Dark matter, detection, an overview of overburdens

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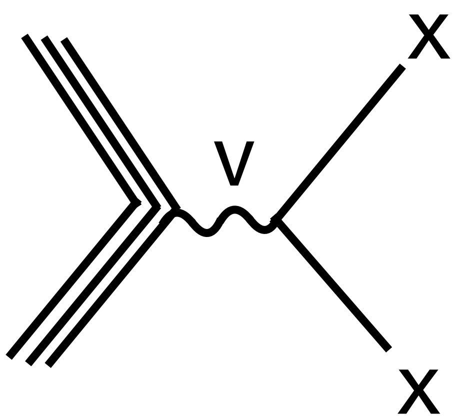
SAPIENTIA ET DOCTRINA STABILITAS

Summary:

On Friday Gopi introduced dark matter.



**(Maybe like this?
Could be totally different.)**

What we know:

-Matter like (not radiation- or energy-like)

-Produced in the early universe before matter-radiation equality at T~eV

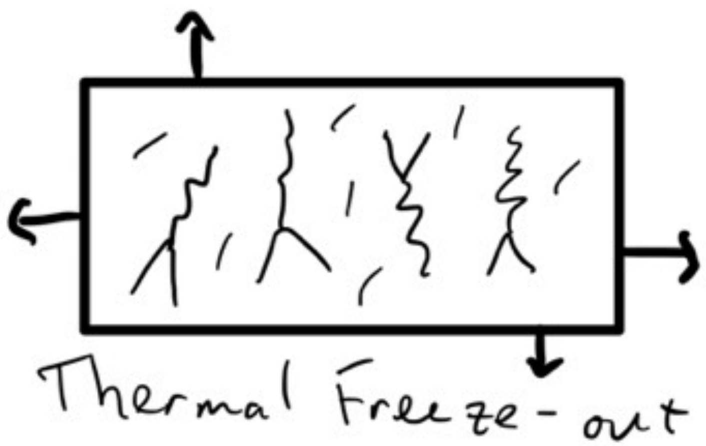
What we know for Milky Way:

Local density ~ 0.3 GeV per cubic cm (GeV ~ proton mass)

Local velocity ~ 10^{-3} c (300 km/s)

Dark matter production

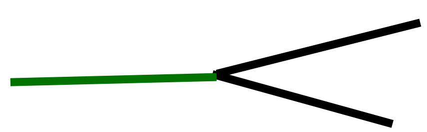
In equilibrium



(talk about soon)

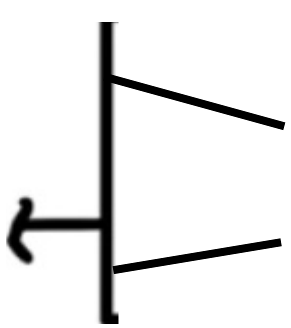
Out of equilibrium 1:

- A particle decays and makes dark matter



Out of equilibrium 2:

- The expanding horizon of the early universe radiates (perhaps heavy) dark matter



Out of equilibrium 3:

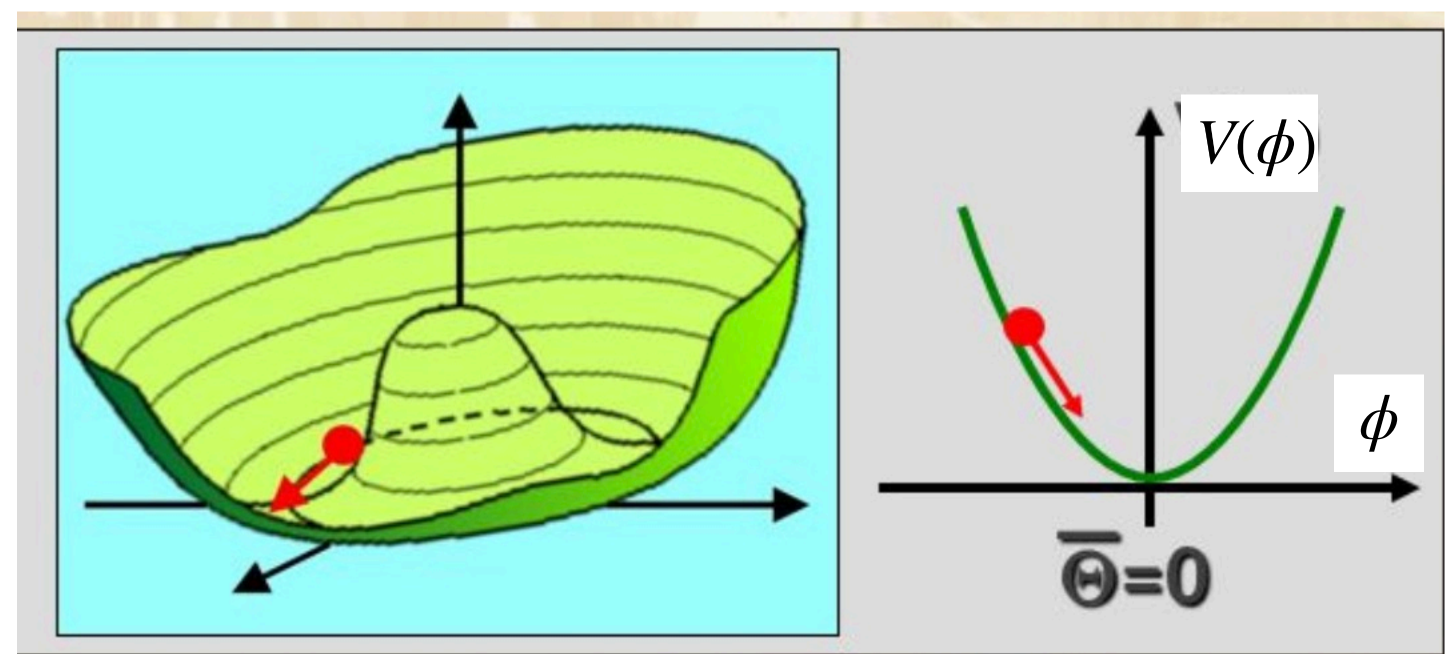
-Misalignment mechanism

$$H = \frac{\dot{a}}{a}$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2 \sin\phi = 0$$

Note! "phi" here is a scalar field

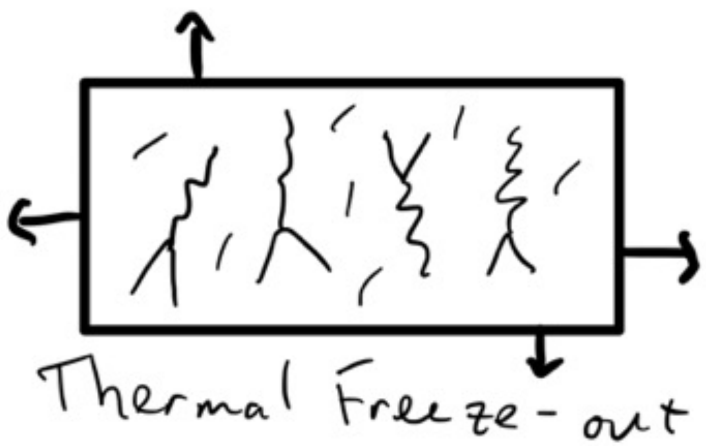
overdamped harmonic oscillator



from Raffelt

After H < m, a light bosonic field will begin oscillation in its potential, acting like matter.

Weakly interacting dark matter "miracle"



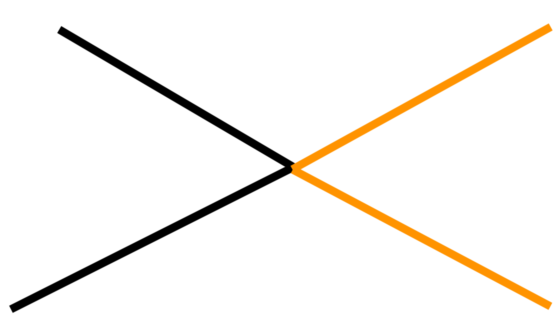
As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

The final relic abundance depends on the annihilation cross-section, but only logarithmically on m_x

$$\frac{m_x n_x}{n_\gamma} \sim \frac{x_f}{m_{pl} \langle \sigma_a v \rangle}$$

$$x_f \sim \log[m_x^3 \langle \sigma_a v \rangle / H(T = m_x)]$$

$$\langle \sigma_a v \rangle \sim 3 \times 10^{-26} \ \frac{\mathrm{cm}^3}{s} \sim 10^{-36} \ \mathrm{cm}^2$$

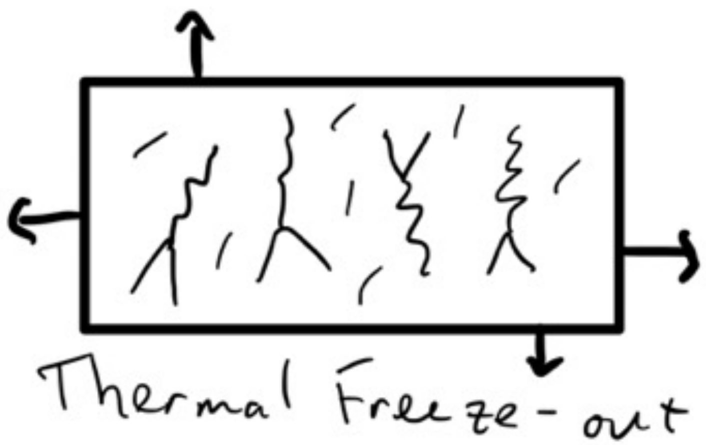


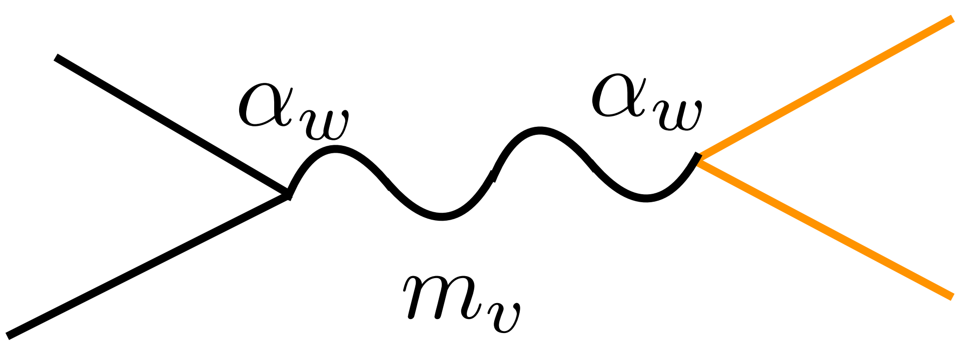
Taking the annihilation cross-section to be

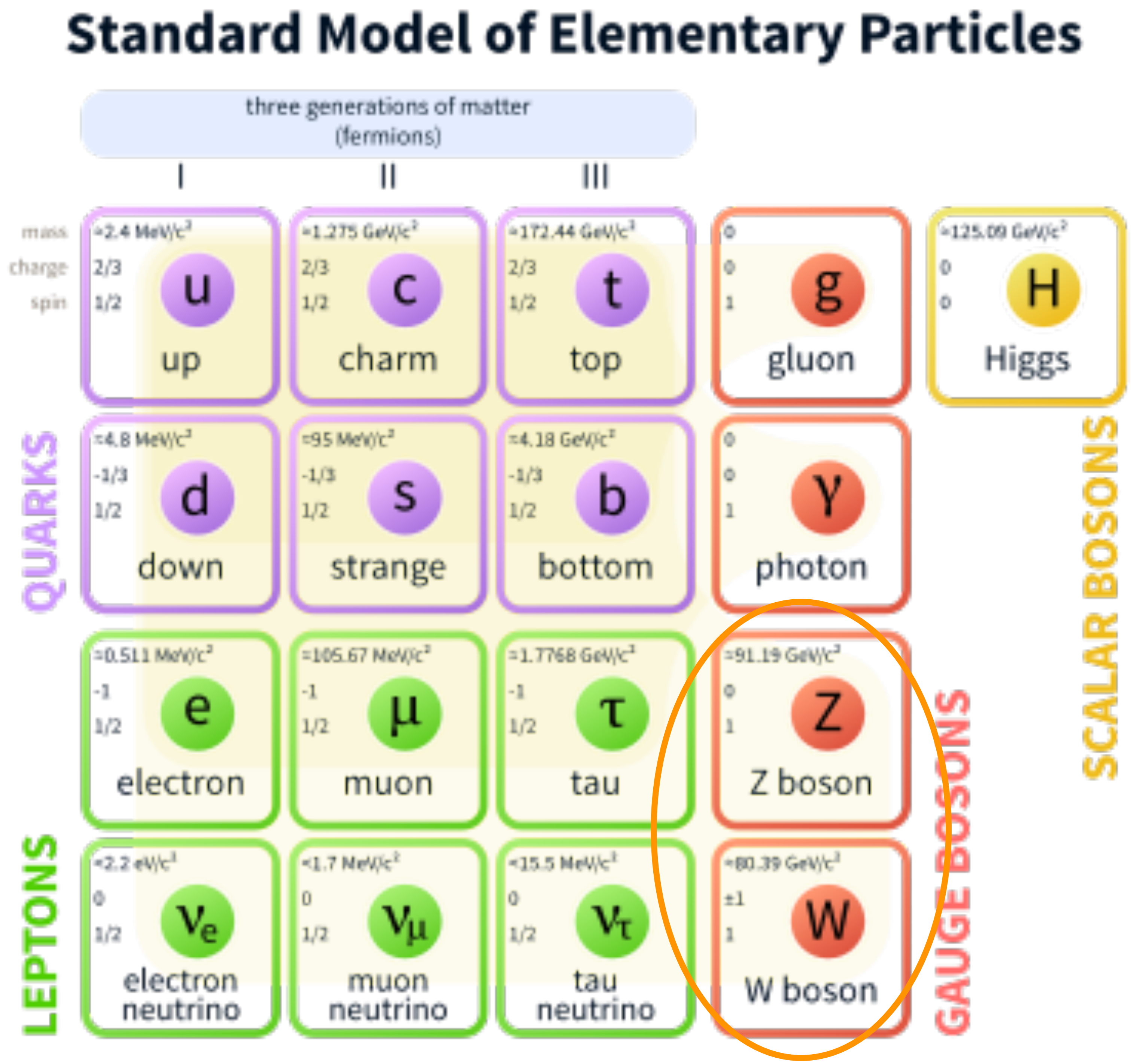
$$\sigma_a \sim \frac{\alpha^2}{m^2}$$

what is m for alpha=1 and alpha=0.03?

WIMP Miracle







$$\Omega_x h^2 \sim 0.1 \left(\frac{m_{\mathrm{v}}}{100\ \mathrm{GeV}}\right)^2 \left(\frac{0.03}{\alpha_w}\right)^2$$

The thermal relic annihilation cross-section roughly matches the couplings and mass of the weak force, "wimp miracle"

The 100 TeV Mass Unitarity "Limit" or Why do the plots stop at $m_x \sim 100$ TeV?

