Cosmological Connections

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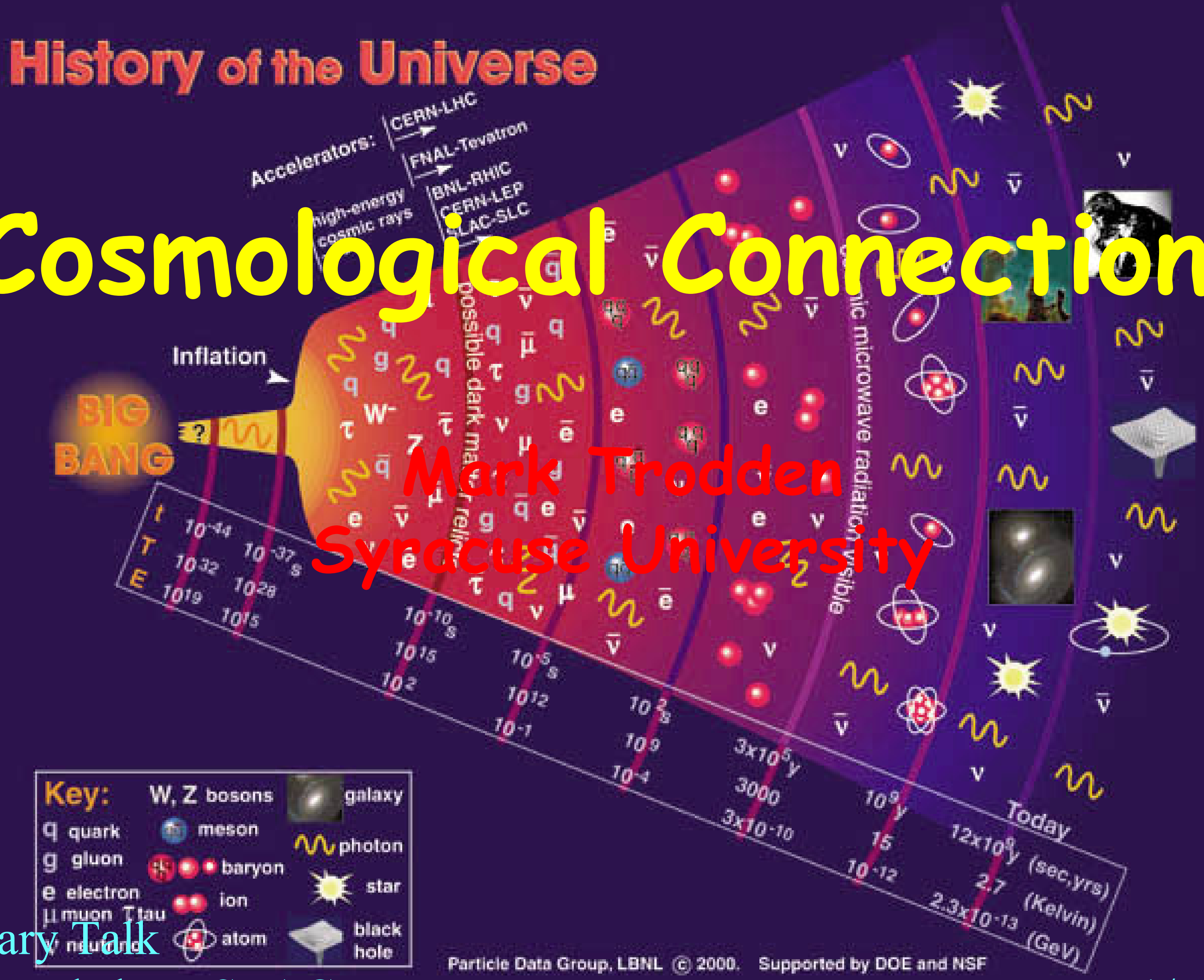


Plenary Talk

LC Workshop, SLAC

1/7/2003

Outline

- The ALCPG Working Group on Cosmological Connections
- Our Motivations
- Our Goals
- Practical Information

Very much an overview here - we have three exciting parallel sessions packed with details that I'll refer to later.

See also Thursday evening (6:15-7:00) talk by Michael Turner: "**Accelerators, Astrophysics and Funding**"

The ALCPG Working Group on Cosmological Connections

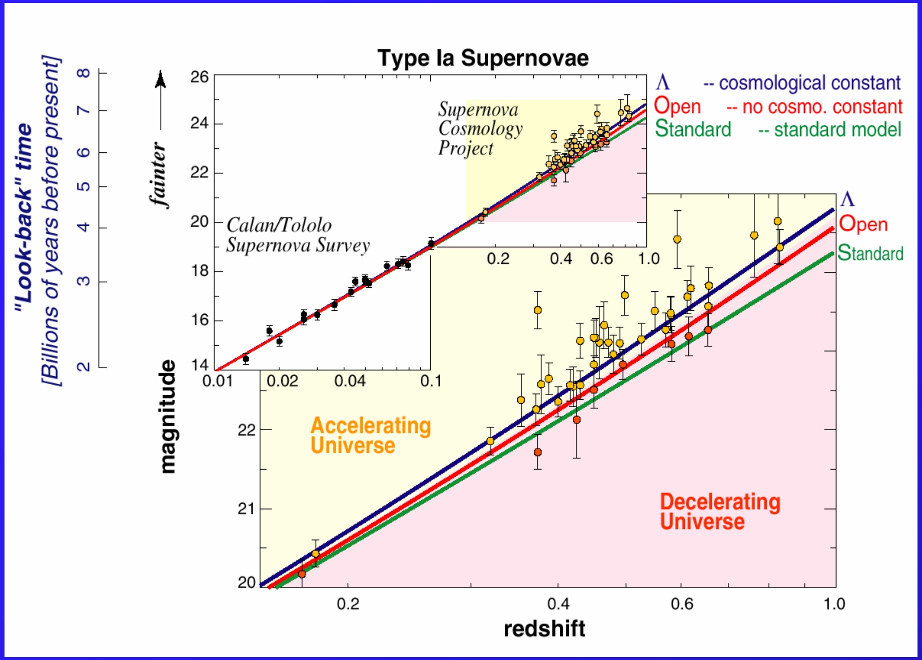
Editorial Committee:

- 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

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

- Have contacted all respondents to initial announcement and are inviting many others to join the effort (~ 60 so far).
- International participation encouraged.
- Anticipate an author list consisting of active participants.

