

Light Dark Matter

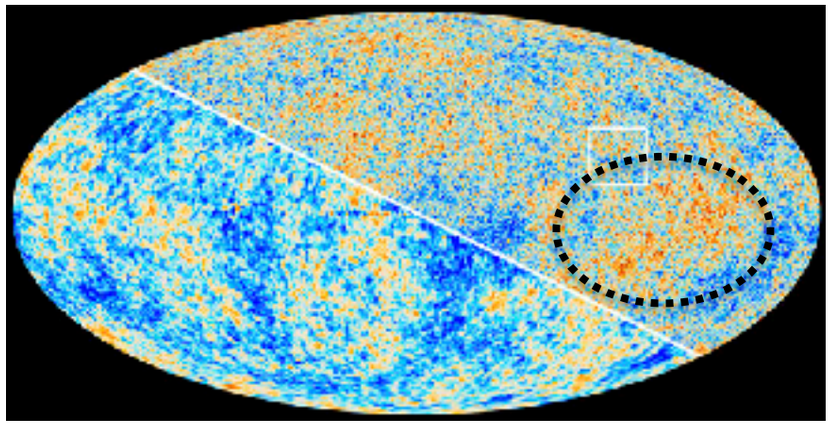
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IPPP, Durham

LAPTH, Annecy

Fayet Fest, 8-9Dec 2016

The physics of DM interactions on primordial fluctuations



Collapse under gravity



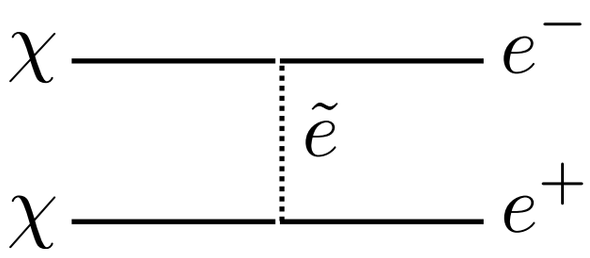


$$\dot{\theta}_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)$$

$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_b)\ ,$$

$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM}\ ,$$

Neutralino = LSP



assume DM = Weakly Interacting Massive Particles
and assume that this really means interactions are negligible

Should not we checked that interactions are negligible?

