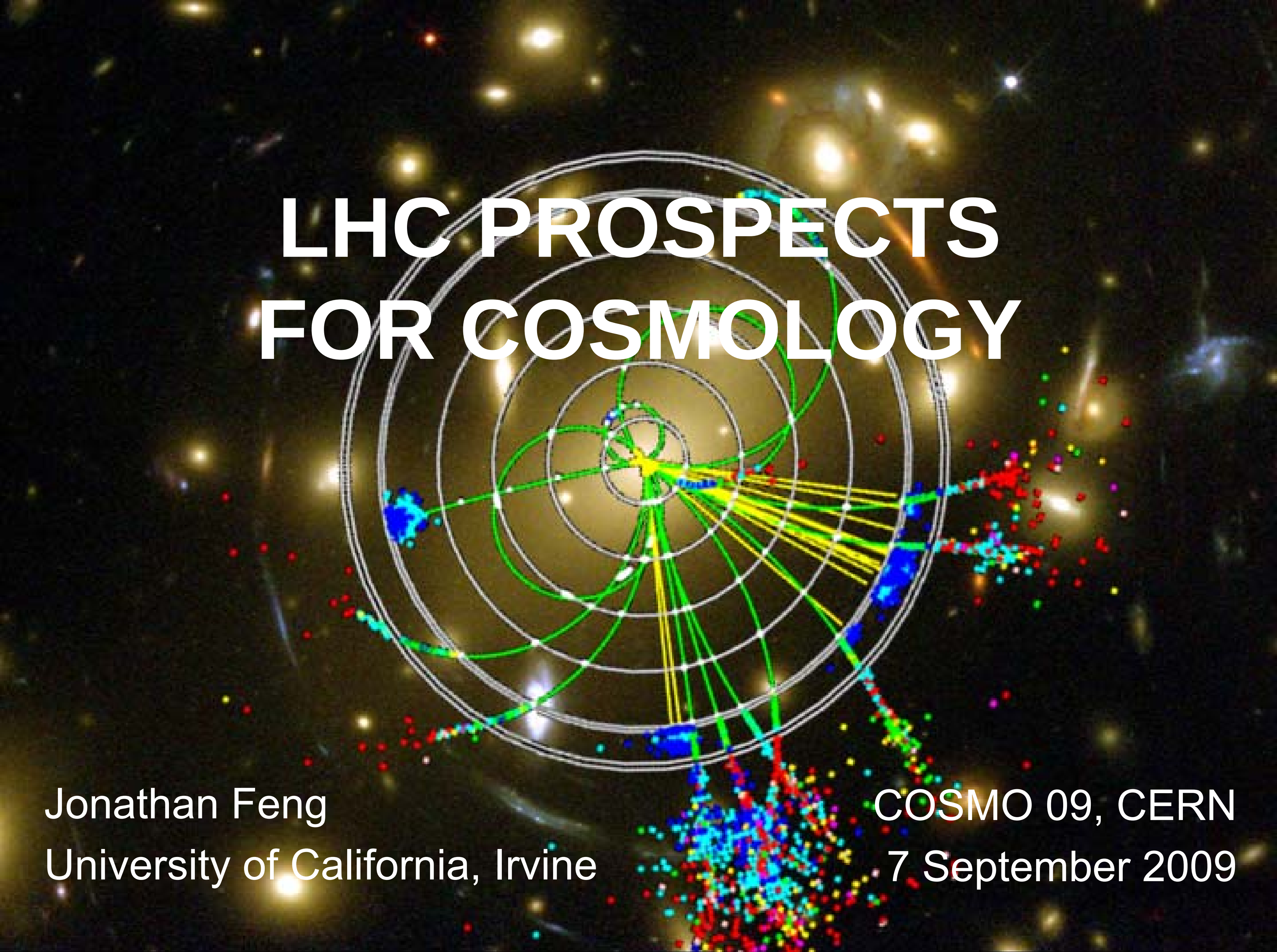
LHC PROSPECTS FOR COSMOLOGY



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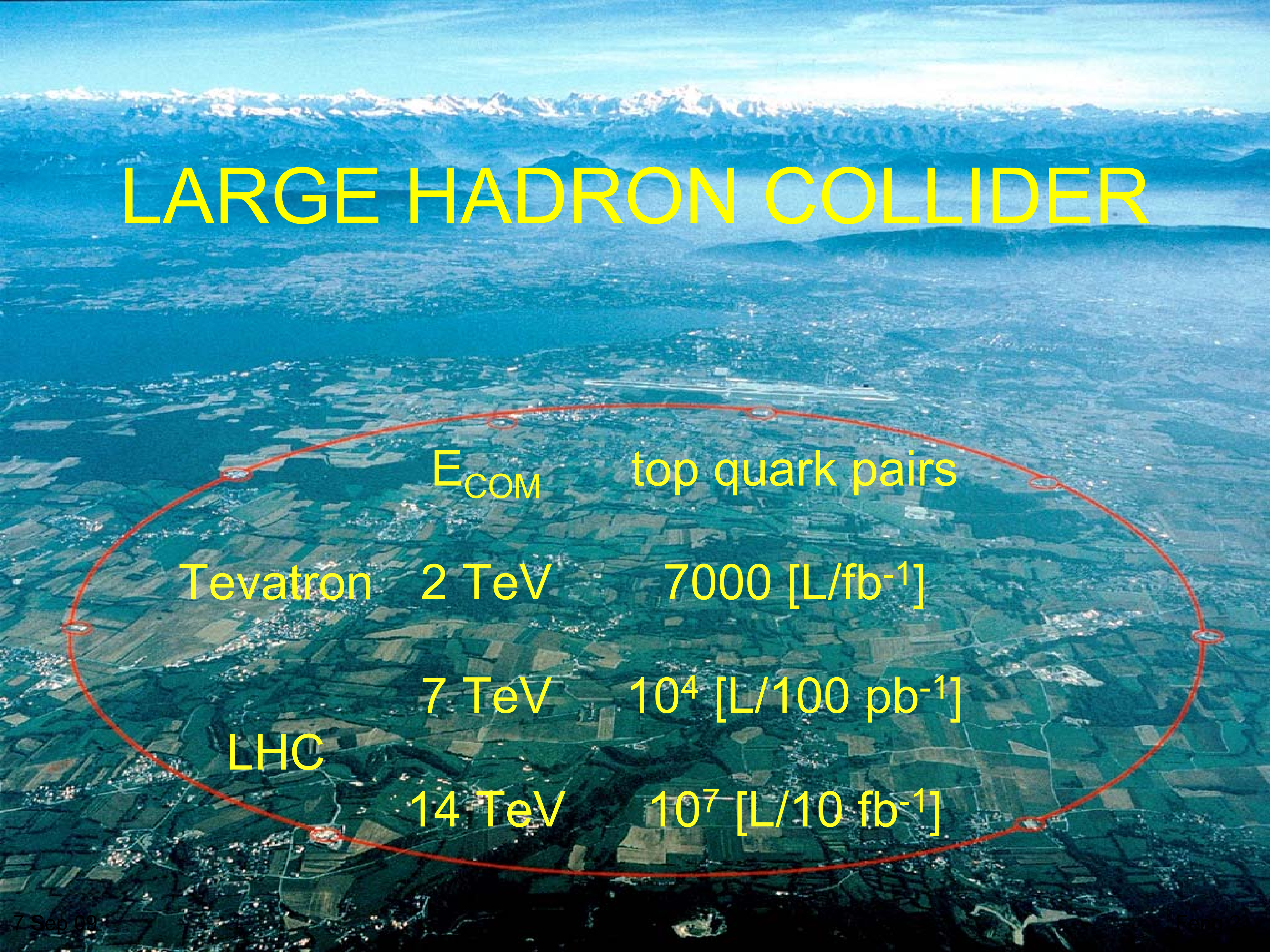
COSMO 09, CERN
7 September 2009


