

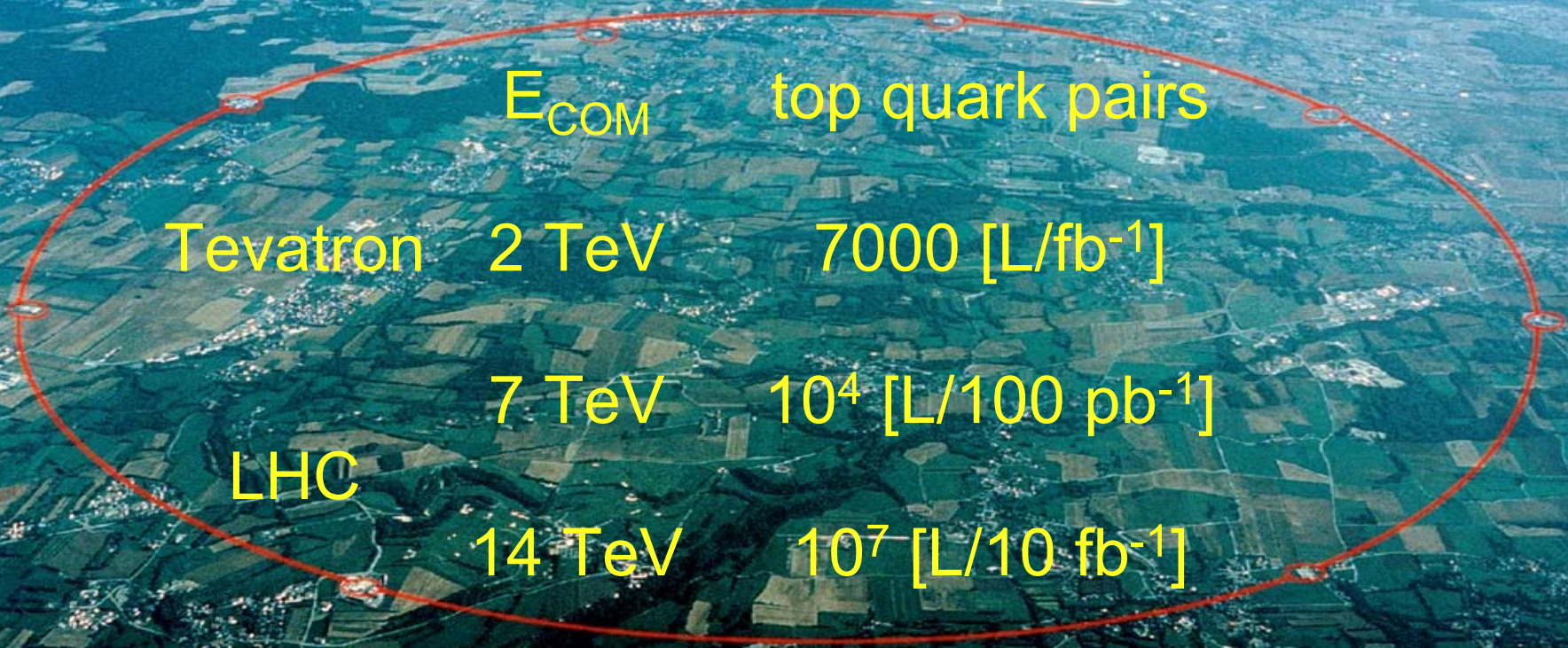
# LHC PROSPECTS FOR COSMOLOGY



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# LARGE HADRON COLLIDER



# LHC PHYSICS

- Higgs Boson
- Particle Physics Beyond the Standard Model
  - Supersymmetry
  - Extra Dimensions
  - 4<sup>th</sup> 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



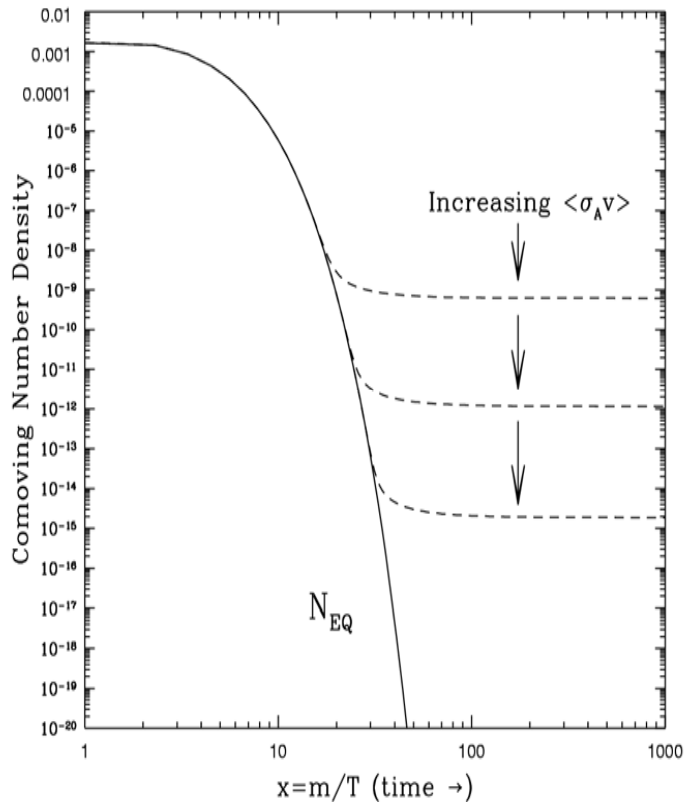
- $G_F \approx 1.1 \cdot 10^{-5} \text{ GeV}^{-2} \rightarrow$  a new mass scale in nature

