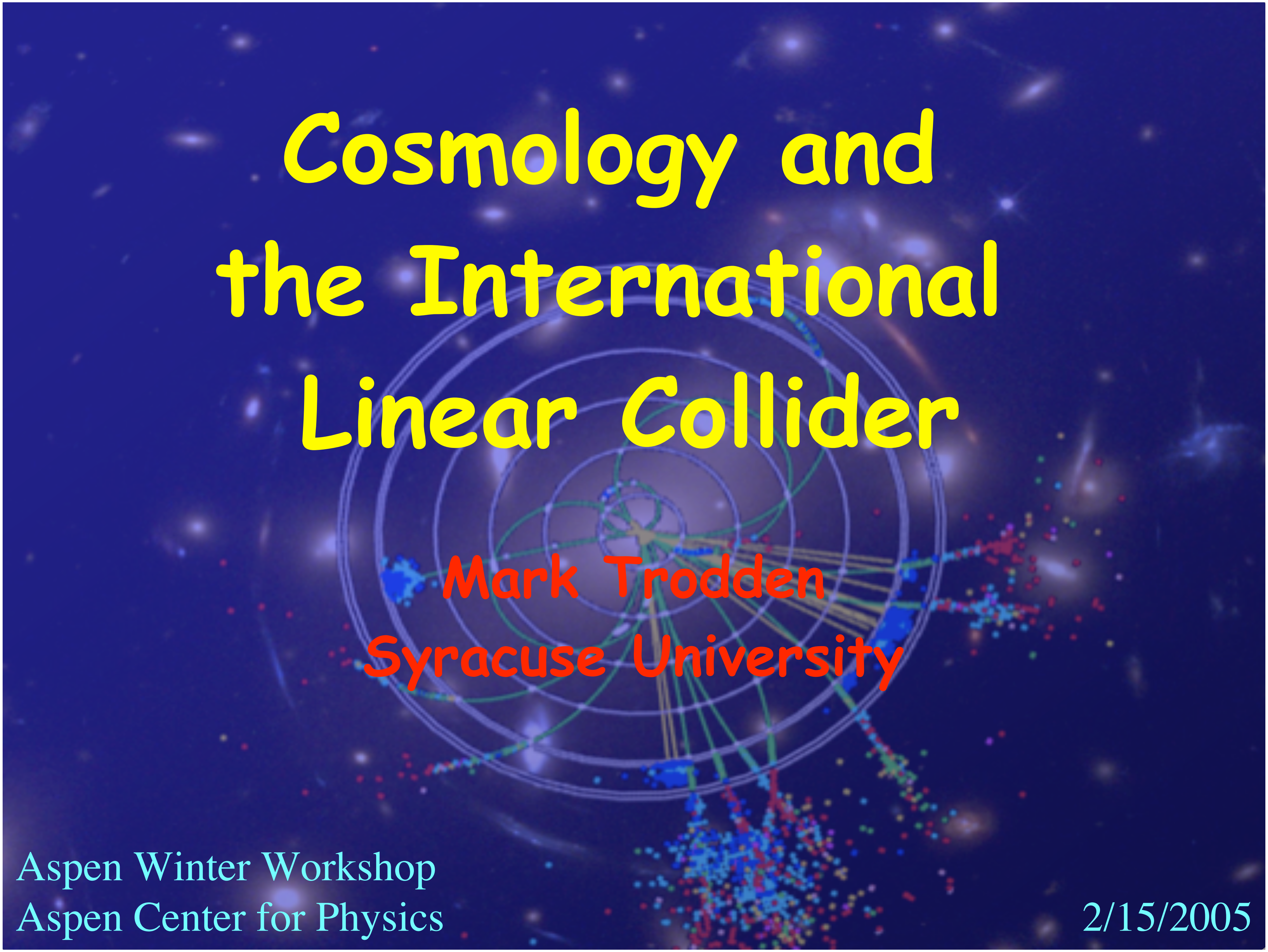

Cosmology and the International Linear Collider

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Aspen Winter Workshop
Aspen Center for Physics

