WIMP AND RELATED MIRACLES

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INTRODUCTION

- The WIMP miracle is the fact that weak scale particles make good dark matter

- It is at the heart of many expectations for connections between particle physics and cosmology and is the driving motivation behind most dark matter searches

- Executive Summary
  - The WIMP miracle is more restrictive than you might think
  - The WIMP miracle is less restrictive than you might think

THE WIMP MIRACLE

- Fermi's constant G_F introduced in 1930s to describe beta decay

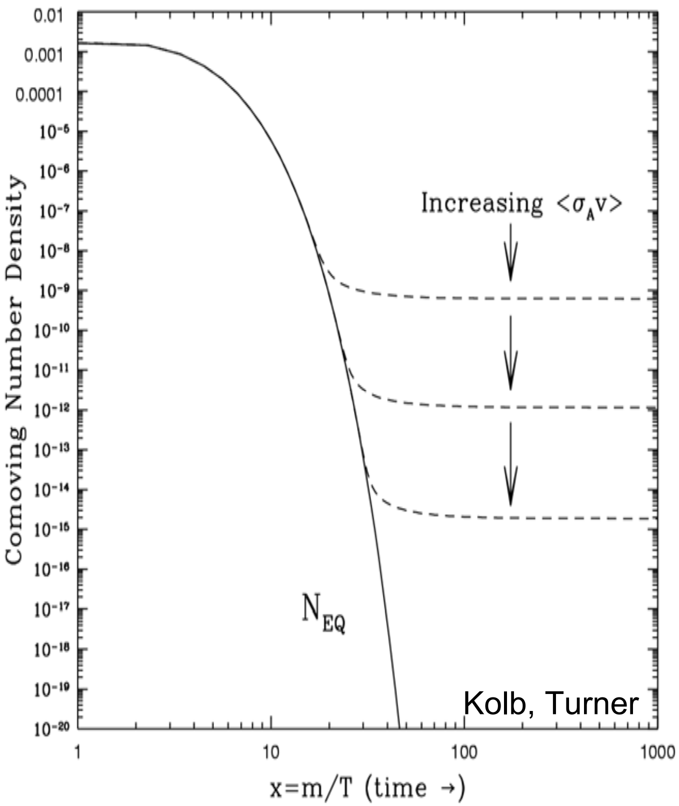
$$n \rightarrow p\, e^- \bar{\nu}$$

- $G_F \approx 1.1\ 10^5\ \text{GeV}^{-2} \rightarrow$ a new mass scale in nature

$$m_{weak} \sim 100\ \text{GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

