This was the provisional title given to me by the organizers:

FUTURE WIMPS

Joseph Bramante

Queen's University

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PI

MI Meeting 2023

Thankfully I had training for this at a recent MI astro & particle theory workshop

The hat game

Particle physics term

Non-abelian
Ultrarelativistic
Weakly interacting
Fluffy
Warm
Scintillating

Astro term

Galactic magnetic fields
Asteroids
Saturn’s hexagon
Lyman alpha forest
Active galactic nuclei

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 WIMPS

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PI

MI Meeting 2023

Delorean

2023 BZ

BACK TO THE FUTURE DM

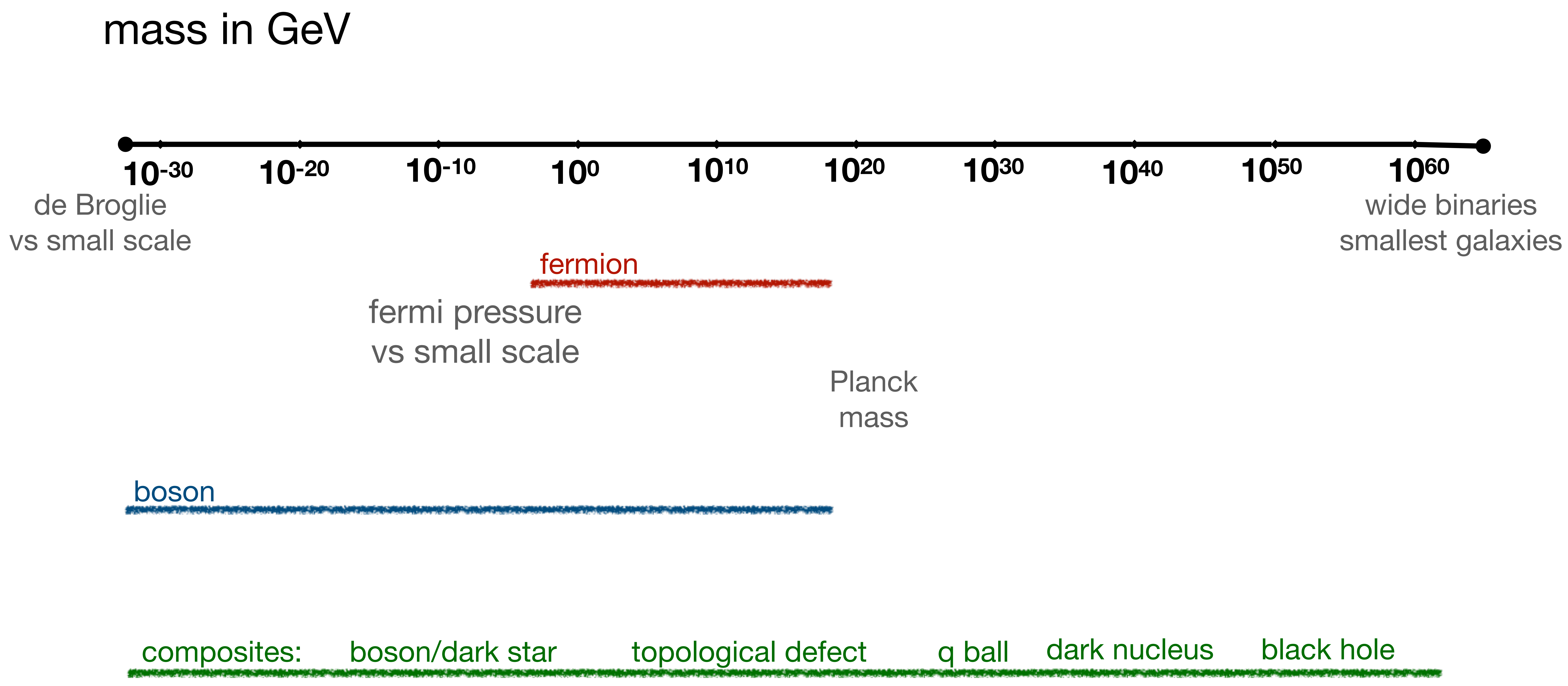
-Most DM models were written down in the 80s.

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

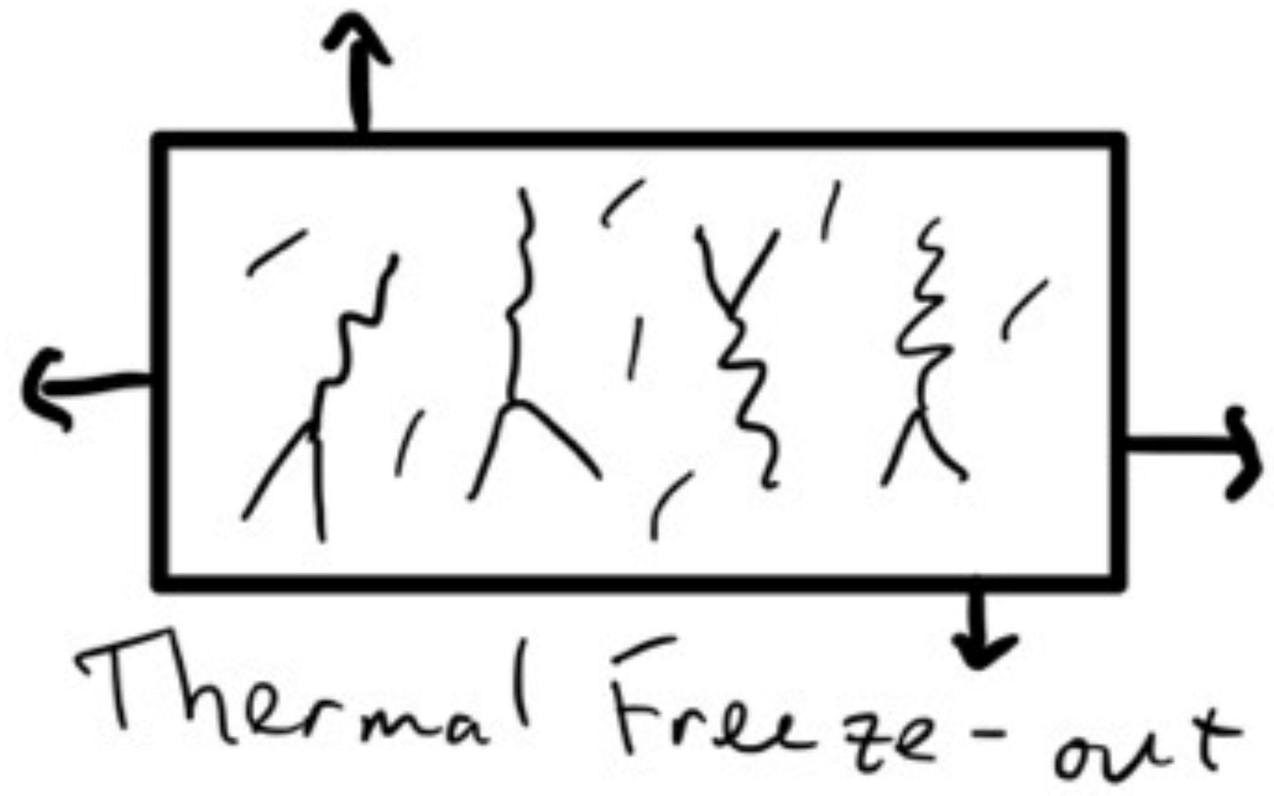
(Simple in formulation, complicated in dynamics)

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

What do we know about dark matter?



The WIMP Miracle

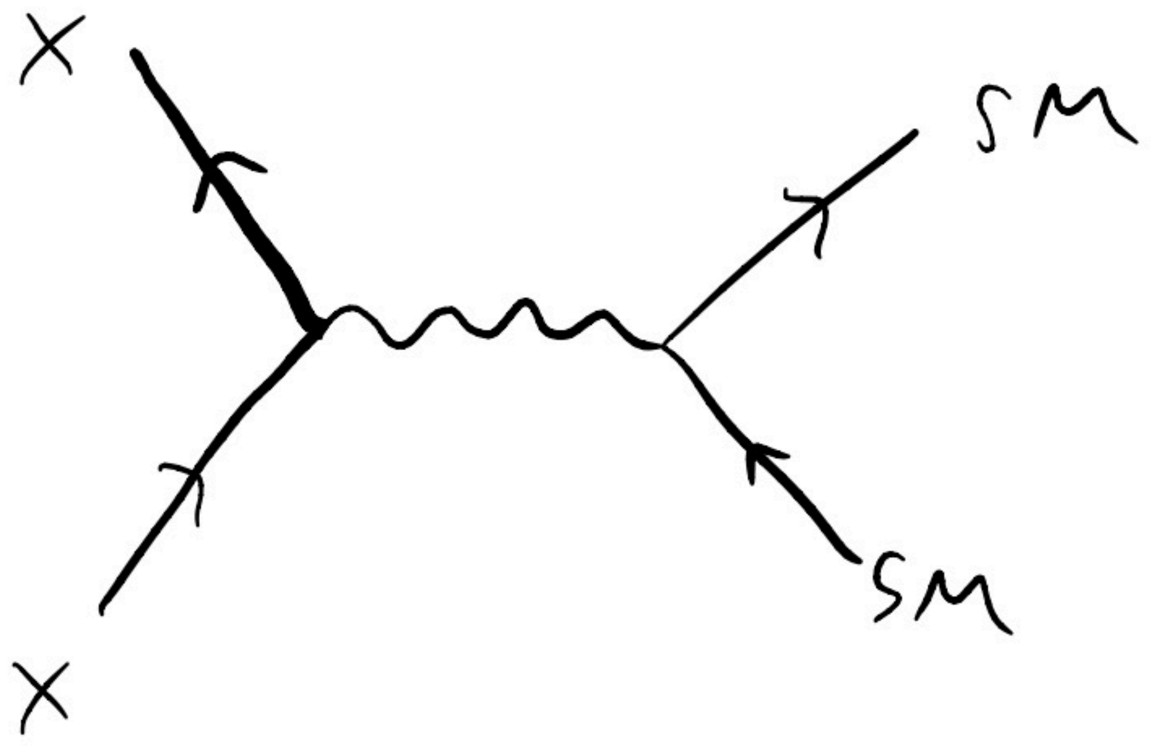


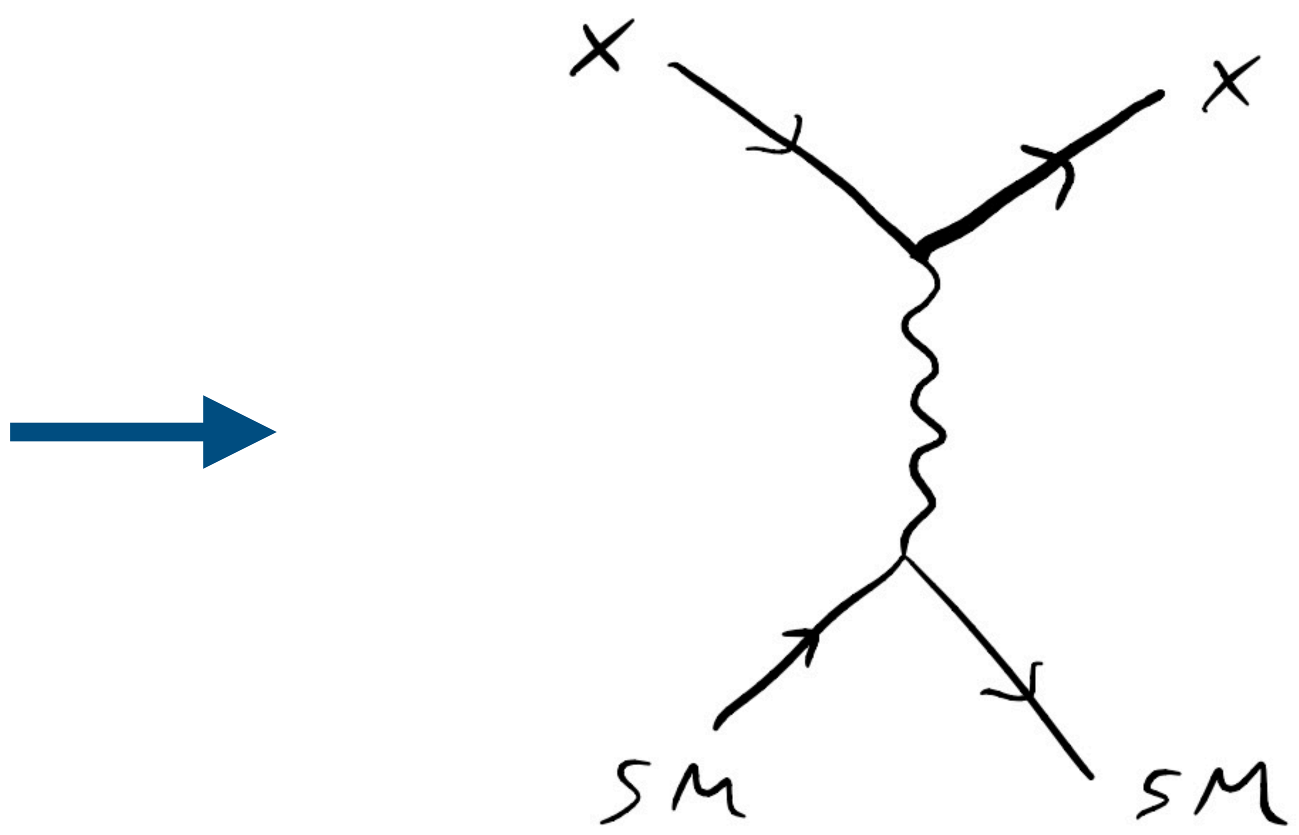
As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles

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

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

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

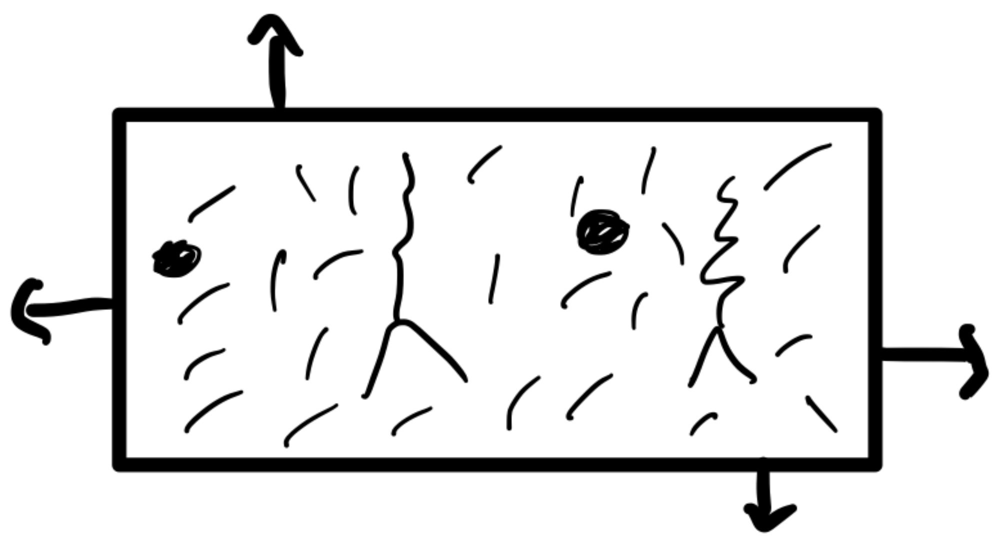




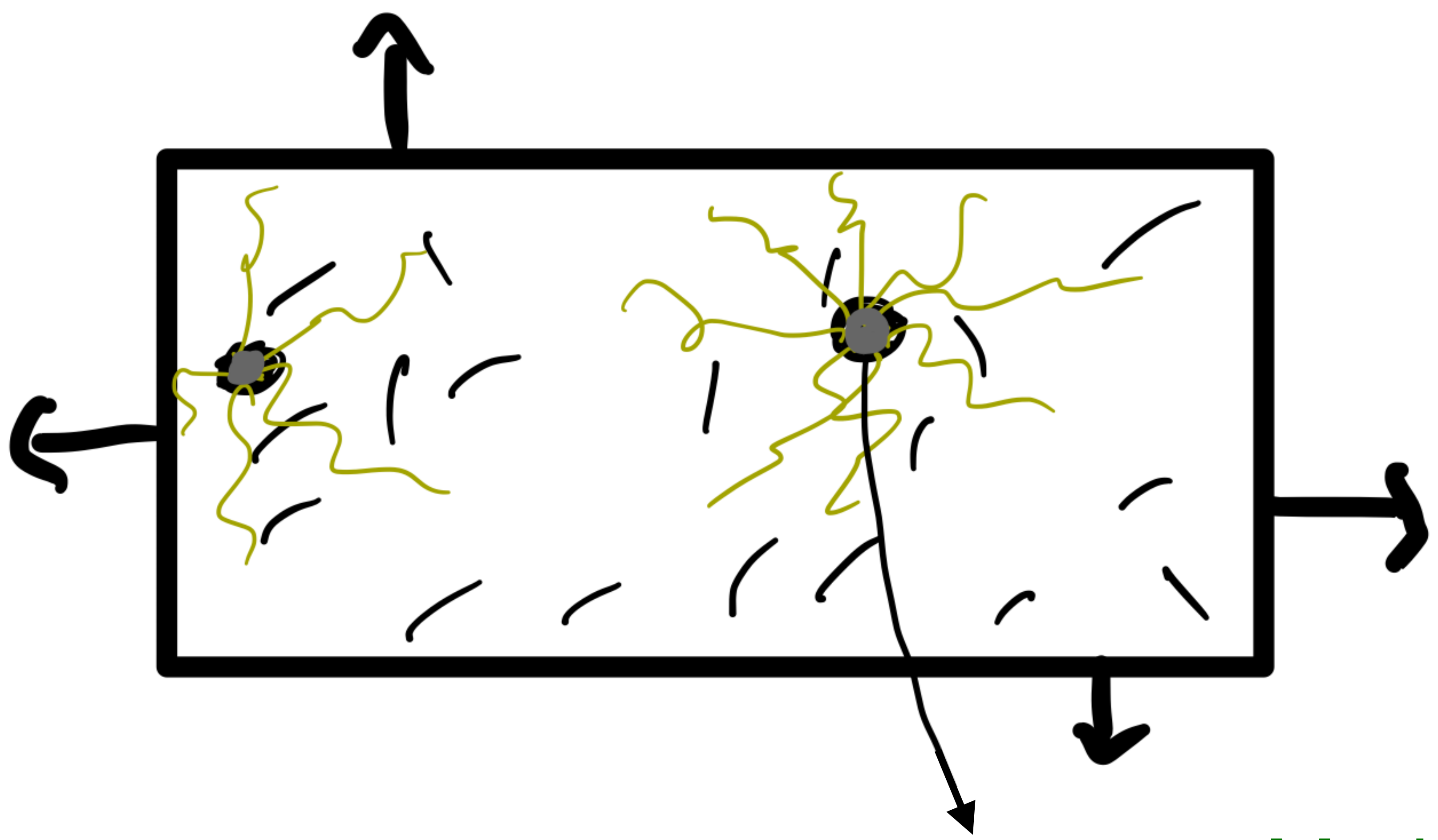
see e.g.
Scherrer Turner '86
Drukier, Freese, Spergel '86

Some symmetry arguments imply interactions at dark matter experiments.

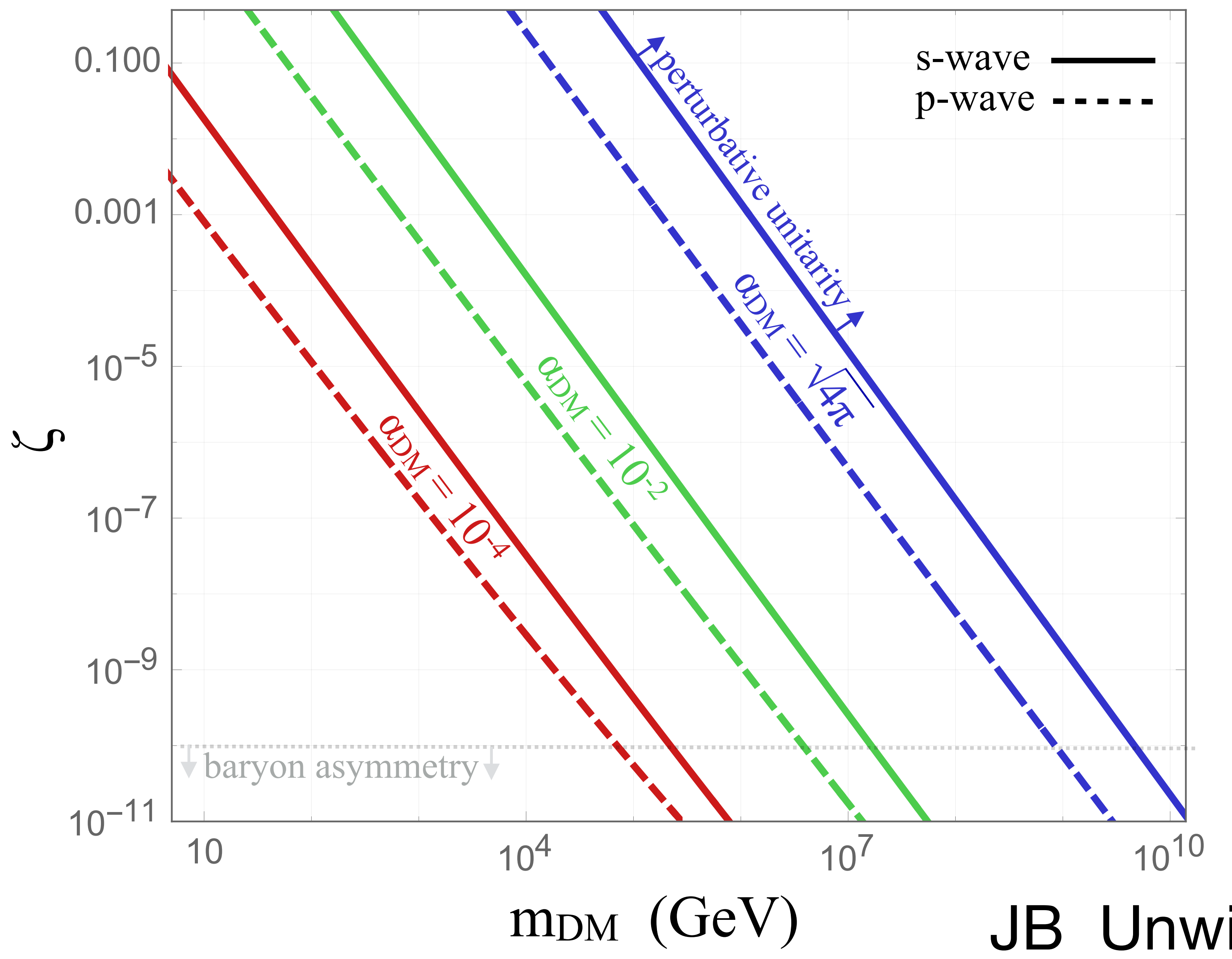
Diluted WIMP Dark Matter: heavier



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

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

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

HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

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

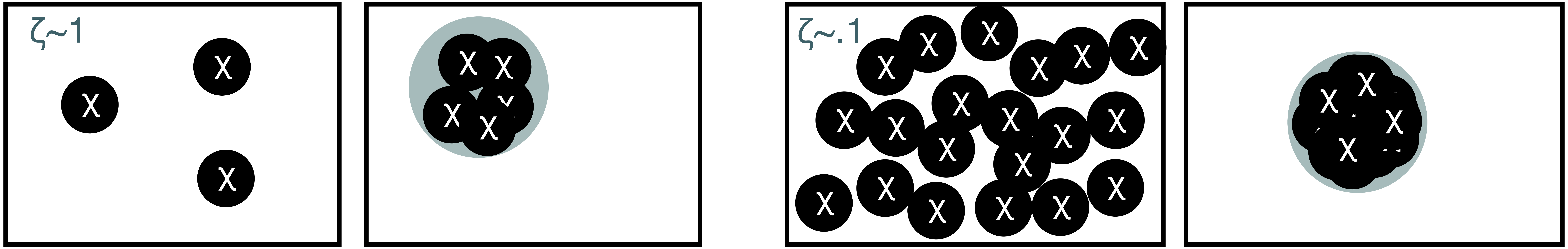
$$\mathscr{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathscr{L}_{SM},$$

see also e.g.
Witten '84
Wise Zhang '14
Krnjaic Sigurdson '14
Hardy Lasenby March-Russell '14
Gresham Lou Zurek '17

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

Acevedo JB Goodman 2012.10998

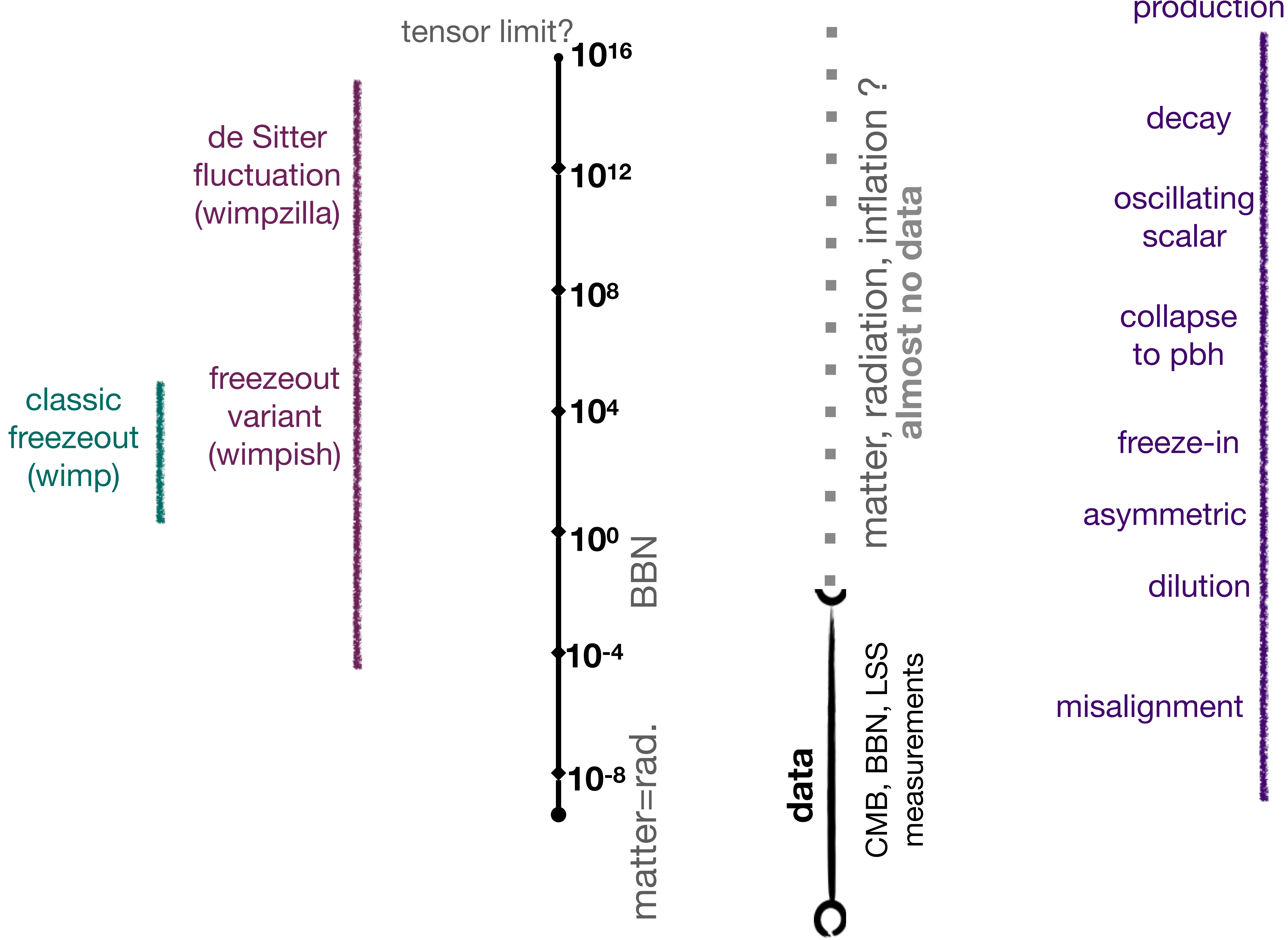


$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5} = \left(\frac{20\sqrt{g_{ca}^*}T_r T_{ca}^{3/2}M_{pl}}{\bar{m}_X^{7/2}\zeta}\right)^{6/5} \simeq 10^{27}\left(\frac{g_{ca}^*}{10^2}\right)^{3/5}\left(\frac{T_{ca}}{10^5\,\mathrm{GeV}}\right)^{9/5}\left(\frac{5\,\mathrm{GeV}}{\bar{m}_X}\right)^{21/5}\left(\frac{10^{-6}}{\zeta}\right)^{6/5}$$

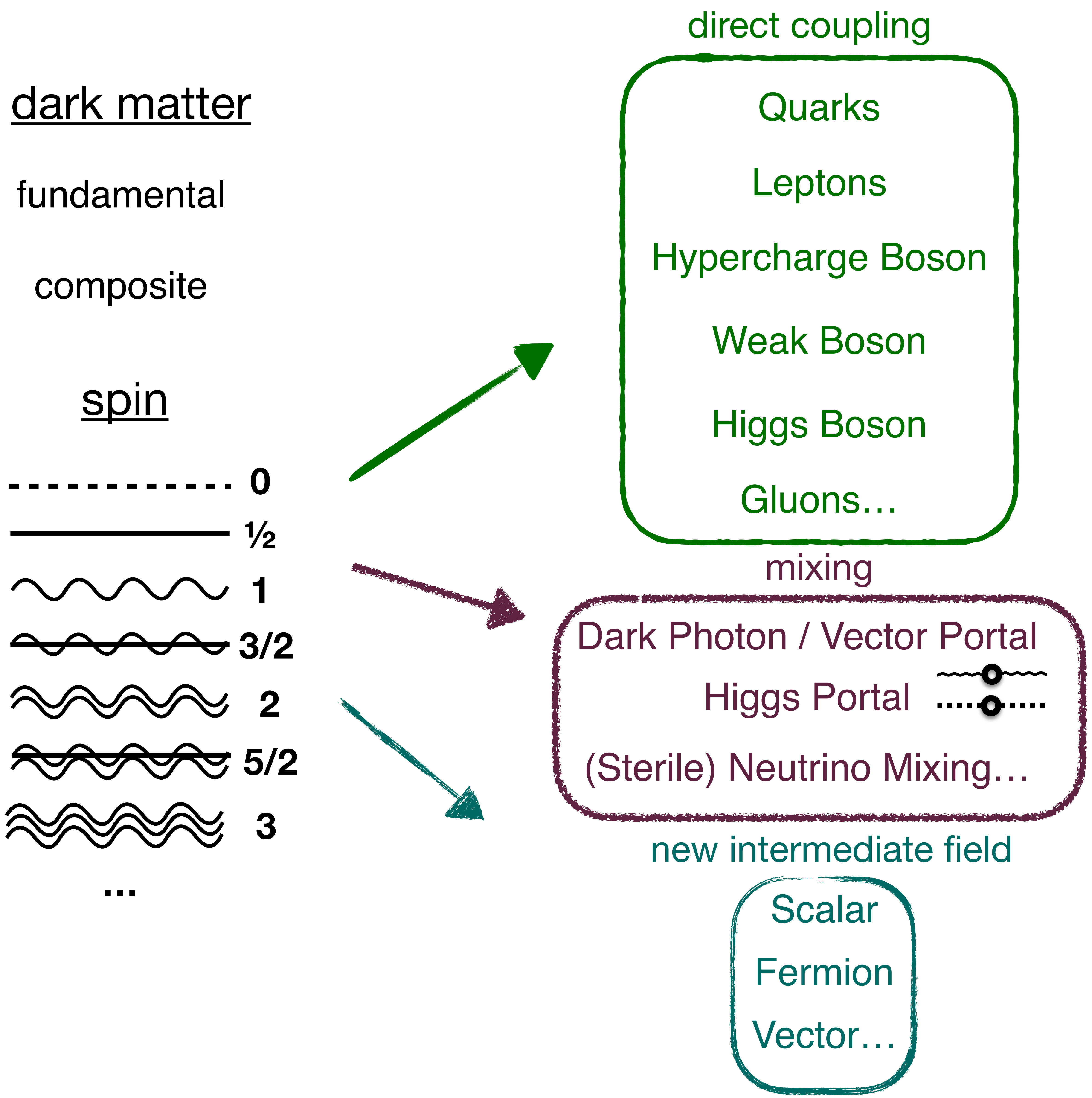
Composite mass ranging from milligrams to thousands of tons

How was dark matter made?

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



Dark Matter Models: SM Coupling and Detection



Dark Matter Models: SM Coupling and Detection

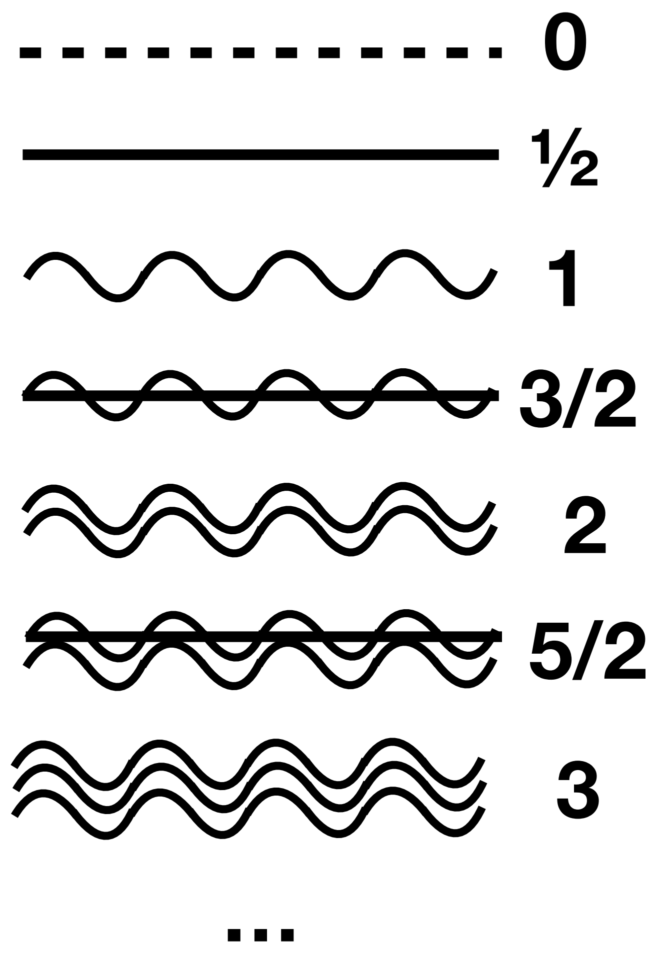
annihilation · scattering · DM production

dark matter

fundamental

composite

spin



direct coupling

- Quarks
- Leptons
- Hypercharge Boson
- Weak Boson
- Higgs Boson
- Gluons…

mixing

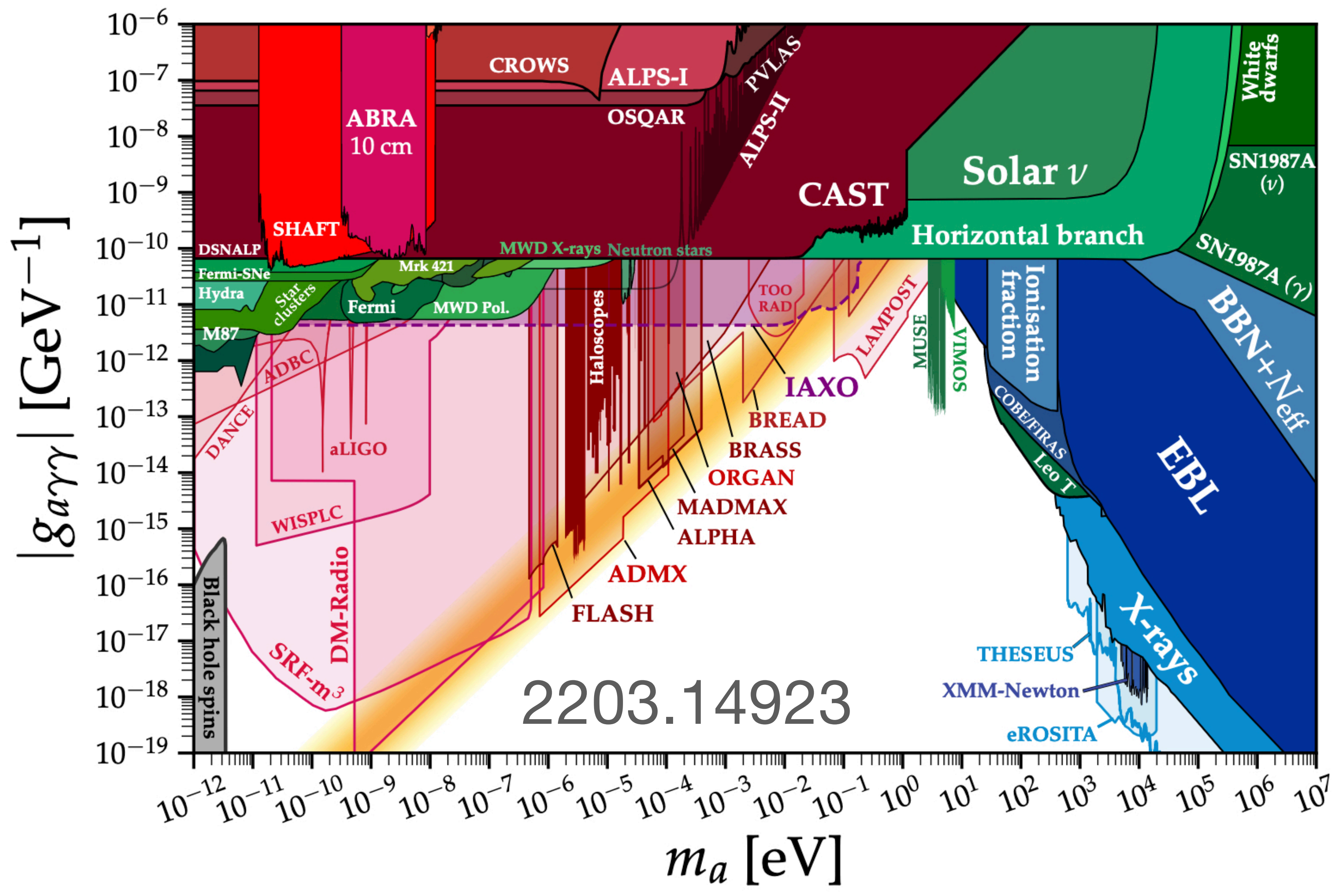
- Dark Photon / Vector Portal
- Higgs Portal
- (Sterile) Neutrino Mixing…

new intermediate field

- Scalar
- Fermion
- Vector…

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

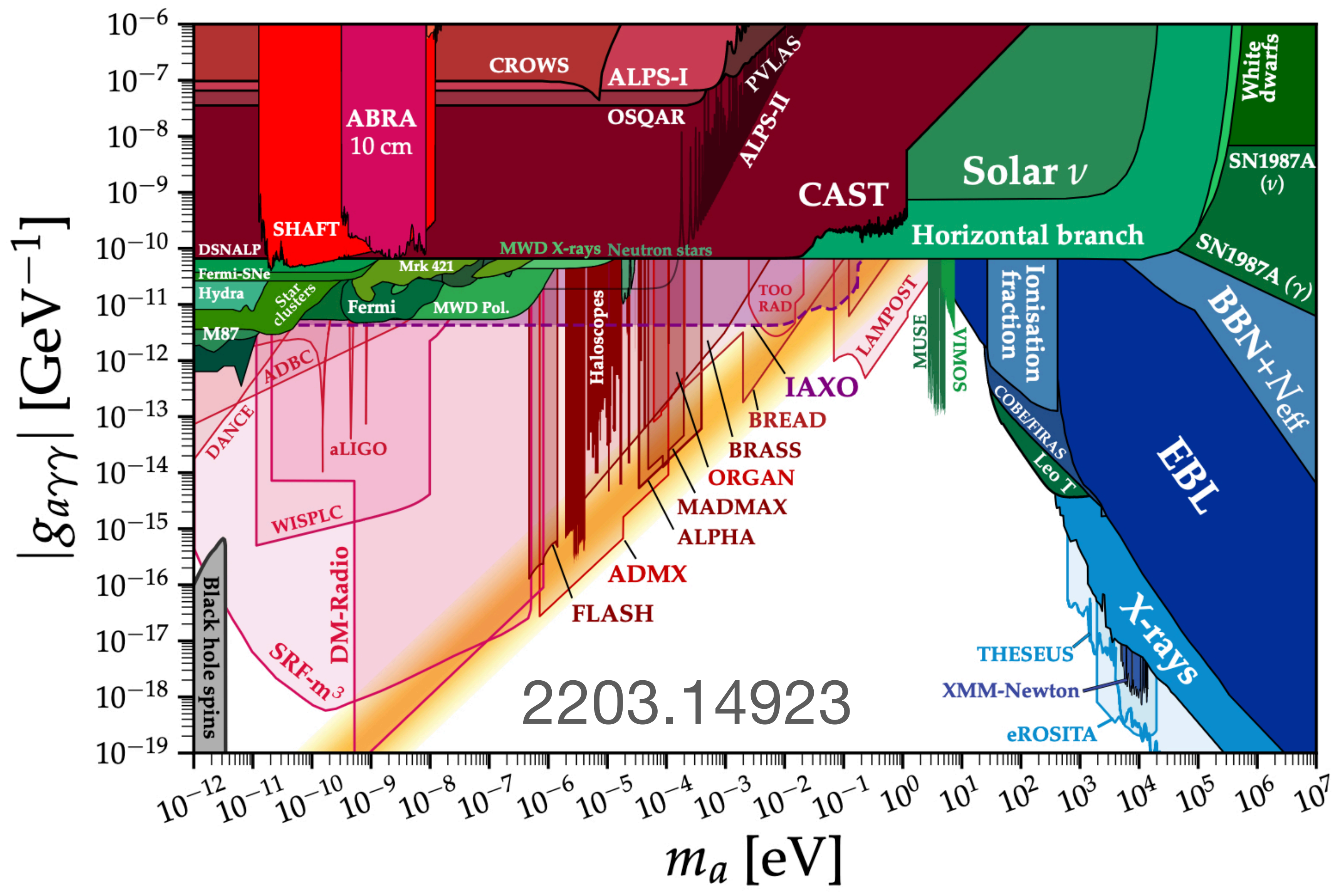
SKIM THROUGH DM SEARCHES



Axion/ DP (wavy bosons)

