Title: Detecting Dark Blobs

Date: Oct 02, 2018 01:00 PM

URL: http://pirsa.org/18100041

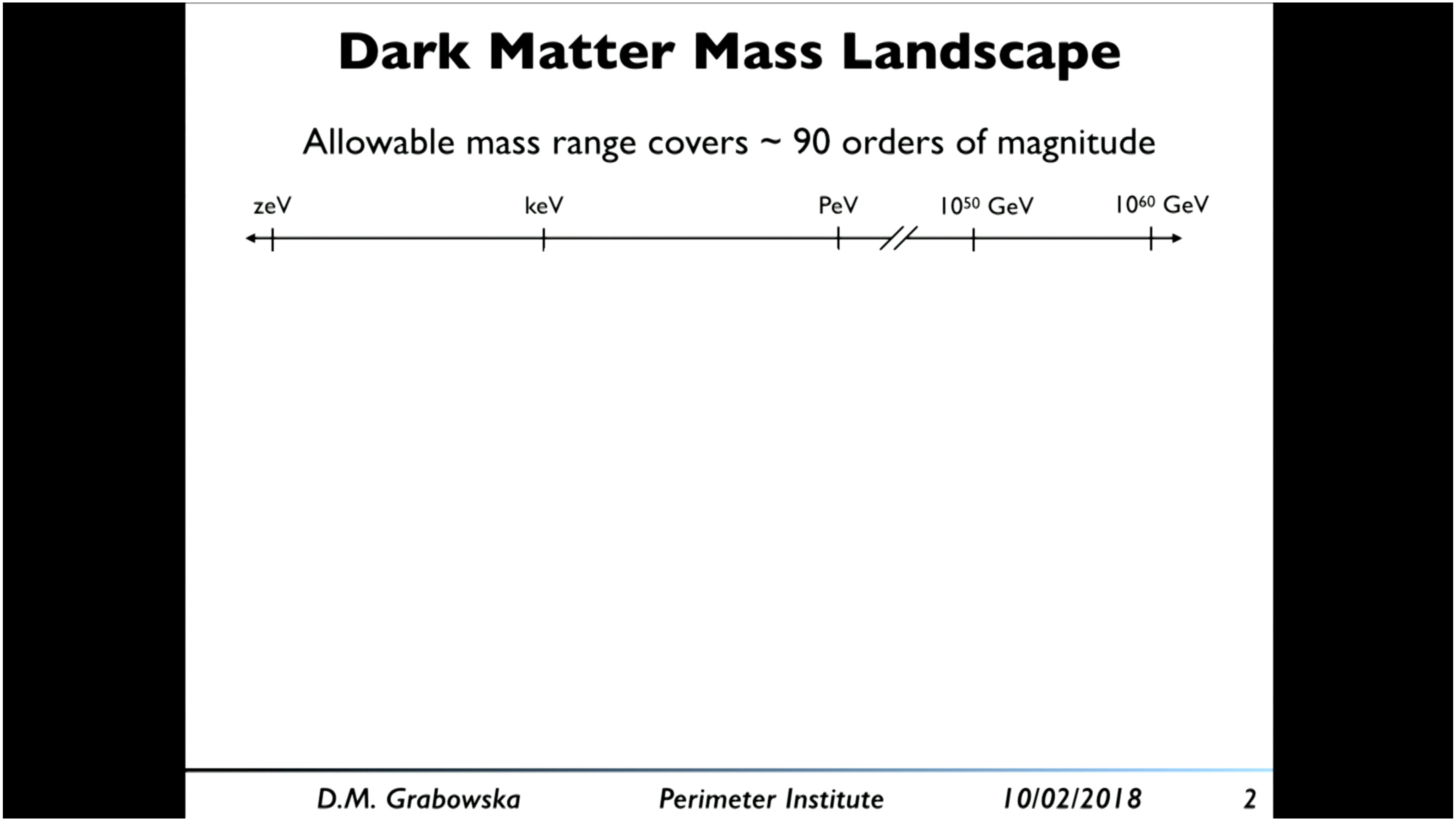
Abstract: <p>Most current dark matter detection strategies, including both direct and indirect efforts, are based on the assumption that the galactic dark matter number density is quite high, allowing for the detection of rare scattering events. Such a paradigm arises naturally if the dark matter self-interactions are weak. However, strong interactions within the dark sector can give rise to large composite objects, whose detection requires a different experimental paradigm. We call these object Dark Blobs. In such theories, the energy transfer due to a single collision with a Standard Model particle tends to be small, below the energy threshold of many nuclear recoil experiments. Fortunately, due to their exponentially large composite nature, the interactions between these objects and a terrestrial detector can be coherently enhanced. Therefore, while the effect on a single probe is small, the large collective effect can be quite dramatic and, importantly, above experimental thresholds. In this talk, I will briefly motivate the early Universe formation of certain types of Dark Blobs and then focus on multiple detection avenues for these objects.</p>

Detecting Dark Blobs

Dorota M Grabowska

UC Berkeley and LBL

Work with Tom Melia and Surjeet Rajendran
arXiv: 1807.03788



Dark Matter Mass Landscape

Allowable mass range covers ~ 90 orders of magnitude

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Ultra Light DM

Axions, ALPS, etc

Classically coherent fields compensate for weak coupling

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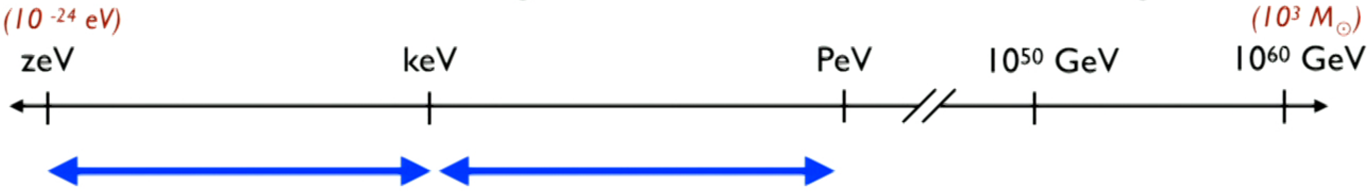

Ultra Light DM

Axions, ALPS, etc

Classically coherent fields compensate for weak coupling

Particle DM

WIMPs, Hidden Sector, Asymmetric, etc

High number density compensates for small cross sections

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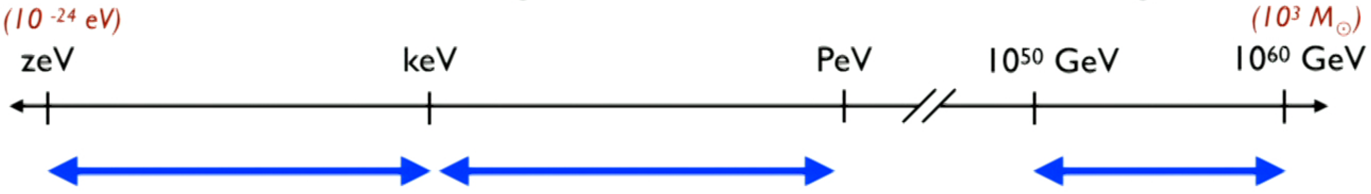
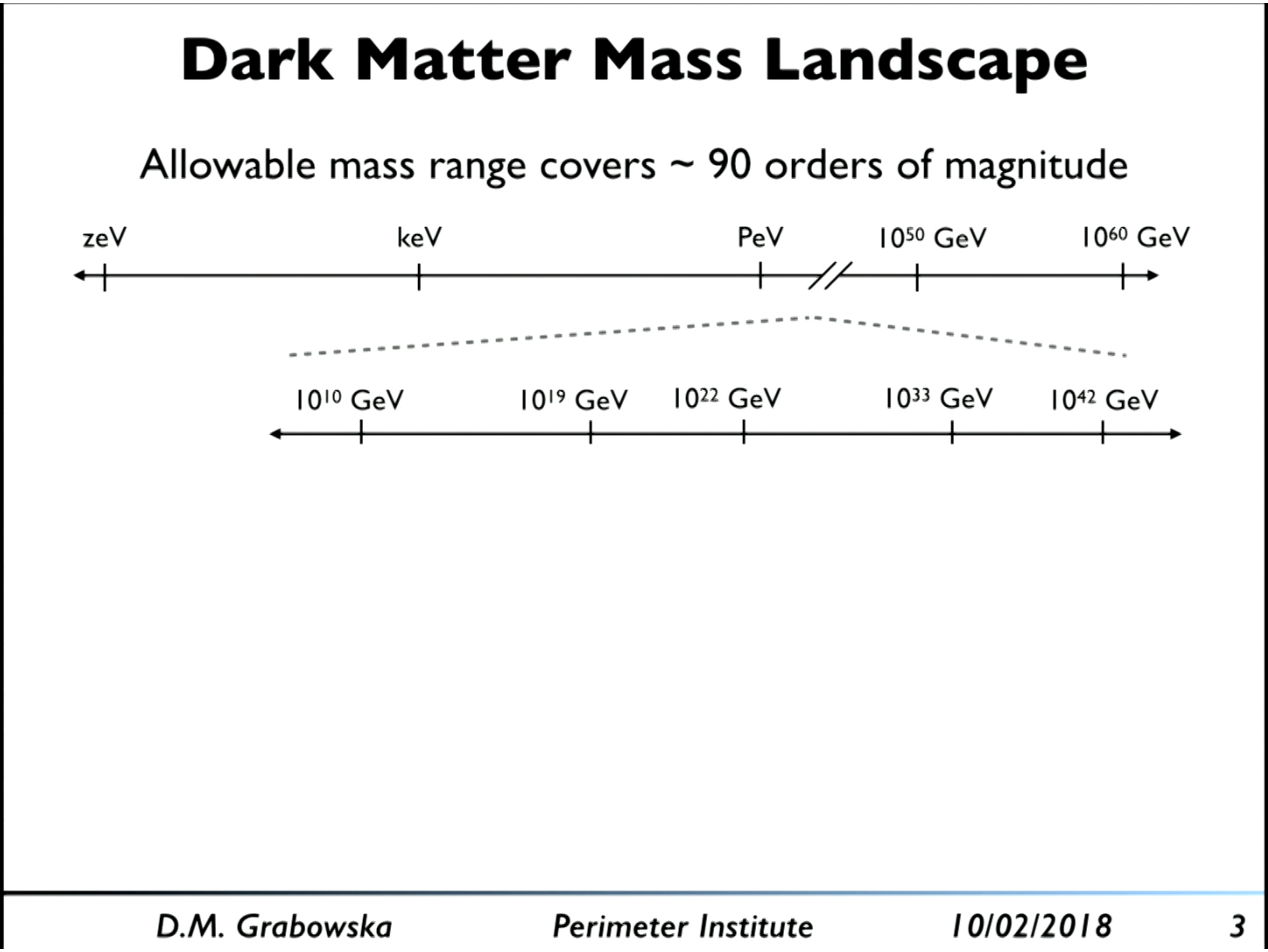


Ultra Light DM	Particle DM	Macroscopic DM
Axions, ALPS, etc	WIMPs, Hidden Sector, Asymmetric, etc	Primordial Black Holes, MACHOS, etc
Classically coherent fields compensate for weak coupling	*High number density compensates for small cross sections*	*High mass compensates for weakness of gravity*



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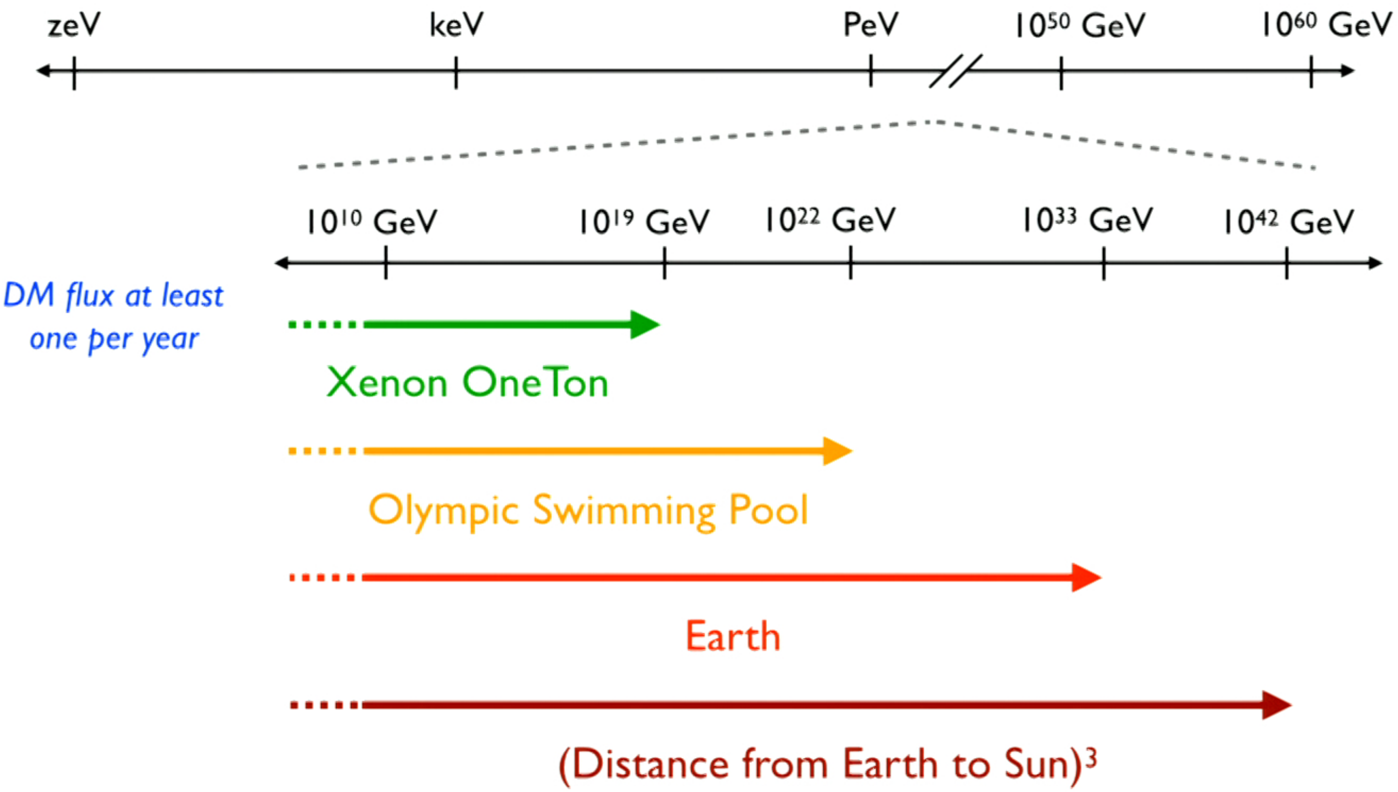


