Dark Matter Creation through the Kinetic Portal

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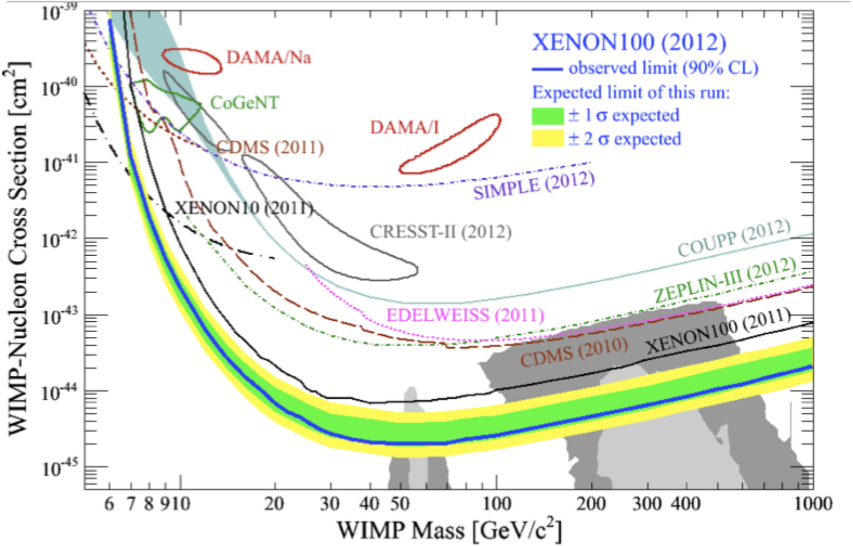
"Beyond the Standard Model in particle physics"

Cosmological/astrophysical observations basically tell us that Dark Matter is Cold and Stable ($\tau > 10^{26}$ sec).
This leaves some freedom.

The particle physics DM models are challenged by direct, indirect and/or collider experiments.
This in particular the case for many WIMP candidates.

Exclusion: latest Xenon100 results - 225 days (E.Aprile, DarkAttack, Ascona, July 18, 2012)



Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

Signature? Gamma-ray lines from Galactic Centre ($E_\gamma \approx 130$ GeV).

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A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

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Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.3σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}$ cm^3 s^{-1} when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

Signature? Gamma-ray lines from Clusters of Galaxies ($E_\gamma \approx 130$ GeV).

An evidence for indirect detection of dark matter from galaxy clusters in Fermi-LAT data

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(Dated: July 19, 2012)

We search for spectral features in Fermi-LAT gamma-rays coming from regions corresponding to six most massive nearby galaxy clusters. We observe a sharp peak at photon energy 130 GeV over the diffuse power-law background with statistical significance up to 3.2σ, confirming independently earlier claims of the 130 GeV gamma-ray line from the Galactic centre. Interpreting this result as a signal of dark matter annihilations to monochromatic photons in galaxy cluster haloes, and fixing the annihilation cross section from Galactic centre data, we determine the annihilation boost factor due to dark matter subhaloes to be of order $\mathcal{O}(10^3)$, in agreement with theoretical expectations for the galaxy clusters.

This talk is about something else:

A generic (but brief) discussion of creation of DM through a Portal

All possible DM production regimes are realized, with a specific "phase diagram" structure.
We also got analytical solutions for all the regimes
(not shown here ;-)

I will focus on a scenario that may be testable,
including in the so-called Freeze-in regime.

Based on:

The Four Basic Ways of Creating Dark Matter Through a Portal,
Xiaoyong Chu, Thomas Hambye, M.T.,
JCAP 1205 (2012) 034

1. The WIMP paradigm = DM as a cold thermal relic.

Define abundance

$$Y = \frac{n}{s}$$

with n the DM number density and s the entropy density.
Simplest case Y satisfies

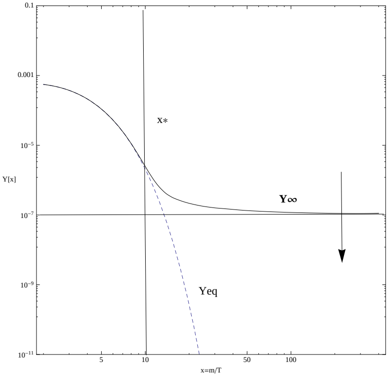
$$\frac{dY}{dx} = \frac{\langle \sigma v \rangle s}{Hx} \left(Y_{\rm eq}^2 - Y^2 \right)$$

with $x = m/T$, $Y_{\rm eq}$ the thermal equilibrium abundance of DM.

