The Dark Universe

Progress, Problems, and Prospects

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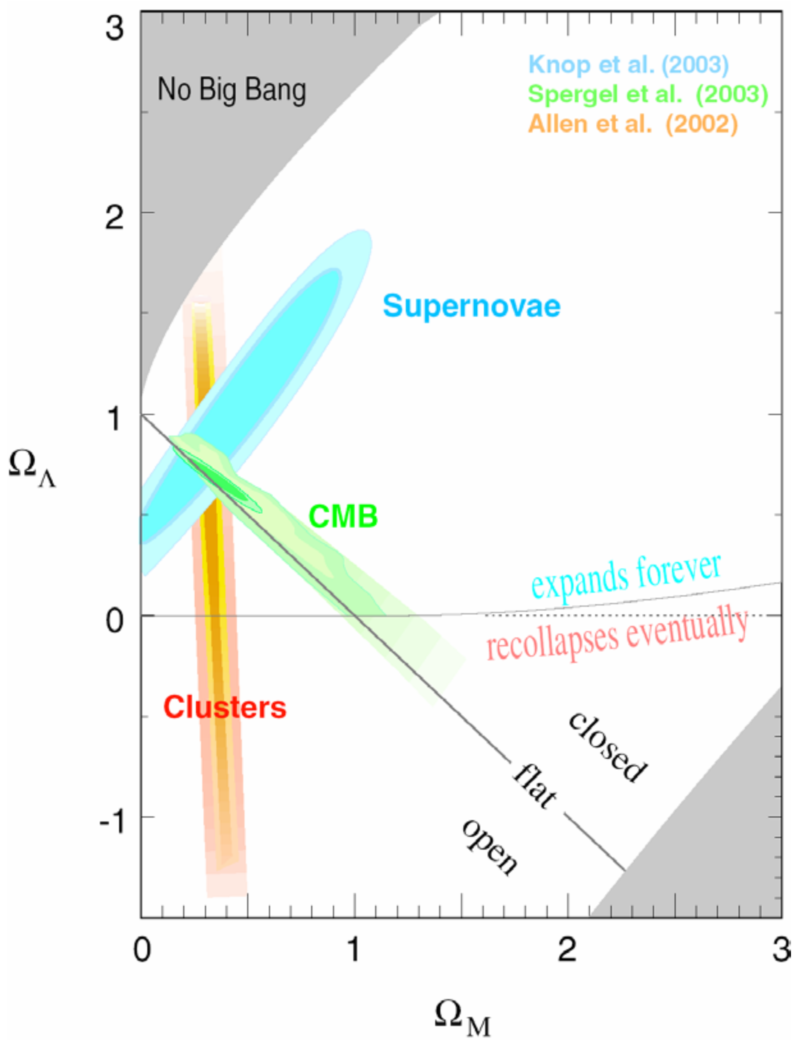
APS April Meeting, Denver
1 May 2004

PROGRESS

What is the Universe made of?

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

We live in interesting times: we now have a complete census of the Universe

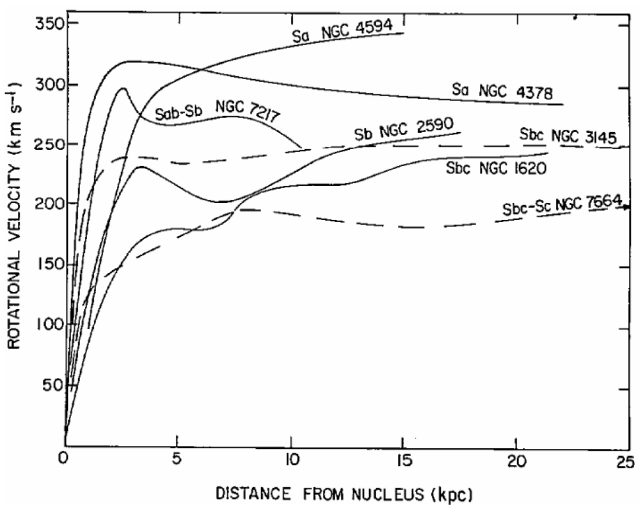


No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

"Clusters"

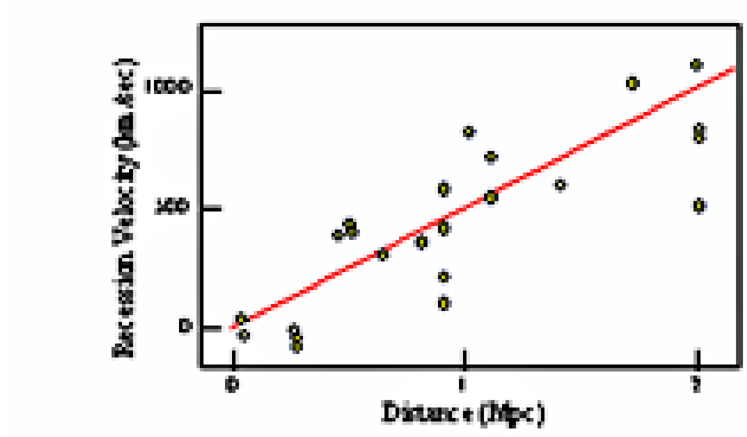
"Supernovae"

Then



Rubin, Ford, Thonnard (1978)

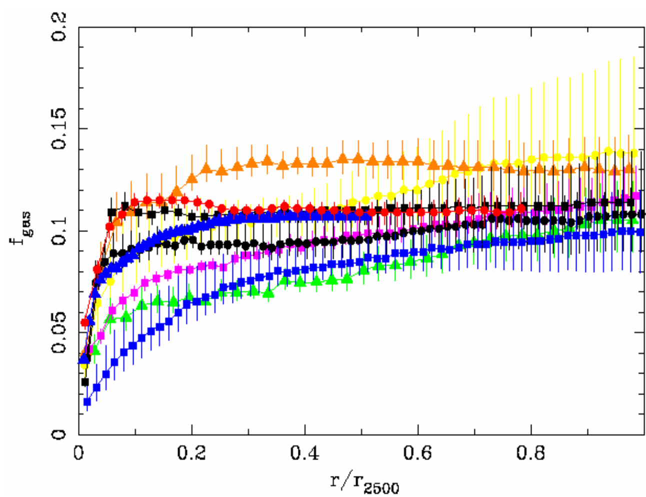
Constrains Ω_M



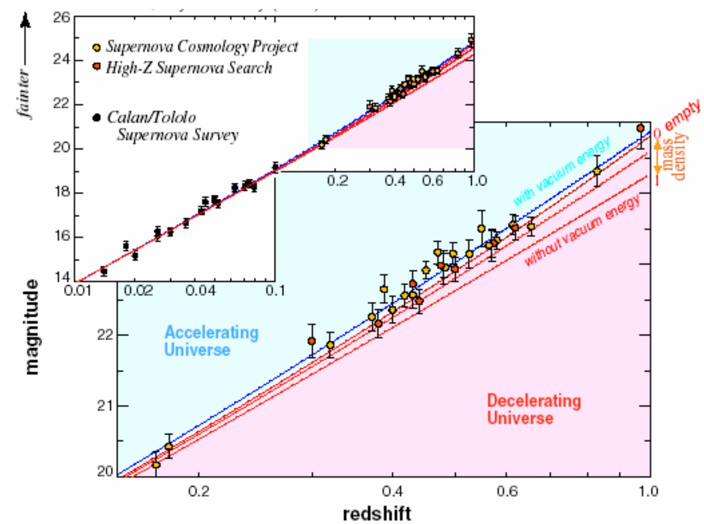
Hubble (1929)

