Review of Cosmology and the Linear Collider

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LC-Cosmology working group

- ⋆ Convenors
  - M. Battaglia, J. Feng, N. Graf, M. Peskin, M. Trodden
  - see `http://www.physics.syr.edu/~trodden/lc-cosmology/`
- ⋆ Call to arms!
  - Europe, Japan contingent
  - Belanger, Djouadi, Okada, $\cdots$

The Standard Model of Particle Physics

Construction

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R,\; d_R; \; \begin{pmatrix} \nu \\ e \end{pmatrix}_L \;,\; e_R \tag{1}$$

- ⋆ Higgs sector ⇒ spontaneous electroweak symmetry breaking:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

- ⋆ Yukawa interactions ⇒ massive quarks and leptons
- ⋆ 19 parameters
- ⋆ good-to-excellent description of (almost) *all* accelerator data!

Data *not* described by the SM

- neutrino masses and mixing
- baryogenesis $\eta \sim 10^{-10}$ (matter anti-matter asymmetry)
- cold dark matter
- dark energy

⋆ Note astro/cosmological origin of all discrepancies!

Neutrino masses

Data on neutrino masses/ mixings

- ⋆ Solar ν oscillations (Homestake to SNO)
  - SNO: Standard Solar Model works, but νs oscillate!
  - $|m^2_{\nu_2} - m^2_{\nu_1}| \sim 7 \times 10^{-5}$ eV^2
- ⋆ Atmospheric oscillations (SuperK): ($\nu_\mu \to \nu_\tau$?)
  - $|m^2_{\nu_2} - m^2_{\nu_3}| \sim 3 \times 10^{-3}$ eV^2
- ⋆ large mixing angles
- ⋆ WMAP gives upper absolute mass limit:
  - $\sum_i m_{\nu_i} < 0.71$ eV

How to explain?

A few of many models

- ⋆ Dirac ν masses? (inelegant)
- ⋆ Bilinear R-violation in SUSY? (Valle, Diaz, Porod, $\cdots$)
- ⋆ Add gauge singlet RHN to SM fermion content
  - large Majorana mass allowed
  - completes a generation in $\psi(\mathbf{16})$ of $SO(10)$
  - easily accommodated in $SO(10)$ SUSY GUT
  - see-saw mechanism $\Rightarrow$ light ν_L
  - heavy $N_R \sim 10^9 - 10^{15}$ GeV
  - mechanism for baryogenesis via leptogenesis
  - LFV: $\mu \to e\gamma$, $\tau \to \mu\gamma$ (Rückl)

Baryogenesis:

what gives rise to matter-antimatter asymmetry?

- ⋆ SM not adequate to describe baryogenesis
- ⋆ Beyond the SM physics needed:
  - EW baryogenesis
    - ∗ can work in SUSY
    - ∗ need strong first order EW phase transition
    - ∗ needs $m_h < 105 - 118$ GeV, $m_{\tilde{t}_1} < m_t$
  - Affleck-Dine baryogenesis
    - ∗ need flat directions in scalar potential
    - ∗ scalar fields carrying baryon number
    - ∗ naturally implemented in SUSY theories
  - GUT baryogenesis
    - ∗ baryogenesis at $Q = M_{GUT}$ washed out below M_{GUT} by sphaleron effects? (but pre-heating?)

- leptogenesis: (Fukugita, Yanagida)
  - out-of-equilibrium asymmetric decays of N, $\tilde{N}$ in early universe generates lepton-antilepton asymmetry
  - EW sphaleron effects convert lepton asymmetry into baryon asymmetry
  - naturally implemented in $SO(10)$ SUSYGUTs
  - test via LFV: $e^+e^- \to \tilde{\ell}_1^+\tilde{\ell}_1^- \to e^+\mu^- + 2\widetilde{Z}_1$

Testing leptogenesis at a LC:

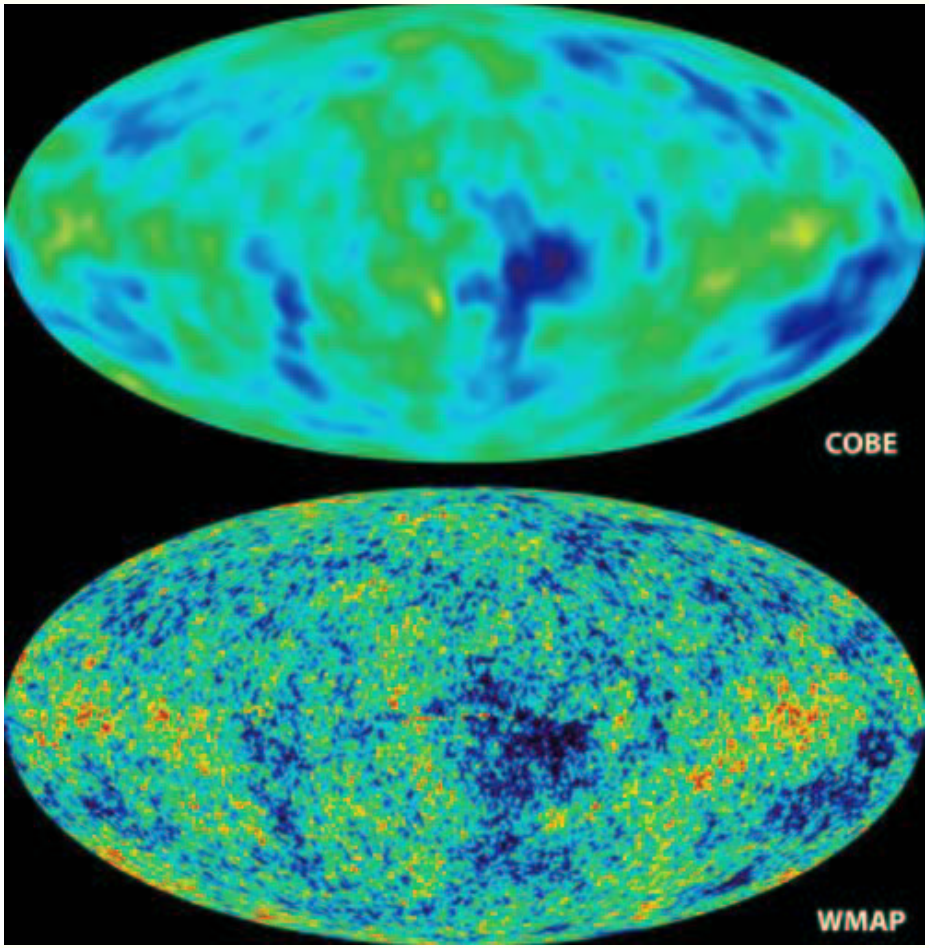
(HB, Balazs, Mizukoshi, Tata)

- ★ Add $\hat{N}_i^c$ to MSSM: $\hat{N}^c \ni (\tilde{\nu}_R^\dagger,\ \psi_{N^cL})$
- ★ $\hat{f} = \hat{f}_{MSSM} + f_\nu \epsilon_{ij} \hat{L}^i \hat{H}_u^j \hat{N}^c + \frac{1}{2} M_N \hat{N}^c \hat{N}^c$
- ★ $\mathcal{L}_{soft} = \mathcal{L}_{MSSM} - m^2_{\tilde{\nu}_R} |\tilde{\nu}_R|^2 + \left[A_\nu f_\nu \epsilon_{ij} \tilde{L}^i \tilde{H}_u^j \tilde{\nu}_R^\dagger + \frac{1}{2} B_\nu M_N \tilde{\nu}_R^2 + h.c. \right]$
- ★ RGEs of MSSM modified to contain terms with f_ν
- ★ $f_{\nu_3} = f_t$ in $SO(10)$
- ★ large f_ν acts to suppress 3rd gen. sleptons compared to 1st and 2nd!
- ★ $\frac{d}{dt}(2\Delta_L - \Delta_R) = \frac{4}{16\pi^2} f_\nu^2 (m^2_{\tilde{\tau}_L} + m^2_{\tilde{\nu}_R} + m^2_{H_u} + A_\nu^2)$
  - $\Delta_L = m^2_{\tilde{e}_L} - m^2_{\tilde{\tau}_L}$; $\Delta_R = m^2_{\tilde{e}_R} - m^2_{\tilde{\tau}_R}$
- ★ correct for stau mixing
- ★ need to measure 1st/3rd gen. slepton masses to $2-3\%$ to test

