Dark Matter (DM) in Grand Unification Theory (GUT) inspired Z' portal scenarios

Mathias Pierre

in collaboration with Yann Mambrini and Giorgio Arcadi
Laboratoire de Physique Théorique d'Orsay

Journées de Recontres des Jeunes Chercheurs
Les Jardins de l'Anjou, 9th of December 2016

1. The Dark Matter problem
   - Introduction
   - Dark matter evidences
   - The WIMP paradigm
   - Dark Matter models
2. From GUT to Z' portal DM
   - Motivations and context
   - Z' from $SO(10)$ GUT
   - Combining Z' and dark matter
3. Distinguish Z' theories and experimental constraints
   - Direct detection
   - Experimental constraints

Introduction

Standard Model issues (non exhaustive...) :

- Complex gauge structure : $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- Hierarchy problem and vacuum stability
- Neutrinos masses
- Why 3 families of quark and leptons?

Gravity related issues :

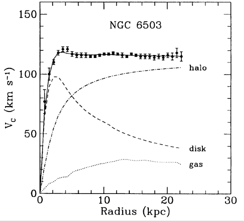
- Quantized gravity? Link with the standard model?
- Dark matter and dark energy : 25% and 70% of the energy budget of the universe

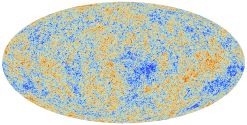
Not easy to solve these issues in a single model... can we find a more general description of the particle content of the Standard Model and include dark matter?

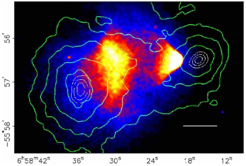
Dark matter : evidences

A missing mass issue :

- Rotation curves : F.Zwicky (1933) et V.Rubin (1970)
- CMB (COBE, WMAP, Planck) : $\Omega_m = 0.049$ et $\Omega_\chi = 0.27$
- The *bullet cluster*







Rotation curve of the galaxy NGC6503 (left), CMB anisotropy map from Planck (center), mass contour from gravitationnal lensing and X-ray emissions from the bullet cluster (right)

S

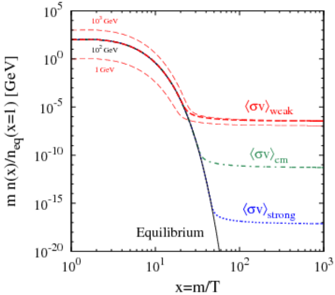
Thermodynamics in an expanding universe

Evolution of the Dark Matter density with Boltzmann equation:

$$\frac{\partial n_\chi}{\partial t} = -3Hn_\chi + (n_{\chi,eq}^2 - n_\chi^2)\langle\sigma v\rangle$$

Decoupling : $H(x_F) = n(x_F)\langle\sigma v\rangle \rightarrow x_F \equiv \frac{m}{T_F} \approx 23$

with F = *Freeze-out* and $H \equiv \dot{a}/a$ (h=H_0/100km.s^{-1}.Mpc^{-1})

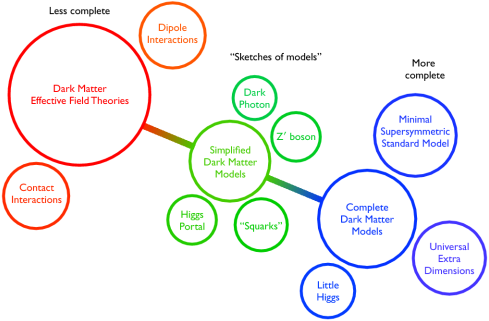


Assuming the DM in thermal equilibrium with the SM at early times

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}$$

The WIMP "miracle"!

Dark Matter models overview



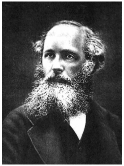
[arXiv:1506.03116]

Important points :

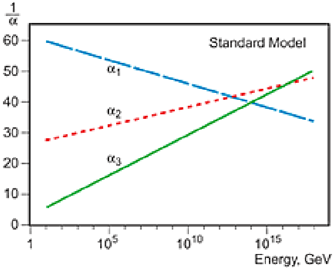
- The WIMP paradigm is not the only explanation! (FIMP, SIMP, ..IMP)
- Where is supersymmetry?
- Symmetry is an essential concept and tool in the Standard Model

Toward Grand Unification Theories?

