Dark Matter and Cosmology III:
Dark Matter: Where to Find It

Joe Bramante
Queen's University
McDonald Institute

Natural units reference for problems.

$$\Delta X \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta T \geq \frac{\hbar}{2}$$

$$\lambda_c = \frac{2\pi\hbar}{m}$$

$$\lambda_d = \frac{2\pi\hbar}{p}$$

Set $\hbar$=c=1

$$G = \frac{1}{m_{pl}^2} \simeq 10^{-38}\ \mathrm{GeV}^{-2}$$

$$\mathrm{GeV} = \frac{1}{2 \times 10^{-14}\ \mathrm{cm}}$$

$$\mathrm{GeV} = \frac{1}{7 \times 10^{-25}\ \mathrm{s}}$$

$$\mathrm{gram} \sim 10^{24}\ \mathrm{GeV}$$

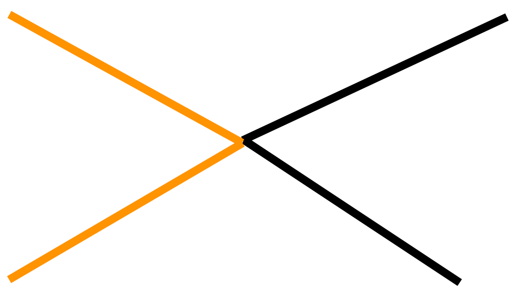
$$\mathrm{Watt} = \frac{\mathrm{J}}{\mathrm{s}}$$

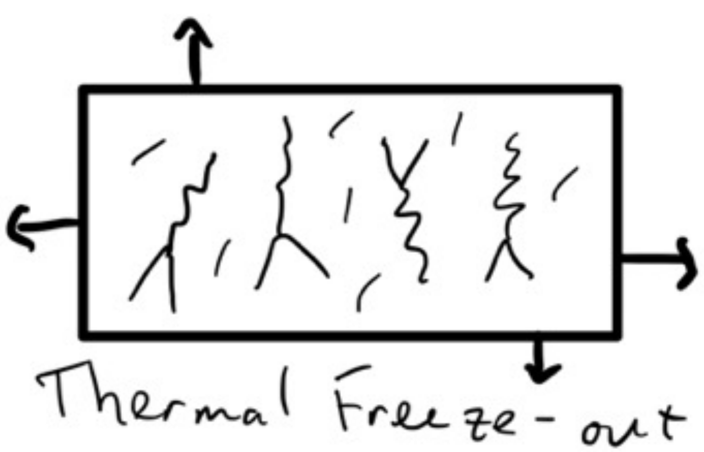
$$\mathrm{J} \sim 10^{10}\ \mathrm{GeV}$$

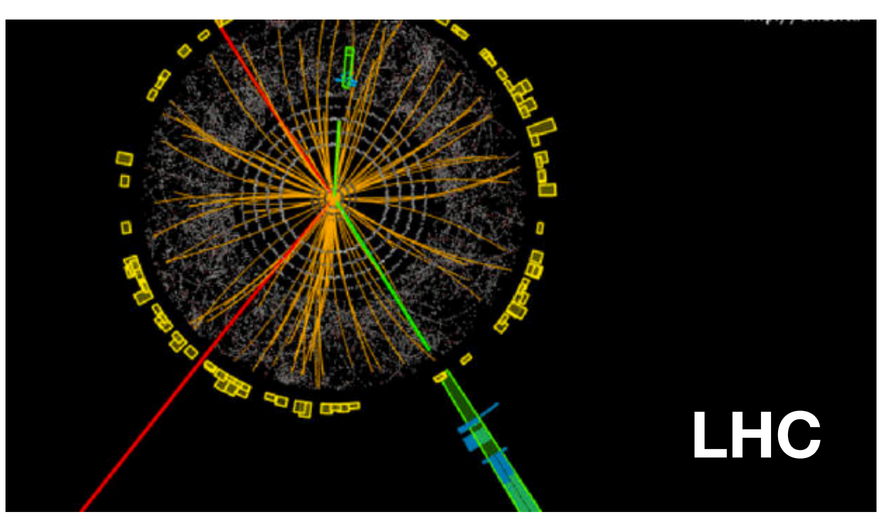
Cross-sections

arrow of time

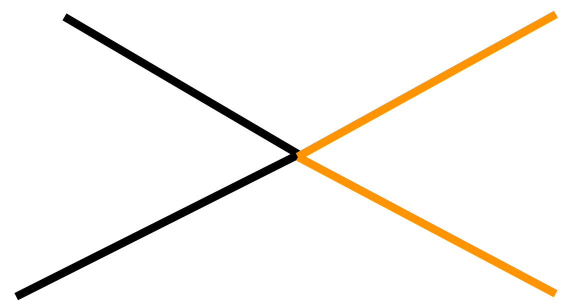
Make it (SM annihilation)

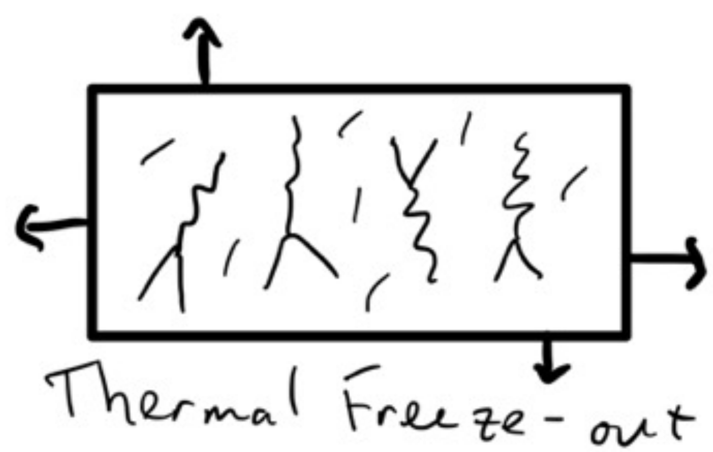


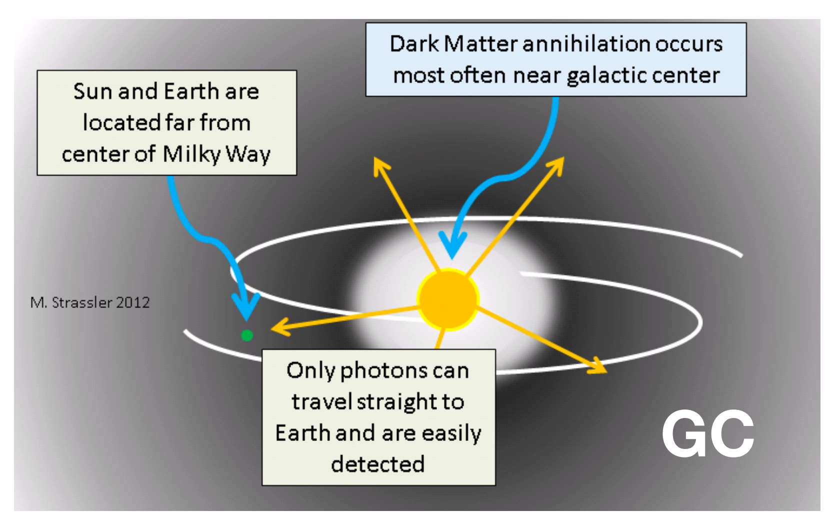




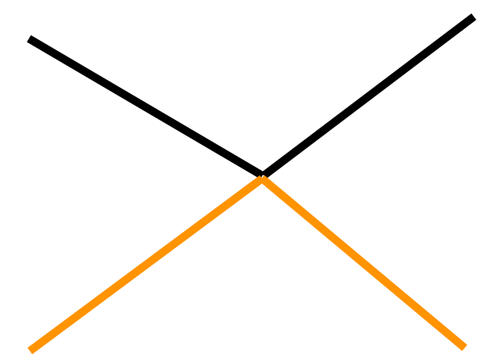
Break it (DM annihilation)

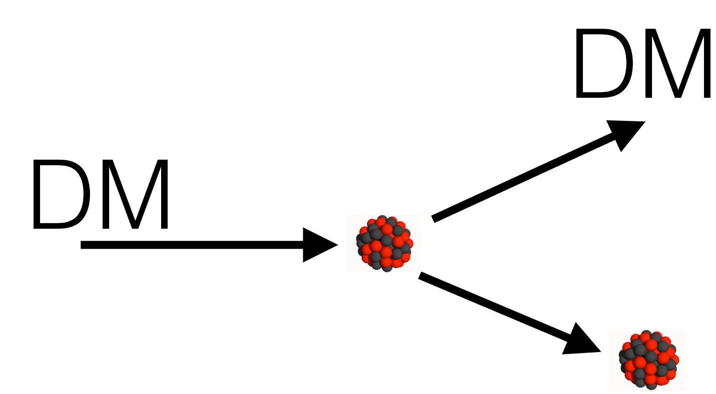






Shake it (DM-SM scattering)



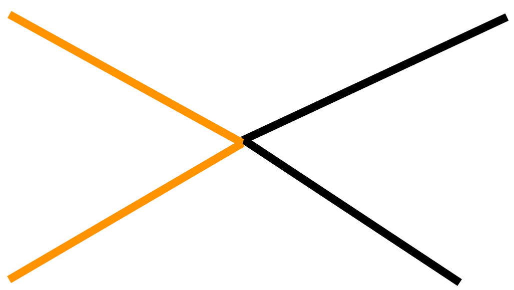


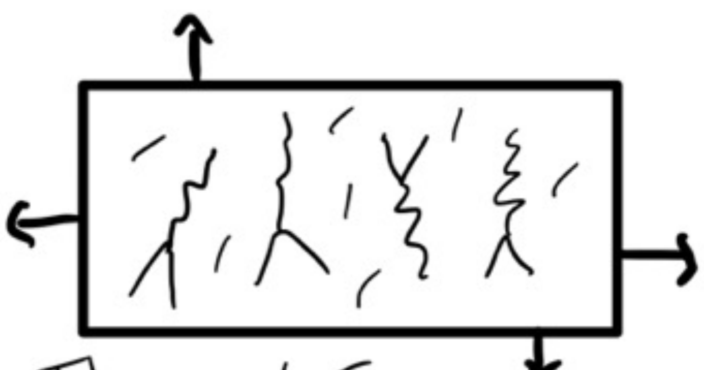
Cross-sections

arrow of time

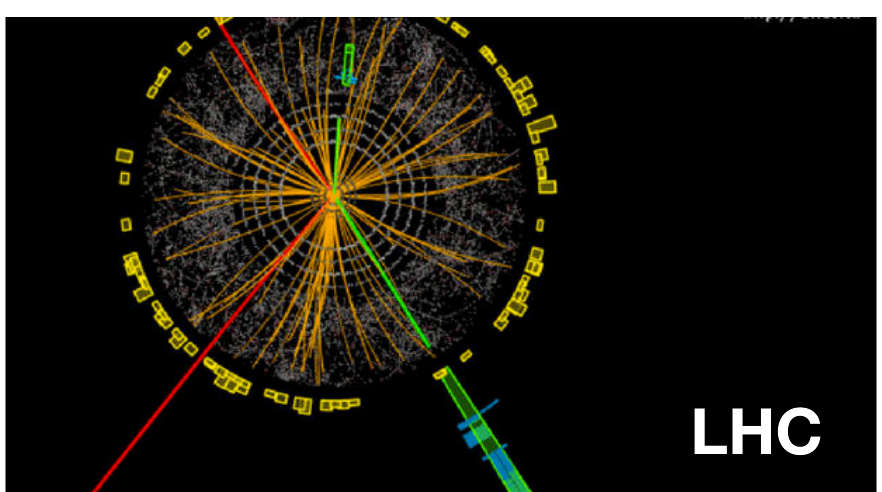
super effective

Make it (SM annihilation)

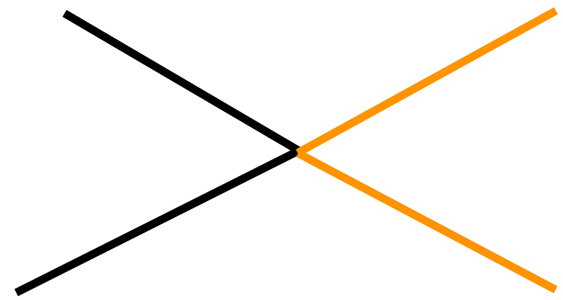




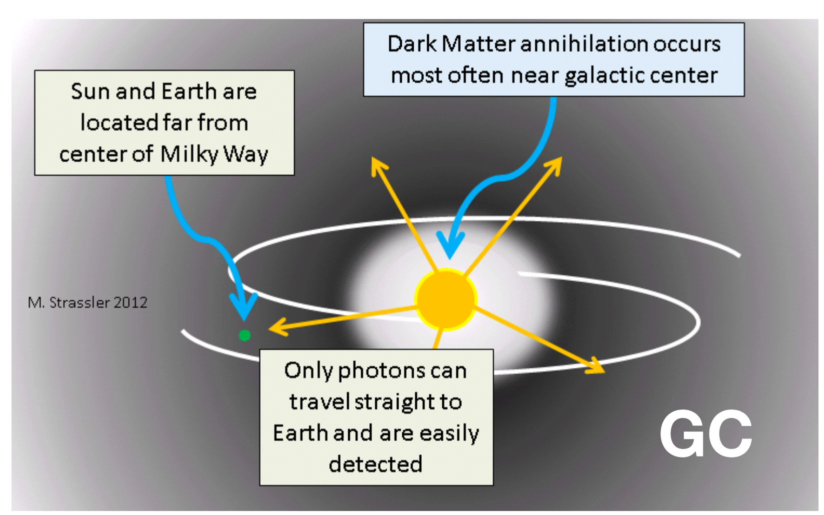
Thermal Freeze-out



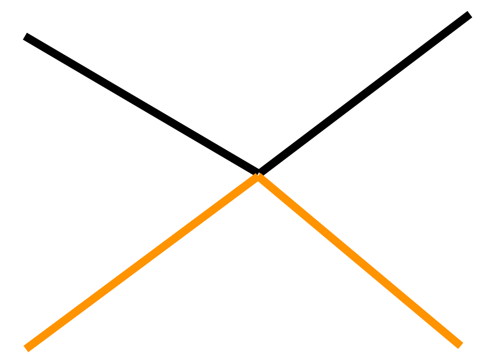
Break it (DM annihilation)

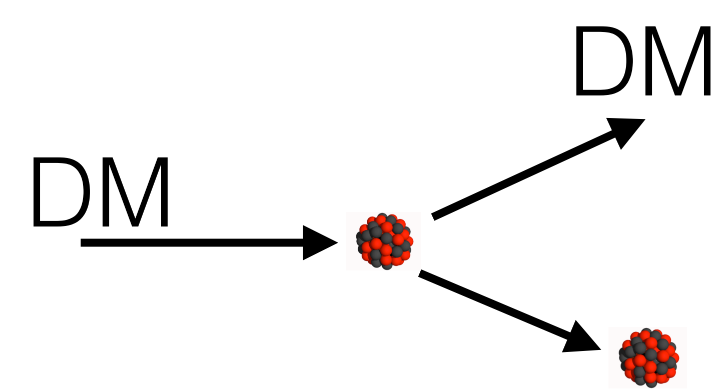


Thermal Freeze-out



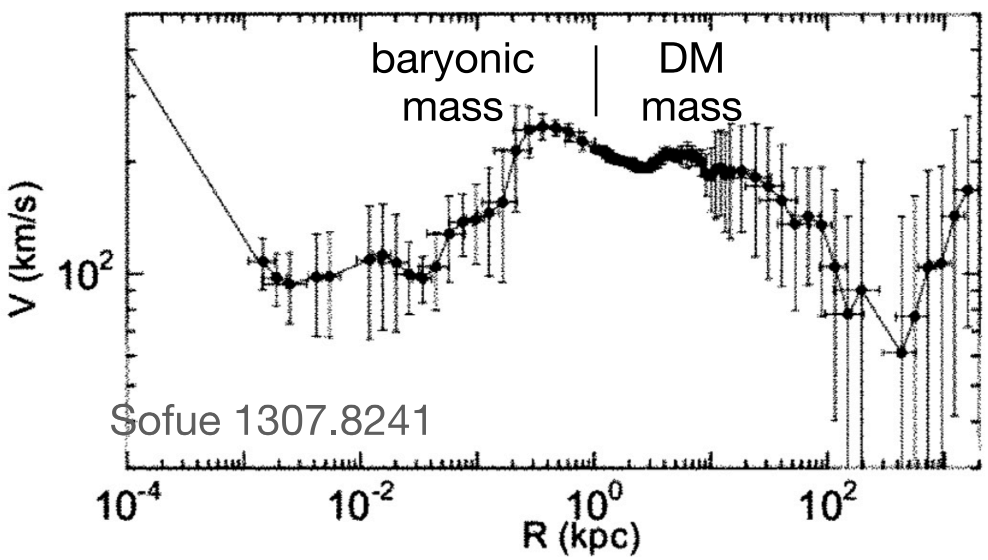
Shake it (DM-SM scattering)

