The Linear Collider and the Rest of the Universe

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I. RECENT PROGRESS

II. OPEN PROBLEMS

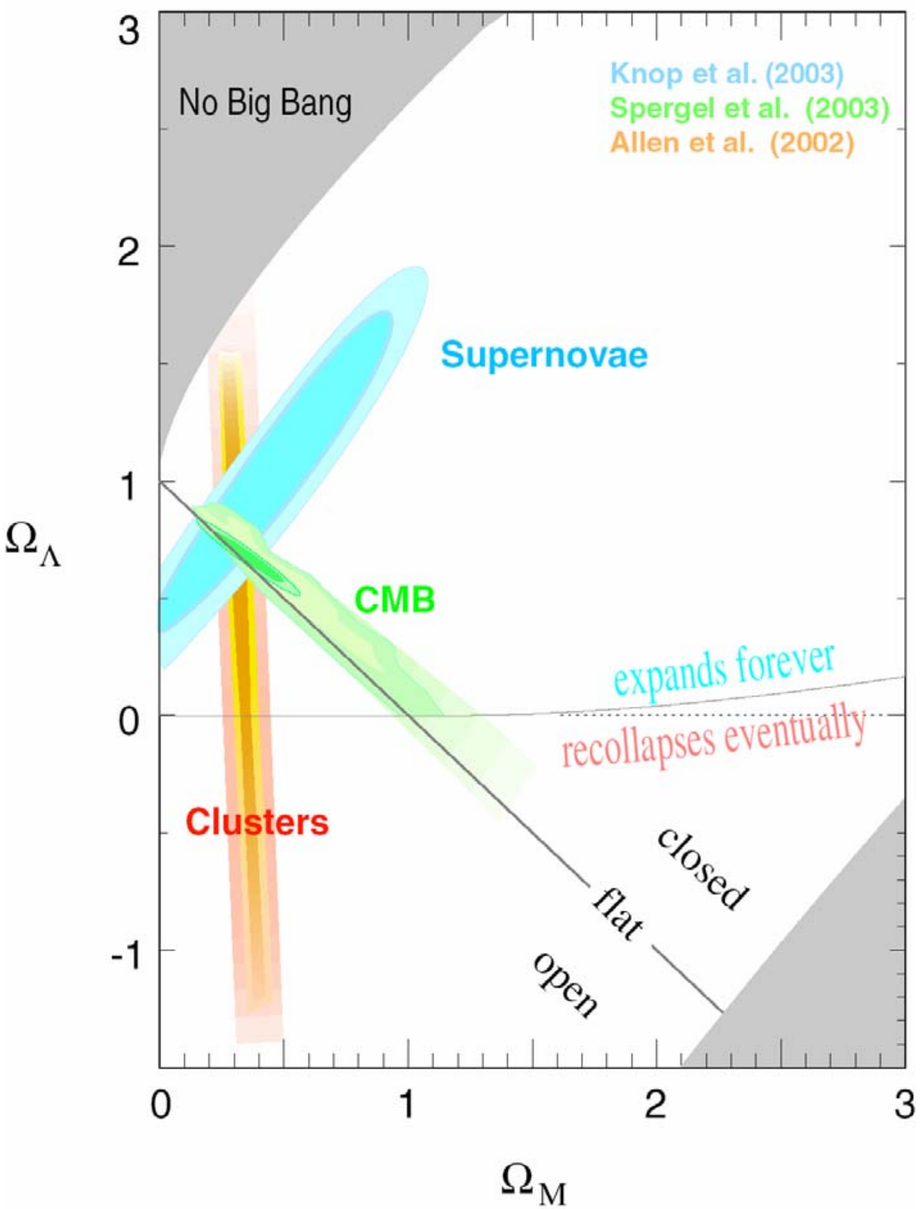
III. OPPORTUNITIES FOR THE LINEAR COLLIDER

RECENT PROGRESS

What is the Universe made of?

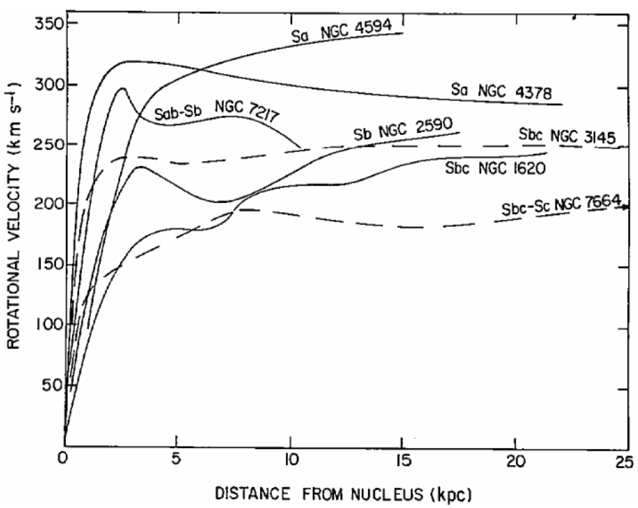
Recently there have been remarkable advances in our understanding of the Universe on the largest scales

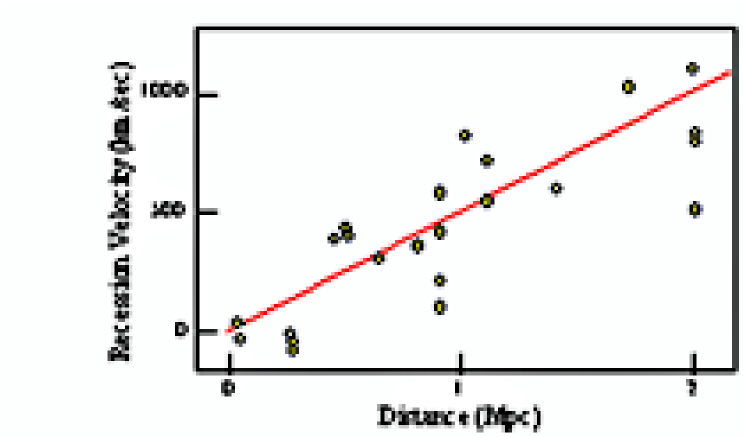
We live at a privileged time: we now have a complete census of the Universe

