Probing the SUSY Origin of Matter at the ILC

Vancouver Linear Collider Workshop
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Based on works done in collaboration with:

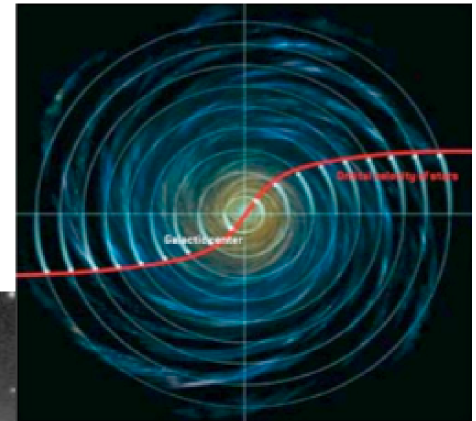
M. Quiros and C. Wagner, Phys. Lett. B380 (1996) ; Nucl. Phys. B524 (1998)
M. Quiros, A. Riotto, I. Vilja and C. Wagner, Nucl. Phys. B503 (1997)
J. Moreno; M. Quiros, M. Seco and C. Wagner, Nucl. Phys. B599 (2001); B650 (2003)

C. Balazs and C. Wagner, Phys. Rev. D70 (2004)
C. Balazs, A. Menon, D. Morrissey and C. Wagner, PRD71 (2005)
A. Finch, A. Freitas, C. Milstene, H. Nowak and A. Sopczak, Phys.Rev.D72 (2005)
A. Freitas, in preparation
C. Balazs, A. Freitas and C.E. M. Wagner, in preparation

Outline

- Cosmology as Motivation for Physics BSM
  -- Dark Matter -- the Baryon Asymmetry
- Electroweak Baryogenesis in the MSSM
  -- Necessary requirements for EWBG
  -- Constraints on the SUSY spectrum
- Dark Matter in the MSSM
  -- Dark Matter in the presence of EWBG
  -- Collider Signatures
  -- Direct DM detection and the effects of CP violation
- A similar study in the NMSSM
- Conclusions

Evidence for Dark Matter:

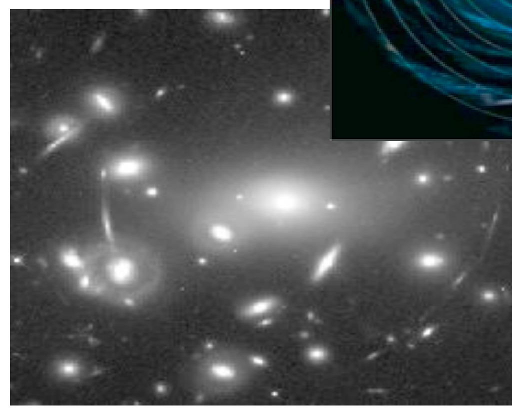


- Rotation curves from Galaxies.

  Luminous disk ==> not enough mass to explain rotational velocities of galaxies ==> Dark Matter halo around the galaxies

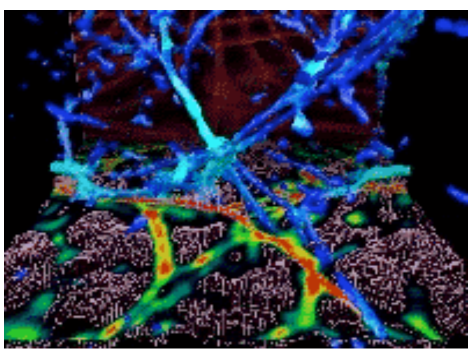
- Gravitational lensing effects

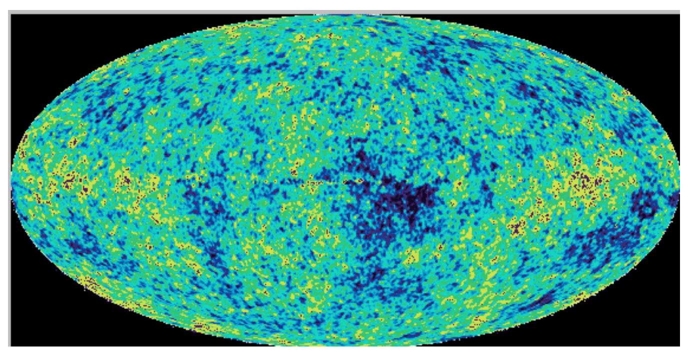
Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies



- Simulations of structure formation:

Large scale structure and CMB Anisotropies



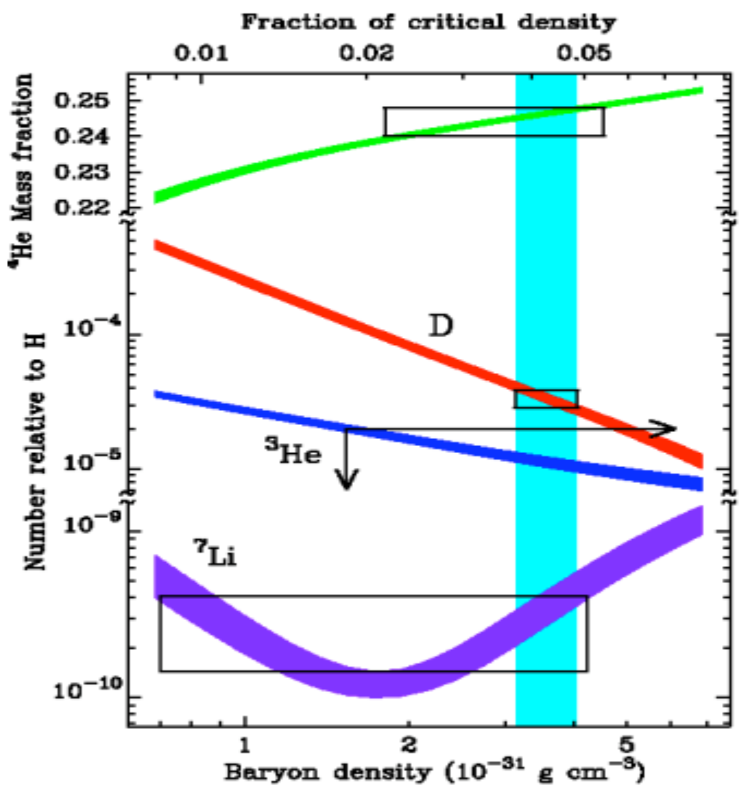


The manner in which structure grows depends on the amount and type of dark matter present.
All viable models are dominated by cold dark matter.

Baryon Abundance in the Universe

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$



- CMBR, tell us

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

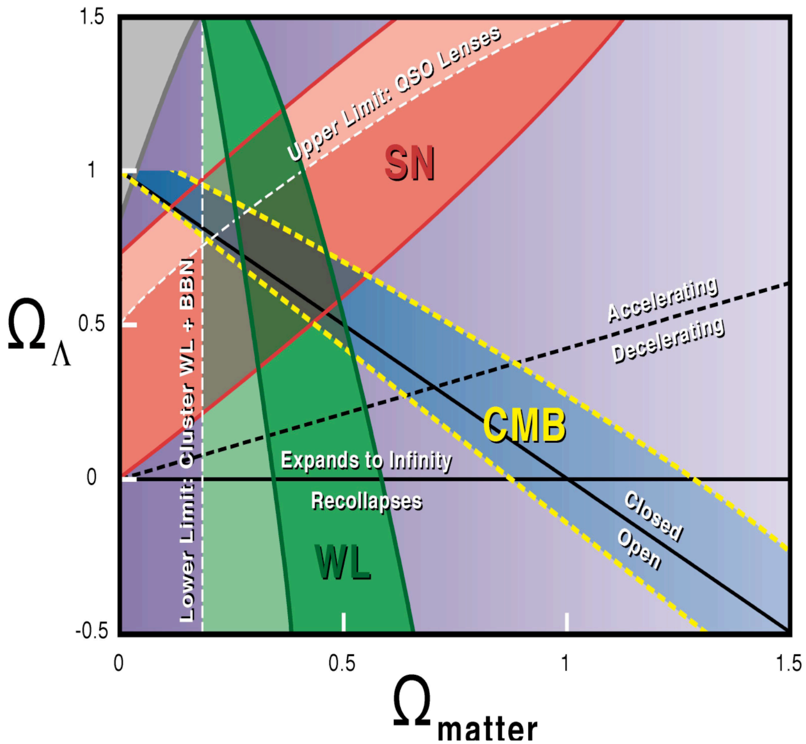
There is a simple relation between These two quantities

$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8} \Omega_B h^2 \approx 6\ 10^{-10}$$

$$1\ GeV = 1.6\ 10^{-24} g$$

- Baryon Number abundance is only a tiny fraction of other relativistic species

From all the information we have ==> Precision Cosmology



CDM energy density:

$$\Omega_{CDM}\, h^2 = 0.1106 \pm^{0.0056}_{0.0075}$$

What is Dark Matter?

- Baryonic and hot DM ==> experiments agree that can only be a tiny part of the total DM
- Cold Dark Matter: many well motivated candidates, but none in the Standard Model

Most suitable candidates beyond the Standard Model:

- Axions
- Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is mostly made of matter: $N_B \gg N_{\bar{B}}$
- Anti-matter only seen in cosmic rays and particle physics accelerators

What generated the small observed baryon--antibaryon asymmetry ?

$$\eta = \frac{n_B}{n_\gamma} \approx \left(6^{+0.3}_{-0.2}\right) 10^{-10}$$

Sakharov's Requirements:

✦ Baryon Number Violation (any B conserving process: $N_B = N_{\bar{B}}$)

✦ C and CP Violation: $(N_B)_{L,R} \neq (N_{\bar{B}})_{L,R}$

✦ Departure from thermal equilibrium

All three requirements fulfilled in the SM

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalous processes violate both B and L number, but preserve B-L.
(Important for leptogenesis idea)

- *At T = 0, Baryon number violating processes exponentially suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_{W})$$

- *At very high temperatures they are highly unsuppressed,*

$$\Gamma_{\Delta B \neq 0} \propto T$$

- *At Finite Temperature, instead, only Boltzman suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T) / T)$$

$$E_{sph} \cong 8 \pi v(T) / g \quad \text{and } v(T) \text{ the Higgs v.e.v.}$$

Klinkhammer and Manton'84; Arnold and Mc Lerran'88, Khlebnikov and Shaposhnikov '88

Baryogenesis at the Electroweak Phase Transition

Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93

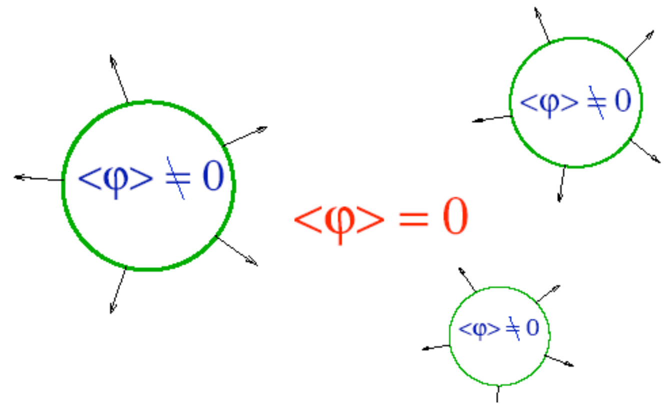
- Start with B=L=0 at T>Tc

- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.

- Net Baryon Number diffuse in the broken phase

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

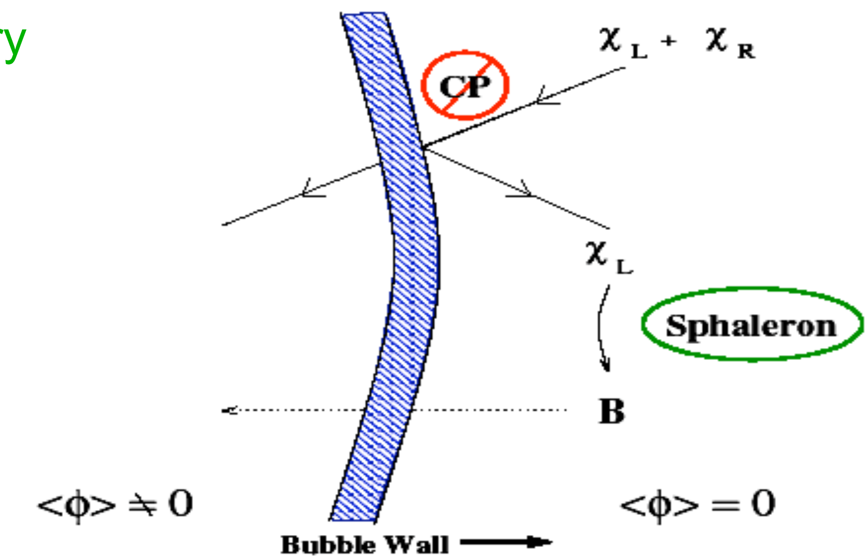
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\ \exp\left(-\frac{10^{16}}{T_c(\mathrm{GeV})}\exp\left(-\frac{E_{sph}(T_c)}{T_c}\right)\right)$$



To preserve the generated baryon asymmetry
strong first order phase transition:

$$v(T_c)/T_c > 1$$ Shaposhnikov '86-'88

Baryon number violating processes out of equilibrium in the broken phase



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **SM Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + E_{SM} T H^3 + \lambda(T) H^4$$

E receives contributions proportional to the sum of the cube of all light boson particle masses and

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV} \quad \Rightarrow \quad \text{ruled out by LEP}$$

- **Independent Problem: not enough CP violation**

Farrar and Shaposhnikov, Gavela et al., Huet and Satter

Electroweak Baryogenesis in the SM is ruled out

Supersymmetry and Cosmology

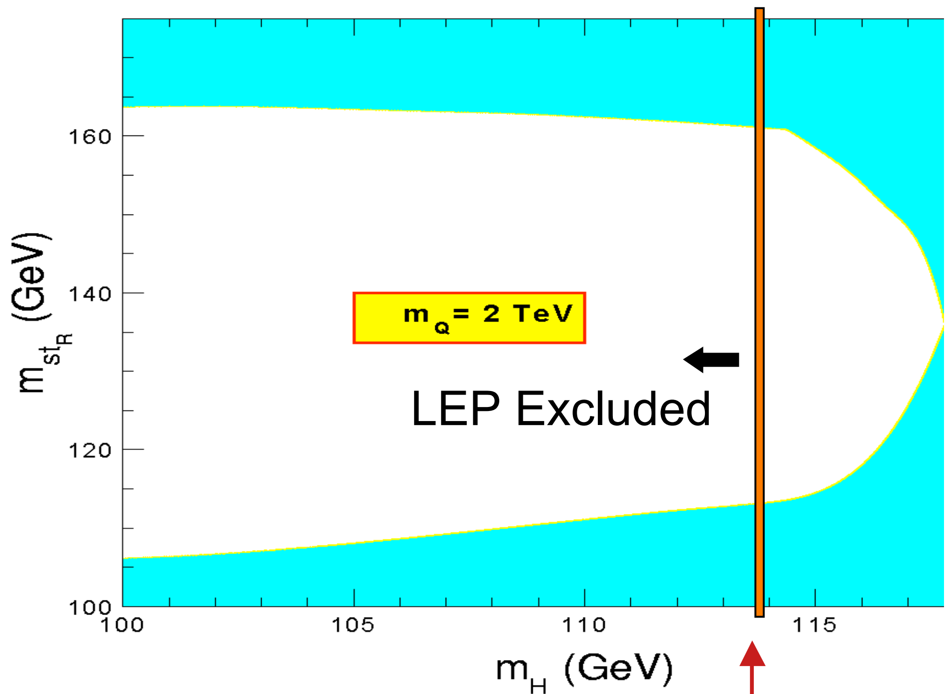
- SUSY is well motivated on purely particle physics grounds.
  The minimal SUSY extension of the SM leads to:
  - stabilization of the electroweak scale.
  - unification of gauge couplings.
- The MSSM also helps with cosmology.
- Dark Matter:
  - The lightest SUSY particle (LSP) is stable because of R-parity.
  - If the LSP is a neutralino, it can account for the dark matter.
- Baryon Asymmetry: [Huet, Nelson '91, Giudice '91, Espinosa, Quiros, Zwirner '93]
  - New CP violating phases can arise when SUSY is softly broken.
  - The baryon asymmetry can be generated within the MSSM by the mechanism of electroweak baryogenesis.
- Can the MSSM explain both simultaneously?