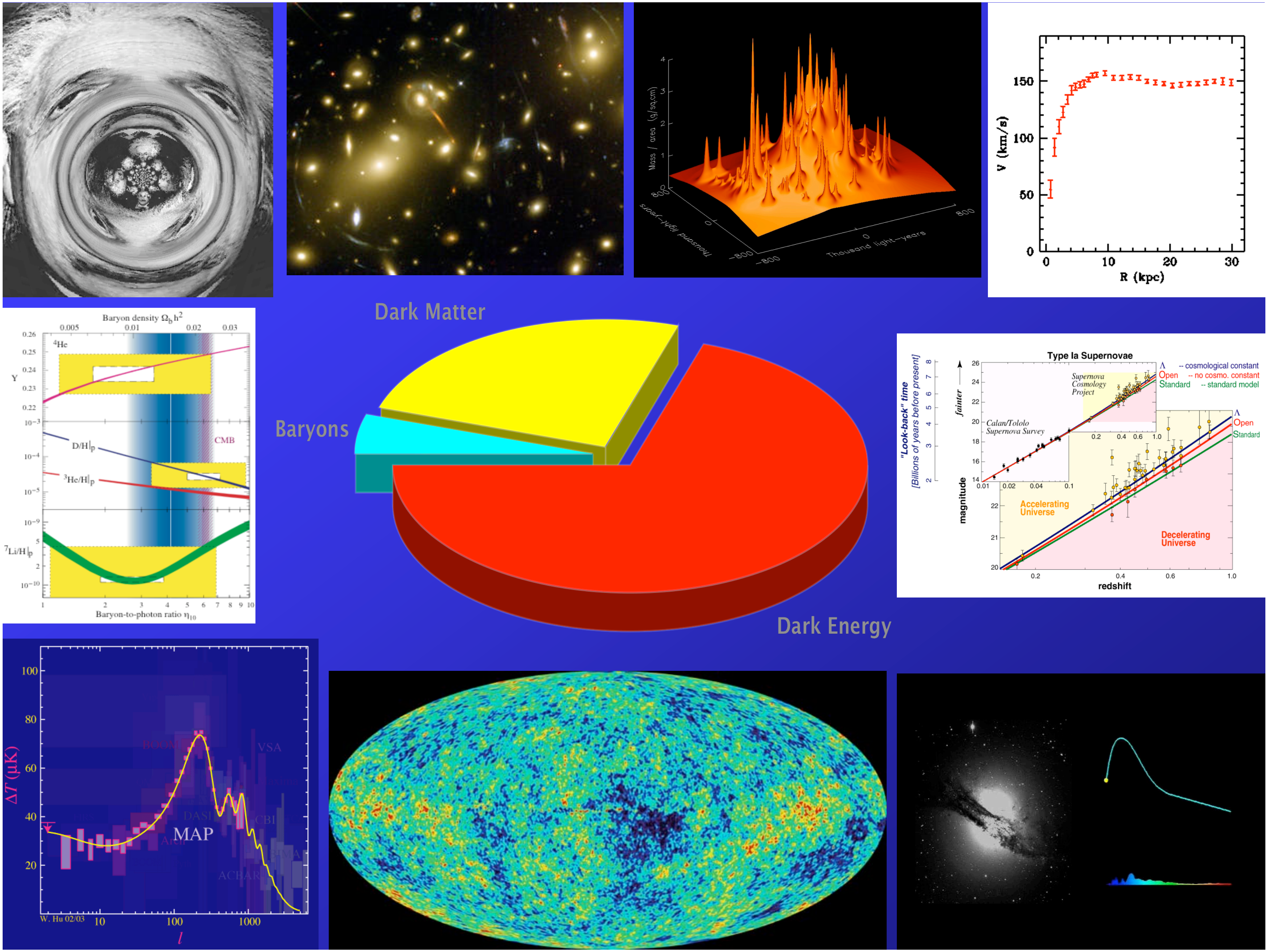
2/15/2005

Outline

- A very brief review, following Josh and Lawrence
- The ALCPG Working Group on Cosmological Connections
- Dark Matter
- The Baryon Asymmetry of the Universe
- Dark Energy and Inflation (!)

[See related talks by Josh Frieman, Lawrence Krauss, Carlos Wagner, Shufang Su, Geraldine Servant, Aaron Chou, Greg Tarle, Sean Carroll, plus talks on neutrinos (which I haven't mentioned here). Sorry if I've missed anyone!]

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.


