Title: Is Self-Interacting Dark Matter Undergoing Dark Fusion?

Date: Dec 01, 2017 01:00 PM

URL: http://pirsa.org/17120002

Abstract: <p>We suggest that two-to-two dark matter fusion may be the relaxation process that resolves the small-scale structure problems of the cold collisionless dark matter paradigm. In order for the fusion cross section to scale correctly across many decades of astrophysical masses from dwarf galaxies to galaxy clusters, we require the fractional binding energy released to be greater than $v^n \sim [10^{-(2-3)}]^n$, where $n=1,2$ depends on local dark sector chemistry. The size of the dark-sector interaction cross sections must be $\sigma \sim 0.1-1$ barn, moderately larger than for Standard Model deuteron fusion, indicating a dark nuclear scale $\Lambda \sim O(100 \text{ MeV})$. Dark fusion firmly predicts constant $\sigma v$ below the characteristic velocities of galaxy clusters. Observations of the inner structure of galaxy groups with velocity dispersion of several hundred kilometer per second, of which a handful have been identified, could differentiate dark fusion from a dark photon model.</p>
IS HINCHLIFFE’S RULE TRUE?

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe’s assertion is false, but only if it is true.

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Is Self-Interacting Dark Matter Undergoing Dark Fusion?

Sam McDermott
1711.00857 and ongoing follow-up work
[and relying heavily on 1508.03339 (Kaplinghat, Tulin, & Yu)]

Dec 1, 2017
Perimeter Institute
Outline

1. Introduction
2. Self-Interacting Dark Matter
3. Velocity Dependence
4. Speculative Ideas
Big Picture

- We have passed through the electroweak scale, completing the Standard Model

- Many deep, as yet unanswered particle physics questions (nature of the dark matter/existence of a nonminimal dark sector? neutrino masses? inflation? dark energy? baryogenesis?...) that require new ideas (hierarchy/CC problems?...), new methods (new experiments to search for DM?...), new measurements (neutrino masses, couplings, cosmological history?...), and new computational tools (mechanism that drives supernova explosions?...)
Big Picture

Where is the new physics?

- What is the correct big picture of particle physics?
- What are the missing pieces in current understanding?
- How do we explore the unknown?
- New techniques (e.g., precision measurements, advanced computing)?
- New experiments (e.g., LHC, with increased sensitivity)?
- New methods (e.g., new experiments to search for DM)?
- New measurements (e.g., neutrino masses, couplings, cosmological history)?
- New computational tools (e.g., mechanism that drives supernova explosions)?
If the Universe was only the Standard Model...

- Large scales would just be gas, stars, etc.
- Galactic *dynamics* and *structure* = how much and what kind of light do galaxies emit/absorb?

Concrete predictions for how largest scale structures should behave
Prediction: Rotation Curve

rotational velocity is a good proxy for gravitational potential

most stars (= most SM mass) are at the center of the cluster

characteristic turn over point

if no dark matter:
Prediction: Rotation Curve

Zwicky (1933): “missing mass” needed to explain rotation curves

\[ V_c (\text{km s}^{-1}) = \sqrt{\frac{GM}{R}} \]

\text{flat!}

NGC3198 (Begeman 1989)
Prediction: Rotation Curve

Zwicky (1933): “missing mass” needed to explain rotation curves

$V_c (\text{km s}^{-1}) = \sqrt{\frac{GM}{R}}$

flat!

halo structure

NGC3198 (Begeman 1989)
Prediction: Rotation Curve

Zwicky (1933): “missing mass” needed to explain rotation curves

NGC3198 (Begeman 1989)

Vc (km s⁻¹) = \sqrt{GM/R}

flat!

halo structure

inner structure
Dark Matter Properties

Massive particle:

- present over many cosmological epochs
- forms gravitational potentials for galaxies and galaxy clusters
- interacts more weakly with EM radiation than Standard Model

This is certainly something, but we’d like to know a lot more!

...mass?
...interaction channels?
...interaction cross sections?
...does it have any friends?
...how was it produced?
...large scale arrangement?
Dark Matter Properties

Massive particle:

- present over many cosmological epochs
- forms gravitational potentials for galaxies and galaxy clusters
- interacts more weakly with EM radiation than Standard Model

This is certainly something, but we’d like to know a lot more! any hints to work with?
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1. Introduction

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Dark Matter...
Dark Matter...
Dark Matter...
Dark Matter with Self-Interactions
Dark Matter with Self-Interactions
characteristic radius $r_1$

inside $r_1$:

$\rho \sim \rho_{iso}$
r_{1} : radius at which nσv×t_{age}=1
Across Many Objects

\[
\langle \gamma \rangle / m \quad (\text{cm}^2 / \text{g} \times \text{km/s})
\]

\[
\langle \gamma \rangle \quad \text{(km/s)}
\]