Constrains $\Omega_\Lambda - \Omega_M$

Now



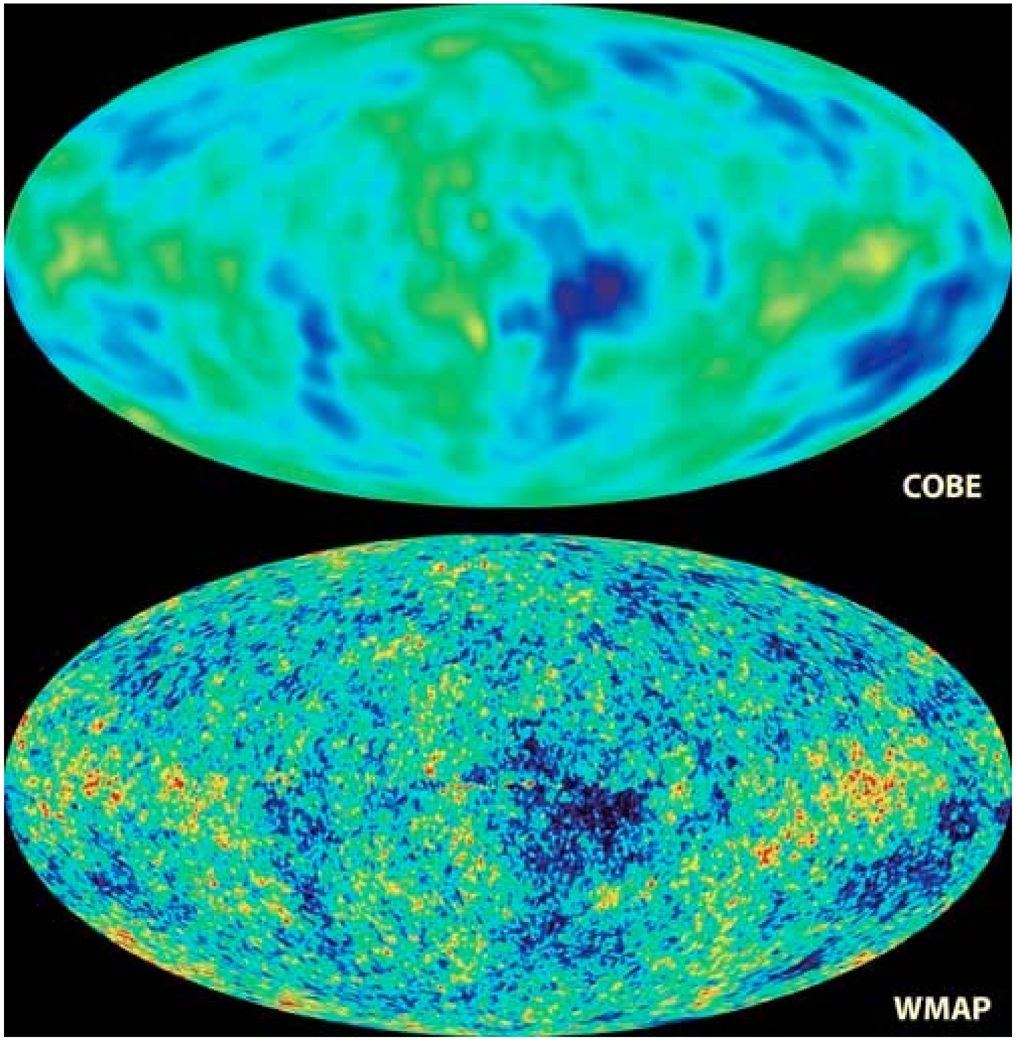
Allen, Schmidt, Fabian (2002)



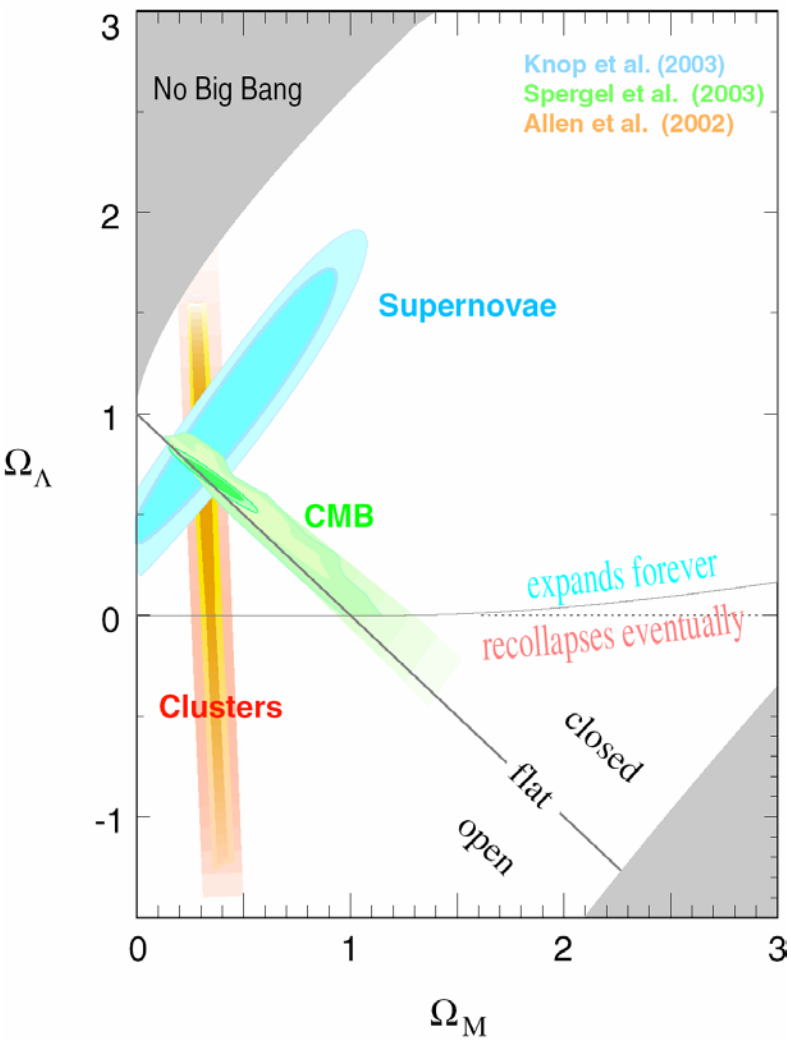
Cosmic Microwave Background

Then

Now



Constrains $\Omega_\Lambda + \Omega_M$



Three measurements agree:

Dark Matter: 25%
Dark Energy: 70%
[Baryons: 5%,
Neutrinos: 0.5%]