Dark Energy

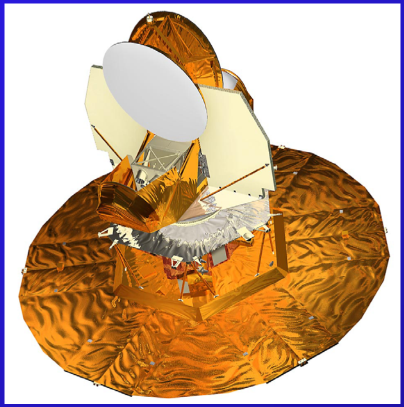


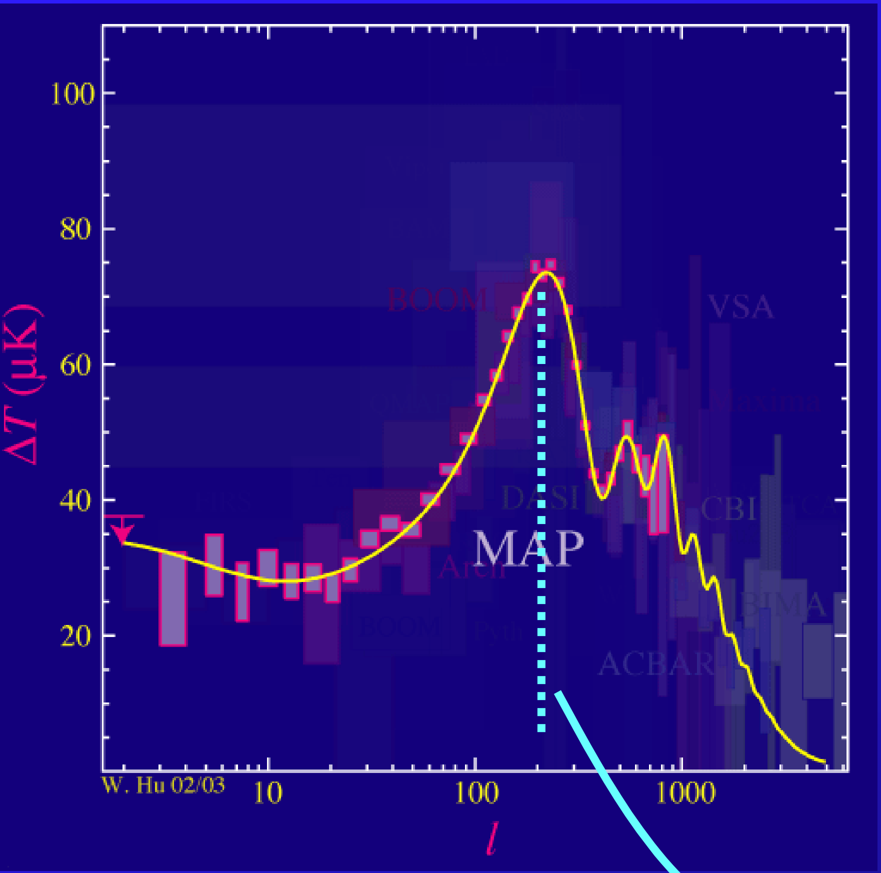
- Positive pressure matter slows the expansion
- Negative pressure matter speeds up the expansion
- So SN IA results depend on $\Omega_{matter}-\Omega_{\Lambda}$

- These observations in wonderful agreement with:
  - weak lensing measurements,
  - large scale structure observations,
  - …
- Plus …

