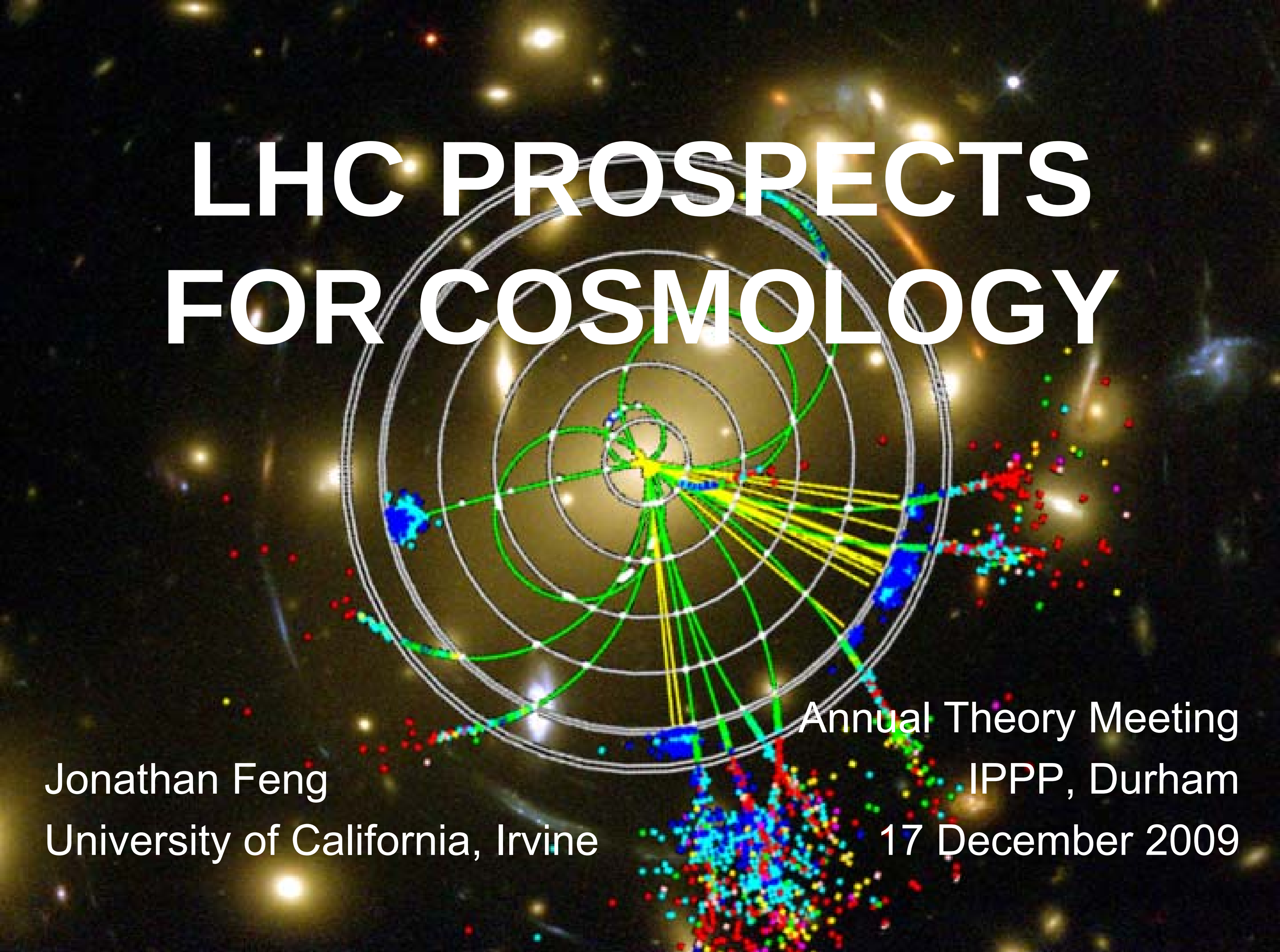


# LHC PROSPECTS FOR COSMOLOGY

Jonathan Feng
University of California, Irvine

Annual Theory Meeting
IPPP, Durham
17 December 2009

# LHC PHYSICS

- Higgs Boson
- Particle Physics Beyond the Standard Model
  - Supersymmetry
  - Extra Dimensions
  - 4th Generation Quarks and Leptons
  - New Forces
  - …
- Cosmology
  - Dark Matter
  - Dark Energy
  - Baryogenesis/Leptogenesis
  - …

# THE WIMP MIRACLE

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

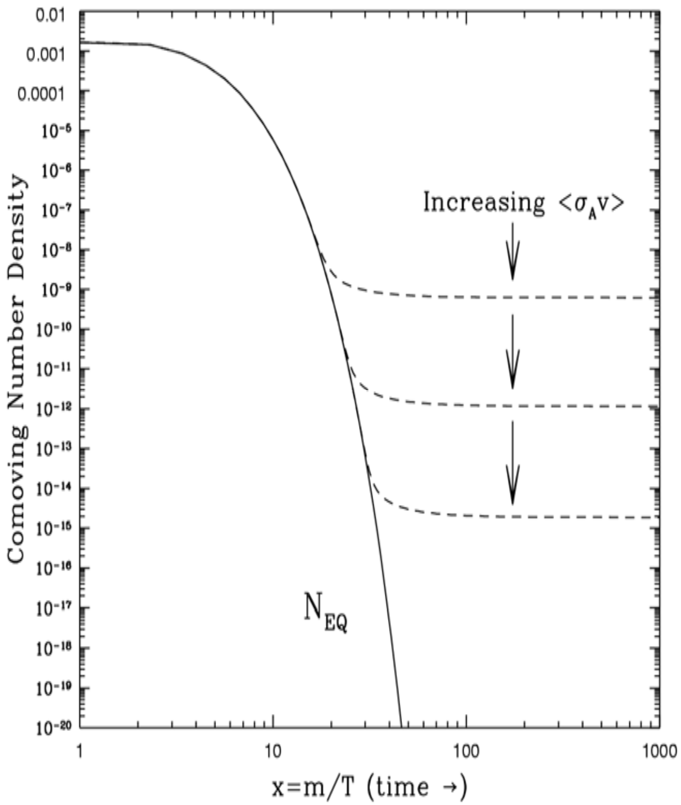
$$n \rightarrow p\, e^- \bar{\nu}$$

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

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

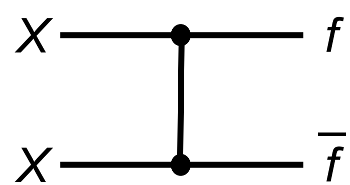
- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

