Searching for Ultra-Heavy Dark Matter

Surjeet Rajendran,
UC Berkeley

(with Dorota Grabowska and Tom Melia)
The Dark Matter Landscape

$10^{-43}$ GeV to $10^{48}$ GeV
The Dark Matter Landscape

Fit in galaxy
The Dark Matter Landscape

10^{-43} \text{ GeV} \quad 10^{-22} \text{ eV} \quad 100 \text{ eV} \quad 10^2 \text{ GeV (SM)} \quad 10^{48} \text{ GeV}

Fit in galaxy

Standard Model scale \sim 100 \text{ GeV}
The Dark Matter Landscape

Fit in galaxy

Standard Model scale ~ 100 GeV

Same scale for Dark Matter?

Weakly Interacting Massive Particles (WIMPs)
The Dark Matter Landscape

Fit in galaxy

Standard Model scale ~ 100 GeV

Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

WIMP Experiments: Sensitive up to $10^{18}$ GeV
The Dark Matter Landscape

Fit in galaxy

Standard Model scale ~ 100 GeV

Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

WIMP Experiments: Sensitive up to $10^{18}$ GeV

What if dark matter is super heavy?

Low number density - need large detectors.

Terrestrial: up to $10^{33}$ GeV
Outline

1. Theory and Phenomenology
2. Constraints
3. Detection
Ultra-heavy Dark Matter?

Large composite blob

Weak constraints on self-interactions of dark matter

Strong self-interactions in dark sector
Ultra-heavy Dark Matter?

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Weak constraints on self-interactions of dark matter

Strong self-interactions in dark sector

Efficient nucleosynthesis? Primordial production? Galactic evolution?
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Observational Effects?
Ultra-heavy Dark Matter?

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Strong self-interactions in dark sector

Efficient nucleosynthesis? Primordial production? Galactic evolution?

Observational Effects?

Key Point: Lots of dark matter partons packed into single blob

Rare but potentially spectacular transit
What does the blob look like?

Self-Interaction Scale $\Lambda$, Parton Mass $\sim \Lambda$
What does the blob look like?

Self-Interaction Scale $\Lambda$, Parton Mass $\sim \Lambda$

Fermionic  \quad  Bosonic
What does the blob look like?

Self-Interaction Scale $\Lambda$, Parton Mass $\sim \Lambda$

$R \sim \left( \frac{M}{\Lambda} \right)^{\frac{1}{3}} \frac{1}{\Lambda}$

Fermionic

Bosonic
What does the blob look like?

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Fermionic

$R \sim \left( \frac{M}{\Lambda} \right)^{\frac{1}{3}} \frac{1}{\Lambda}$

Bosonic

$R \sim \frac{1}{\Lambda}$
What does the blob look like?

Self-Interaction Scale $\Lambda$, Parton Mass $\sim \Lambda$

Fermionic

\[ R \sim \left( \frac{M}{\Lambda} \right)^{\frac{1}{3}} \frac{1}{\Lambda} \]

\[ \mathcal{L} \supset g_\chi \phi \bar{\chi} \chi \]

Bosonic

\[ R \sim \frac{1}{\Lambda} \]

\[ \mathcal{L} \supset g_\chi \Lambda \phi \chi^* \chi \]
What does the blob look like?

Self-Interaction Scale $\Lambda$, Parton Mass $\sim \Lambda$

**Fermionic**

\[ R \sim \left( \frac{M}{\Lambda} \right)^{\frac{1}{3}} \frac{1}{\Lambda} \]

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**Bosonic**

\[ R \sim \frac{1}{\Lambda} \]

\[ \mathcal{L} \supset g_\chi \Lambda \phi \chi^* \chi \]

Standard Model Interactions

\[ + \mu^2 \phi^2 + g_N \phi \bar{N} N + \frac{1}{f_a} \partial_\nu \phi \bar{N} \gamma^\nu \gamma_5 N + \frac{\phi}{\alpha M} F_{\mu\nu} F^{\mu\nu} \]
Observational Effects
Observational Effects

Short Range
\[ \mu^{-1} < \lambda_p \]

Long Range
\[ \mu^{-1} > \lambda_p \]
Observational Effects

Short Range
\[ \mu^{-1} < \lambda_p \]