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

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

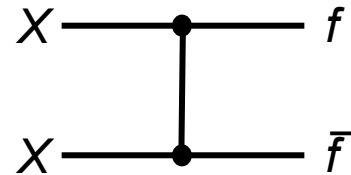


# THE WIMP MIRACLE



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

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

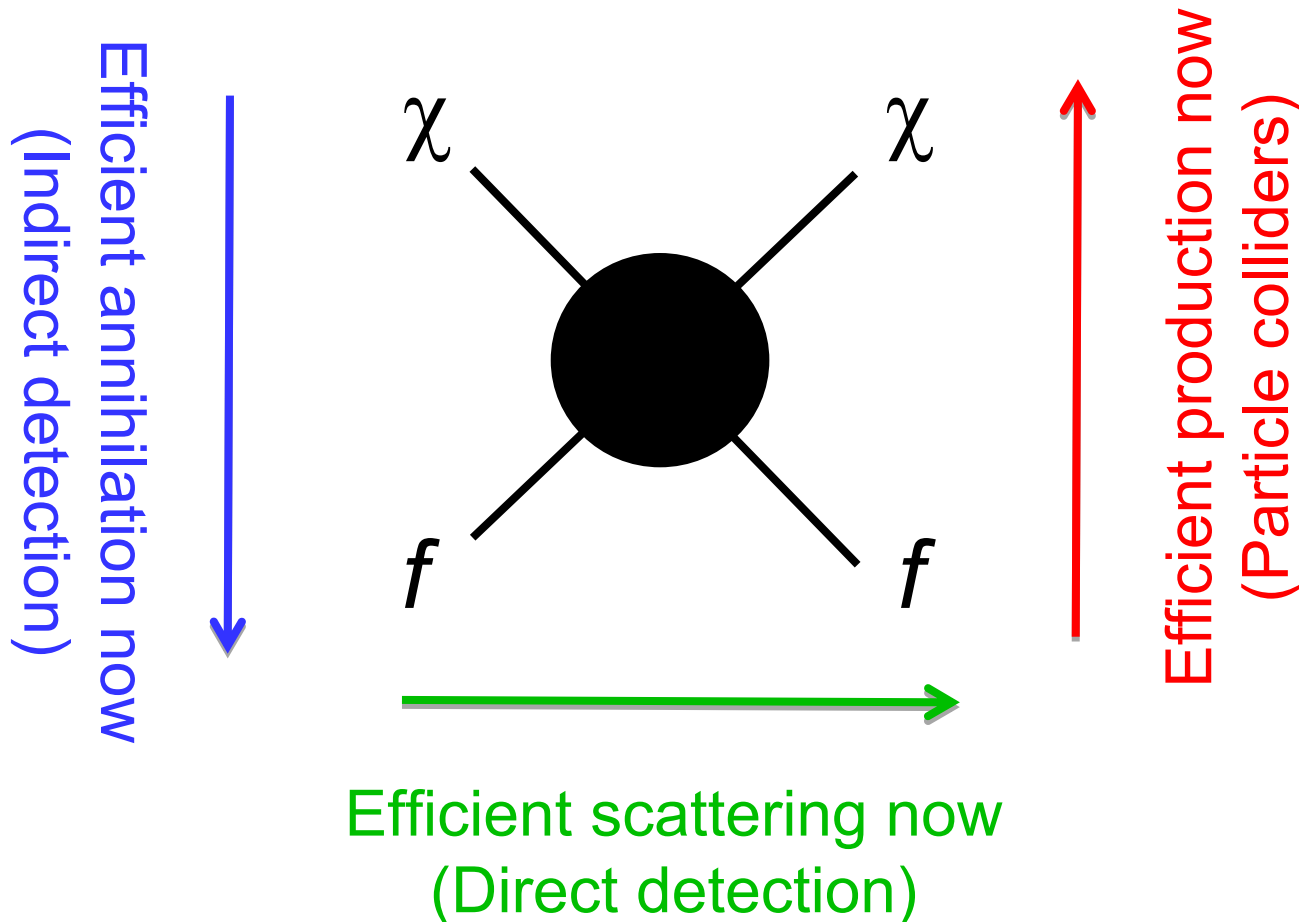


- For a WIMP,  $m_X \sim 100$  GeV and  $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

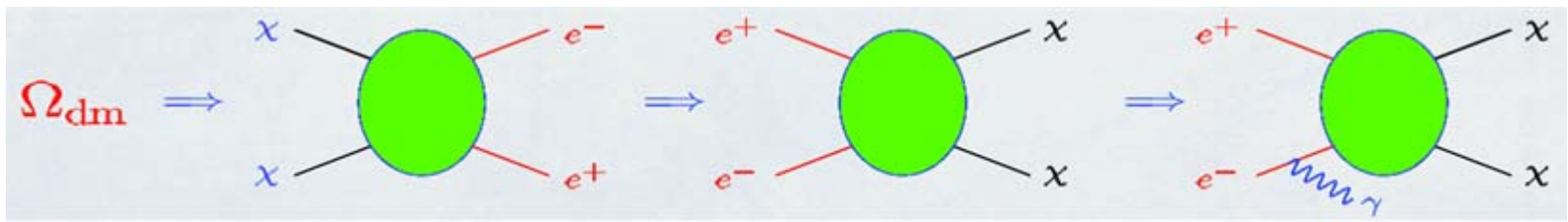
# WIMP DETECTION

Correct relic density  $\rightarrow$  Efficient annihilation then



# DIRECT WIMP 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)

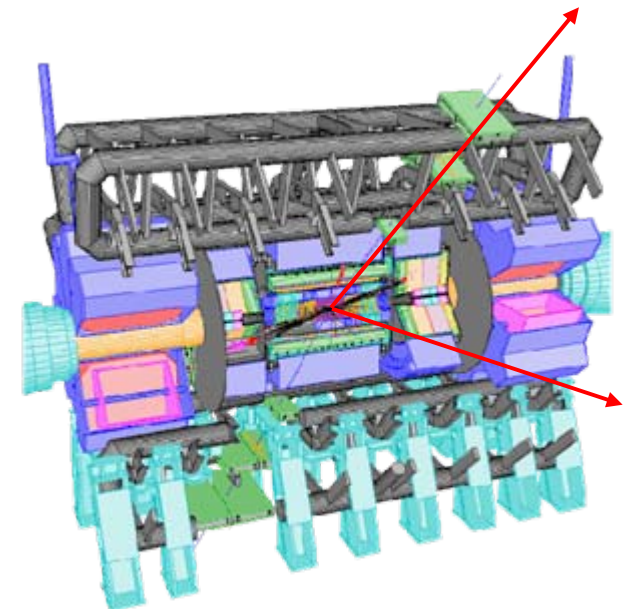
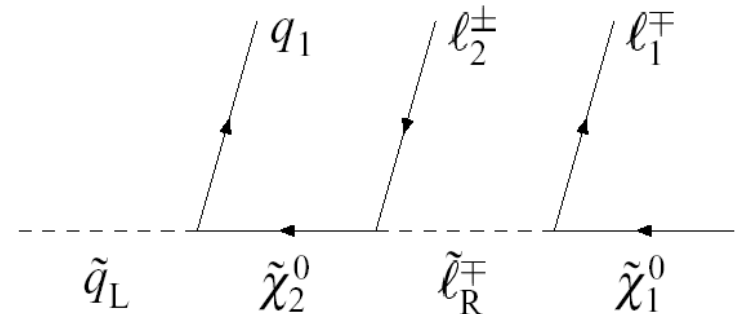
- **WIMP studies at the LHC are therefore highly model-dependent**