In the MSSM:

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs. $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Suficciently strong first order phase transition to preserve generated baryon asymmetry:

- ***Higgs masses up to 120 GeV***
- ***The lightest stop must have a mass below the top quark mass.***



M.C, Quiros, Wagner

A same point in this plane corresponds to different values of the Higgs and stop param.:

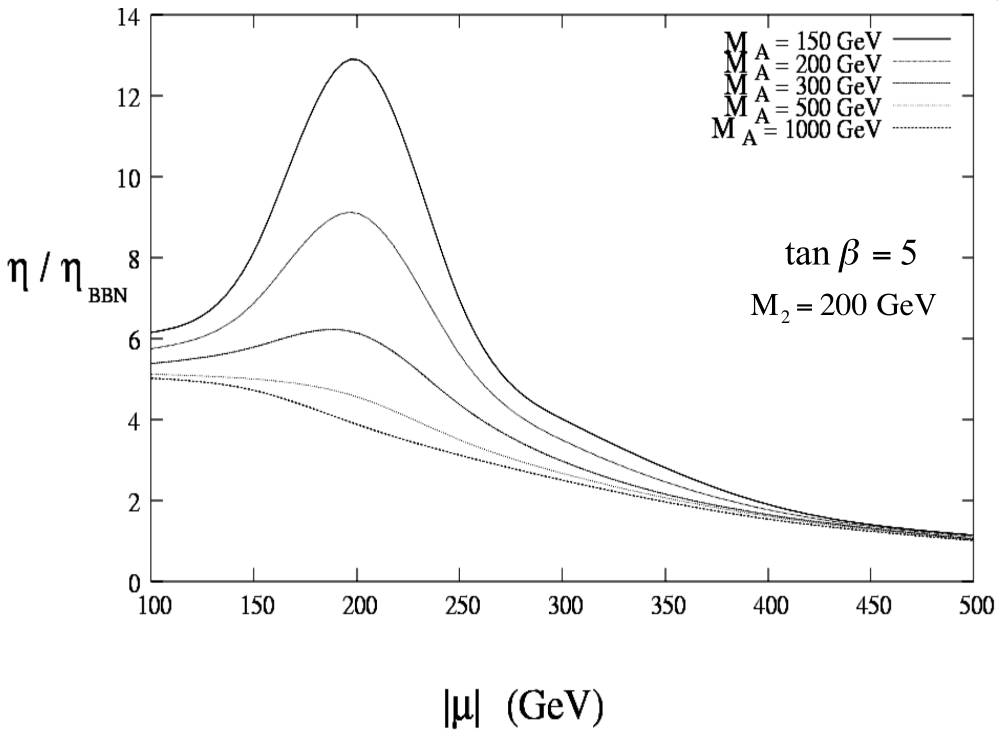
$\tan\beta,\ X_t,\ m_U$ and m_Q

Present LEP bounds on the SM- like Higgs mass

$m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.C., M.Quiros, M. Seco and C. Wagner



• New CP violating phases are crucial

Results for maximal CP violation
$\sin(\arg(\mu\, M_2)) = 1$

• Gaugino and Higgsino masses of the order of the weak scale highly preferred

• Results scale with $\sin(\arg(\mu\, M_2))$
and (approx) with $\sin 2\beta$

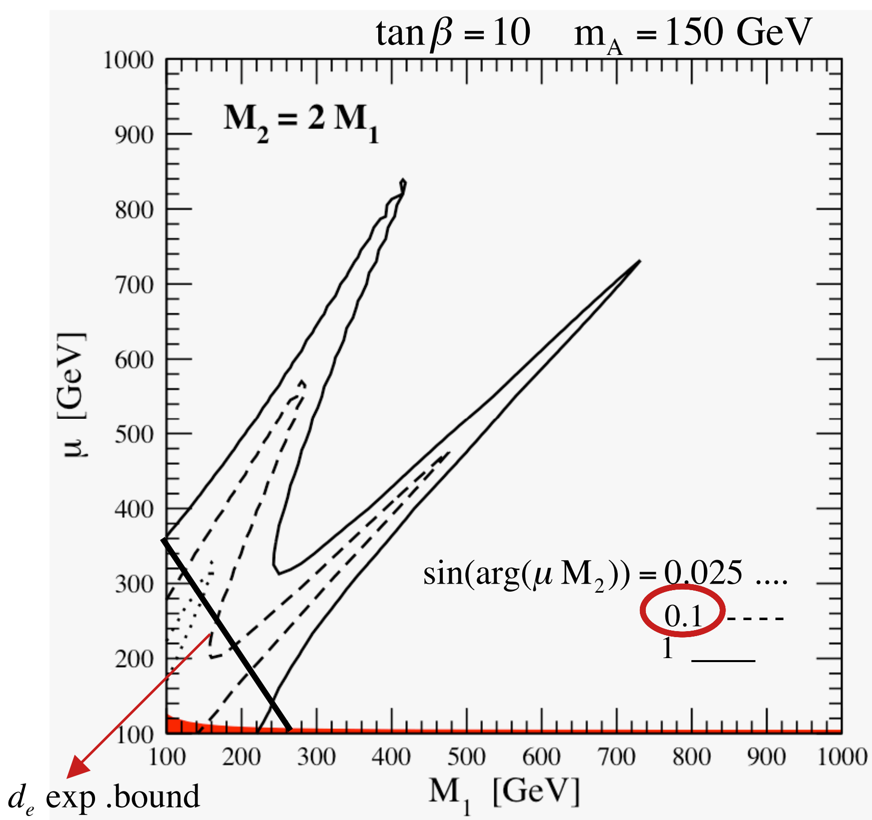
Baryon Asymmetry Enhanced for $M_2 = |\mu|$ ***and smaller values of*** m_A

Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

A different point of view considered by Konstandin, Prokopec, Schmidt and Seco '05

• Similar investigation considering also contributions to the Baryon Asymmetry from CP violating currents involving the lightest neutralino (LSP):

==> depend on $\sin(\arg(\mu\, M_1))$, with resonant behavior for $|\mu| \approx M_1$



Cirigliano, Profumo, Musolf'06

This region of parameter space, with the LSP having a relevant Higgsino-bino admixture, leads to a very efficient pair annihilation

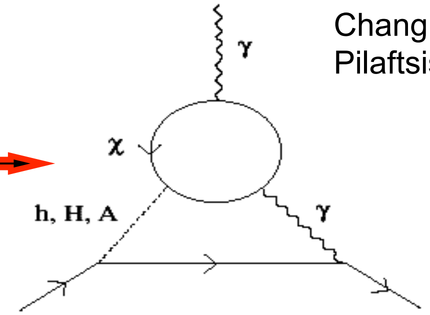
==> too little relic density, below the CDM abundance

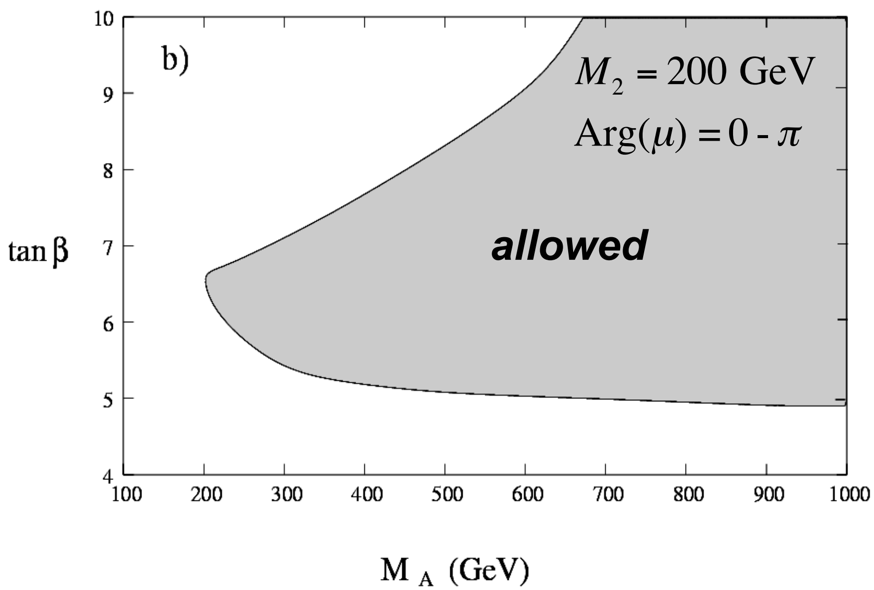
==> neutralino driven EWB would demand some enhancement mechanism to produce the observed DM density

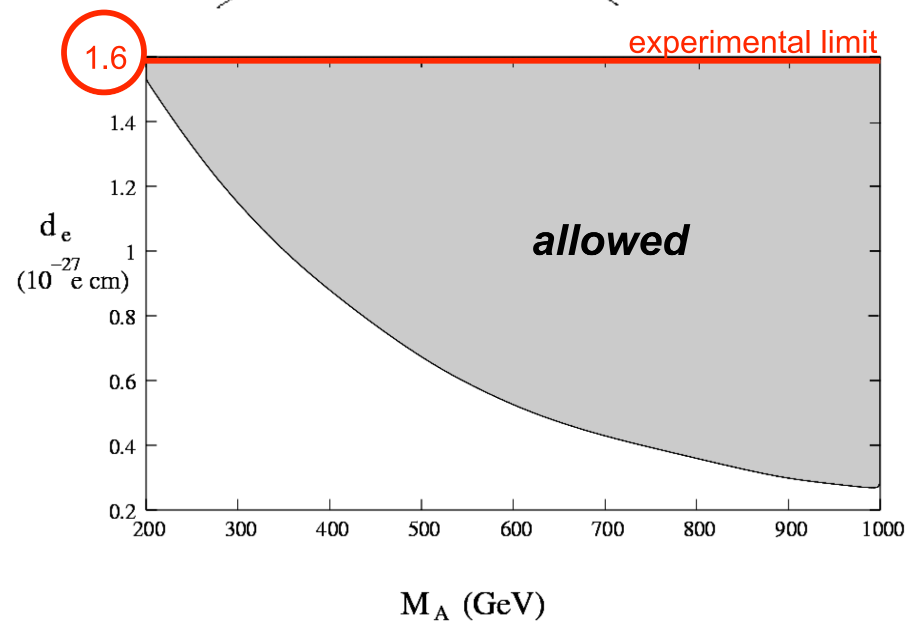
Phases in the MSSM EWBG scenario very constrained by EDM limits

Chang, Chang , Keung '02
Pilaftsis '02

- One loop contributions become negligible for
  $m_{\tilde{f}_{1,2}} \geq 10\,\mathrm{TeV}$
- At two loop order, contributions from virtual charginos and Higgs bosons, proportional to
  $\sin(\arg(\mu\, M_2))$







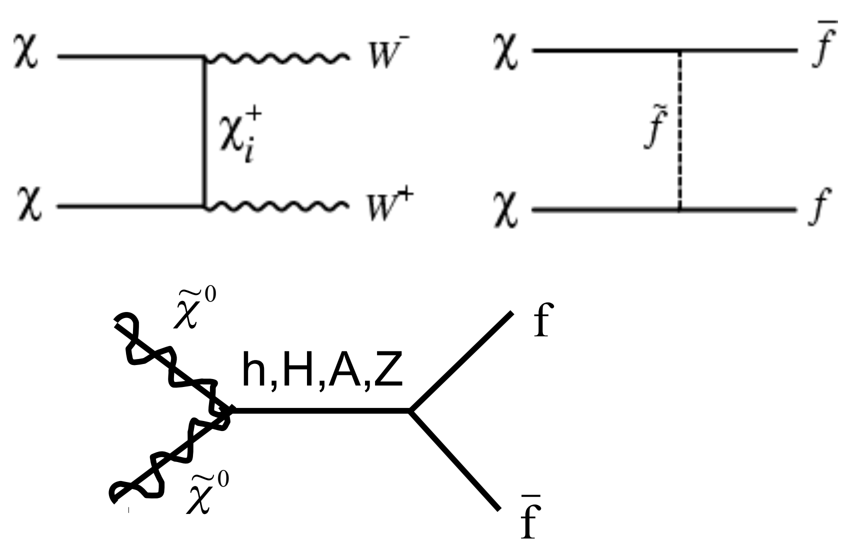
$$\Rightarrow \underbrace{5 \leq}_{m_{Q_3} \leq 1.5\,\mathrm{TeV}} \tan\beta \leq 10 \qquad M_A \geq 200\,\mathrm{GeV} \qquad 110\,\mathrm{GeV} \leq |\mu| \leq 550\,\mathrm{GeV}\ \text{(not shown)}$$