LARGE HADRON COLLIDER
E_{COM} top quark pairs
Tevatron 2 TeV 7000 [L/fb^{-1}]
7 TeV 10^4 [L/100 pb^{-1}]
LHC
14 TeV 10^7 [L/10 fb^{-1}]

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

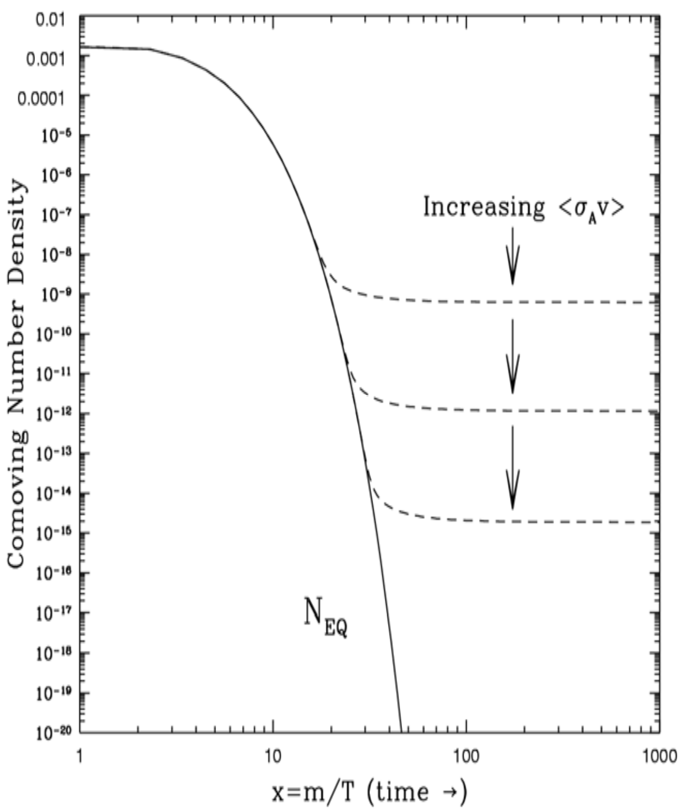
$$n \rightarrow p\, e^- \bar{\nu}$$

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

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

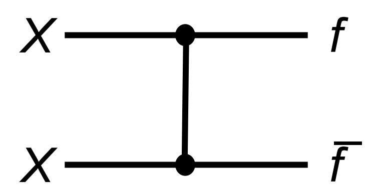
- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

THE WIMP MIRACLE



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

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

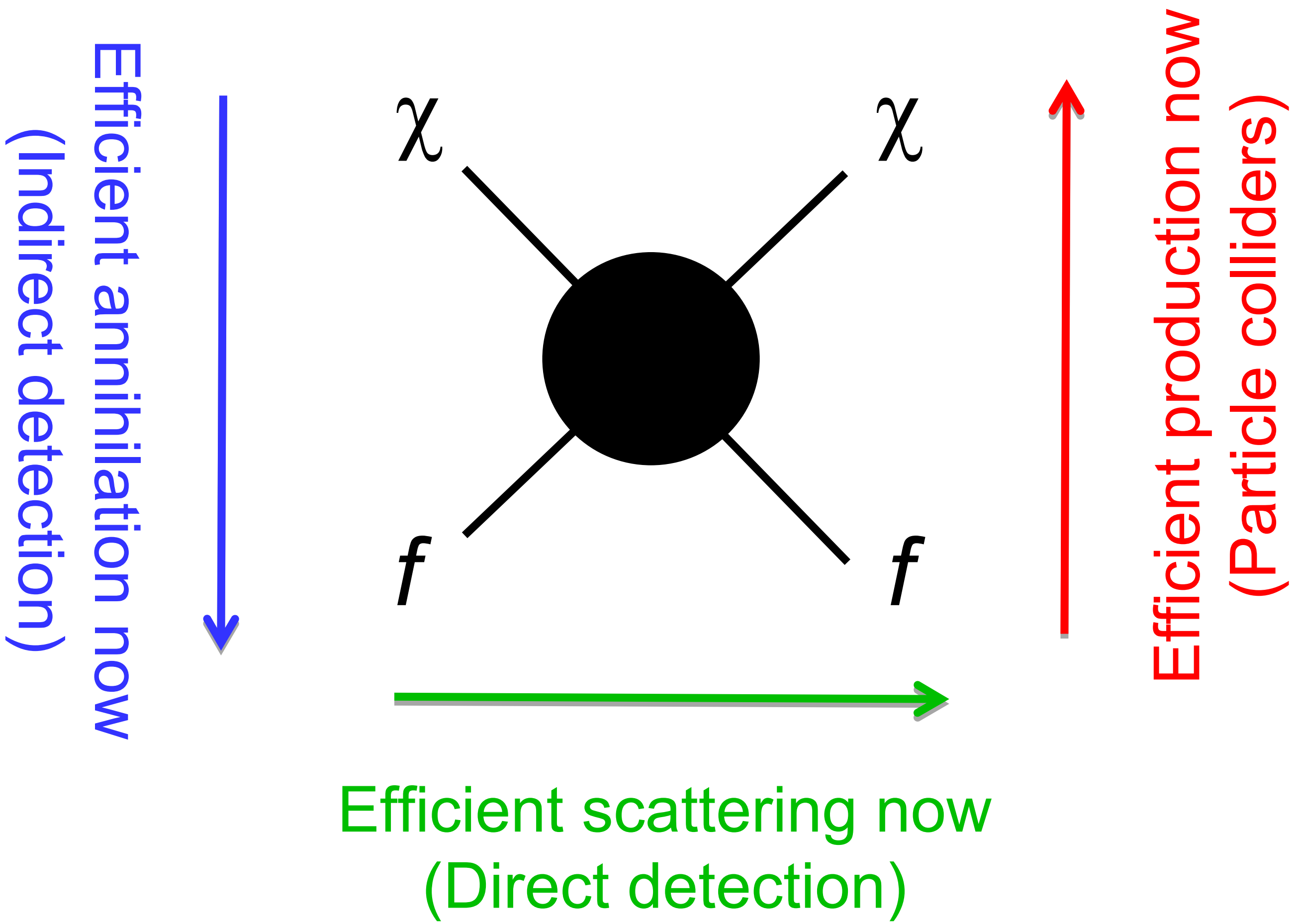


- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

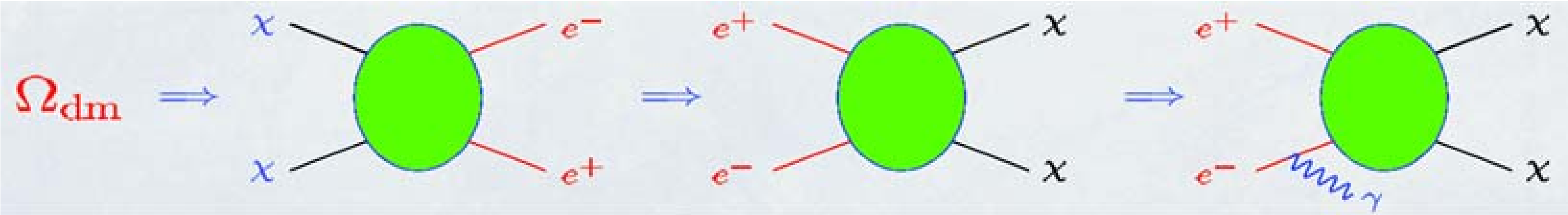
WIMP DETECTION

Correct relic density → 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 $q\bar{q} \rightarrow jZ, Z \rightarrow \nu\bar{\nu}$

