DARK MATTER AND SUPERGRAVITY

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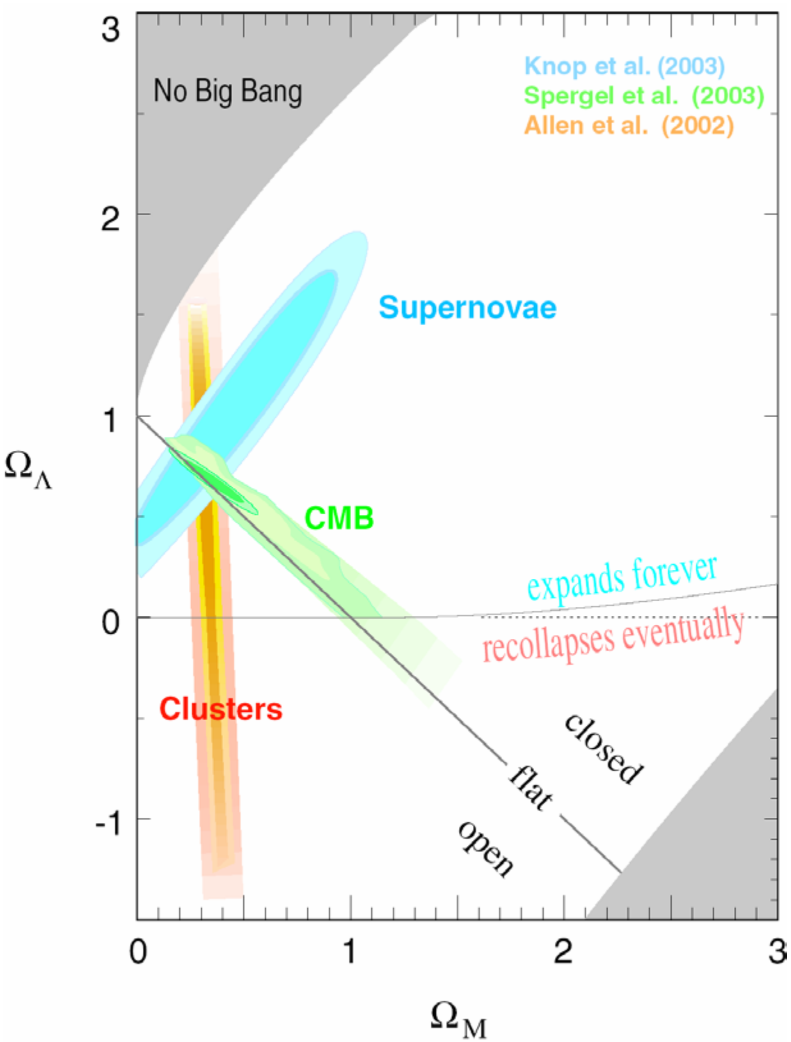
COSMOLOGY → NEW PHYSICS



- Cosmology today provides much of the best evidence for new microphysics
- What can we learn from dark matter about SUSY – SUSY breaking, its mediation, superpartner spectrum, expected signals?
- Work with Arvind Rajaraman, Fumihiro Takayama, Jose Ruiz Cembranos, Shufang Su, Bryan Smith

DARK MATTER: WHAT WE KNOW

- How much there is:

$$\Omega_{DM} = 0.23 \pm 0.04$$

- What it's not:

Not short-lived: $\tau > 10^{10}$ years

Not baryonic: $\Omega_B = 0.04 \pm 0.004$

Not hot: "slow" DM is required to form structure

DARK MATTER: WHAT WE DON'T KNOW

- What is its mass?
- What is its spin?
- What are its other quantum numbers and interactions?
- Is it absolutely stable?
- What is the origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How was it produced?
- 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 Matter Candidates

- Given the few constraints, it is not surprising that there are many candidates: axions, thermal gravitinos, neutralinos, Kaluza-Klein particles, wimpzillas, self-interacting particles, self-annihilating particles, fuzzy dark matter, superWIMPs,…

- Masses and interaction strengths span many, many orders of magnitude

- But independent of cosmology, new particles are required to understand the weak scale. What happens when we add these to the universe?

