DARK MATTER IN EARLY LHC DATA

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West Coast ATLAS Forum
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OUTLINE

- Long-Lived Charged Particles
  - SuperWIMP DM
  - Feng, Rajaraman, Takayama (2003)
- Delayed Photons/Diphotons
  - Light Gravitino DM
  - Lee, Feng, Kamionkowski (in preparation)
- Exotic 4th Generation Quarks
  - WIMPless DM
  - Alwall, Feng, Kumar, Su (1002.3366 hep-ph)

DARK MATTER

As motivation for new collider physics:

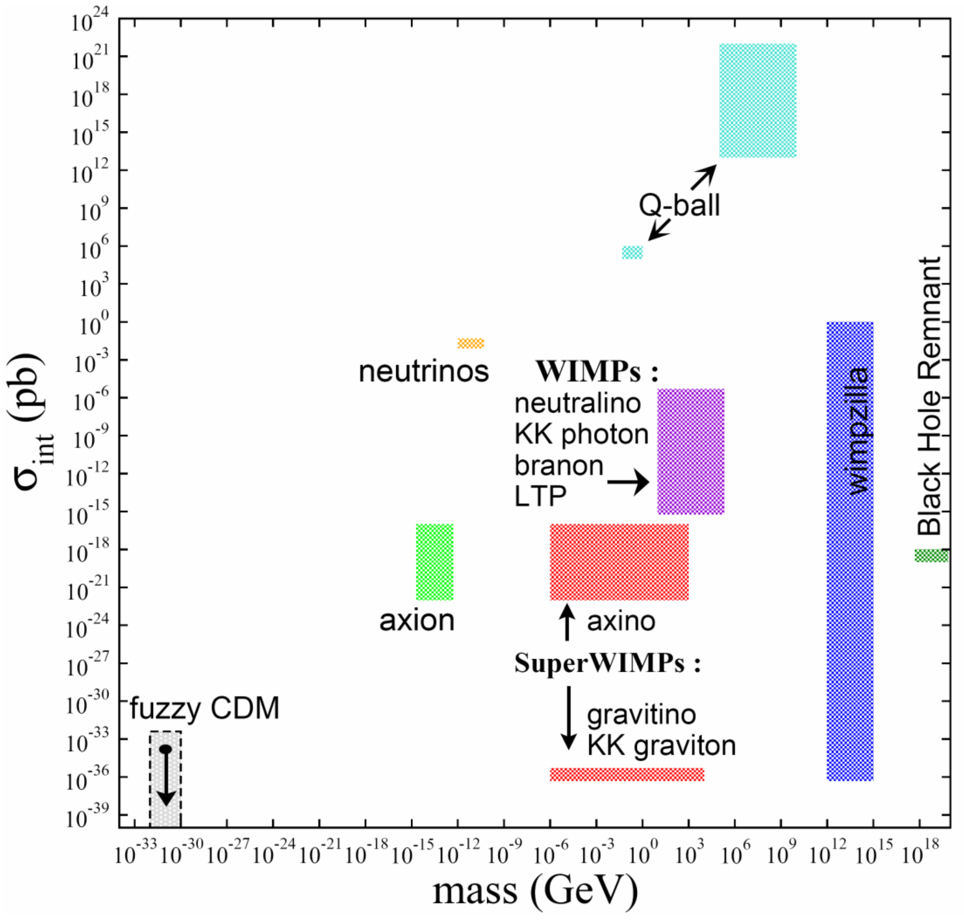
- Not only an aesthetic problem
  - Unlike cosmological constant, gauge hierarchy problems
- Indications it is linked to weak-scale physics
  - Unlike neutrino mass, baryogenesis
- Interesting
  - Highly interdisciplinary, inner space-outer space connections

DARK MATTER CANDIDATES

- The observational constraints are no match for the creativity of theorists

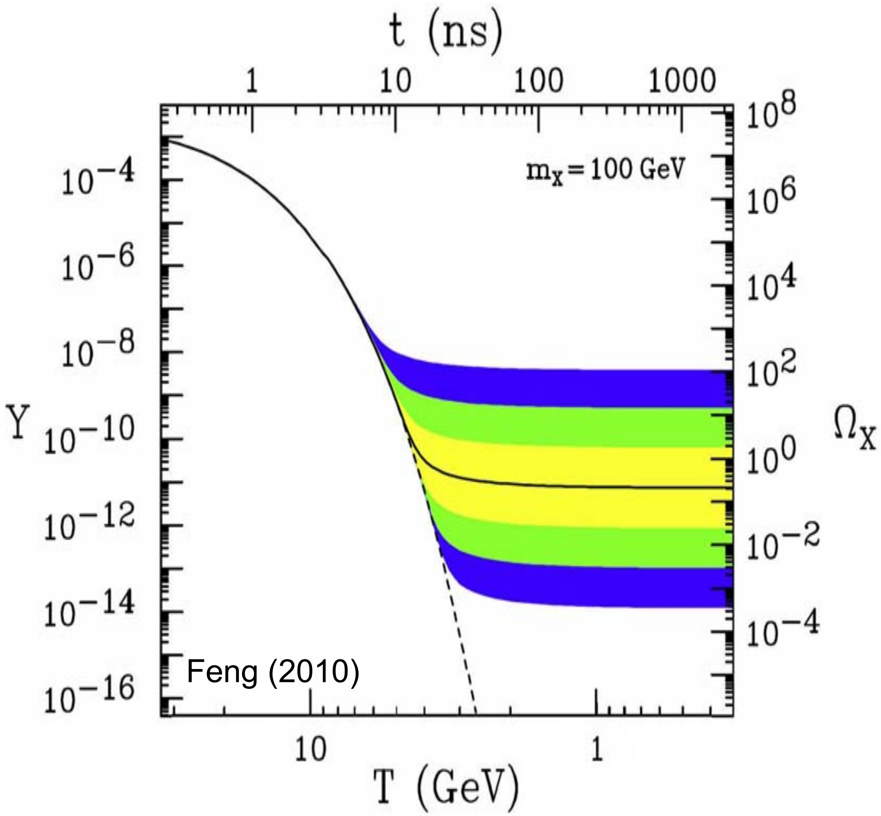
- It could be axions, WIMPzillas, etc., in which case the LHC will have very little to say

"Dark Matter Particle Candidates and Methods of Detection," 1003.0904, to appear in ARAA



HEPAP/AAAC DMSAG Subpanel (2007)

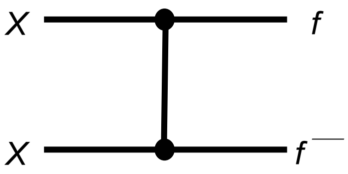
DM @ LHC: RELIC DENSITY



Feng (2010)

- The resulting relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6$ → $\Omega_X \sim 0.1$

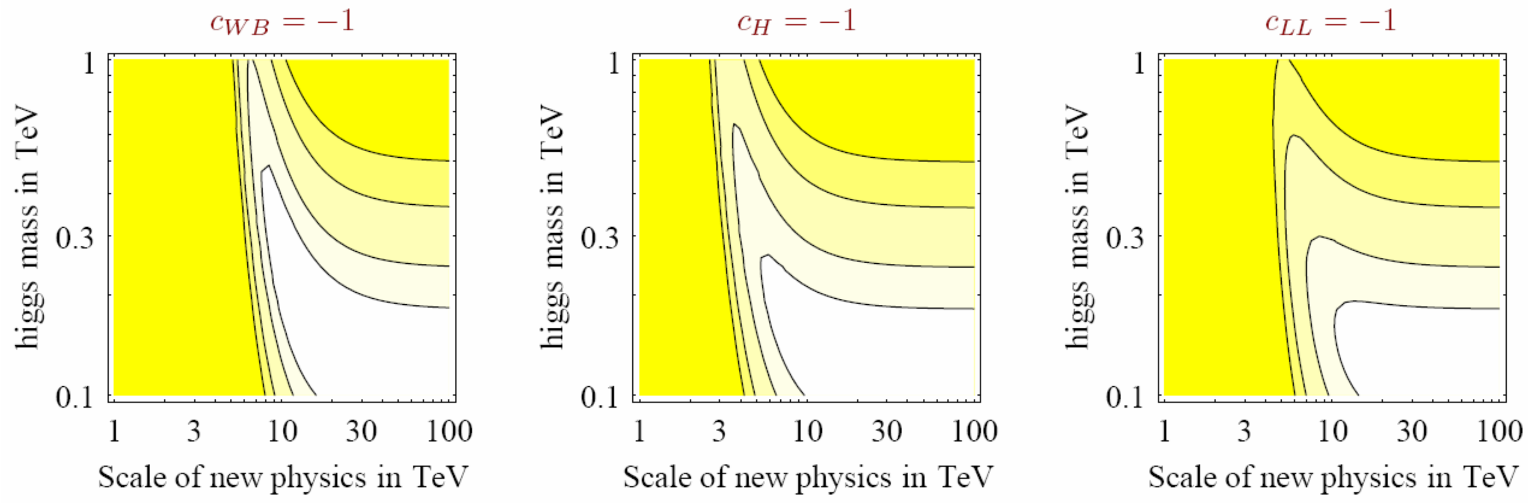
- WIMP miracle: weak-scale particles naturally have the right density to be dark matter

DM @ LHC: STABILITY

- The WIMP miracle assumes a new particle is stable. Why should this be?

- LEP and SLC confirmed the standard model, stringently constrained effects of new particles

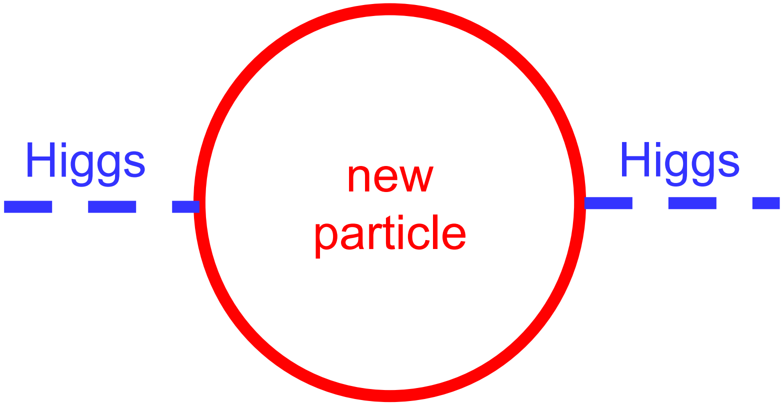
- Problem: Gauge hierarchy → new particles ~100 GeV
  LEP/SLC → new particles > 3 TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)



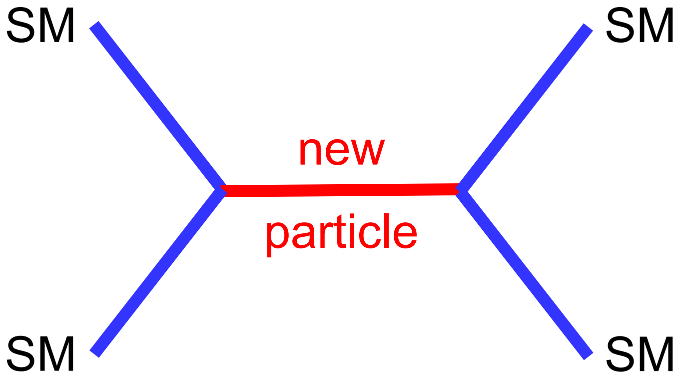
Barbieri, Strumia (2000)

LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy



Precision EW



- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

Cheng, Low (2003); Wudka (2003)

- This is a general argument that the LHC may make DM.

