New Searches for Composite DM

Canadian Astroparticle Annual Meeting

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Based on work: Acevedo, Boukhtouchen, Bramante, Cappiello, Mohlabeng, Tyagi 2408.xxxx

Key points

1. Models where DM forms composite states have been a topic of interest for a long time.

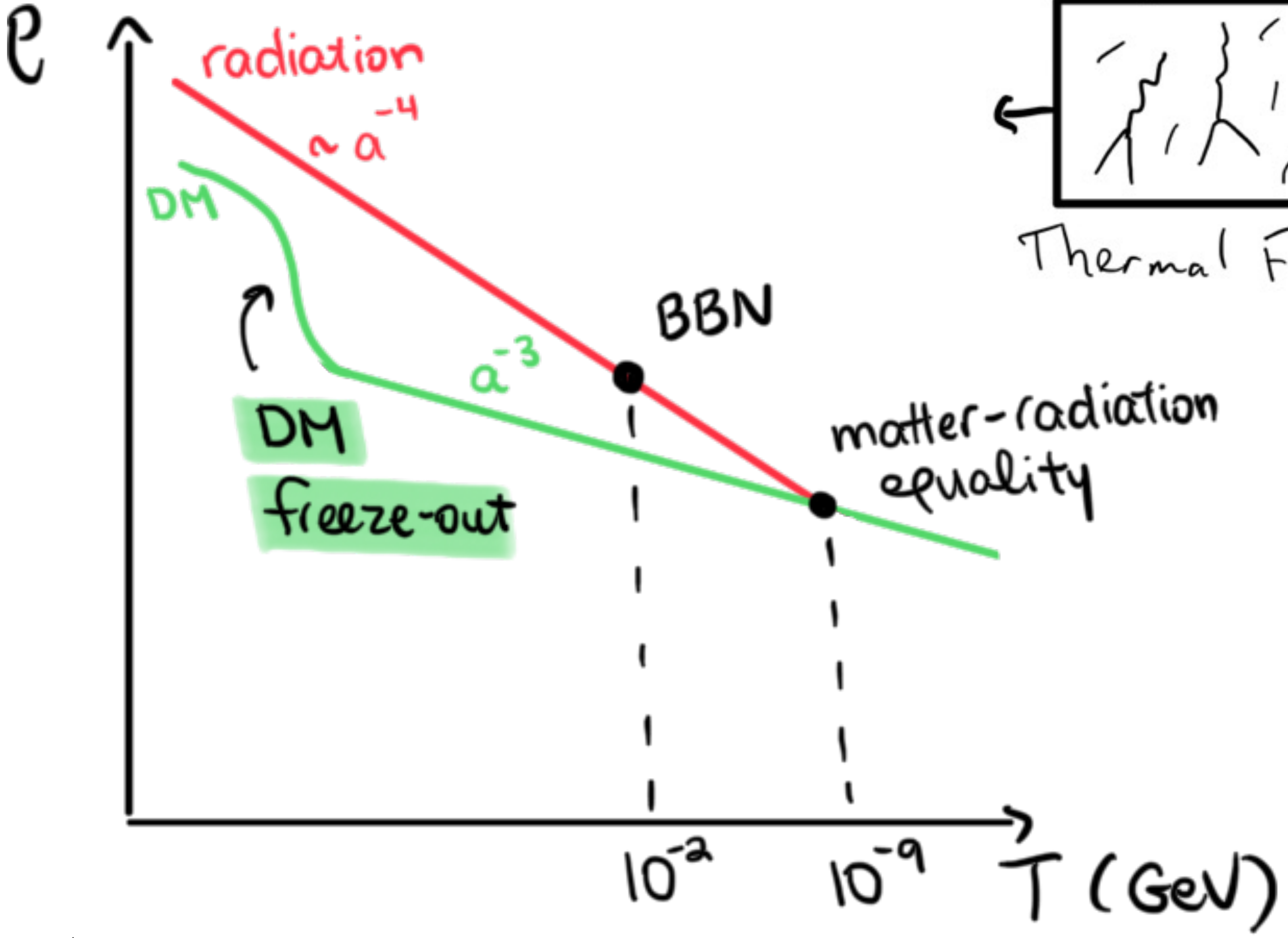
2. These models can lead to an A^4 scaling in the DM-nucleus cross-section, and multi-scattering in DM experiments.

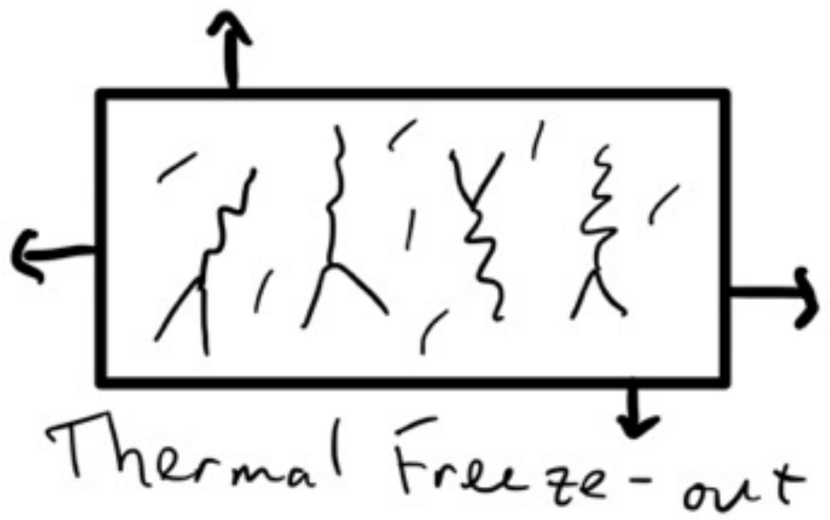
3. There are new possible signatures of large numbers of low-energy scatters, which could be sought in low-threshold detectors e.g. liquid argon

There is a wide dark matter model landscape

The WIMP and thermal freeze-out

relic abundance is achieved through freeze-out mechanism as universe cools.





$$\langle \sigma_{ann} v \rangle \sim 3 \times 10^{-26} \ \frac{\text{cm}^3}{\text{s}} \rightarrow \sigma_{ann} \sim 10^{-36} \ \text{cm}^2$$

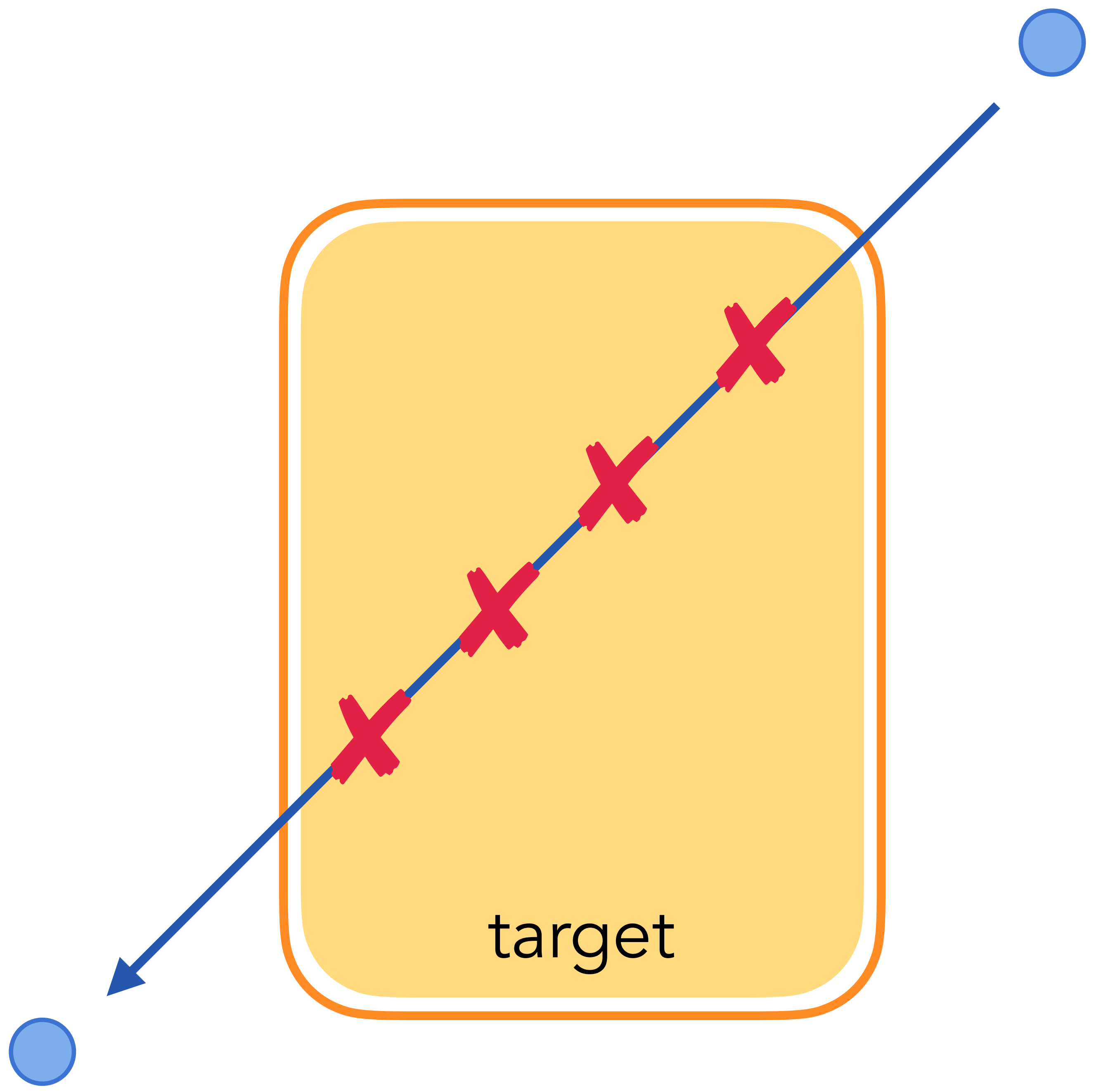
The annihilation cross-section has an upper bound for 2 → 2 self-annihilation

$$\sigma_{ann} \leq 4\pi / m_x \qquad m_x \leq 10^5 \ \text{GeV}$$

Griest, Kamionkowski '90

(there are many ways to get around this!)

What is compelling about heavy dark matter?



relatively unconstrained at higher cross-sections due to its lower flux: multiple scatters are possible.

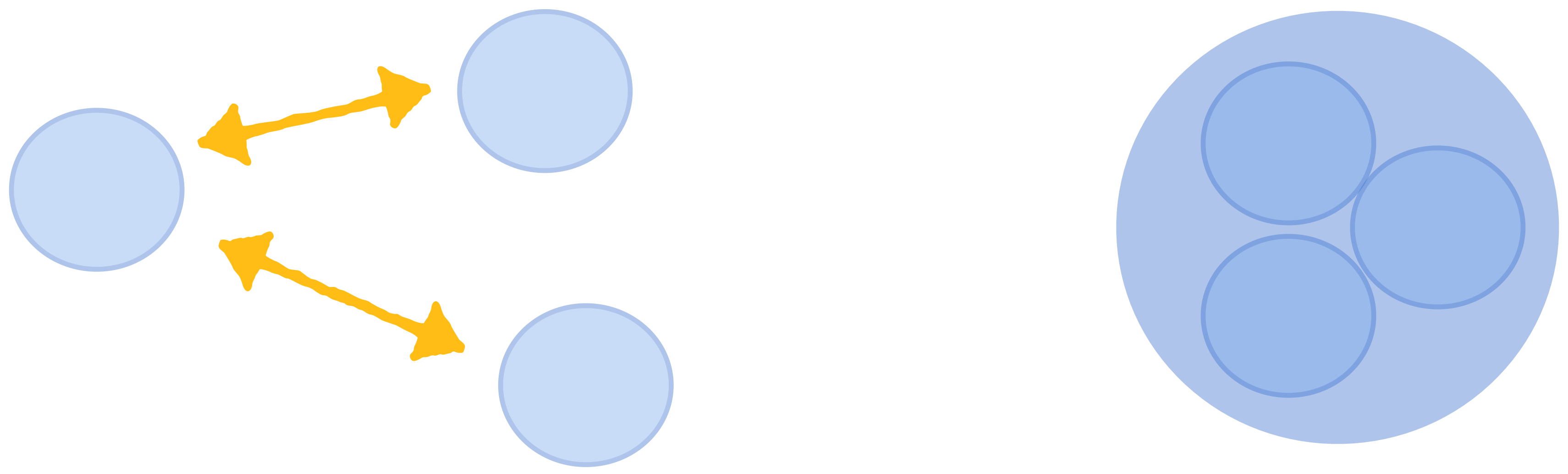
$$\frac{d\sigma_{Ad}}{dE_R} = \frac{d\sigma_{nd}}{dE_R}\left(\frac{\mu_{Ad}}{\mu_{nd}}\right)^2 A^2|F_A(q)|^2 \approx \frac{d\sigma_{nd}}{dE_R}A^4|F_A(q)|^2, \quad m_d \gg m_A$$

How is heavy dark matter produced in early universe?