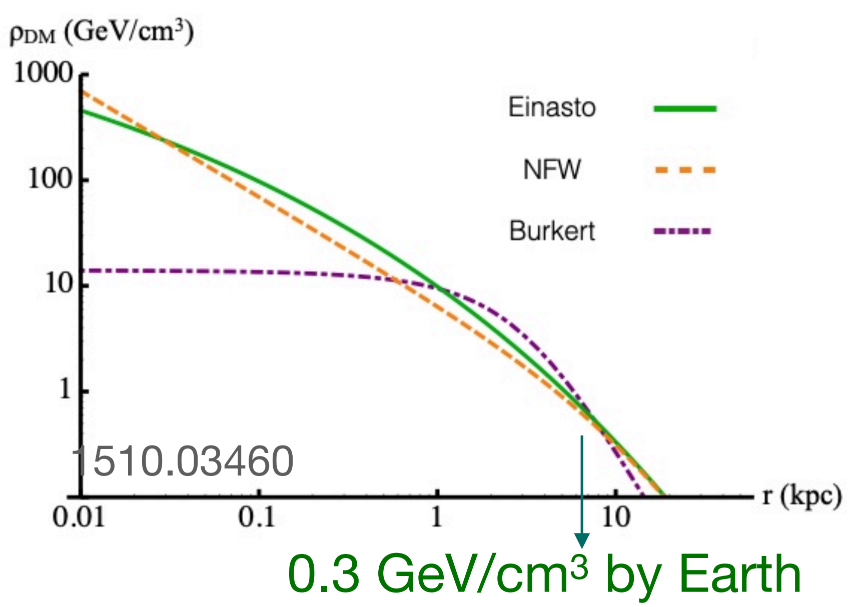




Dark matter near us

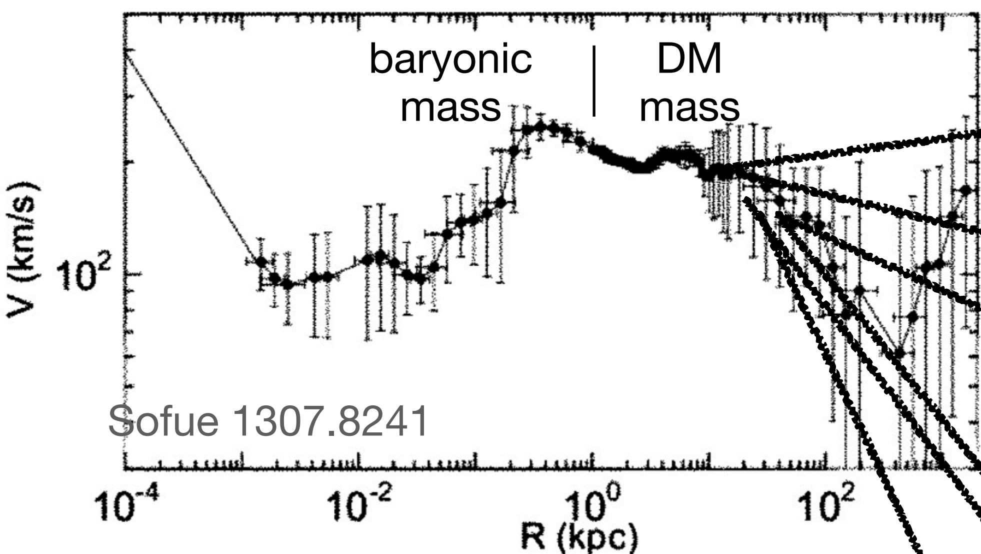
global (~0.001c)

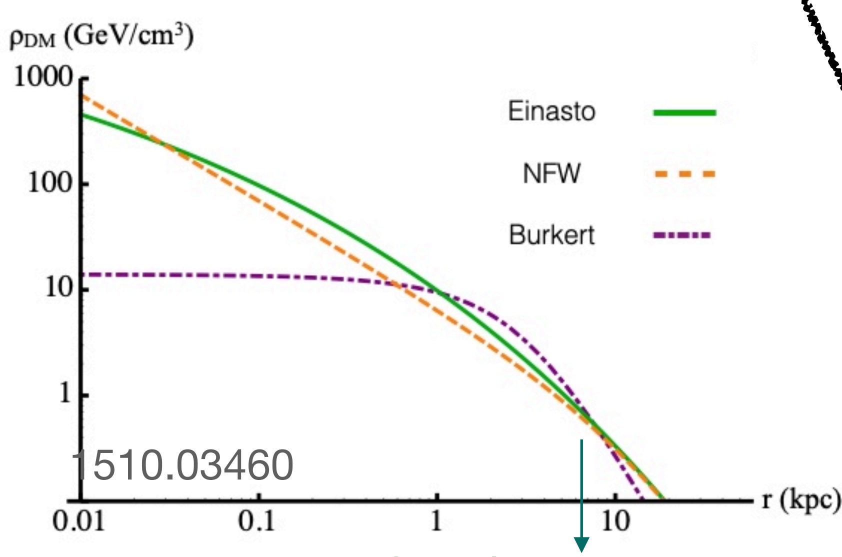




Dark matter near us

global (~0.001c)

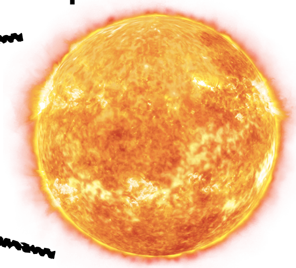




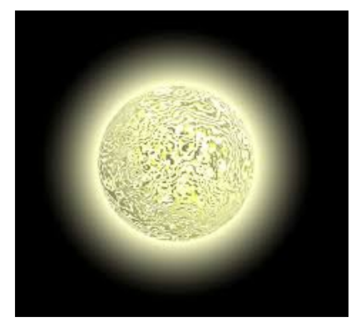
0.3 GeV/cm^3 by Earth

local structure

Main Sequence ~0.002 c

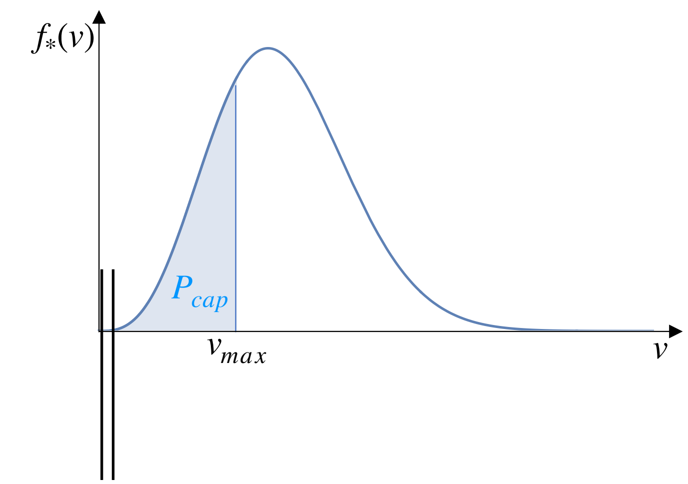


White Dwarf ~0.05 c

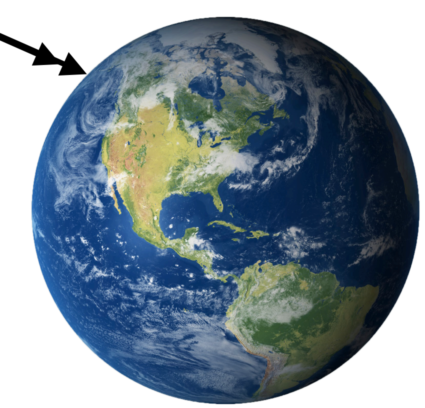


Neutron Star ~0.7 c

local fine structure



minimum DM speed > 11 km/s



Dark Matter Models: SM Coupling and Detection

<u>dark matter</u>

fundamental

composite

<u>spin</u>

0

½

1

3/2

2

5/2

3

...

direct coupling

Quarks

Leptons

Hypercharge Boson

Weak Boson

Higgs Boson

Gluons…

mixing

Dark Photon / Vector Portal

Higgs Portal

(Sterile) Neutrino Mixing…

new intermediate field

Scalar

Fermion

Vector…

Dark Matter Models: SM Coupling and Detection

annihilation scattering DM production

dark matter

fundamental

composite

spin

0

½

1

3/2

2

5/2

3

...

direct coupling

Quarks
Leptons
Hypercharge Boson
Weak Boson
Higgs Boson
Gluons…

mixing

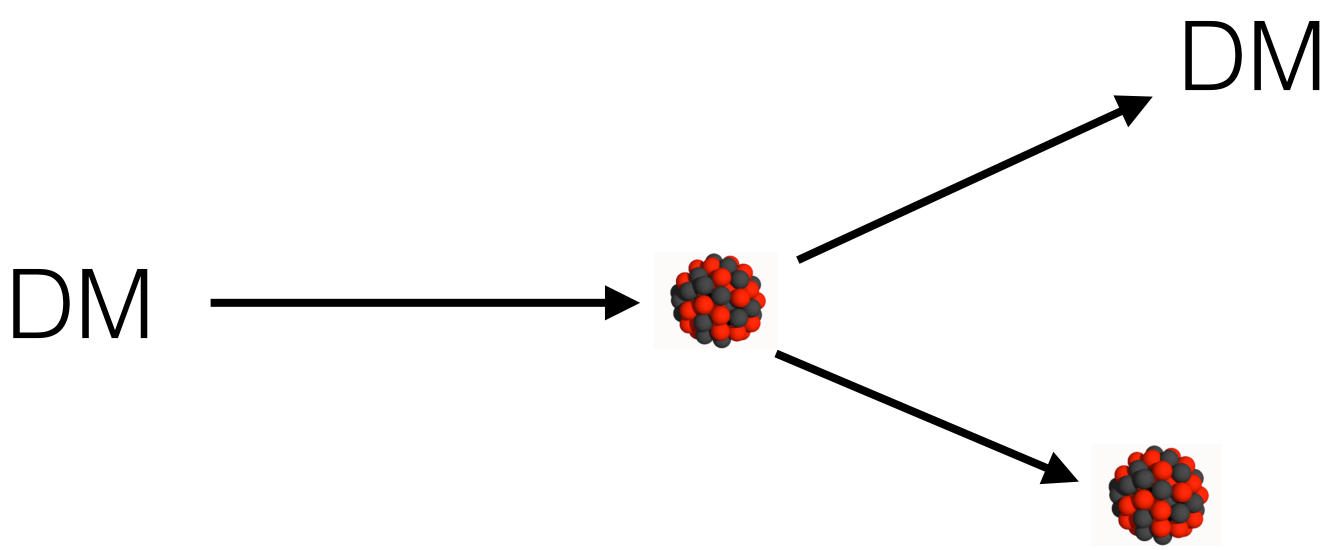
Dark Photon / Vector Portal
Higgs Portal
(Sterile) Neutrino Mixing…

new intermediate field

Scalar
Fermion
Vector…

interactions	detector	mass of interacting SM particles in GeV
	interstellar gas	~10^{60}
+	stars	
+	planets	~10^{50}
	Super-K, IceCube (neutrinos)	~10^{35}
	HAWC, Fermi (gamma rays)	
	XENON1T, LZ, PandaX, SuperCDMS, PICO, SENSEI	~10^{30}
	ADMX, HAYSTAC	
	collider, beam dump	~10^{15}

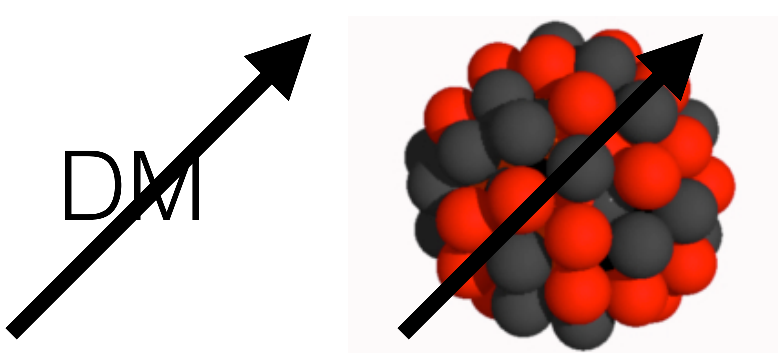
Elastic Cross sections



Nucleus recoil energy:

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

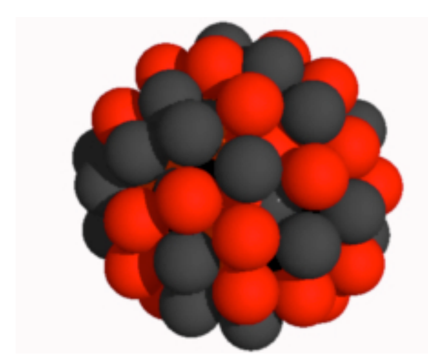
Cross-section, per nucleon, *spin-dependent*



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

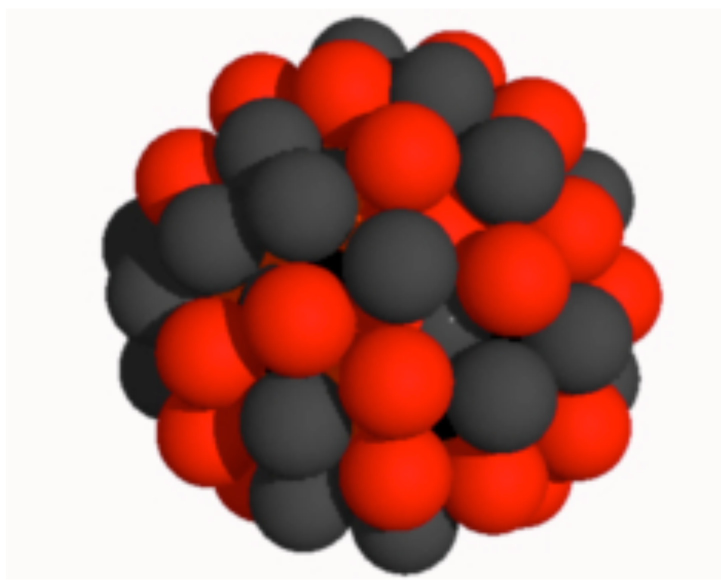
$$\sigma_{Nx} \simeq N^2\frac{\mu_{Nx}^2}{\mu_{nx}^2}\sigma_{nx}$$

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?

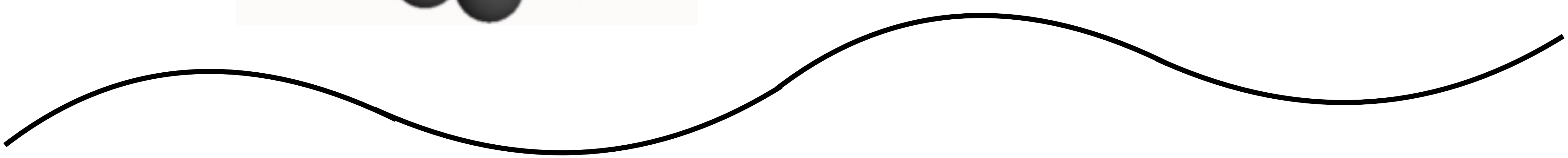
Consider: oxygen, germanium, iodine, xenon



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

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

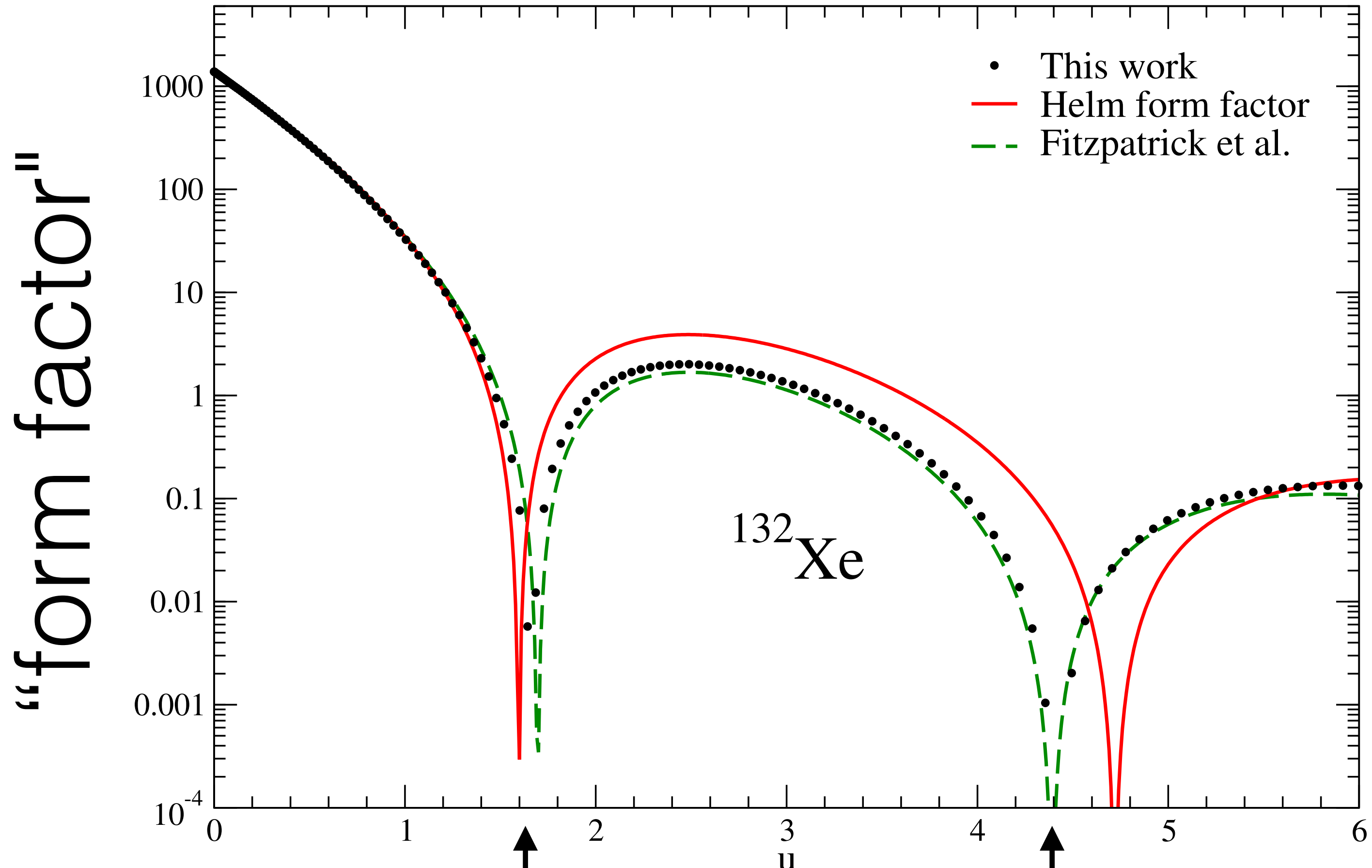
Size of nucleus: $1.2 \times 10^{-13}\, N^{1/3}$ cm



Hint: Use that the wavelength λ of the momentum exchange must be larger than the nucleus for the system to be invariant under exchange of which nucleon was scattered with.

