Connecting Cosmology & the Linear Collider

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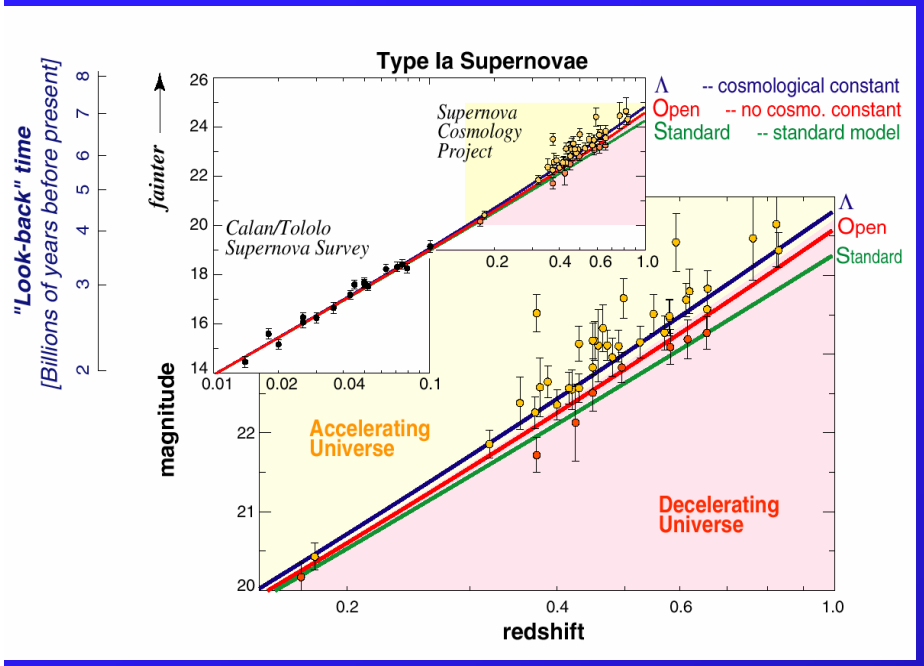
Outline

- The Big Unknowns in Modern Cosmology
- Dark Matter
- Baryogenesis
- Cosmic Rays (brief)
- Dark Energy and Inflation (!)

A basic bottom line

Particle physics and cosmology, as disciplines independent of one another, no longer exist. Our most fundamental questions are now the same and we are approaching them in complementary ways.

Supernovae Ia



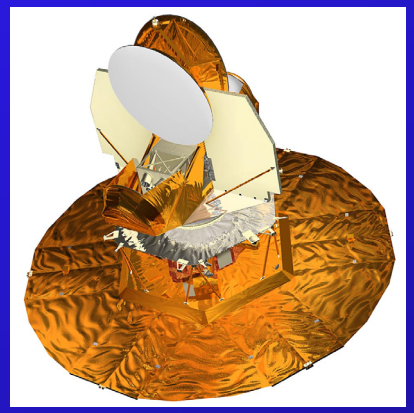
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

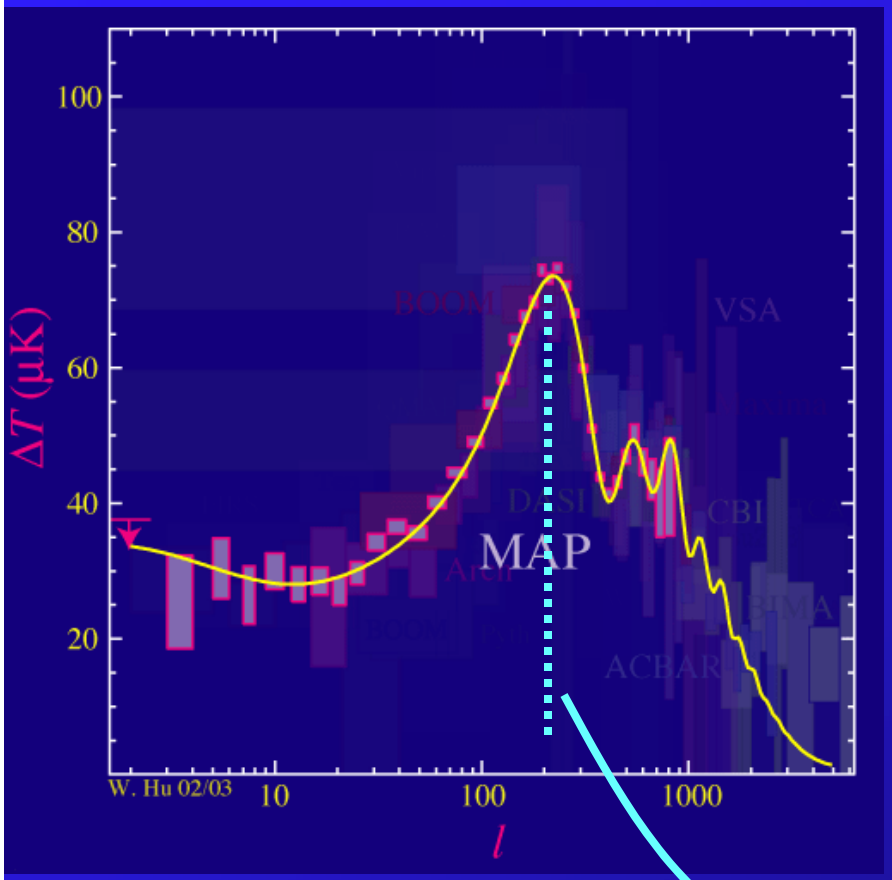
- Positive pressure matter slows the expansion
- Negative pressure matter speeds up the expansion
- So SN IA results depend on Ω_{matter}-Ω_{Λ}

(like throwing up a ball and having it accelerate away!)

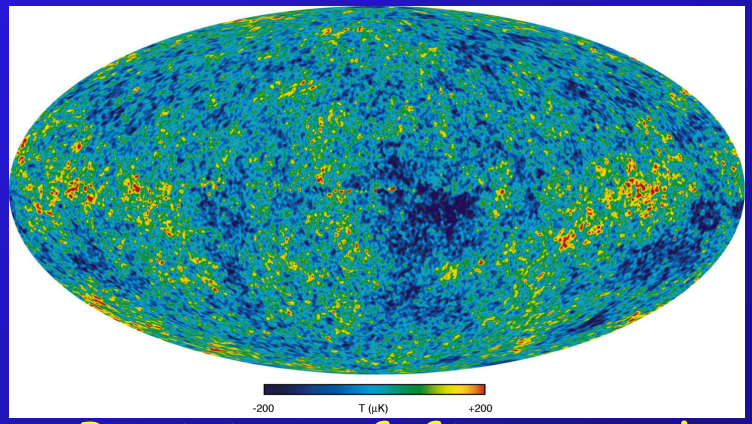
Putting it Together w/the CMB

Increasingly precise CMB measurements
(WMAP, Boomerang, Maxima, DASI, CBI, …)





(Wayne Hu, 2003)

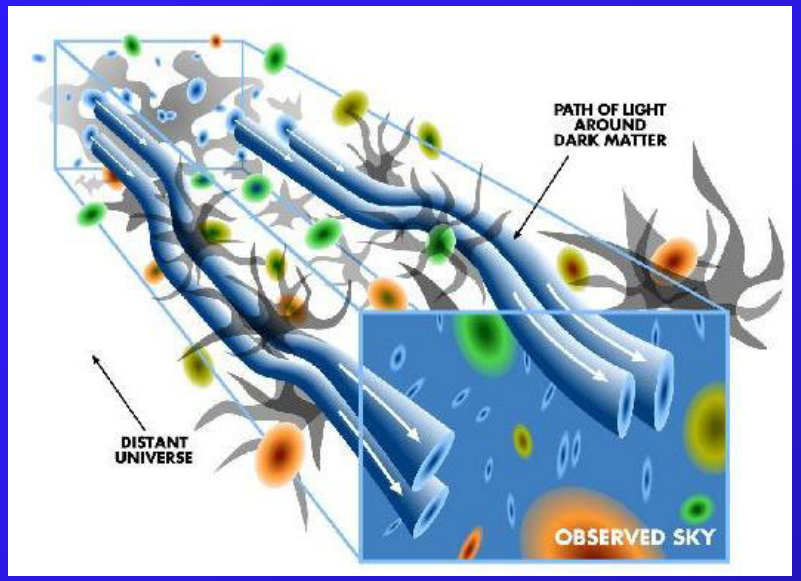


- Position of first peak depends on spatial geometry of universe
- Depends ~ $\Omega_{tot}=\Omega_{matter}+\Omega_{DE}$

