EW Baryogenesis and Dark Matter with an approx. R-symmetry

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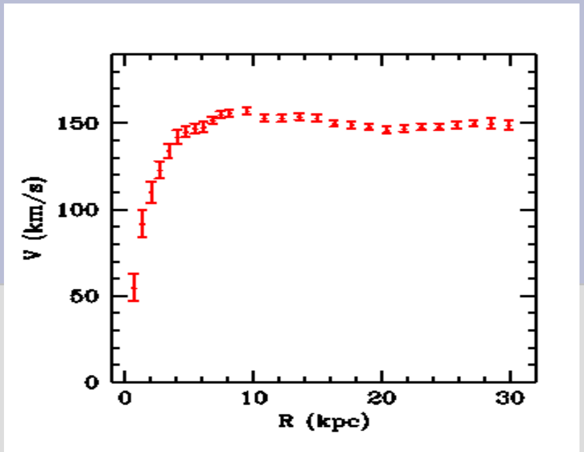
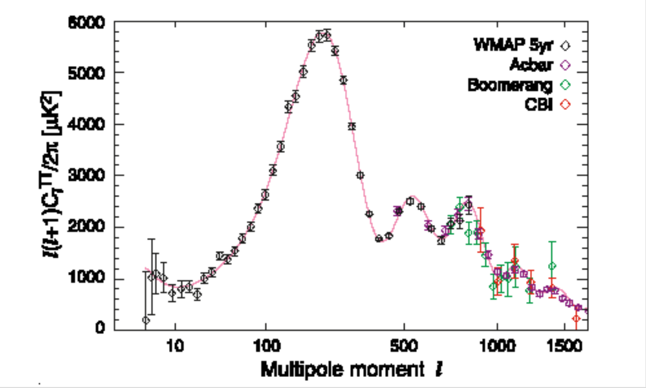
SUSY 2011