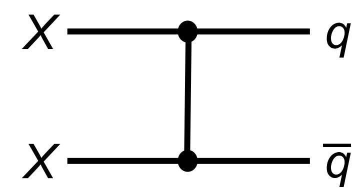
THE WIMP MIRACLE



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

- Its relic density is

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

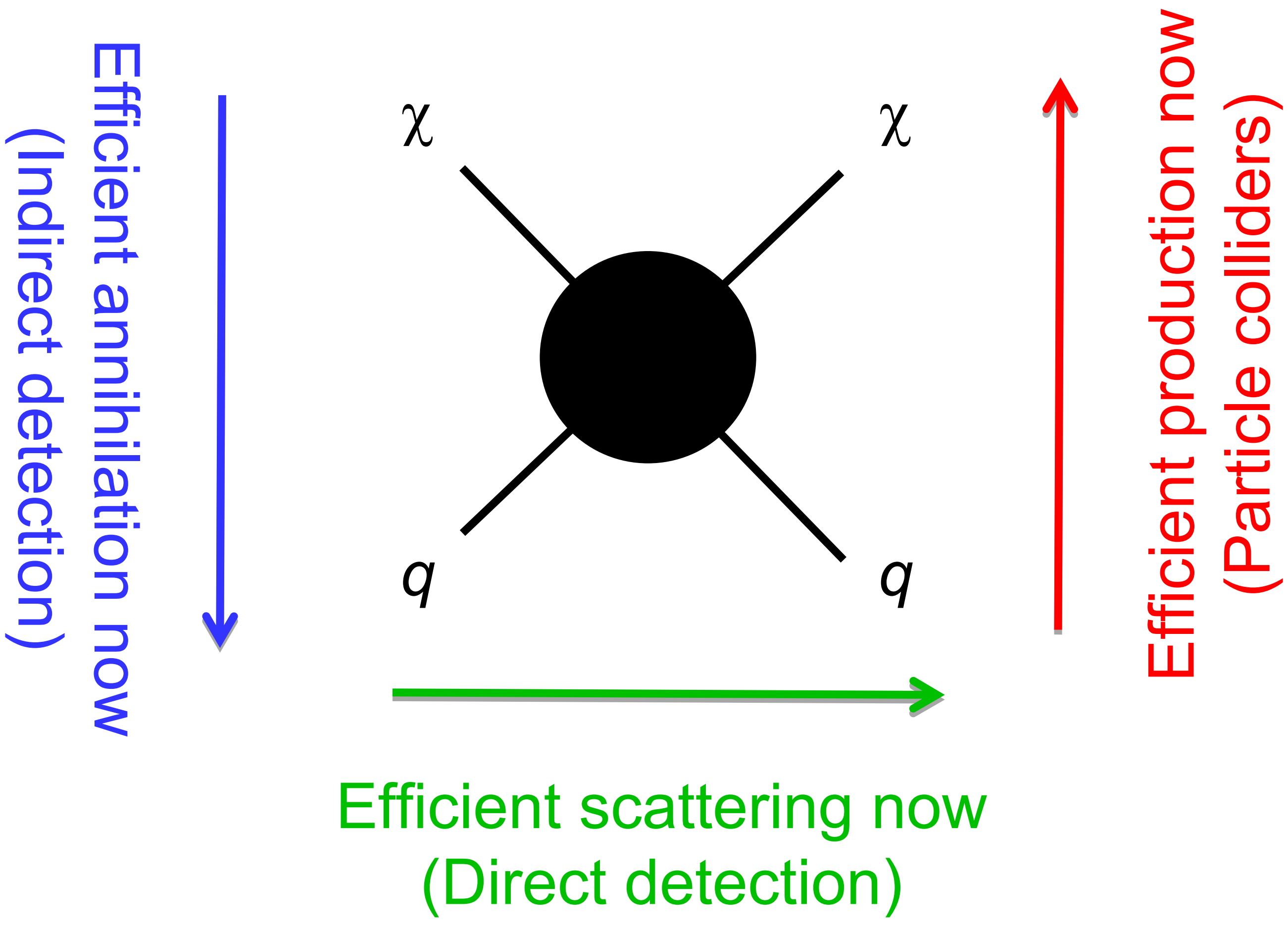


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

WIMP DETECTION

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



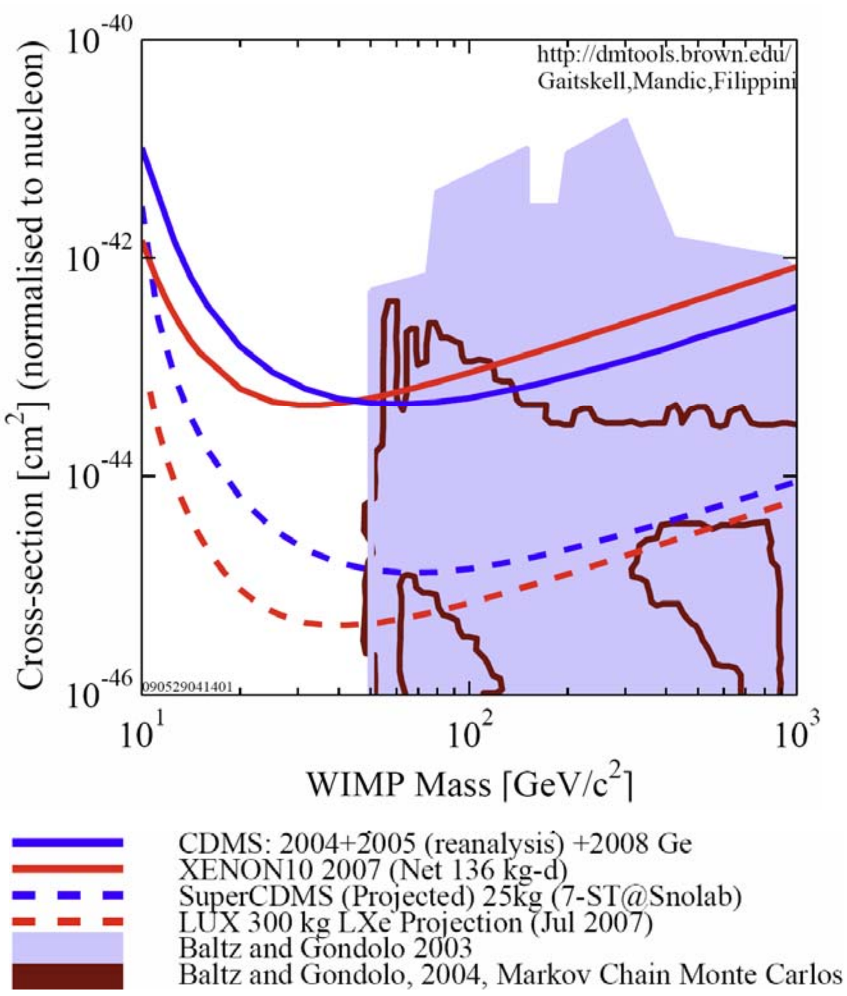
DIRECT DETECTION

- CDMS will announce new results next Friday

- From correspondence with CDMS collaborators, I can tell you that
  - CDMS has not discovered DM
  - or these people would make incredible poker players

CURRENT STATUS

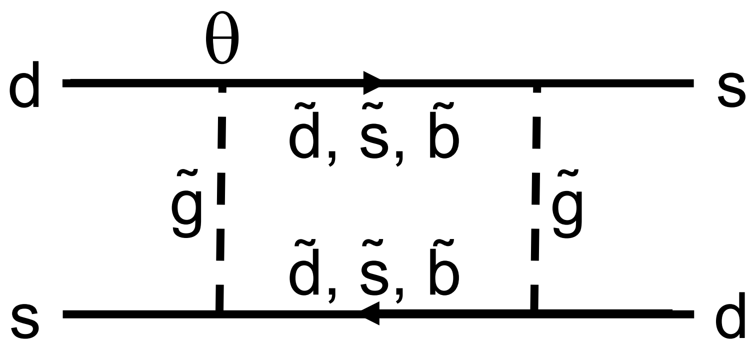
- Direct detection searches for nuclear recoil in underground detectors
- Spin-independent scattering is typically the most promising
- Theory and experiment compared in the (m_X, σ_p) plane
  - Expts: CDMS, XENON, …
  - Theory: Shaded region is the predictions for SUSY neutralino DM – what does this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



NEW PHYSICS FLAVOR PROBLEM

- New weak scale particles generically create many problems

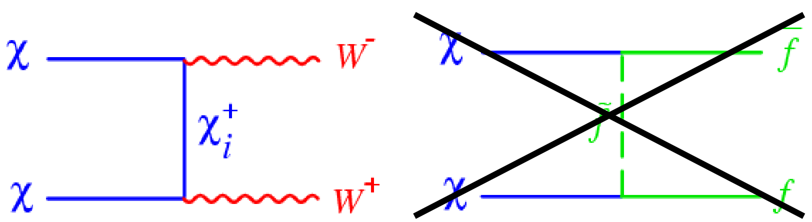
- One of *many* possible examples: K-$\bar{K}$ mixing



