# IMPLICATIONS OF RECENT DATA FOR THEORIES OF DARK MATTER

*Jonathan Feng, UC Irvine*

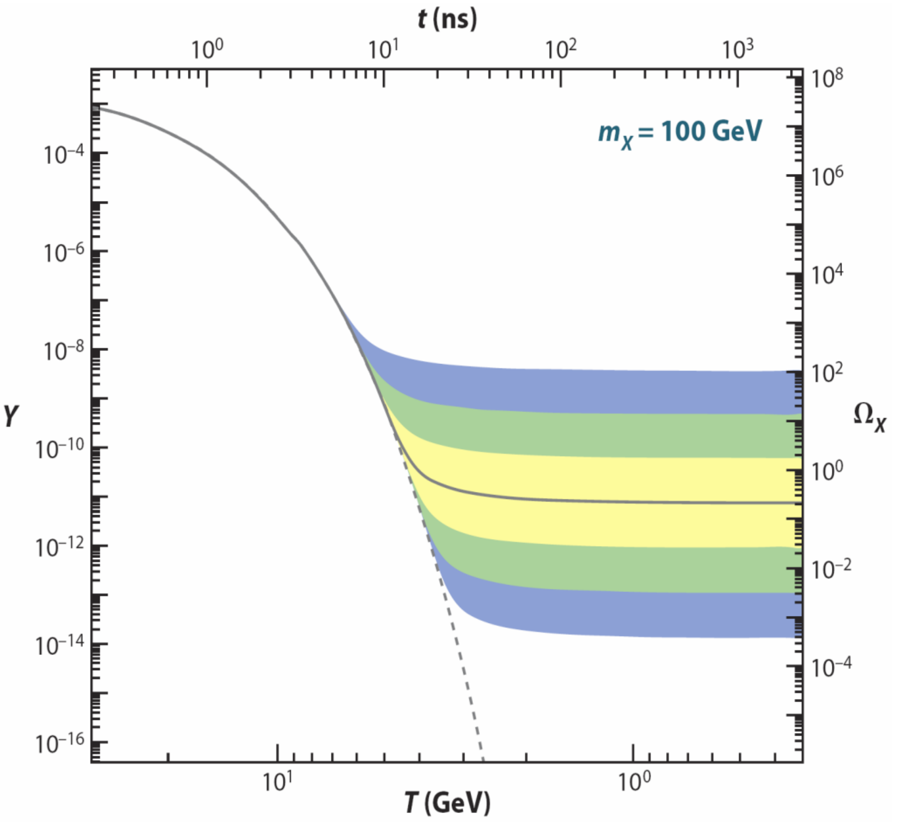
Strings at the LHC and in the Early Universe
KITP Santa Barbara
7 May 2010

# TOPICS

- PAMELA, FERMI, … ↔ BOOSTED WIMPS
- CDMS, XENON, … ↔ WIMPS
- DAMA, COGENT, … ↔ LIGHT WIMPS
- TEVATRON, LHC ↔ SUPERWIMPS
  LIGHT GRAVITINOS

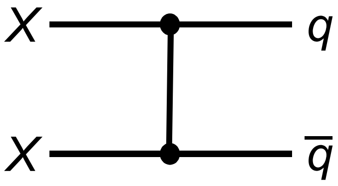
For more, see “Dark Matter Candidates from Particle Physics and Methods of Detection,” 1003.0904, Annual Reviews of Astronomy and Astrophysics

# THE WIMP MIRACLE



- Assume a new (heavy) particle *X* is initially in thermal equilibrium
- Its relic density is

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



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

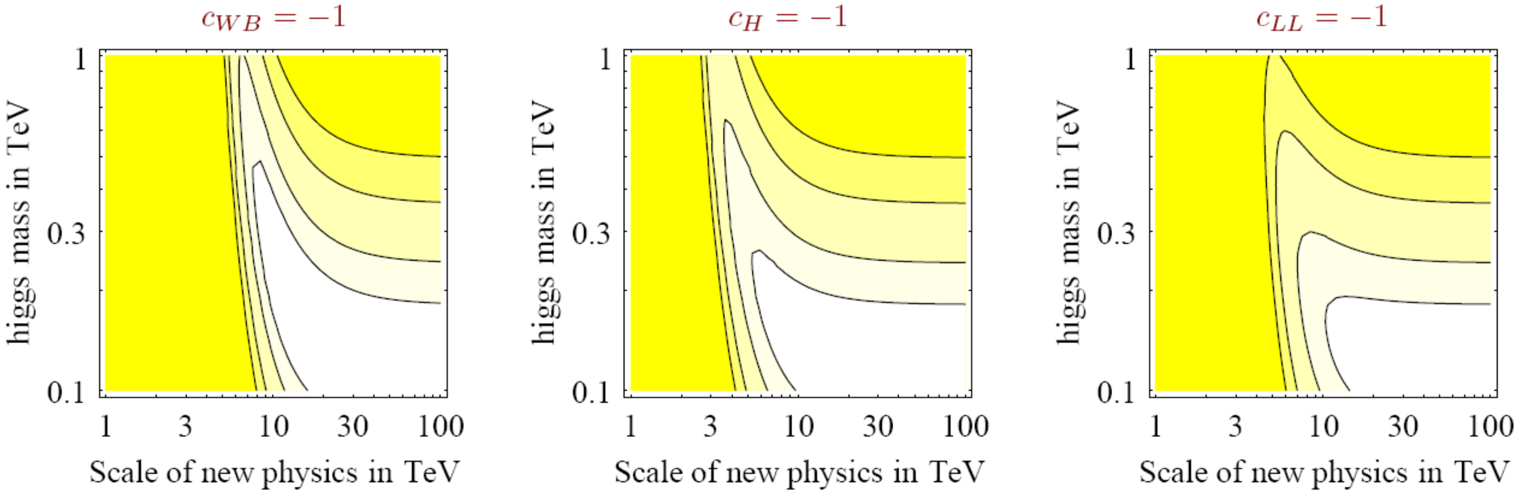
- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

# WIMP STABILITY

- The WIMP miracle assumes a stable new particle. Why should this be?
- LEP and SLC confirmed the standard model, stringently constrained effects of new particles
- Problem: Gauge hierarchy → new particles ~100 GeV

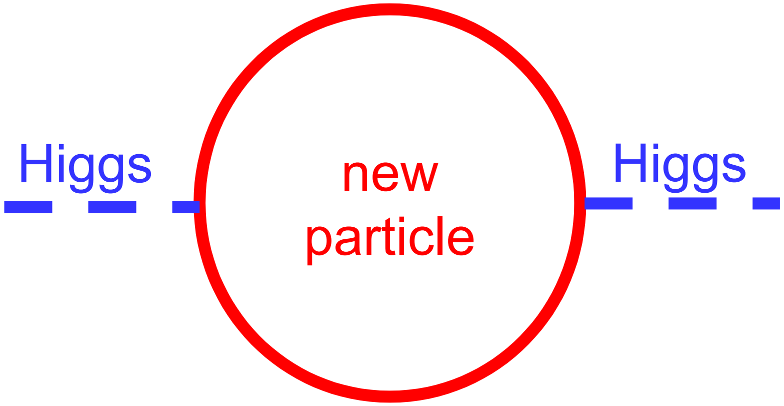
  LEP/SLC → 4-fermi interaction mass scale > 3 TeV

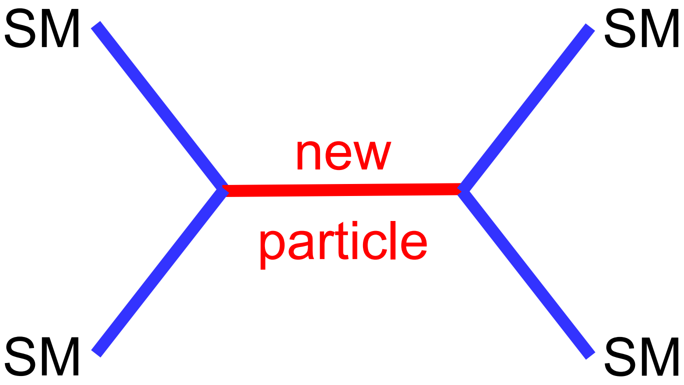
  (even considering only flavor-, CP-, B-, and L-conserving effects)



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 for a stable weak-scale particle

- 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

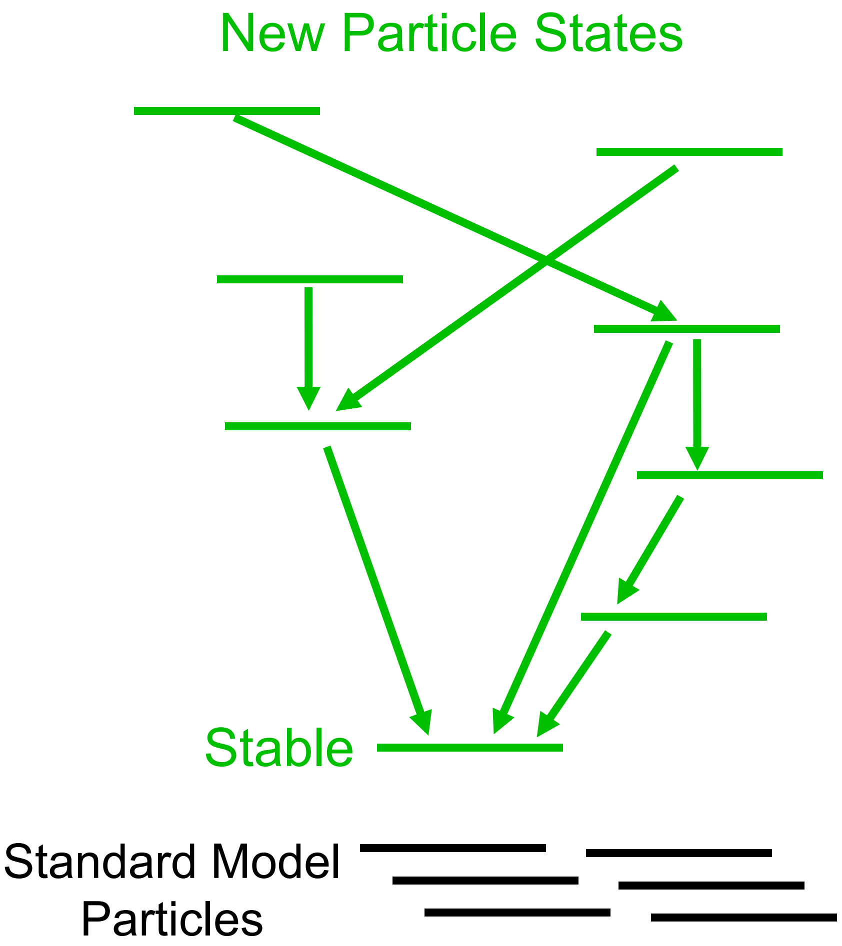
Servant, Tait (2002)
Cheng, Feng, Matchev (2002)

Branes

- Brane-parity
- Branons DM

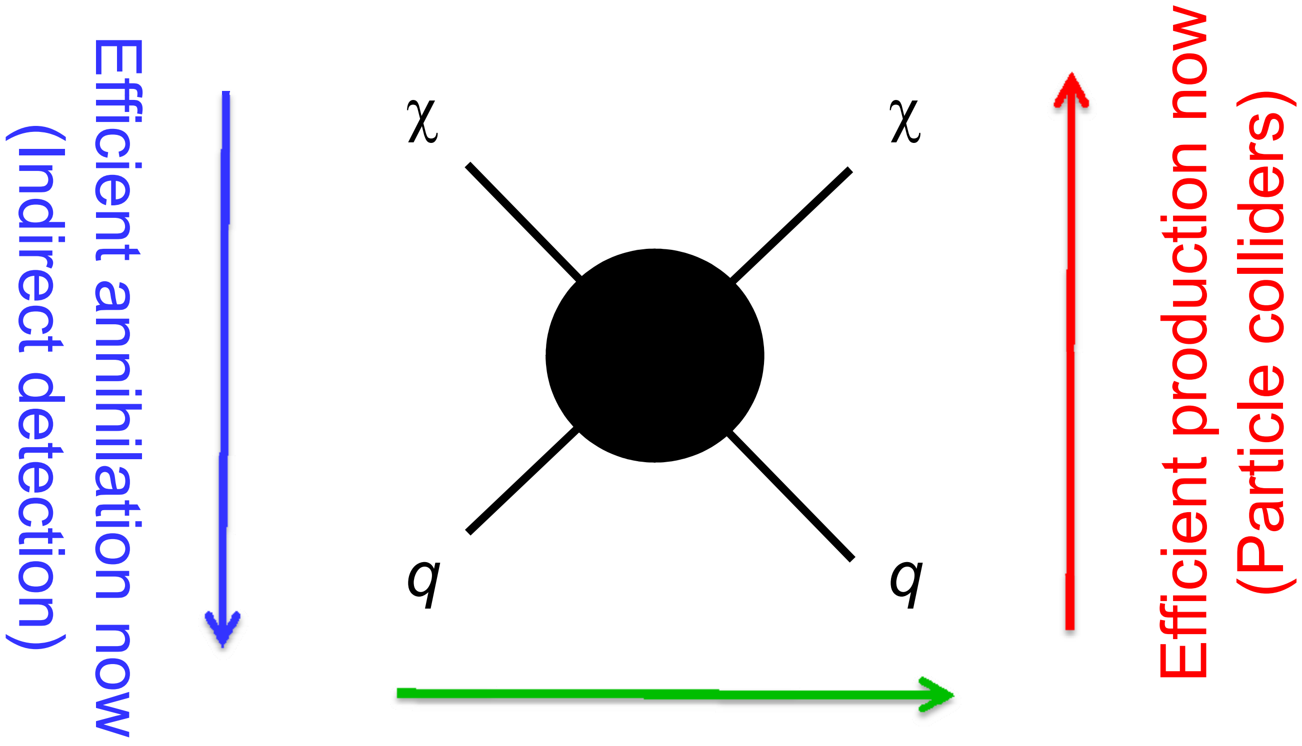
Cembranos, Dobado, Maroto (2003)

