

# Neutralino Dark Matter

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# Outline

- Introduction
- Relic density of WIMPs
- Neutralino LSP as dark matter
  - Properties, annihilation channels,
  - Requirements for `good'  $\Omega h^2$
  - Requirements for collider tests
  - Implications of CP violation
  - Too large  $\Omega h^2$ ?
- Conclusions

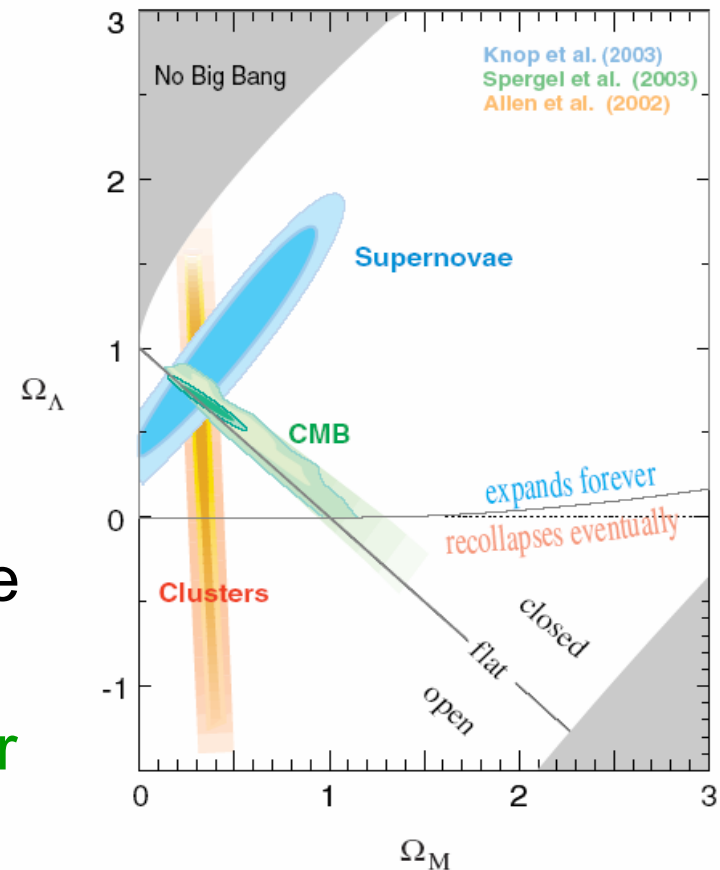
# What is the Universe made of?

## ■ Cosmological data:

- 4%  $\pm 0.4\%$  baryonic matter
- **23%  $\pm 4\%$  dark matter**
- 73%  $\pm 4\%$  dark energy

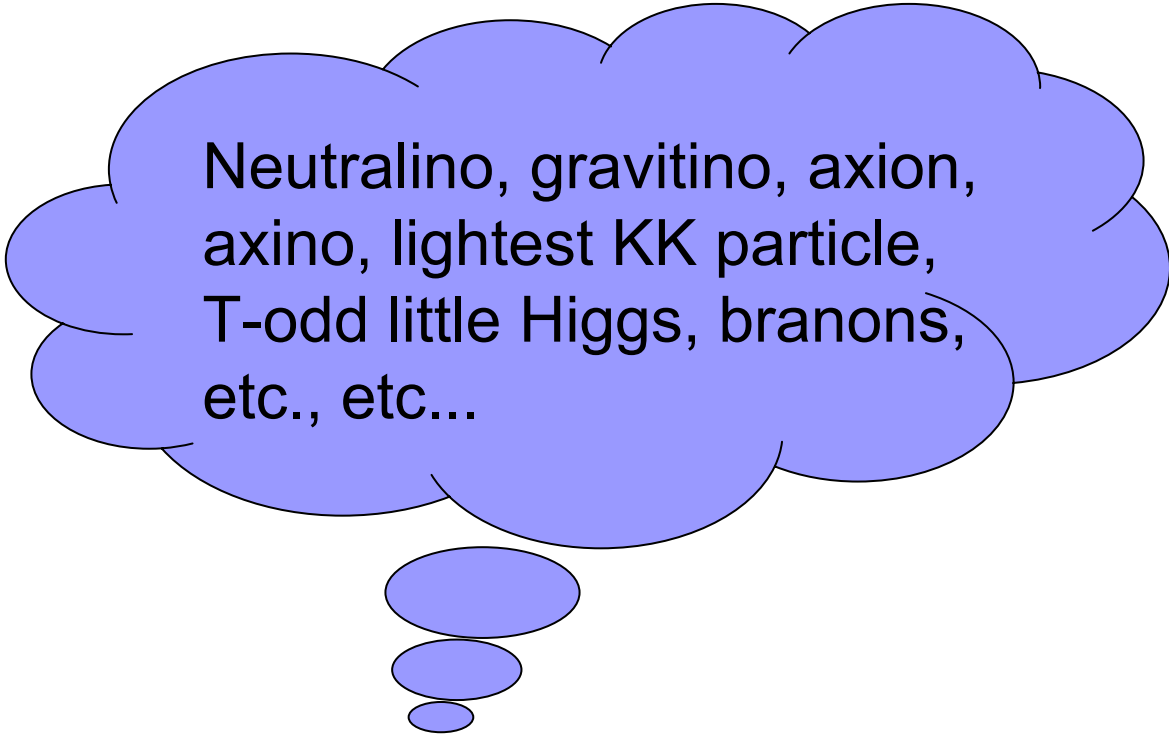
## ■ Particle physics:

- SM is incomplete; expect new physics at the TeV scale
- **Hope that this new physics also provides the dark matter**
- Discovery at LHC, precision measurements at ILC ?





# BSM dark matter candidates



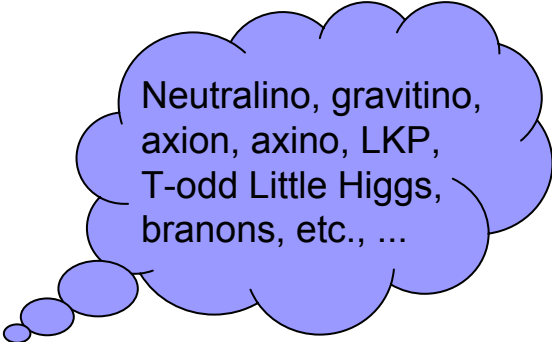
Neutralino, gravitino, axion,  
axino, lightest KK particle,  
T-odd little Higgs, branons,  
etc., etc...

New Physics



# WIMPs (weakly interacting massive particles)

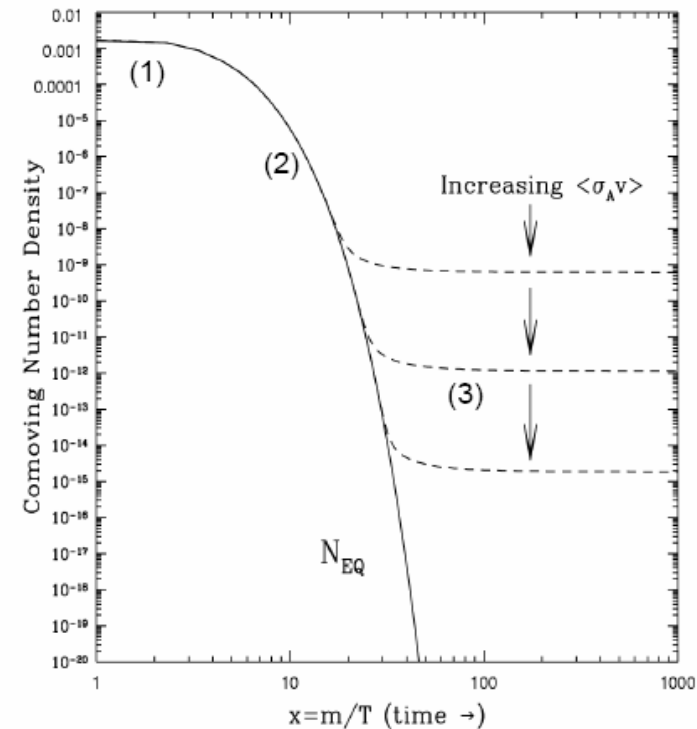
- DM should be stable, electrically neutral, weakly and gravitationally interacting
- WIMPs are predicted by most theories beyond the Standard Model (BSM)
- Stable as result of discrete symmetries
- Thermal relic of the Big Bang
- Testable at colliders!



Neutralino, gravitino,  
axion, axino, LKP,  
T-odd Little Higgs,  
branons, etc., ...