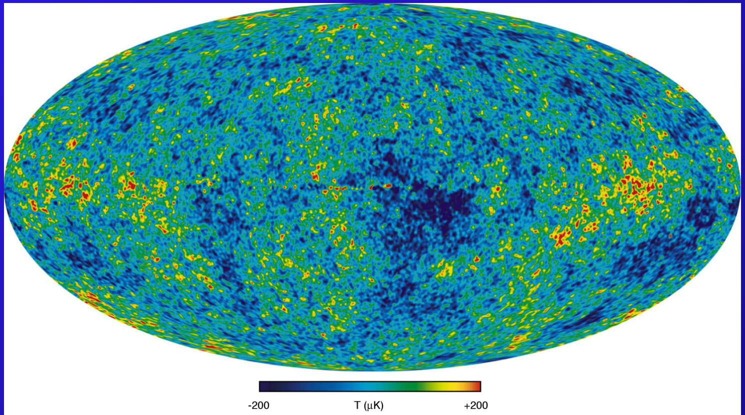
Putting it Together w/the CMB

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





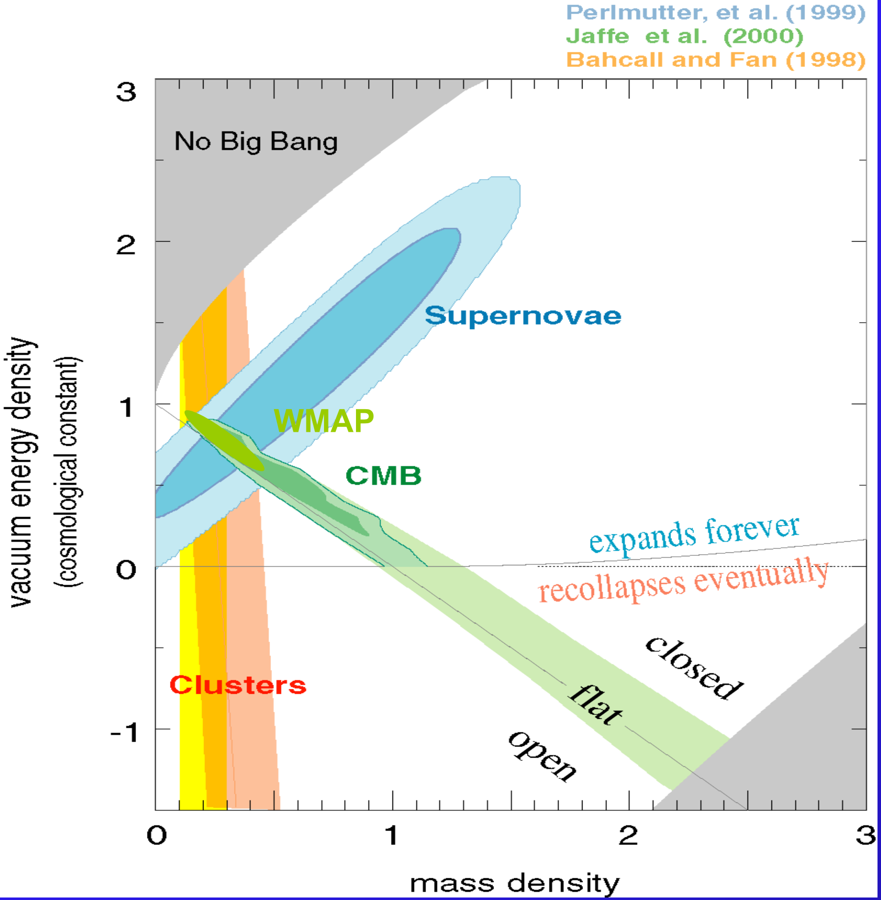
(Wayne Hu, 2003)

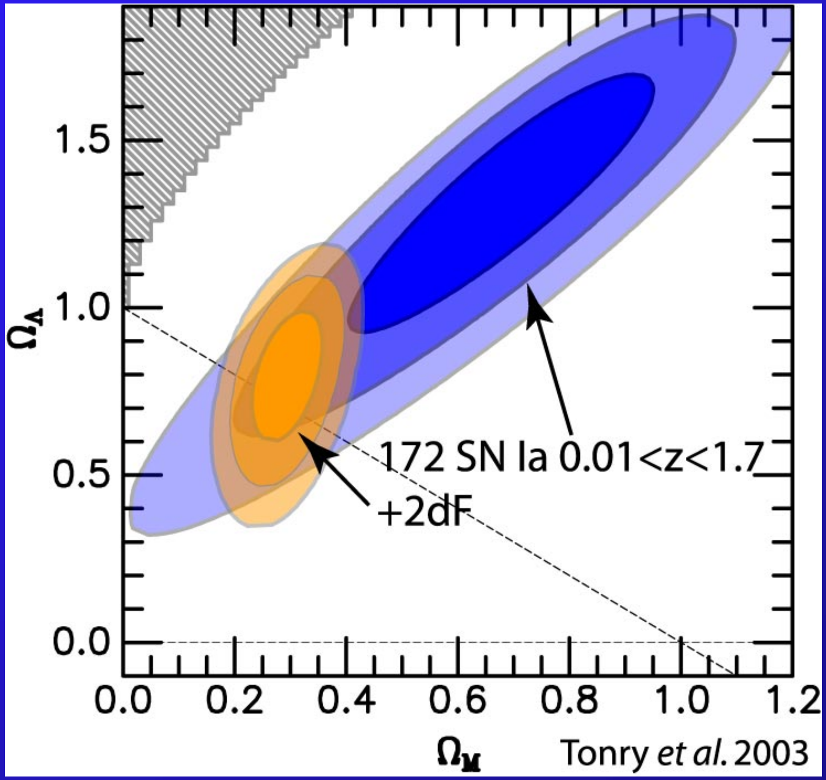


- Position of first peak depends on spatial geometry of universe
- Depends ~ $\Omega_{tot}=\Omega_{matter}+\Omega_{\Lambda}$

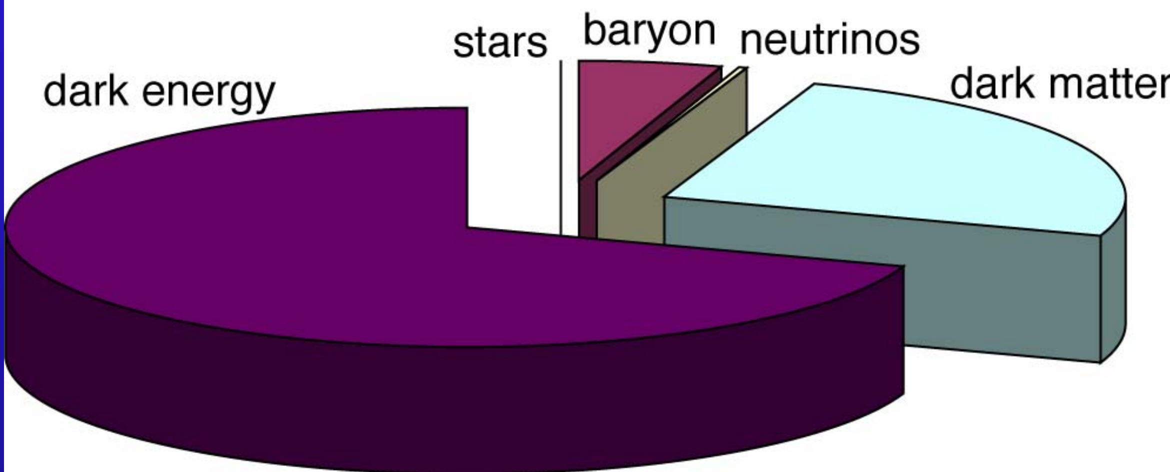
$$\boxed{\Omega_{tot} = 1.02 \pm 0.02}$$