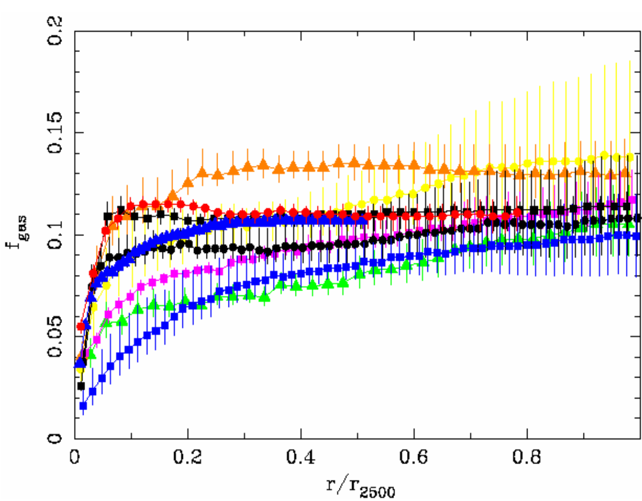


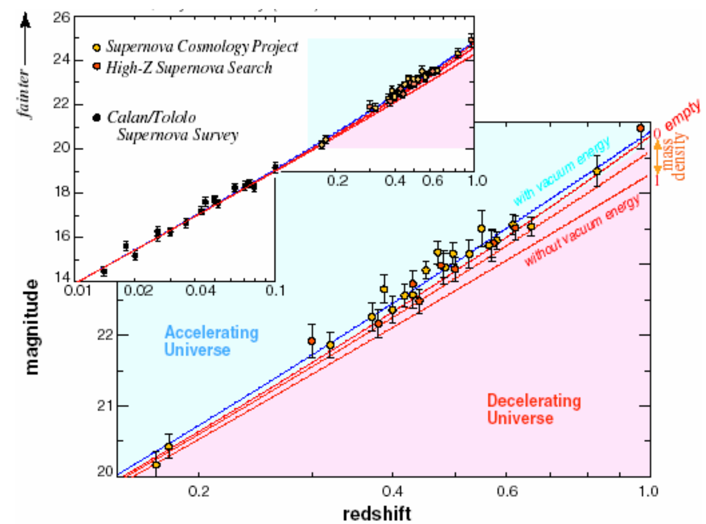
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

	“Clusters”	“Supernovae”
Then	Rubin, Ford, Thonnard (1978)	Hubble (1929)
	Constrains Ω_M	Constrains $\Omega_\Lambda - \Omega_M$
Now	Allen, Schmidt, Fabian (2002)	