(two models among others)

Composite assembly in early universe

analogous to SM nucleosynthesis



in absence of bottlenecks, these can grow very large/heavy

Kjrniak Sigurdson '14
Gresham Lou Zurek '17
Grabowska Melia Rajendra '18
and many others…

Dark matter "squeeze out"

Witten '84
Zhinitzky '02
Baker Kopp Long '19
Asadi, Kramer, Kuflick, Ridgway, Slatyer, Smirnov '21

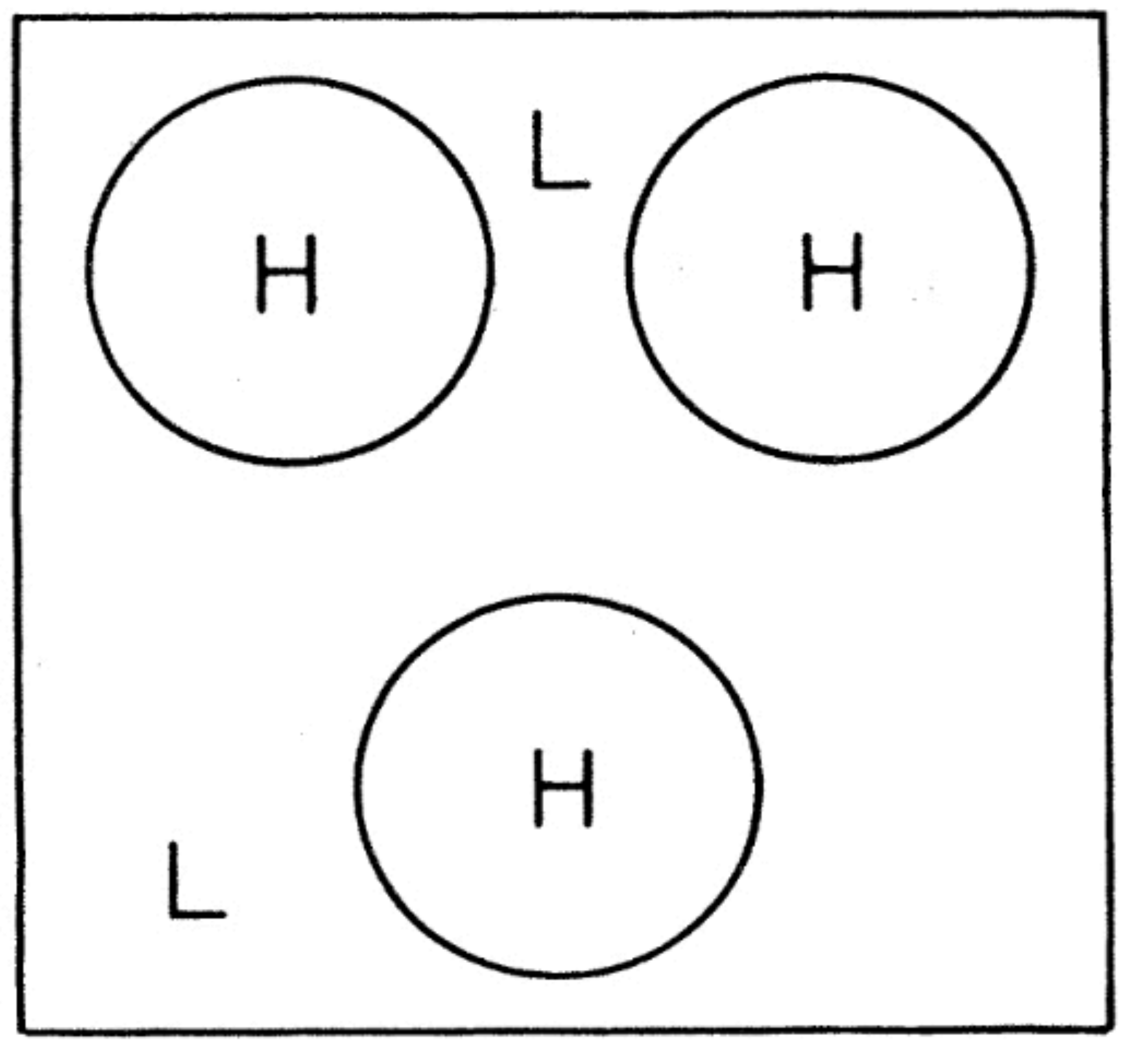


FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

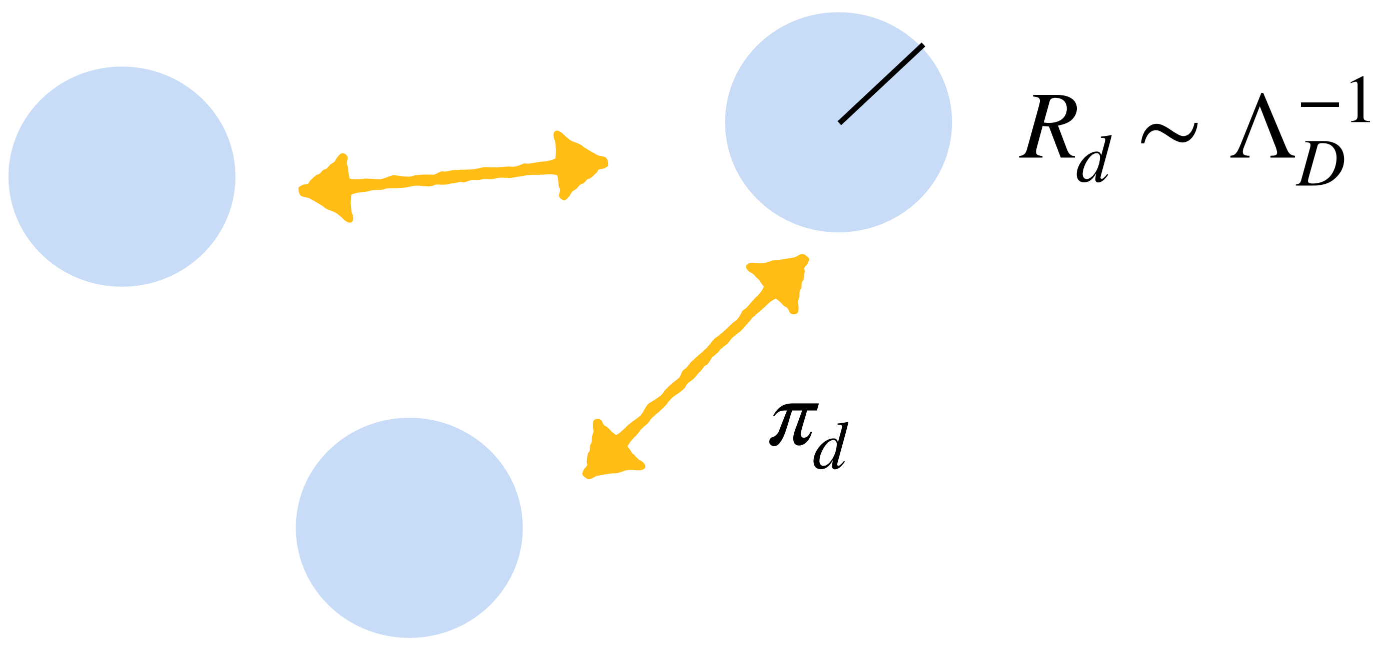
Witten '84

Today's two recipes for composite assembly

"Nuclear" DM

Dark, asymmetric fermions, charged under dark $SU(N)$

form "nucleons" at confinement scale Λ_D

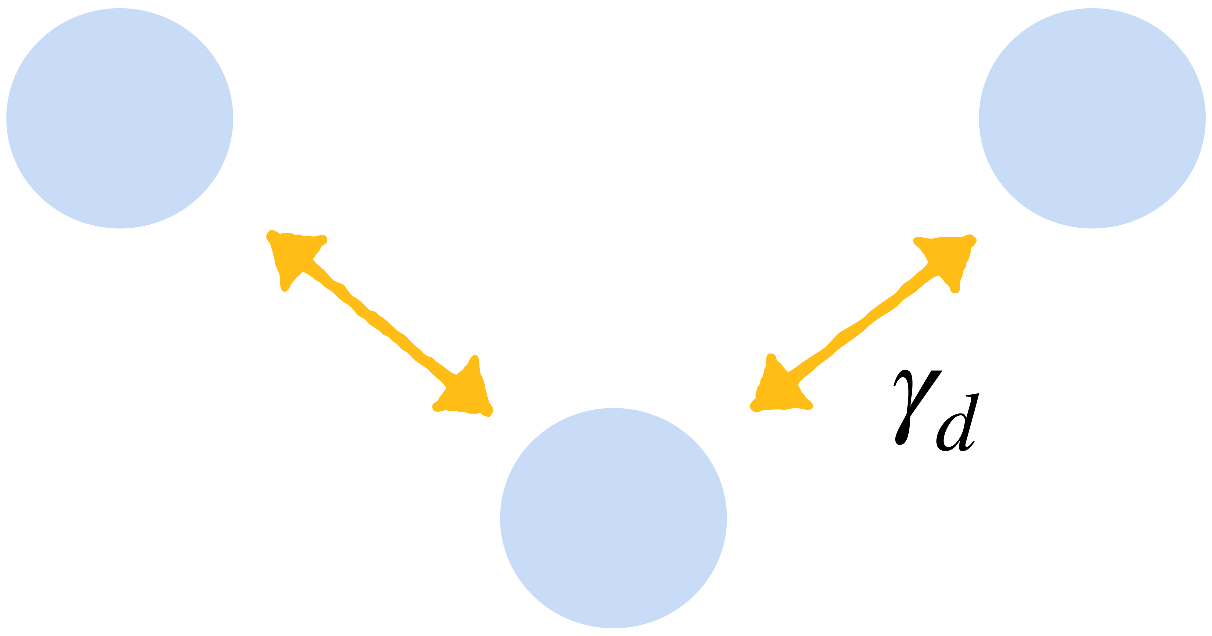


attractive force due to dark pion:
nucleons form nuclei

