Naturalness and Dark Matter in the BLSSM

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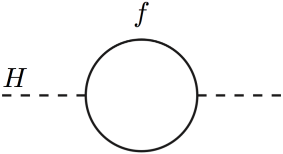
Outline

1. Motivations and Explanation of BLSSM
2. Solving Problems in the SM
3. Results - Fine-Tuning & Dark Matter
4. Conclusions

In collaboration with L. Delle Rose, S. Khalil, C. Marzo, S. Moretti, C.S. Ün [arXiv: 1702.01808]

Motivations

- Hierarchy Problem



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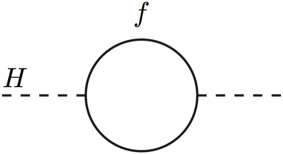

- Dark Matter

Figure: Chandra X-ray Observatory

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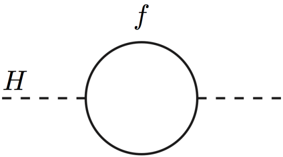


- Dark Matter

- Non-vanishing Neutrino Masses

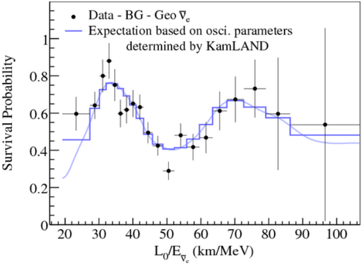
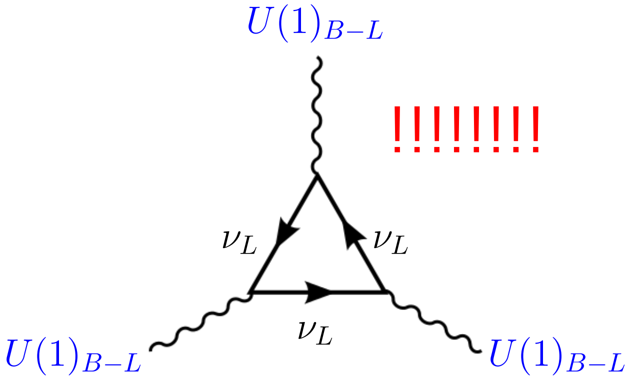


Figure: Chandra X-ray Observatory // KamLAND experiment, 0801.4589

Explaining the BLSSM – "B-L"

- SM has exact B-L conservation
- Promote accidental, global symmetry to local. SM gauge group now extended to: $G_{B-L} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- anomaly cancellation - require SM singlet fermion (right-handed neutrinos)



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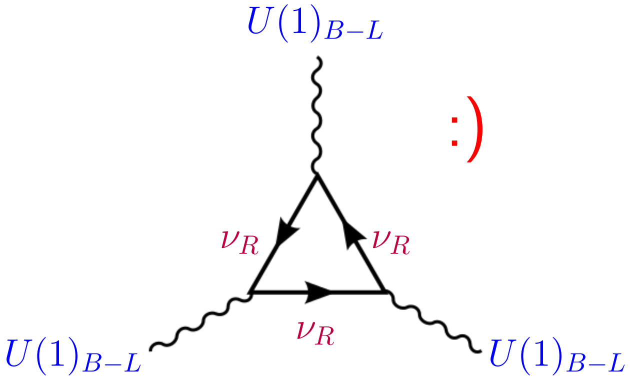


Explaining the BLSSM – “SSM”