- 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

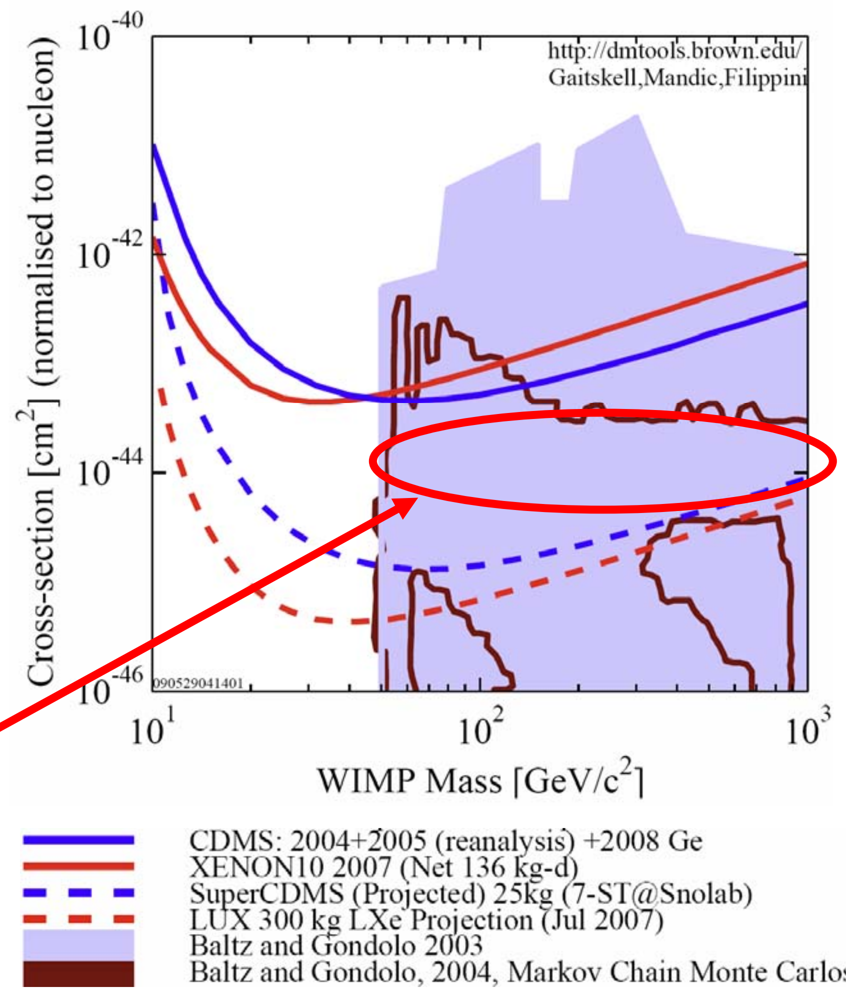
- Decoupling is the strategy taken in many theories
  - focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…
- This eliminates many annihilation diagrams, collapses predictions



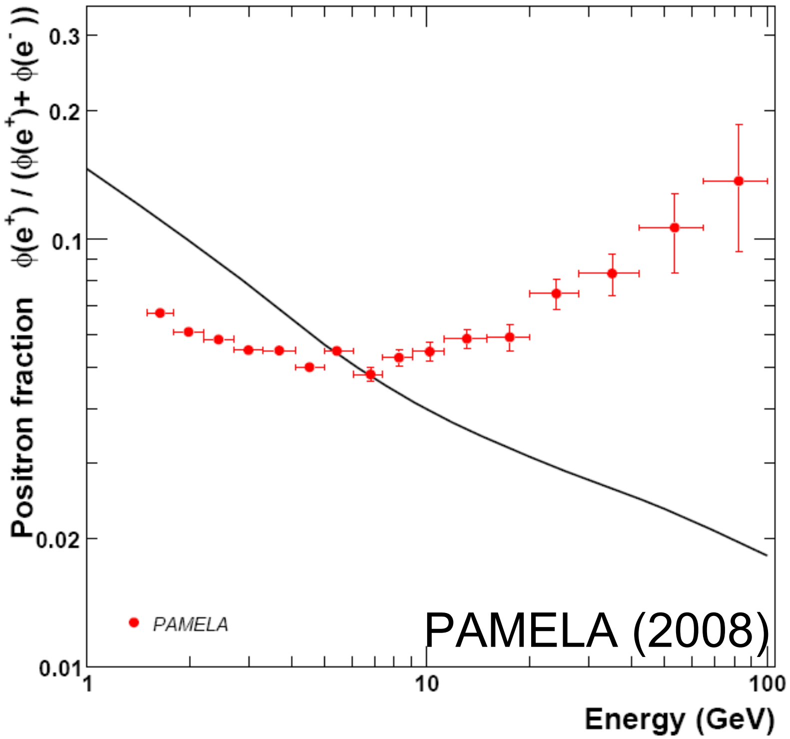
- Universal prediction:

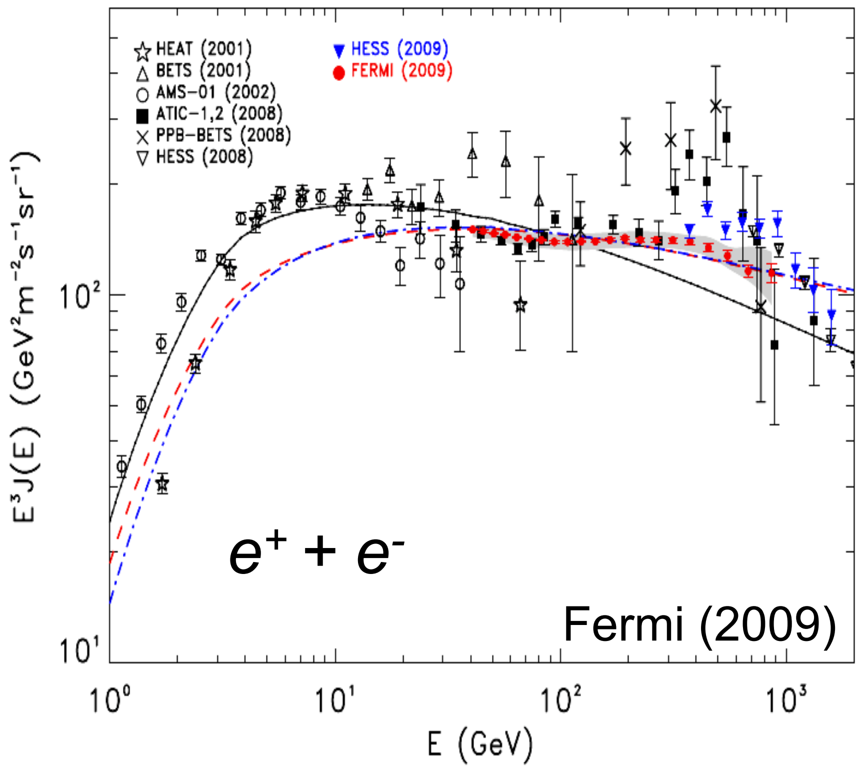
$\sigma_p \sim 10^{-44}$ cm^2

Stay tuned!