Griest, Kamionkowski, '87

1. Assume freeze-out abundance set with annihilation

$$\sigma_a \sim \text{picobarn} = 10^{-36}\ \text{cm}^2$$ {wimp miracle

2. Require the annihilation cross-section not exceed a perturbative bound

$$\sigma_a \lesssim 4\pi/m_x^2$$

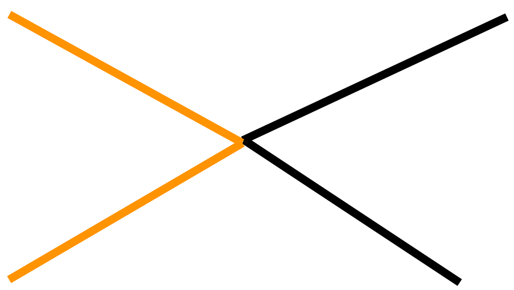
3. Then because this cross-section is a picobarn for thermal freeze-out, the suggestion for frozen out dark matter mass is

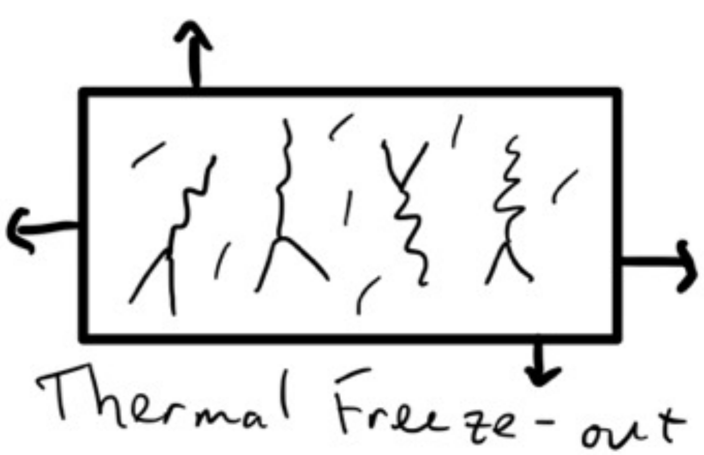
$$m_x \lesssim 10^5\ \text{GeV}$$

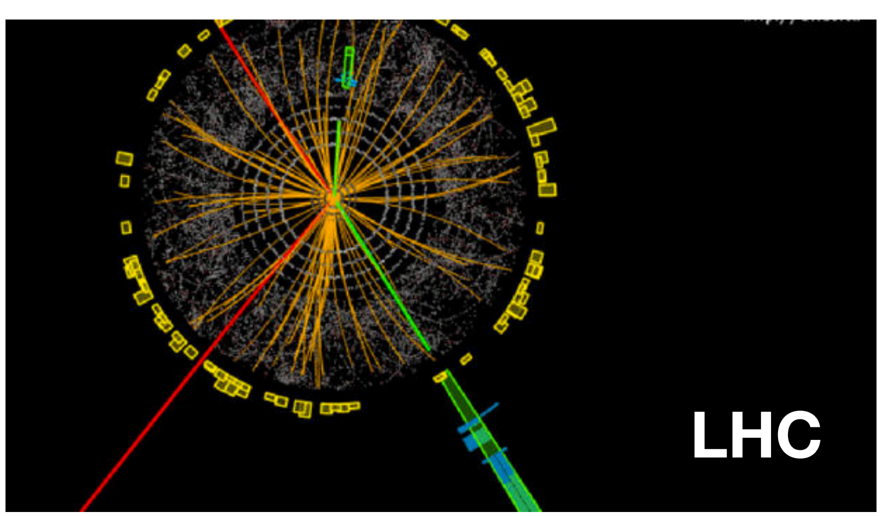
Cross-sections

arrow of time

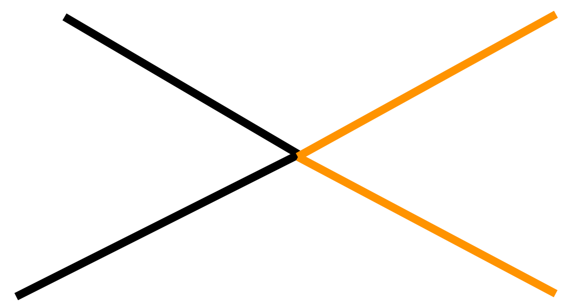
Make it (SM annihilation)

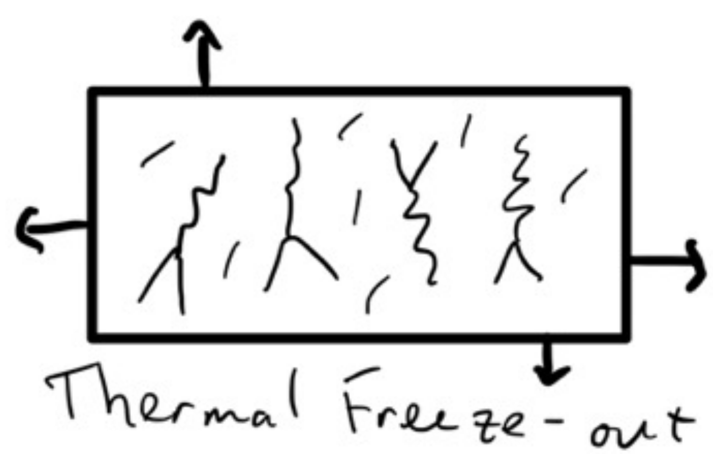


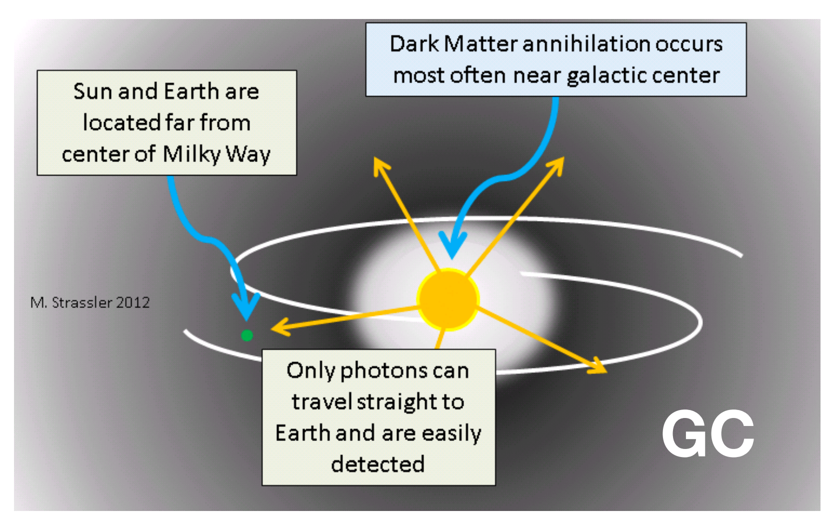




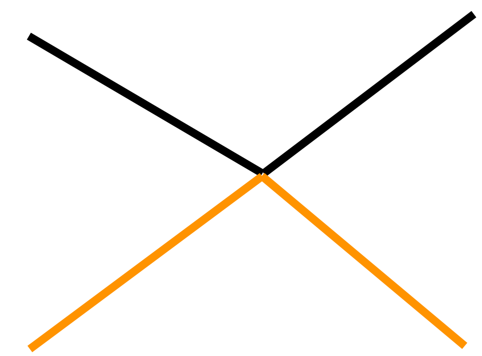
Break it (DM annihilation)

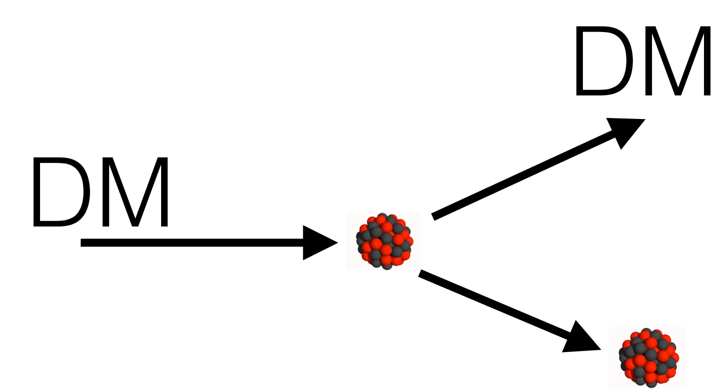






Shake it (DM-SM scattering)



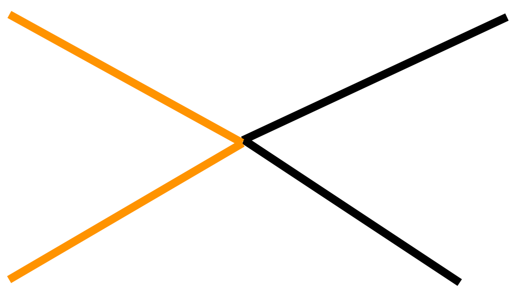


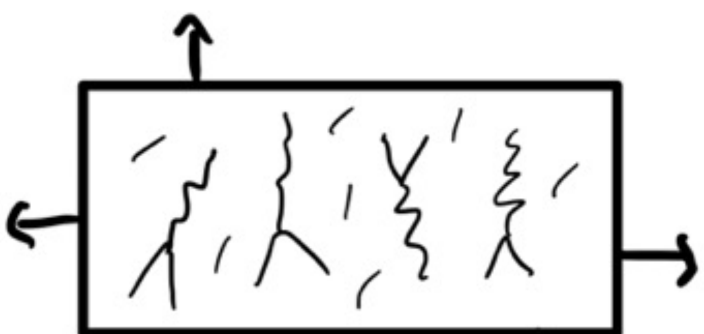
Cross-sections

arrow of time

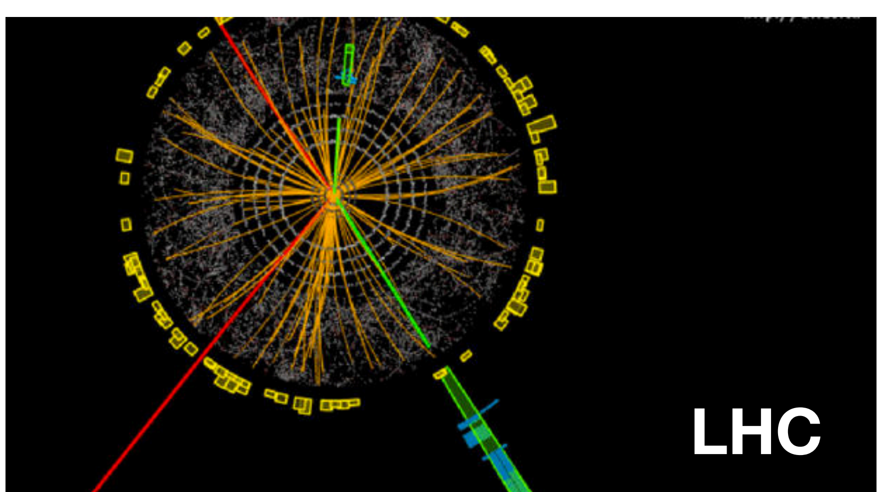
super effective

Make it (SM annihilation)

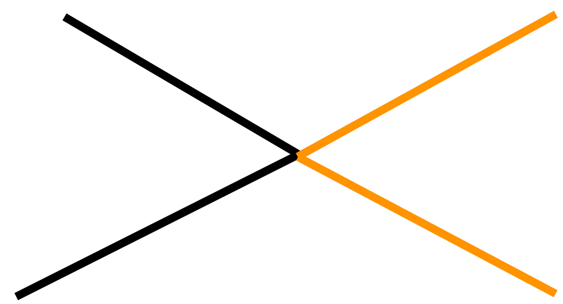


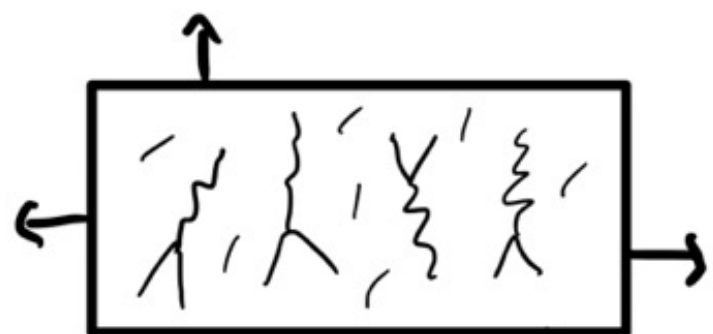


Thermal Freeze-out



Break it (DM annihilation)





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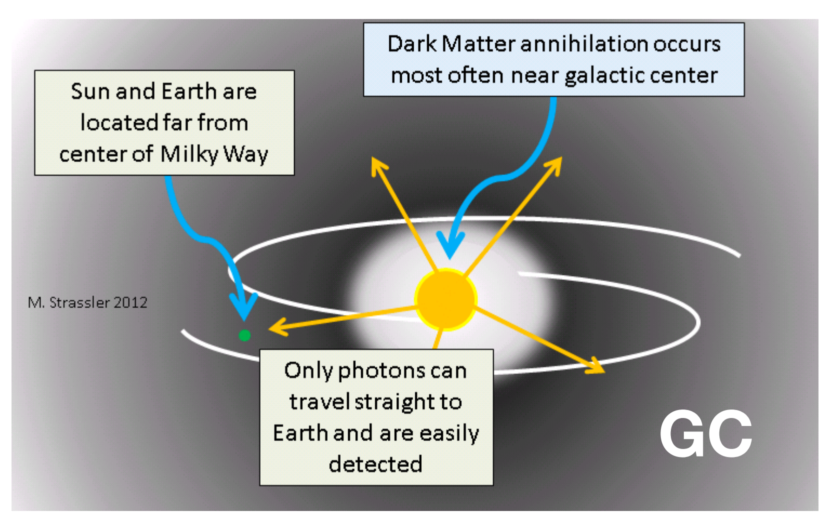
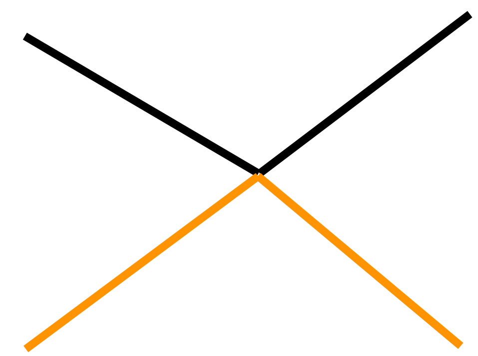
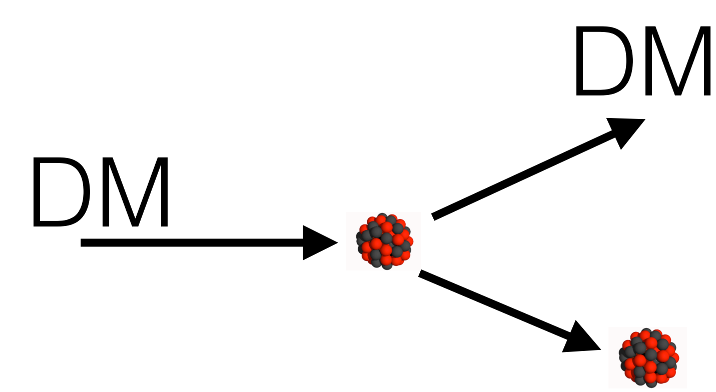
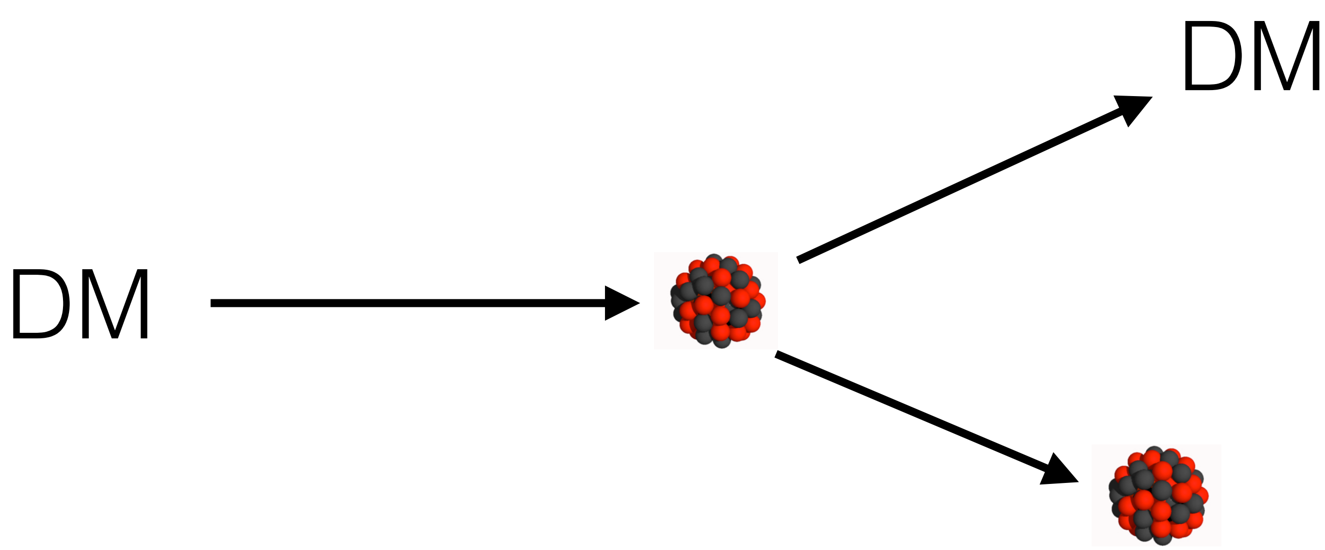


Shake it (DM-SM scattering)





