New results on Sommerfeld enhancement and $\Omega_\chi h^2$ of χ^0 dark matter in the general MSSM

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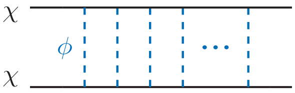
M.Beneke, CH, Pedro Ruiz Femenia: arXiv:1210.7928, 1303.0200, and work in preparation

Introduction

Sommerfeld enhancements ...

- Intrinsic in non-relativistic pair-annihilation or production



e.g. threshold production of heavy particles at colliders

- Coulomb enhancement: $\sigma_{l=0} v_{\text{rel}} \; = \; S(v) \; \sigma^{\text{tree}}_{l=0} \,, \quad S(v) \; = \; \frac{\pi\alpha}{v} \, \frac{1}{1-e^{-\pi\alpha/v}}$

[Sommerfeld '31]

... in DM pair-annihilations

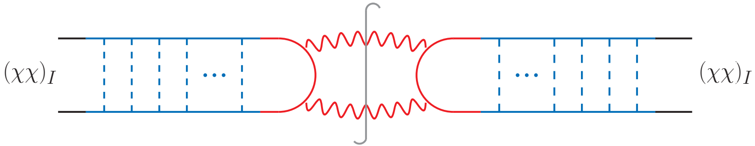
Iengo '09; Cassel '09; Slatyer '10

1. Indirect detection: Explanation of cosmic ray anomalies?
   Constraints on DM candidates: Cohen et al '13; Fan&Reece '13; Hryczuk et al '14
2. Relic density calculation $\left(\Omega_{\text{DM}} h^2 \; = \; 0.1187 \pm 0.0017 \; (68\% CL)\right.$ [PLANCK '13]$\left.\right)$

- DM candidates:
  χ^0_1 LSP in the MSSM: Hisano et al '04,'06; Iengo et al '10,'11; ...
  Minimal DM: Cirelli et al '07,'08,'09
  DM in hidden sector: Arkani-Hamed et al '09; Feng et al '10; Hannestad et al '11; ...

Effective field theory approach: the NRMSSM

Consider nearly mass-degenerate states $(\chi\chi)_I$, $_{I=1,\ldots N}$



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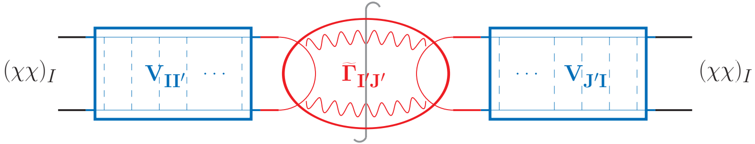

Effective field theory approach: the NRMSSM

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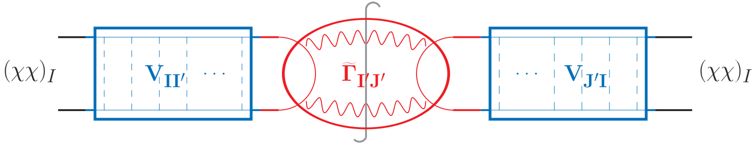


Describe process within non-relativistic effective theory:

$$\sigma_{(\chi\chi)_I\to\text{light}}\; v_{\text{rel}} \;=\; \left(\frac{1}{4}\sum_{s_I}\right) 2\,\Im\, \langle(\chi\chi)_I|\; \delta\mathcal{L}_{\text{ann}}(x)\; |(\chi\chi)_I\rangle$$

Analogous to Bodwin, Braaten, Lepage '95

- Short distance part: accounted for by local four-fermion operators $\mathcal{O}$

$$\delta\mathcal{L}_{\text{ann}}(x) \;=\; \sum_{I,J} \widehat{f}({}^{2s+1}L_{\mathcal{J}})_{IJ}\; \mathcal{O}_{(\chi\chi)_I\to(\chi\chi)_J}({}^{2s+1}L_{\mathcal{J}};x)$$