INDIRECT DETECTION



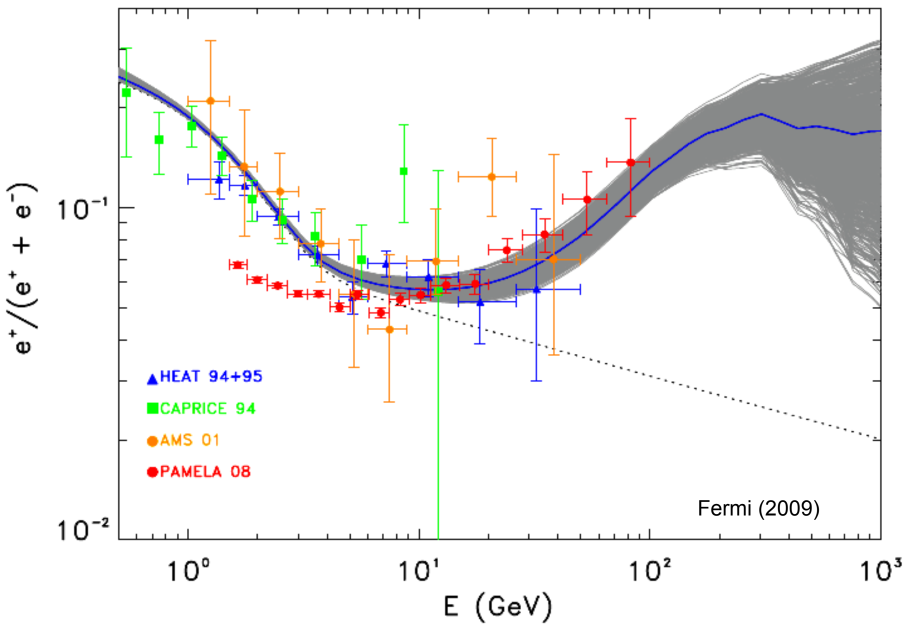


Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- Pulsars can explain PAMELA

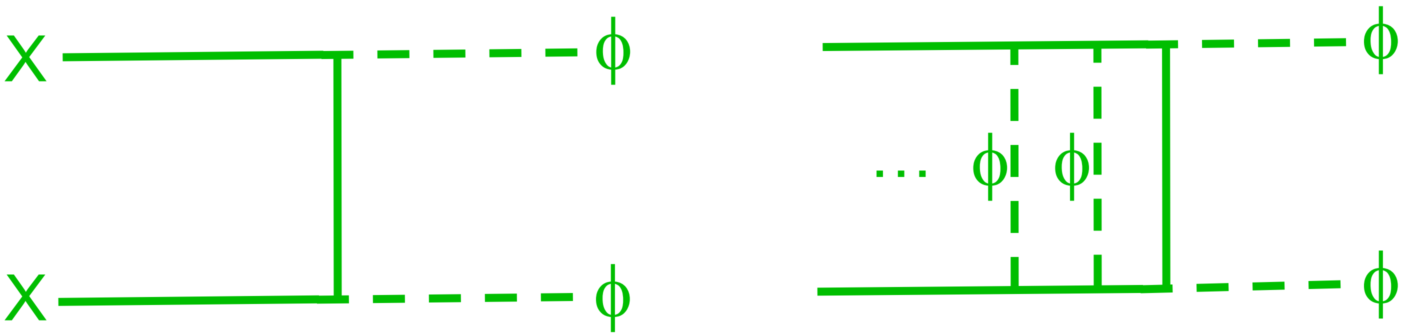
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008)
Profumo (2008) ; Fermi (2009)



- 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

SOMMERFELD ENHANCEMENT

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



- At freezeout: v ~ 0.3, only 1st diagram is significant, $\sigma = \sigma^{th}$
  Now: v ~ 10^{-3}, all diagrams significant, $\sigma = S\sigma^{th}$, $S \sim \min\{\pi\alpha/v, \alpha m_X/m_\phi\}$, boosted at low velocities

Sommerfeld (1931)

Hisano, Matsumoto, Nojiri (2002)

- If S ~ 100-1000, seemingly can explain excesses, get around WIMP miracle predictions

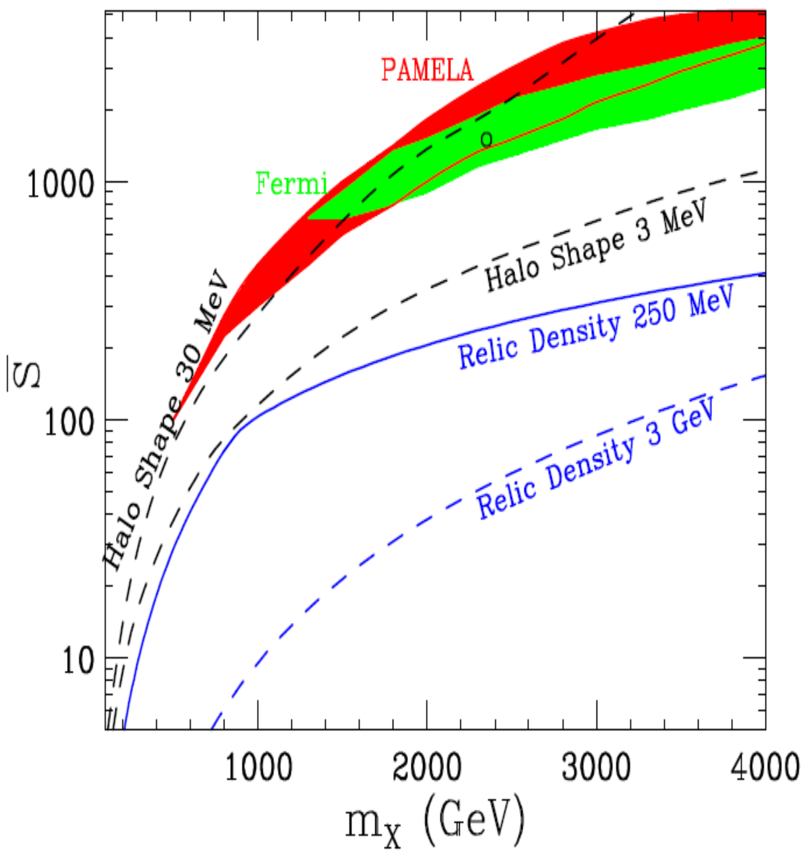
Cirelli, Kadastik, Raidal, Strumia (2008)

