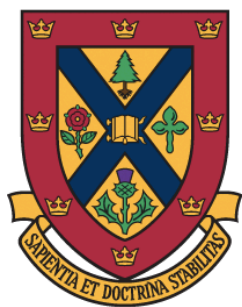


DARK MATTER AT THE HIGH MASS FRONTIER

Joseph Bramante



Queen's
UNIVERSITY



Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

U Hawaii Seminar Jan 28, 2025

DARK MATTER AT THE HIGH MASS FRONTIER

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

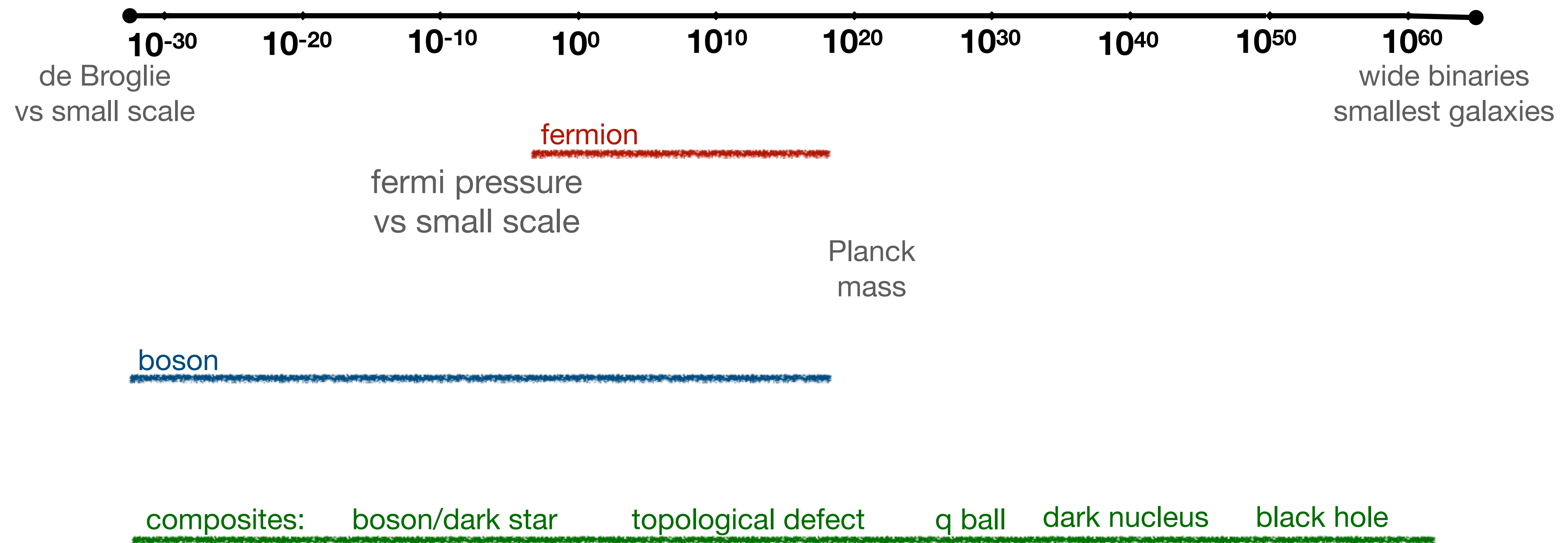
- The simplest DM are well studied, and may be discovered soon.

(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?

mass in GeV



How was dark matter made?

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



classic
freezeout
(wimp)

de Sitter
fluctuation
(wimpzilla)

freezeout
variant
(wimpish)

tensor limit?



