FIMP dark matter from a hidden effective supersymmetric theory

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Supersymmetry (SUSY)

- Dark matter candidates can be proposed with SUSY :

$$\boxed{\text{Fermions}} \leftrightarrow \boxed{\text{Bosons}}$$

- Change of spin $\rightarrow$ space-time symmetry
- Define a superspace : enlarge x^μ with $2+2$ Grassman variables θ_α, $\bar{\theta}_{\dot{\alpha}}$

Supersymmetry (SUSY)

- Superfields in superspace $(y_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}})$ with $y_\mu = x_\mu + i\theta\sigma_\mu\bar{\theta}$:
  - Chiral : $\Phi(y,\theta) = \phi(y) + \sqrt{2}\psi(y)\theta + F(y)\theta^2, \qquad \bar{D}_{\dot{\alpha}}\Phi = 0.$
  - Vector : $V(y,\theta,\bar{\theta}) = \theta\sigma^\mu\bar{\theta}v_\mu(y) + i\theta^2\bar{\theta}\bar{\lambda}(y) - i\theta\bar{\theta}^2\lambda(y) + \frac{1}{2}\theta^2\bar{\theta}^2(D(y) - i\partial_\mu v^\mu(y)).$

* ϕ : scalar field
* ψ_α, λ_α : spinors
* v^μ : vector field
* F, D : auxiliary fields

Supersymmetric extensions of the Standard Model (SM)

- Minimal Supersymmetric Standard Model (MSSM) :

	Superfield	$SU(3)$	$SU(2_L)$	$U(1)_Y$	Particles
Quarks/Squarks	$\hat{Q}$	3	2	1/6	$(u_L, d_L),\ (\tilde{u}_L, \tilde{d}_L)$
	$\hat{U}^c$	$\bar{3}$	1	$-2/3$	$\bar{u}_R,\ \tilde{u}_R^*$
	$\hat{D}^c$	$\bar{3}$	1	1/3	$\bar{d}_R,\ \tilde{d}_R^*$
Leptons/Sleptons	$\hat{L}$	1	2	$-1/2$	$(\nu_L, e_L),\ (\tilde{\nu}_L, \tilde{e}_L)$
	$\hat{E}^c$	1	1	1	$\bar{e}_R,\ \tilde{e}_R^*$
Higgs/Higgsinos	$\hat{H}_u$	1	2	1/2	$(H_u, \tilde{h}_u)$
	$\hat{H}_d$	1	2	$-1/2$	$(H_d, \tilde{h}_d)$
Gauge/Gauginos	$\hat{G}^a$	8	1	0	$G^\mu, \tilde{g}$
	$\hat{W}^i$	1	3	0	$W_i^\mu,\ \tilde{w}_i$
	$\hat{B}$	1	1	0	$B^\mu,\ \tilde{b}$

- Next to Minimal Supersymmetric Standard Model (NMSSM) : MSSM + $\hat{N}$ superfield

Goals

Build a new model where dark matter is produced in a hidden supersymmetric sector

Give first constraints and an estimation of the dark matter relic density in this context

