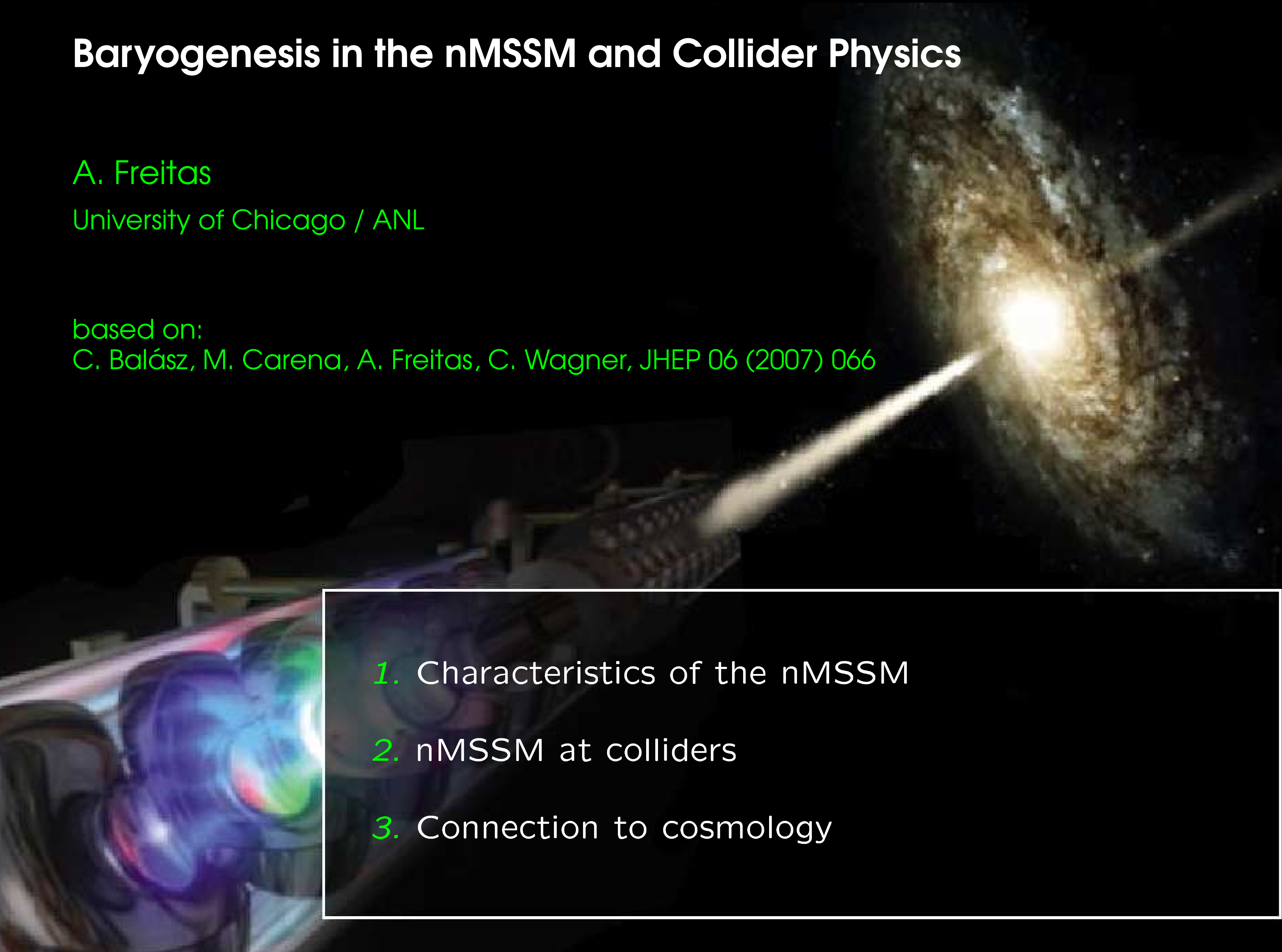
Baryogenesis in the nMSSM and Collider Physics