- Long-range effects: encoded in $(\chi\chi)_I$'s scattering wave-function $\vec{\psi}^{(I)}$

$$\left(-\frac{\vec{\partial}^2}{m_\chi}\,\delta_{JJ'} \;+\; V_{JJ'}(r)\right)\psi^{(I)}_{J'}(\vec{r}) \;=\; m_\chi v^2\;\psi^{(I)}_J(\vec{r})$$

Beyond leading order approximations in the MSSM

Sommerfeld enhancement of the $(\chi\chi)_I,\ _{I=1,\dots,N}$ pair's annihilation rate

$$S^{(I)} = \frac{\vec{\psi}^{(I)\,*}_{(\vec{r}=0)} \cdot \widetilde{\Gamma} \cdot \vec{\psi}^{(I)}_{(\vec{r}=0)}}{\vec{\psi}^{(I)\,*}_{0(\vec{r}=0)} \cdot \widetilde{\Gamma} \cdot \vec{\psi}^{(I)}_{0(\vec{r}=0)}}$$

- Includes off-diagonal scattering and annihilation
- Individual $S^{(I)}$ for each ${}^{2s+1}L_{\mathcal{J}}$-wave

[For generic multi $(\chi\chi)_I$ state model: Slatyer '10]

Extension of previous work:

1. χ_1^0 in the generic MSSM *(beyond pure wino- or higgsino scenarios)*
2. Many nearly mass degenerate $(\chi\chi)_I$ states

   (Including expansion in mass-differences) [At 1-loop level: Drees, Gu '12]
3. Including P- and $\mathcal{O}(v^2)$ S-wave *(beyond leading order S-wave)*
4. Analytic expressions for all (off-diagonal) partial-wave V_{IJ} and Γ_{IJ}
5. Deal with closed channels for larger mass-splittings

Enhanced cross sections and relic density

Sommerfeld enhanced $\chi^0/\chi^\pm$ co-annihilation cross sections

- Active $(\chi\chi)_I$ channels: $\delta M_I \;\leq\; 0.2\, m_{\chi_1^0}$

$$\sigma_{(\chi\chi)_I} v_{\text{rel}} \;=\; \sum_{{}^1S_0,\,{}^3S_1} \left[S_I\, \Gamma_{II}\right] \;+\; \vec{p}_i^{\,2} \left(\sum_{{}^1P_1,\,{}^3P_J} \left[S_I\, \Gamma_{II}\right] + \sum_{{}^1S_0,\,{}^3S_1} \left[S_I\, \Gamma_{II}^{(p^2)}\right] \right)$$

- $S_I \;=\; S_I(v)$ in non-trivial way!

Relic density from solving the Boltzmann equation

- Thermal weighting of all $\sigma_{(\chi\chi)_I} v_{\text{rel}}$: $\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$

$$\frac{dY}{dx} \;=\; \frac{\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle}{H\, x} \left(1 - \frac{x}{3\, g_{*s}} \frac{d\, g_{*s}}{d\, x}\right) s \left(Y^2 - \left(Y^{eq}\right)^2\right)$$

[Gondolo, Gelmini '91; Griest, Seckel '91]

Wino-like χ_1^0

- Active states: $\chi_1^0, \chi_1^\pm$ (approx. $SU(2)_L$ triplet)
- mass-splitting: $\delta m_{\text{rad}} = m_{\chi_1^+} - m_{\chi_1^0} \approx 0.160$ GeV
- (co-)annihilation sectors:

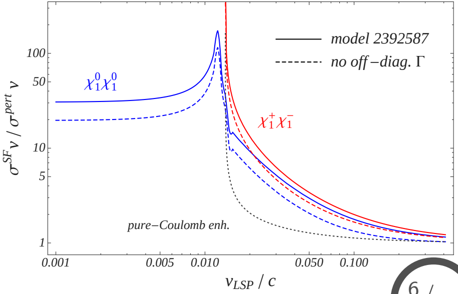
neutral	$\chi_1^0\,\chi_1^0,\ \chi_1^+\,\chi_1^-$
single charged	$\chi_1^0\,\chi_1^+\ (\chi_1^0\,\chi_1^-)$
double charged	$\chi_1^+\,\chi_1^+\ (\chi_1^-\,\chi_1^-)$