data

CMB, BBN, LSS
measurements

matter, radiation, inflation ?
sparse/null data

misalignment

asymmetric

freeze-in

collapse
to pbh

oscillating
scalar

decay

production

Dark Matter Models: SM Coupling and Detection

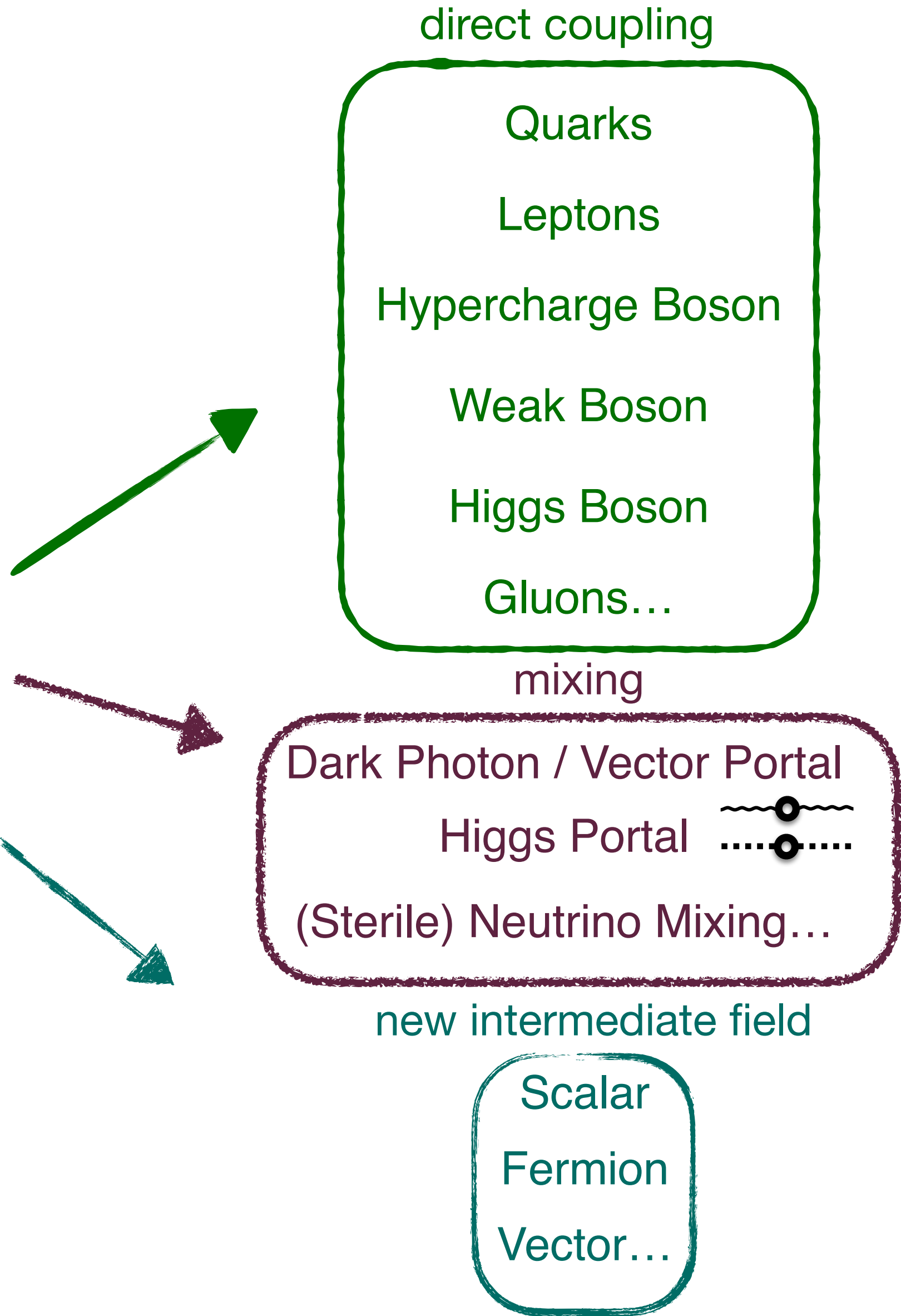
dark matter

fundamental

composite

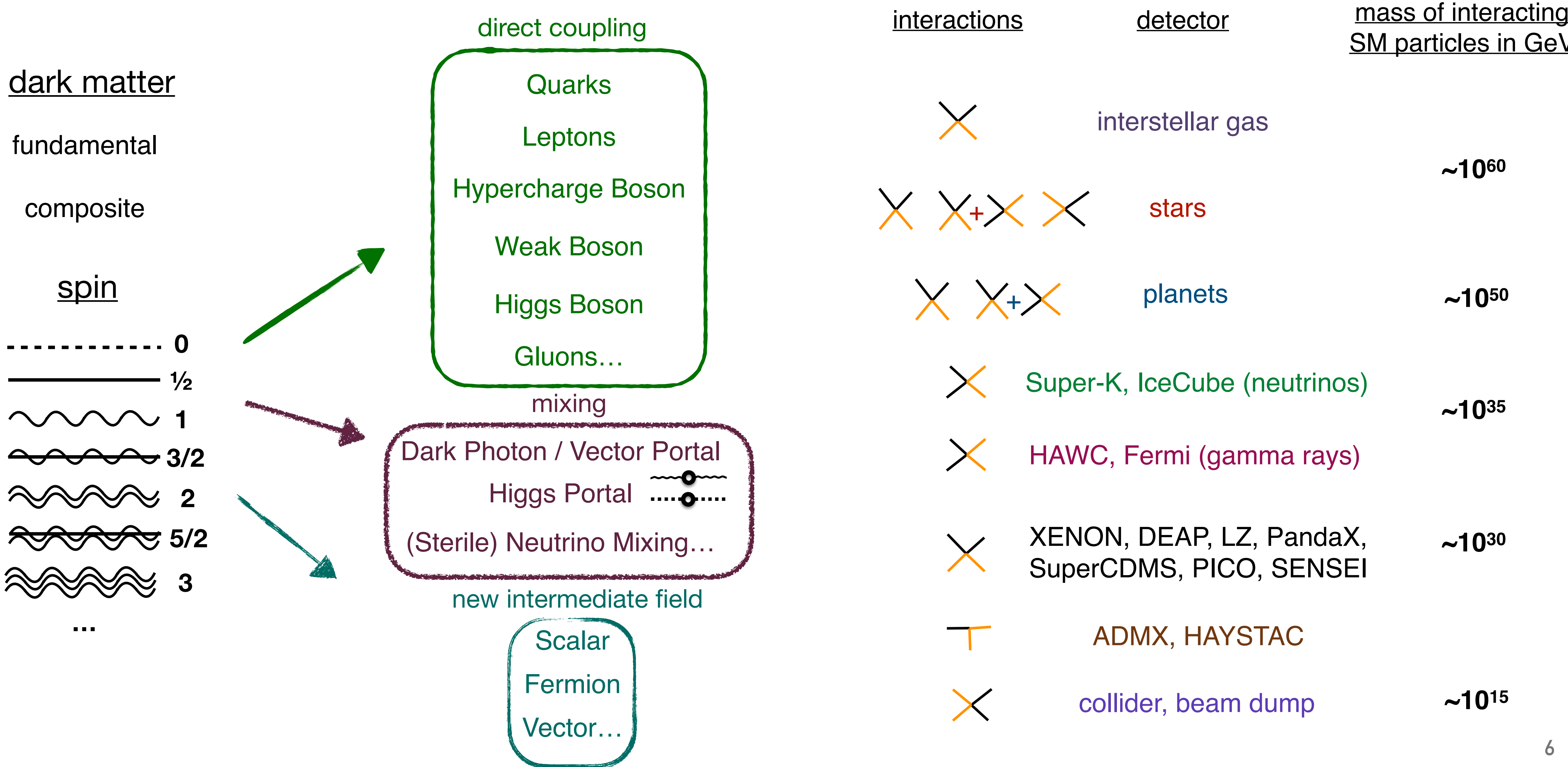
spin

- 0
- 1/2
- ~~~~~ 1
- ~~~~~ 3/2
- ~~~~~ 2
- ~~~~~ 5/2
- ~~~~~ 3
- ...

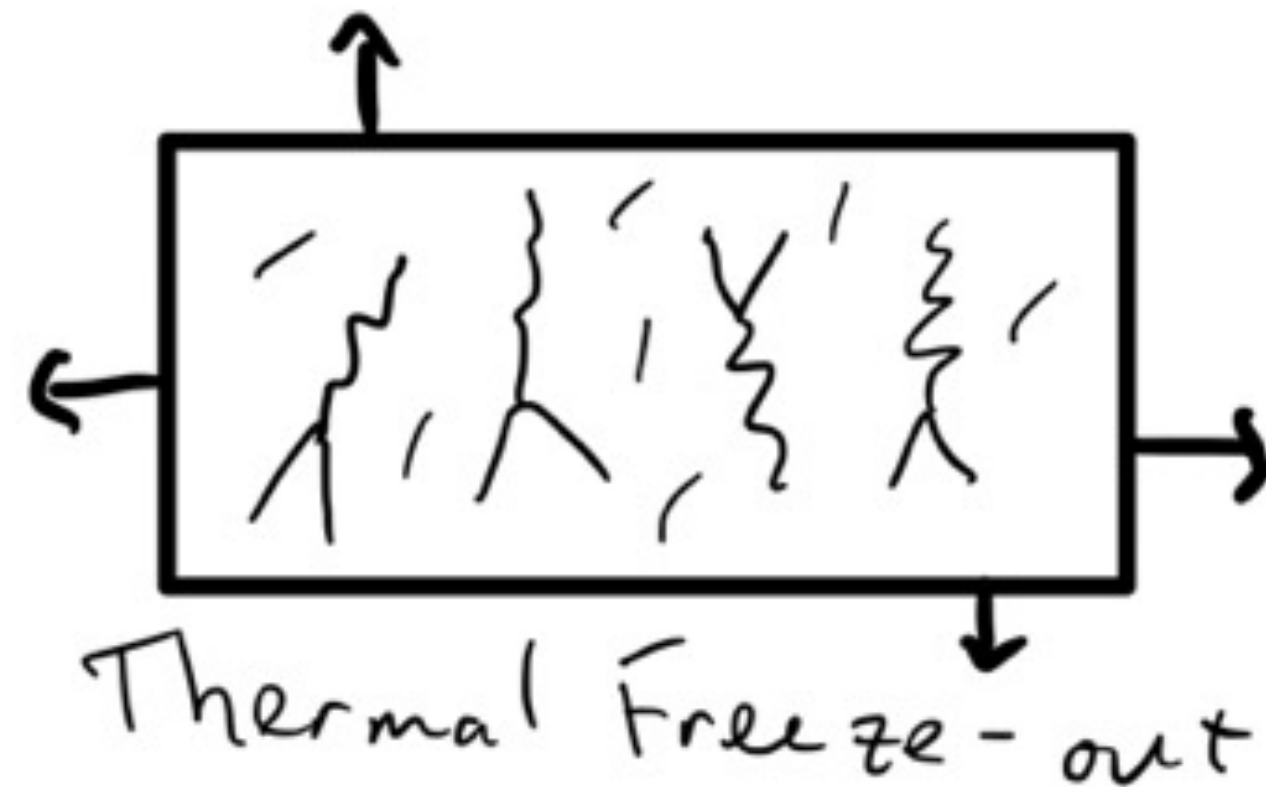


Dark Matter Models: SM Coupling and Detection

 annihilation  scattering  DM production



The WIMP Miracle

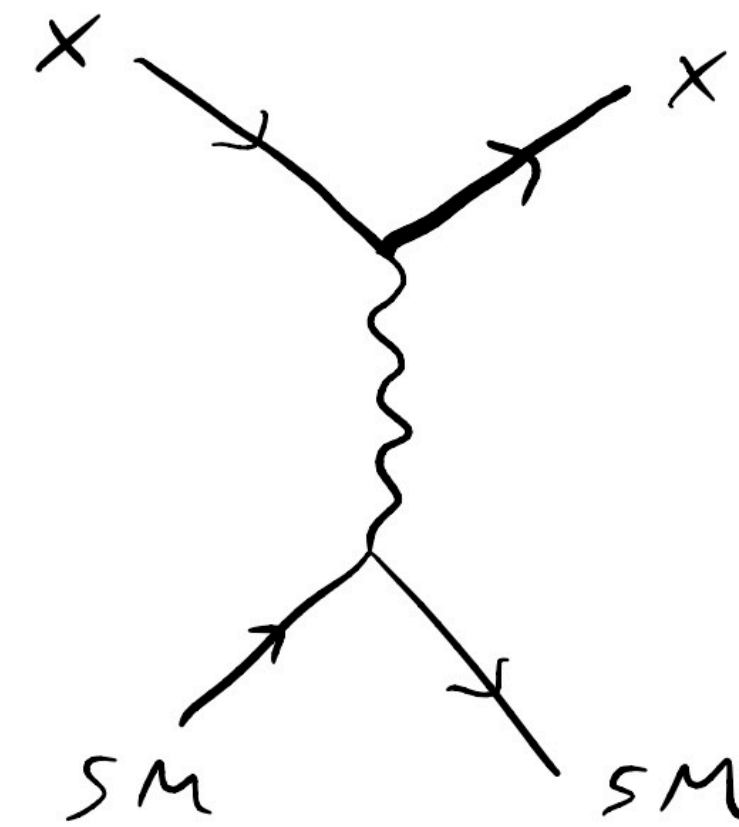
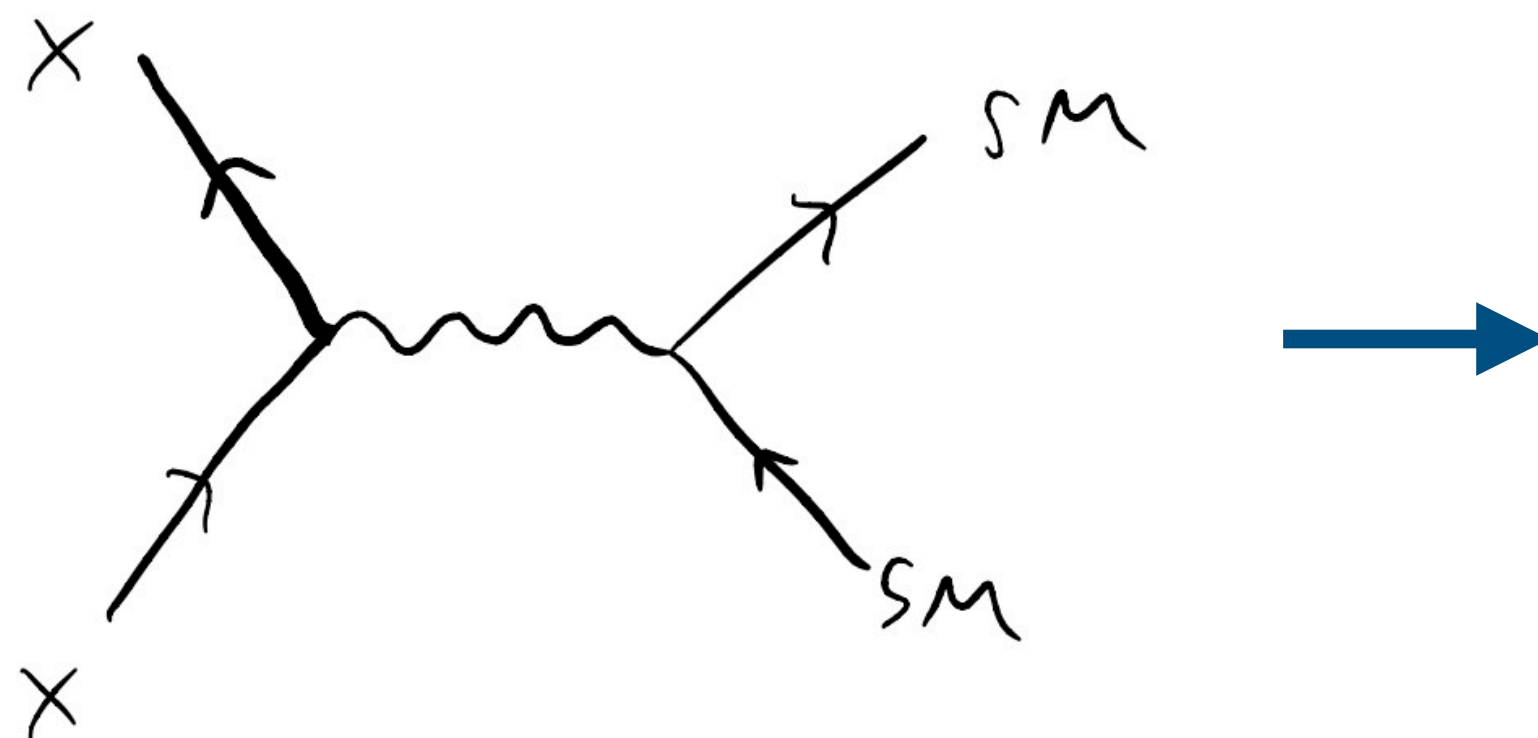


As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

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

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

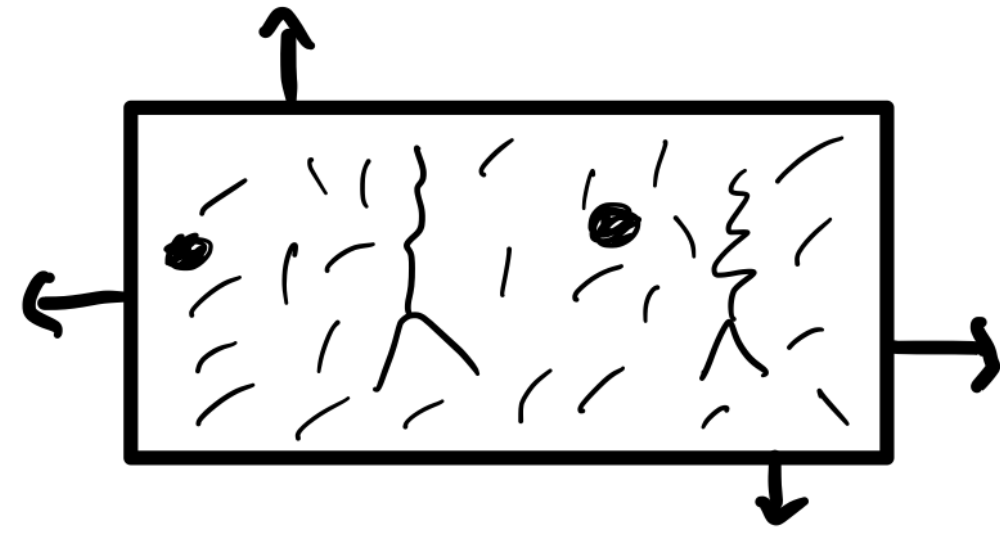
$$\Omega_x h^2 \sim 0.1 \left(\frac{m_v}{100 \text{ GeV}} \right)^2 \left(\frac{0.03}{\alpha_w} \right)^2$$



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

Some symmetry arguments imply interactions at dark matter experiments.

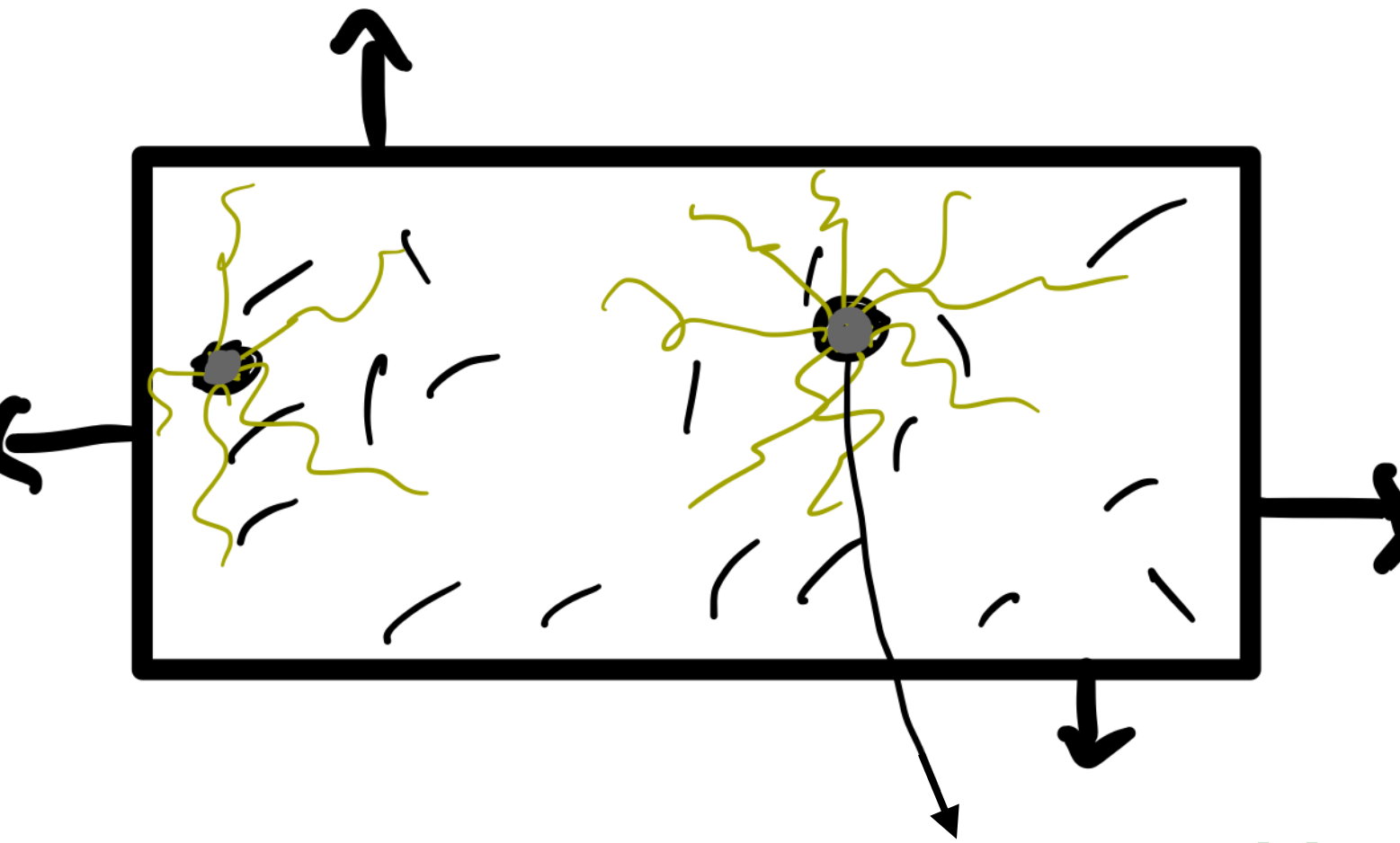
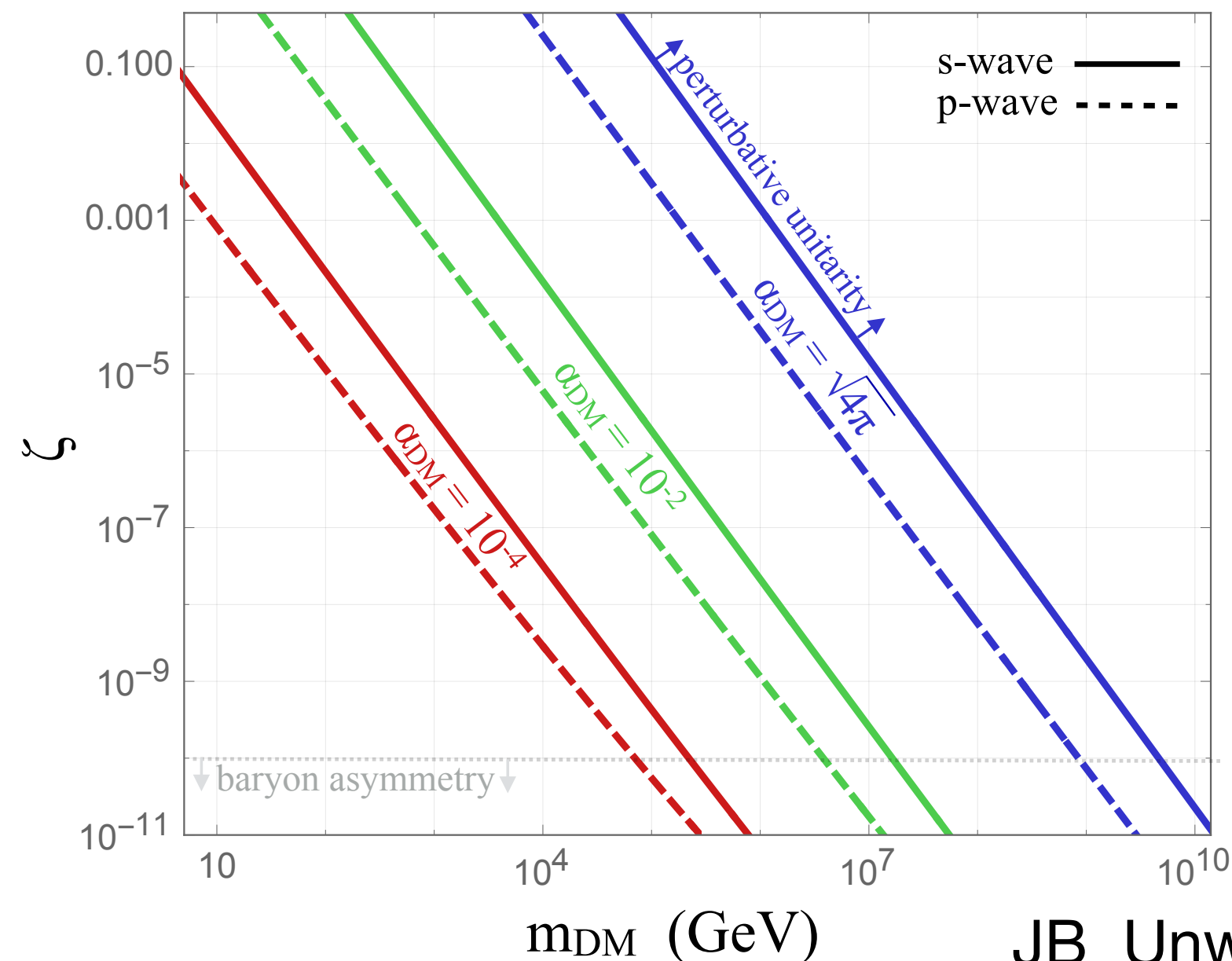
Diluted WIMP Dark Matter: heavier



Overabundant freeze-out

Then dilution from decay →

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



Motivation

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

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

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

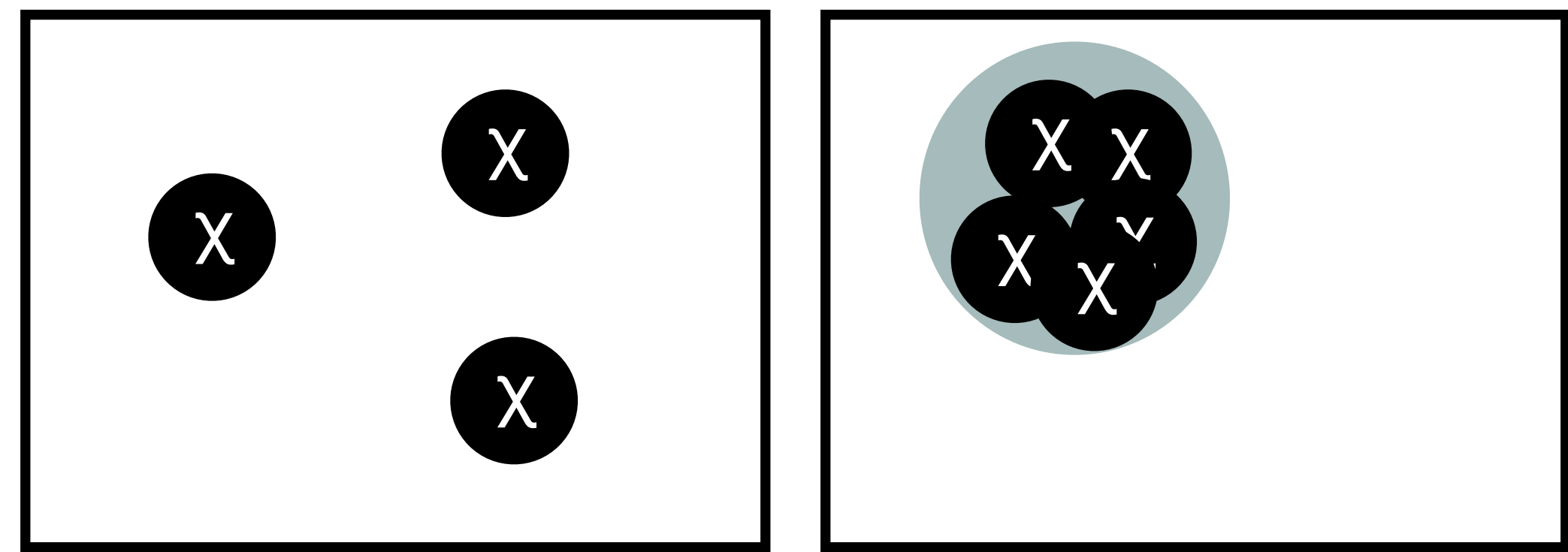
Consider a simple model of fermionic DM coupled by a scalar field

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

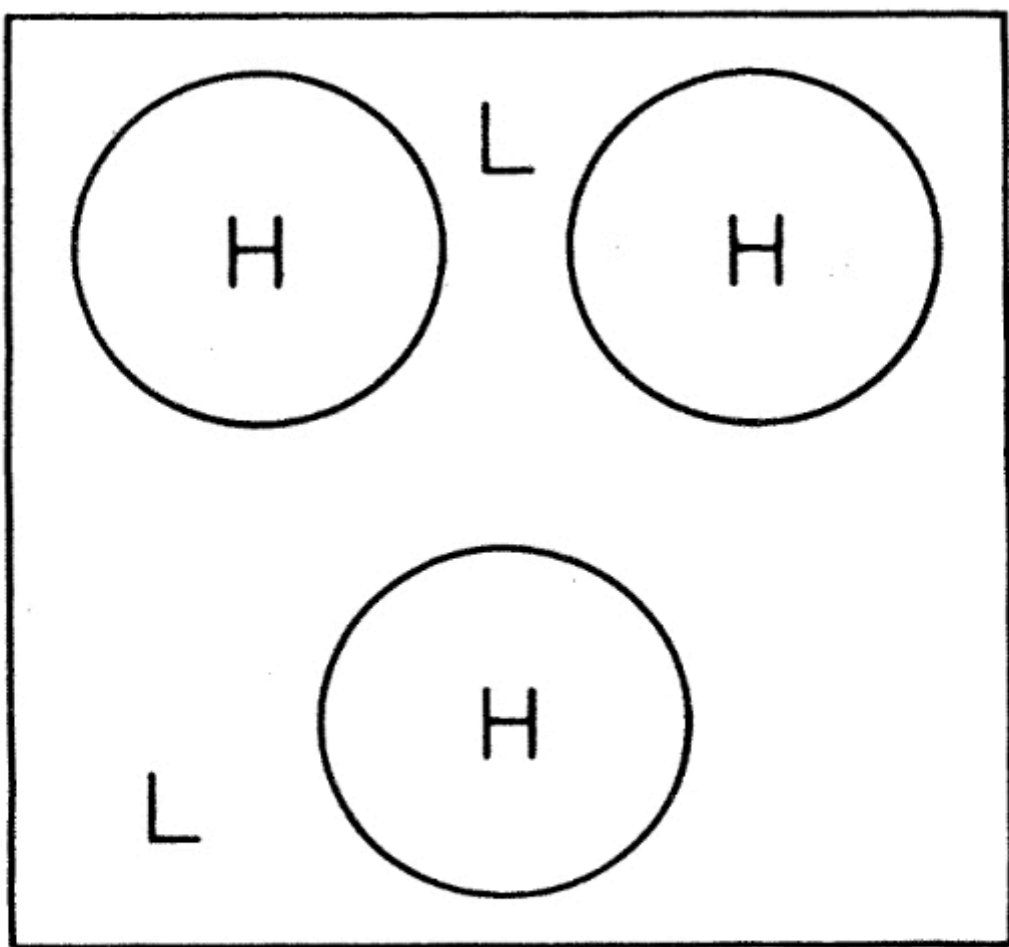
Diluted dark matter has a freeze-out abundance that scales with ζ^{-1}

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



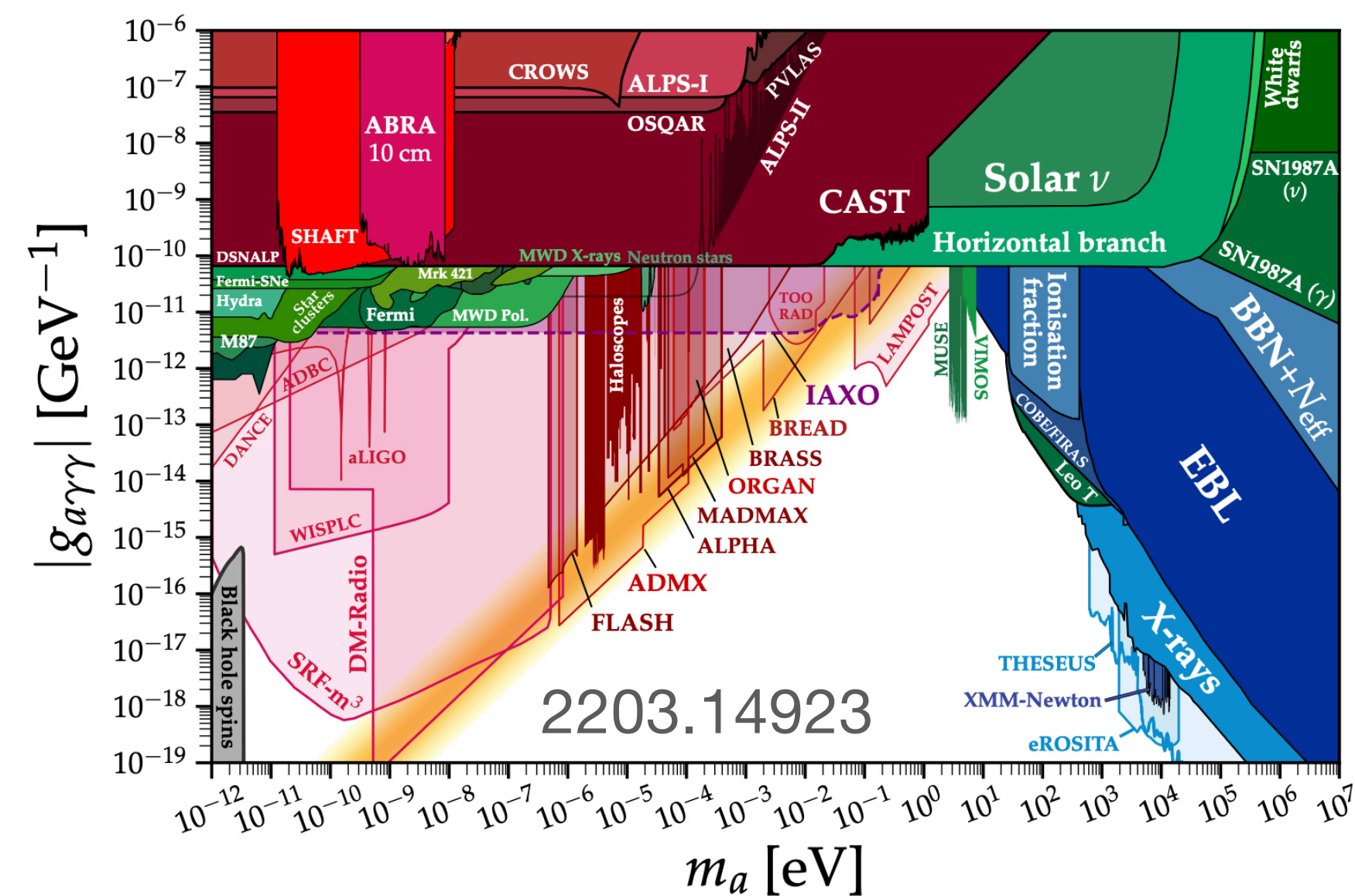
Models of quark matter forming during 1st order PT



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

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

SKIM THROUGH DM SEARCHES



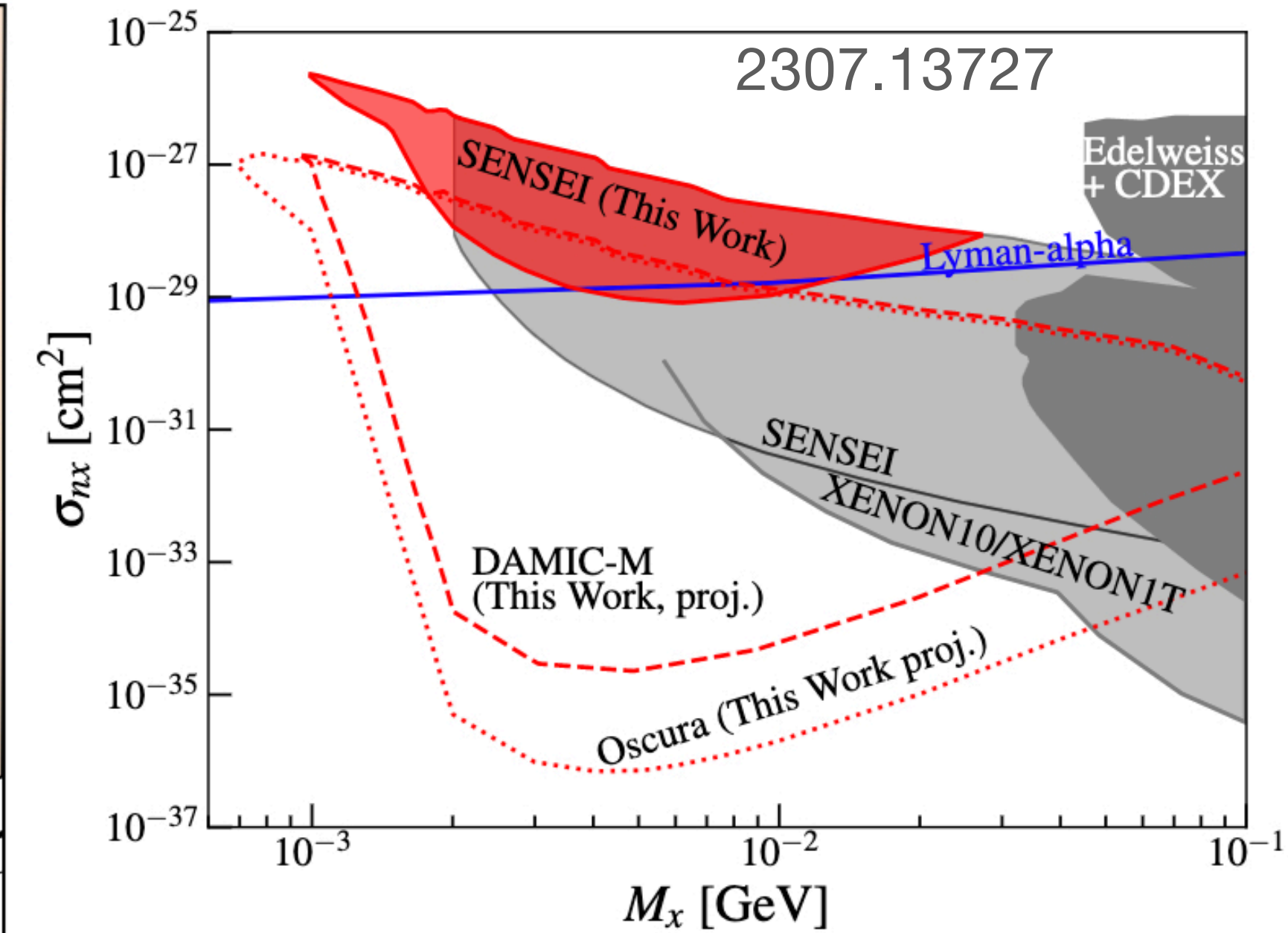
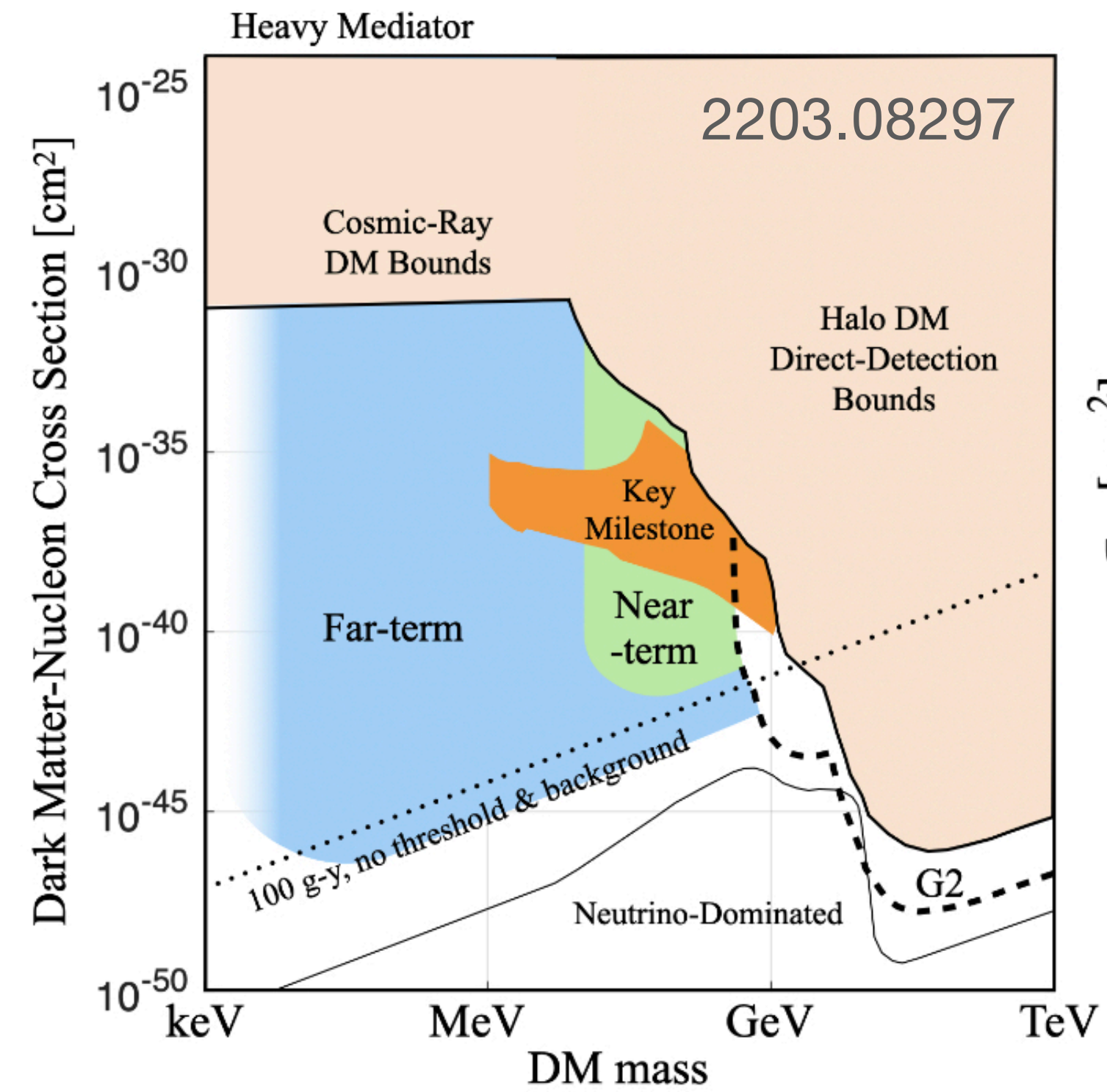
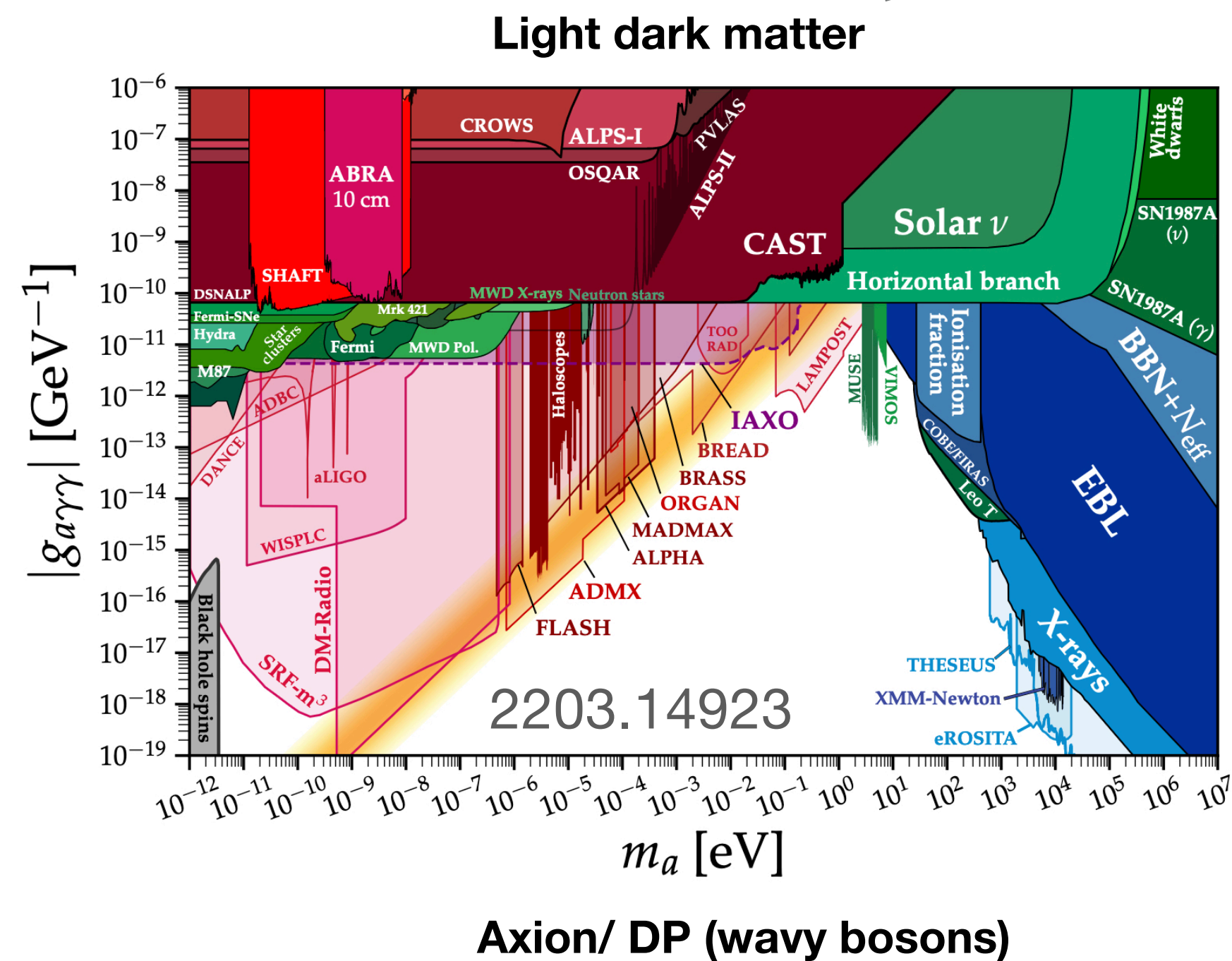
Axion/ DP (wavy bosons)

Preskill, Wise, Wilczek '83
Abbott, Sikivie '83



m_x (GeV)

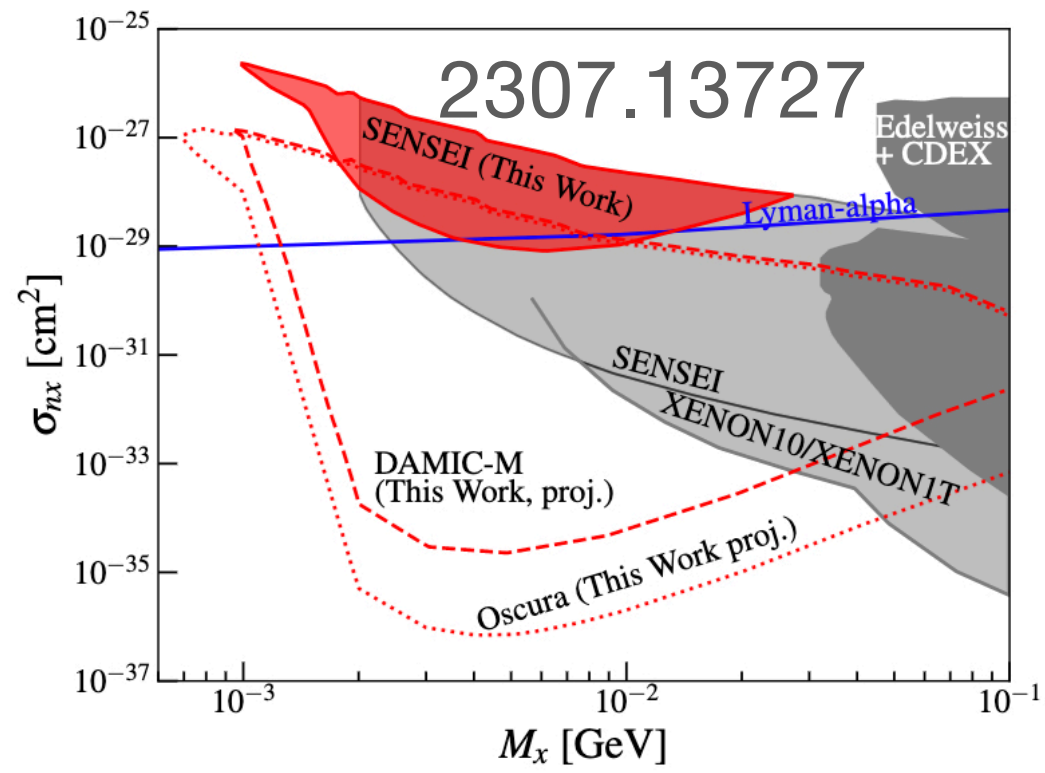
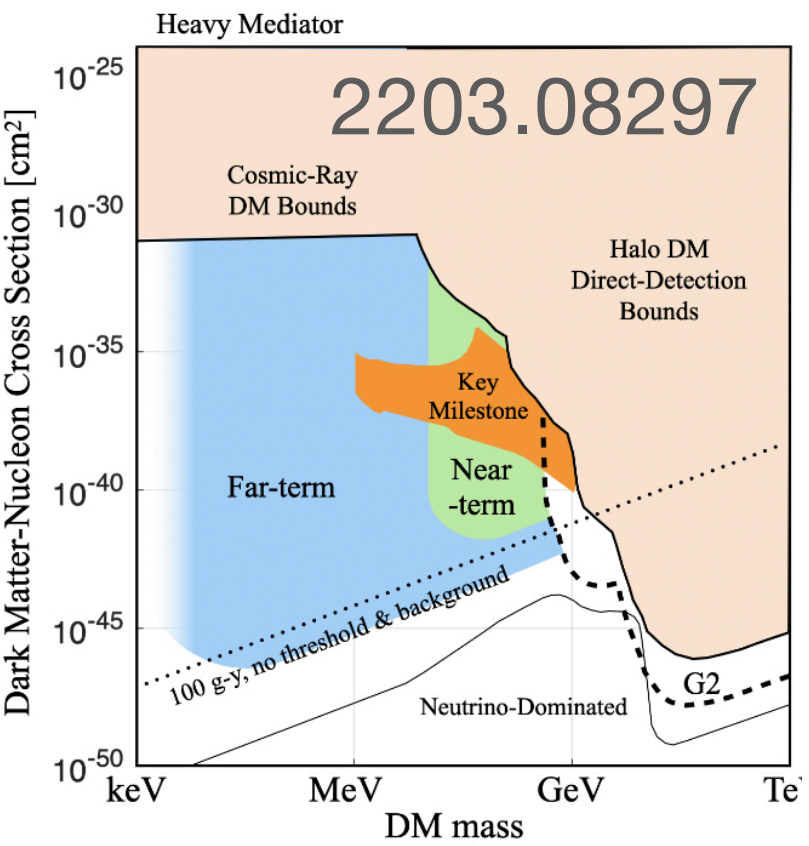
SKIM THROUGH DM SEARCHES



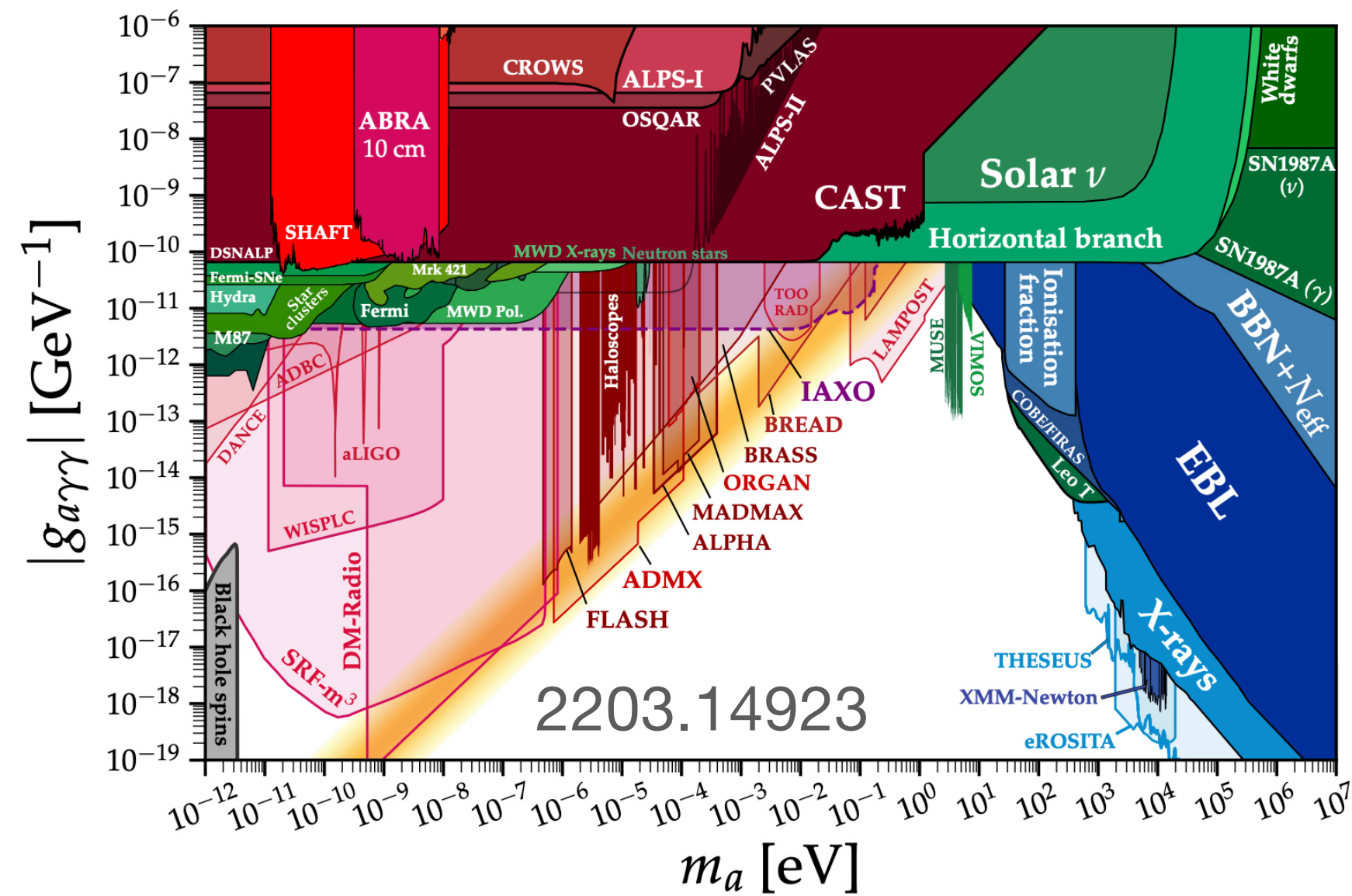