Chiral Superfield		Spin 0	Spin 1/2	G_{B-L}
Quarks/Squarks, (x3 generations)	$\hat{Q}$	$(\tilde{u}_L \tilde{d}_L) \equiv \tilde{Q}_L$	$(u_L d_L)$	$(\mathbf{3},\ \mathbf{2},\ \frac{1}{6},\ \frac{1}{6})$
	$\hat{U}$	$\tilde{u}_R^*$	$\bar{u}_R$	$(\bar{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3},\ -\frac{1}{6})$
	$\hat{D}$	$\tilde{d}_R^*$	$\bar{d}_R$	$(\bar{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3},\ -\frac{1}{6})$
Leptons/Sleptons, (x3 generations)	$\hat{L}$	$(\tilde{\nu}_L \tilde{e}_L) \equiv \tilde{L}_L$	$(\nu_L e_L)$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ -\frac{1}{2})$
	$\hat{E}$	$\tilde{e}_R^*$	$\bar{e}_R$	$(\mathbf{1},\ \mathbf{1},\ 1,\ \frac{1}{2})$
Higgs/Higgsinos	$\hat{H}_u$	$(H_u^+ H_u^0)$	$(\tilde{H}_u^+ \tilde{H}_u^0) \equiv \tilde{H}_u$	$(\mathbf{1},\ \mathbf{2},\ \frac{1}{2},\ 0)$
	$\hat{H}_d$	$(H_d^0 H_d^-)$	$(\tilde{H}_d^0 \tilde{H}_d^-) \equiv \tilde{H}_d$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ 0)$
Vector Superfields		**Spin 1/2**	**Spin 1**	G_{B-L}
Gluino, gluon		$\tilde{g}$	g	$(\mathbf{8},\ \mathbf{1},\ 0{,}0)$
Wino/W bosons		$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm W^0$	$(\mathbf{1},\ \mathbf{3},\ 0,\ 0)$
Bino / B boson		$\tilde{B}^0$	B^0	$(\mathbf{1}\ \mathbf{1},\ 0,\ 0)$

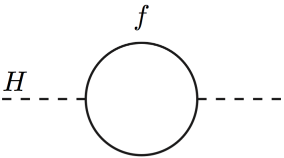
Explaining the BLSSM – "SSM"

- Content in addition to MSSM:

Chiral Superfield		Spin 0	Spin 1/2	G_{B-L}
RH Sneutrinos / Neutrinos (x3)	$\hat{\nu}$	$\tilde{\nu}_R^*$	$\bar{\nu_R}$	$(\mathbf{1}, \mathbf{1}, 0, \frac{1}{2})$
Bileptons/Bileptinos	$\hat{\eta}$	η	$\tilde{\eta}$	$(\mathbf{1}, \mathbf{1}, 0, -1)$
	$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	$(\mathbf{1}, \mathbf{1}, 0, 1)$
Vector Superfields		**Spin 1/2**	**Spin 1**	**G_{B-L}**
BLino / B' boson		$\tilde{B}'^0$	B'^0	$(\mathbf{1}\ \mathbf{1}, 0, 0)$

- Three extra RH neutrinos + SUSY partner (from anomaly cancellation condition)
- Two extra Higgs (for breaking gauged $U(1)_{B-L}$)
- One B' + SUSY partners (from broken $U(1)_{B-L}$)

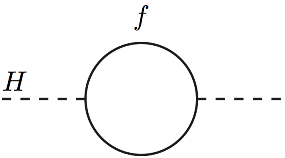
Hierarchy Problem



$$= -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{NP}^2 + \dots$$

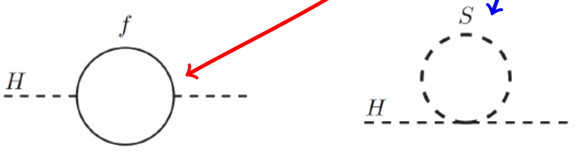
- Self energy correction to bare Higgs mass. Treating Λ_{NP} at GUT scale (10^{16}GeV) means the bare Higgs mass is fine-tuned to $m_H^2/\Lambda_{UV}^2 \sim$ **1 in 10^{30}**!