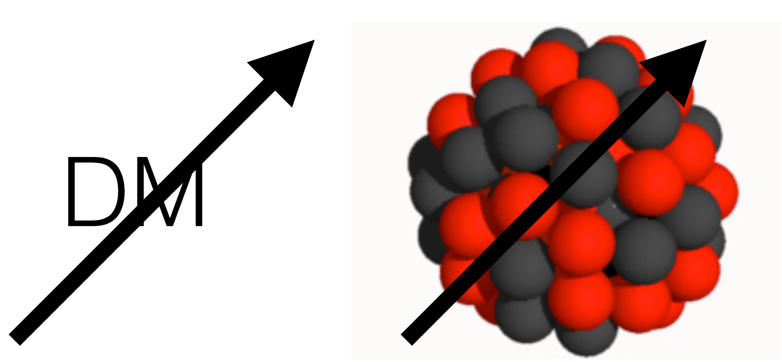
Elastic Cross sections



Nucleus recoil energy:

$$E_R \sim p^2/m_N = \mu_{Nx}^2 v_x^2/m_N$$
$$\sim 10^{-6}\mu_{Nx}^2/m_N$$

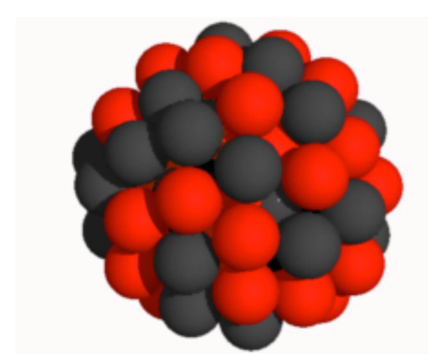
Cross-section, per nucleon,
spin-dependent



interaction depends on spins of DM, nucleus

$$\sigma_{Nx} \simeq (\text{spin factors})\frac{\mu_{Nx}^2}{\mu_{nx}^2}\sigma_{nx}$$

Cross-section, per nucleon,
spin-independent



-could scatter with any nucleon

-quantum: sum over paths, then square

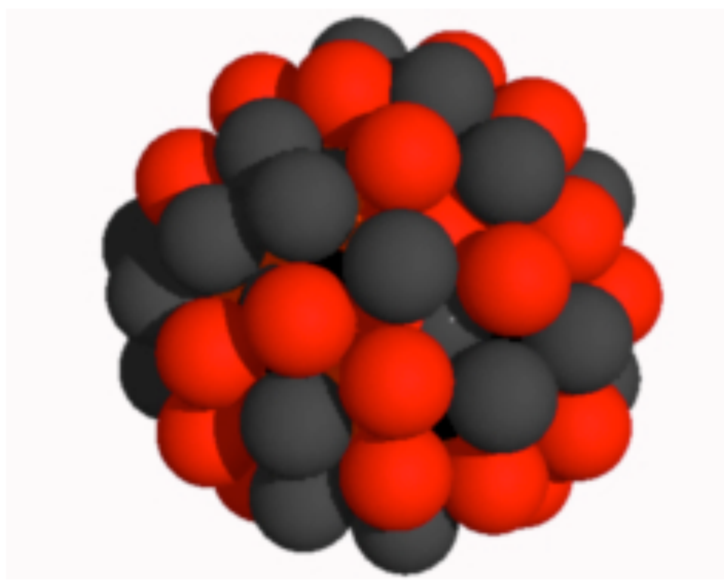
$$\sigma_{Nx} \simeq N^2\frac{\mu_{Nx}^2}{\mu_{nx}^2}\sigma_{nx}$$

N - number of nucleons

Calculate:

What is the recoil energy at which the N^2 enhancement to the spin-independent cross-section begins to break down?

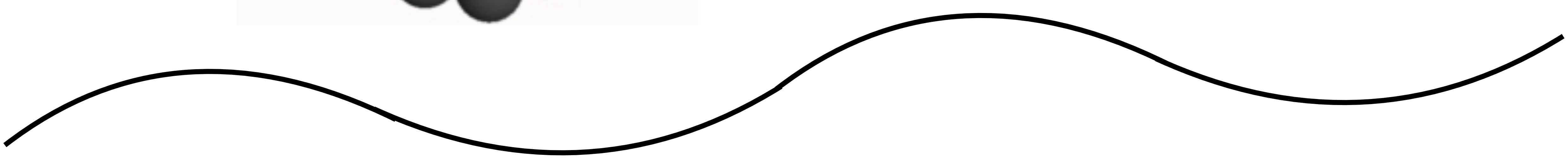
Consider: oxygen, germanium, iodine, xenon



$$E_R \sim \mu_{Nx}^2 v_x^2 / m_N$$

$$p \sim \lambda^{-1}$$

Size of nucleus: $1.2 \times 10^{-13} N^{1/3}$ cm

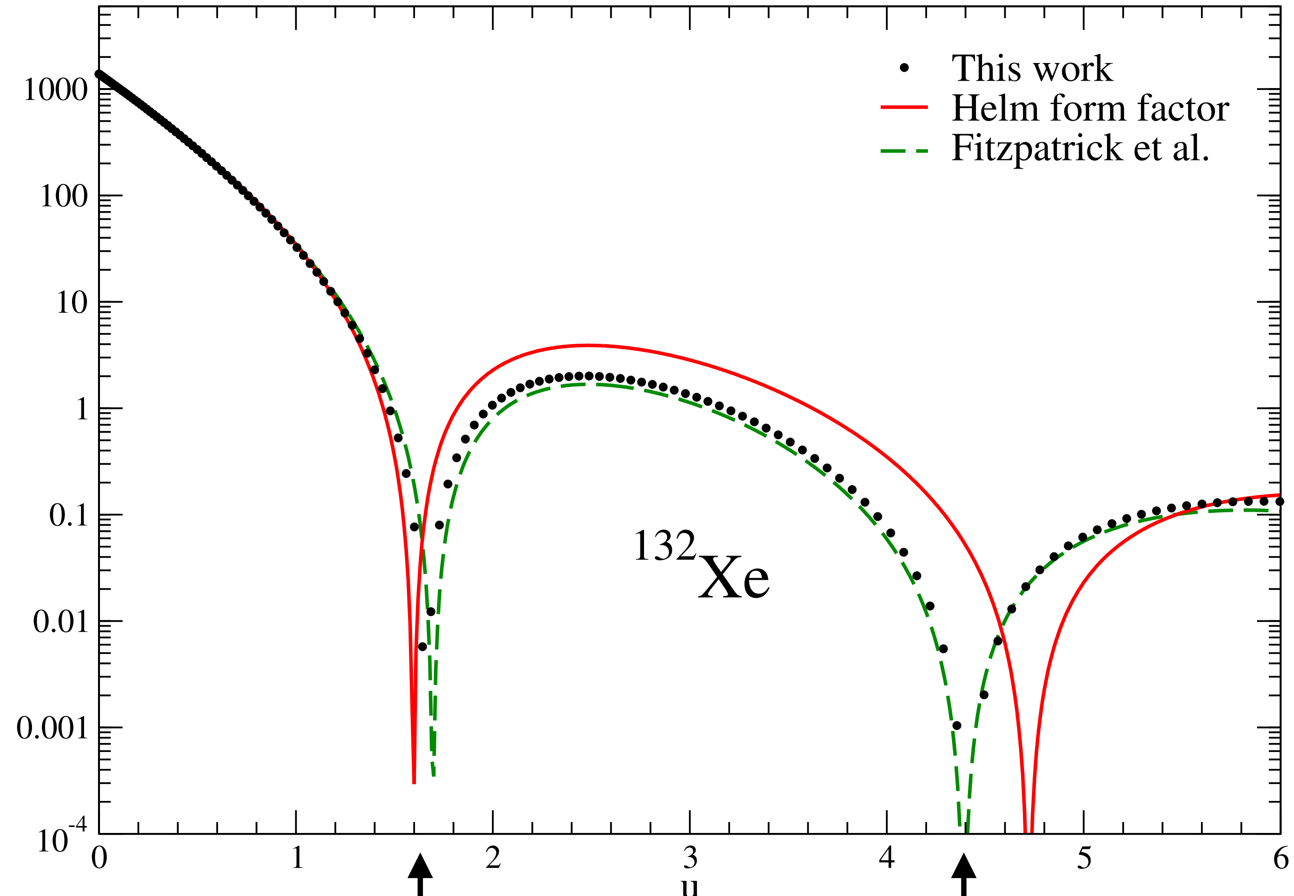


Hint: Use that the wavelength λ of the momentum exchange must be larger than the nucleus for the system to "not know" which nucleon was scattered with.

Nuclear structure “form factor"

1412.6091

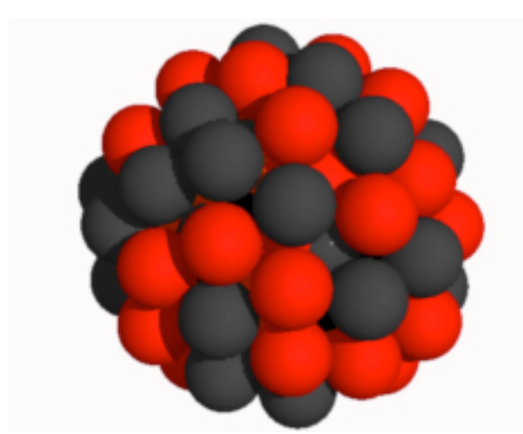
“form factor"

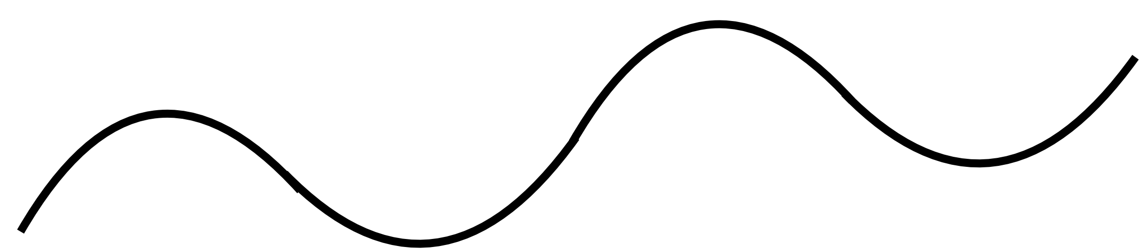


E_R 100 keV 260 keV

$$p \sim \lambda^{-1}$$

$$E_R \sim \lambda^{-2}/m_N$$





Experiment looking for flux of new particles

- **If particles have velocity v (~0.001c for DM)**
- **Then sensitivity of detector to interaction sets a minimum energy threshold (or particle mass) for detection**

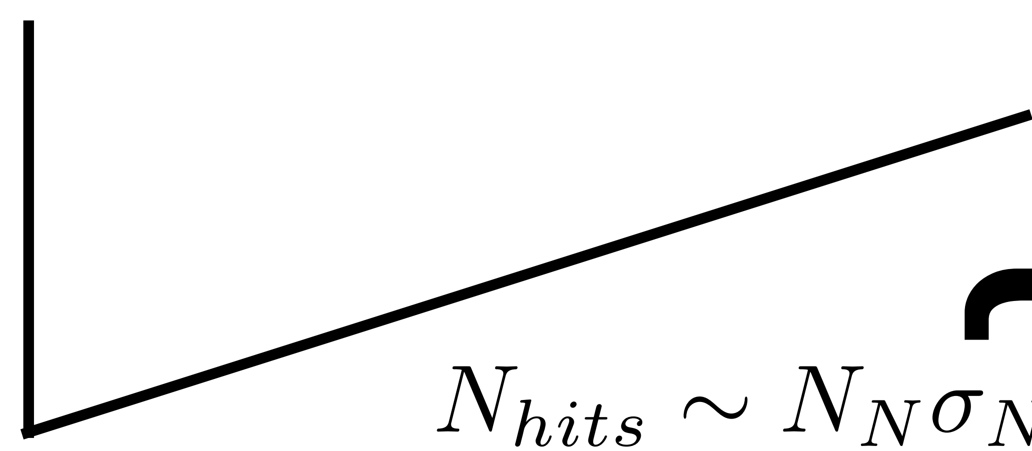
$$E_{th} \sim \mu_{Nx}^2 v_x^2 / m_N$$

cross-section for DM particle to hit detector particle

mass of dark matter

Experiment looking for flux of new particles

- **Detector is composed of N_N atoms and observes for time t**
- **As DM mass increases, DM particle flux decreases, so cross-section sensitivity decreases as $1/m_x$**



$$N_{hits} \sim N_N \overbrace{\sigma_{Nx} n_x v_x t}^{\text{DM hits per atom}}$$

DM number density

cross-section for DM particle to hit detector particle

mass of dark matter

Experiment looking for flux of new particles

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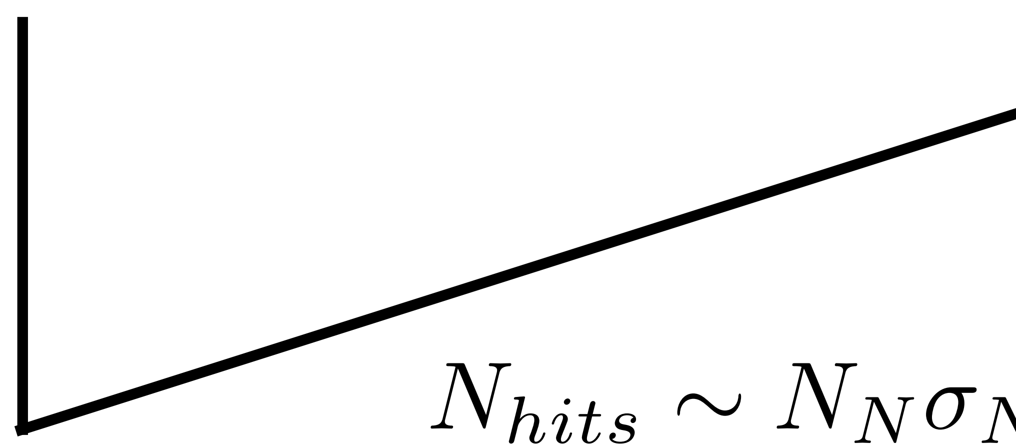


$$N_{hits} \sim N_N \sigma_{Nx} n_x v_x t$$

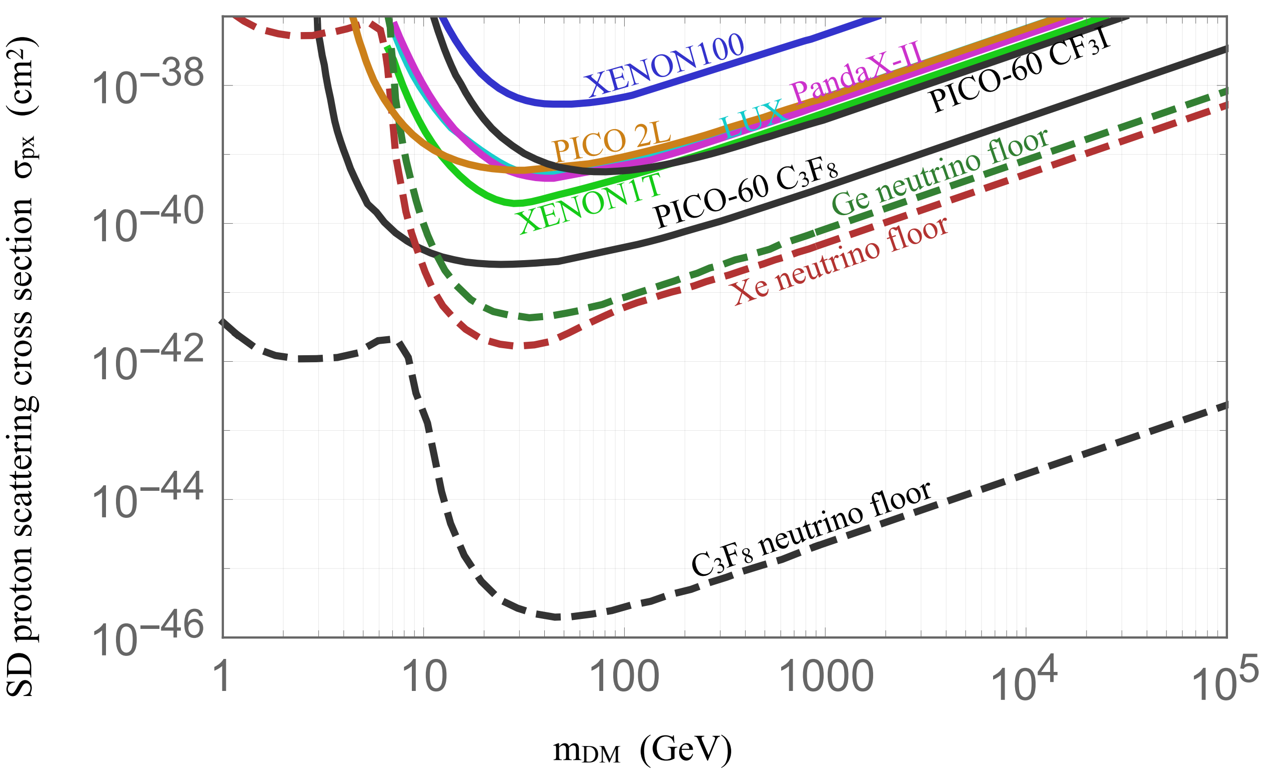
$$\sigma_{Nx} \sim 2 \frac{m_x}{\rho_x N_N v_x t}$$