Cosmological Implications

(1) Assume the new particle is initially in thermal equilibrium:

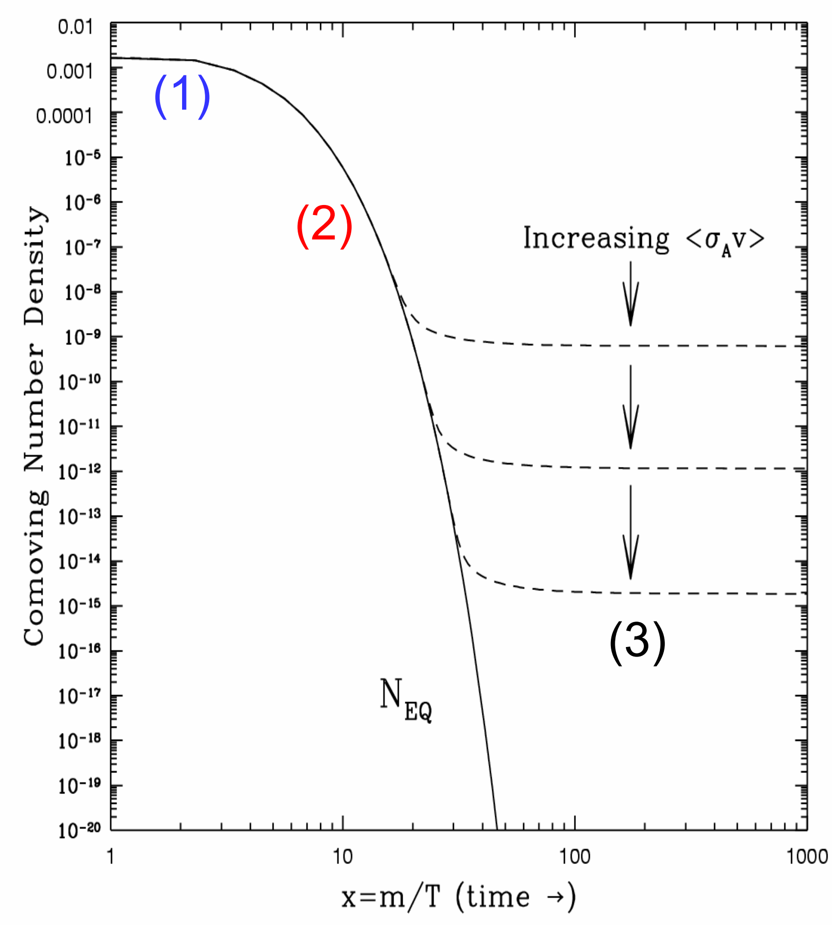
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs "freeze out":

$$N \sim \text{const}$$



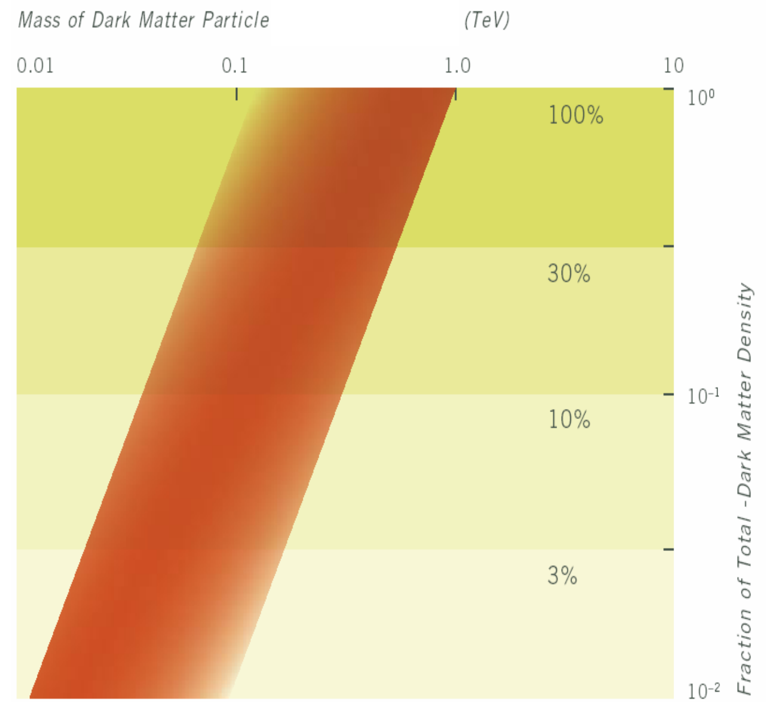
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

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

- 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]

Ω_{DM} ~ 0.1 for m ~ 100 GeV – 1 TeV.

Cosmology alone tells us we should explore the weak scale.