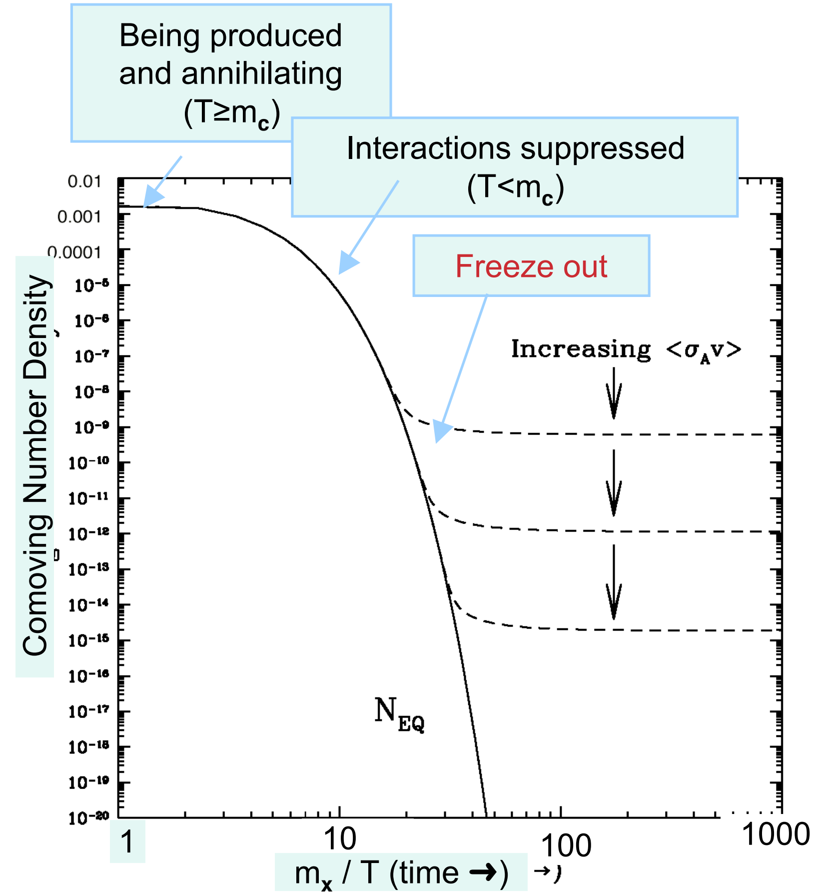
- An order of magnitude improvement in the electron EDM over the present bound will leave little room for this scenario. However, uncertainties of O(1)! and may have some specific cancellations between one and two loop contributions or lower tanb.

Dark Matter in the MSSM

Relic density is inversely proportional to the thermally averaged $\tilde{\chi}^0 \tilde{\chi}^0$ annihilation cross section $\langle \sigma \, v \rangle$

if m_x and σ_A determined by electroweak physics, then $\Omega_x \sim 0.3$





If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation

Dark Matter and Electroweak Baryogenesis

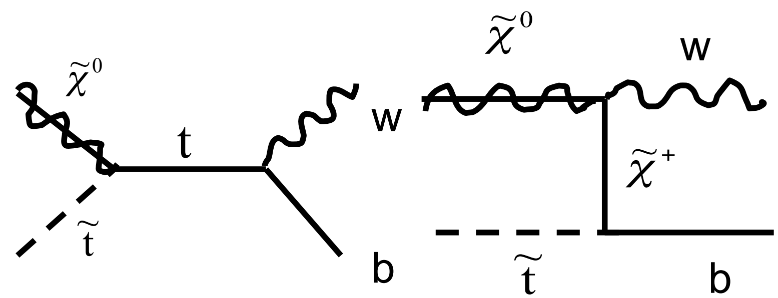
EWBG conditions, Higgs and EDM bounds

- light right handed stop: $m^2_{\tilde{U}_3} \leq 0$ • heavy left handed stop: $m^2_{\tilde{Q}_3} \geq (1\,\mathrm{TeV})^2$
- values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $|X_t| = |A_t - \mu^* / \tan\beta| = (0.3 - 0.5)\mathrm{m}_{\tilde{Q}_3}$
- light charginos with $\mu, \mathrm{M}_2 \leq 500\,\mathrm{GeV}$
- sizeable CP violating phases in the chargino sector $\sin(\arg(\mu\,\mathrm{M}_2)) \geq 0.1$
- $5 \leq \tan\beta \leq 10$ $\mathrm{M_A} \geq 200\,\mathrm{GeV}$
- the rest of the squarks, sleptons (and gluinos) heavy

Implications for Dark Matter:

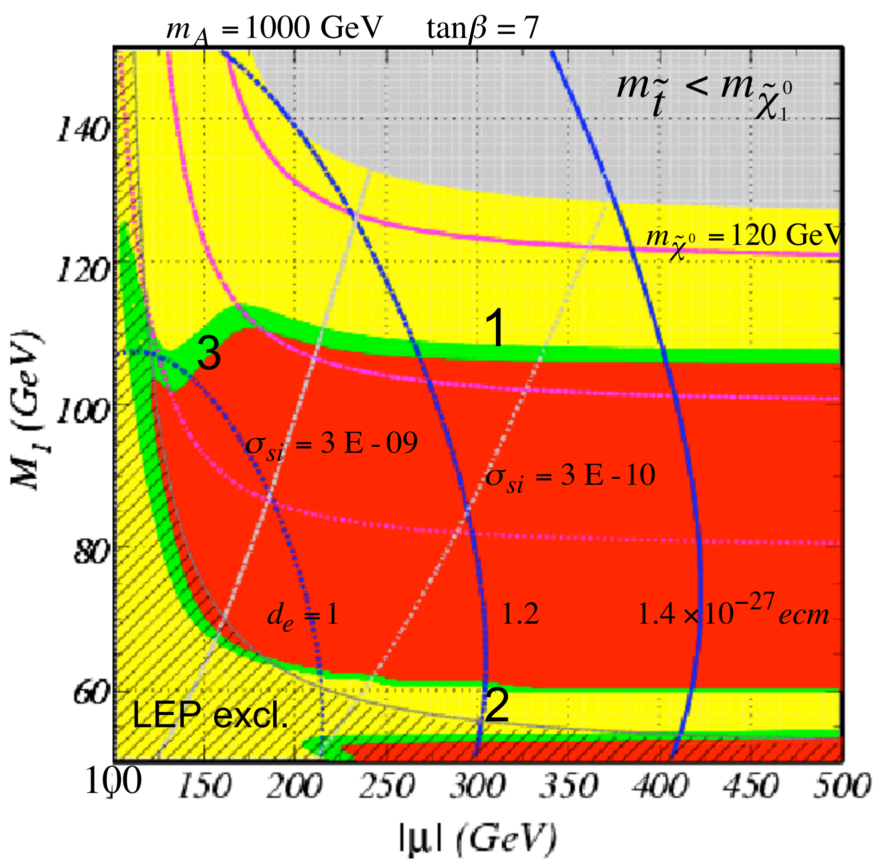
- LSP lighter that the stop $\Rightarrow m_{\tilde{\chi}^0_1} < m_{\tilde{t}} < m_{top}$

If they are close in mass, co-annihilation greatly reduces the relic density.



- If $m_{\tilde{\chi}^0} \cong m_h/2$ neutralino annihilation enhanced by s-channel h resonance
- CP phases in the chargino sector affect the mass and couplings of the LSP

Relic Density Computation



Balazs, MC, Menon, Morrissey, Wagner '04

three interesting regions with neutralino relic density compatible with WMAP obs.

$$0.095 < \Omega_{CDM}h^2 < 0.129$$ (green areas)

new WMAP + SDSS $\Rightarrow$ < 0.122

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

3. annihilation via Z boson exchange

small μ and M_1 (& t-channel χ^0 and $\chi^\pm$)

Similar qualitative results under variations in the phase of mu

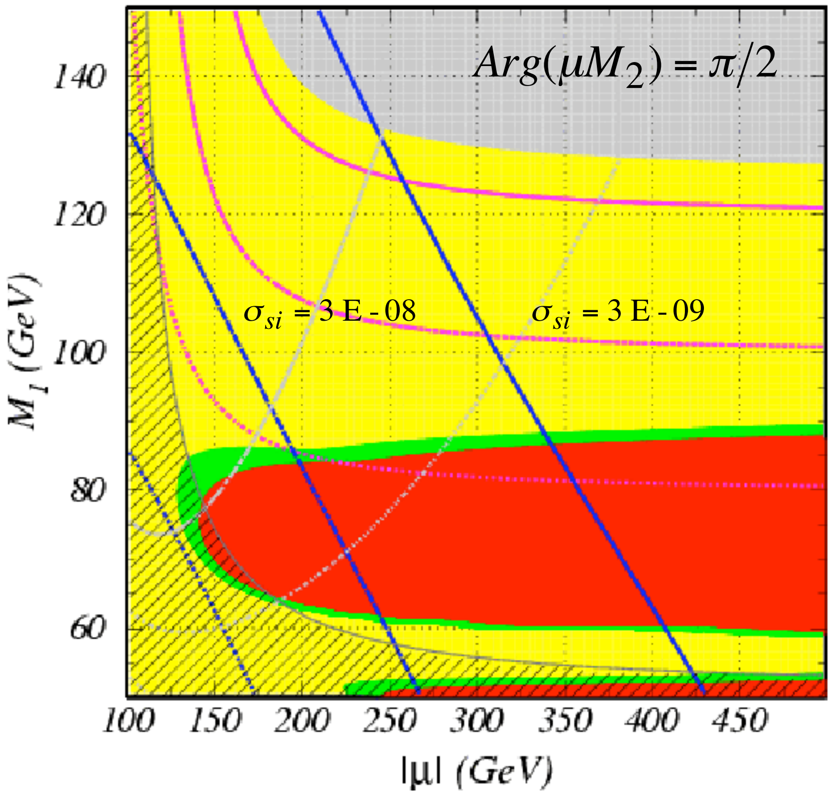
- Some differences in the h resonance region due to variations in the imaginary and real parts of the $\tilde{\chi}^0\tilde{\chi}^0 h$ couplings.
- The $\tilde{\chi}^0 t\,\tilde{t}$ coupling varies somewhat with the phase but the main effect is due to the variation of the LSP mass which affects the co-annihilation contribution.

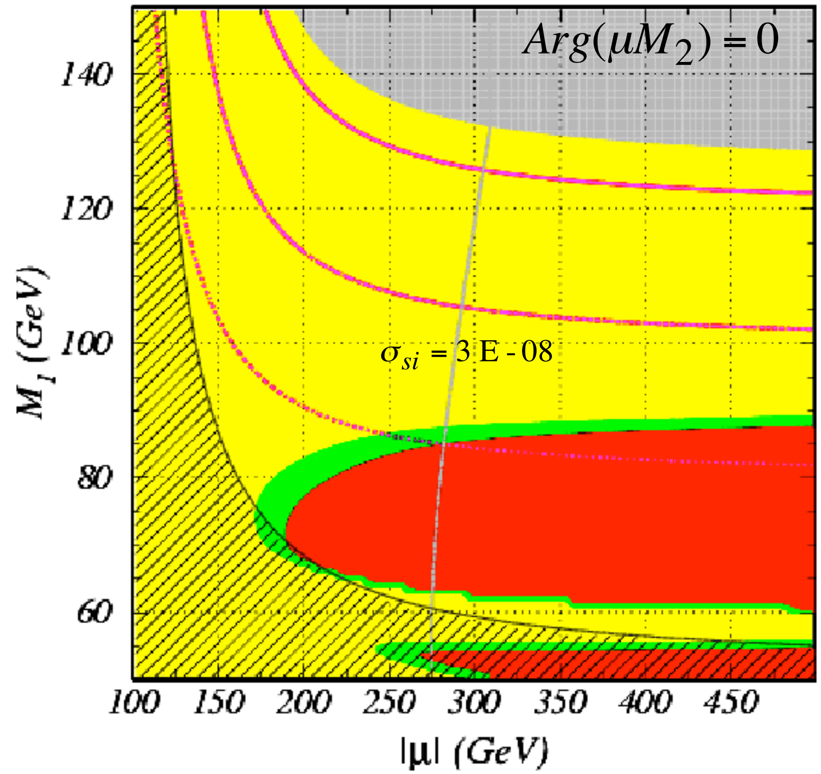
Non-Standard Higgs mass Effects $(m_A = 200\ \text{GeV})$

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 200\ \text{GeV} \Rightarrow$ new resonant region due to A,H s-channel around $m_{\tilde{\chi}_1^0} \approx m_A/2$

-- much wider band than for h due to enhanced $\tan\beta$ bb couplings --





- Ω_{CDM} ==> sum of A and H contributions nearly independent of CP violating phase

(crucial difference in EDM's and Spin-Independent cross sections)

- Larger neutralino-proton scattering cross sections due to heavy Higgs H, tanb enhanced contributions

Balazs, MC, Wagner

Experimental Tests of Electroweak Baryogenesis and Dark Matter

- Higgs searches:

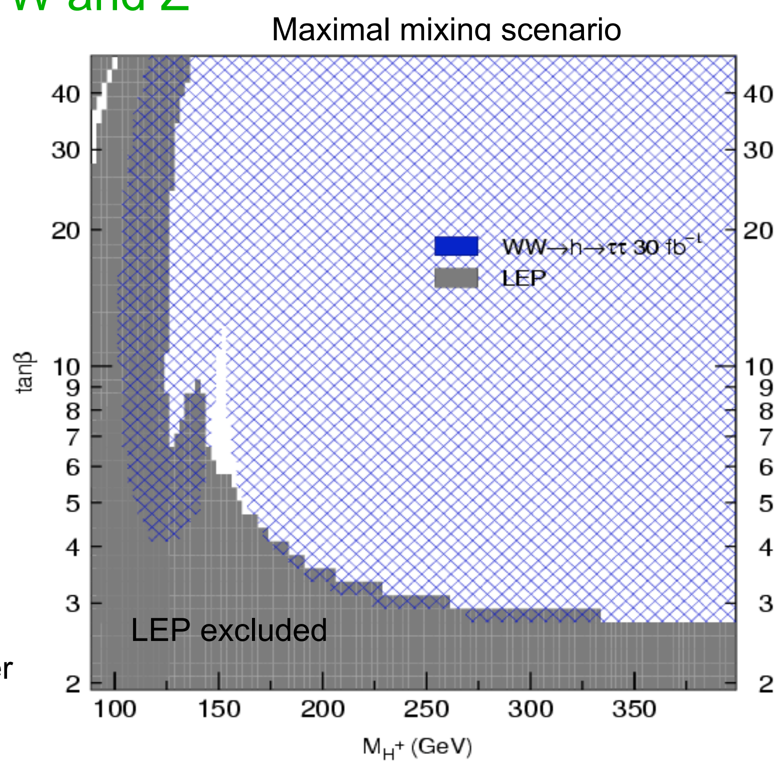
Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \rightarrow qqV^{*}V^{*} \rightarrow qqh$$
$$\text{with } h \rightarrow \tau^{+}\tau^{-}$$