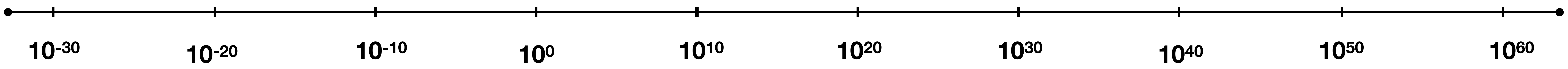
m_x (GeV)

SKIM THROUGH DM SEARCHES



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

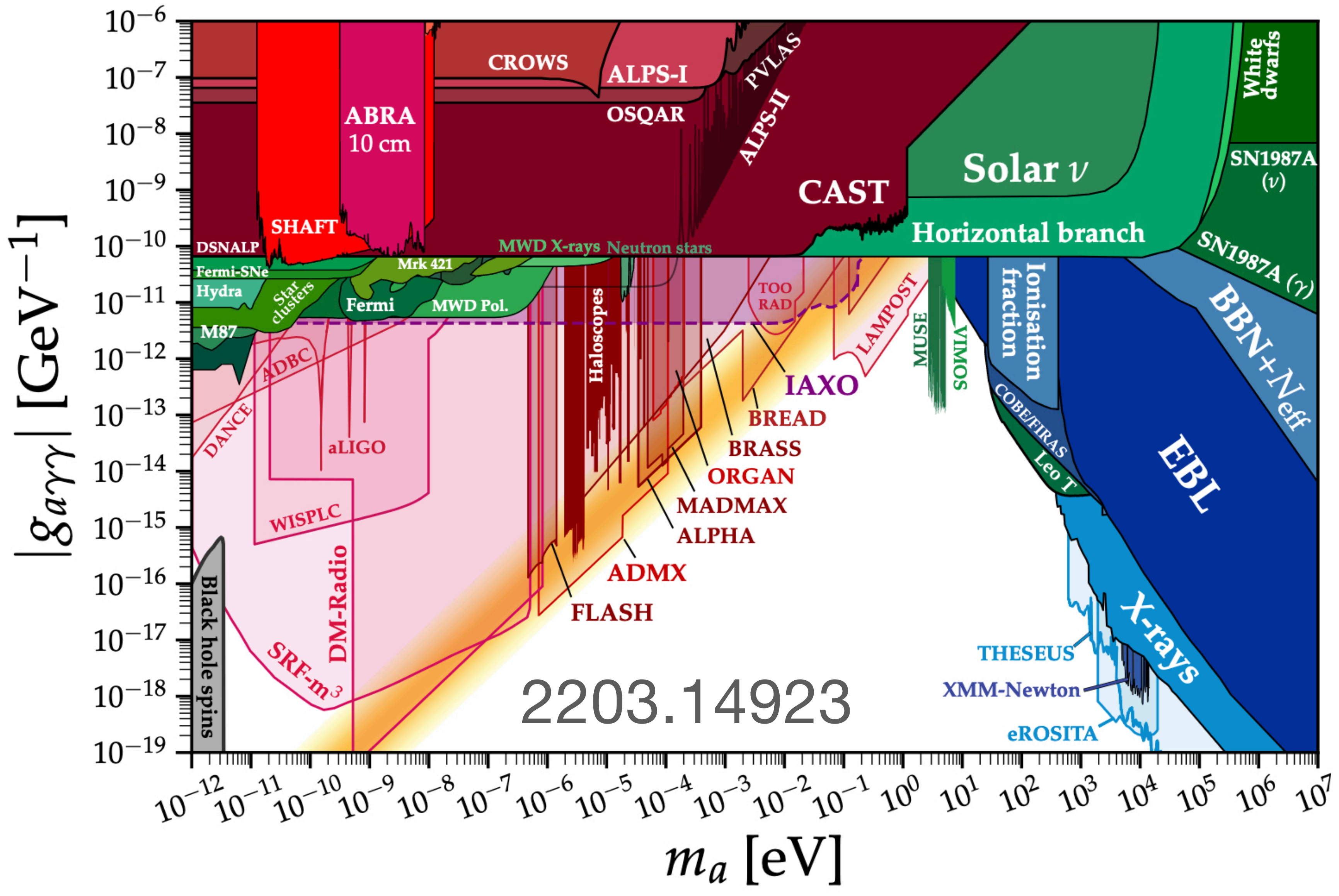
Axion/ DP (wavy bosons)



m_x (GeV)

SKIM THROUGH DM SEARCHES

Light dark matter



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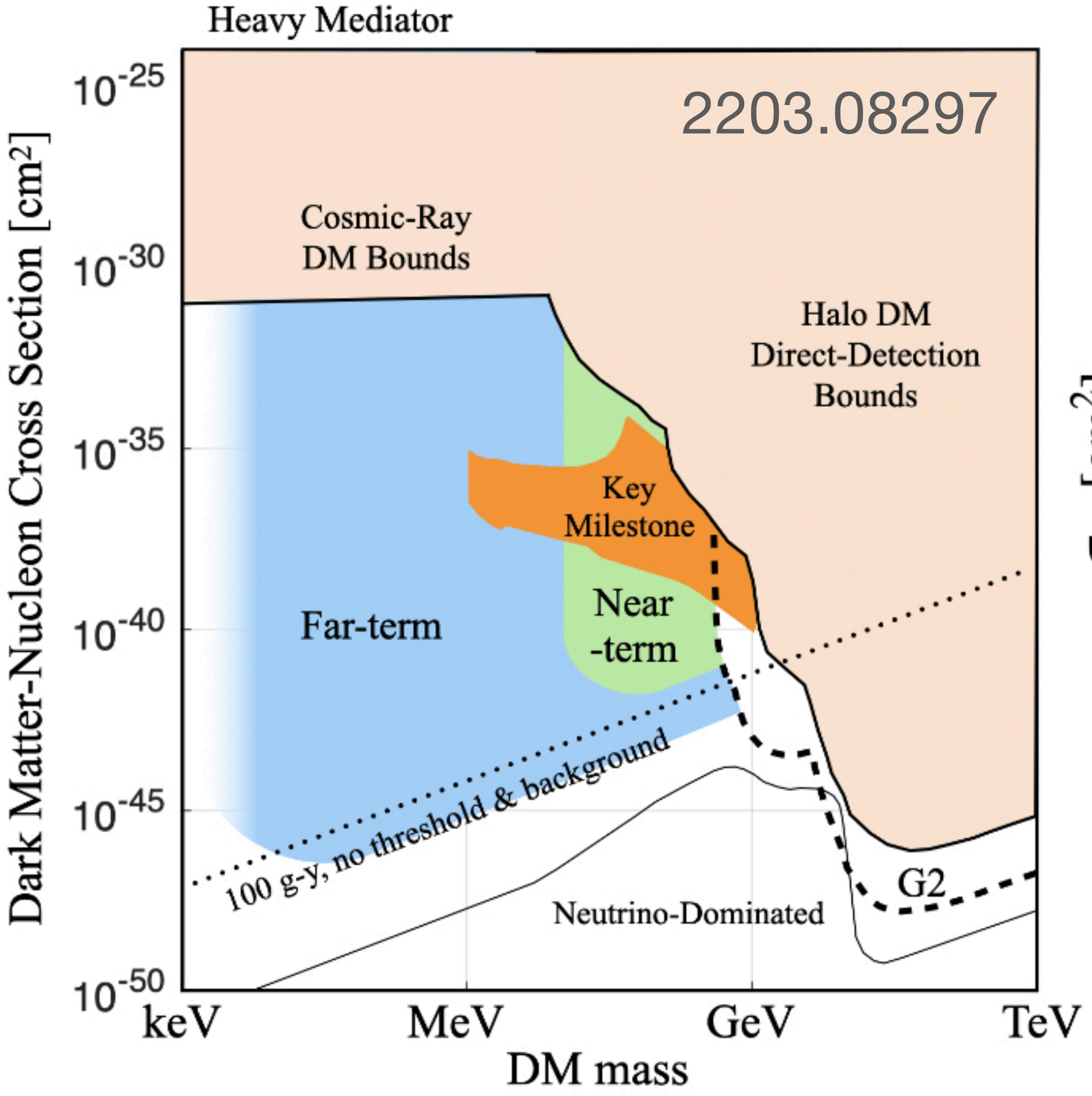
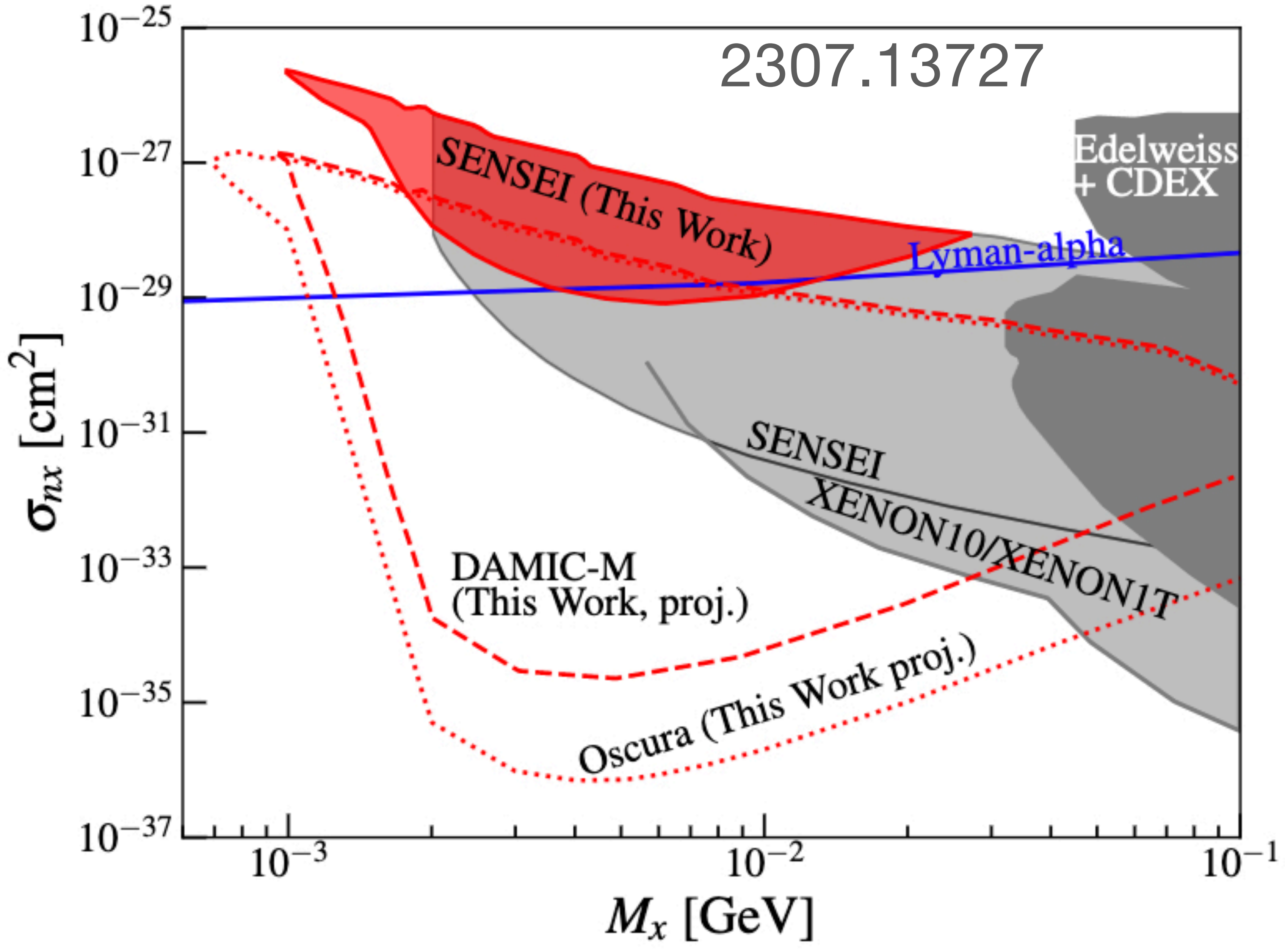
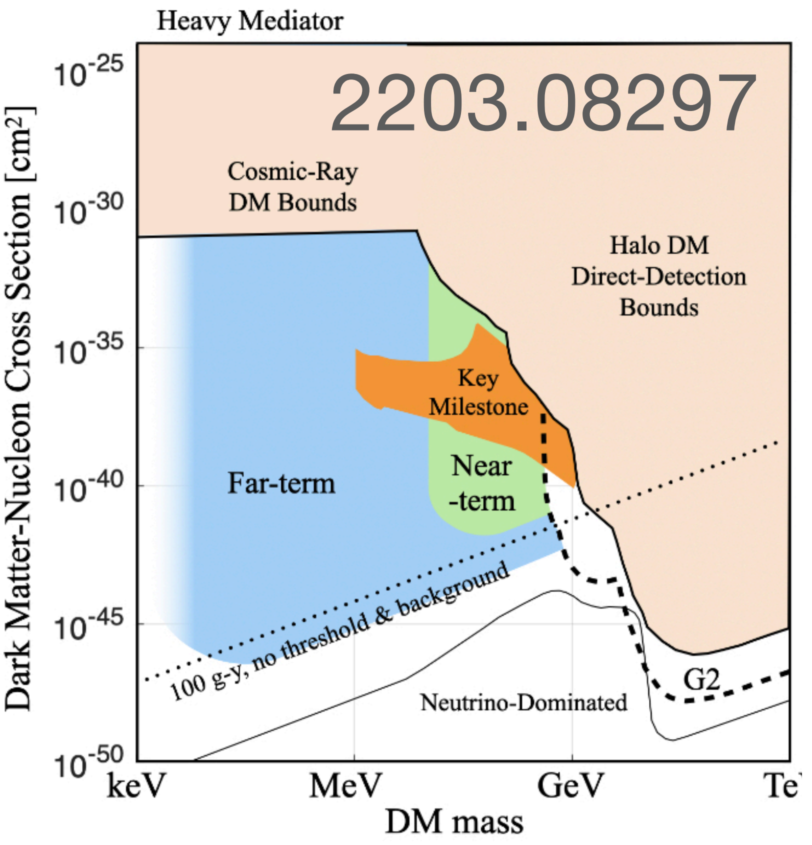


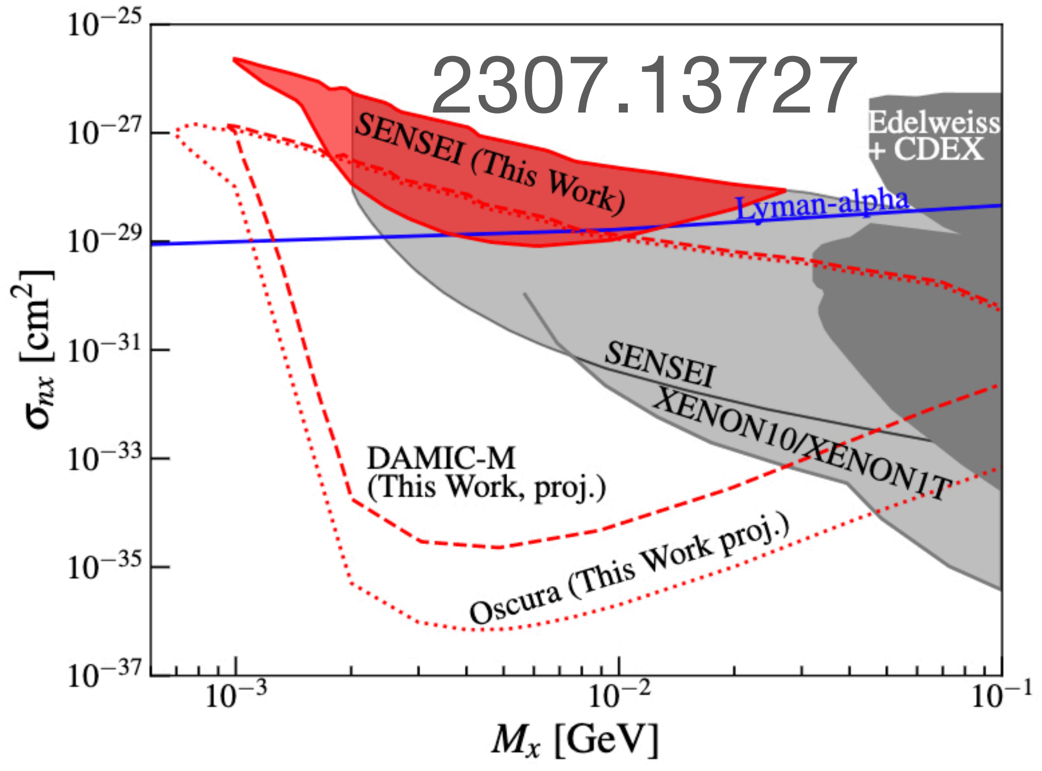


Melissa Diamond, Cappiello, Vincent, JB

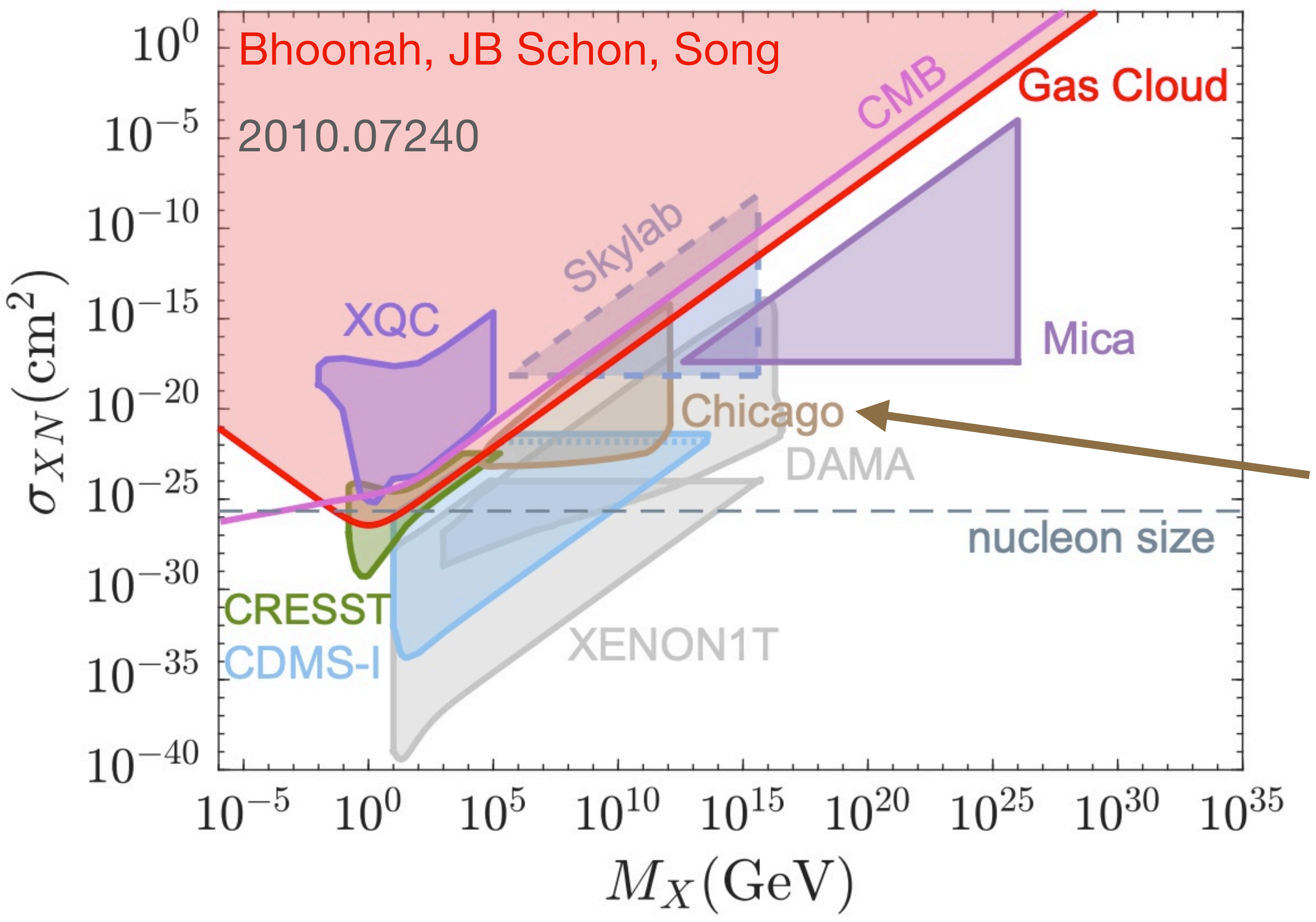
m_x (GeV)

SKIM THROUGH DM SEARCHES



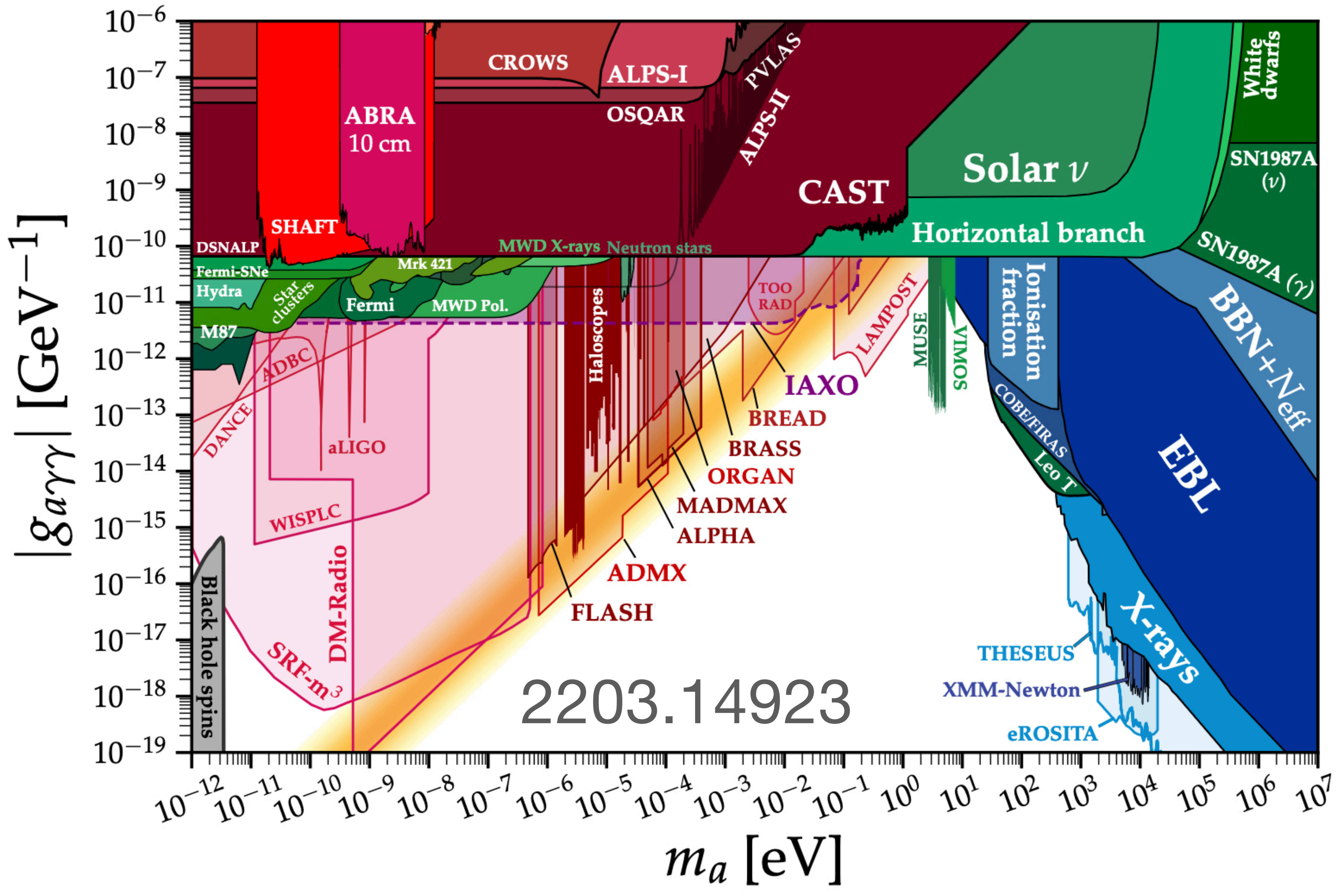


Heavy dark matter



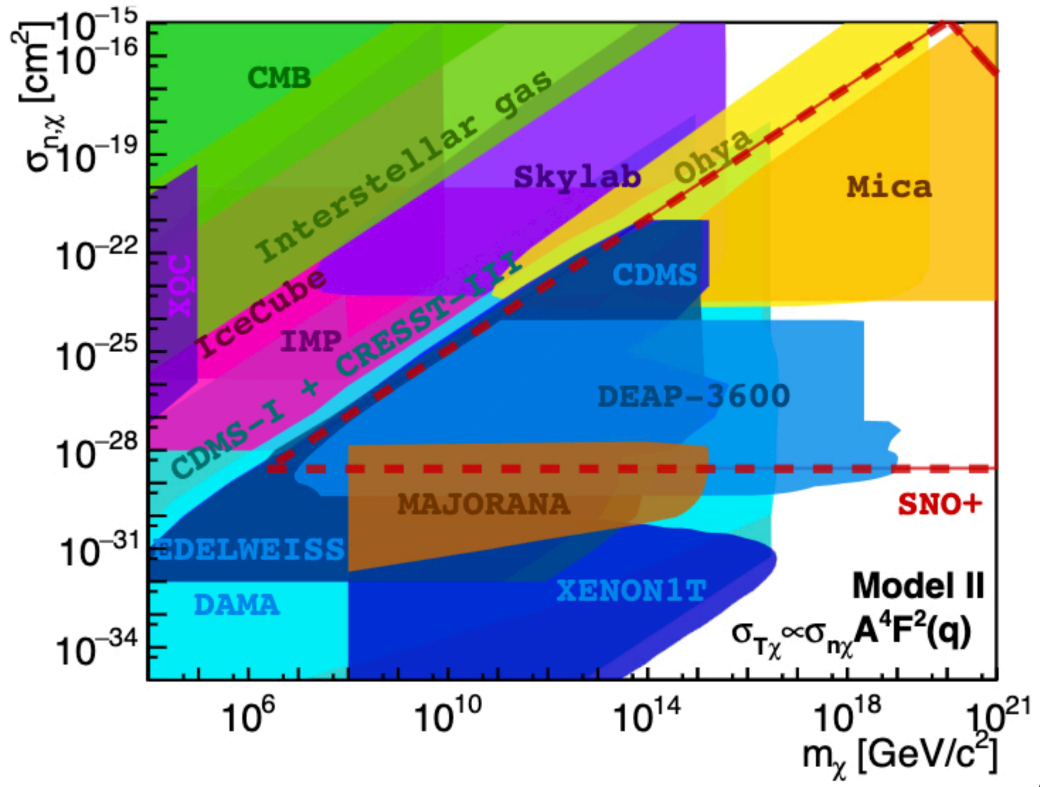
Cappiello, Collar, Beacom

Light dark matter



Axion/ DP (wavy bosons)

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



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

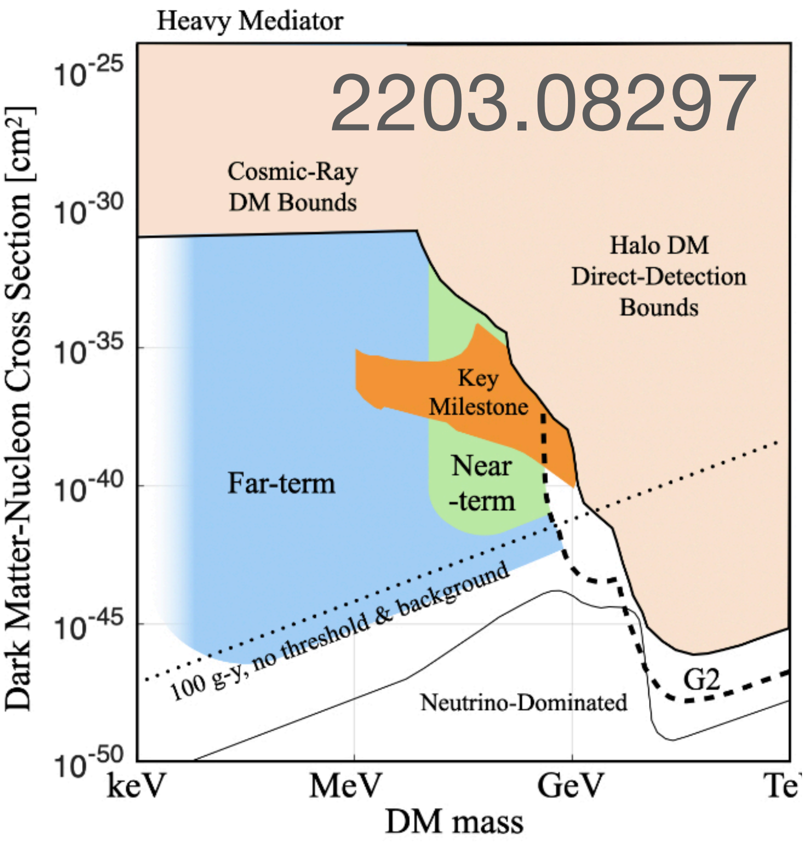
high m,σ composites

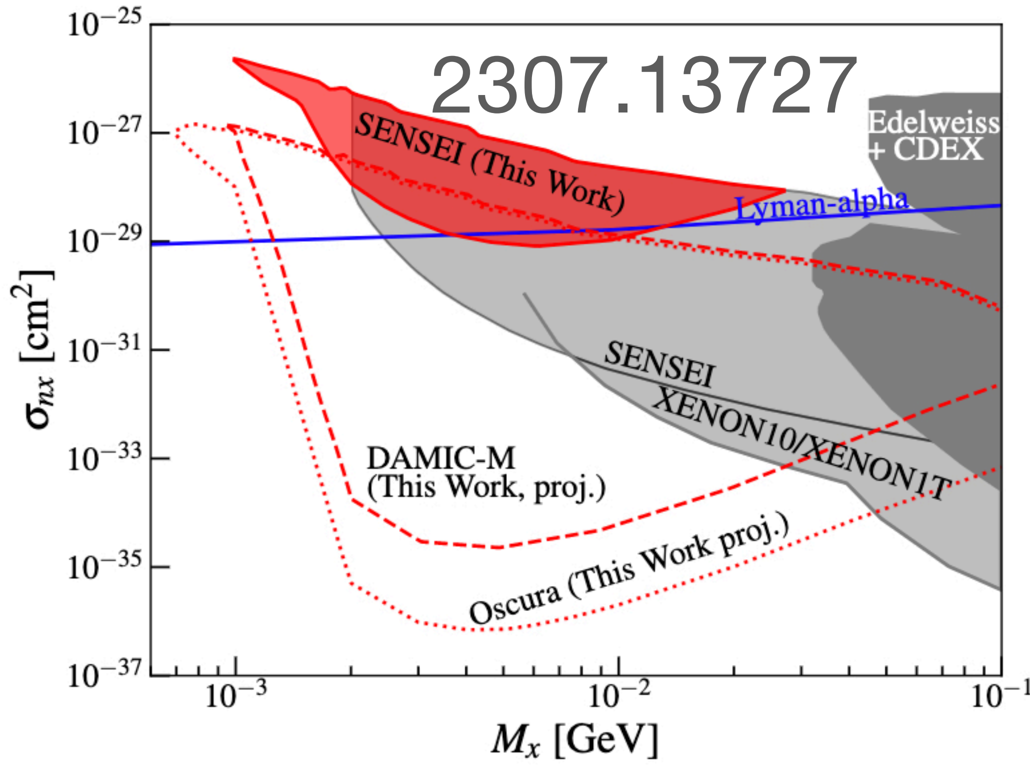
Witten '84

2203.06508

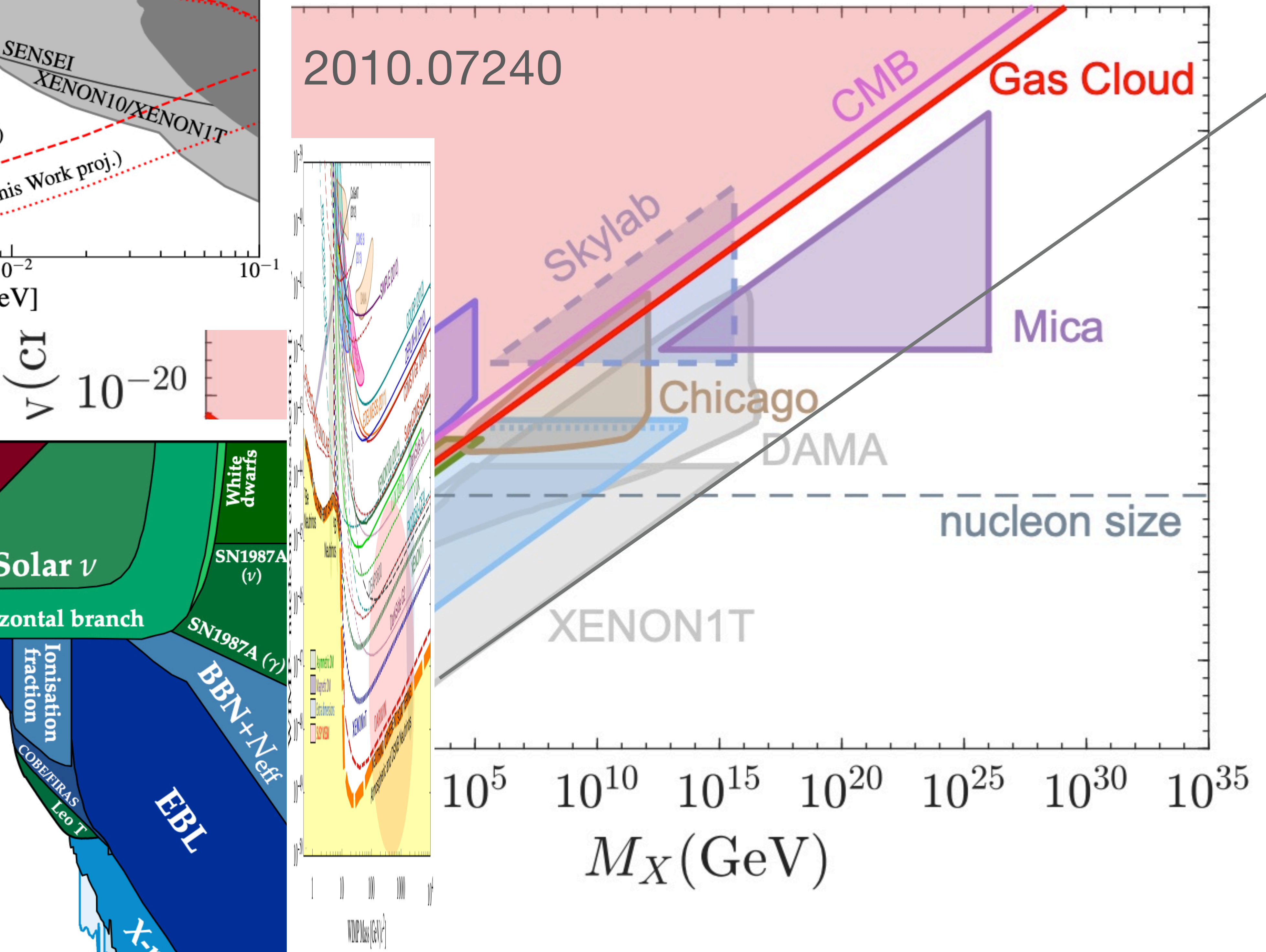
m_x (GeV)

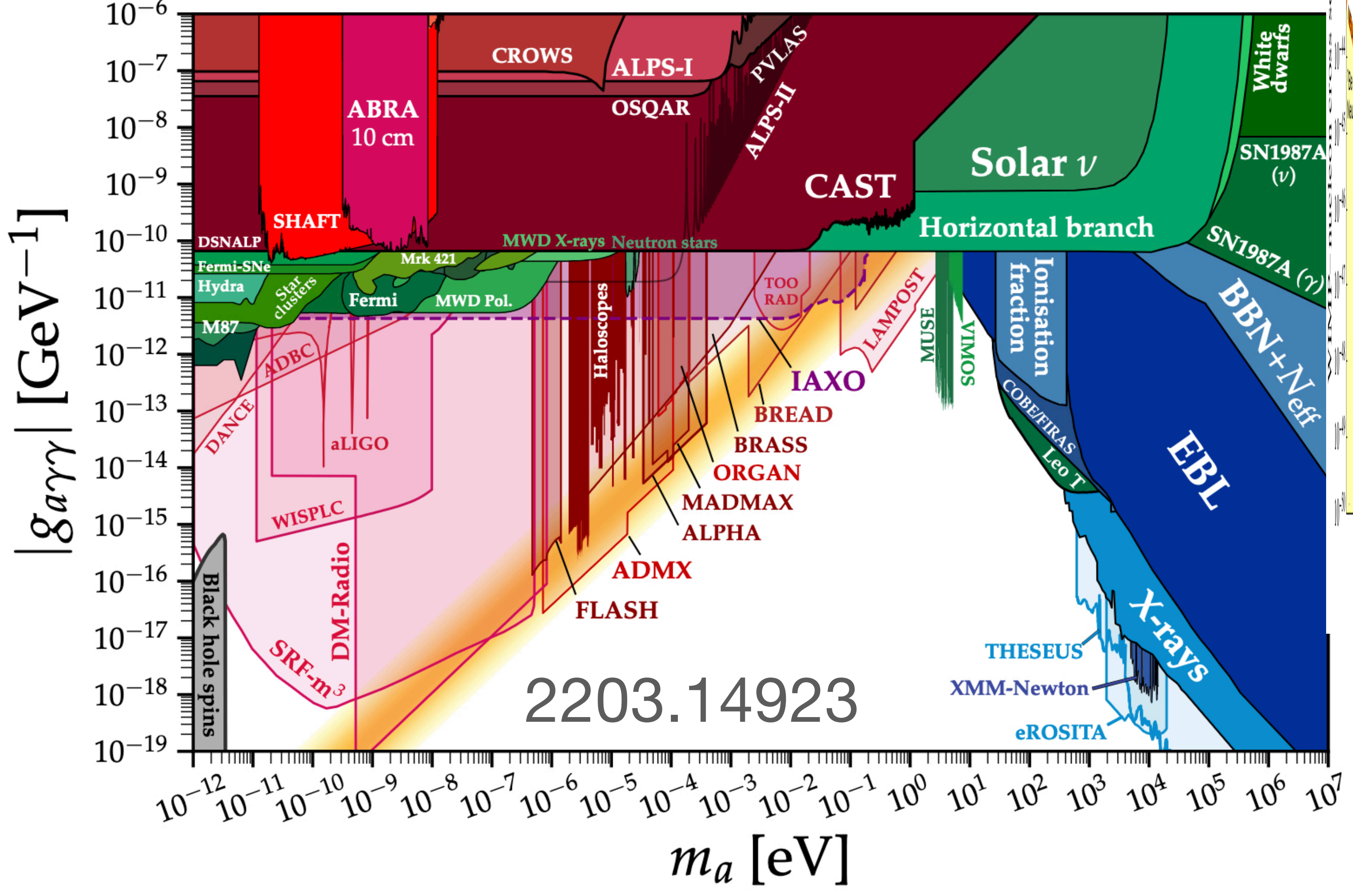
SKIM THROUGH DM SEARCHES





Light dark matter





Axion/ DP (wavy bosons)

Neutron star infrared astr.