# THE WIMP MIRACLE




- Assume a stable weak-scale particle exists. The resulting relic density is

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

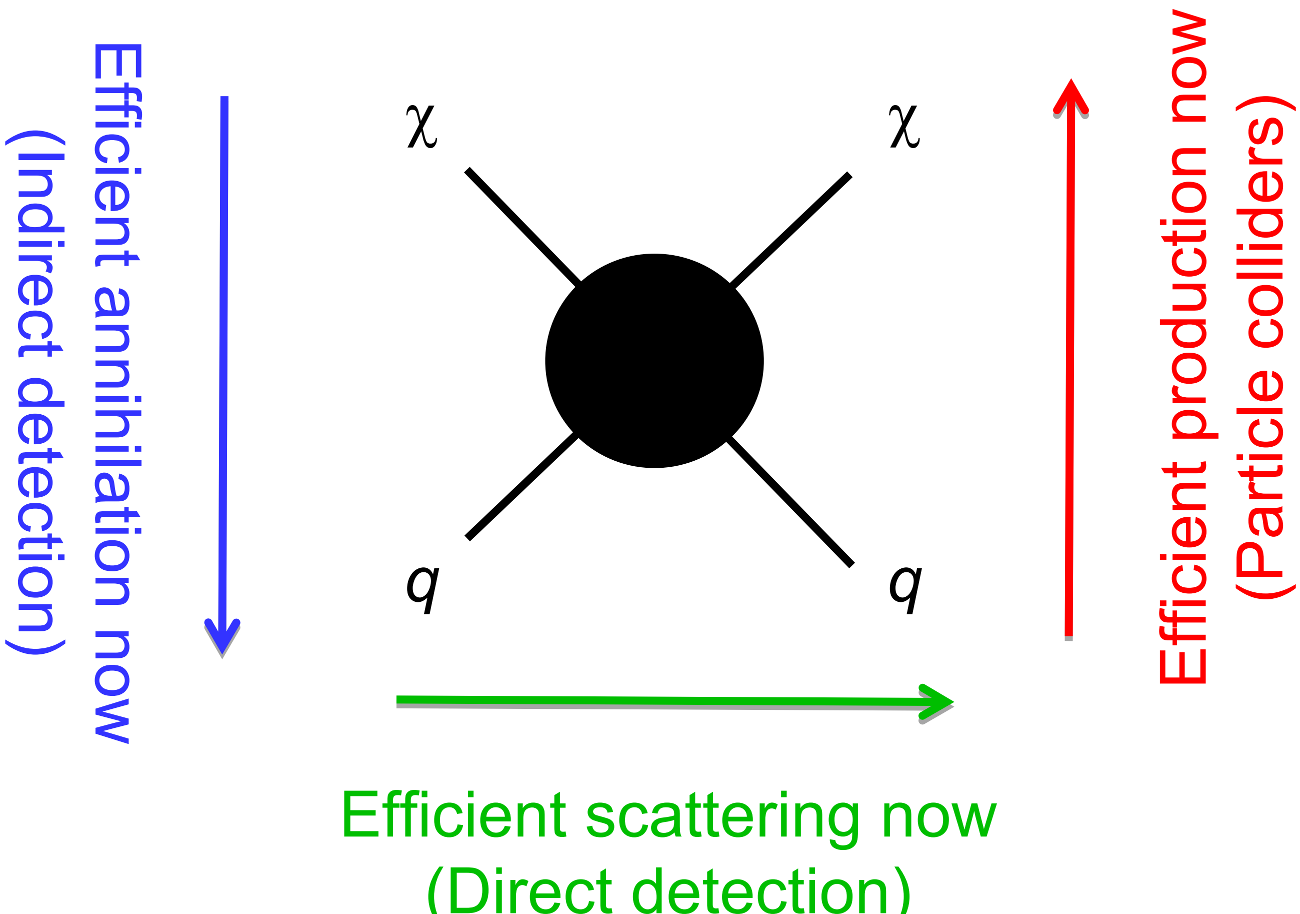



- For a WIMP, $m_X \sim$ 100 GeV and $g_X \sim 0.6$ → $\Omega_X \sim 0.1$

- 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



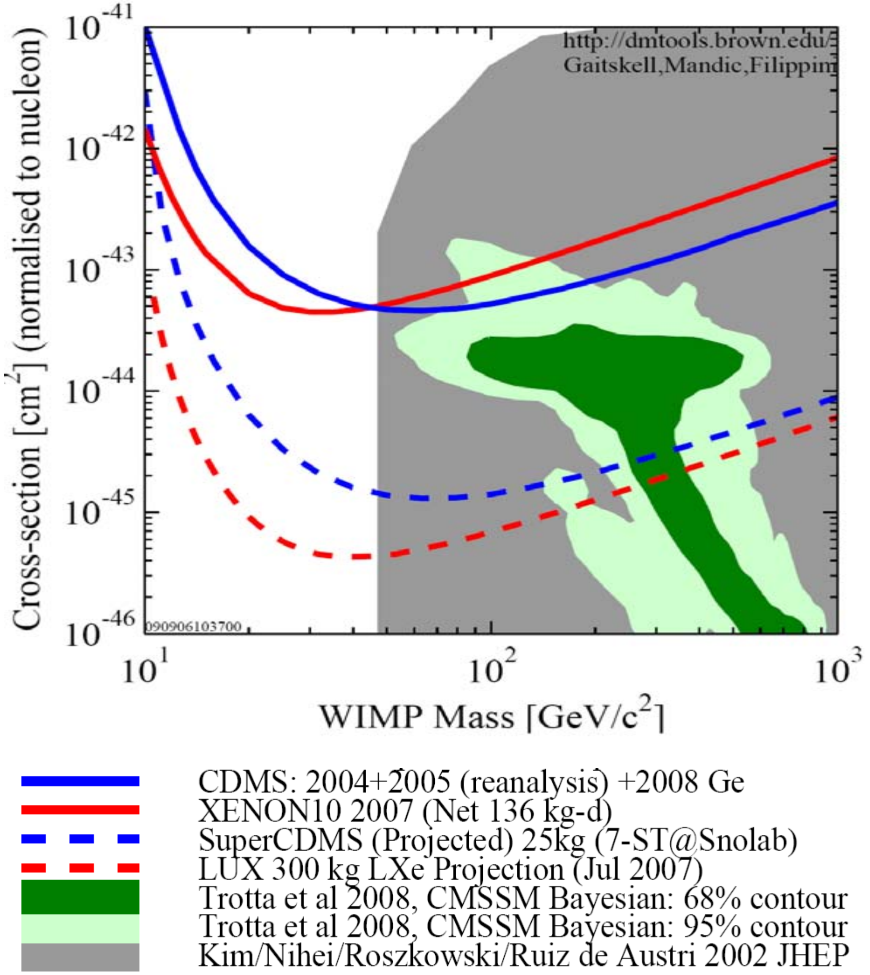
# DIRECT DETECTION

- CDMS will announce new results in 6 hours

- From correspondence with CDMS collaborators, I can say definitively that
  - CDMS has not discovered DM
  - or these people are in the wrong profession: they should be playing poker!

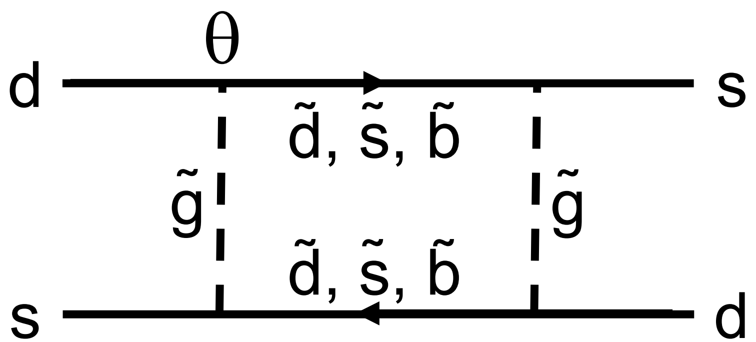
# CURRENT STATUS

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



# NEW PHYSICS FLAVOR PROBLEM

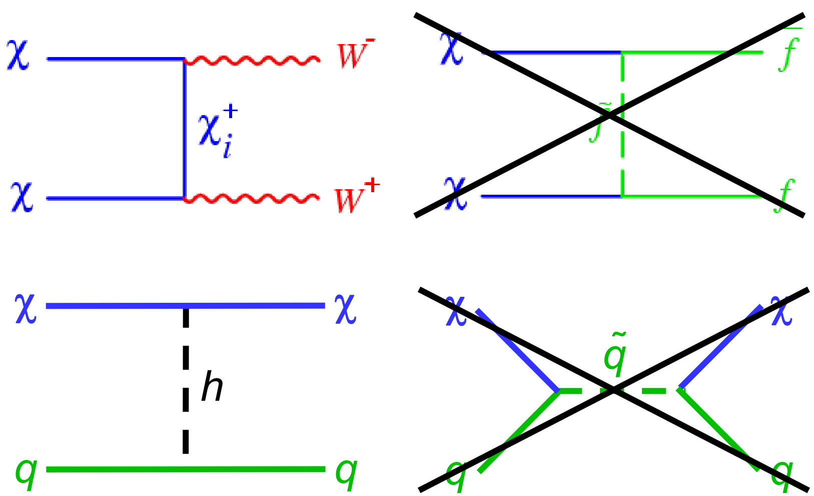
- New weak scale particles generically create many problems
- One of many possible examples: K-$\bar{K}$ mixing

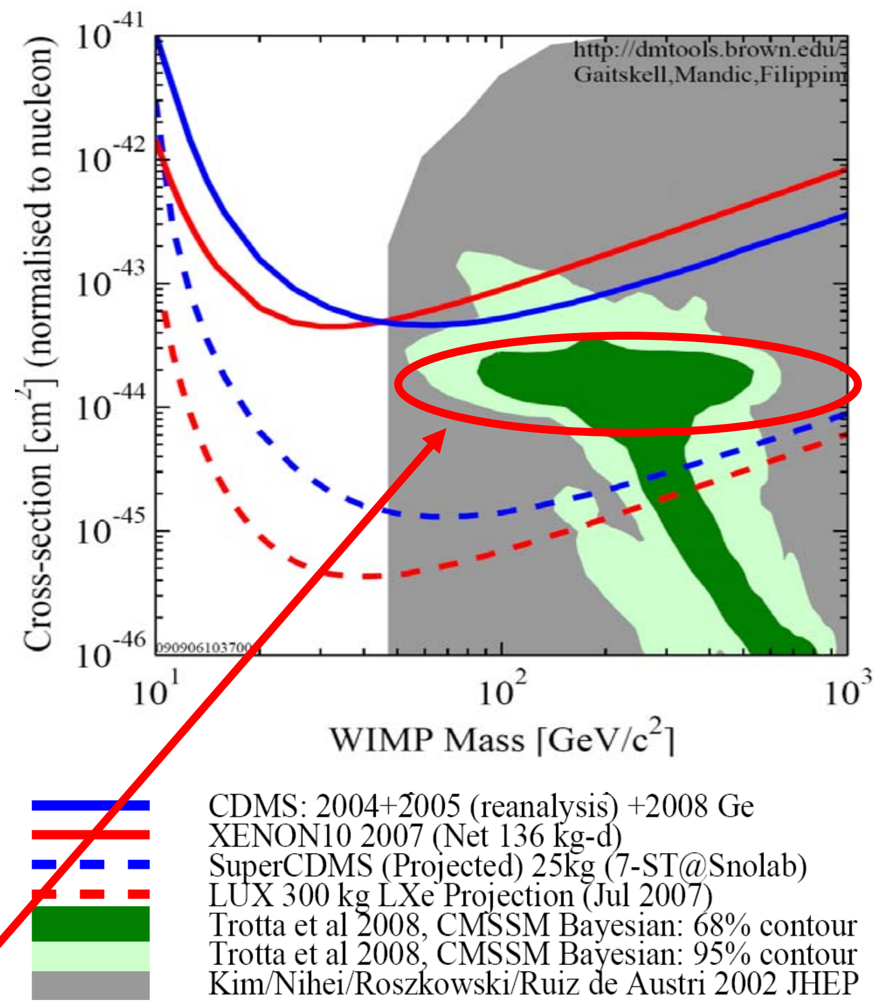



- Three possible solutions
  - Alignment: $\theta$ small
  - Degeneracy: squark $\Delta m \ll m$: typically not compatible with DM, because the gravitino mass is ~ $\Delta m$, so this would imply that neutralinos decay to gravitinos
  - Decoupling: m > few TeV

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

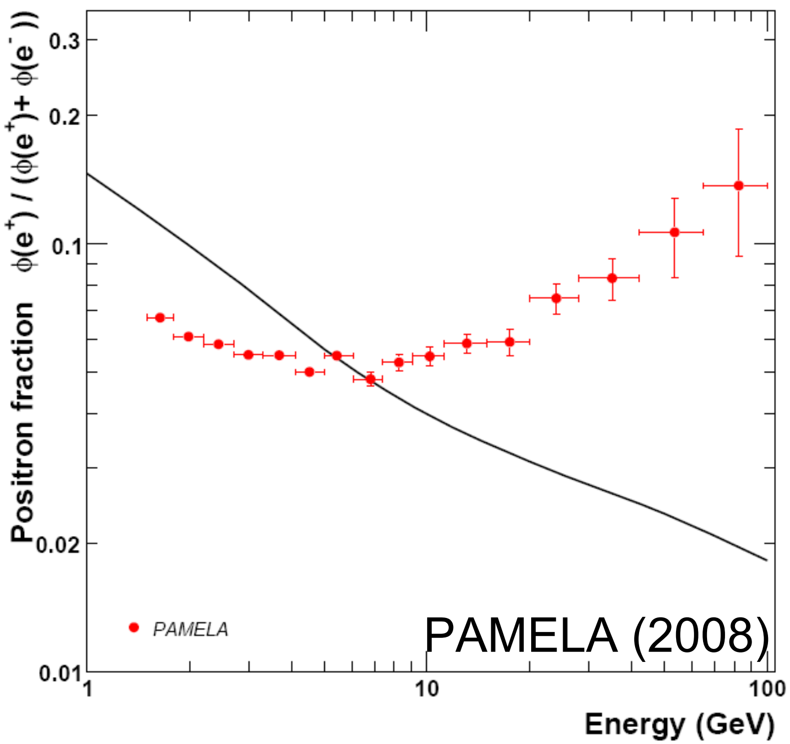
- Decoupling is the strategy adopted in many theories
  - focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…
- This eliminates many diagrams, collapses predictions