IMPLICATIONS

- Electroweak theories often predict relevant amounts of dark matter. In fact, dark matter is easier to explain than no dark matter:

Exp. constraints ↔ discrete symmetries ↔ stable DM

- In SUSY, this requires that the gravitino be heavier than the neutralino. This disfavors low-scale (gauge-mediated) SUSY breaking, favors high-scale (gravity-mediated) SUSY breaking:

$$m_{3/2} \sim F/M_{Pl} > m_\chi \sim F/M_{med} \rightarrow M_{med} \sim M_{Pl},\ F \sim 10^{10}\ \text{GeV}$$

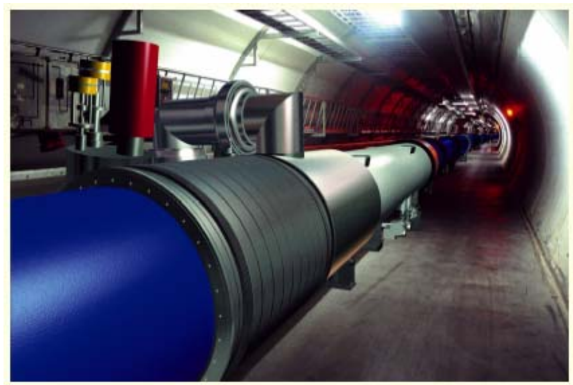
- SUSY does not decouple cosmologically: $\Omega \sim m^2$. Low energy SUSY is motivated independent of naturalness.

