Direct Detection of Composite Dark Matter

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UC Berkeley and LBL

Work with:
- A. Coskuner, S. Knapen, & K. Zurek
  arXiv: 1812.07573
- T. Melia and S. Rajendran
  arXiv: 1807.03788

Dark Matter Mass Landscape

Allowable mass range covers ~ 90 orders of magnitude

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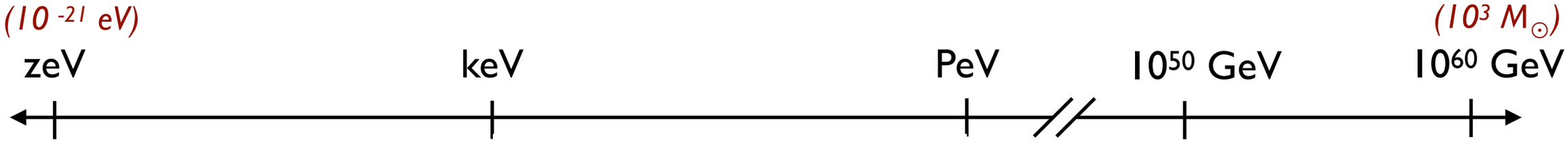

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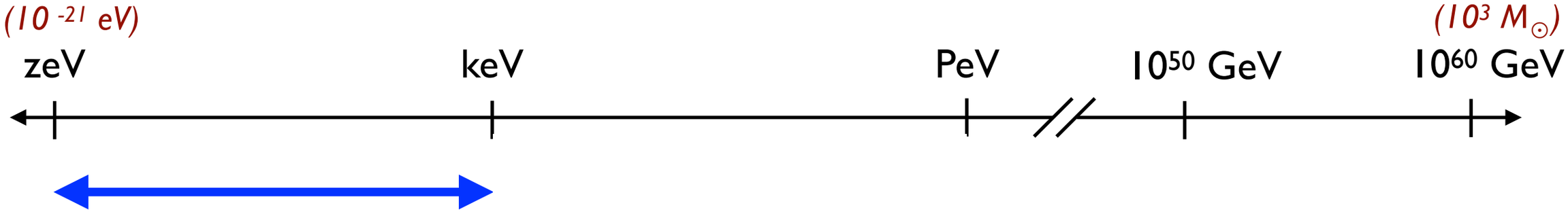

Ultra Light DM

Axions, ALPS, etc

Classically coherent fields compensate for weak coupling

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Axions, ALPS, etc

WIMPs, Hidden Sector, Asymmetric, etc

Classically coherent fields compensate for weak coupling

High number density compensates for small cross sections

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Ultra Light DM	Particle DM	Macroscopic DM
Axions, ALPS, etc	WIMPs, Hidden Sector, Asymmetric, etc	Primordial Black Holes, MACHOS, etc
Classically coherent fields compensate for weak coupling	*High number density compensates for small cross sections*	*High mass compensates for weakness of gravity*

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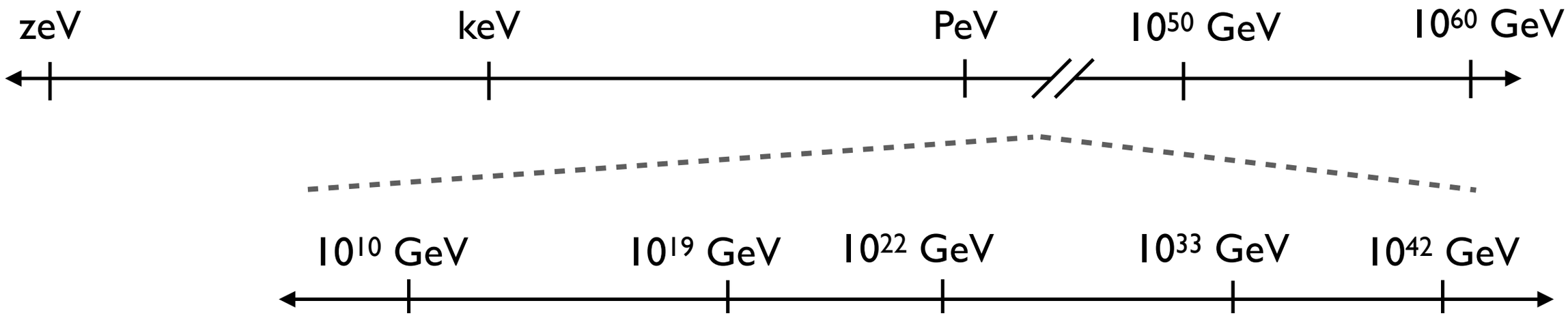

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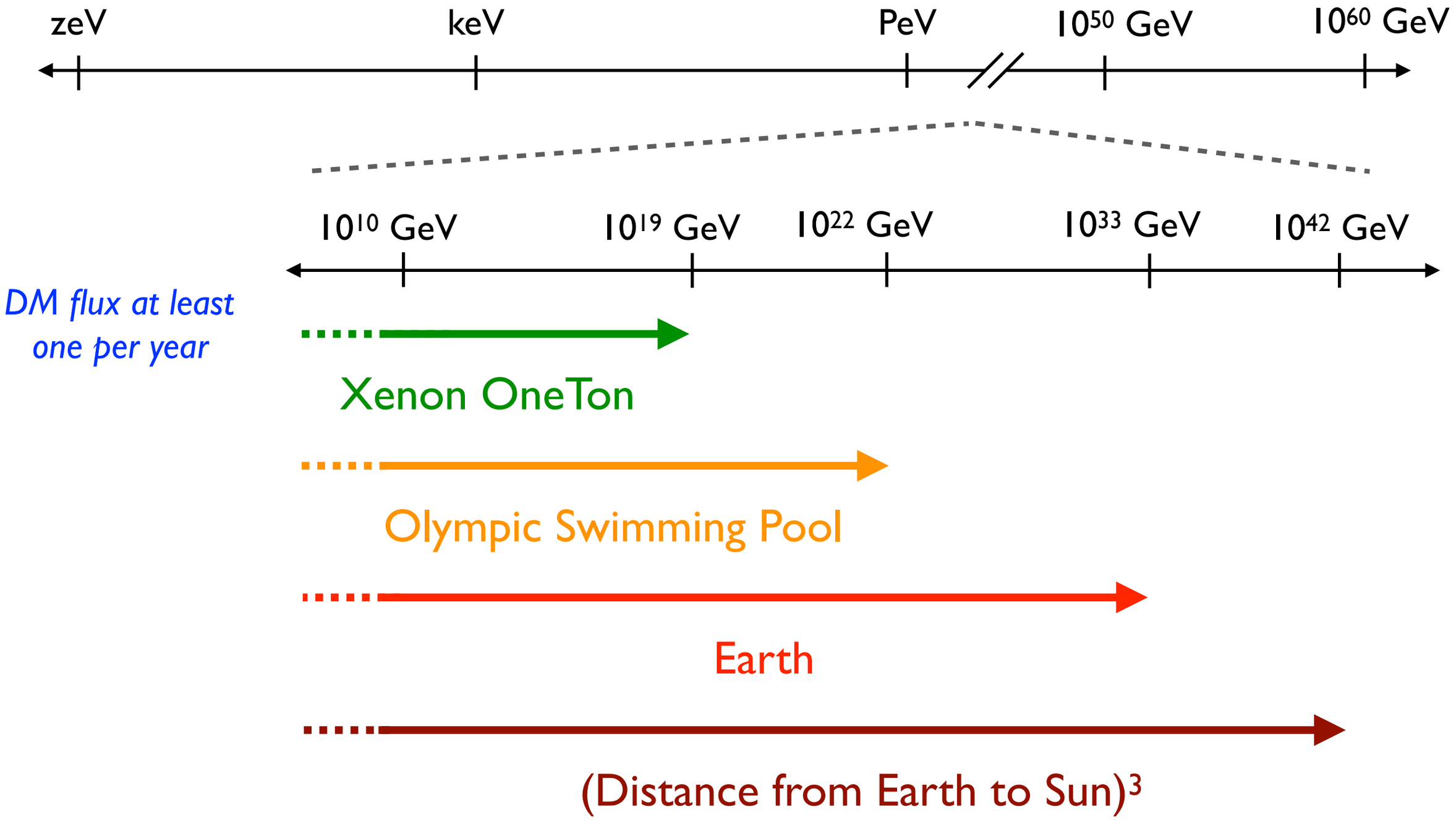


Plan

1. Dark Matter candidates in this mass regime

2. Possible Detection Strategies

Plan

1. Dark Matter candidates in this mass regime

Take Away: *Bound states in strongly interacting dark sectors have masses that span ~40 orders of magnitude*

2. Possible Detection Strategies

Take Away: *Need multi-prog experimental and observational approach*

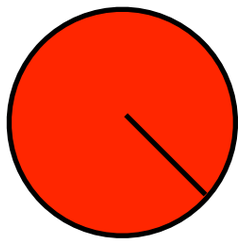
Strongly Interacting Dark Sector

Example: Dark Nuclear Matter

General Properties

- Theory confines at energy scale Λ_χ
- Spectrum contains massive particle with $m_\chi \sim \Lambda_\chi$

"Dark Nucleon"



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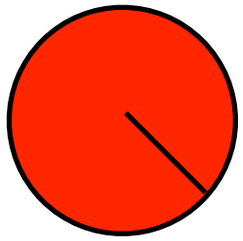
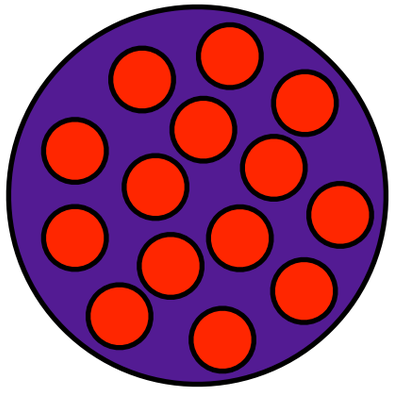