Solution:

$$\frac{\Omega_{dm}}{\Omega_b} \approx 0.2\, x^* \left(\frac{\rm pbarn}{\langle \sigma v \rangle} \right) \approx 5$$

The larger the annihilation cross section, the smaller the relic abundance (assuming no chemical potential).



Typically $x^* = \mathcal{O}(20)$. Observations (WMAP) require

$$\langle \sigma v \rangle \approx 10^{-36}\mathrm{cm}^2 \equiv 3 \cdot 10^{-26}\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

THE WIMP MIRACLE

Very nice.
Dark Matter relic abundance is independent of unknown UV physics.

Yet, quite rigid framework.
Annihilation cross-section fixed by relic abundance.
This is (in part) why many candidates are excluded.

Other DM production regimes?

The hypothesis of Thermal Equilibrium sets the time of decoupling $x = x^*$.

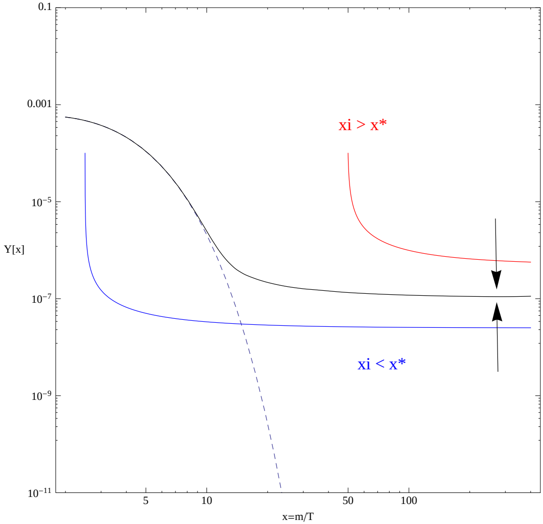
However a "WIMP miracle" occurs in more generic scenarios, including non-thermal setups:*

$$Y_\infty|_{\rm non-thermal} = \frac{x_i}{x^*}\, Y_\infty|_{\rm thermal} \propto \frac{x_i}{\langle \sigma v \rangle}$$

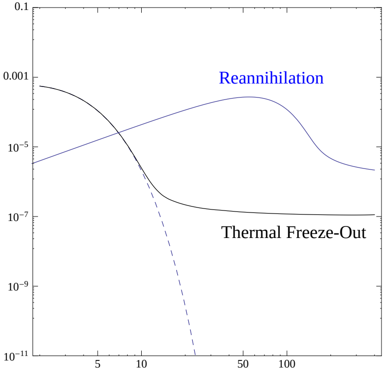
where x_i is the characteristic time of DM "release".

* T. Moroi and L. Randall; B.S. Acharya, G. Kane, S. Watson, P. Kumar;...

For instance $x_i > x^*$ requires $\langle \sigma v \rangle$ to be larger to reach the same relic abundance.



E.g. production of DM (for instance from decay $\Sigma \to X + \ldots$) followed by annihilation of DM: $X + X \to SM + SM$



We will call this a Re-Annihilation Regime.*

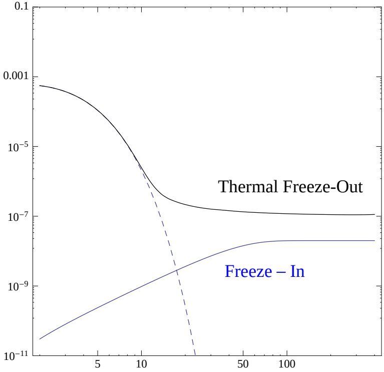
*Cheung, Elor, Hall and Kumar

If

$$Y(x_i) \lesssim Y_\infty|_{\mathrm{thermal\,freeze-out}}$$

there is no re-annihilation. Instead

$$Y_\infty = Y(x_i).$$



We will call this a Freeze-In Regime.*

*Mc Donald (02); Hall, Jedamzik, March-Russell and West (09).