- In specific contexts, this may be augmented by additional arguments. E.g., in SUSY, proton decay → R-parity → stable LSP.

EXAMPLES

Supersymmetry

- R-parity

Fayet, Farrar (1974)

- Neutralino DM

Goldberg (1983)
Ellis et al. (1984)

Universal Extra Dimensions

- KK-parity

Appelquist, Cheng, Dobrescu (2000)

- Kaluza-Klein DM

Servant, Tait (2002)

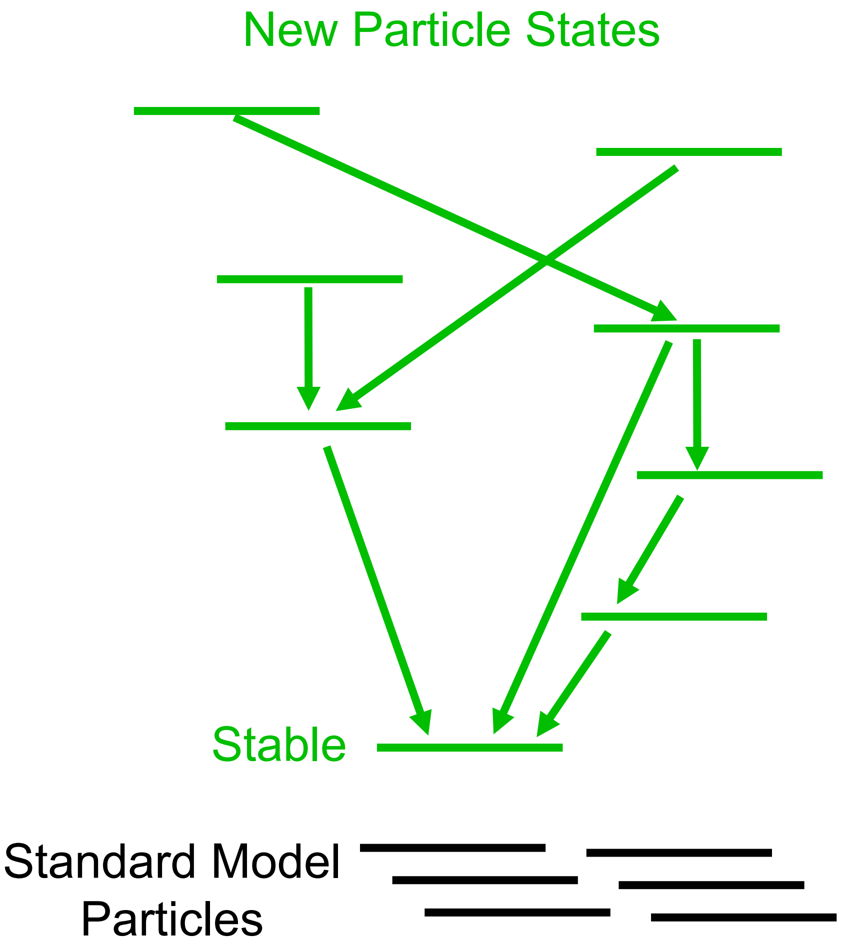
Cheng, Feng, Matchev (2002)

Branes

- Brane-parity
- Branons DM

Cembranos, Dobado, Maroto (2003)

…



THE STANDARD LORE

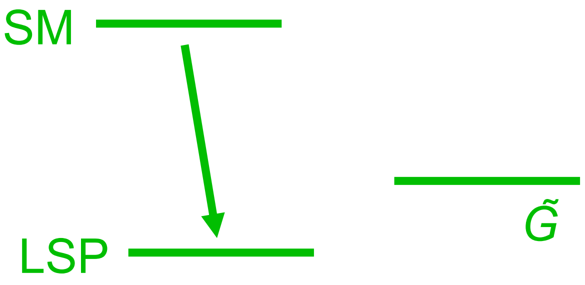
- These observations have led to the commonly heard statement that DM implies MET at the LHC.
- This is unfortunate: MET is not so great for early discoveries, even worse for precision studies.
- Fortunately, it’s also wrong. There are great many other possibilities; focus here on possibilities for early discoveries, spectacular signals.

SUPERWIMP DM

Feng, Rajaraman, Takayama (2003)

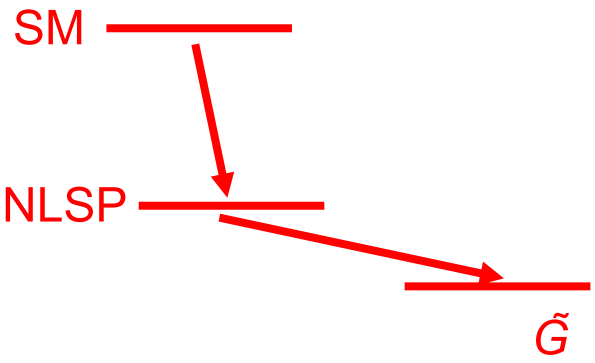
Consider (high-scale) supersymmetry. There is a gravitino, mass ~ 100 GeV, couplings ~ $M_W/M_{Pl} \sim 10^{-16}$

- $\tilde{G}$ not LSP



- Assumption of most of literature

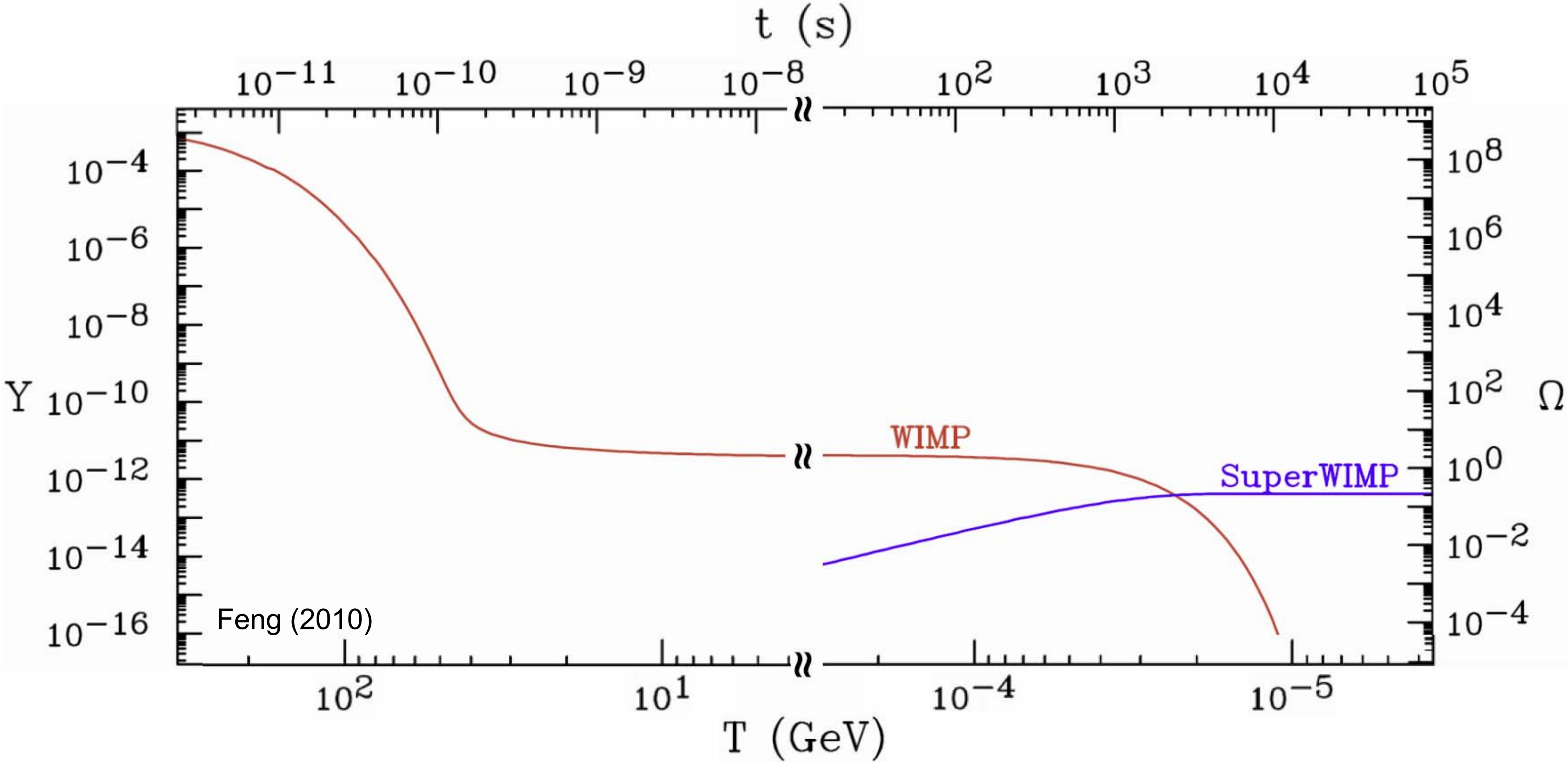
- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS

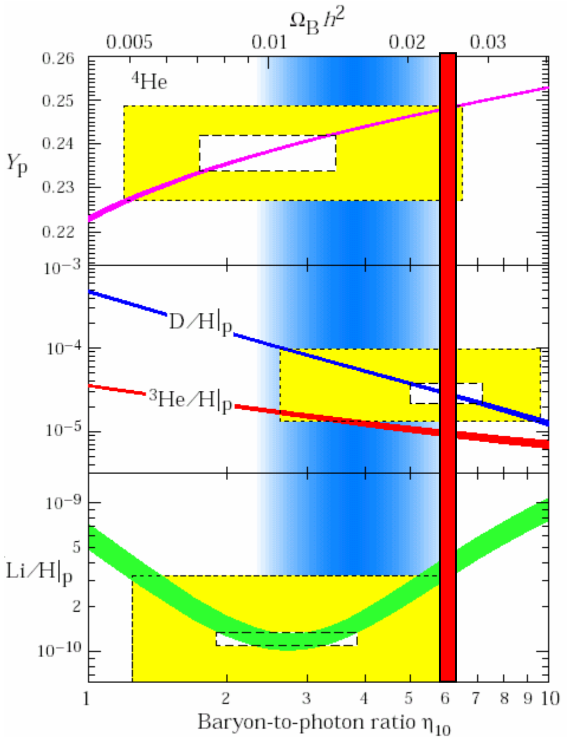
- Consider $\tilde{G}$ LSPs: WIMPs freeze out as usual, but then decay to $\tilde{G}$ after M_{Pl}^2/M_W^3 ~ seconds to months