$r_\chi \sim 1/\Lambda_\chi$

- Massive particles form bound states with $M_X \sim N_X \Lambda_\chi$

"Dark Nucleus"



$R_X \sim N_X^{1/3}/\Lambda_\chi$

- Relic abundance set by dark baryon asymmetry

Maximum Size of Dark Nucleus

Semi-empirical mass formula

Treat dark nucleus as drop of liquid to determine how binding energy depends on number of constituents

$$E_{\rm Bind} \sim \alpha_V N_X - \alpha_S N_X^{2/3} - \alpha_C N_X^{5/3}$$

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Short Range Strong Interaction

Surface Correction

Long Range Weak Interaction

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Short Range Strong Interaction — $\alpha_V N_X$

Surface Correction — $\alpha_S N_X^{2/3}$

Long Range Weak Interaction — $\alpha_C N_X^{5/3}$

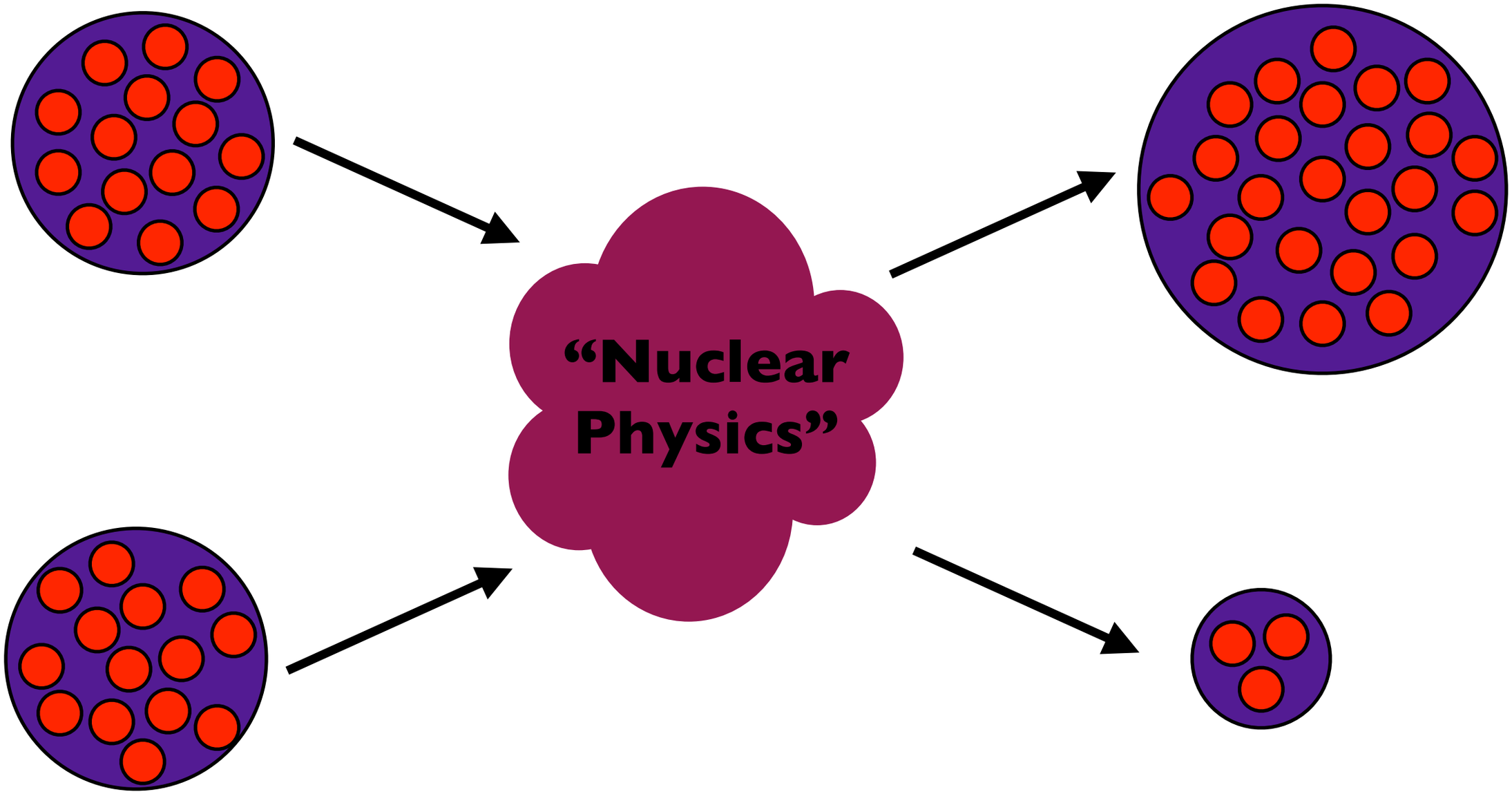
- Assume no long range force to destabilize dark nuclei

Binding energy unbounded from above!

Early Universe Formation

Big Bang Dark Nucleosynthesis

Dark nuclei form via fusion processes in the Early Universe



* Krnjaic & Sigurdson, '14, Hardy et al, '14, Gresham, Lou & Zurek, '17

Dark BBN

Fusion in Early Universe

Dark nuclei size is limited by how long fusion lasts during early Universe

- Compare Fusion rate to Hubble rate for rough estimate

$$\sigma_X \sim \frac{N_X^{2/3}}{\Lambda_\chi^2} \qquad v_X \sim \sqrt{\frac{T_\chi}{N_X \Lambda_\chi}} \qquad n_X \sim \frac{n_0}{N_X}$$

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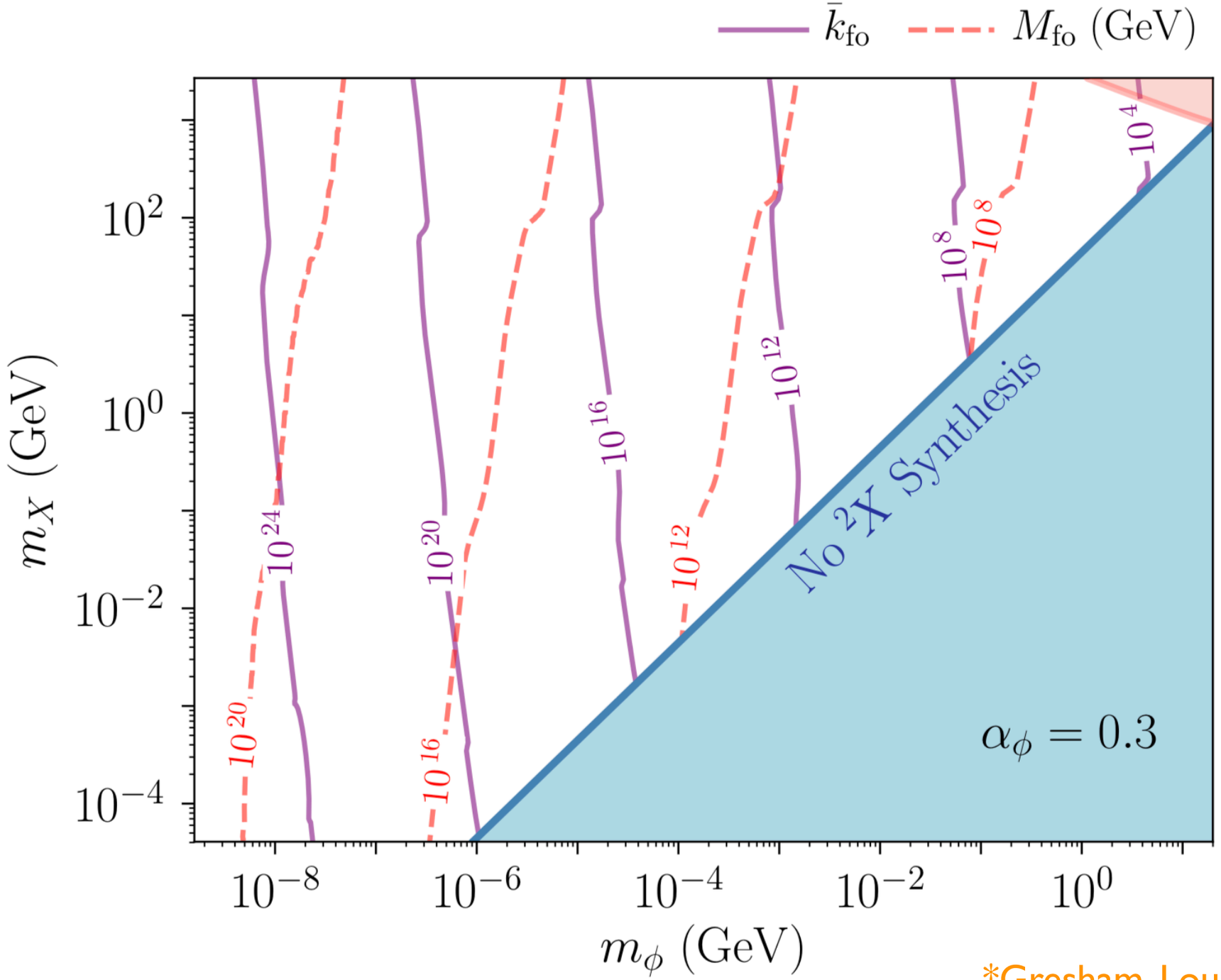
- Generically find exponentially large states

$$M_X \sim 10^{15}\,\mathrm{GeV} \left(\frac{g^*(T)}{10.2}\right)^{3/5} \left(\frac{100\,\mathrm{MeV}}{\Lambda_\chi}\right)^{16/5} \left(\frac{T}{\mathrm{MeV}}\right)^{9/5} \left(\frac{T_\chi}{T}\right)^{3/5}$$

Dark Nuclear Matter

"Dark Nuggets"



