Inelastic Dark Matter in SUSY Inverse Seesaw

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Contents

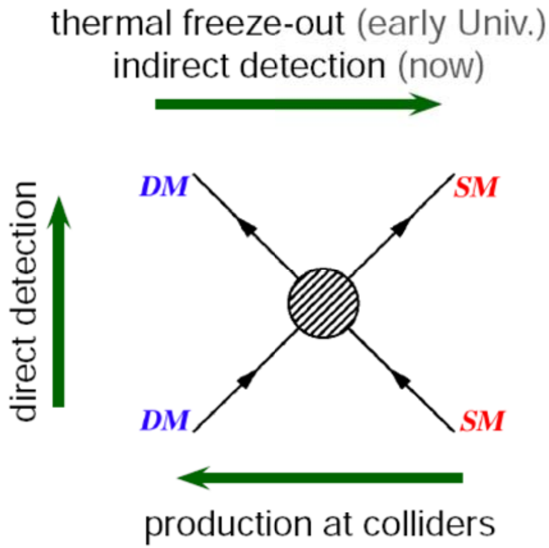
Introduction

- Known:
  - Existence: cosmological observations
    - Galactic rotation curvers
    - Gravitational lensing
    - ...
  - Amount: $\Omega h^2 = 0.11$
- Unknown:
  - Mass
  - Spieces
  - Interaction properties

It's really hiding from us.

Our efforts: Route 1

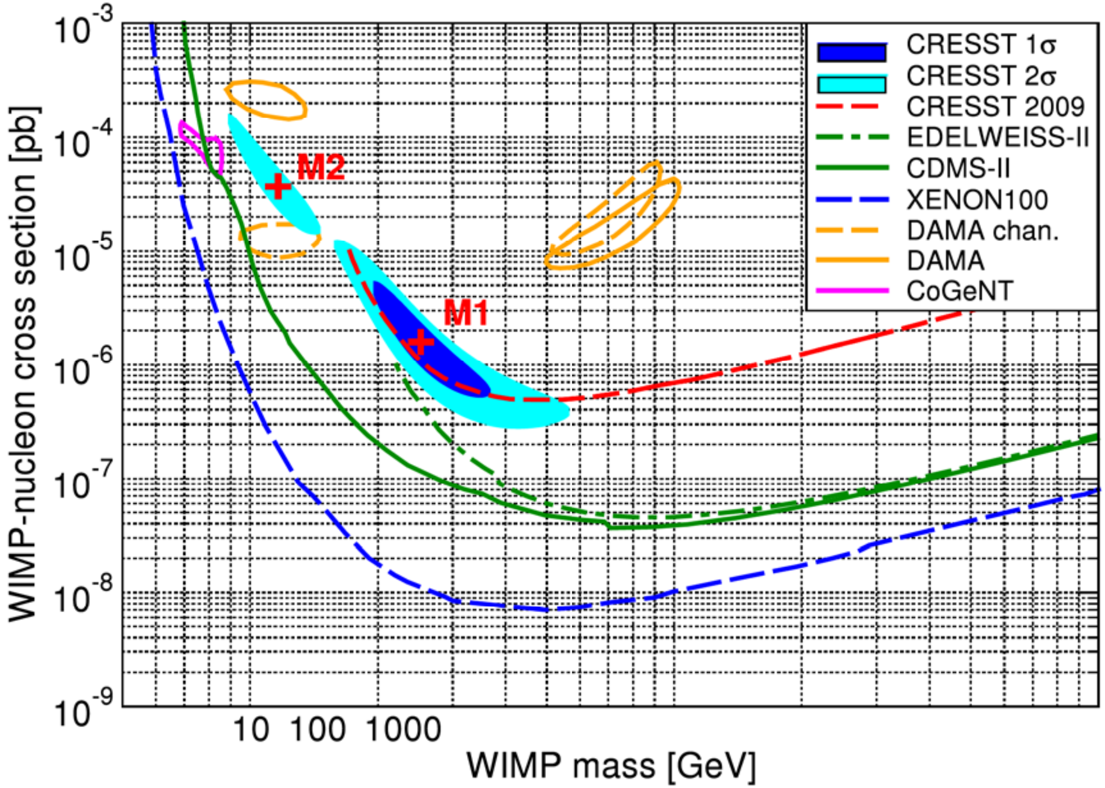
Experimentalists: multiple directions



- Collider: LHC
- Indirect detection: PAMELA, ATIC, WMAP...
- Direct detection: DAMA, CRESST, XENON...