FERMILAB

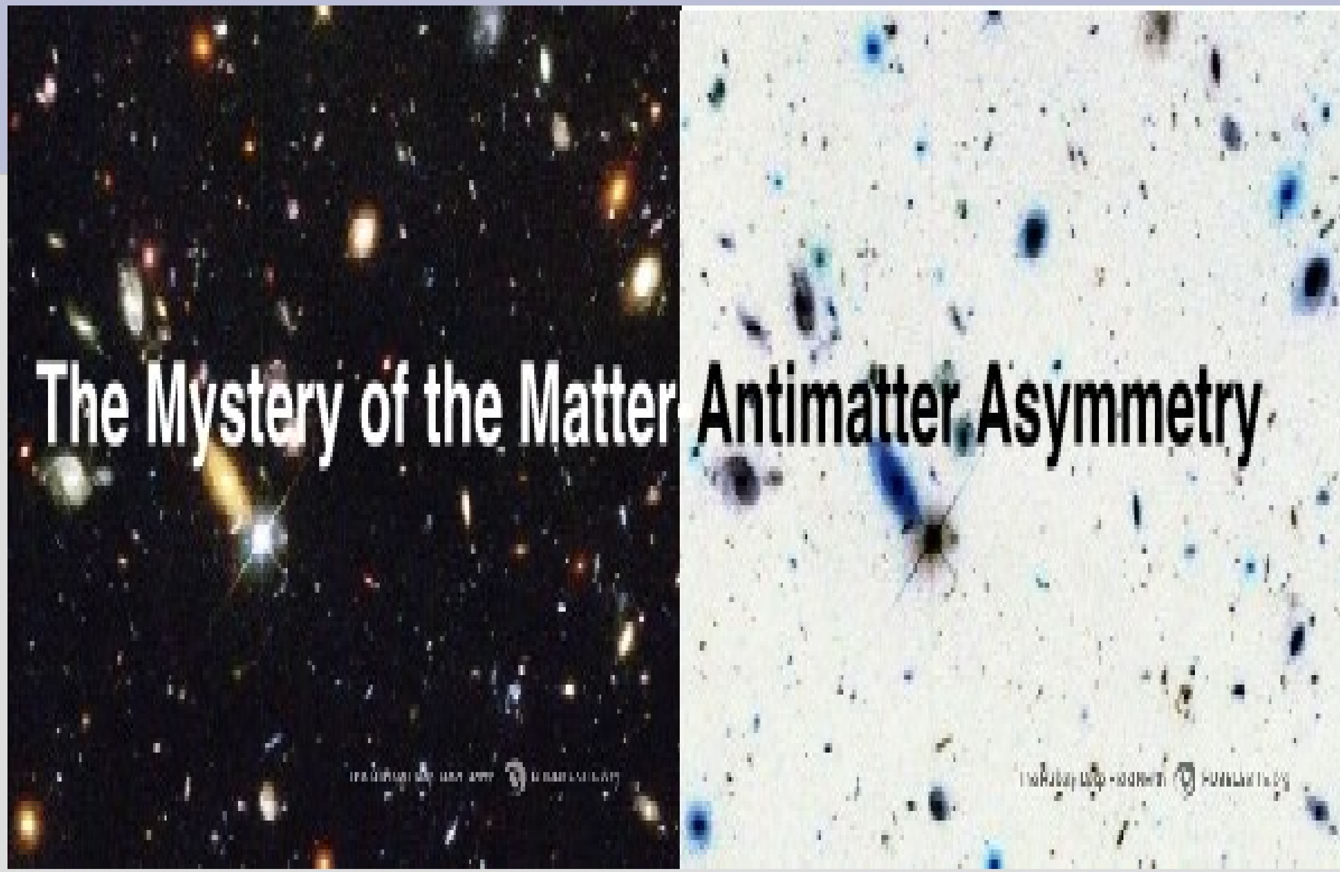
arXiv:1107.1719

P. K. & E. Ponton





Overwhelming evidence for Dark matter exists


The Mystery of the Matter-Antimatter Asymmetry

Is there a connection ?

$$\Omega_{DM} \sim 5\, \Omega_{Baryon}\ !$$

- Recently, a lot of interest in trying to relate the two.

Asymmetric Dark Matter

- DM has an *asymmetry* related to the Baryon asymmetry.

(Large Number of Papers)

This work -- Different Perspective

- Both arise from *Electroweak*-scale Physics.

- Baryon Asymmetry –Electroweak Baryogenesis

- Dark Matter – WIMP Freezeout
  (again EW physics)

Eminently Testable ! At least in principle

- Scalar Sector → Effective Potential relevant for EWBG.
- Fermion Sector → DM candidate (LSP)

Supersymmetry relates the two !

– Properties of DM & EWBG correlated.

– Interesting Signatures – Direct & Indirect Detection, Collider Physics, Gravitational Waves.

– Essentially NO constraint from EDMs

Framework

Models with (approx.) R-symmetry

- Theoretically natural in many susy models.
  - -- Nelson-Seiberg Theorem.
  - -- Superconformal symmetry.

Pheno. studied in many models :

Hall, Randall (NPB352, 289); Fox et al ph/0206096; Chacko et al ph/0406142;Kribs et al 0712.2039; Benakli et al 1003.4957; Benakli et al 1003.4957, Abel et al 1102.0014; Kribs et al 1008.1798; Davies et al 1103.1647; ....

Talks in this conference *(F. Yu, C. Frugiuele, A. Pomarol)*.

General Features

- Well known - Dramatically alleviate SUSY
  Flavor and CP problems.
- Here focus on EWBG & DM.
- **R-symmetry** ⇒ - No Majorana gaugino masses

  - No trilinear “A” terms

  - No left-right squark-slepton mixing

- **Have Dirac Gauginos** – $M_a \lambda_a \Psi_a$ (Adj. Chiral Fermions)

Model (Particular Implementation)

- Spectra & R-charges (Superfields)

Q	1	S	0	Singlet
U^c	1	T	0	Triplet
L	1	O	0	Octet
H_u	0	W_α	1	

- Gives rise to the usual up-type masses and dirac gaugino masses.
- Couple of options for d-type masses consistent with strong EWPT.
- Singlet crucial for EWPT. In particular, want $\lambda_s S H_u H_d$

Fixes R-charge of H_d : 2

- **Option I:** D^c : -1; E^c : -1 H_d : 2

Now d-type Yukawas allowed.

d-type fermion masses from R-breaking

a) Radiative Effects. *(Dobrescu, Fox [1001.3147])*

b) $B\mu$ term.

- **Option II:** D^c : 1; E^c : 1 H_d : 2

d-type Yukawas not allowed.

d-type fermion masses from $\not{SUSY}$, but not necessarily suppressed by M_{mess}

Will consider both since main conclusions independent

SUSY Breaking

- Combination of F- and D -breaking

  R[X] = 2; R[W_α'] = 1.

$$
\begin{aligned}
L_{\rm soft} &= \sqrt{2} c_a \int d^2\theta \left(\frac{W'^{\alpha}}{M_*}\right) \mathcal{W}_\alpha^a \Sigma_a + \text{h.c.} + \\
&\left[c_a^D \int d^2\theta \left(\frac{W'^{\alpha} W'_{\alpha}}{M_*^2}\right) \Sigma_a^2 + \text{h.c.}\right] + c_a^F \int d^4\theta \left(\frac{X^\dagger X}{M_*^2}\right) (\Sigma_a^2 + \text{h.c.}) + \\
&c_{ij}^F \int d^4\theta \left(\frac{X^\dagger X}{M_*^2}\right) Q_i^\dagger Q_j \,.
\end{aligned}
$$