Typically

$$Y_{FI} \sim \alpha_{FI} \times m_{dm} \times \left. t_U \right|_{T \sim m_{dm}}$$

This is to be compared to

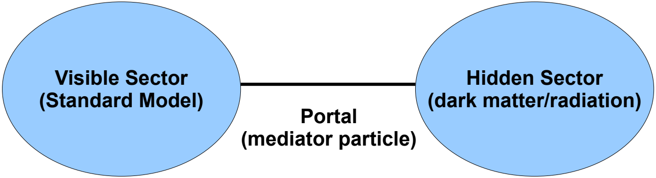
$$Y_{FO} \sim \frac{1}{\alpha_{FO} m_{dm} t_U}$$

Complementary regimes ($\alpha_{FI} \lll \alpha_{FO}$).

Also both independent of, unknown, UV physics.

Drawback: FI needs very tiny couplings. How to test this?

2. Our setup



Remark:
Here, we depart from Hall *et al*: we do not need exotic (*i.e.* odd) particles in the Visible Sector (VS).

Hidden Sector (HS):

$$\mathcal{L}_{HS} = i\bar{\chi}\,\not{D}'\chi - m_\chi\bar{\chi}\chi + \dots$$

χ is Dirac, charged under a massless $U(1)'$ gauge field, B'_μ.

Naturally stable:
χ is simply the lightest charged particle of the HS.*

*Feldman, Kors, Nath (06); Pospelov, Ritz, Voloshin (08) Mambrini (10);... Rem: for a massive Z'.

Kinetic Portal:

$$-\frac{\epsilon}{2}B^{\mu\nu}B'_{\mu\nu}$$

Naturally tiny mixing:*

$$\epsilon \propto e\,e' \log(m_1/m_2)$$

The mediator is the photon.
(rem: we have also studied creation through the Higgs portal)

*B. Holdom (86)

Motivations?

- Among the simplest models
- Only 3 parameters (4 if γ' massive)

$$m_\chi,\ e' \to \alpha',\ \epsilon \to \kappa = \epsilon e'/e$$

- Many natural features (stability, tiny mixing,...)
- Visible Sector = Standard Model only!
- Long range interactions from γ (mediator) and γ' (dark radiation) *

→ Very Rich Phenomenology (both Cosmo and Particles)

→ Very Broad Range of candidates (from sub-MeV to TeV)

- Prototype of many HS/VS structures:

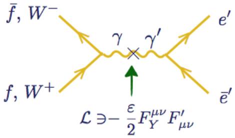
→ generic "phase diagram", with 4 DM creation regimes.

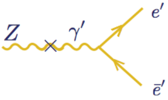
* Dark Radiation studied in details, but with no mediator, by Ackerman, Buckley, Carroll, Kamionkovski (08); Feng, Kaplinghat, Tu, Yu (09); Feng, Tu, Yu (08); see also Foot et al (06-10)

The relevant processes

1. through which DM is created (mediator)

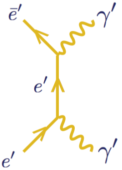
$$\langle \sigma_\gamma v \rangle$$





2. through which the HS may thermalize.

$$\langle \sigma_{\gamma'} v \rangle$$



Remarks:

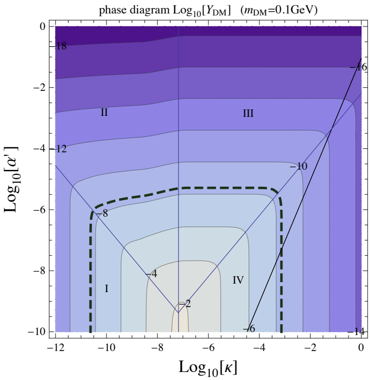
We worked in a basis with diagonal kinetic terms.

It is convenient to take γ as the mediator. Then DM is millicharged and γ' does not couple to SM particles.

Our main result:
Phase diagram = Relic density in $\kappa - \alpha'$ plane

There are 4 regimes:

I. Freeze-in
II. Reannihilation
III. Freeze-out with thermalization of HS
IV. Freeze-out without thermalization of HS



Remark:
The dashed-line corresponds to $\Omega_{dm} = 0.23$ (here for $m_{dm} = 0.1$ GeV).

Boltzmann equation for relic abundance

In "full" generality

$$x\frac{H}{s}\frac{dY}{dx} = \langle\sigma_\gamma v\rangle(Y_{eq}^2(T) - Y^2) + \langle\sigma_{\gamma'} v\rangle(Y_{eq}^2(T') - Y^2)$$

In general, different temperatures in VS and HS.