# Relic density of WIMPs

- (1) Early Universe dense and hot; WIMPs in thermal equilibrium
- (2) Universe expands and cools; WIMP density is reduced through pair annihilation; Boltzmann suppression:  $n \sim e^{-m/T}$
- (3) Temperature and density too low for WIMP annihilation to keep up with expansion rate  $\rightarrow$  freeze out



Final dark matter density:  $\Omega h^2 \sim 1/\langle\sigma v\rangle$

Thermally averaged cross section of all annihilation channels

Boltzmann equation for number density  $n$

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle [n^2 - (n^{\text{eq}})^2]$$

Equilibrium number density

$$n^{\text{eq}} \approx g \left( \frac{mT}{2\pi} \right)^{3/2} \exp(-m/T)$$

$g$  ... number of degrees of freedom,  $m$  ... mass of the relic,  $T$  ... Temperature

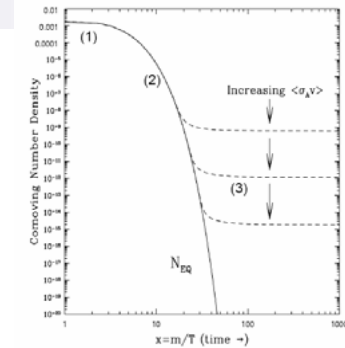
Freeze out point, scaled inverse temperature  $x=m/T \sim 25$

$$x_f = \ln \frac{0.038 g m_{\text{pl}} m \langle \sigma v \rangle}{g_*^{1/2} x_f^{1/2}}$$

Present-day mass density

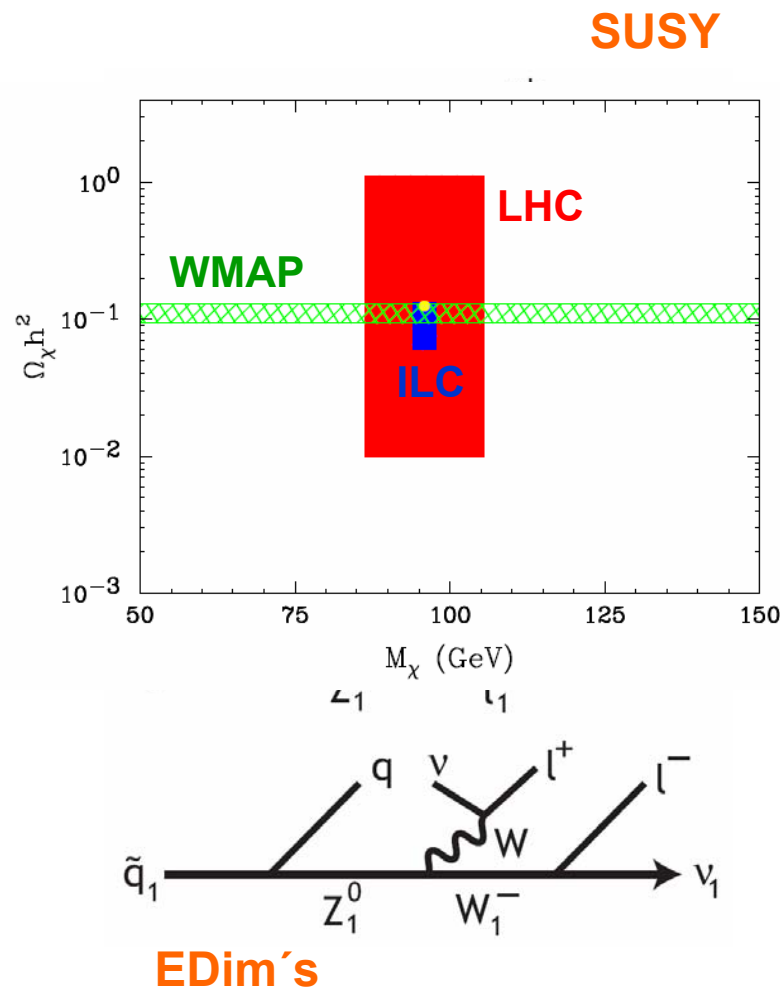
$$\Omega h^2 \approx \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{J g_*^{1/2} m_{\text{pl}}}$$

$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle}{x^2} dx$$



# Collider tests of WIMPs

- WIMP is „invisible“; analyse missing  $E$  and  $p$  in decays of other new particles into it
- Generic WIMP signature at **LHC: jets (+leptons) +  $E_T^{\text{miss}}$**
- Great for discovery; **resolving the nature of the WIMP however not obvious**
- Need **precision measurements** of masses, couplings, quantum numbers, .... **→ ILC**



A futuristic spacecraft is shown in the upper left corner, flying towards the right. The background is a dark blue gradient with several bright, multi-pointed stars scattered across it. The overall aesthetic is clean and modern, typical of a scientific presentation.

# Neutralino-LSP in the MSSM



# Why SUSY?

- SUSY = Symmetry between fermions and bosons, many theoretical beauties
  - Natural and unique extension of relativistic symmetries
  - Low-scale SUSY stabilizes Higgs mass
  - Radiative electroweak symmetry breaking
  - Gauge coupling unification
  - ....
- If R-parity is conserved the lightest SUSY particle (LSP) is stable → LSP as cold dark matter candidate
- LSP could be neutralino, gravitino, axino, singlino, ...
- I have to make a choice: neutralino LSP of the MSSM

# Minimal supersymmetric model

- SUSY = Symmetry between fermions and bosons

SM particles	spin	Superpartners	spin
quarks	1/2	squarks	0
leptons	1/2	sleptons	0
gauge bosons	1	gauginos	1/2
Higgs bosons	0	higgsinos	1/2

mix to  
2 charginos +  
4 neutralinos

2 Higgs doublets → 5 physical Higgs bosons:

neutral states: scalar  $h$ ,  $H$ ; pseudoscalar  $A$

charged states:  $H^+$ ,  $H^-$

Lightest neutralino = LSP

$$M_1 = \frac{5}{3} \tan^2 \theta_W M_2 \simeq M_2/2.$$

# Neutralino system

neutralino mass matrix in the  $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$  basis

**Gaugino m's**

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

**Higgsino mass**

Neutralino mass eigenstates

$$N^* \mathcal{M}_N N^\dagger = \text{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}), \quad m_{\tilde{\chi}_1^0} < \dots < m_{\tilde{\chi}_4^0}.$$

$$\tilde{\chi}_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W} + N_{13} \tilde{H}_1 + N_{14} \tilde{H}_2 \rightarrow \text{LSP}$$

# Chargino system

- Mass matrix

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin \beta \\ \sqrt{2} m_W \cos \beta & \mu \end{pmatrix}$$

diagonalized by the two unitary matrices  $U$  and  $V$ :

$$U^* \mathcal{M}_C V^\dagger = \text{diag}(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}),$$

- Interaction with neutralino and W

$$\mathcal{L}_{\tilde{\chi}\tilde{\chi}W} = g W_\mu^- \overline{\tilde{\chi}_j^0} \gamma^\mu (O_{ji}^L P_L + O_{ji}^R P_R) \tilde{\chi}_i^+$$

$$O_{ji}^L = \underbrace{N_{j2} V_{i1}^*}_{\text{wino}} - \underbrace{\frac{1}{\sqrt{2}} N_{j4} V_{i2}^*}_{\text{higgsino fractions}} \quad \text{and} \quad O_{ji}^R = N_{j2}^* U_{i1} + \underbrace{\frac{1}{\sqrt{2}} N_{j3}^* U_{i2}}_{\text{higgsino fractions}}$$

**wino**

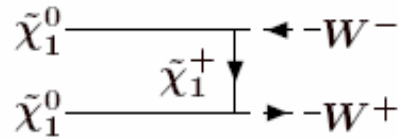
**higgsino fractions** (coupling vanishes in the pure bino case)

# Neutralino relic density

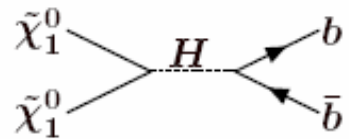
$\chi^0$  LSP as thermal relic: relic density computed as **thermally averaged cross section of all annihilation channels**  $\rightarrow \Omega h^2 \sim 1/\langle\sigma v\rangle$



bino LSP, bulk region  
light  $\tilde{\chi}_1^0$  and  $\tilde{f}$



LSP with strong higgsino component



Higgs funnel  
 $m_H \sim 2m_{\tilde{\chi}_1^0}$

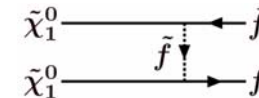


Co-annihilation  
LSP–NLSP mass difference

**$0.094 < \Omega h^2 < 0.129$  puts strong bounds on the parameter space**

# Annihilation into fermions: $\chi\chi \rightarrow ff$

- Can proceed through
  - t-channel sfermion exchange
  - s-channel Z exchange
  - s-channel Higgs exchange



- Sfermion exchange requires light sparticles „bulk region“

$$\Omega \propto m_{\tilde{l}_R}^4 / m_{\tilde{\chi}_1^0}^2,$$

- The Z couples only to the higgsino component of the  $\chi$

$$g_{Z\chi\chi} \sim N_{13}^2 - N_{14}^2$$

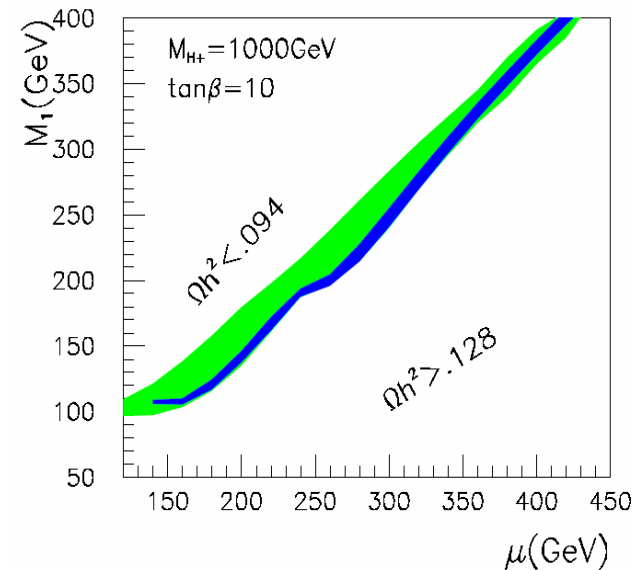
- Higgs couples to gaugino-higgsino combination