Impact of DM interactions on primordial fluctuations

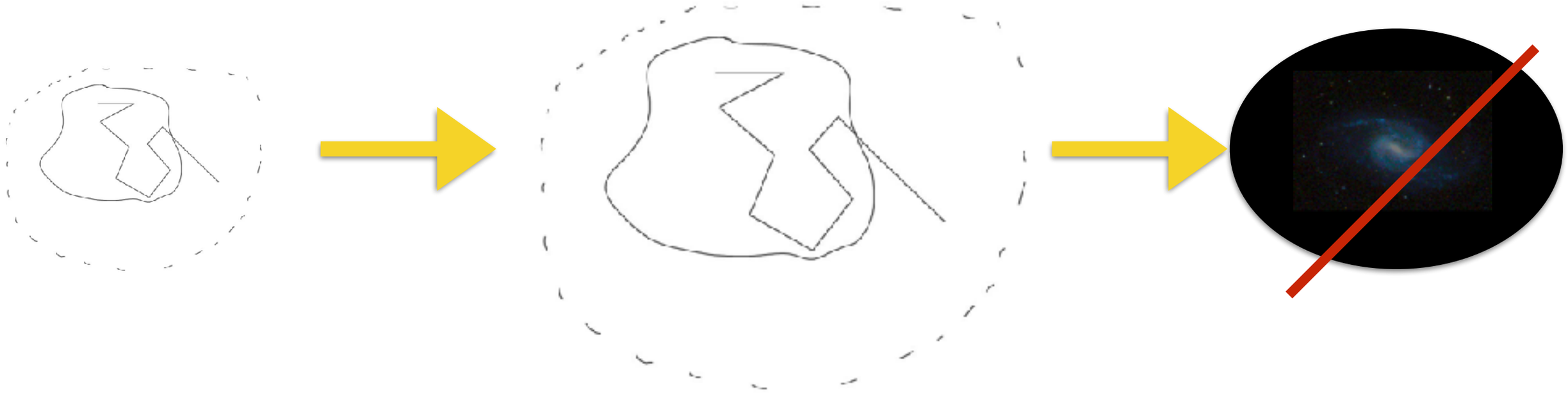
astro-ph/0012504 astro-ph/0410591

with Richard Schaeffer

Collisions → Diffusion → wash out small fluctuations

After

Free & fast → Diffusion → wash out small fluctuations



Generalisation of the Silk damping to DM

Collisional damping scale

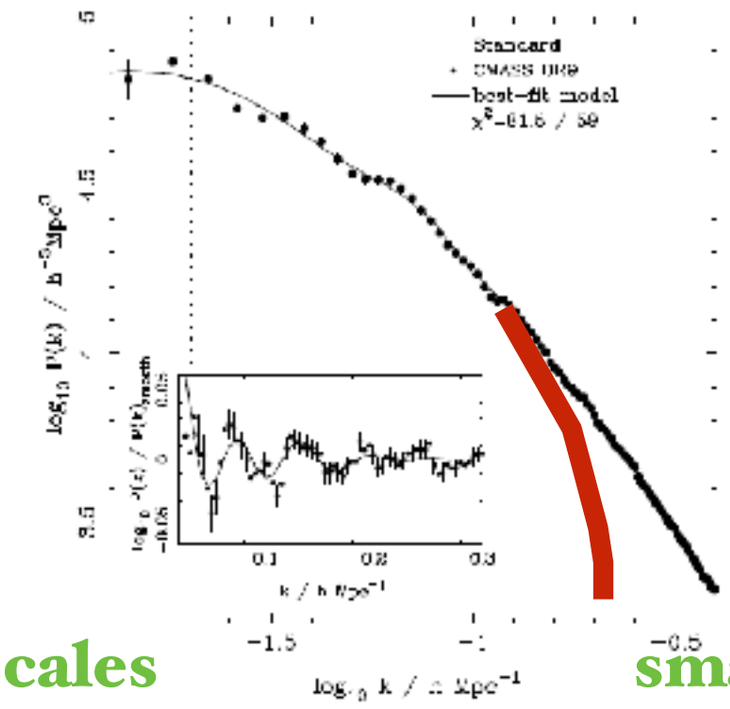
(astro-ph/0012504, astro-ph/0410591)

last until DM stop interacting

efficient if DM is coupled to a relativistic species

$$l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\not{\phi} a^2 \Gamma_i}(1+\Theta_i)\ \frac{dt}{t}$$

efficient if DM is coupled to interacting species



A new damping effect!

(astro-ph/0012504, astro-ph/0410591)

$$l_{id}^2 = \frac{2\pi^2}{3} \int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\cancel{\phi a^2 \Gamma_i}} (1 + \Theta_i) \frac{dt}{t}$$

H

DM - neutrino interactions are the most efficient

- They are relativistic
- There are plenty of neutrinos around
- They free-stream below ~ 1 MeV

Best if MeV DM

Free-streaming scale

(astro-ph/0012504, astro-ph/0410591)

depends on mass

$$l_{\rm fs} = \int_{t_{\rm dec}}^{t_0} \frac{v(t)}{a(t)}\, dt$$

depends on interactions

depends on the history of the Universe

Very different expressions

$$\int_{t_{dec}}^{t_{nr}} \frac{c}{a(t)} dt + \int_{t_{nr}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} < \mathrm{t_{nr}}$$

