Discrete Symmetries and Dark Matter in String/M theory

Bobby Samir Acharya $d\varphi = d * \varphi = 0$ King's College London $\partial^{\mu}F_{\mu\nu} = j^{\nu}$ and ICTP Trieste $\bar{\Psi}(1 - \gamma_5)\gamma_{\nu}\Psi$

Unification and String Theory 01-05.10.2012 Bad Honnef Talk Based on: arXiv:1204.2795(review), 1205.5789, 1102.0556 + to appear Work with: G. Kane, P. Kumar, R. Lu, B. Zheng

Introduction

- Discrete symmetries are prolific in BSM particle physics model building
- Required by proton stability and many other constraints
- If unbroken also provide a rationale for the stability of dark matter
- ► In string/M theory they arise as geometric symmetries of the extra dimensions
- ► There has been much work since 1984 on this topic
- This talk: what do our recent lessons about moduli physics teach us about discrete symmetries
- ► Goal in a slogan: "A (string) theory of R-parity violation"

Introduction: Fermi and LHC data

- Data from the LHC and Fermi/LAT are providing clues about dark matter
- The lack of BSM missing energy results might indicate that dark matter is NOT a visible sector WIMP
- The Higgs data suggests that scalar masses are order 10 100 TeV
- ► In our general approach to string/M theory the simplest models predicted a W-ino LSP and the correct Higgs mass
- ► The analysis of the Fermi data in arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616 +... suggest DM with large annihilation x-section
- ► The cross-section and peak is compatible with that of a 145 GeV W-ino (1205.5789)
- ► BUT: all MSSM wimps have been shown to produce too many low energy (10 GeV) photons (Buchmuller et al/Cohen et al/Cholis et al '2012)
- Suggests breaking of discrete symmetries

LHC SUSY Limits

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)

