Cosmological connection to LC physics

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LC physics study group meeting

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Cosmological connection is one of strong motivations to consider physics beyond the Standard Model

Quest for physics beyond the SM

- **Unification**

  Supersymmetric grand unified theory, Superstring.

- **Neutrino mass**

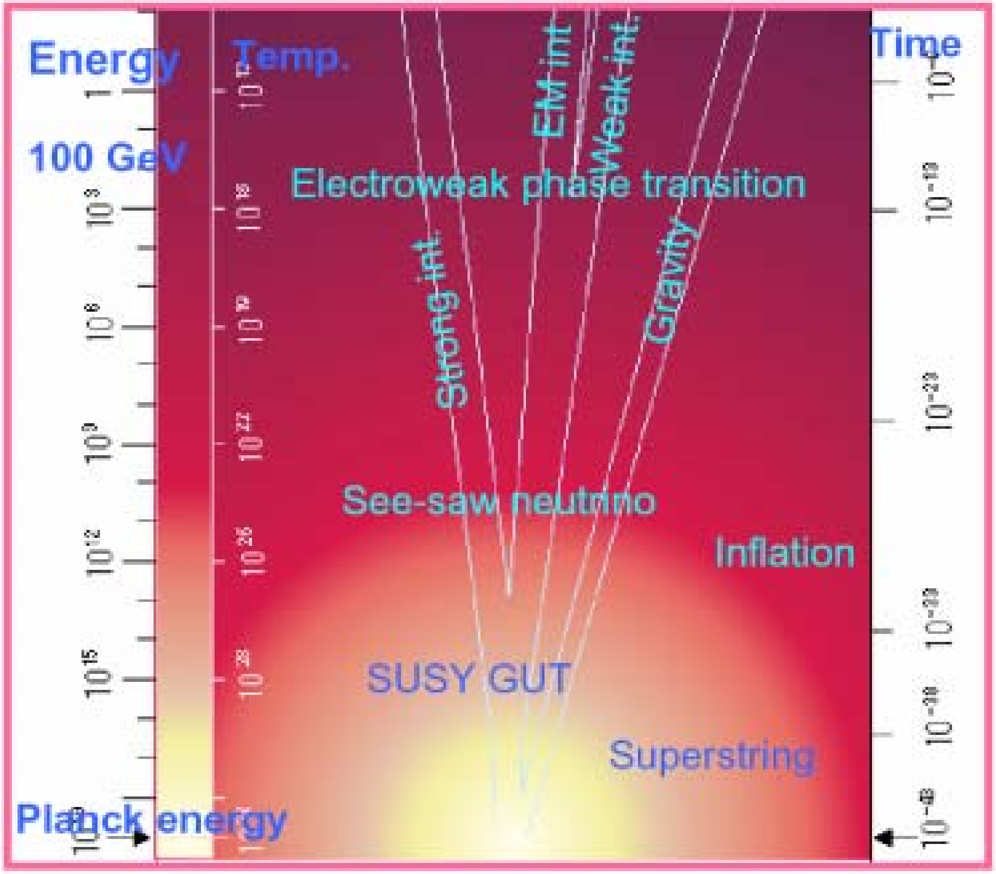
  SuperKamokande, Cl,Ga, exp., K2K, SNO, KamLAND, …

- **Cosmology**

  Dark matter, Baryogenesis, Inflation,…

↓

Need a higher energy than 100 GeV.



How could cosmology be related to LC physics ?

Depends on physics scenario. Some are directly related, and others are indirect.

1. Dark matter
   Dark matter is real (WMAP), but not known what it is.
2. Baryogenesis
   Baryogenesis/leptogenesis from high tempareture vs. Electroweak baryogensis
3. Inflation (no direct consequences to TeV collider physics?)

Find illustrative examples showing that discoveries and measurements at LC have important implications to cosmology.