Melissa Diamond, Chris Cappiello,
Vincent, JB

$m_x (\text{GeV})$

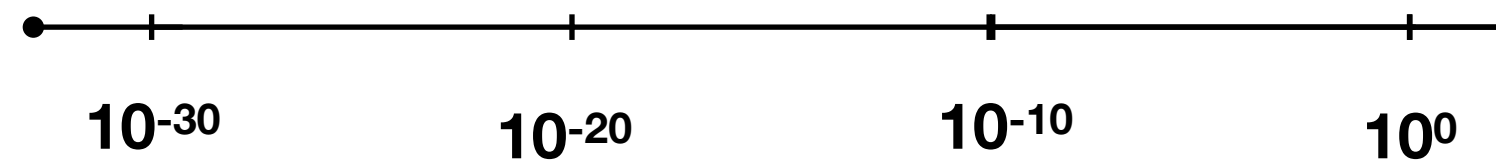
SKIM THROUGH DM SEARCHES



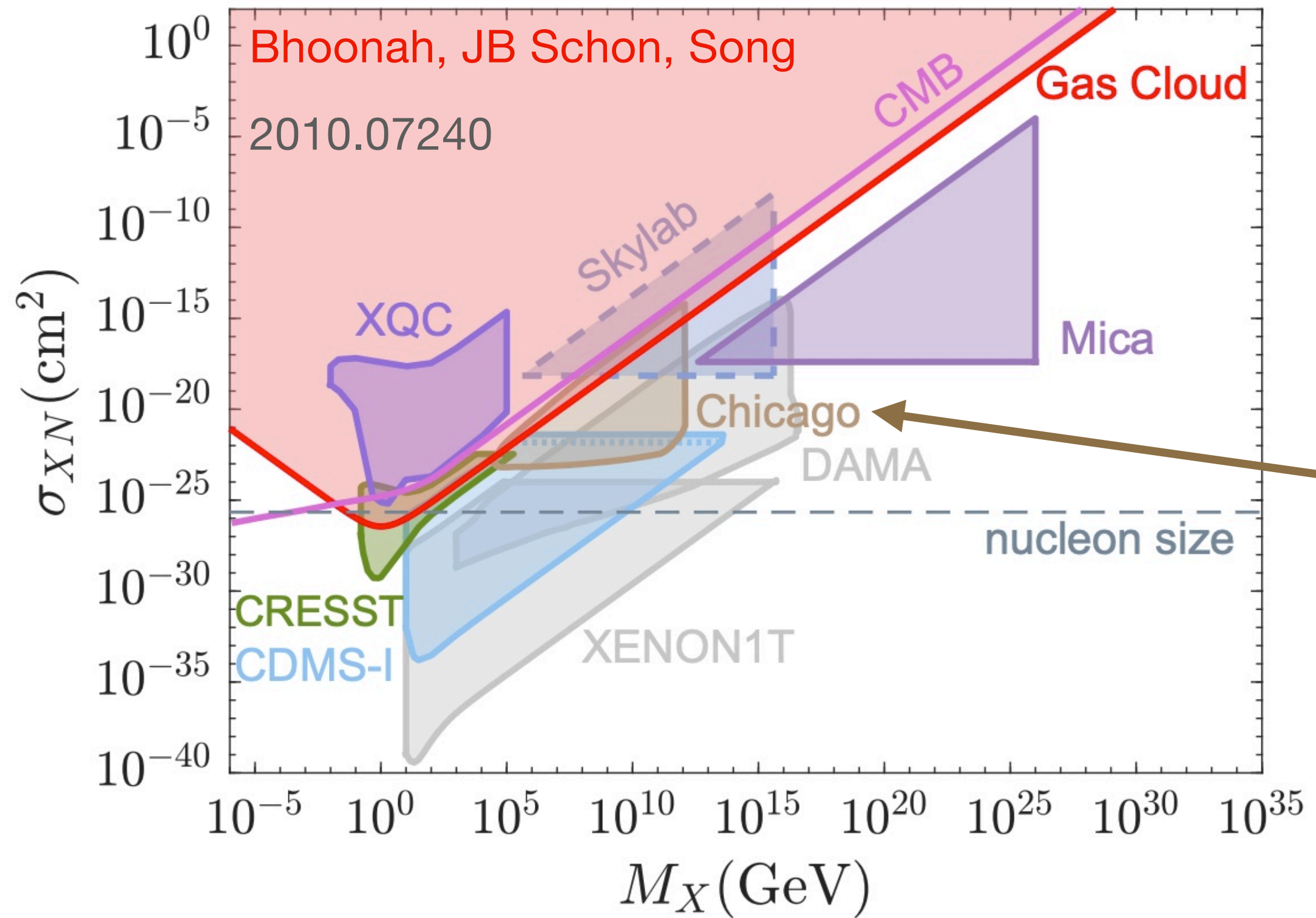
Light dark matter



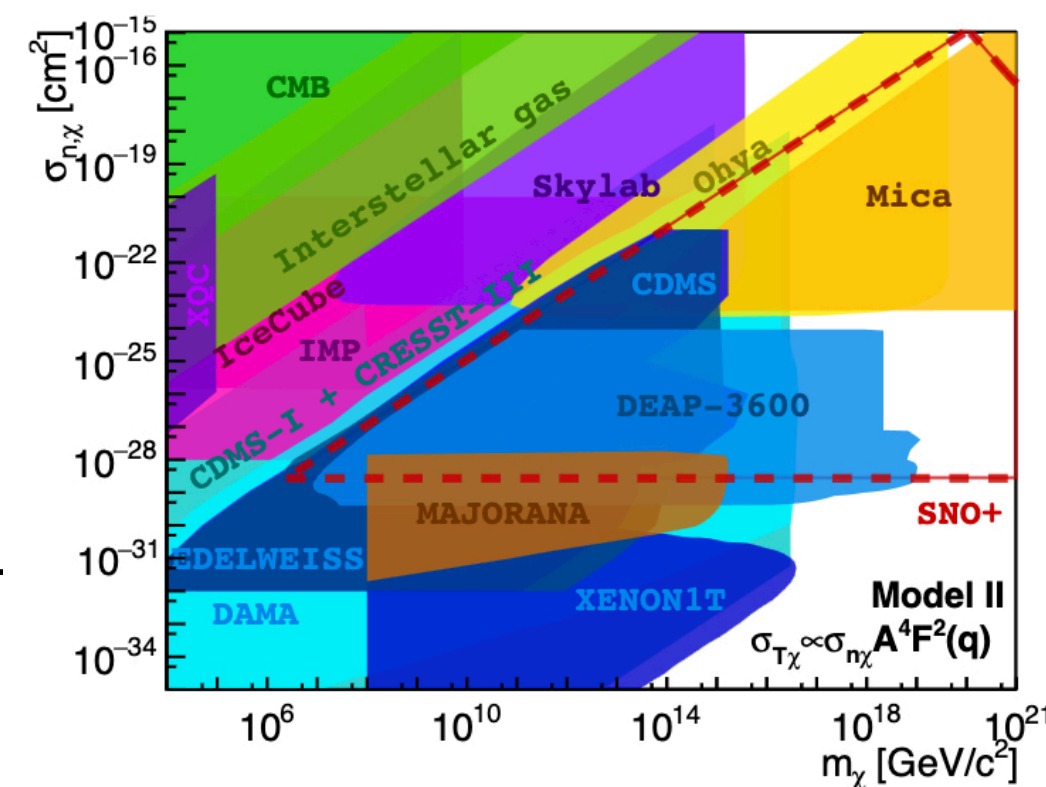
Axion/ DP (wavy bosons)



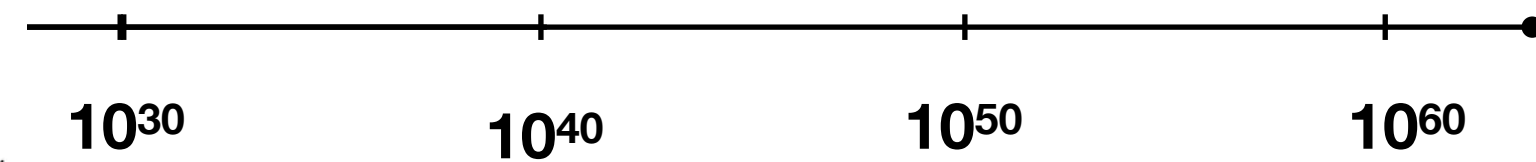
Heavy dark matter



Cappiello, Collar, Beacom

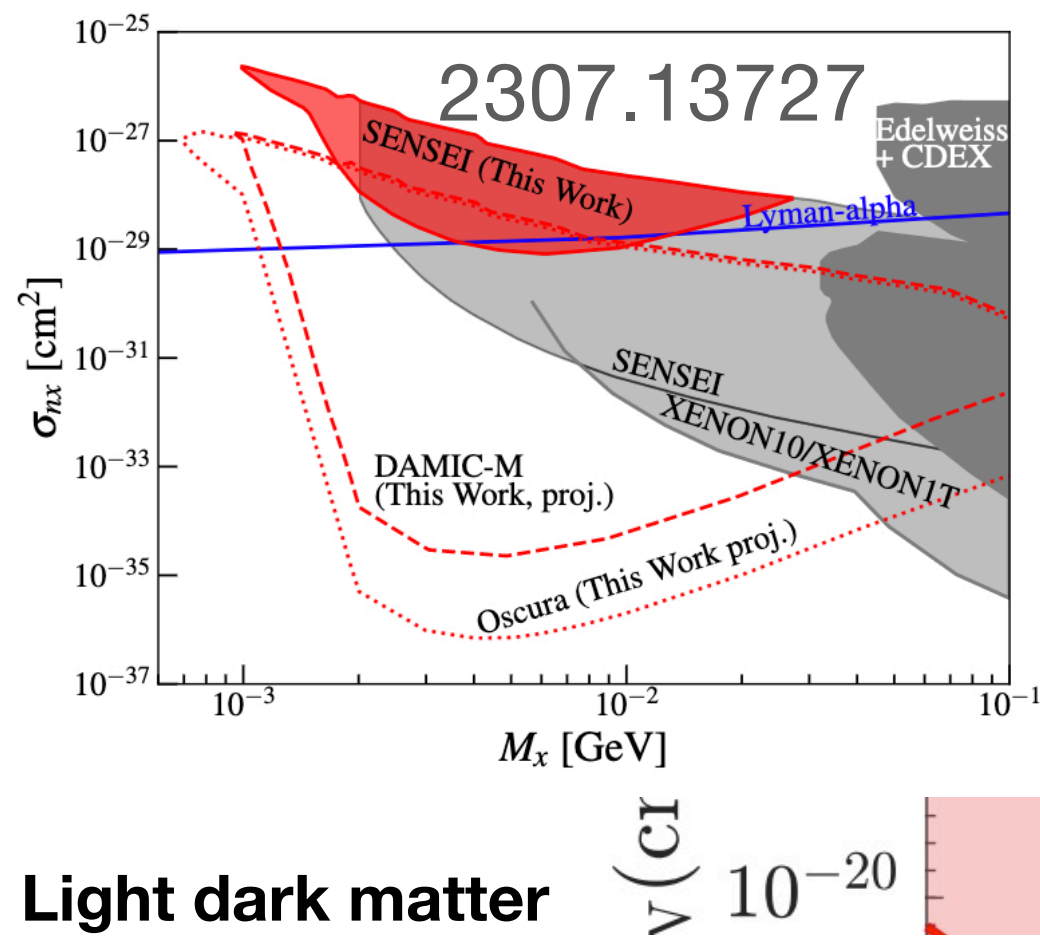
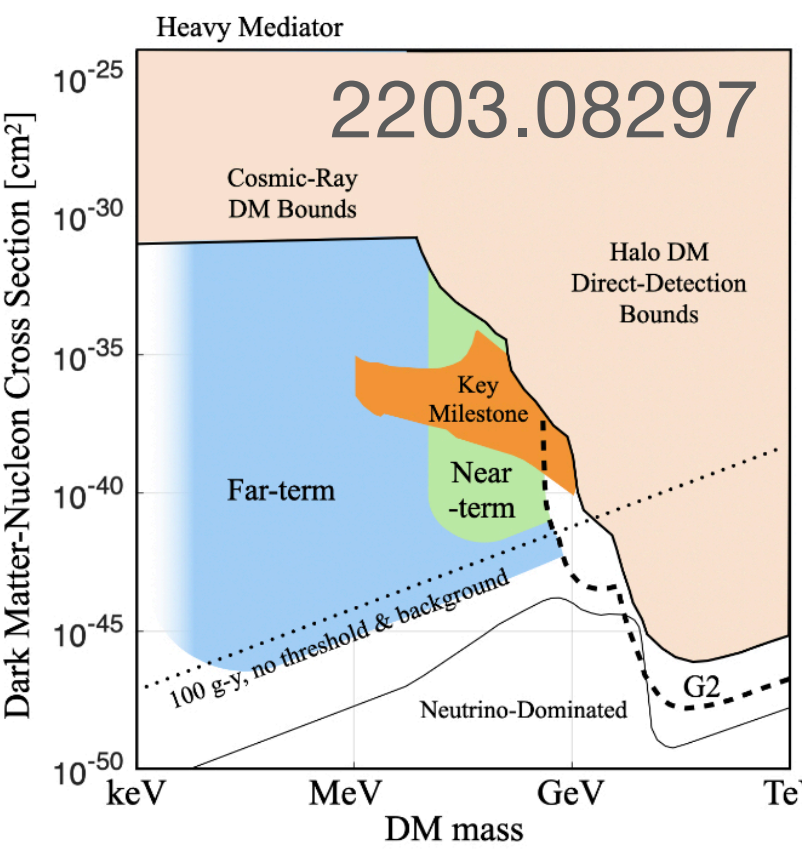


high m, σ composites
Witten '84


$$m_x \text{ (GeV)}$$

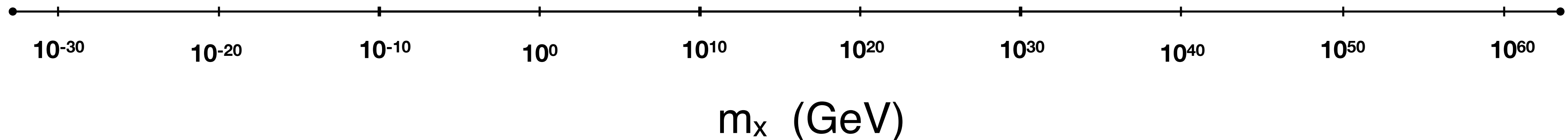
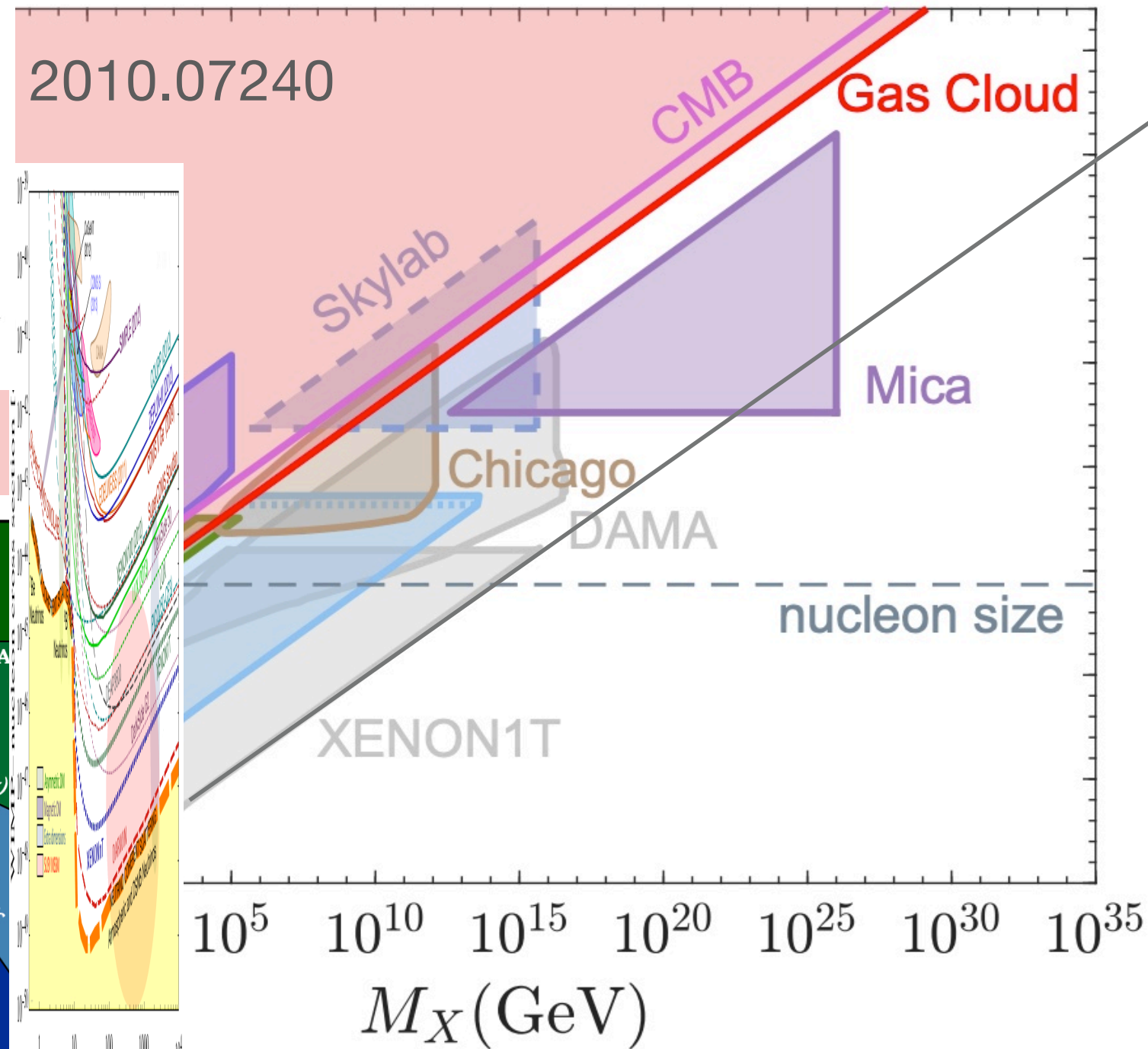
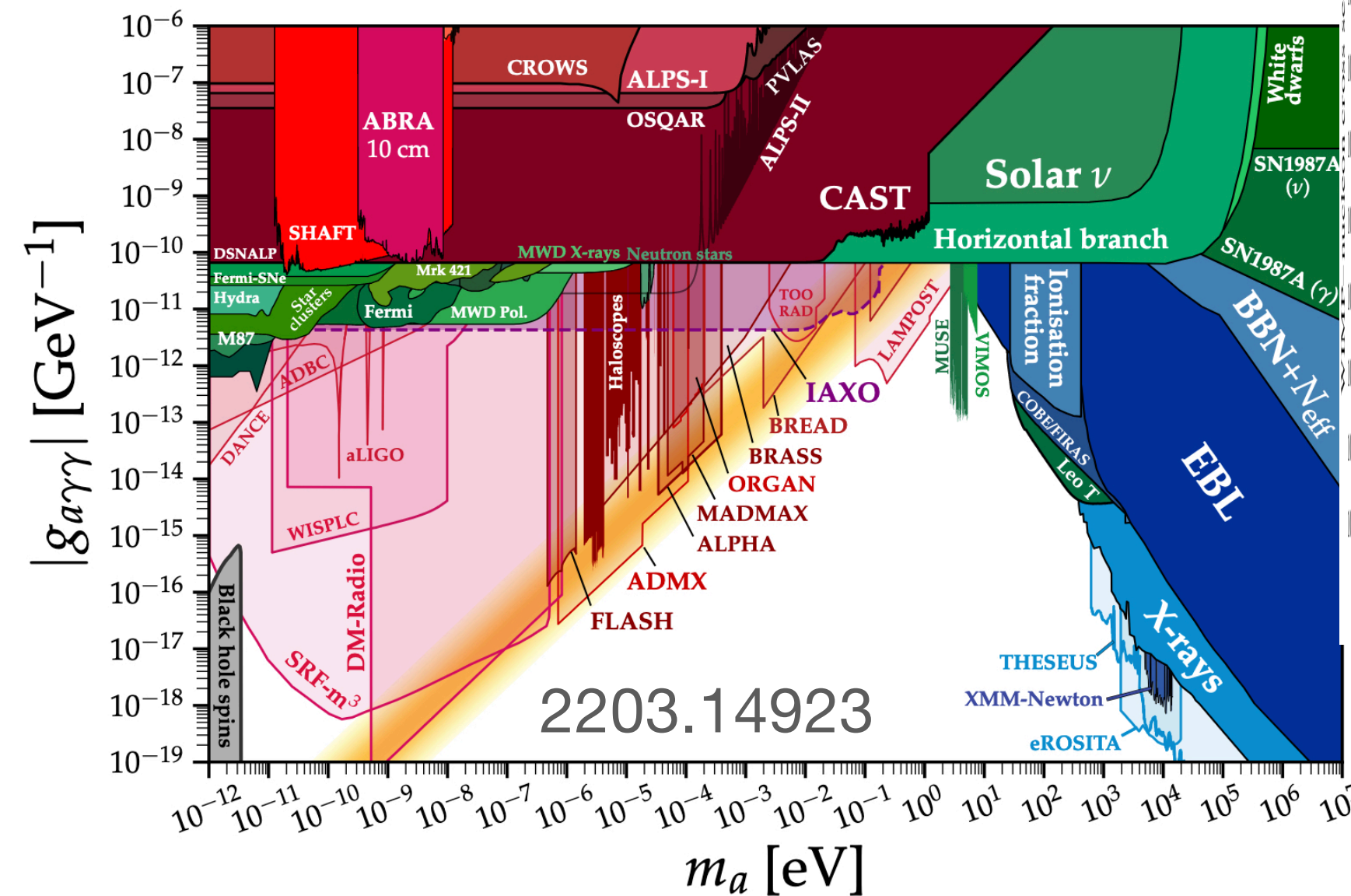
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SKIM THROUGH DM SEARCHES

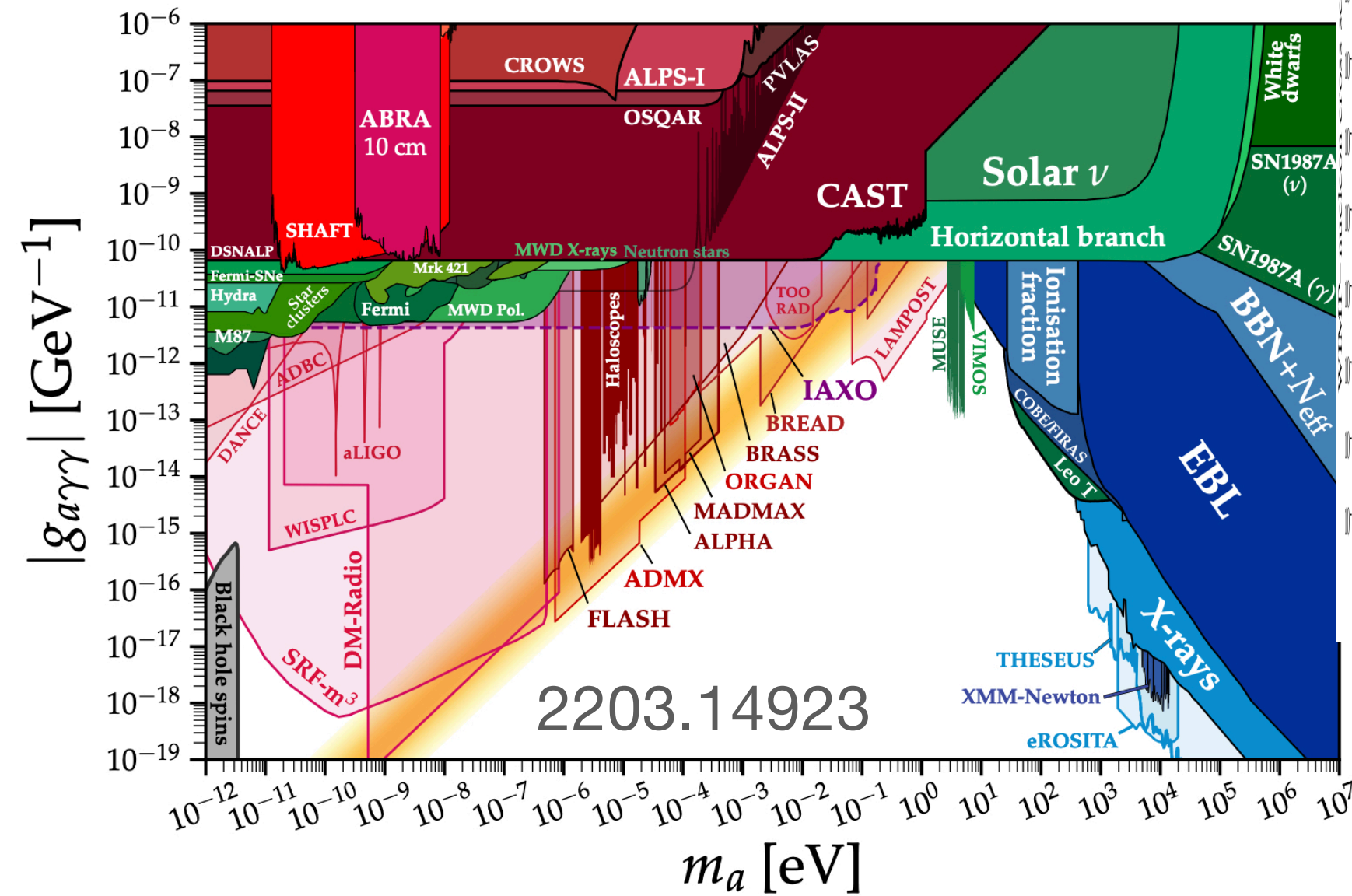
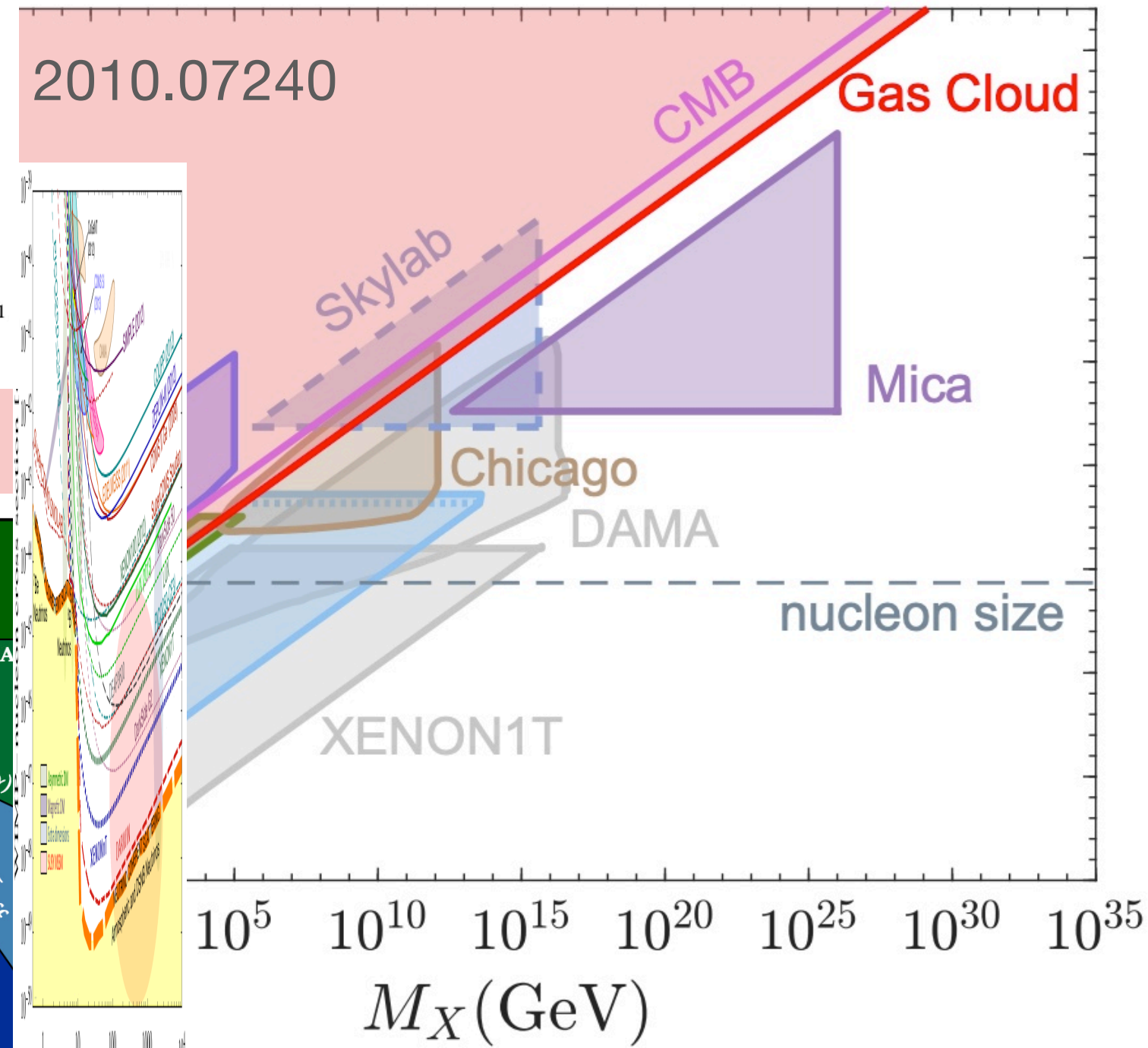
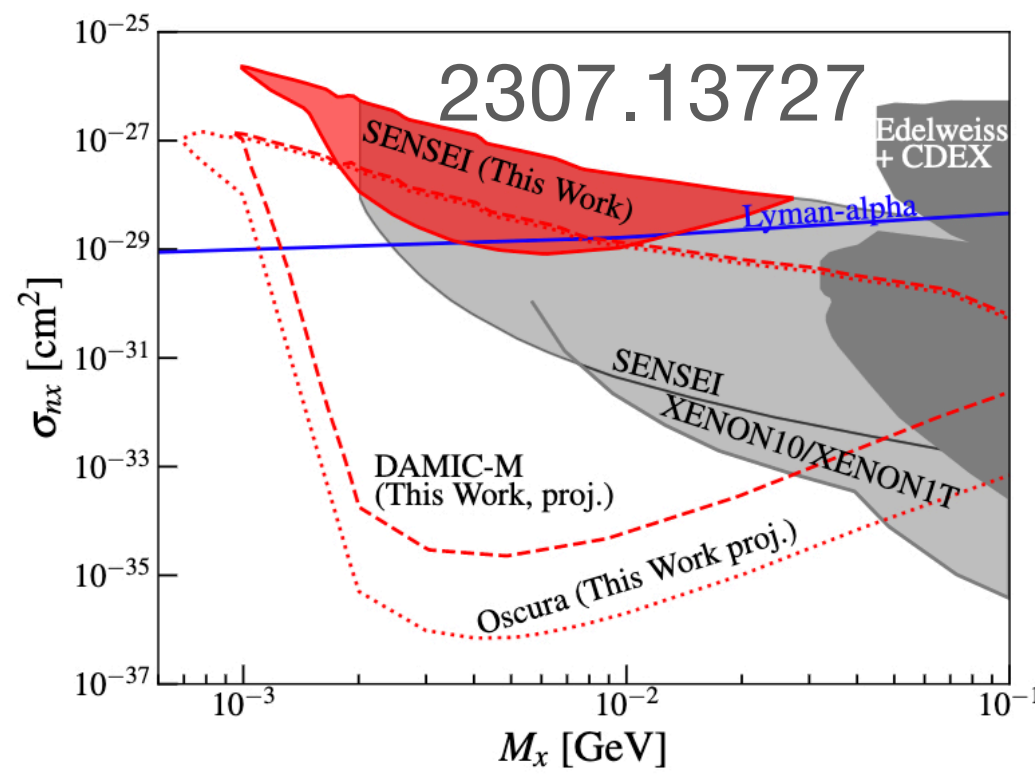
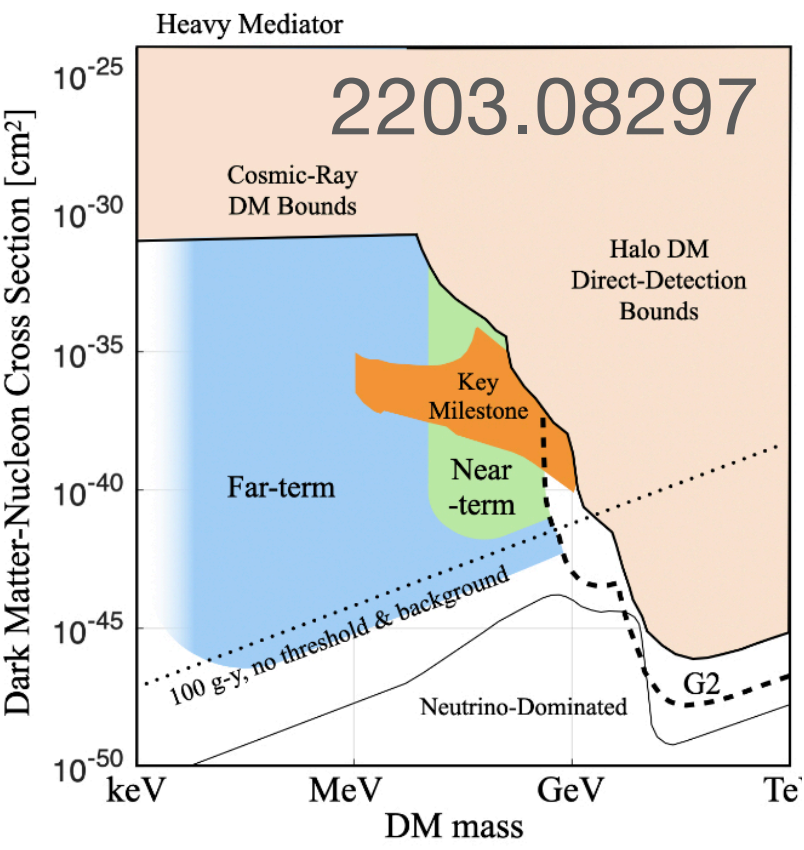


Neutron star infrared astronomy

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



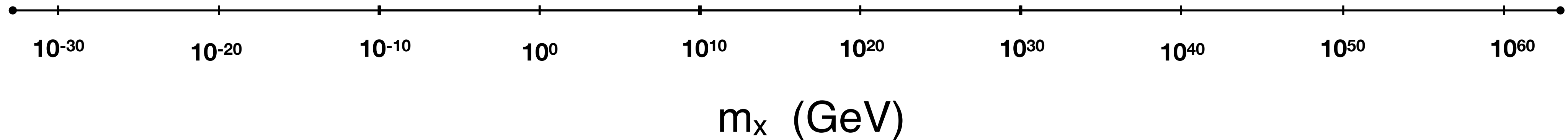
SKIM THROUGH DM SEARCHES



Axion/ DP (wavy bosons)

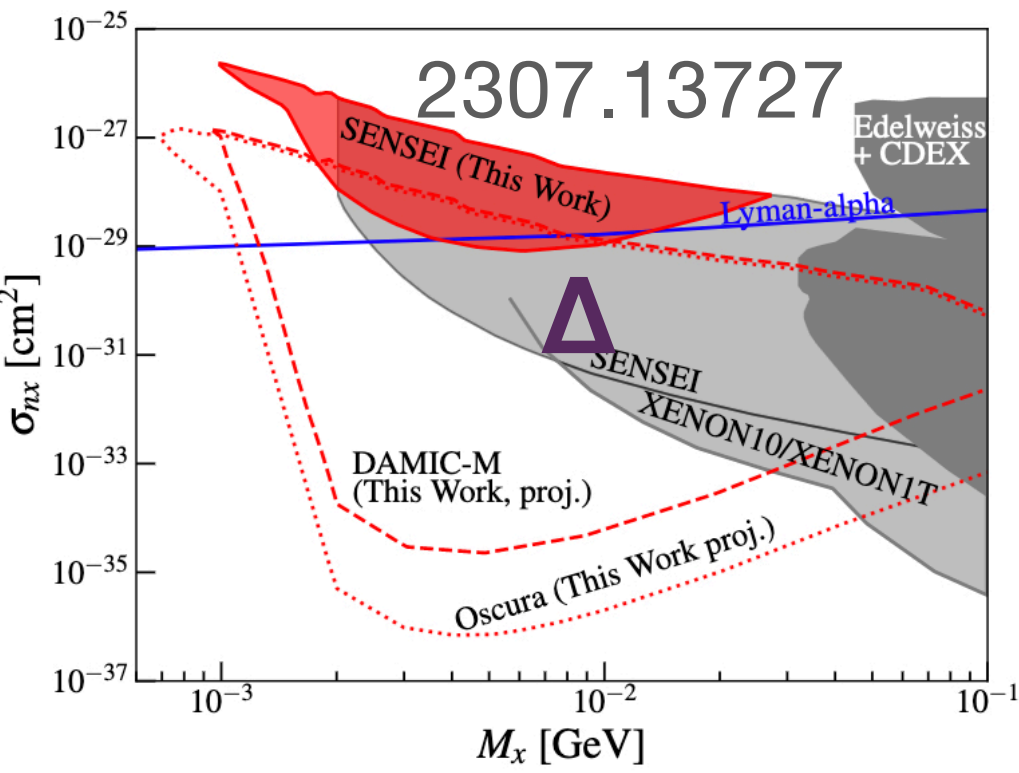
mass of heaviest nuclei
(liquid drop model, condition for fission
equating Coulomb energy with surface term)

$$\frac{(A/2)^2 \alpha_{em}}{A^{1/3} r_f} \sim 2 \Lambda A^{2/3} \quad A \sim \frac{1}{\alpha_{em}} \sim 100$$

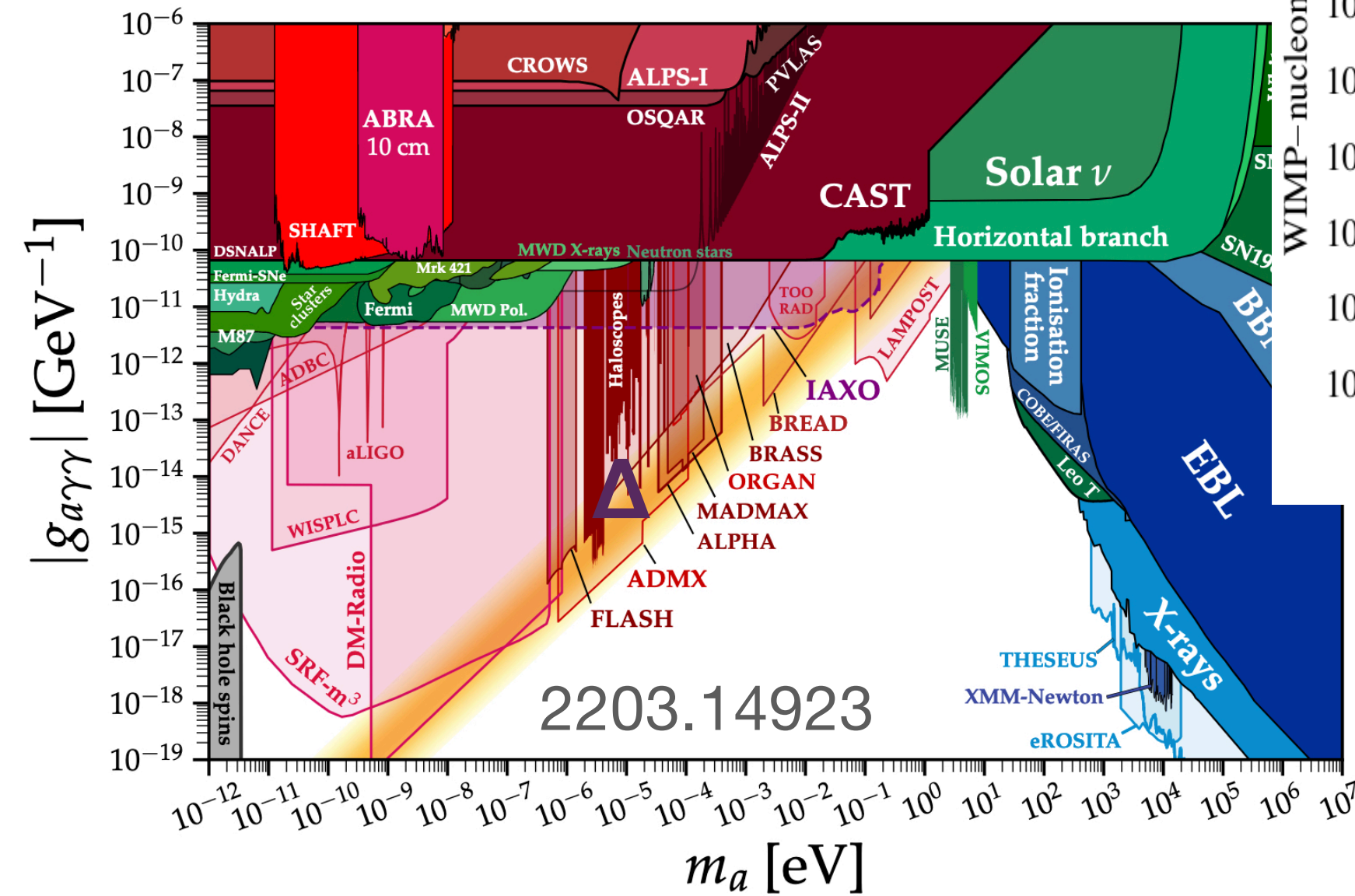


PRICE OF DM DETECTION

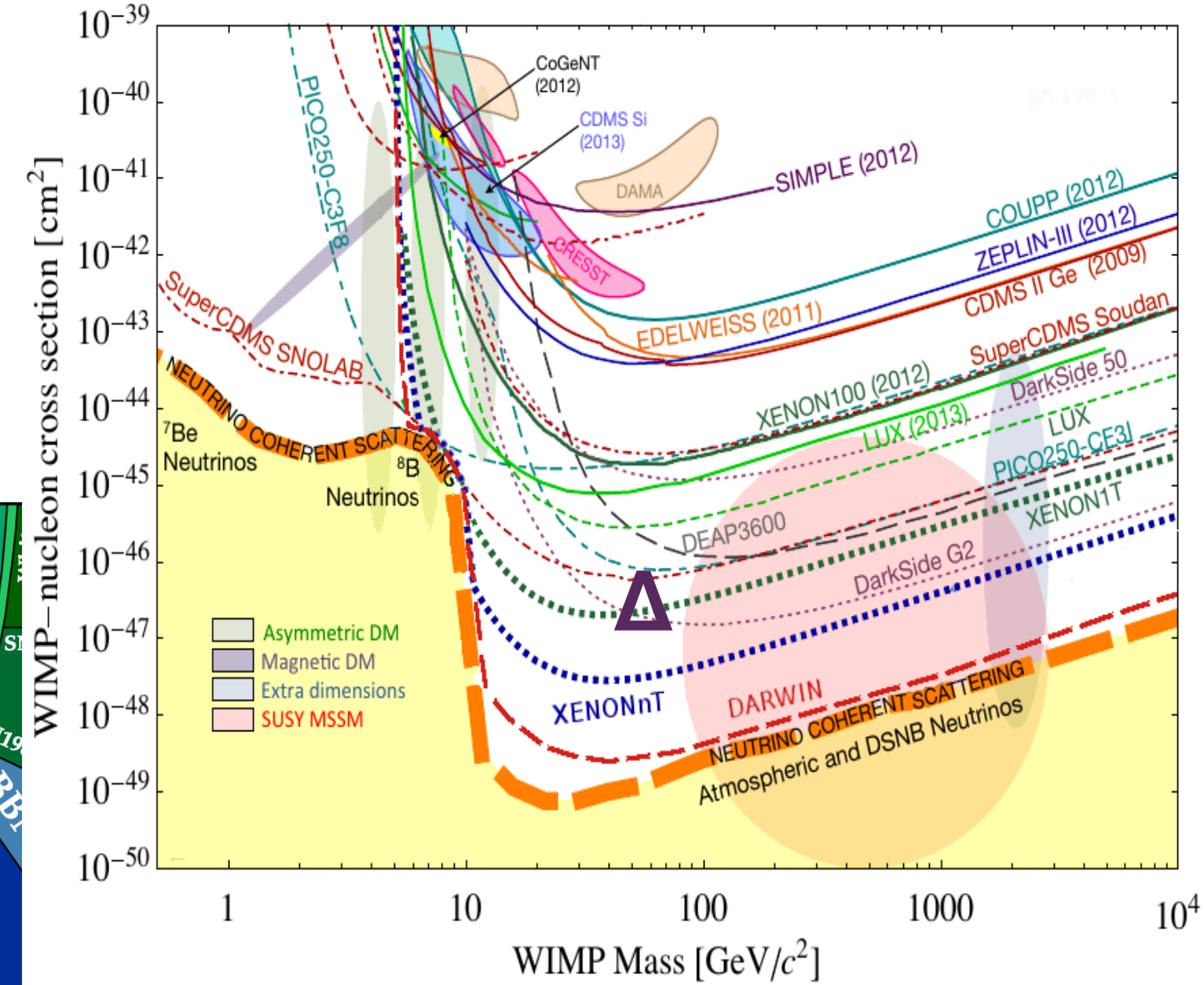
current price of DM $\sim \$ (10^5 - 10^6) \times \log_{10}(\Delta\sigma) \times \log_{10}(\delta m_X)$



Light dark matter

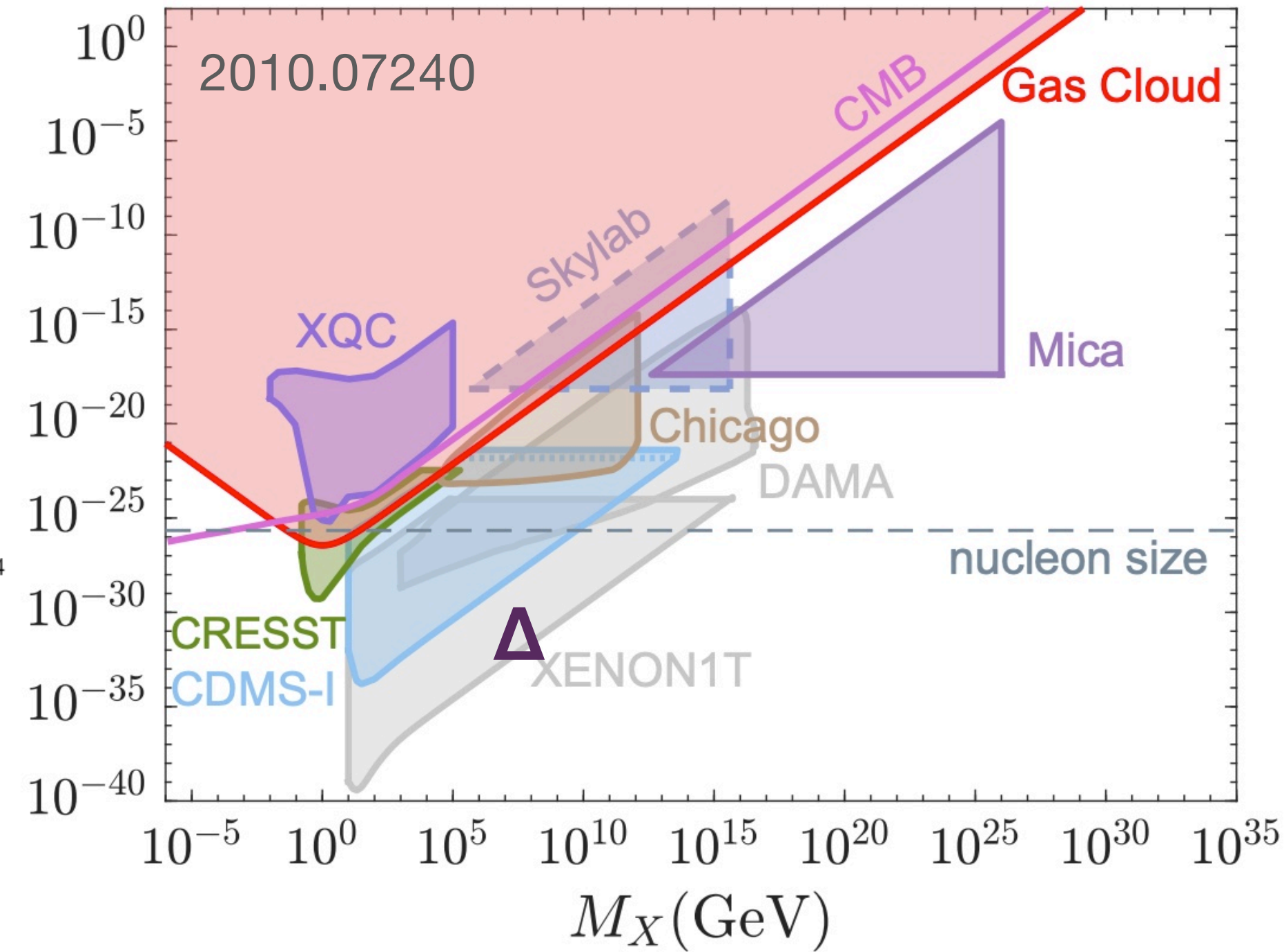


Axion/ DP (wavy bosons)



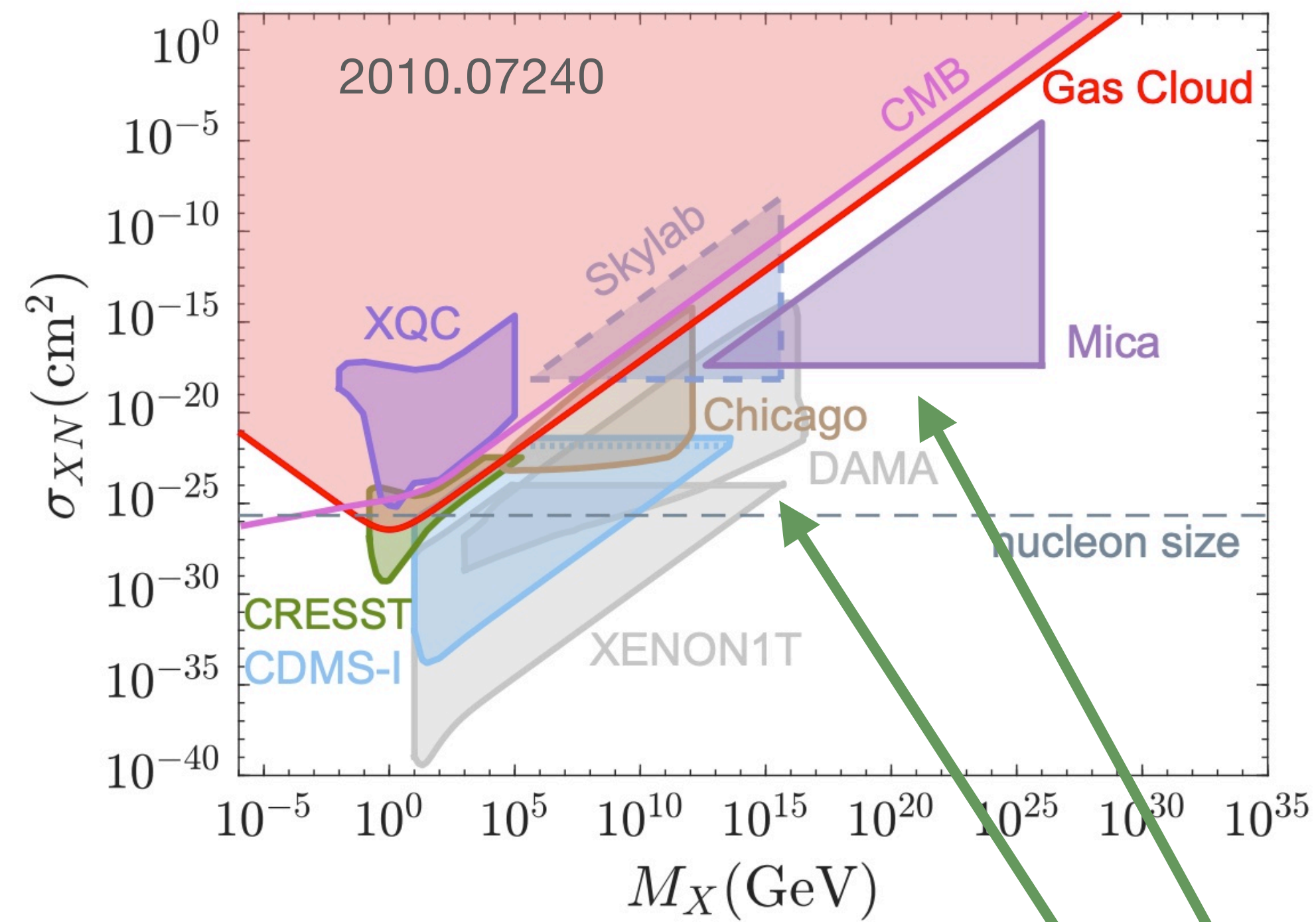
$$\Delta\sigma = \sigma_{\text{old}} / \sigma_{\text{new}}$$

relative to last searches

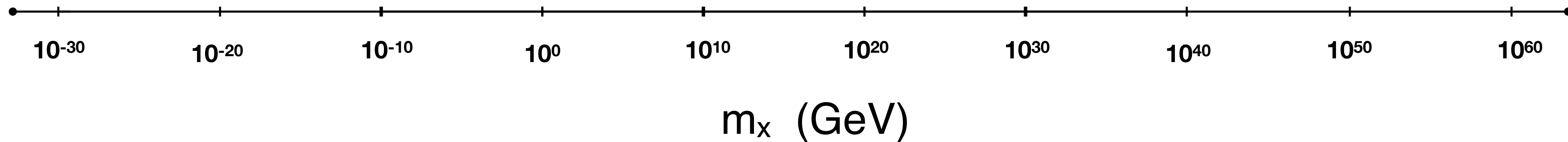


m_X (GeV)

HEAVY DARK MATTER



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



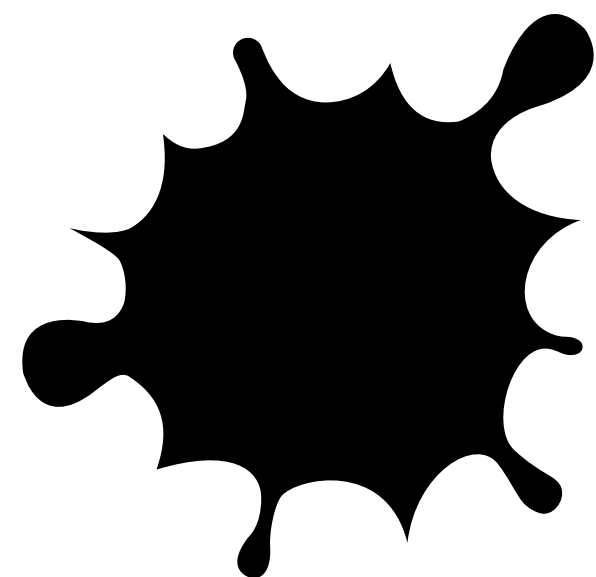
DM Models

Vis-a-vis heavy composite DM

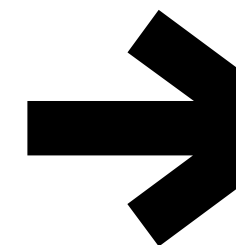
Nice to have a model

- Early matter domination
- Boson stars

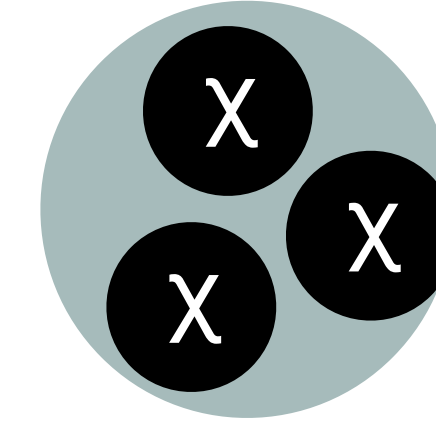
On the other hand: What
Lagrangian / cosmology



Predict masses from 1st principles



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



- Q ball
- Dark QCD/BBN
- Molecular DM

Information still has open
(e.g. pebble accretion).

Composite DM doesn't have
dynamics like single-field
models

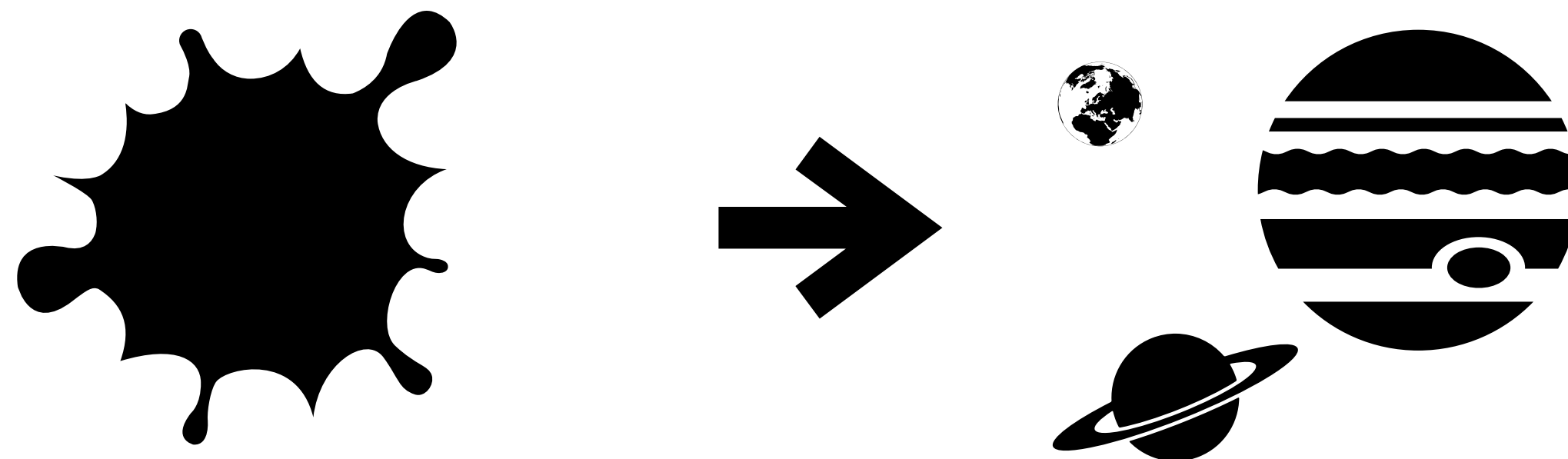
DM Models