# INDIRECT WIMP PRODUCTION

- The classic WIMP: neutralinos from supersymmetry

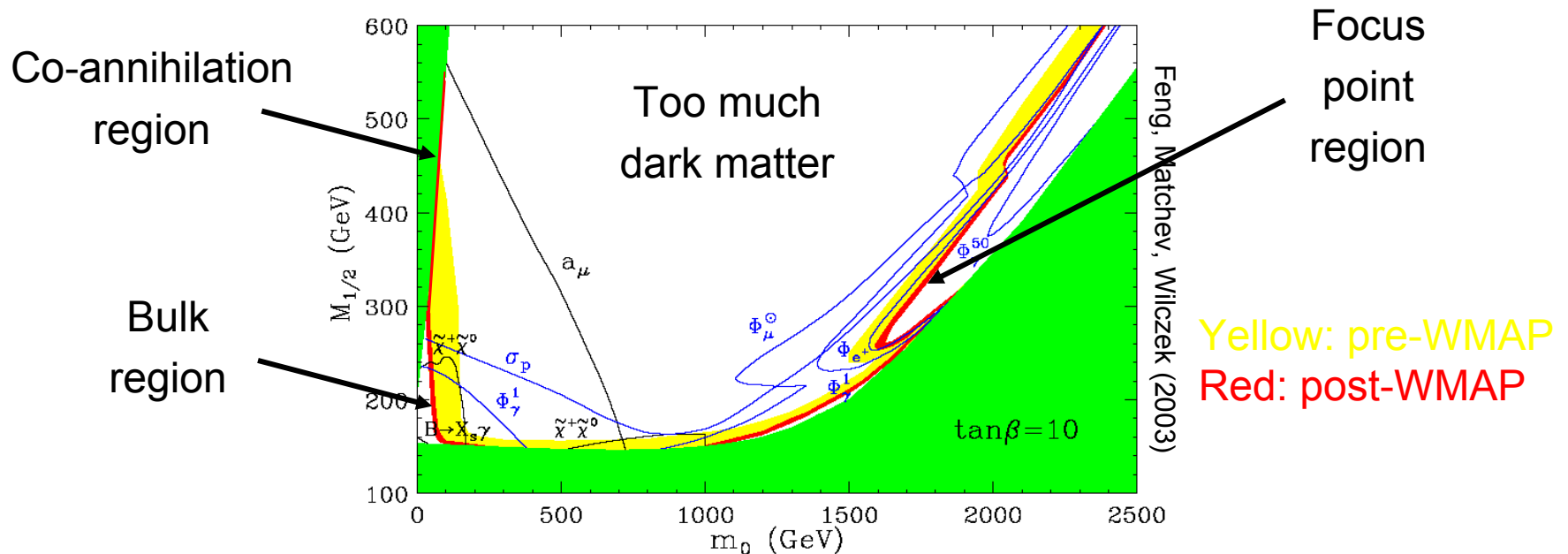
Ellis et al. (1983); Goldberg (1983)

- Neutralino  $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$
- Produced in  $\tilde{q}\tilde{q}$  pair production
  - Each  $\tilde{q} \rightarrow$  neutralino  $\chi$
  - 2  $\chi$ 's escape detector
  - missing transverse momentum, energy



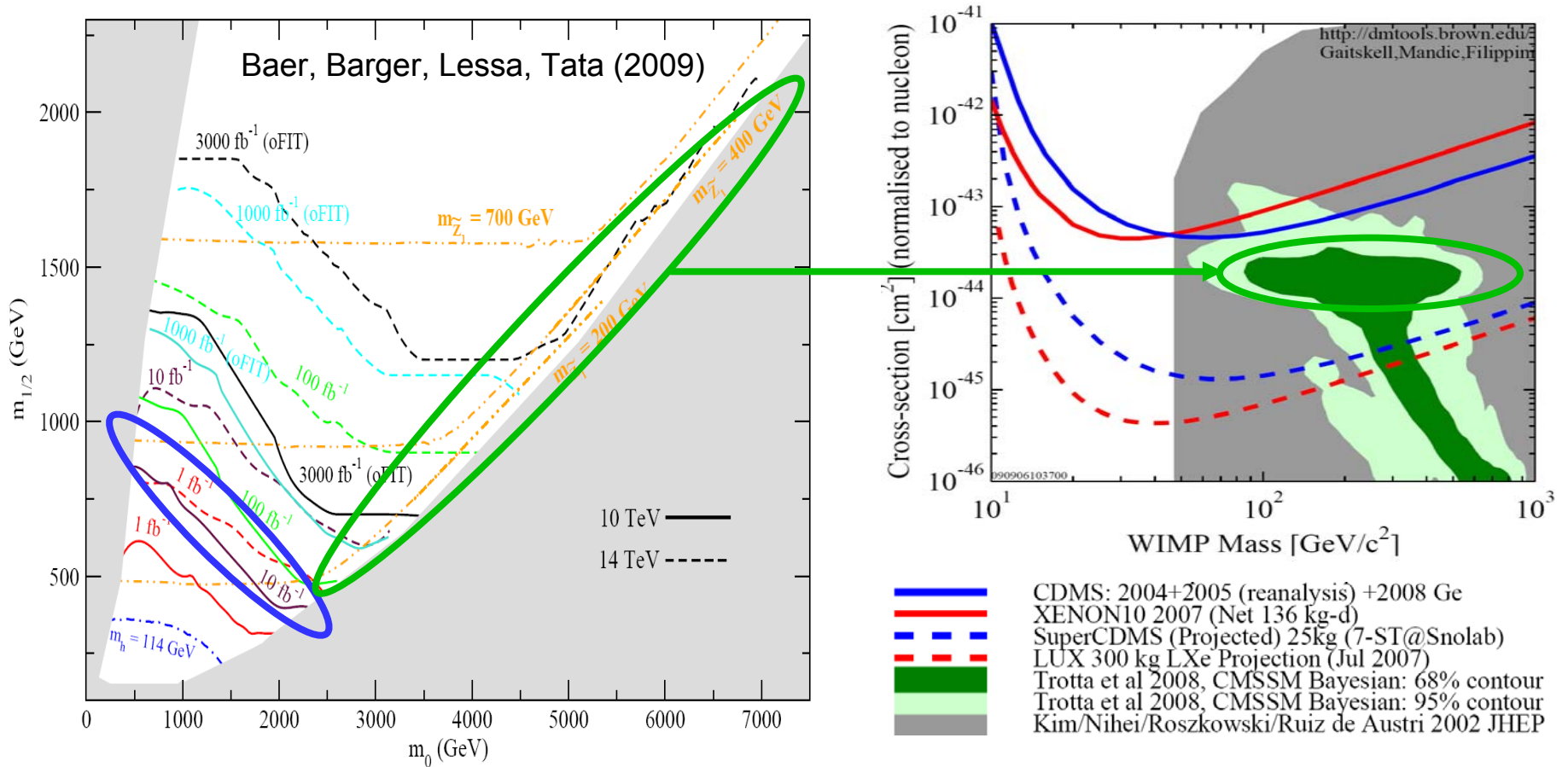


- For quantitative studies
  - pick a specific SUSY model, for example, mSUGRA
  - try to abstract general lessons
- $\Omega_{\text{DM}} = 23\% \pm 4\%$  stringently constrains models



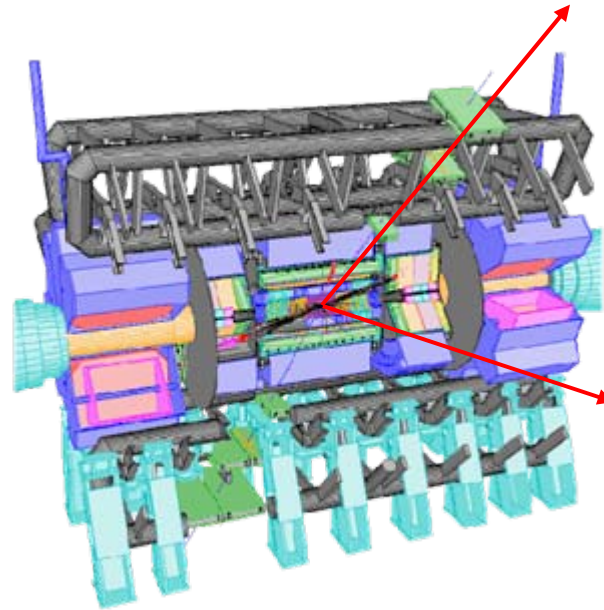
- Assuming standard Big Bang, cosmology excludes many possibilities, favors certain regions

# LHC, FP REGION, DIRECT DETECTION



- LHC with 1-10 fb $^{-1}$  probes all but the far focus point region
- FP (mixed gaugino-Higgsino) region  $\rightarrow \sigma_{SI} \sim 10^{-44}$  cm $^2$
- Probed by direct detection soon (CDMS, XENON, LUX, ...)