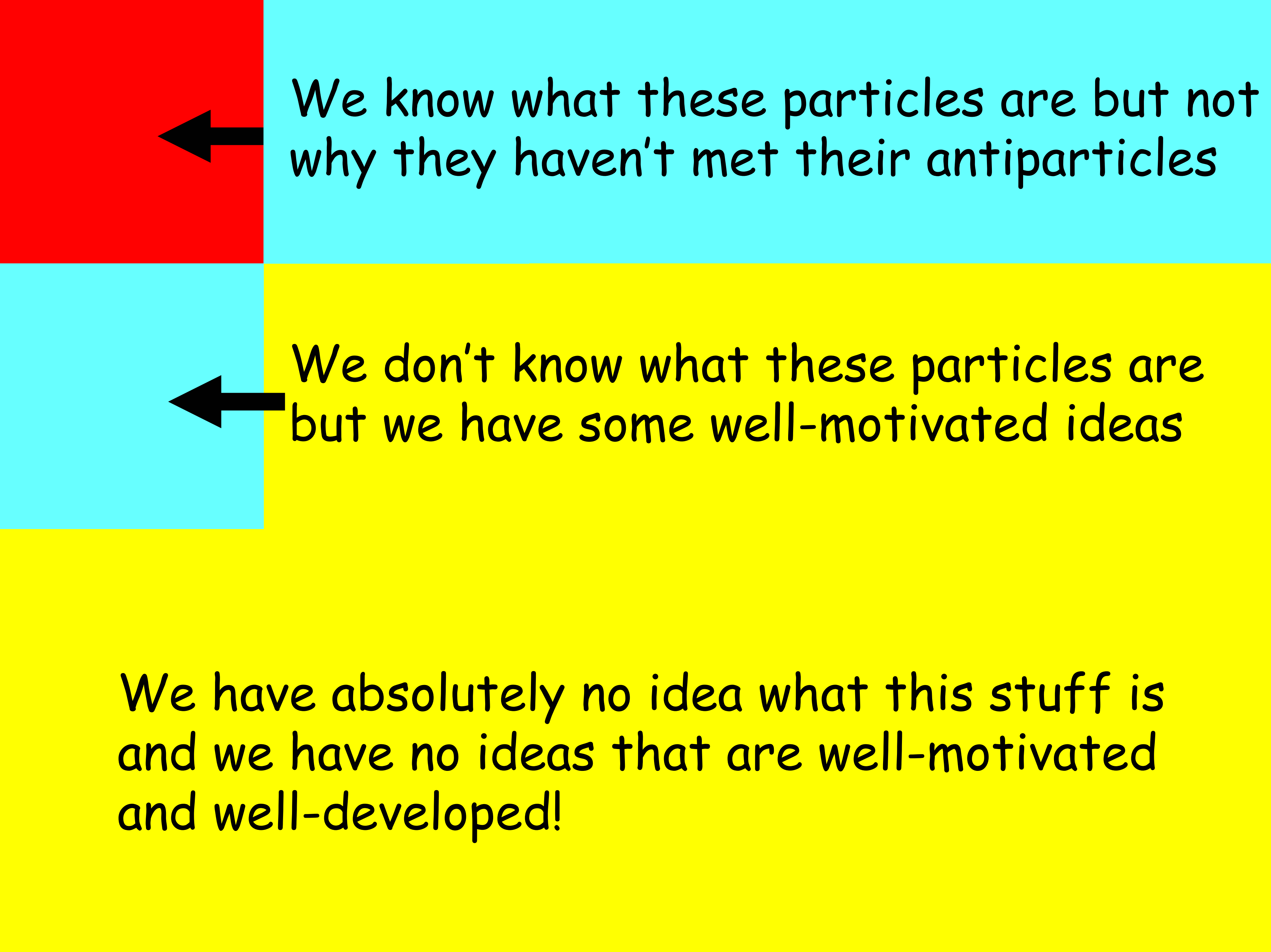
The New Paradigm





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





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.

Have identified 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

Neutralino Dark Matter (joint session with SUSY WG), Thursday 1:45 - 2:05 (Paolo Gondolo, Marco Battaglia, Uriel Nauenberg, Bhaskar Dutta, Howard Baer)
More about Dark Matter, Thursday 4:05 - 6:05 (Yudi Santoso, Andreas Birkedal-Hansen, Michael Peskin, Fumihiro Takayama, Shufang Su, Antonio Dobado