A. Freitas
University of Chicago / ANL

based on:
C. Balász, M. Carena, A. Freitas, C. Wagner, JHEP 06 (2007) 066



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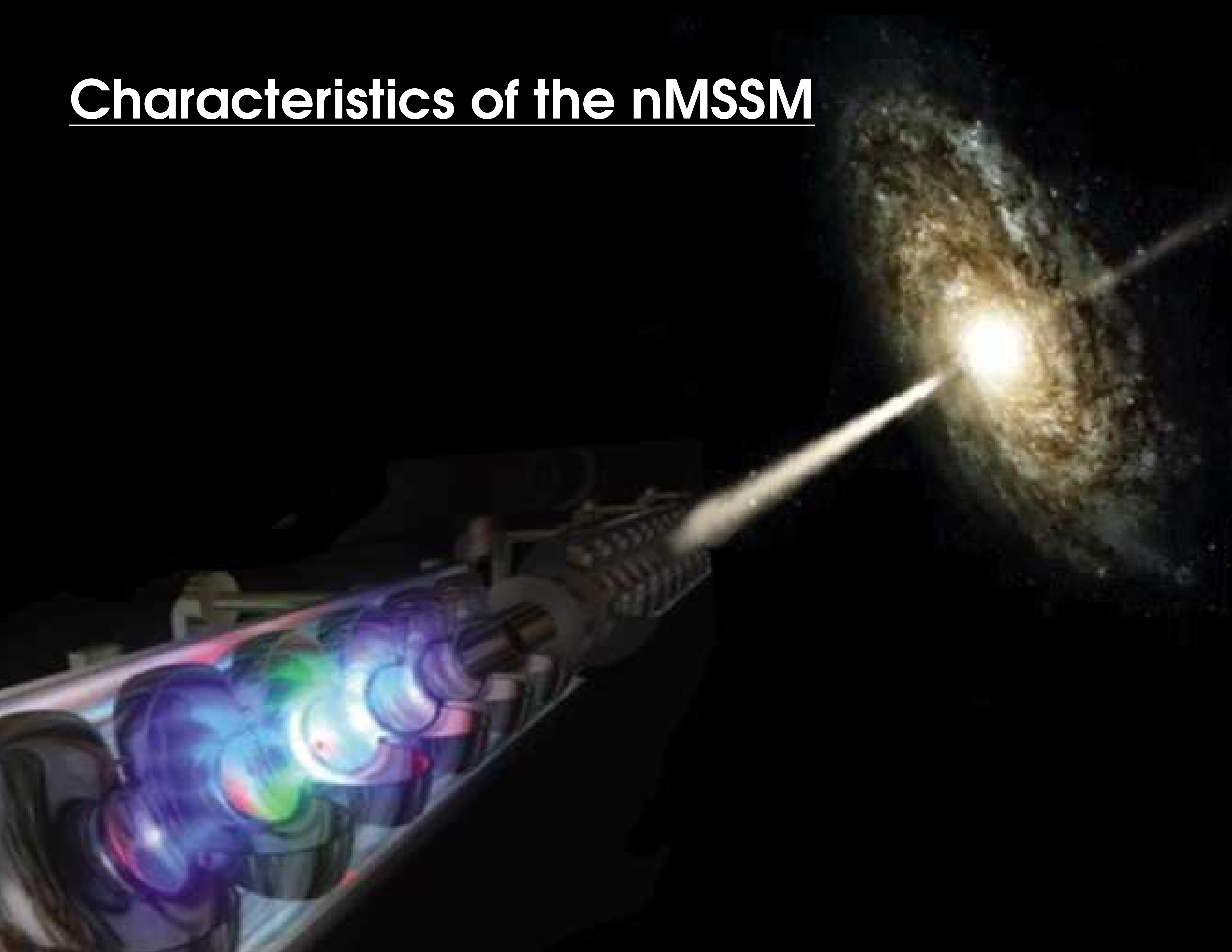
1. Characteristics of the nMSSM
2. nMSSM at colliders
3. Connection to cosmology

Characteristics of the nMSSM



Reminder: Structure of nMSSM

→ talk of D. Morrissey

$$W = \lambda\, \widehat{S}\widehat{H}_1 \cdot \widehat{H}_2 + m_{12}^2/\lambda\, \widehat{S} + \text{ Yukawa terms}$$

$$\mathcal{L}_{\text{soft}} = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_s^2 |S|^2 + (t_s S + a_\lambda S H_1 \cdot H_2 + \text{h.c.})$$
$$+ \text{ gaugino and sfermion terms}$$

- Solve μ-problem:

Effective μ-term through VEV of S: $\mu_{\text{eff}} = -\lambda\langle S\rangle$

- Evade LEP-Higgs bounds

λ coupling allows heavier CP-even Higgs masses than MSSM

$$m_{\text{h}}^2 \leq M_{\text{Z}}^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)$$