Vis-a-vis heavy composite DM

Nice to have a model

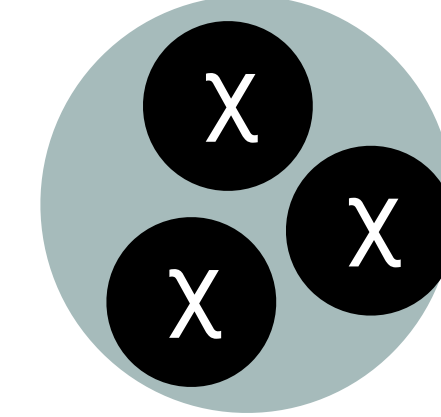
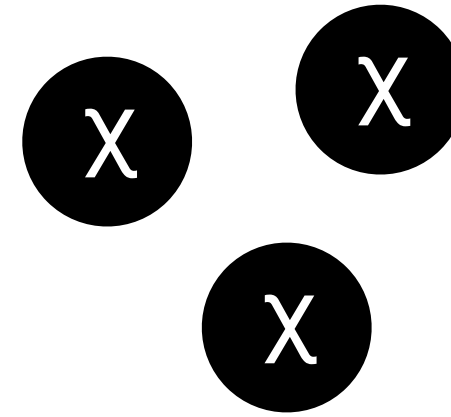
- Early matter domination
- Boson stars
- Dissipative dark sector
- Fermion stars
- Q ball
- Dark QCD/BBN
- Molecular DM

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



Predict masses from 1st principles?

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



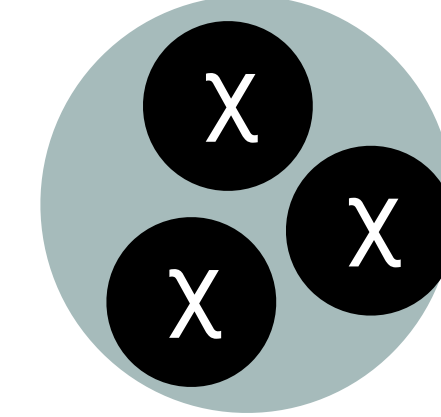
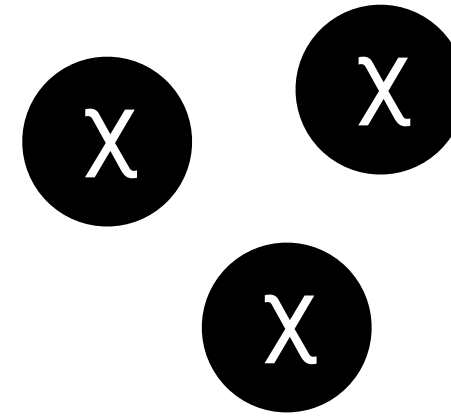
- Planet formation still has open questions (e.g. pebble accretion).
- Heavy composite DM doesn't have simple dynamics like single-field DM models

DM Models

Vis-a-vis heavy composite DM

Nice to have a model

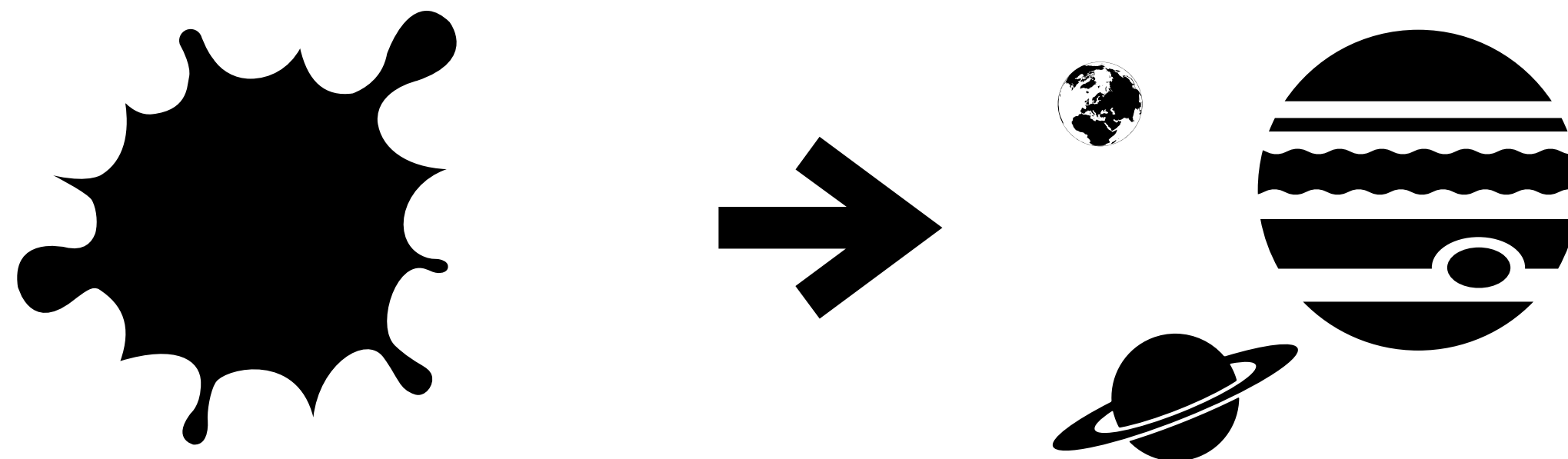
$$- \mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\phi X - \frac{1}{2}m_\phi^2\phi^2 + g_n\bar{n}\phi n + \mathcal{L}_{SM},$$



- 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

HIGH MASS ASYMMETRIC COMPOSITE DM

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

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

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

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

Javier Acevedo, JB, Goodman 2012.10998

see also e.g.

Wise Zhang '14

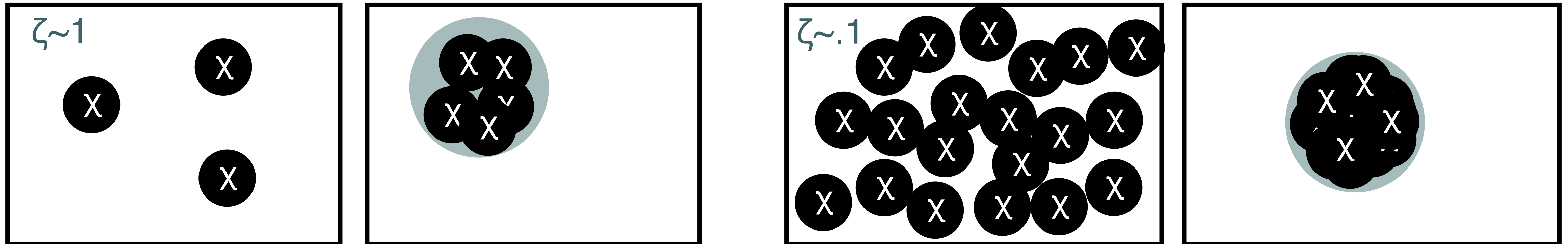
Krnjaic Sigurdson '14

Hardy Lasenby March-Russell '14

Detmold McCullough Pochinsky '14

Gresham Lou Zurek '17

Coskuner, Grabowska, Knapen, Zurek '18



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

Composite mass ranging from milligrams to thousands of tons

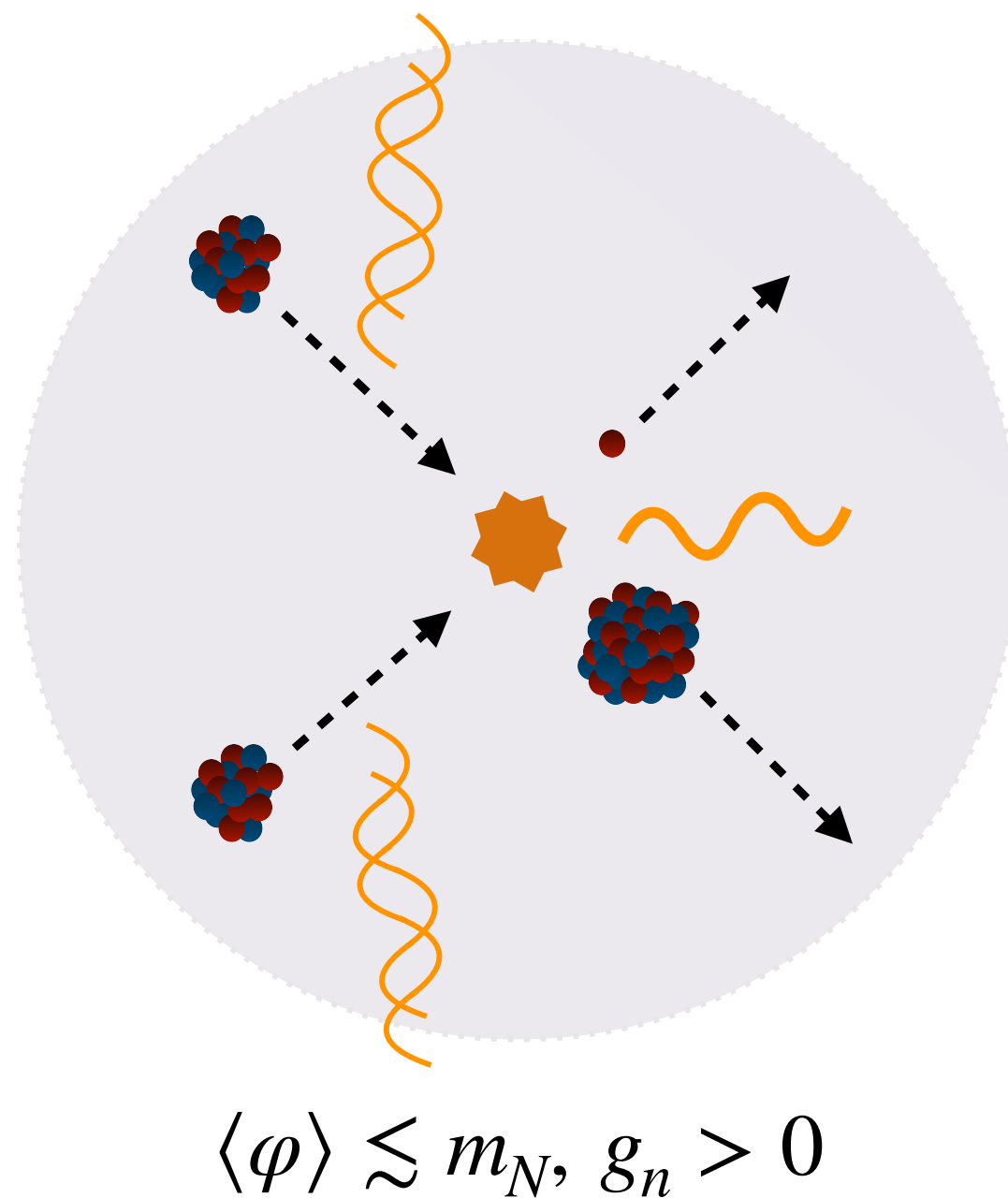
COMPOSITE INTERACTIONS

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

nuclear interactions with DM composite internal potential

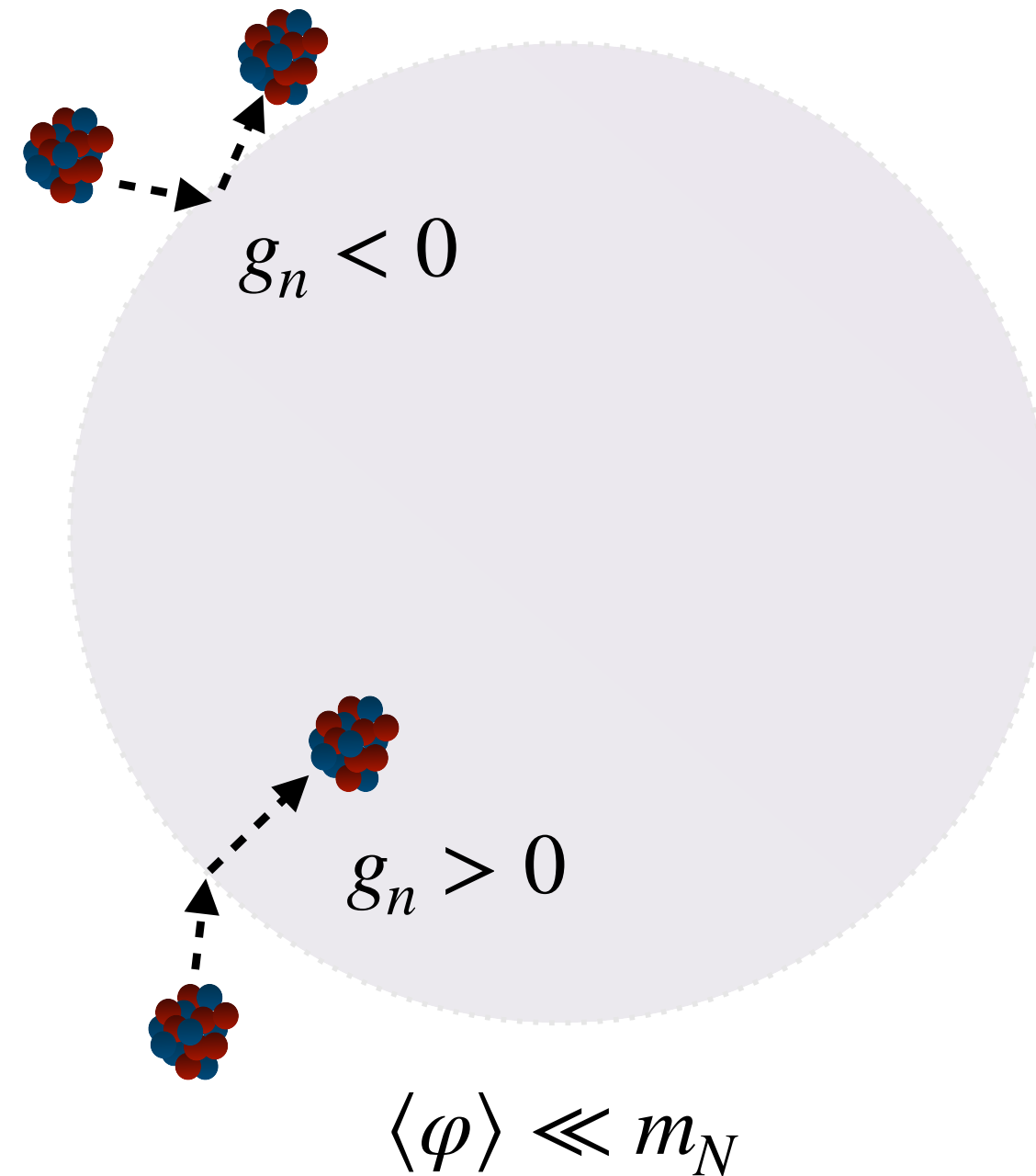
scattering with constituents

1.



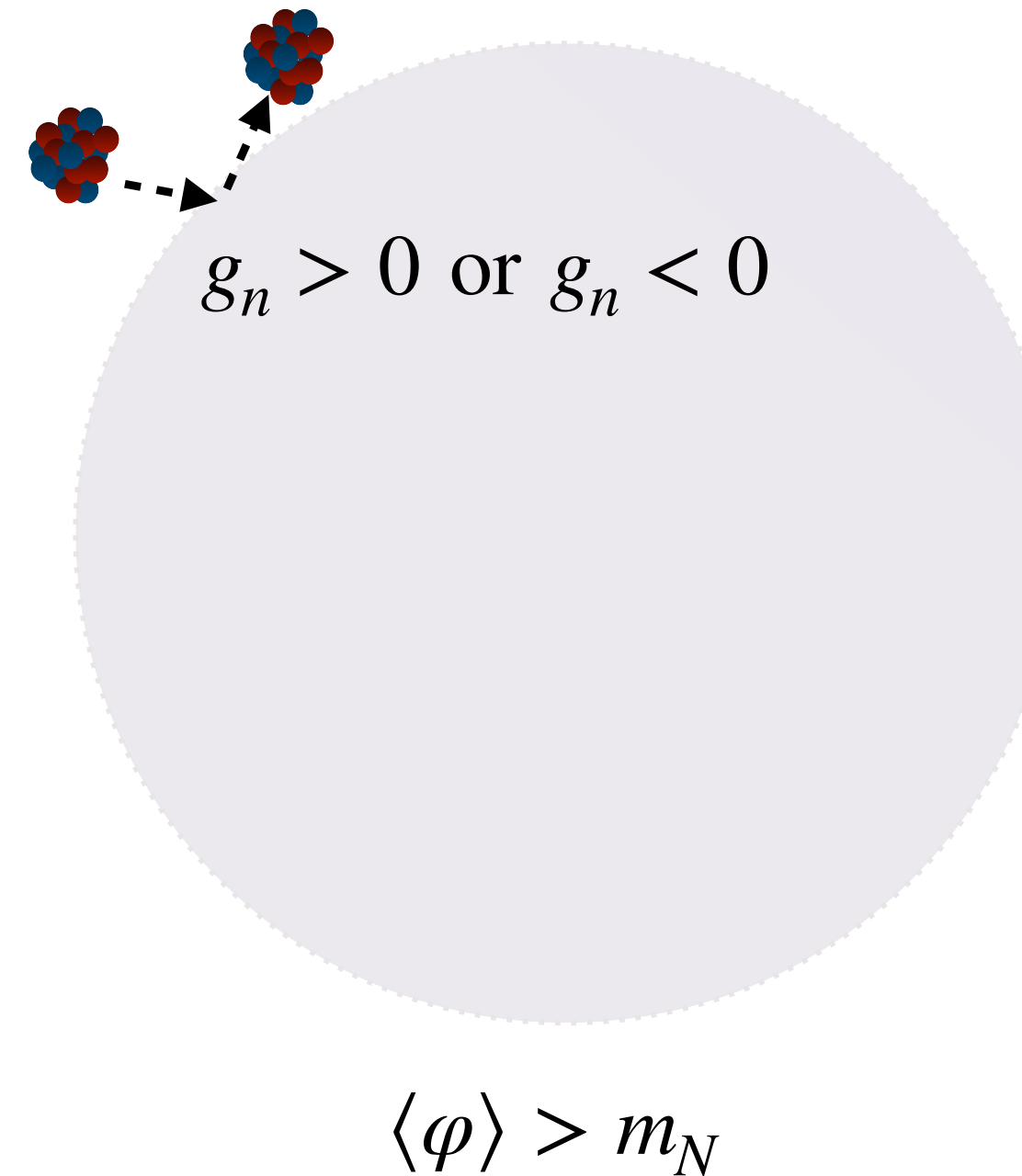
Acevedo, JB, Goodman
2012.10998

2.



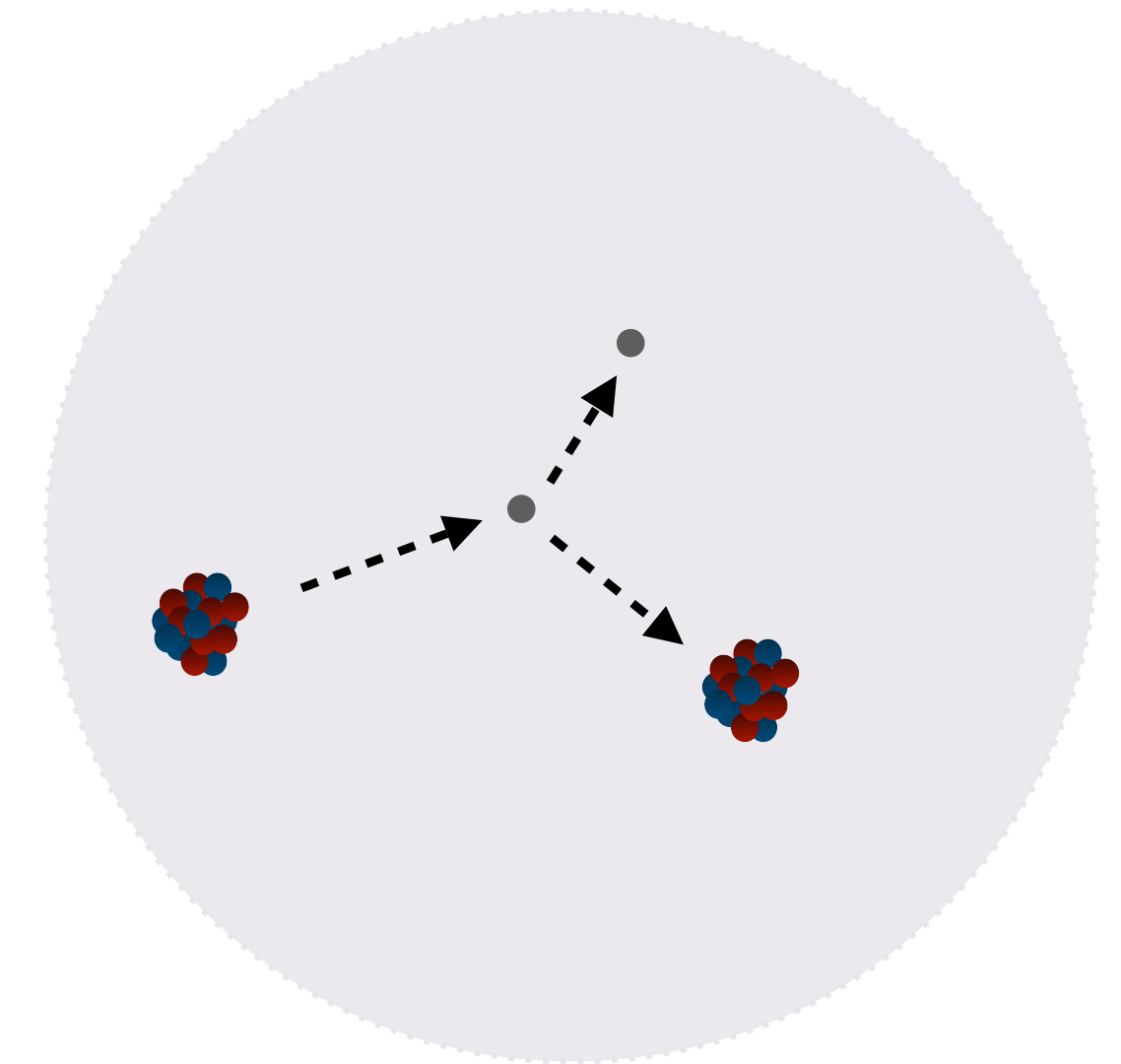
Acevedo, JB, Goodman
2108.10899

3.



(MIMPs)

4.



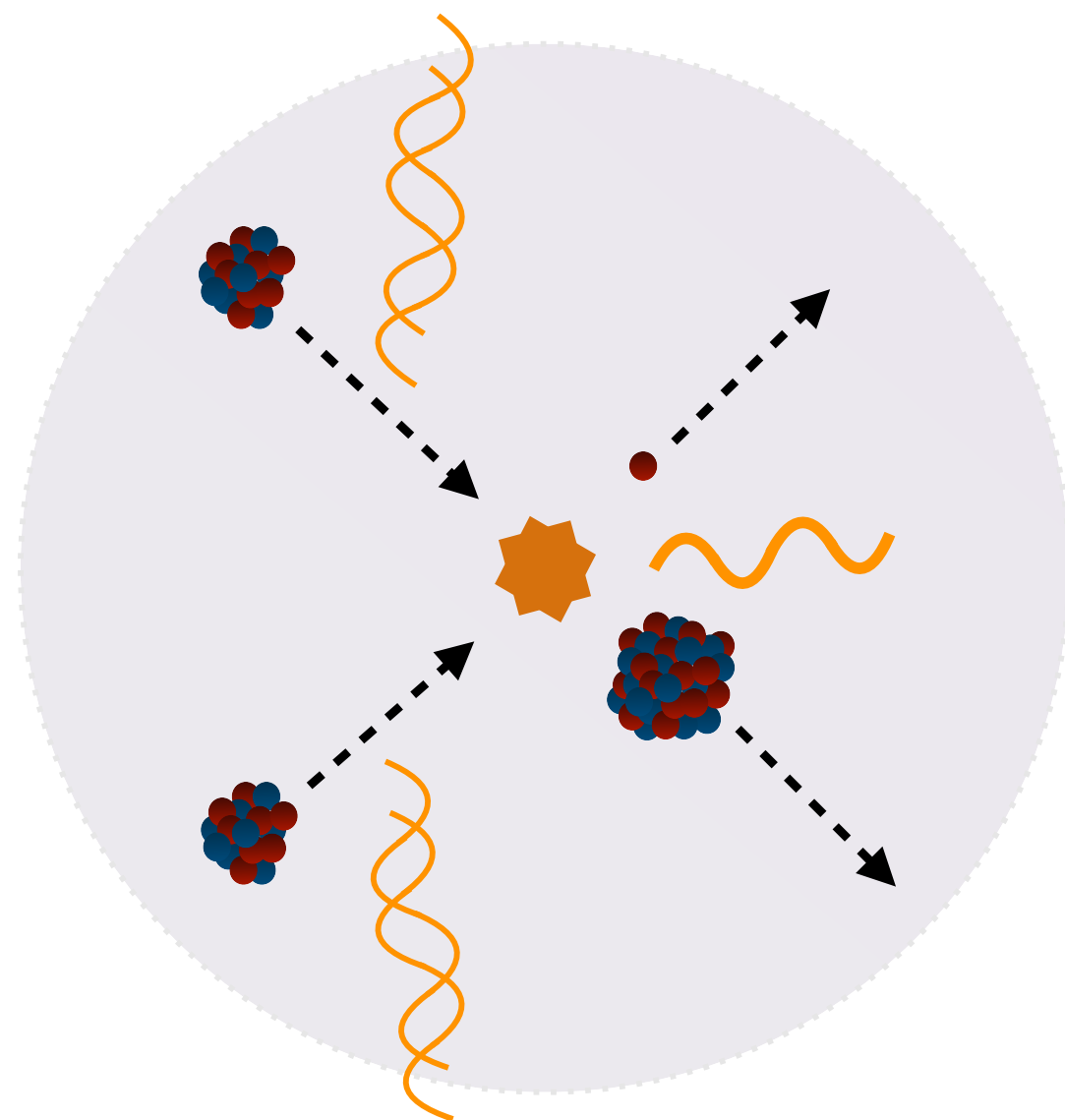
Acevedo, Boukhtouchen, JB, Cappiello,
Mohlabeng, Sheahan, Tyagi, in progress

BREM/NUCLEAR INTERACTIONS

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

nuclear interactions with DM composite internal potential

1.



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

Acevedo, JB, Goodman
2012.10998

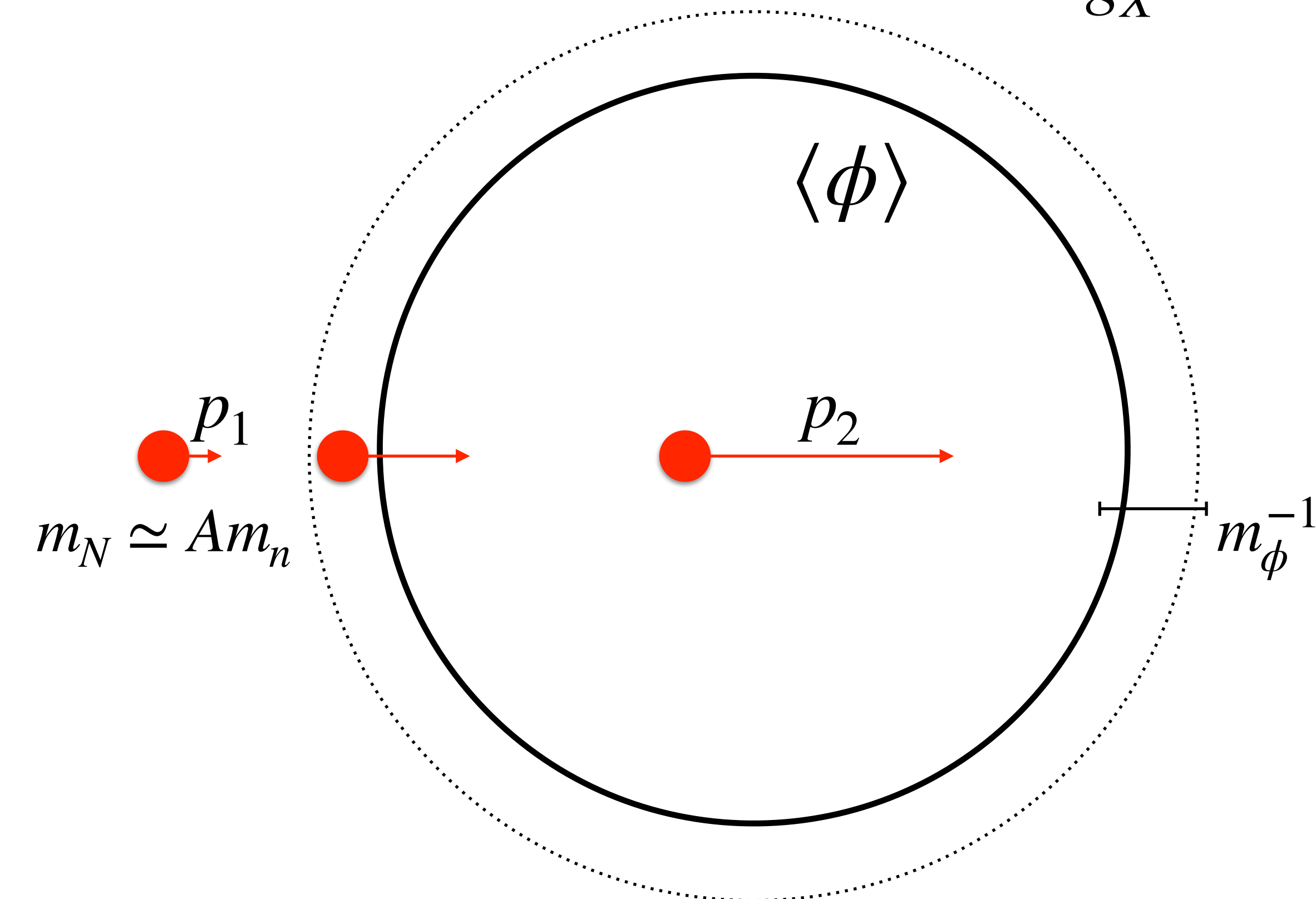
DM-nucleon coupling accelerates nuclei in composites