…



# WIMP DETECTION

Correct relic density → *Lower* bound on DM-SM interaction

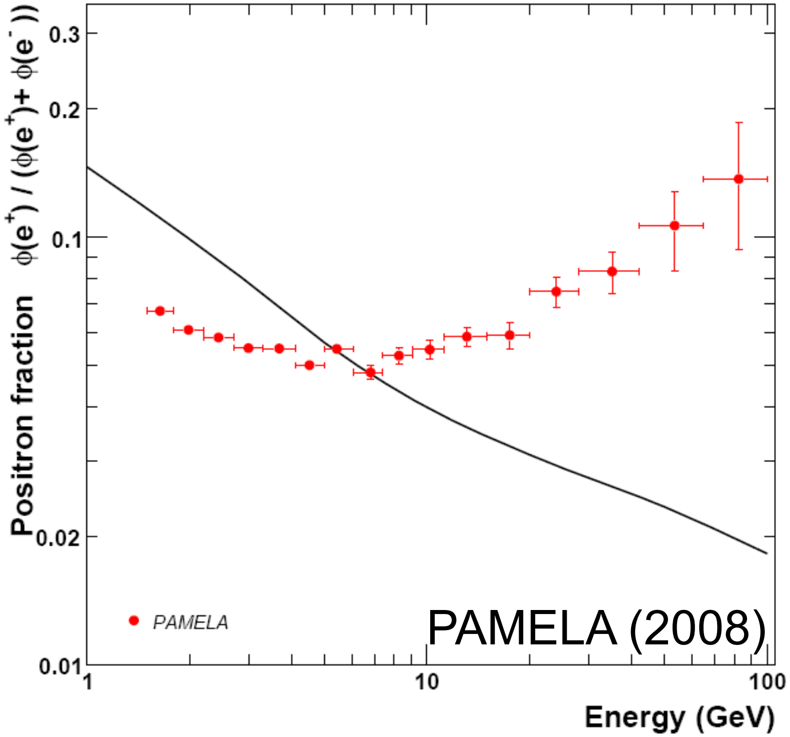


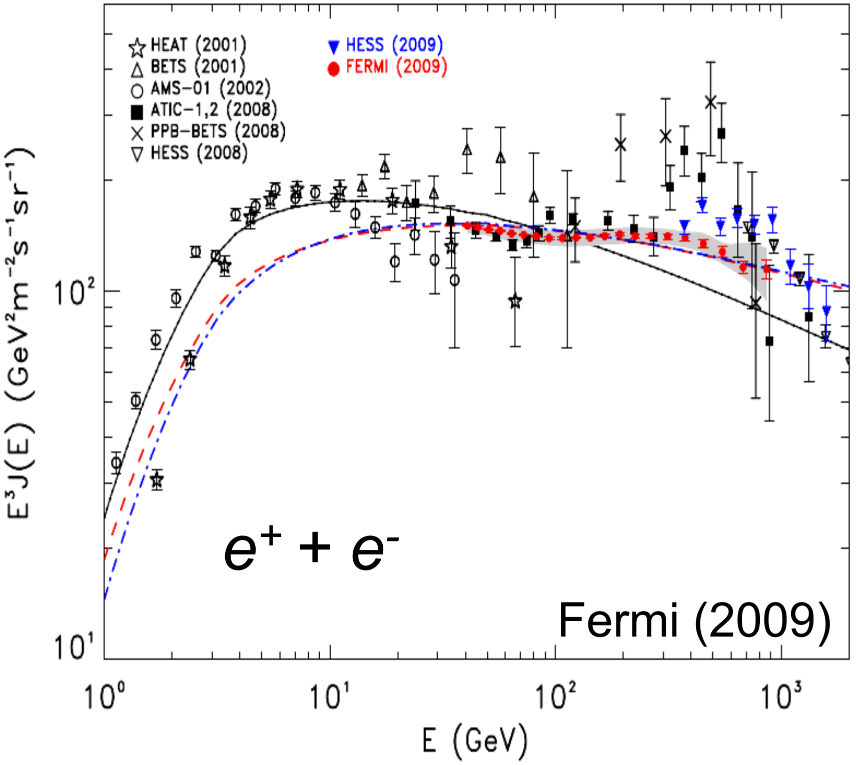
Efficient annihilation now
(Indirect detection)

Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

# INDIRECT DETECTION



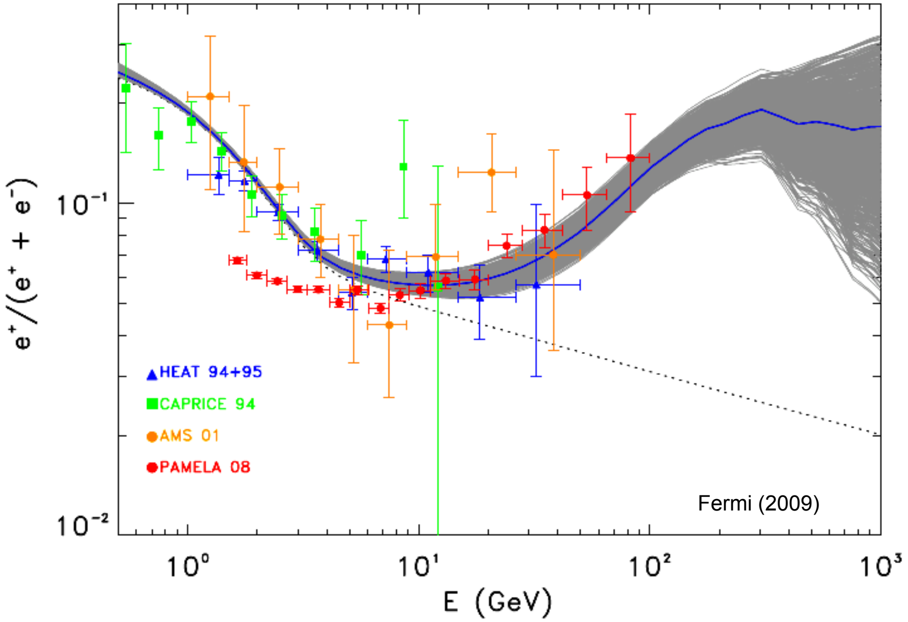


Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

# ARE THESE DARK MATTER?

- Astrophysics can explain PAMELA

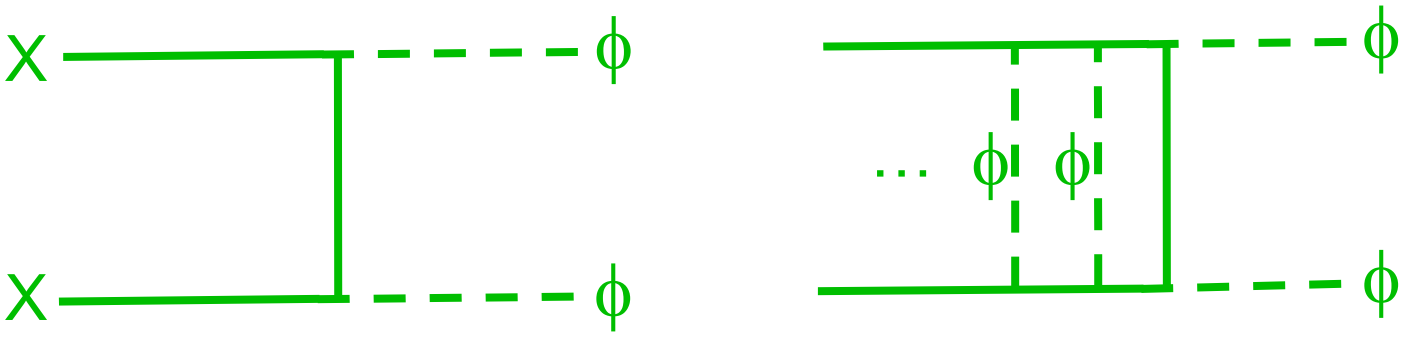
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008)
Profumo (2008) ; Fermi (2009)



- For dark matter, there is both good and bad news
- Good: the WIMP miracle motivates excesses at ~100 GeV – TeV
- Bad: the WIMP miracle also tells us that the annihilation cross section should be a factor of 100-1000 too small to explain these excesses. Need enhancement from
  - astrophysics (very unlikely)
  - particle physics
    - Winos
    - Resonances
    - DM from Decays
    - Sommerfeld enhancements

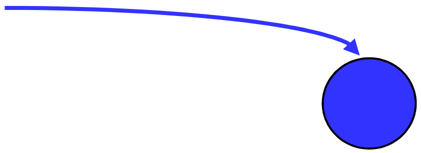
# SOMMERFELD ENHANCEMENT

- If dark matter X is coupled to a hidden force carrier $\phi$, it can then annihilate through $XX \rightarrow \phi\,\phi$



- At freezeout: $v \sim 0.3$, only 1st diagram is significant, $\sigma = \sigma^{th}$

  Now: $v \sim 10^{-3}$, all diagrams significant, $\sigma = S\sigma^{th}$, $S \sim \pi\alpha_X/v$, boosted at low velocities



Sommerfeld (1931)

Hisano, Matsumoto, Nojiri (2002)

- If $S \sim 1000\ [m_X / 2\ \text{TeV}]$ , seemingly can explain excesses, get around WIMP miracle predictions

Cirelli, Kadastik, Raidal, Strumia (2008)

Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)

# CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

Feng, Kaplinghat, Yu (2009, 2010)

- Unfortunately, large S requires large $\alpha_X$, but strongly-interacting DM does not have the correct relic density

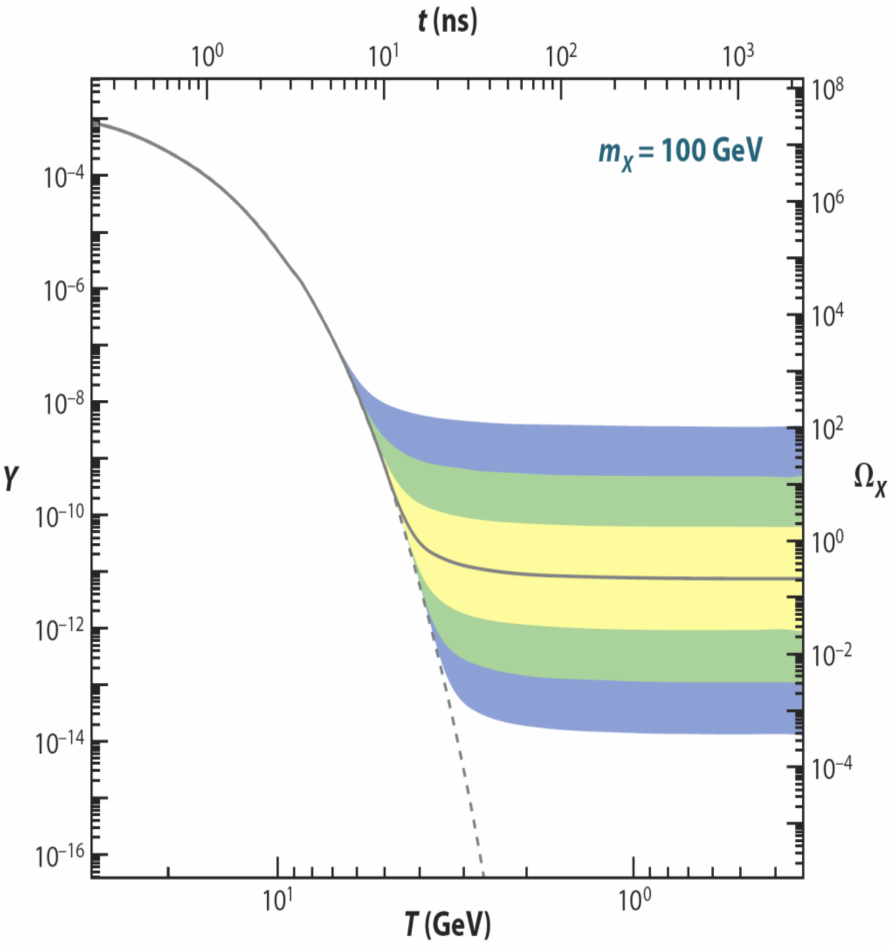
- More quantitatively: for $m_X$ = 2 TeV,

  $$S \sim \pi\alpha_X/v \sim 1000,\ v \sim 10^{-3} \rightarrow \alpha_X \sim 1 \rightarrow \Omega_X \sim 0.001$$