Two must be wrong to change this conclusion

A less charitable view

PROBLEMS

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

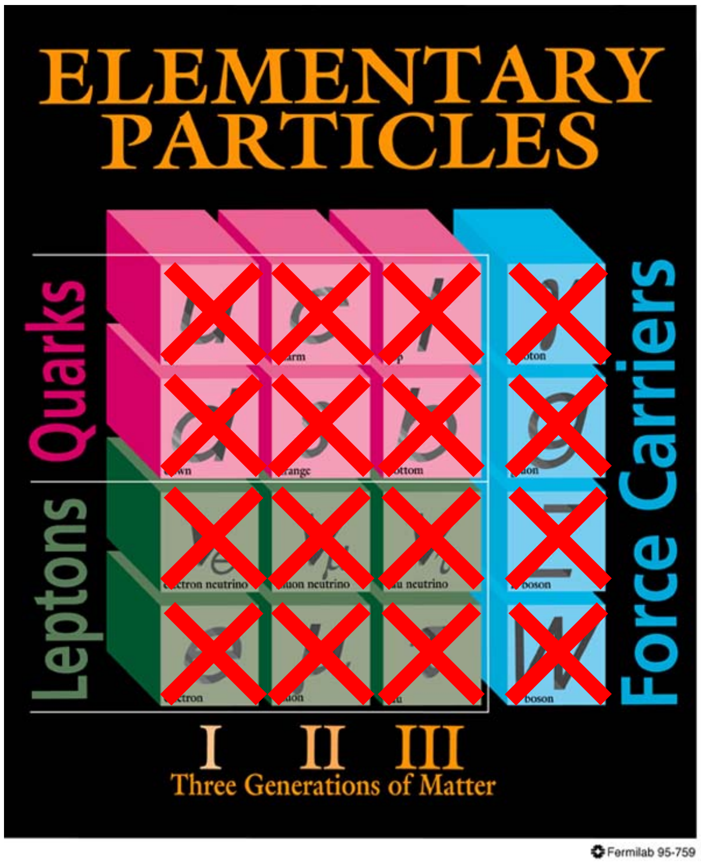
DARK MATTER

- 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 physics beyond the standard model

Dark Matter Candidates

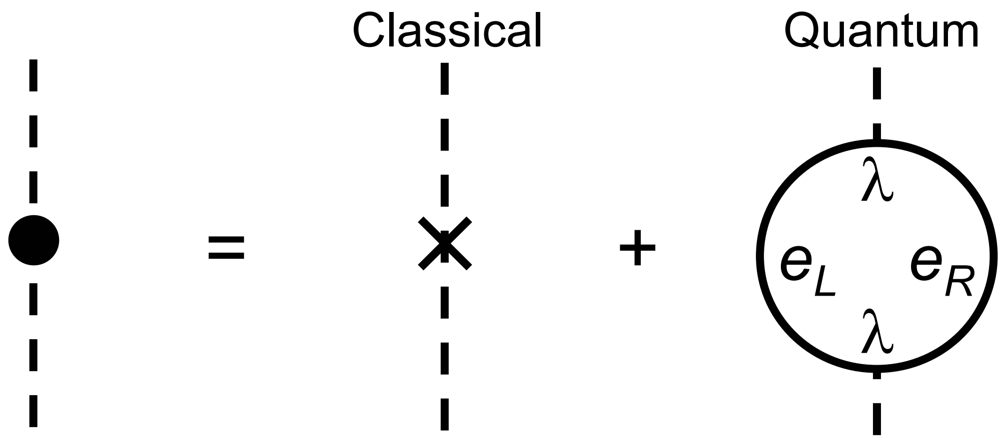
- The Wild, Wild West of particle physics: axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…

- 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:

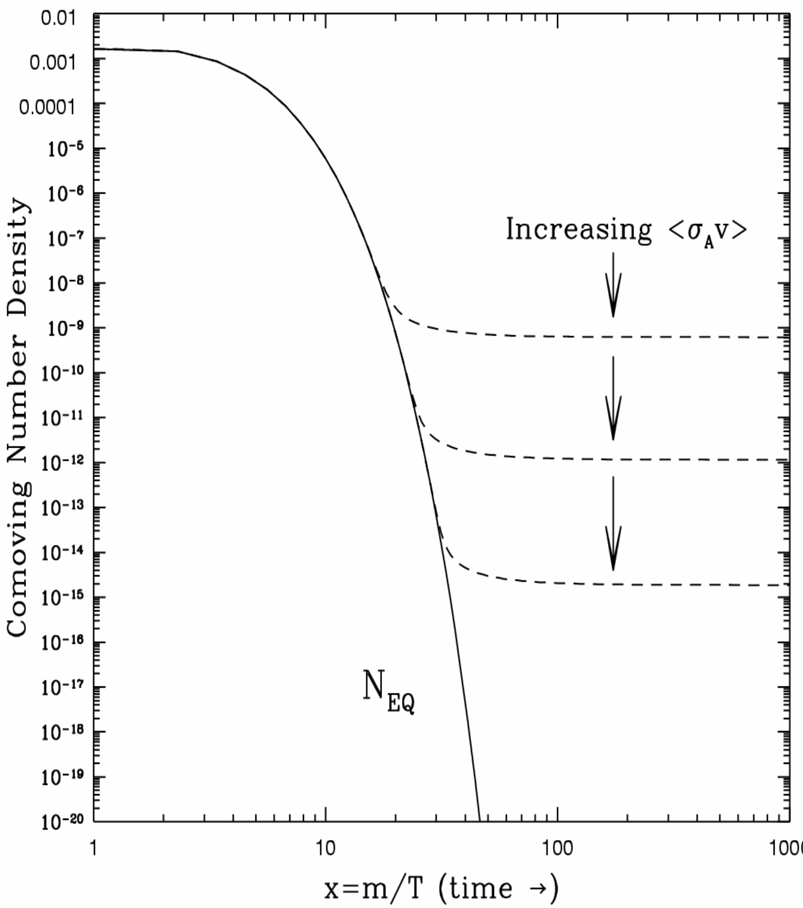
$$\chi\chi \leftrightarrow \bar{f} f$$

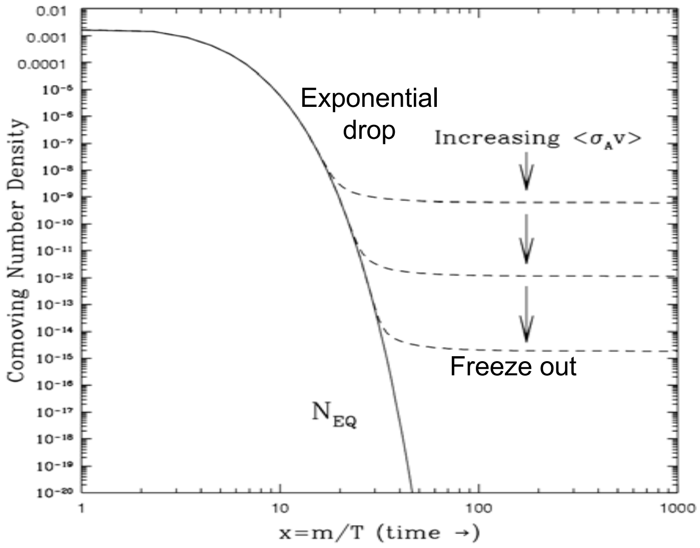
2) Universe cools:

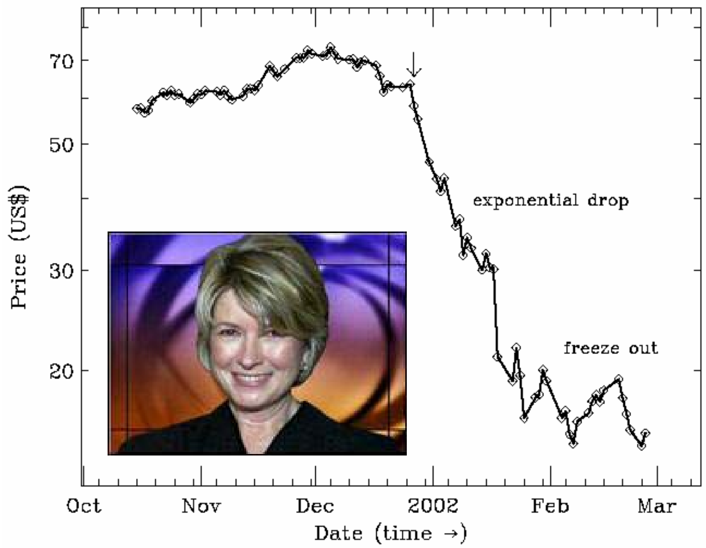
$$N = N_{EQ} \sim e^{-m/T}$$

3) χs "freeze out":

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







- Final *N* fixed by annihilation cross section:

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

  Remarkable!

- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth serious investigation!

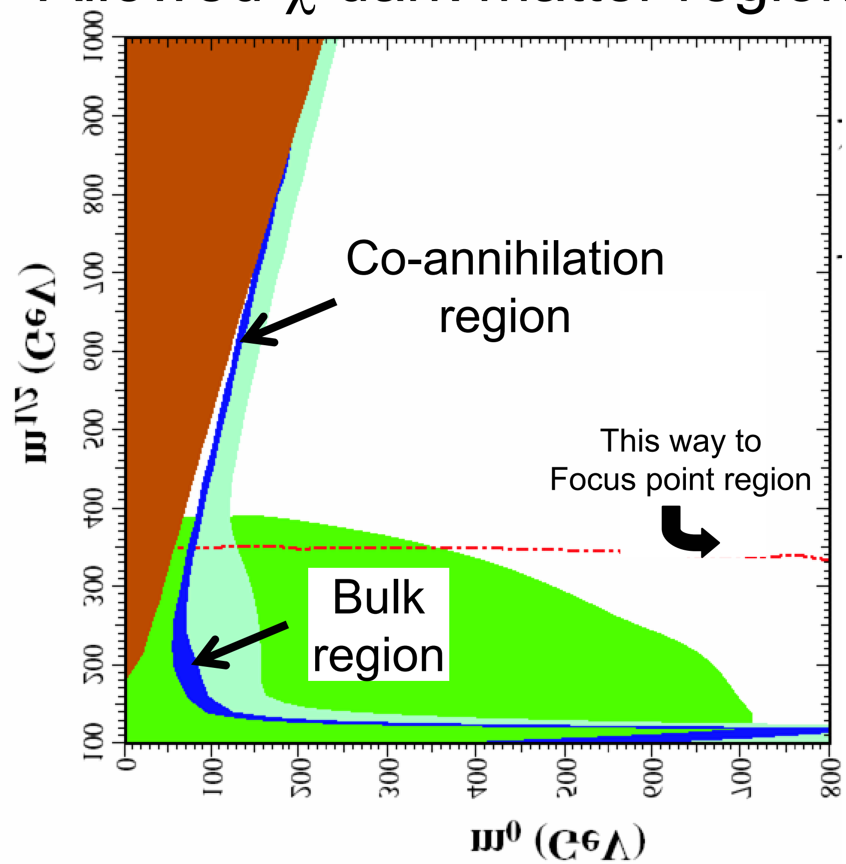
WIMP Dark Matter

- The thermal relic density constraint now greatly restricts model space

- For example: supersymmetry when the neutralino χ is the stable Lightest Supersymmetric Particle (LSP)

Goldberg (1983)

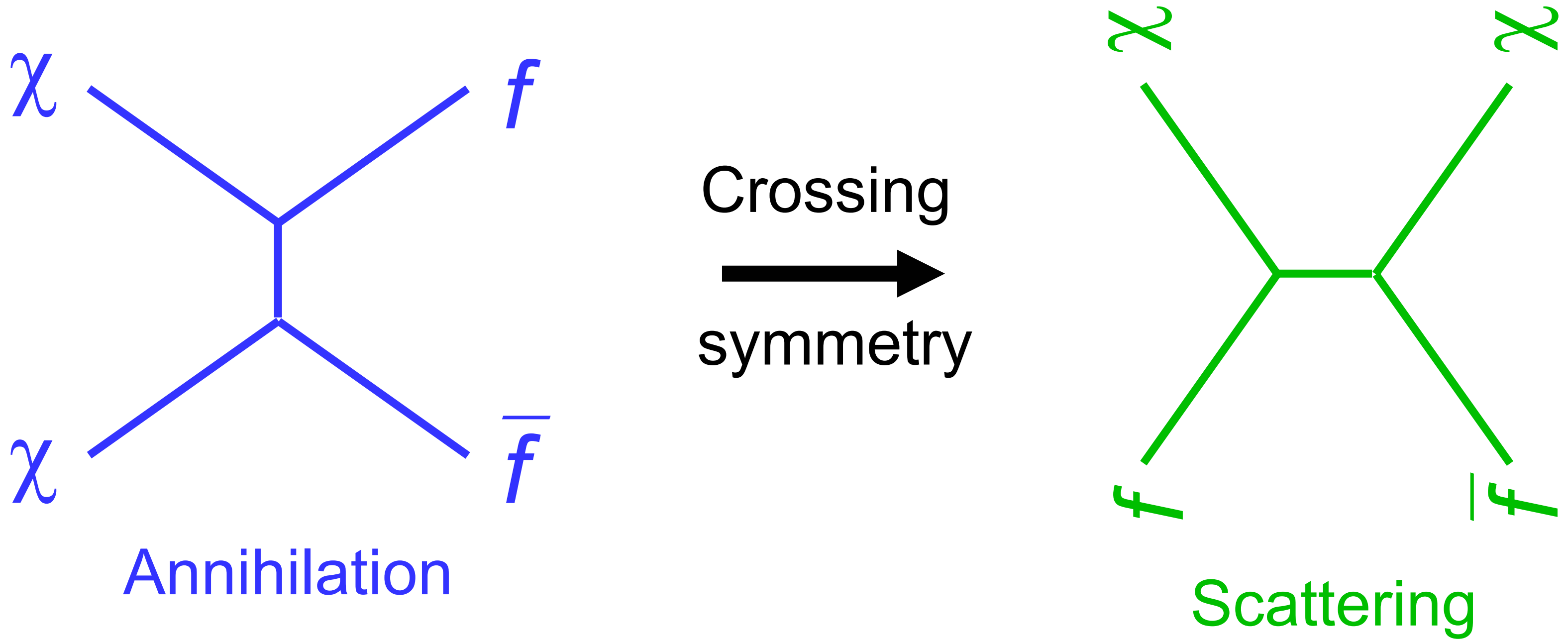
Allowed χ dark matter regions



Ellis, Olive, Santoso, Spanos (2003)

