This was a provisional title given to me by organizers of a McDonald Institute National Meeting a few months ago:

FUTURE WIMPS

Joseph Bramante

Queen's University

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Thankfully I had training for this at a recent MI/CITA astro & particle theory workshop
(shared credit/culpability to other organizers: Juna Kollmeier, David Curtin, Katelin Schutz, Aaron Vincent)

The hat game

Particle physics term	Astro term
Non-abelian	Galactic magnetic fields
Ultrarelativistic	Asteroids
Weakly interacting	Saturn’s hexagon
Fluffy	Lyman alpha forest
Warm	Active galactic nuclei
Scintillating	

One example: “Non-abelian” + “asteroids” →
DM with a non-abelian confining gauge interaction could form ‘dark-quark-ball dm’ macroscopic objects, which may have sufficient EM interaction to be visible and be mistaken for asteroids

Play it loose, this is a game. Perhaps some of it will be fun & eye-opening & perhaps even possible?

BACK TO THE FUTURE WITH HIGH MASS DM

Joseph Bramante

Queen's University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

CETUP Talk June 17 2024

Delorean

2023 BZ concept

BACK TO THE FUTURE WITH HIGH MASS DM

-Most DM models were written down in the 80s.

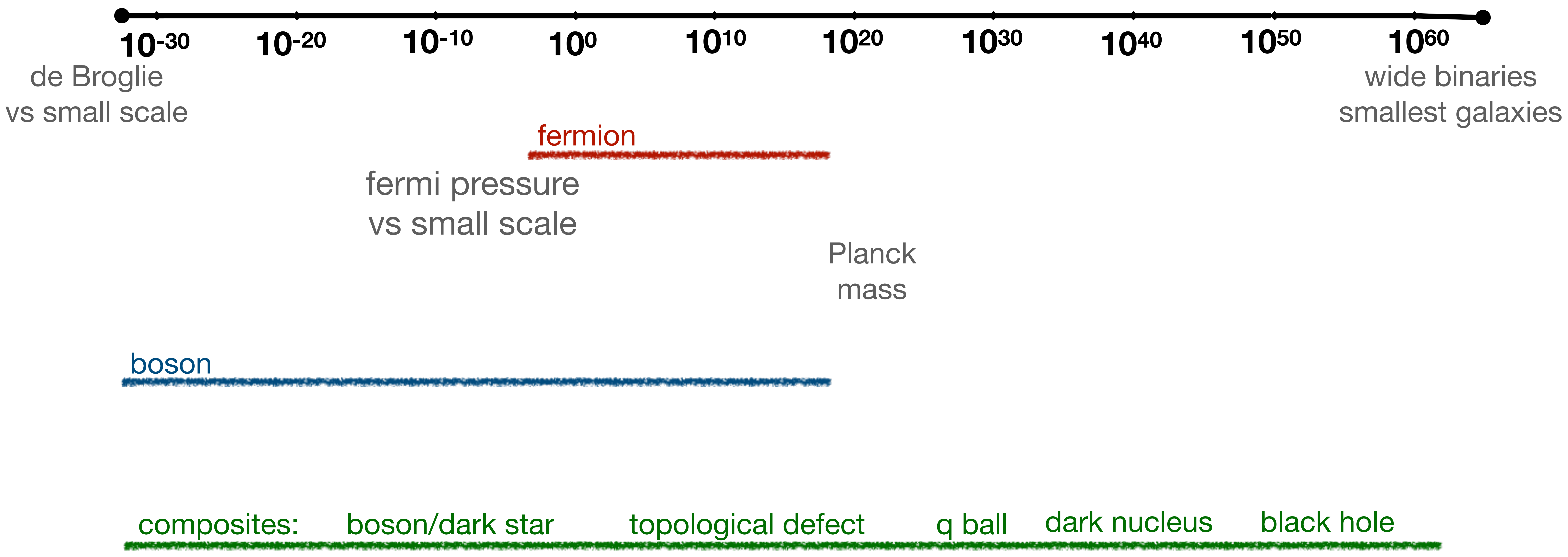
-The simplest DM are well studied, and may be discovered soon.

(Simple in formulation, complicated in dynamics)

-Heavy DM is less studied, and may be discovered soon. Heavy DM is perhaps easier to look for, for now.

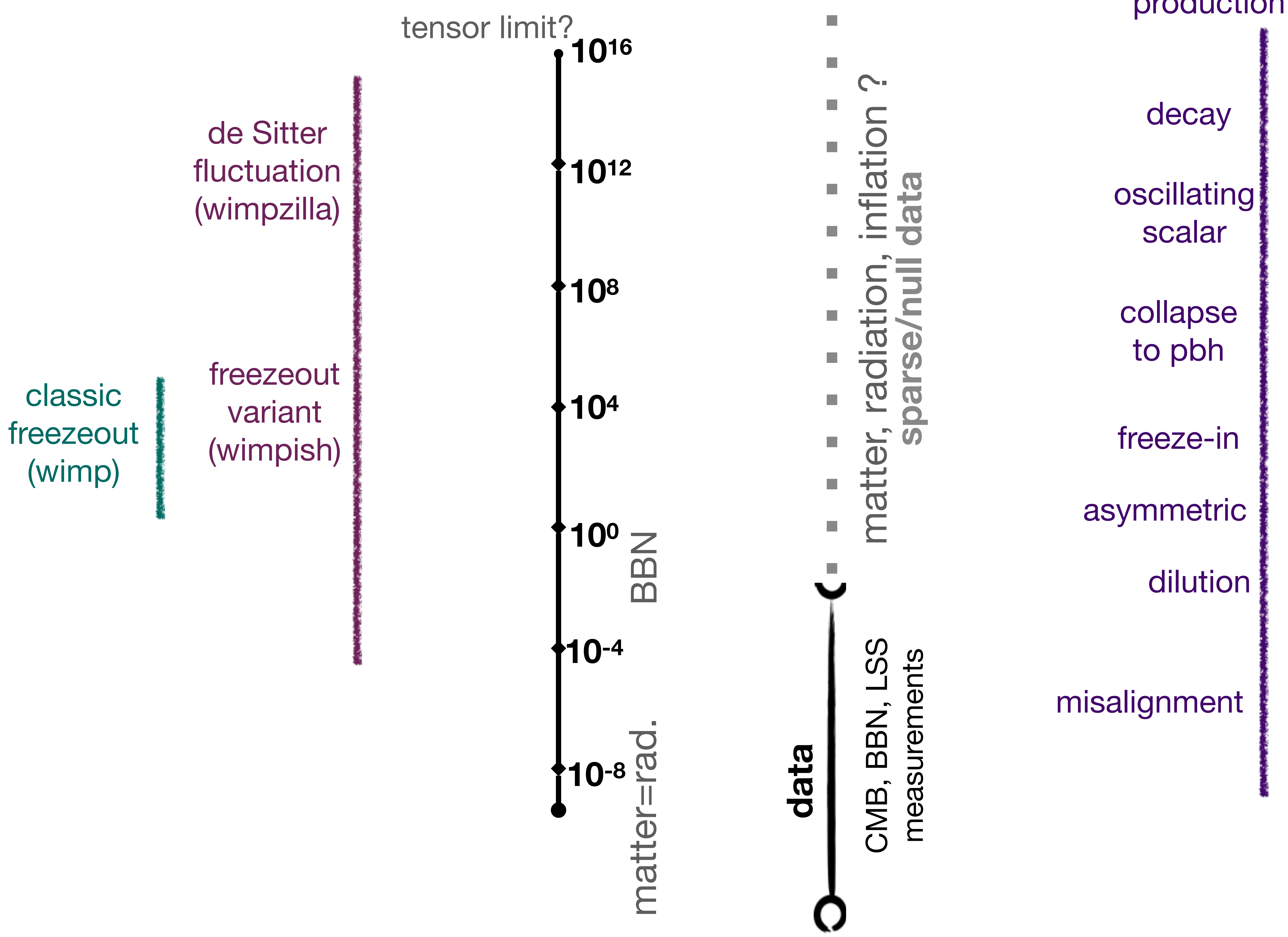
What do we know about dark matter?

mass in GeV



How was dark matter made?

production temperature ($\rho^{1/4}$)
in GeV



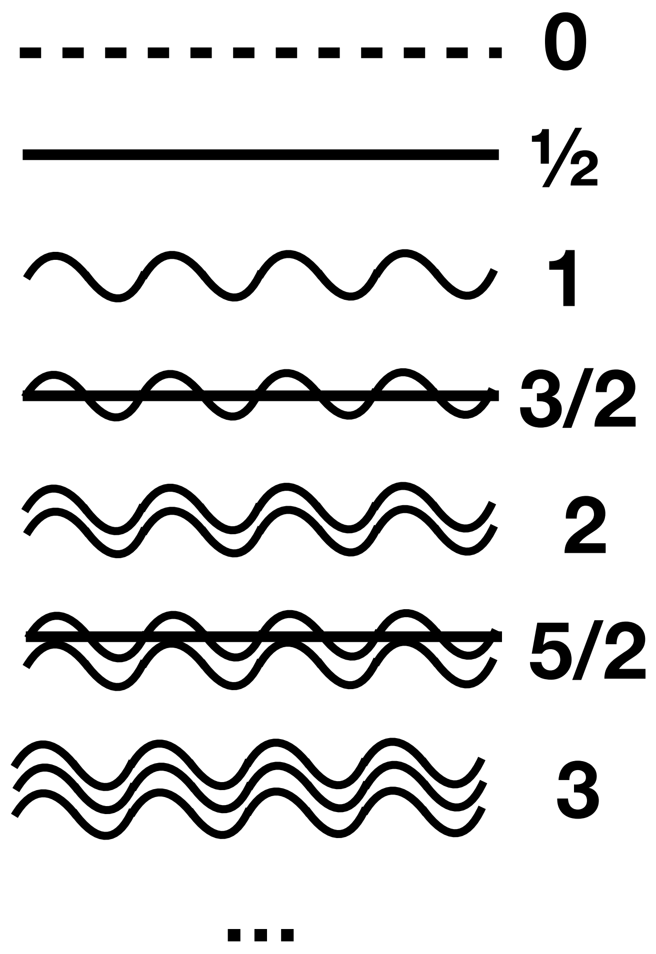
Dark Matter Models: SM Coupling and Detection

dark matter

fundamental

composite

spin



direct coupling

Quarks

Leptons

Hypercharge Boson

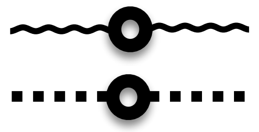
Weak Boson

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

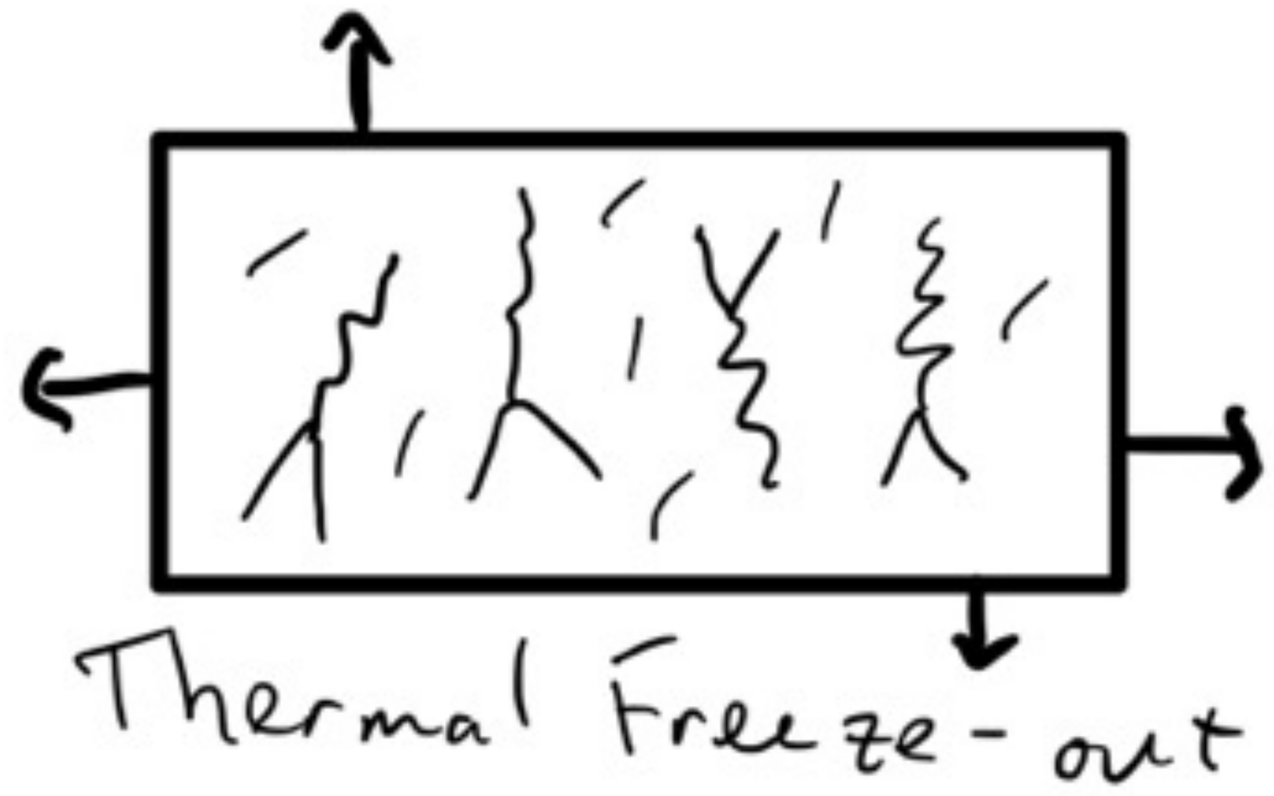
Scalar

Fermion

Vector…

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

The WIMP Miracle

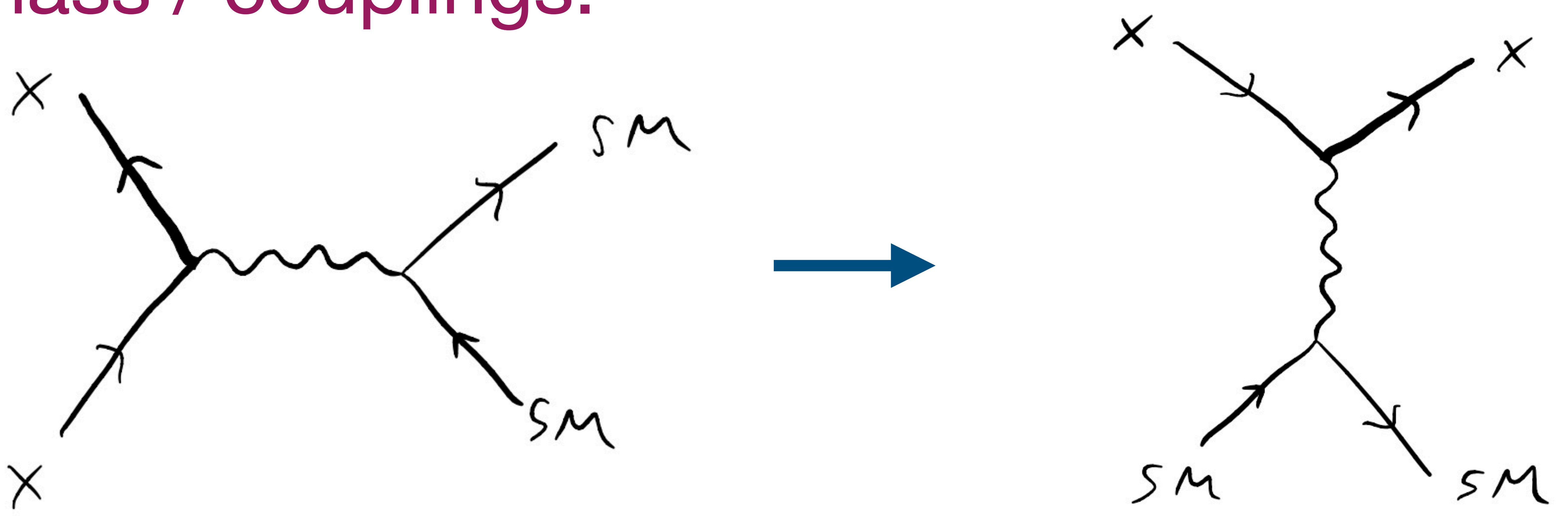


As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

$$\frac{m_x n_x}{n_\gamma} \sim \frac{x_f}{m_{pl} \langle \sigma_a v \rangle} \qquad x_f \sim \log[m_x^3 \langle \sigma_a v \rangle / H]$$

Observed DM relic abundance achieved for annihilation cross-section matching weak scale mass / couplings.

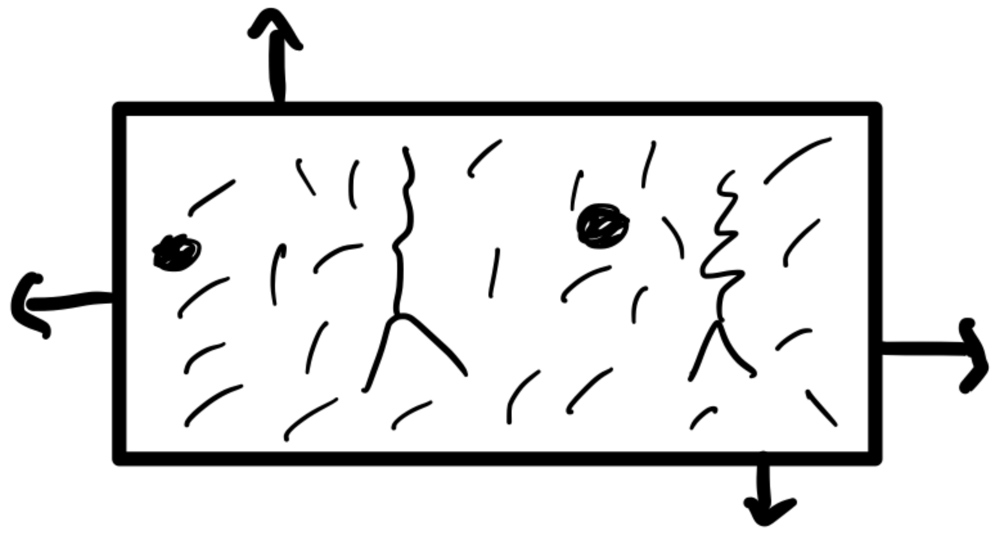
$$\Omega_x h^2 \sim 0.1 \left(\frac{m_{\mathrm{v}}}{100\ \mathrm{GeV}} \right)^2 \left(\frac{0.03}{\alpha_w} \right)^2$$

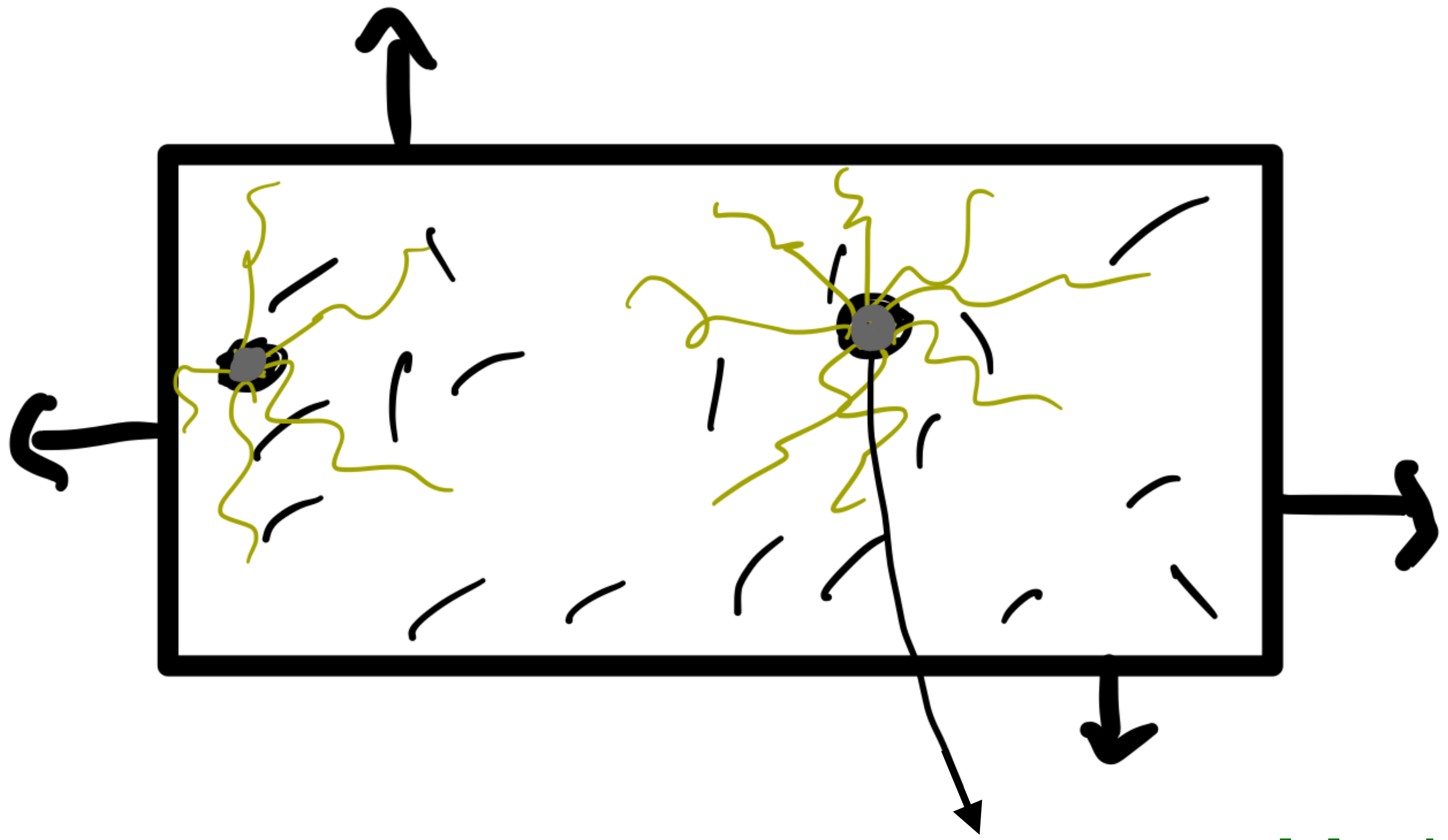


see e.g.
Scherrer Turner '86
Drukier, Freese, Spergel '86

Some symmetry arguments imply interactions at dark matter experiments.

Diluted WIMP Dark Matter: heavier

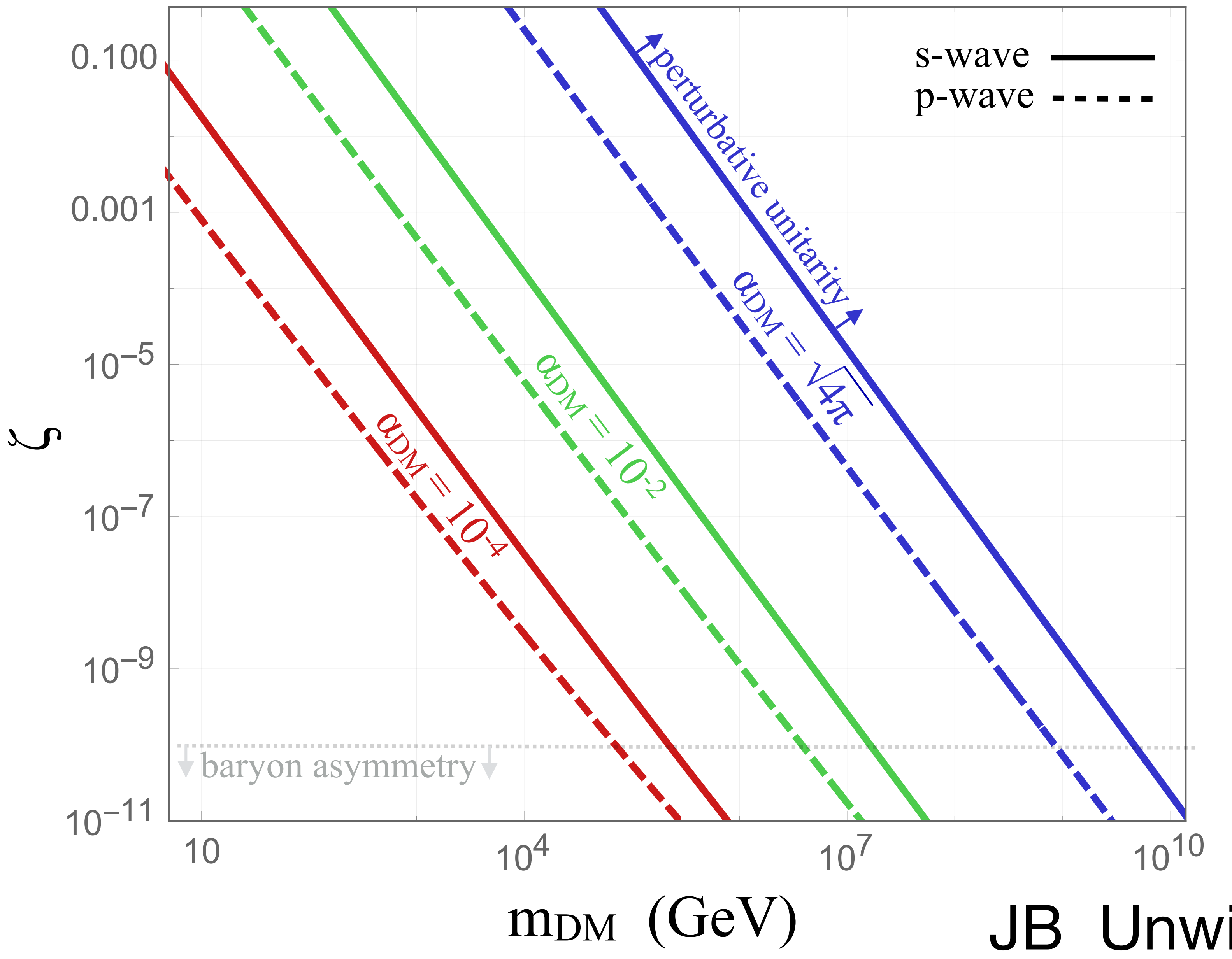




Overabundant freeze-out

Then dilution from decay →

$$\Omega_x h^2 \sim 0.1 \left(\frac{m_V}{PeV}\right)^2 \left(\frac{0.03}{\alpha_D}\right)^2 \left(\frac{\zeta}{10^{-8}}\right)$$



JB Unwin 1701.05859

$$\boxed{\zeta \equiv \frac{s_{ini}}{s_{fin}} = n_x \text{ dilution}}$$

Motivation

-Matter dominated epoch
-Decay of asymmetry field (Affleck-Dine)
-Decay of inflaton
-Decay of modulus / gravitino
-Field associated with ~PeV dark sector

see also e.g.
Affleck Dine '85
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

HEAVY COMPOSITE DM

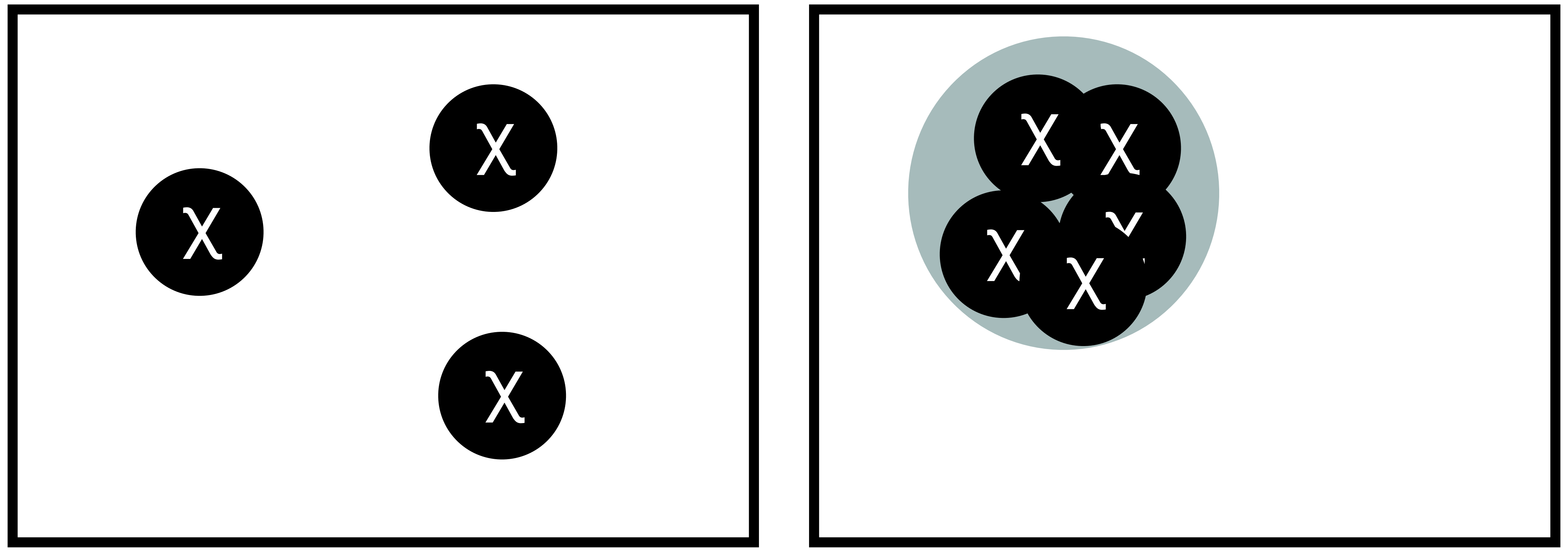
Consider a simple model of fermionic DM coupled by a scalar field

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

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

see 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
Acevedo, JB, Goodman ‘20



Model of quark matter forming during 1st order PT

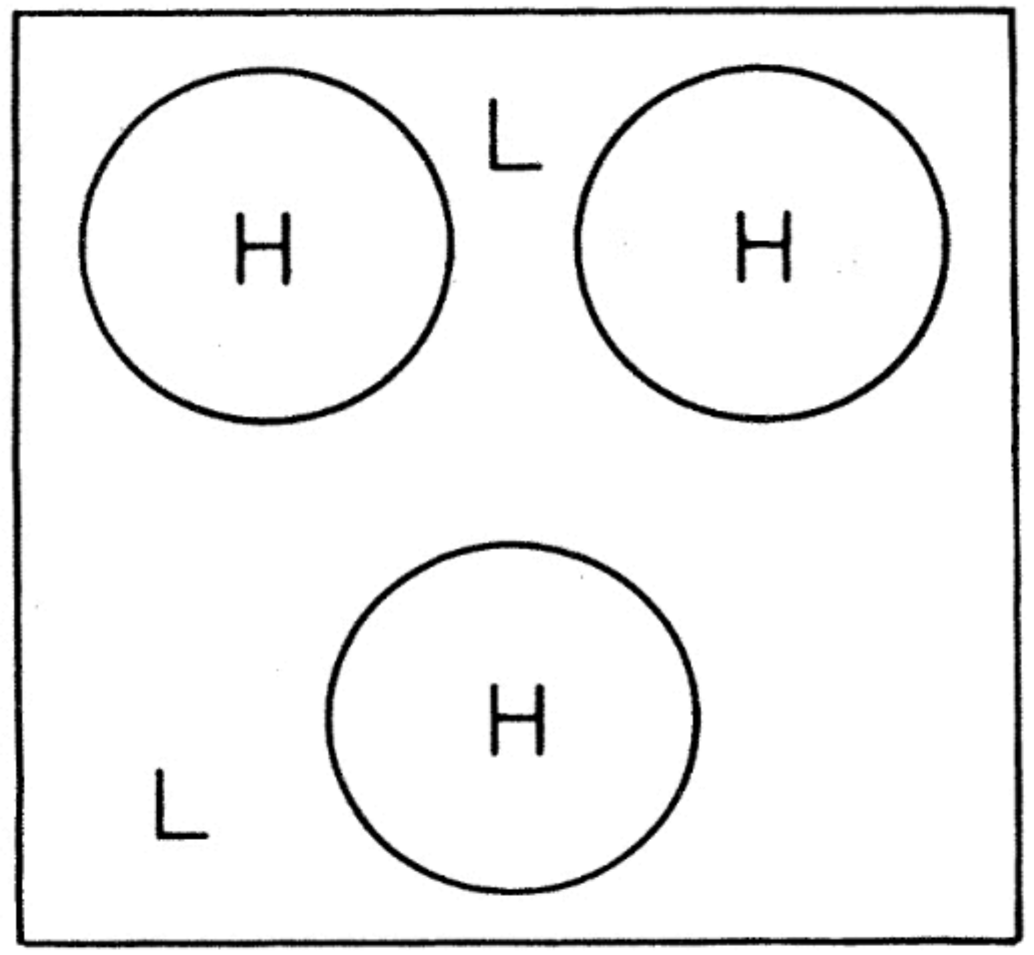
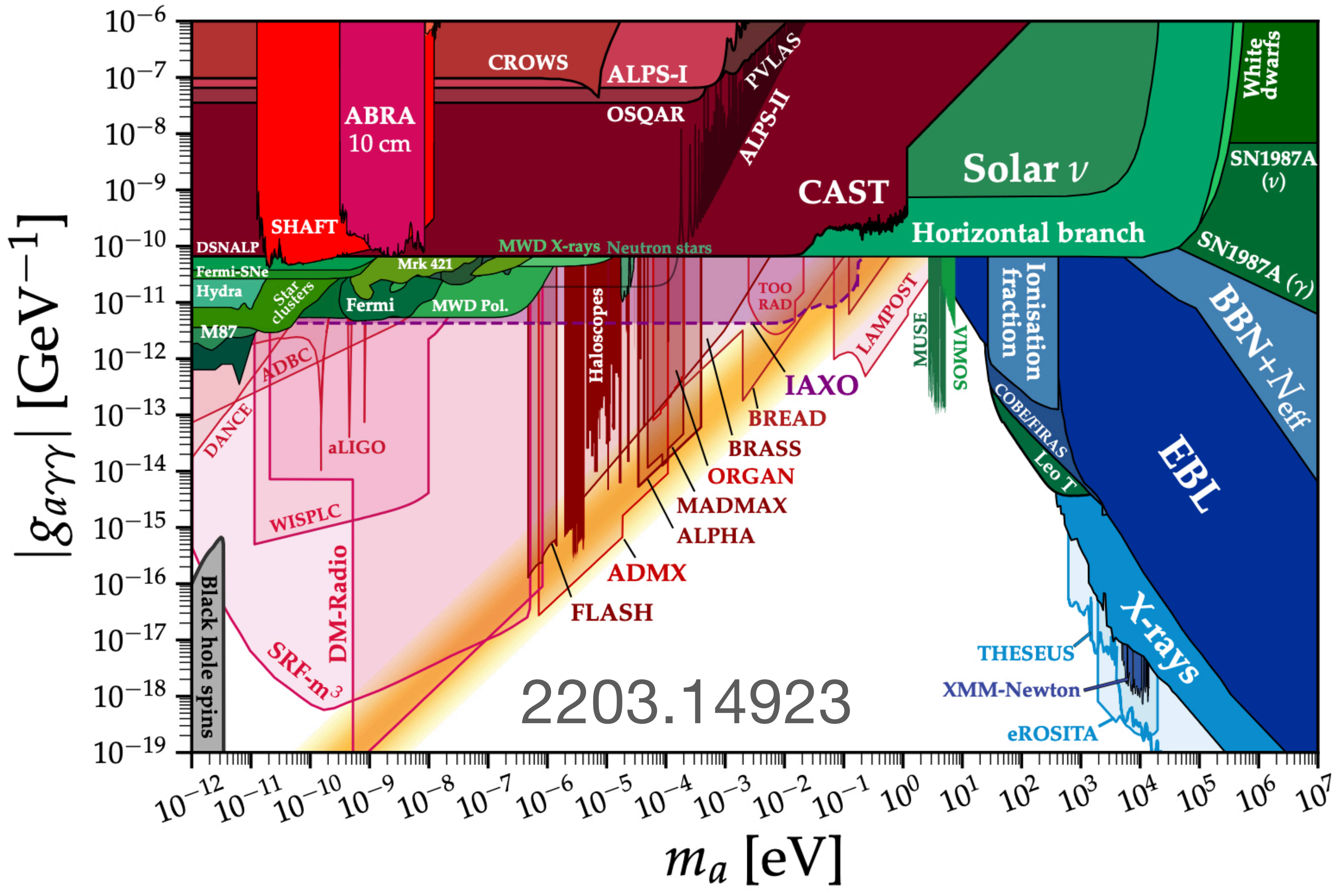


FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

see e.g.
Witten ’84

SKIM THROUGH DM SEARCHES

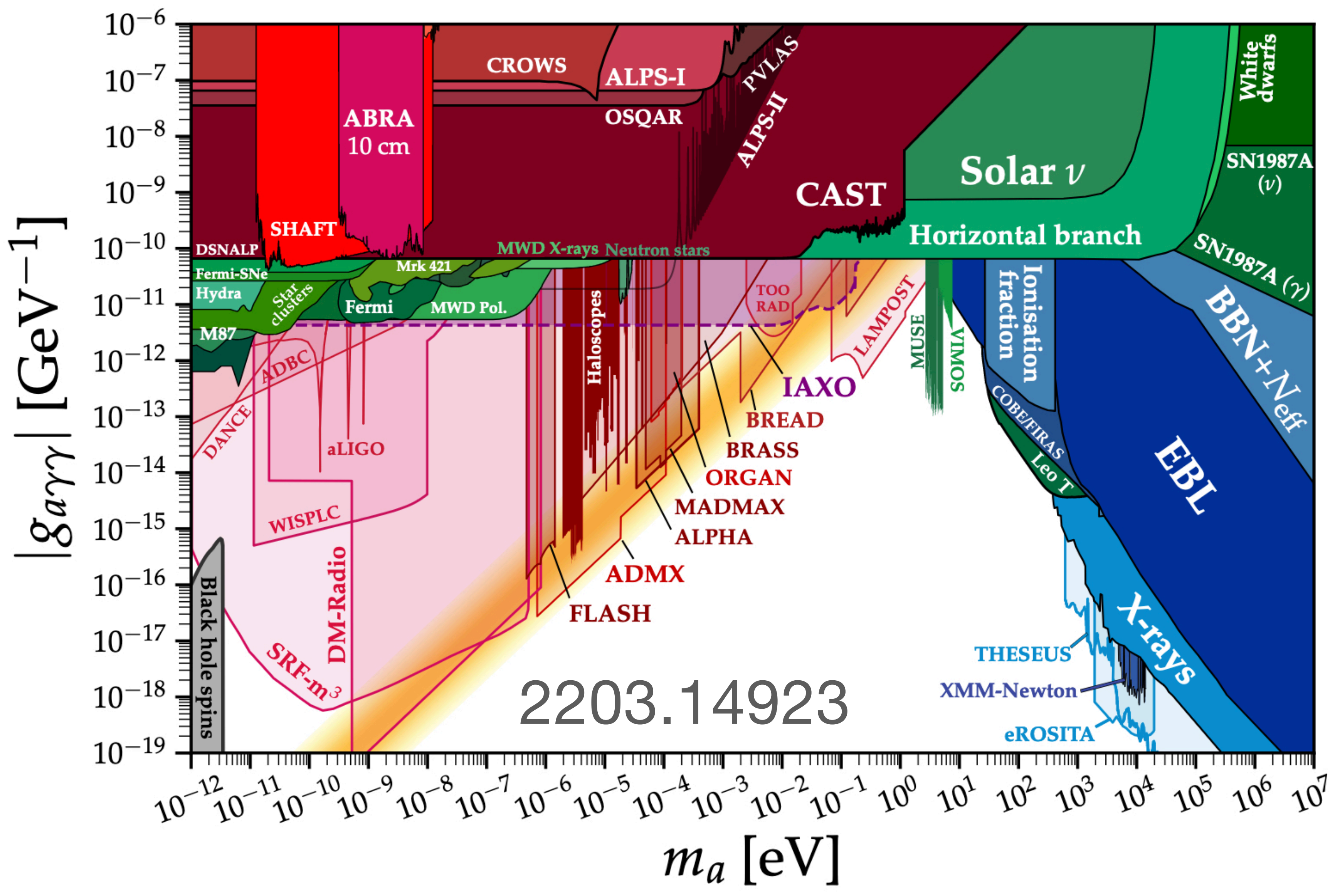


Axion/ DP (wavy bosons)

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



Preskill, Wise, Wilczek ’83
Abbott, Sikivie ‘83

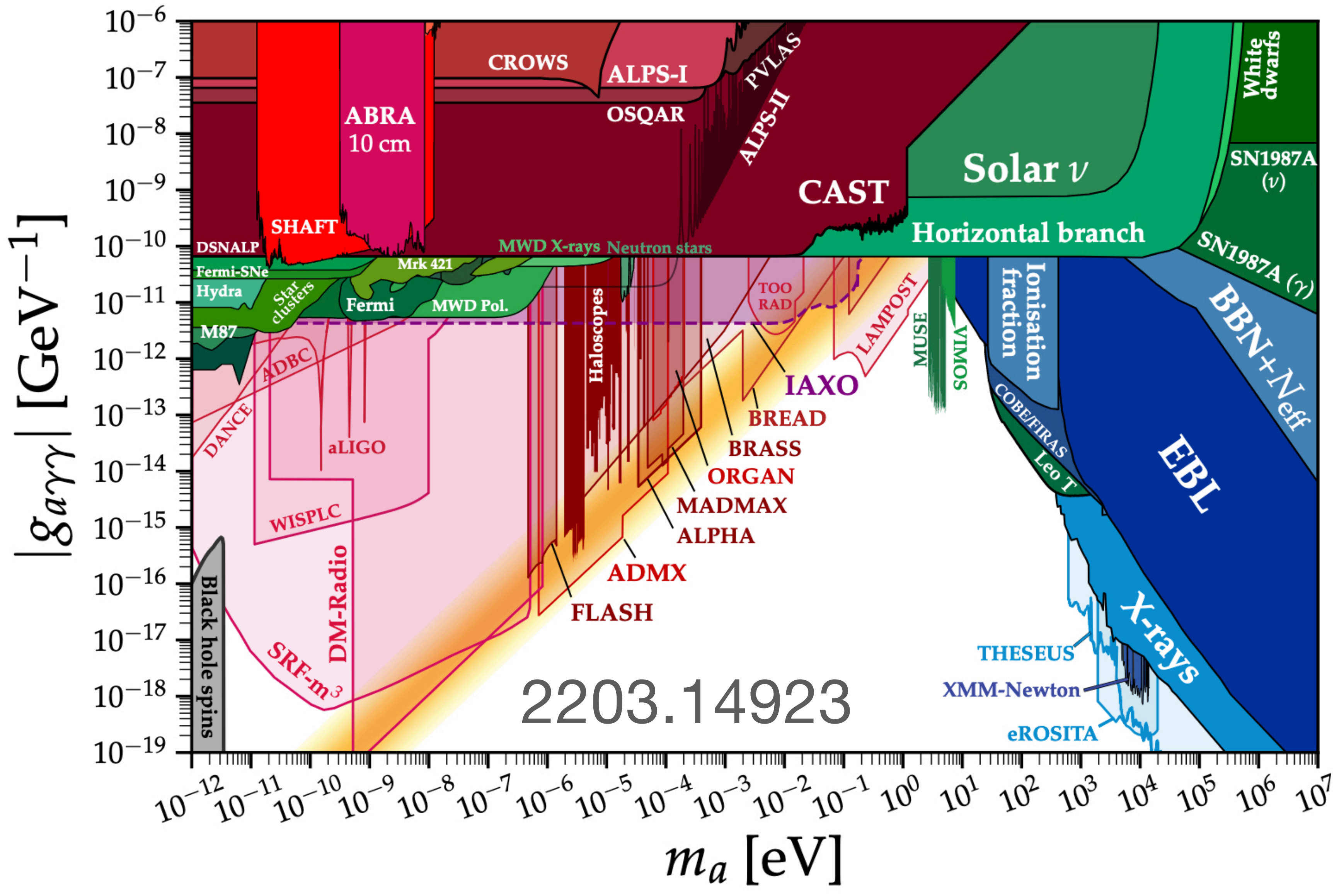
Axion/ DP (wavy bosons)

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

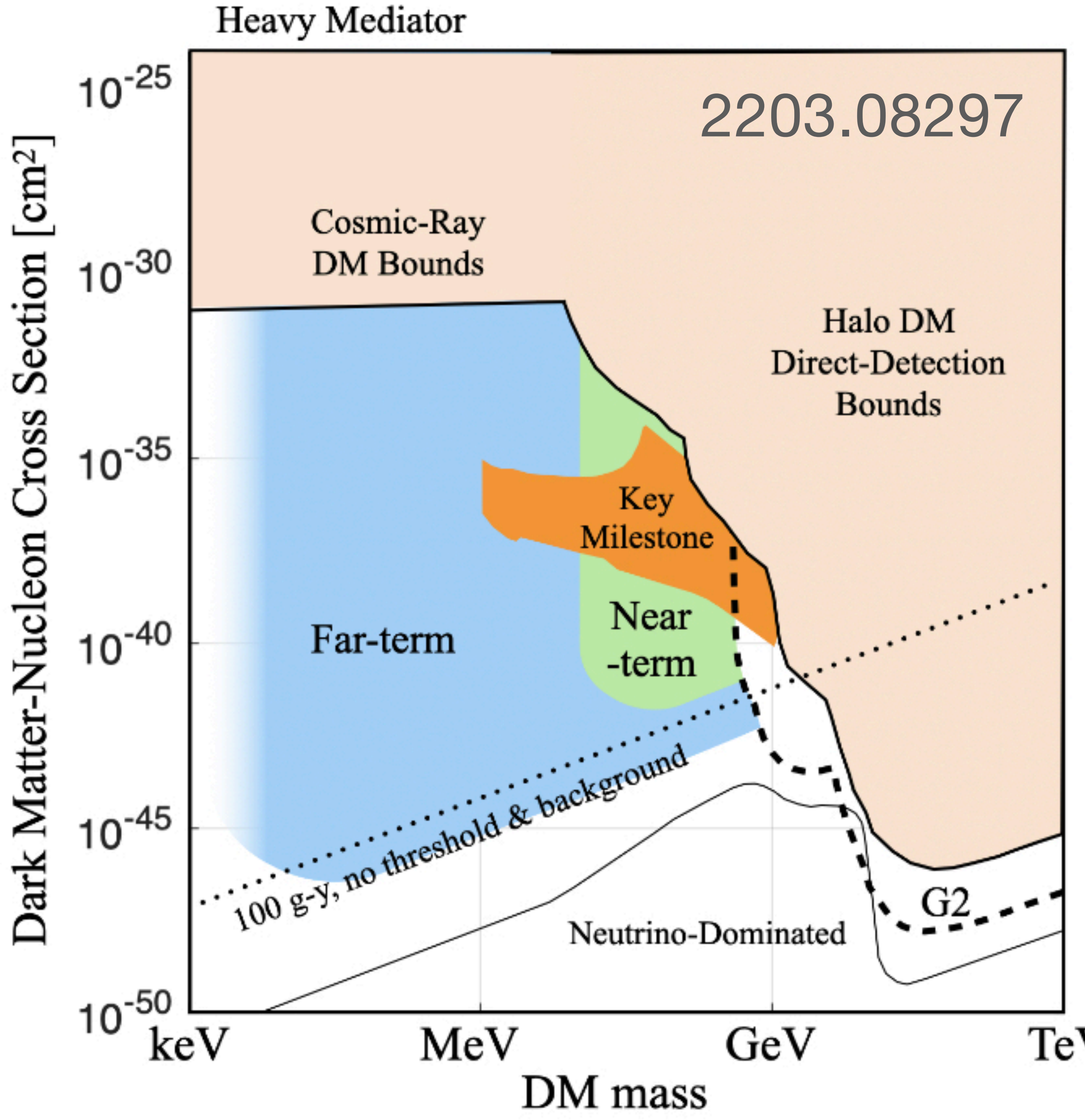
m_x (GeV)

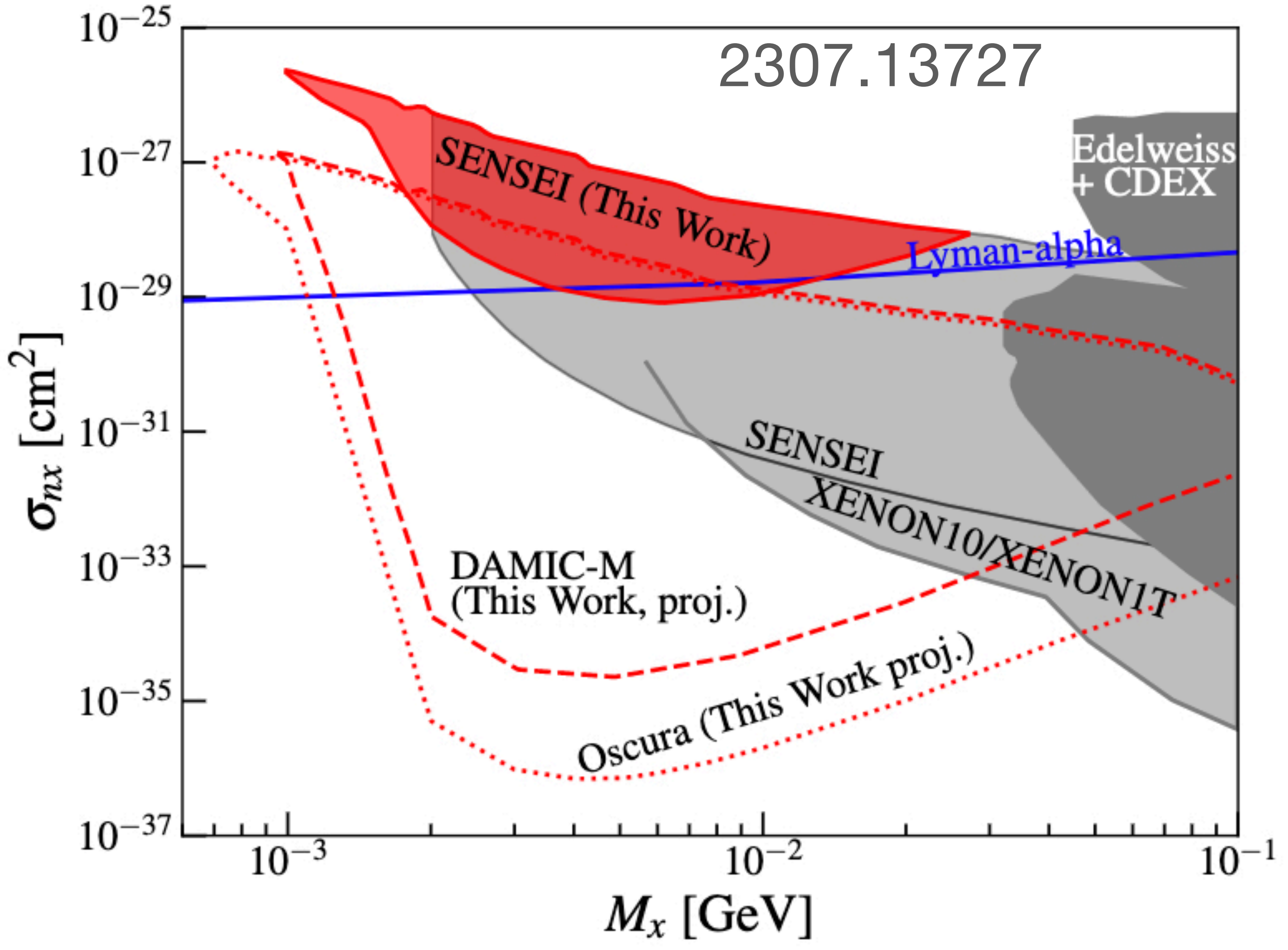
SKIM THROUGH DM SEARCHES

Light dark matter



Axion/ DP (wavy bosons)



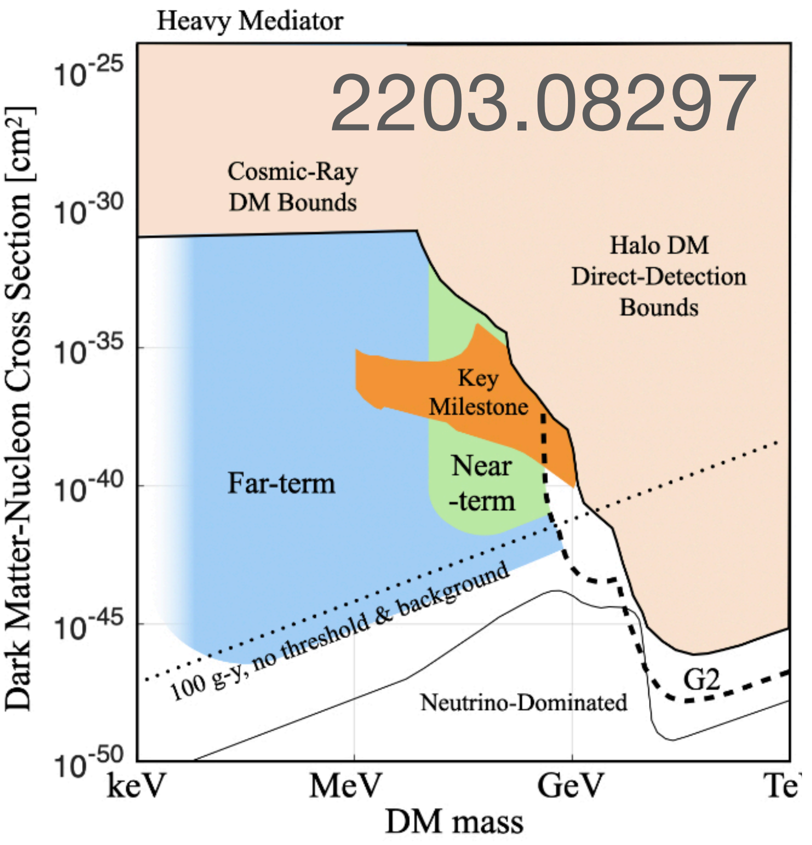


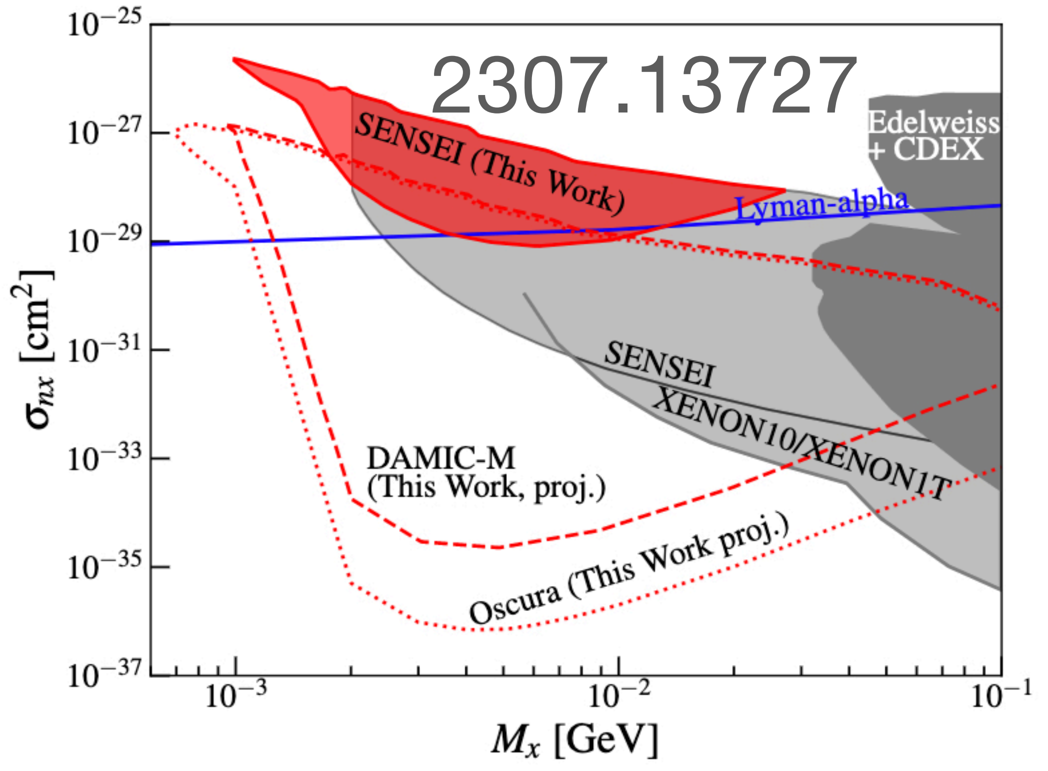
Melissa Diamond, Chris Cappiello, Vincent, JB

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

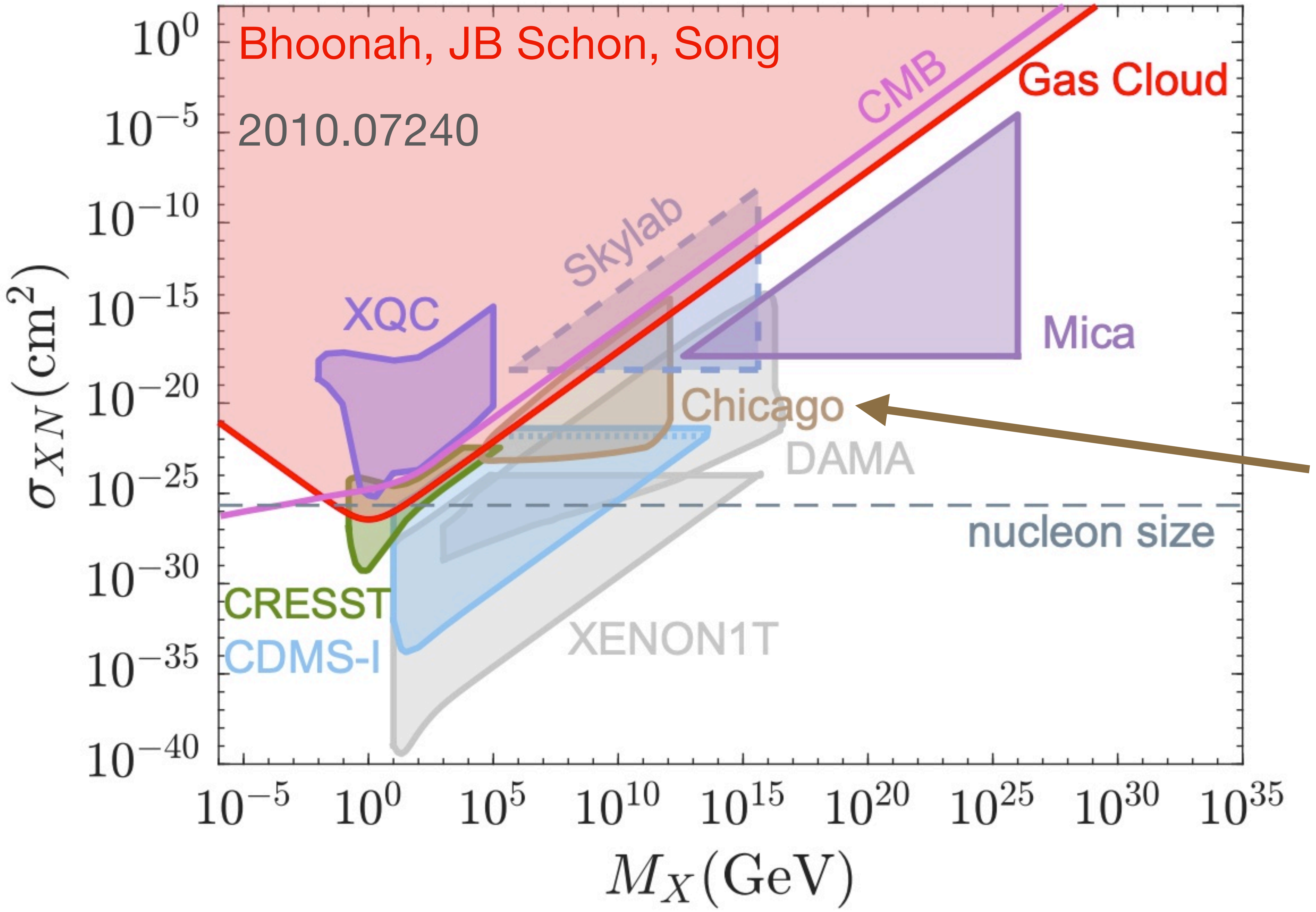
m_x (GeV)

SKIM THROUGH DM SEARCHES



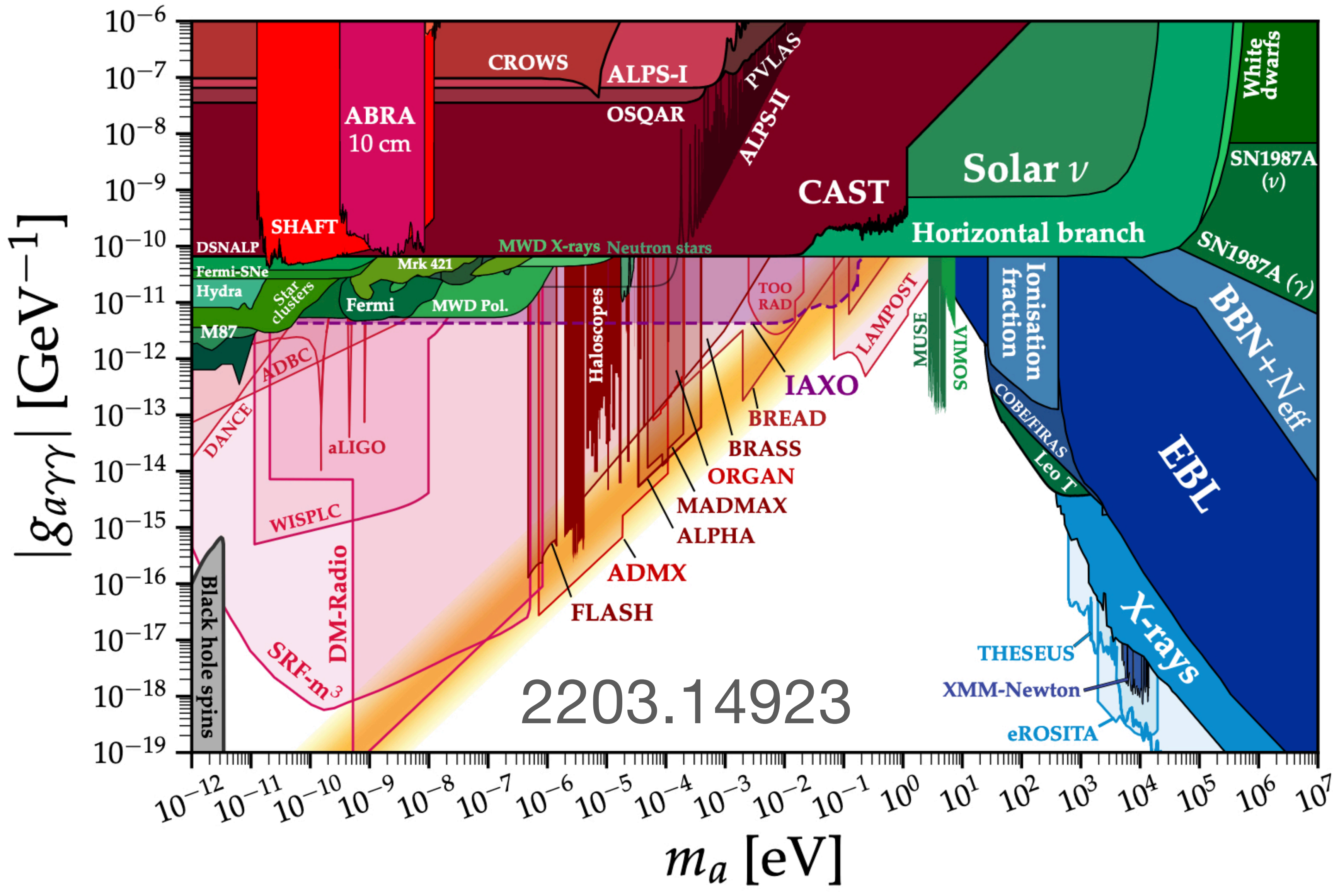


Heavy dark matter



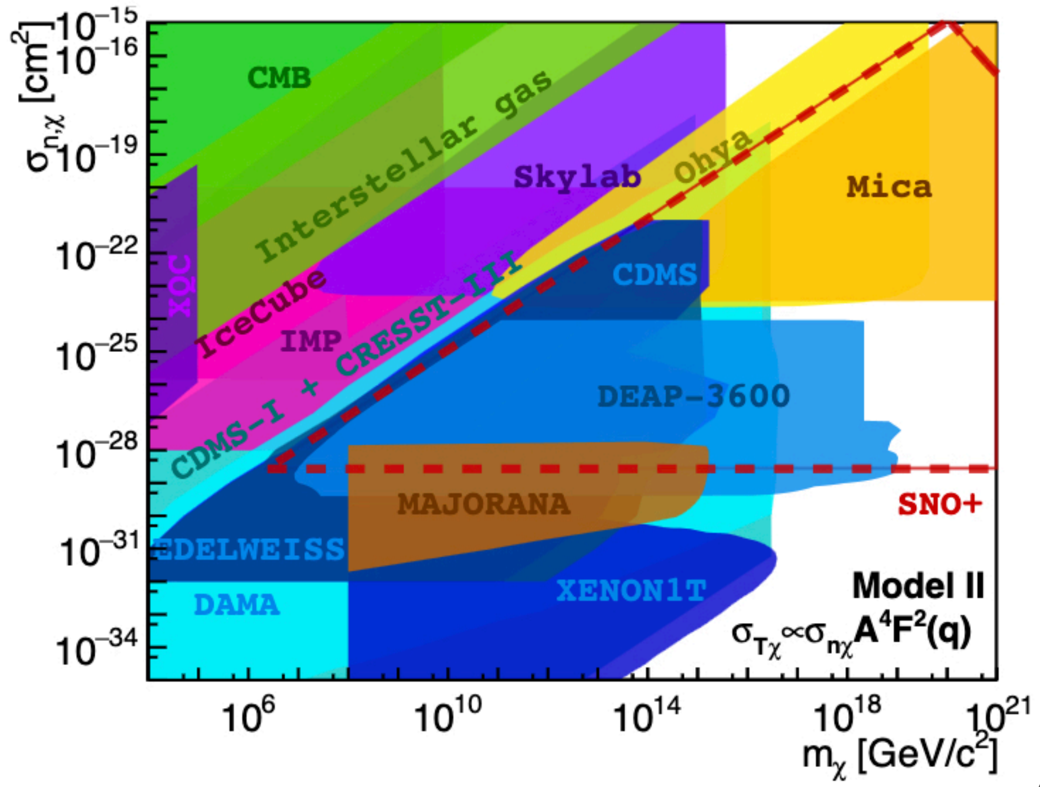
Cappiello, Collar, Beacom

Light dark matter



Axion/ DP (wavy bosons)