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

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

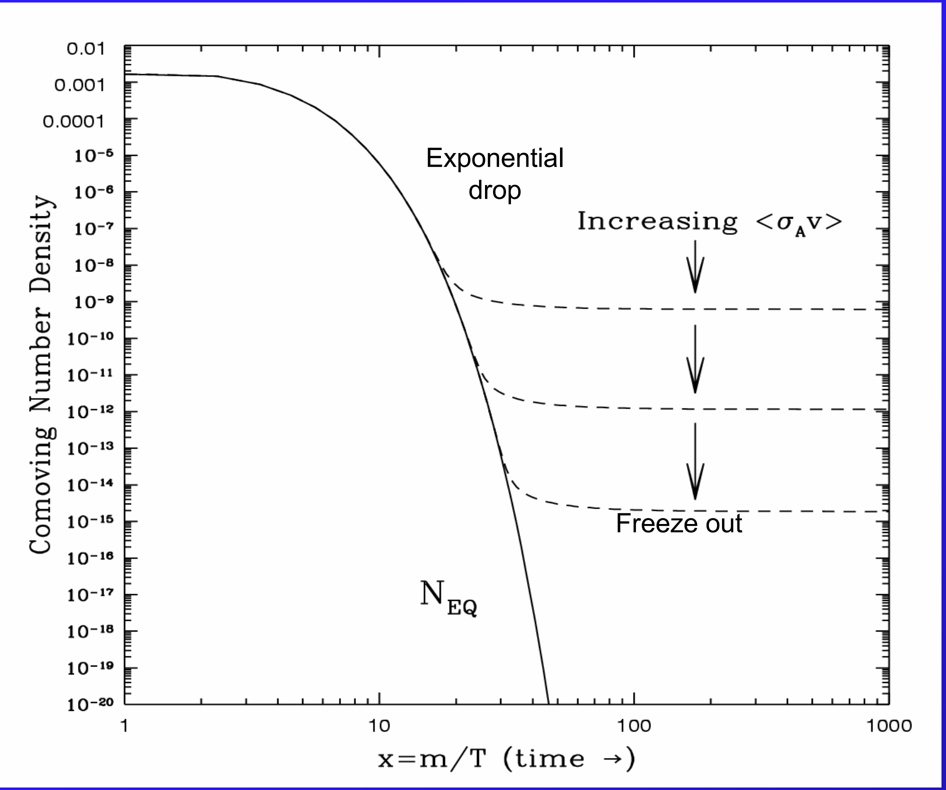
Dilution from expansion

$\chi \bar{\chi} \to f \bar{f}$

$f \bar{f} \to \chi \bar{\chi}$

- 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



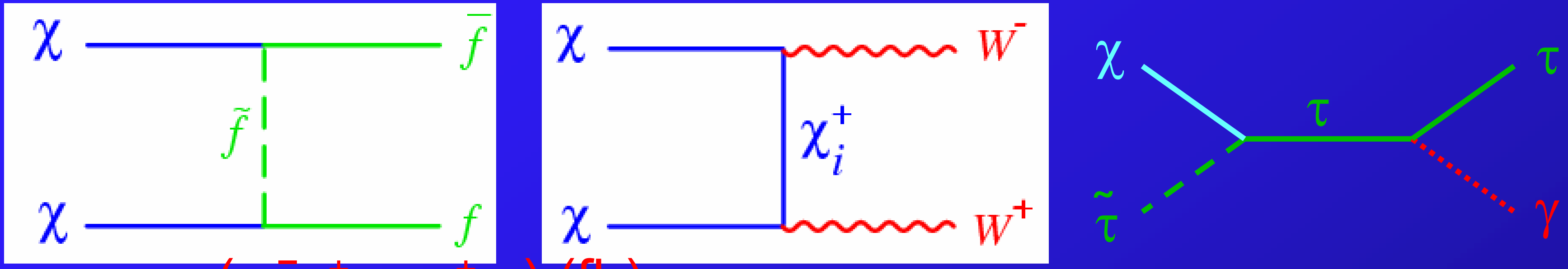
Universe cools, leaves residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$

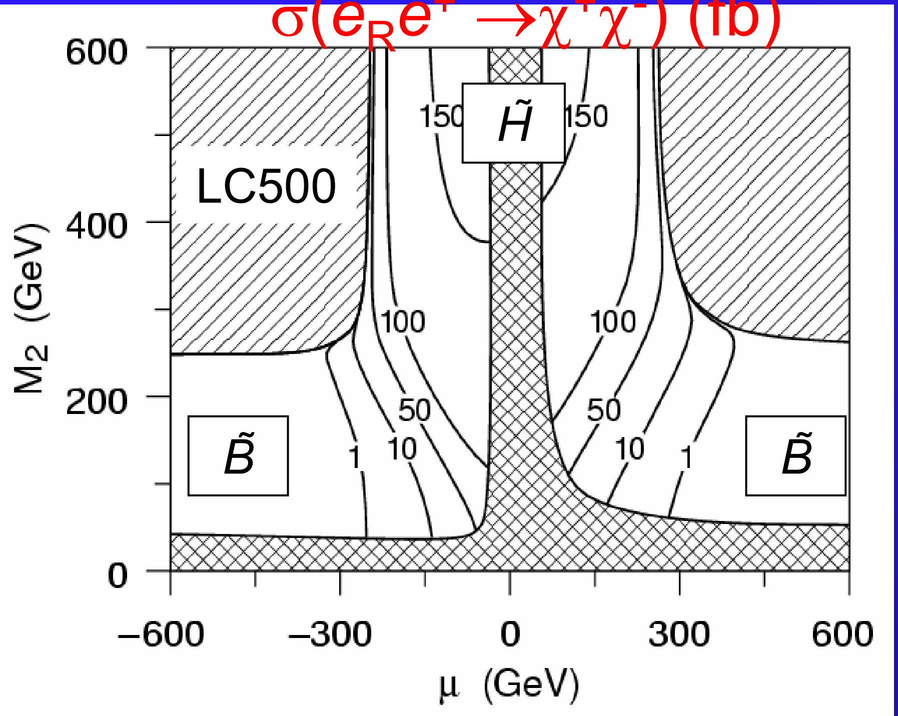
- Weakly-interacting particles w/ weak-scale masses give observed Ω_{DM}
- Strong, fundamental, and independent motivation for new physics at weak scale

- Could use the LC as a *dark matter laboratory*
- 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.

An Example: Neutralinos

- In more detail: 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.