- Dirac gaugino masses,

- “Trilinears” from modified D-terms $\left(M_a \Sigma_a + \text{h.c.}\right)\left(g_a \sum_i \tilde{q}_i^\dagger \mathrm{T}^a \tilde{q}_i\right)$

- Scalar masses

Scalar Potential (T=0)

$$V = V_F + V_D + V_{soft}$$

- $V_{soft} = m_{Hu}^2 |H_u|^2 + m_{Hd}^2 |H_d|^2 + m_s^2 |S|^2 + m_T^2 |T|^2 +$
  $B_T T^a T^a + t_s S + B_s S^2 + h.c.$ (R-symmetric limit)

- Another simplification occurs for $v_T \longrightarrow 0$ (Need for EW precision)

  (large Triplet mass)

- Analysis simplifies considerably! $\langle H_d \rangle \longrightarrow 0,\ v_T \longrightarrow 0$

  - Quite a good approximation. (Full Numerical Analysis in Paper)

- Compute Higgs, Chargino and Neutralino masses.

Potential ($T \neq 0$)

-- Main effects present at "classical-level". So, will only include the effect of thermal masses in the plasma.

-- R-symmetric, large m_T limit – only Φ and Φ_s relevant.

$$V = \underbrace{m^2\phi^2 + \tilde{\lambda}\phi^4}_{\text{``normal'' terms}} + \underbrace{2t_s\phi_s + \tilde{m}_s^2\phi_s^2}_{\text{``singlet'' terms}} + \underbrace{2\tilde{a}_s\phi_s\phi^2 + \tilde{\lambda}_s\phi_s^2\phi^2}_{\text{``crossed'' terms}}$$

$$\begin{aligned} \tilde{m}^2 &= m_{H_u}^2 + c_\phi T^2 , & \tilde{a}_s &= \frac{1}{\sqrt{2}} g' M_{D_1} , & \tilde{\lambda} &= \frac{1}{8}(g^2 + g'^2) + \Delta\lambda , \\ \tilde{m}_s^2 &= m_{S_R}^2 + c_{S^2} T^2 , & \tilde{t}_s &= t_s + \frac{1}{2} c_S T^2 , & \tilde{\lambda}_s &= \lambda_s^2 . \end{aligned}$$

(Analysis similar to that in Menon et al ph/0404184)

Effective parameters – For e.g., soft term a H_u H_d S forbidden but effective "trilinear" present.

The "Instability"

Useful to consider two limiting regimes

Small VEV: $\phi^2 \ll \frac{\lambda_s t_s^2}{\tilde{a}_s m_s^2}$ → ``crossed" terms are a perturbation, hence

$$\phi_s \approx -\frac{t_s}{m_s^2}\left[1 + \left(\frac{\tilde{a}_s}{t_s} - \frac{\tilde{\lambda}_s}{m_s^2}\right)\phi^2 + \mathcal{O}(\phi^4)\right]$$

Replacing back, get an effective potential for ϕ:

$$V_{\text{eff}} = -t_s^2/m_s^2 + m_{\text{eff}}^2\phi^2 + \lambda_{\text{eff}}\phi^4 + \mathcal{O}(\phi^6)$$

$$m_{\text{eff}}^2 = m^2 - \frac{2\tilde{a}_s t_s}{m_s^2} + \frac{\tilde{\lambda}_s t_s^2}{m_s^4}$$

$$\lambda_{\text{eff}} = \tilde{\lambda} + \frac{2\tilde{\lambda}_s \tilde{a}_s t_s}{m_s^4} - \frac{\tilde{a}_s^2}{m_s^2} - \frac{\tilde{\lambda}_s^2 t_s^2}{m_s^6}$$

- May get $\lambda_{\text{eff}} < 0$!
- If $m_{\text{eff}}^2 > 0$: local min. at origin
- Instability at large ϕ ?

The Instability (Contd..)

Large VEV: $\phi^2 \gg \frac{\tilde{\lambda}_s t_s^2}{\tilde{a}_s m_s^2}$ → ``singlet" terms are a perturbation, hence

$$V \supset 2\tilde{a}_s \phi_s \phi^2 + \tilde{\lambda}_s \phi_s^2 \phi^2 \quad \rightarrow \quad \phi_s \approx -\frac{\tilde{a}_s}{\tilde{\lambda}_s}\left[1 + \mathcal{O}(1/\phi^2)\right]$$

Replacing back, get an effective potential for ϕ :

$$V_{\text{eff}} = \text{const.} + \left(m_{\text{eff}}^2 - \frac{\tilde{a}_s^2}{\tilde{\lambda}_s} \right) \phi^2 + \tilde{\lambda}\phi^4$$

Hence the original (positive) quartic coupling bounds the potential from below.