e.g. Kjrniak Sigurdson '14

"Molecular" DM

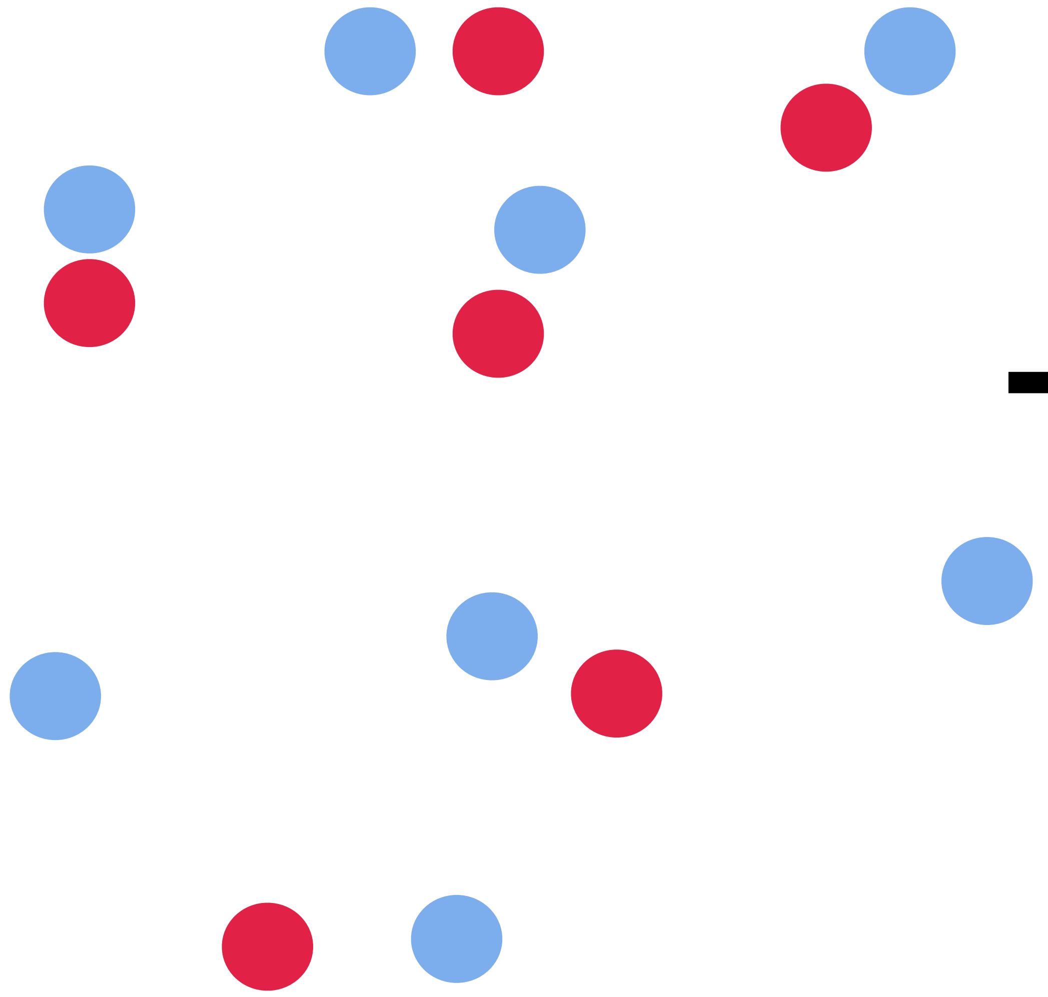
Dark, asymmetric fermions, charged under dark U(1)



attractive force due to dark photon exchange

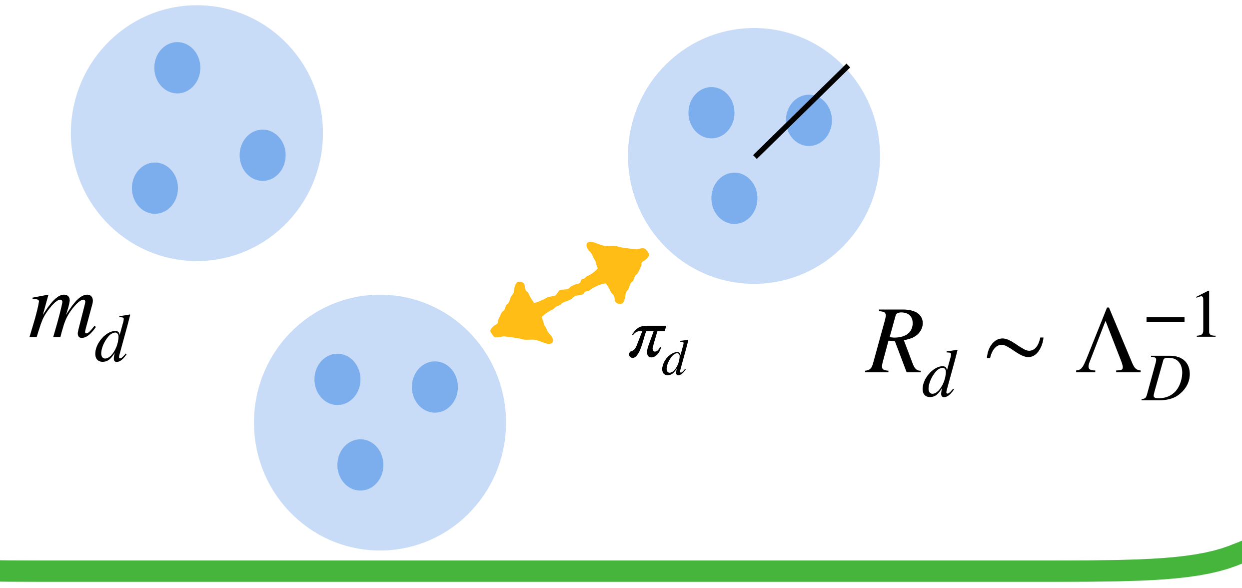
A timeline of composite assembly

dark, asymmetric fermions
asymmetry determines DM abundance



$$\eta_{asym} \equiv \frac{n_d - n_{\bar{d}}}{s}$$

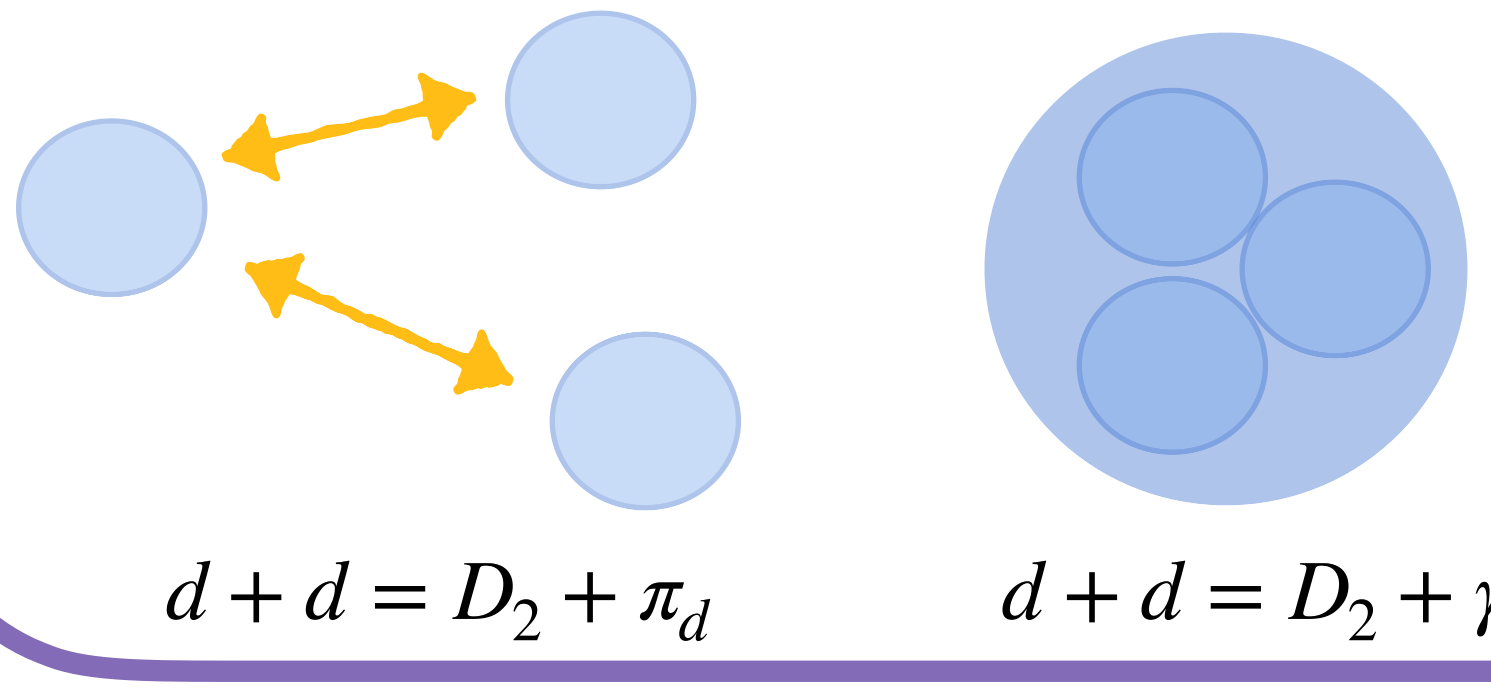
If charged under dark $SU(N)$
form "nucleons" at confinement scale Λ_D



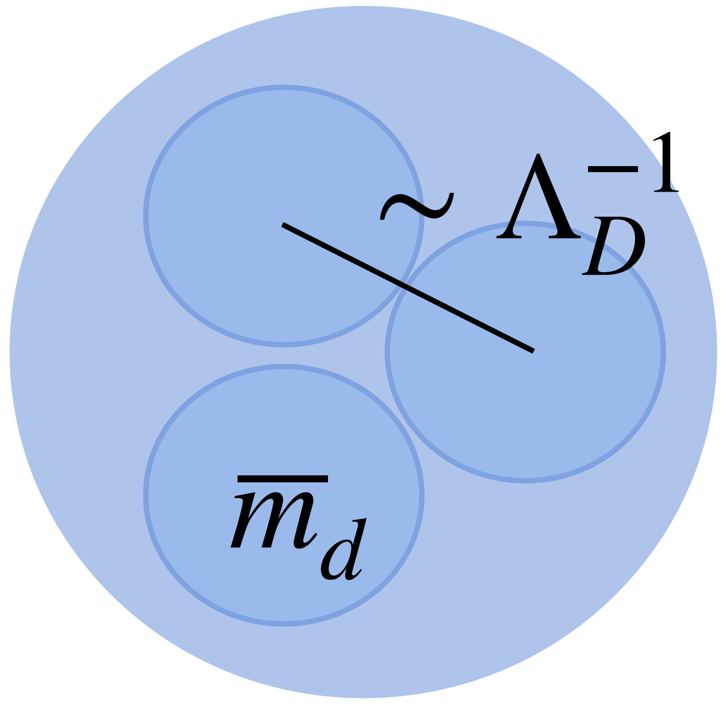
$$N_D = 2.5 \times 10^{13} \left(\frac{10}{g^*_{ca}}\right)^{3/5} \left(\frac{T_{ca}}{0.01\ \text{GeV}}\right)^{9/5} \left(\frac{10^{-5}}{\zeta}\right)^{6/5} \left(\frac{10\ \text{GeV}}{\overline{m}_d}\right)^{9/5} \left(\frac{\text{GeV}}{\Lambda_D}\right)^{12/5}$$