End of the 19th century : First step toward GUTs : James Clerk Maxwell in "A Dynamical Theory of the Electromagnetic Field" unify electricity and magnetism



In the 60's : Glashow, Weinberg and Salam describe weak interactions and electromagnetism with a single gauge structure $SU(2) \otimes U(1)$



GUT beyond the standard model with Georgi & Glashow

In the 70's First attempt at embedding the SM gauge group in a larger gauge structure with SU(5)

$$\mathbf{24} = \underbrace{(\mathbf{8},\mathbf{1},0)}_{g} \oplus \underbrace{(\mathbf{1},\mathbf{3},0)}_{W^{1,2,3}} \oplus \underbrace{(\mathbf{1},\mathbf{1},0)}_{B} \oplus \underbrace{(\mathbf{3},\mathbf{2},-5/6)}_{X} \oplus \underbrace{(\bar{\mathbf{3}},\mathbf{2},+5/6)}_{X}$$

Nice features :

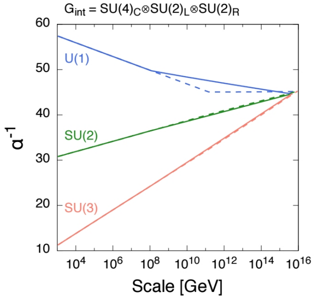
- 1 generation of SM fermions in $\bar{\mathbf{5}} \oplus \mathbf{10}$
- $\sin^2(\theta_w) = 3/8$ predicted at M_{GUT}
- $Q(d) = 1/3Q(e^-)$ natural
- Anomaly free theory

Some remaining issues :

- Proton decay predicted $\rightarrow$ too fast!
- $M_x \approx 10^{12} M_Z \rightarrow$ Hierachy problem!
- No gauge coupling unification and no clue about ν_R

GUT with $SO(10)$: Minkowski and Fritzsch

- One generation of SM fermions + ν_R embedded in the **16** representation
- Unification of gauge couplings at $\sim 10^{15}$GeV
- Intermediate scale at $\sim 10^{10}$GeV $\rightarrow$ natural seesaw?
- Anomaly free
- Respecting proton lifetime constraints
- Remnant $\mathbb{Z}_2$ symmetry $\rightarrow$ DM stability? [Mambrini et al. '15]



$$\Psi_L = \begin{bmatrix} u_r \\ u_g \\ u_b \\ \nu \\ d_r \\ d_g \\ d_b \\ e \\ d_r^c \\ d_g^c \\ d_b^c \\ e^c \\ -u_r^c \\ -u_g^c \\ -u_b^c \\ -\nu^c \end{bmatrix}_L$$

Running of SM gauge couplings in SO(10) GUT [arXiv:1502.06929]

The emergence of a Z'

We consider general GUT inspired scenarios assuming that $SO(10)$ is broken $SO(10) \to G_{int} \to G_{SM} \otimes U'(1)$.

We consider also a larger group E_6 where $E_6 \supset SO(10)$

Grand unification inspired scenarios [Langacker 0801.1345]

- Scenario χ : $SO(10) \to SU(5) \otimes U(1)_\chi$
- Scenario ψ : $E_6 \to SO(10) \otimes U(1)_\psi$
- Scenario η : string inspired $Z'_\eta = \sqrt{3/8} Z'_\chi + \sqrt{5/8} Z'_\psi$
- $B - L$ and LR scenarios

Reference model

- *Sequential Standard Model* (SSM) : couplings Z'-$SM = Z$-SM

Can we include dark matter in those models?

Z' portal : the lagrangian

	χ	ψ	η	LR	B-L	SSM
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}_L^u$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_L^d$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_R^u$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_R^d$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_{L,R}^\chi$	?	?	?	?	?	?

Couplings from the different theories considered $\epsilon^i_{L,R} = \hat{\epsilon}^i_{L,R}/D$

- the couplings between SM particles (f) and Z' are fixed by construction
- the mass of the Z' is not fixed
- To parametrize our ignorance, we suppose an interaction between the DM particles (χ) and Z' of the form :

$$\mathcal{L} = g' \left(\bar{f}\gamma^\mu(V_f - A_f\gamma^5)fZ'_\mu + \bar{\chi}\gamma^\mu(V_\chi - A_\chi\gamma^5)\chi Z'_\mu\right) \qquad \alpha = \frac{A_\chi}{V_\chi}$$

1. The Dark Matter problem
   - Introduction
   - Dark matter evidences
   - The WIMP paradigm
   - Dark Matter models
2. From GUT to Z' portal DM
   - Motivations and context
   - Z' from $SO(10)$ GUT
   - Combining Z' and dark matter
3. Distinguish Z' theories and experimental constraints
   - Direct detection
   - Experimental constraints

Direct detection

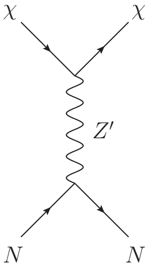
→ Try to measure the energy recoil E_R of a nucleus from an interaction with dark matter : LUX, PICO, XENON100, PANDAX, EDELWEISS, CDMS... and many more in the next years! (XENON1T, LZ,...)