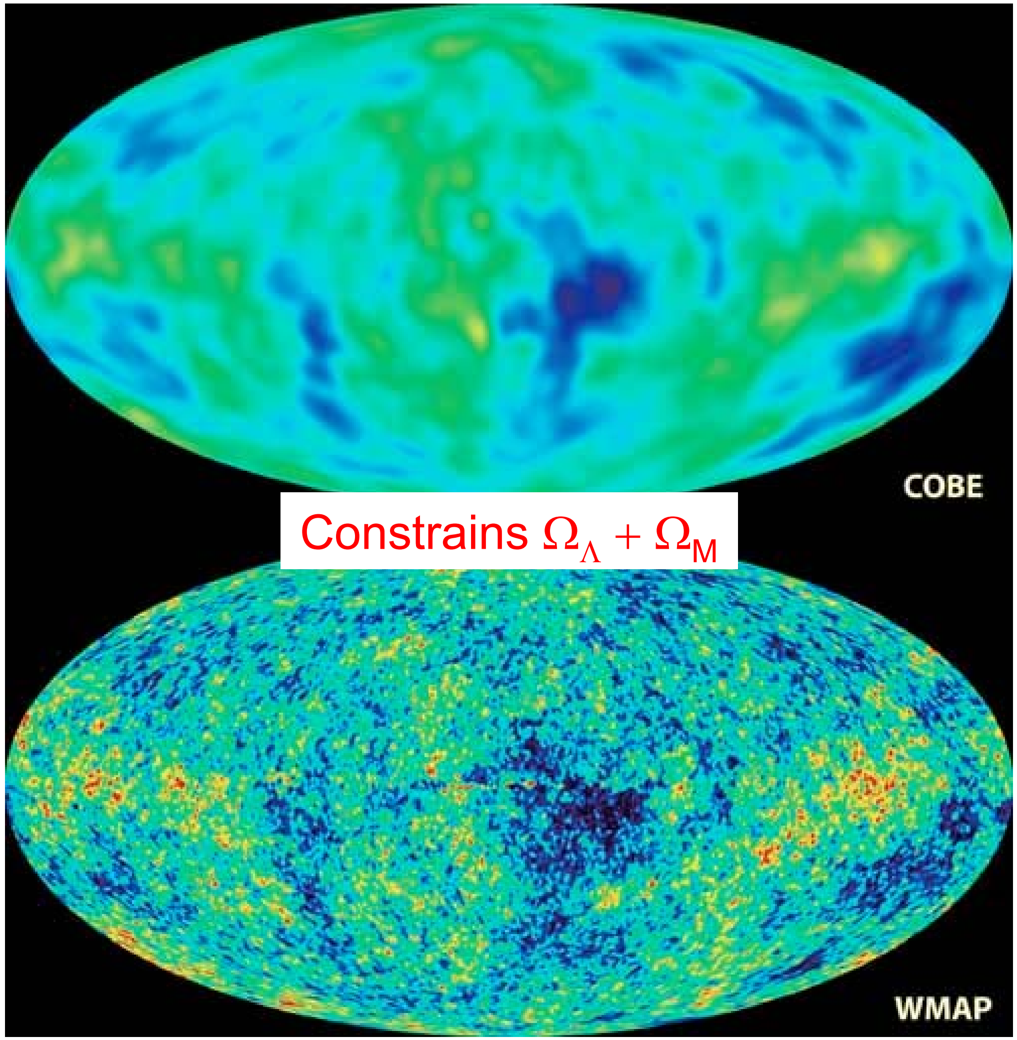


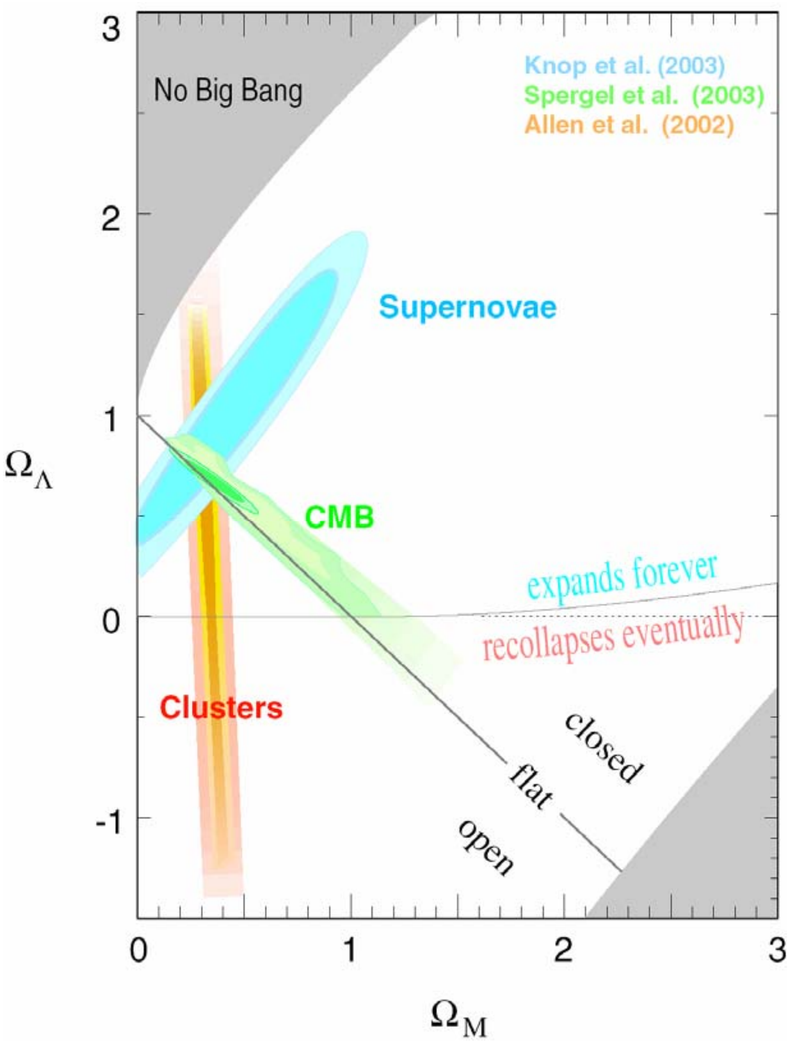


Cosmic Microwave Background

Then

Now





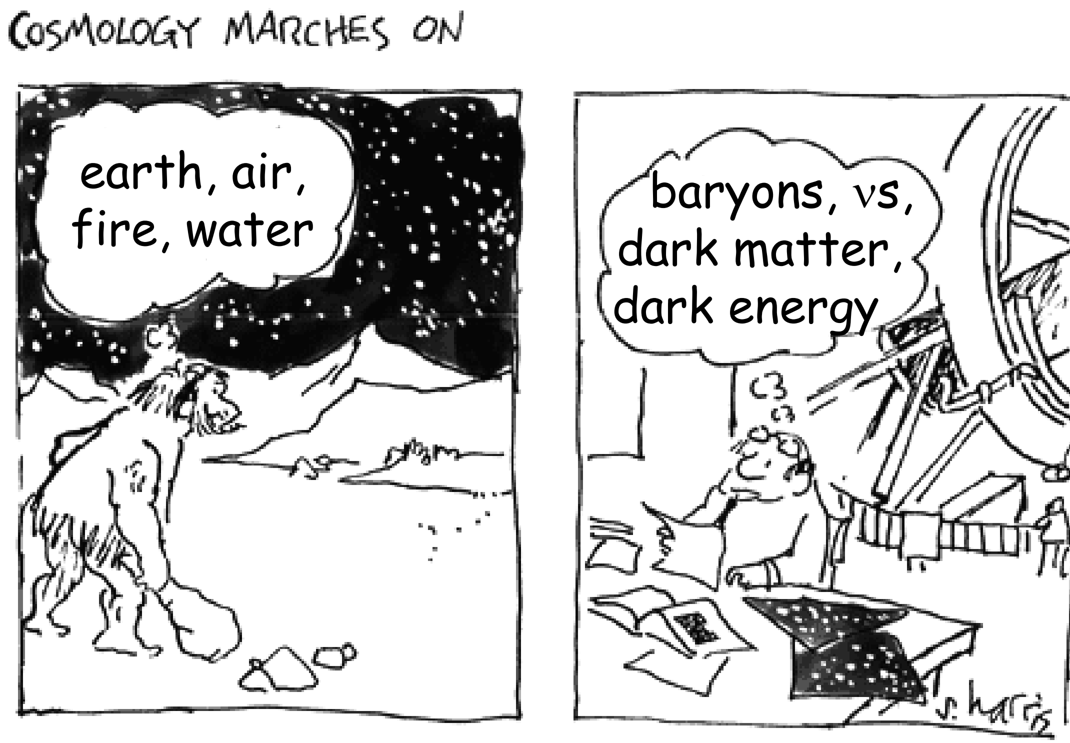
- These three agree:

  Dark Matter: 23 ± 4%
  Dark Energy: 73 ± 4%
  Baryons: 4 ± 0.4%
  [Neutrinos: 0.5%]

- Two must be wrong to change this conclusion

- Stunning progress (cf.1998)

A less charitable view



OPEN PROBLEMS

What are dark matter and dark energy?
These problems appear to be completely different

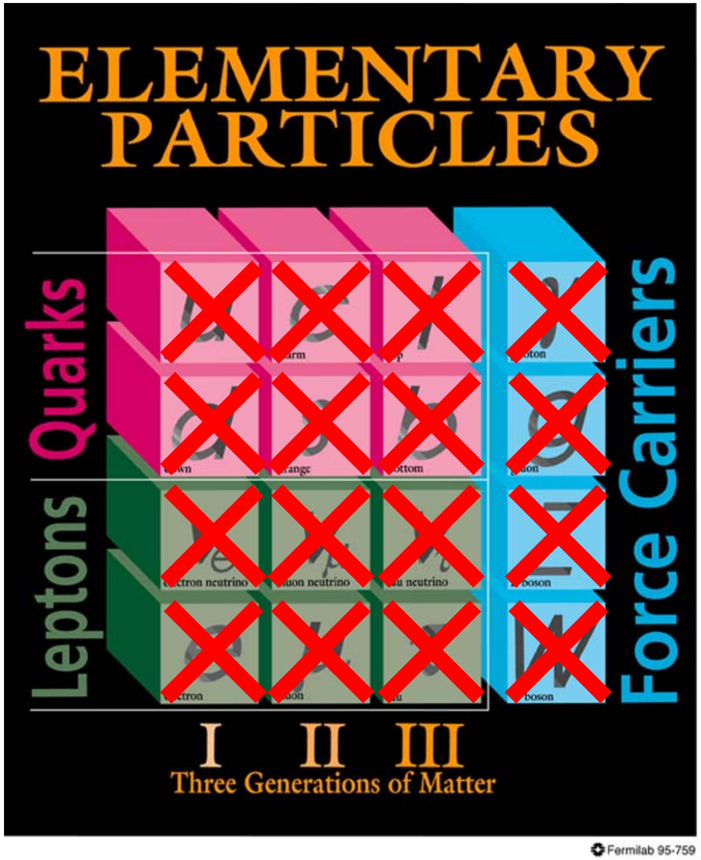
DARK MATTER

- 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

- Stable
- Cold
- Non-baryonic

DM: precise, unambiguous evidence for new physics

Dark Matter Candidates

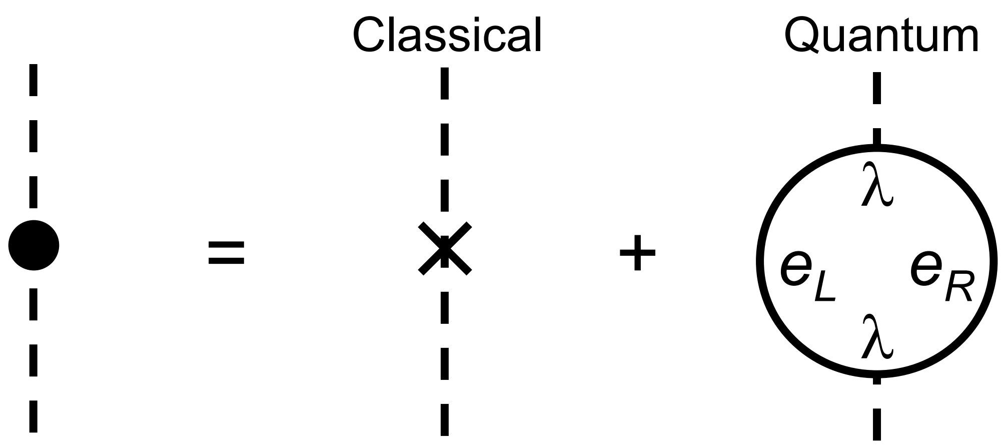
- The Wild, Wild West of particle physics: axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, branons…

- Masses and interaction strengths span many orders of magnitude

- But independent of cosmology, we expect new particles:

  electroweak symmetry breaking

The Problem with Electroweak Symmetry Breaking



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

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

We expect new physics (supersymmetry, extra dimensions, something!) at M_{weak}

Thermal Relic DM Particles

(1) Initially, DM is in thermal equilibrium:

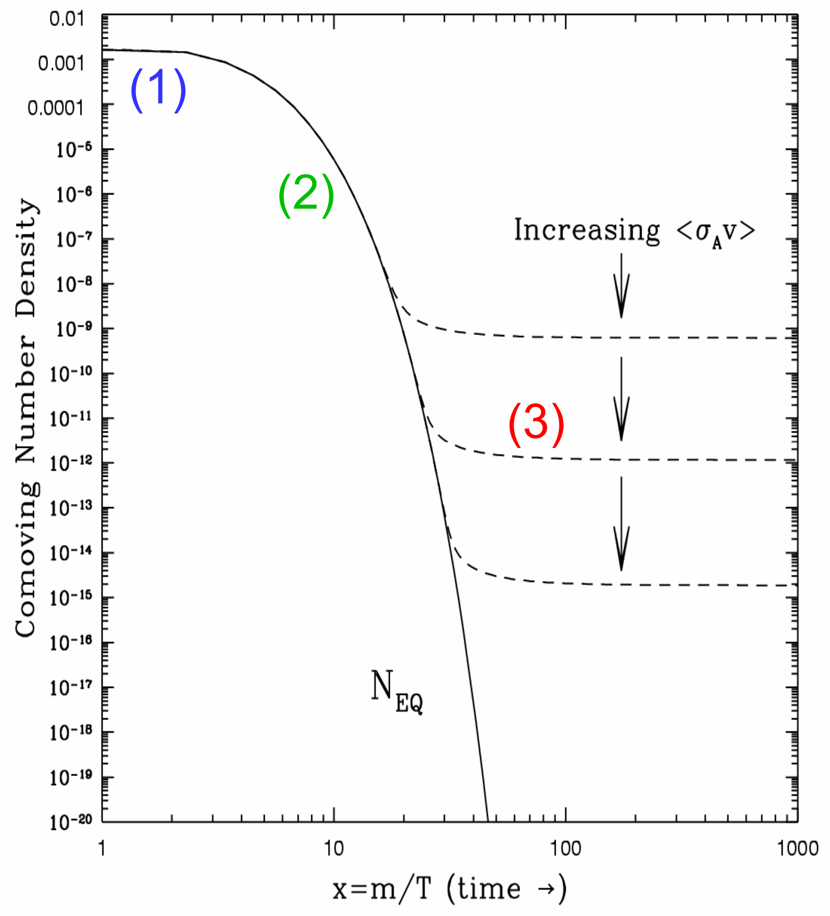
$$\chi\chi \leftrightarrow \bar{f} f$$

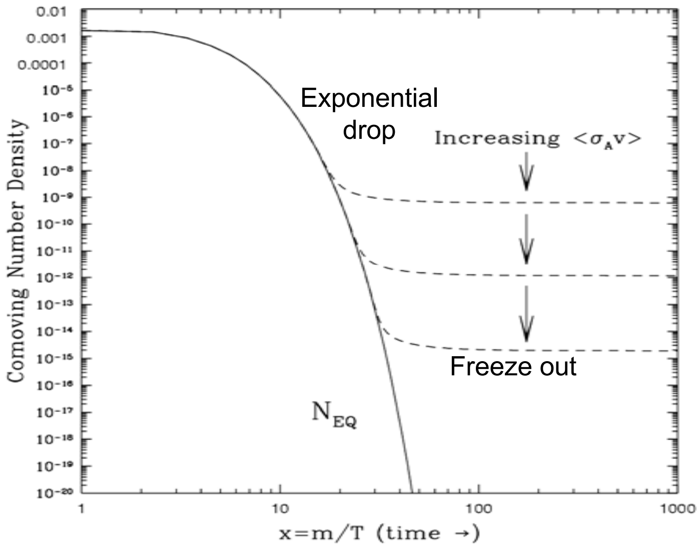
(2) Universe cools:

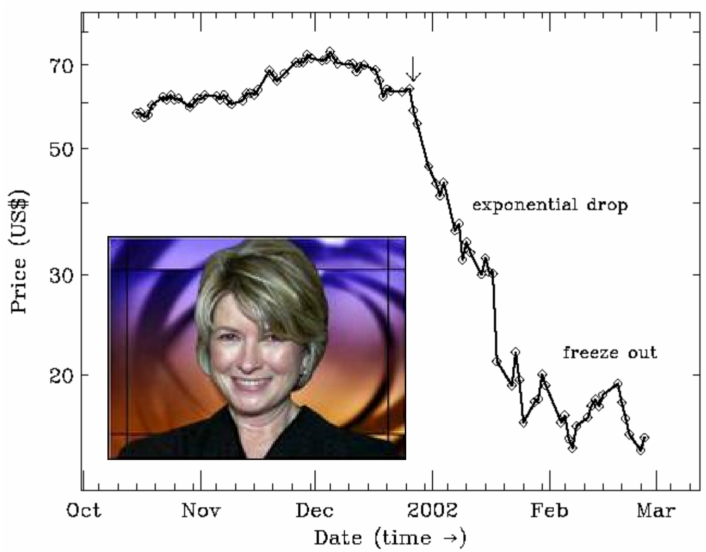
$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs "freeze out":

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







- Final *N* fixed by annihilation cross section:

$$\Omega_{DM} \sim 0.1\ (\sigma_{weak}/\sigma_A)$$

Just right if $\sigma_A \sim \sigma_{weak}$: remarkable!

- Domestic diva Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth serious investigation!

Dark Energy

- Minimal case: vacuum energy

- $p = w\, \rho$ Energy density $\rho \sim R^{-3(1+w)}$

Matter:	$\rho_M \sim R^{-3}$	$w = 0$
Radiation:	$\rho_R \sim R^{-4}$	$w = ⅓$
Vacuum energy:	$\rho_\Lambda \sim$ constant	$w = -1$

- $\Omega_\Lambda \approx 0.7 \rightarrow \rho_\Lambda \sim (\mathrm{meV})^4$

All Fields Contribute to Λ

- Quantum mechanics:

$$\tfrac{1}{2}\hbar\,\omega, \qquad \omega^2 = k^2 + m^2$$

- Quantum field theory:

$$\int^E d^3k\,(\tfrac{1}{2}\hbar\,\omega) \sim E^4,$$

where *E* is the energy scale where the theory breaks down

- We expect

$$(M_{\mathrm{Planck}})^4 \sim 10^{120}\,\rho_\Lambda \qquad (M_{\mathrm{SUSY}})^4 \sim 10^{90}\,\rho_\Lambda$$
$$(M_{\mathrm{GUT}})^4 \sim 10^{108}\,\rho_\Lambda \qquad (M_{\mathrm{weak}})^4 \sim 10^{60}\,\rho_\Lambda$$

One Approach

- Small numbers ↔ broken symmetry

$\rho_\Lambda \sim M_{Pl}^4$

??

