Inelastic Dark Matter and Small Neutrino Mass

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H. An, BD, Y. Cai and R. N. Mohapatra, *Phys. Rev. Lett.* **108**, 081806 (2012) [`1110.1366`]

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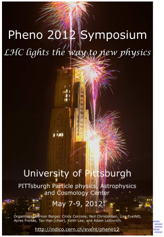
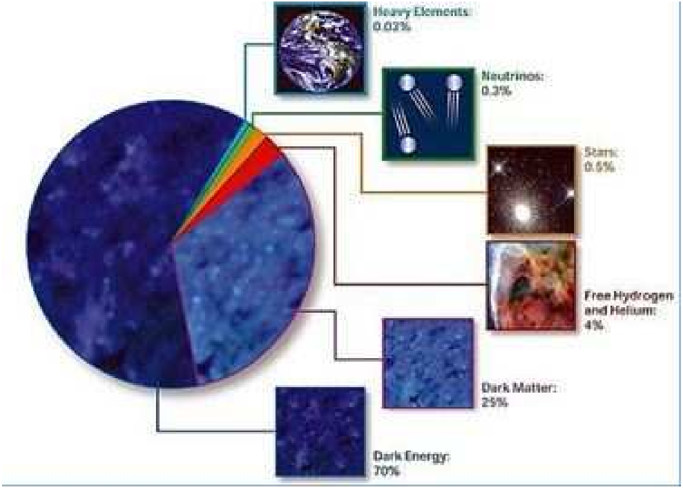


Outline

- Introduction
- Inverse Seesaw for Neutrino Mass
- Inelastic Dark Matter
- Collider Phenomenology
- Conclusion

Our Universe is mostly Dark!



Dark Matter in MSSM

- Neutral LSP is a *natural* DM candidate in SUSY models with R-parity.
- Two CDM candidates in MSSM:
  - Left Sneutrino $\widetilde{\nu}_L$: Ruled out (invisible Z-width + relic density + direct detection constraints).
  - Lightest Neutralino $\widetilde{\chi}_1^0$ ($\widetilde{B}^0$, $\widetilde{W}_{3L}^0$, $\widetilde{h}_u^0$, $\widetilde{h}_d^0$): Only DM candidate.

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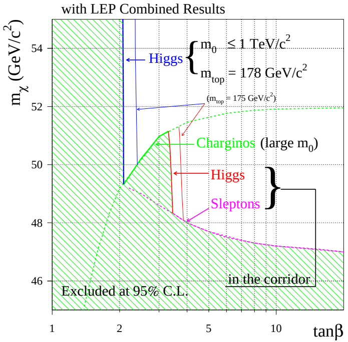
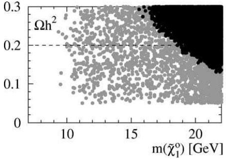
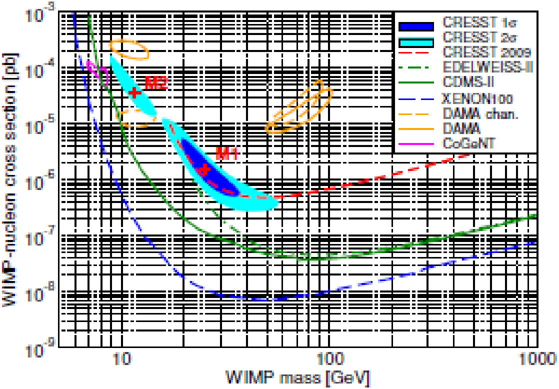


- LEP lower limit: $M_{\widetilde{\chi}_1^0} > 47$ GeV (with gaugino unification). [PDG '10]
- Slightly tighter (> 50 GeV) for cMSSM.
- More generic bound from cosmology: > 18 GeV. [Hooper, Plehn '02]



Light Dark Matter?

[Angloher *et al.* '11]



If confirmed, might need to look beyond MSSM.

Neutrino Mass and Seesaw

- Another reason to go beyond MSSM.
- A simple way is to introduce SM singlets and break $(B-L)$-symmetry at tree-level $\Longrightarrow$ Seesaw mechanism
- Observed baryon asymmetry can be explained by leptogenesis.
- In SUSY seesaw: Superpartner of the singlet neutrino(s) with a small admixture of left sneutrino can be a DM candidate.

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- Another reason to go beyond MSSM.
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- Observed baryon asymmetry can be explained by leptogenesis.
- In SUSY seesaw: Superpartner of the singlet neutrino(s) with a small admixture of left sneutrino can be a DM candidate.
- Could be directly probed at colliders if the seesaw scale is $\mathcal{O}$(TeV).
- Is a TeV-scale SUSY seesaw consistent with neutrino mass, leptogenesis, (light) DM and coupling unification?