- Strong 1st order electroweak phase transition

Triple-Higgs coupling λ already at tree-level

Parameter space

Menon, Morrissey, Wagner '04

Lightest neutralino $\tilde{\chi}_1^0$ is mainly singlino and $m_{\tilde{\chi}_1^0} \sim M_\mathsf{Z}/2$

Electroweak symmetry breaking: $m_{12} \to M_\mathsf{A}$, $m_s \to v_s = \langle S \rangle$

Constraints from CDM density and LEP force

$$\tan\beta \sim \mathcal{O}(1) \qquad \lambda = 0.5...0.8 \qquad |\mu| = |\lambda v_s| = 100...350\ \text{GeV}$$

(upper bound on λ from perturbativity)

Requirement of strong electroweak phase transition for baryogenesis

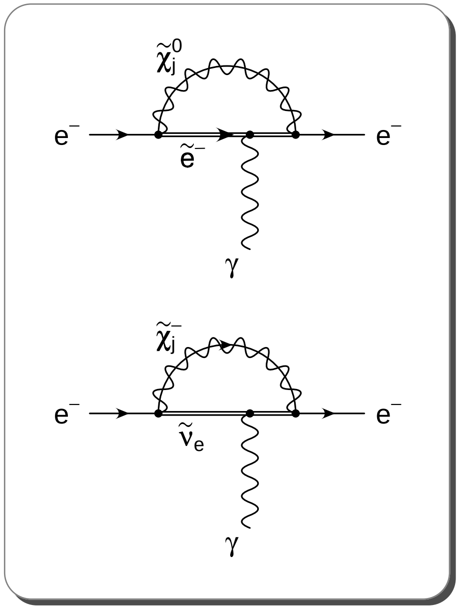
$$a_\lambda = 300...600\ \text{GeV} \qquad t_s = (50...200\ \text{GeV})^3$$

Typical parameter point:

$$v_s = -384\ \text{GeV} \qquad a_\lambda = 373\ \text{GeV} \qquad \tan\beta = 1.7 \qquad \lambda = 0.62$$

$$t_s = (157\ \text{GeV})^3 \qquad M_\mathsf{A} = 923\ \text{GeV} \qquad |M_2| = 245\ \text{GeV} \qquad \phi_{\mu M_2} = 0.14$$