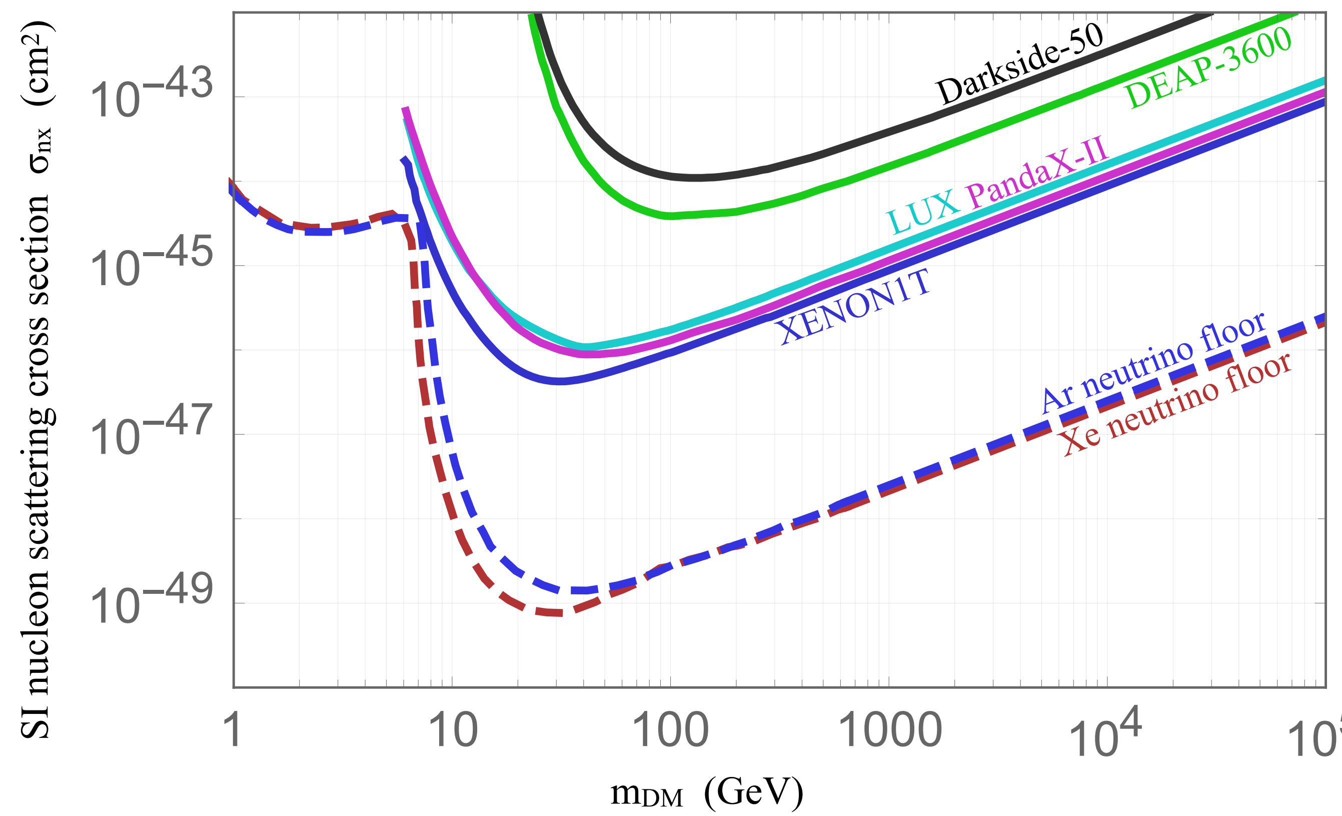
~2 hits for 90% confidence limit

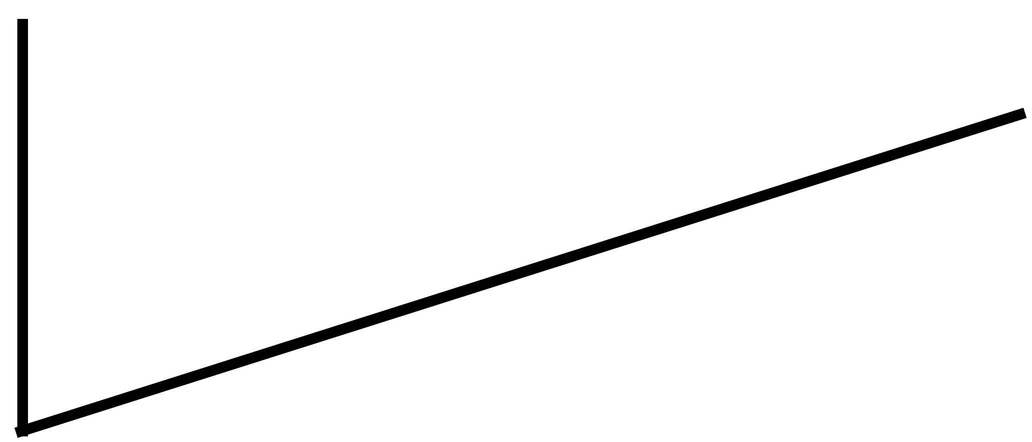
cross-section for DM particle to hit detector particle

mass of dark matter

Experiment looking for flux of new particles



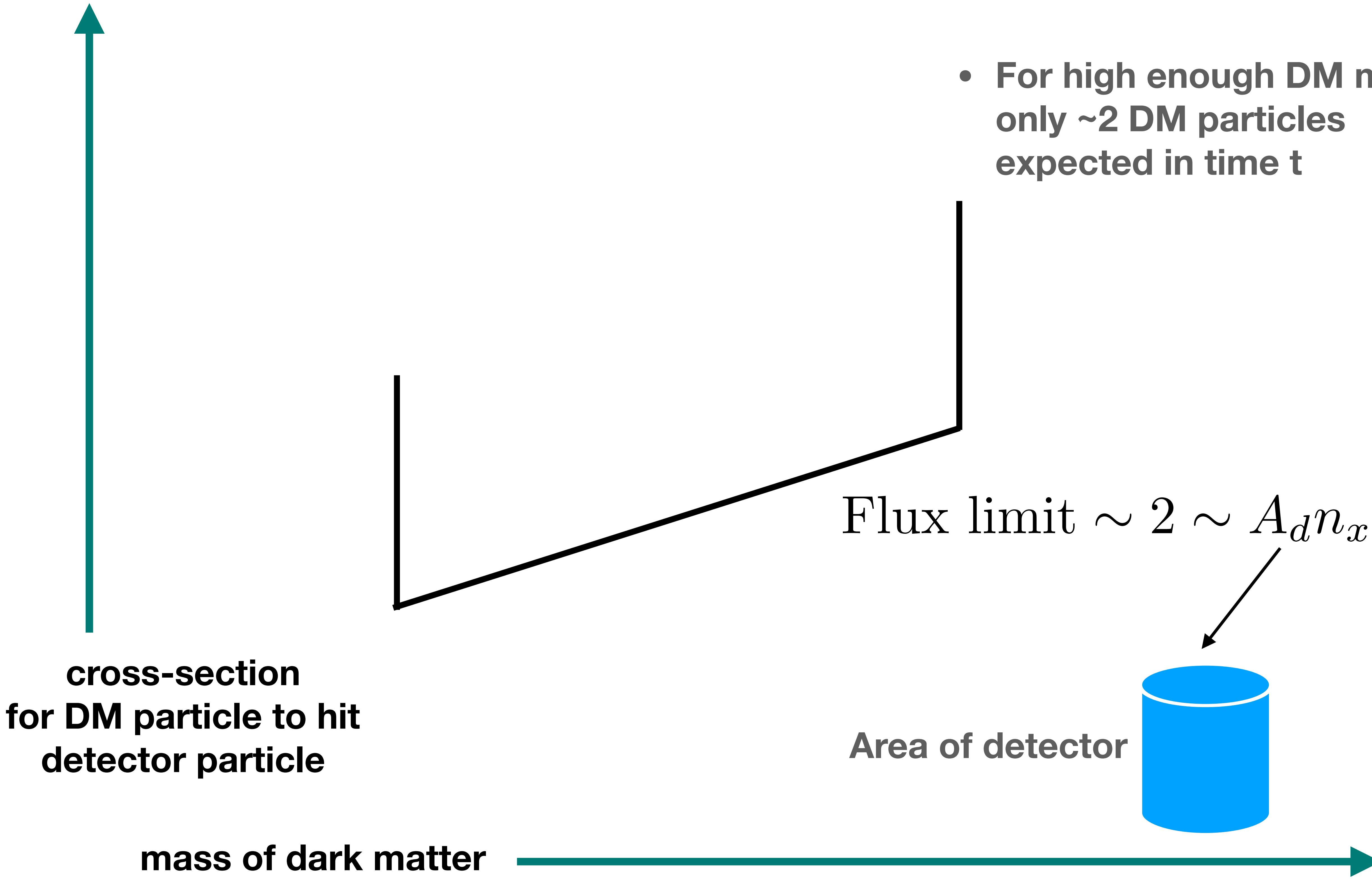




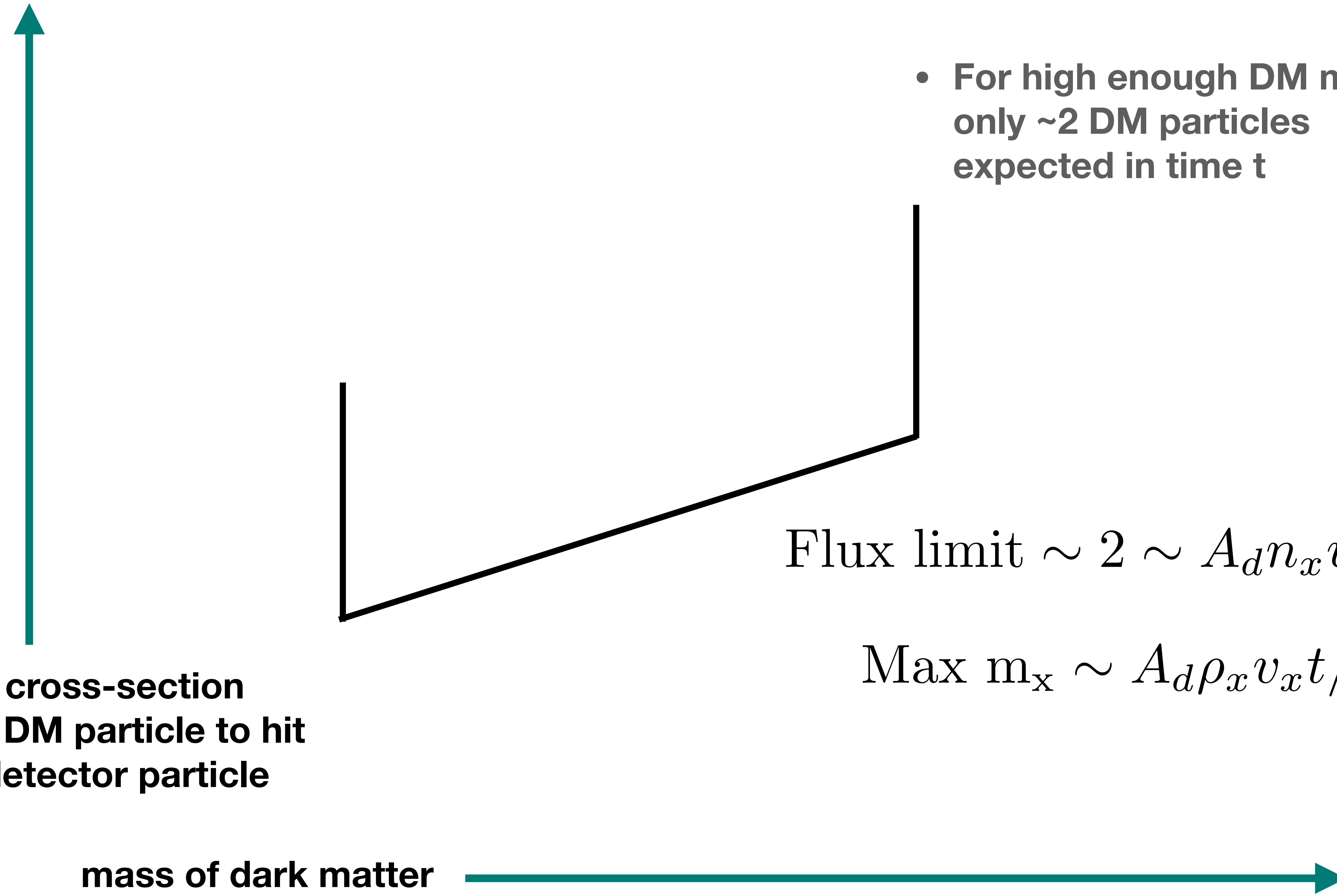
Experiment looking for flux of new particles