Nuclear structure “form factor"

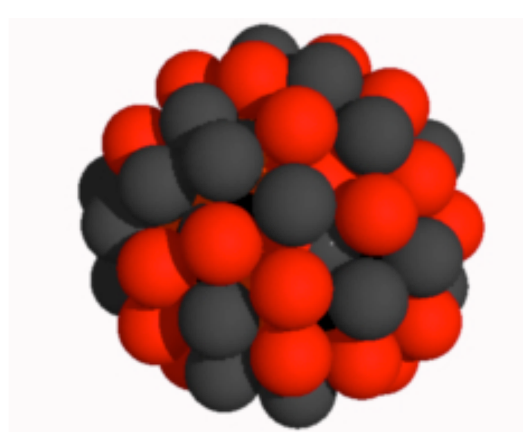
1412.6091

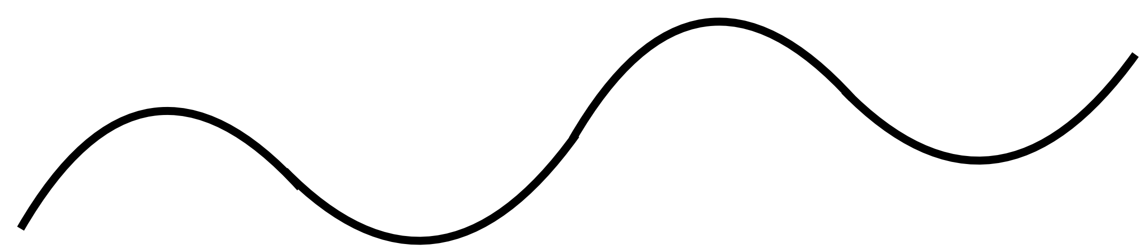


E_R 100 keV 260 keV

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

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





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**

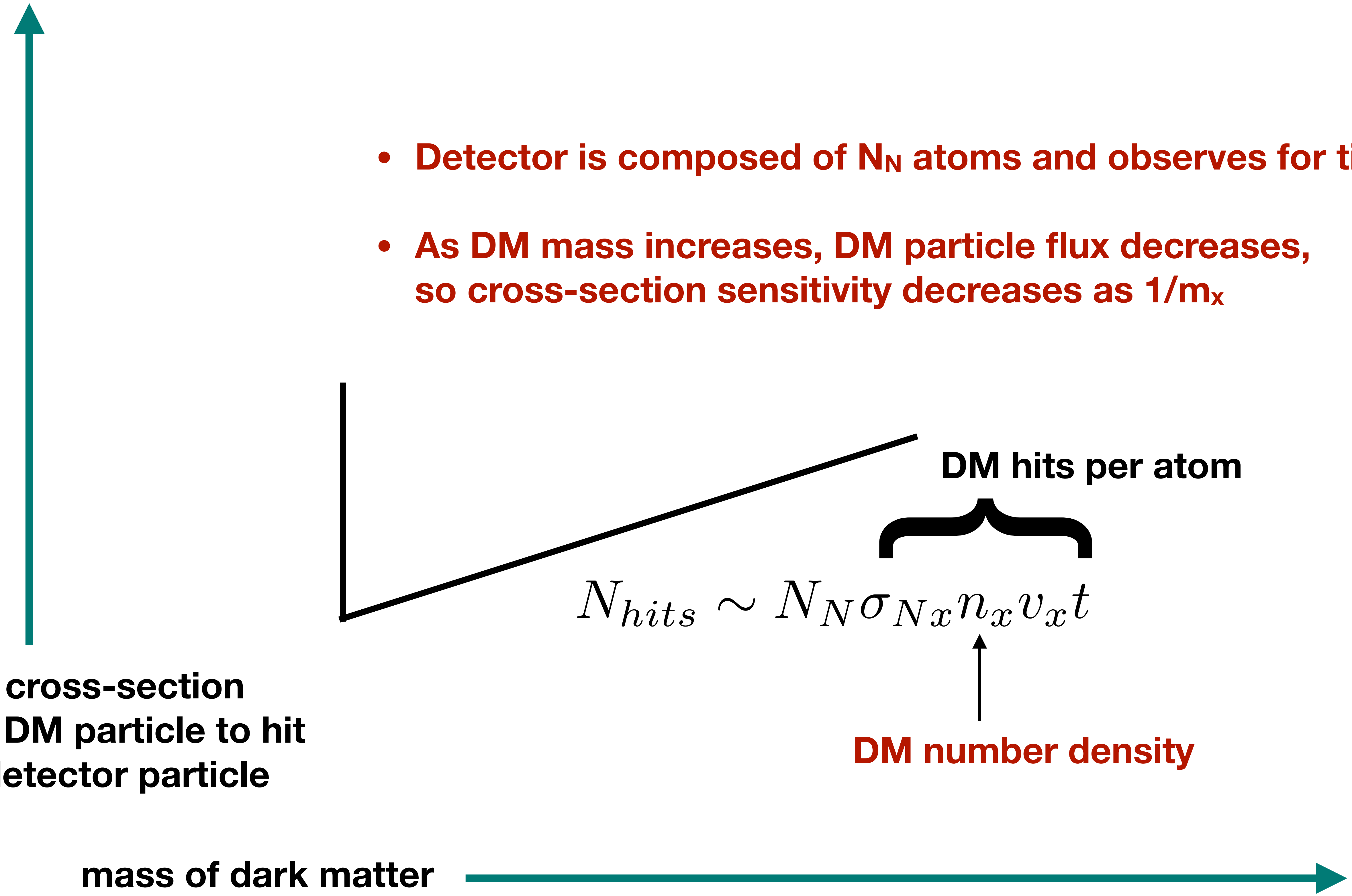
$$E_{th} \sim \mu_{Nx}^2 v_x^2 / m_N$$

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 $1/m_x$**

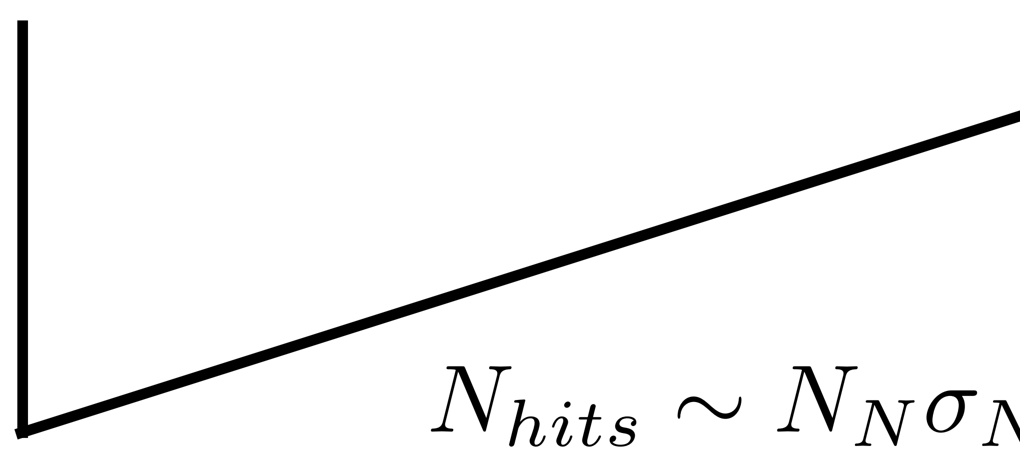


$$N_{hits} \sim N_N \overbrace{\sigma_{Nx} n_x v_x t}^{\text{DM hits per atom}}$$

DM number density

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 $1/m_x$**



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

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

~2 hits for 90% confidence limit

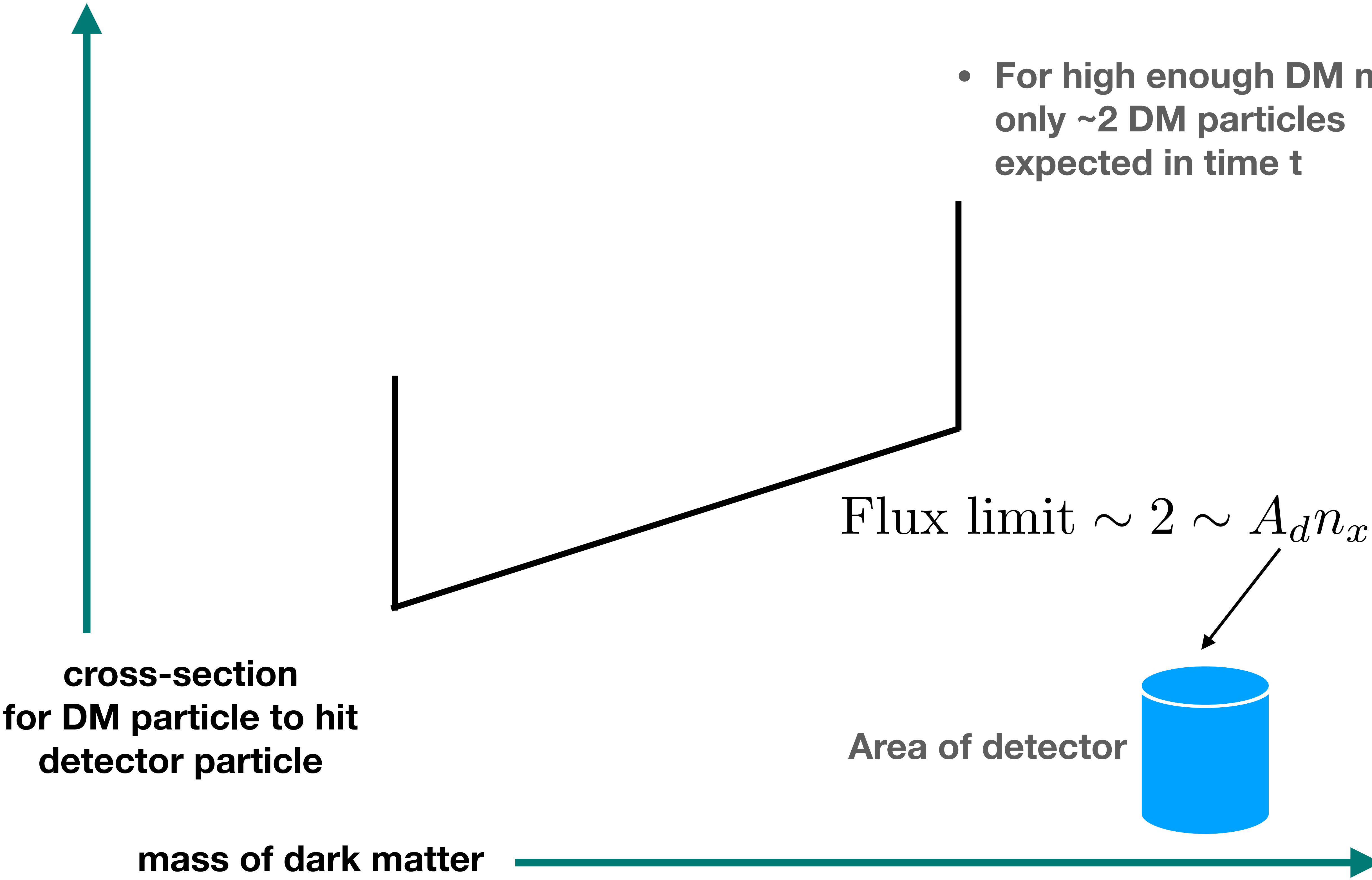
cross-section for DM particle to hit detector particle

mass of dark matter

Experiment looking for flux of new particles

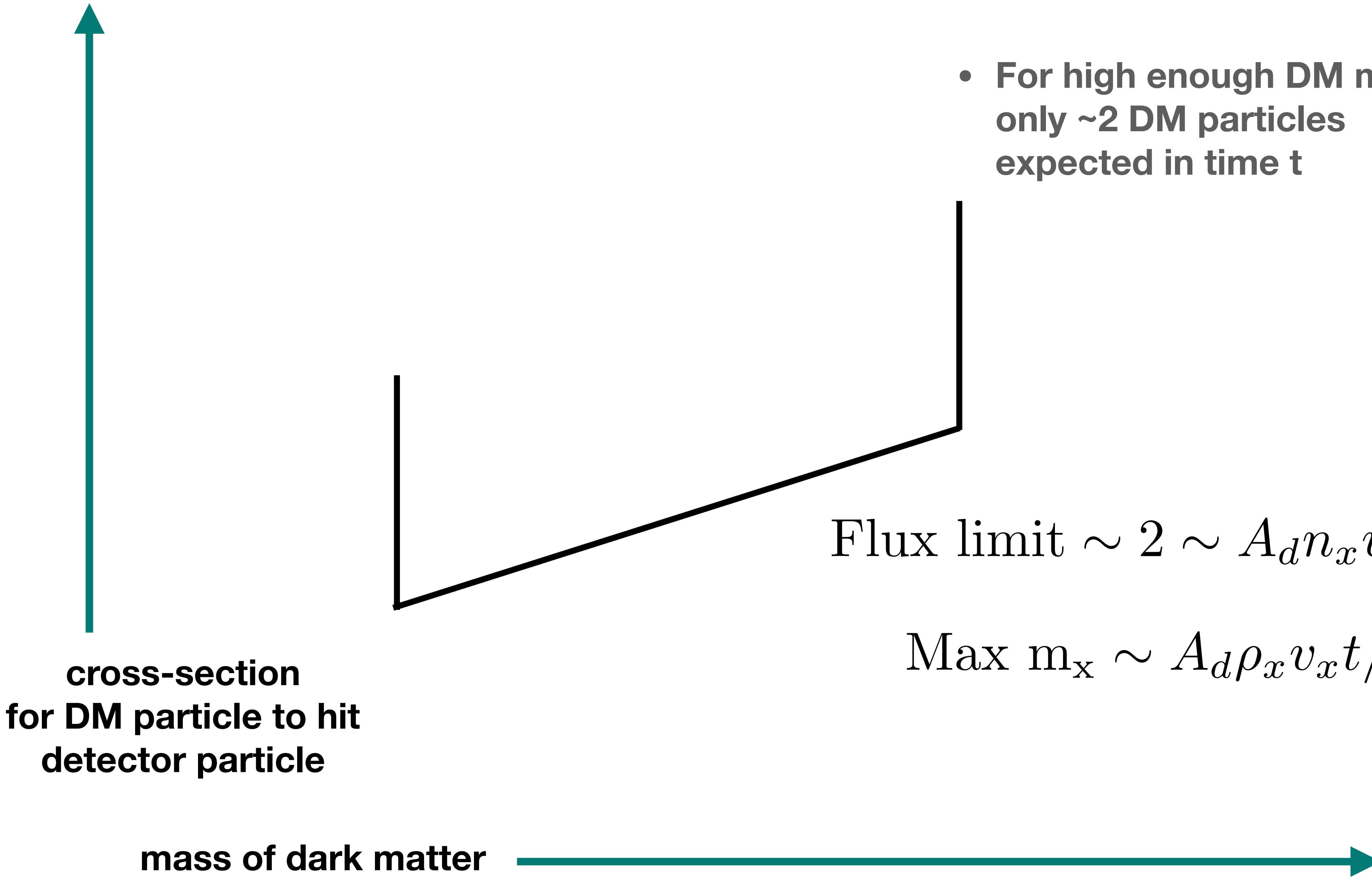
- **For high enough DM mass, only ~2 DM particles expected in time t**