→ **coupled system:** $V_{2\times 2},\ \Gamma_{2\times 2}$

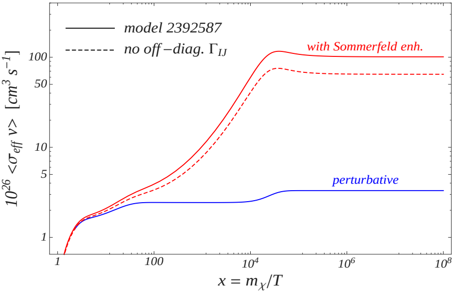
pMSSM benchmark model:

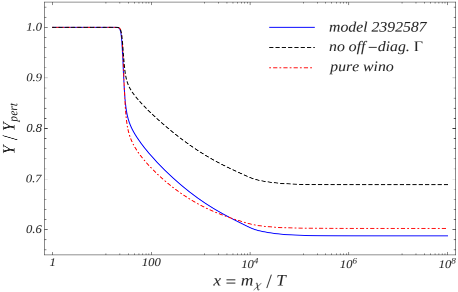
2392587 Cahill-Rowley et al. '13

- $m_{\chi_1^0} = 1650$ GeV
- $|Z_{N\,21}|^2 = 0.999$
- $\delta m_{\chi_1^+} = 0.155$ GeV



Wino-like χ_1^0: Sommerfeld enhancements and $\Omega_\chi h^2$





$\langle \sigma_{\text{eff}}\, v_{\text{rel}} \rangle$:

- $x \simeq 20$:
  Freeze-out if $\langle \sigma_{\text{eff}}\, v_{\text{rel}} \rangle$ calculated pert.
  $\rightarrow$ delayed when considering $\sigma^{\text{SF}} v_{\text{rel}}$

Yield $Y = \sum_i n_{\chi_i}/s$ and $\Omega_\chi h^2$:

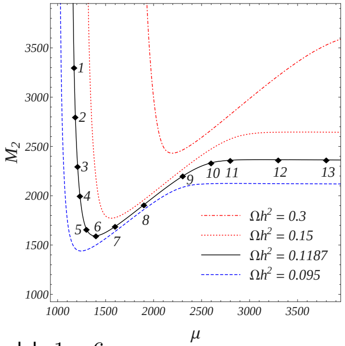
- $\Omega_\chi^{\text{pert}} h^2 \;=\; 0.109$
- $\Omega_\chi^{\text{SF}} h^2 \;=\; 0.064$ $\rightarrow$ **40% reduction**
- $\sim 15\%$ error on $\Omega^{\text{SF}} h^2$ if no off-diag. Γ
- Pure wino: $\Omega_\chi^{\text{pert}} h^2 \;=\; 0.055$
  $\Omega_\chi^{\text{SF}} h^2 \;=\; 0.033$

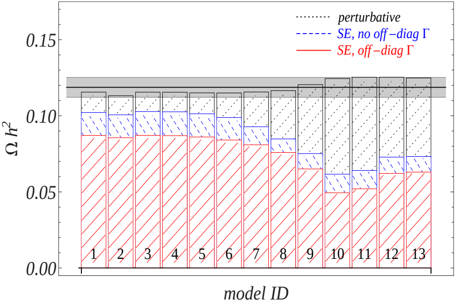
Higgsino-to-wino trajectory

- 13 models, $\Omega^{\text{DarkSUSY}} h^2 = 0.1187$

  [PLANCK+WMAP central value]

- Trajectory in $\mu - M_2$ plane:
  - Model $1-6$: higgsino-like χ_1^0
  - Model $7-9$: mixed higgsino-wino χ_1^0
  - Model $10-13$: wino-like χ_1^0





- Models $1-6$:
  - $\Omega^{\text{SF}}/\Omega^{\text{pert}} \sim 0.75$
  - $\sim 17\%$ error on $\Omega^{\text{SF}} h^2$ if no off-diag. Γ
- Models $7, 8, 9$:
  - $\Omega^{\text{SF}}/\Omega^{\text{pert}} \sim (0.70,\ 0.65,\ 0.54)$
  - $\sim 15\%$ error if no off-diag. Γ
- Models $10-13$:
  - $\Omega^{\text{SF}}/\Omega^{\text{pert}} \sim 0.40 - 0.50$
  - $\sim 25\%$ error if no off-diag. Γ