Incoming  $\chi\chi$  have  $CP=-1$ , so pseudoscalar  $A$  exchange is preferred

Key parameter is distance from pole:  $m_A - 2m_\chi$

# Annihilation into gauge bosons

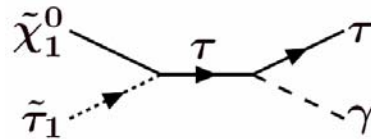
- $\chi\chi \rightarrow WW / ZZ$  mainly through t-channel chargino / neutralino exchange; typically also some annihilation into Zh, hh
- Does not occur for pure bino; LSP needs to be mixed bino-higgsino (or bino-wino)
- Pure wino or higgsino LSP: neutral and charged states are a mass-degenerate triplet, (co)annihilation too efficient
- Right relic density for  $(|\mu| - M_1)/M_1 \sim 0.3$ ,  $(M_2 - M_1)/M_1 \sim 0.1$



# Coannihilations

- Occur for **small mass differences** between LSP and next-to-lightest sparticle(s); **efficient channel for a bino-like LSP**

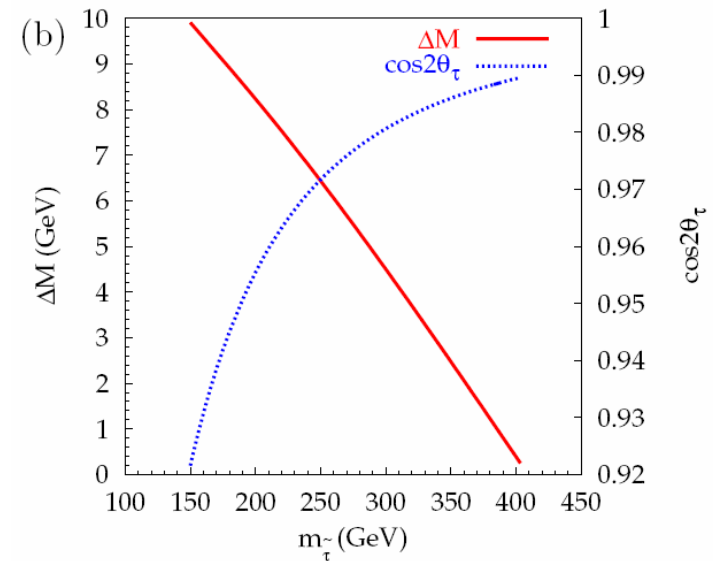
- Typical case: coann. with staus



- Key parameter is the mass difference

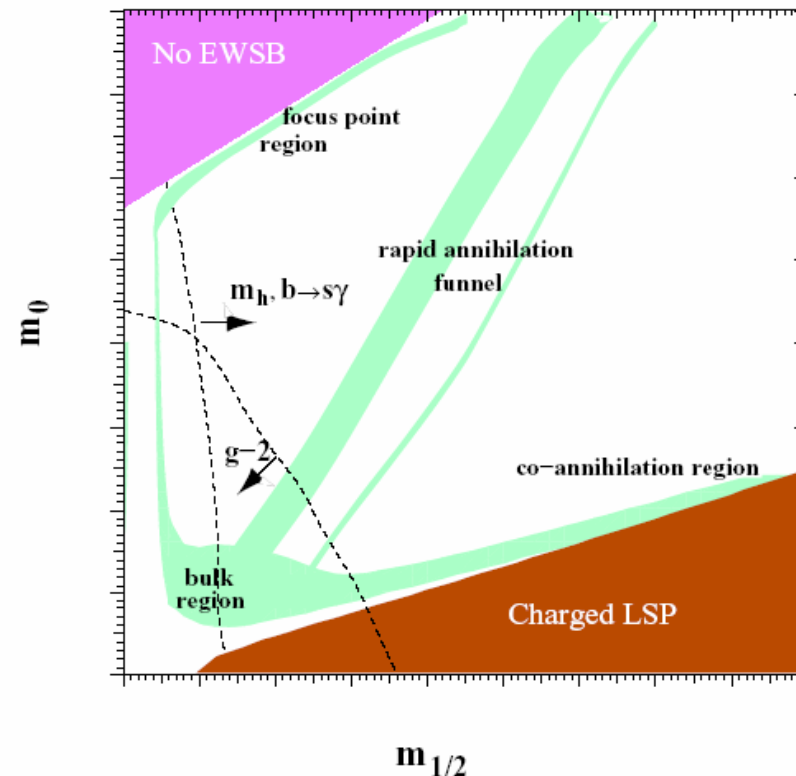
$$\Delta M = m_{\text{NLSP}} - m_{\text{LSP}}$$

- Other possibilities: Coannihilation with stops ( $\Delta M \sim 20\text{-}30\text{ GeV}$ ), coann. with chargino and the 2nd neutralino (in non-unified models)



# mSUGRA parameter space

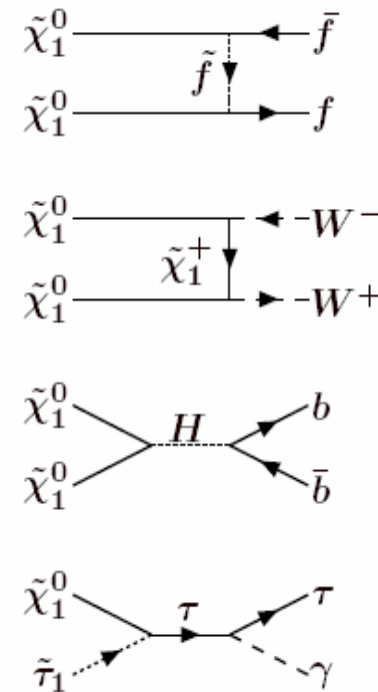
- GUT-scale boundary conditions:  $m_0$ ,  $m_{1/2}$ ,  $A_0$  [plus  $\tan\beta$ ,  $\text{sgn}(\mu)$ ]
- 4 regions with right  $\Omega_{\tilde{h}^2}$ 
  - bulk (excl. by  $m_h$  from LEP)
  - co-annihilation
  - Higgs funnel ( $\tan\beta \sim 50$ )
  - focus point (higgsino scenario)



# Prediction of $\langle\sigma v\rangle$ from colliders: What do we need to measure?

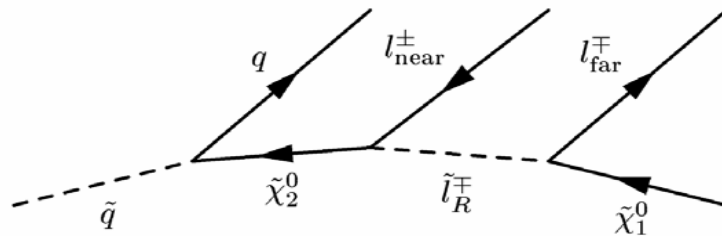
- LSP mass and decomposition  
bino, wino, higgsino admixture
- Sfermion masses (bulk, coannihilation)  
or at least lower limits on them
- Higgs masses and widths:  $h, H, A$
- $\tan\beta$

**With which precision?**



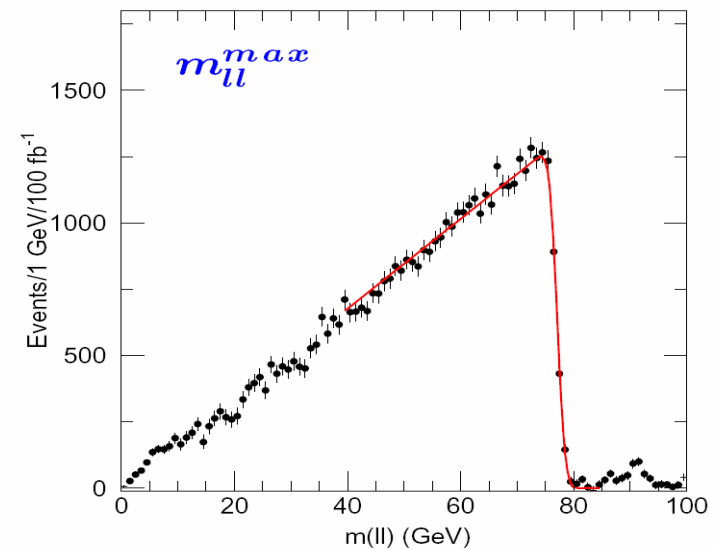
# LHC: exploit cascade decays

Mass reconstruction through kinematic endpoints



$$m_{l+l-}^{max} = m_{\tilde{\chi}_i^0} \sqrt{1 - \frac{m_{\tilde{l}}^2}{m_{\tilde{\chi}_i^0}^2}} \sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}}^2}}$$

$l^+ l^-$	edge	$m_{ll}^{max}$
$l^+ l^- q$	edge	$m_{llq}^{max}$
$l^+ l^- q$	threshold	$m_{llq}^{min}$
$l^\pm q$	high-edge	$m_{lq}^{high}$
$l^\pm q$	low-edge	$m_{lq}^{low}$



Precisions of a few %

# $e^+e^-$ Linear Collider (ILC)

Precision measurements with tunable energy and beam polarization

$$e_L^+ e_R^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^+ \tilde{\chi}_1^0 \mu^- \tilde{\chi}_1^0,$$