Dark Matter scatters, deposits energy.
Calorimetry

Long Range
\[ \mu^{-1} > \lambda_p \]

Compositeness could enable multiple scattering
Observational Effects

Short Range
\[ \mu^{-1} < \lambda_p \]

- Dark Matter scatters,
- deposits energy.
- Calorimetry
- Compositeness could enable multiple scattering

Long Range
\[ \mu^{-1} > \lambda_p \]

- Blob sources classical field
- Use detectors of ultra-light dark matter
Observational Effects

Short Range
\[ \mu^{-1} < \lambda_p \]

Dark Matter scatters, deposits energy.
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Compositeness could enable multiple scattering

Long Range
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Blob sources classical field

Use detectors of ultra-light dark matter

Leverage: \( c > v_{\text{dm}} > v_{\text{human}} \)

Constraints?
Scattering at the partonic level

Parton transfers momentum to blob
Scattering at the partonic level

Parton transfers momentum to blob

Form factor for $q \gg 1/r_\chi \sim \Lambda$

$M \gg m_N$, kinematics set by $m_N$

$q = \text{Min}[m_N v, \Lambda]$
Short Range

Scattering at the partonic level

Parton transfers momentum to blob

Form factor for $q \gg 1/r_{\chi} \sim \Lambda$

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Key Point: $\Lambda < 300$ keV $\Rightarrow$ soft energy transfer, no ionization
Short Range

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Key Point: $\Lambda < 300$ keV $\Rightarrow$ soft energy transfer, no ionization

This Work: $10$ keV $< \Lambda < 10$ MeV

Goal: Robust parameter space, targeted experimental signals
Short Range: Bosonic Blob

\[ R \sim \frac{1}{\Lambda} \]

\[ 10 \text{ keV} < \Lambda < 10 \text{ MeV} \Rightarrow q \sim \frac{1}{R} \]

Cross-section Coherently Enhanced

Easily geometric \( \sigma = \frac{1}{\Lambda^2} \)
Short Range: Bosonic Blob

\[ R \sim \frac{1}{\Lambda} \]

10 keV < \Lambda < 10 MeV \Rightarrow q \sim \frac{1}{R}

Cross-section Coherently Enhanced

Easily geometric \( \sigma = \frac{1}{\Lambda^2} \)

\[
\frac{dE}{dx} = \eta_m \left( \frac{\Lambda^2}{m_N} \right) \frac{1}{\Lambda^2} = \frac{\eta_m}{m_N} \sim \text{keV/cm}
\]
Short Range: Bosonic Blob

\[ R \sim \frac{1}{\Lambda} \]

10 keV < \Lambda < 10 MeV => \( q \sim \frac{1}{R} \)

Cross-section Coherently Enhanced

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\[ \frac{dE}{dx} = \eta_m \left( \frac{\Lambda^2}{m_N} \right) \frac{1}{\Lambda^2} = \frac{\eta_m}{m_N} \sim \text{keV/cm} \]

Form depends on \( \Lambda \) - ionize for \( \Lambda > 300 \text{ keV} \), heat below that
Short Range: Fermionic Blob

$R \sim N^{1/3}/\Lambda$

Coherent enhancement only for soft scattering $\Rightarrow$ low energy deposition

Lots of partons $\Rightarrow$ multiple scattering possible
Short Range: Fermionic Blob

R \sim N^{1/3}/\Lambda

Coherent enhancement only for soft scattering => low energy deposition

Lots of partons => multiple scattering possible

\[
\frac{dE}{dx} = \eta_m \left( \frac{M}{\Lambda} \right) \left( \frac{g^2 g_N^2 m_N^2}{\mu^4} \right) \left( \frac{\Lambda^2}{m_N^2 v_x^2} \right) \left( \frac{\Lambda^2}{m_N} \right)
\]

Form depends on $\Lambda$ - ionize for $\Lambda > 300$ keV, heat below that
Long Range

Take Range $1/\mu >>$ Blob size $R$

Blob sources classical field $g_x N/r$
Long Range

Take Range $1/\mu \gg$ Blob size $R$

Blob sources classical field $g_\chi N/r$

Exerts Force

Energy Loss in Medium due to dynamical friction

$$g_N \phi \bar{N} N$$

$$\frac{dE}{dx} \sim 2\pi \int_0^{\frac{1}{\mu}} drr \eta_m m_N \left( \frac{F(r) r}{m_N v} \right)^2$$
Long Range