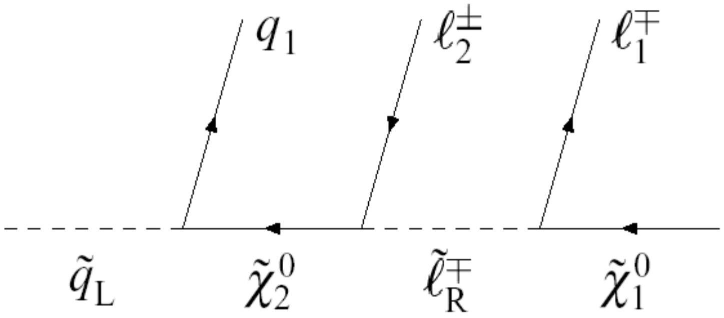
Feng, Su, Takayama (2005)

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

INDIRECT WIMP PRODUCTION

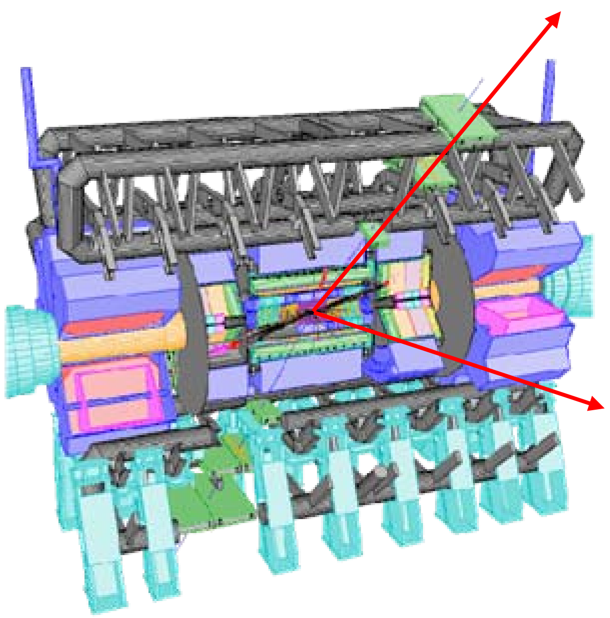
- The classic WIMP: neutralinos from supersymmetry

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



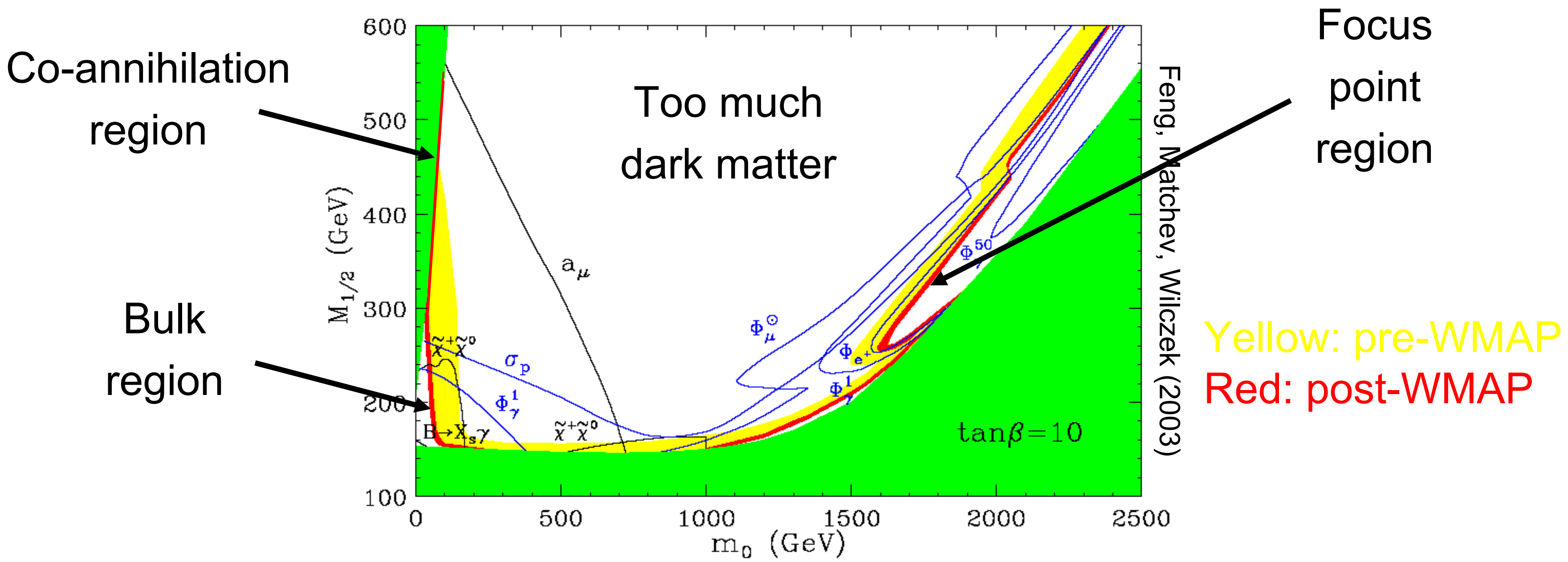
- Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

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



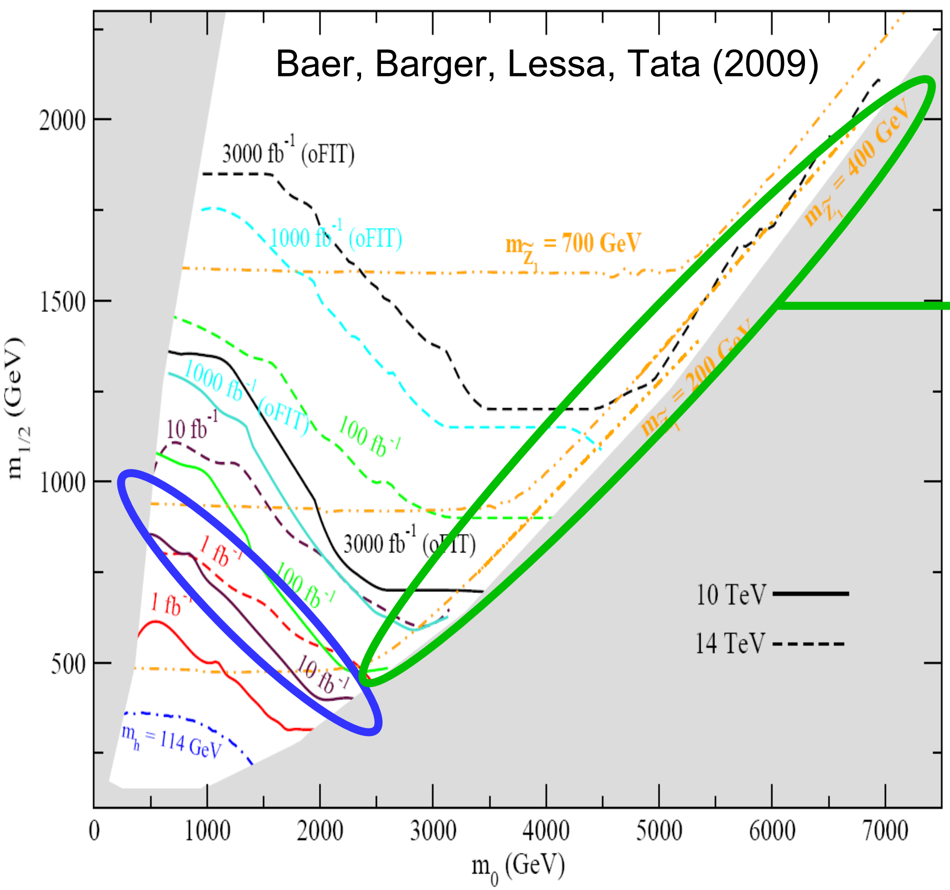
- For quantitative studies
  - pick a specific SUSY model, for example, mSUGRA
  - try to abstract general lessons