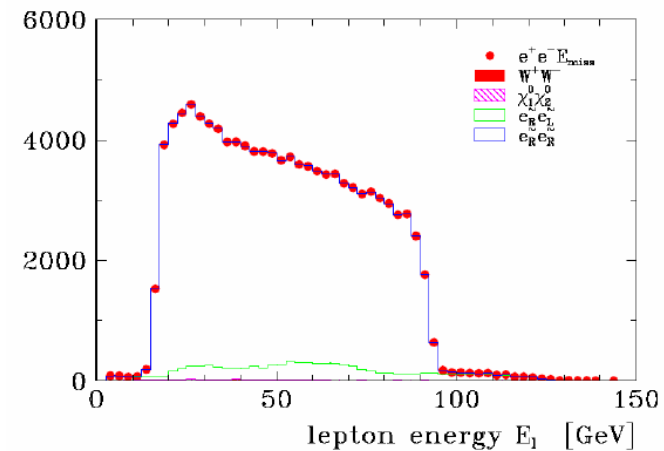
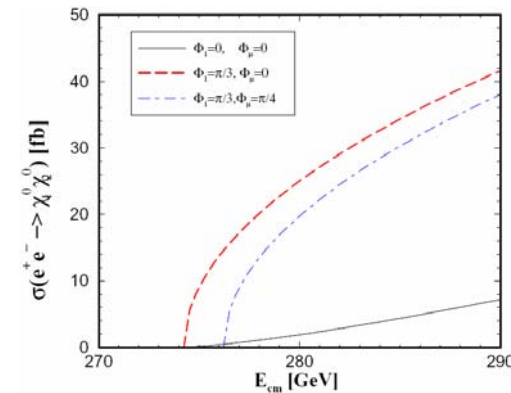
$$e_L^+ e_R^- \rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tau^+ \tilde{\chi}_1^0 \tau^- \tilde{\chi}_1^0.$$

$$E_{+/-} = \frac{\sqrt{s}}{4} \left( \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}^2} \right) \left( 1 \pm \sqrt{1 - 4 m_{\tilde{\ell}}^2 / s} \right)$$

$$m_{\tilde{\ell}} = \sqrt{s} \frac{\sqrt{E_- E_+}}{E_- + E_+},$$

$$m_{\tilde{\chi}} = m_{\tilde{\ell}} \sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}.$$

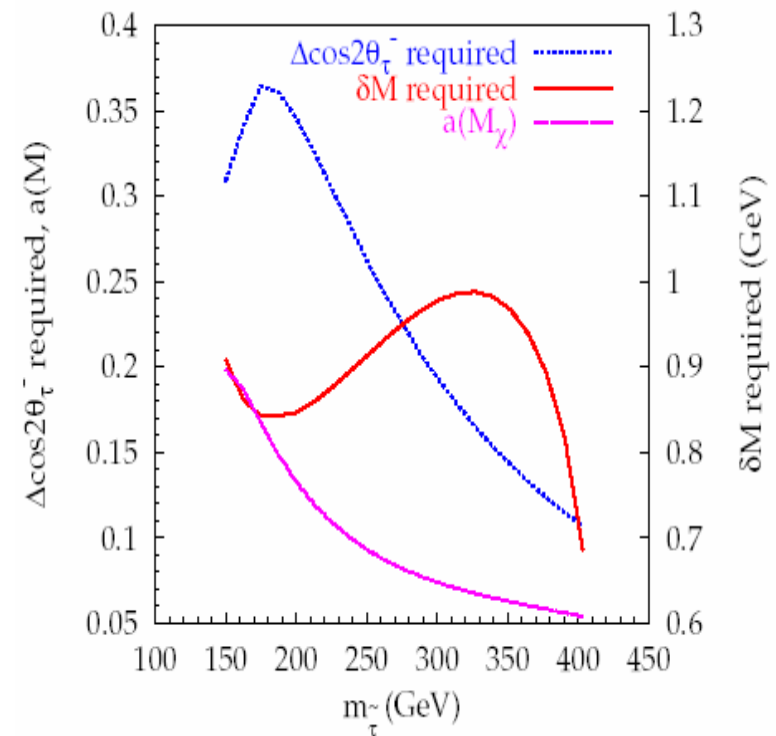
[TESLA TDR] can reach O(0.1%) precision



What do we need to measure with which precision:

## Coannihilation with staus, $\Delta M \lesssim 10$ GeV

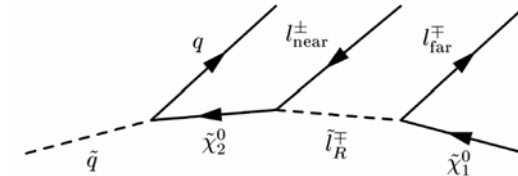
- $\Delta M(\text{stau-LSP})$  to  $< 1$  GeV
  - Precise sparticle mixings
  - Difficult at LHC; soft tau's!
    - Arnowitt et al, hep-ph/0603128
  - Achievable at ILC:
    - Stau mass at threshold  
Bambade et al, hep-ph/040601
    - Stau and Slepton masses  
Martyn, hep-ph/0408226
    - Stau-neutralino mass difference  
Khotilovitch et al, hep-ph/0503165
- Beam polarization essential!



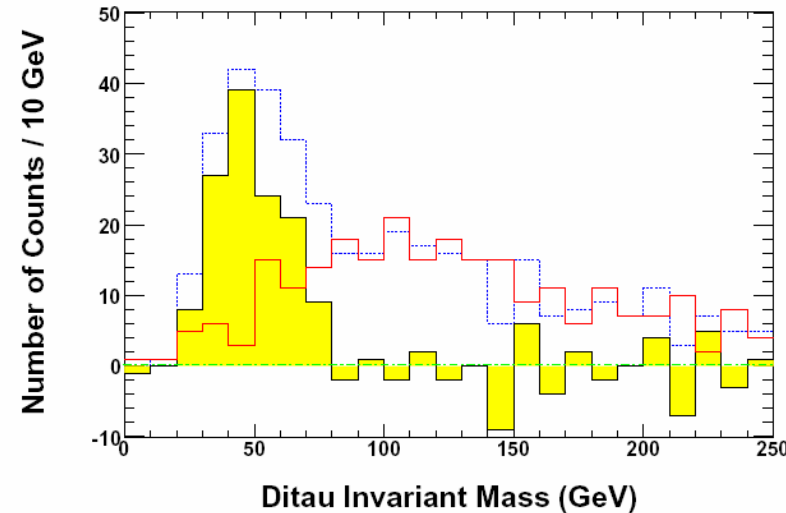
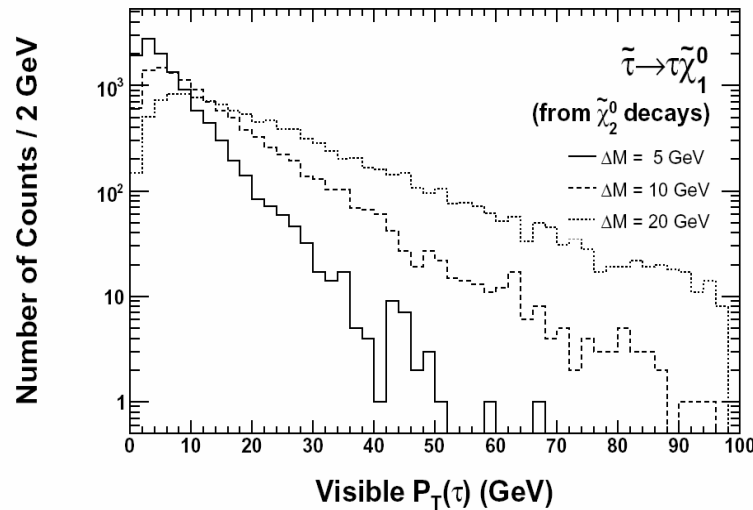
[Allanach et al, hep-ph/0410091]

# Stau coann. scenario at LHC

- Leptons from cascade will mostly be taus
- $\Delta M \leq 10$  GeV leads to soft  $\tau$ 's
- Difficult to measure  $m_{\tau\tau}$  kinematic endpoint



$$M_{\tau\tau}^{\max} = M_{\chi_2^0} \sqrt{1 - \frac{M_{\tau_1}^2}{M_{\chi_2^0}^2}} \sqrt{1 - \frac{M_{\chi_1^0}^2}{M_{\tau_1}^2}}$$

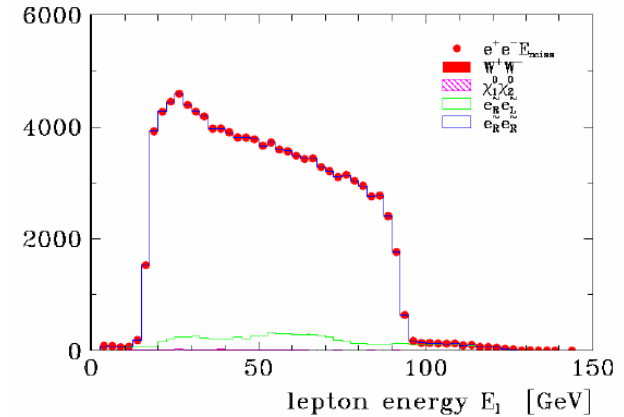


“with  $10 \text{ fb}^{-1}$  we can determine  $\Delta M$  with a statistical uncertainty of 12% for  $\Delta M = 10$  GeV; additional systematic uncertainty of 14% if the gluino mass has an uncertainty of 5%”

[Arnowitz et al, hep-ph/0603128]