Results from direct detection

Somehow controversial



Our efforts: Route 2

Theorists:

- Darkon: SM+ a real gauge singlet
- Extra dimension: the lightest KK particle
- $\cdots$
- Minimal Supersymmetric Standard Model:

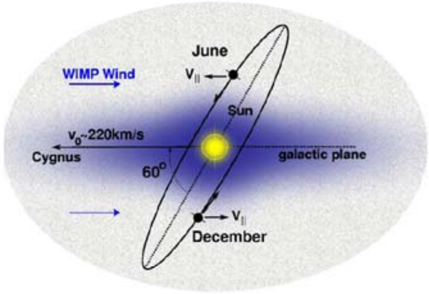
neutralino, gravitino, etc

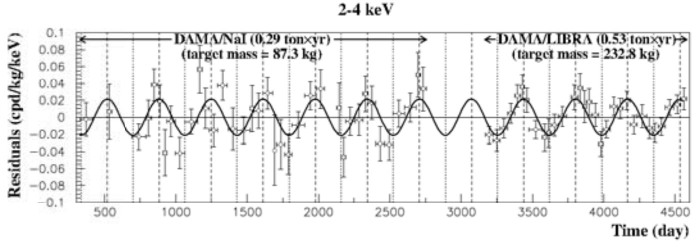
Go beyond the MSSM:

- If dark matter mass is in the few GeV range, MSSM may need to be extended, due to its inability to reproduce the observed DM relic density.
- The same extension may explain small neutrino masses.

One more ingredient

We want to believe DAMA.





Fit count rate with $S_0 + A\cos\omega(t - t_0)$

	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2–4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2–5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2–6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA				
(2–4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2–5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2–6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI+ DAMA/LIBRA				
(2–4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2–5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2–6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ

Excluded by a factor of 30

Solution: Inelastic dark matter

Inelastic Dark Matter

Tucker-Smith, Weiner   hep-ph/0101138, hep-ph/0402065

- Besides χ_1, add an additional particle χ_2 with a slightly heavier mass $M + \delta$.
- To excite the dark matter particle χ_1 to χ_2,

$$\chi_1 + N \to \chi_2 + N$$

lower velocity is kinematically unaccessible,

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

and the differential rate is

$$\frac{dR}{dE_R} \sim \int_{v_{min}}^{v_{esc}} d^3v \frac{d\sigma}{dE_R} e^{-\frac{v^2}{v_0^2}}$$

In order to realize this mechanism, take a detour to neutrino physics.

Inverse Seesaw

Matter content: adds two SM singlet fermions N and S
Mass matrix of the (ν, N, S) fields:

$$\mathcal{M}_{\rm inv} = \begin{pmatrix} 0 & M_D^T & 0 \\ M_D & 0 & M_R \\ 0 & M_R^T & \mu_S/2 \end{pmatrix}$$

This leads to the neutrino mass formula

$$M_\nu = M_D M_R^{-1} \mu_S \left(M_D M_R^{-1}\right)^T$$

$$M_R \sim \text{TeV} \rightarrow \mu_S \sim \text{keV}$$

Dark matter: the lightest supersymmetric particle

- Neutralino?
- Stau?
- A linear combination of the $\{\tilde{\nu}, \tilde{N}, \tilde{S}\}$?

With μ_S, a mass splitting δ appears, which could be the right size.

The Model

The mass matrix arises in the MSSM from the following superpotential:

$$\mathcal{W}_1 = \mathcal{W}_{\text{MSSM}} + Y_\nu N H_u L + M_R N S + \frac{1}{2} S \mu_S S$$

$L H_u S$ and NN are both lepton number violating $\rightarrow$ sizes$\sim \mu_S$

structure of inverse seesaw not spoiled

Or extend the gauge group to $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\mathcal{W}_2 = \mathcal{W}_{\text{MSSM}} + Y_L L \Phi L^c + Y_S S \phi_R L^c + \frac{1}{2} S \mu_S S$$

- Φ is a bi-doublet with $B - L$ charge zero
- ϕ_R is $SU(2)_R$ doublet with a $B - L$ charge 1.
- $L H_u S$ and NN are forbidden by $SU(2)_R$.