- **For high enough DM mass, only ~2 DM particles expected in time t**

$$\text{Flux limit} \sim 2 \sim A_d n_x v_x t$$



Experiment looking for flux of new particles

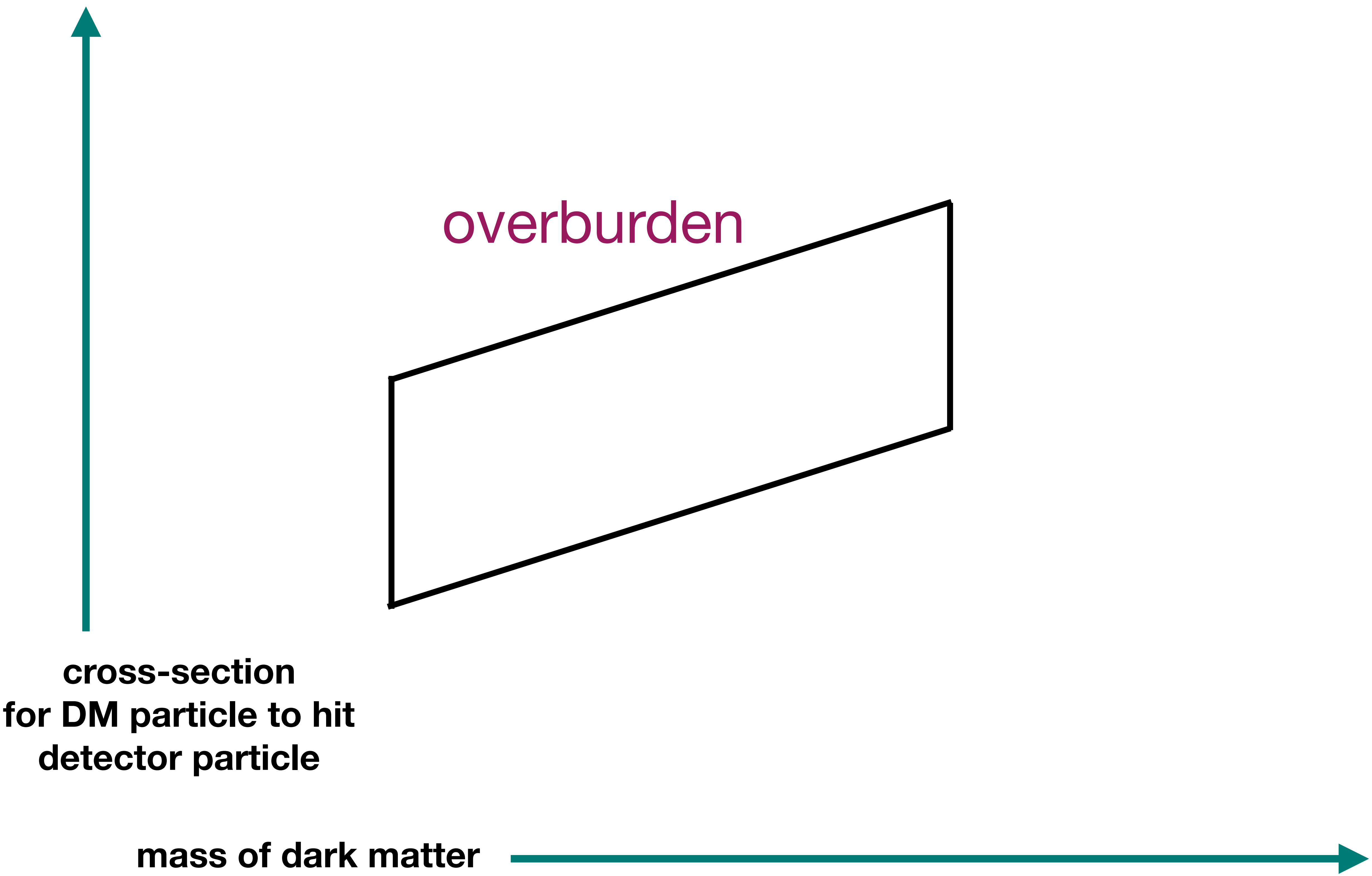


- For high enough DM mass, only ~2 DM particles expected in time t

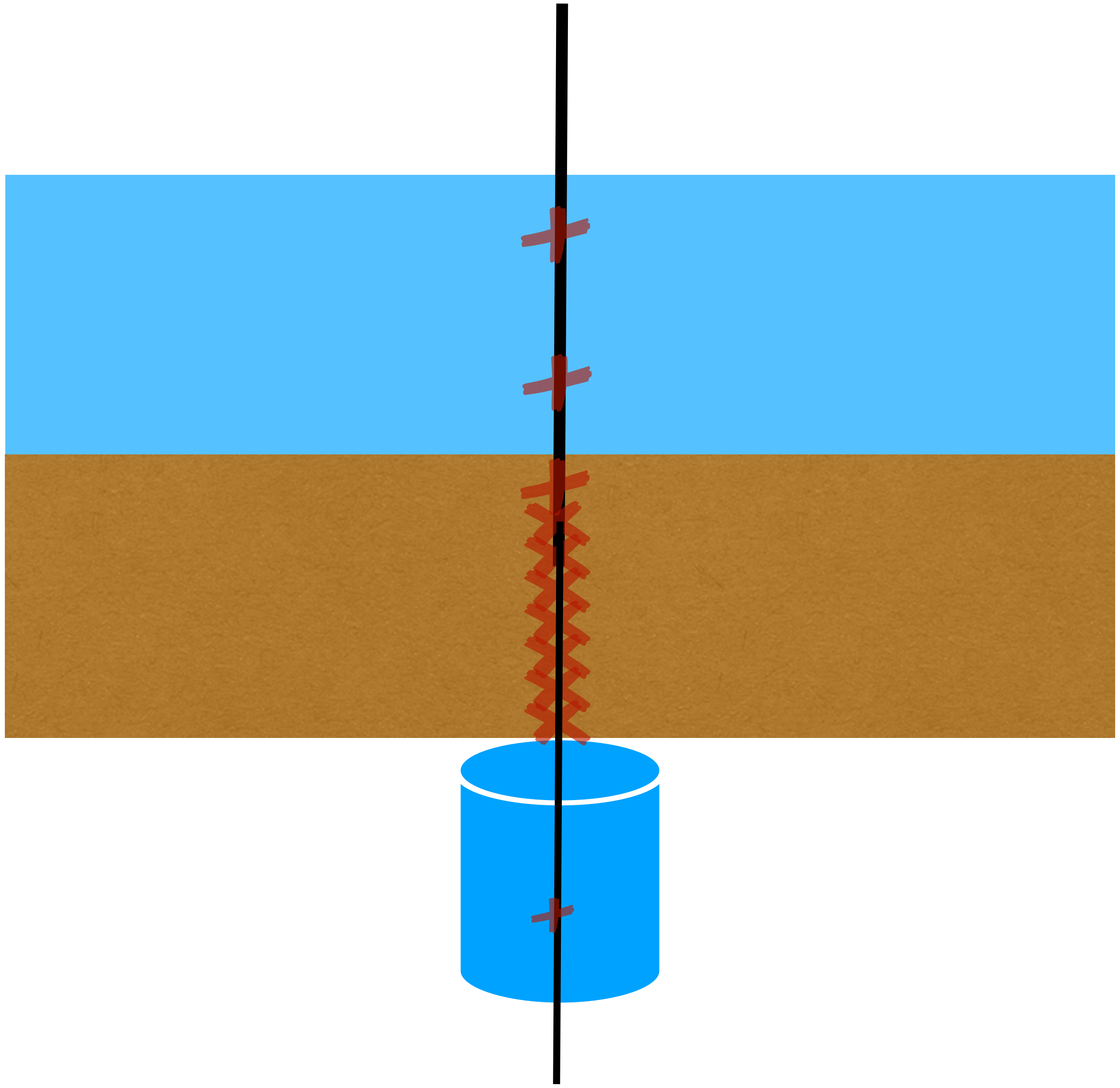
$$\text{Flux limit} \sim 2 \sim A_d n_x v_x t$$

$$\text{Max m}_\text{x} \sim A_d \rho_x v_x t/2$$

Experiment looking for flux of new particles

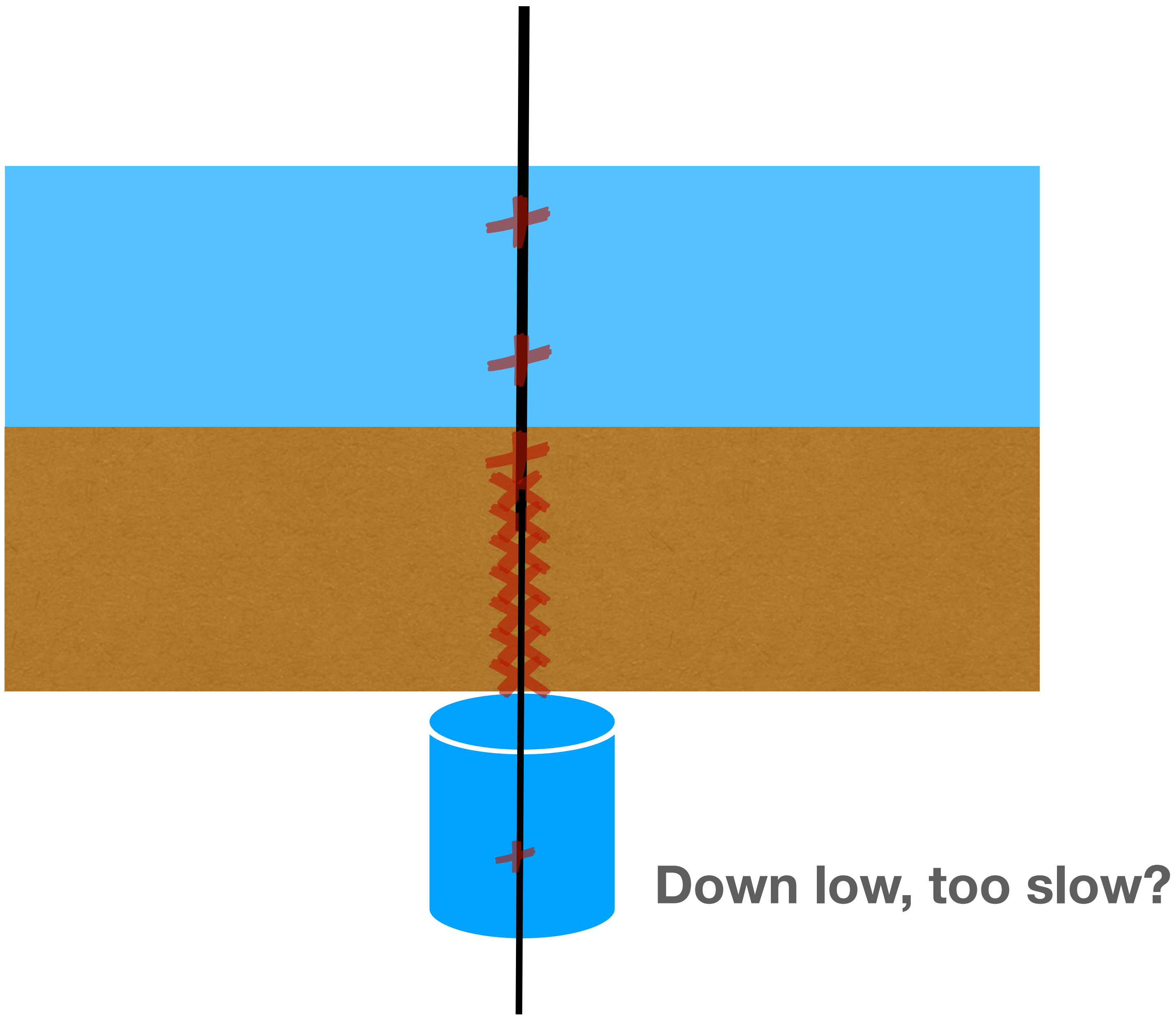


Overburden



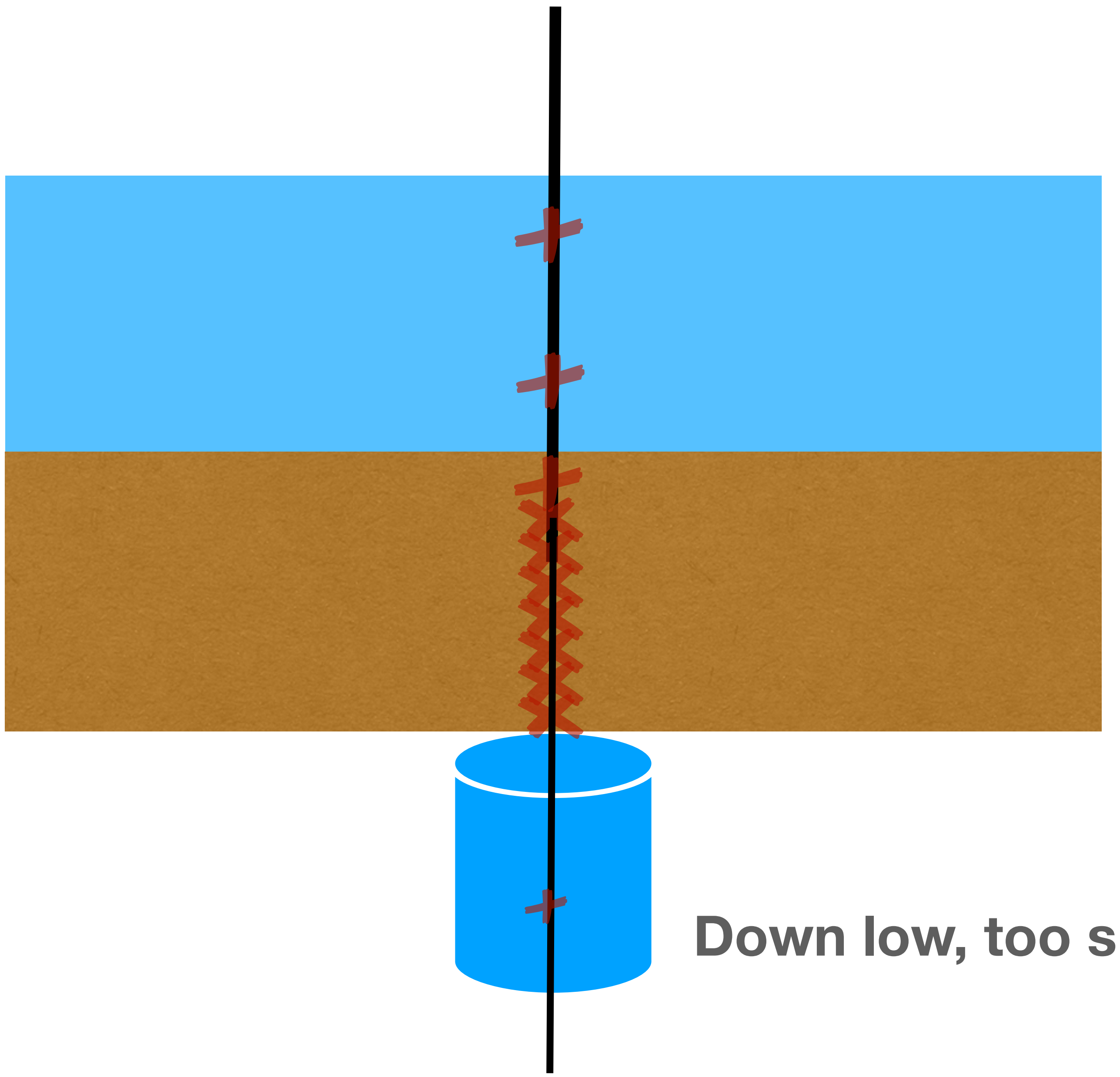
- **DM particles may be slowed through repeated scattering with atmosphere, earth, rocket shielding, concrete.**

Overburden



- **DM particles may be slowed through repeated scattering with atmosphere, earth, rocket shielding, concrete.**
- **If dark matter is moving too slowly, it will no longer deposit enough energy to exceed the detector's energy threshold.**

Overburden



Down low, too slow?

- **DM particles may be slowed through repeated scattering with atmosphere, earth, rocket shielding, concrete.**
- **If dark matter is moving too slowly, it will no longer deposit enough energy to exceed the detector's energy threshold.**

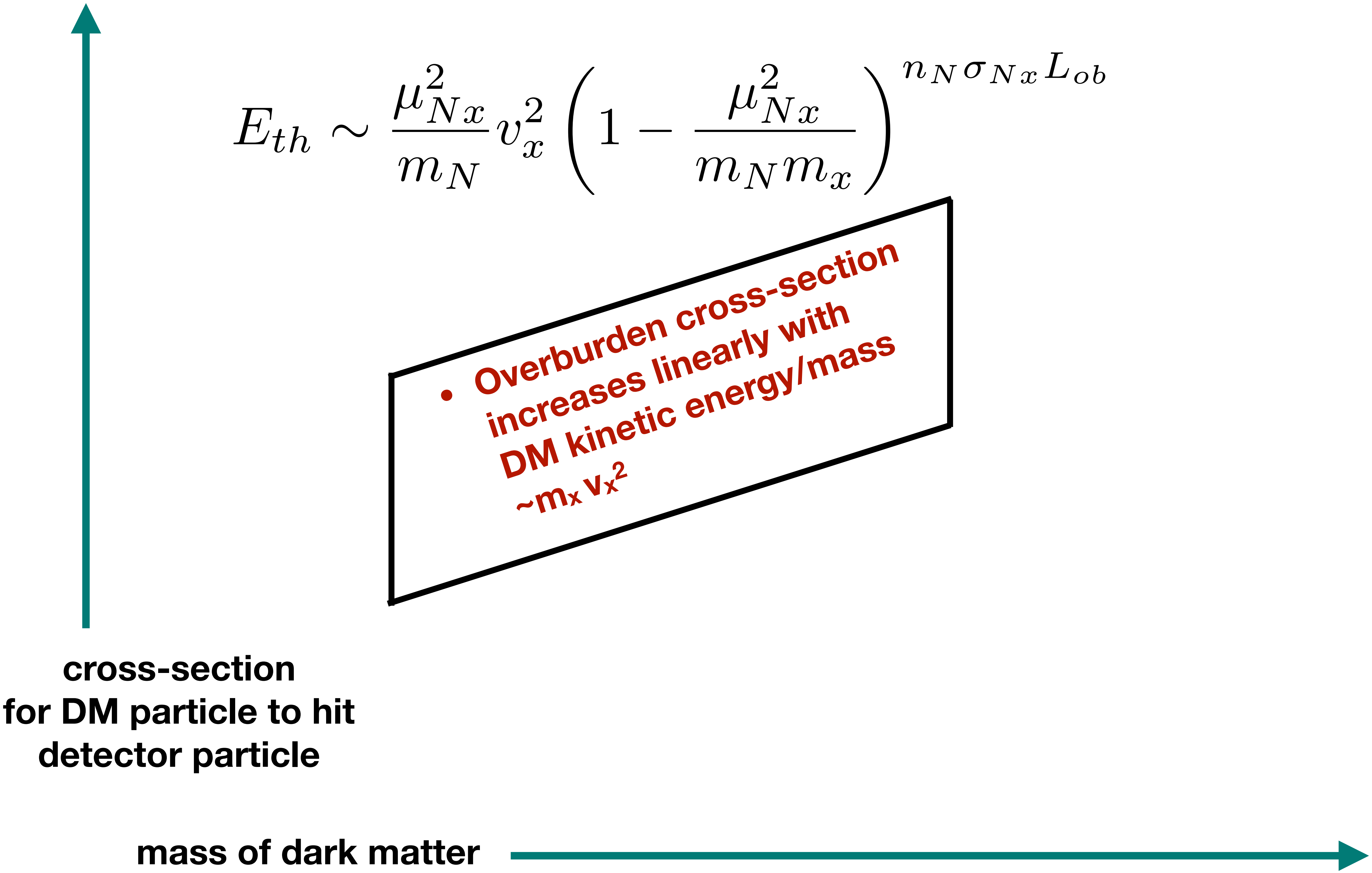
Length of overburden

number density of overburden

$$E_{th} \sim \frac{\mu_{Nx}^2}{m_N} v_x^2 \left(1 - \frac{\mu_{Nx}^2}{m_N m_x}\right)^{n_N \sigma_{Nx} L_{ob}}$$