$$\Omega_{tot} = 1.02 \pm 0.02$$

and Measures of Dark Matter

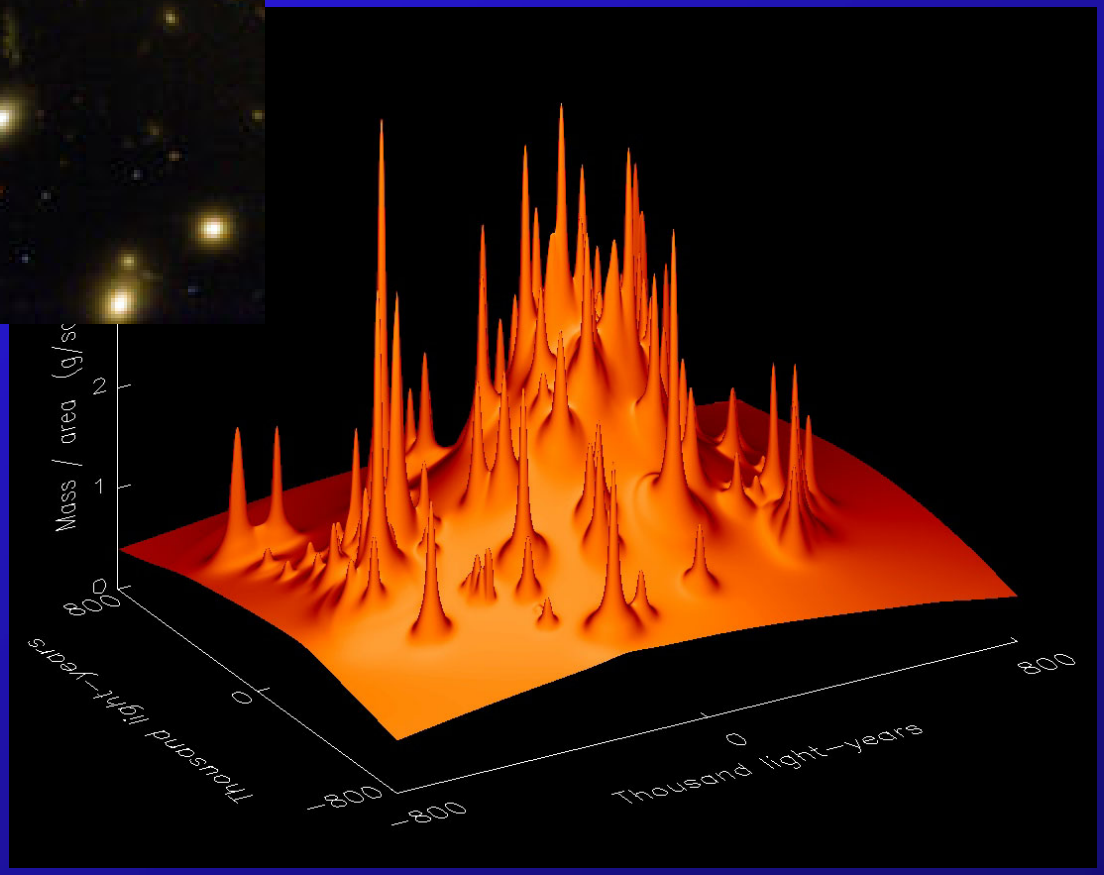
- Originally noticed through galaxy rotation curves
- One modern way to look for it - weak gravitational lensing



How to Use it

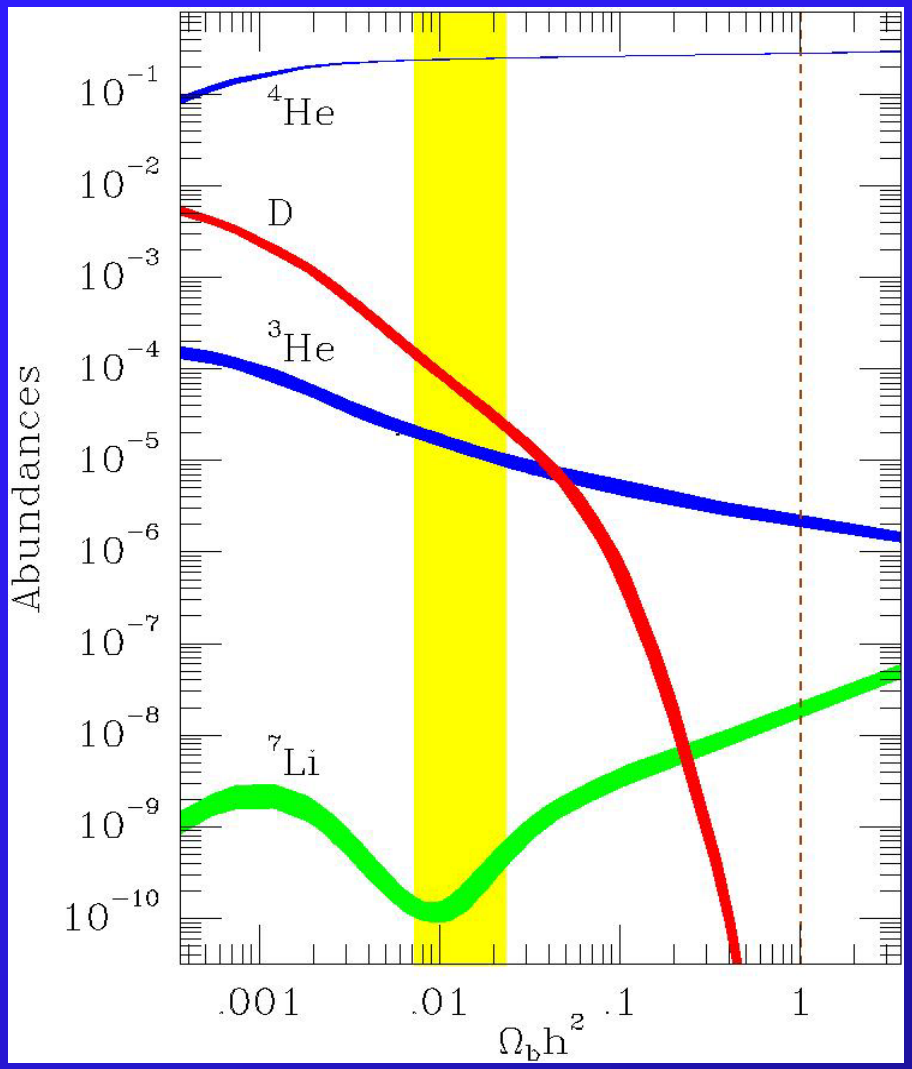
Can reconstruct the density in the cluster

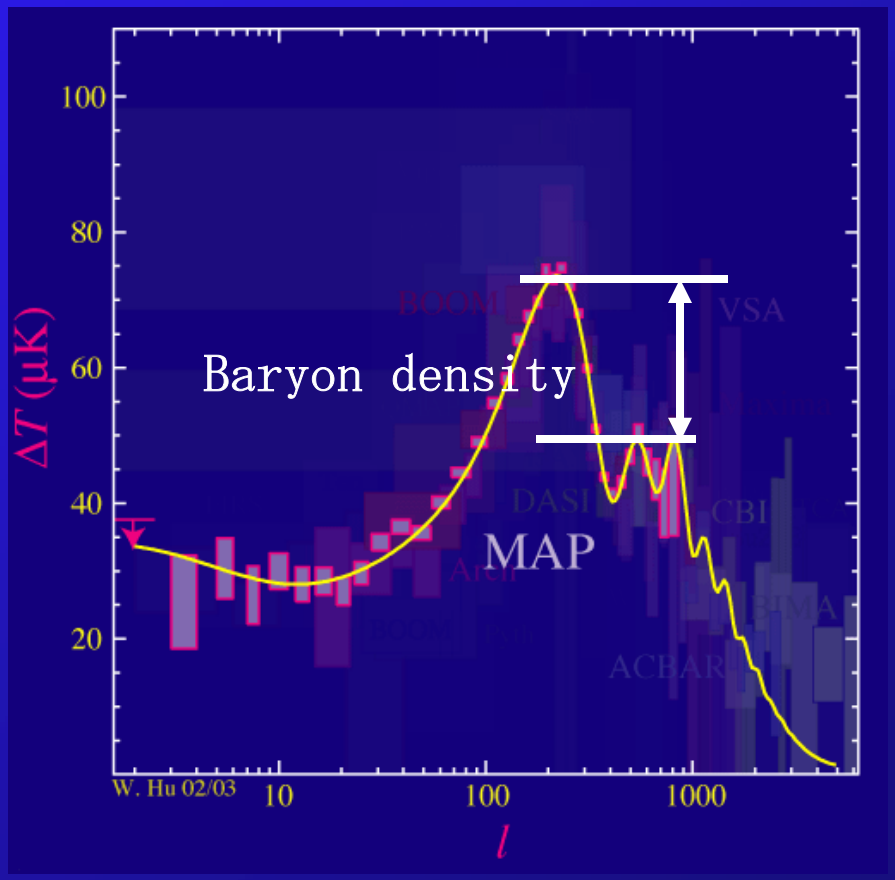
What is this stuff?