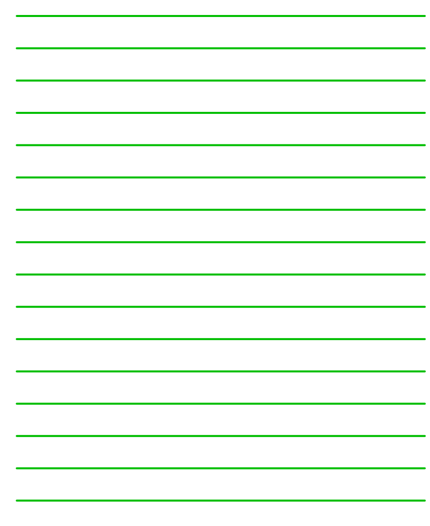
$\rho_\Lambda = 0$

$\rho_\Lambda \sim m_\nu^4,$
$(M_W^2/M_{Pl})^4, \ldots$

Another Approach

$\rho_\Lambda \sim M_{Pl}^4$

Many, densely spaced vacua (string landscape, many universes, etc.)



Anthropic principle:
$-1 < \Omega_\Lambda < 100$

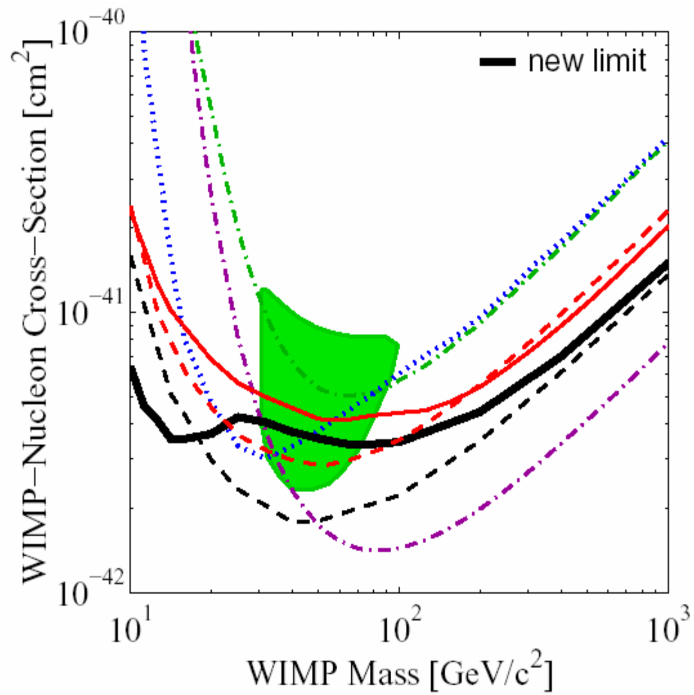
Weinberg (1989)

- Two very different approaches
- There are others, but none is especially compelling
- Dark energy: the black body radiation problem of the 21st century?
- Ways forward:
  - Discover a fundamental scalar particle (Higgs would be nice)
  - $(M_{weak})^4 \sim 10^{60}\ \rho_\Lambda$: map out the EW potential
  - $(M_{SUSY})^4 \sim 10^{90}\ \rho_\Lambda$: understand SUSY breaking
  - $(M_{GUT})^4 \sim 10^{108}\ \rho_\Lambda$: extrapolate to GUT scale
  - $(M_{Planck})^4 \sim 10^{120}\ \rho_\Lambda$: …

Prospects

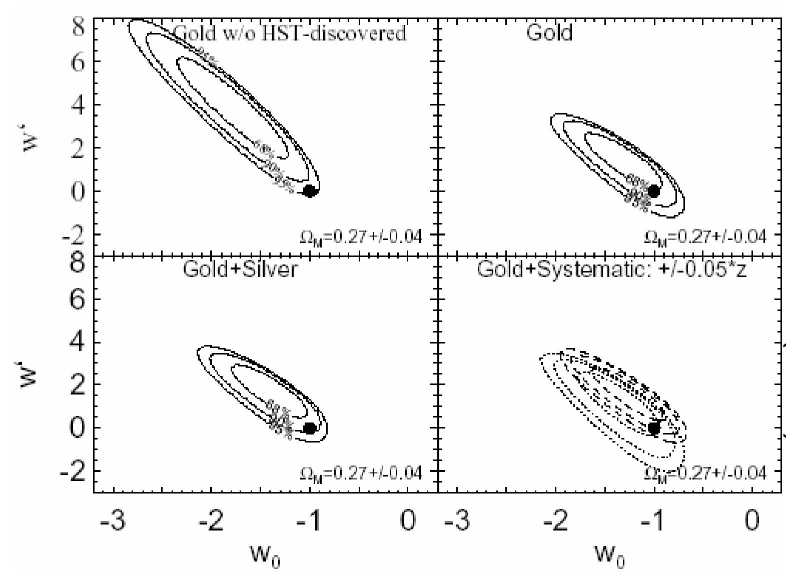
Dark Matter

Constrain *m*, σ



Dark Energy

Constrain *w*, *w'*



Riess et al. (2004)

Many other cosmological and astrophysical probes, but they are unlikely to lead to fundamental understandings of dark matter and dark energy

OPPORTUNITIES FOR THE LINEAR COLLIDER

- Detailed and exhaustive exploration of the weak scale is required to determine its contributions to dark matter

- This is true on general grounds:
  - EWSB → new particles at ~ TeV
  - Constraints → conservation laws → new stable particle
  - Relic density "coincidence" → new stable particle with significant Ω_{DM}

Peskin (2004)

Examples

- Supersymmetry
  - Superpartners
  - R-parity
  - Neutralino χ with significant Ω_{DM}

Goldberg (1983)

- Universal Extra Dimensions
  - Kaluza-Klein partners
  - KK-parity
  - Lightest KK particle with significant Ω_{DM}

Appelquist, Cheng, Dobrescu (2000)

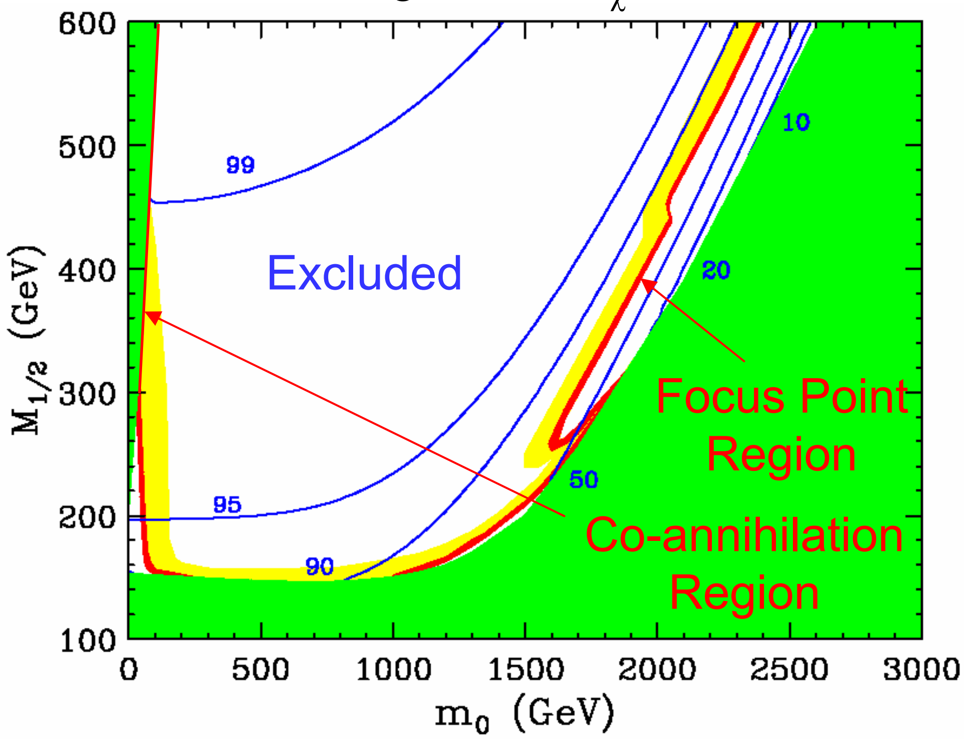
Servant, Tait (2002)