Mass / area (g/sq.cm)
Thousand light-years
V (km/s)
R (kpc)
Dark Matter
Baryons
Dark Energy
Baryon density Ω_b h^2
CMB
Baryon-to-photon ratio η_10
Type Ia Supernovae
-- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
Supernova Cosmology Project
Calan/Tololo Supernova Survey
"Look-back" time [Billions of years before present]
fainter
magnitude
Accelerating Universe
Decelerating Universe
redshift
ΔT (μK)
MAP
VSA
BOOMERanG
DASI
CBI
ACBAR
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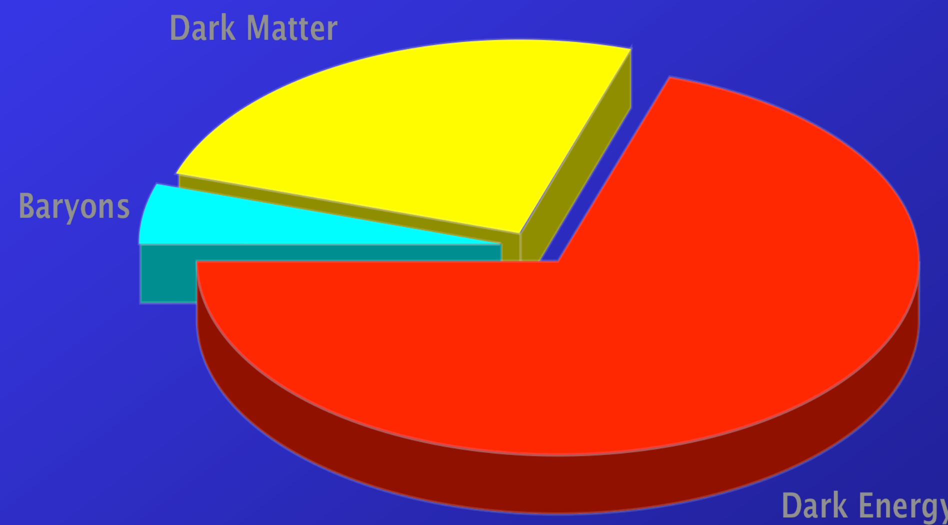
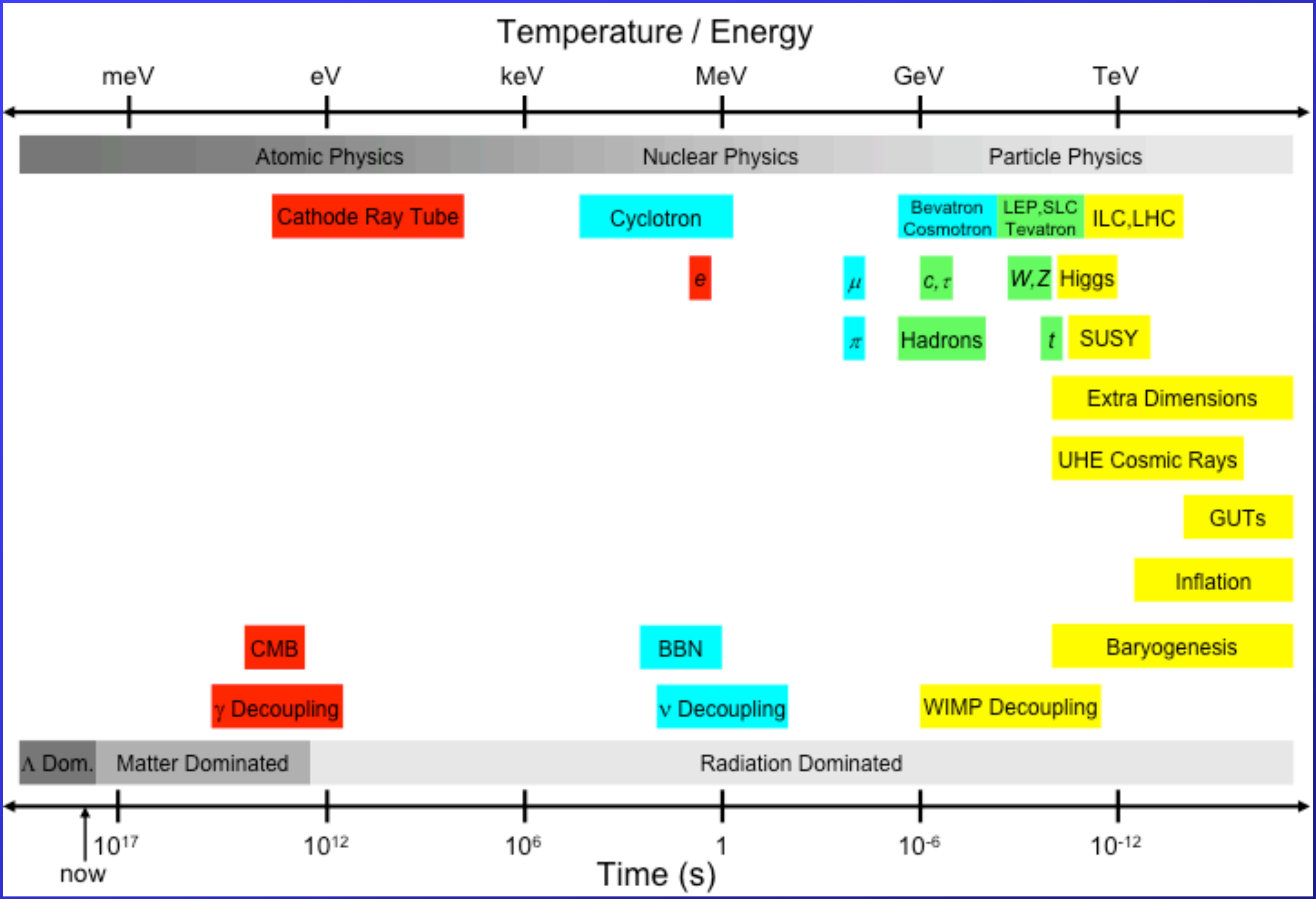
We don't know what these particles are but we have some well-motivated ideas

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



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

Colliders as Time Machines



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

Have commissioned many new studies in addition to Synthesizing existing results into a single coherent picture

Although a couple of months later than anticipated, analyses will be reported at LCWS 2005 at Stanford in March, with white paper following soon after.