Dark Matter

- After WMAP :

  Energy decompositions of Universe

  73% vacuum energy; 23% Dark matter; 4% Baryon

- Well-motivated candidates for Dark Matter

  LSP in R-parity conserving SUSY model

  (Neutralino, gravitino,…)

  Axion

SUSY Dark matter

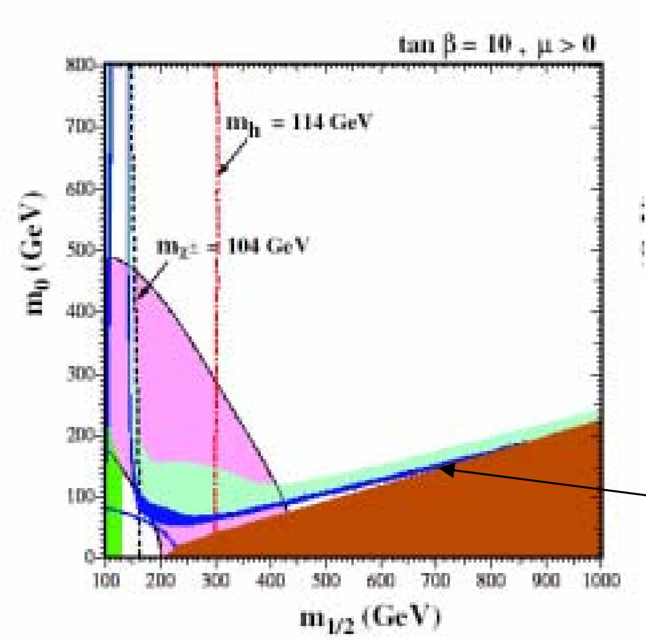
Lightest neutralino =
A natural candidate for dark matter.
A superparner of neutral gauge bosons and Higgs bosons.

Ordinary particle	Super-particle
quark (q)	squark $(\tilde{q})$
lepton (l)	slepton $(\tilde{l})$
gluon (g)	gluino $(\tilde{g})$
W,Z,γ,H	neutralino, chargino $(\tilde{\chi})$

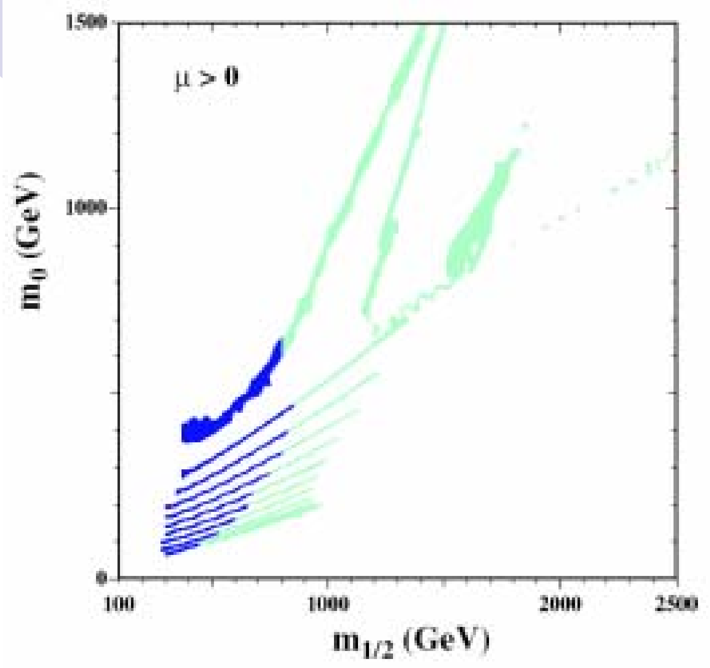
Cosmological abundance can be calculated.
For the minimal SUGRA model, the allowed region is updated after WMAP.