10^{-30} 10^{-20} 10^{-10} 10^{0}



2203.06508

high m,σ composites

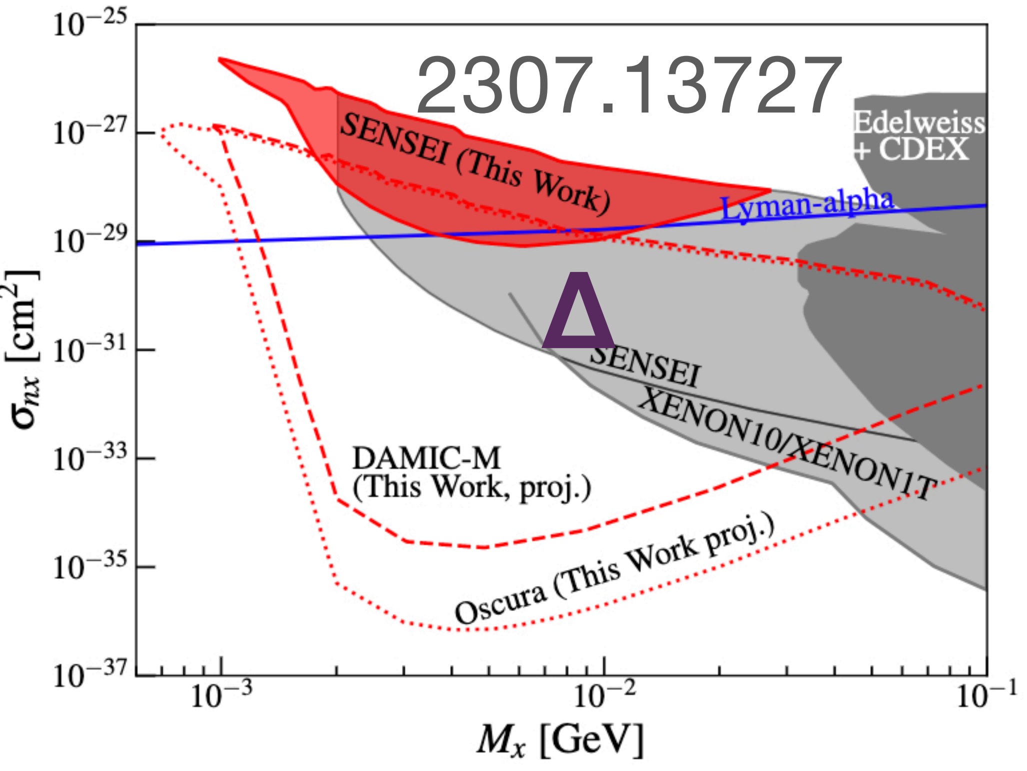
Witten '84

10^{30} 10^{40} 10^{50} 10^{60}

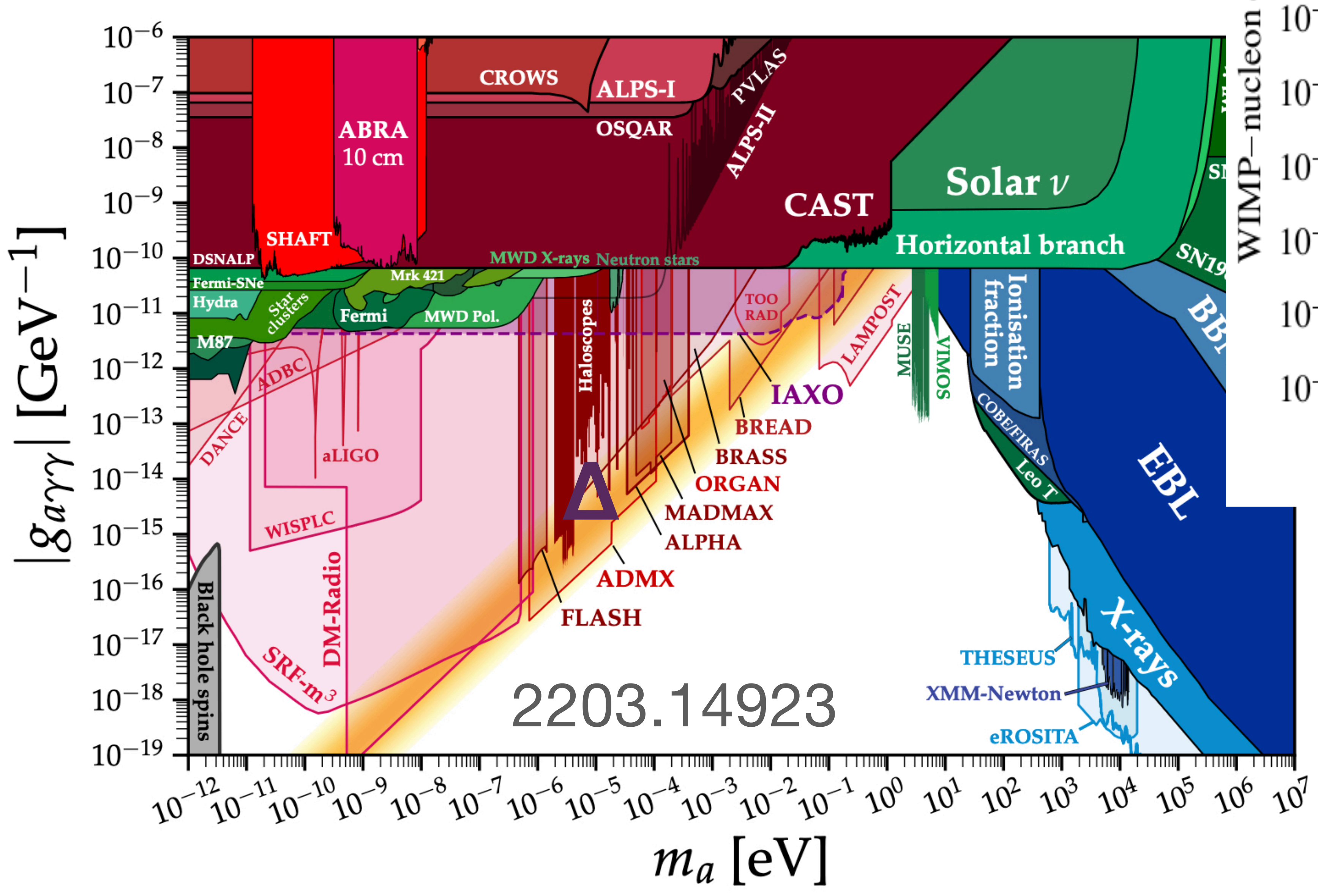
m_X (GeV)

PRICE OF DM DETECTION

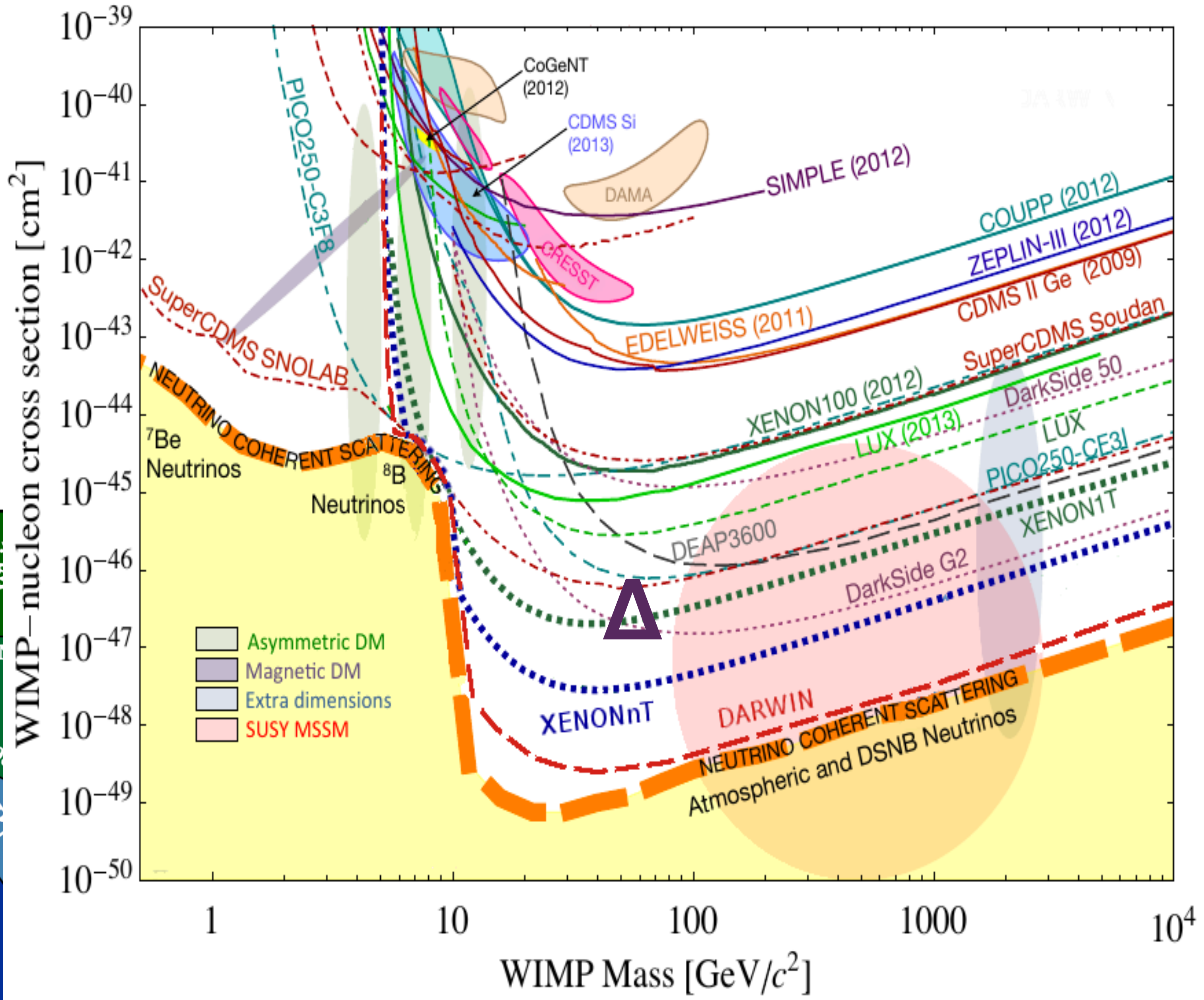
$$\text{current price of DM} \sim \$(10^5 - 10^6) \times \log_{10}(\Delta\sigma) \times \log_{10}(\delta m_X)$$



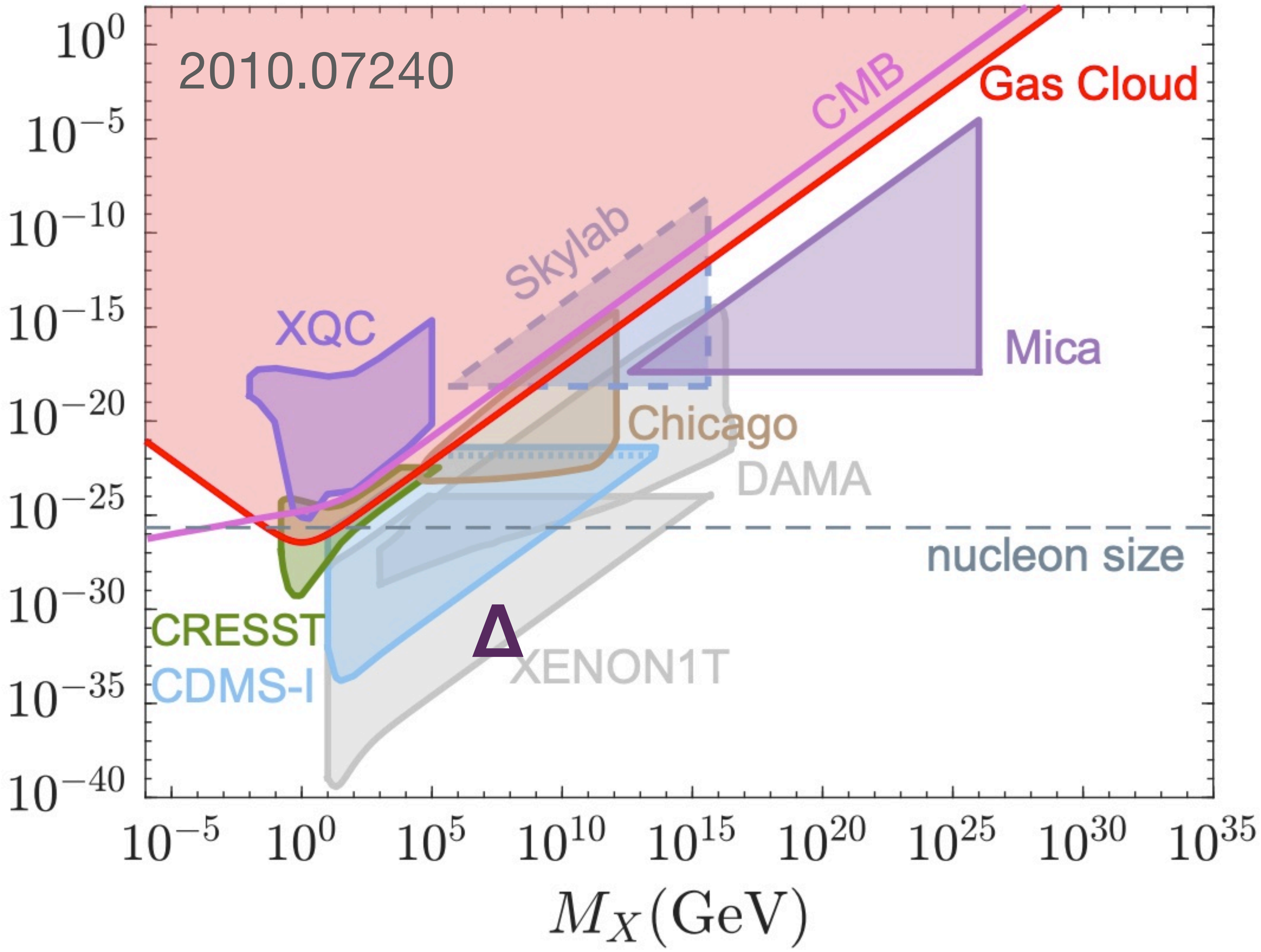
Light dark matter



Axion/ DP (wavy bosons)



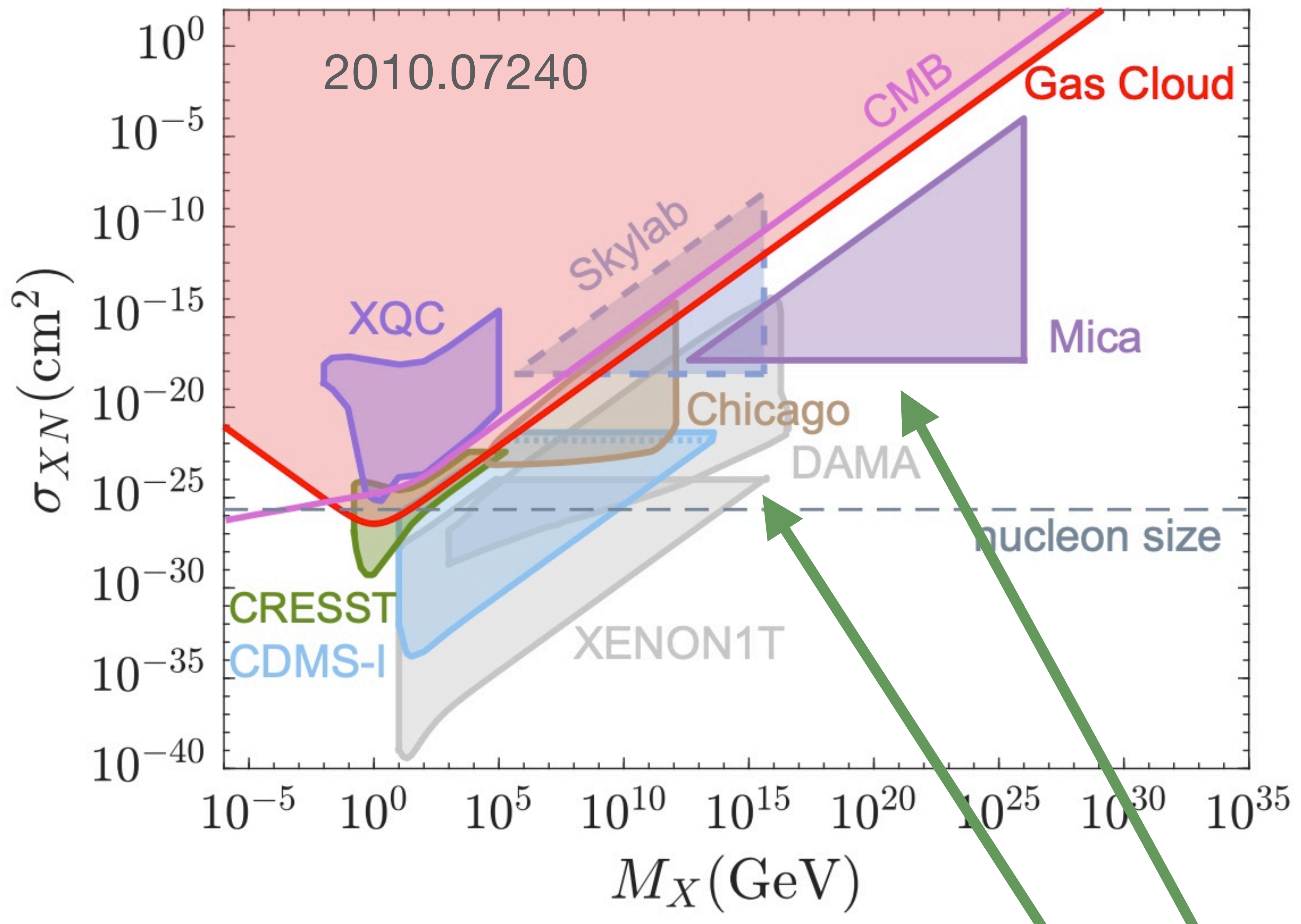
Δσ relative to last generation



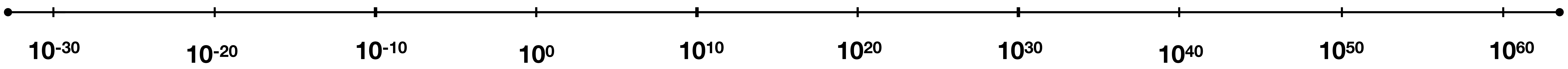
10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

m_x (GeV)

HEAVY DARK MATTER



What kind of dark matter is over here and how do we find it?

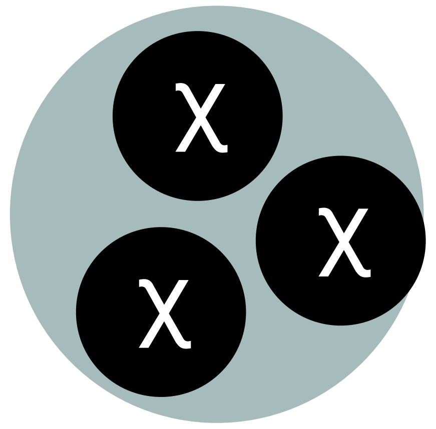


m_x (GeV)

DM Models

Vis-a-vis heavy composite DM

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



Nice to have a model

- Early matter domination
- Boson stars

- Q ball
- Dark QCD/BBN

On the other hand: Wha

Lagrangian / cosmology

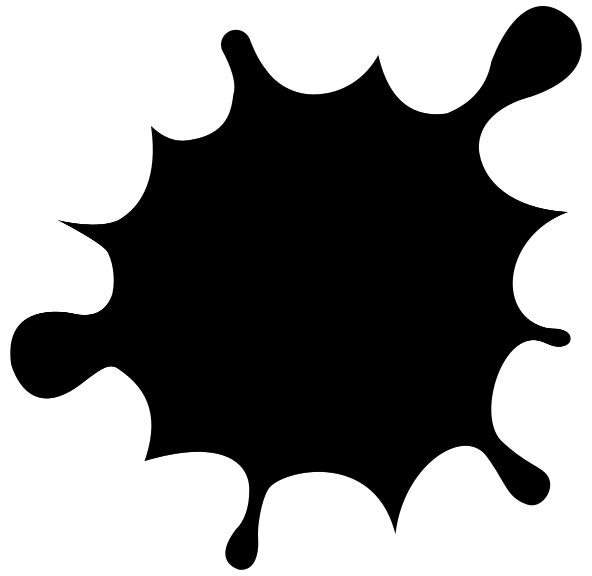
mation still has open

(e.g. pebble accretion).

mposite DM doesn't have

namics like single-field

ls



Predict masses from 1st principl

DM Models

Vis-a-vis heavy composite DM

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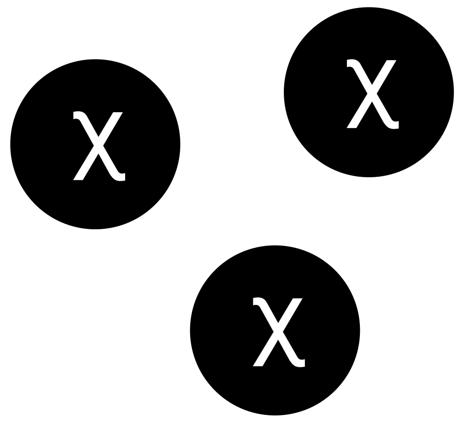
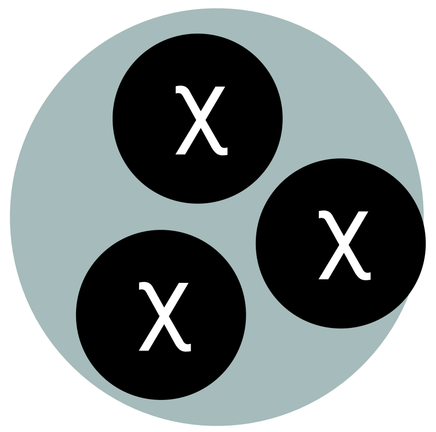
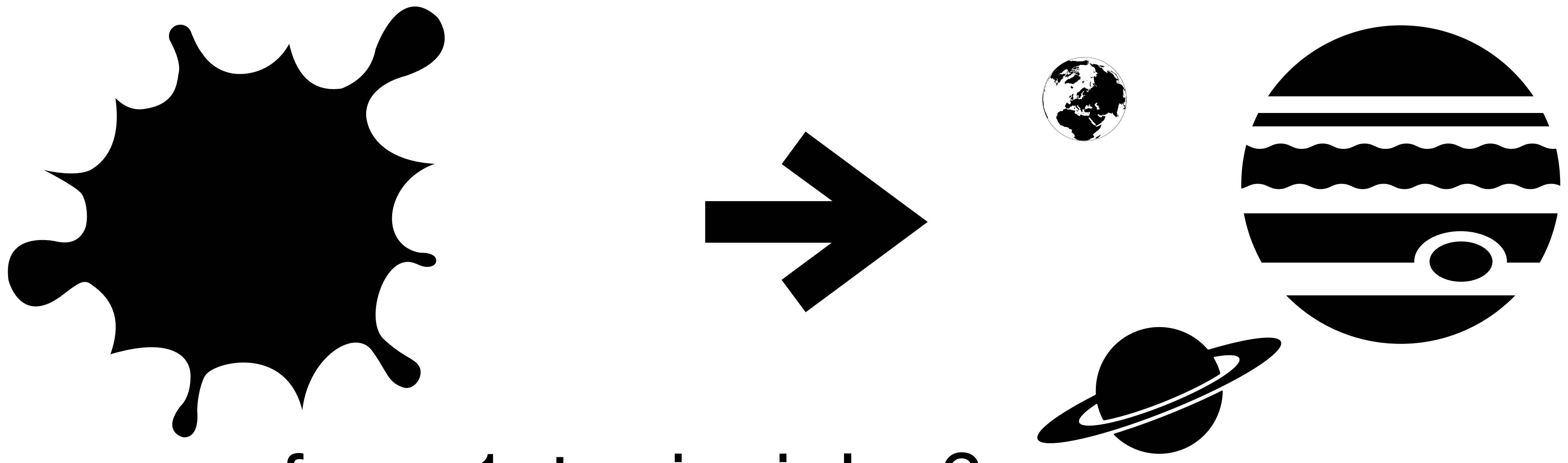




Nice to have a model

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

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



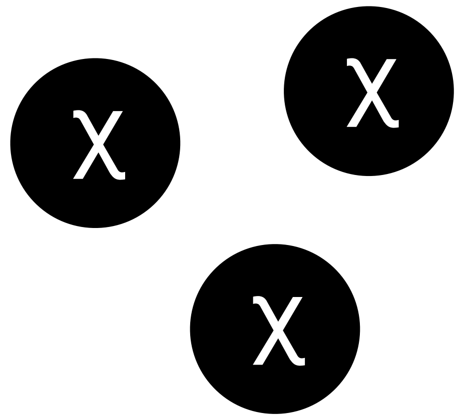
Predict masses from 1st principles?

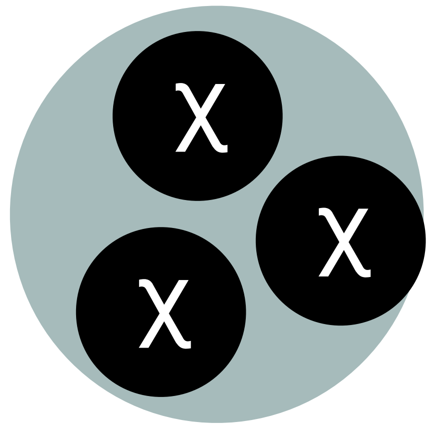
- Planet formation still has open questions (e.g. pebble accretion).
- Heavy composite DM doesn't have simple dynamics like single-field DM models

DM Models

Vis-a-vis heavy composite DM

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



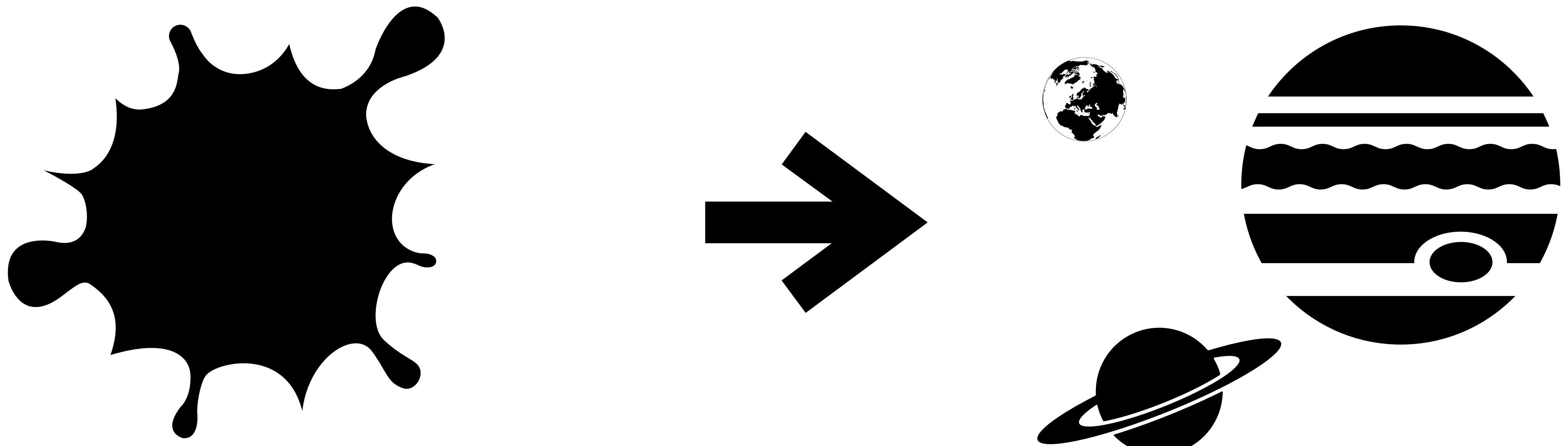


Nice to have a model

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

Perhaps the least explored of these.

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



Predict masses from 1st principles?

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DM Models

Vis-a-vis heavy composite DM

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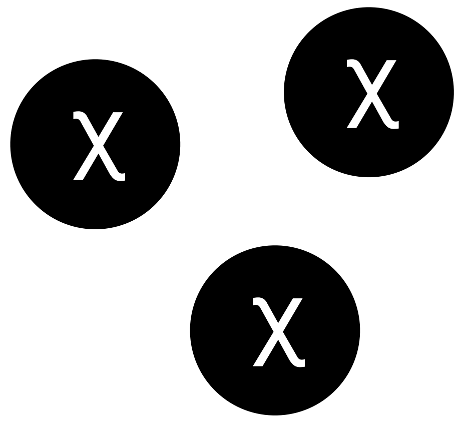
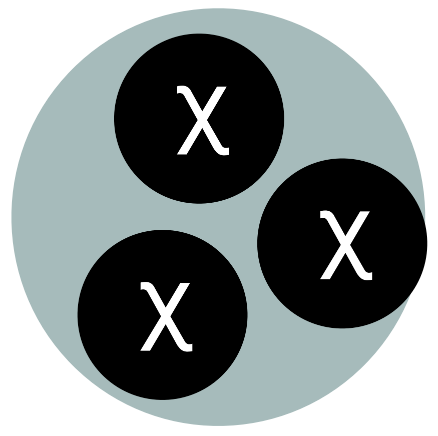




Compare simplicity with Higgsino:

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.} + \mathscr{L}_{SM+2HDM}$$

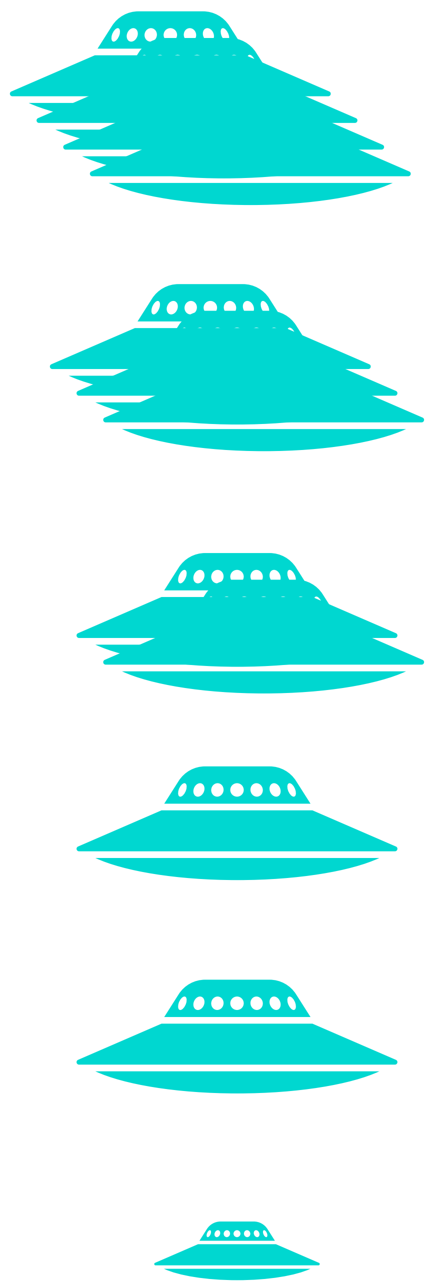
$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & -\mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

(also restricted M1, M2 values to make Higgsino have tree-level inelastic nuclear scattering)

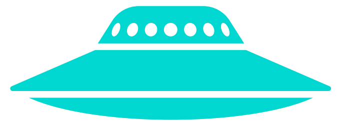
DM Models

if given multiple guesses, five decades of mass and model

1.
2.
3.



Alien Game Show
Win spaceships!

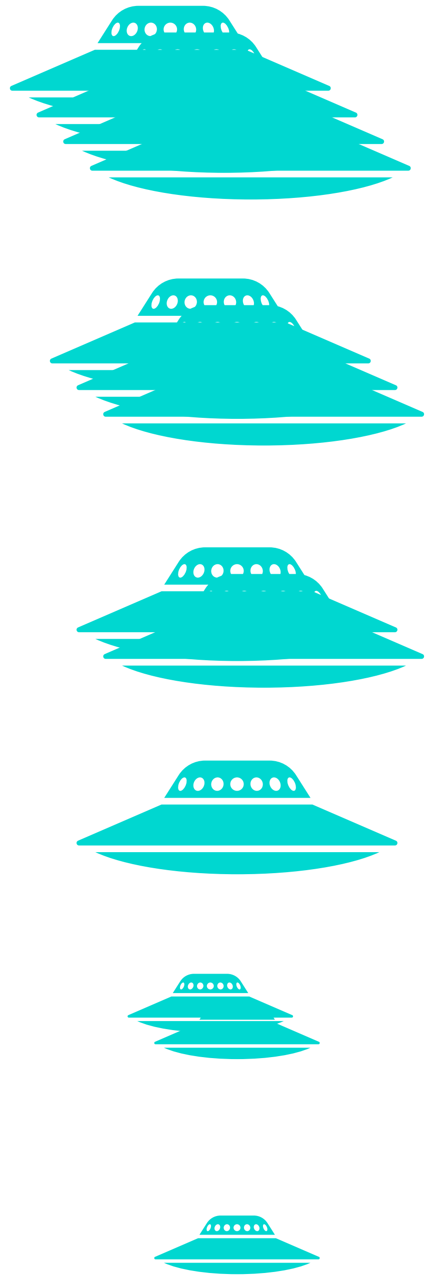


DM Models

if given multiple guesses

my rough prior

1. Heavy asymmetric, 10^{5}-10^{10} GeV — $\lesssim 6\%$
2. Higgsinos/WIMPs, 10^{2}-10^{7} GeV — $\lesssim 4\%$
3. Axions, 10^{-10}-10^{-5} eV — $\lesssim 4\%$
4. Heavy composite, 10^{19}-10^{24} GeV — $\lesssim 4\%$
5. Light dark matter, 10^{-5}-1 GeV — $\lesssim 4\%$
6. …your favorite DM — $\lesssim 4\%$



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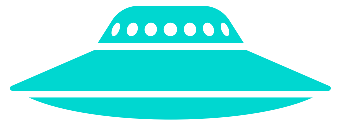

DM Models

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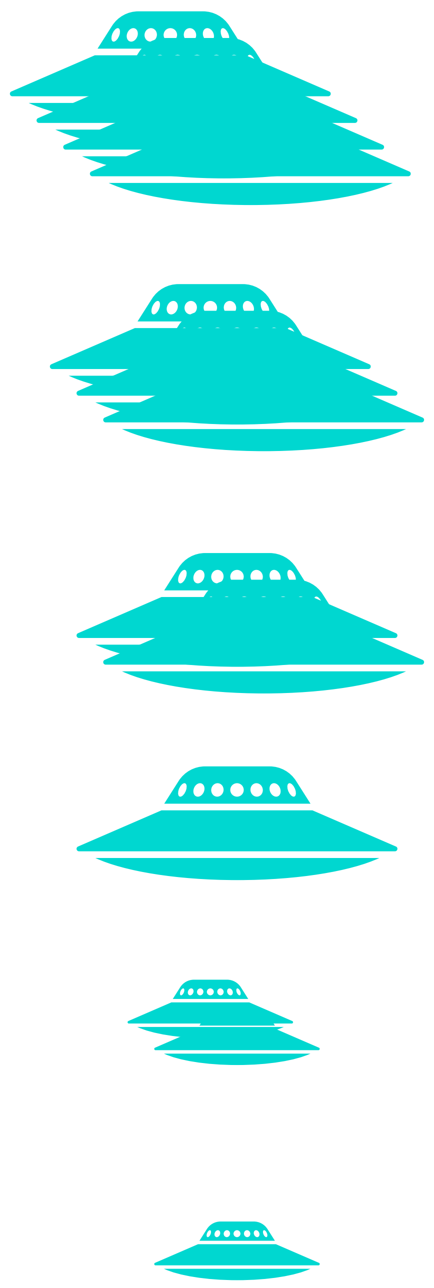
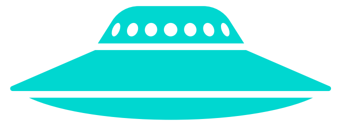


Alien Game Show
Win spaceships!