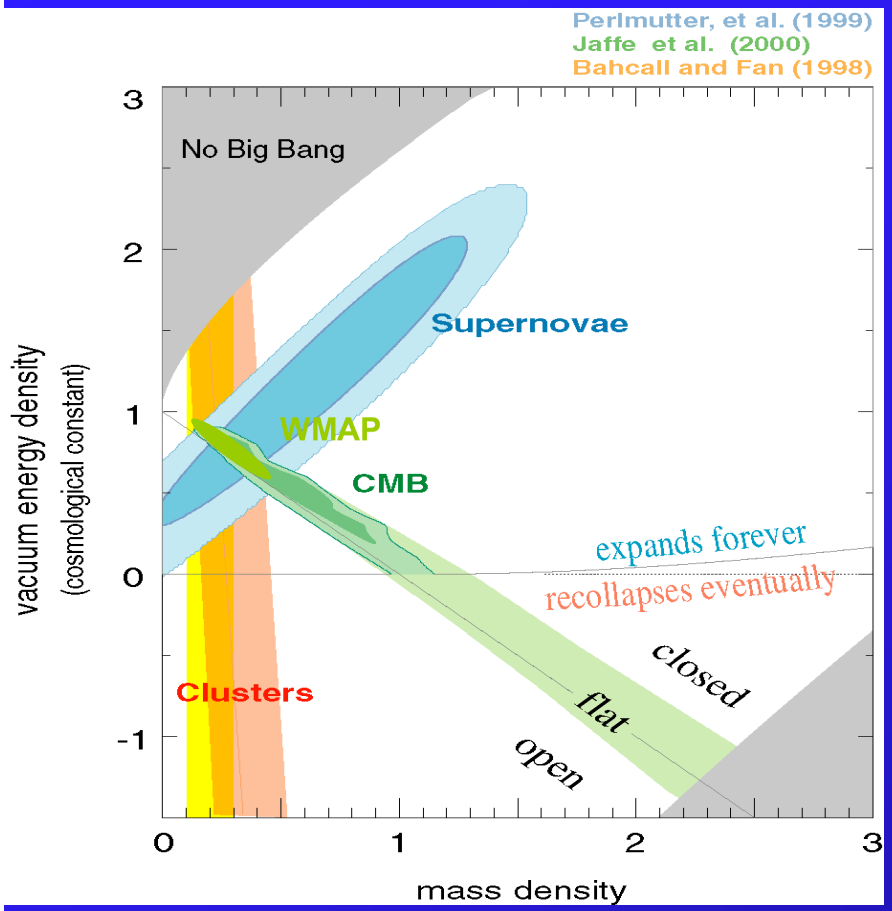
- WIMPs?
- SUSY particles?
- Axions?
- Remnants of GUTs?
- …

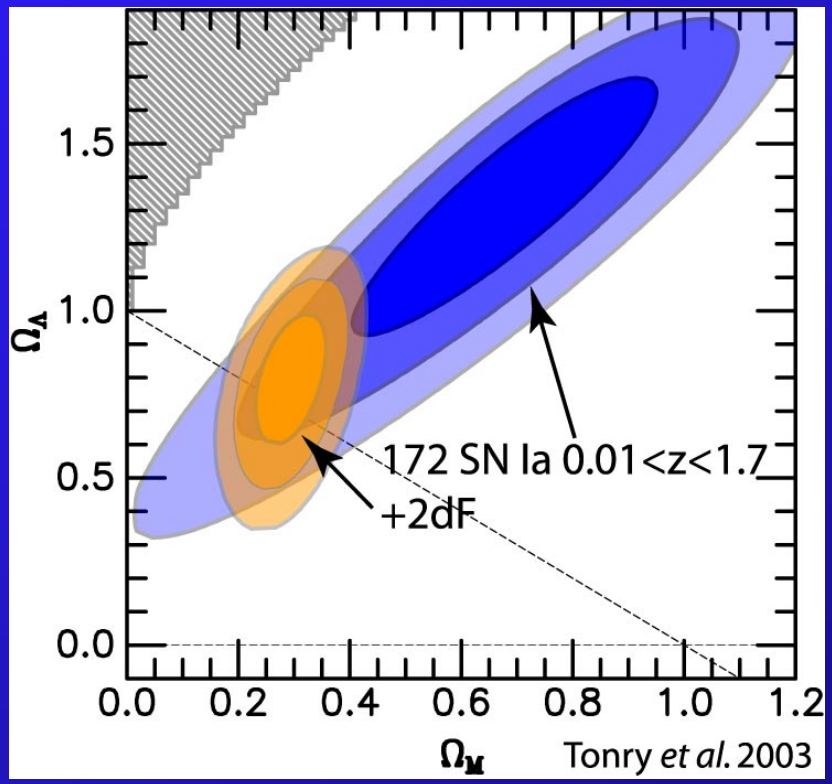
and the Baryon Density



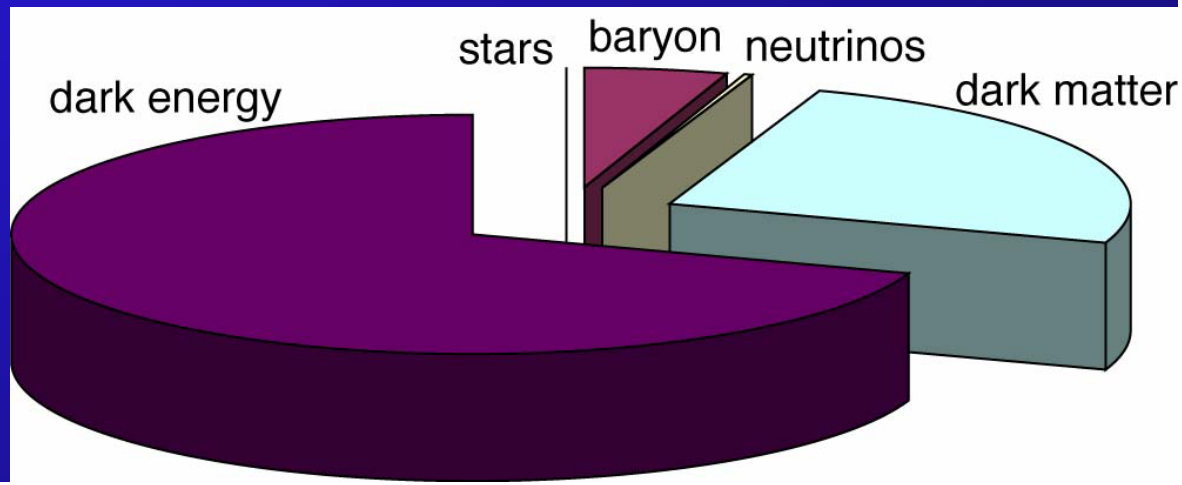


The New Paradigm





- Strange new universe
- $\Omega_{baryon} \sim 0.05$
- $\Omega_{matter} \sim 0.30$
- $\Omega_{DE} \sim 0.65$



We know what these particles are but not why they haven't met their antiparticles

We don't know what these particles are but we have some well-motivated ideas

We have absolutely no idea what this stuff is and we have no ideas that are well-motivated and well-developed!

Topics of Primary Interest

- Issues raised enhance and sharpen the search for the Higgs boson, supersymmetry, extra dimensions…
- Need particle physics and cosmology to find the answers.
- Explore what a Linear Collider will bring to this enterprise.

Focus on four potential areas of connections between linear collider physics and cosmology

- Dark matter
- Baryogenesis
- Cosmic rays
- Inflation and dark energy

Decreasing direct connection

Briefly discuss each of these soon

Dark Matter

A prime dark matter candidate is the WIMP
→ a new stable particle χ.
Number density n determined by

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

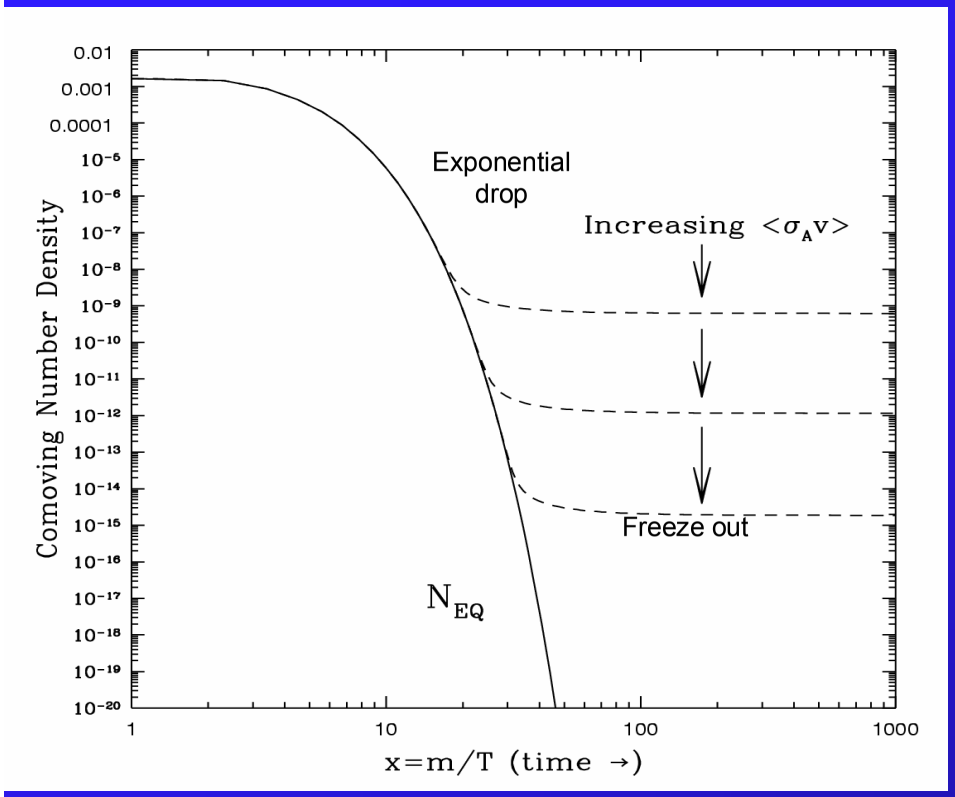
Dilution from expansion

$\chi \bar{\chi} \rightarrow f \bar{f}$

$f \bar{f} \rightarrow \chi \bar{\chi}$

- Initially, $\langle \sigma v \rangle$ term dominates, so $n \approx n_{eq}$.
- Eventually, n becomes so small that the dilution term dominates and the co-moving number density is fixed (*freeze out*).

