# Experimental Opportunities
# ~~LHC~~ C ~~Challenges~~ for String Theory

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**String Pheno' 14**
**July 10, 2014**

Yale University

LUX ET VERITAS

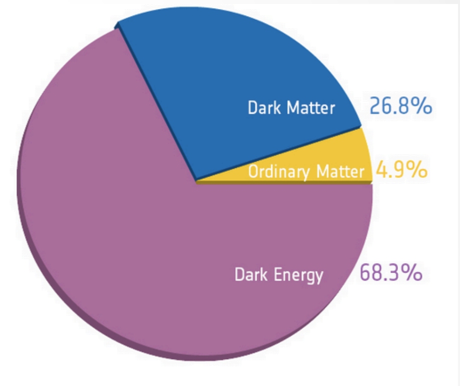
## String Phenomenology :

**Study of aspects of potential solutions of String Theory with features "similar" to those observed in our Universe**

# What are the "Broad Features" of Our Universe ?

- 3 + 1 "Large" dimensions ($R_{extra}$ <~ $10^{-16}$ cm)
- Flat Universe with Dark Energy, Dark Matter

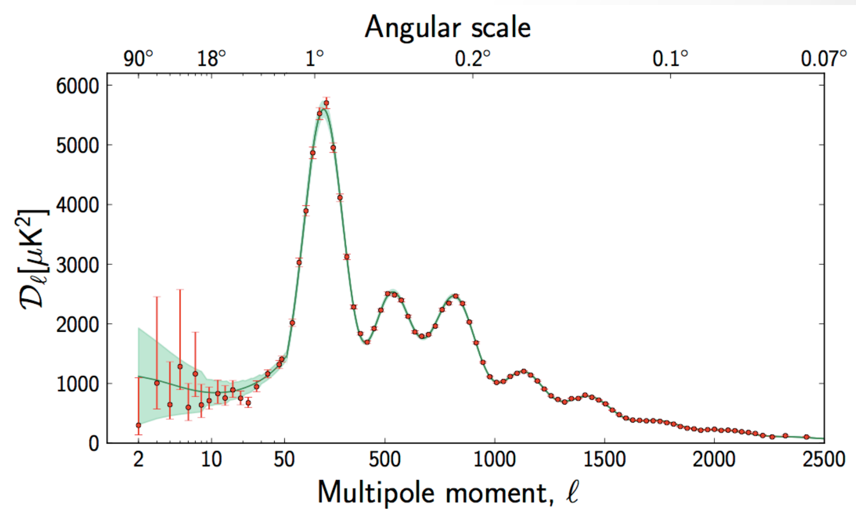
& Ordinary * Matter -- ΛCDM cosmology



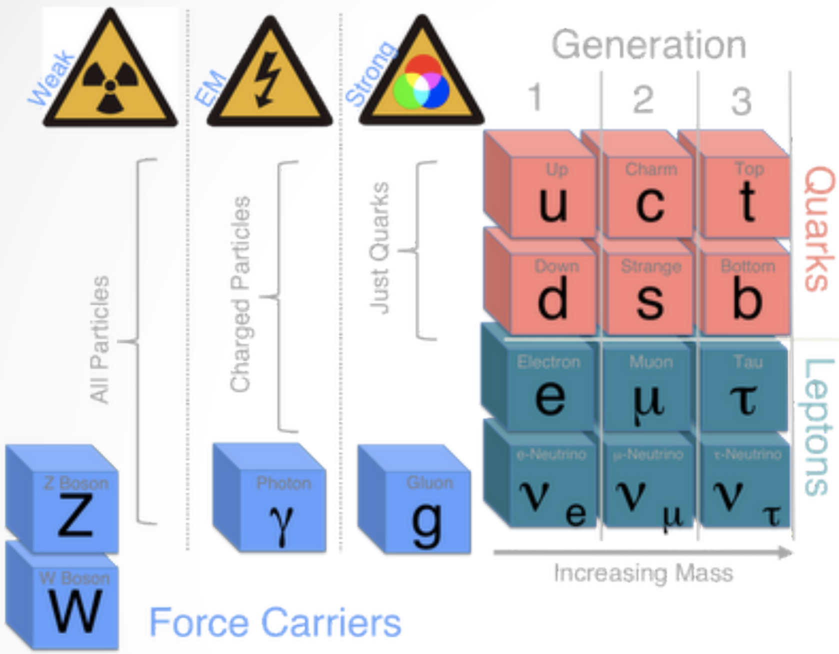

**PLANCK**

- Nearly scale invariant & adiabatic cosmological fluctuations

-- CMB & Large-scale structure



# Ordinary* Matter – Standard Model




* Elementary Matter (point-like)
* Force Carriers (gauge bosons)
* Scalar particle called the Higgs Boson


## Broad Features

- Non-abelian gauge theory.
- Chiral fermions
  -- charged : hierarchical masses & small mixing.
  -- neutral (neutrinos) : tiny, hierarchical masses & large mixing.
- Spontaneous symmetry breaking by the Higgs mechanism.

# Recent Experimental Results

- **Energy Frontier**
  - -- Positive: Discovery of Higgs @ 125 GeV.
  - -- Null : Lack of Beyond SM physics so far

- **Intensity/Precision Frontier**
  - -- Positive : measured PMNS angle -- $\sin^2 \theta_{13}$
  - -- Null : No deviations from SM, more stringent constraints on new physics

- **Dark Frontier**
  - -- Null : LUX (direct detection), FERMI (indirect detection),...
  - -- Hints (?) : X-ray line, Diffuse photons from GC, ...

*D. Marsh, M. Rummel*

- **Cosmic Frontier**
  - -- Null : No sign of non-gaussianity so far
  - -- Hint (?): Primordial Gravitational Waves (BICEP2)

*Westphal, Burgess,Hebecker, Maharana, Takahashi, Sagnotti, Nilles, Grimm, Shiu, Kaloper, Uranga. Also many parallel talks ...*

# Plan of Talk

- **I) Higgs Discovery**
  - -- Summary of Results
  - -- What kinds of New Physics models favored/disfavored by data?

- **II) String motivated SUSY Models – Basic Features & Potential Signals**

  -- "Electroweak-Tuned" → "Imperfectly" Natural / "Mostly" Un-natural

  -- "Electroweak-Natural" – briefly discuss one possibility

  -- R-parity or Not ?

- **III) Dark Matter – motivated from String Theory**

  -- Status of LSP WIMP DM.

  -- Dark sectors.