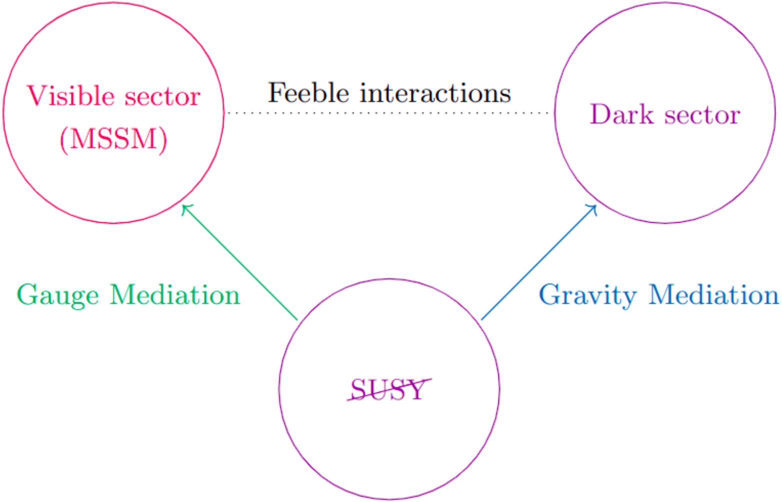
The model

Idea : Construct a model with 3 decoupled sectors

- Visible sector : SM/MSSM/NMSSM
- Dark sector : glueballs and gluinoballs
- SUSY breaking mediation sector
  - $\rightarrow$ SUSY must be broken at low energy (no superpartners observed)
  - $\rightarrow$ Give mass to particles
  - $\rightarrow$ Constraints on those masses given by the LHC ($>$ 10 TeV)

Interactions between the different sectors through mediators

The model


Visible sector
(MSSM)
Feeble interactions
Dark sector
Gauge Mediation
Gravity Mediation
SUSY

I. Dark sector : Super Yang Mills (SYM) and the effective theory of Veneziano-Yankeliowicz

- Super Yang Mills : gluons (v^μ) and gluinos (λ) dynamics, $SU(N)$ gauge group
- Super field strength : $W_\alpha = -\frac{1}{4}\bar{D}\bar{D}\left(e^{-V}D_\alpha e^V\right)$

> ∗ $D_\alpha = \partial_\alpha + i\sigma^\mu_{\alpha\dot{\beta}}\bar{\theta}^{\dot{\beta}}\partial_\mu$

- Lagrangian :

$$\begin{aligned}\mathcal{L}_{\text{SYM}} &= \frac{1}{32\pi}\text{Im}\left(\tau\int \text{d}^2\theta \text{Tr}W^\alpha W_\alpha\right) \\ &= \text{Tr}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - i\lambda\sigma^\mu D_\mu\bar{\lambda} + \frac{1}{2}D^2\right] + \frac{\theta_{\text{SYM}}}{32\pi^2}g^2\text{Tr}F_{\mu\nu}\tilde{F}^{\mu\nu},\end{aligned} \tag{1}$$

> ∗ $\tau = \frac{\theta_{\text{SYM}}}{2\pi} + \frac{4\pi i}{g^2}$
>
> ∗ $D_\mu\bar{\lambda} = \partial_\mu\lambda - ig[v_\mu, \lambda]$
>
> ∗ $F_{\mu\nu} = \partial_\mu v_\nu - \partial_\nu v_\mu - ig[v_\mu, v_\nu]$
>
> ∗ $\tilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

I. Dark sector : Super Yang Mills (SYM) and the effective theory of Veneziano-Yankeliowicz

- Low energy : uncoloured bound states made of gluons and gluinos $\rightarrow$ glueballs $(v^{\mu}v_{\mu})$ and gluinoballs $(\lambda\lambda)$
- Suitable dark matter candidates :

✓Electrically neutral	✓Uncoloured
✓Weakly interacting	✓Stable

Difficulties to describe those bound states from SYM $\rightarrow$ Veneziano-Yankeliowicz effective theory

I. Dark sector : Super Yang Mills (SYM) and the effective theory of Veneziano-Yankeliowicz

- Veneziano et Yankeliowicz idea : introduction of a chiral superfield S such as

$$S = \phi(y) + \sqrt{2}\theta\psi(y) + (\theta\theta)F(y), \tag{2}$$

$$\phi(y) \equiv \frac{\beta(g)}{2g}\lambda^\alpha\lambda_\alpha, \qquad \sqrt{2}\psi_\alpha(y) \equiv -\frac{\beta(g)}{2g}\left(-i\lambda_\alpha D + (\sigma^{\mu\nu}\lambda)_\alpha F_{\mu\nu}\right), \tag{3}$$

$$F(y) \equiv -\frac{\beta(g)}{g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{i}{2}\bar{\lambda}\bar{\sigma}\bar{\nabla}\lambda + \frac{1}{2}D^2 - \frac{i}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{i}{2}\partial_\mu J^{\mu 5}\right). \tag{4}$$