	MSUGRA/CMSSM : 0 lep + j's + ET min	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.50 TeV $\tilde{q} = \tilde{q}$ mass	
hes	MSUGRA/CMSSM : 1 lep + j's + ET miss	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV q = g mass	/ dt = (1.00 E 9) fb ⁻¹
arc	Pheno model : 0 lep + j's + E _{T miss}	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.18 TeV g mass (m(q) < 2 TeV, light χ)	Lut = (1.00 - 5.8) ID
8	Pheno model : 0 lep + j's + E _{T.miss}	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.38 TeV q mass (mg) < 2 TeV, light χ ⁰)	s = 7, 8 TeV
θ	Gluino med. $\overline{\chi}^{\pm}$ ($\overline{q} \rightarrow q \overline{q} \overline{\chi}^{\pm}$) : 1 lep + j's + $E_{T min}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-041]	900 GeV \tilde{g} mass $(m(\chi^0) < 200 \text{ GeV}, m(\chi^0) = \frac{1}{2}(m(\chi^0))$	+m(ĝ))
(ISI)	GMSB : 2 lep (OS) + j's + E _{T.miss}	L=4.7 fb ⁻¹ , 7 TeV [Preliminary]	1.24 TeV g mass (tanβ < 15)	ATLAS
10	GMSB : 1-2 t + 0-1 lep + j's + E	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-112]	1.20 TeV g mass (tanβ > 20)	Preliminary
-	$GGM : \gamma\gamma + E_{T,min}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-072]	1.07 TeV \tilde{g} mass $(m(\tilde{\chi}^0) > 50 \text{ GeV})$	
	$\tilde{g} \rightarrow b \tilde{b} \tilde{\chi}^0$ (virtual \tilde{b}) : 0 lep + 1/2 b-j's + $E_{T miss}$	L=2.1 fb ⁻¹ , 7 TeV [1203.6193]	900 GeV g mass (m(χ̃) < 300 GeV)	
92 74	$\tilde{q} \rightarrow b b \chi$ (virtual \tilde{b}) : 0 lep + 3 b-i's + $E_{T min}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	1.02 TeV \tilde{g} mass $(m(\tilde{\chi}_{4}) < 400 \text{ GeV})$	
tec aut	$\tilde{g} \rightarrow b \tilde{b} \tilde{\chi}^0$ (real \tilde{b}) : 0 lep + 3 b-j's + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	1.00 TeV \tilde{g} mass $(m(\tilde{\chi}^d) = 60 \text{ GeV})$	
a da	$\tilde{g} \rightarrow t \tilde{t} \chi_{i}$ (virtual \tilde{t}) : 1 lep + 1/2 b-j's + $E_{T miss}$	L=2.1 fb ⁻¹ , 7 TeV [1203.6193]	710 GeV \tilde{g} mass $(m(\tilde{\chi}^0) < 150 \text{ GeV})$	
2. S	$\tilde{g} \rightarrow t \tilde{\chi}_{i}^{0}$ (virtual \tilde{t}) : 2 lep (SS) + j's + $E_{T miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-105]	850 GeV g mass (m(χ̃) < 300 GeV)	
9 G	$\tilde{q} \rightarrow t\bar{t}\chi$ (virtual \tilde{t}) : 3 lep + j's + $E_{T,min}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-108]	760 GeV \tilde{g} mass (any $m(\tilde{\chi}_{i}^{0}) < m(\tilde{g})$)	
P II	$\tilde{g} \rightarrow t \tilde{t} \chi^{0}$ (virtual \tilde{t}) : 0 lep + multi-j's + $E_{T miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-103]	1.00 TeV g mass (m(x) < 300 GeV)	
00	$\tilde{q} \rightarrow t\bar{t}\chi$ (virtual \tilde{t}) : 0 lep + 3 b-j's + $E_{T,min}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	940 GeV \tilde{g} mass $(m(\tilde{\chi}^0) < 50 \text{ GeV})$	
	$\tilde{g} \rightarrow t \tilde{t} \chi^0$ (real \tilde{t}) : 0 lep + 3 b-j's + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	820 GeV \widetilde{g} mass $(m(\widetilde{\chi}_{1}) = 60 \text{ GeV})$	
	$bb, b, \rightarrow b\overline{\chi}^0$: 0 lep + 2-b-jets + $E_{T,min}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-106]	480 GeV b mass (m(χ ⁰) < 150 GeV)	
an dia	$b\bar{b}, \bar{b}, \rightarrow t\bar{\chi}^{\pm}$: 3 lep + j's + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-108]	380 GeV \tilde{g} mass $(m(\chi^4) = 2 m(\chi^2))$	
nch Inch	$t\bar{t}$ (very light), $t\to b\bar{\chi}^{\pm}$: 2 lep + $E_{T,min}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-059]135 GeV	\tilde{t} mass $(m(\tilde{\chi}^0) = 45 \text{ GeV})$	
2 do	$\tilde{t}t$ (light), $\tilde{t} \rightarrow b \chi^{\pm}$: 1/2 lep + b-jet + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-070] 120-173 Ge	$t \text{ mass } (m(\tilde{\chi}_i) = 45 \text{ GeV})$	
"D G	tt (heavy), $t \rightarrow t \overline{y}_{1}^{0}$: 0 lep + b-jet + $E_{T min}$	L=4.7 fb ⁻¹ , 7 TeV [1208.1447]	380-465 GeV t mass (m(\u03cc) = 0)	
eci g	$t\bar{t}$ (heavy), $\bar{t} \rightarrow t\bar{\chi}^0$: 1 lep + b-jet + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-073]	230-440 GeV t mass (m(y) = 0)	
66	$\tilde{t}t$ (heavy), $\tilde{t} \rightarrow t \tilde{\chi}_{1}^{0}$: 2 lep + b-jet + $E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-071]	298-305 GeV \tilde{t} mass $(m(\tilde{\chi}^0) = 0)$	
	\overline{tt} (GMSB) $Z(\rightarrow II) + b - jet + E_{\perp}$	L=2.1 fb ⁻¹ , 7 TeV [1204.6736]	310 GeV t mass (115 < $m(\tilde{\chi}_{1})$ < 230 GeV)	
10	$I_{L}I_{L}, I \rightarrow I \overline{\chi}_{A} : 2 \text{ lep } + E_{T, \text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076] 93-180 G	ev I mass $(m(\tilde{\chi}_{i}) = 0)$	
8	$\tilde{\chi}_{\tau}^* \tilde{\chi}_{\tau}^* \rightarrow \tilde{l}v(l\bar{v}) \rightarrow lv \tilde{\chi}_{\tau}^0$: 2 lep + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076]	120-330 GeV $\widetilde{\chi}_{\pm}^{\pm}$ mass $(m(\widetilde{\chi}_{\pm}^{0}) = 0, m(\widetilde{\chi}_{\pm}) = \frac{1}{2}(m(\widetilde{\chi}_{\pm}^{\pm}) + m(\widetilde{\chi}_{\pm}^{0})))$	
	$\overline{\chi}_{,}^{\pm}\overline{\chi}_{,}^{0} \rightarrow 3l(lvv)+v+2\overline{\chi}_{,}^{0}): 3 lep + E_{T miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-077]	60-500 GeV χ_{\perp}^{\pm} mass $(m(\chi_{\perp}^{0}) = m(\chi_{\perp}^{0}), m(\chi_{\perp}^{0}) = 0, m(\tilde{\chi})$ as above)	
ъ	AMSB (direct χ^{\pm}_{1} pair prod.) : long-lived χ^{\pm}_{1}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-111] 210	IGeV $\overline{\chi}_{1}^{\pm}$ mass $(1 < \tau(\overline{\chi}_{1}^{+}) < 10 \text{ ns})$	
9 (NB	Stable g R-hadrons : Full detector	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	985 GeV g mass	
1-0-12	Stable TR-hadrons : Full detector	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	683 GeV t mass	
10 BQ	Metastable g R-hadrons : Pixel det. only	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	910 GeV g mass (t(g) > 10 ns)	
	GMSB : stable ₹	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	310 GeV τ mass (5 < tan β < 20)	
	RPV : high-mass eµ	L=1.1 fb ⁻¹ , 7 TeV [1109.3089]	1.32 TeV V _τ MASS (λ ₂₁₁ =0.10, λ ₂₁₂ =0.05)	
2	Bilinear RPV : 1 lep + j's + E _{T,miss}	L=1.0 fb ⁻¹ , 7 TeV [1109.6606]	760 GeV $\vec{q} = \vec{g} \text{ mass} (cr_{LSP} < 15 \text{ mm})$	
02	BC1 RPV : 4 lep + E _{T,miss}	L=2.1 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-035]	1.77 TeV g mass	
	RPV $\chi_{1}^{-} \rightarrow qq\mu$: μ + heavy displaced vertex	L=4.4 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-113]	700 GeV Q MASS (3.0×10 ⁻⁶ < λ ₂₁₁ < 1.5×10 ⁻⁶ , 1 mm < ct <	: 1 m,g decoupled)
e,	Hypercolour scalar gluons : 4 jets, m _{ij} = m _{kl}	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-110] 10	00-287 GeV Sgluon mass (incl. limit from 1110.2693)	
5	Spin dep. WIMP interaction : monojet + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-084]	709 GeV M* SCale (m ₂ < 100 GeV, vector D5, Dirac _x)	
~ S	pin indep. WIMP interaction : monojet +E _{T,miss}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-084]	548 GeV M [*] SCalΘ (m _χ < 100 GeV, tensor D9, Diracχ)	
		10 ⁻¹	1 1	0