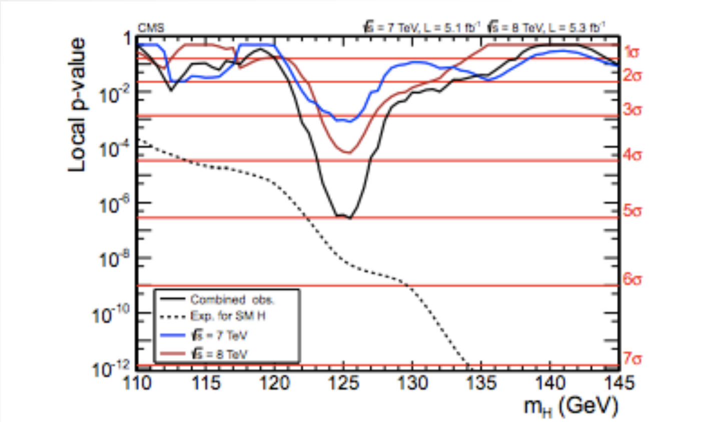
- **IV) Summary & concluding remarks**

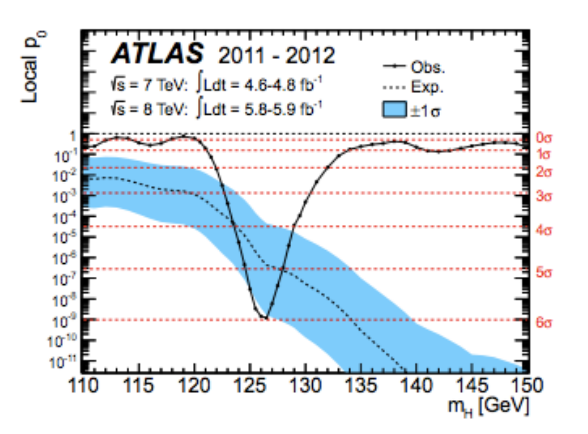
# I) Higgs Discovery

## -- Summary of Results

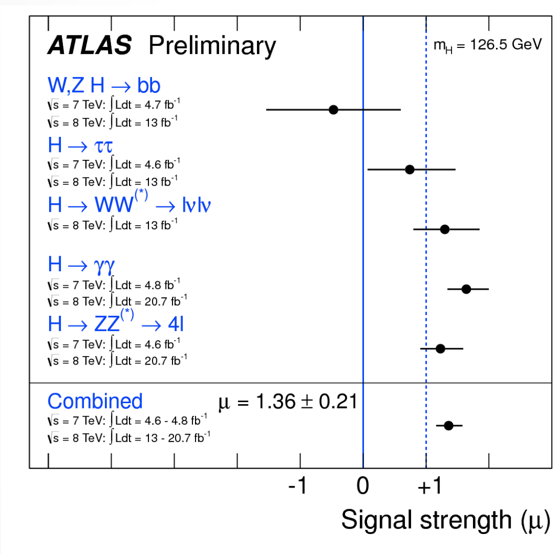
## -- Effect on BSM Models

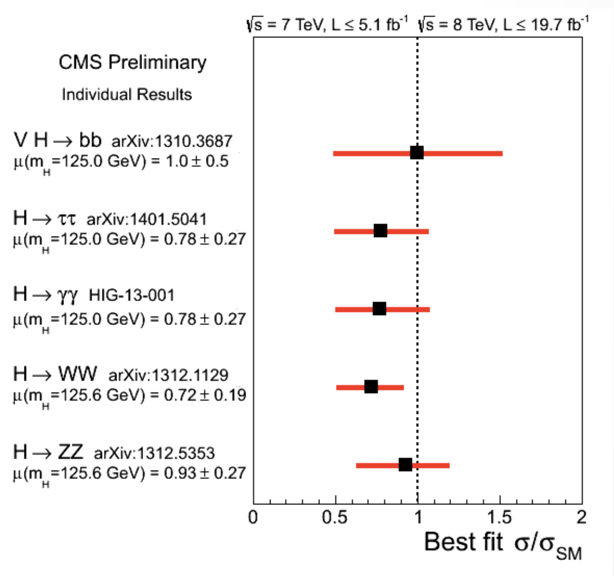
- **Discovery of a Higgs Particle @ 125 GeV**




- **Signal consistent with that of a SM-like Higgs**



# Effect on BSM Physics

- **i) Technicolor Models**
  - $v_{EW} = f$ (scale of New Strong Dynamics)
  - -- All new resonances at $M \sim 4\pi f = 4\pi v_{EW}$

**SM-like "Higgs" resonance at $M <\sim v_{EW}$** → **Strongly Disfavored**

- **ii) Composite Higgs Models**

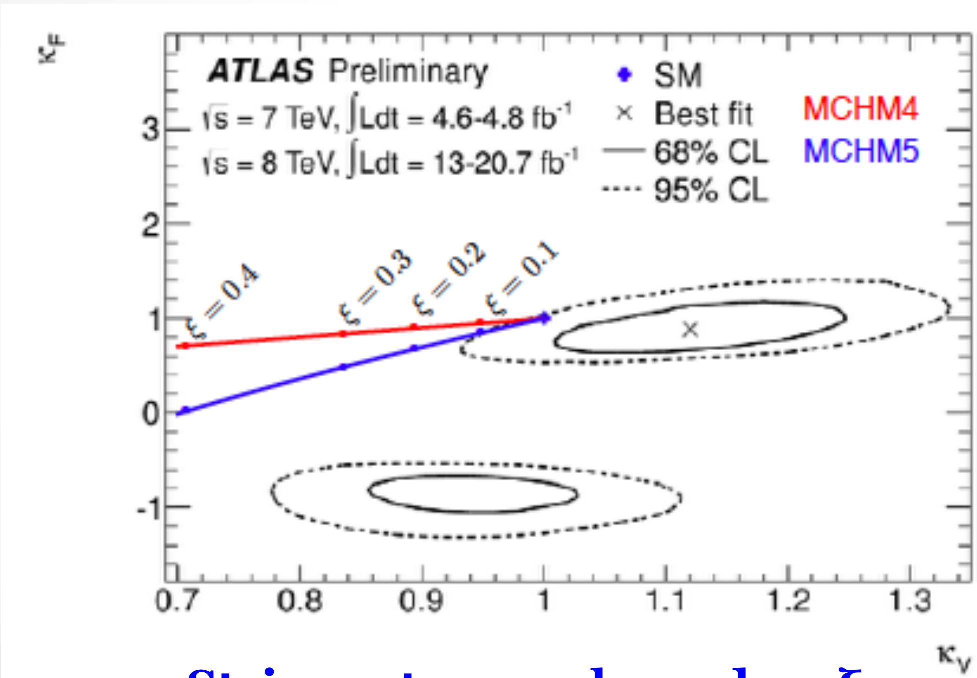
-- Higgs pseudo-NGB of global symmetry (E.g. SO(5)/SO(4))
-- Could be light compared to $4\pi f$
-- EW Precision observables under control, if $\xi = v_{EW}/f < 1$.

**However, composite Higgs models in tension with data**

## Composite Higgs Models (contd.)

- **Higgs couplings different from that in SM at tree-level**
  **-- The parameter $\xi = v_{EW}/f$ controls the deviation.**

- **Also expect "Top-partners" below ~ 1 TeV (None observed )**




**Stringent upper bound on $\xi$**

**$\kappa_F$ ~ Coupling to Fermions**

**$\kappa_V$ ~ Coupling to Gauge bosons**

**Same with Randall-Sundrum Models, since these are "duals" of composite Higgs**

**Still possible, but increasingly disfavored**

# iii) TeV-scale Strings

*Antoniadis; Hashi, Wan-Zhe*

- **Well-known that String scale can be made very small (>~ TeV) at the expense of making extra dimensions very large (relative to $M_s$)**

$$M_P^2 = \frac{1}{g_s^2} M_s^{2+n} R_\perp^n ,$$

*Arkani-Hamed, Dvali, Dimopoulos hep-ph/9803315*
*Antoniadis et al hep-ph/9804398*

- **Experimental Signals**

**-- Kaluza-Klein Excitations**

**-- String Resonances with Regge behavior :** $M_n^2 = nM^2 , \quad j = j_0 + \alpha' M_n^2$

**-- Production of Black-Holes**

**$M_{BH} \sim M_s/g_s^2$ , so threshold higher than that for string resonances.**

**-- Z' bosons with mass $M_{Z'} \sim g\, M_s$ generic in isotropic compactifications.**

**receive mass by Green-Schwarz mechanism : Stuckelberg U(1)**

# Constraints & Interpretation

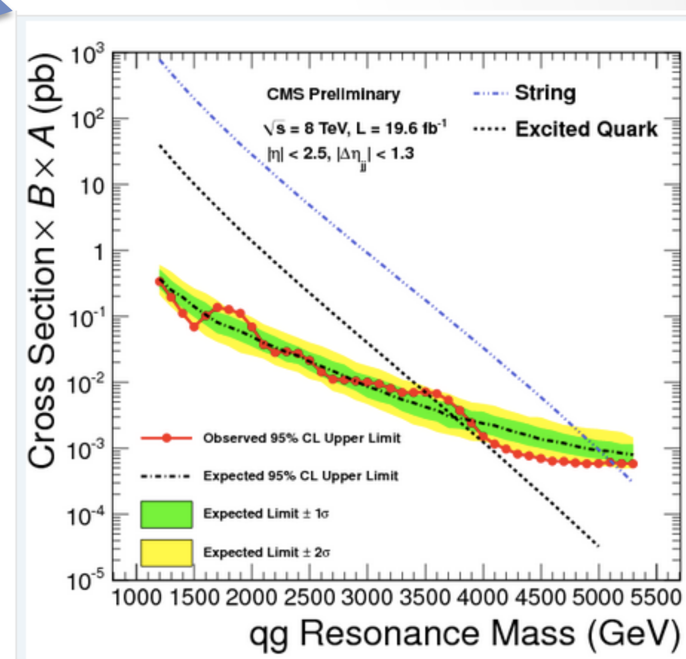
- **String resonances produced in $qg \rightarrow qg$, $gg \rightarrow gg$ scattering**