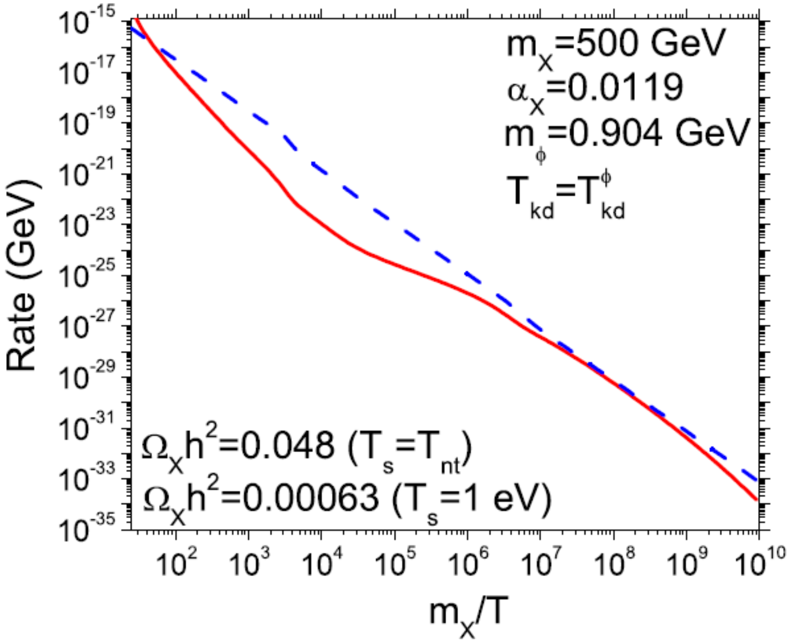
- Alternatively, requiring $\Omega_X \sim 0.25$, what is the maximal S?

- Complete treatment requires including
  - Resonant Sommerfeld enhancement
  - Impact of Sommerfeld enhancement on freeze out
  - Maximize S by pushing all parameters in the most optimistic direction

# FREEZE OUT AND MELT IN

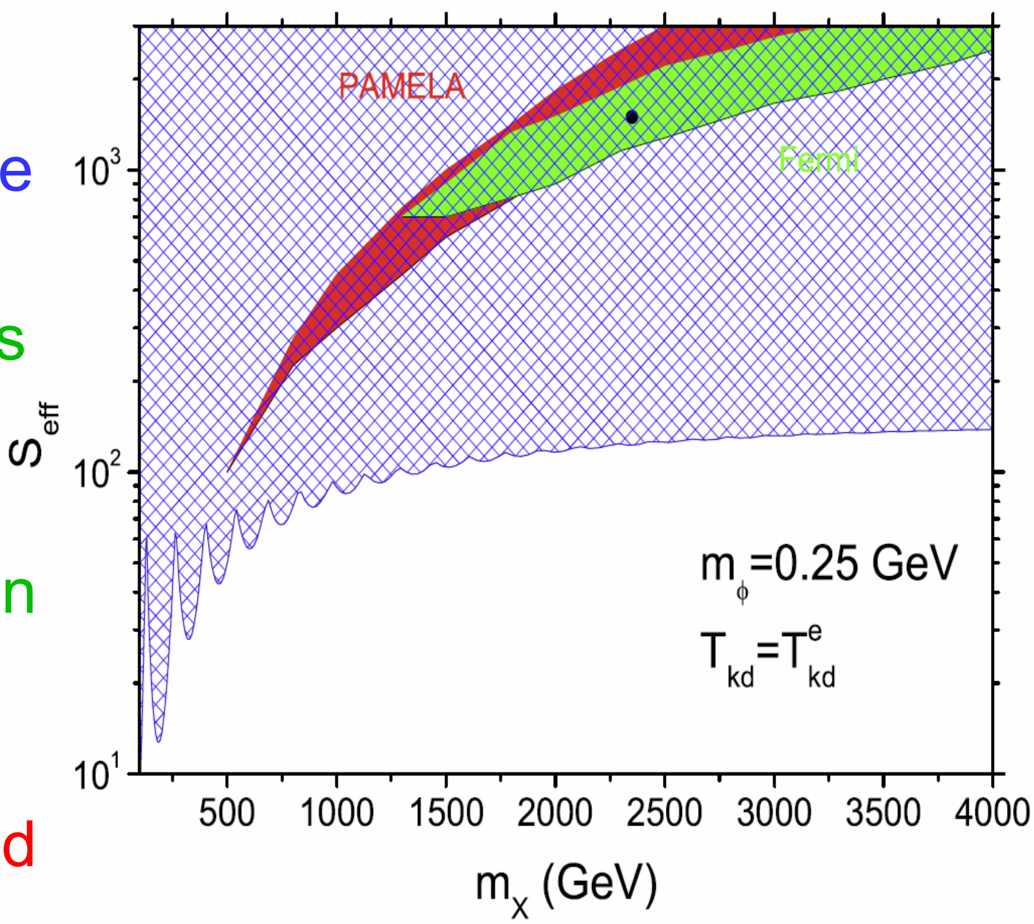


$$\frac{1}{Y(x_\mathrm{s})} = \frac{1}{Y(x_f)} + \sqrt{\frac{\pi}{45}} m_\mathrm{Pl}\, m_X \int_{x_f}^{x_\mathrm{kd}} \frac{(g_{*s}/\sqrt{g_*})\langle\sigma_\mathrm{an} v_\mathrm{rel}\rangle}{x^2} dx$$
$$+ \sqrt{\frac{\pi}{45}} m_\mathrm{Pl}\, m_X \int_{x_\mathrm{kd}}^{x_\mathrm{s}} \frac{(g_{*s}/\sqrt{g_*})\langle\sigma_\mathrm{an} v_\mathrm{rel}\rangle}{x^2} dx \ ,$$



# CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

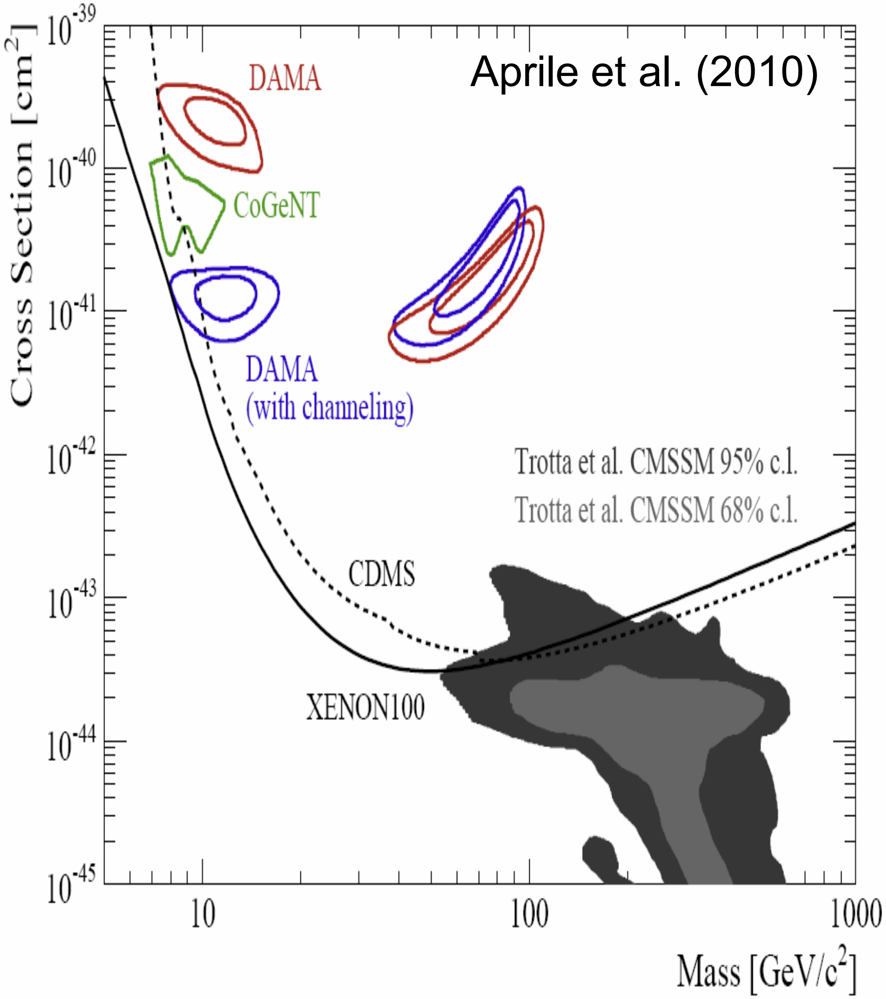
- Best fit region [Bergstrom et al. (2009)] excluded by over an order of magnitude
- Astrophysical uncertainties
  - Local density
  - Small scale structure
  - Cosmic ray propagation
- More complicated models
  - Smaller boosts required
  - Tighter bounds



Feng, Kaplinghat, Yu (2010)

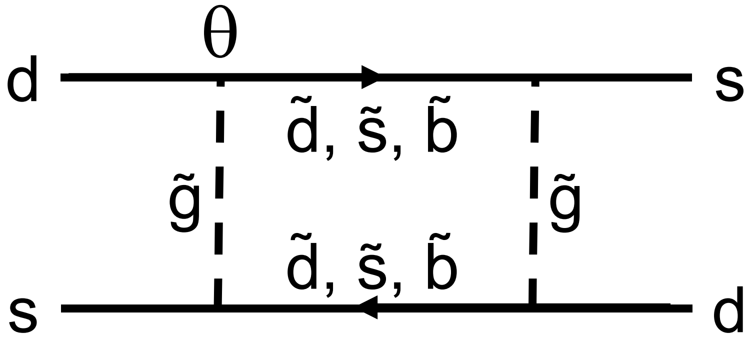
# DIRECT DETECTION

- Direct detection searches for nuclear recoil in underground detectors
- Spin-independent scattering is typically the most promising
- Theory and experiment compared in the ($m_X$, $\sigma_p$) plane
  - Expts: CDMS, XENON, …
  - Theory: Shaded region is the predictions for SUSY neutralino DM – what does this mean?



# NEW PHYSICS FLAVOR PROBLEM

- New weak scale particles generically create many problems
- One of *many* possible examples: K-$\bar{K}$ mixing

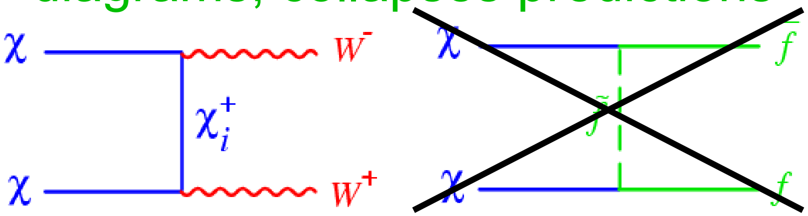


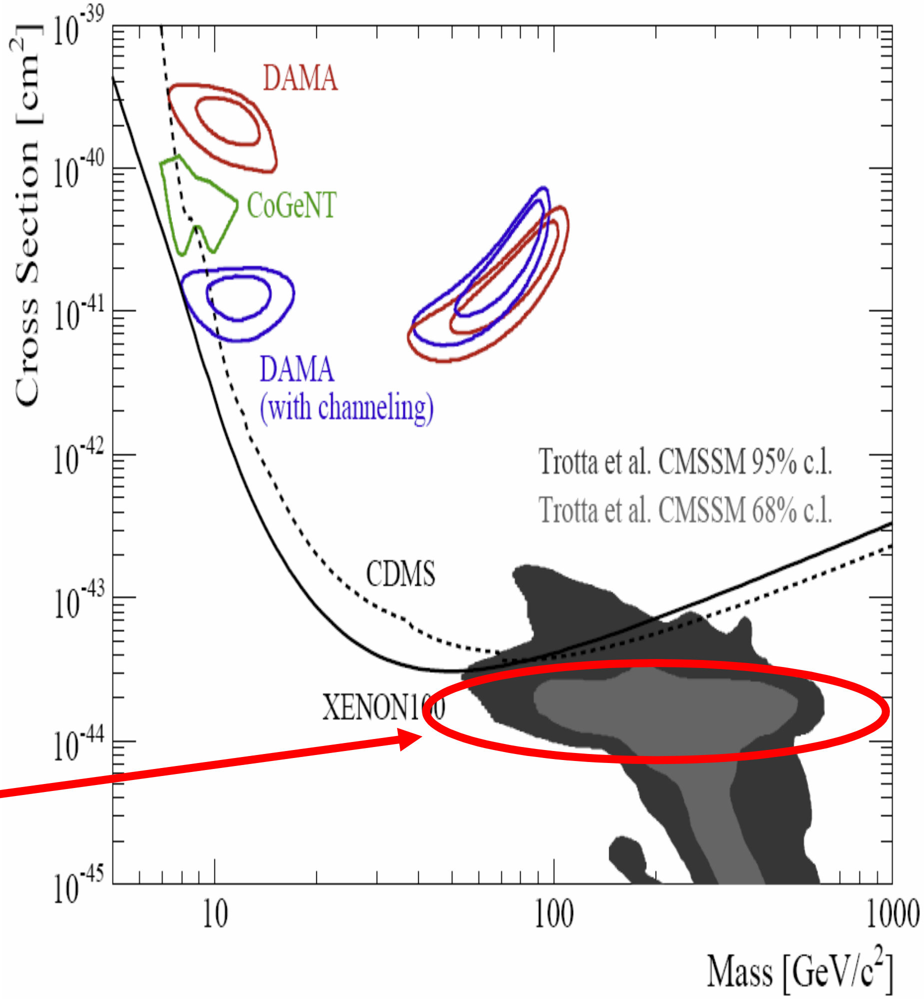
- Three possible solutions
  - Alignment: θ small
  - Degeneracy: squark Δm << m: typically not compatible with DM, because the gravitino mass is ~ Δm, so this would imply that neutralinos decay to gravitinos
  - Decoupling: m > few TeV

# THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- Decoupling is the strategy taken in many theories
  - focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…

- This eliminates many annihilation diagrams, collapses predictions





- Universal prediction:

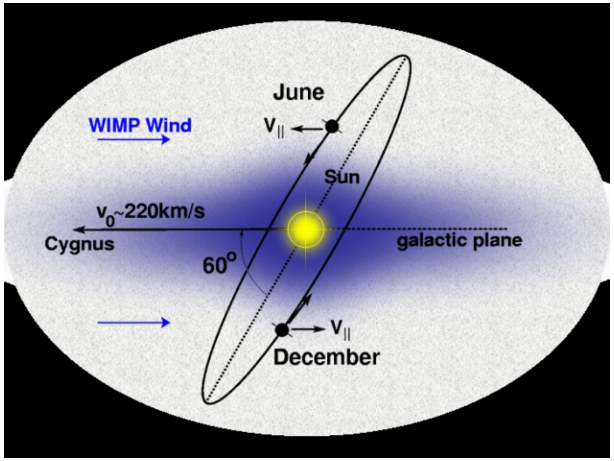
$\sigma_p \sim 10^{-44}$ cm$^2$

Stay tuned!

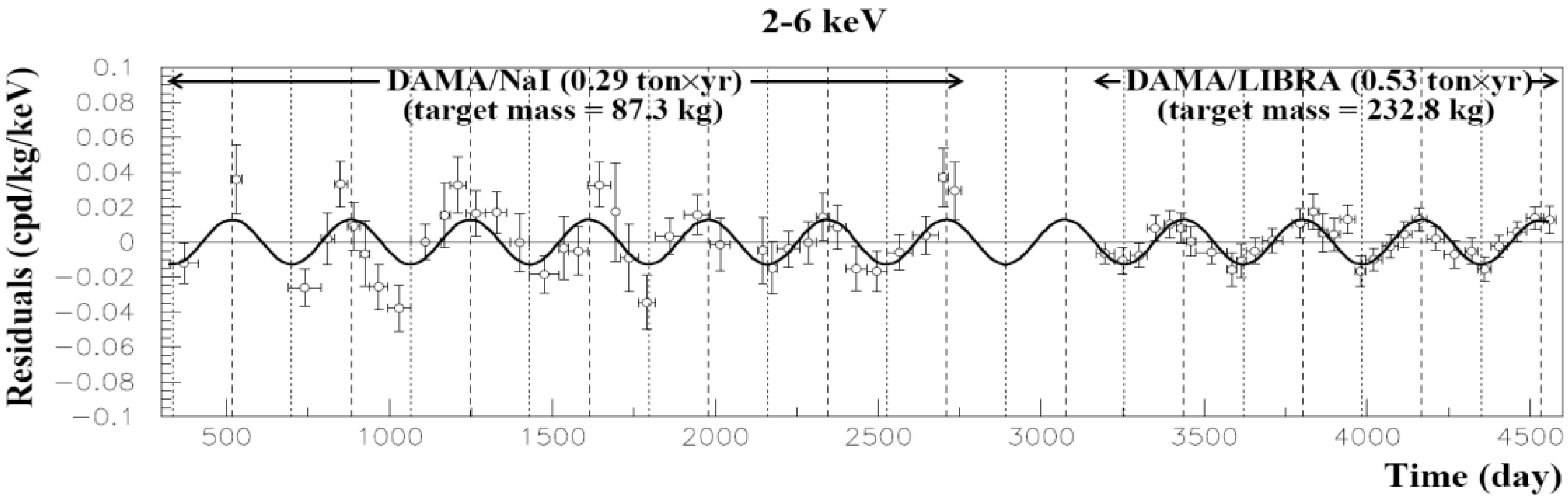
# DIRECT DETECTION: DAMA

- Annual modulation expected

Drukier, Freese, Spergel (1986)



- DAMA: 8.9σ signal with
  - T ~ 1 year, max ~ June 2



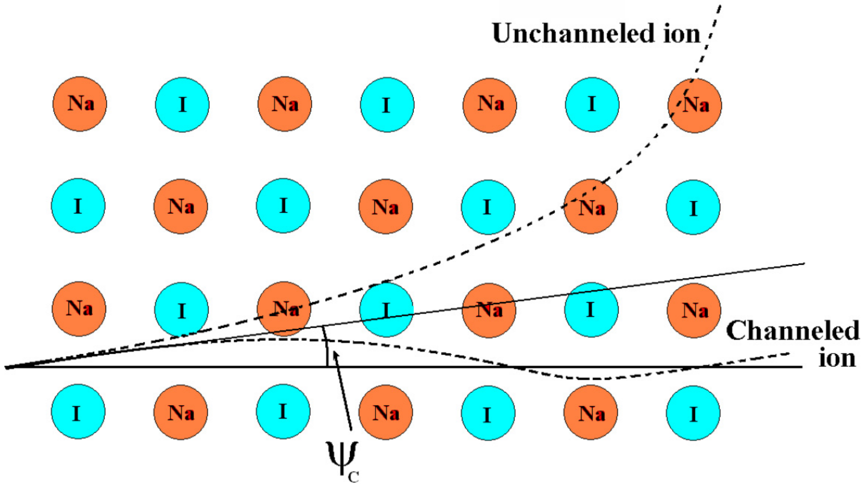
DAMA Collaboration (2008)

# CHANNELING

- DAMA's results have been puzzling, in part because the allowed region is excluded by other experiments

- This may be ameliorated by astrophysics and channeling: in crystalline detectors, efficiency for nuclei recoil energy → electron energy depends on direction

- Channeling reduces threshold, shifts allowed region to lower masses. Consistency restored?



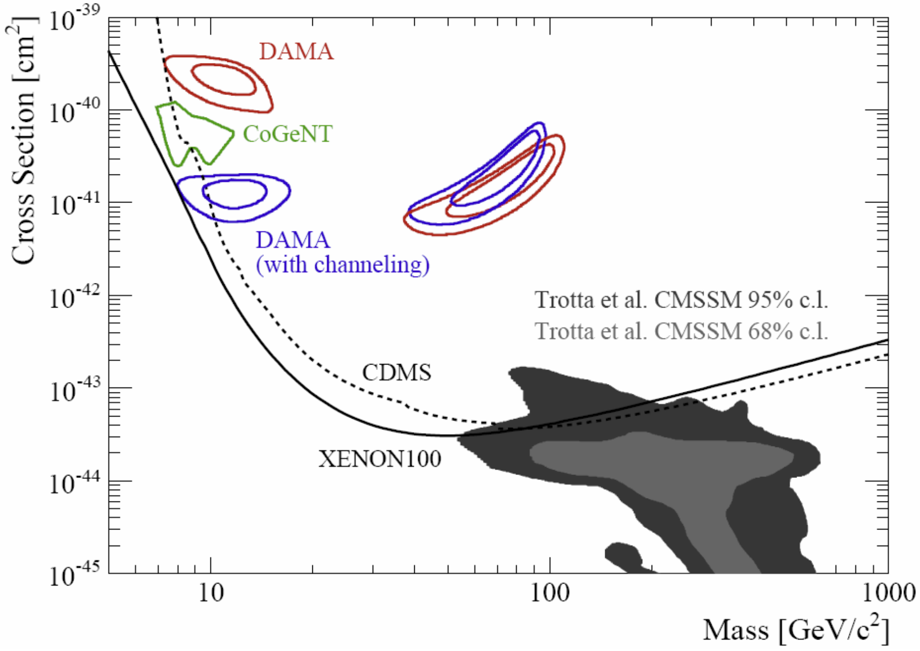
Gondolo, Gelmini (2005)
Drobyshevski (2007), DAMA (2007)

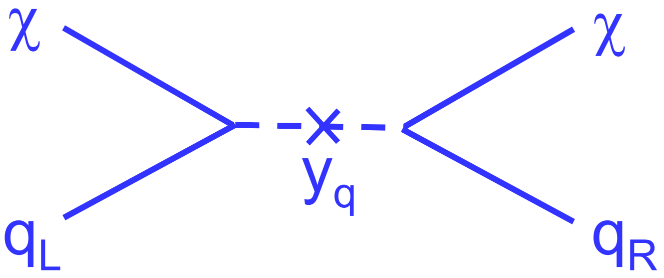
# LIGHT WIMPS

- Channeling may open up a new ~10 GeV region that is marginally acceptable

- This region is now tentatively supported by CoGeNT, disfavored by XENON100

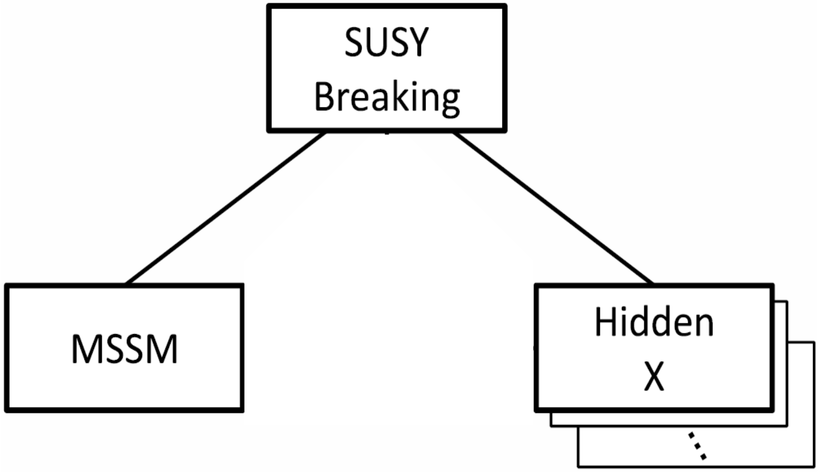
- Low masses and high cross sections are hard to obtain with conventional WIMPs: for example, for neutralinos, chirality flip implies large suppression





# HIDDEN SECTORS

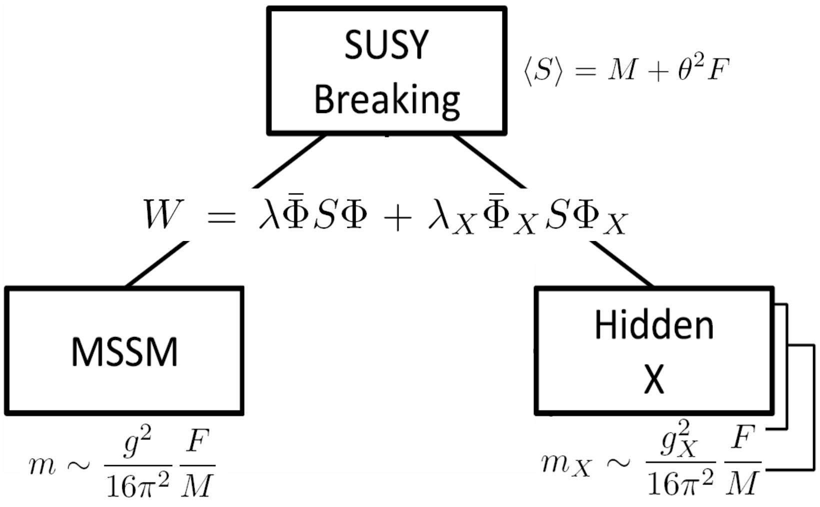
- Can we obtain something like the WIMP miracle, but with hidden DM? Need some structure.
- Consider standard GMSB with one or more hidden sectors
- Each hidden sector has its own gauge groups and couplings