DM flux at least one per year

Xenon OneTon

Olympic Swimming Pool

Earth

(Distance from Earth to Sun)^3

Plan

Goal One: Viable DM candidates in this mass region

- Strongly coupled dark sector
- Early Universe Dark Nucleosynthesis

Goal Two: Detectable with Earth-based experiments

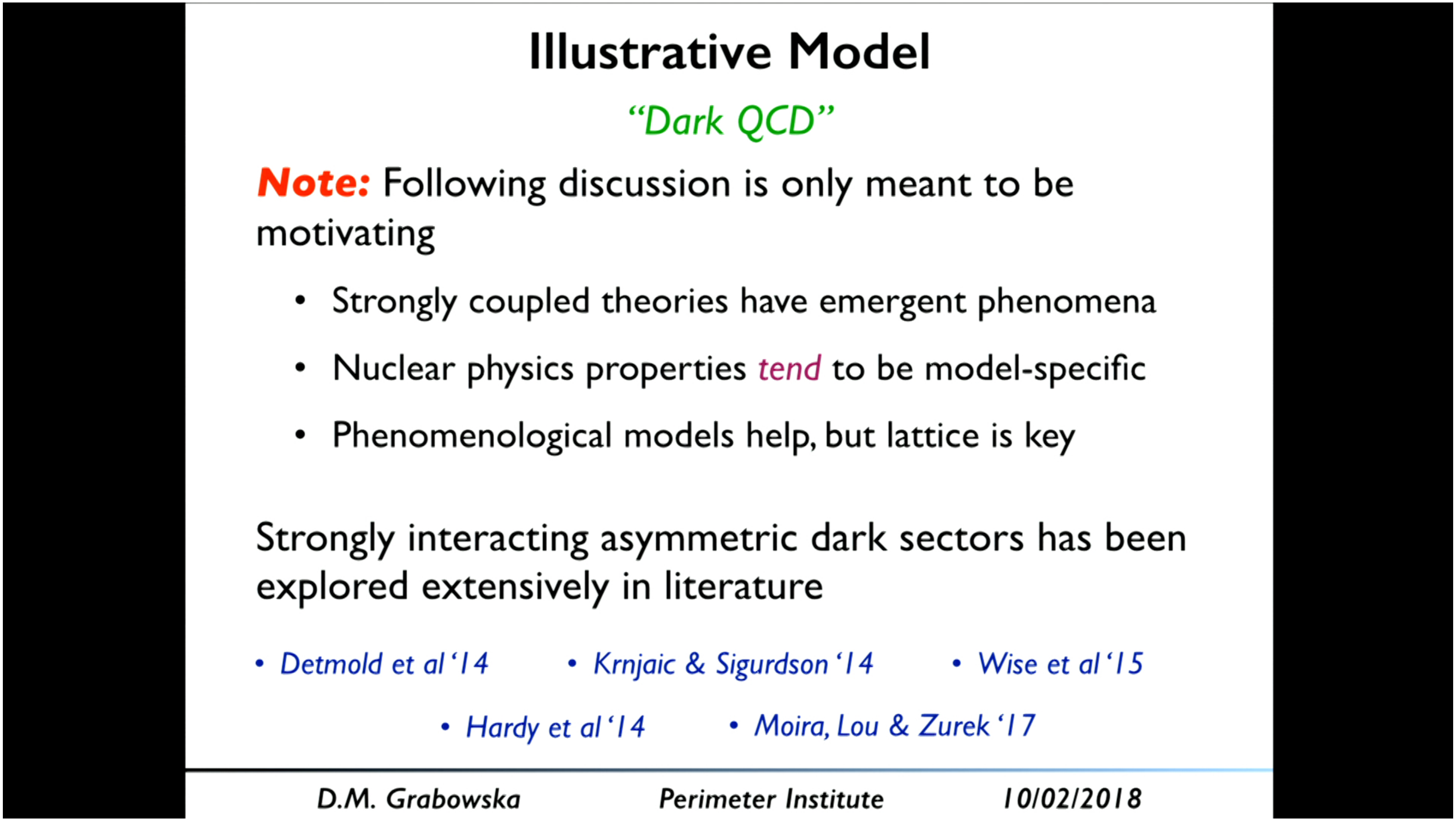
- Large number of constituents compensate for weak coupling
- Constraints on various interaction types possible using existing or near-future experiments

Illustrative Model

"Dark QCD"

Note: Following discussion is only meant to be motivating

- Strongly coupled theories have emergent phenomena
- Nuclear physics properties *tend* to be model-specific
- Phenomenological models help, but lattice is key



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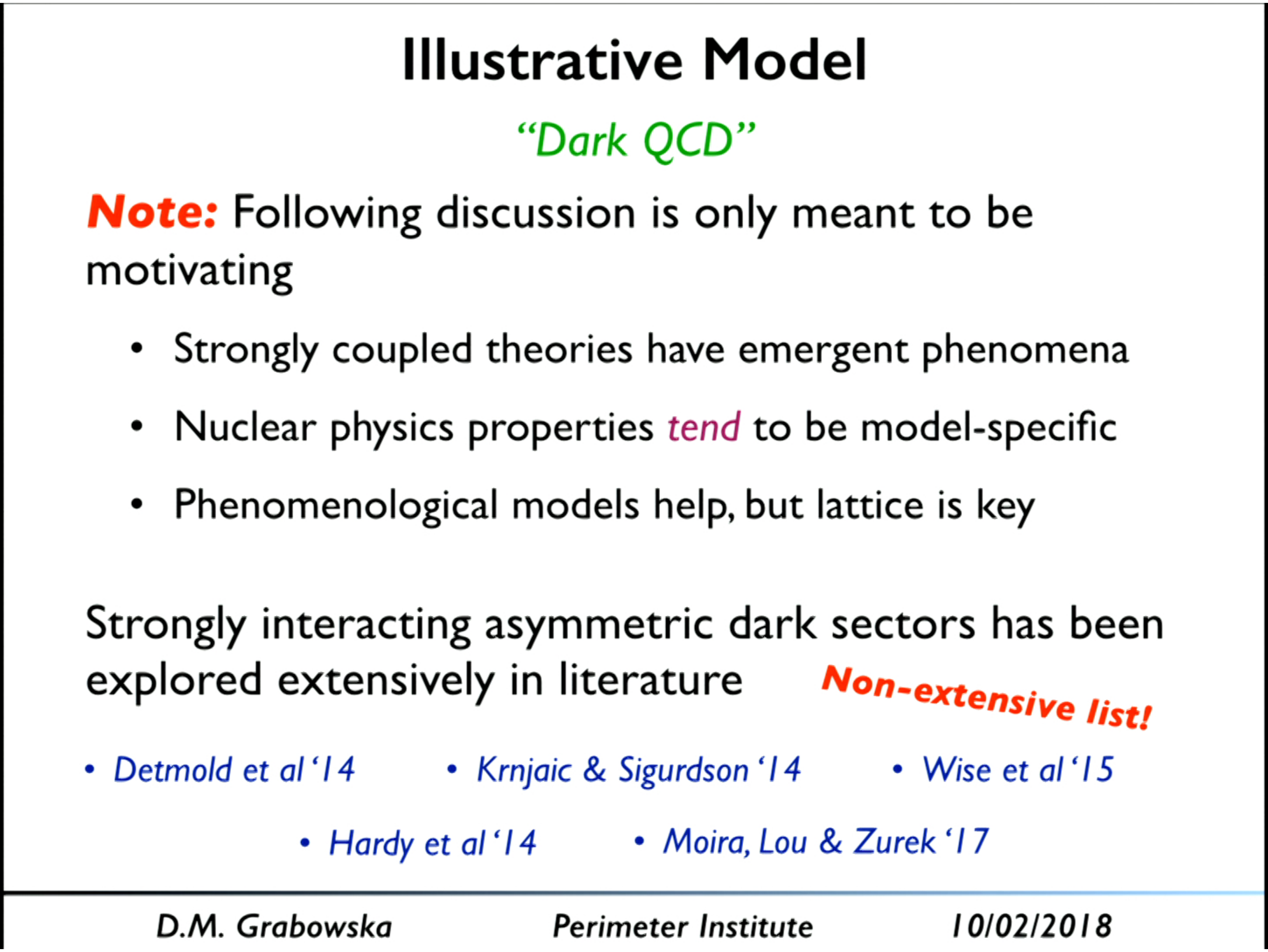
Strongly interacting asymmetric dark sectors has been explored extensively in literature

- *Detmold et al ‘14*
- *Krnjaic & Sigurdson ‘14*
- *Wise et al ‘15*
- *Hardy et al ‘14*
- *Moira, Lou & Zurek ‘17*



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Non-extensive list!

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Strongly Interacting Dark Sector

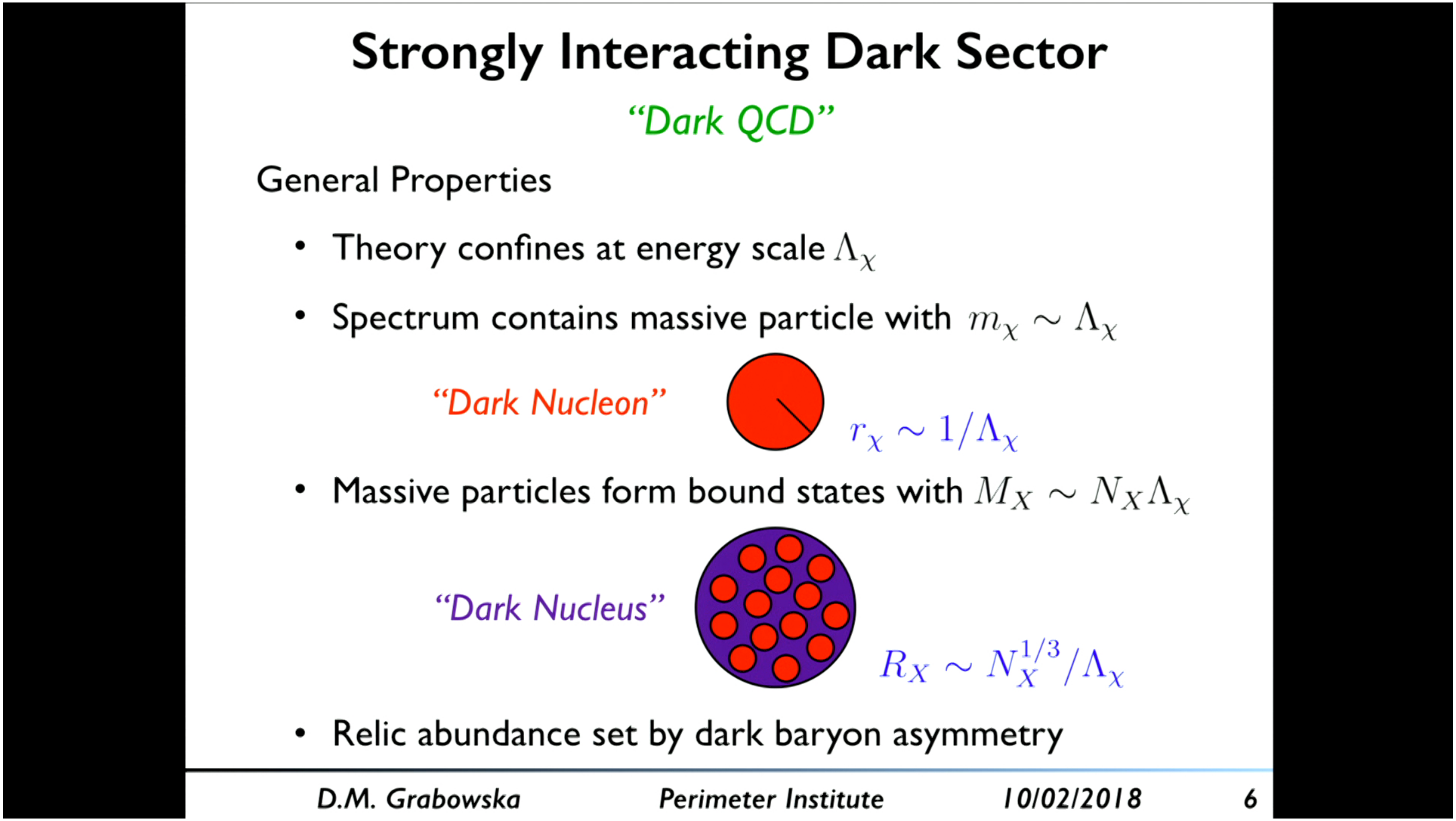
"Dark QCD"

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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"Dark Nucleon"

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

- 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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$$E_{\text{Bind}} \sim \underbrace{\alpha_V N_X}_{\text{Short Range Strong Interaction}} - \underbrace{\alpha_S N_X^{2/3}}_{\text{Surface Correction}} - \underbrace{\alpha_C N_X^{5/3}}_{\text{Long Range Weak Interaction}}$$

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- Assume no long range force to destabilize dark nuclei

Binding energy unbounded from above!

nteraction

ark nuclei

n above!

