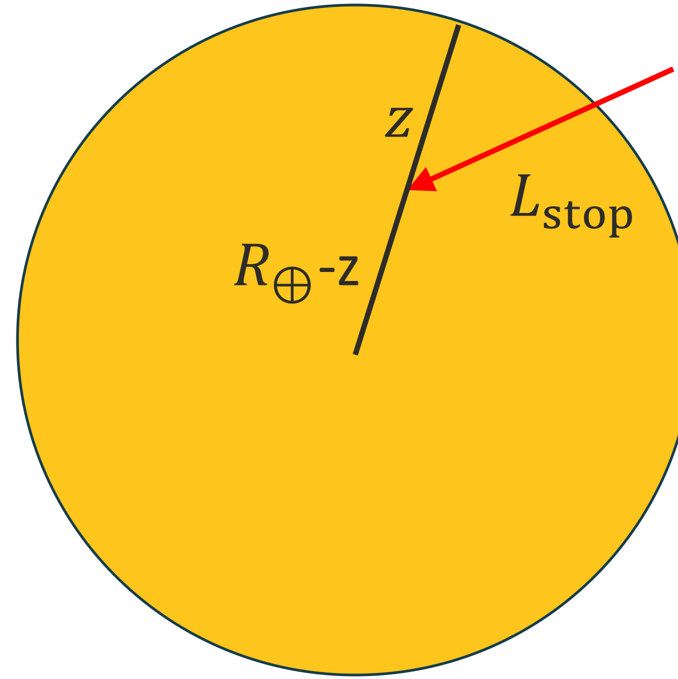
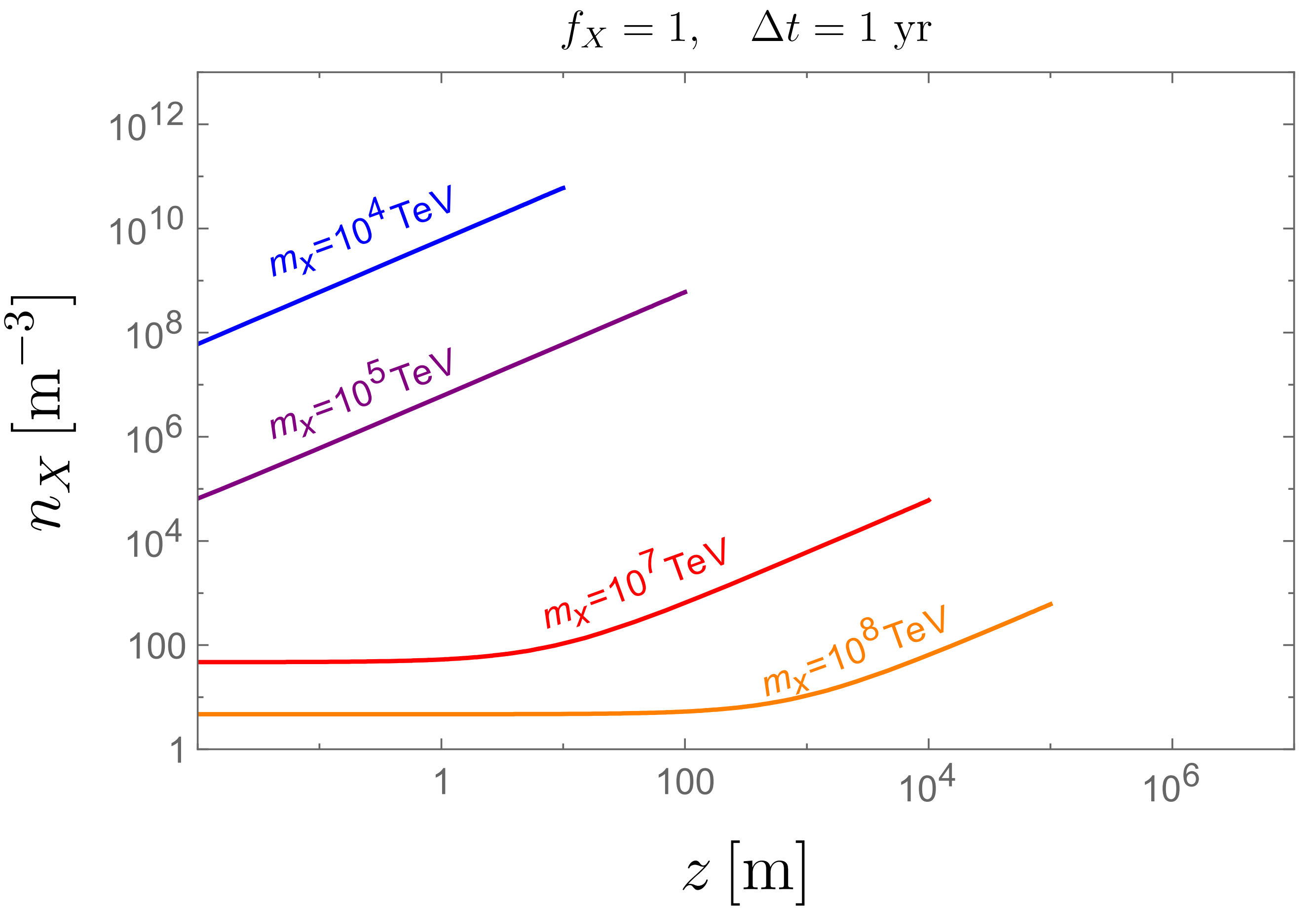


"plateau regime": when $L_{\text{stop}} \gtrsim \sqrt{2R_\oplus z}$, flat Earth does not apply, and L_{stop} drops out of the equation, $n_X \propto m_X^{-1}$.

Distribution in the Earth



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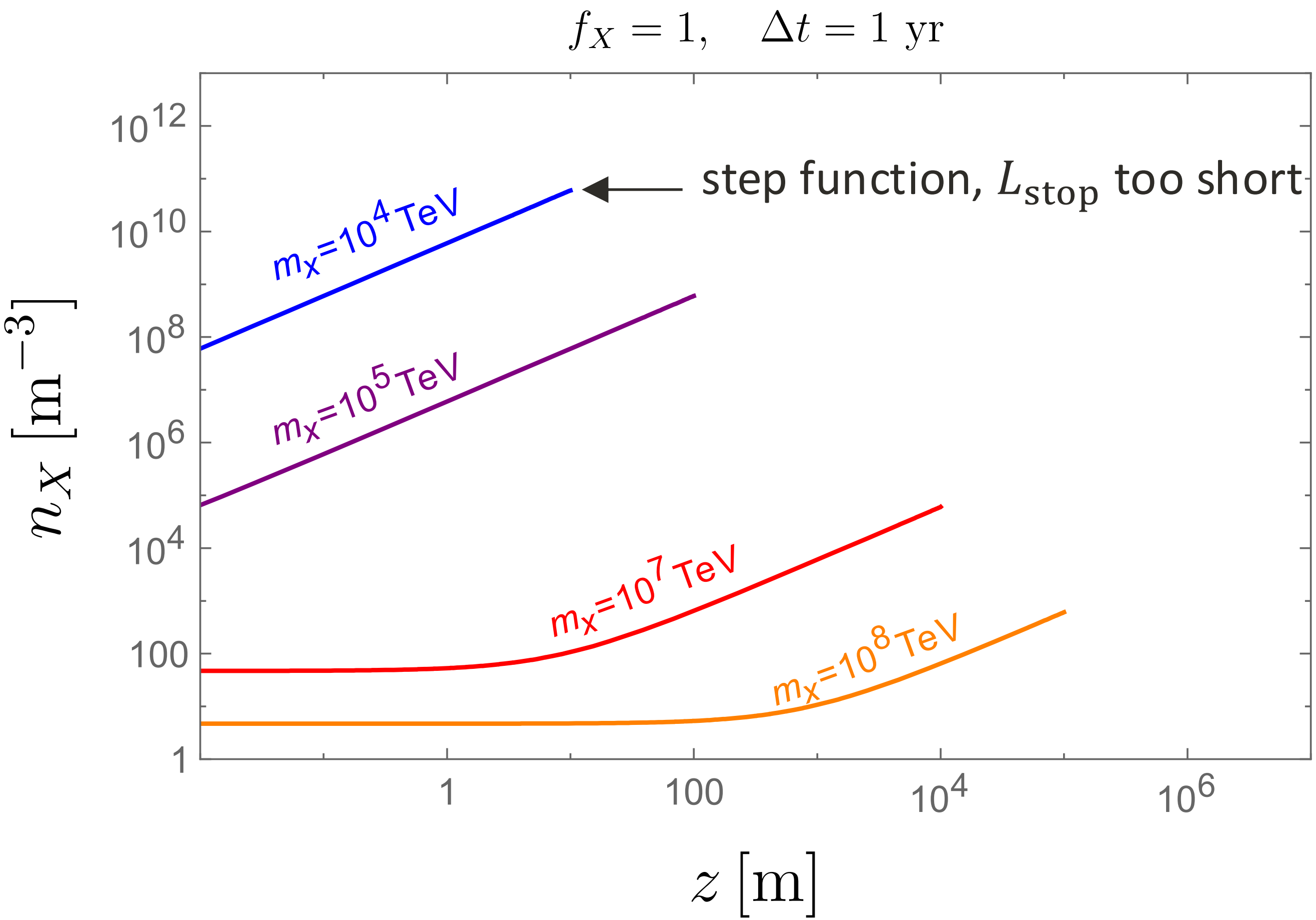