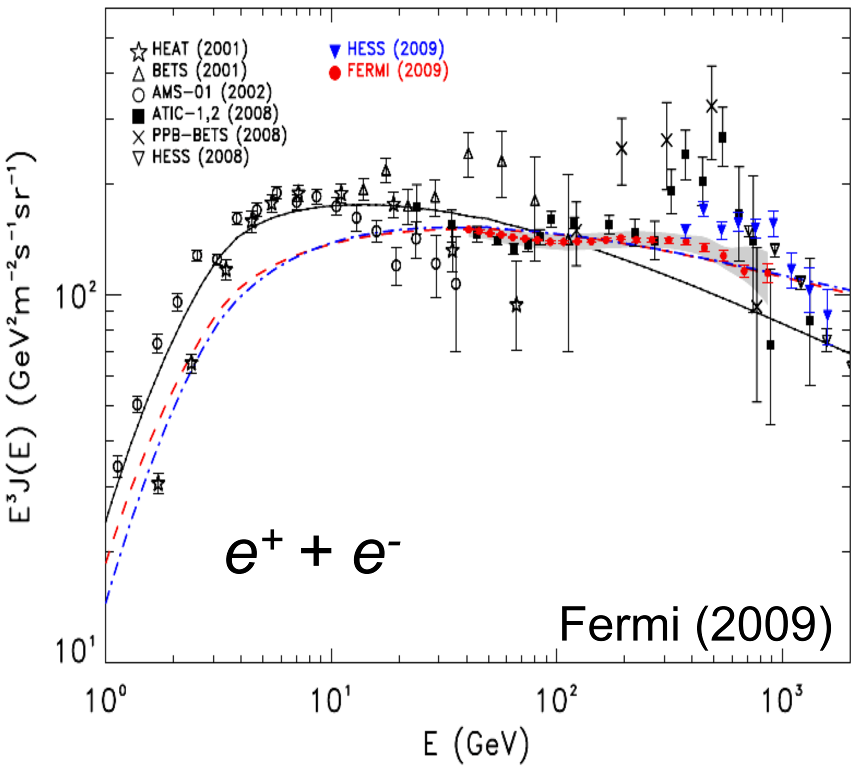



- Universal prediction: $\sigma_p \sim 10^{-44}$ cm$^2$

# INDIRECT DETECTION



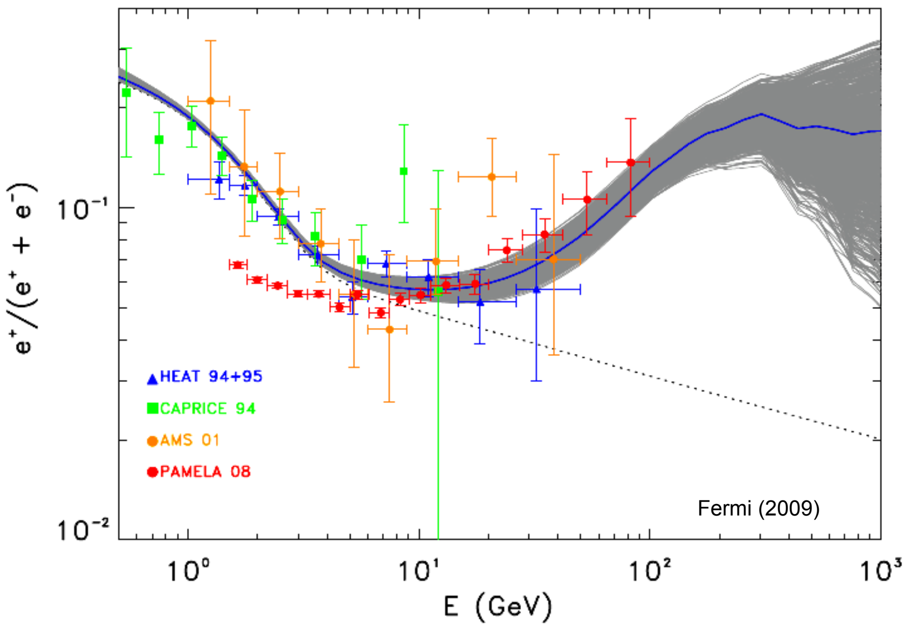




Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

# ARE THESE DARK MATTER?

- Pulsars can explain PAMELA

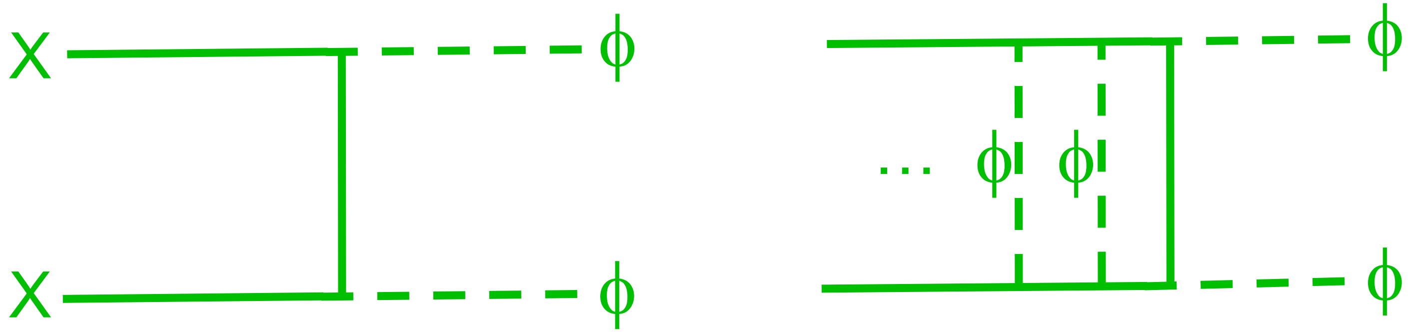
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008)
Profumo (2008) ; Fermi (2009)




- 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

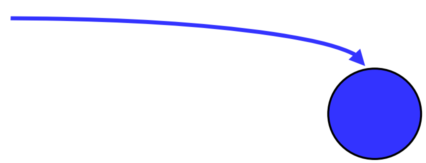
# SOMMERFELD ENHANCEMENT

- If dark matter X is coupled to a hidden force carrier $\phi$, 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 ~ 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

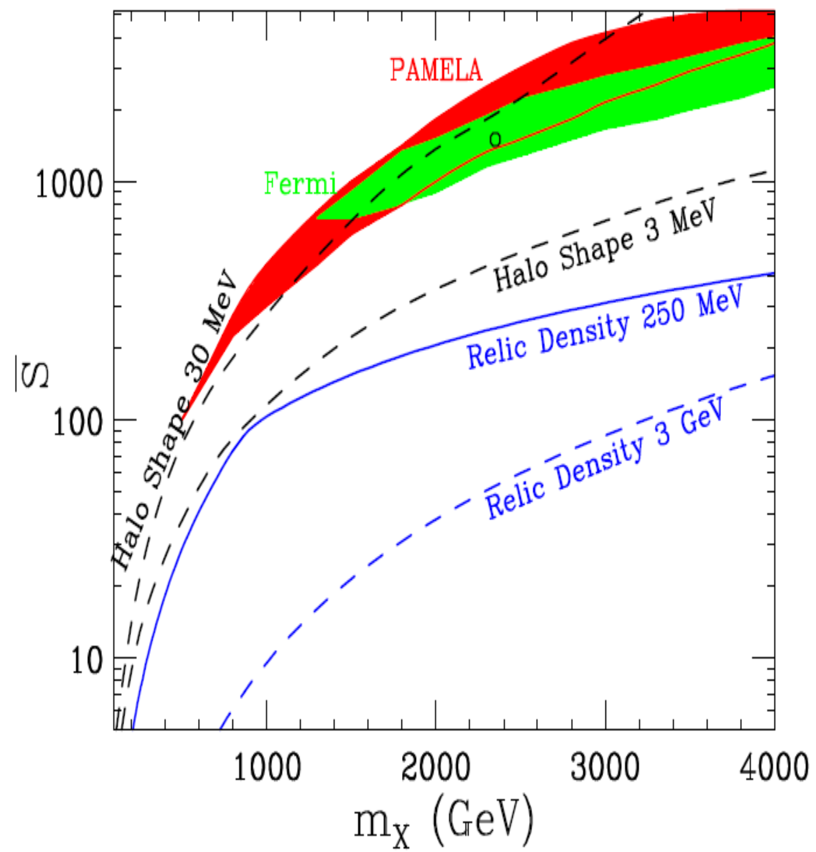
Cirelli, Kadastik, Raidal, Strumia (2008)

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 $\alpha$ and small $m_\phi$
- 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 $\phi$ by halo ellipticity




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

# WAYS OUT?

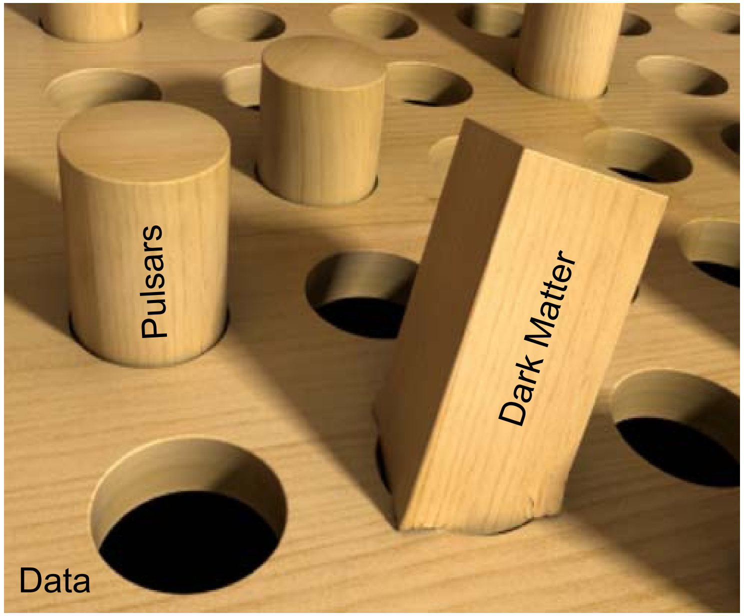
- X is only part of the dark matter: No, flux ~ $n^2 \langle\sigma v\rangle S \sim \alpha^{-1}$, so the flux is always maximized by making X all the DM

- Resonant Sommerfeld enhancement: No

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

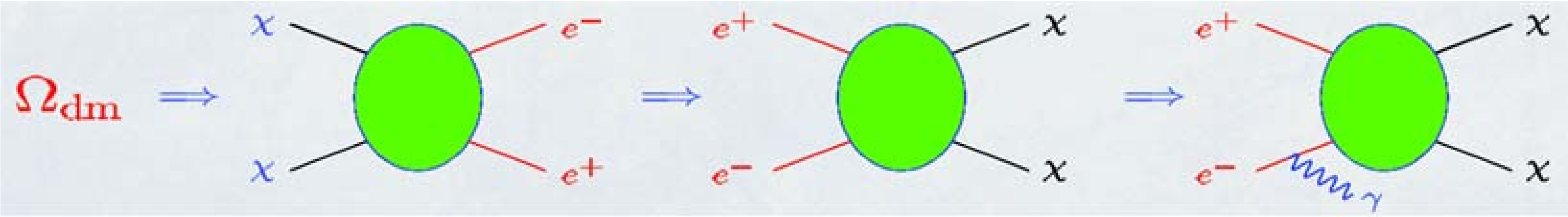
- Alternative production mechanisms, cosmologies at freezeout: Yes – but then why consider Sommerfeld enhancement?