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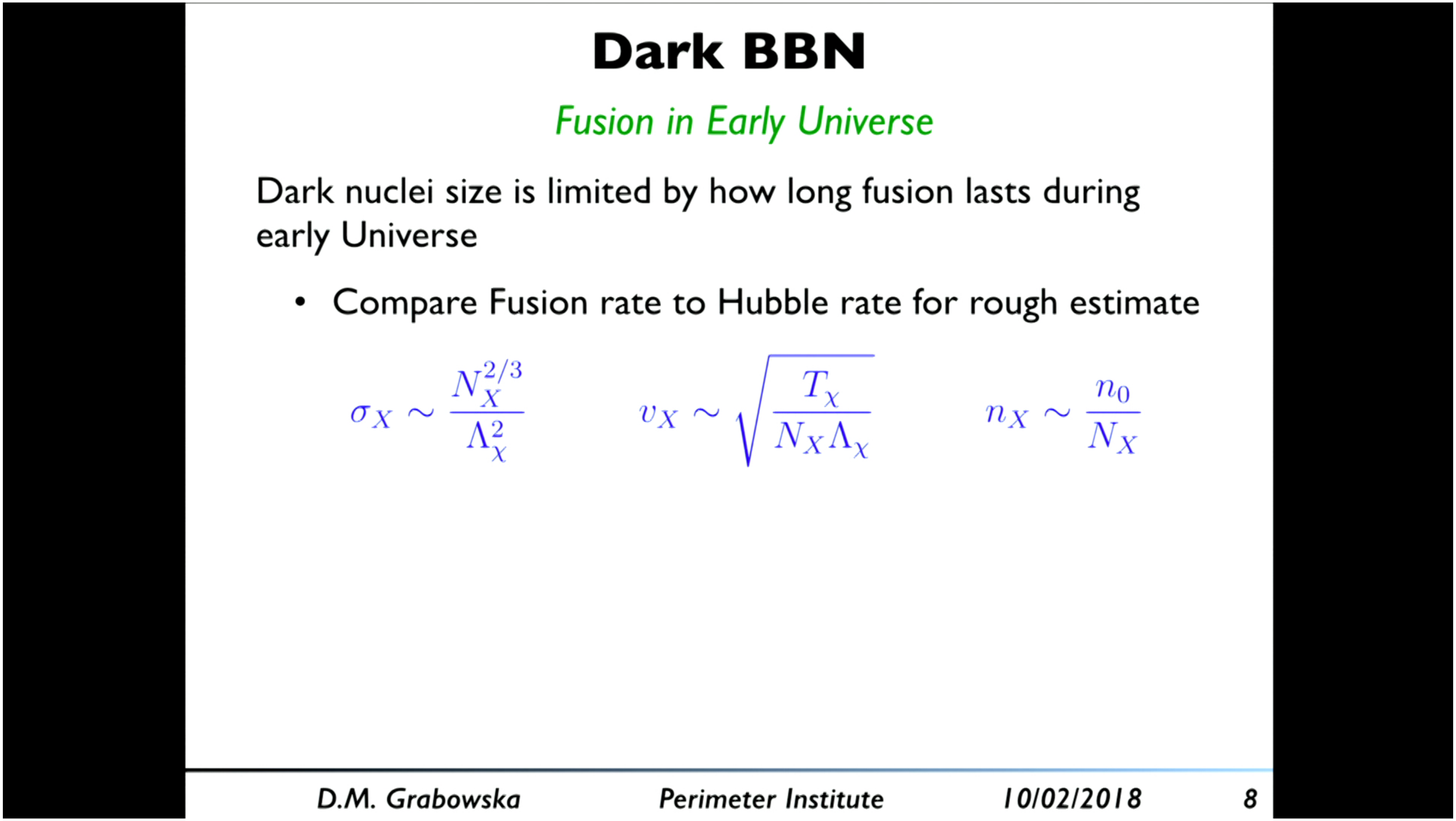
$$\frac{N_x(N_x-1)}{N^{1/3}}$$

all neighbors

⇒ Coulomb



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*

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

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Fermionic blobs

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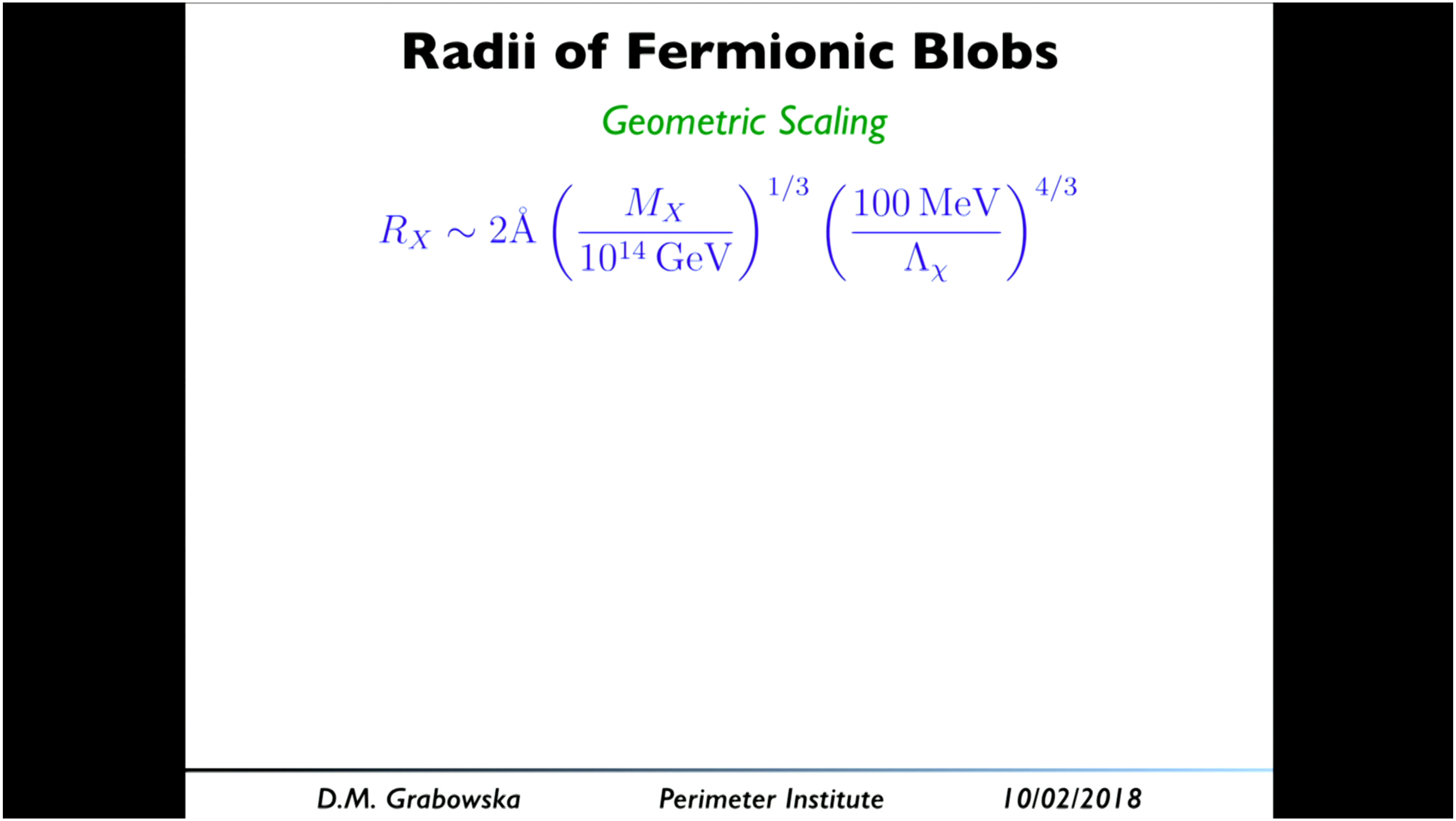

Radii of Fermionic Blobs

Geometric Scaling

$$R_X \sim 2\text{Å}\left(\frac{M_X}{10^{14}\,\text{GeV}}\right)^{1/3}\left(\frac{100\,\text{MeV}}{\Lambda_X}\right)^{4/3}$$

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M_X Λ_χ	10^{10} GeV	10^{33} GeV
MeV		
GeV		

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Λ_χ \ M_X	$10^{10}\,\text{GeV}$	$10^{33}\,\text{GeV}$
MeV	$R_X \sim 5 \times 10^{-9}\,\text{m}$	$R_X \sim 0.2\,\text{m}$
GeV	$R_X \sim 5 \times 10^{-13}\,\text{m}$	$R_X \sim 2 \times 10^{-5}\,\text{m}$

Radii of Fermionic Blobs

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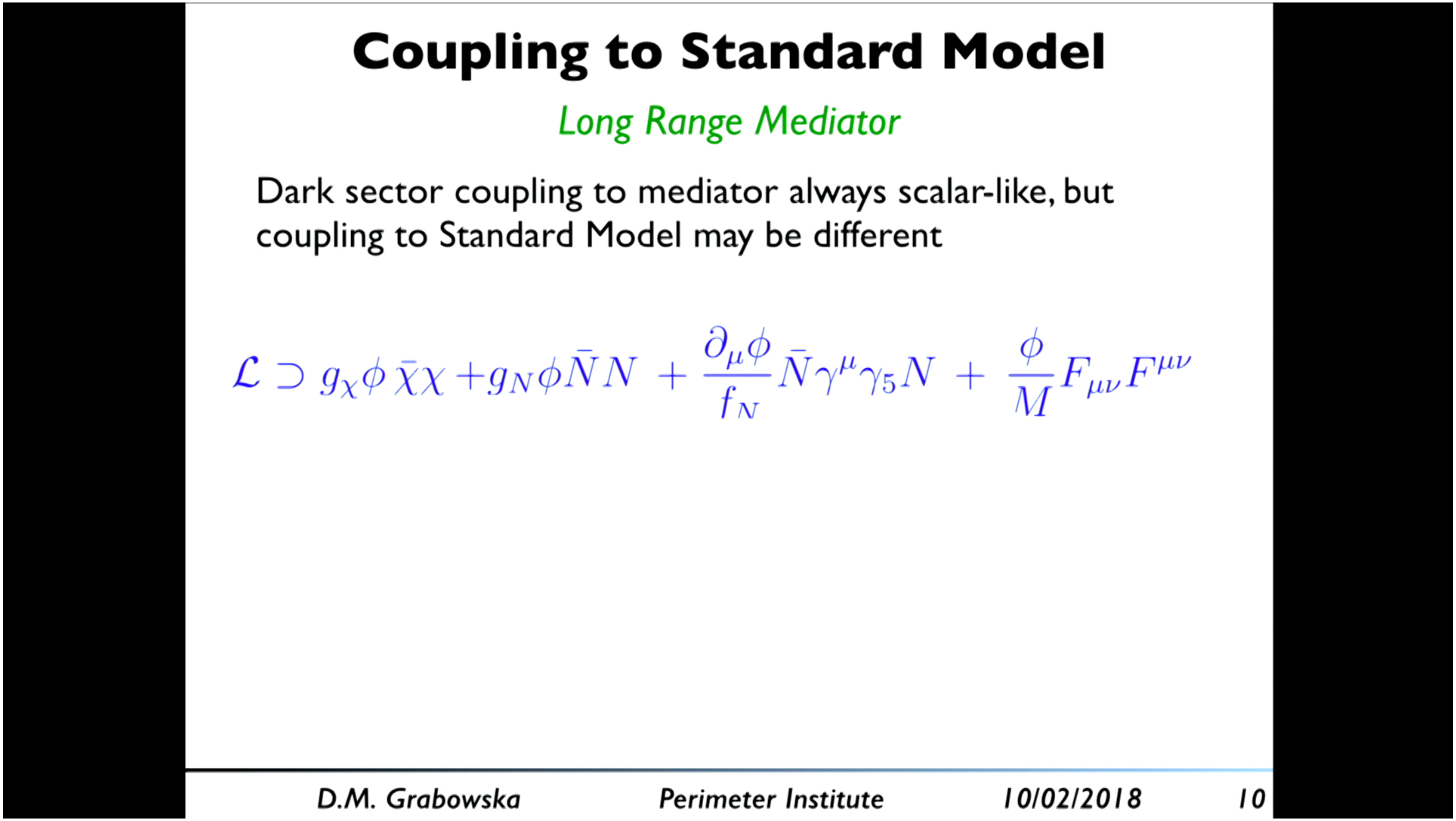
GeV	$R_X \sim 5 \times 10^{-13}\,\text{m}$	$R_X \sim 2 \times 10^{-5}\,\text{m}$
	$R_{\text{Sch.}} \sim 3 \times 10^{-44}\,\text{m}$	$R_{\text{Sch.}} \sim 3 \times 10^{-21}\,\text{m}$



Coupling to Standard Model

Long Range Mediator

Dark sector coupling to mediator always scalar-like, but coupling to Standard Model may be different

$$\mathcal{L} \supset g_\chi \phi\, \bar{\chi}\chi + g_N \phi \bar{N} N + \frac{\partial_\mu \phi}{f_N} \bar{N}\gamma^\mu \gamma_5 N + \frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

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- All can be searched for via ionization or heat deposition
- Different couplings require different detection methods