Take Range $1/\mu >>$ Blob size $R$

Blob sources classical field $g_\chi N/r$

Exerts Force

Energy Loss in Medium due to dynamical friction

\[
\frac{dE}{dx} \sim 2\pi \int_0^{\frac{1}{\mu}} drr\eta m m_N \left( \frac{F(r)r}{m_N v} \right)^2 \left( \frac{v}{c_s} \right)^3
\]

(when adiabatic)
Long Range

\[ g_N \phi \bar{N} N \]

\[ \frac{dE}{dx} \sim 2\pi \int_0^1 drr\eta_m m_N \left( \frac{F(r) r}{m_N} \right)^2 \times \left( \frac{v}{c_s} \right)^3 \]

(when adiabatic)

Causes Spin Precession

\[ \delta \theta \sim \frac{g_x N}{f_a rv} \]
Long Range

\[ g_N \phi \bar{N} N \]

\[ \frac{dE}{dx} \sim 2\pi \int_0^{1/\mu} d\mu \eta_m m_N \left( \frac{F(r) r}{m_N v} \right)^2 \times \left( \frac{v}{c_s} \right)^3 \]

(when adiabatic)

Causes Spin Precession

\[ \delta \theta \sim \frac{g_N N}{f_s r v} \]

Induces Strain

\[ h \sim \frac{g_N N}{r M} \]
Constraints

Bullet Cluster Bounds.
For short range, no constraints on bosons.

Not relevant if blob < 10 percent of dark matter
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Blob - baryon friction bounded by BAO. Not a significant constraint.
Constraints

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Blob - baryon friction bounded by BAO. Not a significant constraint.

No instability from $\phi$

\[
g_\chi \approx \frac{1}{\sqrt{N}} \quad \text{(bosonic)} \quad g_\chi \approx \frac{1}{N^{\frac{1}{3}}} \quad \text{(fermionic)}
\]
Constraints

MACRO Monopole Search
(~ 80 x 10 x 10 m³)

Energy Threshold: 6 MeV/cm
+ Scintillation
Constraints

MACRO Monopole Search
(~ 80 x 10 x 10 m³)

Energy Threshold: 6 MeV/cm + Scintillation

Mediator coupling to Standard Model constrained by new force searches, astrophysical bounds on light particles, collider limits
Detection

Short Range

Ionization
(\Lambda > 300 \text{ keV})

MACRO=> \frac{dE}{dx} < 6 \text{ MeV/cm}
Detection
Short Range

Ionization
($\Lambda > 300$ keV)

MACRO=> $dE/dx < 6$ MeV/cm

Huge Volume?

Hydrophones: $dE/dx \sim$ keV/A
Detection
Short Range

Ionization 
($\Lambda > 300$ keV)

MACRO => $dE/dx < 6$ MeV/cm

Huge Volume?

Acoustic 
($\Lambda < 300$ keV)

Low threshold calorimeter like CDMS

Line of hot cells

Energy depositions ~ keV/cm

Hydrophones: $dE/dx \sim$ keV/A
Detection
Long Range

Rare Transit of Heavy
Dark Matter
Detection

Rare Transit of Heavy Dark Matter

Classical field created by dark matter - correlated excitation of multiple detectors

Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants
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Classical field created by dark matter - correlated excitation of multiple detectors

Same class of effects as light dark matter - excitation of currents, spin precession, acceleration, variation of fundamental constants

Instead of continuous, coherent a/c effect, look for correlated transients in network

Up to dark matter mass $\sim 10^8$ gm
Reach

Fermion Constituents with TeV Scale Mediator

$\Lambda_x \text{[GeV]}$

$M_x \text{[GeV]}$

Hydrophones

MACRO

CDMS

Self Interactions
Reach

MeV Fermion Constituents and 6000 km PseudoScalar Mediator

Perturbative Coupling

Hydro

Stability Bound

Self Interactions

NMR

$M_X[GeV]$
The Dark Matter Landscape

Poor observational constraints on dark matter

Current Experimental Concepts can probe region from $10^{18}$ GeV - $10^{33}$ GeV

Possible to probe above $10^{33}$ GeV using astrophysical systems - particularly white dwarfs