I. Dark sector : Super Yang Mills (SYM) and the effective theory of Veneziano-Yankeliowicz

- Veneziano-Yankeliowicz Lagrangian :

$$\mathcal{L}_{\mathrm{VY}}^{N} = \frac{9N^2}{\alpha}(S^\dagger S)^{\frac{1}{3}}\Big|_D + \left[\frac{2N}{3}\, S\left(\log\left(\frac{S}{\Lambda^3}\right)^N - N\right)\Bigg|_F + \mathrm{h.c.}\right], \quad (5)$$

- $(S^\dagger S)^{\frac{1}{3}}\Big|_D = \int \mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}(S^\dagger S)^{\frac{1}{3}}$ $\quad\quad$ $\left(S\log\frac{S}{\Lambda^3} - S\right)\Big|_F = \int \mathrm{d}^2\theta S \log\frac{S}{\Lambda^3} - S$

✳ Λ : dynamical energy scale

Issue : glueballs appear in the auxiliary field

I. Dark sector : Super Yang Mills (SYM) and the effective theory of Veneziano-Yankeliowicz

- Idea : add a glueball chiral superfield χ :

$$\chi = \phi_\chi + \sqrt{2}\theta\psi_\chi + \theta^2 F_\chi \qquad [\chi] = 0 \qquad \text{[Merlatti 04]} \tag{6}$$

- Generalization of $\mathcal{L}_{\text{VY}}^N$:

$$\mathcal{L}_{\text{gVY}}^N = \frac{9N^2}{\alpha}(S^\dagger S)^{\frac{1}{3}}\left(1+\gamma\chi\chi^\dagger\right)\Big|_D + \frac{2N}{3}S\left(\log\left(\frac{S}{\Lambda^3}\right)^N - N - N\ln\left(-e\frac{\chi}{N}\ln\chi^N\right)\right)\Big|_F + \text{h.c.} \tag{7}$$

✳ γ : parameter

Developing this Lagrangian gives the interactions between the scalar parts of the glueballs (ϕ_χ) and the gluinoballs (ϕ).

II. Interactions

Dark $\leftrightarrow$ ~~SUSY~~ : Gravity mediation

- Messenger : chiral superfield X such as $\langle F_X \rangle \neq 0$
- Interaction with the dark sector :

$$\mathcal{L} \supset \int \mathrm{d}^2\theta \left(\frac{s}{M_P} X W_a^\alpha W_\alpha^a + \text{h.c.} \right) . \tag{8}$$

- Dark gluino mass :

$$m_{\lambda,1} \sim \frac{\langle F_X \rangle}{M_P} . \tag{9}$$

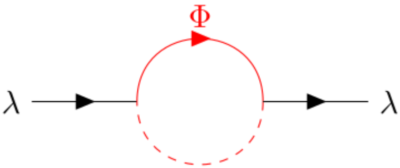
II. Interactions

Visible $\leftrightarrow$ $\not{\text{SUSY}}$: Gauge mediation

- SUSY breaking parameter : spurion X with $\langle X \rangle = M + \theta^2 \langle F_X \rangle$
- Messengers : chiral superfields Φ, $\tilde{\Phi}$
- Interaction :

$$\int \mathrm{d}^2\theta X \Phi \tilde{\Phi}. \tag{10}$$

- Visible sector gluino mass :

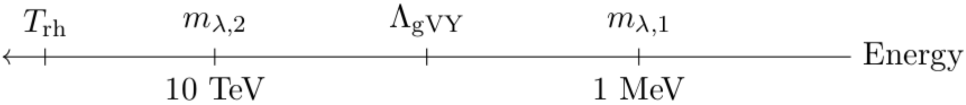


$$m_{\lambda,2} \sim \frac{g^2}{16\pi^2} \frac{\langle F_X \rangle}{M} \tag{11}$$

II. Interactions

Order of magnitudes

- We want :