  **-- universal amplitude:**

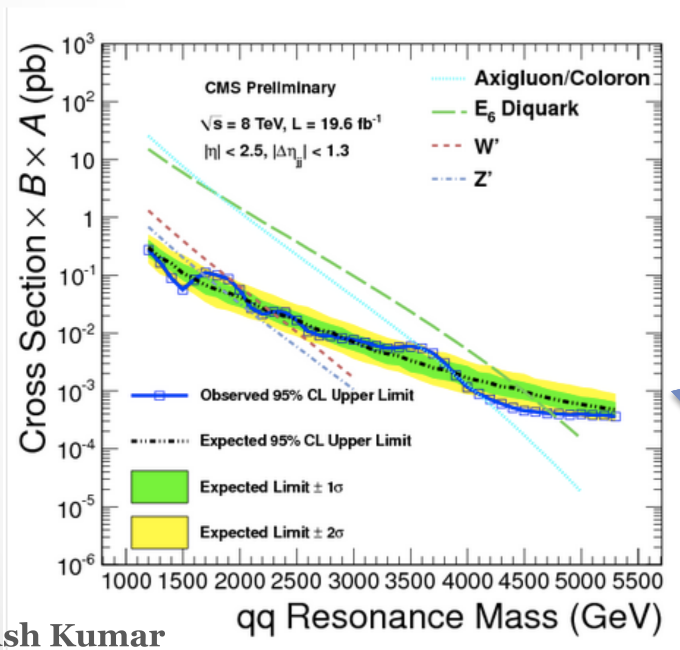
  *Anchordoqui, Goldberg, Lüst, Nawata, Steiberger, Taylor 0808.0497*

  **-- current bound $M_s$ >~ 5 TeV**

  *Also see Lüst, Taylor 1308.1619*




- **FCNCs impose stronger bounds generically**
- **Also, bounds on Z' (for isotropic)**




**$M_{Z'}$ >~ 2 TeV if Z' couples the same as Z**

# Effect of Higgs Discovery @ $M_H$ near 125 GeV

- EWSB can occur with $M_H$ suppressed relative to $M_s$ by loop factor

*Antoniadis, Benakli, Quiros NPB 583 (2000) 35*

*Antoniadis, Dimopoulos, Pomarol, Quiros NPB 544 (1999)503*

$M_s$ >~ 5 TeV

* So, $M_H$ in the correct range, however at tree-level : $M_H = M_Z$

* Need large corrections to Higgs Quartic λ to raise $M_H$ to 125 GeV, from KK and string modes (not clear if fully computable)

**Prospect : Does not seem likely, but may still be a possibility**

# II) (String-motivated) SUSY Models

**(with a high $M_s$)**

# SUSY Models

- **Favored by current Experimental Data over other approaches.**

**Reasons:**

**a) contain a Higgs-like boson with mass $M_h <\sim v_{EW}$**

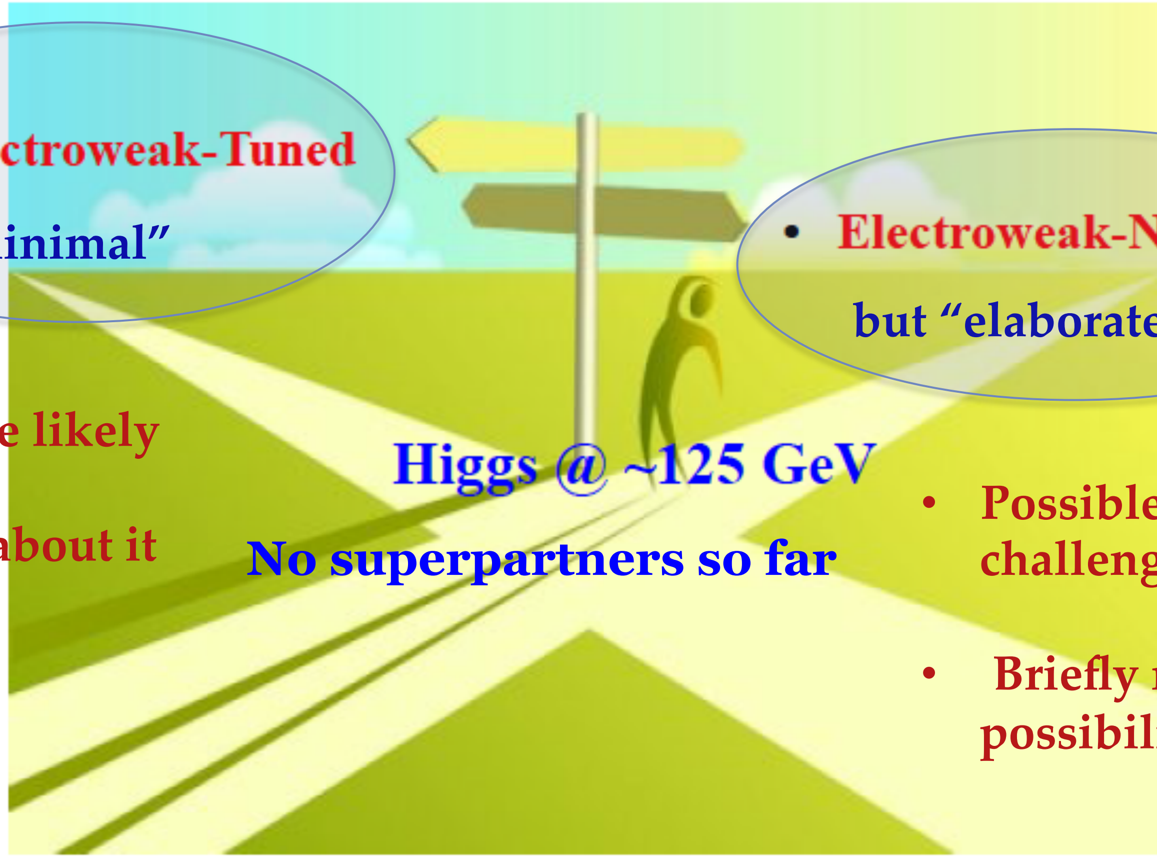
**b) possess a "decoupling limit" :**

**when $M_{soft} >> v_{EW}$, Higgs SM-like & superpartners heavy**

- **Of course, string theory → SUSY at microscopic level**

- **However, nature of favored SUSY models different from naïve expectations ….**

# At Crossroads.....



- **Electroweak-Tuned**

**but "minimal"**

- **Seems more likely**
- **Talk more about it**

**Higgs @ ~125 GeV**

**No superpartners so far**

- **Electroweak-Natural**

**but "elaborate"**

- **Possible, but challenging**
- **Briefly mention one possibility**

**More Data will Decide !**

# Electroweak-Tuned

- **Higgs Mass @ 125 GeV points roughly to two sub-classes**

**A) "Imperfectly" Natural**

* Scalar superpartners $M_{soft}$ – O(10-100) TeV
* Gauginos may be naturally suppressed by (moduli) dynamics
* Can explain **most** of the Hierarchy
* An unexplained Little Hierarchy remains

**B) "Mostly" Un-natural**

* $\lambda_H = 0$ at $M_{soft} \sim O(10^{10})$ GeV
* Gauginos may or may not be suppressed relative to $M_{soft}$
* Most of the Hierarchy is **NOT** explained – invoke fine-tuning

**Talk about both :**

**a) Basic characteristics b) Potential Experimental Signals**

# A) "Imperfectly" Natural

- **Question : What sets the mass-scale of the scalar superpartners?**

**Elegant Solution : Moduli Dynamics**

For "Generic" Kahler potential for Moduli & Matter Fields,

$$M_{modulus} \sim M_{soft} \sim M_{3/2}$$

*Denef, Douglas hep-th/0411183 ; Gomez-Reino, Scrucca hep-th/0602246 ; Acharya, Kane, Kuflik 1006.3272*

$M_{3/2}$ **= O(10-100) TeV**

* Can be obtained from Theory for O(1) choices of microscopic constants

*Acharya, Bobkov, Kane, **PK**, Shao PRD 76 2007, 126010*

* Moduli heavy enough to decay before BBN.