Abundance of WIMPs



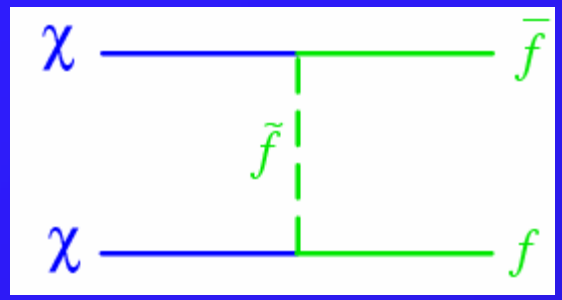
Universe cools, leaves residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$

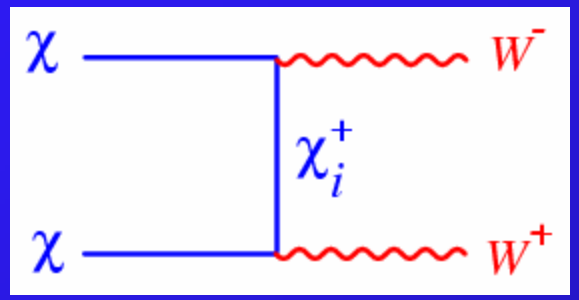
- Weakly-interacting particles w/ weak-scale masses give observed Ω_{DM}
- Strong, fundamental, and independent motivation for new physics at weak scale

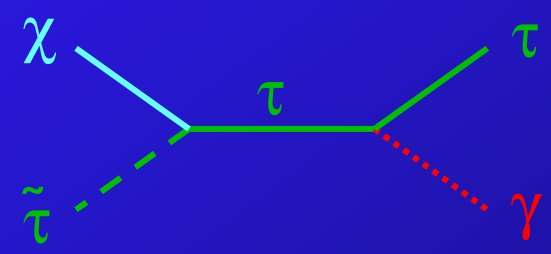
- Could use colliders as ***dark matter laboratories***
- Discover WIMPs and determine their properties
- Consistency between properties (particle physics) and abundance (cosmology) may lead to understanding of Universe at $T = 10$ GeV, $t = 10^{-8}$ s.

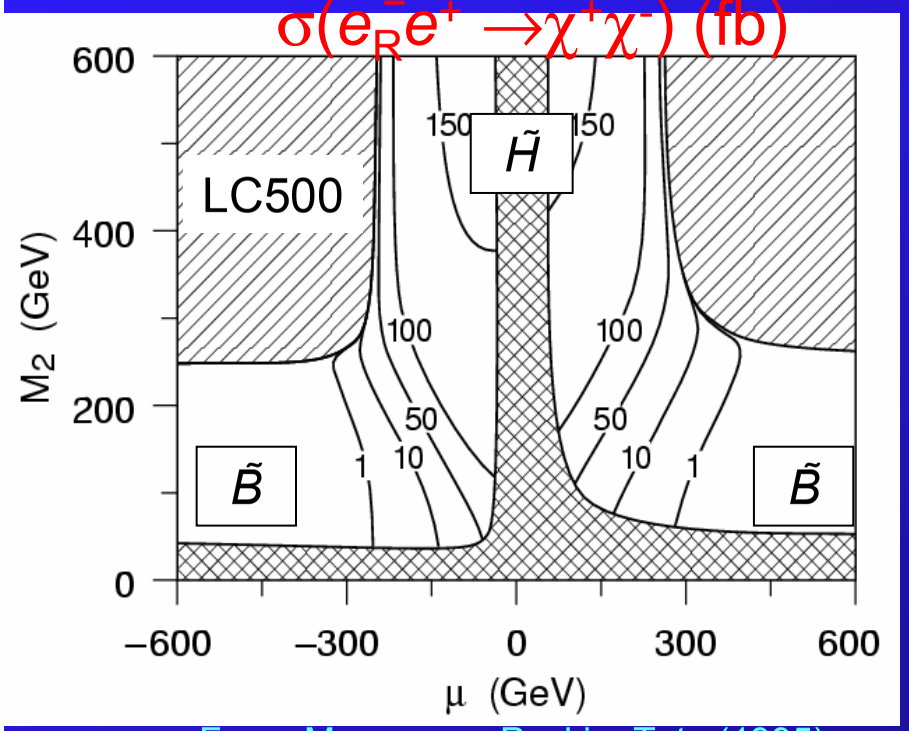
Example: SUSY & Neutralinos

- χ annihilation sensitive to *many* processes.









Feng, Murayama, Peskin, Tata (1995)

- Requires precise knowledge of χ mass and Sfermion masses (from kinematics)
- Also χ gaugino-ness (through polarized cross sections)
- and Δm to ~ few GeV

Model-independent determination of Ω_c to a few % challenging but possible at LHC/LC.

Important Questions

- Axions and superheavy candidates will escape the LC.
- But can the LC carry out this program for all thermal relics (and distinguish the various possibilities)
  - Neutralino dark matter
  - Kaluza-Klein dark matter
  - Scalar dark matter
  - SuperWIMP dark matter
  - Branon dark matter
  - …

- This will require a detailed and specific program of analysis; Currently underway…

What Might the LC Buy Us?

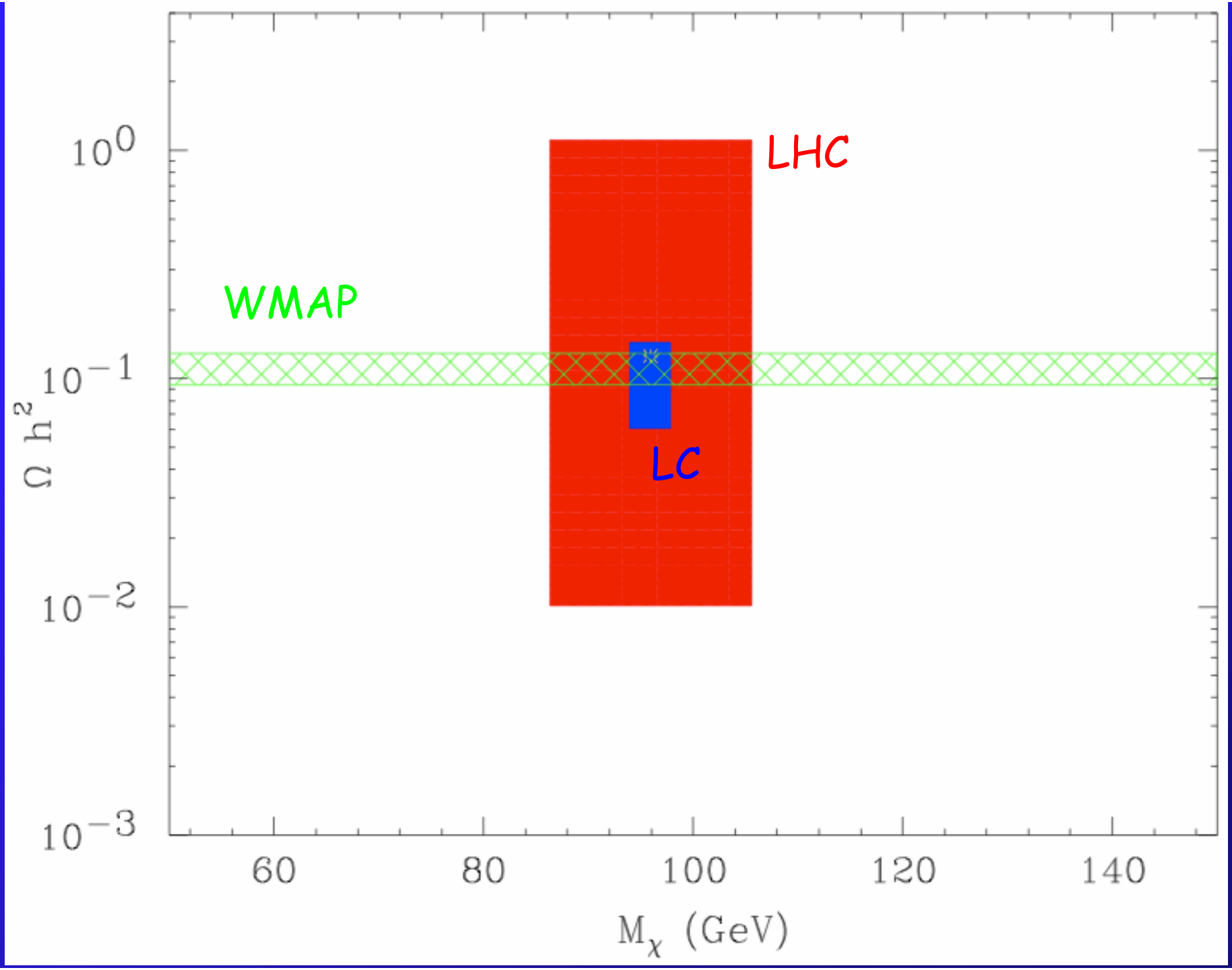
Simple example (courtesy of Andreas Birkedal)

- Suppose important point in SUSY parameter space is one at which not all masses important
- Only need to measure a few masses to get the relic density