Event rate ($\text{kg}^{-1}\text{j}^{-1}\text{kev}^{-1}$)

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_0}{M_{nuc} m_\chi} \int_{v_{min}}^{v_{esc}} f(v) \frac{d\sigma}{dE_R}(v, E_R) v dv}$$

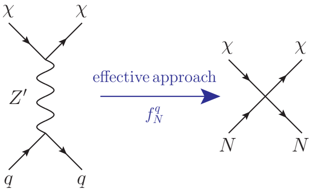
- DM mass m_χ : unknown
- nucleus mass M_{nuc}
- DM density in the solar system ρ_0 and velocity distribution $f(v)$: astrophysical observations
- Differential cross section $d\sigma/dE_R$:

$$\frac{d\sigma}{dE_R} = \frac{M_{nuc}}{2\mu_{nuc}^2 v^2}[\sigma_0^{SI} F_{SI}^2(q) + \sigma_0^{SD} F_{SD}^2(q)]$$



Scattering of a DM particle χ on a nucleus N

Consequences on scattering cross section :



$$\mathcal{L}_{\chi q} = \lambda_{\chi q}\bar{\chi}\chi\bar{q}q \Rightarrow \mathcal{L}_{\chi N} = \lambda_{\chi N}\bar{\chi}\chi\bar{N}N$$

$$\lambda_{\chi N} = \sum_q f_N^q \lambda_{\chi q} \ \textit{with}\ N = n, p$$

f_N^q are the form factors

Spin dependancy from operator decomposition

- At low energy : $\bar{q}q \simeq 2m \rightarrow$ **S**pin **I**ndependant (**SI**)
- At low energy : $\bar{q}\gamma^5 q \simeq 2\vec{p}.\vec{s} \rightarrow$ **S**pin **D**ependant (**SD**)
- Vectorial coupling : $\bar{q}\gamma^\mu q$: **SI**
- Axial coupling : $\bar{q}\gamma^\mu\gamma^5 q$: **SD**

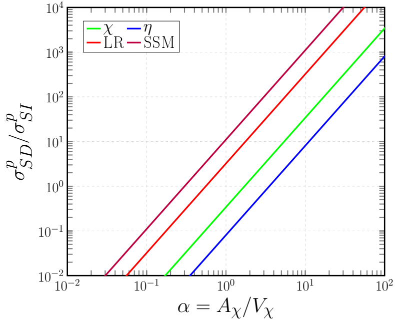
$$\sigma_{SI}^p = \frac{\mu_{\chi p}^2 g'^4 V_\chi^2}{\pi M_{Z'}^4}\alpha_{SI}$$

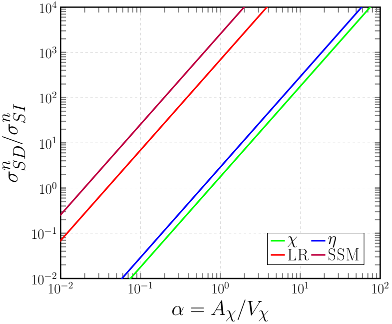
$$\sigma_{SD}^p = \frac{3\mu_{\chi p}^2 g'^4 A_\chi^2}{\pi M_{Z'}^4}\alpha_{SD}$$

Proton and neutron cross sections

$$\frac{\sigma^p_{SD}}{\sigma^p_{SI}} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}}$$

$$\frac{\sigma^n_{SD}}{\sigma^n_{SI}} \propto 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}}$$



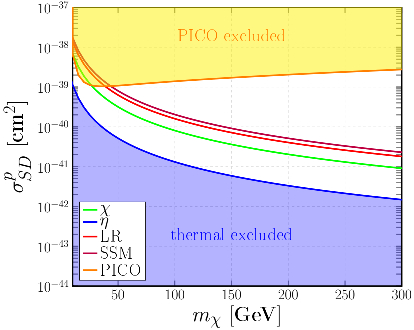


Constraints on σ^p_{SD}

- Assuming a thermally produced DM, we need $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$.
- Velocity of DM in the galaxy $v \sim 10^{-3} c$ $\rightarrow$ velocity expansion of $< \sigma v >$

$$\langle \sigma v \rangle \underset{v \to 0}{\simeq} \frac{m_\chi^2 g'^4}{\pi M_{Z'}^4} \left(V_\chi^2 + A_\chi^2 v^2 \right)$$

We can make a prediction for σ^p_{SD} respecting the strong constraints from the LUX collaboration on σ^p_{SI}, and compare with PICO results [arxiv:1503.00008].



Conclusion

- Main idea of dark matter phenomenology in the GUT context
- Indirect detection and LHC constraints important as well
- We haven't find dark matter yet