SUSY-LR

Multiplet	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Q	3	2	1	$+1/3$
Q^c	3	1	2	$-1/3$
L	1	2	1	-1
L^c	1	1	2	$+1$
χ_p	1	2	1	$+1$
χ^c_q	1	1	2	-1
$\overline{\chi}_p$	1	2	1	-1
$\overline{\chi^c}_q$	1	1	2	$+1$
Φ_a	1	2	2	0
S^α	1	1	1	0
δ	3	1	1	$+4/3$
$\overline{\delta}$	$\bar{3}$	1	1	$-4/3$

- Quarks and leptons: 16_F
- Φ: 10_H
- χs: 16_H
- δs: 45_H, ensure gauge coupling unification

Rotation

- Neglect the keV scale lepton number violation effect

$$\tilde{\chi}_1 \;=\; \sum_{i=1}^{3}(U^\dagger)_{1\nu_i}\tilde{\nu}_i + (U^\dagger)_{1N_i}\tilde{N}_i^\dagger + (U^\dagger)_{1S_i}\tilde{S}_i$$

- Turn on the lepton number violation, the splitting terms

$$\sum_{m,n=1}^{9} A_{mn}\tilde{\chi}_m\tilde{\chi}_n$$

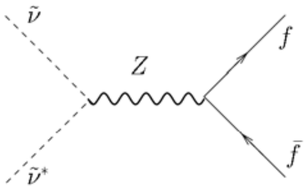
The mass splitting of the LSP can be written as

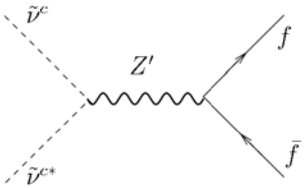
$$\delta M_\chi = 4|A_{11}|/M_\chi$$

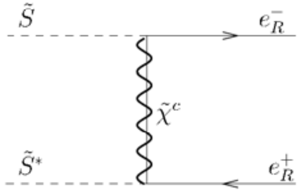
where generically $A_{11} \sim \mu_S M_{SUSY}$

Relic Abundance

Dark matter candidate: a linear combination of the $(\tilde{\nu}, \tilde{N}^\dagger, \tilde{S})$ fields







- The second and third channels are the new contribution in SUSYLR.
- The annihilation cross section for the Z' channel is suppressed compared to the Z-channel by a factor $(c_1/c_0)^2(M_Z/M_{Z'})^4$, where $c_{(0,1)} = \sum_{i=1}^{3} |U_{(\nu,N)i1}|^2$.
- Numerically, we find that the DM relic density constraint restricts c_0 to be less than 16% which also agrees with the invisible Z-decay width constraint.
- For dark matter mass up to 100 GeV, we found enough parameter space with right relic abundance.

Direct Detection

DM is a real scalar field accompanied by its slightly heavier partner field

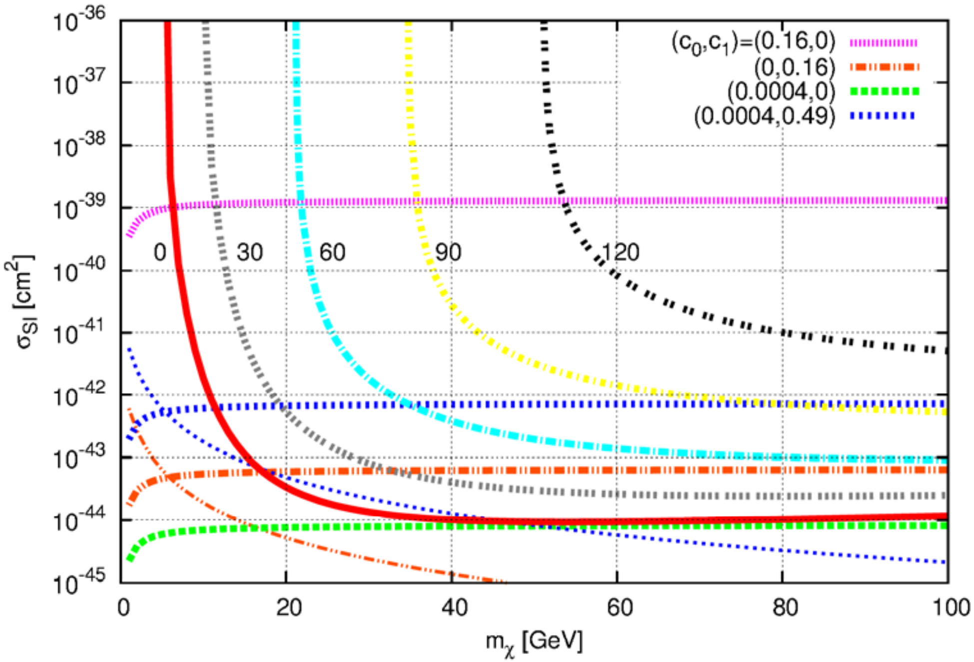
Both elastic and inelastic

- Direct detection channel mediated by SM-like Higgs, $\lambda h_0 \tilde{\chi}_1^\dagger \tilde{\chi}_1$
  With lepton number violation, $\frac{\lambda}{2} h_0 (\chi_1^2 + \chi_2^2)$ is elastic
- Direct detection channel mediated by gauge bosons,

$$\frac{i}{2\cos\theta_W}\left(c_0 g_{2L} Z^\mu + c_1 \frac{\cos^2\theta_W}{\sqrt{\cos 2\theta_W}} g_{2R} Z'^\mu\right) \times (\tilde{\chi}_1 \partial_\mu \tilde{\chi}_1^\dagger - \tilde{\chi}_1^\dagger \partial_\mu \tilde{\chi}_1)$$