# Stau coann. scenario at the ILC

$$\begin{aligned}
 e_L^+ e_R^- &\rightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^+ \tilde{\chi}_1^0 \mu^- \tilde{\chi}_1^0, \\
 e_L^+ e_R^- &\rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tau^+ \tilde{\chi}_1^0 \tau^- \tilde{\chi}_1^0.
 \end{aligned}$$



$e^+e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R$	$m_{\tilde{\mu}_R} = 143.0 \pm 0.18 \text{ GeV}$	$m_{\tilde{\chi}_1^0} = 135.0 \pm 0.17 \text{ GeV}$
$e^+e^- \rightarrow \tilde{e}_R \tilde{e}_R$	$m_{\tilde{e}_R} = 143.0 \pm 0.09 \text{ GeV}$	$m_{\tilde{\chi}_1^0} = 135.0 \pm 0.08 \text{ GeV}$

scenario	$m_{\tilde{\tau}_1}$ [GeV]	$\delta m_{\tilde{\tau}_1}$ [GeV]	$\Delta m$ [GeV]	$\delta \Omega_{CDM} h^2$
SPS 1a inspired	133.2	0.14	8	1.7 %
		0.22	5	4.1 %
		0.28	3	6.7 %
model D'	217.5	0.15	5.1	1.9 %

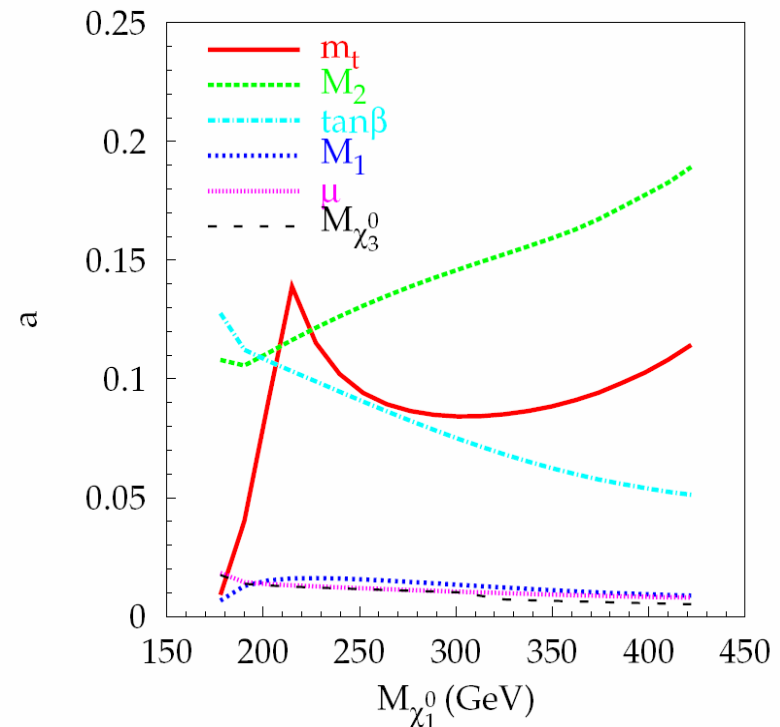
[Martyn, hep-ph/0408226]

What do we need to measure with which precision:

## Higgsino LSP, $\mu \sim M_1$

- Annihilation into  $WW$  and  $ZZ$  via t-channel  $\chi^\pm$  or  $\chi^0$
- Rate determined by higgsino fraction  $f_H = N_{13}^2 + N_{14}^2$
- **1% precision on  $M_1$  and  $\mu$**
- All neutralinos/charginos; mixing via pol.  $e^+e^-$  Xsections
- **LHC: Drell-Yang production?  
3-body gluino decays?**

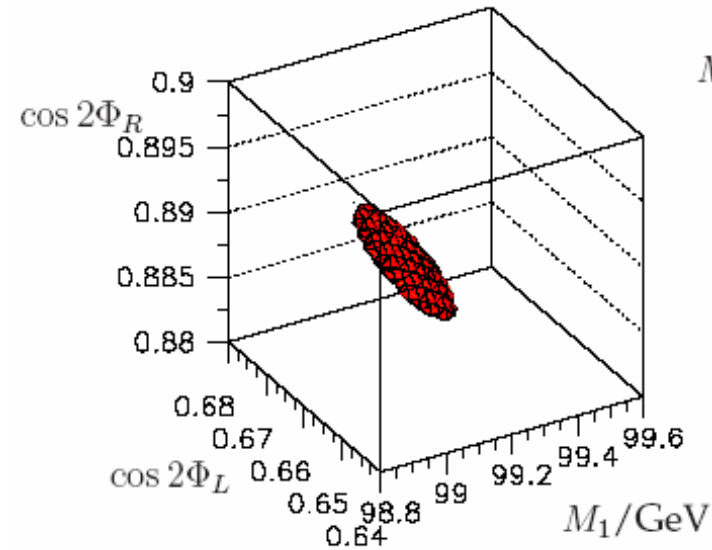
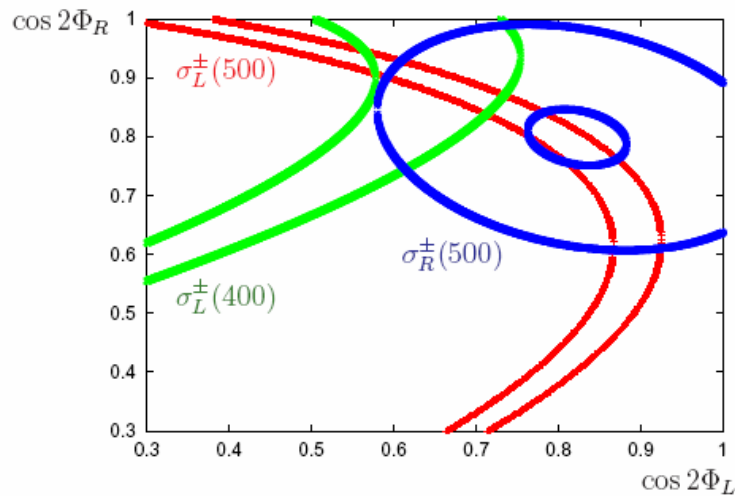
Fractional accuracies needed



[Allanach et al, hep-ph/0410091]

# Determination of the $\tilde{\nu}$ -ino system

LHC+ILC case study for SPS1a: light  $\tilde{\nu}$ -inos at ILC; neutralino4 at LHC

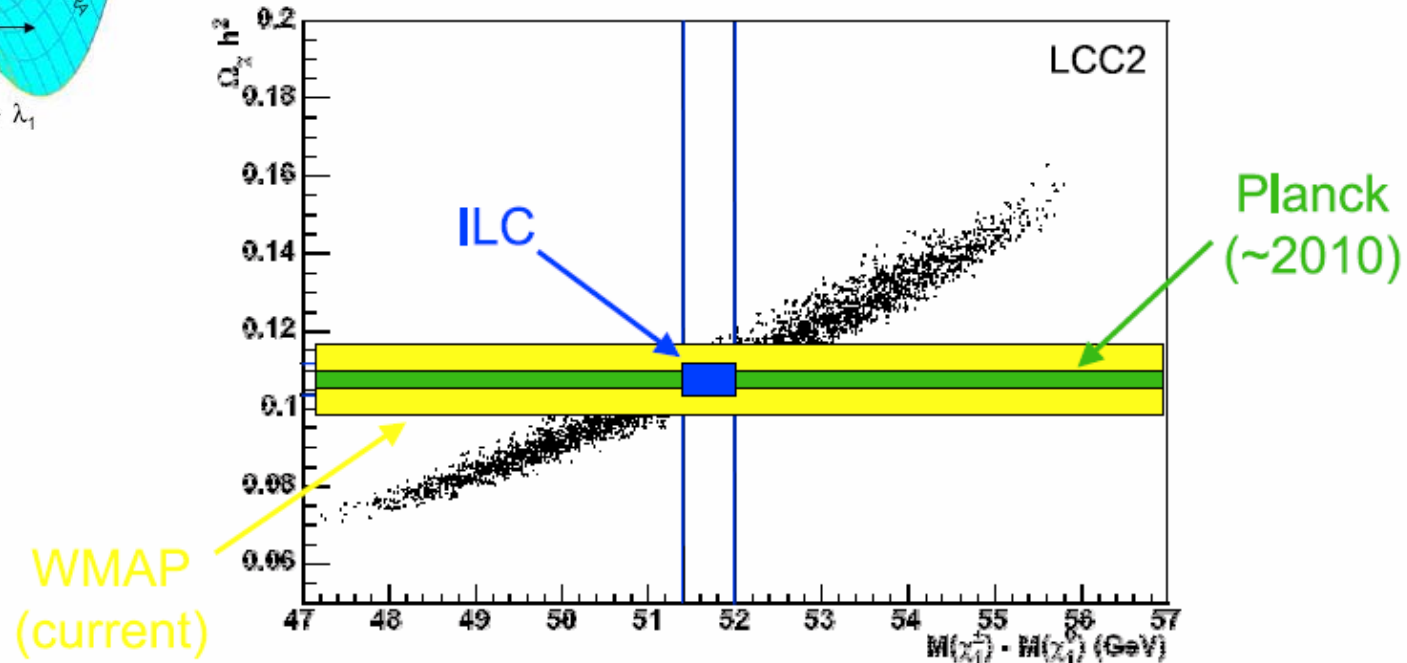
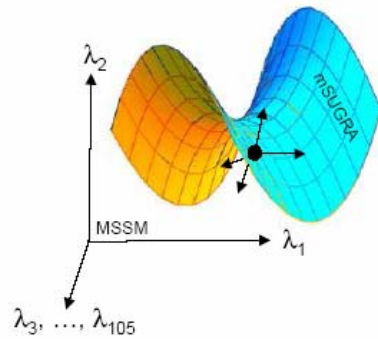