> ✳ $T_{\rm rh}$: reheating temperature,
>
> ✳ $\Lambda_{\rm gVY}$: confinement scale of gluons/gluinos into glueballs/gluinoballs

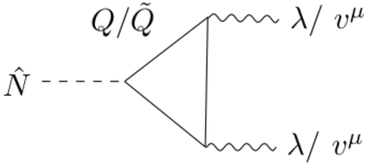
$$\rightarrow \quad \langle F_X \rangle \sim 10^{15}\ \text{GeV}^2, \qquad M \sim 10^{9}\ \text{GeV}. \tag{12}$$

Visible ↔ Dark Interactions

- Consider heavy chiral superfields Q, $\tilde{Q}$ and $\hat{N}$ in the NMSSM :

$$\mathcal{L} \supset \int \mathrm{d}^2\theta \mathrm{d}^2\bar{\theta} \left(\bar{Q} e^{2gV} Q + \bar{\tilde{Q}} e^{2gV} \tilde{Q} \right) + \int \mathrm{d}^2\theta \; \alpha_N \hat{N} Q \tilde{Q}. \tag{13}$$

- Integrate out Q et $\tilde{Q}$ at low energy :



$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SYM}} \left(1 + \frac{1}{M_N^2} \hat{N} \hat{N}^{\dagger} + \ldots \right). \tag{14}$$

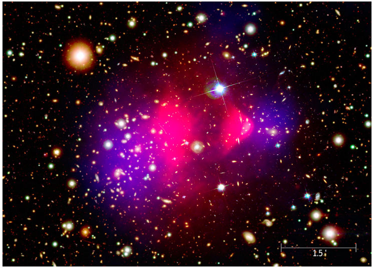
✳ M_N : energy scale

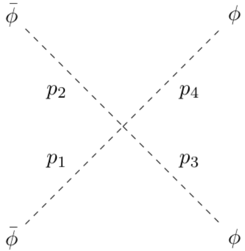
III. Constraints and viability of the model

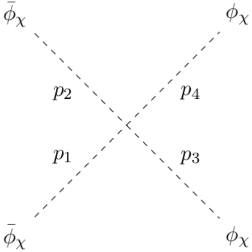
Dark matter scattering

- Bullet cluster : with $v \approx 1000$ km.s^{-1} the velocity of incident particles

$$\frac{\sigma_{\mathrm{DM}}}{m_{\mathrm{DM}}} \leq 2 \ \mathrm{cm}^2.\mathrm{g}^{-1} \qquad \text{[Robertson 16]} \tag{15}$$

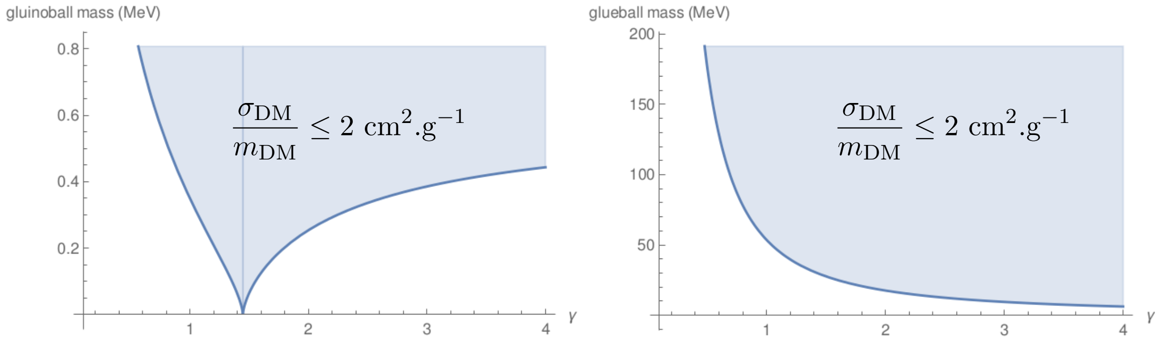






III. Constraints and viability of the model

Dark matter particles mass depending on γ with $\alpha = N = 1$



$\rightarrow$ $m_{\rm DM} \geq 50$ MeV for $\gamma \geq 1$

Dark matter production

- Production in the dark sector before the confinement of gluons/gluinos
- Operator allowing the production of dark gluons/gluinos from $\hat{N}$:

$$\mathcal{L} \supset \frac{1}{32\pi M_N^2} \mathrm{Im}\left(\tau \int \mathrm{d}^2\theta W^\alpha W_\alpha \hat{N}\hat{N}^\dagger\right) \qquad \hat{N} = N + \psi_N\theta + F_N\theta^2. \tag{16}$$