Hierarchy Problem



$$= -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{NP}^2 + \ldots$$

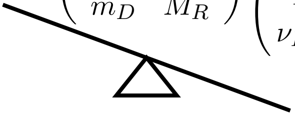
- Self energy correction to bare Higgs mass. Treating Λ_{NP} at GUT scale (10^{16}GeV) means the bare Higgs mass is fine-tuned to $m_H^2/\Lambda_{UV}^2 \approx$ **1 in 10^30^**!
- Supersymmetry - for every fermion, there is a scalar partner providing the opposite sign contribution



Non-vanishing Neutrino Masses I

- ν_L have mass!
- Introducing RH neutrinos can explain mass for ν_L

$$(\bar{\nu_L} \bar{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$



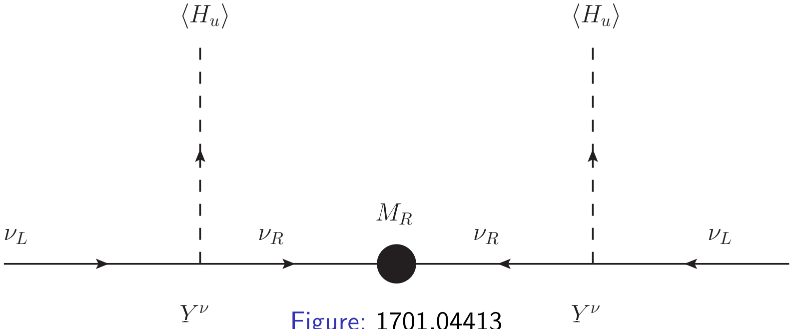
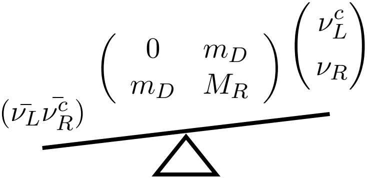


Figure: 1701.04413

Non-vanishing Neutrino Masses I

- ν_L have mass!
- Introducing RH neutrinos can explain mass for ν_L
- Large RH mass can explain small LH mass in a see-saw mechanism



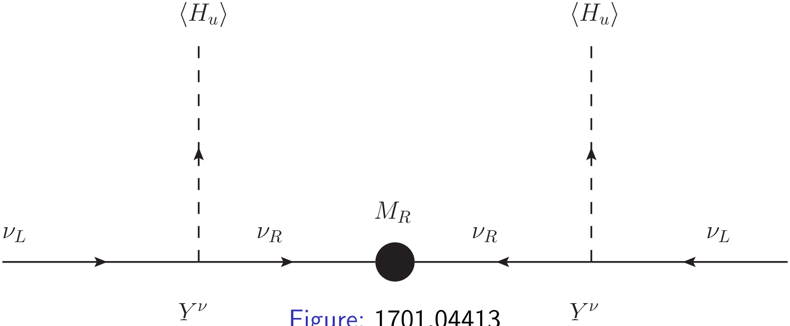


Figure: 1701.04413

Non-vanishing Neutrino Masses II

- ...However, this leads to $B - L$ violation, as in $0\nu 2\beta$-decay

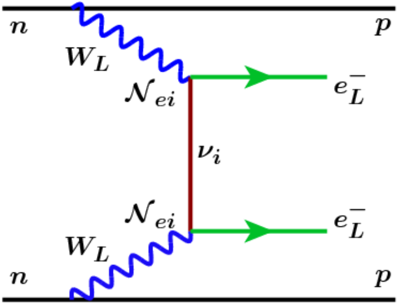


Figure: 1301.4784

- In BLSSM, gauge symmetry is broken with a Higgs mechanism

BLSSM Review

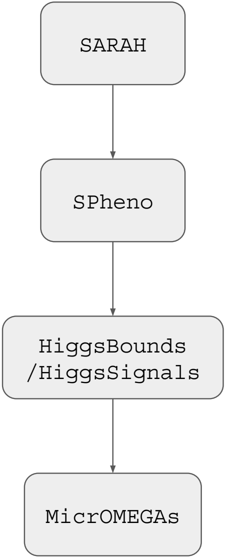
- Superpotential:

$$\begin{aligned} W &= \mu H_u H_d + Y_u^{ij} Q_i H_u u_j^c + Y_d^{ij} Q_i H_d d_j^c + Y_e^{ij} L_i H_d e_j^c \\ &+ Y_\nu^{ij} L_i H_u N_i^c + Y_N^{ij} N_i^c N_j^c \eta_1 + \mu' \eta_1 \eta_2 \end{aligned}$$