SUSY Parameters				Mass Predictions	
$M_1$	$M_2$	$\mu$	$\tan \beta$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_3^0}$
$99.1 \pm 0.1$	$192.7 \pm 0.3$	$352.4 \pm 2.1$	$10.2 \pm 0.6$	$378.5 \pm 2.0$	$358.8 \pm 2.1$

[Desch et al., hep-ph/0312069]

# Scan of focus point scenario, LCC2

$m_0 = 3280 \text{ GeV}$ ,  $m_{1/2} = 300 \text{ GeV}$ ,  $A_0 = 0$ ,  $\tan\beta = 10$



[J.L. Feng et al., ALCPG]

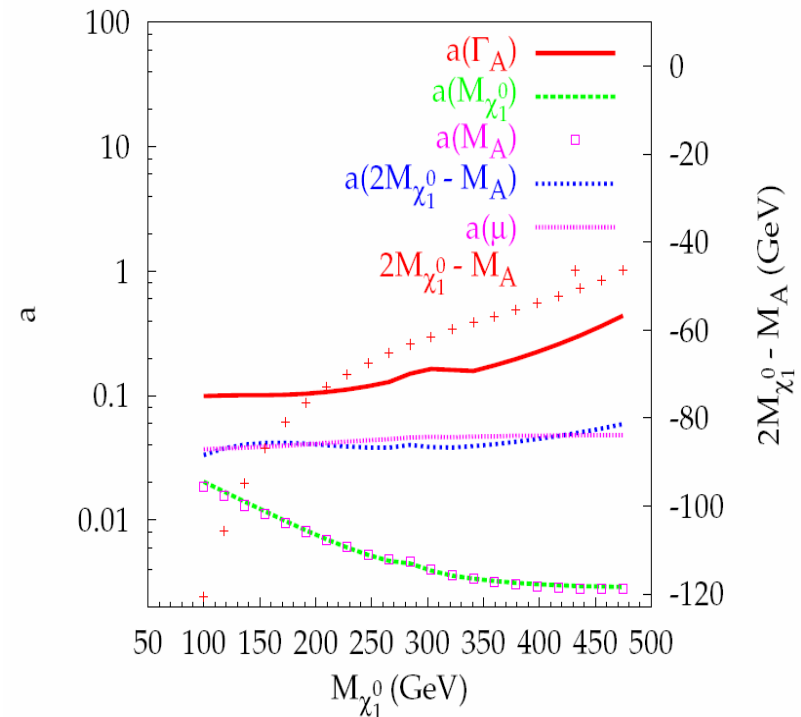
# What do we need to measure with which precision: Annihilation through Higgs

- Mainly  $\chi\chi \rightarrow A \rightarrow bb$
- CP even H exchange is P-wave suppressed
- $m_\chi$  and  $m_A$  to 2%-2‰
- $(m_A - 2m_\chi)$  and  $\mu$  to 5%
- $A$  width to 10%

$g(A\chi\chi) \sim N_{13}^2 - N_{14}^2$ ,  $g(A\bar{b}b) \sim h_b$ , ....

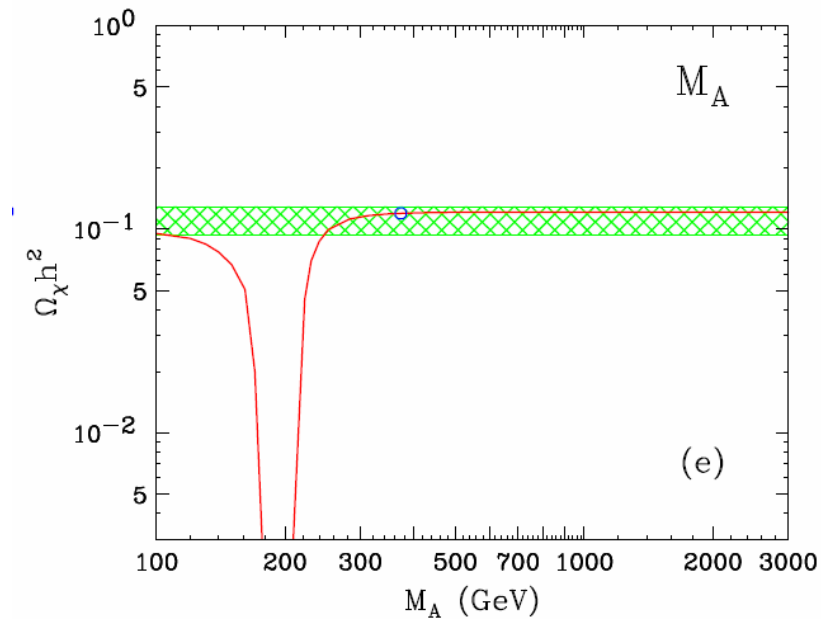
$$\langle \sigma v \rangle_{v=0}^{-1} \propto \frac{4m_{\tilde{\chi}_1^0}\Gamma_A}{g_{\tilde{\chi}_1^0\tilde{\chi}_1^0A}^2} \left( 4 \left( \frac{M_A - 2m_{\tilde{\chi}_1^0}}{\Gamma_A} \right)^2 + 1 \right)$$

Fractional accuracies needed



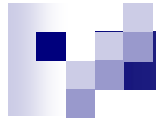
[Allanach et al, hep-ph/0410091]

## Influence of $m_A$ on evaluation of $\Omega h^2$



→ large uncertainty if lower limit on  $m_A$  is not  $\gg 2 m_{\text{LSP}}$

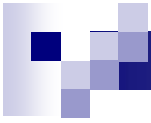
[Birkedal et al, hep-ph/0507214]



For a precise prediction of  $\Omega h^2$   
we need precision measurements  
of most of the SUSY spectrum

(LHC+ILC)

see also Baltz et al., hep-ph/0602187



So far considered CP conserving MSSM

## What if CP is violated?

[we actually need new sources of CP violation  
beyond the SM for baryogenesis]

# MSSM with CP phases

- In the general MSSM, gaugino and higgsino mass parameters and trilinear couplings can be complex:

$$M_1 = |M_1|e^{i\phi_1}, \mu = |\mu|e^{i\phi_\mu}, A_f = |A_f|e^{i\phi_f}$$

- Sparticle production and decay rates strongly depend on CPV phases → **expect similar influence on  $\langle\sigma v\rangle$**
- Caution: also the sparticle *masses* depend on phases → **disentangle effects from kinematics and couplings**

NB1:  $M_2$  can also be complex, but its phase can be rotated away.

NB2: CPV phases are strongly constrained by dipole moments;

we set  $\phi_\mu=0$  and assume very heavy 1st+2nd generation sfermions

# Recall the neutralino system

neutralino mass matrix in the  $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$  basis

$$\mathcal{M}_N = \begin{pmatrix} |M_1|e^{i\phi_1} & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & |\mu|e^{i\phi_\mu} \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & |\mu|e^{i\phi_\mu} & 0 \end{pmatrix}$$

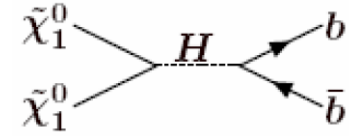
Neutralino mass eigenstates

$$N^* \mathcal{M}_N N^\dagger = \text{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}), \quad m_{\tilde{\chi}_1^0} < \dots < m_{\tilde{\chi}_4^0}.$$

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

CP phases induce shifts in masses and couplings

# Higgs sector



- Non-zero phases induce **CP violation in the Higgs sector through loop effects** → **mixing of h,H,A:**

$$(\phi_1, \phi_2, a)_\alpha^T = O_{\alpha i} (H_1, H_2, H_3)_i^T,$$

$$O^T \mathcal{M}_H^2 O = \text{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2) \text{ with } M_{H_1} \leq M_{H_2} \leq M_{H_3}.$$

- Couplings to neutralinos: scalar and pseudoscalar parts

$$\mathcal{L}_{H^0 \tilde{\chi}^0 \tilde{\chi}^0} = -\frac{g}{2} \sum_{i,j,k} H_k \overline{\tilde{\chi}_i^0} \left( g_{H_k \tilde{\chi}_i^0 \tilde{\chi}_j^0}^S + i\gamma_5 g_{H_k \tilde{\chi}_i^0 \tilde{\chi}_j^0}^P \right) \tilde{\chi}_j^0 :$$

$$g_{H_k \tilde{\chi}_i^0 \tilde{\chi}_j^0}^S = \frac{1}{2} \Re[(N_{j2}^* - t_W N_{j1}^*)(N_{i3}^* G_k^{\phi_1} - N_{i4}^* G_k^{\phi_2}) + (i \leftrightarrow j)]$$

$$g_{H_k \tilde{\chi}_i^0 \tilde{\chi}_j^0}^P = -\frac{1}{2} \Im[(N_{j2}^* - t_W N_{j1}^*)(N_{i3}^* G_k^{\phi_1} - N_{i4}^* G_k^{\phi_2}) + (i \leftrightarrow j)]$$

$$G_k^{\phi_1} = (O_{\phi_1 k} - i s_\beta O_{ak}), \quad G_k^{\phi_2} = (O_{\phi_2 k} - i c_\beta O_{ak})$$



# CPV-MSSM » micrOMEGAS

- We have implemented the general MSSM Lagrangian with CP-violating phases in `CalcHEP/micrOMEGAS` (started as project of Les Houches 2005 workshop)
- Higgs and sparticle masses and mixing matrices are computed with `CPsuperH`
- Fully automatical computation of the relic density; all contributing channels automatically included!
- Now performing general analysis of CPV-MSSM parameter space ....