$\zeta \equiv s_{before}/s_{after}$

form large composite states



Λ_D is convenient for parametrizing composite characteristics



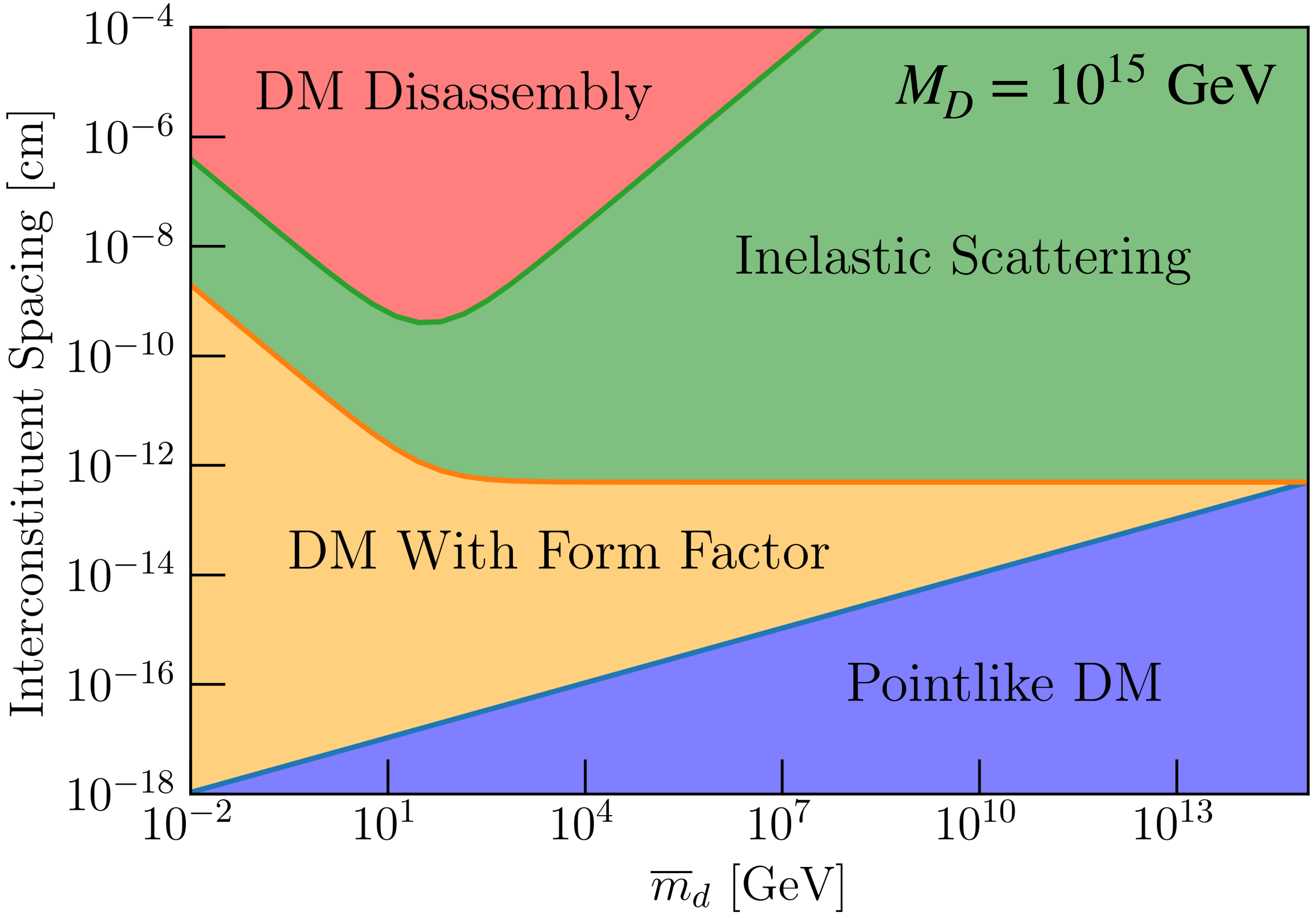
Binding energy

$$BE(N_D)/N_D \sim \alpha\Lambda_D$$

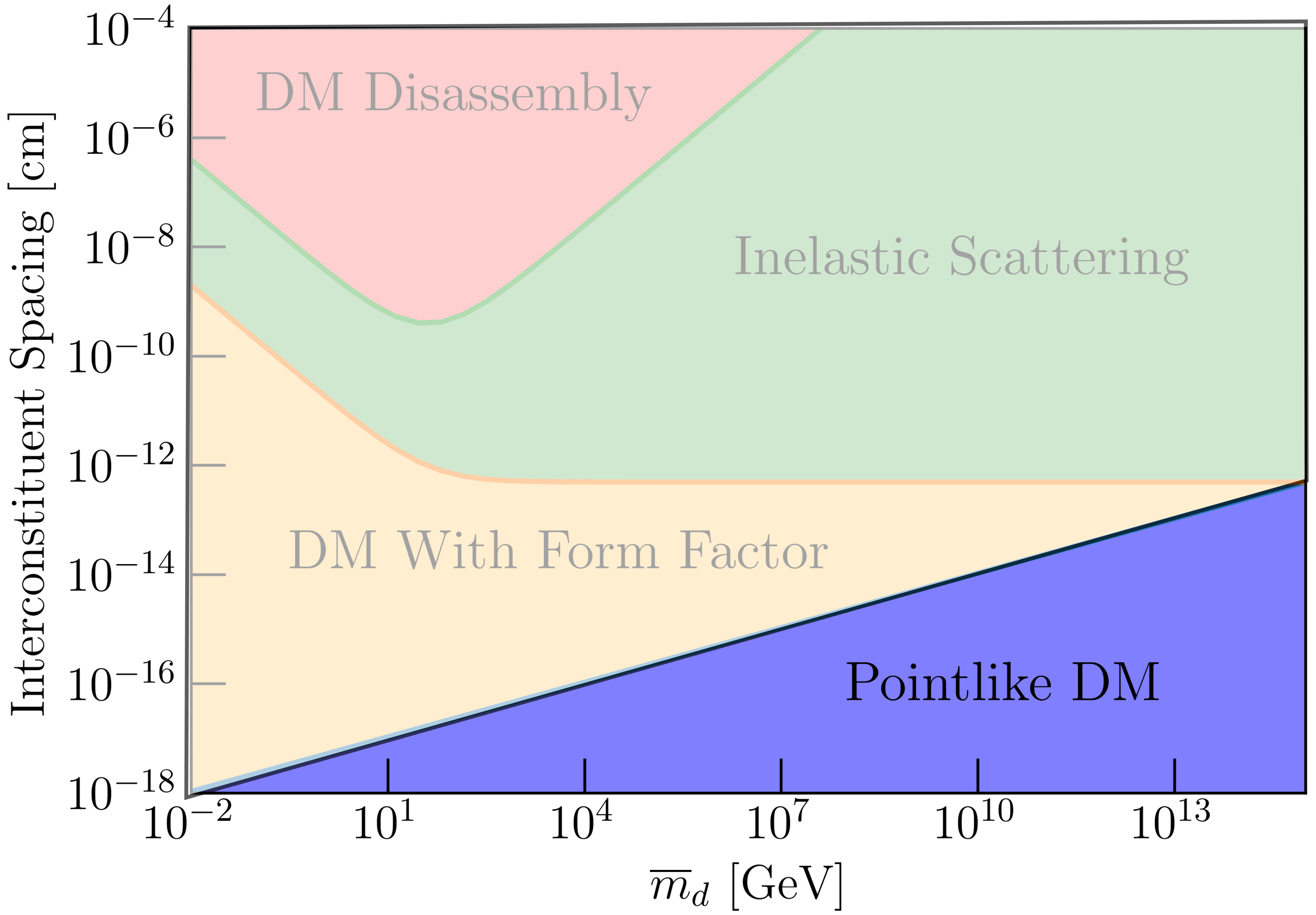
Size

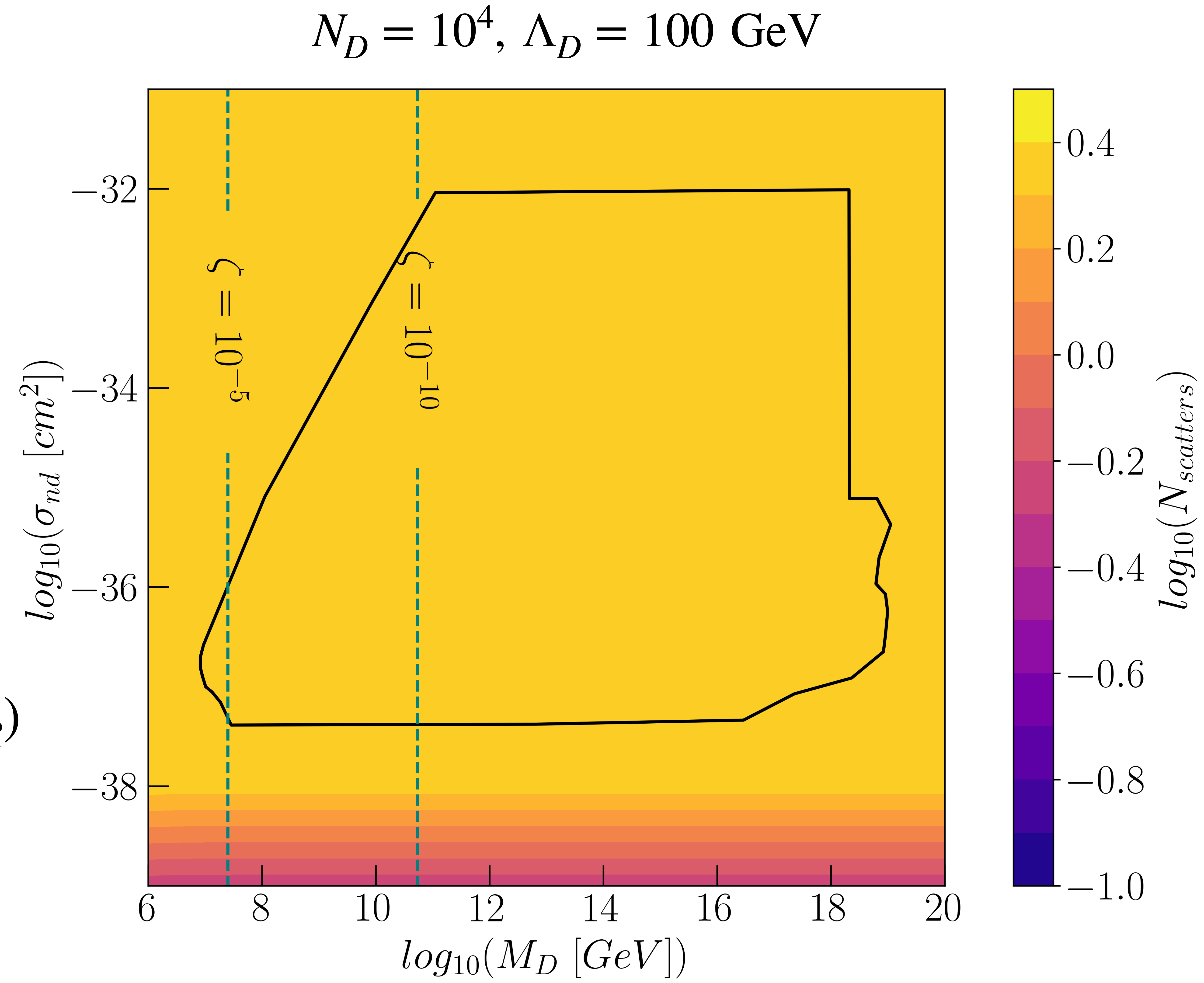
$$R_D \sim \frac{N_D^{1/3}}{\Lambda_D}$$

