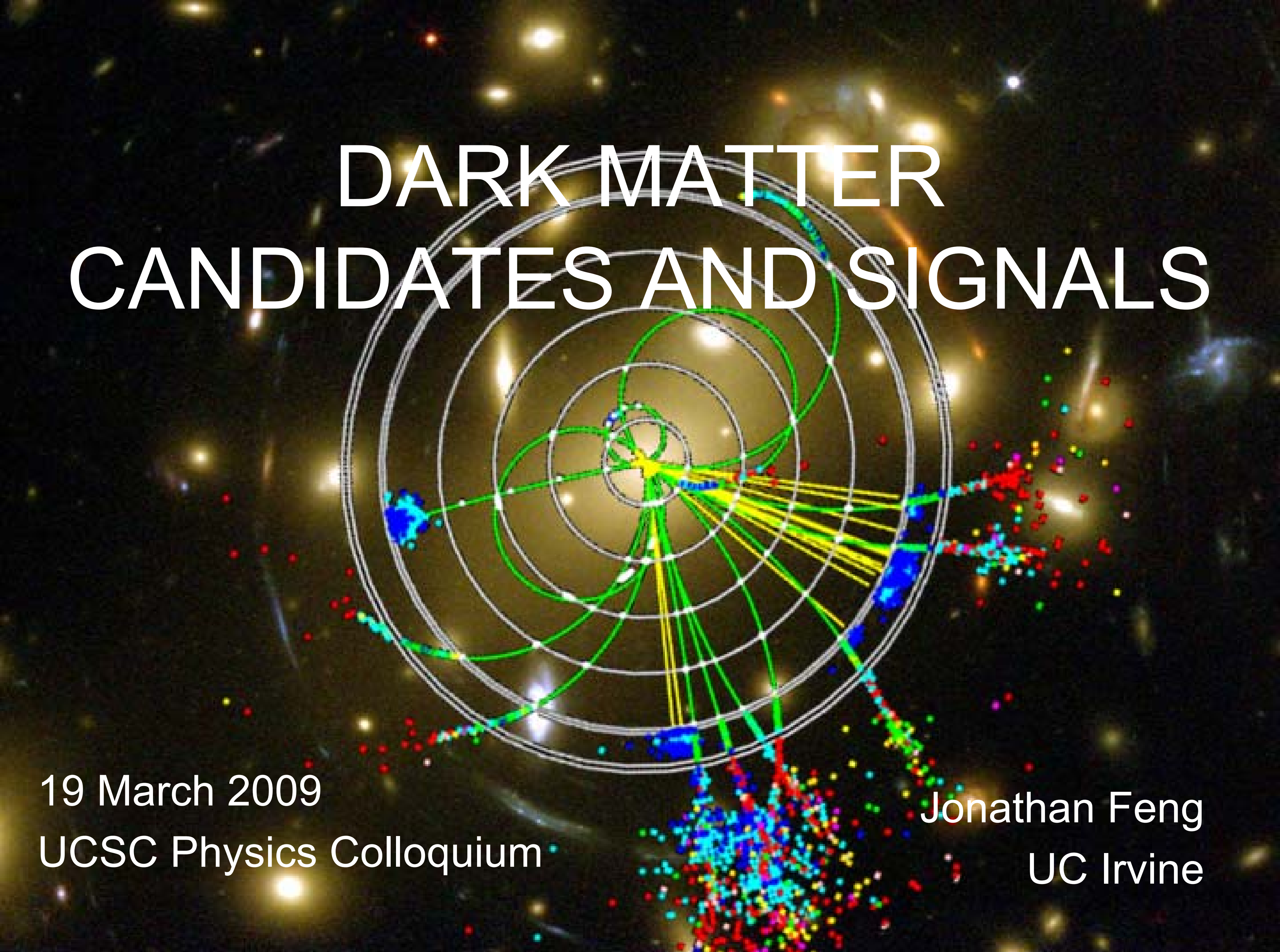


# DARK MATTER CANDIDATES AND SIGNALS

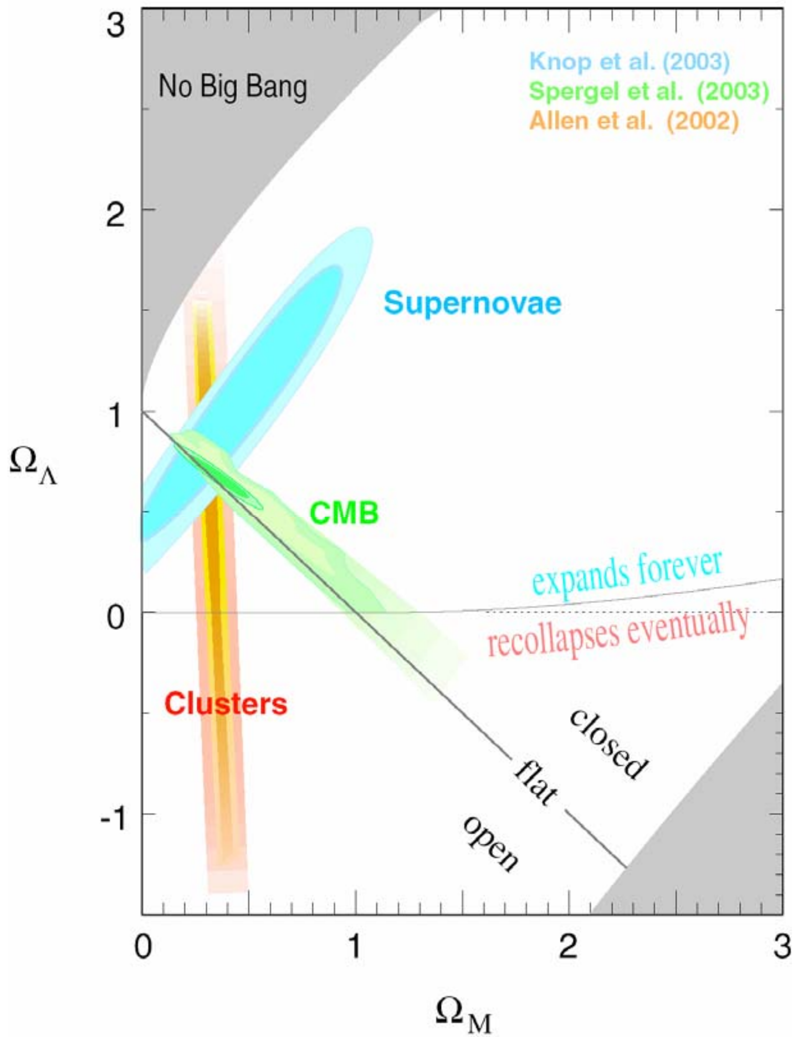
19 March 2009

UCSC Physics Colloquium

Jonathan Feng

UC Irvine

# COSMOLOGY NOW




- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  Neutrinos: 0.2% ($\Sigma m_\nu$/0.1eV)

- Remarkable precision

- Remarkable results

# OPEN QUESTIONS

## DARK MATTER

- Is it a fundamental particle?
- What are its mass and spin?
- How does it interact?
- Is it absolutely stable?
- What is the symmetry origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How and when was it produced?
- Why does $\Omega_{DM}$ have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?

## DARK ENERGY

- What is it?
- Why not $\Omega_\Lambda \sim 10^{120}$?
- Why not $\Omega_\Lambda = 0$?
- Does it evolve?

## BARYONS

- Why not $\Omega_B \approx 0$?
- Related to neutrinos, leptonic CP violation?
- Where are all the baryons?

# THE DARK UNIVERSE

The problems appear to be completely different

## DARK MATTER

- No known particles contribute
- Probably tied to $M_{\text{weak}}$ ~ 100 GeV
- Several compelling solutions

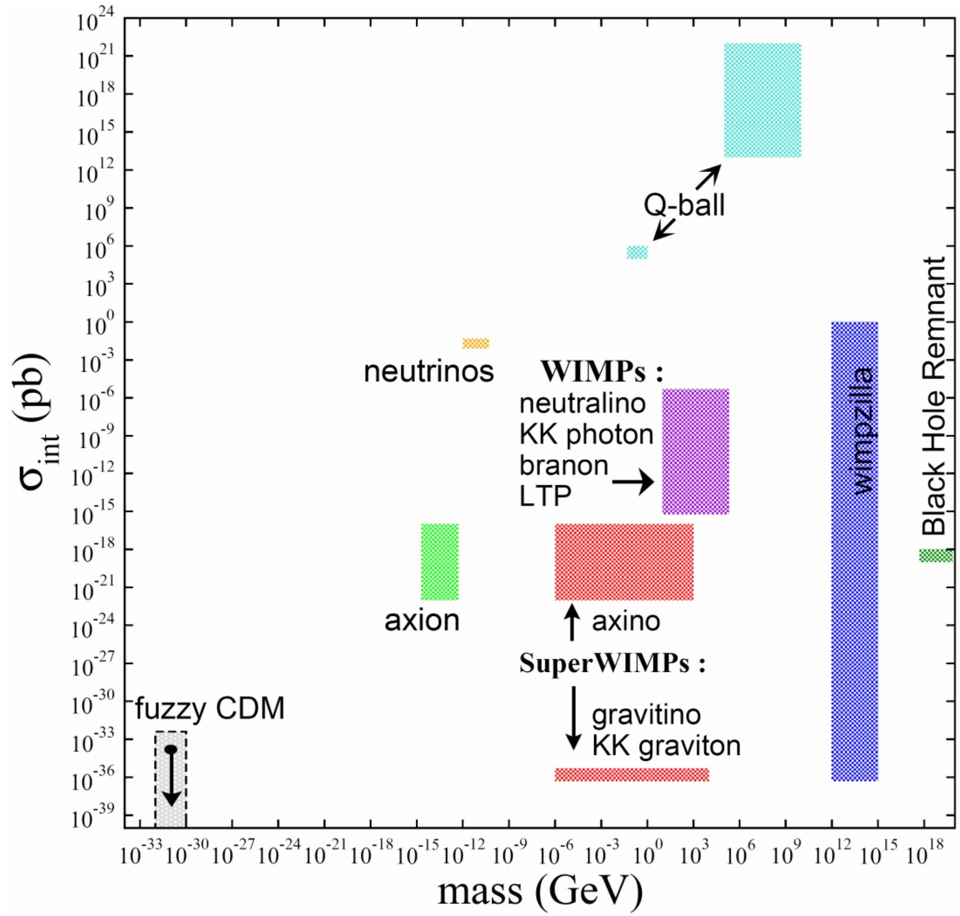
## DARK ENERGY

- All known particles contribute
- Probably tied to $M_{\text{Planck}}$ ~ $10^{19}$ GeV
- No compelling solutions

# DARK MATTER CANDIDATES

- The observational constraints are no match for the creativity of theorists

- Masses and interaction strengths span many, many orders of magnitude, but not all candidates are equally motivated




HEPAP/AAAC DMSAG Subpanel (2007)

# THE WEAK SCALE

- 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"

(1) Assume a new (heavy) particle $\chi$ is initially in thermal equilibrium:

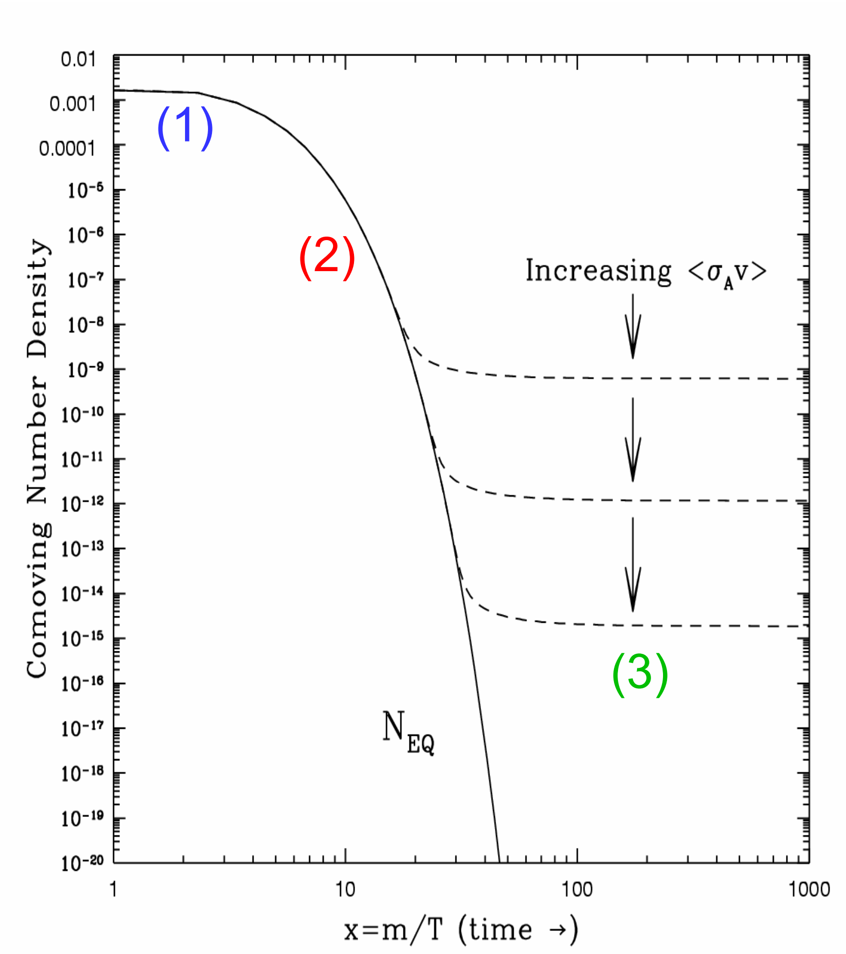
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \;\overset{\rightarrow}{\not\leftarrow}\; \bar{f} f$$

(3) $\chi$s "freeze out":

$$\chi\chi \;\overset{\not\rightarrow}{\not\leftarrow}\; f f$$




Zeldovich et al. (1960s)

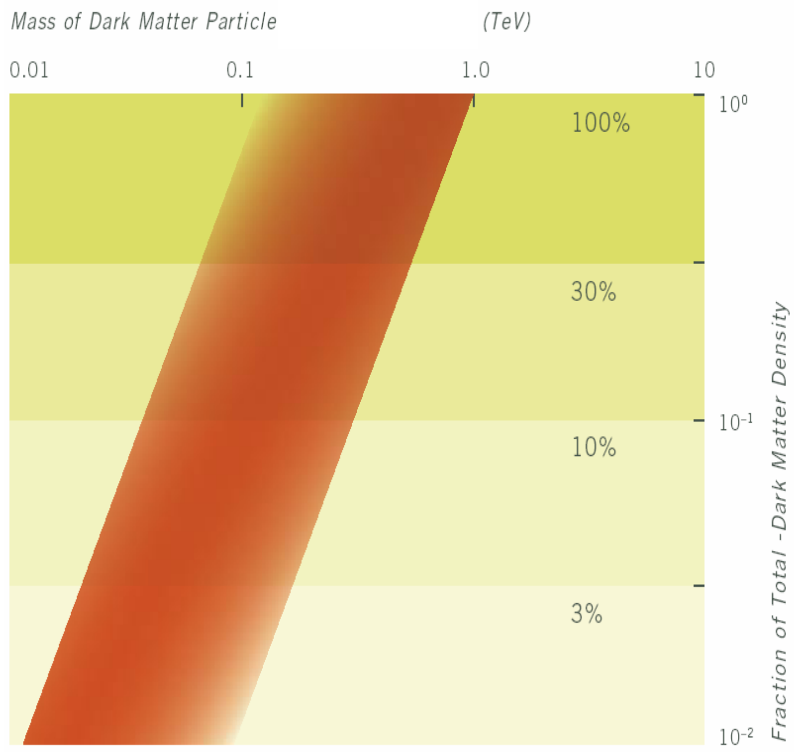
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

- What is the constant of proportionality?

- Impose a natural relation:

$$\sigma_A = k\alpha^2/m^2 \;,\;\; \text{so } \Omega_{DM} \sim m^2$$




HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

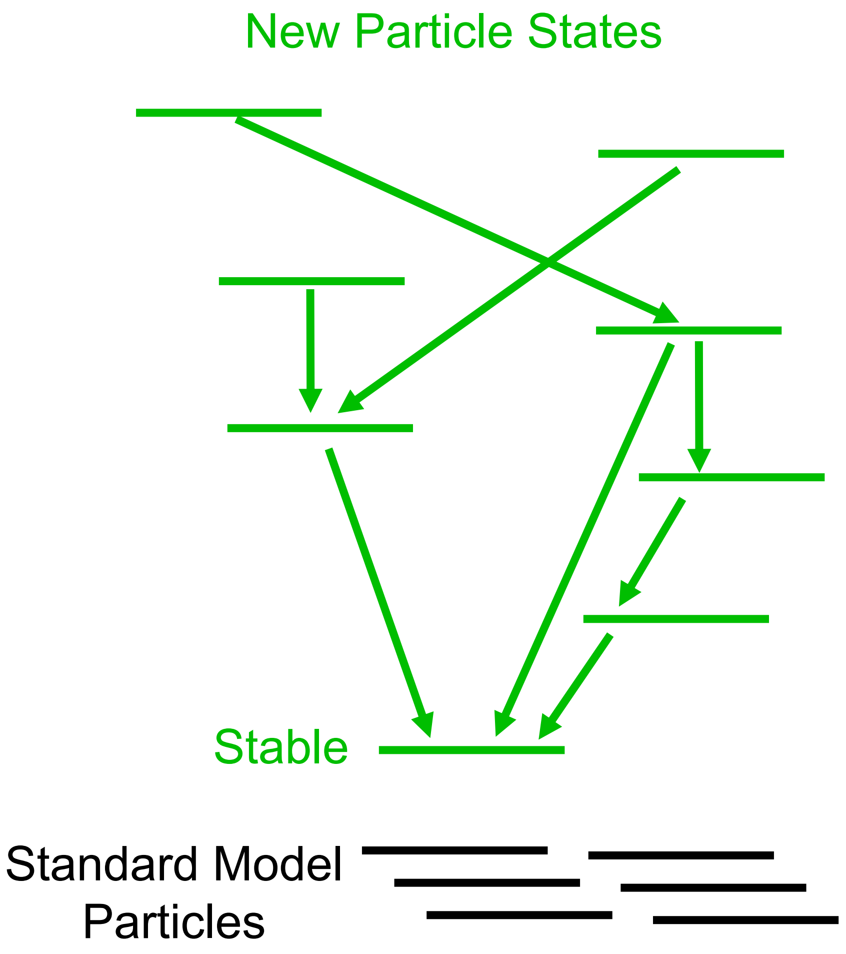
Remarkable "coincidence": $\Omega_{DM} \sim 0.1$ for m ~ 100 GeV – 1 TeV

# STABILITY

- This all assumes the new particle is stable. Why should it be?

- Problems
  ↕
  Discrete symmetry
  ↕
  Stability

- In many theories, dark matter is easier to explain than no dark matter



# WIMPs from Supersymmetry

The classic WIMP: neutralinos predicted by supersymmetry

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

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle $\tilde{X}$

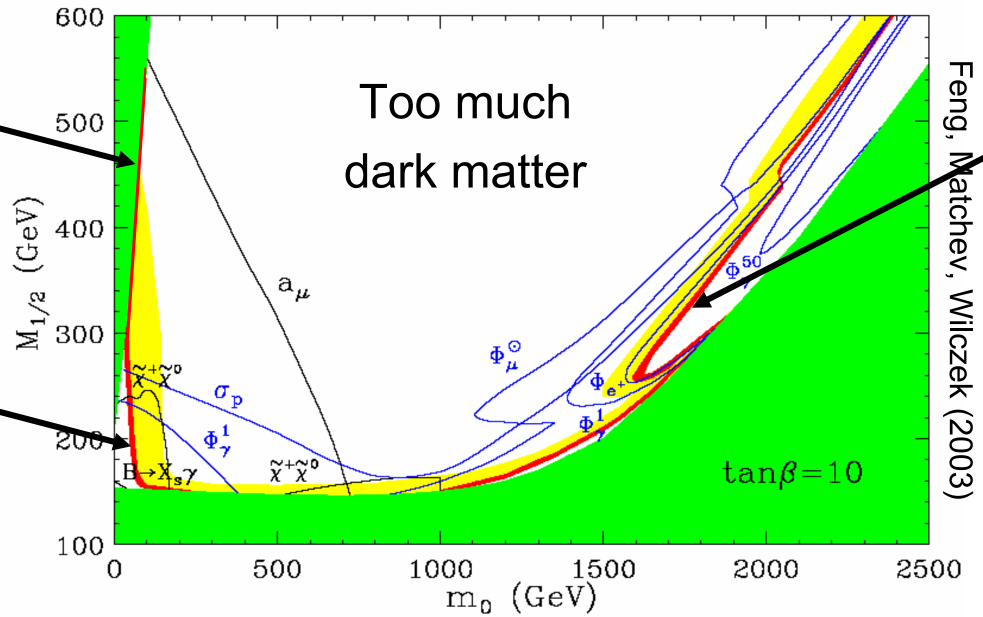
Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}u, \tilde{H}d)$

Particle physics alone → $\chi$ is lightest supersymmetric particle, stable, mass ~ 100 GeV. All the right properties for WIMP dark matter!

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

Co-annihilation region

Bulk region




Focus point region

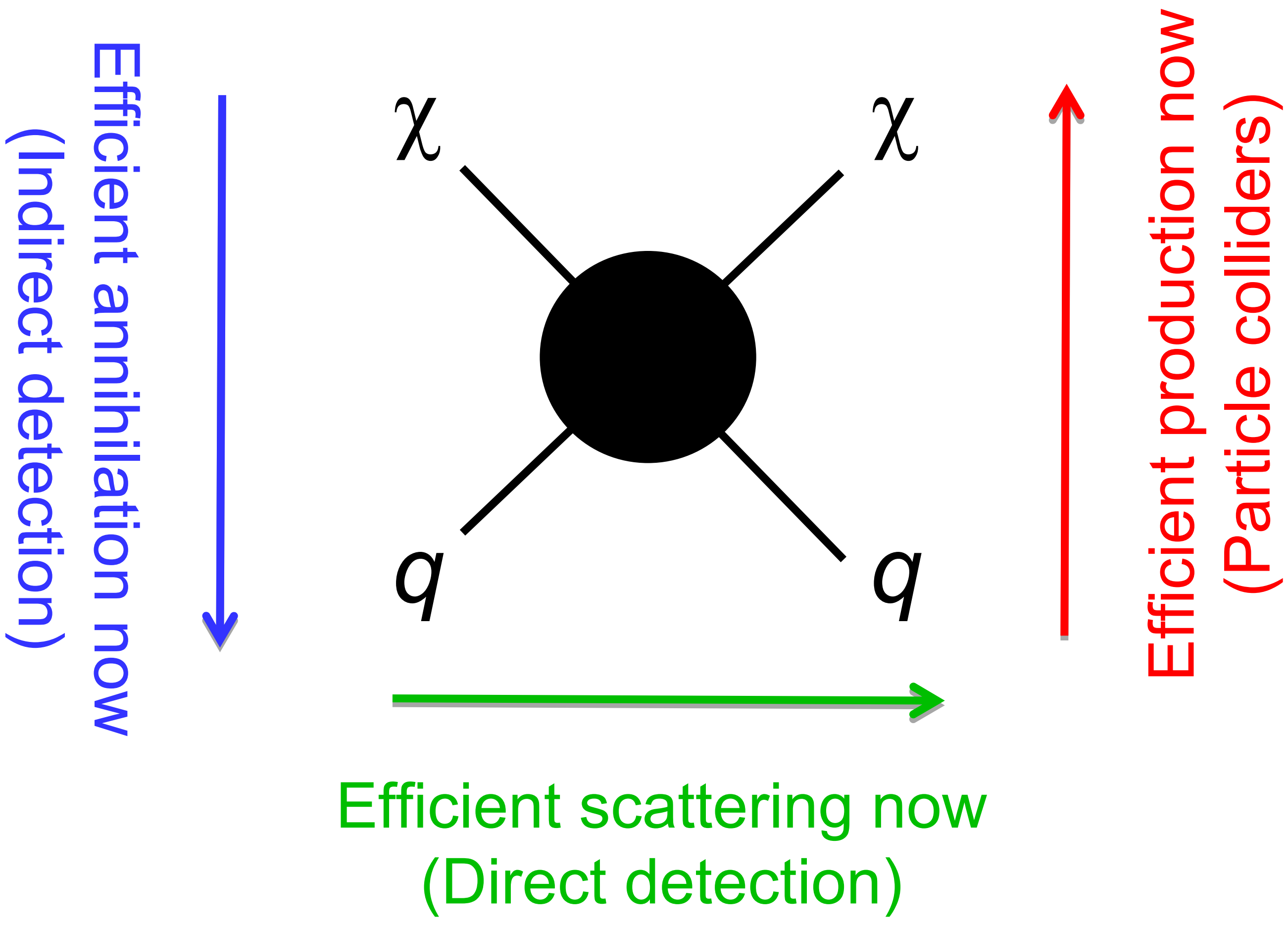
Yellow: pre-WMAP

Red: post-WMAP

Cosmology excludes many possibilities, favors certain regions

# WIMP DETECTION

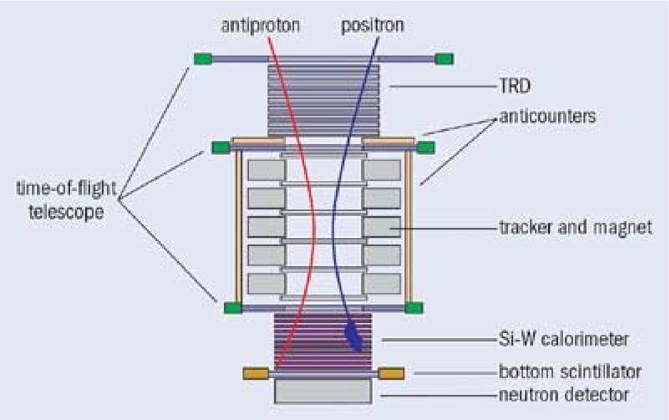
Correct relic density → Efficient annihilation then

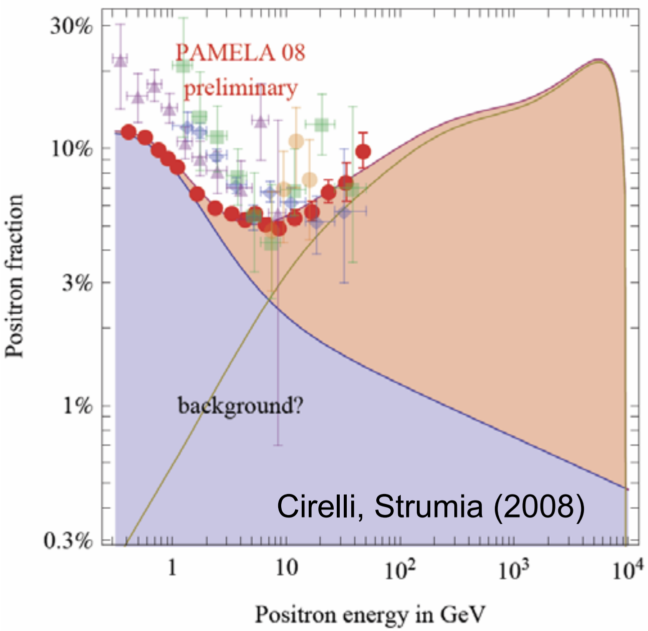


# INDIRECT DETECTION

Dark Matter annihilates in ___the halo___ to
a place

___positrons___ , which are detected by ___PAMELA___.
some particles an experiment

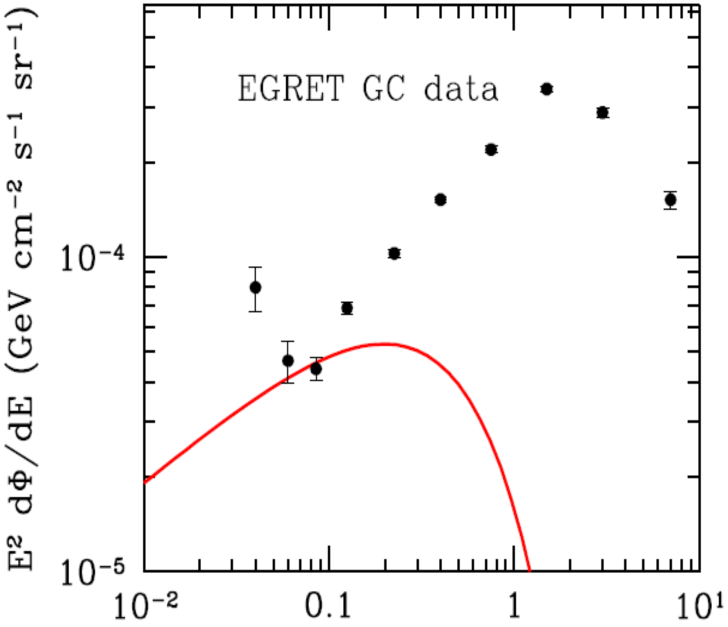



# INDIRECT DETECTION

Dark Matter annihilates in __the Galactic center__ to
a place

__photons__ , which are detected by __FermiGST__ .
some particles an experiment

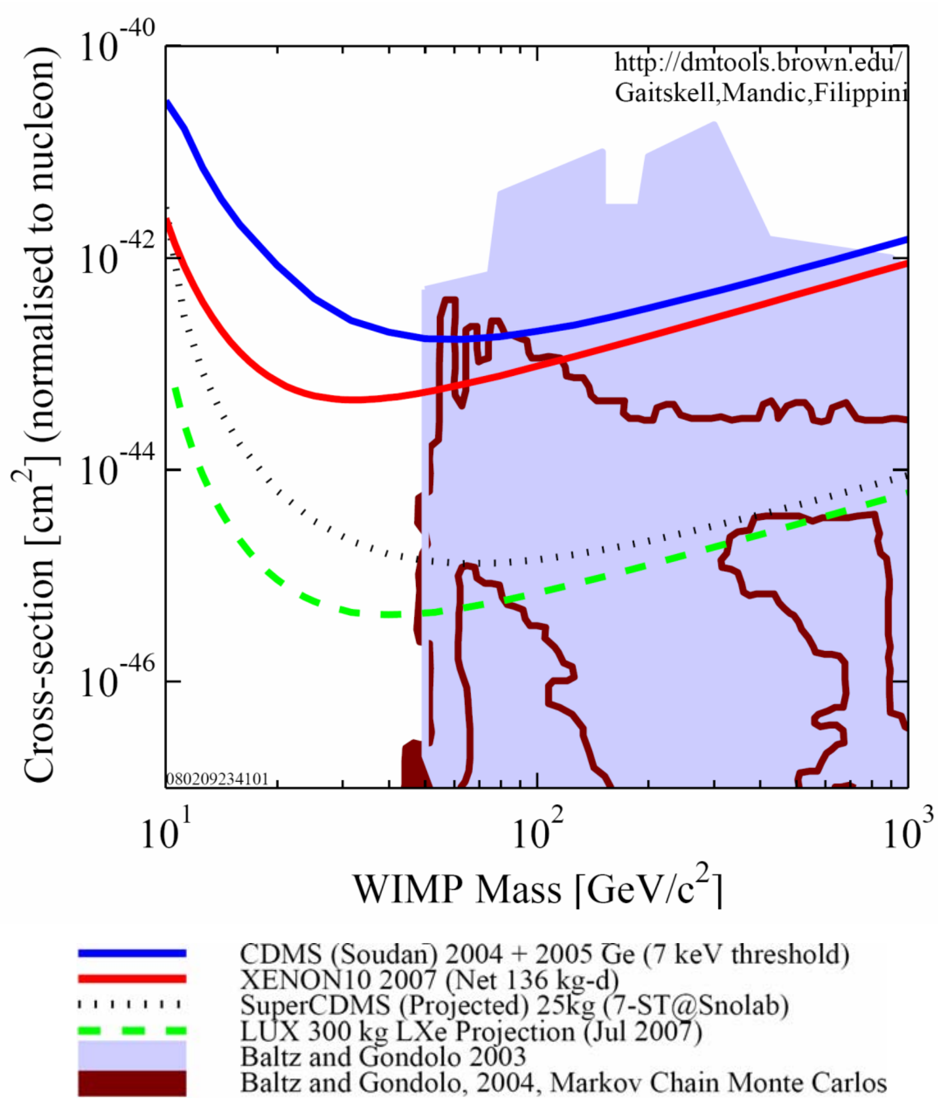
# DIRECT DETECTION

- WIMP properties:
  v ~ $10^{-3}$ c
  Kinetic energy ~ 100 keV
  Local density ~ 1 / liter

- Detected by recoils off ultra-sensitive underground detectors

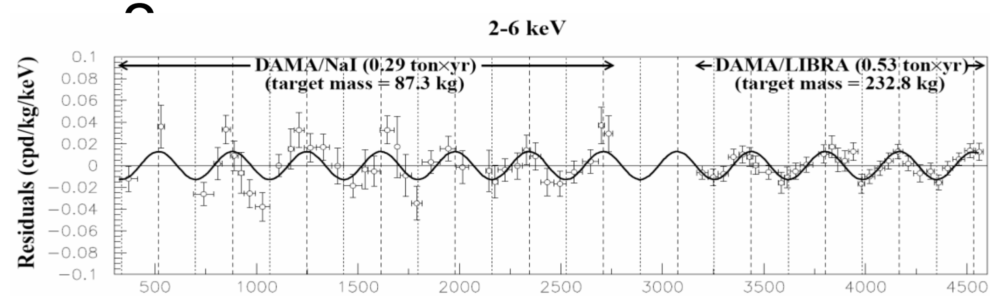
- DAMA has reported a signal in annual modulation

- Theory predictions vary, but many models→ $10^{-44}$ cm

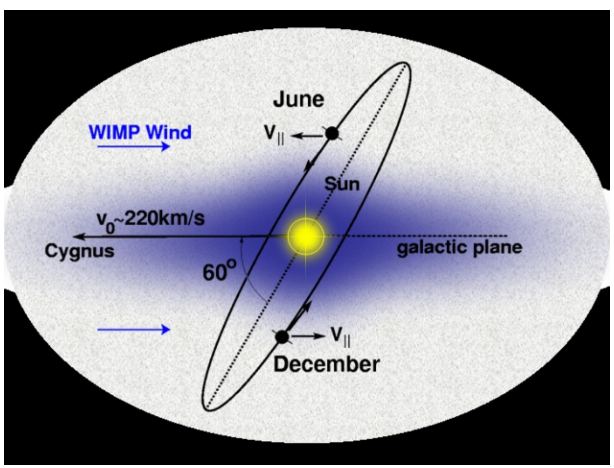


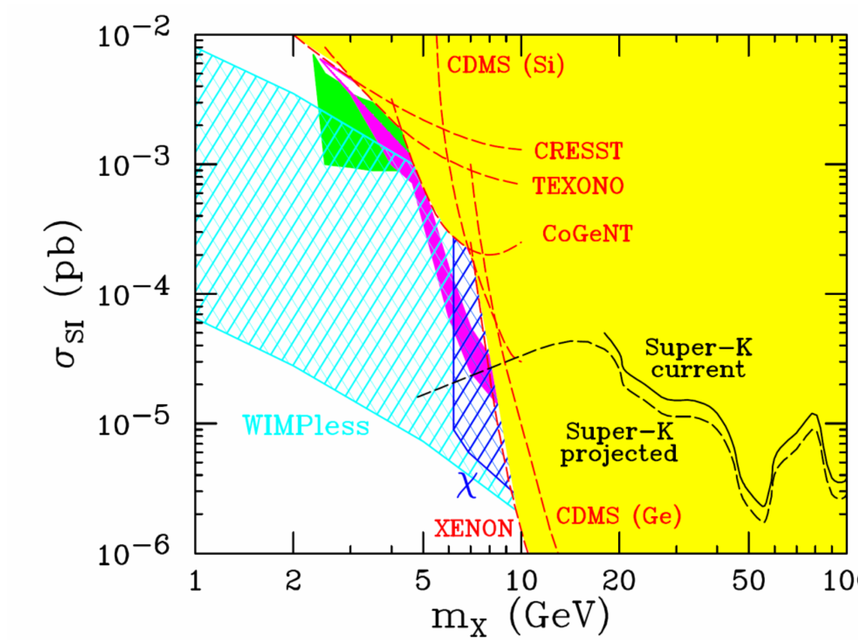
# DIRECT DETECTION: DAMA

$8\sigma$ signal for annual modulation with T ~ 1 year, max ~ June 2



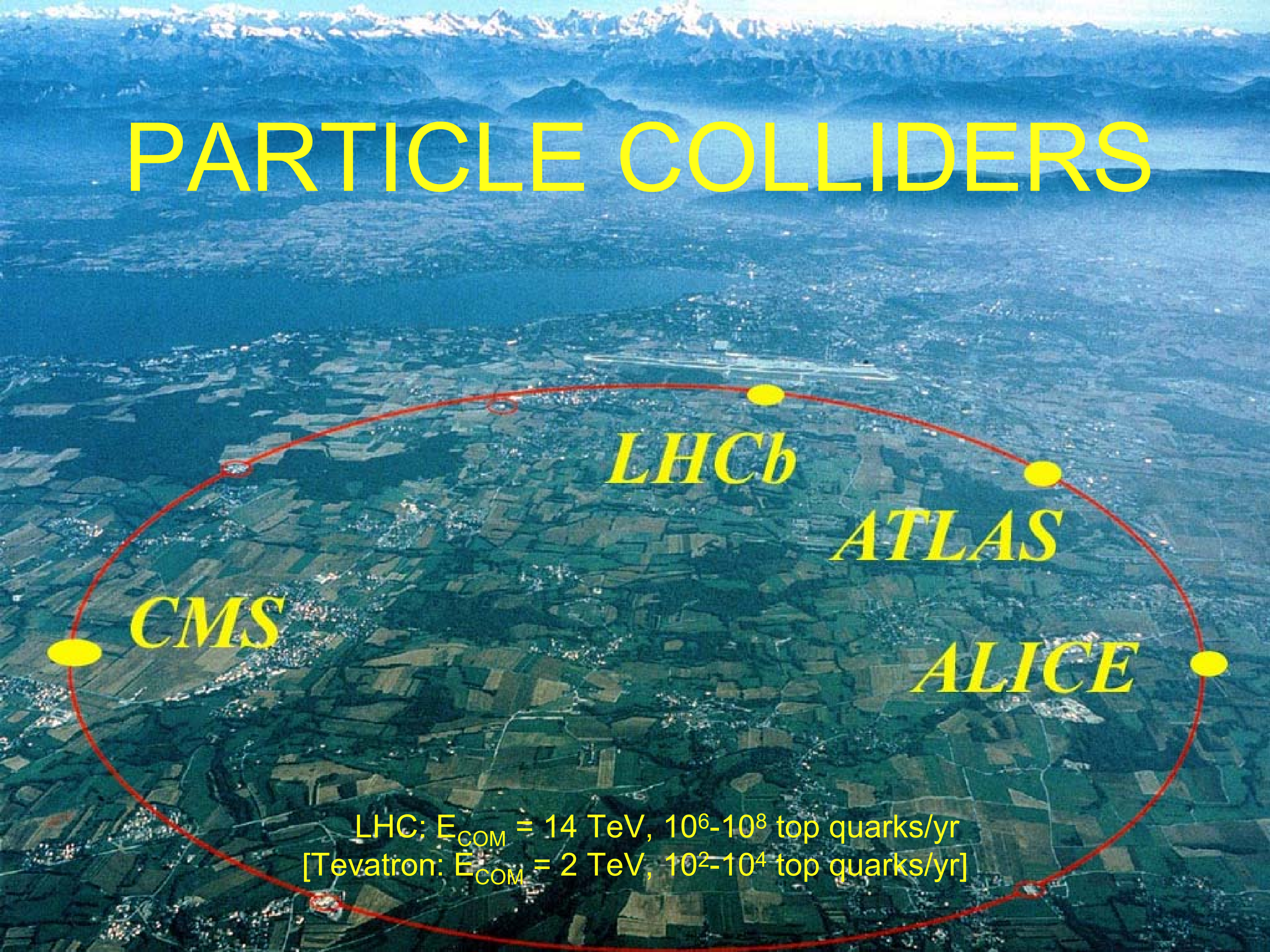

DAMA Collaboration (2008)




Hooper, Petriello, Zurek, Kamionkowski (2008)
Feng, Kumar, Learned, Strigari (2008); many others

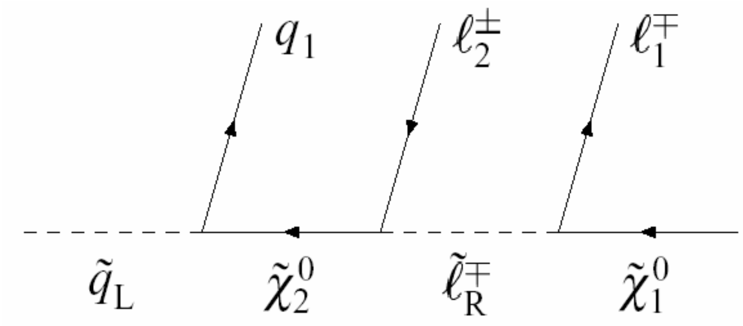
# PARTICLE COLLIDERS

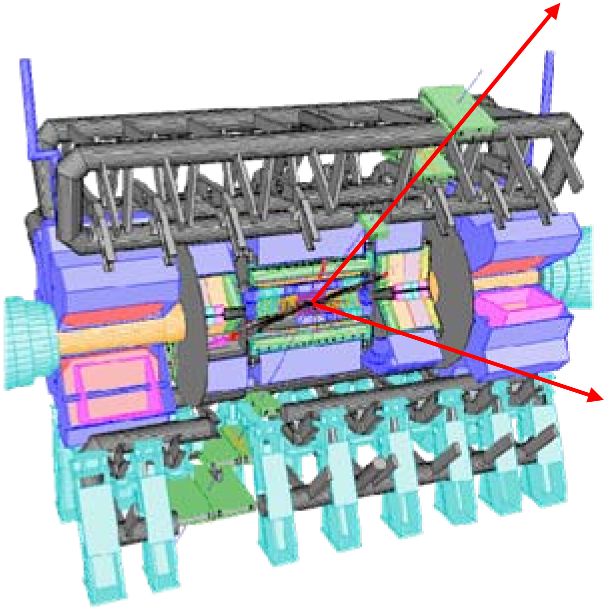



LHC: $E_{COM}$ = 14 TeV, $10^6$-$10^8$ top quarks/yr
[Tevatron: $E_{COM}$ = 2 TeV, $10^2$-$10^4$ top quarks/yr]

# WHAT THEN?

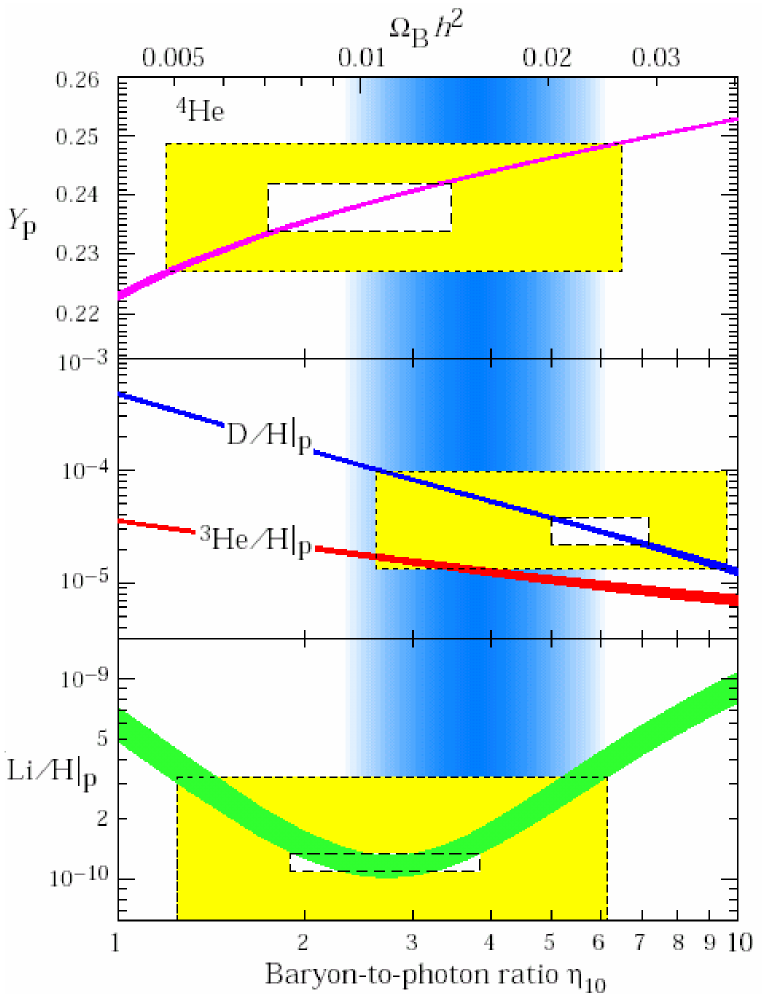
- What LHC actually sees:
  - E.g., $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q}$ → neutralino $\chi$
  - 2 $\chi$'s escape detector
  - missing momentum



- This is not the discovery of dark matter
  - Lifetime > $10^{-7}$ s → $10^{17}$ s?

# THE EXAMPLE OF BBN

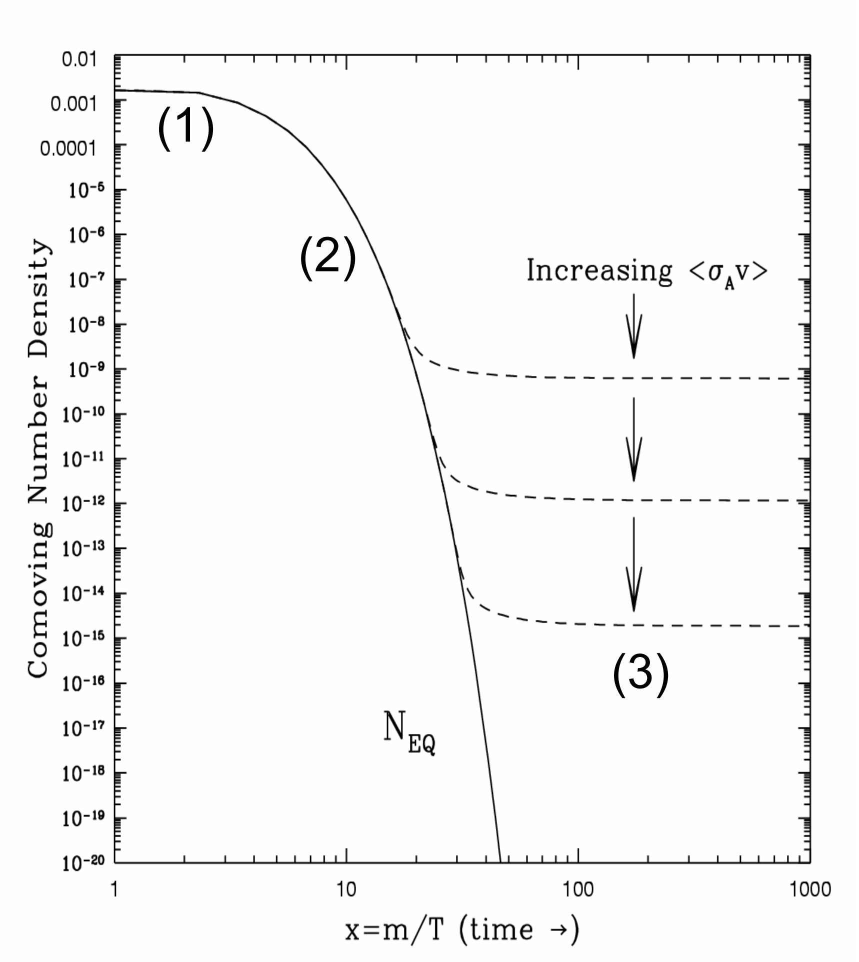



- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

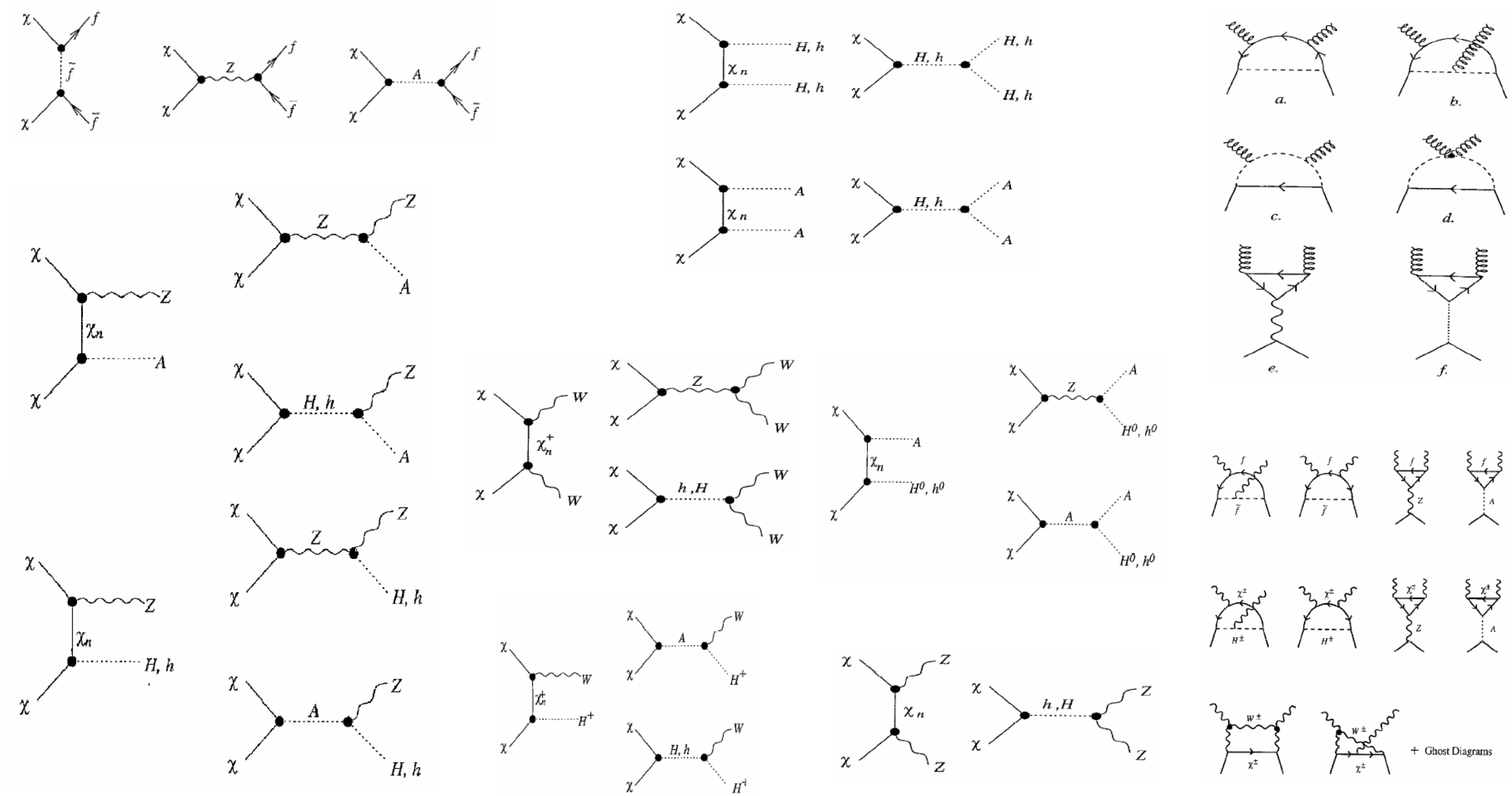
  t ~ 1 sec

# DARK MATTER ANALOGUE




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

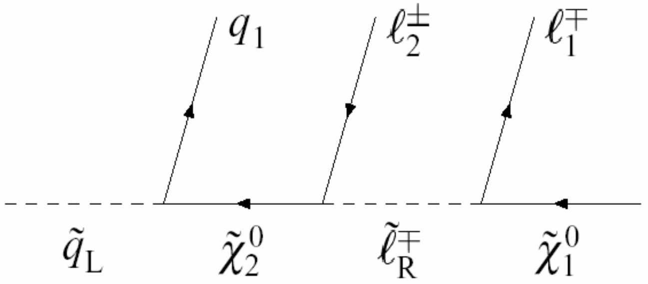
# Contributions to Neutralino WIMP Annihilation



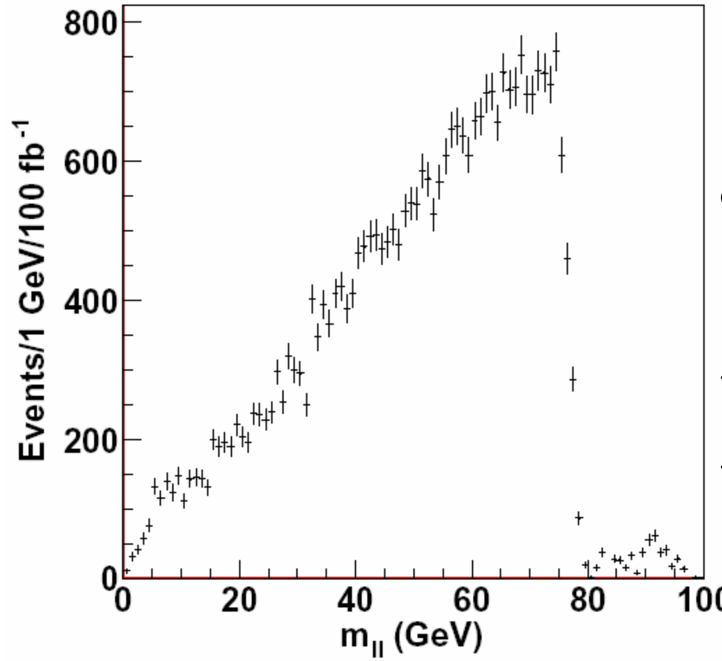

Jungman, Kamionkowski, Griest (1995)

# PRECISION SUSY @ LHC

- Masses can be measured by reconstructing the decay chains

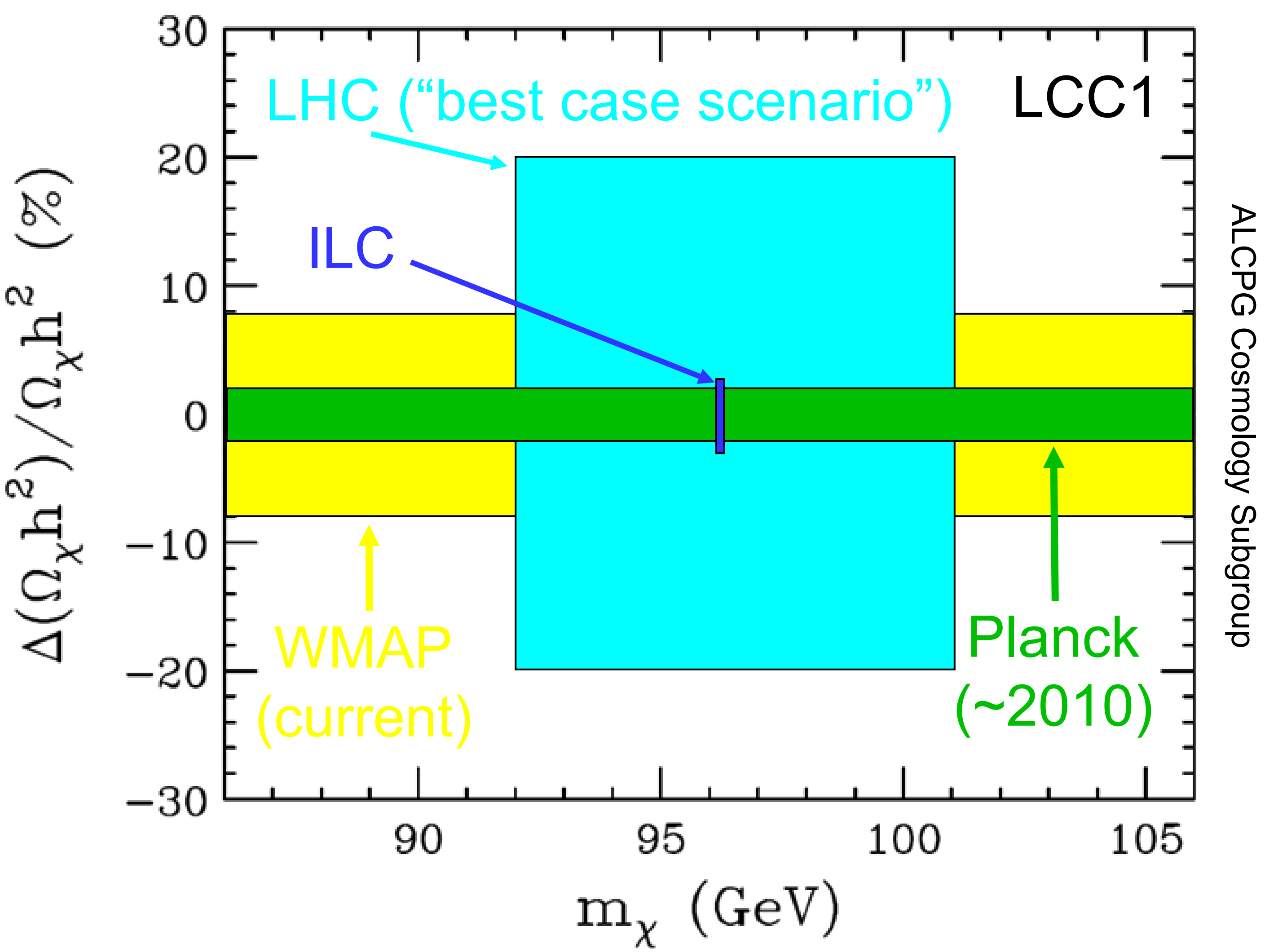



$$
\begin{aligned}
\left(m_{ll}^2\right)^{\rm edge} &= \frac{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\rm edge} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)^{\rm edge}_{\rm min} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)^{\rm edge}_{\rm max} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\rm thres} &= [(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2) \\
&\quad -(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)\sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{\tilde{l}_R}^2)^2(m_{\tilde{l}_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16 m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}_R}^4 m_{\tilde{\chi}_1^0}^2} \\
&\quad +2m_{\tilde{l}_R}^2(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)]/(4m_{\tilde{l}_R}^2 m_{\tilde{\chi}_2^0}^2)
\end{aligned}
$$



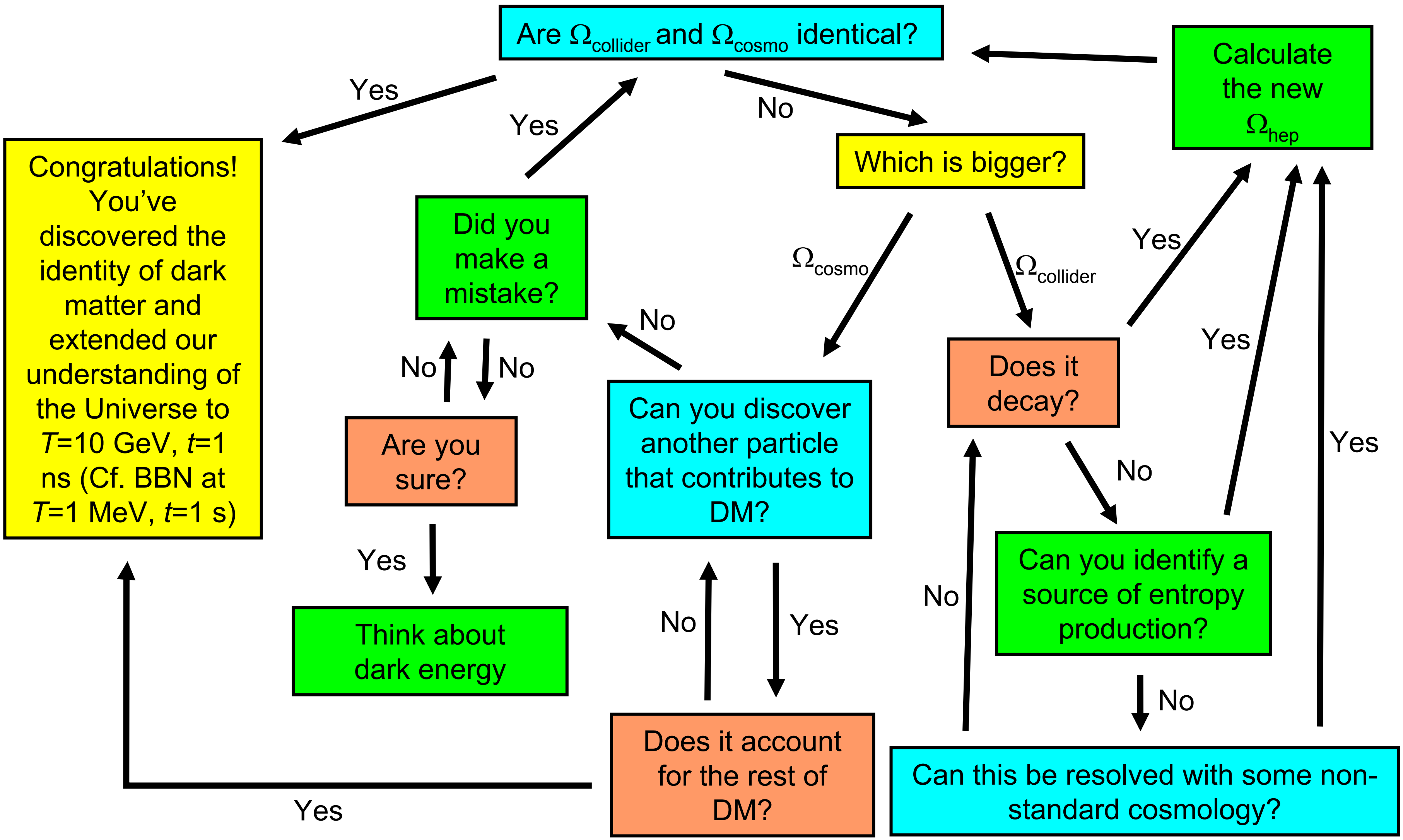

Weiglein et al. (2004)

# RELIC DENSITY DETERMINATIONS




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

# IDENTIFYING DARK MATTER



# TAKING STOCK

- WIMPs are astrophysically identical
  - Weakly-interacting
  - Cold
  - Stable

- Is this true of all DM candidates?

- No.  But is this true of all DM candidates independently motivated by particle physics and the “WIMP miracle”?

- No!  SuperWIMPs, WIMPless dark matter: identical motivations, but qualitatively different implications

# SUPERWIMPS: BASIC IDEA

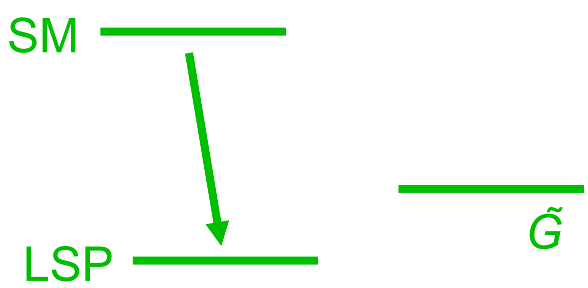
Feng, Rajaraman, Takayama (2003)

Supersymmetry: Graviton → Gravitino $\tilde{G}$

Pagels, Primack (1982)

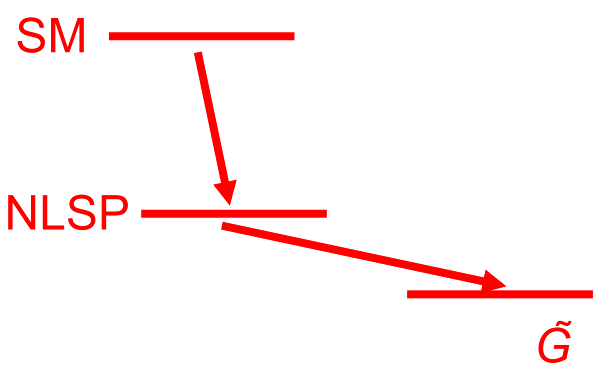
Mass ~ 100 GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP



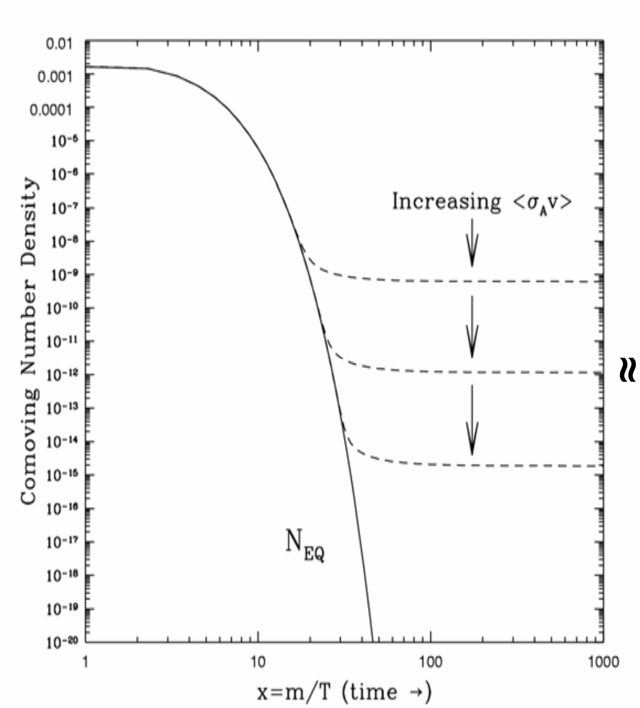

- Assumption of most of literature

- $\tilde{G}$ LSP




- Completely different cosmology and particle physics

# SUPERWIMP RELICS




- Suppose gravitinos $\tilde{G}$ are the LSP

- WIMPs freeze out as usual

WIMP → $\tilde{G}$

- But then all WIMPs decay to gravitinos after

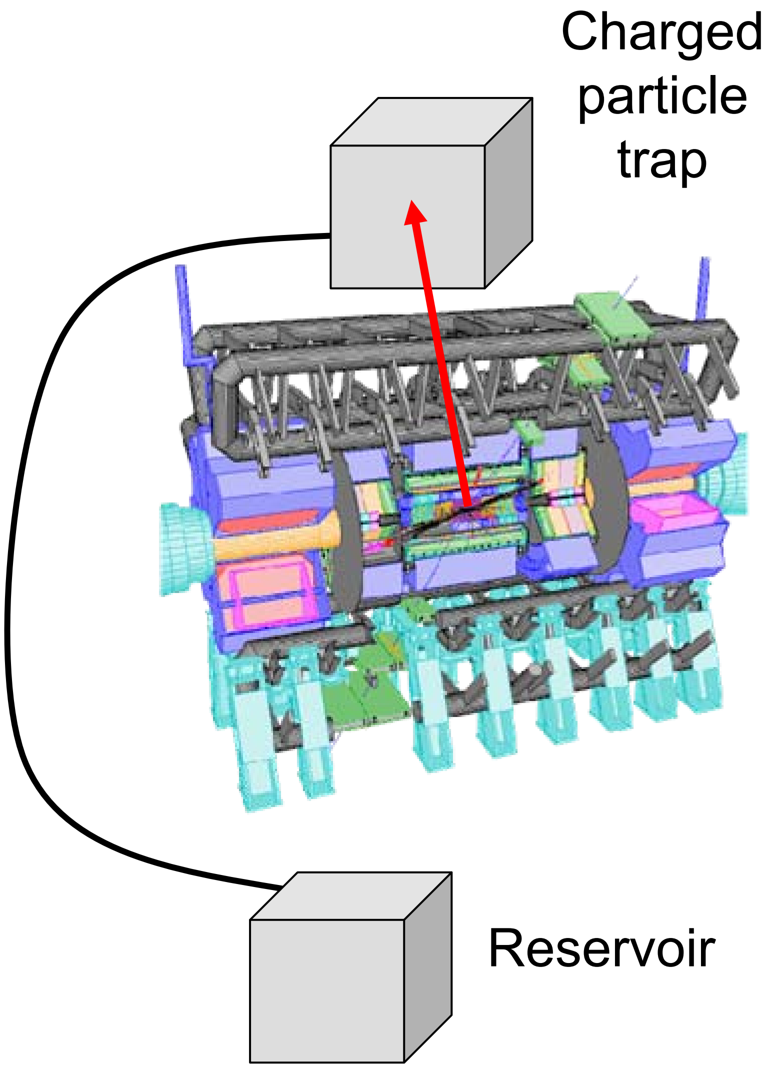
  $M_{Pl}^2/M_W^3$ ~ seconds to months

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); …

# Charged Particle Trapping

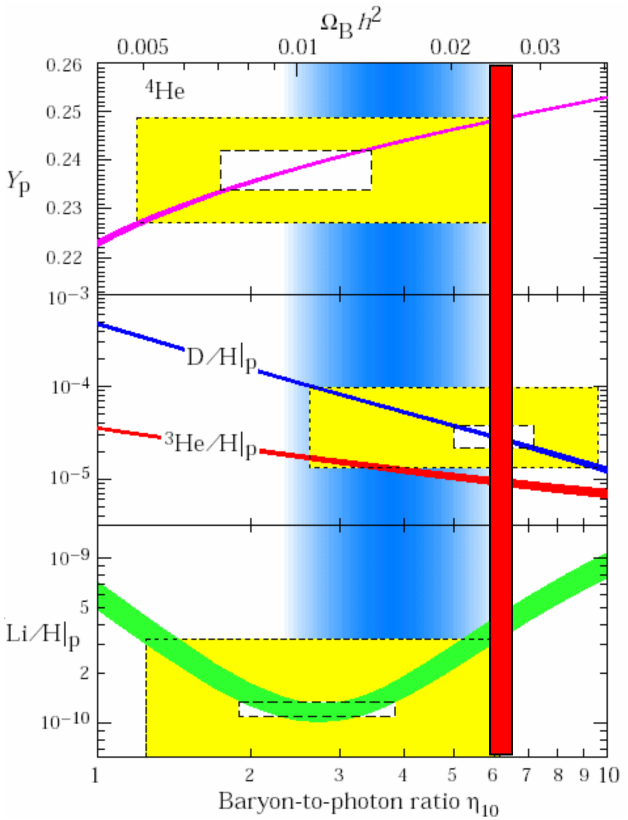
- SuperWIMPs are produced by decays of metastable particles. These can be charged.
- Charged metastable particles will be obvious at colliders, can be trapped and moved to a quiet environment to study their decays.
- Can catch 1000 per year in a 1m thick water tank




Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)

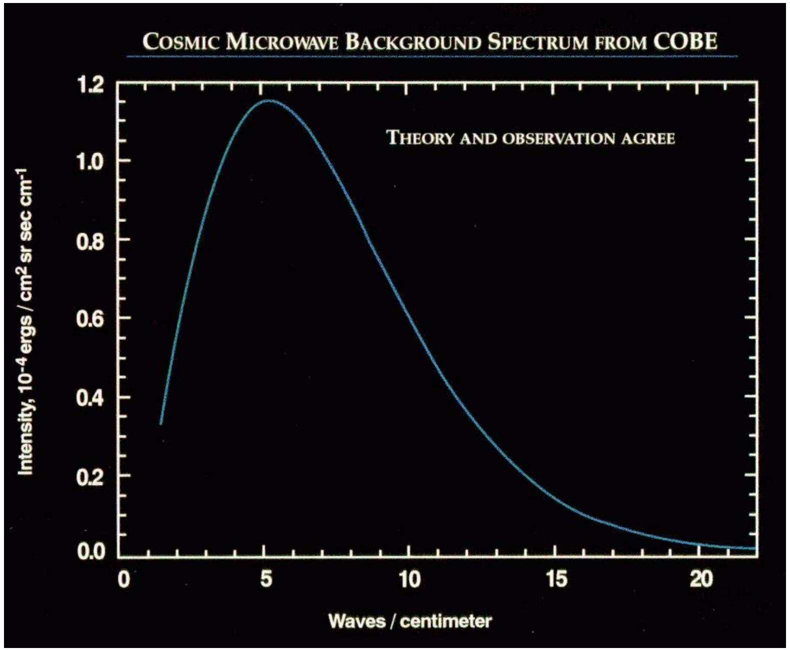
# SUPERWIMP COSMOLOGY

Late decays can modify BBN
(Resolve $^{6,7}$Li problems?)




Fields, Sarkar, PDG (2002)

Late decays can modify CMB
black body spectrum
($\mu$ distortions)




Fixsen *et al.* (1996)

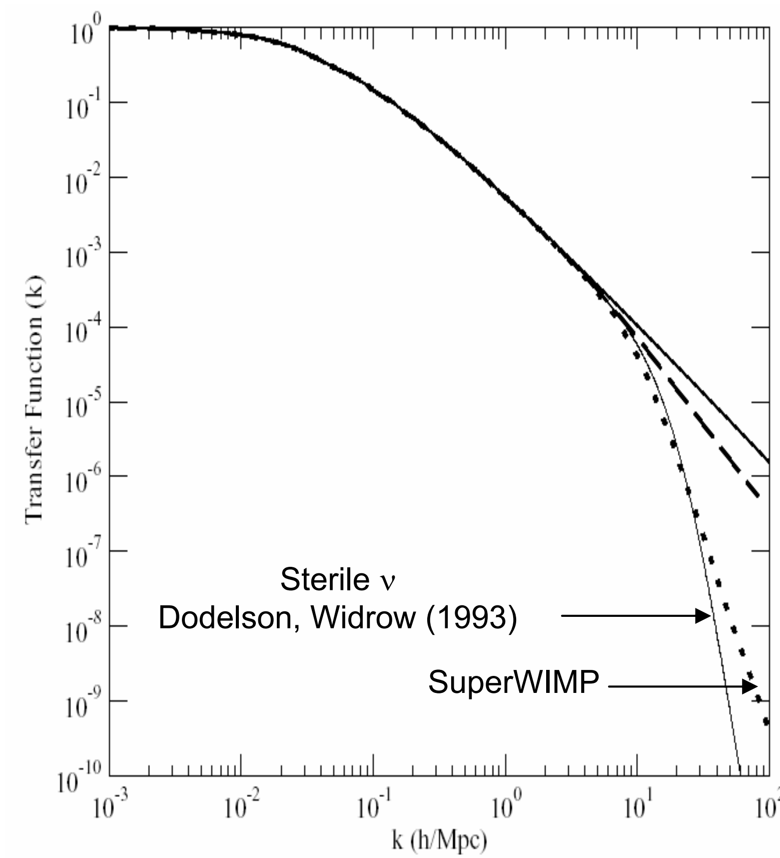
# SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)

- Suppresses small scale structure, as determined by $\lambda_{FS}$, 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)

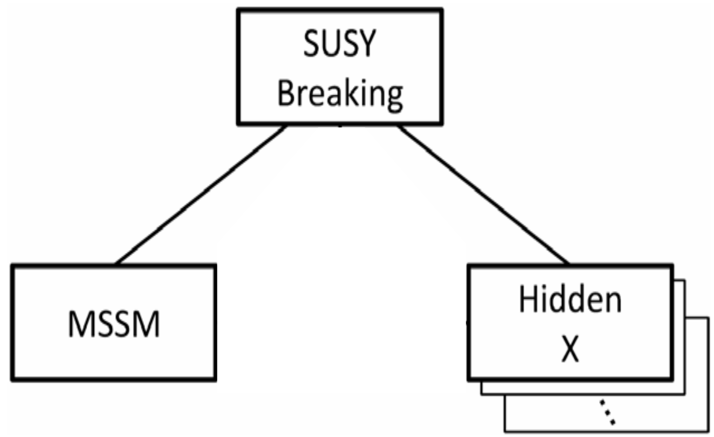



Kaplinghat (2005)

# WIMPLESS DARK MATTER

Feng, Kumar (2008)

- Suppose there are additional “hidden” sectors linked to the same SUSY breaking sector




- These sectors may have different
  - masses $m_X$
  - gauge couplings $g_X$

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

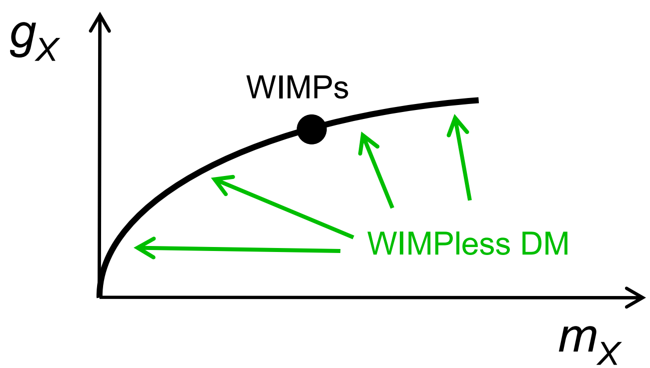
- But $m_X/g_X^2 \sim \Omega_X \sim$ constant

# THE WIMPLESS MIRACLE

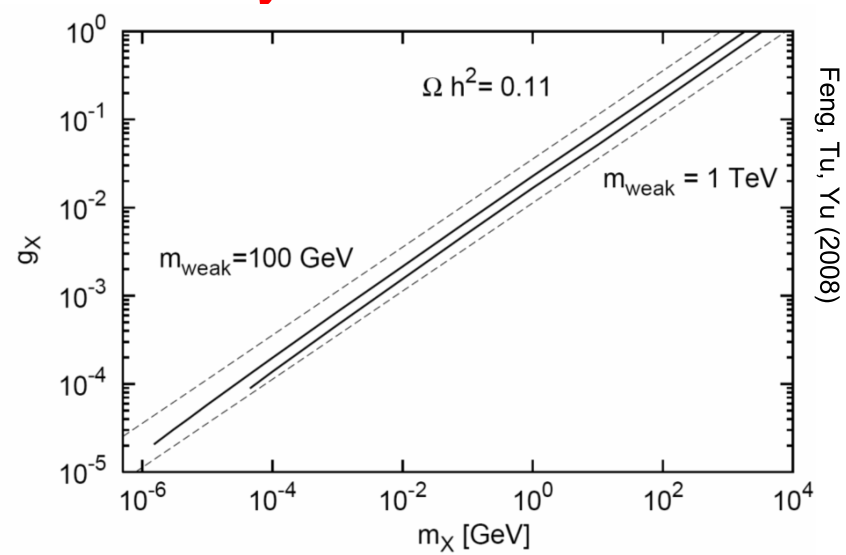
- The thermal relic density constrains only one combination of $g_X$ and $m_X$

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

- These models map out the remaining degree of freedom




- This framework decouples the WIMP miracle from WIMPs, candidates have a range of masses/couplings, but always the right relic density



# CONCLUSIONS

- Particle Dark Matter
  - Central topic at the interface of cosmology and particles
  - Both cosmology and particle physics → weak scale ~ 100 GeV
- Candidates
  - WIMPs: Many well-motivated candidates
  - SuperWIMPs, WIMPless dark matter: Qualitatively new possibilities (warm, only gravitationally interacting)
  - Many others
- LHC collisions begin in 2009, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed soon