Light blue: pre-WMAP
Dark blue: post-WMAP

WIMP Detection: No-Lose Theorem

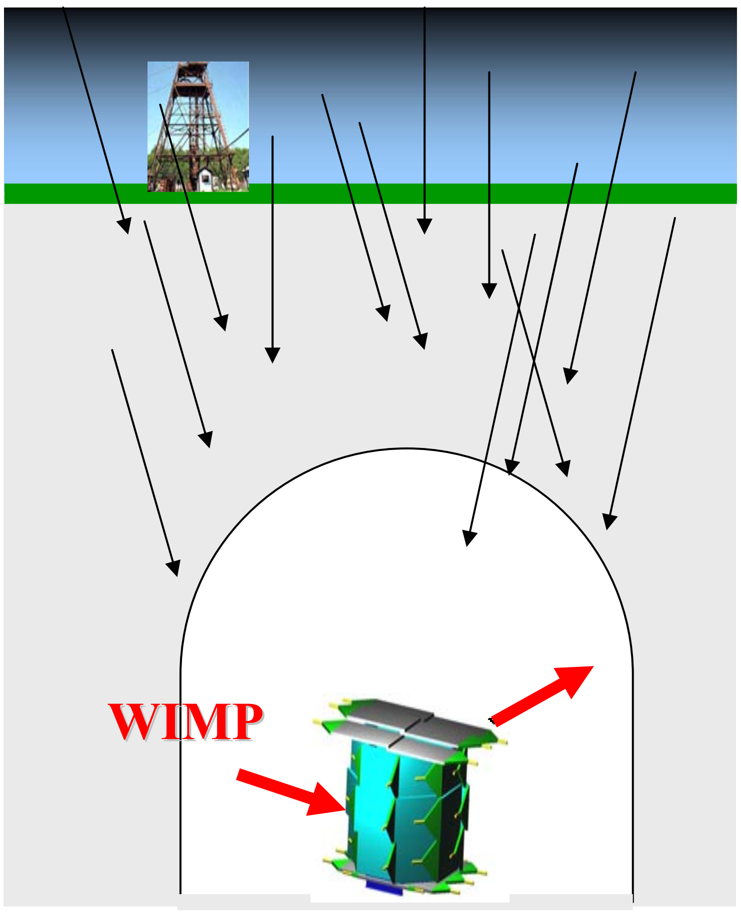


Correct relic density → efficient annihilation then

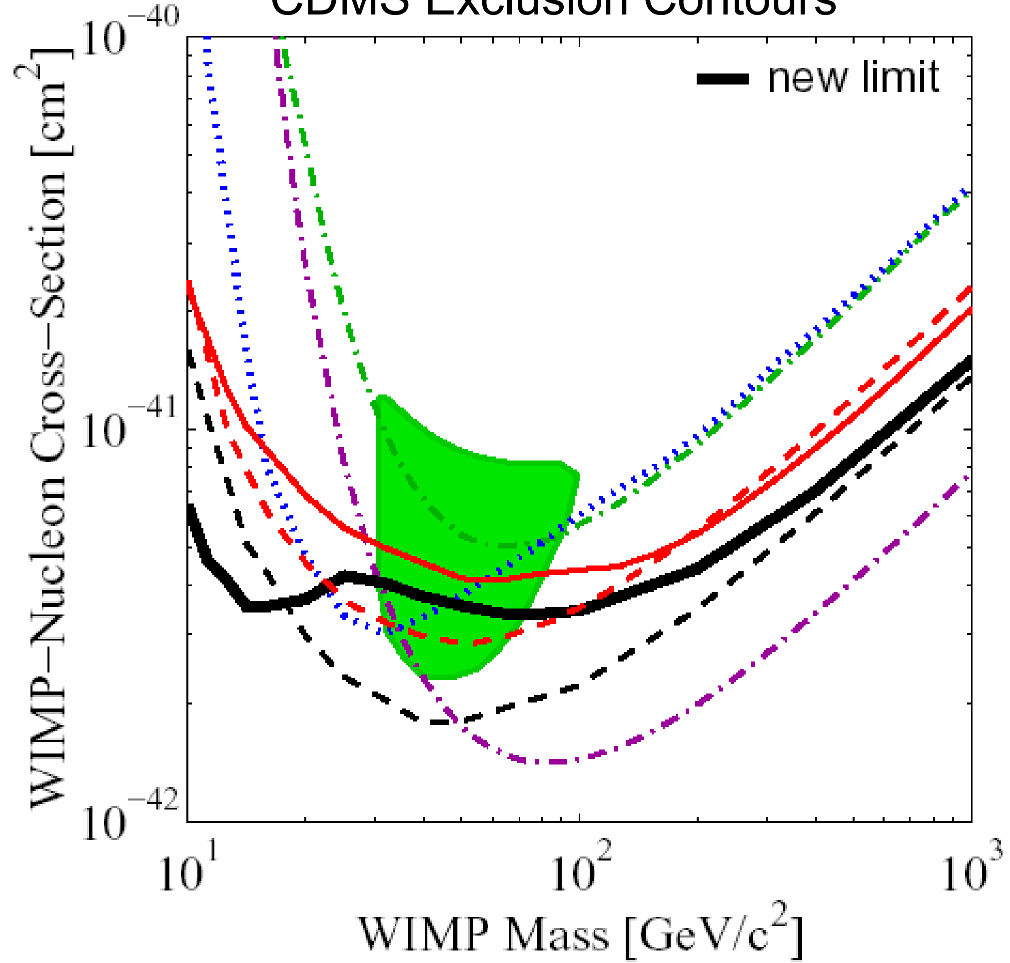
→ Efficient annihilation now

→ Efficient scattering now

Direct Detection

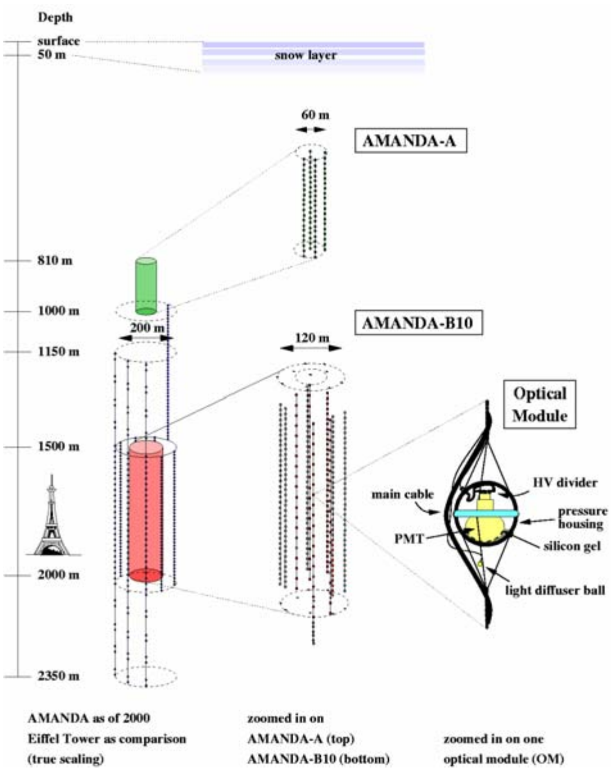


DAMA Signal and
CDMS Exclusion Contours



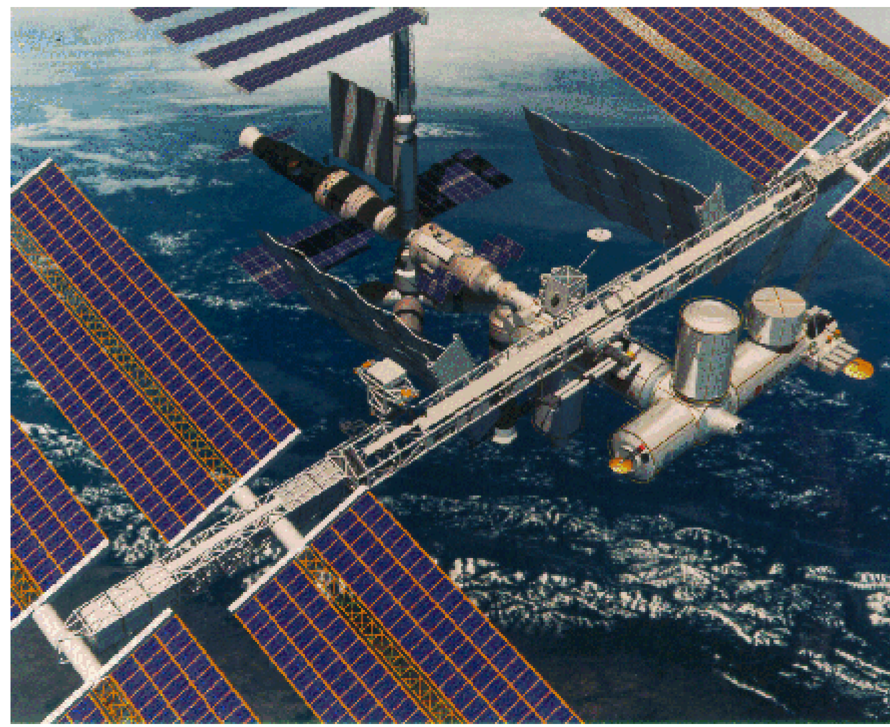
Indirect Detection

$\chi\chi \rightarrow$ neutrinos in the Sun



AMANDA in the Antarctic Ice

$\chi\chi \rightarrow$ positrons in the halo



AMS on the International Space Station

SuperWIMP Dark Matter

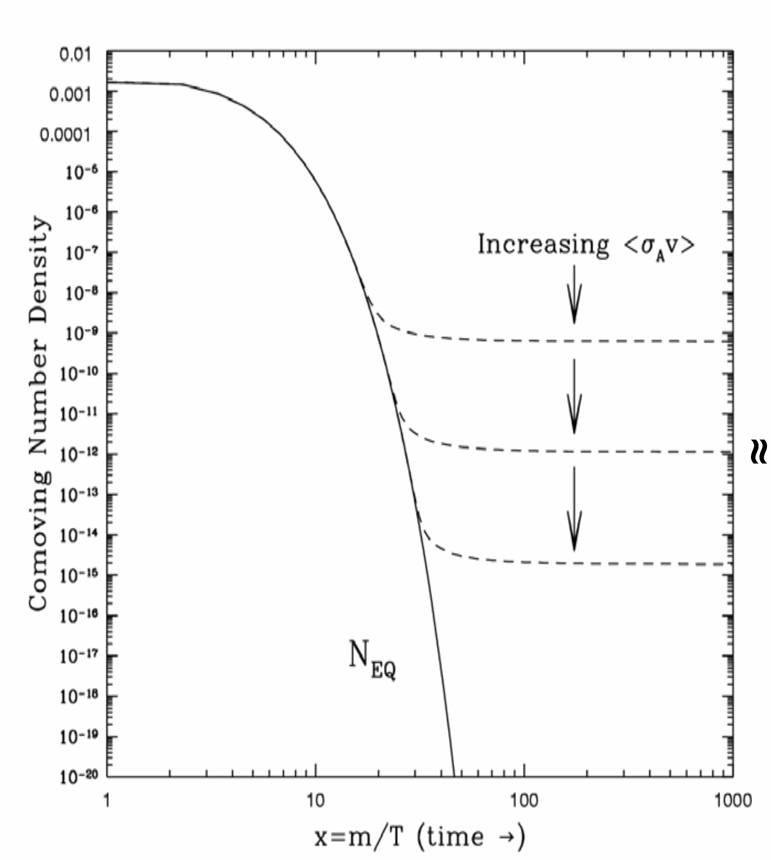
- Both SUSY and extra dimensions predict partner particles for all known particles. What about the gravitino $\tilde{G}$ or the 1st graviton excitation G^1?

- *Light* $\tilde{G}$ was actually the first SUSY DM candidate.

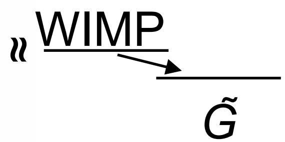
Pagels, Primack (1982)

- Can weak scale gravitinos be dark matter with naturally the right relic density?

No-Lose Theorem: Loophole



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



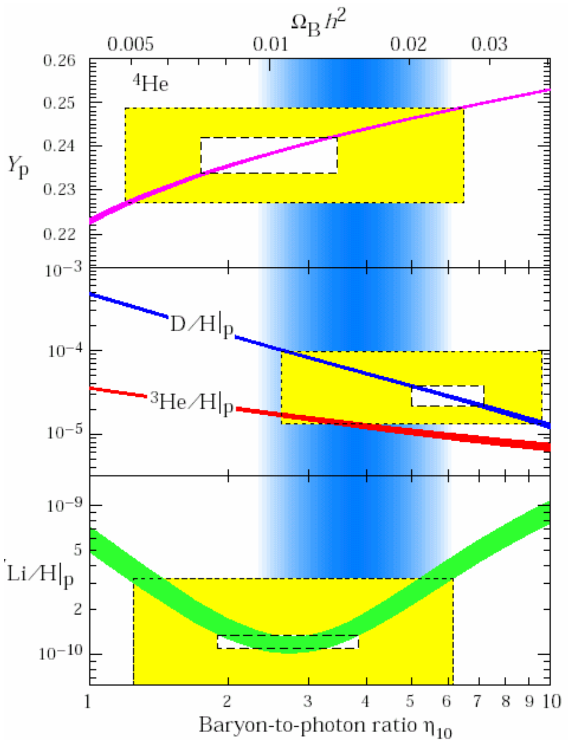