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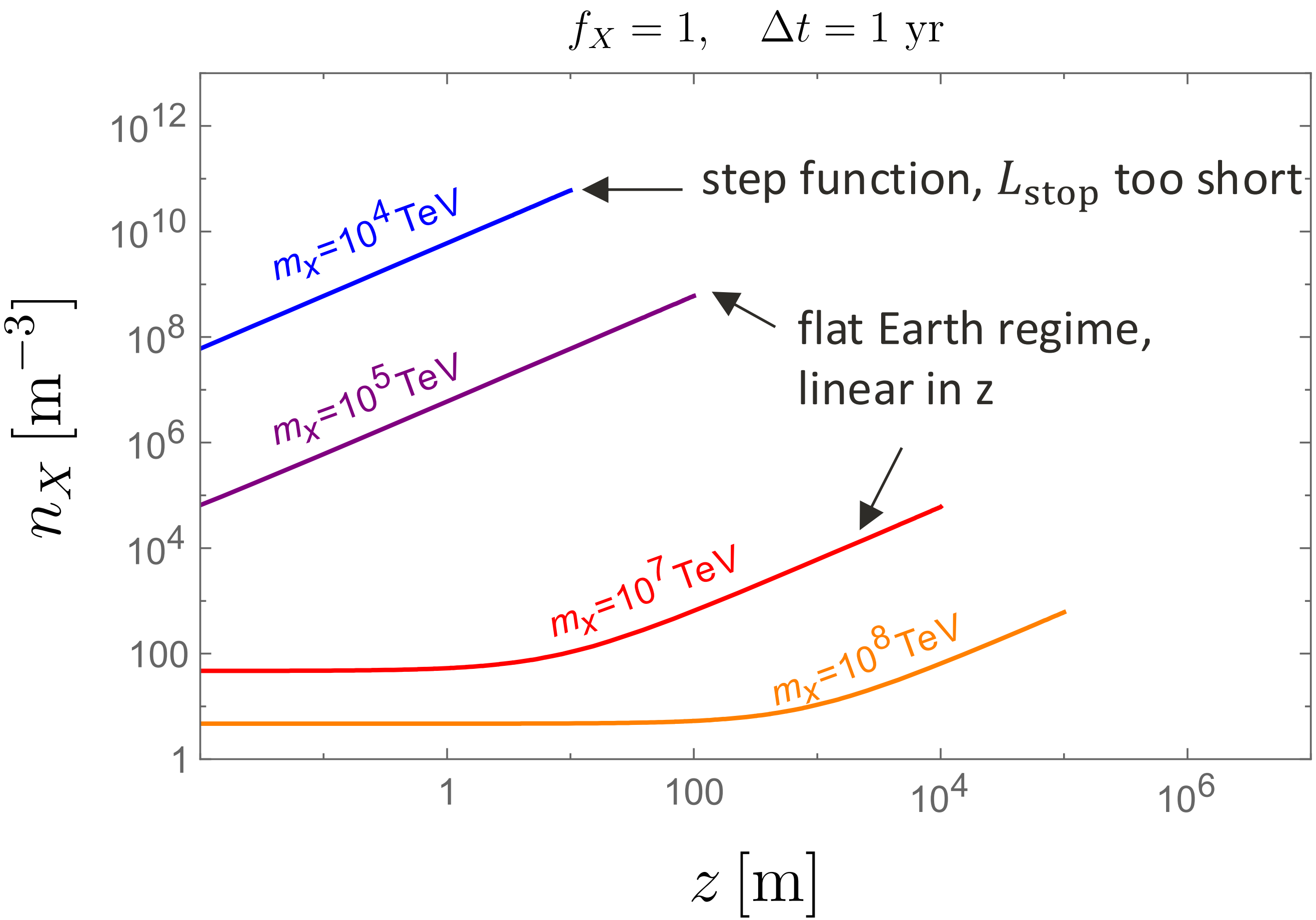

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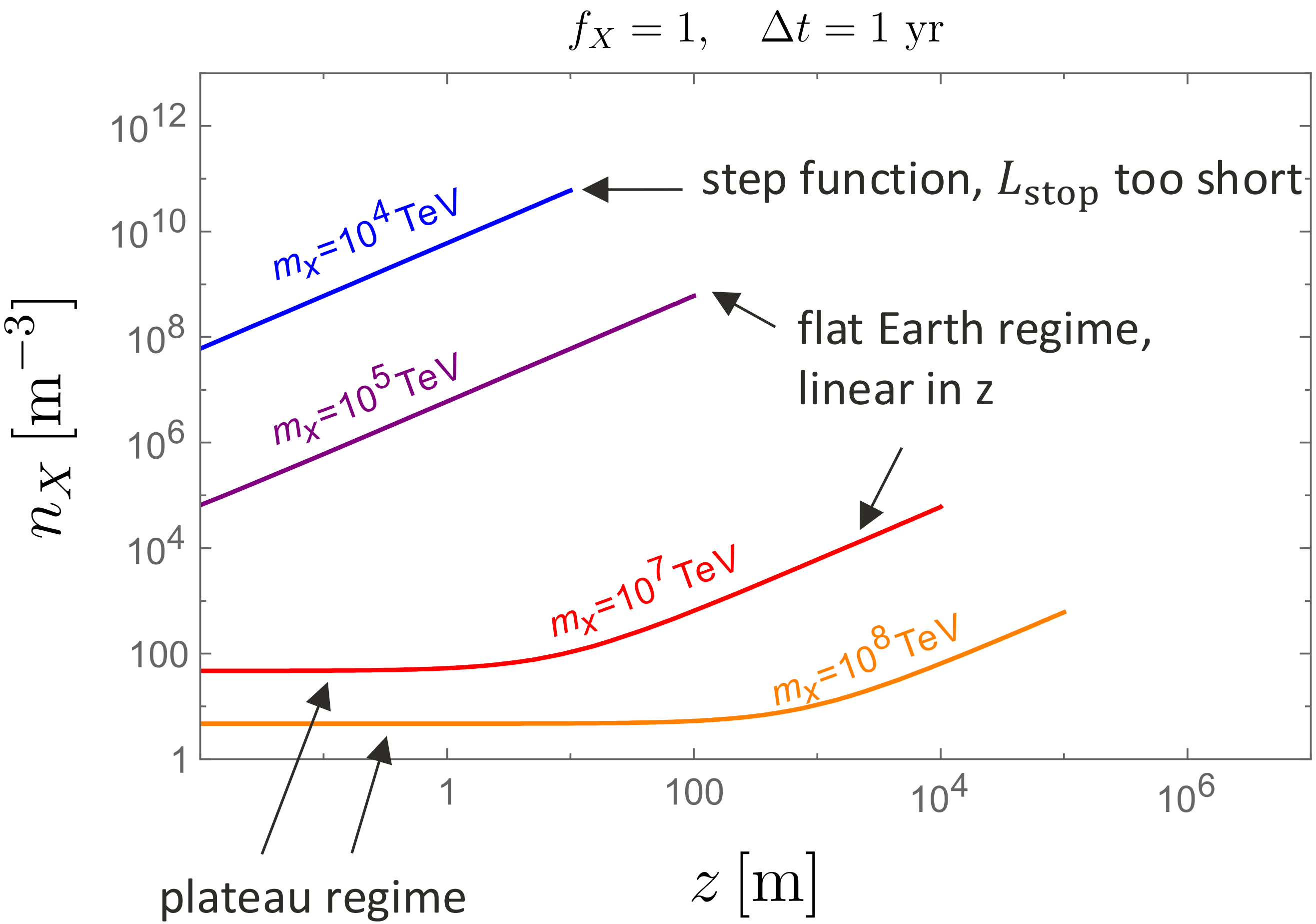

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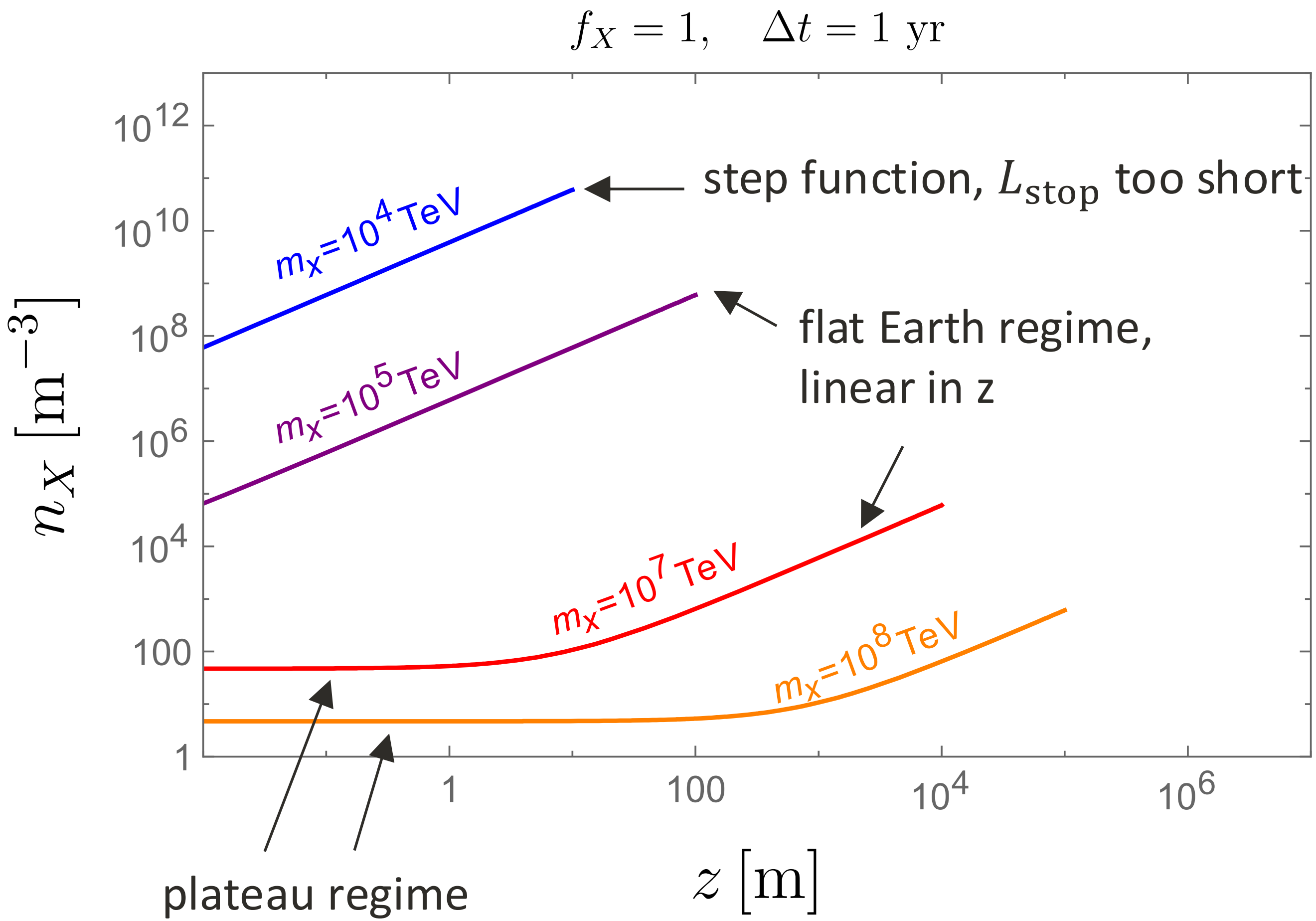