Regimes for DM-nucleus scattering

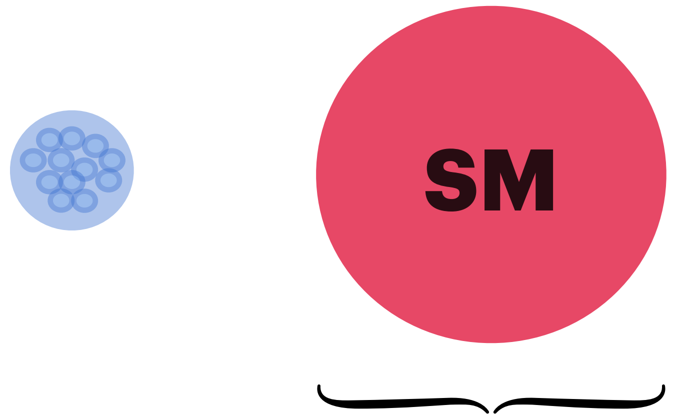


Pointlike Regime



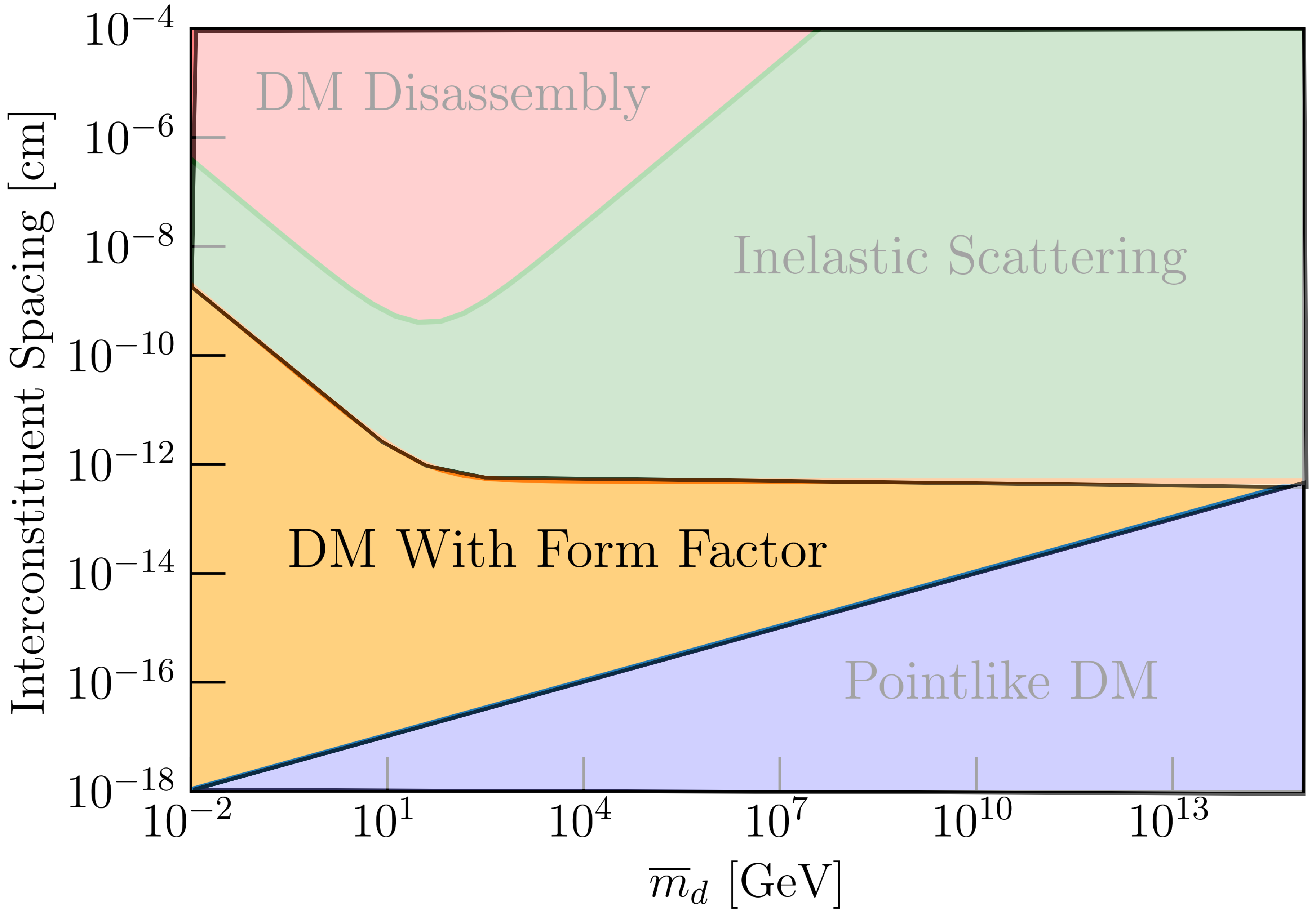


$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{AD}}{\mu_{nd}}\right)^2 A^2 N_D^2 \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R)$$

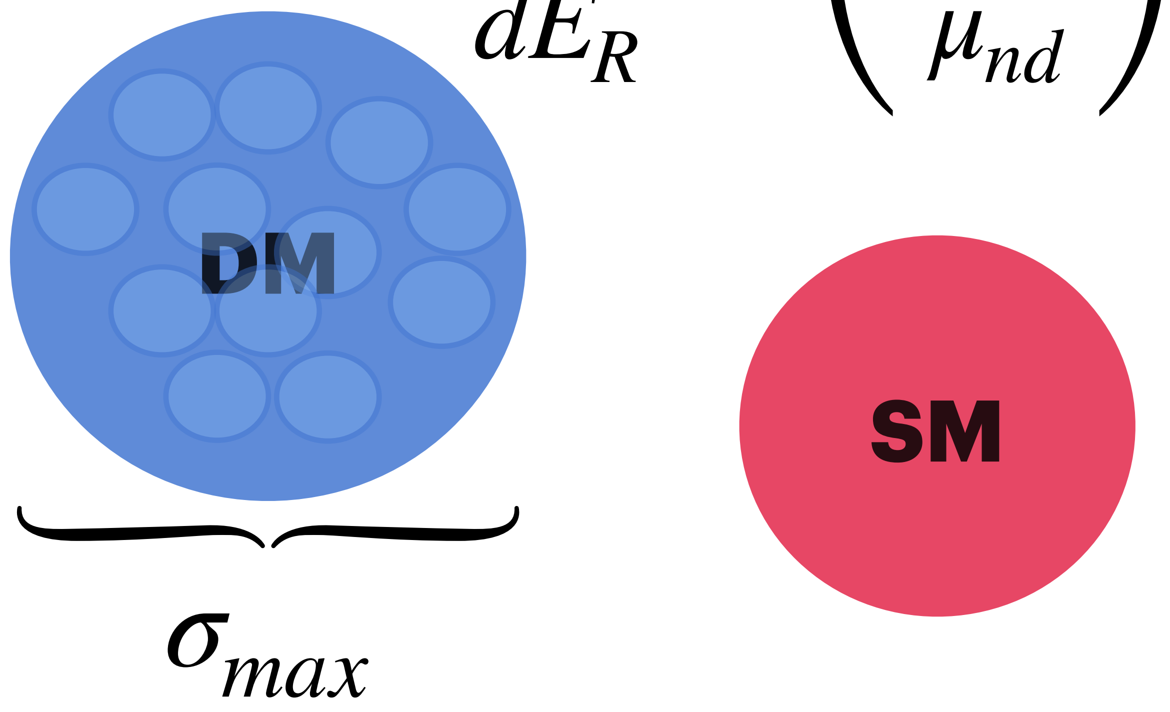


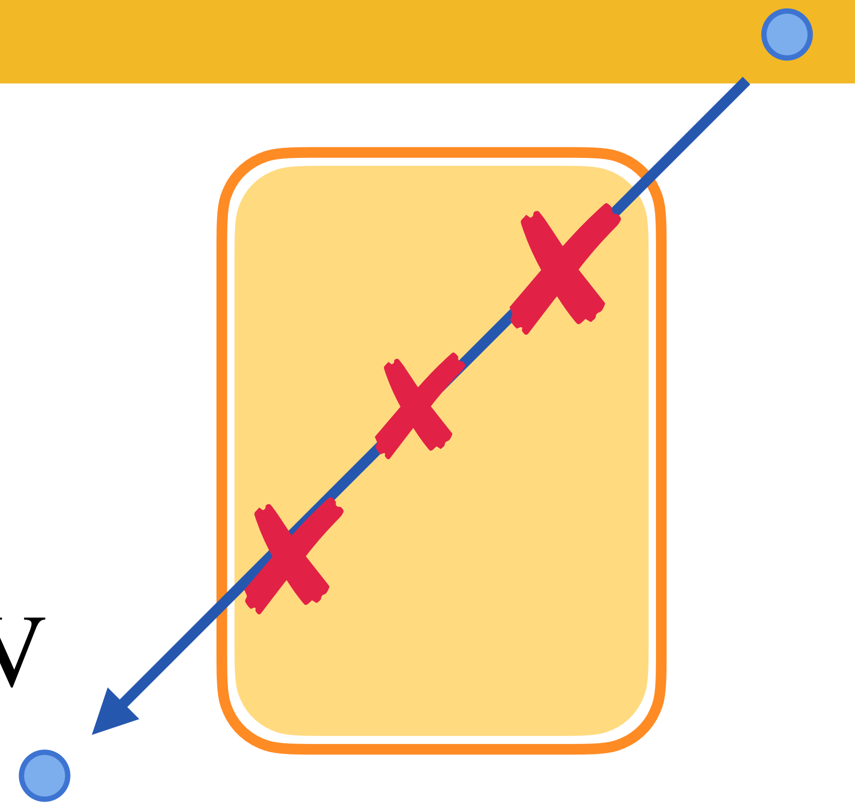
σ_{max}

Dark Form Factor

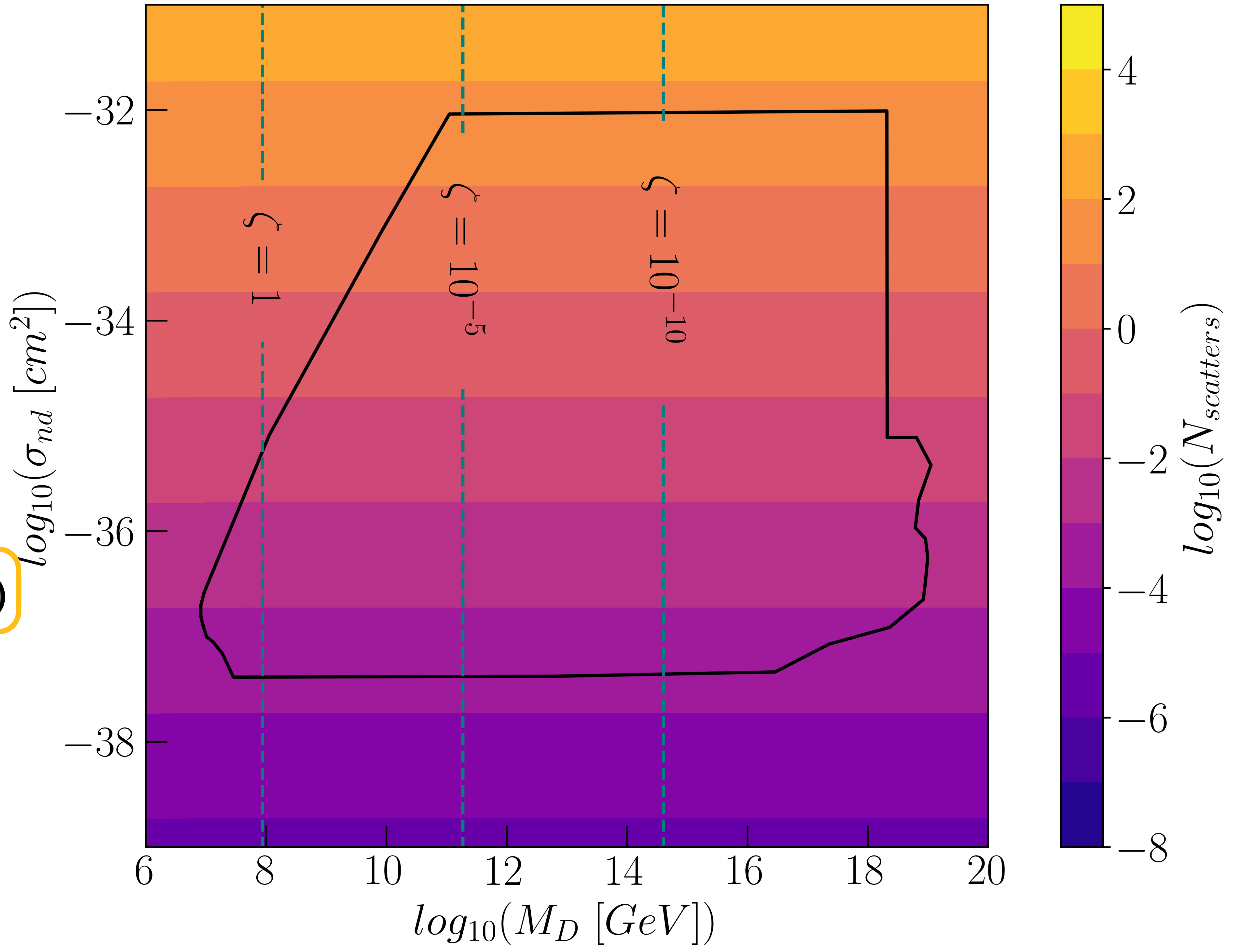


$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{AD}}{\mu_{nd}}\right)^2 A^2 N_D^2 \boxed{g^2} \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R) \boxed{F_D^2(E_R)}$$