- Thermally decoupled sectors and non-renormalizable operator $\rightarrow$ UV freeze-in mechanism

III. Constraints and viability of the model

Freeze-in mechanism

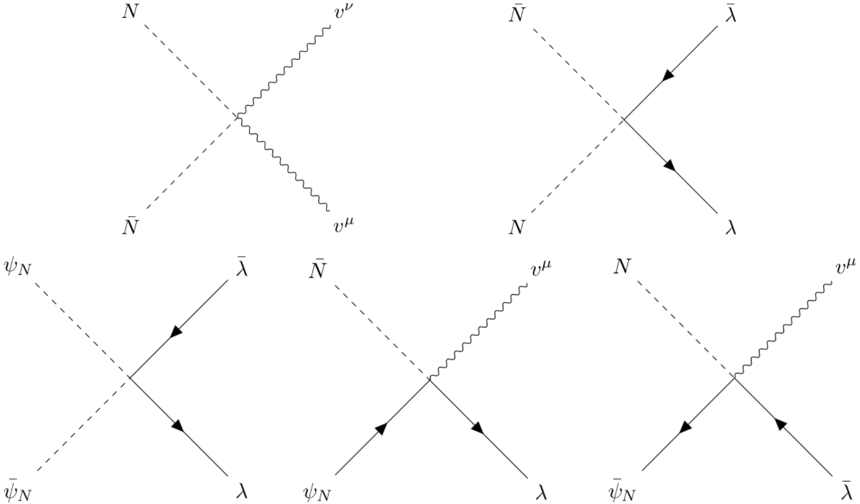
- Hypotheses :

  - Dark and visible sectors are never at thermal equilibrium
  - Inflaton decays in the visible sector $\rightarrow$ dark sector not reheated
  - Confinement energy of gluons/gluinos in glueballs/gluinoballs is negligible
  - Gluon n_v and gluinos n_λ number densities are initially negligible

- Interval for the value of DM relic density $\Omega_{\mathrm{DM}} = \rho_{\mathrm{DM}}/\rho_c$ with 99% confidence and 10% theoretical uncertainty :

$$0.068 < \Omega_{\mathrm{DM}} h^2 < 0.155. \quad [\textbf{WMAP } 1001.4538] \tag{17}$$

Production of dark gluons/gluinos



III. Constraints and viability of the model

- Boltzmann equations (simplified) for $n_{v,\lambda} = n_v + n_\lambda$:

$$\frac{\mathrm{d}n_{v,\lambda}}{\mathrm{d}t} + 3Hn_{v,\lambda} \simeq \frac{T}{512\pi^5}\int_0^\infty \mathrm{d}s|\mathcal{M}|^2\sqrt{s}K_1(\sqrt{s}/T). \tag{18}$$

- With :

$$|\mathcal{M}|^2 = 2\Big(|\mathcal{M}_{N\bar{N}\to vv}|^2 + \left|\mathcal{M}_{\bar{N}\psi_N\to v\lambda}\right|^2 + \left|\mathcal{M}_{N\bar{\psi}_N\to v\bar{\lambda}}\right|^2 + |\mathcal{M}_{N\bar{N}\to\lambda\bar{\lambda}}|^2 + \left|\mathcal{M}_{\psi_N\bar{\psi}_N\to\lambda\bar{\lambda}}\right|^2\Big) \tag{19}$$