Coupling to Standard Model

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Dark sector coupling to mediator always scalar-like, but coupling to Standard Model may be different

$$\mathcal{L} \supset g_\chi \phi \, \bar{\chi}\chi + \underbrace{g_N \phi \bar{N} N}_{\text{Acceleration}} + \underbrace{\frac{\partial_\mu \phi}{f_N} \bar{N} \gamma^\mu \gamma_5 N}_{\text{Spin Precession}} + \underbrace{\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}}_{\text{Change Fine Structure Constant}}$$

- All can be searched for via ionization or heat deposition
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Mediator Coupling Constraint

Standard Model Constraints

Scalar Coupling, g_N: Fifth force and weak equivalence principle tests

PseudoScalar Coupling, F_N: White dwarf cooling, SN 1987A neutrino emission

Dilaton Coupling, M: Fifth force and weak equivalence principle tests

- Dilaton mediator affects electromagnetic contributions to nuclear mass

Mediator Coupling Constraints

Dark Sector Constraints

Scalar Coupling g_x Bound: Bullet Cluster

- Only applies if Dark Nuclei aren't subcomponent

Scalar Coupling g_x Bound: Stability of Dark Nuclei

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

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Mediator Coupling Constraints

Dark Sector Constraints

Scalar Coupling g_χ Bound: Bullet Cluster

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Scalar Coupling g_χ Bound: Stability of Dark Nuclei

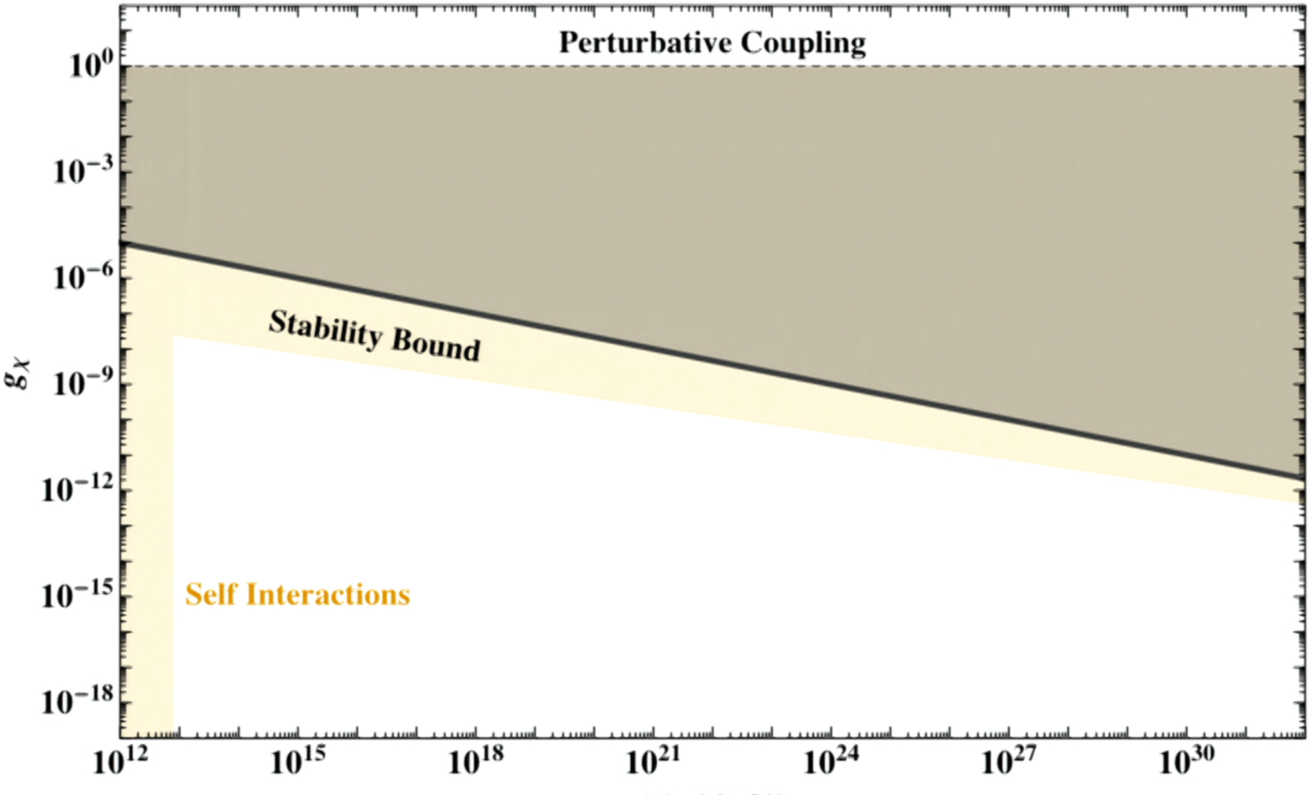
$$E_{\text{Bind}} \sim \underbrace{\alpha_V}_{\sim \Lambda_\chi} N_X - \alpha_S N_X^{2/3} - \underbrace{\alpha_C}_{\sim g_\chi^2 \Lambda_\chi} N_X^{5/3}$$

- For high enough number of constituents, dark nuclei unstable

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

Scalar Mediator to Nucleons

Λ_X = MeV, λ = 200 km



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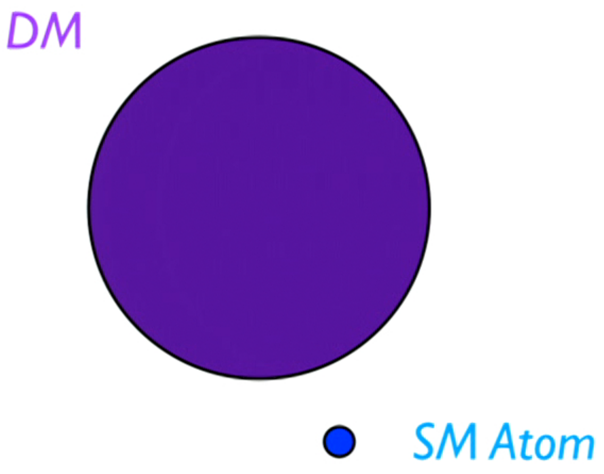
Ionization and Scintillation Signals

Standard Dark Matter Search

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



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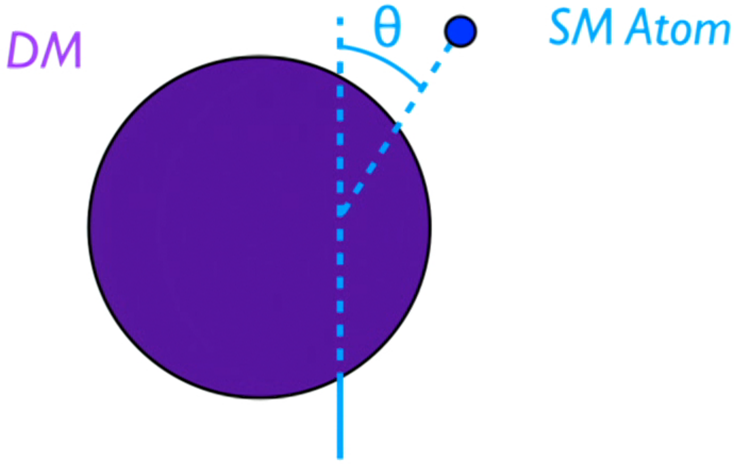

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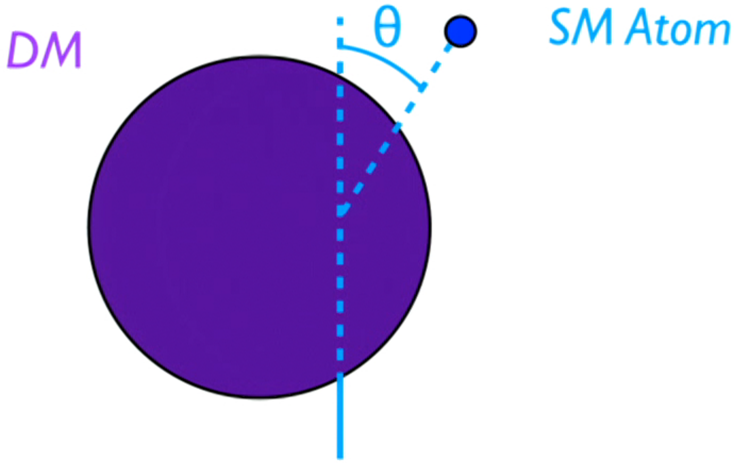
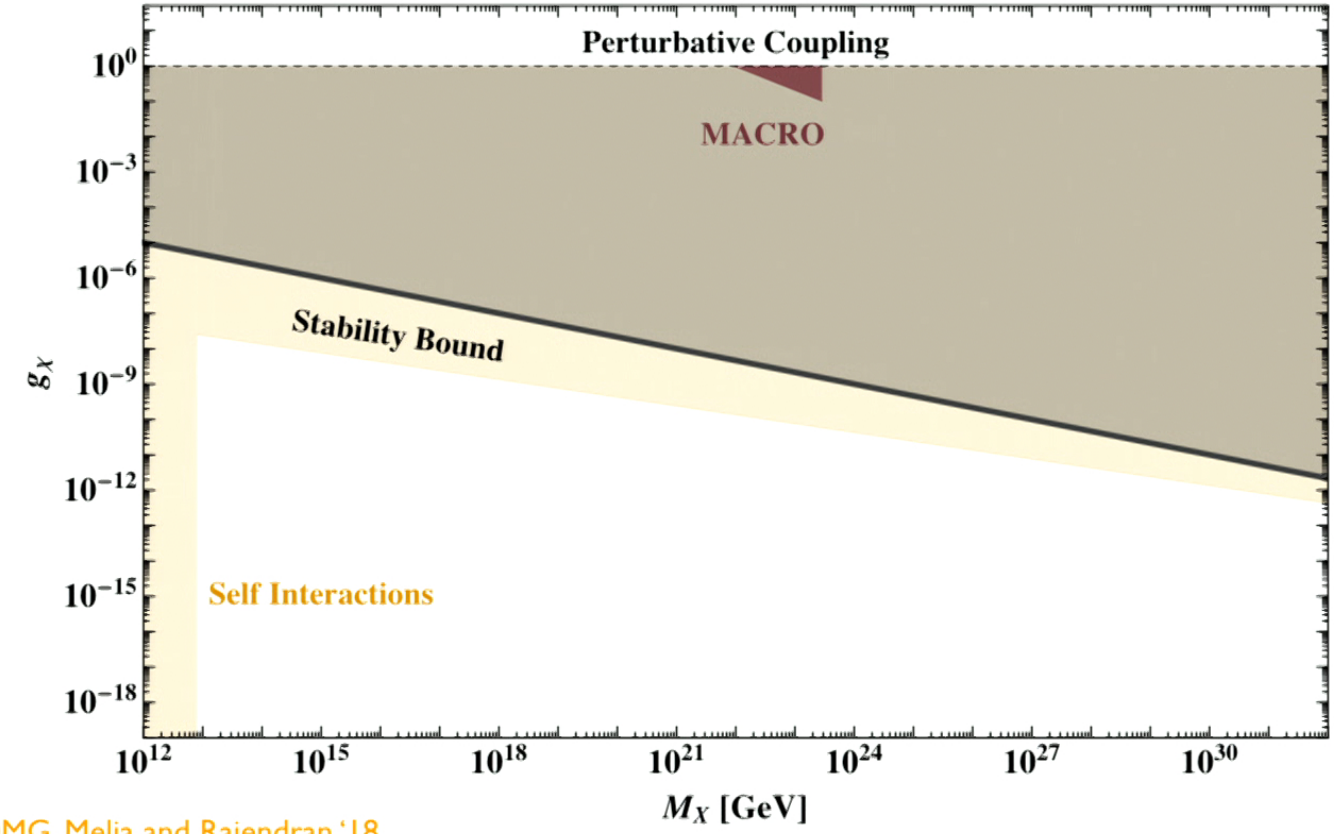


- Only small angle scattering due to weak coupling
- Ionization occurs if mom. transfer above ~100 keV

Scalar Mediator to Nucleons

Λ_x = MeV, λ = 200 km



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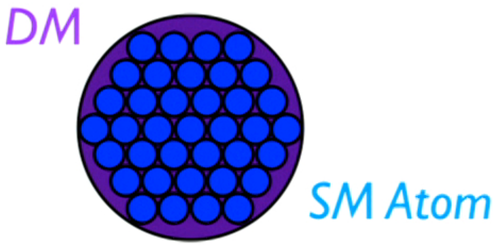
Heat Deposition

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



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

Relies on "guaranteed hit"

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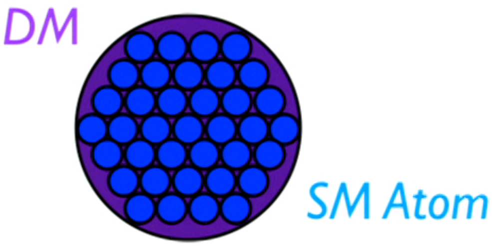