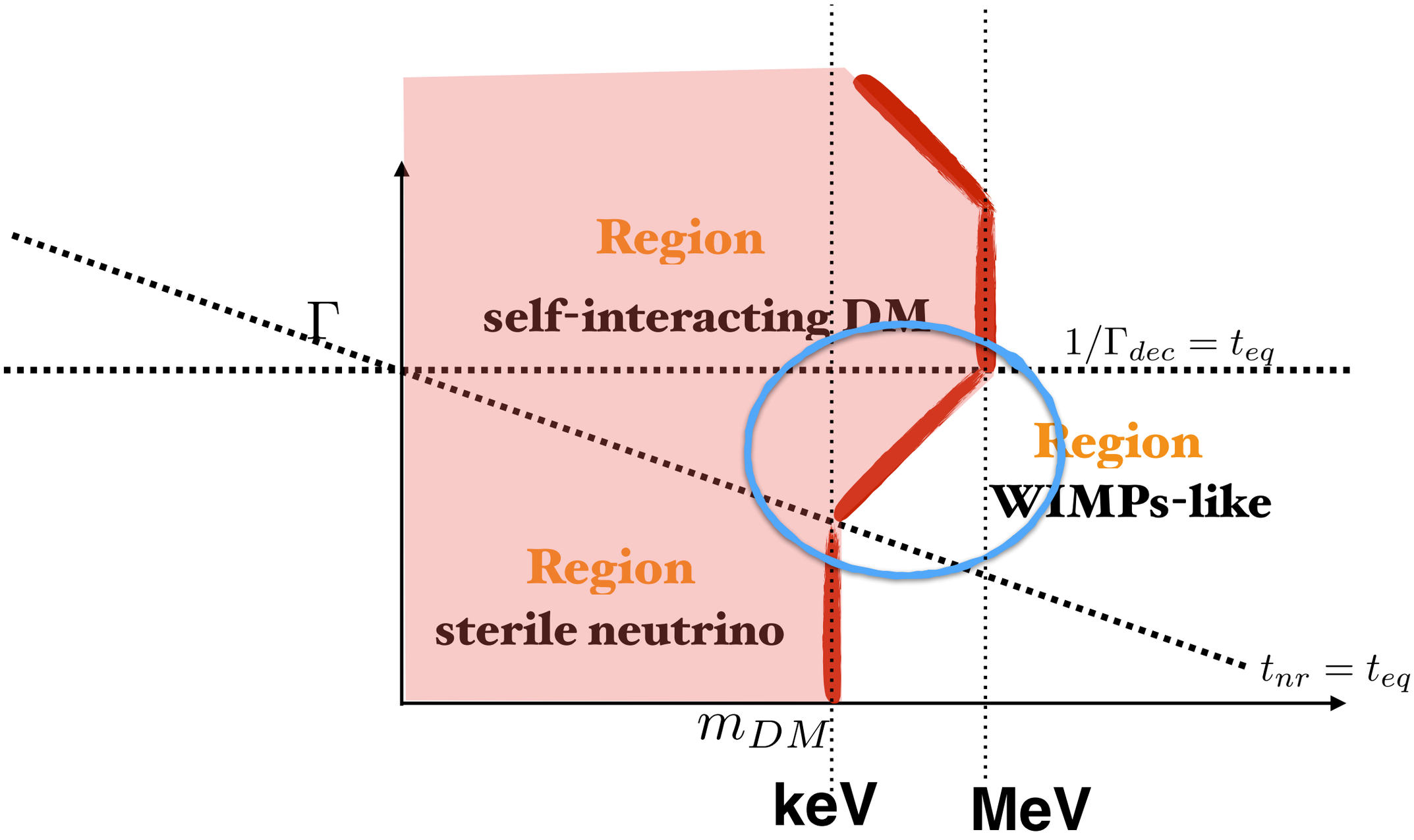
Decoupling, the non-relativistic

$$\int_{t_{dec}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} > \mathrm{t_{nr}}$$

non-relativistic, then decoupling

Free-streaming as a way to classify DM candidates

(astro-ph/0012504, astro-ph/0410591)



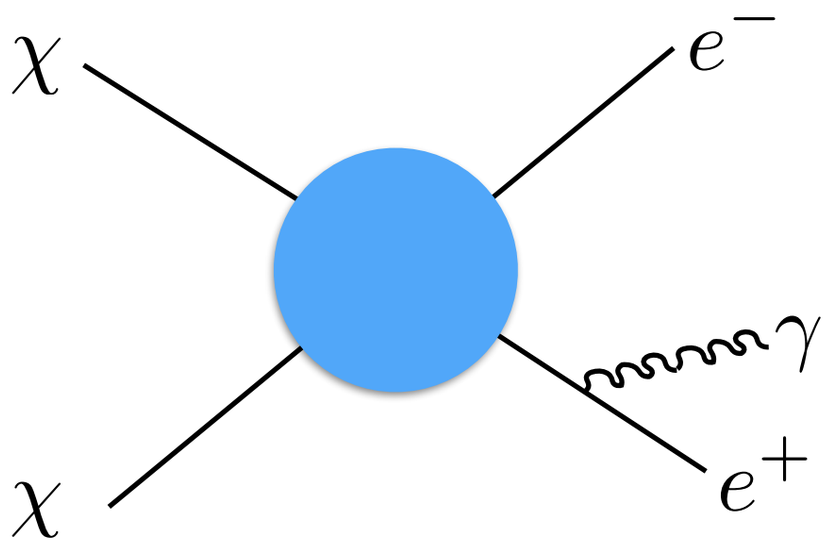
MeV (WIMP) DM can suffer from large free-streaming effect!