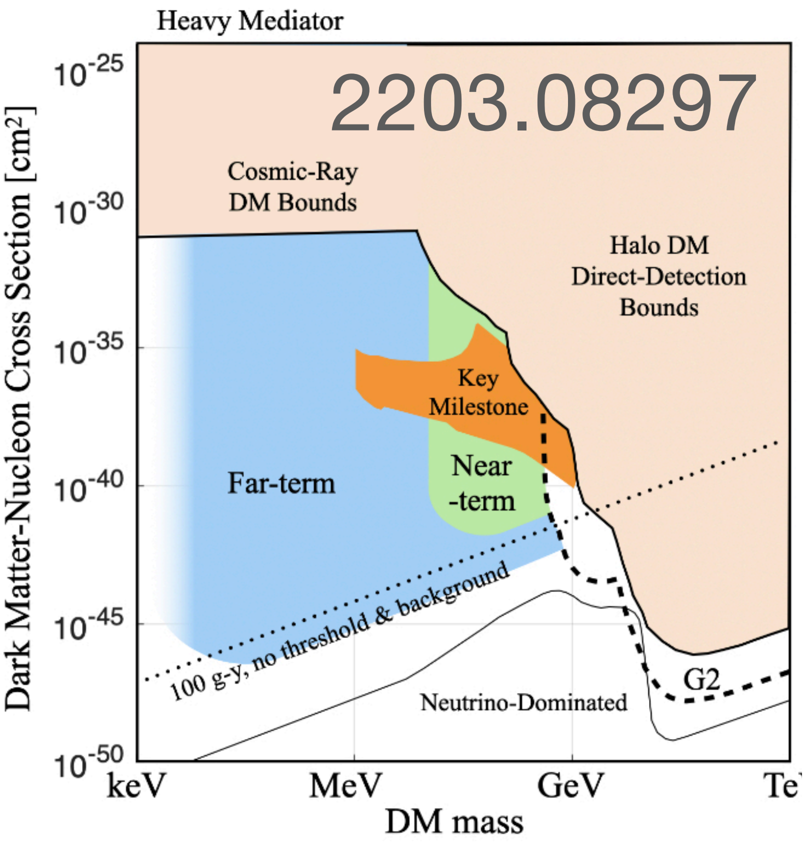
Tyagi et al., in progress

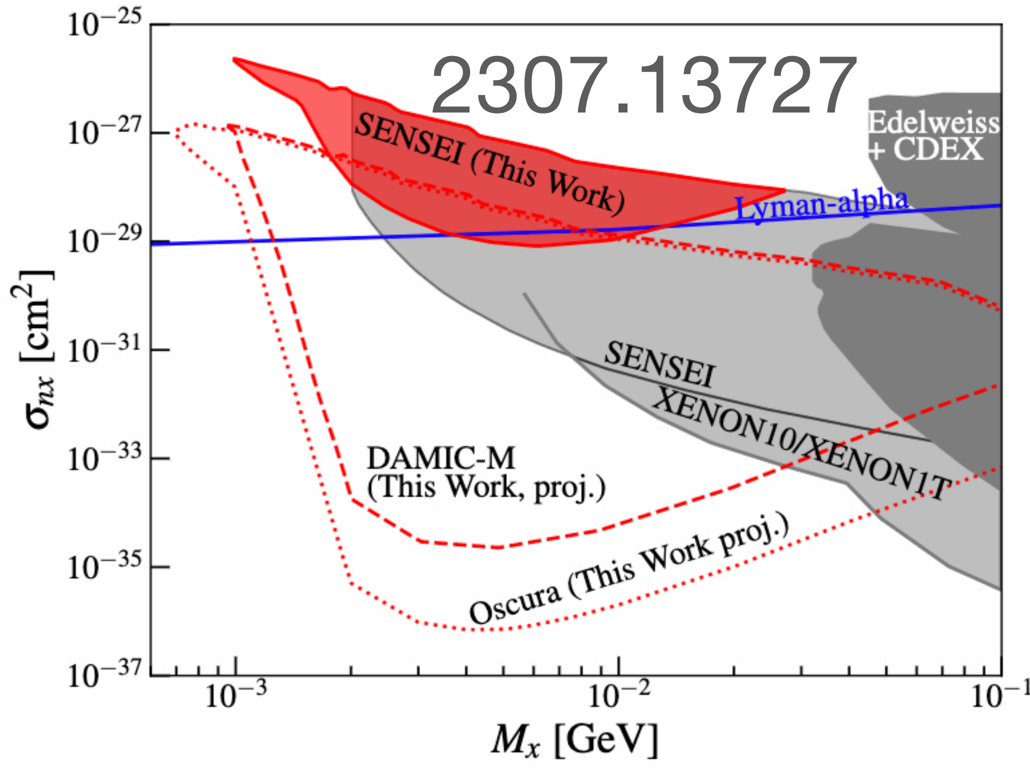
m_x (GeV)

PRICE OF DM DETECTION

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

Δ relative to last generation





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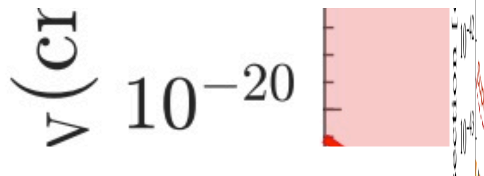

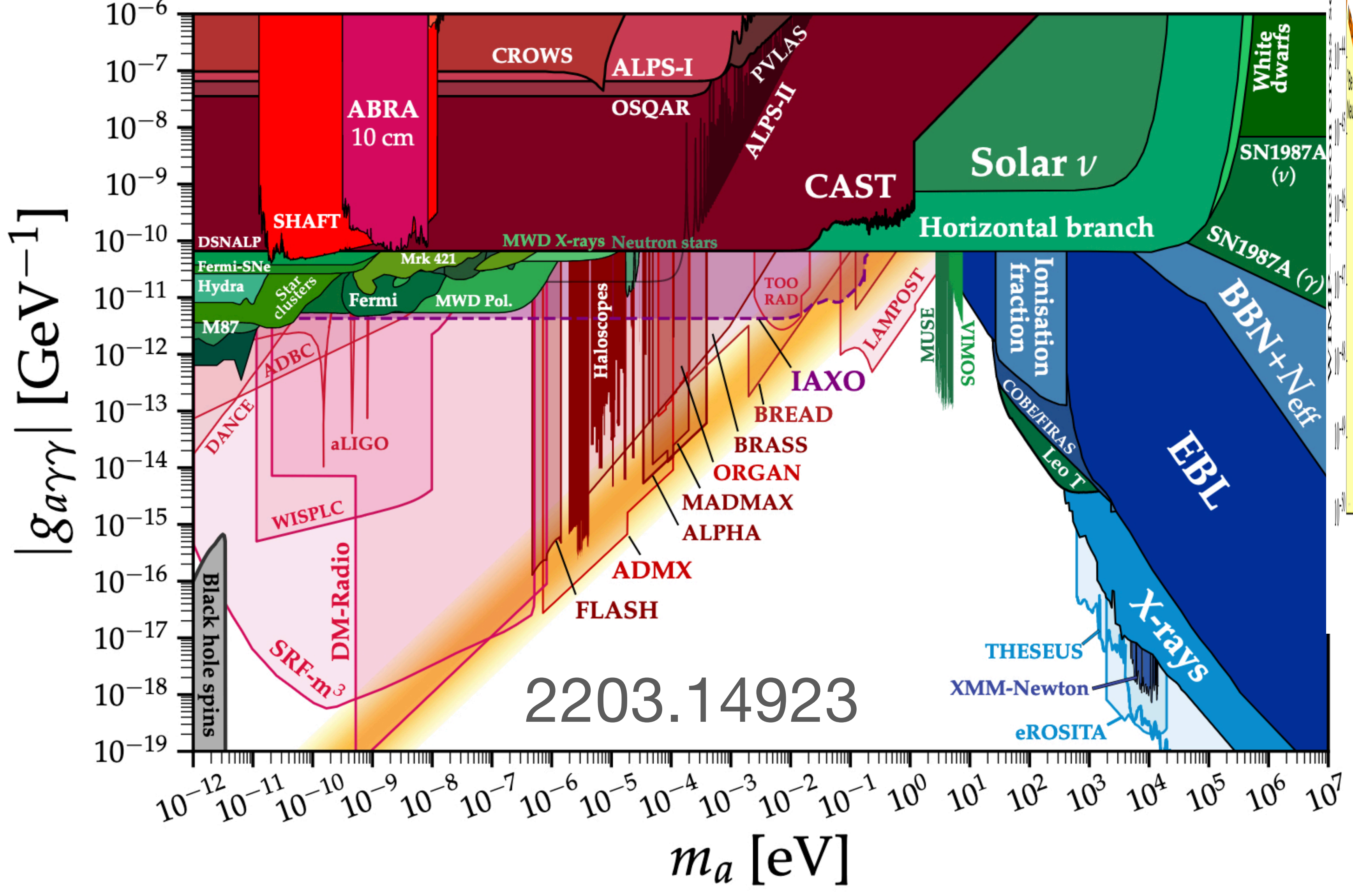

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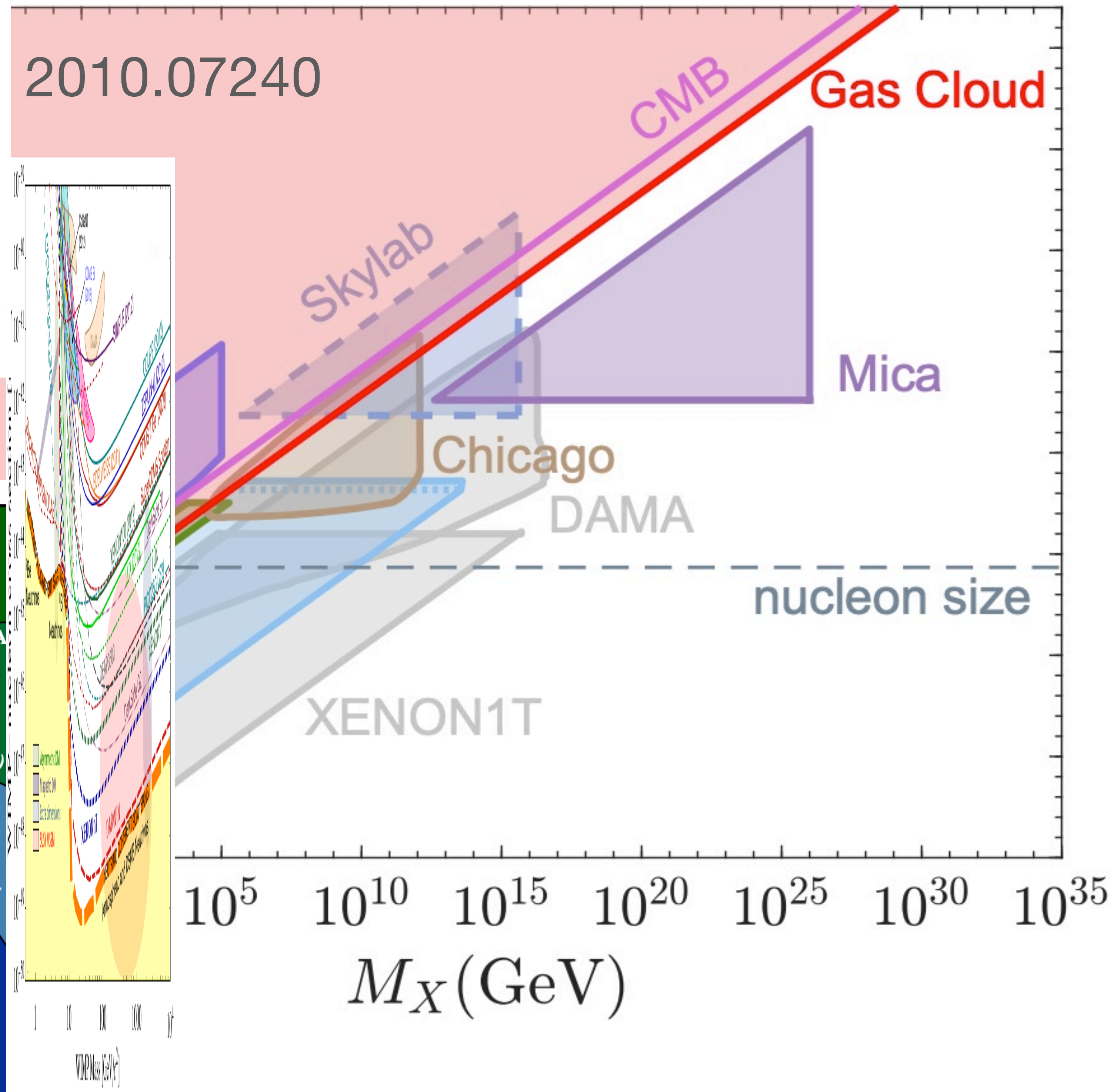
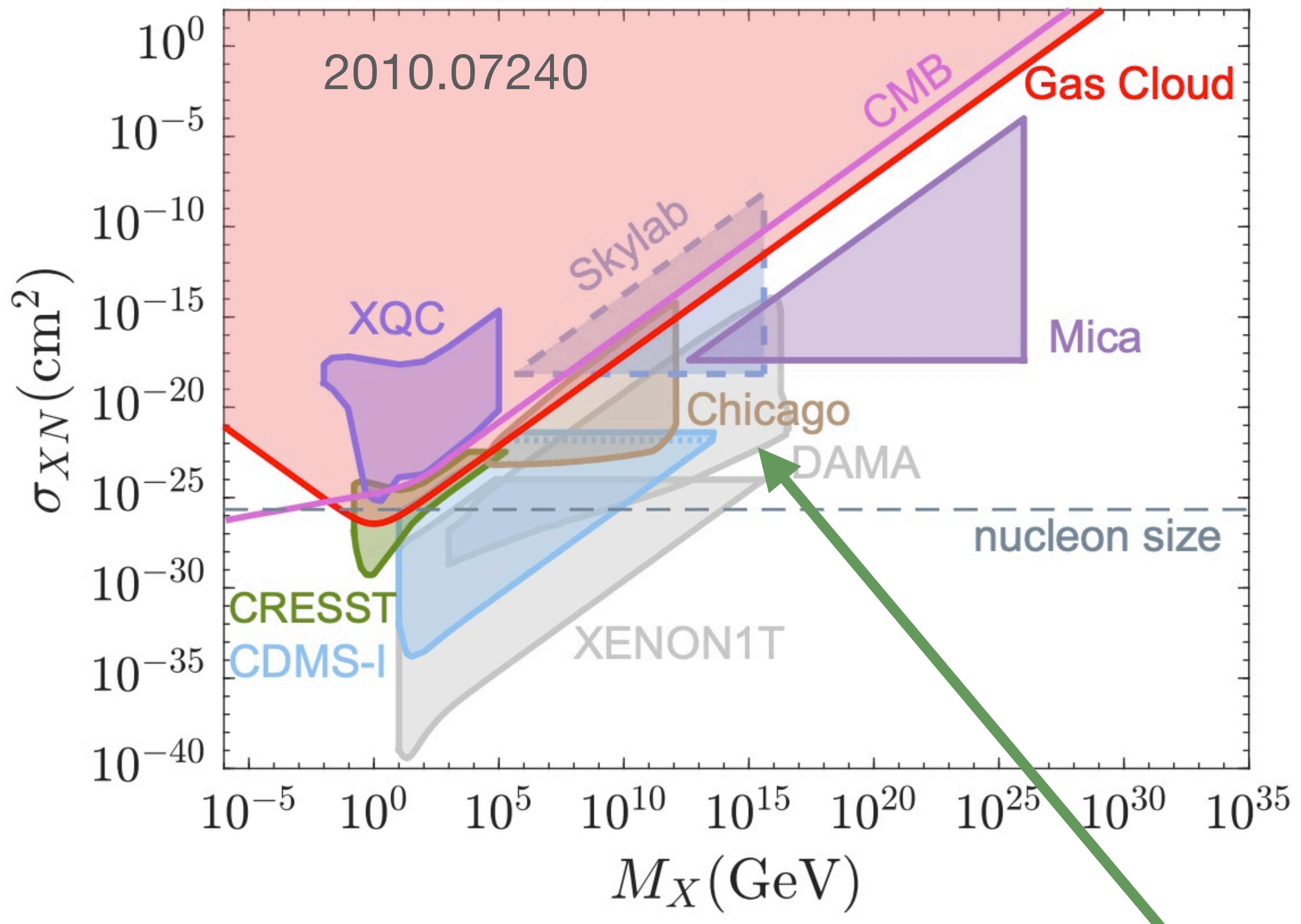


10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

m_X (GeV)

HEAVY DARK MATTER



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

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

m_x (GeV)

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see also e.g.
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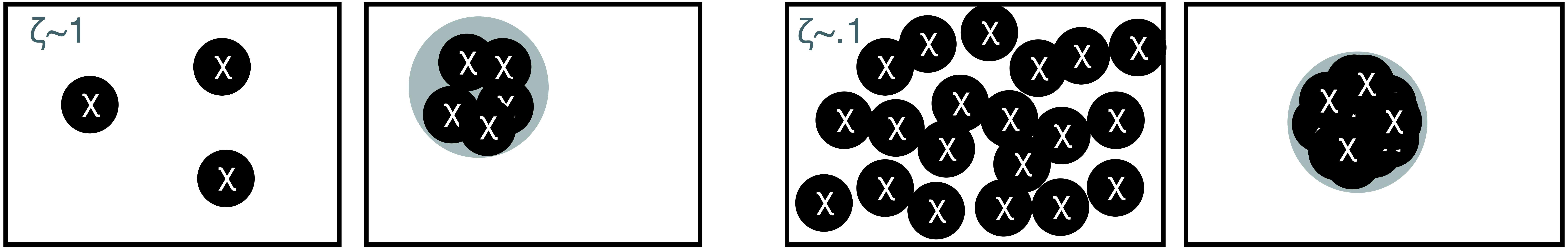

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Composite mass ranging from milligrams to thousands of tons

DM Models

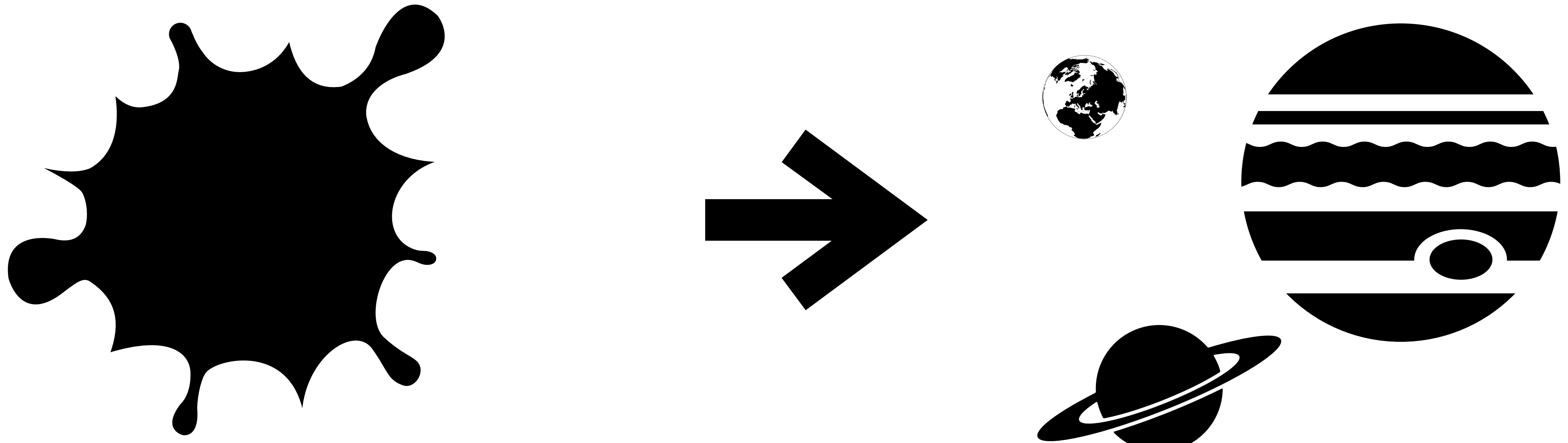
Vis-a-vis heavy composite DM

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

Nice to have a model:

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

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



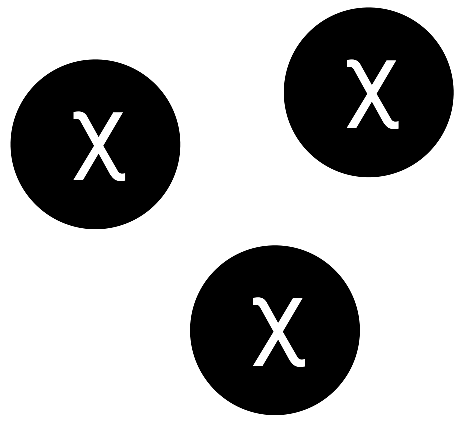
Predict masses from 1st principles?

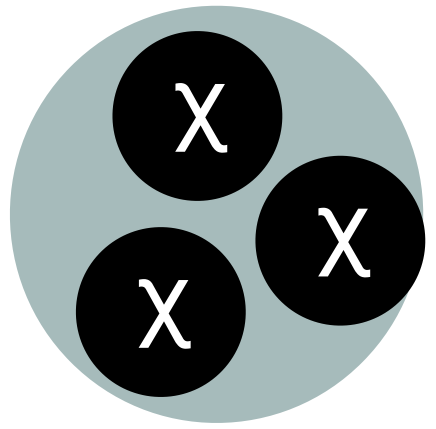
- Planet formation still has open questions (e.g. pebble accretion).
- Naive to ask heavy composites to have simple dynamics like single-field DM models, often selected for convenience.

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

DM Models

Vis-a-vis heavy composite DM





Compare simplicity with Higgsino:

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

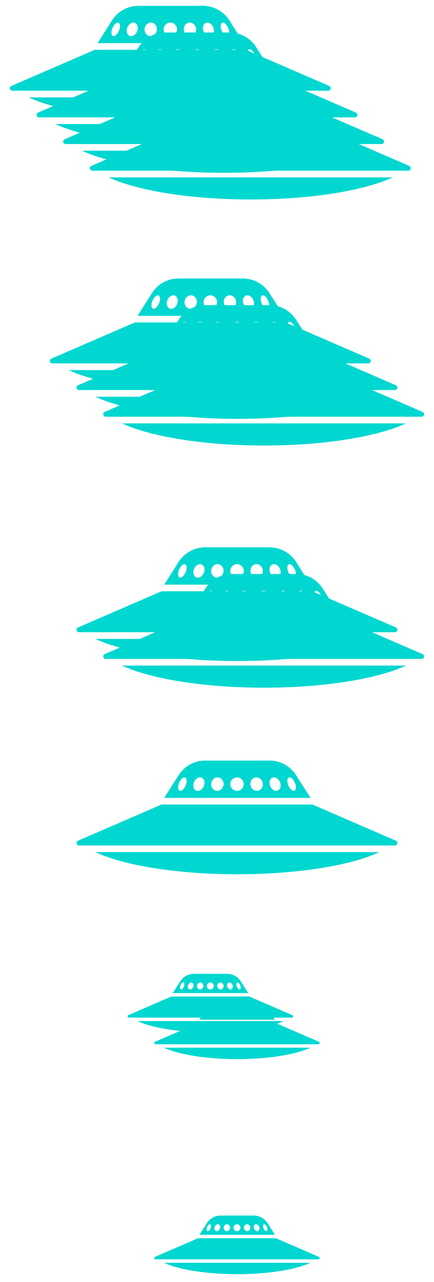
$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & -\mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

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

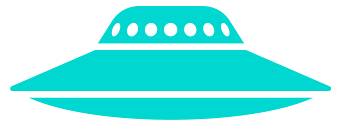
DM Models

my rough prior

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



Alien Game Show
Win spaceships!



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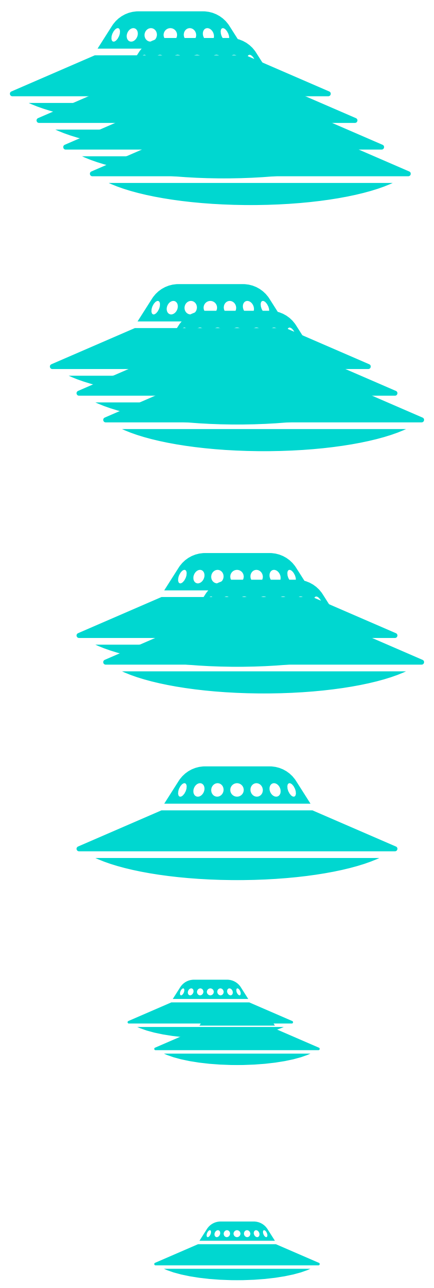


Alien Game Show
Win spaceships!

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

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

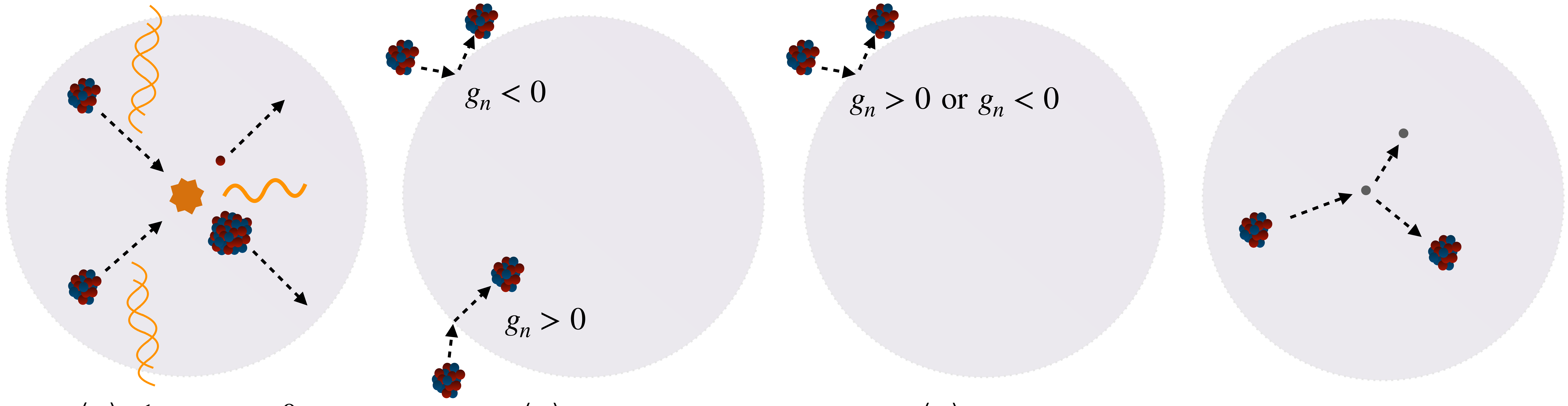
SOME COMPOSITE INTERACTIONS

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

nuclear interactions with DM composite internal potential

scattering with constituents

1. 2. 3. 4.



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

$\langle\varphi\rangle \ll m_N$

$\langle\varphi\rangle > m_N$

(MIMPs)

Acevedo, JB, Goodman
2012.10998

Acevedo, JB, Goodman
2108.10899

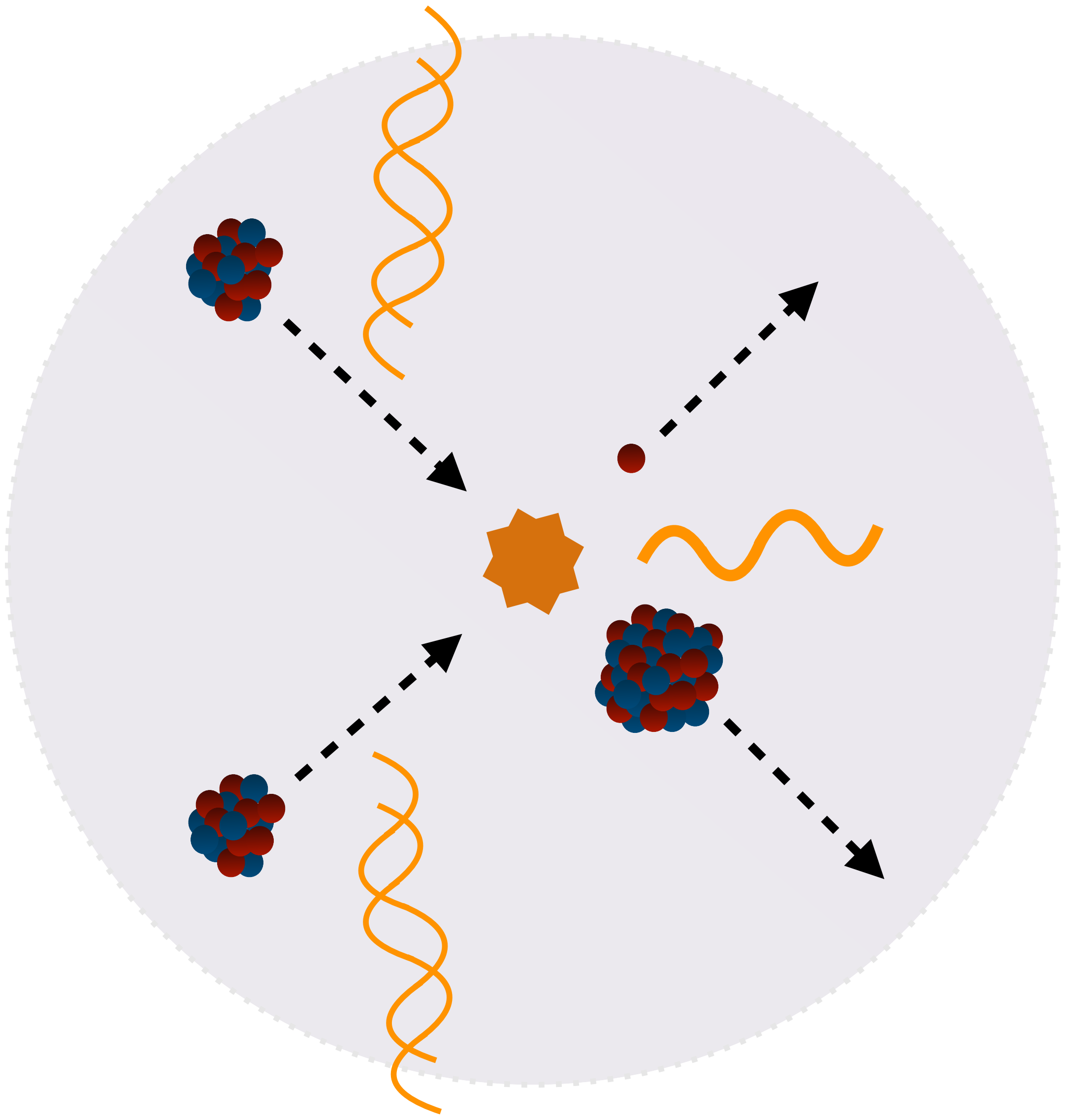
Acevedo, Boukhtouchen, JB, Cappiello, Mohlabeng, Sheahan, Tyagi, in progress

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.