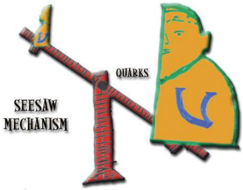
Canonical Seesaw

Add one set of SM singlet Majorana neutrinos. [Minkowski '77; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanović '80]

$$W \supset y_{\nu_{ij}} L_i H_u N_j^c + M_{N_i} N_i^c N_i^c ,$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

$$\boxed{m_\nu^{\text{light}} = -M_D M_N^{-1} M_D^T}$$



Sub-eV m_ν for heavy M_N.

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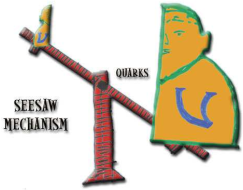

Sub-eV m_ν for heavy M_N.

- TeV scale M_N possible for tiny $M_D \lesssim m_e$ (unless fine-tuned) $\Longrightarrow$ Hard to test MSSM+seesaw at colliders.
- $SO(10)$-GUT embedding $\Longrightarrow$ relates M_D to charged fermion sector.
- Predicts the seesaw scale $M_N \sim 10^{10-14}$ GeV.

Inverse Seesaw

Add two sets of SM singlets: One Dirac (N) and one Majorana (S) fermion. [Mohapatra '86; Mohapatra, Valle '86]

$$
\begin{aligned}
W &\supset y_{\nu_{ij}} L_i H_u N_j^c + M_{N_{ij}} N_i^c S_j + \mu_{S_{ij}} S_i S_j , \\
\mathcal{M}_\nu &= \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & \mu_S \end{pmatrix}
\end{aligned}
$$

$$
\boxed{m_\nu^{\rm light} \simeq \left(M_D M_N^{-1}\right) \mu_S \left(M_D M_N^{-1}\right)^T \quad \text{for } \mu \ll M_N}
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$$\left(\frac{m_\nu}{0.1~{\rm eV}}\right) \simeq \left(\frac{M_D}{100~{\rm GeV}}\right)^2 \left(\frac{\mu_S}{1~{\rm keV}}\right) \left(\frac{M_N}{10~{\rm TeV}}\right)^{-2}$$

- TeV scale M_N possible even with large $M_D \sim m_t$.
- Smallness of μ_S is "technically natural".

SUSY Inverse Seesaw

- Inverse seesaw within MSSM gauge group $SU(2)_L \times U(1)_Y$ – Needs to omit terms like LH_uS and NN allowed by gauge symmetry.
- Could extend the gauge symmetry to $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [Khalil, Okada, Toma '11].

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- Could extend the gauge symmetry to $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [Khalil, Okada, Toma '11].
- However, this scenario does not arise from GUT.
- To realize inverse seesaw at TeV scale within a GUT framework, we must use the SUSYLR gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. [BD, Mohapatra '09]
- Minimal inverse seesaw structure arises *naturally* as the $SU(2)_R$ gauge symmetry forbids other terms in the superpotential:

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + h_\nu L\Phi L^c + h_S S\phi_R L^c + S\mu_S S$$

Sneutrino LSP in Inverse Seesaw

$$\mathcal{M}_{\tilde{\nu}} = \begin{pmatrix} m^2_{\tilde{\nu}^\dagger \tilde{\nu}} & m^2_{\tilde{\nu}^\dagger \tilde{\nu}^{c\dagger}} & m^2_{\tilde{\nu}^\dagger \tilde{S}} \\ \left(m^2_{\tilde{\nu}^\dagger \tilde{\nu}^{c\dagger}}\right)^\dagger & m^2_{\tilde{\nu}^c \tilde{\nu}^{c\dagger}} & m^2_{\tilde{\nu}^c \tilde{S}} \\ \left(m^2_{\tilde{\nu}^\dagger \tilde{S}}\right)^\dagger & \left(m^2_{\tilde{\nu}^c \tilde{S}}\right)^\dagger & m^2_{\tilde{S}^\dagger \tilde{S}} \end{pmatrix}$$

- In the limit $\mu_S \to 0$, the complex scalar eigenstate for sneutrino LSP:

$$\widetilde{\chi}_1 = \sum_{i=1}^{3} \left[(U^\dagger)_{1\nu_i} \widetilde{\nu}_i + (U^\dagger)_{1\nu_i^c} \widetilde{\nu}_i^{c\dagger} + (U^\dagger)_{1S_i} \widetilde{S}_i \right]$$

$c_{(0,1,2)} \equiv \sum_{i=1}^{3} |U_{1(\nu_i,\nu_i^c,S_i)}|^2$ determines the fraction of each component.