*Only a selection of the available mass limits on new states or phenomena shown. All limits auded are observed minus 1 a theoretical signal cross section uncertainty. Mass scale [TeV]

Outline

- Summary of predictions
- Comments on discrete symmetries
- Moduli vevs and breaking discrete symmetries
- Attempt "classification" of different possibilities
- ► All have very different DM and LHC phenomenology

Basic Predictions Summary (review:1204.2795)

- Early Universe (post-inflation but pre BBN) is MATTER dominated by moduli fields
 - Many phenomenologists assume that this era is radiation dominated (i.e. a thermal history)
 - \blacktriangleright String/M theory predicts a **non-thermal** history
- ► Dark matter consists of *both* axions and *W*-ino like WIMPS.
- ► The Fermi LAT experiment should see mono-chromatic photons somewhere in the few hundred GeV region.
- Scalar superpartners of quarks and leptons have masses in the 10's of TeV region i.e. are unobservable at the LHC
- ► Gauginos, including gluinos and W-inos will be observed at the LHC since their masses ≤ O(TeV)
- ► The Higgs mass, m_h: 115 GeV ≤ m_h ≤ 129, but in the M-theory G₂-manifold case:
- ► 122 GeV ≤ m_h ≤ 129 GeV due to a correlation with Witten's solution of doublet-triplet splitting!

Summary of the Basic Predictions

- ▶ Note that both the 2011 ATLAS and CMS data may be indicating $m_h \sim 126 \text{ GeV}$
- ► Recent analyses of the Fermi data (arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616 +..) are all concluding an excess of high energy, monochromatic galactic photons at E_γ ~ 130 GeV
- ► Both of these are included in the generic predictions above.