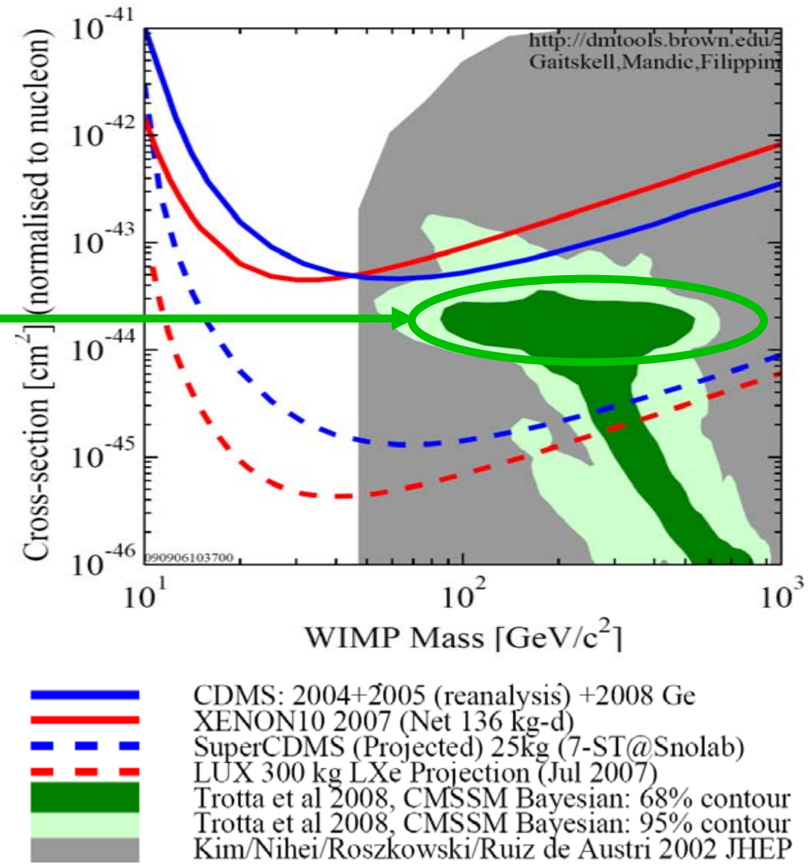
- Ω_{DM} = 23% ± 4% stringently constrains models



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

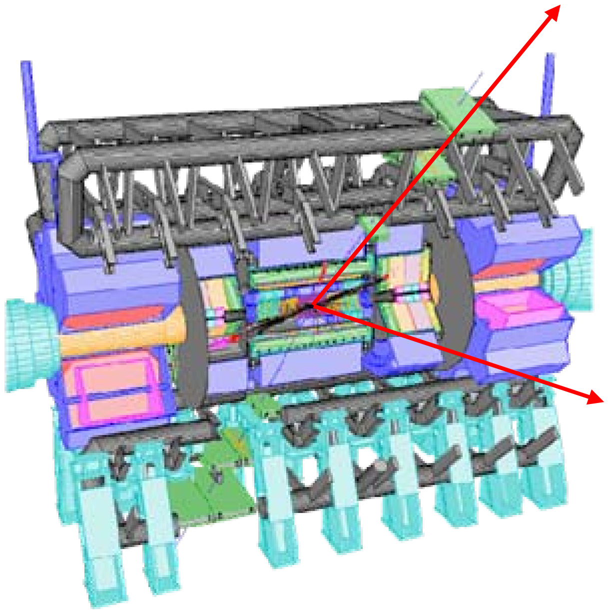
LHC, FP REGION, DIRECT DETECTION





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

WHAT IF THE LHC PRODUCES WIMPS?