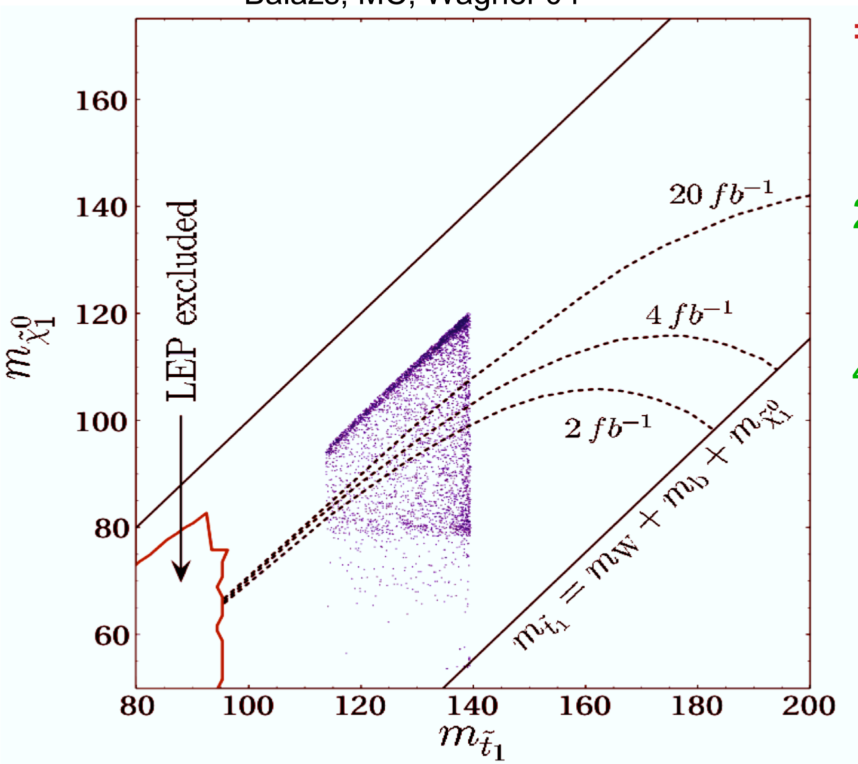


M.C, Mrenna, Wagner

Searches for a light stop at the Tevatron

Light-stop models with neutralino LSP dark matter ⟶ $\not{E}_T$ signal

Balazs, MC, Wagner'04



- For small stop-LSP mass difference $\Delta_{m_{\tilde{t}\tilde{\chi}}}$

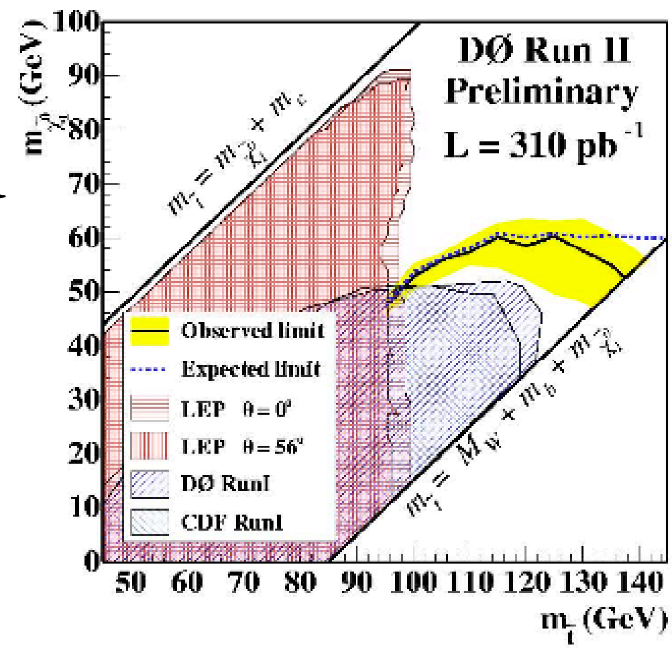
==> dominant decay mode

$$\tilde{t}_1 \to c\, \tilde{\chi}_1^0$$

2- and 3 body decays kinematically forbidden:

$\tilde{t}_1 \to b\, \tilde{\chi}_1^+$ $\quad \tilde{t}_1 \to bW^+\, \tilde{\chi}_1^0$ $\quad \tilde{t}_1 \to bl^+ \tilde{\nu}_l$

4 body decays $\tilde{t}_1 \to bl^+ \nu_l\, \tilde{\chi}_1^0$ sub-dominant



Blue: Relic density compatible with WMAP

Co-annihilation for $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

==> Problematic searches at Hadron Colliders

Light Stops at the LHC

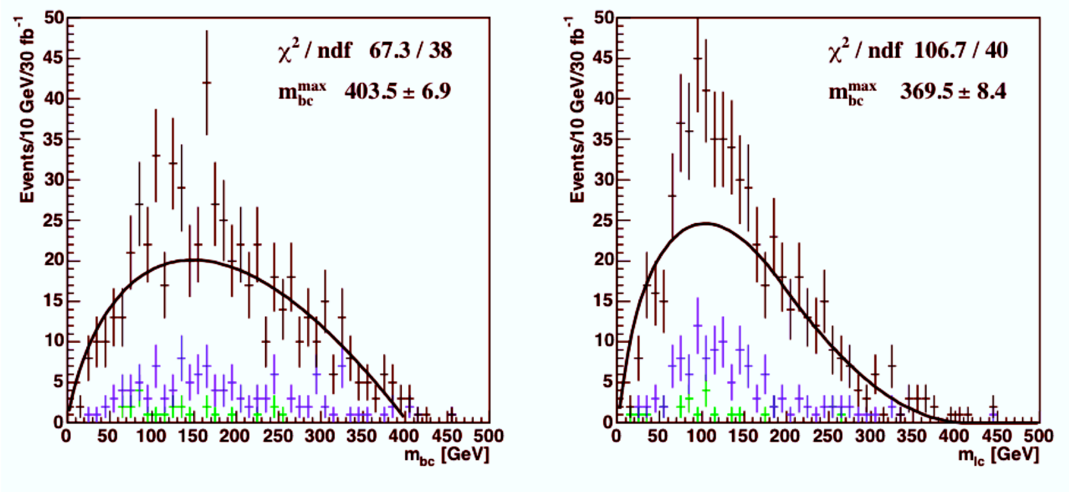
Kraml, Raklev '06

- Dominant decay mode for small mass differences $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$
- Look for same-sign tops in gluino decays

$$pp \to \tilde{g}\tilde{g} \to \mathrm{tt}\ \tilde{\mathrm{t}}_1^*\tilde{\mathrm{t}}_1^*, \qquad \mathrm{t} \to \mathrm{b}l^+\,\overline{\nu}_1 \qquad \tilde{\mathrm{t}}_1^* \to c\tilde{\chi}_1^0$$

Signal: 2 SS leptons, 2 SS bottoms, jets plus Missing Energy

Mass measurements from distributions,
==> but not enough independent
distributions to get absolute masses

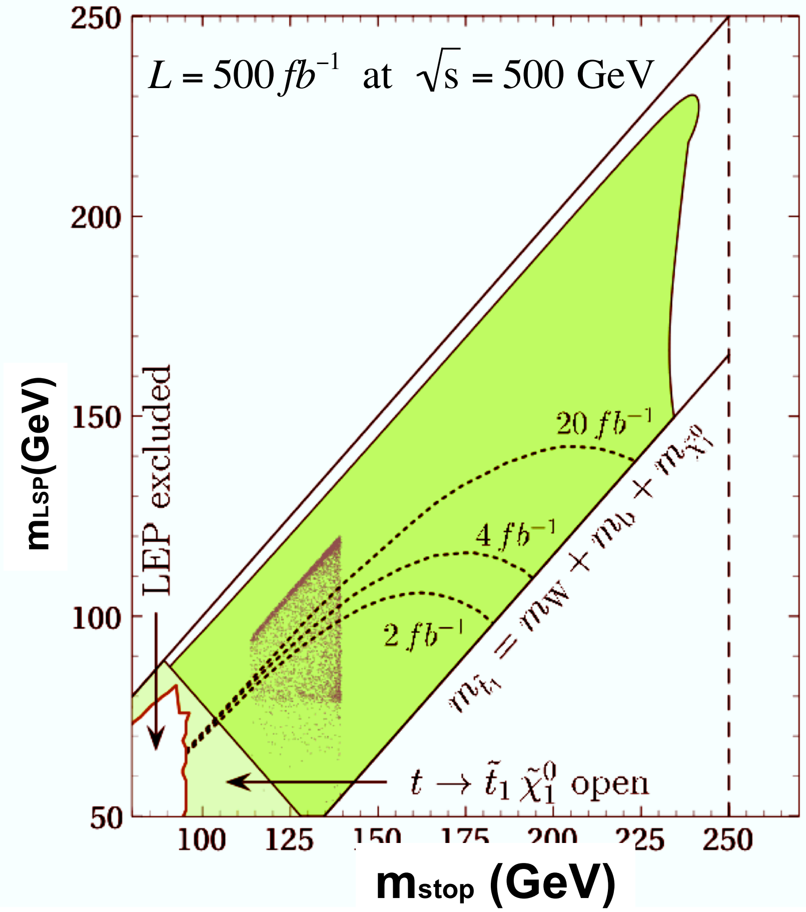


Caveat: Study done for relatively light squarks ~ 1 TeV.
For heavier squarks, gluino signal decreased by 50% from absense of squark-gluino production: still may be possible to see the stops (under study)

The power of the ILC

• Detect light stop in the whole regime compatible with DM and EWBG

MC, Finch, Freitas, Milstene, Nowak, Sopczak



Assume 100% BR for $\tilde{t} \longrightarrow c + \tilde{\chi}^0$

Signature: 2 soft charm jets plus missing E

$$e^+e^- \to \tilde{t}_1\tilde{t}_1^* \to c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

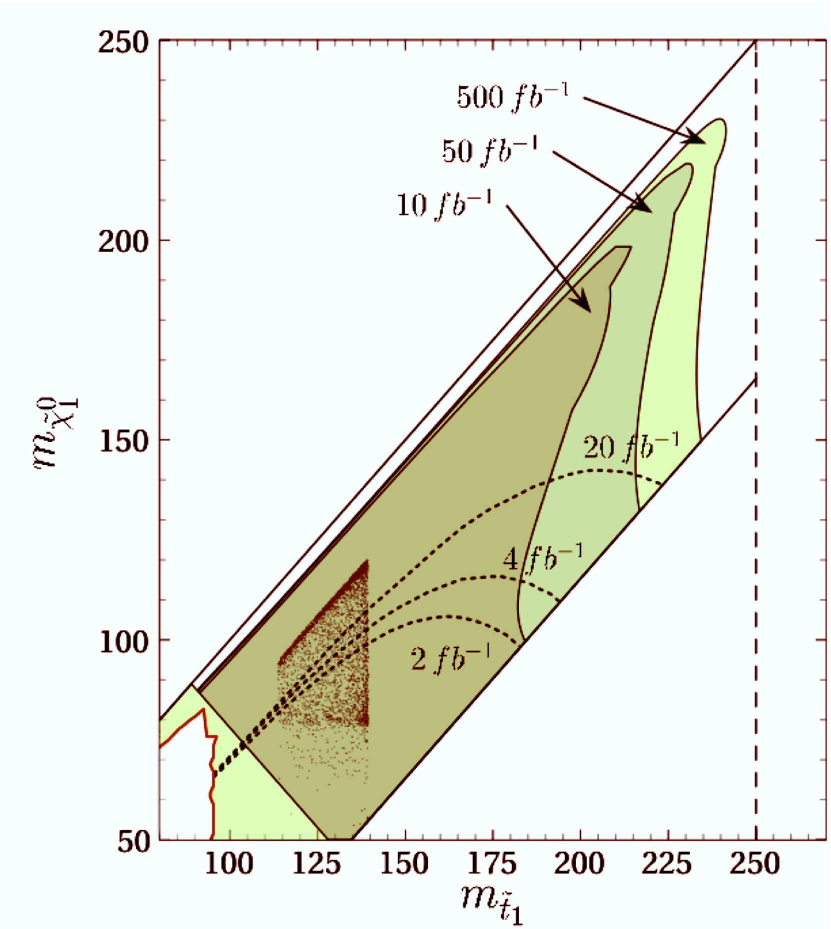
Discrimination of two-jet signature from B requires detector simulation

- Event generation with Pythia
- Detector Simulation with fast simulation Simdet for "typical" ILC detector
- Include beamstrahlung according to cold technology with Circe.