Can we have (thermal) MeV DM?

Can we have sub GeV DM?

No! Well... hold on...

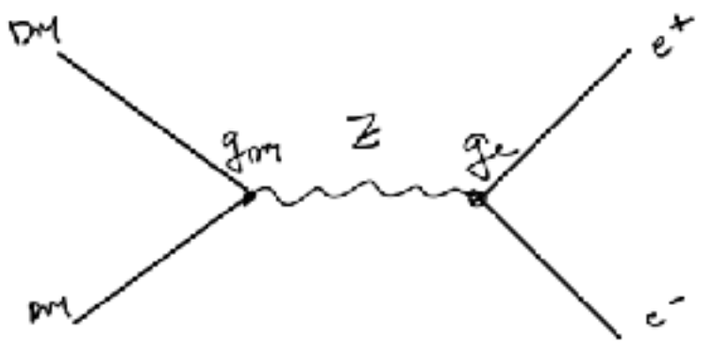
astro-ph/0208458v3

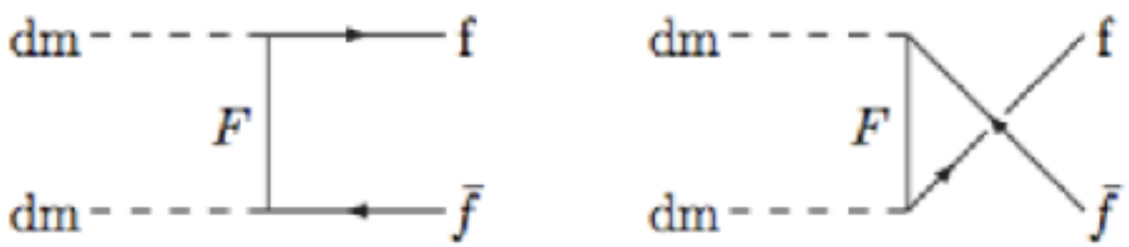




$$\sigma v \propto v^2$$

or constant cross section
but suppressed!





But do not explain the RD...

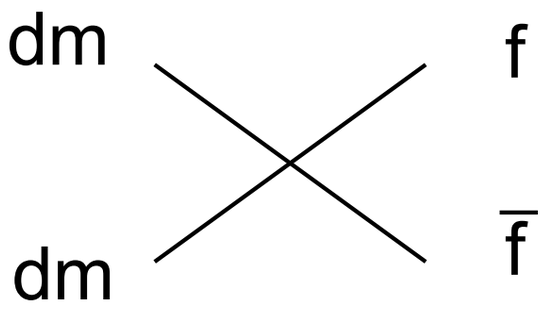
Can we have MeV DM?

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

using WMAP/Planck values



$$\sigma\ \mathrm{v}\ \propto\ \frac{\mathrm{m_{dm}}^2}{\mathrm{m_w}^4}$$ similar in SUSY $\Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$

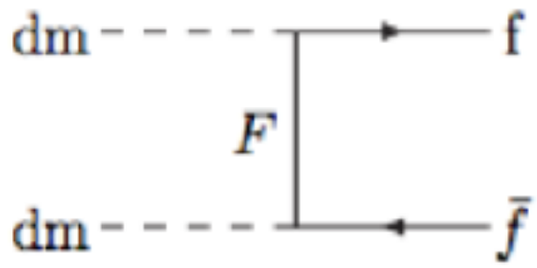
Dark Matter heavier than a proton!

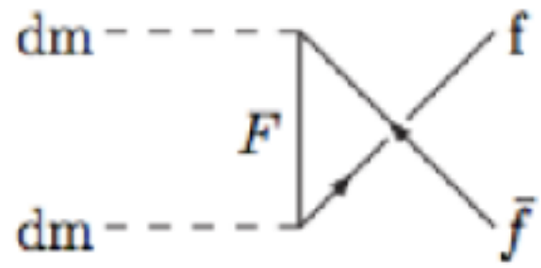
1) Unless the cross section is independent of mDM!

2) Unless the mediator is light !

