Dark Blobs

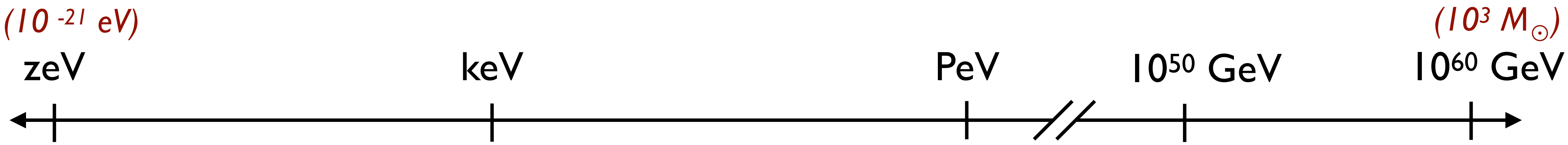
Exponentially Large Composite Dark Matter

Dorota M Grabowska

UC Berkeley → CERN

Dark Matter Mass Landscape

Allowable mass range covers ~ 90 orders of magnitude



Dark Matter Mass Landscape

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Ultra Light	Particle	Macroscopic
Axions, ALPS, etc	WIMPs, Hidden Sector, Asymmetric, etc	Primordial Black Holes, MACHOS, etc
Semi-Classical Field	*Quantum Mechanics*	*General Relativity*

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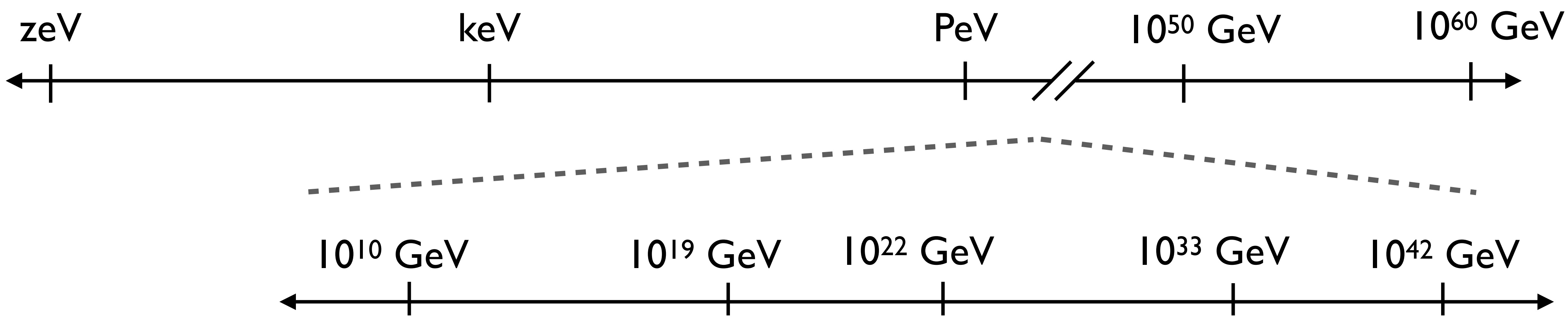

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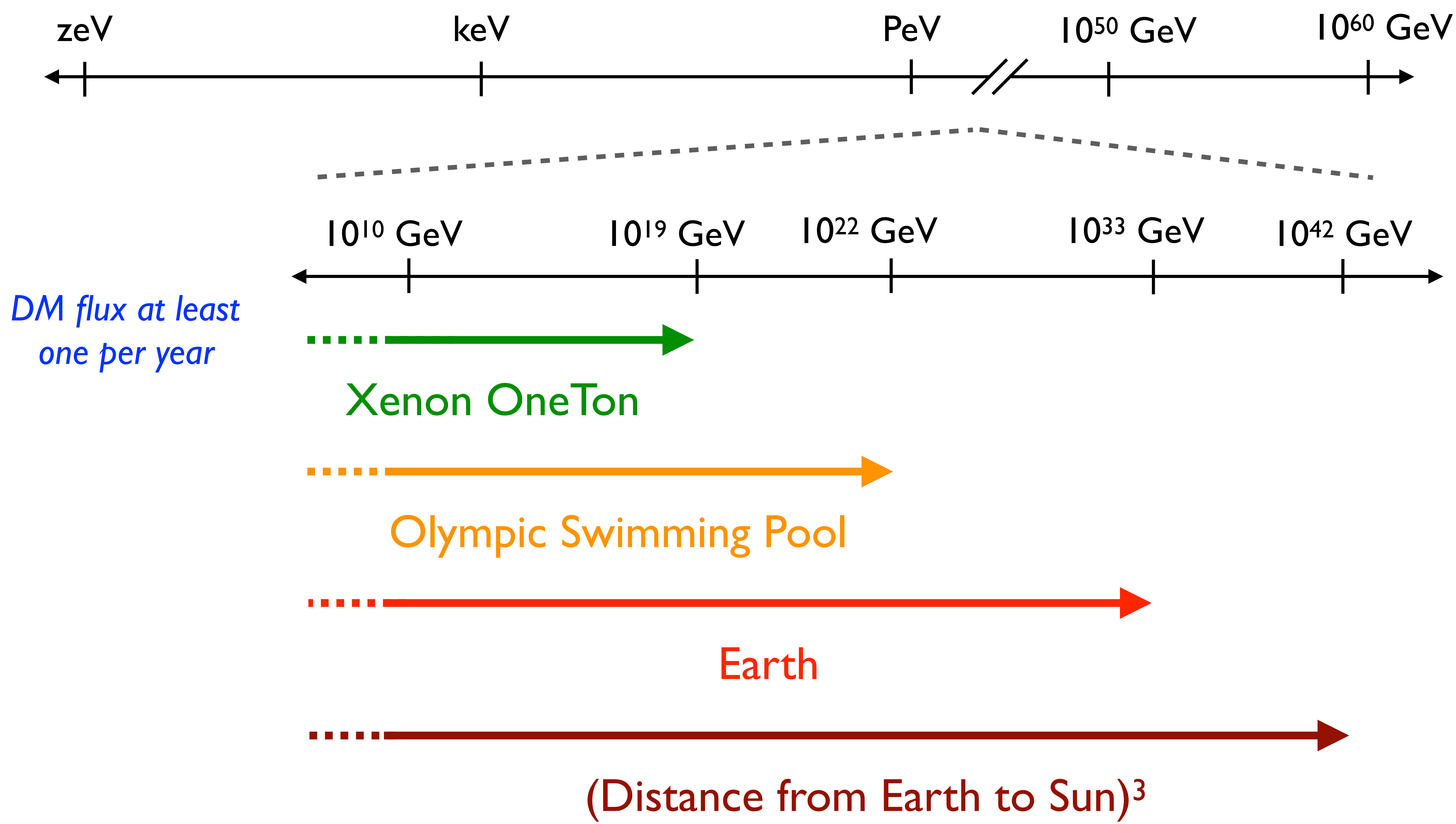


The Plan

1. Interesting paradigm for heavy dark matter

2. Several Detection Strategies

The Plan

1. Interesting paradigm for heavy dark matter

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

2. Several Detection Strategies

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

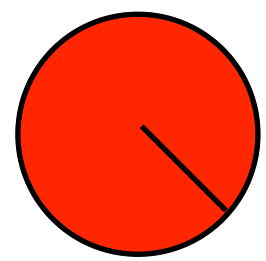
Strongly Interacting Dark Sector

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"



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

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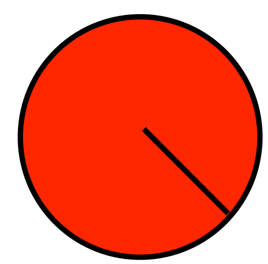
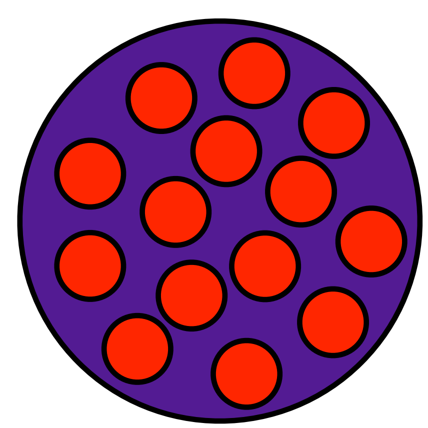


$r_\chi \sim 1/\Lambda_\chi$

- 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

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

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Short Range Strong Interaction

Surface Correction

Long Range Weak Interaction

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Short Range Strong Interaction — ***Surface Correction*** — ***Long Range Weak Interaction***

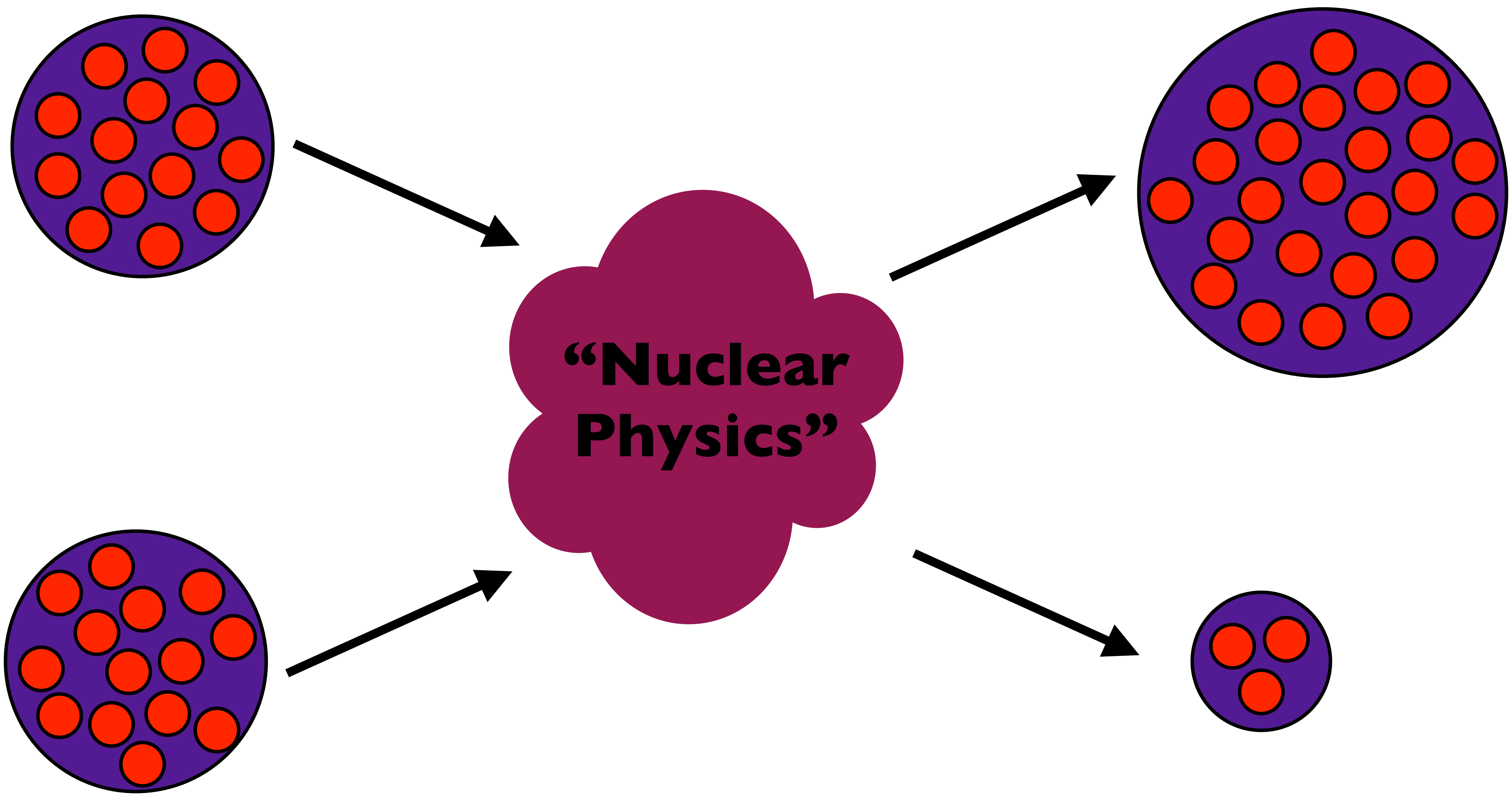
- Assume no long range force to destabilize dark nuclei

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

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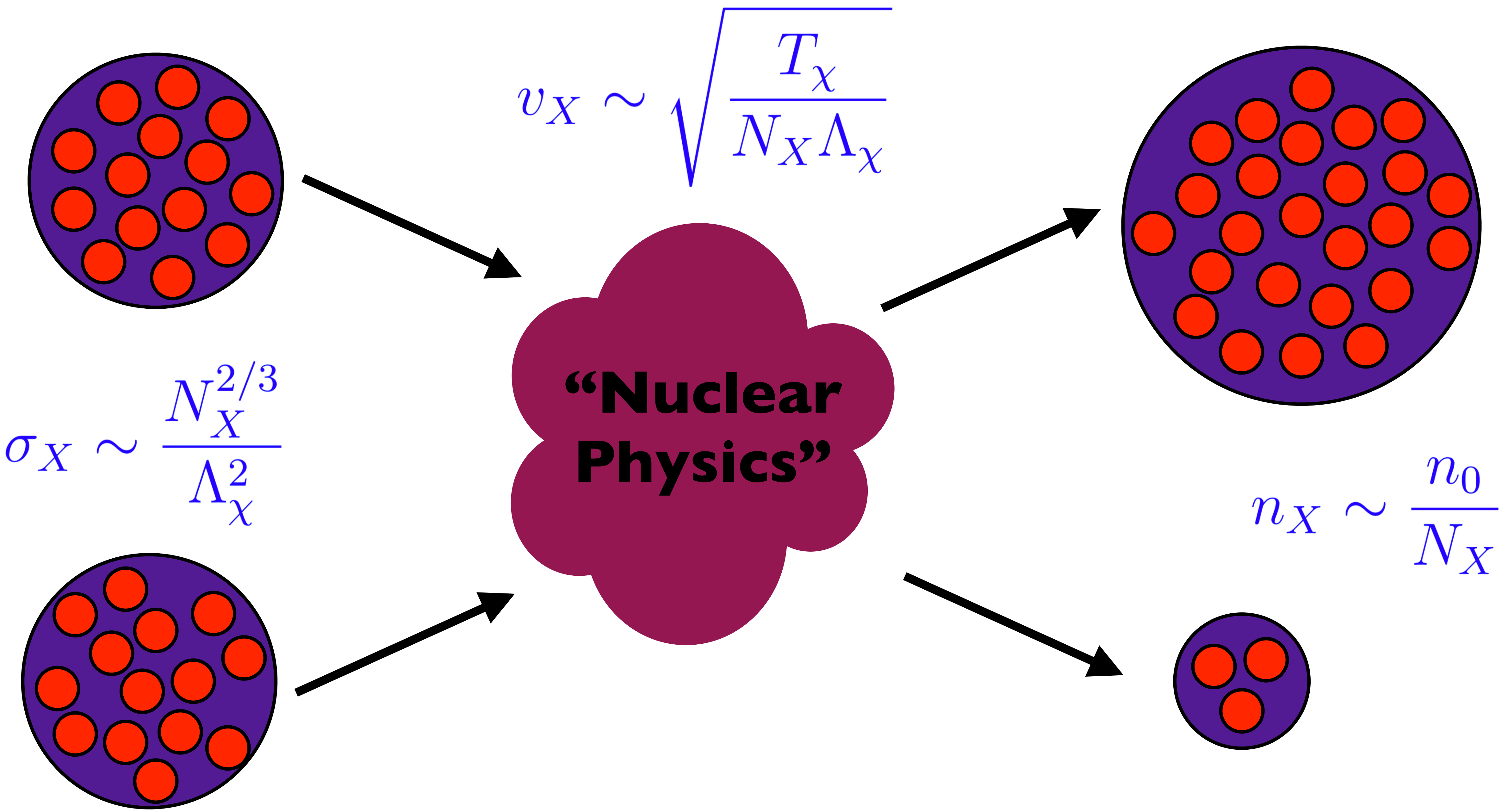

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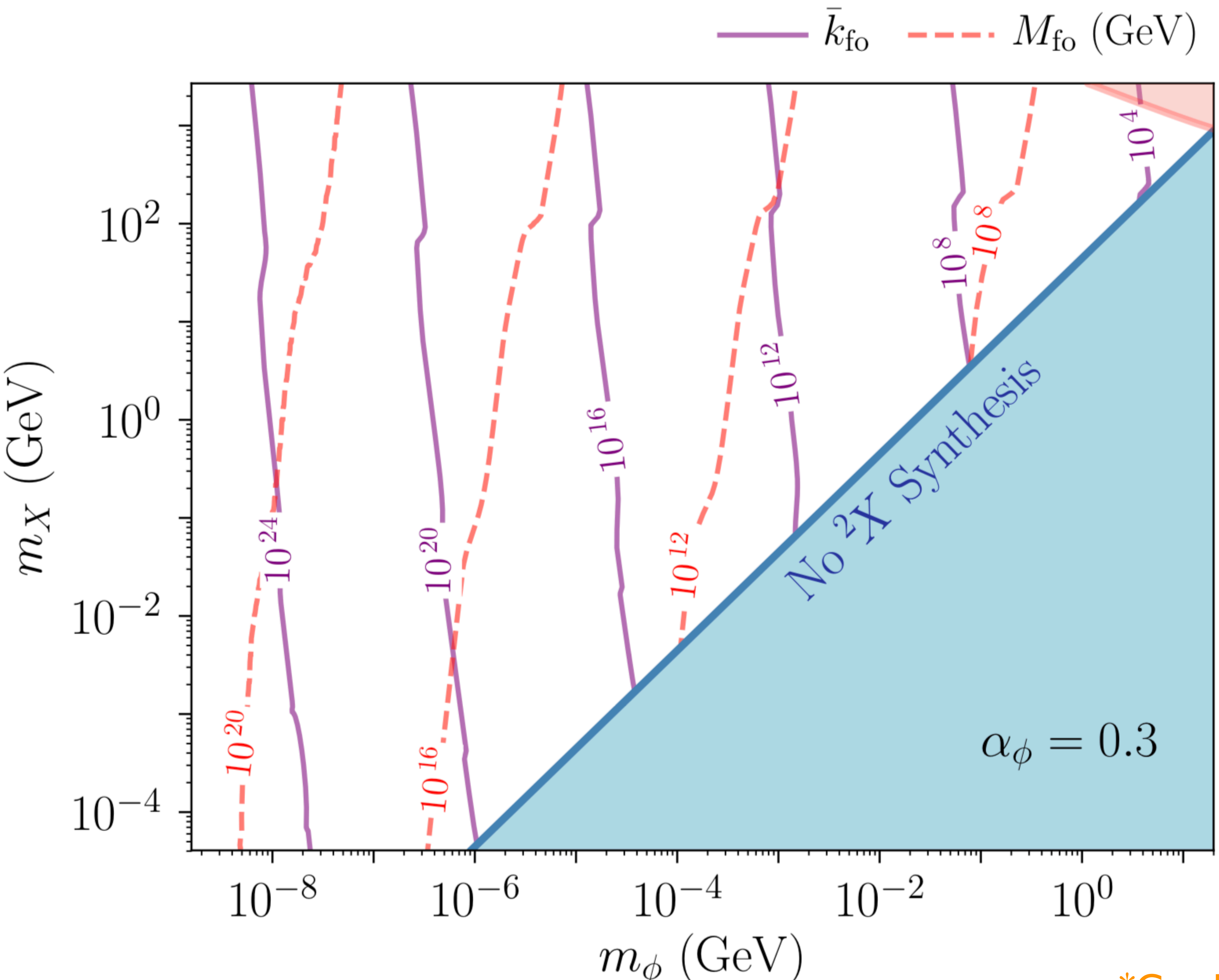
Dark Nuclear Matter

"Dark Nuggets"



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Detection

Standard Model Couplings

Nucleon Coupling

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

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

There are multiple constraints on g_n and g_χ depending on the mass of the mediator

Detection strategy depends heavily on the mass of mediator

Mediator Mass

Three Regimes

Heavy

$m_\varphi >> q_T$

Light

$m_\varphi << q_T$

Ultralight

Macroscopic λ_φ

Mediator Mass

Three Regimes

Heavy	**Light**	**Ultralight**
$m_\varphi >> q_T$	$m_\varphi << q_T$	Macroscopic λ_φ

Quantum Mechanical Scattering

Form Factor Effects

Classical Scattering

DM Sources Potential

Mediator Mass

Three Regimes

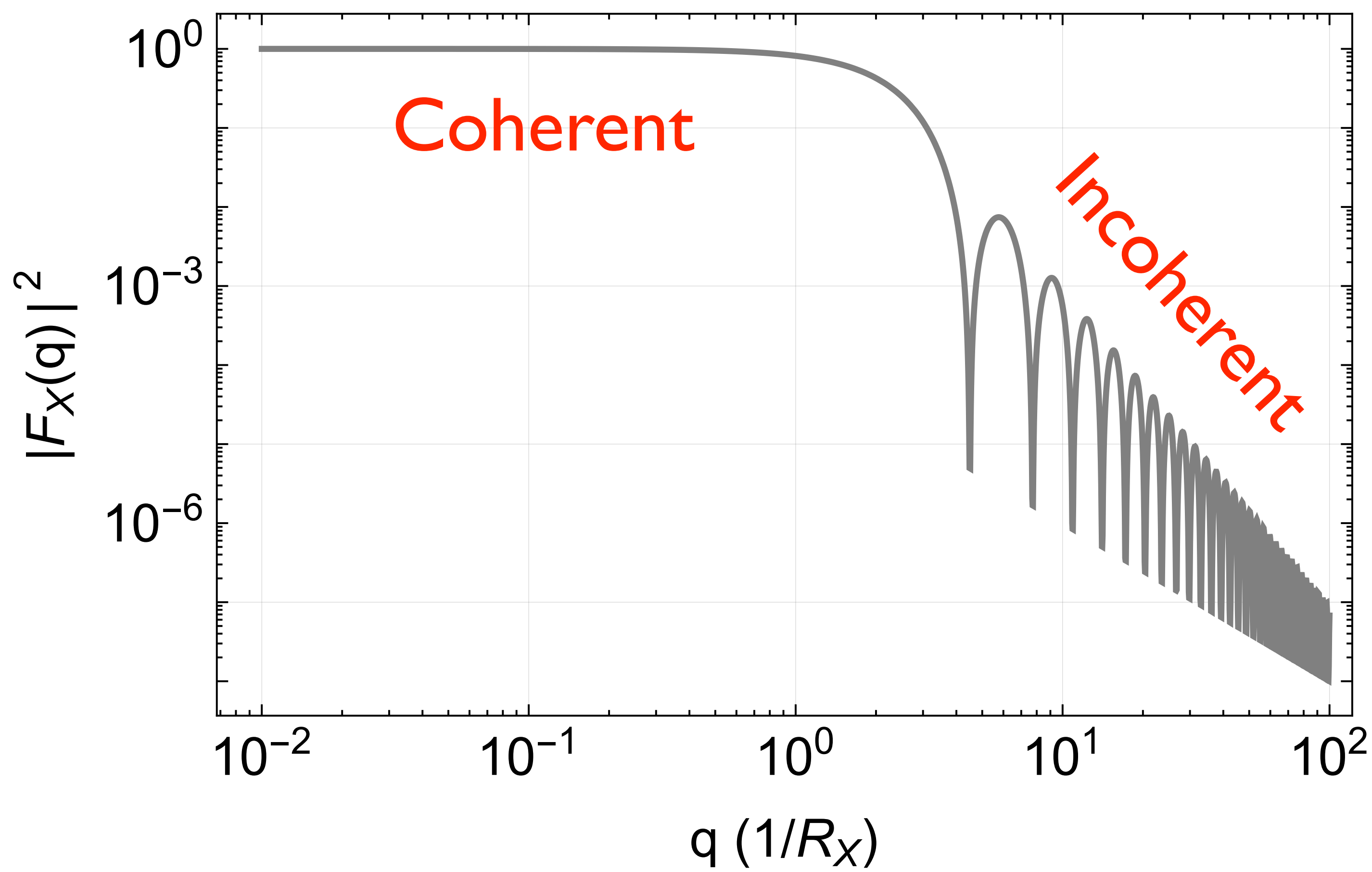
Heavy	Light	Ultralight
$m_\varphi \gg q_T$	$m_\varphi \ll q_T$	Macroscopic λ_φ
Quantum Mechanical Scattering		Classical Scattering
Form Factor Effects		DM Sources Potential
High Momentum Dominated	Low Momentum Enhancement	Need Precision Experiments

Dark Matter Form Factor

Finite Size effects

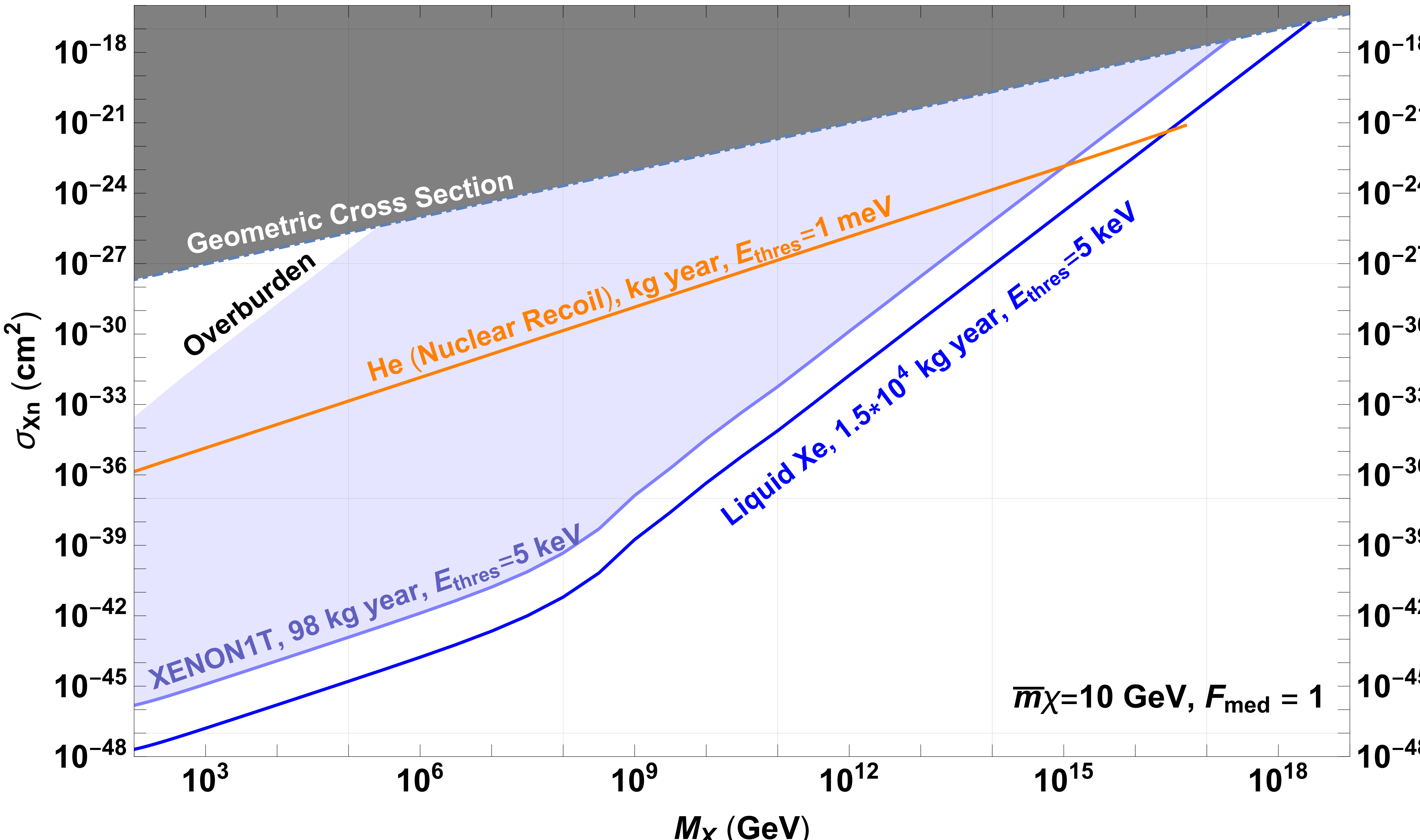
General Idea: Form factors "encode" the deviation of scattering amplitudes from the point particle limit

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



Heavy Mediator

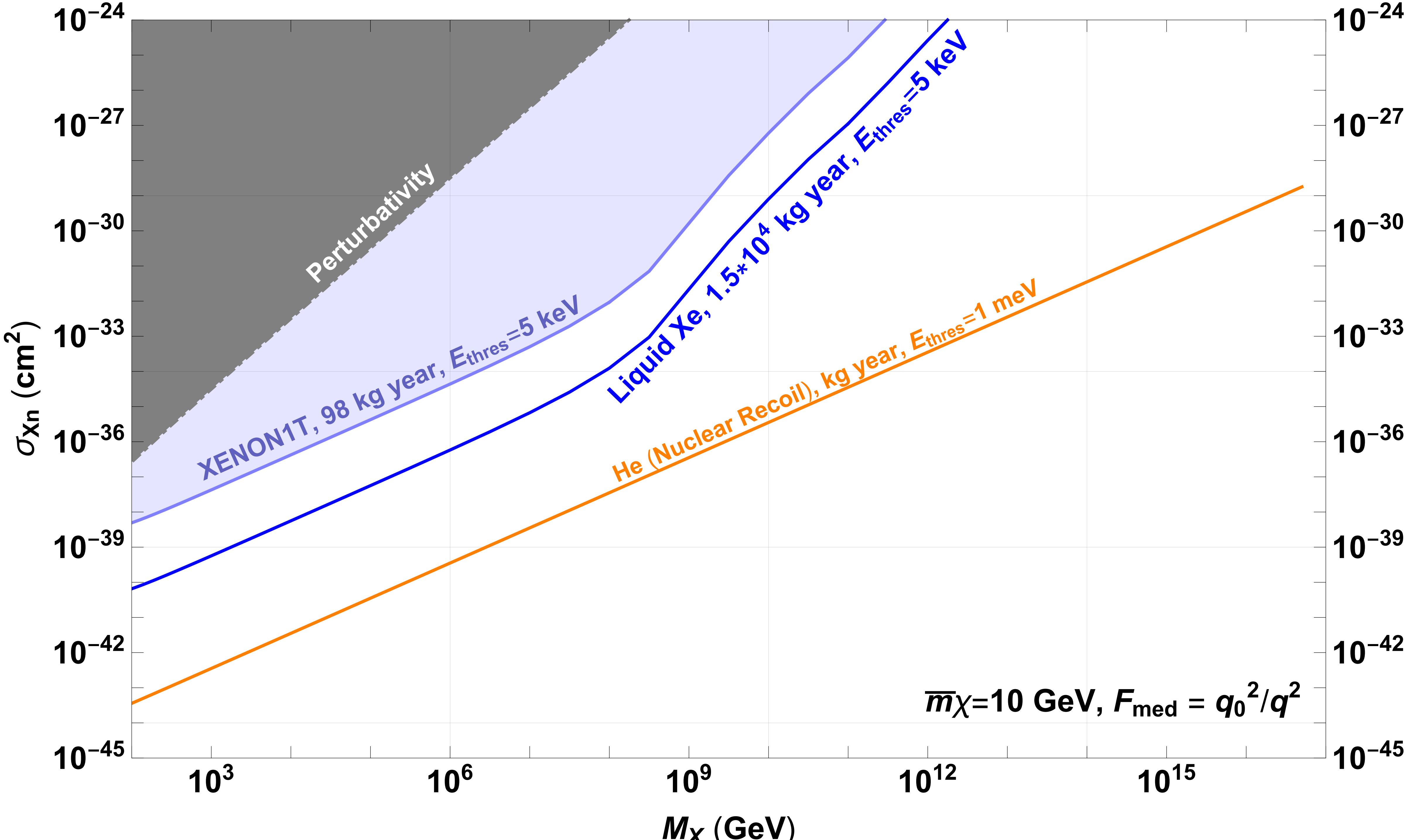
Mediator Mass: 10 GeV



*Coskuner, DMG, Knapen & Zurek '18

Light Mediator

Mediator Mass: eV



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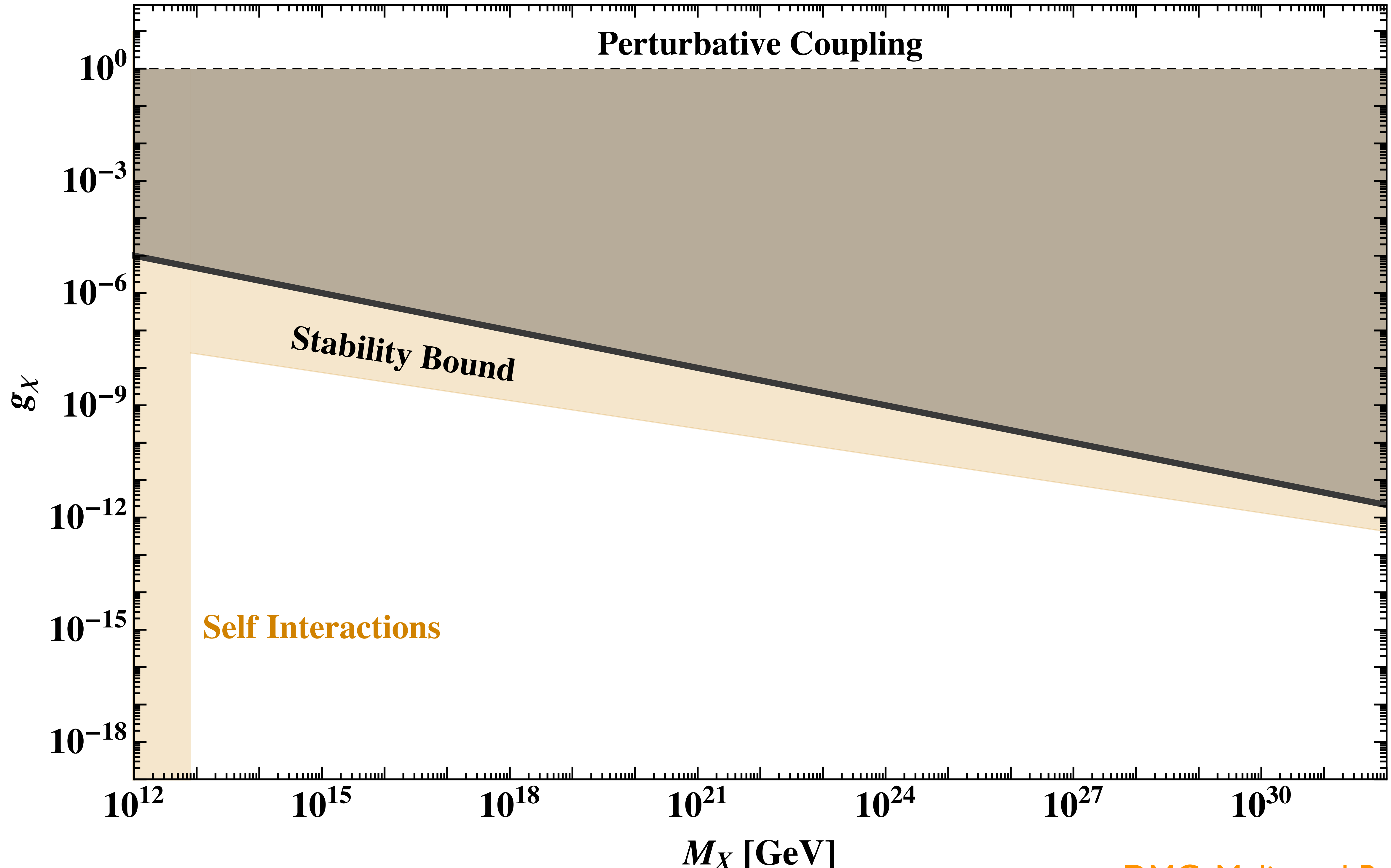
Ultralight Mediator

Λ_x = MeV, λ = 200 km, $g_n \sim 10^{-23}$



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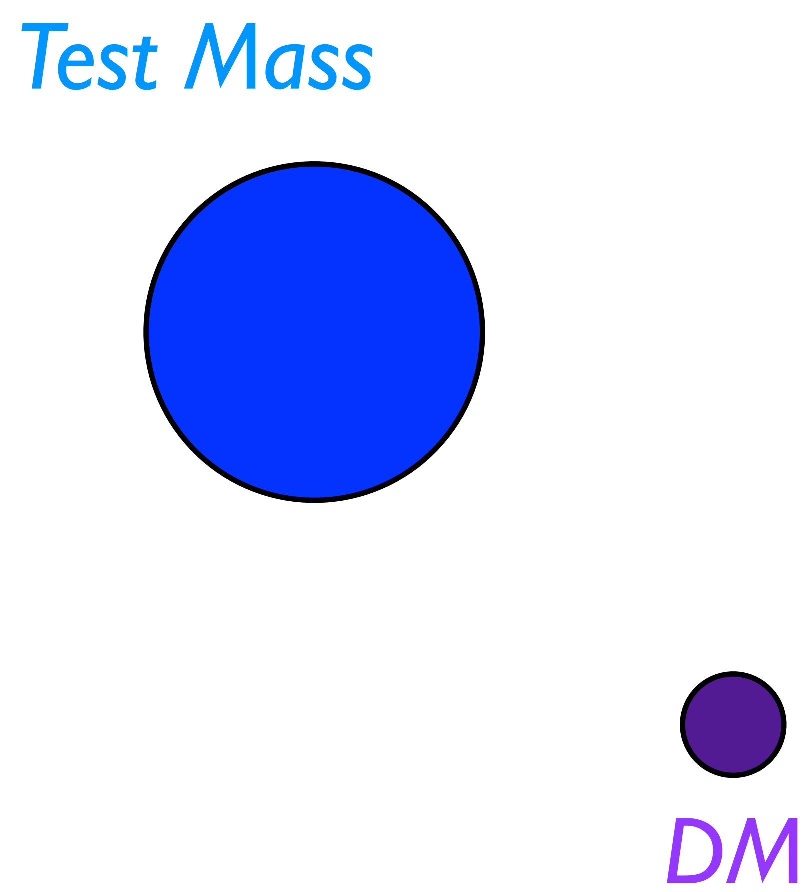
Acceleration

Free hanging test mass

General Idea: Passing DM induces motion in test mass



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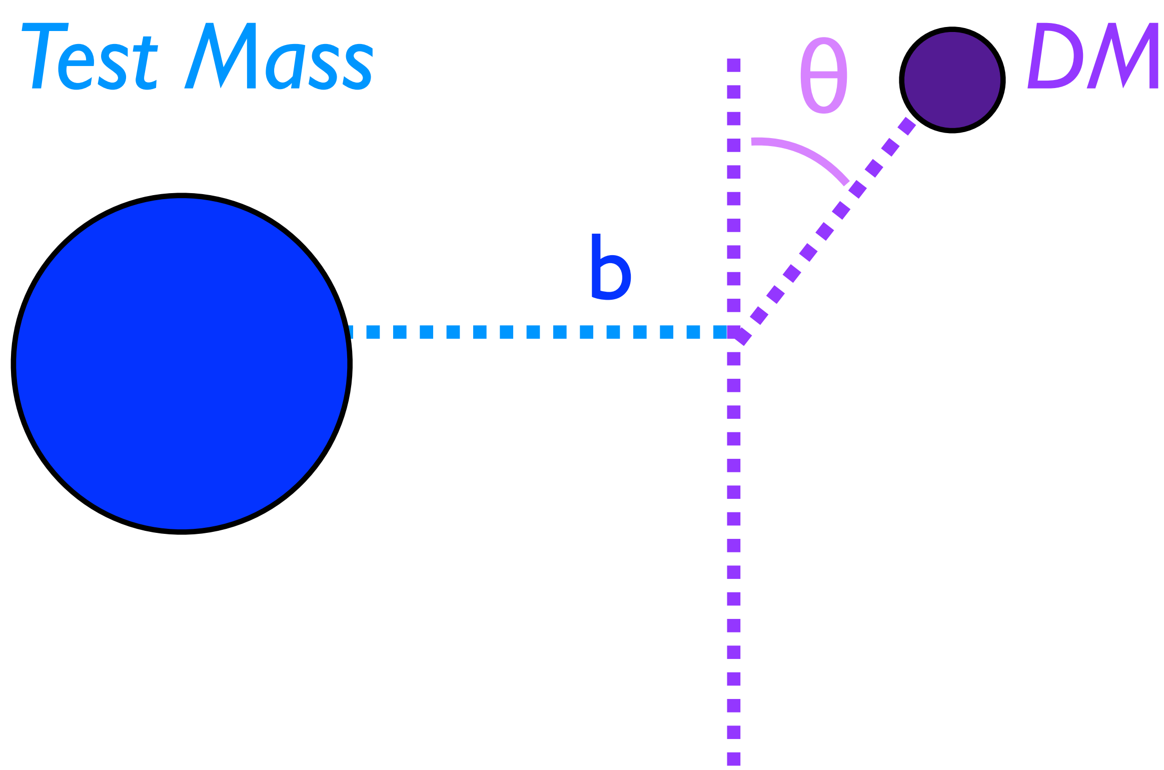

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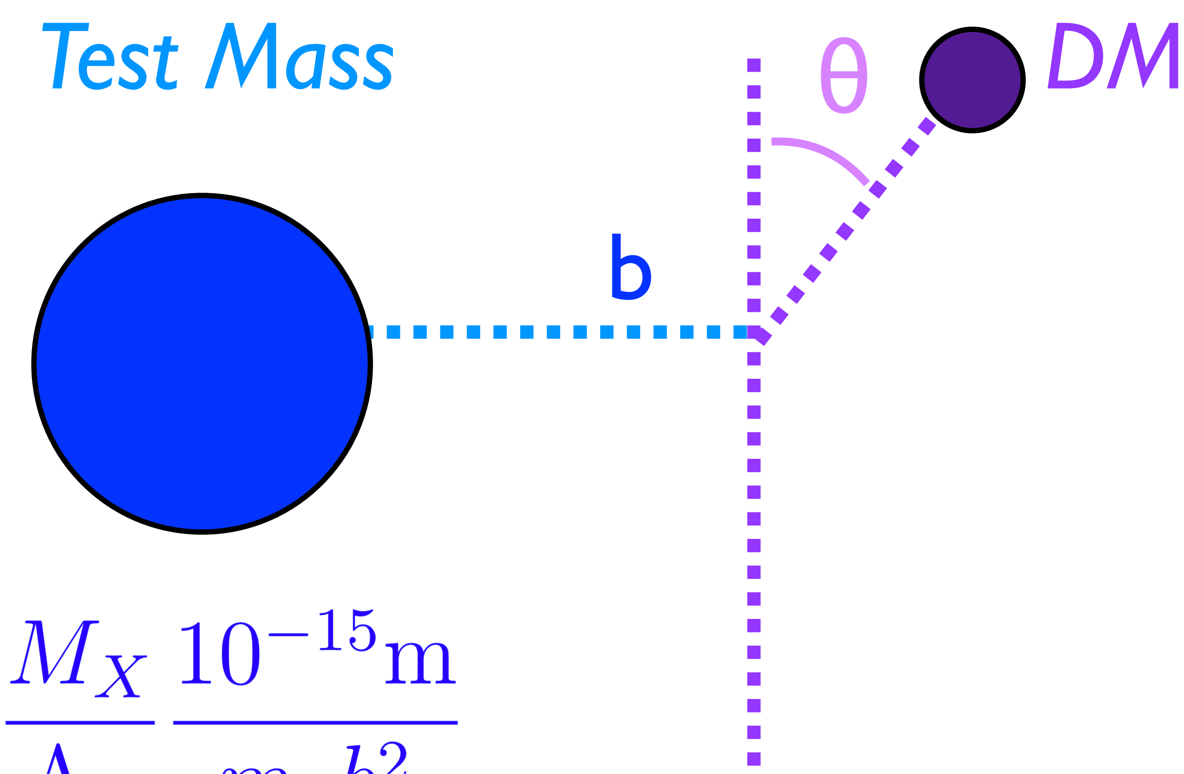

$$h \sim \frac{g_N g_\chi}{v^2} \frac{M_X}{\Lambda_\chi} \frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

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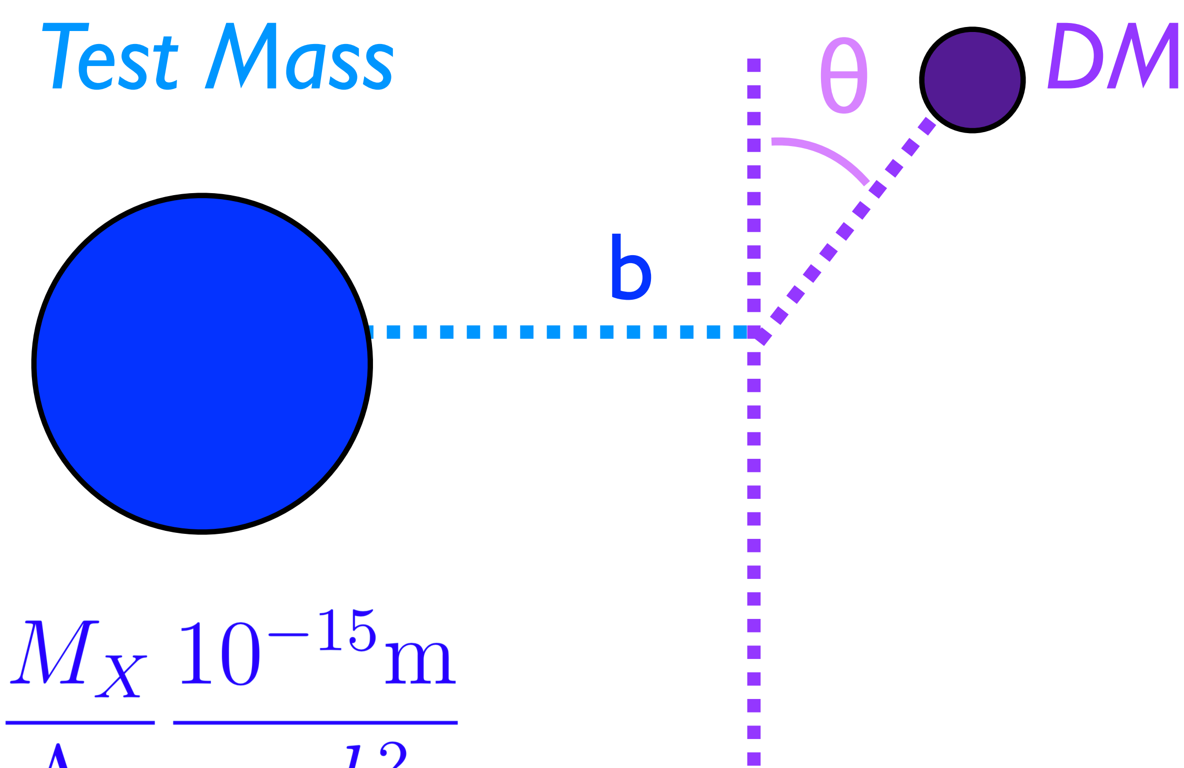
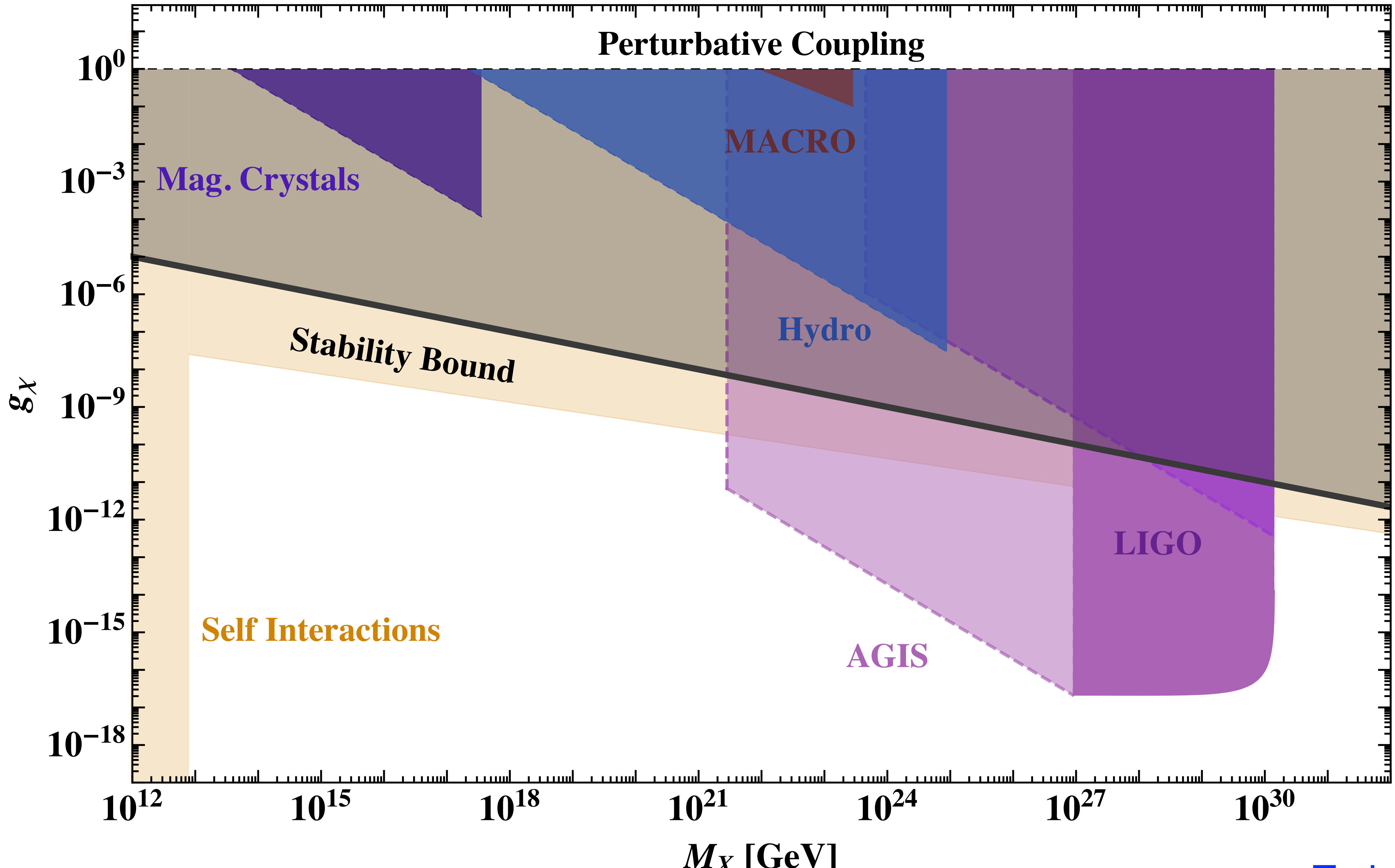


$$h \sim \frac{g_N g_\chi}{v^2}\frac{M_X}{\Lambda_\chi}\frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

- **Example:** LIGO sensitive to Δx ~ 0.1 fm/Hz$^{1/2}$

Extremely Long Range Mediator

Λ_x = MeV, λ = 200 km



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Tank: (500 m)^3

Conclusions

Focus: Exponentially large composite dark matter

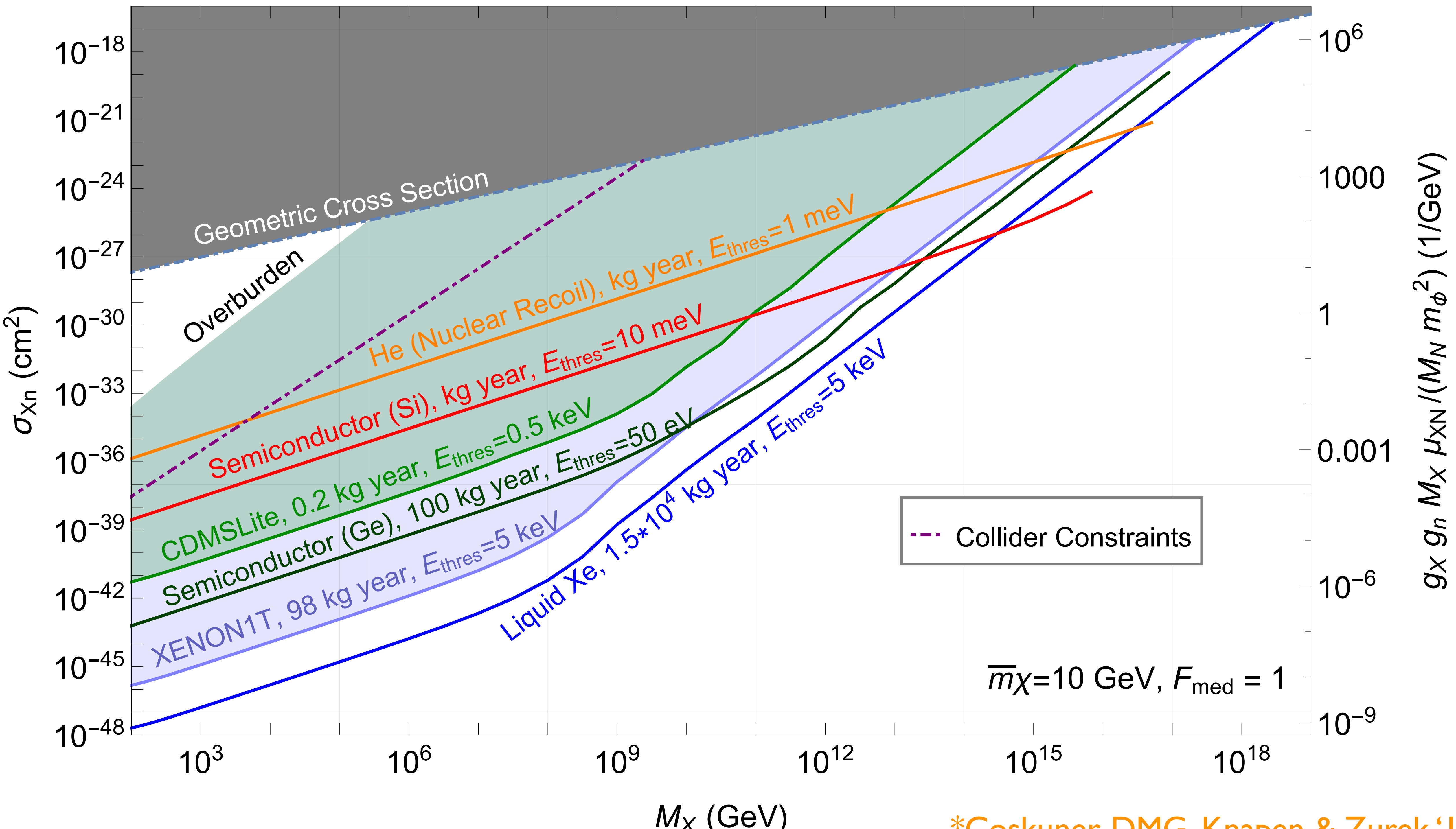
Take Away: Strongly interacting dark sector can give DM whose mass ranges over 40 orders of magnitude

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

BACK UP

Heavy Mediator

Mediator Mass: 10 GeV



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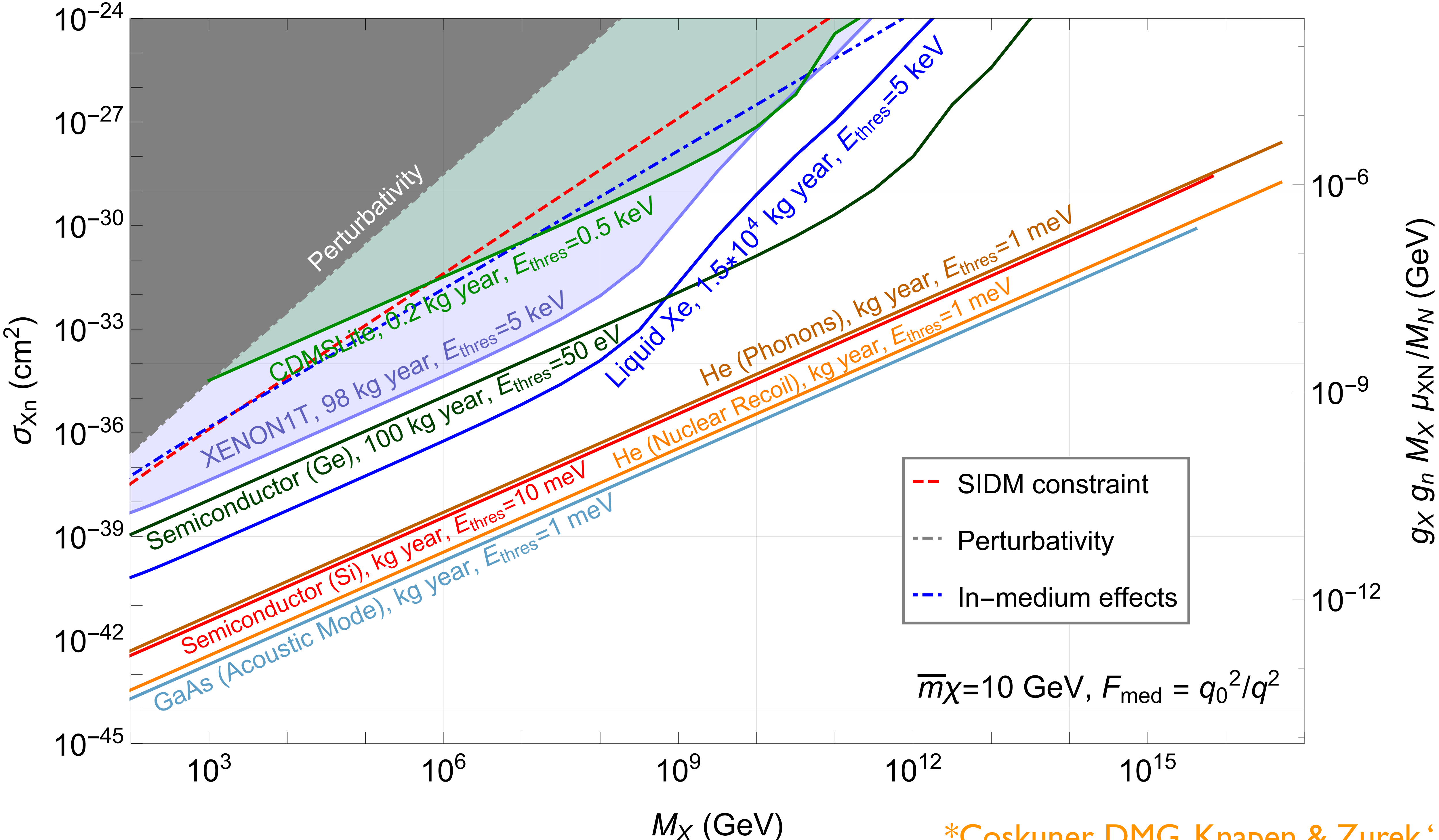
Long Range Mediator

Mediator Mass: eV



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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

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

DM Form Factor

Finite Size effects

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

$$F_X(\mathbf{q}) = \frac{1}{M_X} \int d^3\mathbf{r}\; e^{i\mathbf{q}\cdot\mathbf{r}} \rho_X^{(\text{ch.})}(\mathbf{r})$$

Charge Density

ASSUME: Uniform charge density inside dark nucleus

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

q: Momentum Transfer

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Mediator Coupling Constraints

Dark Sector Constraints

Scalar Coupling g_χ 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

Mediator Coupling Constraints

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Scalar Coupling g$_\chi$ 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

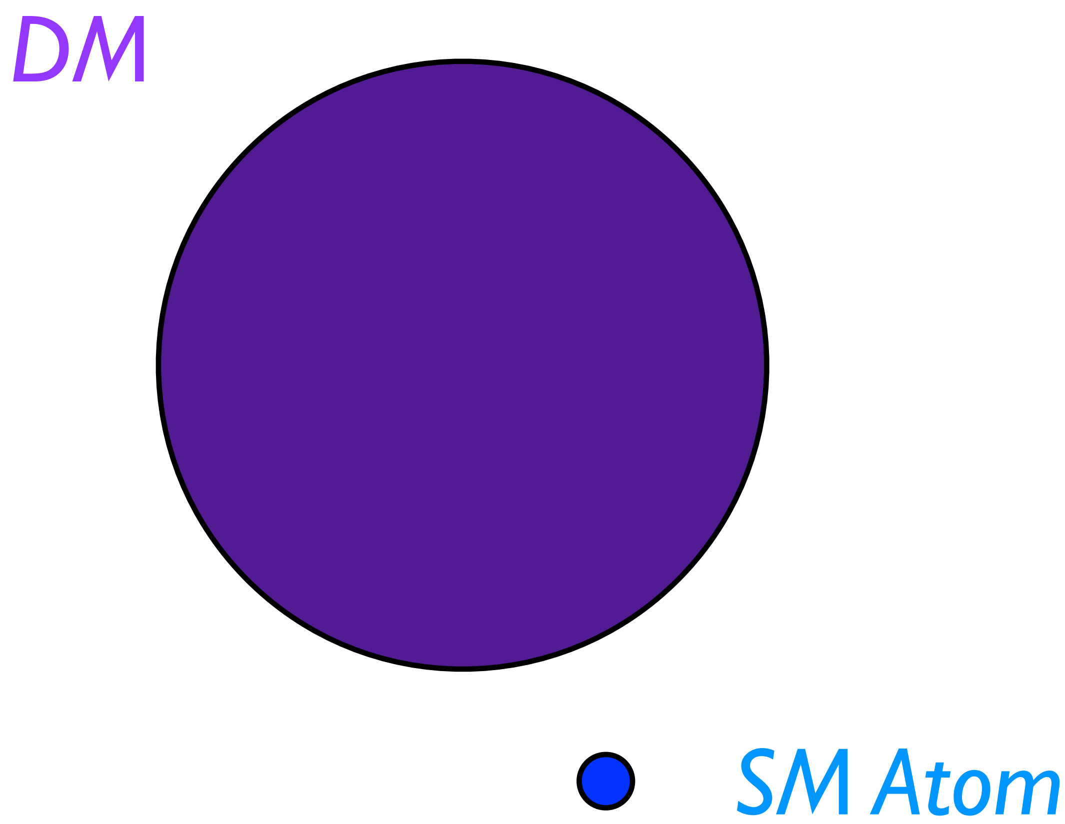
$$E_{\rm Bind} \sim \underline{\alpha_V} N_X - \alpha_S N_X^{2/3} - \underline{\alpha_C} N_X^{5/3}$$

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

Ionization and Scintillation Signals

Standard Dark Matter Search

General Idea: momentum transfer during collision between blob and ***single*** SM atom



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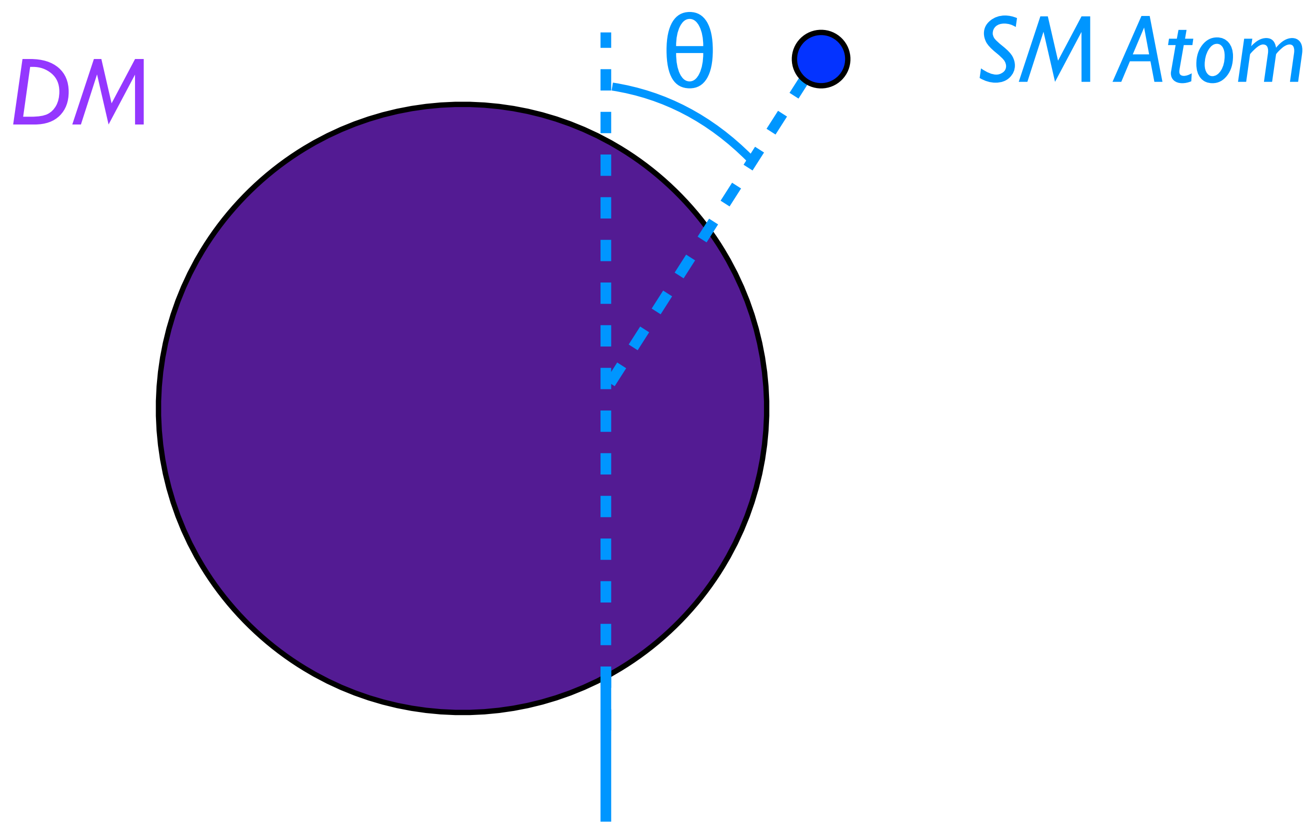

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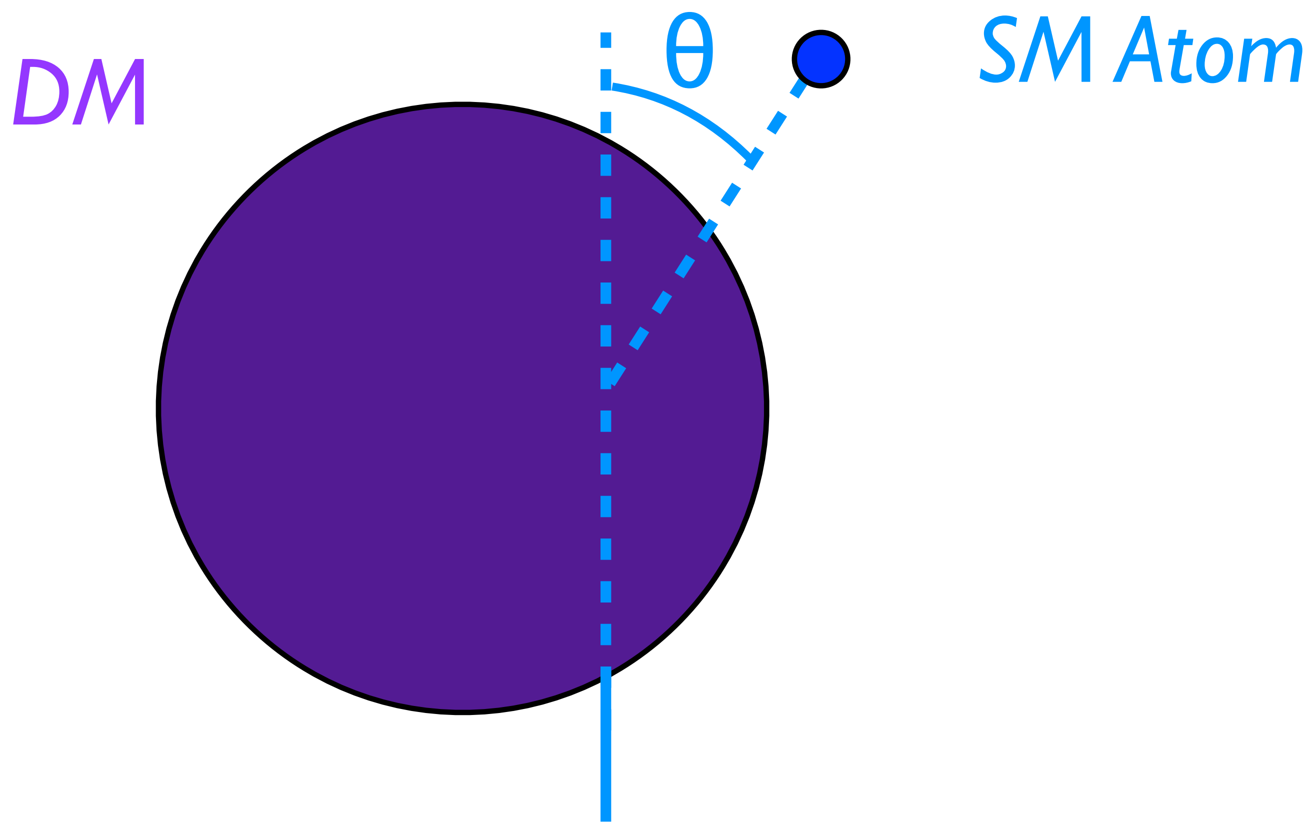
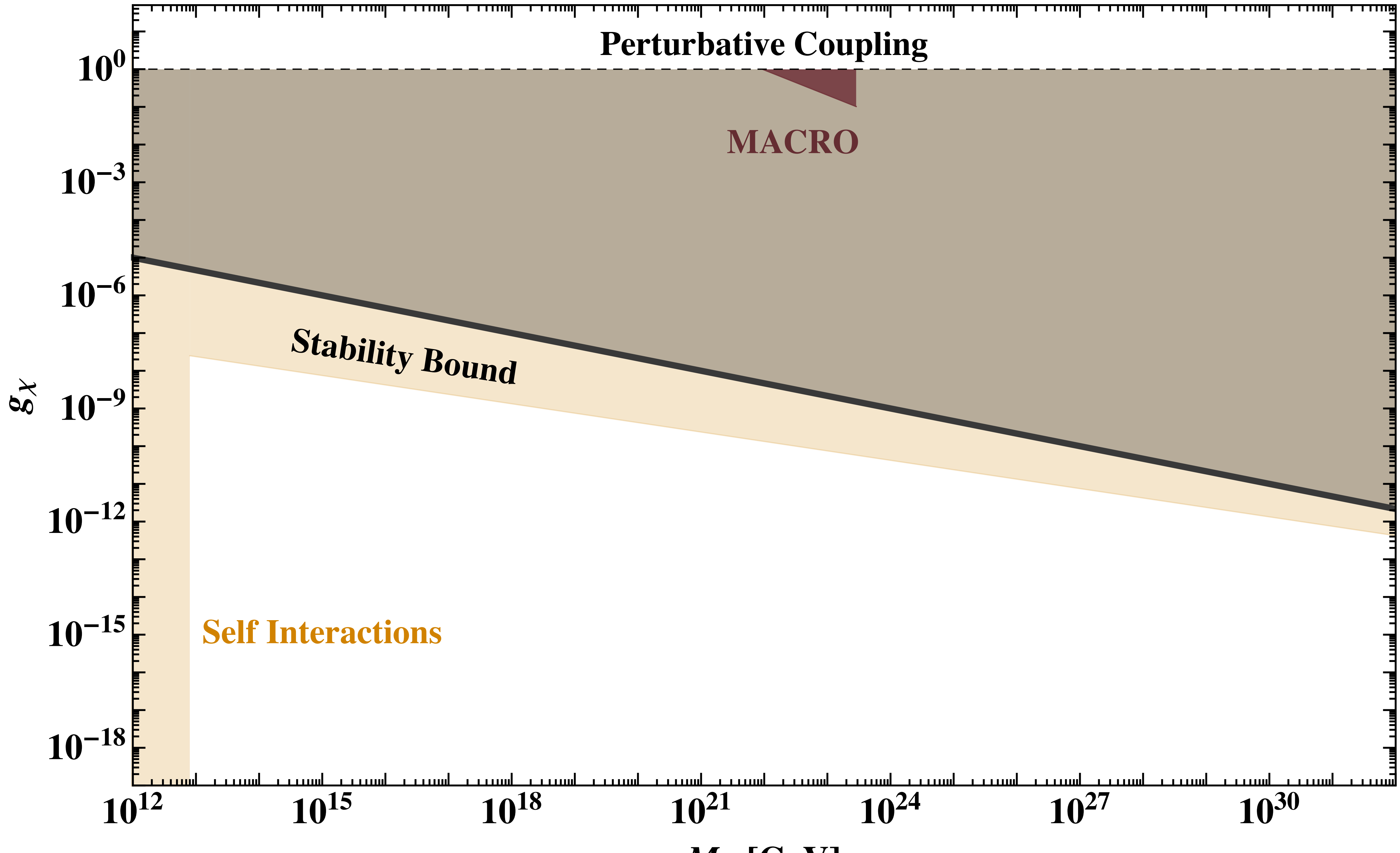


- Only small angle scattering due to weak coupling
- Ionization occurs if mom. transfer above ~100 keV

Scalar Mediator to Nucleons

Λ_x = MeV, λ = 200 km



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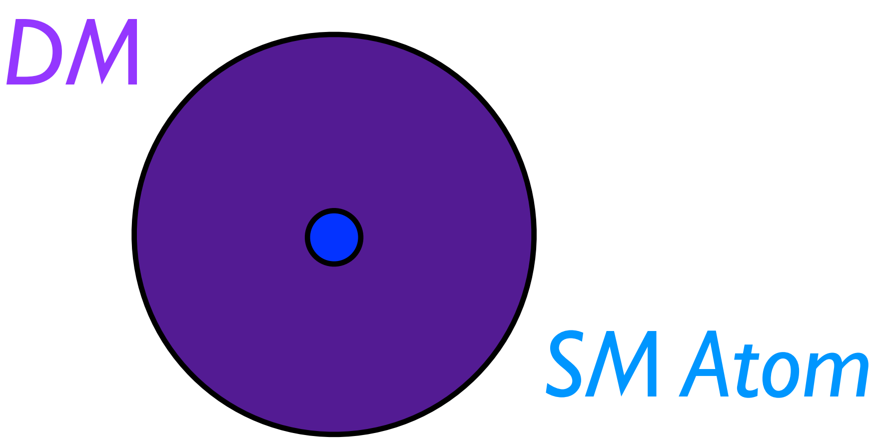
Heat Deposition

Blobs with large radius

General Idea: Blobs deposit large amounts of energy without necessarily causing ionization/scintillation

- Large blob radius allows multiple SM atoms to experience significant change in momentum



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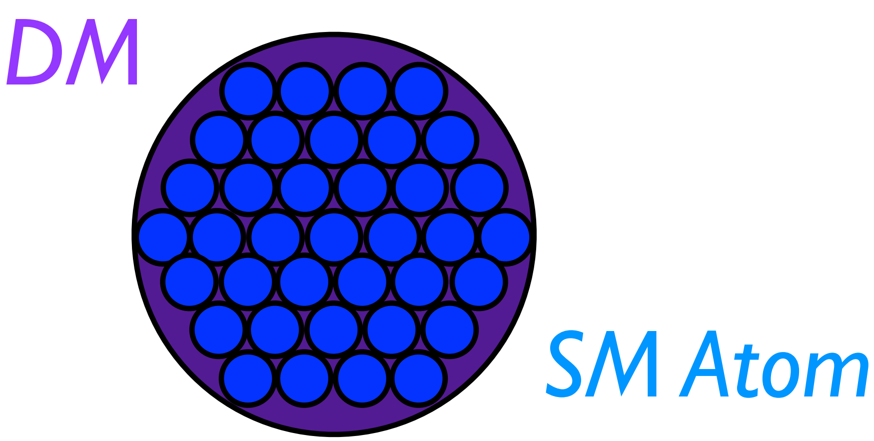

$$\Delta E_{\mathrm{Tot}} \sim \left(\frac{R_X}{R_0}\right)^2 \Delta E^{\mathrm{Max}}_{\mathrm{Single}}$$

Relies on "guaranteed hit"

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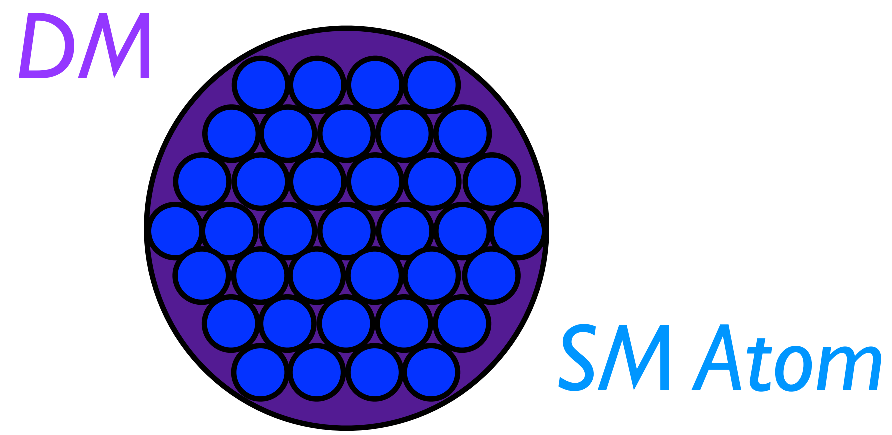

$$\Delta E_{\text{Tot}} \sim \left(\frac{R_X}{R_0}\right)^2 \Delta E_{\text{Single}}^{\text{Max}}$$

Relies on "guaranteed hit"

- **Example:** Hydrophones in tank of water are sensitive to energy deposition of ~ 10 keV/Angstrom

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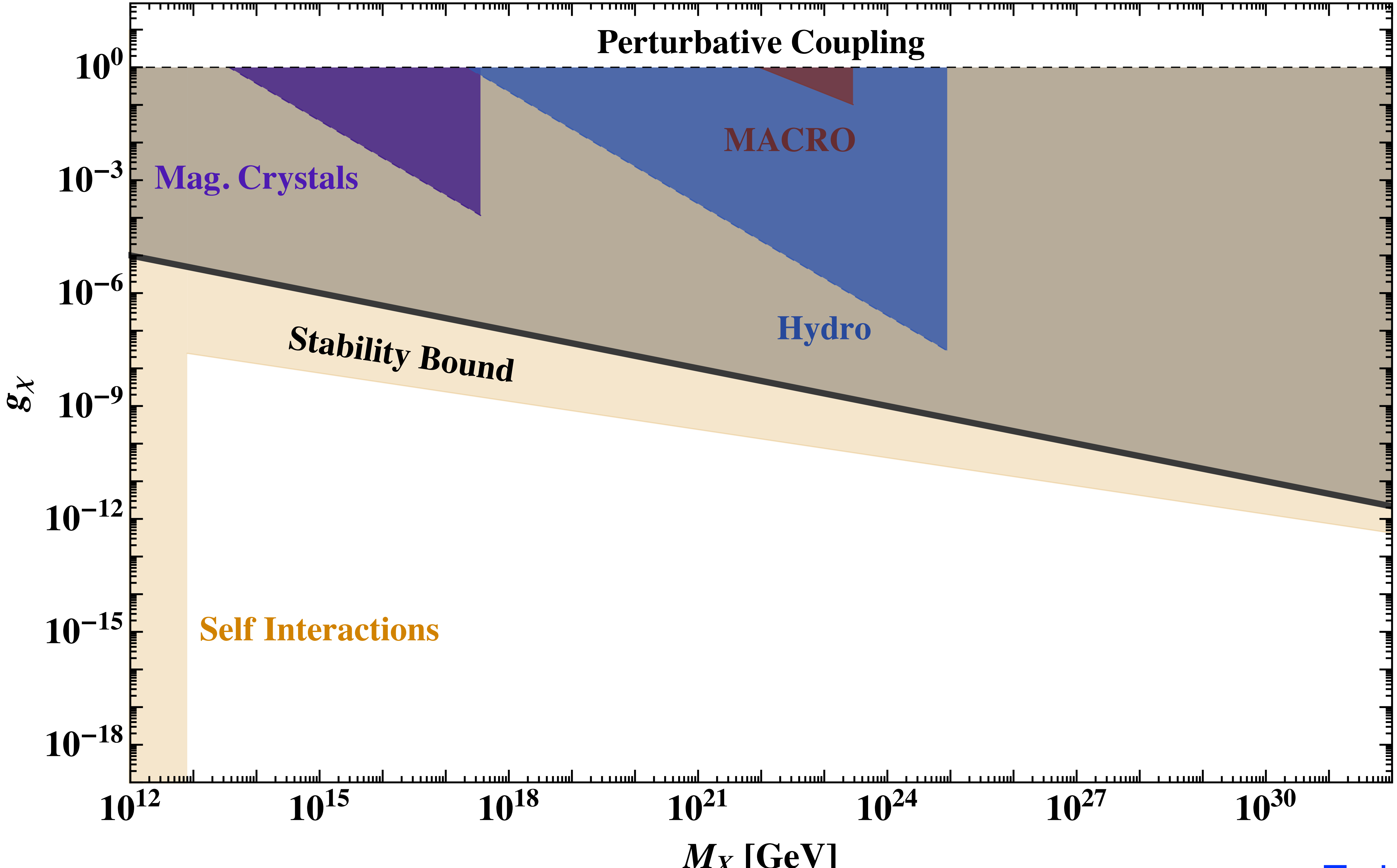

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