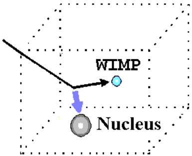
- The $\not{L}$ term $S\mu_S S$ induces the splitting terms $\sum_{m,n=1}^{9} A_{mn} \widetilde{\chi}_m^\dagger \widetilde{\chi}_n$ through the F-term:

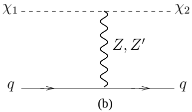
$$\left| \frac{\partial \mathcal{W}}{\partial \hat{S}} \right|^2_{\hat{S}=S} = \left| \mu_S \widetilde{S} + h_S v_{Rd} \widetilde{\nu}^c \right|^2$$

- Leads to two real scalar fields ($\chi_{1,2}$) for the LSP with mass splitting

$$\delta M_\chi = \frac{|A_{11}|}{M_\chi} \quad (A_{11} \sim \mu_S v_R)$$

A Natural Inelastic DM Candidate





- Gauge bosons *necessarily* connect χ_1 to χ_2 through $iZ^\mu(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1)$
- Naturally leads to inelastic DM for direct detection.
- The elastic channel through Higgs is typically small due to Yukawa suppression.
- Typical splitting $\delta M_\chi \sim$ a few keV is comparable to recoil energy of the nucleus $\Longrightarrow$ Observable effects in direct detection.
- **Inelasticity of the DM intimately linked to the small Majorana mass of the neutrino.** [An, BD, Cai, Mohapatra '11]

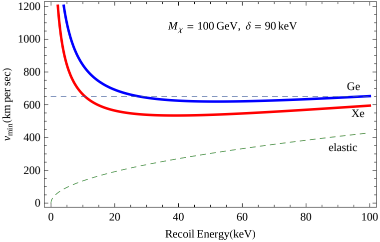
iDM Scattering

[Tucker-Smith, Weiner '01]

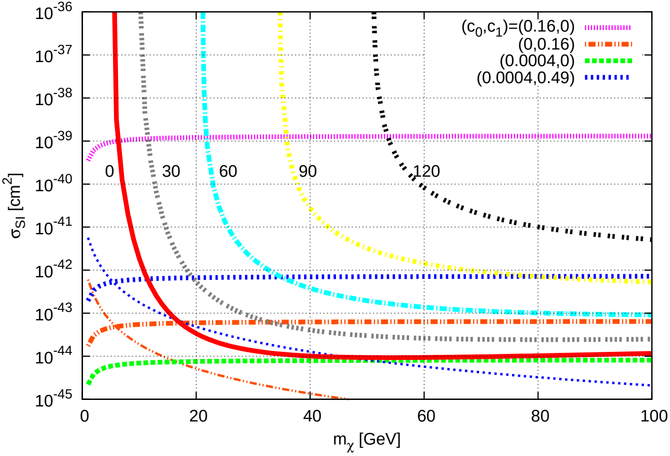
$$\frac{dR}{dE_r} = \frac{\rho_{\chi_1}}{M_\chi} \int_{|\mathbf{v}|>v_{\min}} d^3\mathbf{v} \frac{f(\mathbf{v})}{|\mathbf{v}|} \frac{A_{\text{eff}}^2 \bar{\sigma}_N}{2\mu_{\chi N}} F^2(|\mathbf{q}|)$$

$$v_{\min} = \frac{1}{\sqrt{2M_A E_r}} \left(\frac{M_A E_r}{\mu_{\chi A}} + \delta \right)$$

- Sampling only high-velocity tail of Maxwellian velocity distribution.
- Favors target nuclei with heavier mass.
- Threshold velocity for iDM scattering to occur: $v_{\text{threshold}} = \sqrt{2\delta/\mu_{\chi A}}$.
- No events at low recoil energies.
- A peak in the scattering rate.
- Enhanced annual modulation.



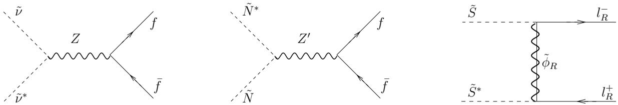
Direct Detection Cross Section



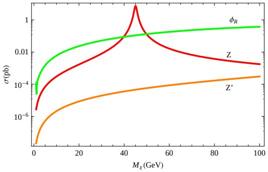
XENON100 constraints restrict the sneutrino DM to be light. [An, BD, Cai, Mohapatra '11]