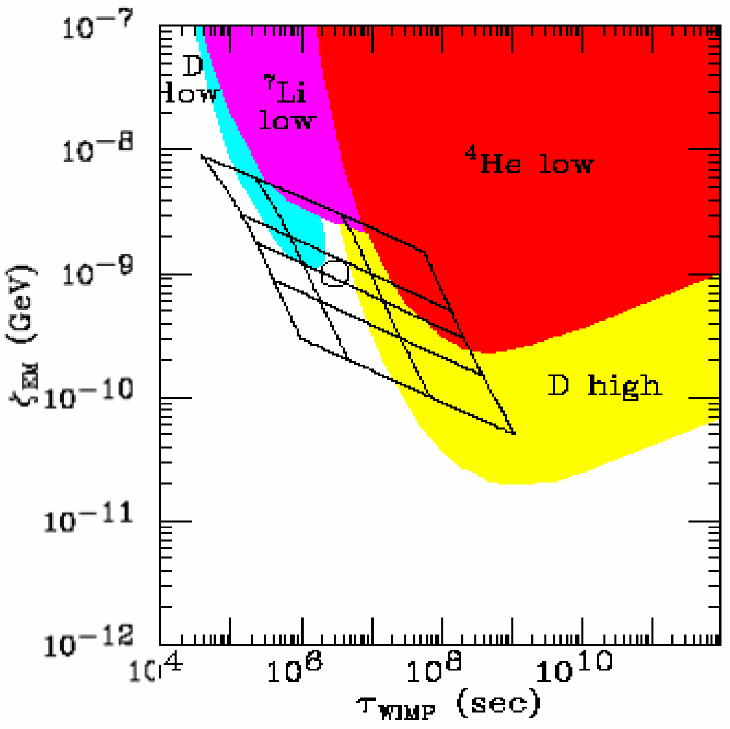
Feng (2010)

COSMOLOGY OF LATE DECAYS

Late decays impact light element abundances



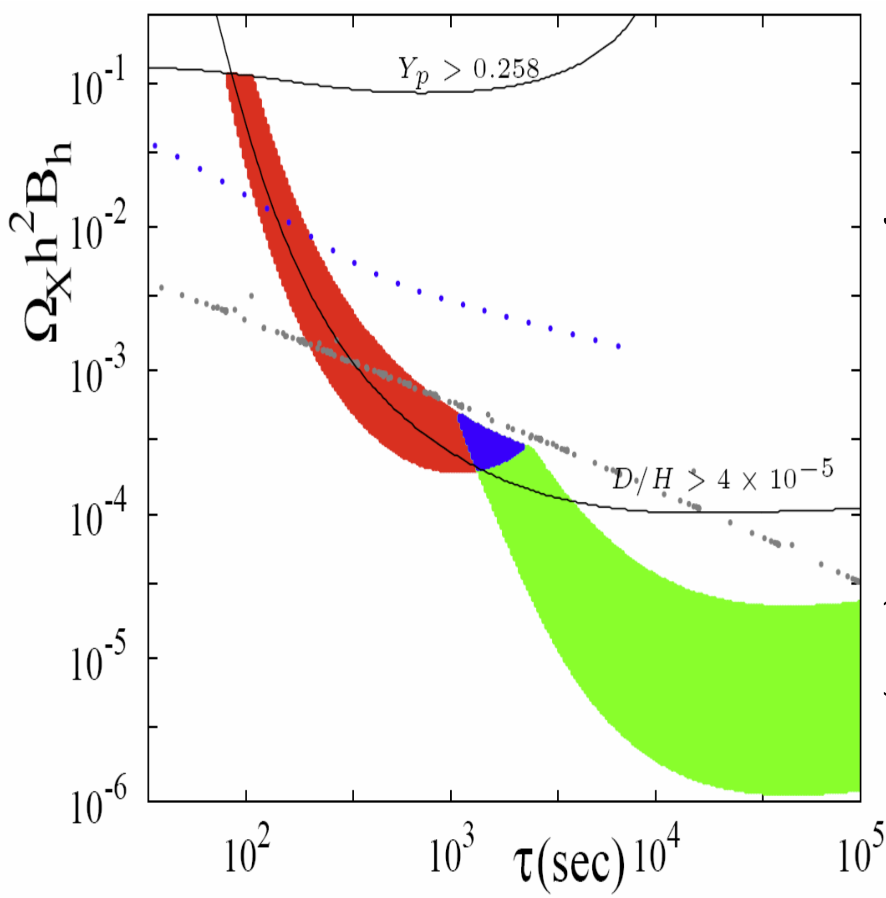
Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

- Lots of complicated nucleoparticlecosmochemistry
- BBN typically excludes very large lifetimes
- BBN excludes $\chi \to Z \tilde{G}$, but $\tilde{l} \to l \tilde{G}$ ok

LATE DECAYS AND ^{7}Li/^{6}Li



Bailly, Jedamzik, Moultaka (2008)

- ^{7}Li does not agree with standard BBN prediction
  - Too low by factor of 3, ~5σ at face value
  - May be solved by convection in stars, but then why so uniform?
- ^{6}Li may also not agree
  - Too high
- Late decays can fix either one or both
- For mSUGRA, fixing both, and requiring $\Omega_{\tilde{G}} = 0.1$ → heavy sleptons > TeV

BOTTOM LINE

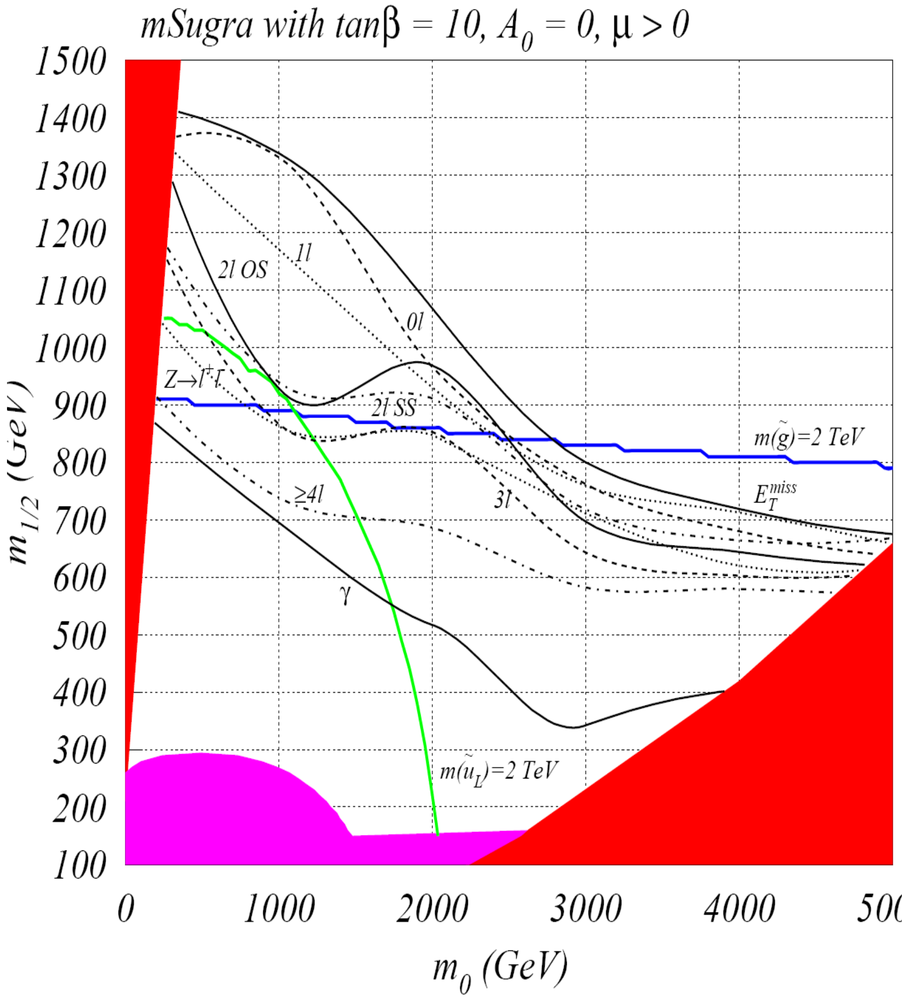
- This scenario
  - Solves the gauge hierarchy problem
  - Has DM with naturally the right relic density
  - Is consistent with EW precision constraints
  - Is consistent with all other constraints
  - Collider signal is CHAMPs, not MET

MODEL FRAMEWORKS

- mSUGRA's famous 4+1 parameters:

$$m_0^2, M_{1/2}, A_0, \tan\beta, \ \mathrm{sign}(\mu)$$

- Excluded regions
  - LEP limits
  - Stau LSP
- But this is incomplete
  - Missing $m_{\tilde{G}}$
  - Assumes $m_0^2 > 0$



Baer, Balazs, Belyaev, Krupovnickas, Tata (2003)

THE COMPLETE MSUGRA

- Extend the mSUGRA parameters to

$$m_0^2, M_{1/2}, A_0, \tan\beta,\ \mathrm{sign}(\mu),\ \text{and } m_{3/2}$$

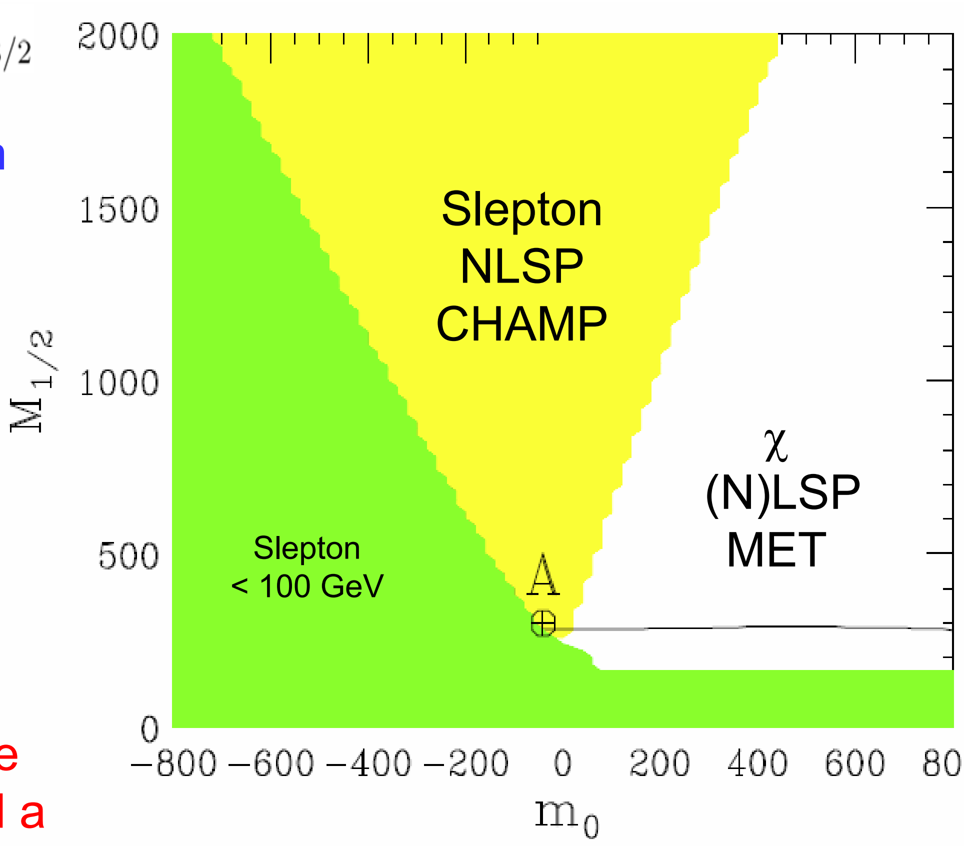
- If LSP = gravitino, then no reason to exclude stau NLSP region