BSM Physics & Dark Matter

There is a very broad connection between models of beyond the standard model physics (particularly those addressing the hierarchy problem) and dark matter

- Almost any model involves new particles at the TeV scale, related to the SM particles through symmetries (SUSY partners, KK partners, extra gauge and scalar partners, ...)
- Typically, to avoid things like proton decay and precision EW tests, an extra symmetry is required (R-parity, KK-parity, T-parity, ...).
- This symmetry renders stable some new particle at the weak scale

Often, this stable new particle is an ideal WIMP candidate!

Dark Matter

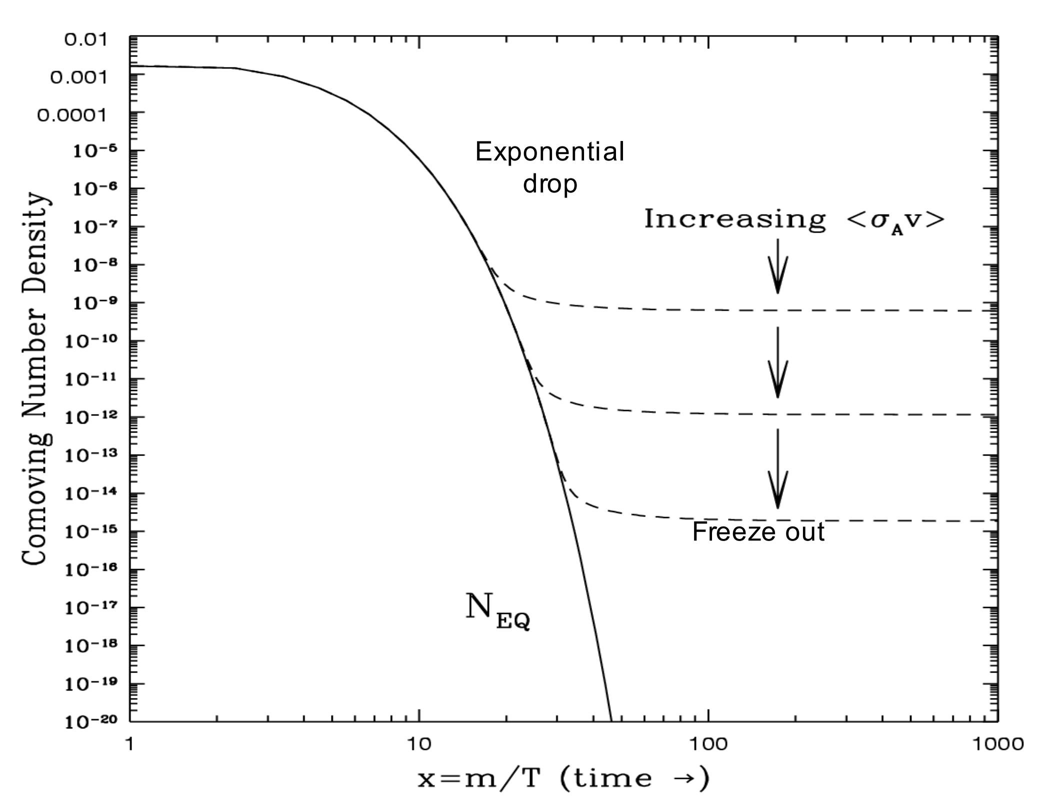
- A prime dark matter candidate is the WIMP
- → a new stable particle χ.
- Number density n determined by

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

Dilution from expansion ($-3Hn$)

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

- Initially, $\langle\sigma v\rangle$ term dominates, so $n \approx n_{eq}$.
- Eventually, n becomes so small that dilution term dominates
- 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 ILC 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.

Can compare this program with the one that led (with spectacular success) to our understanding of BBN via a detailed understanding of nuclear physics

What are the Challenges?

- Definitive predictions depend on detailed studies.
- Mass and cross-section expectations depend on the modes of annihilation, determining the freeze-out abundance.
  - P-wave proceses require larger $\langle \sigma v \rangle$ than S-wave ones
  - Spin of DM particle is crucial
  - Coannihilation channels must be understood
  - …

Can the ILC identify all the candidate thermal relics (and distinguish the various possibilities)?

- In SUSY (well, mSUGRA anyway) detailed studies exist
- In other models, one can currently only broadly quote typical values and bounds

Rough Examples

Model	DM Mass
Universal Extra Dimensions	~ 600 GeV
Branon Dark Matter	> 100 GeV
Randall-Sundrum Dark Matter	> 20 GeV
(insert favorite model here)	....

[Report will summarize new commissioned results for many of these]

- Initial stage of ILC already sensitive to large part of parameter space.
- Much theoretical effort needed to make precision predictions before ILC.
- Obviously helpful if a candidate is found at the LHC.