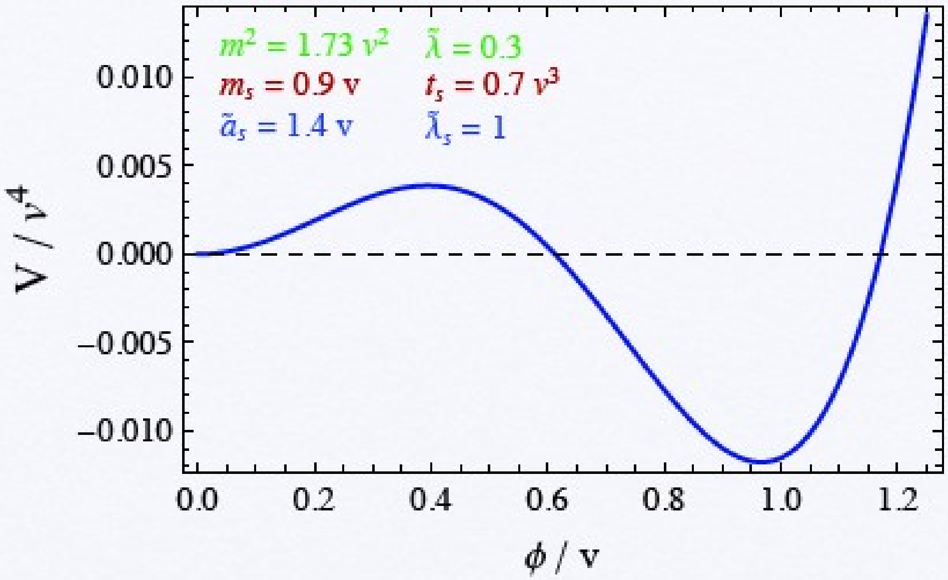
In the small ϕ expansion, the stabilization occurs via higher-dimension operators.

A Strong First-Order Phase Transition

Thus, provided

- $\lambda_{\text{eff}} < 0$
- $m^2_{\text{eff}} < \lambda_{\text{eff}} \langle \phi \rangle^2$

$$\begin{cases} m^2_{\text{eff}}(T=0) < 0 \\ 0 < m^2_{\text{eff}}(T=0) < \lambda_{\text{eff}} \langle \phi \rangle^2 \end{cases}$$



$$m^2_{\text{eff}} \approx (0.24v)^2$$

$$\lambda_{\text{eff}} \approx -0.26$$

A lower temperature can:

a) Create a local min. at origin.

b) Lift the T=0 global minimum to be degenerate with that at origin.

Expect sizable $v_c/T_c >\sim 1$.