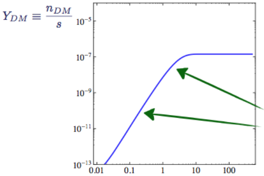
The different regimes depend on which term(s) on the RHS is (are) relevant.

This, in turn, depends on the couplings α', κ and, indirectly, on whether the hidden sector has reached thermal equilibrium.

I. Freeze-in *

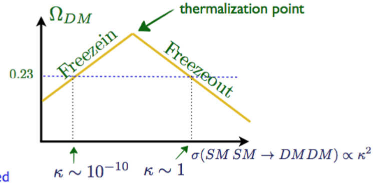
Small α', no (or negligible) DM present $\rightarrow$ production through the mediator:

$$
\begin{aligned}
x\frac{H}{s}\frac{dY}{dx} &= \langle\sigma_\gamma v\rangle\left(Y_{eq}^2(T) - Y^2\right) + \langle\sigma_{\gamma'} v\rangle\left(Y_{eq}^2(T') - Y^2\right) \\
&\rightarrow \\
&\approx \langle\sigma_\gamma v\rangle\, Y_{eq}^2(T)
\end{aligned}
$$



$Y_{DM} \propto 1/T$ down to $T \sim m_{DM}$ where n_A^{eq} becomes Boltz. suppressed

DM production IR dominated



* McDonald, 02'; Hall, Jedamzik, March-Russel, West, 09'

II. The reannihilation regime

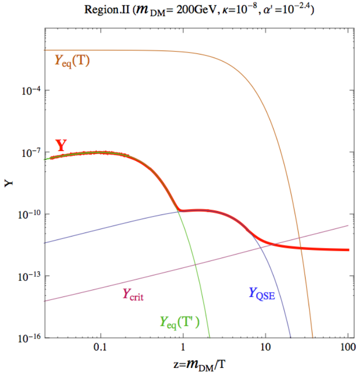
$$
\begin{aligned}
x\frac{H}{s}\frac{dY}{dx} &= \langle\sigma_\gamma v\rangle(Y_{eq}^2(T) - Y^2) + \langle\sigma_{\gamma'} v\rangle(Y_{eq}^2(T') - Y^2) \\
&\rightarrow \\
&\approx \langle\sigma_\gamma v\rangle\, Y_{eq}^2(T) - \langle\sigma_{\gamma'} v\rangle Y^2
\end{aligned}
$$

i.e. $SM\,SM \rightarrow \chi\bar{\chi}$, but as $\alpha' \nearrow$ the channel $\chi\bar{\chi} \rightarrow \gamma'\gamma'$ opens up.

E.g. $T' \ll T$, hence $Y_{eq}(T') \ll Y_{eq}(T)$
Initially $Y = Y_{eq}(T')$.
But eventually $m/T' \gg 1$, $Y_{eq}(T') \ll 1$.

$\chi\bar{\chi} \rightarrow \gamma'\gamma'$, but replenished by $SM\,SM \rightarrow \chi\bar{\chi}$
$\rightarrow$ delayed annihilation, or reannihilation.

Then $Y \approx x_f/\langle\sigma_{\gamma'} v\rangle$ but x_f determined by both $\langle\sigma_\gamma v\rangle$ and $\langle\sigma_{\gamma'} v\rangle$.



Phase diagram = Relic density in $\kappa - \alpha'$ plane

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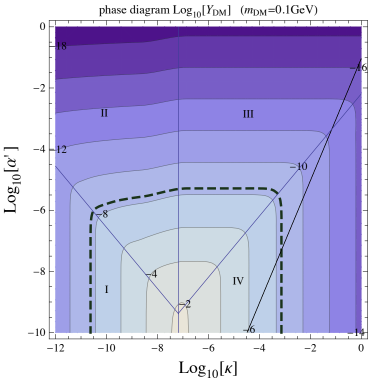


Remark:
The dashed-line corresponds to $\Omega_{dm} = 0.23$ (here for $m_{dm} = 0.1$ GeV).