- Boosts part Sommerfeld (~100), part astrophysical (~10): Maybe



# WIMPS AT COLLIDERS: DIRECT PRODUCTION

- $f\bar{f} \rightarrow \chi\chi$ This is invisible
- $f\bar{f} \rightarrow \chi\chi\gamma, \chi\chi j$ Mono-photon, monojet signal




  - Signal may be detectable at a Linear $e^+e^-$ Collider

    Birkedal, Matchev, Perelstein (2004)

  - But not at the LHC: swamped by $q\bar{q} \rightarrow j\,Z,\ Z \rightarrow \nu\bar{\nu}$

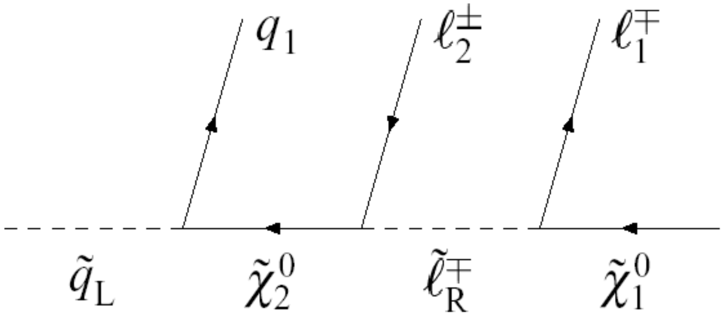
    Feng, Su, Takayama (2005)

- WIMP studies at the LHC are therefore highly model-dependent

# WIMPS AT COLLIDERS: INDIRECT PRODUCTION

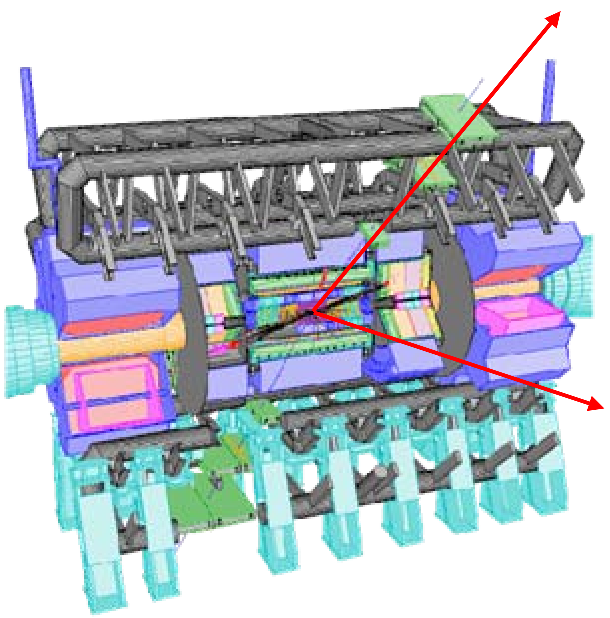
- The classic WIMP: neutralinos from supersymmetry

Ellis et al. (1983); Goldberg (1983)




- Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

- Produced in $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q}$ → neutralino $\chi$
  - 2 $\chi$'s escape detector
  - missing transverse momentum, energy

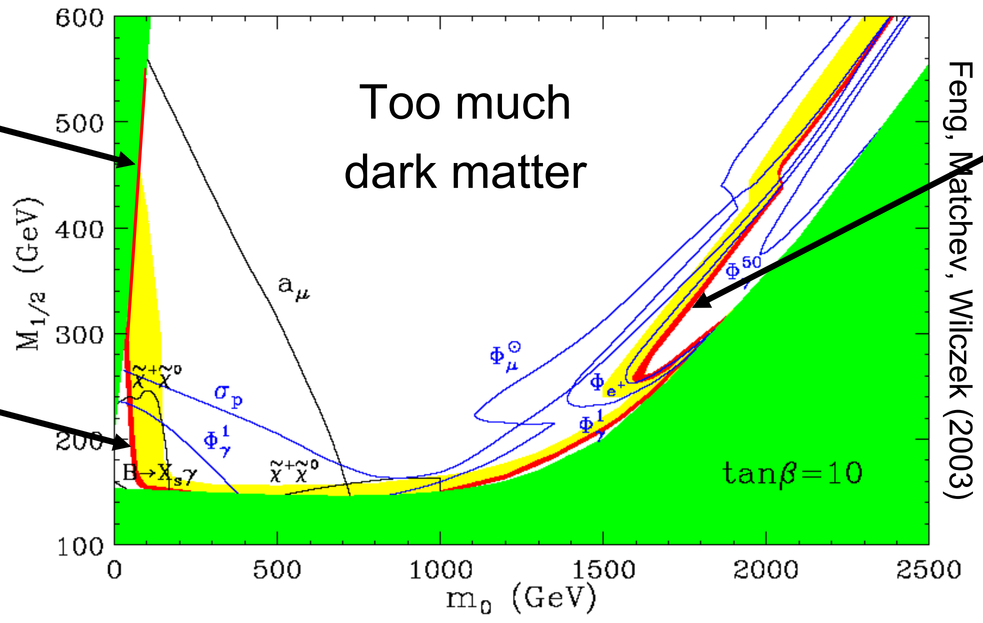


- For quantitative studies
  - pick a specific SUSY model, for example, mSUGRA
  - try to abstract general lessons

- $\Omega_{DM}$ = 23% ± 4% stringently constrains models

Co-annihilation region

Bulk region

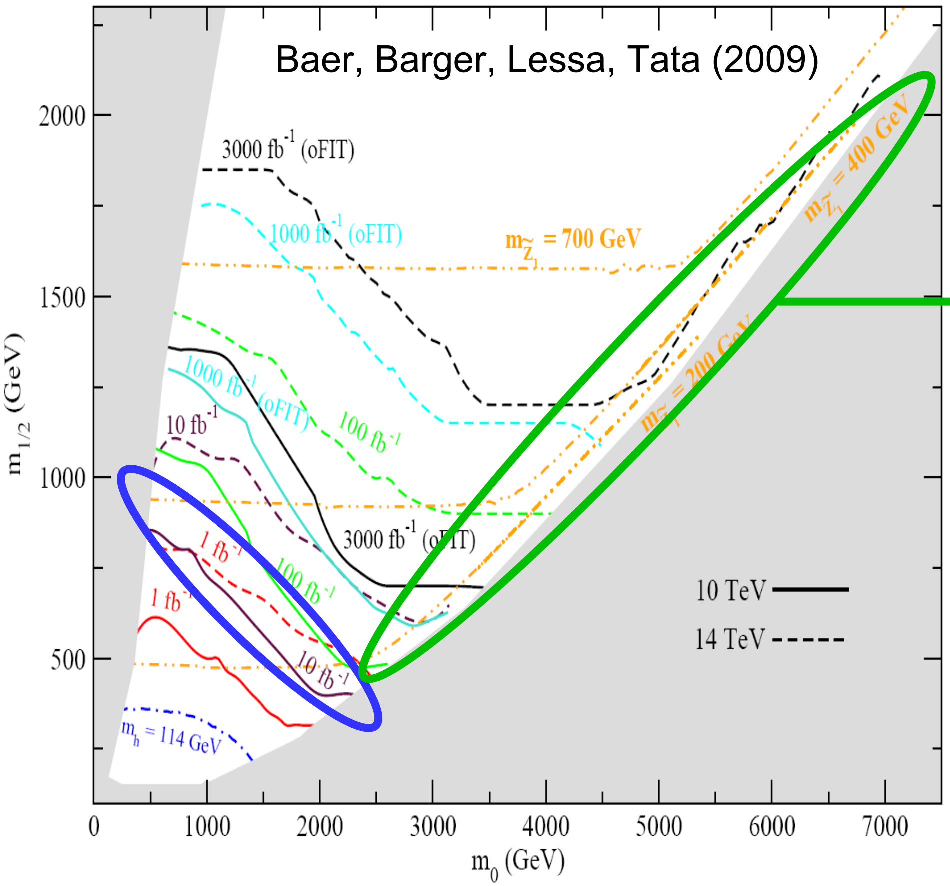


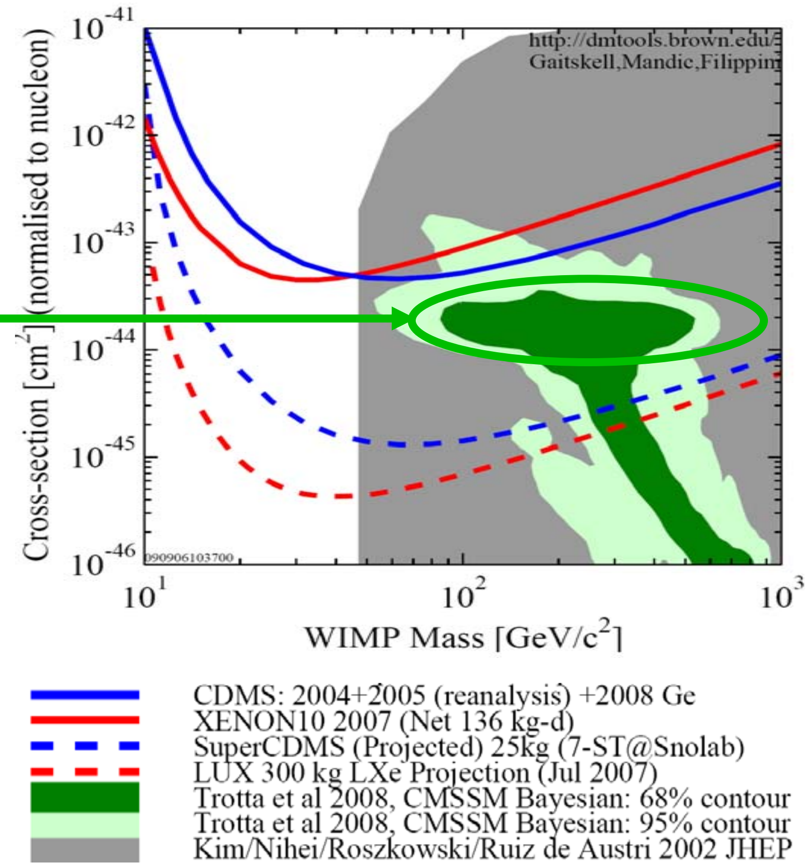

Focus point region

Yellow: pre-WMAP
Red: post-WMAP

- Assuming standard Big Bang, cosmology excludes many possibilities, favors certain regions