- Branes
  - Brane fluctuations
  - Brane-parity
  - Branons with significant Ω_{DM}

Cembranos, Dobado, Maroto (2003)

Supersymmetry

Regions of Ω_χ



Pre-WMAP Post-WMAP

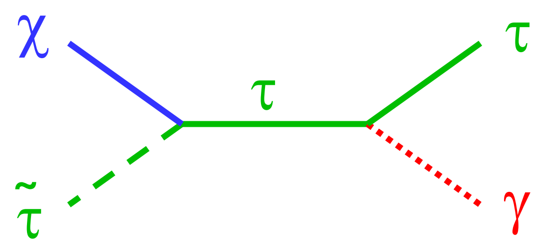
Cosmology excludes much of parameter space (Ω_χ too big)

Cosmology focuses attention on particular regions (Ω_χ just right)

Co-annihilation Region

- If other superpartners are nearly degenerate with the χ LSP, they can help it annihilate

Griest, Seckel (1986)



- Requires similar $e^{-m/T}$ for χ and $\tilde{\tau}$, so (roughly)

$$\Delta m < T \sim m_\chi/25$$

- Motivates theoretical studies of co-annihilation effects, and experimental studies of $\tilde{\tau} \to \tau\chi$ with Δm ~ few GeV

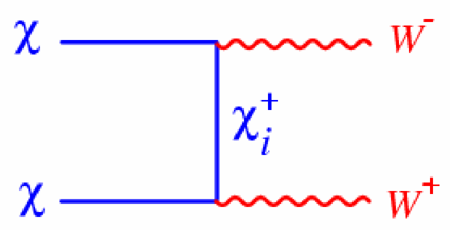
Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz (2002)
Ellis, Olive, Santoso, Spanos (2003)
Baer, Belyaev, Kruovnickas, Tata (2003)
Belanger, Boudjema, Cottrant, Pukhov, Semenov (2004)

Nauenberg et al.
Dutta, Kamon
Battaglia et al.
...

Focus Point Region

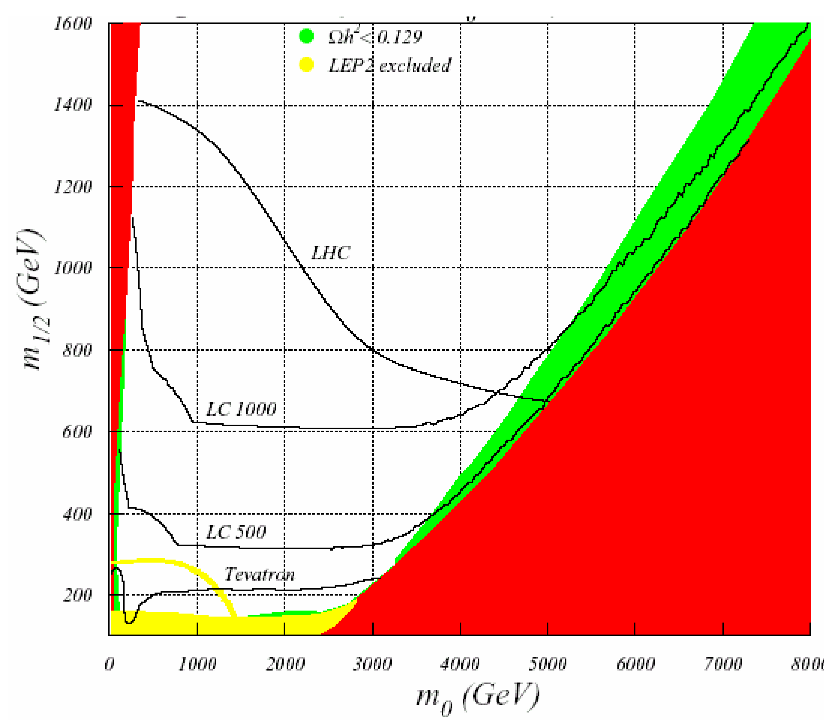
- Relic density can also be reduced if χ has significant Higgsino component to enhance

Feng, Matchev, Wilczek (2000)



- Motivates SUSY with
  - multi-TeV $\tilde{g}$, $\tilde{q}$, $\tilde{l}$
  - $\chi^{\pm}/\chi^0$ highly degenerate

- Such SUSY would be missed at LHC, discovered at LC



Baer, Belyaev, Krupovnickas, Tata (2003)

Synergy

Collider Inputs

Weak-scale Parameters

$\chi\chi$ Annihilation

χN Interaction

Particle Physics ↔ Cosmology : Freeze out at T = 10 GeV, t = 10^{-8} s
[Nuclear Physics ↔ Astrophysics : BBN at T = 1 MeV, t = 1 s]