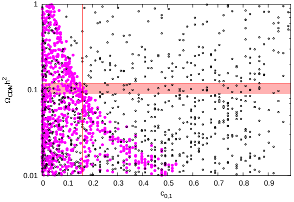
Annihilation of Sneutrino DM in SUSYLR

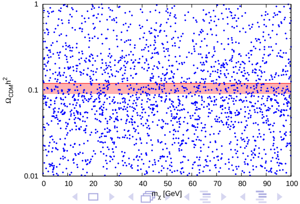
Recall $\widetilde{\chi}_1 \equiv (\widetilde{\nu}, \widetilde{N}^\dagger, \widetilde{S})$. Dominant channels:



- Both *s*- and *t*-channel are *p*-wave scattering.
- Need LH component < 40% to satisfy relic density and invisible *Z*-decay width constraints.
- Relic Density: Very light sneutrino DM allowed. [An, BD, Cai, Mohapatra '11]







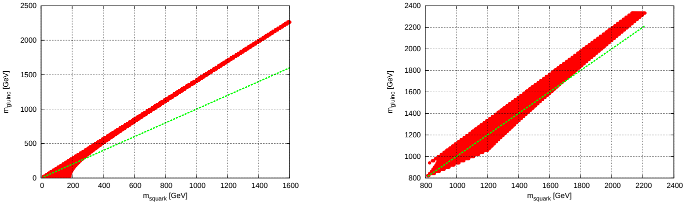
Sneutrino vs Neutralino DM at Collider

- Cascade decay of squarks and gluinos through charginos and neutralinos, which further go to sneutrino LSP with large $\not{E}_T$:

$$\widetilde{\chi}_1^0 \to \nu \widetilde{\nu}_1, \quad \widetilde{\chi}_1^\pm \to \ell^\pm \widetilde{\nu}_1,$$

  whereas for neutralino LSP, $\widetilde{\chi}_1^\pm \to W^\pm \widetilde{\chi}_1^0, f\bar{f}\widetilde{\chi}_1^0$

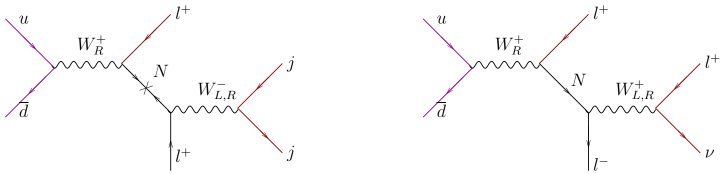
- For detailed analysis, need the sparticle spectrum.
  - (SN1) $m_{\widetilde{g}} < m_{\widetilde{q}}$: 4 jets + $\not{E}_T$ + (0,1,2) leptons.
  - (SN2) $m_{\widetilde{g}} \simeq m_{\widetilde{q}}$: 2-3 jets + $\not{E}_T$+(0,1,2) leptons.
  - (SN3) $m_{\widetilde{g}} > m_{\widetilde{q}}$, two hard jets + $\not{E}_T$+ 1-2 leptons.
- For SUSY inverse seesaw (in mSUGRA):



[BD (preliminary)]

Type I vs. Inverse seesaw at Collider

- TeV scale heavy RH neutrinos $\Longrightarrow$ may be produced on shell at LHC.
- Pseudo-Dirac fermions (with small Majorana component), unlike in type I case (purely Majorana).
- The "smoking gun" LHC signature for type-I, $pp \to l_\alpha^\pm l_\beta^\pm$+jets, will be suppressed for inverse seesaw.
- The dominant signal will be the trilepton event $pp \to l_\alpha^\pm l_\beta^\pm l_\gamma^\mp \nu(\overline{\nu})$+jets.
- Can be used to distinguish a heavy Dirac neutrino from a Majorana. [del Aguila, Aguilar-Saavedra, de Blas '09; Chen, BD '11]



(a) Majorana N (b) Dirac N

Summary and Outlook

- SUSY inverse seesaw naturally leads to iDM with inelasticity linked to the small Majorana mass.
- Light sneutrino dark matter ($\lesssim$ 20 GeV) allowed by relic density, unlike in typical MSSM scenario.
- Could be important if the DM mass is in the few GeV range.
- Distinct collider signatures for sneutrino LSP could be searched for.
- Inverse seesaw can be identified at LHC in multi-lepton channel.