`micrOMEGAS`: G. Bélanger et al., *Comput. Phys. Commun.* 149 (2002), [hep-ph/0112278](#)

`CPsuperH`: J.S. Lee et al., *Comput. Phys. Commun.* 156 (2004), [hep-ph/0307377](#)



# Previous studies

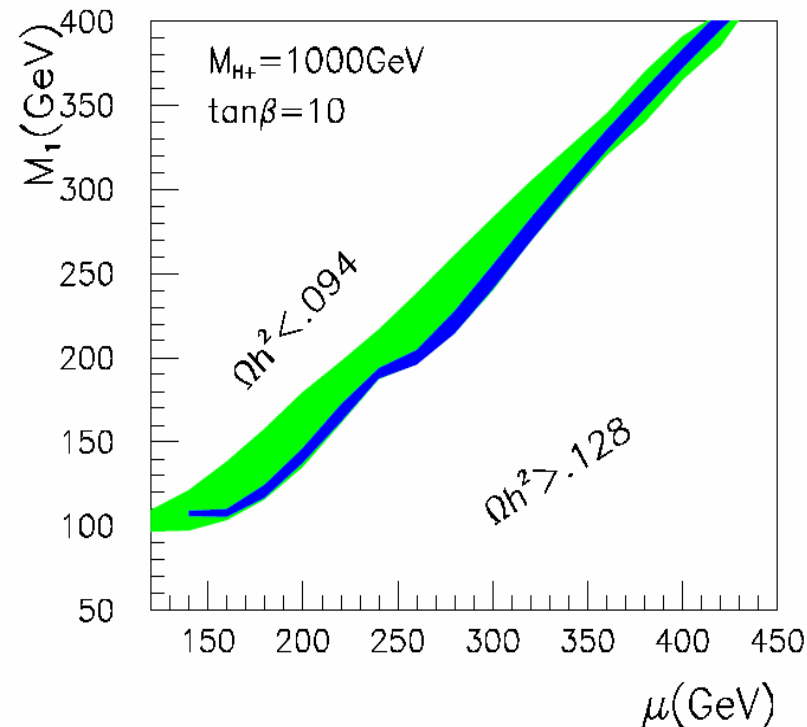
- S.Y. Choi, J.G. Kim, hep-ph/0602109
- T. Nihei, hep-ph/0508285
- M. E. Gomez, et al., hep-ph/0506243
- C. Balazs, et al., hep-ph/0412264
- M. Argyrou, et al., hep-ph/0404286
- T. Nihei, M. Sasagawa, hep-ph/0404100
- P. Gondolo, K. Freese, hep-ph/9908390

.... concentrated on particular aspects; sometimes found huge effects, but did not distinguish between effects on masses and on couplings ....

♪ we are hence performing a coherent, general analysis

♪ micrOMEGAs2.0 as public tool

# Scan over phases in $M_1$ - $\mu$ plane



$M_1 \sim \mu$

main channel is  
annihilation into WW

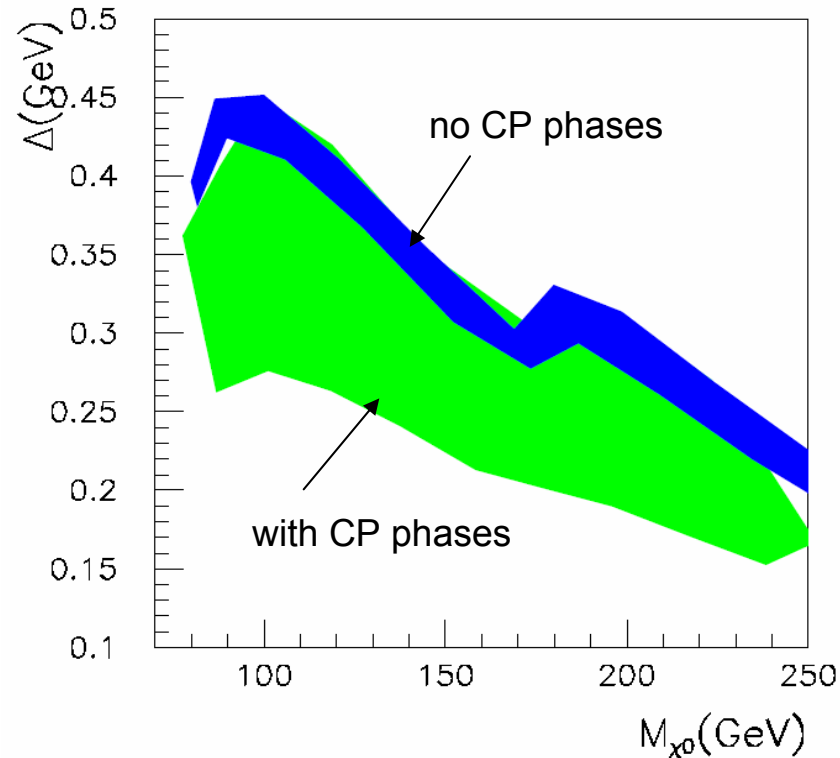
LSP has  $\sim 25\%$   
higgsino admixture

**Blue:** WMAP-allowed range in the CP-conserving MSSM

**Green:** same for the CP-violating case (arbitrary phases of  $M_1$ ,  $\mu$ , ...)

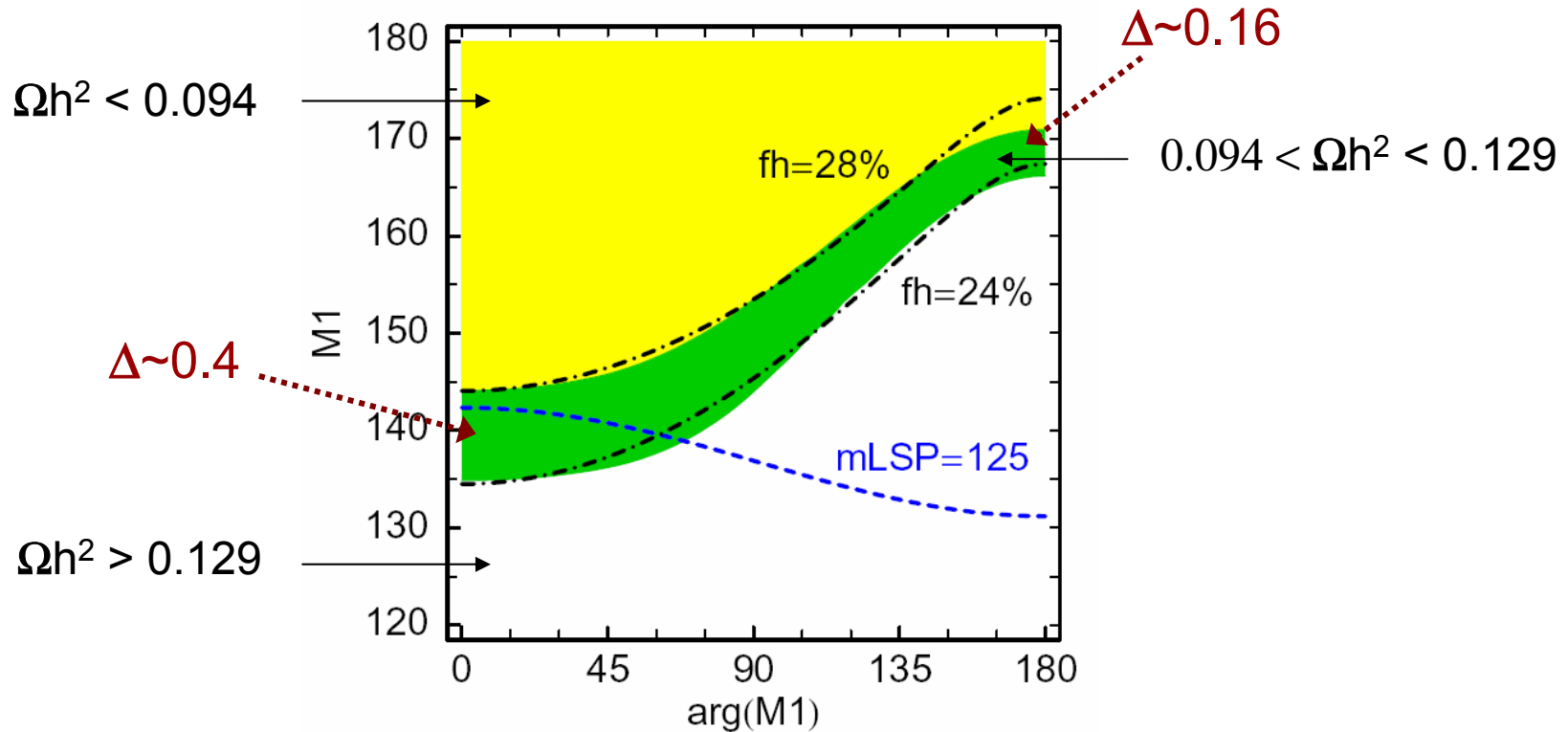
Same in terms of neutralino and chargino masses