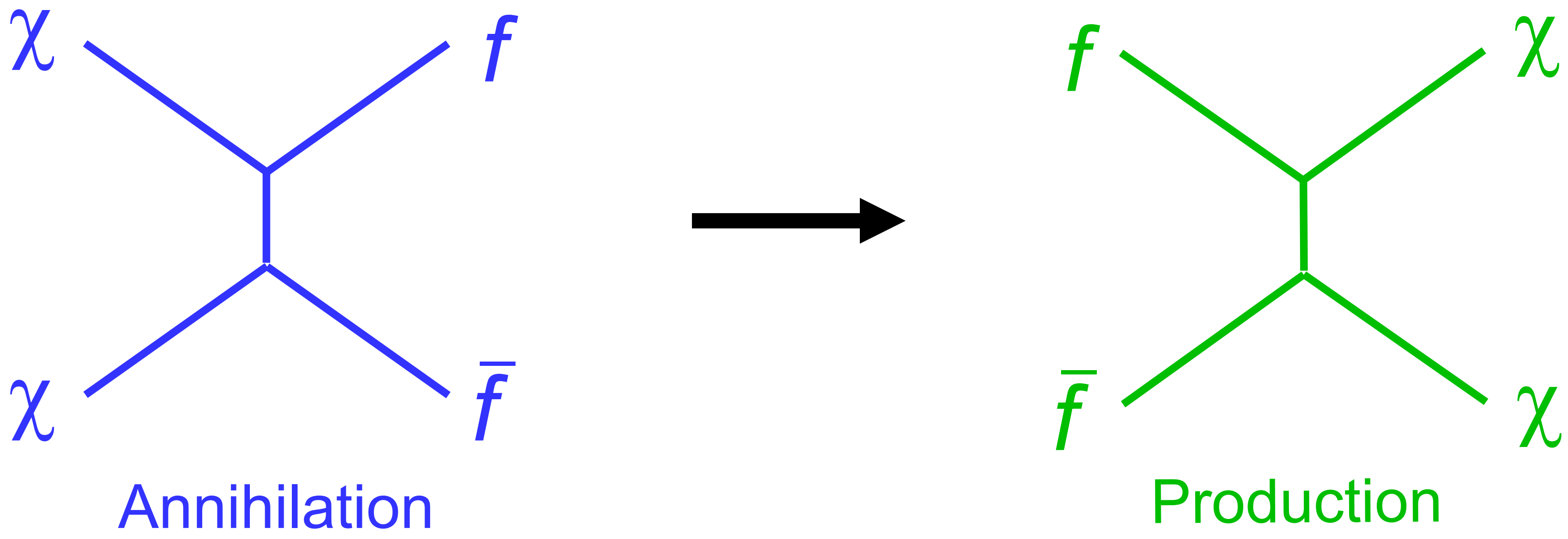
Relic Density

Indirect Detection

Direct Detection

Astrophysical and Cosmological Inputs

DM at Colliders: No-Lose Theorem



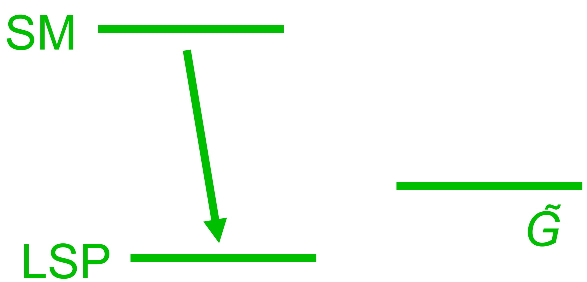
Correct relic density → efficient annihilation then

→ Efficient production now

No-Lose Theorem: Loophole

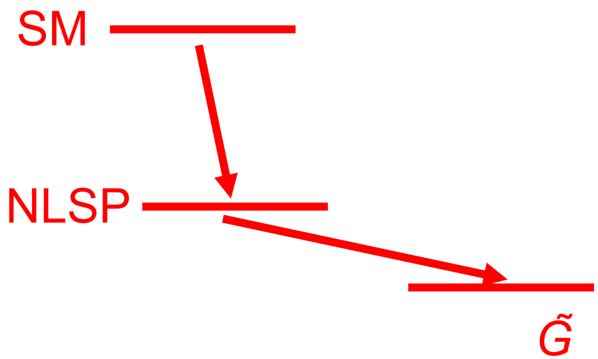
- SUSY predicts gravitinos: mass ~ M_W , couplings ~ M_W/M_{Pl}

- $\tilde{G}$ not LSP

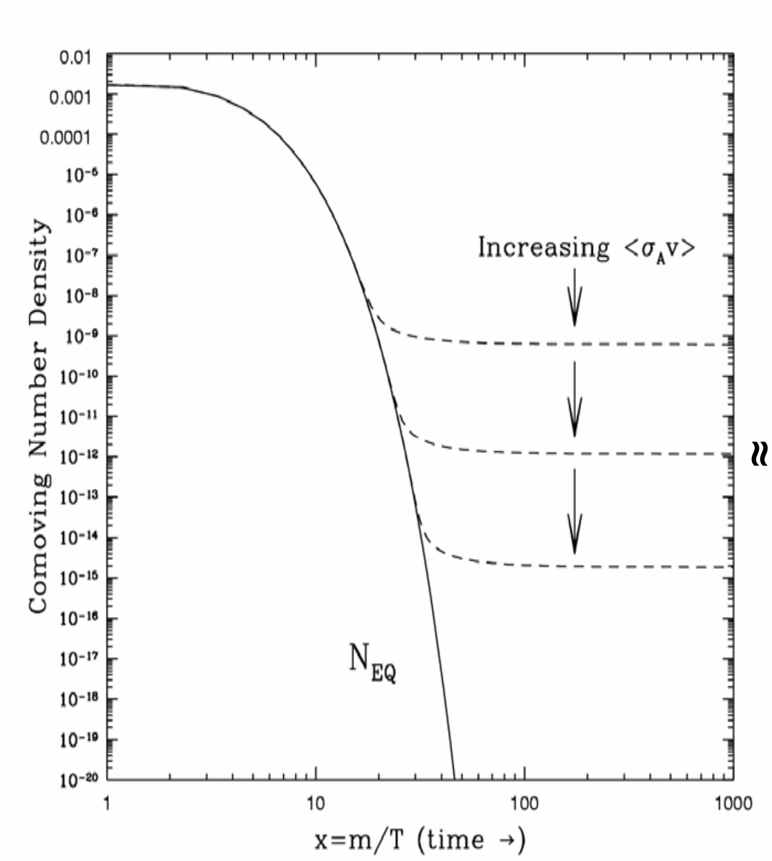


- Assumption of most of literature

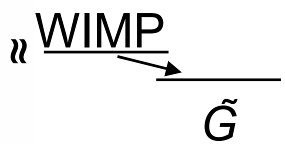
- $\tilde{G}$ LSP



- Completely different cosmology and phenomenology



- Assume gravitino is LSP. Early universe behaves as usual, WIMP freezes out with desired thermal relic density



$M_{Pl}^2/M_W^3 \sim$ year

- A year passes…then all WIMPs decay to gravitinos

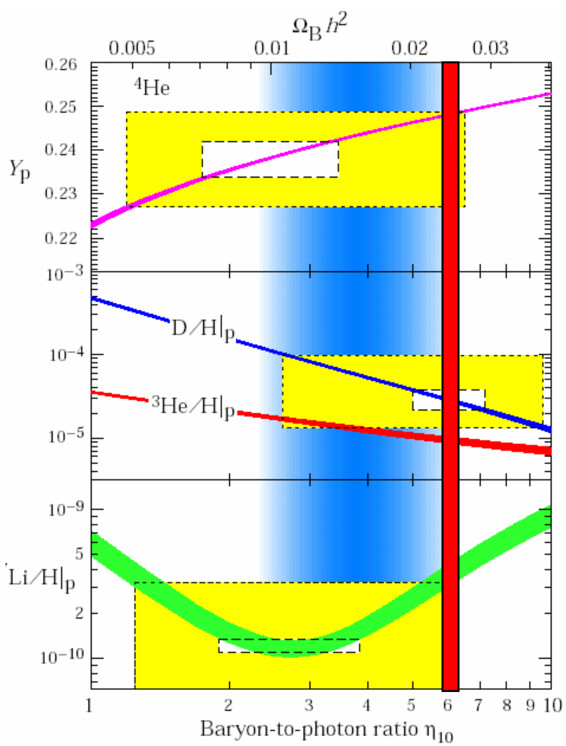
Gravitinos become dark matter, naturally inherit the right density, but are seemingly impossible to produce at colliders

SuperWIMPs

- Gravitinos are superweakly-interacting massive particles – "superWIMPs"
- all interactions are suppressed by $M_W/M_{Pl} \sim 10^{-16}$
- Are there *any* observable consequences?