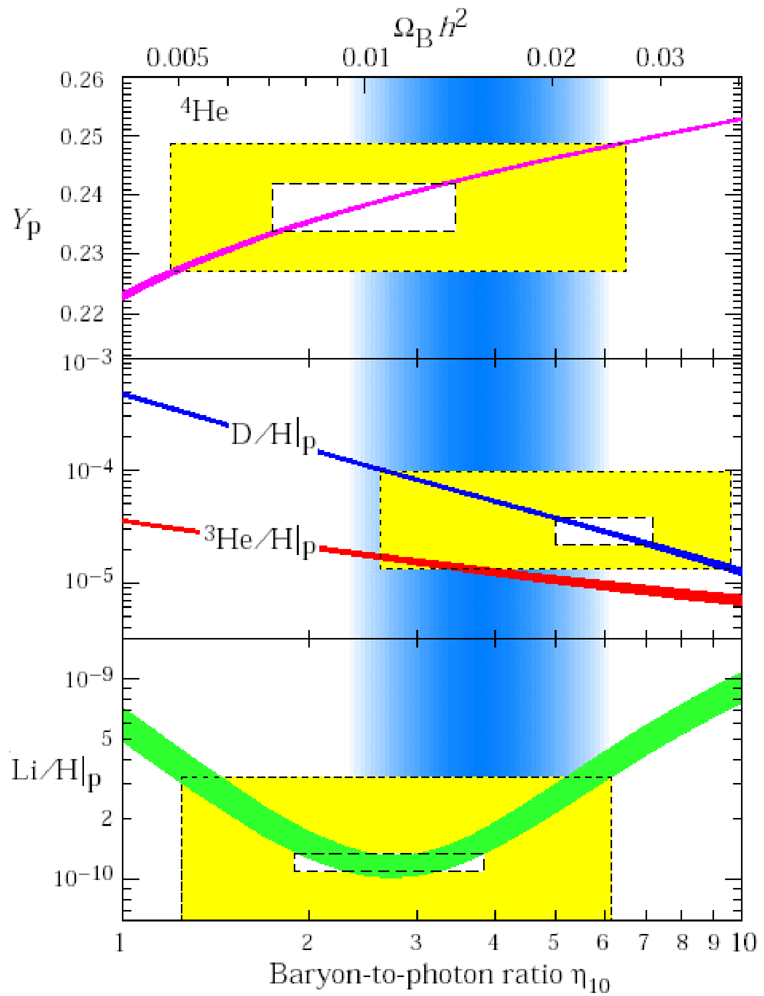


This is not the discovery of dark matter

- 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

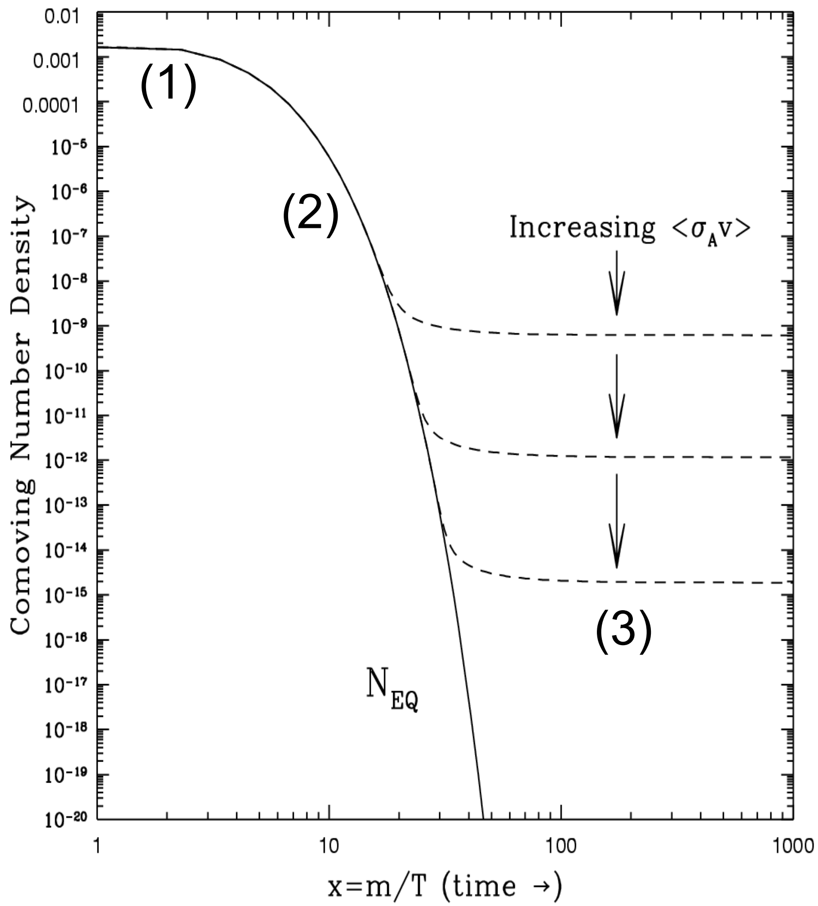


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

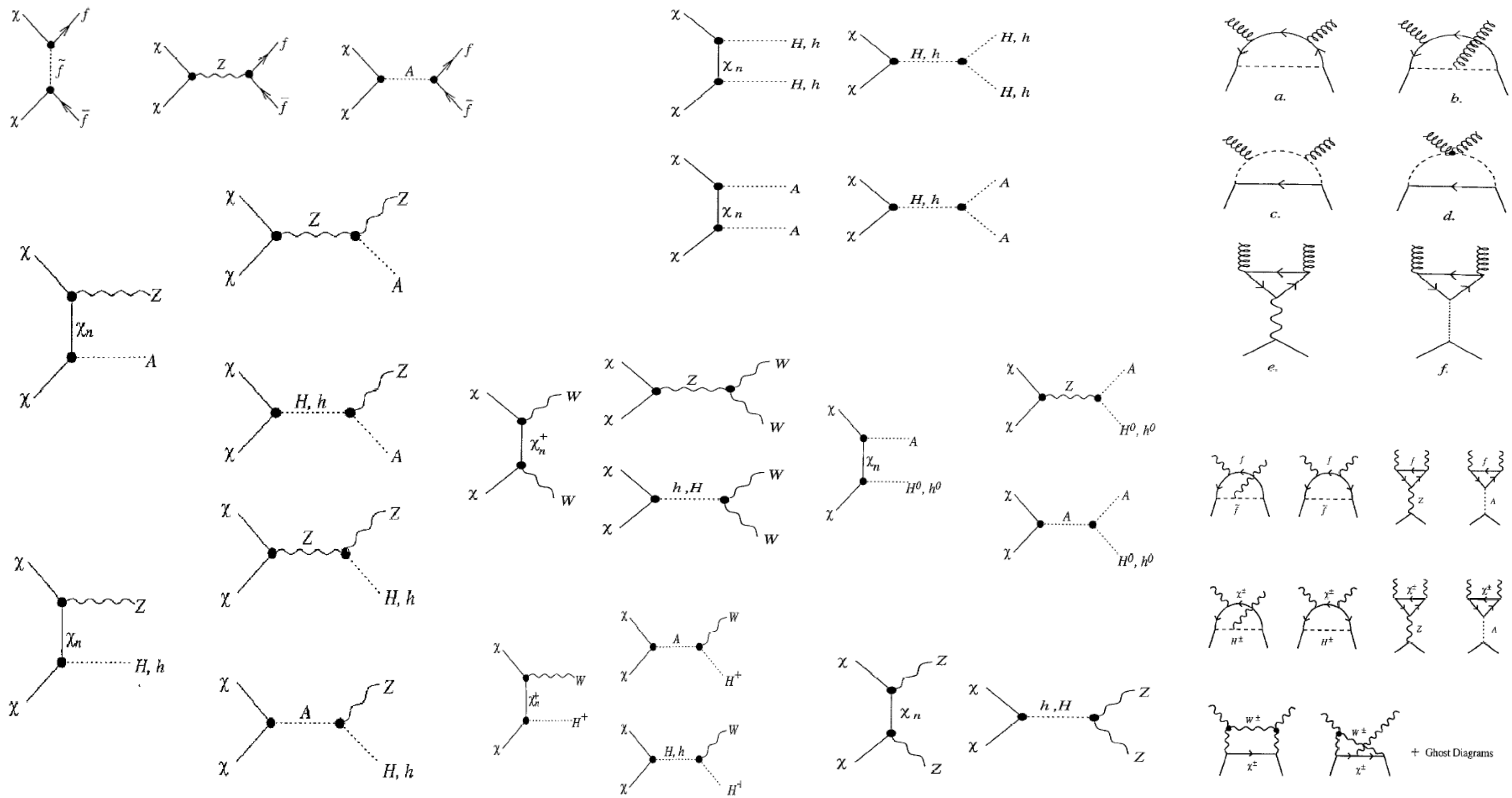
  t ~ 1 sec

DARK MATTER ANALOGUE



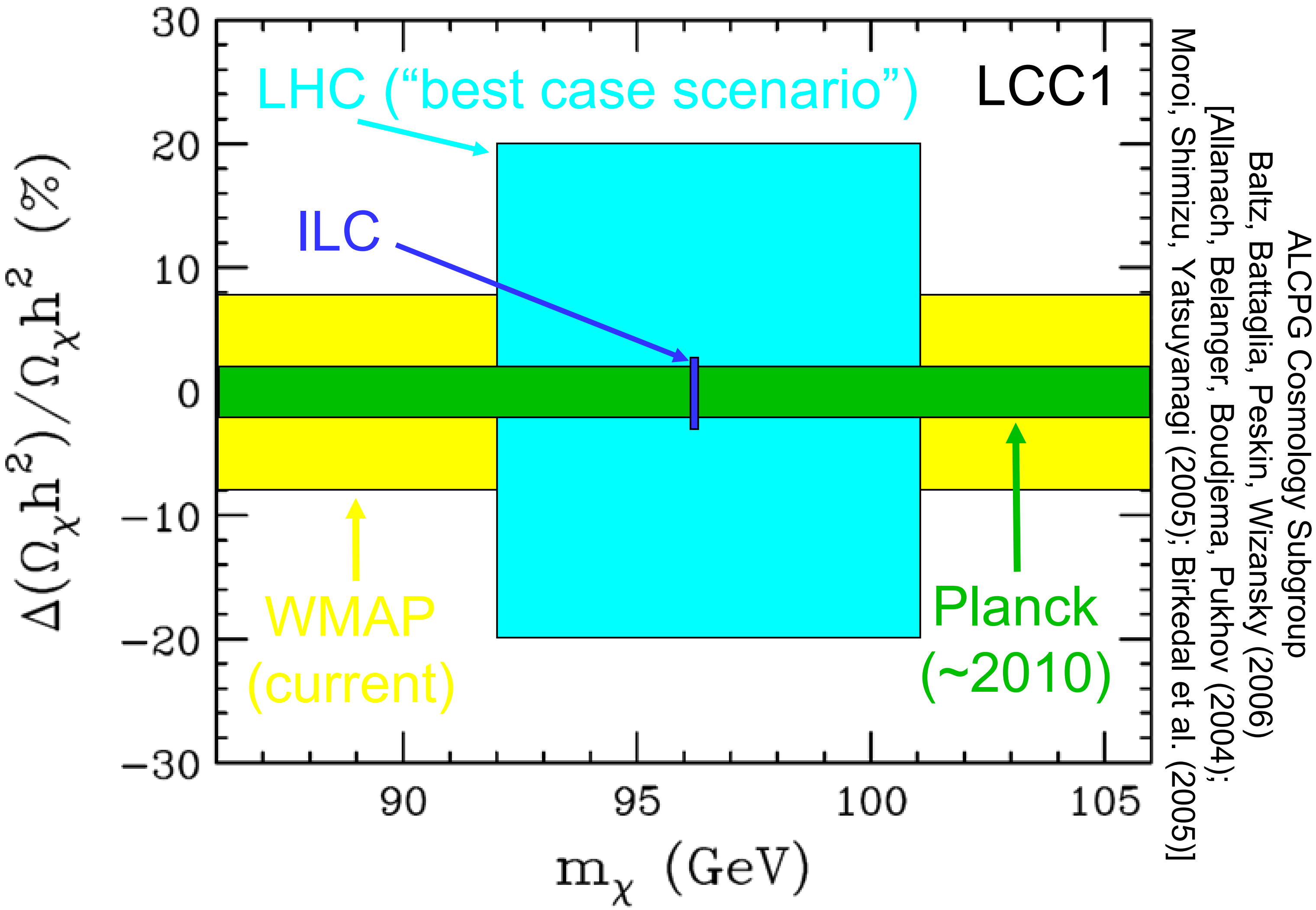
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

NEUTRALINO ANNIHILATION



Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



% level comparison of predicted $\Omega_{collider}$ with observed Ω_{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.