$$\Delta = (m\chi_1^+ - m\text{LSP}) / m\text{LSP}$$



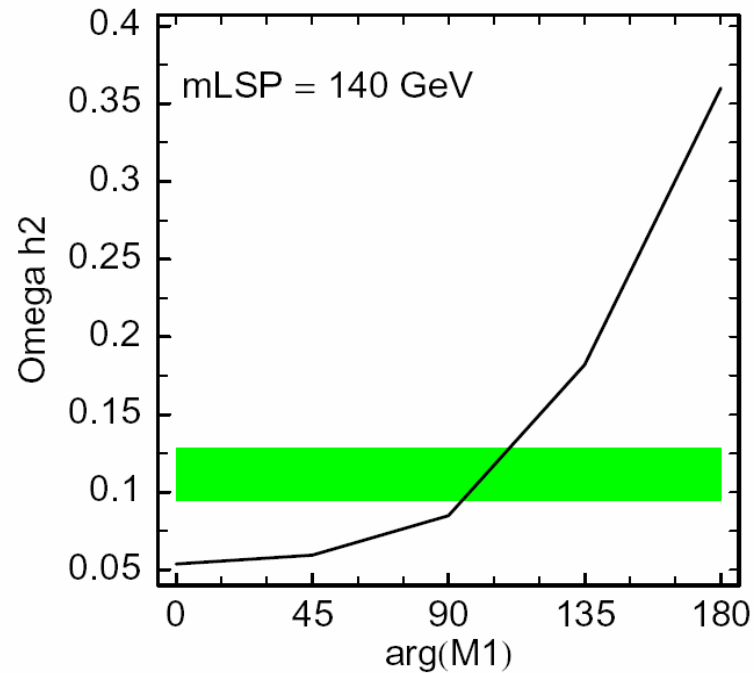
**With CP phases, much smaller neutralino-chargino mass differences can be in agreement with WMAP bound !**

In  $M_1$ - $\arg(M_1)$  plane,  $\mu = 200$  GeV,  $\tan\beta = 10$



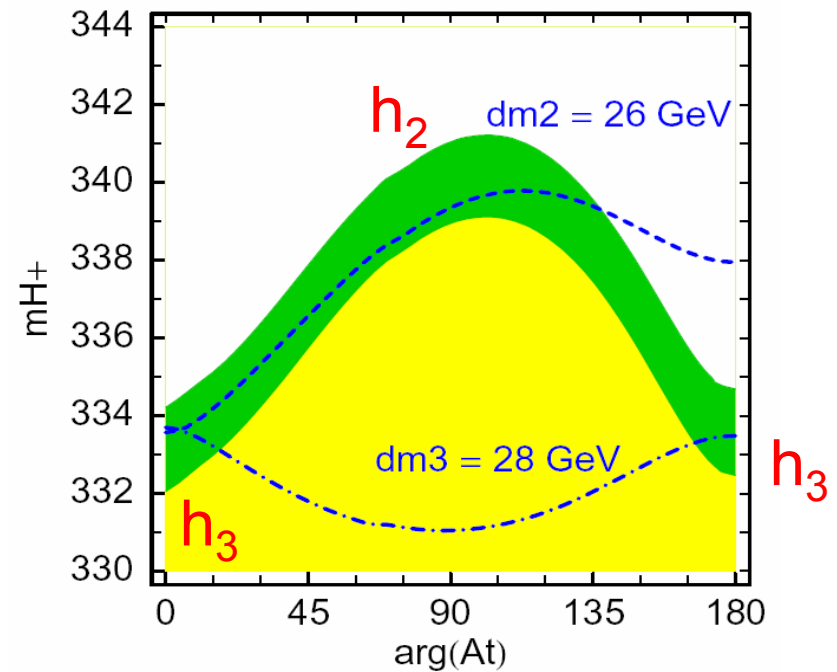
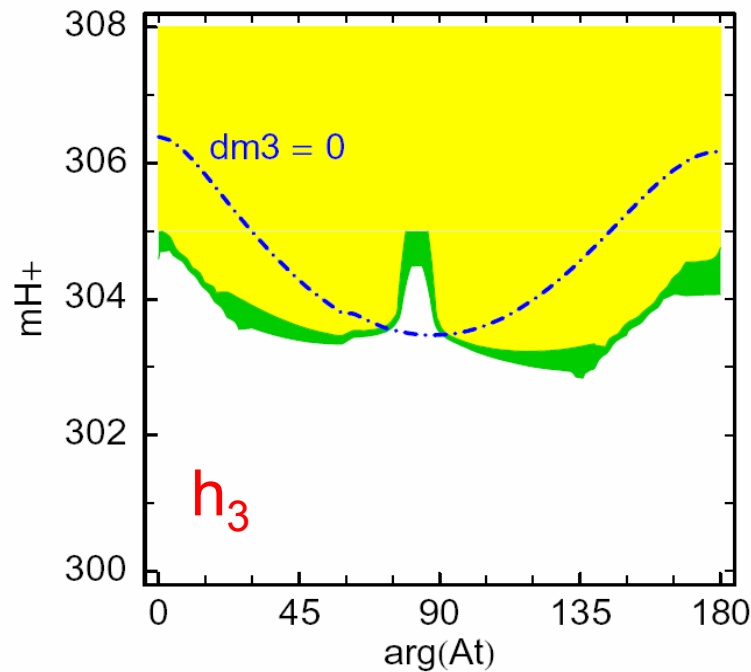
Key parameter is higgsino fraction  $f_h \rightarrow \chi^0 \chi^\pm W$  coupling  
 $f_h$  decreases with  $\arg(M_1)$ , hence  $\Omega h^2$  increases for const  $M_1$

# Disentangling effect on LSP mass




Up to order-of-magnitude effect for constant LSP mass


# Annihilation through Higgs




Green bands:  $0.94 < \Omega h^2 < 0.129$   
 Order-of-magnitude effects due to  $\phi_t$   
 $dm_i = m_{h_i} - 2m_{LSP}, i=2,3$



For a precise prediction of  $\Omega h^2$  we need  
not only precision measurements of  
most of the SUSY spectrum  
but of all the relevant couplings,  
including possible CP phases

- 
- G. Bélanger, F. Boudjema, SK, A. Pukhov and A. Semenov, in: **Les Houches „Physics at TeV colliders“** workshop 2005, BSM working group report, [hep-ph/0602198](https://arxiv.org/abs/hep-ph/0602198), pp.37-44. (analysis of Higgs funnel with CPV)
  - Order-of-magnitude effects on  $\Omega h^2$  due to CP phases
  - Journal publication with general analysis is in preparation

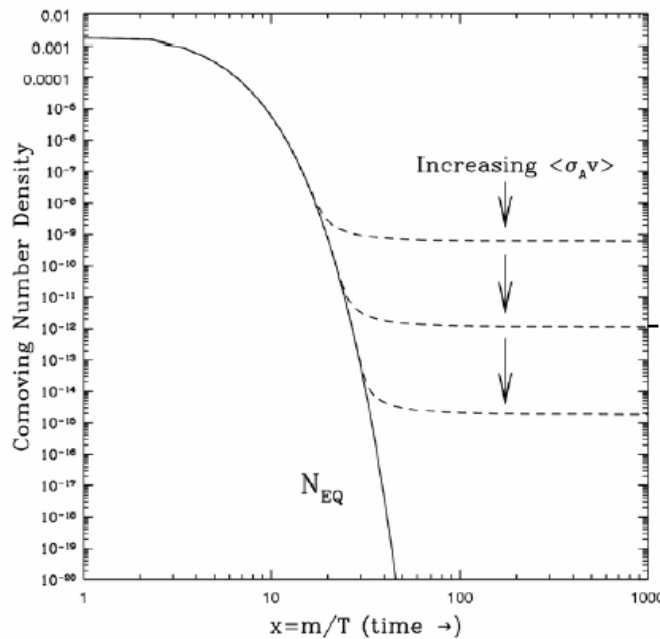


Assume we have found SUSY with  
a neutralino LSP and made very precise  
measurements of all relevant parameters:

What if the inferred  
 $\Omega h^2$  is too high?

# Solution 1: Dark matter is superWIMP

e.g. gravitino or axino



$$\Omega_{\text{superWIMP}} = \frac{m_{\text{superWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$$



Solution 2:

## R-parity is violated after all

- RPV on long time scales
- Late decays of neutralino LSP reduce the number density; actual CDM is something else
- Very hard to test at colliders
- Astrophysics constraints?



Solution 3:

## Cosmological assumptions are wrong

- Our picture of dark matter as a thermal relic from the big bang may be too simple
- Universe after Inflation not radiation dominated
- Reheating temperature below freeze-out temp.
- Non-thermal production?
- Assumptions in WMAP data  $\leftrightarrow \Omega h^2$  ?



# Conclusions:

- We expect **new physics beyond the SM**
  - to show up at the TeV energy scale
  - to provide (part of) the dark matter
- In order to **test a LSP dark matter candidate** at colliders, (infer its relic density) we need **precision measurements**
  - of the sparticle mass spectrum
  - **of all the relevant couplings (!)**
- This also applies for other BSM theories
- In addition, **in/direct detection is indispensable** to pin down the dark matter of the Universe