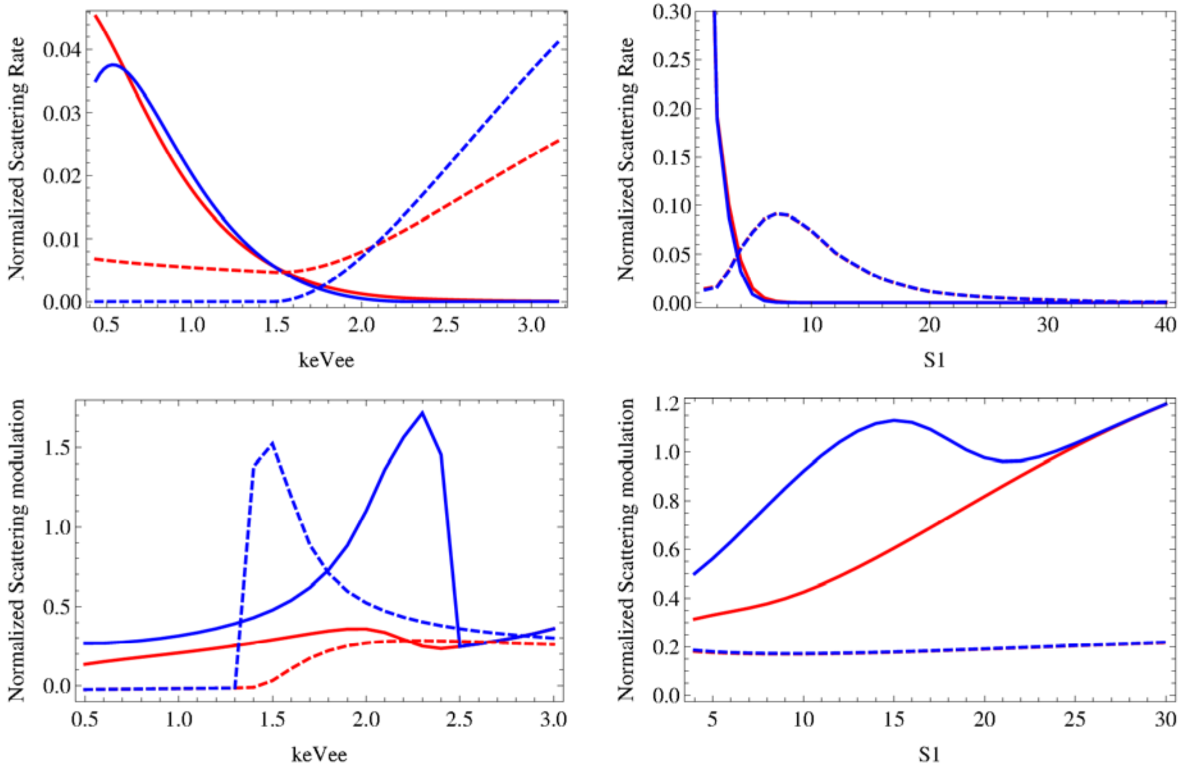
  With lepton number violation, $iZ^\mu(\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1)$, thus is inelastic
- For large fractions of the left snuetrino component($c_0 > 10^{-3}$), inelastic
  - Z'-exchange channel suppressed by its large mass
  - The elastic channel mediated by Higgs is suppressed by light quark masses.
- For small fractions of the left neutrino component($c_0 < 10^{-4}$ and large c_1) , Z' channel could be comparable

Direct detection cross section



- small c_0 and large c_1, blue and orange: elastic dominated(thin) for low mass DM and inelastic Z' exchange (thick) for higher DM mass
- small or zero c_1, pink and green curves, always dominated by inelastic channel mediated by Z

Annual modulation



Red and blue: $(c_0, c_1) = (0.001, 0.1)$ and $(0.1, 0.001)$
Solid and dashed: $(M_\chi, \delta) = (10GeV, 20keV)$ and $(50GeV, 60keV)$

Conclusion

- We have shown that the supersymmetric inverse seesaw model for neutrinos naturally leads to an inelastic scalar dark matter.
- The differential scattering rate and annual modulation predicted in these models might be tested in future direct detection experiments.
- At colliders, the signatures are four(two) jets + like(opposite)-sign dilepton signals with missing energy if the gluino is lighter(heavier) than the squarks.
- The collider phenomenology will be explored in detail.