- Type-I see-saw mechanism, RH neutrinos have $\lesssim$ TeV mass
- Natural R-parity: $R = (-1)^{3(B-L)+2S}$. If $B-L$ broken by Higgs with even $B-L$ charge, then Z_2 remains unbroken
- $M_{Z'}$ fixed at 4 TeV, from LEP-II EWPOs and LHC di-lepton searches
- Complete universality at GUT scale, $g_{bl} = g_1 = g_2 = g_3,\ \tilde{g} = 0$. From RGE evolution, at EW scale, $\tilde{g} \simeq -0.1$ and $g_{bl} \simeq 0.5$

Numerical work

- Mathematica package SARAH makes a spectrum generator based on SPheno
- SPheno then calculates the full spectrum, for 60,000 data points, over a range of the GUT parameters (m_0, $m_{1/2}$, A_0, μ, $B\mu$, μ', $B\mu'$)
- Current Higgs constraints are applied in HiggsBounds / HiggsSignals
- Finally, MicroOMEGAs finds the relic density.



Introduction to Fine-Tuning

- We use the Ellis / Barbieri-Giudice definition of fine-tuning
$$\Delta = Max \left\{ \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i,m_t)}{\partial a_i} \right| \right\}$$
- Definition applied for two scales:
  - GUT-scale parameters (m_0, $m_{1/2}$, A_0, μ, $B\mu$, μ', $B\mu'$)
  - SUSY-scale parameters (m_{H_u}, m_{H_d}, $m_{Z'}$, μ, Σ_u, Σ_d), where $\Sigma_{u,d} = \dfrac{\partial \Delta V}{\partial v_{u,d}^2}$
- Recent work[1] has shown that loop contributions to tadpole equations may be important to GUT fine-tuning
- Both CMSSM and the BLSSM with universality have GUT-FT reduced by factor ~ 2

[1] Ross, Schmidt-Hoberg, Staub, 1701.03480

GUT Scale Fine-Tuning

- Simply input GUT parameters into fine-tuning measure: $a_i = (m_0, m_{1/2}, A_0, \mu, B\mu, \mu', B\mu') \longrightarrow \Delta = Max\left\{\left|\frac{a_i}{M_Z^2}\frac{\partial M_Z^2(a_i,m_t)}{\partial a_i}\right|\right\}$, tadpole loop effects absorbed into parameters
- Histogram: Counts for each parameter determining fine-tuning

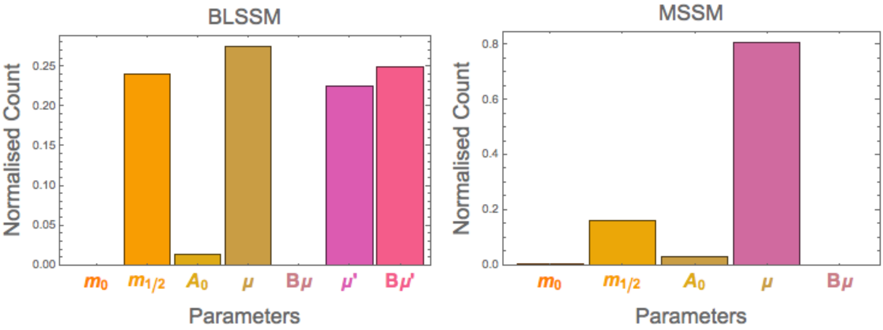


Figure: 1702.01808 - This work

SUSY Scale Fine-Tuning - CMSSM

- Fine-tuning measure may also be applied to MSSM SUSY-Scale parameters:
- $\frac{1}{2}M_Z^2 = \left(\frac{(m_{H_d}^2+\Sigma_d)-(m_{H_u}^2+\Sigma_u)\tan^2\beta}{\tan^2\beta-1} - \mu^2 \right) \longrightarrow \Delta = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i,m_t)}{\partial a_i} \right|$
- $\Delta_{\mathrm{SUSY}} \equiv \mathrm{Max}(C_i)/(M_Z^2/2)$,
- $C_{H_d} = \left| m_{H_d}^2 \frac{1}{(\tan^2\beta - 1)} \right|$,
- $C_{\Sigma_d} = \left| \Sigma_d \frac{1}{(\tan^2\beta - 1)} \right|$,
- $C_\mu = \left| \mu^2 \right|, \ldots$