- Also include small or negative

$$m_0 \equiv \mathrm{sign}(m_0^2)\sqrt{|m_0^2|}$$

- This includes no-scale/gaugino-mediated models with $m_0 = 0$

- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP

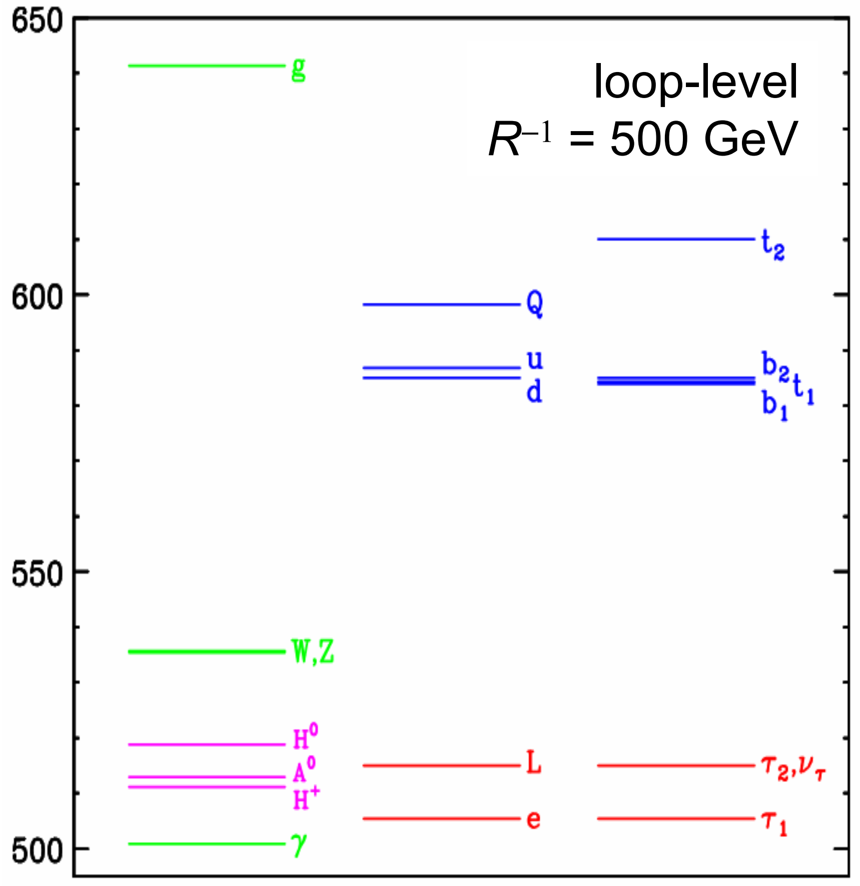


Feng, Rajaraman, Smith (2005)

UNIVERSAL EXTRA DIMENSIONS

Appelquist, Cheng, Dobrescu (2000)

- Assume 1 extra dimension, where the 5th dimension is a circle with radius R
- All Kaluza-Klein level 1 states have mass R^{-1}
- This is broken by many effects, but the lightest KK states are still highly degenerate



Cheng, Matchev, Schmaltz (2002)

UED COMMON LORE

- UED looks like SUSY
  - n=2 and higher levels typically out of reach
  - n=1 Higgses → A, H^0, $H^\pm$
  - Colored particles are heavier than uncolored ones
  - LKP is stable B^1 → MET at LHC

- Spectrum is more degenerate, but basically similar to SUSY

"Bosonic supersymmetry"

Cheng, Matchev, Schmaltz (2002)

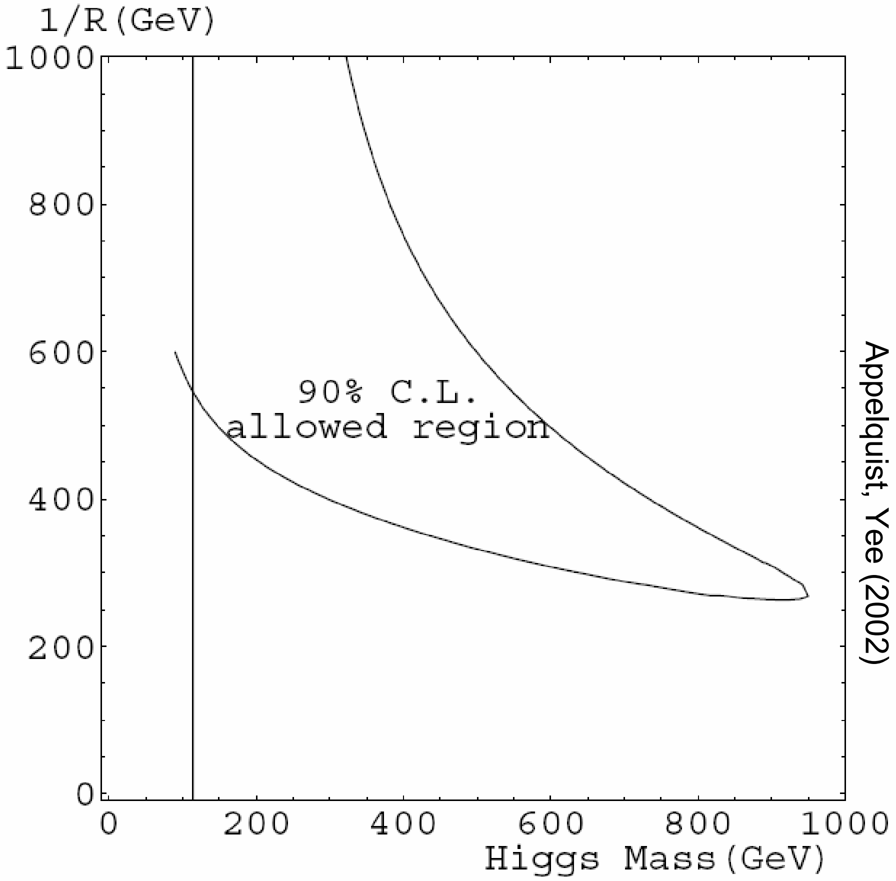
BUT THERE'S MORE

- *R* is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown

- Original collider studies set m_h=120 GeV, but it can be larger (KK towers modify EW precision constraints)

- H^0, A, $H^\pm$ masses depend on m_h

- Also, there's another state in the theory: the KK graviton G^1



Appelquist, Yee (2002)

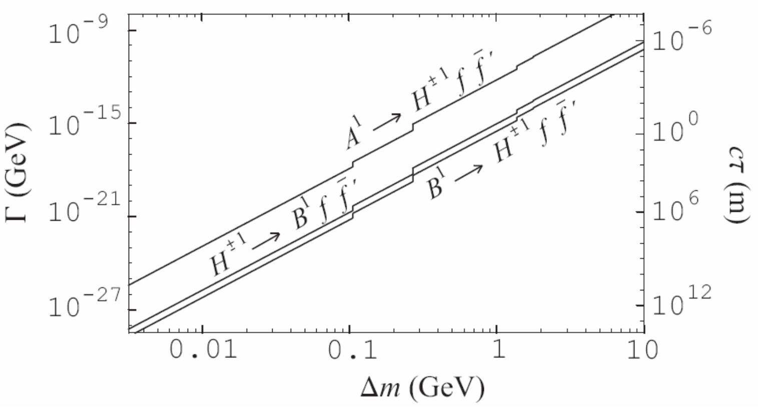
THE COMPLETE (MINIMAL) UED

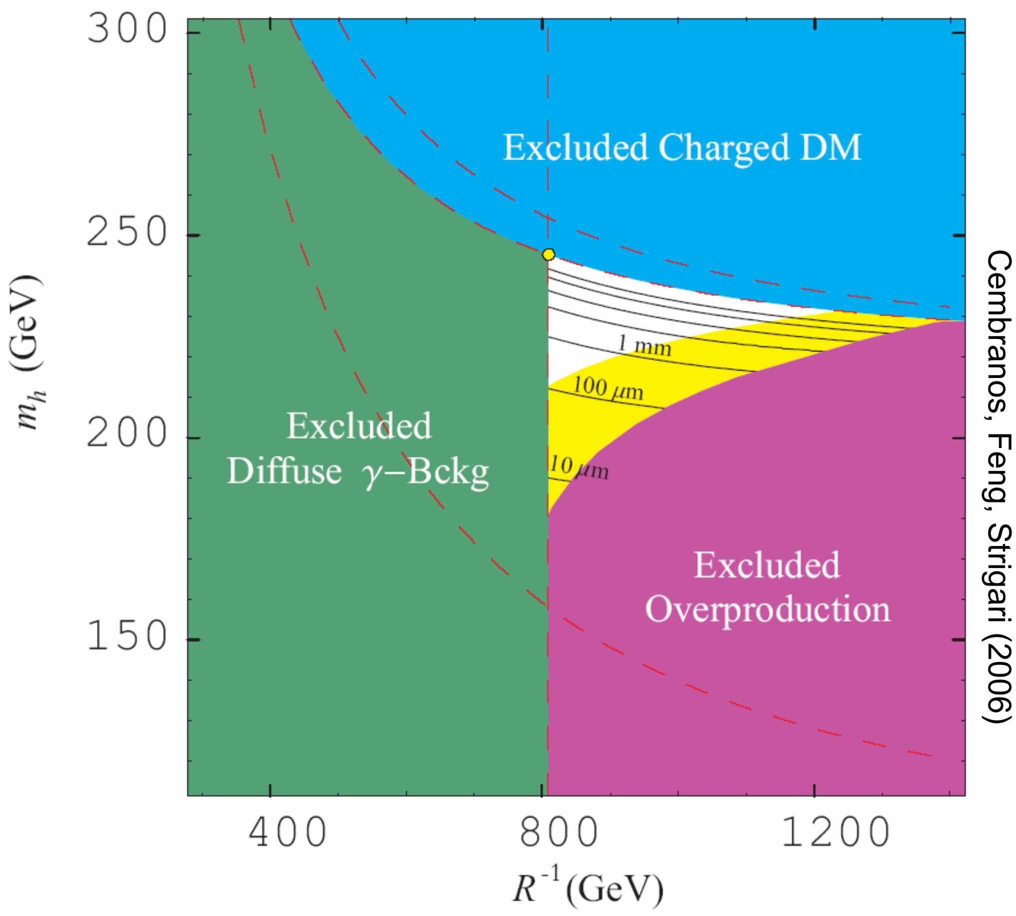
- In minimal UED, after all particle and astrophysical constraints, NLKP → LKP is