Spectrum



- 1st/2nd gen. sfermions heavy (few TeV) to avoid EDM constraints

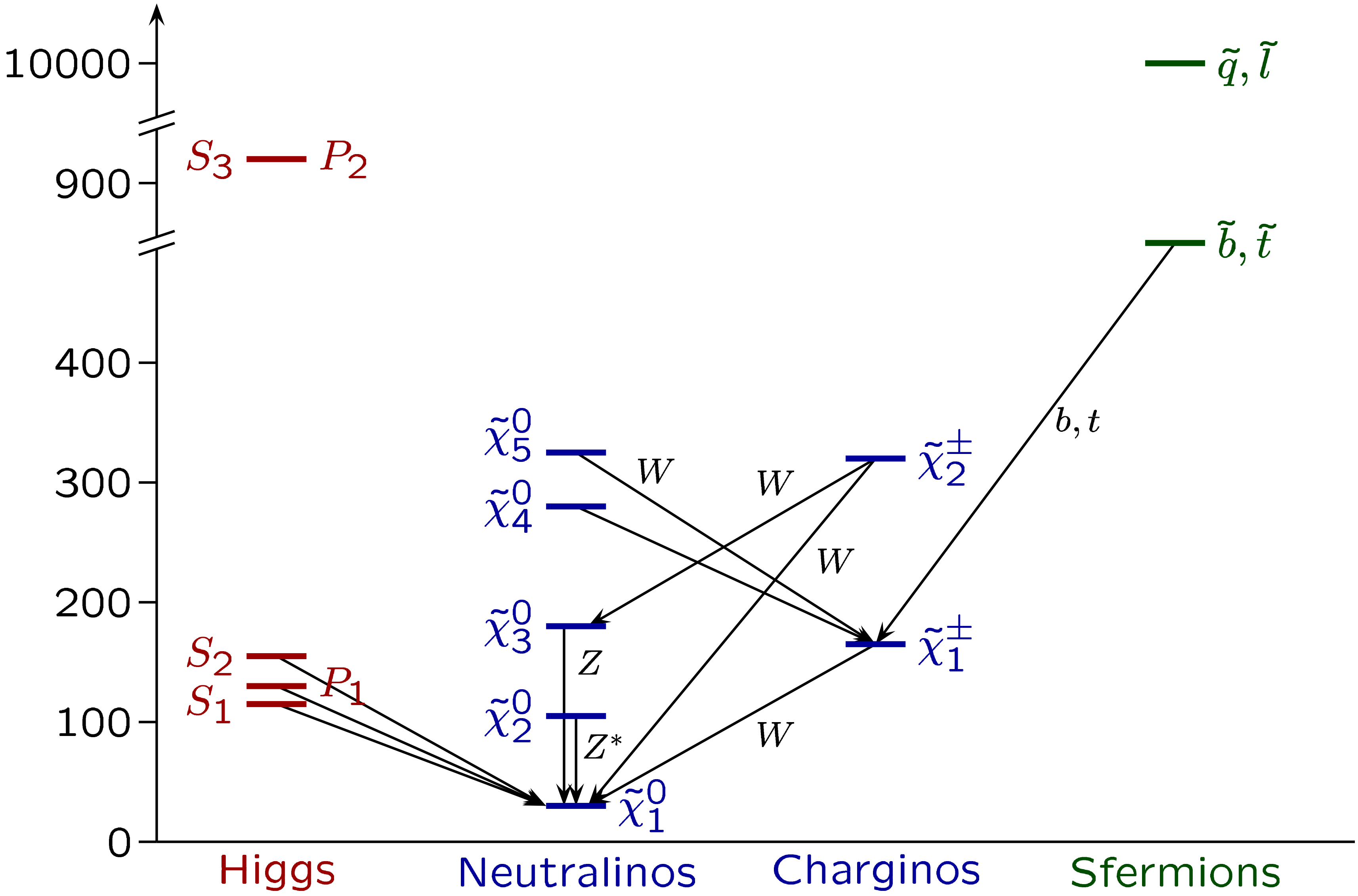
- 3rd generation sfermions at ~ 500 GeV
  for baryogenesis and Higgs naturalness

- All neutralinos/charginos have $m < 500$ GeV
  Mainly decay through gauge bosons

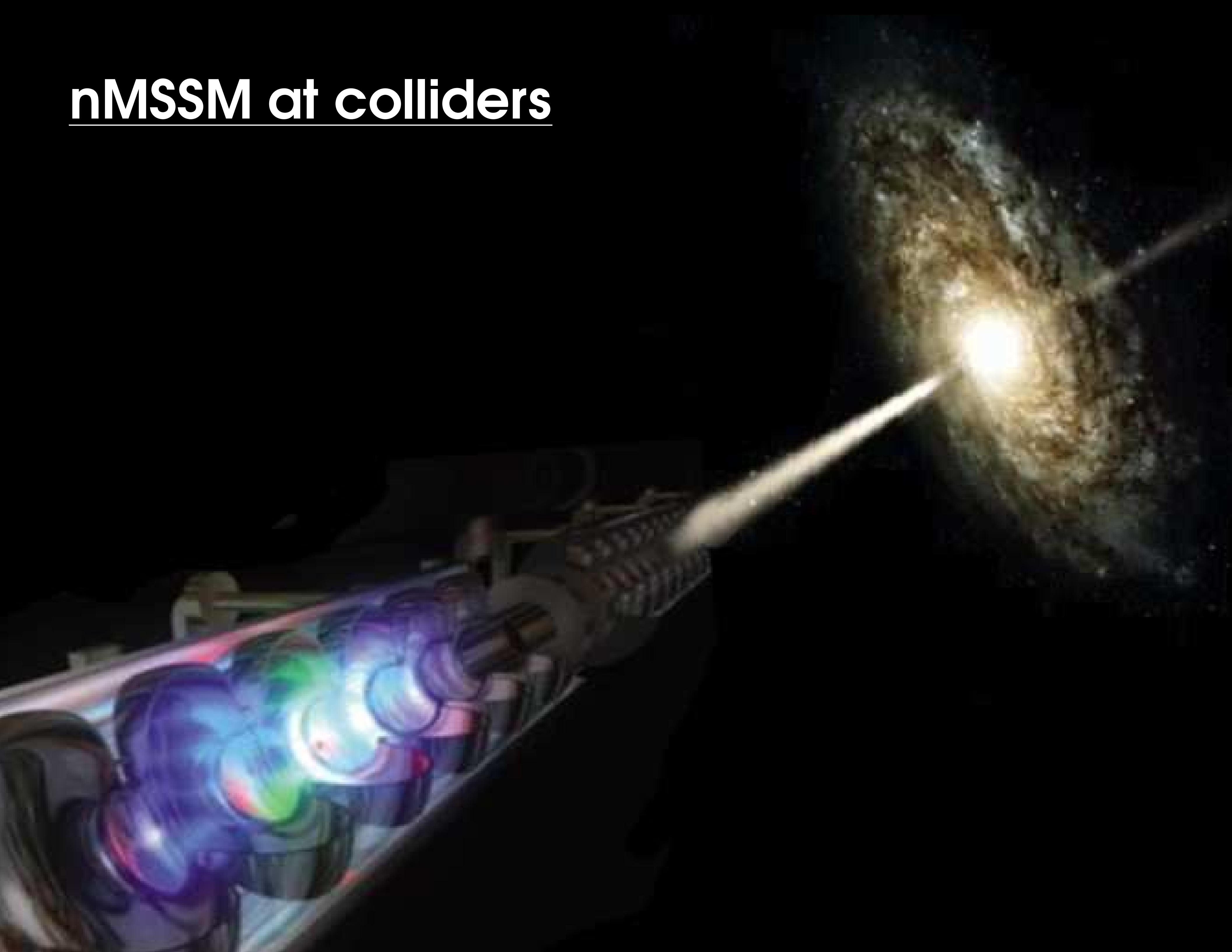
- 3 CP-even Higgs states $S_{1,2,3}$
  2 CP-odd Higgs states $P_{1,2}$