Green region: $\frac{S}{\sqrt{S+B}} > 5$ with $S = \varepsilon\sigma$

Detection of light stops possible for $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ ~5 GeV

Light Stop Discovery reach at the ILC



Even small integrated Luminosity

of order 10 fb-1 covers cosmologically preferred region

MC, Finch, Freitas, Milstene, Nowak, Sopczak '05

Measurement of SUSY parameters for DM density computation

Sample parameter point:
consistent with EDM's, EWB and
Higgs mass bound

$M_1 = 118.8$ GeV	$M_{u3}^2 = -99^2$ GeV^2
$M_2 = 225$ GeV	$M_{q3} = 4330$ GeV
$\|\mu\| = 225$ GeV	$A_t = -1100$ GeV
$\phi_\mu = 0.2$	$\tan\beta = 5$

1st and 2nd generation sfermions = 10 TeV

$m_{\tilde{\chi}_1^0} = 106.6$ GeV $\quad m_{\tilde{t}_1} = 122.5$ GeV $\quad \cos\theta_{\tilde{t}} = 0.01 \quad \Omega_{CDM}h^2 \approx 0.108$

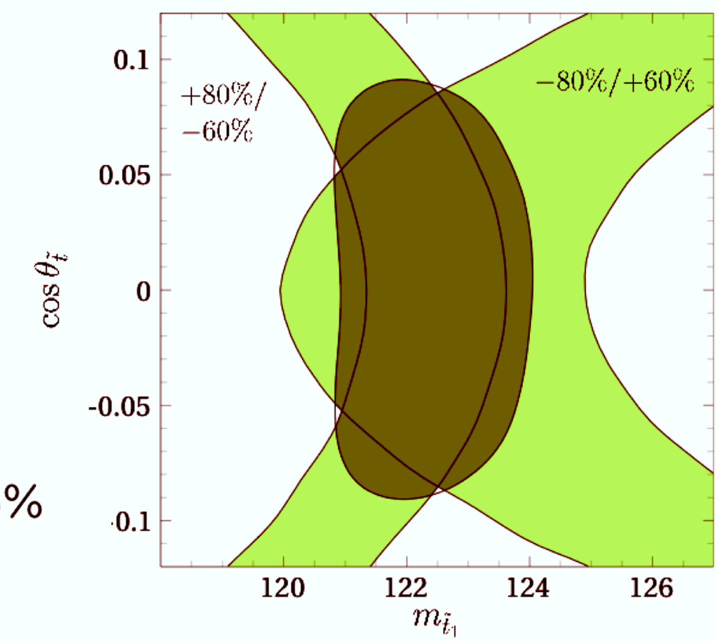
-- Stop mass and mixing angles

Consider stop production cross sections
with two different polarizations (250 fb^{-1} each)

$$P(e^-)/P(e^+) = -80\%/+60\%$$
$$+80\%/-60\%$$

Systematic Errors

- $\delta m_{\tilde{\chi}_1^0} = 0.1$ GeV
- $\delta P/P = 0.5\%$
- backgr. $\delta B/B = 0.3\%$
- $\delta\mathcal{L}/\mathcal{L} = 5 \times 10^{-4}$
- $\tilde{t}_1$ hadroniz./fragment.: $\sim 1\%$
- charm tagging/fragm.: 0.5%
- detector calibration: 0.5%
- beamstrahlung



Result: $m_{\tilde{t}_1} = 122.5 \pm 1.0$ GeV

$|\cos\theta_{\tilde{t}}| < 0.074$

$\Rightarrow |\sin\theta_{\tilde{t}}| > 0.9972$

-- Chargino/Neutralino parameters

MASS MEASUREMENTS

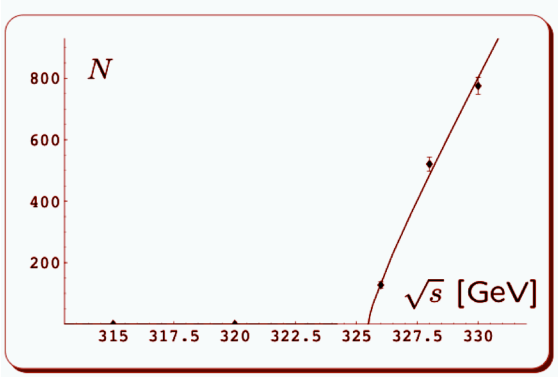
Heavy 1st/2nd generation squarks and sleptons ==> masses from squark cascades at LHC difficult

Light Neutralino/Charginos accesible at ILC with $\sqrt{s} = 500\ \mathrm{GeV}$

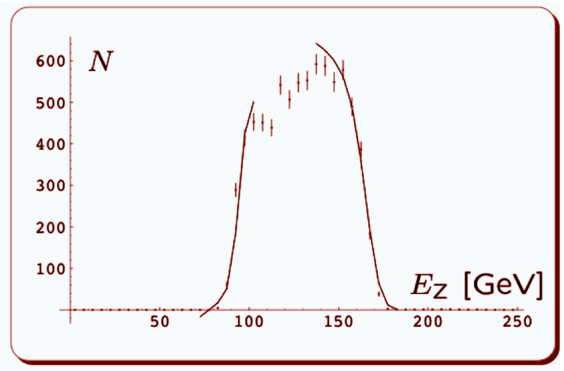
Main decay modes:

$$\tilde{\chi}_1^{\pm} \to \tilde{t}_1 \bar{b} \to c\, \bar{b}\, \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \to Z^* \tilde{\chi}_1^0 \qquad \tilde{\chi}_3^0 \to Z\, \tilde{\chi}_1^0$$

$\tilde{\chi}_1^{\pm}$ mass from threshold scan,



$\tilde{\chi}_{2,3}^0$ masses from energy distribution endpoints.



From parton-level simulation with SM and SUSY backgrounds:

	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_1^{\pm}$
m	107	171	231	163 GeV
δm	0.3	0.6	2	0.06 GeV

-- Chargino/Neutralino parameters

CROSS SECTION MEASUREMENTS

$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \sim 660$ fb

$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_3^0 \sim 110$ fb

$P(e^-)/P(e^+) = -80\%/+60\%$ and $+80\%/-60\%$ at $\sqrt{s} = 500$ GeV

Signal and background studied in generator-level simulation

Combine mass and cross-section measurements:
Use χ^2 fit to extract fundamental SUSY parameters:

$$M_1 = 118.8 \pm 0.4 \text{ GeV} \qquad |\phi_\mu| < 0.7$$
$$M_2 = 225.0 \pm 1.0 \text{ GeV} \qquad \tan\beta = 5^{+0.5}_{-1.4}$$
$$|\mu| = 225.0 \pm 1.7 \text{ GeV}$$

Large correlation between $\tan\beta$ and ϕ_μ

Cosmological Implications

Precise measurement of SUSY parameters for DM computation

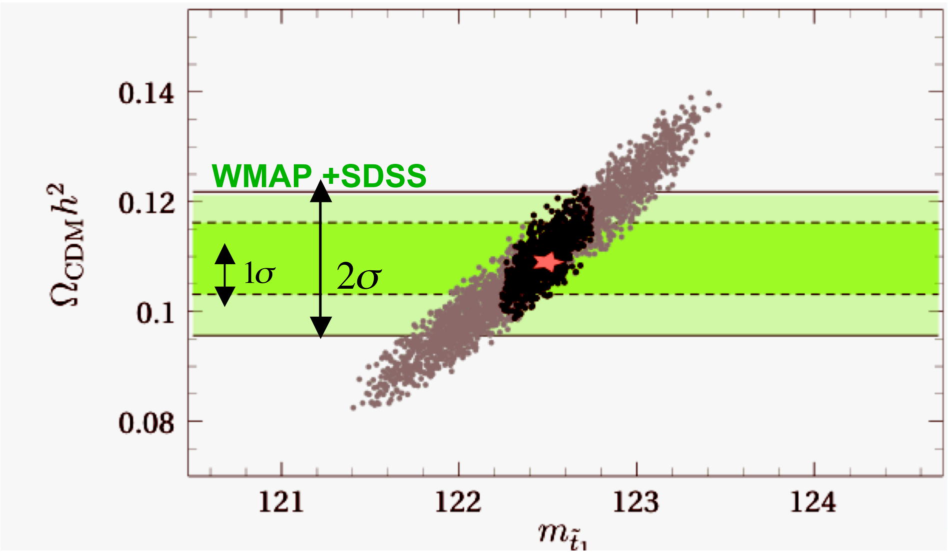
-- stop mass and mixing angles

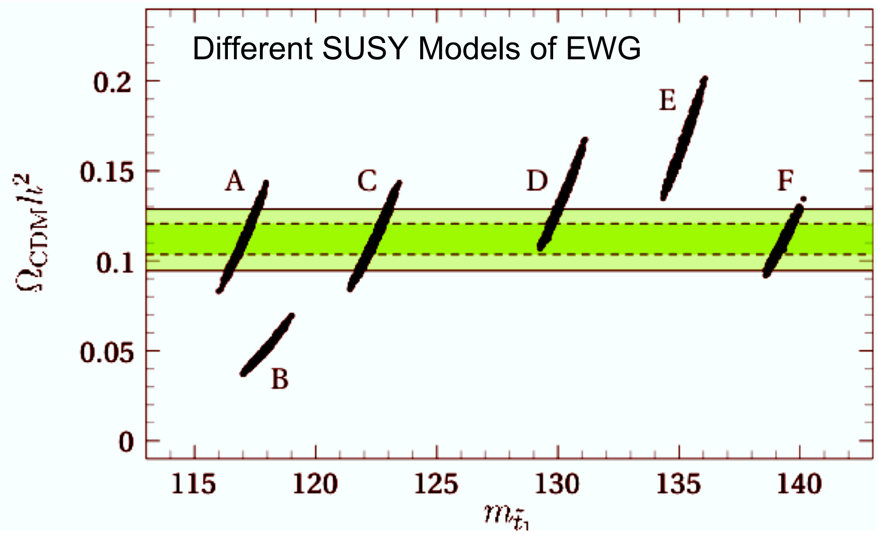
from production cross sections at different polarizations.

-- LSP mass and composition

from threshold scan ($\tilde{\chi}_1^{\pm}$), energy distribution endpoints ($\tilde{\chi}_{2,3}^0$) and cross sections

-- Higgs properties -- other relevant light SUSY particles





1σ constraints from ILC measurements: $0.082 < \Omega_{CDM} h^2 < 0.139$

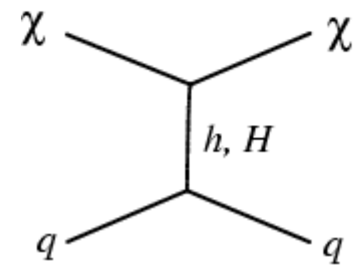
==> dominated by error on stop mass

• ILC measurements can provide insightful information on the nature of Dark Matter

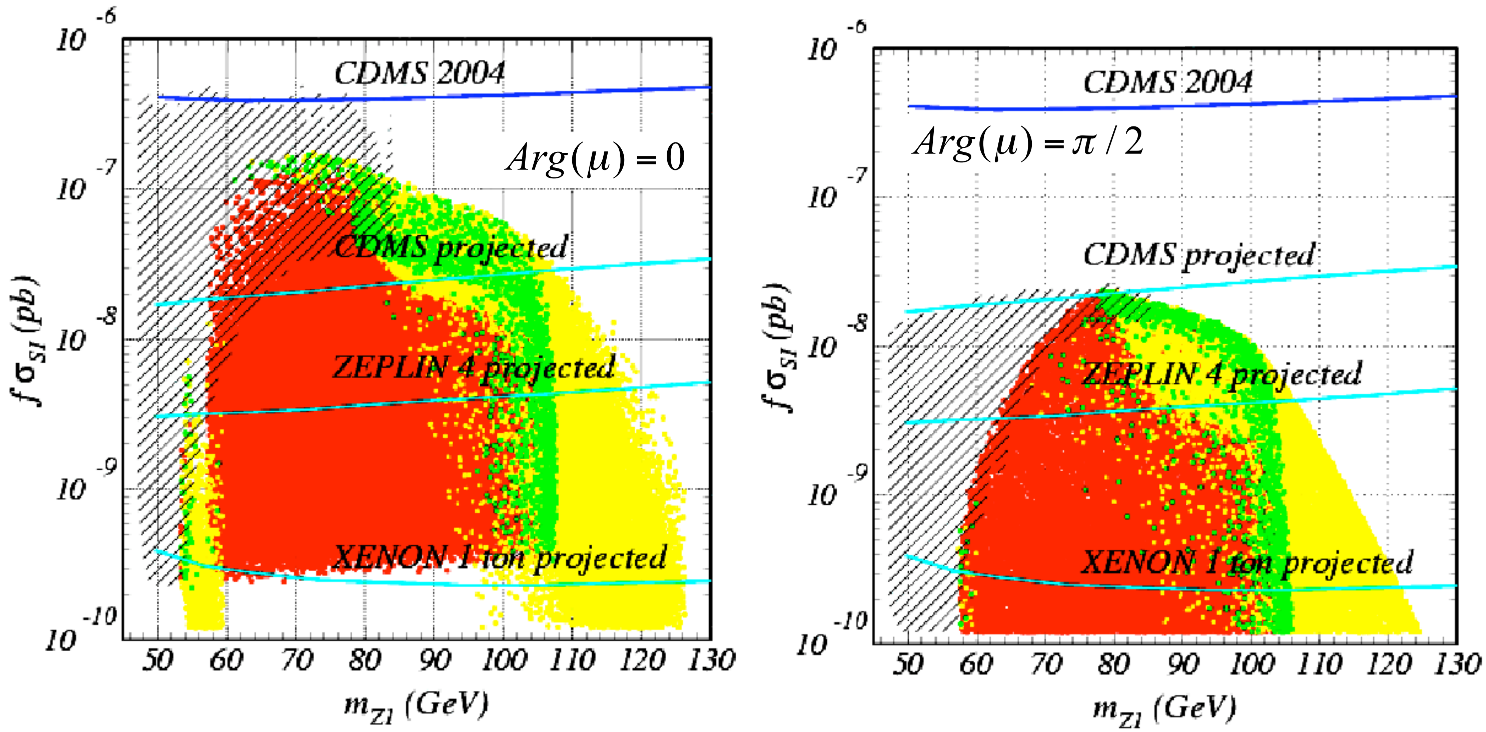
Direct Dark Matter Detection

$\not{E}_T$ at colliders → important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



Spin Independent Neutralino-proton scattering cross section as a function of $m_{\tilde{\chi}^0}$