But if told, "hey for heavy composites, you can have 10 orders of magnitude in mass"

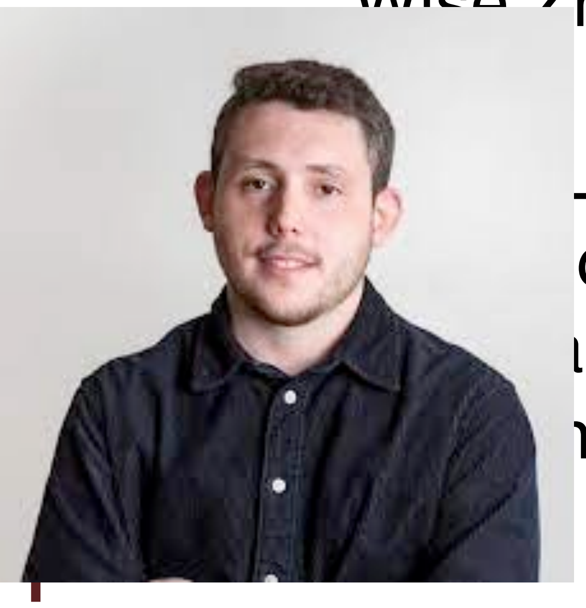
1. Heavy composite 10^{19}-10^{29} GeV
2. Heavy asymmetric, 10^{5}-10^{10} GeV

HIGH MASS ASYMMETRIC COMPOSITE DM

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

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

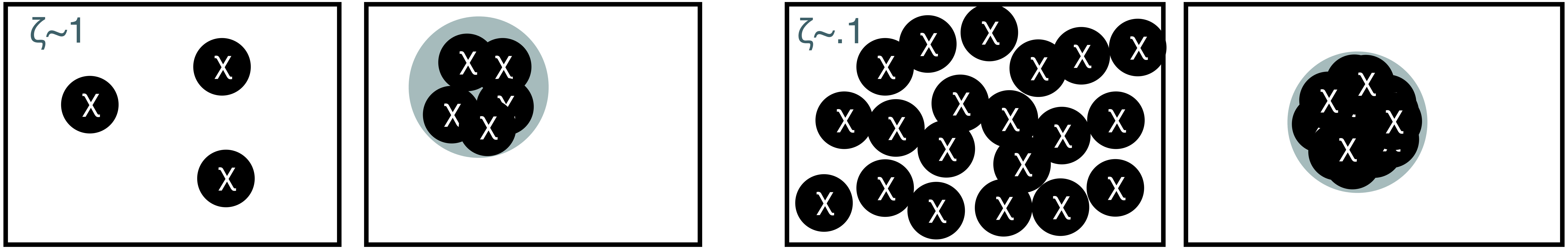
see also e.g.
Wise Zhang ’14
Sigurdson ’14
Lasenby March-Russell ’14
d McCullough Pochinsky ’14
m Lou Zurek ’17
er, Grabowska, Knapen, Zurek ’18



Diluted dark matter has a freeze-out abundance that scales with ζ

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

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

HIGH MASS ASYMMETRIC COMPOSITE DM

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

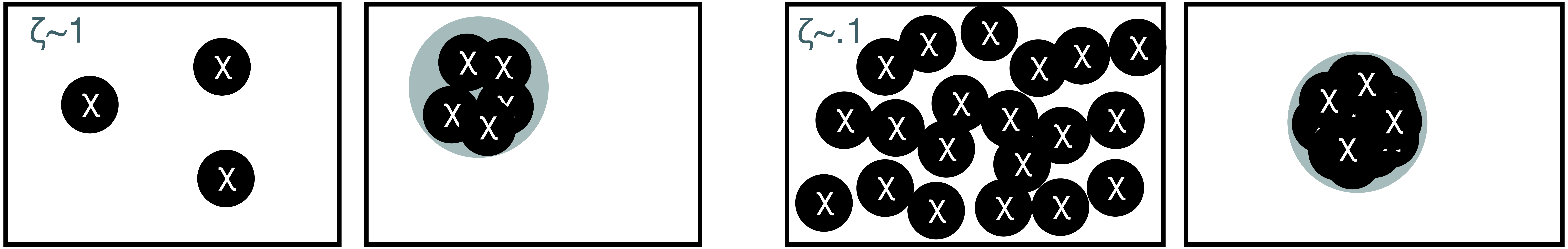
$$\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathcal{L}_{SM},$$

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

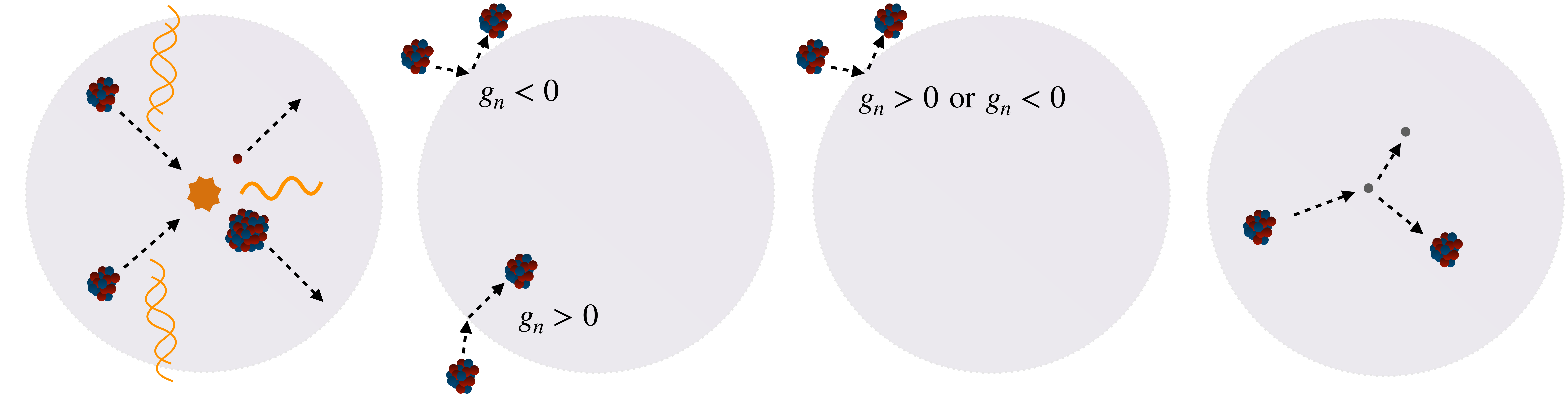
COMPOSITE INTERACTIONS

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

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

<u>scattering with constituents</u>

1. 2. 3. 4.



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

2. $\langle\varphi\rangle \ll m_N$

3. $\langle\varphi\rangle > m_N$

(MIMPs)

Acevedo, JB, Goodman
2012.10998

Acevedo, JB, Goodman
2108.10899

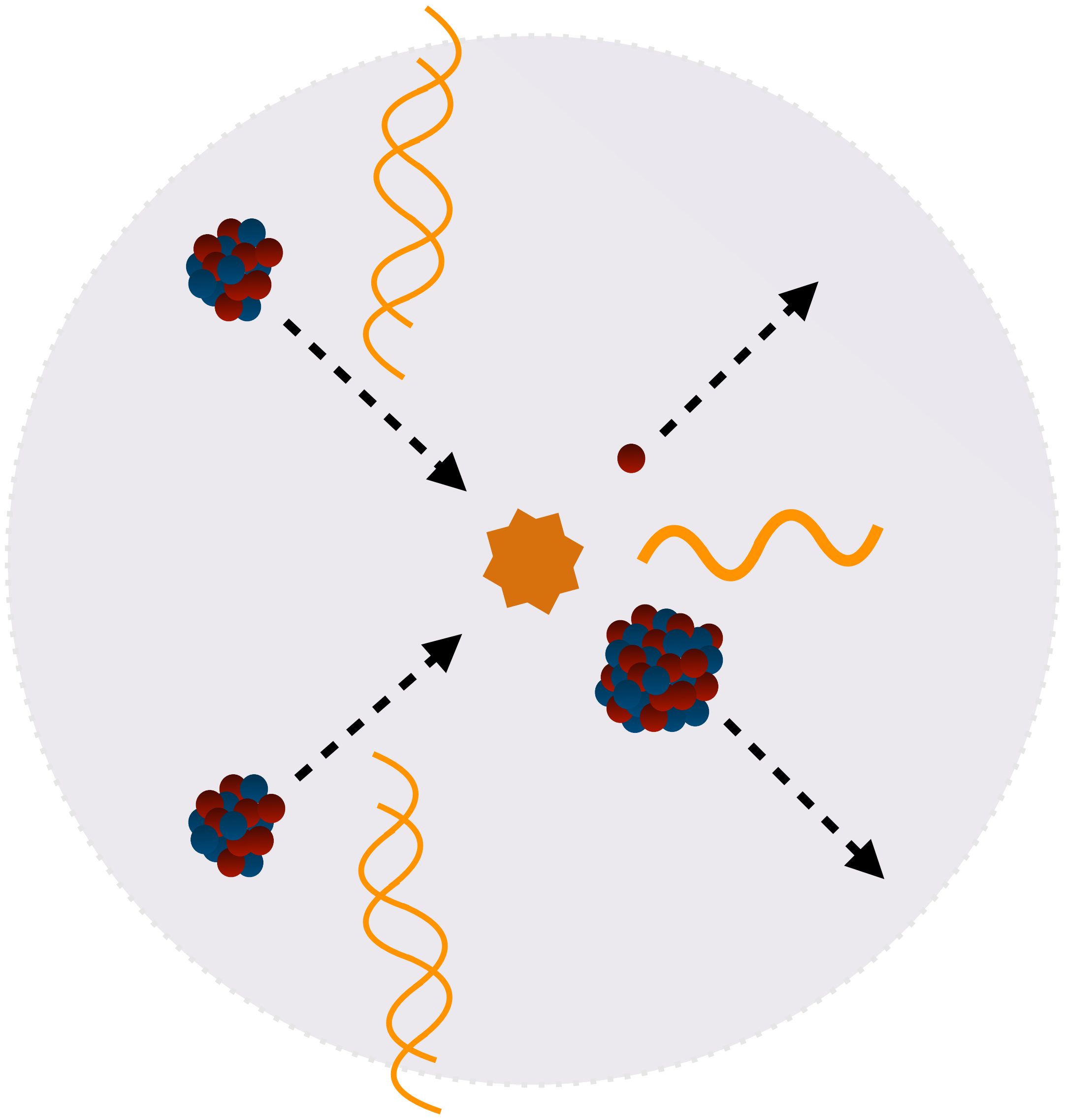
Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Sheahan, Tyagi, in progress

BREM/NUCLEAR 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

1.



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

Acevedo, JB, Goodman
2012.10998

Saturated ADM composite parameters

bremsstrahlung + fusion requires
a few nuclei per composite

$$R_X \gtrsim 10^{-7}\ \text{cm} \longrightarrow M_X \gtrsim 10^{21}\ \text{GeV}$$

$$R_X = \left(\frac{9\pi N_c}{4\bar{m}_X{}^3}\right)^{\frac{1}{3}} \qquad N_c \simeq \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5}$$

for large N_c composite interior has a potential determined by:

Minimize $\varepsilon = \frac{1}{2}m_\phi^2\langle\phi\rangle^2 + \frac{1}{\pi}\int_0^{p_F} dp\ p^2\left(p^2+m_*^2\right)^{1/2}$

with interior mass $\bar{m}_X \simeq [3\pi m_X^2 m_\varphi^2/(2\alpha_X)]^{1/4}$

leading to $\langle\phi\rangle \simeq \frac{m_X}{g_X}, \quad r < R_X$

(DM fusion conditions)

$$\alpha_X^2 m_X \gtrsim m_\phi$$

$$\alpha_X \gtrsim 0.3\left(\frac{m_X}{10^7\,\text{GeV}}\right)^{\frac{2}{5}}\left(\frac{\zeta}{10^{-6}}\right)^{\frac{1}{5}}$$

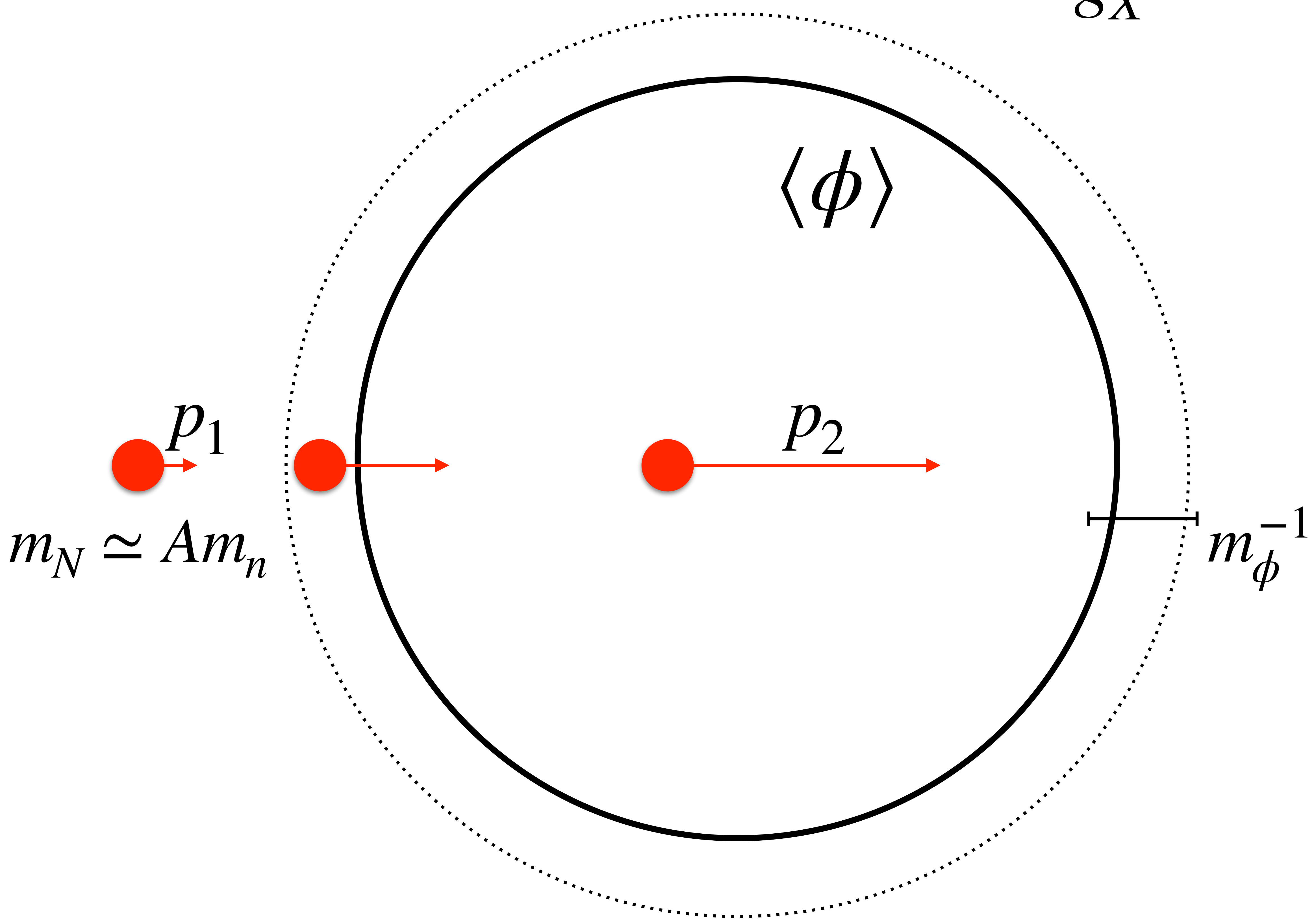
edge of composite screened

$$\phi(r) = \langle\phi\rangle\ e^{-m_\phi(r-R_X)}\left(\frac{R_X}{r}\right), \quad r \geqslant R_X$$

DM-nucleon coupling accelerates nuclei in composites

Consider an interaction term with SM nucleons $\mathscr{L} = \mathscr{L}_0 + g_n \bar{n} \phi n$

for large N composite: $\langle \phi \rangle \simeq \dfrac{m_X}{g_X}$



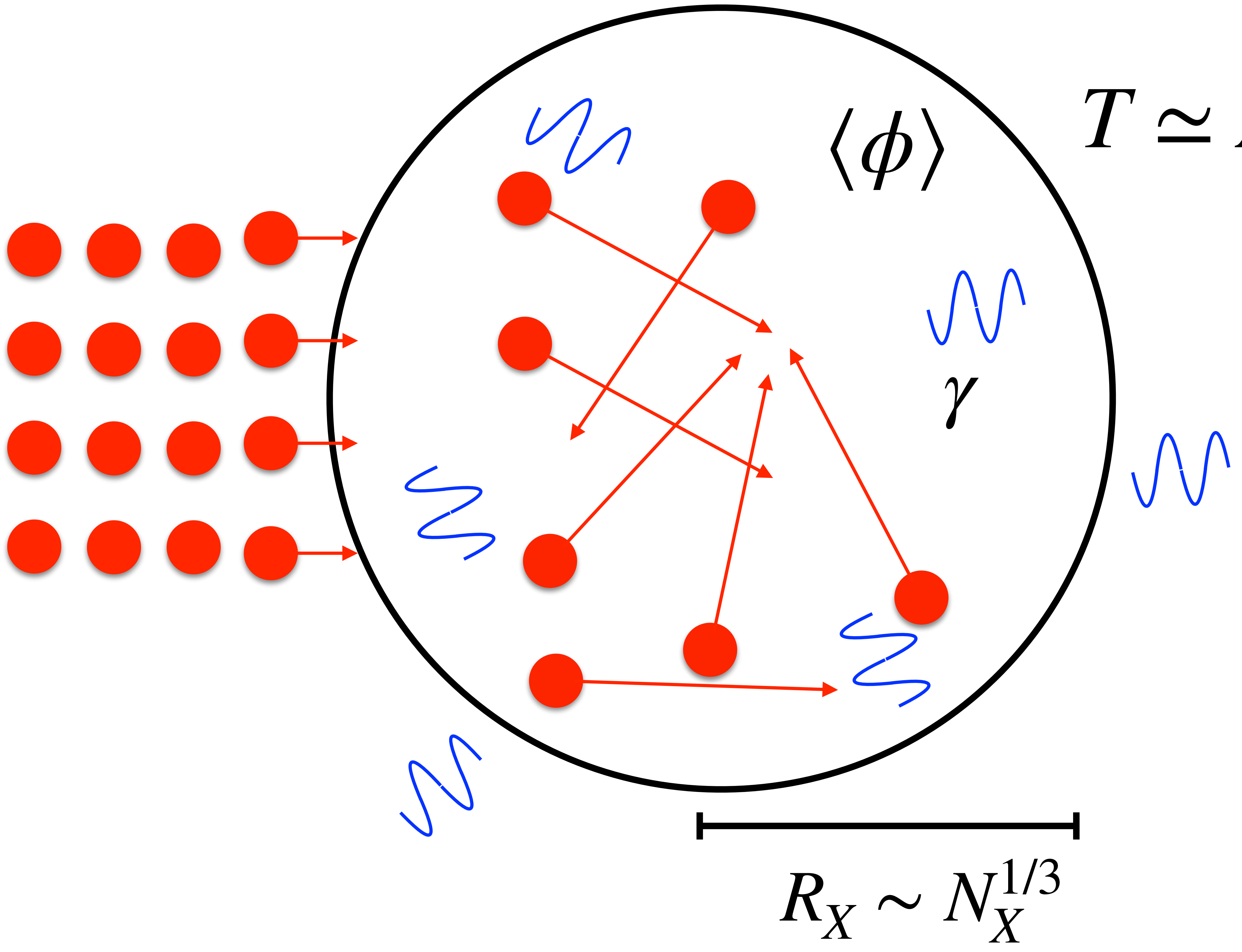
Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential sourced by X fermions, like gravity but stronger and shielded

$$p_1^2 + m_N^2 = p_2^2 + (m_N - A g_n \langle \phi \rangle)^2$$

$$A g_n \langle \phi \rangle = \frac{A g_n m_X}{g_X} = \frac{p_2^2 - p_1^2}{2 m_N}$$

Heated nuclei in composite interior

$\langle\phi\rangle \propto m_X \sim \mathrm{TeV} - \mathrm{EeV}$ acceleration is substantial even for $g_n \ll 1$



$T \simeq A g_n \langle\phi\rangle$

Ionization (Migdal, collisions)

Thermal bremsstrahlung

Thermonuclear fusion

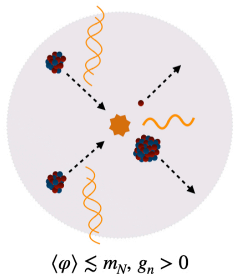
increasing temperature/energy

Potential signatures of this effect?

→ Ionizing dark matter

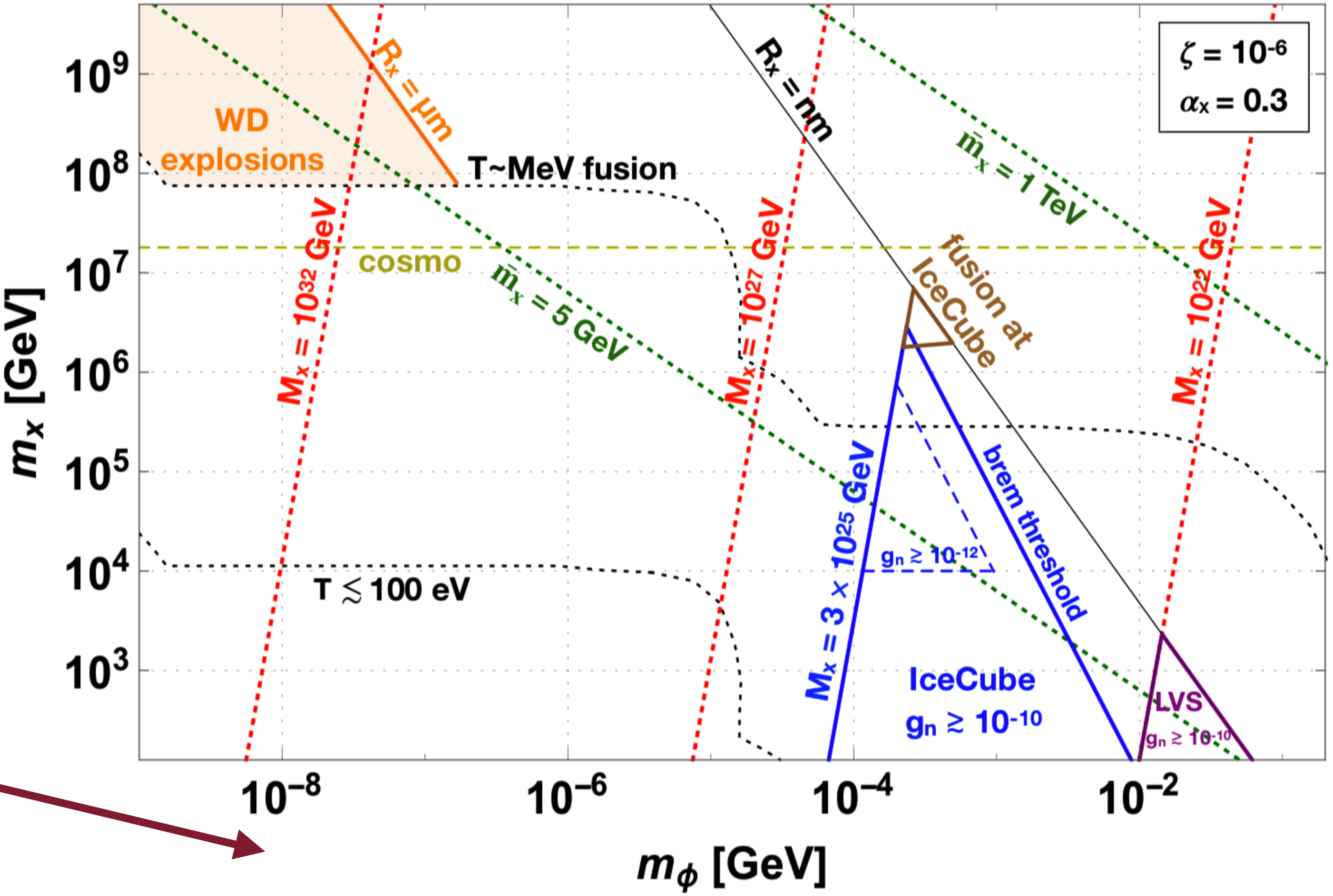
→ Neutrino detectors

→ Type Ia supernovae



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

BREM/NUCLEAR FUSION IN COMPOSITES



Each point fixes composite R and M to give observed DM abundance

Where in parameter space do experiments have sensitivity?

To trigger detectors:

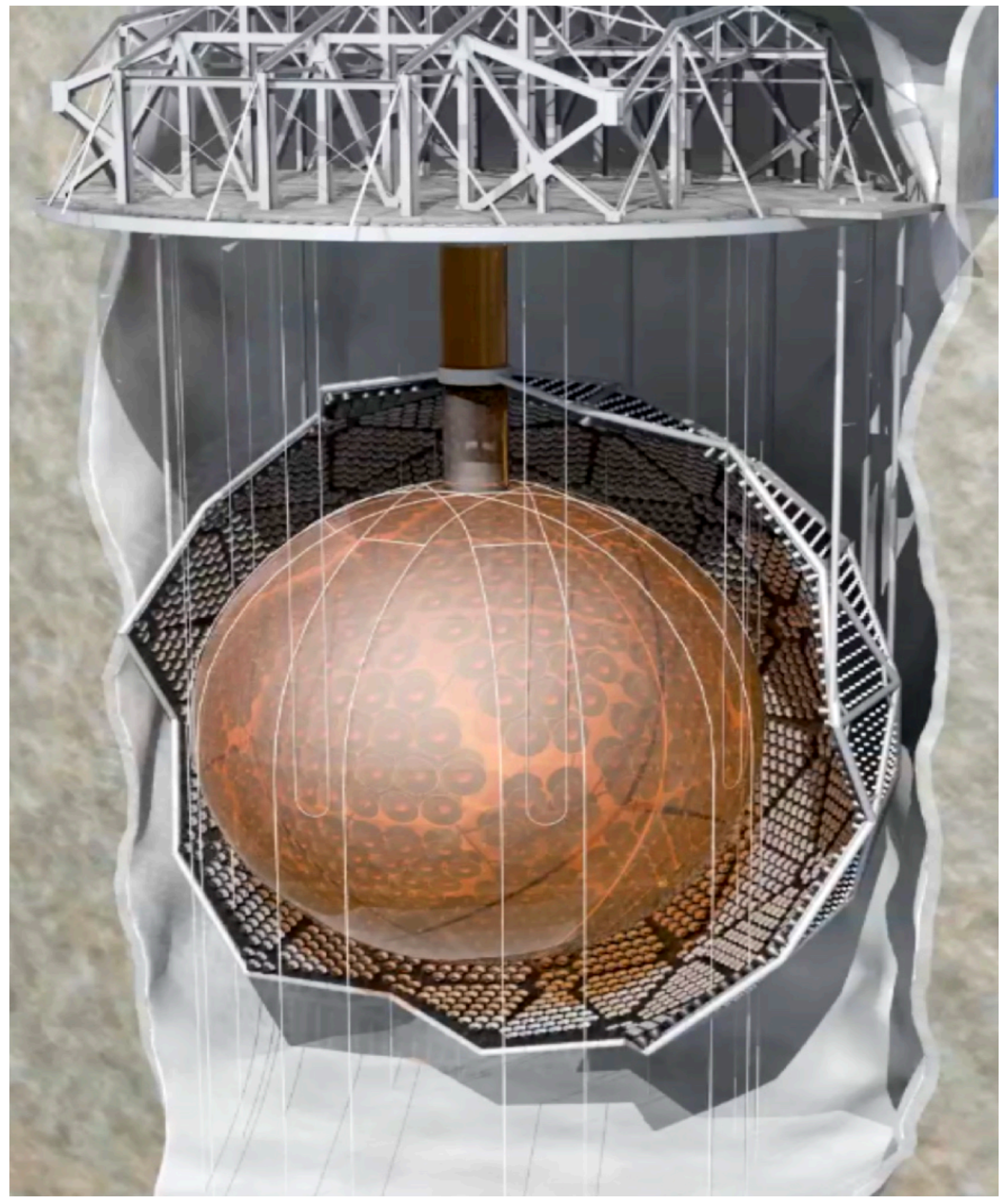
SNO+: ~1 MeV per 100 ns

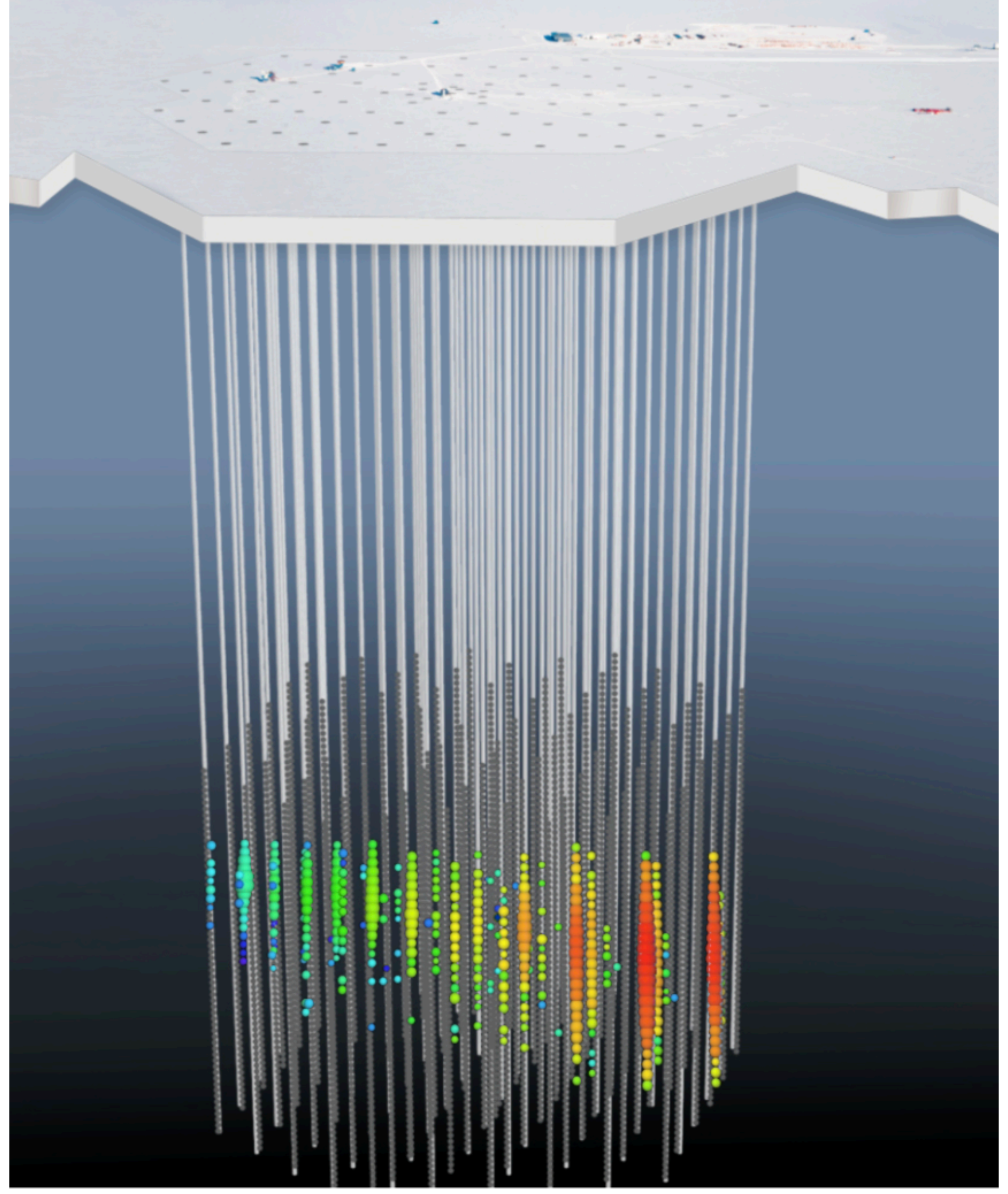
IceCube: ~10 TeV per 100 ns (~100 PeV in single crossing)

Composites radiate continuously along path:

$$\dot{E}_{SNO+} \simeq 10^4 \text{ GeV s}^{-1} \qquad \dot{E}_{IC} \simeq 10^{11} \text{ GeV s}^{-1}$$

$$M_X^{max} \simeq 10^{22} \text{ GeV} \qquad M_X^{max} \simeq 3 \times 10^{25} \text{ GeV}$$