✳ K_1 : Bessel function of 2nd kind

III. Constraints and viability of the model

- Compute glueballs/gluinoballs yield $Y_{S,\chi} = n_{S,\chi}/s \simeq n_{v,\lambda}/s$:

$$\frac{\mathrm{d}Y_{S,\chi}}{\mathrm{d}T} = -\frac{1}{sH}\frac{105T^7}{8\pi^5 M_N^4}. \tag{20}$$

- Where s and H are given by :

$$s = \frac{2\pi^2 g_*^s T^3}{45} \quad \text{and} \quad H = \frac{1.66\sqrt{g_*^\rho}T^2}{M_P}, \tag{21}$$

$$\rightarrow \boxed{\mathrm{Y}_{S,\chi} \simeq \frac{1575 M_P T_{\mathrm{rh}}^3}{16\pi^7 1.66 g_*^s \sqrt{g_*^\rho} M_N^4},} \tag{22}$$

$\ast$ g_*^s/g_*^ρ : number of effective degrees of freedom

III. Constraints and viability of the model

- glueballs/gluinoballs relic density Ω_{DM} :

$$\Omega_{\text{DM}} = \frac{m_{S,\chi} Y_{S,\chi} s_0}{\rho_c}, \quad (23)$$

- $\ast$ $s_0 = 2970 \text{ cm}^{-3}$: entropic density at $T_0 = 2.75$ K
- $\ast$ $\rho_c = 1.1 \times 10^{-5} h^2$ GeV.cm$^-3$

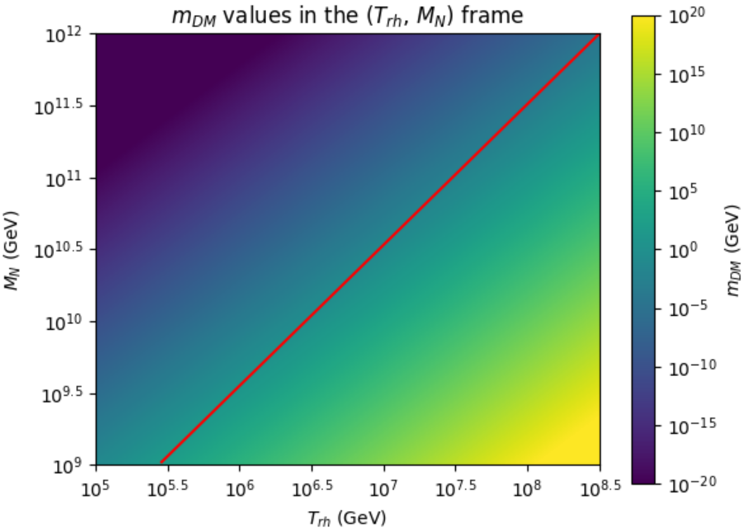
[Elahi 15]

$$\rightarrow \quad \boxed{\Omega_{\text{DM}} h^2 \simeq 0.125 \times 10^{23} \frac{T_{\text{rh}}^3 m_{S,\chi}}{M_N^4}} \quad (24)$$

- For $m_{S,\chi} \simeq 10^{-2}$ GeV and $\Omega_{\text{DM}} h^2 \simeq 0.1$, we can have M_N depending on T_{rh} :

T_{rh} (GeV)	10^5	10^{10}	10^{16}
M_N (GeV)	10^9	10^{13}	10^{17}

III. Constraints and viability of the model



Conclusion

- Proposition of a new dark matter model :
  - Dark matter : gluons and gluinos bound states in a hidden supersymmetric sector called glueballs and gluinoballs
  - Constraints on the DM mass using Bullet Cluster data
  - DM production through $\hat{N}$ superfield of the NMSSM
  - Decoupled sectors $\rightarrow$ Freeze-in
- Ideas to further develop the model :
  - Phase transition gluons/gluinos $\rightarrow$ glueballs/gluinoballs
  - Elaborating on SUSY breaking mechanism
  - Origins of glueball superfield χ ?
  - Signatures visible at the LHC ? Other cosmological implications ?
  - Possibility to construct the same kind of model using a different SUSY theory