  $H^{\pm 1} \rightarrow B^1 f f'$

- Mass splitting $\Delta m < 7$ GeV

- Decay length $c\tau > 10\ \mu m$

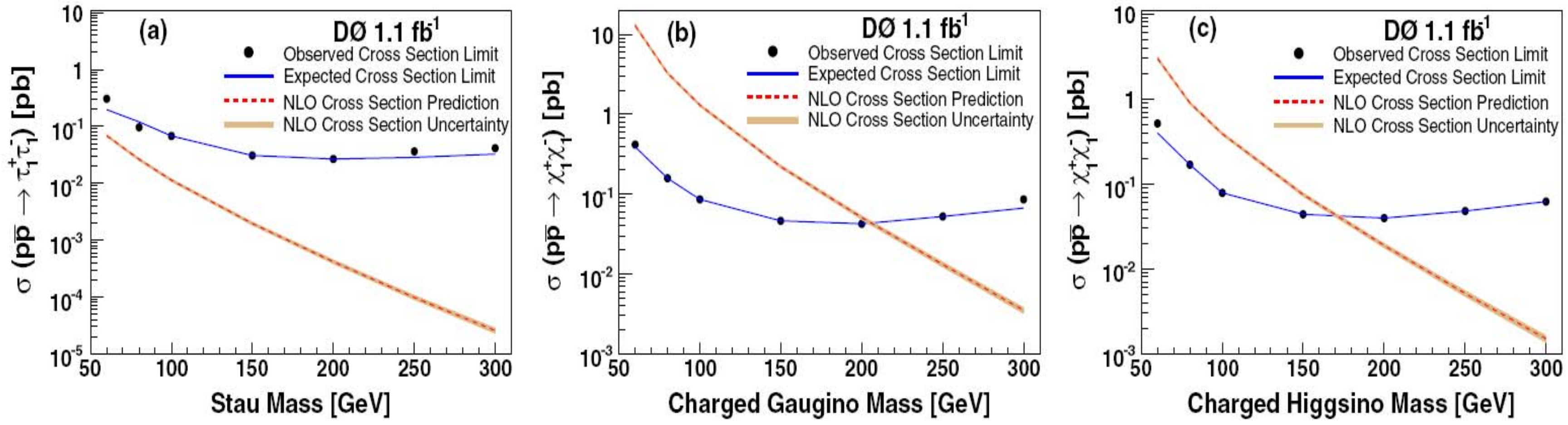




Cembranos, Feng, Strigari (2006)

CURRENT BOUNDS

- Current Bounds
  - LEP: slepton mass > 97.5 GeV, chargino > 102.5 GeV
  - CDF Run I: slepton cross section < 1 pb
  - D0 Run II: slepton cross section < 0.1 pb
    - assumes only Drell-Yan pair production (no cascades)
    - require 2 slow, isolated “muons”
    - about a factor of 5 from unexplored mass territory



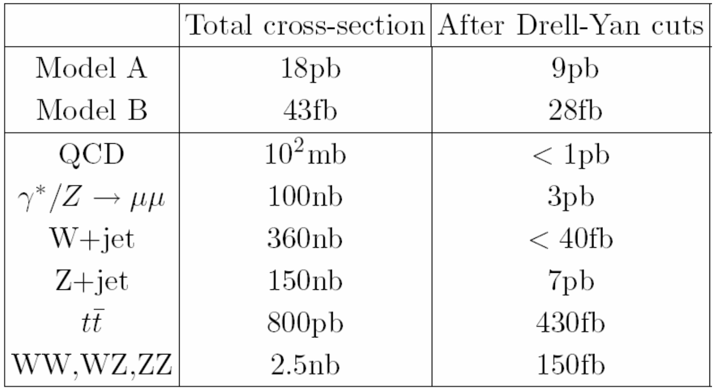
LHC DISCOVERY POTENTIAL

Rajaraman, Smith (2006)

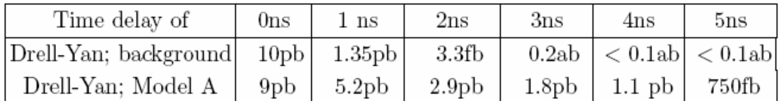
- Look for Drell-Yan slepton pair production

- Require events with 2 central, isolated “muons” with
  - $p > 100$ GeV
  - $p_T > 20$ GeV

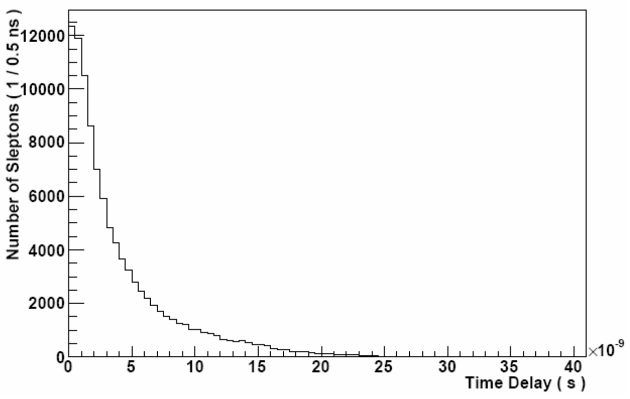
- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays > 3 ns



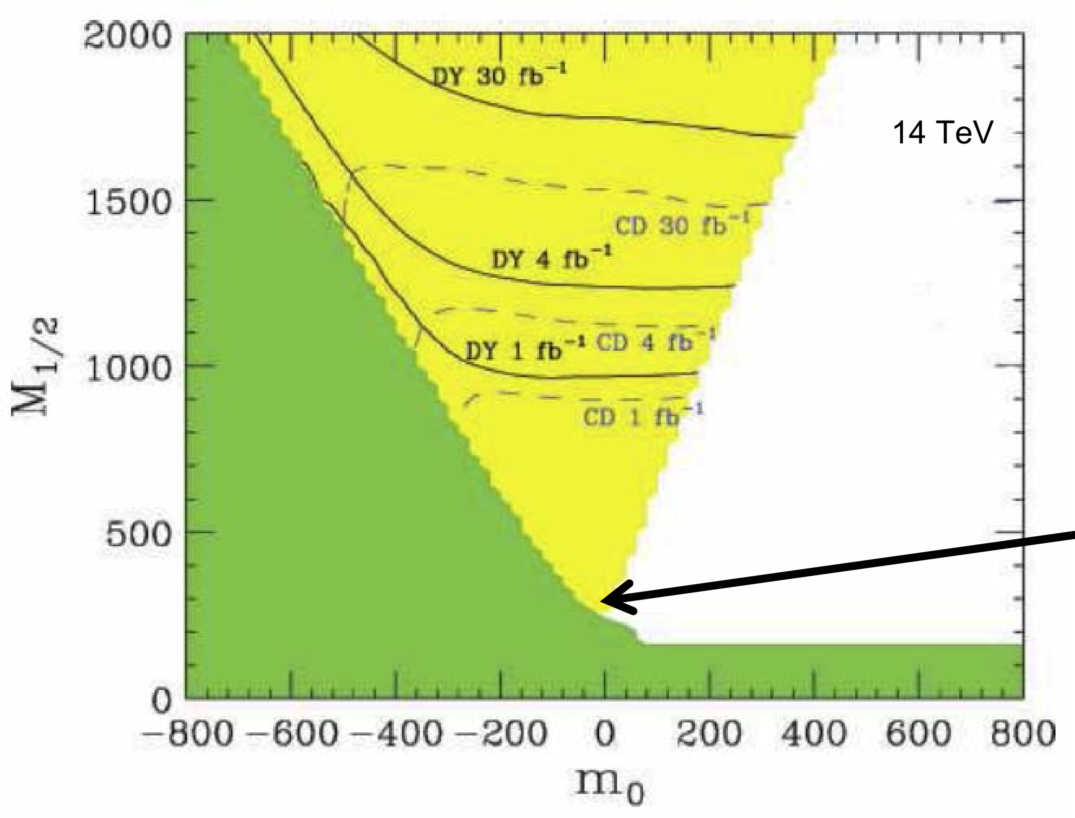
	Total cross-section	After Drell-Yan cuts
Model A	18pb	9pb
Model B	43fb	28fb
QCD	10^2mb	$<$ 1pb
$\gamma^*/Z \to \mu\mu$	100nb	3pb
W+jet	360nb	$<$ 40fb
Z+jet	150nb	7pb
$t\bar{t}$	800pb	430fb
WW,WZ,ZZ	2.5nb	150fb



Time delay of	0ns	1 ns	2ns	3ns	4ns	5ns
Drell-Yan; background	10pb	1.35pb	3.3fb	0.2ab	$<$ 0.1ab	$<$ 0.1ab
Drell-Yan; Model A	9pb	5.2pb	2.9pb	1.8pb	1.1 pb	750fb



