New Searches for Composite DM

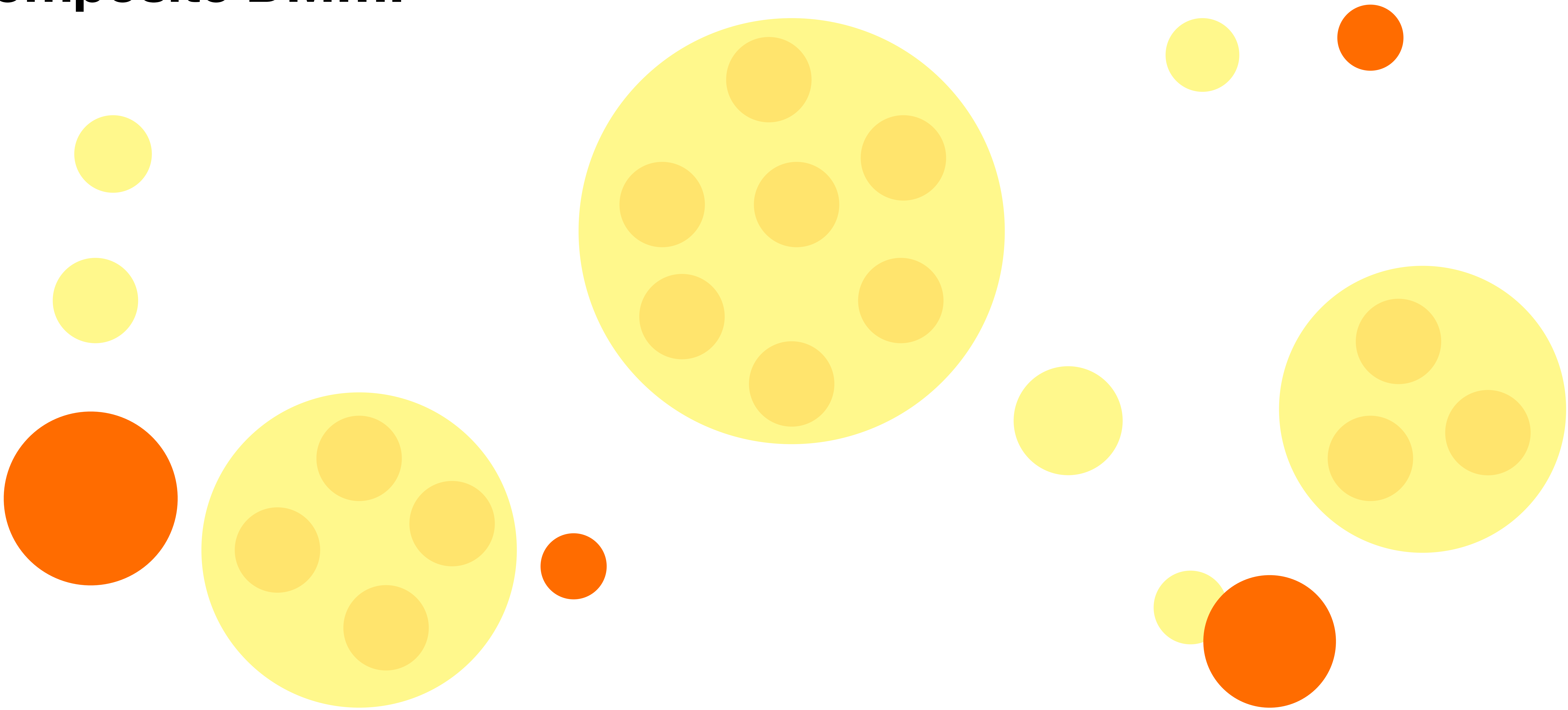
Yilda Boukhtouchen

arxiv:2408.03983

with Javier F. Acevedo, Joseph Bramante, Christopher Cappiello, Gopolang Mohlabeng and Narayani Tyagi

Key points for today

Composite DM....



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has been a **topic of interest** for a long time.

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could cause large numbers of **low-energy scatters**

can lead to A^4 scaling and **multi-scattering** in DM experiments.

There is a wide dark matter model landscape!

But first: why is heavy DM compelling?

Relatively unconstrained at higher cross-sections due to its low flux.

For $m_d \gg m_A$: A^4 **scaling** in cross-section.

$$\frac{d\sigma_{Ad}}{dE_R} = \frac{d\sigma_{nd}}{dE_R}\left(\frac{\mu_{Ad}}{\mu_{nd}}\right)^2 A^2 |F_A(q)|^2$$

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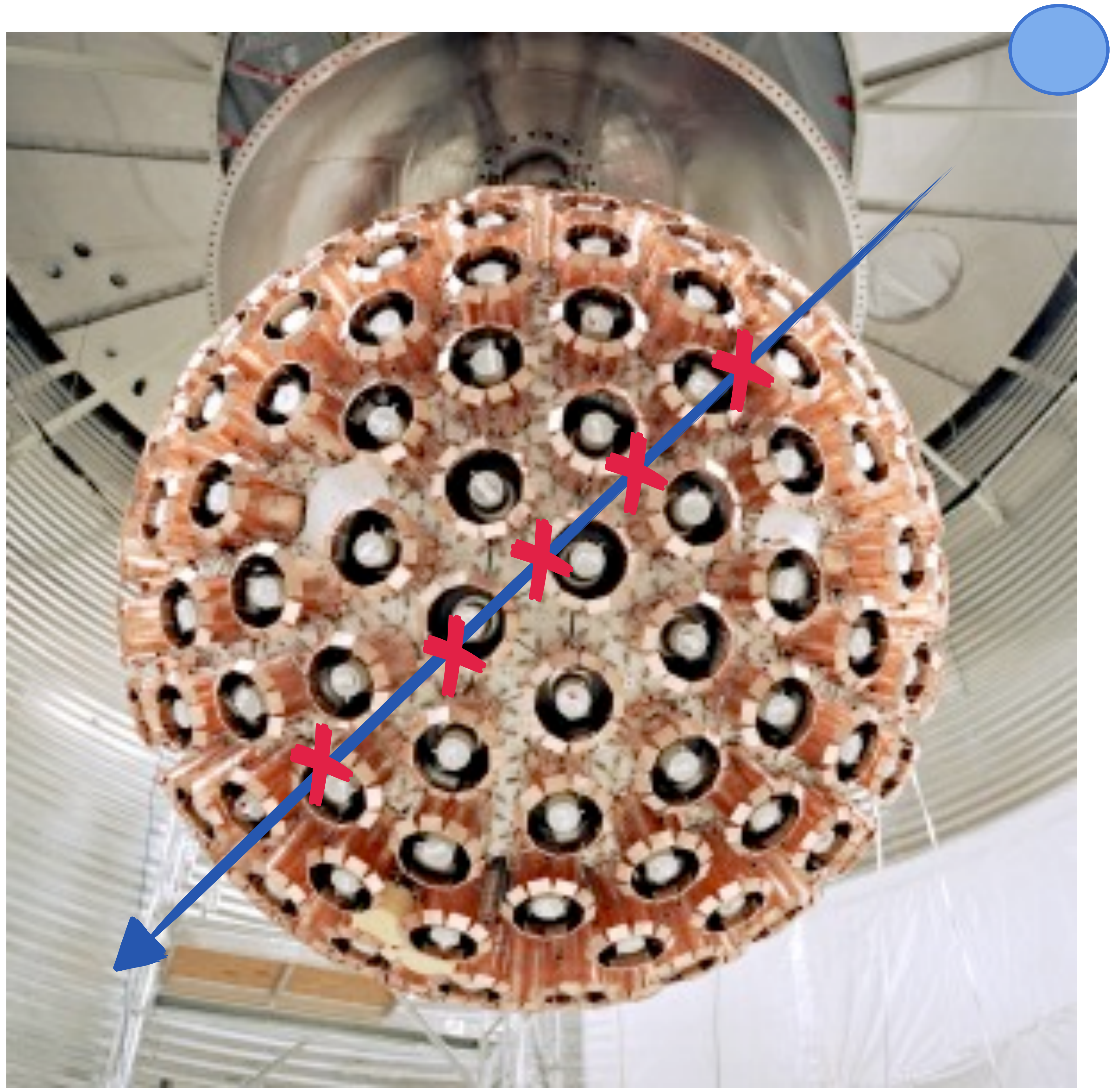
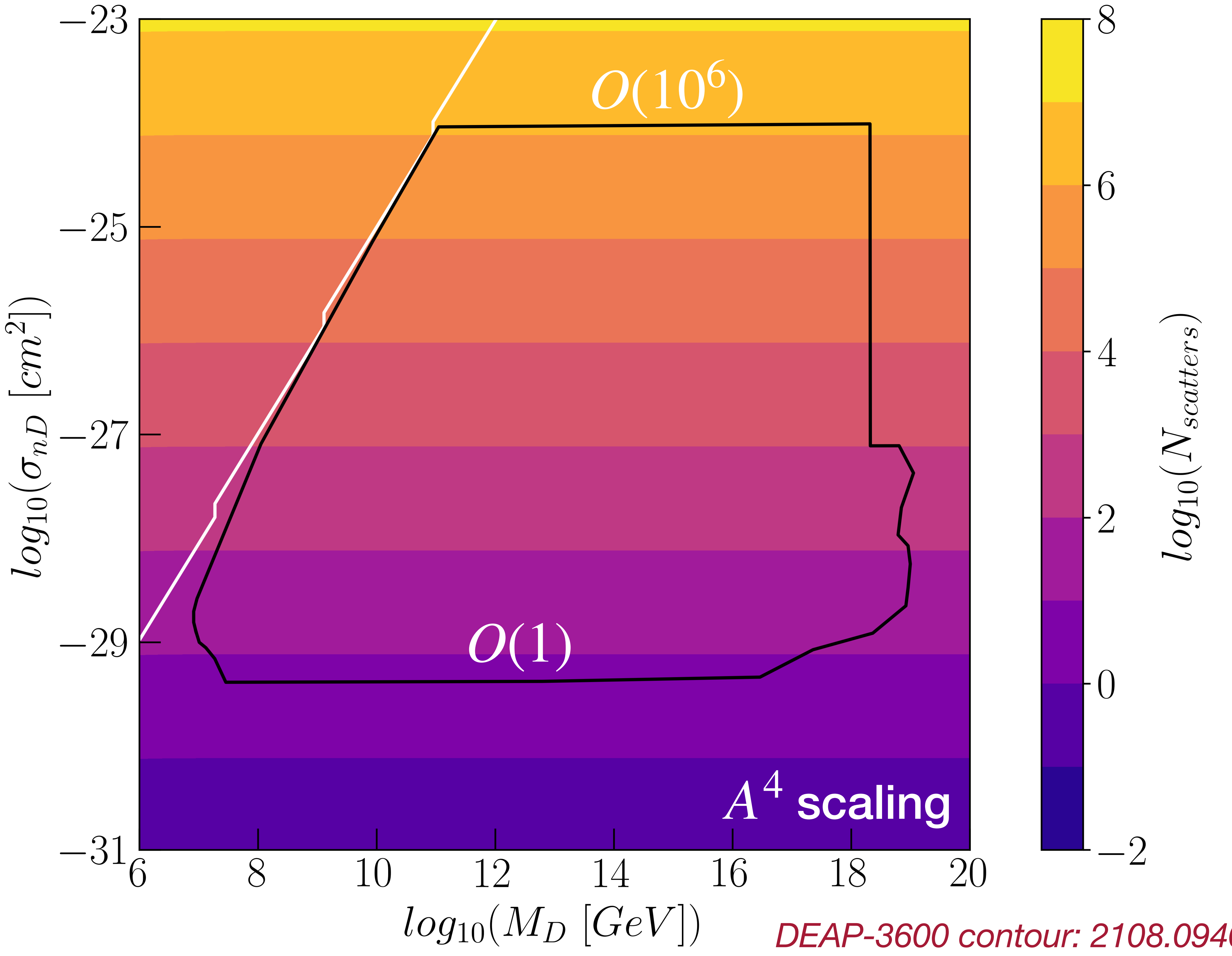
Multi-scattering in detector!



But first: why is heavy DM compelling?