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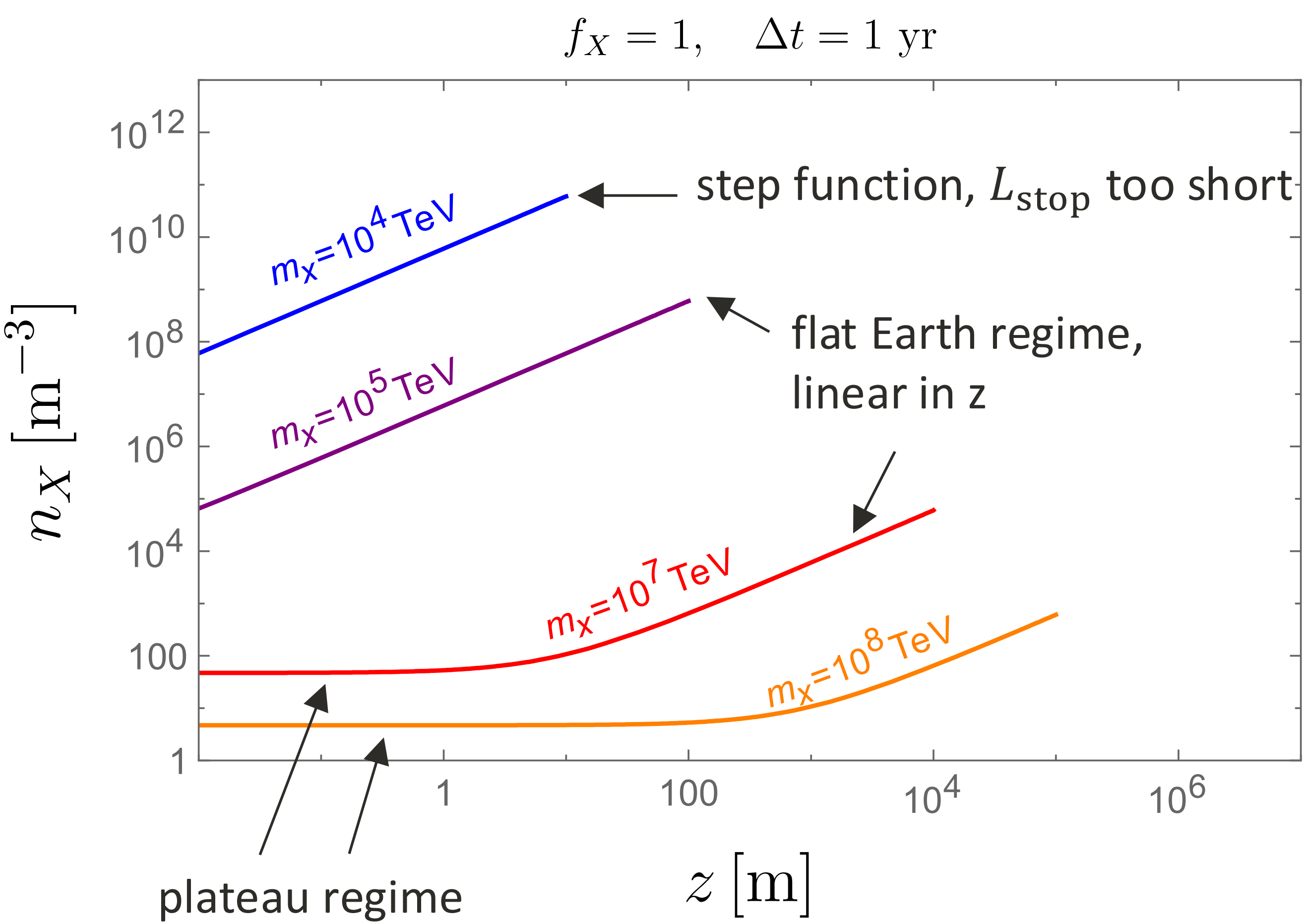

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Benchmark depths:

d = 10 m;

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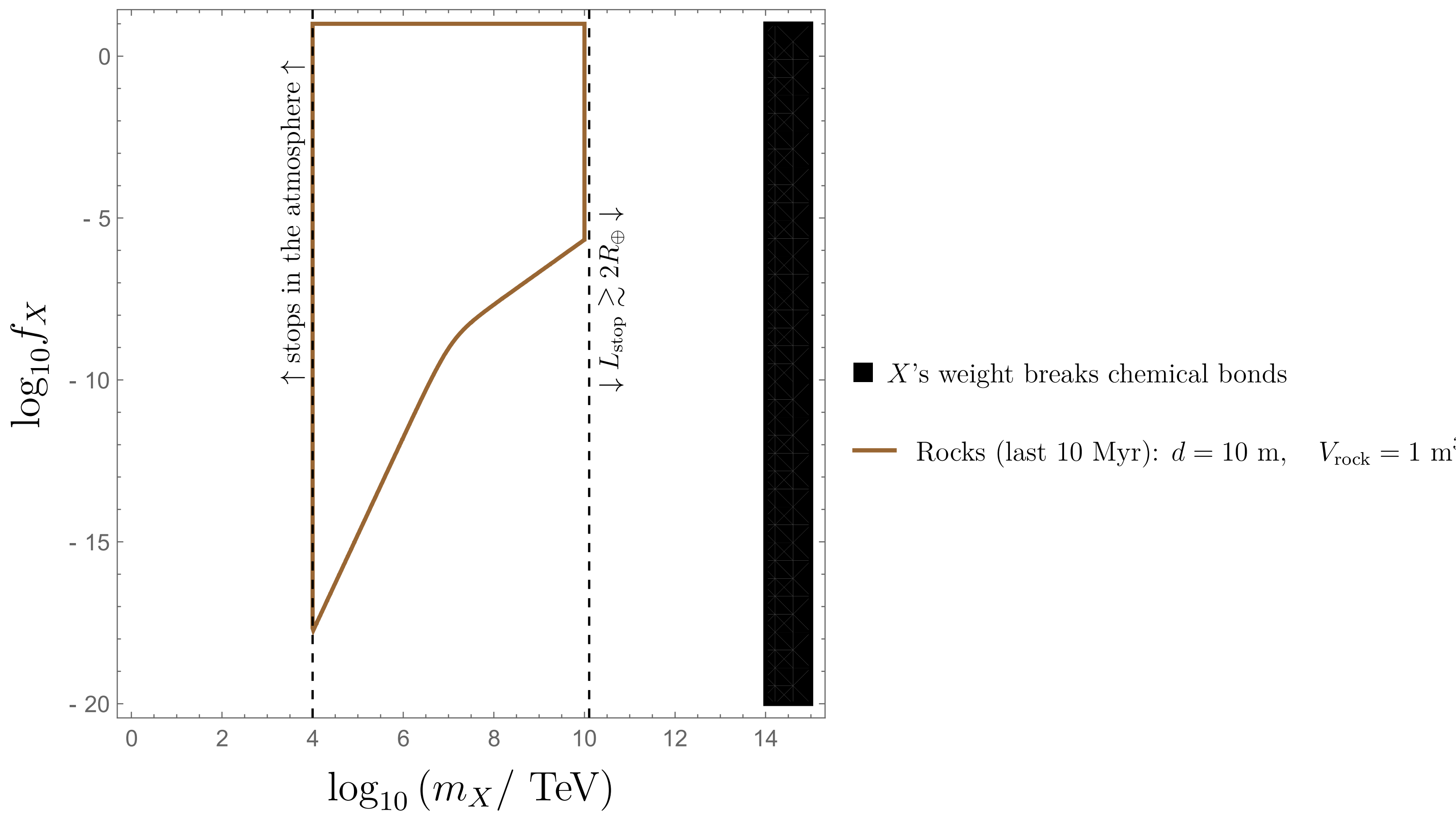
Benchmark rock volume: $V_{\mathrm{rock}} = 1\ \mathrm{m}^3$.

Assume we can find a single heavy particle in 1 m^3, detection scheme explained later.

10 Myr Rock, 10 m Depth



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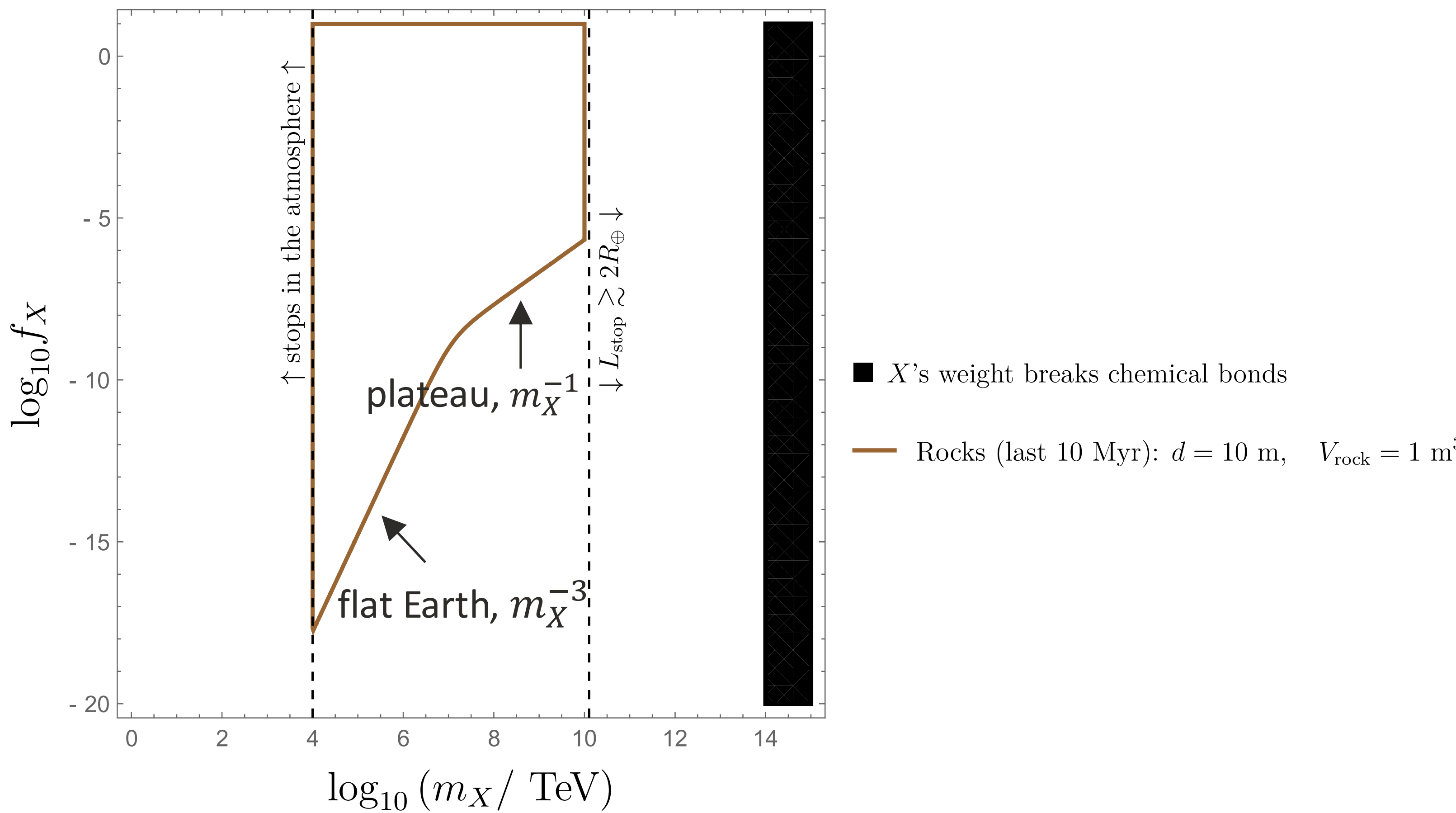