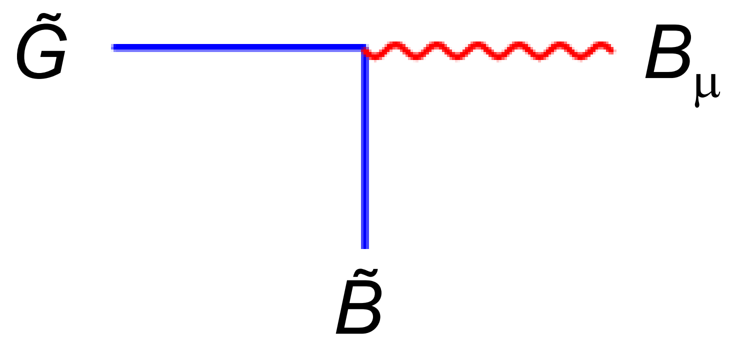
GRAVITINOS

- No more exotic than neutralinos

  SUSY: graviton G → 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 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)

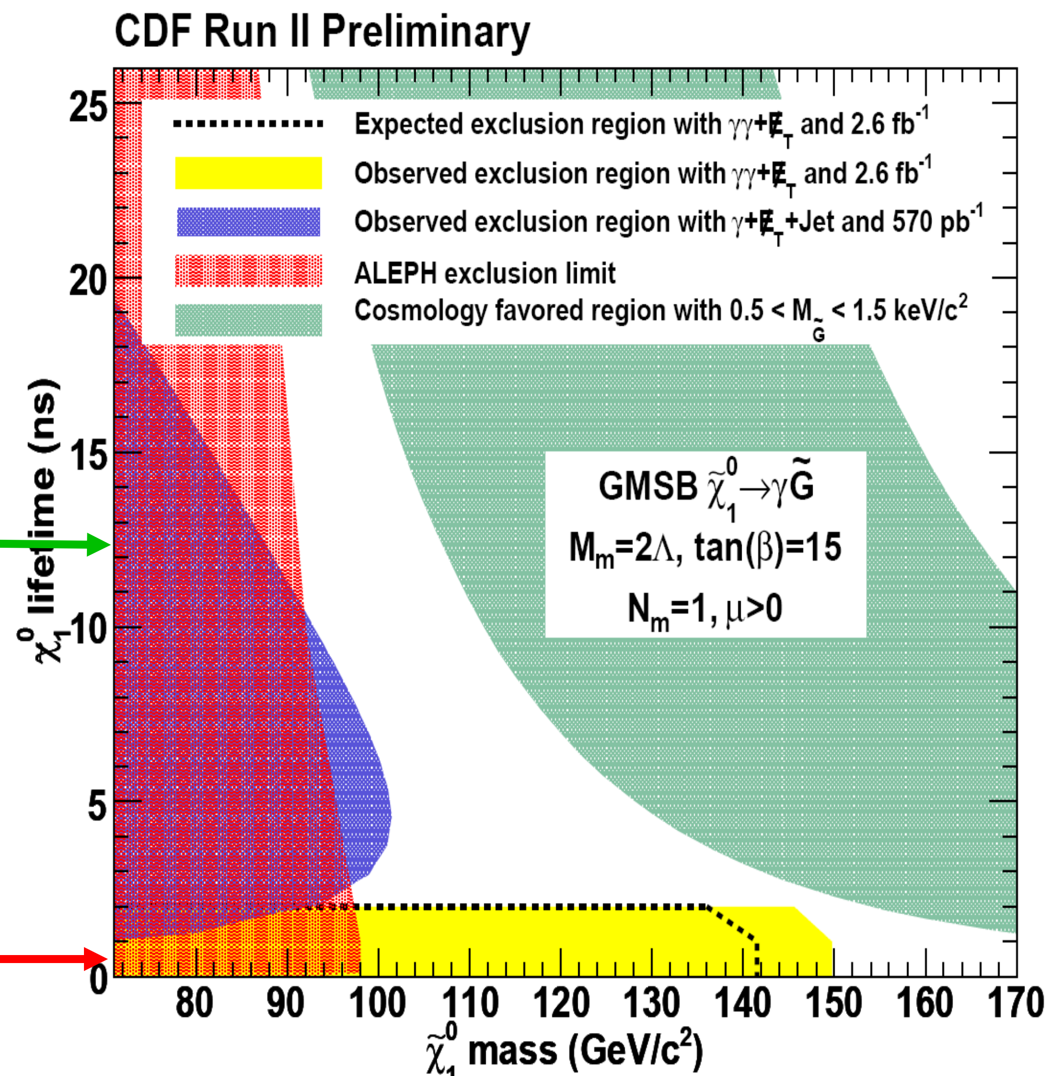
- Two ways out
  - ΛWDM: $m_{\tilde{G}}$ > few keV. Gravitinos are all the DM, but thermal density is diluted by low reheating temperature, late entropy production, …
  - ΛWCDM: $m_{\tilde{G}}$ < 16 eV. Gravitinos are only part of the DM, mixed warm-cold scenario