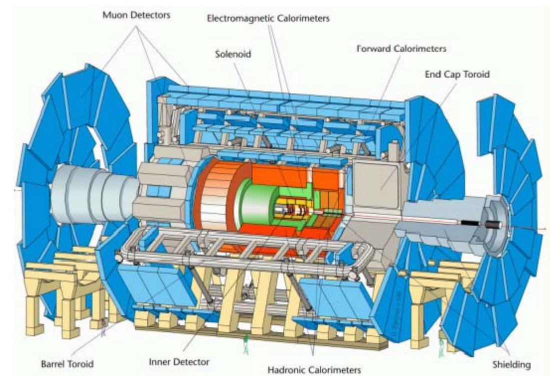
NEAR FUTURE PROSPECTS

LHC

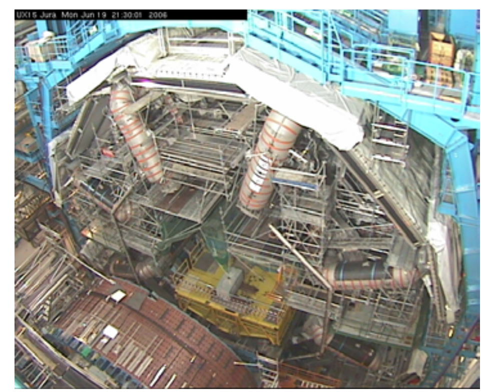
ATLAS

Drawings



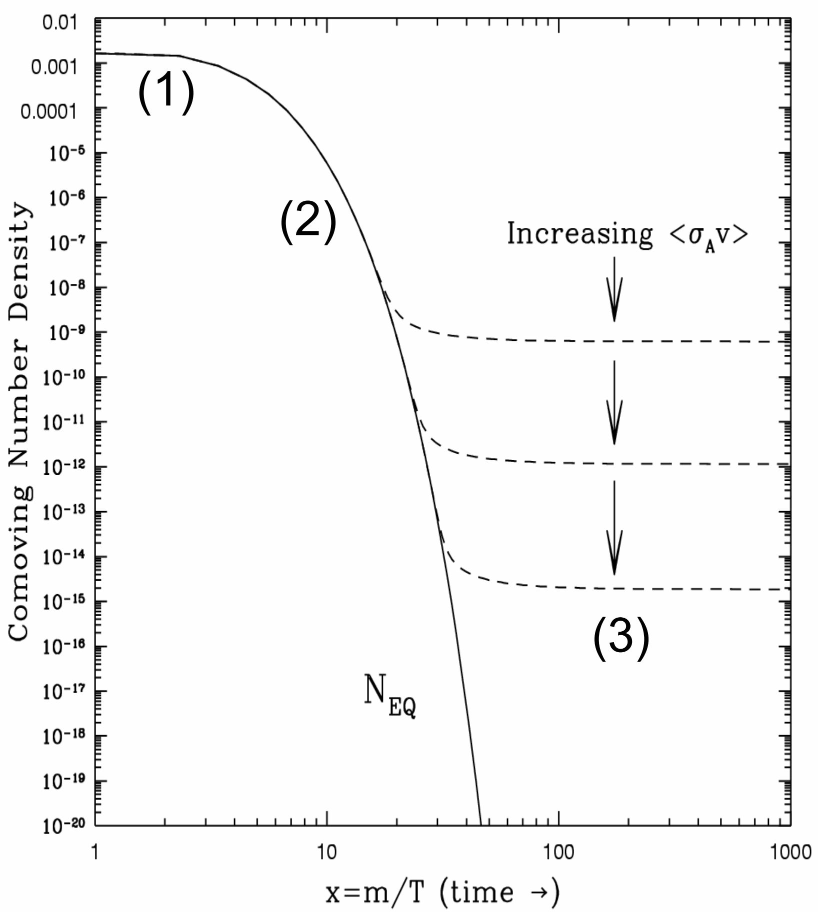


Reality



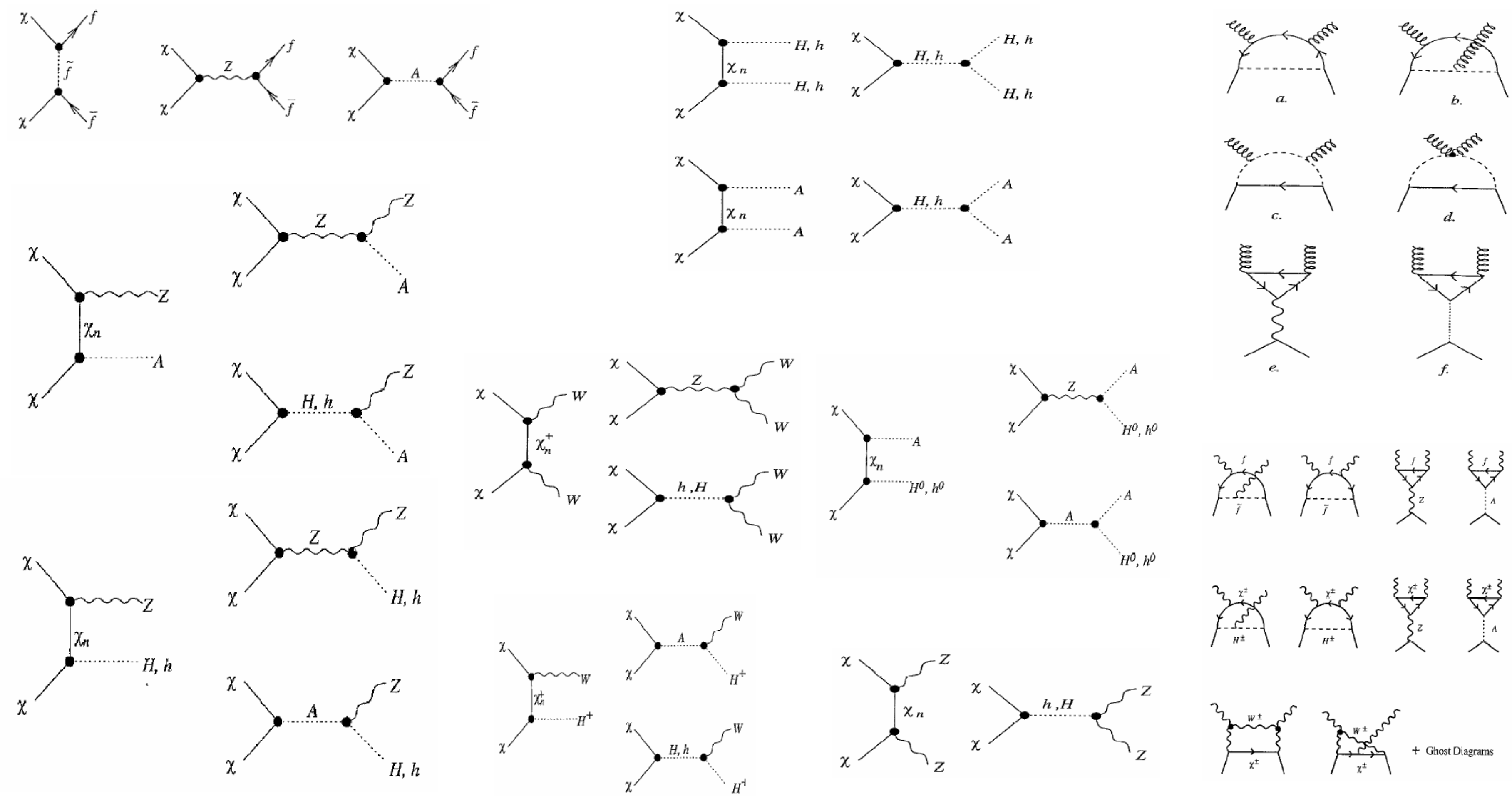
Lyn Evans: 1 fb^{-1} in 2008 is guaranteed