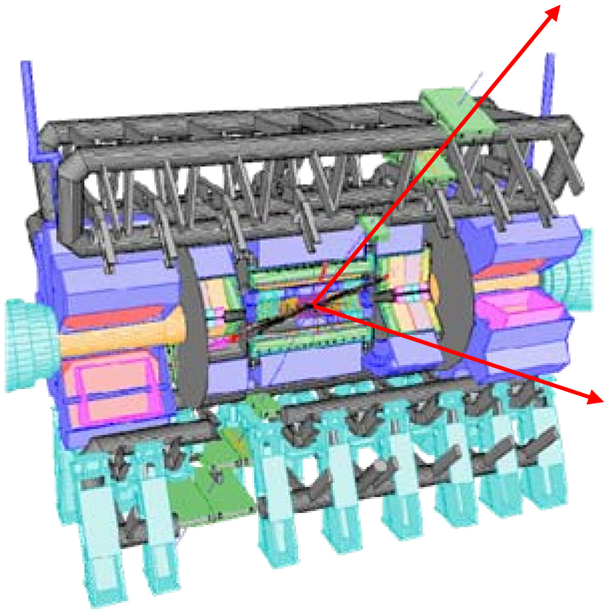
# LHC, FP REGION, DIRECT DETECTION




- LHC with 1-10 $fb^{-1}$ probes all but the far focus point region
- FP (mixed gaugino-Higgsino) region → $\sigma_{SI} \sim 10^{-44}$ $cm^2$
- LHC and direct detection experiments are complementary

# WHAT IF THE LHC PRODUCES WIMPS?

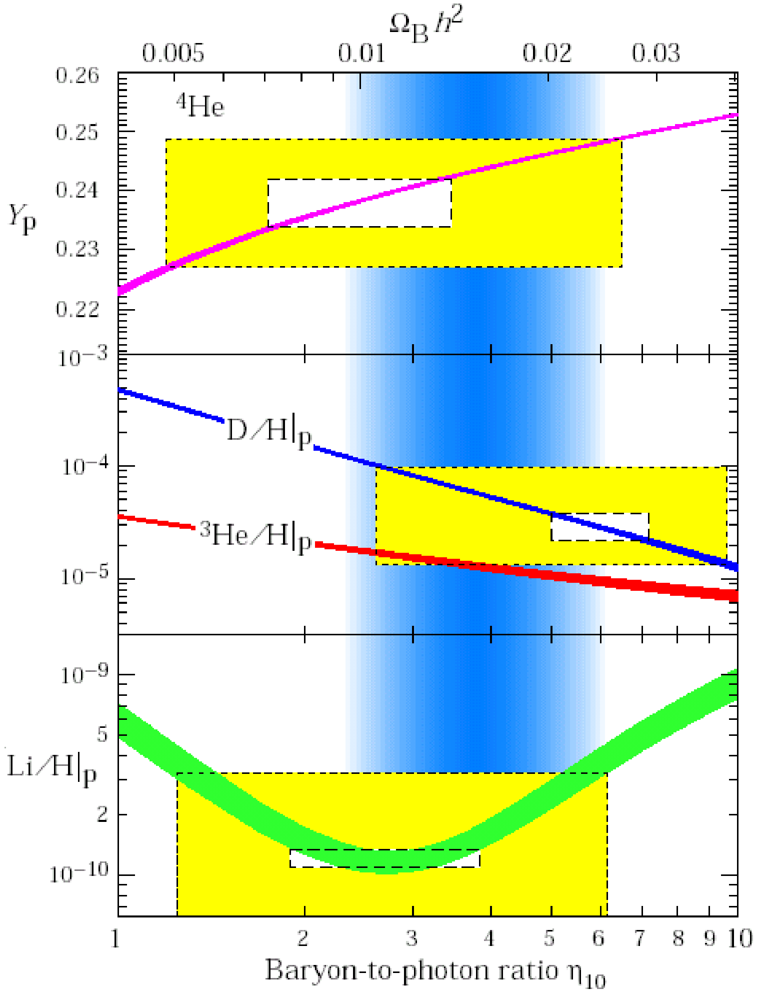


This is not the discovery of dark matter

- Particle leaves the detector: Lifetime > $10^{-7}$ s
- Particle is DM candidate: Lifetime > $10^{17}$ s

What else can be done?