Qualitatively similar to *Huber et al ph/0606298*

Viable Parameter Space

m_{D1} =35 GeV, m_{SR} = 100 GeV

Simple Finite-temp.Analysis

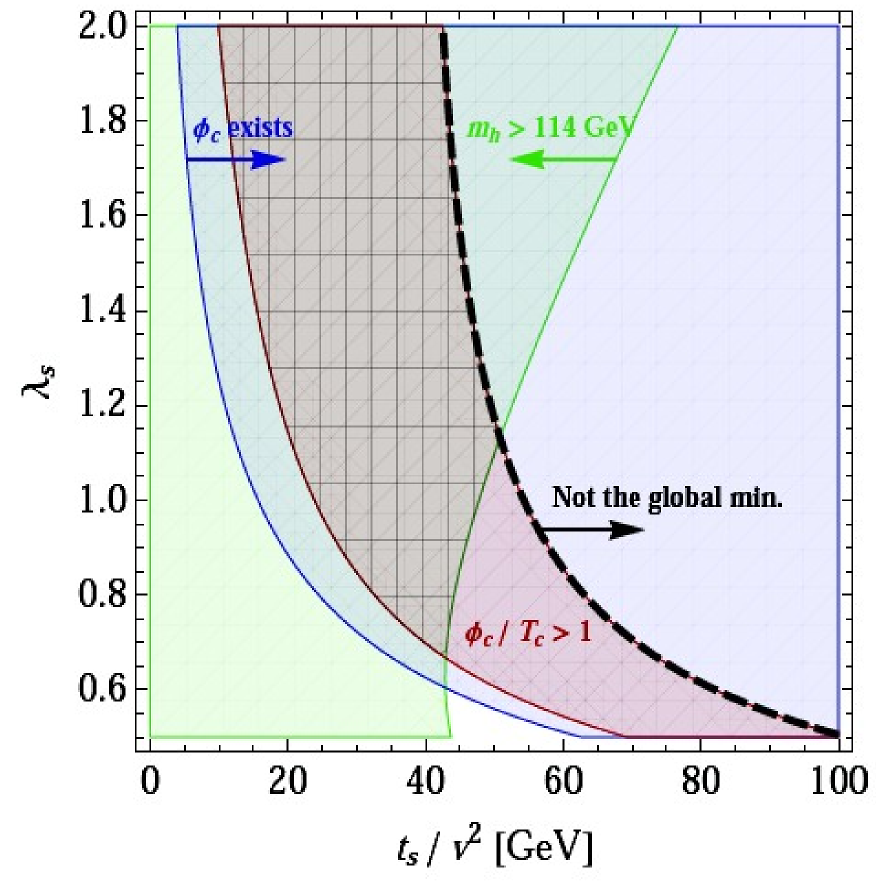
-- T^2 terms

-- 1-loop correction to T=0 V_{eff}

Lifts m_H above the LEP bound

Depends on only 4-parameters in R-symmetric limit

$\{m_{D1}, \ m_{SR}, t_s, \lambda_s\}$



(Pseudo) Dirac DM

Now look at fermion sector

– superpartner of S (~S) – Forms Dirac Bino

In general, Dirac neutralino (R-symmetric limit)

But pure-Dirac Neutralino ruled out if it has significant Higgsino component. However since R-symmetry broken by SUGRA effects,

Dirac Neutralino ⟶ Pseudo – Dirac Neutralino

Pseudo-Dirac DM: General Properties

If few GeV > Δm > 100 keV, (quite natural)

a) DM behaves like Dirac-particle during freezeout.

b) Behaves like a Majorana particle for Direct and Indirect-detection.

Relic Abundance

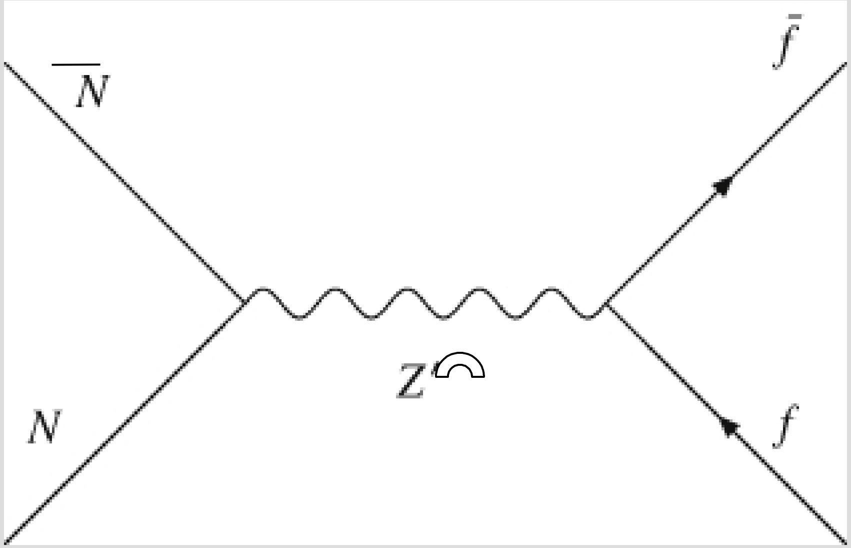
DM behaves more like a Dirac particle since Δm <~ T_F