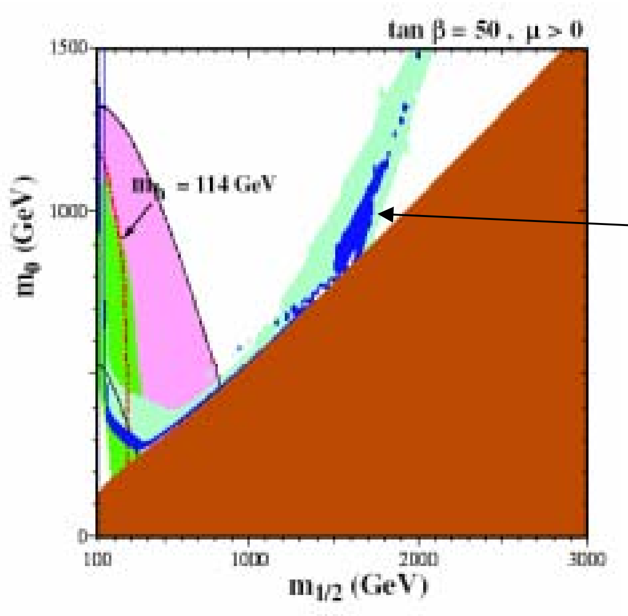
$$0.094 \leq \Omega_\chi h^2 \leq 0.129$$

J.Ellis, K.Olive, Y.Santoso, and V.Spanos



Stau-Neutralino coannihilation





Rapid annihilation funnel

WMAP lines
(tan β =5-55)

Implications to LC SUSY physics

R.Arnowitt, D.Dutta, T.Kamon, and V.Khotilovich

- Mass relation

  coannihilation tail $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < 15\mathrm{GeV}$

  -> soft tau in stau decay
- Composition of neutralino

  Stau decay, selectron/smuon production

  chargino production
- Rapid annihilation funnel $m_A \sim 2m_{\tilde{\chi}_1^0}$

Baryogenesis

- How to explain the baryon-to-entropy ratio of the Universe from zero baryon number.

$$\frac{n_B}{s} = (0.21 - 0.90) \times 10^{-10}$$

- Three conditions

  Baryon number violation, C&CP violation, Out-of equilibrium

- A basic fact

  Baryon number violation at high temperature in the SM.

  (At and above the EW phase transition, B+L violation and B-L conservation)

- Two basic scenarios

  1. B-L generation above the EW phase transition temp.

     (GUT baryogenesis, leptogenesis)

  2. Baryogenesis at the electroweak phase transition.

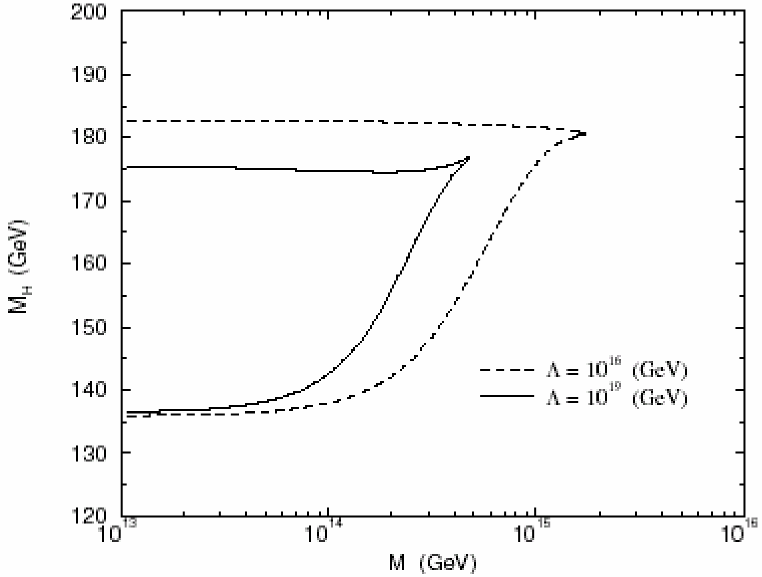
B-L generation at a high temp

- Leptogenesis in the see-saw neutrino model is the most “standard” scenario.

Little consequence on collider physics.

The Higgs mass bound as a function of the heavy Majorana neutrino mass.