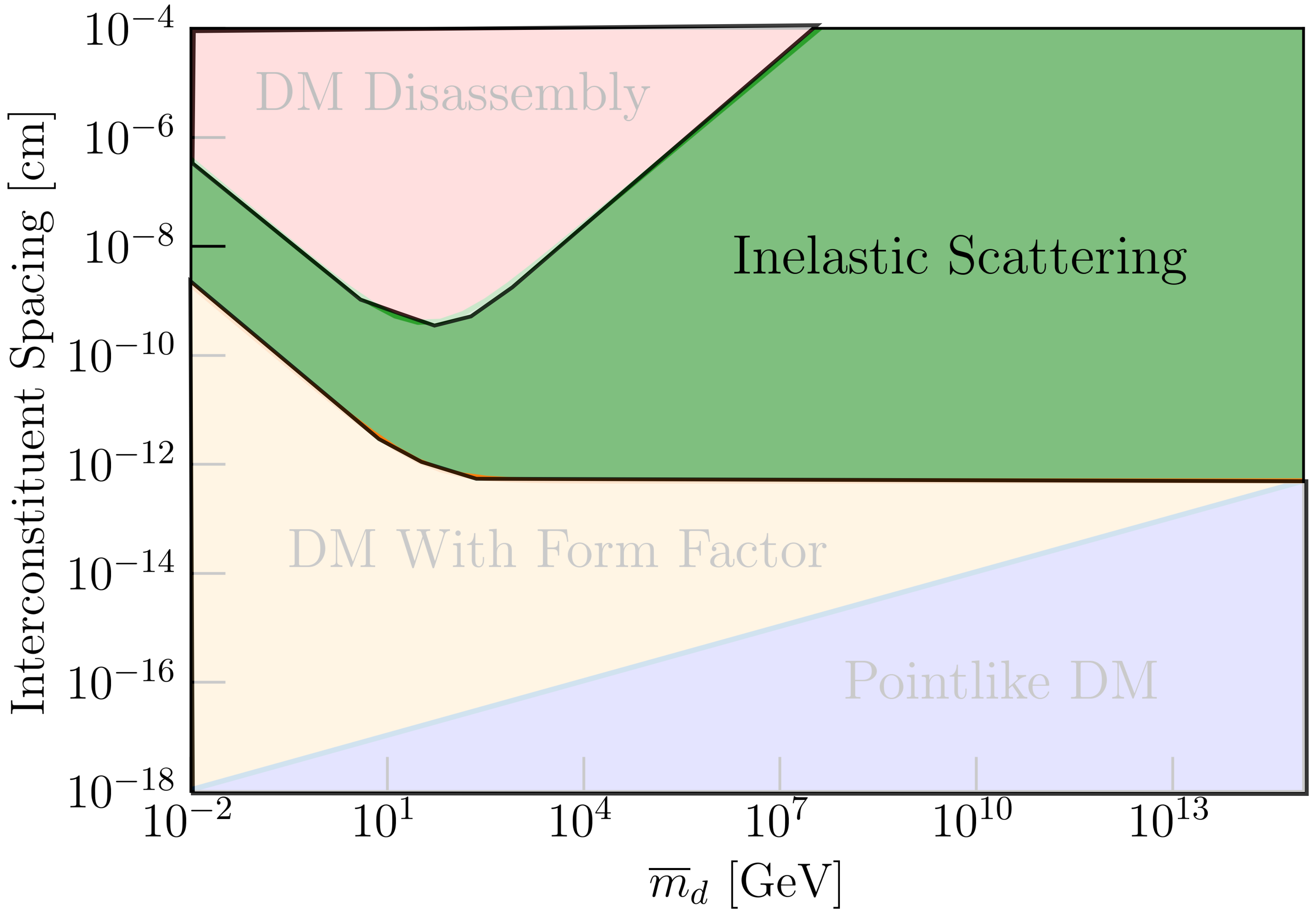


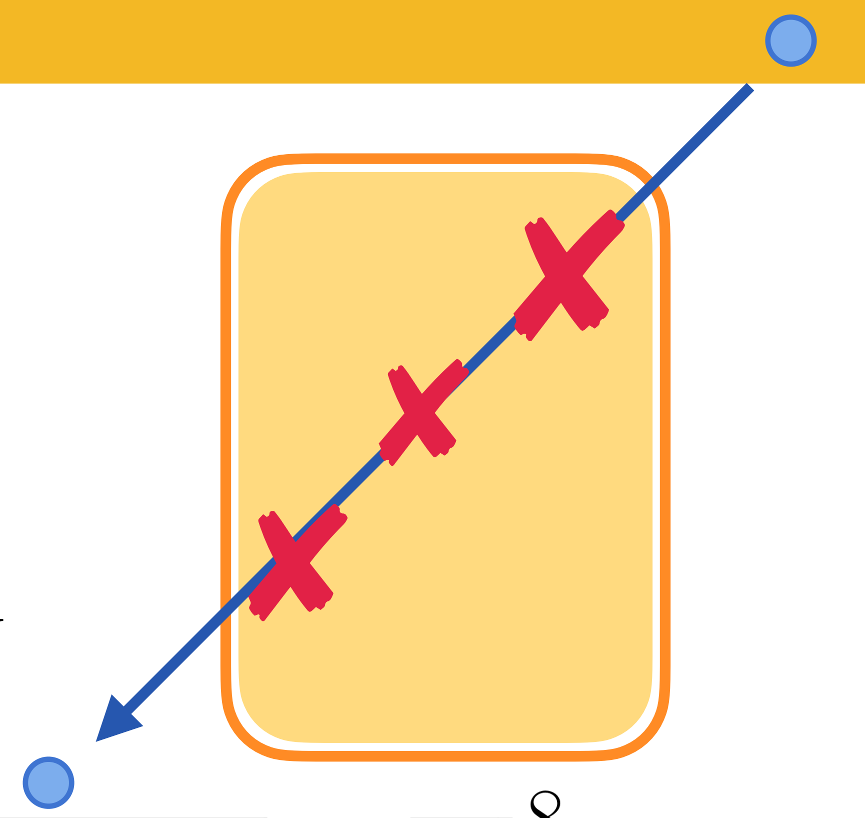


$N_D = 10^4,\ \Lambda_D = 10$ MeV

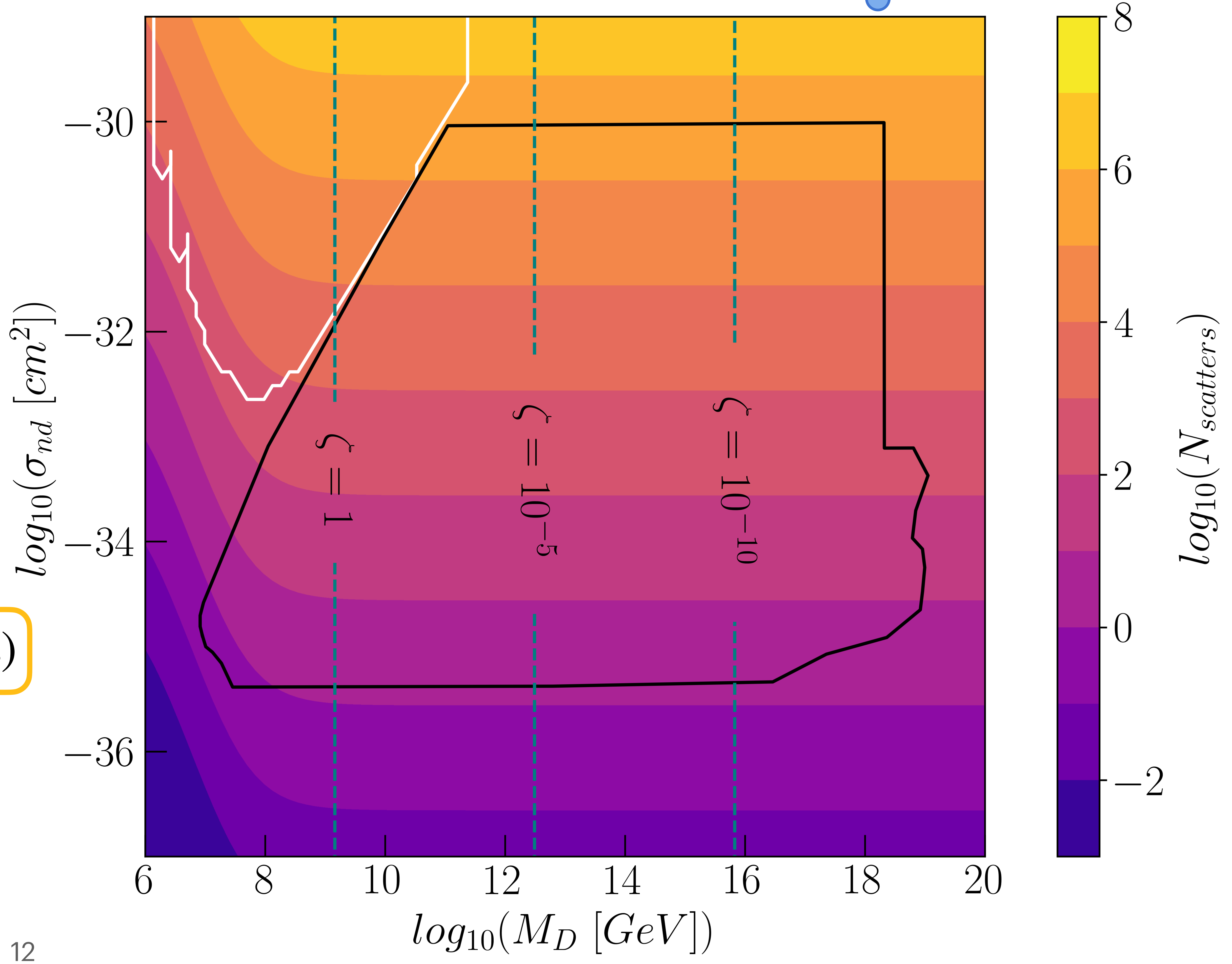


Inelastic Scattering

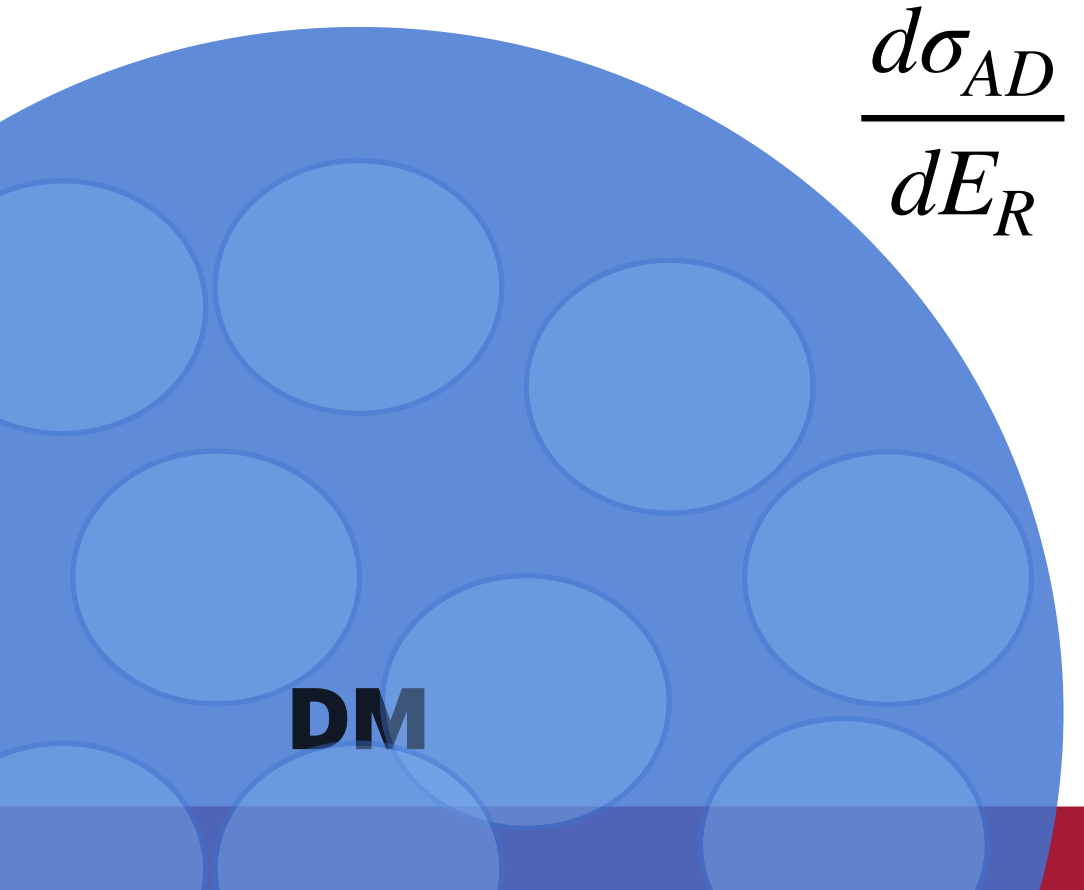




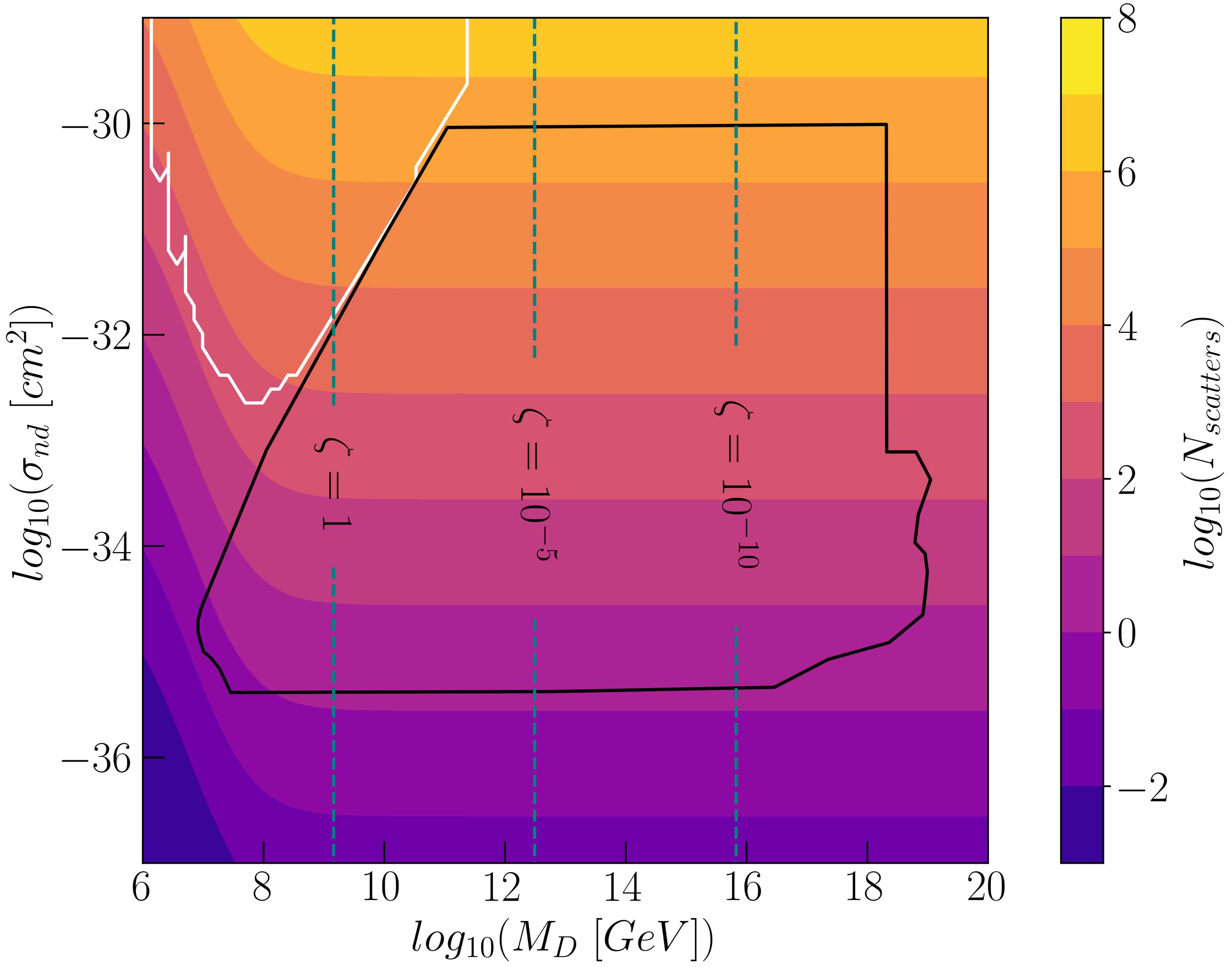
$N_D = 10^6,\ \Lambda_D = 1$ MeV



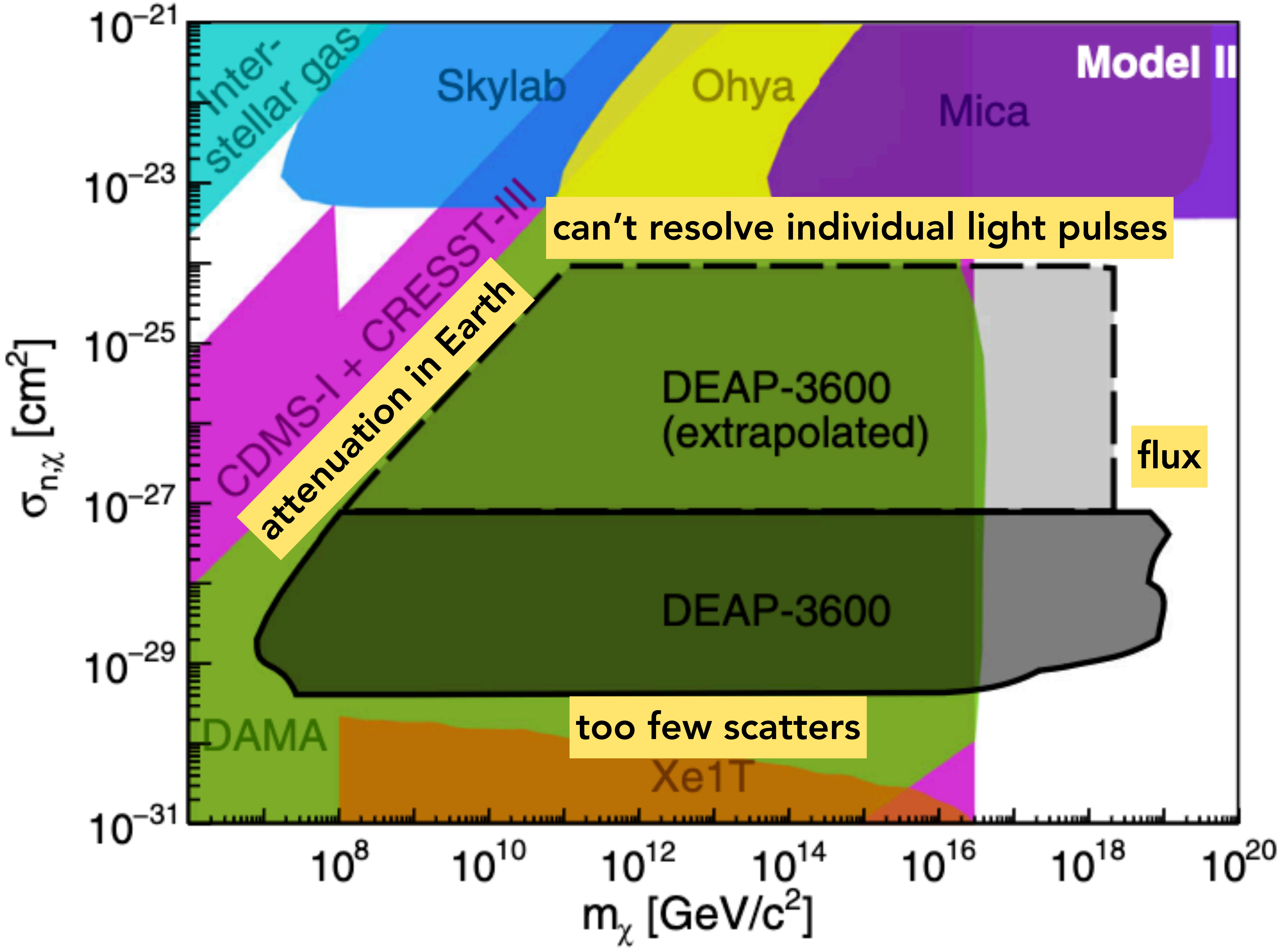