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

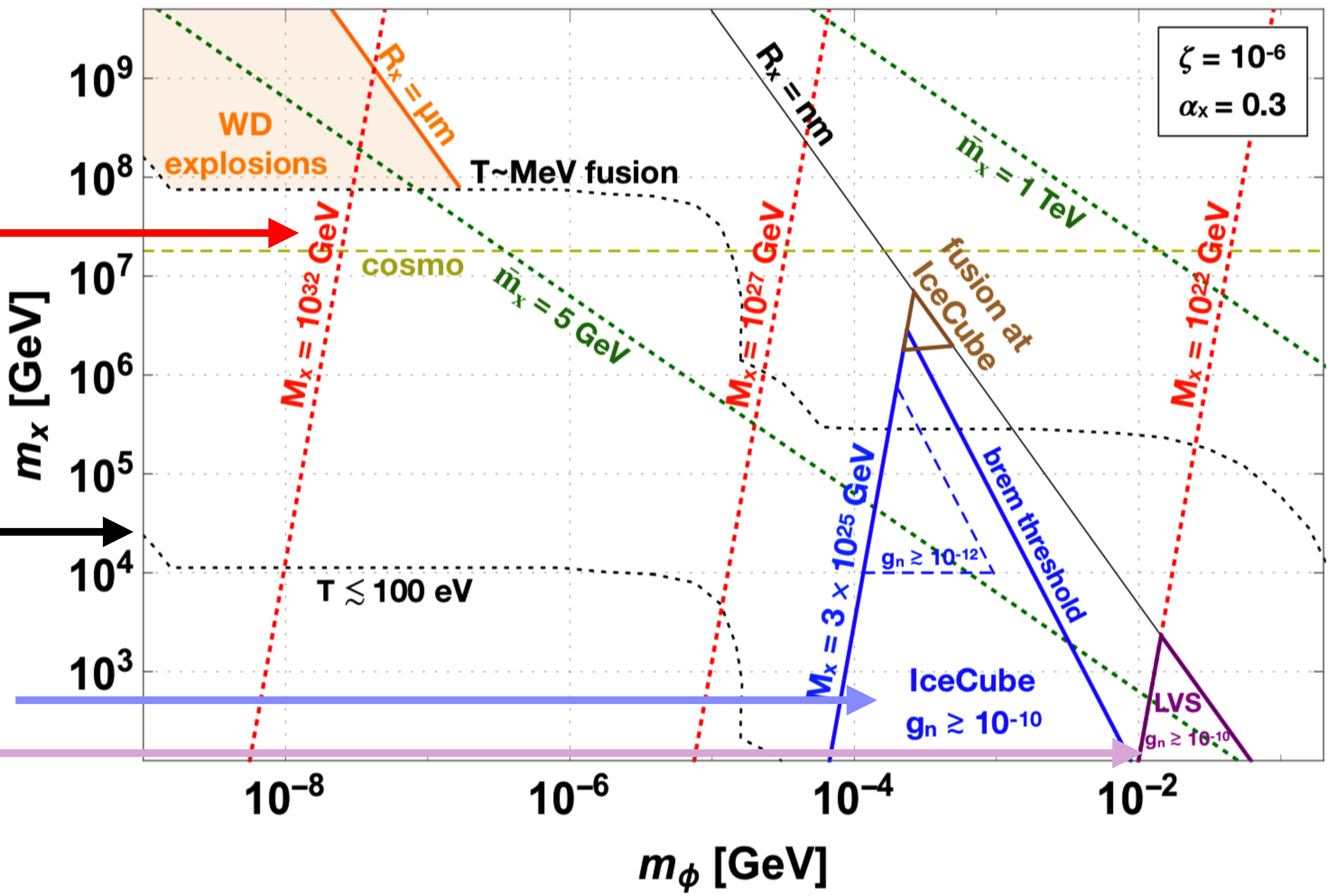
BREM/NUCLEAR FUSION IN COMPOSITES

Composite mass

Max temperature of baryons flowing through composite

Find composite Brem at Ice Cube

Find composite Brem at SNO+/JUNO



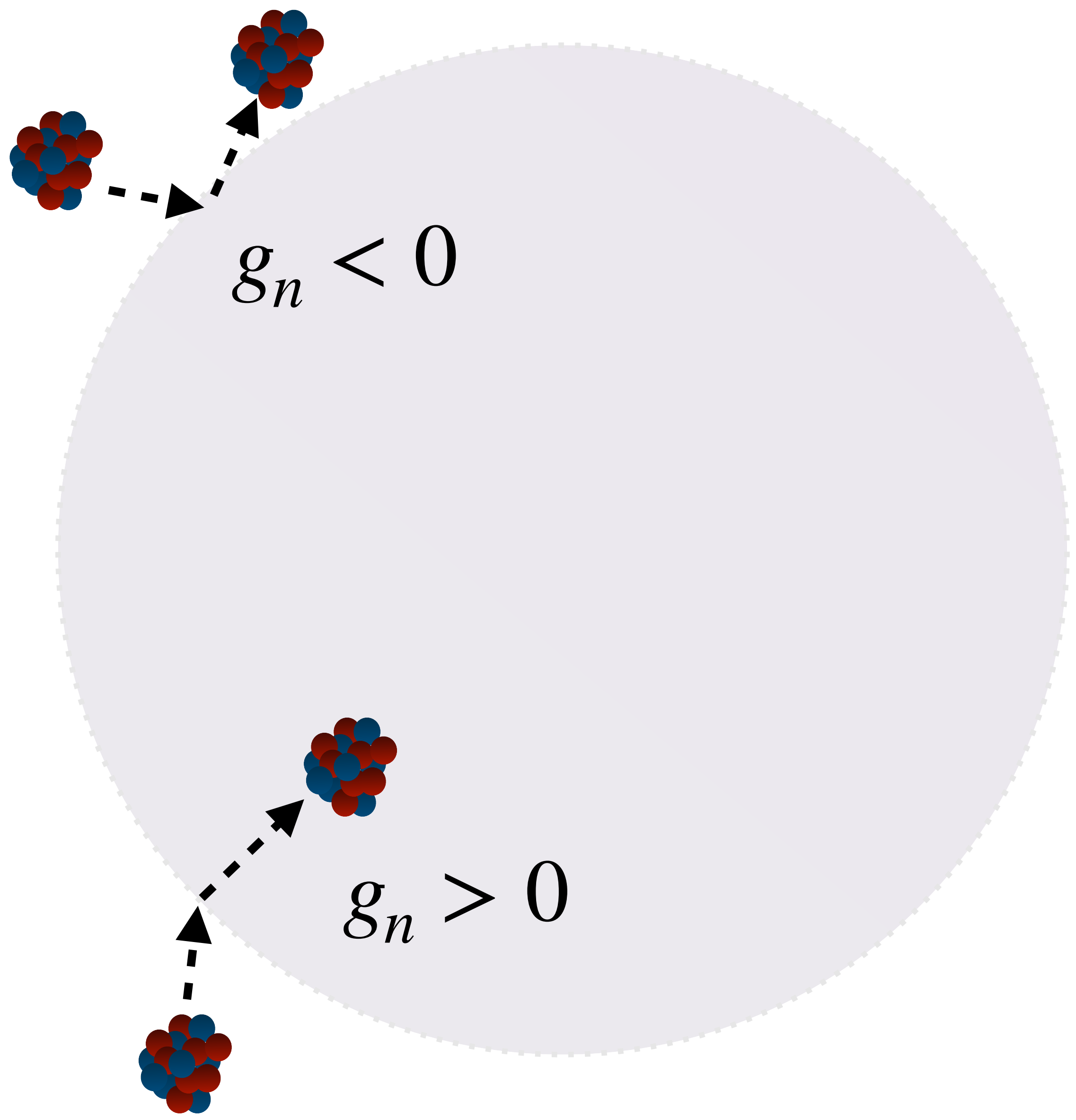
Acevedo, JB, Goodman 2012.10998

LOW E RECOIL 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

2.

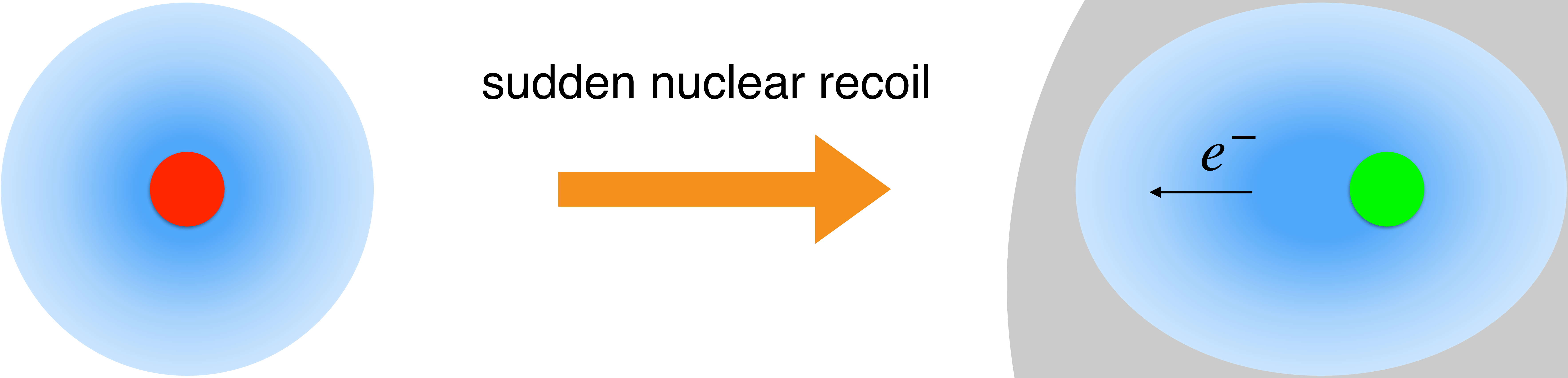


$\langle\varphi\rangle \ll m_N$

Acevedo, JB, Goodman
2108.10899

Composite Migdal Effect at DD Experiments

$\Delta t_{\text{interact}} \ll \tau_{e^-}\ ,\ R_a/v_N$ Migdal approximation



$$\psi\rangle \simeq e^{\left(-im_e \sum_j \mathbf{v}\cdot\hat{\mathbf{x}}_j\right)}\ \psi_0\rangle$$

$\tau_{e^-} \sim 10^{-17}$ s electron orbital period

$$\frac{R_a}{v_N} \sim 10^{-15}\ \text{s} \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{m_X}{\text{TeV}}\right)^{-\frac{1}{2}}$$

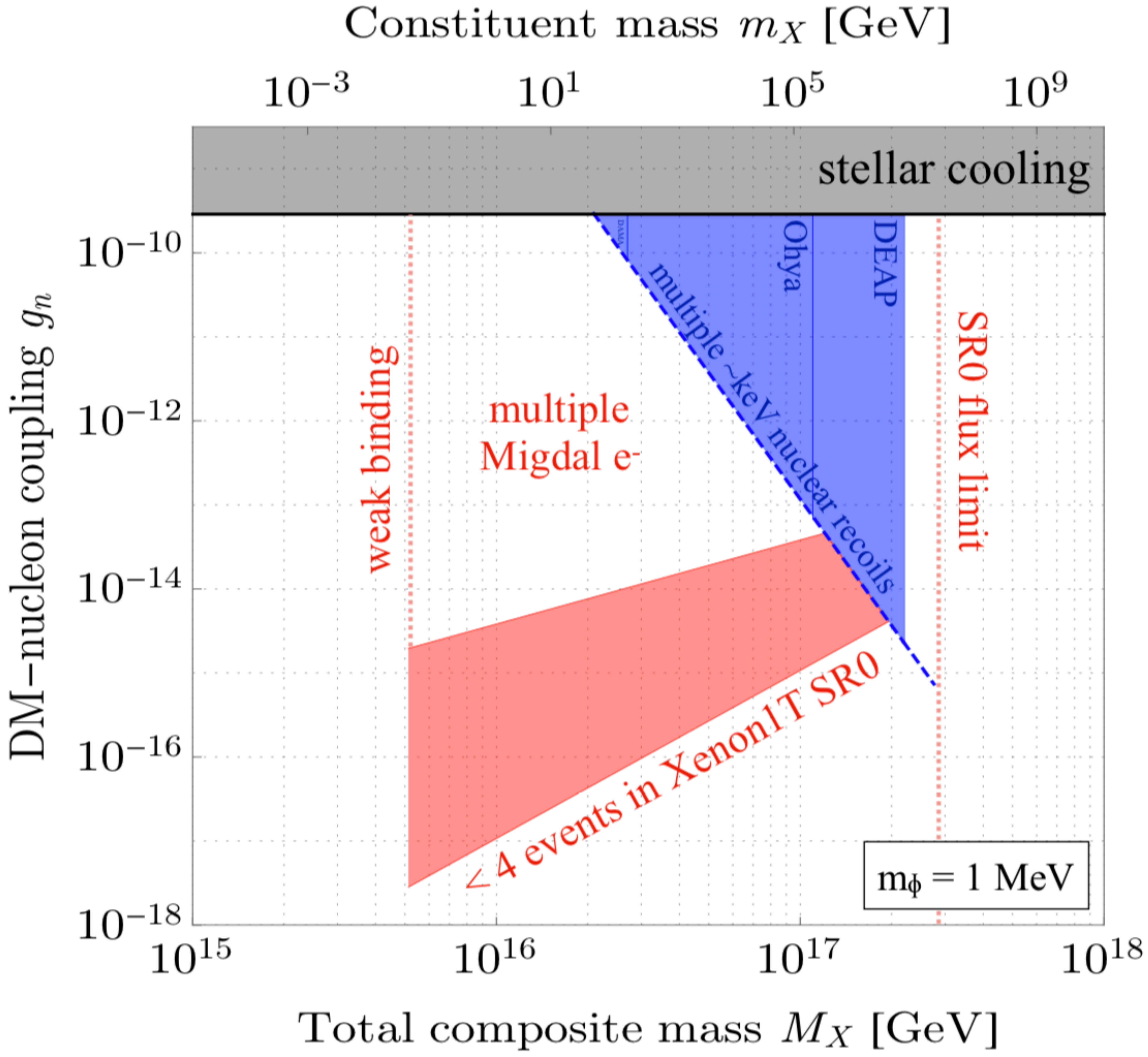
$(R_a \sim 10^{-8}$ cm$)$

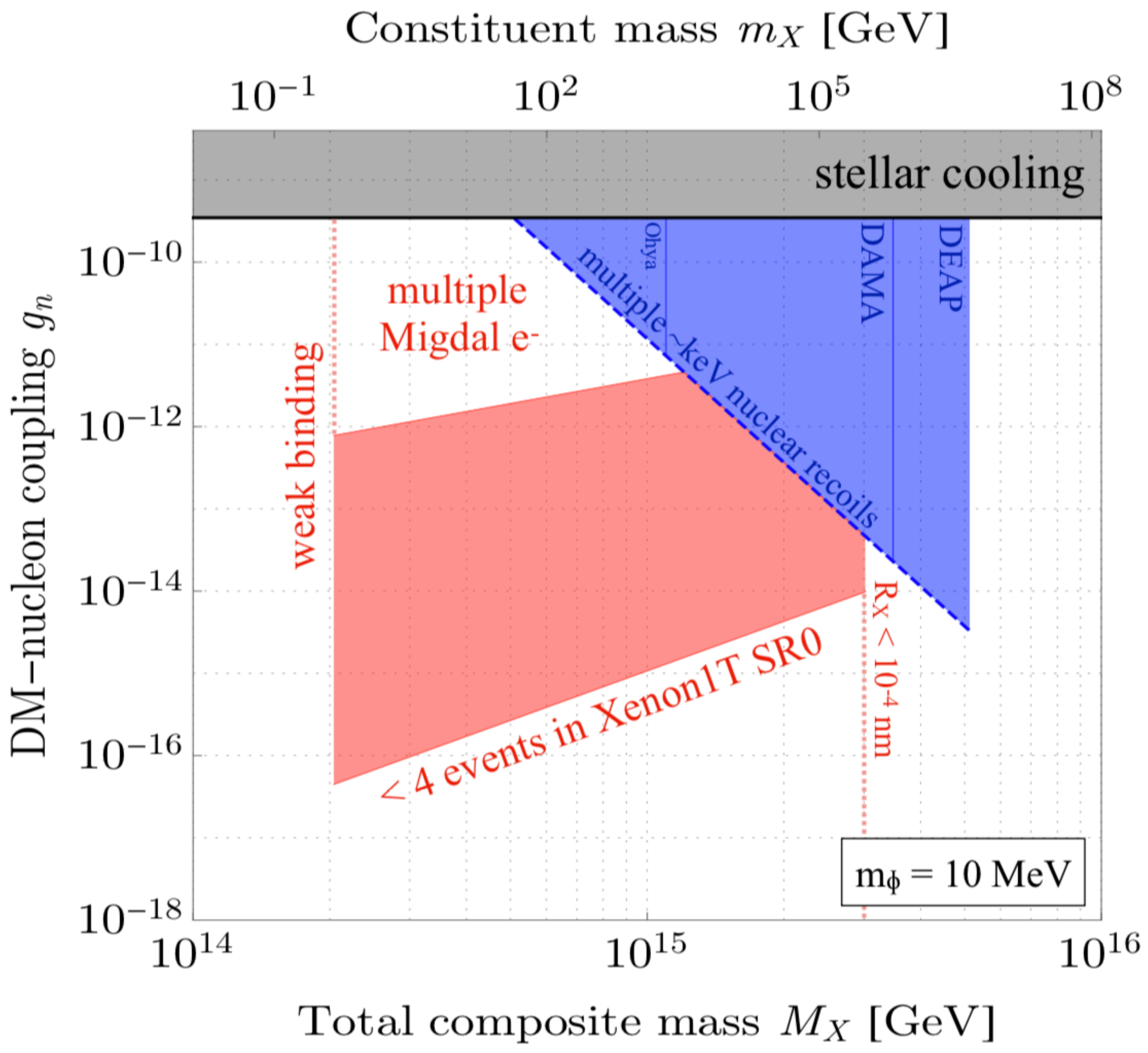
$$\Delta t_{\text{interact}} = \tau_{\text{accel}} \simeq \frac{1}{m_\phi v_X} \simeq 10^{-19}\ \text{s} \left(\frac{m_\phi}{\text{MeV}}\right)^{-1} \ll \tau_{e^-}$$

Migdal Bounds

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

Composite masses/radii determined by mX, cosmology with $\alpha_X = 0.3$





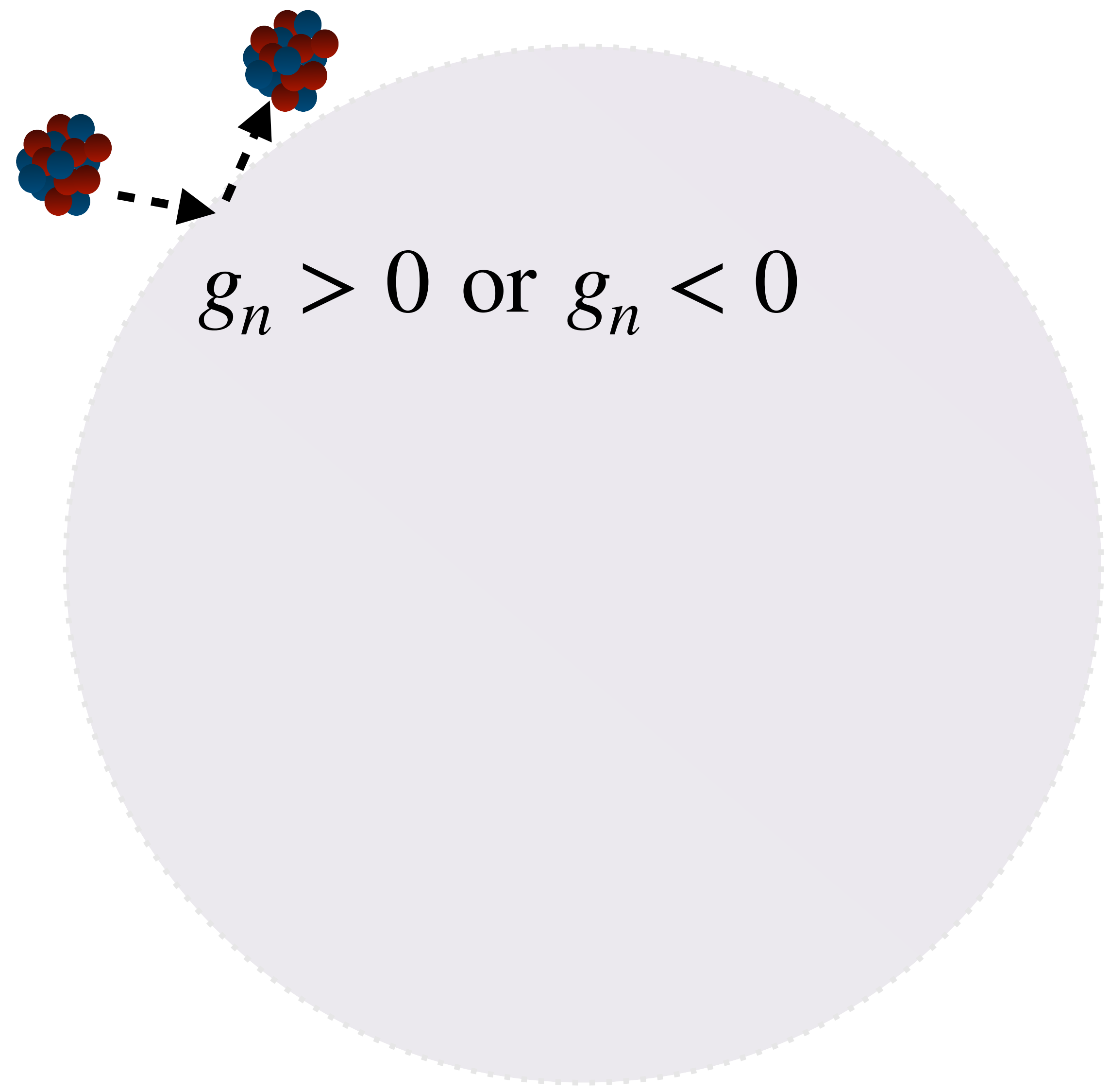
Acevedo, JB, Goodman, 2108.10889

MIMP INTERACTIONS

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

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

<u>3.</u>



$\langle\varphi\rangle > m_N$

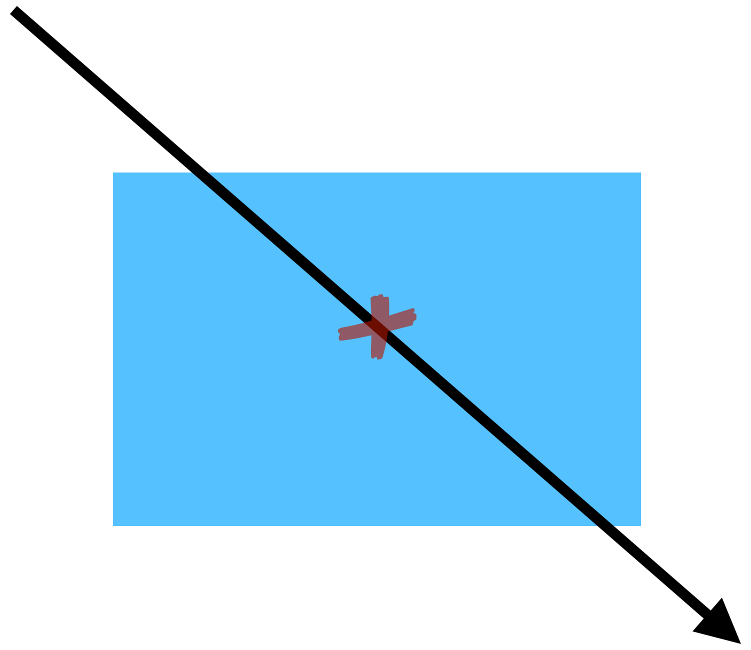
(MIMPs)

Acevedo, JB, Goodman
2108.10899

Multiscatter: models of dark matter interact many times in detectors.

New searches for multiply interacting dark matter (MIMPs)

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



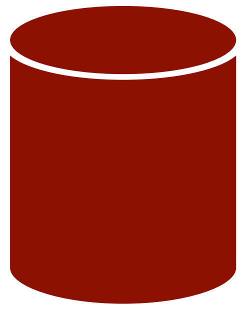
- If particles have velocity v (~0.001c), then sensitivity of detector sets a minimum energy threshold for detection

$$E_{th} \sim \mu_{nx}^2 v^2 / m_n$$

cross-section for DM to hit detector particle

mass of dark matter

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



- Detector is composed of N_a atoms, observes for time t
- As DM mass increases, DM flux decreases, sensitivity decreases as $1/m_x$

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

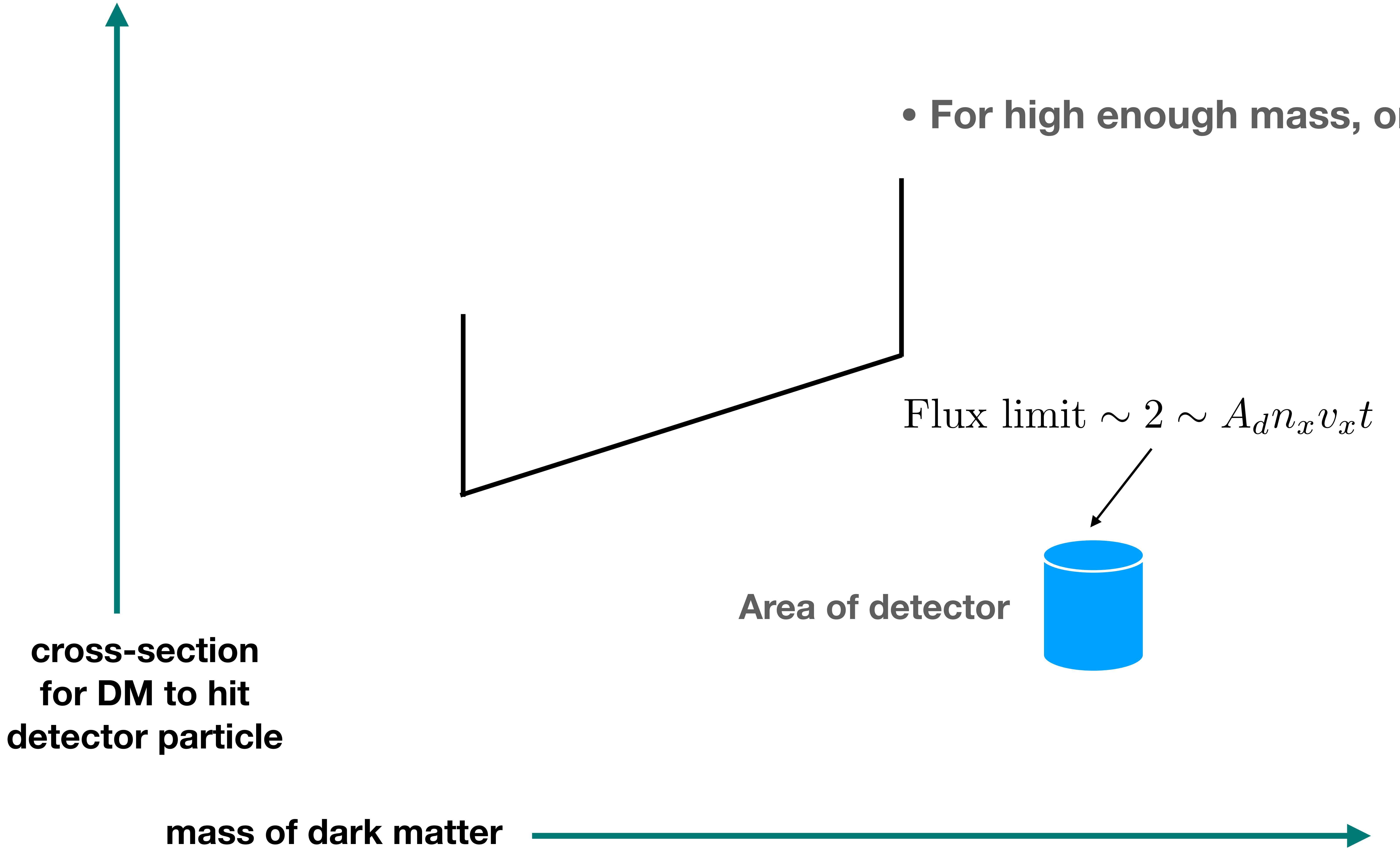
DM number density ρ_x / m_x

cross-section
for DM to hit
detector particle

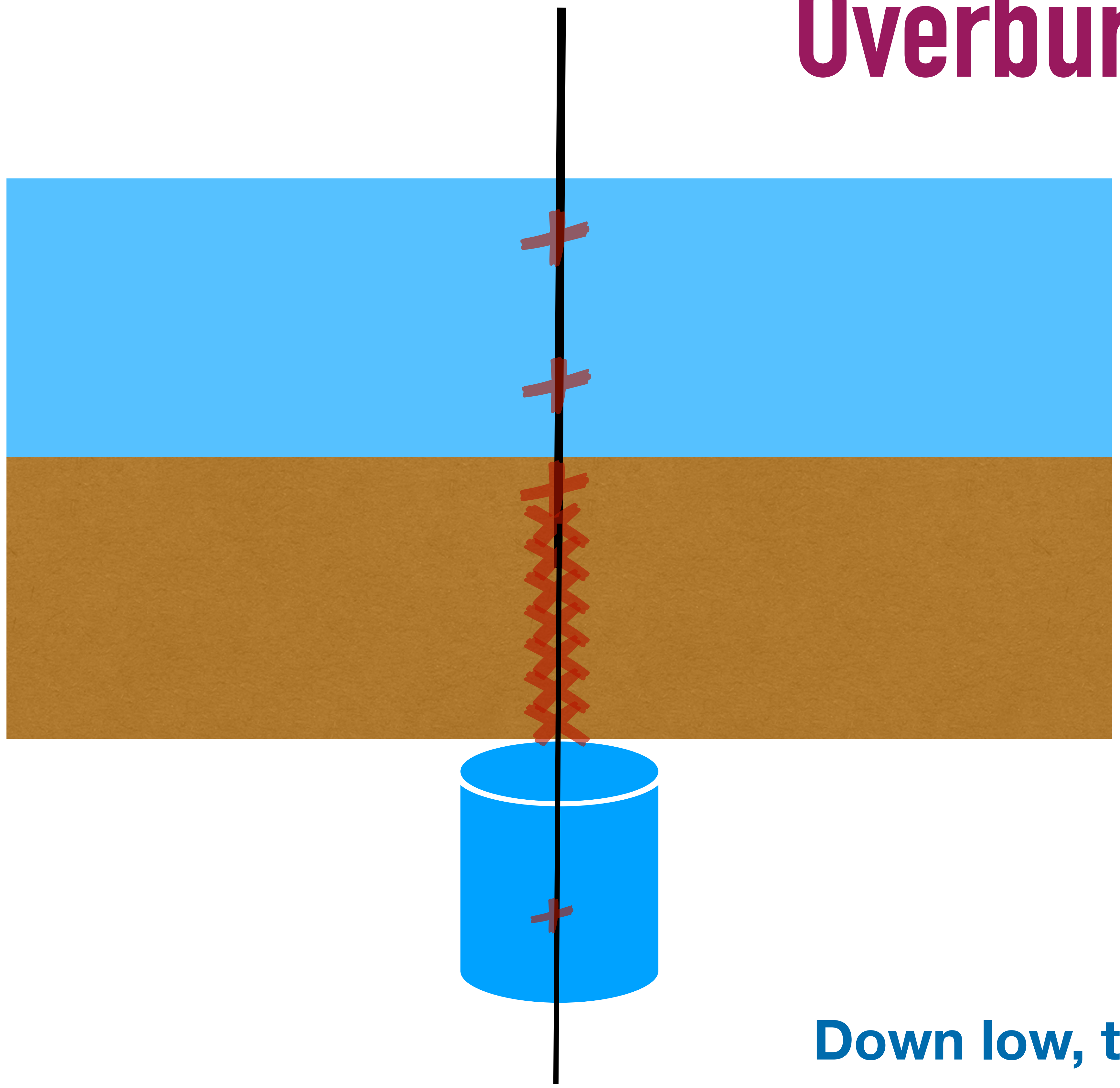
mass of dark matter

EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

- For high enough mass, only a few DM in time t



Overburden attenuation



- DM particles can be slowed through scattering with atmosphere, earth, aluminum space station wall.

Down low, too slow?