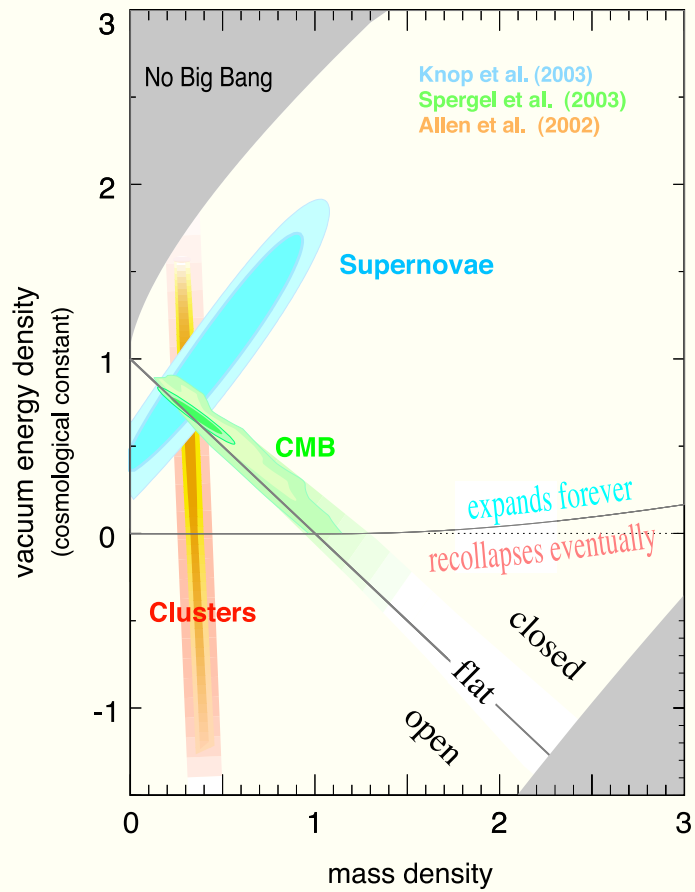
Evidence for dark matter in the universe

- ⋆ binding of galactic clusters (Zwicky, 1930s)
- ⋆ galactic rotation curves
- ⋆ large scale structure formation
- ⋆ gravitational lensing
- ⋆ inflation $\Rightarrow \Omega = \rho/\rho_c = 1$
- ⋆ anisotropy in cosmic microwave background (WMAP)
- ⋆ surveys of distant galaxies via supernovae (DE)
- ⋆ Big Bang nucleosynthesis
  - $\Omega_\Lambda \simeq 0.7$
  - $\Omega_{CDM} \simeq 0.25$
  - $\Omega_{baryons} \simeq 0.045$ (dark baryons ~ 0.040)
  - $\Omega_\nu \simeq 0.005$

Cosmic μ-wave background anisotropies (COBE to WMAP)



Dark matter versus dark energy



Candidates for cold dark matter

- ⋆ axions (Sikivie)
- ⋆ gravity mediated SUSY with R-parity
  - lightest neutralino $\widetilde{Z}_1$ (Goldberg; Ellis, Hagelin, Nanopoulos, Olive and Srednicki)
  - gravitino $\tilde{G}$ (superWIMP) (Feng, Rajaraman, Takayama)
- ⋆ UED: lightest KK-odd boson $e.g.$ B_1 (Servant, Tait)
- ⋆ little Higgs scalar DM: (Birkedal, Wacker)
- ⋆ SUSY Q-balls: (Kusenko, Shaposhnikov)
- ⋆ branons: (Cembranos, Dobado, Maroto)