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

CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

Feng, Kaplinghat, Yu (2009)

- Unfortunately, this scenario is internally inconsistent, at least in its original form
- Large S requires large α and small m_ϕ
- This also maximizes the annihilation cross section; requiring that X be all the dark matter → upper bounds on S
- These scenarios also induce dark matter self-interactions XX → XX, are excluded for light ϕ by halo ellipticity



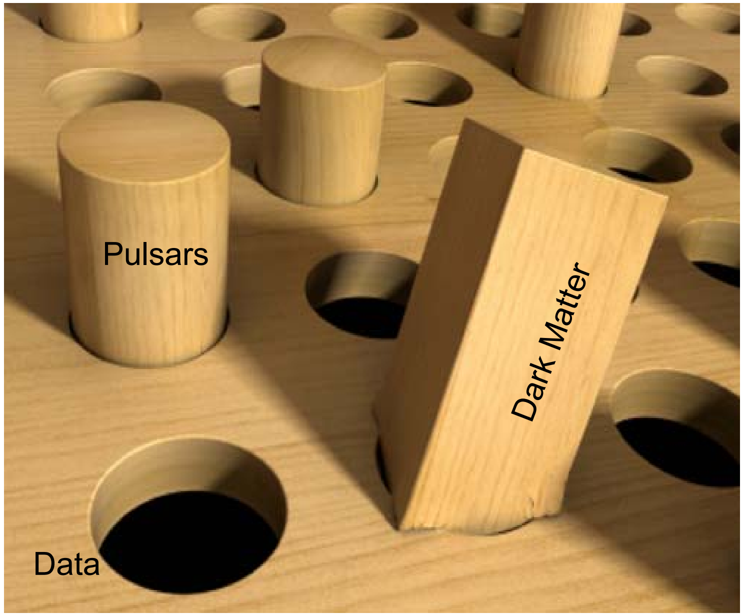
Spergel, Steinhardt (1999); Miralda-Escude (2000)
Ackerman, Buckley, Carroll, Kamionkowski (2009)
Feng, Tu, Yu (2009), Buckley, Fox (2009)

WAYS OUT?

- X is only part of the dark matter: No, flux ~ $n^2 \langle\sigma v\rangle S \sim \alpha^{-1}$
- Resonant Sommerfeld enhancement: No

Dent et al. (2009), Zavala et al. (2009)

- Alternative production mechanisms, cosmologies at freezeout: Yes – but then why consider Sommerfeld enhancement?
- Boosts part Sommerfeld (~100), part astrophysical (~10)? Maybe



DOES THE WIMP MIRACLE REQUIRE WIMPS?

- The WIMP miracle seemingly implies vanilla dark matter
  - Weakly-interacting
  - Cold
  - Collisionless

- Are all WIMP miracle-motivated candidates astrophysically equivalent?

- No! There are dark matter candidates that preserve the virtues of WIMPs, including the WIMP miracle, but have qualitatively different implications

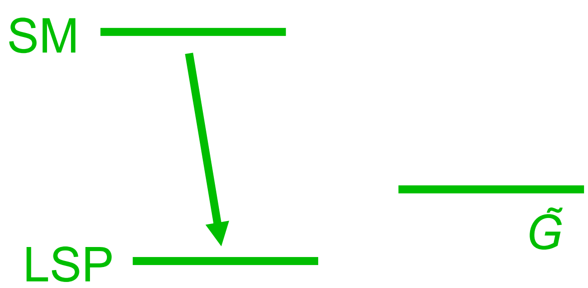
THE SUPERWIMP MIRACLE

Feng, Rajaraman, Takayama (2003)

An example: in supersymmetry, Graviton → Gravitino $\tilde{G}$

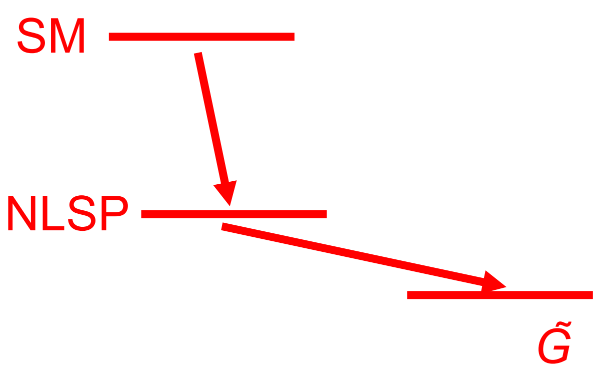
Mass ~ 100 GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP



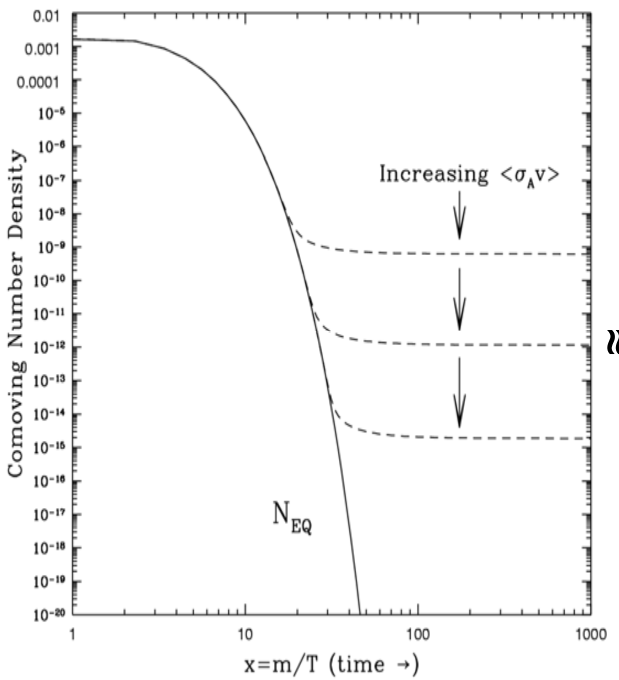
- Assumption of most of literature

- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose gravitinos $\tilde{G}$ are the LSP
- WIMPs freeze out as usual