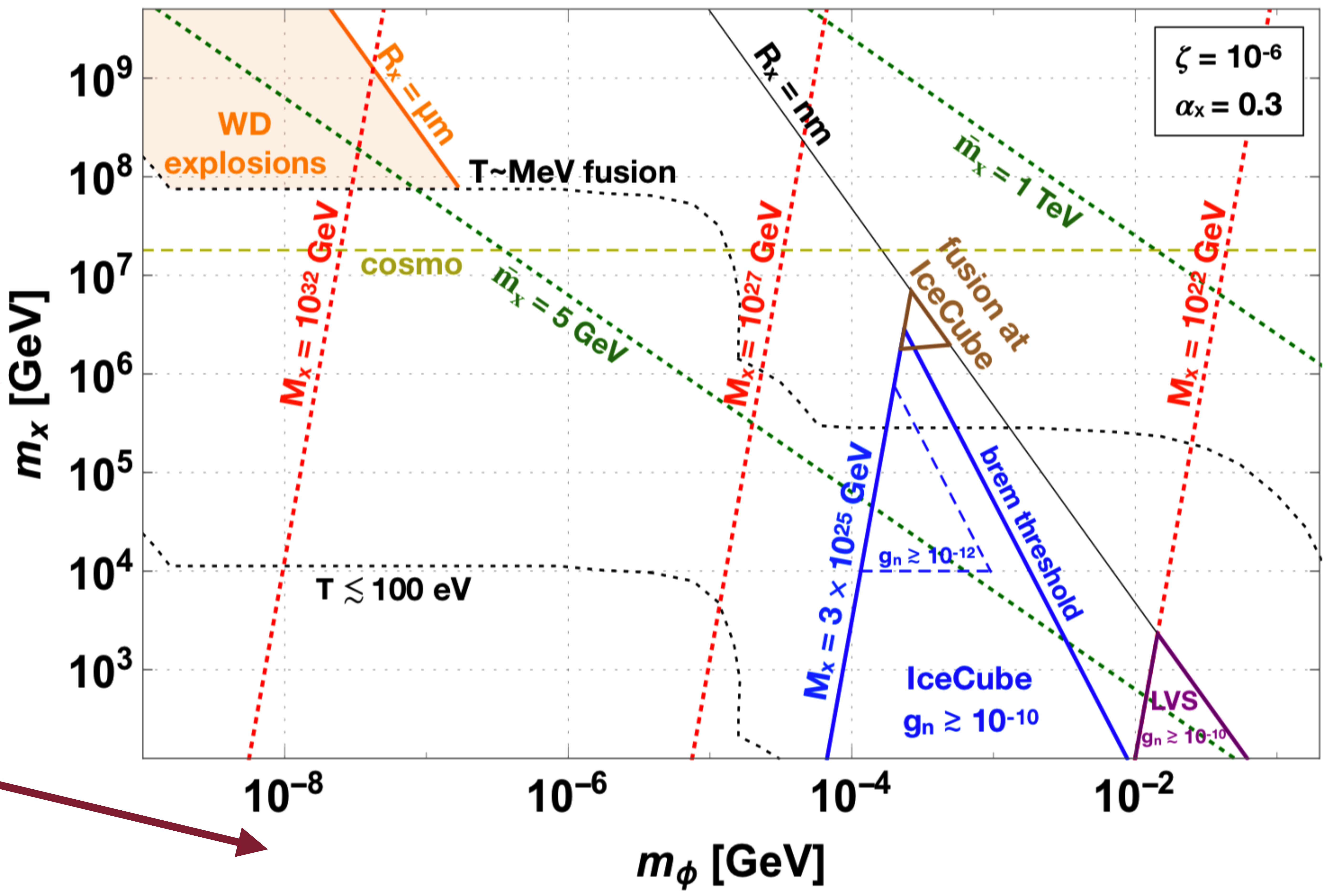


$\langle\varphi\rangle \lesssim m_N,\ g_n > 0$

Acevedo, JB, Goodman
2012.10998

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

BREM/NUCLEAR FUSION IN COMPOSITES



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

Acevedo, JB, Goodman 2012.10998

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

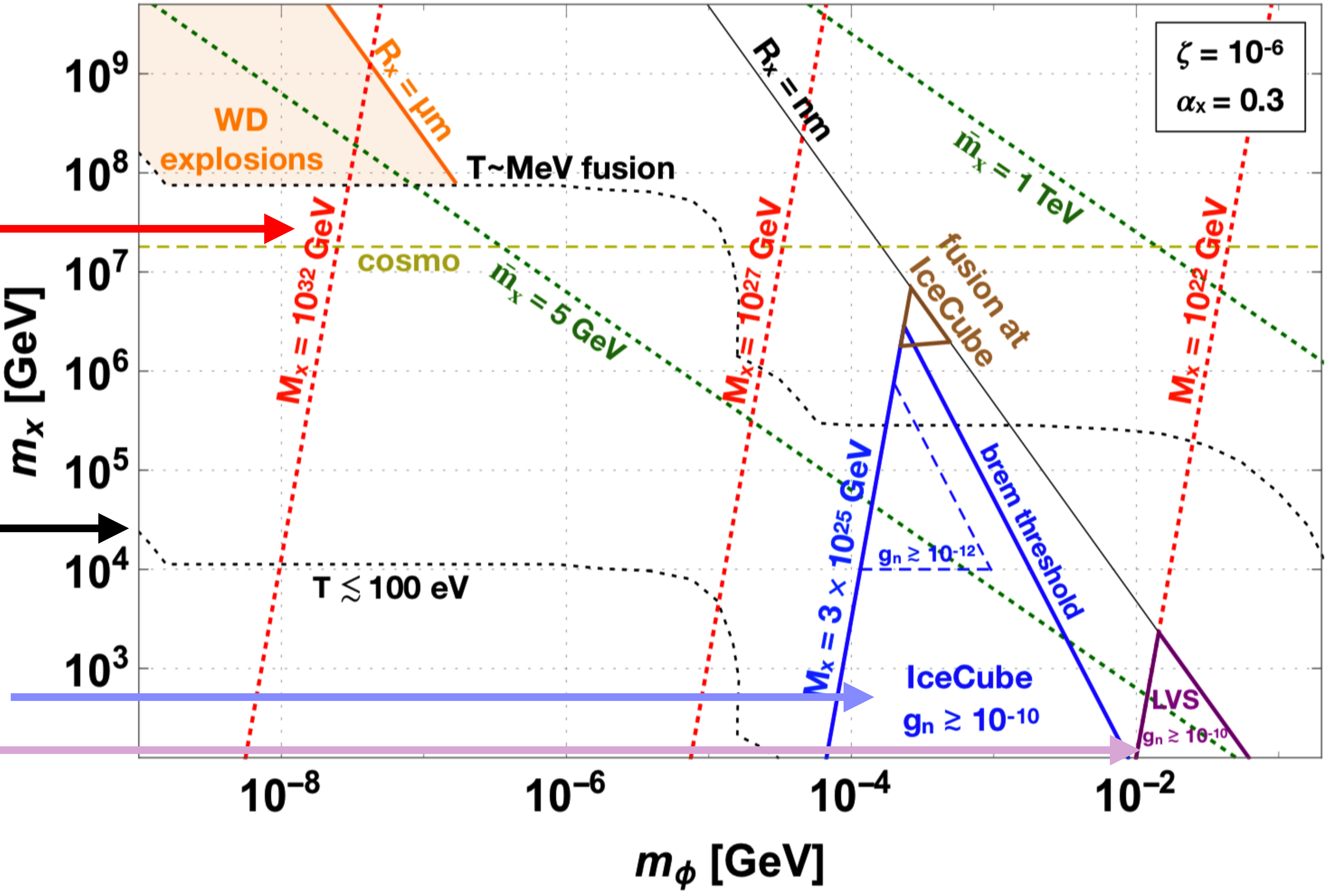
BREM/NUCLEAR FUSION IN COMPOSITES

Composite mass

Temperature of baryons flowing through composite

Find composite Brem at Ice Cube

Find composite Brem at SNO+/JUNO



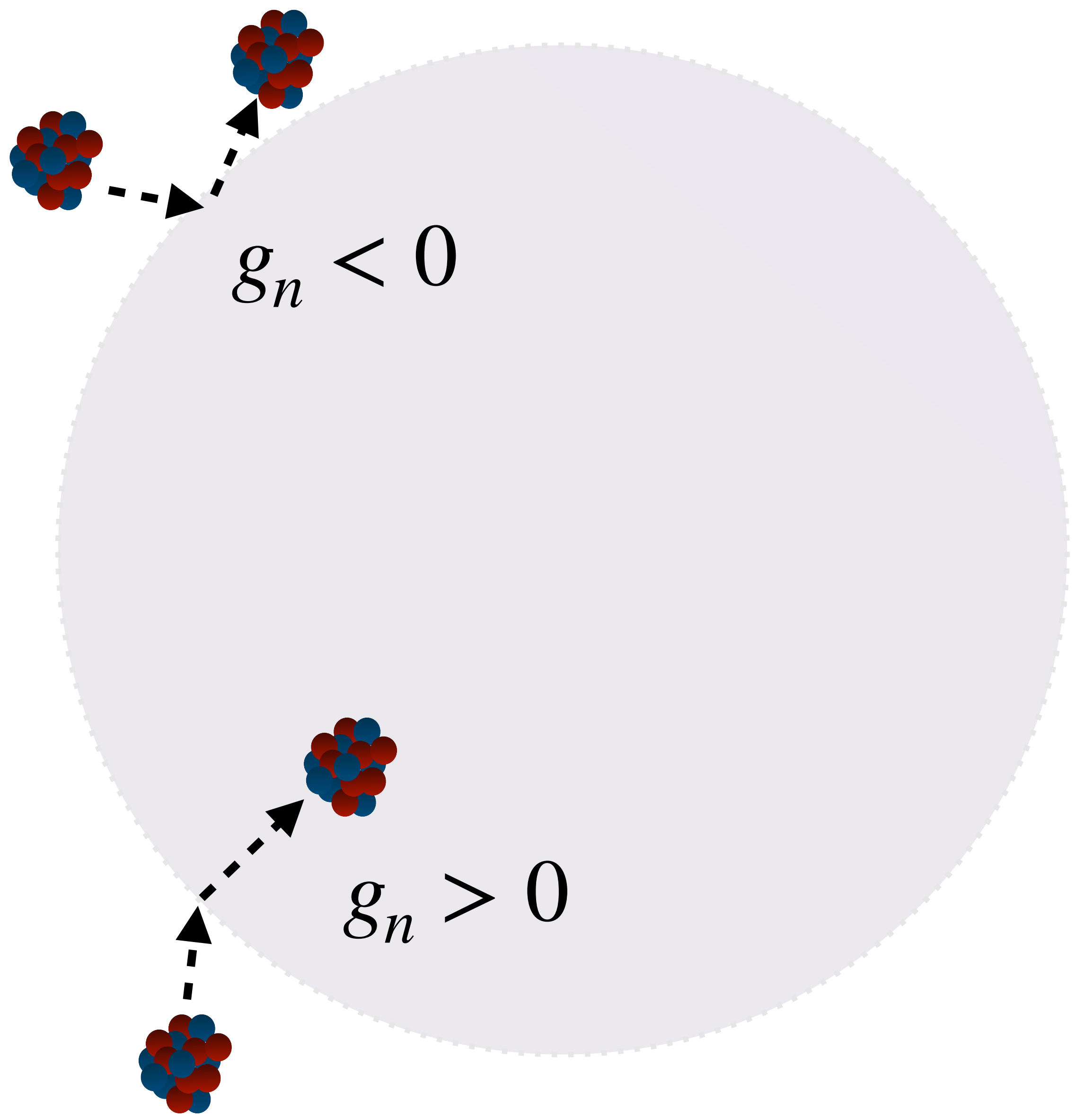
Acevedo, JB, Goodman 2012.10998

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.



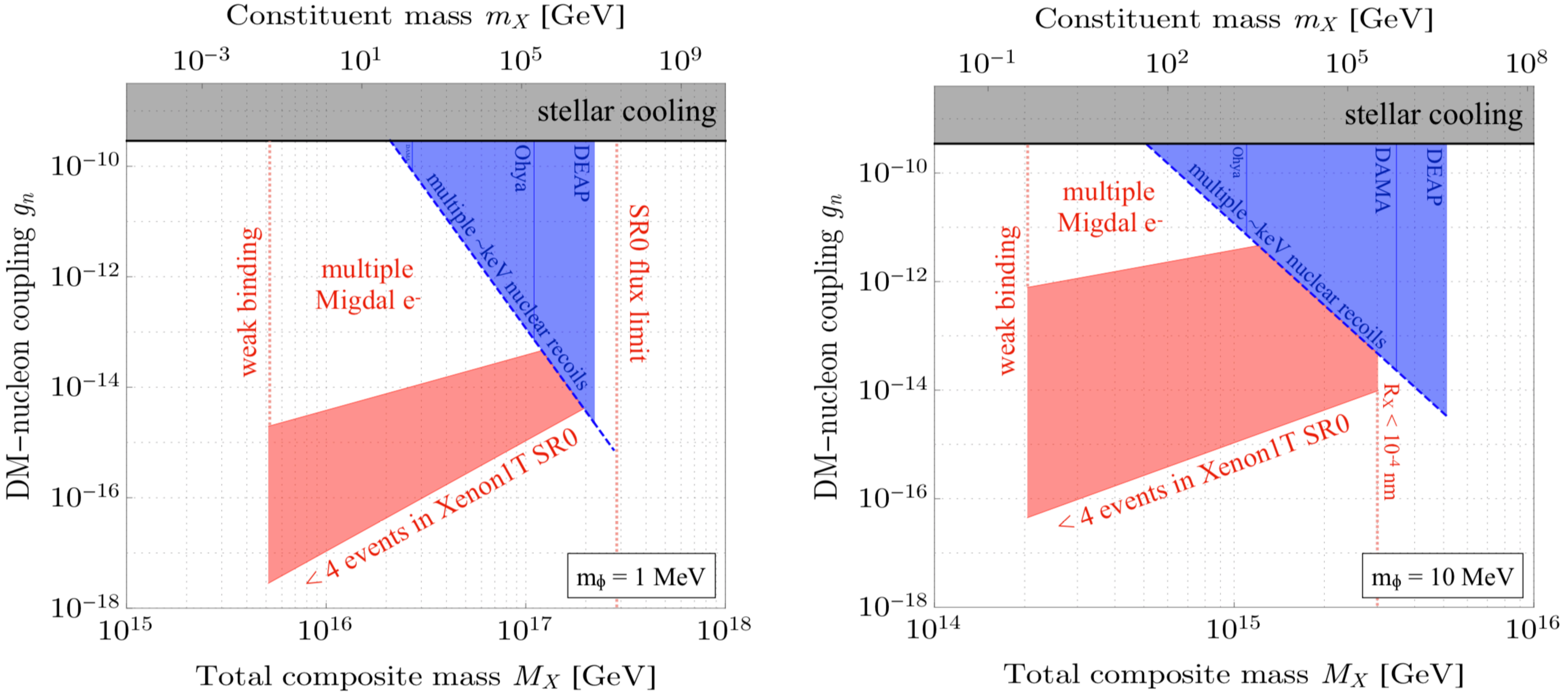
$\langle\varphi\rangle \ll m_N$

Acevedo, JB, Goodman
2108.10899

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 $\alpha_X = 0.3$



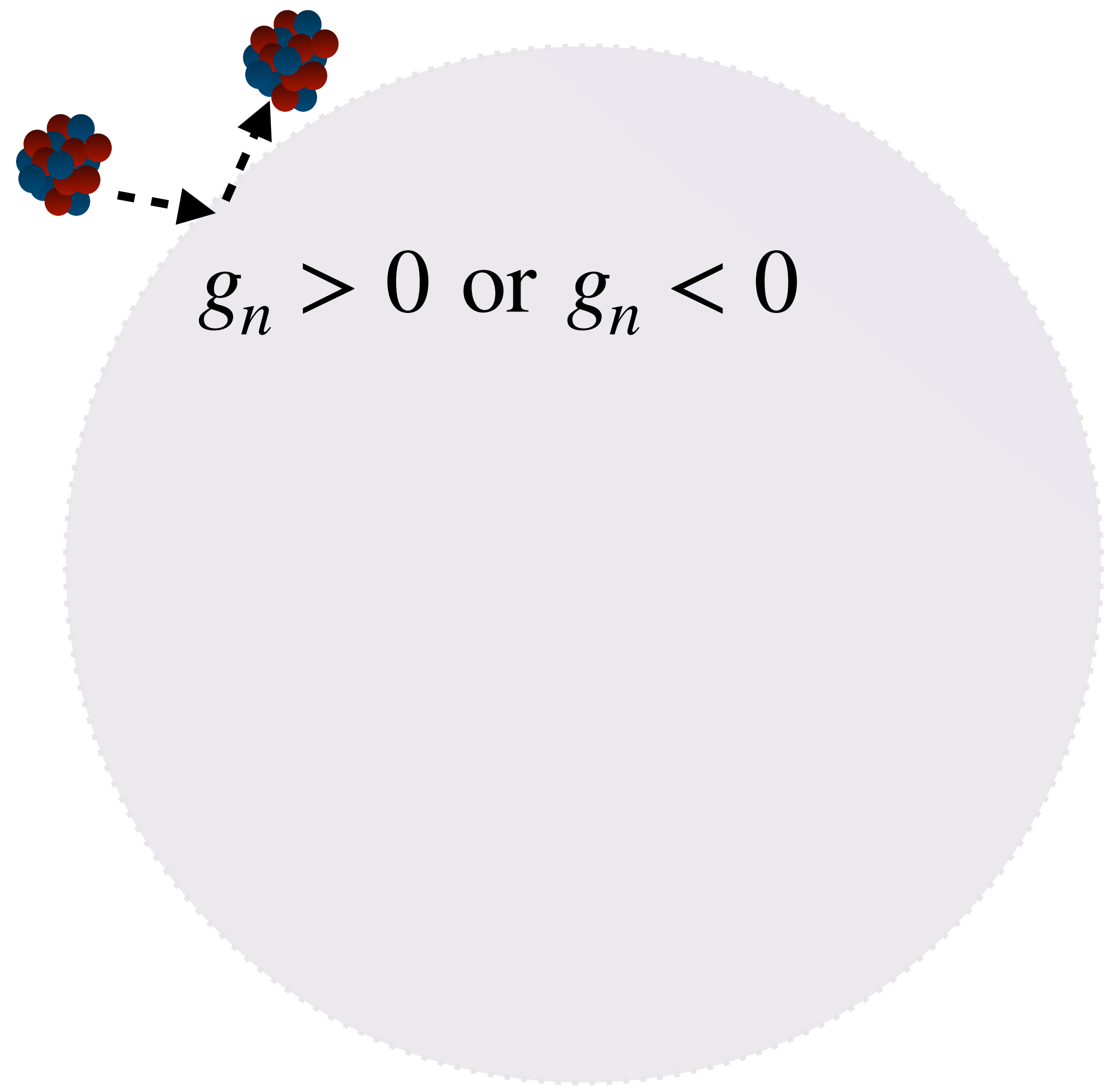
Acevedo, JB, Goodman, 2108.10889

MIMP INTERACTIONS

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

nuclear interactions with DM composite internal potential

3.



$\langle\varphi\rangle > m_N$

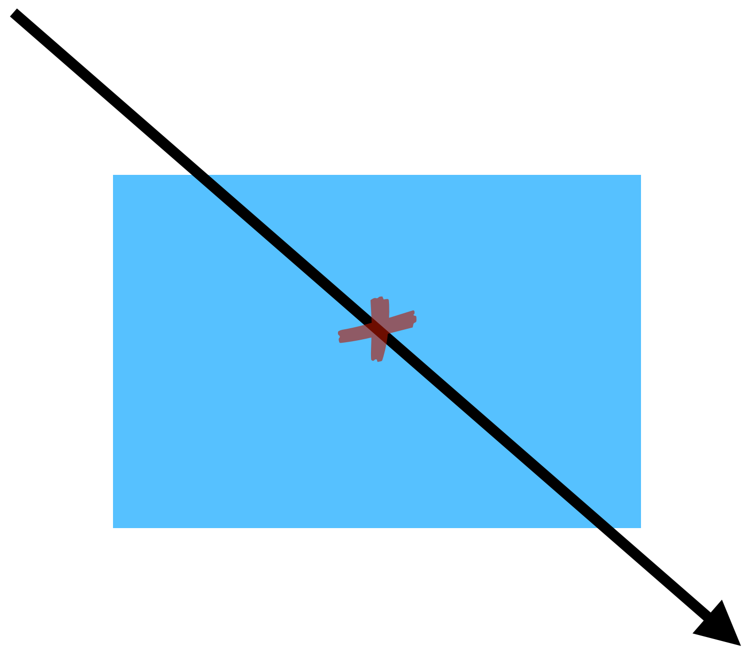
(MIMPs)

Acevedo, JB, Goodman
2108.10899

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



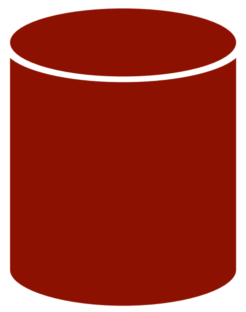
- If particles have velocity v (~0.001c), then sensitivity of detector sets a minimum energy threshold for detection

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

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 $1/m_x$

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

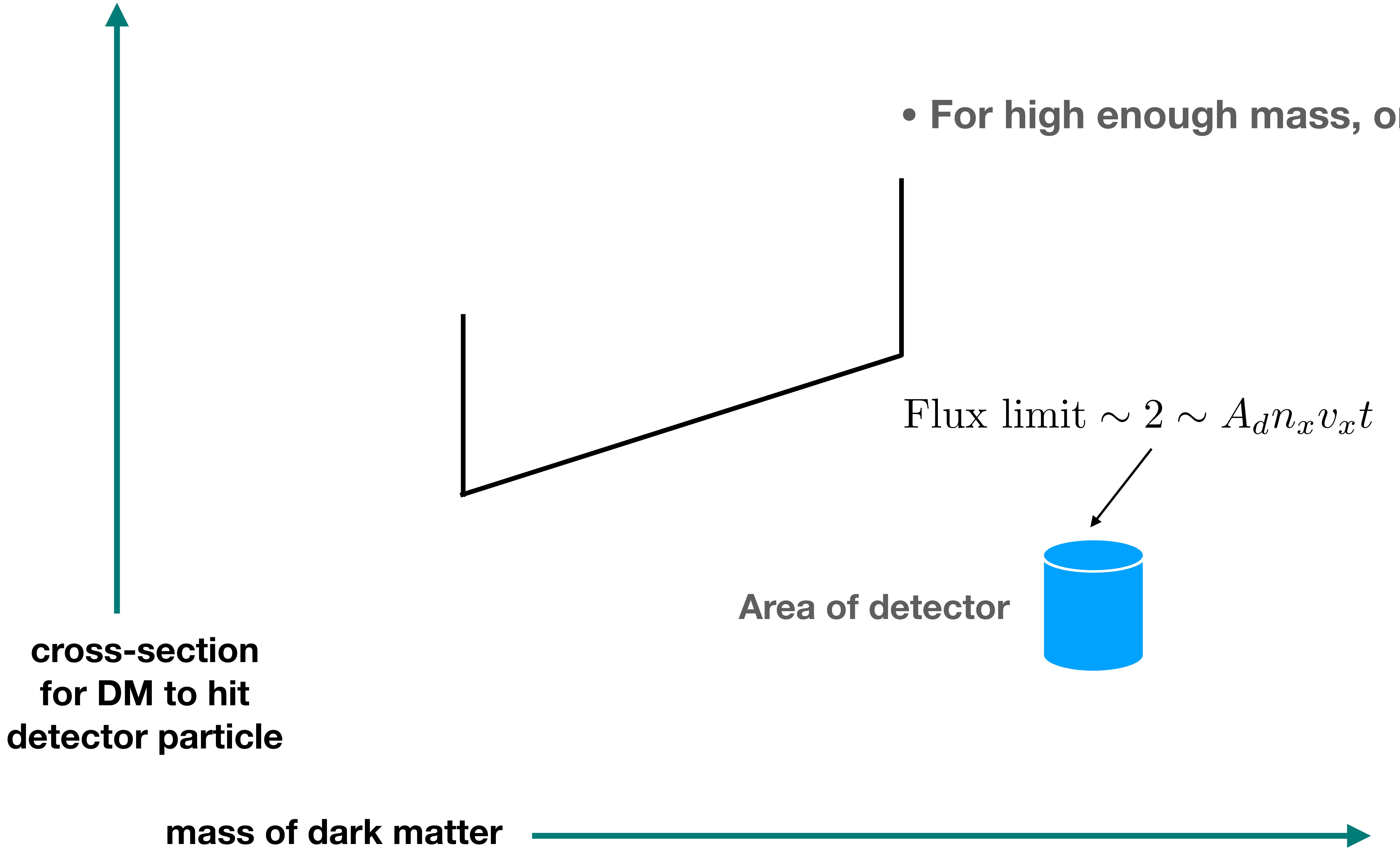
DM number density ρ_x / m_x

cross-section
for DM to hit
detector particle

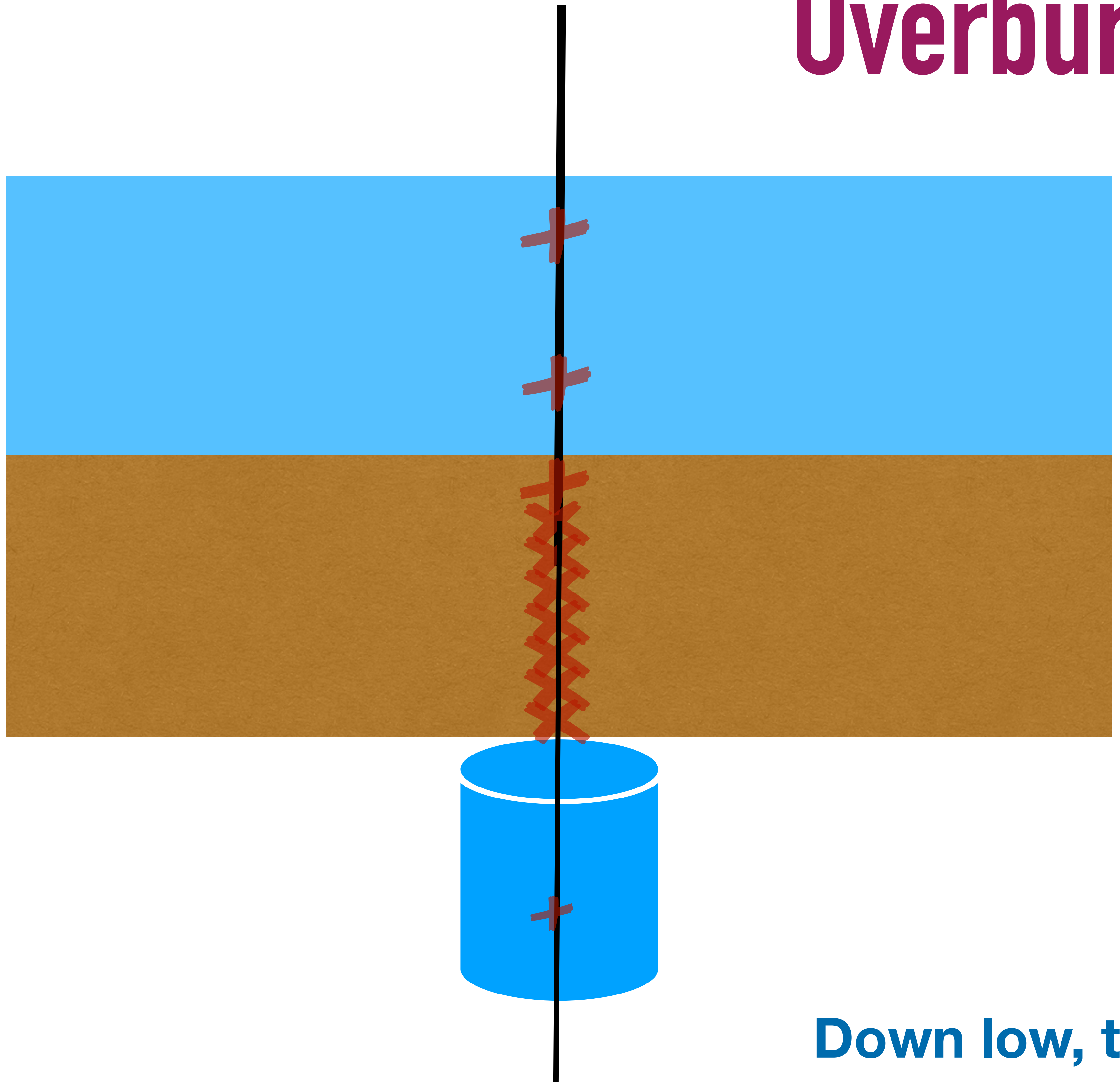
mass of dark matter

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?

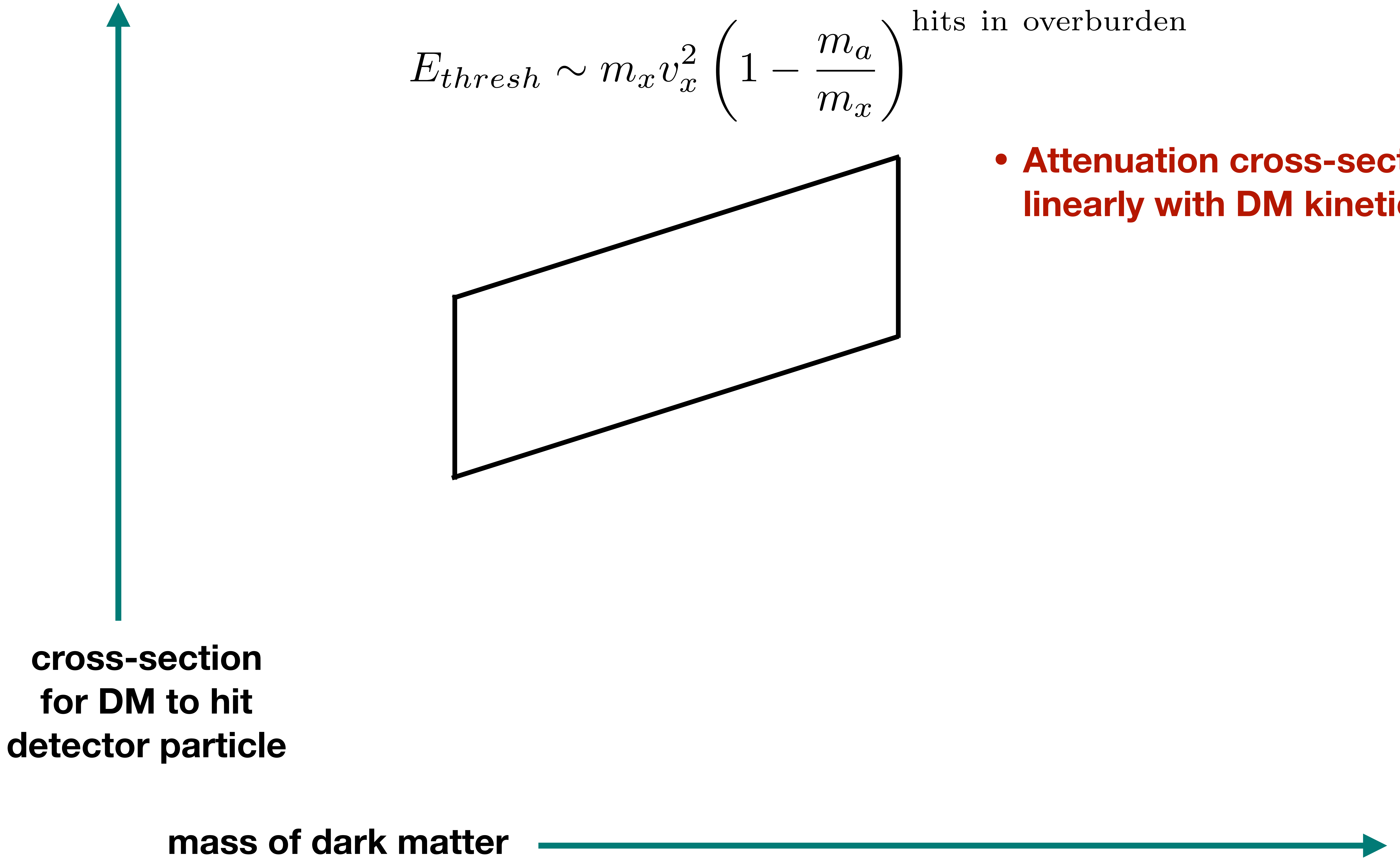
Length of overburden

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

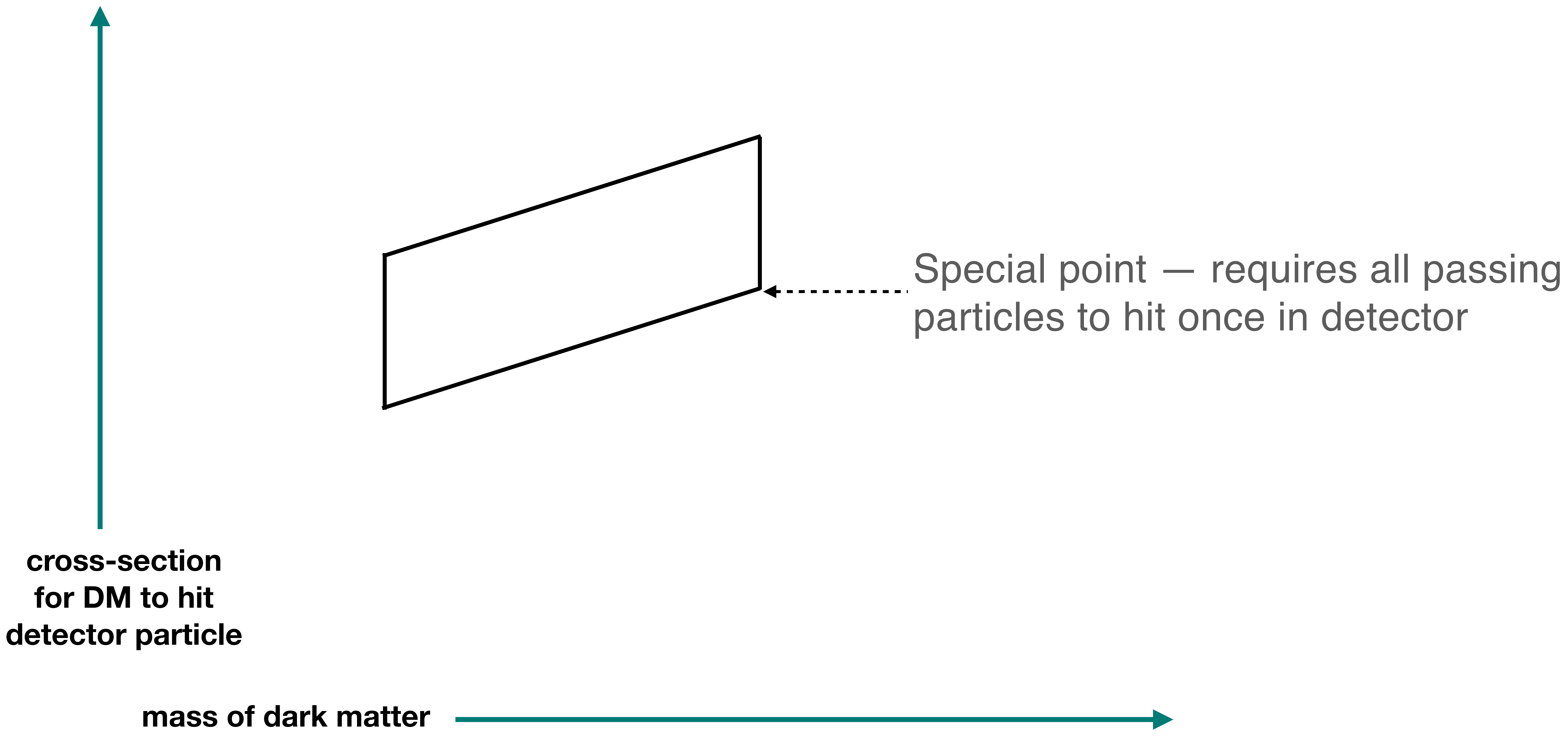
EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES

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

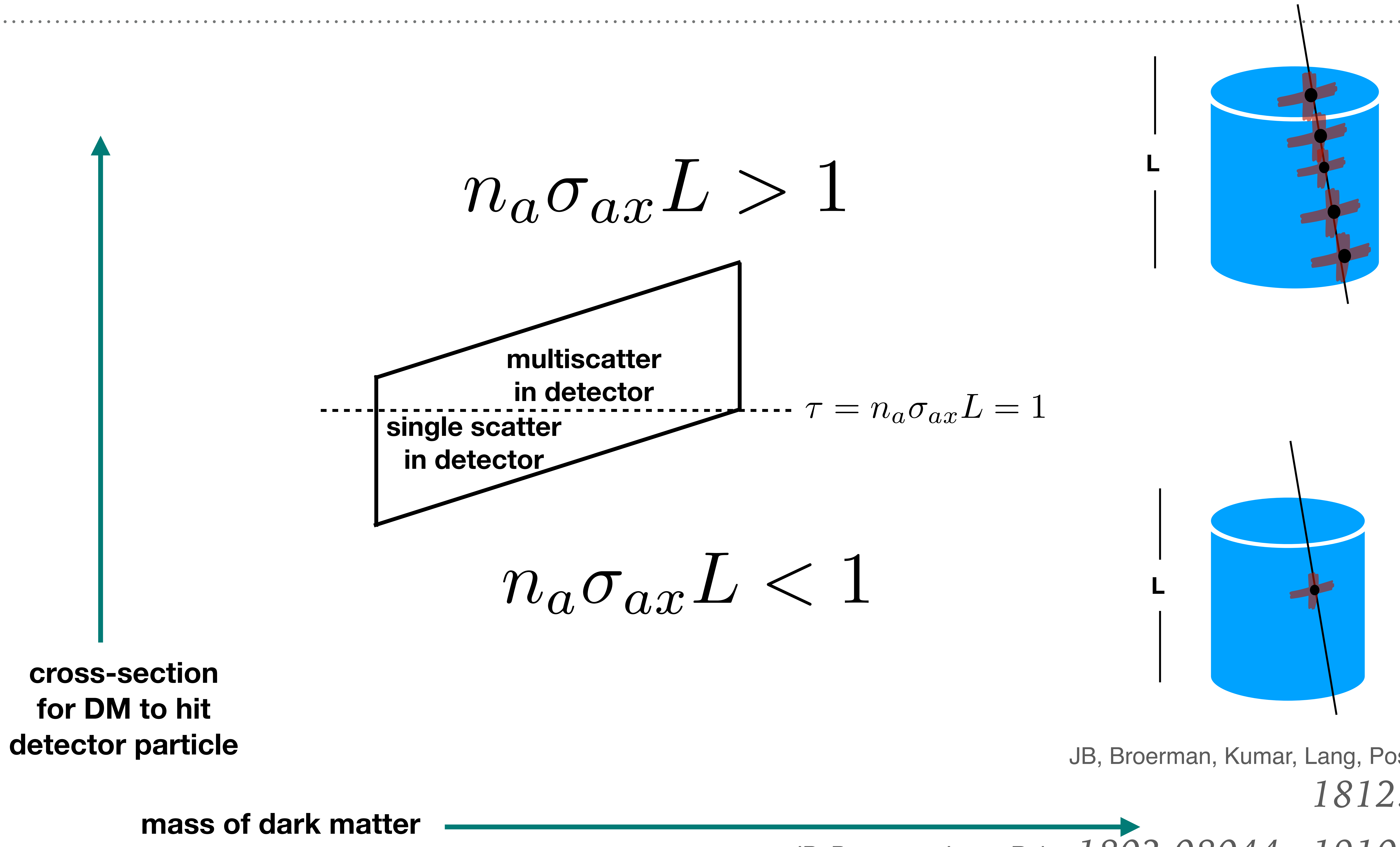
- **Attenuation cross-section increases linearly with DM kinetic energy ~$m_x v_x^2$**