III. Hidden Sector Freeze-out

As $\kappa \nearrow$ further then $T' \to T$:
VS and HS are in thermal equilibrium with each others.
$\to$ loads of γ'
$\to$ competition between $\chi\bar{\chi} \to \gamma'\gamma'$ and $\chi\bar{\chi} \to \gamma'\gamma'$.
Otherwise like freeze-out,

$$Y_\infty \approx x_f / \langle \sigma_{\gamma'} v \rangle.$$

IV. Visible Sector Freeze-out

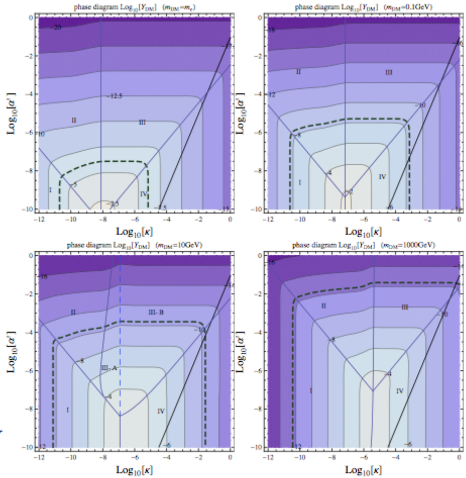
For even larger κ, whether there is Dark Radiation becomes essentially irrelevant.
$\to$ freeze-out as usual: $SM\, SM \leftrightarrow \chi\bar{\chi}$ and

$$Y_\infty \approx x_f / \langle \sigma_\gamma v \rangle.$$

This phase diagram is a generic result: Kinetic Portal

$m_{DM} = m_e$

$m_{DM} = 0.1\,\mathrm{GeV}$



$m_{DM} = 10\,\mathrm{GeV}$

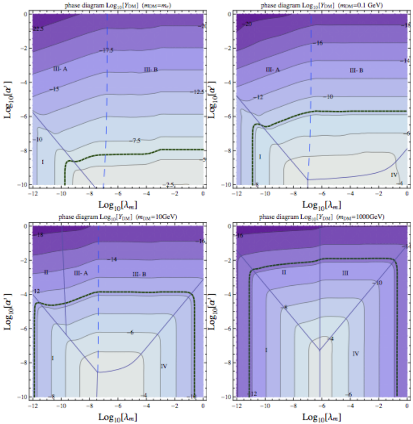
$m_{DM} = 1\,\mathrm{TeV}$

The Mesa Phase Diagram

This phase diagram is a generic result: Higgs Portal

$m_{DM} = m_e$

$m_{DM} = 0.1\,\mathrm{GeV}$



$m_{DM} = 10\,\mathrm{GeV}$

$m_{DM} = 1\,\mathrm{TeV}$

3. Direct Detection

Dark Matter is milli-charged $\longrightarrow$ enhanced (Rutherford) scattering in t-channel:

$$\frac{d\sigma}{dE_r} \propto \frac{1}{E_r^2} \times \frac{\kappa^2(\alpha Z)^2}{v^2 m_A} \times (\text{Nuc. Form Factor})$$

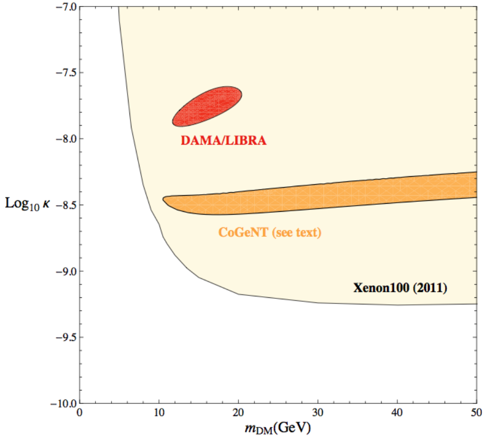
to be compared with the usual (Spin Independent, contact interaction)

$$\frac{d\sigma}{dE_r} \propto \sigma_{\rm SI} \times \frac{m_A A^2}{v^2 \mu^2} \times (\text{Nuc. Form Factor})$$

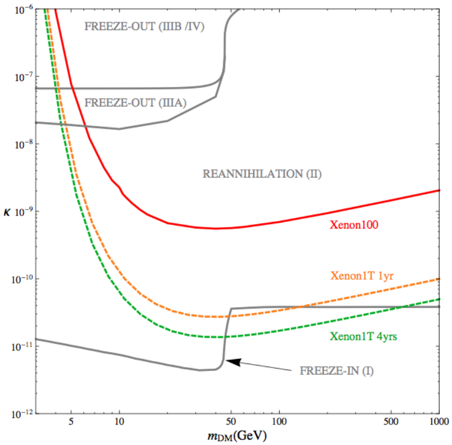
where $\sigma_{SI} = $ cst.