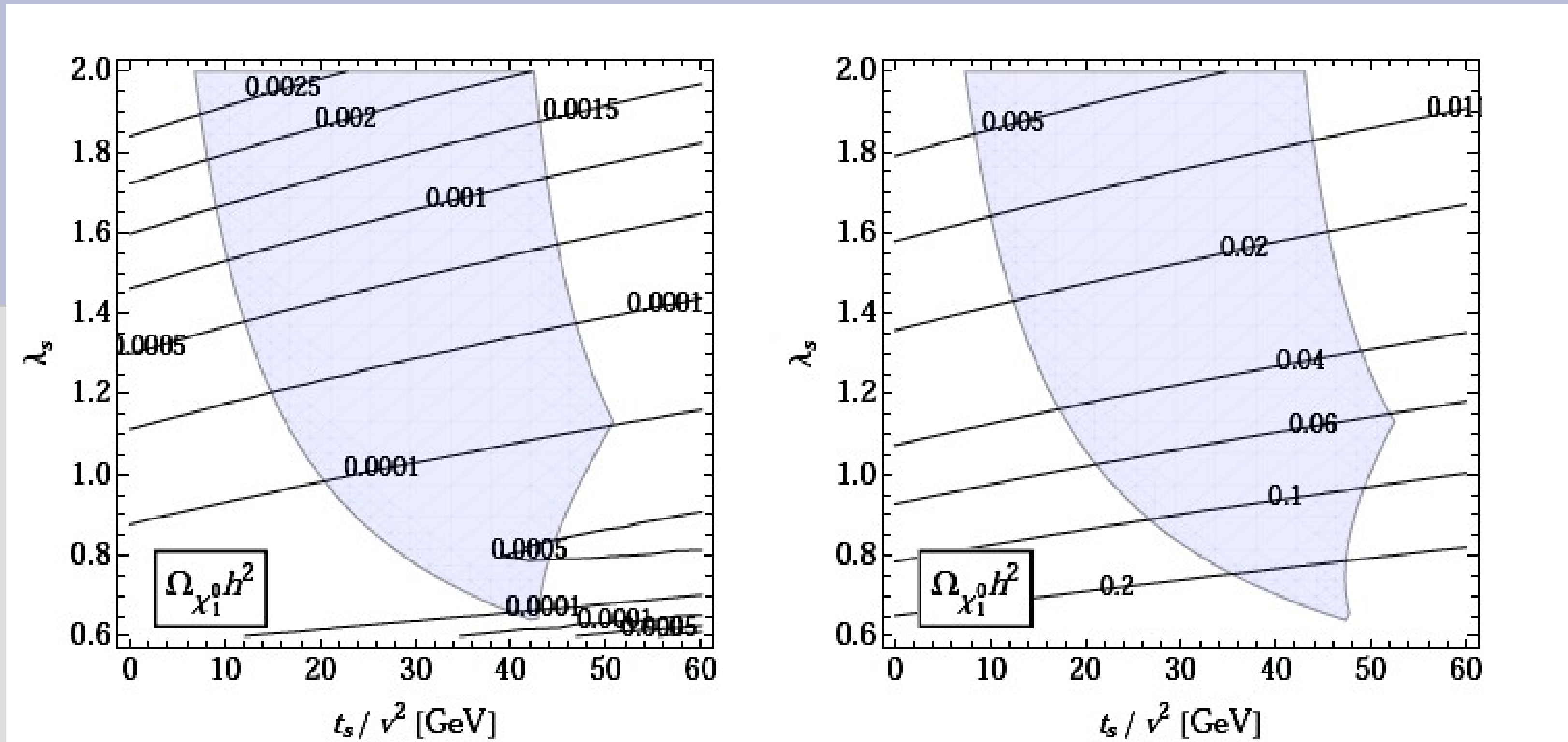
Dominant Channel: Fermion pairs– s-wave

Higgs/W/Z -- suppressed from kinematics (m_χ <~ m_W)

Gluon/photon – suppressed from loops.

Z-exchange to fermions dominates typically. (Co-annihilation)





M$_1$=5 GeV; M$_{LSP}$ ~ 46 GeV

M$_1$=10 GeV,M$_{LSP}$ ~ 56 GeV

Both possibilities arise : a) O(1) fraction of DM.

b) Negligible fraction of DM. (should consider both)

A priori unknown. Depending on fraction of DM, prospects for DM direct and indirect detection can vary.

Depends on ρ_{local}

Direct Detection

Dominant Channel – Higgs Exchange

Z-Exchange suppressed by p-wave since Majorana for direct -detection.

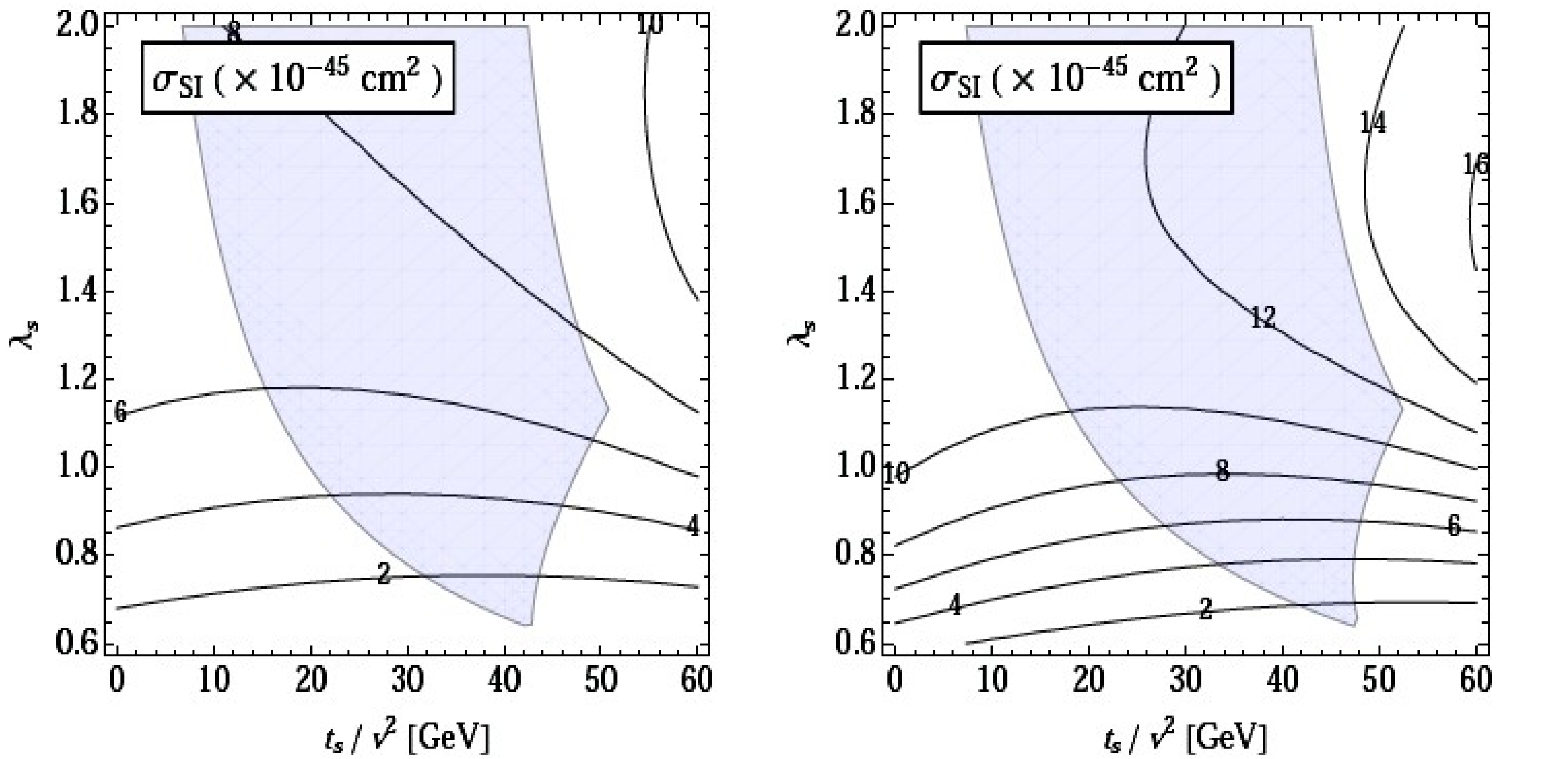
Higgs exchange only if LSP has non-trivial Higgsino component.