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



Experiment looking for flux of new particles

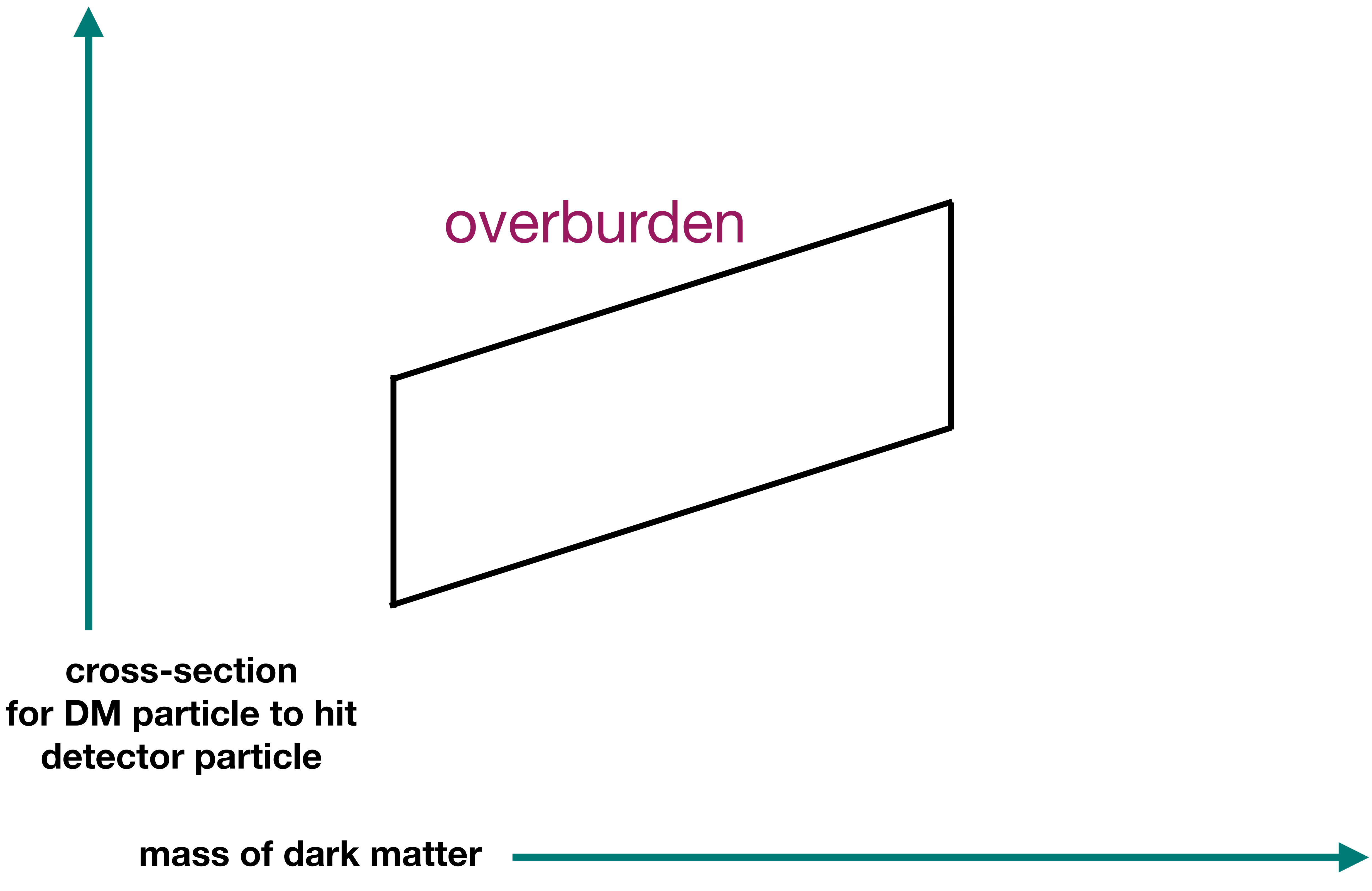
- **For high enough DM mass, only ~2 DM particles expected in time t**



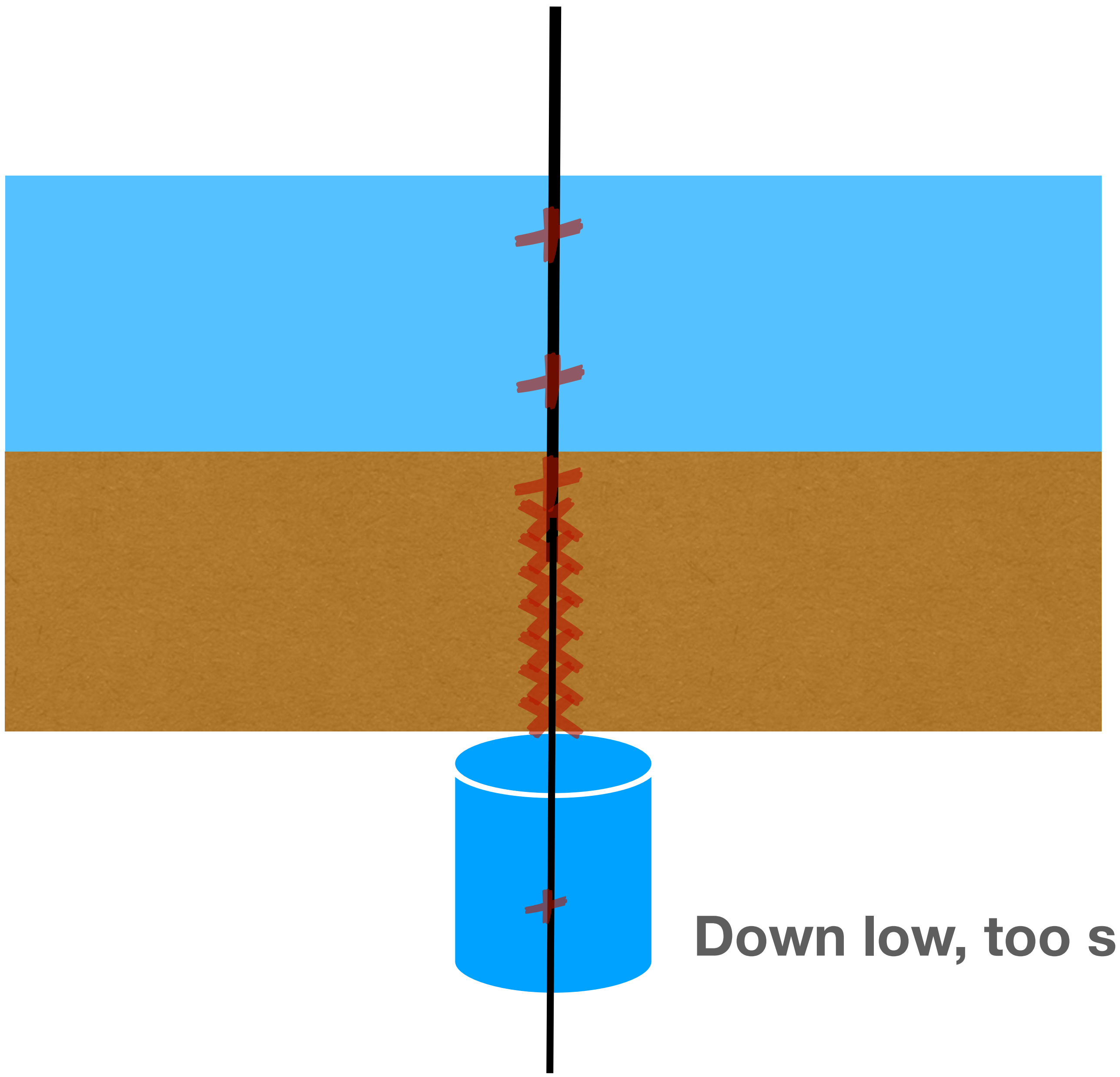
$$\text{Flux limit} \sim 2 \sim A_d n_x v_x t$$

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

Experiment looking for flux of new particles

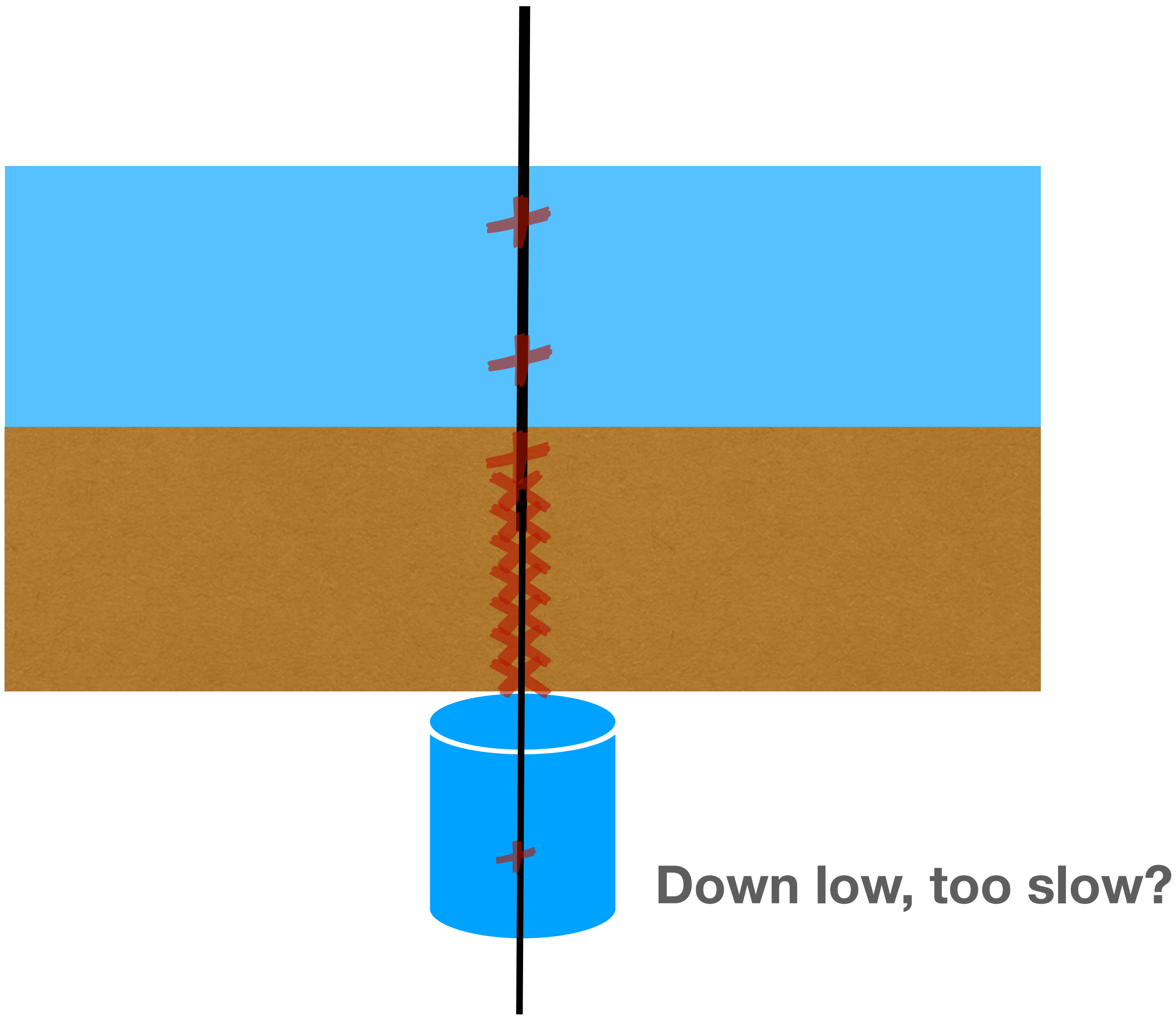


Overburden



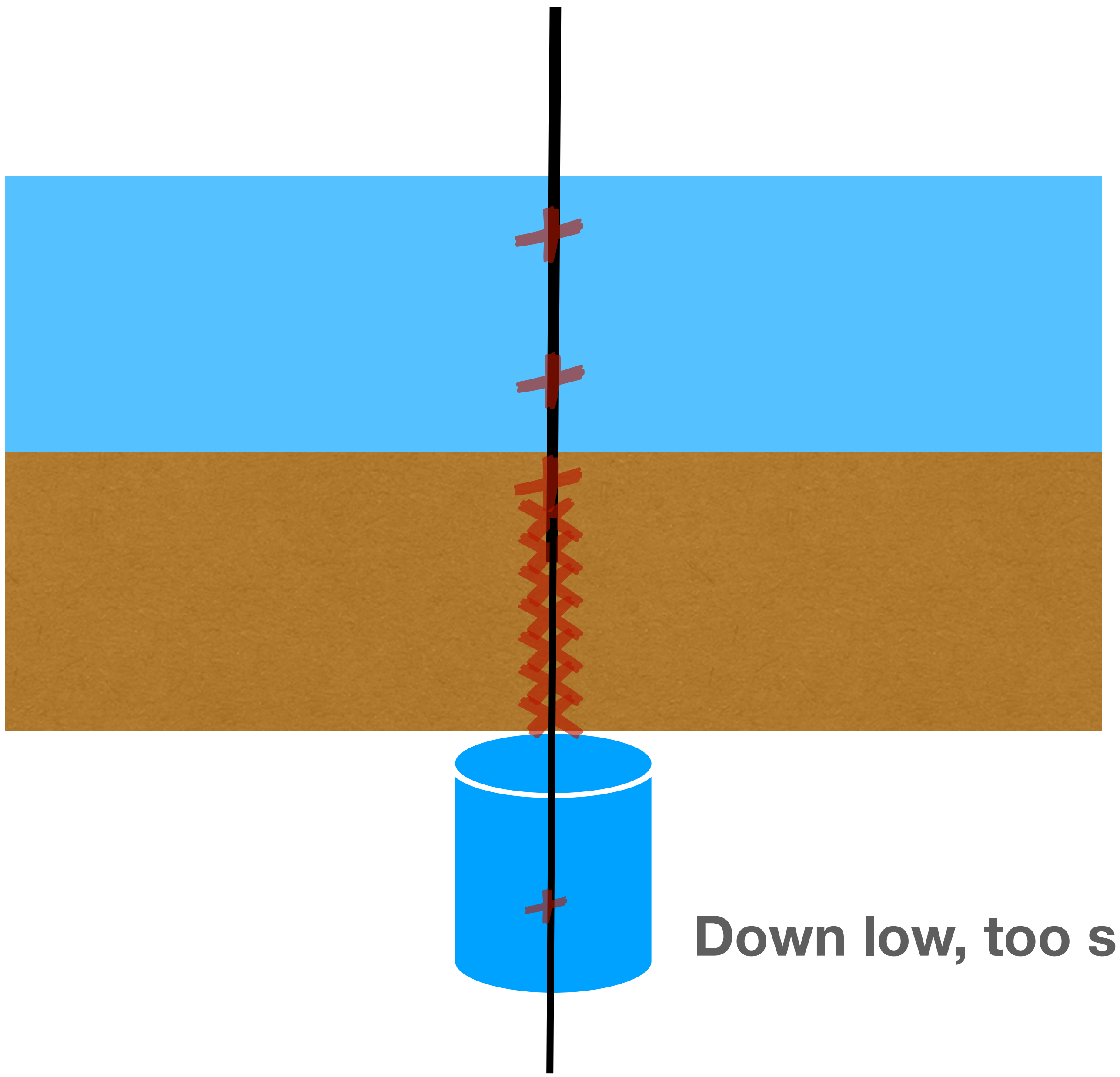
- **DM particles may be slowed through repeated scattering with atmosphere, earth, rocket shielding, concrete.**

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

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

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 $\sim m_x v_x^2$**

cross-section for DM particle to hit detector particle

mass of dark matter

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

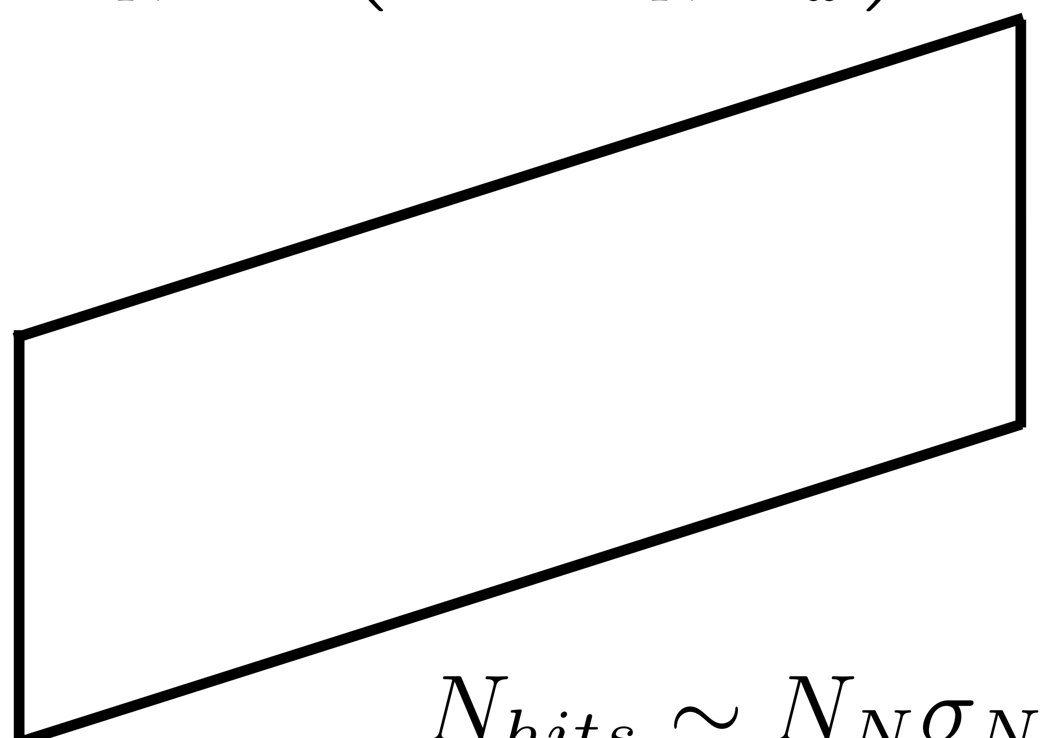
Experiment looking for flux of new particles