Can the cross section not depend on mDM?

hep-ph/0305261





sneutrinos..

$$\sigma v \propto \frac{1}{m_F^4} \left(\left(C_l^2 + C_r^2 \right) \; m_f + 2 C_l \; C_r \; m_F \right)^2$$

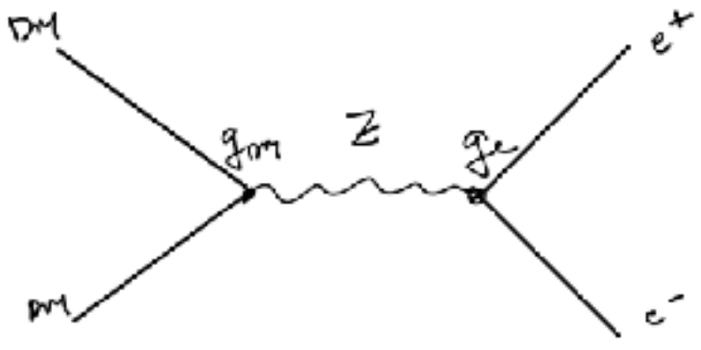
non chiral couplings

$$\sigma v \propto \frac{1}{m_F^2}$$

Pierre: Mirror fermions!! Like N=2 SUSY et voila ...

We finally discuss a theoretical framework for scalar candidates, **inspired** from theories with **N = 2 extended supersymmetry** and/or extra space dimensions, in which the Dark Matter stability results from a **new discrete (or continuous) symmetry**.