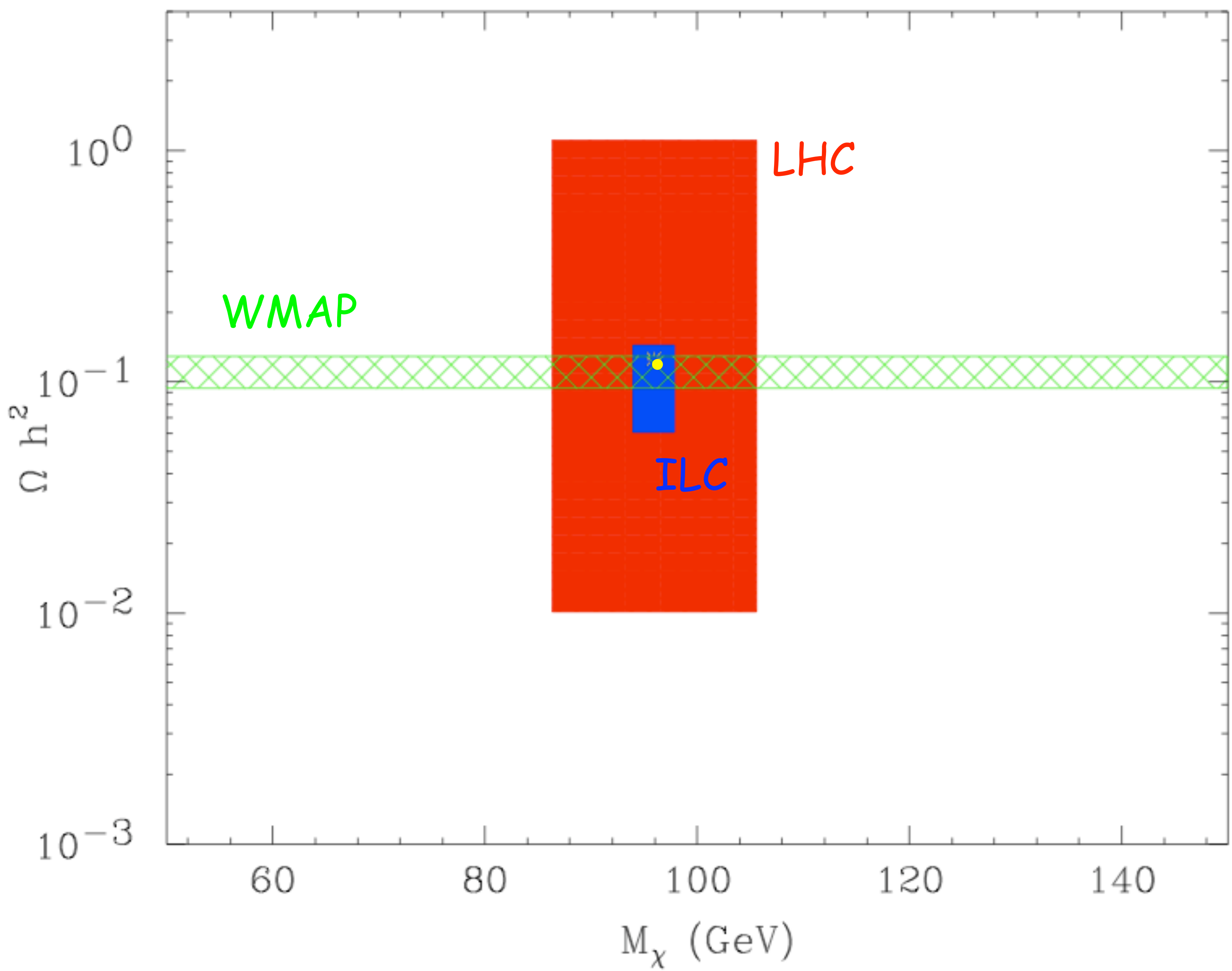
What Might an ILC Buy Us?

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

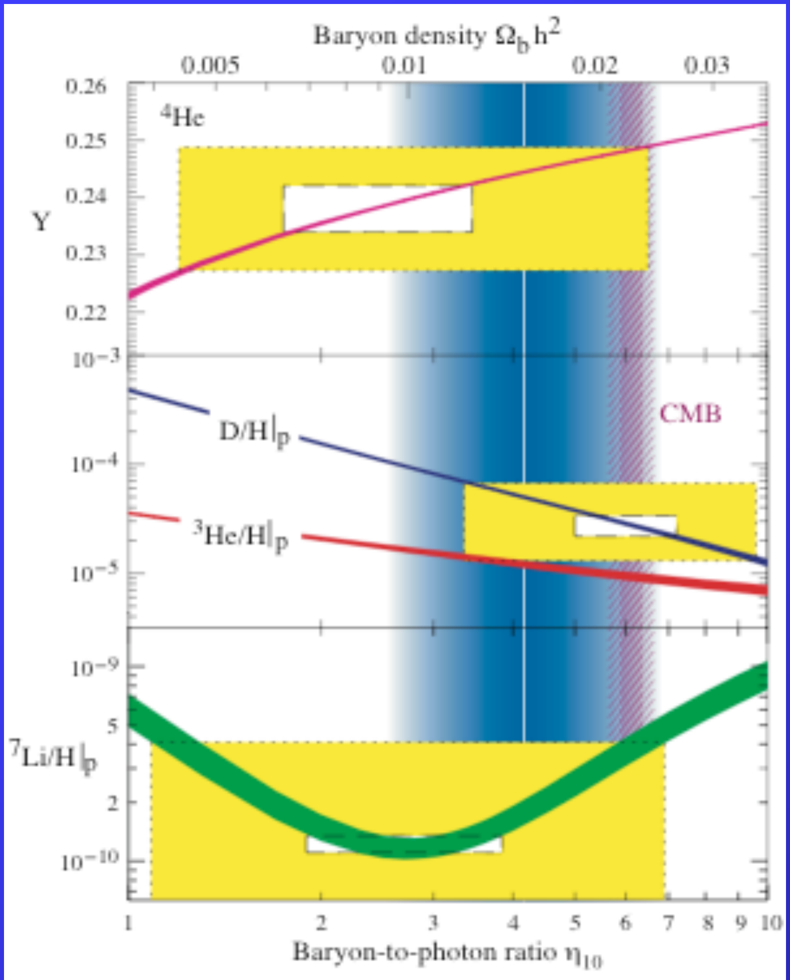
Concrete example - point B′ of "updated benchmark" points:
mSUGRA w/ $\tan\beta = 10$, $\mathrm{sgn}(\mu)=+1$, $m_0=57$, $m_{1/2}=250$, $A_0=0$