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

Flux limit $\sim 2 \sim A_d n_x v_x t$

Max $\mathrm{m_x} \sim A_d \rho_x v_x t/2$

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



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

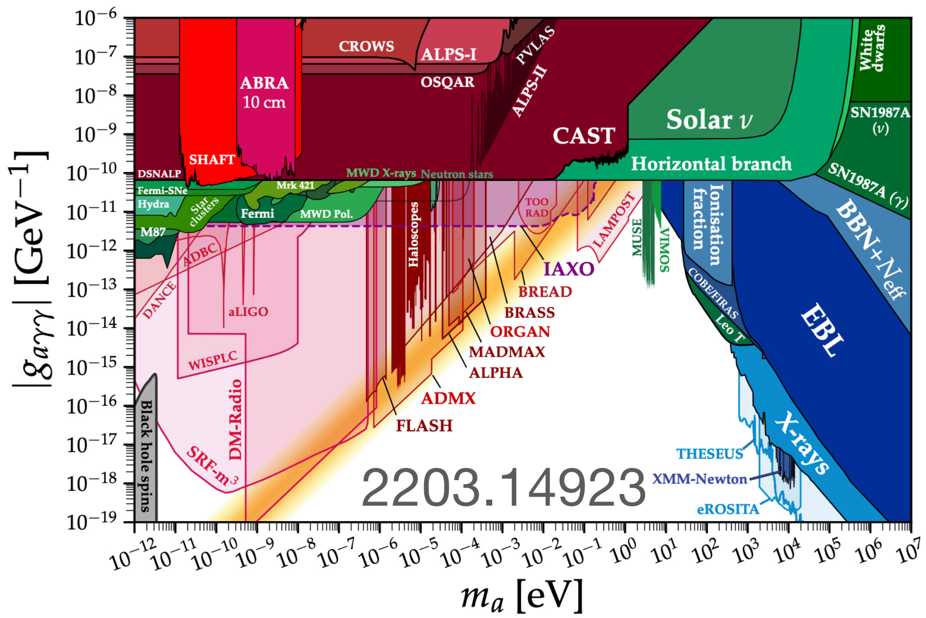
cross-section for DM particle to hit detector particle

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

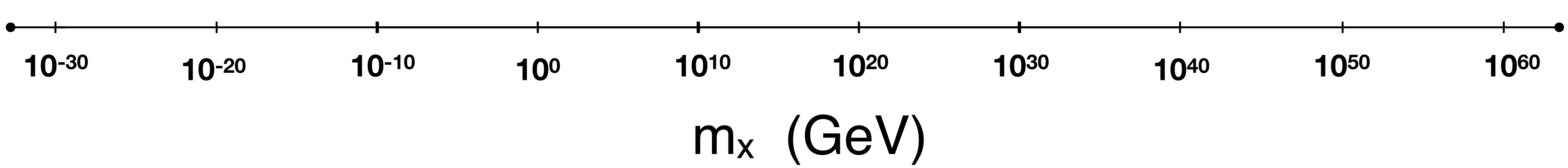
mass of dark matter

SKIM THROUGH DM SEARCHES

Light dark matter

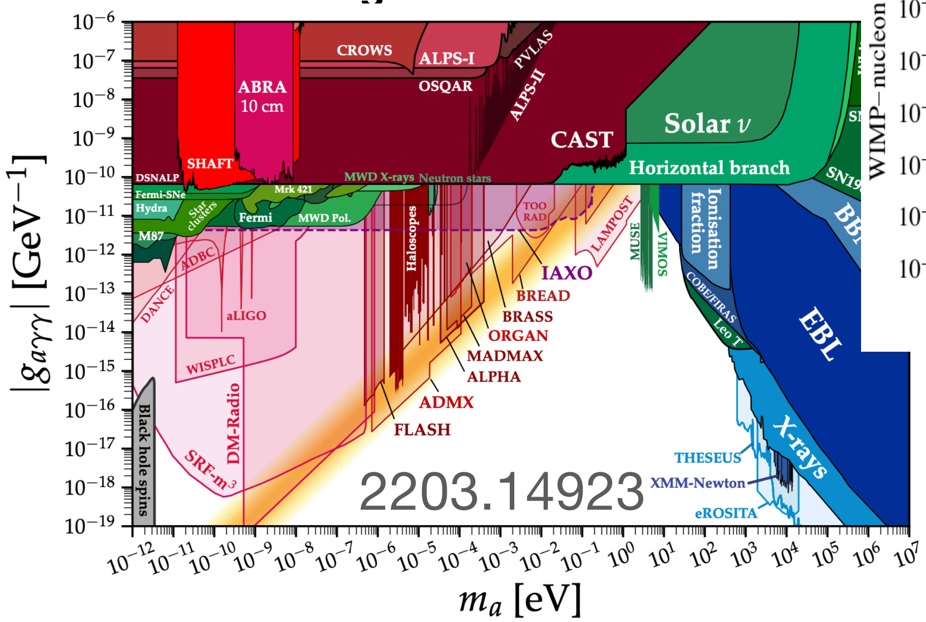


Axion/ DP (wavy bosons)

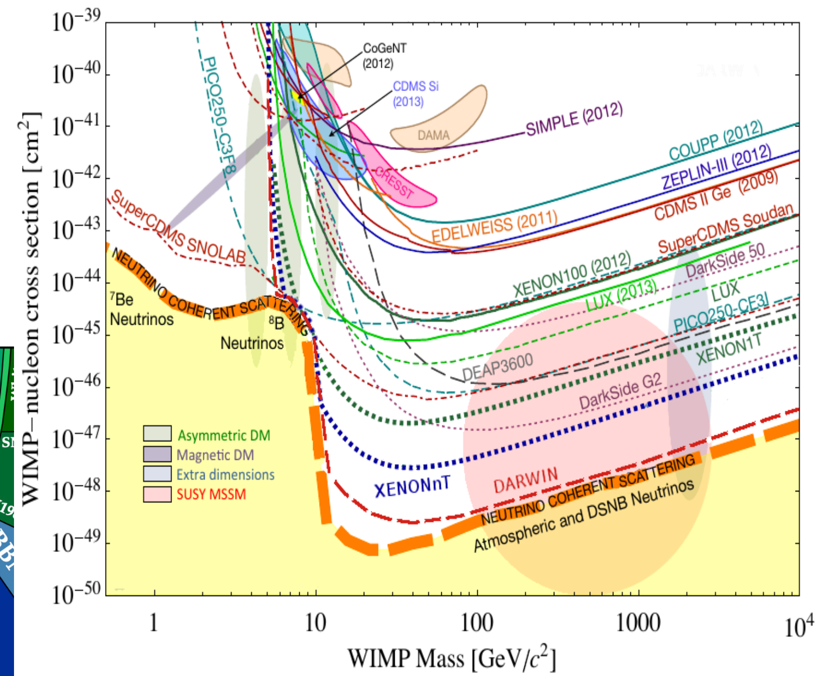


SKIM THROUGH DM SEARCHES

Light dark matter



Axion/ DP (wavy bosons)

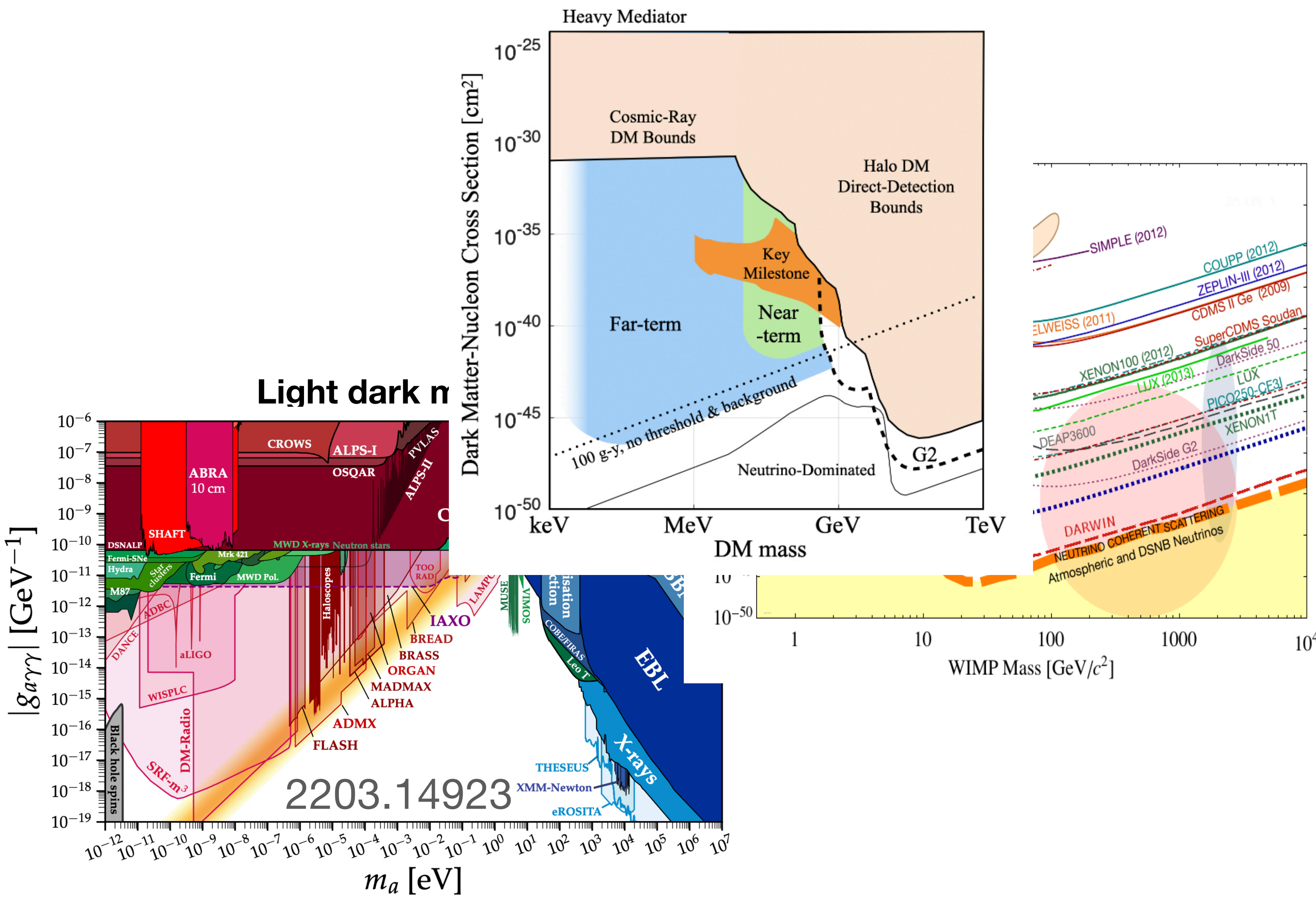


10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

m_x (GeV)

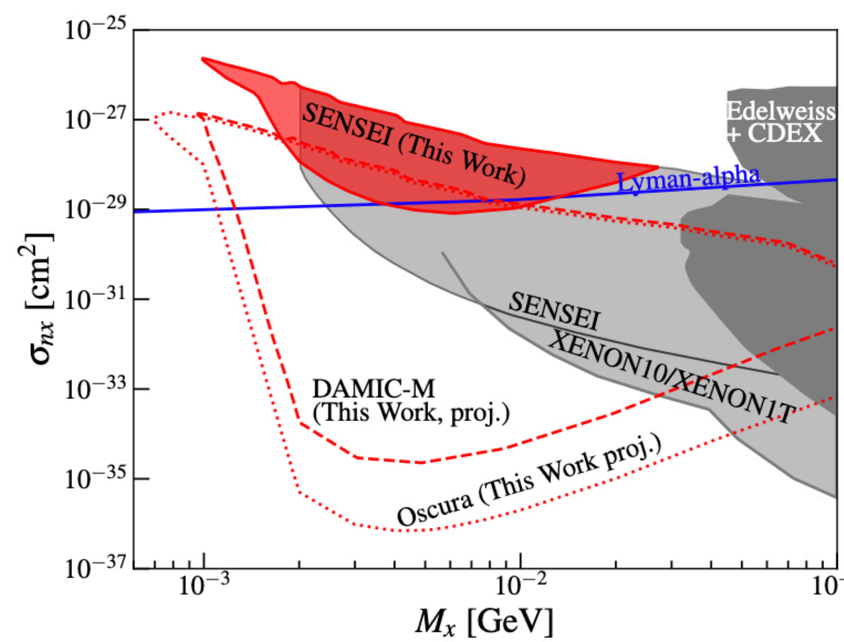
SKIM THROUGH DM SEARCHES

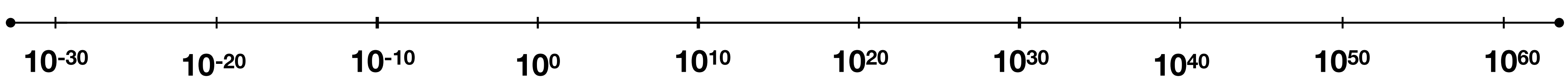
2203.08297



Axion/ DP (wavy bosons)

2307.13727

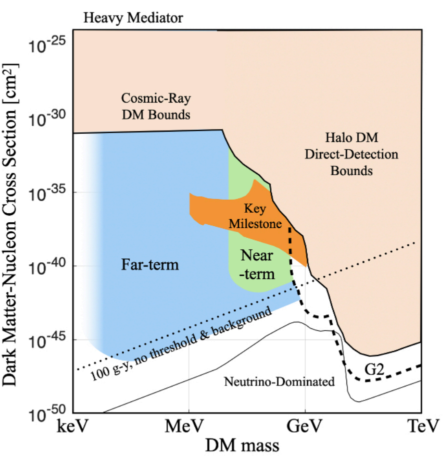




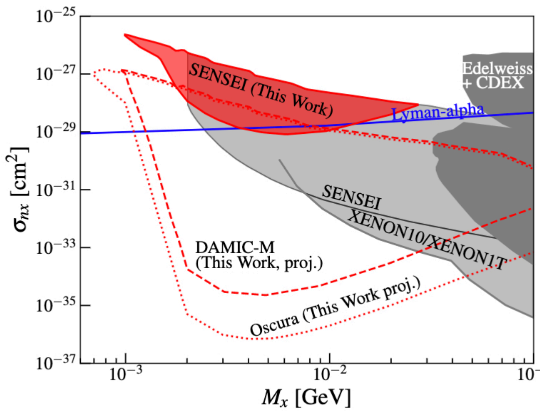
m_x (GeV)

SKIM THROUGH DM SEARCHES

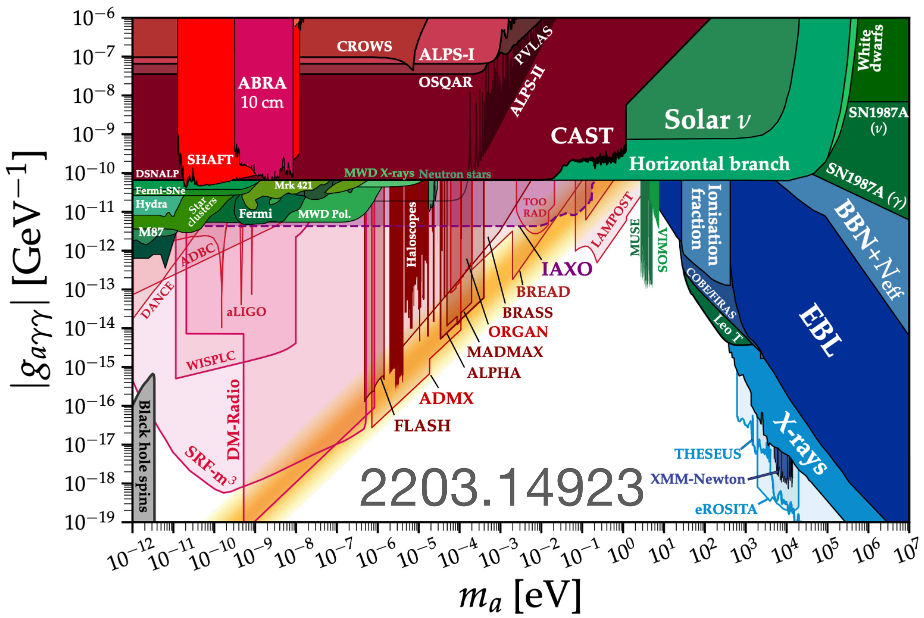
2203.08297



2307.13727

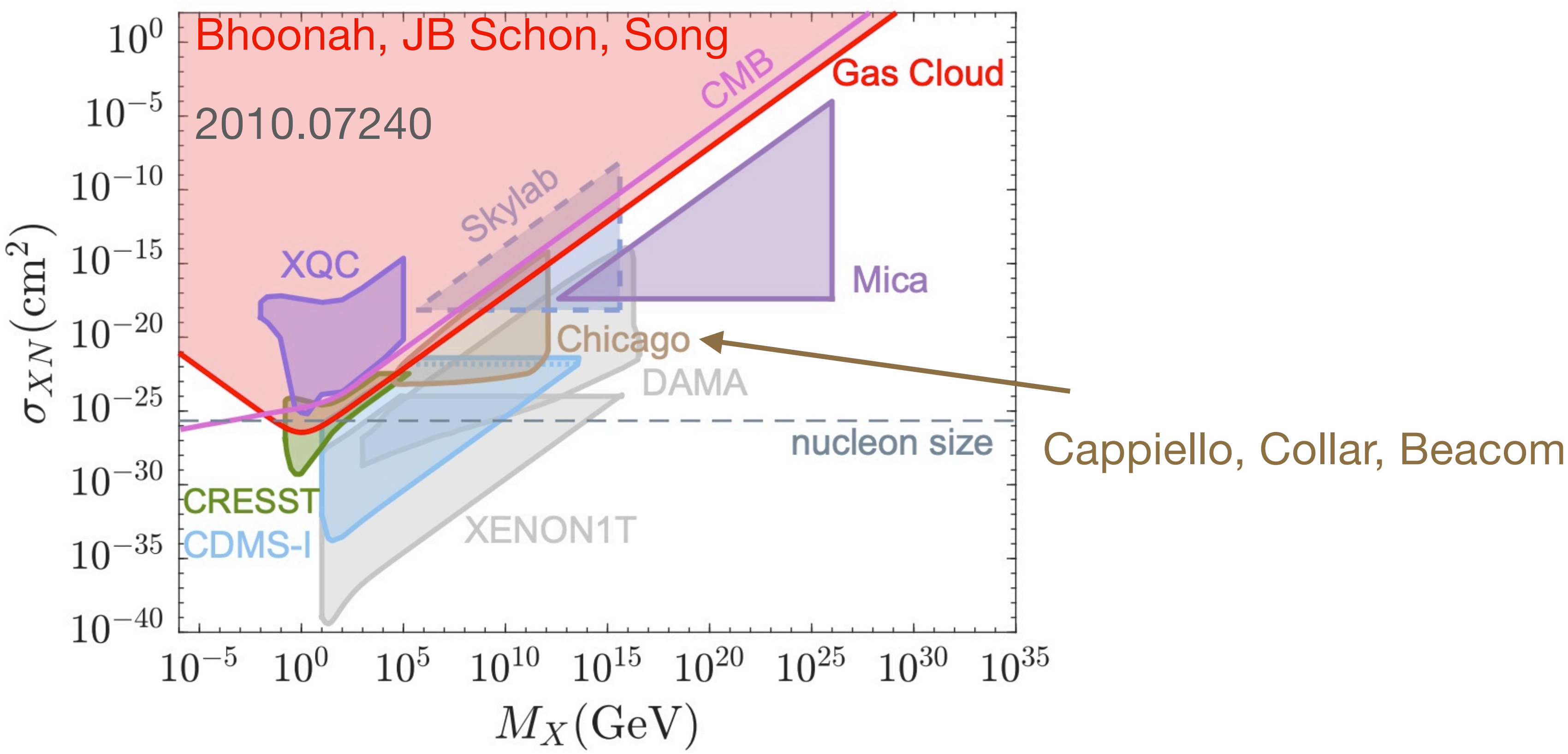


Light dark matter



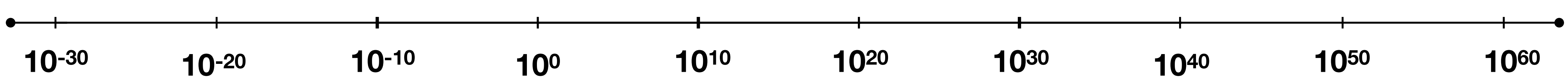
Axion/ DP (wavy bosons)