Why Discrete Symmetries?

- Discrete symmetries seem to be required, though they often seem "ad hoc"
- Bottom up: proton decay and the doublet triplet splitting problem
- They can arise in string/M theory as geometric symmetries of the extra dimensions (Strominger/Witten, Ibanez/Ross, Banks/Dine, Recent work in heterotic theory H.M. Lee,S. Raby,G. Ross,M.Ratz, R. Schieren, K. SchmidtHoberg P. Vaudrevange/ R. Kappl, B. Petersen, S. Raby, M.Ratz., R. Schieren P. Vaudrevange /M. Fallbacher, M.Ratz P. Vaudrevange /M.C. Chen, M.Ratz, C. Staudt P. Vaudrevange, /M. Fischer, M.Ratz, J. Torrado P. Vaudrevange)
- ▶ BUT: such symmetries MUST be broken, at least partially : μ and Higgsino mass ≥ 120 GeV.
- ► Moduli fields are charged under discrete symmetries and their VEVs ⟨z⟩ in the late time minimum of the potential where we are today generically will spontaneously break the symmetry.

A (string) Theory of R-parity Breaking

- ► The "offending" operators are (flavour indices suppressed)
- $\blacktriangleright \ W_{RPV} \sim \lambda' LLE^c + \lambda'' LQD^c + \lambda''' U^c U^c D^c$
- $\blacktriangleright W_{RPV} \sim \epsilon \mu L H_u$
- Now that we have a better understanding of moduli potentials we can calculate the couplings generated via the moduli vevs

In M theory on a G_2 -manifold

- ► Witten (hep-ph-0201018) showed that discrete symmetries (G) can
- Solve doublet triplet splitting and removing the "offending" operators
- \blacktriangleright Since $\mu=0$ the symmetry must be broken
- ▶ In arXiv:1102.0556 we showed that μ is generated by moduli vevs which break G
- But, for generic breaking there are phenomenological constraints on the LSP lifetime

Consider this Z_{18} example

Q_L	U_R	D_R	L	E	H_u	H_d	T_u	T_d
4	15	7	10	1	17	7	9	9

The anomaly coefficients are:

$$A_{3} = \frac{3}{2} \left(2q_{Q_{L}} + q_{U_{R}} + q_{D_{R}} \right) + \frac{1}{2} \left(q_{T_{u}} + q_{T_{d}} \right) = 54 = 0 \mod 9$$

$$A_{2} = \frac{3}{2} \left(3q_{Q_{L}} + q_{L} \right) + \frac{1}{2} \left(q_{H_{u}} + q_{H_{d}} \right) = 45 = 0 \mod 9$$

$$A_{1} = \frac{9}{5} \left(\frac{1}{6} q_{Q_{L}} + \frac{4}{3} q_{U_{R}} + \frac{1}{3} q_{D_{R}} + \frac{1}{2} q_{L} + q_{E} \right)$$

$$+ \frac{3}{10} \left(q_{H_{u}} + q_{H_{d}} \right) + \frac{1}{5} \left(q_{T_{u}} + q_{T_{d}} \right) = 63 = 0 \mod 9$$

Z_{18} example

Q_L	U_R	D_R	L	E	H_u	H_d	T_u	T_d
4	15	7	10	1	17	7	9	9

NOTE: the charges of different elements of GUT matter multiplets are different!

This does not disturb gauge coupling unification CF Mu-Chun Chen and Michael Ratz's talks – they assume that $L + D_R = 5$ both have the same charge. Similar for 10 So can have anomaly free *non-R*-symmetries.

The size of these couplings arXiv:1102.0556

- G sets the terms in W_{RPV} to zero
- ► The moduli vevs do not enter W perturbatively due to axion shift symmetries
- So, all couplings are generated by Kahler potential terms (Giudice-Masiero)
- ▶ Furthermore, $rac{\langle z
 angle}{m_{pl}} \sim 0.1$ and $F_z \sim rac{lpha_{GUT}}{4\pi} m_{3/2} m_{pl}$

• Result :
$$\mu \sim \frac{\langle z \rangle m_{3/2}}{m_{pl}} \sim fewTeV$$
 and λ 's $\sim \frac{\langle z \rangle m_{3/2}}{m_{pl}^2} \sim 10^{-15}$

New Results, to appear

- \blacktriangleright Since μ and $\lambda{}'s$ are known we can consider several possibilities
- ► Class A (General RPV): G is completely broken
- ► Class B (No RPV): G is partially broken to R-parity so only µ is allowed
- ► Class C (Leptonic RPV): G is partially broken to a subgroup which allows LH_u and LQD^c only e.g. $\mathbf{Z_{18}} \rightarrow \mathbf{Z_3}$
- ► Class D (Baryonic RPV): G partially broken and allows U^cU^cD^c only
- ► Others?..