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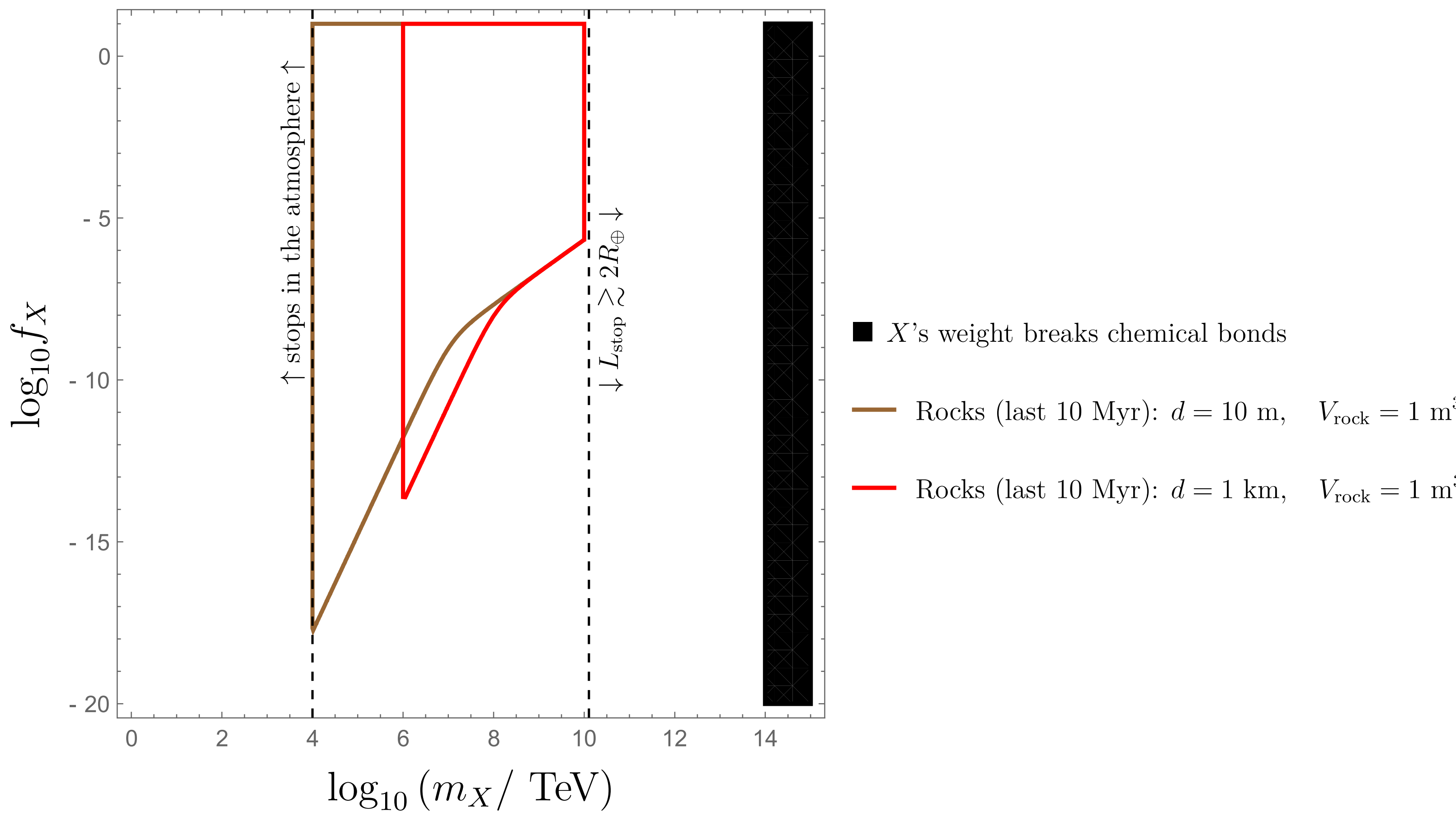

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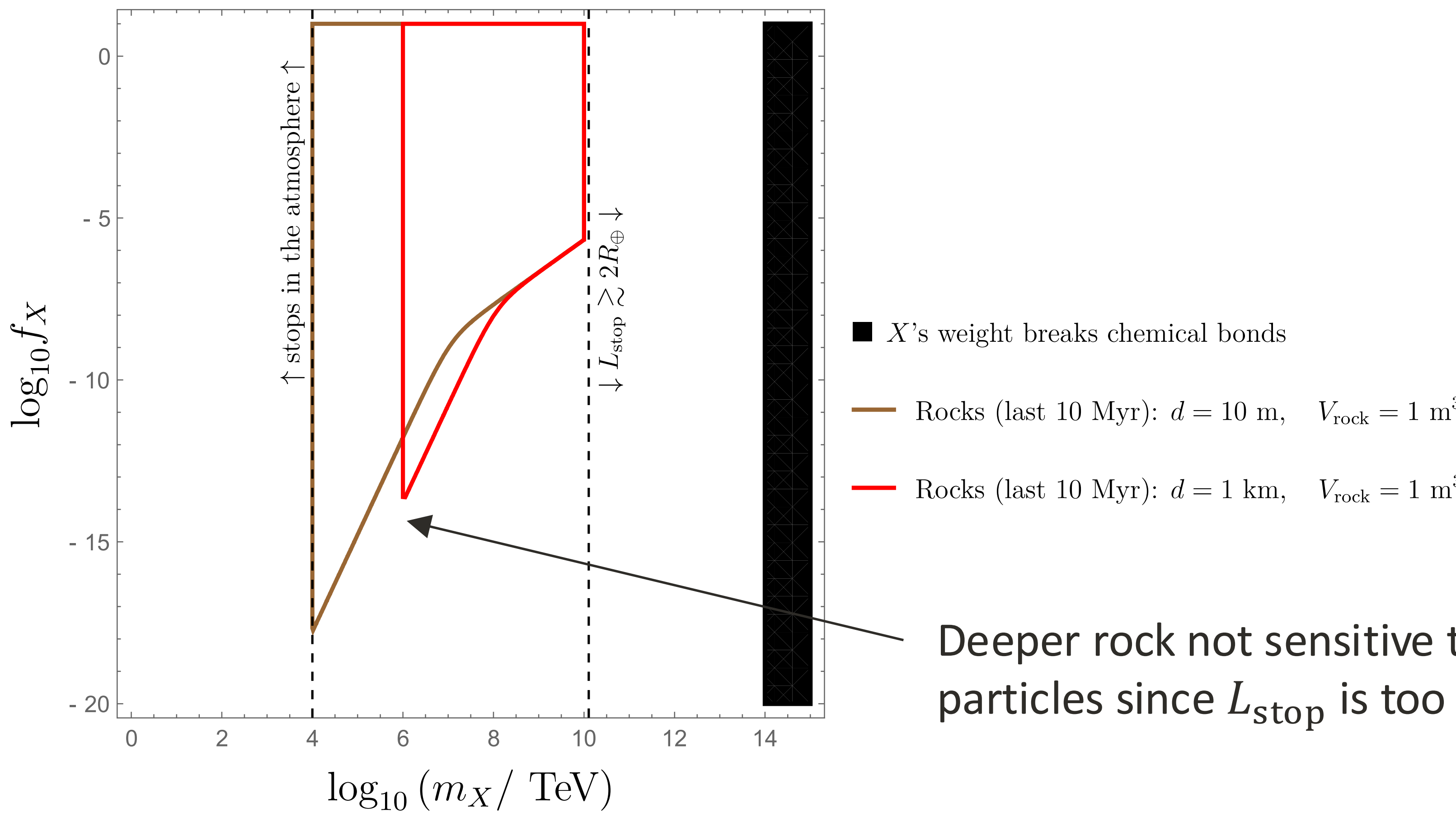