Neutralino dark matter

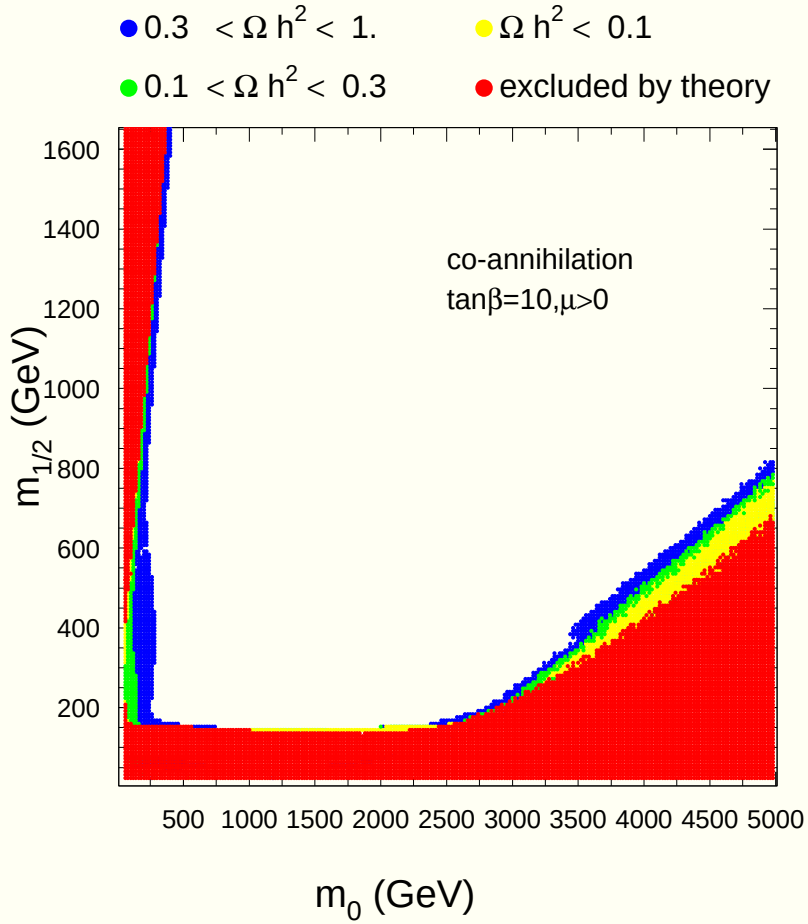
- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ equally many computer codes
  - Neutdriver (Jungman; not maintained)
  - DarkSUSY: (Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz)

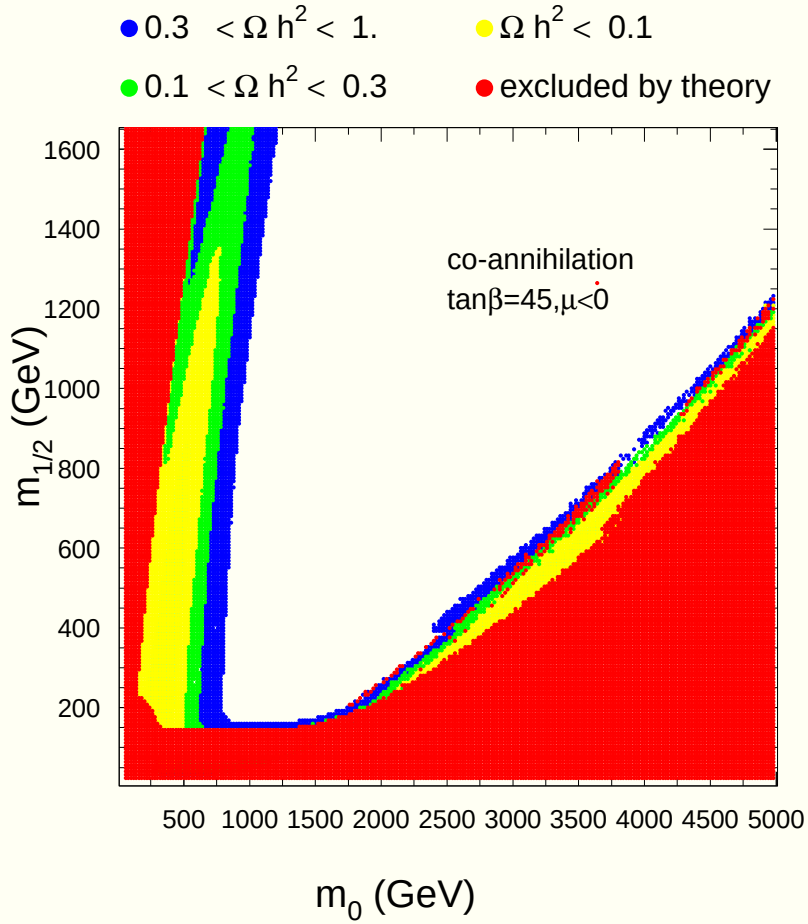
- Micromegas (Belanger, Boudjema, Pukhov, Semenov)
- SSARD: (Ellis, Falk and Olive)
- IsaRED: (HB, Balazs, Belyaev)
- Drees/ Nojiri code
- Roszkowski code
- Arnowitt/ Nath code
- Lahanas/ Nanopoulos code
- Bottino/ Fornengo *et al.* code
- $\cdots$ (I am sure I am omitting many...)