Neutralino Dark Matter (joint session with SUSY WG), Thursday 1:45 - 2:05
(Paolo Gondolo, Marco Battaglia, Uriel Nauenberg, Bhaskar Dutta, Howard Baer)

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

Baryogenesis

Baryogenesis and Exotica, Friday 10:50 - 12:50
(Daniel Chung, Hitoshi Murayama, Shamit Kachru, Zacharia Chacko,
Sean Carroll, Jonathan Feng)

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 the Charge conjugation and Charge-Parity symmetries (C & CP)
- Depart from thermal equilibrium (because of the CPT theorem !!! More about this later.)
- There are LOTS of ways to do this!

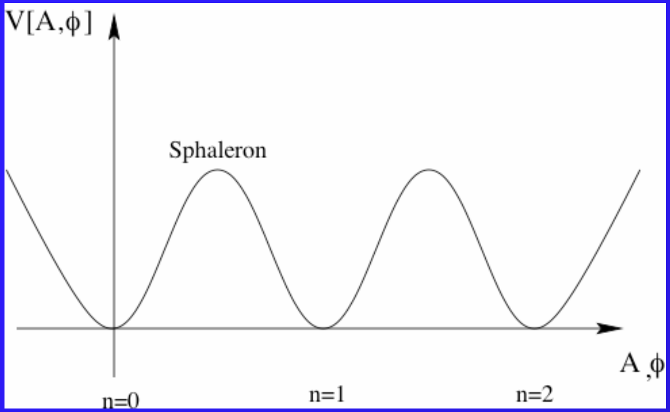
An Important Clue for Particle Physics

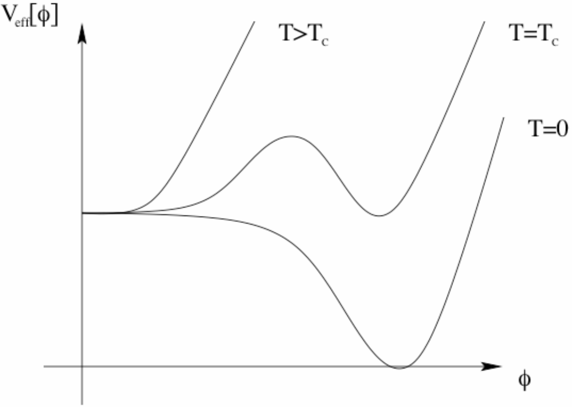
- Many scenarios for baryogenesis rely on physics at the GUT scale. In these cases the LC will have little to add.

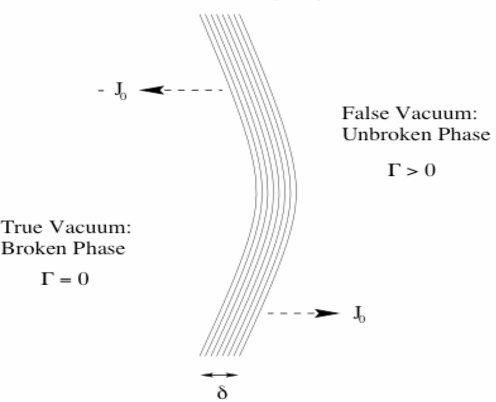
- However, an attractive and testable possibility is that the asymmetry is generated at the weak scale.

- 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!

Electroweak Baryogenesis





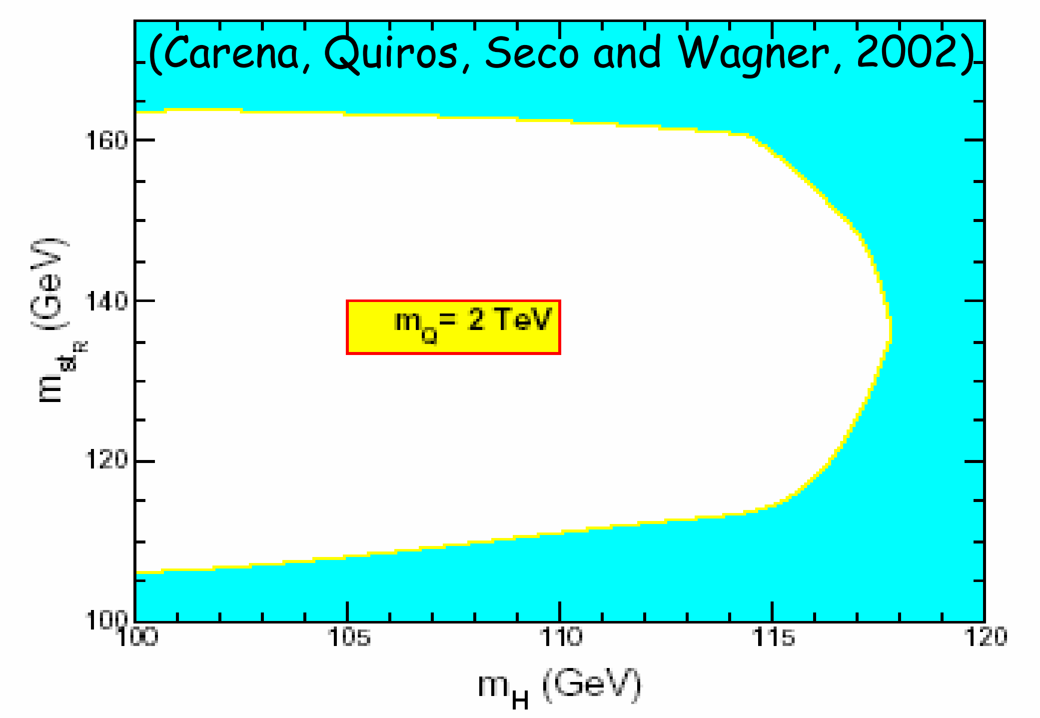


- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe

Physics involved is all testable in principle at colliders.
Small extensions needed can all be found in SUSY,
Testability of electroweak scenarios 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.