For $E_r \sim$ keV, this is a very large enhancement! Opens the possibility to probe very small values of κ!

Does it help to reconcile CoGeNT/DAMA/Xenon/CDMS etc?
Not quite, unfortunately.
(warning: we assume canonical, Maxwell velocity distribution in Earth vicinity)*



*See R.Foot for an alternative possibility (mirror DM)

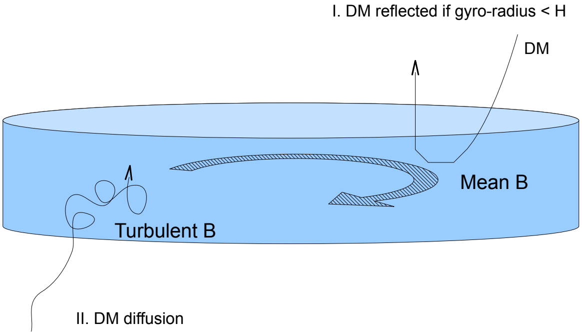


Part of reannihilation parameter space excluded by Xenon100 (2011) data.

Freeze-in may be tested by Xenon1T.

Also specific $1/E_r^2$ spectral signature.

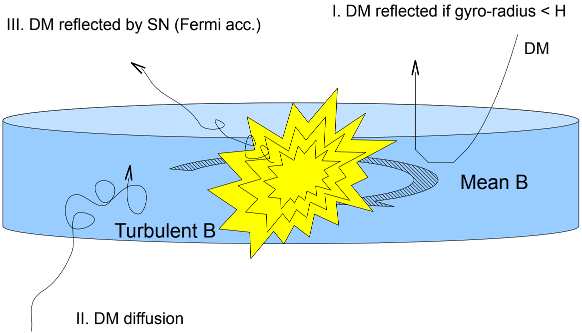
Local Dark Matter density and magnetic shielding?*



Depleted at the Sun's location, except for (part of) reannhilation and freeze-in regimes.

*Chuzhoy, Kolb, 09'; McDermoot, Yu, Zurek, 11'; Sanchez-Salcedo, Martinez-Gomez, Magana, 10'

Local Dark Matter density and magnetic shielding?*



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*Chuzhoy, Kolb, 09'; McDermoot, Yu, Zurek, 11'; Sanchez-Salcedo, Martinez-Gomez, Magana, 10'

5. Cosmological and Astrophysical Constraints

I. Big Bang Nucleosynthesis

Extra relativistic degrees of freedom (*e.g.* γ') affect expansion.
Usually phrased as a bound on extra light neutrinos

$$\Delta N \leq 1.4 \qquad 95\%\mathrm{C.L.})$$

Translates into a bound on T'/T:

$$\frac{T'}{T} \leq 1.05$$

Hence no problem.

II. Galactic and Extra-galactic Constraints

$\rightarrow$ DM Rutherford scattering may affect halo formation/structure

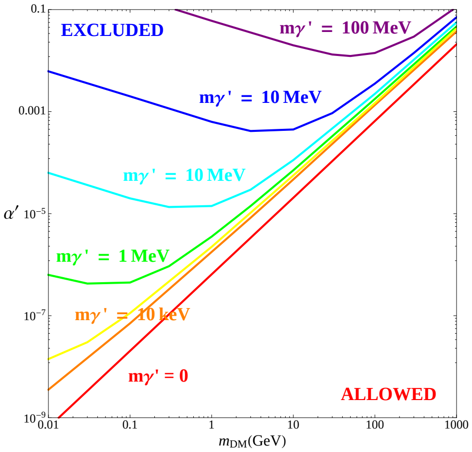
Turns out that the strongest limit is from the shape of galactic halos (ellipticity)*
They are "observed" to be elliptic. Significant scattering would make them spherical.

Ask, on average, less than one scattering over the lifetime of a galaxy.
$\rightarrow$ constrains DM-DM and DM-Baryons interactions (resp. α' and κ).