Kaplinghat, Tulin, Yu 1508.03339
Across Many Objects

\[ \langle \sigma v \rangle / m \quad (\text{cm}^2/\text{g} \times \text{km/s}) \]

\[ \langle v \rangle \quad (\text{km/s}) \]

Kaplinghat, Tulin, Yu 1508.03339

n.b. — cm^2/g \sim b/\text{GeV}
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What Causes Dark-Sector Energy Redistribution?

two possibilities:

- elastic scattering
- inelastic scattering
  - large mass energy release
  - small binding energy release / de-excitation
Elastic Scattering with a Massive Mediator

velocity dependence of scattering depends on characteristic $v$ of astrophysical object:

$$n \sigma v \sim \rho \sigma v/m_{DM} \sim \rho \alpha_{DM}^{2} m_{DM} v/(m_{\Phi}^{2} + q_{\text{galaxy}}^{2})^{2},$$
so for $m_{\Phi} \sim m_{DM}$ $v_{\text{galaxy}}$:

- at $v_{\text{dwarf}} < v_{\text{galaxy}}$, we have $n \sigma v \sim v$
- at $v_{\text{cluster}} > v_{\text{galaxy}}$, we have $n \sigma v \sim v^{-3}$

Kaplinghat, Tulin, Yu 1508.03339
Across Many Objects

\[ \langle \sigma v \rangle / m = \text{(cm}^2\text{/g} \times \text{km/s)} \]

\[ \langle v \rangle \text{ (km/s)} \]

\[ \sigma v \sim v \]

\[ \sigma v \sim v^{-3} \]

Kaplinghat, Tulin, Yu 1508.03339
Massive Mediator?

pros and cons:

• provides a mechanism for different θv across objects of different size
2-to-2 Scattering

\[ \sigma = \frac{|p_{\text{out}}^*|}{|p_{\text{in}}^*|} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} |\mathcal{M}|^2 \]
2-to-2 Scattering

\[ \sigma = \frac{|p_{\text{out}}^*|}{|p_{\text{in}}^*|} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} |\mathcal{M}|^2 = mv \]
2-to-2 Scattering

\[
\sigma = \left| \frac{p_{\text{out}}^*}{p_{\text{in}}^*} \right| \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} |M|^2
\]

~v only if scattering is elastic

= mv
\[ \sigma \sim \frac{1}{p_{\text{out}}^*} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} \left| \mathcal{M} \right|^2 \]

- \( \sigma_{\text{ann}} \sim 1/\nu \) (or: \( \sigma_{\text{ann}} \) is constant) because of different \( \nu \) dependence of \( p_{\text{out}} \) and \( p_{\text{in}} \)
Across Many Objects

Kaplinghat, Knox, Turner
astro-ph/0005210
Across Many Objects

Kaplinghat, Knox, Turner
astro-ph/0005210

exactly the same $\sigma_v$!
Fuel?

“To ensure that early annihilations do not reduce CDM particles to negligible numbers, they must be protected against annihilation in the early Universe… The requirements on a model for annihilating CDM are stringent, but by no means impossible.”

the problem: $\sigma v \sim 10^{-17}$ cm$^3$/sec is a %&#(!$ing huge cross section!
Anihilations?

pros and cons:

• naturally explains constant $\sigma v$
• but all of the “fuel” is necessarily depleted in the early universe

  Kaplinghat, Knox, Turner astro-ph/0005210

• e.g., if asymmetric DM (to avoid thermal relic catastrophe), necessarily no antiparticles remain
Dark fusion

\[ \sigma = \frac{|p^*_{\text{out}}|}{|p^*_{\text{in}}|} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} |\mathcal{M}|^2 \]
Dark fusion

\[ \sigma = \frac{|\vec{p}_{\text{out}}^*|}{|\vec{p}_{\text{in}}^*|} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} \left| \mathcal{M} \right|^2 \]

=mv
Dark fusion

\[ \sigma = \frac{|\vec{p}_{\text{out}}^*|}{|\vec{p}_{\text{in}}^*|} \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} |\mathcal{M}|^2 \]

\[ |\vec{p}_{\text{out}}^*| = \frac{1}{2\sqrt{s}} \sqrt{[s - (m_3 + m_4)^2][s - (m_3 - m_4)^2]} \quad (m_3 \sim m_4) \]

\[ \simeq \frac{1}{2\sqrt{s}} \sqrt{[(m_1 + m_2)(1 + v_{\text{cm}}^2) - (m_1 + m_2)^2(1 - b)^2][(m_3 + m_4)^2 - (m_3 - m_4)^2]} \]