J.Casas, V.Di Clemento, A.Ibarra and M.Qiuros

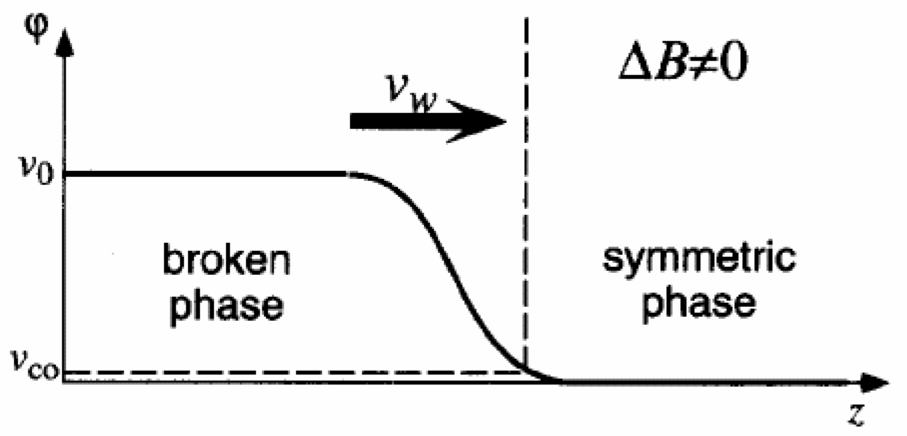


- SUSY variant of leptogenesis

Heavy sneutrino decay, Affleck-Dine mechanism, etc

Electroweak baryogenesis

- Baryon number generation at the electroweak phase transition.
- Expansion of bubble wall.
- Charge flow of fermion due to CP violation at the wall.
- Baryon number violation in the symmetric phase.



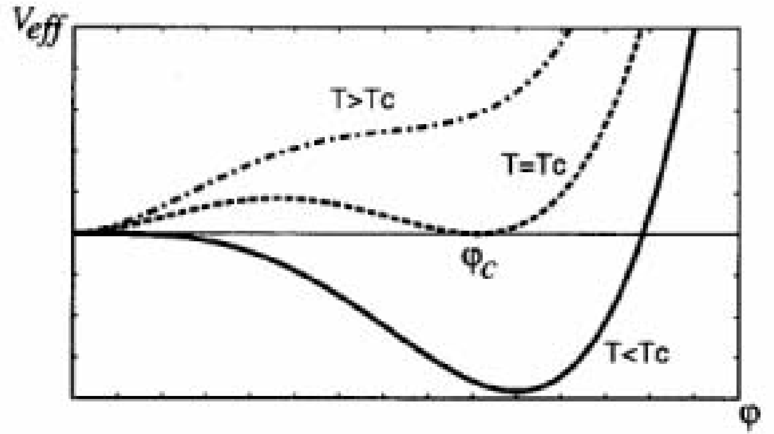
Two Higgs doublet model

- One Higgs doublet SM does not generate a large enough baryon asymmetry. (No first order phase transition, small CPV parameter)
- A simplest candidate is two Higgs doublet model.
- We need a first order phase transition and CP phase in the finite temperature Higgs potential .

-> Consequences in collider physics

Condition of the strong first order phase transition.

$$
\begin{aligned}
V_0 \;=\; & -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \mu_3^2\Phi_1^\dagger\Phi_2 - \mu_3^{2*}\Phi_2^\dagger\Phi_1 + \\
& \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - \\
& \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_5^*(\Phi_2^\dagger\Phi_1)^2\right]
\end{aligned}
$$



$$
V(\phi,T) = V_0(\phi) - \frac{N_{eff}\pi^2 T^4}{90} + V_2(\phi,T) + V_3(\phi,T)
$$