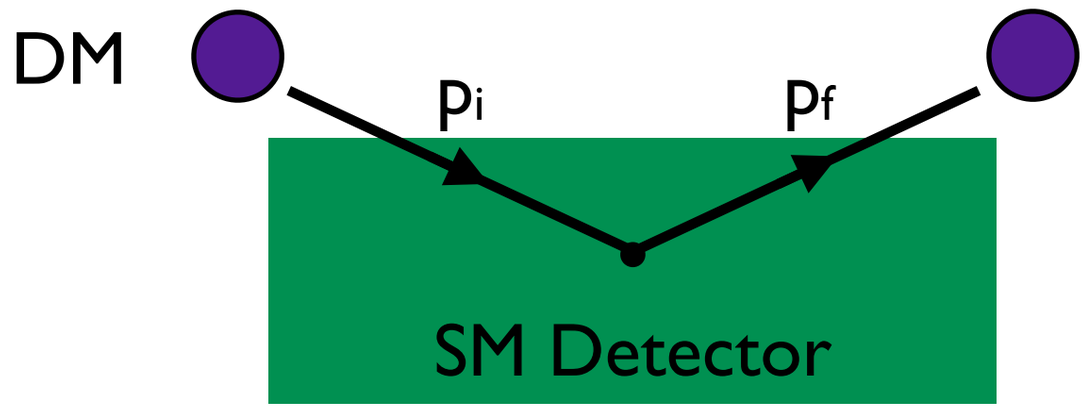
*Gresham, Lou and Zurek, 1707.02316

Detection

Dark Matter Direct Detection

DM Scattering

General Idea: DM passes through detector, resulting in either nuclei/electron recoil or collective mode excitation



Differential Scattering Rate per Unit Target Mass

$$\frac{dR}{d\omega} = \frac{\rho_X}{M_X}\frac{n_T}{\rho_T}\int d^3\mathbf{v}\, f(\mathbf{v}) \int_{|p_i - p_f|}^{p_i + p_f} dq\, \frac{d^2\Gamma}{d\omega dq}$$

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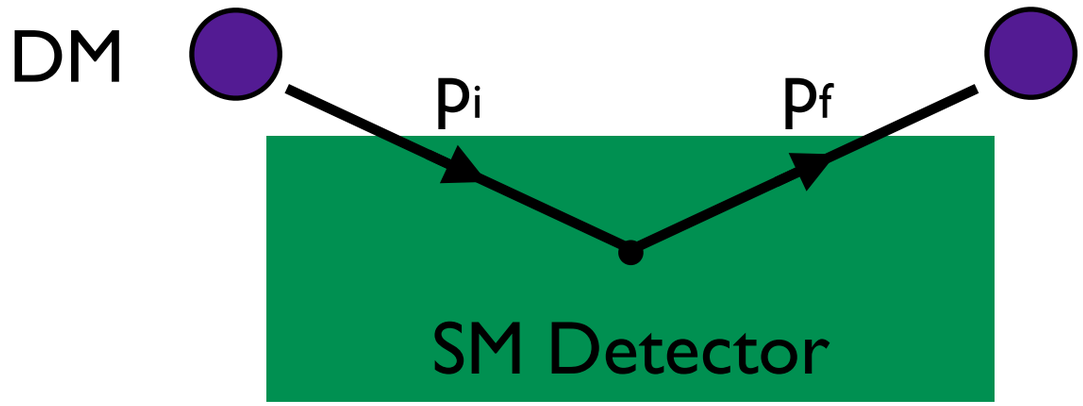

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Target and DM Dependent!

Dynamic Structure Function

Parameterizes Target Response

General Idea: Structure Function S(q, ω) quantifies response of target to injection of momentum, q, and energy, ω

$$\frac{dR}{d\omega} = \frac{\rho_X}{M_X}\frac{n_T}{\rho_T}\frac{\overline{\sigma}_0}{2\mu_{Xt}^2}\int dv\ \frac{1}{v}f(v)\int dq\ q\ |F_X(q)|^2\ |F_{\rm med}(q)|^2\ S(q,\omega)$$

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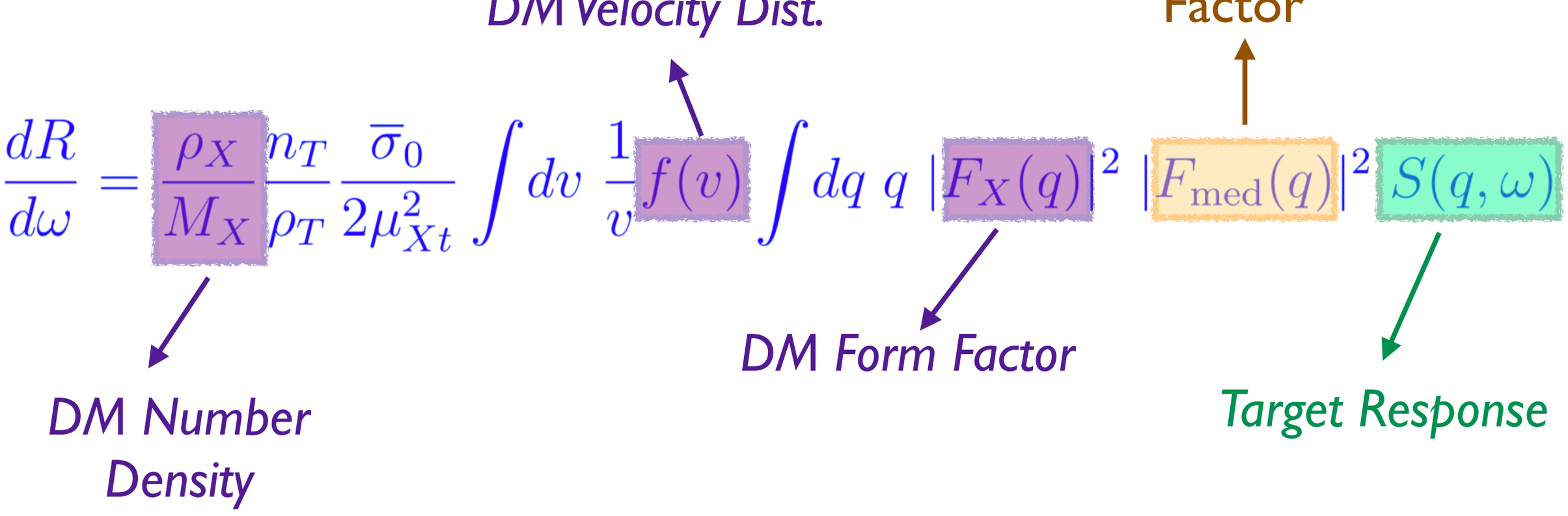


Standard Model Couplings

Nucleon Coupling

General Idea: Dark Matter couples to Standard Model nucleons via mediator of mass m_ϕ

$$\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + g_\chi \phi \bar{\chi} \chi + g_n \phi \bar{n} n$$

Results in spin-independent four fermion interaction with specific mediator "form factor"

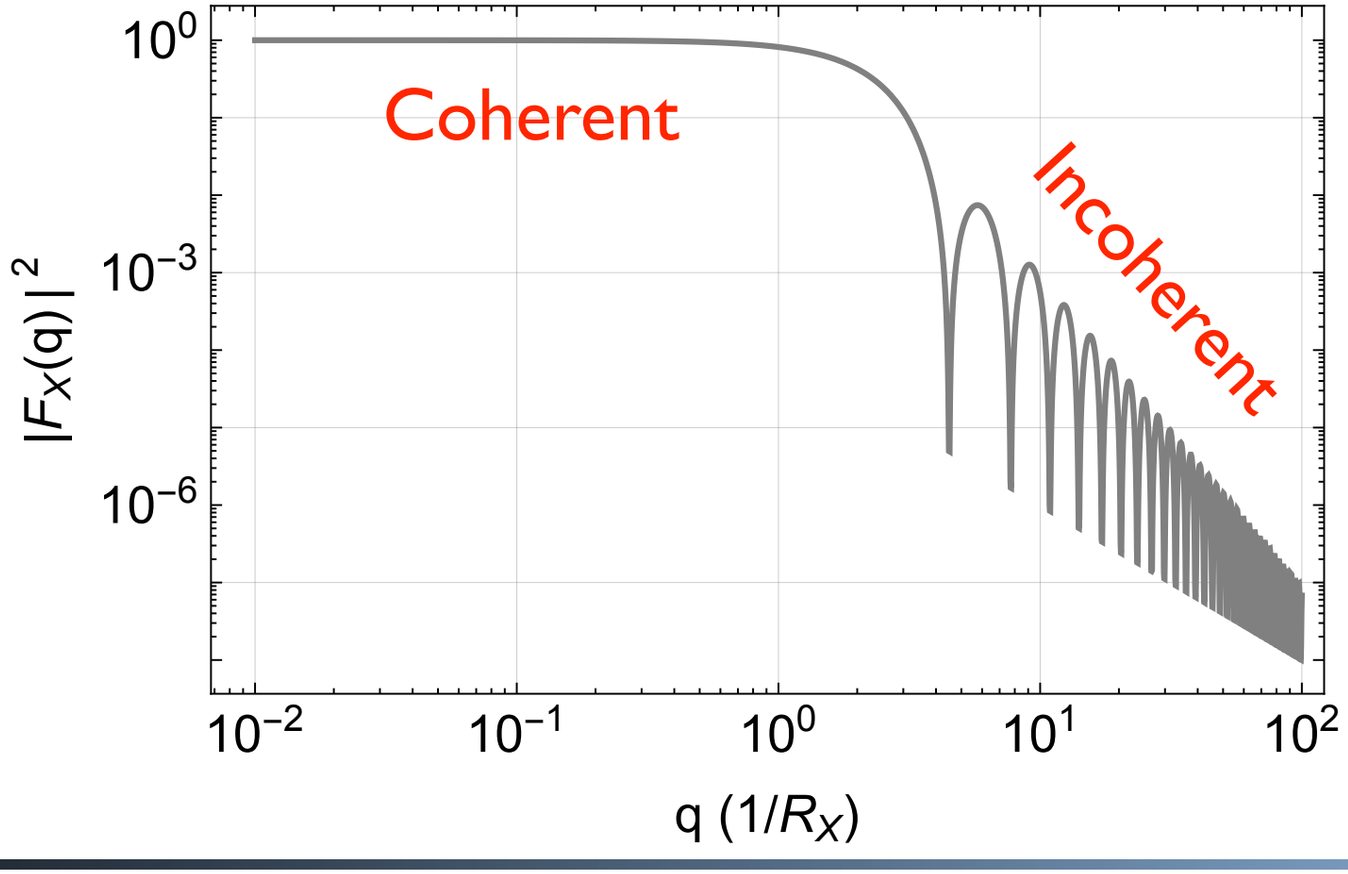
$$F_{\rm med}(q) = \begin{cases} 1 & (\text{heavy mediator}) \\ q_0^2/q^2 & (\text{light mediator}) \end{cases}$$