LIGHT GRAVITINOS AT THE LHC

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

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

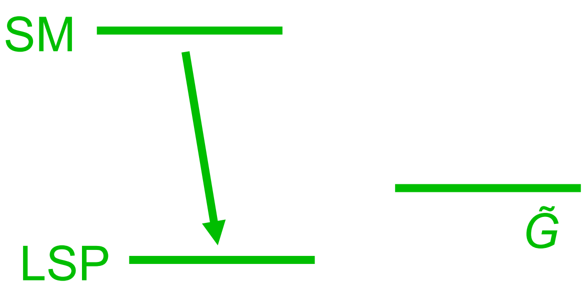
- $m_{\tilde{G}}$ < 16 eV: Prompt photon signatures



HEAVY GRAVITINOS

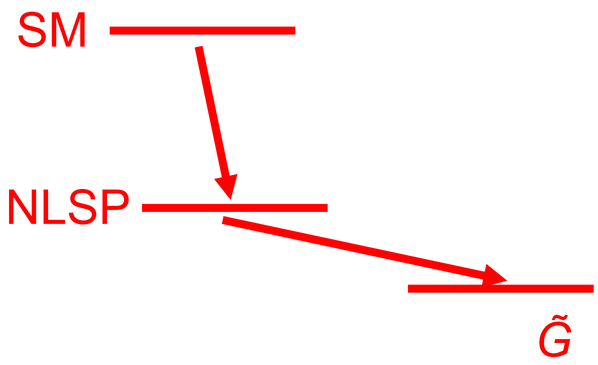
Mass ~ 100 GeV; Interactions: ~ gravitational (superweak)

- $\tilde{G}$ not LSP



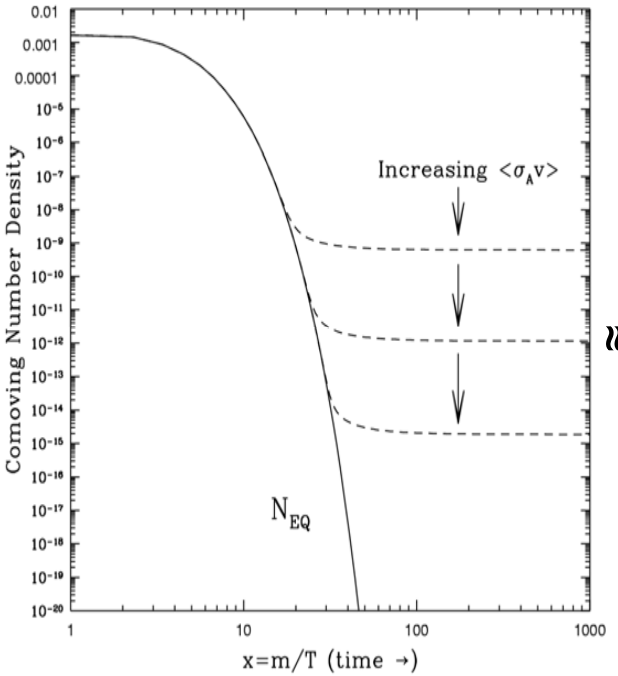
- Assumption of most of literature

- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose ~100 GeV gravitinos are the LSP
- WIMPs freeze out as usual

WIMP → $\tilde{G}$ (+ γ, 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, ...)

SUPERWIMP IMPLICATIONS

- No direct, indirect signals, but potential cosmological signals
  – BBN

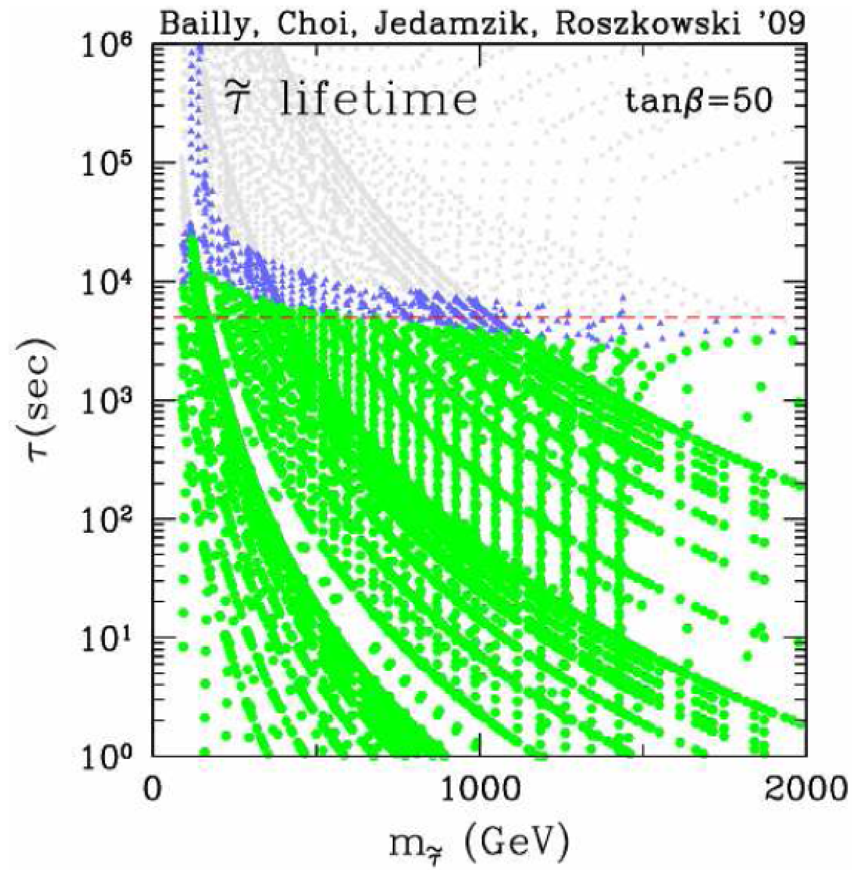
    Jedamzik talk

  – CMB

    Lamon, Durrer (2005)

  – warm DM

    Kaplinghat (2005)
    Cembranos, Feng, Rajaraman, Takayama (2005)



- BBN → decaying WIMP ≠ χ

    Feng, Rajaraman, Takayama (2003)
    Feng, Su, Takayama (2004)

- Decaying slepton mass > 100 GeV, lifetime ~ 1 – 10^7 s

CHARGED PARTICLE TRAPPING

- SuperWIMP DM implies charged metastable particles, far more spectacular than misssing E_T (1^{st} year LHC discovery)