Experiment looking for flux of new particles

$$E_{th} \sim \frac{\mu_{Nx}^2}{m_N} v_x^2 \left(1 - \frac{\mu_{Nx}^2}{m_N m_x}\right)^{n_N \sigma_{Nx} L_{ob}}$$



Experiment looking for flux of new particles

$$E_{th} \sim \frac{\mu_{Nx}^2}{m_N} v_x^2 \left(1 - \frac{\mu_{Nx}^2}{m_N m_x}\right)^{n_N \sigma_{Nx} L_{ob}}$$

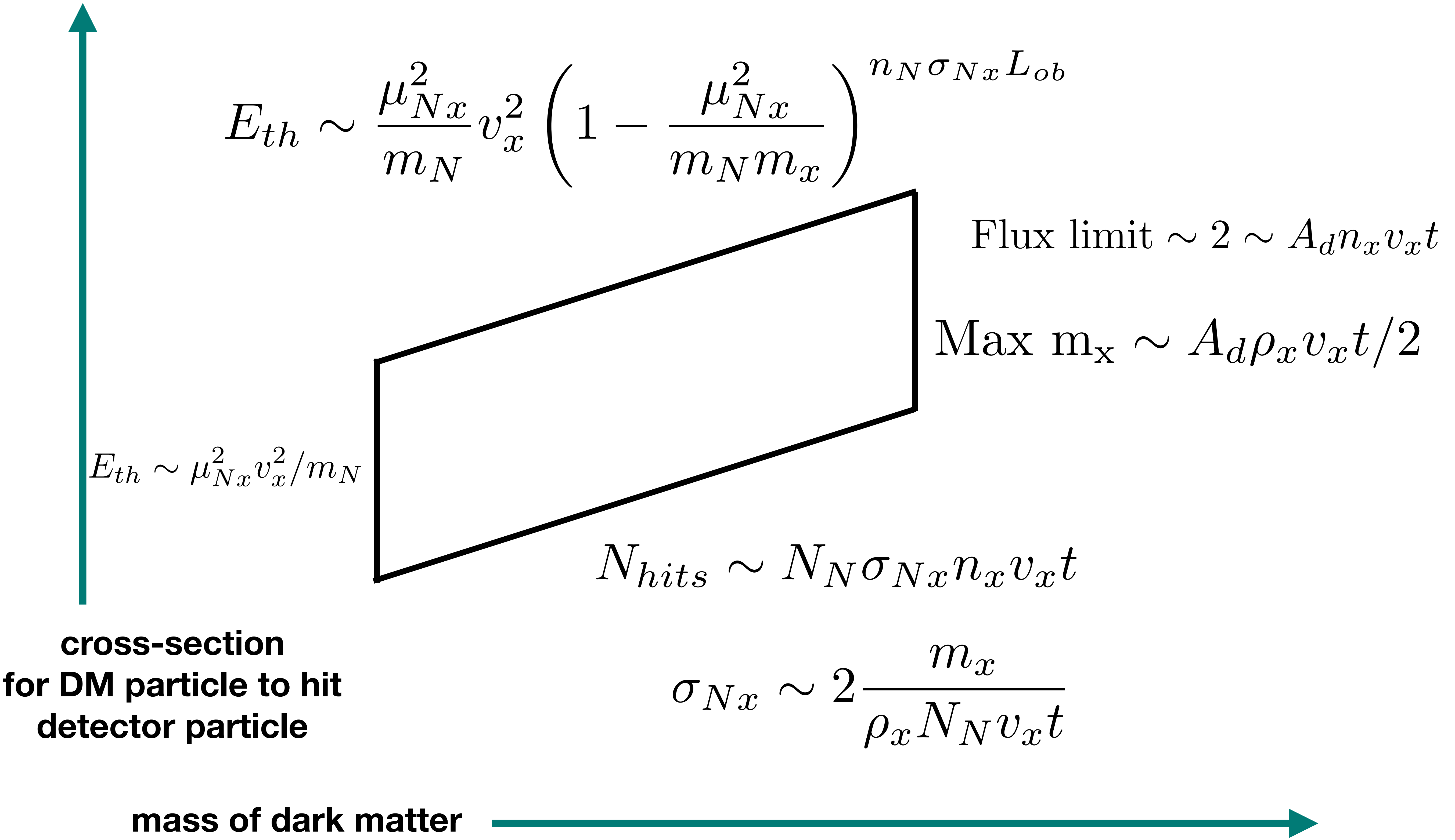
- Overburden cross-section increases linearly with DM kinetic energy/mass $\sim m_x v_x^2$

- One order of magnitude increase in cross-section (and number of scatters)
  …for every one order of magnitude increase in m_x (and initial DM kinetic energy)

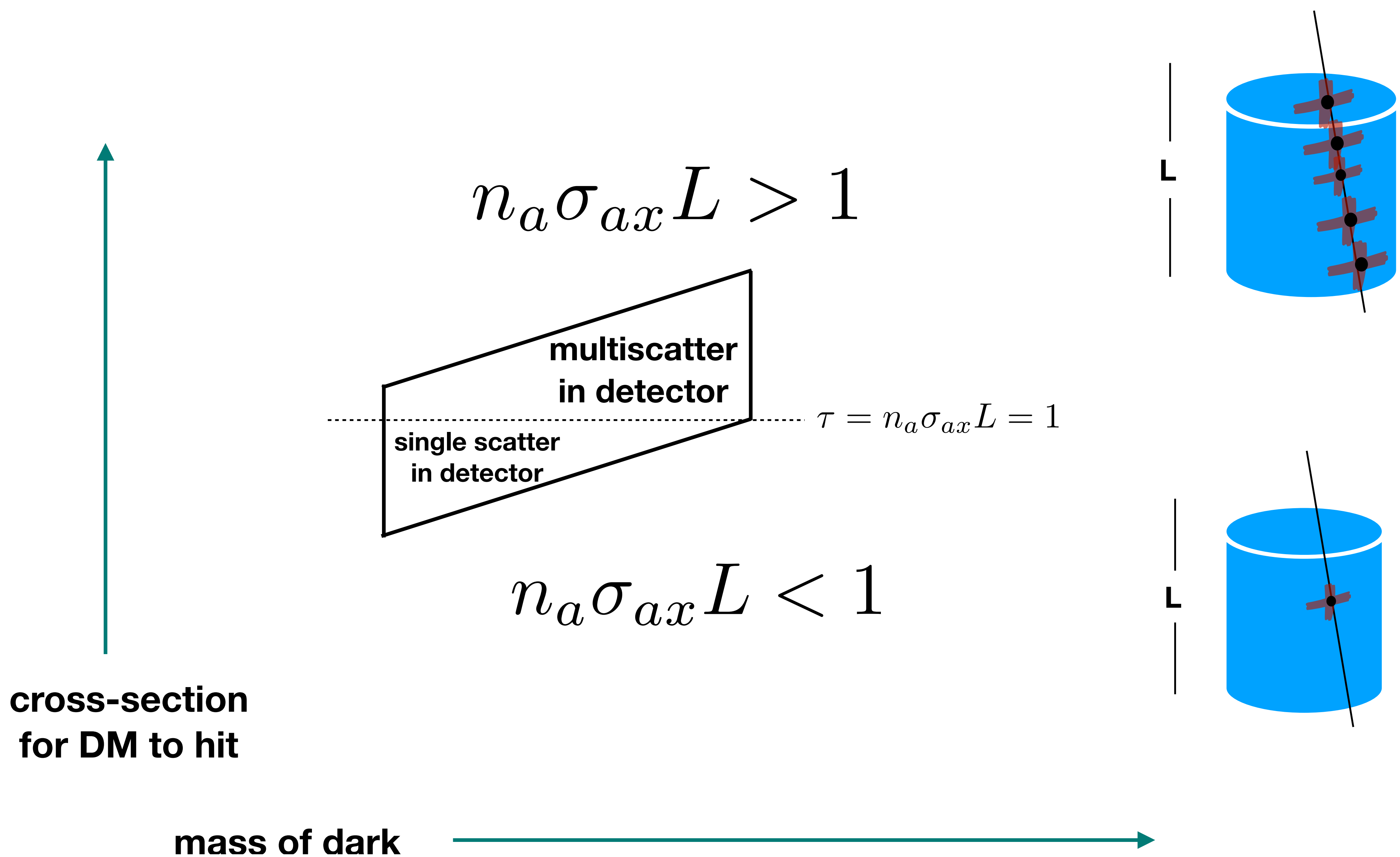
cross-section for DM particle to hit detector particle

mass of dark matter

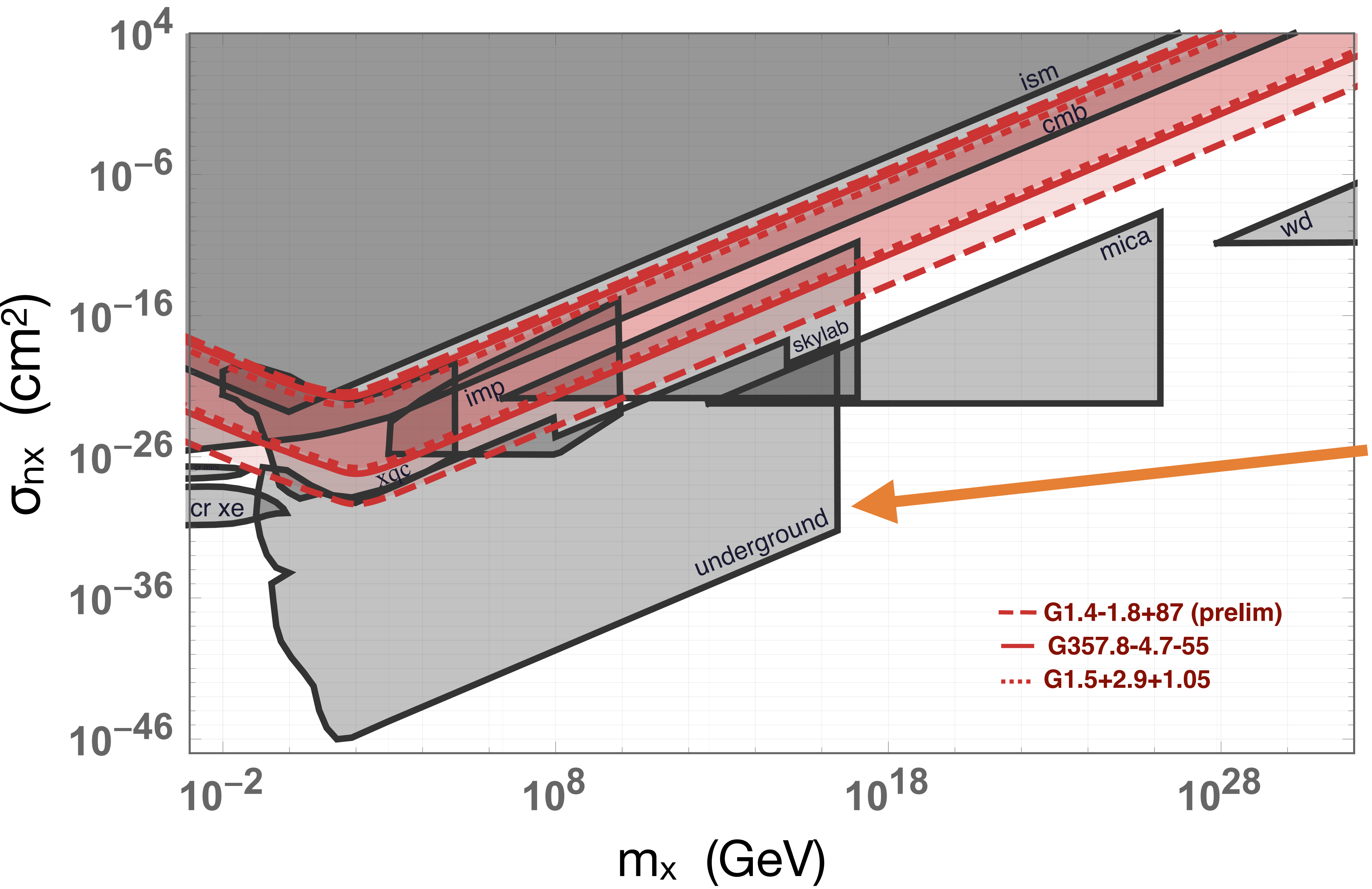
Experiment looking for flux of new particles



MULTISCATTER DARK MATTER DETECTION



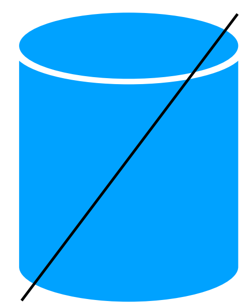
EXTRAPOLATING TO HIGH MASS DARK MATTER



Naive extrapolation fails, need new analyses.

Multiscatter frontier

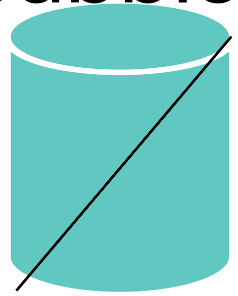
Transit time for a MIMP through
a meter is five microseconds



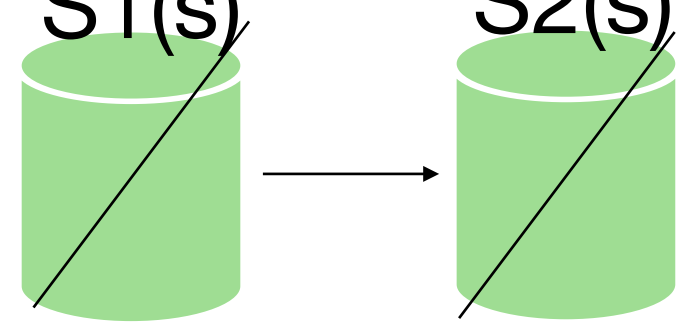
MIMP
5 μs

Individual nuclear scattering events typically
deposit ~10 keV

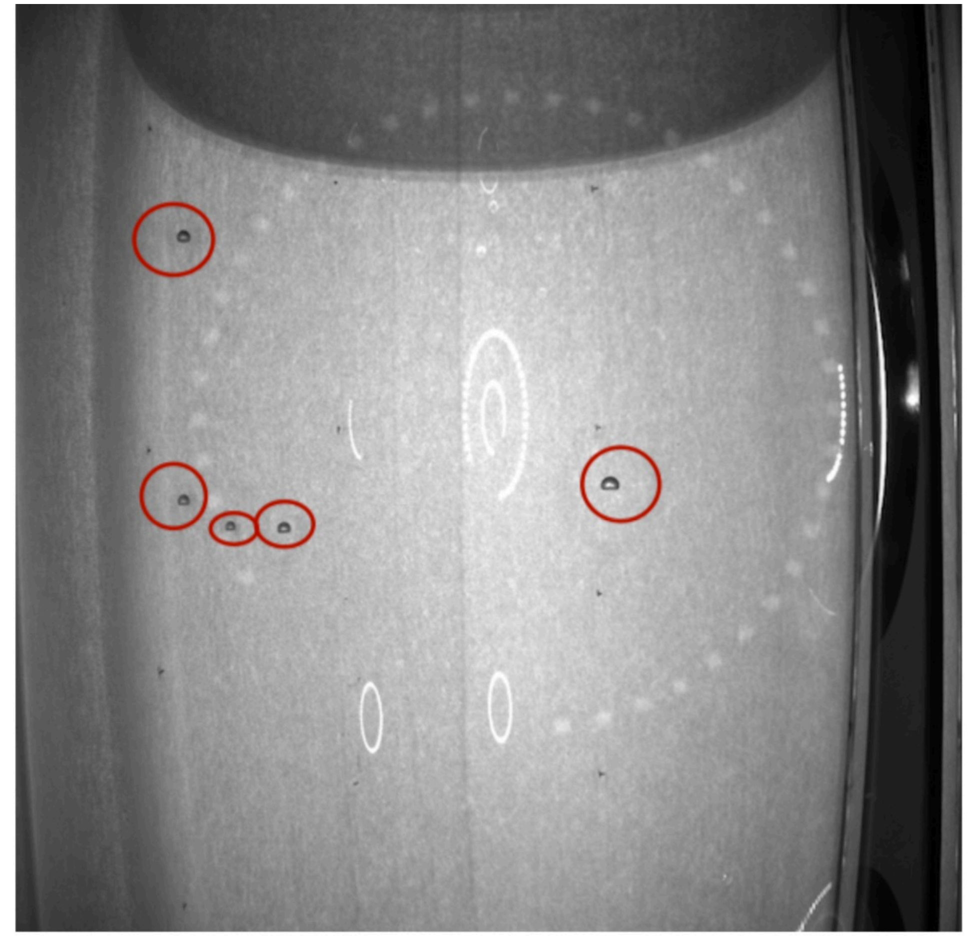
Bubble Chamber
bubble(s)