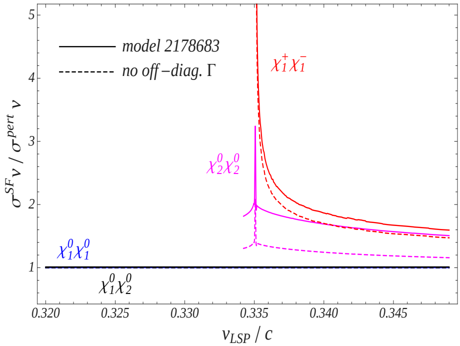
Bino χ_1^0 with enhancements in $\chi\chi$ co-annihilations

- Bino-like χ_1^0 is $SU(2)_L$ singlet state
  $\rightarrow$ no Sommerfeld enhancement in $\chi_1^0\chi_1^0$ annihilations
- BUT enhancements can potentially arise in co-annihilations

pMSSM benchmark model:

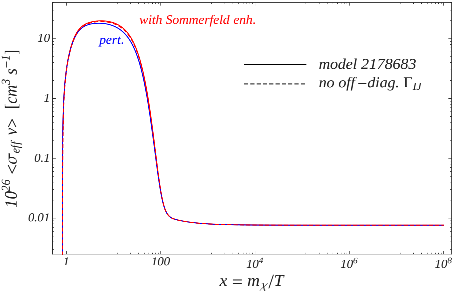
2178683 Cahill-Rowley et al. '13

- $m_{\chi_1^0} = 489$ GeV
- Wino-like $\chi_2^0, \chi_1^\pm$ at 516 GeV



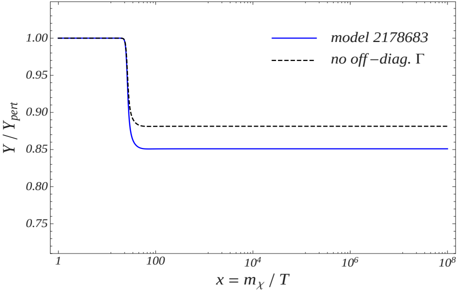
[Absolute χ_1^0 rates are $\mathcal{O}(10^{-3})$ smaller than those of the wino-like states]

Bino-like χ_1^0: enhanced co-annihilations and $\Omega_\chi h^2$



$\langle \sigma_{\text{eff}}\, v_{\text{rel}} \rangle$:

- $x \simeq 50$: $\chi_2^0, \chi_1^\pm$ decoupling
- Sommerfeld enhancement: $15-37\%$ correction for $x \sim 20-100$



Yield $Y = \sum_i n_{\chi_i}/s$ and $\Omega_\chi h^2$:

- $\Omega_\chi^{\text{pert}} h^2 \ = \ 0.115$
- $\Omega_\chi^{\text{SF}} h^2 \ = \ 0.099 \rightarrow 14\%$ **reduction**
- 4% error on $\Omega^{\text{SF}} h^2$ if no off-diag. Γ

Conclusions

- Sommerfeld enhancement is essential in χ_1^0 DM $\Omega_\chi h^2$ calculation
- Provide method for $\Omega_\chi h^2$ calculation including $\sigma^{\mathsf{SF}} v$:
  - Applicable in the general MSSM
  - Dealing with many nearly mass-degenerate $(\chi\chi)_I$ states
  - Including all off-diagonal potential and annihilation rates

- Largest effect for wino-like χ_1^0 : $\sim 40 - 60\%$ reduction of $\Omega_\chi h^2$
- Milder effect for higgsino-like χ_1^0 models: $\sim 20 - 25\%$ reduction
- First rigorous study of interpolating mixed wino-higgsino χ_1^0 models
- Effect on $\Omega_\chi h^2$ for bino-like χ_1^0, if co-annihilations are enhanced

- In preparation: scan of the general MSSM parameter space to investigate the effect of Sommerfeld enhancements on $\Omega_\chi h^2$