Concrete example - point B' of "updated benchmark" points:
mSUGRA w/ $\tan\beta = 10$, $\mathrm{sgn}(\mu)=+1$, $m_0=57$, $m_{1/2}=250$, $A_0=0$

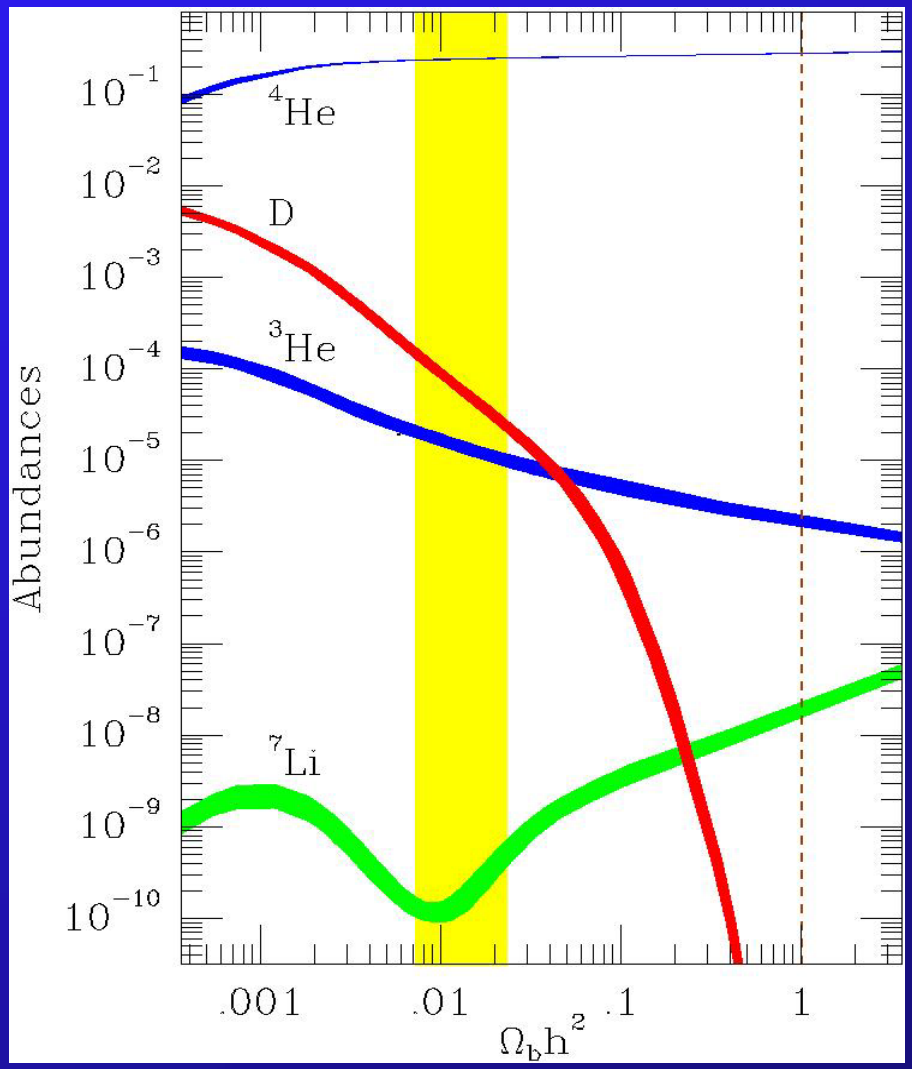
- Dark matter candidate is the neutralino
- Half the neutralinos and charginos are below 200 GeV
- All of the sleptons are below 200 GeV
- All of the squarks are below 600 GeV
- Heaviest particle - gluino - 611 GeV

(Don't take numbers on this slide very seriously - work in progress)


LHC
WMAP
LC
10^0
10^{-1}
10^{-2}
10^{-3}
Ωh^2
60
80
100
120
140
M_χ (GeV)

Baryogenesis

- Wherever you look you see matter and not antimatter.
- Particle physics teaches us matter and antimatter are the same.
- Cosmology teaches us they must exist in equal abundances in the early universe.
- What happened between then and now?



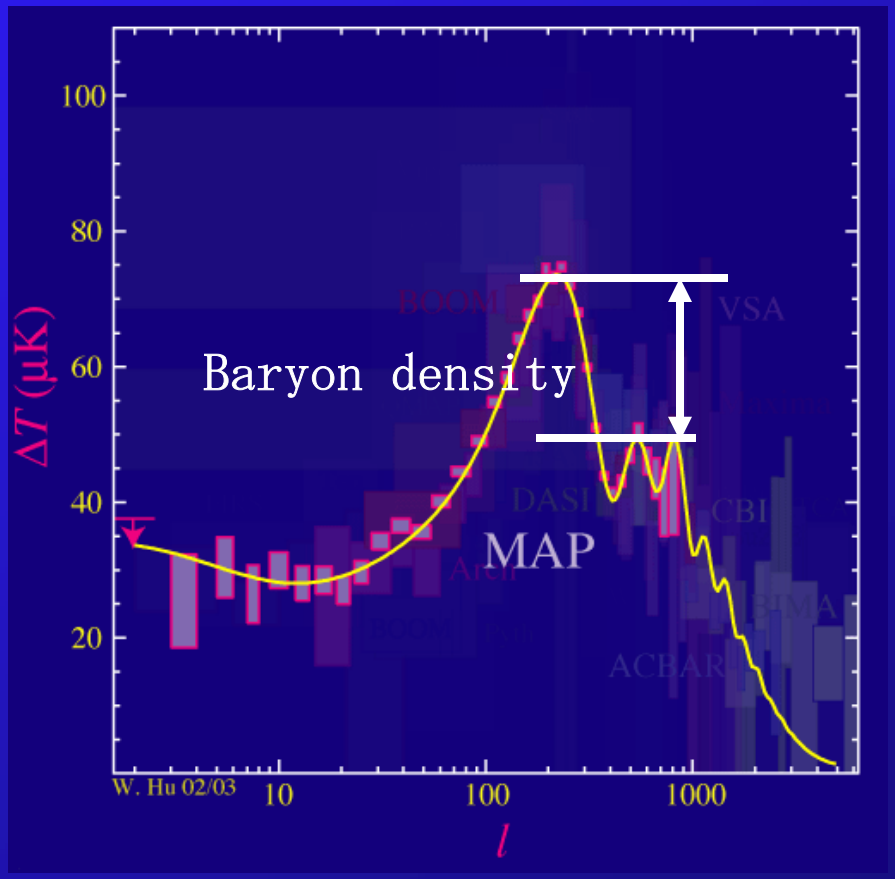
Matter vs Antimatter

- Remarkable region of concordance.
- Possible for a single value of $\eta \sim 10^{-10}$

Baryogenesis

BBN and CMB have determined the cosmic baryon content:

$$\Omega_B h^2 = 0.024 \pm 0.001$$



To achieve this a particle theory requires (Sakharov, 1968) :

- Violate Baryon number (B) symmetry
- Violate C & CP
- Depart from thermal equilibrium
- There are <u>LOTS</u> of ways to do this!

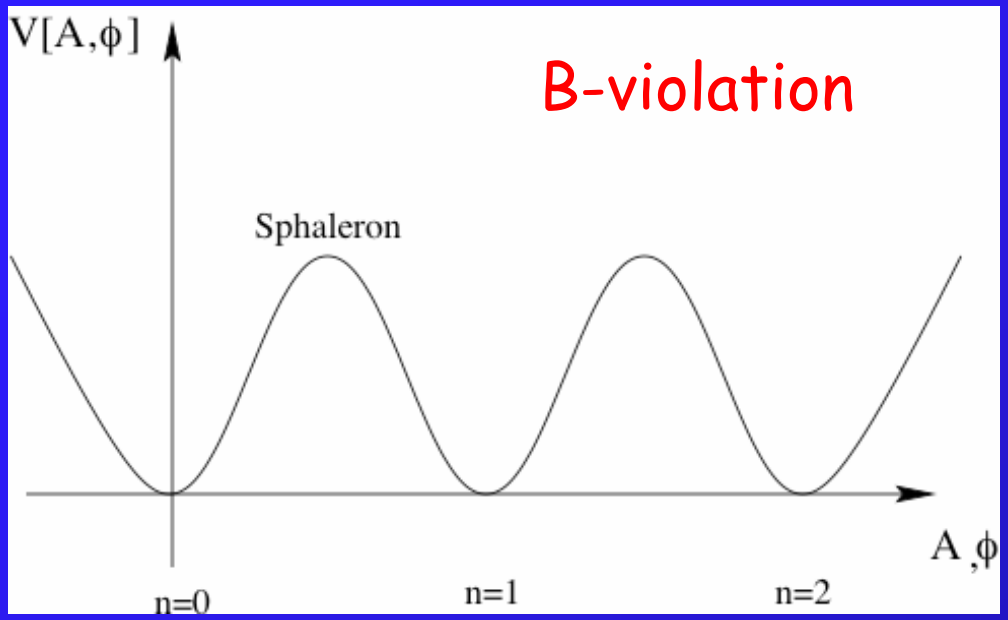
Clue for Particle Physics

- Many scenarios for baryogenesis rely on physics at the GUT scale
- However, an attractive and testable possibility is that the asymmetry is generated at the weak scale.