# WHAT IF THE LHC PRODUCES WIMPS?

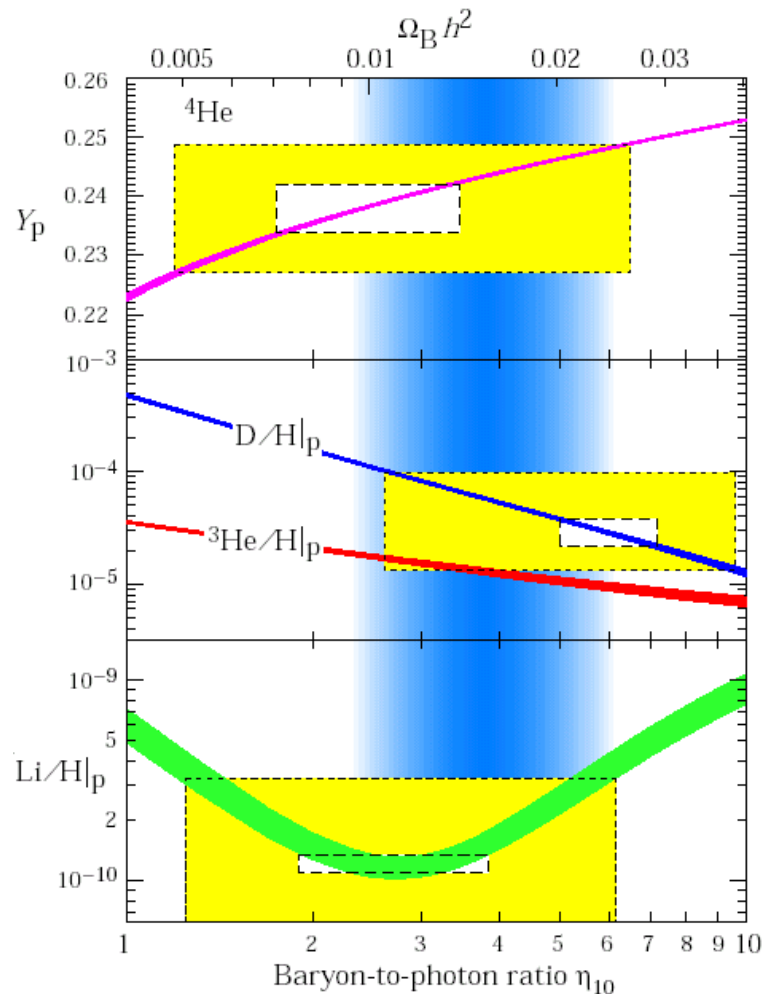


This is not the discovery of dark matter

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

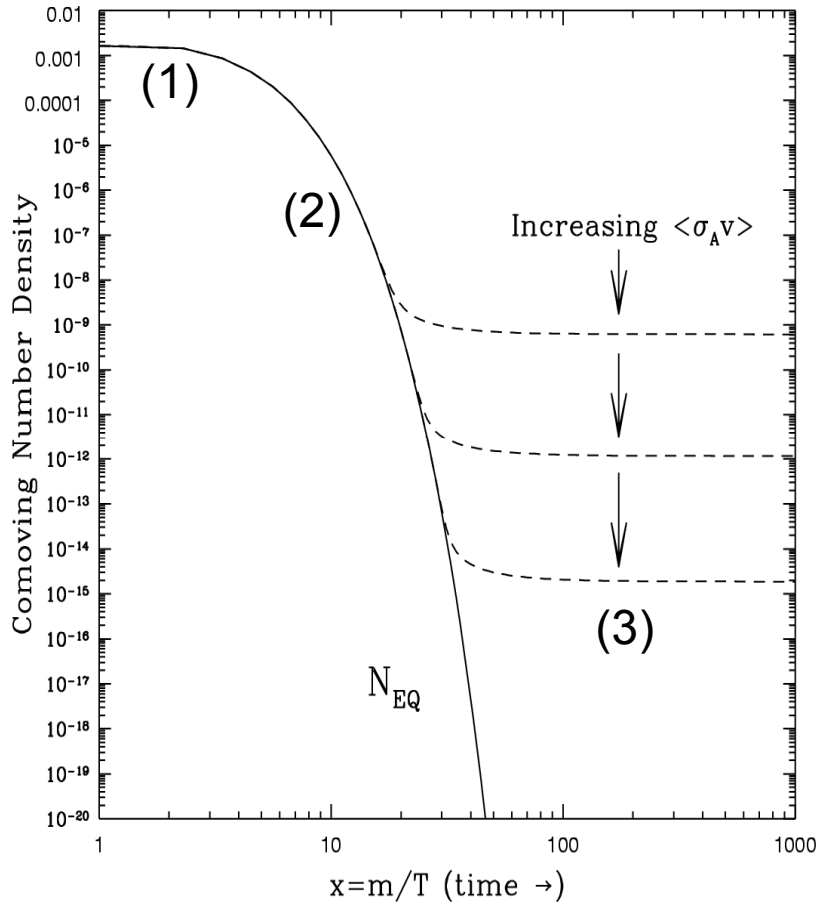
What else can be done?