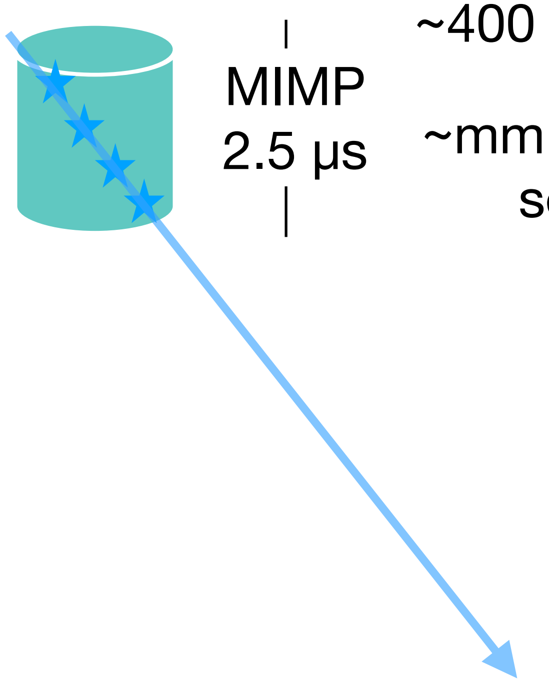


Time Projection Chamber
S1(s) S2(s)



PICO-60 multiscatter search ongoing





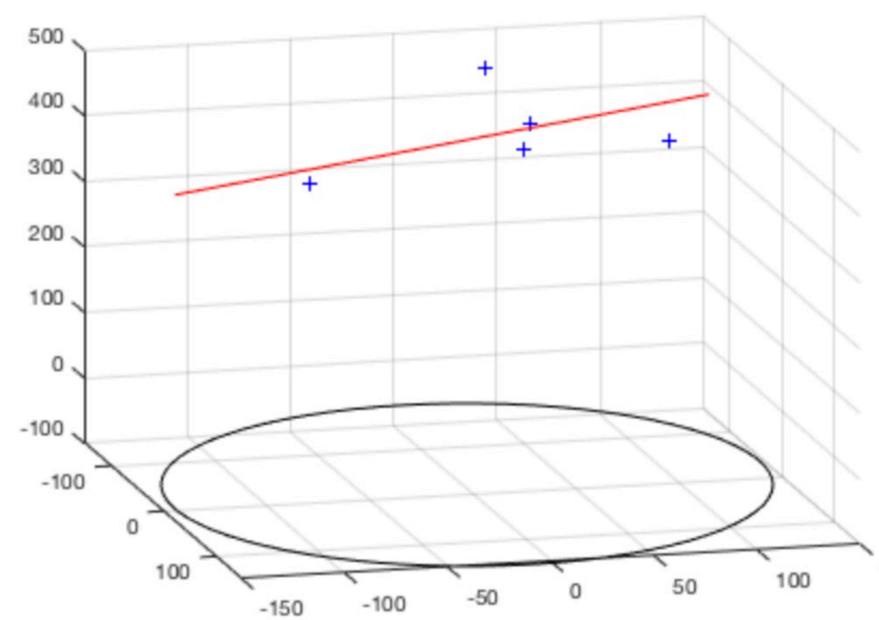
MIMP
2.5 μs

~400 ns acoustic sensors

~mm resolution stereo cameras
see bubbles (up to 500)

MIMP scatter should be highly collinear.
For <kilobarn cross-section.

$$\Omega_{\max} \lesssim \quad 1.7^\circ \left(\frac{m_a}{100\ \mathrm{GeV}}\right)\left(\frac{10^{13}\ \mathrm{GeV}}{m_x}\right)\left(\frac{L}{100\ \mathrm{cm}}\right)\left(\frac{n_a}{10^{22}/\mathrm{cm}^3}\right)^{1/3}.$$



Courtesy Ben Broerman, Queen's PhD student
ongoing analysis

ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *Two searches in 1978 and 1990 for cosmic rays and monopoles using acid-etched plast track detectors*
- *Still have best sensitivity for some high mass dark matter, for different reasons*

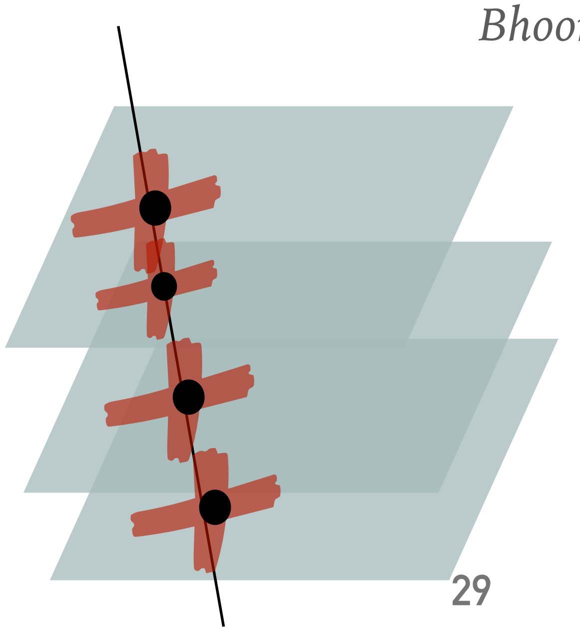
Skylab

	Skylab	**Ohya**
Area A	1.17 m^2	2442 m^2
Duration t	0.70 yr	2.1 yr
Zenith cutoff angle	$\theta_D = 60°$	$\theta_D = 18.4°$
Detector material	0.25 mm thick Lexan × 32 sheets	1.59 mm thick CR-39 × 4 sheets
Detector density	1.2 g cm^{-3} Lexan	1.3 g cm^{-3} CR-39
Detector length at θ_D	1.6 cm	0.66 cm
Overburden density	2.7 g cm^{-3} Aluminum	2.7 g cm^{-3} Rock
Overburden length at θ_D	0.74 cm	39 m

Bhoonah, JB, Courtman, Song

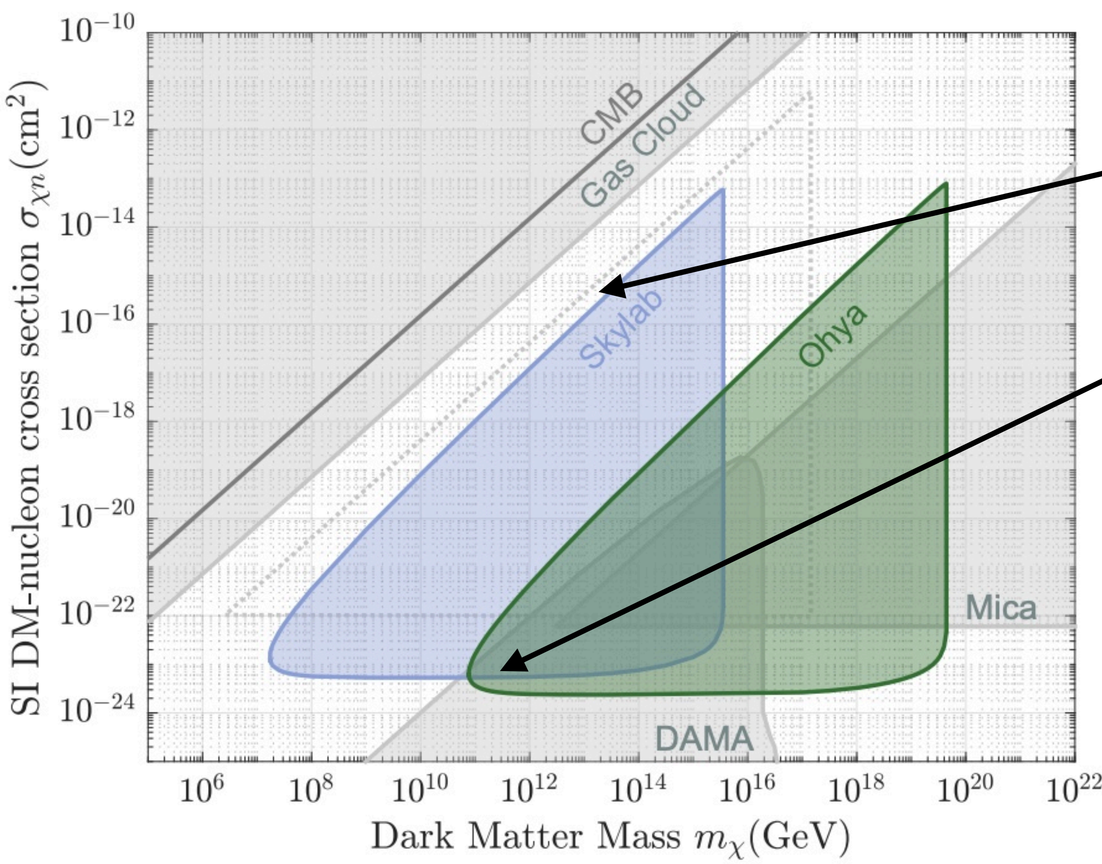
2012.13406

Ohya Quarry



- *Use dark matter density and velocity distribution, solve for overburden+etching sensitivity*

$$\left.\frac{dE}{dx}\right|_{th} = \frac{2E_i}{m_\chi}\left(\sum_{A\subset O}\frac{\mu_{\chi A}^2}{m_A} n_A \sigma_{\chi A}\right)\exp\left[\frac{-2}{m_\chi}\left(x_O\sum_{A\subset O} n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A} + x_D\sum_{A\subset D} n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}\right)\right]$$

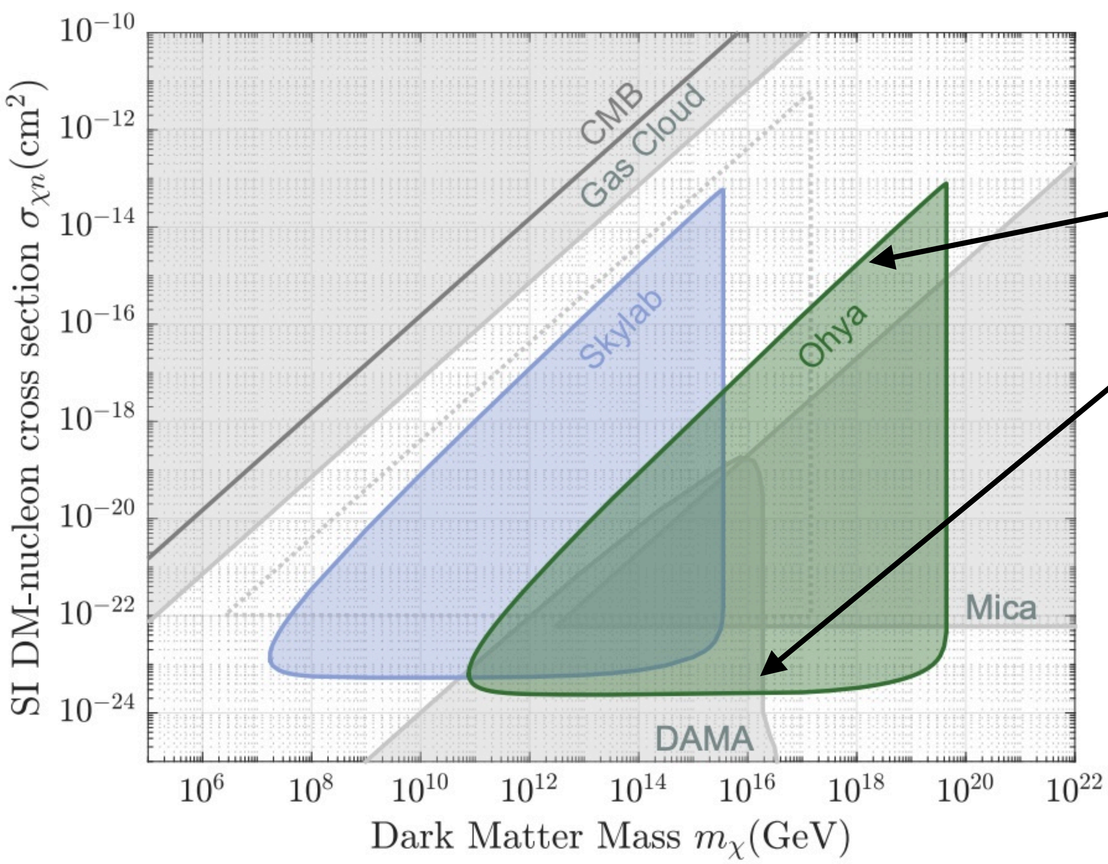


Overburden from space station aluminum shield

Threshold from plastic sheet damage

- *Use dark matter density and velocity distribution, solve for overburden+etching sensitivity*

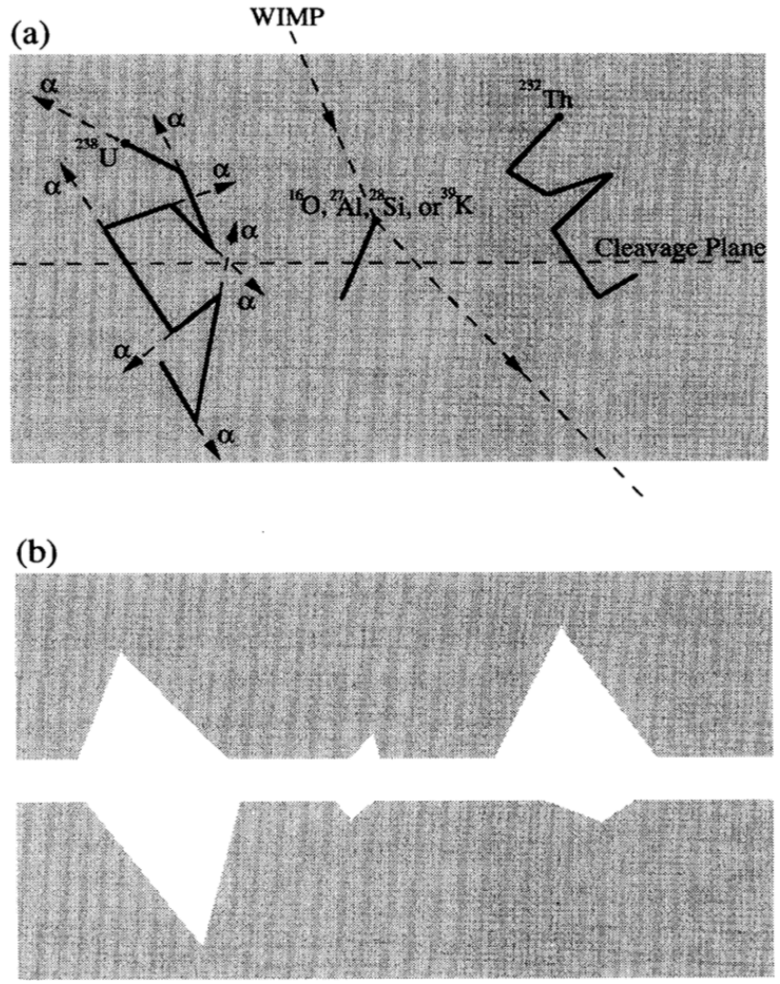
$$\left.\frac{dE}{dx}\right|_{th} = \frac{2E_i}{m_\chi}\left(\sum_{A\subset O}\frac{\mu_{\chi A}^2}{m_A}n_A\sigma_{\chi A}\right)\exp\left[\frac{-2}{m_\chi}\left(x_O\sum_{A\subset O}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}+x_D\sum_{A\subset D}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}\right)\right]$$