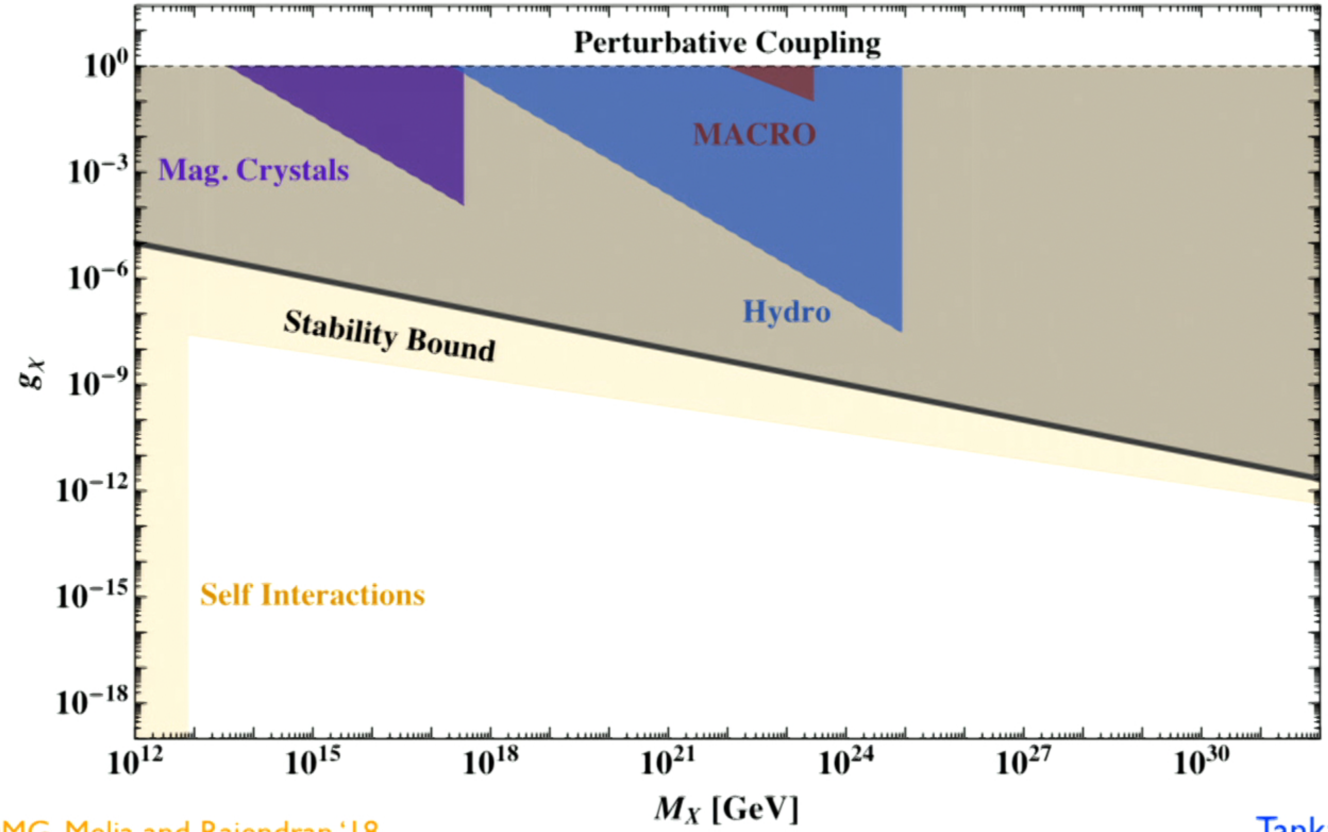
$$\Delta E_{\text{Tot}} \sim \left(\frac{R_X}{R_0}\right)^2 \Delta E^{\text{Max}}_{\text{Single}}$$

Relies on "guaranteed hit"

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

Scalar Mediator to Nucleons

Λ_x = MeV, λ = 200 km



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Tank: (500 m)^3

Scalar Mediator to Nucleons

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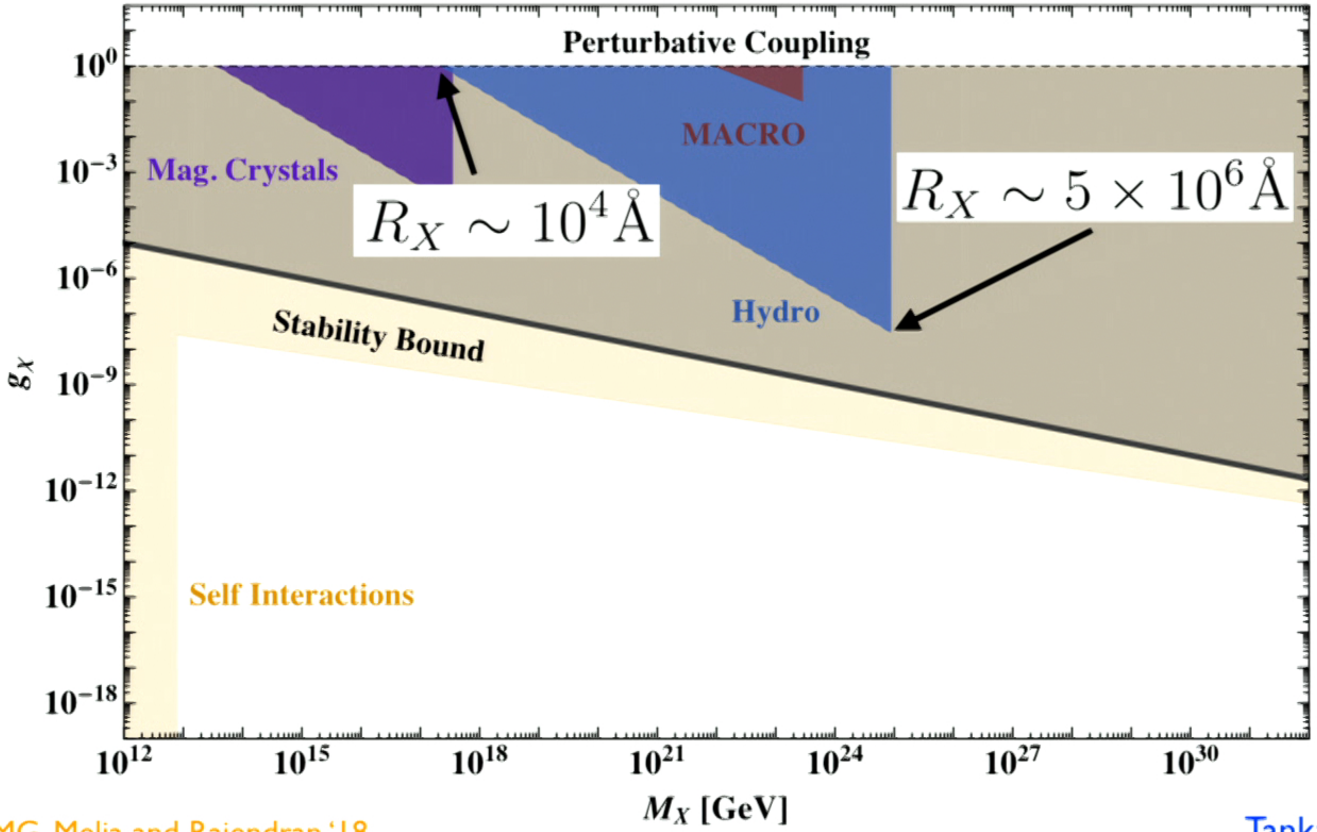

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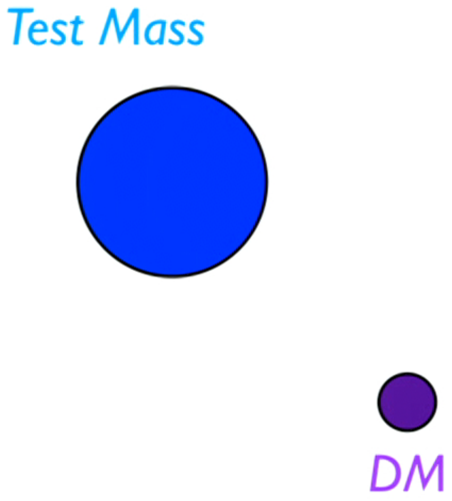
Tank: (500 m)^3

Acceleration

Free hanging test mass

General Idea: Passing blob induces motion in test mass



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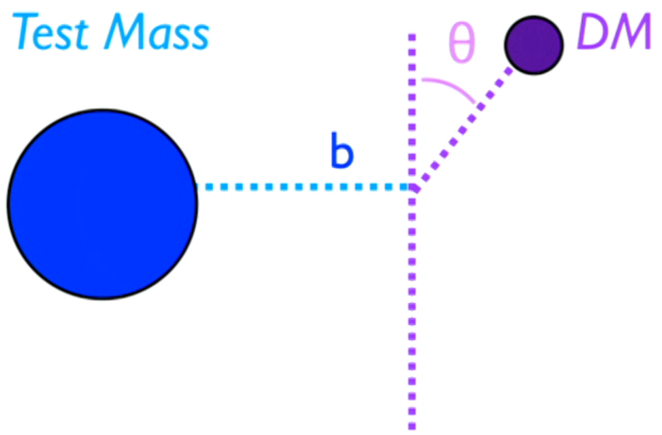

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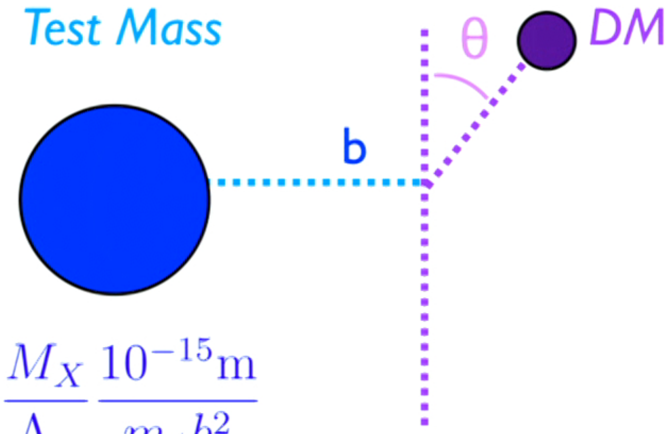

$$h \sim \frac{g_N g_\chi}{v^2} \frac{M_X}{\Lambda_\chi} \frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

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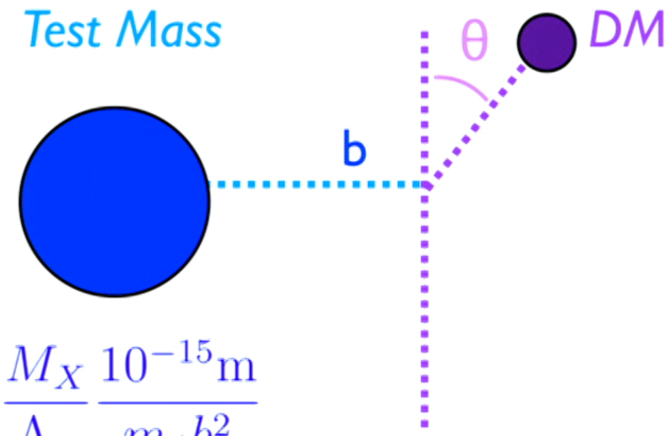
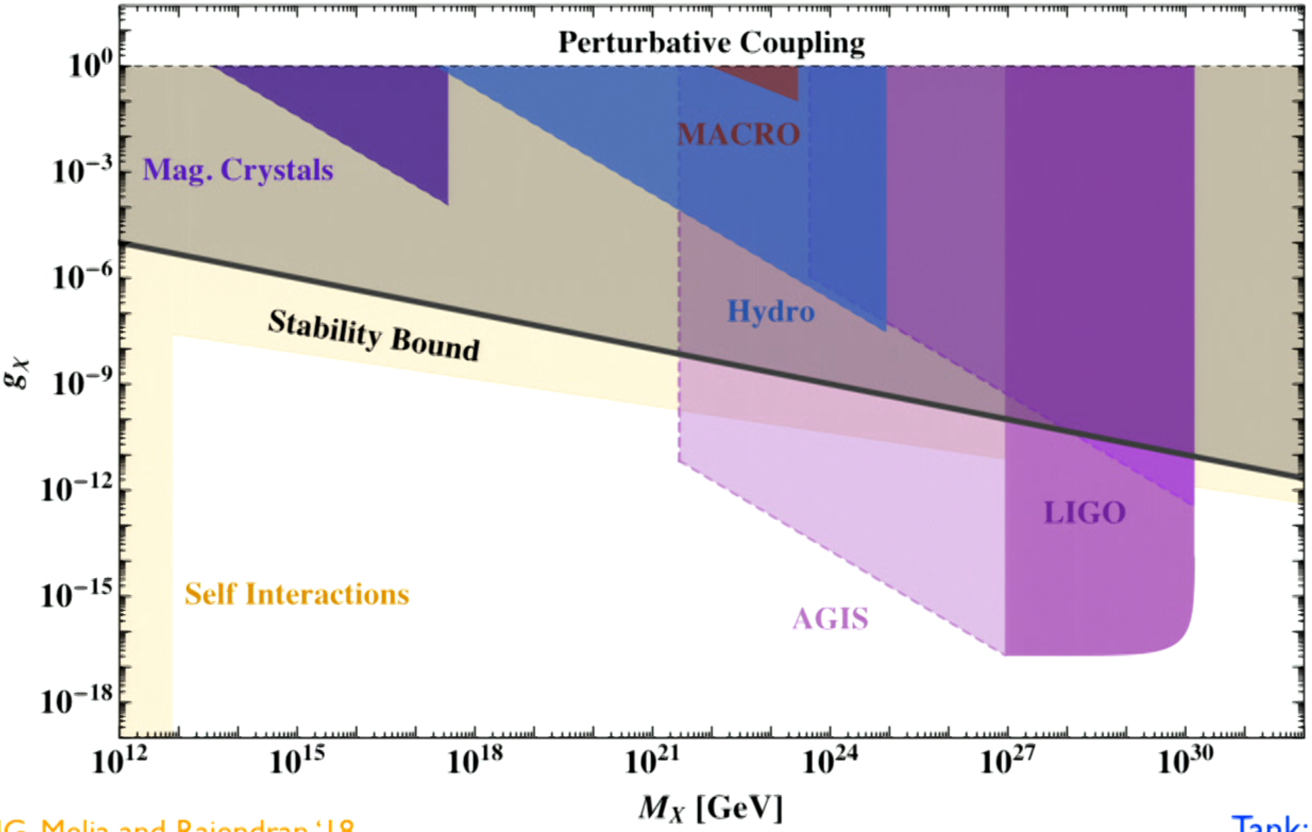


$$h \sim \frac{g_N g_\chi}{v^2} \frac{M_X}{\Lambda_\chi} \frac{10^{-15}\mathrm{m}}{m_\phi b^2}$$