* Higgs mass can be successfully computed

*Kane, **PK**, Lu, Zheng PRD 85 2012, 075026*

- **If $H_{inf} > M_{3/2}$, then Moduli dominated Universe before BBN.**

  - Potentially important implications for Cosmology/Astrophysics,
    E.g. growth of substructure at small scales *Erickcek, Sigurdson 1106.0536*
    *Fan, Ozsoy, Watson 1405.7373*
  - Crucial implications for Dark Matter in terms of candidates, abundance, interactions

    **One example : "Non-thermal WIMP Miracle"** **Talk about DM later**

    *Moroi, Randall hep-ph/9906527; Acharya, Kane, PK, Watson 0908.2430, Many follow-up works in the literature*

- **What about gaugino masses?**

Gaugino masses naturally suppressed relative to scalars in many string frameworks:

*Choi, Falkowski, Nilles, Olechowski, Pokorski hep-th/0411066; hep-th/0503216*
*Conlon, Quevedo hep-th/0605141; Acharya, Bobkov, Kane, PK, Shao hep-th/0701034*

# A i) Collider Phenomenology of Framework with

# “Heavy” scalars & “Light” Gauginos

- Broad features applicable to all models in this framework.
- Precise constraints & signals depend on particular models.

# Constraints & Prospects @ LHC

- **Since light(er) particles – chargino, neutralino, gluino**

**-- Main Production Processes at the LHC:**

$$pp \rightarrow \tilde{g}\tilde{g} \quad \chi_2^0\chi_1^{\pm} \quad \chi_1^{\pm}\chi_1^{\pm}$$

**Strong** **Electroweak**

**Other channels, such as $X_1^0X_2^0$, $X_1^0X_1^0$, $X_2^0X_2^0$ more model dependent**

**-- Decays at the LHC:**

gluino $\longrightarrow$ $\chi_1^0 t\bar{t}$, $\chi_2^0 t\bar{t}$, $\chi_1^{\pm} b\bar{t}$, $t\bar{b}$ $\chi_2^0 b\bar{b}$, $\chi_1^0 b\bar{b}$

$X_2^0$ $\longrightarrow$ $X_1^0\ Z$ ; $X_1^0\ h$, ...

$X_1^+$ $\longrightarrow$ $X_1^0\ W^+$ ; ...

Again, precise BR's model-dependent

**Typical Final State: High $p_T$ multi-jets, >= 3 b jets + 0 or 1 lepton + $\not{E}_T$**

# Constraints and Future Prospects

- **Analysis of LHC data presented in terms of "simplified models"**

  -- assume 100% BR of $\tilde{g}$ to one channel, for e.g. $\tilde{g} \to \chi_1^0 t\bar{t}$

  -- Real Models → BR's to many channels can be non-trivial.

  -- Should compute bound on masses for each model.

**E.g. 1 : String-Motivated SO(10) Yukawa Unification Models**

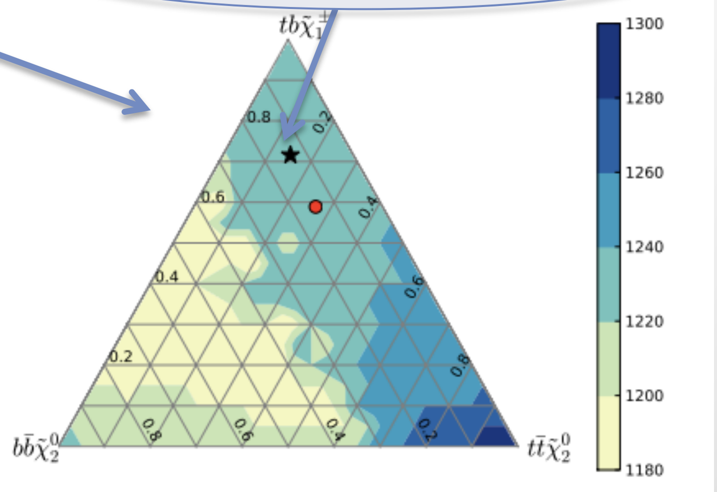
Bounds on Gluino Masses : *Raby 1309.3247*
*Anandakrishnan, Bryant, Raby 1404.5628, 1303.5125*

**E.g. 2 : M-theory motivated $G_2$-MSSM**

*S. Ellis, Kane : To be published*

**Similar technique** : $\mathbf{M_{gluino} > 0.9\text{-}1}$ **TeV**

Benchmark Models



**Implicit Assumption:** **Gluino reasonably heavier than the LSP**

→ **jets, leptons "hard", i.e. have large $p_T$.**

- **However, if Gluino and LSP close in mass, then**

  **-- spectra "compressed"**

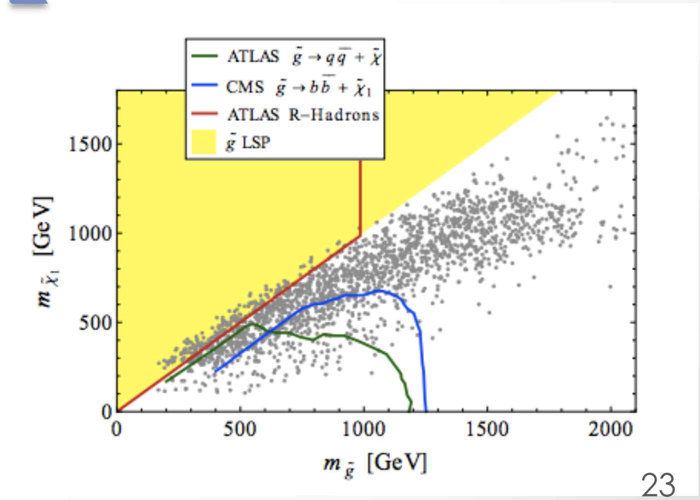
  **-- jets & leptons "soft", many do not pass cuts.**

**Eg :** **"Mirage Mediation Models" with Precision Gauge Unification**

*Choi, Jeong, Kobayashi, Okumura hep-ph/0508029*

*Krippendorf, Nilles, Ratz, Winkler 1306.0574*

Also see Pheno. Papers on 'compressed SUSY'




- Gluino bounds considerably relaxed.
- Gluino may be long-lived (10μm – 1 mm)
- Co-annihilation effects important
  for LSP annihilation in early Universe.

# Prospects @ ~100 TeV Collider

*I. Antoniadis' Talk*

- **LHC sensitive to gluino masses <~ 2-2.5 TeV.**
- **A larger CM-Energy Collider will increase the reach.**
- **Studies quite preliminary. Lot to do .**

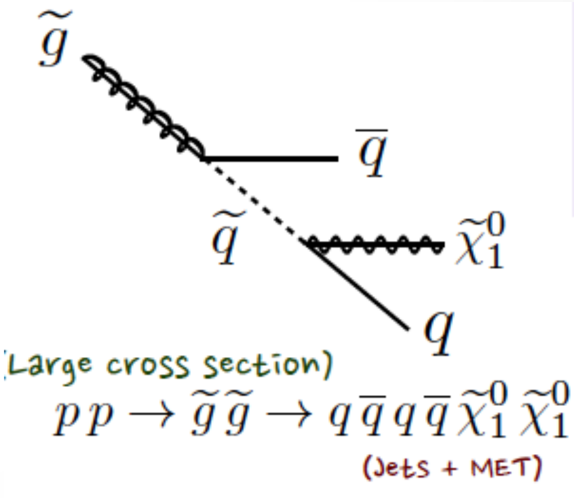
*Cohen et al 1311.6480*

- **Some work done for "simplified models"**

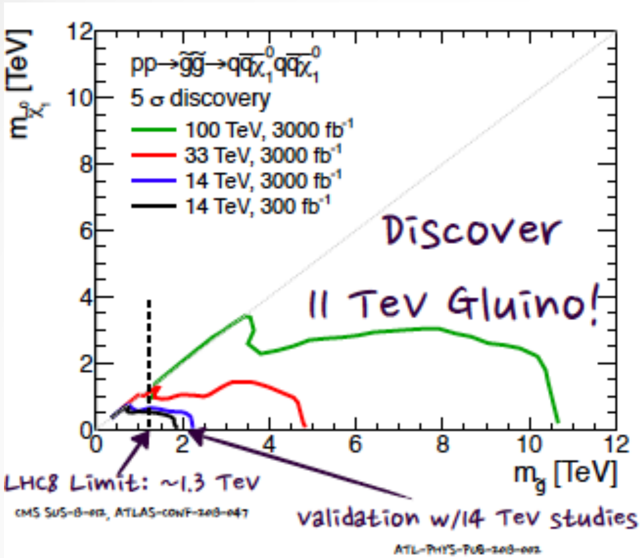
**E.g. Gluino-Neutralino Simplified Model**