# THE EXAMPLE OF BBN

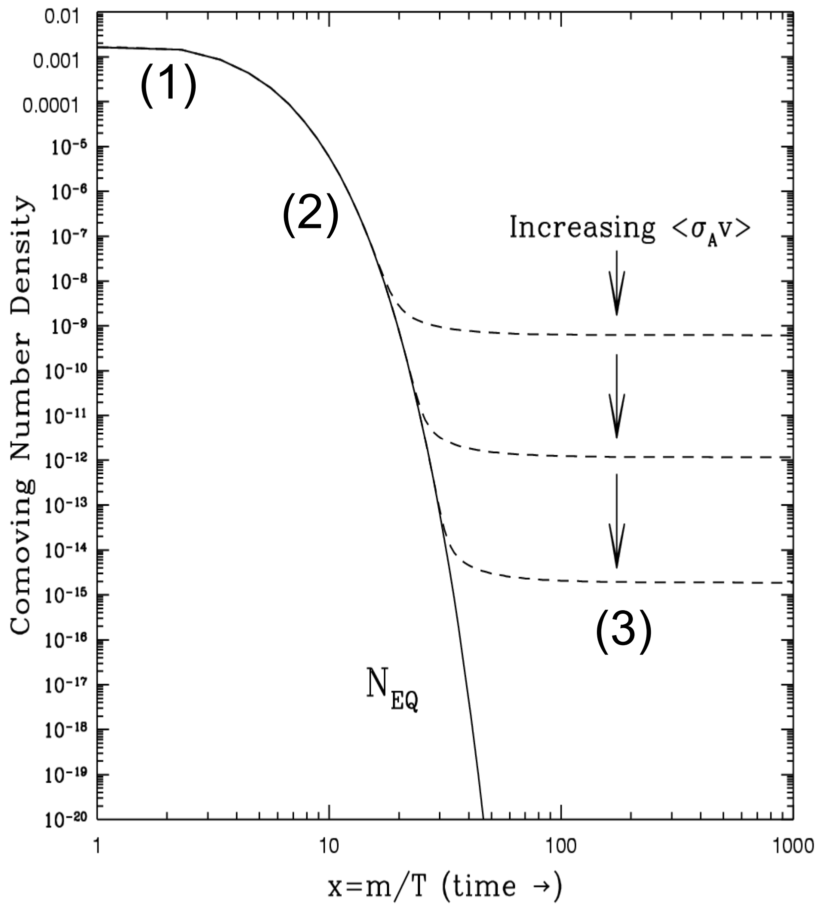



- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

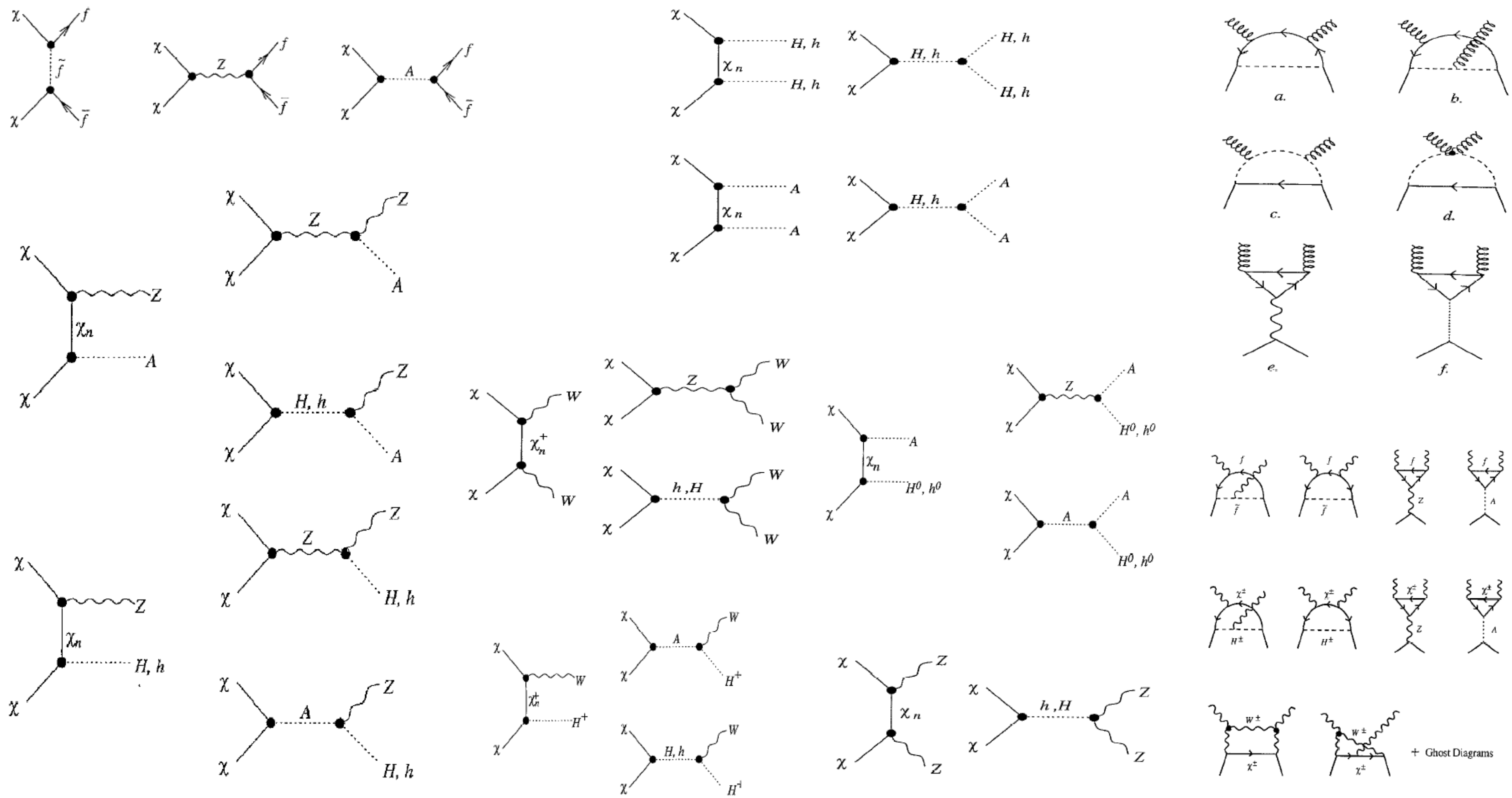
  t ~ 1 sec

# DARK MATTER ANALOGUE



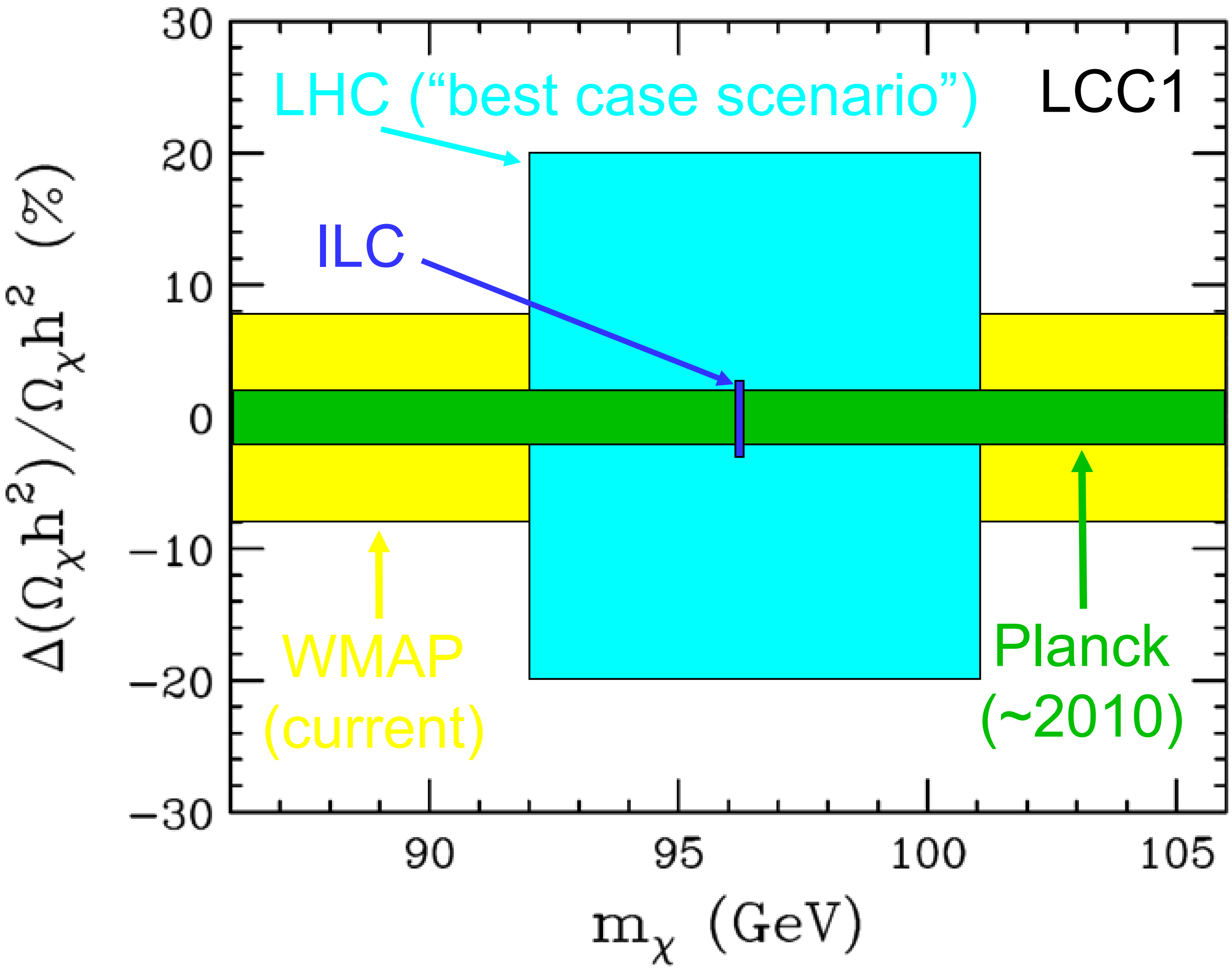

- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

# NEUTRALINO ANNIHILATION




Jungman, Kamionkowski, Griest (1995)

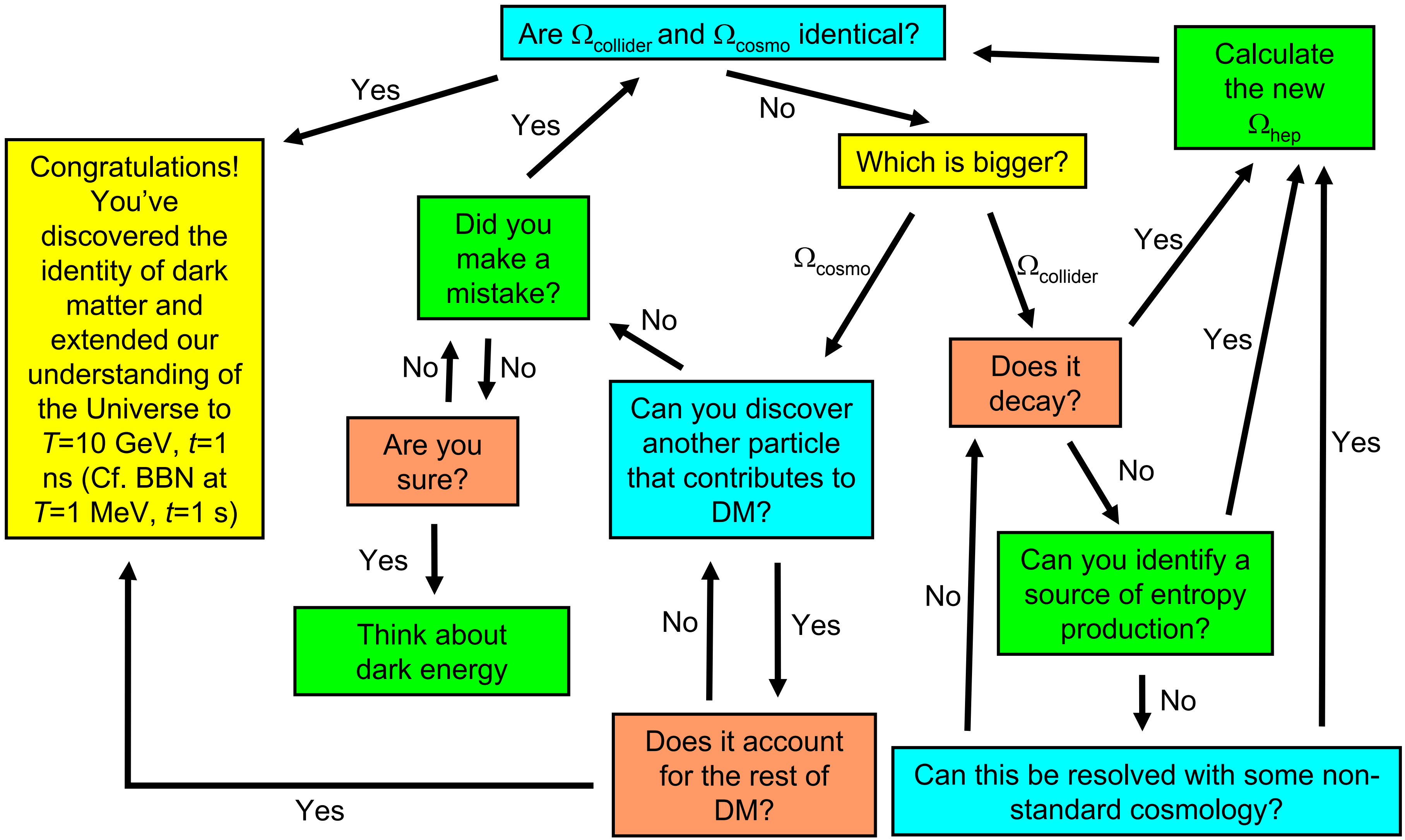
# RELIC DENSITY DETERMINATIONS




ALCPG Cosmology Subgroup
Baltz, Battaglia, Peskin, Wizansky (2006)
[Allanach, Belanger, Boudjema, Pukhov (2004);
Moroi, Shimizu, Yatsuyanagi (2005); Birkedal et al. (2005)]

% level comparison of predicted $\Omega_{\text{collider}}$ with observed $\Omega_{\text{cosmo}}$

# IDENTIFYING DARK MATTER



# BEYOND WIMPS

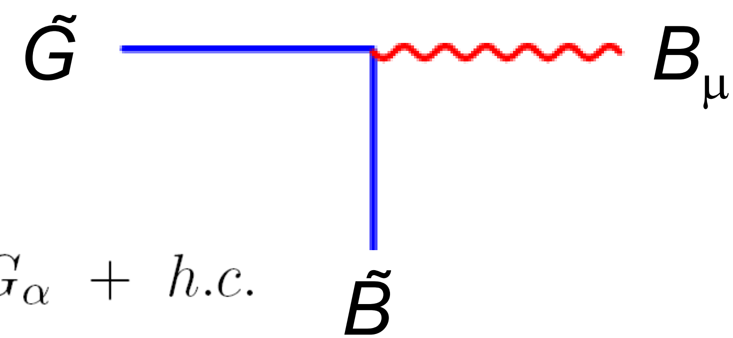
- WIMP characteristics
  - Colliders: missing $E_T$ signals at colliders
  - Astroparticle physics: interesting direct and indirect detection signals
  - Astrophysics: cold, collisionless

- Is this true of all dark matter candidates? No.
  Is this true for all EWSB DM candidates? No!
  Is this true for all WIMP miracle-inspired candidates? No!!

- There are many other classes of candidates that preserve some (or even all) of the theoretical motivations of WIMPs, but have qualitatively different implications. In the rest of this talk, I will discuss a few examples.

# GRAVITINOS

- SUSY: graviton $G$ → gravitino $\tilde{G}$
- Mass: eV – 100 TeV $$m_G = \frac{F}{\sqrt{3} M_p}$$
- Interactions: Gravitinos couple particles to their superpartners




$$\mathcal{L} = -\frac{1}{F} j^{\alpha\mu} \partial_\mu G_\alpha \; + \; h.c.$$

TeV gravitinos couple gravitationally; light gravitinos couple more strongly

# LIGHT GRAVITINOS

- The original SUSY DM scenario
  - Universe cools from high temperature
  - gravitinos decouple while relativistic
  - $n_{\tilde{G}} \sim n_{\mathrm{thermal}}$ , $\Omega_{\tilde{G}}\, h^2 \approx 0.1\ (m_{\tilde{G}}\ /\ 80\ \mathrm{eV})$ (cf. neutrinos)

Pagels, Primack (1982)