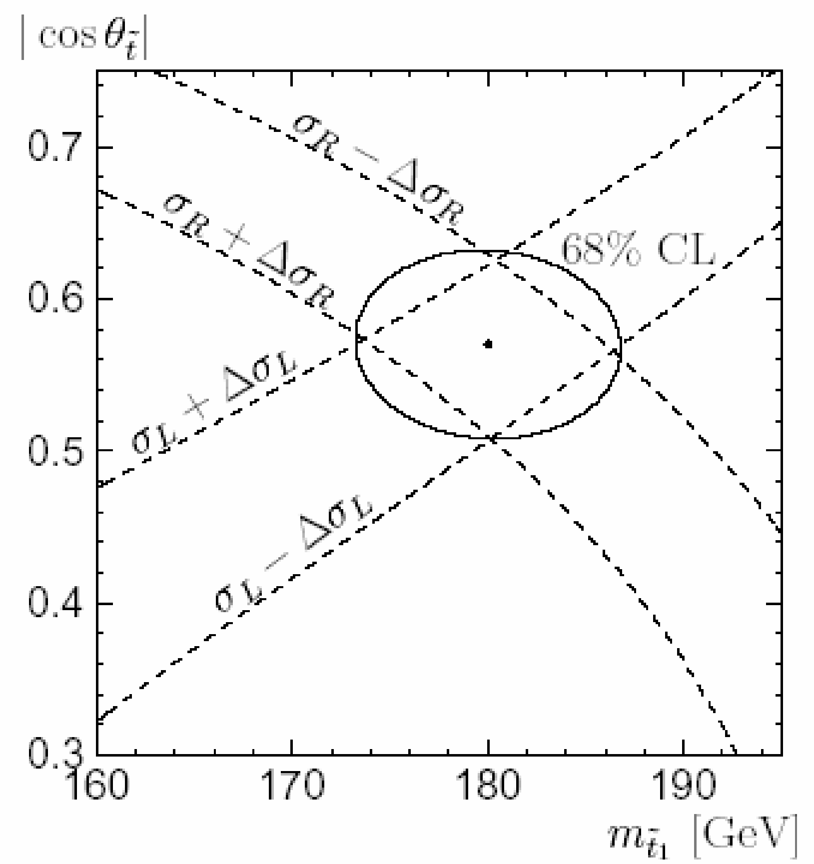


CP-violation

- In allowed parameter space - BR($b \to s\gamma$) different from SM case.
- For typical spectrum (light charged Higgs) BR($b \to s\gamma$) somewhat > SM case, but not always

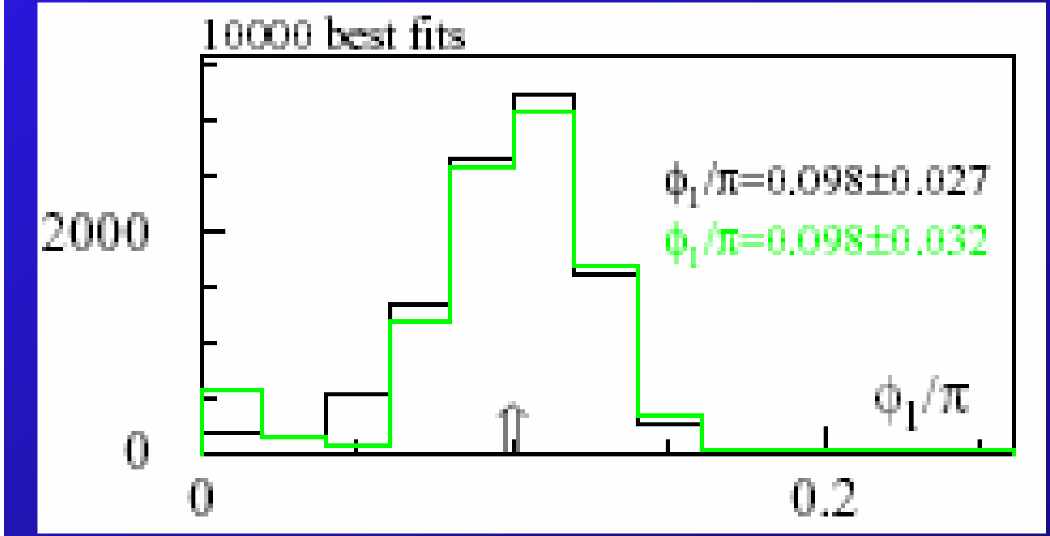
Baryogenesis Parameters at the LC

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



Bartl et al. (1997)