= m \times (2b + v^2)^k

b = (m_1 + m_2 - m_3 - m_4) / (m_1 + m_2)

is the fractional binding energy release
Dark fusion

\[ \sigma = \left| \frac{p_{out}^*}{p_{in}^*} \right| \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} \left| \mathcal{M} \right|^2 \]

\[ = m \times (2b + v^2)^k \]

\[ = mv \]

\[ b = \frac{(m_1 + m_2 - m_3 - m_4)}{(m_1 + m_2)} \]

is the fractional binding energy release

- \( \sigma \sim b^k/v \) at low \( v \) (or: \( \sigma v \) is constant) because of the different velocity dependence of \( p_{out} \) and \( p_{in} \)
Dark fusion

\[ \sigma = \frac{1}{16\pi s} \int \frac{d\Omega}{4\pi} \left| \mathcal{M} \right|^2 \]

= \text{m} \times (2b+v^2)^k

= m v

- suggest: “black disk” scattering \( \sigma v \sim 1/m_{DM}^2 \) at low \( v \),
  \( b \sim 10^{-3} \) as in SM nuclear physics

\[ b = (m_1 + m_2 - m_3 - m_4)/(m_1 + m_2) \]

is the fractional binding energy release

Pirsa: 17120002
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\[ \sigma = m \times (2b - 1) \]

- suggest \( b \sim 10^{-3} \) at low \( v \),

Across Many Objects

intriguing (1606.02305): $\sigma v \sim \alpha^5/m_{DM} \phi$, $b \sim \alpha^2/4$

An, Wise, Zhang
Dark Fusion

pros and cons:

- constant $\sigma v$ at small $v$ (fusion with small $b$ is compressed annihilation without antiparticles)
Dark Fusion

pros and cons:

- constant $\sigma v$ at small $v$ (fusion with small $b$ is compressed annihilation without antiparticles)

Table 2: Catalog of galaxy groups

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<th>V_L</th>
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The complete version of this catalog is available online.

Kourkchi and Tully, 1705.08068
Dark Fusion

pros and cons:

• constant $\sigma v$ at small $v$ (fusion with small $b$ is compressed annihilation without antiparticles)

• $b \sim 10^{-3}$ and large $\sigma v$ observed in SM: small binding energy, large $\sigma$ defines nuclear physics

• heterogeneous populations may survive from early universe, or $A_{\text{max}}$ from fusion at early times can fuse to higher $A$ (or partially fission to different $A_{i-1}, A_{i+1}$) at late times
Dark Fusion

- Pros
  - 
  - 
  - 
- Cons
  - 
  - 
  - 
- Kolb & Turner
- McDermott 1711.00857
Dark Fusion

\[ \frac{m_\pi}{T} \]

\[ R_N = 1, R_\pi = R_\rho = R_D = 1 \]
\[ (\sigma v)_0 = 50 \times 10^{-26} \text{ cm}^3/\text{s} \]
Asymmetric DM

\[ \Omega h^2 \]

\[ \rho \]
\[ \pi \]
\[ D \]

(Ai-1, Ai+1) at late times

Detmold, McCullough, Pochinsky 1406.2276
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Outline

1. Introduction
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4. (Even More) Speculative Ideas
Fusion at Late Times

Ways to avoid “fuel catastrophe”:
- fusion falls out of equilibrium in early universe before dissociation does
- fusion products “fall apart” at late times
- there is a “CNO-like cycle”
- ...
Other Signals

outgoing states have \( v = v_{\text{min}} = (2b)^k \)

- this can be greater than the escape velocity of dwarf galaxies, so could evaporate small objects
- this can be more than \( v_{\text{MW}} \): some DM appears “warm,” some appears cold, may lead to interesting Nbody signatures
- This can be greater than the escape velocity of dwarf galaxies.
- This can be even “warm,” so interesting.

Wang, Peter, et al. 1406.0527
There is No Missing Satellites Problem

- this can be explained by "warm," sub-halos...
Other Signals

assume that $\sigma v \sim 10^{-17}$ cm$^3$/sec is somehow attained in the dark sector at the present time

- if there is some small Br to SM...
  - $\sigma v_{\text{vis}} \sim 10^{-26}$ cm$^3$/sec for $\sigma v_{\text{tot}} \sim 10^{-17}$ cm$^3$/sec
    $\rightarrow \epsilon \sim 10^{-4}\text{ish}$
  - in HPS range (above supernova bounds)
  - because $v > v_{\text{MW}}$, boosted DD signal?
  - would require a nonminimal dark sector
Conclusions

hints of self-interactions allow investigation of nuclear-scale dark matter physics

• elastic vs inelastic scattering have different qualitative features
  
  • $\sigma v_{\text{tot}} \sim 10^{-17}$ cm$^3$/sec across many objects
  
  • mediator with $m_\phi \sim m_{\text{DM}} v_{\text{cluster}}$ vs. fusion with fractional binding energy release $b \geq v_{\text{cluster}}^2$

• possibility to explore interesting early and late universe physics
Conclusions

unresolved issues:

- major
  - how to ensure fuel survival at late times?
  - does this have (an even kind of) CDM-like cosmology?
- less major but still important
  - other observational signatures?
  - ...
Thank you!