# THE EXAMPLE OF BBN



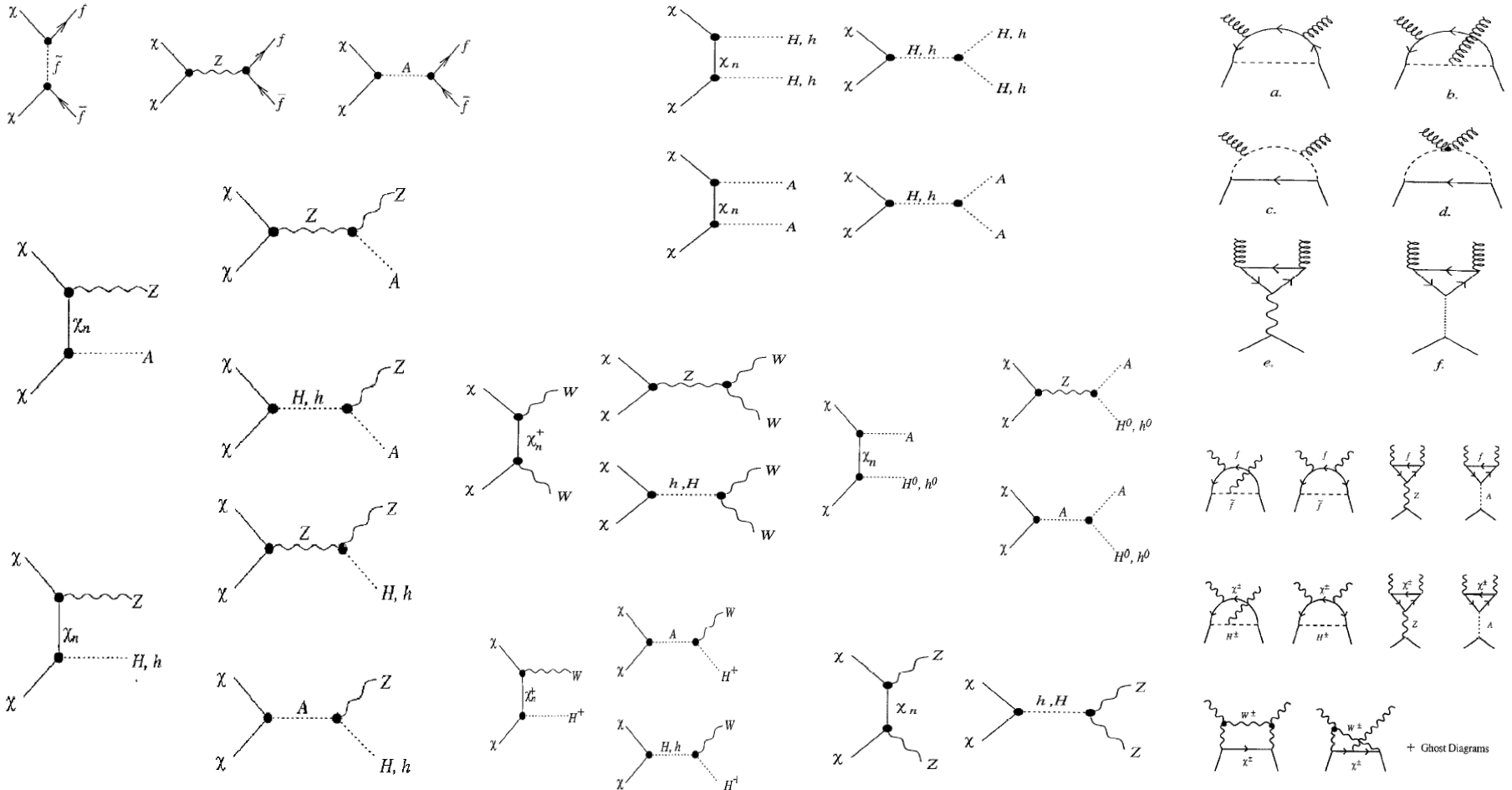
- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to
  - $T \sim 1 \text{ MeV}$
  - $t \sim 1 \text{ sec}$

# DARK MATTER ANALOGUE



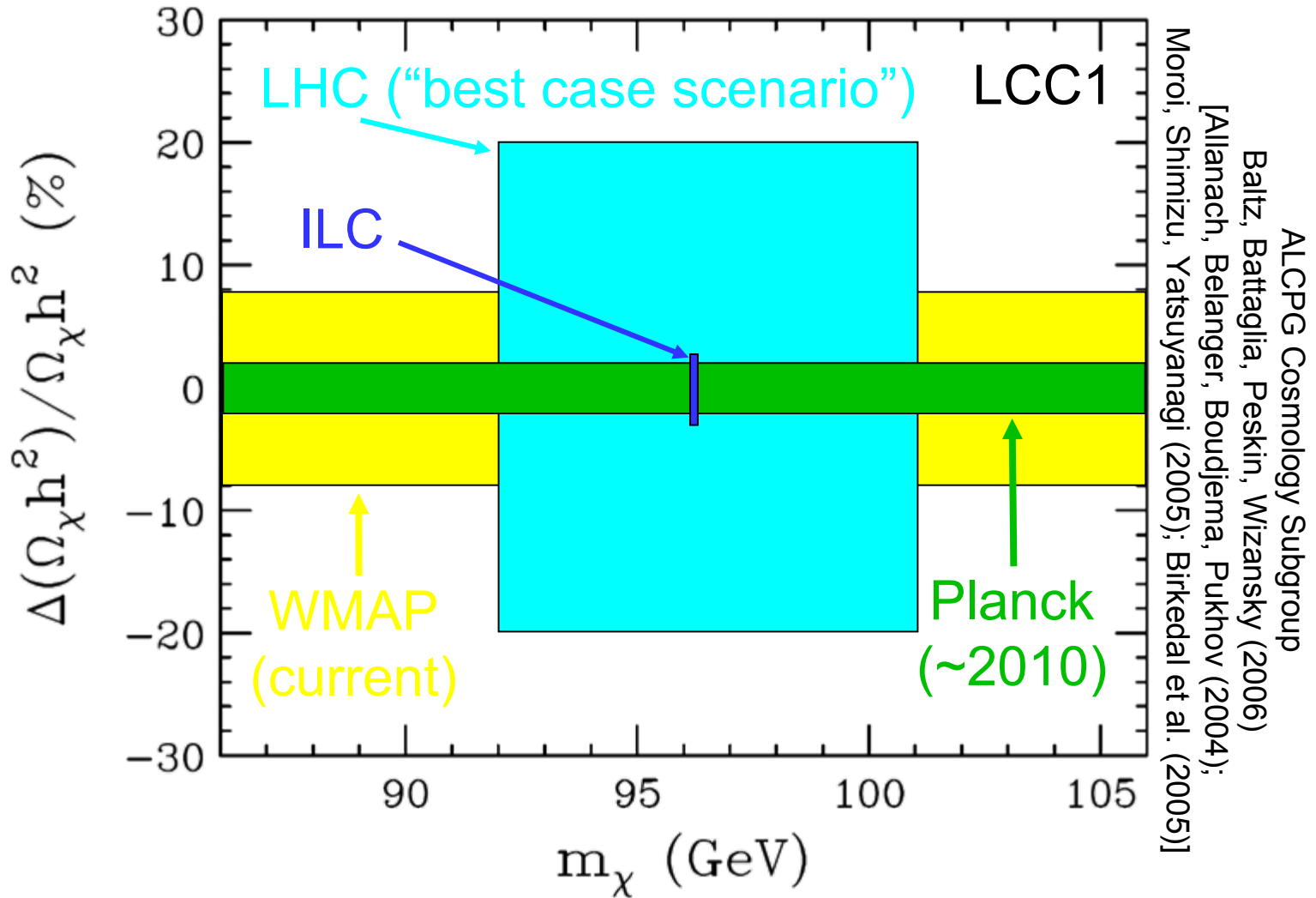
- Particle physics  $\rightarrow$  dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

# NEUTRALINO ANNIHILATION



Jungman, Kamionkowski, Griest (1995)