# THE WIMPLESS MIRACLE

Feng, Kumar (2008)

- Particle Physics



SUSY Breaking

$\langle S \rangle = M + \theta^2 F$

$$W = \lambda \bar{\Phi} S \Phi + \lambda_X \bar{\Phi}_X S \Phi_X$$

MSSM

$m \sim \frac{g^2}{16\pi^2} \frac{F}{M}$

Hidden X

$m_X \sim \frac{g_X^2}{16\pi^2} \frac{F}{M}$

Superpartner masses, interaction strengths depend on gauge couplings

- Cosmology

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

$\Omega$ depends only on the SUSY Breaking sector:

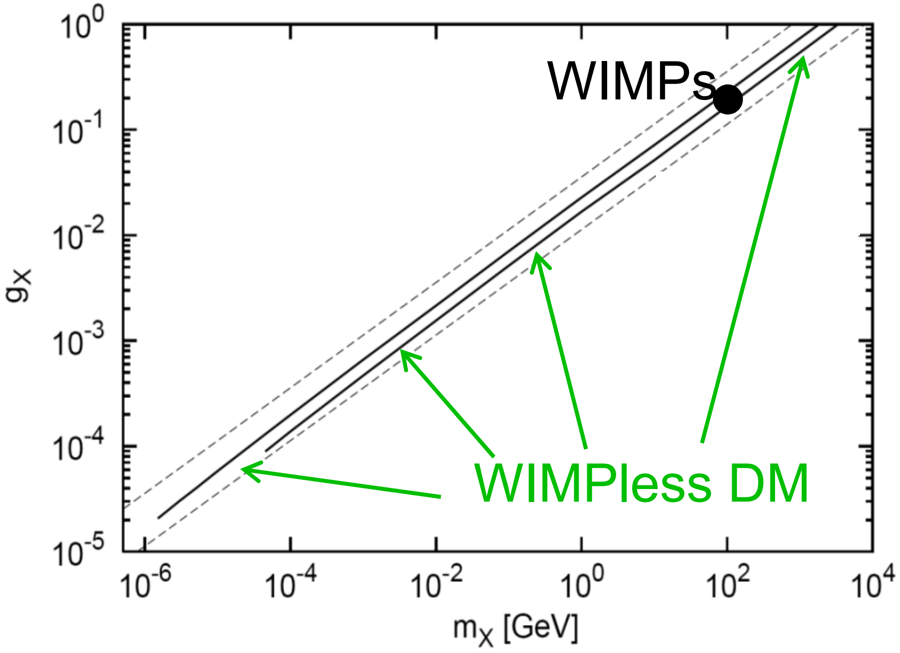
$$\Omega_X \sim \Omega_{WIMP} \sim \Omega_{DM}$$

Any hidden particle with mass ~ $m_X$ will have the right thermal relic density (for *any* $m_X$)

# THE WIMPLESS MIRACLE

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

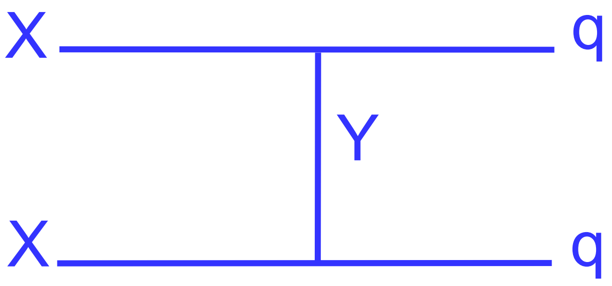
- The thermal relic density constrains only one combination of $g_X$ and $m_X$. These models map out the remaining degree of freedom; candidates have a range of masses and couplings, but always the right relic density.

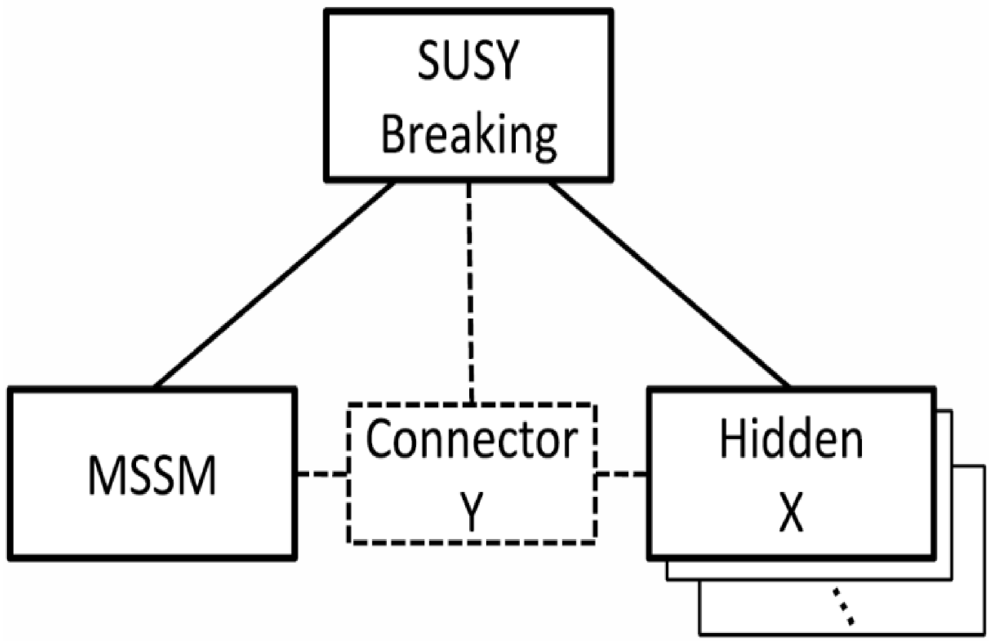


- This decouples the WIMP miracle from WIMPs (is this what the flavor problem is really trying to tell us?)

# WIMPLESS SIGNALS

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





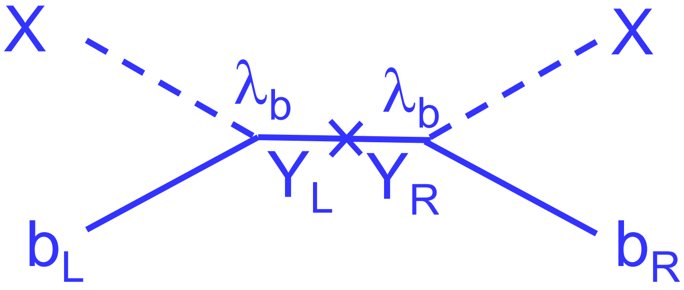
# WIMPLESS DIRECT DETECTION

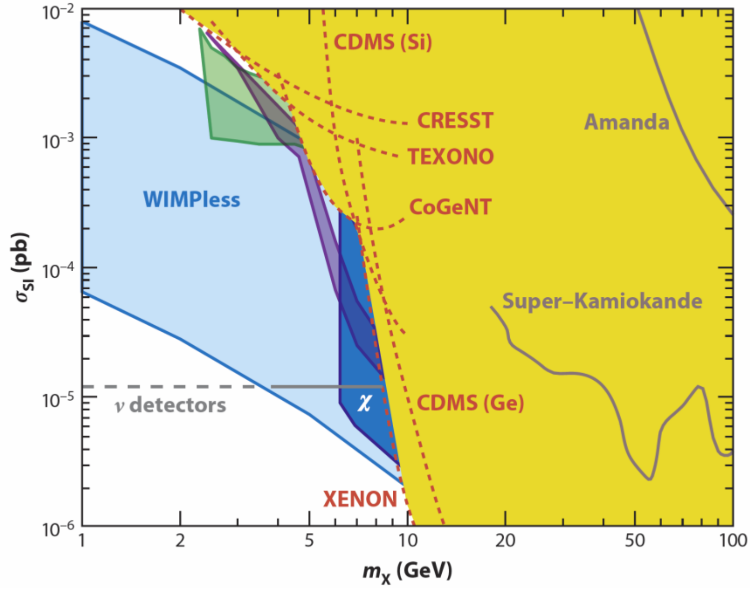
- The DAMA/CoGeNT region is easy to reach with WIMPless DM

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

  $\lambda_b\,(\,XY_Lb_L + XY_Rb_R\,) + m_YY_LY_R$

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





Kumar, Learned, Smith (2009)

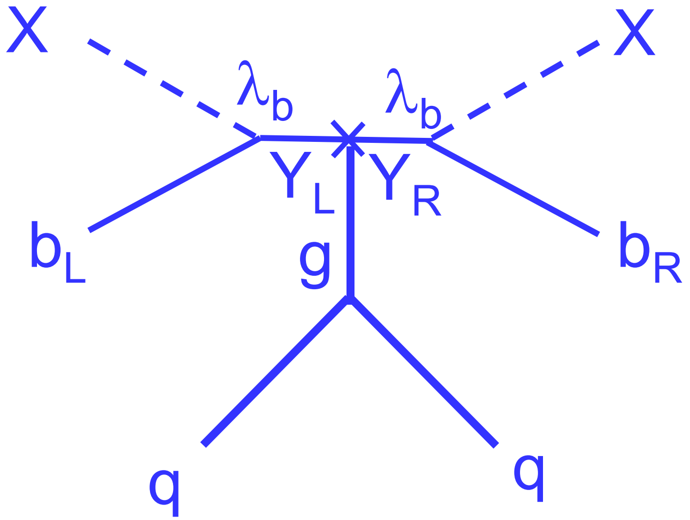
# FUTURE PROSPECTS

- SuperK can probe this region

Hooper, Petriello, Zurek, Kamionkowski (2009)
Feng, Kumar, Strigari, Learned (2009)
Kumar, Learned, Smith (2009)

- Tevatron and LHC can find connector particles: colored, similar to 4th generation quarks

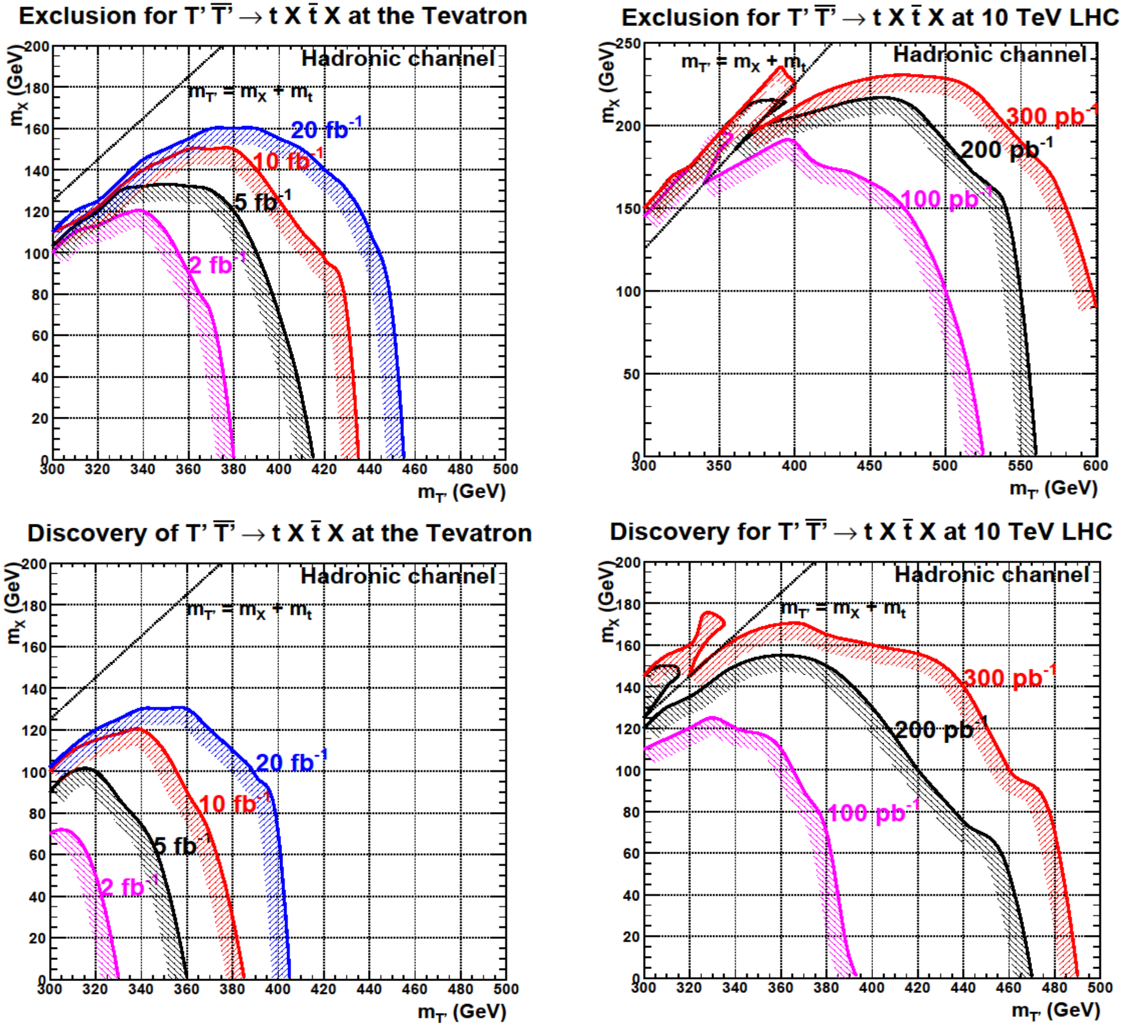
- EW precision studies, direct searches, perturbativity → 300 GeV < $m_Y$ < 600 GeV