Can mediators be light? hep-ph/0305261

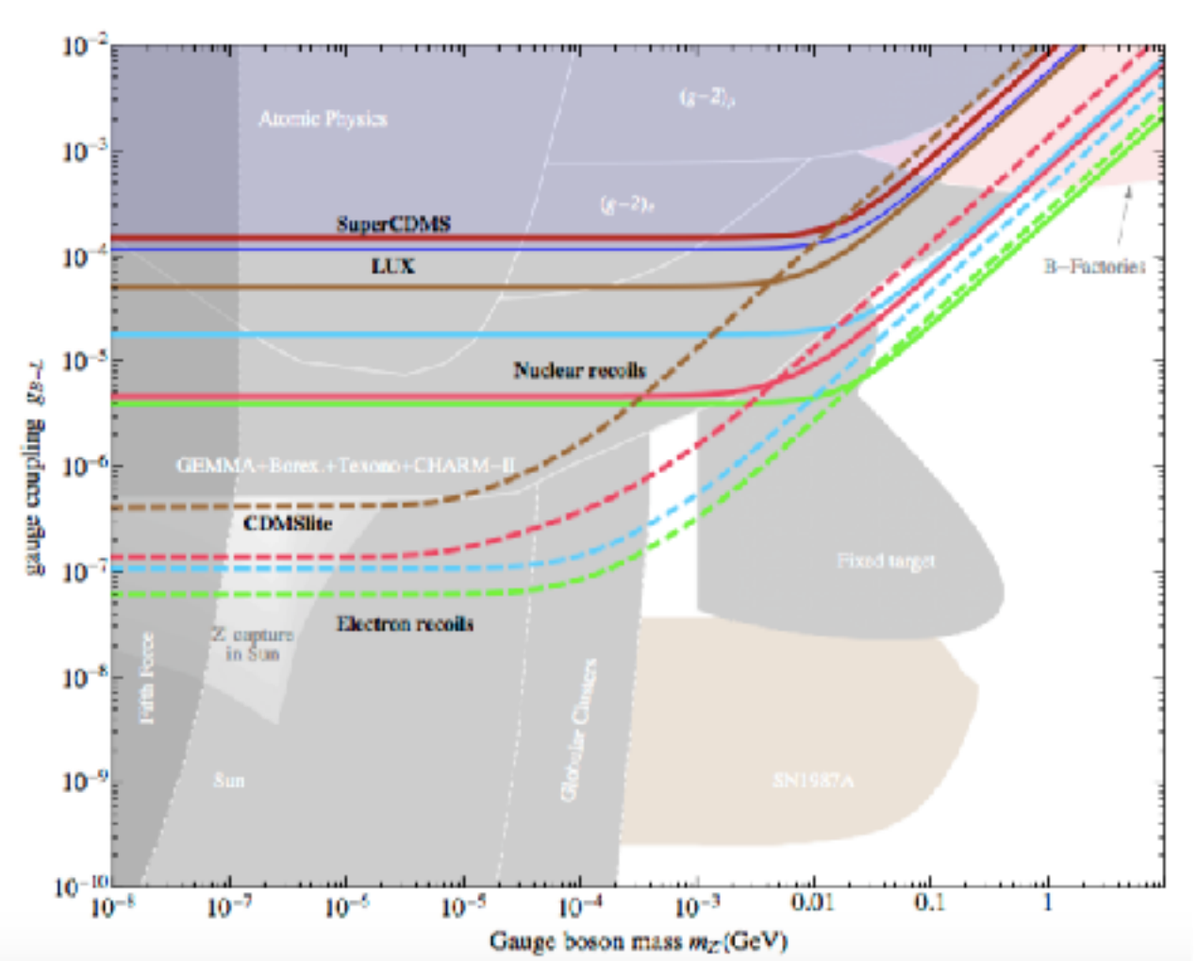


$$\sigma v \propto v^2 \frac{m_{\rm DM}^2}{m_{Z'}^4} g_{\rm DM}^2 g_e^2$$

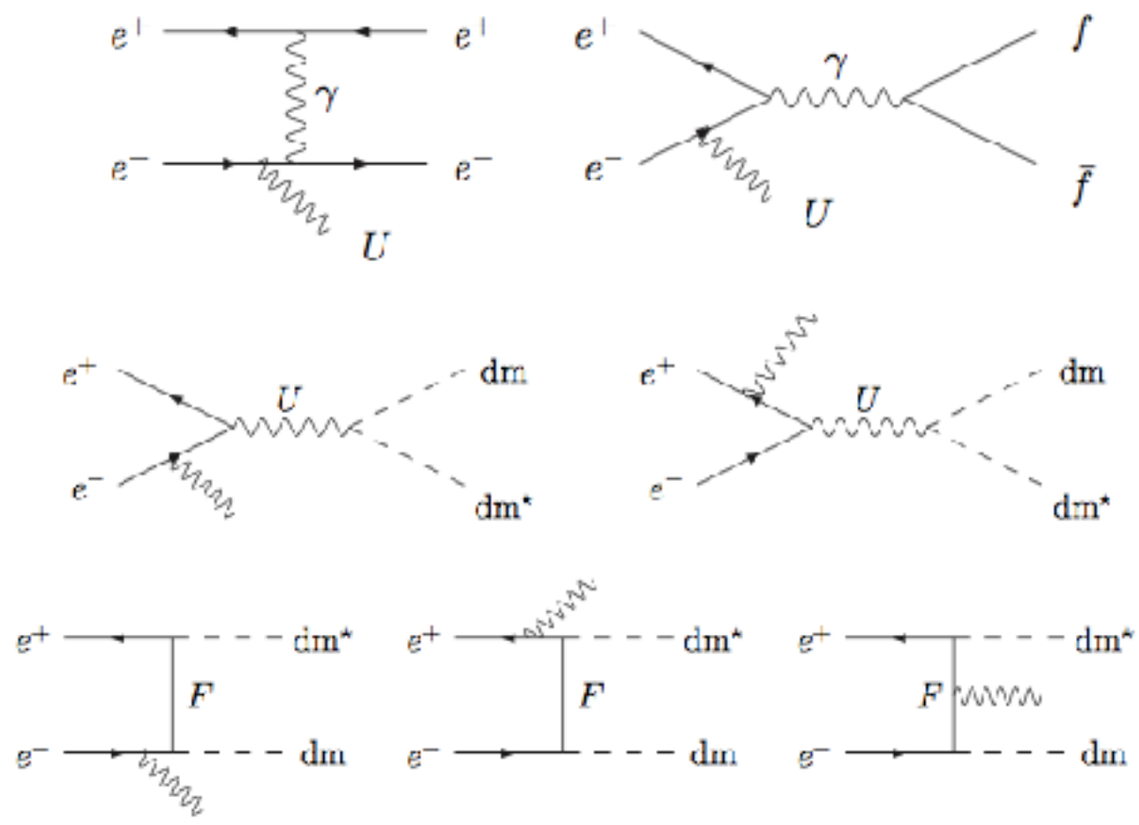
Yes if it is a U-boson!!

$$\sigma v \propto v^2 \frac{m_{\rm DM}^2}{m_{\mathbf{U}}^4} g_{\rm DM}^2 g_e^2$$

can we have a light Z-like boson?



U-strahlung.



Scalar Dark Matter candidates

9 months, 56pages, to show that DM can be lighter than O(1) GeV!