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

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

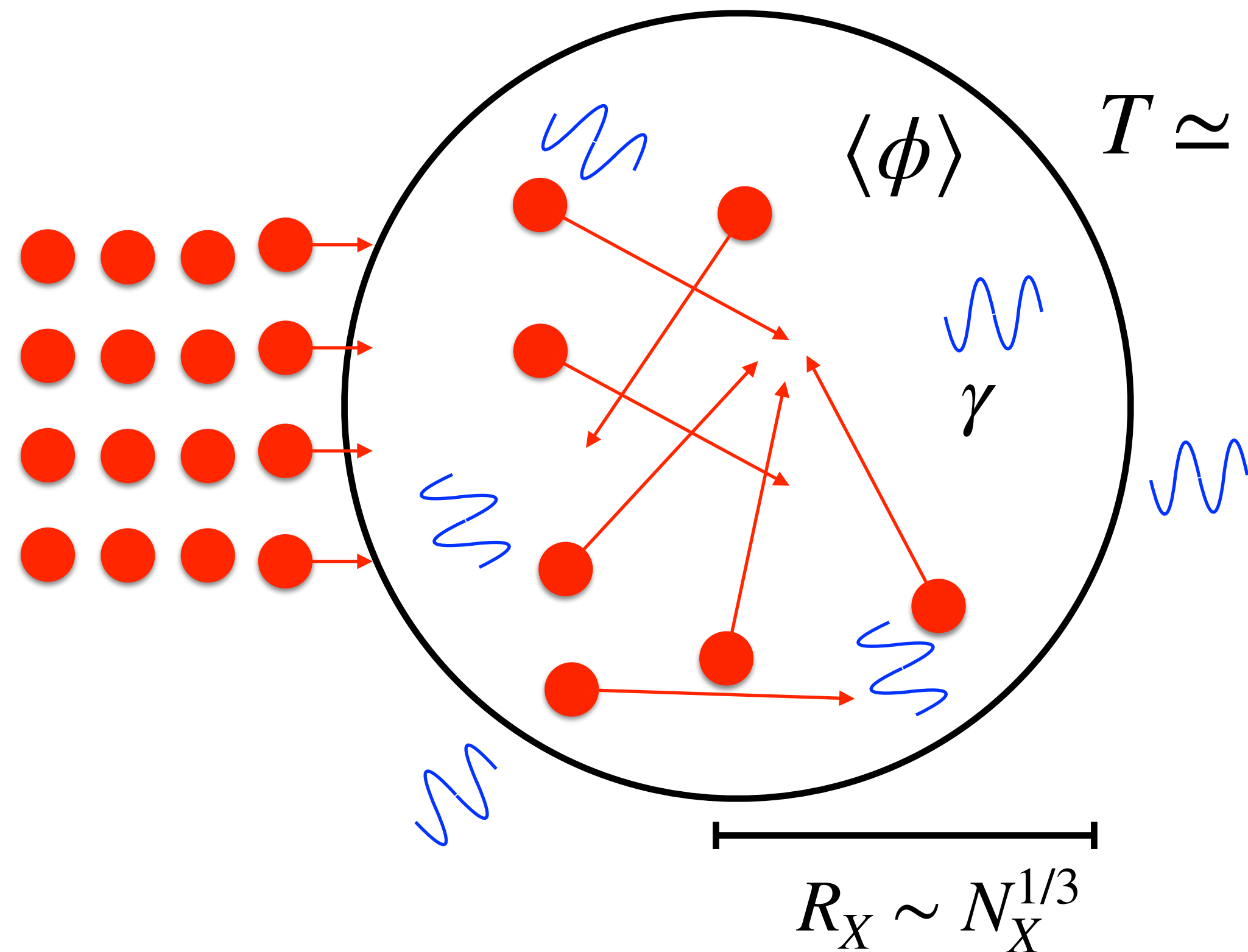
Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential sourced by X fermions, like gravity but stronger and shielded

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



Heated nuclei in composite interior

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



Ionization (Migdal, collisions)

Thermal bremsstrahlung

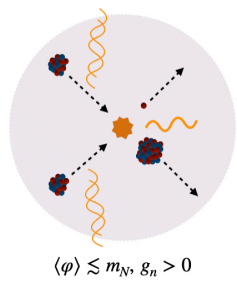
Thermonuclear fusion



increasing temperature/energy

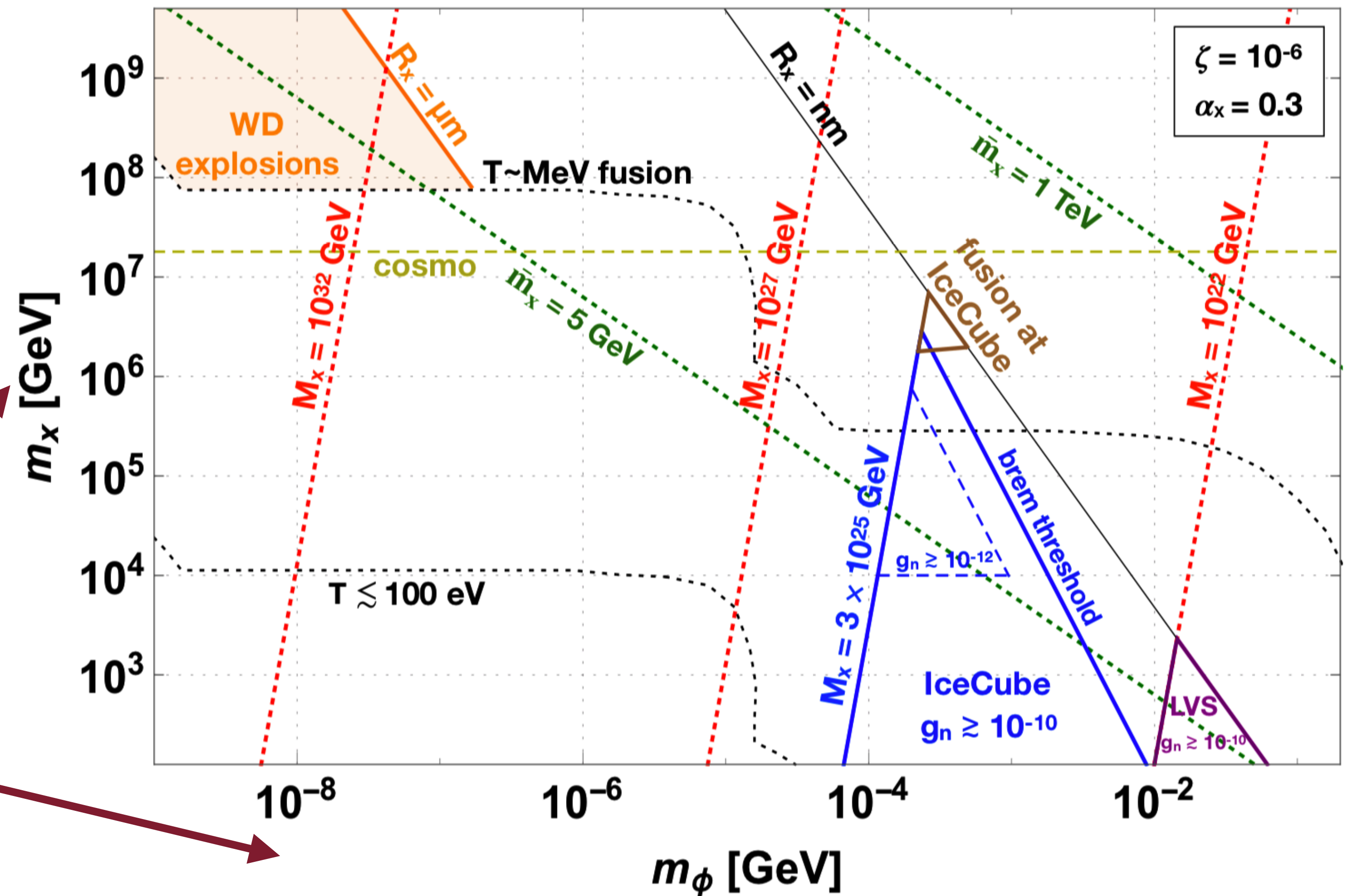
Potential signatures of this effect?

- 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)

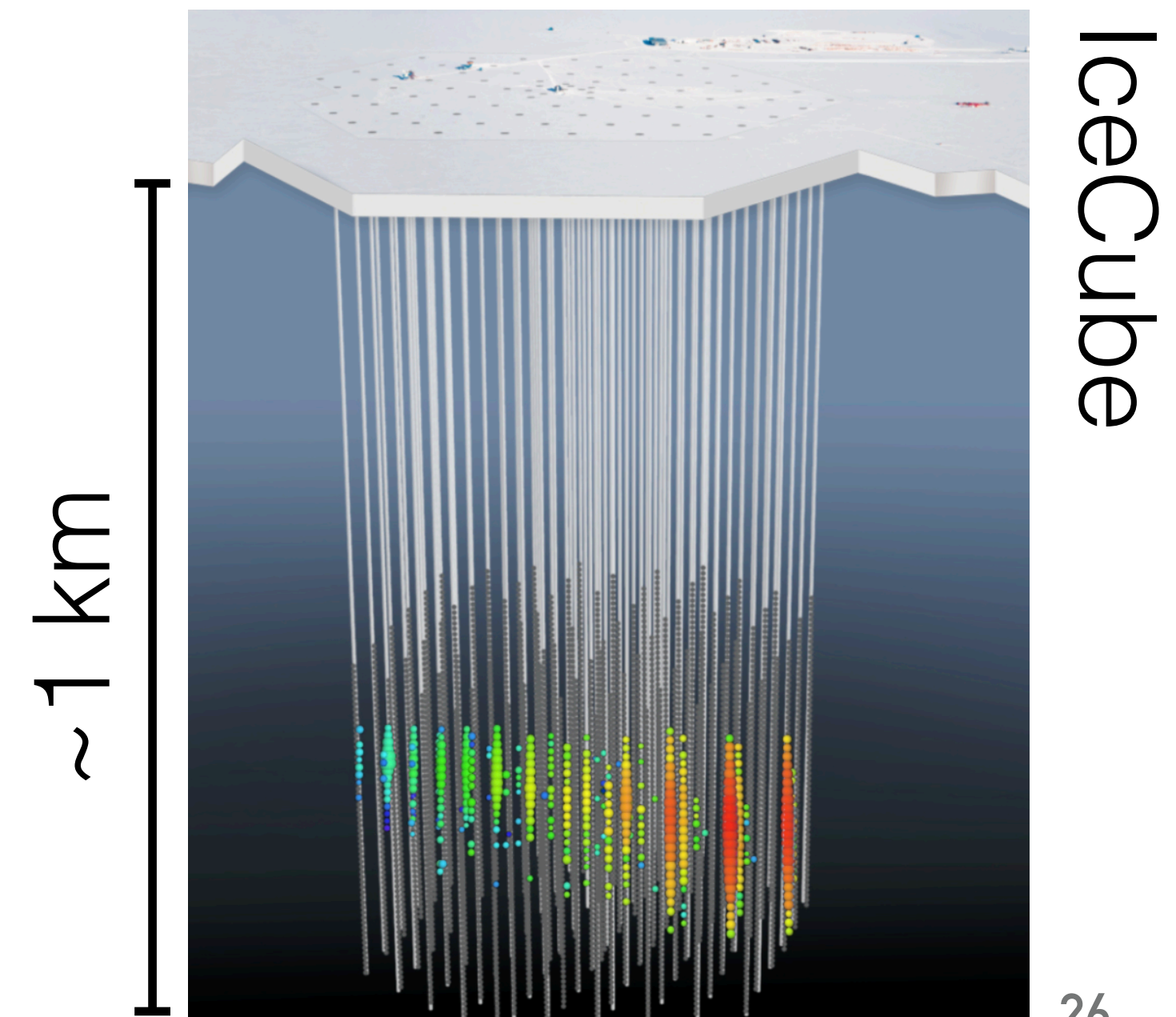
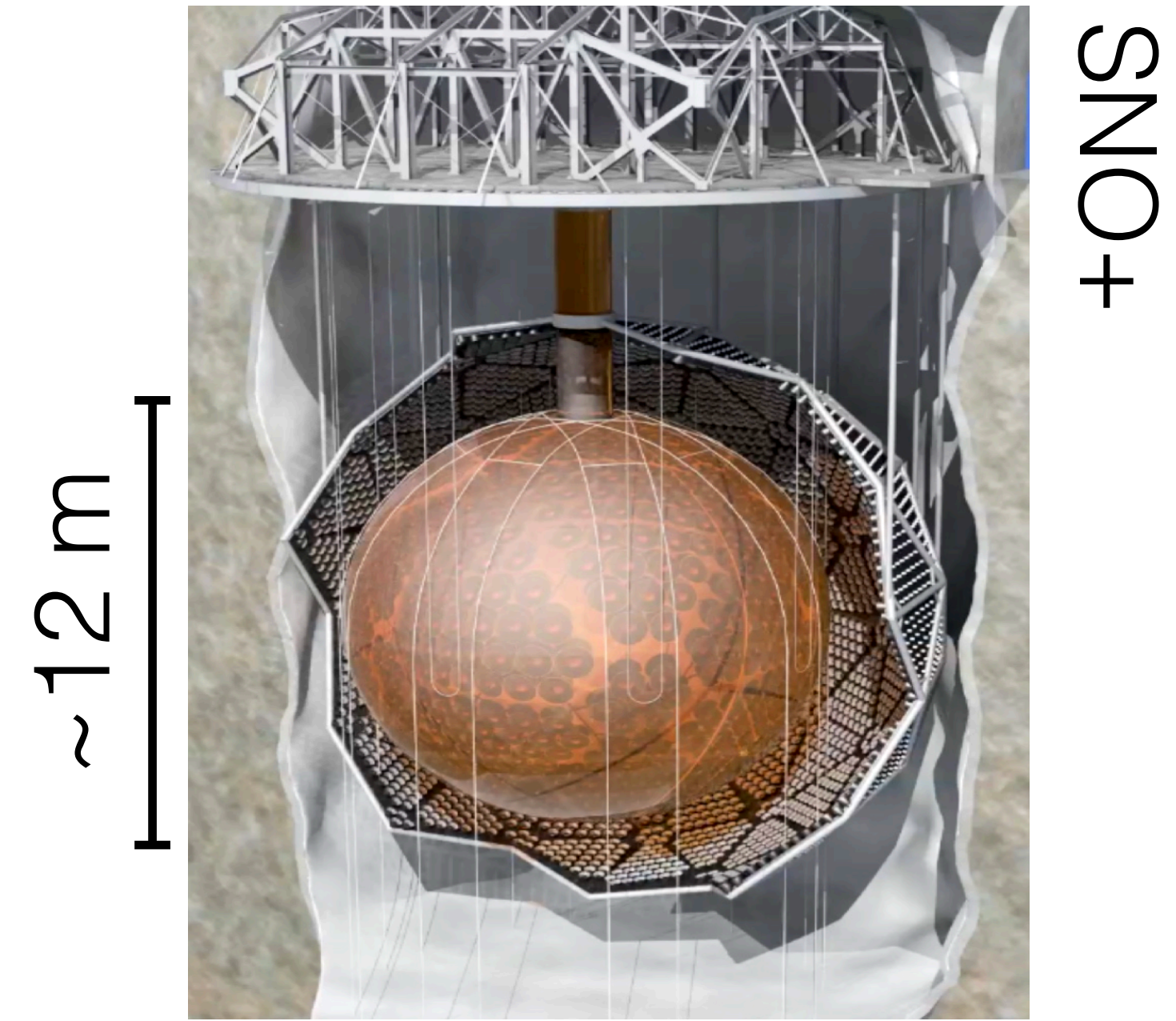
Composites radiate continuously along path:

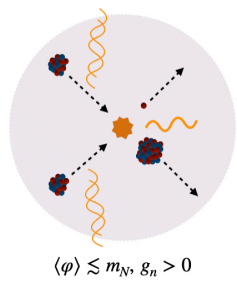
$$\dot{E}_{SNO+} \simeq 10^4 \text{ GeV s}^{-1}$$

$$M_X^{max} \simeq 10^{22} \text{ GeV}$$

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

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





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

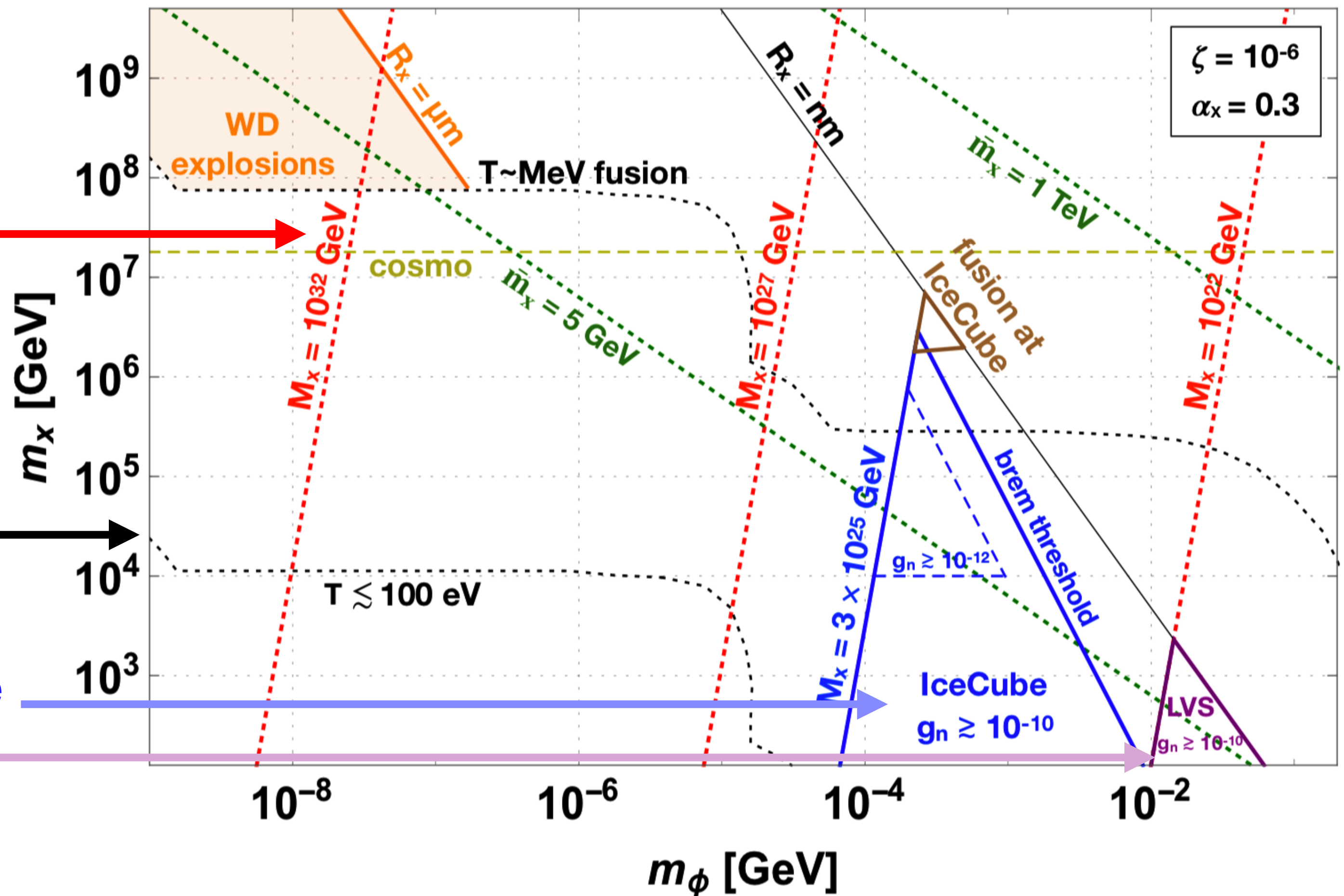
BREM/NUCLEAR FUSION IN COMPOSITES

Composite mass

Max temperature of baryons
flowing through composite

Find composite Brem at Ice Cube

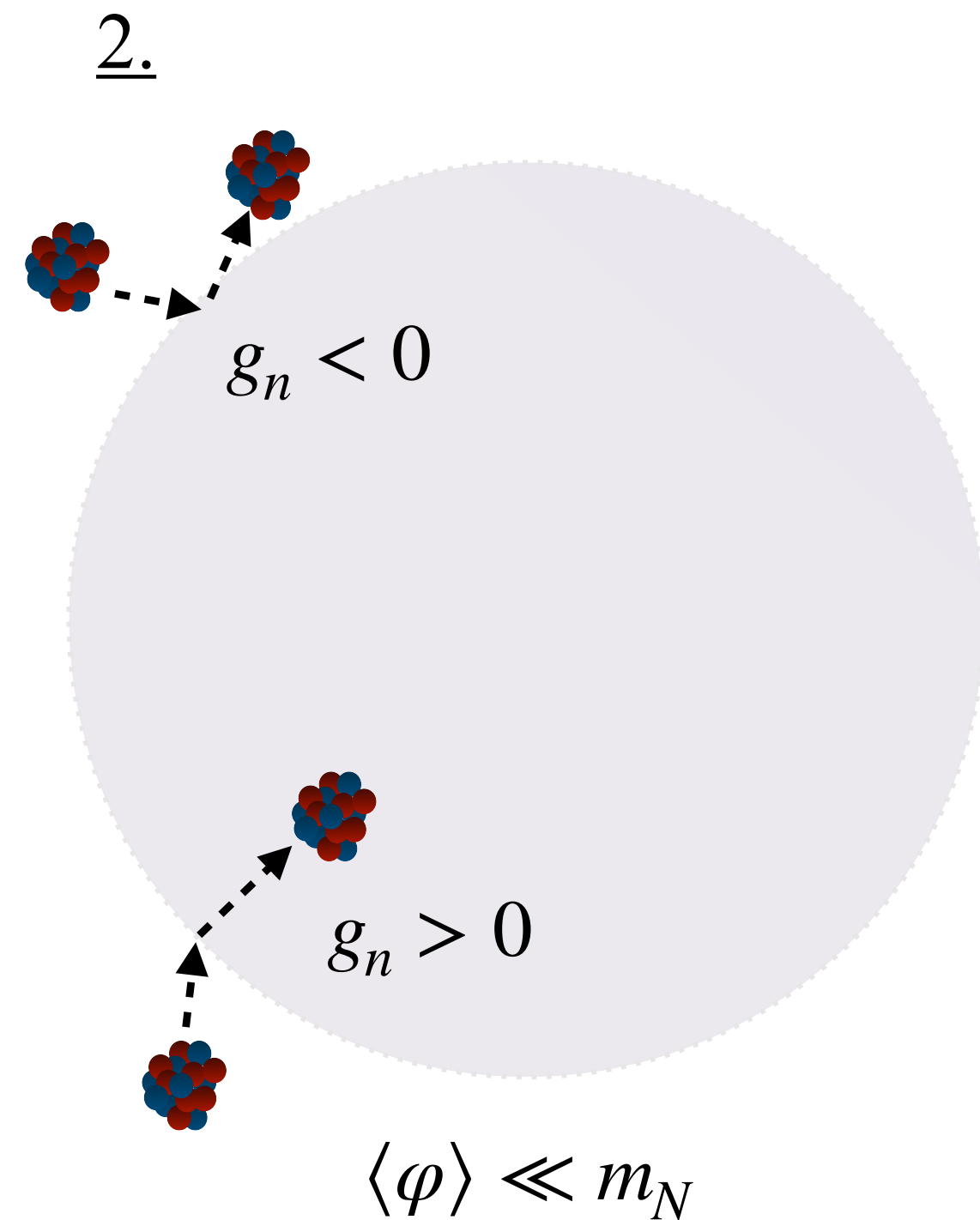
Find composite Brem at SNO+/JUNO



LOW E RECOIL INTERACTIONS

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

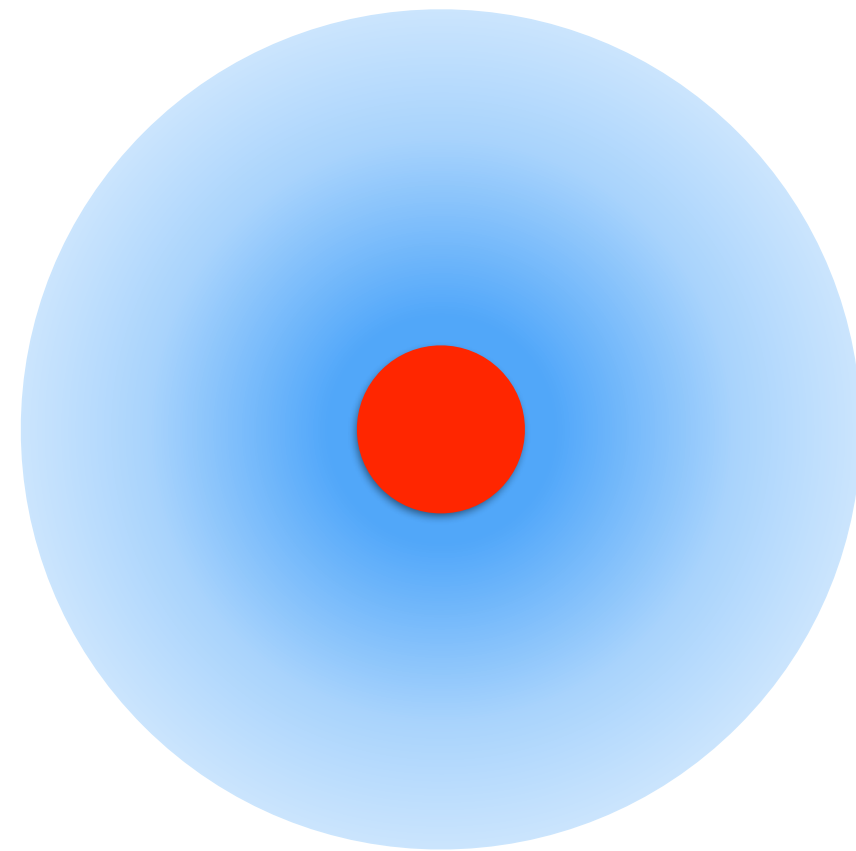
nuclear interactions with DM composite internal potential



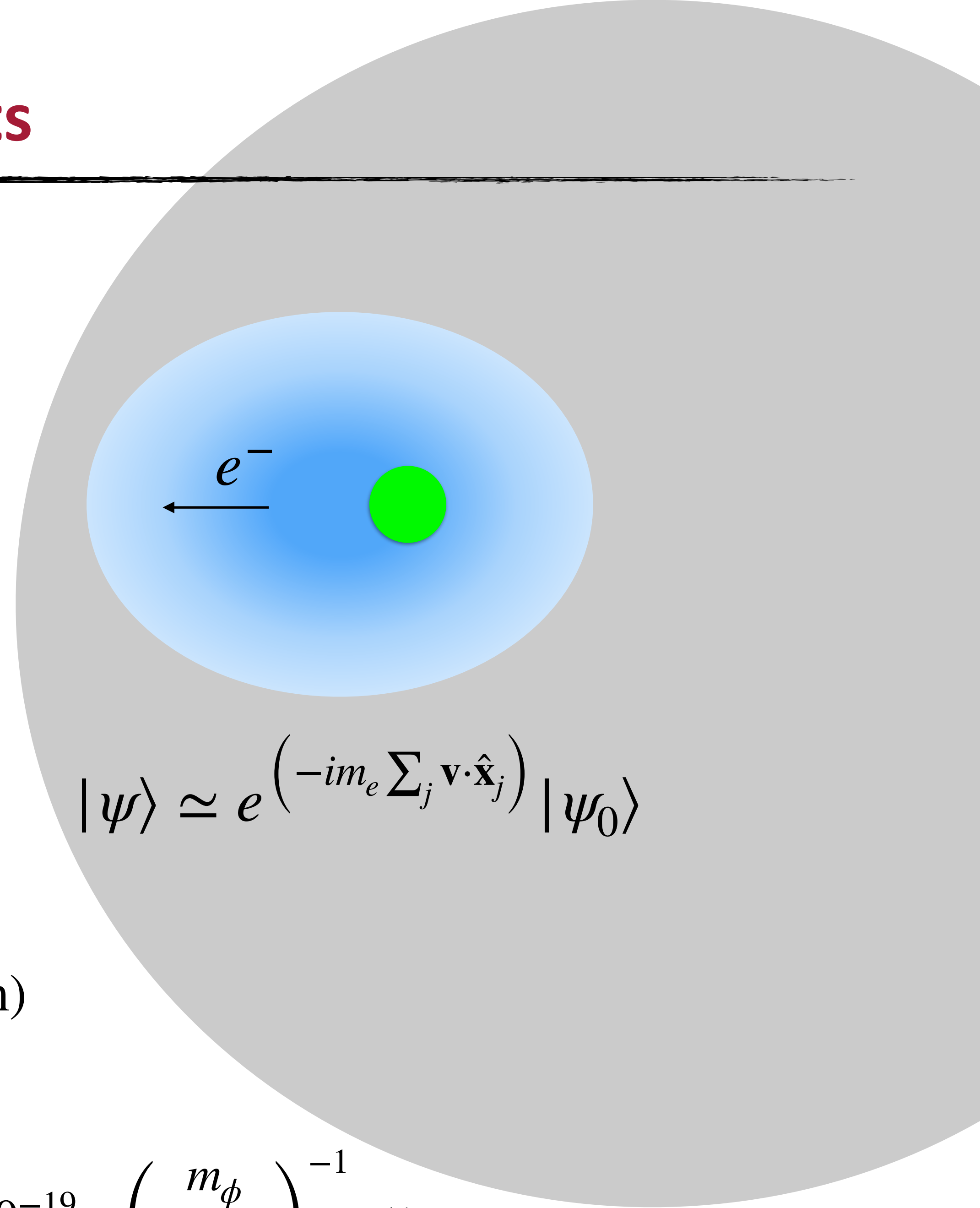
Acevedo, JB, Goodman
2108.10899

Composite Migdal Effect at DD Experiments

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



sudden nuclear recoil

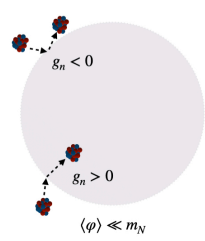


$$|\psi\rangle \simeq e^{\left(-im_e \sum_j \mathbf{v} \cdot \hat{\mathbf{x}}_j\right)} |\psi_0\rangle$$

$$\left[\begin{array}{l} \tau_{e^-} \sim 10^{-17} \text{ s} \quad \text{electron orbital period} \\ \frac{R_a}{v_N} \sim 10^{-15} \text{ s} \left(\frac{g_n}{10^{-10}} \right)^{-\frac{1}{2}} \left(\frac{m_X}{\text{TeV}} \right)^{-\frac{1}{2}} \quad (R_a \sim 10^{-8} \text{ cm}) \end{array} \right.$$

cf. timescales for nuclei
in assym. composites:

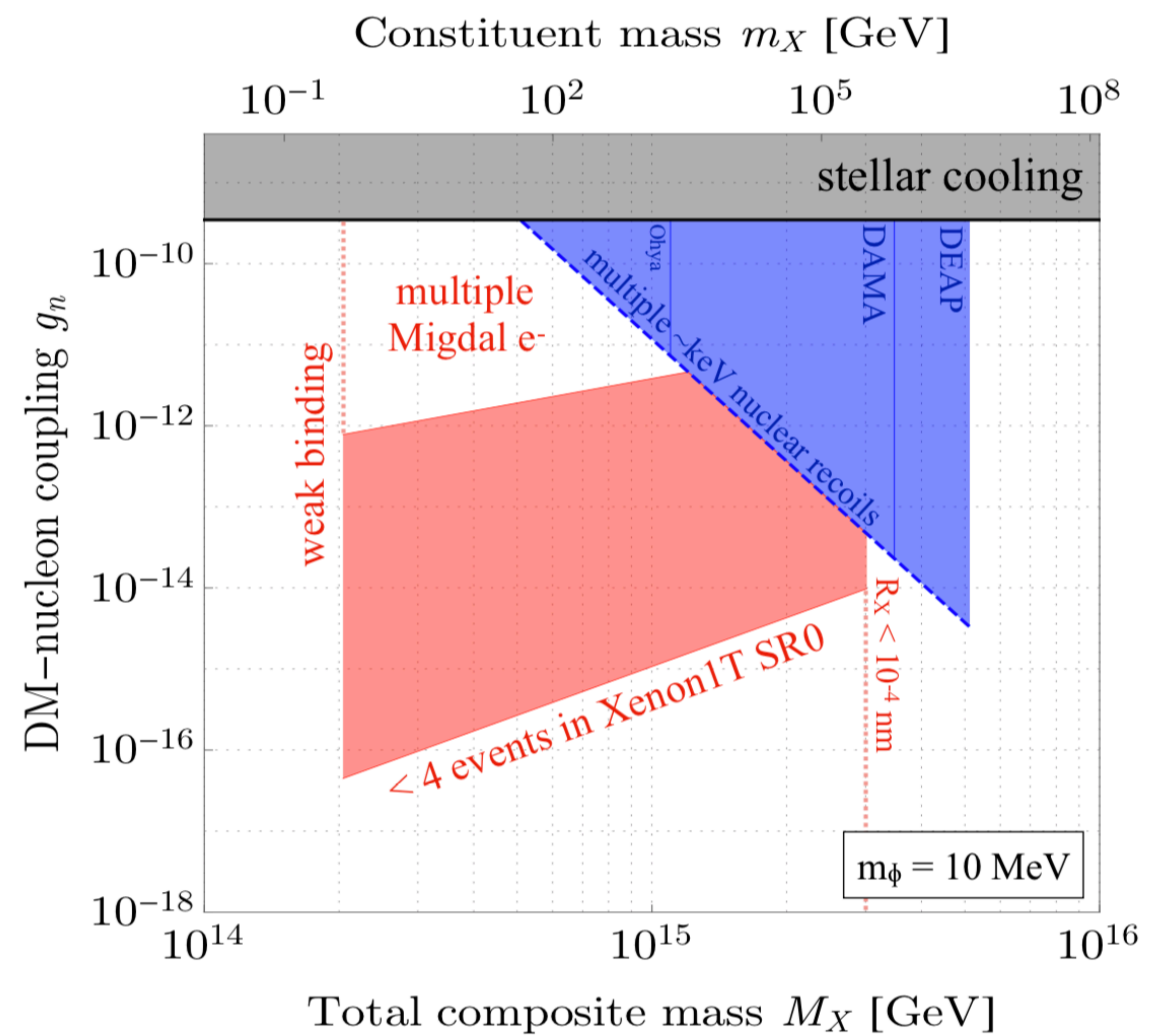
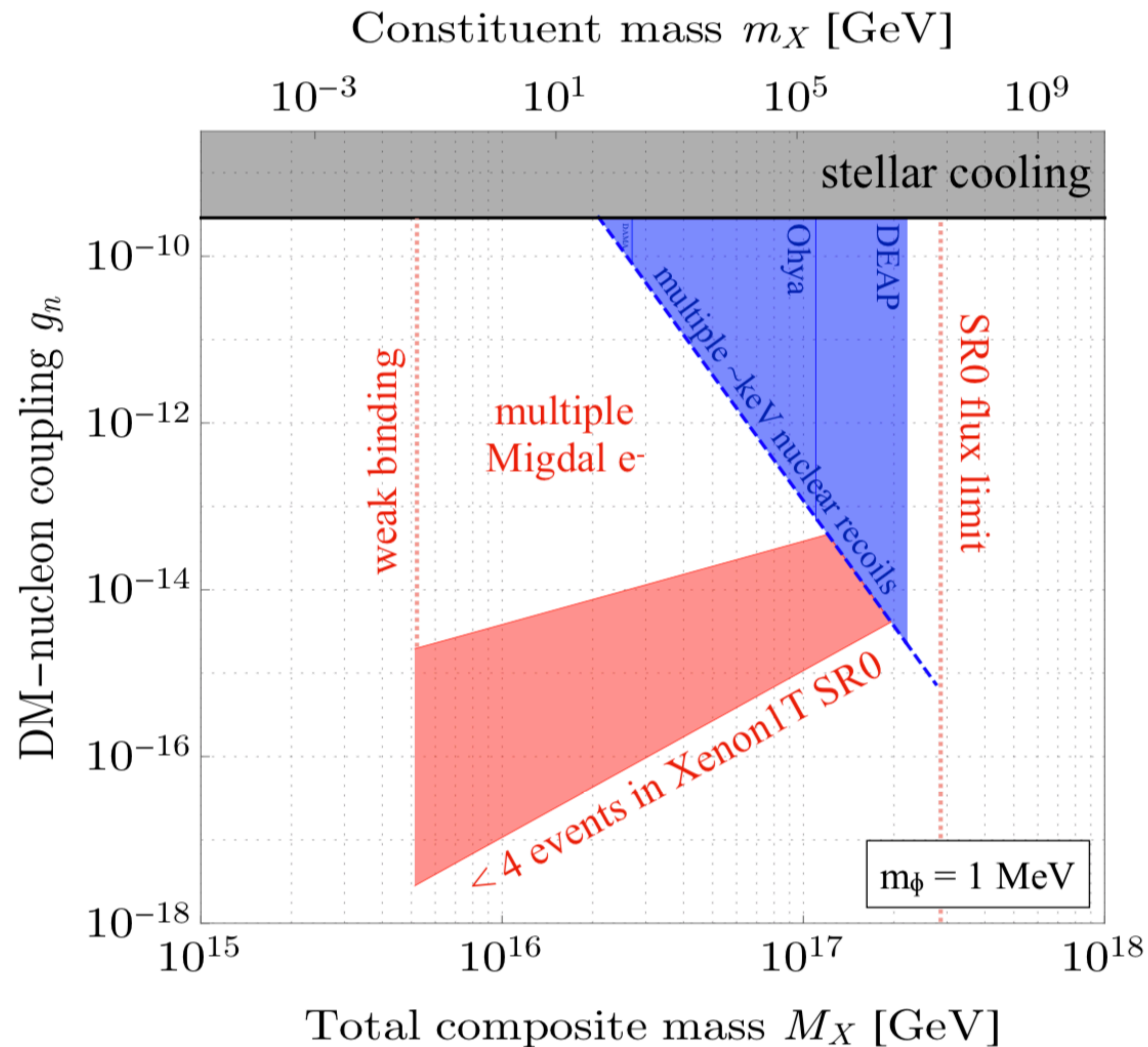