- Light Higgses have large coupling λ to singlet
  $\rightarrow$ BR$(S_1, S_2, P_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 90\%$

Spectrum


10000
900
400
300
200
100
0
$\tilde{q}, \tilde{l}$
S_3
P_2
$\tilde{b}, \tilde{t}$
b, t
$\tilde{\chi}_5^0$
W
W
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_4^0$
W
$\tilde{\chi}_3^0$
$\tilde{\chi}_1^\pm$
Z
S_2
P_1
S_1
$\tilde{\chi}_2^0$
Z^*
W
$\tilde{\chi}_1^0$
Higgs
Neutralinos
Charginos
Sfermions

nMSSM at colliders



nMSSM at LHC

- Invisible Higgs(es) can be seen, but mass measurement difficult

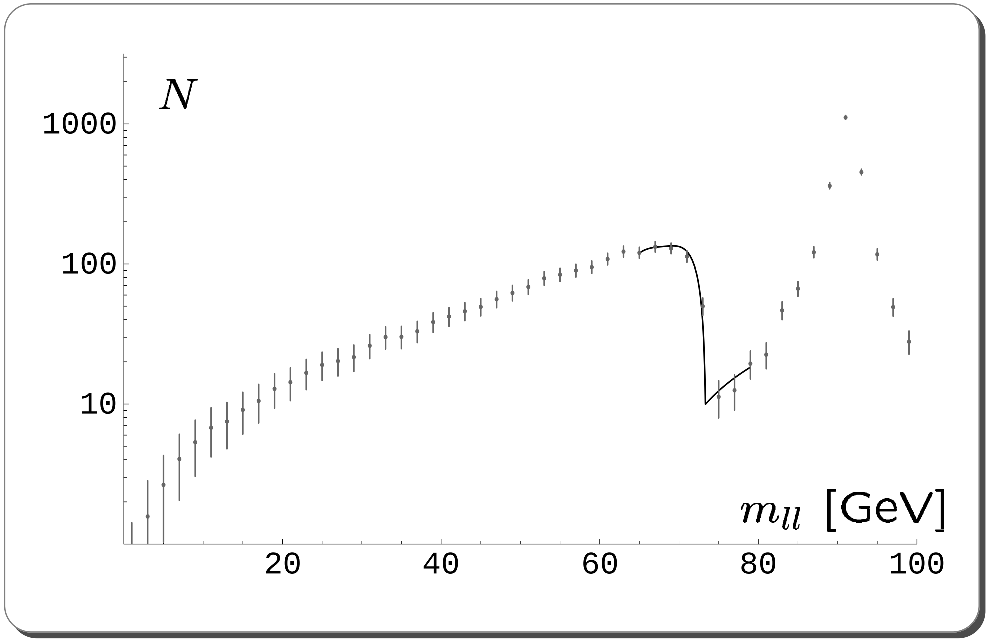
Choudhury, Roy '94
Eboli, Zeppenfeldt '00