DM Form Factor

Finite Size effects

General Idea: Form factors "encode" the deviation of scattering amplitudes from the point particle limit

$$F_X(q) = 3\frac{\sin(qR_X) - qR_X\cos(qR_X)}{(qR_X)^3}$$



Short Range Mediator

Nuclear Recoil

Traditional WIMP Search

General Idea: Dark Matter scatters of single nucleus, which then recoils

$$S(q,\omega) = A^2 |F_N(q)|^2 \delta\left(\omega - \frac{q^2}{2m_N}\right)$$

Effect of DM's finite radius on detectability depends on how much of scattering phase space is suppressed by form factor

$$q_{\min} = \sqrt{2 m_N E_{\text{thres}}} \qquad q_{\max} \sim 2 m_N v_0$$

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Form Factor of Nucleus

On-Shell recoil

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$$q_{\rm min} = \sqrt{2 m_N E_{\rm thres}} \qquad q_{\rm max} \sim 2 m_N v_0$$

Form Factor Effects

Massive Mediator

General Idea: Effect of form factor depends on how DM radius compares to q_{max} and q_{min}

$$\sigma_{NR}^{\text{short}} \approx \overline{\sigma}_0 \times \begin{cases} A^4 & \frac{1}{R_X} \gtrsim q_{\max} \\ \frac{1}{R_X^2}\left(\frac{A}{m_n v_0}\right)^2 & q_{\max} \gtrsim \frac{1}{R_X} \gtrsim q_{\min} \\ \frac{1}{R_X^4}\frac{A}{m_n^2 v_0^2}\frac{1}{m_n E_{\text{thres}}} & q_{\min} \gtrsim \frac{1}{R_X} \end{cases}$$

- $\overline{\sigma}_0$: Cross section for point-like DM scattering off nucleon

Maximizing target's atomic number is key

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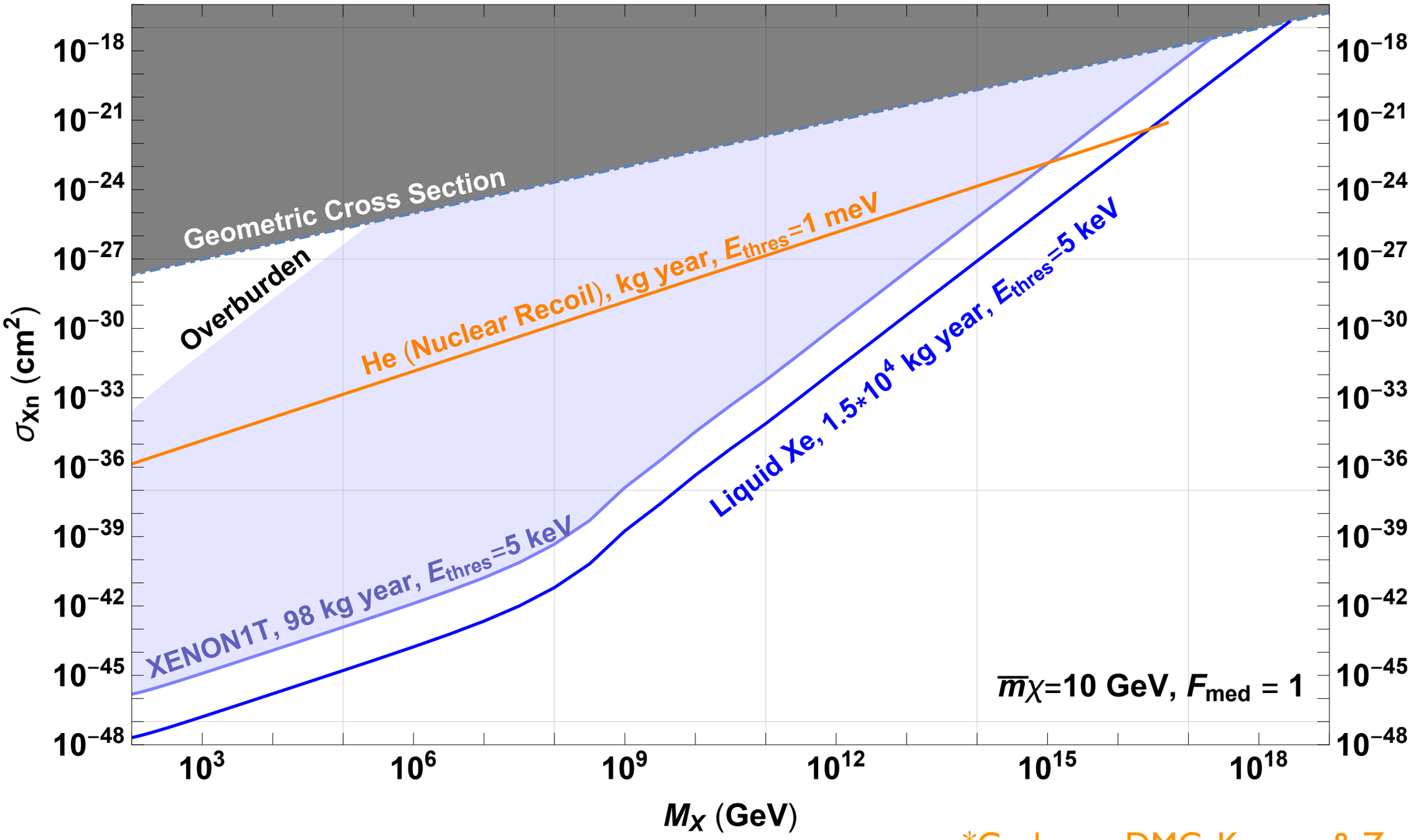
Short Range Mediator

10 GeV



*Coskuner, DMG, Knapen & Zurek '18

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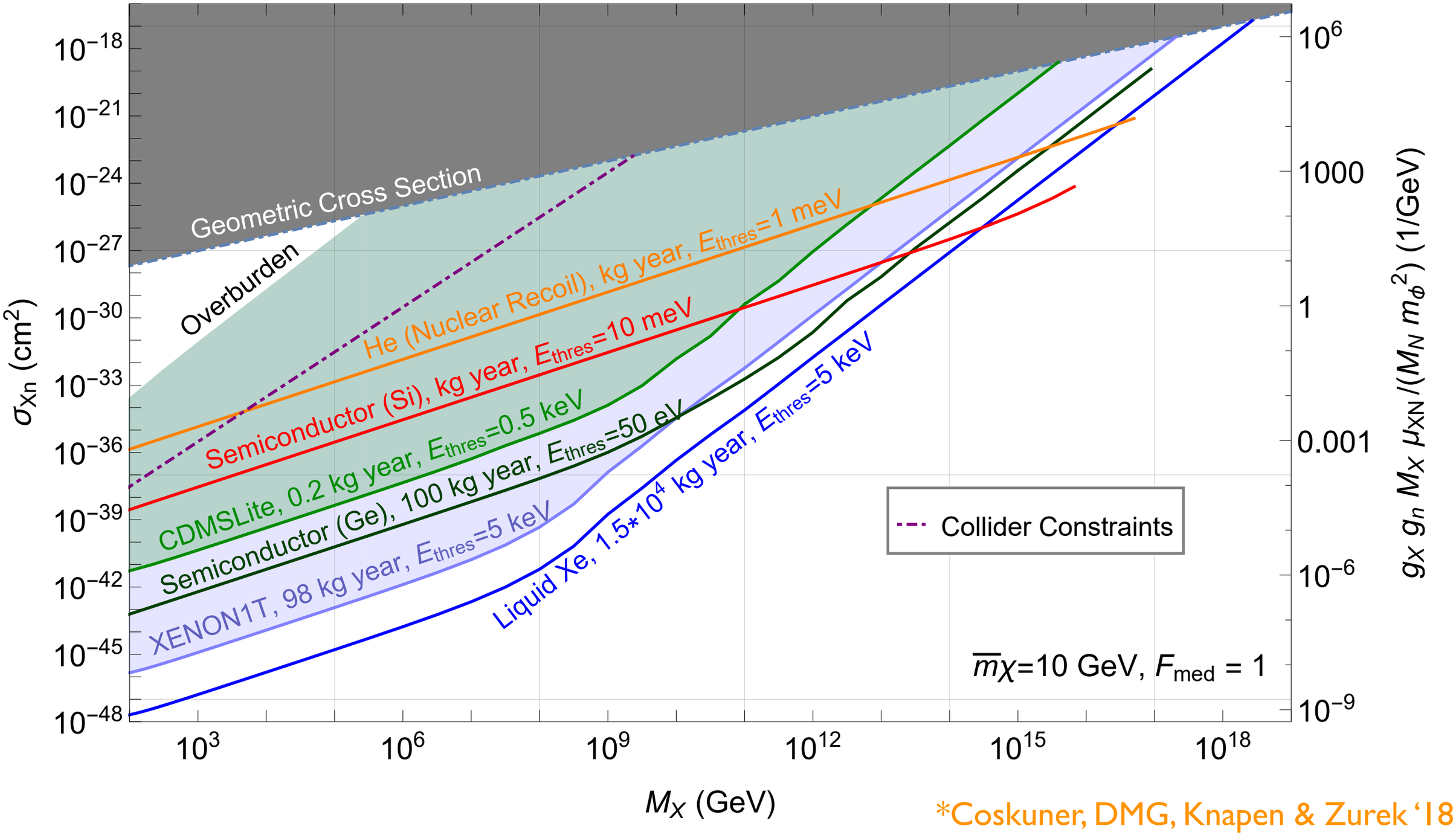