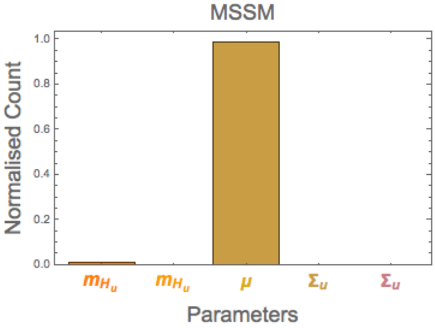


Figure: 1702.01808 - This work

SUSY Scale Fine-Tuning - BLSSM

- Fine-tuning measure may also be applied to BLSSM SUSY-Scale parameters:
- $\frac{1}{2}M_Z^2 = \frac{1}{X}\left(\frac{m_{H_d}^2 + \Sigma_d}{(\tan^2(\beta)-1)} - \frac{(m_{H_u}^2 + \Sigma_u)\tan^2(\beta)}{(\tan^2(\beta)-1)} + \frac{\tilde{g}M_{Z'}^2 Y}{4g_{BL}} - \mu^2\right)$

$X = 1 + \frac{\tilde{g}^2}{(g_1^2+g_2^2)} + \frac{\tilde{g}^3 Y}{2g_{BL}(g_1^2+g_2^2)}$

$Y = \frac{\cos(2\beta')}{\cos(2\beta)}$

- $\Delta_{\text{SUSY}} \equiv \text{Max}(C_i)/(M_Z^2/2)$,
- $C_{Z'} = \left|M_{Z'}^2 \frac{\tilde{g}Y}{4g_{BL}X}\right|$
- $C_{\Sigma_d} = \left|\Sigma_d \frac{1}{X(\tan^2\beta - 1)}\right|$,
- $C_\mu = \left|\frac{\mu^2}{X}\right|, \ldots$

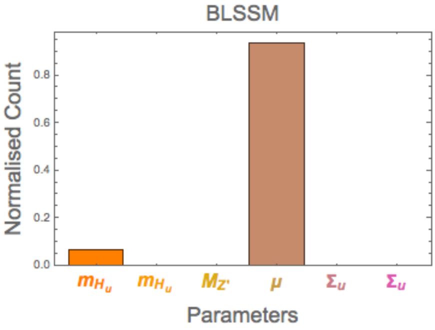
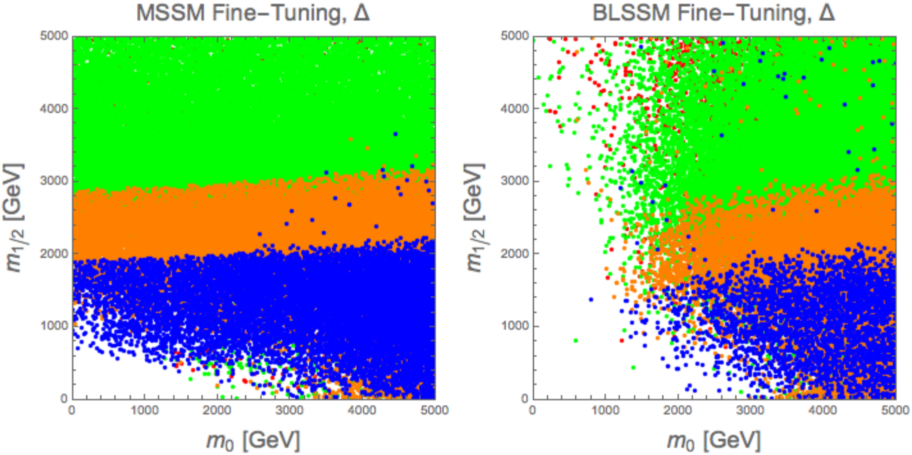