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

Scalar Mediator to Nucleons

Λ_x = MeV, λ = 200 km



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Spin Precession

SQUIDs to the rescue

General Idea: Passing blob causes nucleon spins to rotate

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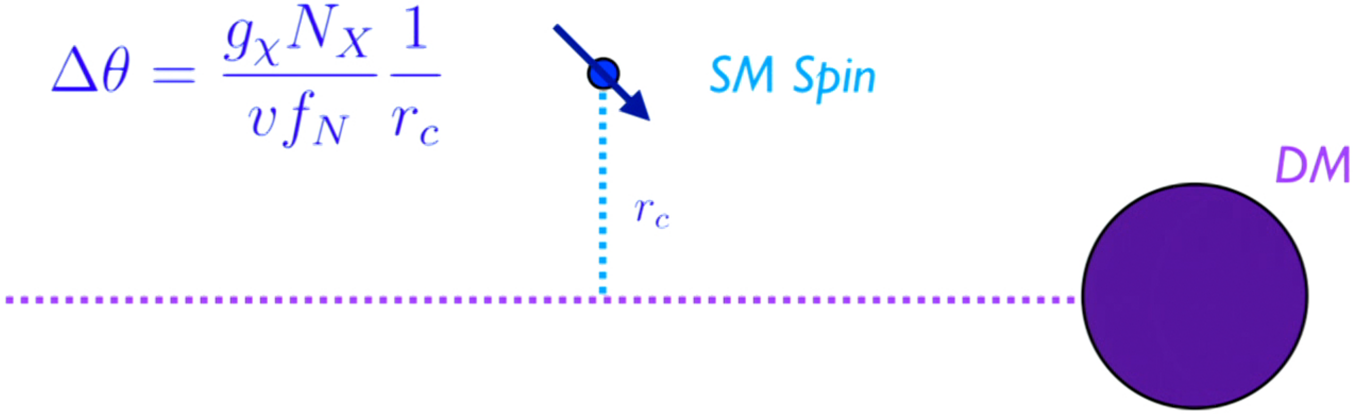
$$\Delta\theta = \frac{g_\chi N_X}{v f_N}\frac{1}{r_c}$$



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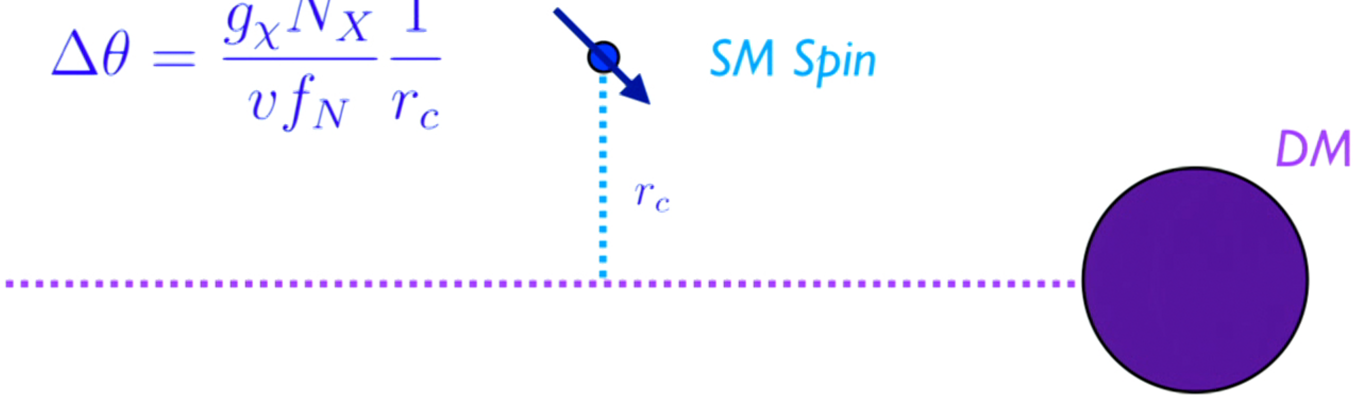
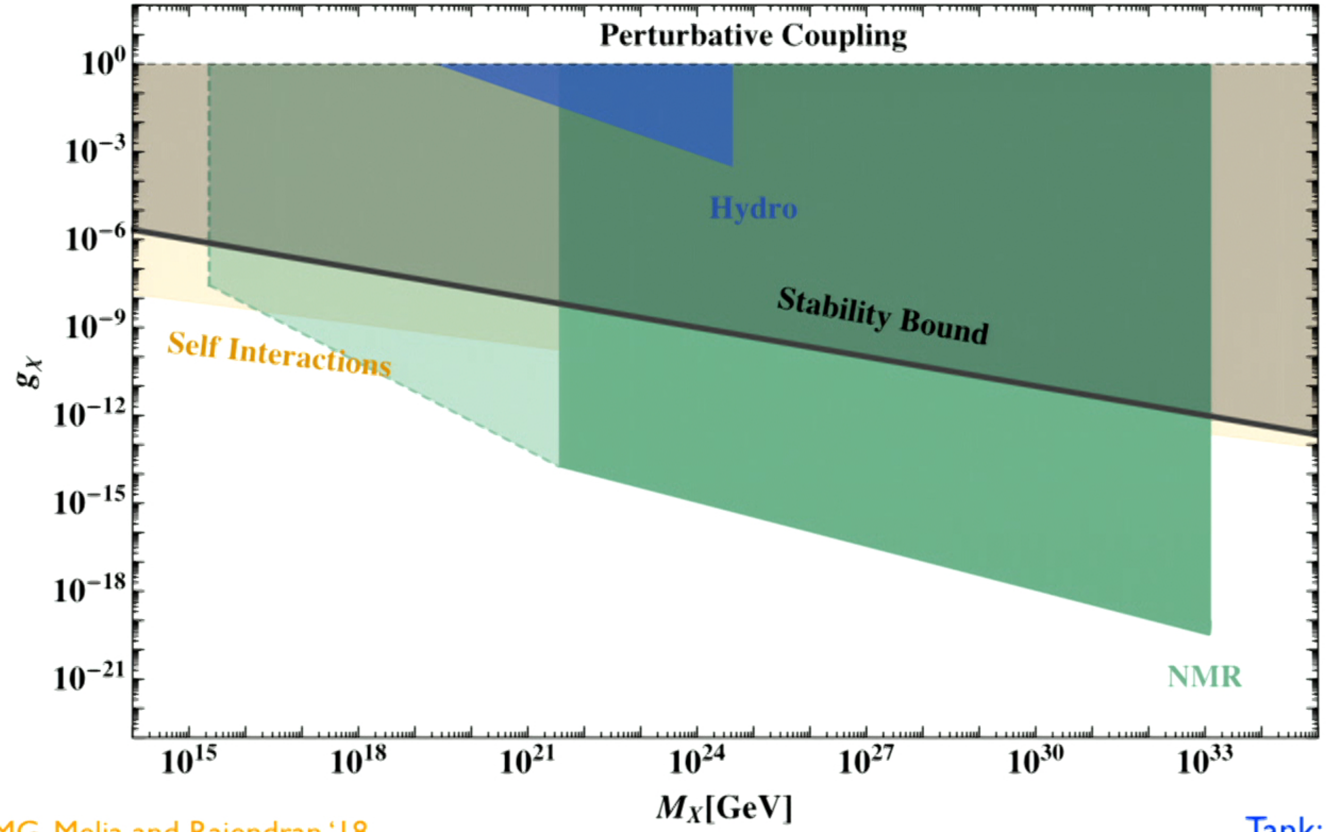


- Change in spin orientation causes change in material's magnetization
- **Example:** SQUID in CASPEr sensitive to ΔM ~ 0.1 fT

PseudoScalar Mediator to Nucleons

Λ_x = MeV, λ = 6000 km



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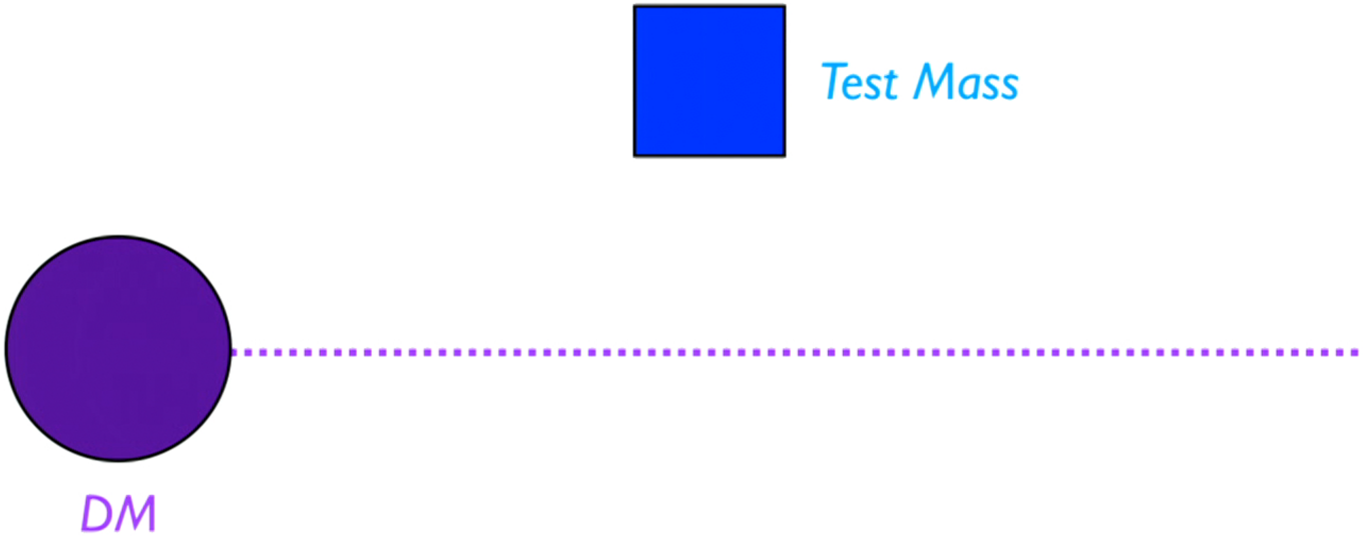
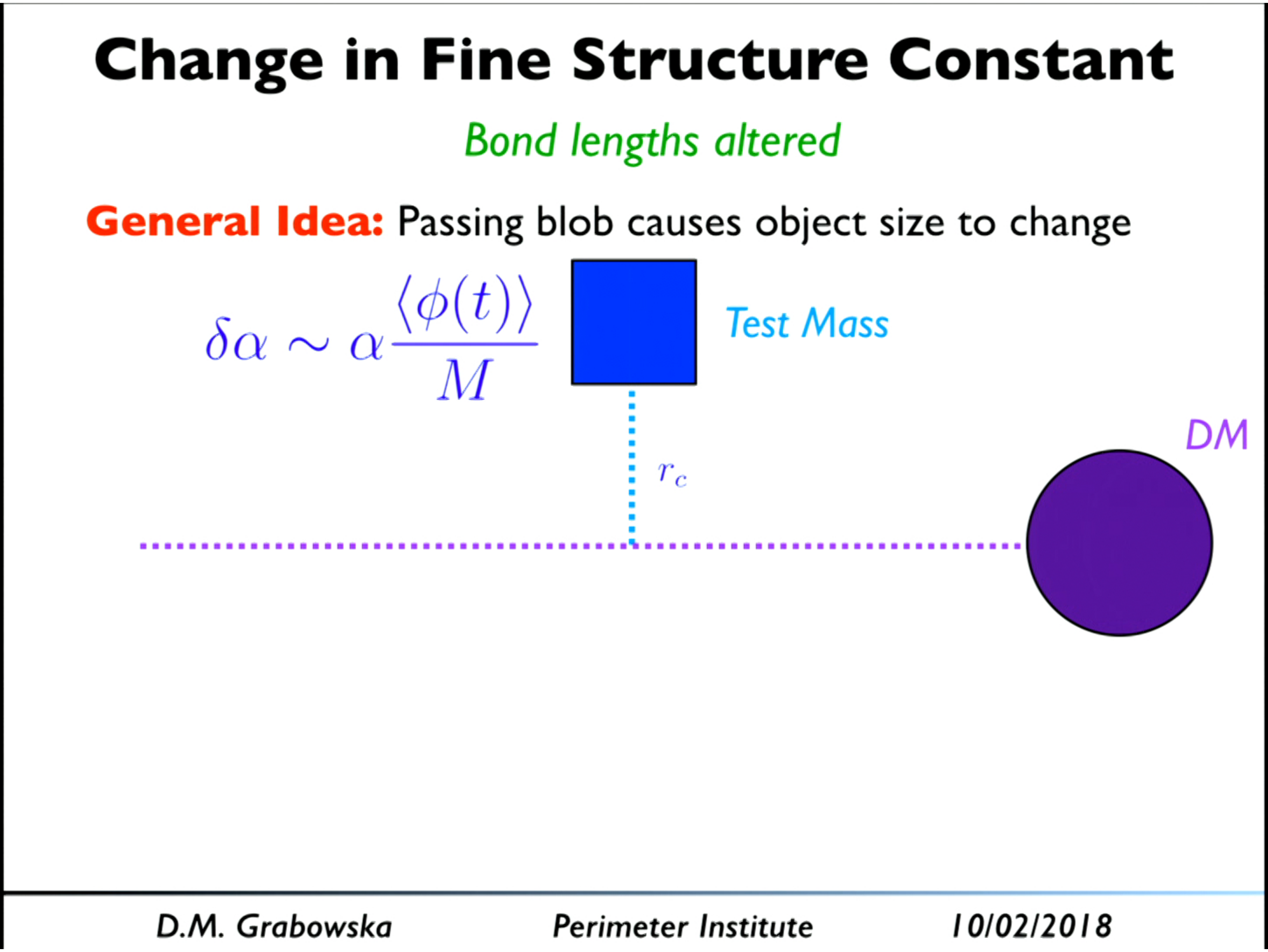
Tank: (500 m)^3