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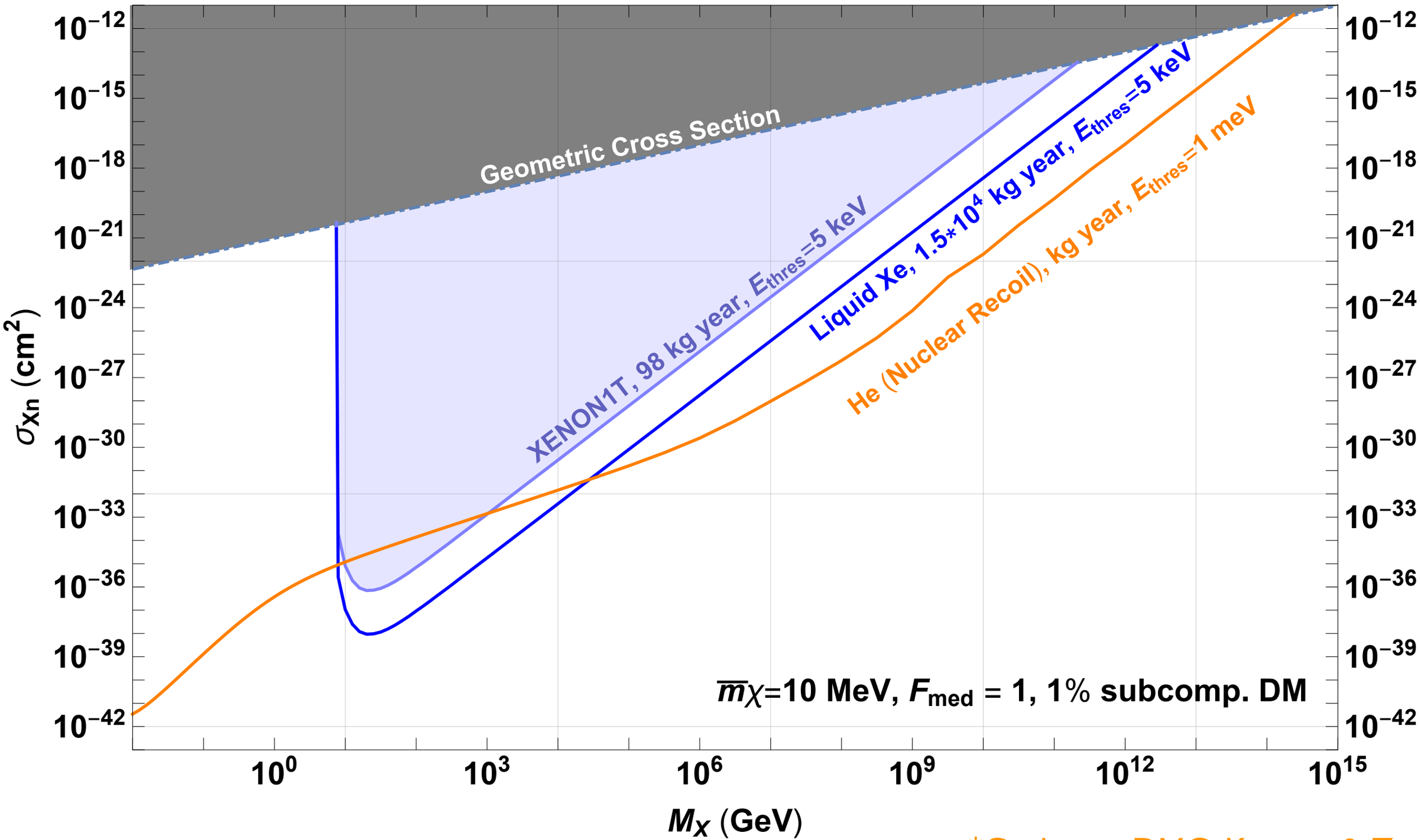

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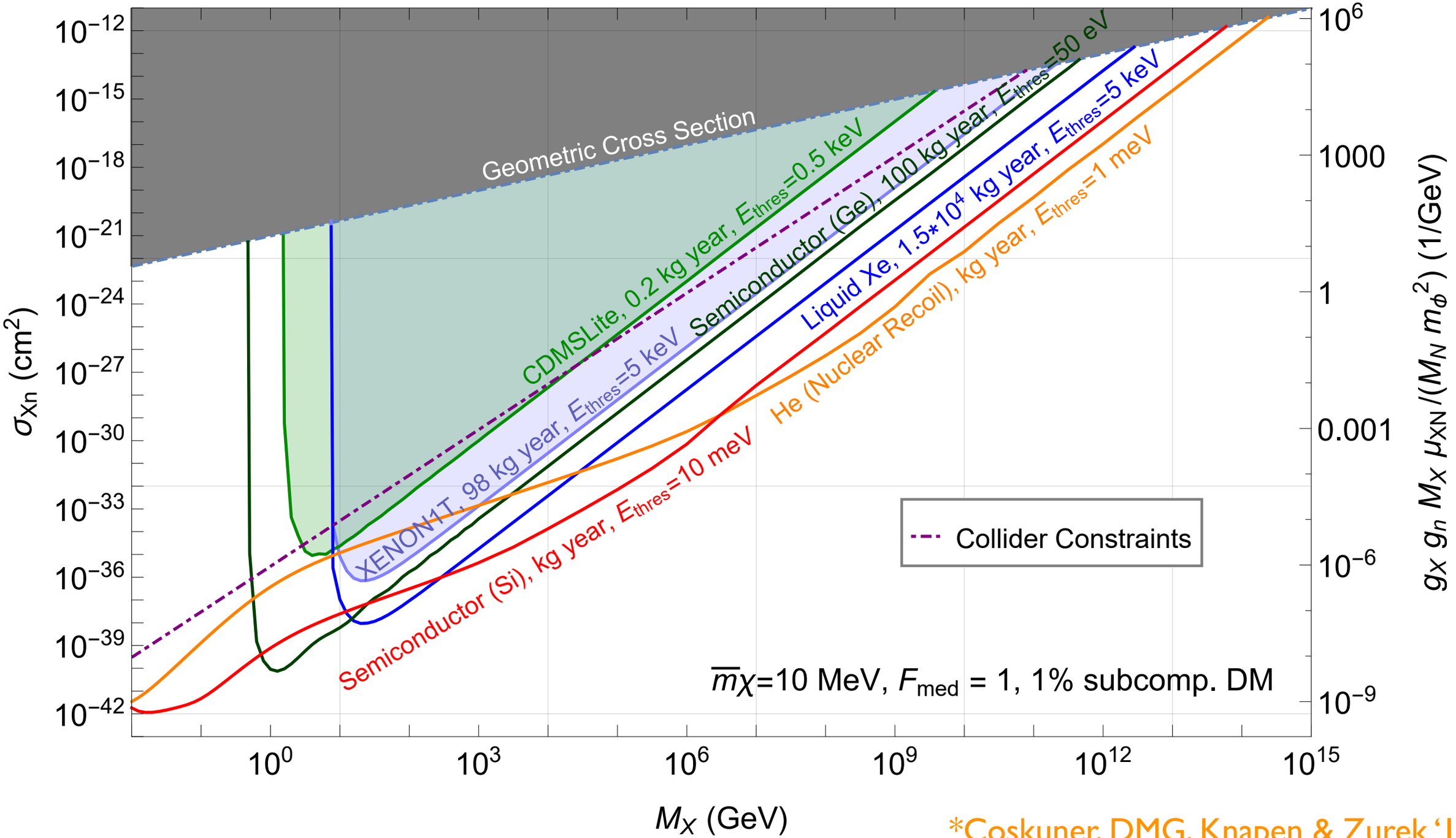

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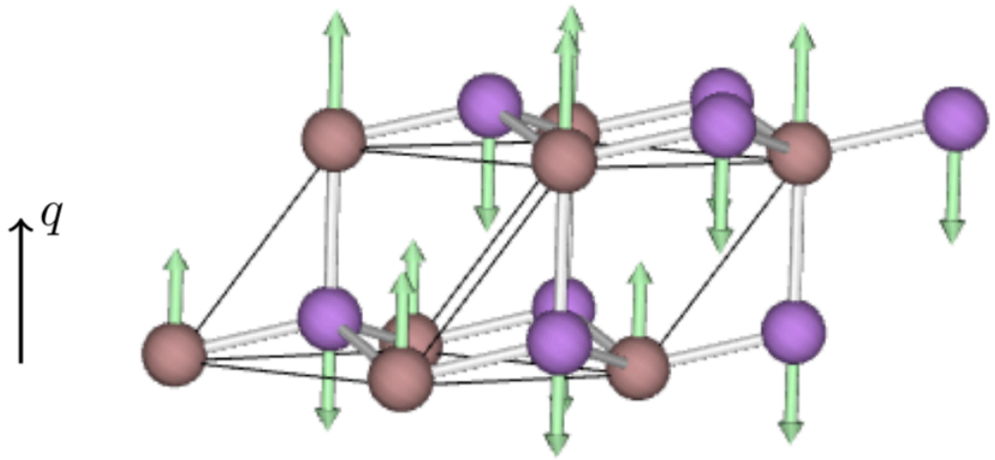
Long Range Mediator