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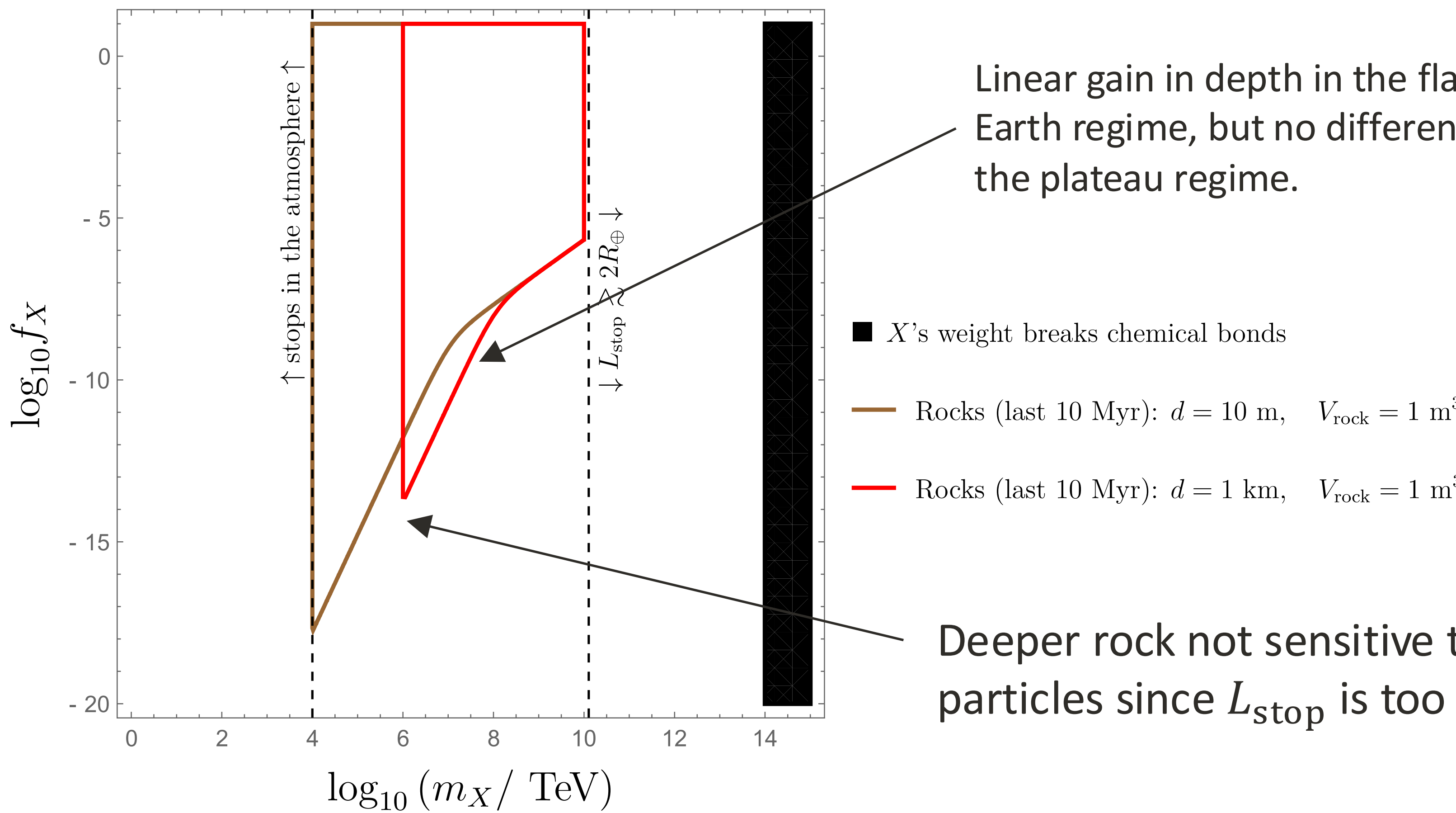

Linear gain in depth in the flat Earth regime, but no difference in the plateau regime.

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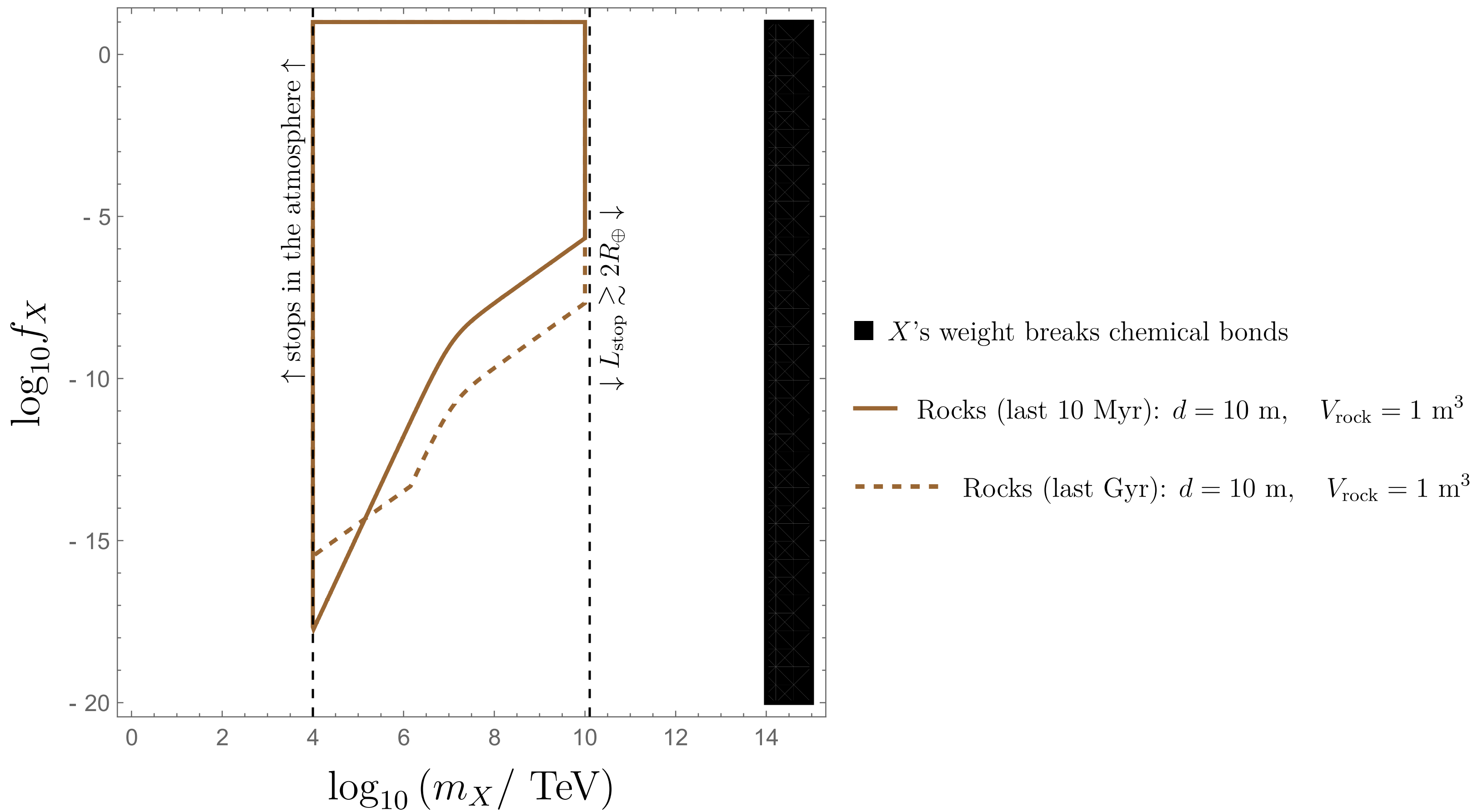
Maximally conservative approach: compare 2 scenarios,

(1) the sample stayed at the spot we found it for 1 Gyr;

(2) the sample spent equal amount of time at all depth < 100 km.

We conservatively take the smaller N_X between the two.

1 Gyr Rock, 10 m Depth



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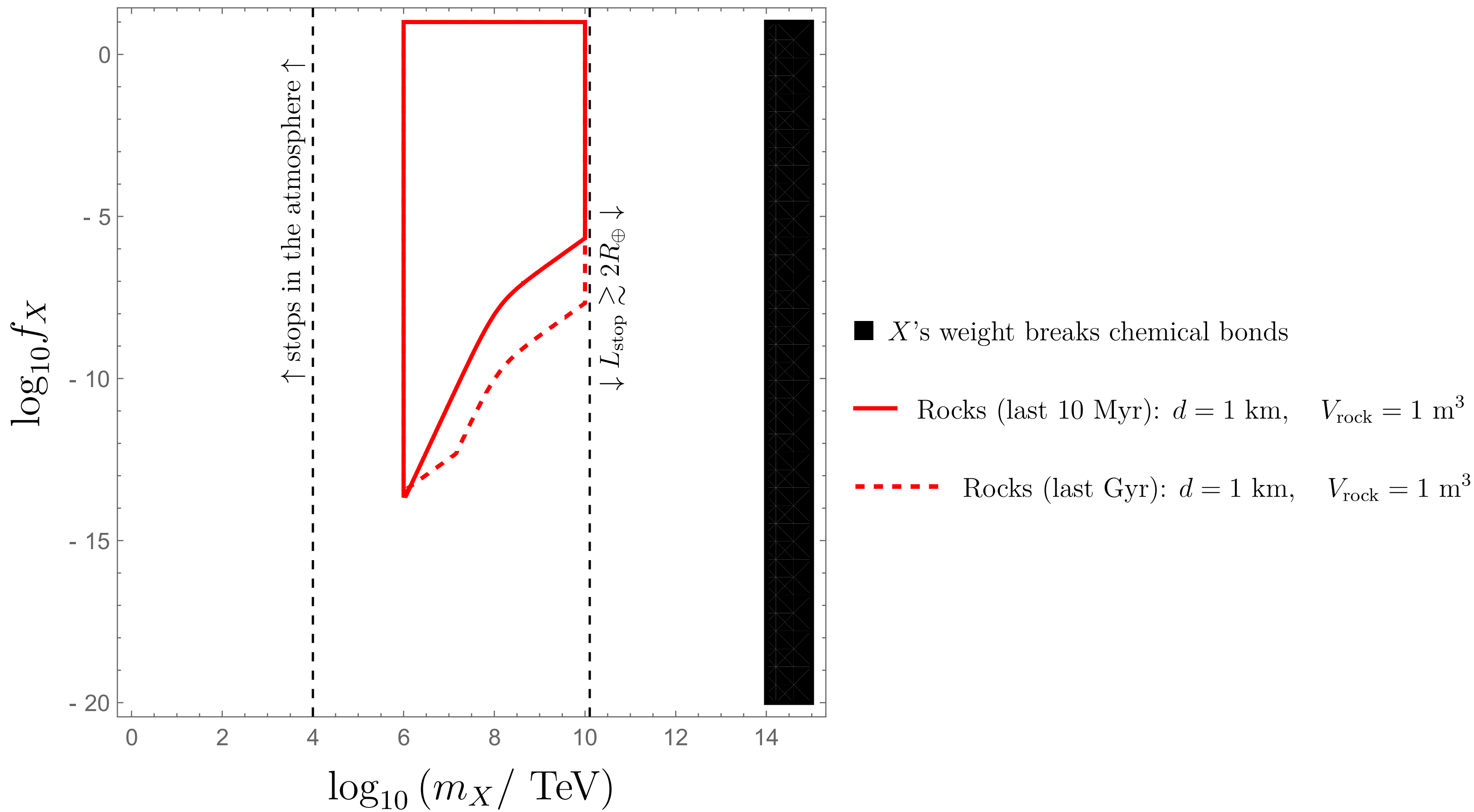