Big Bang Nucleosynthesis

Late decays, $\tilde{\tau} \rightarrow \tau \tilde{G}$,…modify light element abundances



Fields, Sarkar, PDG (2002)

After WMAP

- $\eta_D = \eta_{CMB}$
- Independent ^{7}Li measurements are all low by factor of 3:

$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$
$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10}\ (1\sigma + \mathrm{sys})\ [28]$$
$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10}\ (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

- ^{7}Li is now a serious problem

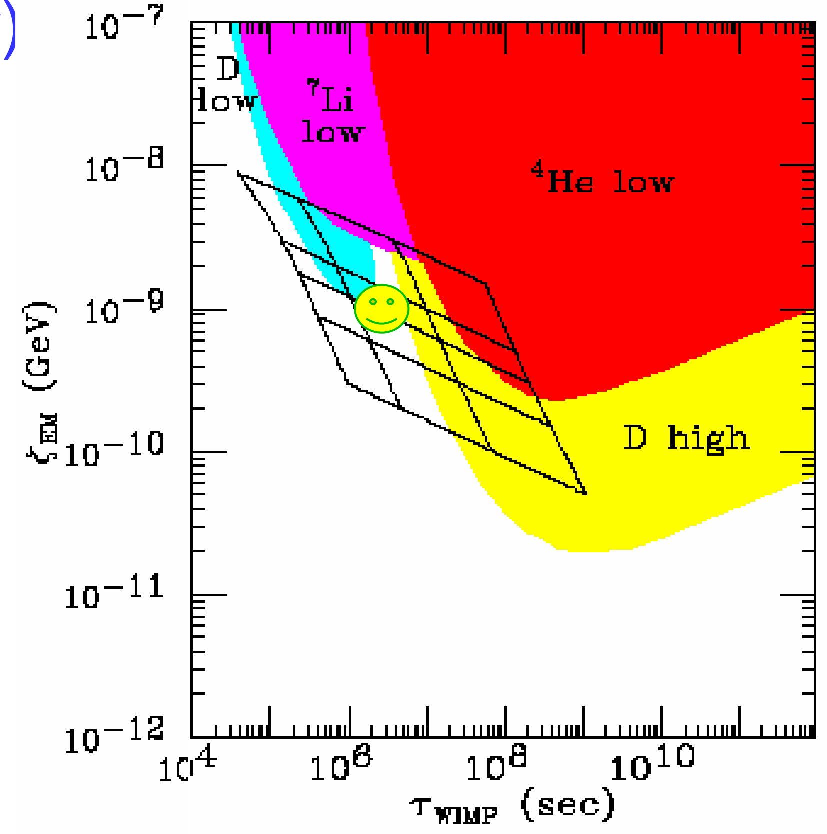
Jedamzik (2004)

Effects on BBN

- Consider $\tilde{\tau} \rightarrow \tilde{G}\, \tau$ (others similar)
  Its impact depends on
  - Decay time τ
  - Energy release ζ_{EM}

- Grid: Predictions for
  $m_{\tilde{G}}$ = 100 GeV – 3 TeV (top to bottom)
  Δm = 600 GeV – 100 GeV (left to right)

- SuperWIMP DM naturally explains ^{7}Li !



Feng, Rajaraman, Takayama (2003)

Collider Phenomenology

Drees, Tata (1990)
Goity, Kossler, Sher (1993)
Feng, Moroi (1996)
Hoffman, Stuart et al. (1997)
Acosta (2002)

Buchmuller, Hamaguchi, Ratz, Yanagida (2004)
Feng, Su, Takayama (2004)
Ellis, Olive, Santoso, Spanos (2004)
…

- Each SUSY event produces 2 metastable sleptons
  Spectacular signature: highly-ionizing charged tracks

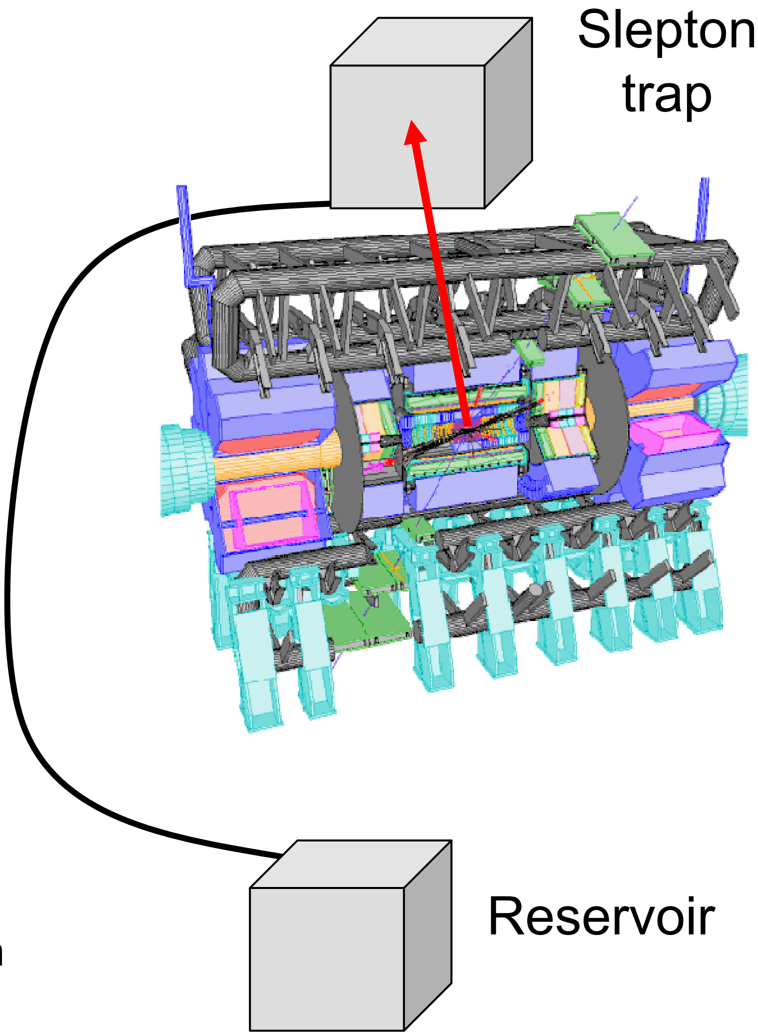
Current bound (LEP): $m_{\tilde{l}} > 99$ GeV

Tevatron Run II reach: $m_{\tilde{l}} \sim 150$ GeV

LHC reach: $m_{\tilde{l}} \sim 700$ GeV in 1 year

Slepton Trapping

- Sleptons live a year, so can be trapped then moved to a quiet environment to observe decays
- LHC: 10^6 sleptons/yr possible, but most are fast. By optimizing trap location and shape, can catch ~100/yr in 1000 m^3we.
- LC: tune beam energy to produce slow sleptons, can catch ~1000/yr in 1000 m^3we.



Feng, Smith

Measuring $m_{\tilde{G}}$ and M_*

- Decay width to $\tilde{G}$:

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

- Measurement of Γ → $m_{\tilde{G}}$
  - → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - → *F*. Supersymmetry breaking scale, dark energy
  - → Early universe (BBN, CMB) in the lab

- Measurement of Γ *and* E_l → $m_{\tilde{G}}$ *and* M_*
  - → Precise test of supergravity: gravitino is graviton partner
  - → Measurement of G_{Newton} on fundamental particle scale
  - → Probes gravitational interaction in particle experiment

CONCLUSIONS

IMPRESSIVE RECENT PROGRESS

FUNDAMENTAL OPEN PROBLEMS

EXTRAORDINARY OPPORTUNITIES FOR THE LINEAR COLLIDER