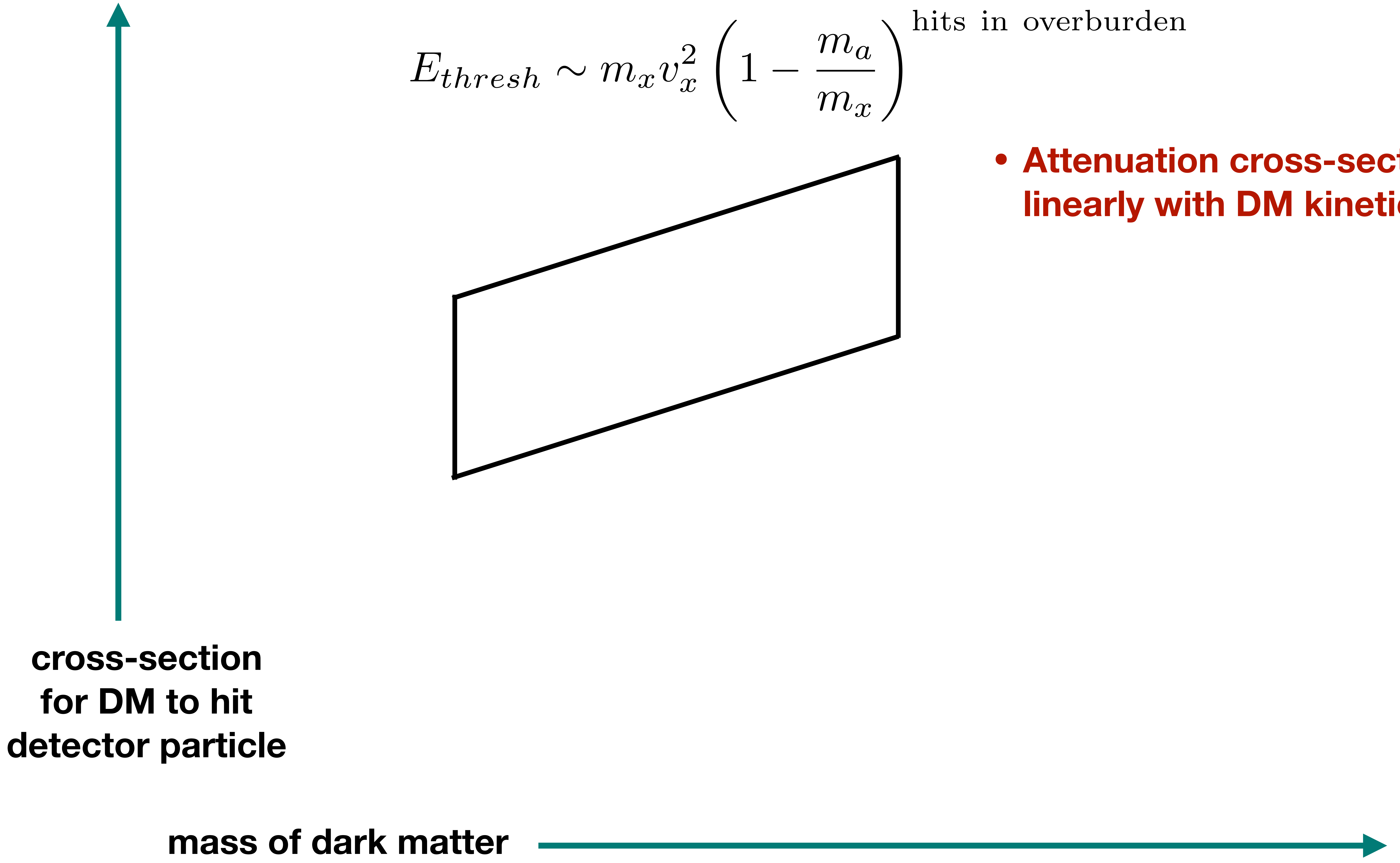
Length of overburden

$$E_{thresh} \lesssim E_i(1 - m_a/m_x)^{n_a \sigma_{ax} L_{ob}}$$

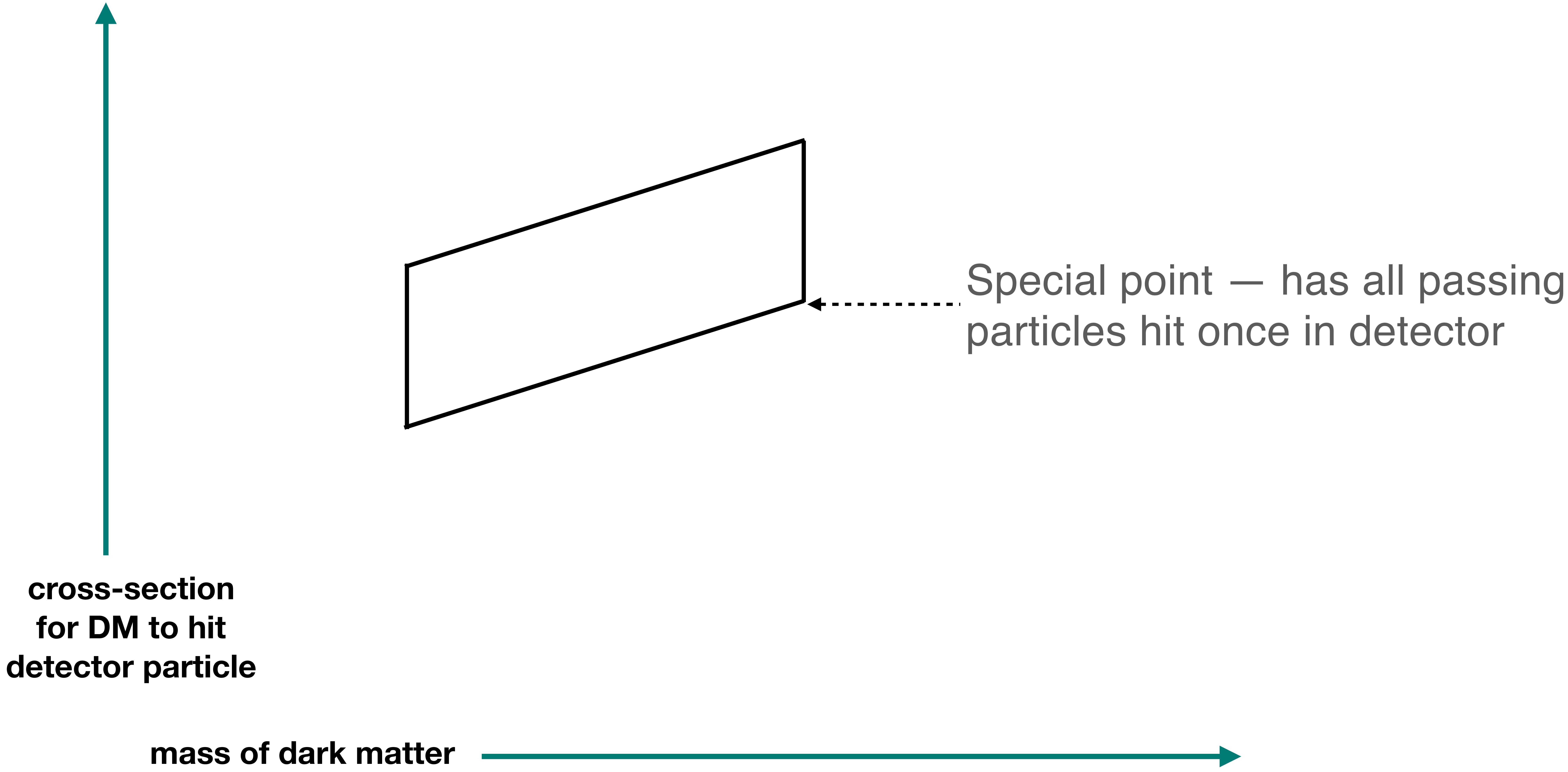
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

$$E_{thresh} \sim m_x v_x^2 \left(1 - \frac{m_a}{m_x}\right)^{\text{hits in overburden}}$$

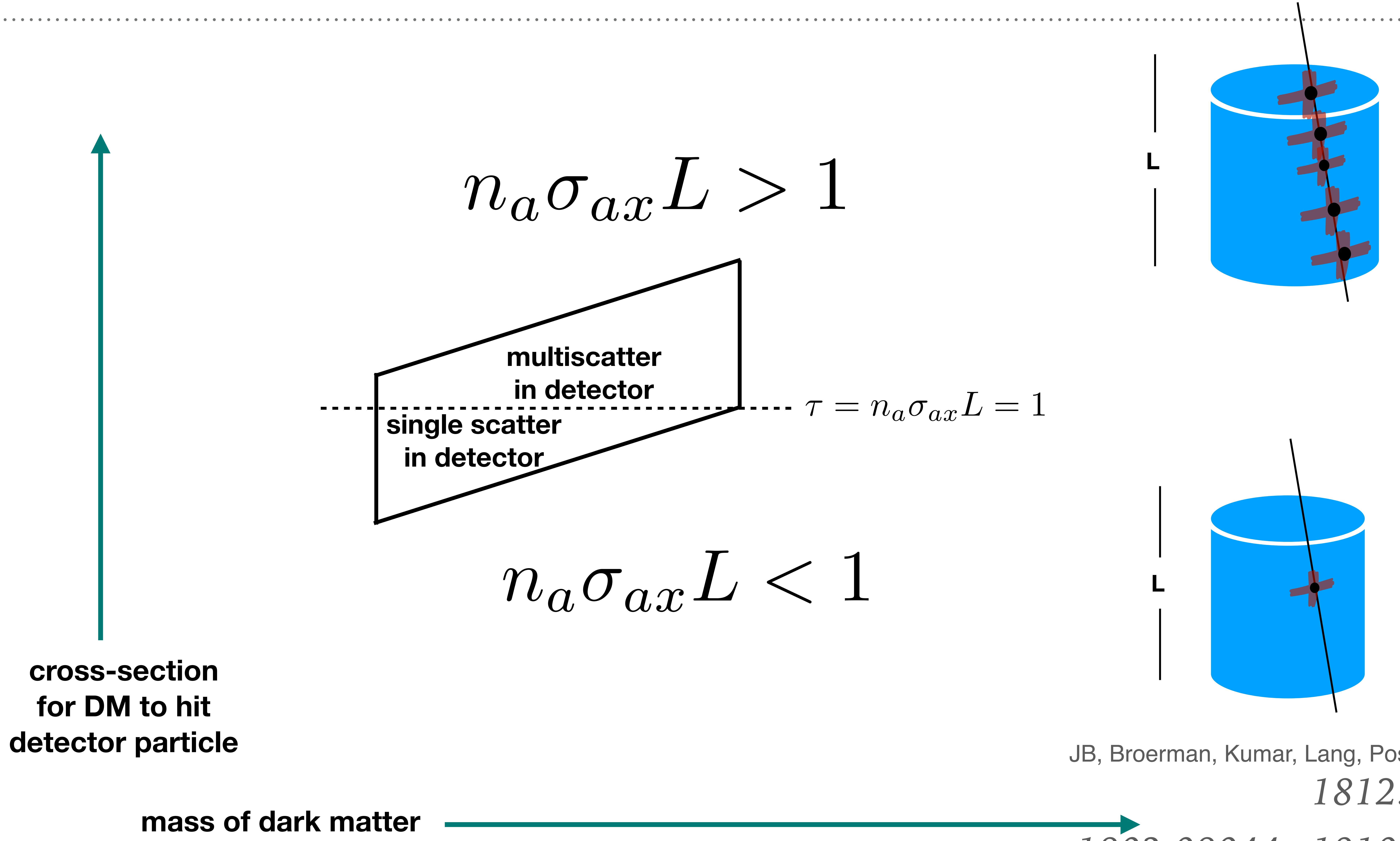
- **Attenuation cross-section increases linearly with DM kinetic energy ~m_x v_x^2**



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



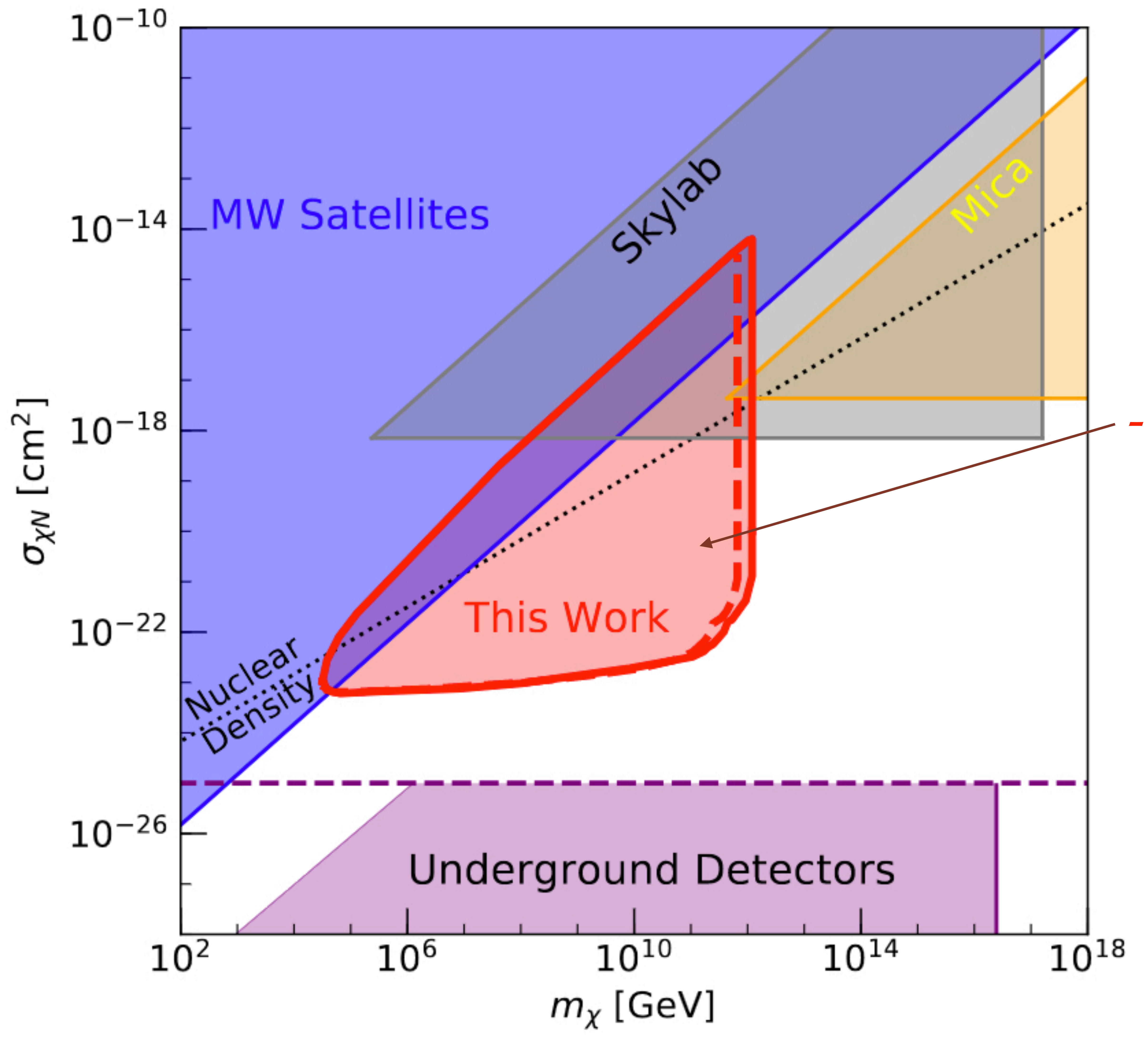
MULTISCATTER DARK MATTER DETECTION



JB, Broerman, Kumar, Lang, Pospelov, Raj
1812.09325

JB, Broerman, Lang, Raj *1803.08044* *1910.05380*

CHICAGO, MULTISCATTER DARK MATTER DETECTION



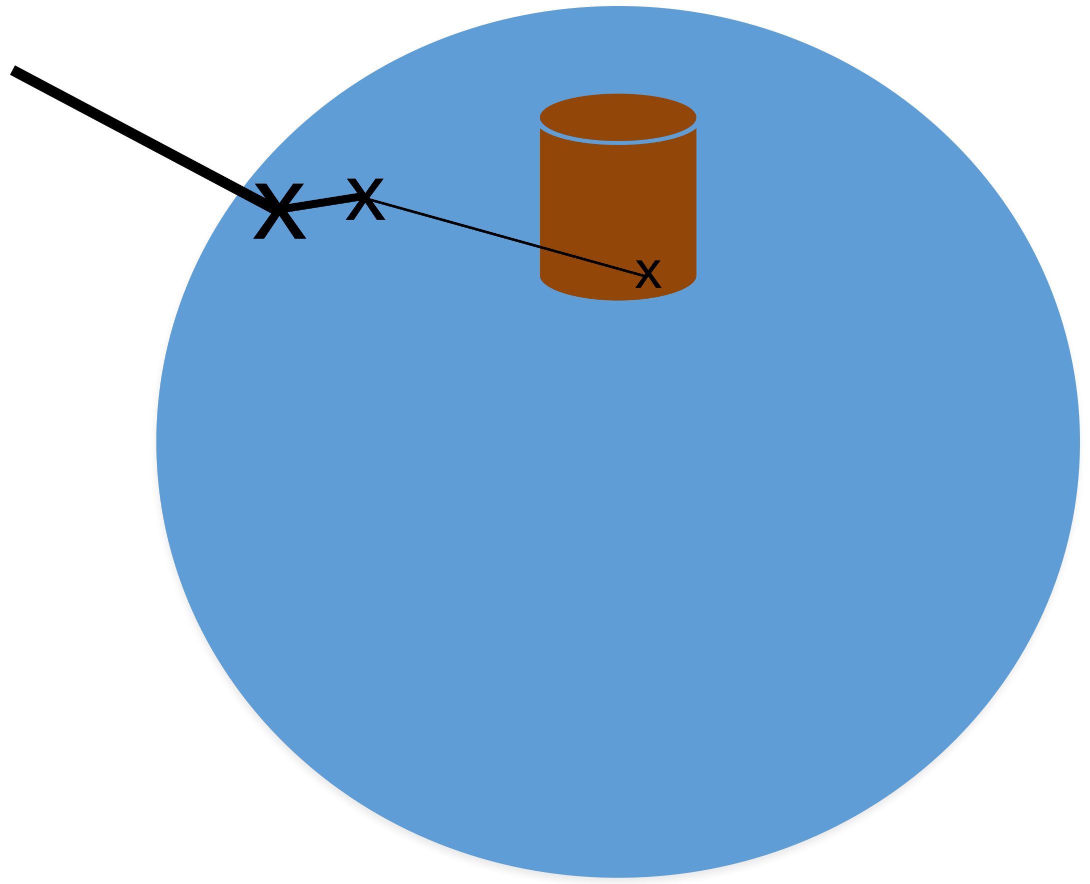
- Liquid scintillator test modules at U Chicago

Chris Cappiello, Collar, Beacom

2008.10646

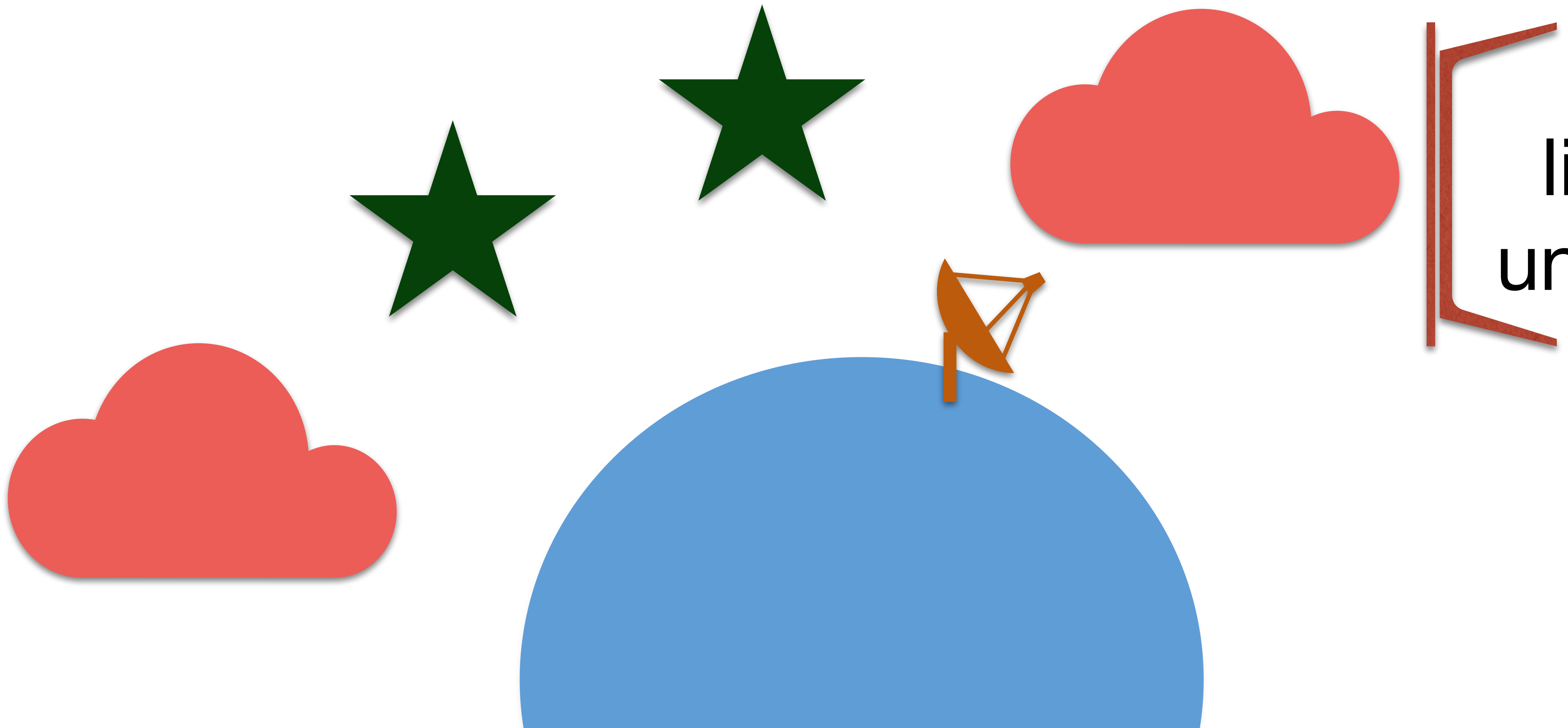
GAS CLOUDS

The earth and atmosphere block detection of strongly-interacting dark matter



dark matter kinetic energy < recoil threshold

use detectors in space



Interstellar gas

big

little overburden

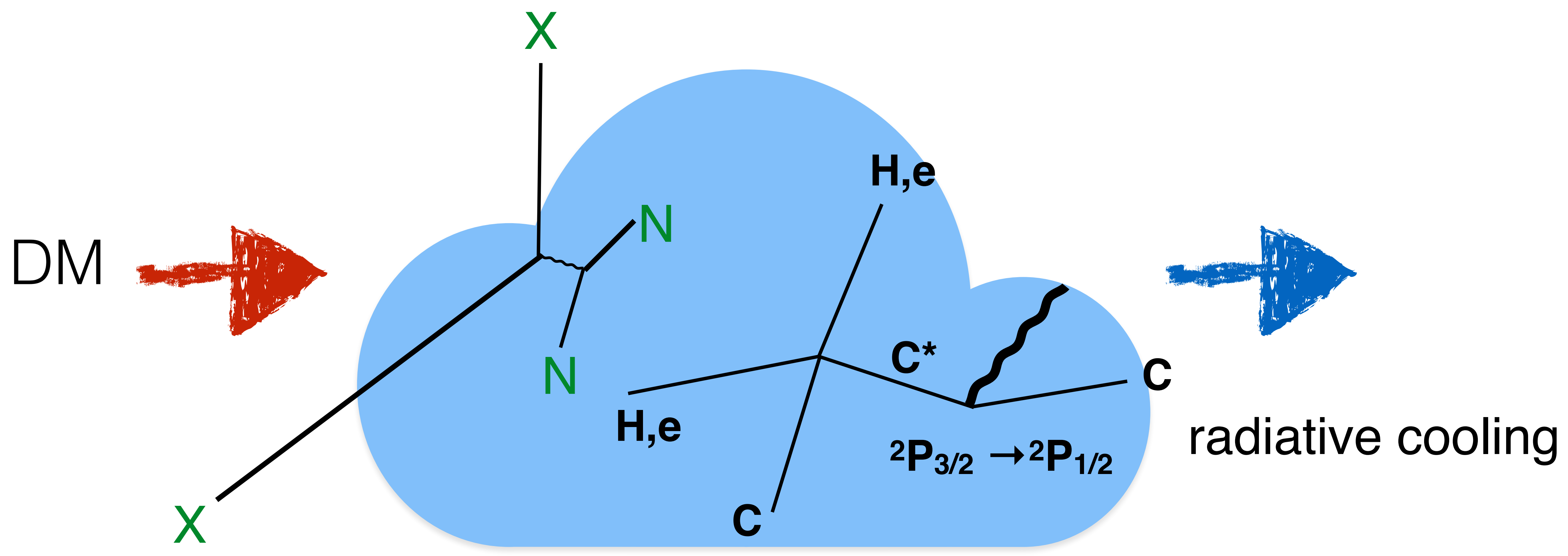
unbound electrons

2010.07240

1812.10919

1806.06857

GAS CLOUD BOUNDS



$\boxed{\text{Conservative: assume all heating by DM}}$

In reality:

(DM +)

cosmic rays

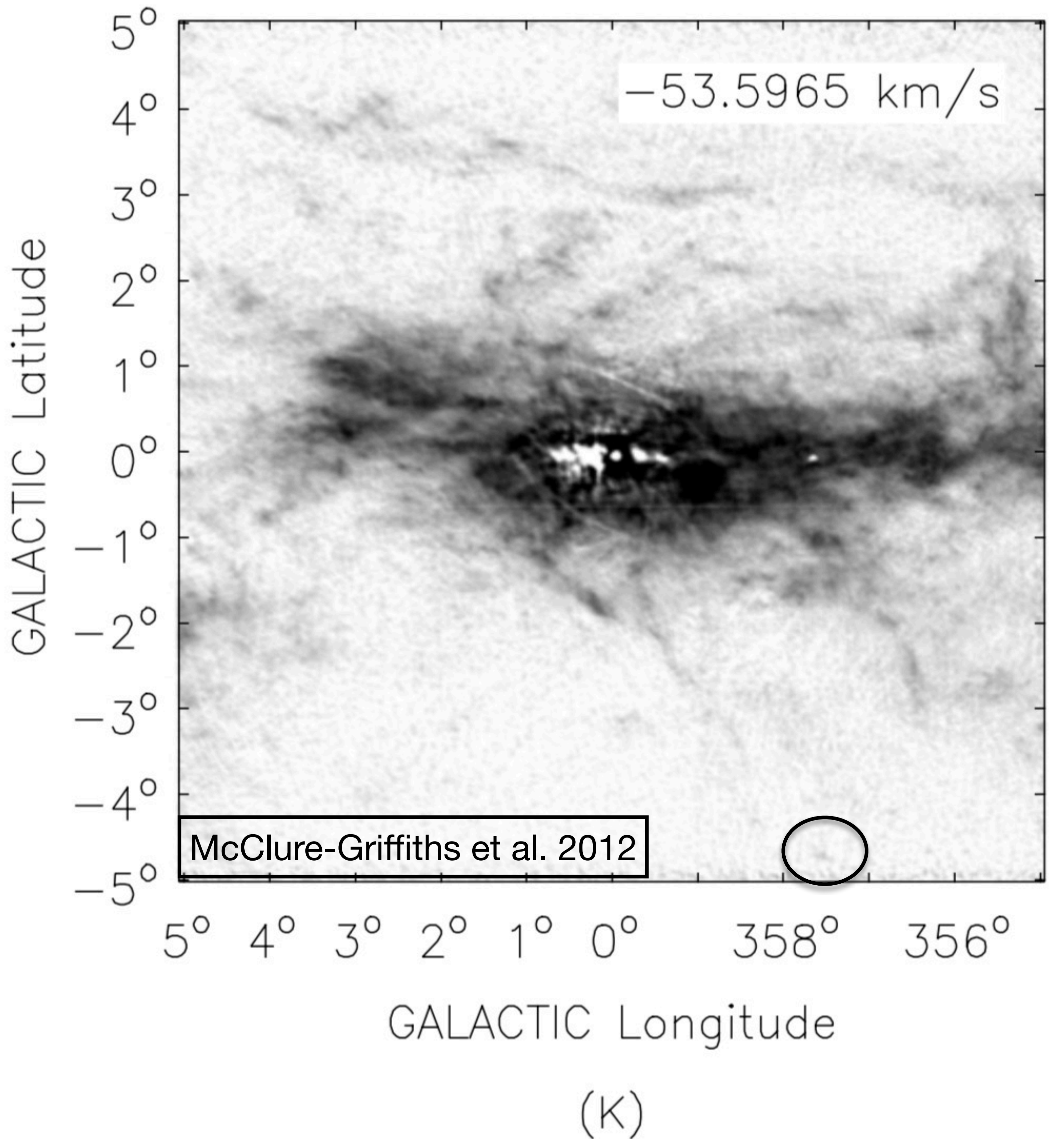
Xray/UV background

photoelectric heating
via dust grains

There are known ubiquitous heating sources, like cosmic UV background, cosmic rays, dust grain heating.

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

Gas Cloud 357.8-4.7-55



Δv from 21cm emission gives T<137 K

G357.8-4.7-55

$M = 237\ M_\odot$

$r_{gc} = 12.9$ pc

$n_n = 0.4\ cm^{-3}$

$T_g < 137$ K

$r_{los} \sim 800$ pc

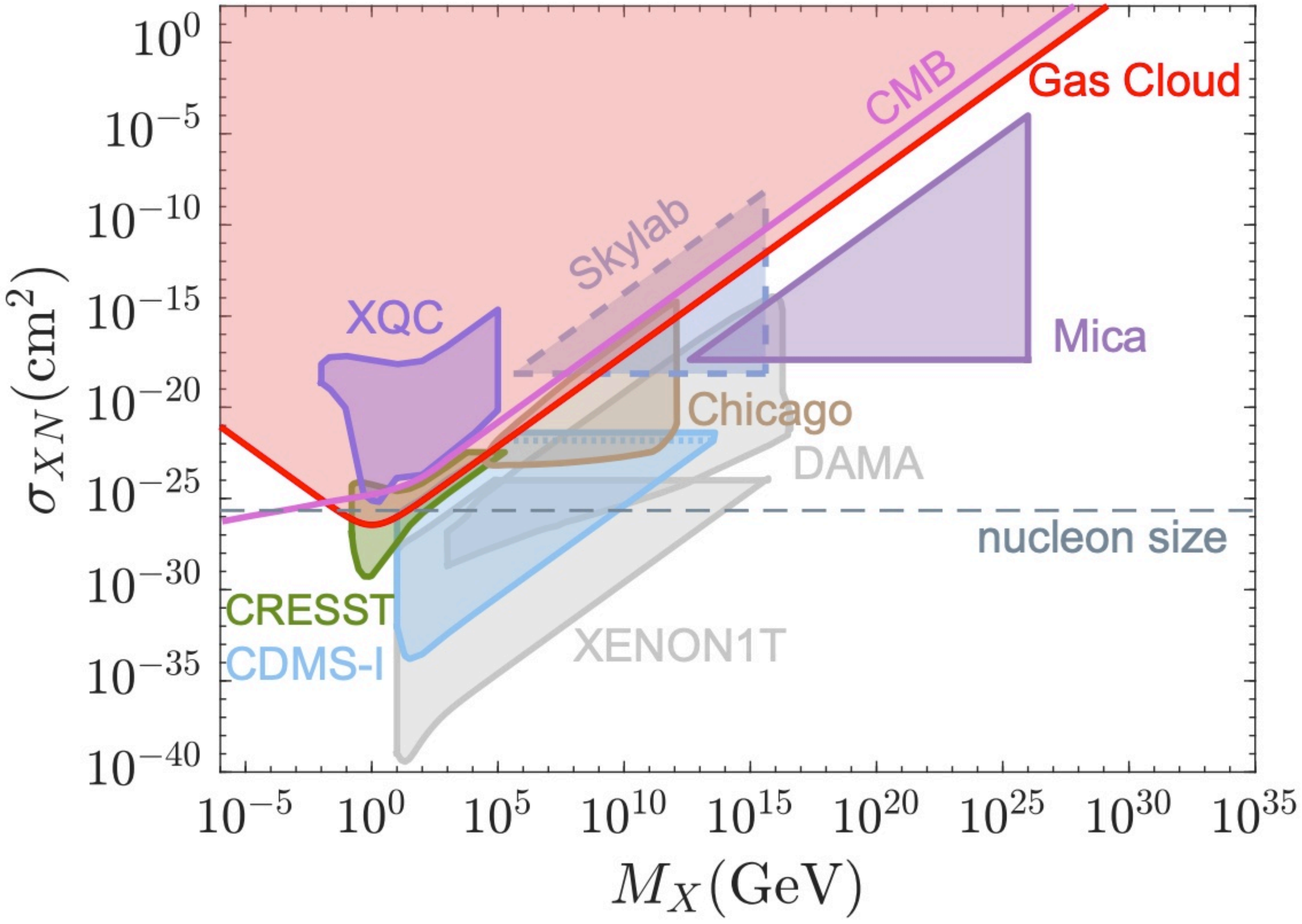
$v_g = -54$ km/s

5°

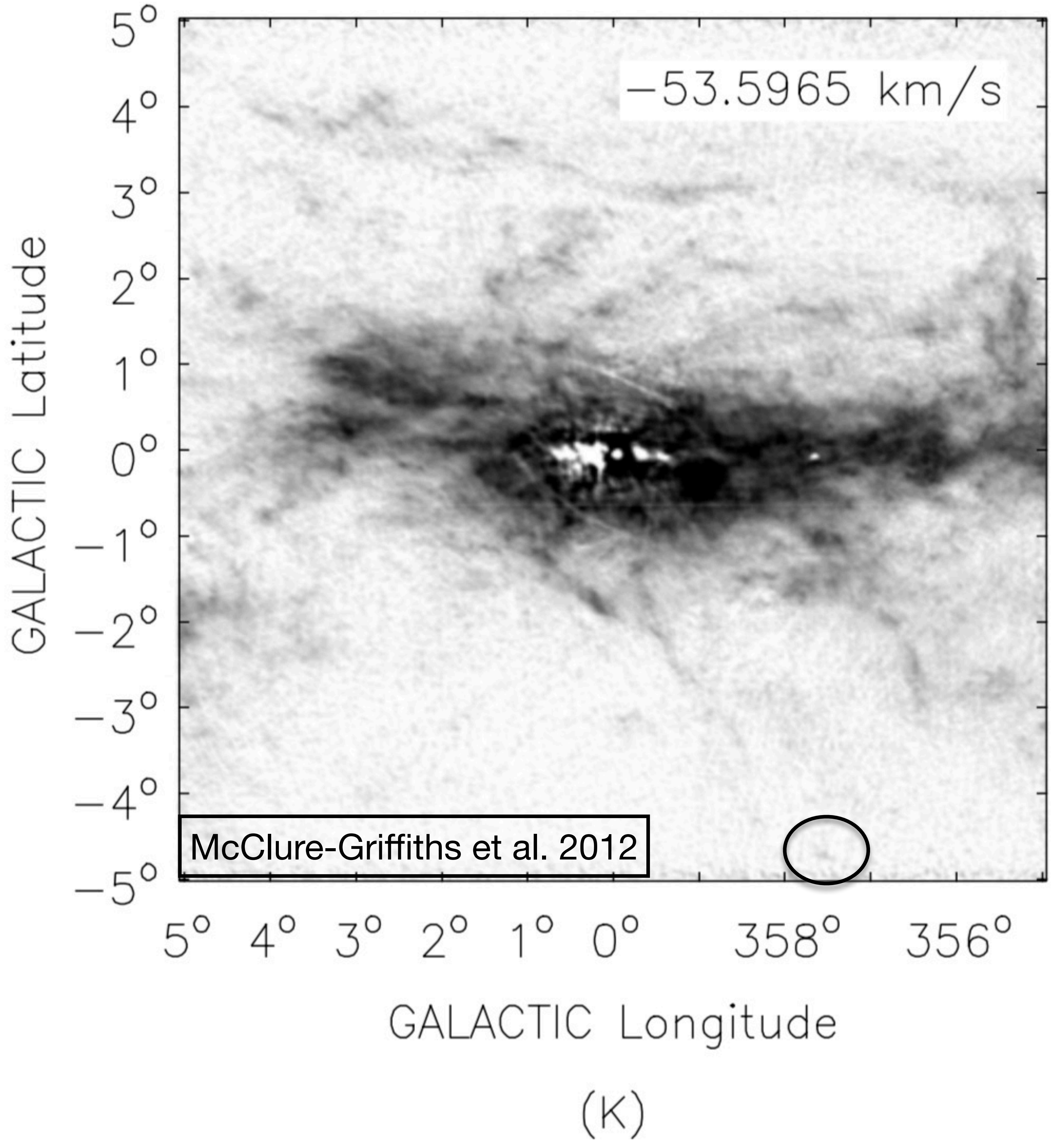
(assume spherical cloud)

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

➤ Fixed cross-section for scattering off all nuclei



Gas Cloud 357.8-4.7-55



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Amit Bhoonah, JB, Schon, Song 2010.07240

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

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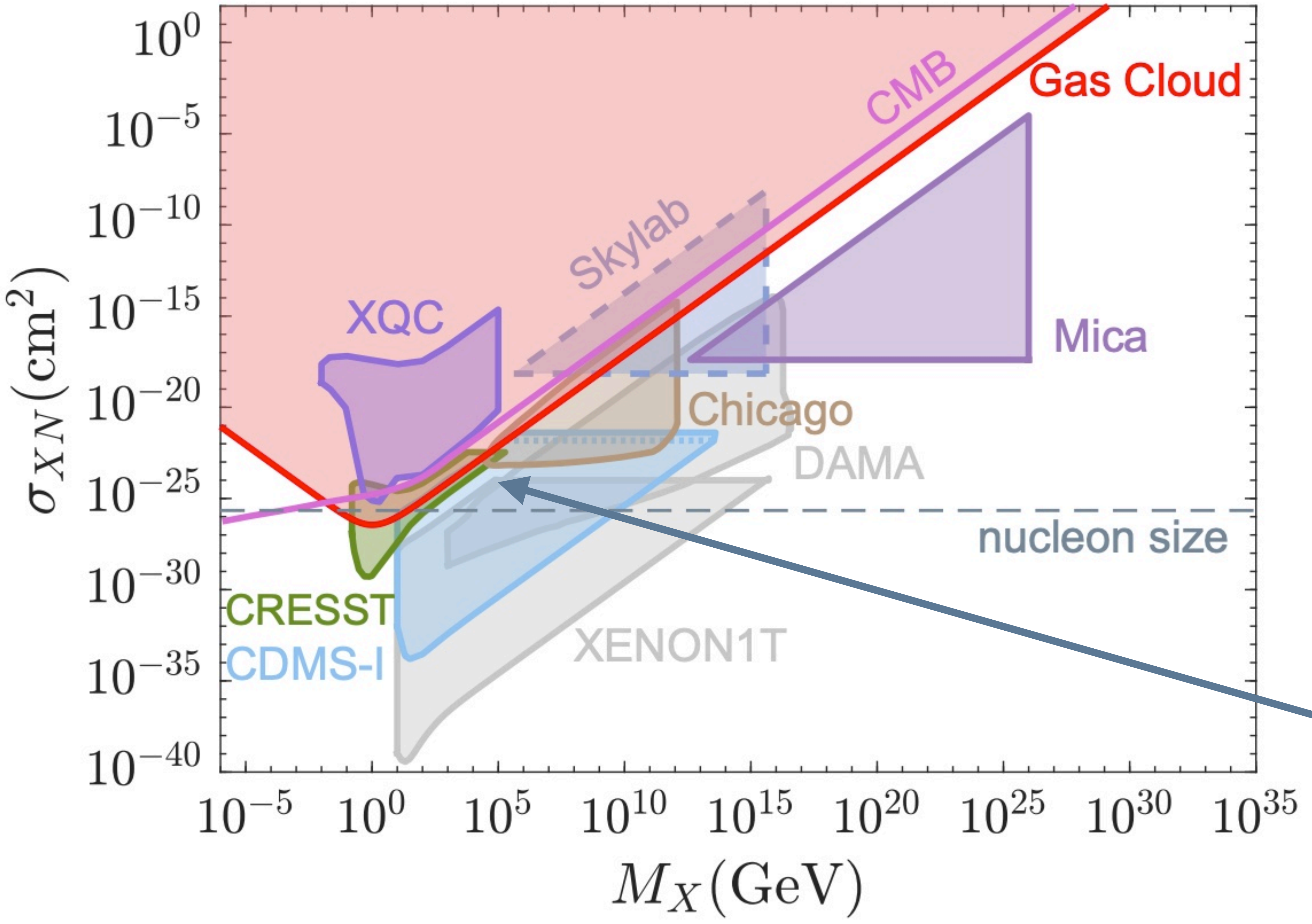
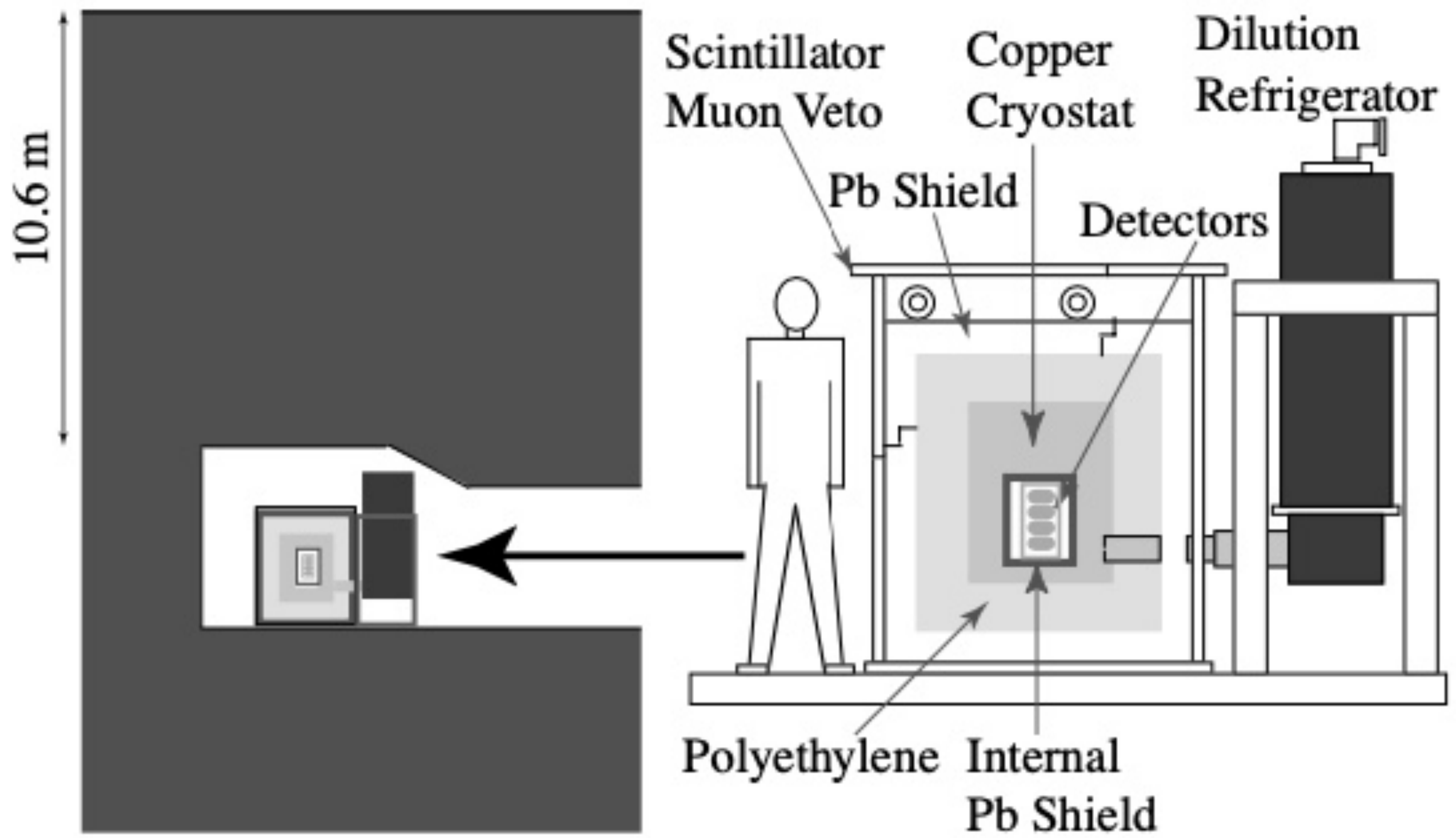




Recast CDMS-I limit using multi scatter

(Muon veto rejects very strong interactions)

Amit Bhoonah, JB, Schon, Song 2010.07240

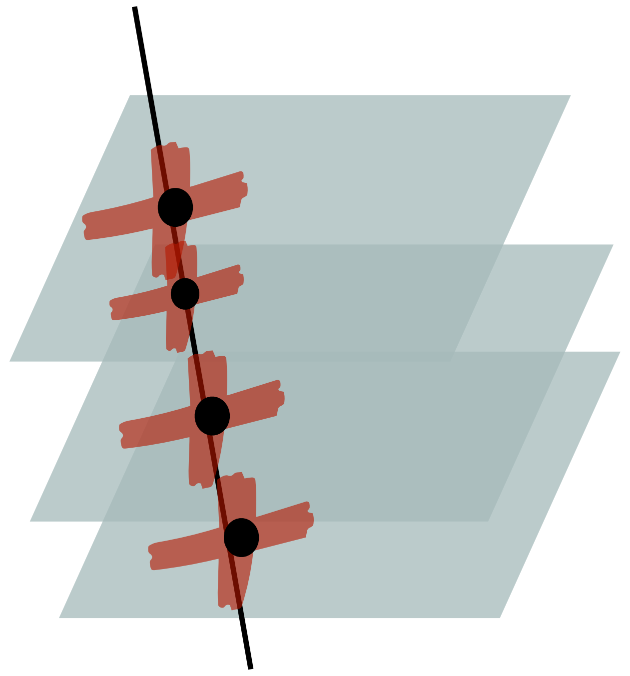
ETCHING PLASTIC SEARCHES FOR DARK MATTER

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

see also e.g. Starkman, Gould, Esmailzadeh, Dimopoulos 1990

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

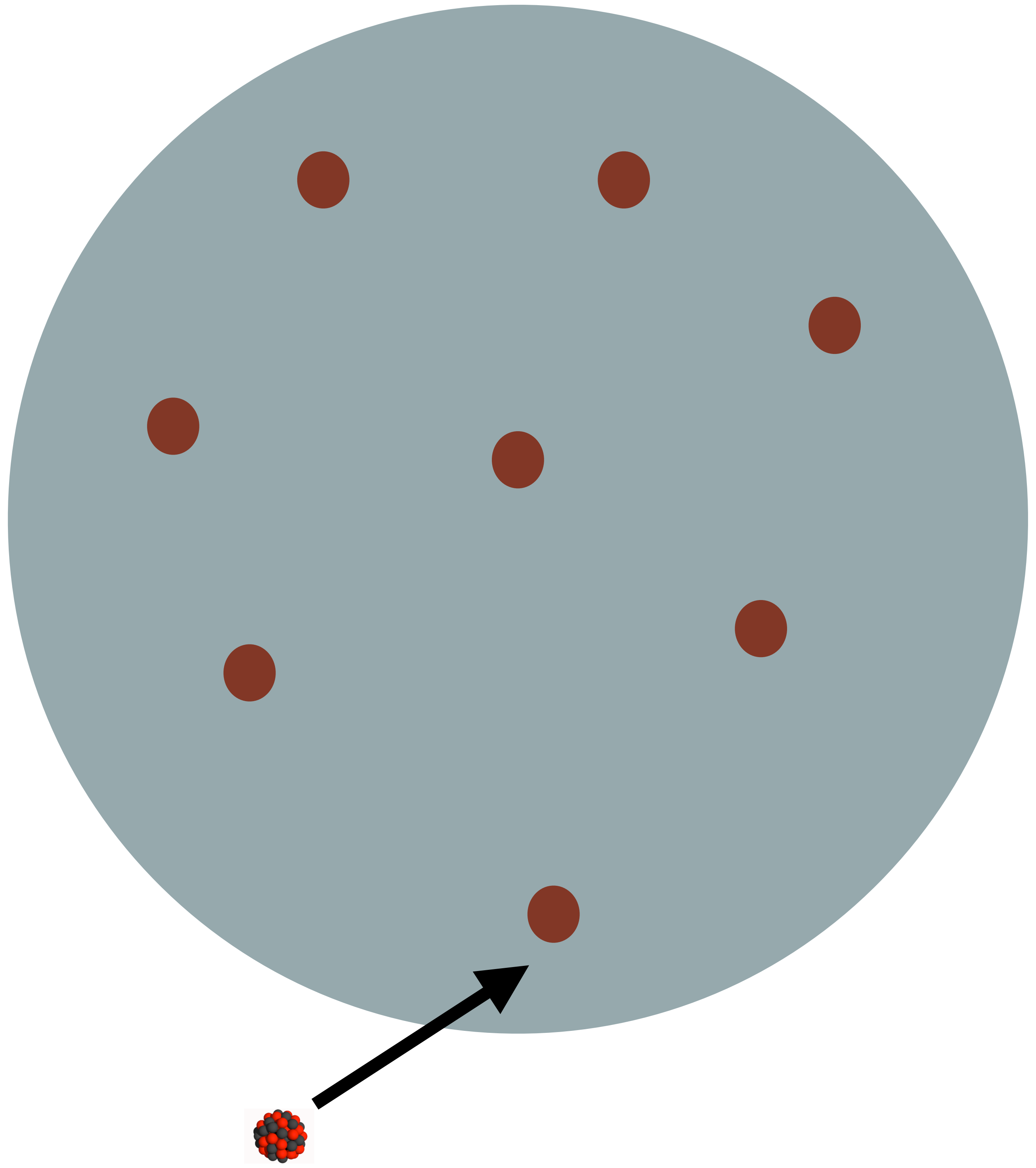
Ohya Quarry

LOOSELY BOUND COMPOSITES

Javier Acevedo, Yilda Boukhtouchen, JB, Chris Cappiello, Gopolang Mohlabeng, Narayani Tyagi

$m_d > \Lambda_D > E_B^{(dark)}$

Cf. SM nuclei: 1 > 0.1 > 0.01 GeV



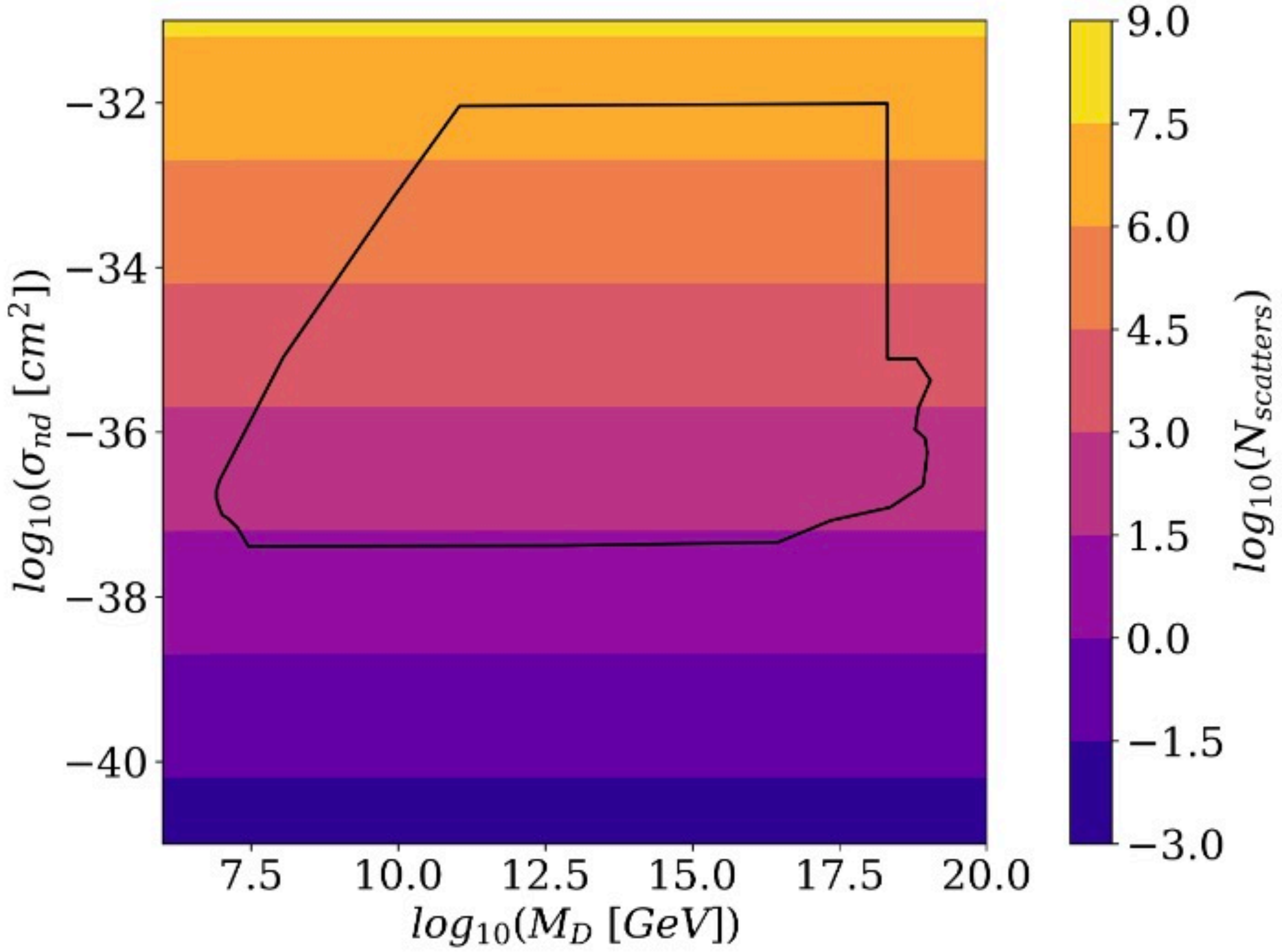
LOOSELY BOUND COMPOSITES

Javier Acevedo, Yilda Boukhtouchen, JB, Chris Cappiello, Gopolang Mohlabeng, Narayani Tyagi

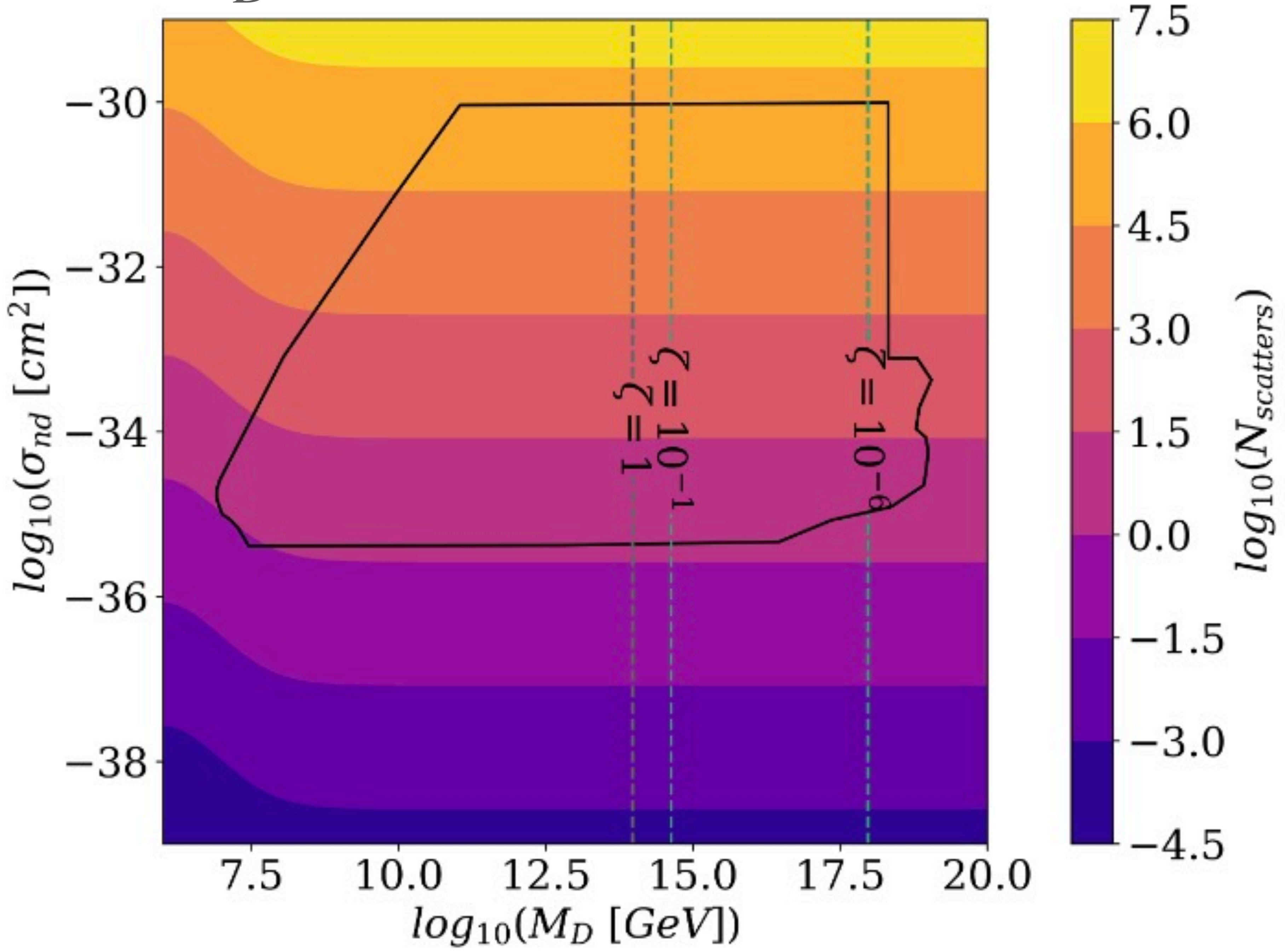
2406.xxxx

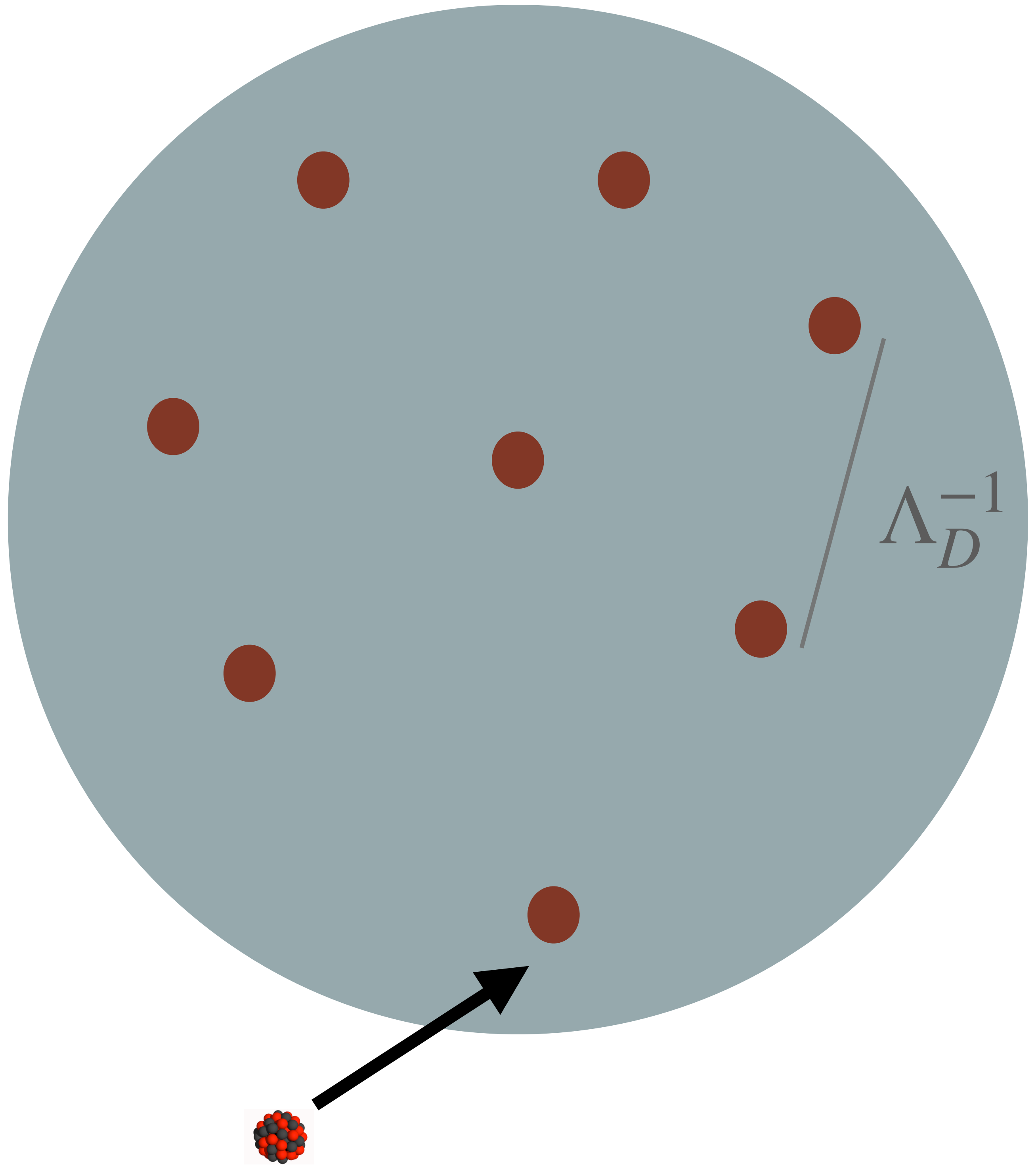
$m_d > \Lambda_D > E_B^{(dark)}$

assume A⁴



$\Lambda_D = 100$ KeV ~A⁴



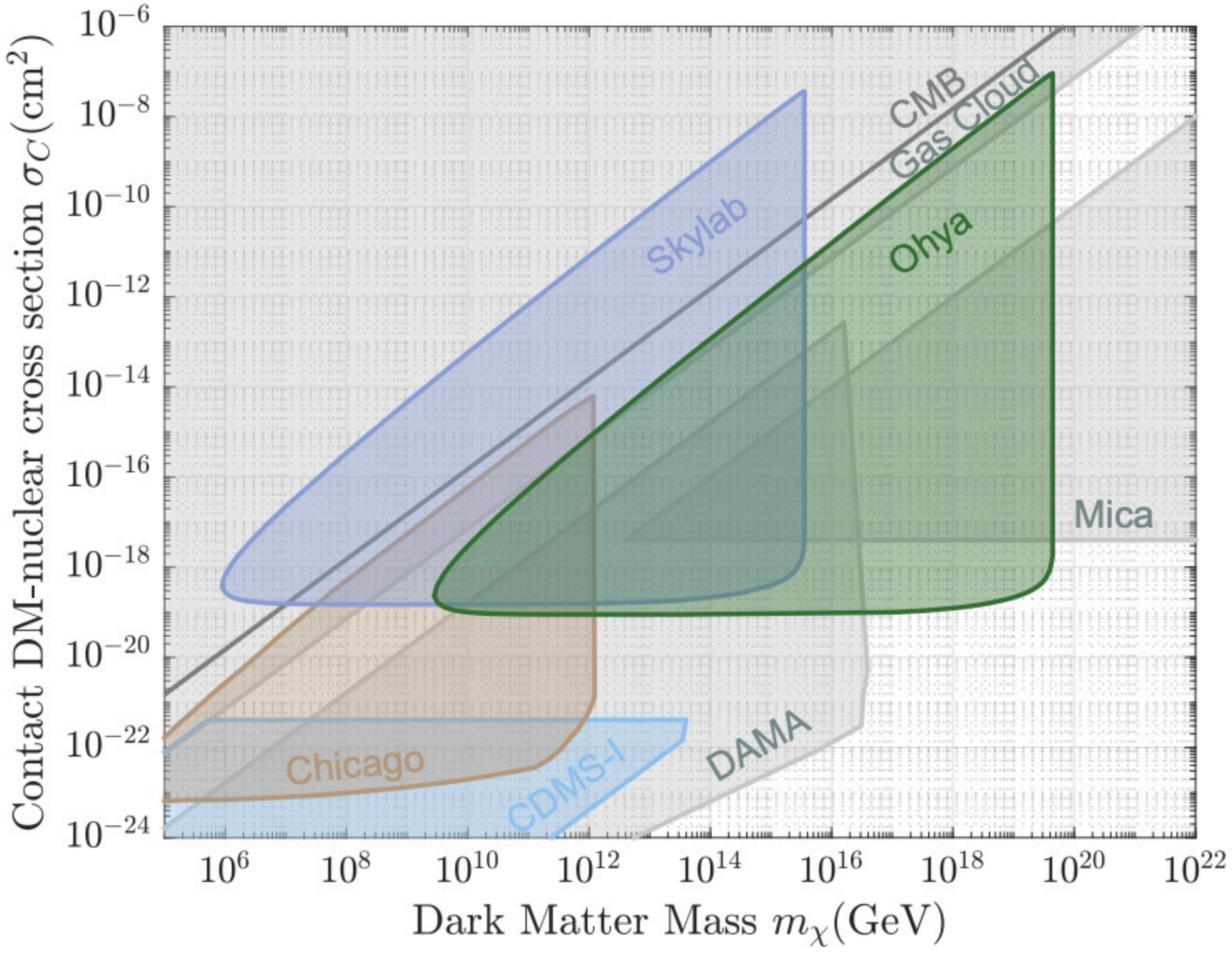


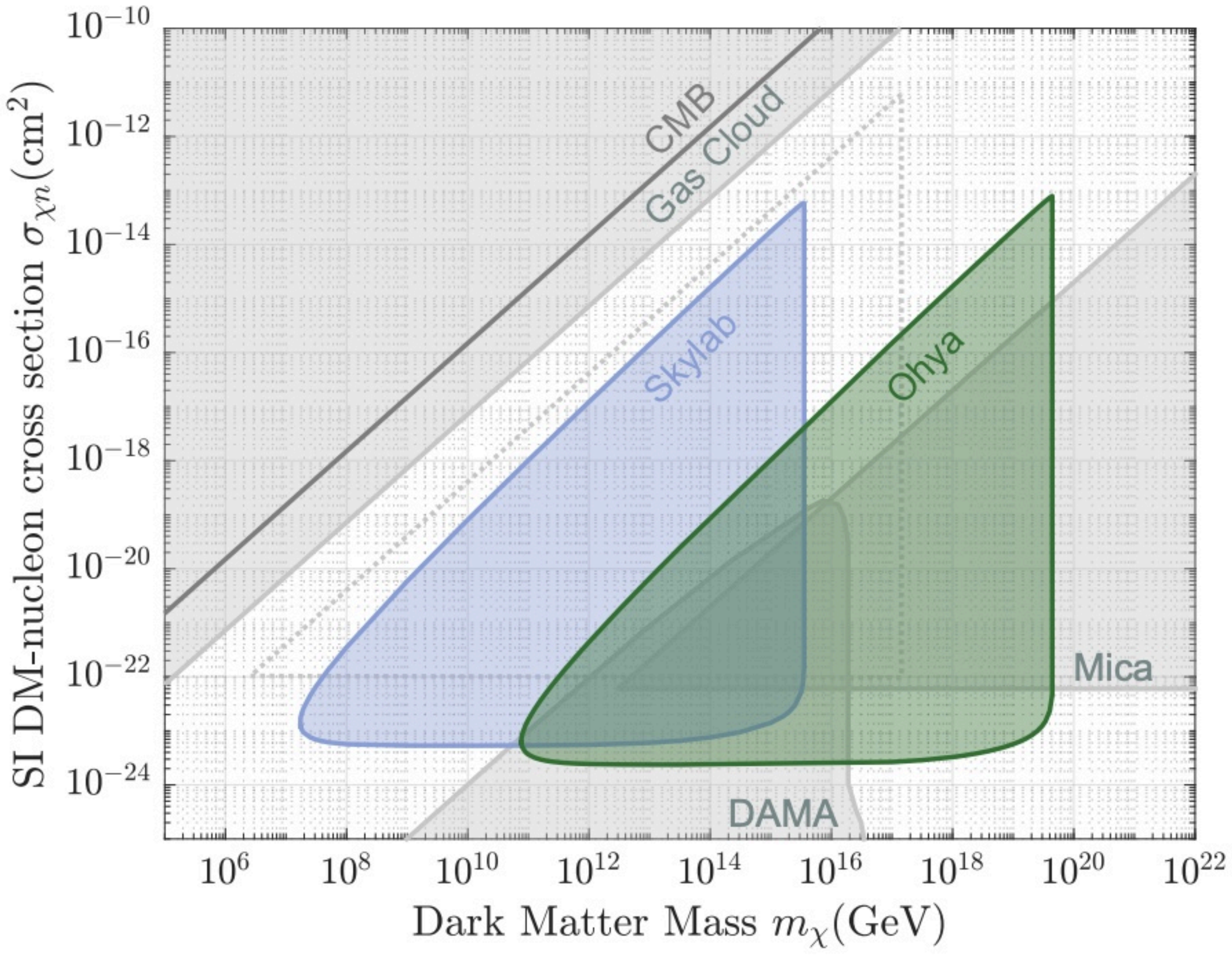
- DM-nuclear scattering cross sections that scales with ~A⁴ for larger than nuclear cross sections

ETCHING PLASTIC SEARCHES FOR DARK MATTER

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

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





Amit Bhoonah, JB, Courtman, Song 2012.13406

ANCIENT SEARCH FOR NEW PARTICLES: MICA

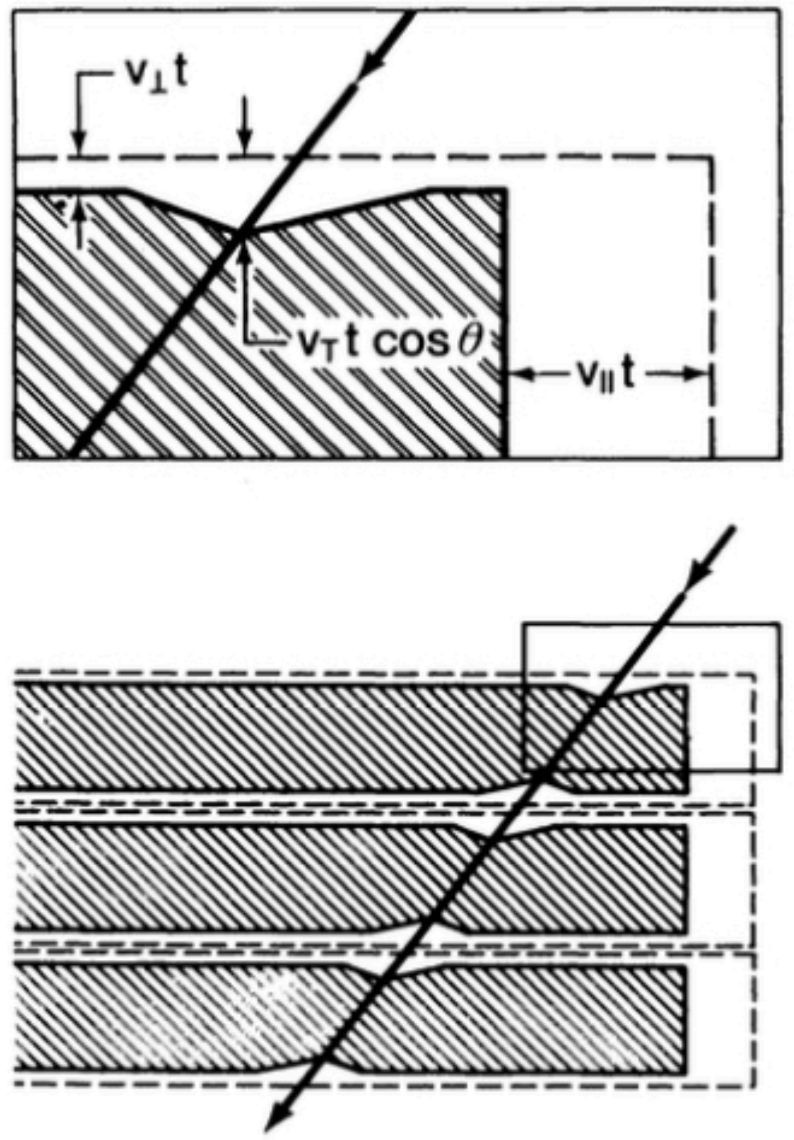
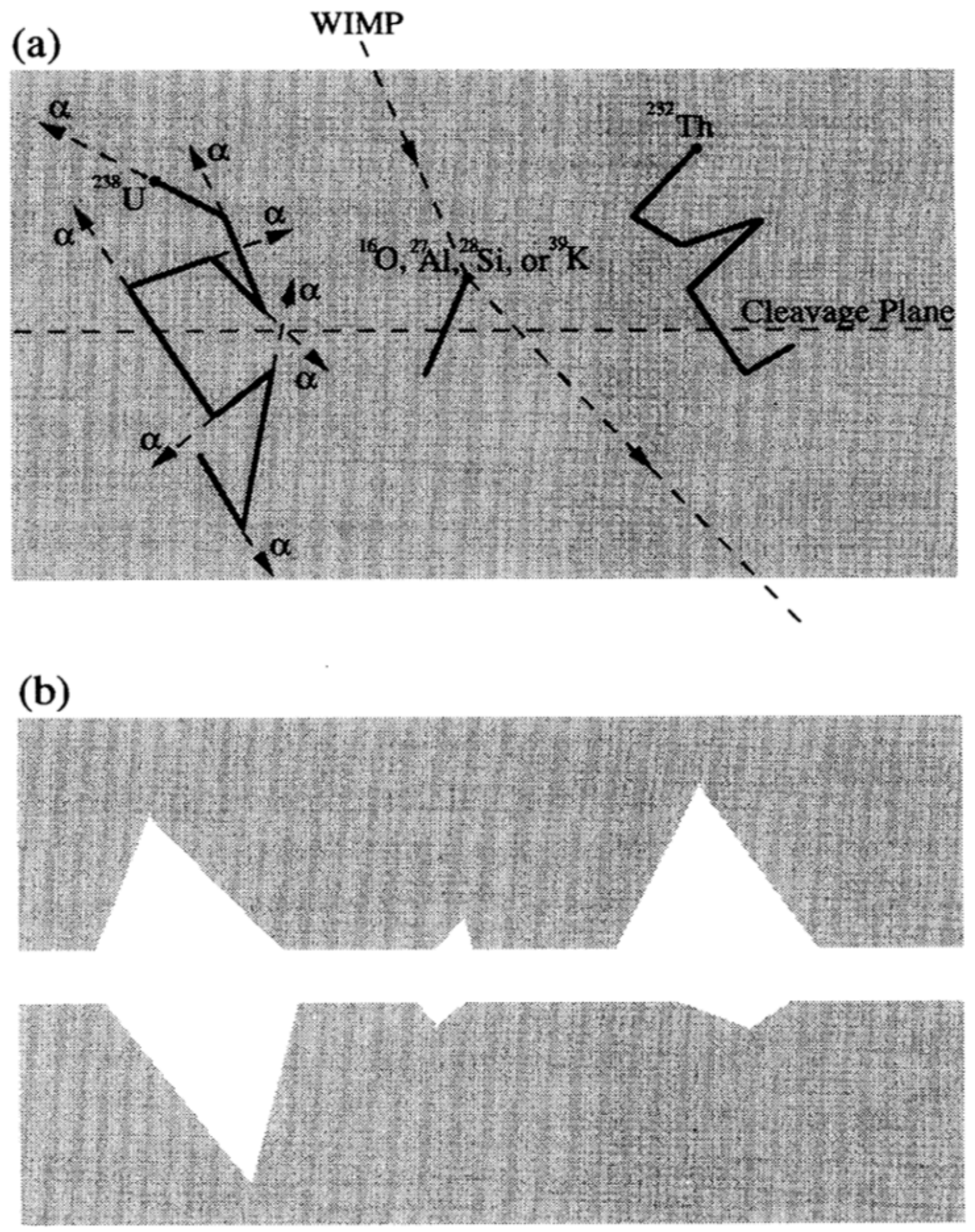
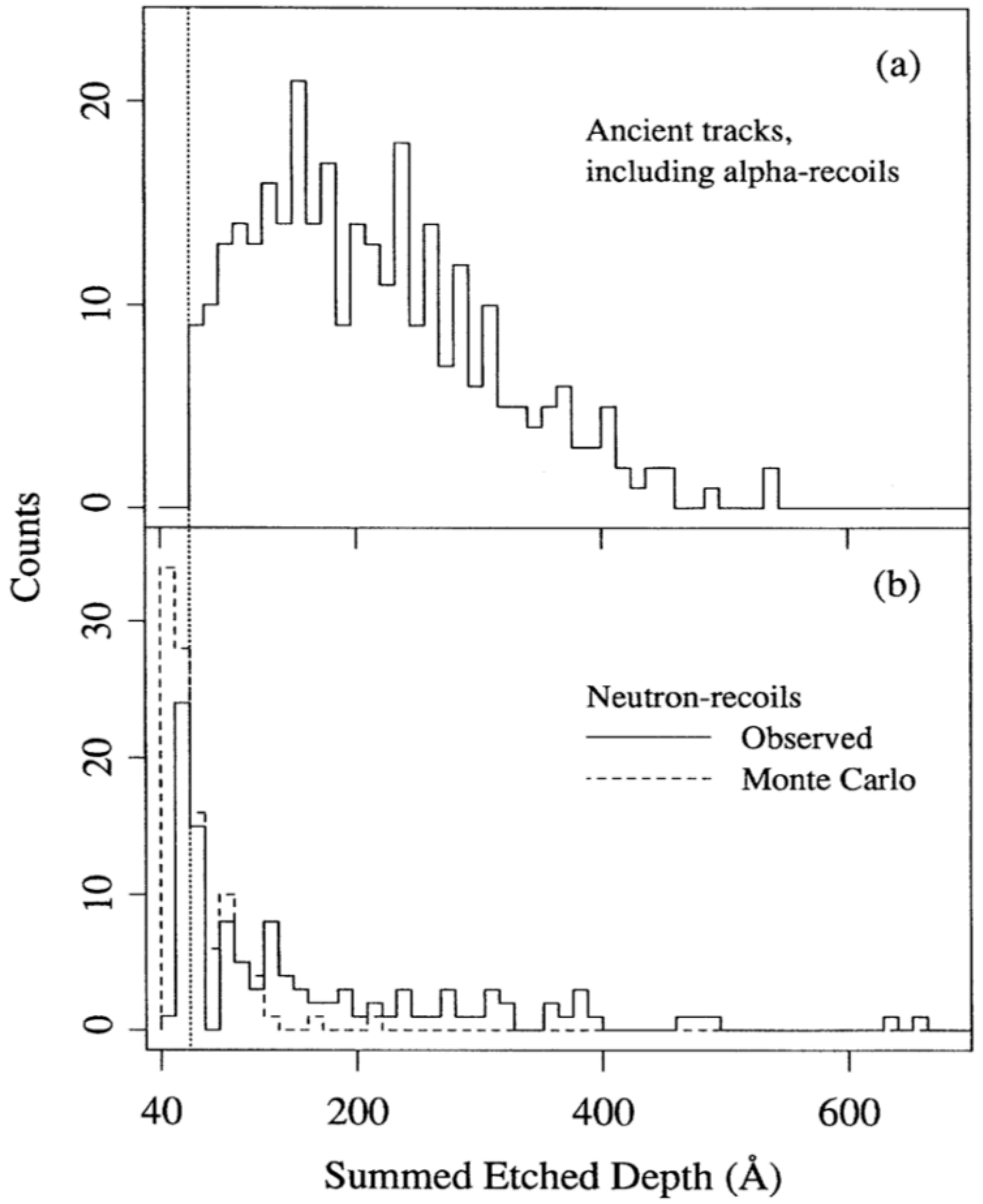


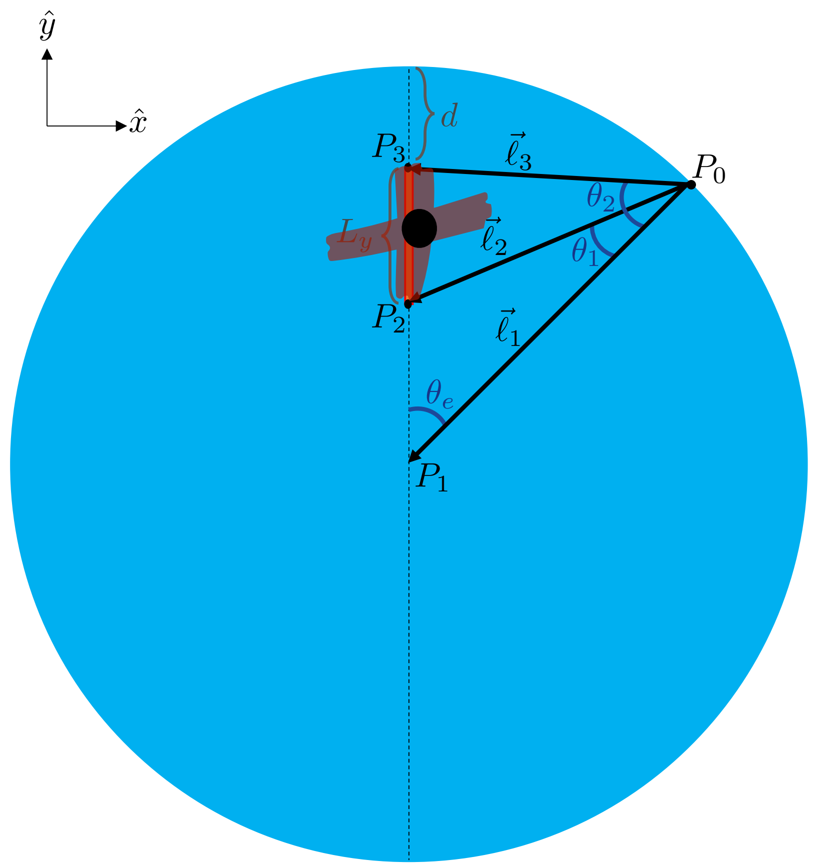
FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.





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

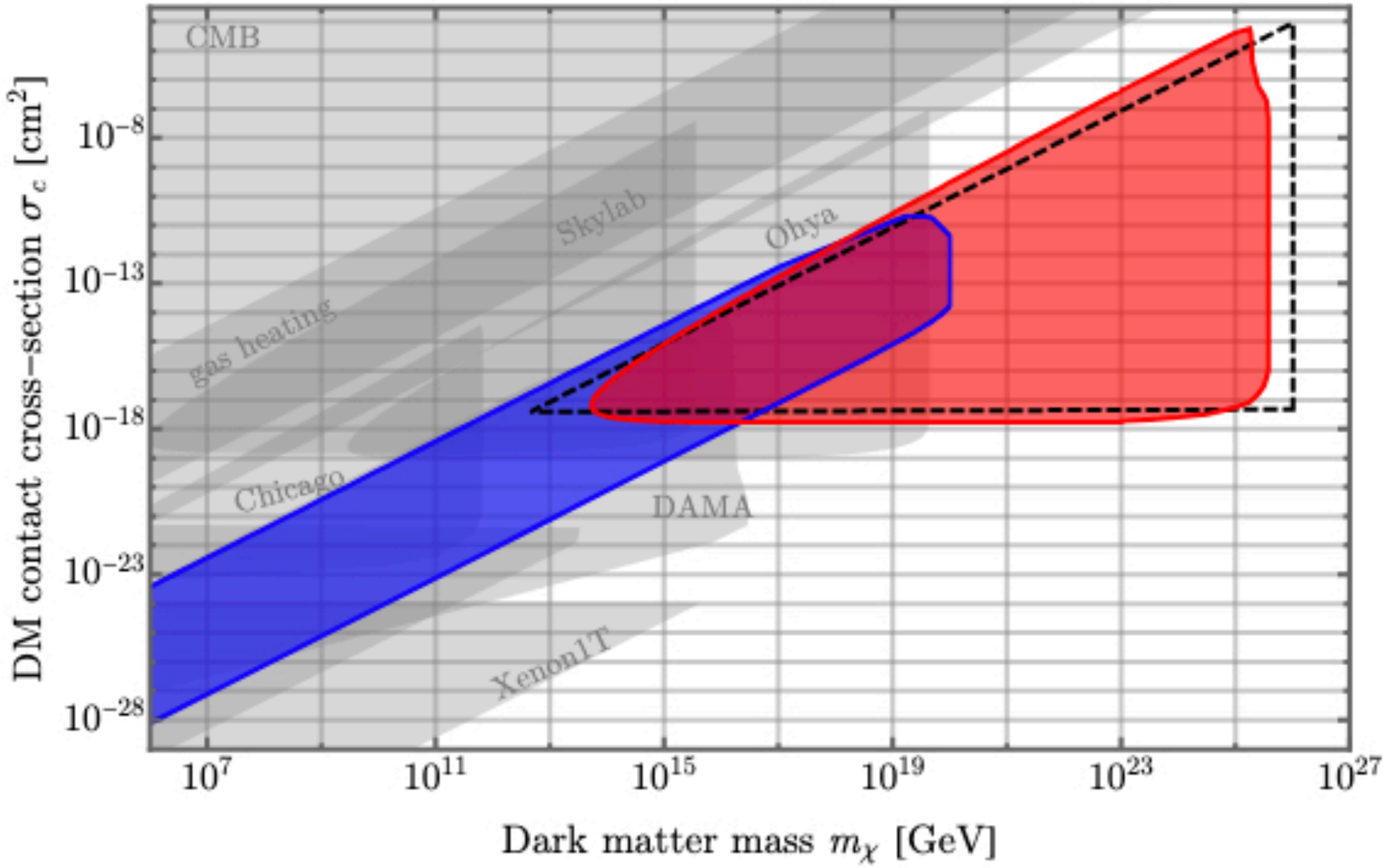
ANCIENT SEARCH FOR NEW PARTICLES: MICA



- 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

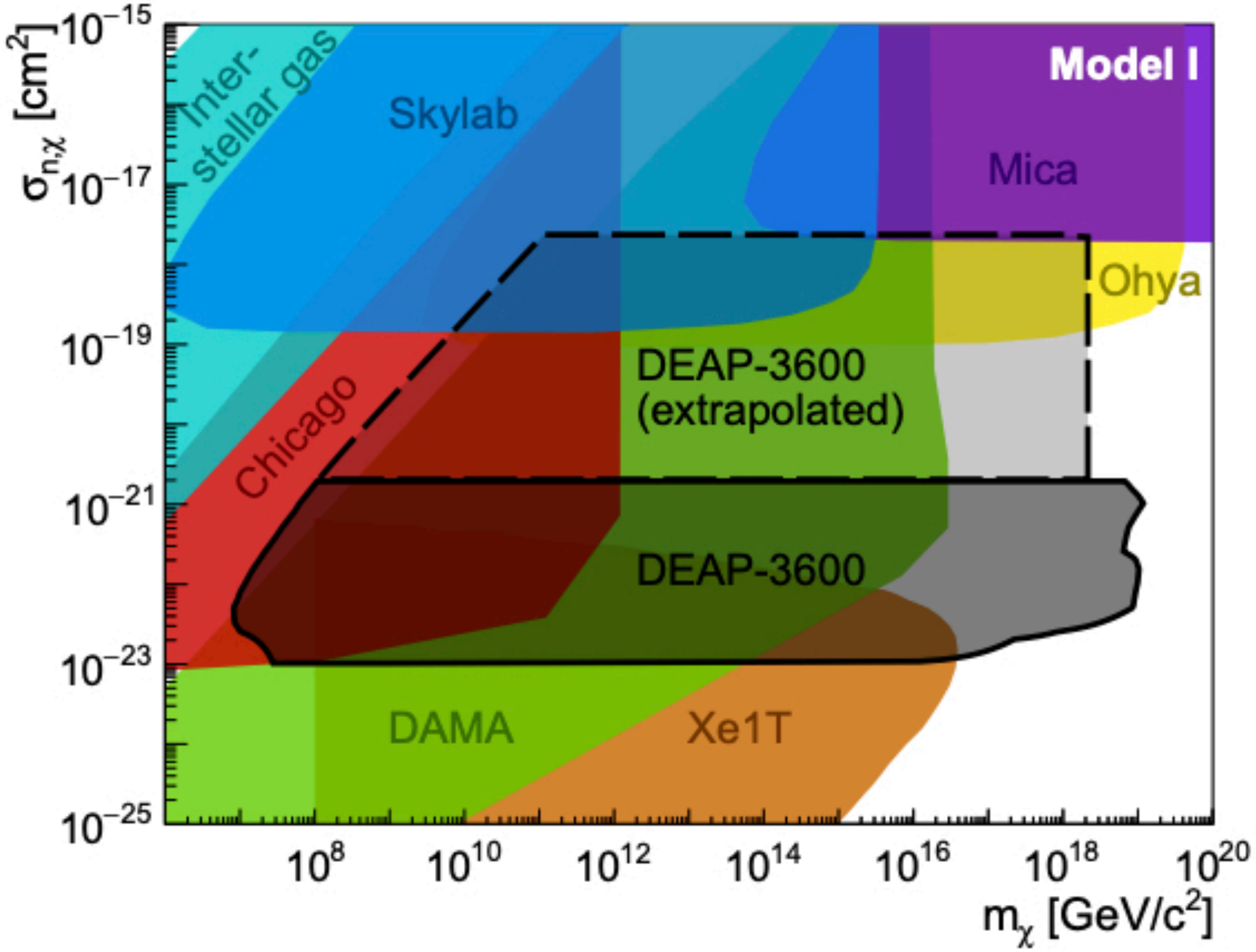


Also a mineral DM detection collaboration at Queen's

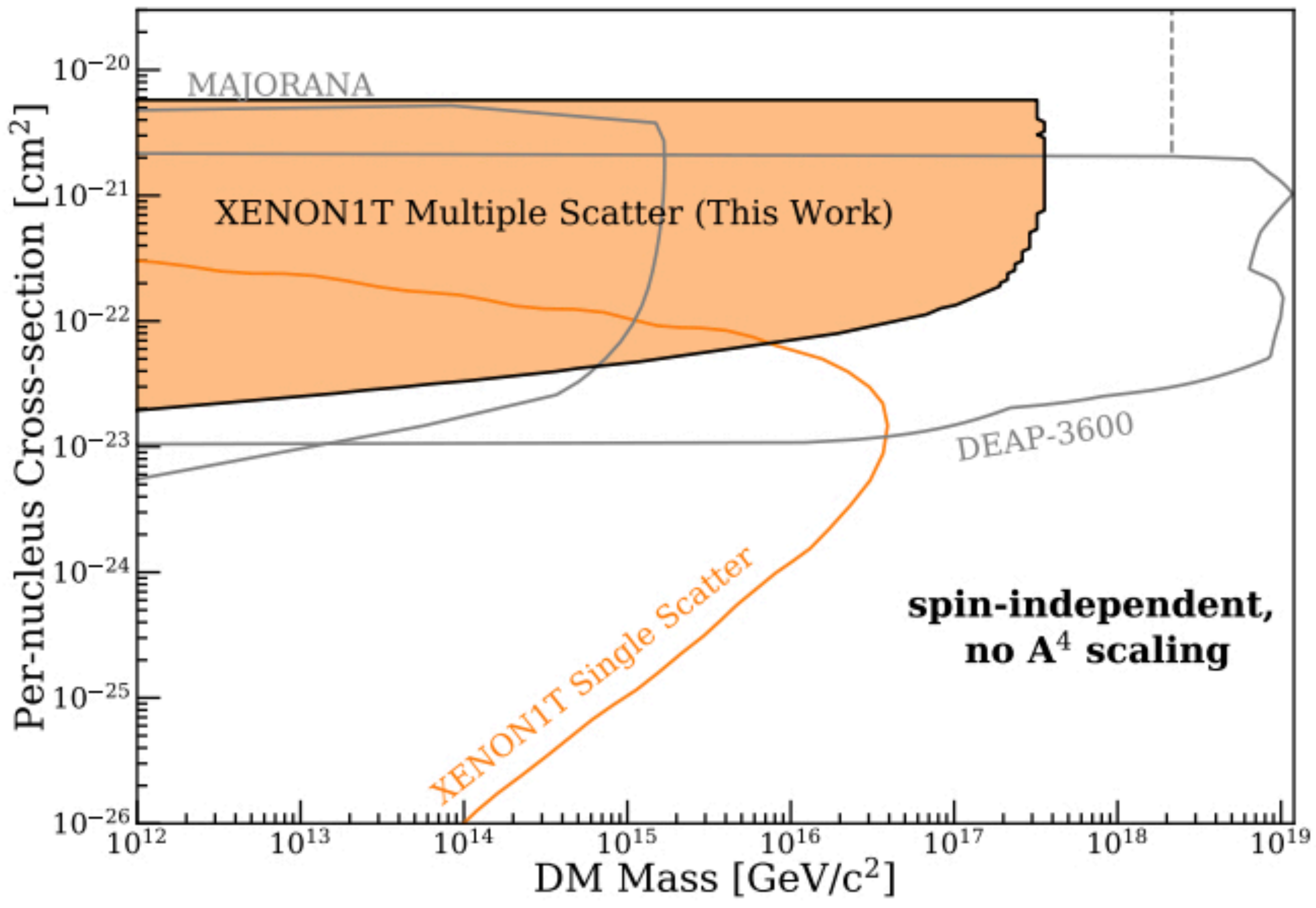
Balogh, Boukhtouchen, JB, Fung, Leybourne, Lucas, Mkhonto, Vincent

See e.g. recent whitepaper: 2301.07118

HEAVY MIMP RESULTS FROM DEAP-3600, XENON1T

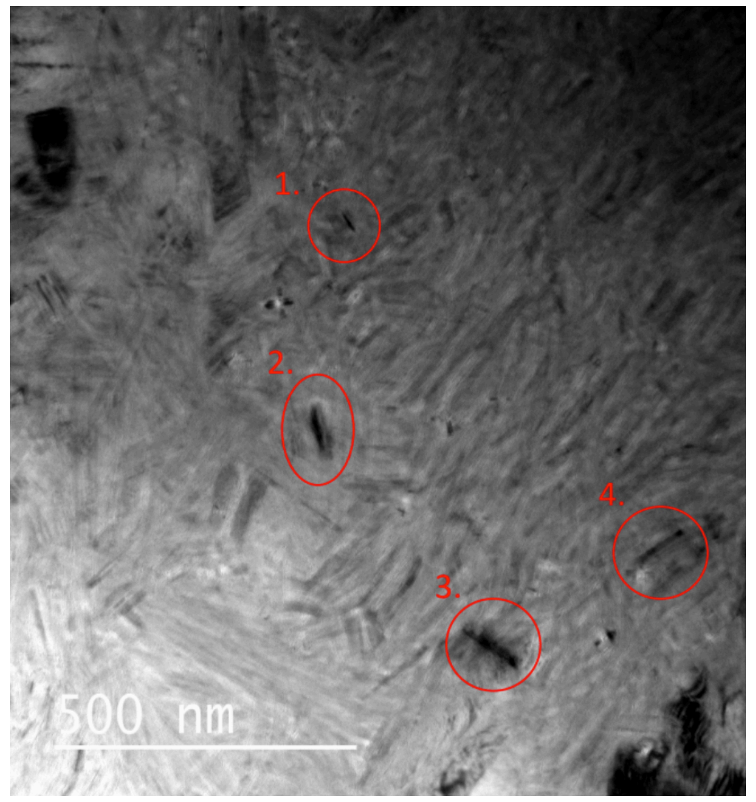


2108.09405, PRL



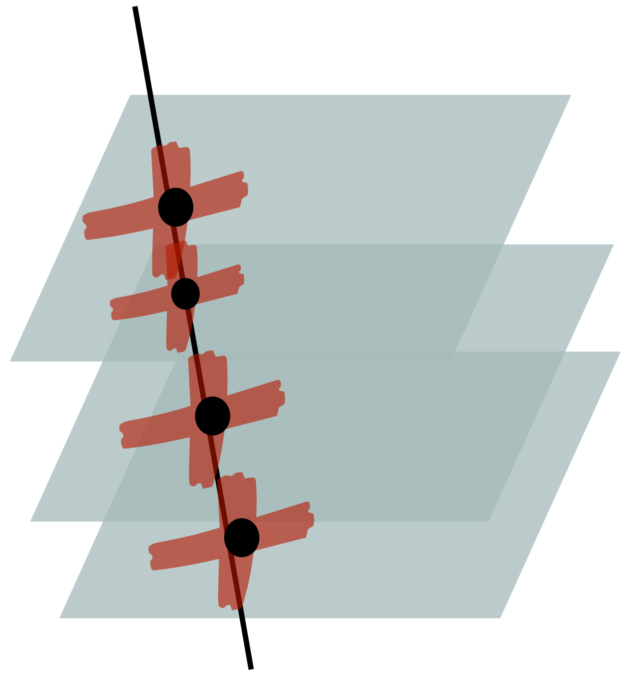
2304.10931, PRL

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

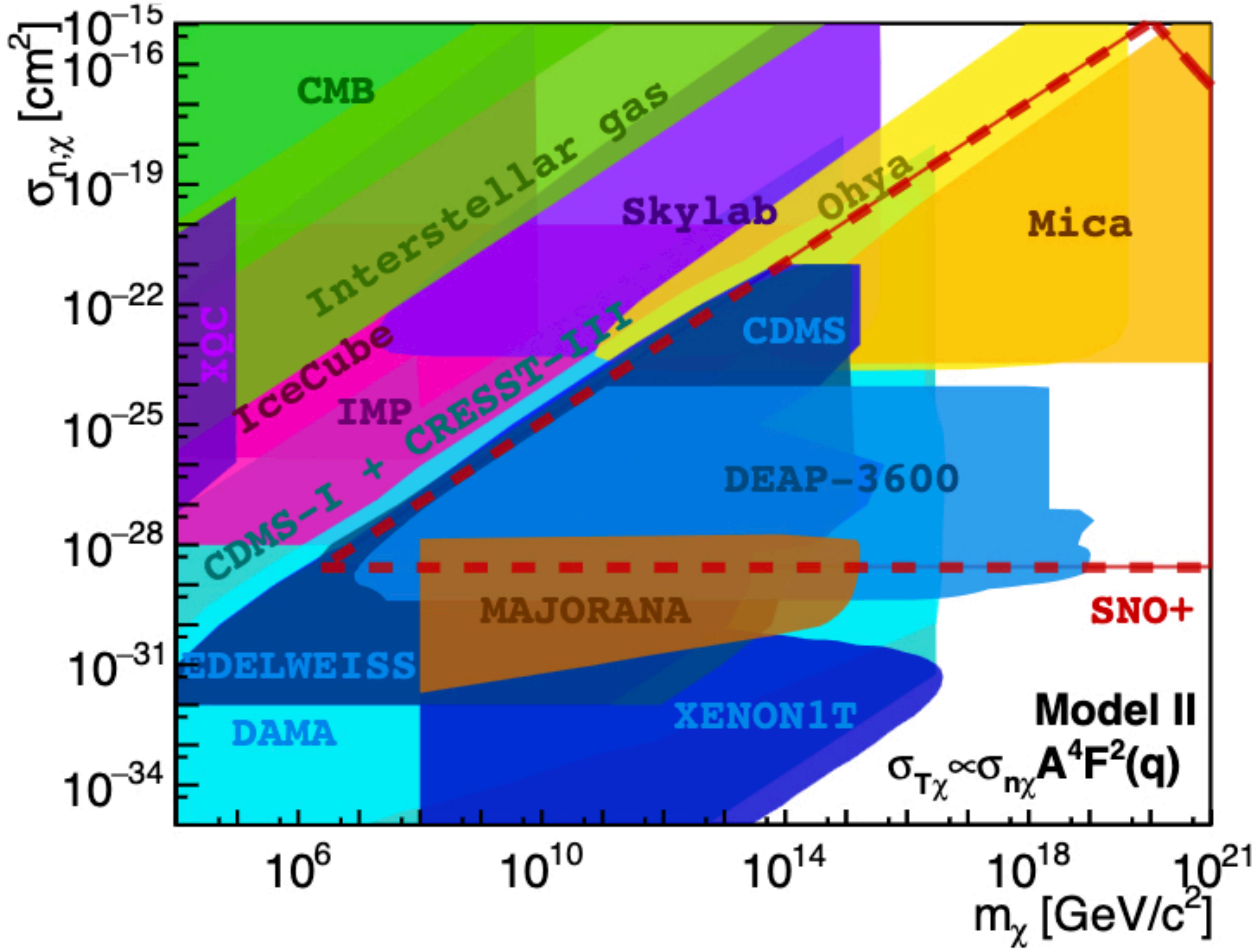


Q Paleo (QCumber? - name suggestions welcome) 2301.07118

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



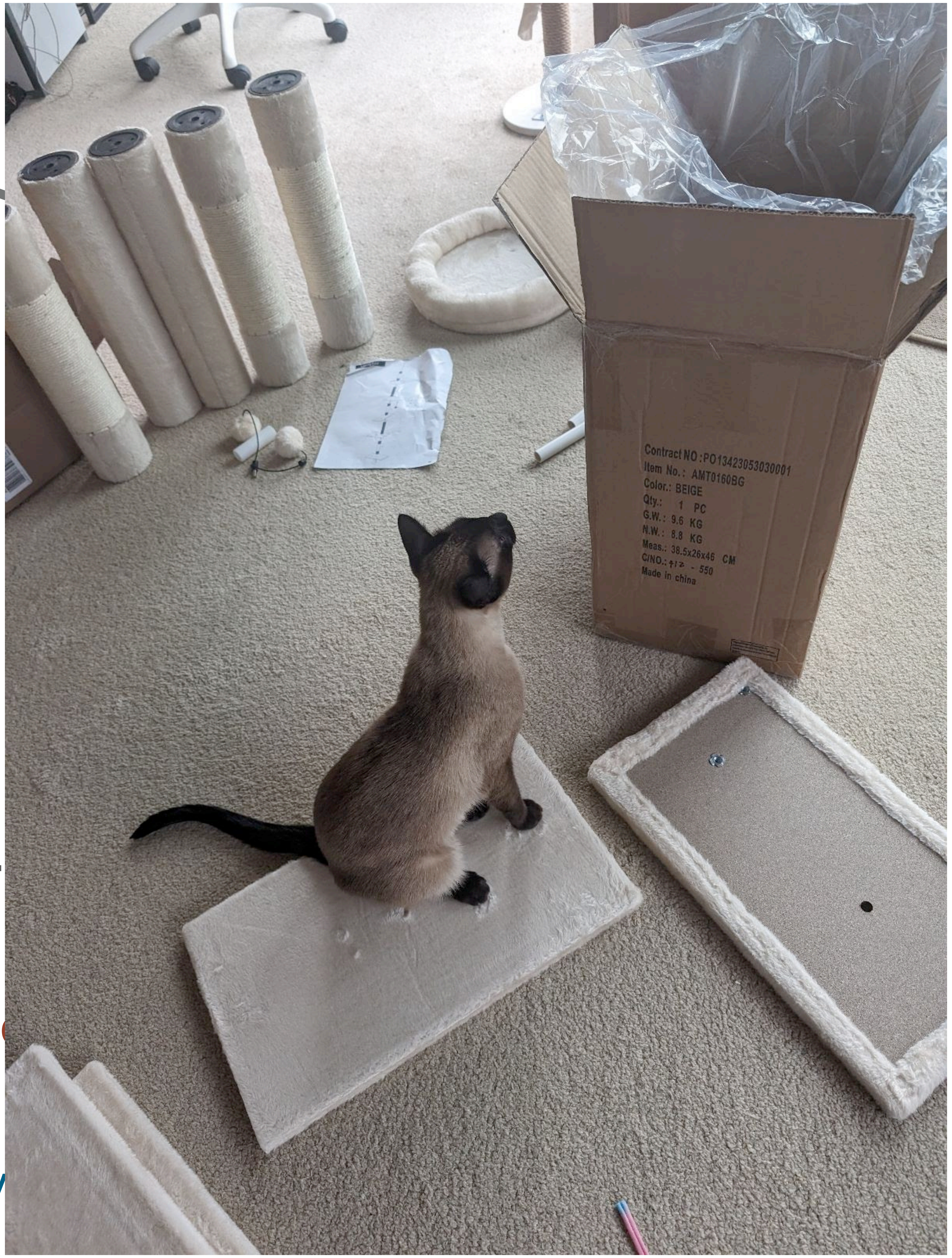
Future CR-39 experiment or similar



Snowmass Ultraheavy dark matter

Carney, Raj et al. 2203.06508

Delorean



BACK TO THE FUTURE WITH HIGH MASS DM

-Most DM models were written down in the 80s.

-The simplest DM are well studied, and may be

(Simple in formulation, complicated in dynamics)

-Less simple heavy DM is less studied, and may
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Delorean

2023 BZ

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2023 BZ

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