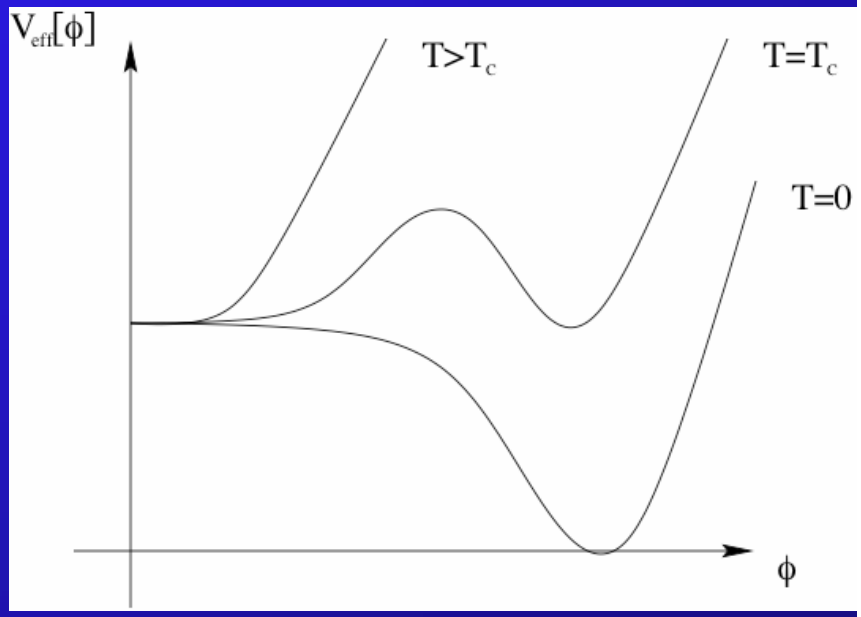
- The Standard Model of particle physics, even though in principle it satisfies all 3 Sakharov criteria, (anomaly, CKM matrix, finite-temperature phase transition) cannot be sufficient to explain the baryon asymmetry!
- This is a clear indication, from observations of the universe, of physics beyond the standard model!

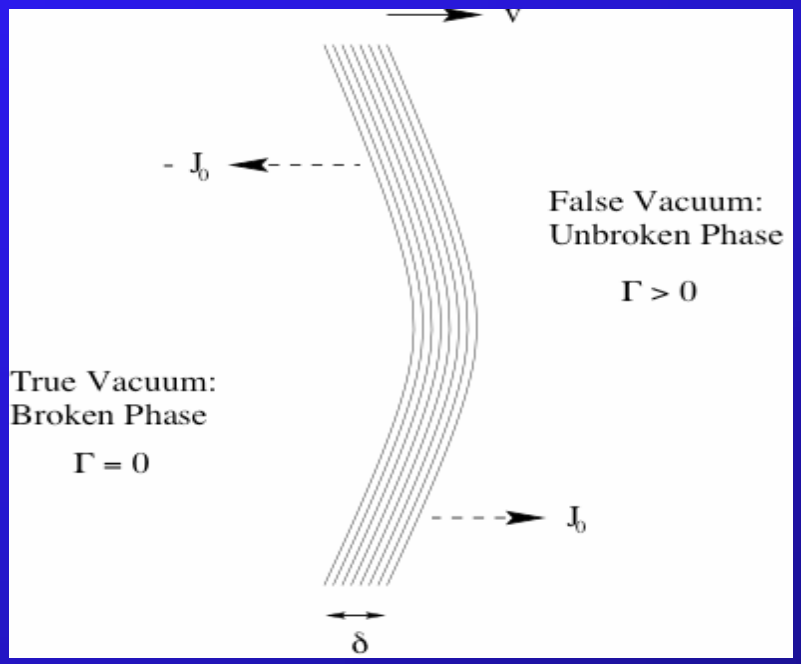
- What new possibilities are there in theories beyond SM?
  - Supersymmetric particles?, Neutrinos?

Electroweak Baryogenesis I



TE-violation





CP-violation + TE-violation

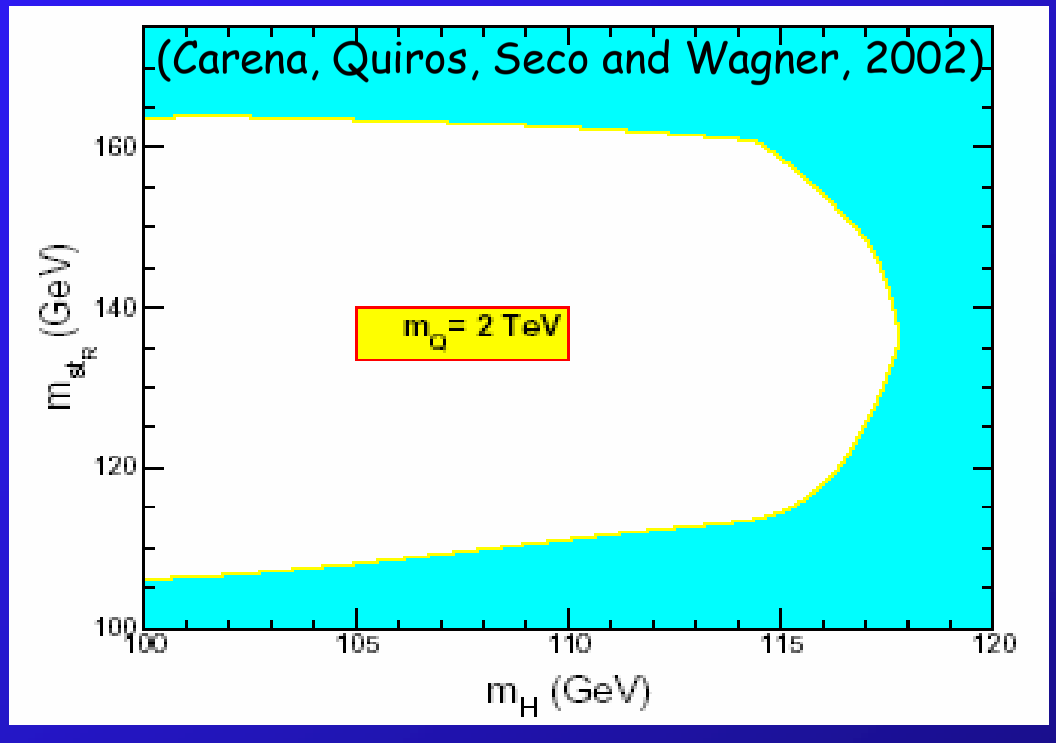
Electroweak Baryogenesis II

- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe.
- Our most popular model of recent years

- Popularity of this idea is tightly bound to its testability.
- Physics involved is all testable in principle at realistic colliders.
- Small extensions needed can all be found in SUSY, which is an independently attractive
- However, the testability of electroweak scenarios also leads to tight constraints.

Bounds and Tests

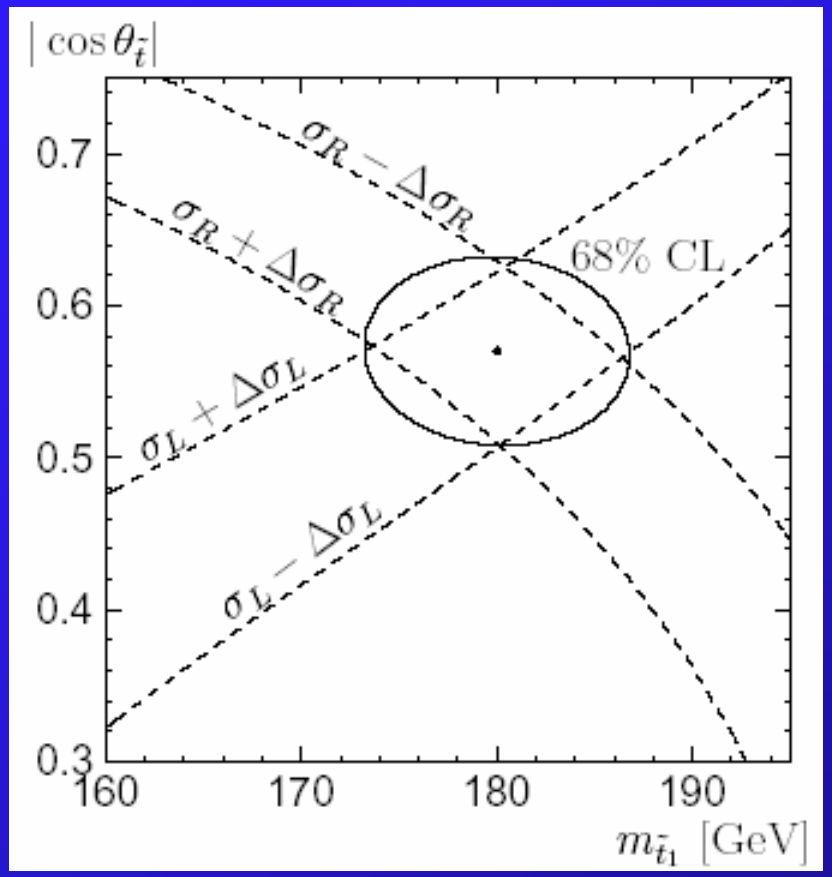
- In supersymmetry, sufficient asymmetry is generated for *light Higgs, light top squark, large CP phases*
- Promising for LC!
- Severe upper bound on lightest Higgs boson mass, m_h <120 GeV (in the MSSM)
- Stop mass may be close to experimental bound and must be < top quark mass.