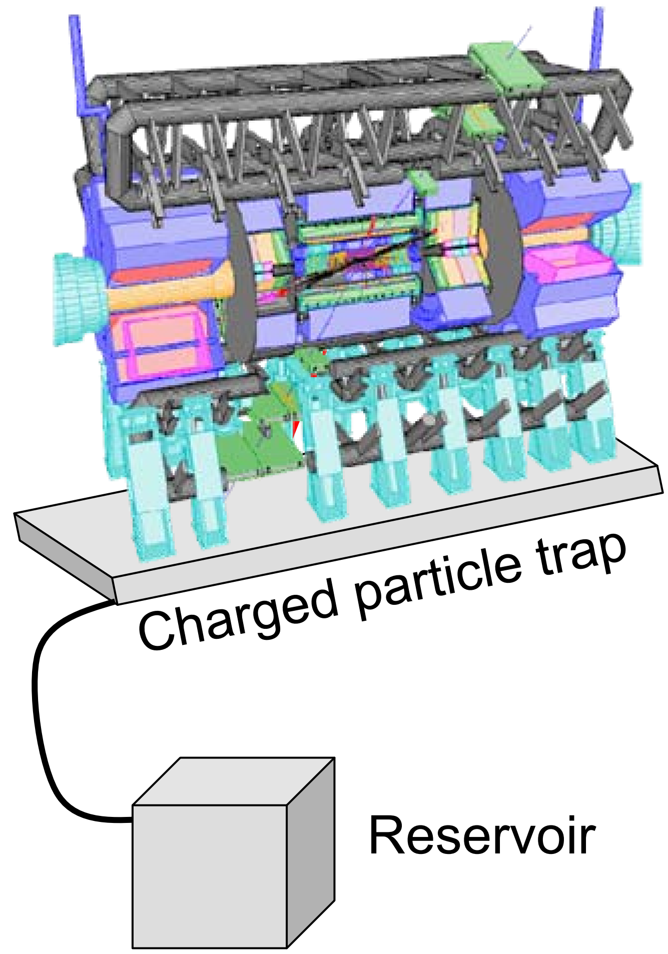
- Can collect these particles and study their decays

- 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

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

- Measurement of τ , $m_{\tilde{l}}$ 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)

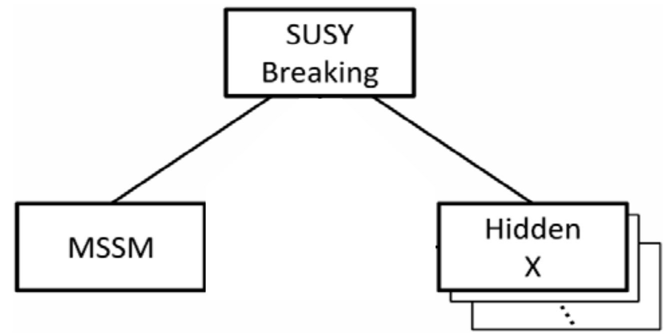
WIMPLESS DARK MATTER

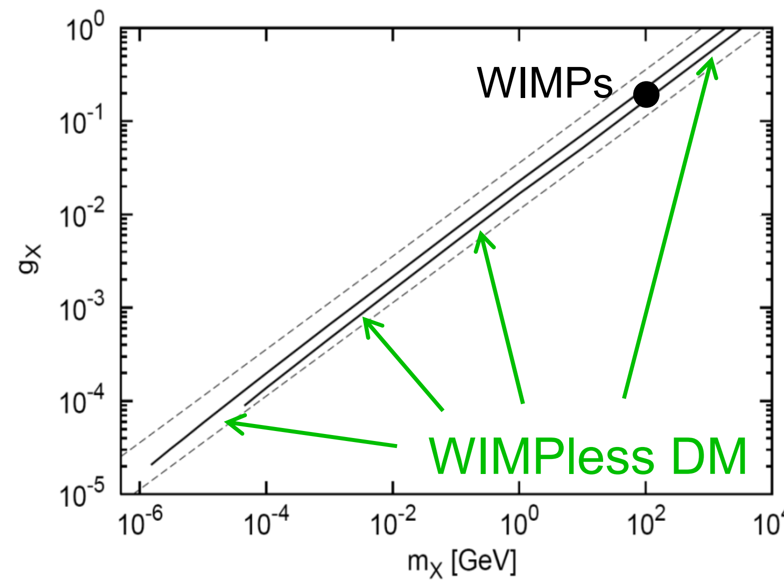
Feng, Kumar (2008); Feng, Tu, Yu (2008)

- 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 Ω

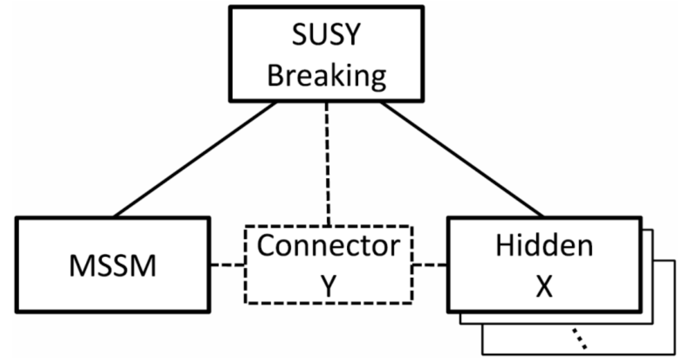




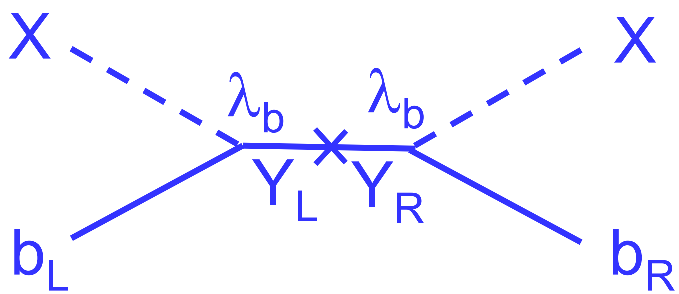
HIDDEN DM SIGNALS

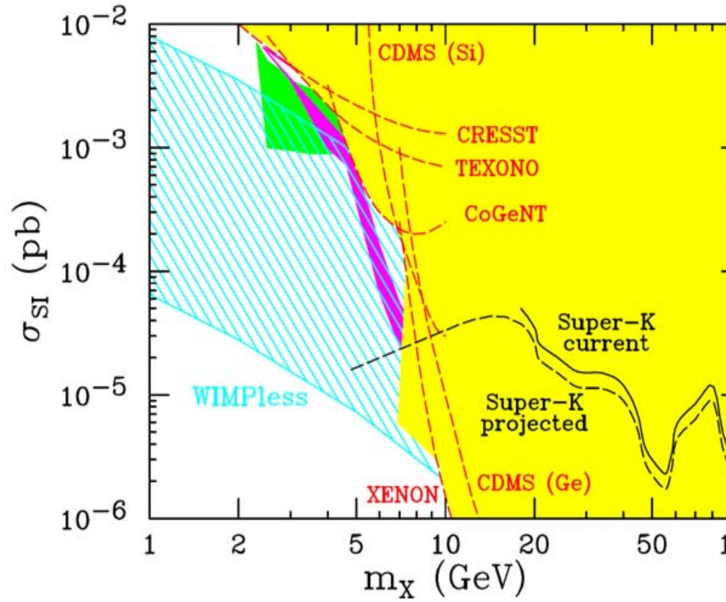
- Hidden DM may have only gravitational effects, but still interesting: e.g., it may have hidden charge and be self-interacting through Rutherford scattering

Feng, Kaplinghat, Tu, Yu (2009)



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





Feng, Kumar, Learned, Strigari (2008)

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

CONCLUSIONS

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

- WIMPs → 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