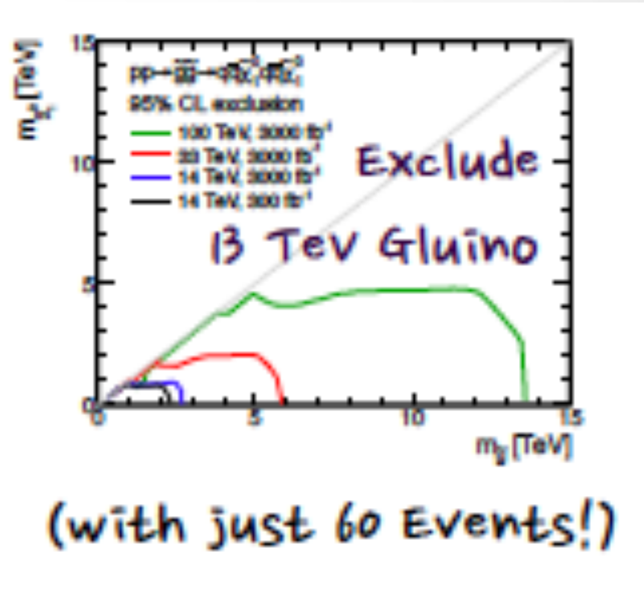
**Final State : Multi-jets + No Leptons + $\not{E}_T$**

**Dominant Background : t tbar + jets**
**(in contrast to W/Z+jets @ LHC)**



- **Significant improvement compared to the LHC** *Cohen et al 1311.6480*




- **What about stops & heavier electroweak-inos?**

**-- No detailed studies yet.** *Acharya, Bozek, Pongkitivanichkul,Sakurai: To appear*

**-- May be possible to detect these for $M_{3/2}$ <~ 30 TeV**

*** LHC has a good chance of discovering "Imperfect-Naturalness"**

*** 100 TeV collider would be a wonderful development**

**- would greatly help in confirming/ruling out the above and also other ideas**

# B) "Mostly" Un-natural

*L. Ibanez's Talk*

* **Basic Motivation:**

**SM -- well-known that certain values of Higgs Mass can be tied to vanishing of Higgs quartic λ at some High scale.**

**Higgs near 125 GeV – λ vanishes at M ~ $10^{10}$ GeV**

**(uncertain due to $M_{top}$ uncertainty)**

*Elias-Miro et al 1112.3022 ; Holthausen et al 1112.2415; Wetterich 1112.2910,...*

Most of the Hierarchy NOT explained, just fine-tuned

- **Proposal:**

**~~SUSY~~ @ High scale $M_{soft}$ such that $\lambda(M_{soft})$ → 0 at $M_{soft}$**

**But** $$\lambda(m_S) = \frac{g^2(m_S) + g'^2(m_S)}{8} \cos^2 2\beta$$ → **tan β = 1 @ $M_{soft}$**

**Can be motivated from theoretical approaches:**

*Hebecker, Knochel, Weigand 1204.2551; 1304.2567*

*Ibanez, Marchesano, Regalado, Valenzuela 1206.2655; Ibanez, Valenzuela 1301.5167*

- ~~SUSY~~ at M ~ $10^{10}$ GeV can be combined with Gauge Unification in F-Theory : **Both scales can be related**

$$M_{SS} = ((2g_s)^{1/2}/\alpha_G^{1/2})\frac{M_c^2}{M_p}$$

**Unification @ $M_c$ ~ $10^{14}$ GeV with threshold corrections.**

*Ibanez, Marchesano, Regalado, Valenzuela 1206.2655*

*Camara, Ibanez, Valenzuela 1404.0817*

- **Can give rise to QCD Axion with decay constant $F_a$ ~ $10^{12}$ GeV**

- **However, proton decay with a low Unification scale a challenge**

*Hebecker, Unwin 1405.2930*

***"Fake Split-SUSY"*** – *Goodsell's talk.*

*Hebecker's talk*

## Experimental Probes (if no light fermions)

- **Precise Measurements of Higgs & Top Mass & couplings.**
- **Possible discovery of QCD Axion DM in ADMX with $F_a$ ~ $10^{12}$ GeV.**
- **Observation of Proton Decay.**

# “Electroweak-Natural”

- **As mentioned earlier, current data makes it challenging to realize this possibility.**
- **However, Nature may still work this way. Within SUSY, have to go beyond the MSSM :**

**-- Additional contributions to Physical Higgs Mass**

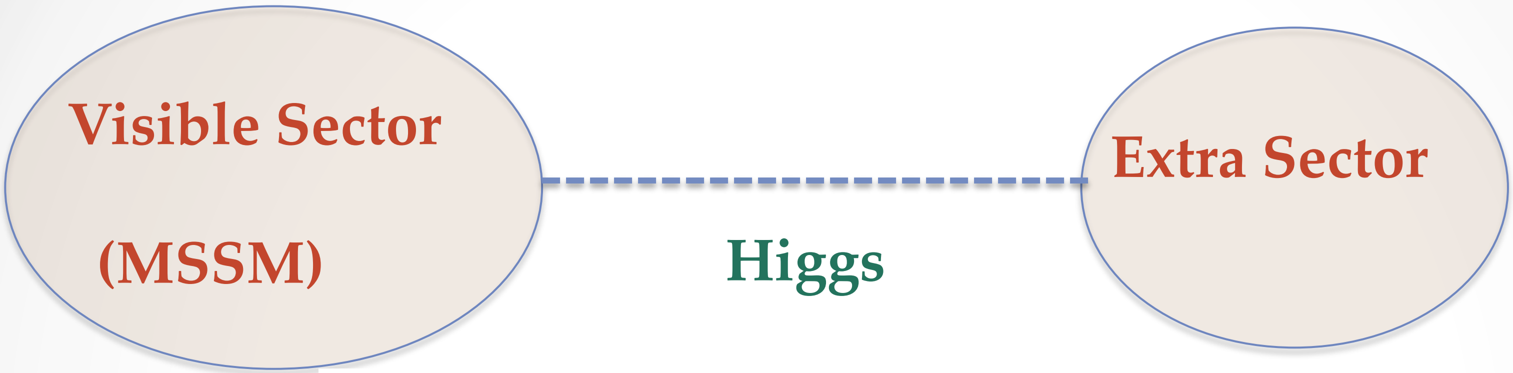
**-- New contributions to the Higgs potential**

* **may improve naturalness of EWSB**

**-- No Beyond-the-SM physics so far → models more "elaborate"**

- **Fully explicit and viable models hard to construct. Nevertheless many attempts in literature.**
- **Talk about one possibility.**

# “Holomorphic” Higgs Portal




$$W = \lambda_u \mathcal{H}_u \mathcal{O}_u + \lambda_d \mathcal{H}_d \mathcal{O}_d .$$

Higgs couples to operators in the Extra sector (in the superpotential).

$O_u$, $O_d$ -- part of SUSY breaking sector or part of messenger sector which couples to another SUSY sector -- extension of Gauge Mediation to Higgs sector.

Such terms considered in various field-theoretic contexts ...