DEAP Search for Multi-Scattering Events



DEAP-3600 contour: 2108.09405

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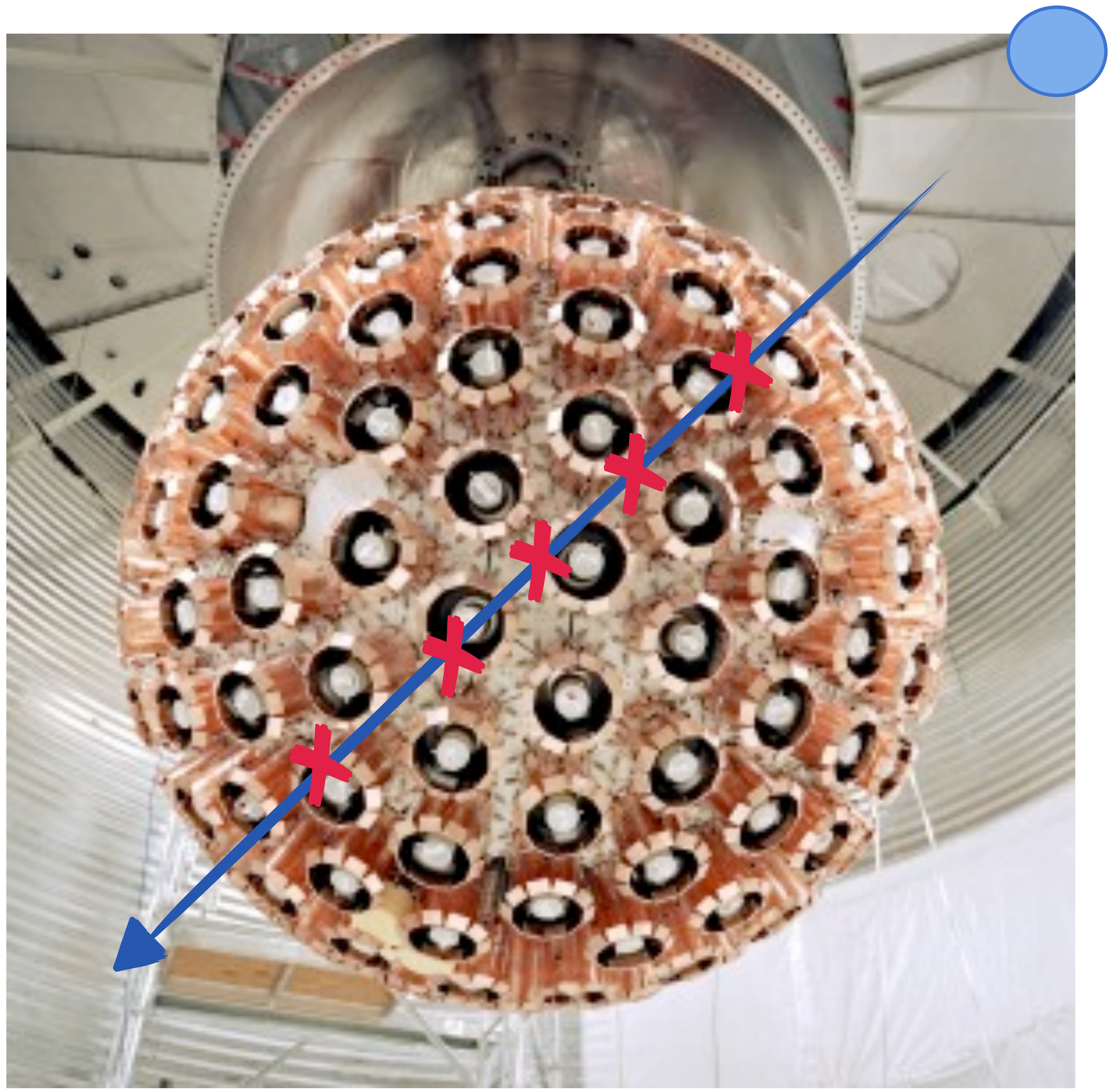
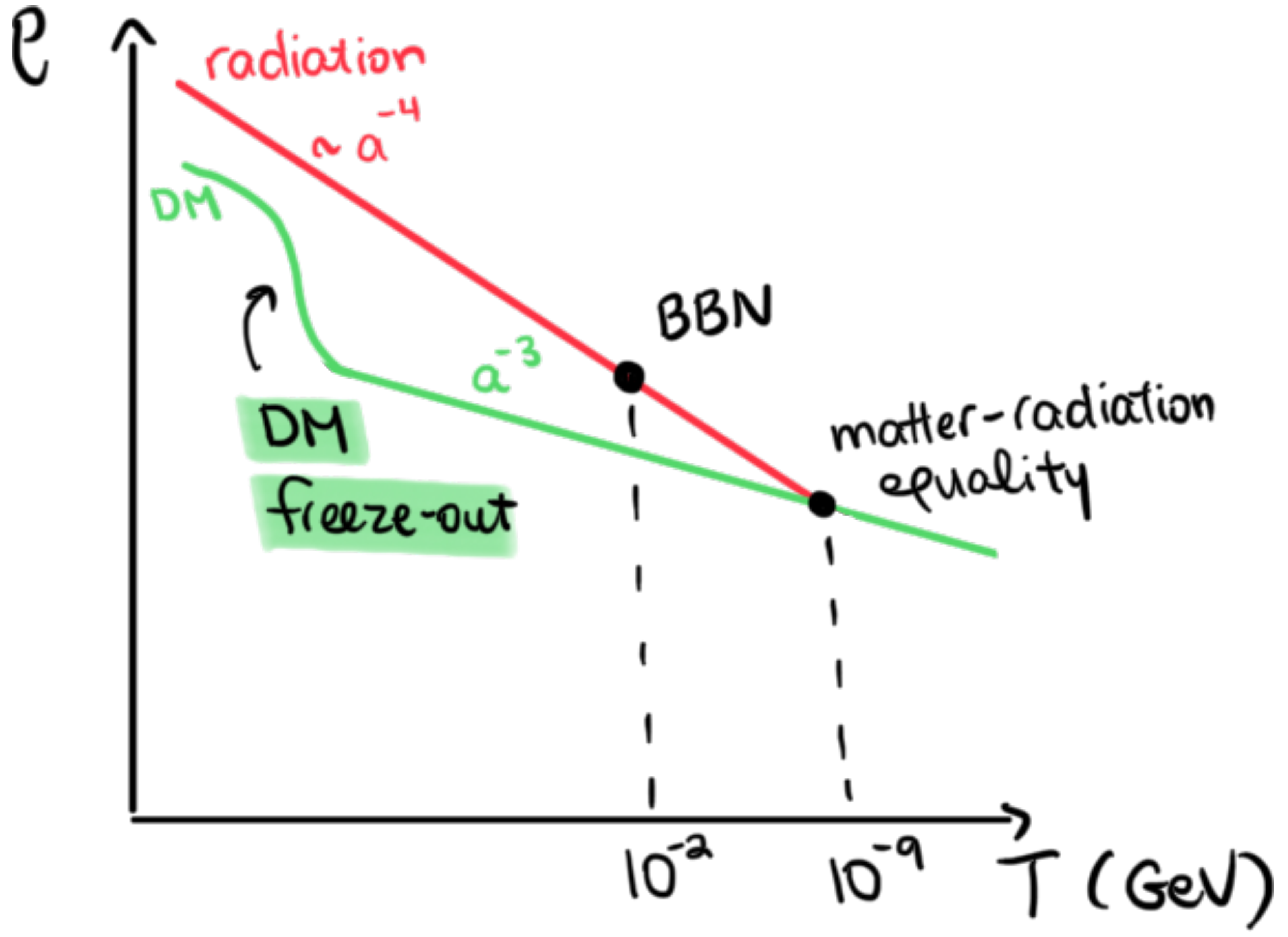


How is heavy DM produced in the early universe?

For context, WIMPs

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



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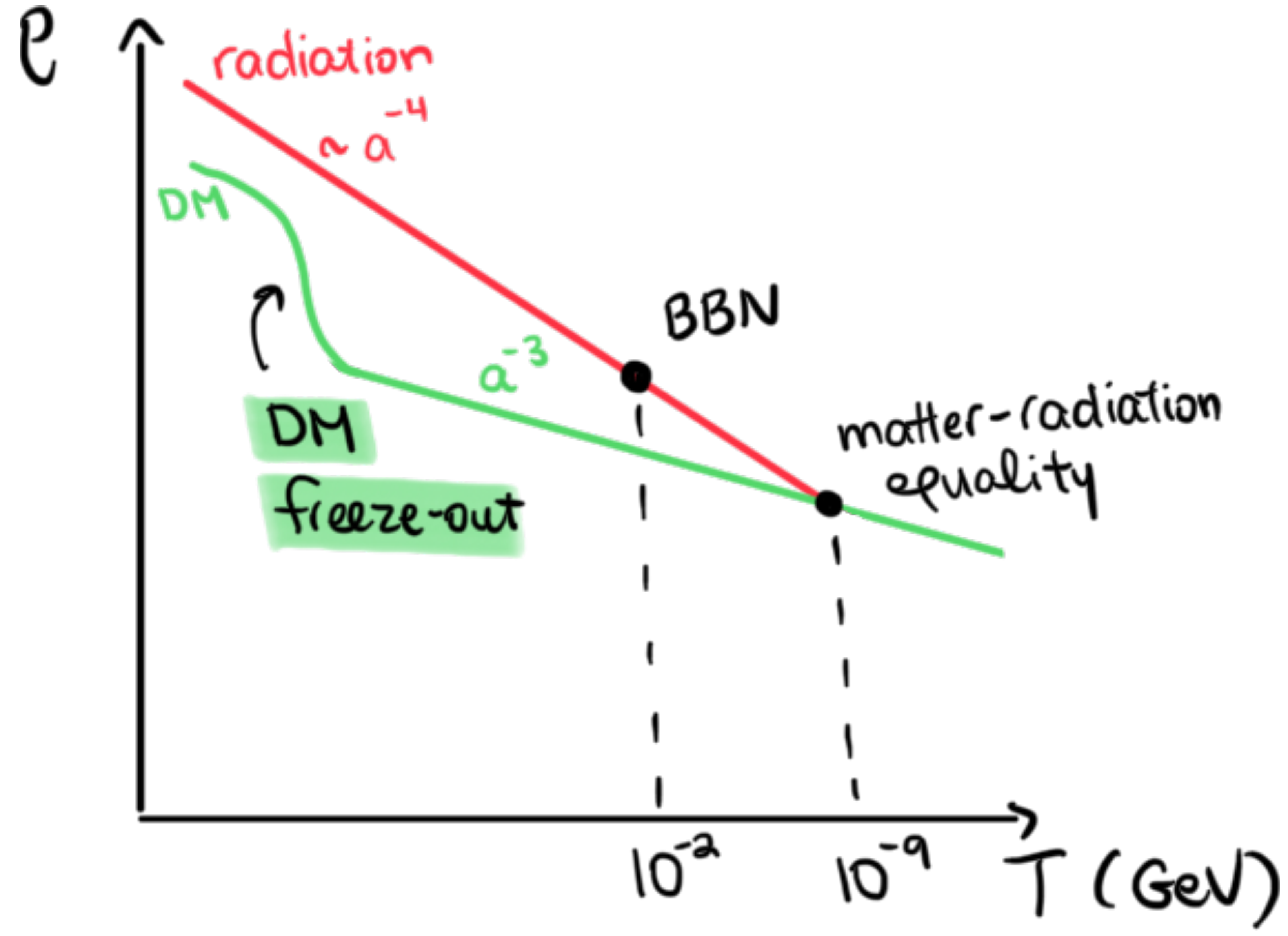


upper bound for $2 \rightarrow 2$ self-annihilation

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

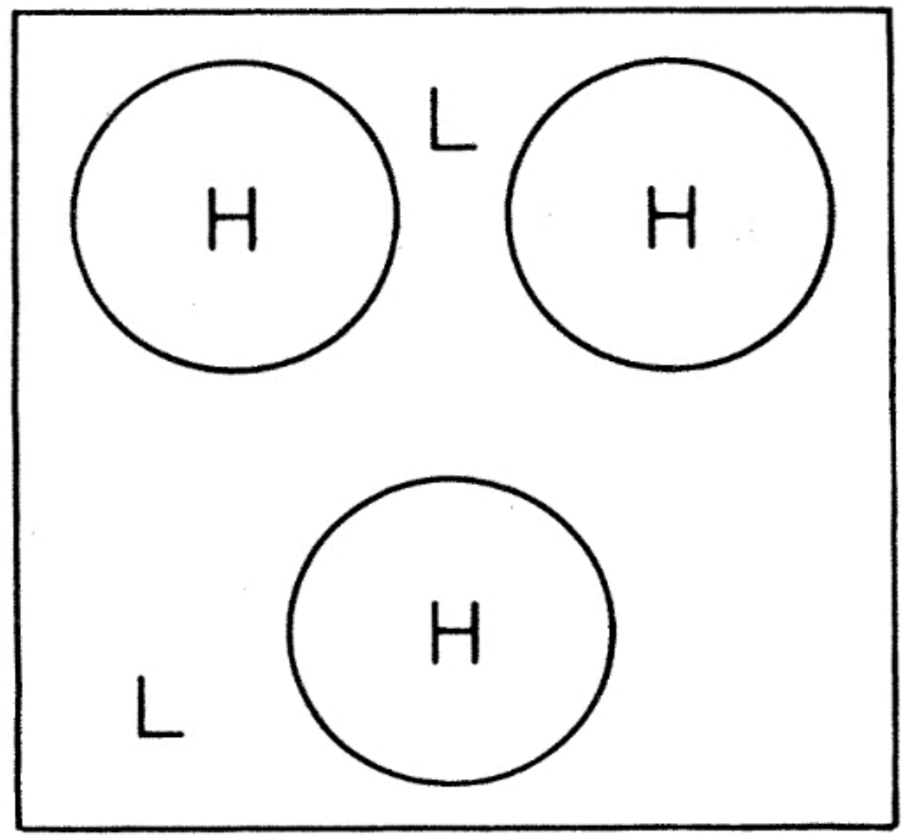
Griest, Kamionkowski '90

There are many ways to get to higher masses!

How is heavy DM produced in the early universe?

no freeze-out

“Squeeze out”

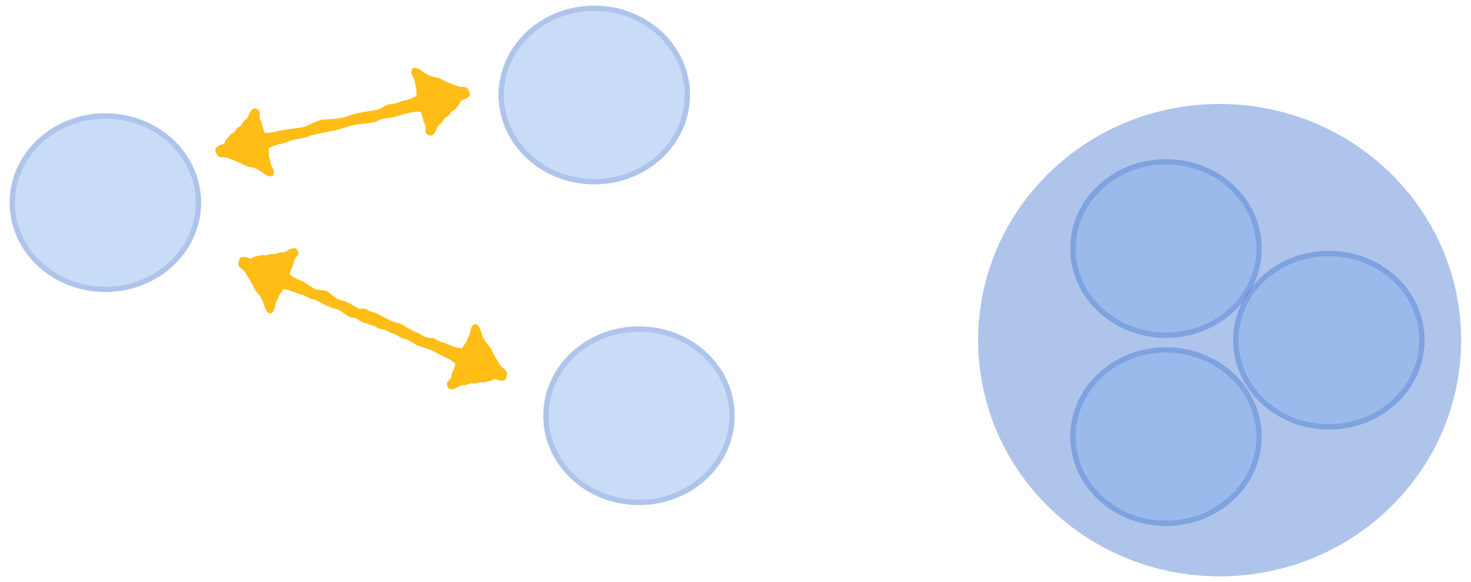


Witten ‘84

phase transition

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

Composite assembly



analogous to SM nucleosynthesis

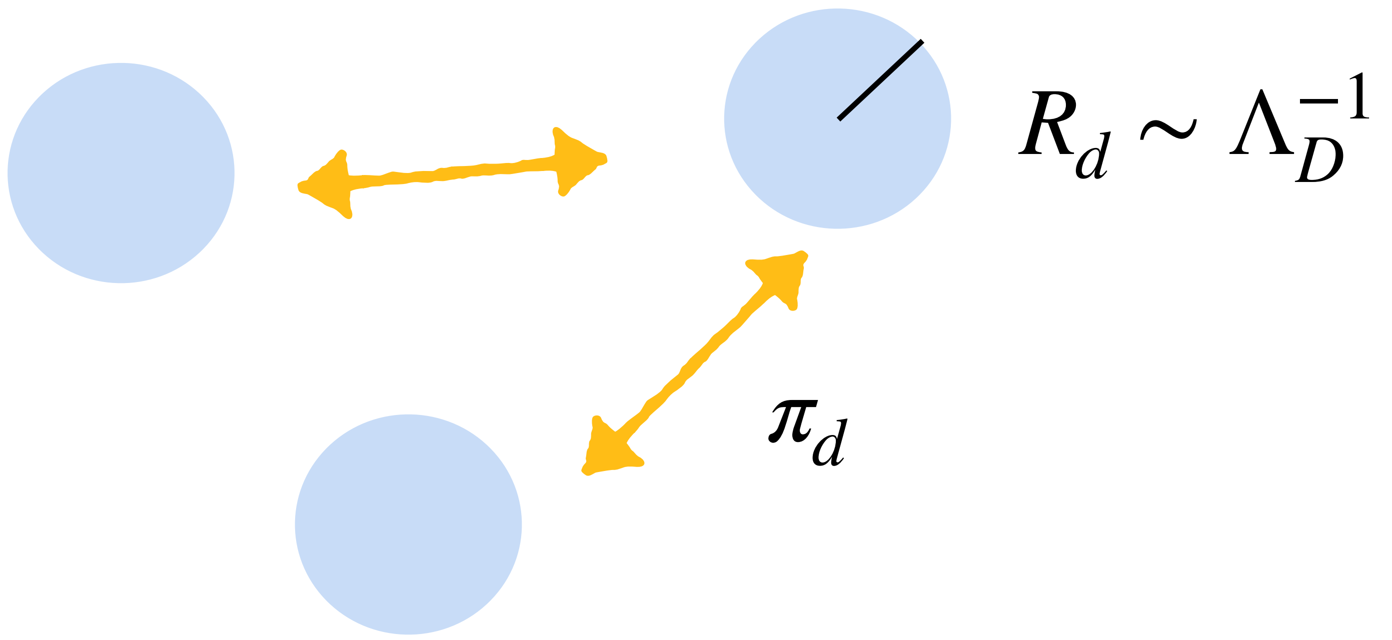
Kjrniak Sigurdson ‘14
Gresham Lou Zurek ’17
Grabowska Melia Rajendra ‘18
and many others…