Change in Fine Structure Constant

Bond lengths altered

General Idea: Passing blob causes object size to change





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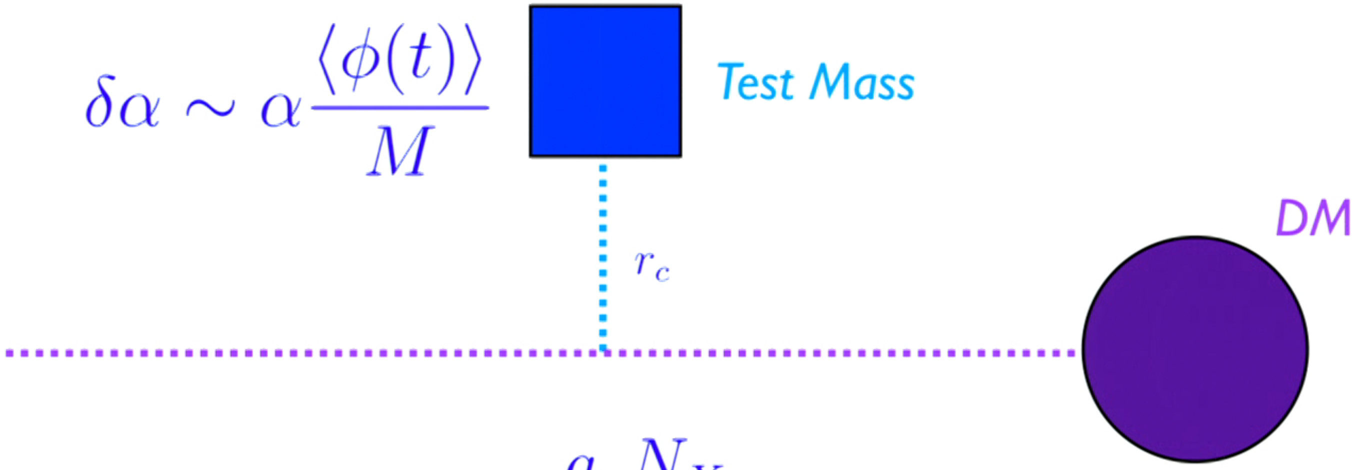
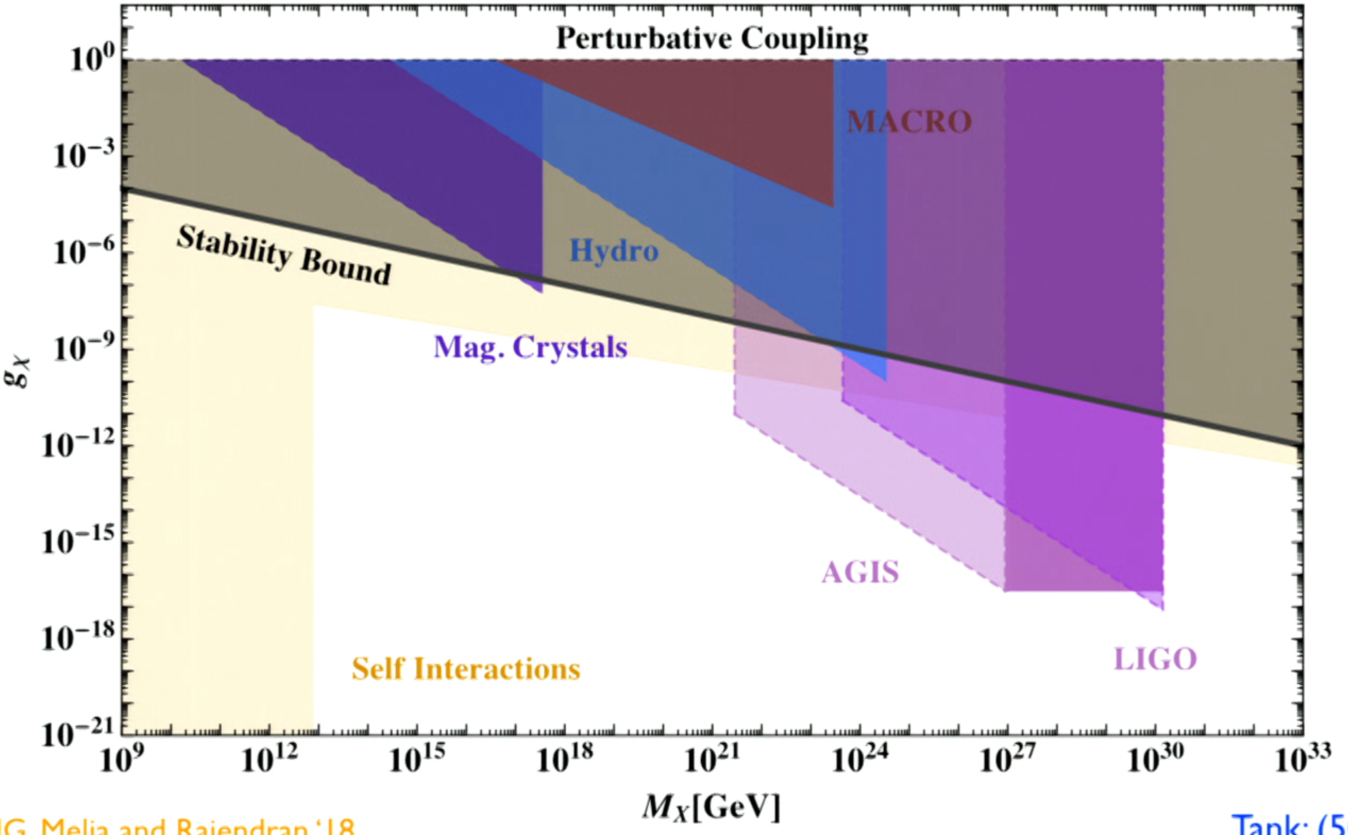


$$h \sim \frac{g_\chi N_X}{r_c M}$$

- **Example:** LIGO sensitive to strains of $10^{-23}/\mathrm{Hz}^{1/2}$

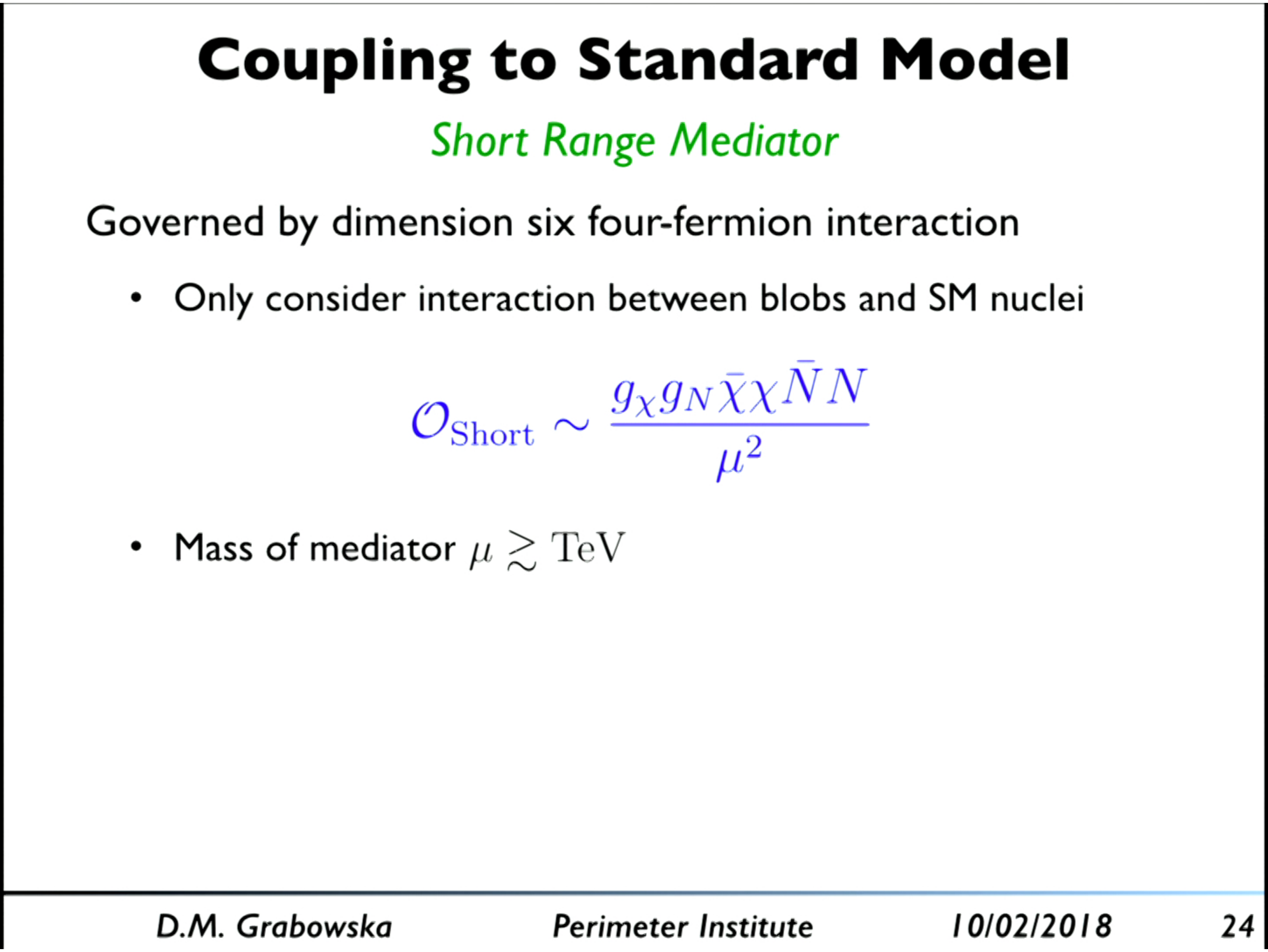
Dilaton Mediator to Nucleons

Λ_x = MeV, λ = 200 km



DMG, Melia and Rajendran '18

Tank: (500 m)^3



Coupling to Standard Model

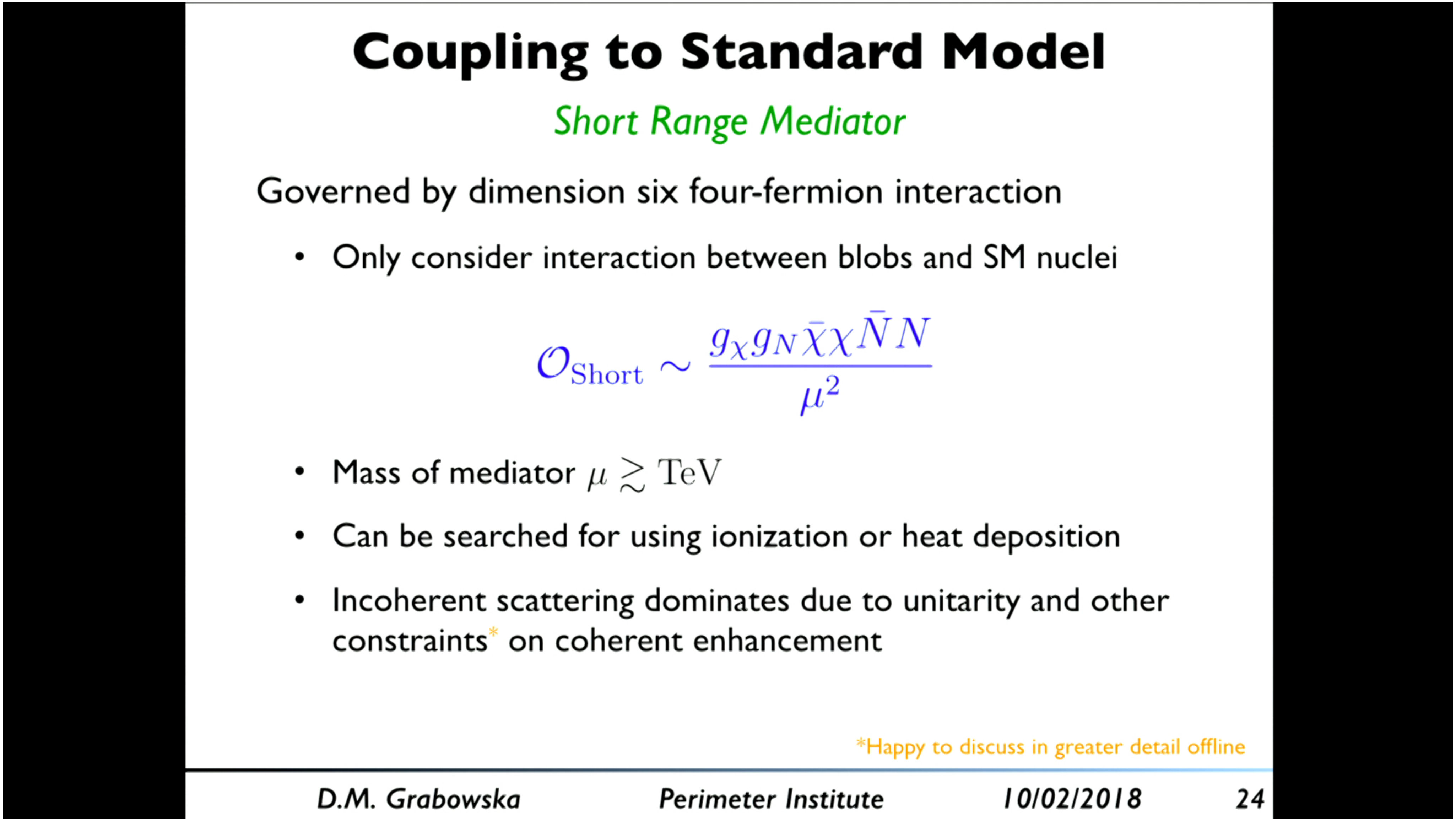
Short Range Mediator

Governed by dimension six four-fermion interaction

- Only consider interaction between blobs and SM nuclei

$$\mathcal{O}_{\rm Short} \sim \frac{g_\chi g_N \bar{\chi}\chi \bar{N} N}{\mu^2}$$