Heavy dark matter



high m,σ composites

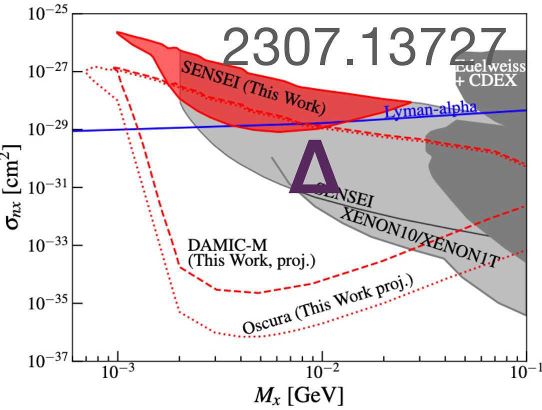
Witten '84



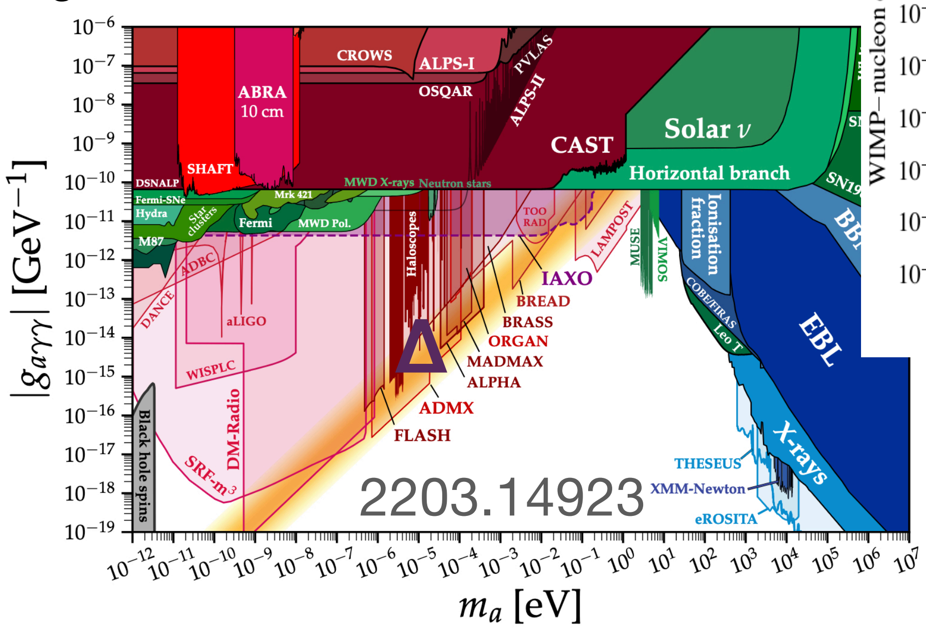
m_x (GeV)

PRICE OF DM DETECTION

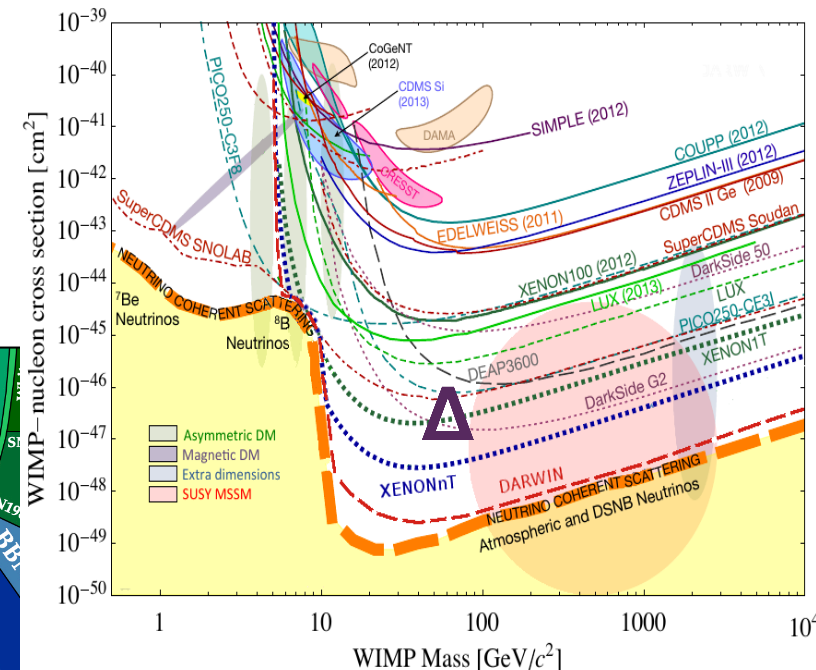
$$\text{current price of DM} \sim \$(10^5 - 10^6) \times \log_{10}(\Delta\sigma) \times \log_{10}(\delta m_X)$$



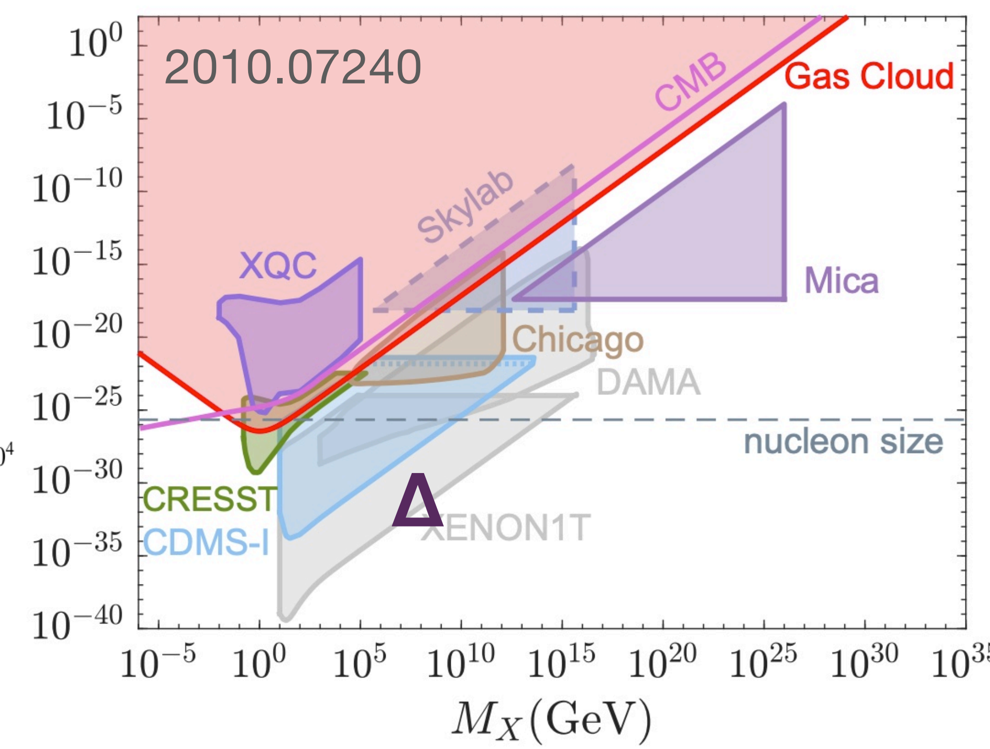
Light dark matter

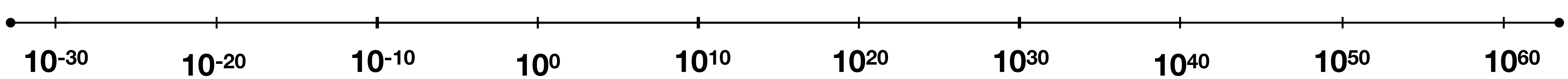


Axion/ DP (wavy bosons)



Δσ relative to last generation





m_X (GeV)

Capstone exercise III:

Density of earth crust: 3 g/cm^3
Mostly made of oxygen
Mass of nucleon = 1 GeV

The NaI crystal in this room is sensitive to >1 keV recoil energies and transforms ~10% of the recoil energy to visible photons. What bounds can be placed on dark matter? It may be useful to know that we could probably notice a pulse of ~10^5 visible yellow photons~200 keV in a burst. Assume a 10 m thick overburden made of water (oxygen).

Bonus: Treat the entire earth as a detector.
We are alive — earth's surface temperature is < 1000 K.
What does that tell us about dark matter?

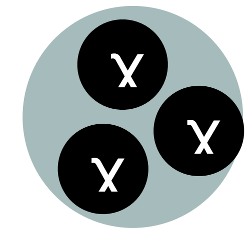
Consider: DM that annihilates with itself to energy in the earth, and DM that co-annihilate baryons.

DM Models

Vis-a-vis heavy composite DM

$$\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathcal{L}_{SM},$$

-Composite



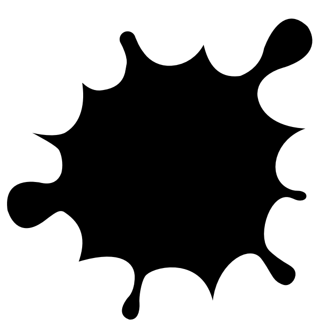
Nice to have a model

- Early matter domi dark sector
- Boson stars ars
- Dark QCD/BBN

On the other hand: Wha
Lagrangian / cosmolog

ormation still has
uestions (e.g. pebble
on).

composite DM
have simple
cs like single-field
DM models



Predict masses from 1st principles?

DM Models

Vis-a-vis heavy composite DM

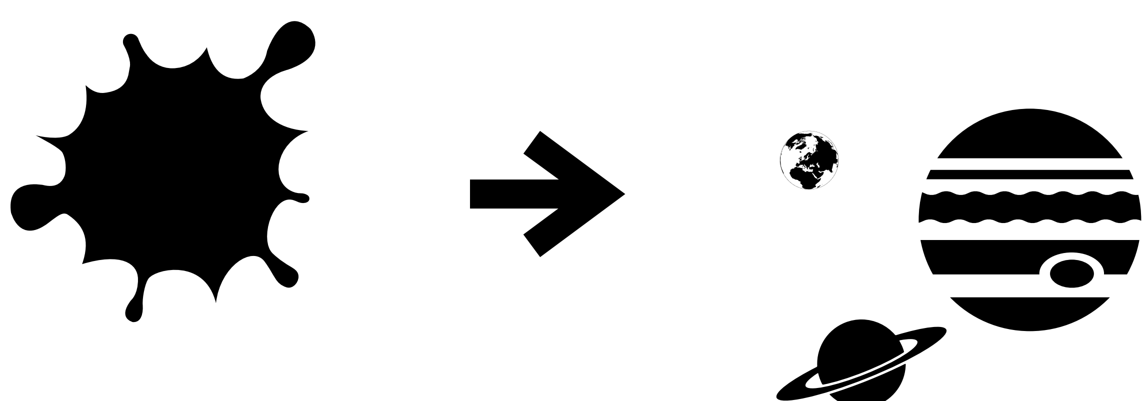
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

-Composite

Nice to have a model

- Early matter domination
- Boson stars
- Dark QCD/BBN
- Dissipative dark sector
- Fermion stars

On the other hand: What is the Lagrangian / cosmology for planets?



Predict masses from 1st principles?

- Planet formation still has open questions (e.g. pebble accretion).
- Heavy composite DM doesn't have simple dynamics like single-field DM models

HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

Consider a simple model of fermionic DM coupled by a scalar field

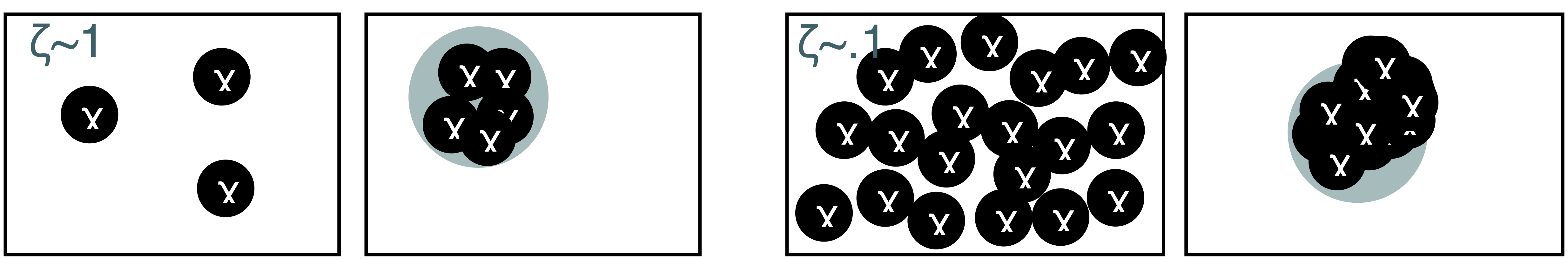
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

see also e.g.
Wise Zhang '14, Krnjaic Sigurdson '14, Hardy Lasenby March-Russell '14, Detmold McCullough Pochinsky '14
Gresham Lou Zurek '17, Coskuner, Grabowska, Knapen, Zurek '18

Diluted dark matter has a freeze-out abundance that scales with ζ^{-1}

This overabundance of dark matter leads to very large $\varphi - X$ composites

Javier Acevedo, JB, Goodman 2012.10998



$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5} = \left(\frac{20\sqrt{g_{ca}^*}T_r T_{ca}^{3/2} M_{pl}}{m_X^{*7/2}\zeta}\right)^{6/5} \simeq 10^{27}\left(\frac{g_{ca}^*}{10^2}\right)^{3/5}\left(\frac{T_{ca}}{10^5\,\mathrm{GeV}}\right)^{9/5}\left(\frac{5\,\mathrm{GeV}}{m_X^*}\right)^{21/5}\left(\frac{10^{-6}}{\zeta}\right)^{6/5}$$