$$\Delta t_{\text{interact}} = \tau_{\text{accel}} \simeq \frac{1}{m_\phi v_X} \simeq 10^{-19} \text{ s} \left(\frac{m_\phi}{\text{MeV}} \right)^{-1} \ll \tau_{e^-}$$



Migdal Bounds

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

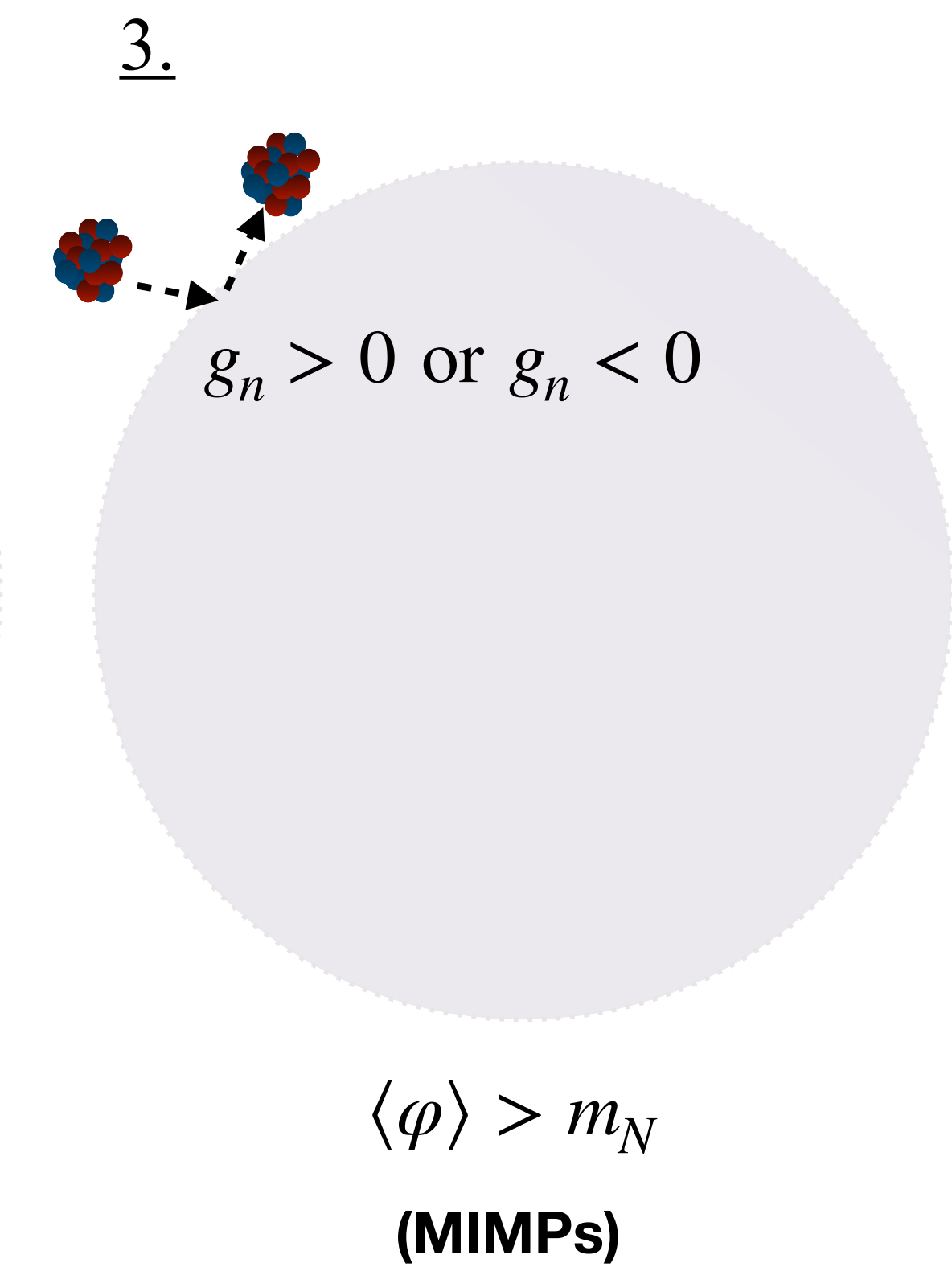
Composite masses/radii determined by m_X , cosmology with $\alpha_X = 0.3$



MULTISCATTER INTERACTIONS

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

nuclear interactions with DM composite internal potential



Acevedo, JB, Goodman
2108.10899



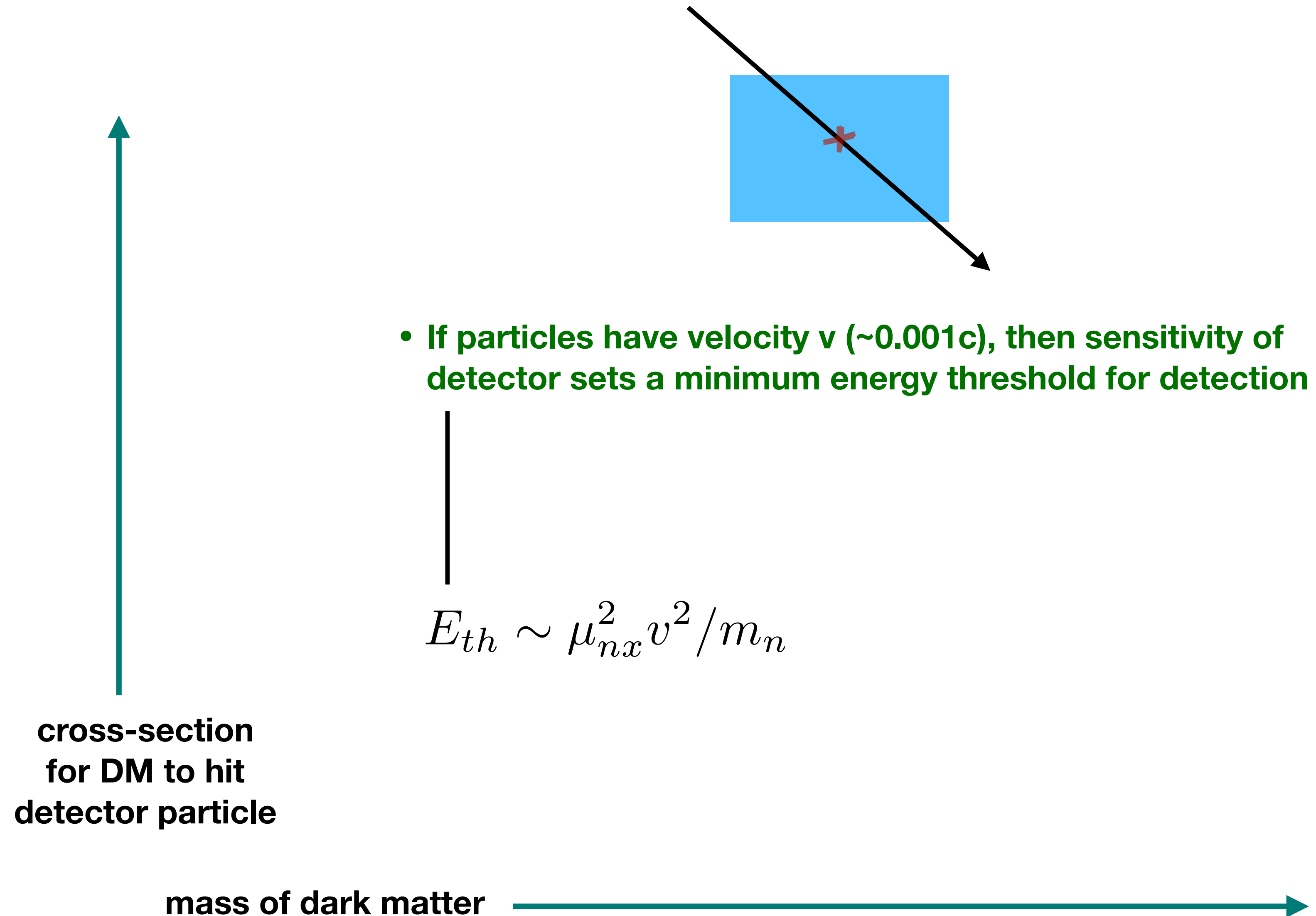
Multiscatter: models of dark matter interact many times in detectors.



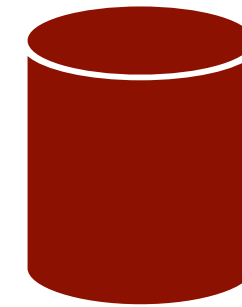
New searches for multiply interacting dark matter (MIMPs)



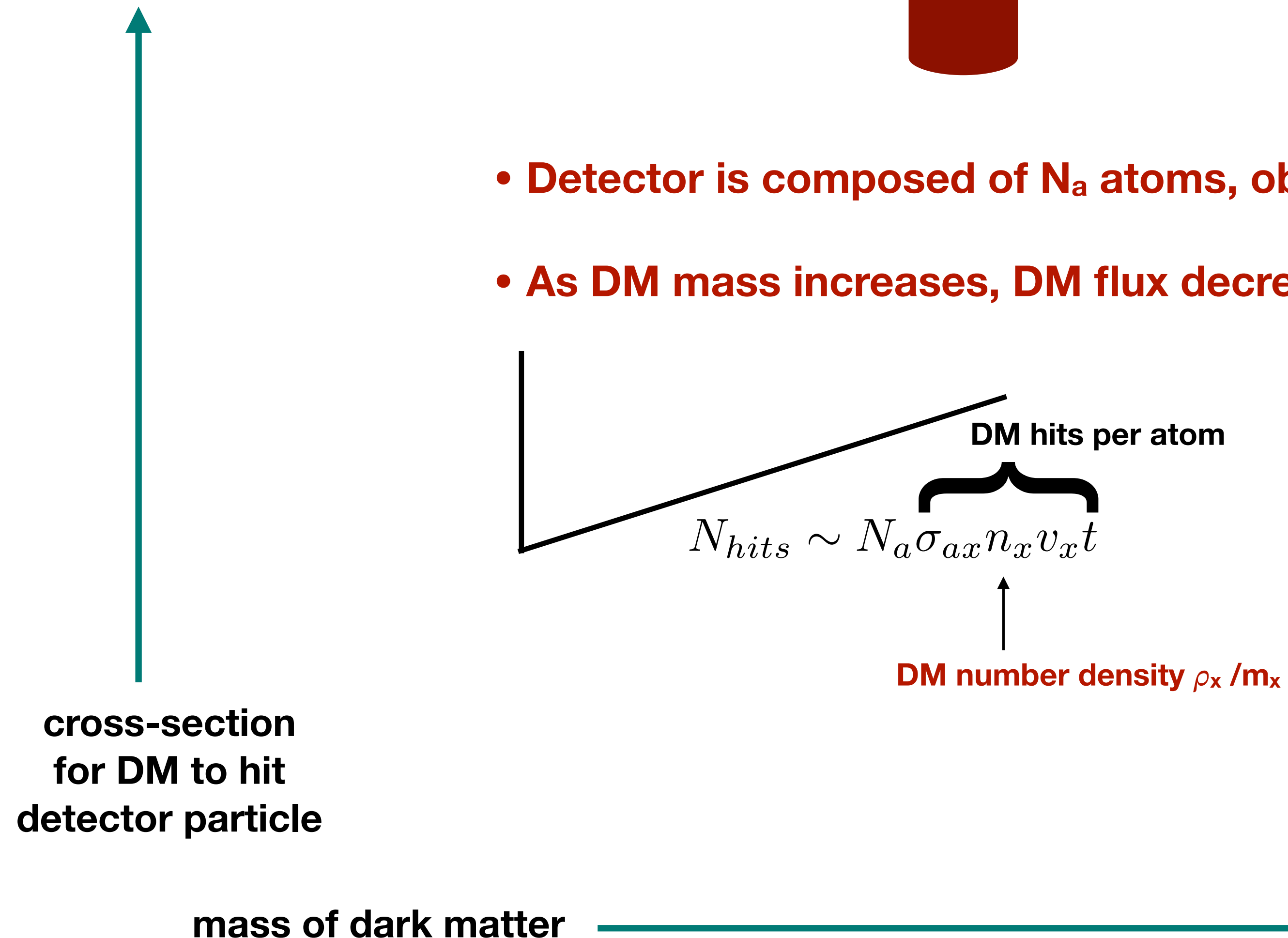
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



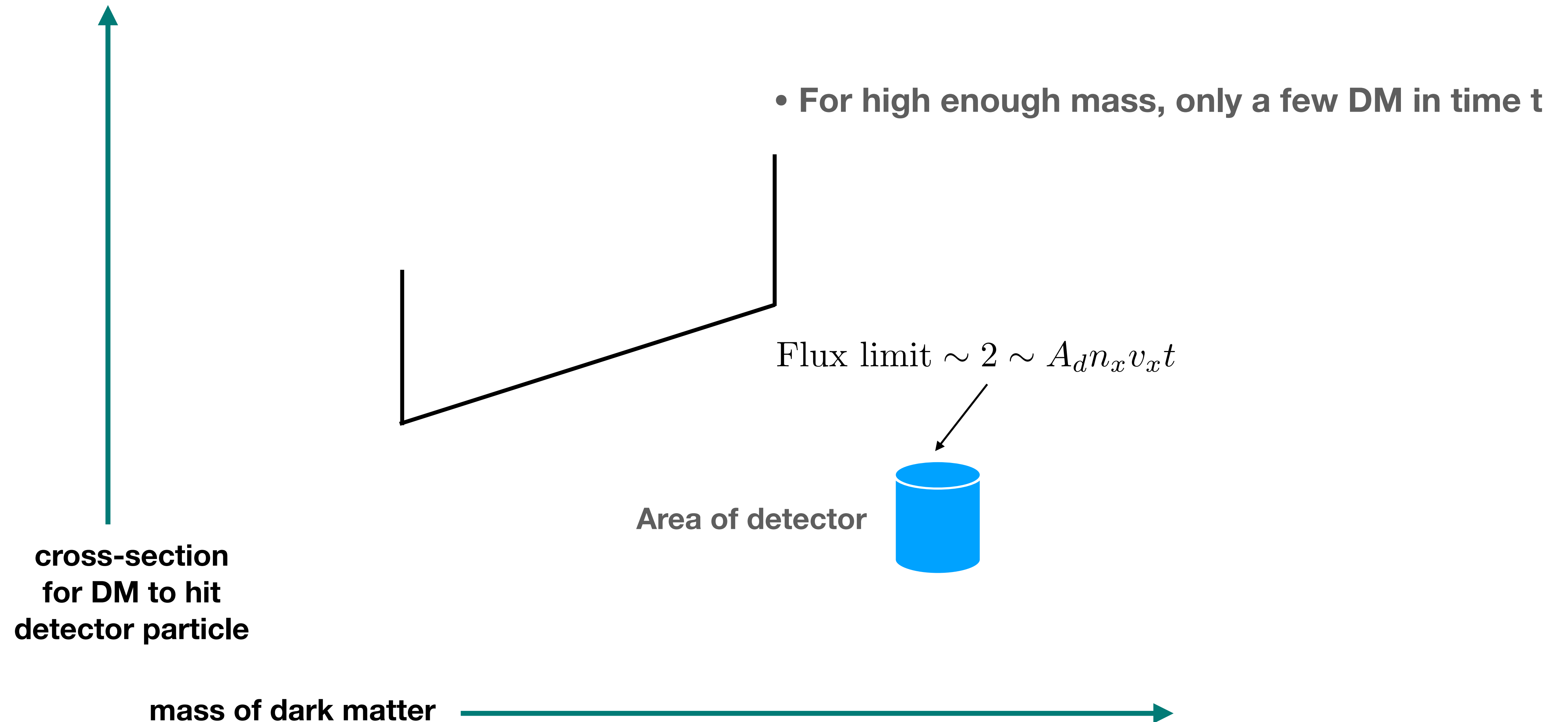
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



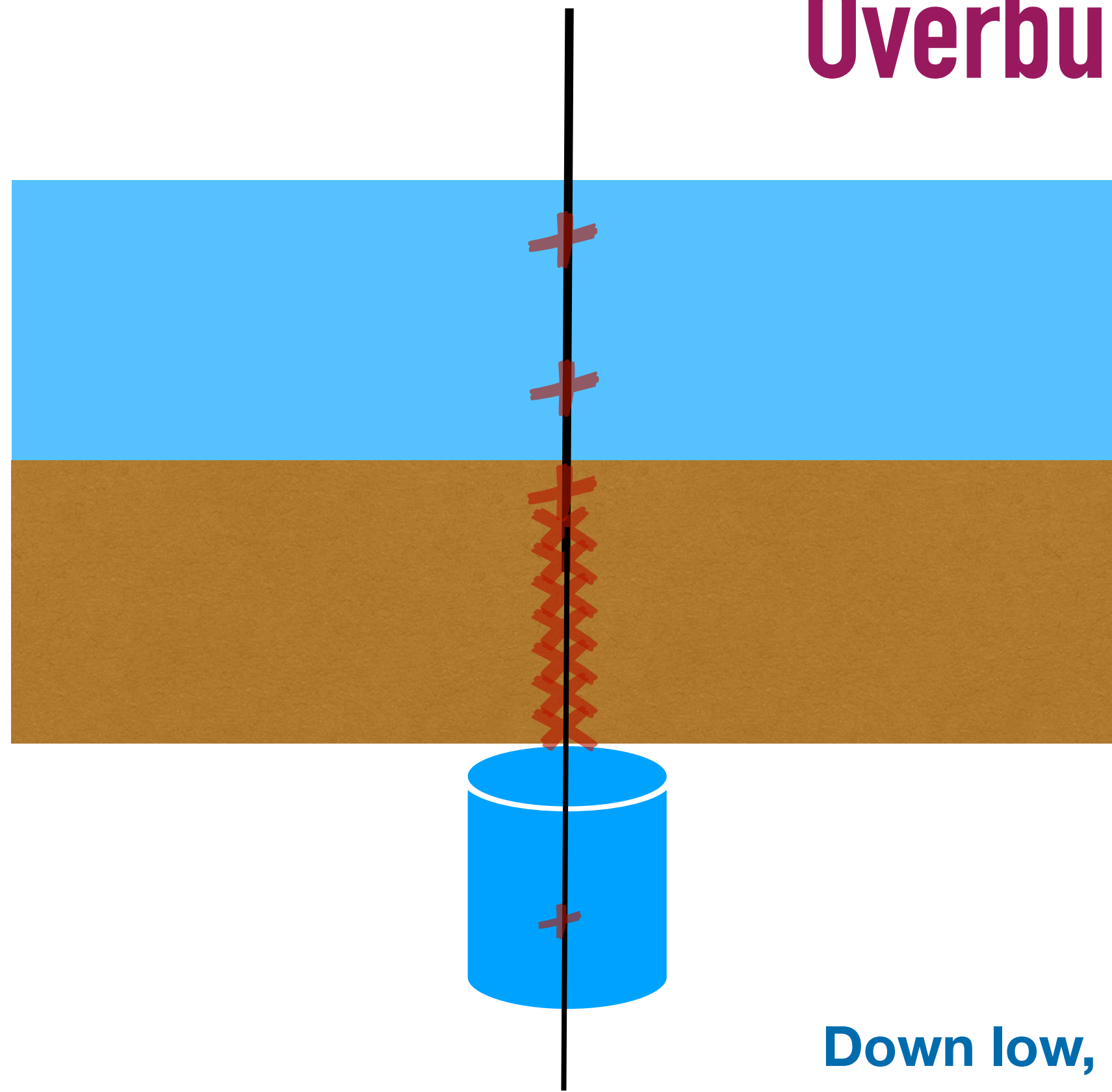
- Detector is composed of N_a atoms, observes for time t
- As DM mass increases, DM flux decreases, sensitivity decreases as $1/m_x$



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



Overburden attenuation



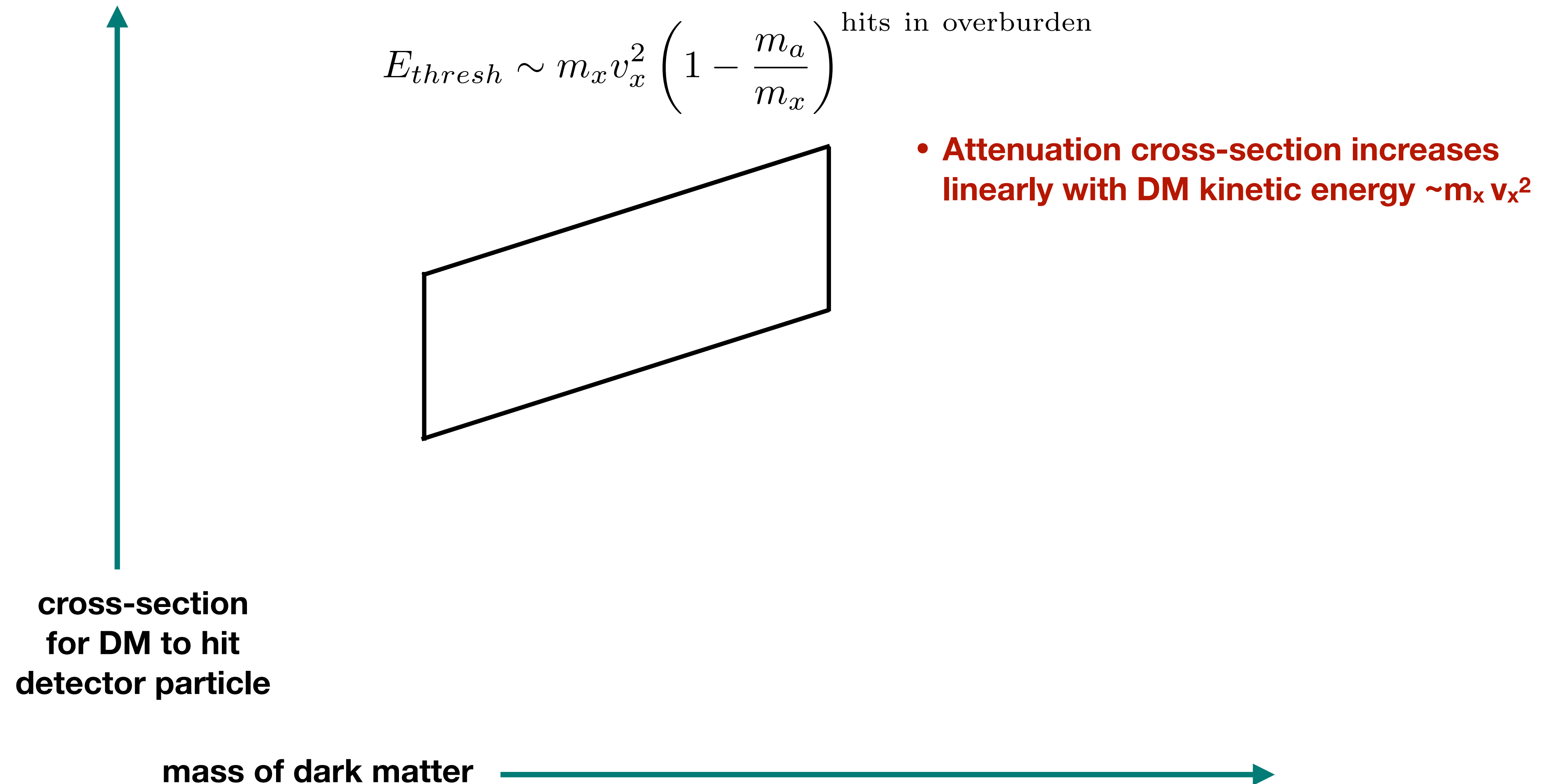
- DM particles can be slowed through scattering with atmosphere, earth, aluminum space station wall.

Down low, too slow?

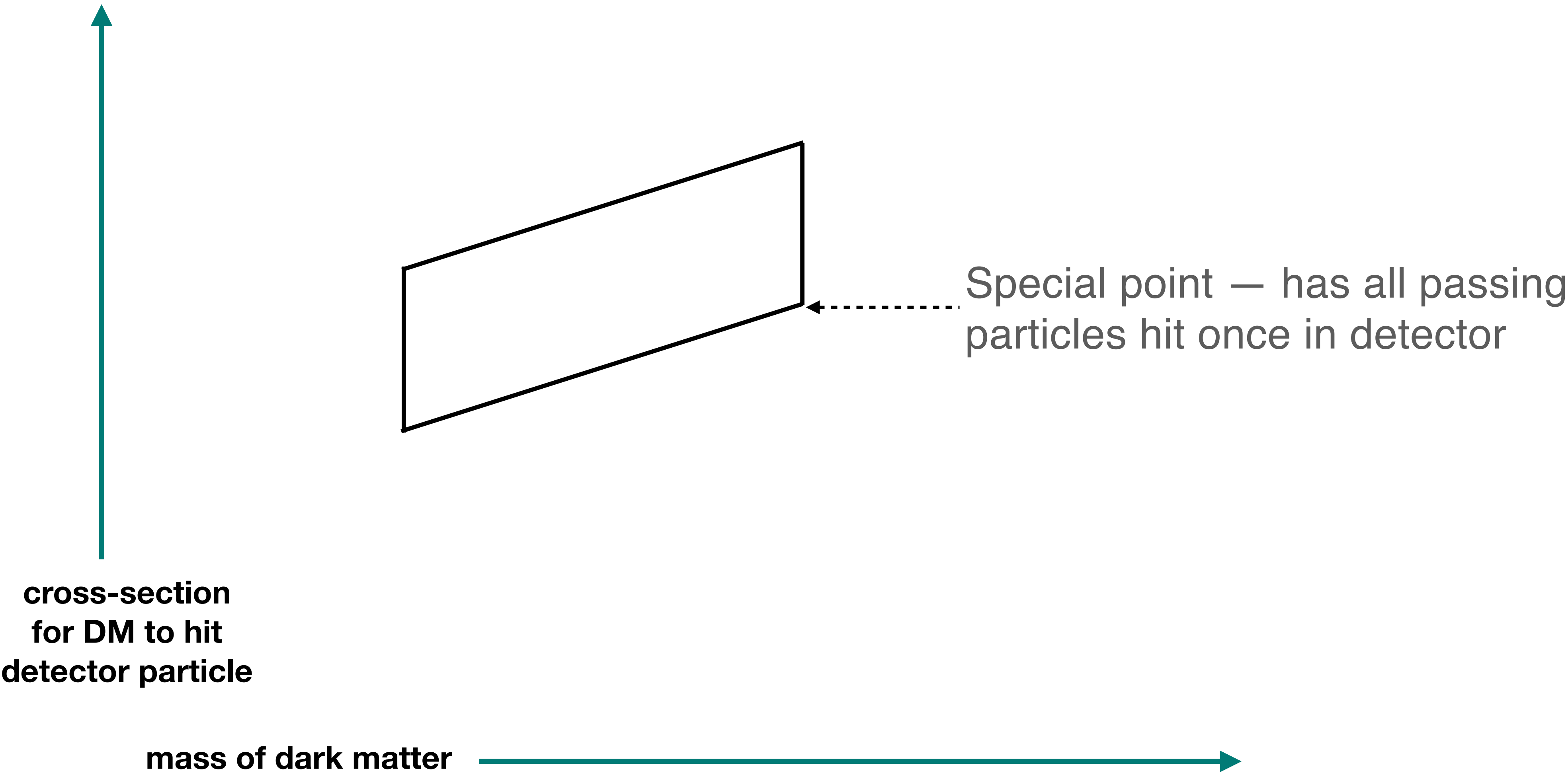
Length of overburden

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

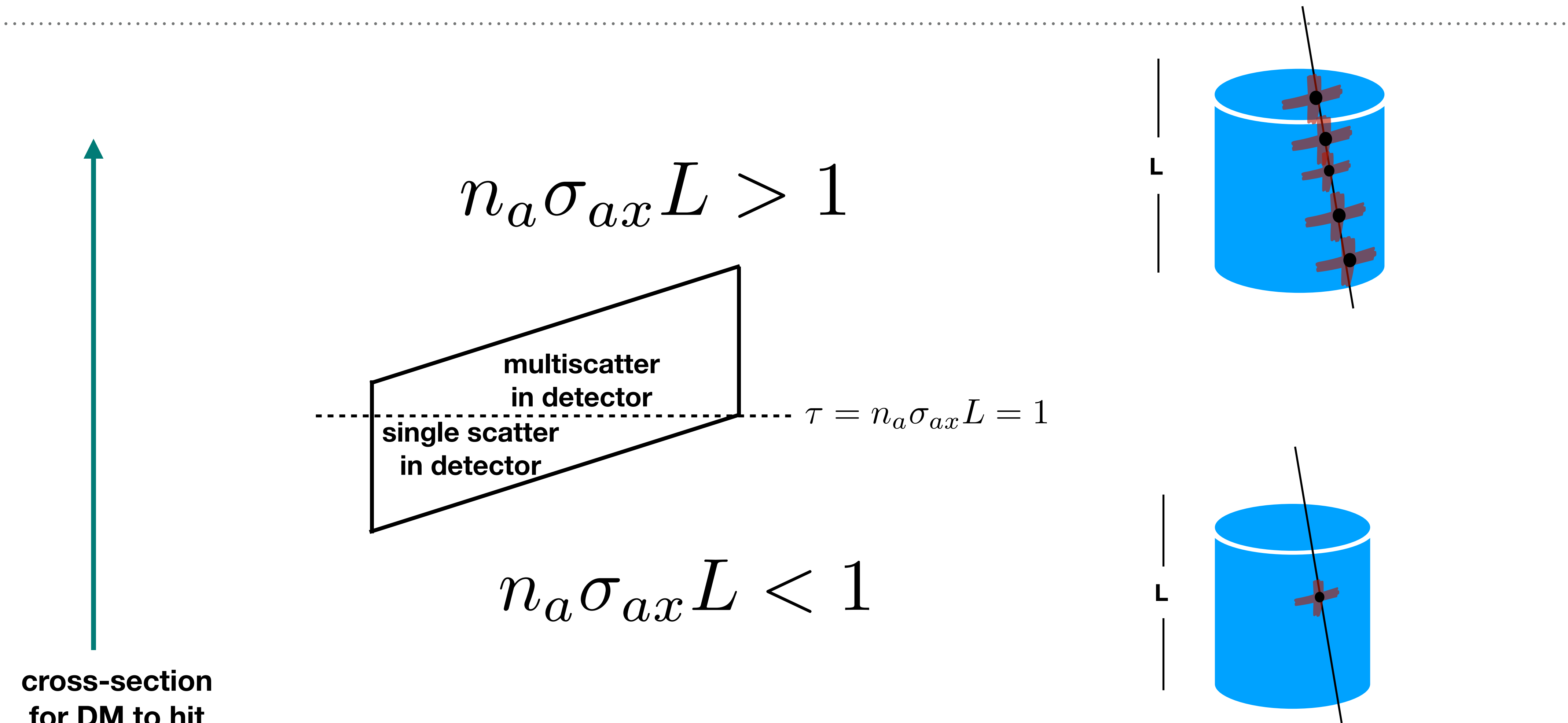
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

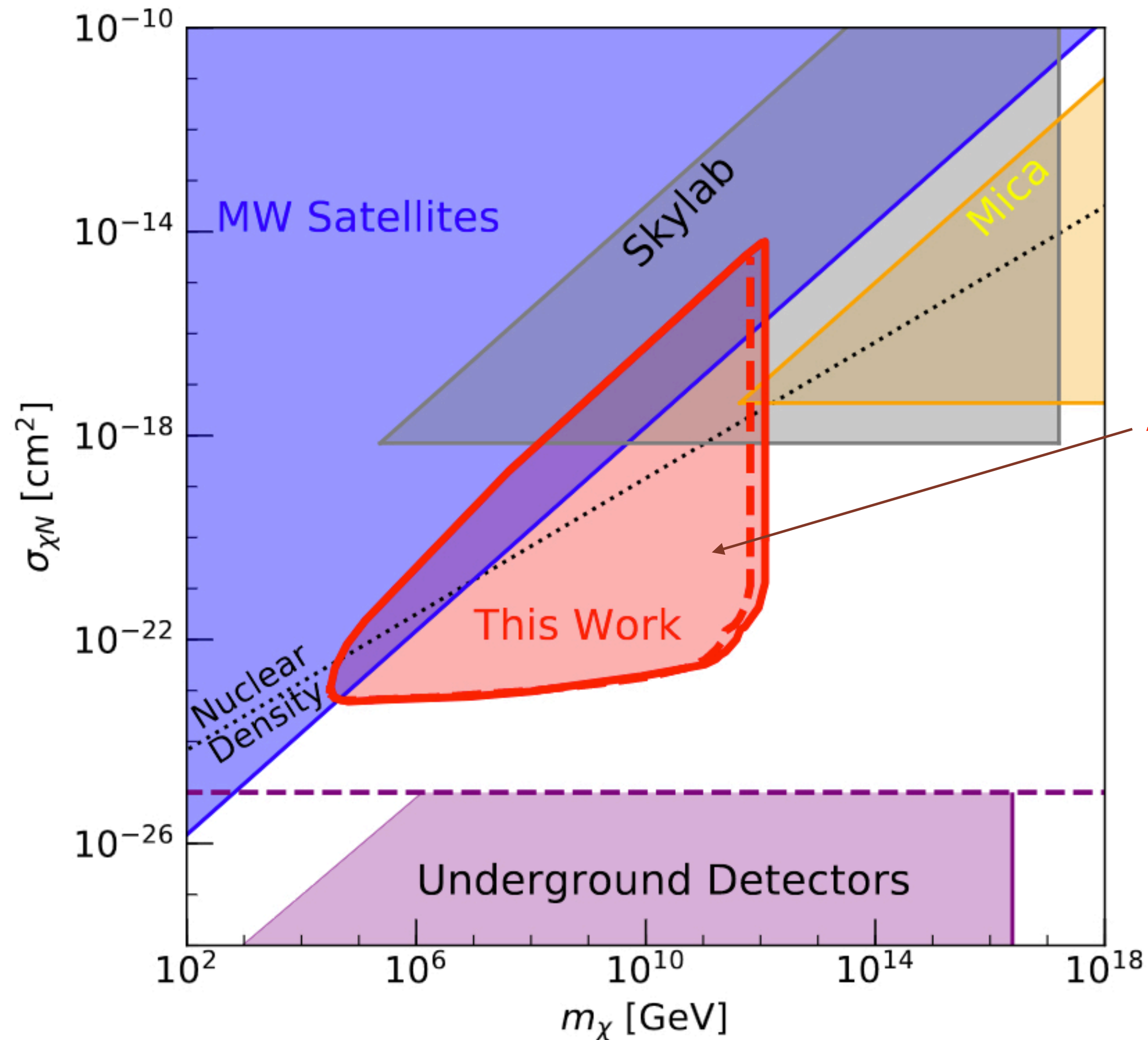


MULTISCATTER DARK MATTER DETECTION



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

CHICAGO, MULTISCATTER DARK MATTER DETECTION



- Liquid scintillator test modules at U Chicago
Chris Cappiello, Collar, Beacom
2008.10646

ETCHING PLASTIC SEARCHES FOR DARK MATTER

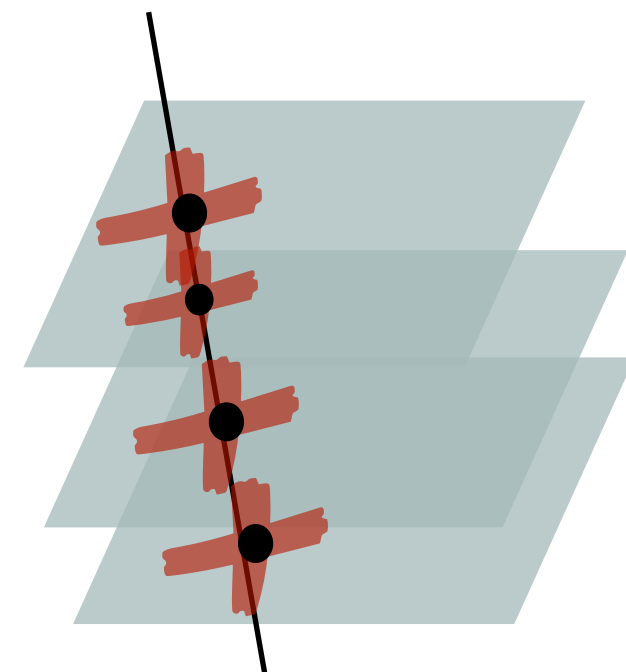
- *Two searches in 1978 and 1990 for cosmic rays and monopoles using acid-etched plastic track detectors*
- *Still have best sensitivity for some high mass dark matter, for different reasons*

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	$\theta_D = 60^\circ$	$\theta_D = 18.4^\circ$
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



Bhoonah, JB, Courtman, Song
2012.13406

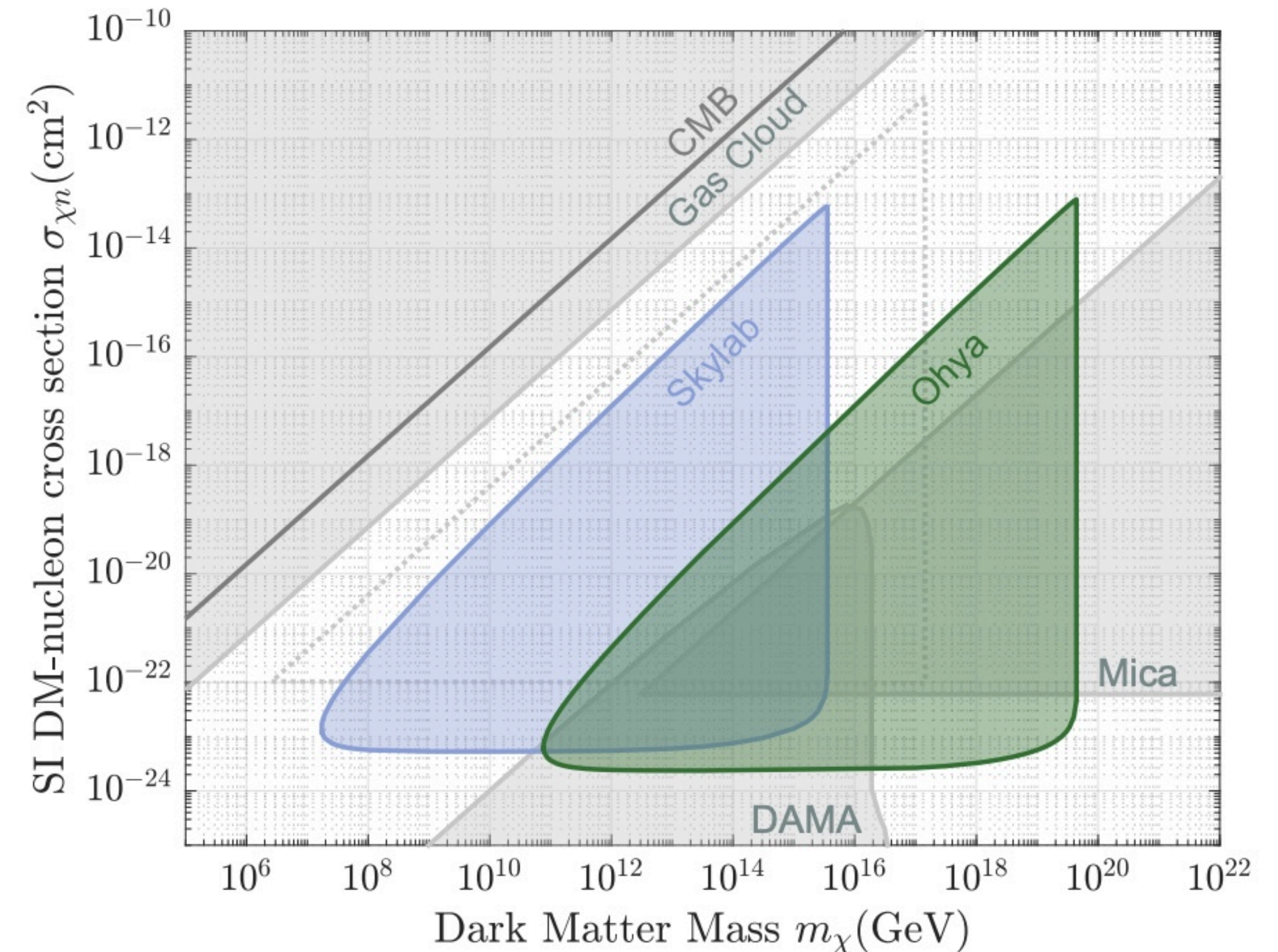
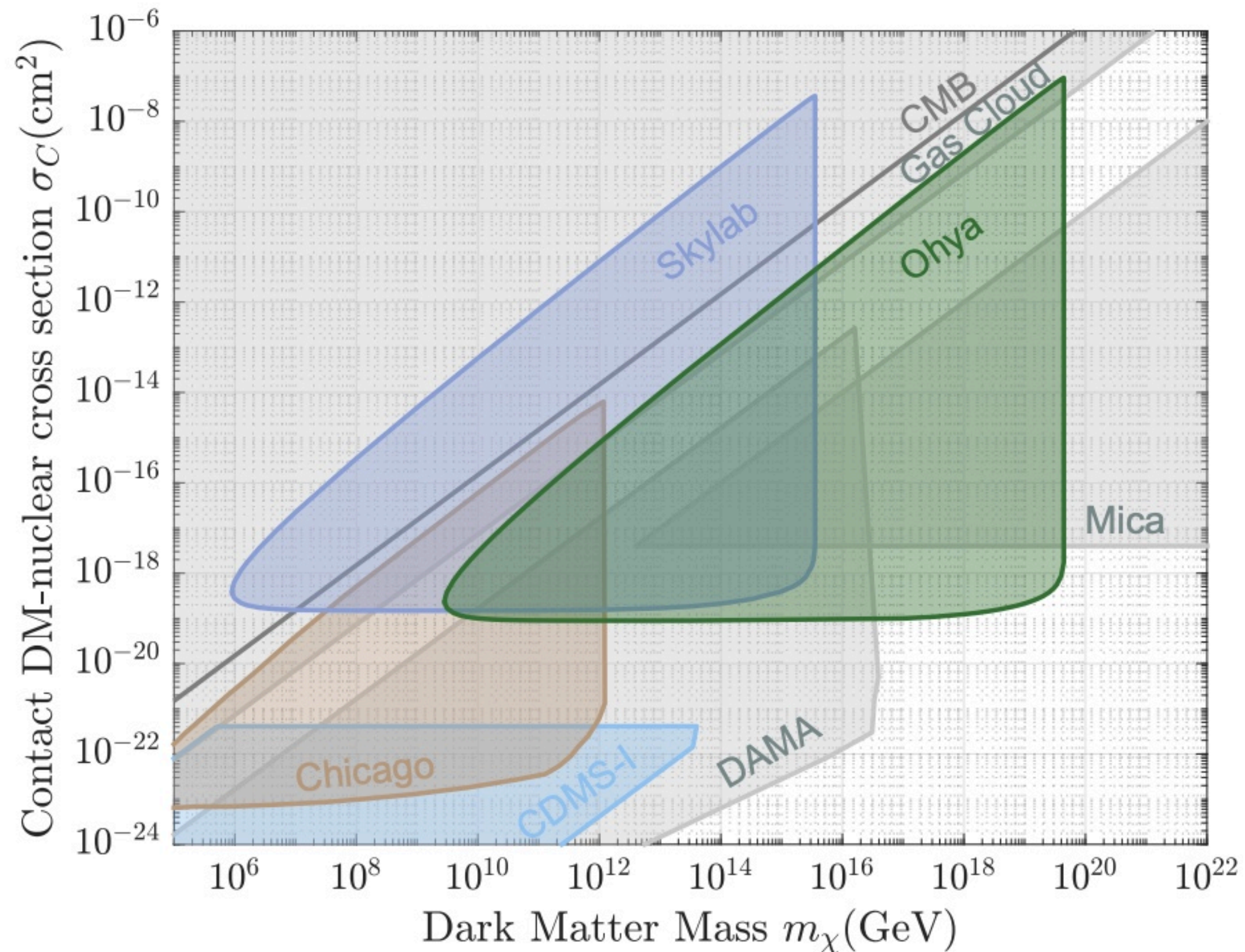


Ohya Quarry

ETCHING PLASTIC SEARCHES FOR DARK MATTER

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