IDENTIFYING DARK MATTER

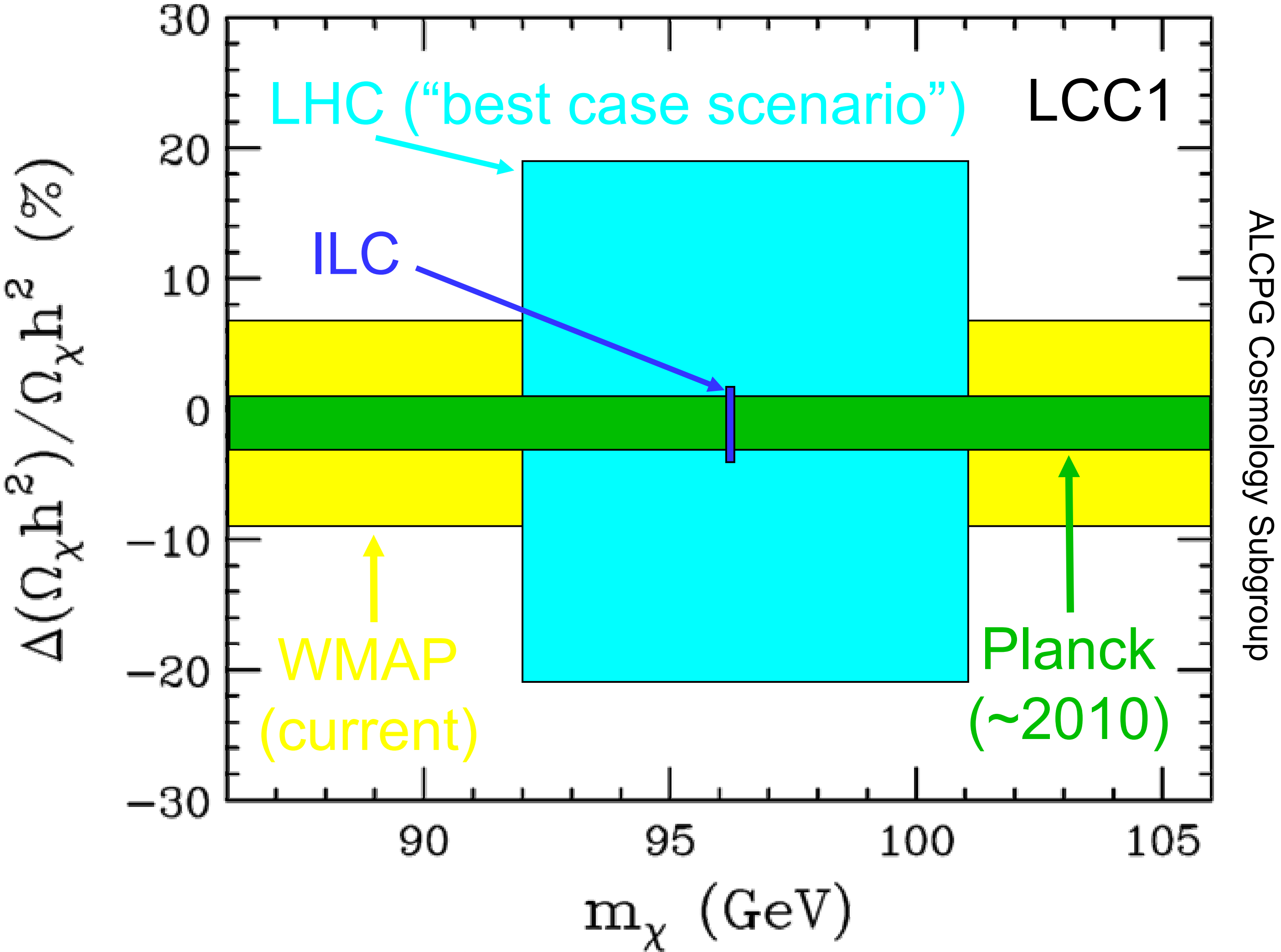


- Particle physics → σ_A, dark matter abundance prediction
- Compare to observed dark matter abundance
- How well can we do?