Main mSUGRA regions consistent with WMAP

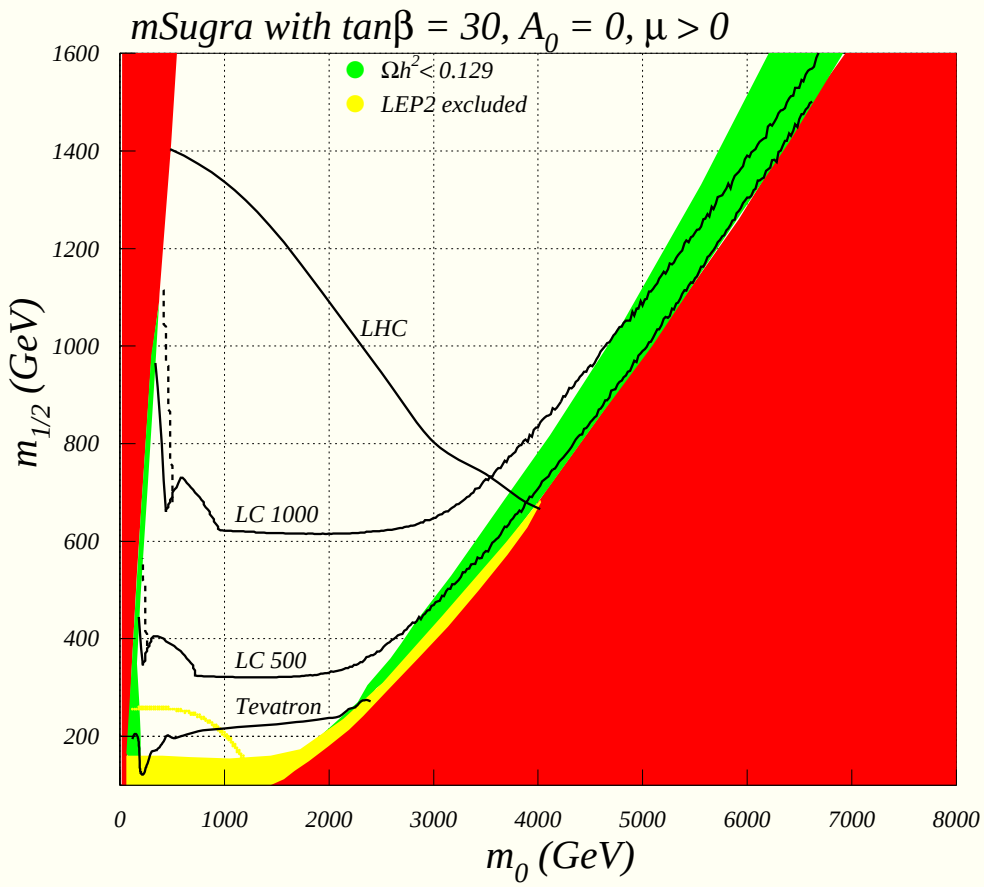
- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\tilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \to small$)
- ⋆ A-funnel ($2m_{\tilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\tilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\tilde{Z}_1}$)