M_{Pl}^2/M_W^3 ~ year

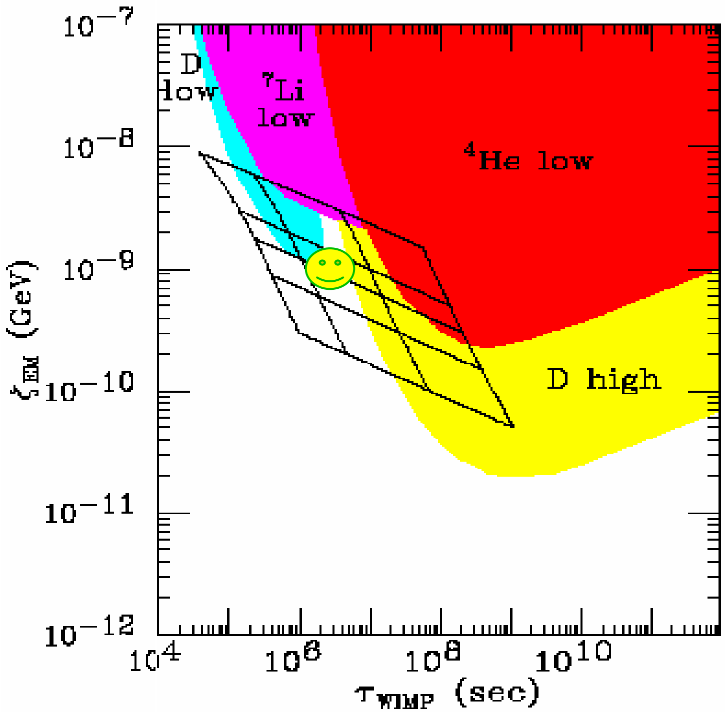
- A year passes…then all WIMPs decay to gravitinos

Gravitinos naturally inherit the right density, but escape all searches – they are superweakly-interacting “superWIMPs”

SuperWIMP Detection

- SuperWIMPs evade all conventional dark matter searches. But the late decays $\tilde{l} \rightarrow \tilde{G}\, l$ release energy that may be seen in BBN (or CMB μ distortions).





Feng, Rajaraman, Takayama (2003)

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	$w = -1$

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

All Fields Contribute to Λ

- Quantum mechanics:

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

- Quantum field theory:

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

where E is the energy scale where the theory breaks down

- We expect

$(M_{\text{Planck}})^4 \sim 10^{120} \rho_\Lambda$ $\qquad$ $(M_{\text{SUSY}})^4 \sim 10^{90} \rho_\Lambda$

$(M_{\text{GUT}})^4 \sim 10^{108} \rho_\Lambda$ $\qquad$ $(M_{\text{weak}})^4 \sim 10^{60} \rho_\Lambda$

One Approach

- Small numbers ↔ broken symmetry

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

↓ ??