# RELIC DENSITY DETERMINATIONS



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

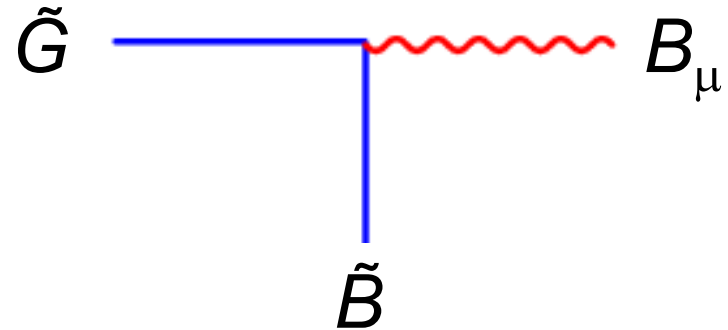
# BEYOND WIMPS

- 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

- No more exotic than neutralinos  
SUSY: graviton  $G \rightarrow$  gravitino  $\tilde{G}$
- Mass: eV – 100 TeV
- Interactions: Gravitinos couple particles to their superpartners



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
  - $n_{\tilde{G}} \sim n_{\text{thermal}}$  ,  $\Omega_{\tilde{G}} h^2 \approx 0.1 (m_{\tilde{G}} / 80 \text{ eV})$  (cf. neutrinos)

Pagels, Primack (1982)

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

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

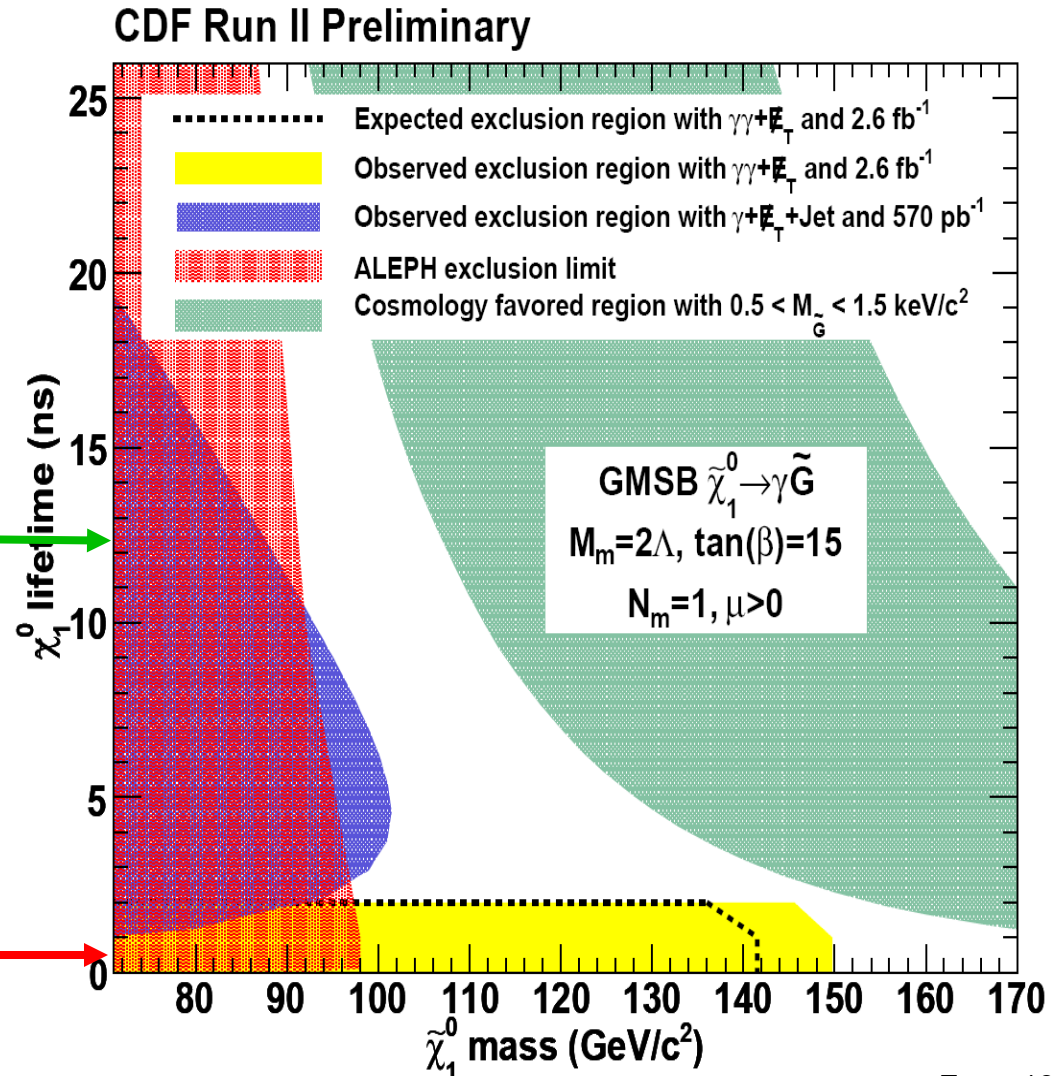
- Two ways out
  - $\Lambda$ WDM:  $m_{\tilde{G}} > \text{few keV}$ . Gravitinos are all the DM, but thermal density is diluted by low reheating temperature, late entropy production, ...
  - $\Lambda$ WCDM:  $m_{\tilde{G}} < 16 \text{ eV}$ . Gravitinos are only part of the DM, mixed warm-cold scenario

# LIGHT GRAVITINOS AT THE LHC

- $m_{\tilde{G}} \rightarrow \tau(\chi \rightarrow \gamma\tilde{G})$ ;  
remarkably, this lifetime  
difference is observable  
at colliders!

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

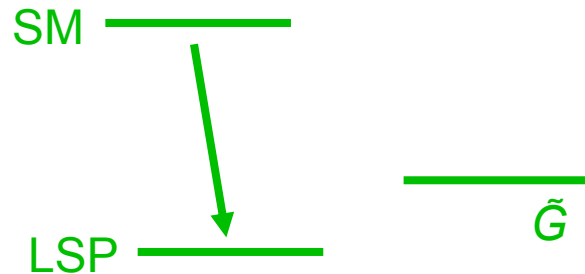
- $m_{\tilde{G}} < 16 \text{ eV}$ :  
Prompt photon  
signatures



# HEAVY GRAVITINOS

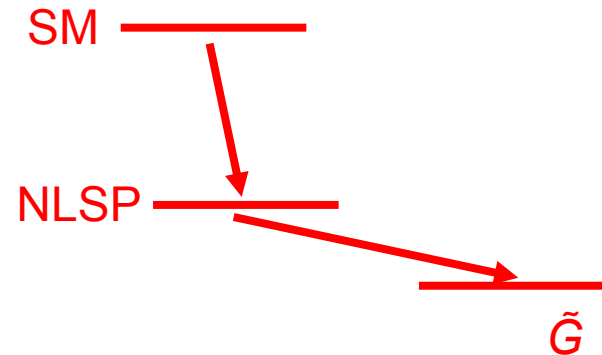
Mass  $\sim 100$  GeV; Interactions:  $\sim$  gravitational (superweak)