Figure: 1702.01808 - This work

Fine-Tuning Results GUT scale

- Fine-tuning plotted in m_0, $m_{1/2}$ frame. Points are blue for FT < 500, orange $500 < \text{FT} < 1000$, green $1000 < \text{FT} < 5000$, red FT > 5000



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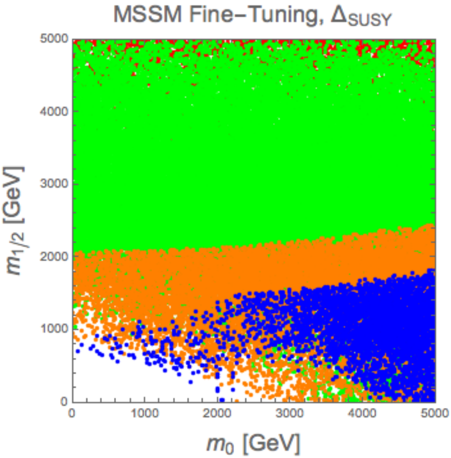


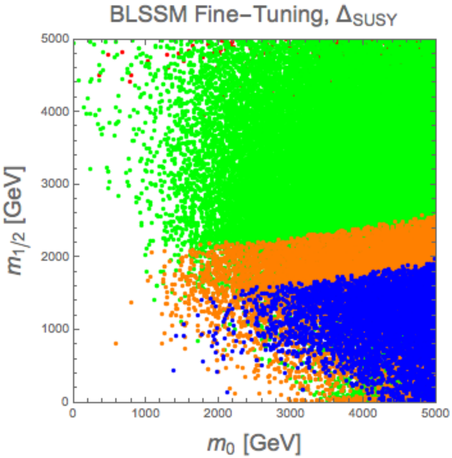


Figure: 1702.01808 - This work

Dark Matter

- In SUSY models, the lightest super-partner is *stable* from R-parity conservation.
- CMSSM only candidate Bino ($\tilde{B}^0$). BLSSM also has Sneutrino ($\tilde{\nu}_R^*$), Bileptino ($\tilde{\eta}$, $\tilde{\bar{\eta}}$) , BLino ($\tilde{B}'^0$)

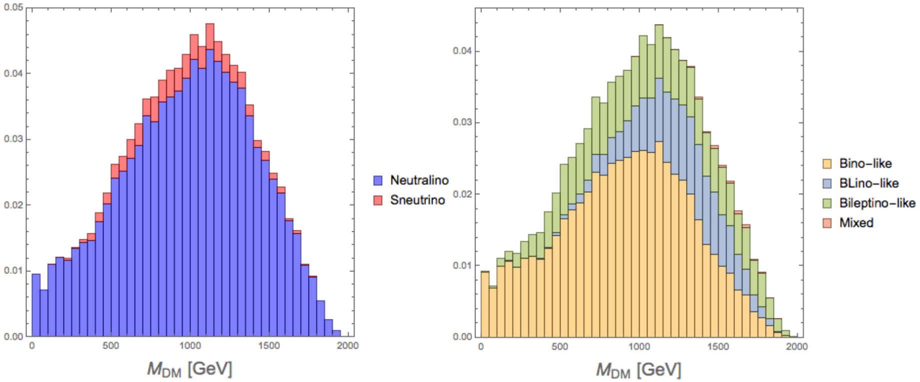


Figure: BLSSM DM candidates - 1702.01808 - This work

Dark Matter

- CMSSM severely constrained by relic-density limits
- Bino ($\tilde{B}^0$), Sneutrino ($\tilde{\nu}_R^*$), Bileptino ($\tilde{\eta}$, $\tilde{\bar{\eta}}$) , BLino ($\tilde{B}'^0$)