Very nice description of bounds in Dan Chung's parallel talk at the SLAC linear collider meeting (Linked from ALCPG cosmology subgroup page - more later!)

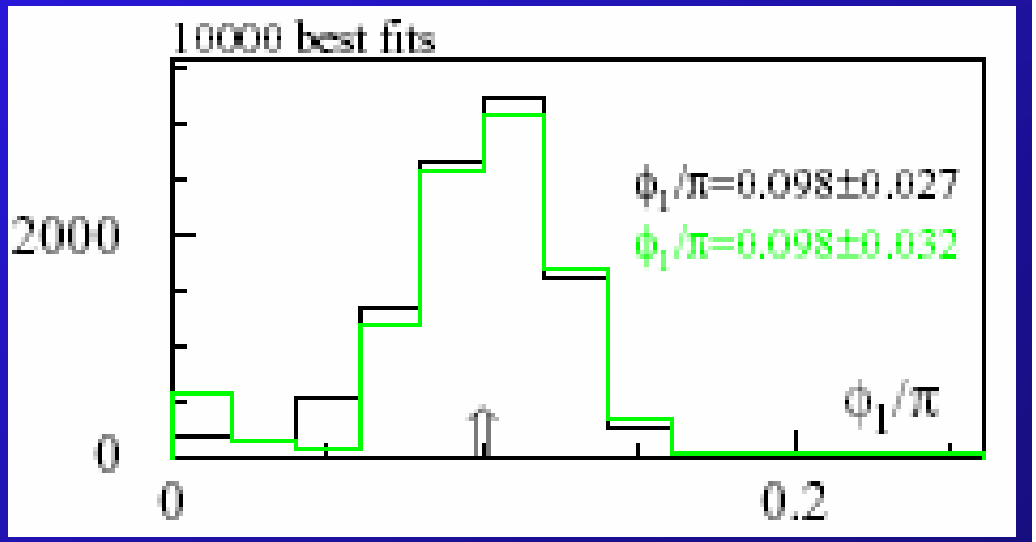
Baryogenesis Parameters at the LC

Top squark parameter constraints for 10 fb^{-1} using $e^-_{R,L}e+ \rightarrow$ stop pairs



Bartl et al. (1997)

CP phase constraints using chargino/neutralino masses and cross sections



Barger et al. (2001)

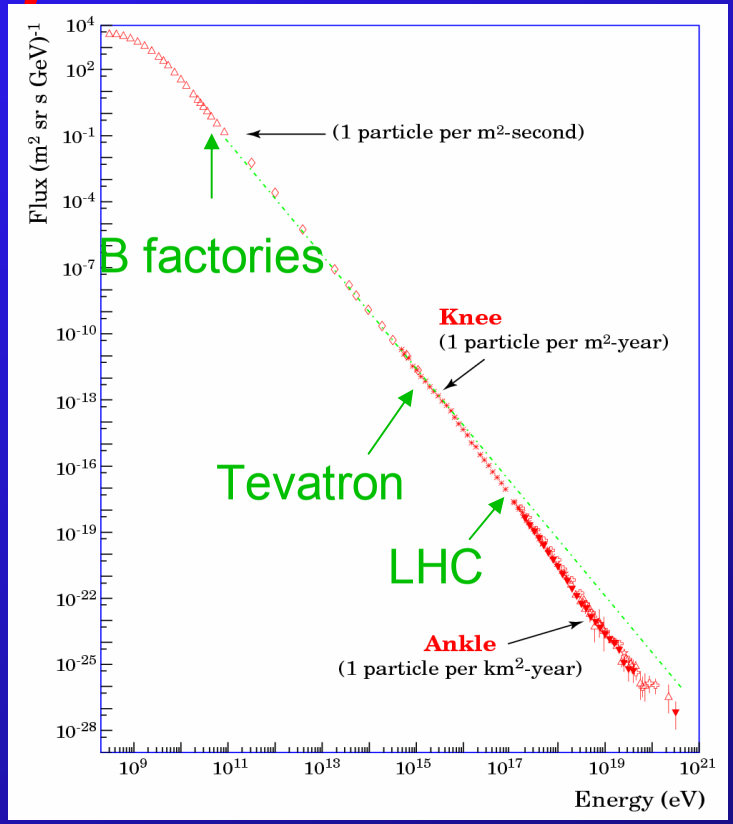
Other Connections

- Another important test for EWBG may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector

- Important to remember that BG may be due to different and entirely new TeV scale physics (e.g. Langacker et al. Z' model)
- May learn indirectly about leptogenesis (Peskin et al.)
- How well can we determine Ω_B in these scenarios?
- Does the LC have anything to say about GUT-scale baryogenesis/leptogenesis?

Cosmic Rays

- Observed with energies ~10^{19} eV $\Rightarrow E_{CM}$~100 TeV in collisions.
- E_{CM} > any man-made collider.
- Cosmic rays are already exploring energies above the weak scale!



Drawbacks:

- Miniscule luminosities.
- Event reconstruction sparse and indirect.

Colliders may help interpret upcoming ultrahigh energy data.

The GZK Paradox

- Protons with ~10^{20} eV energies quickly lose energy through

$$p\,\gamma_{CMB} \rightarrow n\,p^{+}$$

so probably must be emitted from nearby, but no local sources found.

- Solutions:
  - Bottom-up: e.g., CRs are gluino-hadrons.
  - Top-down: CRs result from topological defect decays, should produce up-going cosmic neutralinos if SUSY exists.

Testable predictions for colliders.

Dark Energy - Theory

Evolution of the universe governed by Einstein eqns

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 \propto \rho$$ The Friedmann equation

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$ The "acceleration" equation

Parameterize different types of matter by equations of state: $p_i = w_i \rho_i$

When evolution dominated by type i, obtain

$$a(t) \propto t^{2/3(1+w_i)} \qquad \rho(a) \propto a^{-3(1+w_i)} \qquad (w_i \neq -1)$$

Cosmic Accelelation

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

So, accelerating expansion means $p < -\rho/3$ or

$$\boxed{w_{DE} < -1/3}$$

<u>Three Broad Possibilities</u> $a(t) \propto t^{2/3(1+w_i)}$ $\rho(a) \propto a^{-3(1+w_i)}$

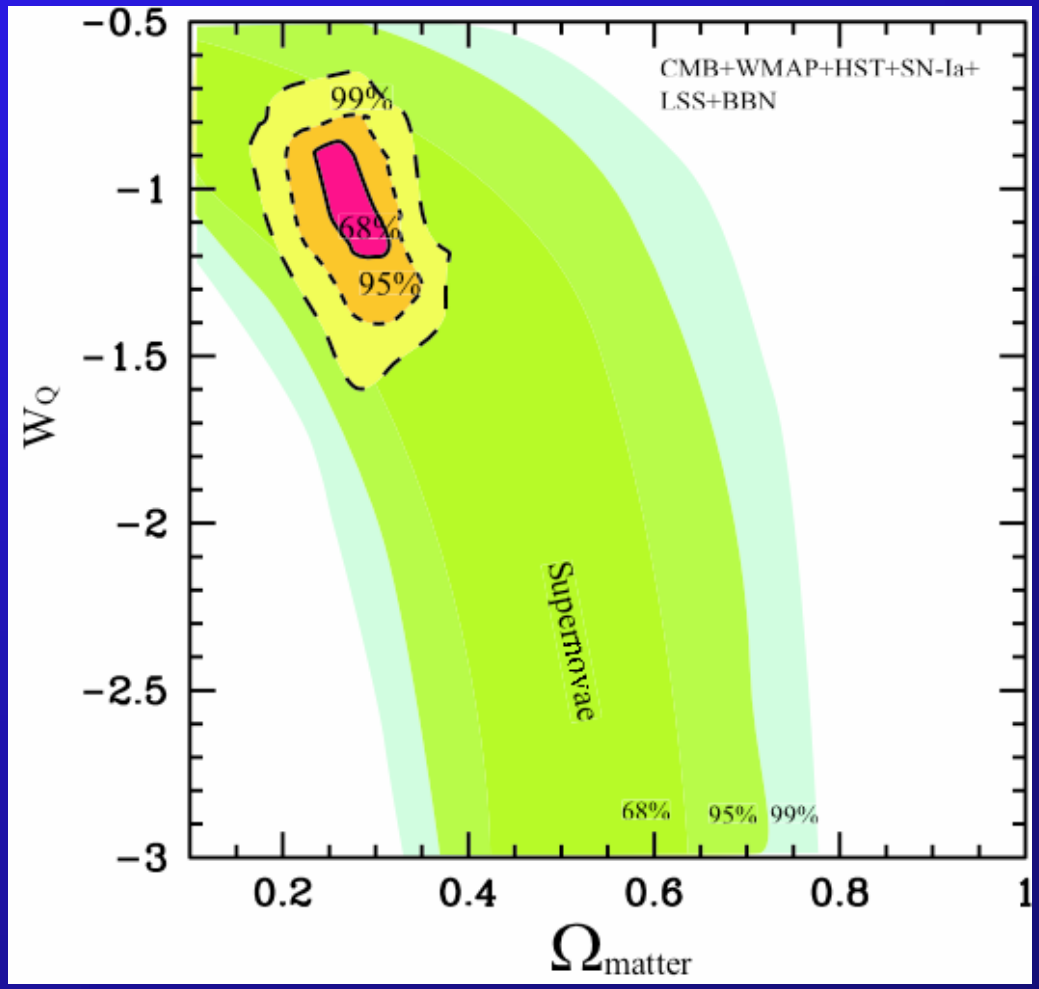
	$-1<w<-1/3$	$w=-1$	$w<-1$
Evolution of Energy Density	Dilutes slower than any matter	Stays absolutely constant (Λ)	Increases with the expansion!!
Evolution of Scale Factor	Power-law quintessence	Exponential expansion	Infinite value in a finite time!!