Contributions to Neutralino WIMP Annihilation



RELIC DENSITY DETERMINATIONS



Agreement → identity of dark matter, understanding of universe back to t ~ 1 ns, T ~ 10 GeV (cf. BBN at t ~ 1 s, T ~ MeV)

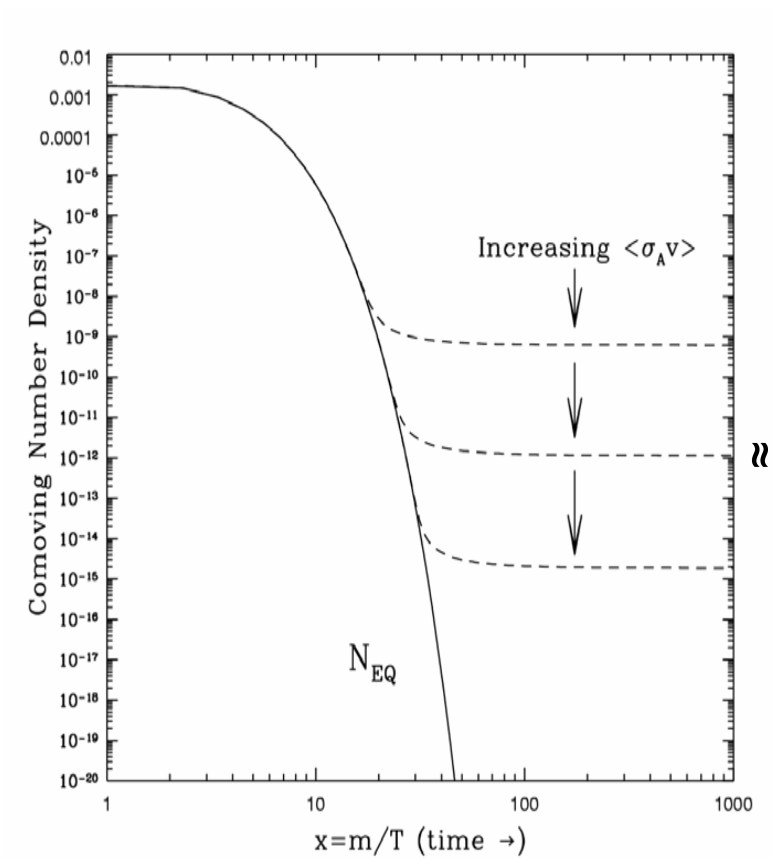
SuperWIMP Dark Matter

Feng, Rajaraman, Takayama (2003)

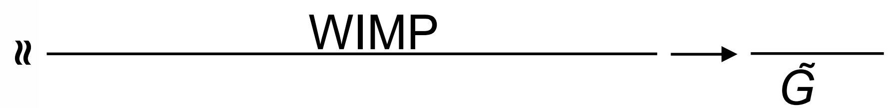
- Collider signals (and other dark matter searches) rely on DM having weak force interactions. Is this required?
- Strictly speaking, no – the only required DM interactions are gravitational.
- But the relic density “coincidence” strongly prefers weak interactions.

Is there an exception to this rule?

SuperWIMPs: The Basic Idea



- High-scale SUSY breaking supergravity has a weak-scale mass $\tilde{G}$. Suppose it's the LSP.
- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after

$$M_{Pl}^2/M_W^3 \sim \text{a month}$$

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs

SuperWIMP Implications

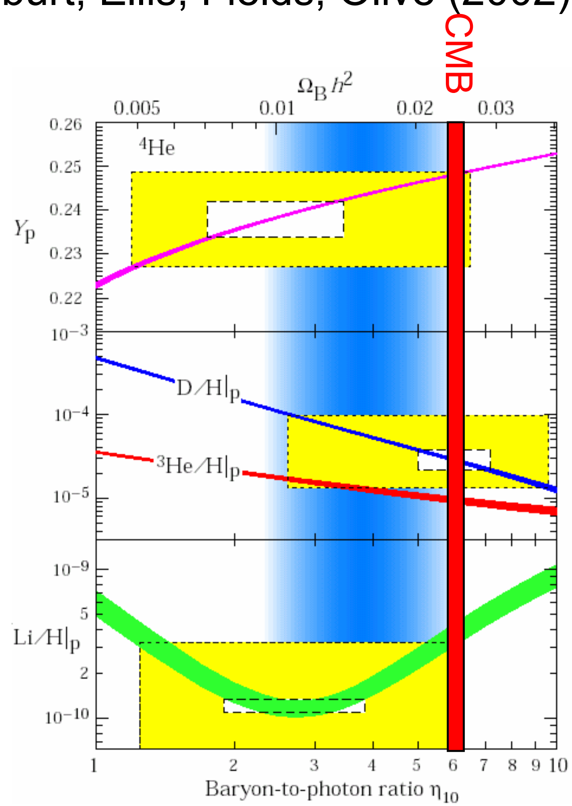
- SuperWIMPs evade all particle dark matter searches; all event rates R → 10^{-32} R.
- Apparently even more troubling is the gravitino problem: late decays to the gravitino destroy the successes of Big Bang nucleosynthesis. Weinberg noted that the superpartner mass scale should be > 10 TeV for decays to happens before BBN.
- The scenario appears excluded by cosmology and untestable in particle/astroparticle experiments.