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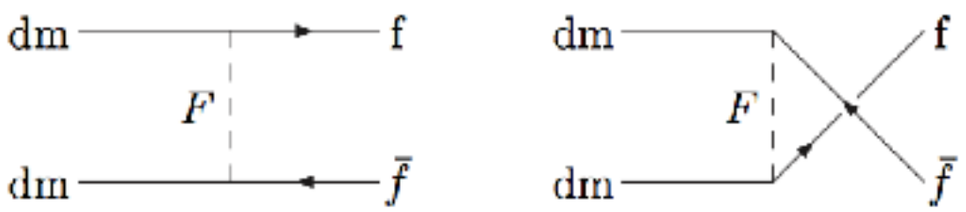
Abstract

We investigate the possibility that Dark Matter could be made of scalar candidates and focus, in particular, on the unusual mass range between a few MeV's and a few GeV's. After showing why the Lee-Weinberg limit (which usually forbids a Dark Matter mass below a few GeV's) does not necessarily apply in the case of scalar particles, we discuss how light candidates ($m_{dm} < O(\,\mathrm{GeV}\,)$) can satisfy both the gamma ray and relic density constraints. We find two possibilities. Either Dark Matter is coupled to heavy fermions (but if $m_{dm} \lesssim 100$ MeV, an asymmetry between the Dark Matter particle and antiparticle number densities is likely to be required), or Dark Matter is coupled to a new light gauge boson U. The (collisional) damping of light candidates is, in some circumstances, large enough to be mentioned, but in most cases too small to generate a non linear matter power spectrum at the present epoch that differs significantly from the Cold Dark Matter spectrum. On the other hand, heavier scalar Dark Matter particles (*i.e.* with $m_{dm} \gtrsim O(\,\mathrm{GeV}\,)$) turn out to be much less constrained. We finally discuss a theoretical framework for scalar candidates, inspired from theories with $N = 2$ extended supersymmetry and/or extra space dimensions, in which the Dark Matter stability results from a new discrete (or continuous) symmetry.

Birth of DM simplified models!

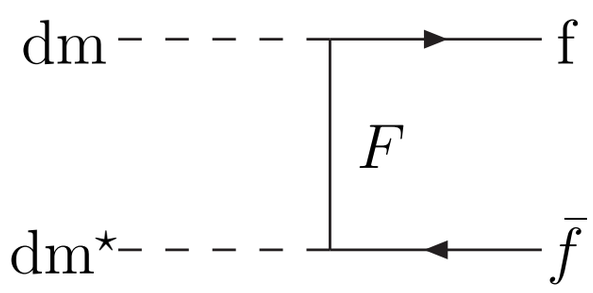
hep-ph/0305261

9.1.1 *Majorana Dark Matter*



$$
\begin{aligned}
|\mathcal{M}|^2 = {} & 8T_0\, m_{dm}^2 \left(2\, C_l\, C_r\ m_{dm} + (C_l^2 - C_r^2)\, m_f\right)^2 \\
& + \frac{8\, p_{dm}^2}{3}\Big[\, 2T_0 \left(2\ m_{dm}^2\ (2C_l^4 + 9C_l^2\, C_r^2 + 2C_r^4\,) \right. \\
& \qquad \left. + 6\ C_l\ C_r\ (C_l^2 + C_r^2)\ m_{dm}\ m_f - (C_l^4 + 12C_l^2\ C_r^2 + C_r^4)\ m_f^2\right) \\
& - 4\ T_1\ (C_l^2 + C_r^2)\ m_{dm} \sqrt{m_{dm}^2 - m_f^2}\ \left((C_l^2 + C_r^2)\, m_{dm} + 2\, C_l\, C_r\ m_f\right) \\
& + 3\ m_{dm}^2\ T_{20}\ \left(2\ C_l\, C_r\ m_{dm}\ + (C_l^2 + C_r^2)\, mf\right)^2 \\
& + m_{dm}^2\ T_{21}\ \Big(4\ (C_l^4 + 3C_l^2\ C_r^2 + C_r^4)\ m_{dm}^2 \\
& \qquad + 20\ C_l\ C_r\ (C_l^2 + C_r^2)\, m_{dm}\ m_f + (C_l^4 + 18\ C_l^2\ C_r^2 + C_r^4)\ m_f^2\Big)/3\,\Big].
\end{aligned}
$$