# 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



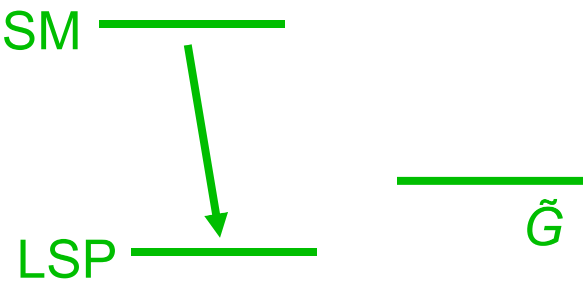
Alwall, Feng, Kumar, Su (2010)

# SUPERWIMP DM

Feng, Rajaraman, Takayama (2003)

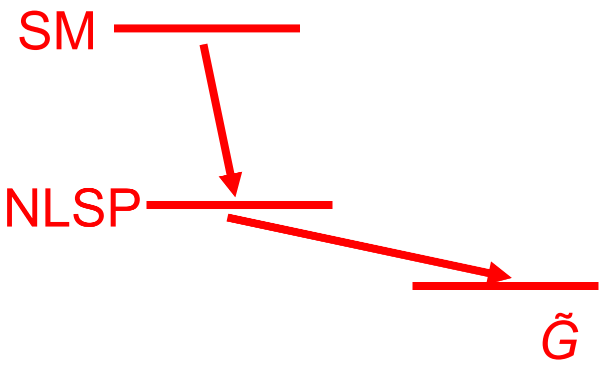
Consider supersymmetry (similar story in UED). There is a gravitino, mass ~ 100 GeV, couplings ~ $M_W/M_{Pl} \sim 10^{-16}$

- $\tilde{G}$ not LSP



- Assumption of most of literature

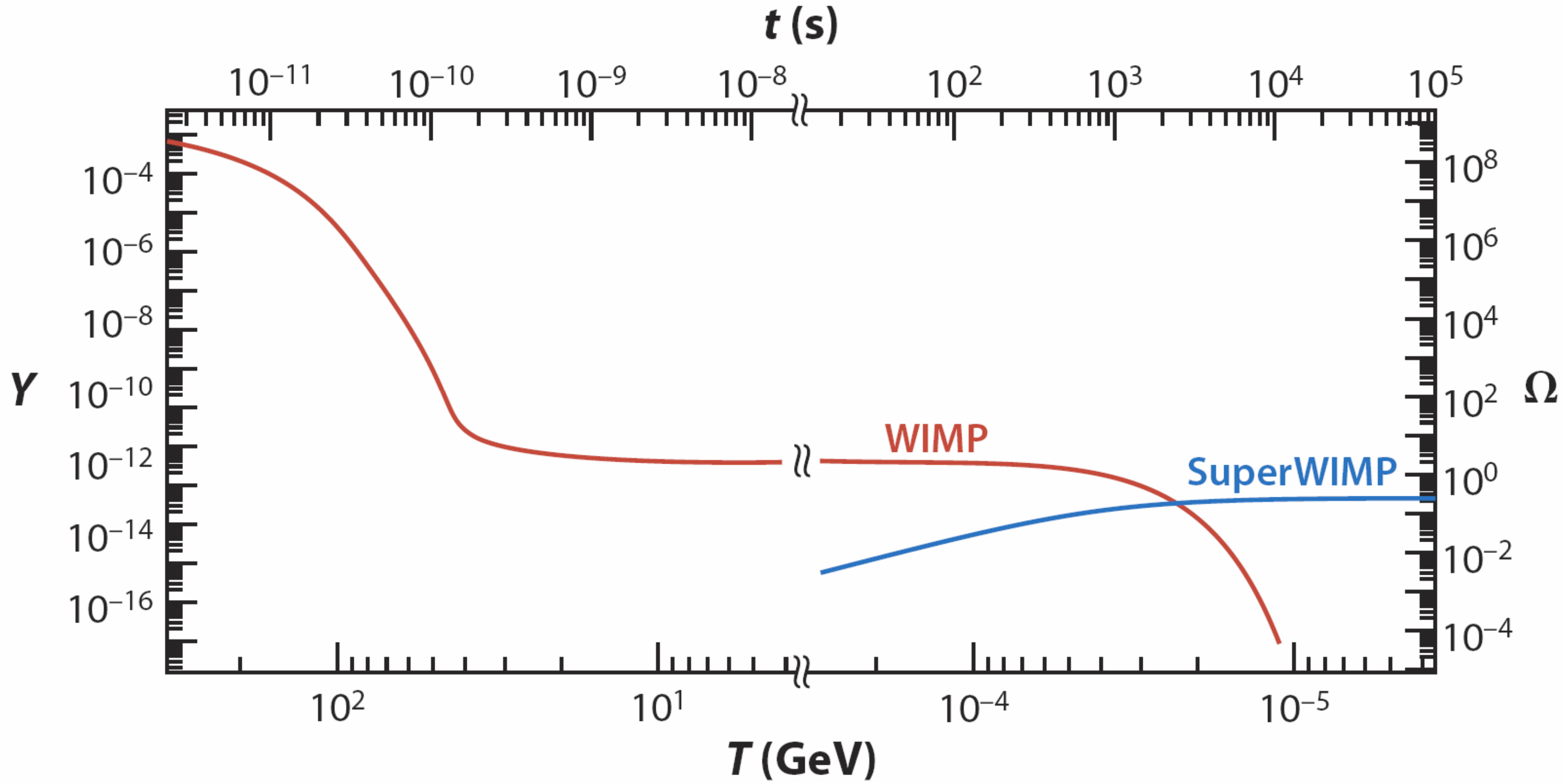
- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

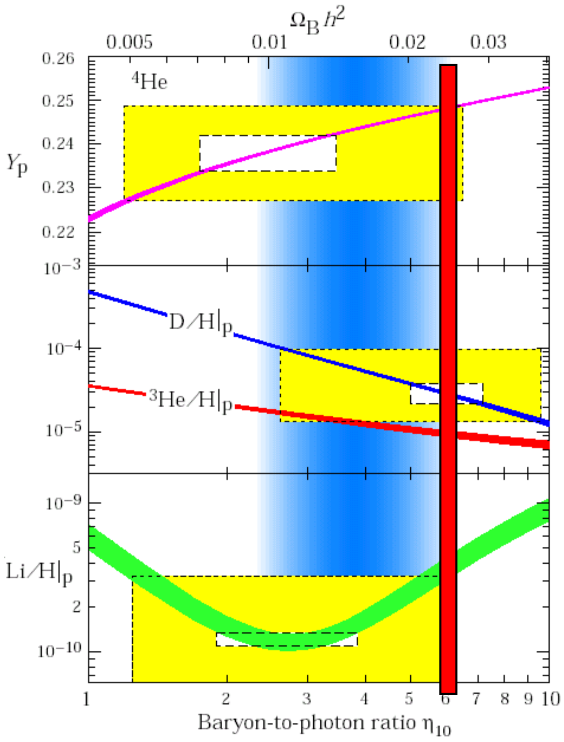
# SUPERWIMP RELICS

- 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

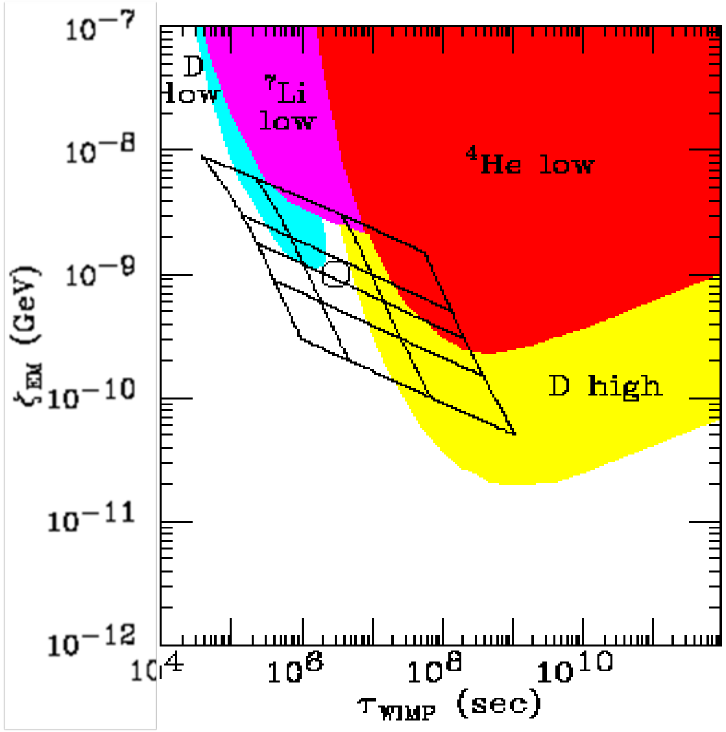


# COSMOLOGY OF LATE DECAYS

## Late decays impact light element abundances



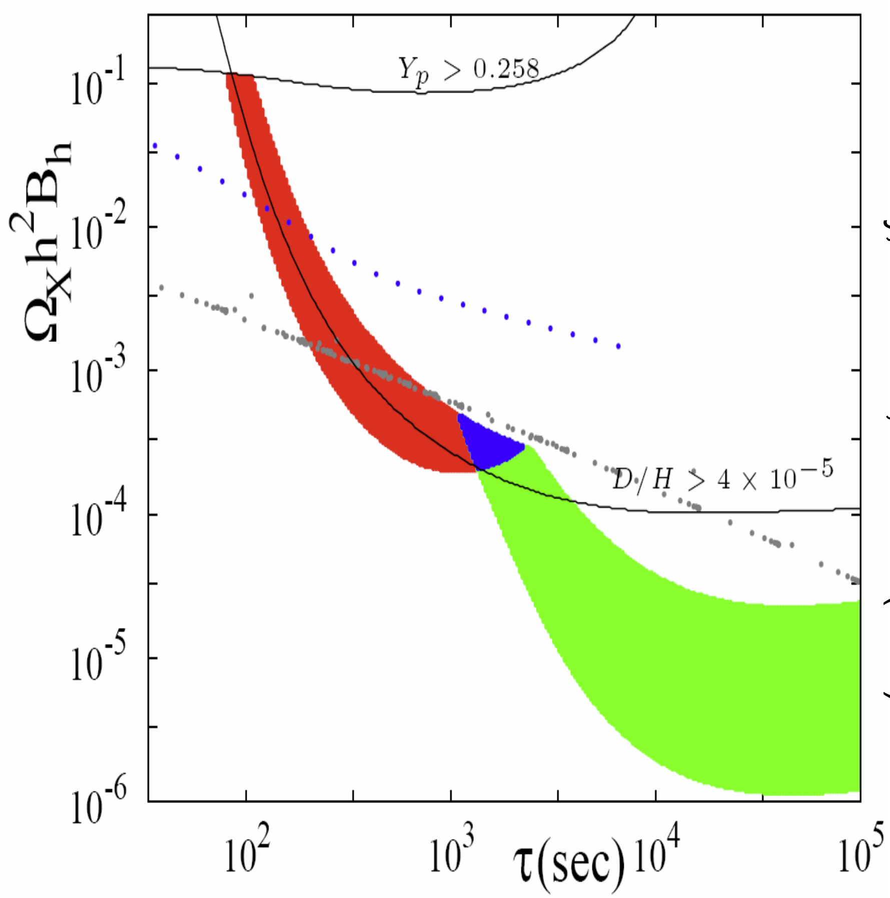
Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