Detection Scheme

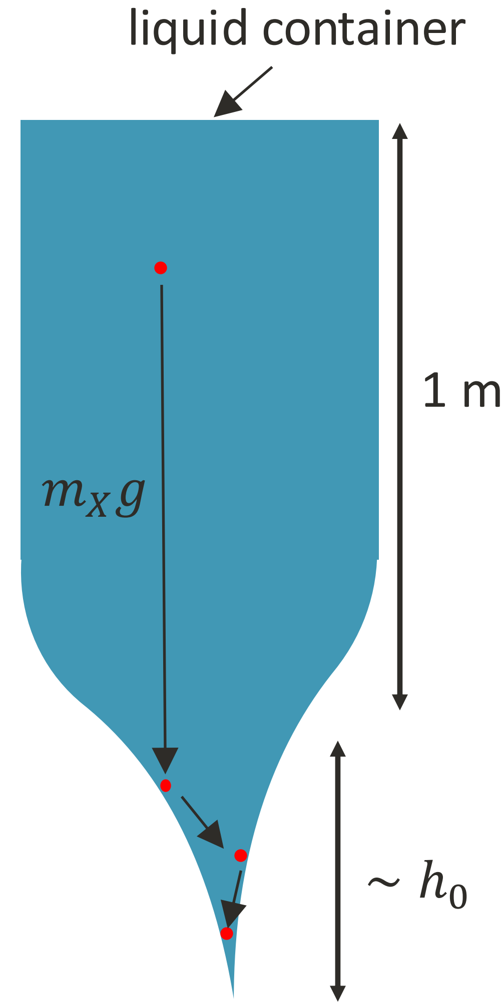
Detection Overview

We envision a 3-step search to reach single particle sensitivity:

1. Convert sample to liquid (melting, chemical processing).
2. Enrich the liquid.
3. Mass spectrometry.

Gravitational Enrichment

Since heavy particles sink, collect the liquid at the bottom of a funnel-shape container.



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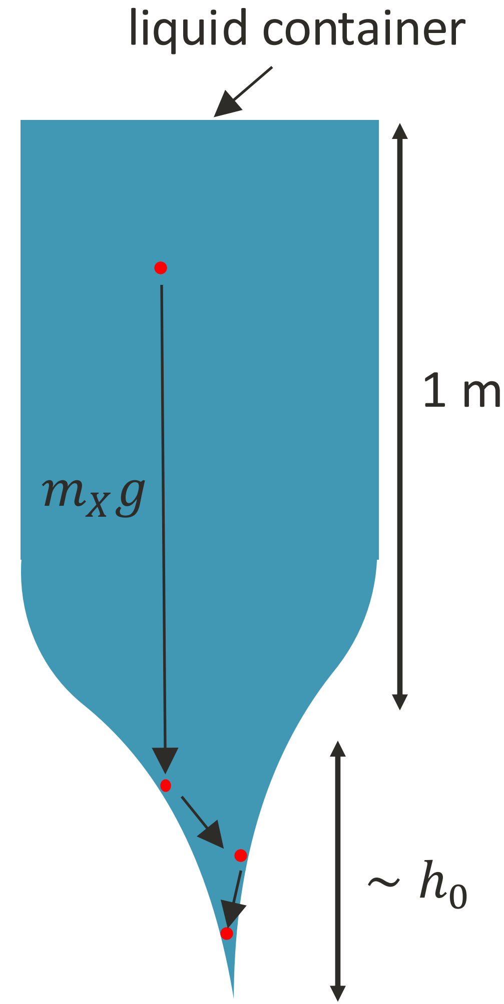

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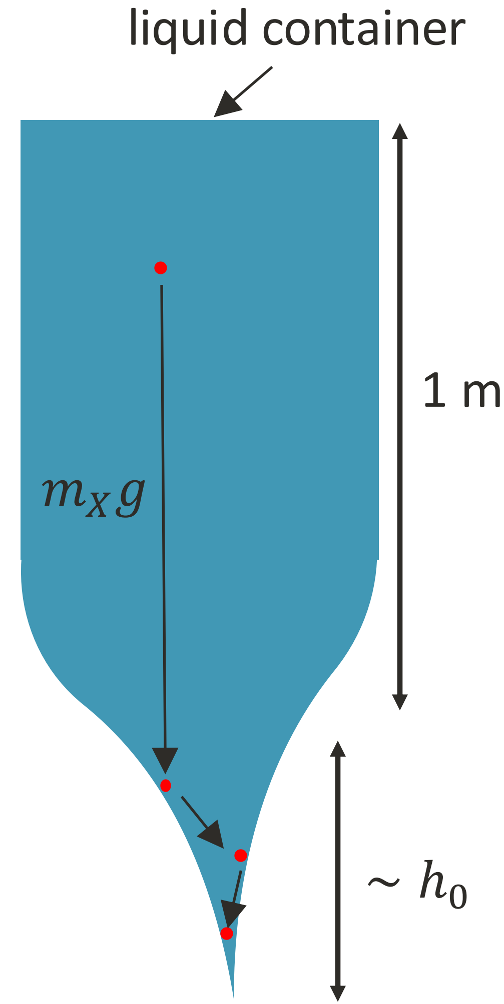
Using bias random walk (Drude model) with ballistic motion:

$$t_{\rm sink} = 10\ \mathrm{min}\left(\frac{10^4\ \mathrm{TeV}}{m_X}\right)^{3/2}\left(\frac{L_{\rm sink}}{1\ \mathrm{m}}\right)$$



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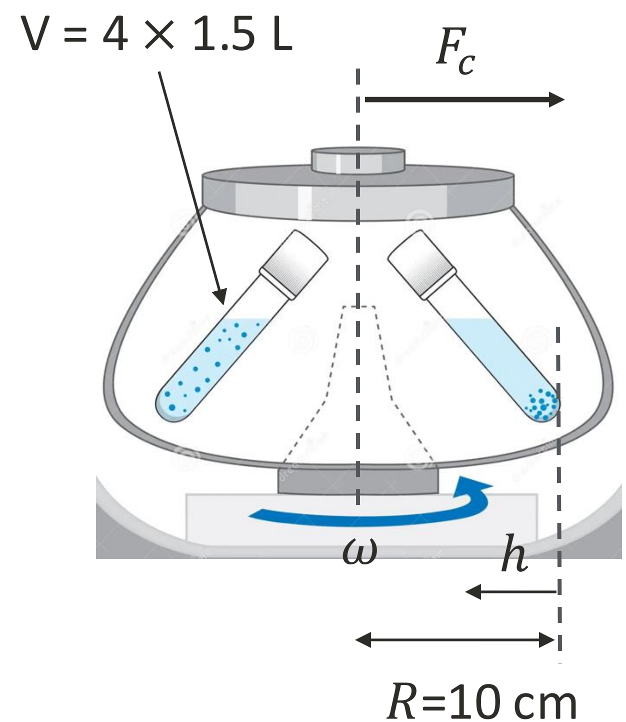

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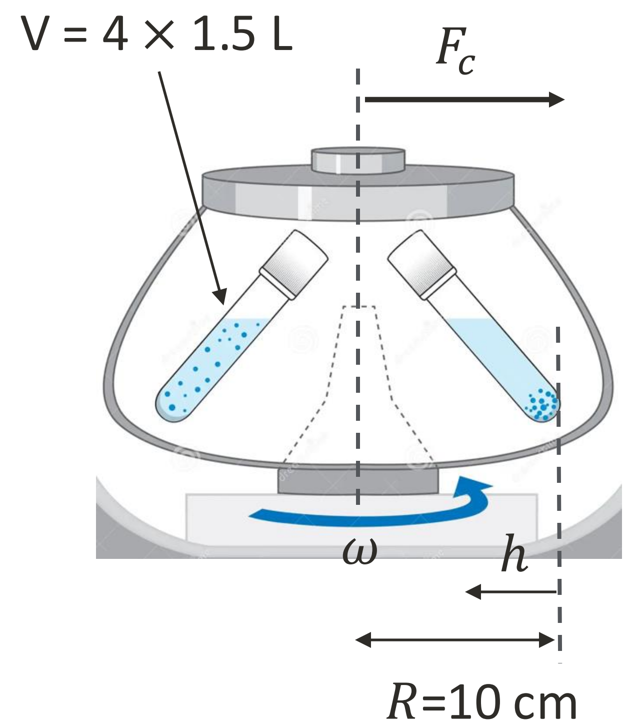

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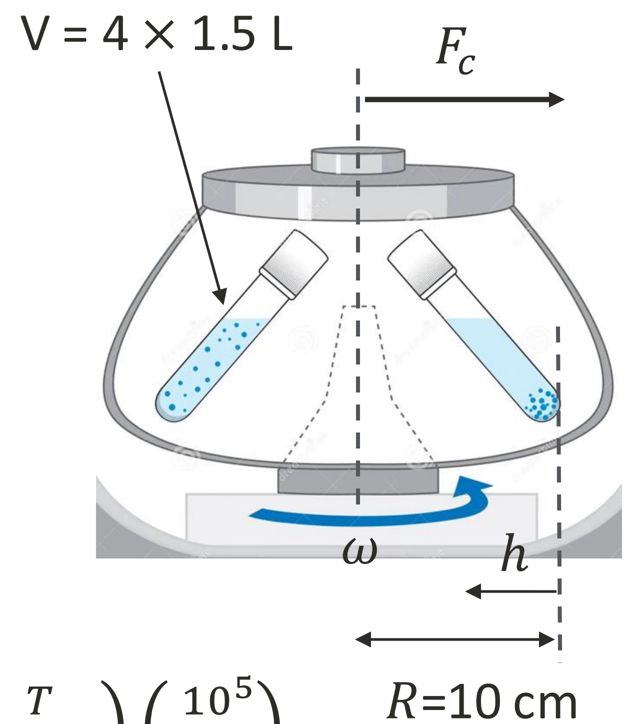