WIMP ≈ → $\tilde{G}$ (+ γ, e, …)

- But then all WIMPs decay to gravitinos after

M_{Pl}^2/M_W^3 ~ seconds to months

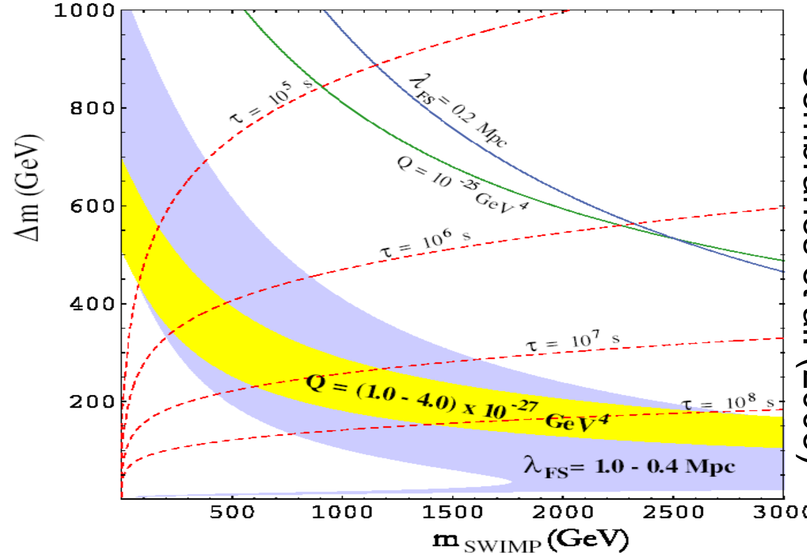
Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also KK gravitons, quintessinos, axinos, etc.)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandeburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …

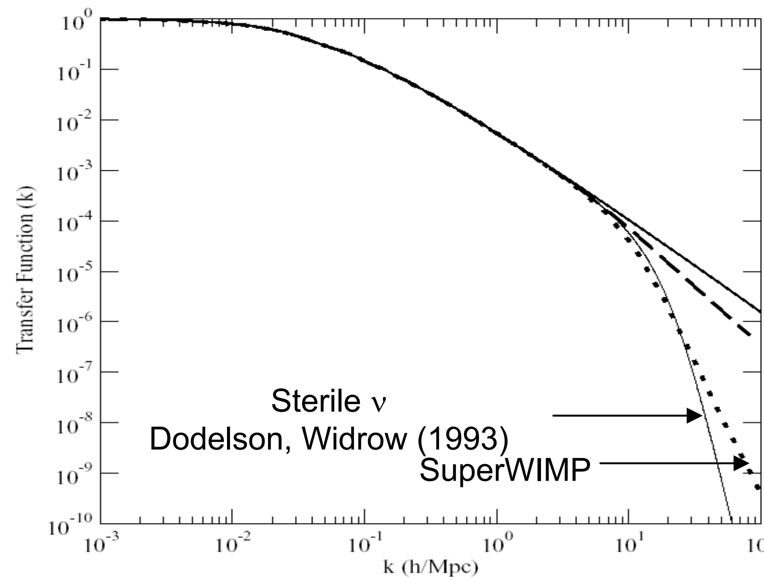
WARM SUPERWIMPS

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by λ_{FS}, Q
- Warm DM with cold DM pedigree

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)



Cembranos et al. (2005)



Kaplinghat (2005)

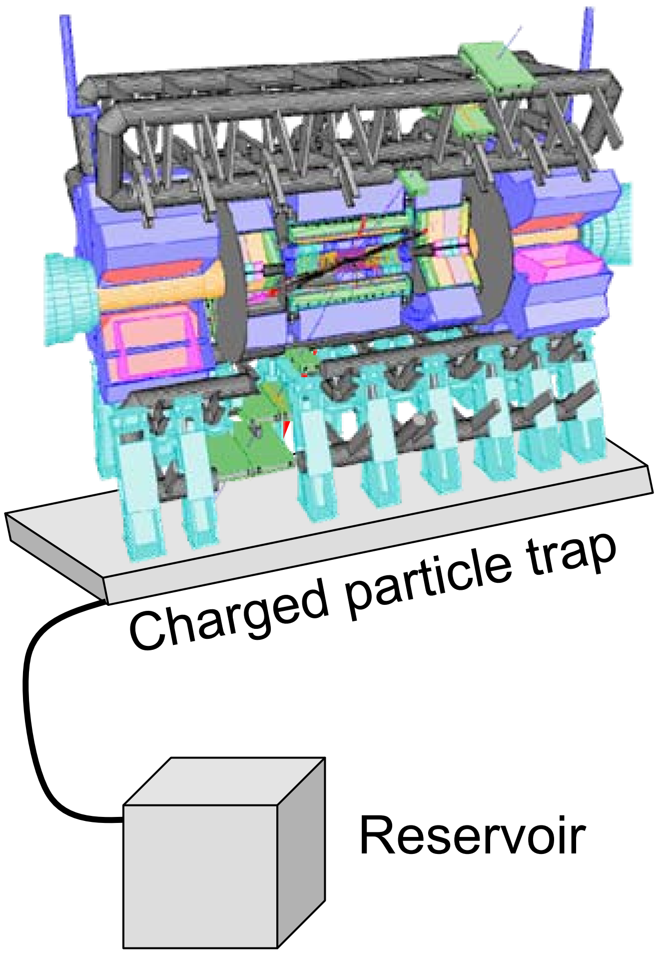
CHARGED PARTICLE TRAPPING

- 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)



THE WIMPLESS MIRACLE

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

- Start over: What do we really know about dark matter?
  - All solid evidence is gravitational
  - Also solid evidence *against* strong and EM interactions
- A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is *hidden*

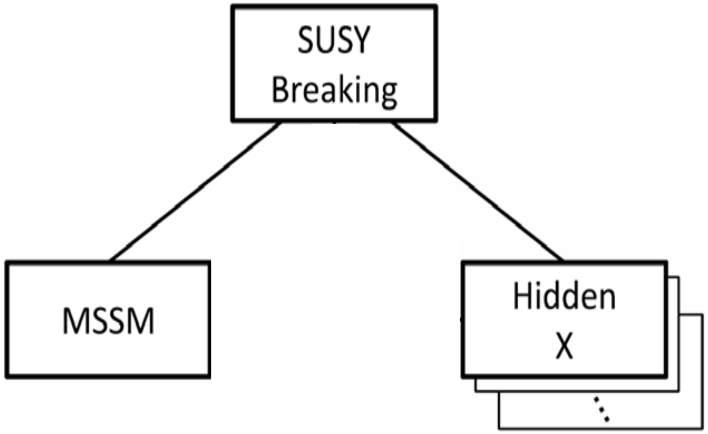
Kobsarev, Okun, Pomeranchuk (1966); many others

- What one seemingly loses
  - Connections to central problems of particle physics
  - The WIMP miracle
  - Signals

Can hidden dark matter be rehabilitated?