- 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



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

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) :

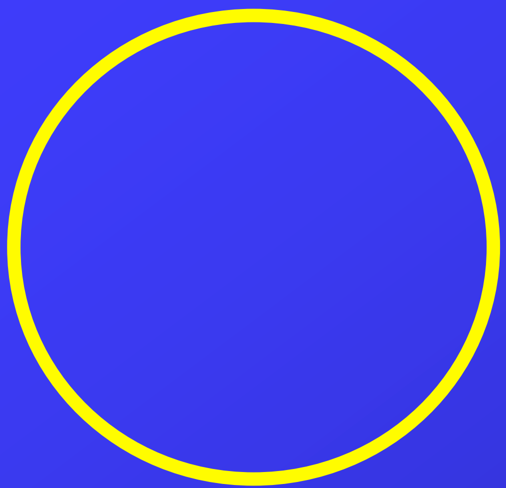
- Violate Baryon number (B) symmetry
- Violate Charge and Charge-Parity symmetries (C & CP)
- Depart from thermal equilibrium
- (LOTS of ways to do this!)

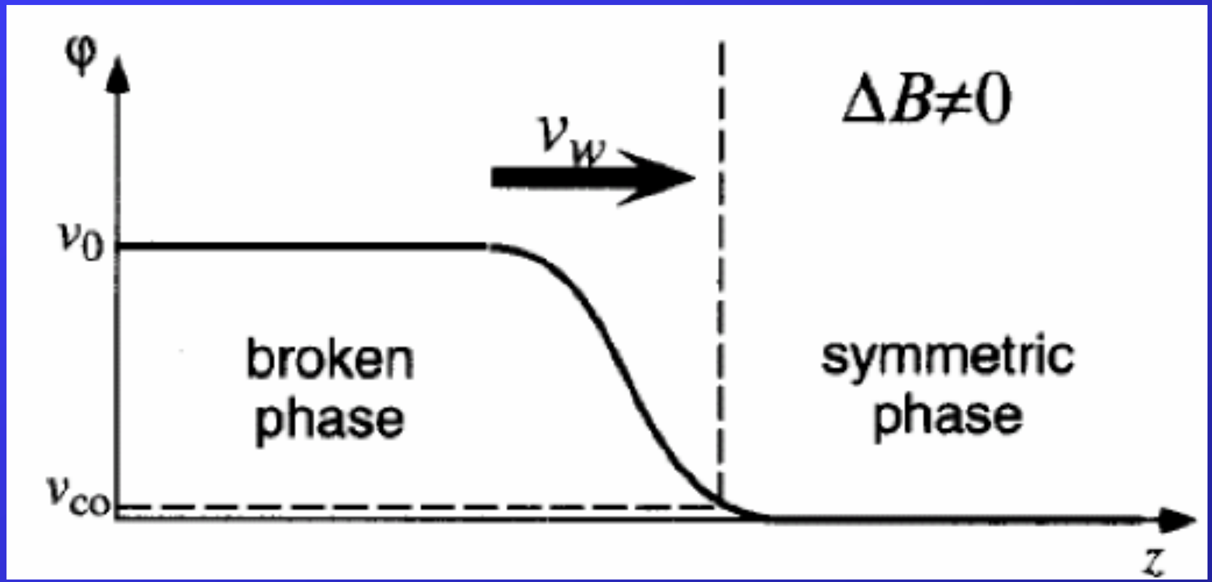
(See talk by Carlos Wagner for many details of this)

A Connection to TeV Physics

- Many scenarios for baryogenesis rely on physics at the GUT scale. In these cases the ILC 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, satisfies all 3 Sakharov criteria in principle, (anomaly, CKM matrix, finite-temperature phase transition)
- Exciting, but turns out not enough CPV and a continuous EWPT. Therefore, 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