Phenomenology of Case A, "Generic RPV"

- \blacktriangleright *G* broken completely
- All operators are present
- ▶ Proton stability requires, in particular, that $\lambda''' \epsilon y_b \leq 10^{-25}$
- ▶ In particular, ϵ is required to be $\leq 10^{-10}$ TUNED
- If it were, then W-ino would decay quickly inside the LHC detectors
- ► The Fermi *γ*-ray line might then be produced via the hidden sector
- LHC limits on gluino mass are reduced to ~ 500 GeV.

Phenomenology of Case B, "No RPV"

- ▶ G broken to R-parity
- Only μ generated
- LSP is stable
- ► LHC predictions as reviewed in 1204.2794
- ► Cannot explain Fermi line

Phenomenology of Case C, "Leptonic RPV"

- G broken but allows μ , LH_u and QLD
- Proton stable
- ▶ Neutrino masses require \epsilon ≤ 10⁻³ (Banks,Grossman,Nadir,Nir hep-ph/9505248; Nilles, Polansky hep-ph/9606388; Hempfling ph/9511288)
- \blacktriangleright If μ and $B\mu$ are "aligned" in flavour space ϵ suppressed
- ▶ This happens in M theory and probably other moduli vacua in string theory (see next slide) due to suppressed F_z and slightly suppressed $\langle z \rangle$
- ► Now, LSP lifetime becomes order 10⁻⁸ 10⁻¹⁰ seconds i.e. centimetres to metres
- ► So, W-ino decay will produced displaced charged tracks $(\tilde{W^0} \rightarrow W^+ \mu^- \rightarrow e^+ \nu_e \mu^-)$
- ► Very interesting LHC phenomenology, under investigation.
- This case also allows the possibility of "explaining Fermi" with the hidden sector

$$\mu_{\alpha} = m_{3/2} K_{H_{u}\alpha} - F^{\bar{k}} K_{H_{u}\alpha\bar{k}}$$

$$B\mu_{\alpha} = (2 m_{3/2}^{2} K_{H_{u}\alpha} - m_{3/2} F^{\bar{k}} K_{H_{u}\alpha\bar{k}} + m_{3/2} F^{k} K_{H_{u}\alpha\bar{k}}) - (m_{3/2} F^{m} K^{n\bar{l}} K_{\bar{l}mH_{u}} K_{n\alpha} + (H_{u} \leftrightarrow L_{\alpha})) - F^{n} F^{\bar{m}} (\frac{1}{2} K_{H_{u}\alpha n\bar{m}} - K^{j\bar{l}} K_{\bar{l}nH_{u}} K_{j\bar{m}\alpha} + (H_{u} \leftrightarrow L_{\alpha})) (1)$$

From the leading contribution to the Kahler potential terms:

$$K \supset P_{\alpha} \frac{(S^1)^{\dagger}}{m_{pl}} H_u L_{\alpha} + Q_{\alpha} \frac{(S^2)}{m_{pl}} H_u L_{\alpha}, \qquad (2)$$

where P_{lpha}, Q_{lpha} are $\mathcal{O}(1)$ coefficients in general, one finds :

$$\mu_{\alpha} = P_{\alpha} \frac{(S^{1})^{\dagger}}{m_{pl}} m_{3/2} + P_{\alpha} \frac{\langle F^{S_{1}} \rangle}{m_{pl}}$$

$$B\mu_{\alpha} = 2P_{\alpha} \frac{(S^{1})^{\dagger}}{m_{pl}} m_{3/2}^{2} + P_{\alpha} \frac{(S^{1})^{\dagger}}{m_{pl}} m_{3/2} + Q_{\alpha} \frac{\langle F^{S_{2}} \rangle}{m_{pl}} m_{3/2} (3)$$