Composite mass ranging from milligrams to thousands of tons

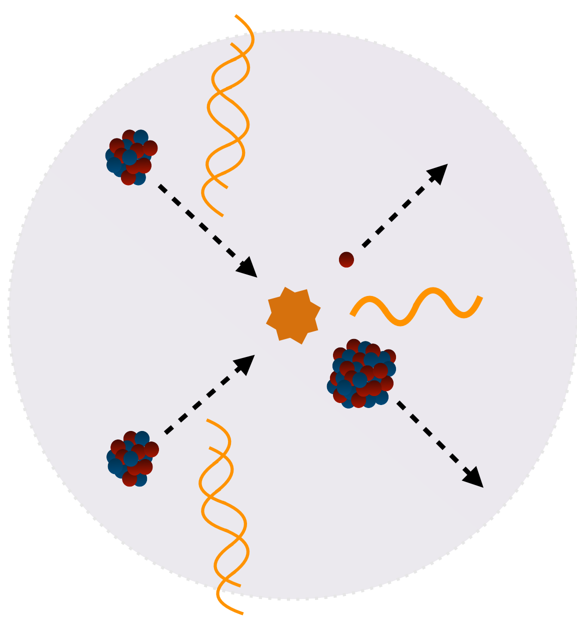
COMPOSITE INTERACTIONS

$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

<u>nuclear interactions with DM composite internal potential</u>

<u>scattering with constituents</u>

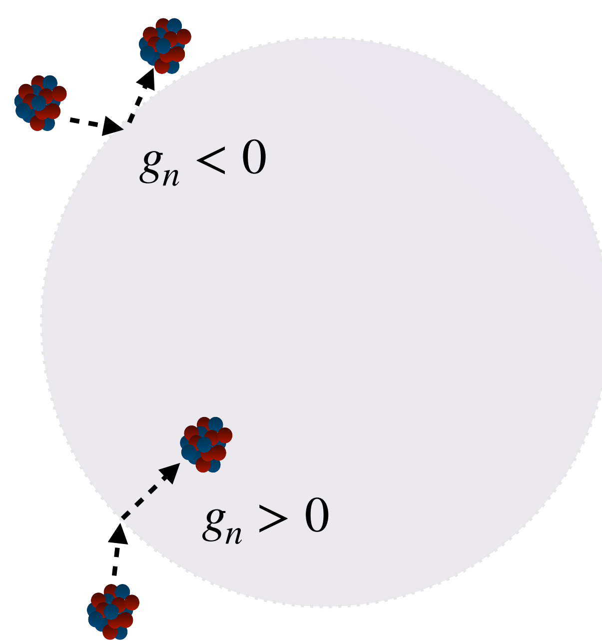
<u>1.</u>



$\langle\varphi\rangle \lesssim m_N,\ g_n > 0$

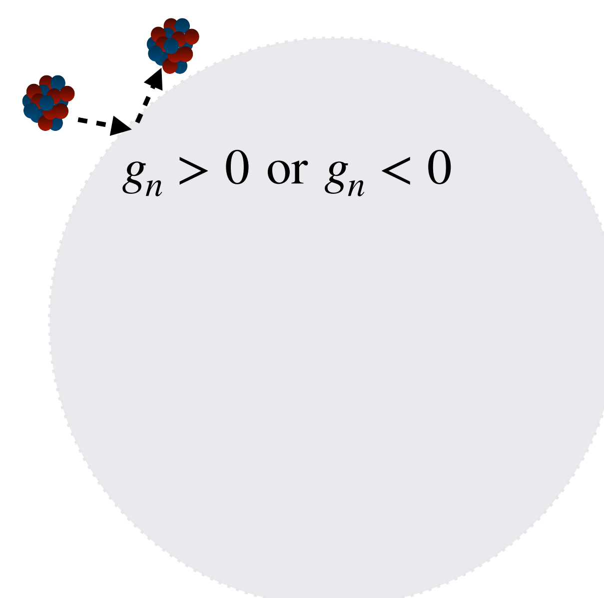
Acevedo, JB, Goodman
2012.10998

<u>2.</u>



$\langle\varphi\rangle \ll m_N$

<u>3.</u>

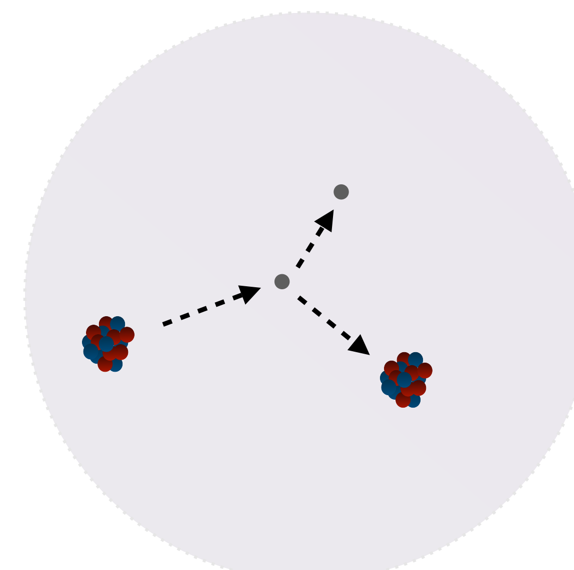


$\langle\varphi\rangle > m_N$

(MIMPs)

Acevedo, JB, Goodman
2108.10899

<u>4.</u>



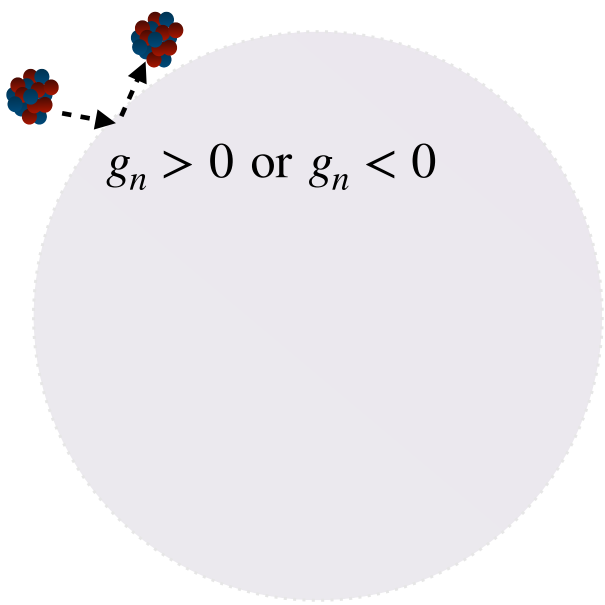
Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Tyagi, coming soon

MIMP INTERACTIONS

$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

nuclear interactions with DM composite internal potential

3.



$\langle\varphi\rangle > m_N$

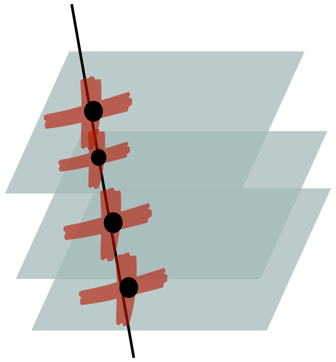
(MIMPs)

Acevedo, JB, Goodman
2108.10899

ANCIENT SEARCHES FOR NEW PARTICLES

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

Skylab



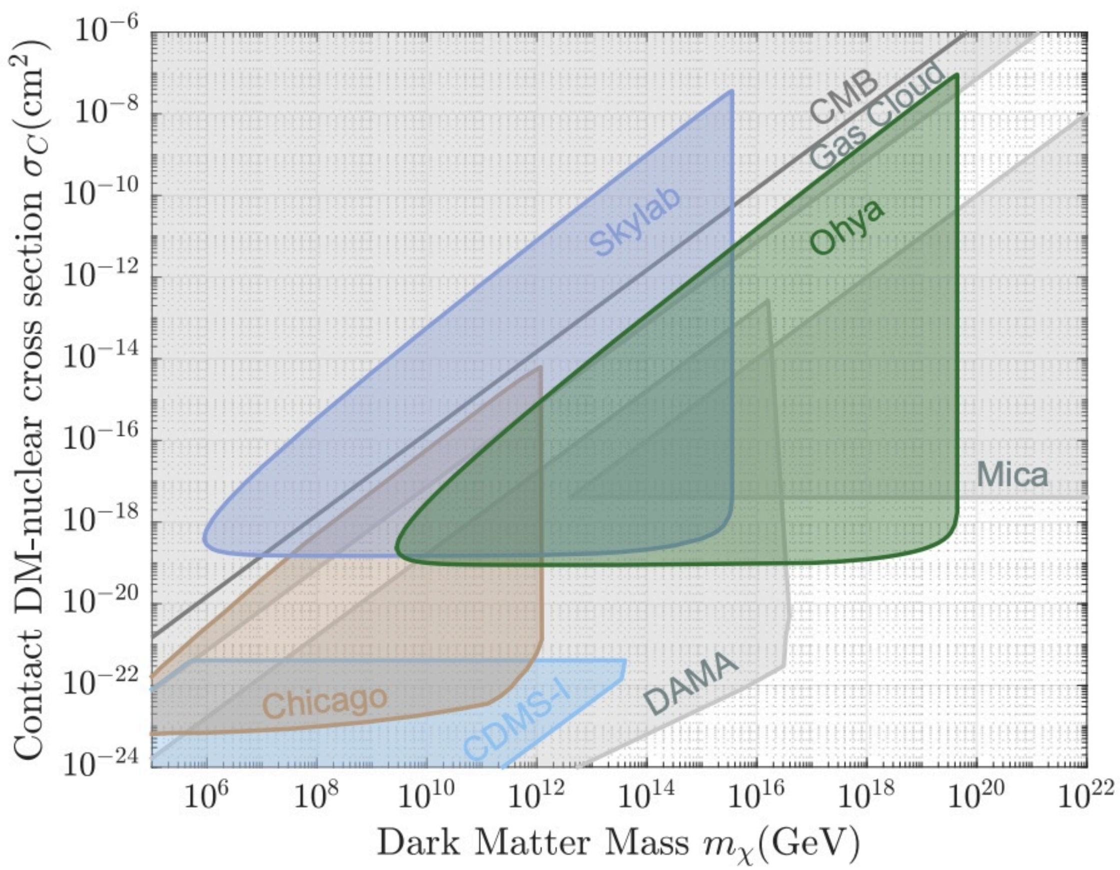
Ohya Quarry

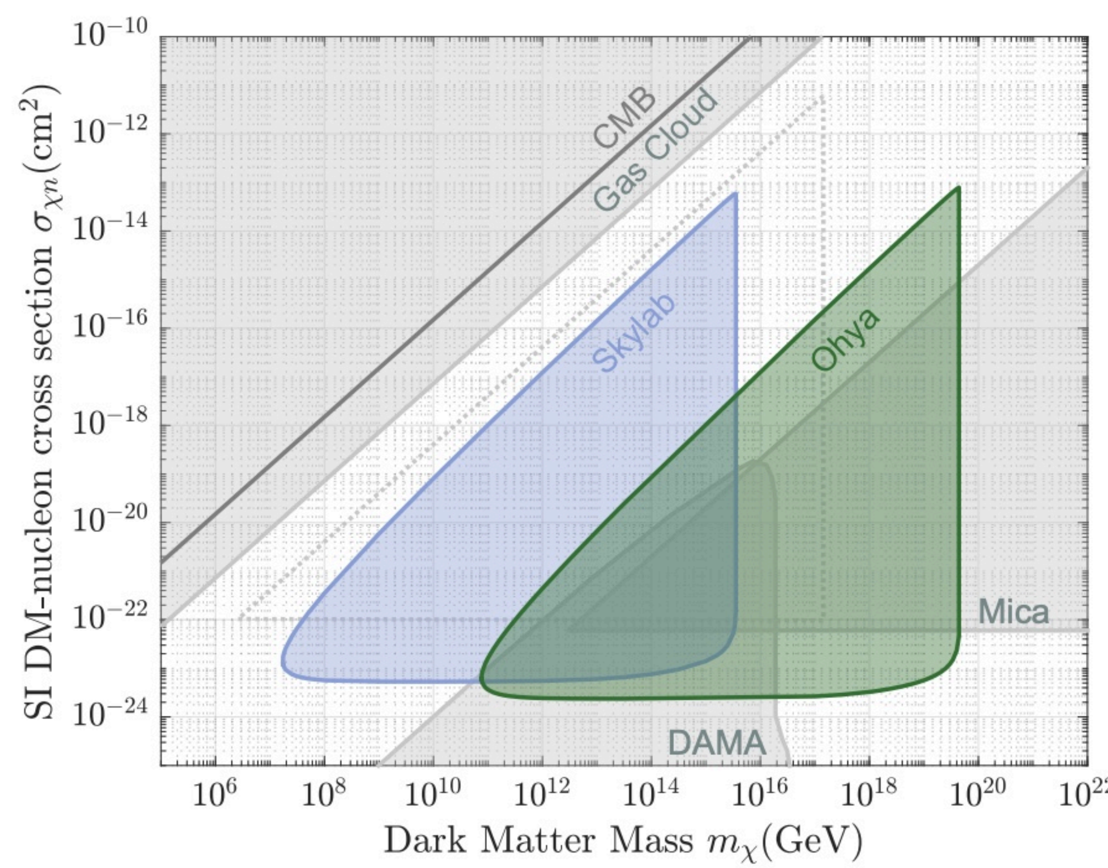
	Skylab	**Ohya**
Area A	1.17 m^2	2442 m^2
Duration t	0.70 yr	2.1 yr
Zenith cutoff angle	$\theta_D = 60°$	$\theta_D = 18.4°$
Detector material	0.25 mm thick Lexan $\times$ 32 sheets	1.59 mm thick CR-39 $\times$ 4 sheets
Detector density	1.2 g cm^{-3} Lexan	1.3 g cm^{-3} CR-39
Detector length at θ_D	1.6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

ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *Incorporate DM distribution, single solution for overburden+etching sensitivity*

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





Bhoonah, JB, Courtman, Song
2012.13406

ANCIENT SEARCH FOR NEW PARTICLES: MICA

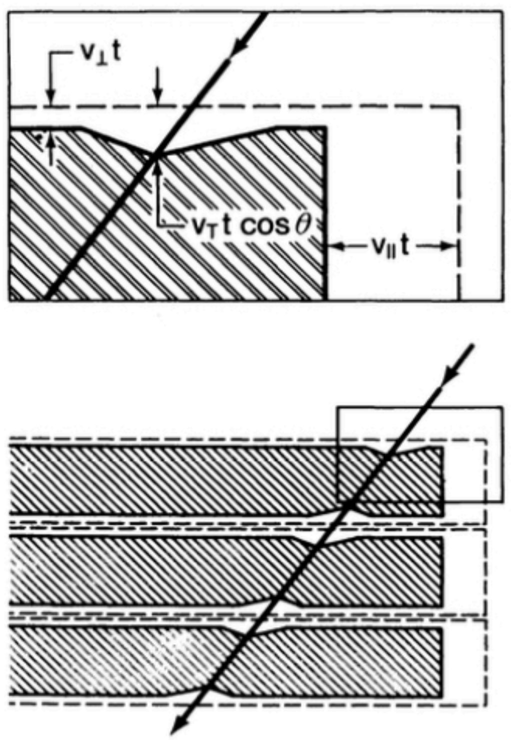
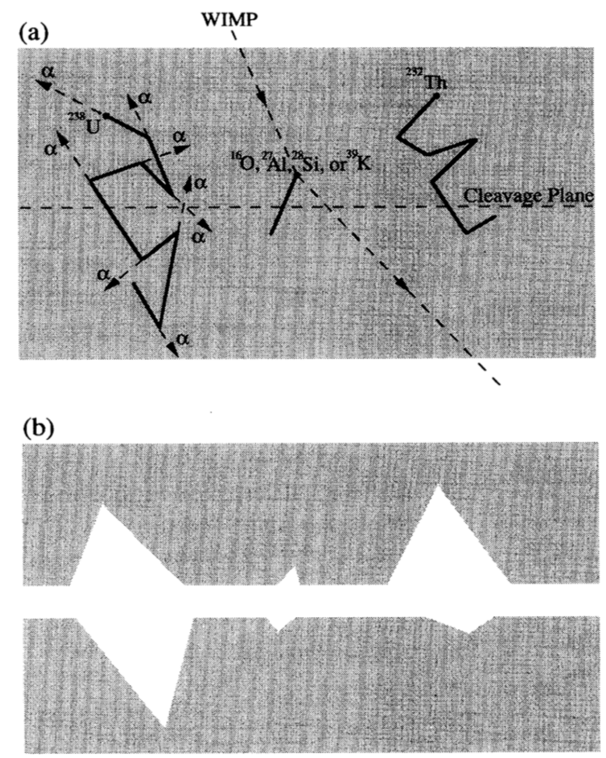
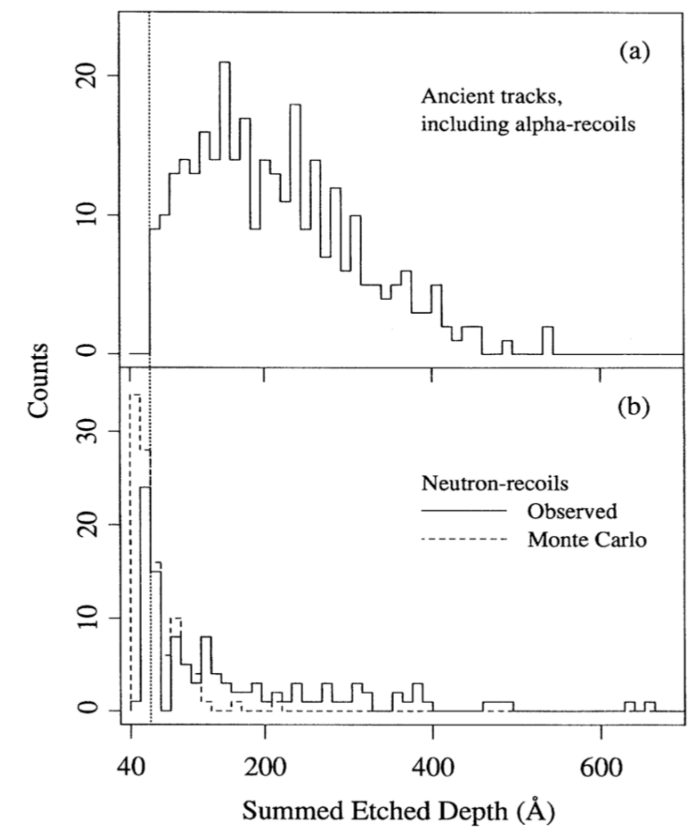


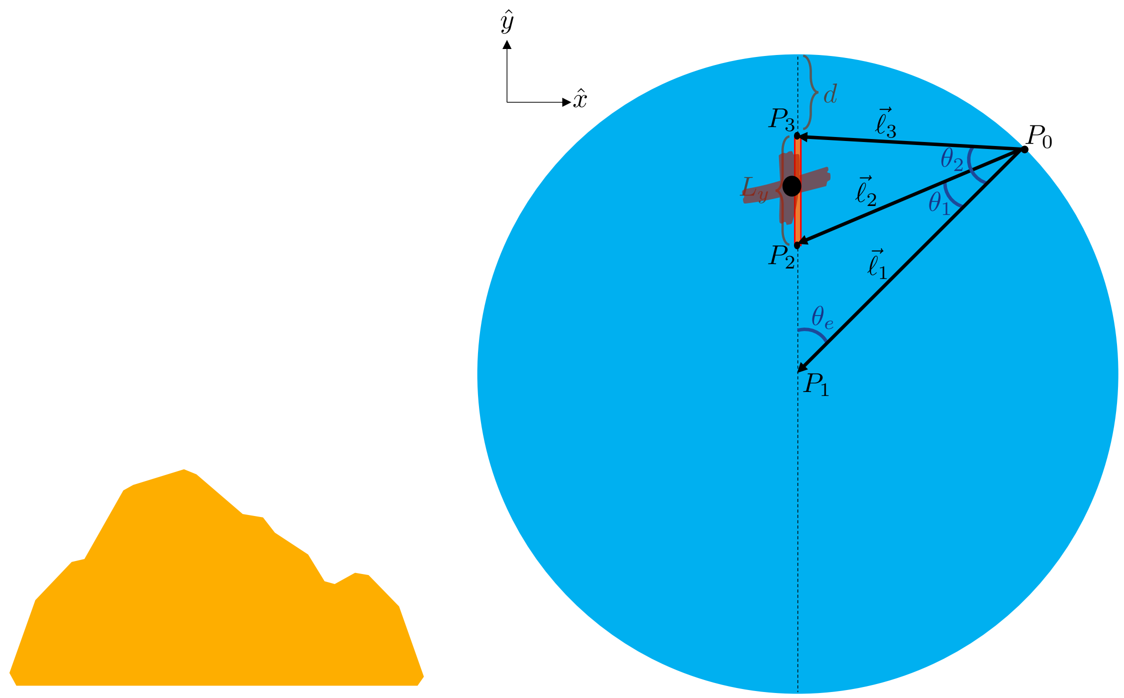
FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.