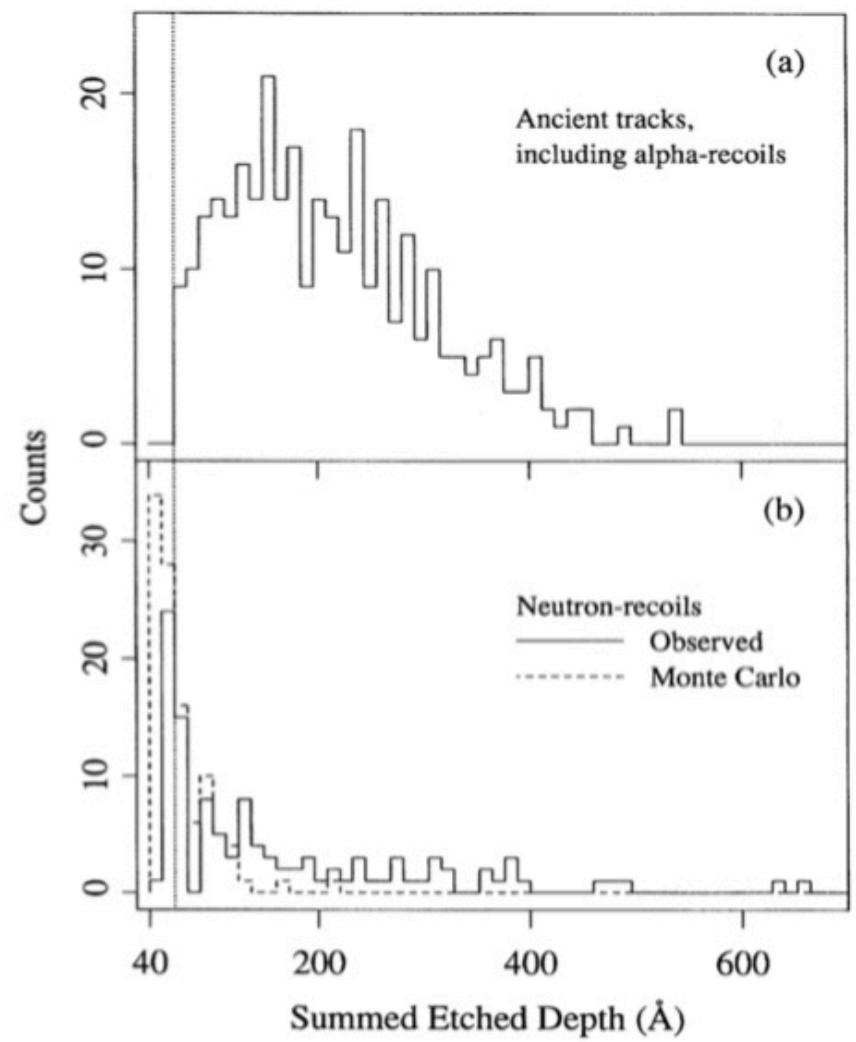


Overburden from quarry rock overhead

Threshold from plastic sheet damage

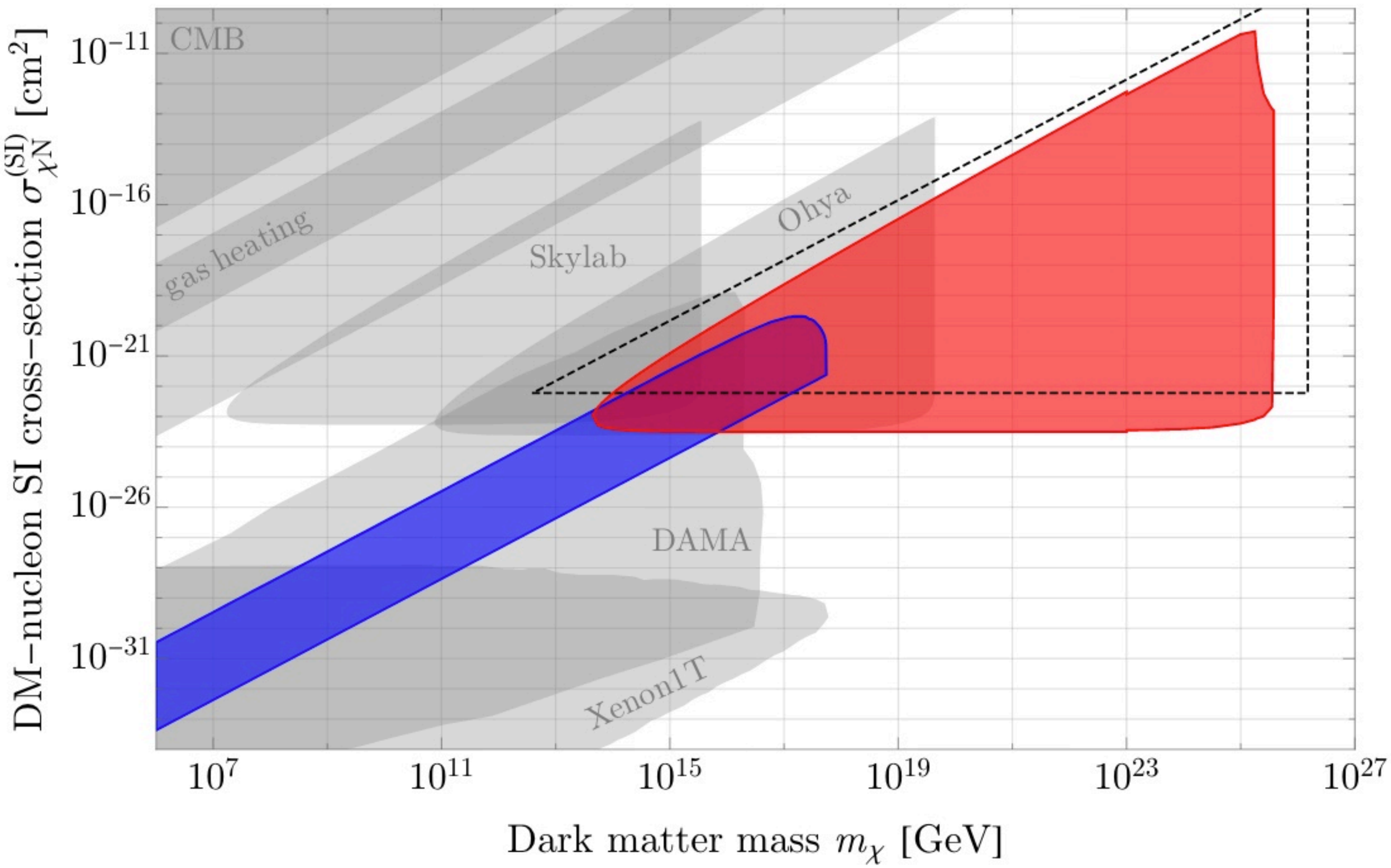
ANCIENT MICA SEARCH FOR DARK MATTER





➤ 1995 Snowden-Ifft et al. calibrated mica samples

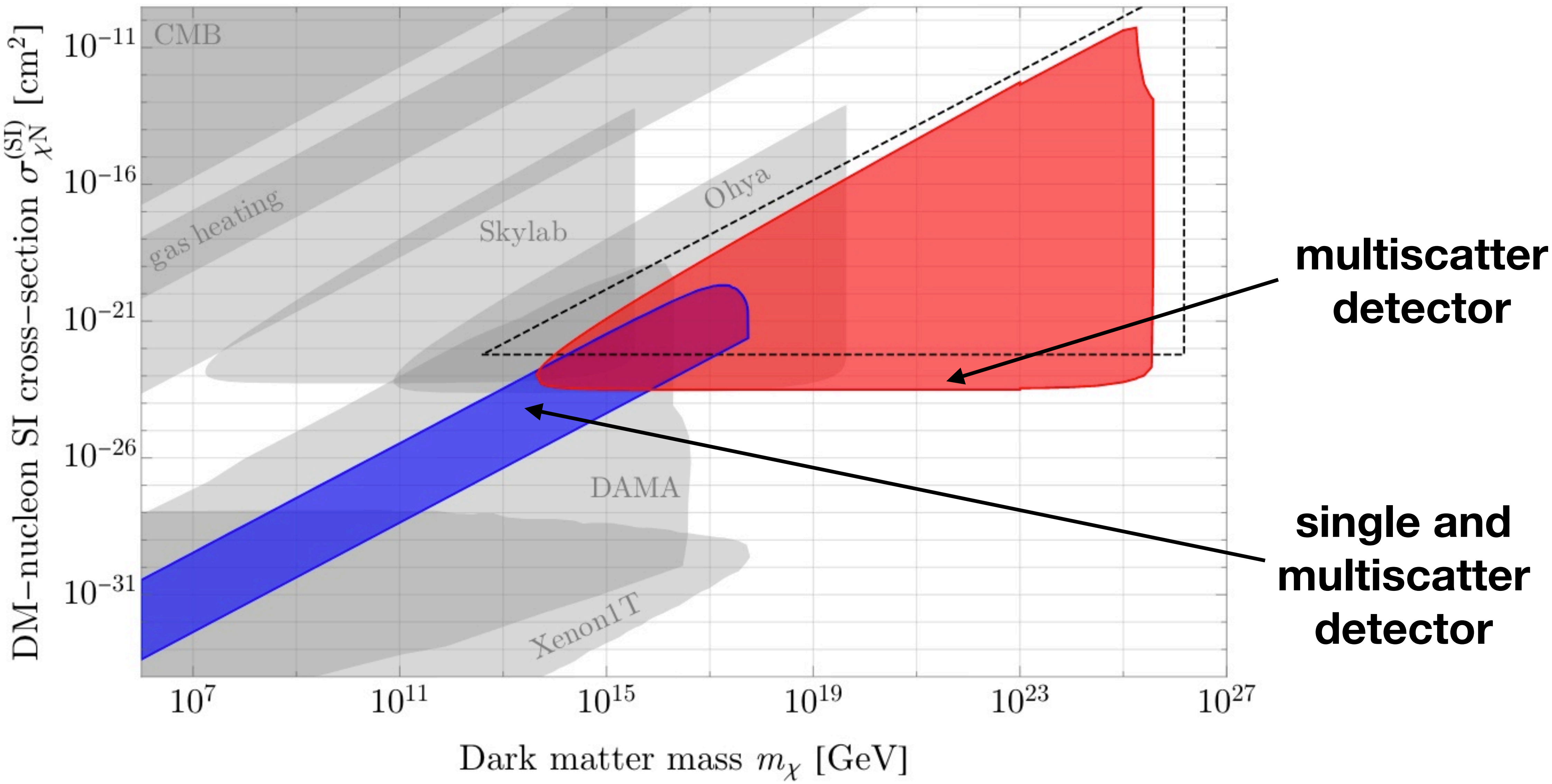
ANCIENT MICA SEARCH FOR DARK MATTER



Acevedo, JB, Goodman in prep

- Recast using crust and mica MC methods

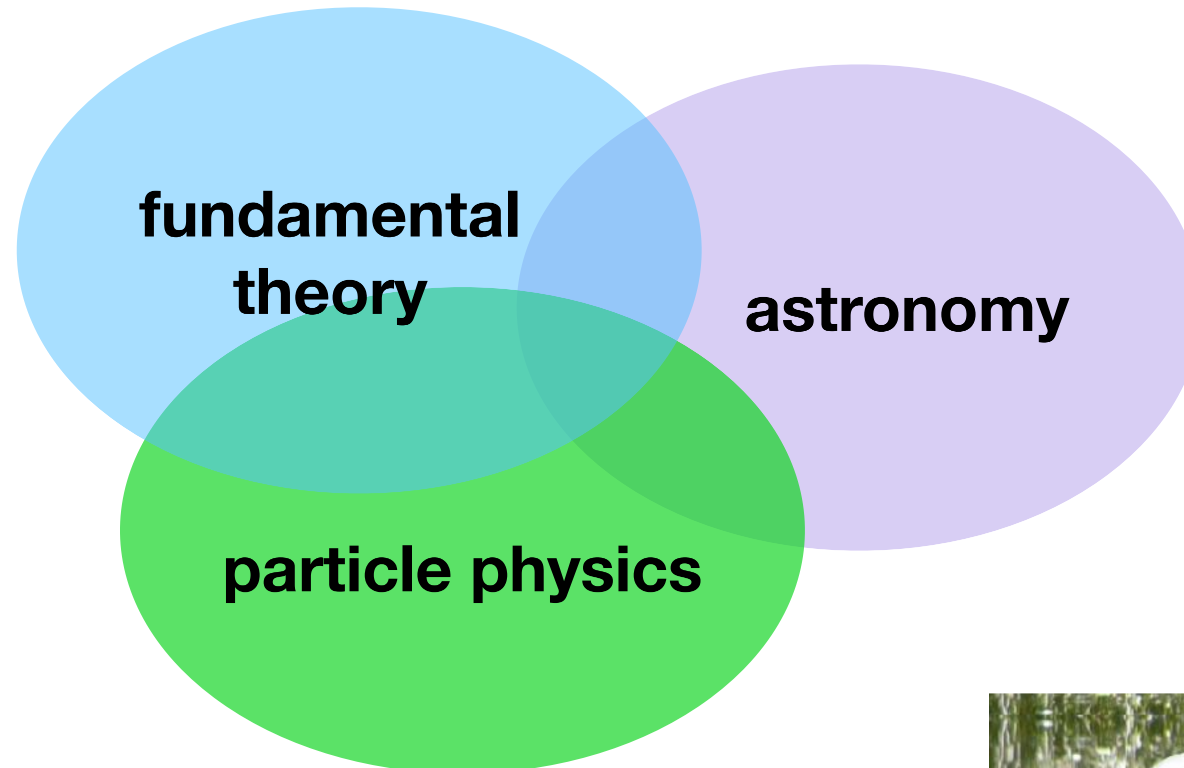
ANCIENT MICA SEARCH FOR DARK MATTER



Recast using crust and mica MC methods

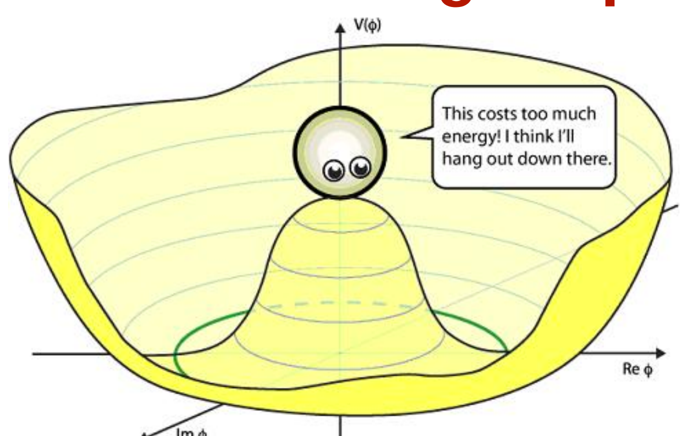
Acevedo, JB, Goodman in prep

Particle Theory and Phenomenology



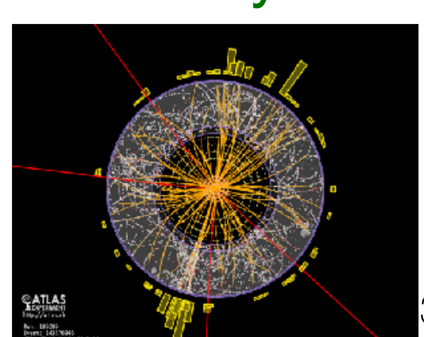
What are we missing?

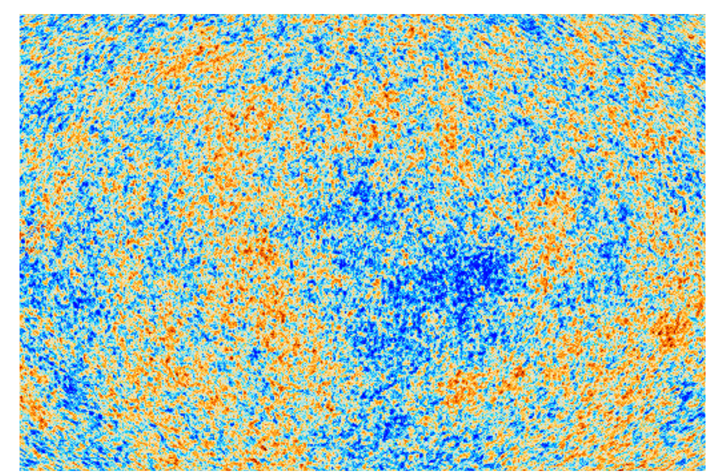
- Dark Matter
- Matter-Antimatter Asymmetry
- New forces and interactions
- The nature of neutrinos
- Physics at super-TeV energies
- Axions & the strong CP problem



How do we find out?

- New Particle Searches
  - A. Underground
  - B. **In space** x-/gamma/cosmic rays
  - C. **Colliders** LHC, future





- **Develop and test new theories**
  - Early universe — inflation & CMB
  - Effective field theories
  - Fifth forces / new bosons / extra dimensions
  - SUSY or something wild and new at high E?

Thanks!