- Require 5σ signal with S > 10 events for discovery

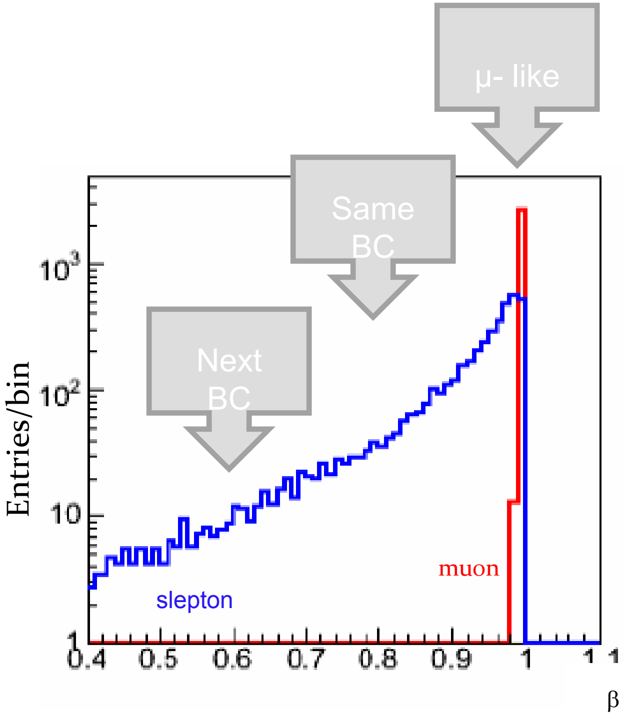


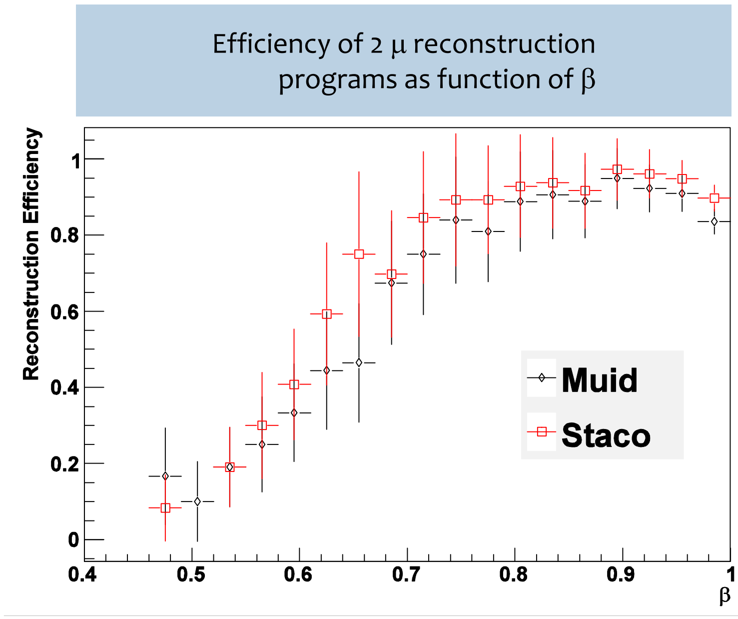
Model A discovered with 5 pb^{-1}

- Model A is “best case scenario”
- Lesson: Very early on, the LHC will probe new territory

CMS/ATLAS ANALYSES

- Ongoing work on CHAMP search and reconstruction
  - ATLAS (Tarem et al.): added ToF calculation to level 2 trigger to improve reconstruction efficiency
  - CMS (Rizzi): studied both dE/dx and ToF (Analysis Note (2006))




Efficiency of 2 μ reconstruction programs as function of β

Tarem, Bressler, Nomoto, De Mattia (2008)

LIGHT GRAVITINO DM

- The original SUSY DM scenario
  - Universe cools from high temperature
  - Gravitinos decouple while relativistic, $\Omega_{\tilde{G}} h^2 \approx m_{\tilde{G}} / 800$ eV
  - Favored scenario: keV gravitinos

Pagels, Primack (1982)

- This minimal scenario is now excluded
  - $\Omega_{\tilde{G}} h^2 < 0.1 \rightarrow m_{\tilde{G}} < 80$ eV
  - Gravitinos not too hot → $m_{\tilde{G}} >$ few keV
  - Disfavored scenario: keV gravitinos

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)
Seljak, Makarov, McDonald, Trac (2006)

- Two ways out
  - ΛWDM: $m_{\tilde{G}} >$ few keV. Gravitinos are all the DM, but thermal density is diluted by low reheating temperature,…
  - ΛWCDM: $m_{\tilde{G}} < 16$ eV. Gravitinos are only part of the DM, mixed warm-cold scenario

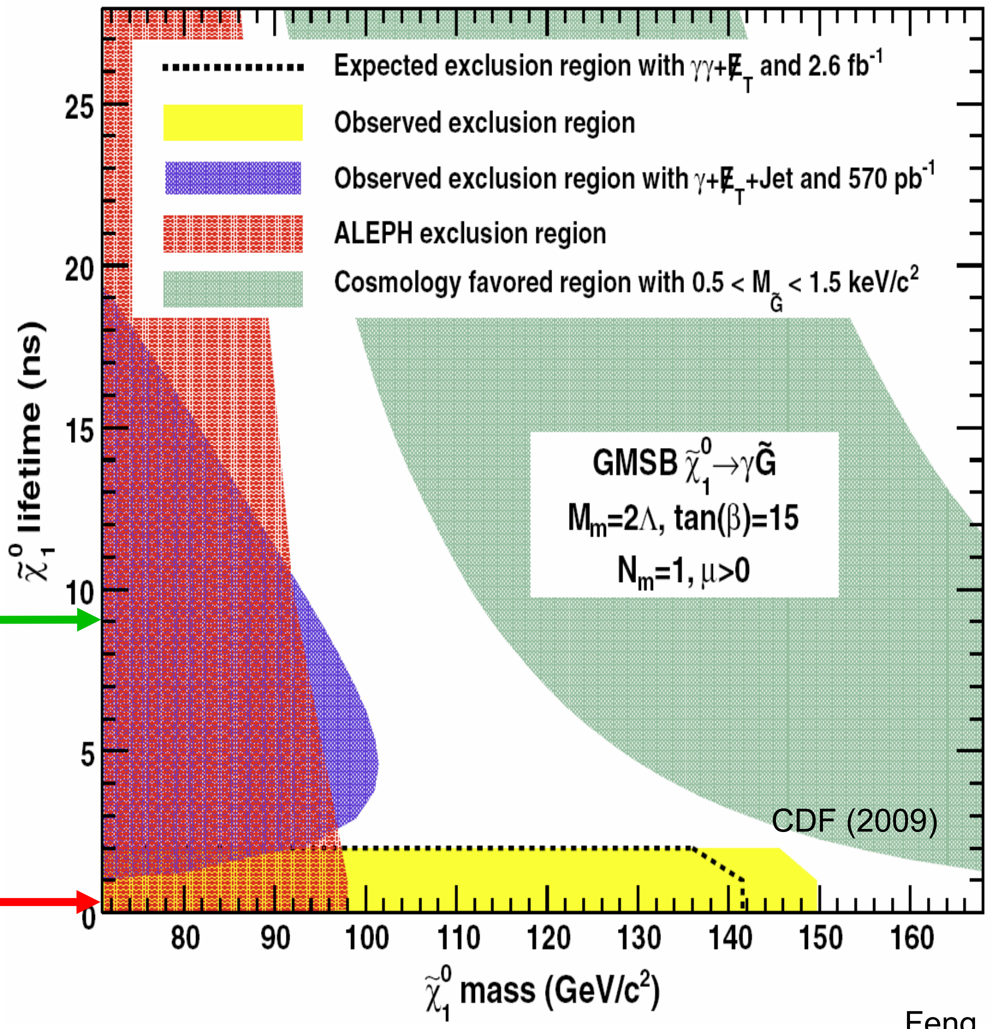
CURRENT BOUNDS

- Remarkably, this lifetime difference is observable at colliders!

$$c\tau_{\mathrm{NLSP}} \approx 50\ \mathrm{cm}\left(\frac{200\ \mathrm{GeV}}{m_{\mathrm{NLSP}}}\right)^5\left(\frac{m_{\tilde{G}}}{\mathrm{keV}}\right)^2$$

- $m_{\tilde{G}}$ > few keV: Delayed photon signatures

- $m_{\tilde{G}}$ < 16 eV: Prompt photon signatures



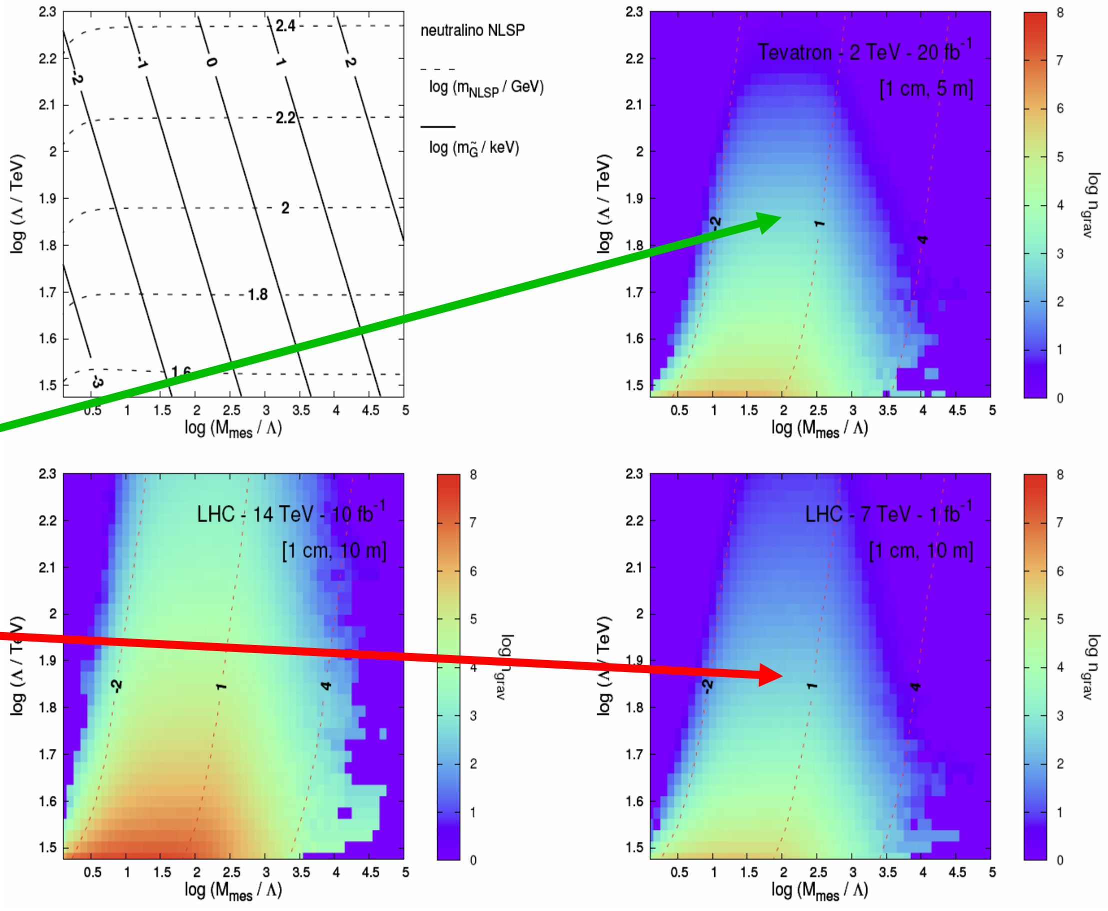
CDF (2009)

LIGHT GRAVITINOS AT THE LHC

- Hundreds to thousands of delayed photon events are possible at

Tevatron (20 fb^{-1})

LHC (7 TeV, 1 fb^{-1})



Lee, Feng, Kamionkowski (in preparation)

WIMPLESS DM

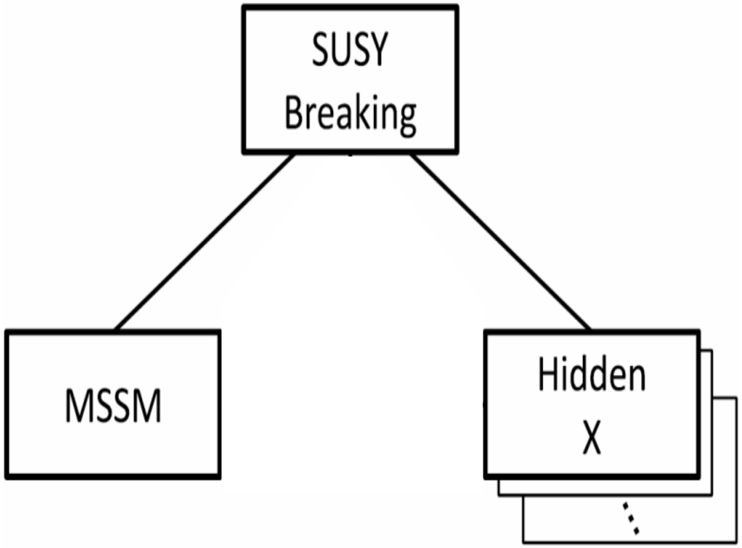
Feng, Kumar (2008); Feng, Tu, Yu (2008)

- Consider hidden DM, that is, DM with no SM gauge interactions. What can we say?