Correlation between Strong EWPT and Direct-Detection!

-- Strong EWPT -- λ_s >~ 0.6

-- But U_{11} linearly related to λ_s

$$U_{11} = \left(-\frac{g}{\sqrt{2}} U_{\tilde{W}} + \frac{g'}{\sqrt{2}} U_{\tilde{B}}\right) U_{\tilde{H}_u} + (\lambda_s U_{\tilde{S}} + \lambda_T U_{\tilde{T}}) U_{\tilde{H}_d},$$



$M_{\chi 1} \sim 46$ GeV $M_{\chi 1} \sim 56$ GeV

Compare with XENON100 bound = 7 * 10^{-45} cm^2 for m ~ 50 GeV

Lower bound on Higgsino component implies a lower bound on SI cross-section.

Next round of experiments sensitive to this class of Models, if LSP density O(1) fraction of Total relic abundance.

Indirect-Detection

Again, Majorana like for Indirect-detection.

- Annihilation cross-section small (compared to at freezeout).
- Also, $m_\chi <\sim m_W$

⇨ **No signal for cosmic ray Positrons, Anti-protons & Photons.**

(In particular, consistent with FERMI constraints)

What about Cosmic-ray Neutrinos (from the Sun)?

Situation different **:** Signal depends on σ_{SI} and σ_{SD}, & NOT $<\sigma v>$!

σ_{SD} (Z exchange) >> σ_{SI} (H-exchange) ⟶ constraints on σ_{SD} much weaker.

So, good detection prospects for ICECUBE/DEEPCORE

(for O(1) fraction of DM) *Halzen et al (0910.4513)*

$\not{CP}$ Phases: EWBG and EDMs

(only qualitative comments)

a) <S> can have a phase.

Significant baryon asymmetry (relative to MSSM)

Huber et al ph/0606298

b) λ_S, λ_T can have a phase.

c) Phases in (suppressed) Majorana gaugino masses.

Crucial Difference from MSSM

In MSSM, tension between EDM constraints and EWBG.

– EDMs arise from left-right squark/slepton mixing.

(A-terms and μ term)

Presence of R-symmetry

a) Suppresses A term.

b) Effects of "tanβ" enhanced couplings absent.

– both up and down-type masses from H_u.

⟹ **No Constraints from EDMs in this Framework.**

Collider Signals

Share general features of R-symmetric Models

Choi et al 0808.2410, 0911.1951,1005.0818,1012.2688

Features particular to the above Framework :

- h, lightest chargino and neutralino <~ 120 GeV.
- Lightest Chargino should be discovered at the LHC.
- Almost all results independent of squark/slepton masses.
  So can vary in a large range (note no constraints from EDMs)

Lightest CP-Even Higgs : harder to discover (than SM Higgs)

- Generically has singlet component.
- $h \longrightarrow \chi_1 \chi_1$ available in many cases. Invisible BR.