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

# LATE DECAYS AND $^7$Li/$^6$Li

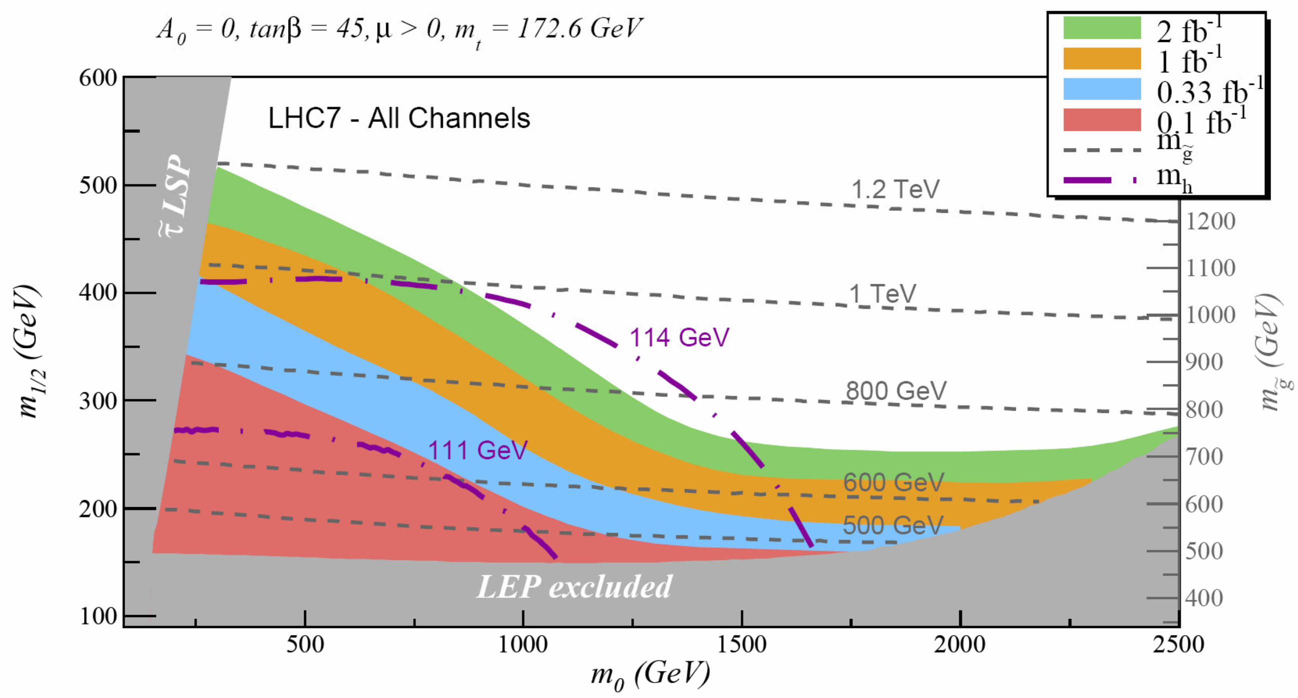


Bailly, Jedamzik, Moultaka (2008)

- $^7$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 both
- For mSUGRA, fixing both, and requiring $\Omega_{\tilde{G}} = 0.1$ → heavy sleptons > TeV

# 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, Barger, Lessa, Tata (2010)

# THE COMPLETE MSUGRA

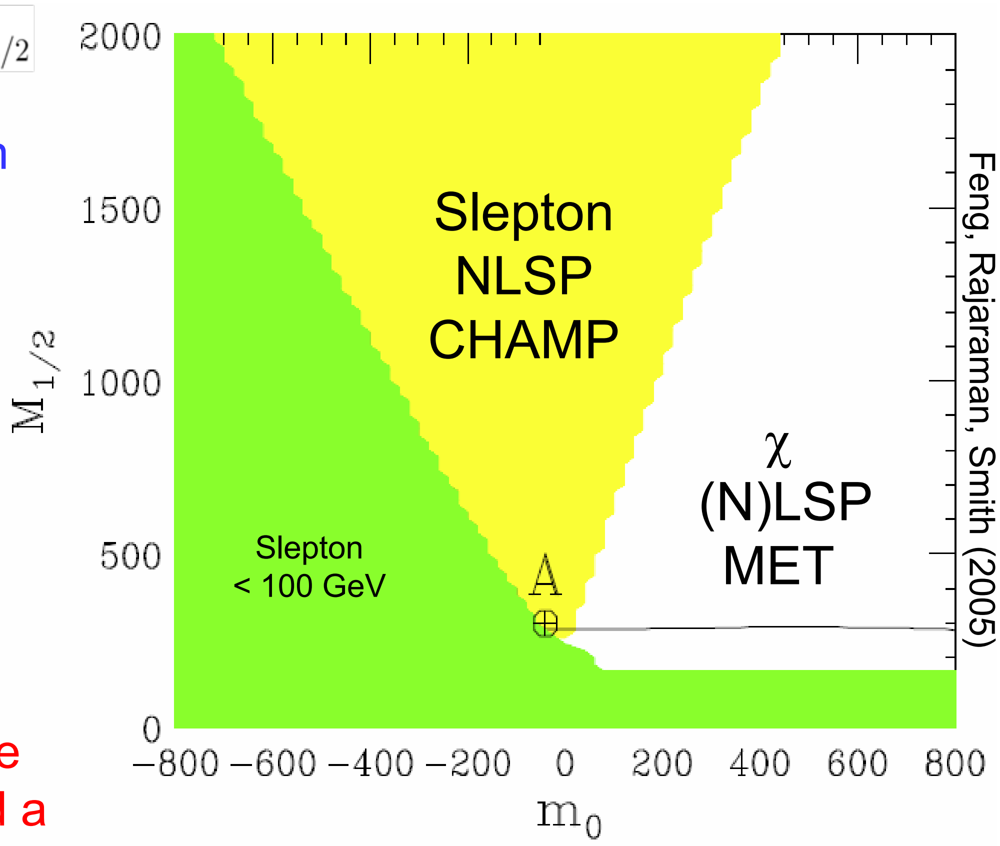
- Extend the mSUGRA parameters to

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

- If LSP = gravitino, then no reason to exclude stau (N)LSP region
- Also include small or negative

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

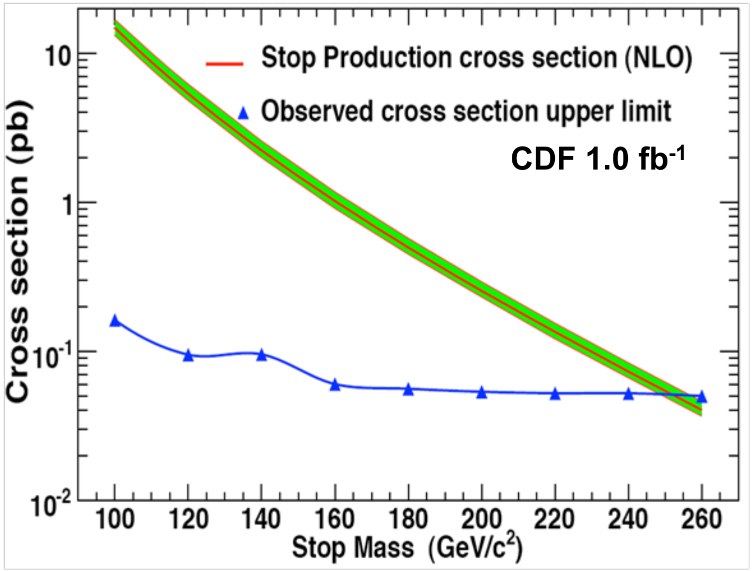
- This includes no-scale/gaugino-mediated models with $m_0 = 0$
- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP



Feng, Rajaraman, Smith (2005)

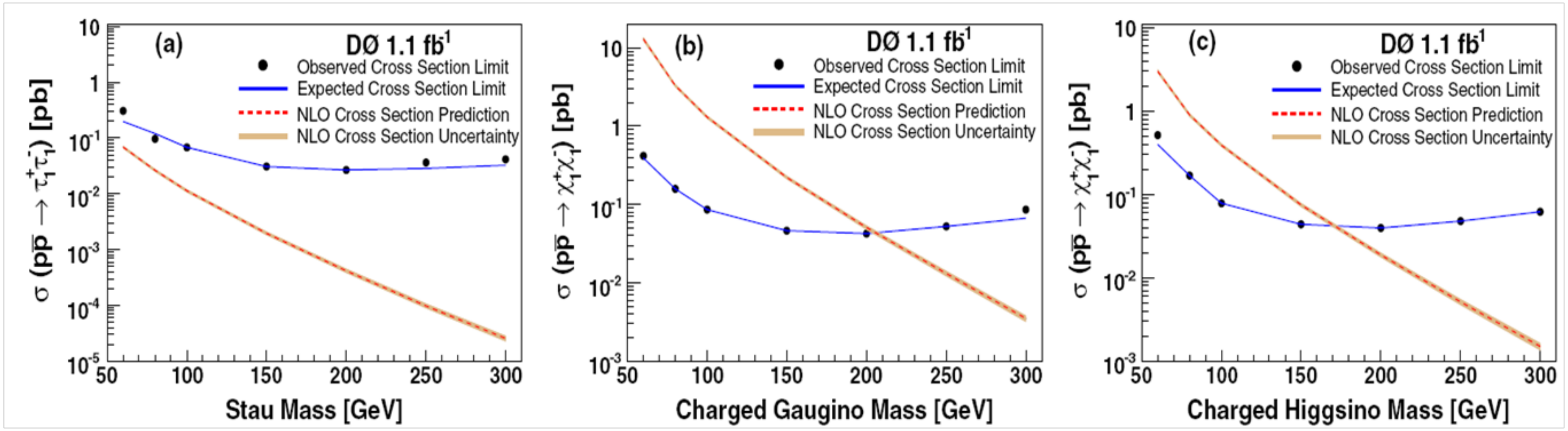
# CURRENT BOUNDS

- Current Bounds
  - LEP: slepton mass > 97.5 GeV, chargino > 102.5 GeV
  - CDF Run I: slepton cross section < 1 pb
  - CDF Run II: top squark mass > 249 GeV



- D0 Run II: chargino mass > 200 GeV

- 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



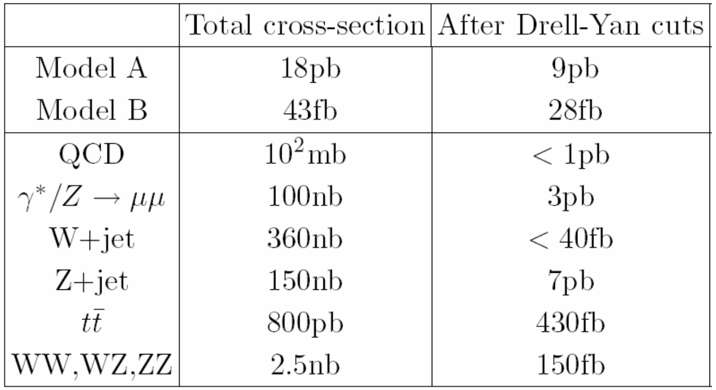
# LHC DISCOVERY POTENTIAL

Rajaraman, Smith (2006)

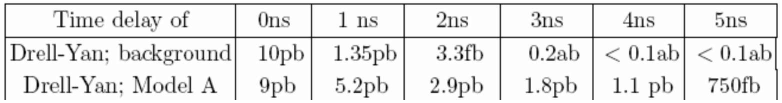
- Look for Drell-Yan slepton pair production

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

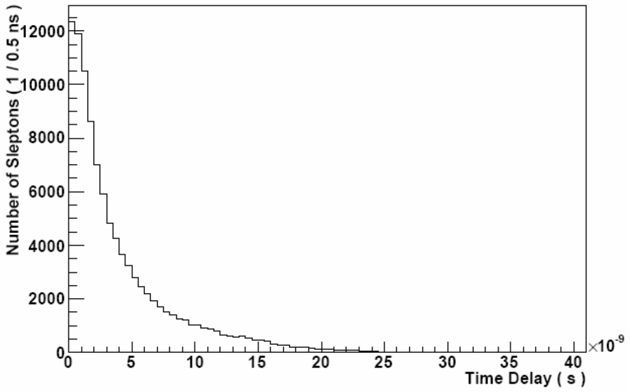
- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays > 3 ns