Luckily, both conclusions are too hasty…

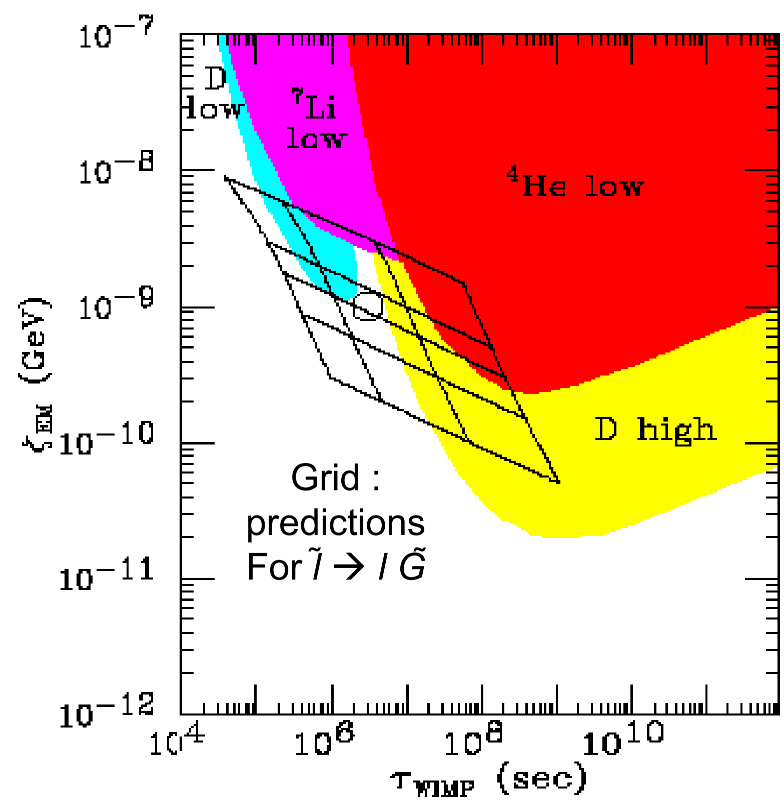
Big Bang Nucleosynthesis

Late decays may modify light element abundances

Cyburt, Ellis, Fields, Olive (2002); Kawasaki et al. (2004); Jedamzik (2004); Cerdeno et al. (2005)



Fields, Sarkar, PDG (2002)

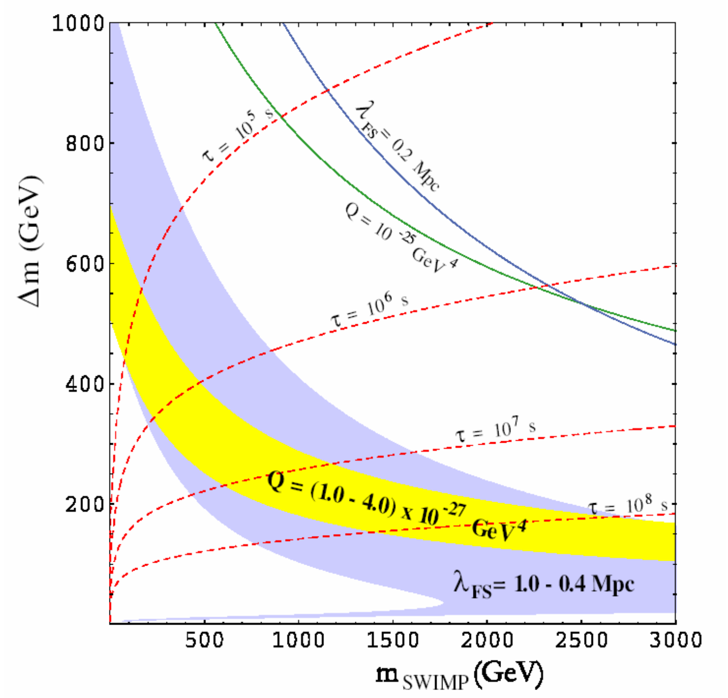


Feng, Rajaraman, Takayama (2003)

$\chi \to (Z, \gamma, h)\, \tilde{G}$ excluded, but much of $\tilde{l} \to l\, \tilde{G}$ ok

Structure Formation

Cold dark matter (WIMPs) seeds structure formation. Simulations may indicate more central mass and more cuspy halos than observed – cold dark matter is too cold.