EXPERIMENT LOOKING FOR FLUX OF NEW PARTICLES



MULTISCATTER DARK MATTER DETECTION

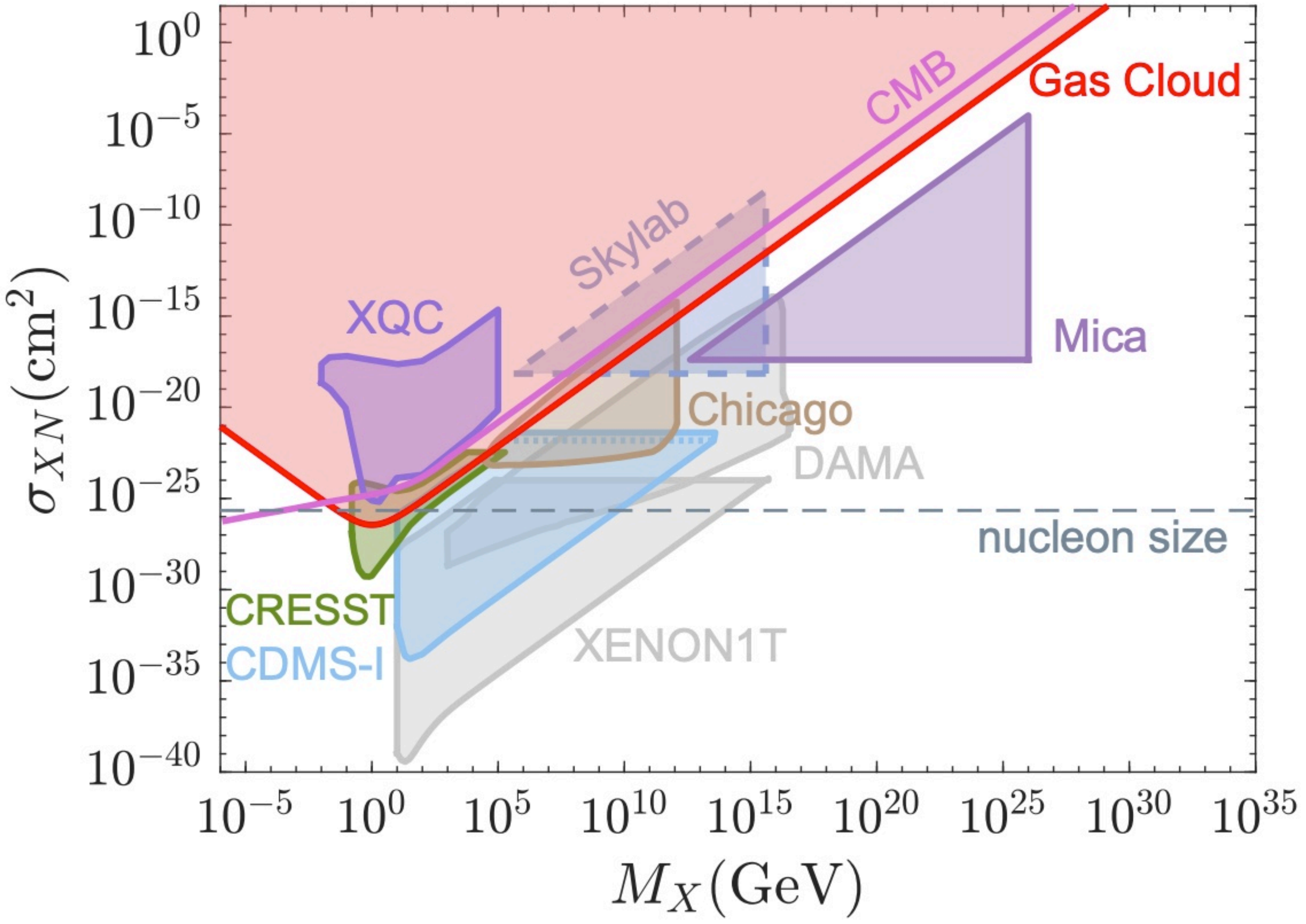


JB, Broerman, Kumar, Lang, Pospelov, Raj *1812.09325*

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

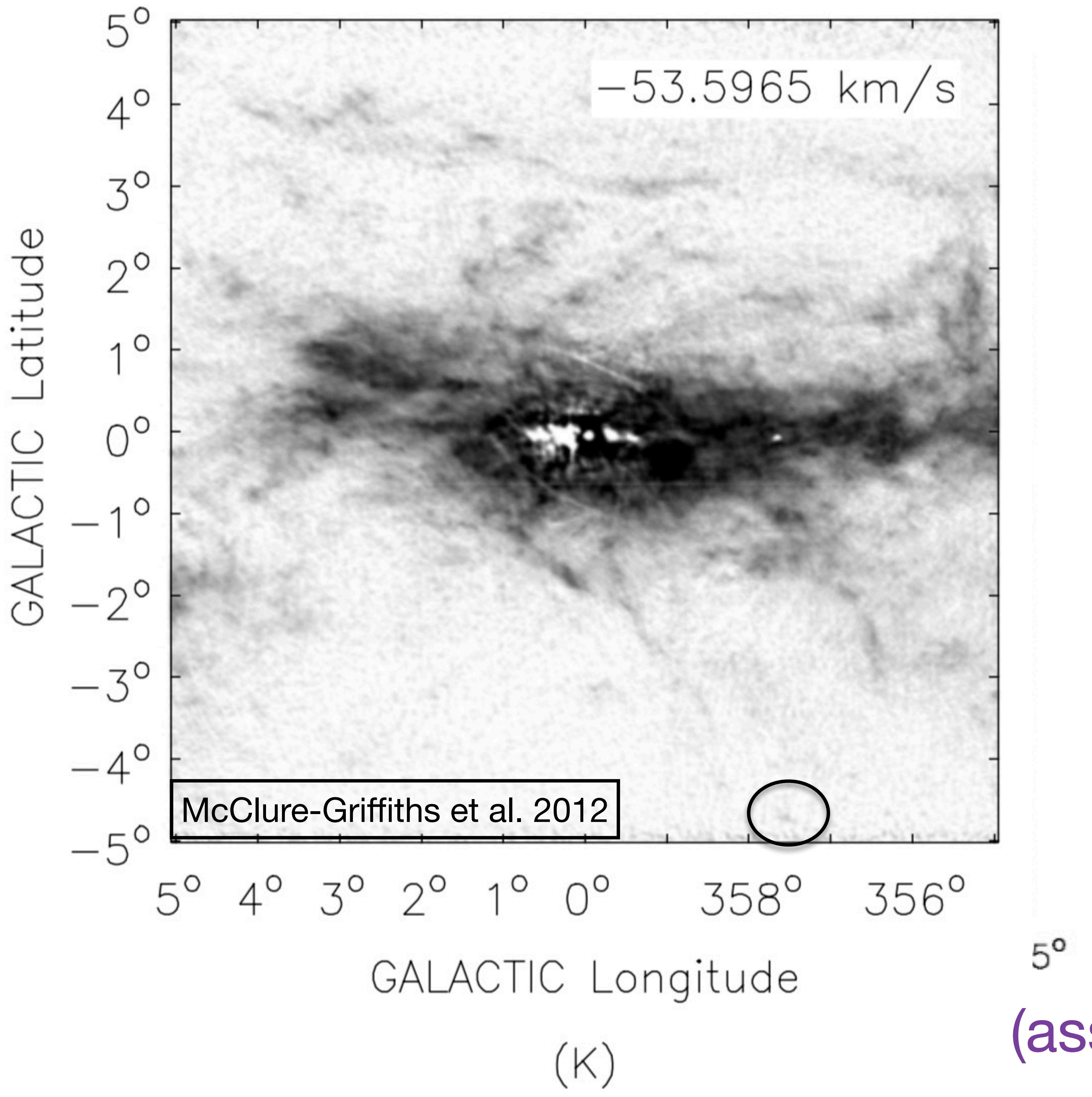
HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei



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

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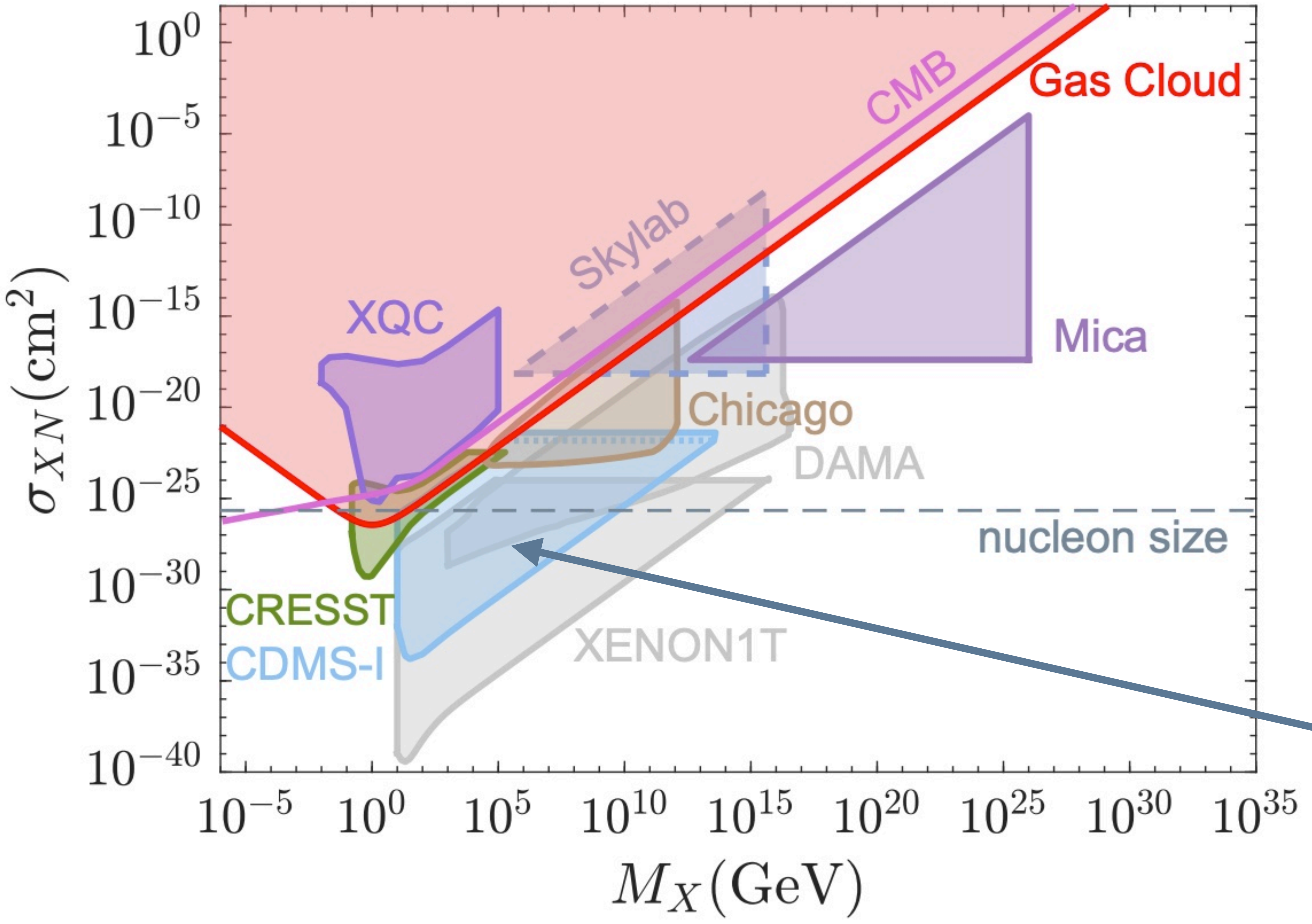
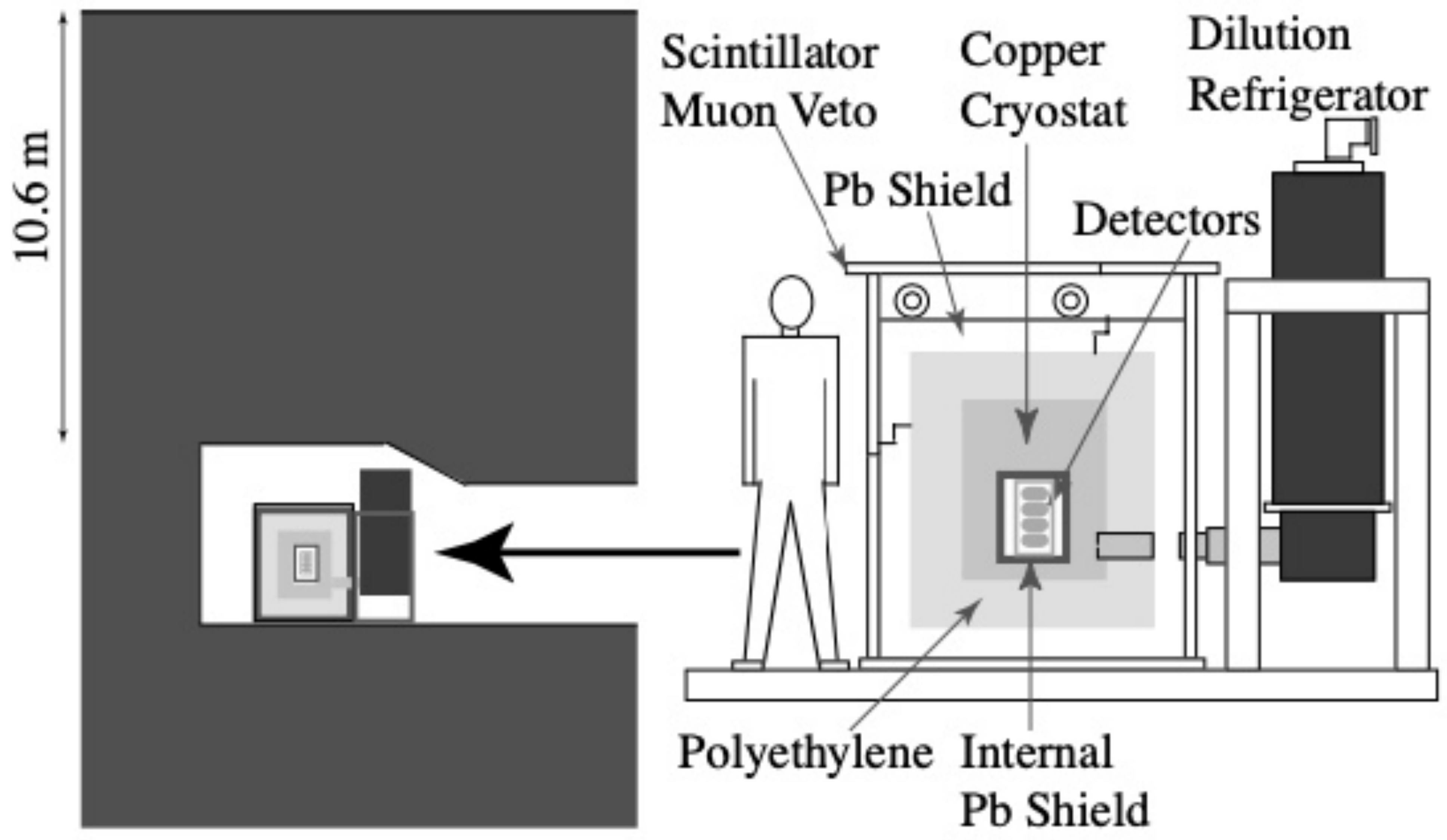




Recast CDMS-I limit using multi scatter

(Muon veto rejects very strong interactions)

Bhoonah, JB, Schon, Song 2010.07240

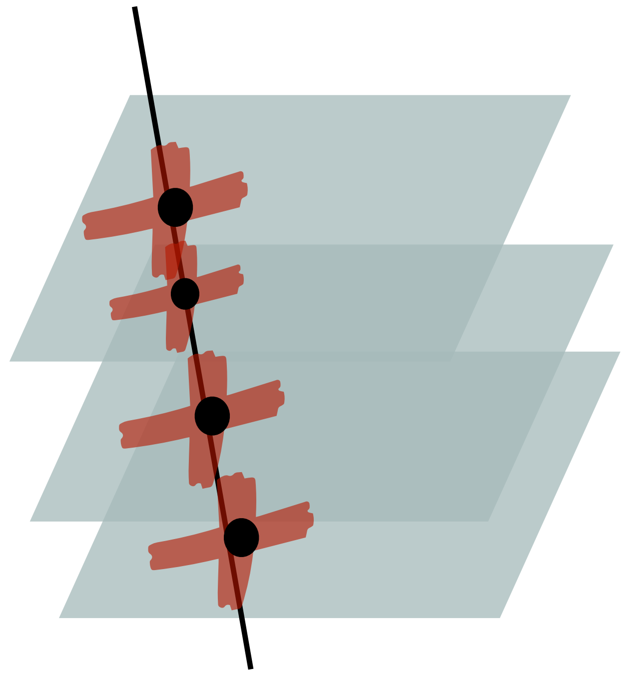
ETCHING PLASTIC SEARCHES FOR DARK MATTER

- *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*

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



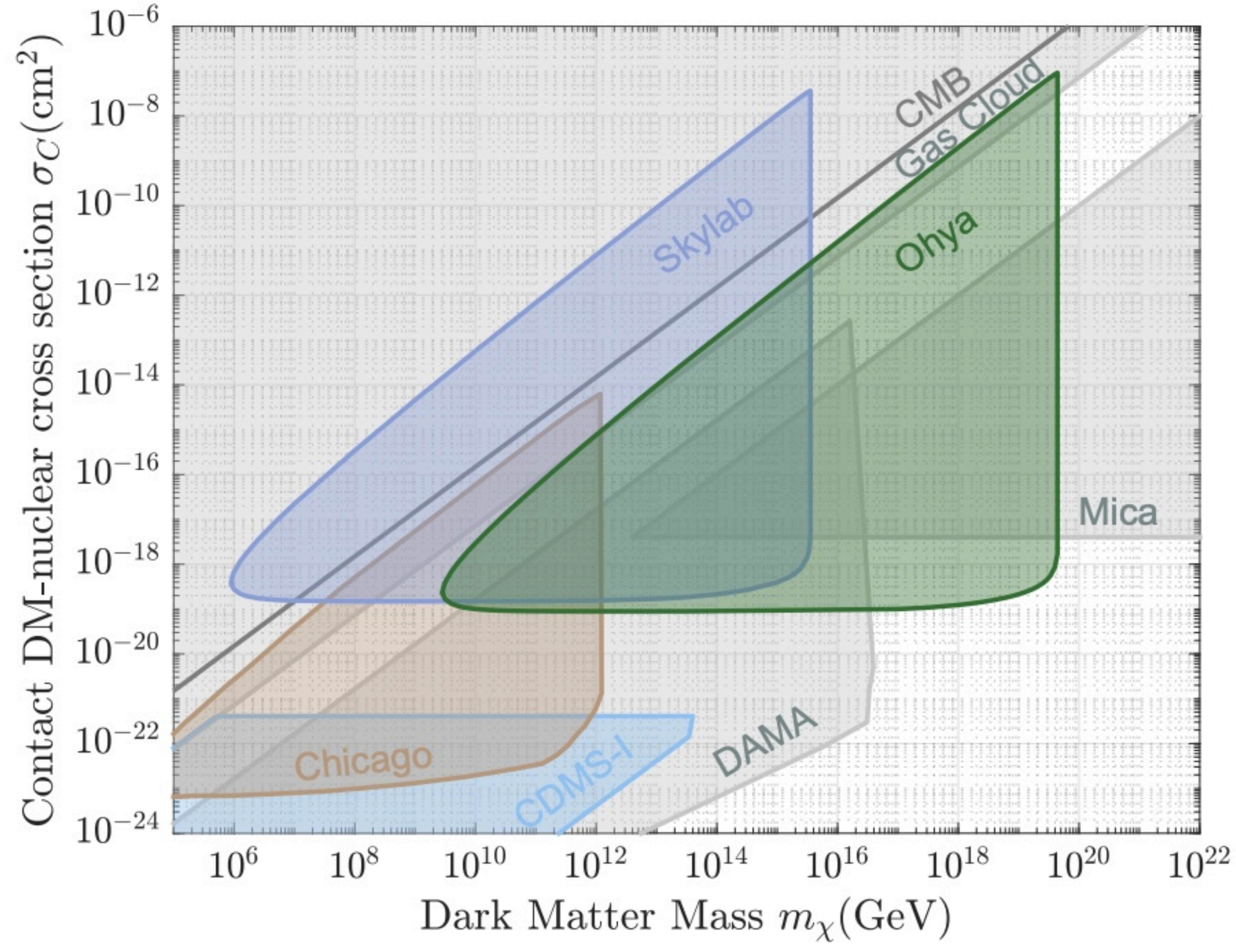
Ohya Quarry

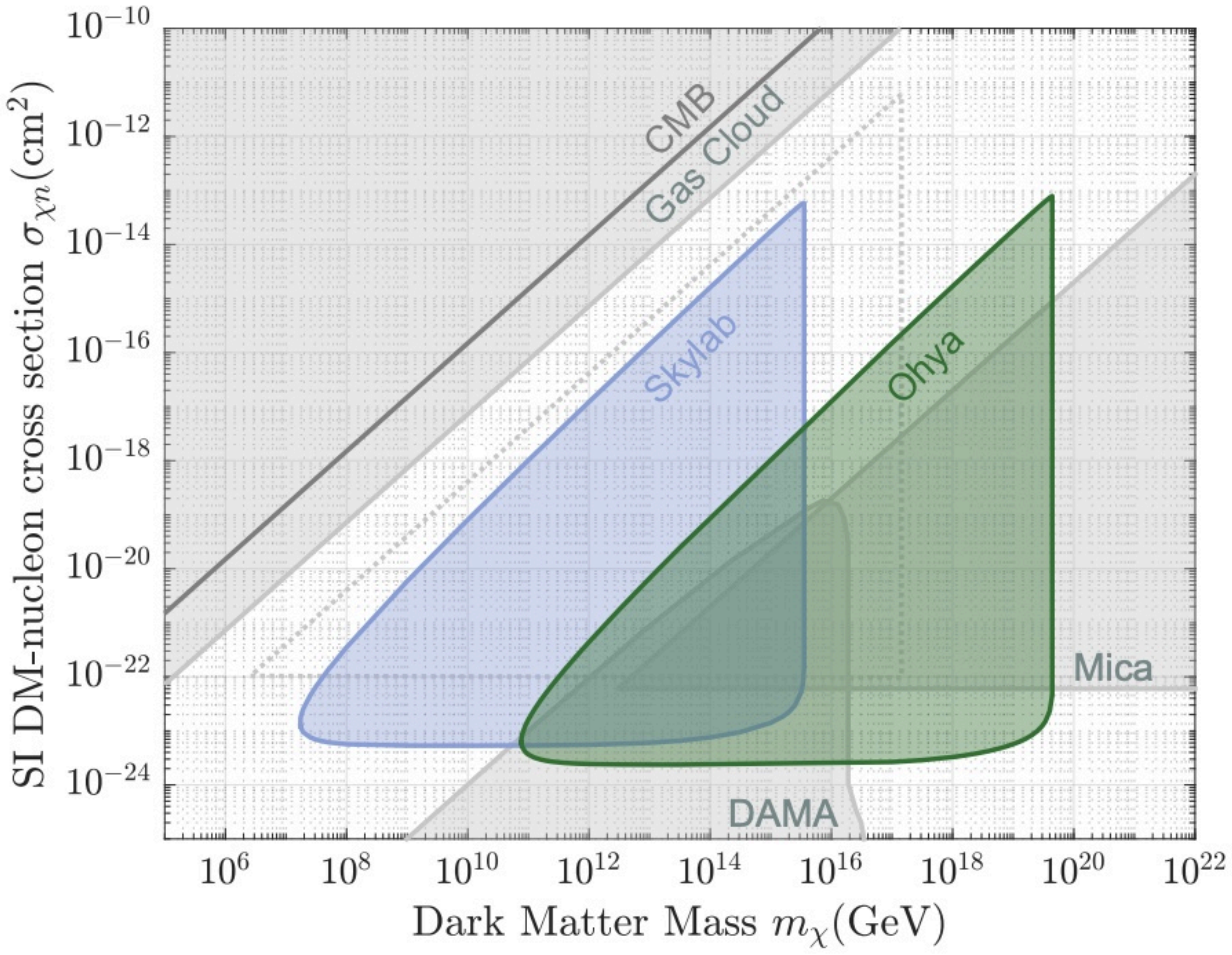
(see also Starkman, Gould, Esmailzadeh Dimopoulos 1990)

ETCHING PLASTIC SEARCHES FOR DARK MATTER

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

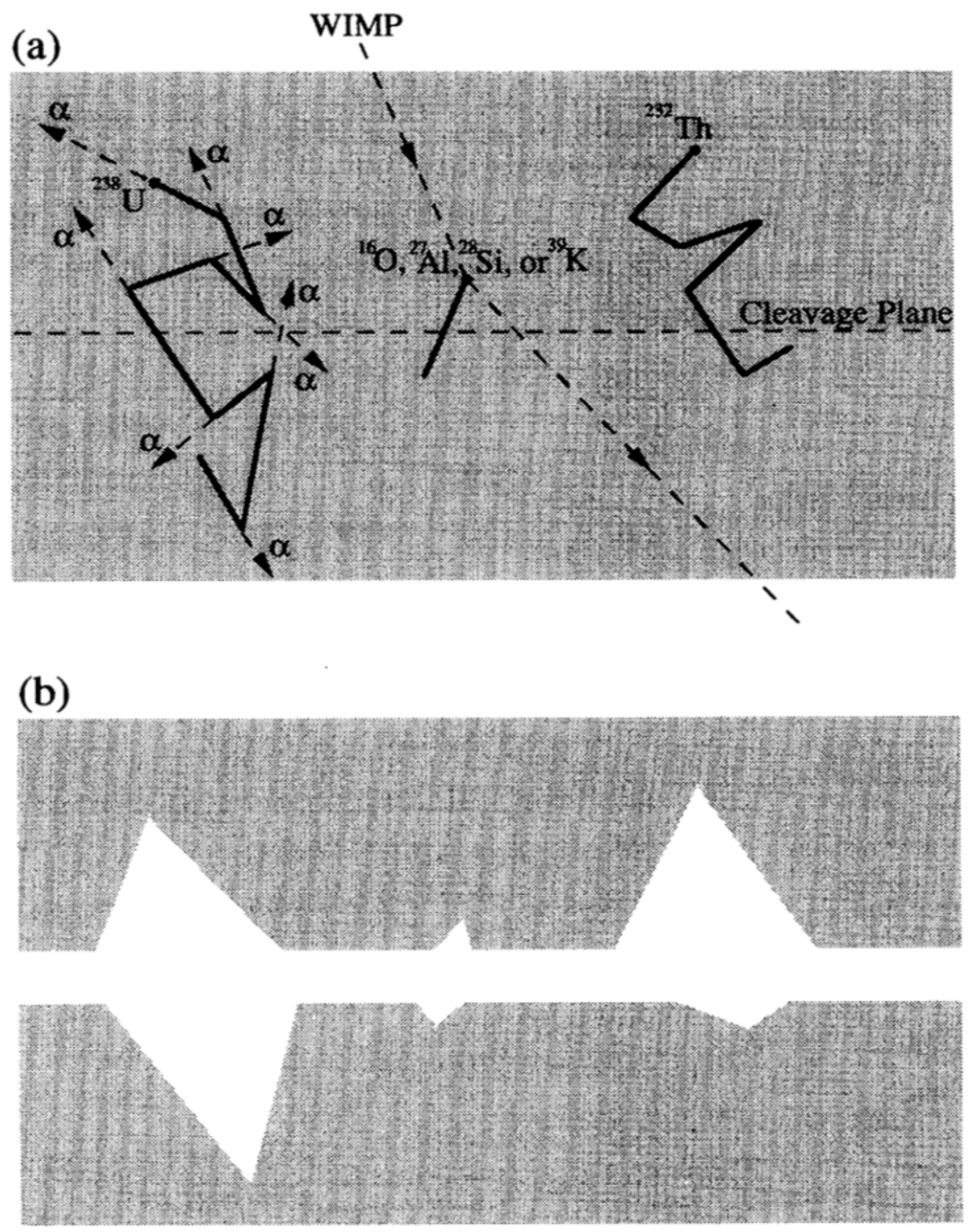
$$\left.\frac{dE}{dx}\right|_{th} = \frac{2E_i}{m_\chi}\left(\sum_{A\subset O}\frac{\mu_{\chi A}^2}{m_A}n_A\sigma_{\chi A}\right)\exp\left[\frac{-2}{m_\chi}\left(x_O\sum_{A\subset O}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}+x_D\sum_{A\subset D}n_A\frac{\mu_{\chi A}^2}{m_A}\sigma_{\chi A}\right)\right]$$

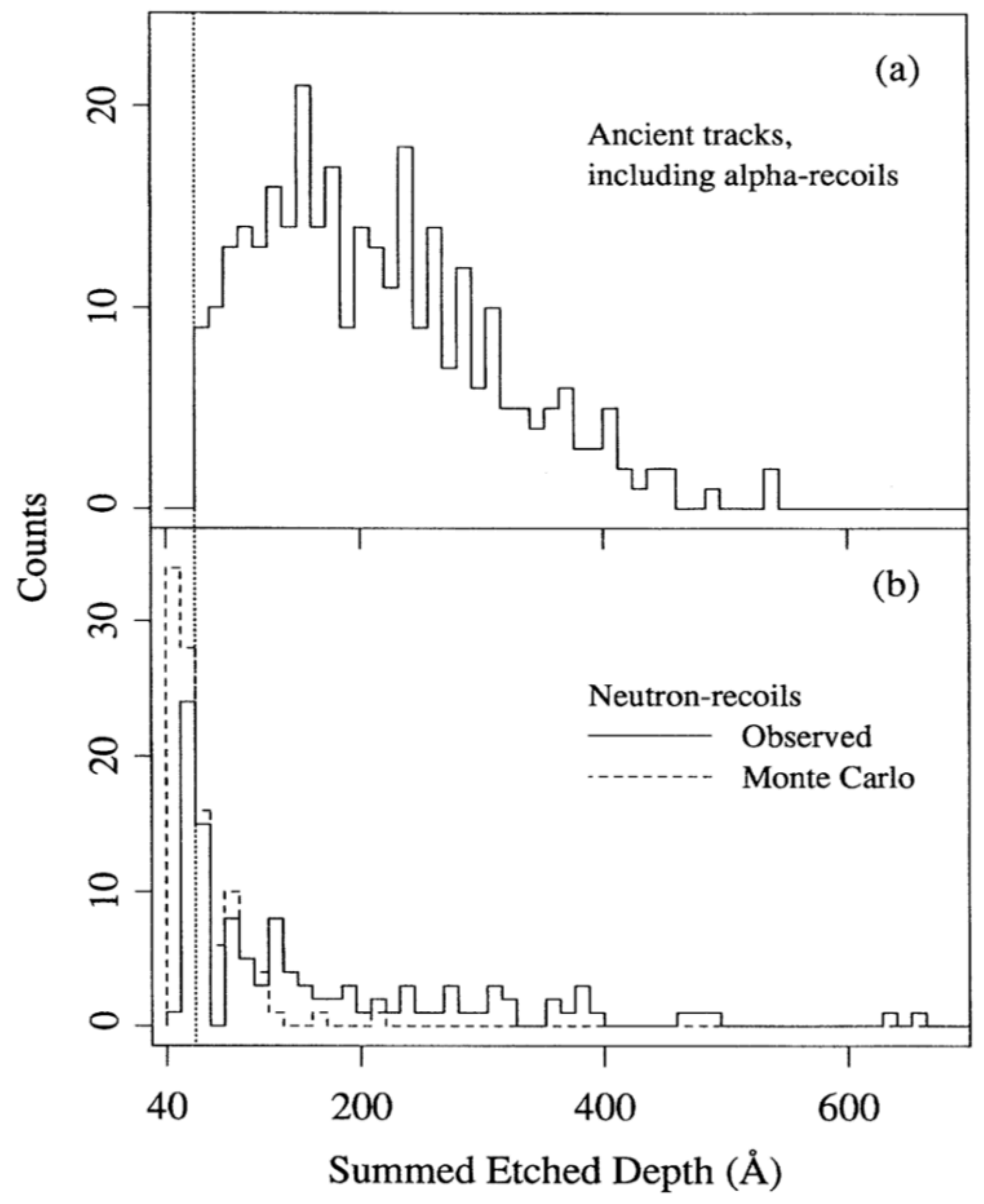




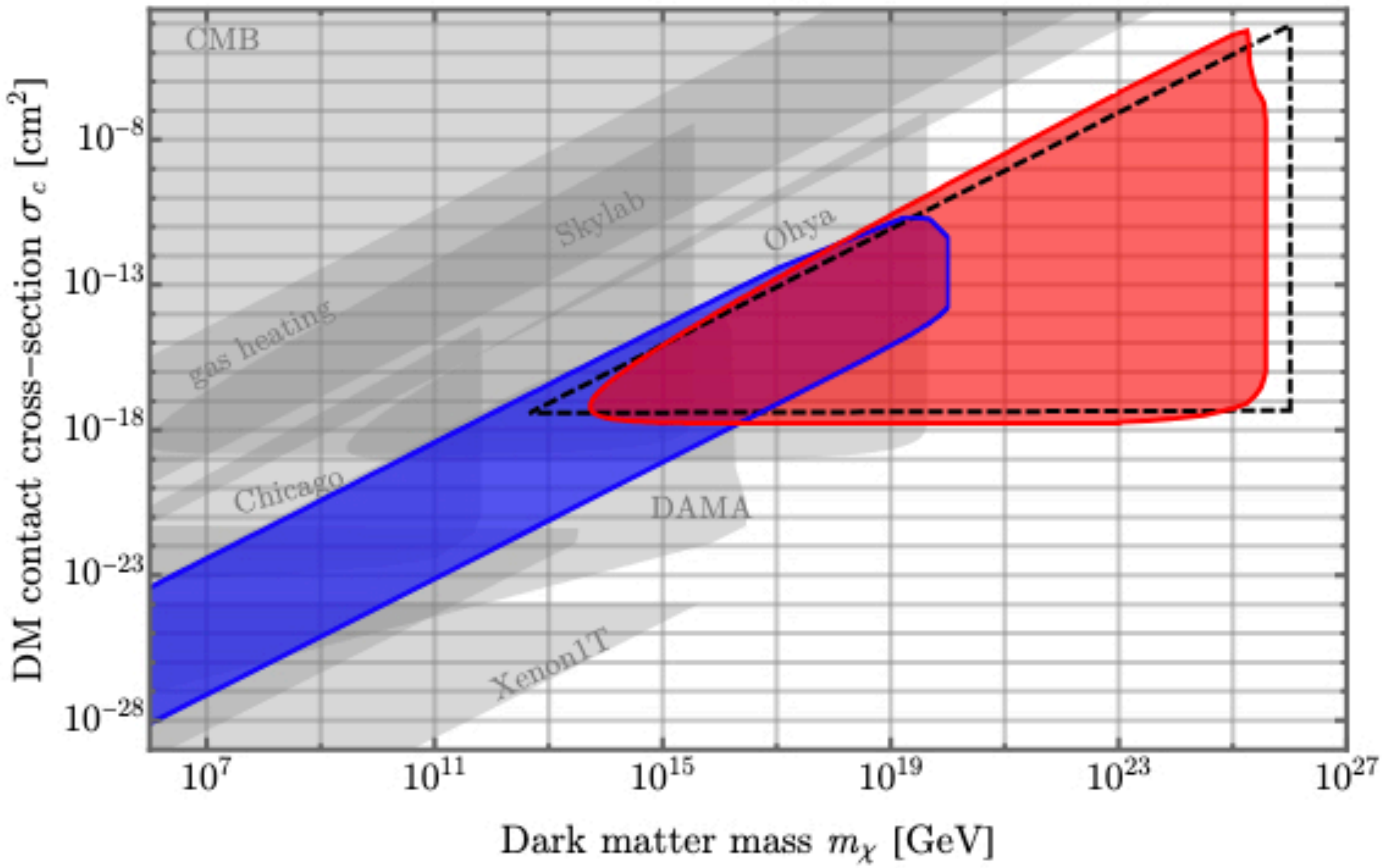
Bhoonah, JB, Courtman, Song 2012.13406

ANCIENT MICA SEARCH FOR DARK MATTER





➤ Recast using crust and mica MC



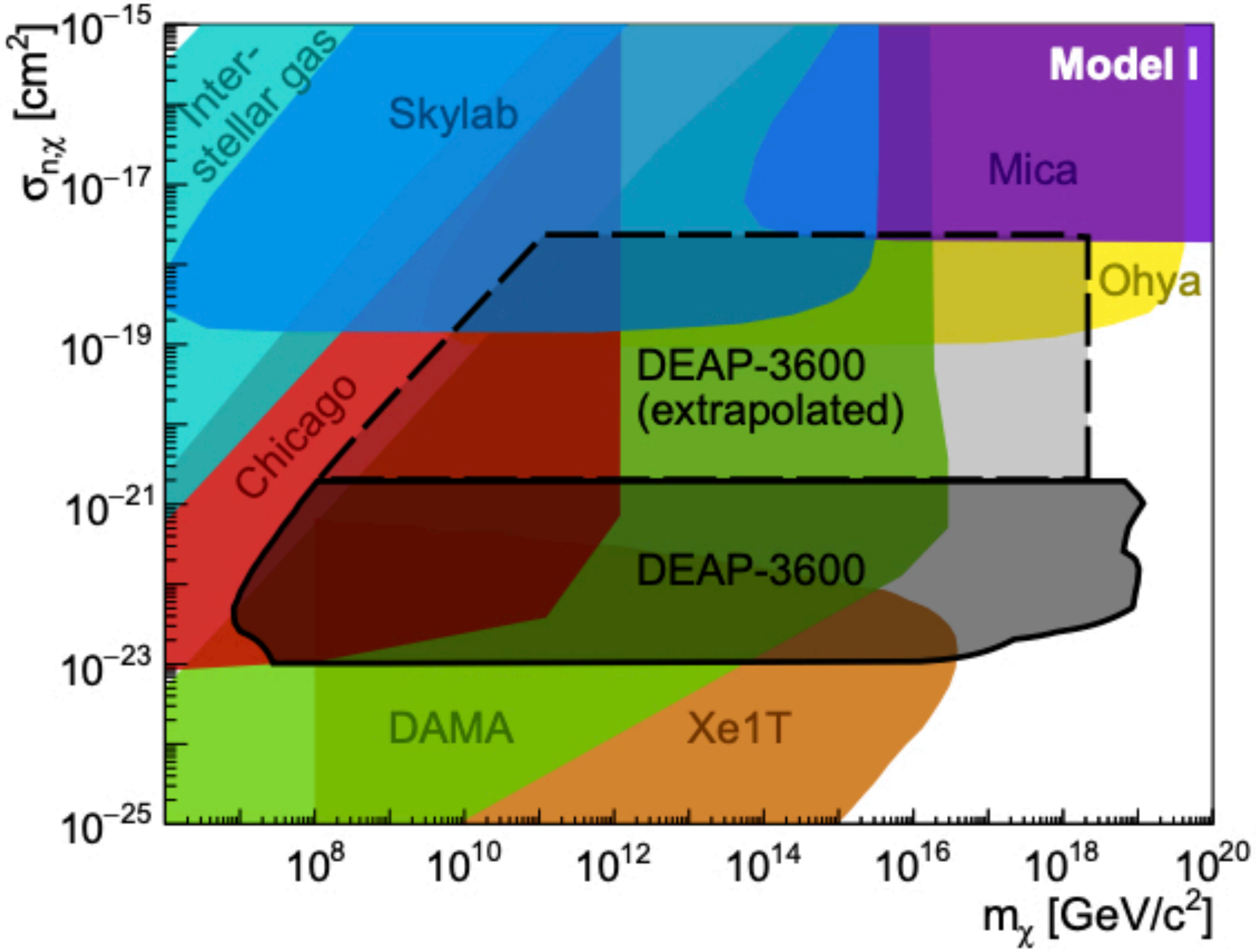
➤ 1995 Snowden-Ifft et al. calibrated mica samples