Rem: The latter a rather mild *e.g.* $\kappa \leq 10^{-2}$ for $m_{dm} \sim 10$ GeV $\rightarrow$ stronger constraints from decoupling of DM at recombination.**

*Ackerman, Buckley, Carroll, Kamionkovski, 08'; Feng, Kaplinghat, Tu, Yu, 09'; Feng, Tu, Yu, 08'

**McDermott, Bu, Zurek, 10'



Strong constraints on α' from ellipticity of galaxies. Very much relaxed by giving a (small) mass to the mediator. Does not change any of our previous conclusions regarding relic abundance, direct detection, etc.

Conclusions

Very simple model, yet rich phenomenology

Thermal relic abundance from 4 characteristic regimes (covering all the parameter space)

Universal phase diagram (also applies to massive mediators, Higgs portal, Z', etc)

For some models, even very feebly interacting particles may be accessible to direct detection experiments (including potentially for sub-GeV particles)

Interesting cosmological/astrophysical phenomenology

Backup slides

Redondo, Ringvald 10'

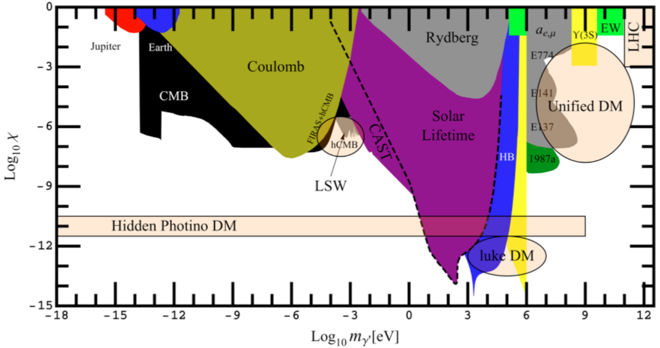


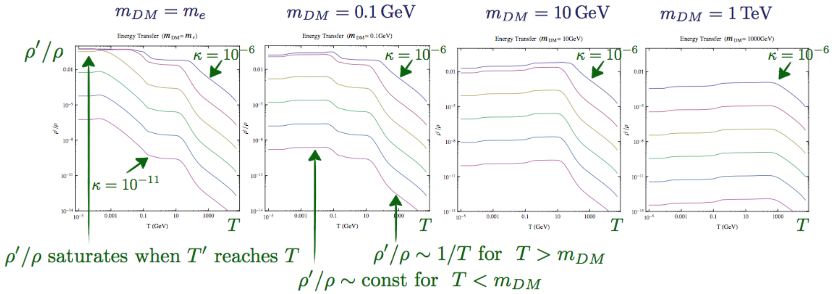
Figure 10. Summary of astrophysical, cosmological and laboratory constraints for hidden photons (kinetic mixing χ vs. mass $m_{\gamma'}$). At higher mass we have electroweak precision measurements (EW), bounds from upsilon decays (Υ_{3S}) and fixed target experiments (EXXX)). Areas that are especially interesting are marked in light orange. Compilation from Ref. [93].

As $\kappa \nearrow$ more DM is created.
As $\alpha' \nearrow$ dark radiation (γ') is created.
$\Longrightarrow$ both contribute to thermalization of the HS.

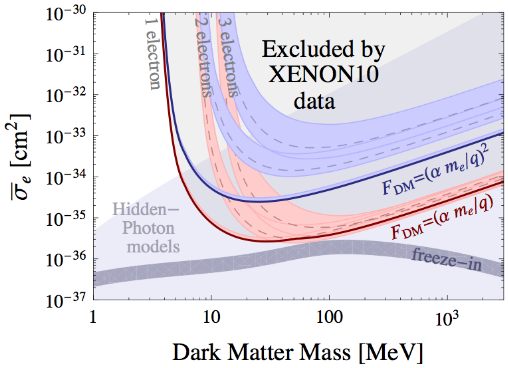
We may define T':

$$n_{\gamma'} \propto T'^3 \qquad \text{and} \qquad \rho' \propto T'^4$$

Yet another Boltzmann equation for energy transfer $\rightarrow \rho'$



New DD limits on sub-GeV dark matter from Xenon10 *
$\rightarrow$ use electron recoils instead of nuclear recoils (ionization signal)



Blue line is 95 % C.L. limit on millicharged DM.
Freeze-in also testable in near future.

*R. Essig, A.Manalaysay, J. Mardon, P. Sorensen, T.Volansky