$\rho_\Lambda = 0$

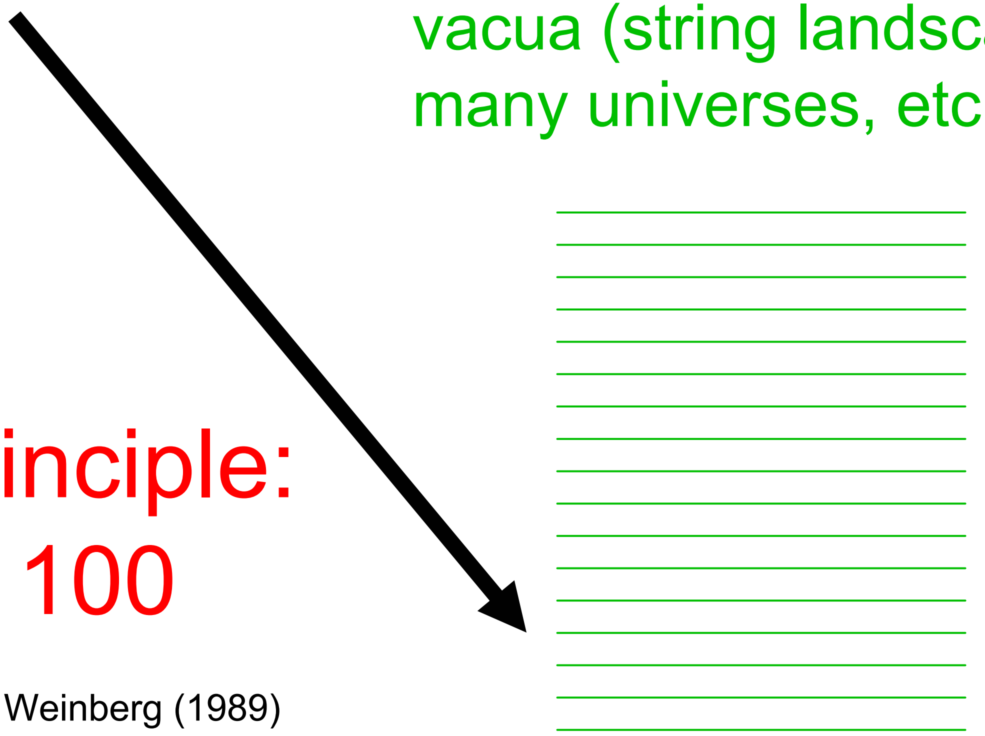
↗

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

Another Approach

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

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



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

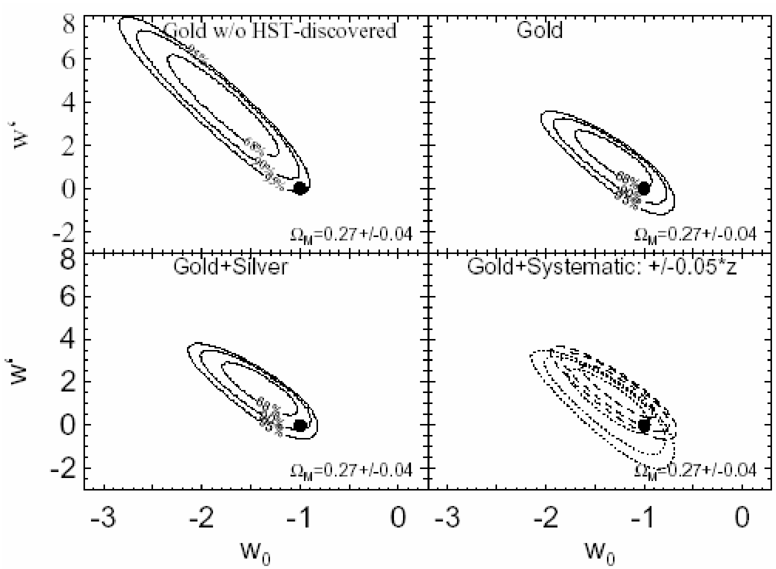
Weinberg (1989)

- Two very different approaches
- There are others, but none is especially compelling
- Dark energy: the black body radiation problem of the 21^{st} century?

PROSPECTS

Dark Energy

- Constrain *w* , *w'*



Riess et al. (2004)

- Discover a fundamental scalar particle (Higgs boson would be nice)

  Map out its potential with the LHC and e+e- Linear Collider

PROSPECTS

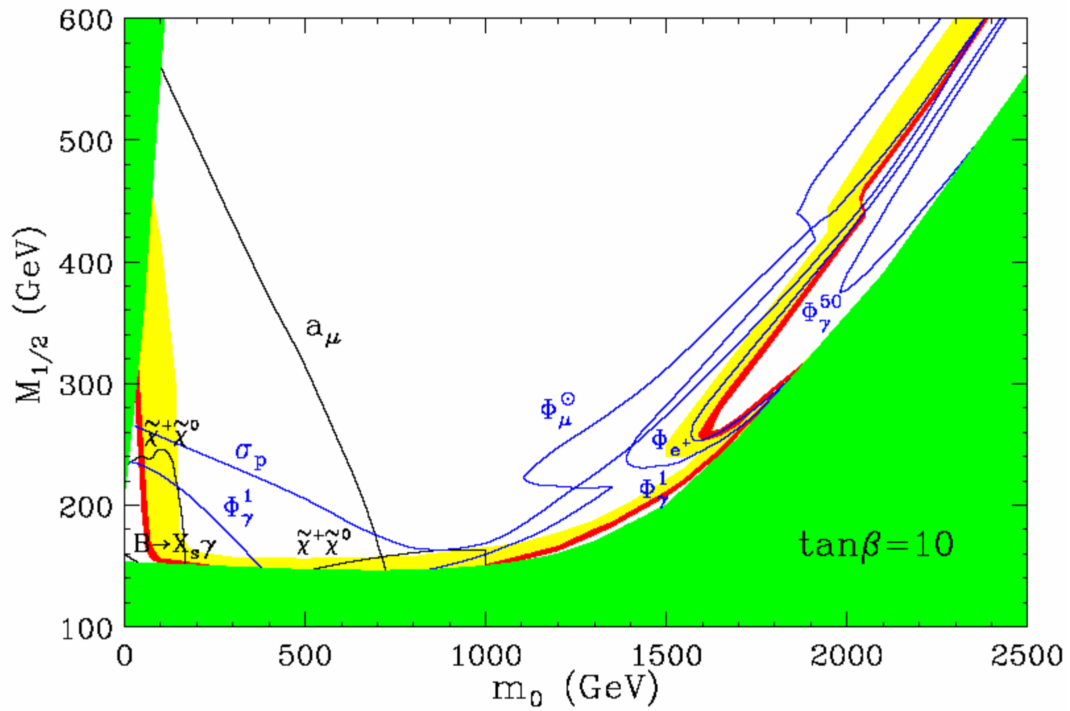
Dark Matter

If the relic density "coincidence" is no coincidence (WIMP or superWIMP DM), detection is likely this decade:

Particle experiments

Dark matter detectors

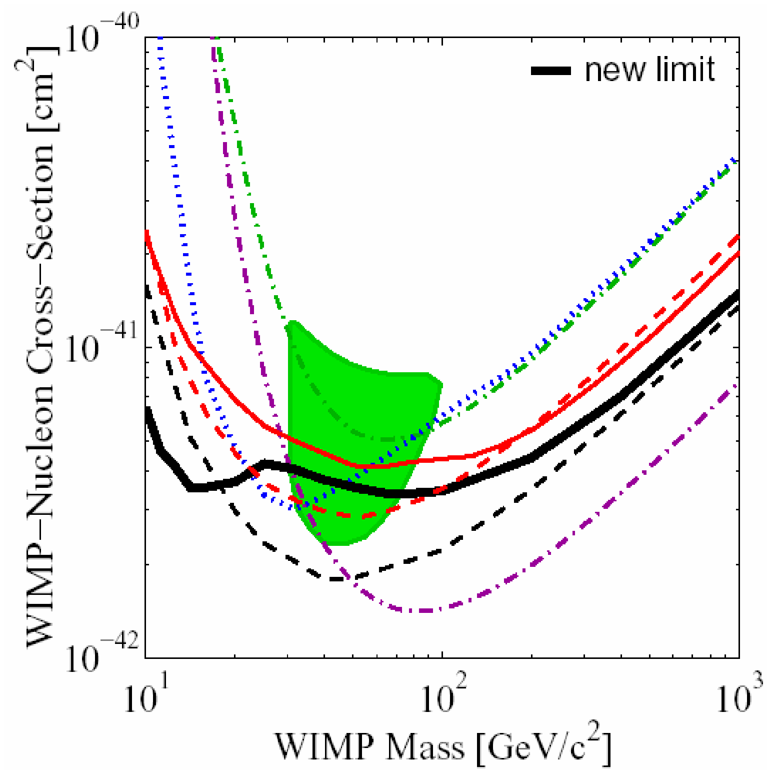
and the LHC



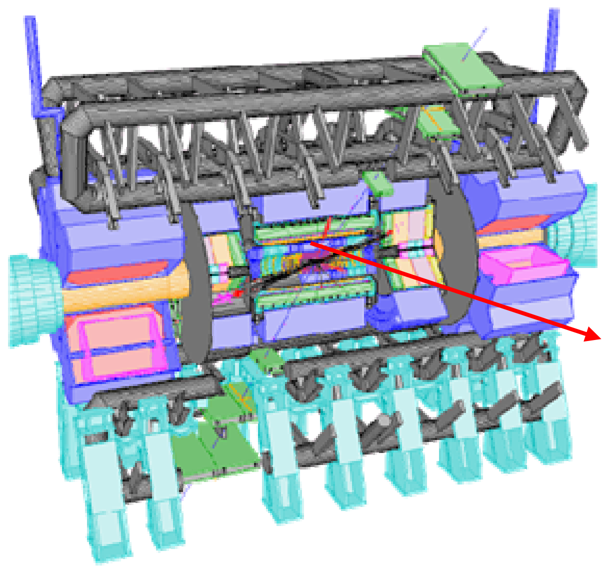
Feng, Matchev, Wilczek (2000)

What then?

- Cosmology can't discover SUSY

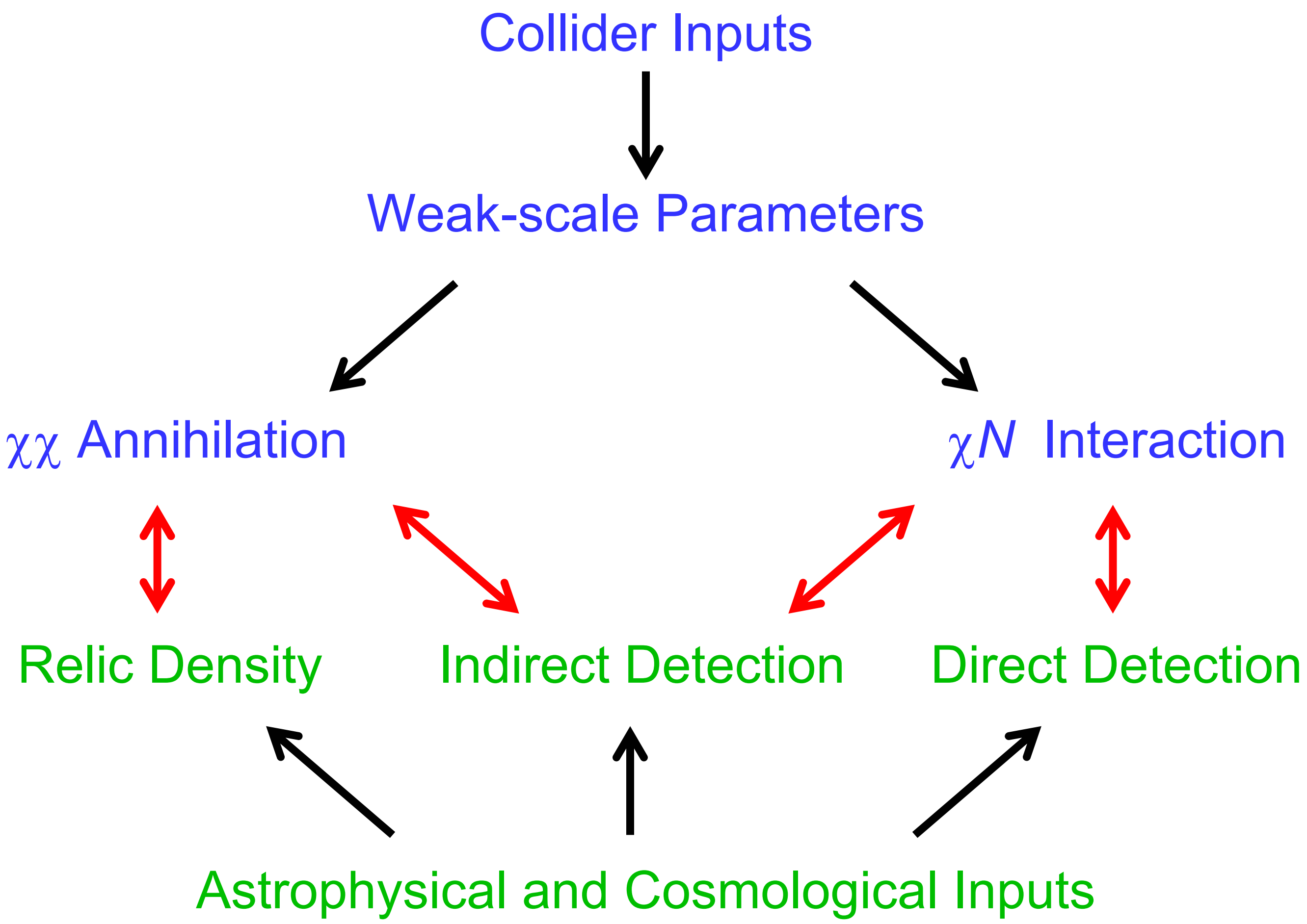


- Particle physics can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

Synergy


Collider Inputs
Weak-scale Parameters
χχ Annihilation
χN Interaction
Relic Density
Indirect Detection
Direct Detection
Astrophysical and Cosmological Inputs

Colliders as Dark Matter Labs

- The LHC and an e^+e^- Linear Collider will discover WIMPs and determine their properties.

- The Linear Collider will be able to determine SUSY parameters at the % level. Consistency of

WIMP properties (particle physics)
WIMP abundance (cosmology)

pushes our understanding of the Universe back to

T = 10 GeV, $t = 10^{-8}$ s

(Cf. BBN at T = 1 MeV, t = 1 s)

CONCLUSIONS

The Dark Universe

Extraordinary progress

Fundamental problems

Bright prospects