Then, using the result that $\langle F^{S_i} \rangle \ll \langle S_i \rangle m_{3/2}$ [1102.0556] so that the terms proportional to $\langle F^{S_1} \rangle$ and $\langle F^{S_2} \rangle$ are negligible to a very good approximation, one gets:

$$B\mu_{\alpha}\simeq 2\,m_{3/2}\,\mu_{\alpha}$$

Conclusions

- In vacua with suppressed gaugino masses, the moduli potential allows one to estimate the size of R-parity violating effects
- This seems to require that discrete symmetries are only partially broken
- Leads to a rich phenomenology at the LHC
- Allows the possibility of finding a hidden sector explanation of the Fermi γ-ray line if it is DM

BACKUP

Example: Moduli Stabilization in M theory

- Basic (old, but great) idea that strong dynamics in the hidden sector:
 - 1. Generates the hierarchy between m_{pl} and M_W
 - 2. That supersymmetry breaking will also stabilize the moduli
- ► Realised for the first time in string/M theory by considering M theory on G₂-manifolds
- In fact, strong hidden sector dynamics generates the hierarchy, the moduli potential and supersymmetry breaking simultaneously!
- ► There are two INTEGER parameters P, Q which determine α_{GUT}, M_{GUT}, M_{pl}, m_{3/2} all consistently.

Moduli Stabilzation in M theory

► Moduli vevs $s_i \sim 3Q = \frac{1}{\alpha_{GUT}}$ ► So, eg, Q=6,7,8,9► $m_{pl}^2 = Vol(X)M_{11}^2 \sim \frac{1}{\alpha_{GUT}^{7/3}}M_{11}^2$ ► $M_{GUT} = M_{11}\alpha_{GUT}^{1/3}$ ► $m_{cl} = m_{11}\alpha_{GUT}^{7/2}|Q-P|_{Q} - \frac{P_{eff}}{Q-P}$

•
$$m_{3/2} = m_{pl} \frac{GOI}{\sqrt{\pi}} \frac{QOI}{Q} e$$

- ▶ $P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})} \sim 60$ when Q P = 3
- ▶ So, $m_{3/2} \sim O(50)$ TeV.Note: $Q P \ge 3$, so Q P = 4 doesn't work.
- ► So, moduli can decay before BBN.
- ► There are two INTEGER parameters P, Q which determine α_{GUT}, M_{GUT}, M_{pl}, m_{3/2} all consistently.

The Spectrum in String/M theory

- In string/M theory in the classical limit a positive cosmological constant is not possible.
- 'Pure moduli dynamics has an anti de Sitter vacuum'
- Therefore, the field which dominates supersymmetry breaking is not a modulus
- ▶ e.g. a matter field
- ► In M theory this is a hidden sector matter field
- $F_{moduli} \sim \alpha_{GUT} m_{3/2} m_{pl}$
- Leads to a Wino LSP
- Note: this is NOT pure AMSB in the gaugino sector, but similar to it.

A New Mass Scale

- Direct consequences of having moduli with masses of order 10
 100 TeV include:
- The upper limit on the axion decay constant is lifted to close to the GUT scale.
- This solves a long outstanding problem in string/M theory. Hence, axions will make up a significant fraction of dark matter without fine tuning!
- If the LSP is stable, it will be produced when the moduli decay.
- The relic density comes out about right for a 100-200 GeV W-ino like LSP.
- This is a non-thermal WIMP 'Miracle'.So dark matter is mixed: W-ino and axion.
- ► The W-ino has the right annihilation cross-section to explain the gamma line 'signal' (eg arXiv:1204.2797) in Fermi data (see arXiv:1205.5789)

Axion-Wino dark matter and the Fermi 'signal'

- ► Several recent analyses of the Fermi data (arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616) are all concluding an excess of high energy, monochromatic galactic photons at $E_{\gamma} \sim 130 \text{ GeV}$
- ► The cross-section for DM annihilation for the photon signal is roughly $\sigma v(\chi \chi \rightarrow \gamma X) \sim 10^{-27} \text{ cm}^3 \text{s}^{-1}$.
- ► Thermal WIMP relics have σv_{total} ~ 3 × 10⁻²⁶ cm³s⁻¹. Since annihilation to photons is a one-loop process this implies that typical thermal WIMPs *cannot* produce the required number of photons.
- Non-thermal WIMP relics, such as a W-ino with mass 145 GeV have a much larger total σv of the right order to produce the 130 GeV γ-line by 1-loop annihilating to Zγ.
- Further: fitting the signal in detail shows that roughly 50% of dark matter is W-ino like. The rest is interpreted as axions!!