# (LET'S GET) OVERVIEW(S) OF DARK MATTER

Joseph Bramante

Queen's University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Dark Interactions 2024

# (LET'S GET) OVERVIEW(S) OF DARK MATTER

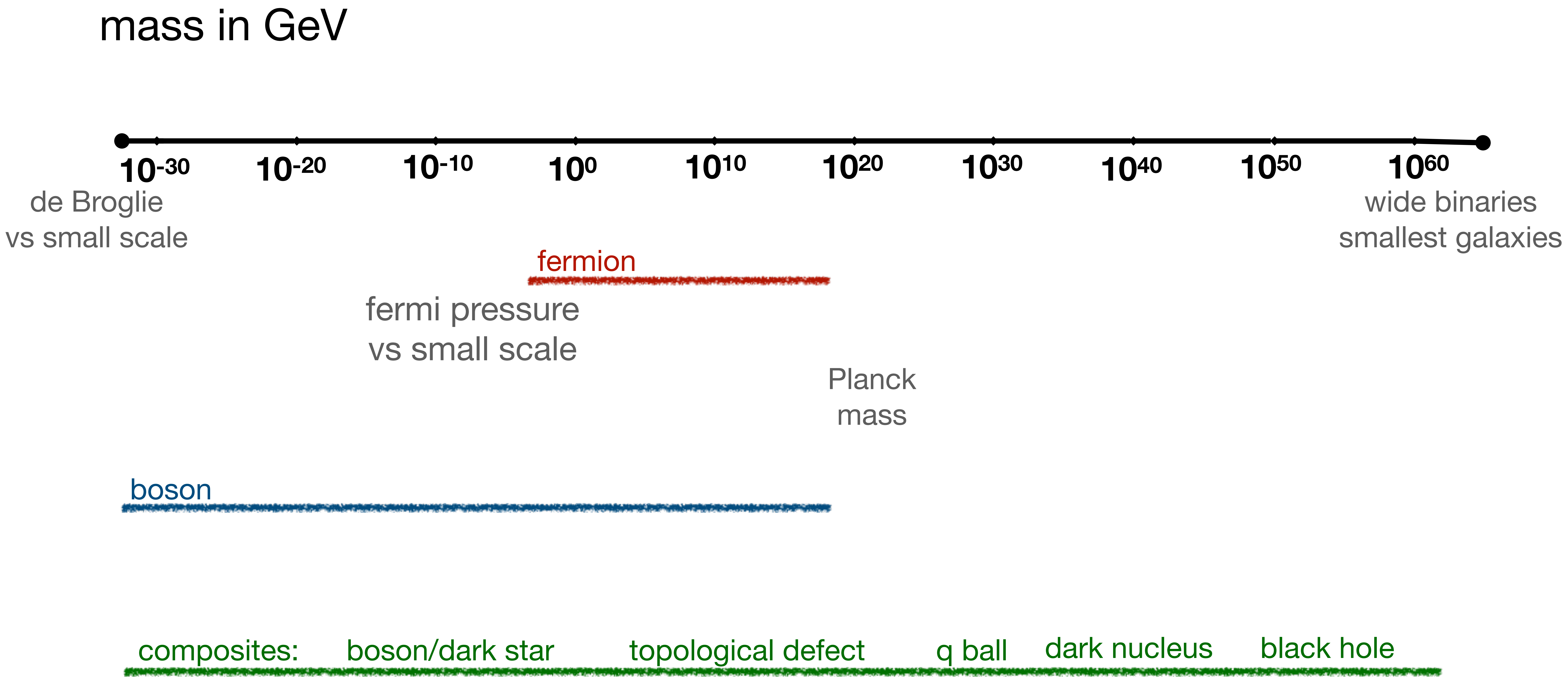
-Most DM models were written down in the 80-90s.

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

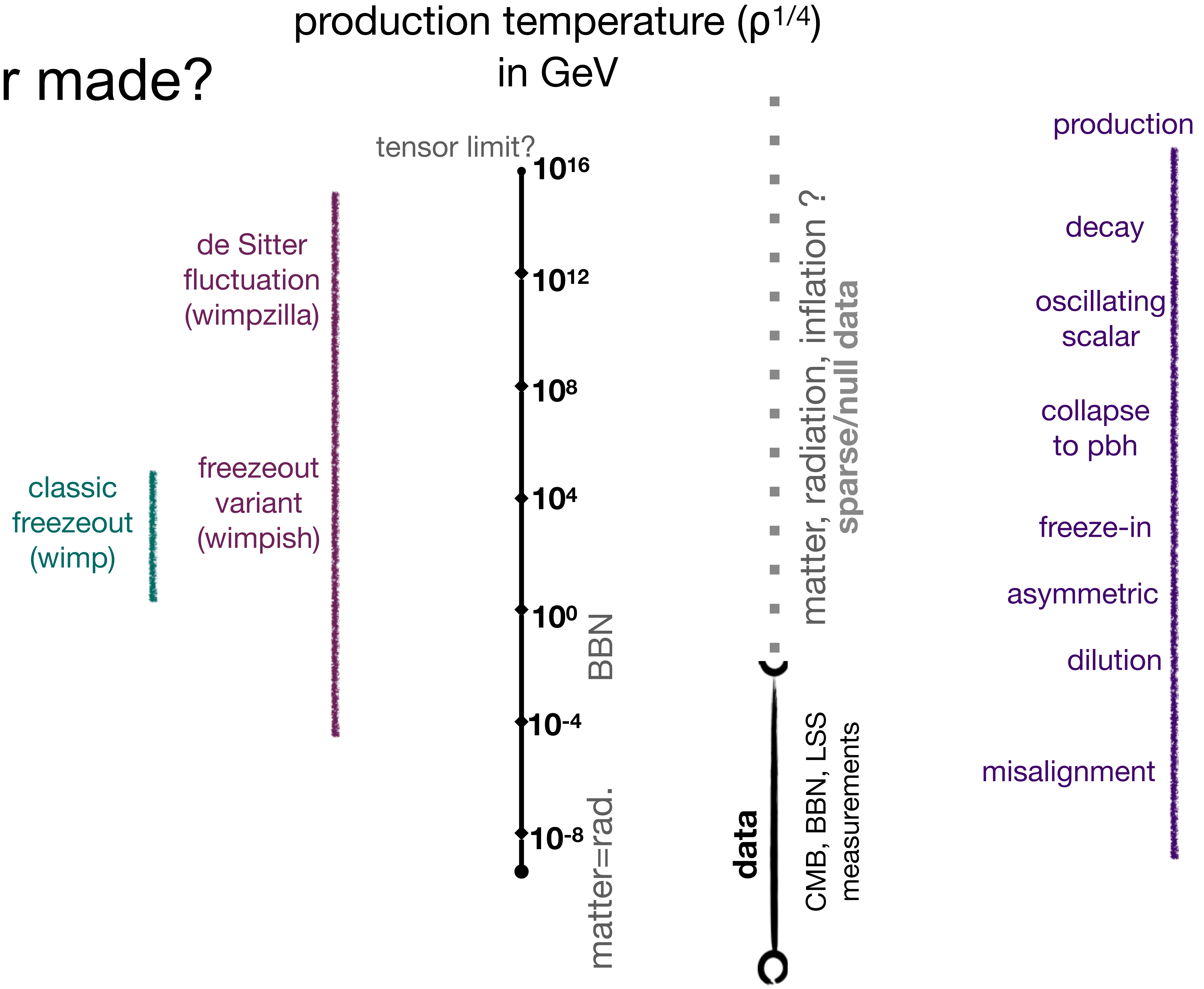
(Simple in formulation, sometimes complicated in dynamics)

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

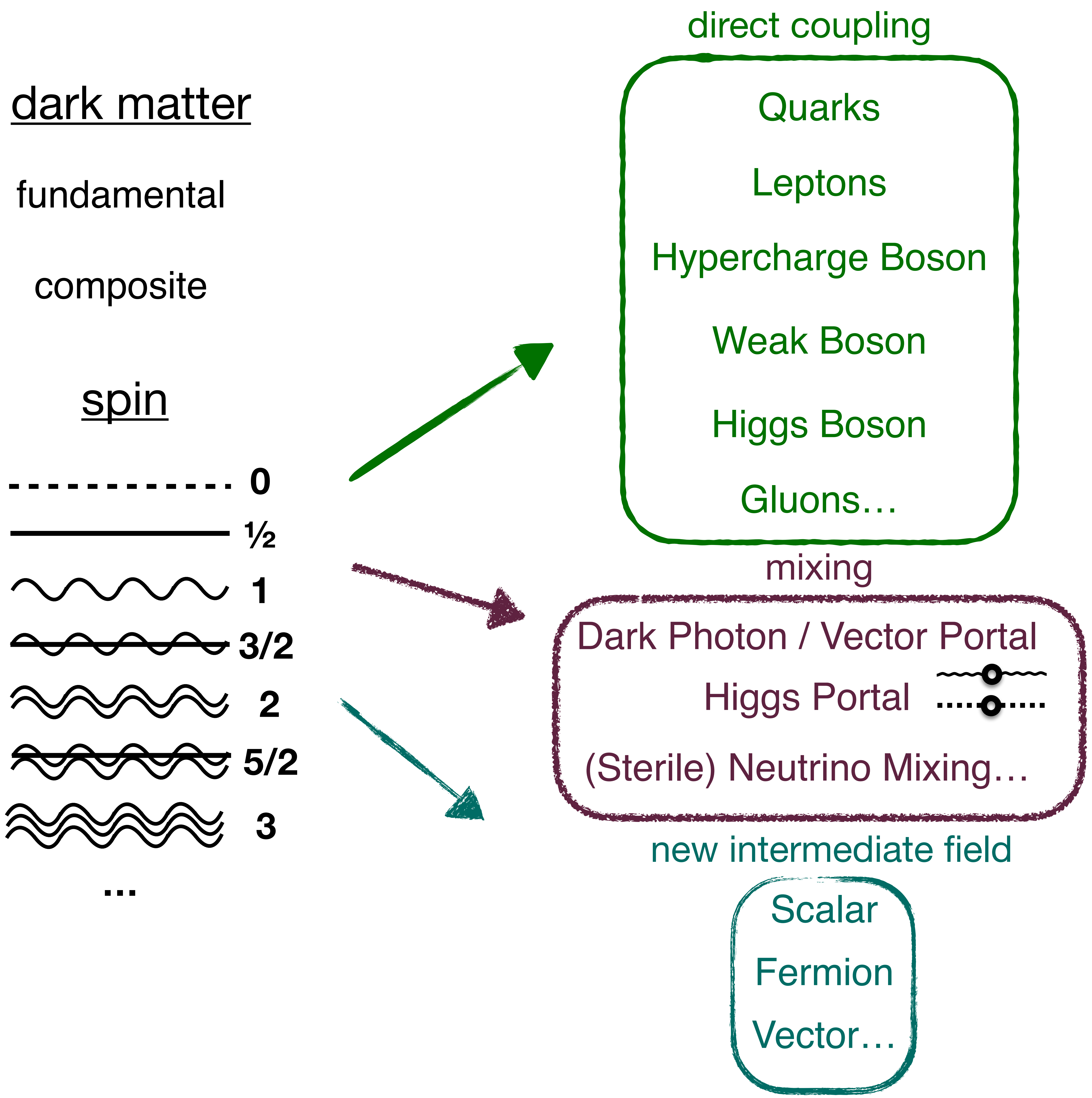
# What do we know about dark matter?



# How was dark matter made?



# Dark Matter Models: SM Coupling and Detection



# Dark Matter Models: SM Coupling and Detection

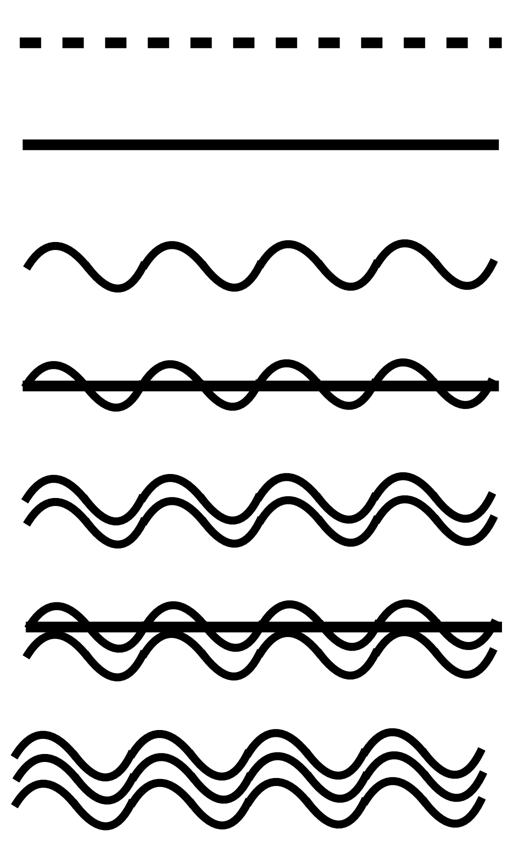
annihilation scattering DM production

## 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**

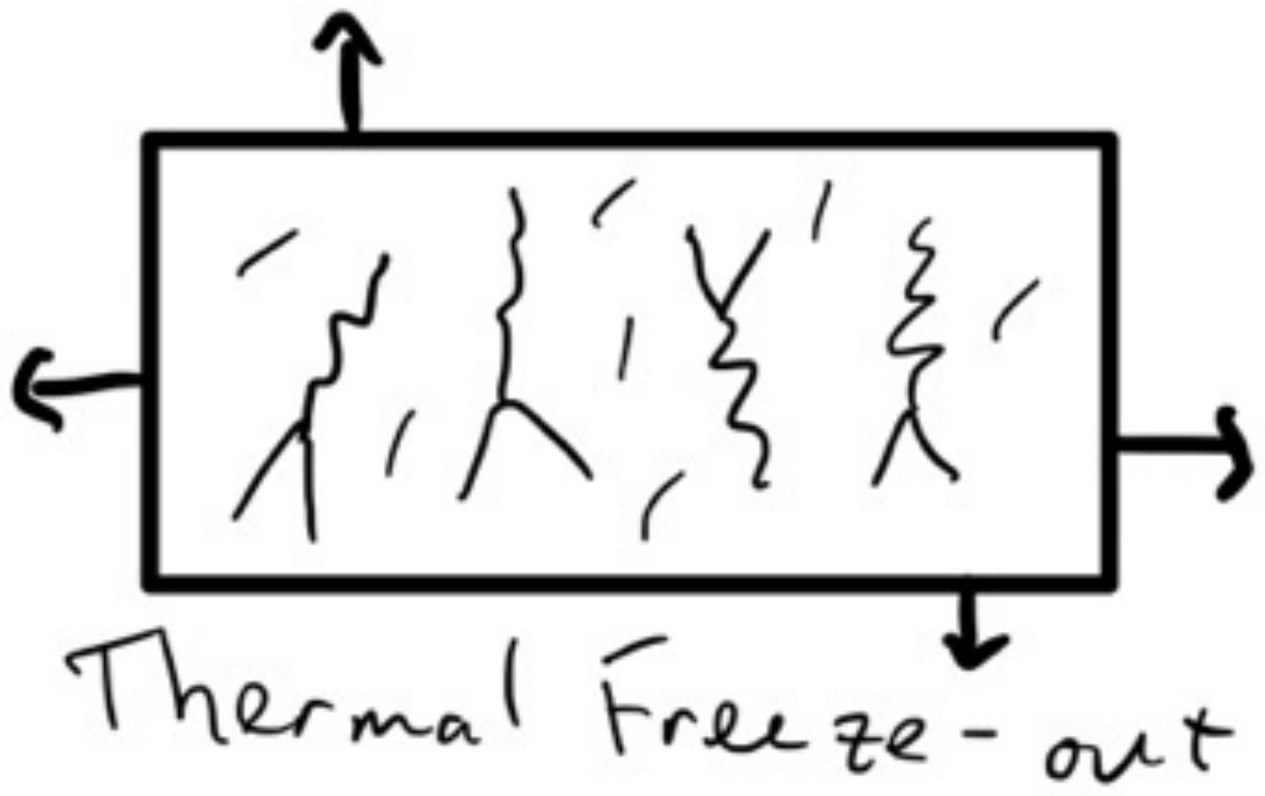
- Dark Photon / Vector Portal
- Higgs Portal
- (Sterile) Neutrino Mixing…

**new intermediate field**

- Scalar
- Fermion
- Vector…

| 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) | |
| XENON, DEAP, LZ, PandaX, SuperCDMS, PICO, SENSEI | ~$10^{30}$ |
| ADMX, HAYSTAC | |
| collider, beam dump | ~$10^{15}$ |

# The WIMP Miracle

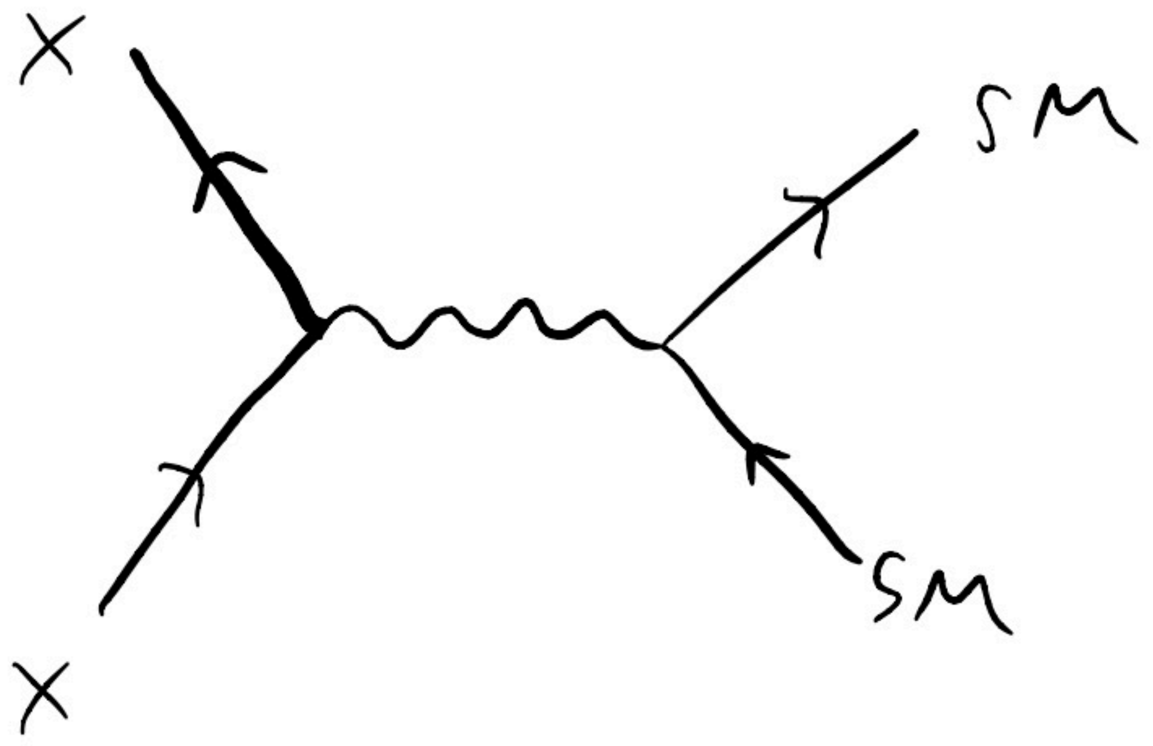


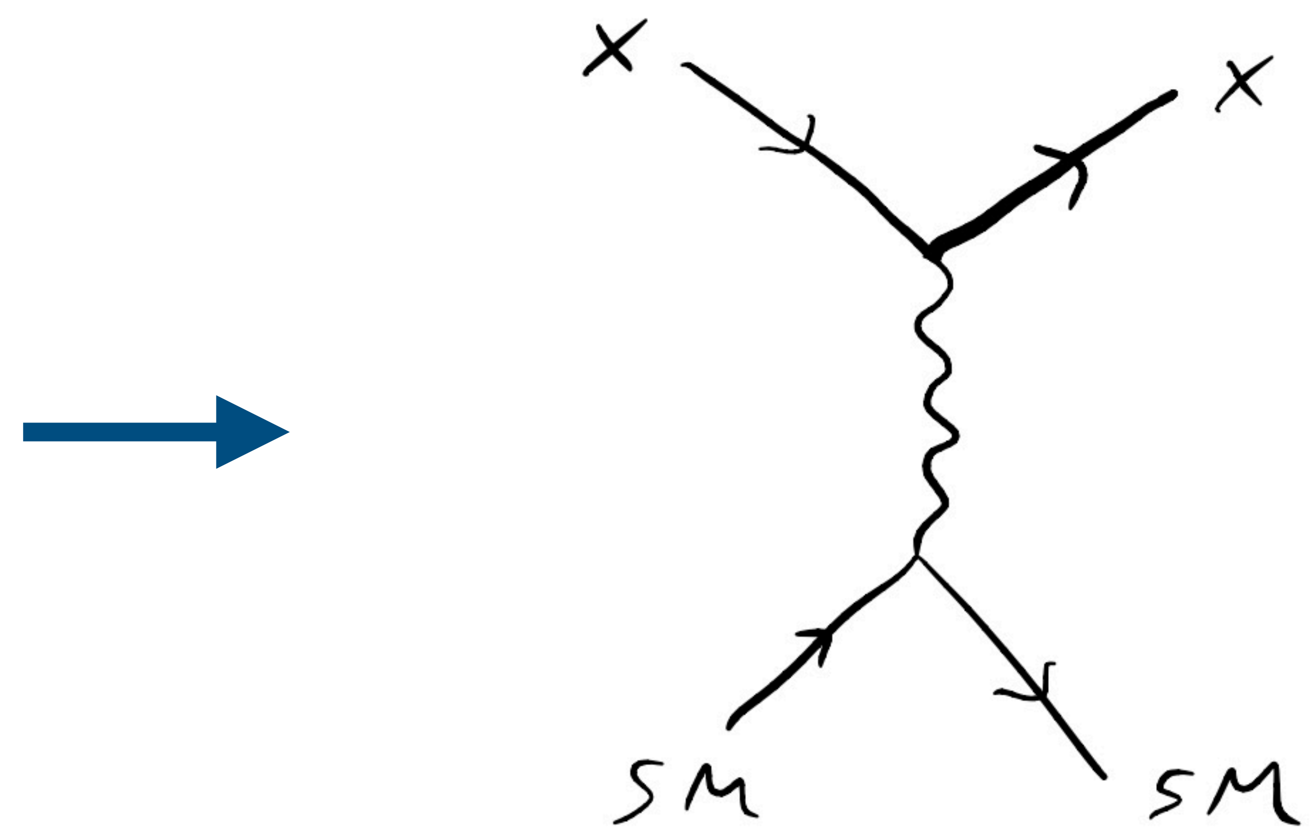

As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

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

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

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

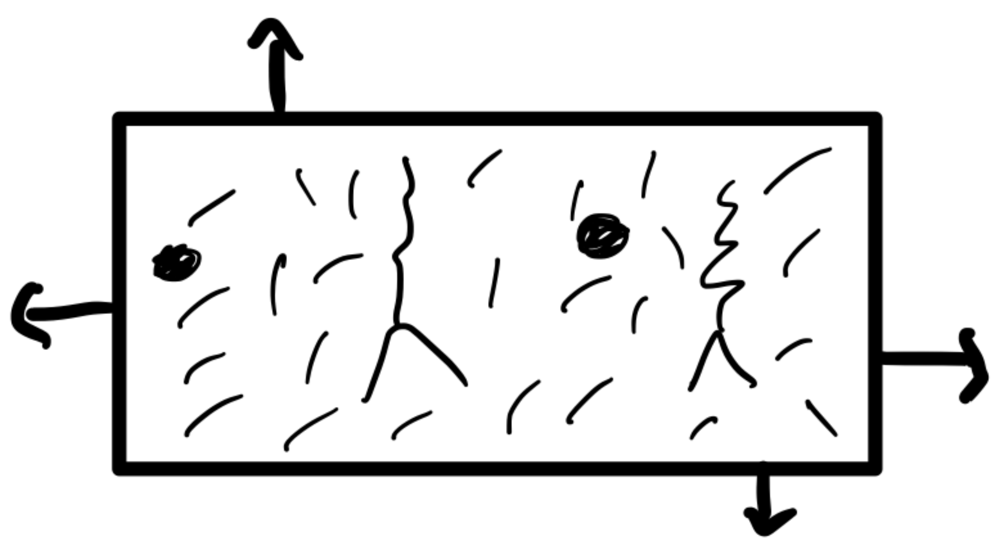


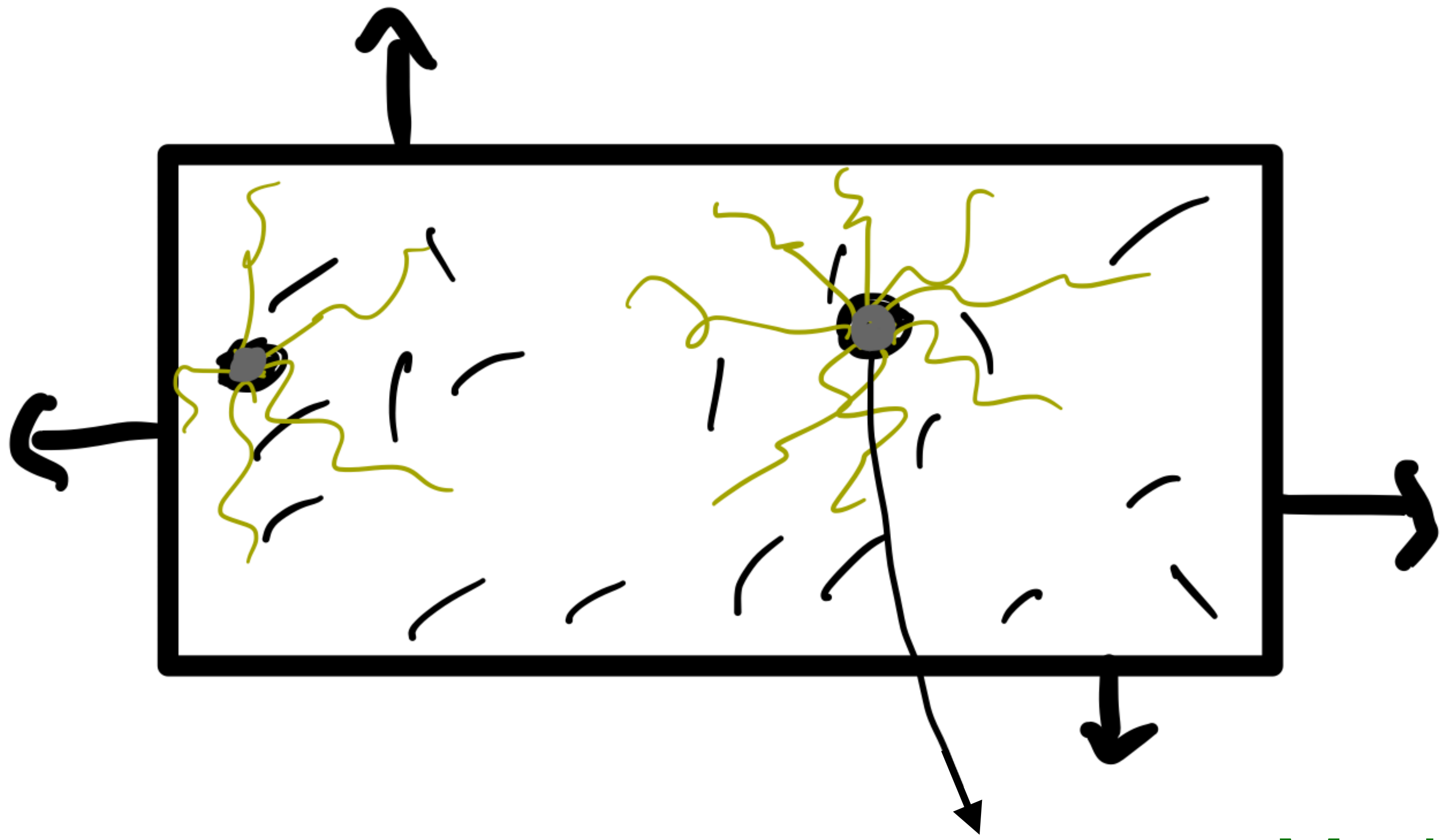




see e.g.
**Scherrer Turner '86**
**Drukier, Freese, Spergel '86**

Some symmetry arguments imply interactions at dark matter experiments.

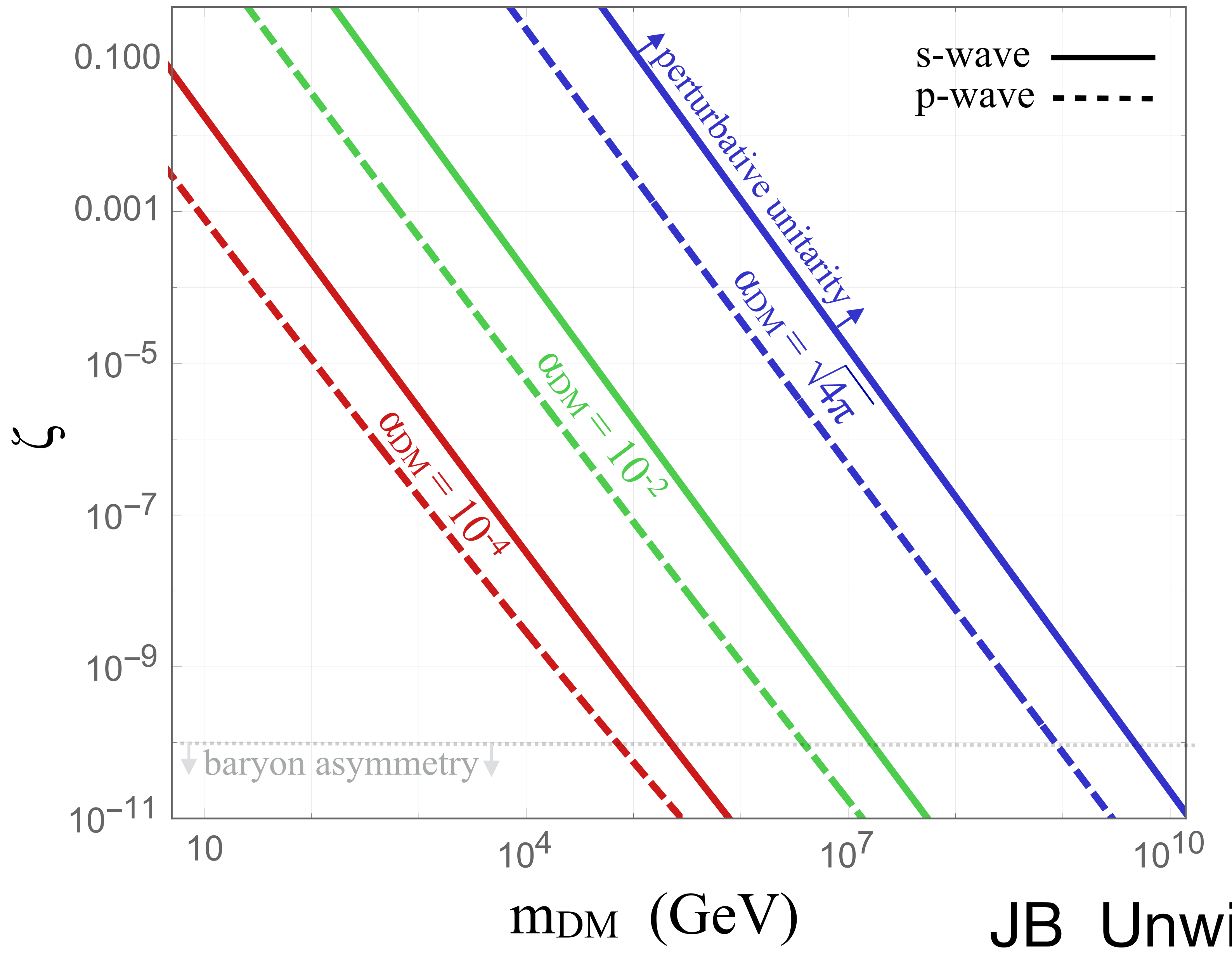
# Diluted WIMP Dark Matter: heavier





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

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

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**
**Dimopoulos Hall '88**
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16

# HEAVY COMPOSITE DM

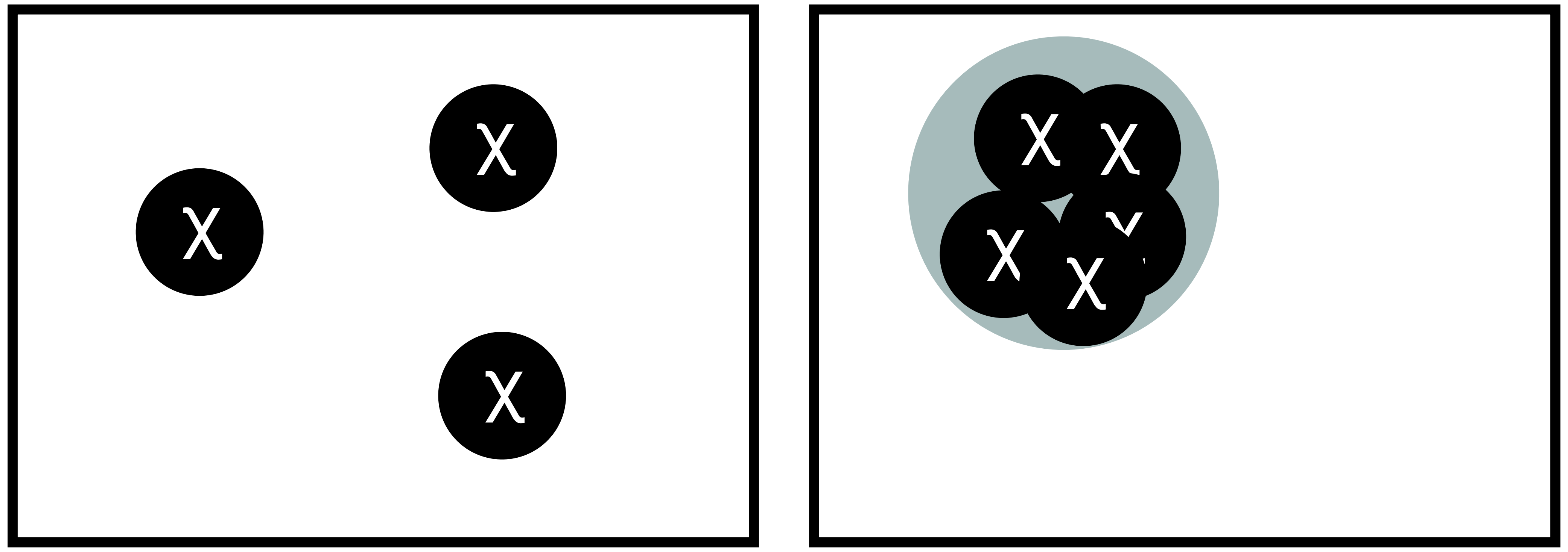
Consider a simple model of fermionic DM coupled by a scalar field