Data on w_{DE}

Basically measuring (luminosity) distance as fn of redshift.

CMB+HST	$-1.65 < w < -0.54$ $0.19 < \Omega_m < 0.43$
CMB+HST+BBN	$-1.61 < w < -0.57$ $0.20 < \Omega_m < 0.42$
CMB+HST+BBN +SNIa	$-1.45 < w < -0.74$ $0.21 < \Omega_m < 0.36$
CMB+HST+BBN +SNIa+2dF	$-1.38 < w < -0.82$ $0.22 < \Omega_m < 0.35$

[From: Melchiorri, Mersini, Odman and M.T. (2002)]



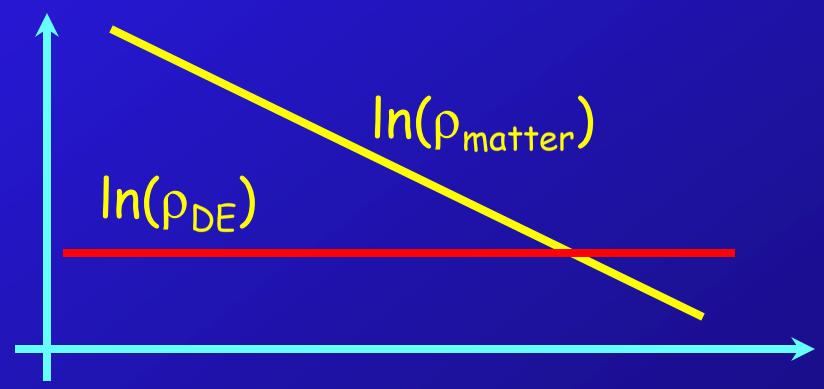
Our Problems

Really two problems associated with dark energy.

1. Its magnitude - we need to show why dark energy is the (ridiculous, as we'll soon see) size it is today.

2. The coincidence problem.

$$\frac{\rho_{\text{matter}}}{\rho_{\text{DE}}} \propto a^{-\alpha} \quad \text{with} \quad \alpha > 1$$



So even if dark energy wasn't important in the past, it will dominate in the future. Why do we observe it at a time when it is comparable to matter - why now?
Remember, we could have lived easily with no dark energy.

What Might Explain These?

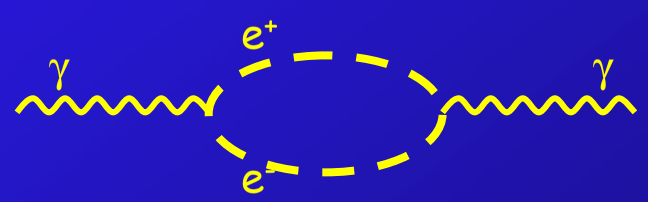
Vacuum Energy

- We know essentially nothing about dark energy
- Tied to our ignorance about the cosmological constant.
- Exploration of Higgs boson(s) and potential may give insights into scalar particles, vacuum energy.

- Vacuum is full of virtual particles carrying energy.
- Should lead to a constant vacuum energy. How big? - ∞

BUT…

- While calculating branching ratios - easy to forget SUSY is a *space*-time symmetry.
- A SUSY state $|\psi\rangle$ obeys $Q\,|\psi\rangle=0$, so $H\,|\psi\rangle \propto \{Q,Q\}\,|\psi\rangle=0$
- Only vacuum energy comes from SUSY breaking!



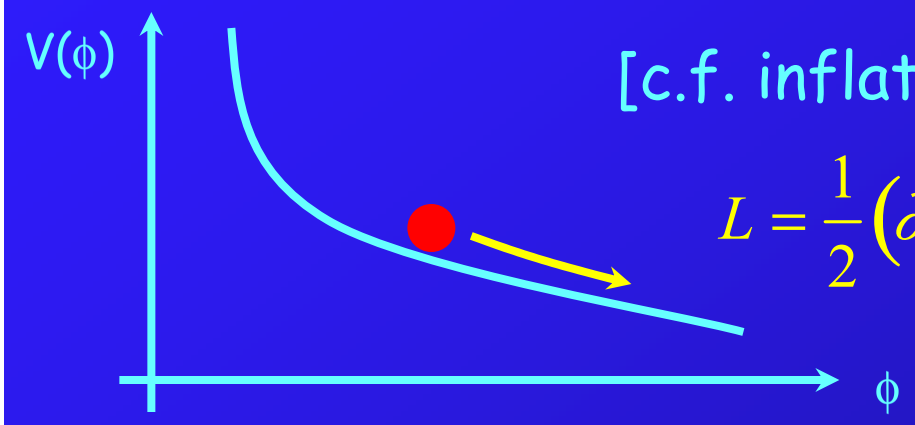
$$\rho_\Lambda \sim M_{SUSY}^4$$

Still 10^{60} too big!

Other Possibilities

Inflation and dark energy may be due to fundamental scalars or extra-dimensional dynamics:

Use scalar fields to source Einstein's equation.



[c.f. inflation - no minimum or reheating]

$$L = \frac{1}{2}\left(\partial_\mu \phi\right)\partial^\nu \phi - V(\phi)$$

$$w = -\left[\frac{2V(\phi) - \dot{\phi}^2}{2V(\phi) + \dot{\phi}^2}\right]$$

- Possible LC will provide much-needed insight into these
- The LC can probe details of the Higgs potential - don't expect it to be the inflaton, but would be our first prototype of a scalar potential.

- Dvali-Kachru new-old inflation idea requires new field at TeV scale to generate perturbations - specific LC signatures …

Other Approaches

- The Anthropic Principle
  In brief: Assume cosmological constant varies, either from place to place, or over time, or in different universes

We live here because we can!

- Holography (Don't want to say much about it)
  Maybe these ideas will lead us to a new picture of the vacuum

- Quantum Gravity
  e.g. string theory …

Where Do We Stand?

There are ***no*** compelling, natural suggestions to date.

In one way this demonstrates the current ugly frog nature of particle cosmology when compared to the handsome prince of observational cosmology

On the other hand, in more grant proposal-friendly terms, this makes for perhaps the most exciting and challenging time in particle cosmology.

It may pay to explore radical options - but we are in the wonderful position of holding such speculation accountable to increasingly accurate data.

(Abbreviated) To-Do List of a Theoretical Cosmologist

How did fundamental physics set the values of input parameters to the standard cosmology?

w Ω_b Ω_{dm} Λ Ω_Q Q η $\frac{\delta\rho}{\rho}$ ϕ

- Baryogenesis
- Inflation
- Dark Matter
- Dark Energy
- Extra Dimensions
- Topological Remnants
- Moduli
- Axions
- Neutrino Physics
- Cosmic Rays…

Cosmology has already given us direct evidence of beyond the standard model physics.
This is just the beginning!

The ALCPG Working Group on Cosmological Connections

http://www.physics.syr.edu/~trodden/lc-cosmology/

Editorial Committee:

- Marco Battaglia (Berkeley)
- Jonathan Feng (Irvine, co-Chair) jlf@uci.edu
- Norman Graf (SLAC)
- Michael Peskin (SLAC)
- Mark Trodden (Syracuse, co-Chair) trodden@physics.syr.edu

Expect to produce white paper by Fall 2004

- Very successful (3 full parallel sessions) outing at SLAC
- Would be great to see this duplicated at all meetings

Although we are an extremely international group, would be useful to see a complementary international committee, beyond our 3-person task force (Abdelhak Djouadi, Nobuchika Okada & M.T.) devoted to these connections

A Cautionary Comment

(Echoing Howie Haber's talk yesterday and Michael Peskin's this morning)

I am not a conservative! (and neither are most of you)

- It is important to have a common framework - so it *is* extremely useful to think about mSUGRA in this context.
- However, should recognize this is a unlikely constraint on possibilities, even within SUSY. An appeal for nonminimality!
- Shouldn't fool ourselves that we are covering "a large part of parameter space" - more work is needed - don't give up! Some of the important work of our group involves more general studies and techniques.

[e.g. Interesting general work by Birkedal, Matchev & Perelstein]

- On topic of not giving up - despite fairly solid theoretical arguments, too early to say we won't learn about dark energy from terrestrial physics - we know nothing about this!
- Would be nice to see a proof-of-principle model.

Final Comments

- Science: A linear collider may help address some of the biggest and most pressing issues in cosmology - dark matter, baryogenesis, cosmic rays and perhaps even give hints about dark energy and inflation.

- Science: A strong collider program is a necessary and natural complement to cosmological observations if we are to unravel the fundamental physics reasons behind the universe we observe.

- Obvious PR: This is important because people can see stars and galaxies, and feel that the universe is much more tangible than, say, the Higgs boson or supersymmetry - as beautiful as they may be to most of us.

A plea: If the connections between the LC and cosmology are to be taken seriously by both communities, by policy-makers and by the public - will need subgroups devoted to this in each region and separate parallel sessions at all LCWS meetings

-Thank You -