- Generically, nothing

- But in SUSY models that solve the new physics flavor problem (gauge-mediated models, anomaly-mediated models) the superpartner masses are determined by gauge couplings

$$m_X \sim g_X^2$$

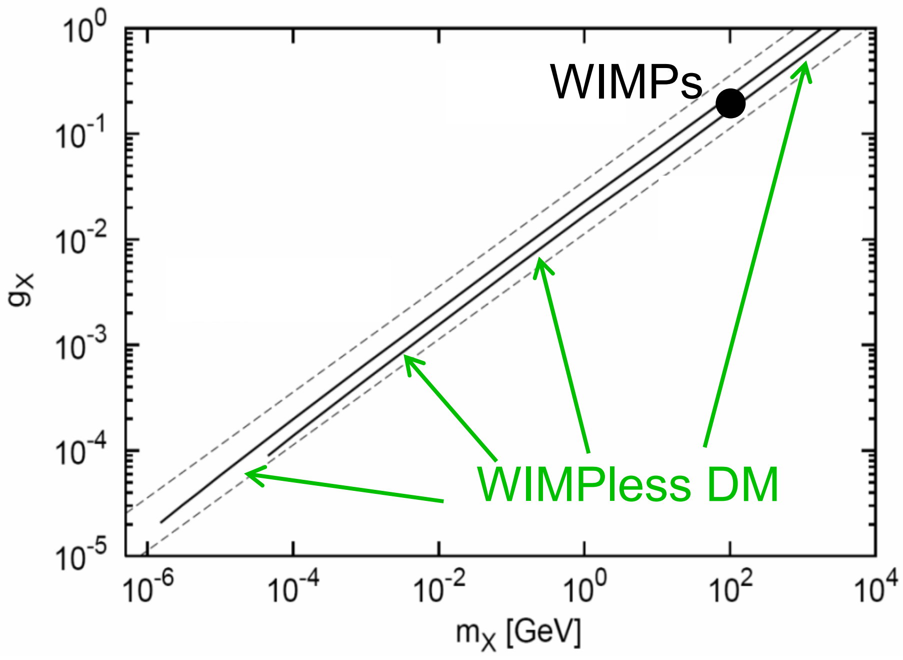


THE WIMPLESS MIRACLE

- This leaves the thermal relic density invariant:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- The thermal relic density constrains only one combination of g_X and m_X. These models map out the remaining degree of freedom; candidates have a range of masses and couplings, but always the right relic density.



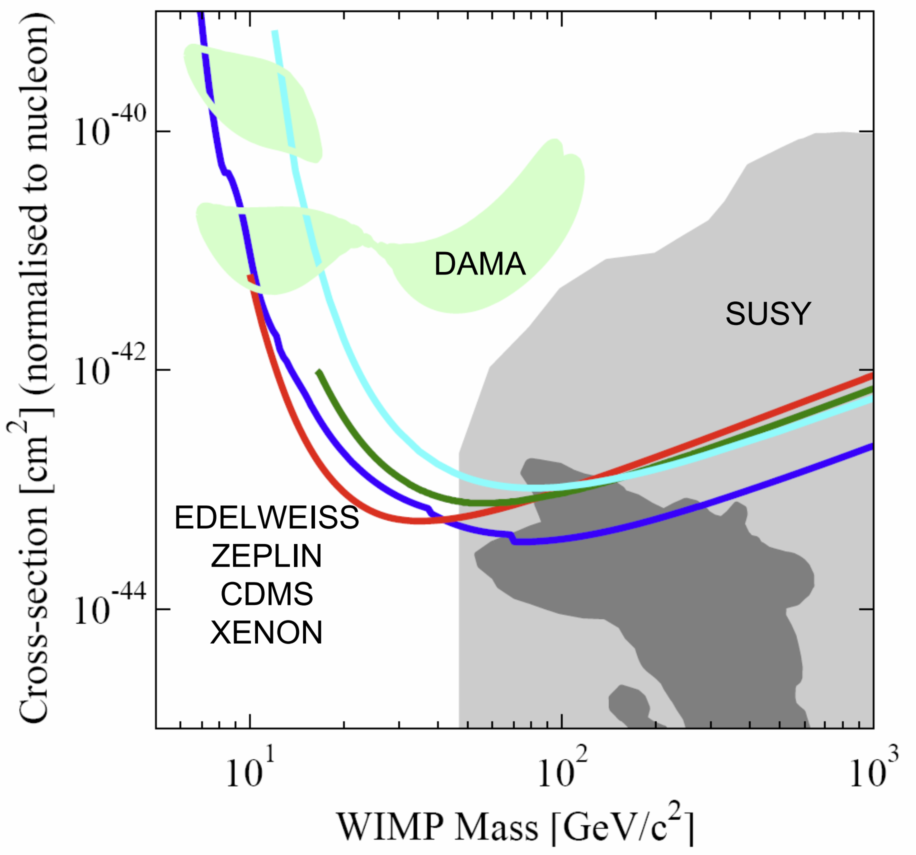
- This decouples the WIMP miracle from WIMPs (is this what the flavor problem is really trying to tell us?)

DAMA

- The DAMA signal is now at 8.9σ
- The m_X ~ 100 GeV favored region is excluded by many other experiments
- One marginally viable solution is light dark matter with very large cross section

$$m_X \sim 5\text{-}10 \text{ GeV}$$

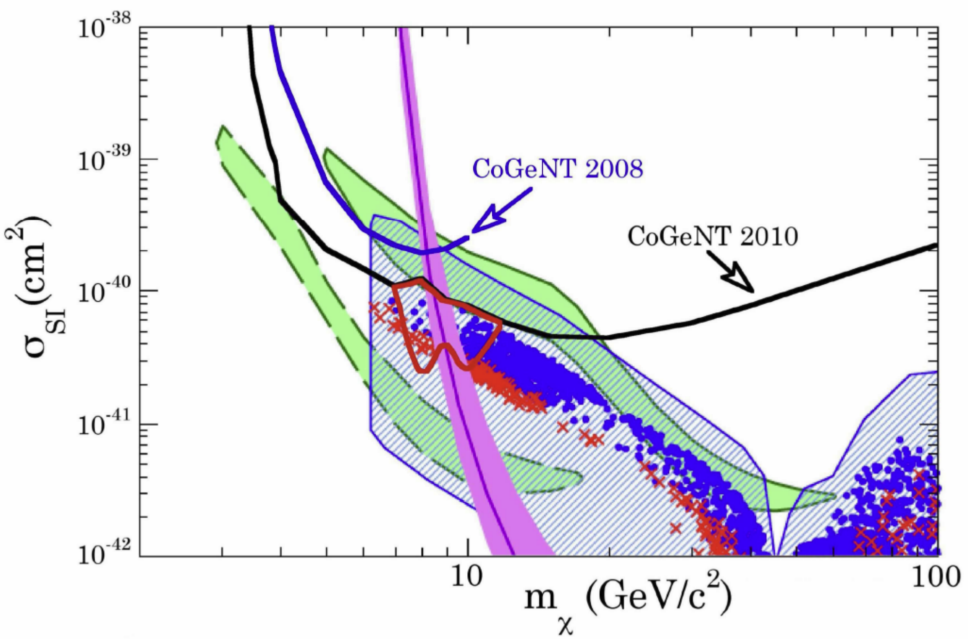
$$\sigma_{SI} \sim 10^{-40} \text{ cm}^2$$

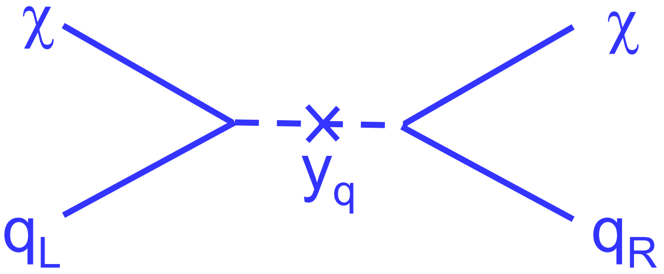


COGENT

- The light DM scenario is, however, now tentatively supported by CoGeNT

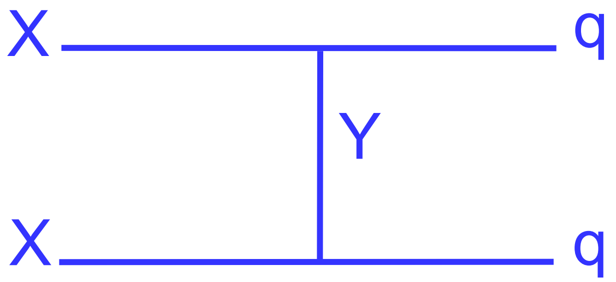
- This region of parameter space is very hard to obtain with conventional WIMPs: for example, for neutralinos, chirality flip implies large suppression