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

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

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

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
Acevedo, JB, Goodman '20




Models of quark matter forming during 1st order PT

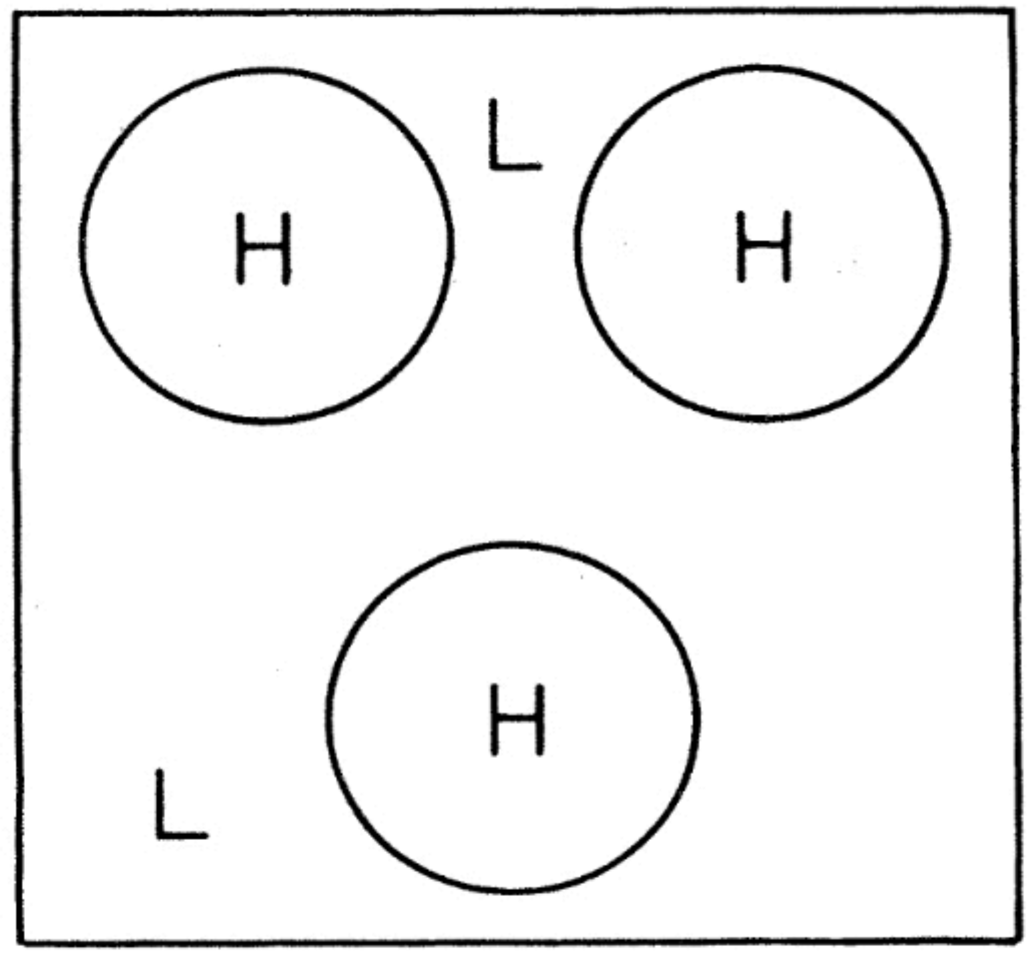
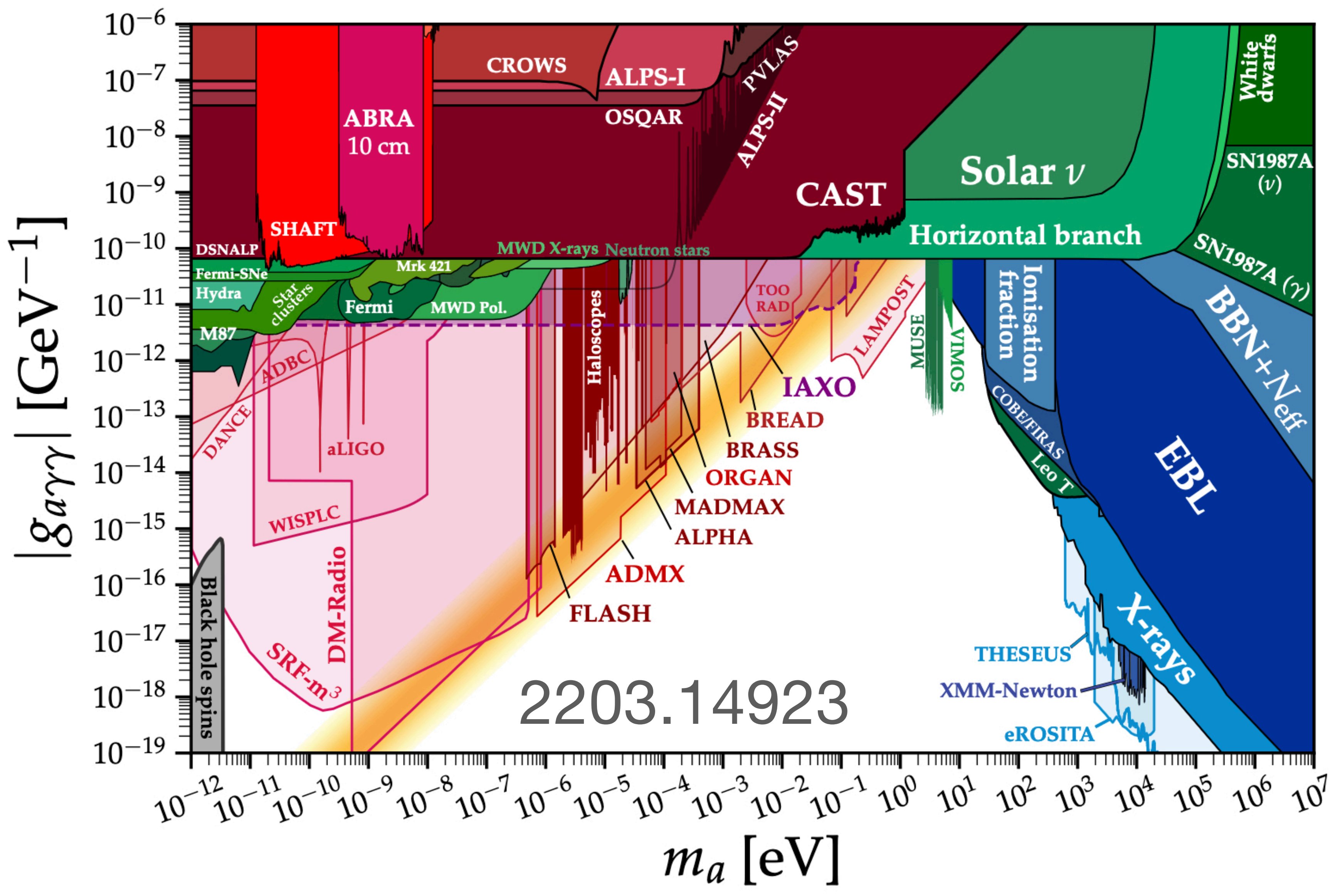



FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

see e.g.
**Witten '84**
Zhitnitsky '02
Asadi, Kramer, Kuflik, Slatyer, Smirnov '21

# SKIM THROUGH DM SEARCHES

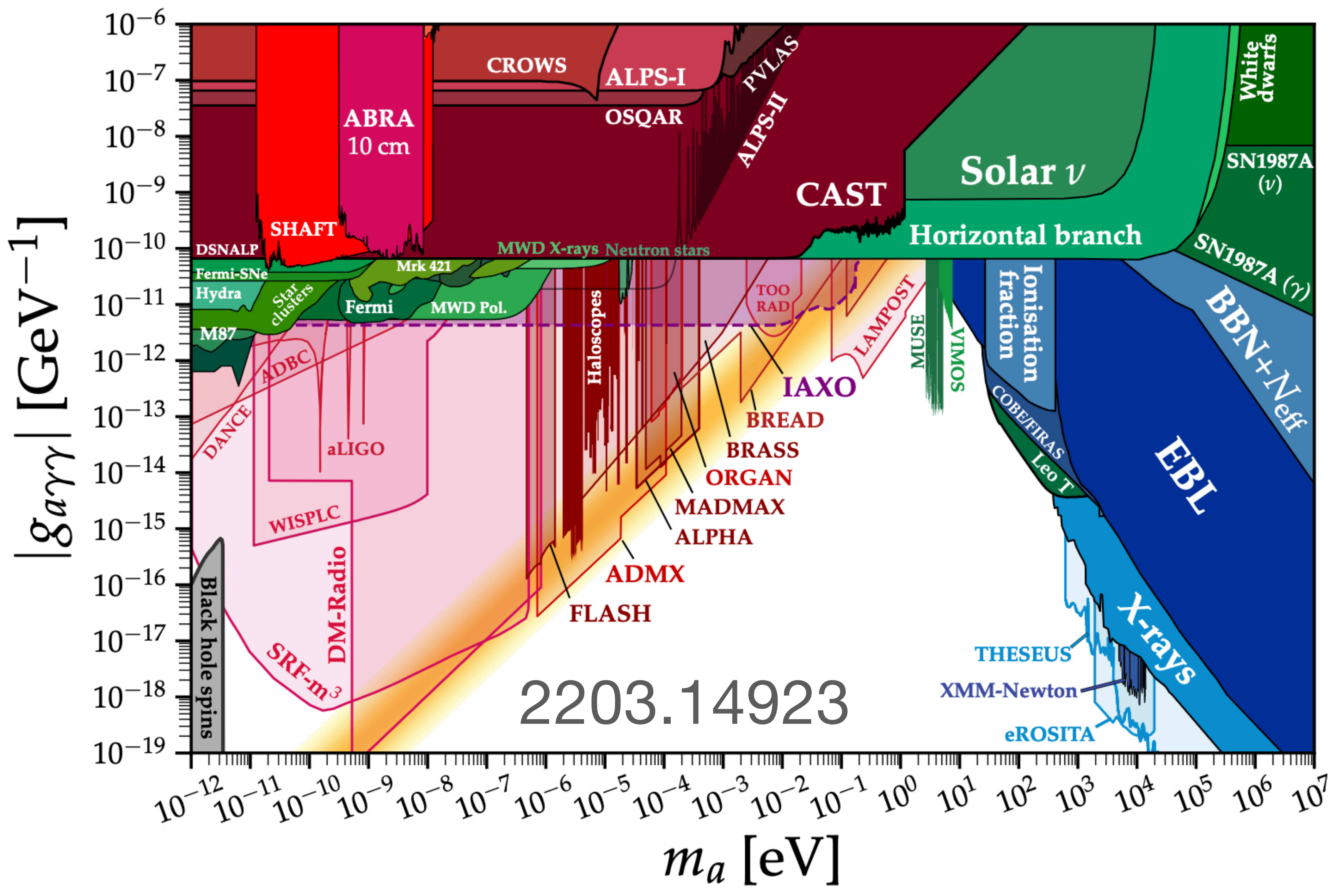



**Axion/ DP (wavy bosons)**

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

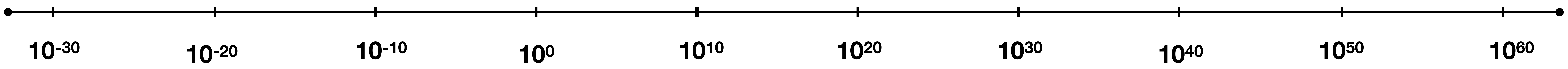
$m_X$ (GeV)

# SKIM THROUGH DM SEARCHES




Axion/ DP (wavy bosons)

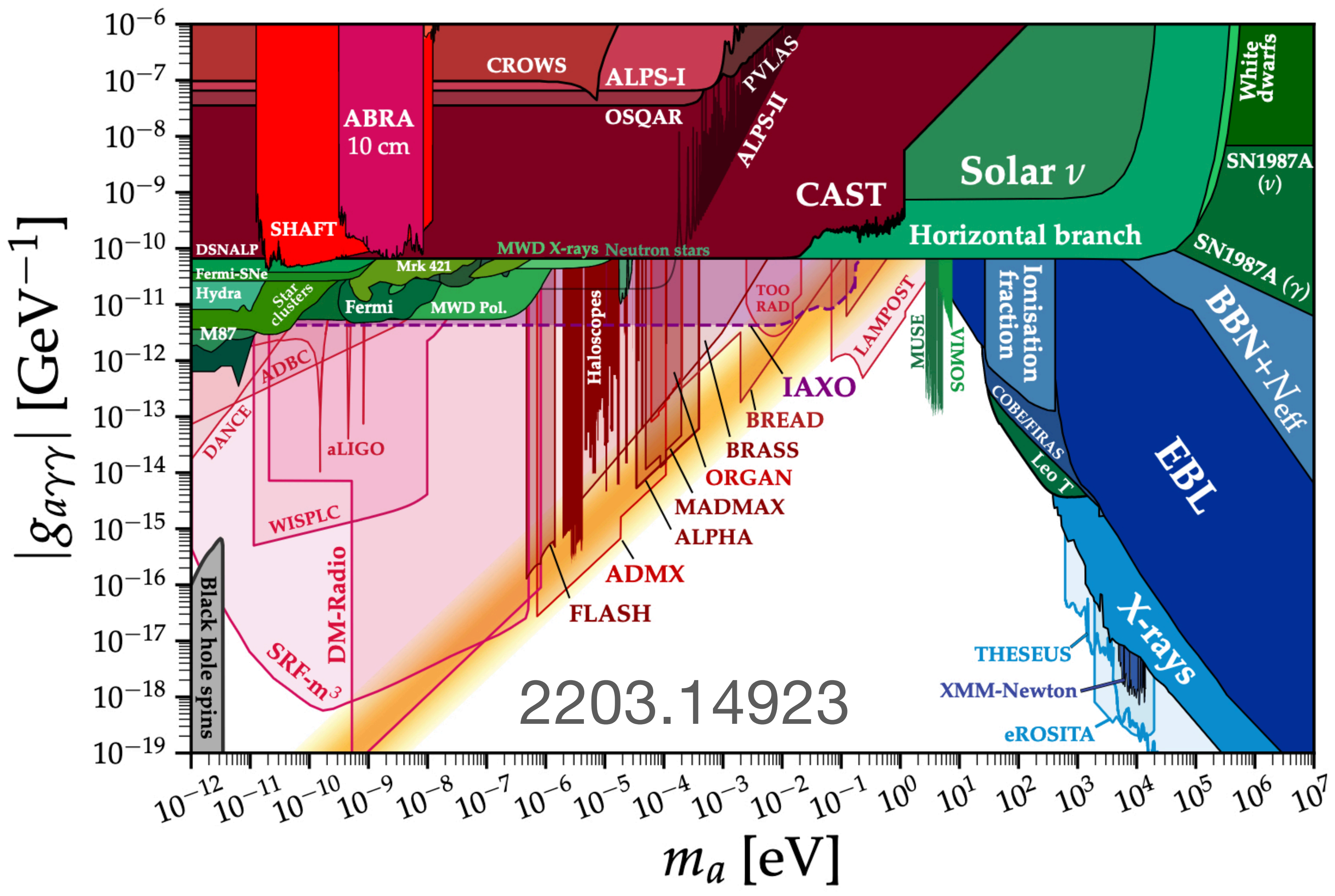
Preskill, Wise, Wilczek ’83
Abbott, Sikivie ‘83



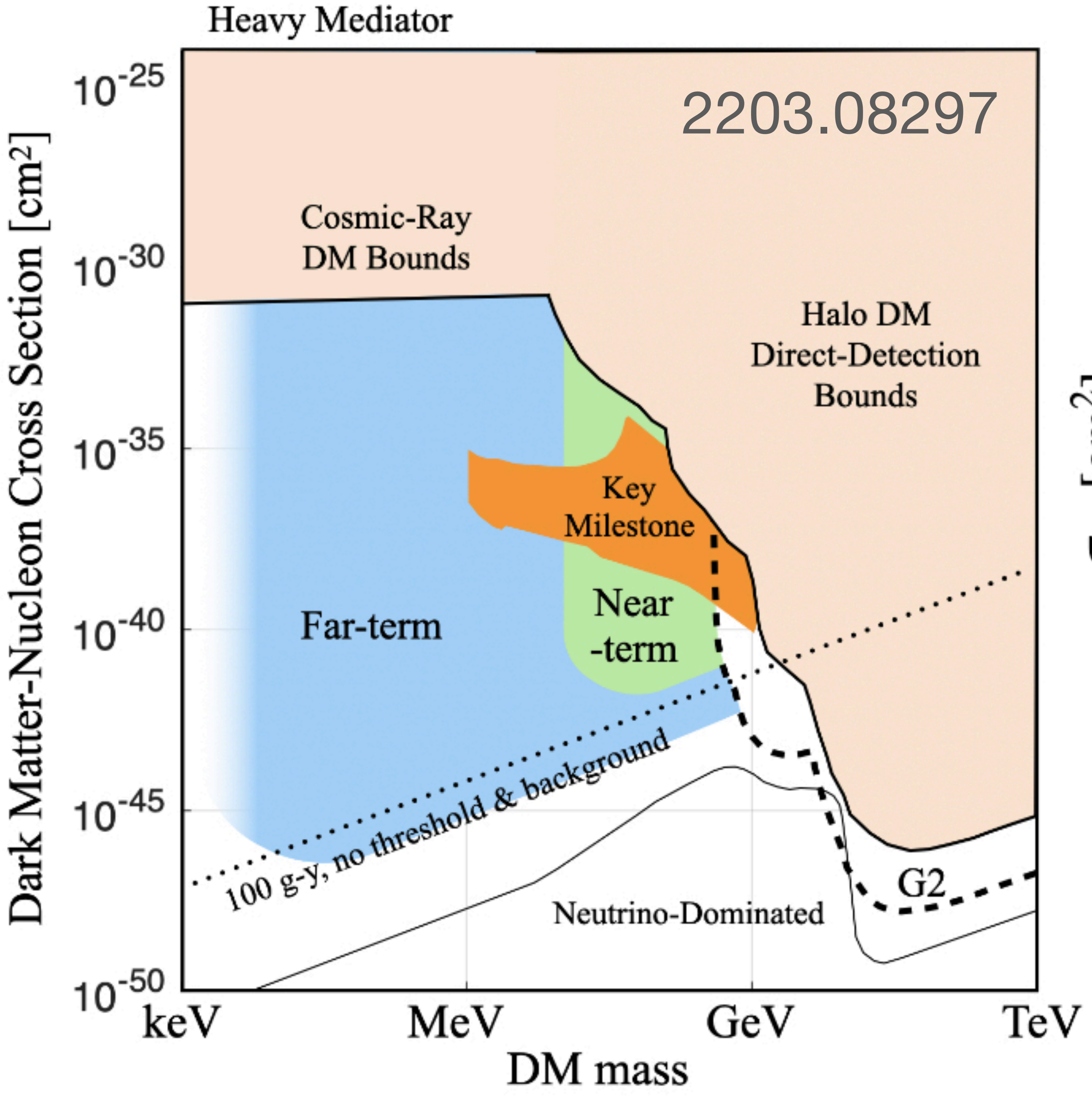

$m_x$ (GeV)

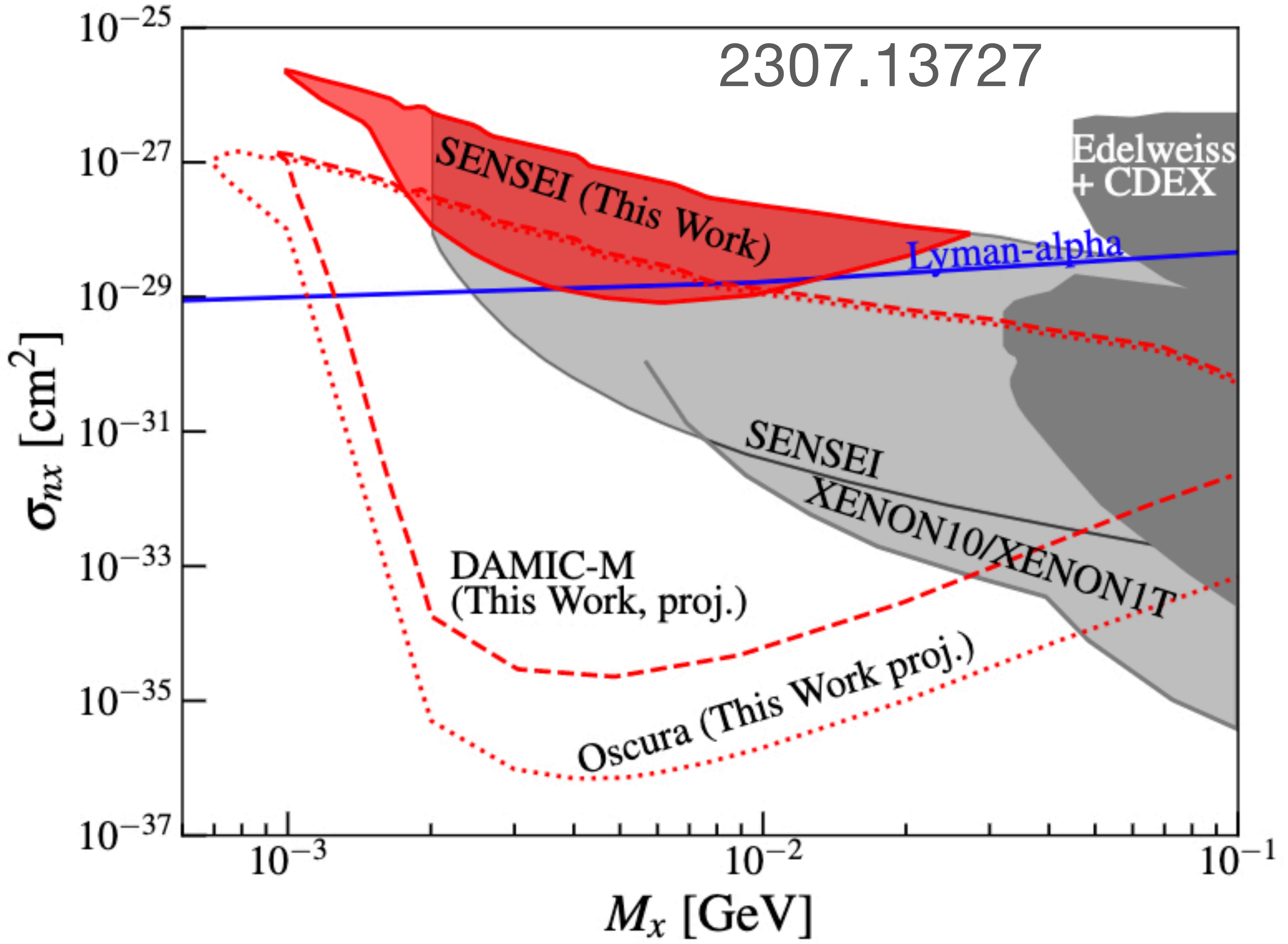
# SKIM THROUGH DM SEARCHES

**Light dark matter**




**Axion/ DP (wavy bosons)**



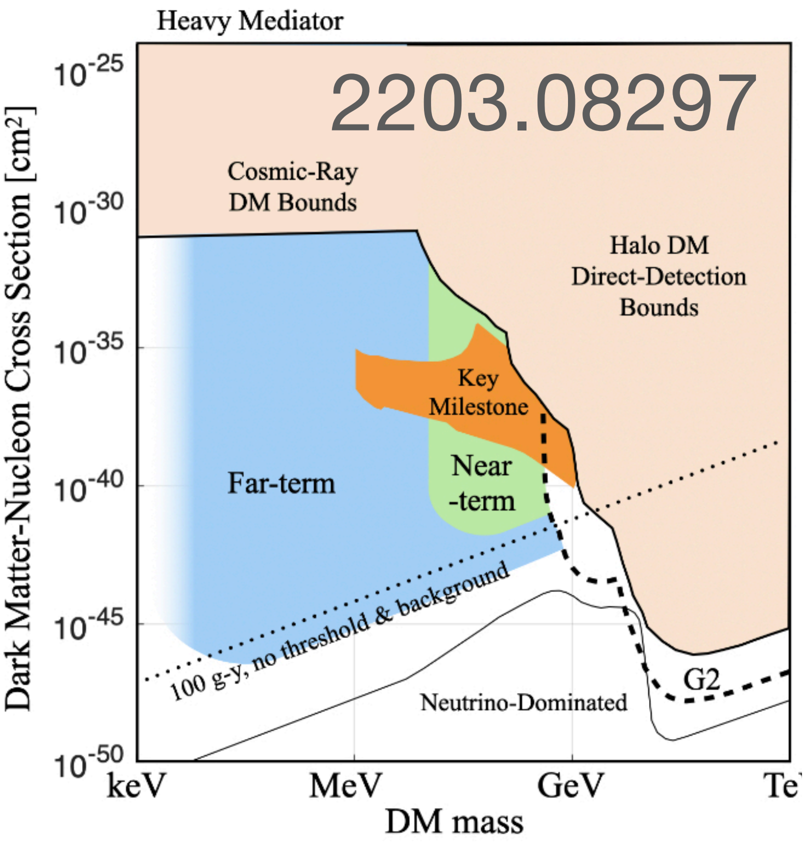



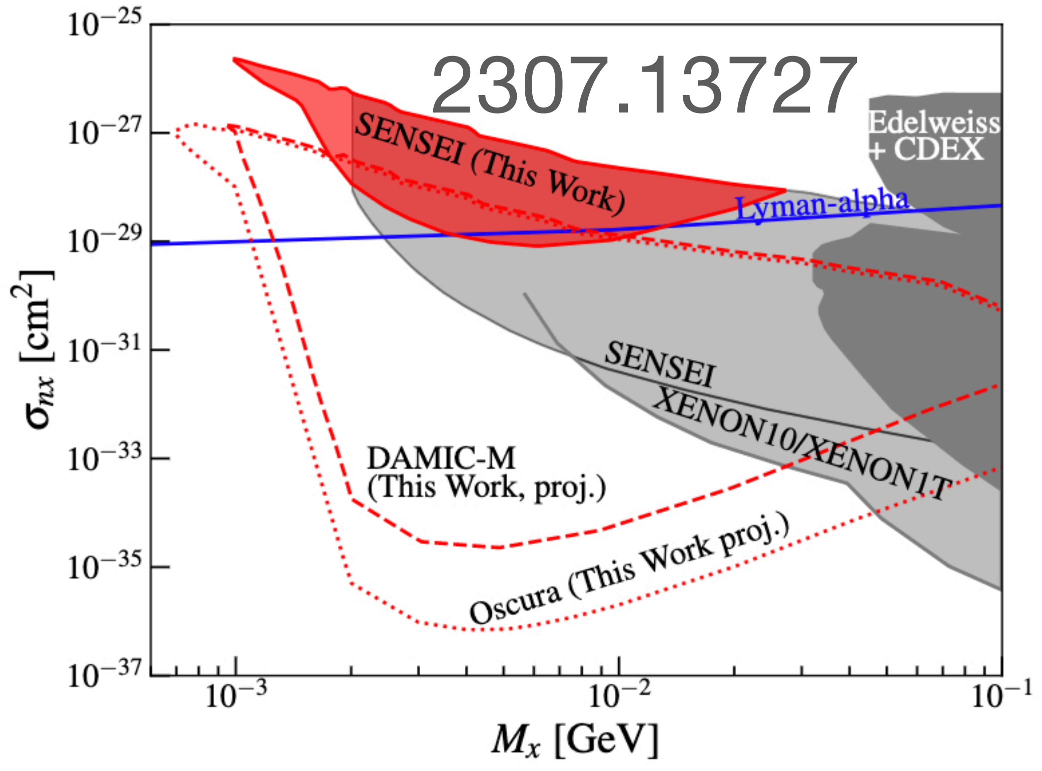

Melissa Diamond, Chris Cappiello, Vincent, JB

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

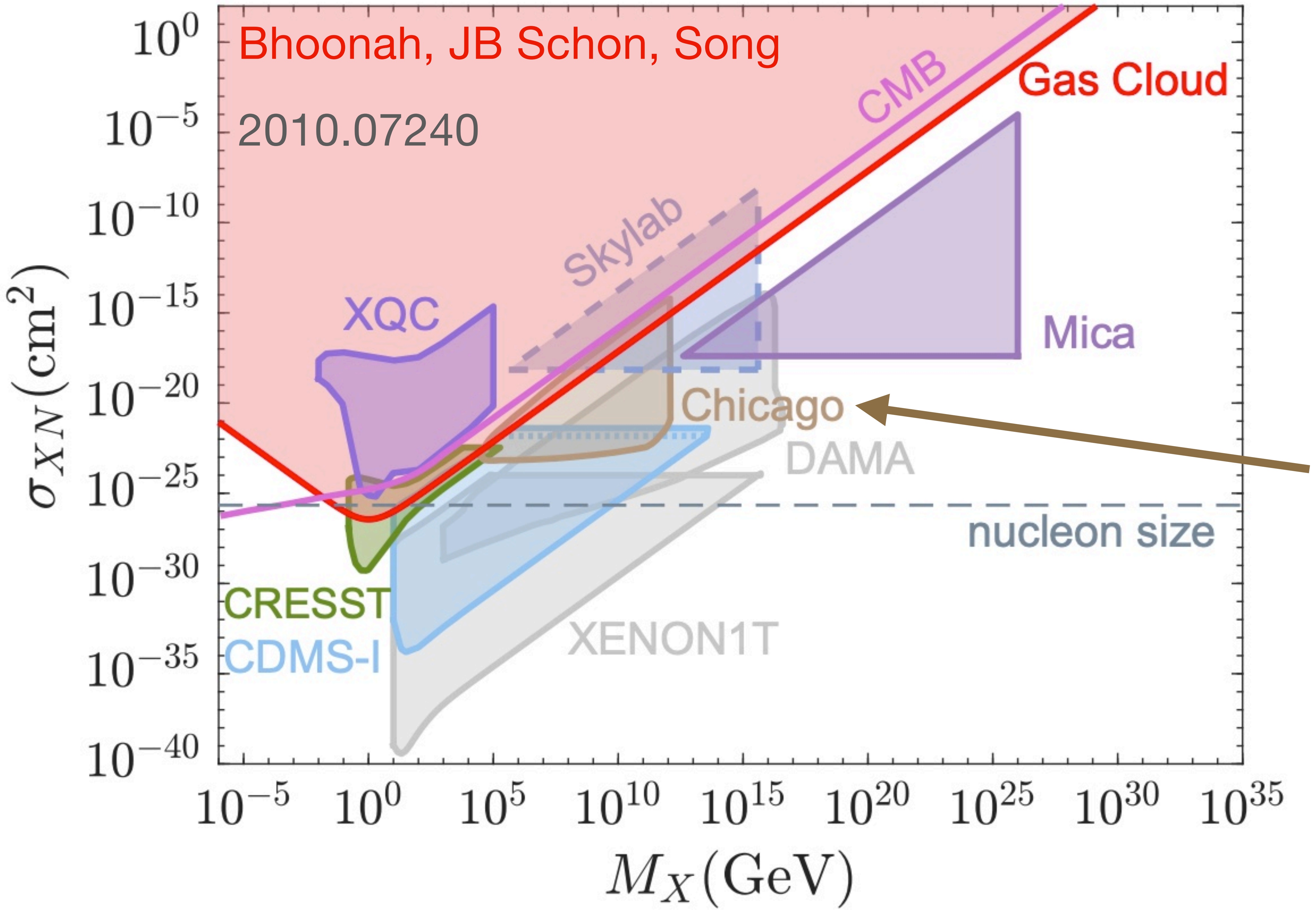
$m_x$ (GeV)