CONNECTIONS TO CENTRAL PROBLEMS IN PARTICLE PHYSICS

- We want hidden sectors



- Consider SUSY
  - Connected to the gauge hierarchy problem
  - Hidden sectors are already required to break SUSY

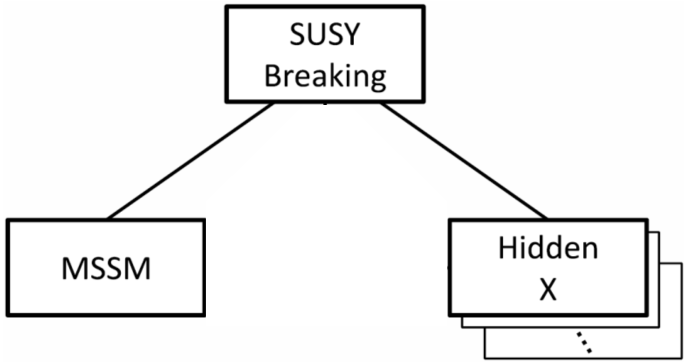
- Hidden sectors each have their own
  - particle content
  - mass scales m_X
  - Interactions, gauge couplings g_X

- What can we say about hidden sectors in SUSY?

- 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

$$m_X \sim g_X^2$$

- This leaves the relic density invariant!



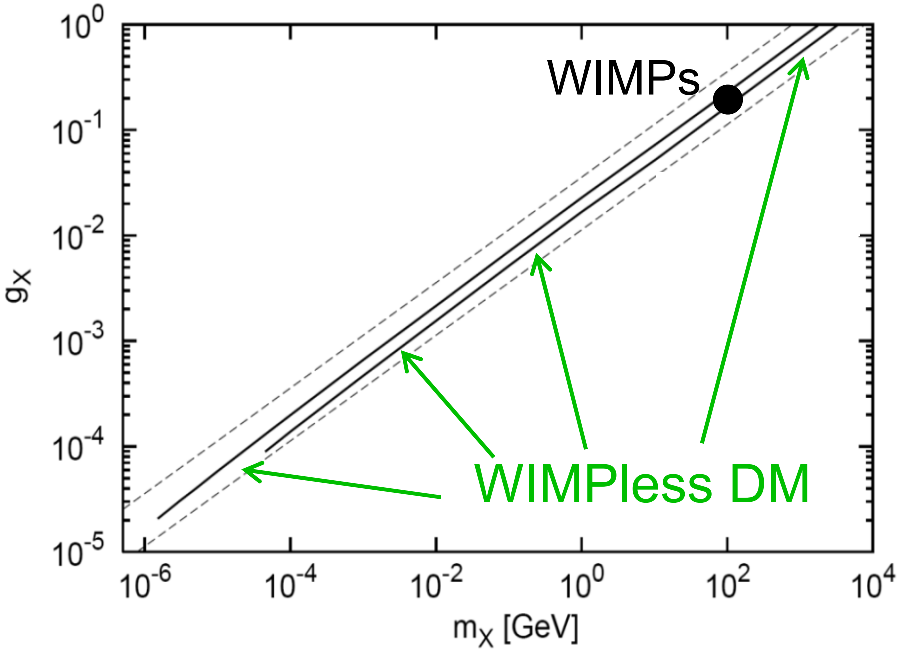
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

THE WIMPLESS MIRACLE

- The thermal relic density constrains only one combination of g_X and m_X

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

- 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?)

SIGNALS

How is hidden dark matter stabilized?

If the hidden sector is standard model-like, the most natural possibility is that the DM particle has hidden charge, and so is stabilized by charge conservation (cf. the electron)

MSSM	
m_W	sparticles, W, Z, t
~GeV	q, l
0	p, e, γ, ν, $\tilde{G}$

Hidden, flavor-free MSSM	
m_X	sparticles, W, Z, q, l, $\tilde{\tau}$ (or τ)
0	g, γ, ν, $\tilde{G}$

DM-DM SIGNALS

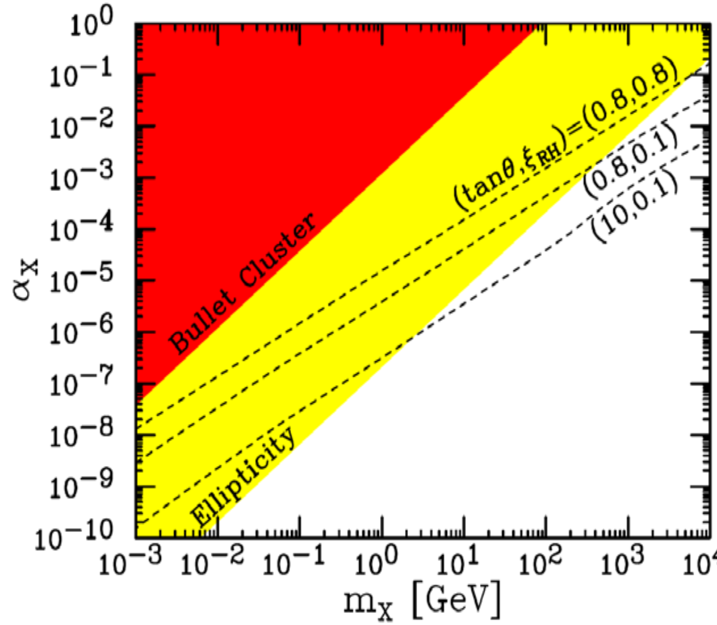
- Such WIMPless DM self-interacts through Rutherford scattering
  - Highly velocity-dependent
  - constrained by existence of non-spherical halos, bullet cluster