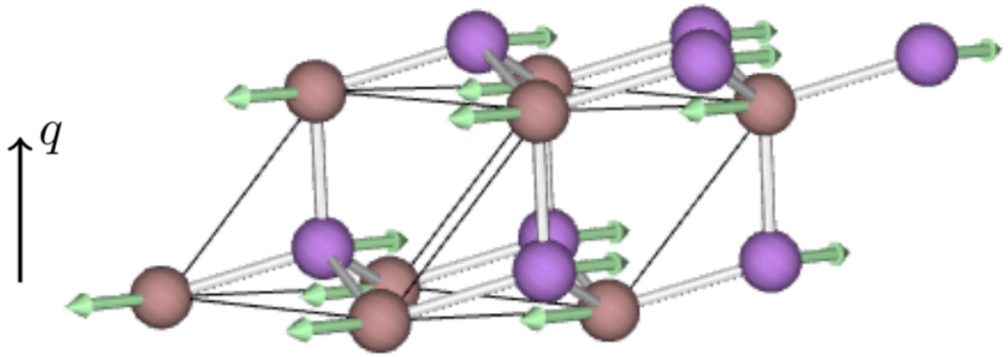
Collective Excitations

Polar Crystals

General Idea: Low momentum transfer excites phonon modes in crystal lattice



(a) LO mode



(b) TO mode

$$S(\mathbf{q},\omega) = \frac{1}{2}\sum_{\nu}\frac{|F_{\nu}(\mathbf{q})|^2}{\omega_{\nu,\mathbf{q}}}\delta(\omega_{\nu,\mathbf{q}}-\omega)$$

*Griffin et al, 1807.1029

Nuclear Recoil Long Range

Enhancement at Low Momentum

Recall: Scattering due to light mediator is enhanced at low momentum by $1/q^4$

$$\sigma_{NR}^{\text{long}} \approx \overline{\sigma}_0 \times q_0^4 \times \begin{cases} \dfrac{A}{8E_{\text{thres}} v_0^2 m_n^3} & \text{Region I \& II} \\ \dfrac{3}{64 A R_X^4 v_0^2 m_n^5 E_{\text{thres}}^3} & \text{Region III} \end{cases}$$

$$\sigma_{LA}^{\text{long}} \approx \overline{\sigma}_0 \times q_0^4 \times \frac{A}{m_n^3 v_0^2 c_s} \begin{cases} \dfrac{c_s}{E_{\text{thres}}} & \text{Region I \& II} \\ \dfrac{9 c_s^5}{10 R_X^4 E_{\text{thres}}^5} & \text{Region III} \end{cases}$$

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Minimizing detector's energy threshold is key

Long Range Mediator

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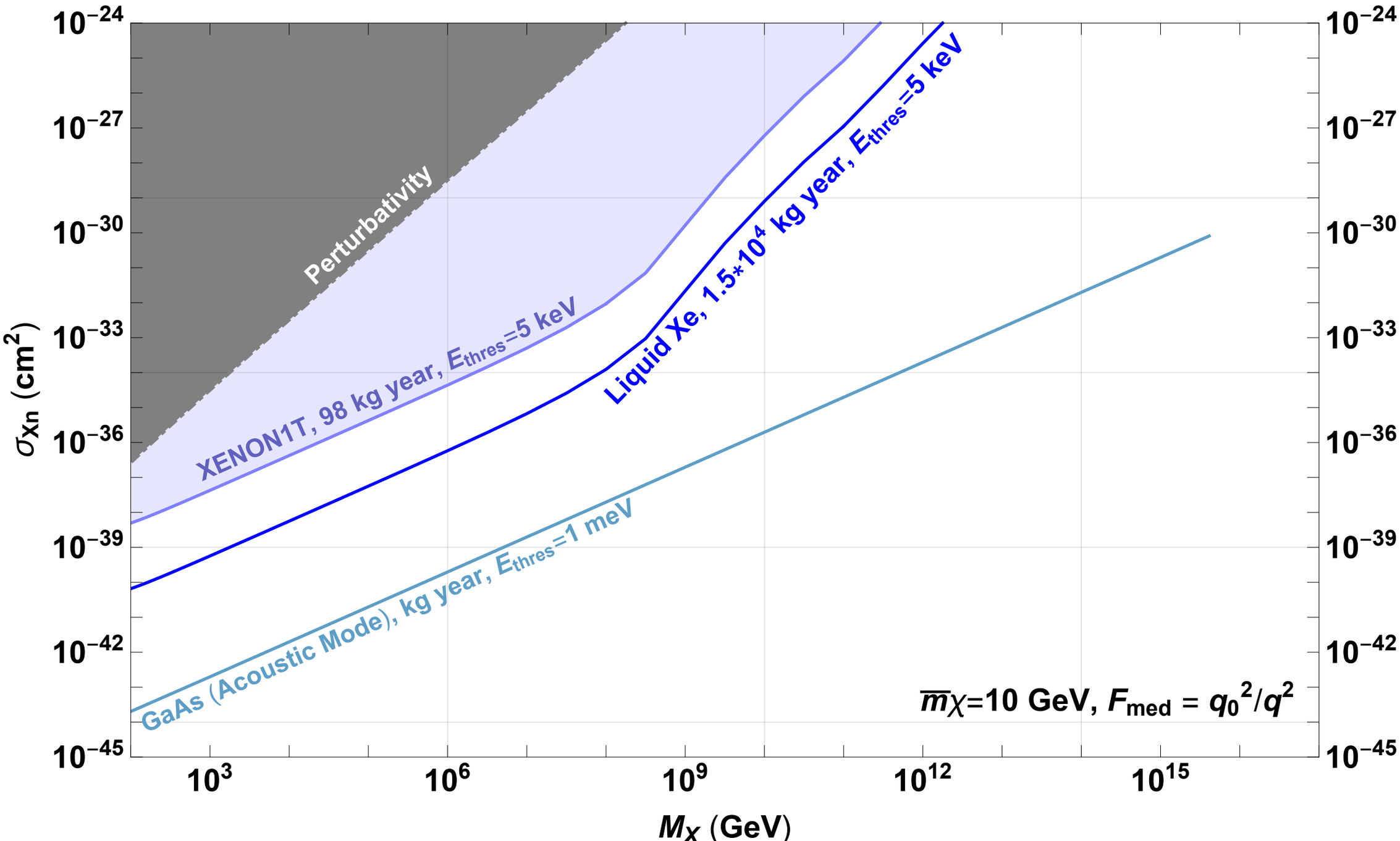

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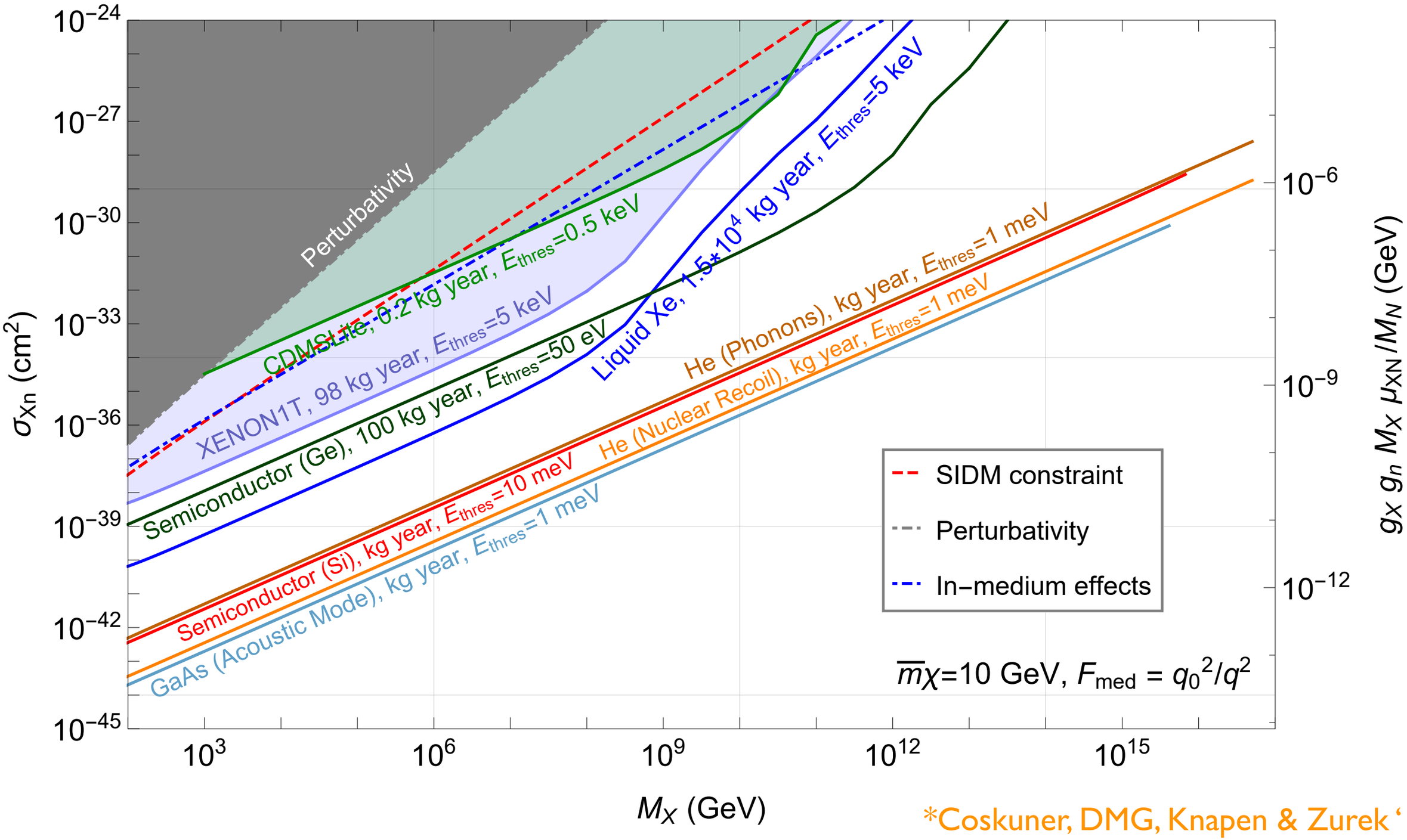

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Extremely Long Range Mediator

Mediator Coupling Constraints

Dark Sector Constraints

Scalar Coupling g_x Bound: Stability of Dark Nuclei

- Fermi degeneracy pressure must balance self-energy due to long range attractive interaction*

$$g_\chi \lesssim N_X^{-1/3}$$

* Akin to gravitational collapse

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Scalar Coupling g_x Bound: Stability of Dark Nuclei