# SKIM THROUGH DM SEARCHES



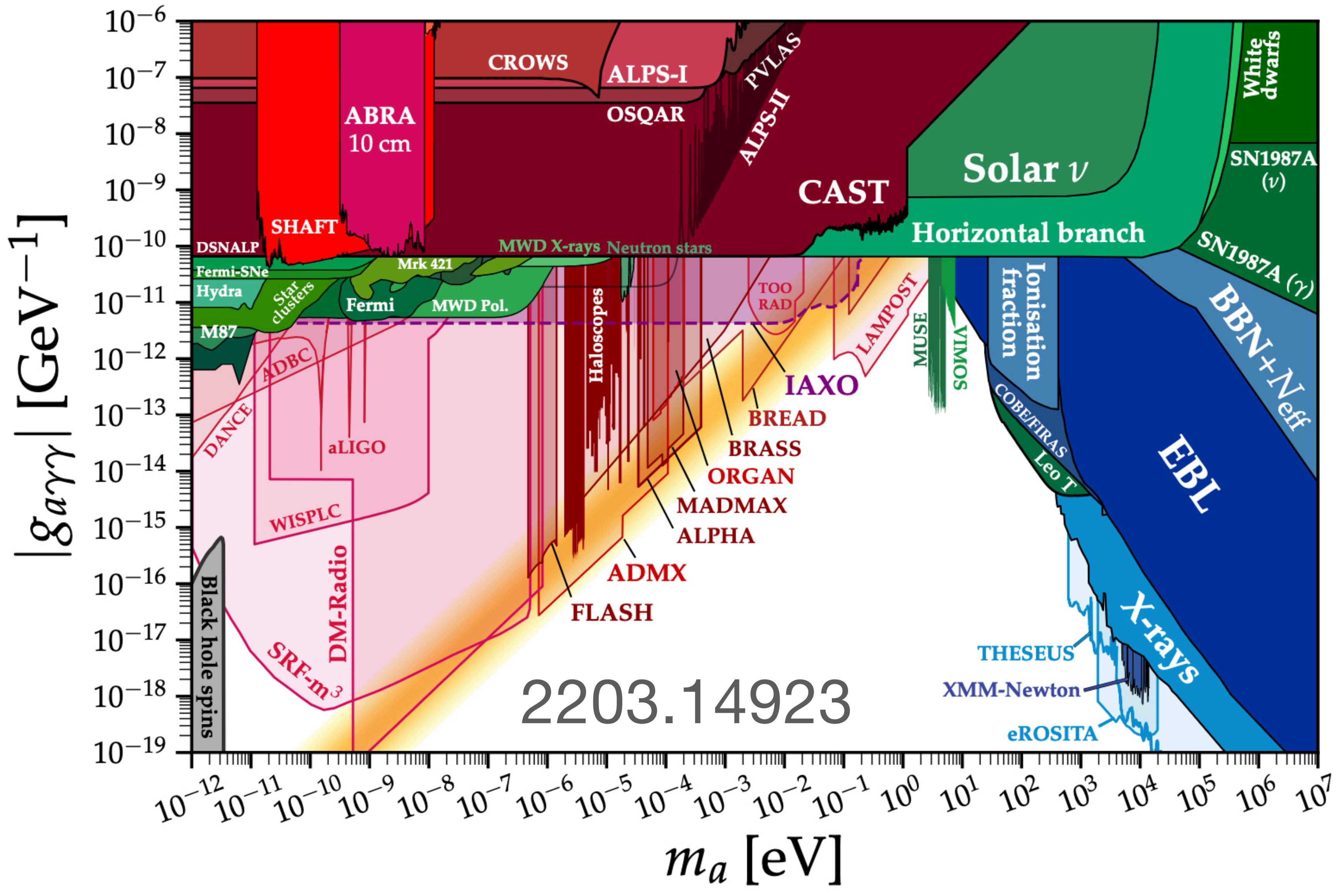




**Heavy dark matter**



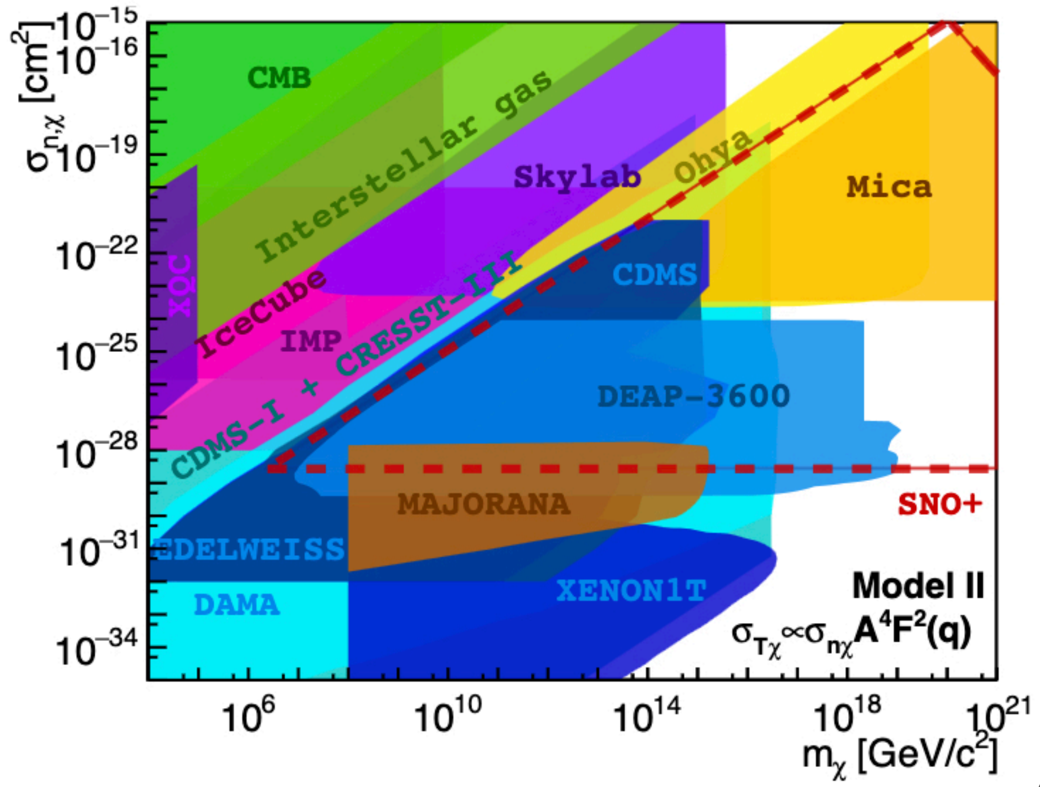

Cappiello, Collar, Beacom

**Light dark matter**




**Axion/ DP (wavy bosons)**

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




2203.06508

$m_X$ (GeV)

high m,σ composites

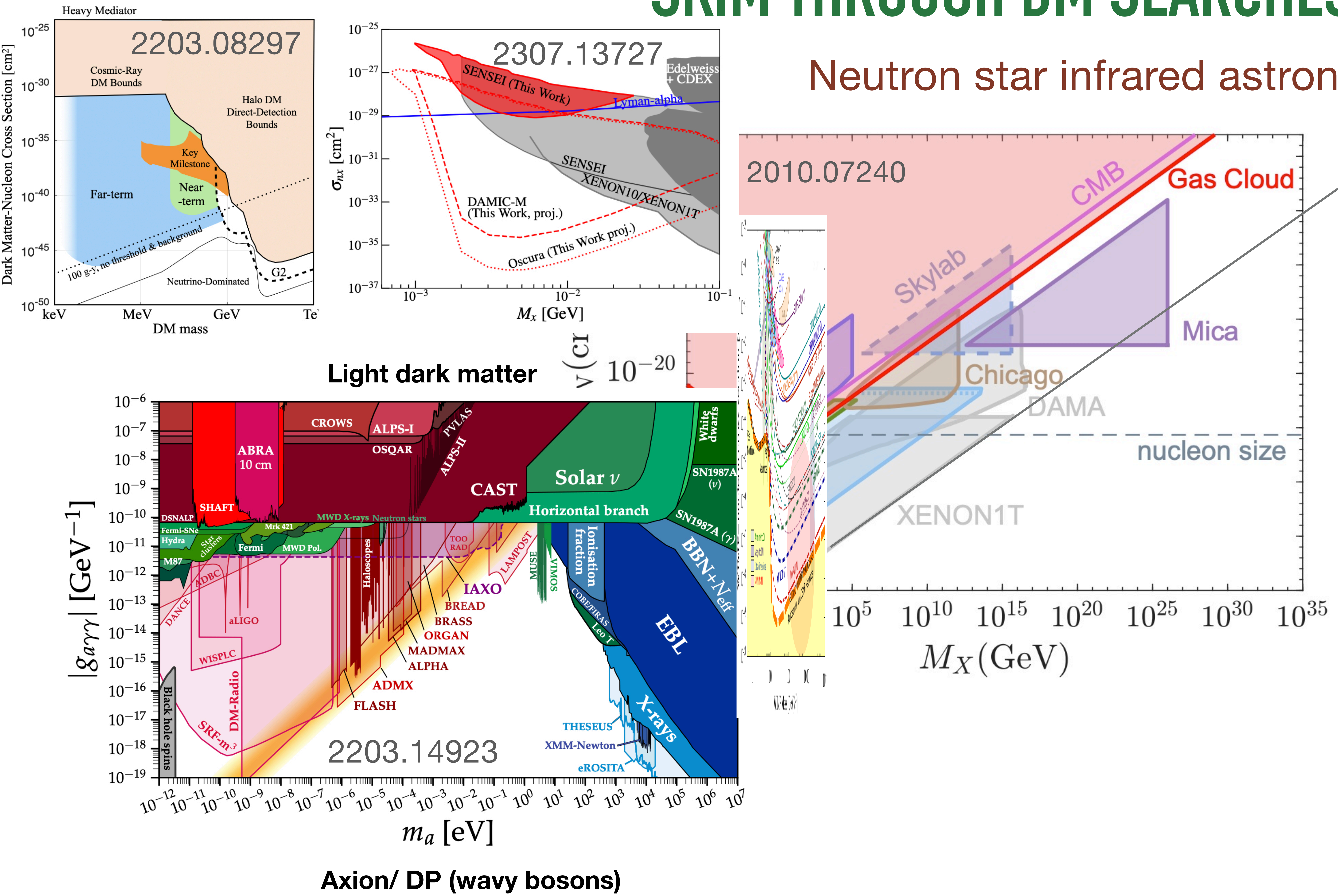
**Witten '84**

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

# SKIM THROUGH DM SEARCHES

Neutron star infrared astronomy

Narayani Tyagi, JB, Mack, Raj, Shao 24xx.xxxx

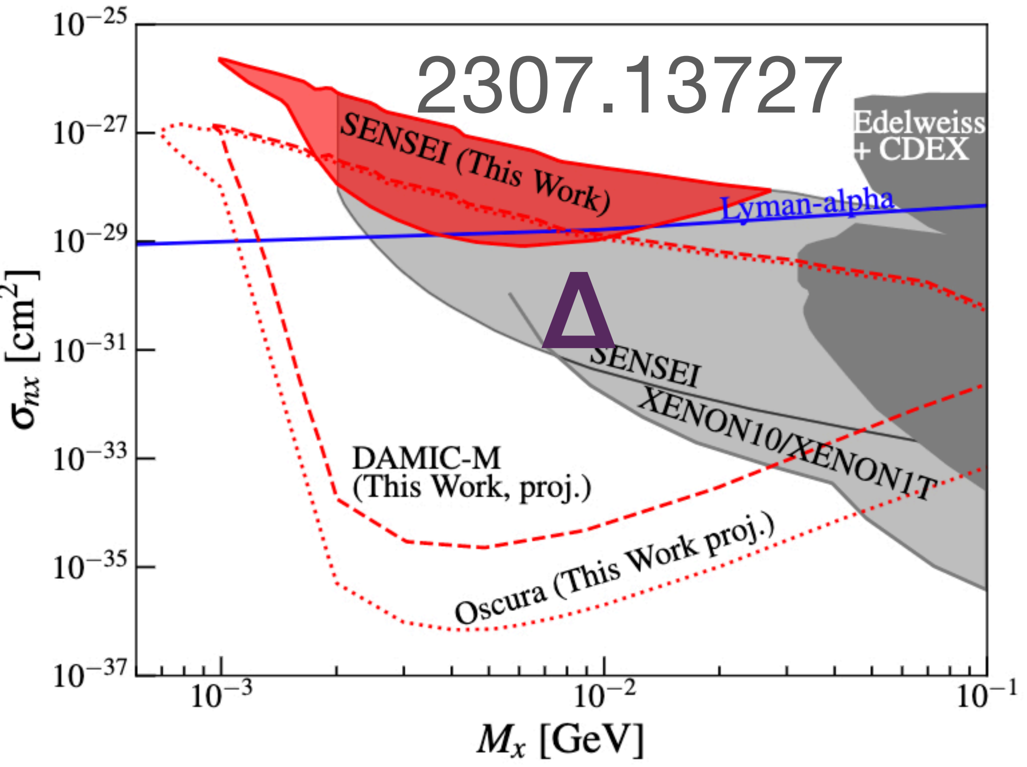



$10^{-30}$ $10^{-20}$ $10^{-10}$ $10^{0}$ $10^{10}$ $10^{20}$ $10^{30}$ $10^{40}$ $10^{50}$ $10^{60}$

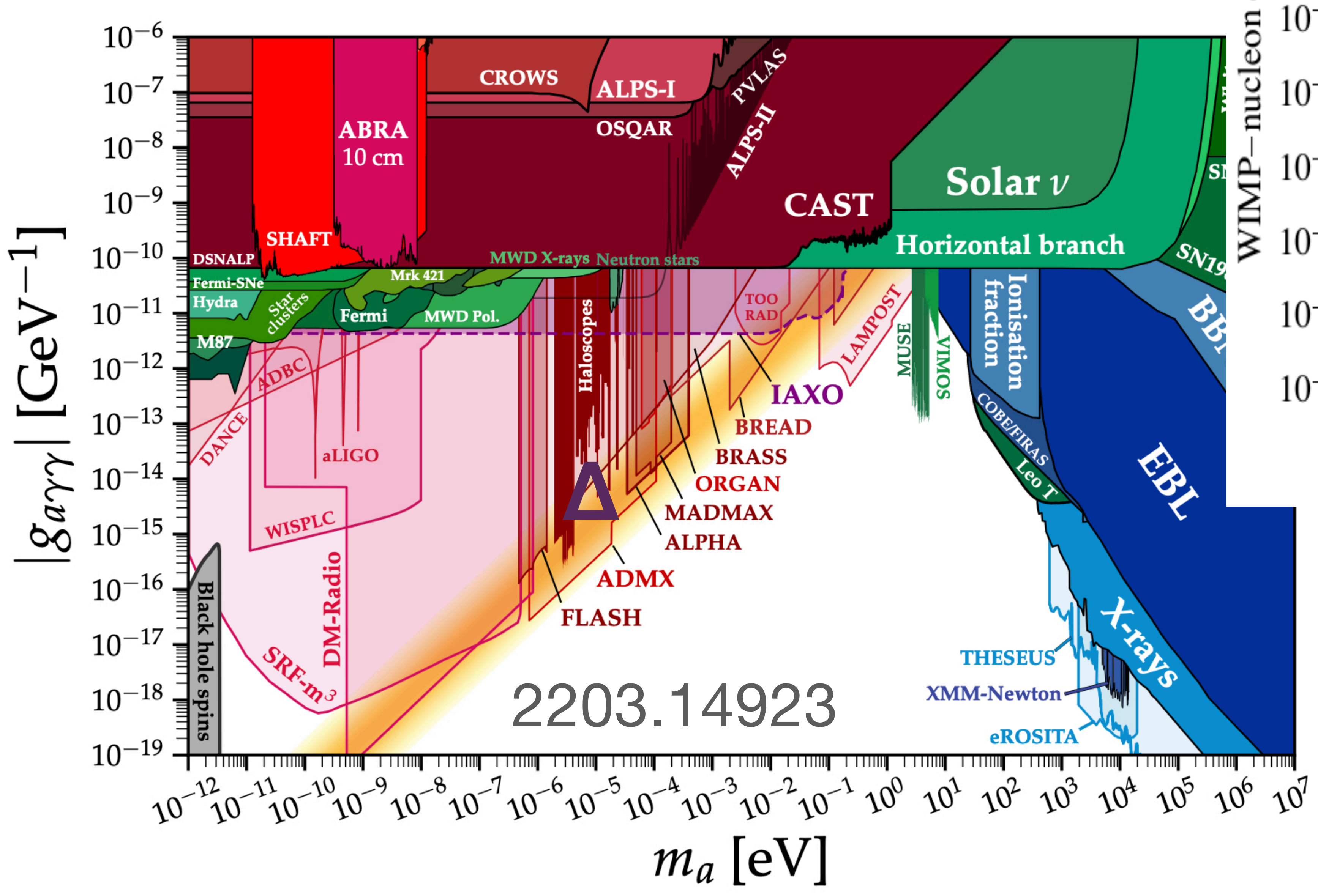
$m_x$ (GeV)

# PRICE OF DM DETECTION

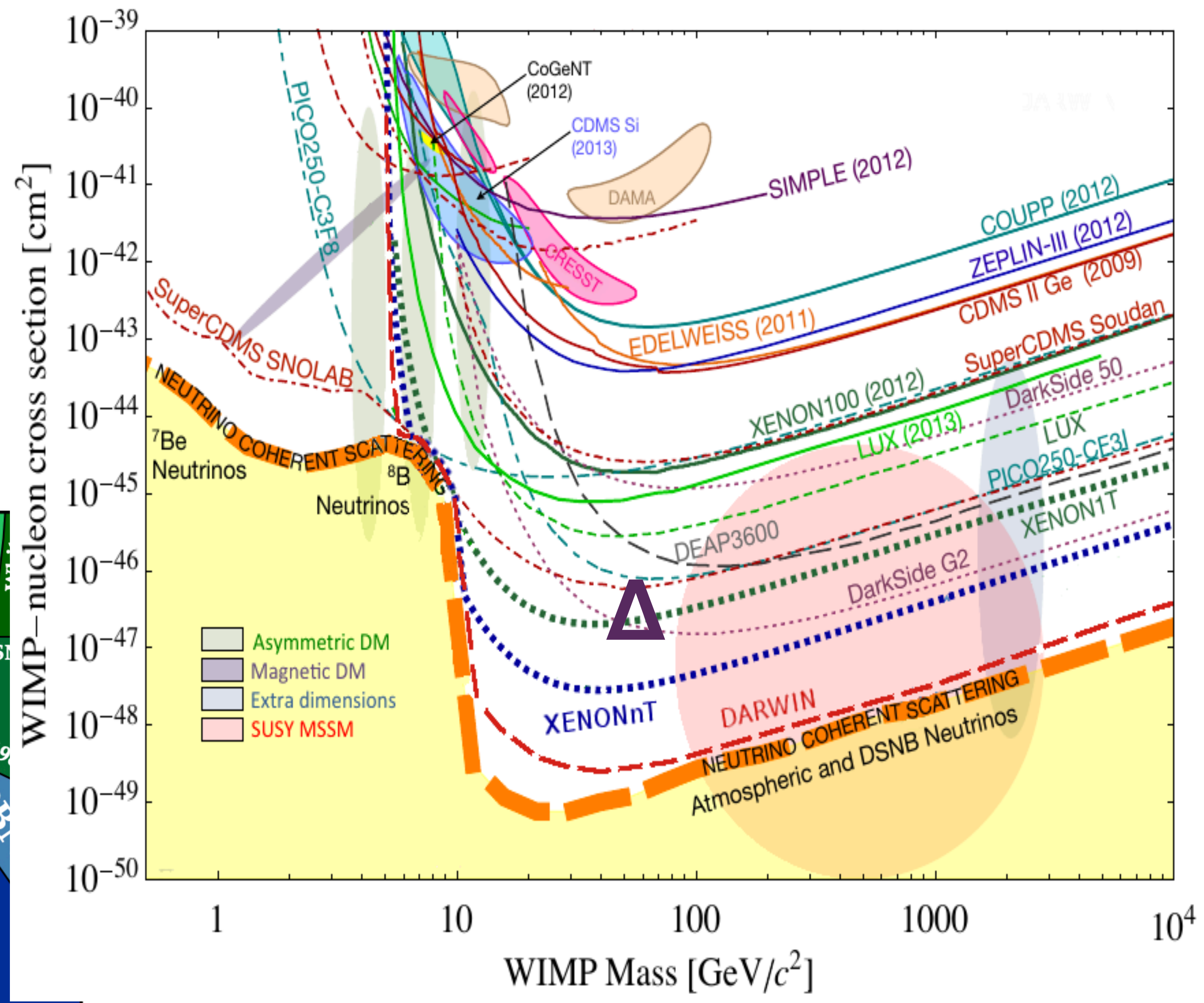
current price of DM $\sim \$(10^5 - 10^6) \times \log_{10}(\Delta\sigma) \times \log_{10}(\delta m_X)$



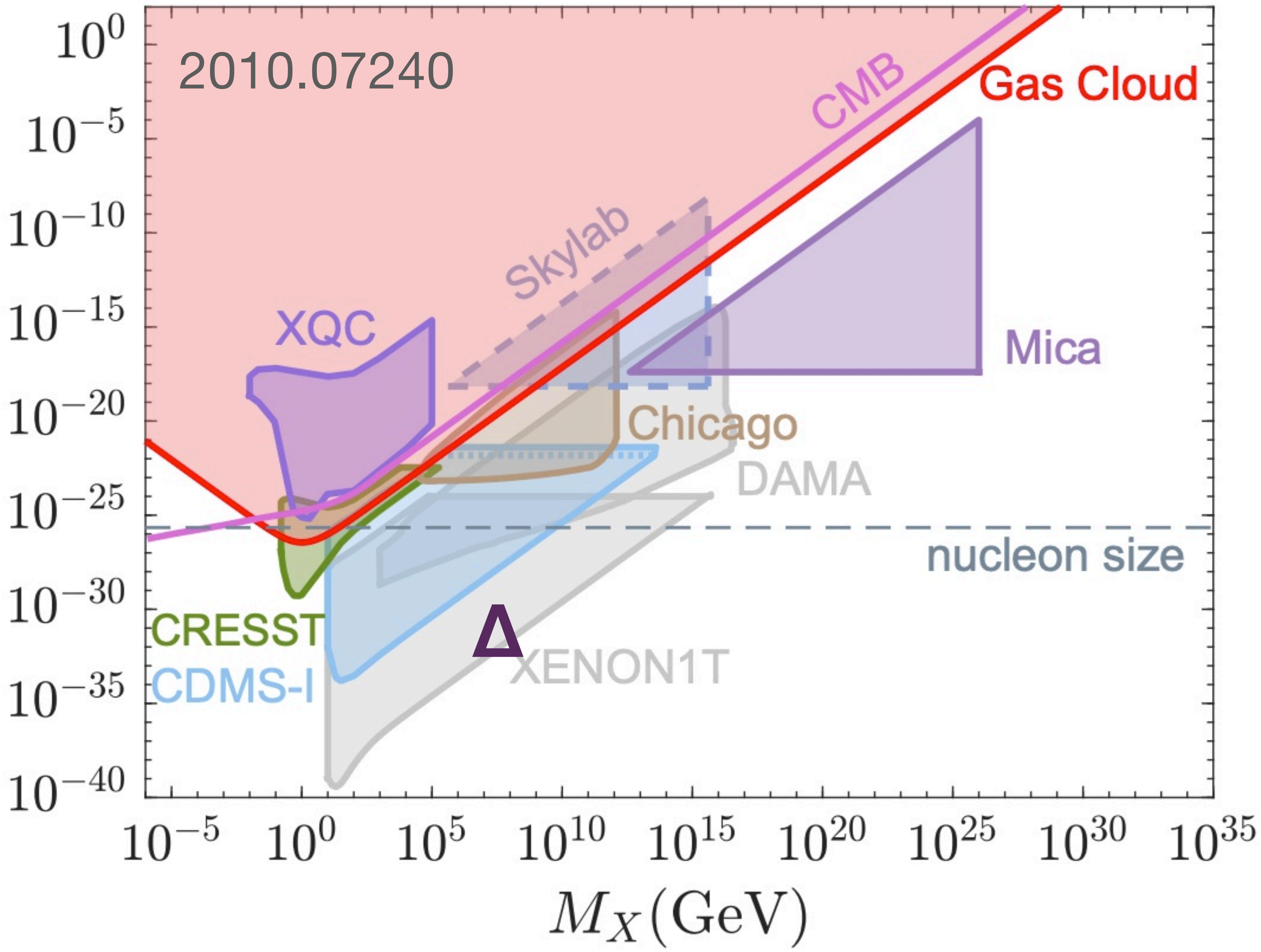

Light dark matter




Axion/ DP (wavy bosons)



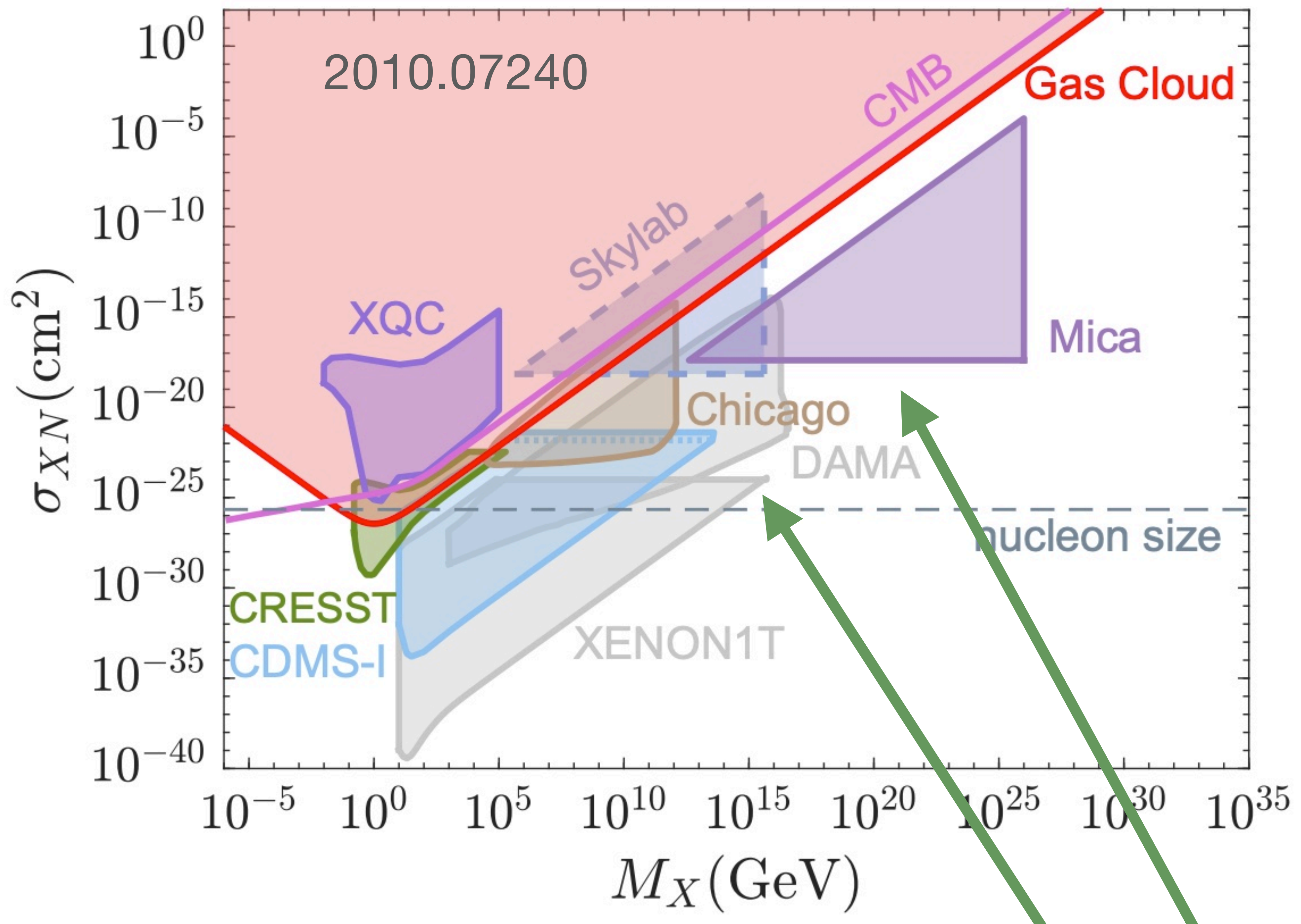

Δσ relative to last generation



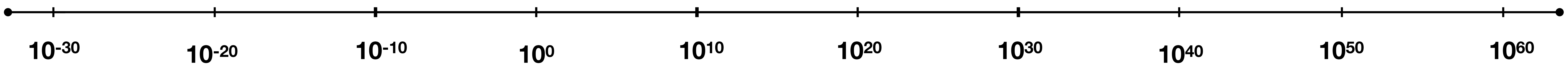

$10^{-30}$ $10^{-20}$ $10^{-10}$ $10^{0}$ $10^{10}$ $10^{20}$ $10^{30}$ $10^{40}$ $10^{50}$ $10^{60}$

$m_x$ (GeV)

# HEAVY DARK MATTER




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




$m_x$ (GeV)

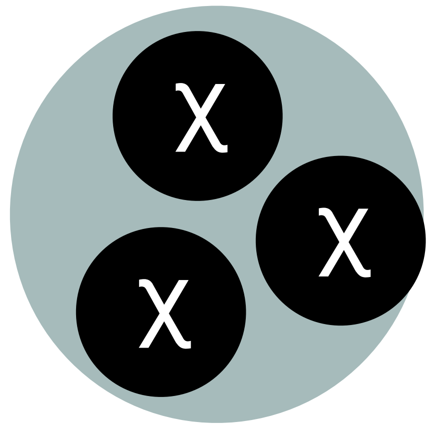
- $\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$

# DM Models

*Vis-a-vis heavy composite DM*

Nice to have a model

- Early matter domination
- Boson stars

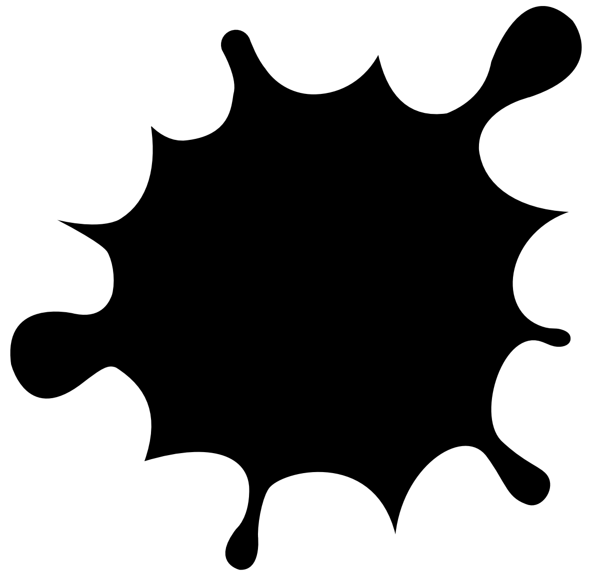




- Q ball
- Dark QCD/BBN
- Molecular DM

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

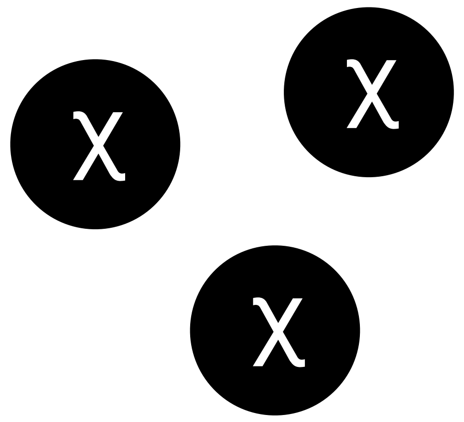


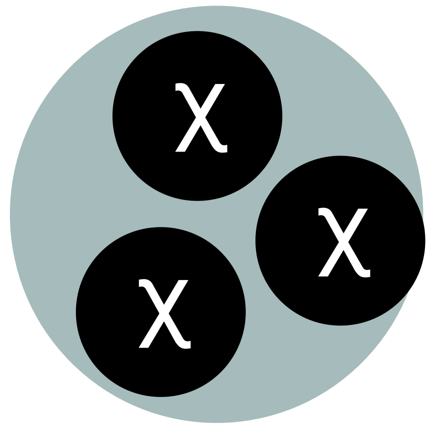
Predict masses from 1st principl

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

# DM Models

*Vis-a-vis heavy composite DM*

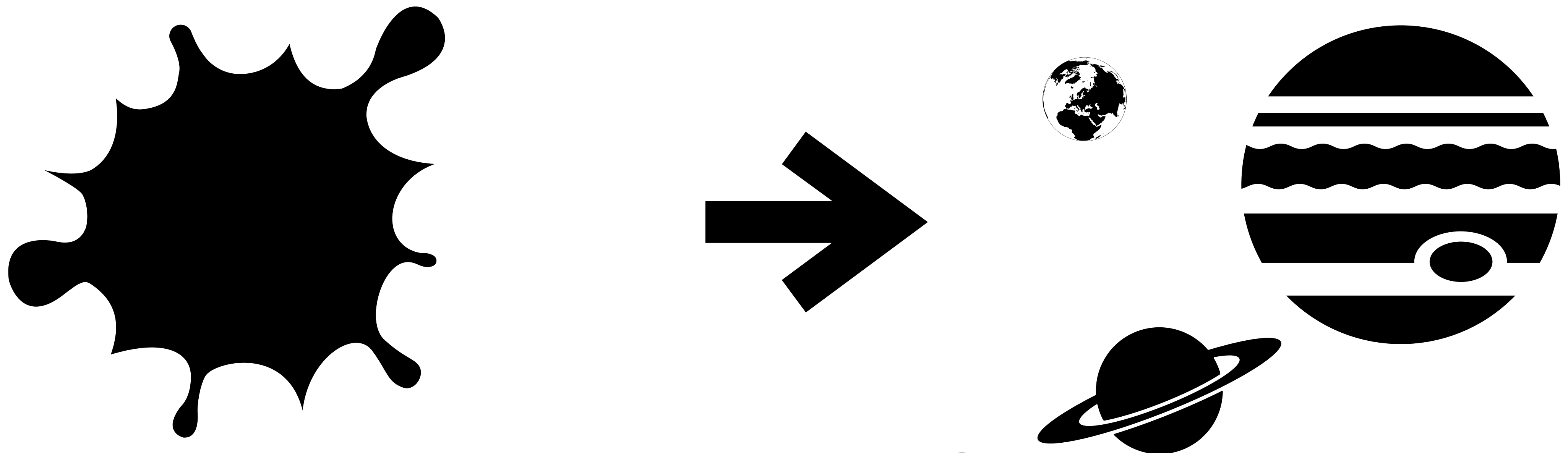



Nice to have a model

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

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



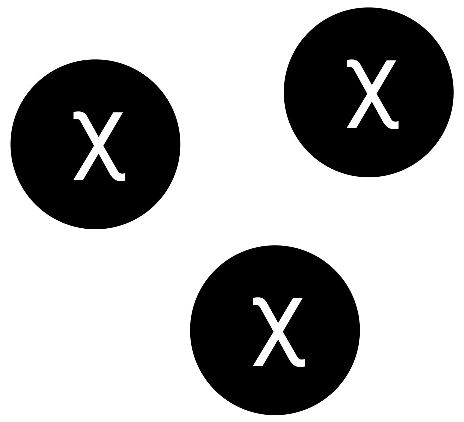
Predict masses from 1st principles?

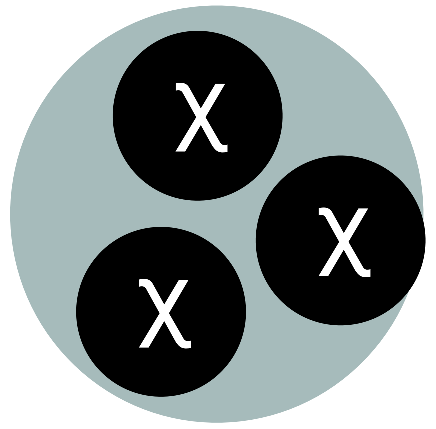
- Planet formation still has open questions (e.g. pebble accretion).
- Heavy composite DM doesn't have simple dynamics like single-field DM models

# DM Models

*Vis-a-vis heavy composite DM*

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



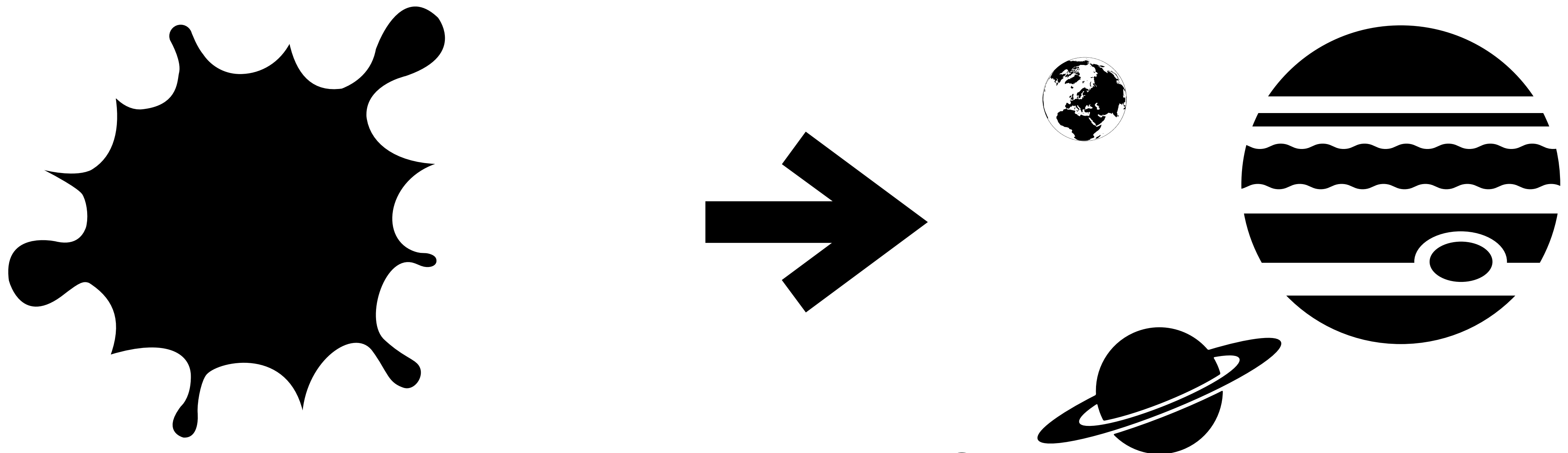




Nice to have a model

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

Perhaps the least explored of these.

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

if given multiple guesses, five decades of mass and model

1.

2.

3.


Alien Game Show
Win spaceships!

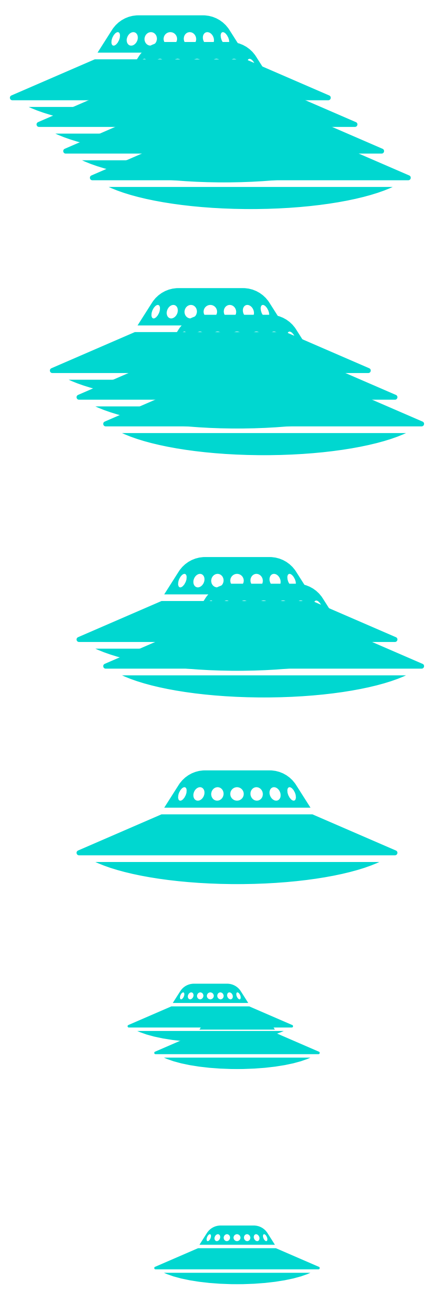
# DM Models

| 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% |

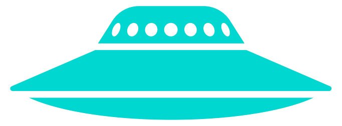

Alien Game Show
Win spaceships!

# DM Models

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




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

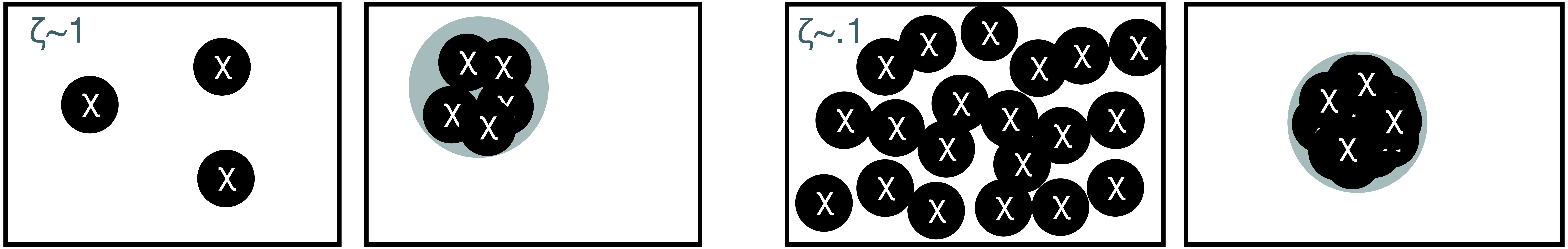
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

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

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

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

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

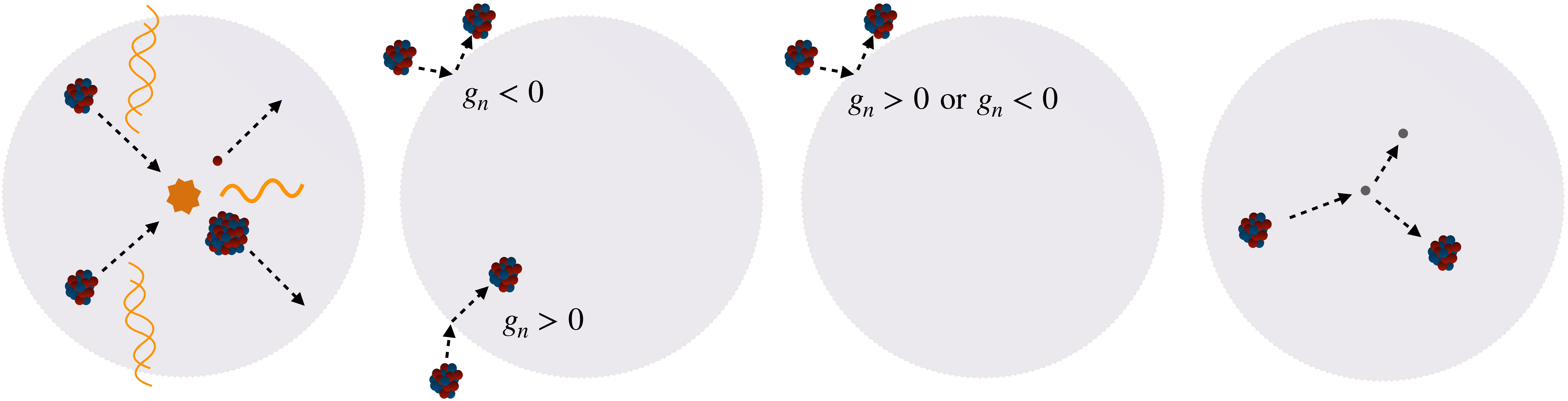
# COMPOSITE INTERACTIONS

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

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

<u>scattering with constituents</u>

1. 2. 3. 4.




1. $\langle\varphi\rangle \lesssim m_N$, $g_n > 0$ — Acevedo, JB, Goodman 2012.10998
2. $\langle\varphi\rangle \ll m_N$
3. $\langle\varphi\rangle > m_N$ **(MIMPs)**

Acevedo, JB, Goodman 2108.10899

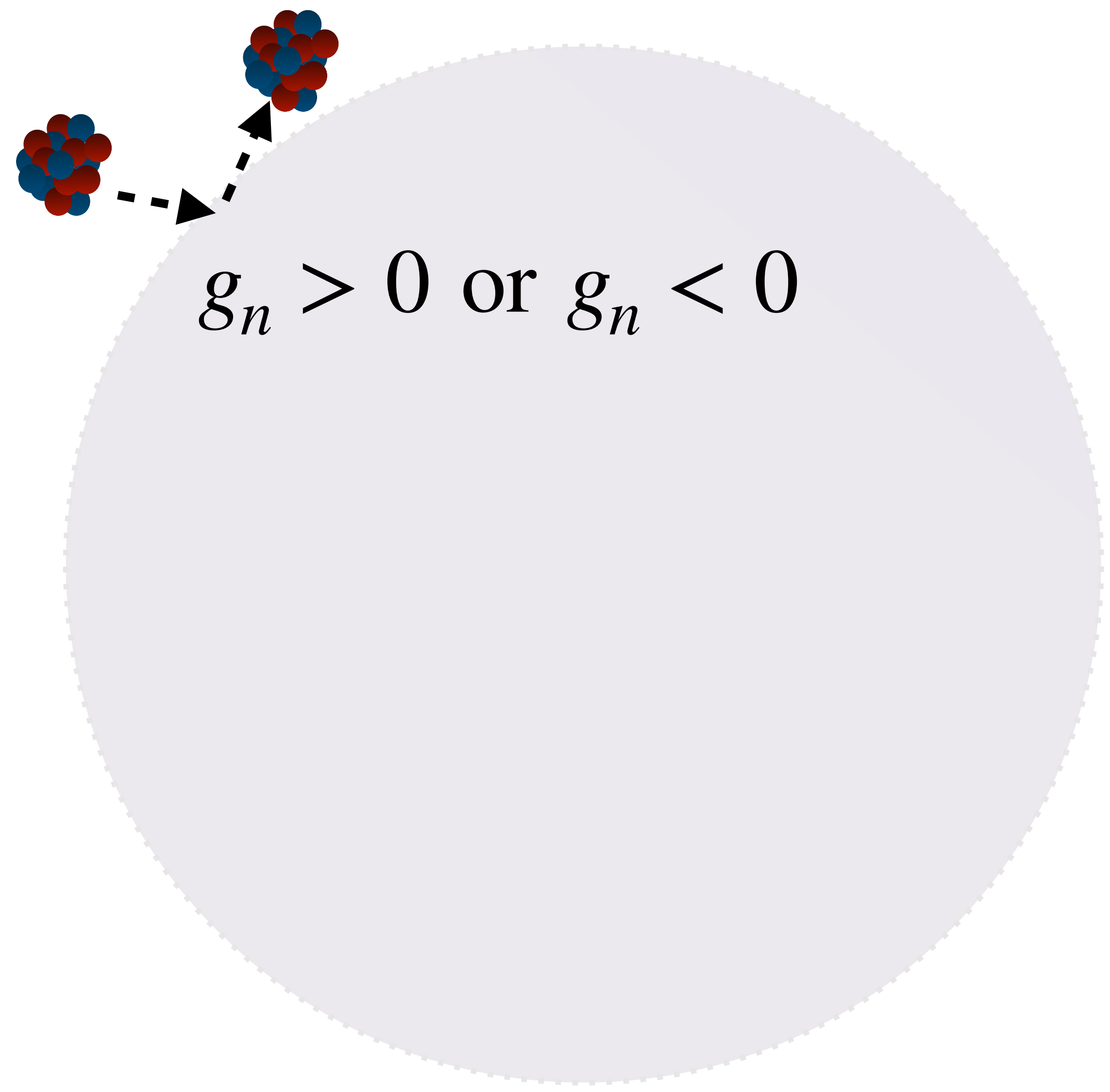
4. Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Sheahan, Tyagi, in progress

# MULTISCATTER 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>




$\langle\varphi\rangle > m_N$

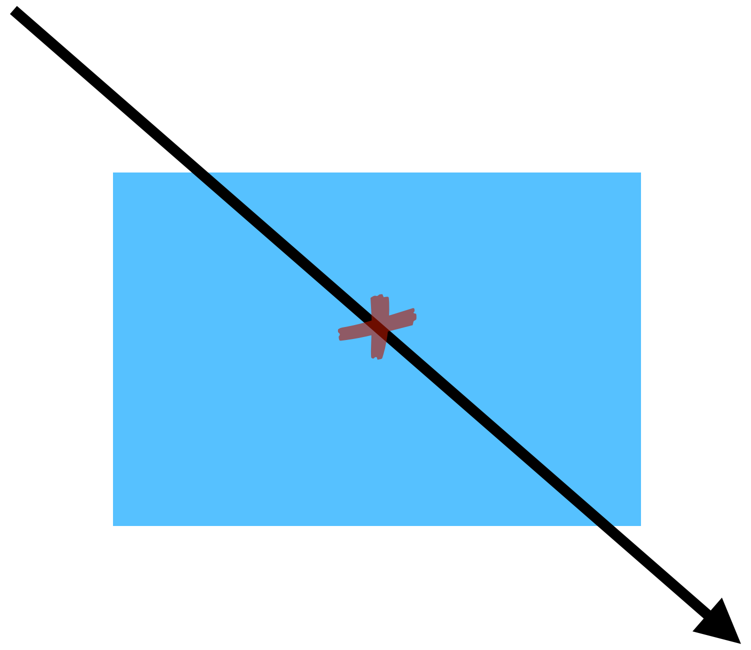
**(MIMPs)**

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



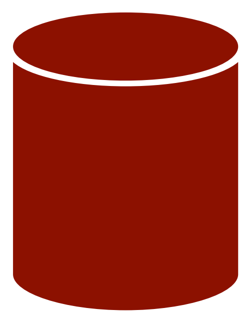
- If particles have velocity v (~0.001c), then sensitivity of detector sets a minimum energy threshold for detection

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

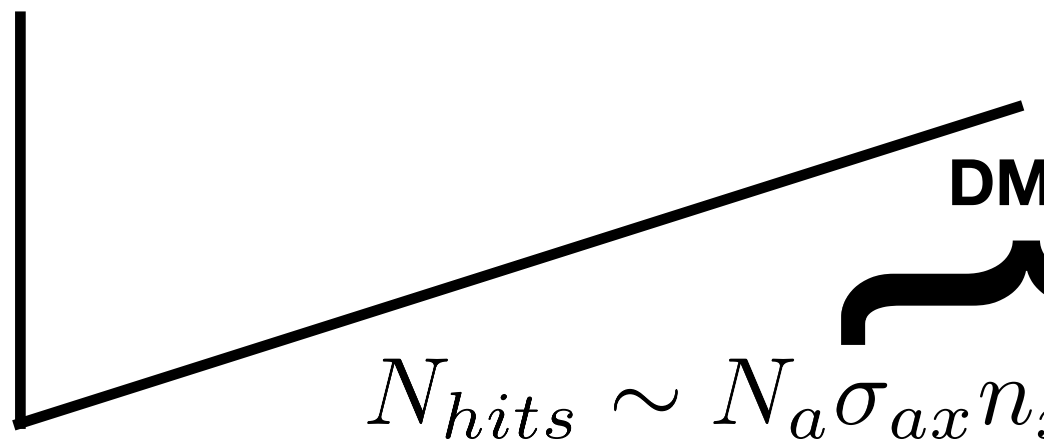
**cross-section for DM to hit detector particle**

**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 $1/m_x$



DM hits per atom

$$N_{hits} \sim N_a \underbrace{\sigma_{ax} n_x v_x t}$$

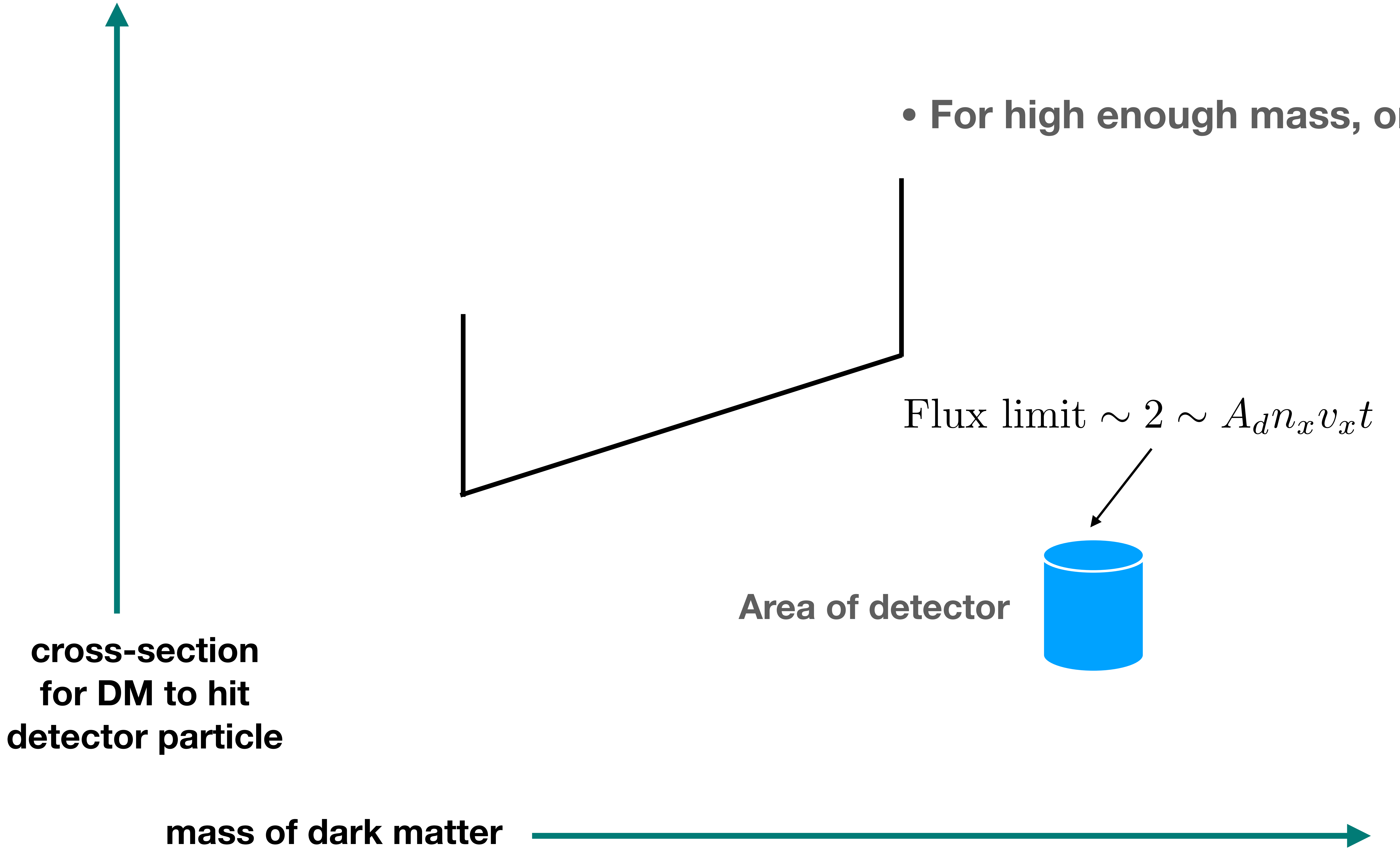
DM number density $\rho_x / m_x$

cross-section for DM to hit detector particle

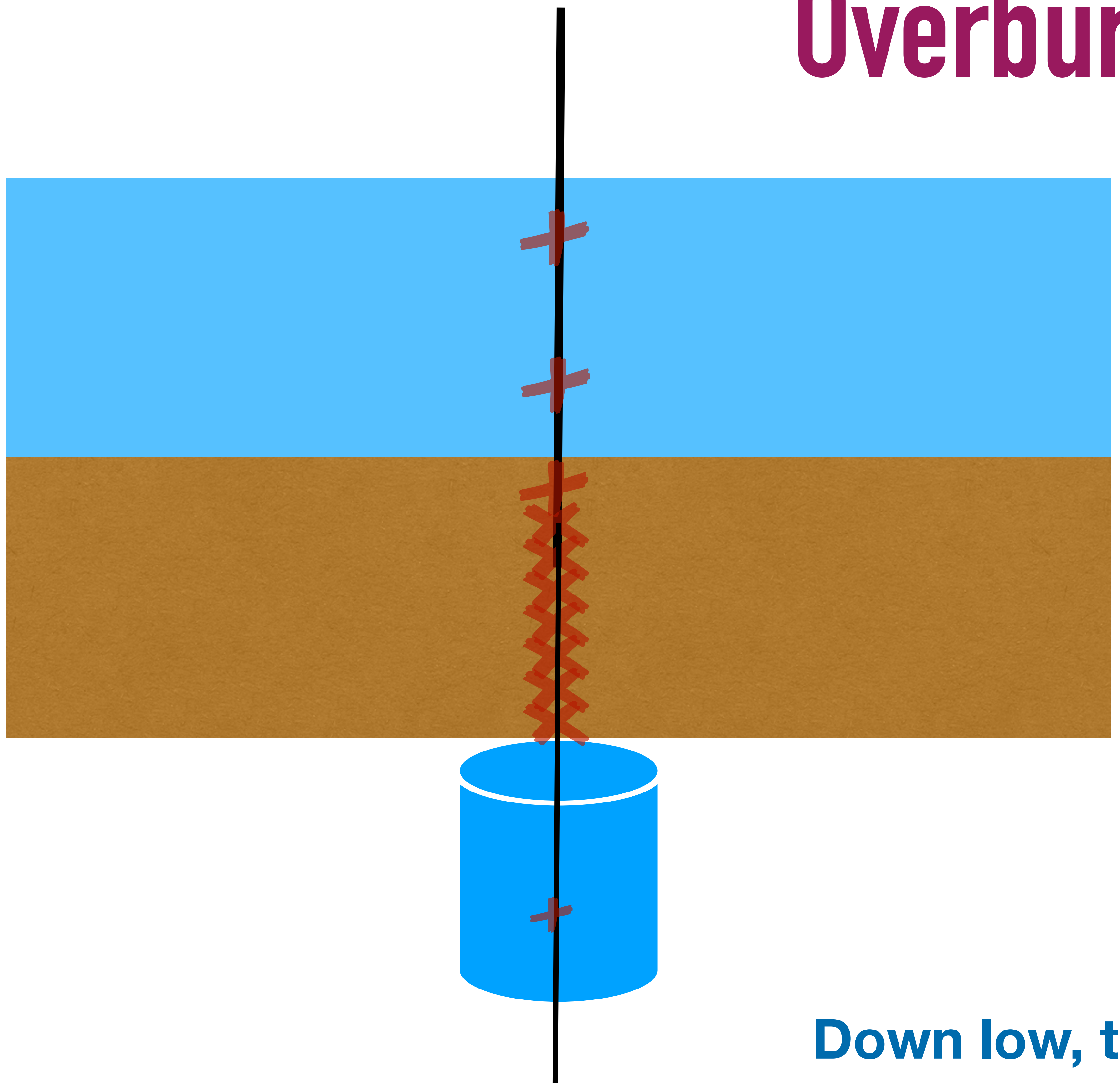
mass of dark matter

# 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.

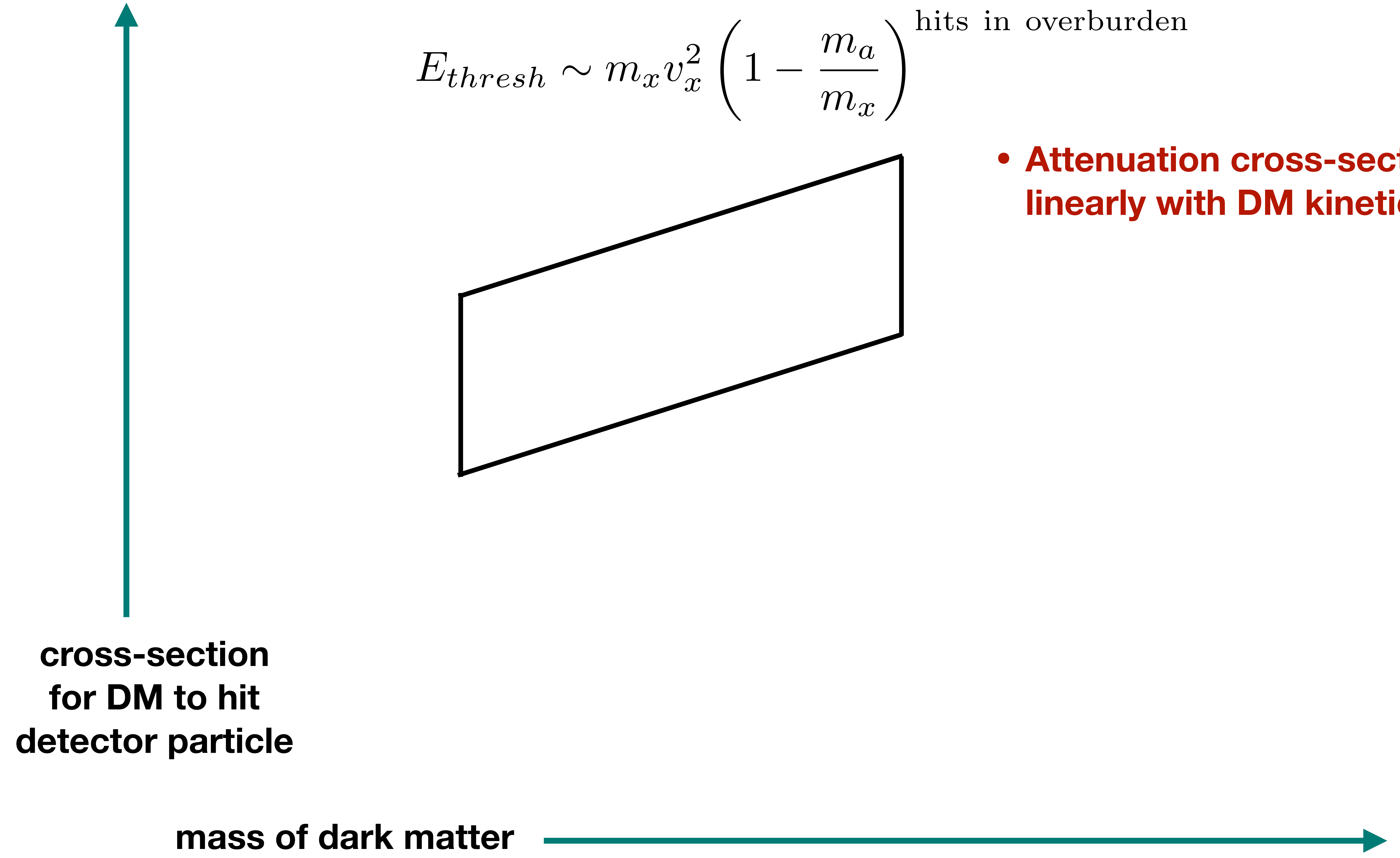
Down low, too slow?

Length of overburden

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

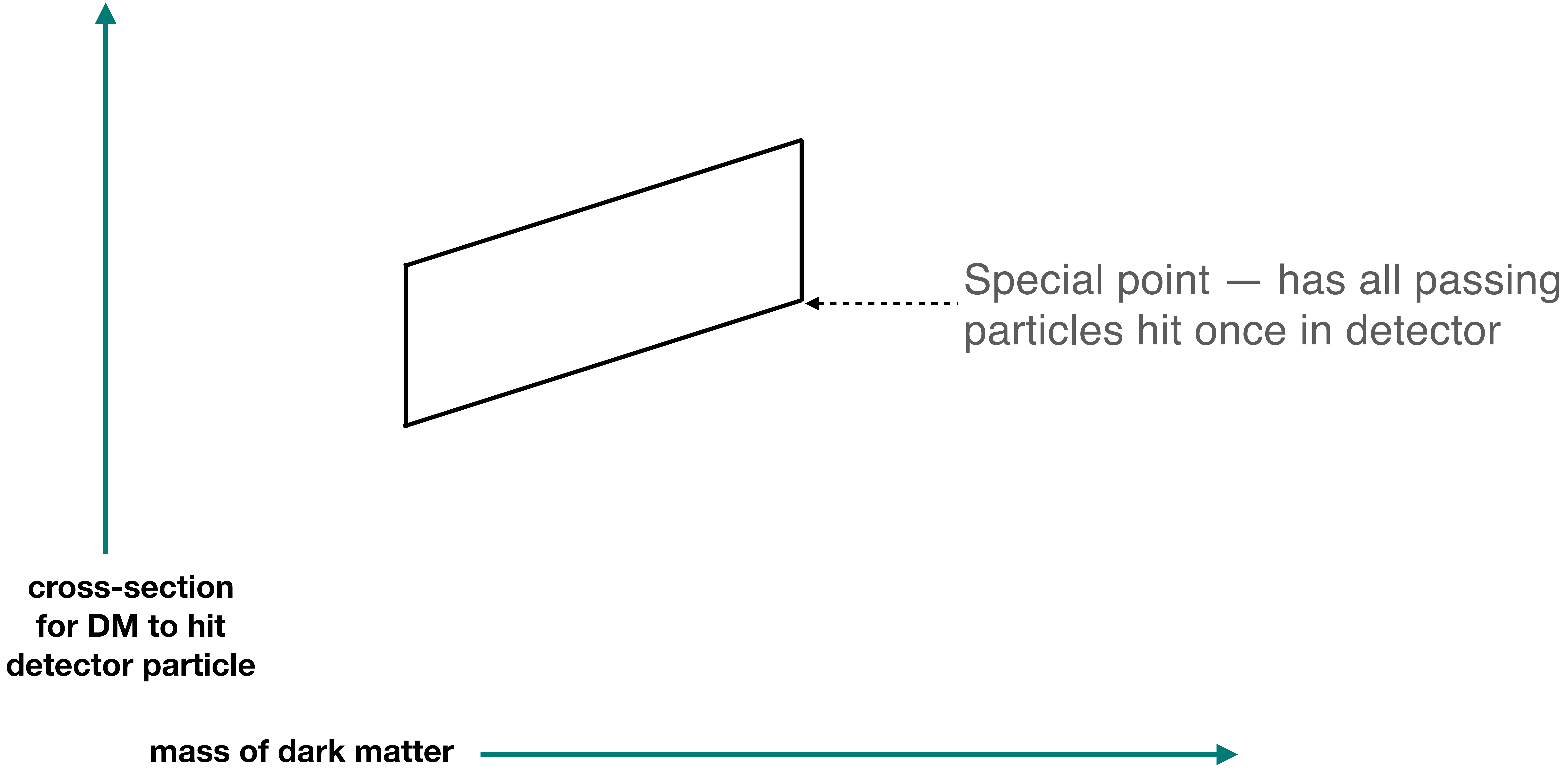
# EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

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

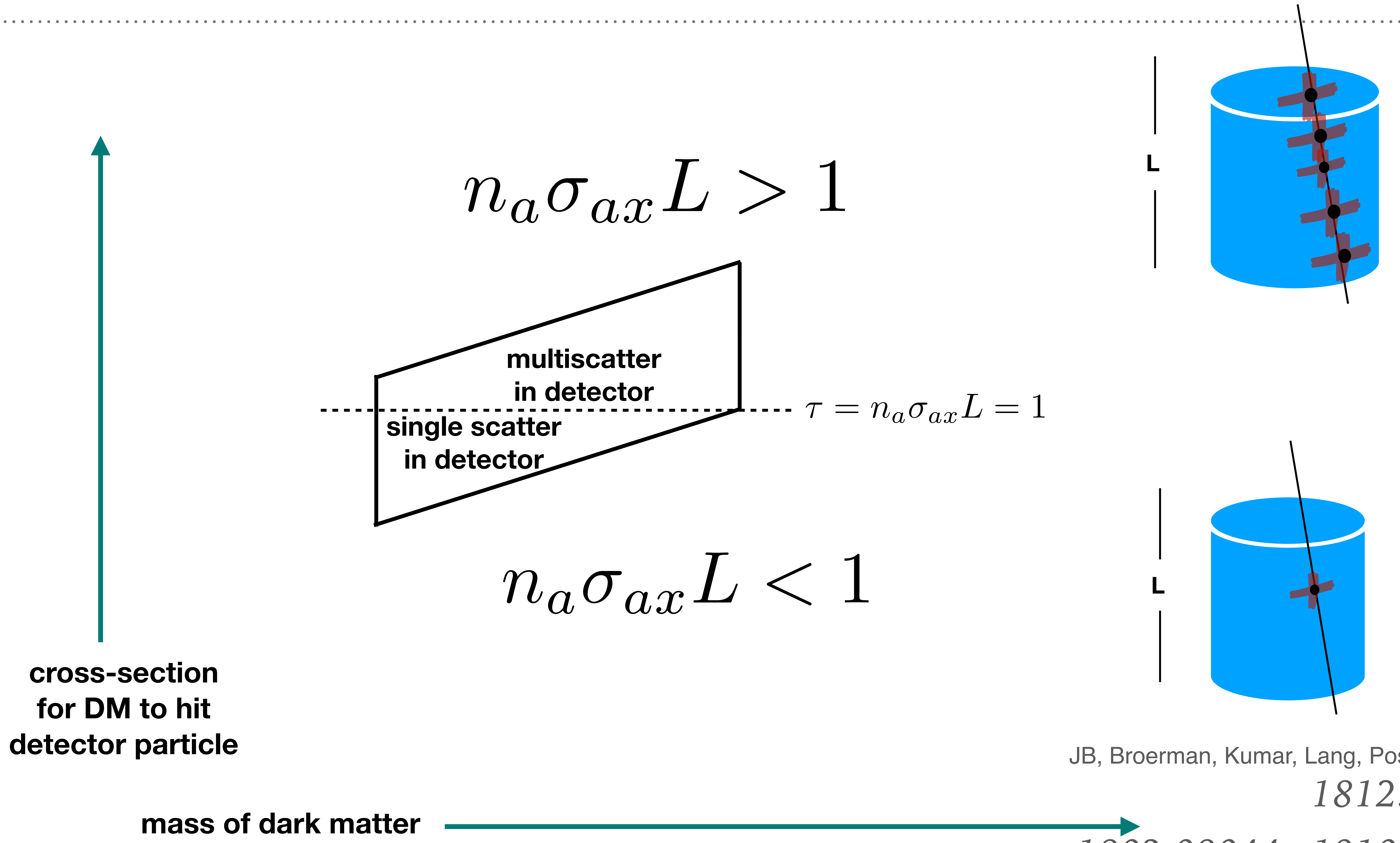



- **Attenuation cross-section increases linearly with DM kinetic energy ~$m_x v_x^2$**

# EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



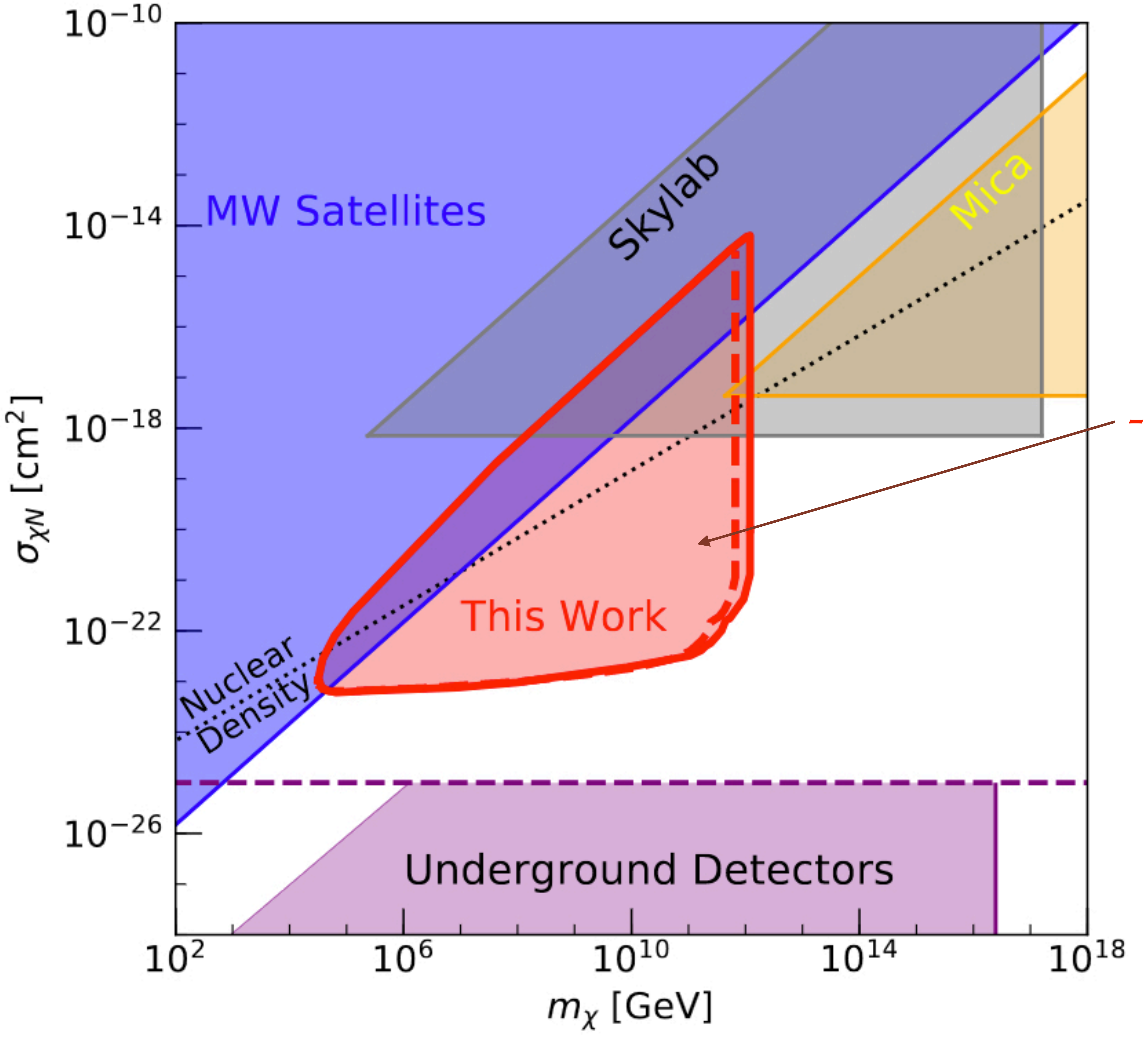
# MULTISCATTER DARK MATTER DETECTION




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

# ETCHING PLASTIC SEARCHES FOR DARK MATTER

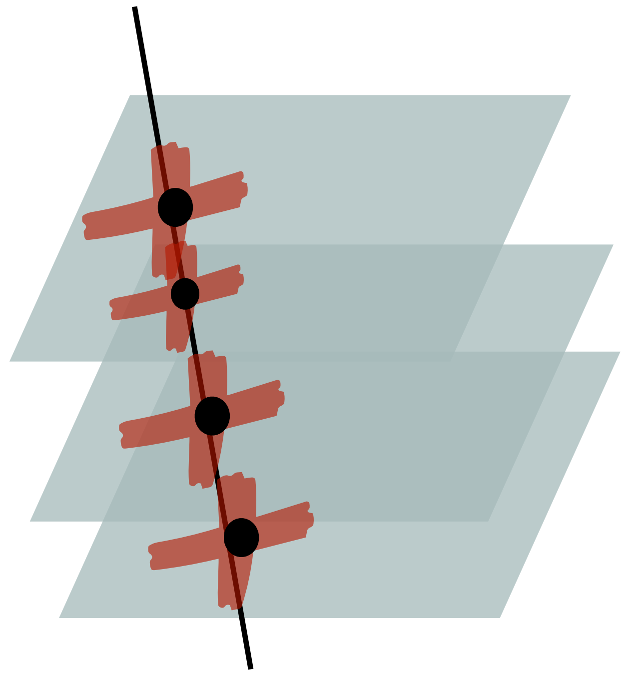
- *Two searches in 1978 and 1990 for cosmic rays and monopoles using acid-etched plastic track detectors*
- *Still have best sensitivity for some high mass dark matter, for different reasons*

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 $\times$ 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 $\theta_D$ | 1.6 cm | 0.66 cm |
| Overburden density | 2.7 g cm$^{-3}$ Aluminum | 2.7 g cm$^{-3}$ Rock |
| Overburden length at $\theta_D$ | 0.74 cm | 39 m |

Bhoonah, JB, Courtman, Song
2012.13406

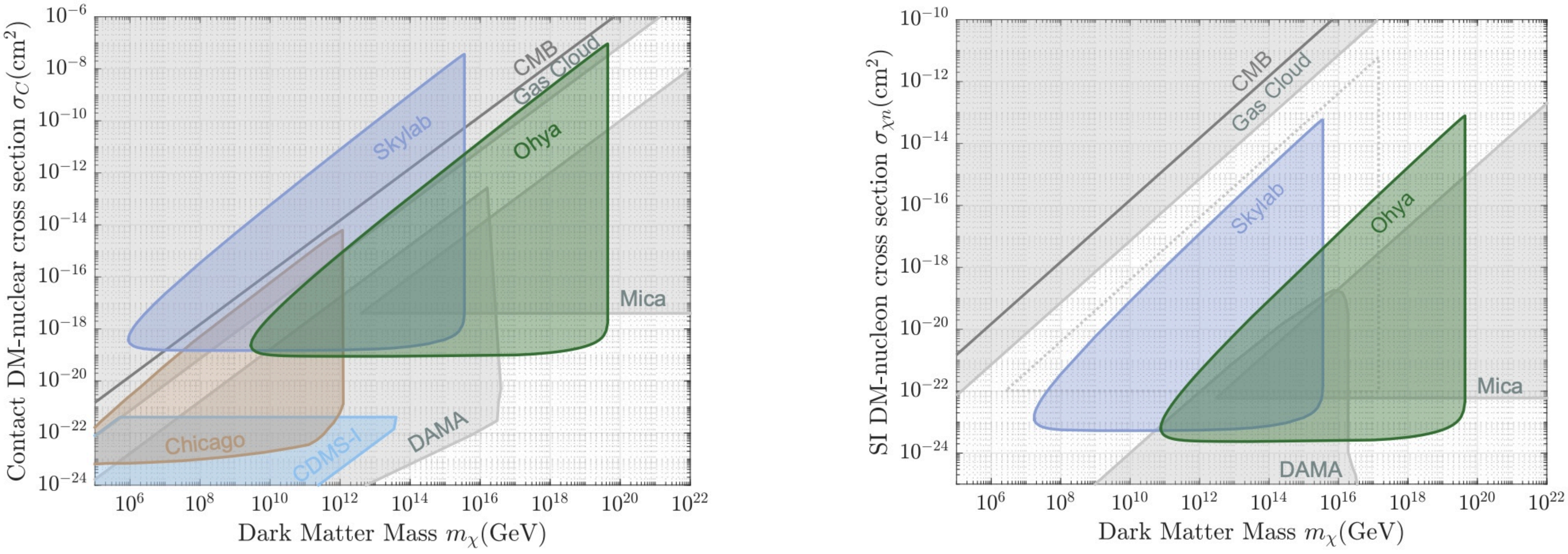


Ohya Quarry

# 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

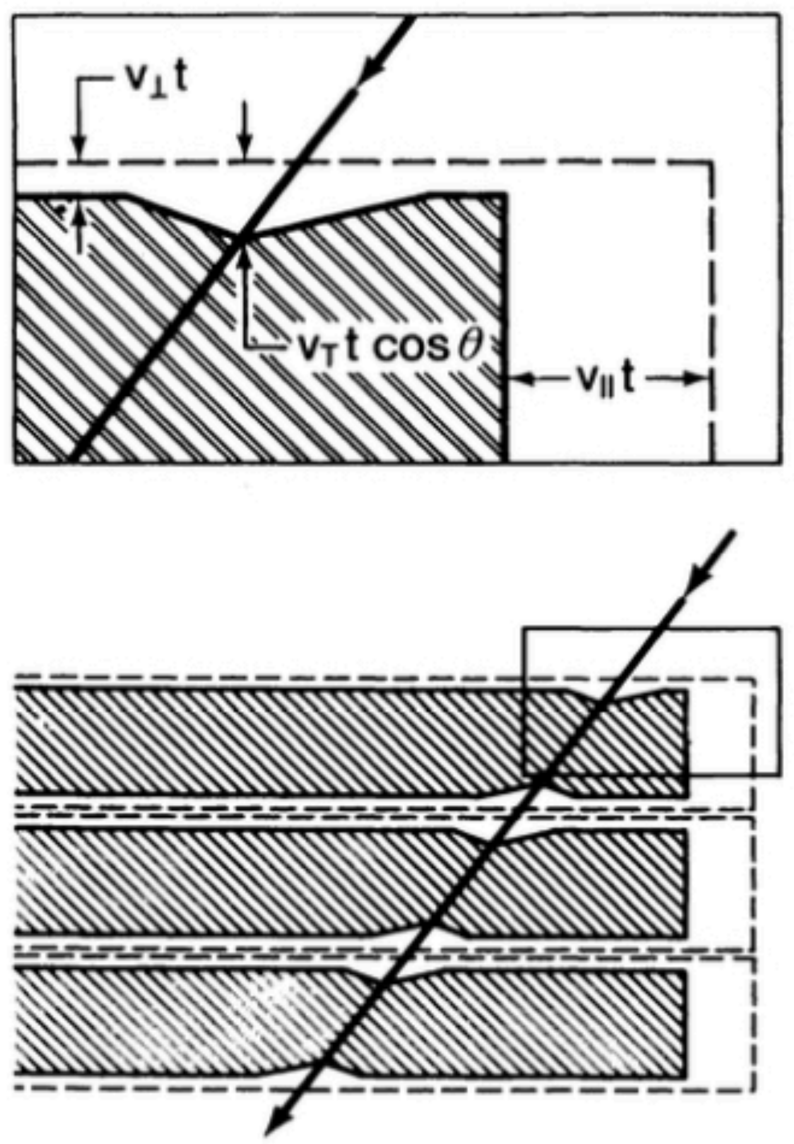
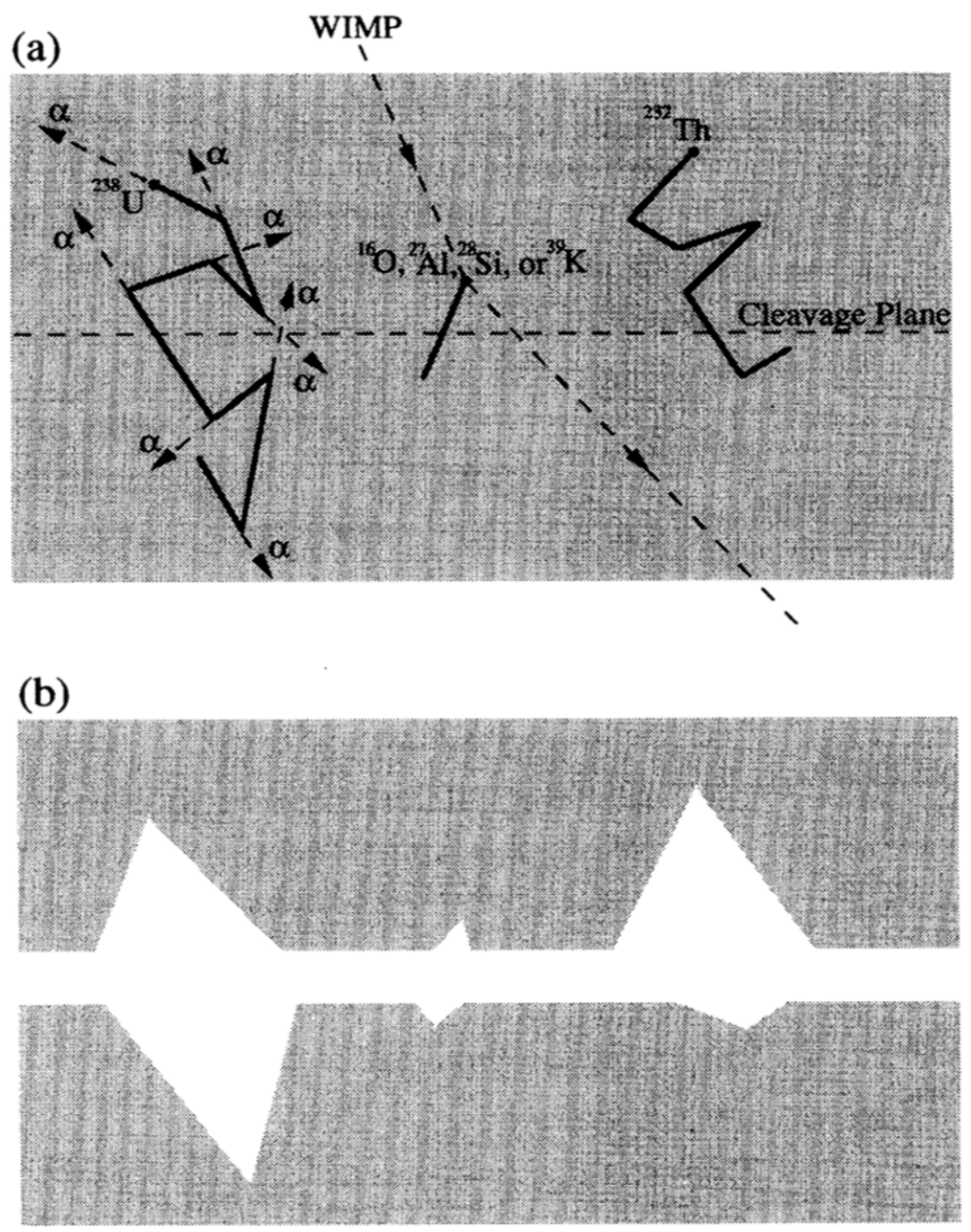
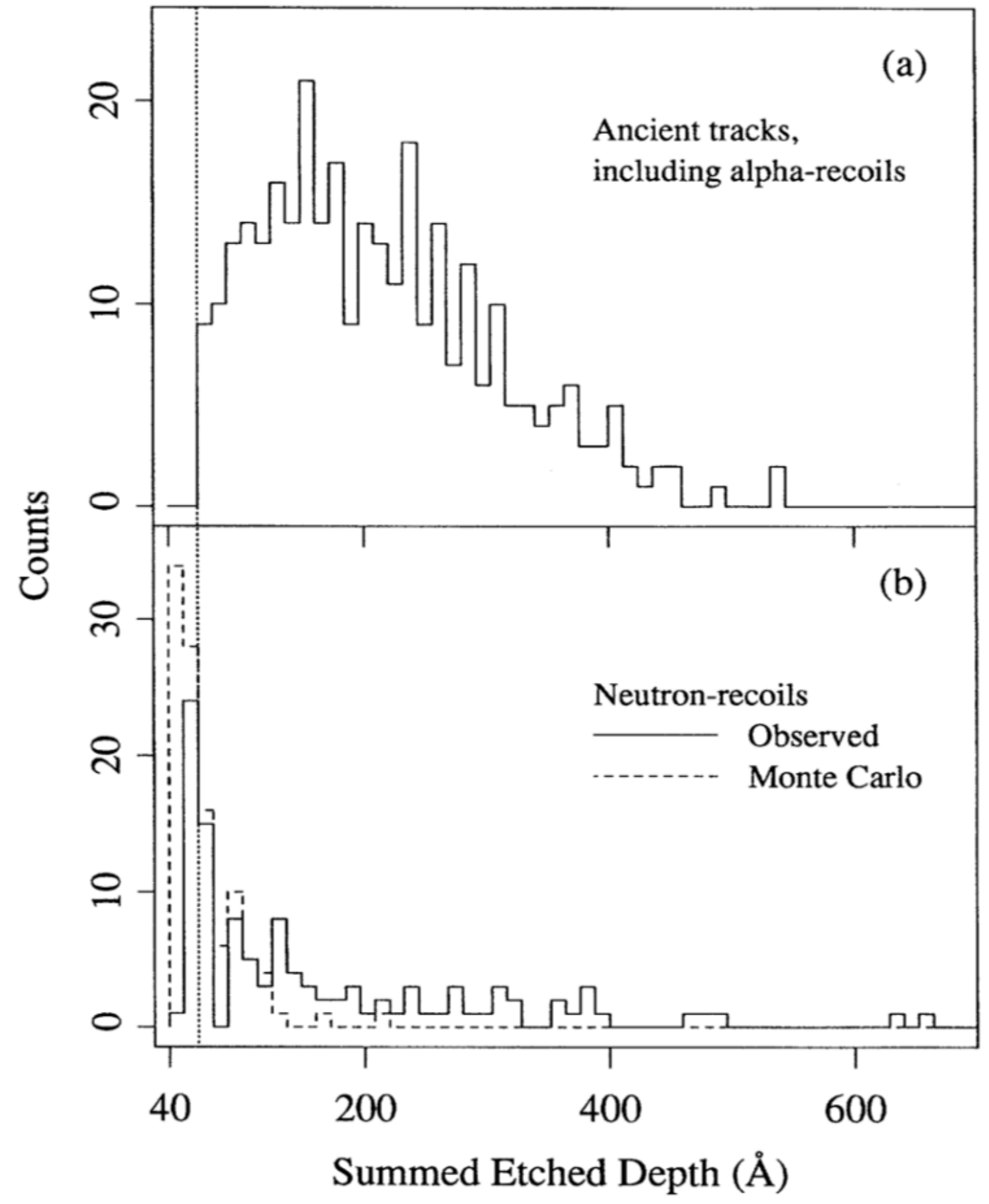


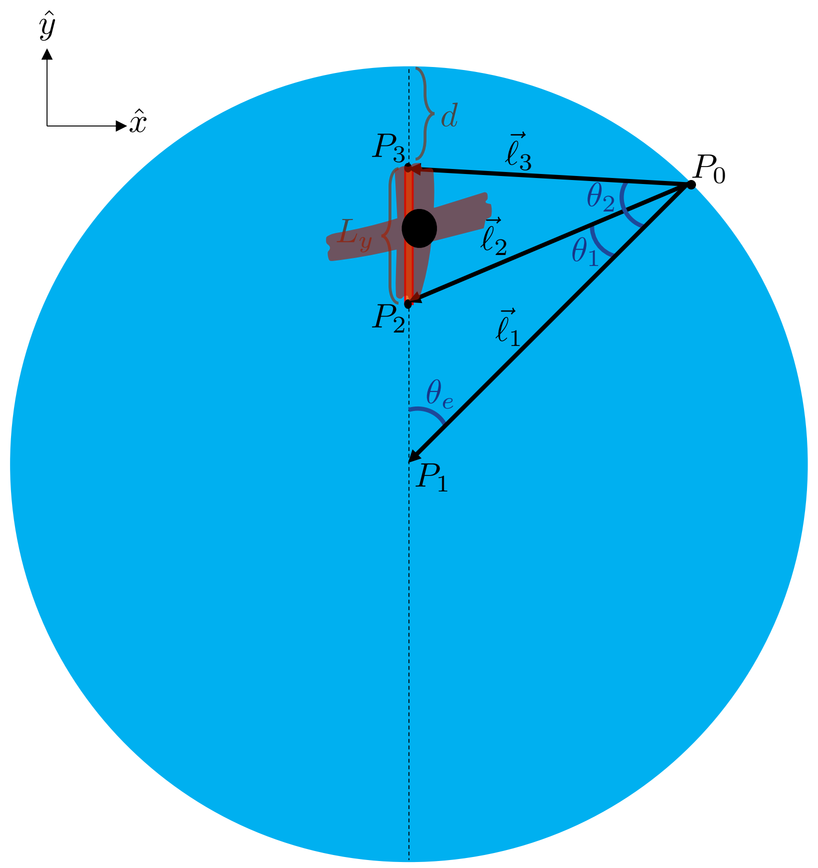

FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.




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

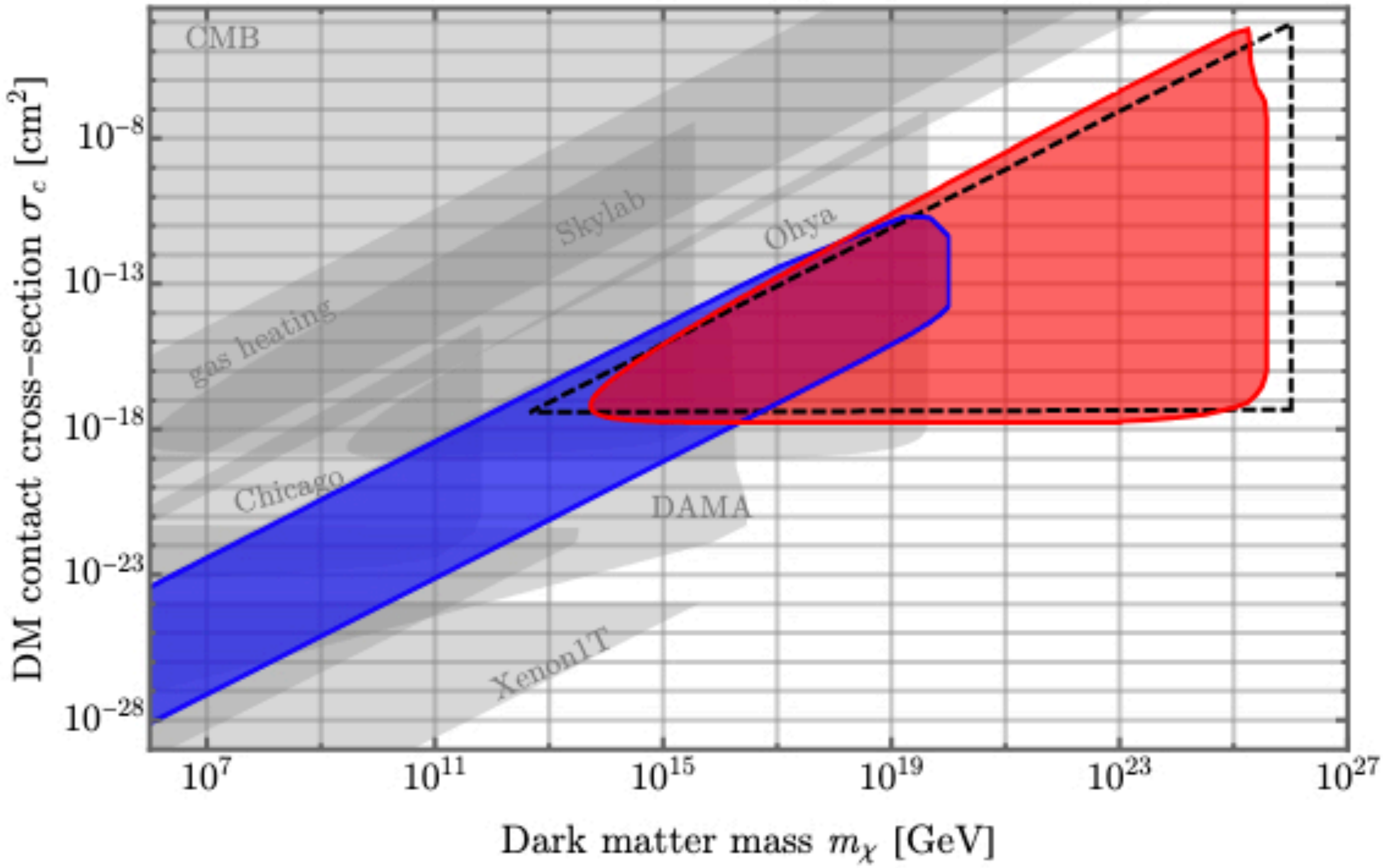
# ANCIENT SEARCH FOR NEW PARTICLES: MICA




- 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

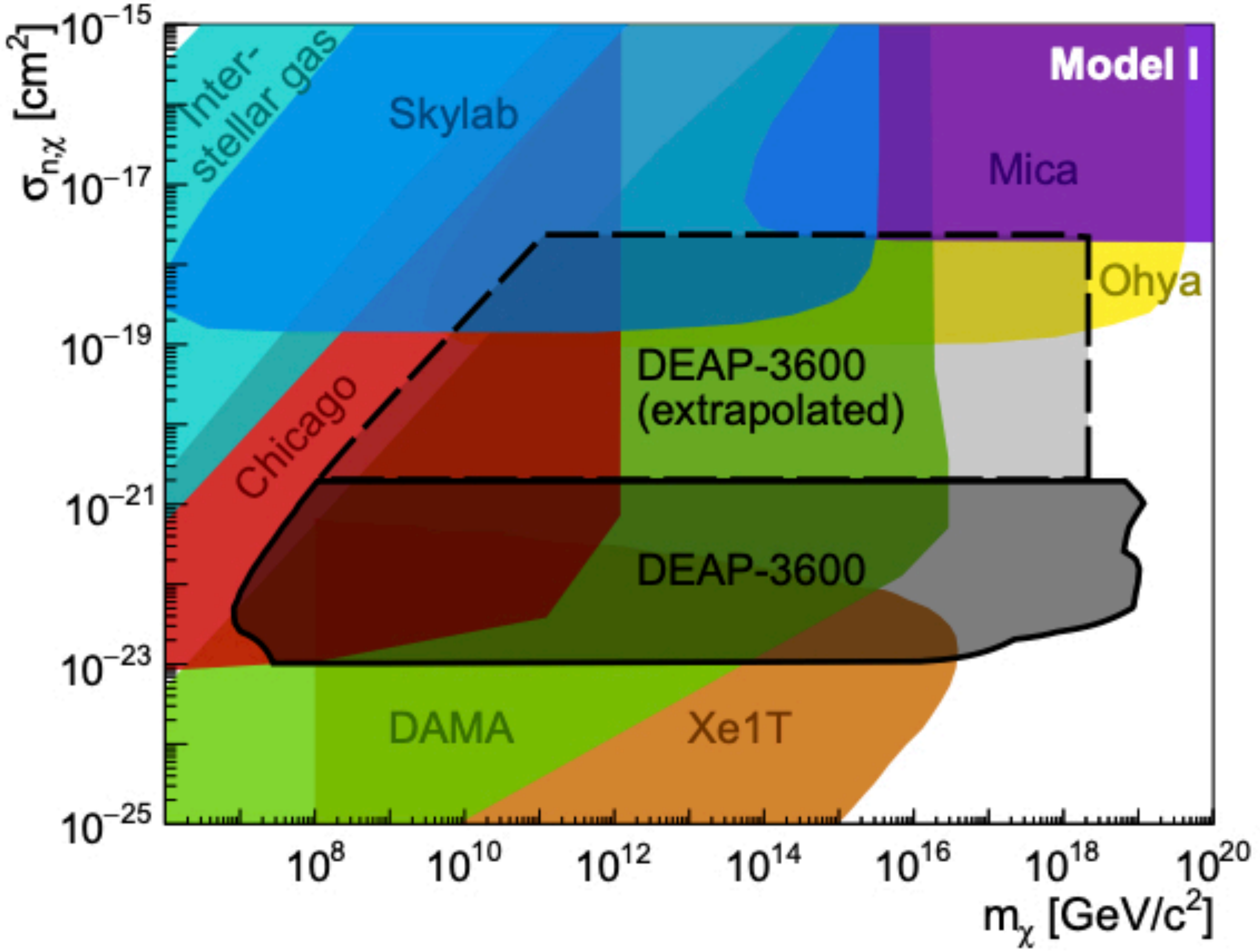



Also a mineral DM detection collaboration at Queen's

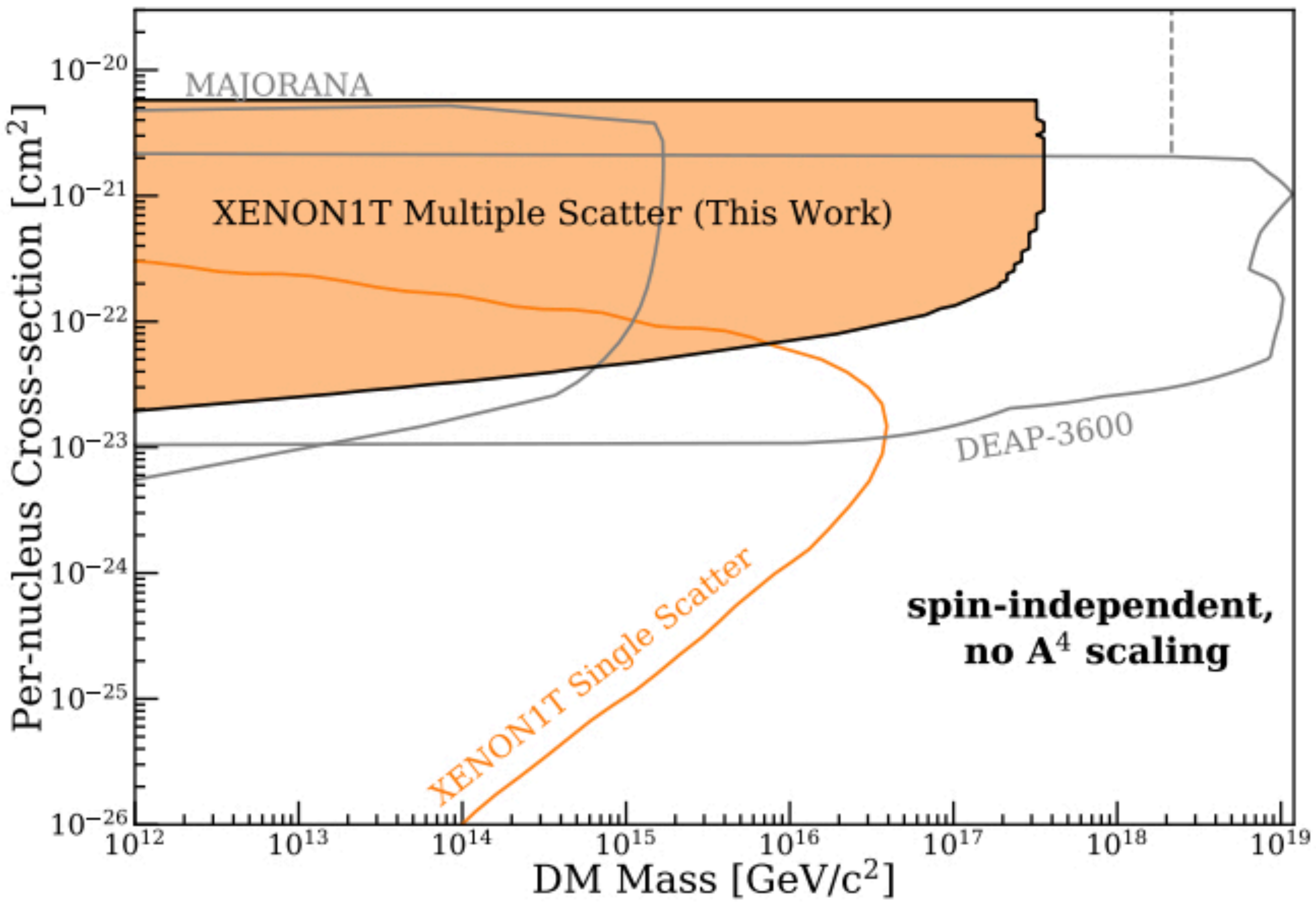
Balogh, Boukhtouchen, JB, Fung, Leybourne, Lucas, Mkhonto, Vincent

See e.g. recent whitepaper: 2301.07118

# HEAVY MIMP RESULTS FROM DEAP-3600, XENON1T

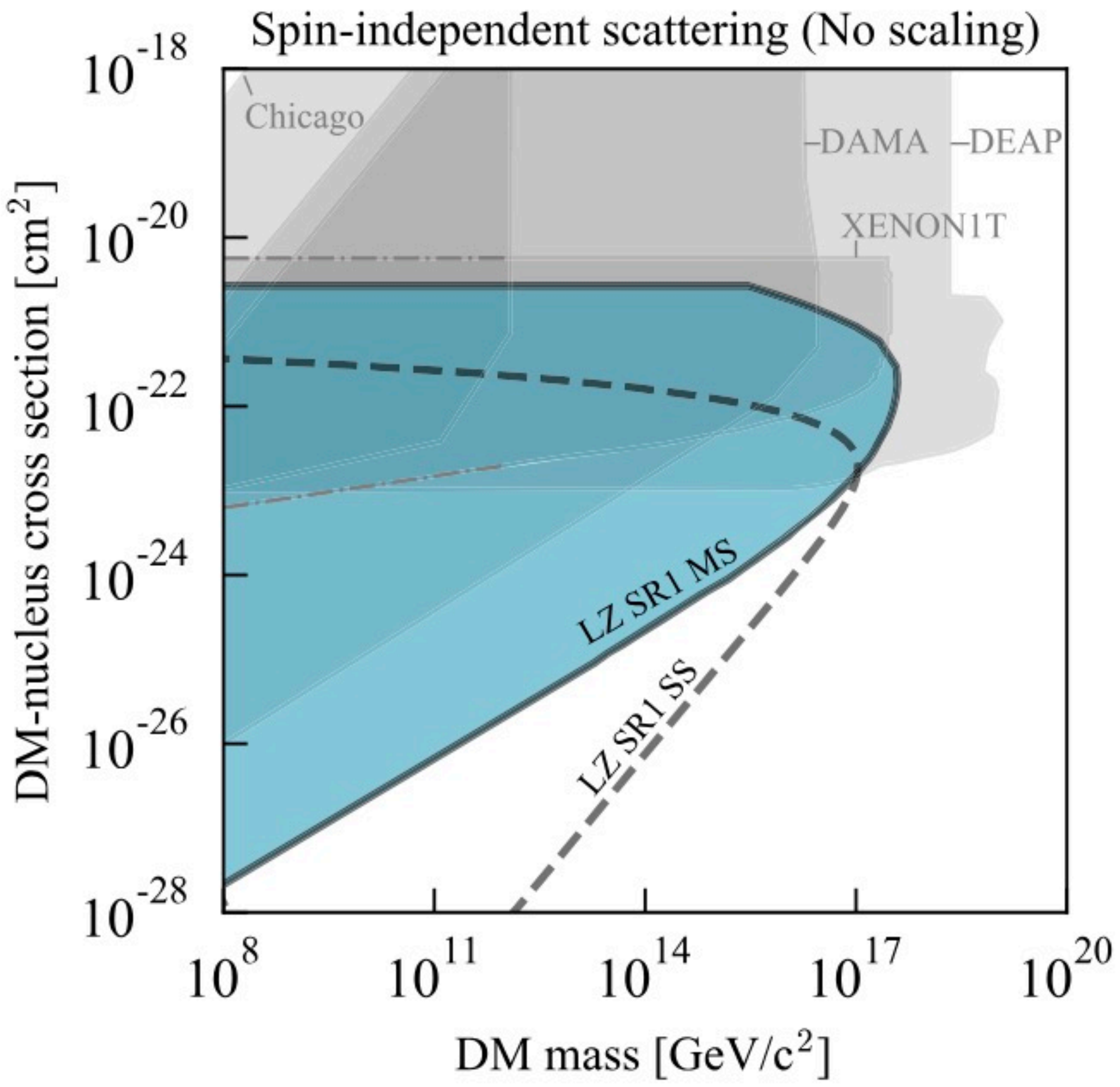



2108.09405

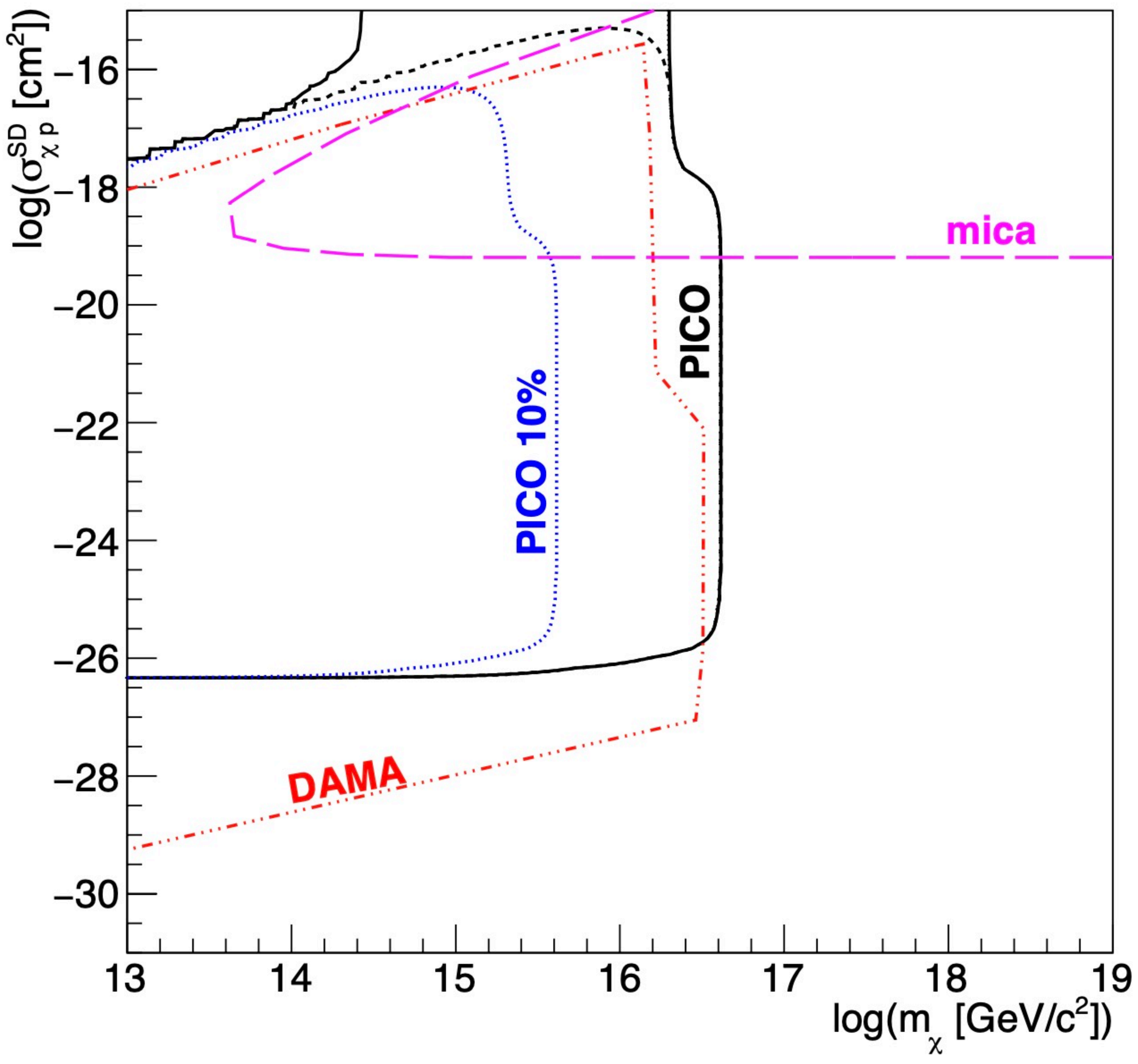



2304.10931

# HEAVY MIMP RESULTS FROM LZ, PICO-60




2402.08865




PICO-60, 2022 (Broerman PhD thesis)

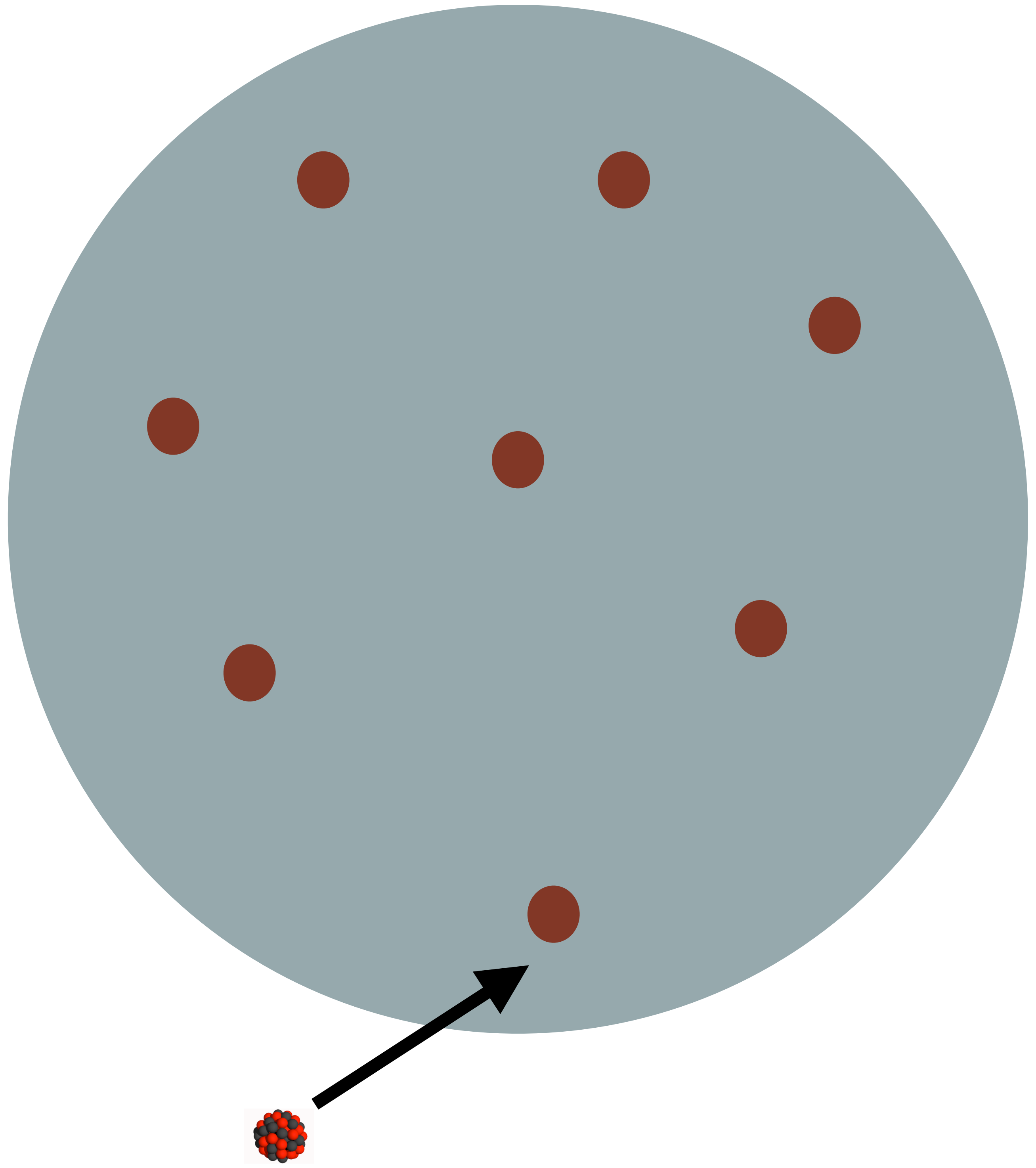
What kind of dark matter produces SD interactions at this mass?

# 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

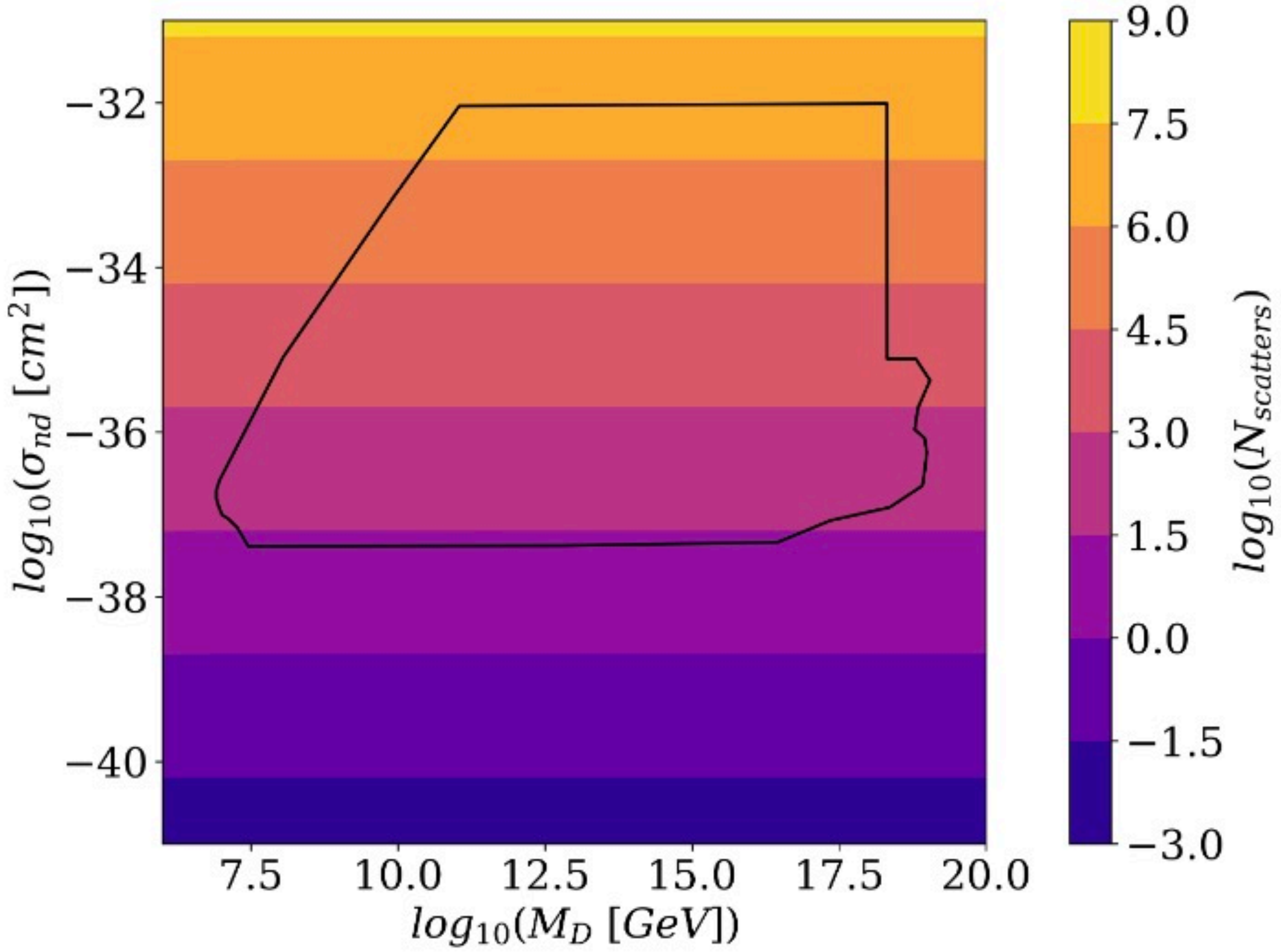


# LOOSELY BOUND COMPOSITES

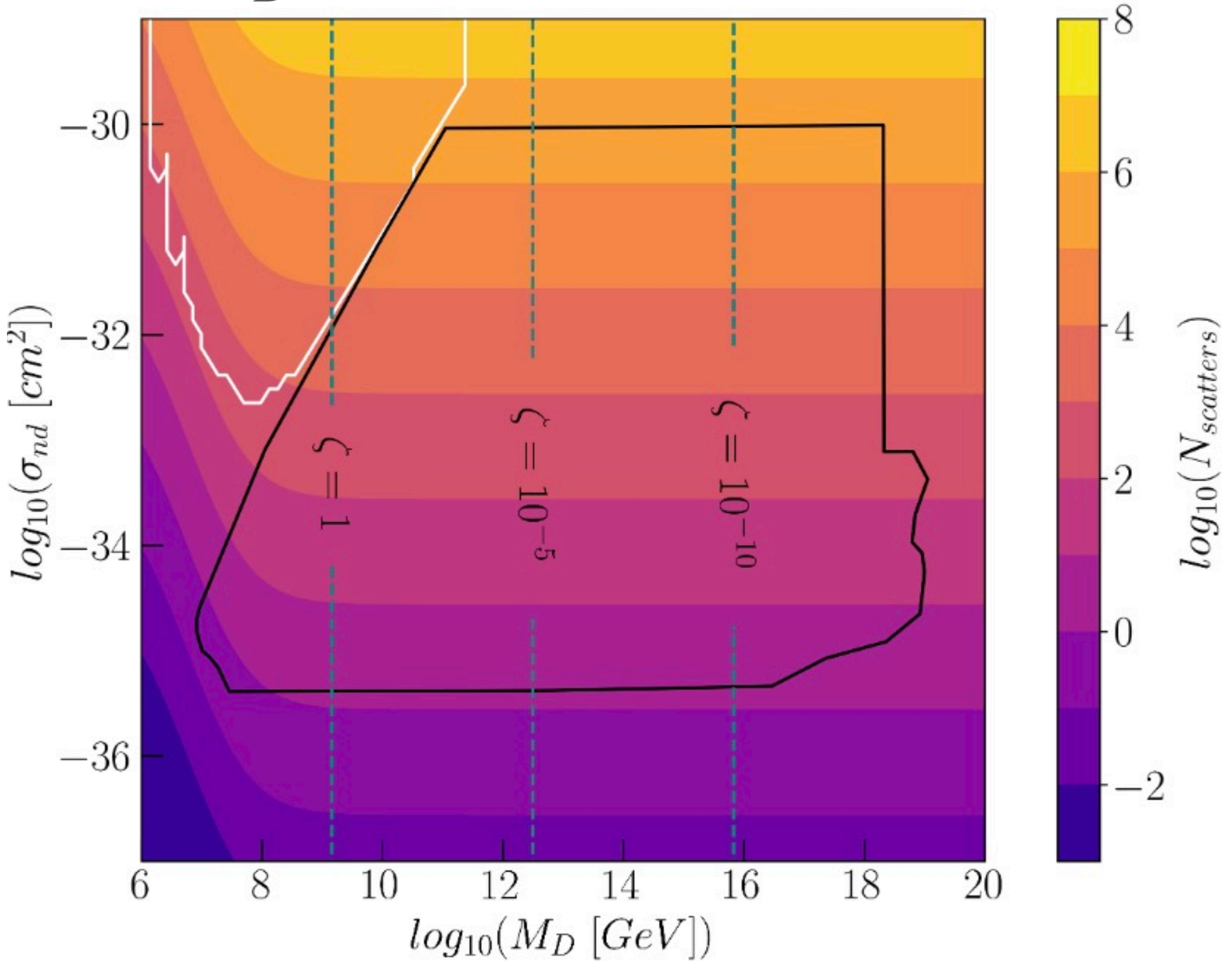
Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Tyagi 2408.03983

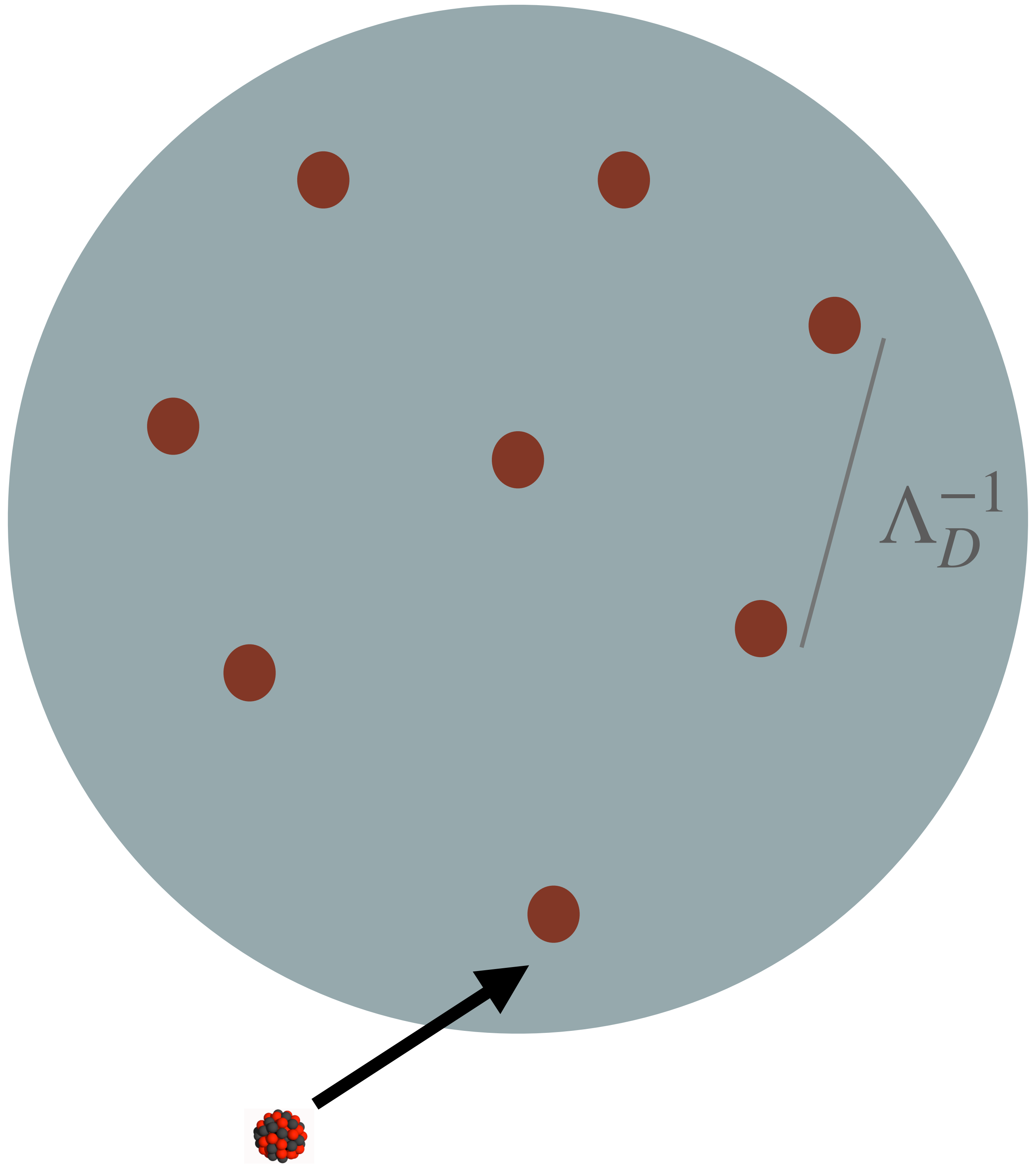
$m_d > \Lambda_D > E_B^{(dark)}$

assume A⁴



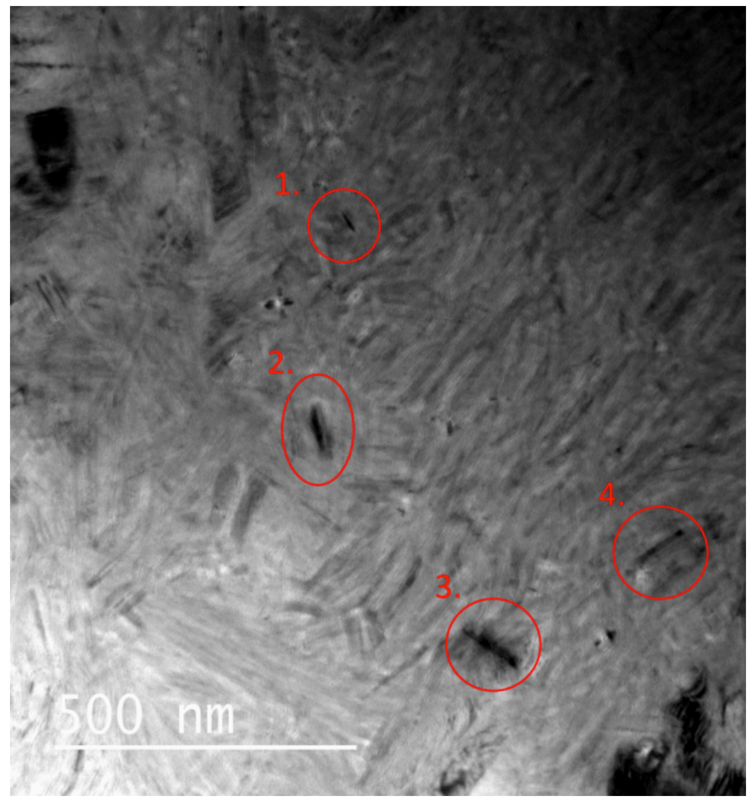

$\Lambda_D = 1\ \mathrm{MeV}$ ~A⁴



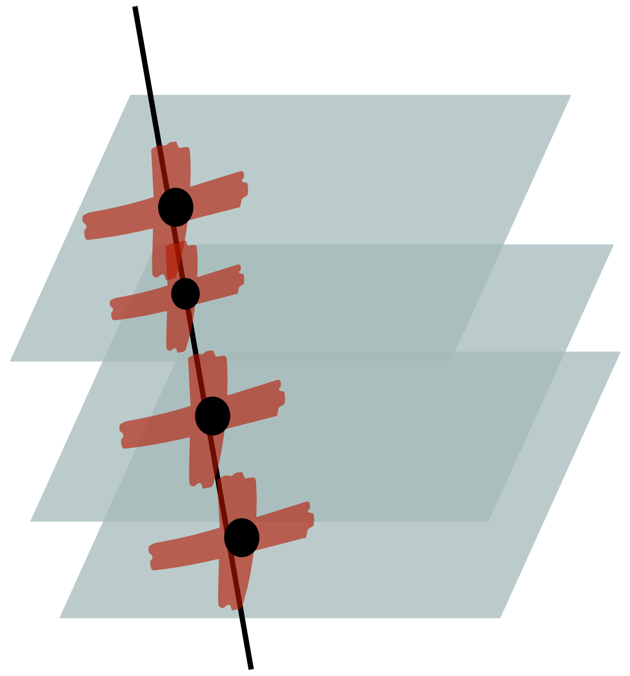

- DM-nuclear scattering cross sections that scales with ~$A^4$ for larger than nuclear cross sections

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

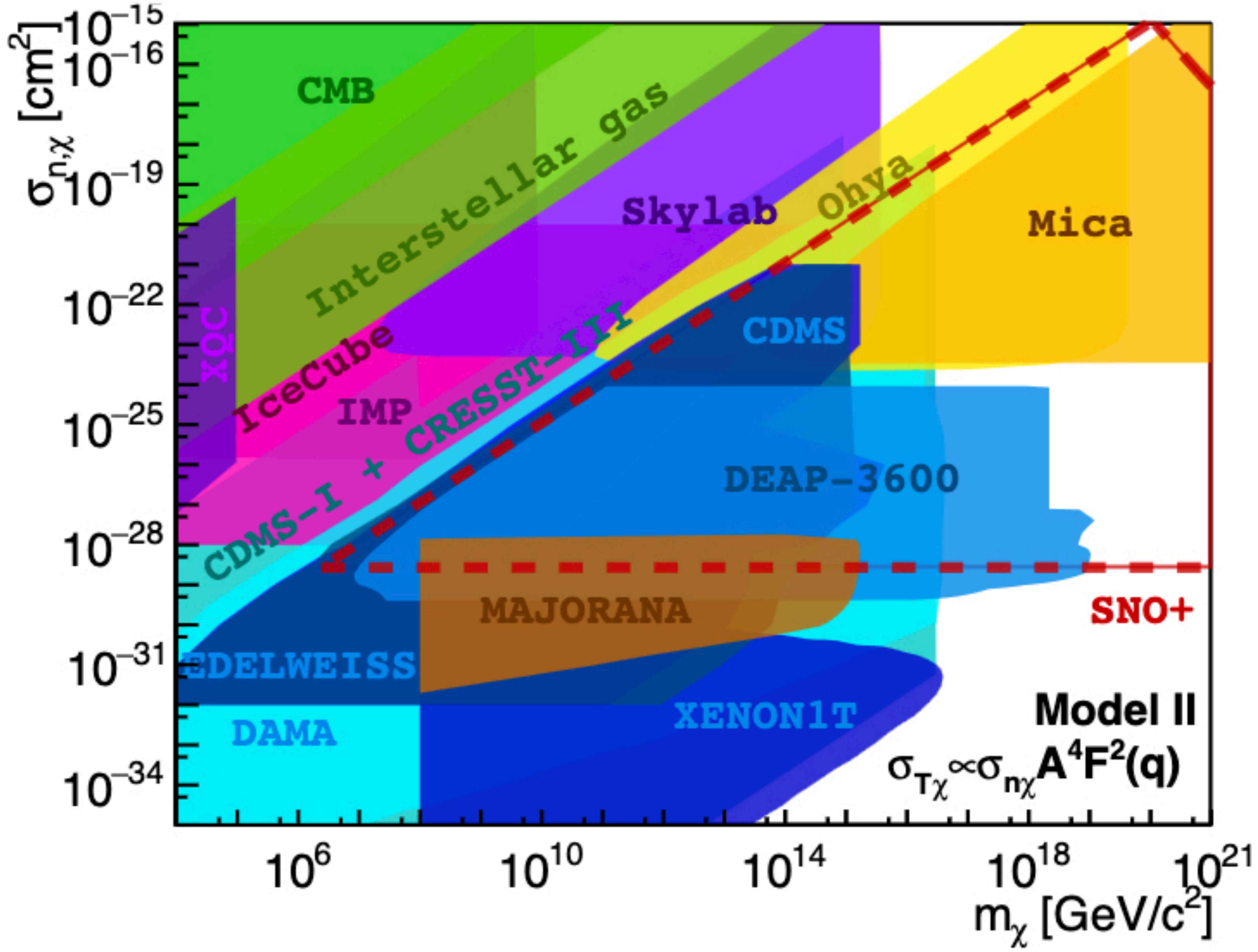



Q Paleo (QCumber? - name suggestions welcome) 2301.07118

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



Future CR-39 experiment or similar




Snowmass Ultraheavy dark matter

Carney, Raj et al. 2203.06508

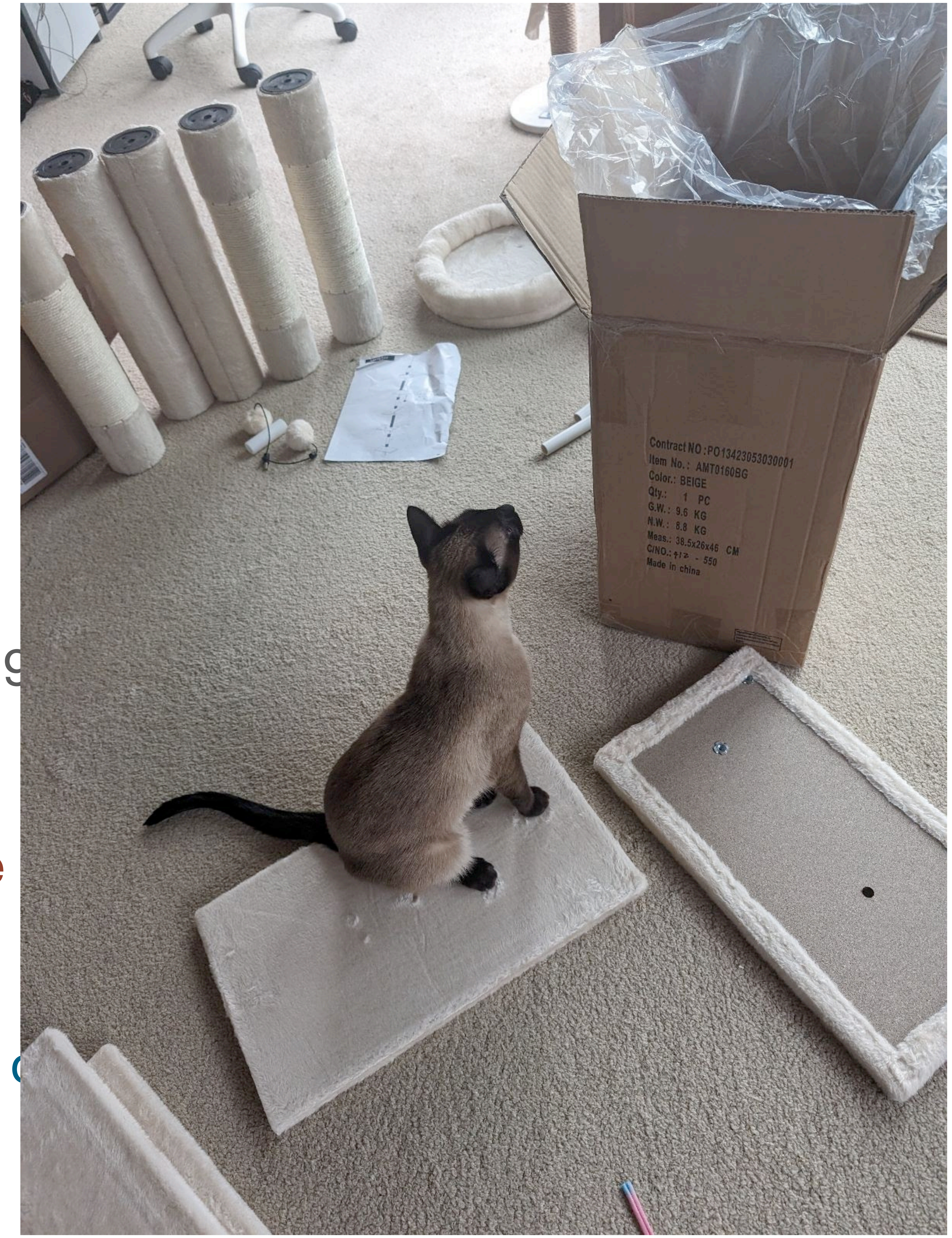
# (LET'S GET) OVERVIEW(S) OF DARK MATTER

-Most DM models were written down in the 80-9

-The simplest DM are well studied, and may be

(Simple in formulation, sometimes complicated in dynamics)

- Simple heavy DM is less studied, and may be 
easier to look for, for now.



# (LET'S GET) OVERVIEW(S) OF DARK MATTER

-Most DM models were written down in the 80-90s.

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

(Simple in formulation, sometimes complicated in dynamics)

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

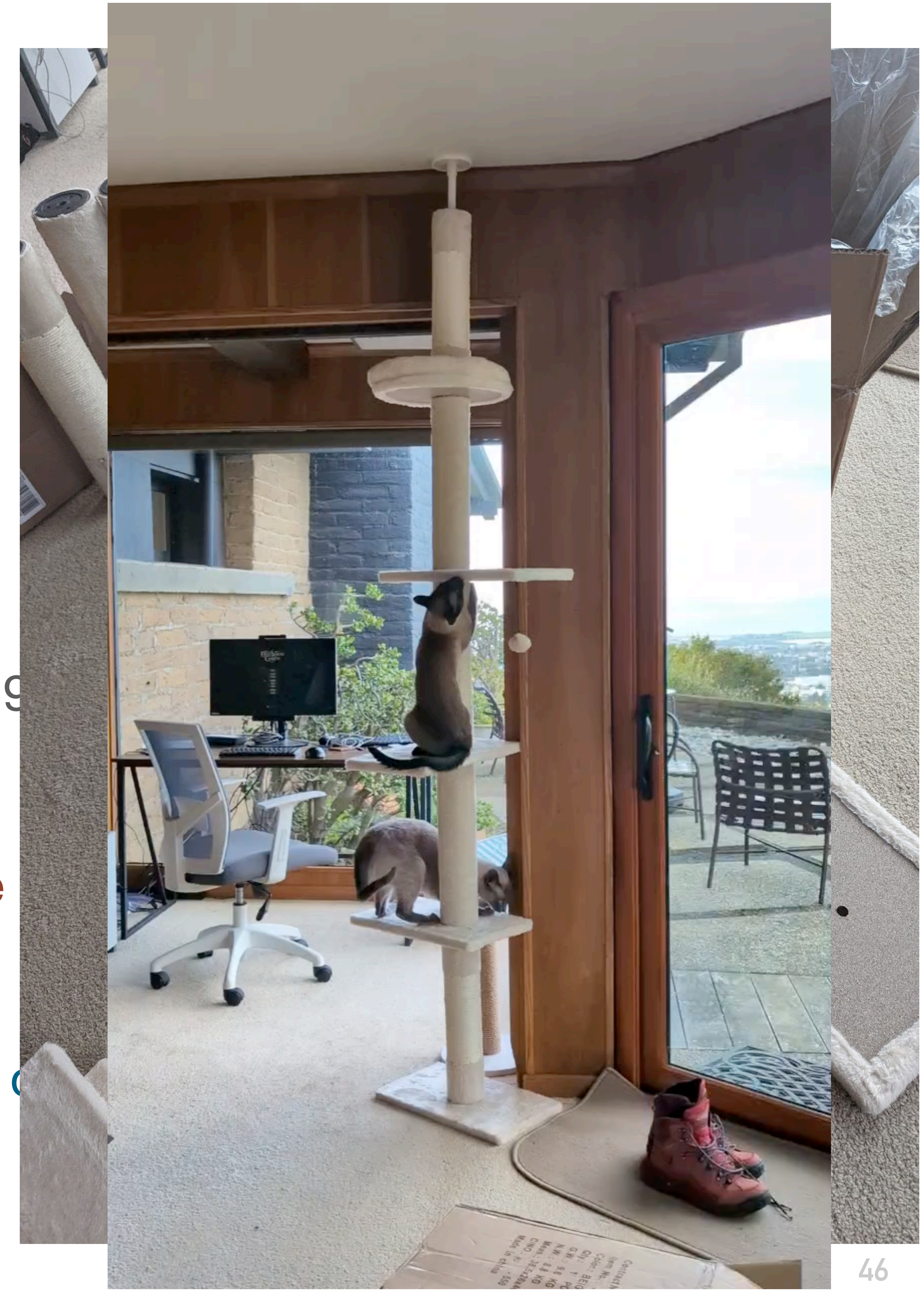
# (LET'S GET) OVERVIEW(S) OF DARK MATTER

-Most DM models were written down in the 80-9

-The simplest DM are well studied, and may be

(Simple in formulation, sometimes complicated in dynamics)

- Simple heavy DM is less studied, and may be e
easier to look for, for now.

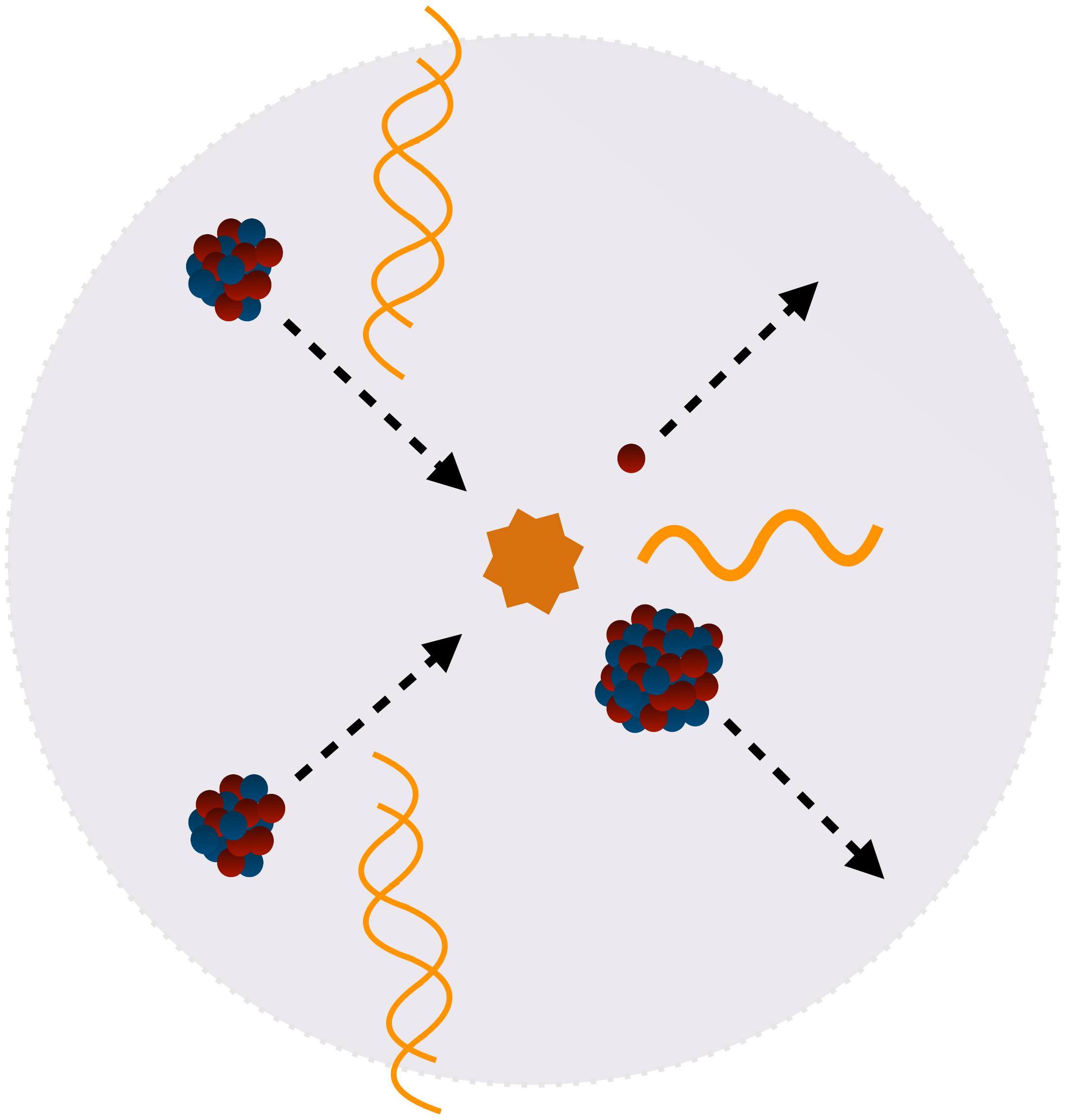


# BREM/NUCLEAR INTERACTIONS

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

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

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

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

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)

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

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

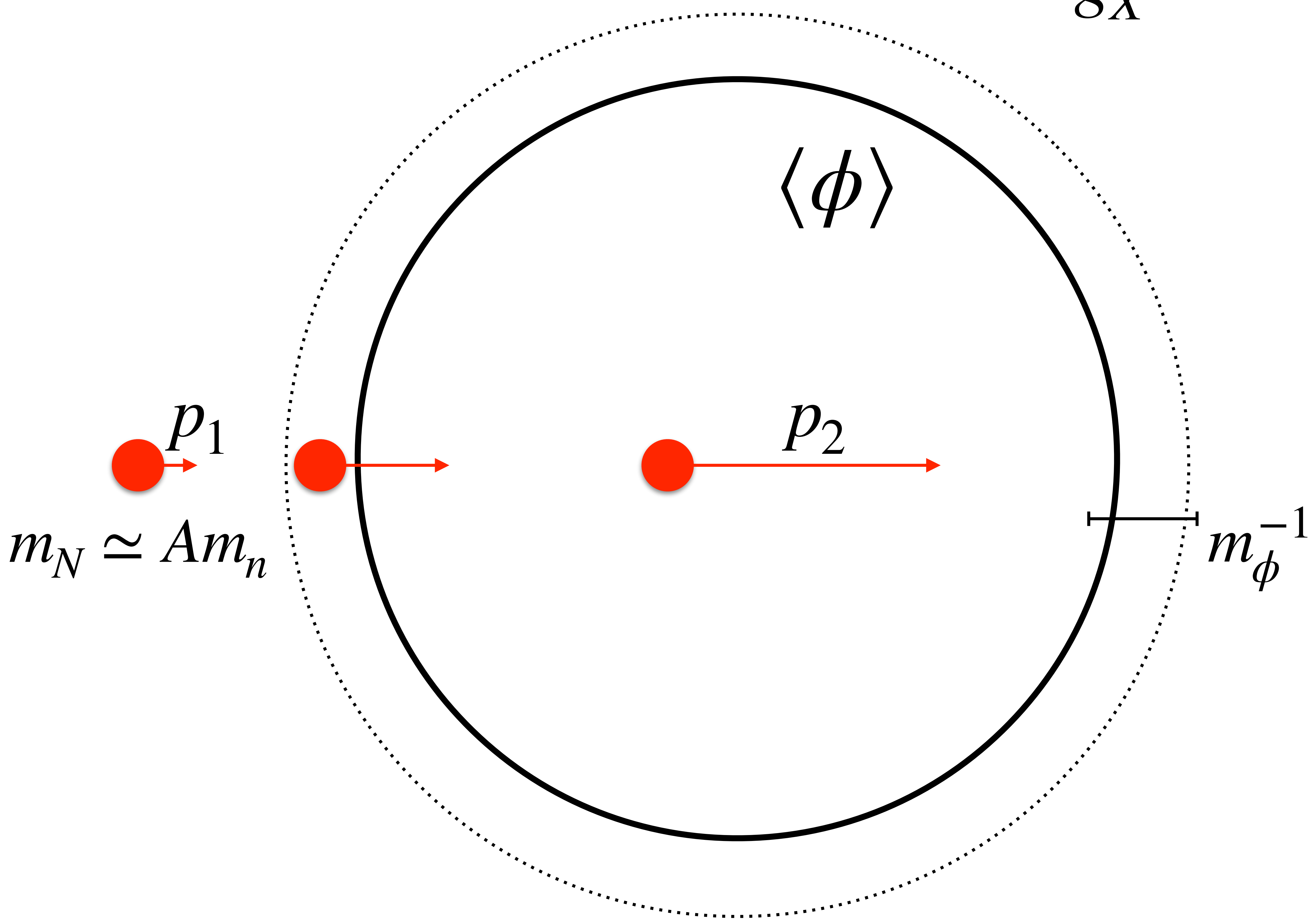
edge of composite screened

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

# 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: $\langle \phi \rangle \simeq \dfrac{m_X}{g_X}$



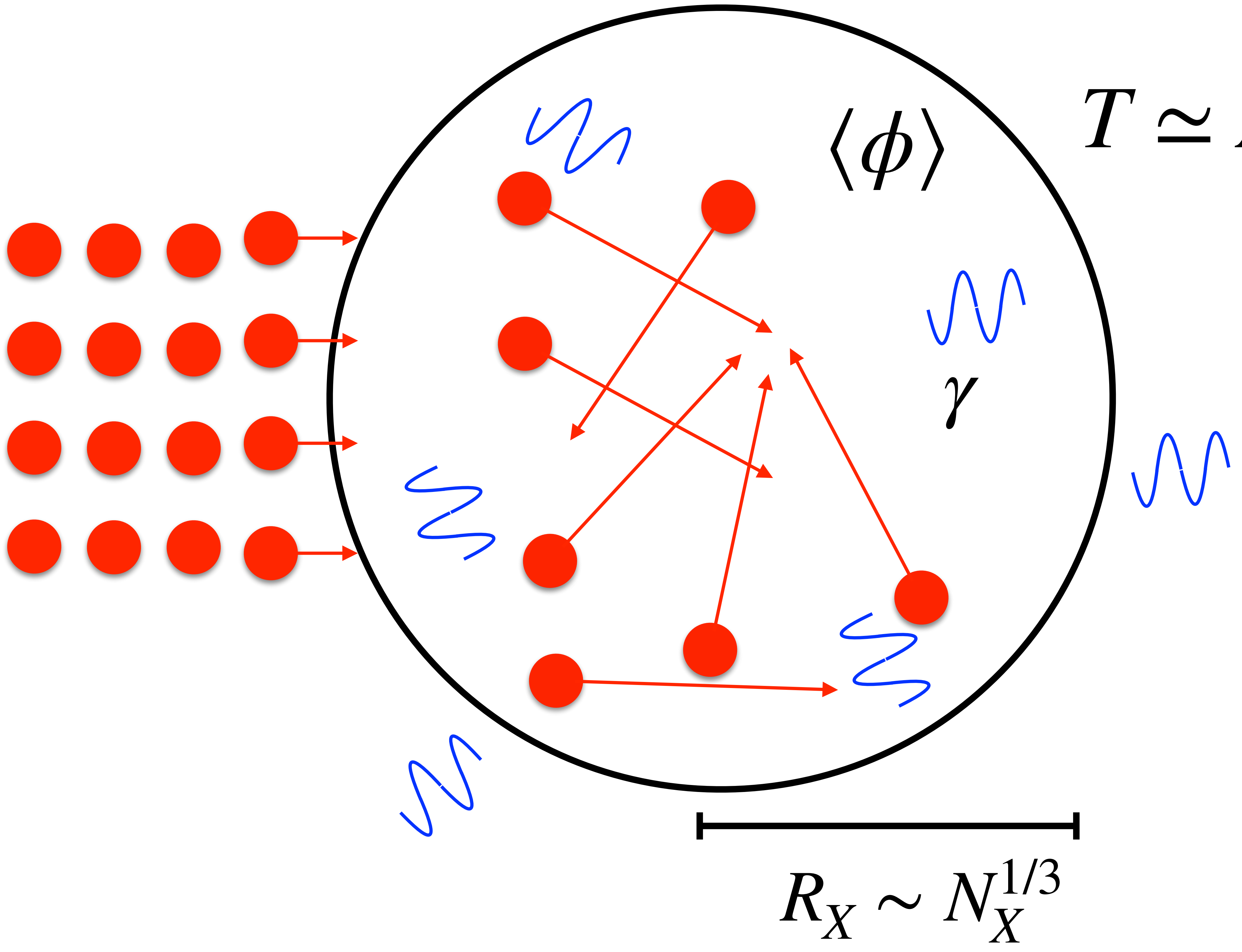

Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential sourced by X fermions, like gravity but stronger and shielded

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

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

# Heated nuclei in composite interior

$\langle\phi\rangle \propto m_X \sim \text{TeV} - \text{EeV}$ 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?**

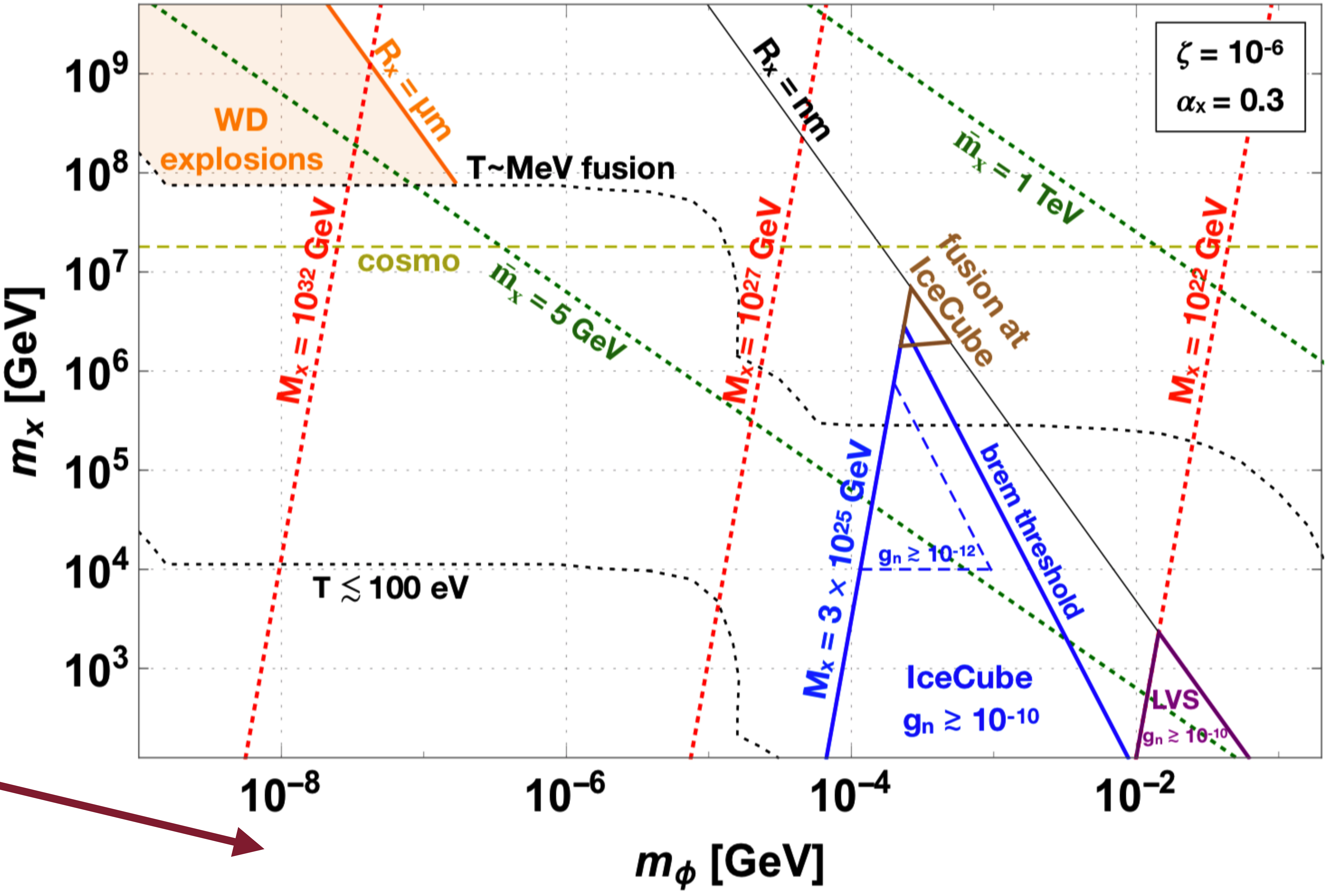
→ Ionizing dark matter

→ Neutrino detectors

→ Type Ia supernovae

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

# 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:

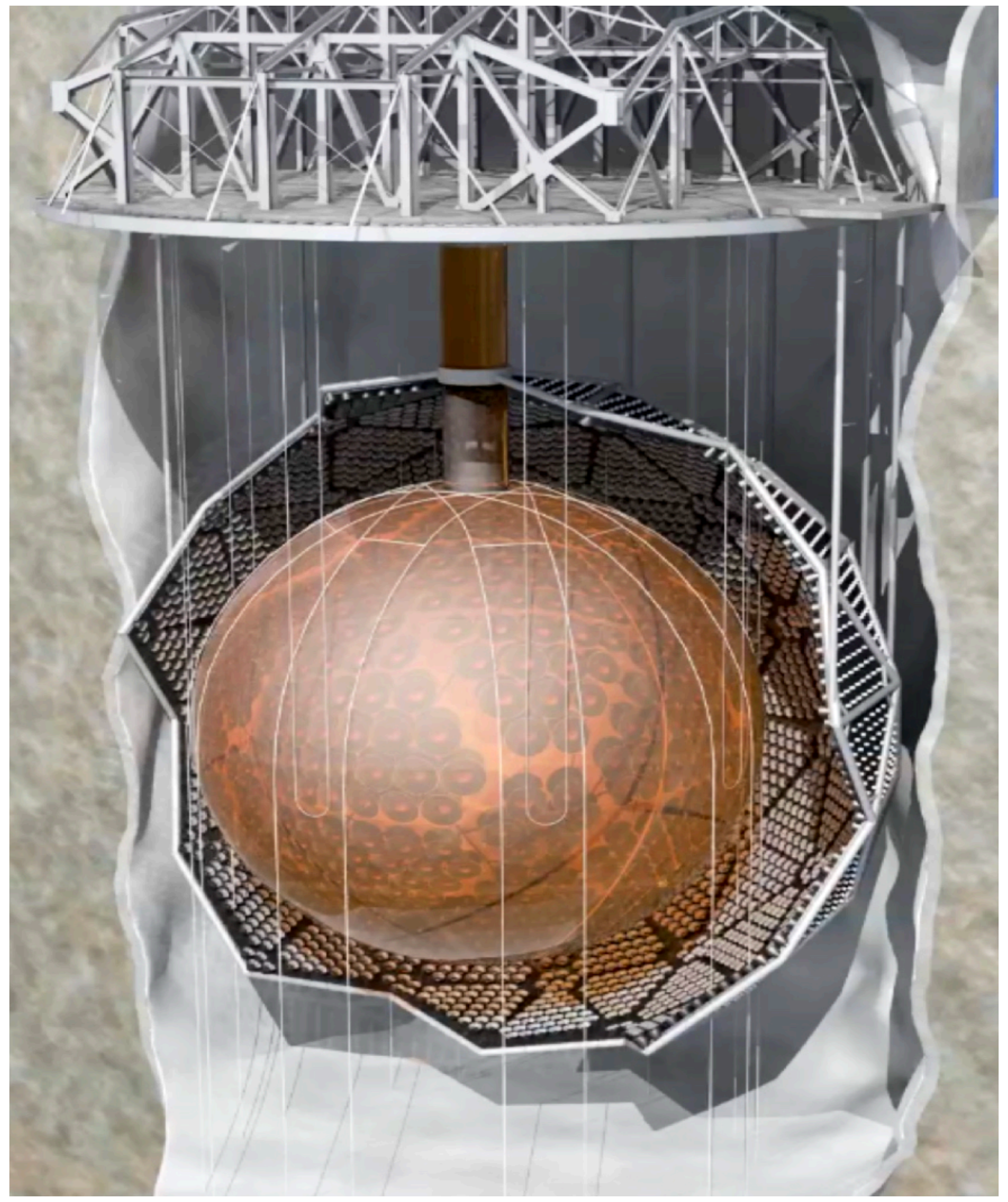
SNO+: ~1 MeV per 100 ns

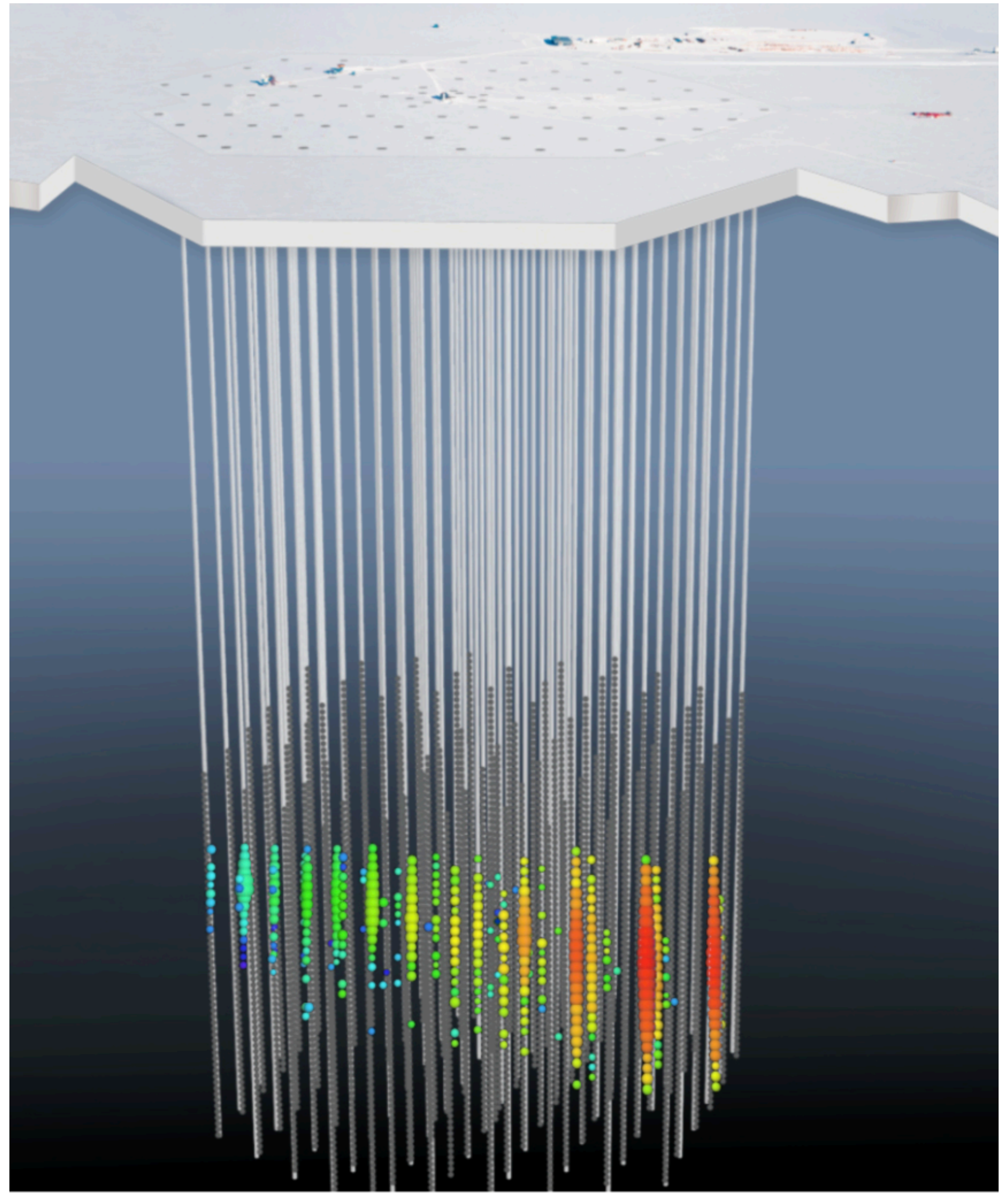
IceCube: ~10 TeV per 100 ns (~100 PeV in single crossing)

Composites radiate continuously along path:

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

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



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

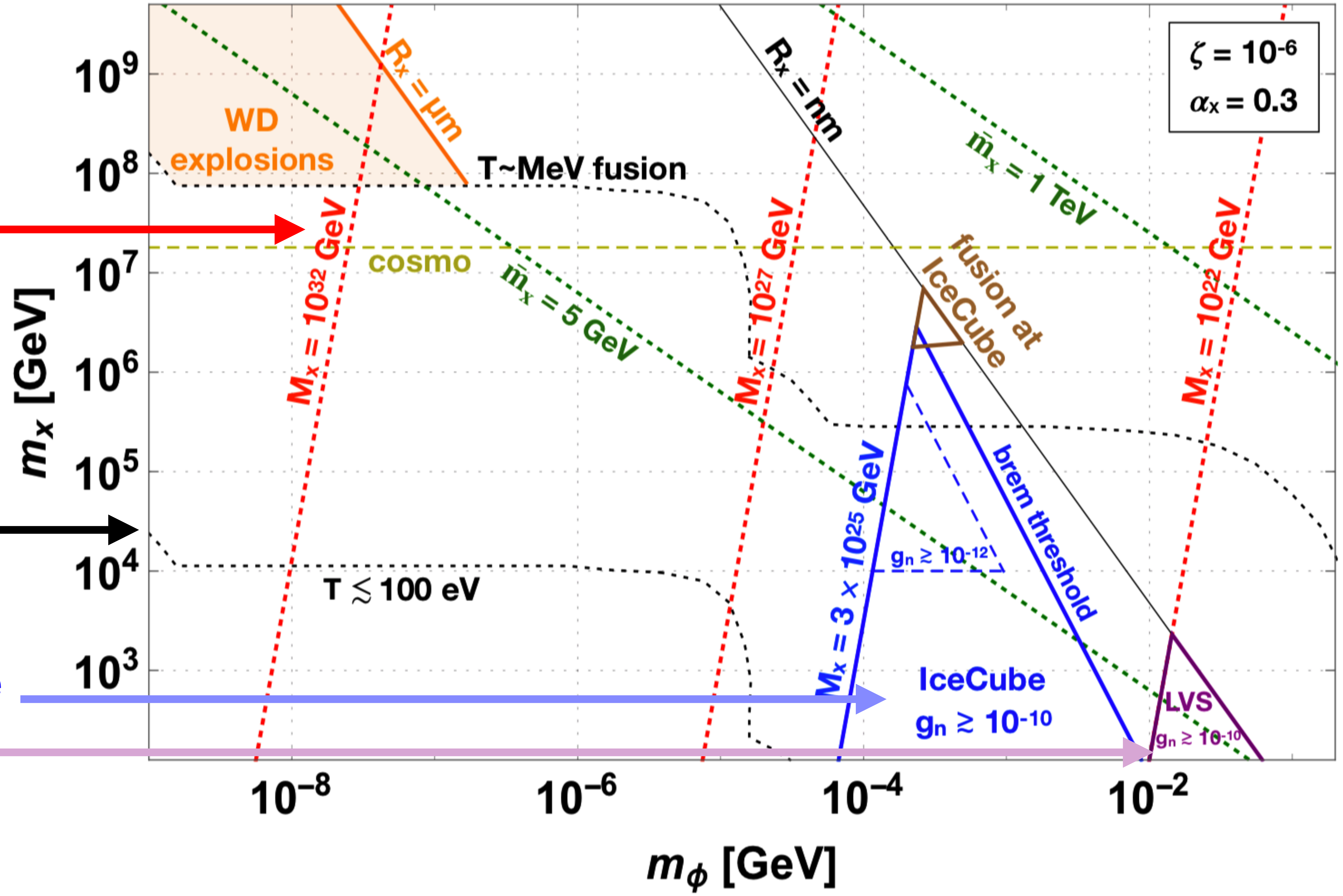
# BREM/NUCLEAR FUSION IN COMPOSITES

Composite mass

Max temperature of baryons flowing through composite

Find composite Brem at Ice Cube

Find composite Brem at SNO+/JUNO



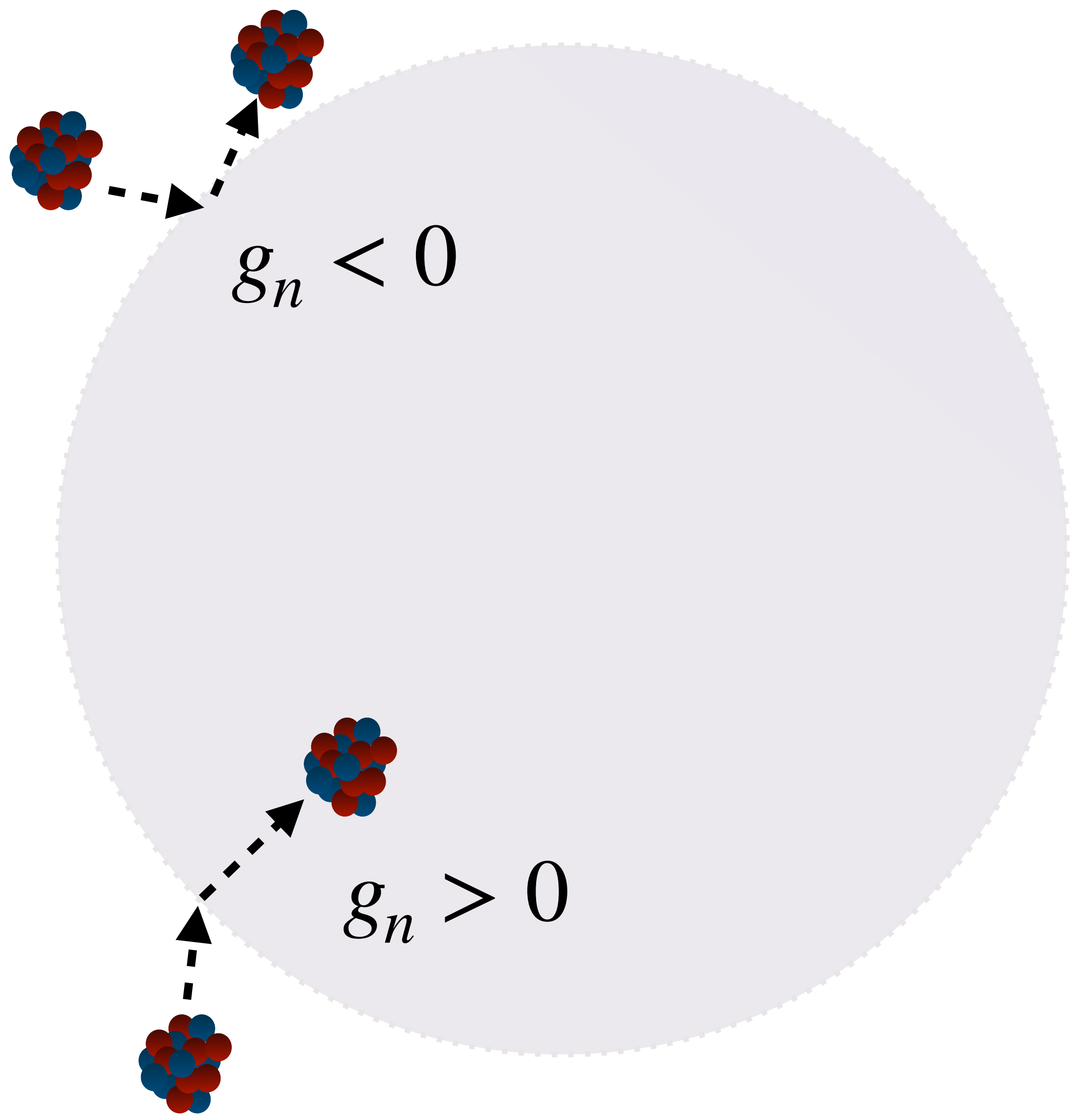

Acevedo, JB, Goodman 2012.10998

# 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.

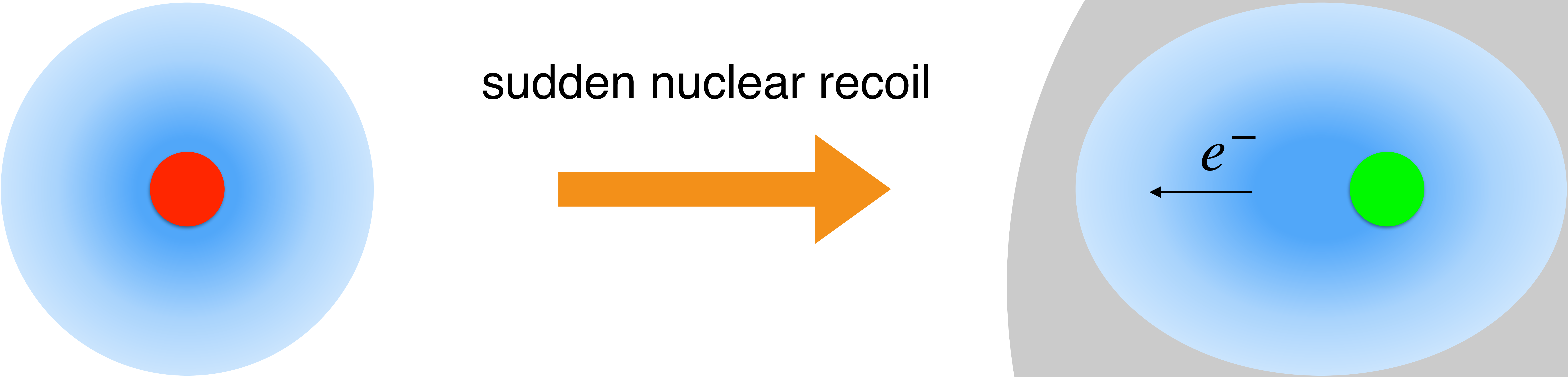



$\langle\varphi\rangle \ll m_N$

Acevedo, JB, Goodman
2108.10899

# Composite Migdal Effect at DD Experiments

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




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

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

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

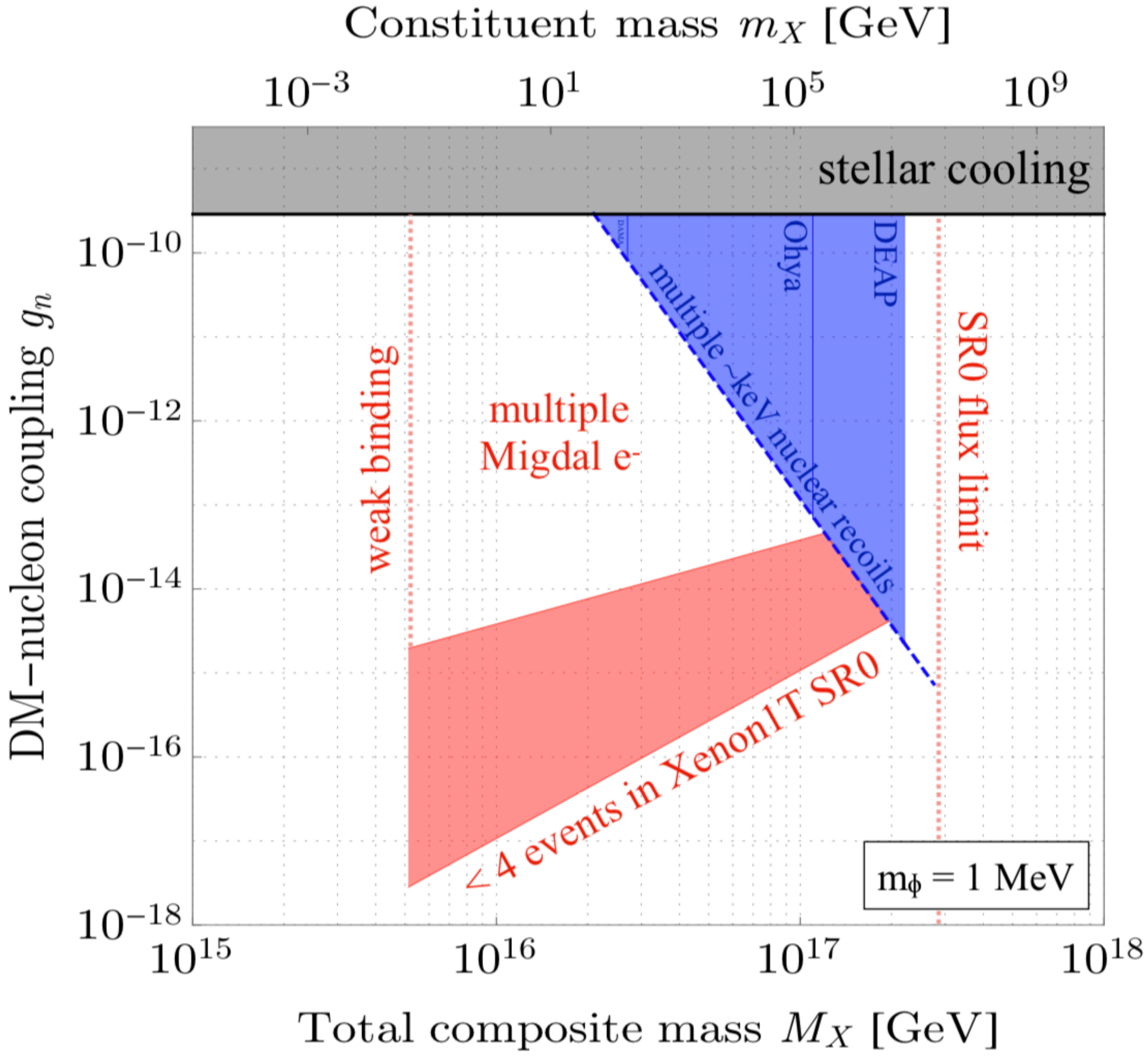
$(R_a \sim 10^{-8}\ \text{cm})$

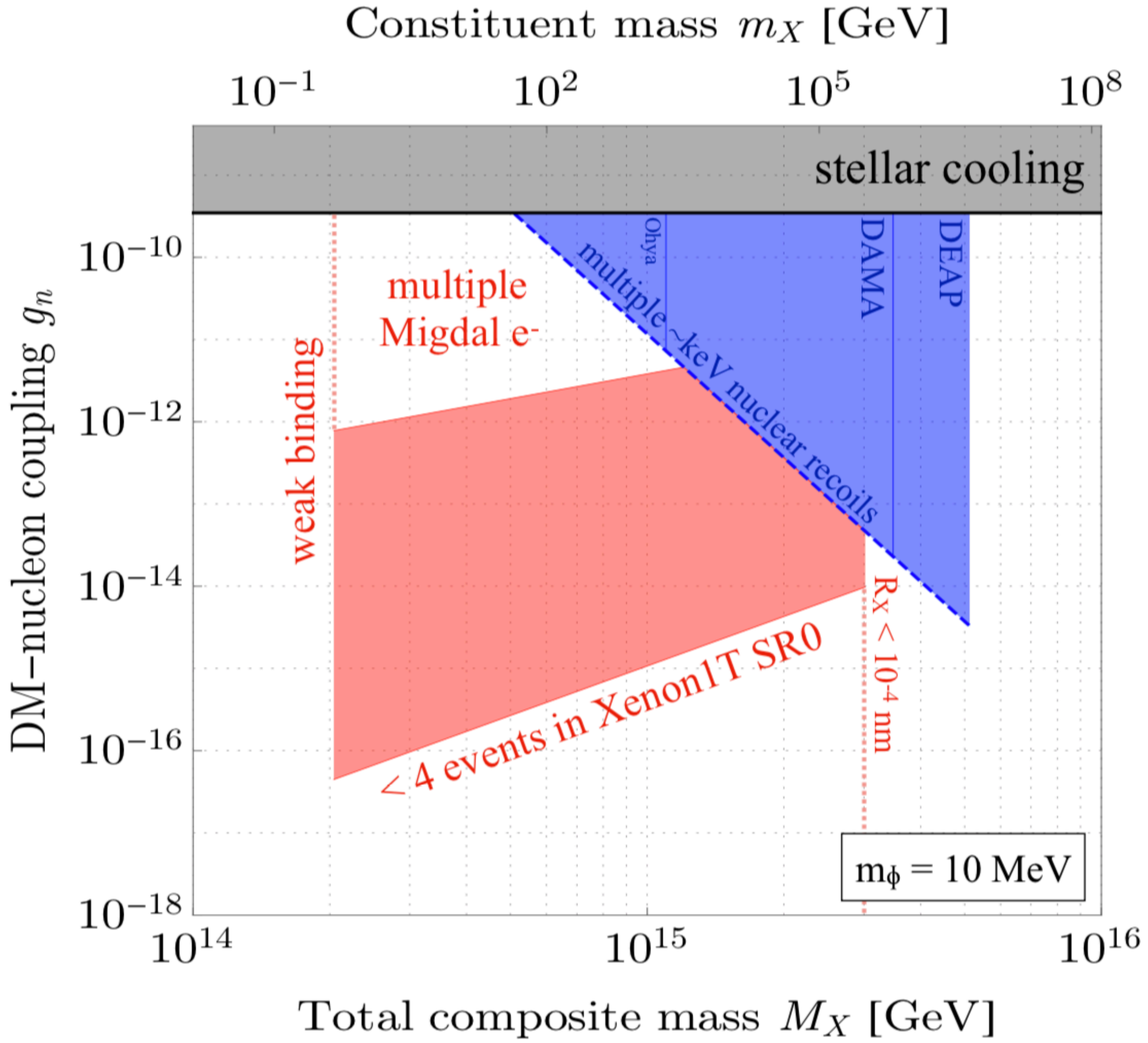
$$\Delta t_{\text{interact}} = \tau_{\text{accel}} \simeq \frac{1}{m_\phi v_X} \simeq 10^{-19}\ \text{s}\left(\frac{m_\phi}{\text{MeV}}\right)^{-1} \ll \tau_{e^-}$$

# 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 $m_X$, cosmology with $\alpha_X = 0.3$

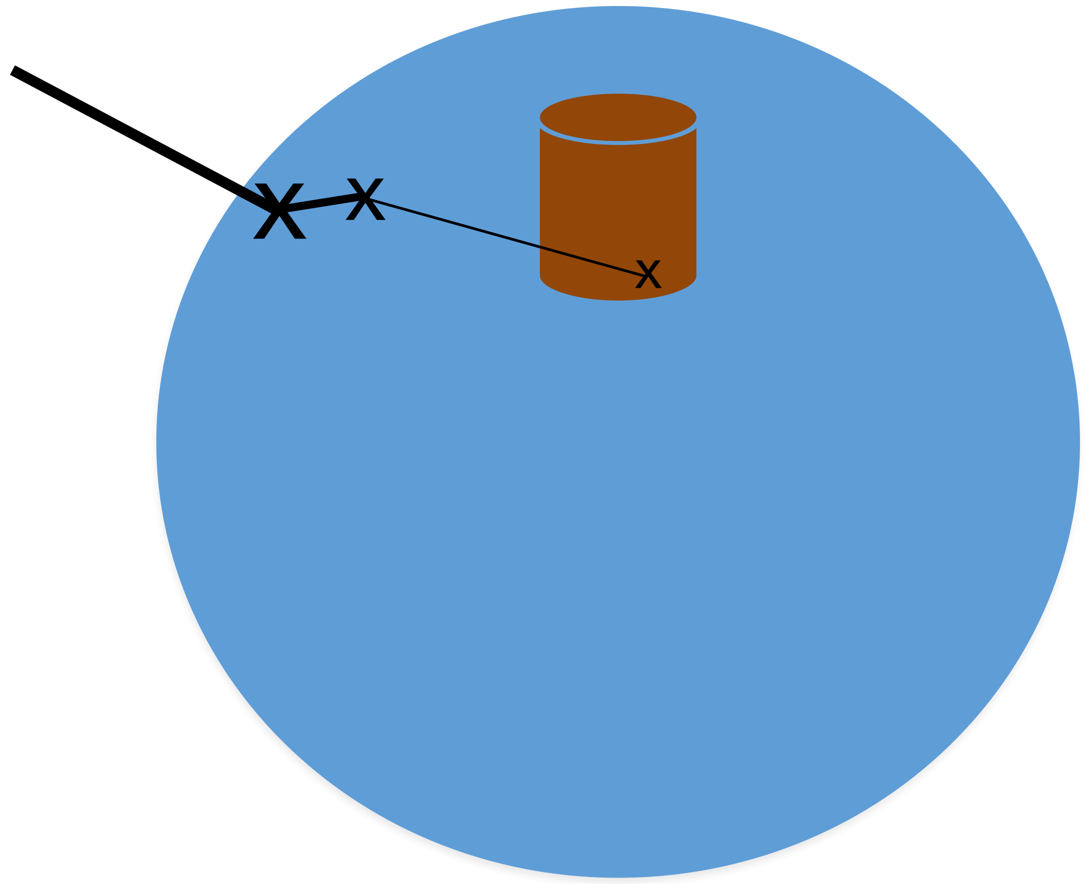



Acevedo, JB, Goodman, 2108.10889

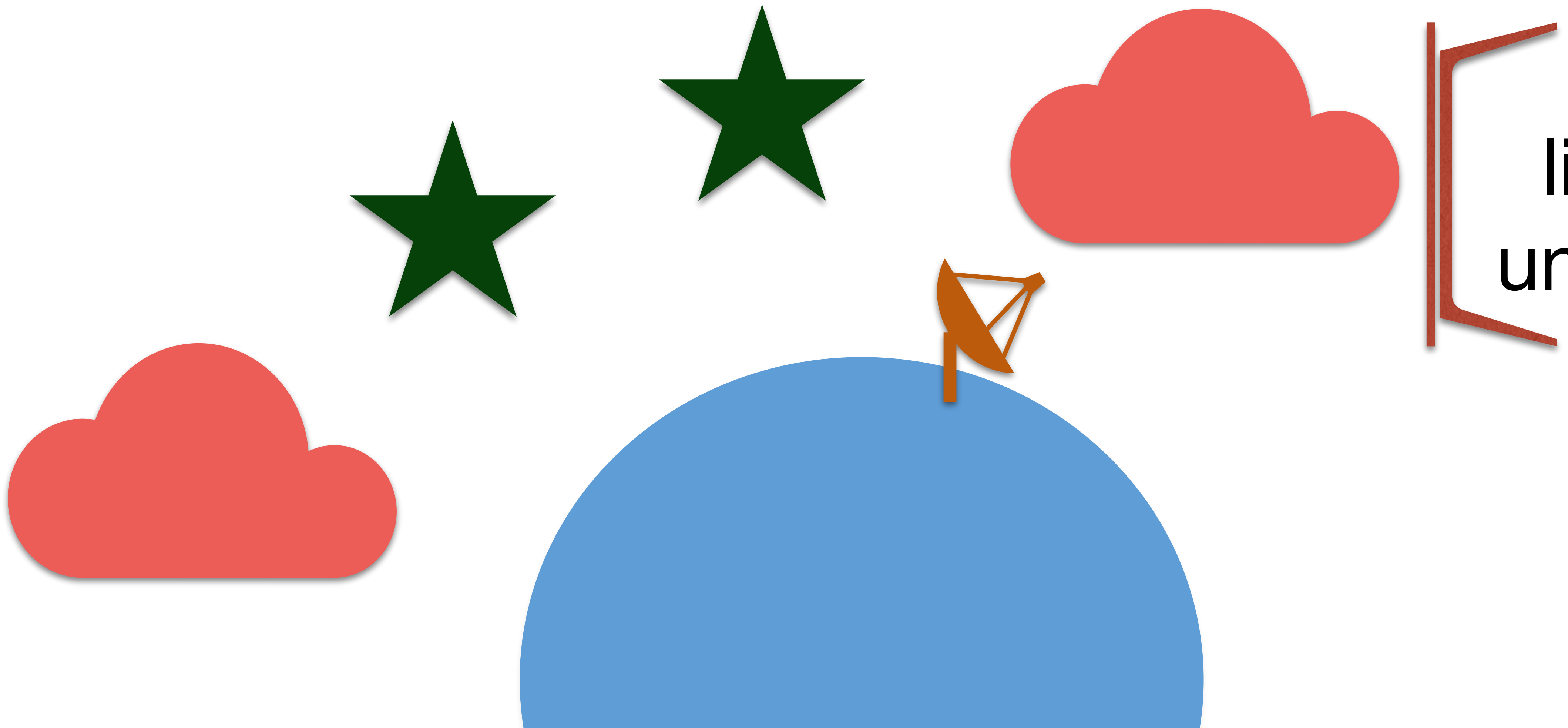
# GAS CLOUDS

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



dark matter kinetic energy < recoil threshold

use detectors in space

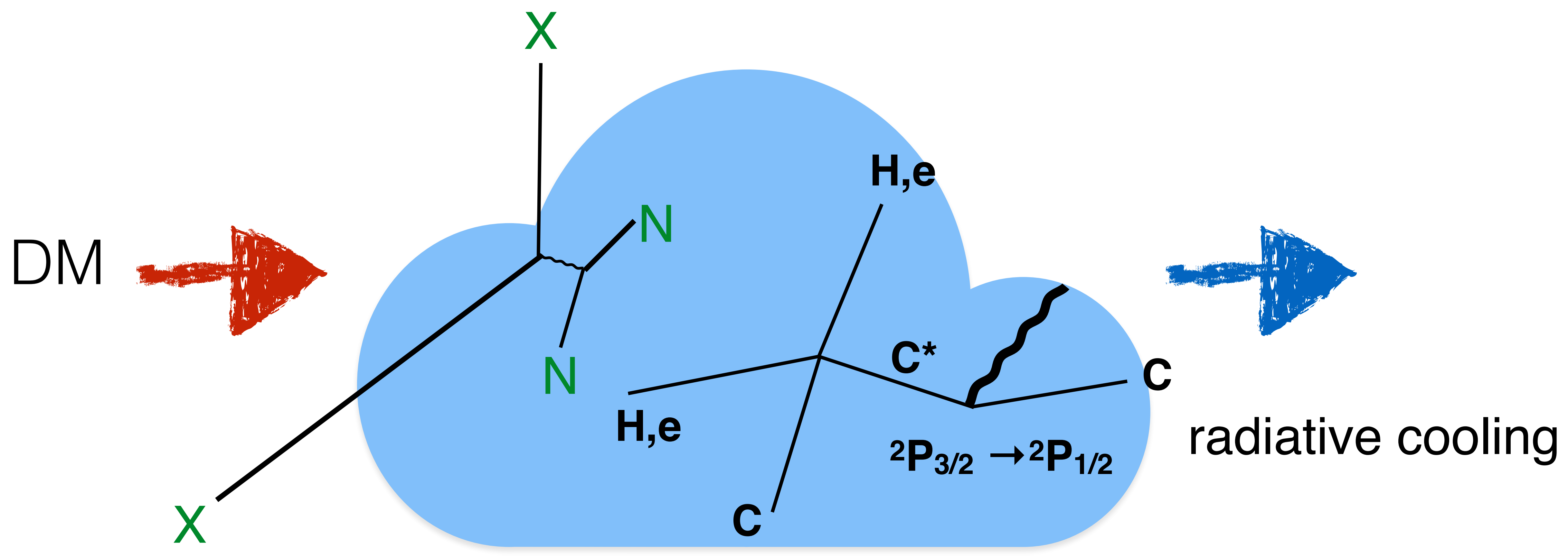


Interstellar gas

big
little overburden
unbound electrons

*2010.07240*
*1812.10919*
*1806.06857*

# GAS CLOUD BOUNDS




**Conservative: assume all heating by DM**

**In reality:**

(DM +)

cosmic rays

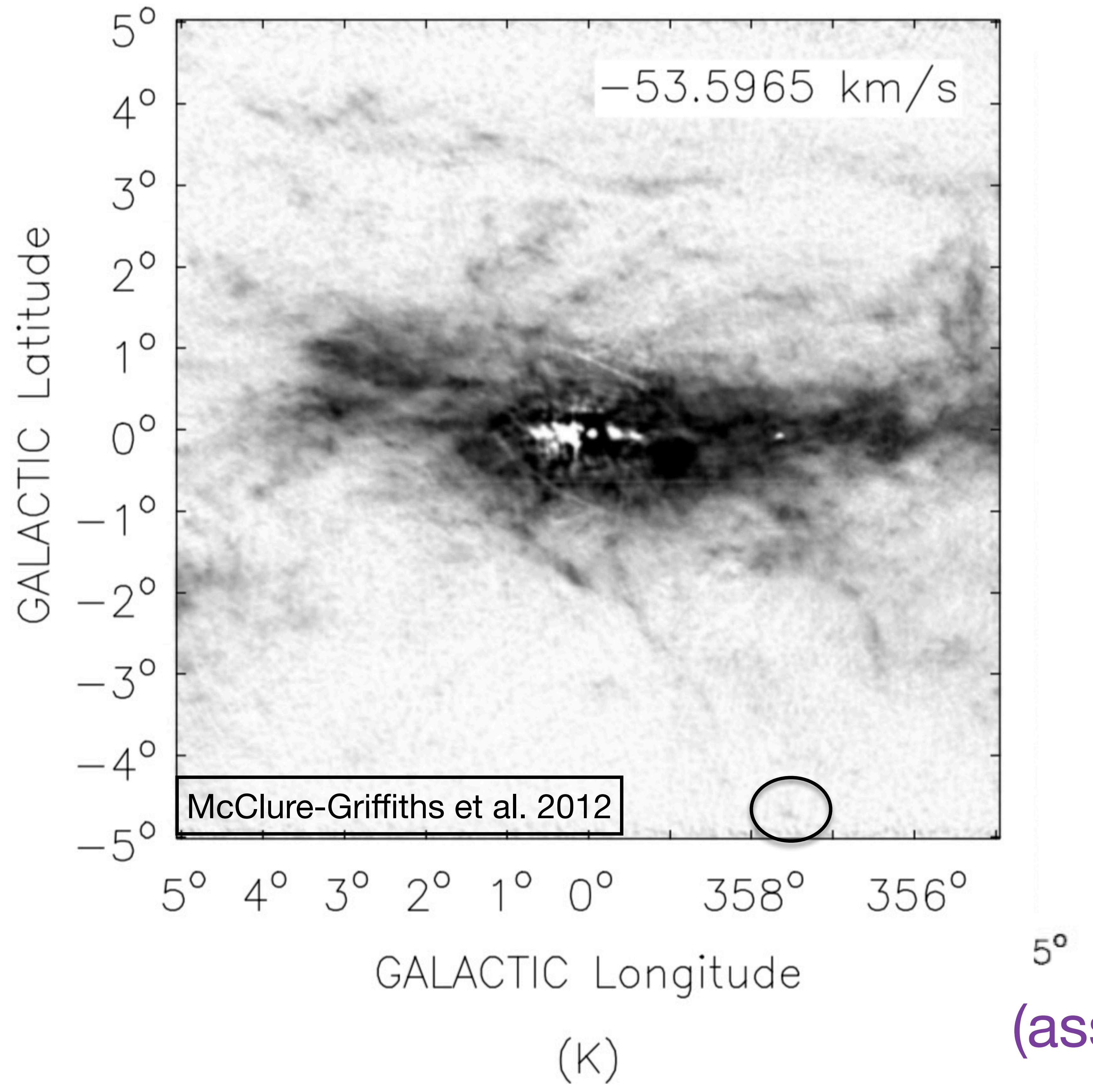
Xray/UV background

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

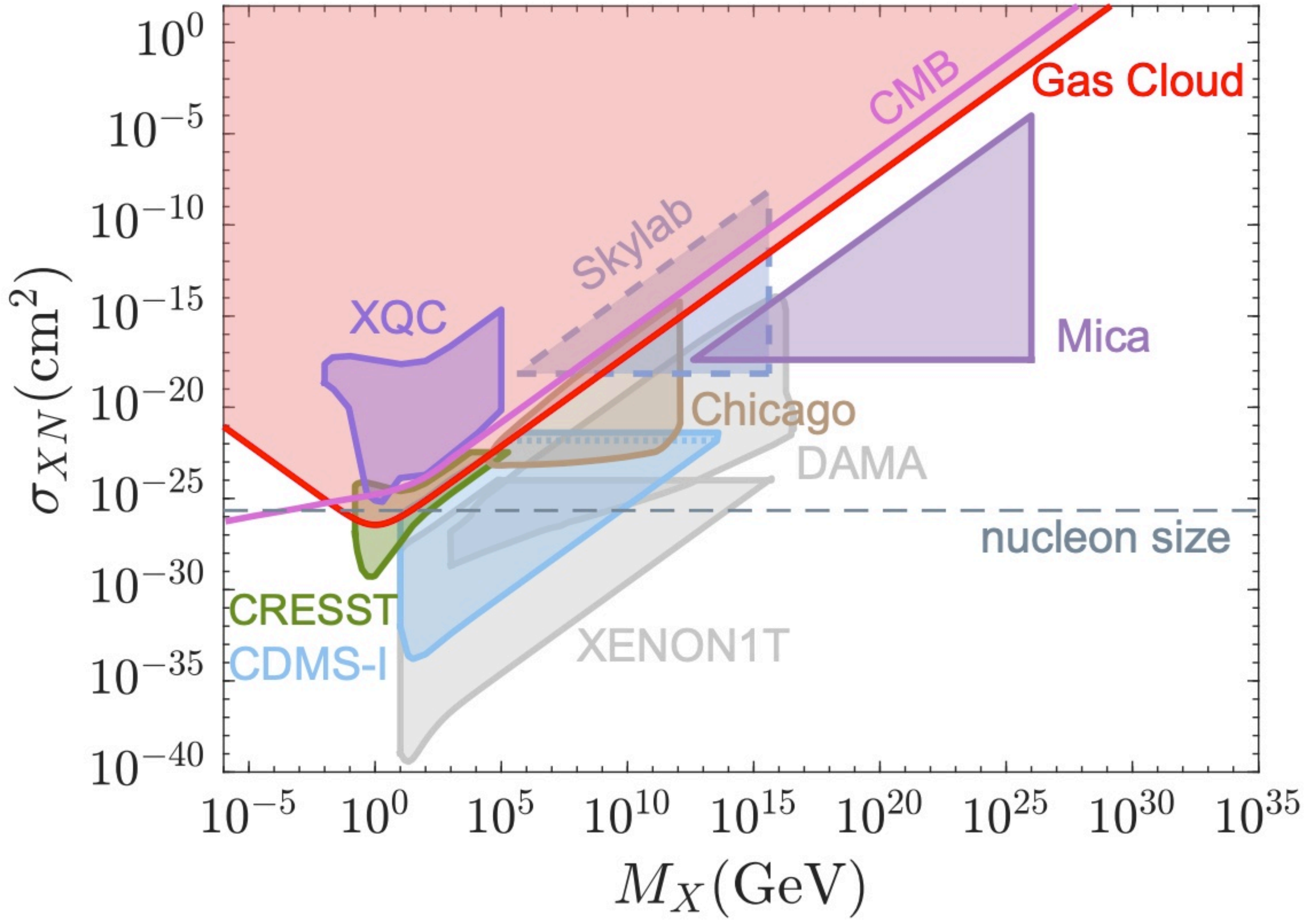
$r_{los} \sim 800$ pc

$v_g = -54$ km/s

(assume spherical cloud)

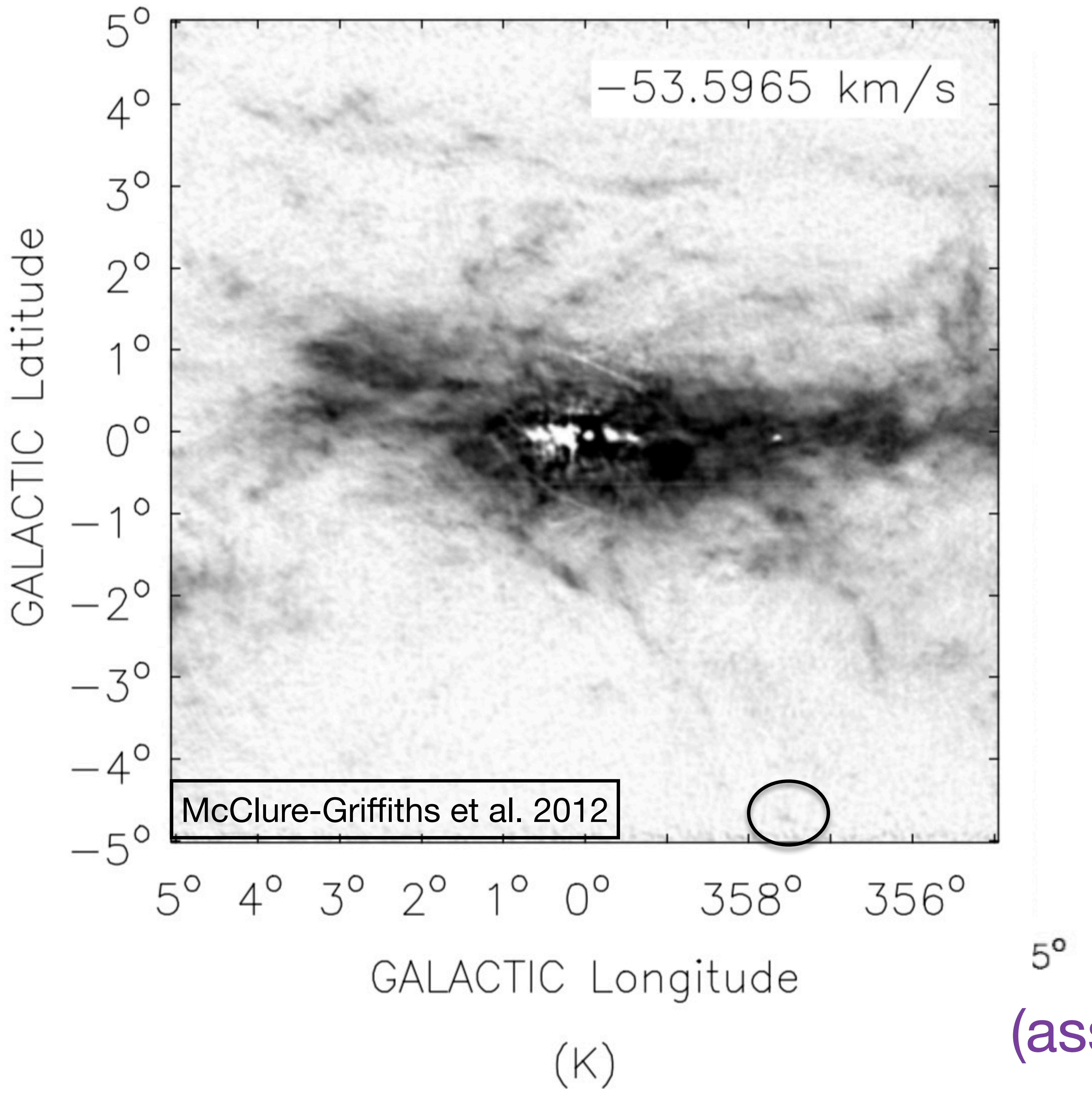
# HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei




Amit Bhoonah, JB, Schon, Song 2010.07240

## 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

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

$T_g < 137$ K

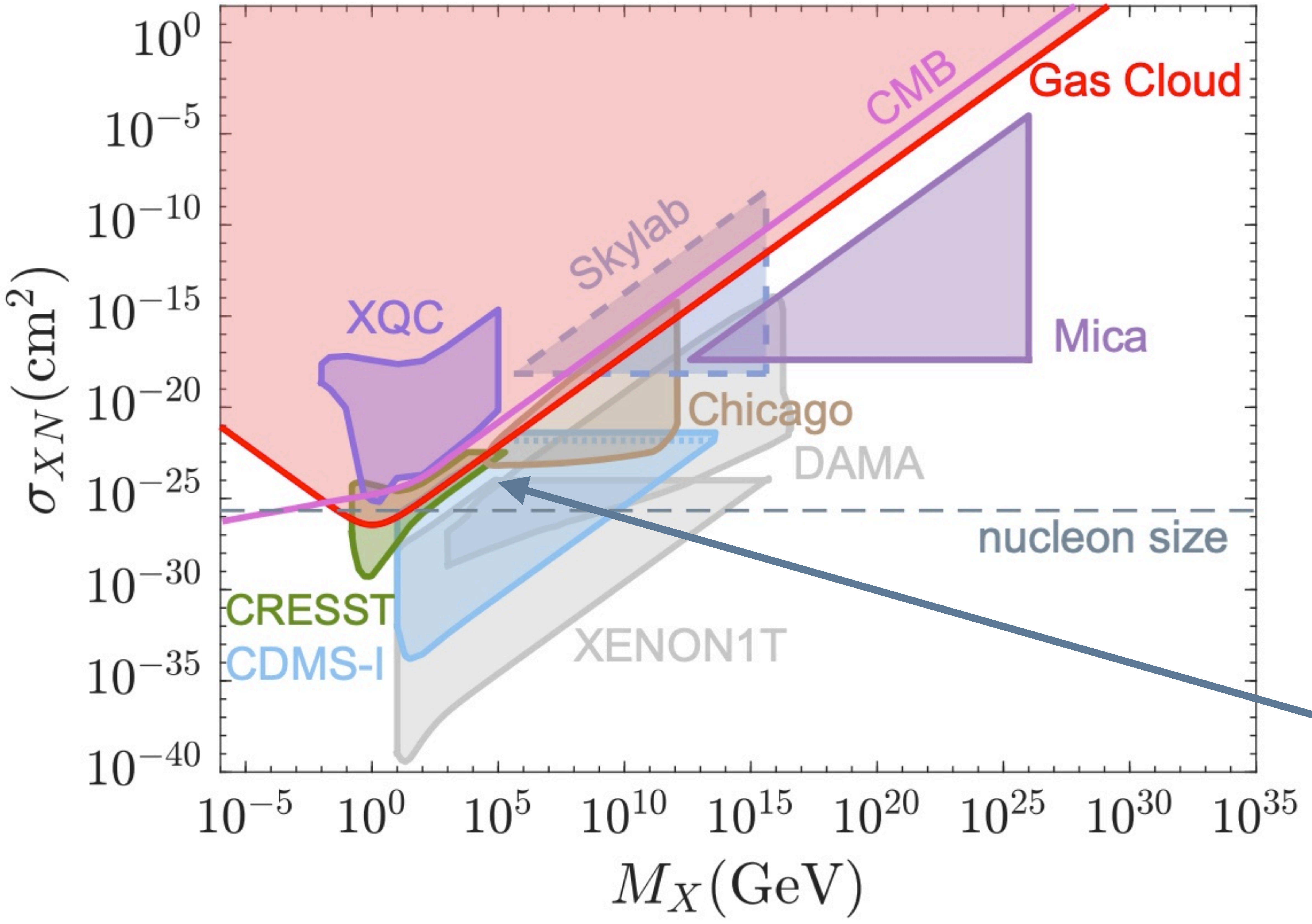
$r_{los} \sim 800$ pc

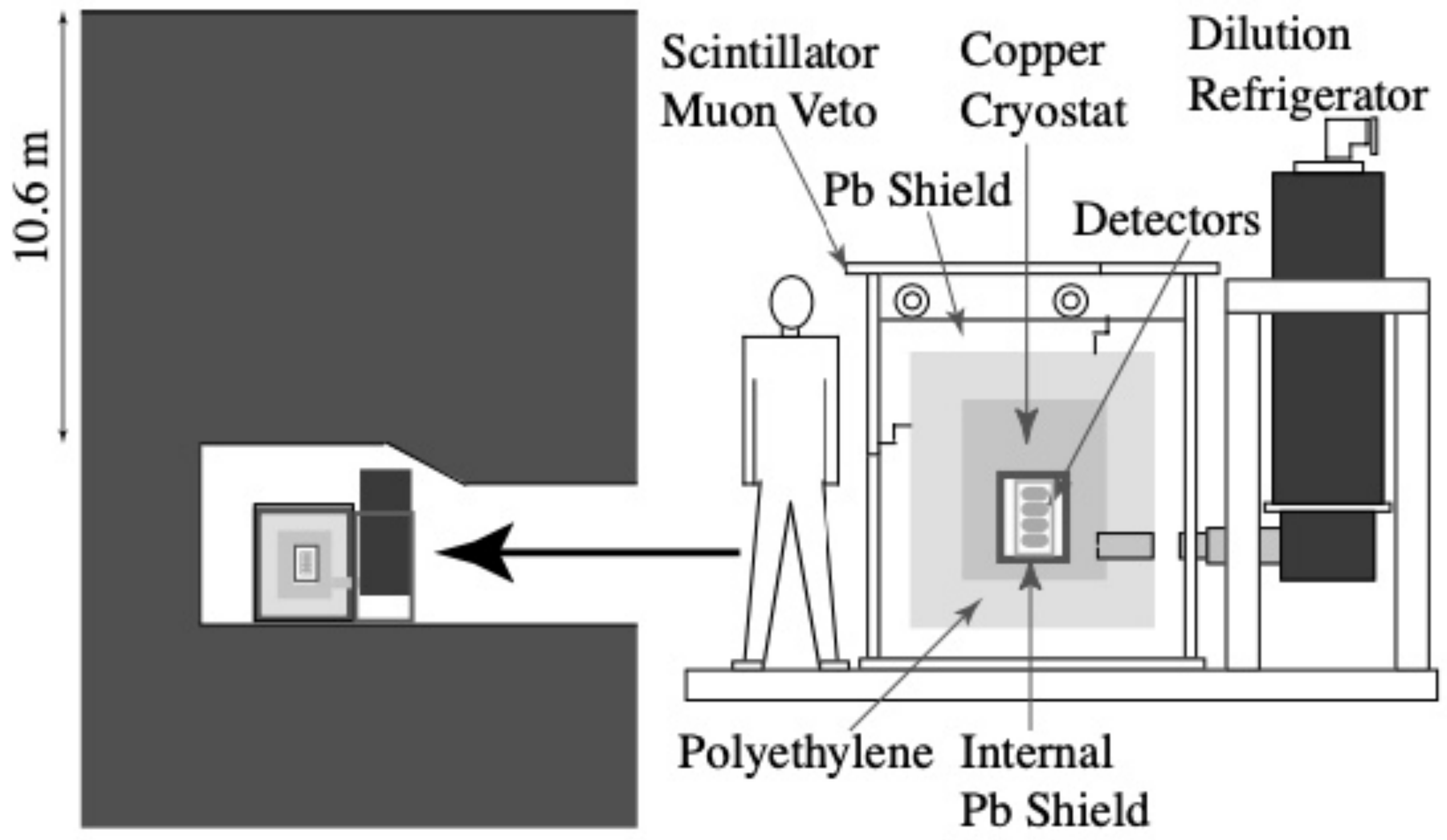
$v_g = -54$ km/s

(assume spherical cloud)

# HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei




Recast CDMS-I limit using multi scatter

(Muon veto rejects very strong interactions)

Amit Bhoonah, JB, Schon, Song 2010.07240