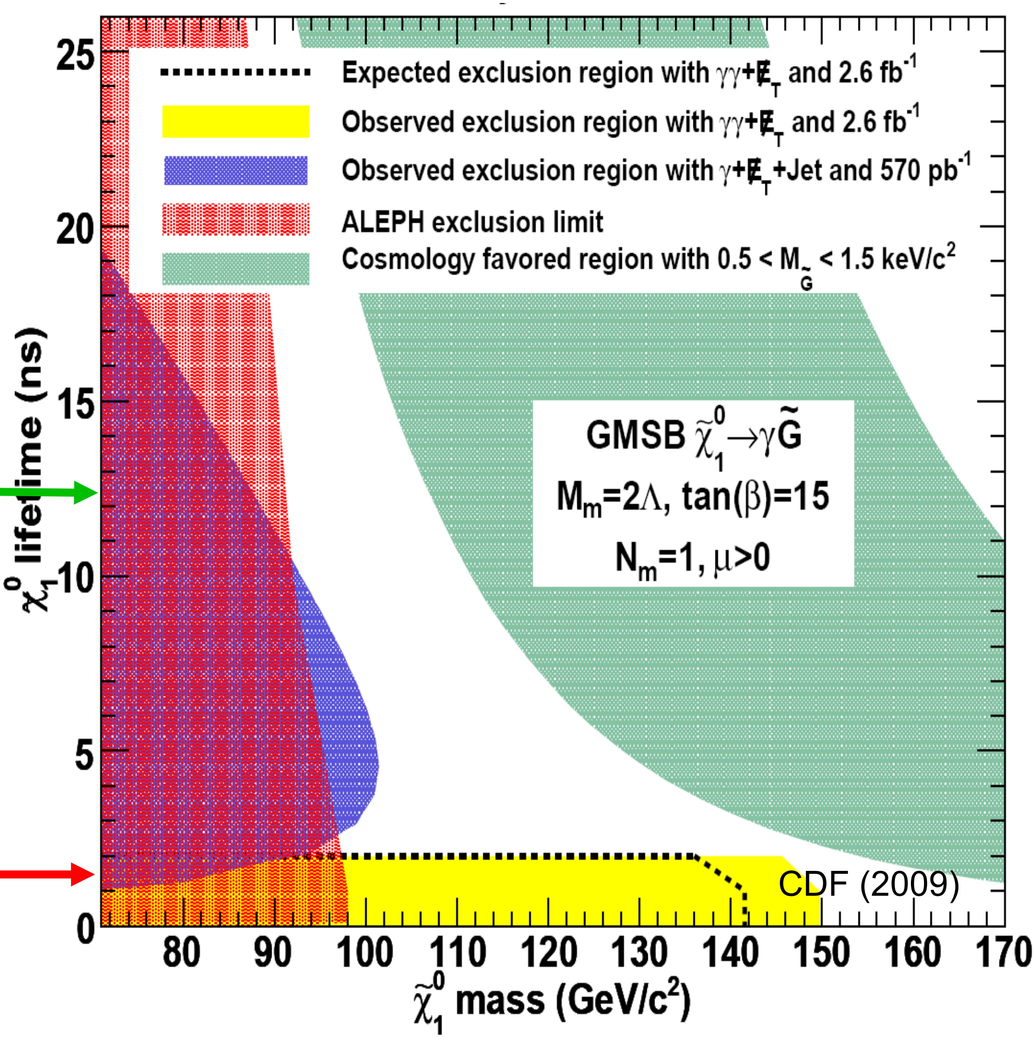
- This minimal scenario is now excluded
  - $\Omega_{\tilde{G}}\, h^2 \approx 0.1 \rightarrow m_{\tilde{G}} \approx 80$ eV
  - Gravitinos not too hot → $m_{\tilde{G}} >$ few keV

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: $m_{\tilde{G}} < 16$ eV. Gravitinos are only part of the DM, mixed warm-cold scenario

# LIGHT GRAVITINOS AT THE LHC

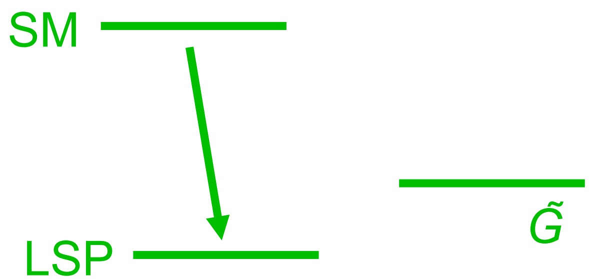
- $m_{\tilde{G}}$ fixes $\tau(\chi \rightarrow \gamma\tilde{G})$; remarkably, this lifetime difference is observable at colliders!
- $m_{\tilde{G}}$ > few keV: Delayed photon signatures
- $m_{\tilde{G}}$ < 16 eV: Prompt photon signatures



# HEAVY GRAVITINOS

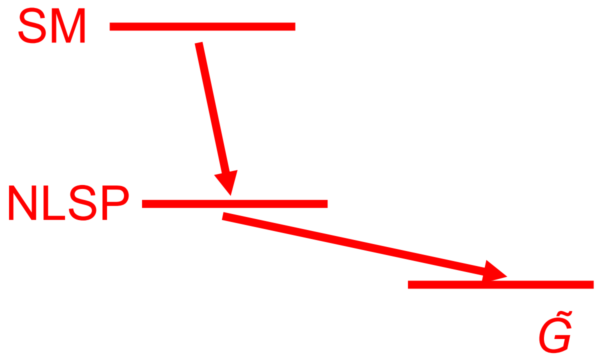
Mass ~ 100 GeV; Interactions: ~ gravitational (superweak)

- $\tilde{G}$ not LSP



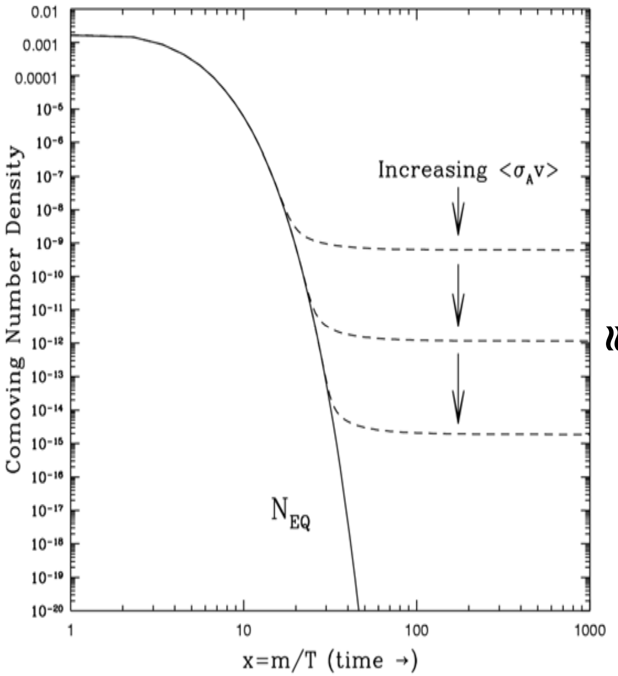

- Assumption of most of literature

- $\tilde{G}$ LSP




- Completely different cosmology and particle physics

# SUPERWIMP RELICS




- Suppose ~100 GeV gravitinos are the LSP

- WIMPs freeze out as usual

WIMP → $\tilde{G}$ (+ $\gamma$, e, …)

but then all WIMPs decay to gravitinos after

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

- SuperWIMPs share all WIMP motivations
  - Naturally correct relic density: $m_{\tilde{G}} \sim m_{WIMP} \rightarrow \Omega_{\tilde{G}} \sim \Omega_{WIMP} \sim 0.1$
  - Same theoretical frameworks: ~1/2 of the parameter space (also axinos, KK gravitons, ...)

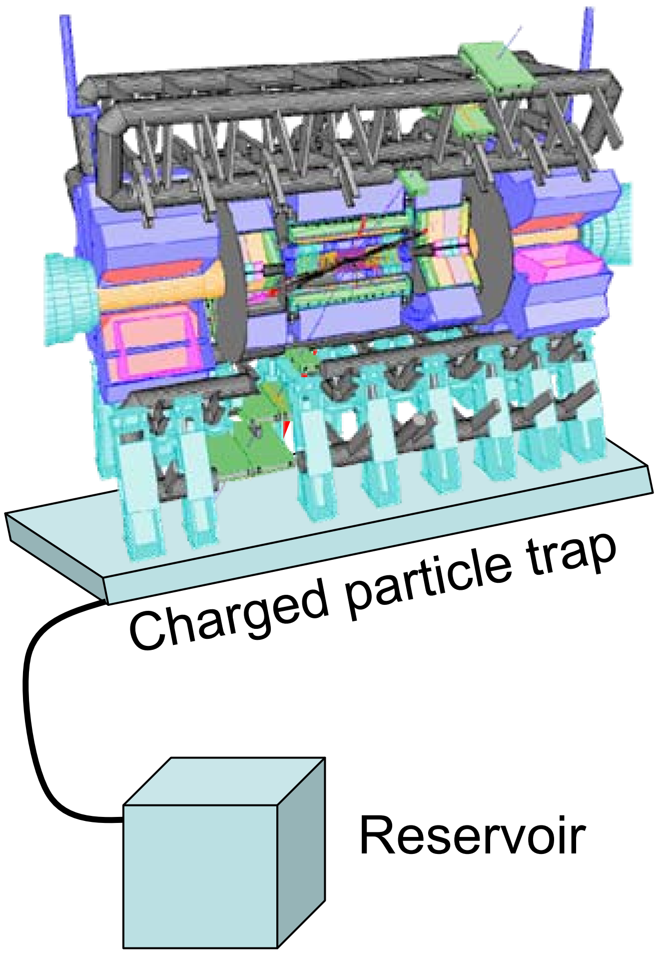
# CHARGED PARTICLE TRAPPING

- 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)



# WHAT WE COULD LEARN FROM CHARGED PARTICLE DECAYS

$$\tau(\tilde{l} \rightarrow l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of $\tau$ , $m_{\tilde{l}}$ and $E_l$ → $m_{\tilde{G}}$ and $G_N$
  - Probes gravity in a particle physics experiment
  - Measurement of $G_N$ on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines $F$ : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)

# HIDDEN DARK MATTER

- 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

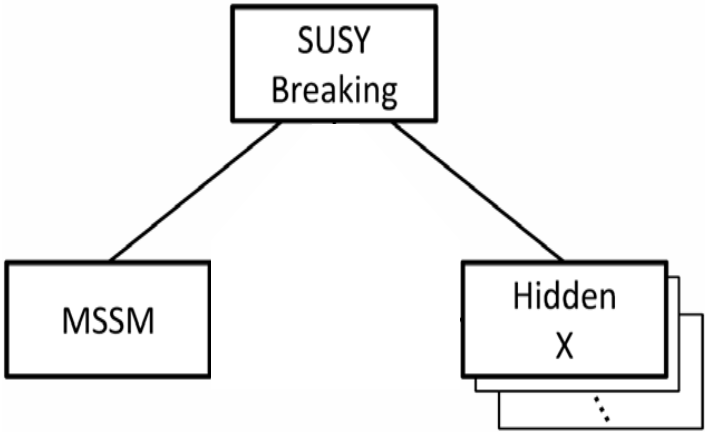
- What one seemingly loses
  - Connections to central problems of particle physics
  - The WIMP miracle
  - Signals

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



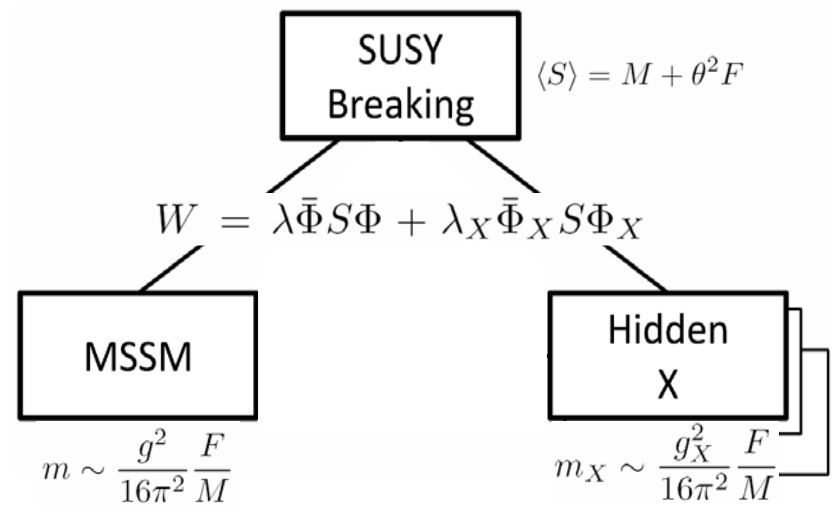

- Hidden sectors each have their own
  - particle content
  - mass scales $m_X$
  - Interactions, gauge couplings $g_X$

- 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!