- $\tilde{G}$  not LSP



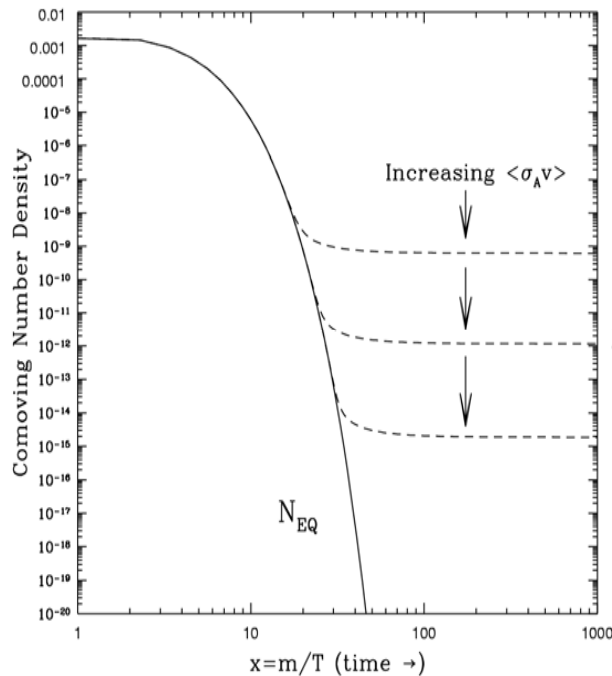
- Assumption of most of literature

- $\tilde{G}$  LSP



- Completely different cosmology and particle physics

# SUPERWIMP RELICS



- Suppose  $\sim 100$  GeV gravitinos are the LSP
  - WIMPs freeze out as usual
- $\xrightarrow{\text{WIMP}} \tilde{G} (+ \gamma, e, \dots)$

but then all WIMPs decay to gravitinos after  $M_{\text{Pl}}^2/M_W^3 \sim$  seconds to months

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

# SUPERWIMP IMPLICATIONS

- No direct, indirect signals, but potential cosmological signals

- BBN

Jedamzik talk

- CMB

Lamon, Durrer (2005)

- warm DM

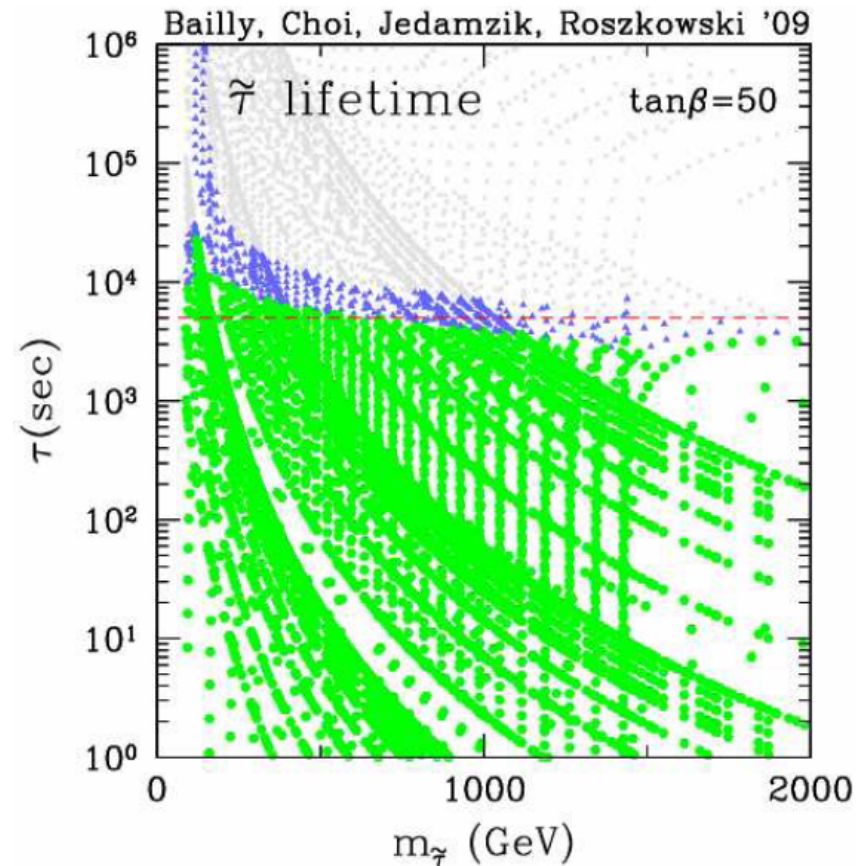
Kaplinghat (2005)

Cembranos, Feng, Rajaraman, Takayama (2005)

- BBN  $\rightarrow$  decaying WIMP  $\neq \chi$

Feng, Rajaraman, Takayama (2003)

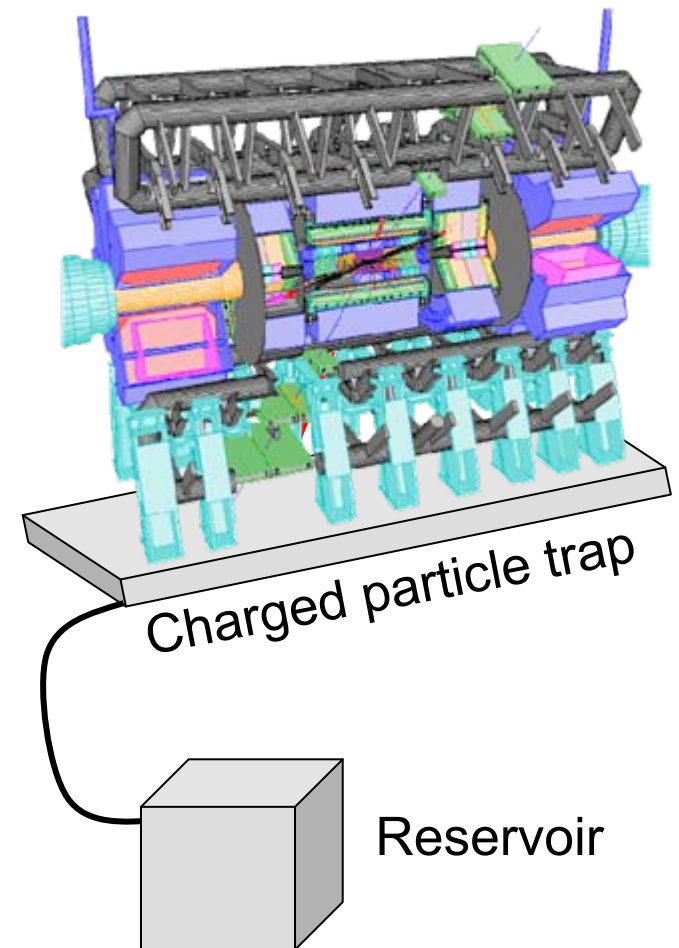
Feng, Su, Takayama (2004)



- Decaying slepton mass  $> 100$  GeV, lifetime  $\sim 1 - 10^7$  s

# CHARGED PARTICLE TRAPPING

- SuperWIMP DM implies charged metastable particles, far more spectacular than missing  $E_T$  (1<sup>st</sup> 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  $E_l \rightarrow m_{\tilde{G}}$  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