*Azatov et al 1106.3646,1106.4815; Kitano et al 1206.4053; Stancato et al 0807.3961 Gherghetta, Pomarol 1107.4697; Komargodski, Seiberg 0812.3900; Craig et al 1302.2642, Knapen et al 1311.7107, Schafer-Nameki et al 1005.0841, ....*

- **Setup could arise naturally in a class of string frameworks**

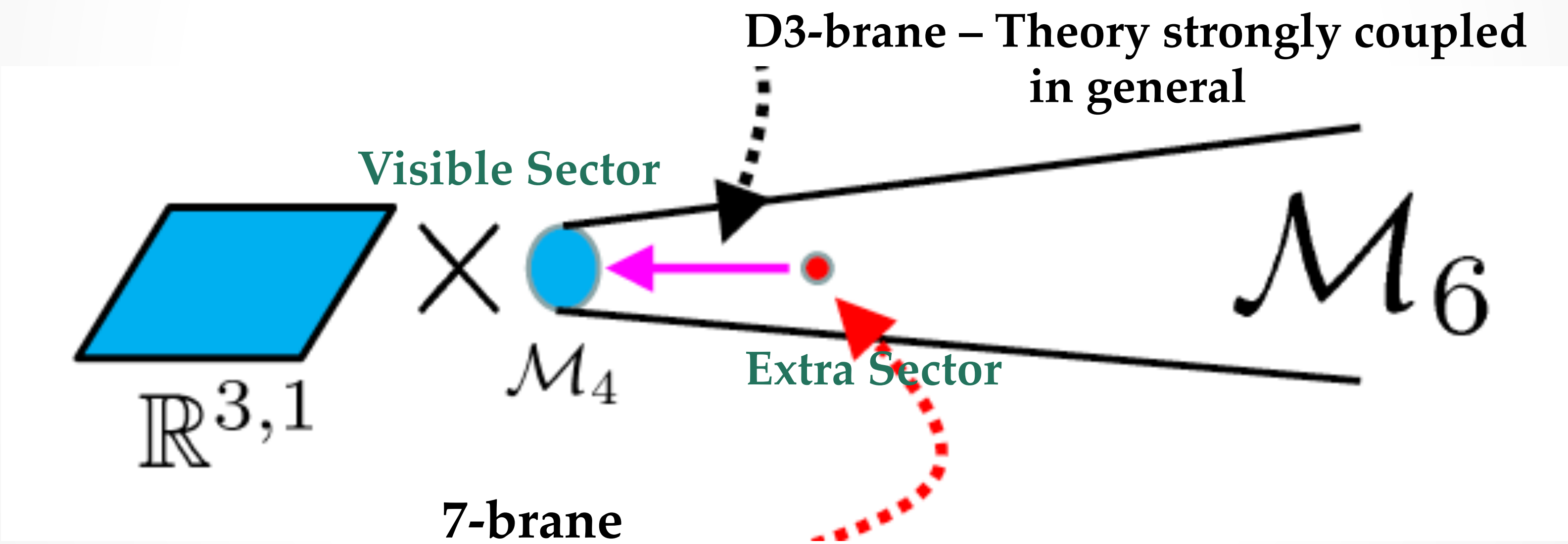
  **"F-Theory" --- 7-brane probed by a D3-brane**

*Heckman, Vafa 1006.5459*

*Follow-ups with collaborators*

Visible Sector

Extra Sector




**Local Model -- study region in which D3-brane is close to the 7-brane**

# Phenomenologically interesting Features

-- Higgs Potential could change relative to the MSSM

*Heckman, PK, Vafa, Wecht JHEP 1201 (2012)*

-- Consistent with gauge coupling unification in the MSSM.

*Heckman, Vafa, Wecht 1103.3287*

-- Possible to compute Higgs couplings : *(Using SUSY, Holomorphy & Gauge invariance)*

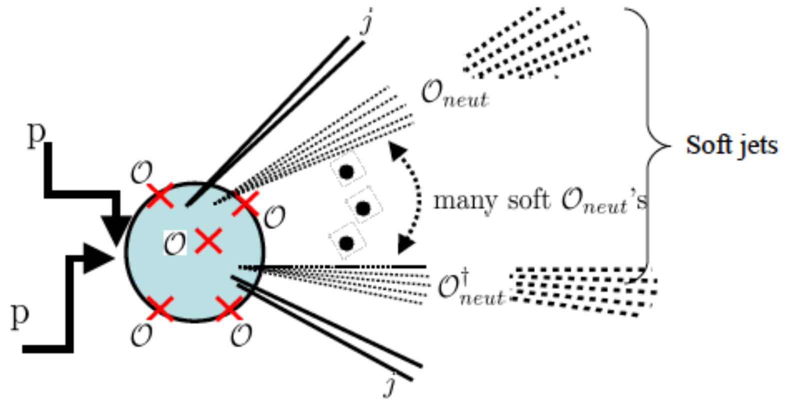
*Heckman, PK, Wecht 1204.3640; Heckman, PK, Wecht 1212.2979*

**MSSM coupled to sector which is superconformal in the UV :**

-- Imagine conformal symmetry broken with a "mass-gap" M and ~~SUSY~~ at scale $(F)^{1/2}$.

-- very interesting to understand this dynamically.

**Possible Collider Signal :**




**interesting to explore …**

RPV RPV

**III) To ~~be~~, or not to ~~be~~ , that is the question…**

- **Until now, implicitly assumed R-parity conservation.**

- **However, possibility of R-parity violation quite interesting:**

  **-- LSP no-longer stable.**

  **-- Significant reduction in missing $E_T$ @ LHC**

  → **constraints on superpartners weakened.**

  **-- Viable RPV models can be constructed phenomenologically**

- **What about R-parity violation from top-down point of view?**

**Talk about : i) SU(5) GUT models, ii) SO(10) GUT models.**

*B. Ovrut's Talk*

Any RPV disfavored

Spontaneous RPV a possibility

- **SU(5) GUTs:** **appealing due to simplicity**

-- GUT breaking to $G_{SM}$ and doublet-triplet splitting.

→ employ some global symmetry H′ arising in string theory

-- To solve $\mu/B\mu$ problem, either by KN/CM or GM mechanism.

*Kim, Nilles PLB138 (1984) 158; Casas, Munoz hep-ph/9302227; Giudice, Masiero PLB206 (1988) 480*

H′ forbids $\mu$ parameter at High scale, but H′ must be broken to $H \subset H'$

**True in both Heterotic orbifolds & M-theory constructions**

*Kappl, Nilles, Ramos-Sanchez, Ratz, Schmidt-Hoberg 0812.2120;*
*Lee, Raby, Ratz, Ross, Schieren 1009.0905; 1102.3595;*
*Chen, Ratz, Staudt, Vaudrevange 1206.5375; Witten hep-ph/0201018;*
*Acharya, Kane, Kuflik, Lu 1102.0556*

*M. Ratz's Talk*

**Then, can show that bilinear RPV coefficient $\kappa$ in $\int d^2\theta \kappa \, L H_u$ is such that**

either a) $\kappa/\mu = O(1)$ (H is trivial), or b) $\kappa/\mu = 0$ (H equivalent to R-parity)

*Acharya, Kane, **PK**, Lu, Zheng 1403.4948*

**But stringent constraints on bilinear RPV from neutrino masses : $\kappa/\mu <\sim 10^{-3}$**

**R-parity violation disfavored**

**Any observation of R-parity violation → disfavor above class of Models**

- **SO(10) GUTs :**

  **-- appealing, since 16 of SO(10) contains all SM particles + RH neutrino.**

**Eg : $E_8 \rightarrow SO(10) \rightarrow G_{SM} * U(1)_{B-L}$**

**Heterotic M-theory : "Exact" MSSM spectrum -- Minimal**

*Braun, He, Ovrut, Pantev hep-th/0501070; hep-th/0512177;hep- th/0602173*

- **$U(1)_{B-L}$ must be broken to make $Z_{B-L}$ sufficiently massive.**

- **Since only candidate $\langle \tilde{\nu}^c \rangle$ has odd B-L,**

**→ R-parity, a $Z_2$- even subgroup of B-L, is spontaneously broken**

**For $\langle \tilde{\nu}^c \rangle$ to obtain a pheno. viable vev, need :**

**-- large flavor-dependent non-universality in the sneutrino soft masses relative to that for sleptons & selectrons**

*Amboroso, Ovrut, 0910.1129; Acharya, Kane, PK, Lu, Zheng 1403.4948*

**→ Option: Have extra 10's, 16's of SO(10)**

*Acharya et al : To appear*

# Broad Experimental Signals

*B. Ovrut's talk*

- **$Z_{B-L}$ gauge boson with mass >~ few TeV**
- **Existence of two light RH neutrinos.**
- **Leptonic RPV through the L $H_u$ operator**