- 1986 Price and Salamon mica monopole search
- 1995 Snowden-Ifft et al. calibrated mica samples

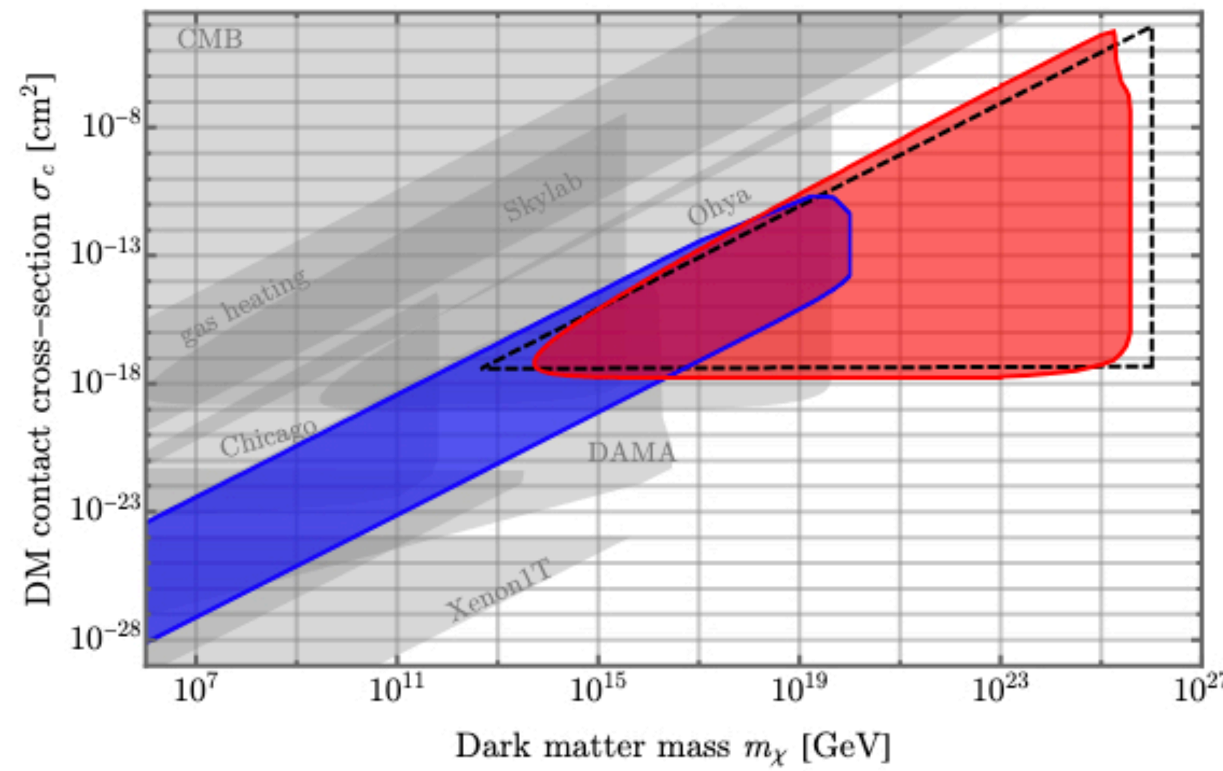
ANCIENT SEARCH FOR NEW PARTICLES: MICA



- ➤ Calibrated and etched mica samples from Price and Salamon 1986, Snowden-Ifft 1995

- ➤ Reanalyzed mica data using overburden model / custom MC

Acevedo, JB, Goodman
2105.06473

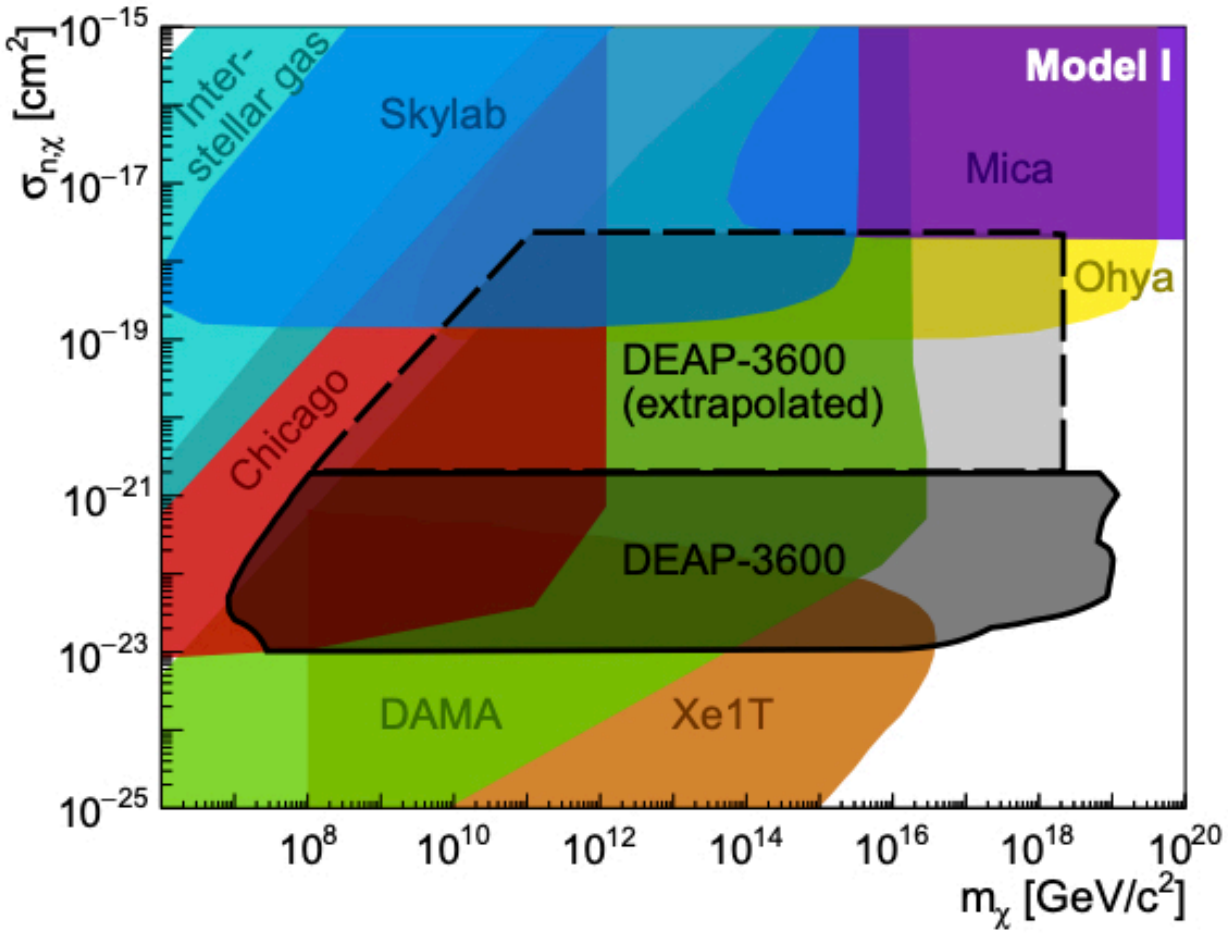


Also a mineral DM detection collaboration at Queen’s

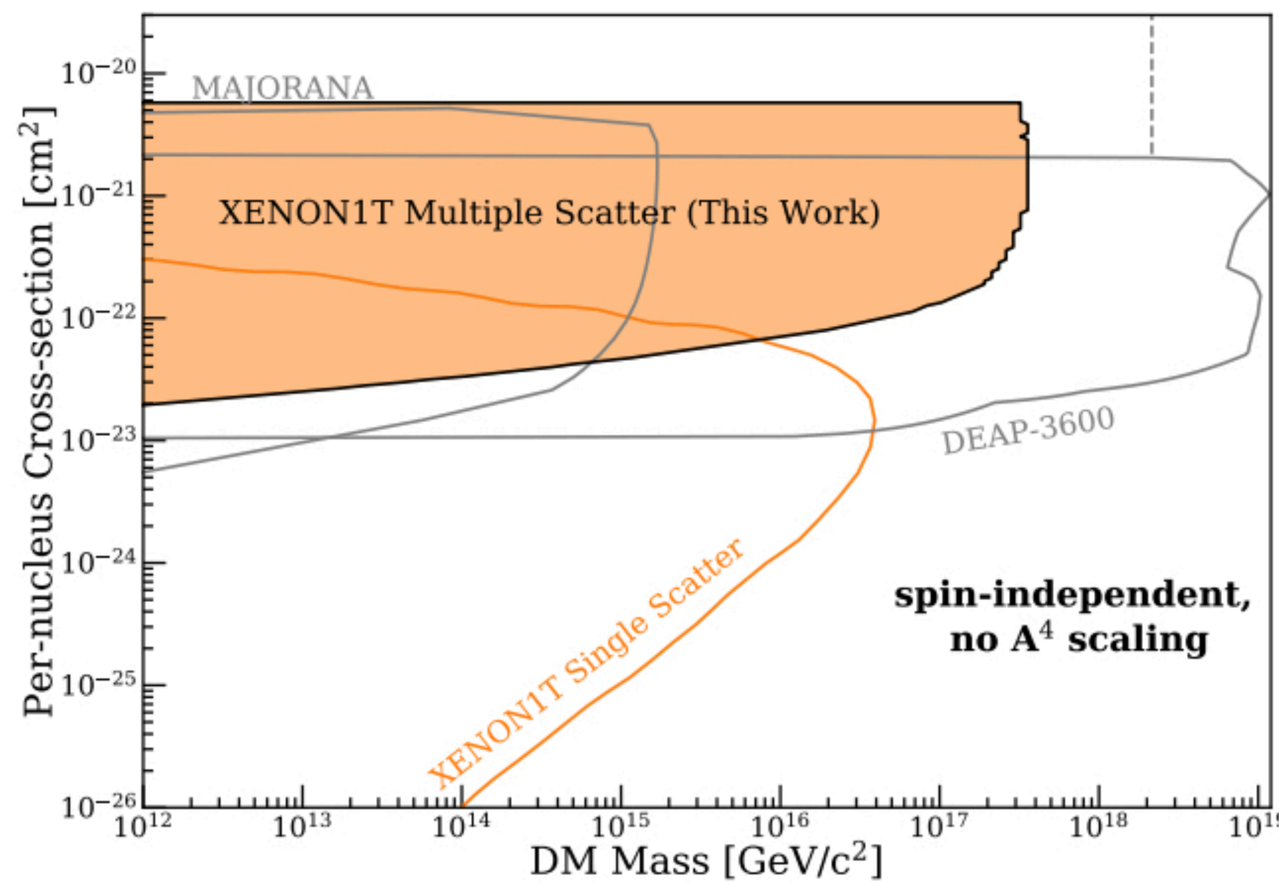
Balogh, Boukhtouchen, JB, Fung, Leybourne, Lucas, Mkhonto, Vincent

See e.g. recent whitepaper: 2301.07118

HEAVY MIMP RESULTS FROM DEAP-3600, XENON1T

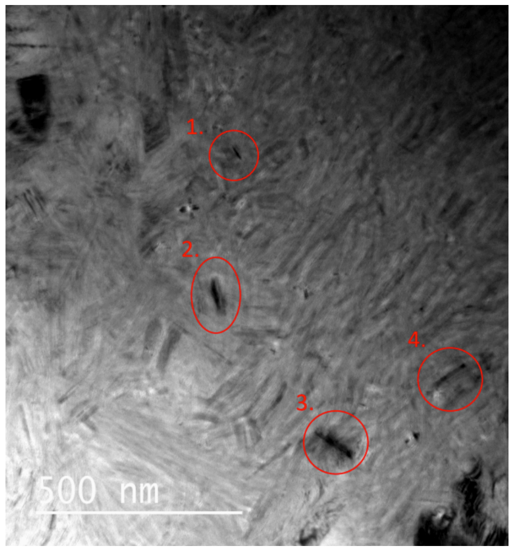


2108.09405, PRL



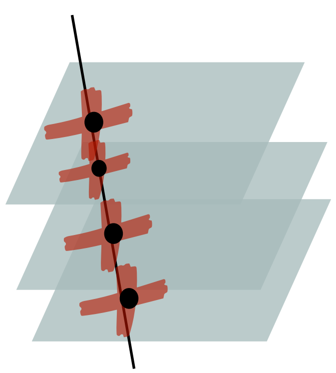
2304.10931, PRL

FUTURE HEAVY DM: CR-39, SNO+, QCUMBER, YOUR EXPERIMENT?

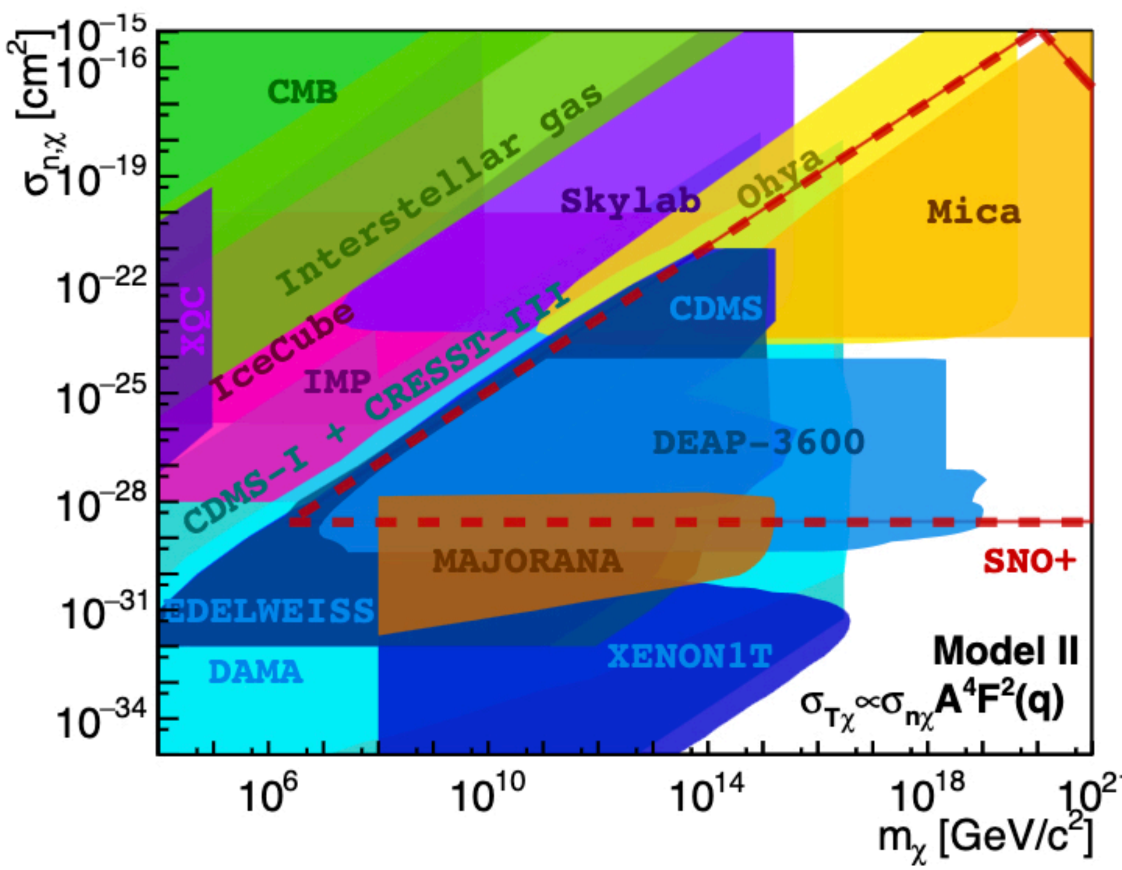


Q Paleo (QCumber? – name suggestions welcome) 2301.07118

Boukhtouchen, JB, Balogh, Fung, Leybourne, Lucas, Mkhonto, Vincent



Future CR-39 experiment or similar



Snowmass Ultraheavy dark matter
Carney, Raj et al. 2203.06508