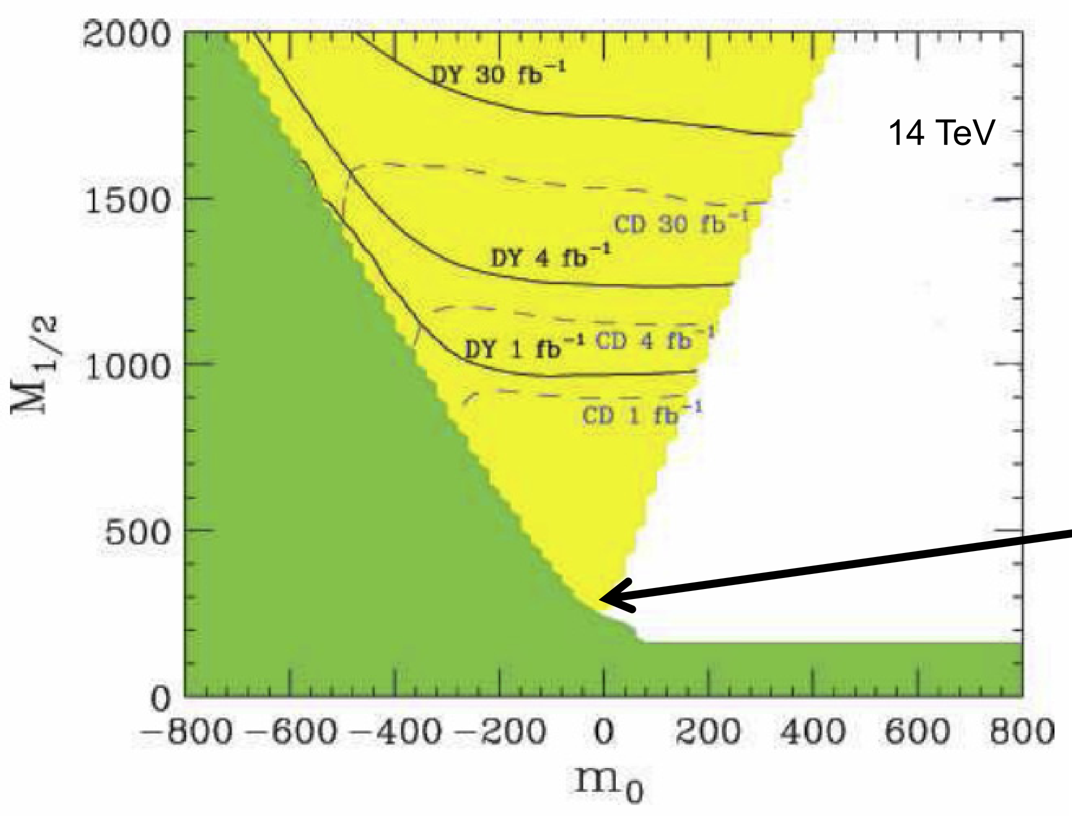
| | Total cross-section | After Drell-Yan cuts |
|---|---|---|
| Model A | 18pb | 9pb |
| Model B | 43fb | 28fb |
| QCD | $10^2$mb | $< 1$pb |
| $\gamma^*/Z \to \mu\mu$ | 100nb | 3pb |
| W+jet | 360nb | $< 40$fb |
| Z+jet | 150nb | 7pb |
| $t\bar{t}$ | 800pb | 430fb |
| WW,WZ,ZZ | 2.5nb | 150fb |



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



- Require 5$\sigma$ 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

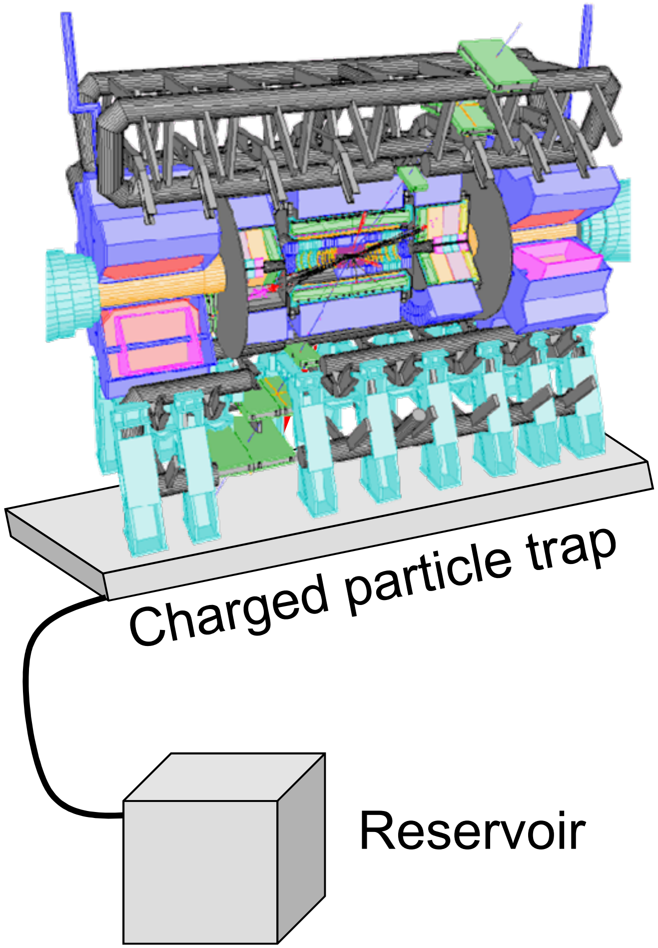
# CHARGED PARTICLE TRAPPING

- SuperWIMP DM → metastable particles, may be charged, far more spectacular than misssing $E_T$ (1st year LHC discovery)
- Can collect these particles and study their decays
- Several ideas
  - Catch sleptons in a 1m thick water tank (up to 1000/year)

    Feng, Smith (2004)
  - Catch sleptons in LHC detectors

    Hamaguchi, Kuno, Nakawa, Nojiri (2004)
  - Dig sleptons out of detector hall walls

    De Roeck et al. (2005)



# LIGHT GRAVITINO DM

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

Pagels, Primack (1982)

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

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

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

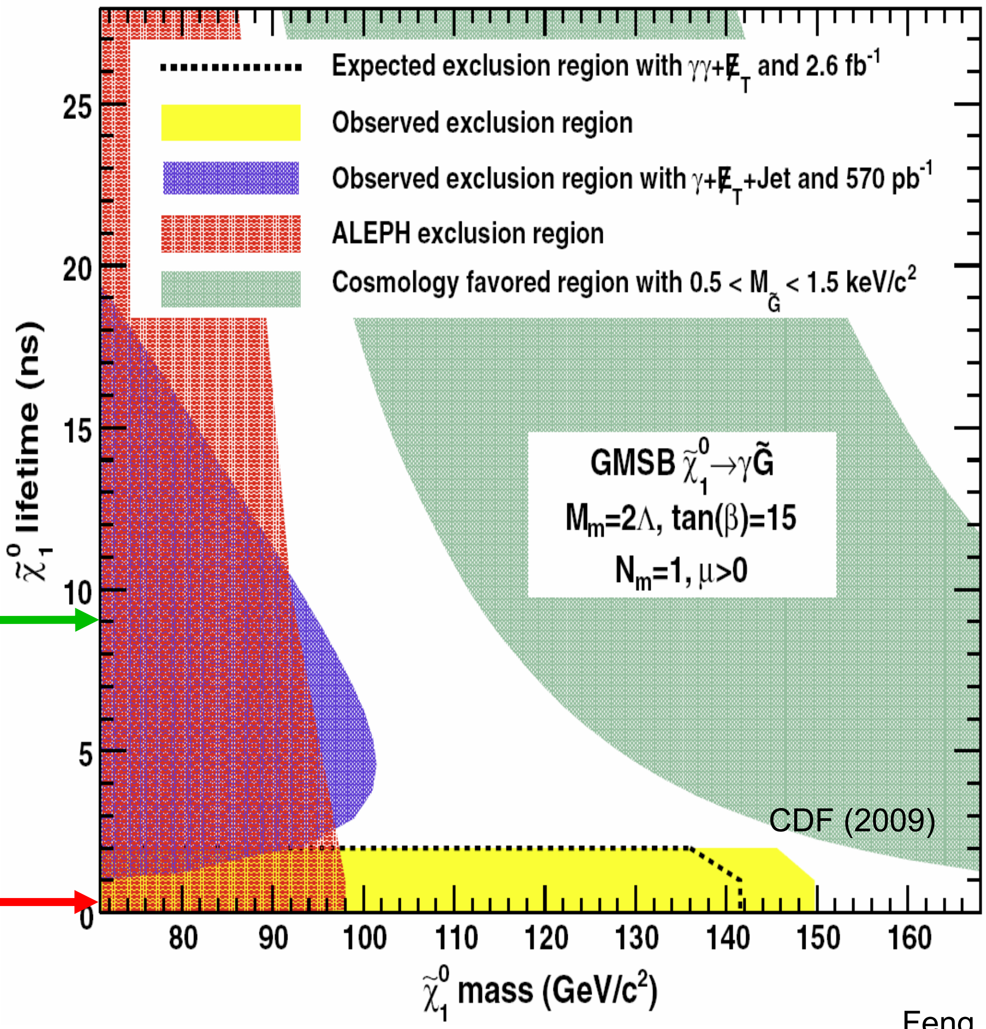
# CURRENT BOUNDS

- Remarkably, this lifetime difference is observable at colliders!

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

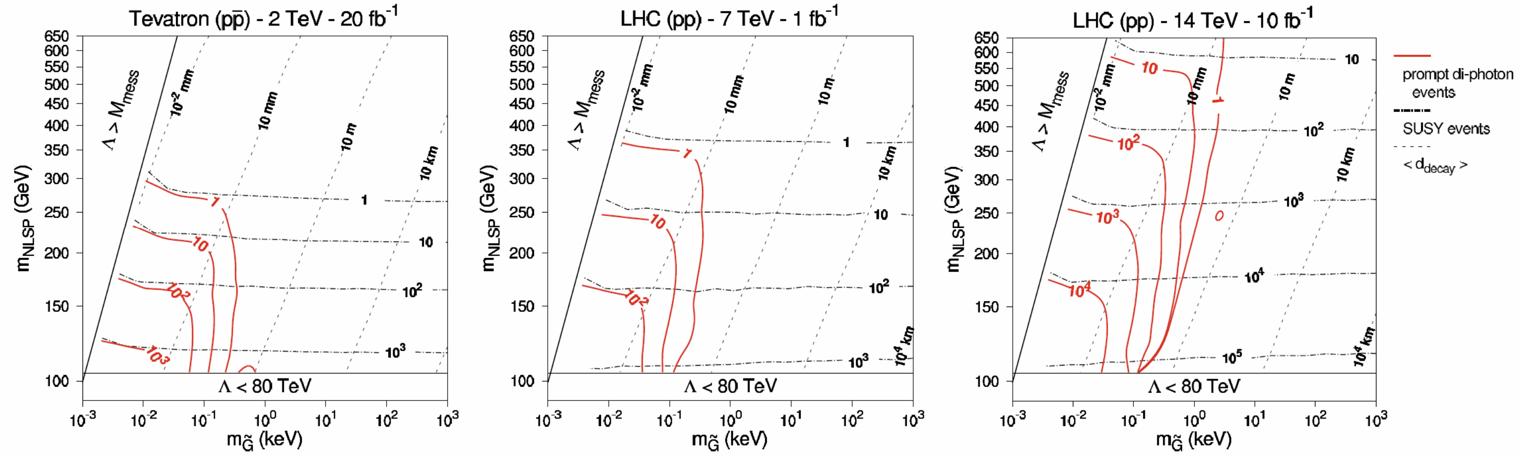
- $m_{\tilde G}$ > few keV: Delayed photon signatures

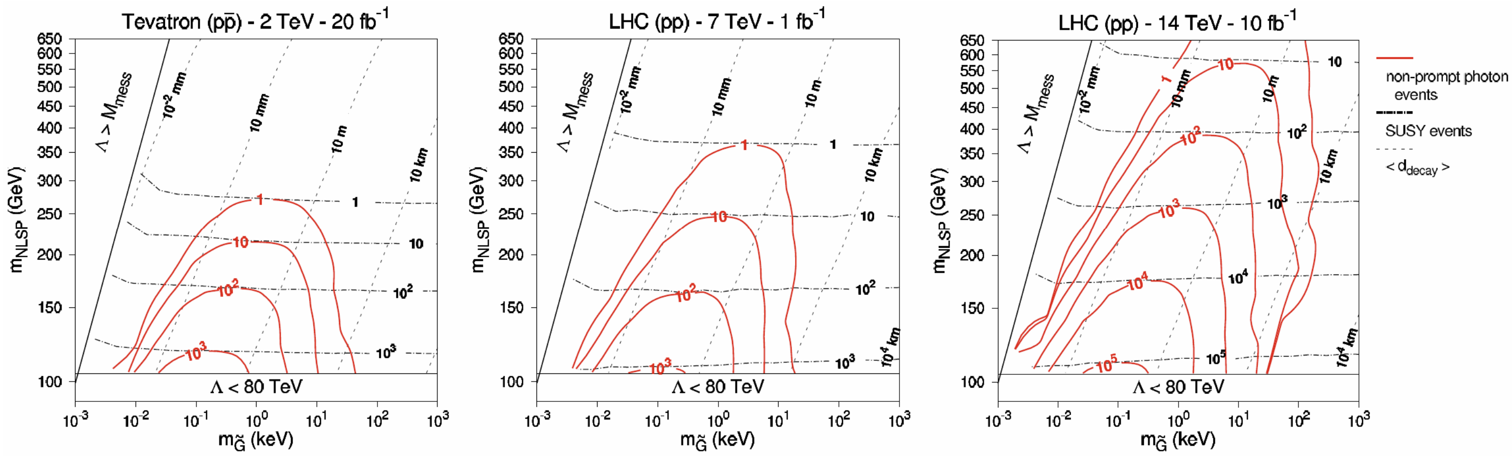
- $m_{\tilde G}$ < 16 eV: Prompt photon signatures



CDF (2009)

# LIGHT GRAVITINOS AT THE LHC





Lee, Feng, Kamionkowski (2010)

# CONCLUSIONS

- DM searches are progressing rapidly on all fronts
  - Direct detection
  - Indirect detection
  - LHC

- Proliferation of DM candidates, but many are tied to the weak scale

- In the next few years, these DM models will be stringently tested