Relic density of neutralinos in mSUGRA model





Sparticle reach of all colliders and relic density



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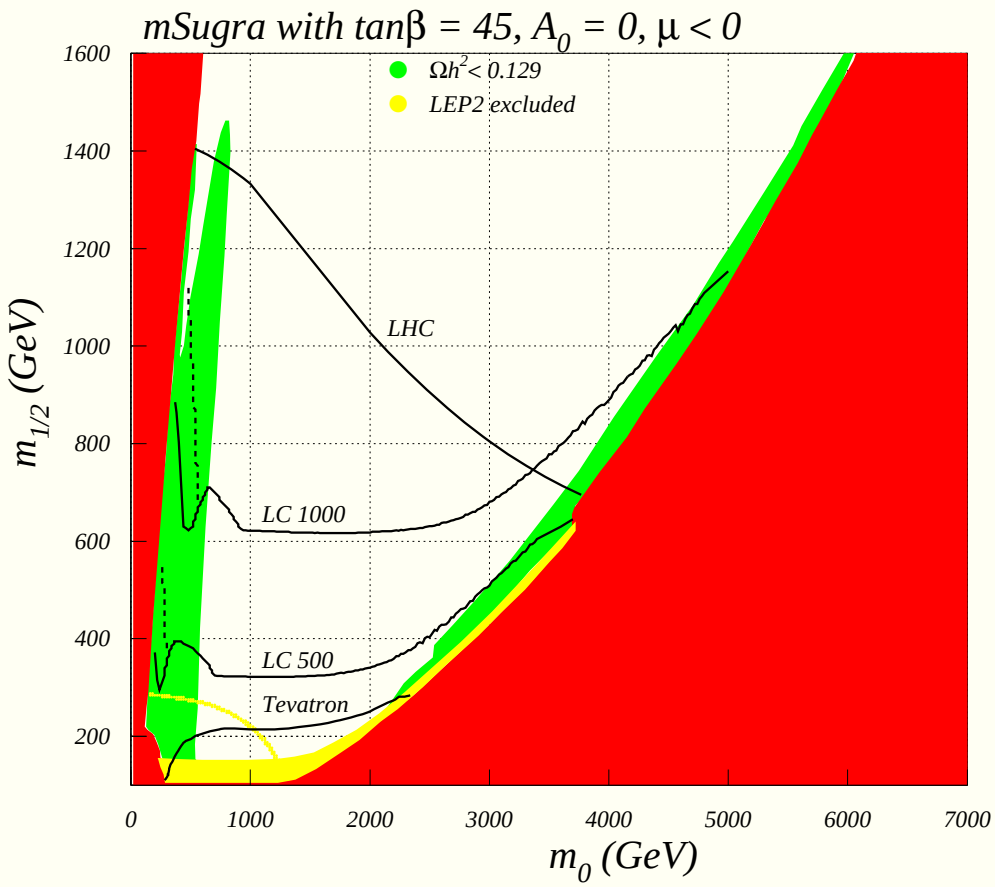

Group activities: 6 simulation points

- ⋆ bulk region (Battaglia)
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu) = 57\ \text{GeV},\ 250\ \text{GeV},\ 0,\ 10,\ +1)$
- ⋆ HB/FP region (Alexander, Matchev, students)
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu) = 3280\ \text{GeV},\ 300\ \text{GeV},\ 0,\ 10,\ +1\ )$
- ⋆ $\tilde{\tau}$co-ann. region (Arnowitt, Dutta, Kamon, Khotilovich)(Banbade, Berggren, Martyn, Richard, Zhang)
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu) = 213\ \text{GeV},\ 360\ \text{GeV},\ 0,\ 40,\ +1\ )$
- ⋆ A funnel (Battaglia)
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu) = 340\ \text{GeV},\ 400\ \text{GeV},\ 0,\ 51,\ +1\ )$
- ⋆ light stop (Strube, Lu, Graf)
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu) =$
    $600\ \text{GeV},\ 200\ \text{GeV},\ -1300\ \text{GeV},\ 30,\ +1\ )$

Goals of exercise:

- ⋆ determine mass, spin etc. of DM particle
- ⋆ determine $\Omega_{CDM}h^2$ from LC measurements?

Conclusions

Strong motivations for physics BSM from astro/cosmology!

- ⋆ ν mass $\Rightarrow$ SUSYGUTSs?!
- ⋆ baryogenesis ($\Rightarrow SUSY$)
- ⋆ LC possible test of leptogenesis via precision slepton mass measurements
- ⋆ neutralino dark matter
  - bulk region
  - stau co-annihilation
  - HB/FP region: mixed higgsino/bino LSP
  - A annihilation funnel
- ⋆ Depending on what is found, can determine neutralino annihilation mechanism in early universe!