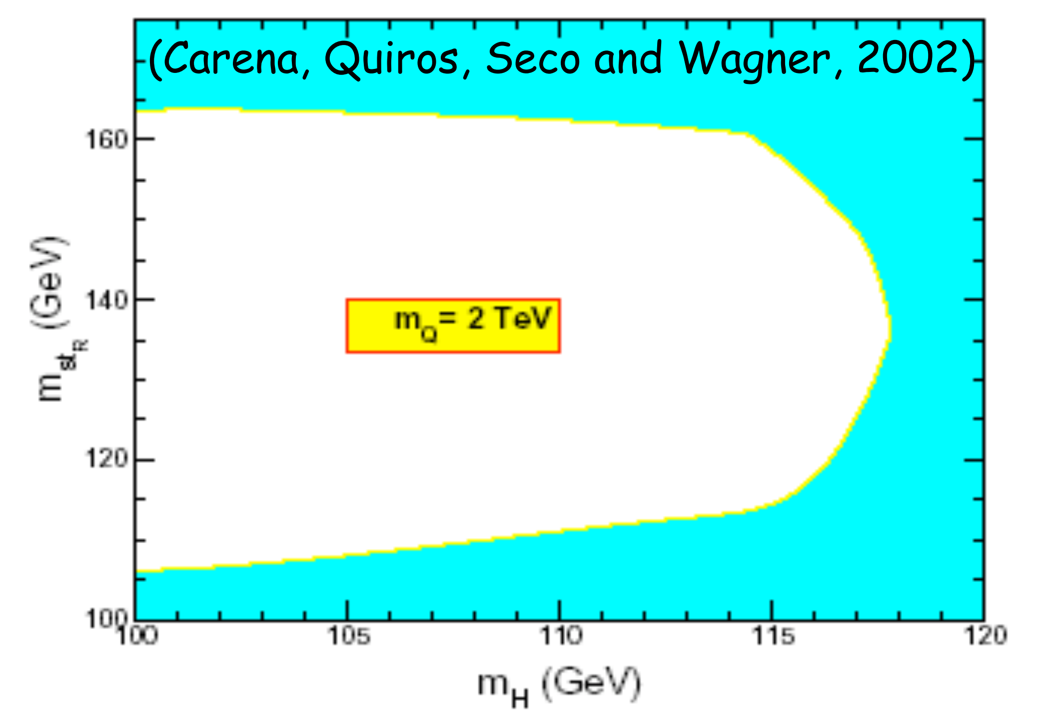


- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe

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

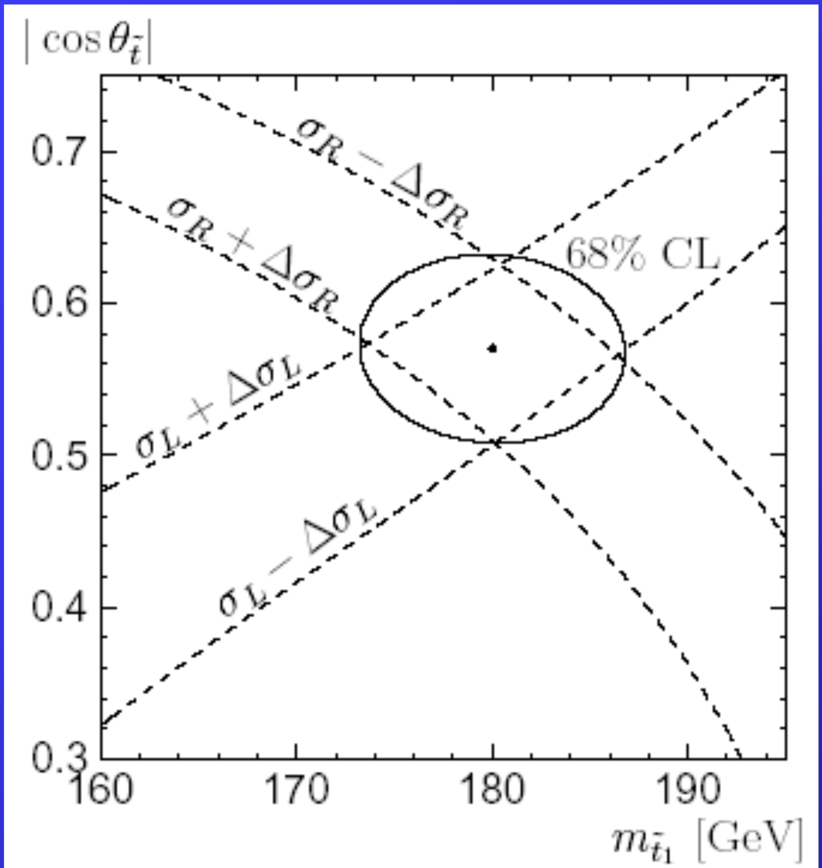
- In supersymmetry, sufficient asymmetry is generated for *light Higgs, light top squark, large CP phases*
- Promising for ILC!
- Severe upper bound on lightest Higgs boson mass, m_h <120 GeV (in the MSSM)
- Stop mass may be close to experimental bound and must be < top quark mass.