Balazs, MC, Menon, Morrissey, Wagner '04

small σ_{si} for large μ : co-annihilation and h-resonant regions

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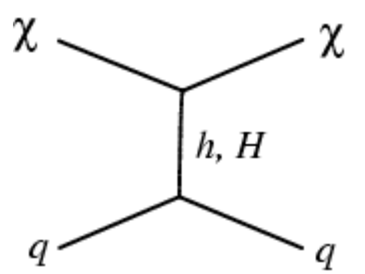
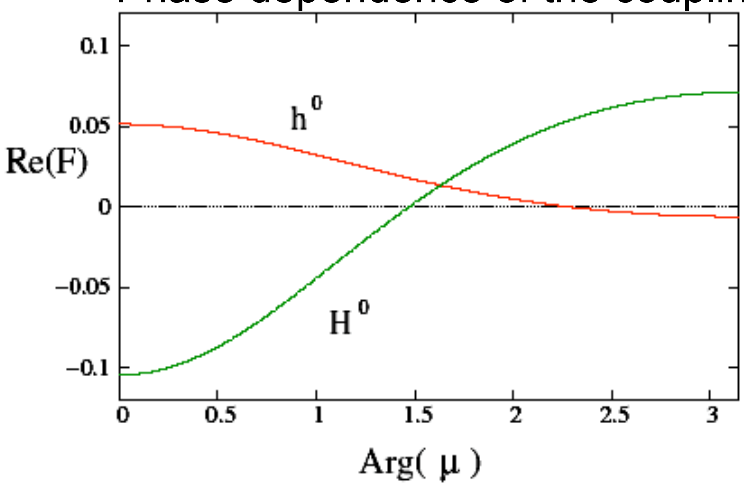
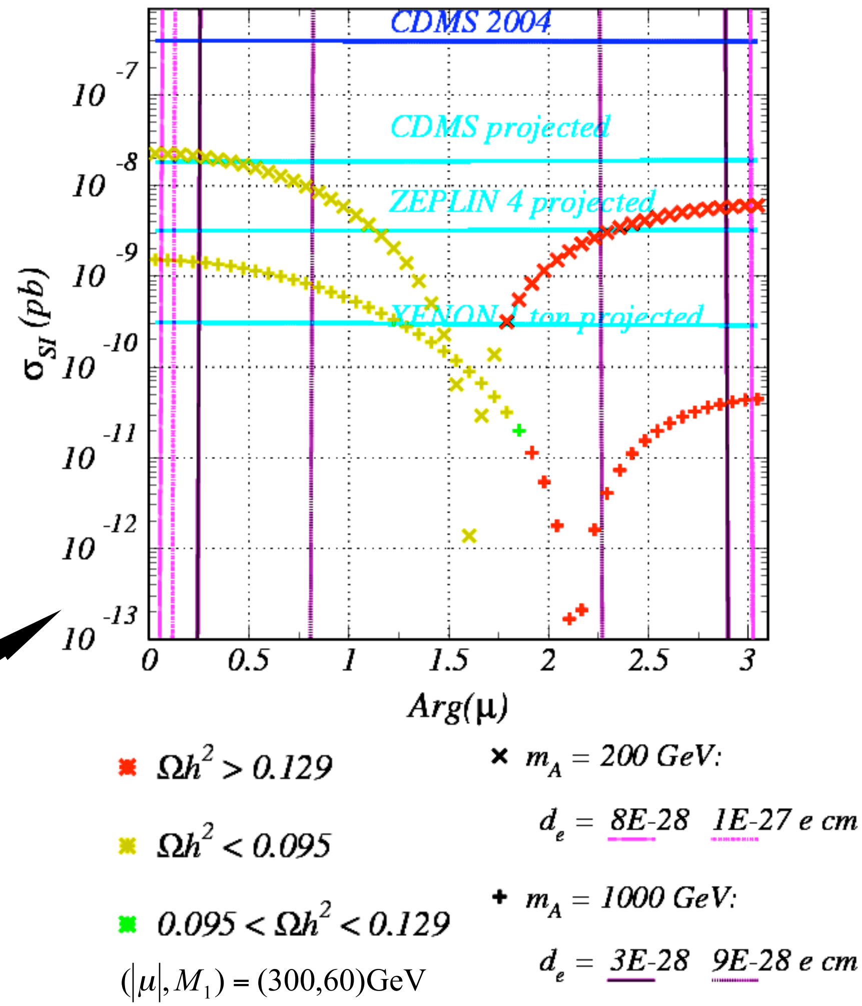


Only scalar (real) part of $\tilde{\chi}^0\tilde{\chi}^0 h/H$ couplings relevant

Phase dependence of the couplings





Balazs, MC, Menon, Morrissey, Wagner '04

Conclusions

Supersymmetry with a light stop and a light SM-like Higgs

$m_{stop} < m_{top} \qquad m_h < 120 \text{ GeV}$

opens the window for electroweak baryogenesis and allows for a region of SUSY parameter space compatible with Dark Matter

also Gaugino and higssino masses of order of the electroweak scale and moderate CP-odd Higgs mass preferred

EWBG and DM in the MSSM → interesting experimental framework

Strong constraints on CP phases from EDM's !

stop-neutralino co-annihilation → challenging for hadron colliders

Tevatron: good prospects in searching for a light stop

stop-LSP co-annihilation region provides motivation to search in the $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ regime

LHC: New stop search channels under study.

LC: covers completely co-annihilation region

gives information on nature and composition of light gauginos and stop

→prediction of Ω_{CDM} with precision comparable to cosmological measurements

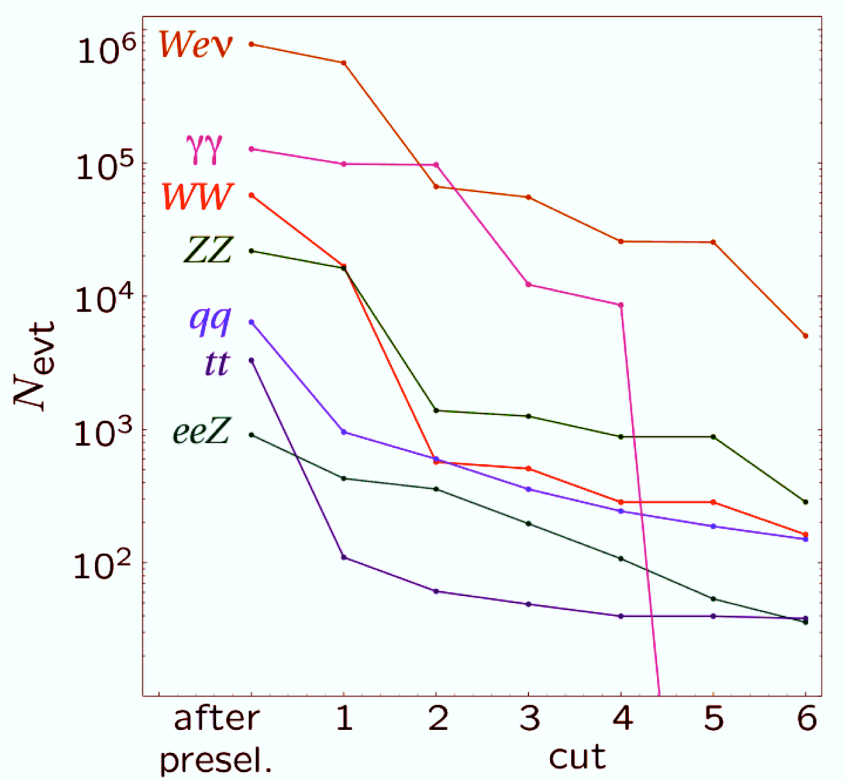
Direct Dark Matter detection: nicely complementary to collider searches

becomes more challenging for larger CP phases

Reduction of background

Preselection:

1. $4 < N_{\text{chargedtracks}} < 50$
2. $p_t > 5$ GeV
3. $|\cos\theta_{\text{Thrust}} < 0.8|$
4. $|p_{\text{long,tot}}/p_{\text{tot}}| < 0.9$
5. $E_{\text{vis}} < 0.75\sqrt{s}$
6. $m_{\text{inv}} < 200$ GeV



Selection:

1. $N_{\text{jets}} = 2$
   (Durham $y_{\text{cut}} = 0.003$)
2. $E_{\text{vis}} < 0.4\sqrt{s}$
3. $\cos\phi_{\text{aco}} > -0.9$
4. $|\cos\theta_{\text{Thrust}} < 0.7|$
5. $p_t > 12$ GeV
6. $3500\ \text{GeV}^2 < m^2_{\text{inv}} < 8000\ \text{GeV}^2$, c-tagging

Analysis results

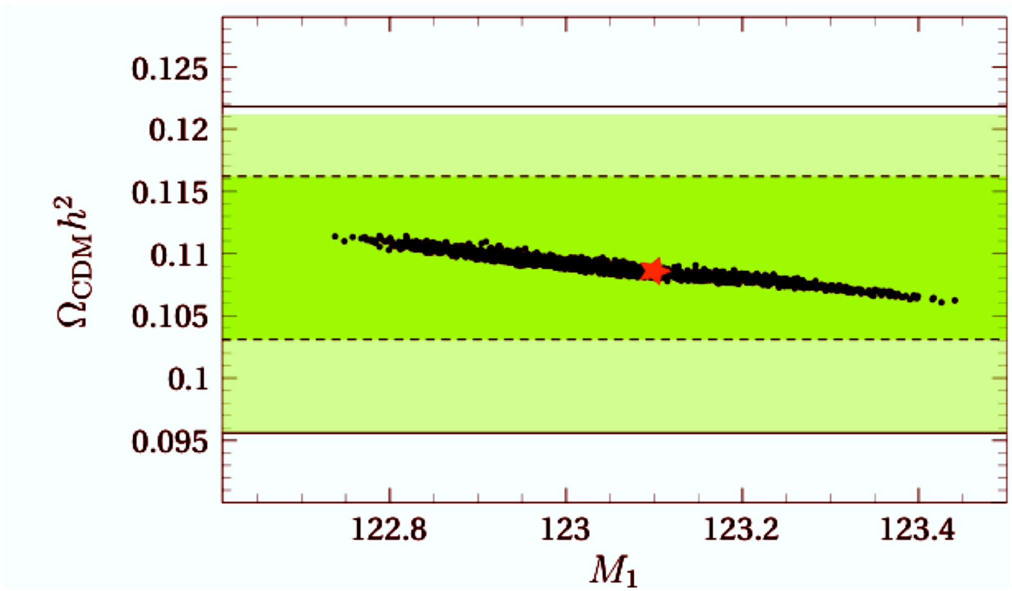
Largest remaining background from $e^+e^- \to W^\pm e^\mp \nu$, about 5000 events for $\mathcal{L} = 500$ fb^{-1}

$\to$ Good theoretical control

Signal rates after selection
for $\Delta m \sim 10\ldots50$ GeV and $m_{\tilde{t}_1} \lesssim$ 150 GeV:
5000...20000 events

$\to$ Signal same order as remaining background

Precision in MSSM models with heavy scalars
==> Split SUSY, Focus point



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V_{\mathrm{eff}}^{\mathrm{SM}} = - m^2(T) H^2 + E_{SM}\, T\, H^3 + \lambda(T)\, H^4$$

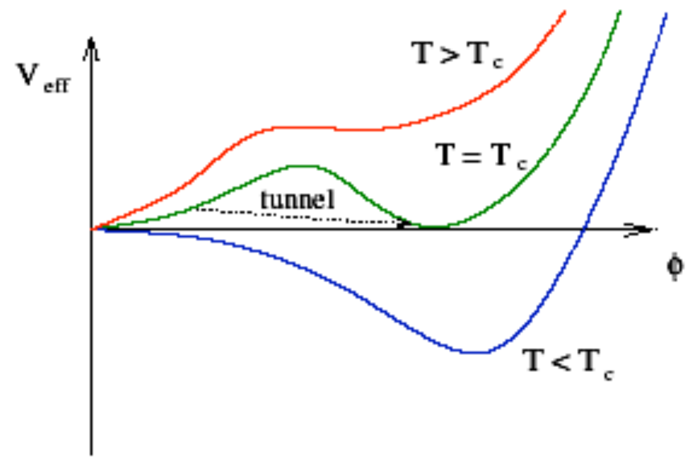
a cubic term is induced, proportional to the sum of the cube of all light boson particle masses

$$-\sum_b \frac{m_b^3(H)}{12\pi} T \quad \text{with} \quad m_b^2(H) \approx g_{bH}^2 H^2$$

In general: $m_b^2(H,T) = m_b^2 + g_{bH}^2 H^2 + \Pi(T)$ which can spoil the behaviour of the cubic term therefore jeopardizing first order phase transition

In the SM the only contribution comes from the transversal components of the gauge bosons

$$E_{SM} \approx \frac{2}{3}\left(\frac{2M_W^3 + M_z^3}{\sqrt{2}\pi\, v^3}\right)$$



➡ hence a first order first transition occurs

$$\frac{v(T_c)}{T_c} \approx \frac{\sqrt{2}\, E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV} \Rightarrow \quad \text{ruled out by LEP!}$$

- **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

Light Stop Effects on Electroweak Baryogenesis

The left- and right-handed stops mix:

$$M_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{bmatrix}$$

with $X_t = A_t - \dfrac{\mu^*}{\tan\beta}$

and $m_t = h_t H_2 = h_t \sin\beta \; \phi$

Hierarchy in soft SUSY breaking param:

$m_Q^2 >> m_U^2$ ⟹ best fit to precision electroweak data

The lightest stop ⟹ $m_{\tilde{t}}^2(T=0) \approx m_U^2 + D^2{}_R + m_t^2\left(1 - \dfrac{X_t^2}{m_Q^2}\right)$

has six degrees of freeedom and a coupling of order one to the Higgs

$$V_{eff}^{MSSM} = -m^2(T)\;\phi^2 - T\left[E_{SM}\phi^3 + 2N_c\,\frac{(m_{\tilde{t}}^2 + \Pi_R(T))^{3/2}}{12\;\pi}\right] + \frac{\lambda(T)}{2}\phi^4$$

No stop contrib. to cubic term unless $m_U^2 + \Pi_R(T) \approx 0$, very light right-h. stop!

$$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

One Stop should be quite light, lighter than the top and the stop mixing moderate to enhance E_{MSSM}

Computation of the baryon asymmetry

New CP violating phases in the stop and chargino sector are crucial
[for large values of m_Q, only the chargino –neutralino currents are relevant]

- Interaction with varying Higgs background in the bubble wall creates net neutral and charged Higgsino currents through CP-violating interactions

- Higgsino interactions with plasma creates an excess of left-handed anti-baryons (right-handed baryons)

- Left-handed baryon asymmetry is partially converted to lepton asymmetry via anomalous processes (weak sphalerons: net B violation)

- Baryon asymmetry diffuses into broken phase and gets frozen there since $v(T) / T > 1$

Assuming time relaxation of charge is large (no particle decays)

1. compute CP-violating currents
2. solve diffusion equations describing the above processes

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : $\tan\beta$, $\mathrm{m_A}$
Chargino sector : mass param. μ, M_2 with physical phase $\arg(\mu^* M_2)$

currents proportional to sin($\arg(\mu^* M_2)$), with resonant behavior for $\mathrm{M}_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $\varepsilon_{ij} \mathrm{H}_i \, \partial_\mu \, \mathrm{H}_j = \mathrm{v}^2(\mathrm{T}) \, \partial_\mu \beta$

suppressed for large $\mathrm{m_A}$ and $\tan\beta$ due to $\Delta\beta$ dependence

★ $\mathrm{H}_1 \partial_\mu \mathrm{H}_2 + \mathrm{H}_2 \partial_\mu \mathrm{H}_1 = \mathrm{v}^2 \cos(2\beta) \, \partial_\mu \beta + \mathrm{v} \, \partial_\mu \mathrm{v} \sin(2\beta)$

unsuppressed for large CP-odd masses

In the MSSM: $$\mathrm{E_{MSSM}} \approx \mathrm{E_{SM}} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

one stop should be quite light and the stop mixing moderate to enhance $\mathrm{E_{MSSM}}$

- For small stop mixing: $\mathrm{E_{MSSM}} \approx 9\,\mathrm{E_{SM}}$ hence $\mathrm{m_{h_{MSSM}}^{max.}} \approx 3\mathrm{m_{H_{SM}}^{max.}} \approx 120\ \mathrm{GeV}$

it can work!!

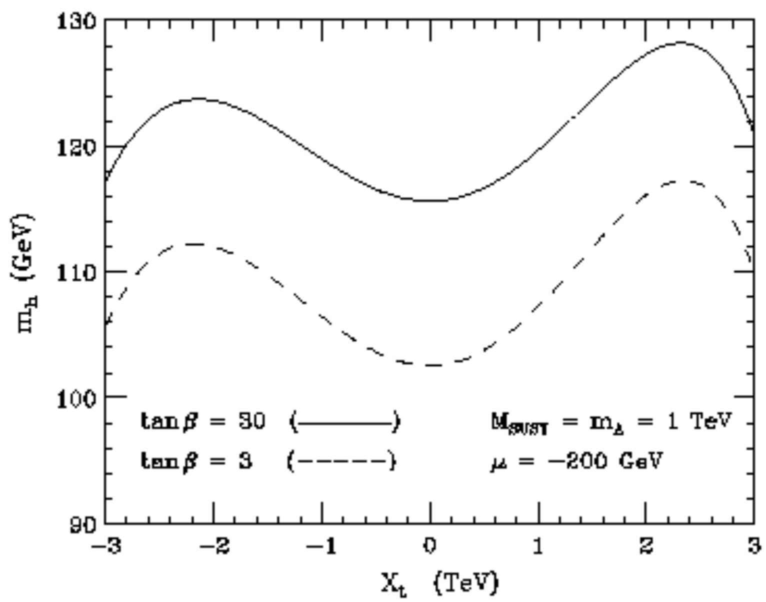
Present LEP bounds on the SM- like Higgs mass imply extra demands!

$$m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$$

- MSSM lightest Higgs mass depends crucialy on m_t^4, on the stop mixing X_t and logarithmically on the stop masses

$$\mathrm{m_h^2} \approx M_Z^2 \cos^2 2\beta + \frac{3\mathrm{m}_t^4}{8\pi^2 \mathrm{v}^2}\left[\log\left(\frac{m_{\tilde{t}_l}^2 m_{\tilde{t}_H}^2}{m_t^4}\right) + 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde{t}_H}^2}{m_{\tilde{t}_l}^2}\right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4}\right)\right]$$

hence $\mathrm{m_Q} \geq 1\,\mathrm{TeV}$ and $X_t \geq 0.3\mathrm{m_Q}$ needed



Direct Dark Matter Detection

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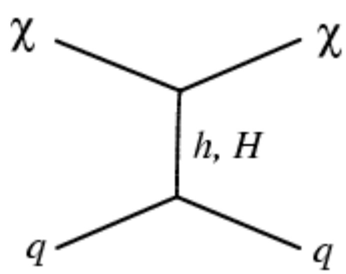
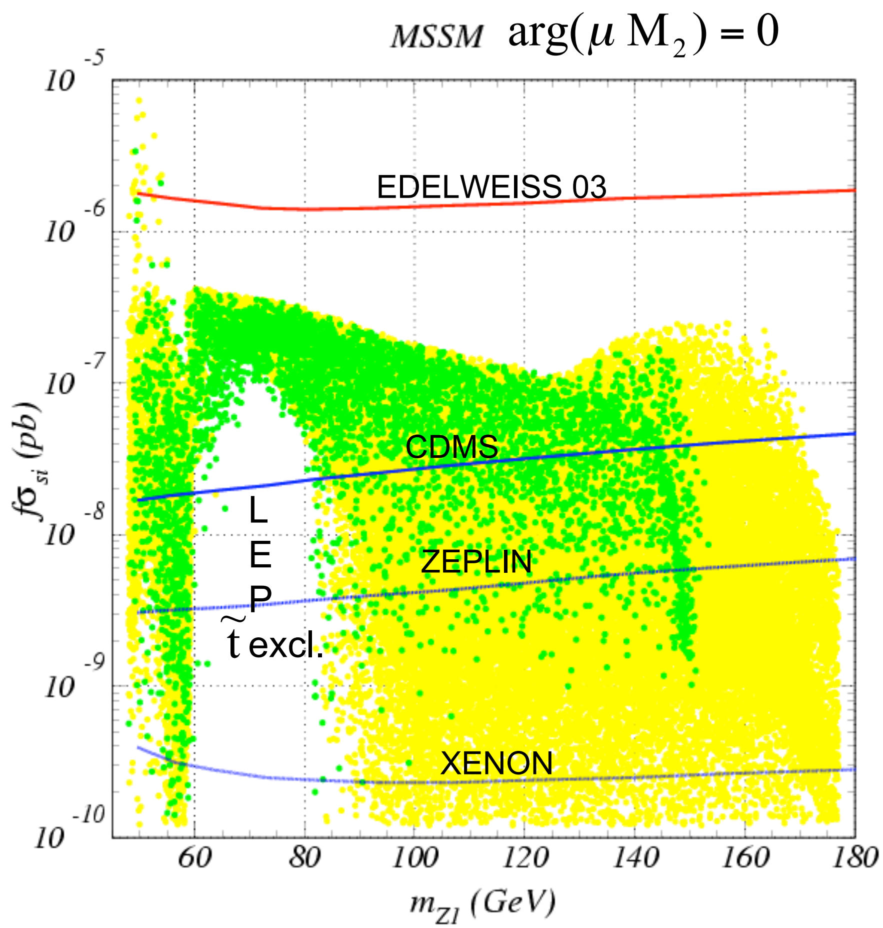
but, stability of LSP on DM time scales cannot be chekced at colliders

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



→ upper bounds on Spin independent cross sections

Next few years: $\sigma_{SI} \approx 10^{-8}\,\mathrm{pb}$
Ultimate goal: $\sigma_{SI} \approx 10^{-10}\,\mathrm{pb}$

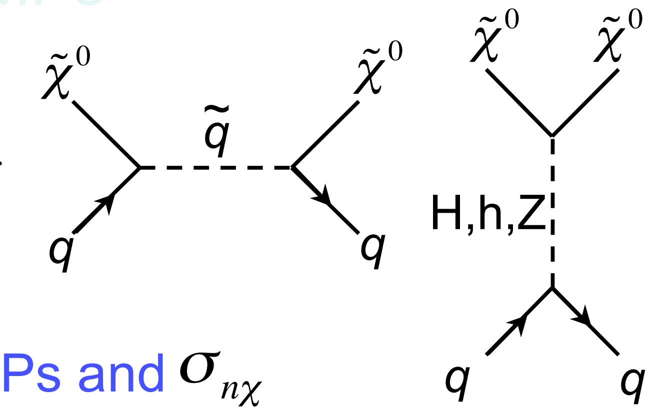


small σ_{si} for large μ : co-annihilation and h-resonant regions

Balazs, MC, Wagner '04

Direct Detection of WIMPs

- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils with $\sigma_{n\chi} \Rightarrow$



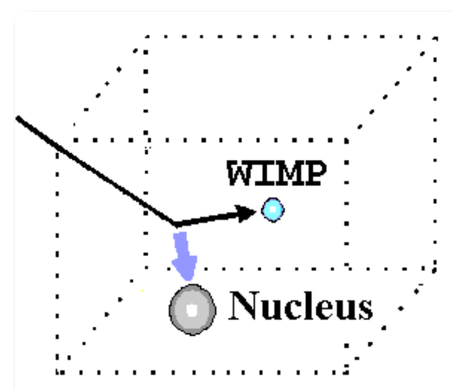
Main Ingredients to calculate signal:
Local density & velocity distribution of WIMPs and $\sigma_{n\chi}$
==> rate per unit time, per unit detector material mass

$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$

$\langle \sigma_{i\chi} \rangle$ → Scattering Cross section off nuclei averaged over relative wimp velocity

N_i → Number of target nuclei in the detector prop.to Detector mass/Atomic mass

η_χ → local WIMP density



<u>Direct detection has two big uncertainties</u>:

- The local halo density, inferred by fitting to models of galactic halo: assumed ==> $\eta_\chi \approx 0.3$ GeV / cm^3
- The galactic rotation velocity ≈ (230 +- 20) km/sec

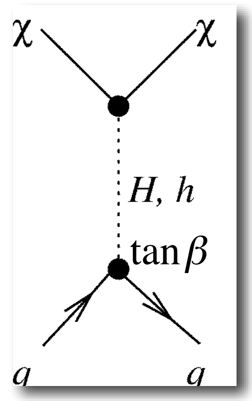
Neutralino Elastic Scattering Cross Section -- CDMS Reach

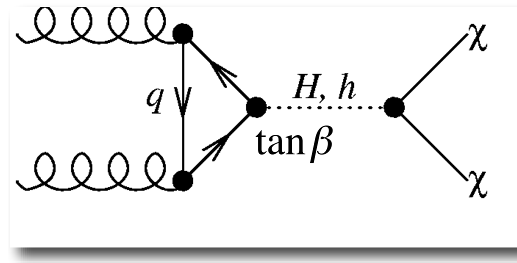
Current and near future experiments sensitive only to spin-independent scattering

$$\sigma_{SI} \leq 10^{-8}\, pb$$

==> dominated by t-channel exchange of H and h, coupling to strange quarks and to gluons via bottom loops

$\tan\beta$ enhanced couplings





Bino-like Neutralino example:

$$\sigma_{SI} \approx 4\times 10^{-7}\left(\frac{N_{11}^2}{0.9}\right)\left(\frac{N_{13}^2}{0.1}\right)\left(\frac{300\text{GeV}}{m_A}\right)^4\left(\frac{\tan\beta}{50}\right)^2$$

If m_A and $\tan\beta$ are within Tevatron reach, a substantial elastic cross section, at the reach of CDMS , is expected

CDMS DM searches Vs the Tevatron H/A searches

•If the lightest neutralino makes up the DM of the universe

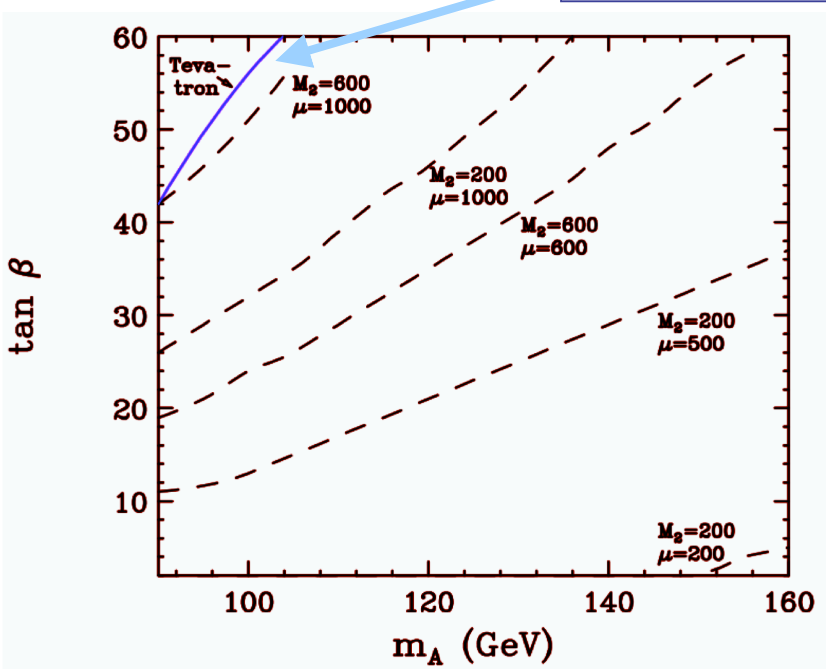
==> CDMS current limits disfavor discovery of H/A at the Tevatron, unless the neutralino has a large higgsino component $\Rightarrow \mu >> M_2$

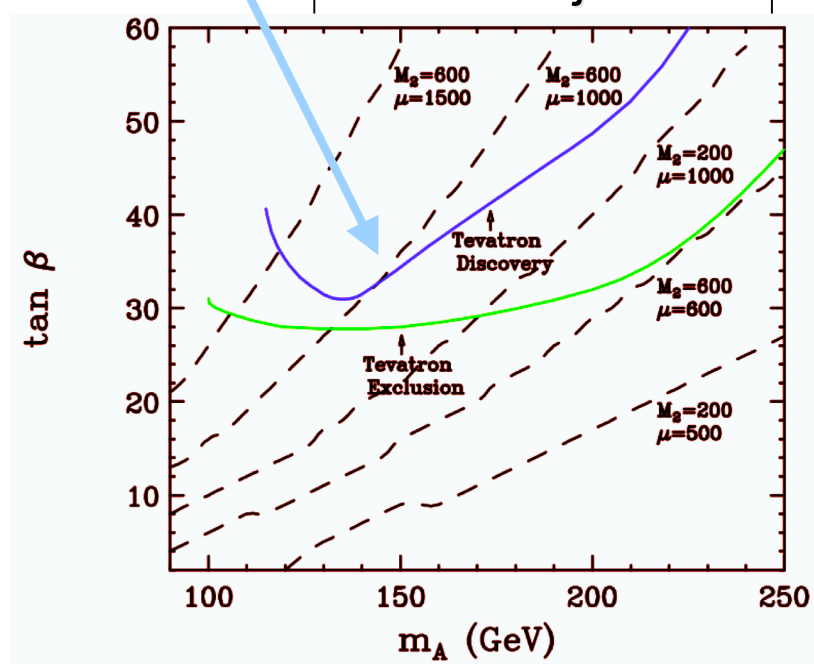
==> a positive signal at CDMS will be very encouraging for Higgs searches

==>Evidence for H/A at the Tevatron without a CDMS signal would suggest a large value of μ

Tevatron reach in $p\bar{p} \rightarrow A/H \rightarrow \tau^+\tau^-$

2007 Projection



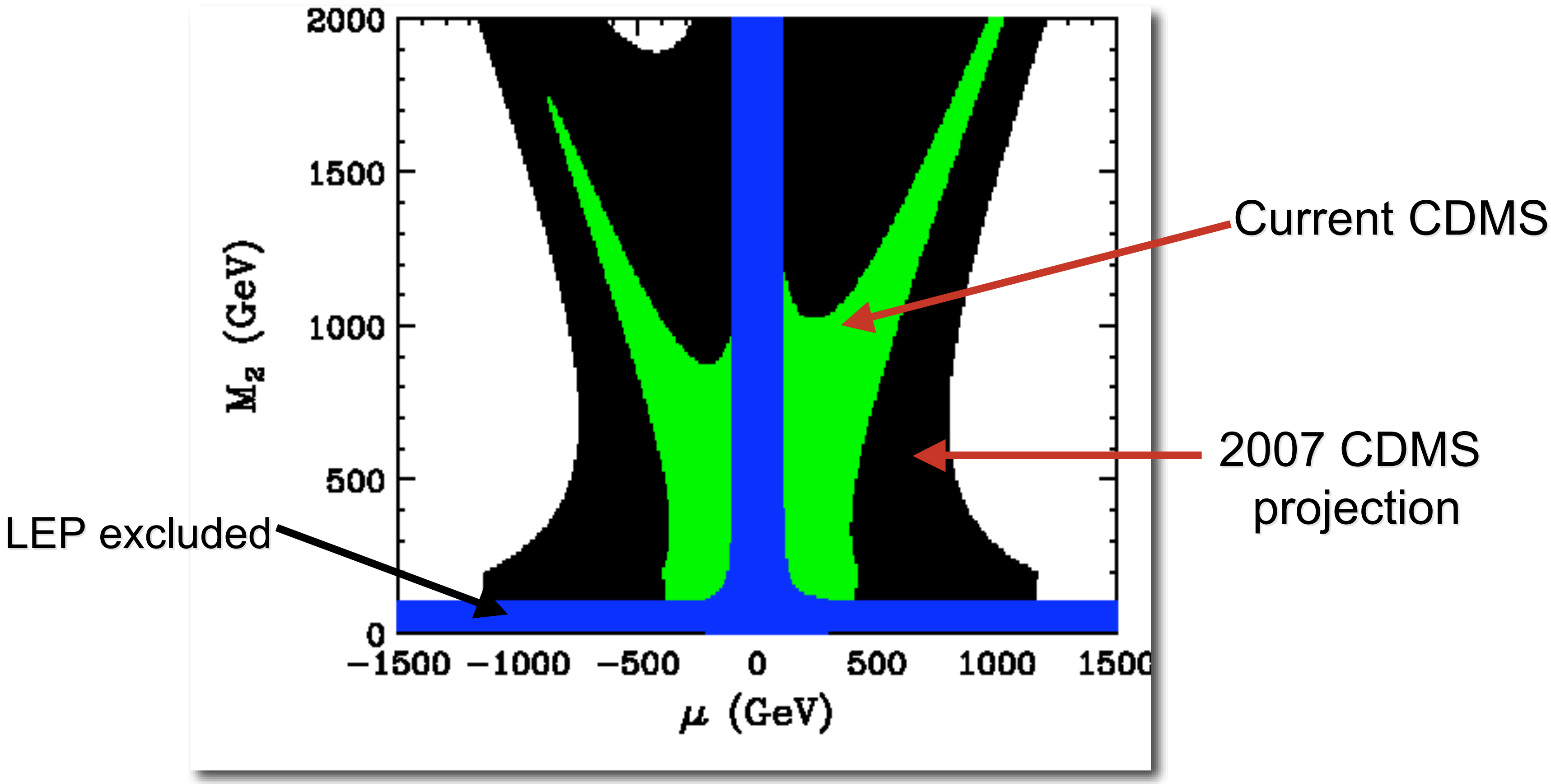


Current exclusion Comparison

M.C, Hooper, Skands, hep-ph/0603180

Direct Detection and Collider Searches

Constrained H/A discovery potential at the Tevatron (4 fb^{-1})



M.C, Hooper, Skands, hep-ph/0603180

Dark Matter: one of the fundamental open questions

==> it demands new physics and it may be intimately related to EWSB

- **Most suitable candidates beyond the Standard Model**:

==> Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

SUSY with R-parity discrete symmetry conserved $R_P = (-1)^{3B+L+2S}$

==> naturally provides a neutral stable DM candidate: LSP ==> $\tilde{\chi}^0$

- **Collider experiments will find evidence of DM through $\not{E}_T$ signature**

and knowledge of new physics particle masses and couplings will allow to compute DM-annihilation cross sections and elastic scattering WIMP -proton cross sections

But only Direct Detection Experiments will confirm the existence of Dark Matter particles

Evolution of the Dark Matter Density

- Produced in big bang, but also annihilate with each other.
- Annihilation stops when number density drops to the point that

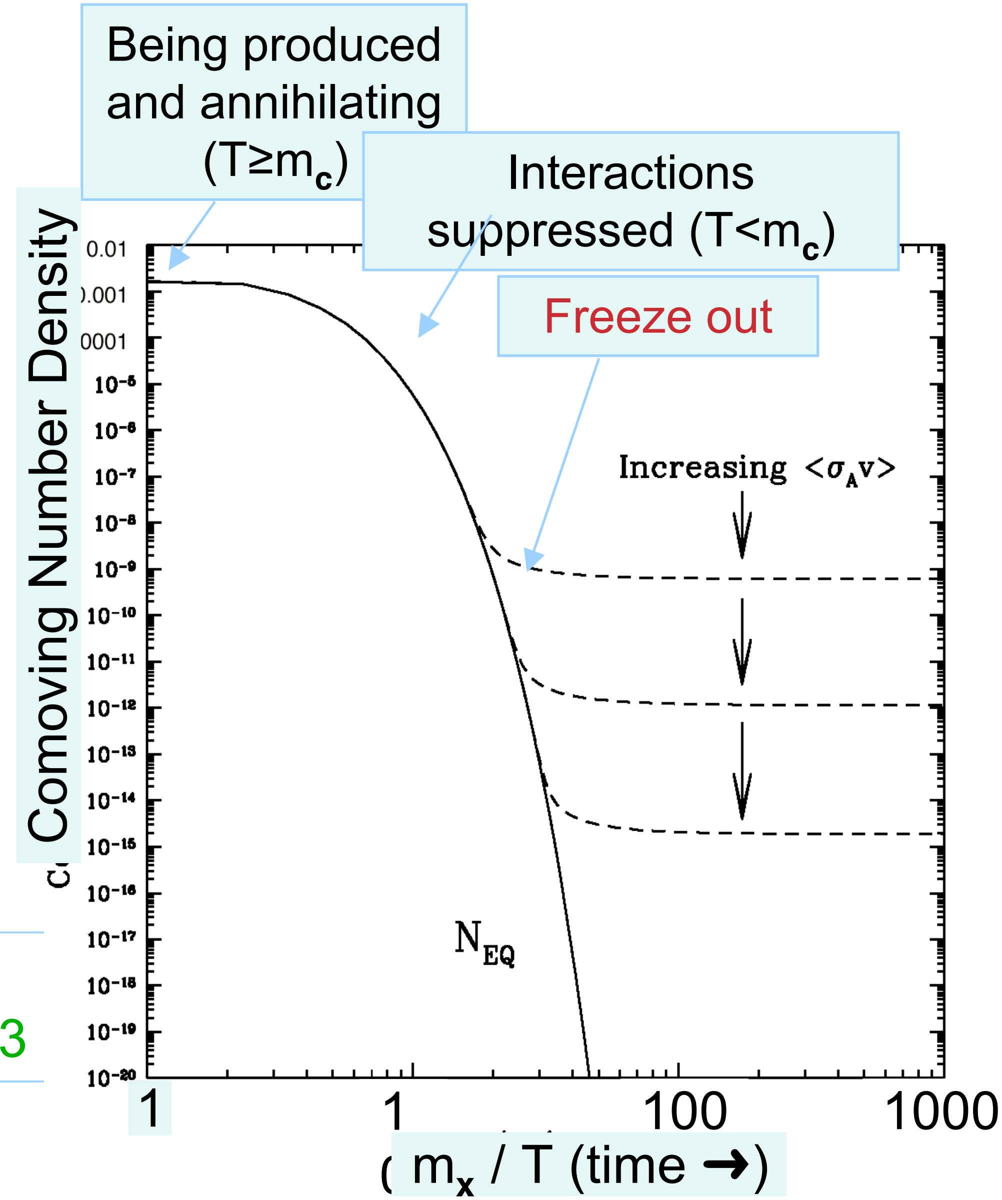
$$H > \Gamma_A \approx n_\chi < \sigma_A \mathrm{v} >$$

- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")
- Leaves a relic abundance:

$$\Omega_\chi h^2 \approx 10^{-27} cm^3 s^{-1} / < \sigma_A \mathrm{v} >_{\mathrm{fr}}$$

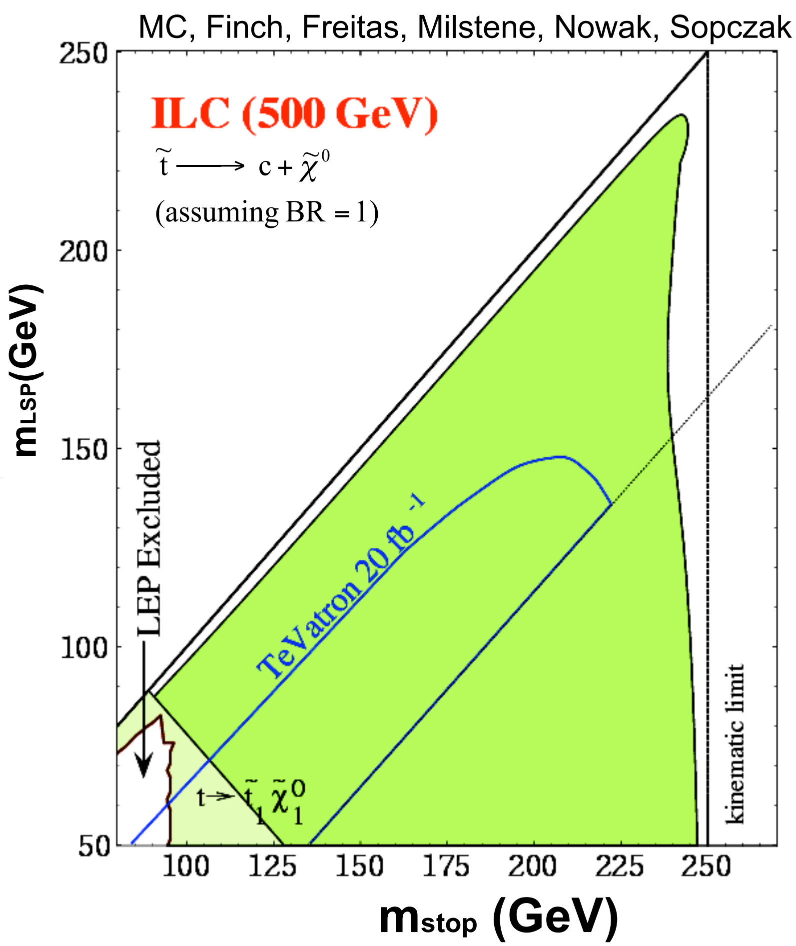
if m_x and σ_A determined by electroweak physics, then $\Omega_x \sim 0.3$

$$\sigma_{ann.} \approx \text{a few pb} \approx \alpha_W^2 / M_W^2$$



The power of the ILC

- Detect light stop in the whole regime compatible with DM and EWBG



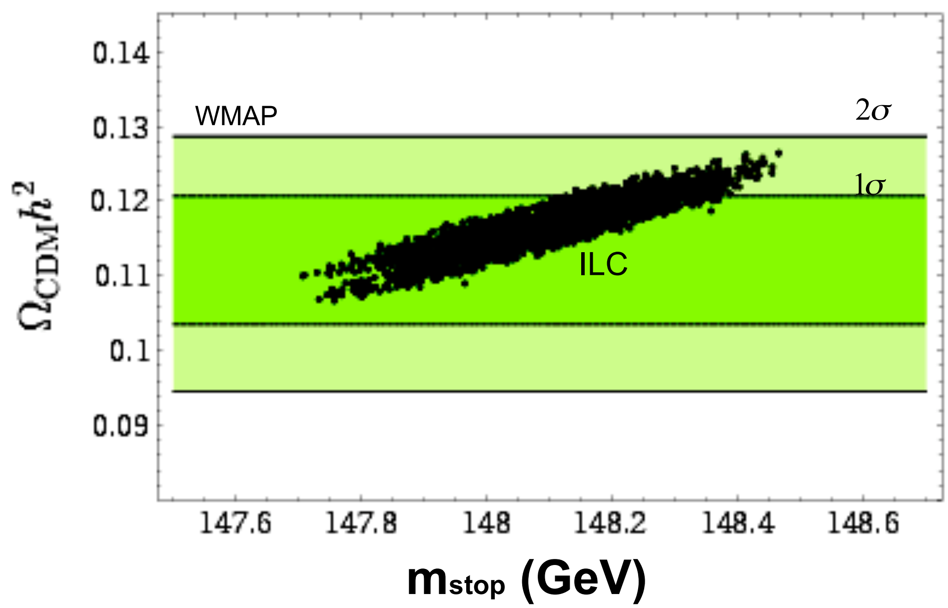
- Measurement of SUSY parameters for Dark Matter density computation

-- stop mass and mixing angles

-- LSP mass and composition

-- Higgs properties

-- other relevant light SUSY particles



A particle physics understanding of cosmological questions!