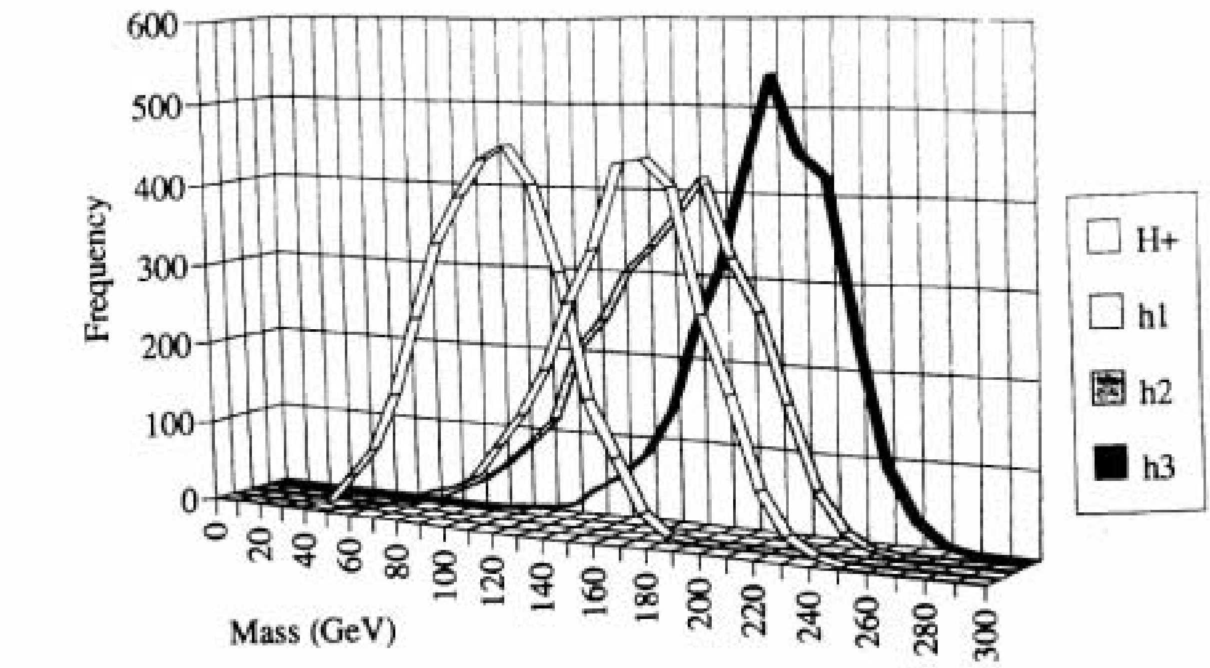
$$
V_2(\phi,T) = \frac{T^2}{24}\left\{
\begin{array}{c}
-4(\mu_1^2+\mu_2^2) + (6\lambda_1 + 2\lambda_3 + \lambda_4 + 3g_b^2 + g_\tau^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2)\sum_{i=1}^{4}\phi_i^2 \\
+(6\lambda_2 + 2\lambda_3 + \lambda_4 + 3g_t^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2)\sum_{i=5}^{8}\phi_i^2
\end{array}
\right\}
$$

$$
V_3(\phi,T) = -\frac{T}{12\pi}\left[\sum_{i=1}^{8}\left[m_i^2(\phi,T)\right]^{\frac{3}{2}} + 4\left[\frac{g^2}{4}\sum_{i=1}^{8}\phi_i^2\right]^{\frac{3}{2}} + 2\left[\frac{g^2+g'^2}{4}\sum_{i=1}^{8}\phi_i^2\right]^{\frac{3}{2}}\right]
$$

Need almost massless boson fields in the symmetric phase.

A.Devies, C.Frogatto, G.Jenkins, and R. Moorhouse

"Frequency "of various Higgs boson masses which satisfy the non-baryon washout condition. .



CPV phase in the finite temperature effective potential is not necessary related to CPV in the zero-temp. potential

-> Various possibilities. (K. Funakubo, et.al)

- Interesting to investigate how LC study on the Higgs potential will give an insight on the scenario of the electroweak baryogenesis .
- SUSY electroweak baryogenesis

  Well-known phenomenological consequenses

  Light right-handed stop and chargino with complex phases, very heavy left-handed stop.

Summary

- It is very important to figure out roles of measurements at LC in understanding cosmological problems.
- Study of SUSY Dark matter candidates and determination of the Higgs sector in connection to the electroweak baryogenesis are good examples.
- Many interesting possibilities.