Acevedo, JB, Goodman, 2105.06473

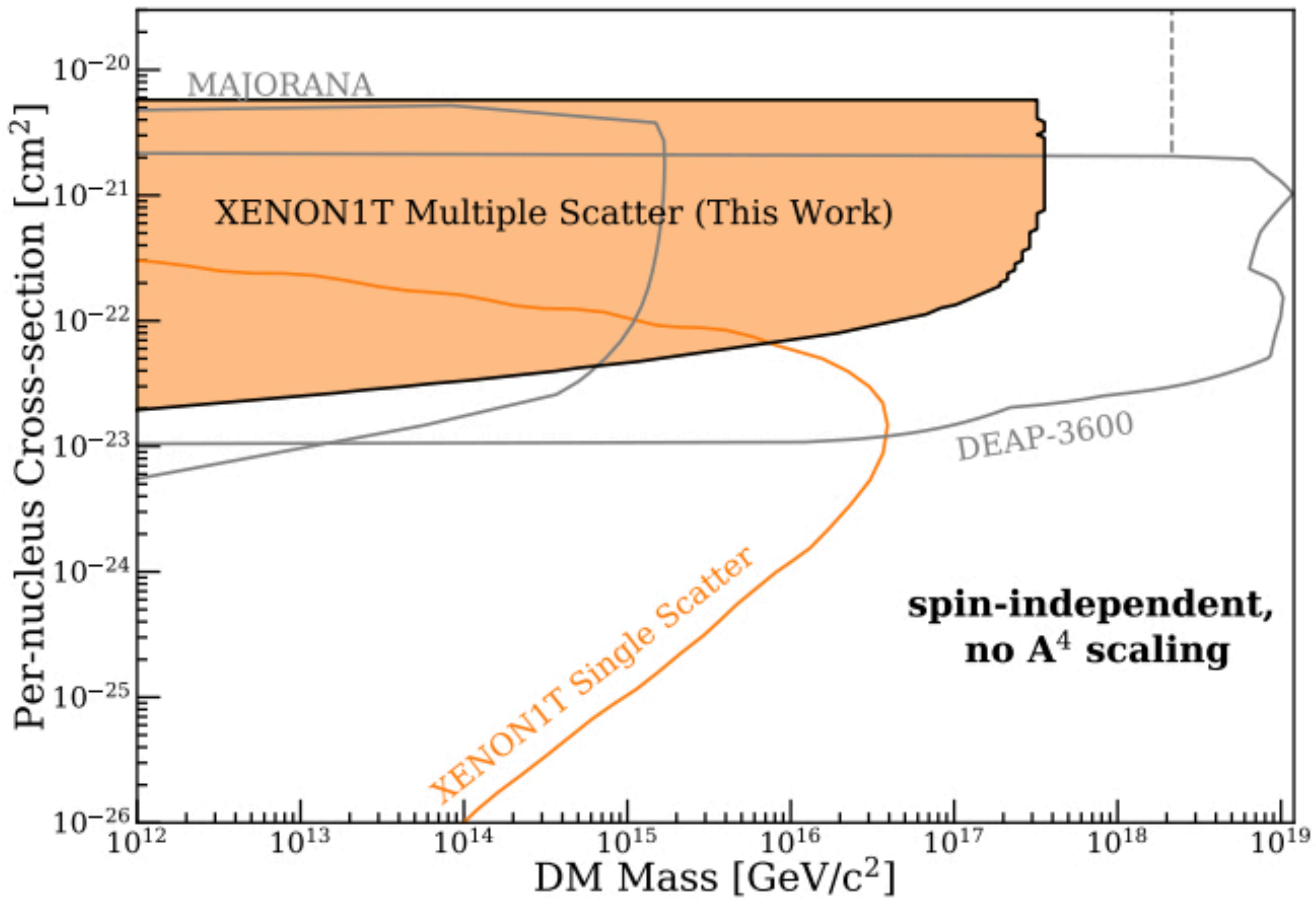
Also a mineral DM detection collaboration at Queen's

Balogh, Boukhtouchen, JB, Fung, Leybourne, Lucas, Mkhonto, Vincent
2301.07118

HEAVY DM RESULTS FROM DEAP-3600, XENON1T

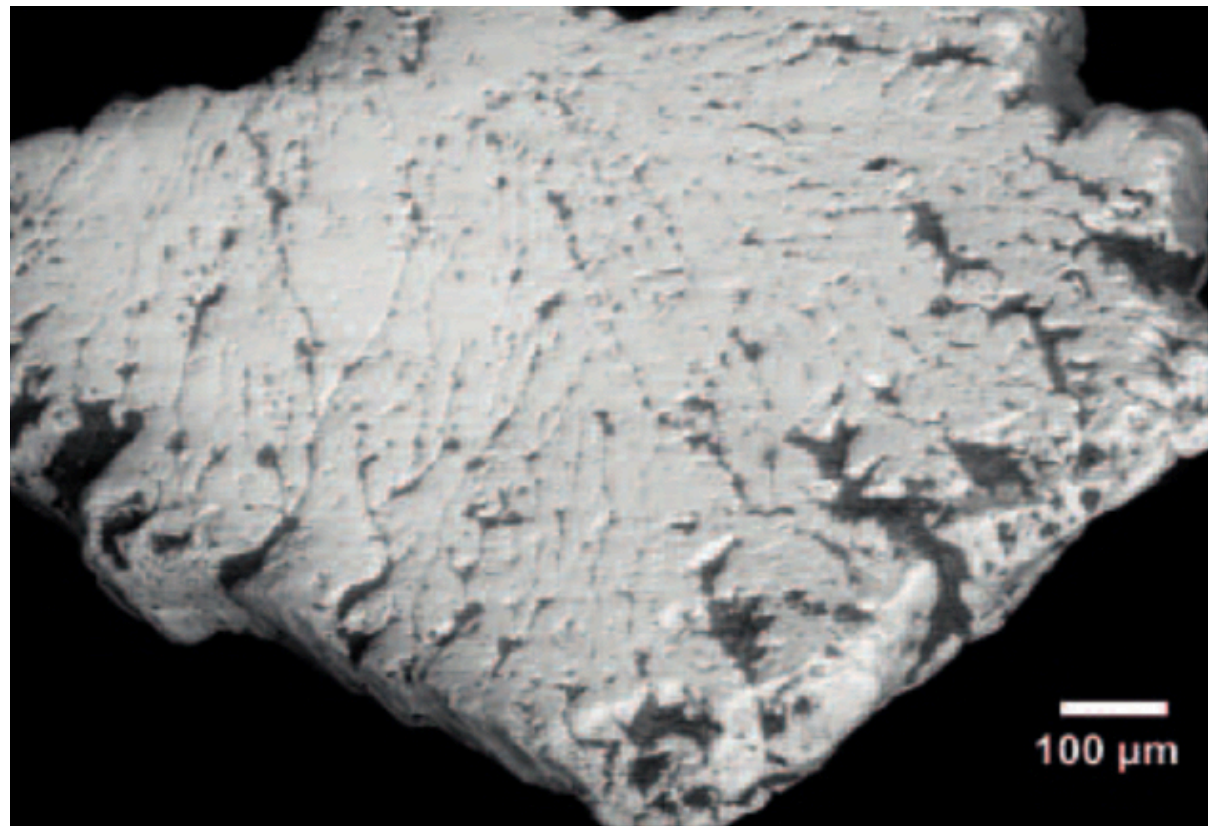


2108.09405, PRL



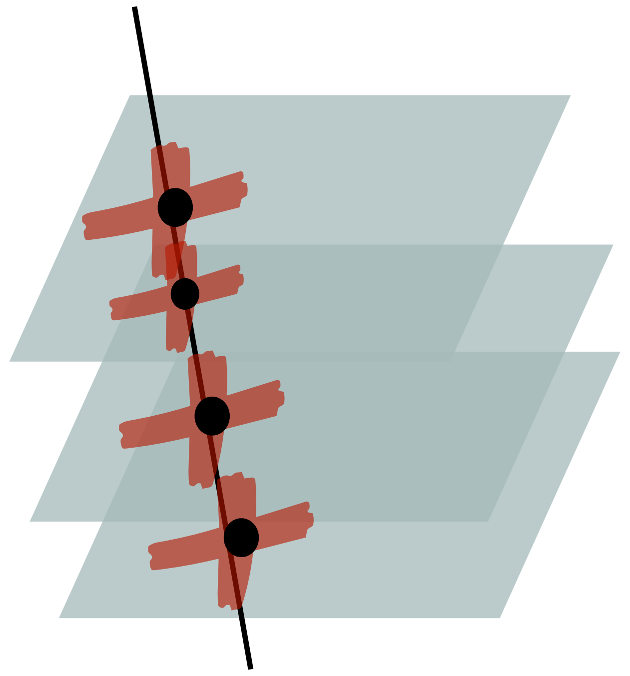
2304.10931, PRL

FUTURE HEAVY DM: QPALEO, CR-39, SNO+, AND BEYOND

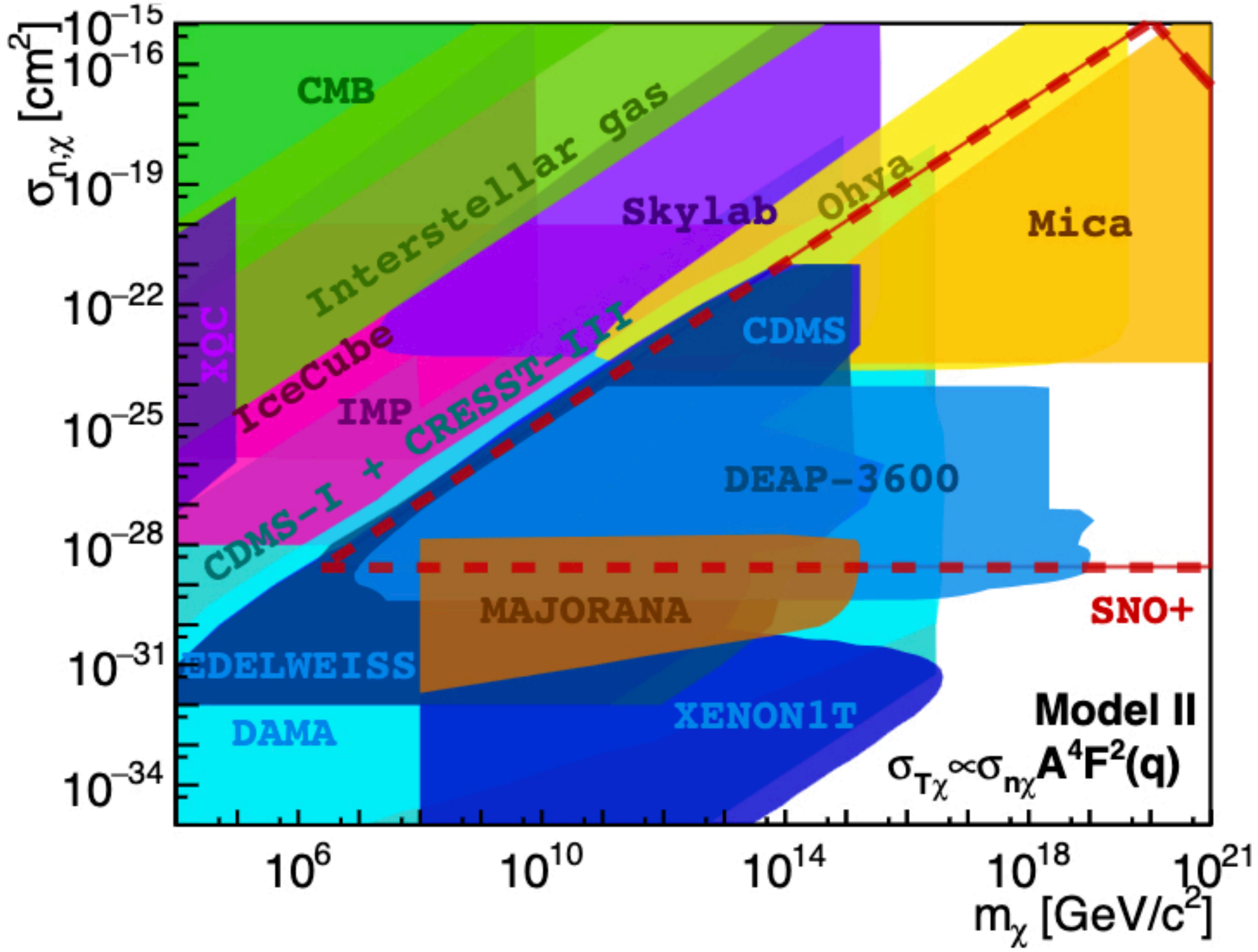


Q Paleo (Q Rocks? - name suggestions welcome) 2301.07118

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



Future CR-39 experiment or similar



Snowmass Ultraheavy particle dark matter 2203.06508

Delorean

2023 BZ

BACK TO THE FUTURE 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)

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

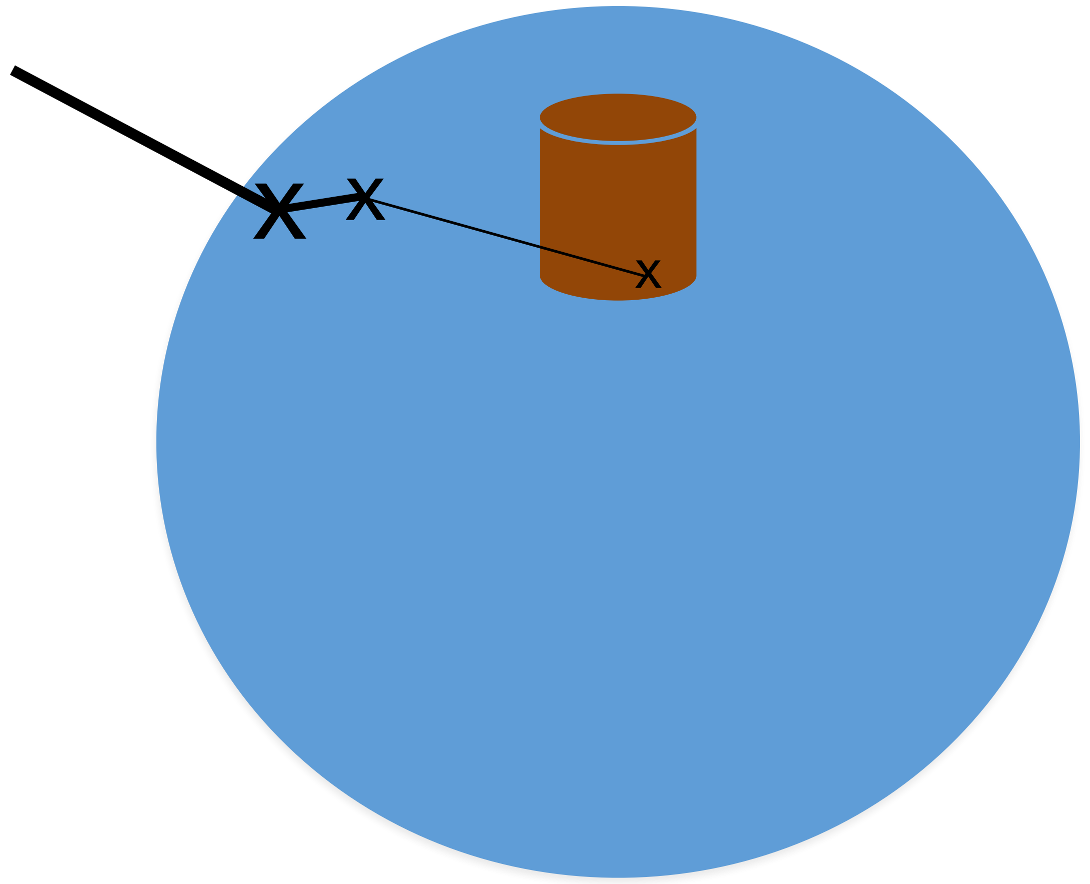
Delorean

2023 BZ

BACK TO THE FUTURE BACKUP SLIDES

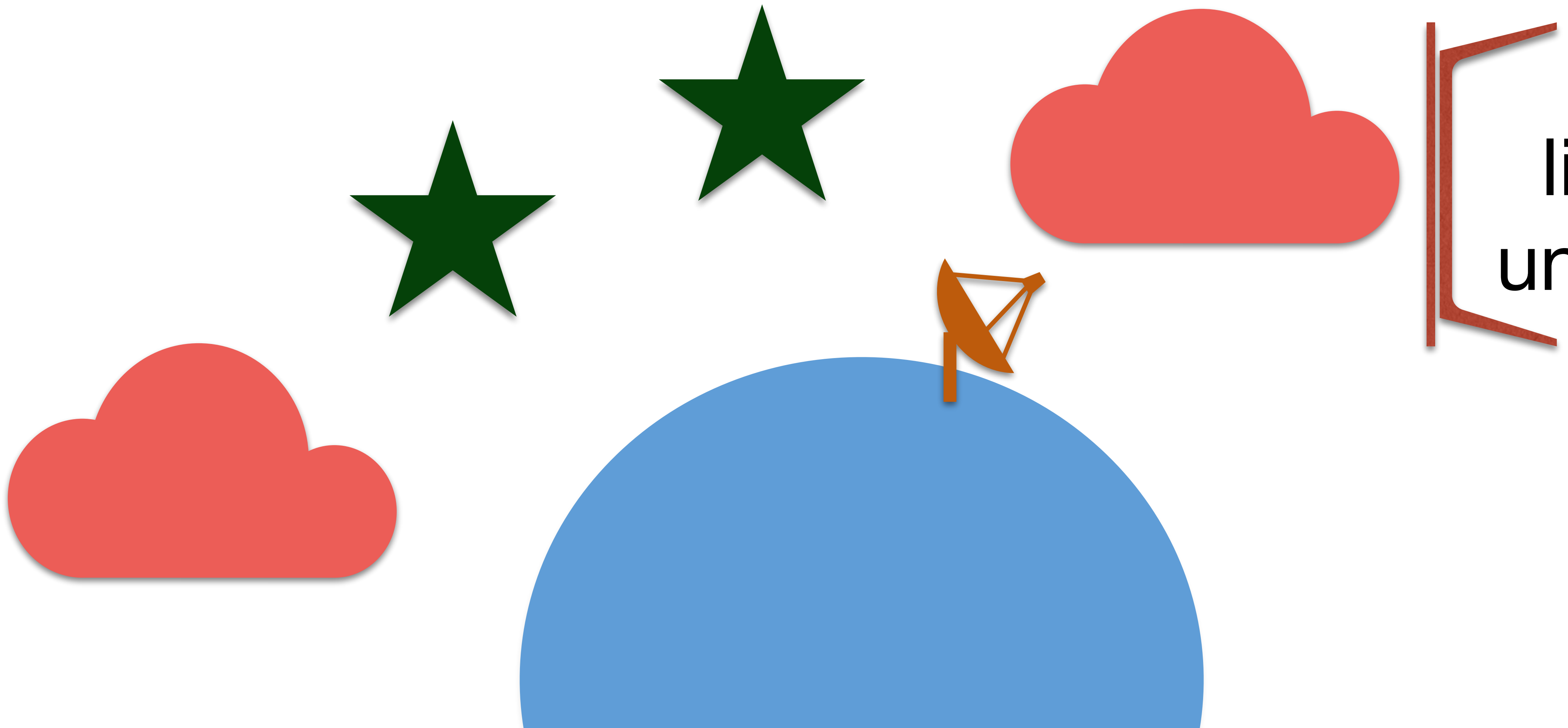
GAS CLOUDS

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



dark matter kinetic energy < recoil threshold

Use detectors in space!



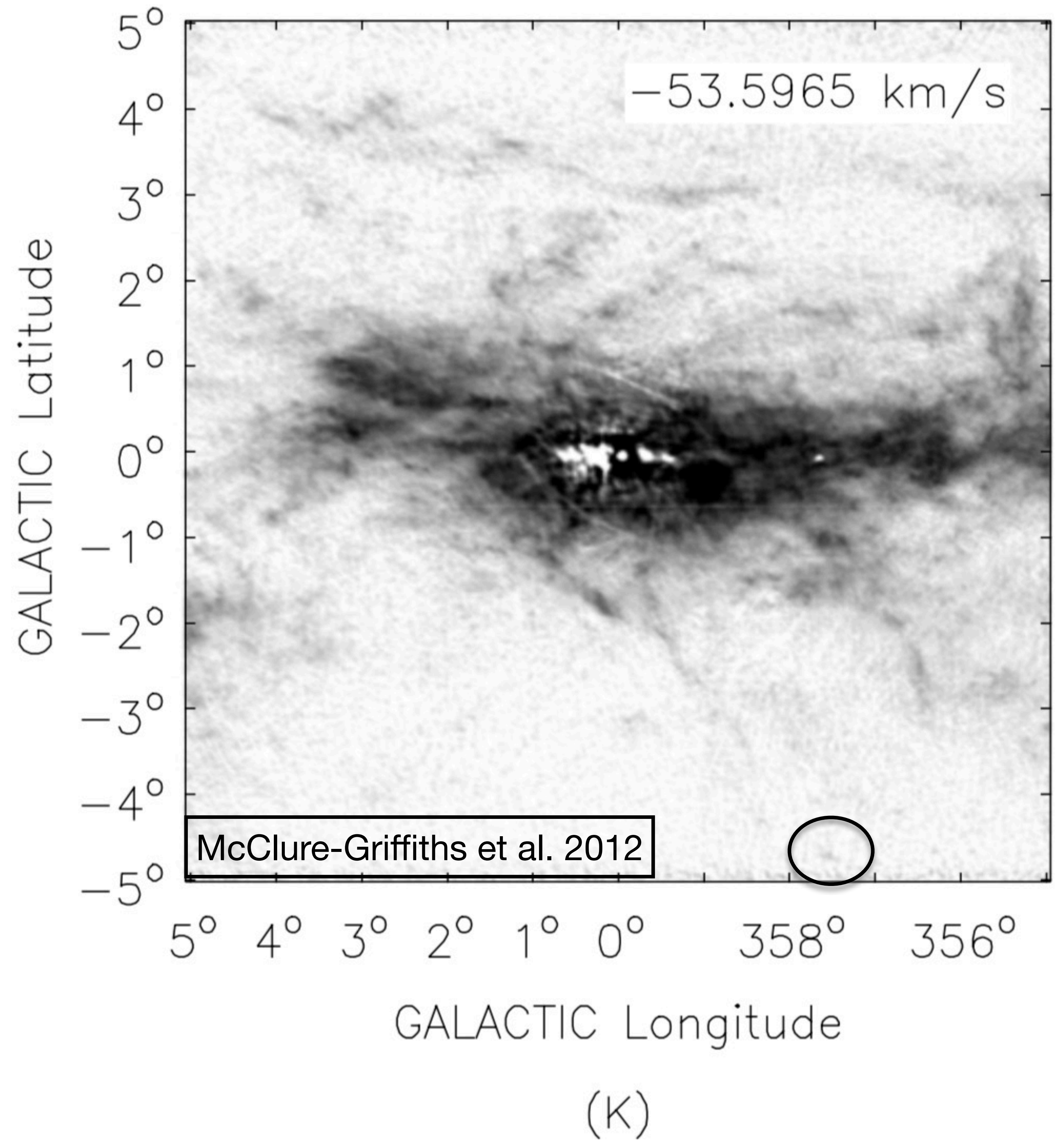
<u>Interstellar gas</u>

big
little overburden
unbound electrons

2010.07240
1812.10919
1806.06857

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

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

Tg ? < 137 K

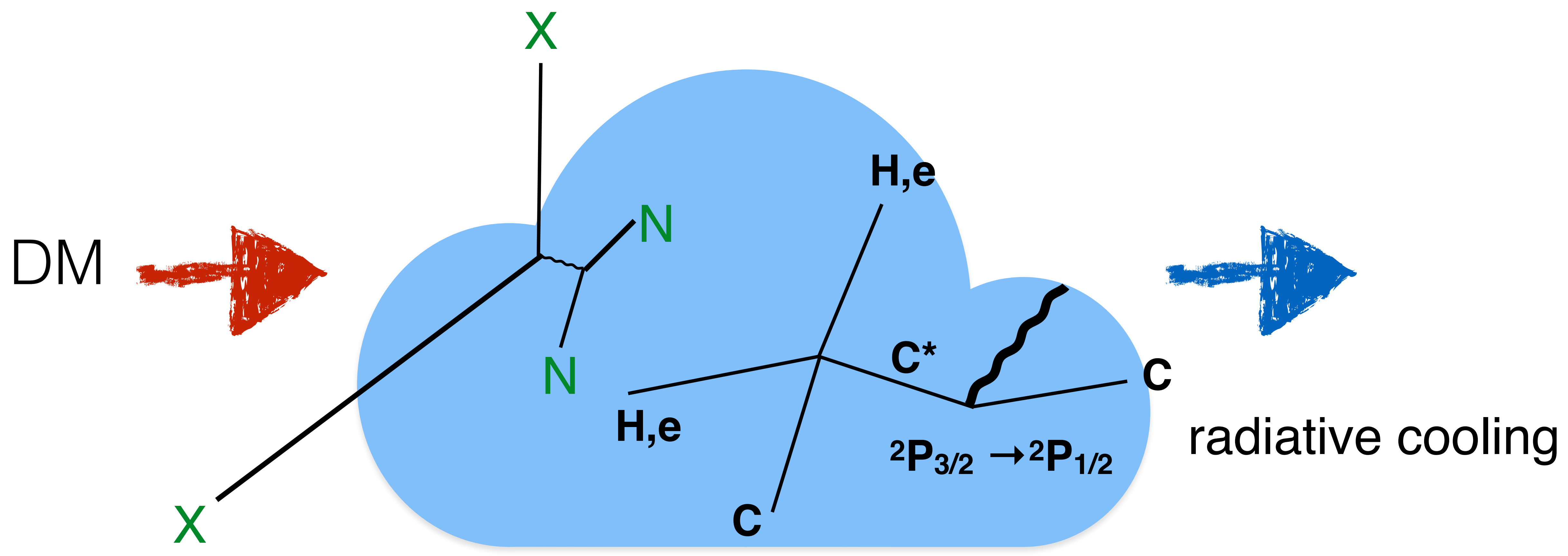
$r_{los} \sim 800$ pc

$v_g = -54$ km/s

5°

(assume spherical cloud)

GAS CLOUD BOUNDS



Conservative: assume all heating by DM

In reality:

(DM +)

cosmic rays

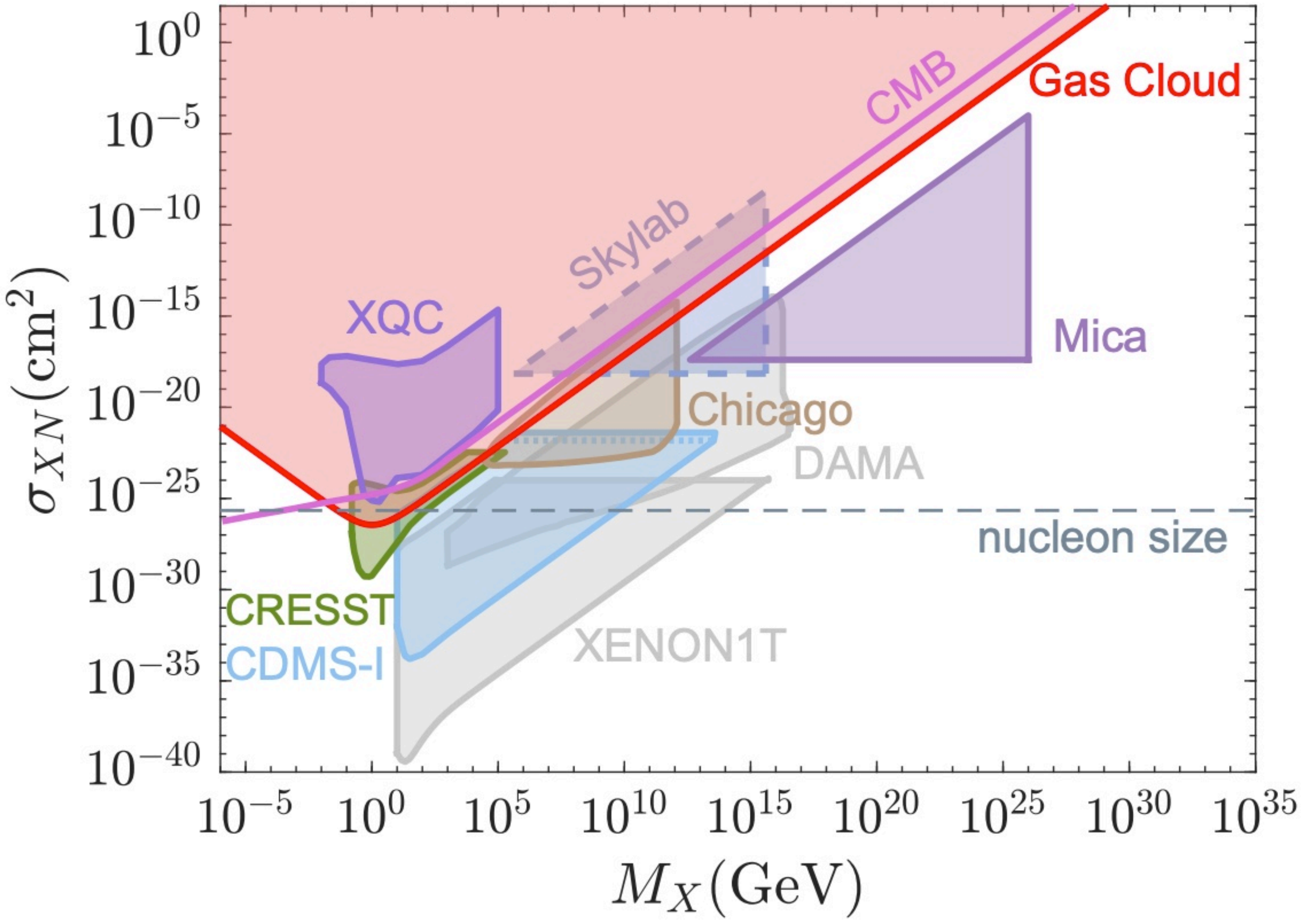
Xray/UV background

photoelectric heating
via dust grains

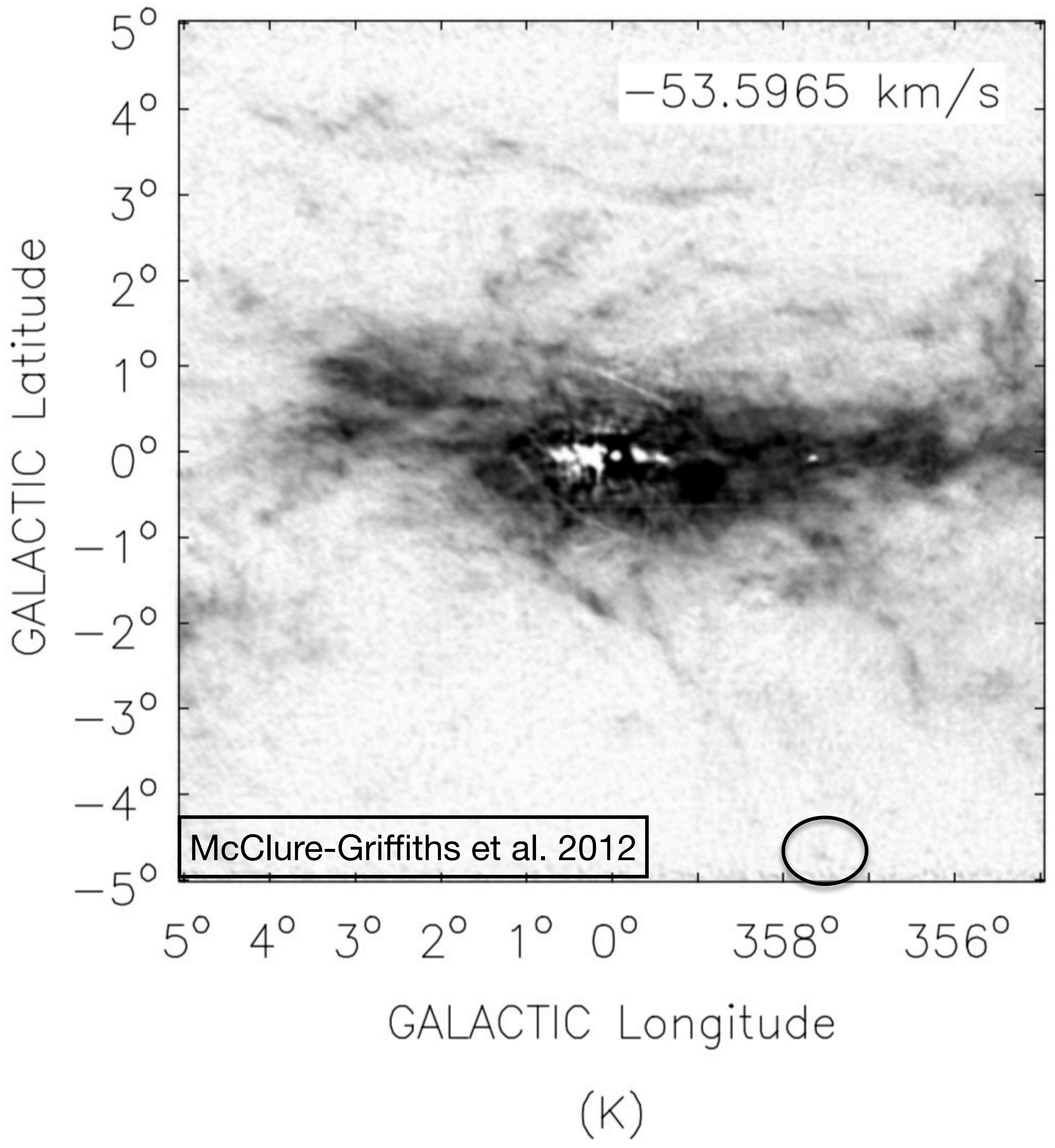
There are known ubiquitous heating sources, like cosmic UV background, cosmic rays, dust grain heating.

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS

- Fixed cross-section for scattering off all nuclei



Gas Cloud 357.8-4.7-55



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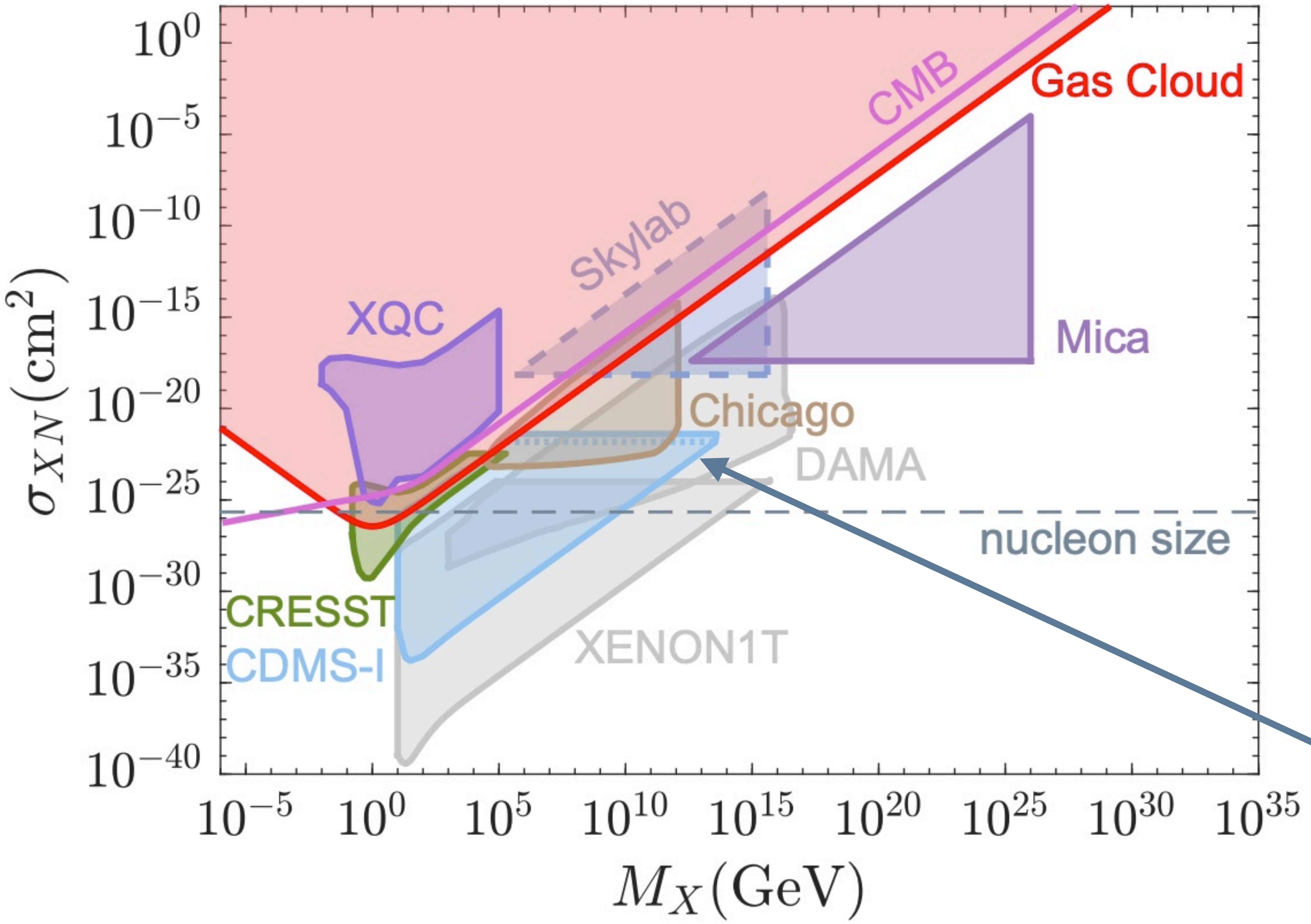
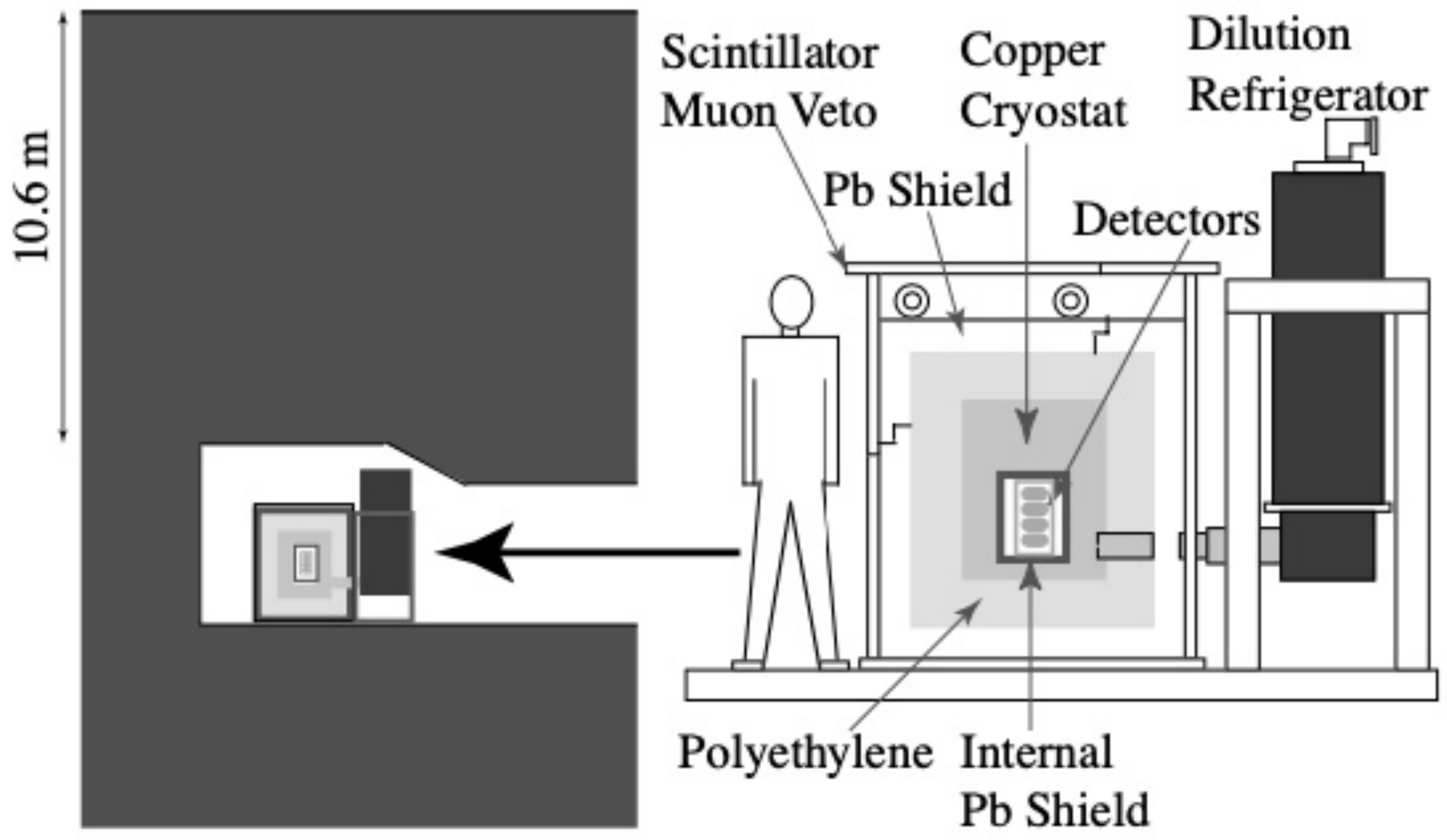
(assume spherical cloud)