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



ANCIENT SEARCH FOR NEW PARTICLES: MICA

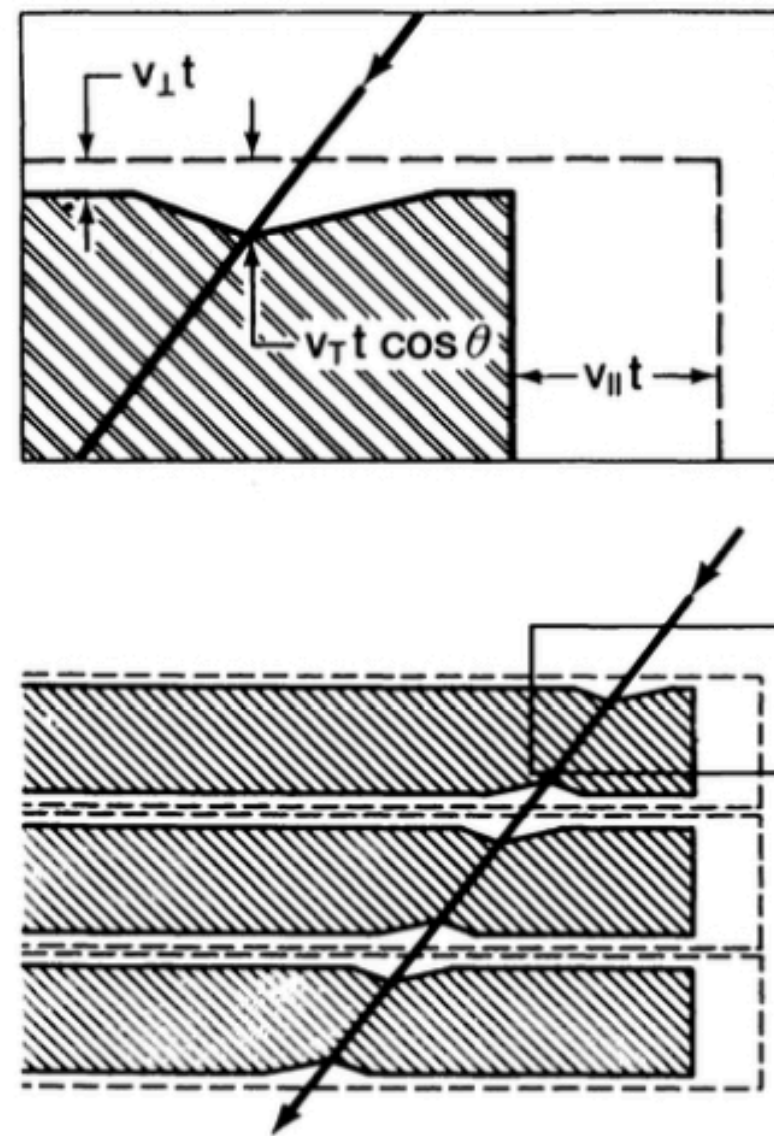
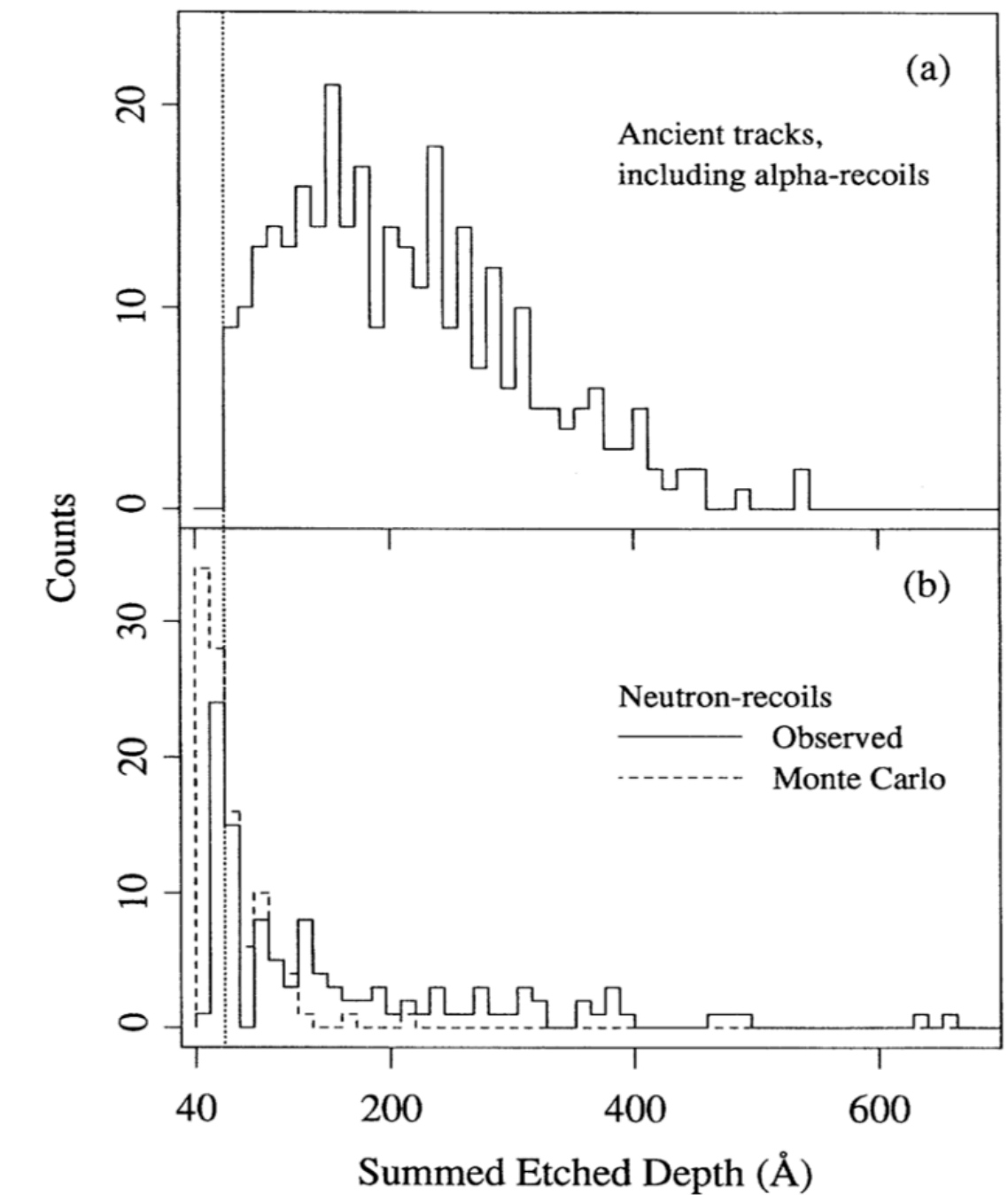
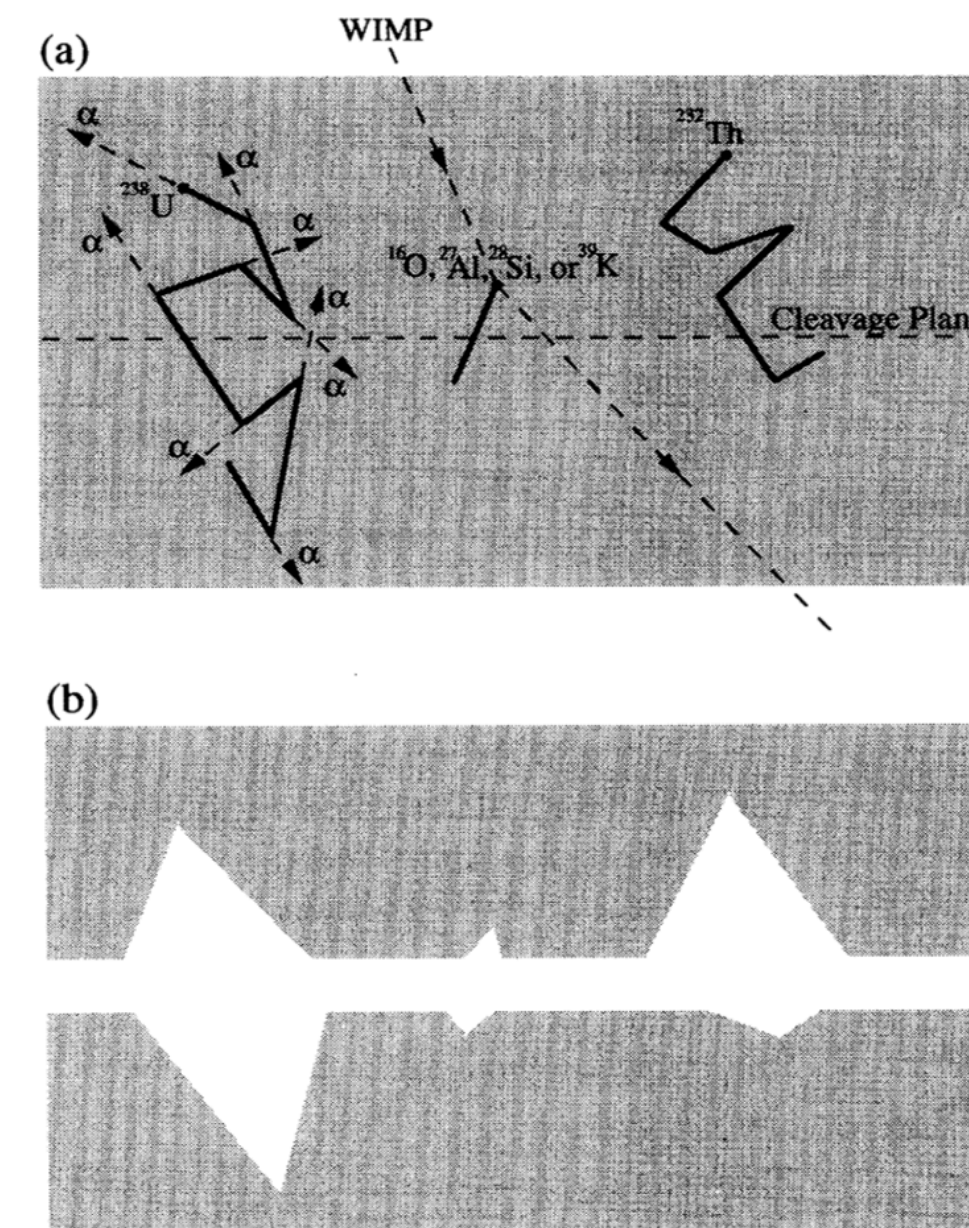
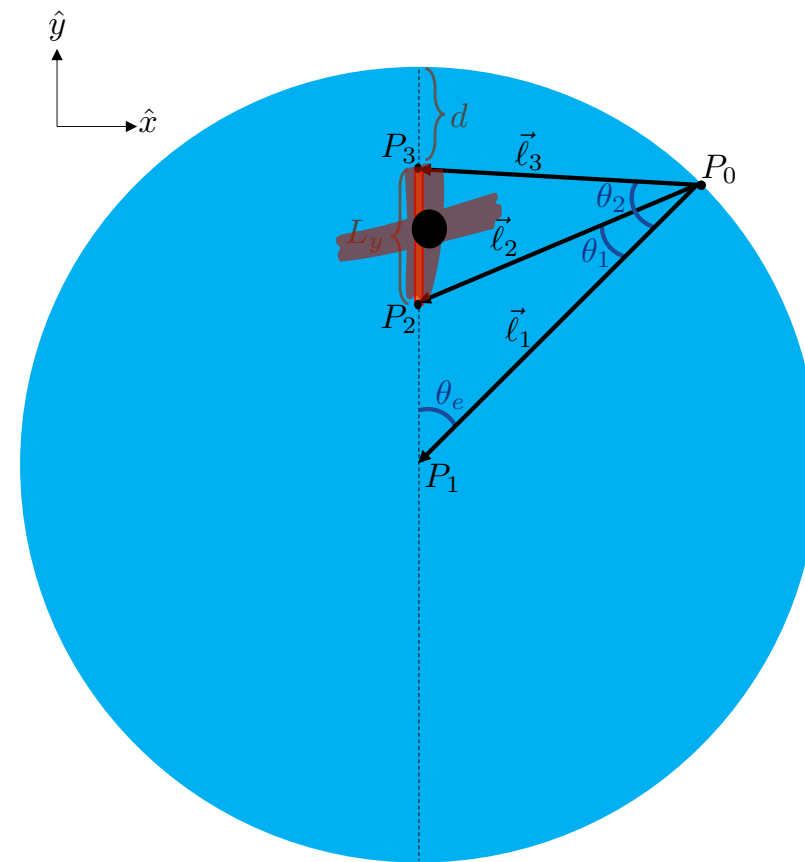


FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.



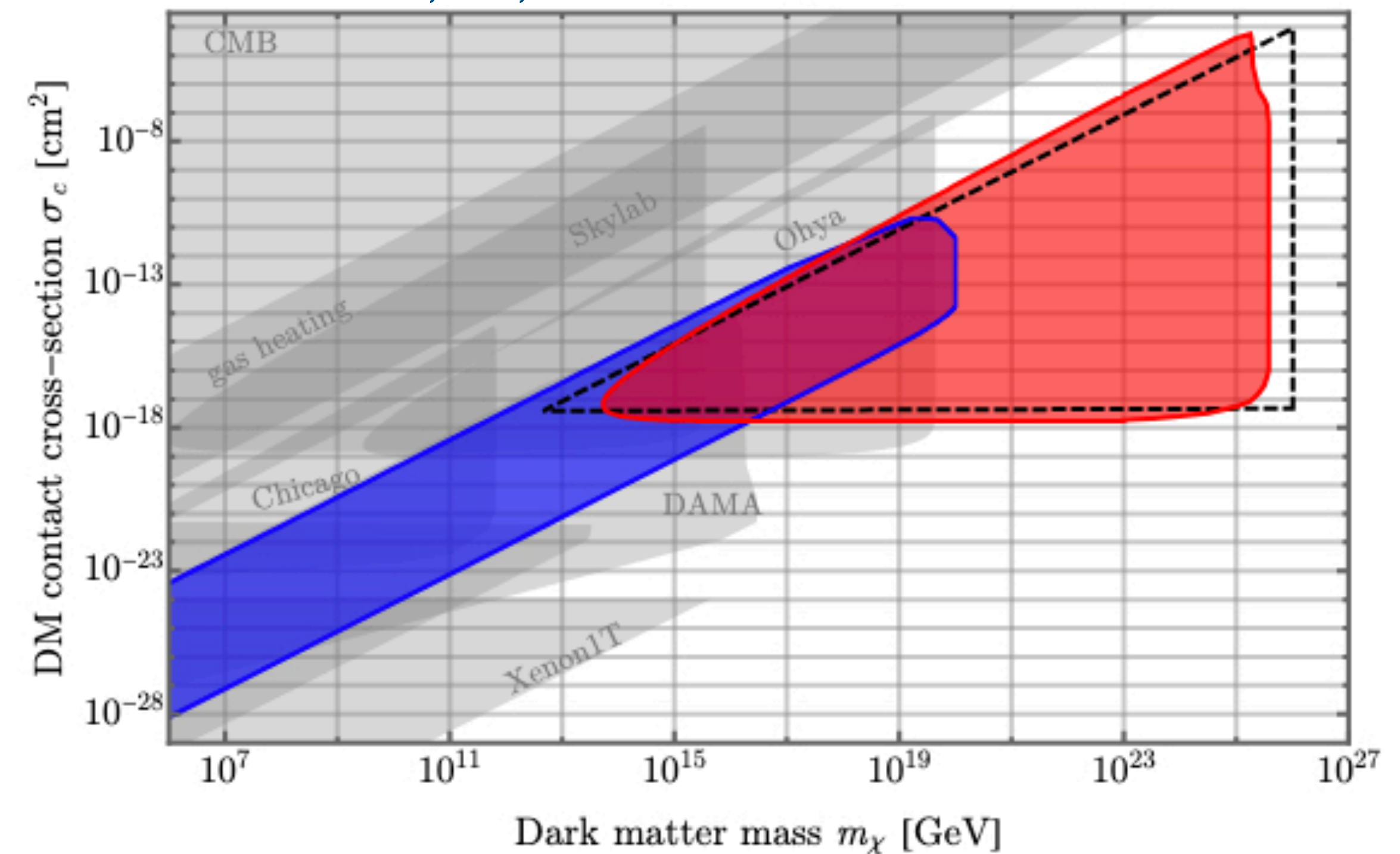
- 1986 Price and Salamon mica monopole search
- 1995 Snowden-Ifft et al. calibrated mica samples

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

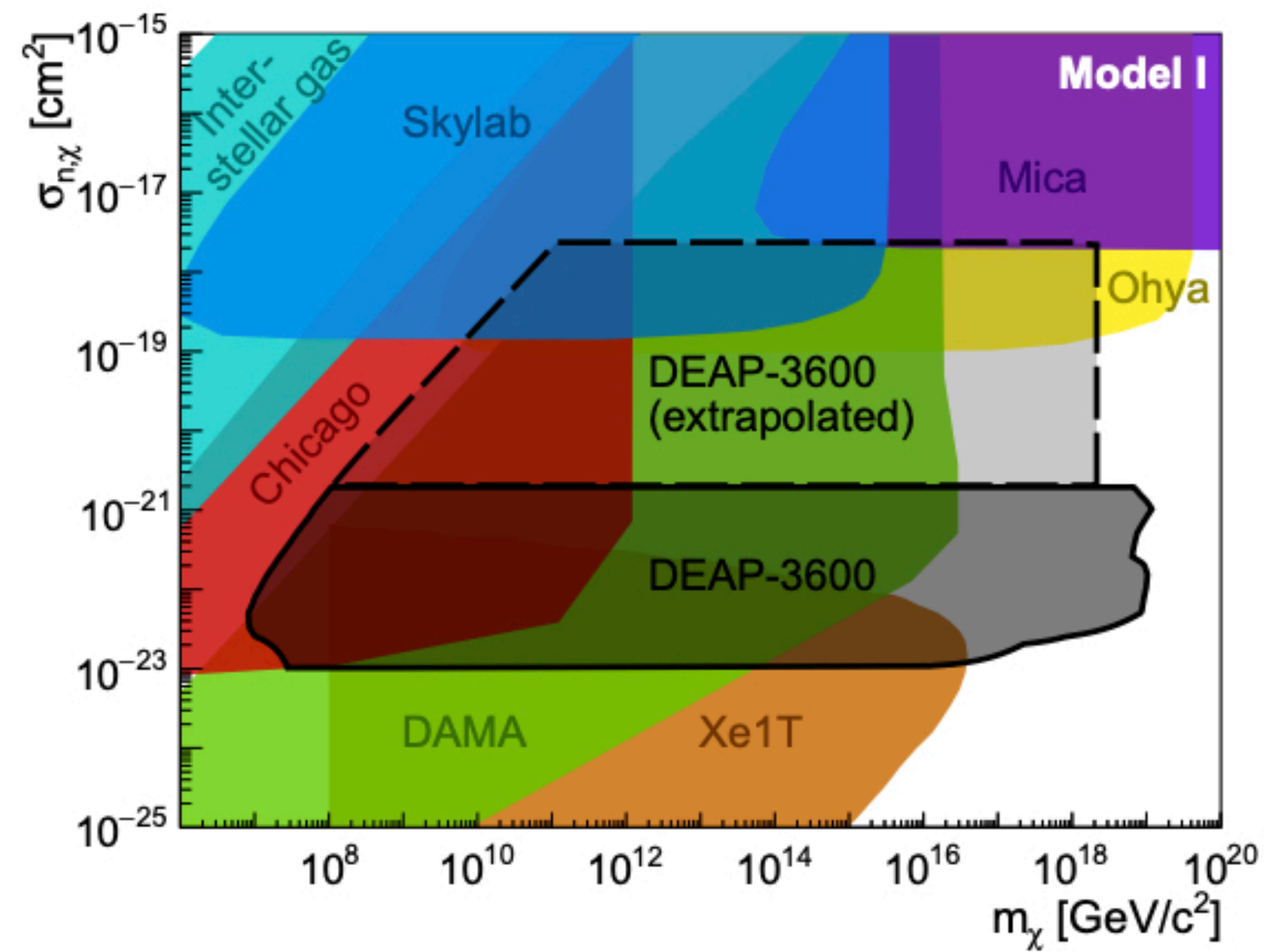


Also a mineral DM detection collaboration at Queen's

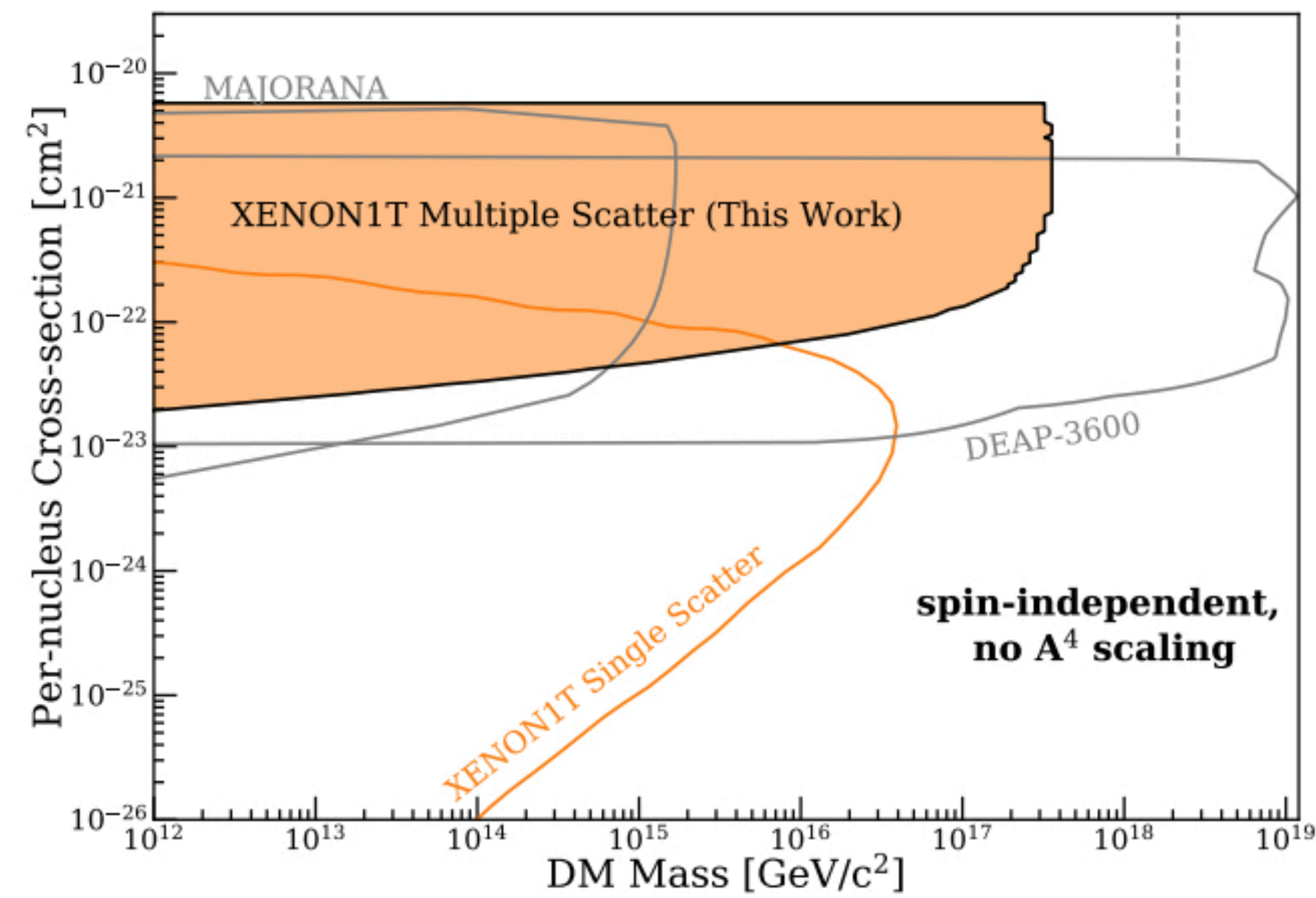
Balogh, Boukhtouchen, JB, Fung, Leybourne, Lucas, Mkhonto, Vincent

See e.g. recent whitepaper: 2301.07118

HEAVY MIMP RESULTS FROM DEAP-3600, XENON1T

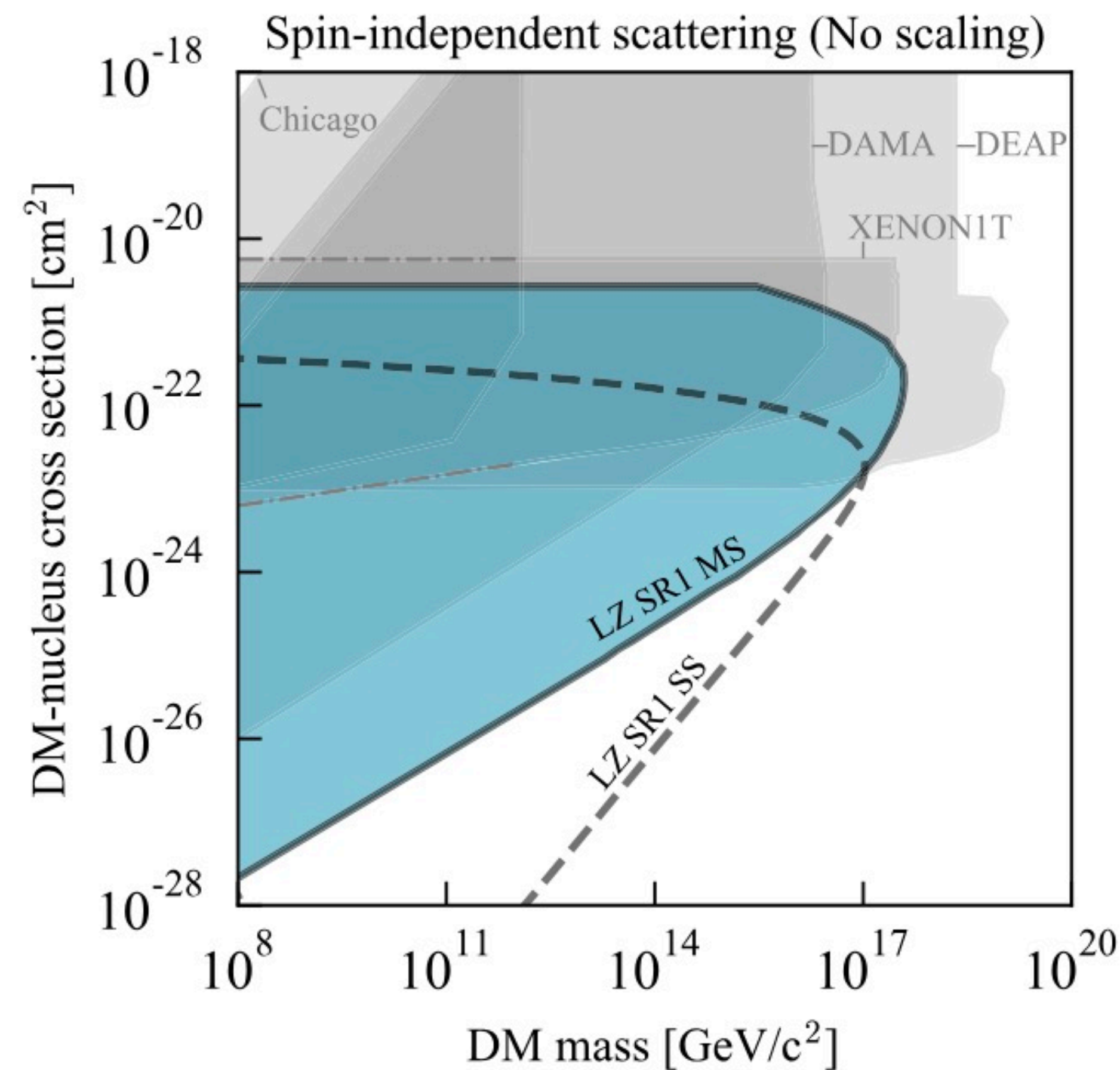


2108.09405

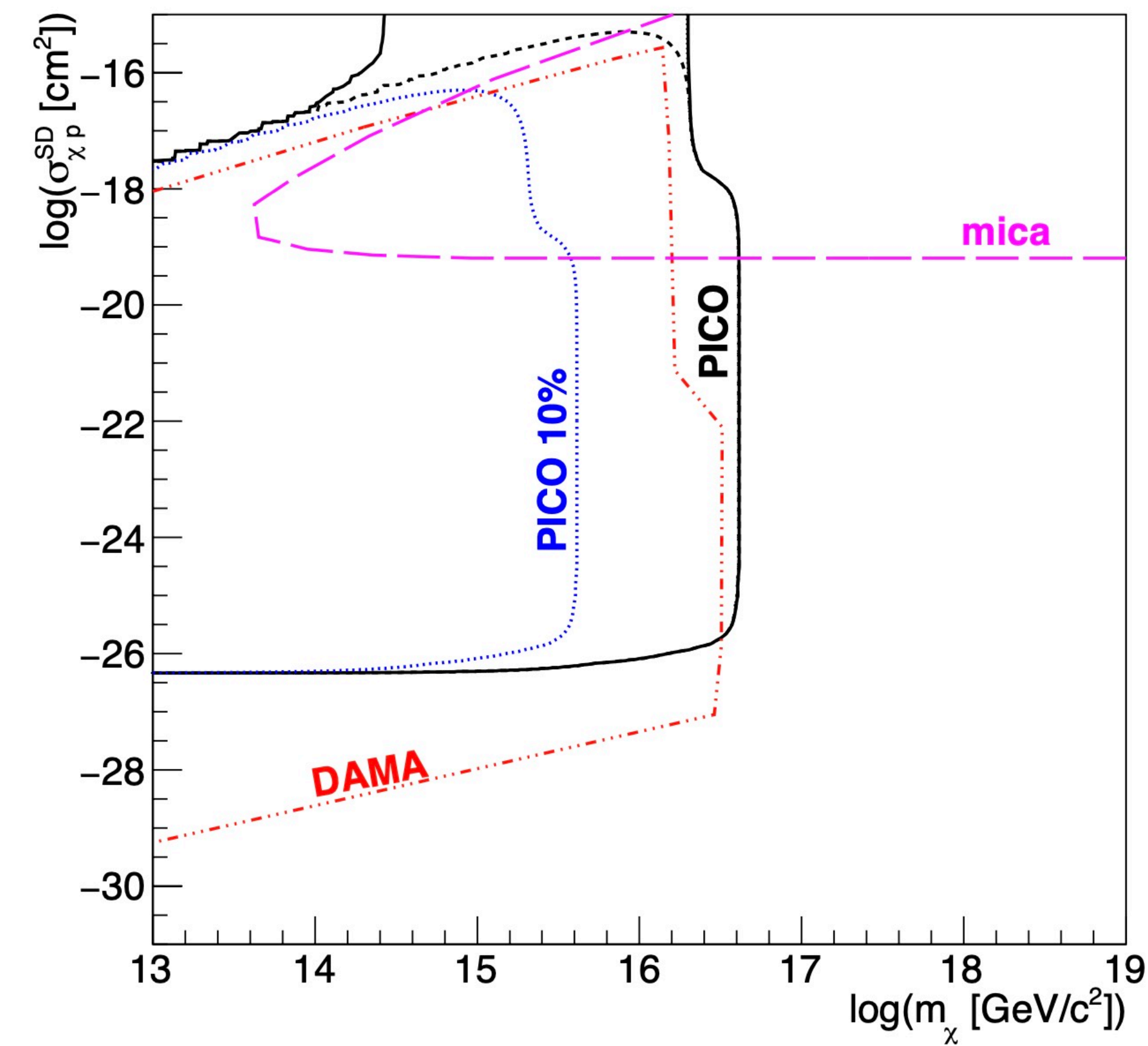


2304.10931

HEAVY MIMP RESULTS FROM LZ, PICO-60



2402.08865



PICO-60, 2022 (Broerman PhD thesis)

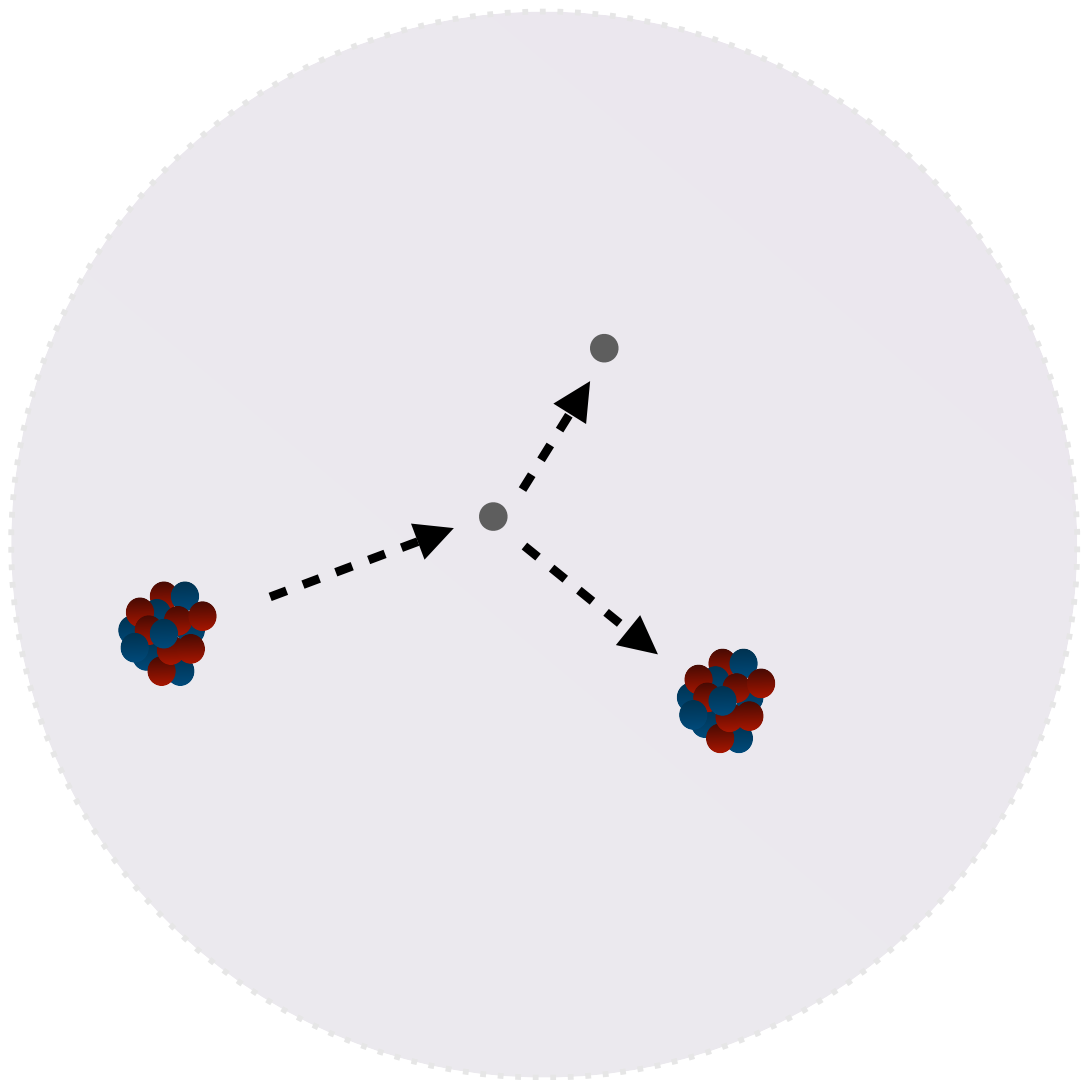
What kind of dark matter produces SD interactions at this mass?

LOOSELY-BOUND COMPOSITES

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

scattering with constituents

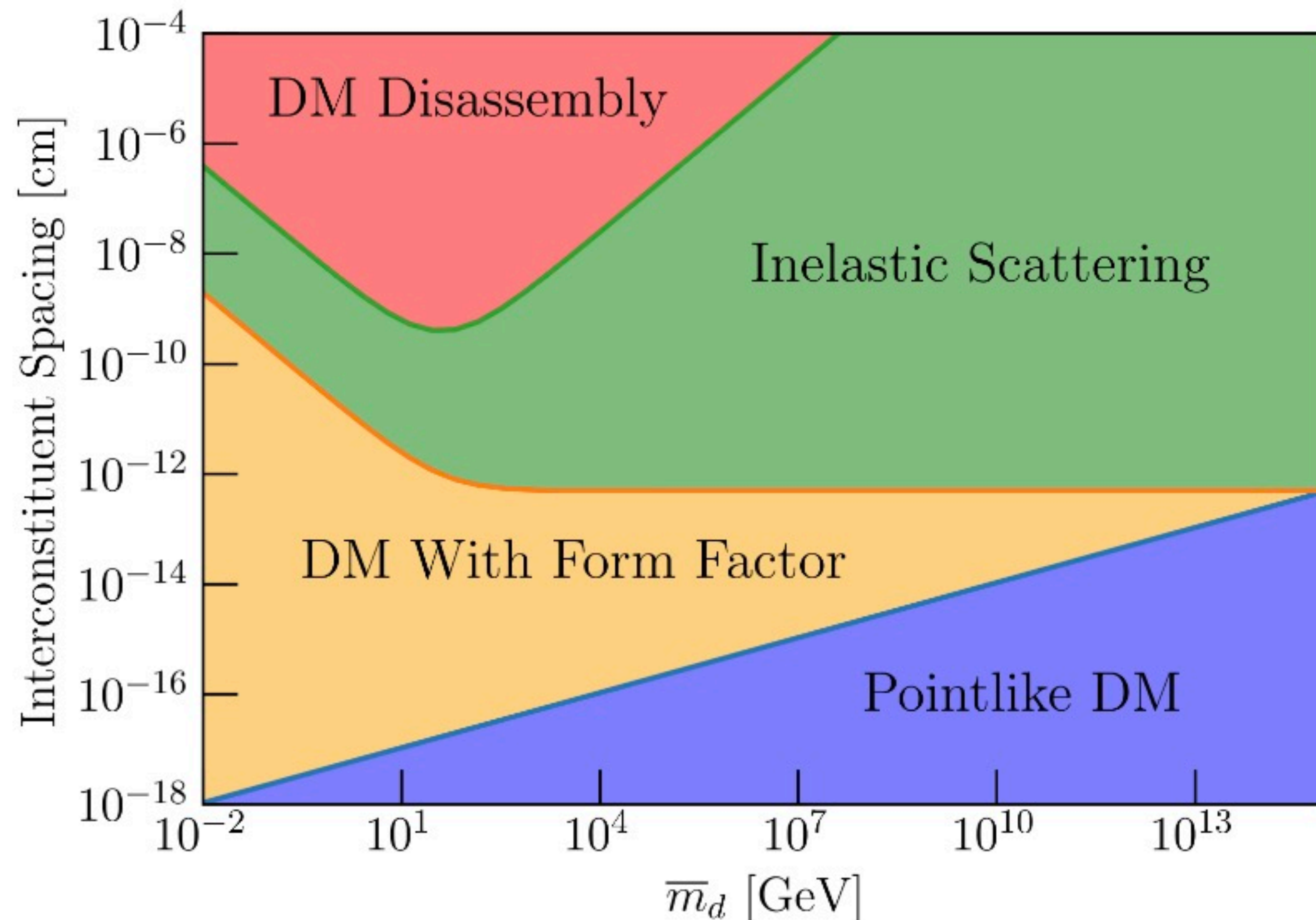
4.



Acevedo, Boukhtouchen, JB, Cappiello,
Mohlabeng, Sheahan, Tyagi, [2408.03983](#)

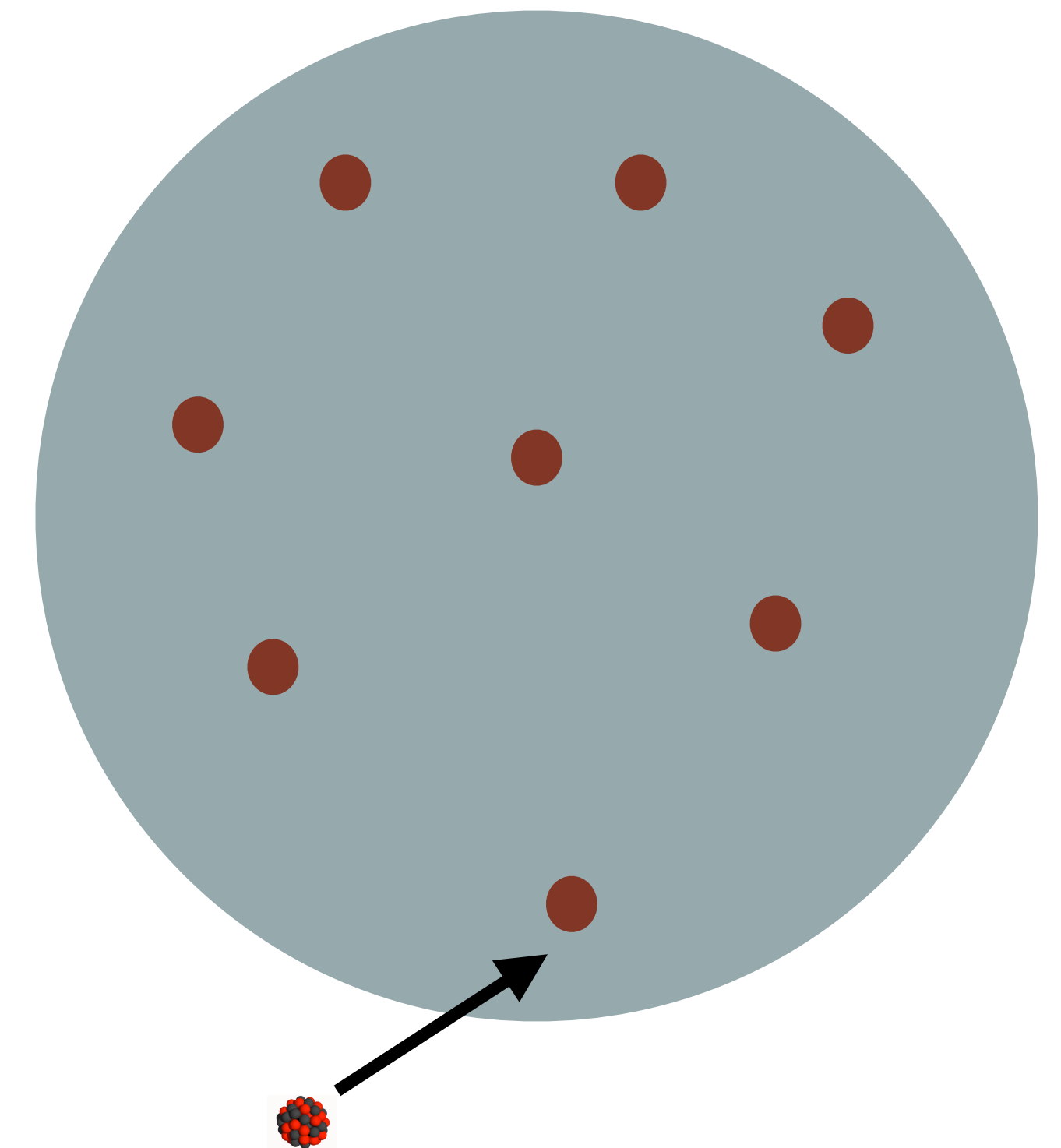
LOOSELY BOUND COMPOSITES

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



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

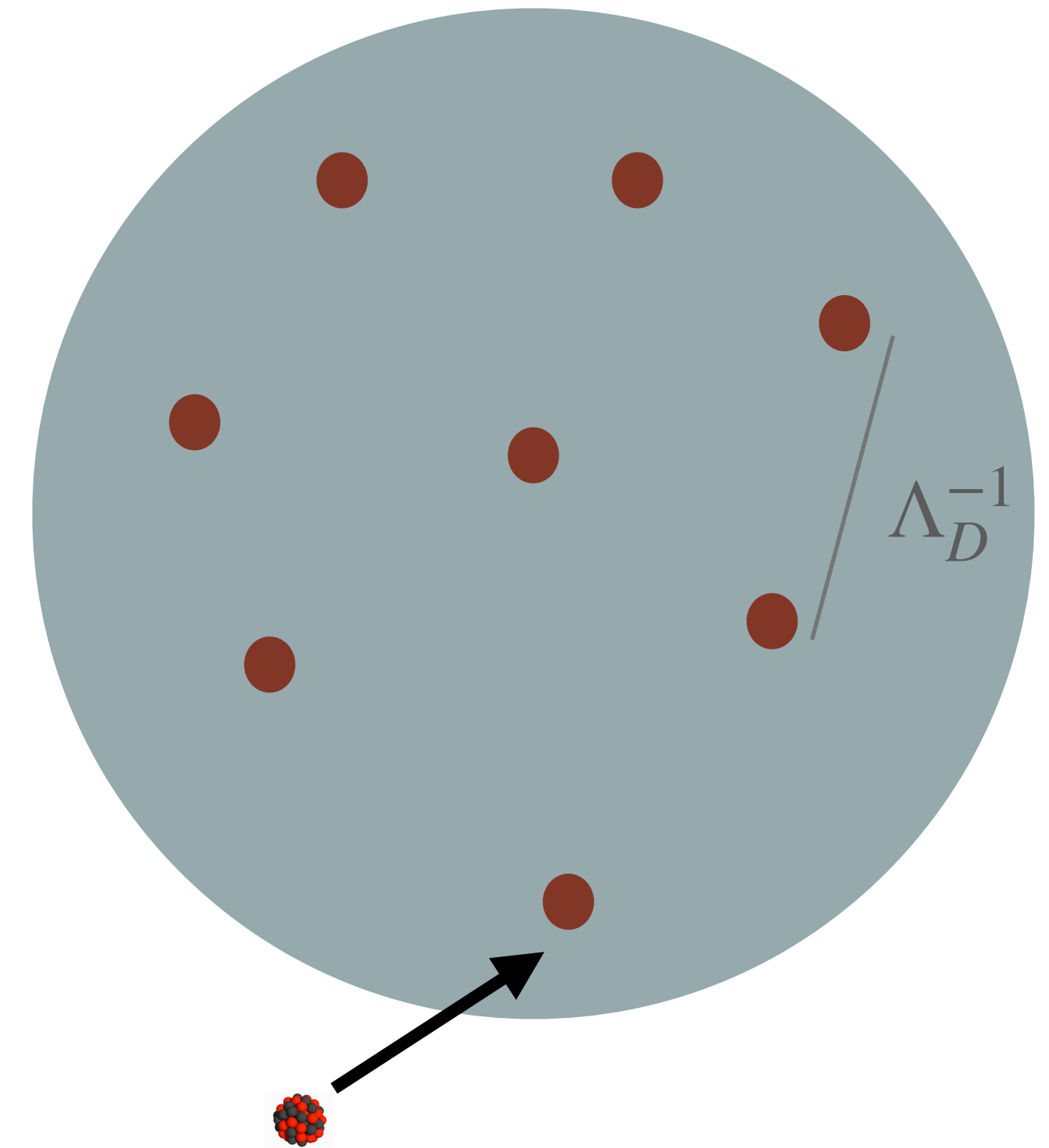
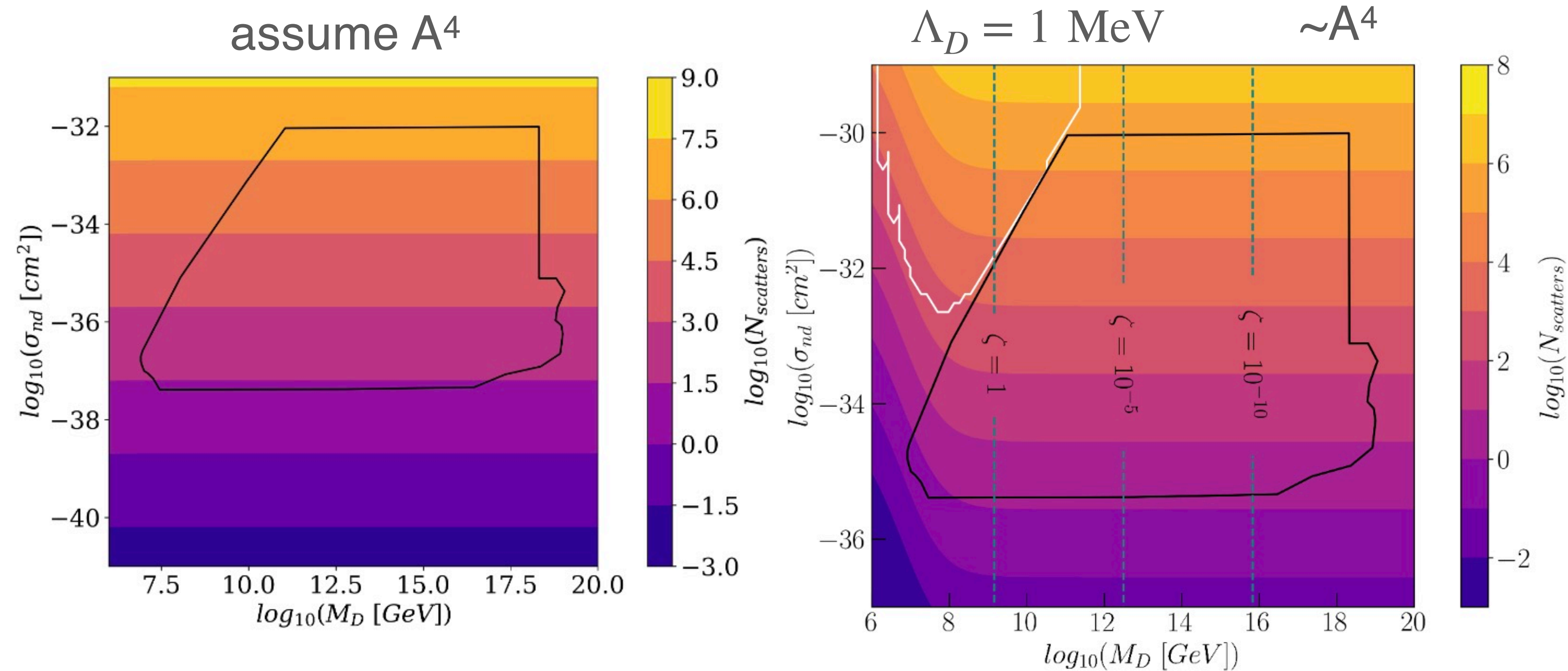
Cf. SM nuclei: $1 > 0.1 > 0.01$ GeV



LOOSELY BOUND COMPOSITES

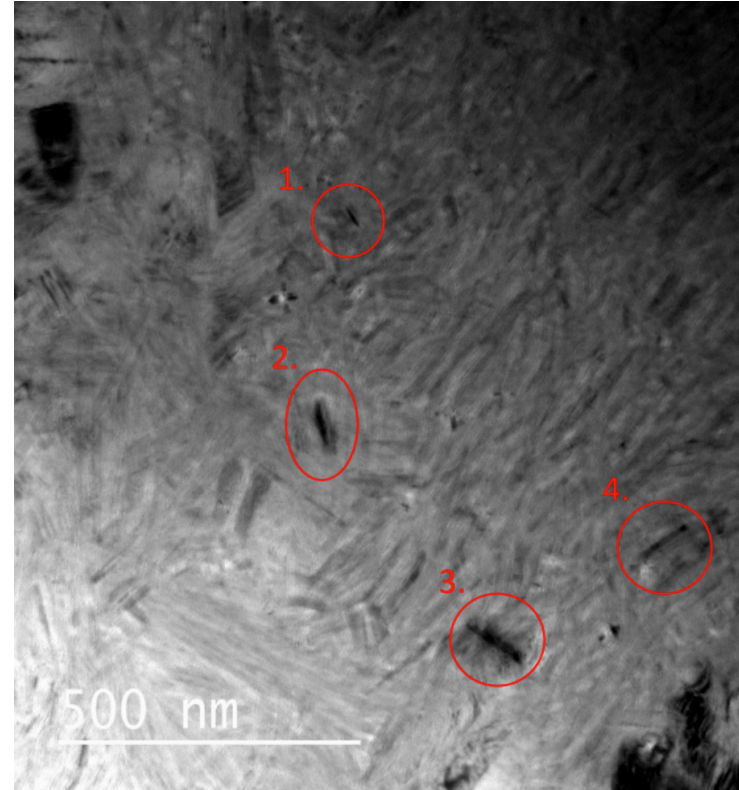
Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Tyagi 2408.03983

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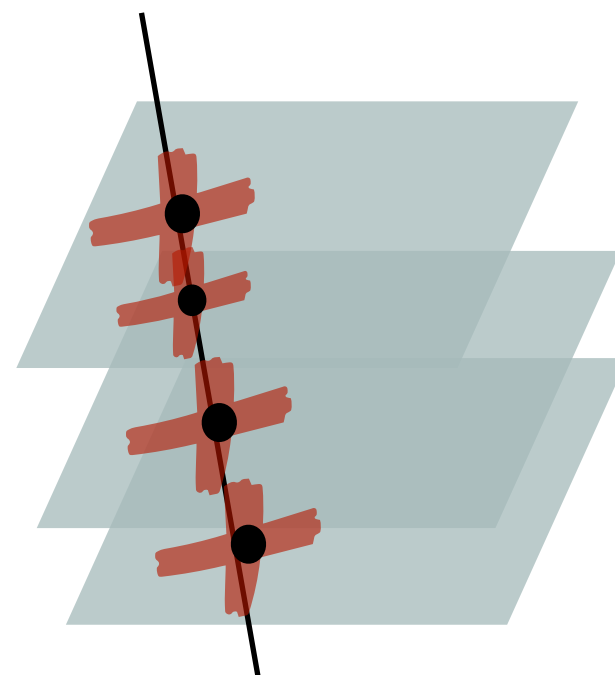
- DM-nuclear scattering cross sections that scales with $\sim A^4$ for larger than nuclear cross sections

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

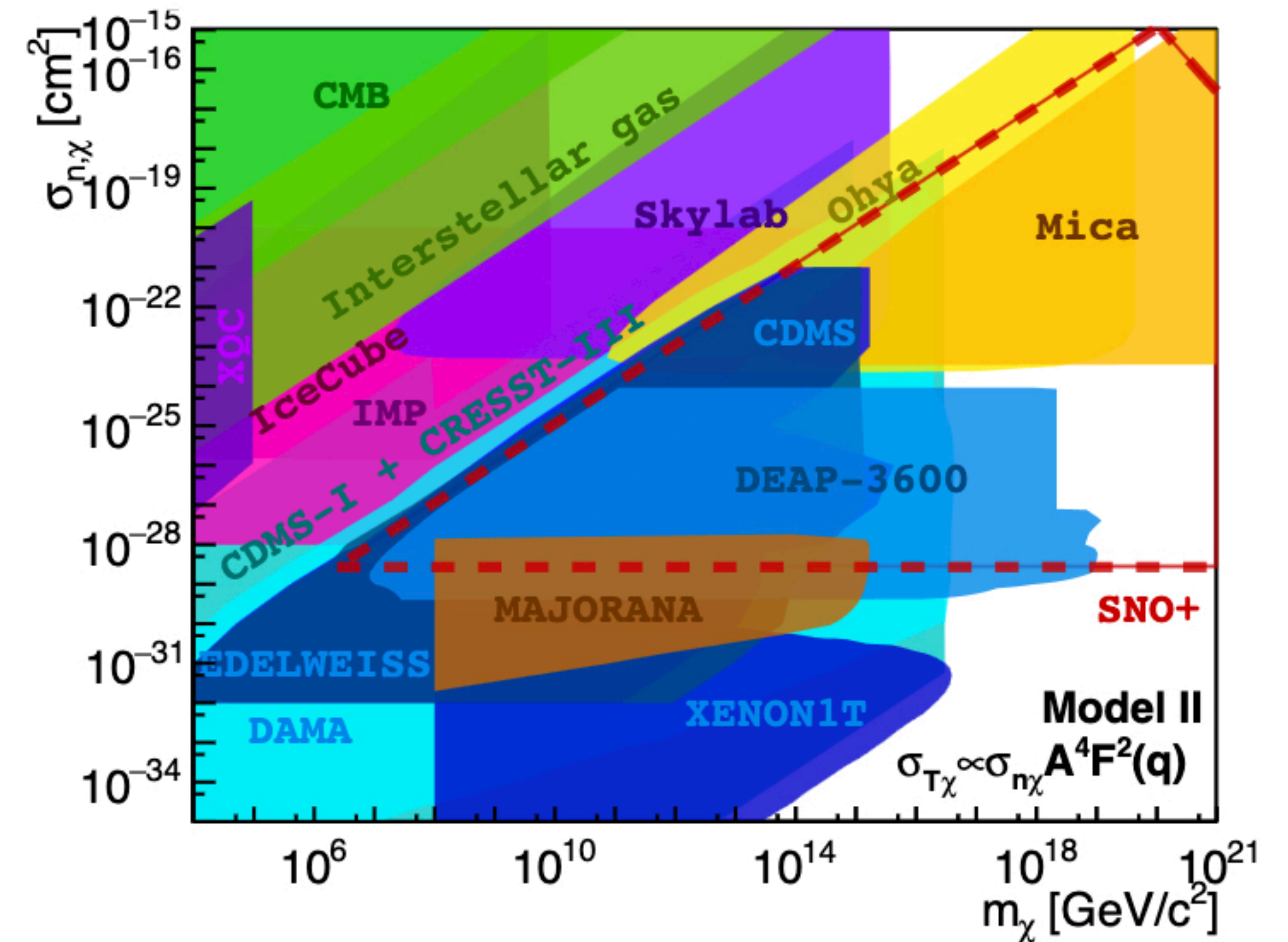


Q Paleo (QCumber? – name suggestions welcome) 2301.07118

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



Future CR-39 experiment or similar



Snowmass Ultraheavy dark matter

Carney, Raj et al. 2203.06508

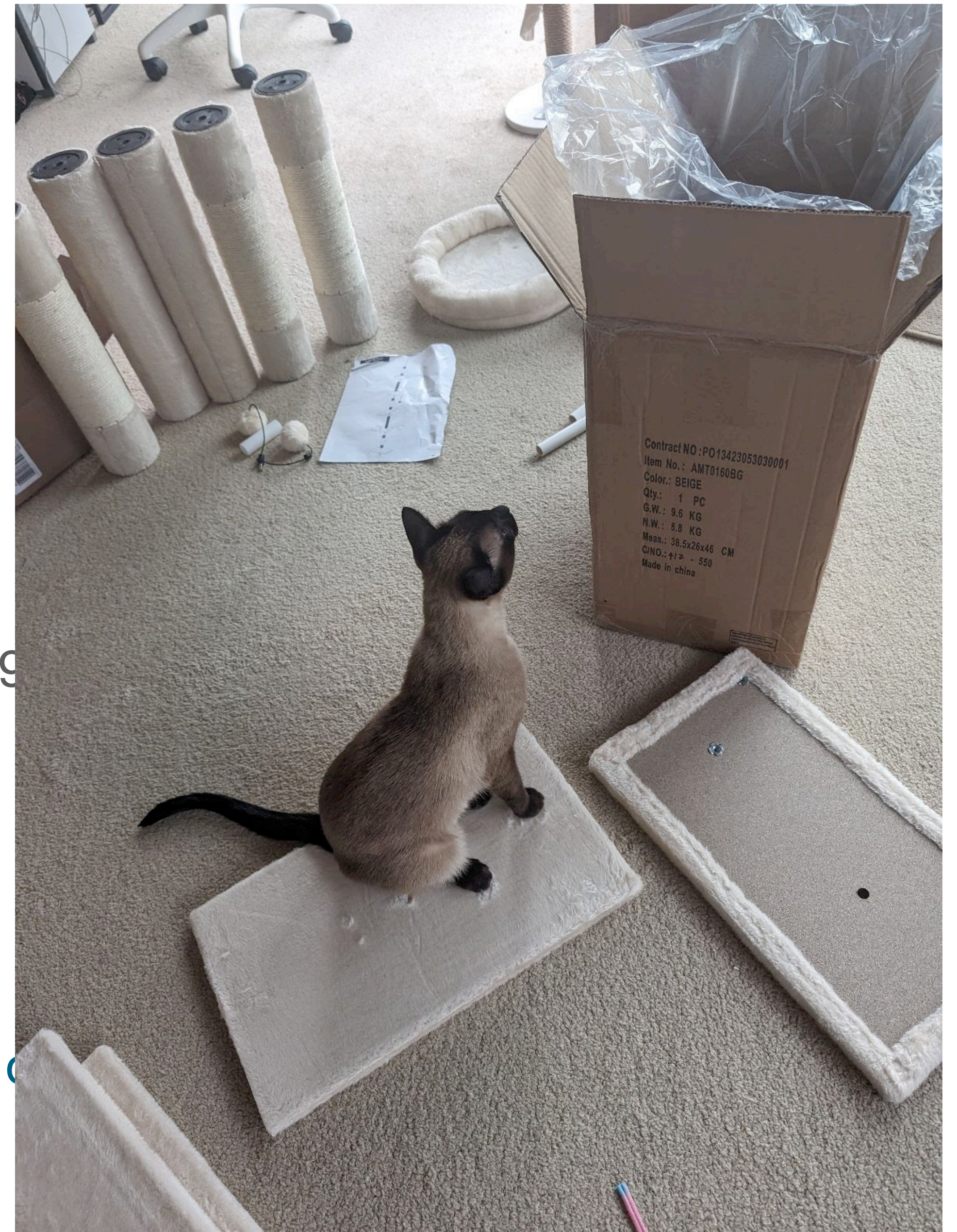
DARK MATTER AT THE HIGH MASS FRONTIER

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