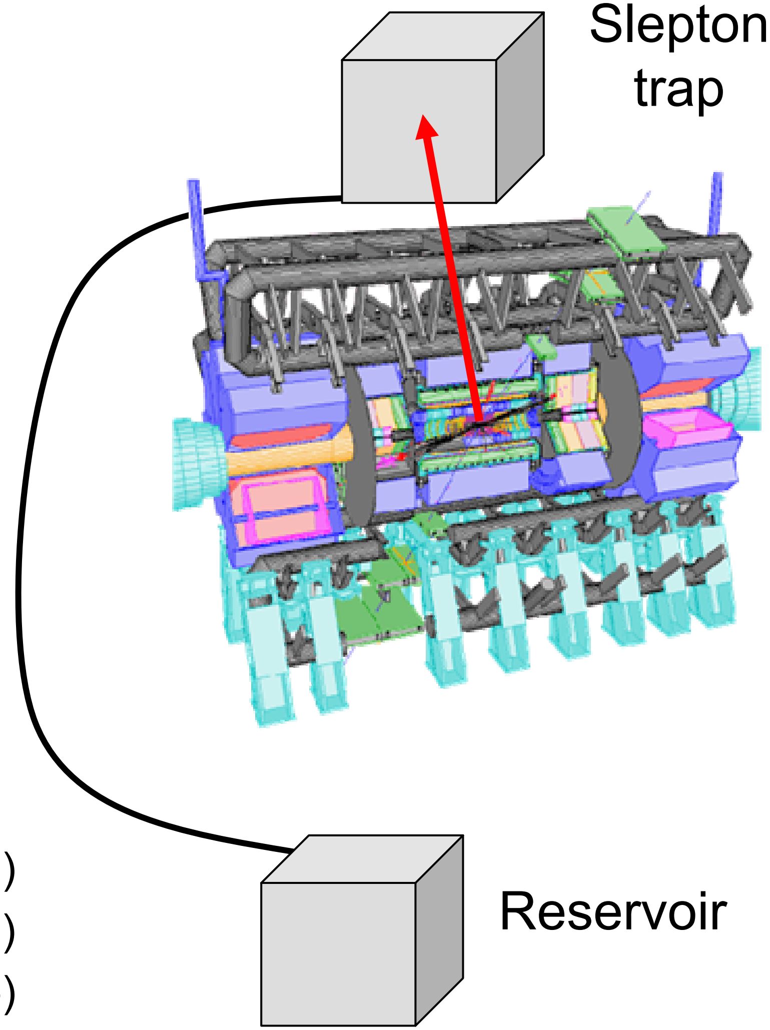
Cembranos, Feng, Rajaraman, Takayama (2005)
Kaplinghat (2005), Jedamzik (2005)

SuperWIMPs are produced at t ~ month with large velocity, smooth out small scale structure.

SuperWIMPs combine Cold DM (Ω ~ 0.1) and Warm DM (structure formation) virtues.

SUPERWIMPS AT THE LHC

- Cosmology → metastable charged sleptons with lifetimes of days to months
- Sleptons can be trapped and moved to a quiet environment to study their decays $\tilde{l} \to l\ \tilde{G}$
- A 1 m thick shell of water can catch ~ 10^4 sleptons per year



Feng, Smith (2004)
Hamaguchi, Yuno, Nayaka, Nojiri (2004)
Ellis et al. (2005)

What we learn from slepton decays

- We are sensitive to (M_*-suppressed) gravitational effects in a particle physics experiment

$$\Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right]^4$$

Buchmuller, Hamaguchi, Ratz, Yanagida (2004)
Feng, Rajaraman, Takayama (2004)

- Measurement of $m_{\tilde{l}}$, Γ → $m_{\tilde{G}}$
  - → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - → *F*. Supersymmetry breaking scale
  - → BBN, CMB, structure formation in the lab
- Measurement of $m_{\tilde{l}}$, Γ and E_l → $m_{\tilde{G}}$ *and* M_*
  - → Measurement of G_{Newton} on fundamental particle scale
  - → Gravitino is graviton partner, can quantitatively confirm supergravity

CONCLUSIONS

- Cosmology suggests there may be new particles at the weak scale, independent of naturalness
- In SUSY, dark matter relic density “coincidence” → high-scale (gravity-mediated) SUSY breaking
- If neutralino WIMPs, LHC will discover them in the next few years
- If gravitino superWIMPs, LHC is likely to produce long-lived sleptons that decay to gravitinos, allowing the quantitative confirmation of supergravity