Bhoonah, JB, Schon, Song 2010.07240

HEAVY DM IN GAS CLOUD, NUCLEAR INTERACTIONS





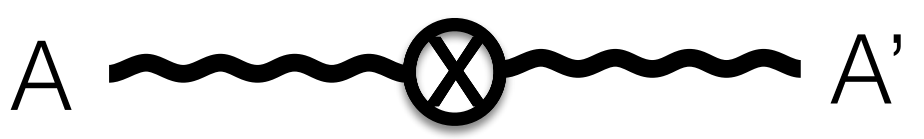
Also update on CDMS-I limit using multi scatter

(Muon veto rejects strong interactions)

2010.07240

HEAVY COMPOSITE DM IN GAS CLOUD, LONG-RANGE INTERACTIONS

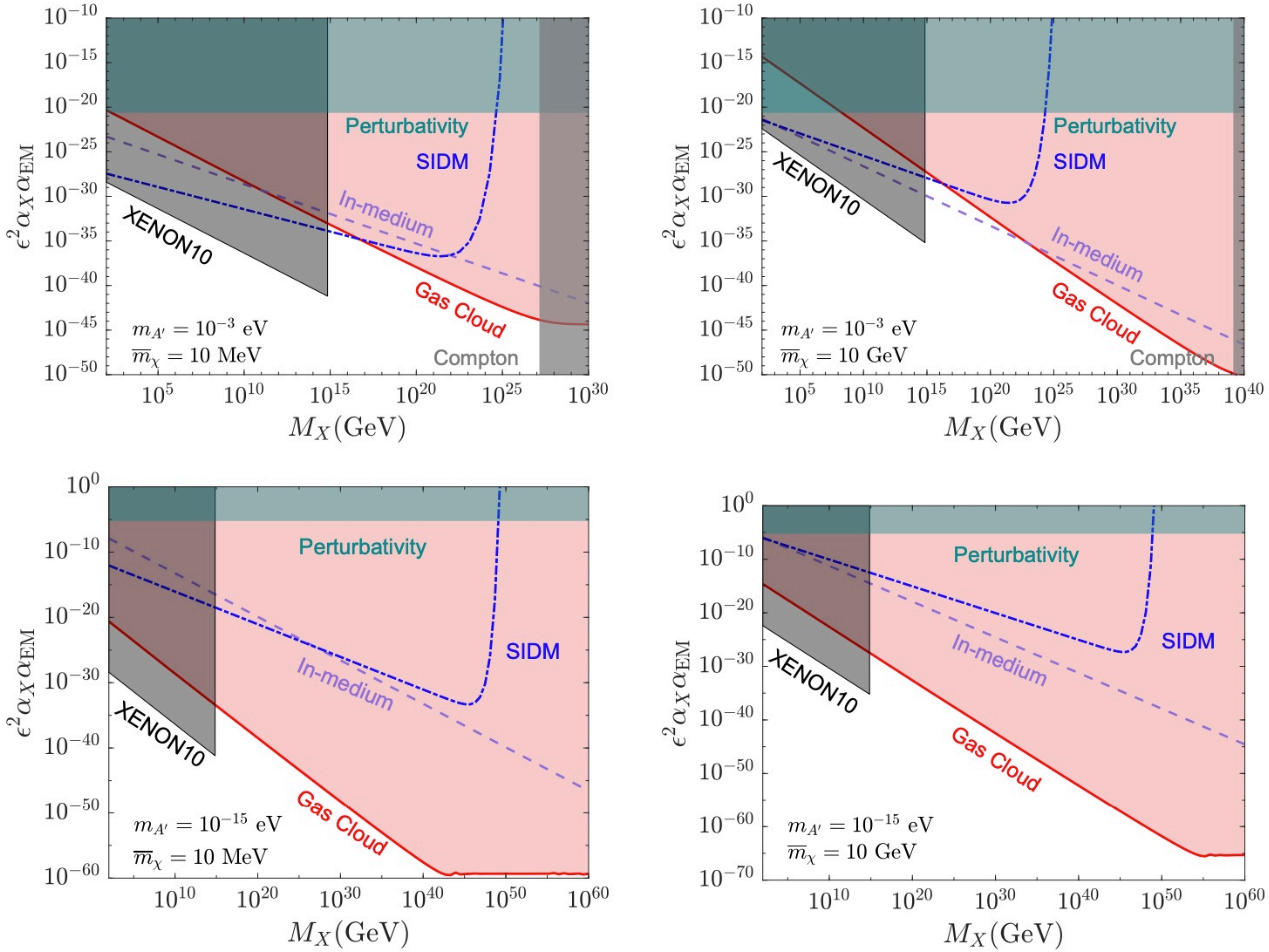
Vector Portal Dark Matter



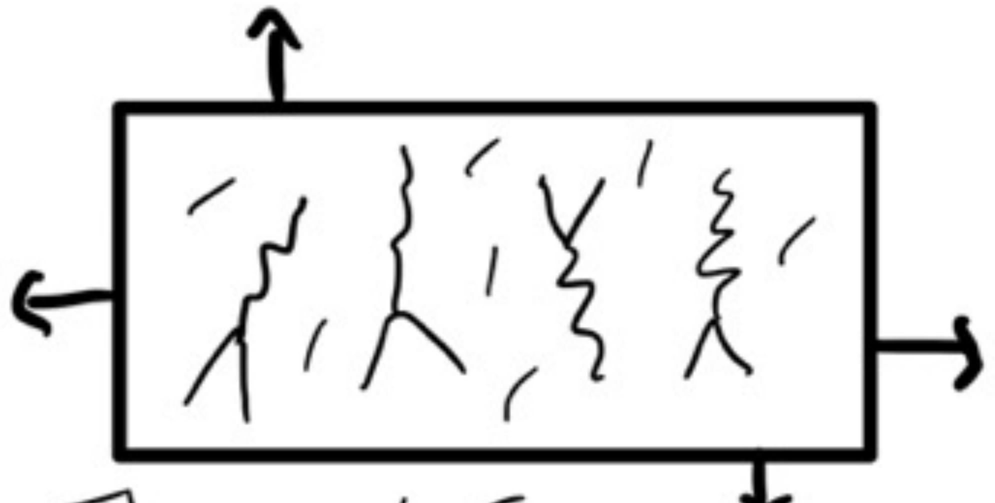
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\kappa}{2} F_{\mu\nu} F'^{\mu\nu} - g_D A'_\mu \bar{\chi} \gamma^\mu \chi$$

Mediator with a mass, can be applied to millicharged in the nearly massless limit.

2010.07240



Weakly interacting dark matter "miracle"



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

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

$$\Omega_x h^2 \propto \frac{x_{FO}}{\sigma_0} \quad | \quad x_{FO} \propto \ln[m_x]$$

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

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

DM Mass Unitarity Limit

Griest, Kamionkowski, '87

1. Assume freeze-out abundance set with annihilation

$$\sigma_0 \sim \text{picobarn} = 10^{-36}\ \text{cm}^2$$

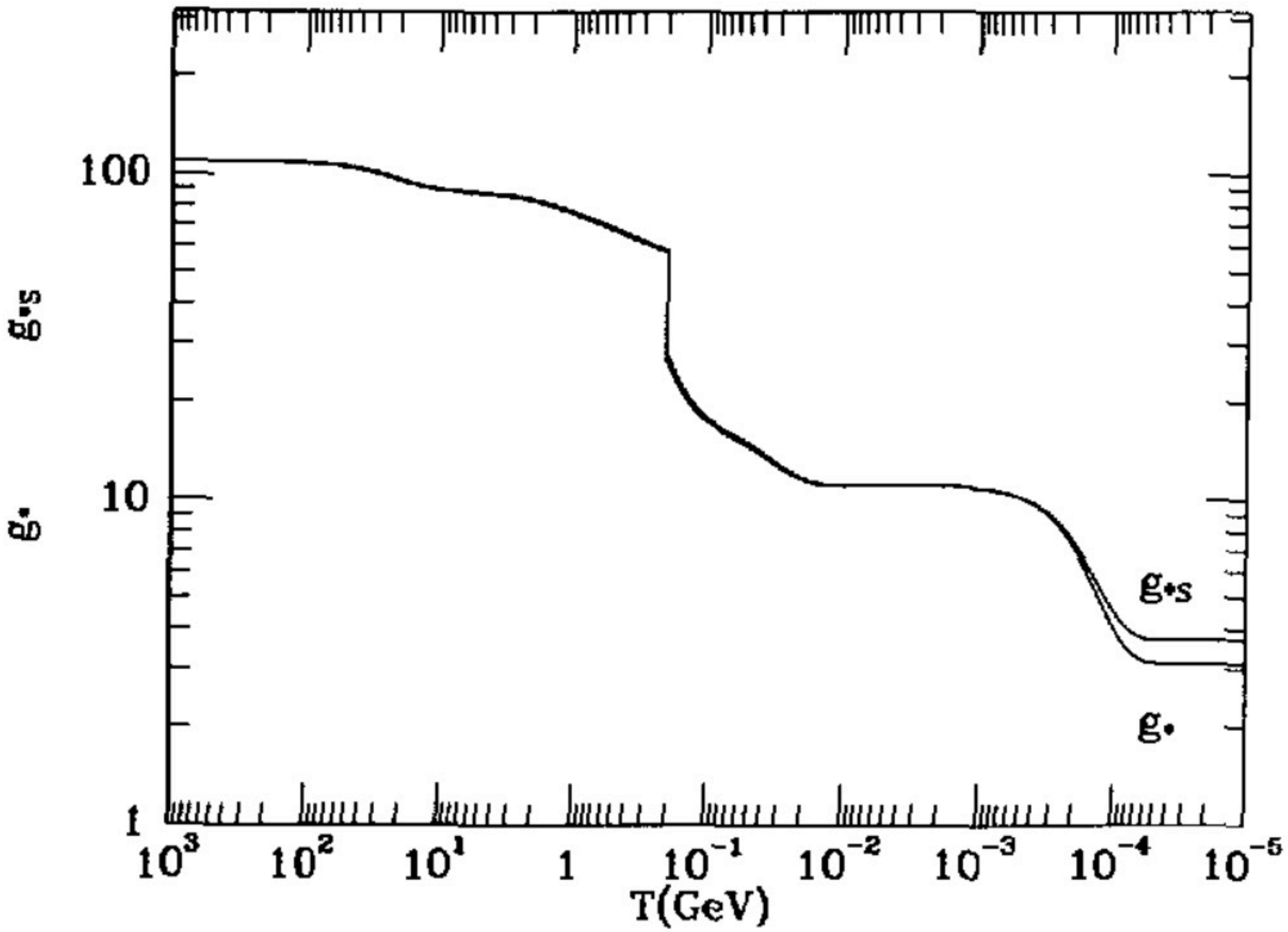
2. Require the annihilation cross-section not exceed a perturbative bound

$$\sigma_0 \lesssim 4\pi/m_{\rm DM}^2$$

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

$$m_{\rm DM} \lesssim 100\ \text{TeV}$$

Unitarity mass limit caveat: Entropy changes in the early universe



Kolb and Turner 1988

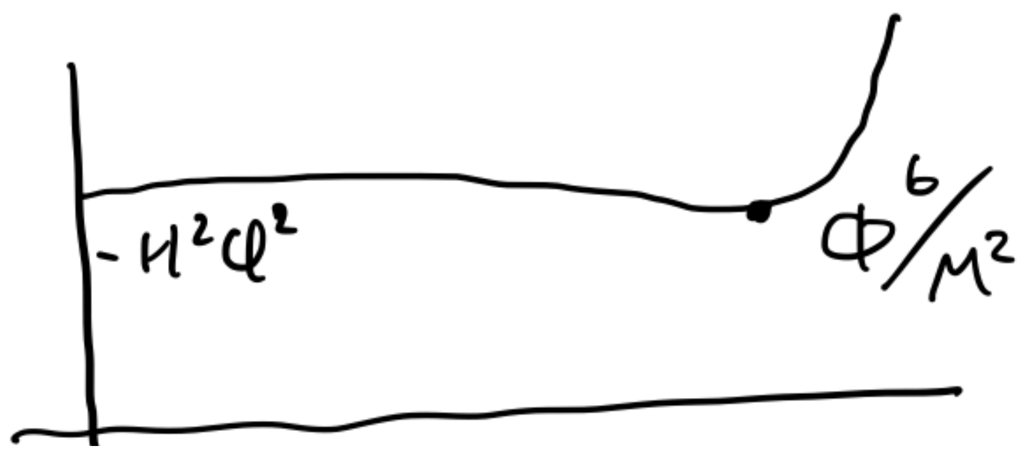
Degrees of Freedom in SM-only Universe

AD Baryogenesis

Afleck, Dine '85
Linde '85
Dine, Randall, Thomas '95

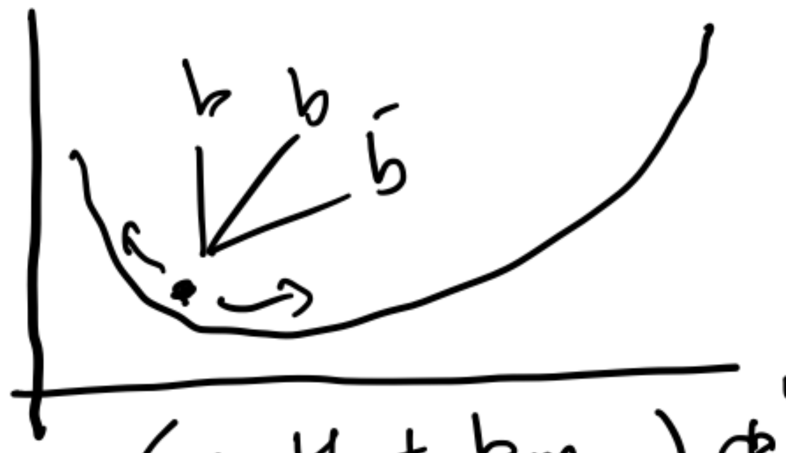
1. Baryo-charged scalar gets vev during inflation

$$V_{AD} = m_\phi^2 |\phi|^2 - H^2 |\phi|^2 + \frac{\phi^6}{M^2} + \not{CP}$$



2. Baryo-charged scalar decays (CP violating)

after inflation $H \lesssim M_\phi$



$$(aH + b m_\phi)\phi^4/M + h.c.$$

AD Baryogenesis

Afleck, Dine '85
Linde '85
Dine, Randall, Thomas '95

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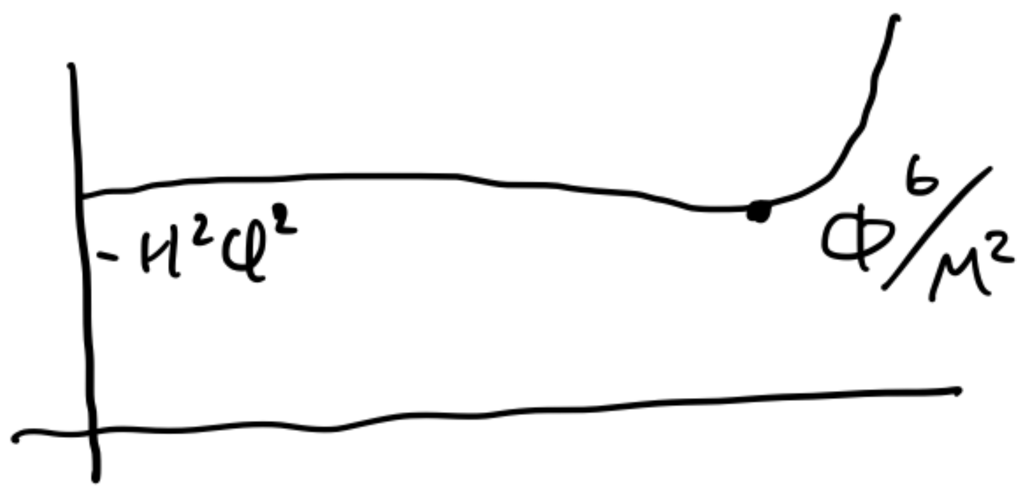

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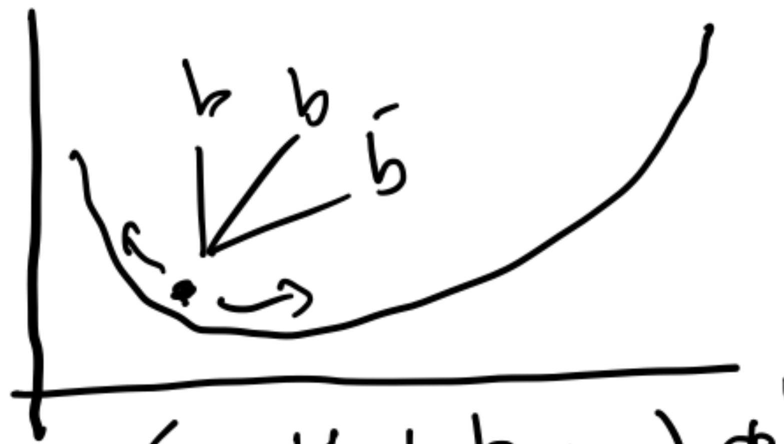
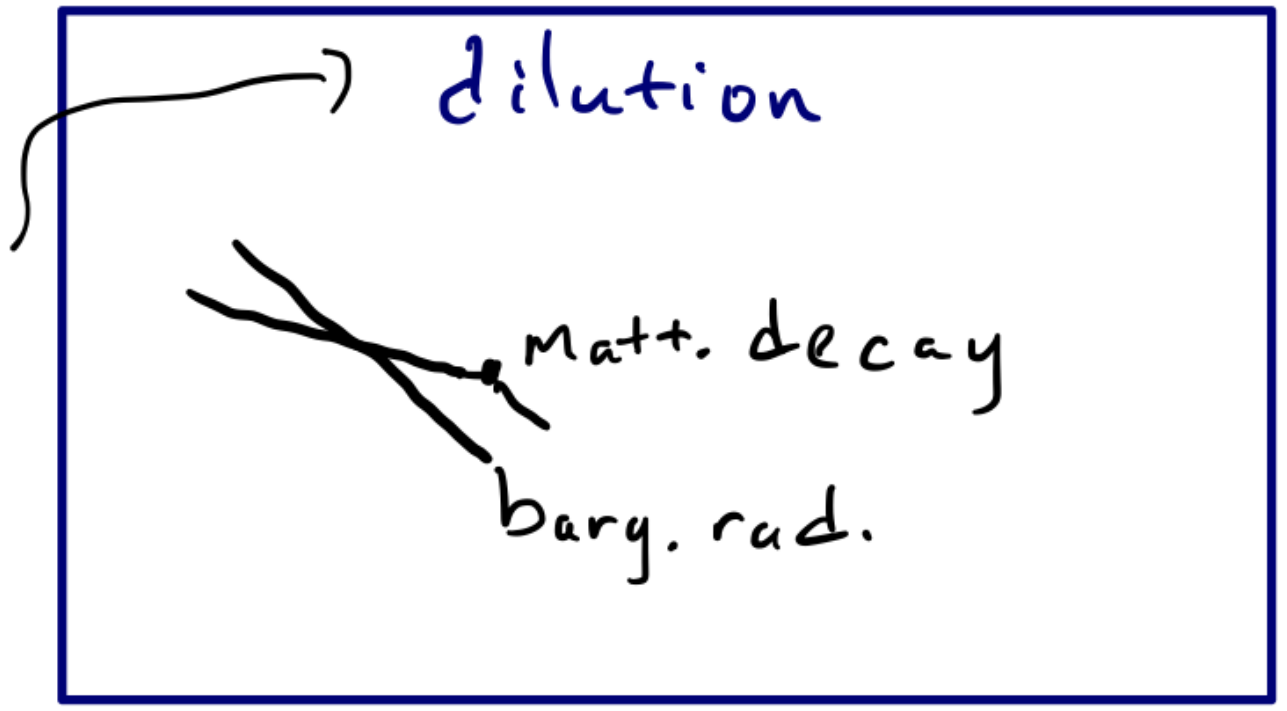


$$(aH + b m_\phi)\,\phi^4/M + h.c.$$

3. Oops! too many baryons, need

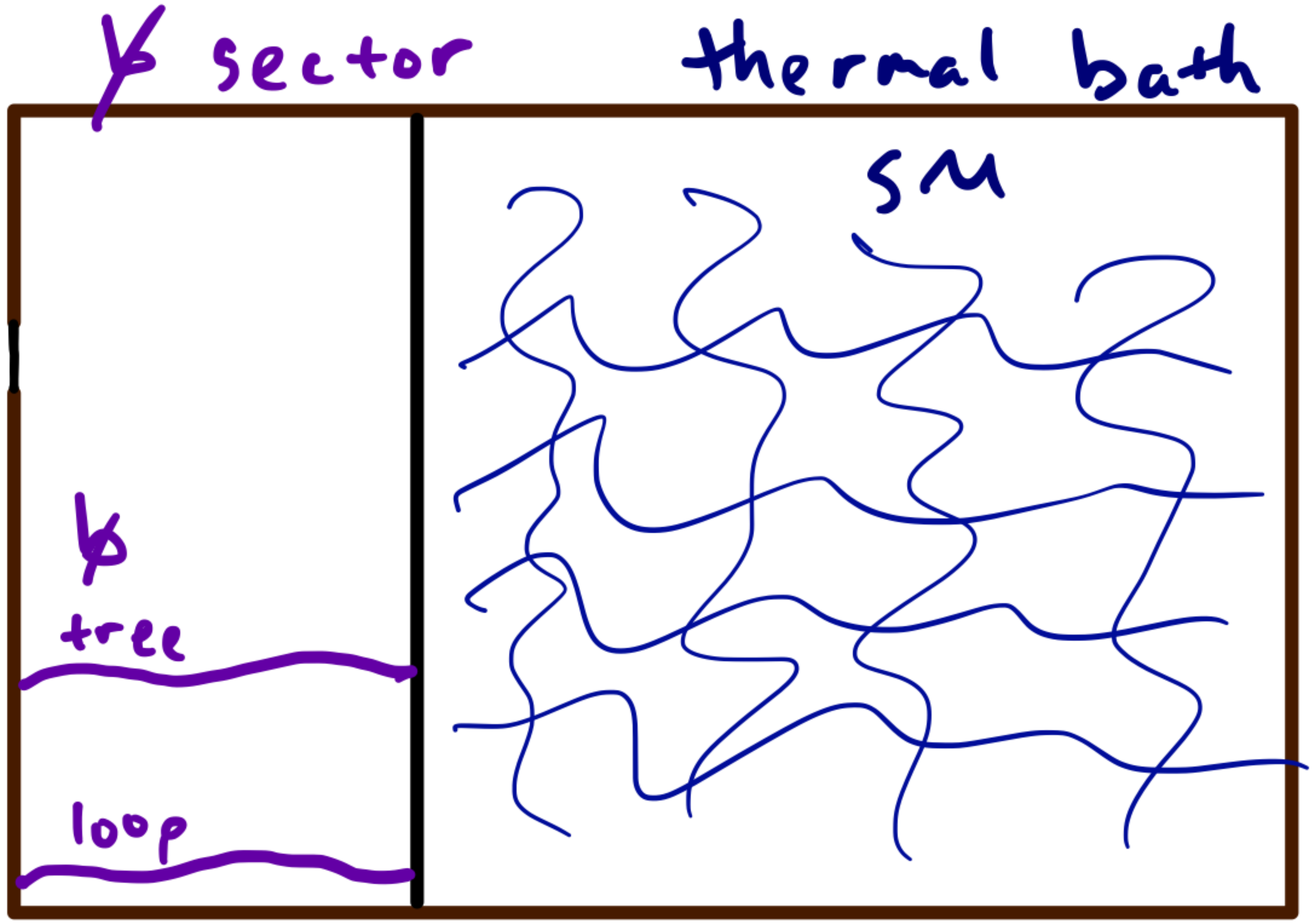


Main point: $\eta_b \sim 1 - 10^{-8}$ for a simple baryo-charged scalar
$\eta_b = 10^{-10}$ observed, need dilution.

Why too many baryons?

If: $\mathcal{O}(1)$ CP violating decays

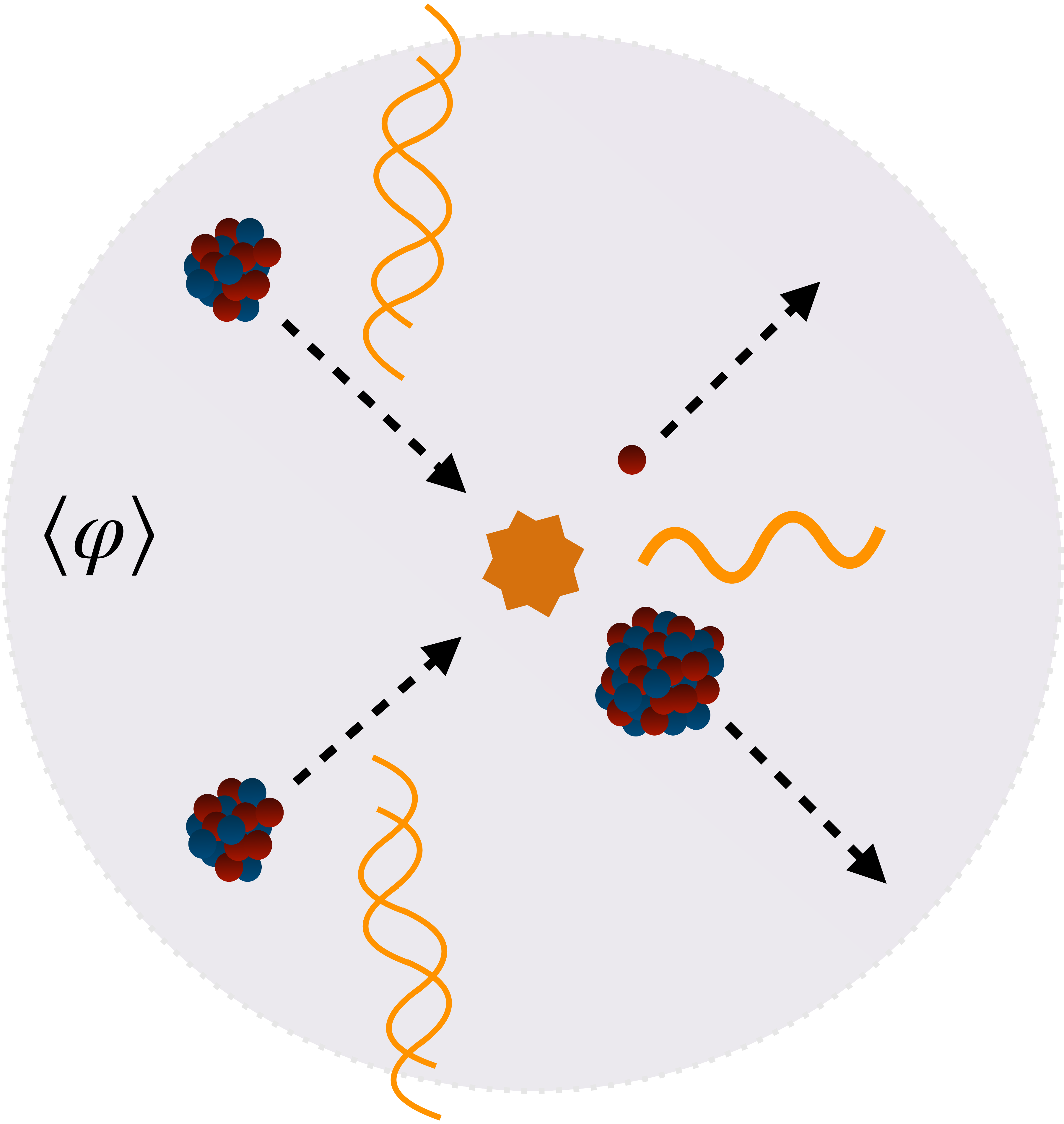
And: $\rho_\phi \sim \rho_u$ ← $\not{b}$ sector



$$\eta_B \simeq \frac{n_b}{\rho_u^{3/4}} \left(\zeta \right)$$

$n_b \sim [10^{-5} - 1]$ for any $\not{b}$ sectors with $\mathcal{O}(1)$ couplings

FOR BIG ENOUGH COMPOSITES

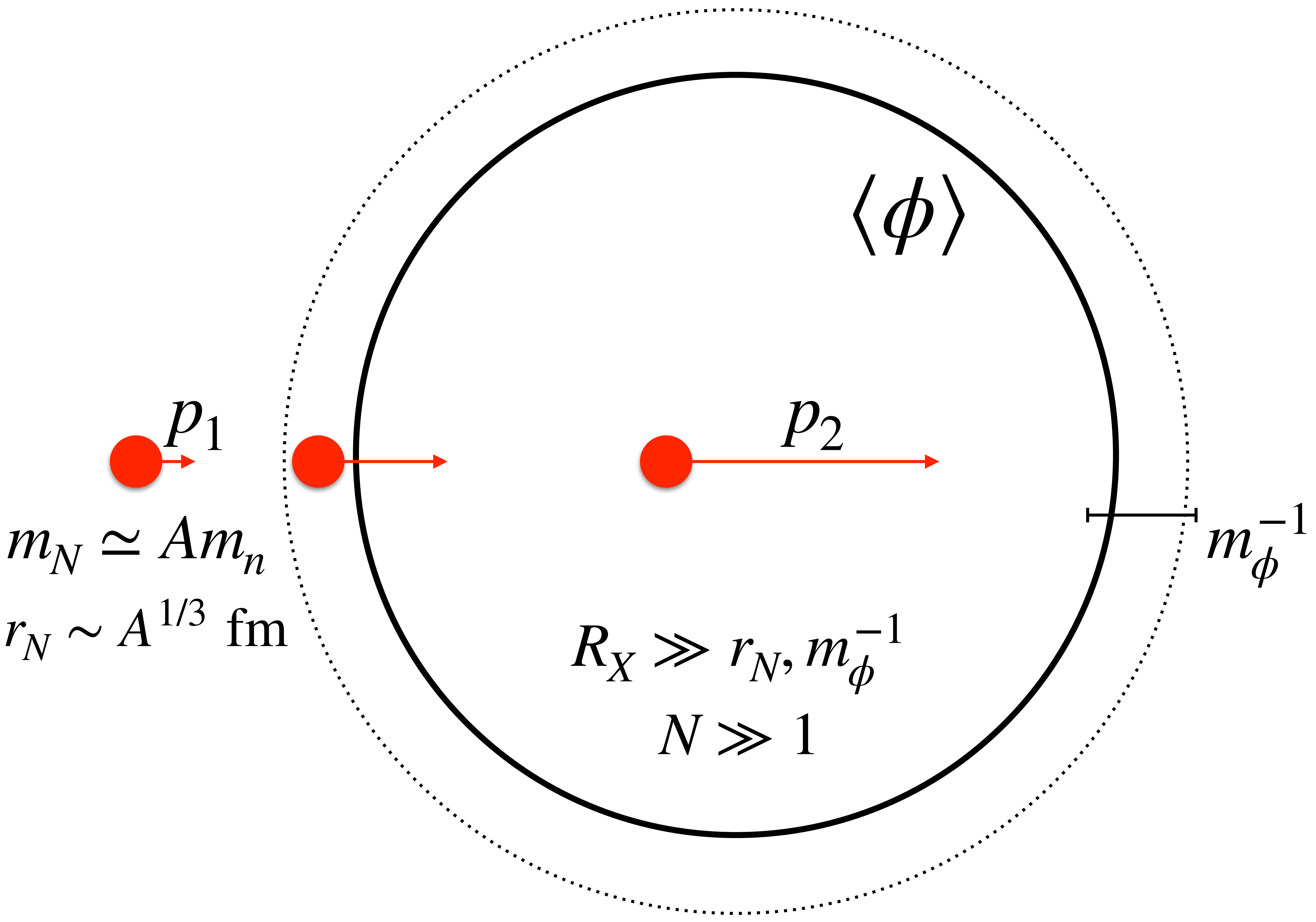


Nuclear fusion and bremsstrahlung inside large dark matter composites

Javier Acevedo, JB, Alan Goodman *2012.10998*

Nuclear coupling

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

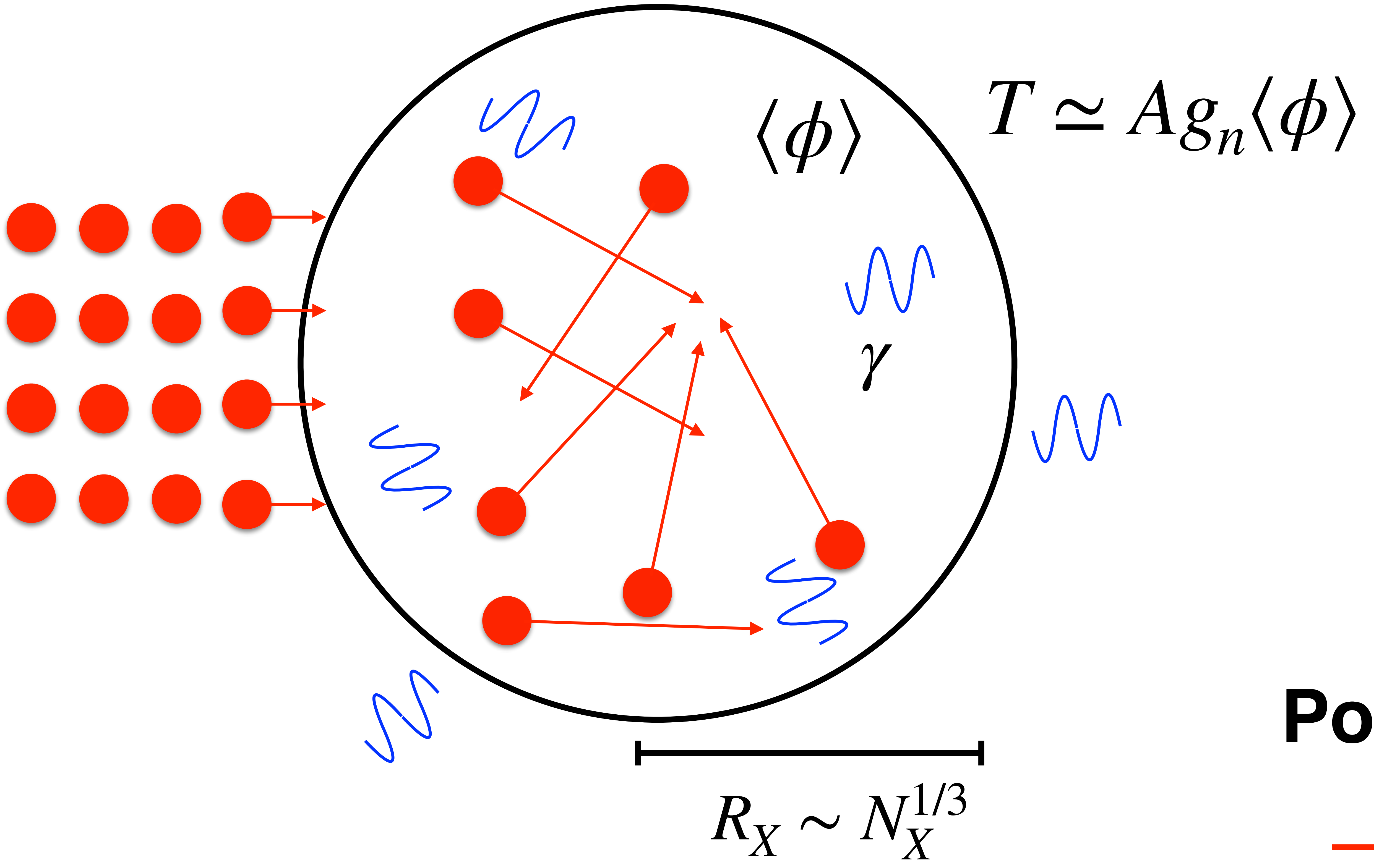


Nuclei will accelerate across the DM composite's boundary layer, because of the attractive potential, like gravity but stronger and shielded:

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

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

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



Ionization (Migdal, collisions)

Thermal bremsstrahlung

Thermonuclear fusion

↓ temperature/energy

Potential signatures of this effect?