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- Other observable low-energy effects in leptonic sector.
- A natural realization of resonant leptogenesis, with quasi-degeneracy explained by smallness of Majorana neutrino mass.
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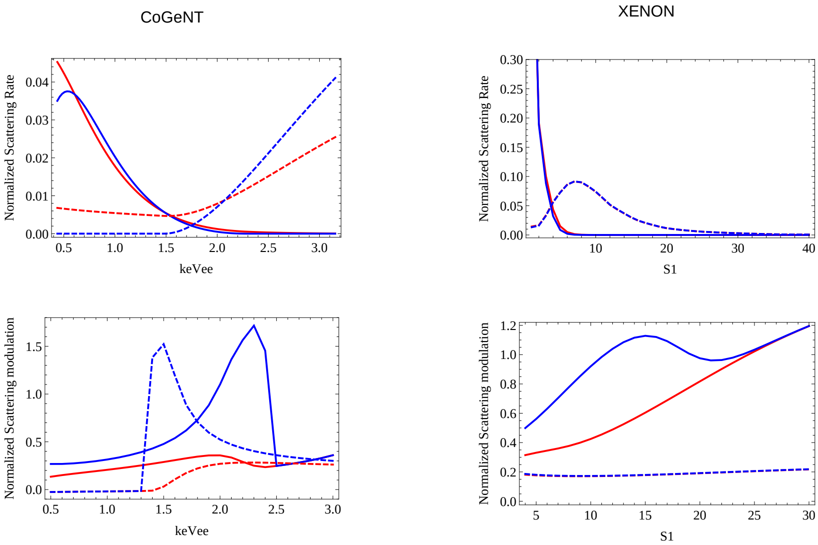
Thank You.

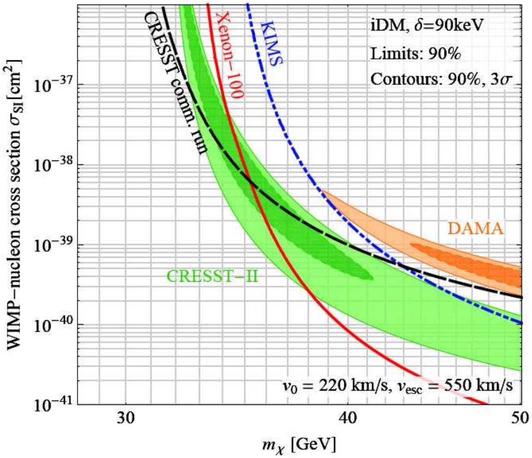
Scattering Rate and Annual Modulation



$$(c_0, c_1) = \begin{cases} (0.001, 0.1) \\ (0.1, 0.001) \end{cases}, \qquad (M_\chi, \delta) = \begin{cases} (10\ \text{GeV},\ 20\ \text{keV}) & \text{(solid)} \\ (50\ \text{GeV},\ 60\ \text{keV}) & \text{(dashed)} \end{cases}$$

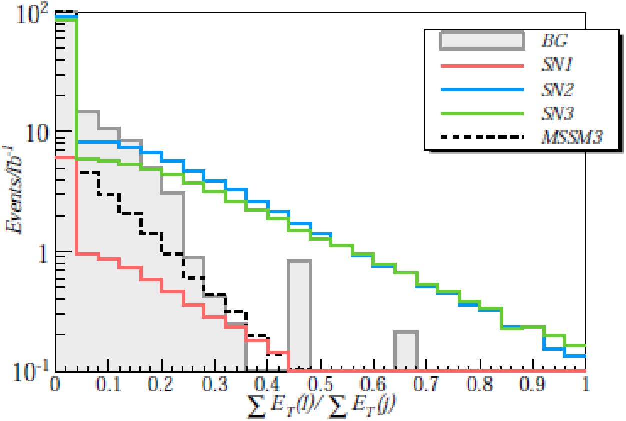
[An, BD, Cai, Mohapatra '11]

Fitting CRESST, DAMA, . . .



[Kopp, Schwetz, Zupan '11]

Signal Distribution for LHC7

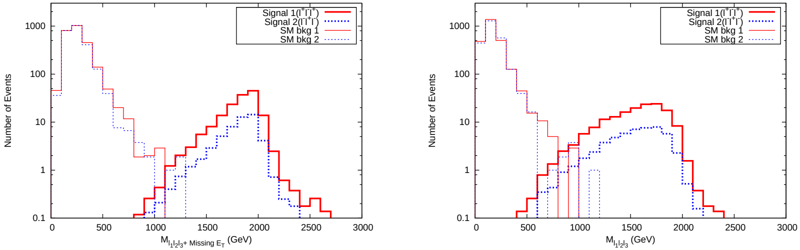


$\not{E}_T > 300$ GeV, $n(j) > 2$, $p_T(j_1) > 100$ GeV, $p_T(j) > 50$ GeV

[Belanger, Kraml, Lessa '11]

Trilepton Signal for Inverse Seesaw

[Chen, BD '11]



Can also be used to discover the heavy gauge boson W_R.