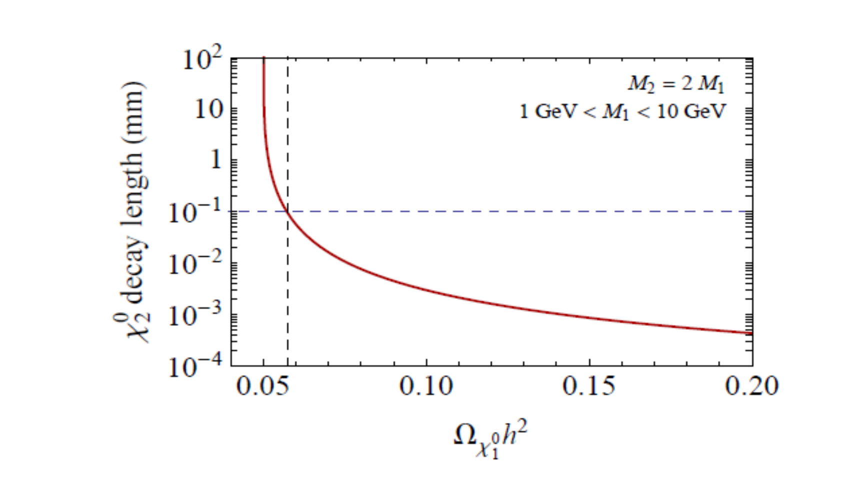
Collider Signals of (N)LSP

Both $\chi_1\,\chi_2 \longrightarrow f\,f$ co-annihilation (during freezeout)

$\chi_2 \longrightarrow \chi_1\,f\,f$ decay arise from same operator.

Correlation between Ωh^2 and Decay Length L

(for measurable m_χ, Δm)



Possible to have macroscopic L

for O(1) relic-abundance of LSP.

Compute a Cosmological Observable from a Collider Measurement!

Gravitational Waves

Strong First-Order EWPT :

– Formation of Bubbles of Broken Phase.

– Bubbles collide ⟶ Break spherical symmetry.

⇒ **Gravitational Waves**

Stronger Phase Transition – GW spectrum at lower frequencies.

– Milder fall-off.

– Should be seen by BBO.

(Huber et al 0806.1828; No 1103.2159)

Conclusions

• Studied a variant of R-symmetric Models sharing all good features, AND lead to very interesting connections between Baryon Asymmetry and DM.

Theoretical: a) SUSY relates the two sectors.

b) Presence of a common scale (EW scale).

Experimental: a) EWBG & Direct/Indirect detection of DM.

b) EWBG & Lack of EDM constraints.

c) Relic Abundance and Decay Length of NLSP.

BACKUP SLIDES

Benchmark Example

$m_{H_u}^2$	$m_{H_d}^2$	b	λ_s	t_s	B_s	m_s^2
$-(100)^2$	$(100)^2$	$(20)^2$	0.8	$(111)^3$	$-(100)^2$	$(125)^2$

λ_T	B_T	m_t^2	M_{D_1}	M_{D_2}	M_1	M_2
1	$(300)^2$	$(2000)^2$	60	-110	7.5	16

$v_{crit}/T_{crit} \approx 1.34$

$\sigma_{\chi N} \approx 4.5*10^{-45}$ cm^2

The spectrum of CP-even (m_{H_i}), CP-odd (m_{A_i}) and charged ($m_{H_i^\pm}$) Higgses, in GeV, is

m_{H_1}	m_{H_2}	m_{H_3}	m_{H_4}	m_{A_1}	m_{A_2}	m_{A_3}	$m_{H_1^\pm}$	$m_{H_2^\pm}$	$m_{H_3^\pm}$
116	184	245	2060	234	245	1960	129	1960	2060

while the neutralino and chargino spectra are given by

$m_{\chi_1^0}$	$m_{\chi_2^0}$	$m_{\chi_3^0}$	$m_{\chi_4^0}$	$m_{\chi_5^0}$	$m_{\chi_6^0}$	$m_{\chi_1^\pm}$	$m_{\chi_2^\pm}$	$m_{\chi_3^\pm}$
63.2	70.7	107	120	241	244	107	127	270

It also of interest to note the composition of the two lightest neutral CP-even Higgses:

$$H_1 \sim 0.88\, h_u^0 - 0.003\, h_d^0 + 0.48\, s - 0.003\, T_R^3 \,,$$
$$H_2 \sim 0.47\, h_u^0 - 0.008\, h_d^0 - 0.88\, s + 0.005\, T_R^3 \,,$$

and of the LSP:

$$\chi_1^0 \sim 0.67\, \tilde{b} + 0.12\, \tilde{w}^3 + 0.05\, \tilde{H}_d^0 + 0.35\, \tilde{T}^3 - 0.54\, \tilde{S} - 0.35\, \tilde{H}_u^0 \,.$$