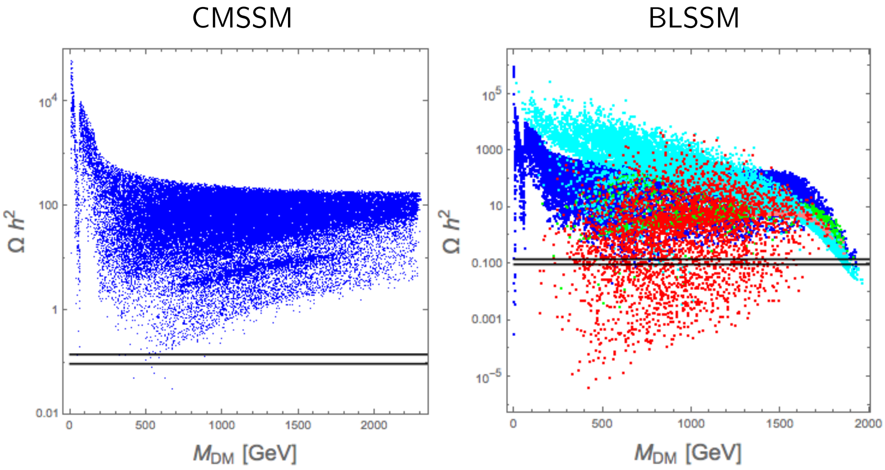


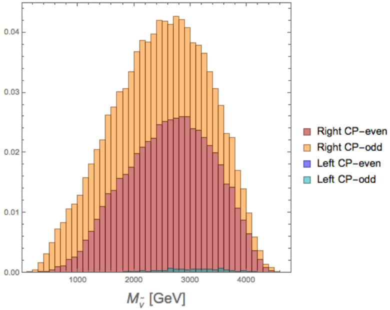
Figure: 1702.01808 - This work

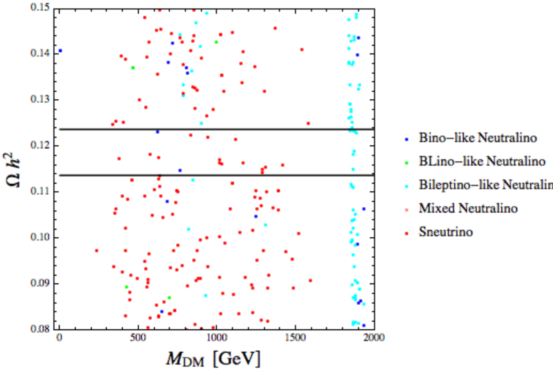
Conclusions

- The BLSSM . . .
  - Solves the hierarchy problem
  - predicts light, non-vanishing left-handed neutrino masses
  - offers multiple dark matter candidates
- Fine-tuning in BLSSM is comparable to CMSSM
- ...But with *much* larger parameter space available

For more details, see:
arXiv: 1702.01808

Back-up slides





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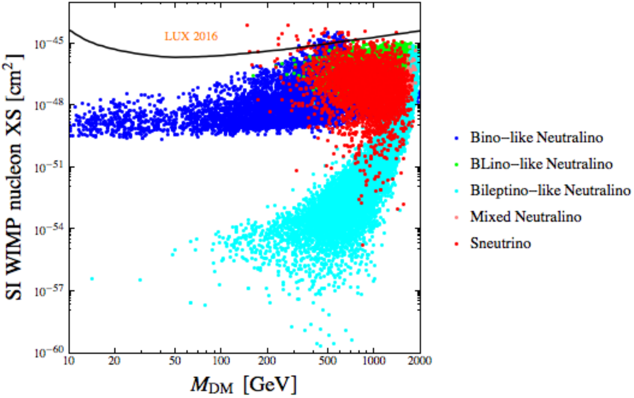

Scan range:

Parameter	range
m_0	[0, 5] TeV
$m_{1/2}$	[0, 5] TeV
$\tan(\beta)$	[0, 60]
$\tan(\beta')$	[0, 2]
A_0	[-15, 15] TeV
$Y^{(1,1)}$	[0,1]
$Y^{(3,3)}$	[0,1]
$M_{Z'} =$	4.0TeV