$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{Ad}}{\mu_{nd}}\right)^2 A^2 N_D\, g \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R) S_D(E_R)$$



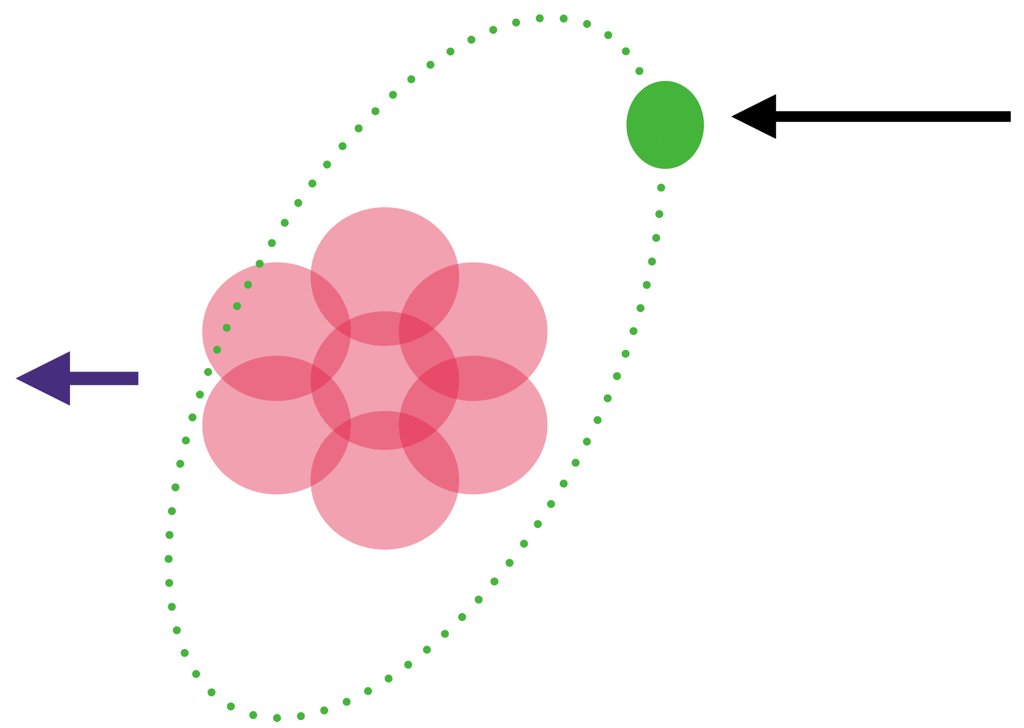
Compare with DEAP Multiscatter Search



2108.09405, DEAP



What if composites interact with electrons?

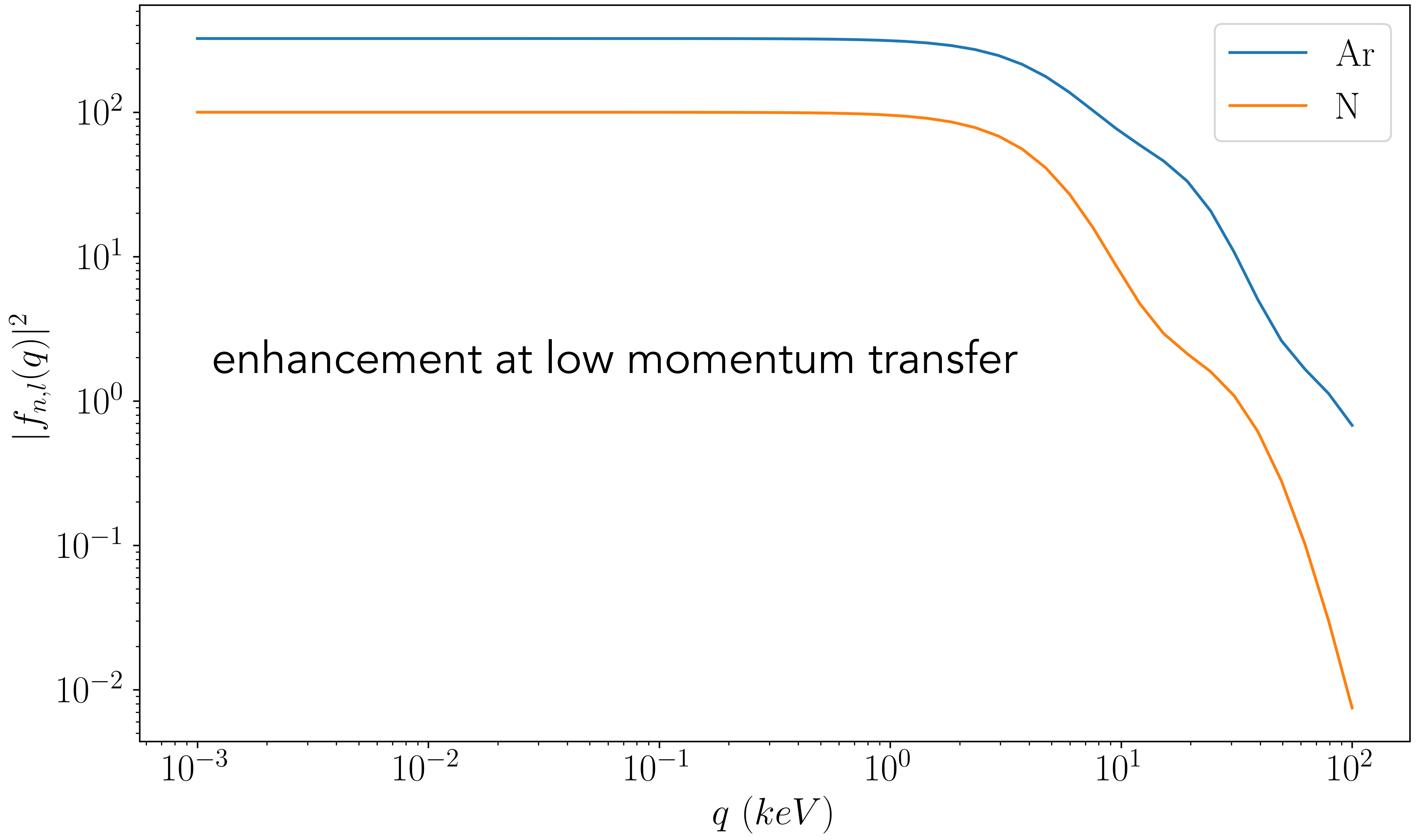


DM-electron recoil could induce a recoil of the whole atom.

probability of electron remaining in same orbital

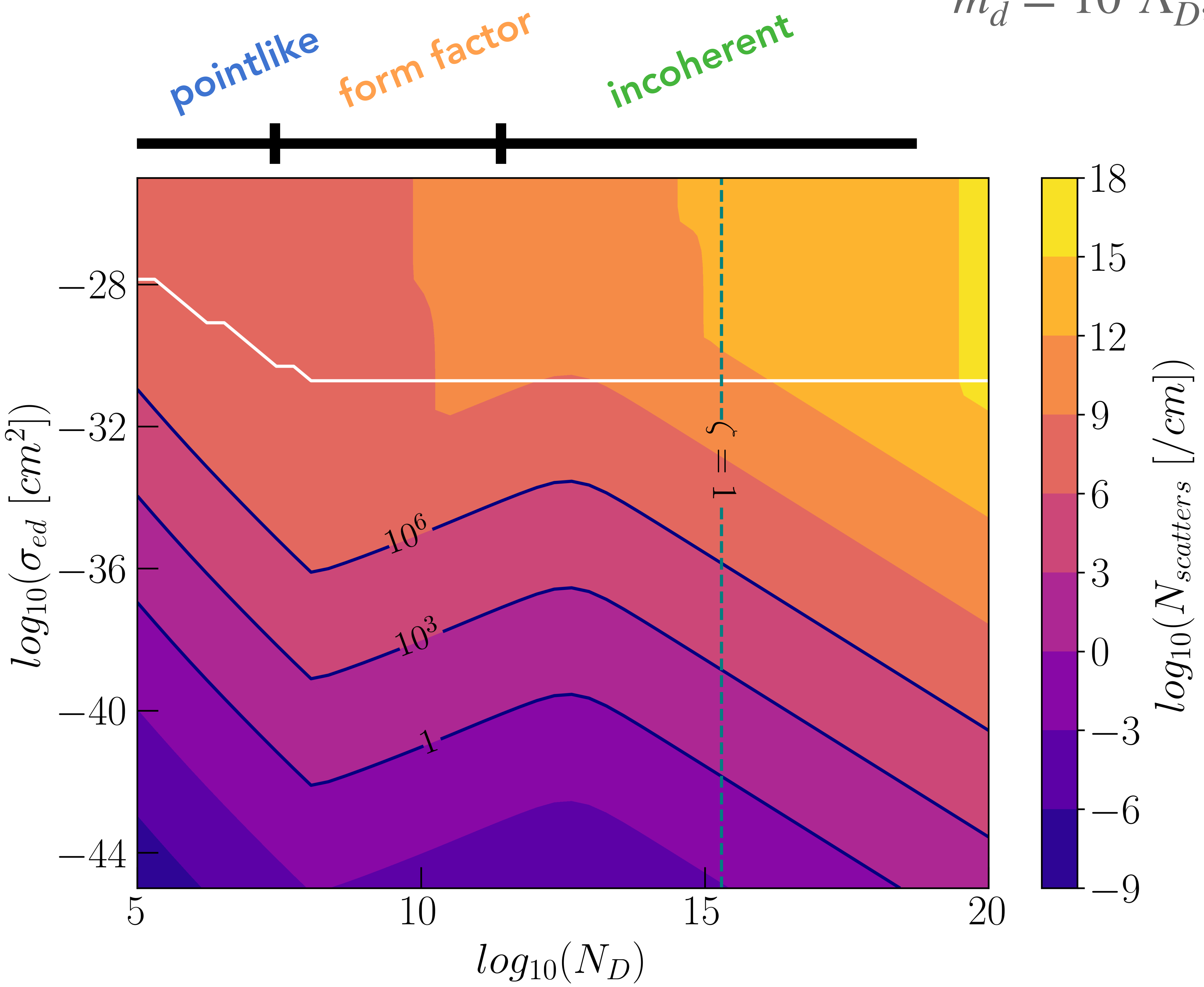
$$\frac{d\sigma_{Ad}}{dE_R} = \sum_{n,l} \frac{d\sigma_{ed}}{dE_R} |f_{n,l}(q)|^2 |F_\phi(q)|^2$$

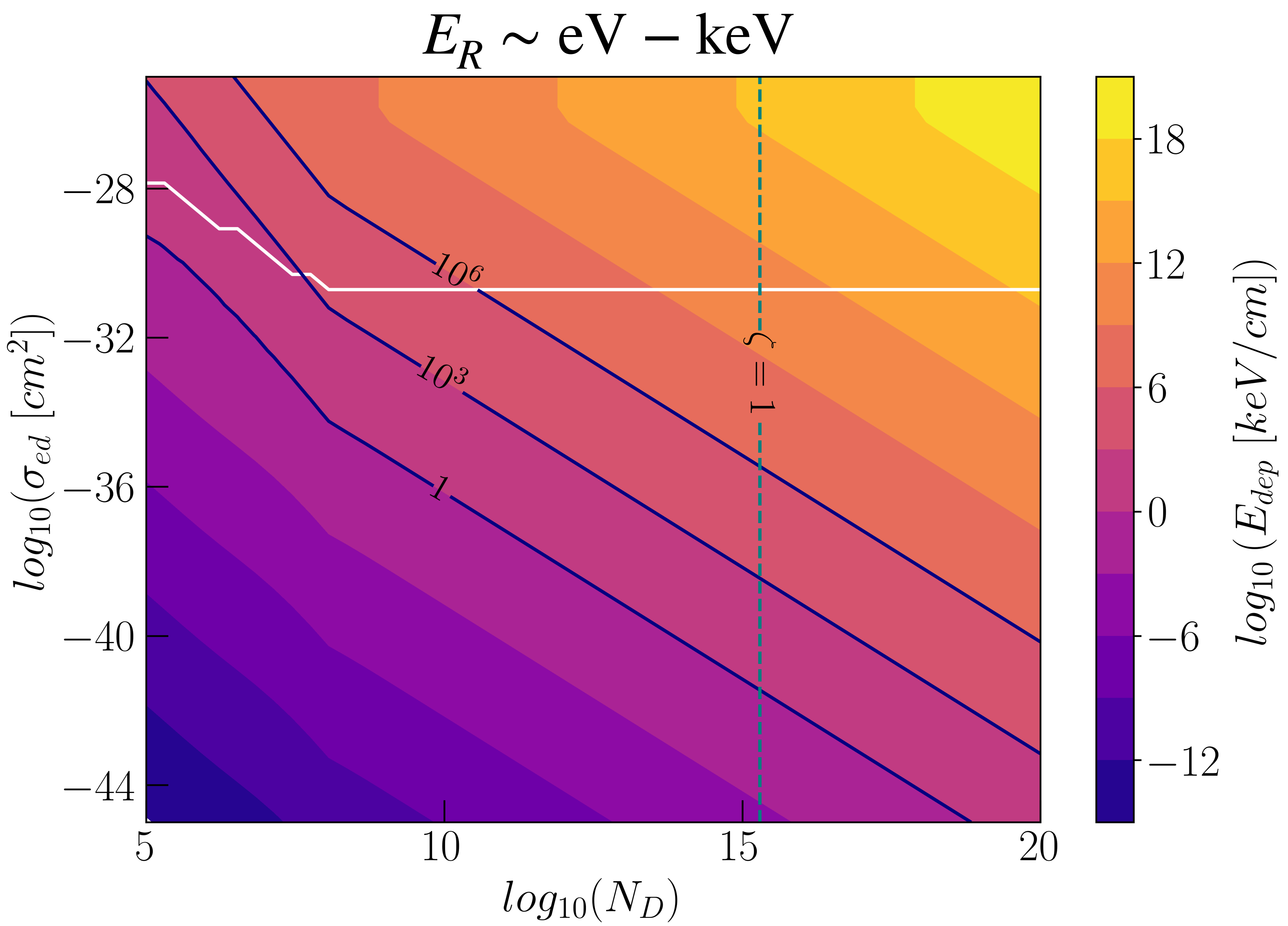
DM-electron mediator form factor



Searching for Atomic Scattering in Liquid Argon

$\overline{m}_d = 10\ \Lambda_D,\ \Lambda_D = 1\ \text{MeV}$





Conclusions

1. Models where DM forms composite states have been a topic of interest for a long time.

2. An A^4 scaling and multi-scattering can be achieved by simple models of "nuclear" and "molecular" composite DM.

3. A large number of low-energy recoils could be a new signature of composite DM in low-threshold experiments.

Reference slides

Estimating N_D

When binding rate falls below the Hubble rate:

$$\Gamma/H = \langle \sigma_{D_N} v_{D_N} \rangle n_{D_N} / H \sim 1 \longrightarrow N_D = \left(\frac{4\pi n_d v_d}{\Lambda_D^2 H} \right)^{6/5}$$

With Friedmann eq. and estimate number density of DM at composite assembly

$$3H^2 M_{pl}^2 = g_{ca}^* \pi T^4 / 30, \qquad n_d = g_r^* \pi^2 T_{ca}^3 T_r / 30\zeta \overline{m}_d$$

Composite Binding Energy

Liquid drop model, like the SM:

$$\frac{\mathrm{BE}(N_D)}{N_D} \propto a_V - a_S N_D^{-1/3} - a_C N_D^{2/3}$$

Rewrite coefficients in terms of Λ_D

$$\frac{\mathrm{BE}(N_D)}{N_D} = a'_V \frac{\Lambda_D^3}{(m_{\pi_d})^2} - a'_S \frac{\Lambda_D^4}{(m_{\pi_d})^3} N_D^{-1/3} - a'_c \Lambda_D N_D^{2/3}$$

Rewrite coefficients in terms of Λ_D

$$\frac{\mathrm{BE}(N_D)}{N_D} \approx a'_V \Lambda_D \qquad a'_V \lesssim 0.1$$

DM-Atom Scattering

$$\frac{d\sigma_{Ad}}{dE_R} = \sum_{n,l} \frac{d\sigma_{ed}}{dE_R} |f_{n,l}(q)|^2 |F_\phi(q)|^2$$

reference cross-section:

$$\sigma_{ed} = \frac{\mu_{ed}^2}{16\pi m_d^2 m_e^2} \overline{|\mathcal{M}_{ed}(q)|^2}|_{q^2=\alpha^2 m_e^2}$$

$$\overline{|\mathcal{M}_{ed}(q)|^2} = \overline{|\mathcal{M}_{ed}(q)|^2}|_{q^2=\alpha^2 m_e^2} \times |F_\phi(q)|^2$$

$$F_\phi(q) = \frac{\alpha^2 m_e^2 + m_\phi^2}{q^2 + m_\phi^2}$$

Bunge Barrientos Vivier-Bunge ‘93

Atomic form factor

Kopp Niro Schwetz Zupan ‘09

$$f_{n,l}(q) = \sum_m \langle nlm| e^{i(\mathbf{k}-\mathbf{k}')\mathbf{x}} |nlm\rangle$$
$$= (2l+1) \int dr\, r^2 |R_{nl}|^2 \frac{\sin qr}{qr}$$

$$R_{n,l} = \sum_j S_{jl} C_{jln}$$ Bunge Barrientos Vivier-Bunge ‘93

sum of Slater-type orbitals