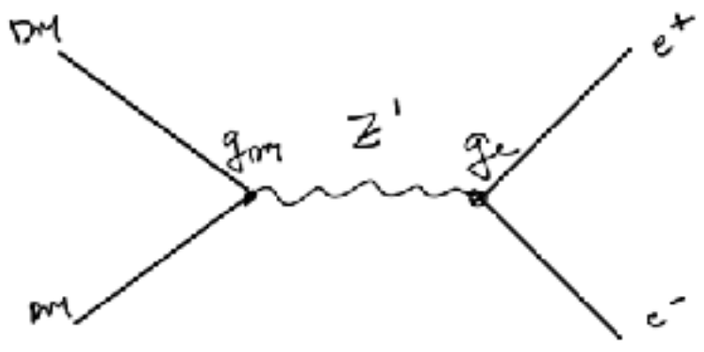
9.1.4 *Non self-conjugate scalar Dark Matter*



$$
\begin{aligned}
|\mathcal{M}|^2 = {} & 4\ T_0\ (m_{dm}^2 - m_f^2)\ \left((C_l^2 + C_r^2)\, m_f + 2\, C_l\ C_r\ m_F\right)^2 \\
& + \frac{4p_{dm}^2}{3}\Big[- \left((C_l^2 + C_r^2)\, m_f + 2\, C_l\ C_r\ m_F\right) \\
& \left(2\, T_1\ (C_l^2 + C_r^2)\ m_f\ \sqrt{m_{dm}^2 - m_f^2}\ + \right. \\
& \qquad \left. (3\ T_{20} + T_{21})\ (-m_{dm}^2 + m_f^2)\ (\ (C_l^2 + C_r^2)\, m_f + 2\, C_l\ C_r\ m_F\,) \right. \\
& + 2\ T_0\ \left(6\ C_l\ C_r\ (C_l^2 + C_r^2)\ m_f\ m_F\ + (C_l^4 + C_r^4)\ (2\, m_{dm}^2 + m_f^2)\right. \\
& \qquad \left. + 6\ C_l^2\ C_r^2\ (m_f^2 + m_F^2)\right.
\end{aligned}
$$

Slight regret...

In general, however, a mixing between the H (doublet) and h (singlet) real scalar fields is expected to occur, as indicated above. As a result of this $H - h$ mixing, the single Higgs boson of the standard model H would then get replaced by a pair [8] of Higgs mass eigenstates $H_{1,2}$. Each of them would be coupled to quarks and leptons proportionally to their mass (m_q and m_l), as in the standard model, times the cosine, or sine, of the mixing angle (ξ) between the two doublet and singlet components (originating from the real parts of the φ and σ fields, respectively). The corresponding decay rates of such Higgs bosons H_i into standard model particles would then be obtained as e.g. $\Gamma_{SM}(m_{H_2})\cos^2\xi$ and $\Gamma_{SM}(m_{H_1})\sin^2\xi$, in terms of the standard model decay rates for a Higgs boson of the corresponding mass. This would of course significantly affect the experimental searches for Higgs boson signals. Given the possible hints for the direct observation of a Higgs signal at LEP [23], one could even contemplate the possibility of having one of these Higgs mass eigenstates arond 116 GeV's, for example, and the other at a different mass.



We could have generalised to Higgs'! Argh!

Pierre's latex style :)

negligible, even in the limit in which *the extra* $U(1)$ *gauge coupling constant* g" *gets extremely small* ! Indeed an equivalence theorem shows that, in this low

gauge bosons:	2 spin-$\frac{1}{2}$ gauginos:	2 spin-0 gauge scalars:
$\|++>$	$\begin{cases} \|-+> \\ \|+-> \end{cases}$	$\|-->$
$R_p = +1,\ M_p = +1$	$R_p = -1,\ M_p = \pm 1$	$R_p = +1,\ M_p = -1$
leptons, quarks: $l,\ q:\ \|++>$	sleptons, squarks: $\tilde{l},\ \tilde{q}\ :\ \|-+>$ *"smirrors"* $\widetilde{l}_{\rm M}\ ,\ \widetilde{q}_{\rm M}: \|+->$	*mirror* leptons and quarks: $l_{\rm M}\ ,\ q_{\rm M}\ :\ \|-->$
$R_p = +1,\ M_p = +1$	$R_p = -1,\ M_p = \pm 1$	$R_p = +1,\ M_p = -1$

[5] The $|q^2|$ term then remains essential it the exp
tor, while it may be neglected compared to m_Z^2,
propagator.
[6] This scale F is determined by the v.e.v.'s of t
singlets ... responsible for the spontaneous breaking

3.7 Back to Dark Matter candidates

Conclusion

THANK YOU FOR All your advices!!!!

I HOPE YOU ARE PROUD OF THE WORK WE HAVE DONE TOGETHER!

I certainy am...!!!!