- Mass of mediator $\mu \gtrsim \mathrm{TeV}$



Coupling to Standard Model

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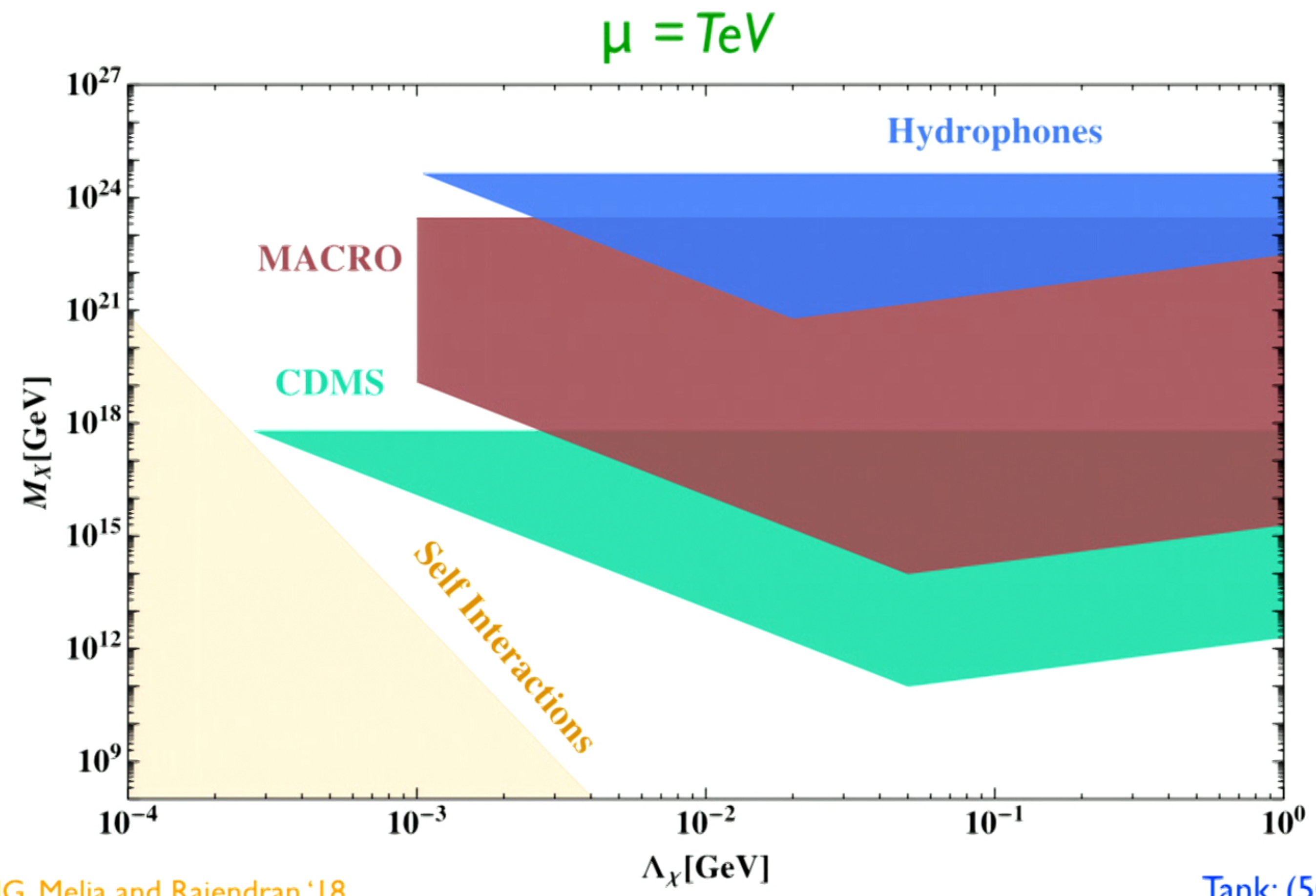
$$\mathcal{O}_{\text{Short}} \sim \frac{g_\chi g_N \bar{\chi}\chi \bar{N} N}{\mu^2}$$

- Mass of mediator $\mu \gtrsim \text{TeV}$
- Can be searched for using ionization or heat deposition
- Incoherent scattering dominates due to unitarity and other constraints* on coherent enhancement

*Happy to discuss in greater detail offline

Short Range Mediator



DMG, Melia and Rajendran '18

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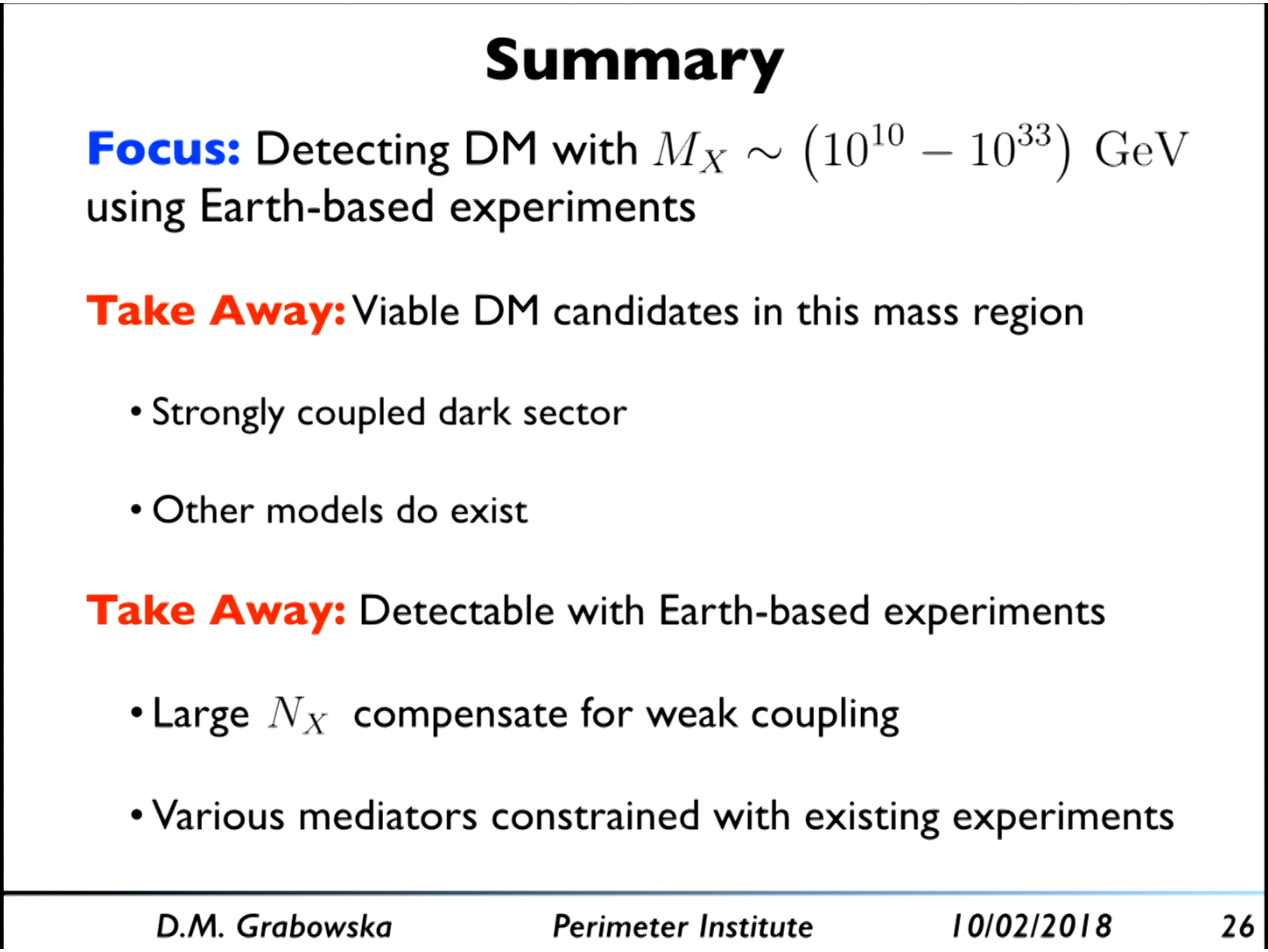


Summary

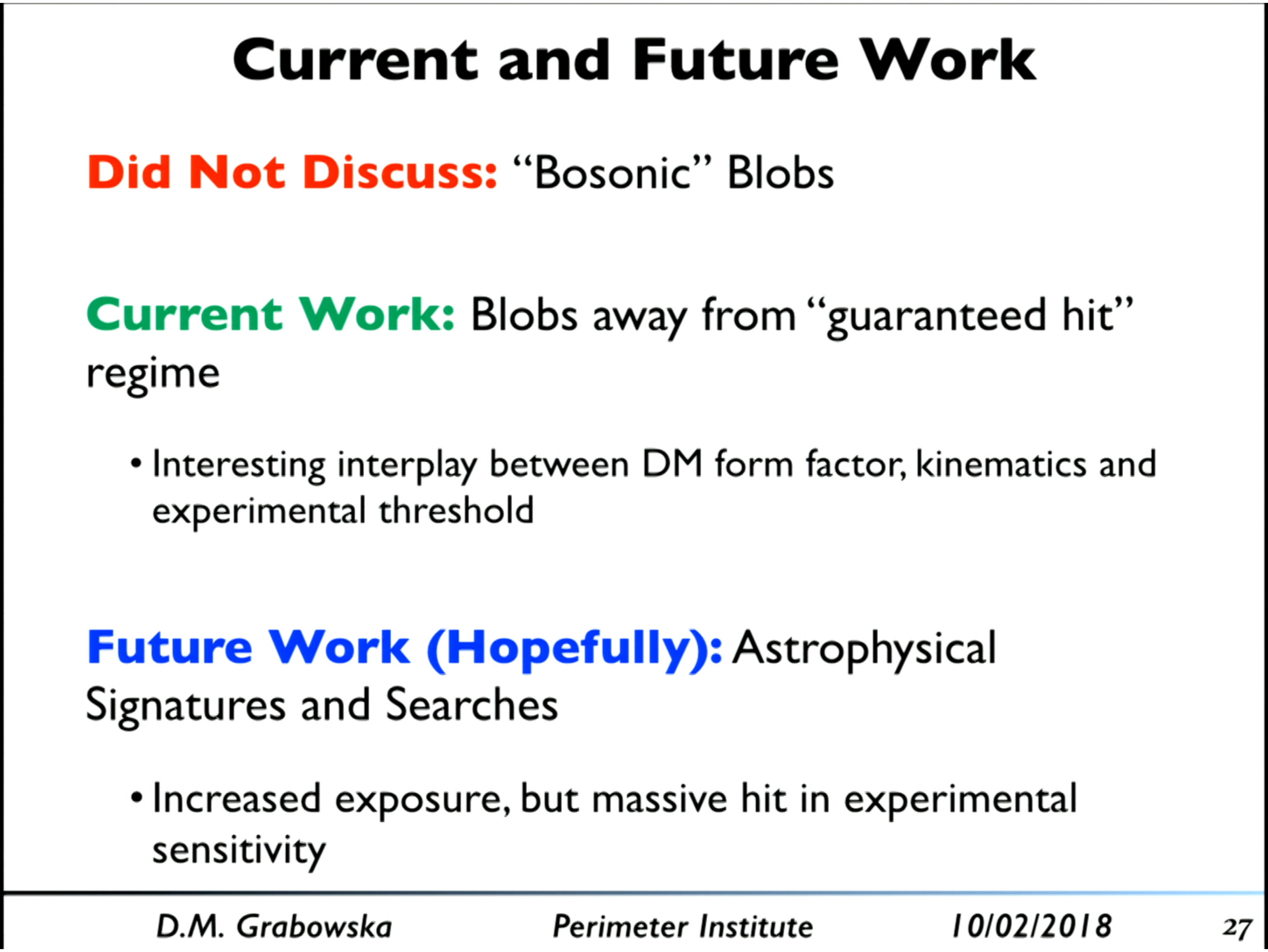
Focus: Detecting DM with $M_X \sim (10^{10} - 10^{33})$ GeV using Earth-based experiments

Take Away: Viable DM candidates in this mass region

- Strongly coupled dark sector
- Other models do exist

Take Away: Detectable with Earth-based experiments

- Large N_X compensate for weak coupling
- Various mediators constrained with existing experiments



Current and Future Work

Did Not Discuss: “Bosonic” Blobs

Current Work: Blobs away from “guaranteed hit” regime

- Interesting interplay between DM form factor, kinematics and experimental threshold

Future Work (Hopefully): Astrophysical Signatures and Searches

- Increased exposure, but massive hit in experimental sensitivity