→ **"LSP" can decay. Also, "LSP" can be charged or colored.**

- **Neutrino-Neutralino Mixing**

**-- generate majorana neutrino masses at tree level.**

- **Can also have correlation between LSP decays & Neutrino Hierarchy !**

*Marshall, Ovrut, Purves, Spinner 1401.7989, 1402.5434*

**More details/signals should be explored….**

# III) Dark Matter

**(motivated from String Theory)**

** B. Dutta's Talk*

# The Dark Matter Zoo

**Just an illustration – many more candidates possible …**

**Most popular candidates –**

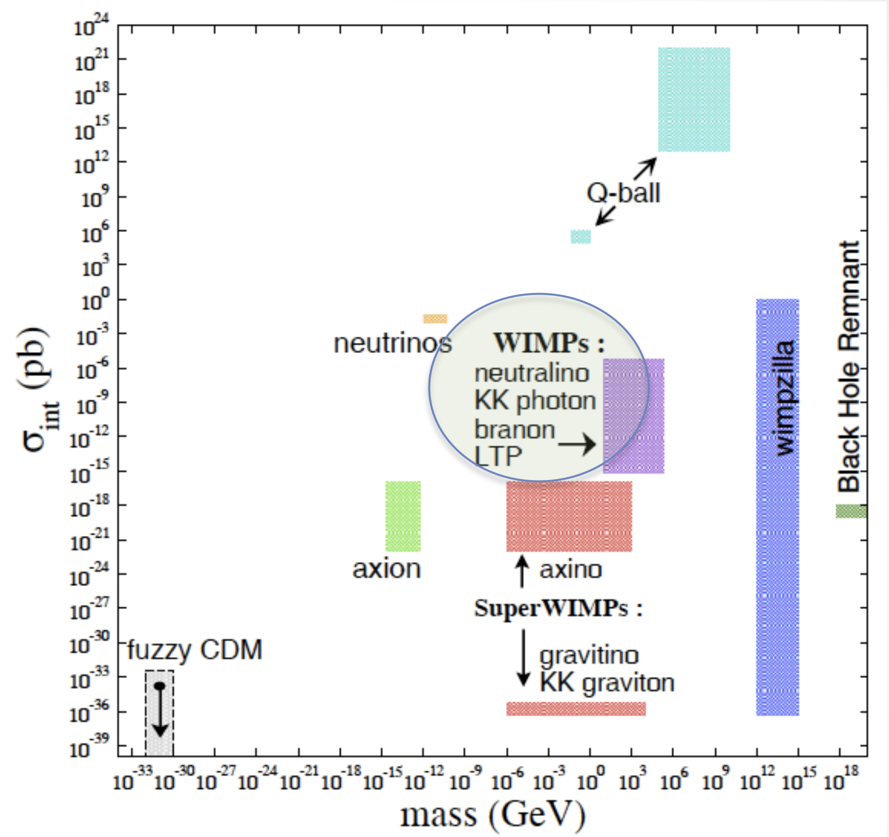
**WIMPs & Axions**

- **String Axions – many talks**

  **-- could be important during inflation.**

  **-- could also naturally comprise Dark Matter.**

*Arvanitaki et al 0905.4720*
*Acharya, Bobkov, PK 1004.5138*
*Cicoli et al 1206.0819; Arias et al 1201.5902*
*Allahverdi et al 1401.4364; Honecker et al 1312.4517, Sik Jeong et al 1310.1774;*
*Many others..*




*Gardner et al 1303.4758*

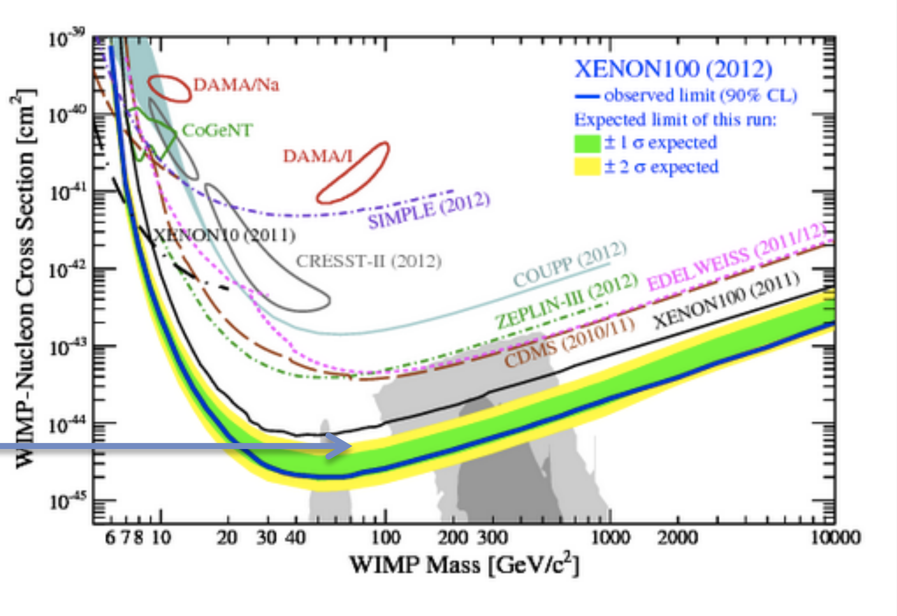
**Proposal to detect QCD axion with GUT scale $F_a$**
*Graham, Rajendran 1306.6088*

**Finally, Axions can be Dark Radiation**
*Talks by D. Marsh, Angus, Pongkitvanichkul*

# (SUSY) WIMPs – minimal, since part of BSM Model.

## Direct Detection

- **Many hints in the past few years**
- **All of them killed by LUX**
- **A large chunk of SUSY WIMP parameter space ruled out, and large chunks still left..**



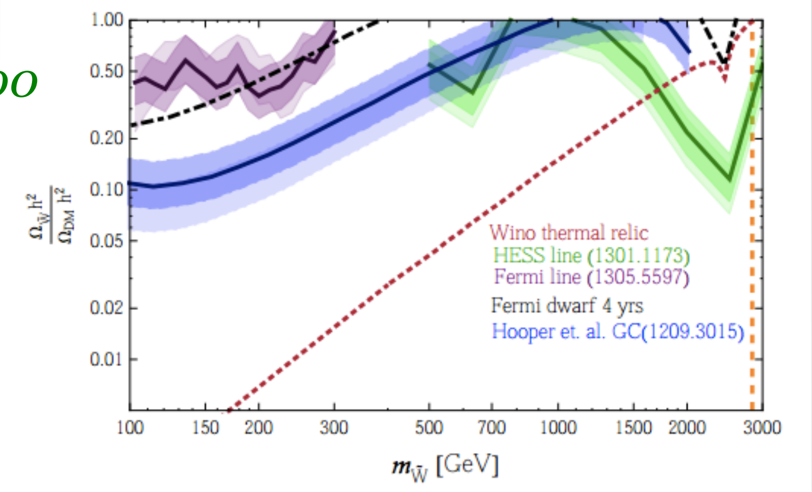

**Example of SUSY WIMP not ruled out by direct detection – Wino LSP,**

-- Winos do not interact via Z-exchange or Higgs-exchange at tree level.
-- Winos can also give rise to the correct abundance via the "non-thermal WIMP miracle"

**However, …**

# Indirect detection

*Fan et al 1307.4400*




**Latest bounds disfavor Wino DM.**

**E.g. FERMI diffuse γ from Galactic Center**

**Also, recent hints for WIMP indirect detection less convincing now**

* 130 GeV "γ–line" from GC
* PAMELA Antipositron fraction from nearby region of Milky way.

**Although LSP-WIMPs still viable,**

-- Constraints more & more stringent.

-- In some sense, "Lamp-post" Physics.