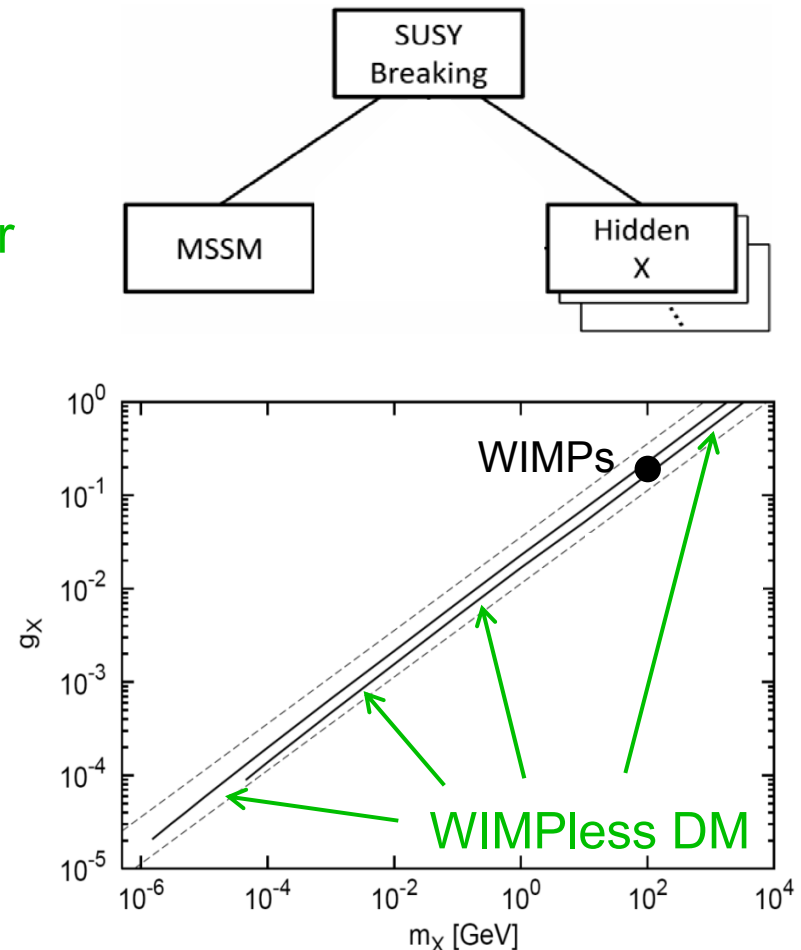
Hamaguchi et al. (2004); Takayama et al. (2004)



# WIMPLESS DARK MATTER

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

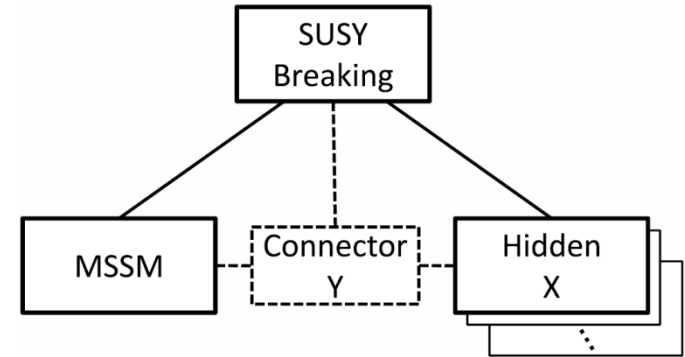
- DM may be hidden (no SM gauge interactions); generically, anything is possible
- But in SUSY models motivated by flavor problem (GMSB, ...), superpartner masses are determined by gauge couplings:  $m_X \sim g_X^2$
- This implies that stable particles in hidden sectors have the same relic density
 
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$
- “WIMPLess Miracle”: hidden DM candidates with a range of masses/couplings, but always the right  $\Omega$



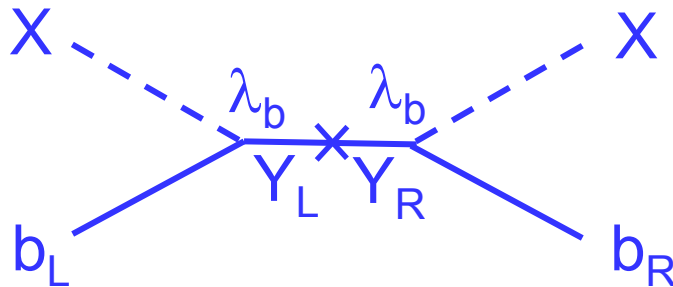
# HIDDEN DM SIGNALS

- Hidden DM may have only gravitational effects, but still interesting: e.g., it may have hidden charge and be self-interacting through Rutherford scattering

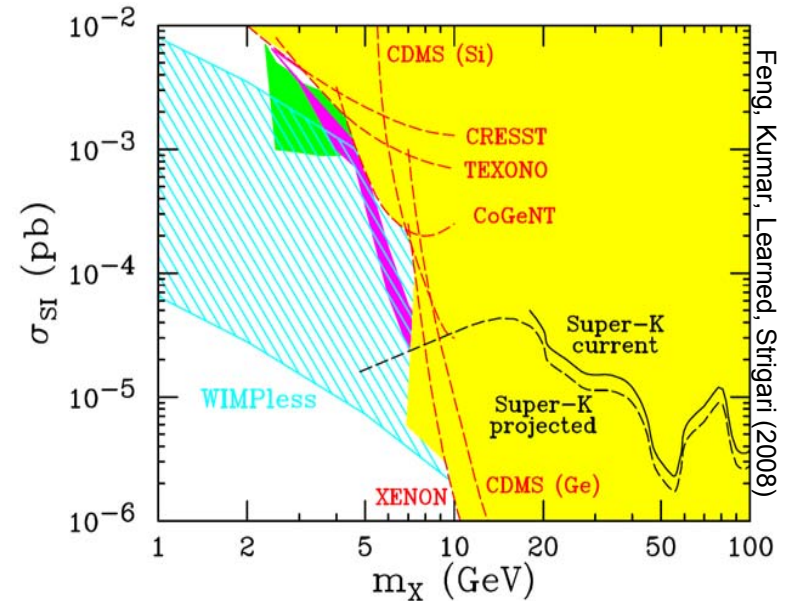
Feng, Kaplinghat, Tu, Yu (2009)



- Alternatively, hidden DM X may have Yukawa couplings through connectors Y with normal matter, explain DAMA



- Y particles will appear at LHC as exotic 4<sup>th</sup> generation quarks, windows on the hidden sector; many related ideas



# CONCLUSIONS

- WIMP miracle  $\rightarrow$  fascinating interaction of LHC with cosmology; many specific realizations with greatly varying phenomenology and implications
- WIMPs  $\rightarrow$  missing  $E_T$ , but also many other, even more striking, possibilities
  - Prompt or delayed photons
  - Heavy charged particles
  - Connector particles to hidden sectors
- LHC begins in 2009-10, may have far-reaching implications soon