Very nice description of bounds in Dan Chung's parallel talk at the 2004 SLAC LC meeting (Linked from ALCPG cosmology subgroup page)

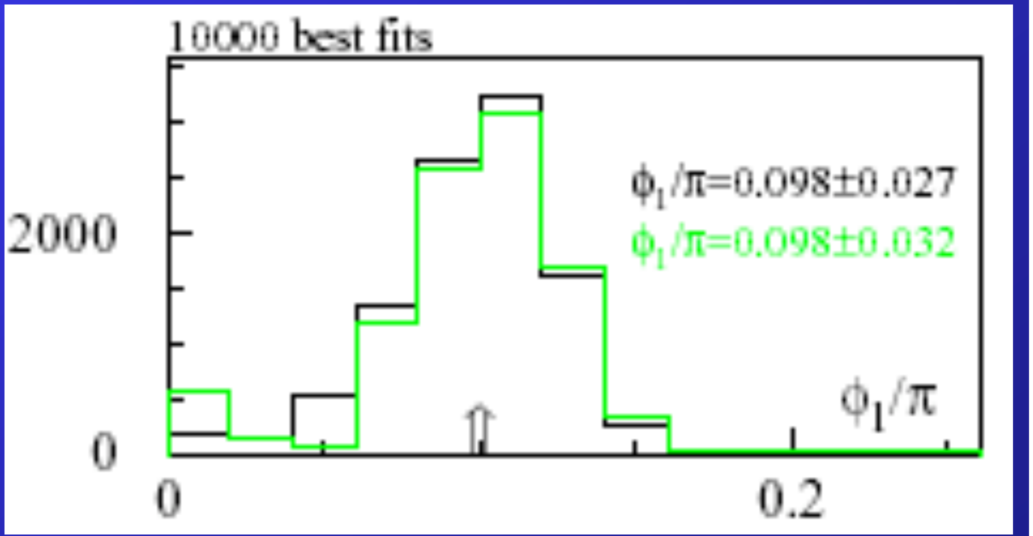
Baryogenesis Parameters at the ILC

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

- How well can we determine Ω_B in these scenarios?

- Does the ILC have anything to say about GUT-scale baryogenesis/leptogenesis?

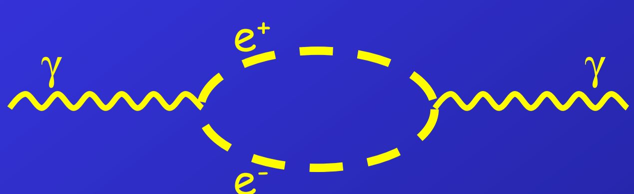
Dark Energy

- 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 scalars, vacuum energy, SUSY breaking.

- 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!



$$\rho_\Lambda \sim M^4_{SUSY}$$

Still 10^{60} too big!

Inflation

There are several possible connections to low-scale inflation

A proof-of-principle example that one shouldn't give up on collider signatures of some of our most esoteric physics.

- The moduli space of string vacua is extremely complicated
- Expect universe travels a convoluted path through this space before settling in the true vacuum

(Dvali-Kachru) e.g. $$V(\Phi,\Psi) = m_\Phi^2\Phi^2 + \lambda\Phi^2\Psi^2 + \frac{1}{2}\alpha\left(\Psi^2 - m_p^2\right)^2$$

$$m_\Phi^2 \quad \frac{M^4}{m_p^2} \qquad \alpha \quad \frac{M^4}{m_p^4}$$

Number of e-foldings satisfies

$$N \sim \frac{1}{3}\log\frac{m_p^2}{m_\Phi^2} \sim \frac{1}{3}\log\frac{m_p^4}{M^4} \sim 50$$

For M~1TeV

Density Perturbations

(Dvali, Gruzinov, Zaldariaga)

- Requires a new field χ, nearly massless during inflation
- Transfers energy to quarks and leptons during reheating

Mixes with the Higgs $\quad V_\chi = m_h^2 h^\dagger h - c\Psi\chi h^\dagger h \qquad c\langle\Psi\rangle \sim \mathrm{TeV}$

- Clear consequences for an ILC:
- Mixing with h leads to extra peaks in recoil in $e^+e^- \to Z^0 + X$

- Observable to ~ 1% of SM, (10% mixing)
- χ and h should have the same branching ratios (unlike, e.g., Higgs-radion mixing)
- Supersymmetry may require additional singlets to raise the Higgs mass above 120 GeV - could be this

A Cautionary Comment

- 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 ALCPG cosmology group involves more general studies and techniques.

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

Final Comments

- Cosmology provides strong, independent arguments for new physics at the TeV scale.
- These come primarily from the observation of a baryon asymmetry and the evidence for dark matter.
- There is a marvelous opportunity for the interplay between precision cosmological observations, terrestrial dark matter searches and collider experiments (LHC/ILC) to yield an understanding of the universe at $t \sim 10^{-8}$ s, comparable with that obtained through BBN at $t \sim 10$ s.
- Clearly, we all have a lot of work to do.

-Thank You -