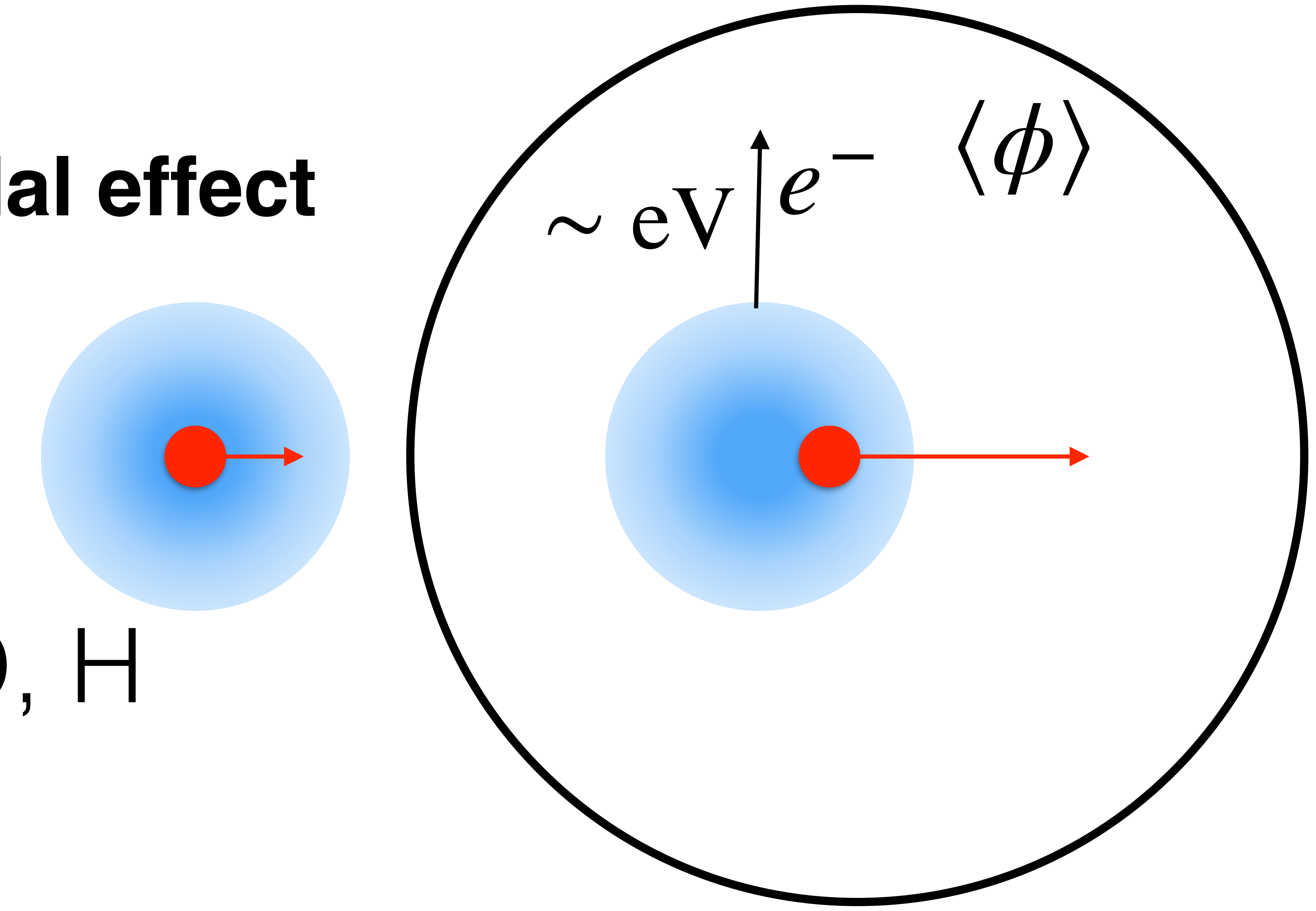
⟶ Direct detection

⟶ Type Ia supernovae

1) Ionization

$R_X m_\phi \gg 1$

Migdal effect



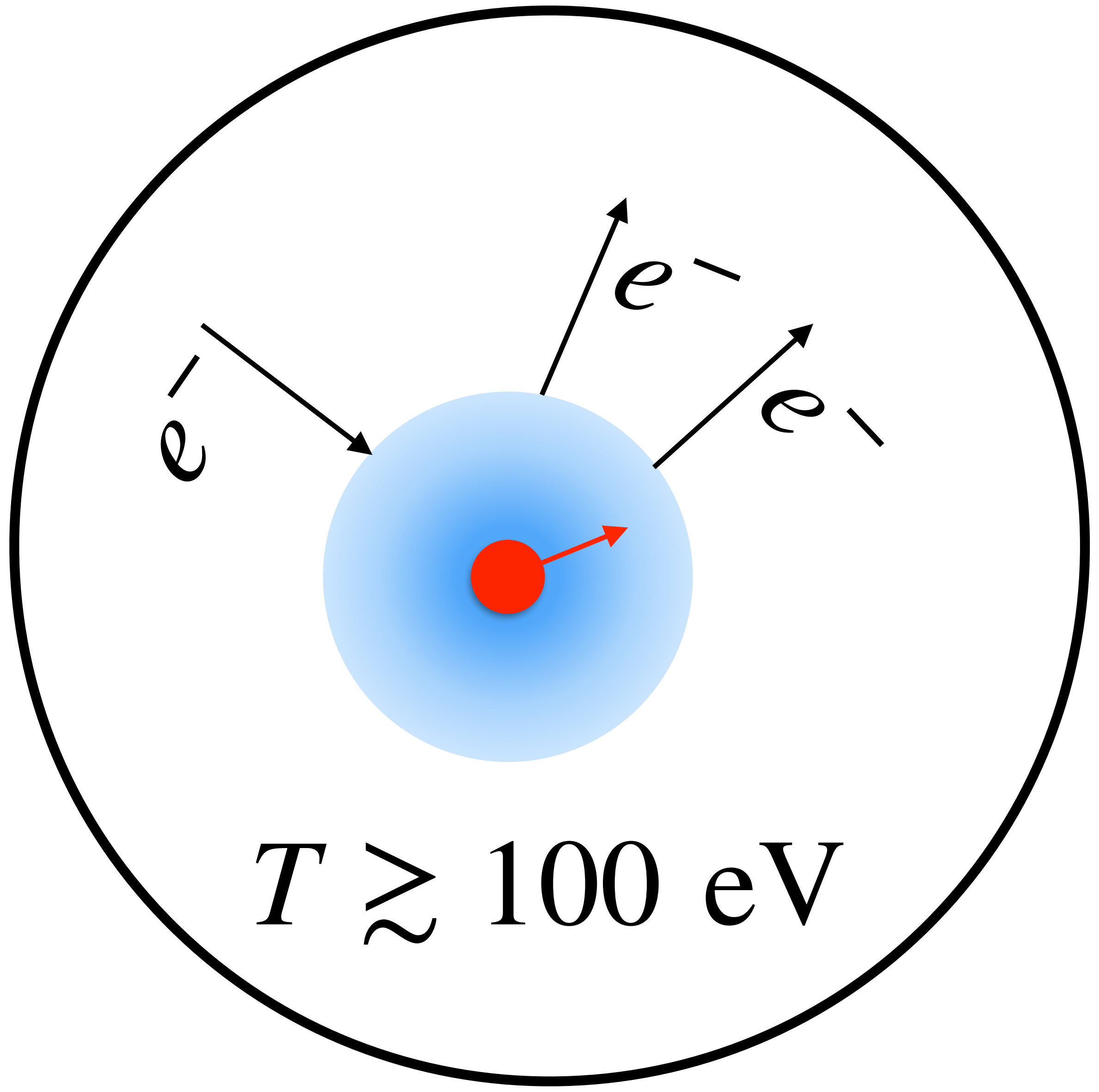
C, O, H

acceleration timescale:

$$\tau_{accel} \simeq (m_\phi v_X)^{-1} \left(1 + \frac{2V_n}{m_N v_X^2}\right)^{-\frac{1}{2}} \lesssim 10^{-18}\ \mathrm{s} \left(\frac{10\ \mathrm{keV}}{m_\phi}\right)$$

electrons are unbound w/ prob $f_e \gtrsim 10^{-2}$

Collisional ionization



ionization from e- impacts:

$$\left(f_e n_e v_N \sigma_i\right)^{-1} \lesssim 10^{-15}\ \mathrm{s}$$

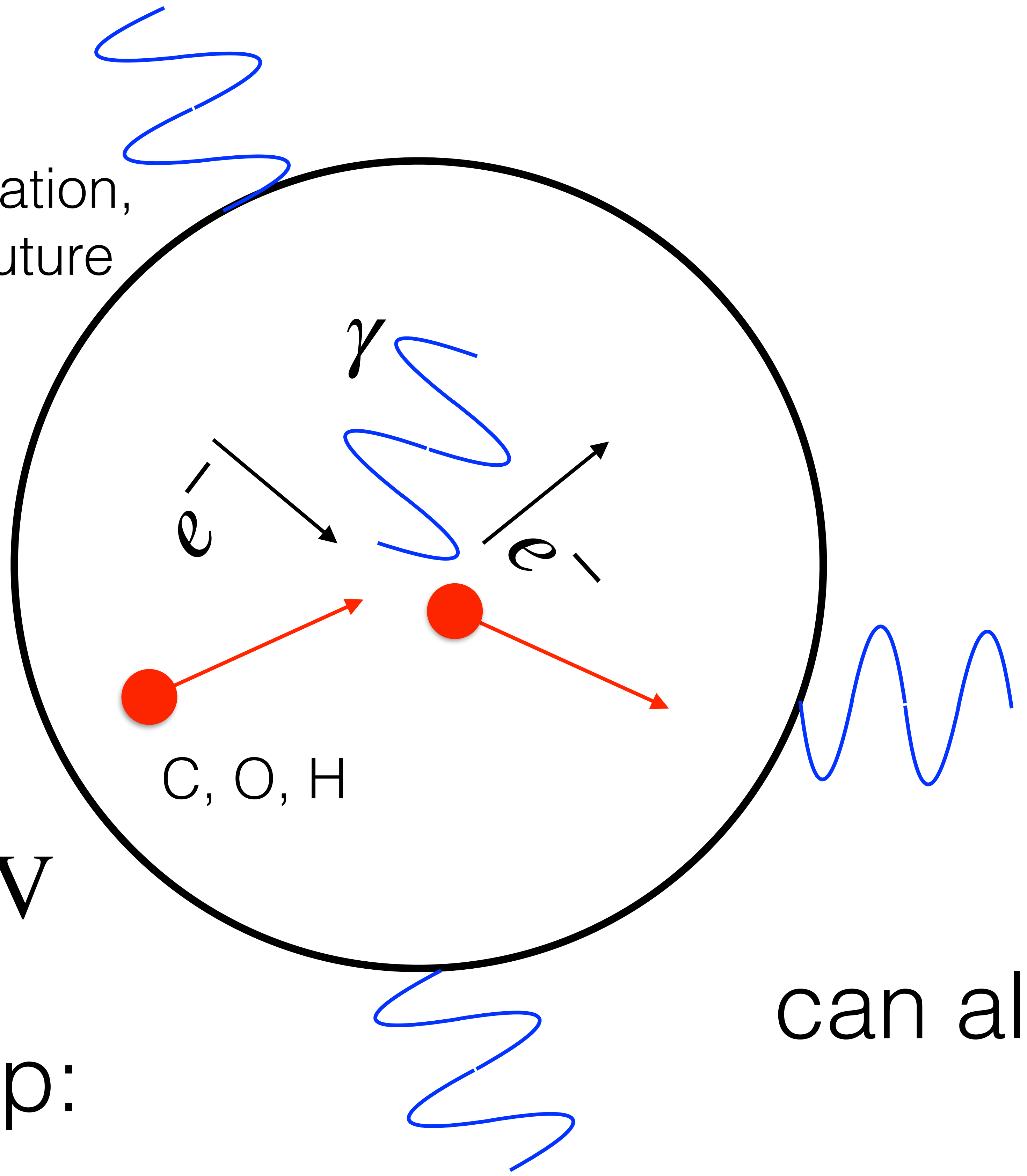
$n_e \sim 10^{23}\ \mathrm{cm}^{-3}$

$\sigma_i \gtrsim 10^{-17}\ \mathrm{cm}^2$

$T \gtrsim 100$ eV → ionized composite interior

2) Bremmsstrahlung

radiative recombination, line emission for future work



$T \gtrsim 100$ eV

photon mfp:

$$(n_e \sigma_T)^{-1} \simeq 5 \text{ cm} \gg R_X$$

$$\sigma_T \simeq 10^{-24} \text{ cm}^2$$

radiated energy rate for plasma:

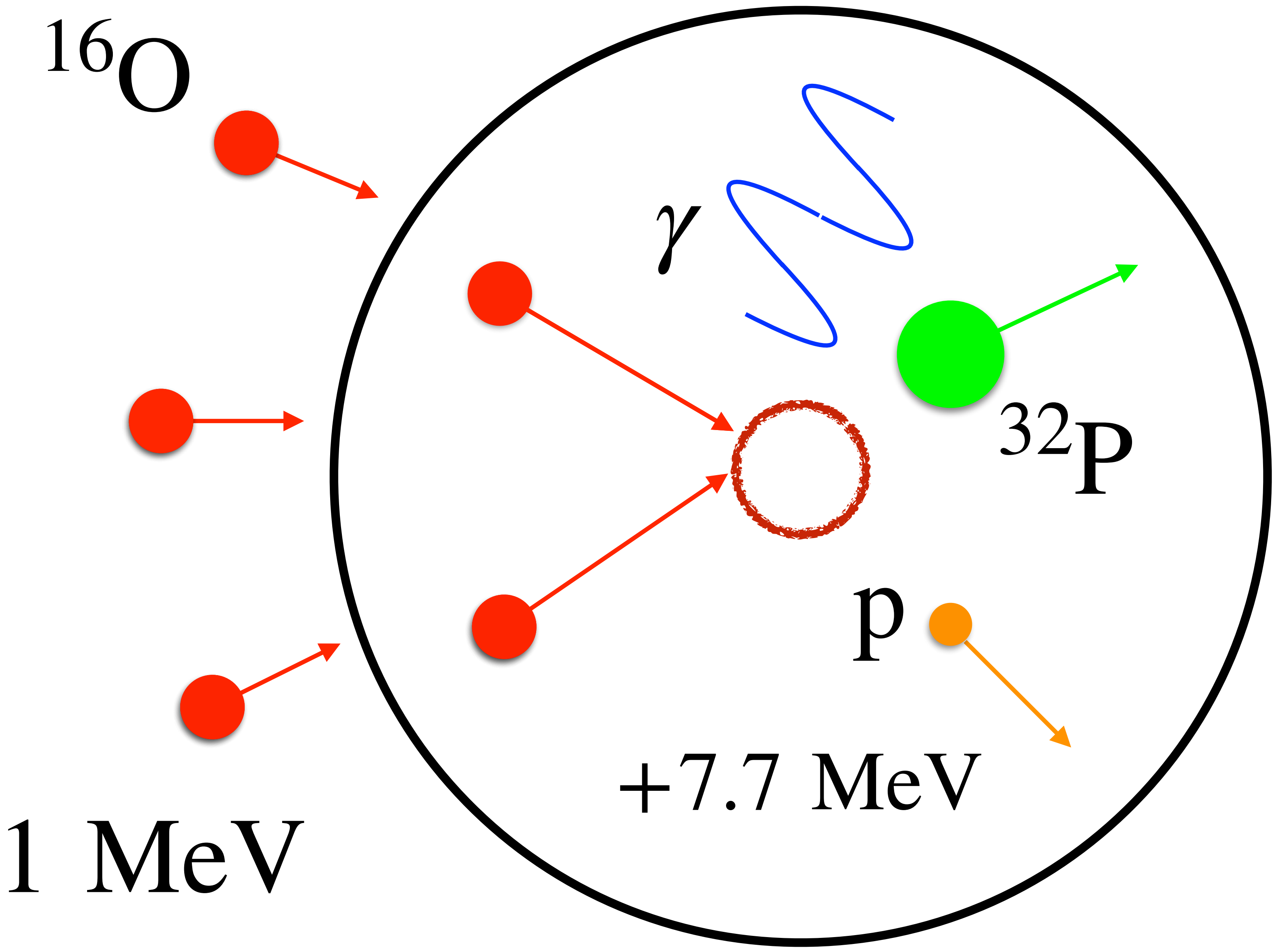
$$\dot{E}_{brem} = \int j_\omega(T)\, d\omega dV \simeq$$

$$\simeq 10^{10} \text{ GeV s}^{-1} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{R_X}{\text{nm}}\right)^3 \left(\frac{g_\phi}{1}\right)^{-\frac{1}{2}} \left(\frac{g_n}{10^{-10}}\right)^{\frac{1}{2}}$$

can also compute stopping length:

$$L_{stop} \simeq 2 \text{ km} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{10 \text{ keV}}\right)^2 \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{g_\phi}{1}\right)^{-\frac{3}{2}} \left(\frac{v_X}{200 \text{ km s}^{-1}}\right)^3$$

3) Fusion



$T \gtrsim 1$ MeV

reaction rate per unit volume:

$$R_{th}(T \simeq \text{MeV}) \sim 10^{24}\ \text{cm}^{-3}\ \text{s}^{-1} \left(\frac{\rho}{1\ \text{g cm}^{-3}}\right)^2$$

Caughlan & Fowler, 1988

average energy release: $\bar{Q} \sim 10$ MeV

rare to occur while in detection volume:

more complete reaction network left for future work

(e.g. disintegration/recapture)

SNO+ too small $\longrightarrow$ $M_X \lesssim 10^{22}$ GeV

IceCube requires $T \gtrsim 5$ MeV $\longrightarrow$ ~1 reaction per crossing

Direct detection signatures

bremsstrahlung + fusion requires
a few nuclei per composite

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

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

~1 detectable DM event per year requires: $\dfrac{\rho_X v_X A_{det} t_{exp}}{M_X} \simeq 1$

$$M_X^{max} \simeq \rho_X v_X A_{det} t_{exp} \longrightarrow M_X^{max} \simeq 10^{18} \text{ GeV}$$

$\rho_X \simeq 0.3 \text{ GeV cm}^{-3}$

$v_X \simeq 220 \text{ km s}^{-1}$

$t_{exp} \sim 10 \text{ yrs}$

e.g. Xenon
Lux
PandaX

Need $A_{det} \gtrsim 10^6 \text{ cm}^2$ $\longrightarrow$ neutrino obs., e.g. IceCube, SNO+

1812.09325

Where in parameter space do these experiments have sensitivity?

To trigger detectors:

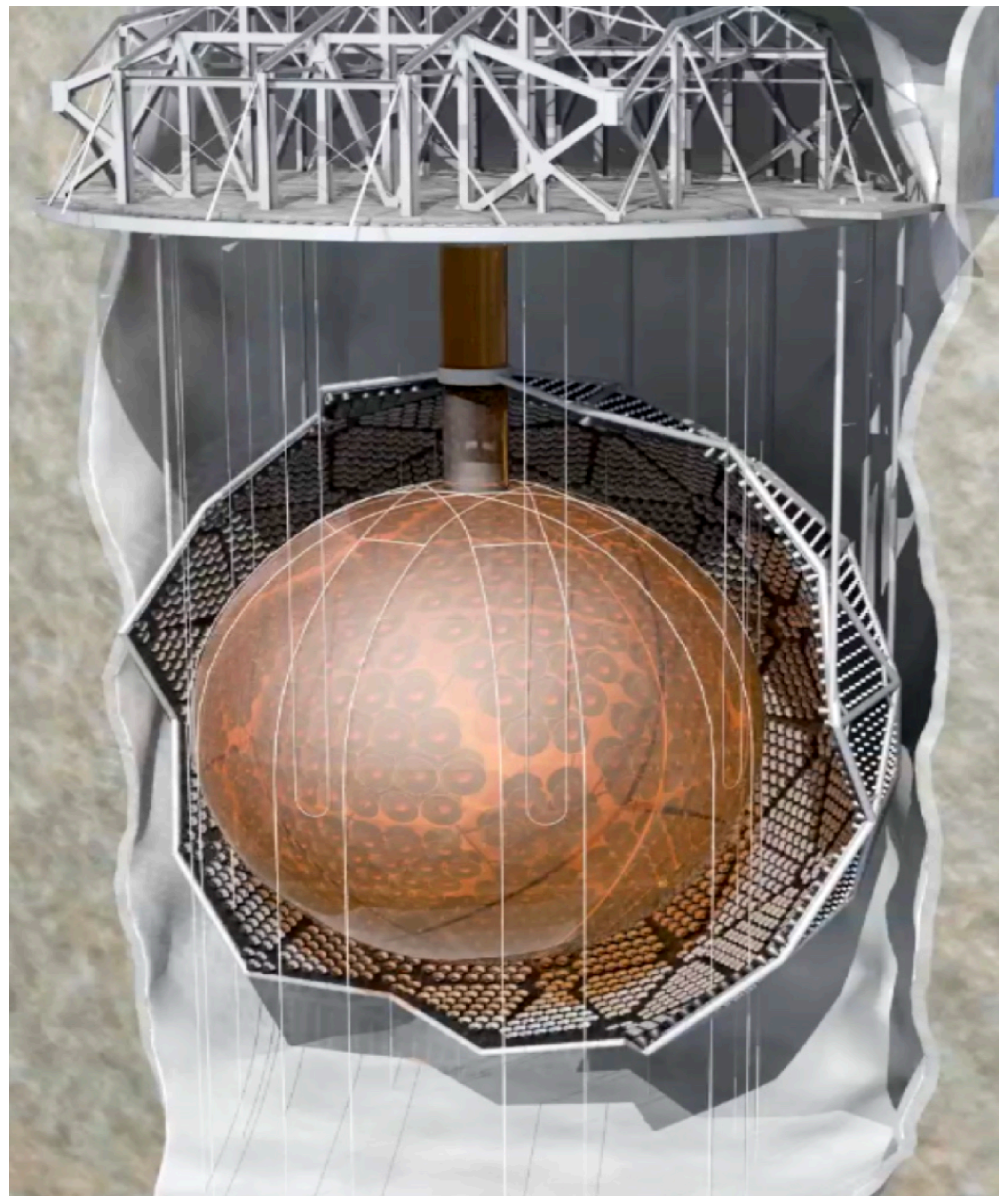
SNO+: ~1 MeV per 100 ns

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

Composites radiate continuously along path:

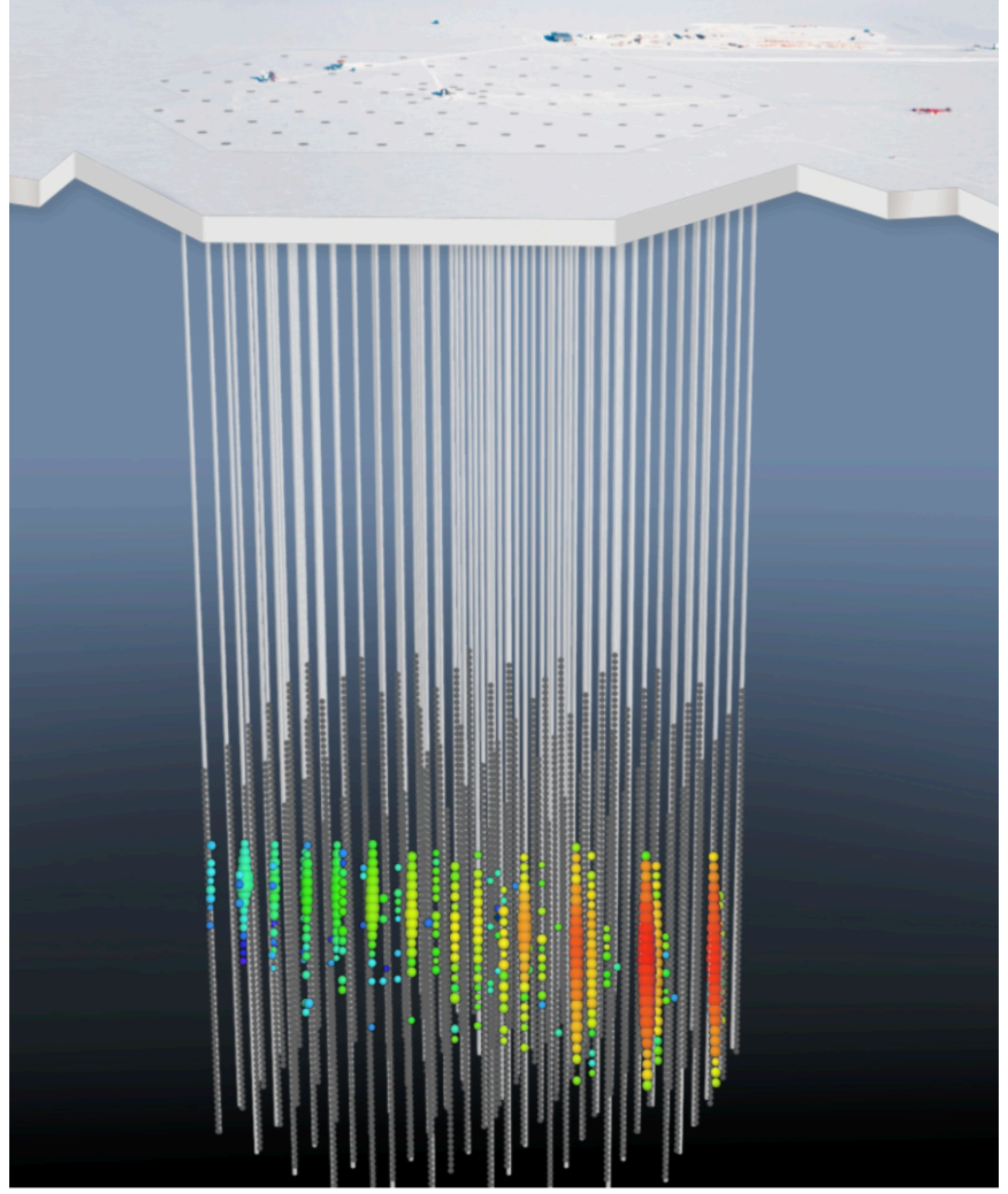
$$\dot{E}_{SNO+} \simeq 10^4 \text{ GeV s}^{-1} \qquad \dot{E}_{IC} \simeq 10^{11} \text{ GeV s}^{-1}$$

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



~12 m

SNO+

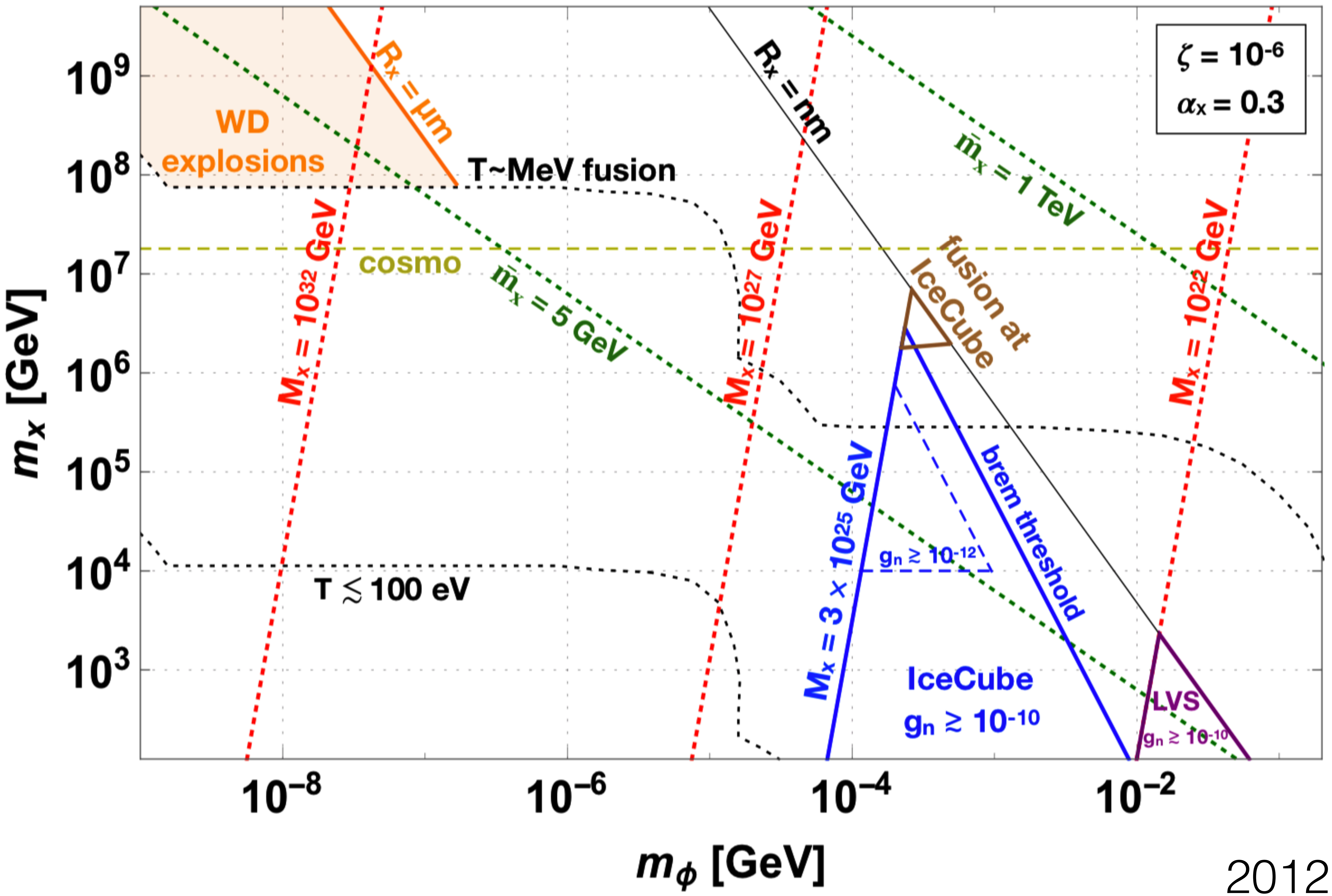


~1 km

IceCube

Parameter space for detection:

2012.10998

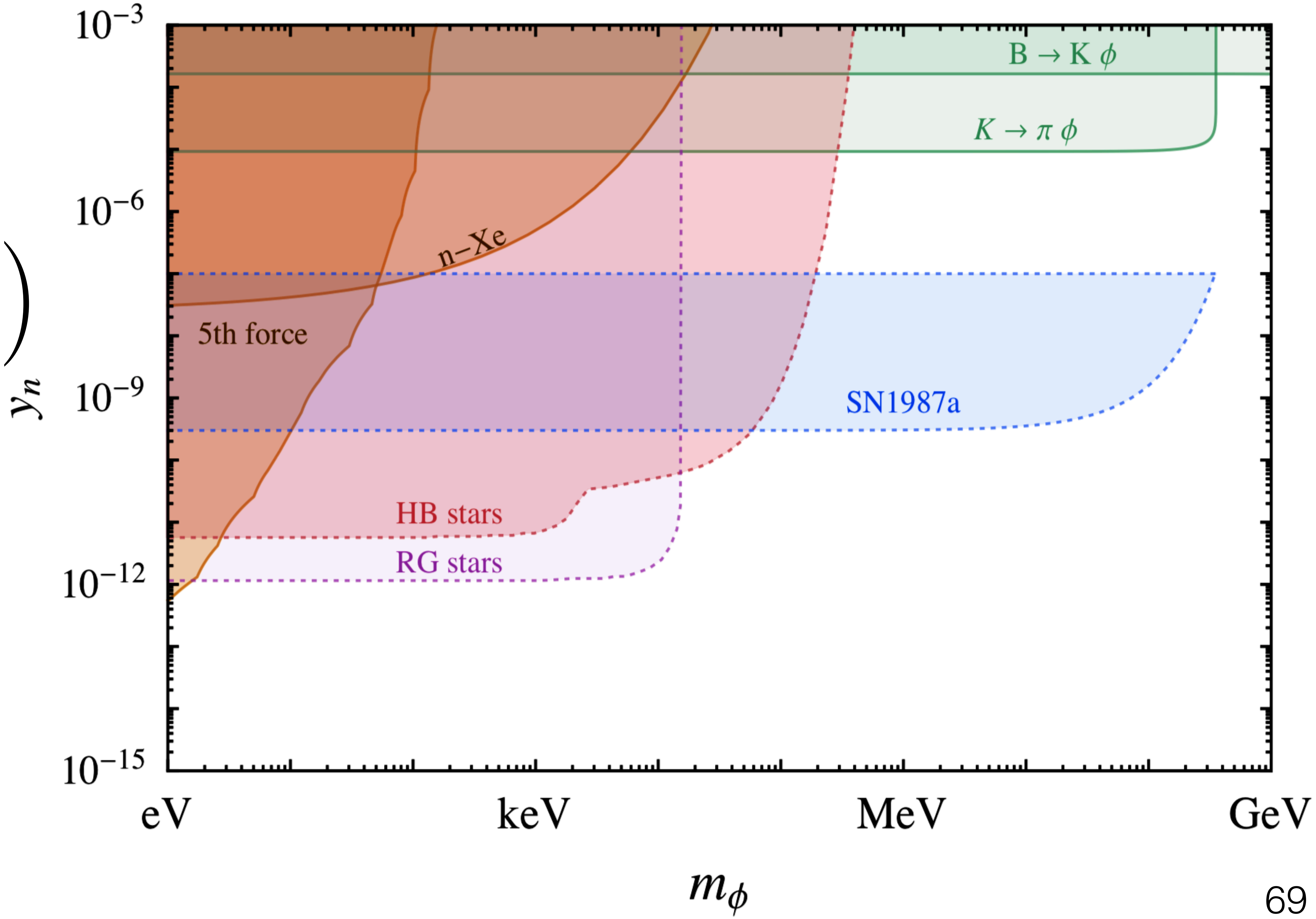


2012.10998

1611.05852
1709.07882

Stellar cooling bounds on coupling limit the kinetic energy:

$$\Delta E \simeq A g_n \left(\frac{m_X}{g_\phi}\right)$$
$$\lesssim \text{keV} \left(\frac{g_n}{10^{-10}}\right)\left(\frac{m_X}{\text{TeV}}\right)\left(\frac{1}{g_\phi}\right)\left(\frac{A}{10}\right)$$



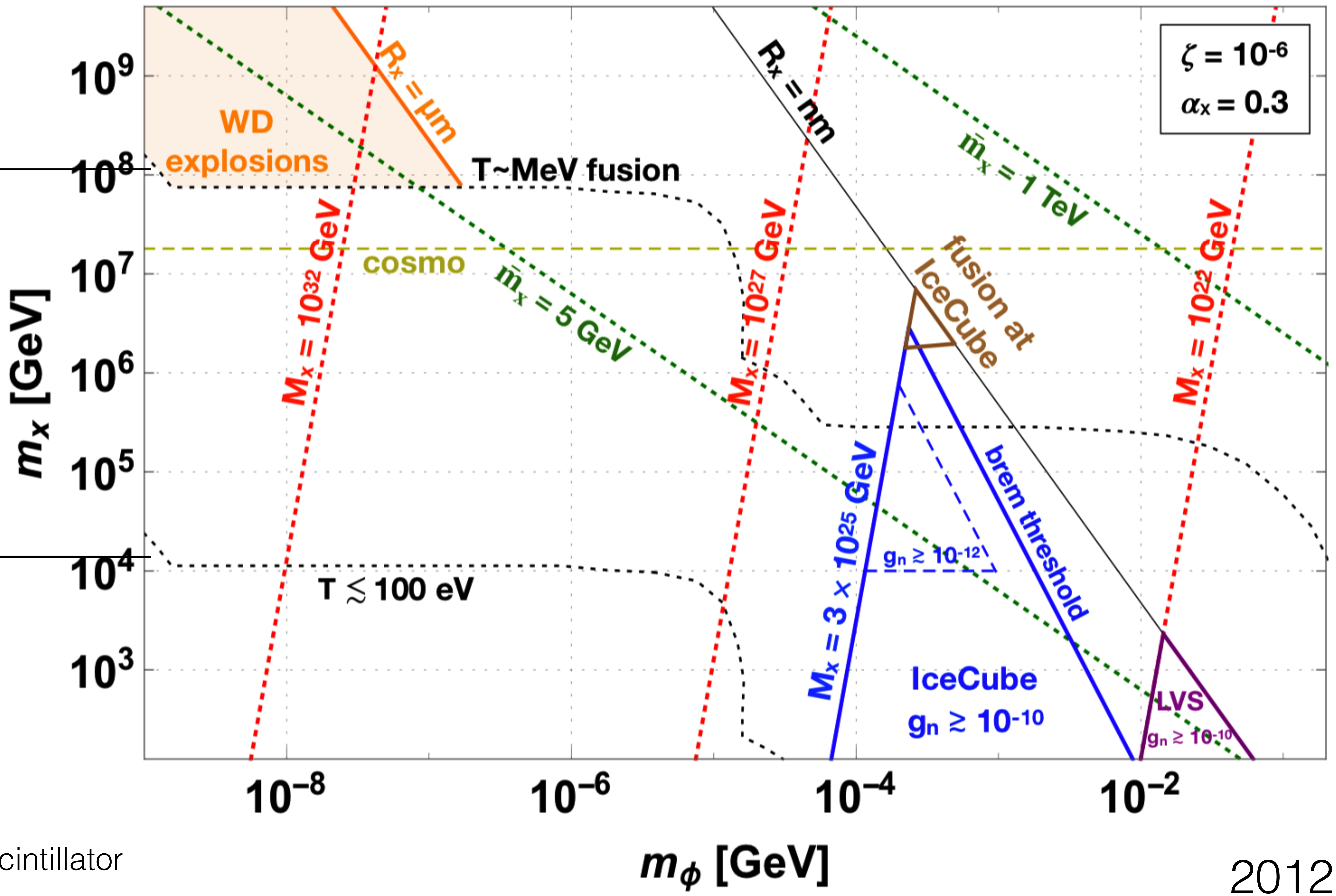
for ϕ masses < eV
5th force searches
further constrain coupling

Parameter space of potential detectability:

increasing radius/mass

stellar cooling constraints

stellar cooling constraints



increasing temperature (fixed coupling)

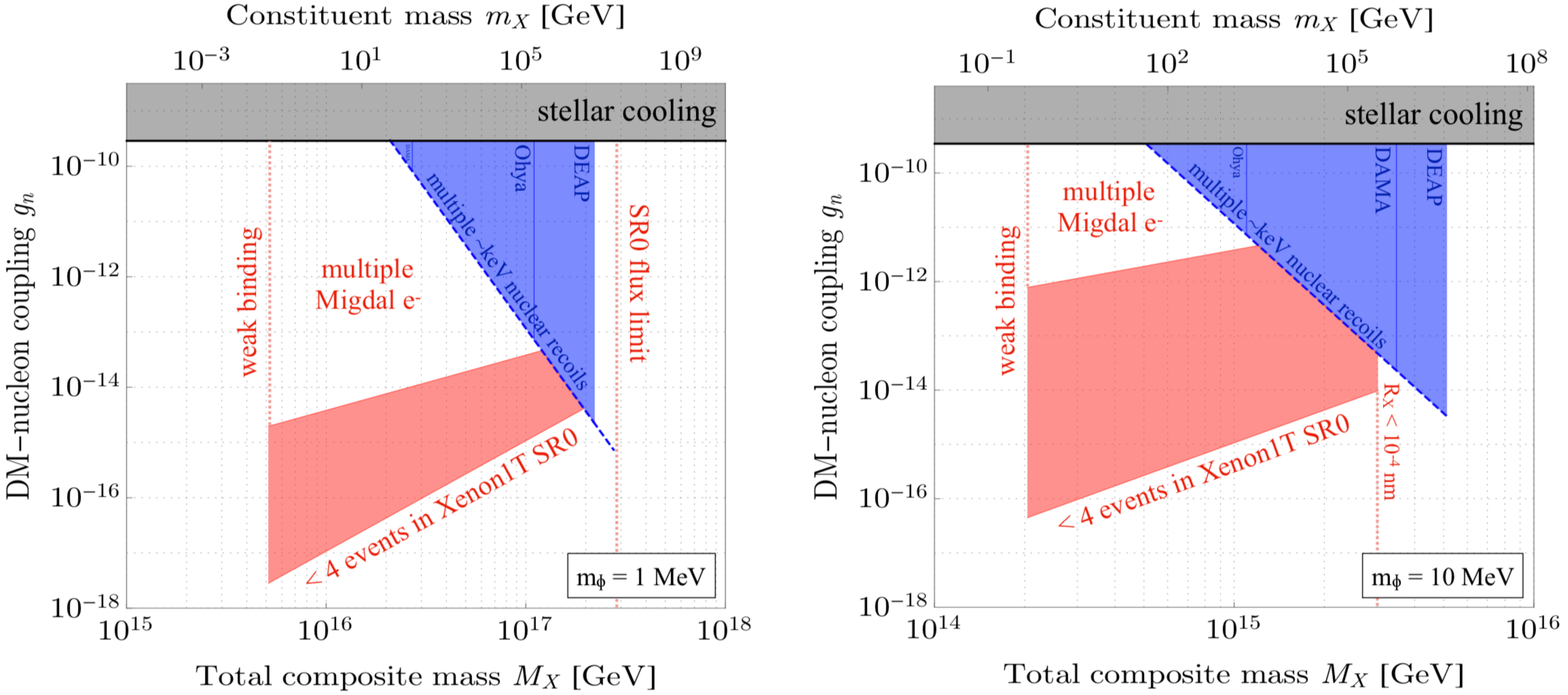
increasing composite binding energy

LVS = large volume scintillator

2012.10998

Migdal Bounds

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



Acevedo, JB, Goodman, 2108.10889

Acevedo, **JB**, Goodman, 2105.06473
Adhikari et. al., DEAP collaboration, 2108.09405

Summary of multi scatter bounds: