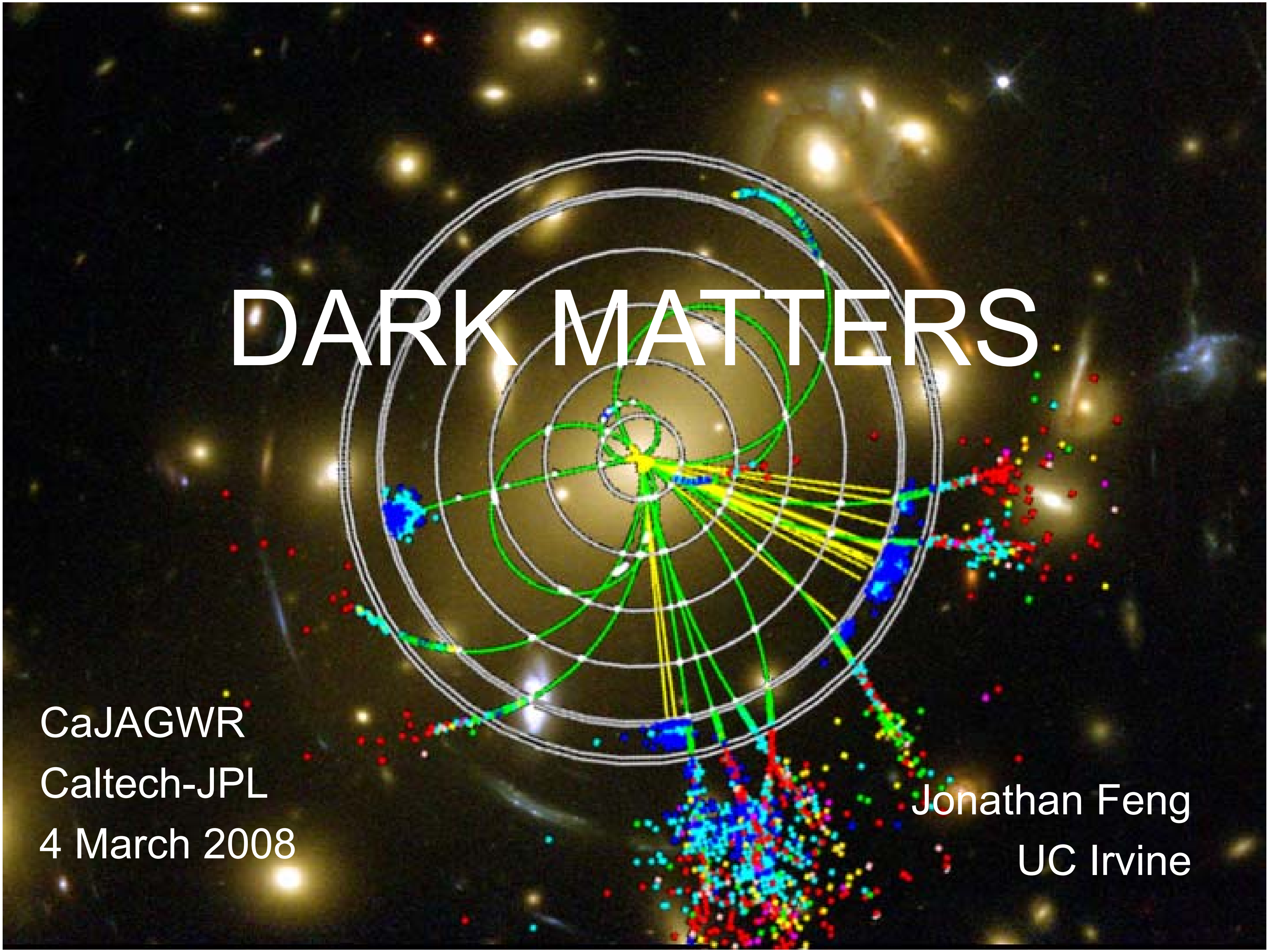
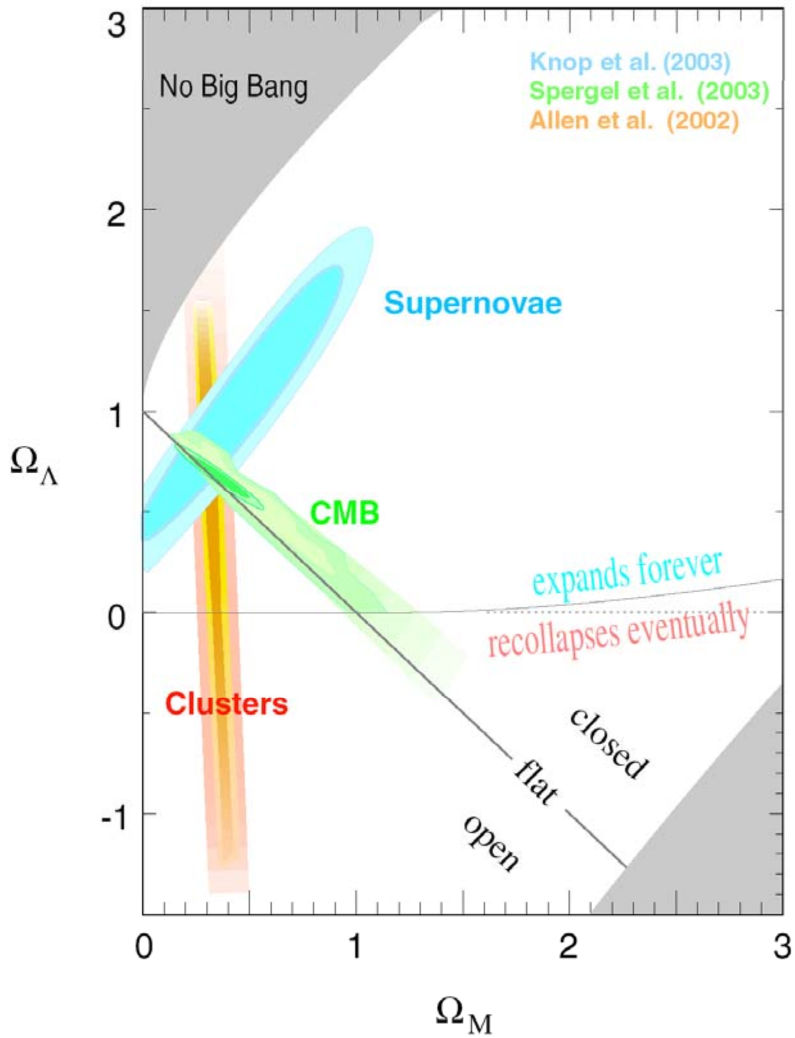

DARK MATTERS
CaJAGWR
Caltech-JPL
4 March 2008
Jonathan Feng
UC Irvine

COSMOLOGY NOW



- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  Neutrinos: 0.2% (Σm_ν/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 Ω_{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

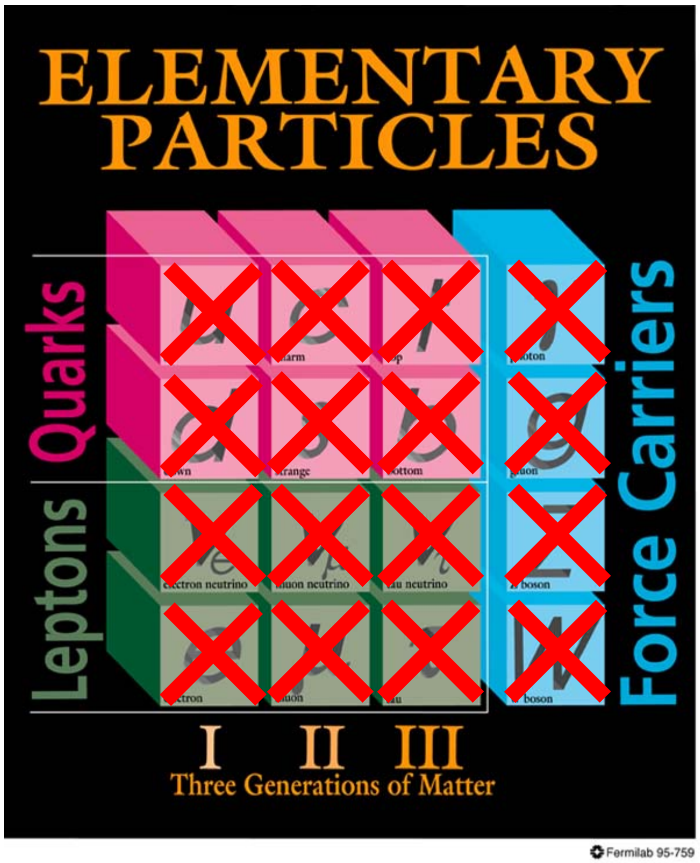
DARK MATTER

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

DARK ENERGY

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

DARK MATTER



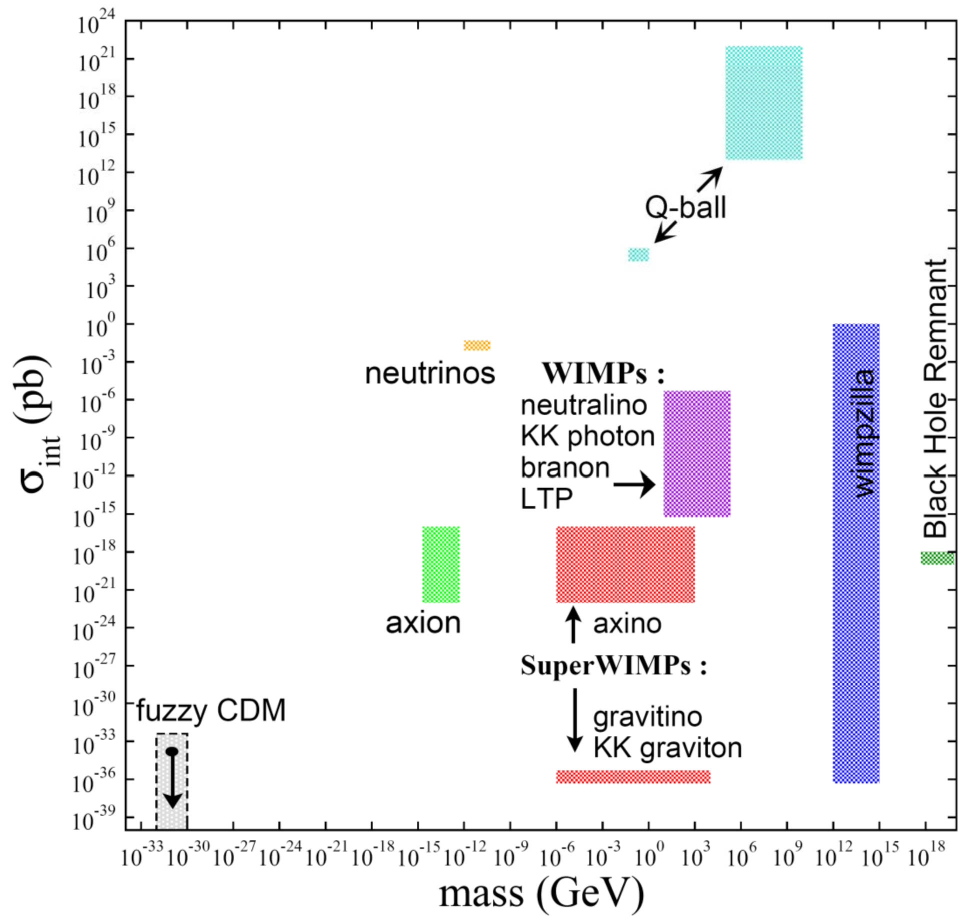
Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new physics

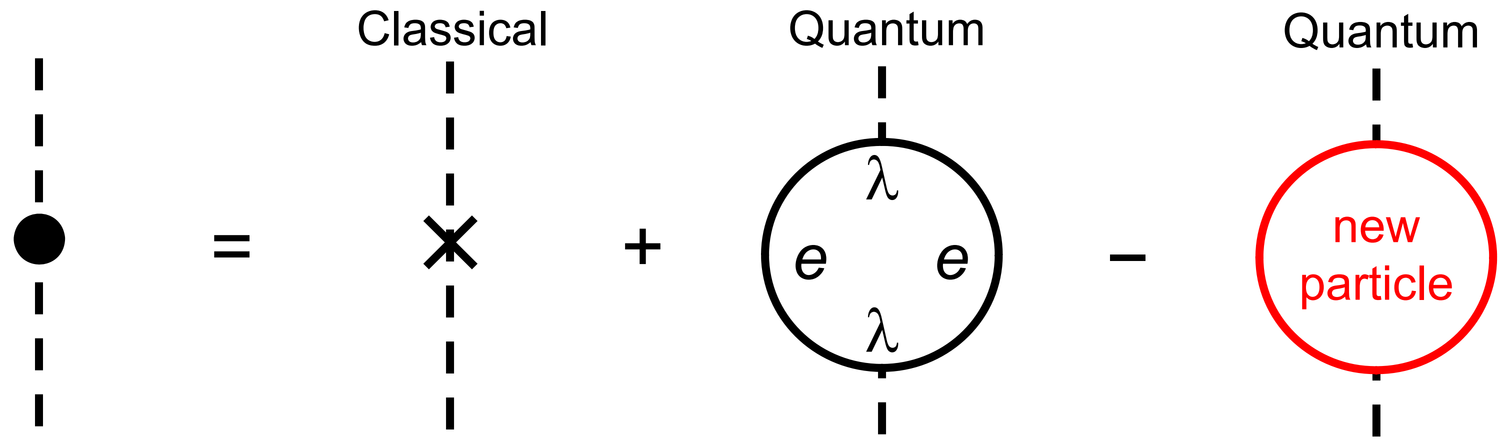
DARK MATTER CANDIDATES

- 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)

NEW PARTICLES AND NATURALNESS



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

$m_h \sim 100$ GeV, $\Lambda \sim 10^{19}$ GeV → cancellation of 1 part in 10^{34}

At ~ 100 GeV we expect new particles:
supersymmetry, extra dimensions, something!

THE "WIMP MIRACLE"

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

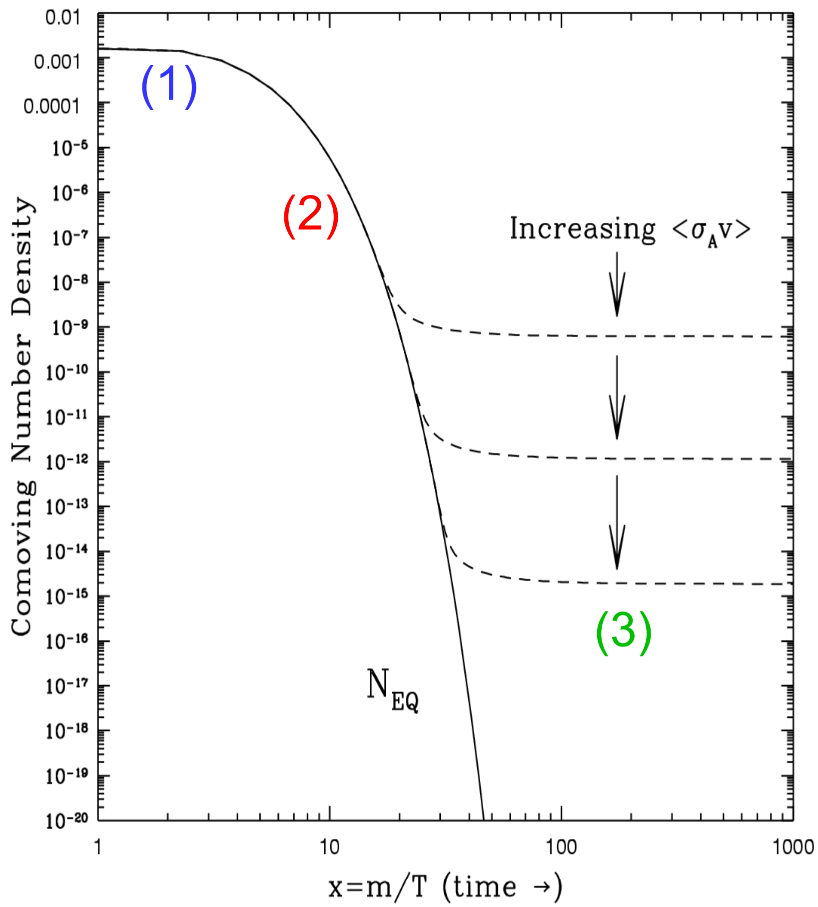
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \rightleftarrows\!\!\!\!\!\!/\;\; \bar{f} f$$

(3) χs "freeze out":

$$\chi\chi \;\not\rightleftarrows\; \bar{f} f$$



Zeldovich et al. (1960s)

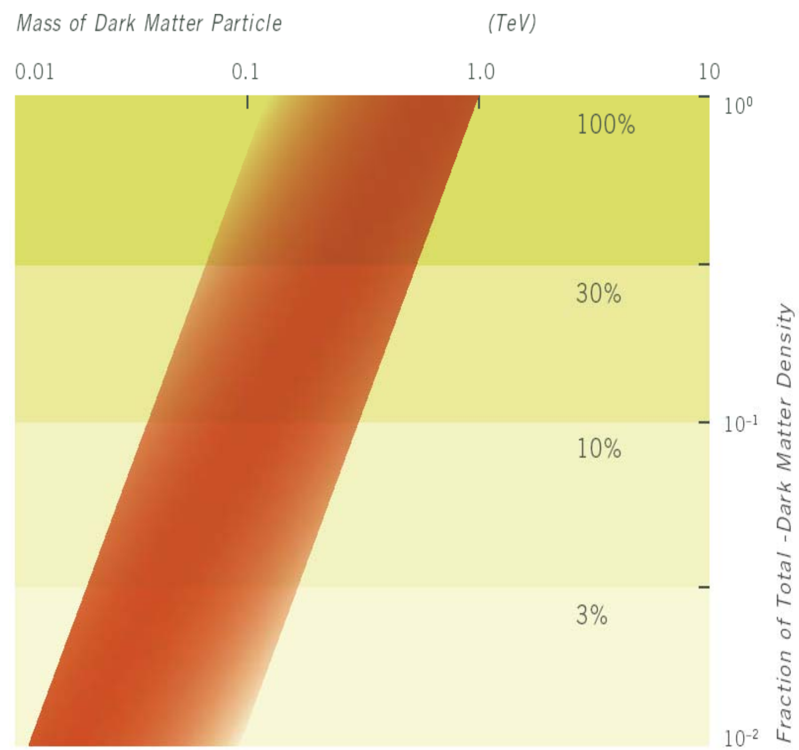
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

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

- What is the constant of proportionality?

- Impose a natural relation:

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



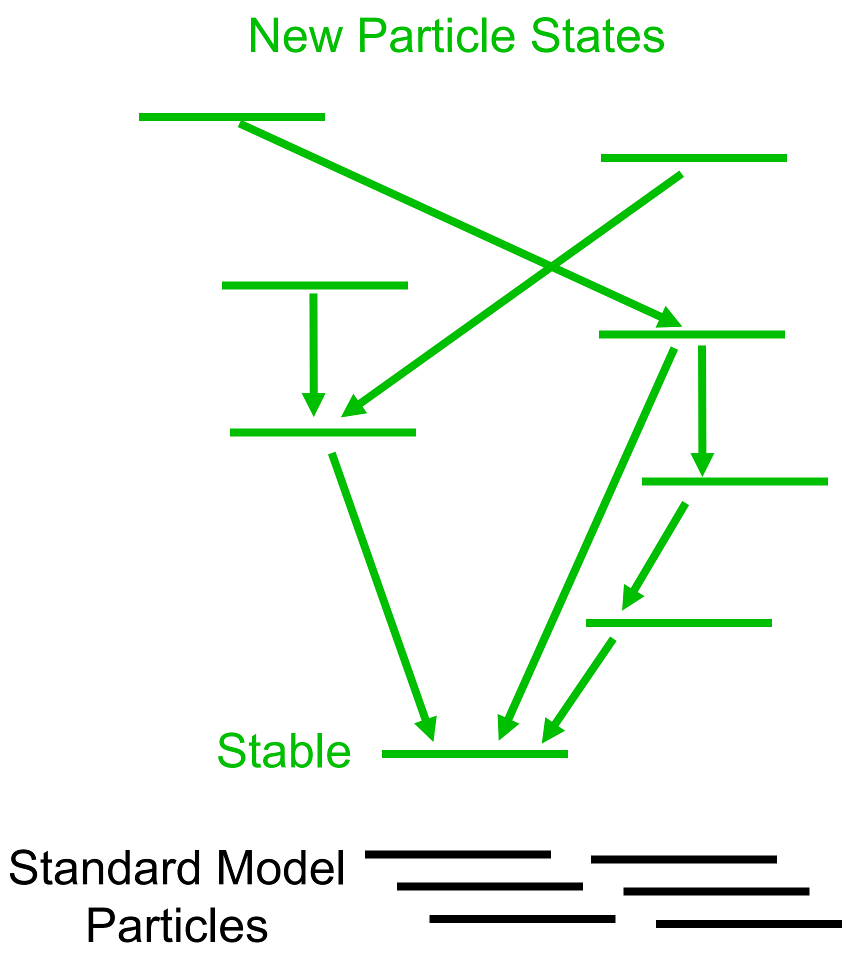
HEPAP LHC/ILC Subpanel (2006)

[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

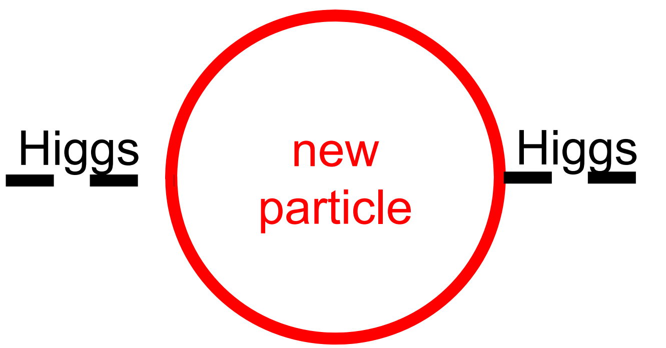
- This all assumes that the new particle is stable.
- Why should it be?



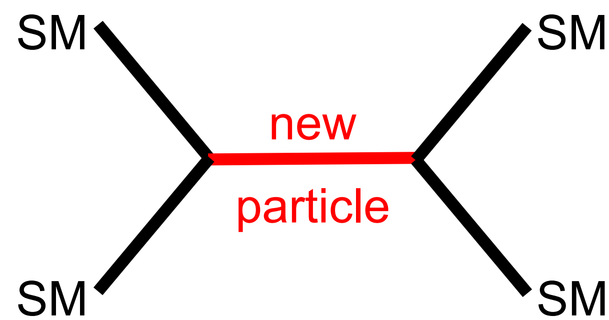
PRECISION CONSTRAINTS

- Problem: Large Electron Positron Collider, 1989-2000, provided precision constraints on new particles

Good: Naturalness



Bad: Precision Constraints



- Solution: discrete parity → new particles interact in pairs. Lightest new particle is then stable. Cheng, Low (2003); Wudka (2003)
- Dark Matter is easier to explain than no dark matter.

PROLIFERATION OF WIMPS

The WIMP paradigm is thriving. Examples:

- Supersymmetry
  - R-parity → Neutralino DM

Goldberg (1983); Ellis et al. (1984)

- Universal Extra Dimensions
  - KK-parity → Kaluza-Klein DM

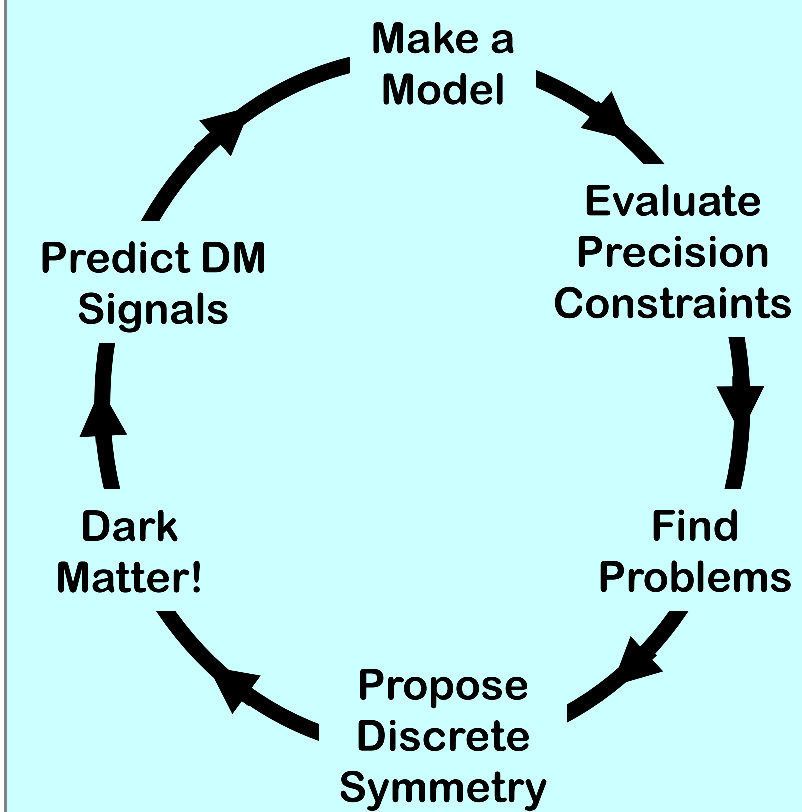
Servant, Tait (2002); Cheng, Feng, Matchev (2002)

- Branes
  - Brane-parity → Branon DM

Cembranos, Dobado, Maroto (2003)

- Little Higgs
  - T-parity → T-odd DM

Cheng, Low (2003)



WIMPS FROM SUPERSYMMETRY

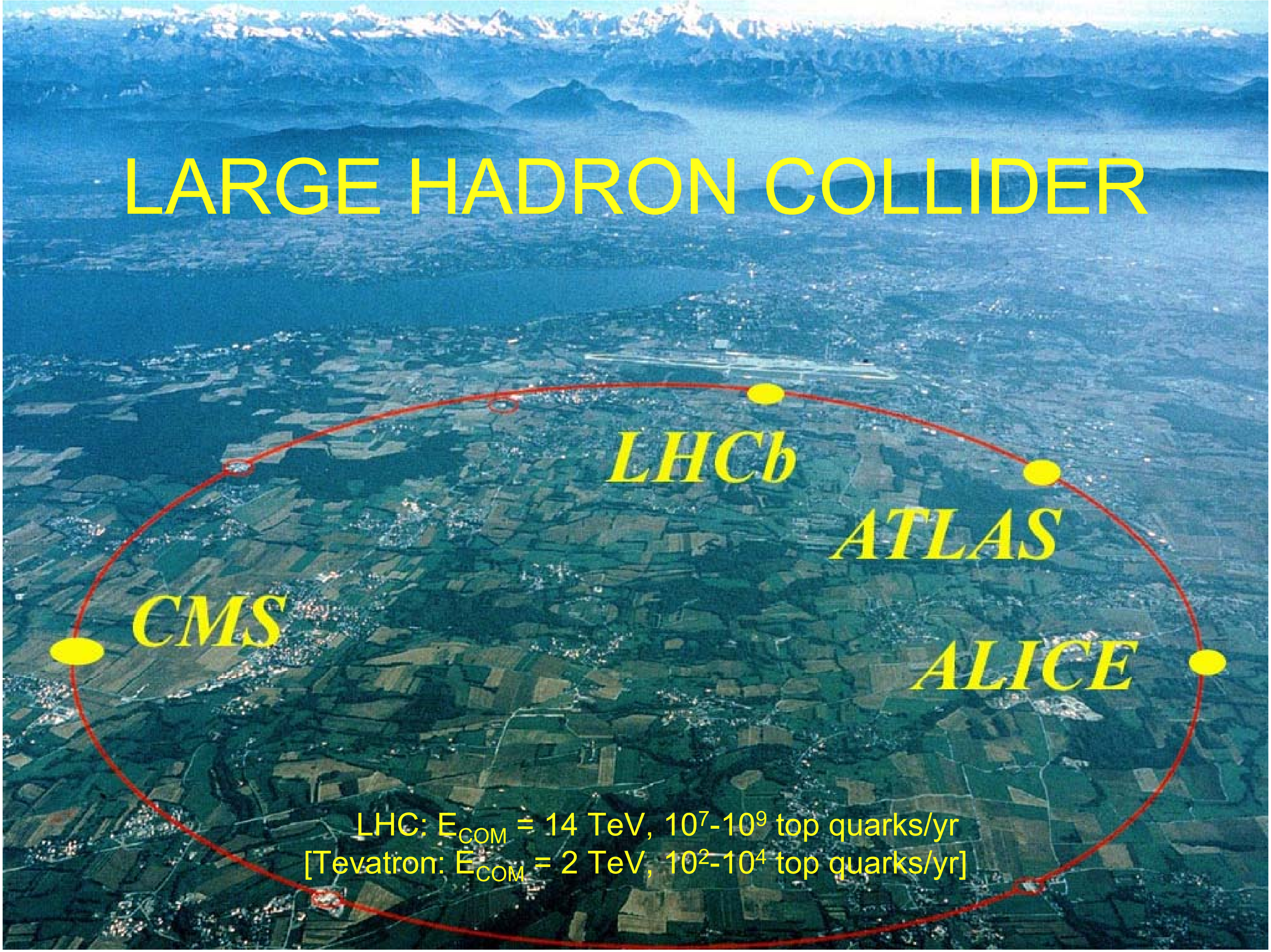
Goldberg (1983); Ellis et al. (1983)

Supersymmetry: many motivations. For every known particle X, predicts a partner particle $\tilde{X}$

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

In many models, χ is the lightest supersymmetric particle, stable, neutral, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter.

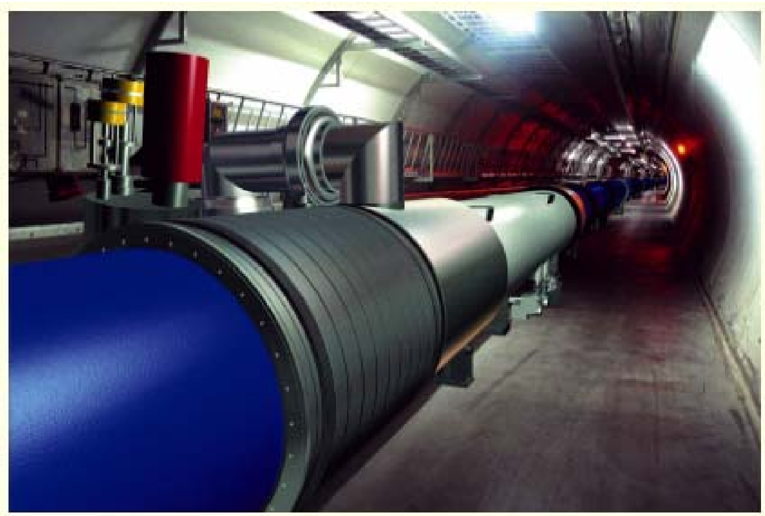
In these scenarios, the LHC will see SUSY soon after beginning in 2008-09.

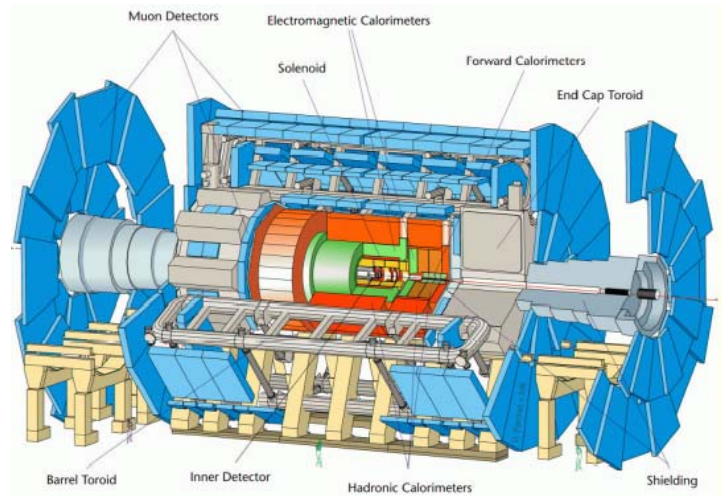

LARGE HADRON COLLIDER
LHCb
ATLAS
CMS
ALICE
LHC: E_{COM} = 14 TeV, 10^7-10^9 top quarks/yr
[Tevatron: E_{COM} = 2 TeV, 10^2-10^4 top quarks/yr]

LHC

ATLAS

Drawings

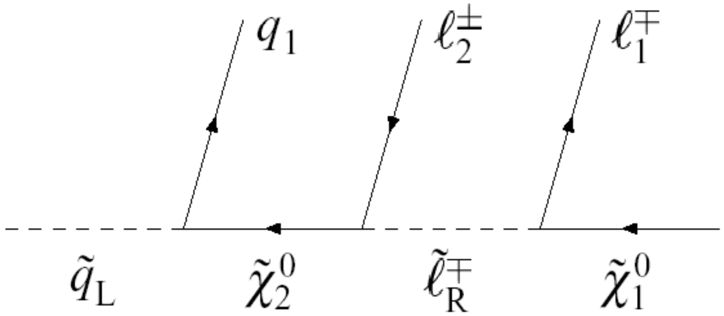


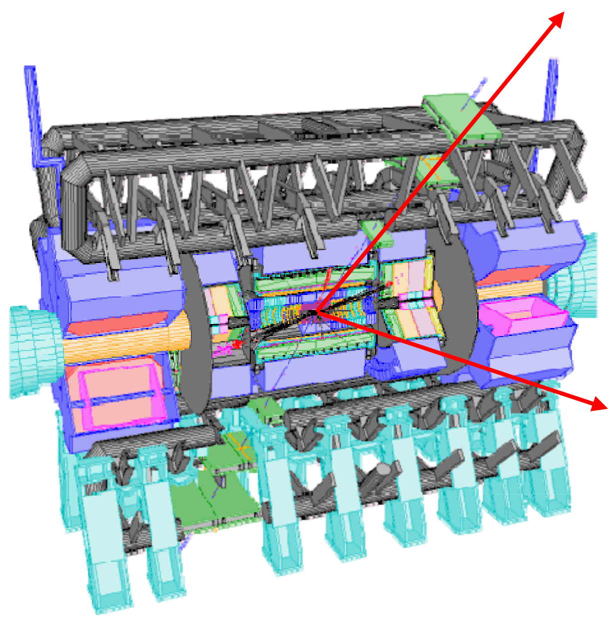


Reality

WHAT THEN?

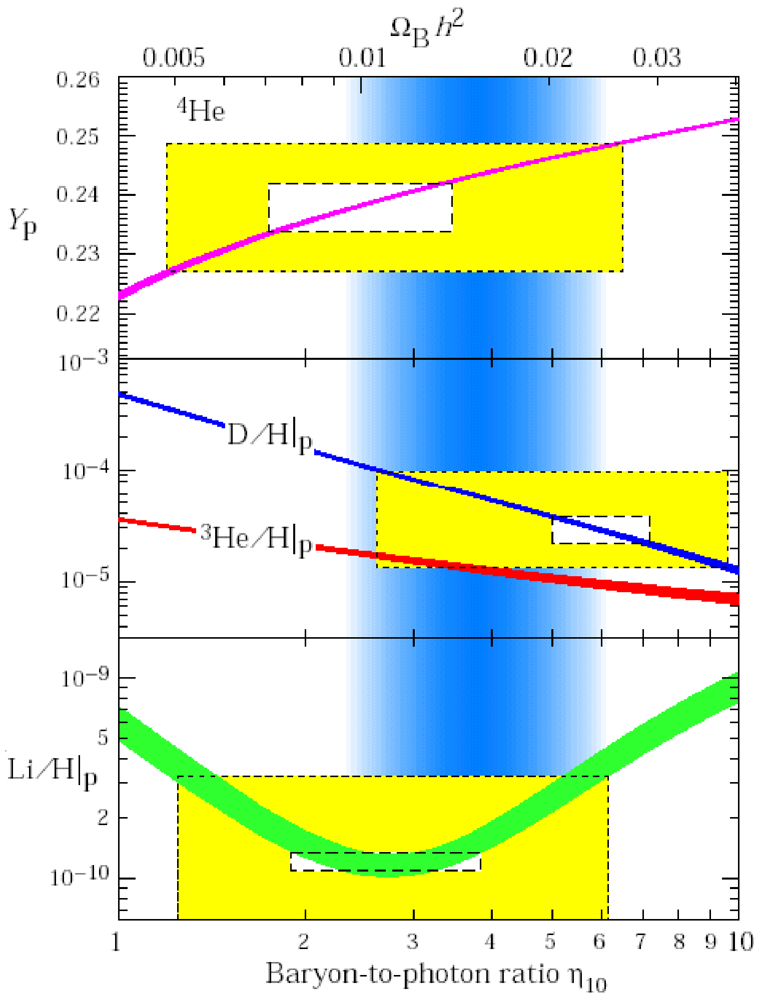
- What LHC actually sees:
  - E.g., $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q} \rightarrow$ neutralino χ
  - 2 χ's escape detector
  - missing momentum





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

THE EXAMPLE OF BBN

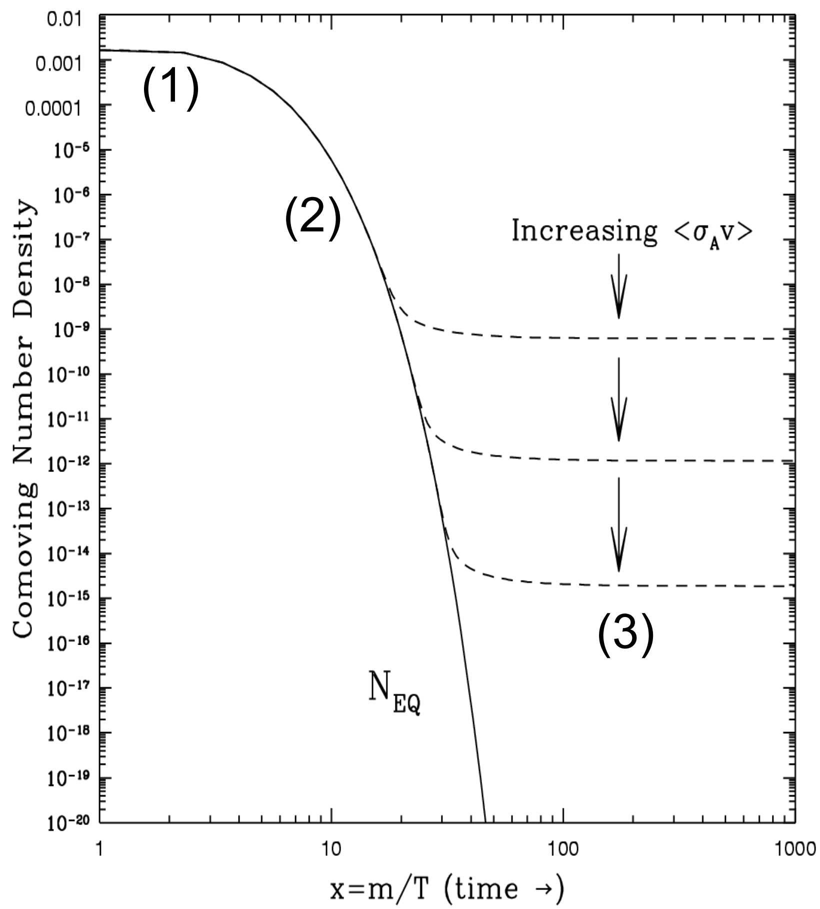


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

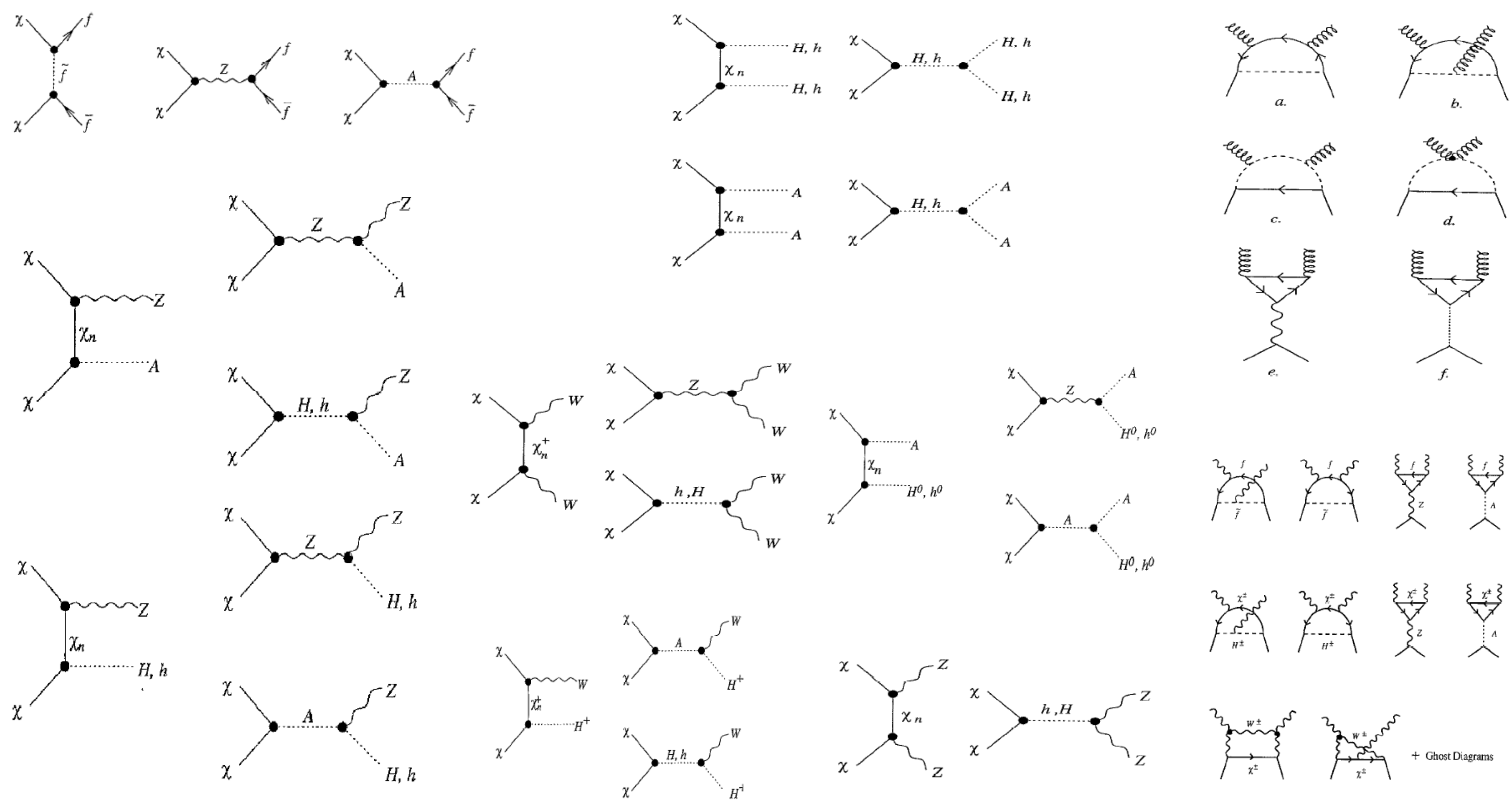
  t ~ 1 sec

DARK MATTER ANALOGUE



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

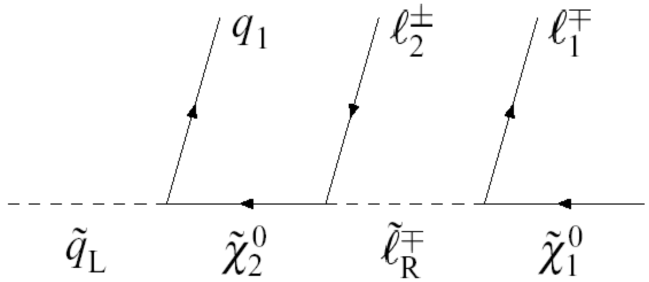
Contributions to Neutralino WIMP Annihilation



Jungman, Kamionkowski, Griest (1995)

PRECISION SUSY @ LHC

- Masses can be measured by reconstructing the decay chains



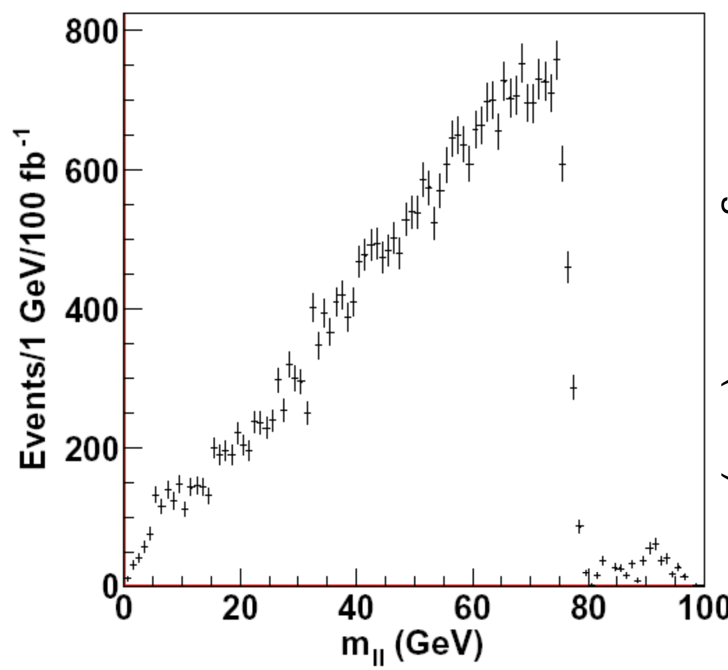
$$\left(m^2_{ll}\right)^{\rm edge} = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

$$\left(m^2_{qll}\right)^{\rm edge} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{\chi}^0_2}}$$

$$\left(m^2_{ql}\right)^{\rm edge}_{\rm min} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)}{m^2_{\tilde{\chi}^0_2}}$$

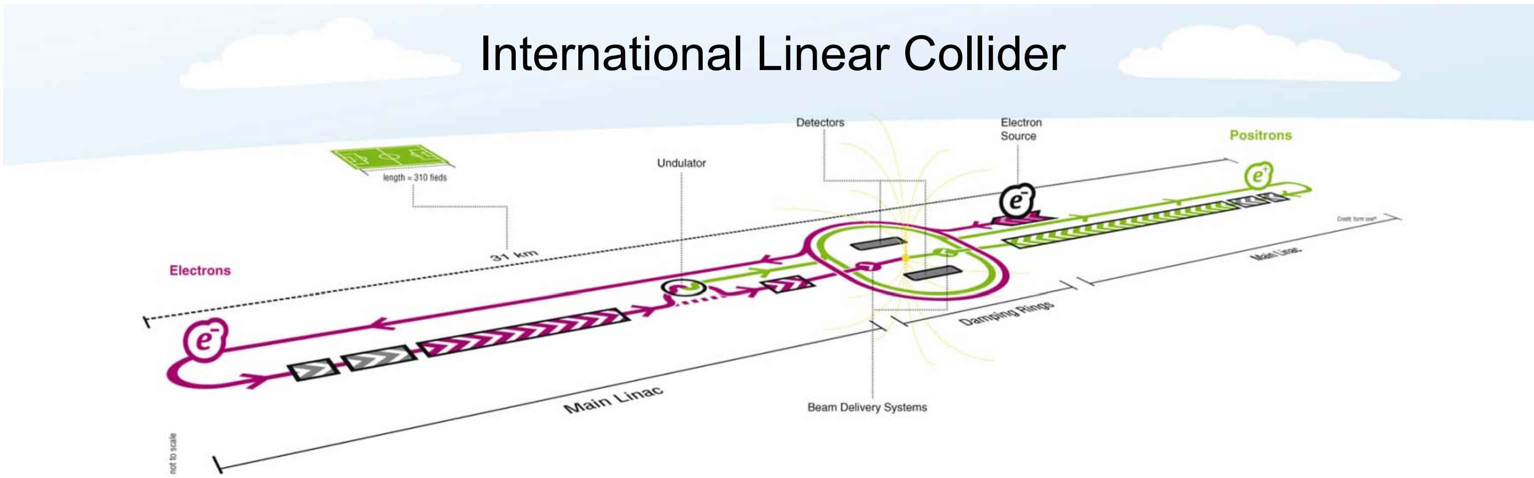
$$\left(m^2_{ql}\right)^{\rm edge}_{\rm max} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

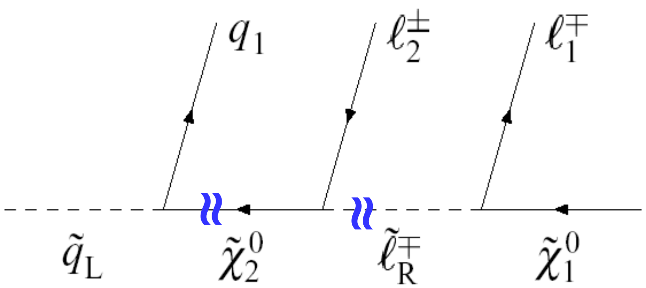
$$\begin{aligned}\left(m^2_{qll}\right)^{\rm thres} = \; & [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\ & -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\ & +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})\end{aligned}$$



Weiglein et al. (2004)

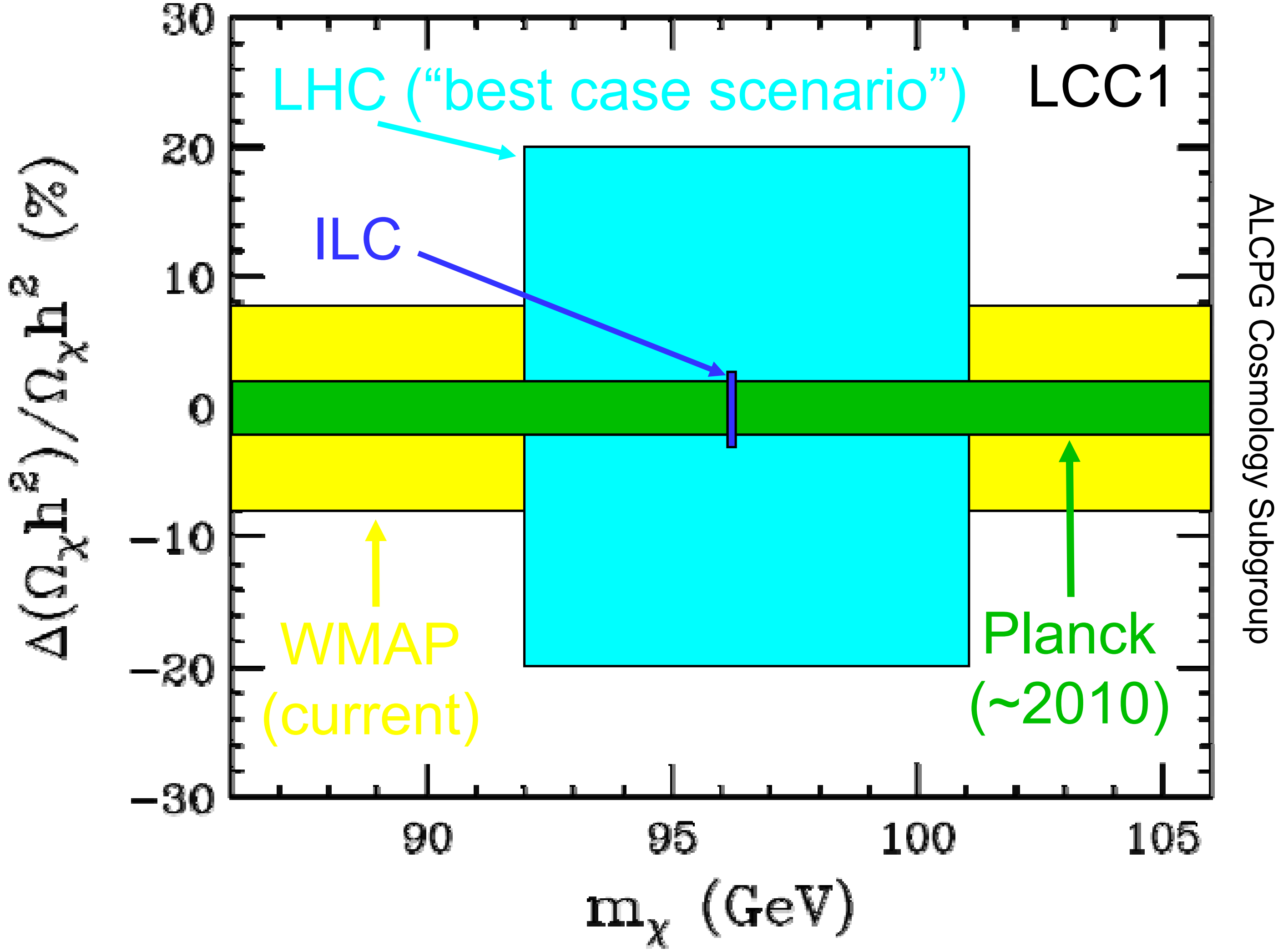
PRECISION SUSY @ ILC





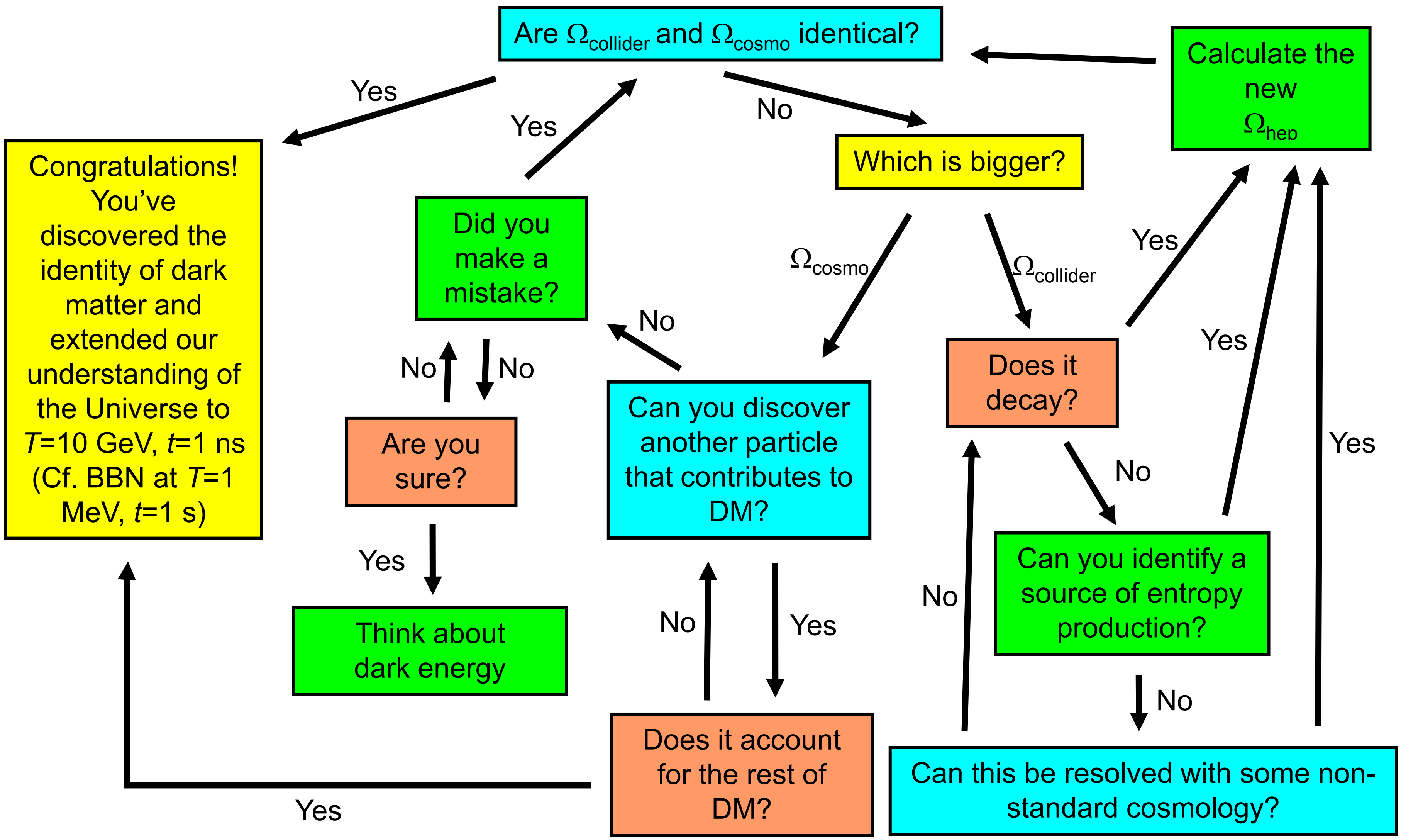
- Collides e^+e^-
- Variable beam energies
- Polarizable e^- beam
- Starts 20??

RELIC DENSITY DETERMINATIONS



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

IDENTIFYING DARK MATTER



DARK ENERGY

- Freezeout provides a window on the very early universe:

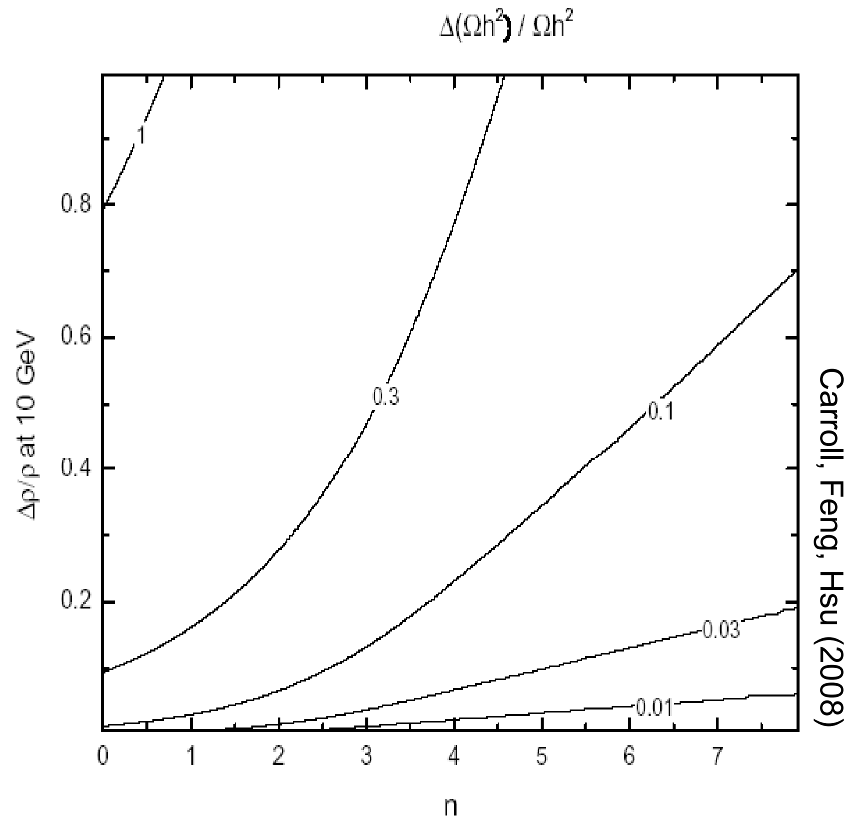
$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Dilution from expansion

- Probe Friedmann at T ~ 10 GeV:

$$H^2 = \frac{8\pi G_N}{3} (\rho + \Delta\rho) \ , \quad \Delta\rho \propto T^n$$

n=0 to 8: cosmological constant, tracking dark energy, quintessence, varying G_N, …

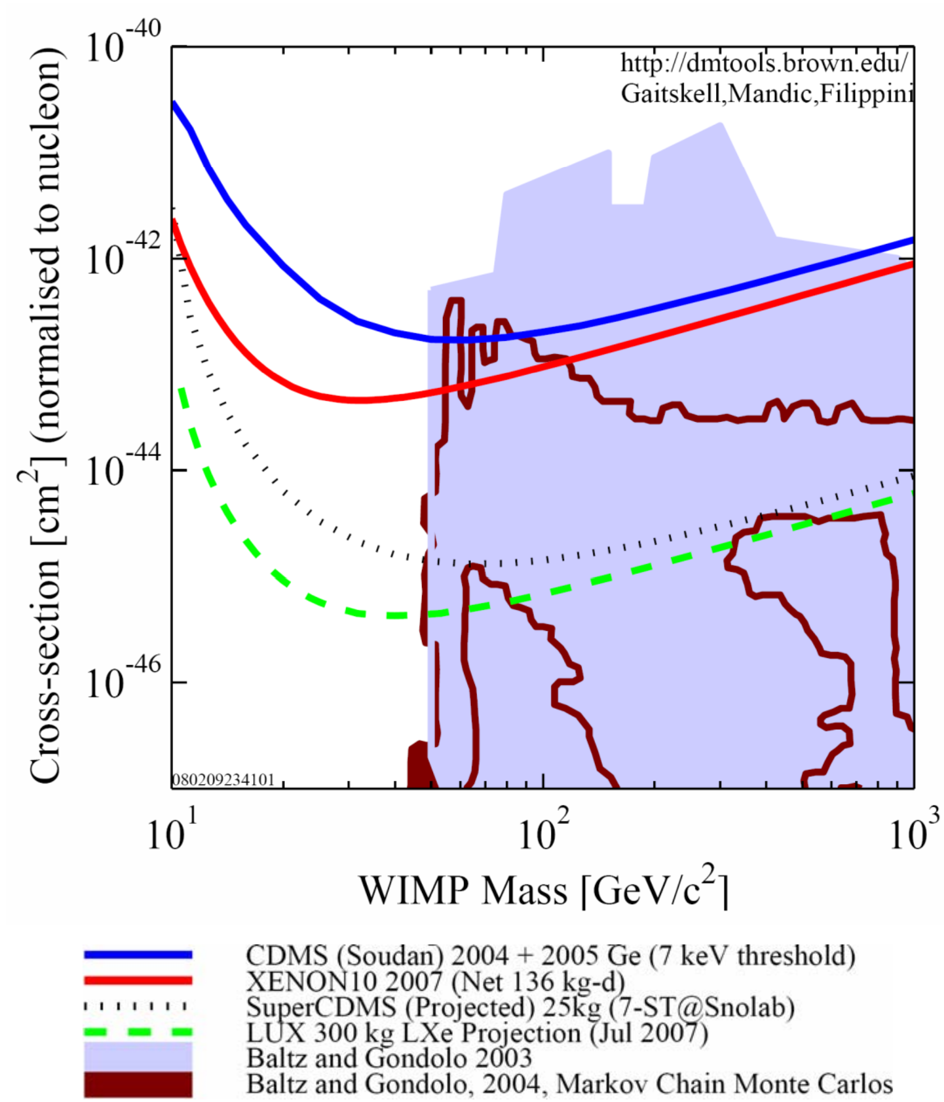


Drees, Iminniyaz, Kakizaki (2007)
Chung, Everett, Kong, Matchev (2007)

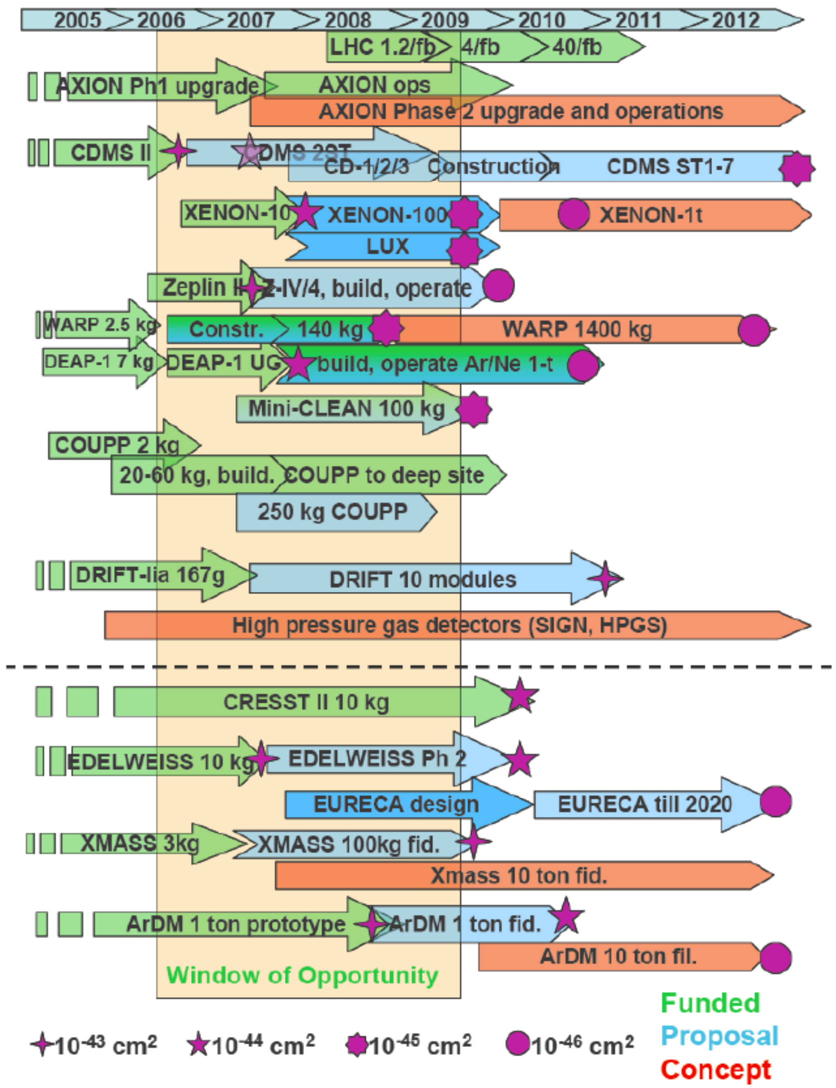
DIRECT DETECTION

- WIMP properties:
  v ~ 10^{-3} c
  Kinetic energy ~ 100 keV
  Local density ~ 1 / liter
- Detected by recoils off ultra-sensitive underground detectors
- Theory predictions vary, but many* SUSY models→ 10^{-44} cm

*mSUGRA, focus point, gaugino-mediated, more minimal, 2-1 models, split SUSY, …



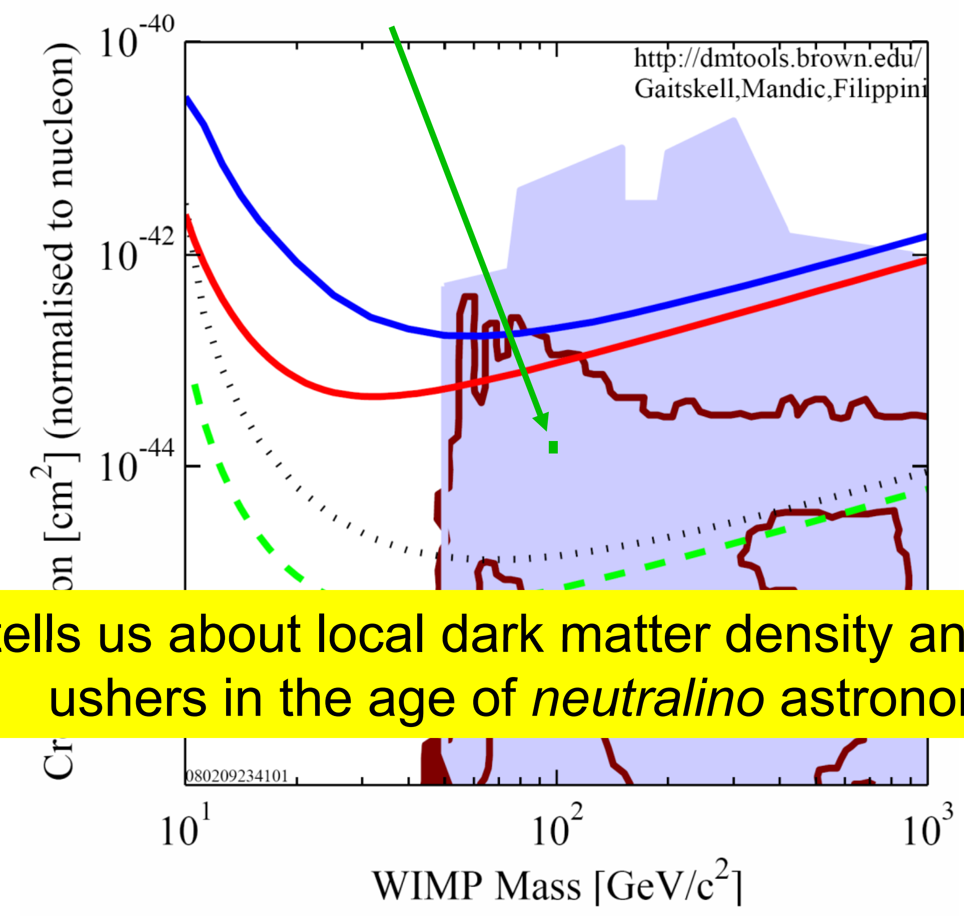
Future Direct Detection



HEPAP/AAAC DMSAG Subpanel (2007)

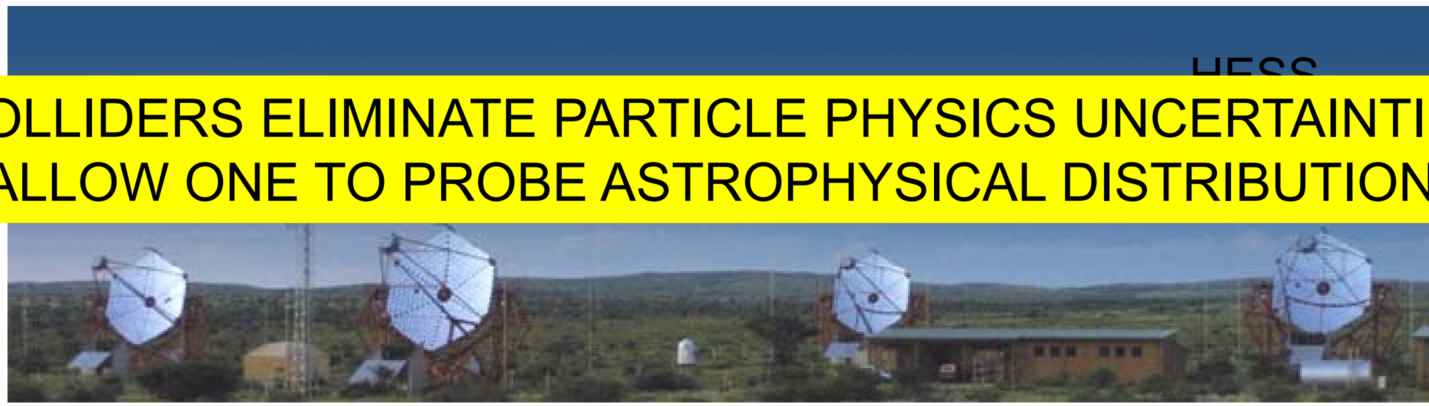
DIRECT DETECTION IMPLICATIONS

LHC + ILC → Δm < 1 GeV, Δσ/σ < 20%



Comparison tells us about local dark matter density and velocity profiles, ushers in the age of *neutralino* astronomy

INDIRECT DETECTION IMPLICATIONS



COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Very sensitive to halo profiles near the galactic center

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: identical motivations, but qualitatively different implications

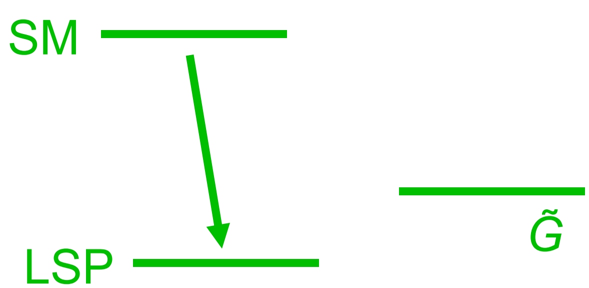
SUPERWIMPS: BASIC IDEA

Feng, Rajaraman, Takayama (2003)

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

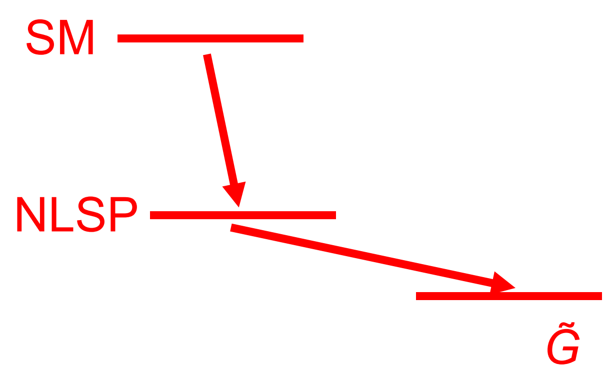
Mass ~ 100 GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP



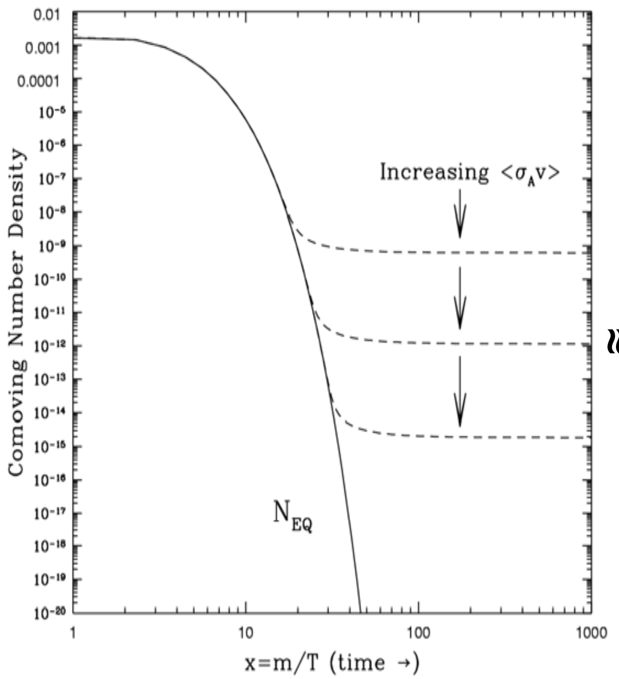
- Assumption of most of literature

- $\tilde{G}$ LSP



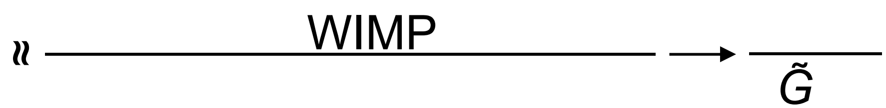
- Completely different cosmology and particle physics

SUPERWIMP RELICS



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

- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after

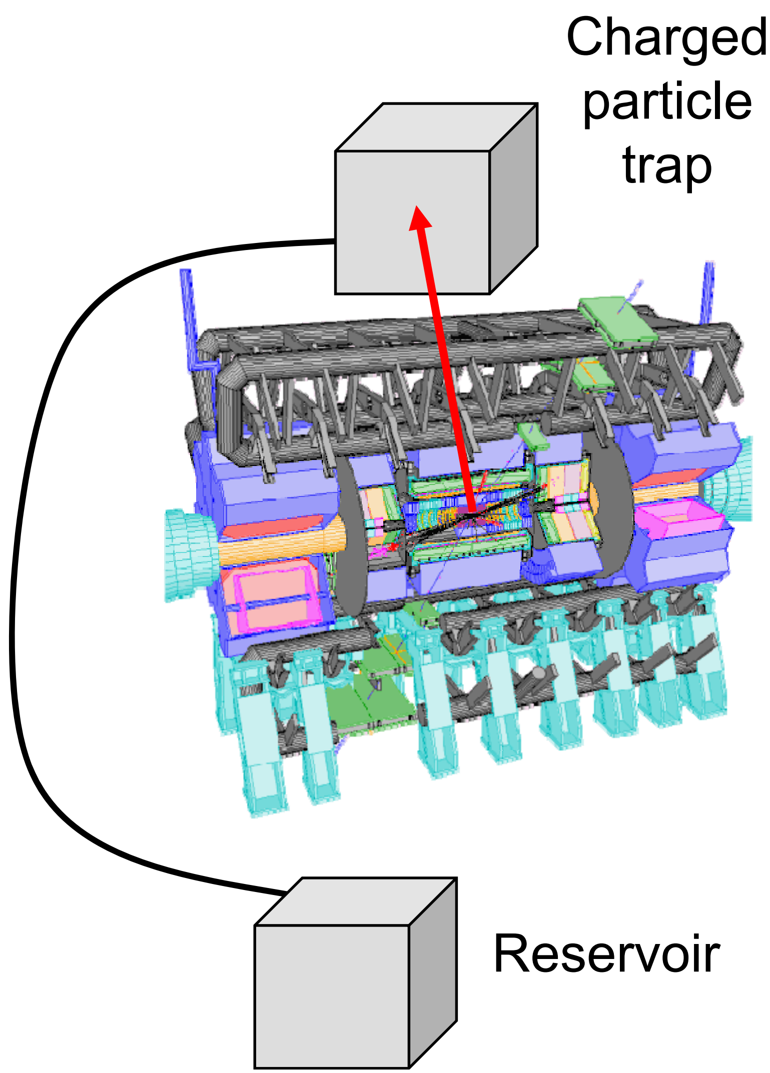
M_{Pl}^2/M_W^3 ~ seconds to months

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)

IMPLICATIONS FROM CHARGED PARTICLE DECAYS

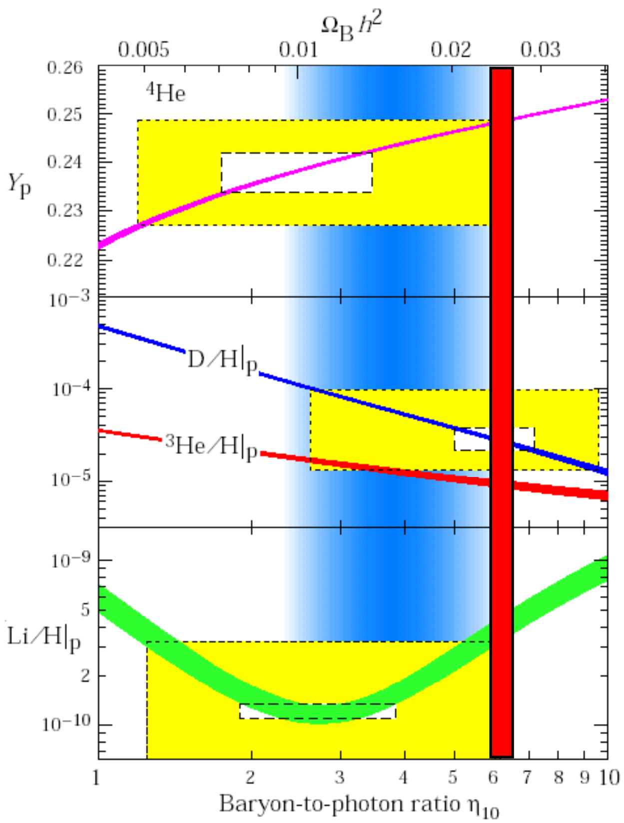
$$\tau(\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- 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)

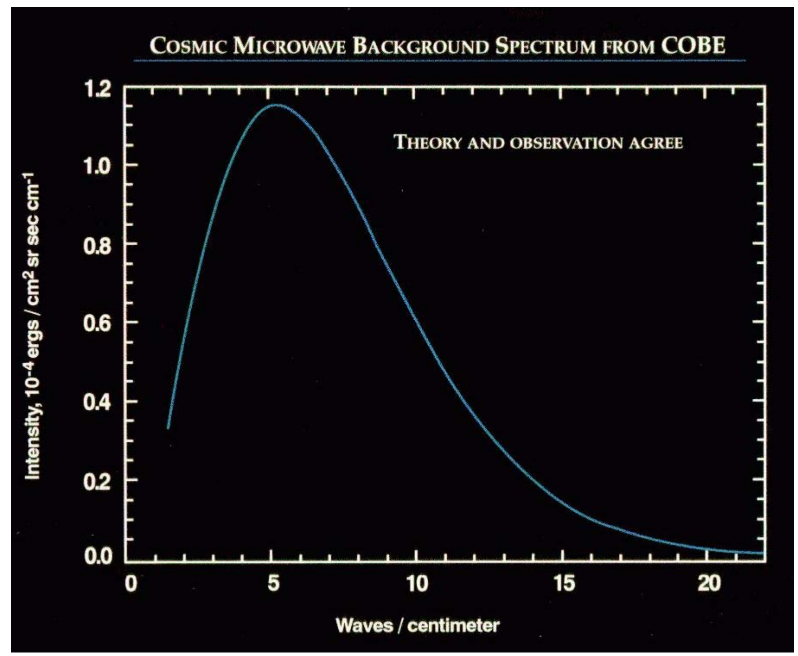
SUPERWIMP COSMOLOGY

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



Fields, Sarkar, PDG (2002)

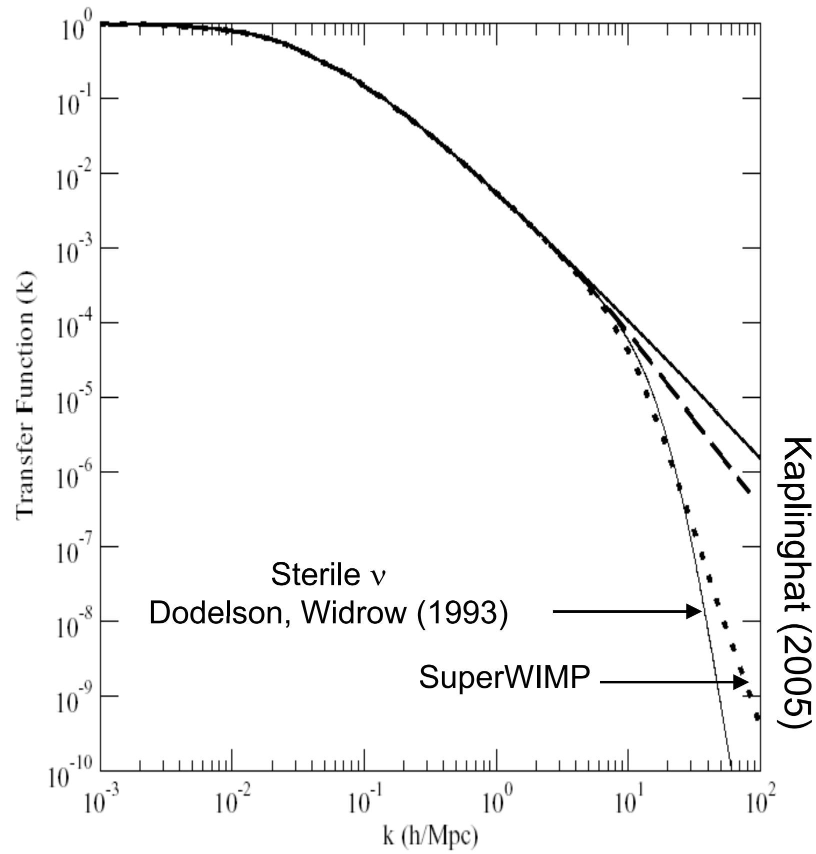
Late decays can modify CMB
black body spectrum
(μ distortions)



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 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)

CONCLUSIONS

- Particle Dark Matter
  - As well-motivated as ever
  - WIMPs: Proliferation of candidates
  - SuperWIMPs: Qualitatively new possibilities (warm, metastable, only gravitationally interacting)

- If dark matter is WIMPs or superWIMPs, colliders
  - will produce it
  - may identify it as dark matter
  - may open up a window on the universe at $t \sim 1$ ns

- LHC begins in 08-09, direct and indirect detection are improving rapidly – this field will be transformed soon