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

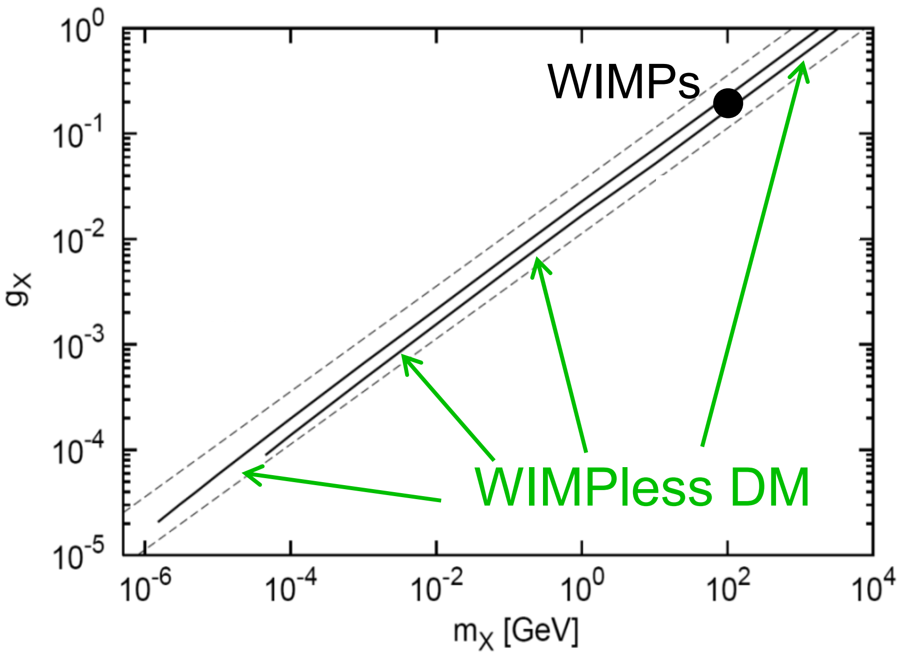
# THE WIMPLESS MIRACLE

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

- 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 | $p$, $e$, $\gamma$, $\nu$, $\tilde{G}$ |

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

# DM-DM SIGNALS

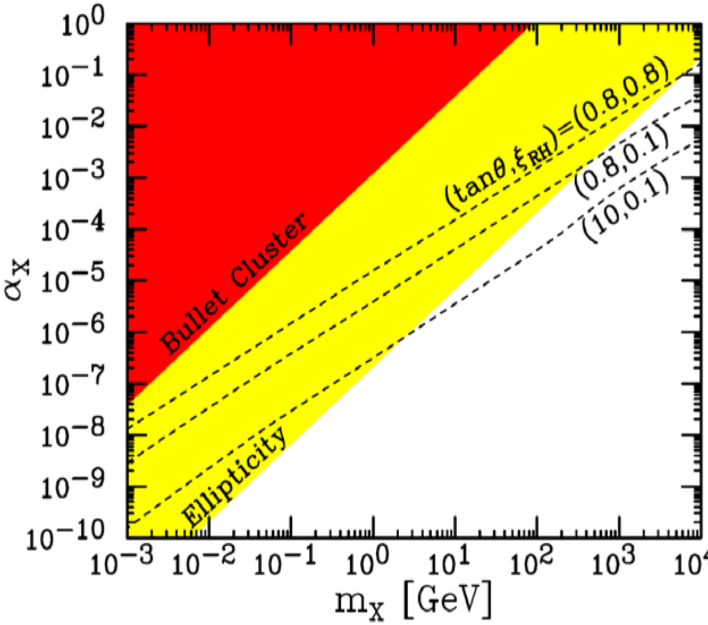
- Such WIMPless DM self-interacts through Rutherford scattering
  – Highly velocity-dependent
  – constrained by existence of non-spherical halos, bullet cluster

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

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

Ackerman, Buckley, Carroll, Kamionkowski (2008)

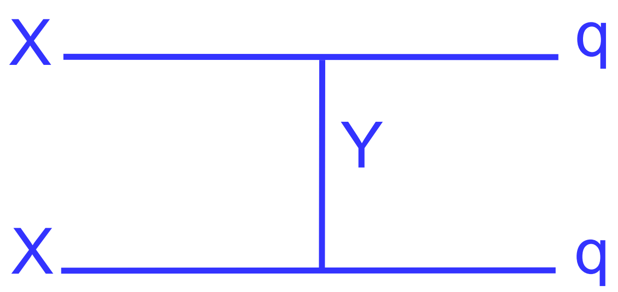
- With dark SM, weak interactions can give the right Ω, lots of freedom

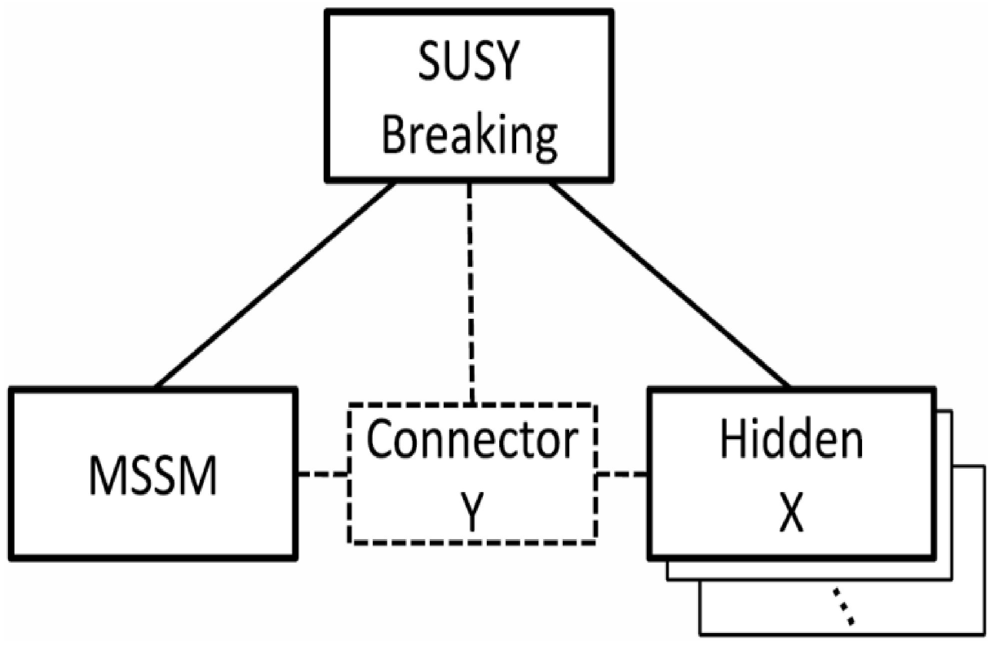



Feng, Kaplinghat, Tu, Yu (2009)

# DM-SM SIGNALS

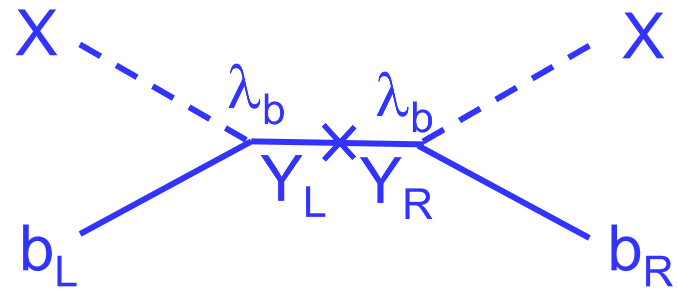
- Alternatively, hidden DM may interact with normal matter through non-gauge interactions

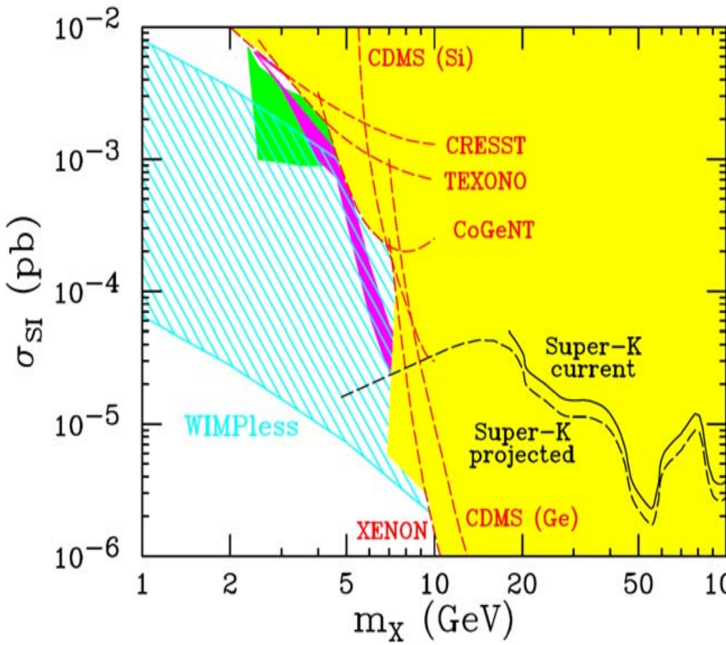


# EXAMPLE

- Assume WIMPless DM X is a scalar, Y is a fermion, interact with b quarks
- May explain DAMA without contradicting CDMS, XENON
  - $m_X \sim 5$ GeV (WIMPless miracle)
  - Naturally gives large $\sigma_{SI}$ (chirality flip on heavy Y fermion line)
- Such Y's look like exotic 4th generation quarks, provide interesting targets for Tevatron, LHC




Feng, Kumar, Learned, Strigari (2008)

# CONCLUSIONS

- WIMP miracle → fascinating interaction of LHC with cosmology; many specific realizations with greatly varying phenomenology and implications

- WIMPs imply missing $E_T$, but there are also other candidates with similar motivations but even more striking signatures
  - Prompt or delayed photons
  - Heavy charged particles
  - Connector particles to hidden sectors

- LHC may have far-reaching cosmological implications soon