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2}{4 m_X^2 v^4 \sin^4(\theta/2)}$$

- Related to “dark photons” where there is hidden U(1) only

Ackerman, Buckley, Carroll, Kamionkowski (2008)

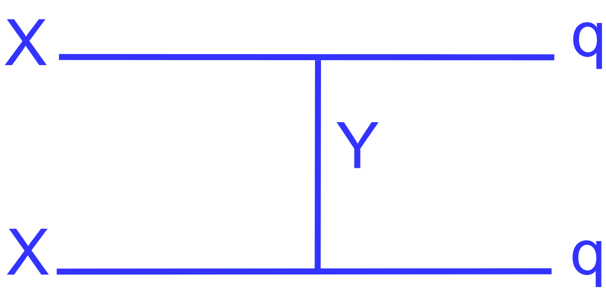
- With dark SM, weak interactions can give the right Ω, lots of freedom

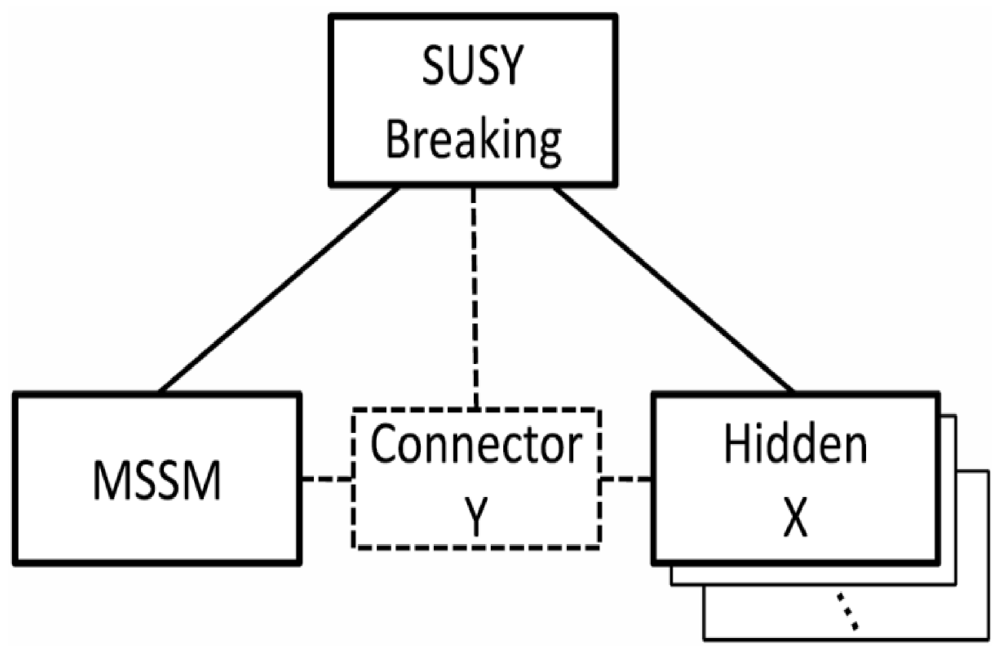


Feng, Kaplinghat, Tu, Yu (2009)

DM-SM SIGNALS

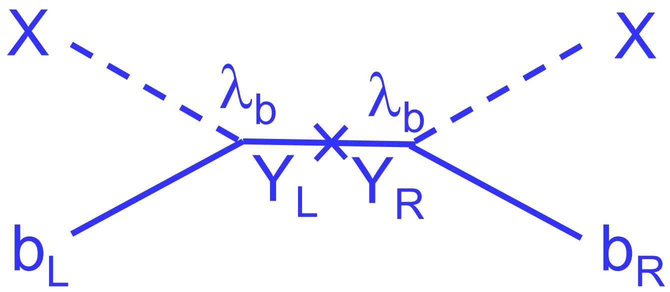
- Alternatively, hidden DM may interact with normal matter through non-gauge interactions





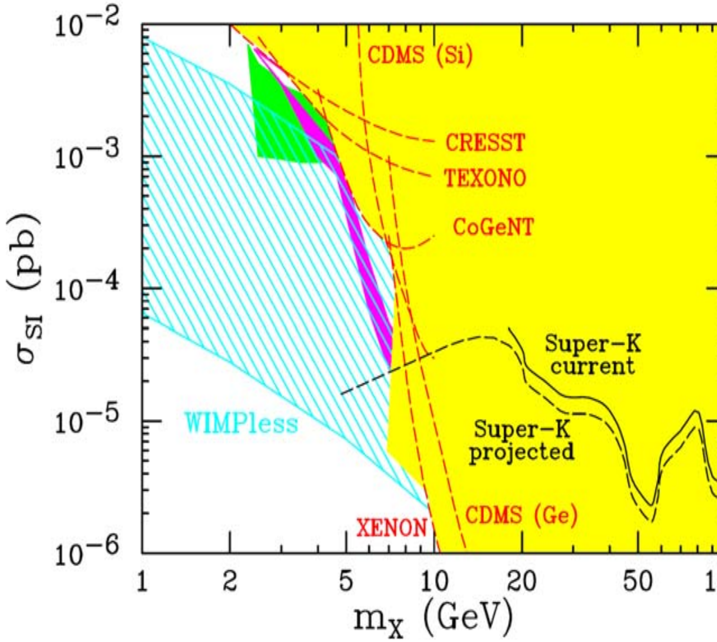
EXAMPLE

- Assume WIMPless DM X is a scalar, Y is a fermion, interact with b quarks



- May explain DAMA without contradicting CDMS, XENON
  - m_X ~ 5 GeV (WIMPless miracle)
  - Naturally gives large σ_{SI}

- Such Y's look like exotic 4th generation quarks, will be seen at Tevatron, LHC



Feng, Kumar, Learned, Strigari (2008)

CONCLUSIONS

- The WIMP miracle connects central questions in particle physics and astrophysics
- WIMP searches are progressing rapidly on every front
  - Direct detection
  - Indirect detection
  - LHC
- Proliferation of DM candidates that satisfy the WIMP miracle, but have completely different implications for particle physics, astrophysics
  - SuperWIMP dark matter
  - WIMPless dark matter
- In the next few years, all of these DM models will be stringently tested