- The simplest DM are well studied, and may be easier to look for, for now.

(Simple in formulation, sometimes complicated in dynamics)

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



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(Simple in formulation, sometimes complicated in dynamics)

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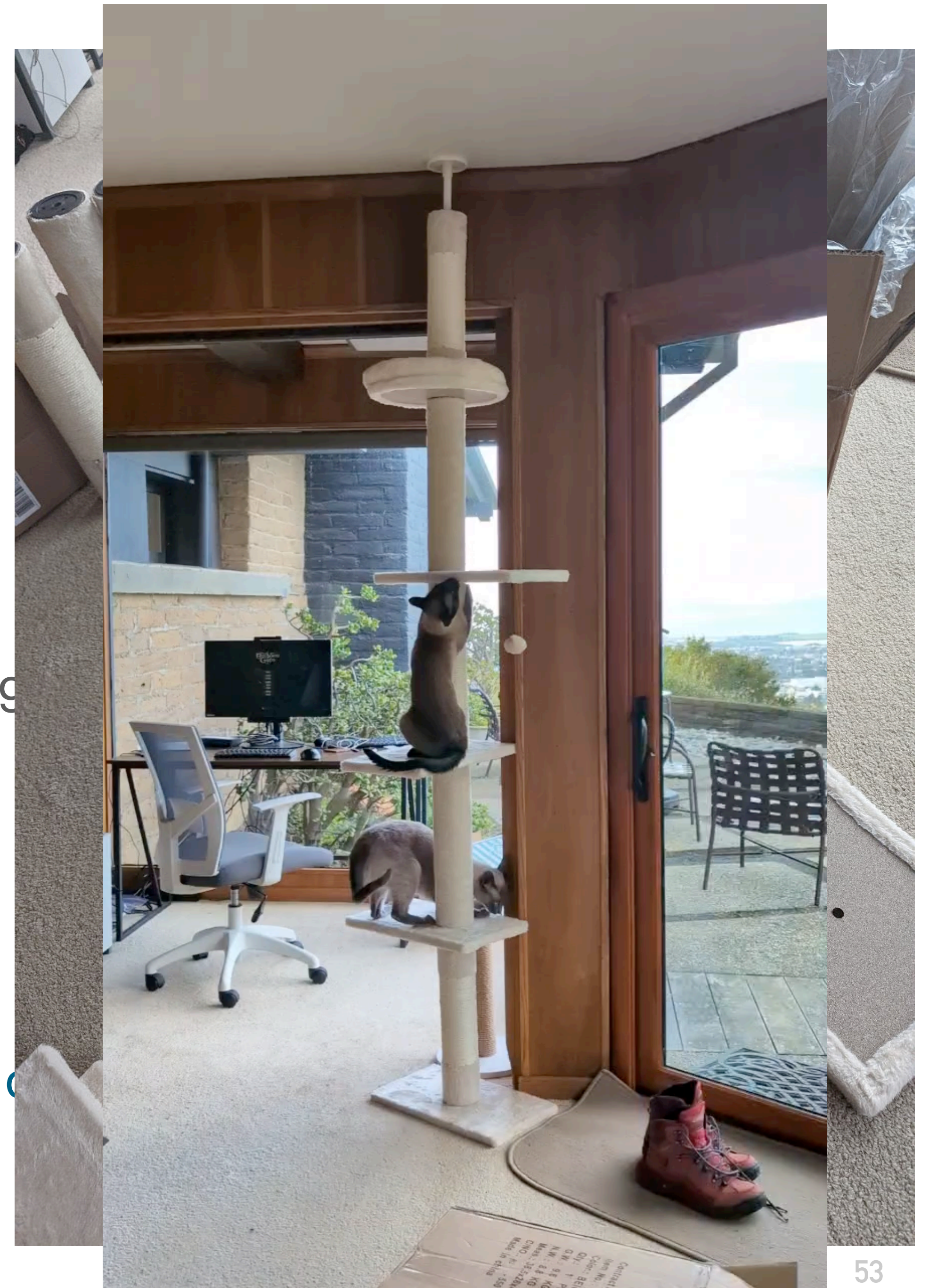
DARK MATTER AT THE HIGH MASS FRONTIER

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(Simple in formulation, sometimes complicated in dynamics)

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



Saturated ADM composite parameters

bremsstrahlung + fusion requires
a few nuclei per composite

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

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

for large N_c composite interior has a potential determined by:

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

with interior mass

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

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

(DM fusion conditions)

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

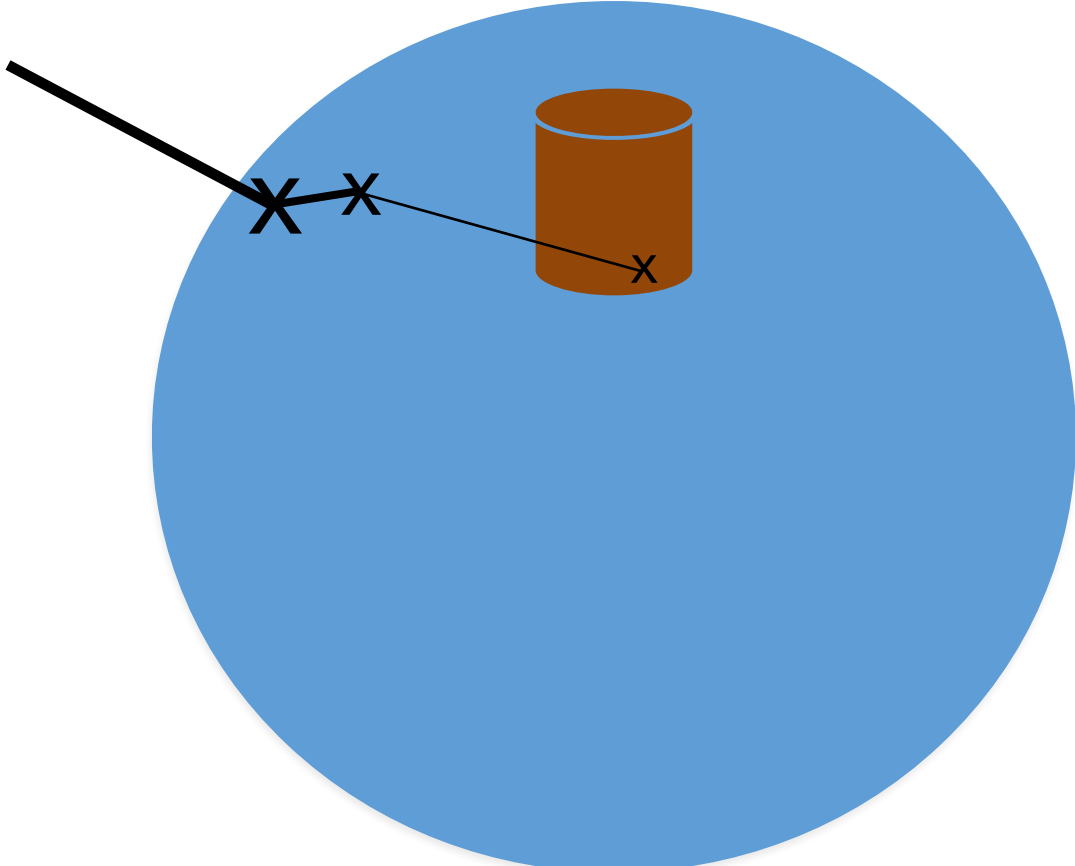
$$\alpha_X \gtrsim 0.3 \left(\frac{m_X}{10^7 \text{ GeV}} \right)^{\frac{2}{5}} \left(\frac{\zeta}{10^{-6}} \right)^{\frac{1}{5}}$$

edge of composite screened

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

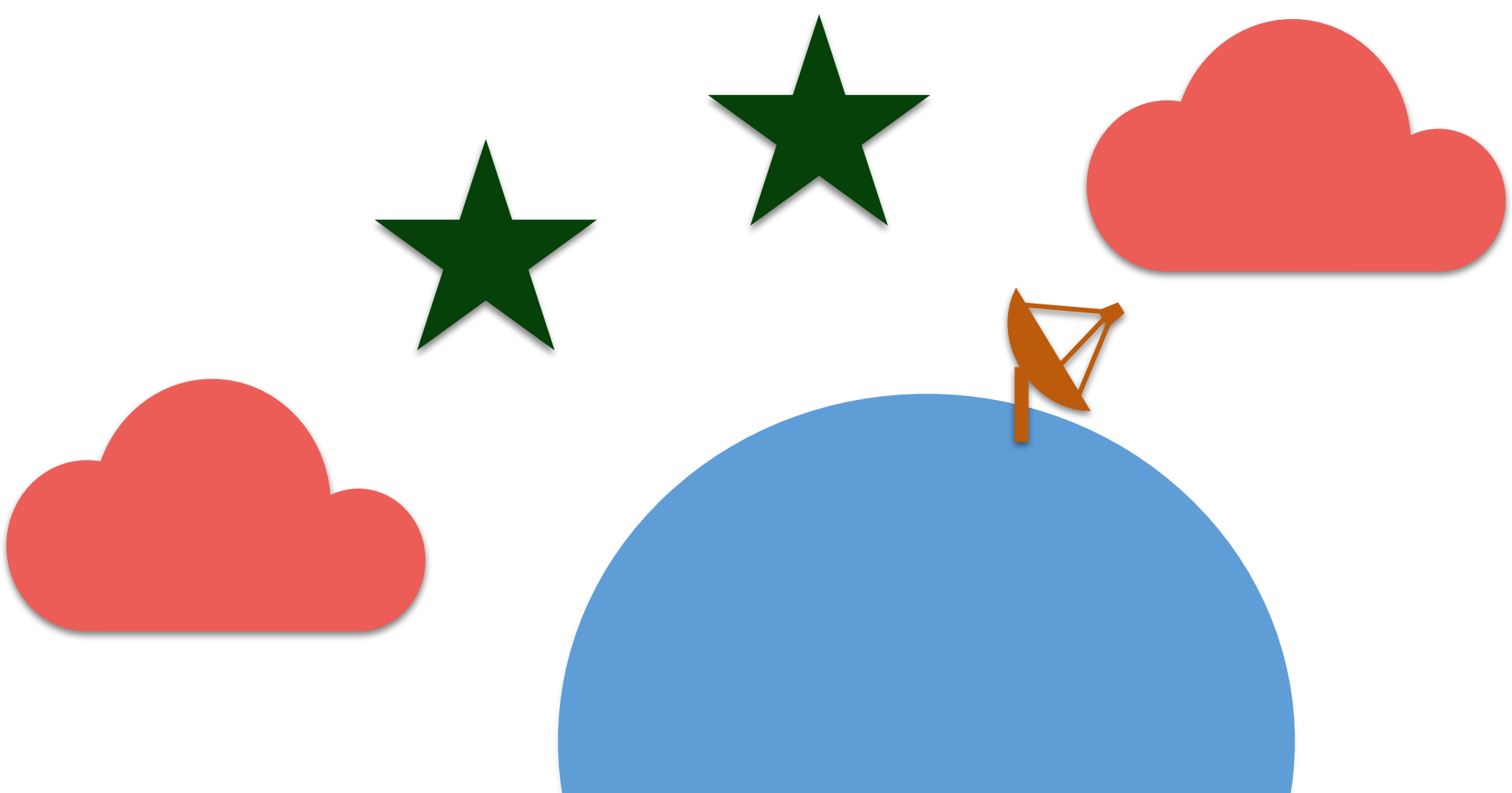
GAS CLOUDS

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



dark matter kinetic energy < recoil threshold

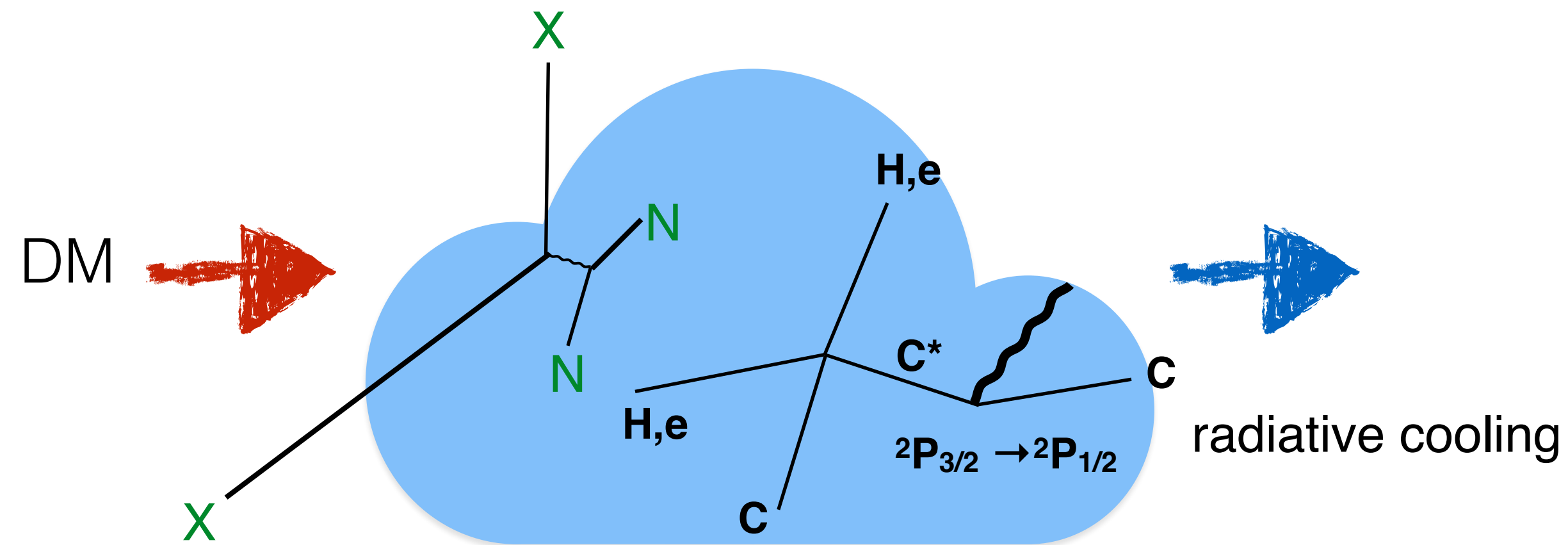
use detectors in space



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

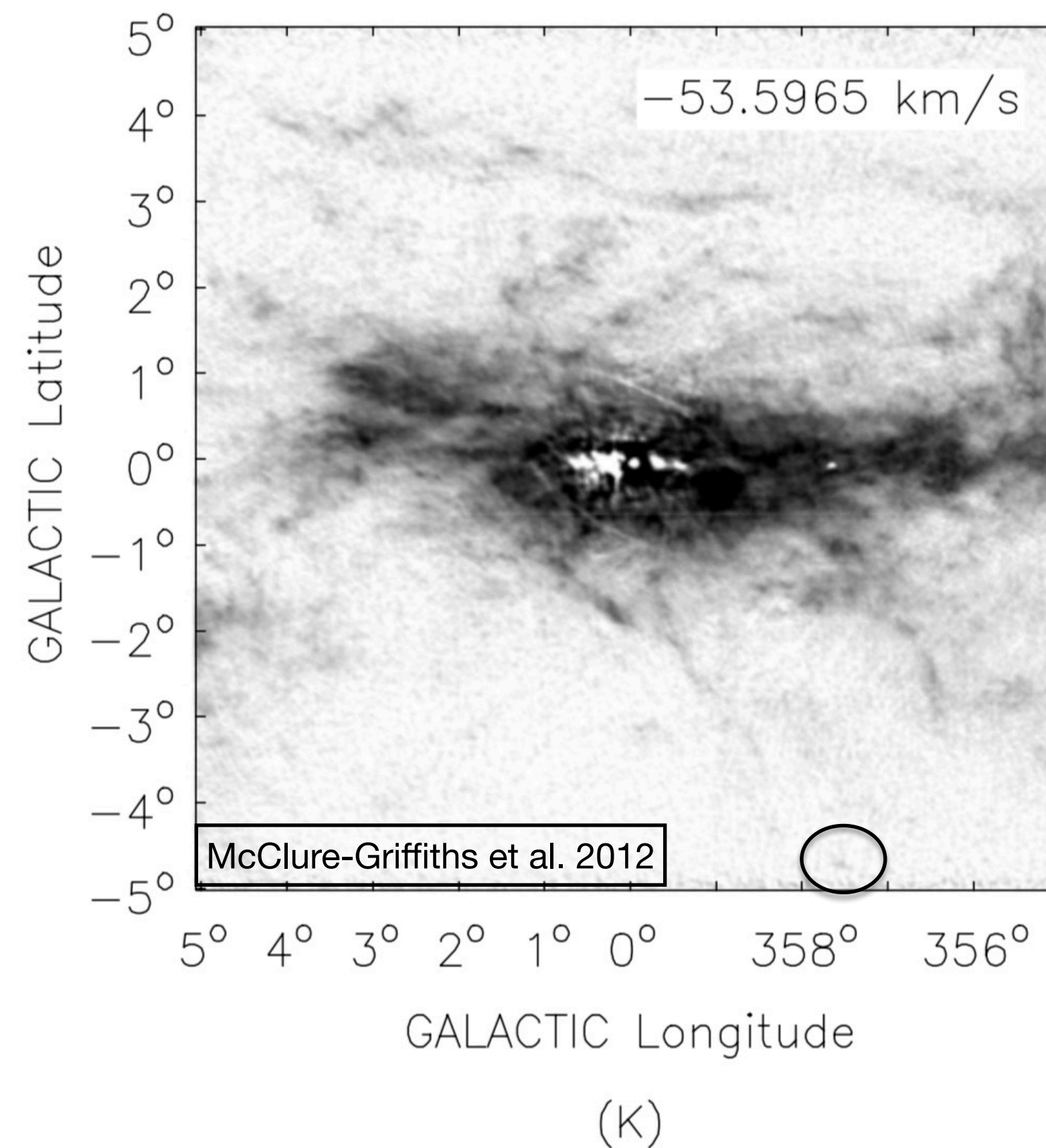
photoelectric heating
via dust grains



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

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

$T_g < 137$ K

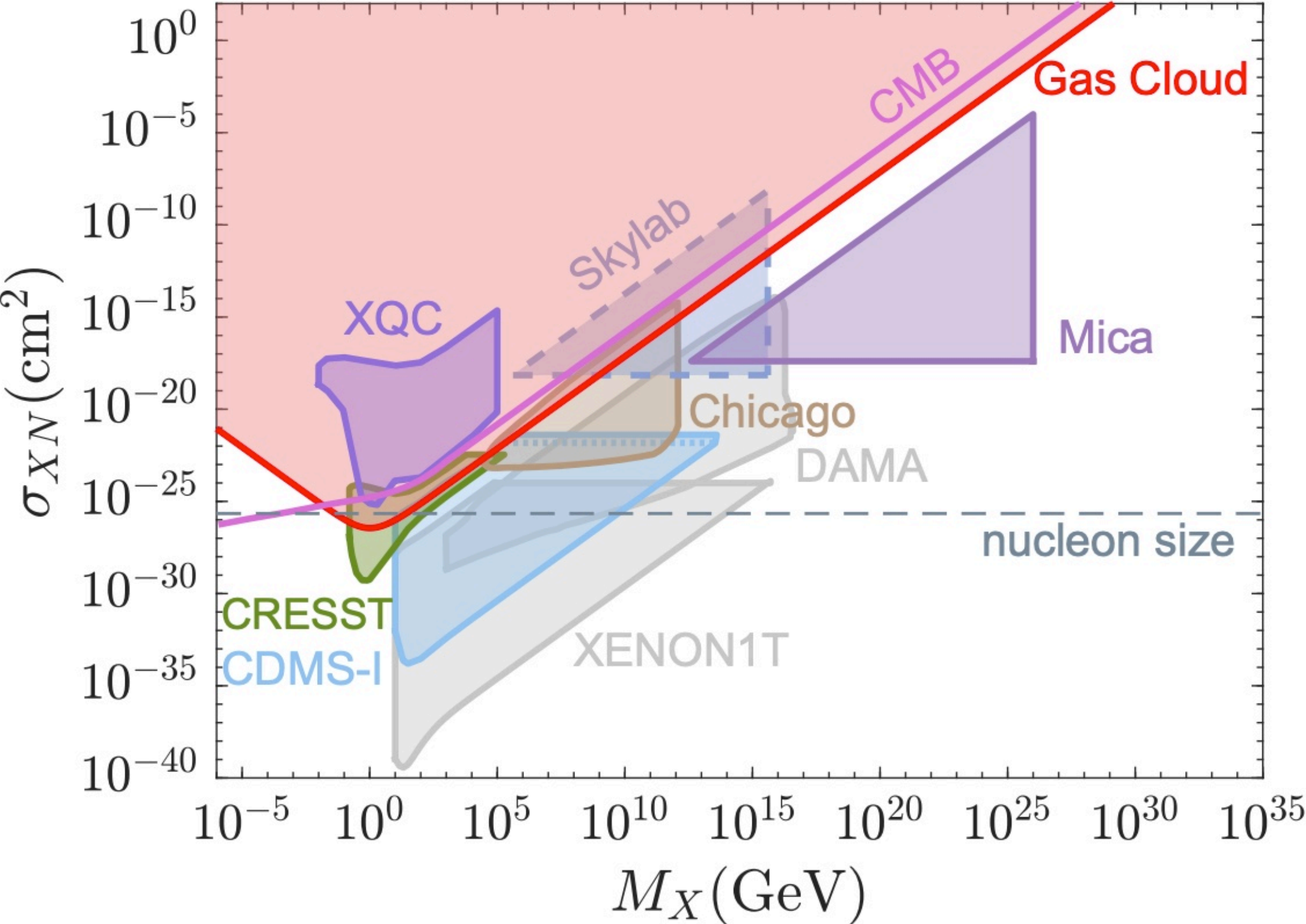
$r_{los} \sim 800$ pc

$v_g = -54$ km/s

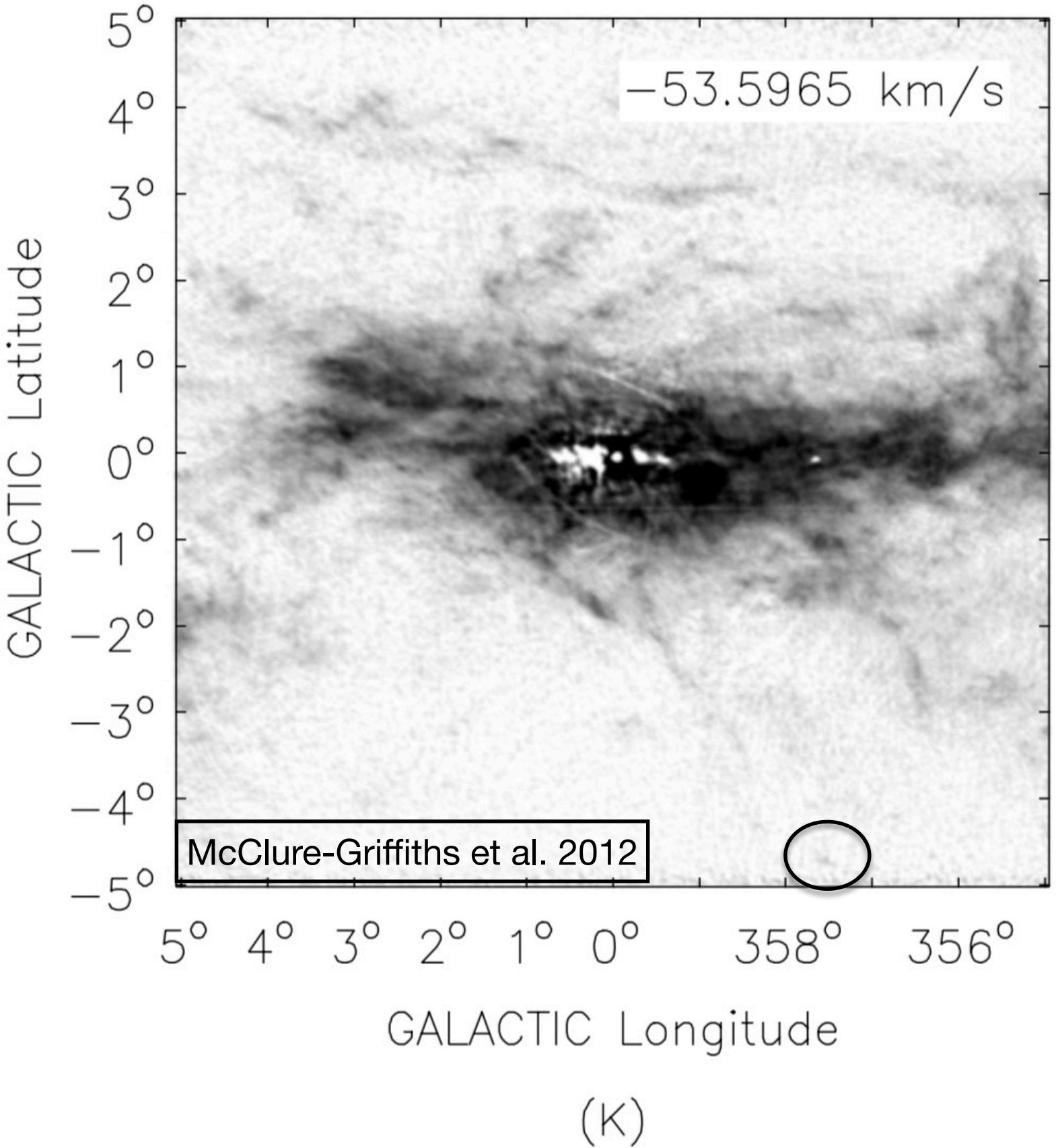
(assume spherical cloud)

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei



Gas Cloud 357.8-4.7-55



Δv from 21cm emission gives $T < 137 \text{ K}$

G357.8-4.7-55

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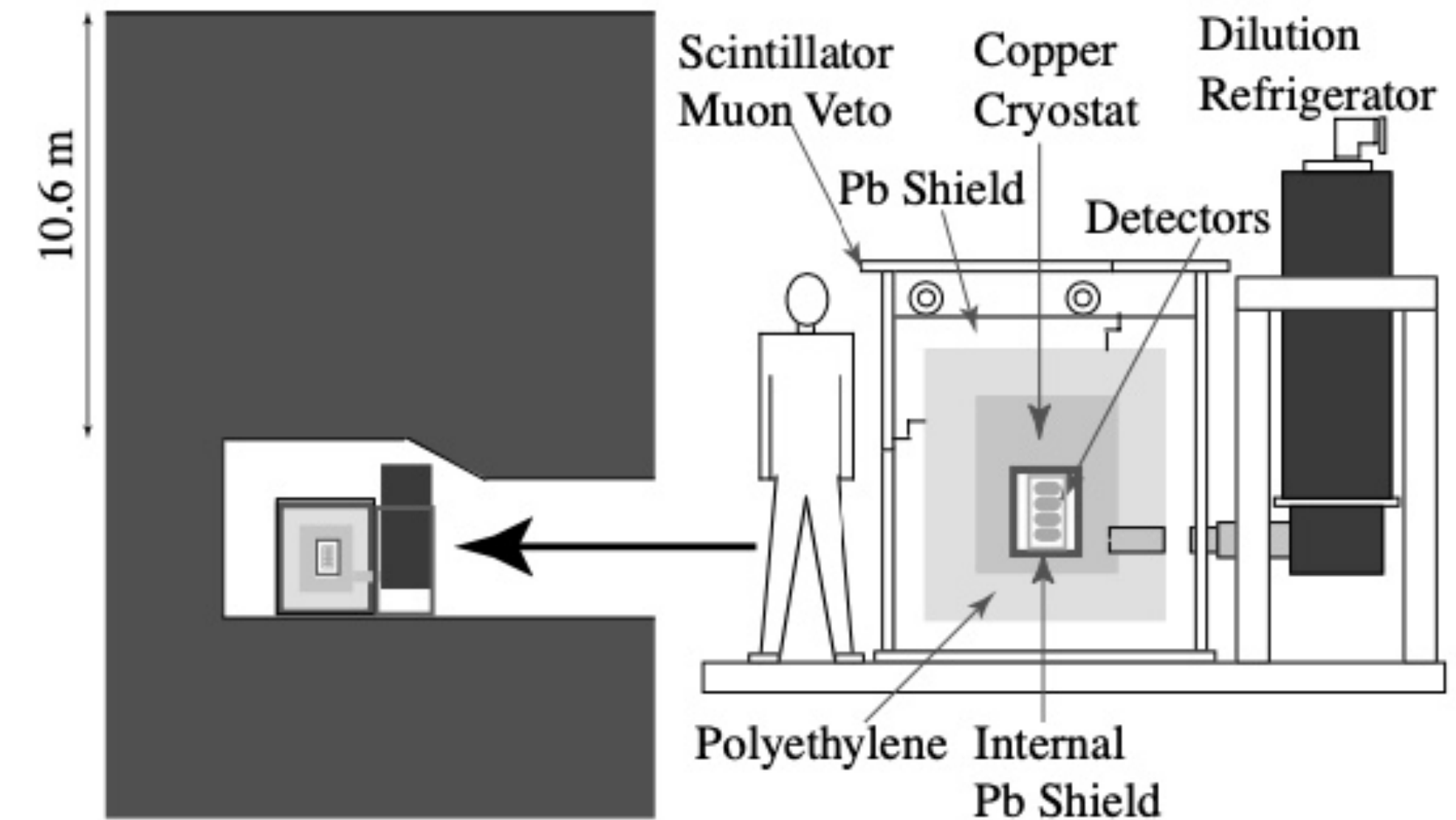
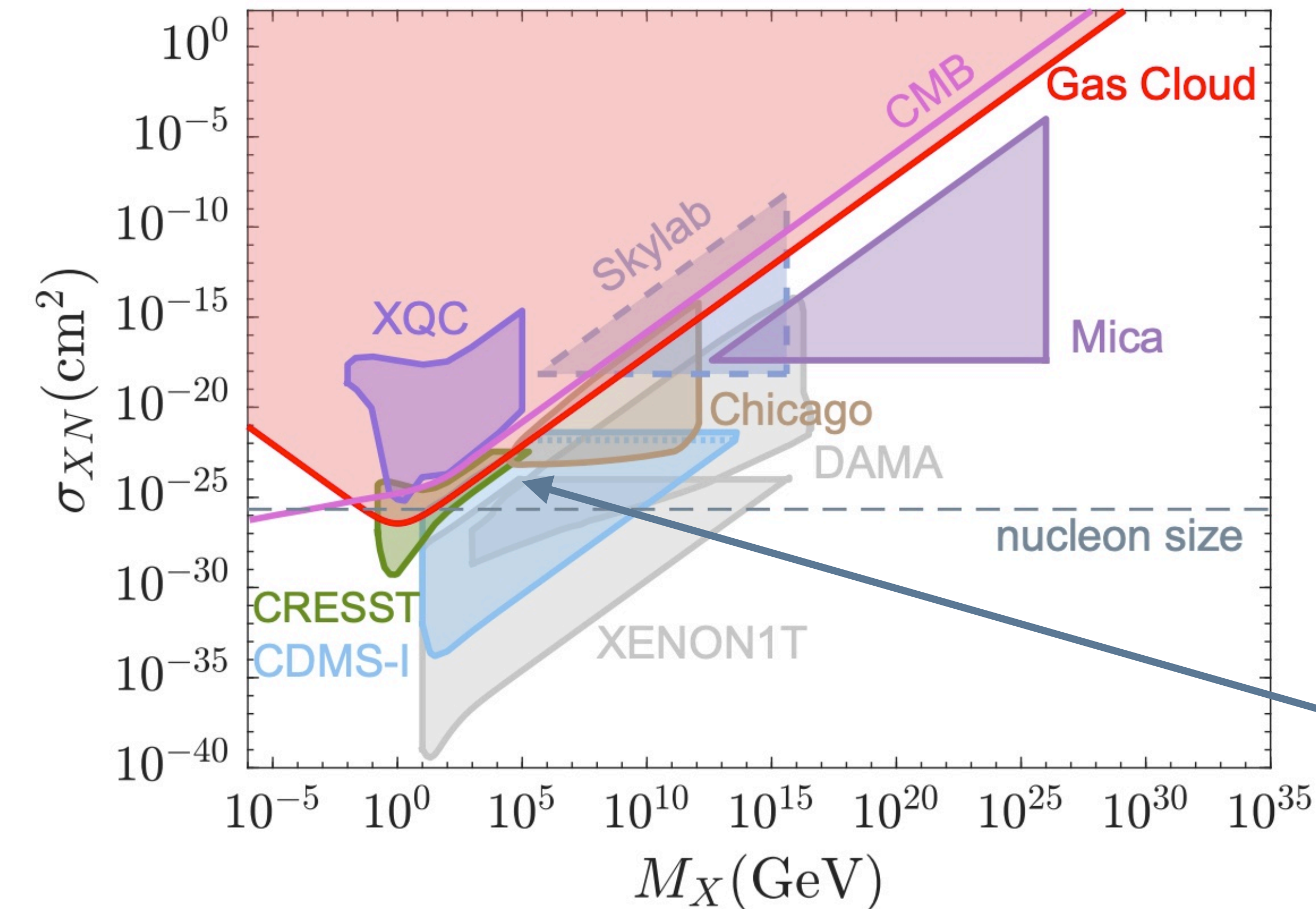
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(assume spherical cloud)

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)