**Worth considering other approaches**

# Dark Sectors

**Motivation :**

- **Additional sectors in String Theory very common/natural.**

**-- UV completion of SM has additional gauge/matter spectra in most cases.**
**-- String-consistency conditions "demand" it.**

**E.g. Hidden $E_8$ in Heterotic, RR-Tadpole cancellation in Type II.**

**Dark Matter could naturally be part of these additional sectors.**

- **Some "common" observations :**

*Many talks on massive U(1)s in string theory*

**-- Extra U(1) gauge bosons** -- **Z′ (massive) , γ′ (massless)**

**a) Z′ – Stuckelberg; b) Z′ –Higgs; c) γ′ - massless**

**-- Hidden sector DM or "Light" Messenger DM**

*Cvetic, Halverson, Piragua 1210.5245; Feng, Shiu, Soler, Ye 1401.5880, 1401.5890; Halverson, Orlofsky, Pierce 1403.1592; Many others….*

# Portals


*Talks by Marchesano, Ramos-Sanchez, Mehta*

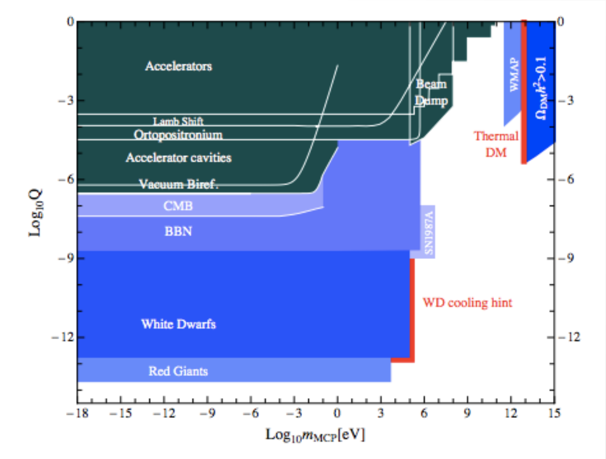
**Kinetic Mixing :** $L \supset \int d^2\theta\, \epsilon W_Y W_X + h.c.$

- **Marginal coupling** ⟶ **If generated, will persist to low energies**

- **Phenomenology depends on {$M_{A'}$, ε} & {$M_\chi$}**

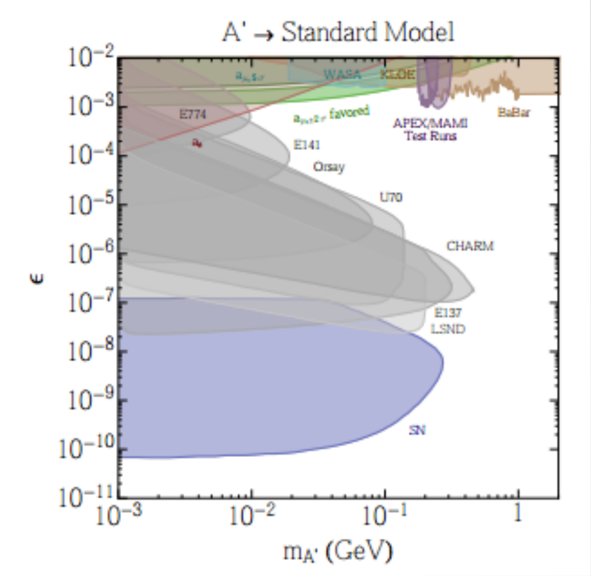
  **a) $M_{A'}$ = 0, Hidden sector fields acquire milli-charge ~ ε.**

*Holdom PLB 166 (1986); Banks, Seiberg 1011.5120; Abel, Schofeld hep-th/0311051, Marchesano et al 1406.27*



**b) $M_{A'} \neq 0$. Variety of $\{M_{A'}, \varepsilon\}$ can be generated.**

*Abel et al hep-ph/0608248, 0803.1449;*
*Goodsell et al 0909.0515; 11110.6901; Cicoli et al 1103.3705*




**Dark Gauge boson will have small coupling ~ ε to visible sector & vice-versa**

**Interesting Consequence:**

**"LSP" will decay to Dark Sector before BBN even with R-parity conservation.**

**E.g. Bounds on Winos can be evaded**

**Mass Mixing :**

-- **Physical Z' eigenstates: generically couple with O(1) strength to SM fermions**

*Feng, Shiu, Soler, Ye 1401.5880, 1401.5890*

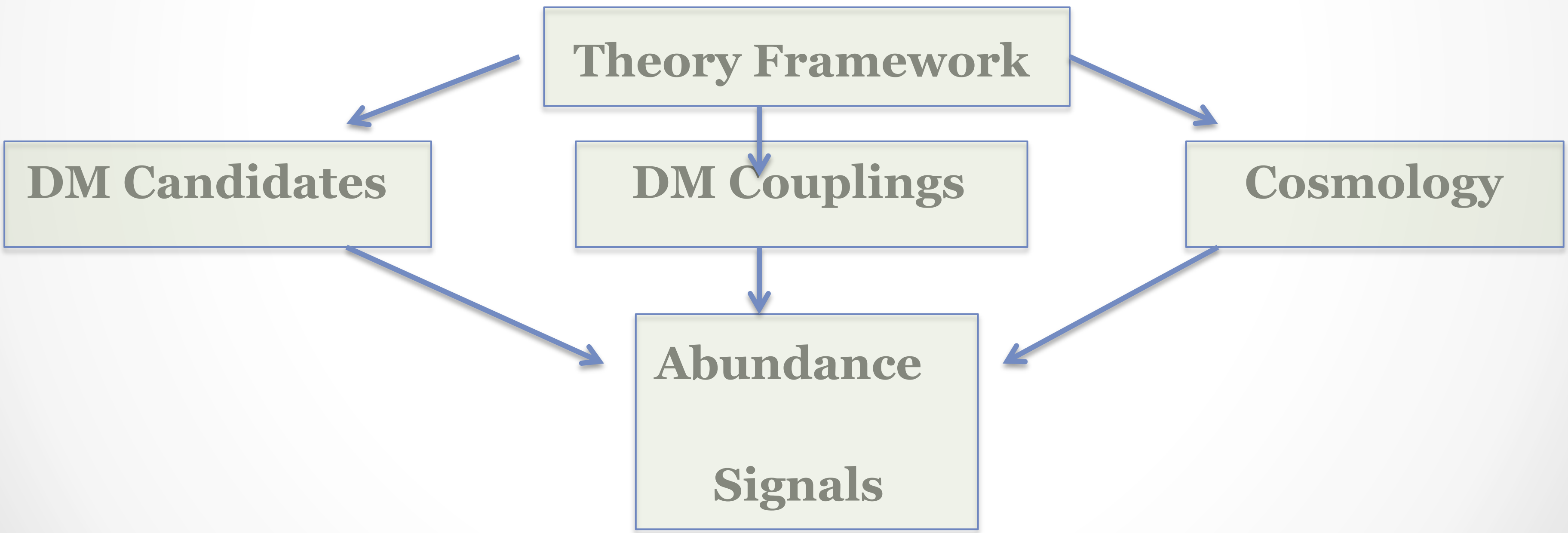
-- $M_{Z'}$ can only be suppressed by a few orders of magnitude relative to $M_{string}$.

-- Phenomenologically relevant only for low string scale.

-- Bound on $M_{Z'}$ >~ few TeV

# Only the tip of the DM Iceberg…

- **Until now, only talked about $U(1)_{dark}$**
- **Many other possibilities : $G_{dark}$ ; $G_{dark}$ * $U(1)_{dark}$ ; $G_{dark}$* $G_{flavor}$ ; ….**
- **Important and useful to have well-motivated theoretical guide**




**Tons to explore …**

# Summary & Concluding Remarks

- **We are living in a data-rich era.**

  **-- Data, even if "Null", can provide important insights.**

- **Talked about some aspects of recent data in High-energy physics, and the insights it provides for string-motivated frameworks vis-à-vis :**

  **-- Higgs and Beyond-SM physics.**

  **-- Dark Matter Physics.**

- **SUSY still the most probable framework for Beyond-SM physics.**

  **-- However, SUSY models different from what naively expected.**

  **-- Most "simple" models appear to be "electroweak-tuned"**

  **Imperfectly Natural** | **Mostly Un-natural**

  **-- Studied potential signals of each**

- **R-parity violation** – interesting implications for string-GUT models.

  * Observation of RPV will disfavor SU(5) GUT models.
    (with mild assumptions)
  * SO(10) models compatible with *spontaneous* RPV in principle
    -- can give rise to interesting signals.

- **Dark Matter** -- Variety of possibilities

  * Status of LSP WIMP DM -- still viable but under increasing strain.

  * Worth looking at other frameworks:

    E.g. Dark Sectors very well motivated

    -- incredible array of possibilities, just scratched the tip …
    -- very important to have an underlying theoretical framework for understanding different aspects in a coherent manner.

- **“Electroweak-Natural” Models seem rather challenging.**

**-- Should not give up hope, however. May still be possible…**

**Think outside the Box !**

- **Hope that Nature is kind to us and provides us with opportunities to make String Theory an experimental science.**