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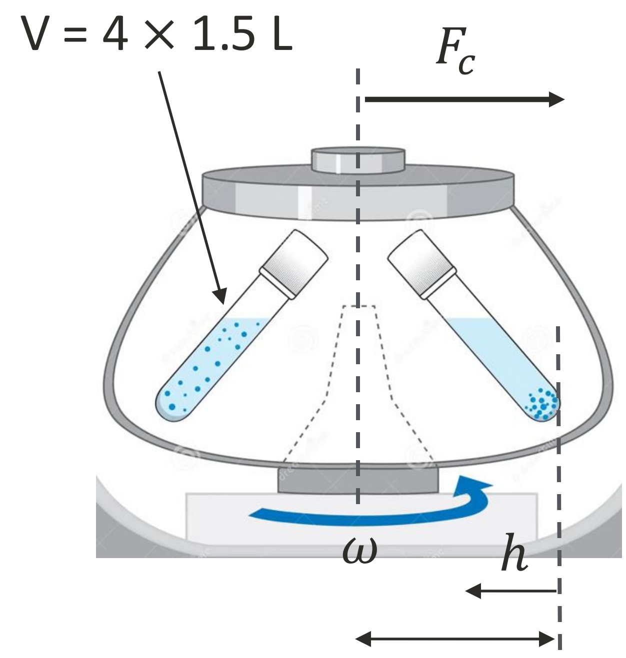

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Limited by smallest cut on smallest test tube (100 μL): 1 mm → 1 μL.

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Performed on natural water in 1980s [Smith et. al., Nucl. Phys. B 206, 333 (1982)]:

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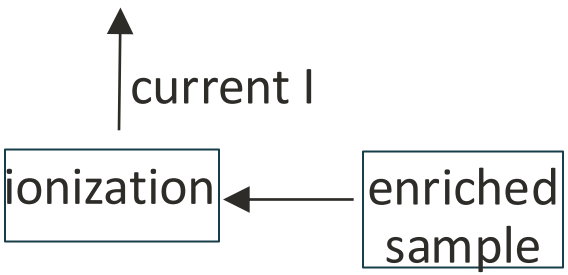

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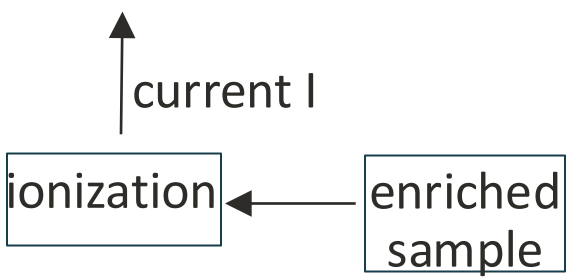

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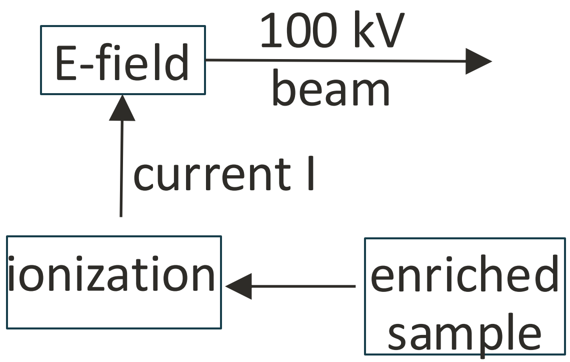

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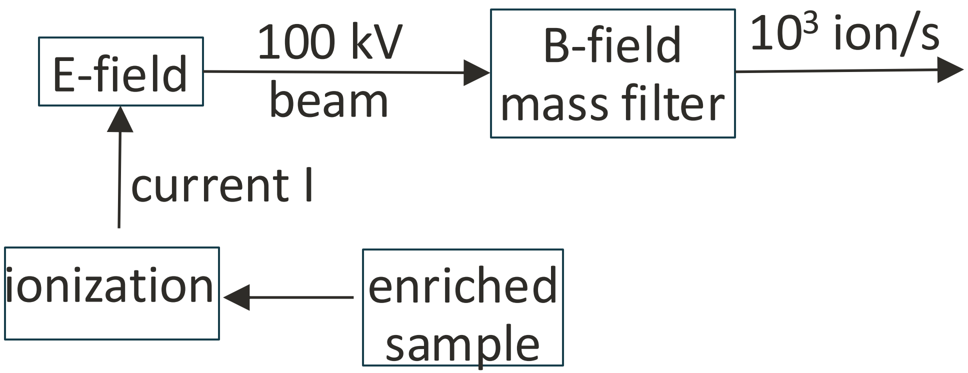

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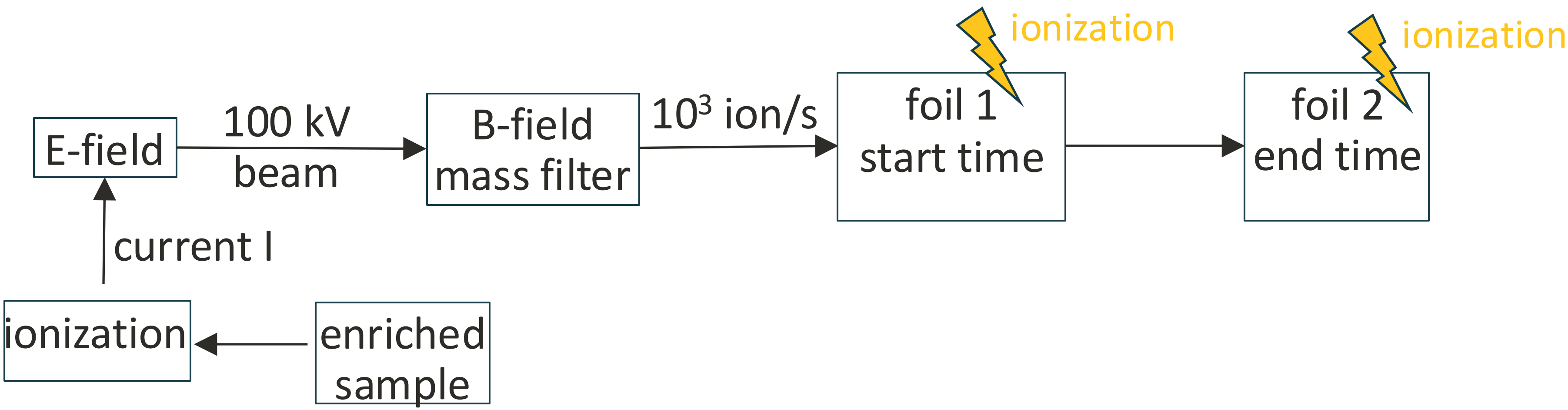

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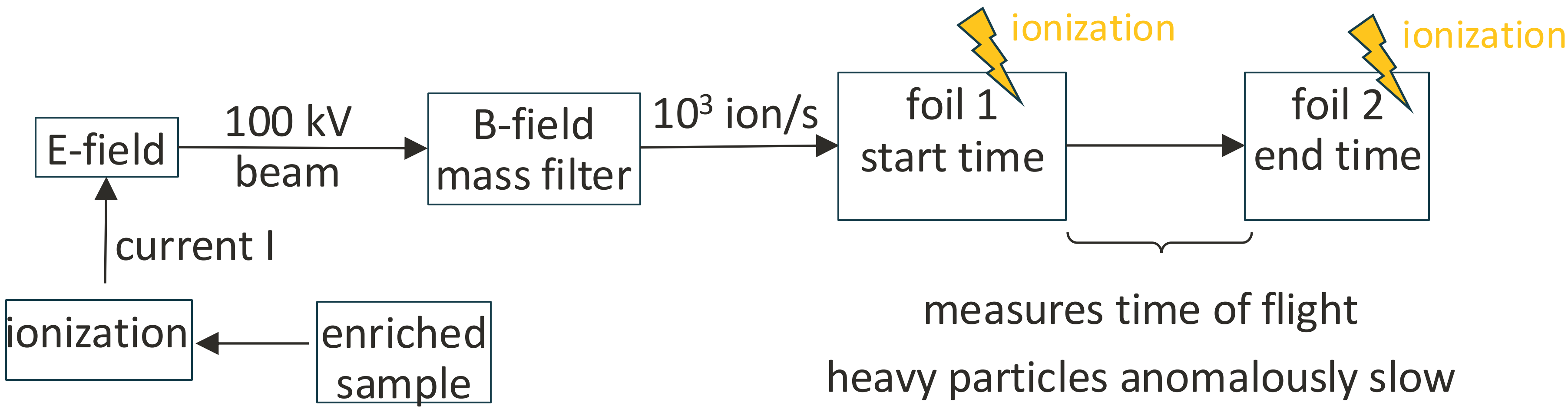
Time-of-Flight Mass Spectrometry

Performed on natural water in 1980s [Smith et. al., Nucl. Phys. B 206, 333 (1982)]:



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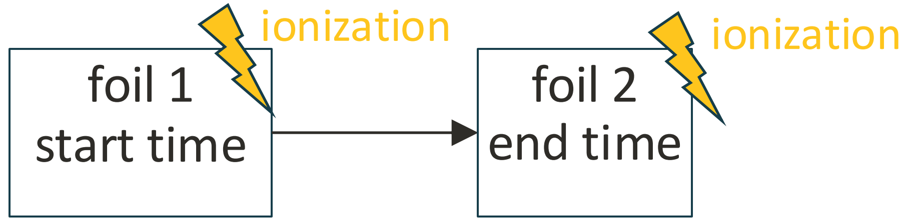
Modified Time-of-Flight Detection



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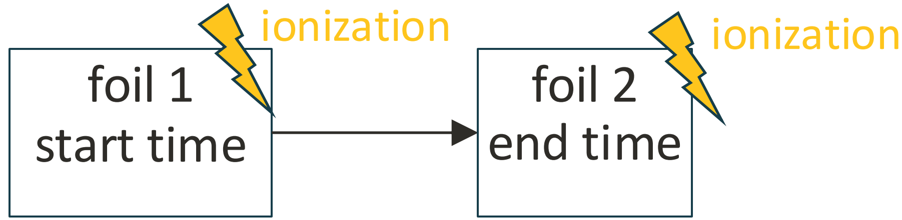

Thin-foil ToF detection not directly applicable to $m_X > 10^4$ TeV because their slow velocity, $v \sim 10^{-6} \left(\frac{10^5\ \mathrm{TeV}}{m_X}\right)^{1/2}$, means they cannot ionize.