- Fermi degeneracy pressure must balance self-energy due to long range attractive interaction*

$$g_\chi \lesssim N_X^{-1/3}$$

* Akin to gravitational collapse

- Additional repulsive interactions does not help as blobs become unbound

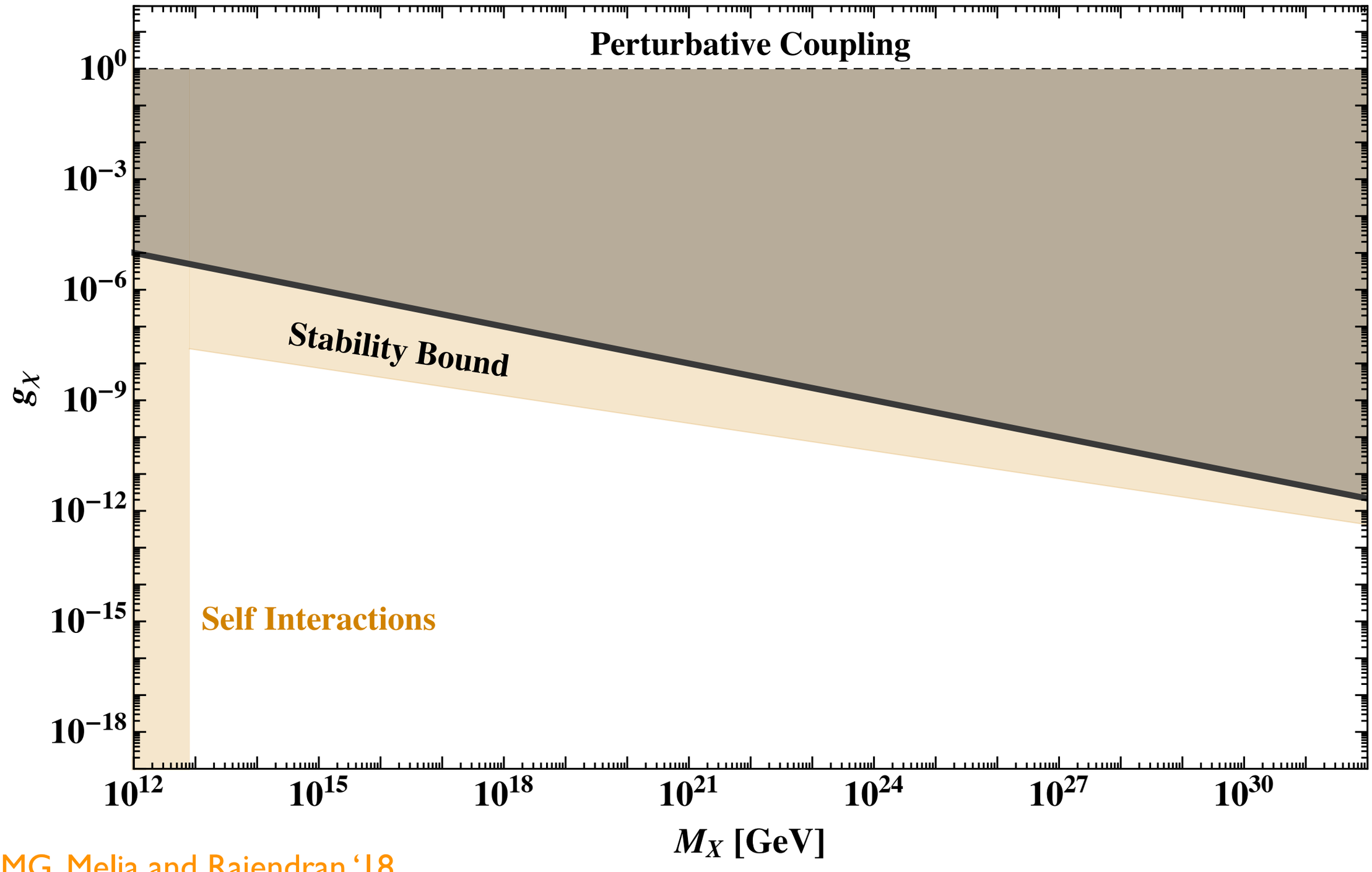
$$E_{\rm Bind} \sim \alpha_V N_X - \alpha_S N_X^{2/3} - \alpha_C N_X^{5/3}$$

$\alpha_V \sim \Lambda_\chi$

$\alpha_C \sim g_\chi^2 \Lambda_\chi$

Extremely Long Range Mediator

Λ_x = MeV, λ = 200 km



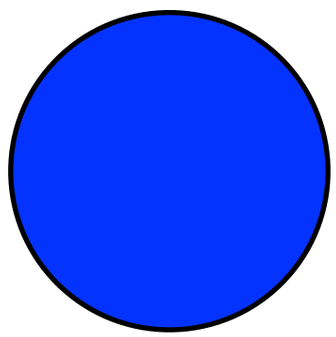
DMG, Melia and Rajendran '18

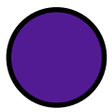
Acceleration

Free hanging test mass

General Idea: Passing DM induces motion in test mass

Test Mass





DM

Acceleration

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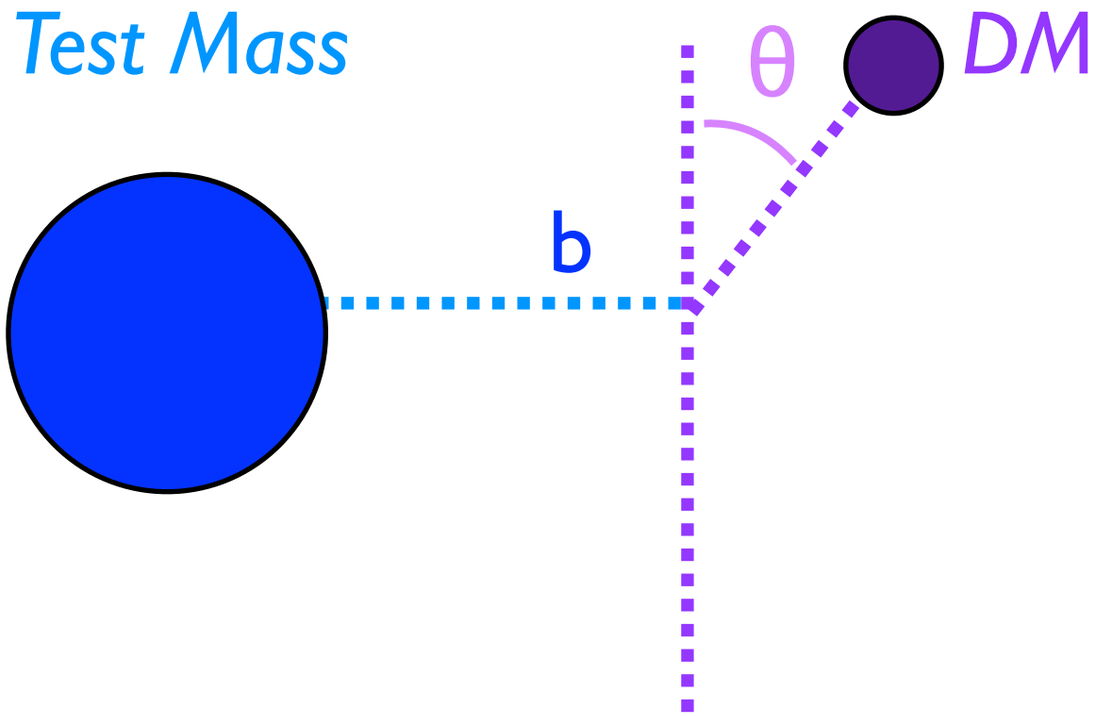

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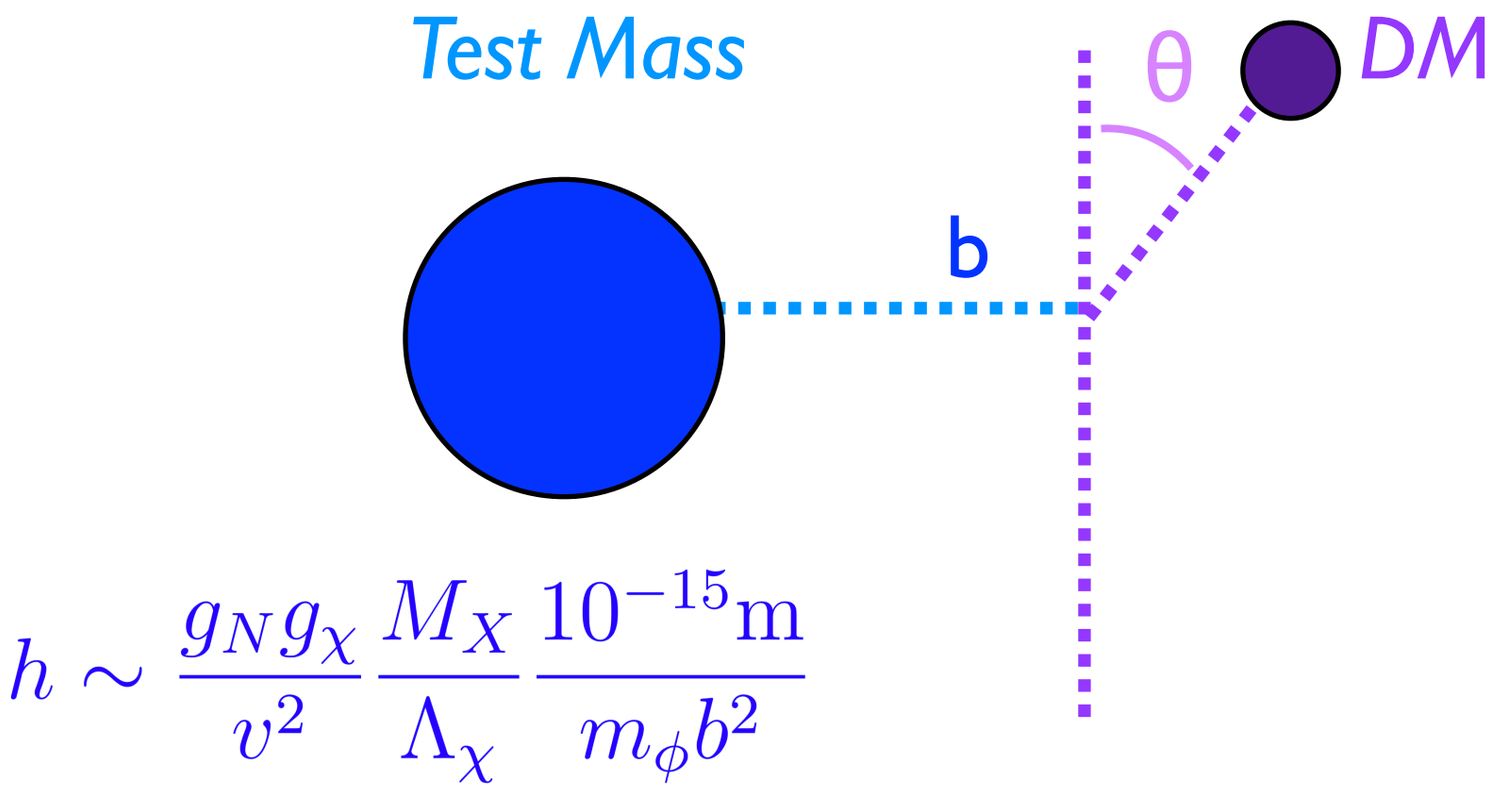

$$h \sim \frac{g_N g_\chi}{v^2} \frac{M_X}{\Lambda_\chi} \frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

Acceleration

Free hanging test mass

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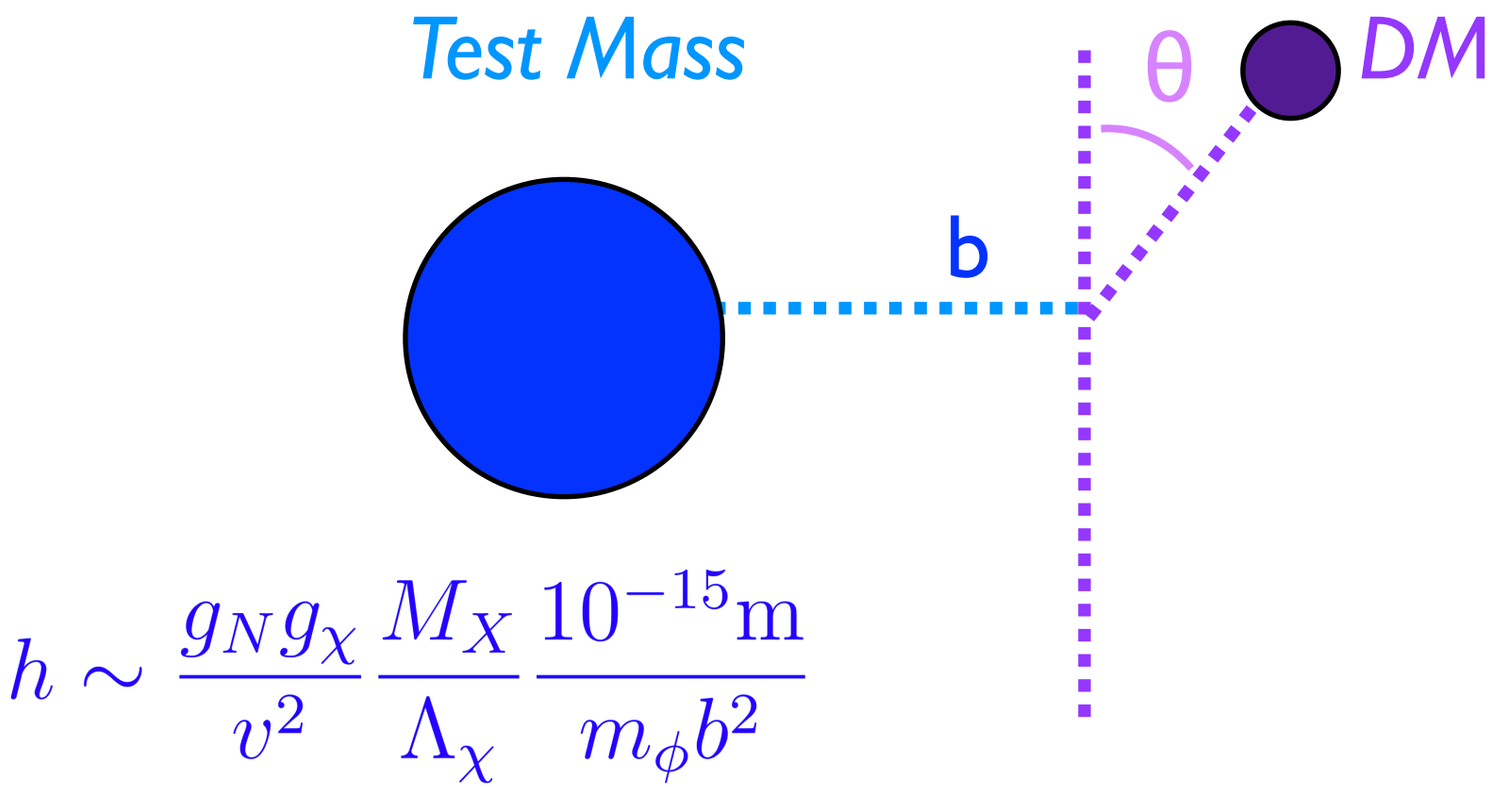
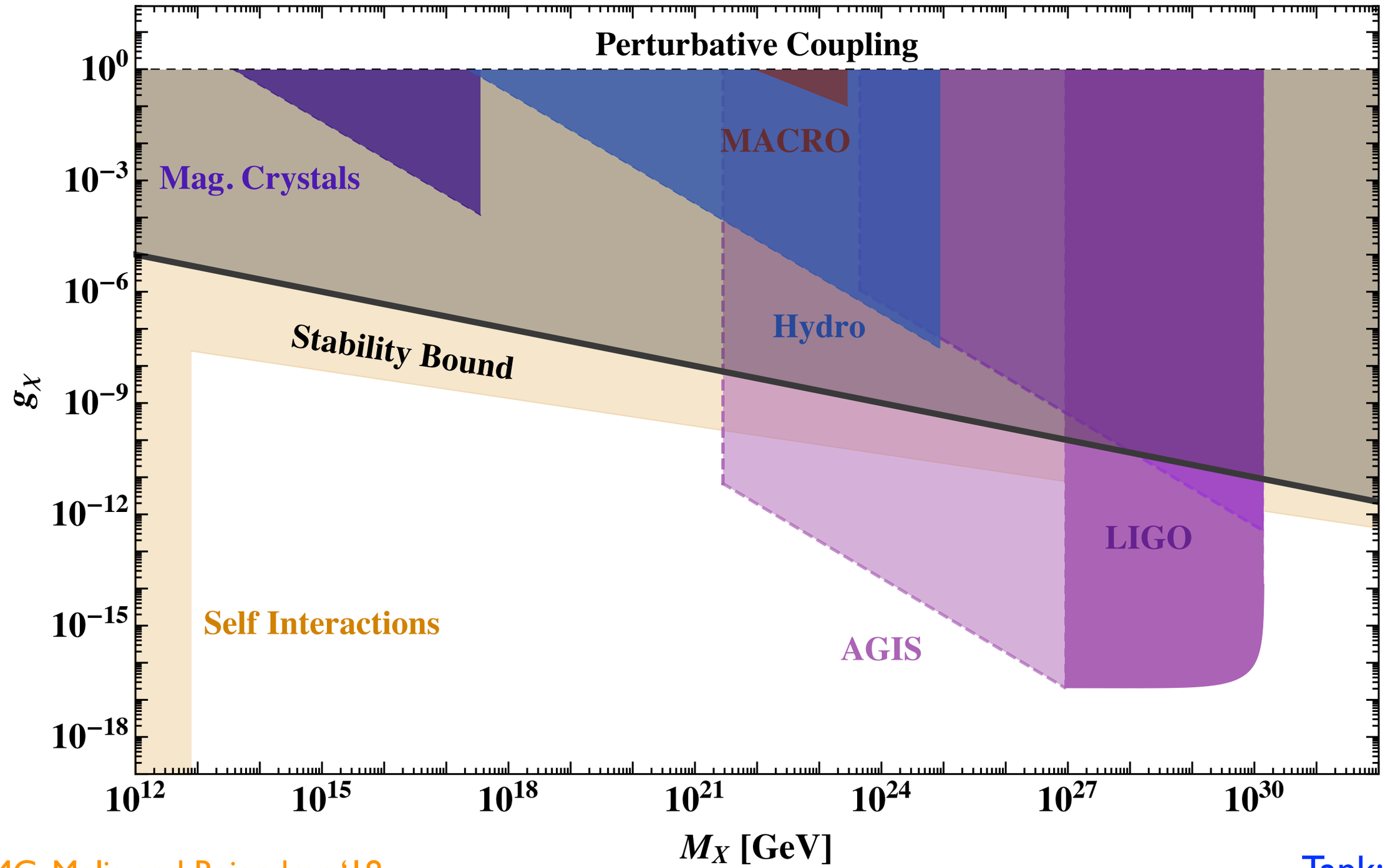


$$h \sim \frac{g_N g_\chi}{v^2} \frac{M_X}{\Lambda_\chi} \frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

- **Example:** LIGO sensitive to $\Delta x \sim 0.1$ fm/Hz$^{1/2}$

Extremely Long Range Mediator

Λ_x = MeV, λ = 200 km



DMG, Melia and Rajendran '18

Tank: $(500\ \text{m})^3$

Conclusions

Focus: Detecting composite dark matter

Take Away: Strongly interacting dark sector can give DM whose mass ranges over 40 orders of magnitude

- Dark Nuclear Matter
- Dark Quark Matter *(Not discussed here)*

Take Away: Need multi-prong approach to span the full parameter space of masses and confinement scales

- Both existing and near future direct detection experiments are important