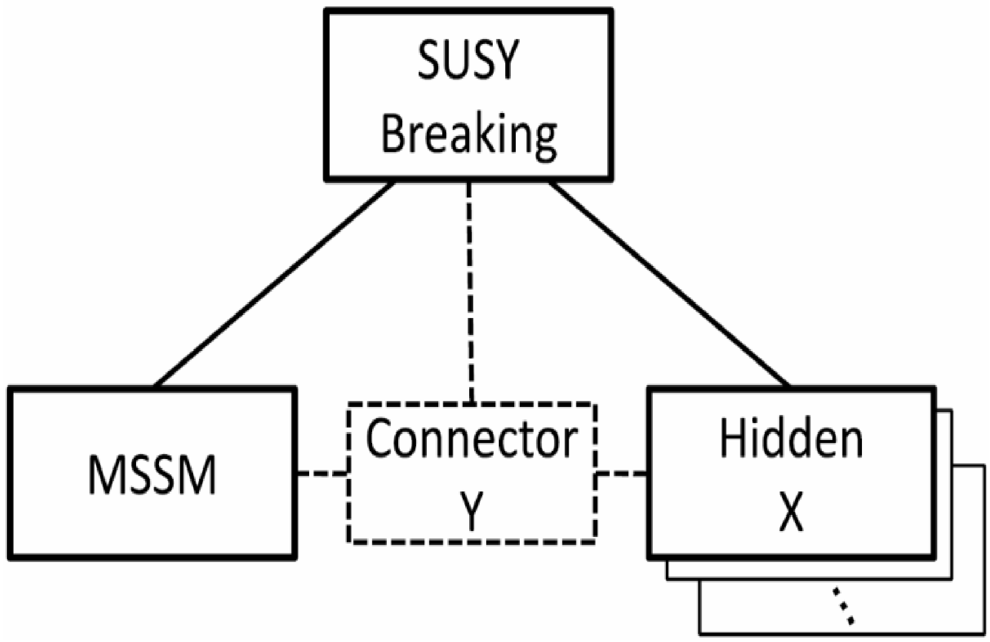




WIMPLESS SIGNALS

- Hidden DM may interact with normal matter through non-gauge interactions





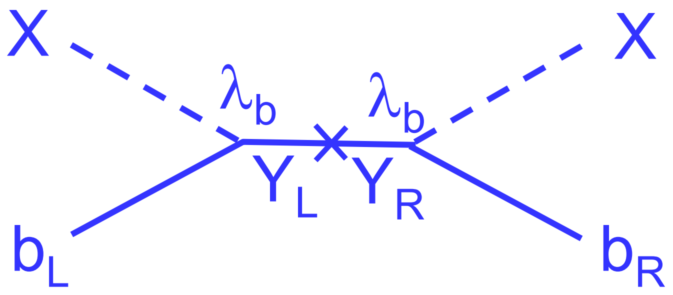
WIMPLESS DIRECT DETECTION

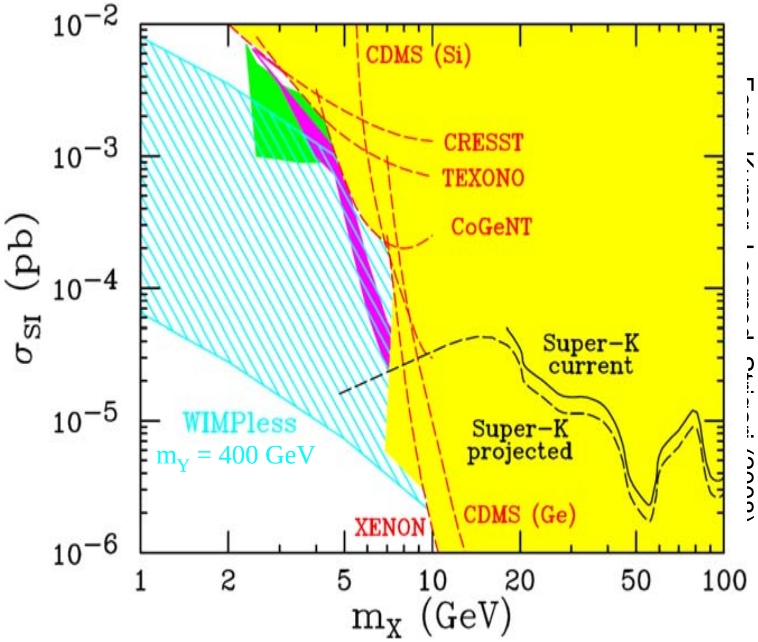
- The DAMA/CoGeNT region is easy to reach with WIMPless DM

- E.g., assume WIMPless DM X is a scalar, Y is a fermion, interact with b quarks through

  $\lambda_b \, (XY_L b_L + XY_R b_R) + m_Y Y_L Y_R$

- Naturally correct mass, cross section
  - m_X ~ 5-10 GeV (WIMPless miracle)
  - large σ_{SI} for λ_b ~ 0.3 – 1 (flip chirality on heavy Y propagator)





EXOTIC T’, B’ AT LHC

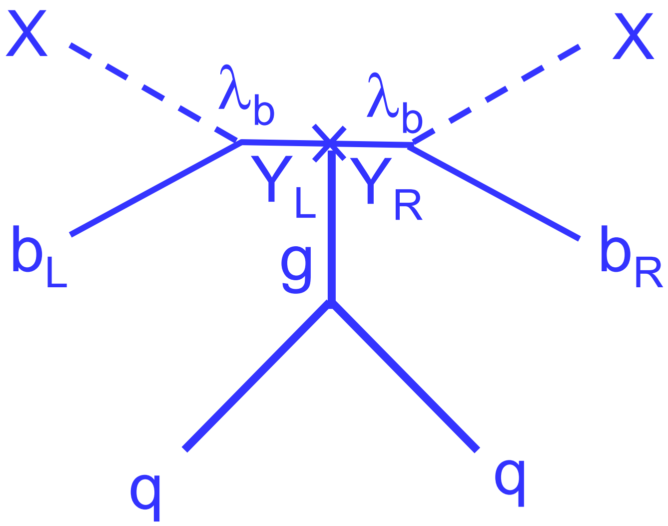
- Gauge invariance → Y’s are colored, similar to 4th generation quarks

- EW precision studies, direct searches, perturbativity →

  300 GeV < m_Y < 600 GeV

- Signals
  - T’ T’ → tXtX, B’ B’ → bX bX
  - different from standard 4th generation quarks (T’ → b W)
  - best channel is all hadronic

Alwall, Feng, Kumar, Su (2010)

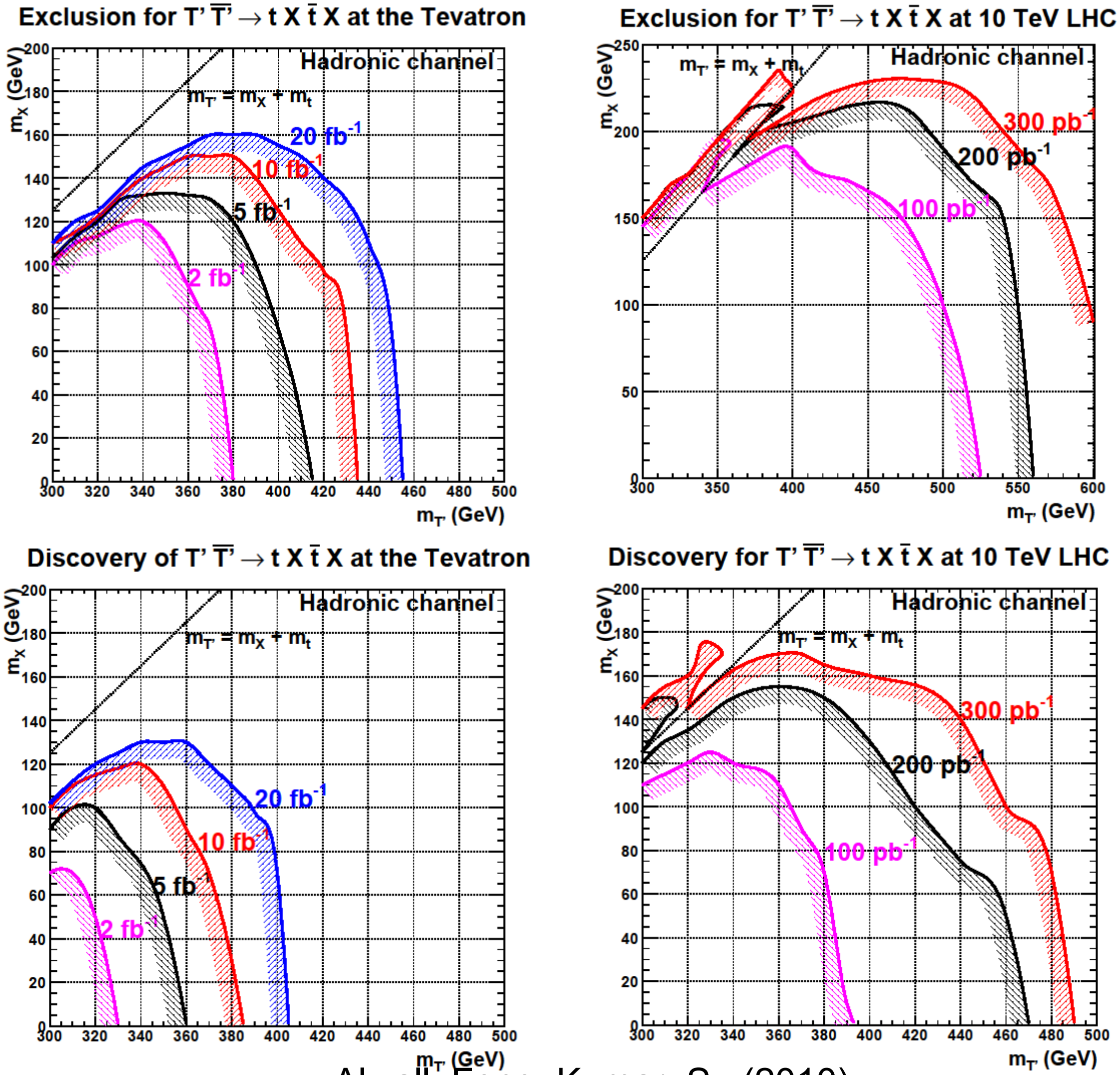


MadGraph, MadEvent, Pythia 6.4.20, PGS4)

Cut	T' (300)	T' (400)	T' (500)	$t\bar{t}$ (1 τ)	$t\bar{t}$ (1 e/μ)	$t\bar{t}$ (had)	W+jets	Z+jets
No cut	14.89	3.16	0.922	43.96	66.67	104.59	(42.28)	(18.86)
0 isolated leptons	6.75	1.5	0.45	16.88	13.11	72.29	(16.8)	(15.71)
$\not{E}_T > 100$ GeV	4.15	1.21	0.394	3.91	2.67	0.097	(11.25)	(11.48)
≥ 5 jets	1.34	0.406	0.135	0.664	0.47	0.031	0.305	0.212
$\Delta\phi$ cuts	1.19	0.374	0.125	0.56	0.41	0.01	0.265	0.187

EXOTIC 4^{TH} QUARKS AT LHC

- Entire m_X ~ 10 GeV region can be excluded by 10 TeV LHC with 300 pb^{-1} (~7 TeV LHC with 1 fb^{-1})
- Significant discovery prospects with early LHC data



Alwall, Feng, Kumar, Su (2010)

CONCLUSIONS

- There are many signals that are just as well-motivated by dark matter, the gauge hierarchy problem, and all other existing constraints as MET
  - CHAMPS
  - Delayed photons, diphotons
  - Exotic 4th generation quarks

- Real possibilities for early LHC data (and in some cases, for the Tevatron)