CP phase constraints using chargino/neutralino masses and cross sections



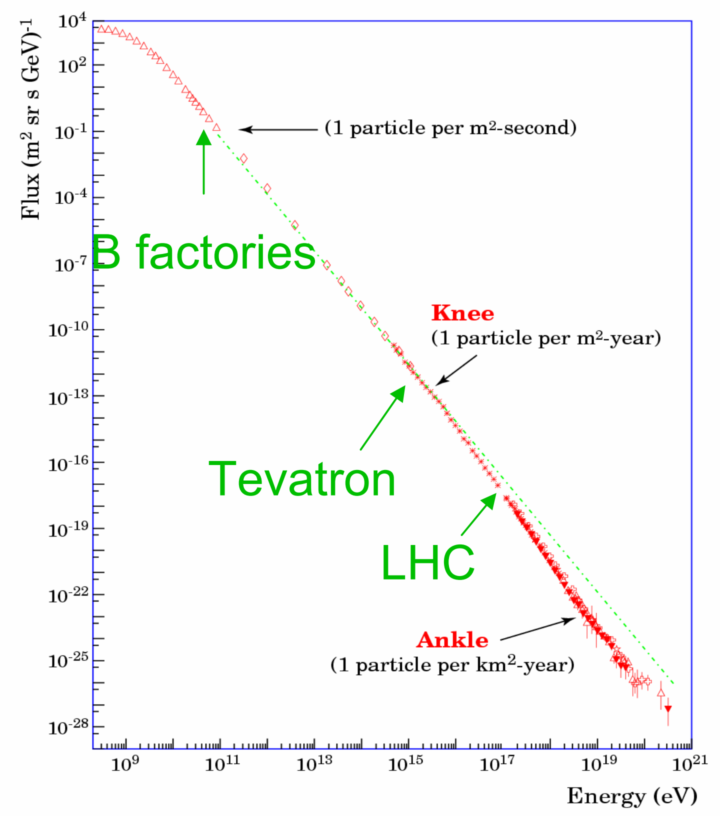
Barger et al. (2001)

Important Questions

- How well can we determine Ω_B in this scenarios?
- Are there other weak-scale scenarios the LC can explore?
- 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 must be emitted from nearby, but no local sources found.

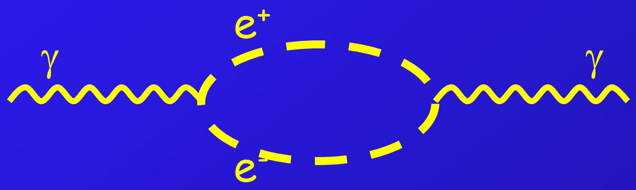
- Solutions:
  - Bottom-up: e.g., CRs are gluino-hadrons.
  - Top-down: CRs result from topological defect decays, should produce up-going cosmic neutralinos if SUSY exists.

Testable predictions for colliders.

Inflation and Dark 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?



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

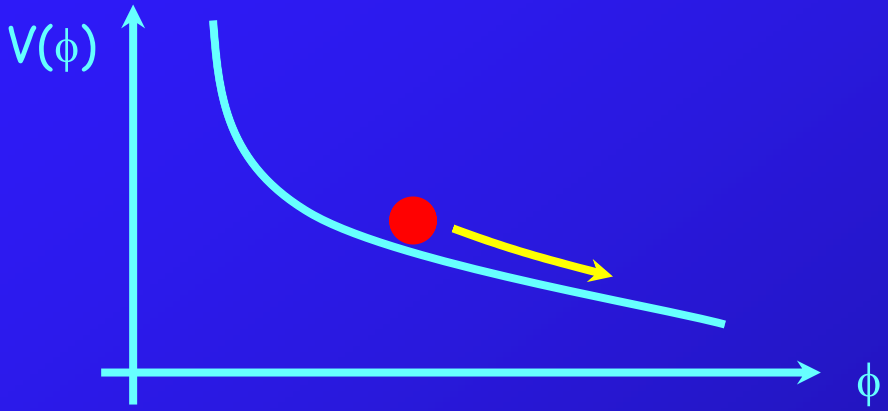
Still 10^{60} too big!

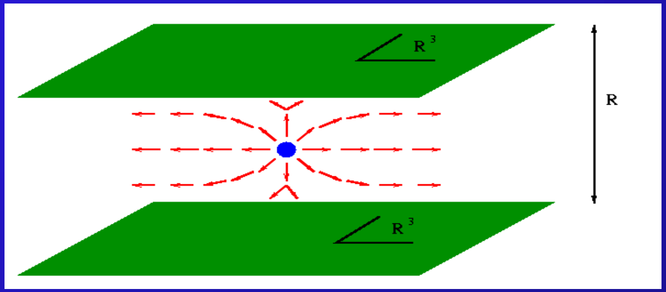
- While calculating branching ratios - easy to forget SUSY is a *space*-time symmetry.
- A SUSY state $|\psi\rangle$ obeys Q $|\psi\rangle=0$, so H $|\psi\rangle \propto \{Q,Q\} |\psi\rangle=0$
- Only vacuum energy comes from SUSY breaking!

Other Possibilities

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

Use scalar fields to source Einstein's equation.





Gravity in the bulk, SM fields only on the (visible) brane.

- Possible LC will provide much-needed insight into these
- The LC alone 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.

Goals

- Particle physics/cosmology connection is of growing interest to researchers, policy makers, and the general public.
- This role of all accelerators in exploring this connection is worth highlighting. A new HEPAP Committee, chaired by Persis Drell, will do exactly this.

Our charge from Jim Brau and Mark Oreglia

- Form working group in ALCPG framework
- Determine and prioritize topics with potential connections
- Produce white paper by Fall 2004

Some Specifics

- Detector effects and (machine-induced) backgrounds may be important - address with serious program of studies.

- If LC/Cosmo connection is to boost the LC physics case need realistic and robust simulation result.

- Use cosmology data to understand regions of parameters/ physics signatures challenging for the LC - motivate studies.

- Interplay with the LHC data very important - what improvements will LC bring over LHC alone?

- Which are the LC energy thresholds important to ensure sensitivity to cosmology-motivated phenomenology ?

Timeline

- Produce a white paper focused on the LC, stating the case in a clear and balanced way. Expect ~50 page document, summarizing old and new work, and targeting audience of particle physicists, astrophysicists, cosmologists, and astronomers.

- [April 2004: Possible meeting at LCWS 04, Paris.]
- July 2004: Parallel sessions at ALCPG Meeting, Victoria. Contributions finalized.

- September 2004: White paper submitted to ALCPG Executive Committee.

We're hoping you'd like to sign on and help us - you'll find examples of what is going on in our 3 parallel sessions!

-Thank You -