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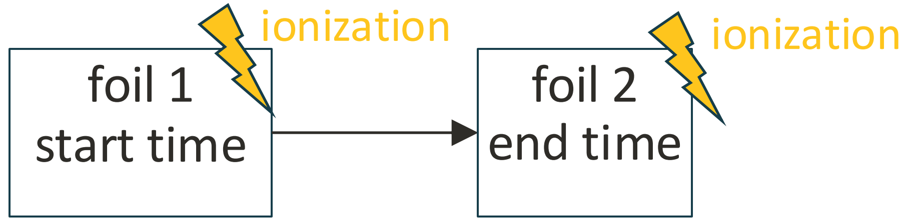

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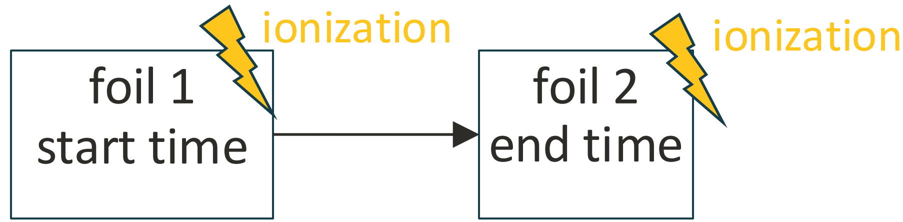

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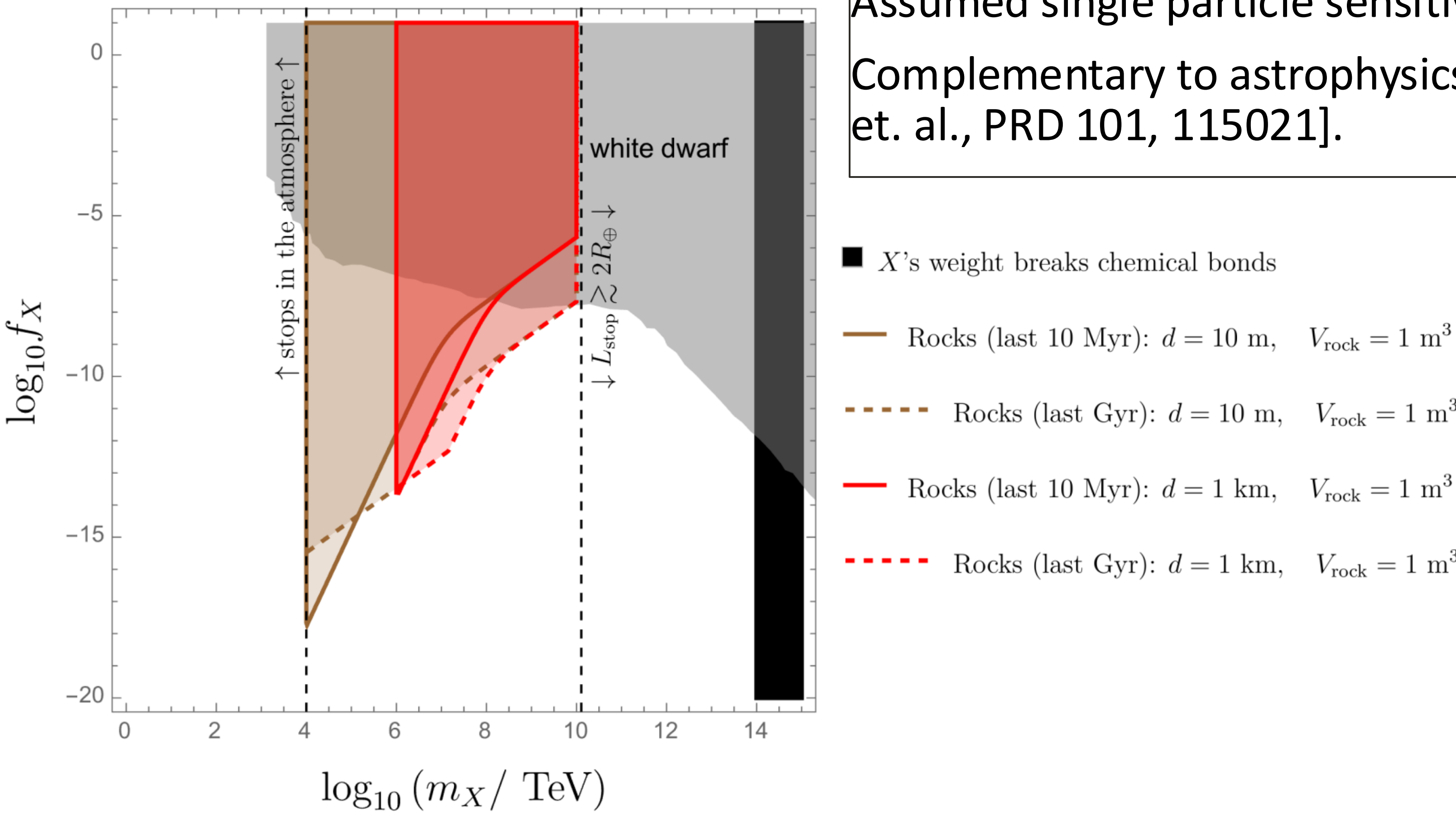
One possibility:

[Gao et. al. 2502.16437] claims a series of SQUID detectors can detect single charged particle with v between 3×10^{-11} and 3×10^{-6}.

Summary and Outlook

Parameter Space



Liquify old rocks, enrichment, mass spec.

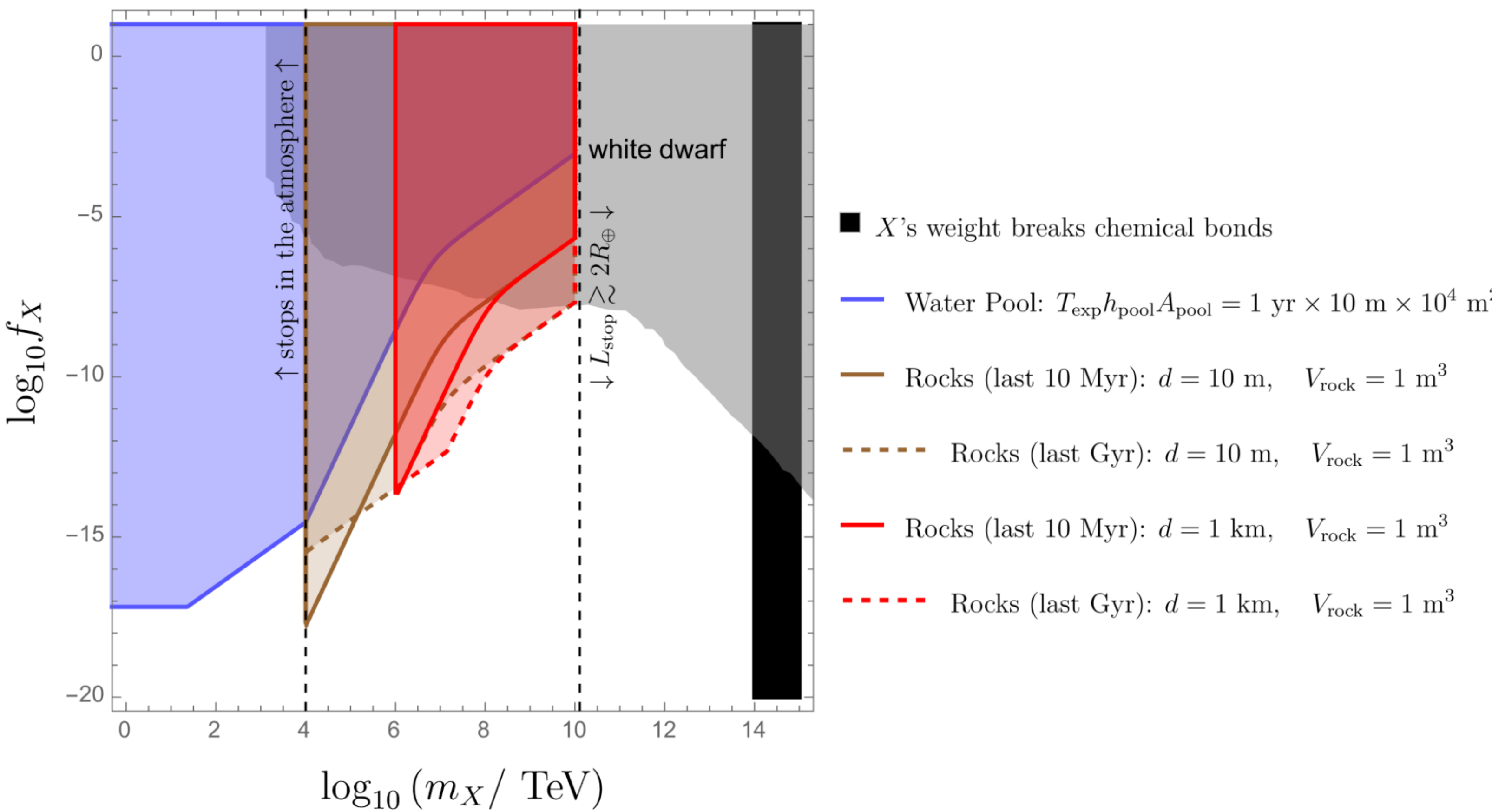
Assumed single particle sensitivity.

Complementary to astrophysics [Fedderke et. al., PRD 101, 115021].

Complementary Search: Water Pool

- Monitor a large water pool for a year, which collects the X particles thermalized in the air, targeting lighter parameter space.
- 50 simultaneous centrifuges over a year can process $10^5\,\mathrm{m}^3$ of water.

Parameter Space



Thank You