Today's two recipes for composite assembly

"Nuclear" DM

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

form "nucleons" at confinement scale Λ_D

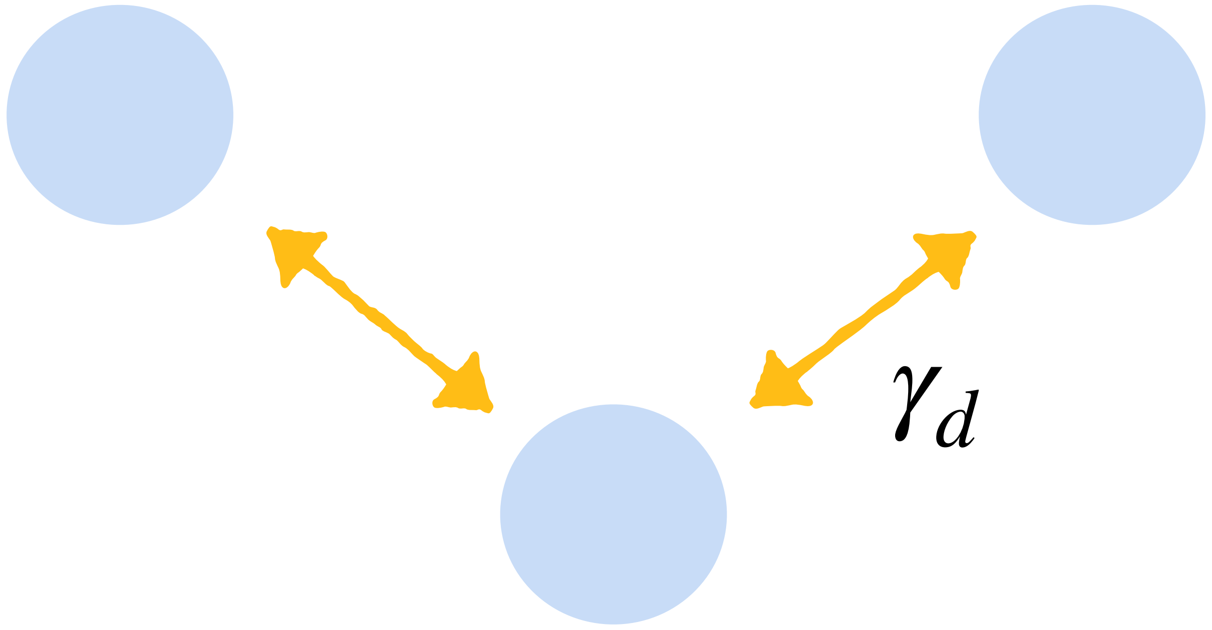


e.g. Krnjaic Sigurdson '14

attractive force due to dark pion:
nucleons form nuclei

"Molecular" DM

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

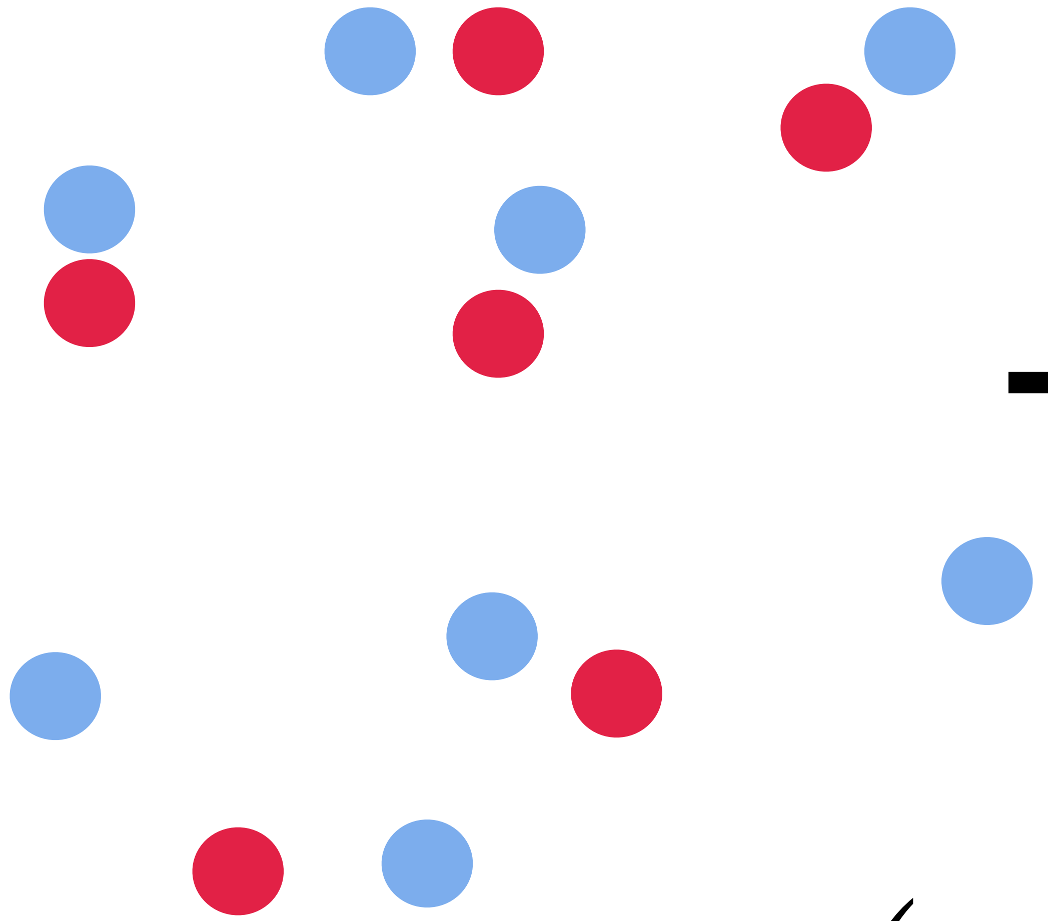


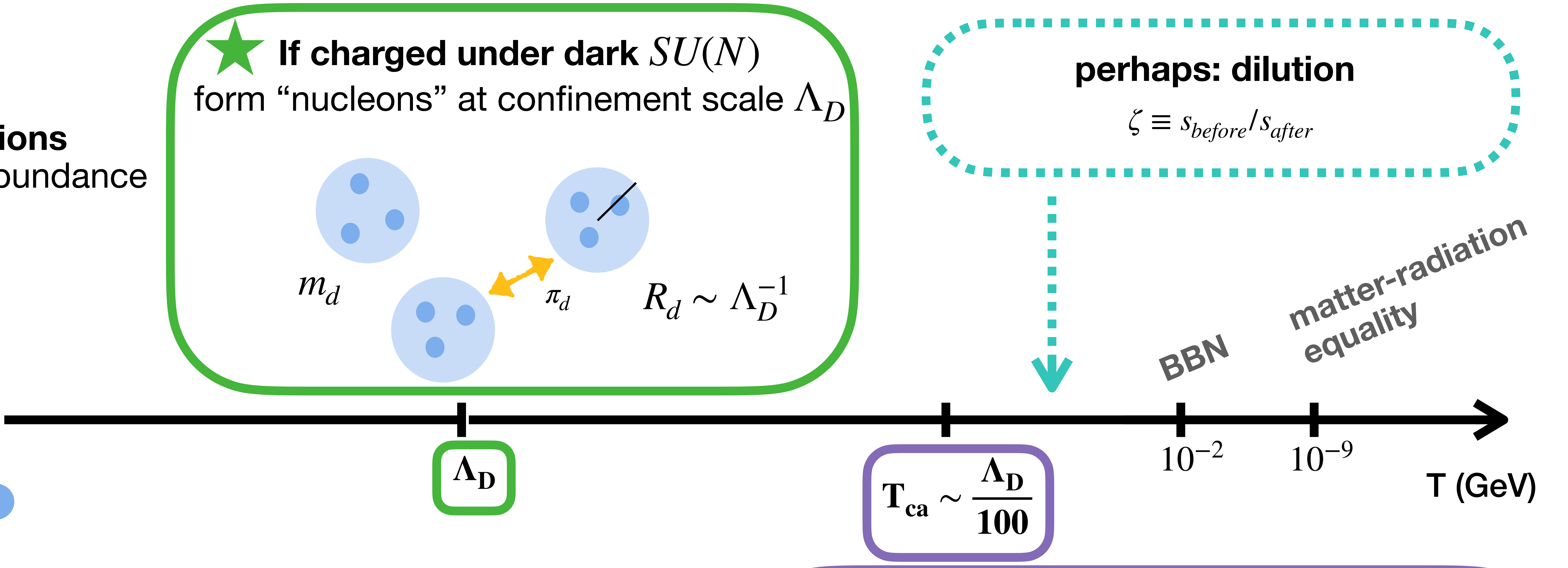
attractive force due to dark photon exchange

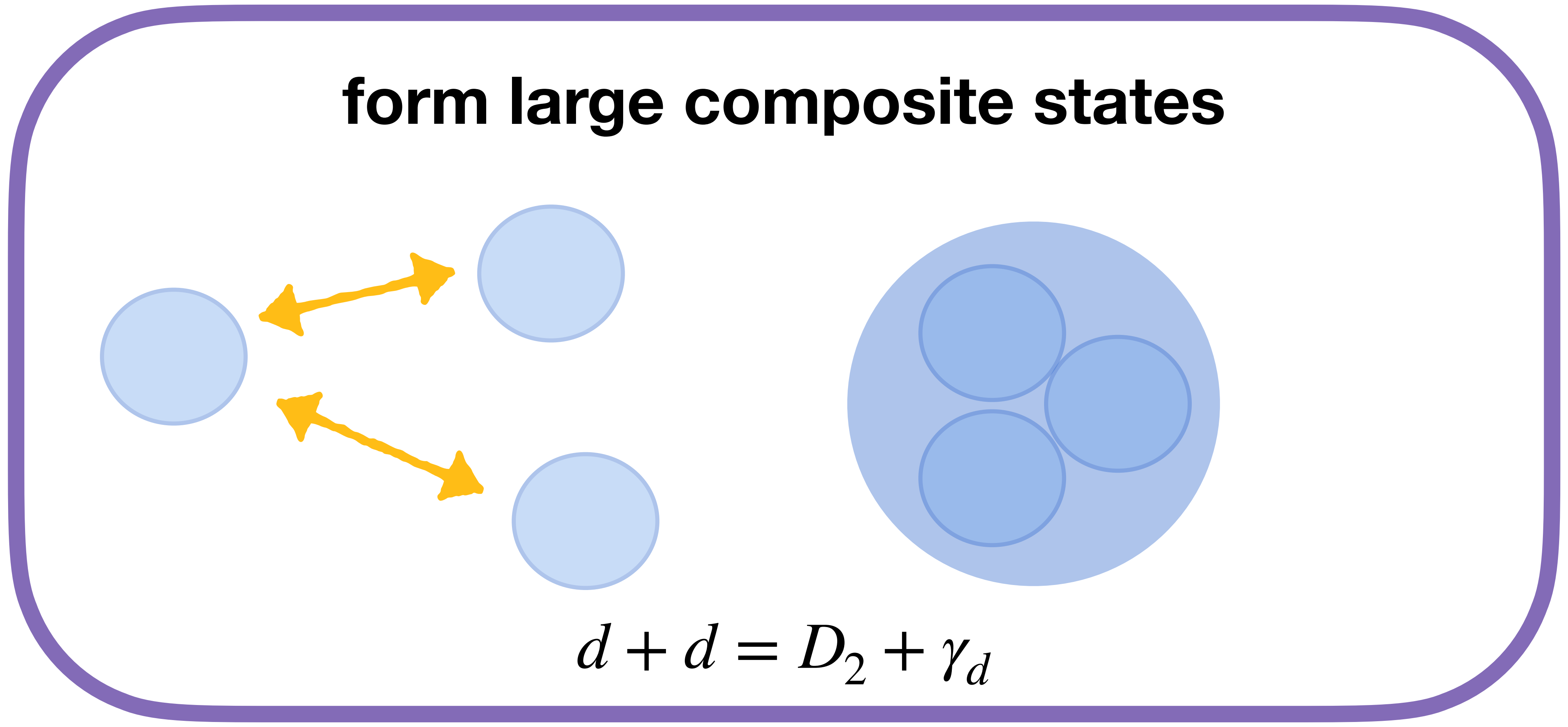
Λ_D^{-1} = interconstituent spacing

A timeline of composite assembly

dark, asymmetric fermions
asymmetry determines DM abundance



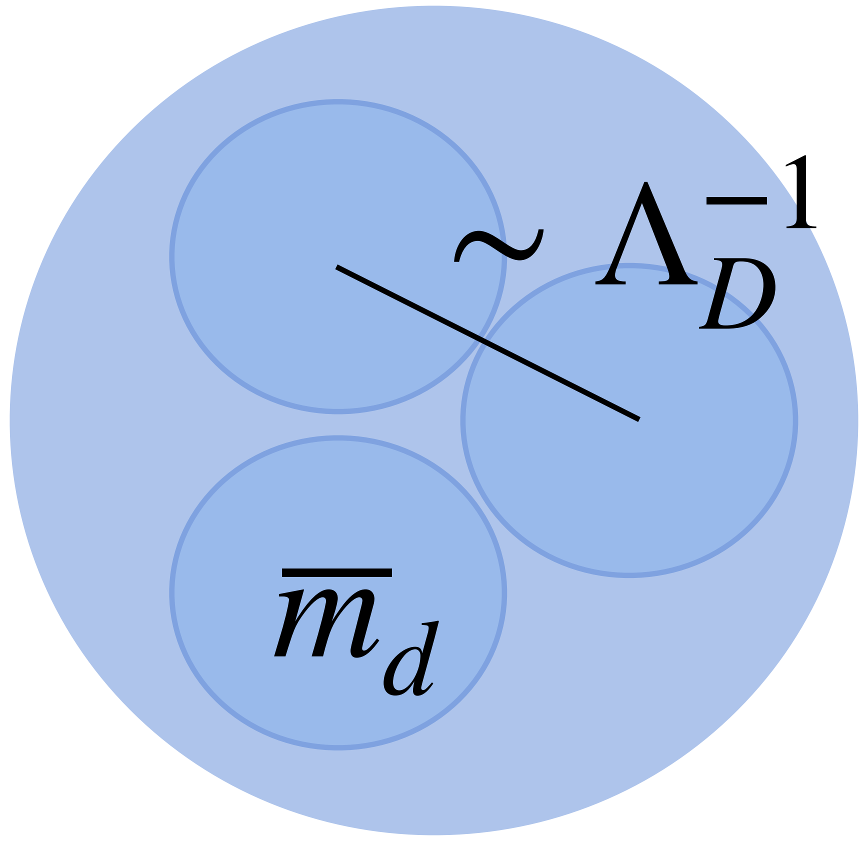




$$N_D = 2.5 \times 10^{13} \left(\frac{10}{g_{ca}^*}\right)^{3/5} \left(\frac{T_{ca}}{0.01\ \mathrm{GeV}}\right)^{9/5} \left(\frac{10^{-5}}{\zeta}\right)^{6/5} \left(\frac{10\ \mathrm{GeV}}{\overline{m}_d}\right)^{9/5} \left(\frac{\mathrm{GeV}}{\Lambda_D}\right)^{12/5}$$

Parametrizing composites with Λ_D

Λ_D^{-1} = interconstituent spacing



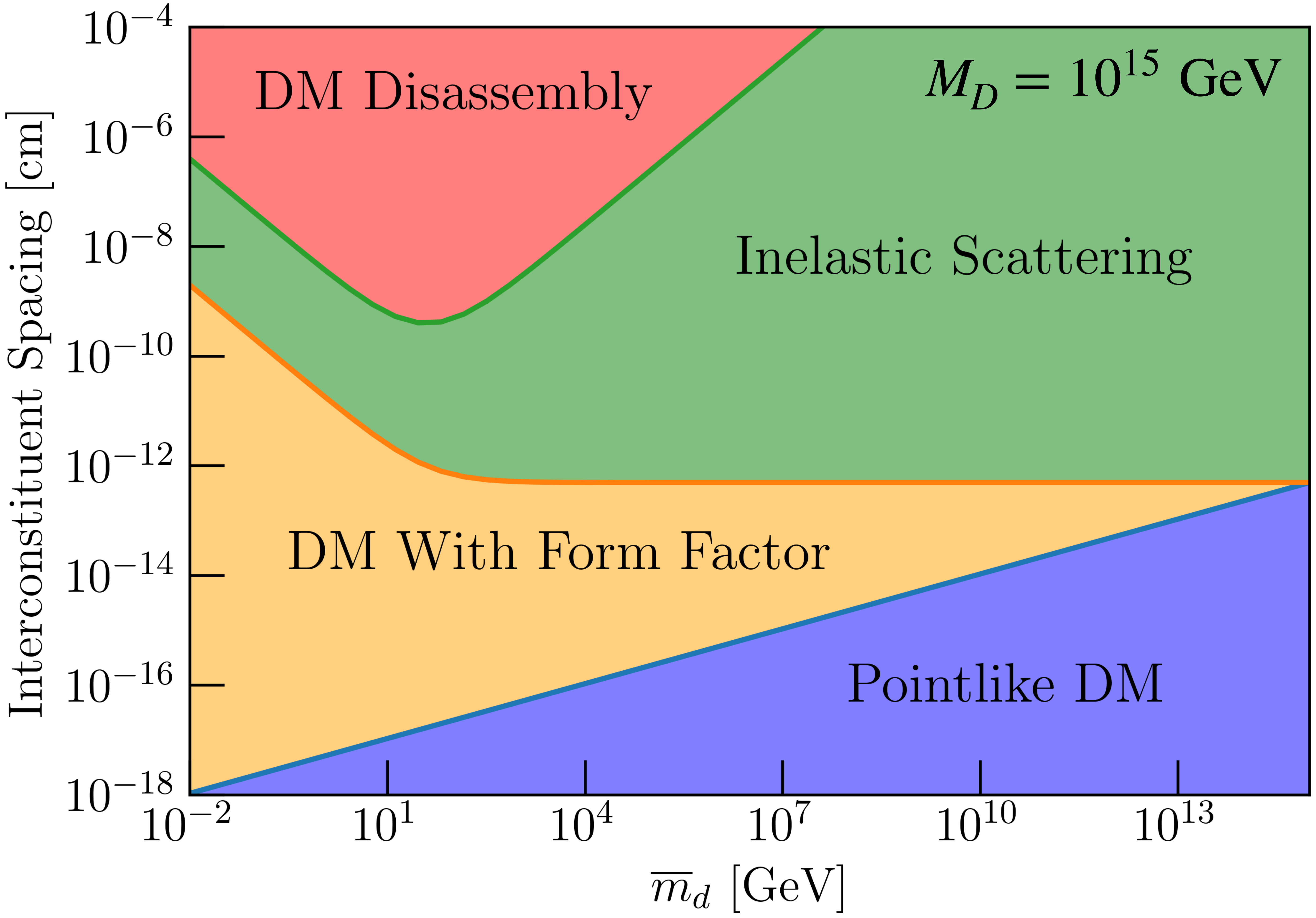
Binding energy

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

Size

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

Regimes for DM-nucleus scattering



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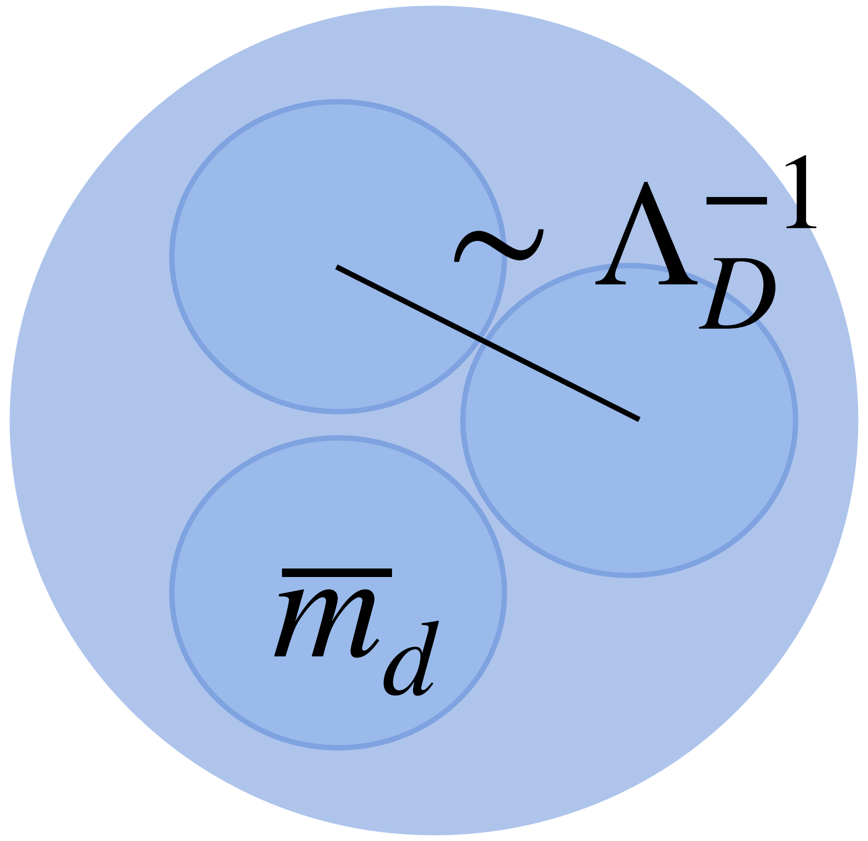

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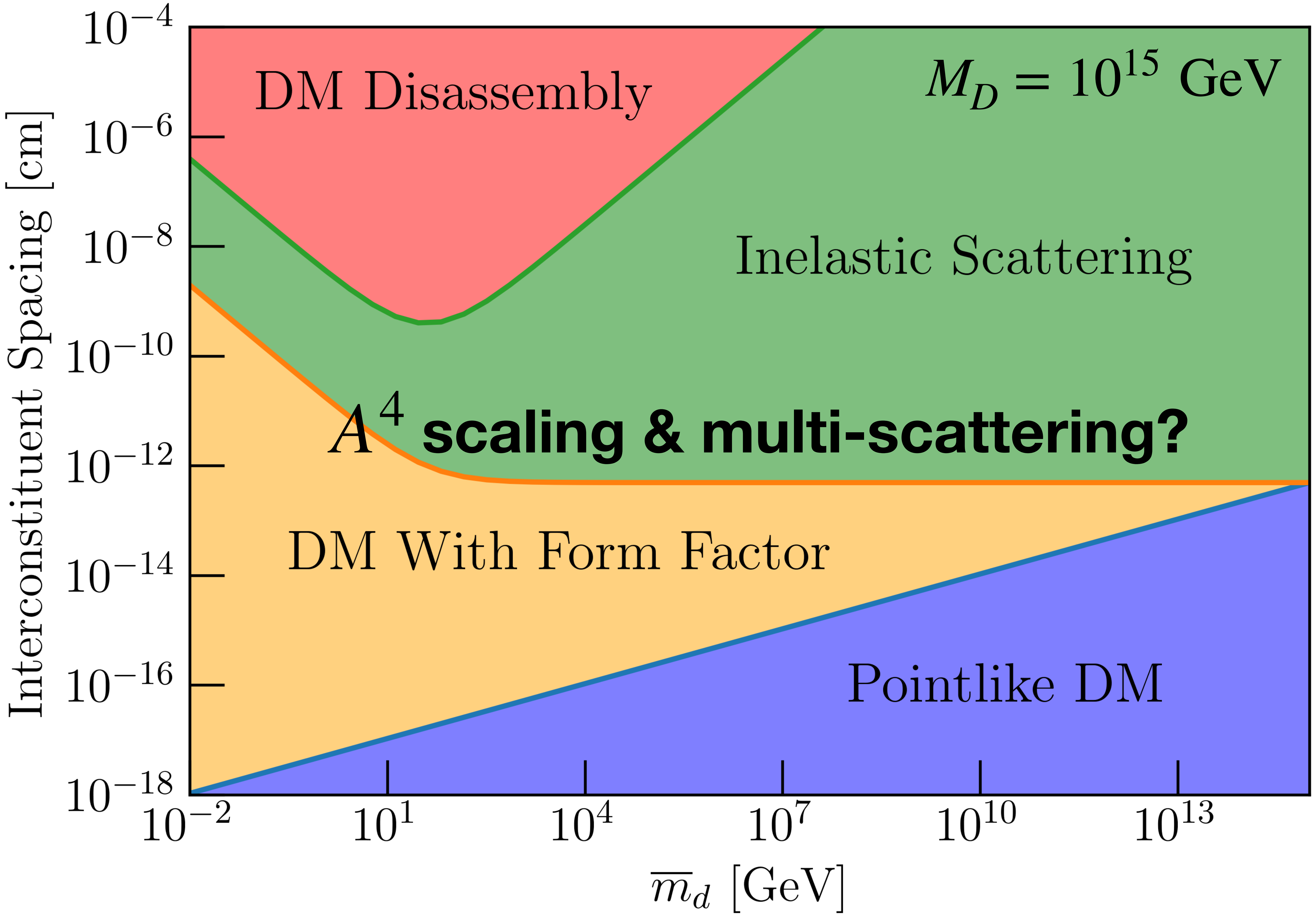
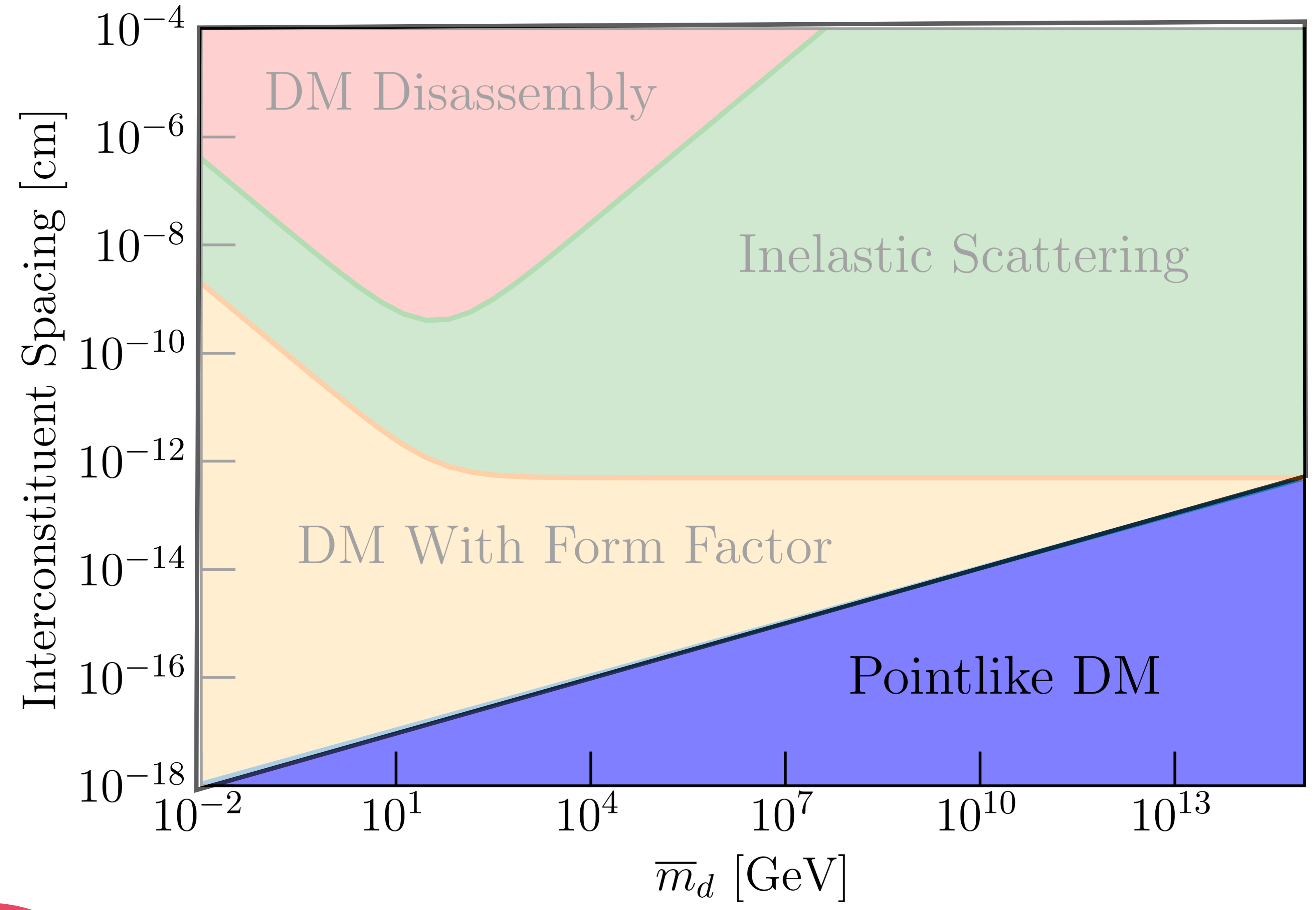
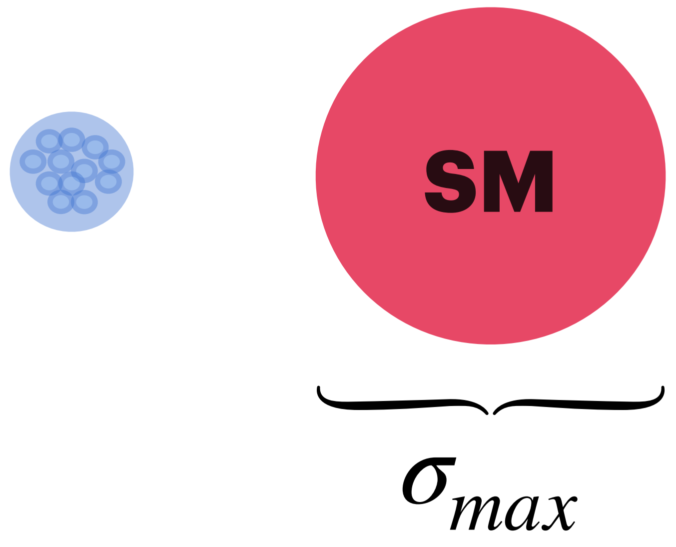
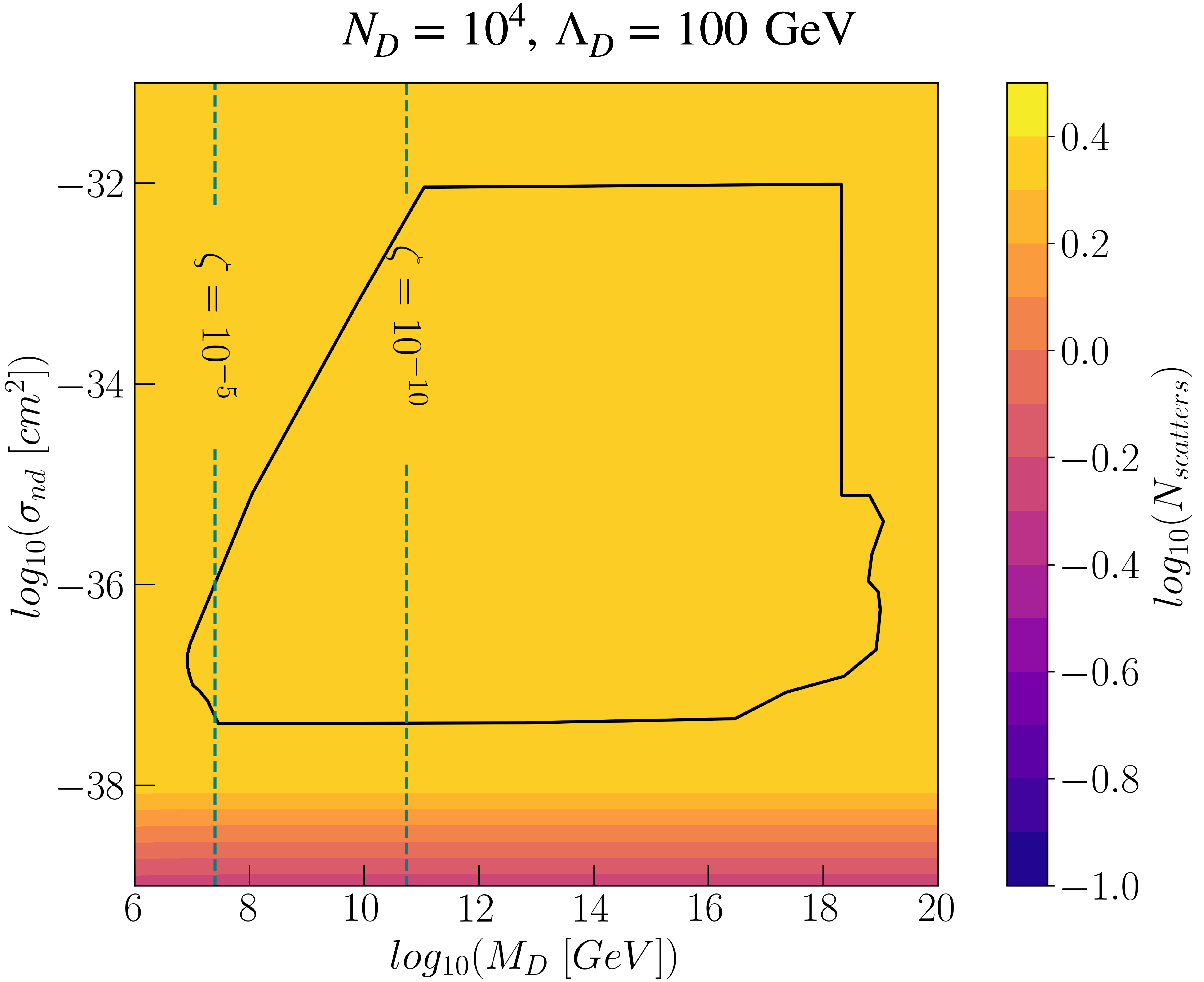


Pointlike regime

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

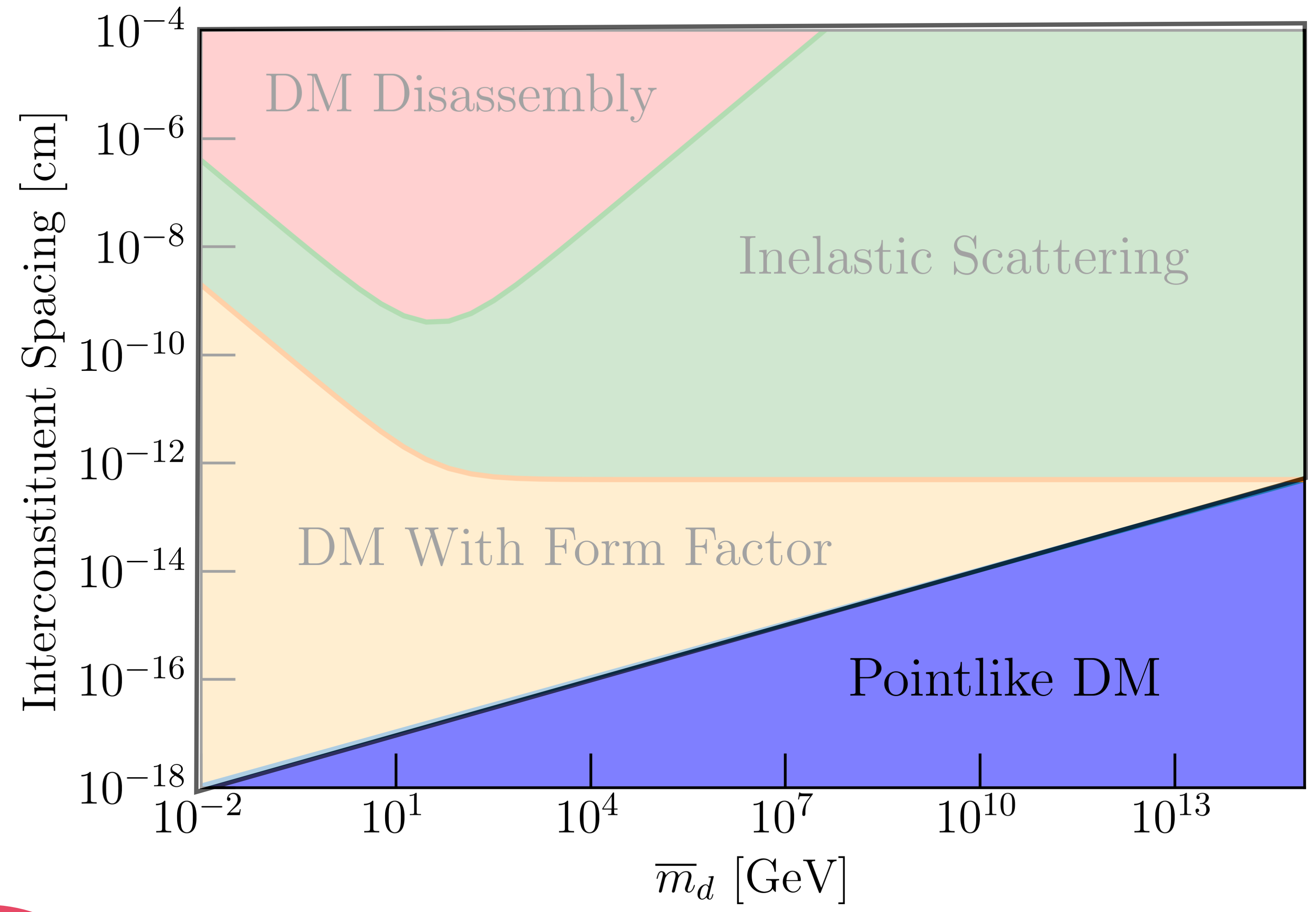


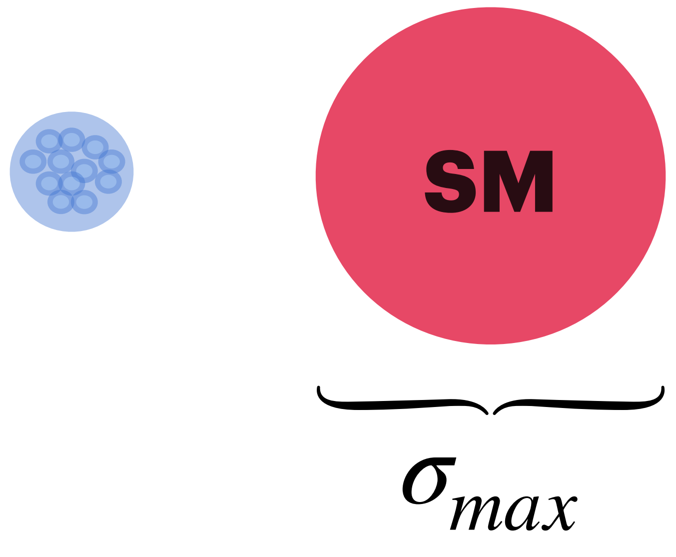


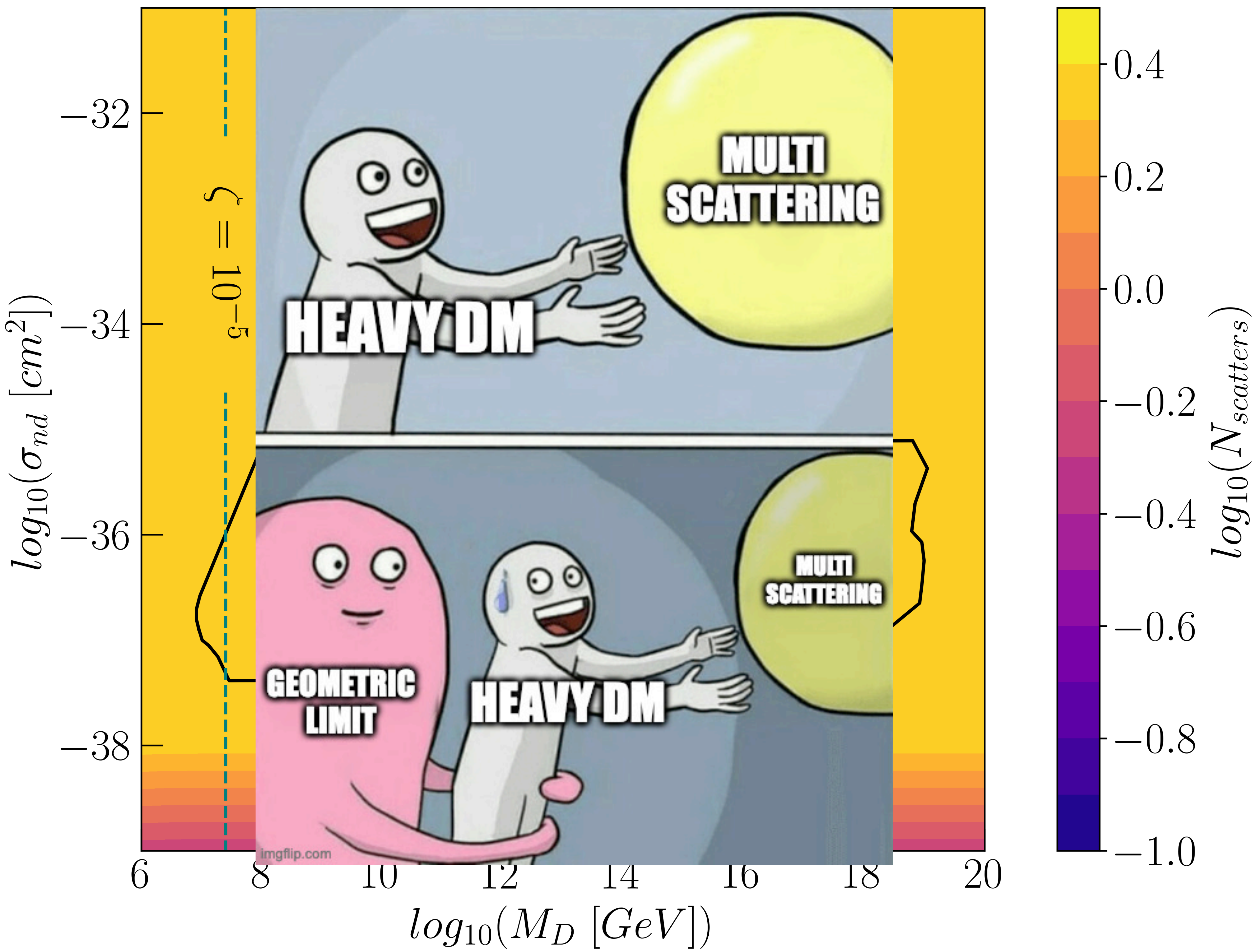


Pointlike regime: no multi-scattering

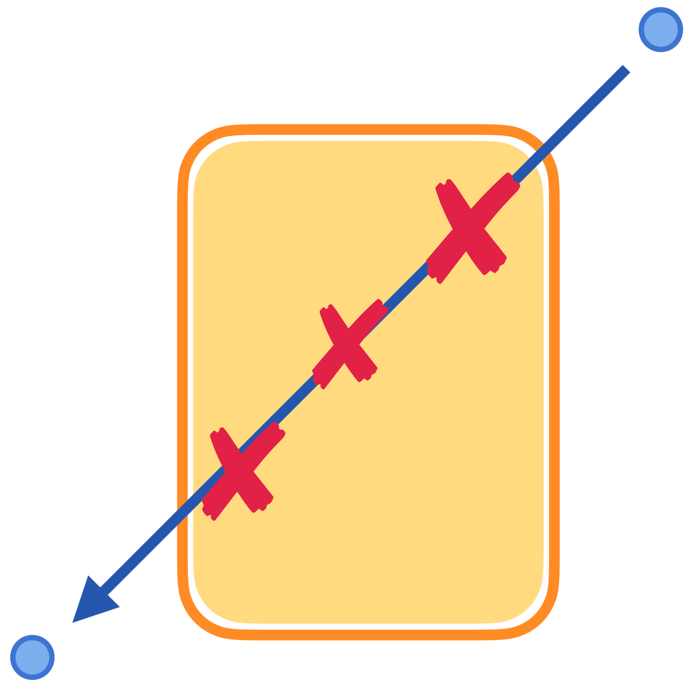
$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{AD}}{\mu_{nd}}\right)^2 A^2 N_D^2 \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R)$$



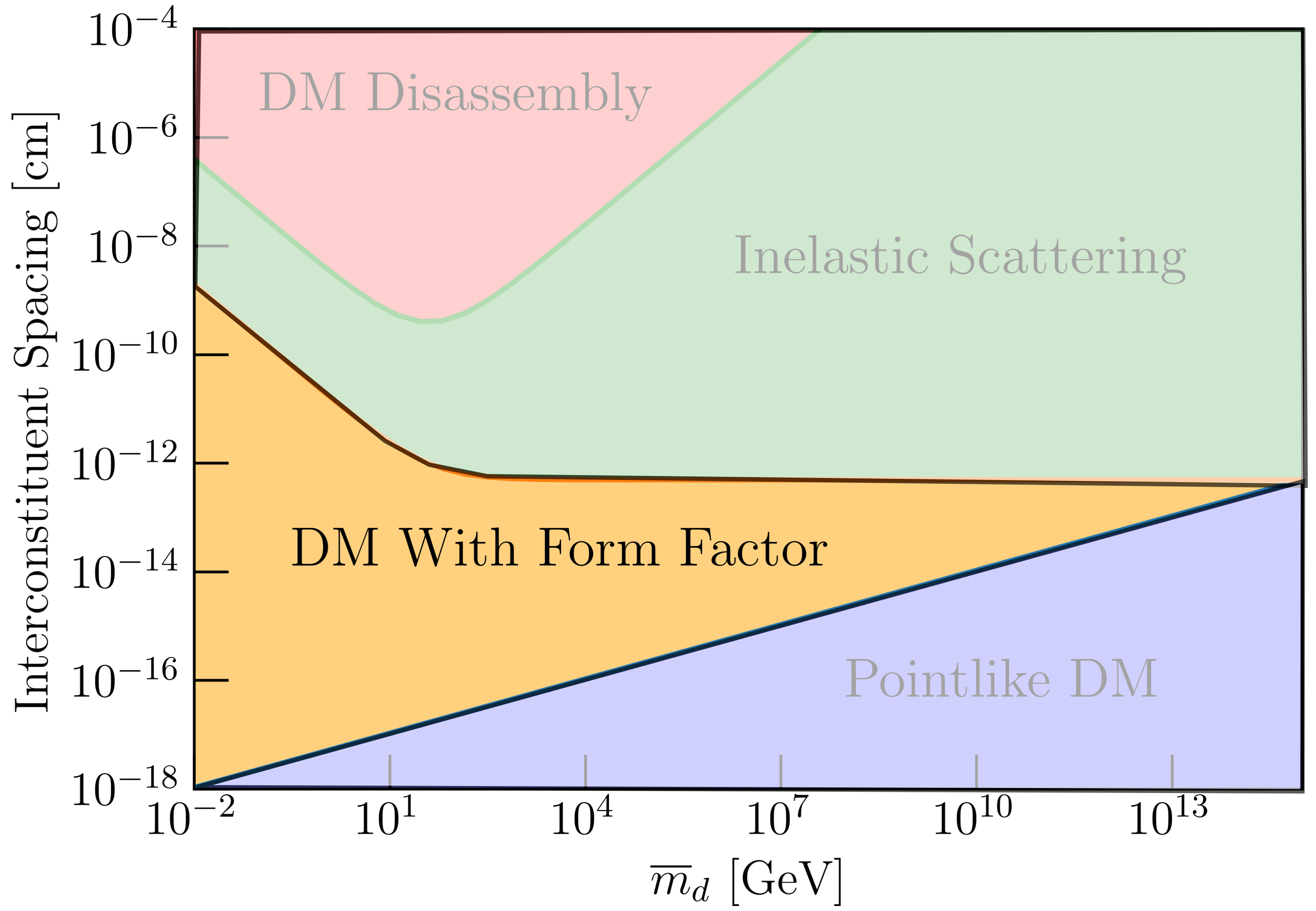




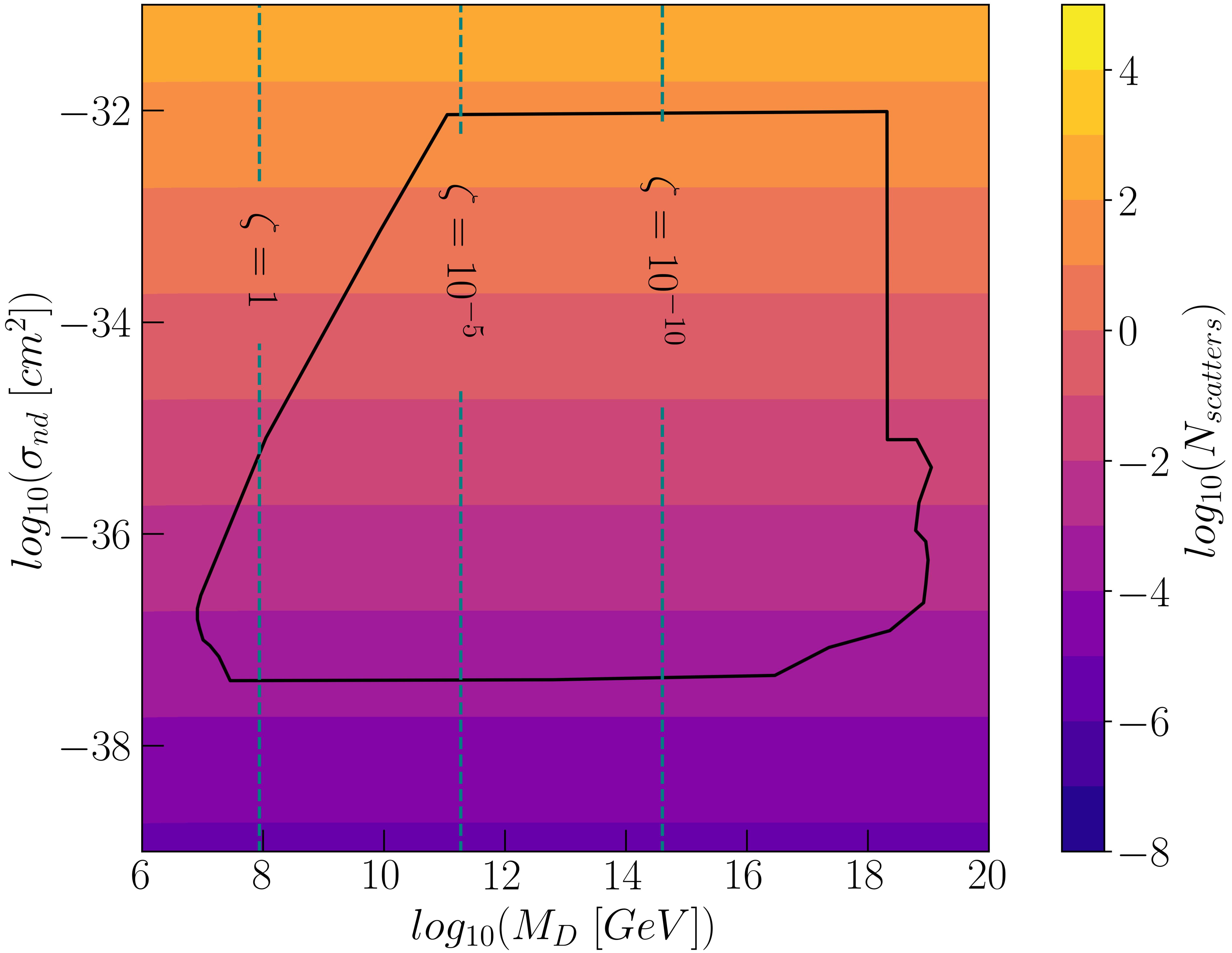
DM with form factor: doing better

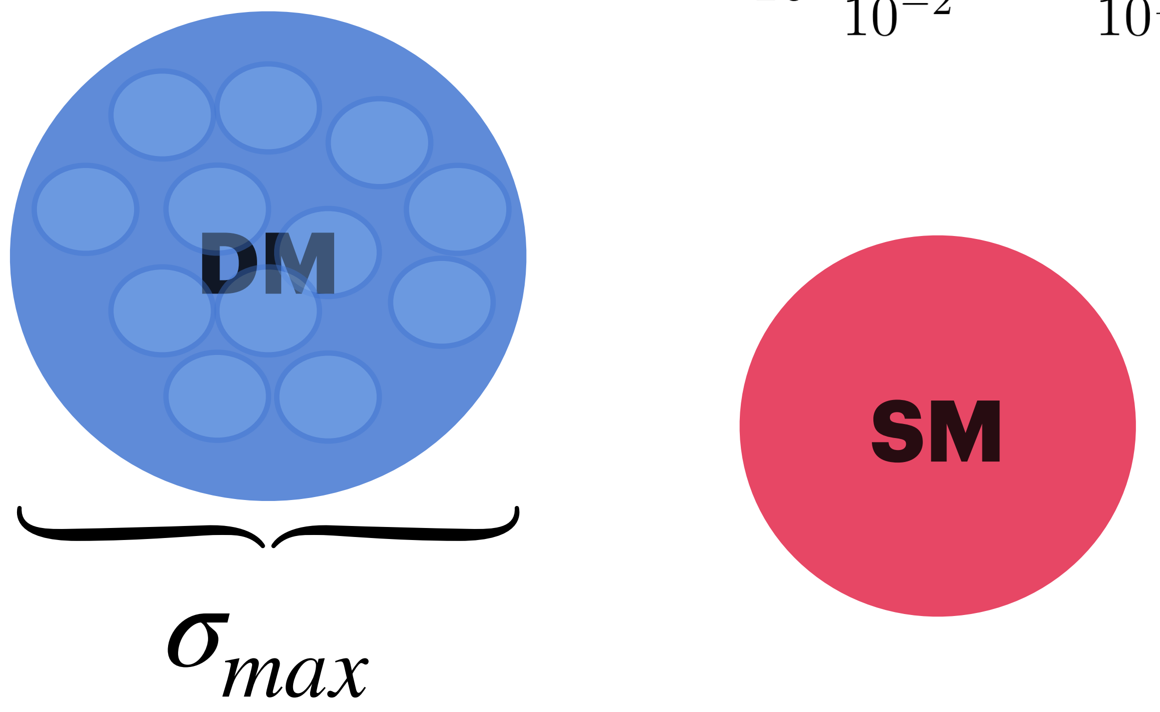


$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{AD}}{\mu_{nd}}\right)^2 A^2 N_D^2\, g^2 \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R) F_D^2(E_R)$$

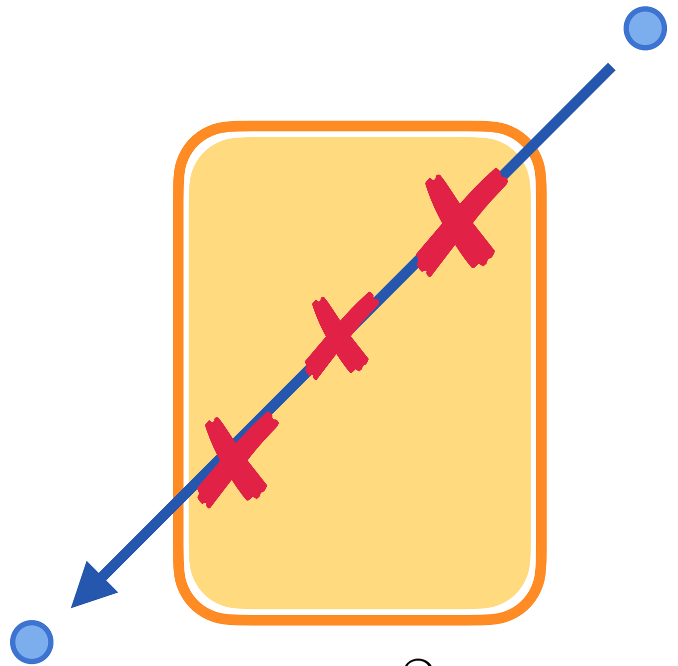


$N_D = 10^4,\ \Lambda_D = 10$ MeV

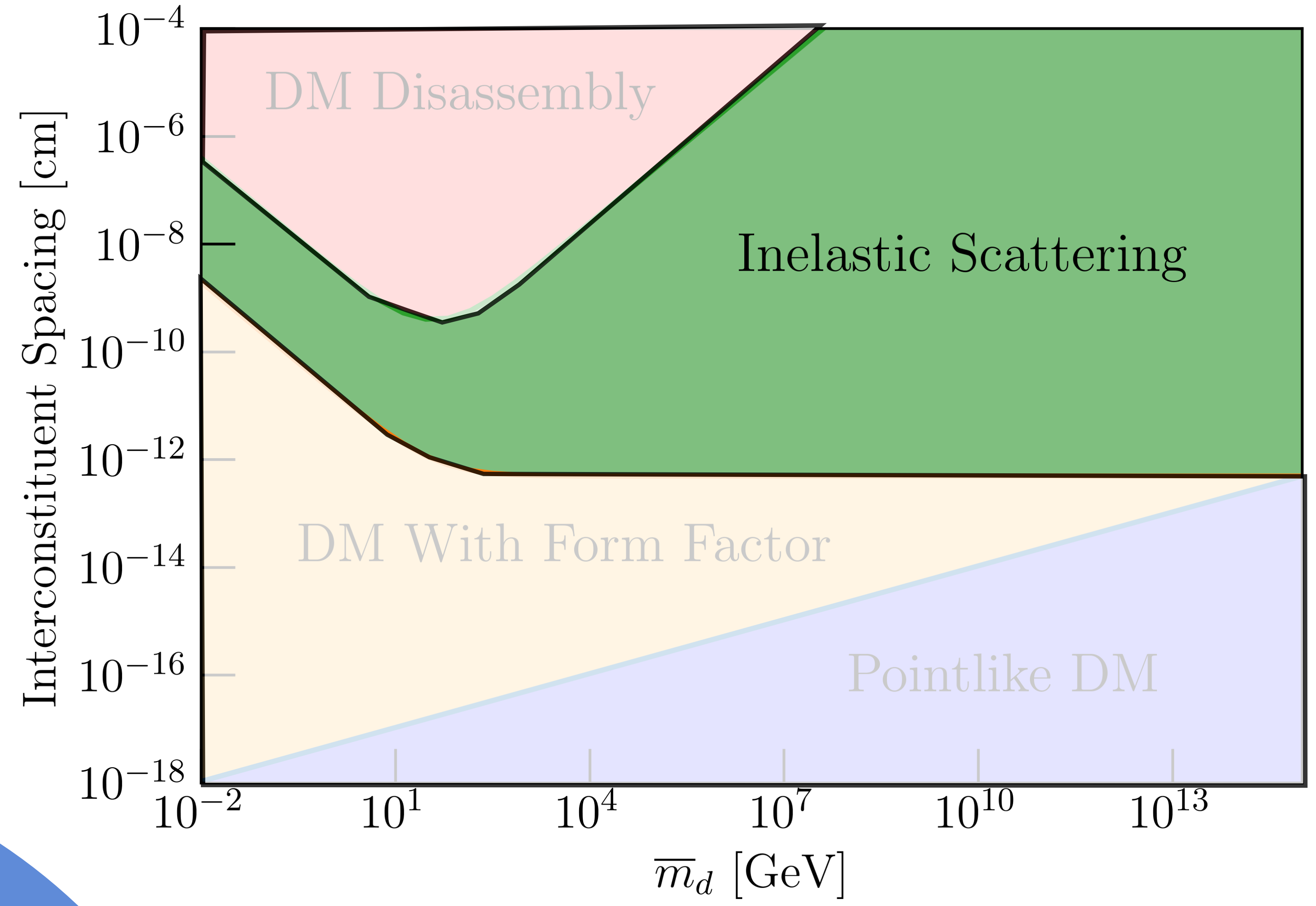




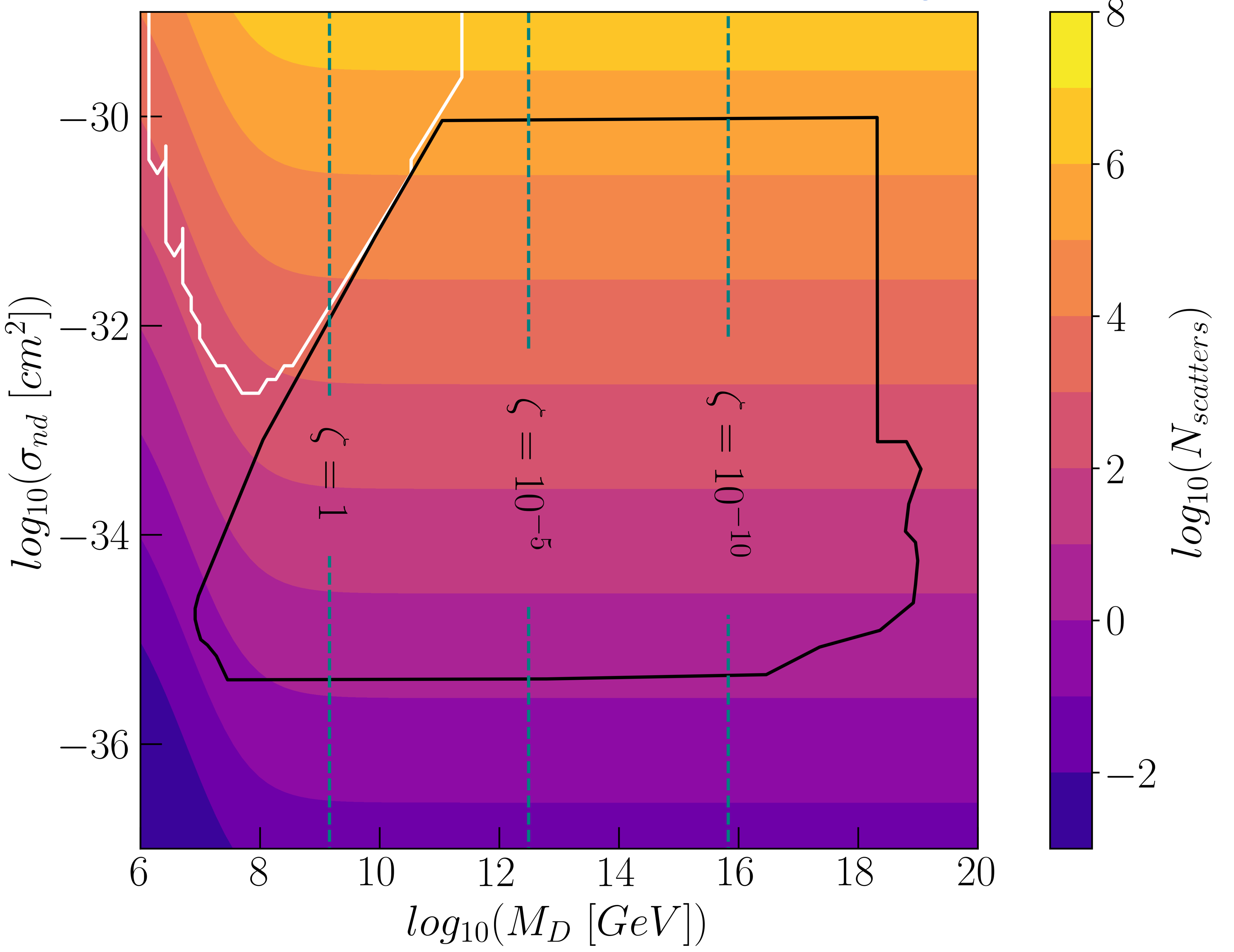
Inelastic scattering regime: hooray!

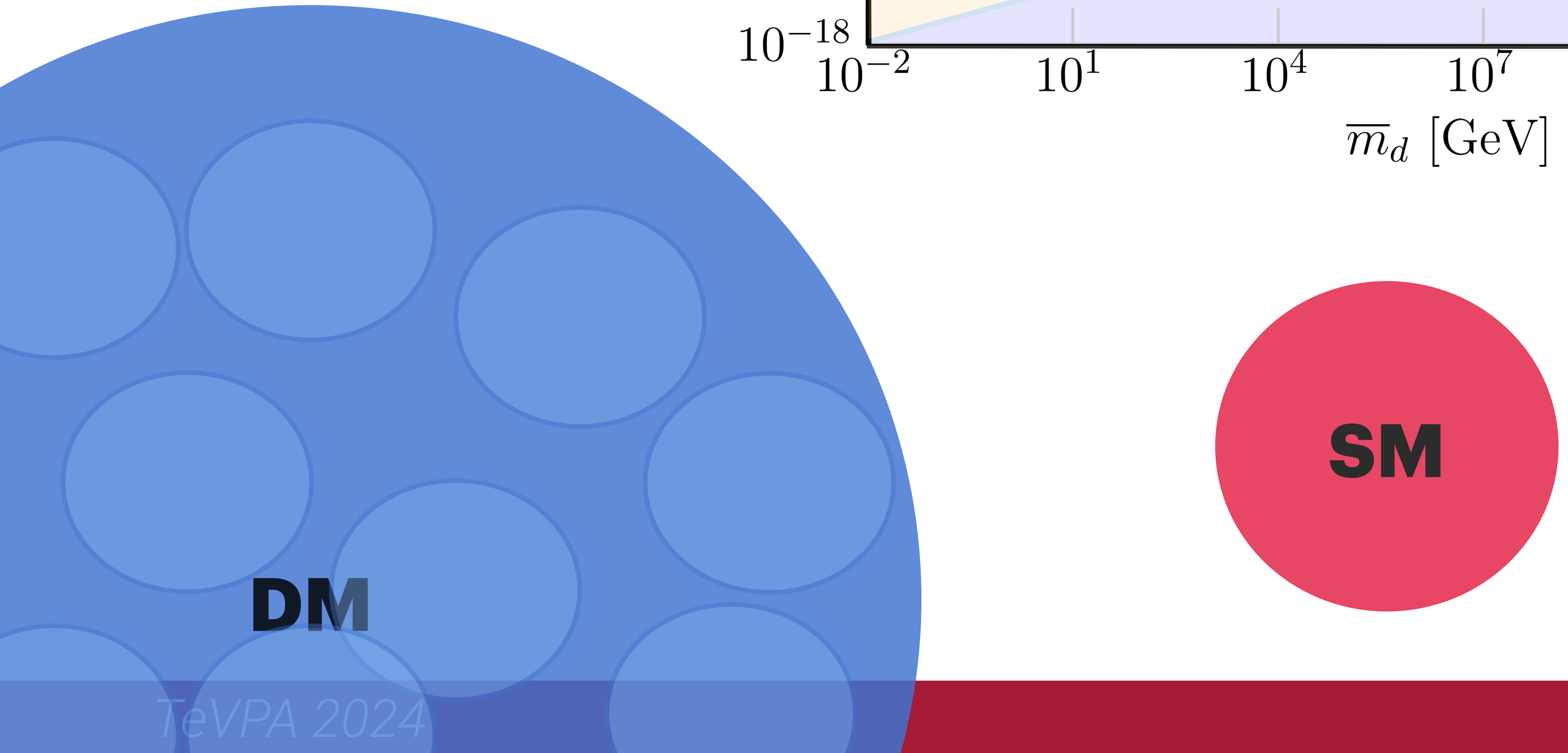


$$\frac{d\sigma_{AD}}{dE_R} = \left(\frac{\mu_{Ad}}{\mu_{nd}}\right)^2 \boxed{A^2 N_D}\, g \frac{d\sigma_{nd}}{dE_R} F_A^2(E_R) \boxed{S_D(E_R)}$$



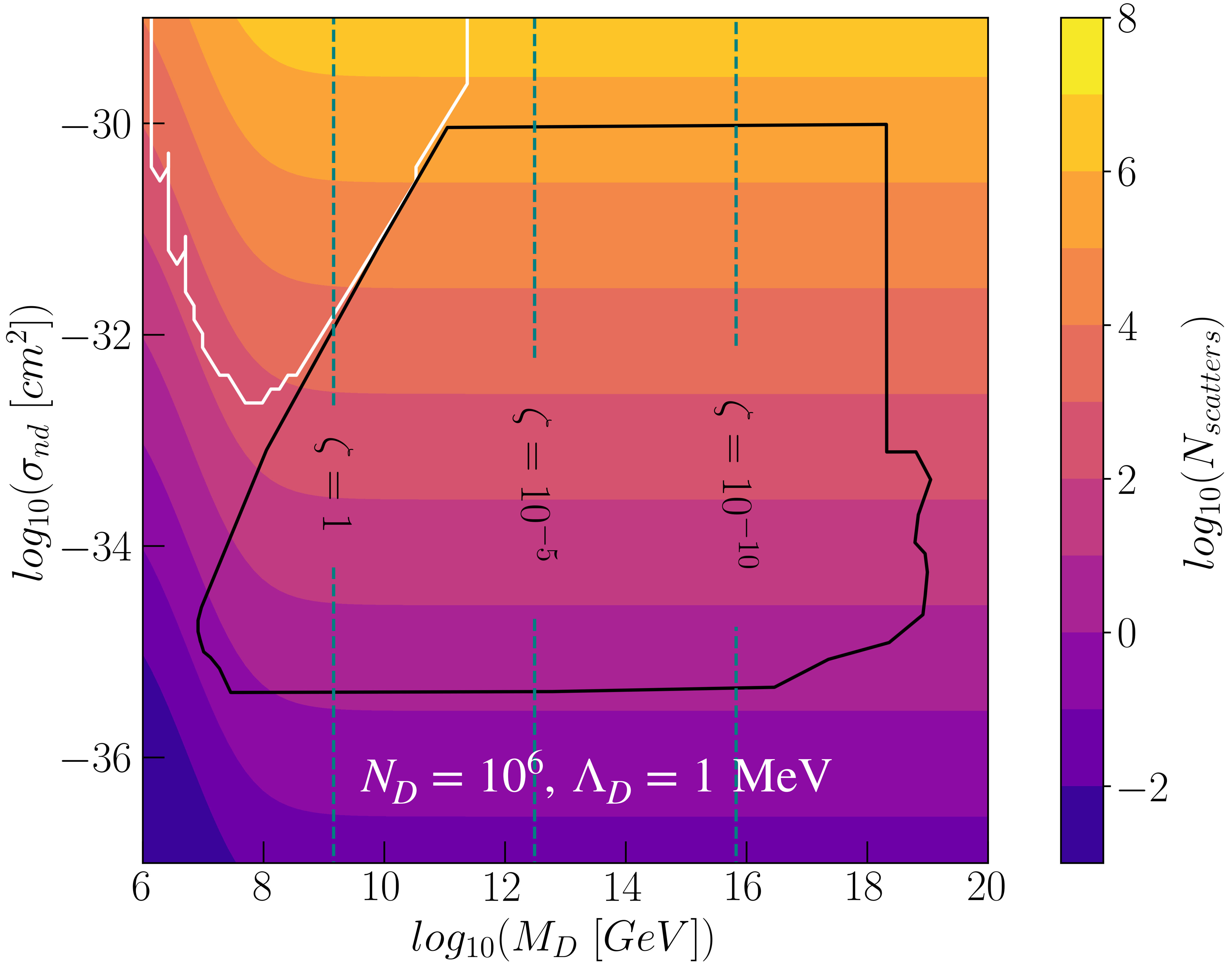
$N_D = 10^6,\ \Lambda_D = 1$ MeV



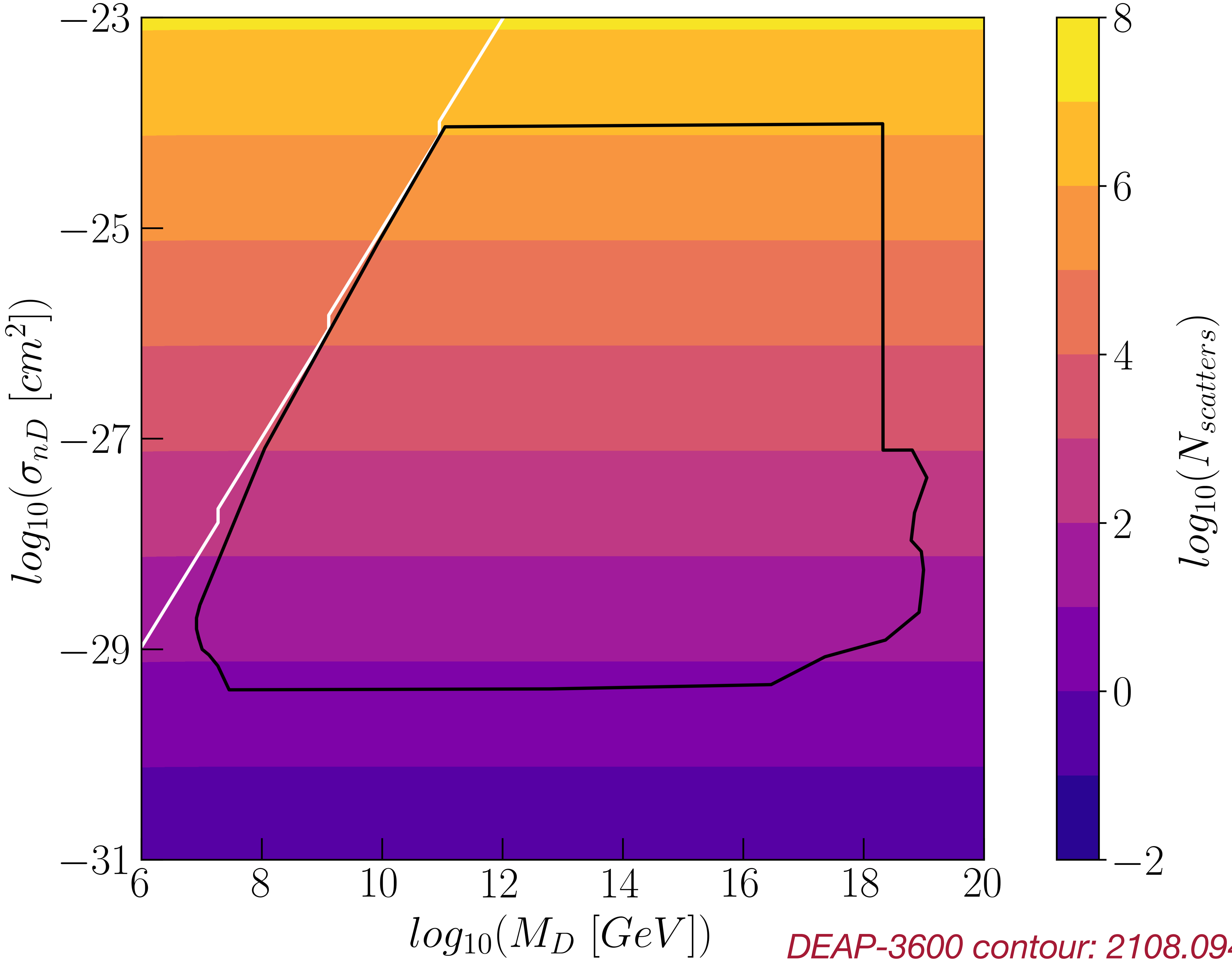


Let's look again at DEAP multiscatter search

Incoherent scattering

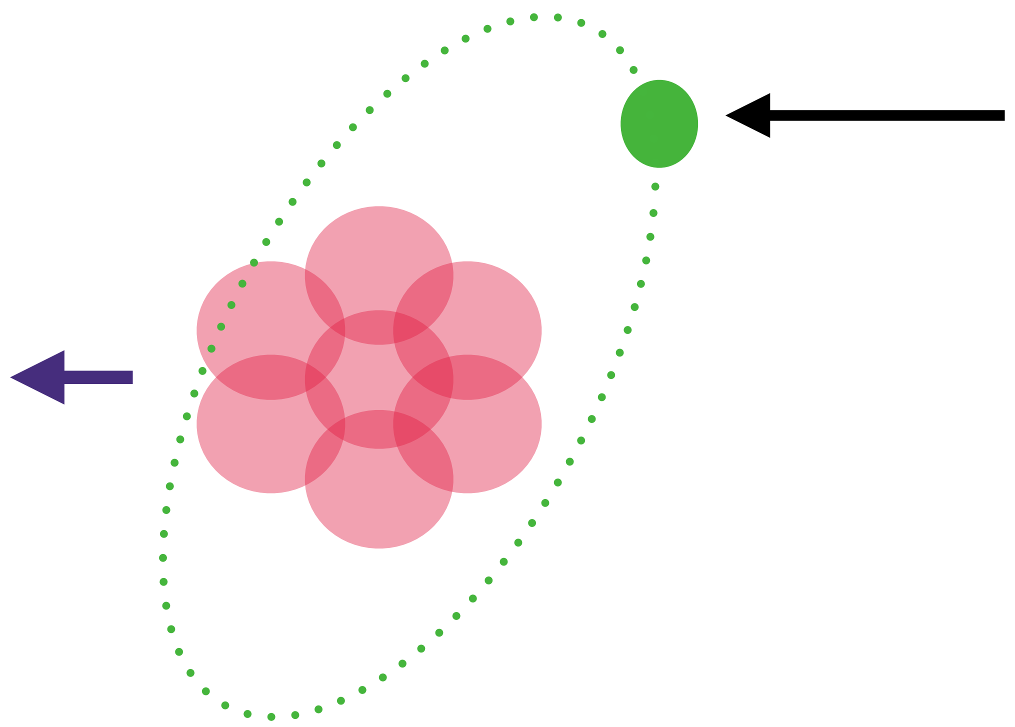


A^4 scaling



DEAP-3600 contour: 2108.09405

What if composites interact with electrons?

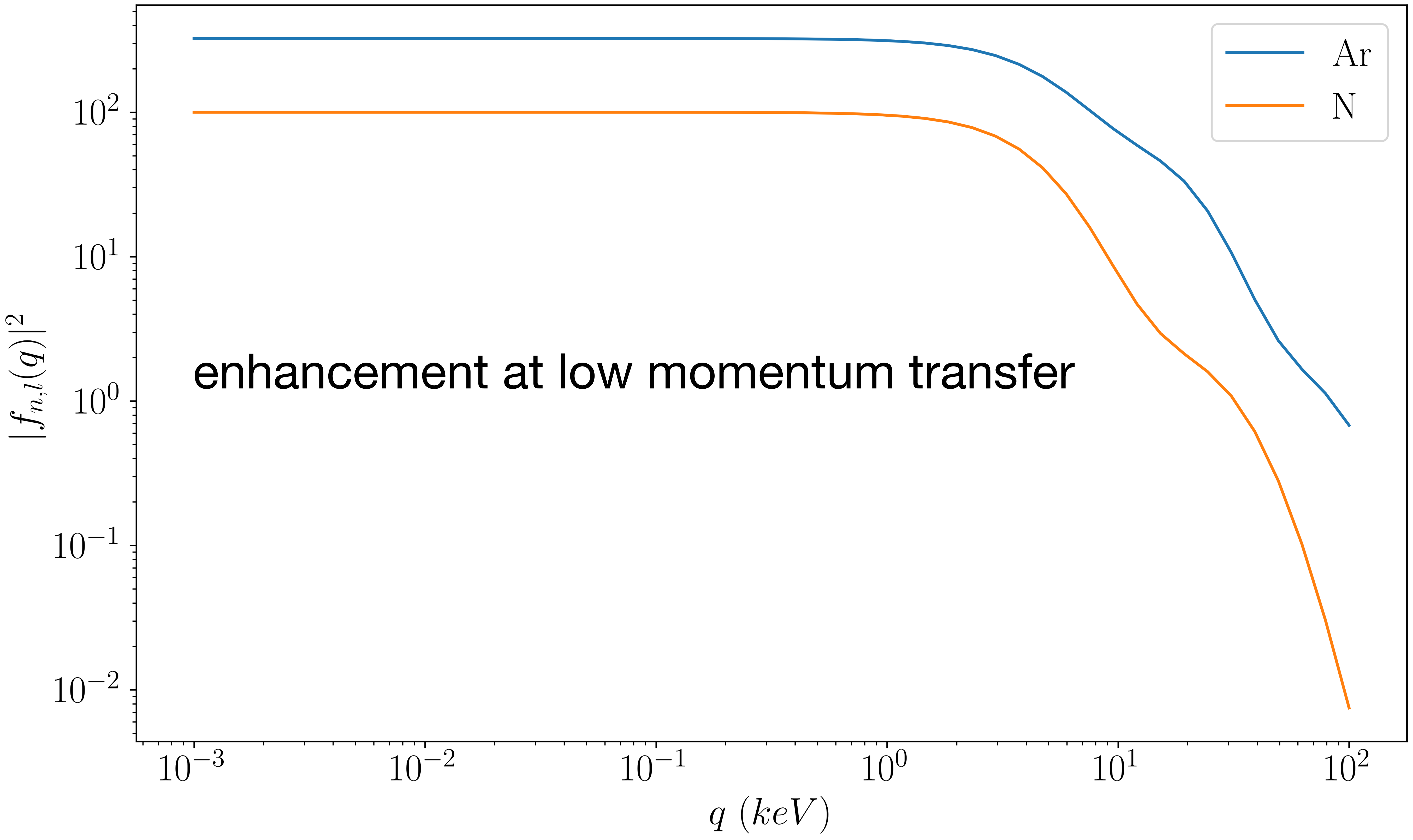


DM-electron recoil could induce a recoil of the whole atom.

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



enhancement at low momentum transfer

Searching for Atomic Scattering in Liquid Argon

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

To conclude, composite DM…

has been a **topic of interest** for a long time.

could cause large numbers of **low-energy scatters**

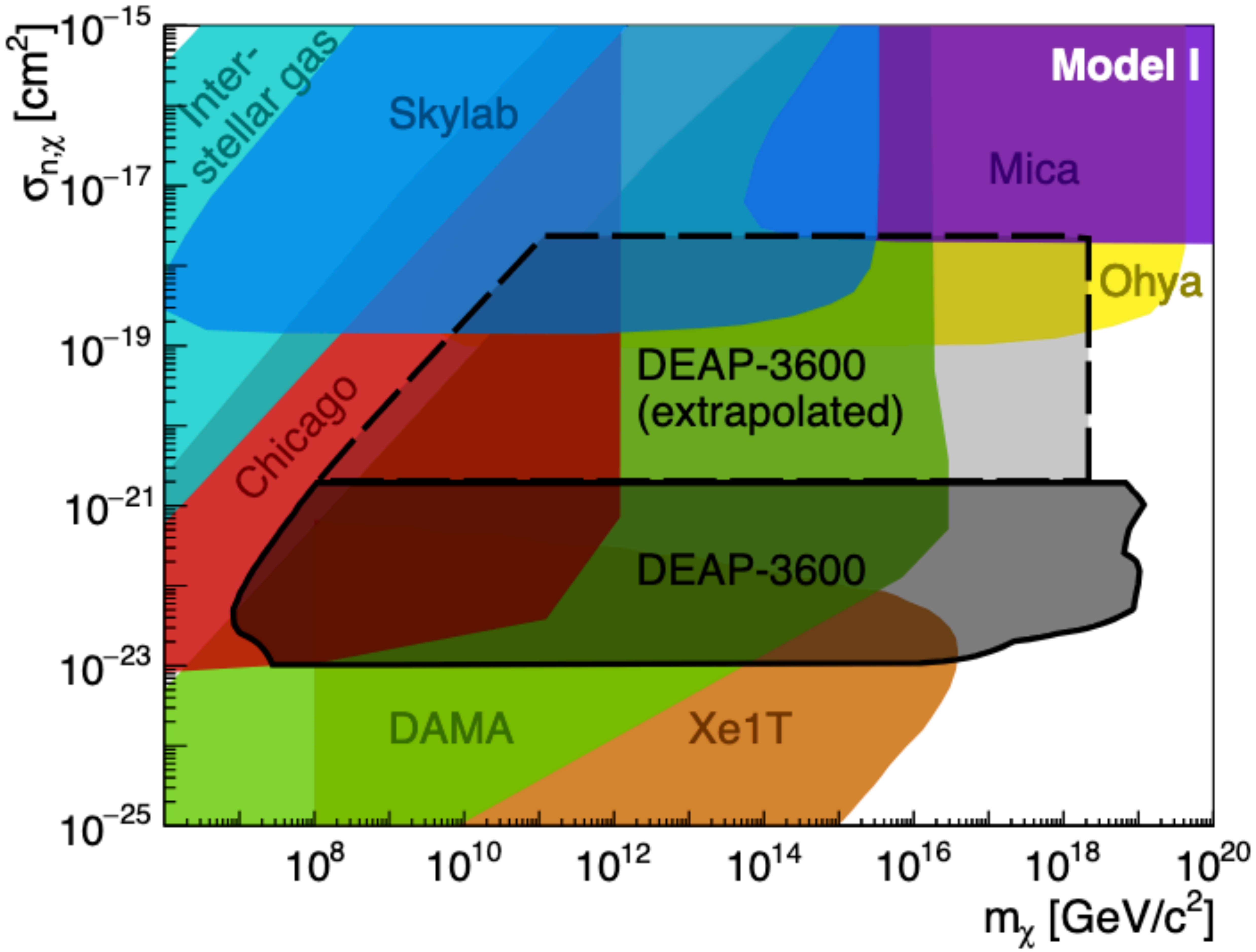
can lead to A^4 scaling and **multi-scattering** in DM experiments.

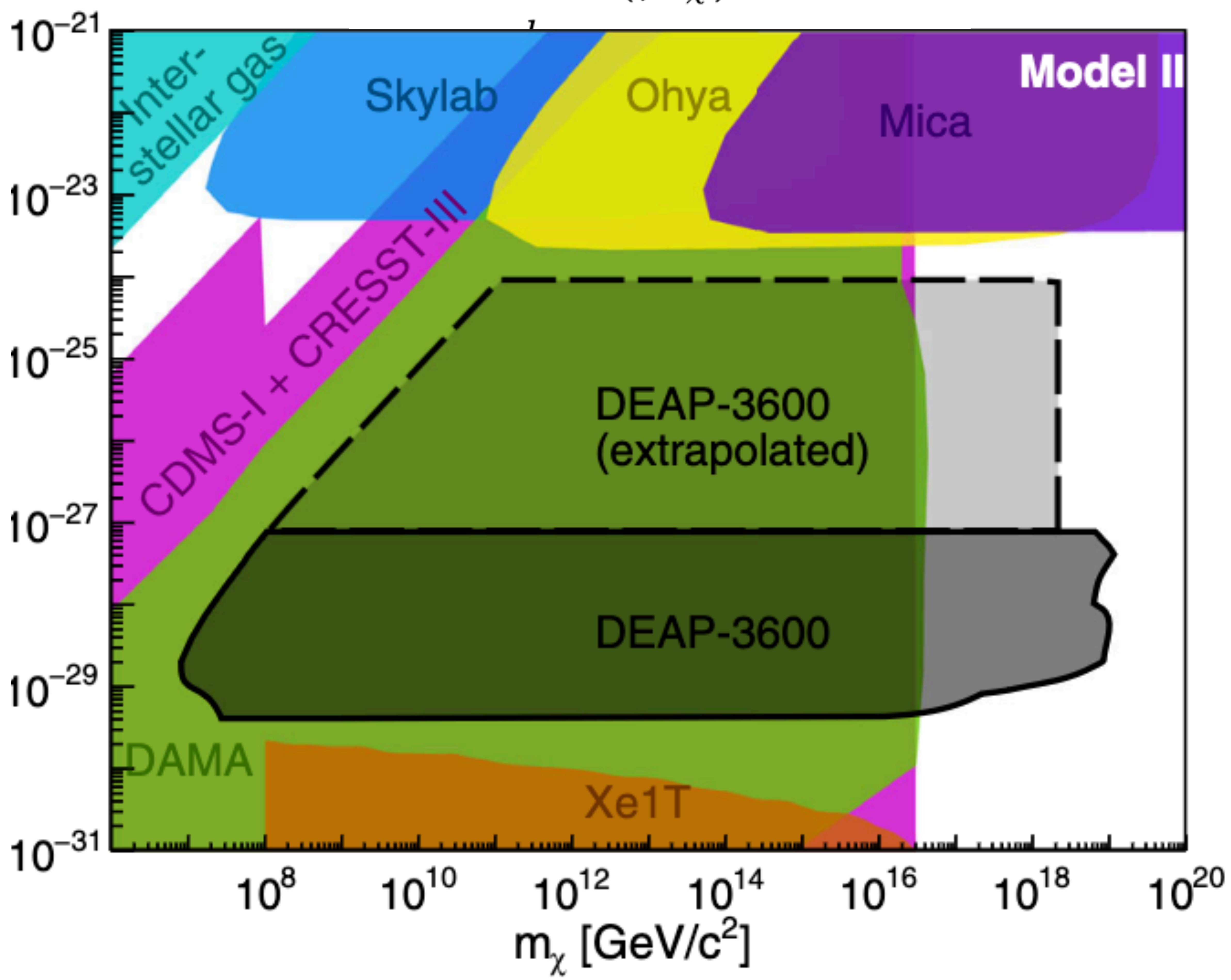
Backup Slides

DEAP-3600 Search

$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R}|F_T(q)|^2$$

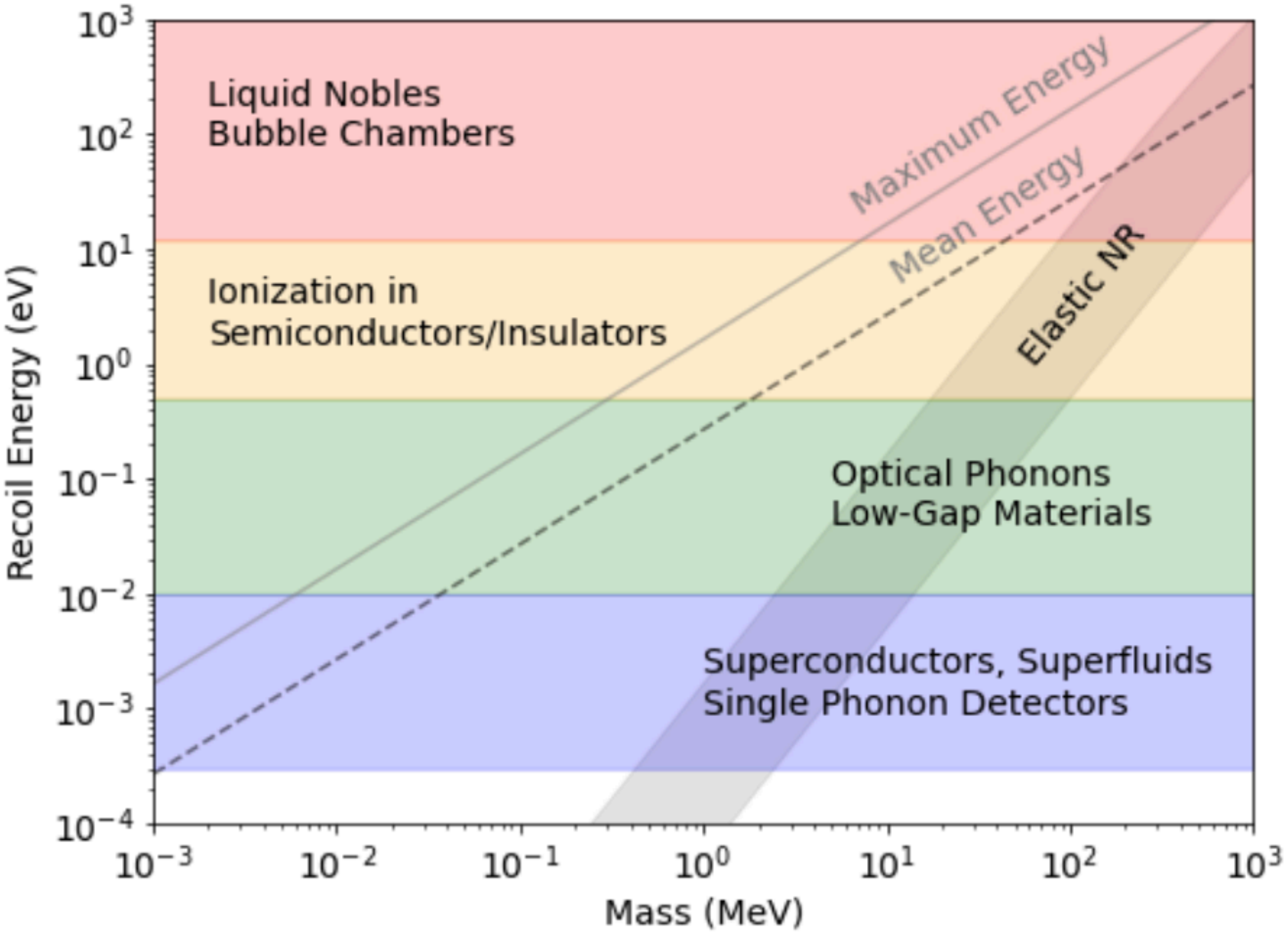
$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R}\left(\frac{\mu_{T\chi}}{\mu_{n\chi}}\right)^2 A^2|F_T(q)|^2$$





2108.09405, DEAP Collaboration

Sub-GeV DM detection landscape



Snowmass 2021 2203.08297

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:

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

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

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

Essig Mardon Volansky '12

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