- Neutralinos produced in stop/sbottom cascades

  e.g. $\tilde{g} \to b\,\tilde{b}^* \to b\bar{b}\,\tilde{\chi}_2^0 \to b\bar{b}\,l^+l^-\,\tilde{\chi}_1^0$

Mass measurements in invariant mass distributions

→ Good determination of mass differences



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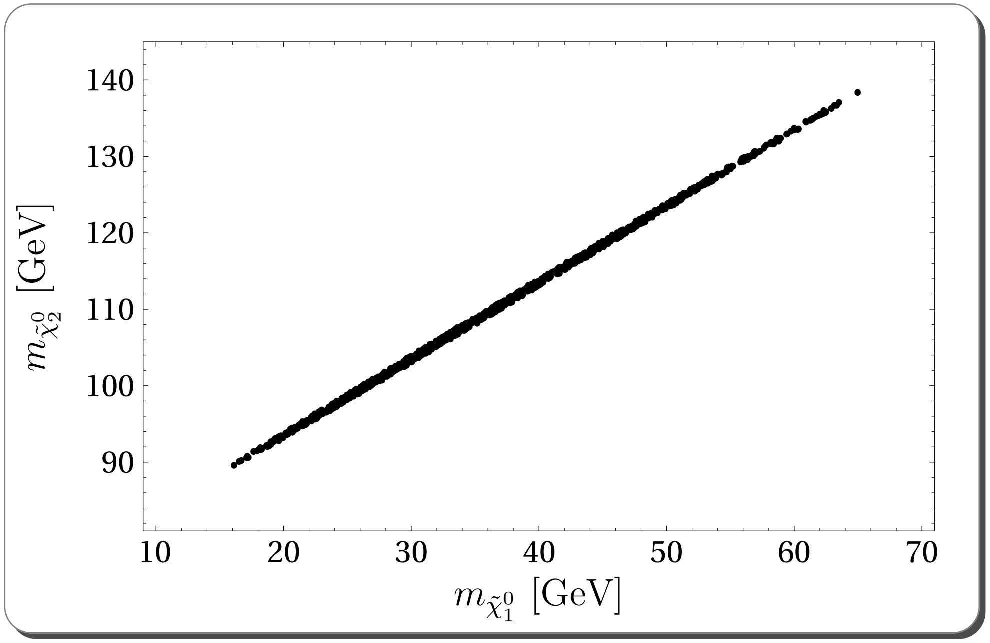
Mass measurements in invariant mass distributions

→ Good determination of mass differences

→ Poor determination of abolute masses

Typical errors for $m_{\tilde{\chi}^0_{1,2,3}}$:

20–30 GeV



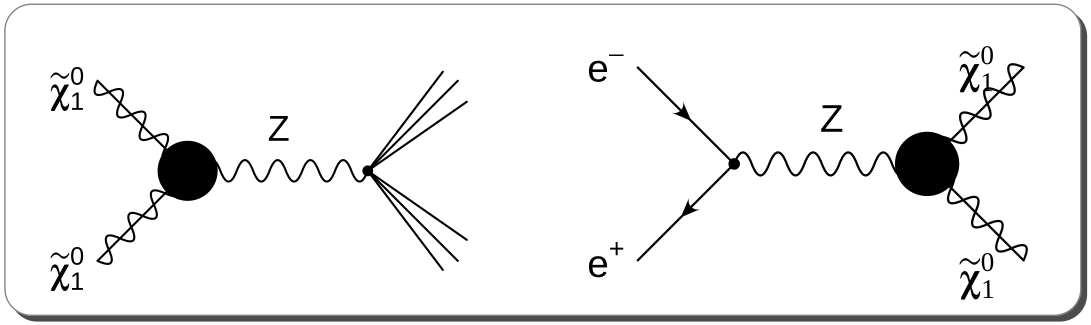
nMSSM at GigaZ

Since $m_{\tilde{\chi}_1^0} < M_Z/2$, constraints can be obtained from ILC at Z- pole

Carena, Freitas, de Gouvêa, Schmitt '03

Dark matter annihilation proceeds through s-channel Z-exchange

- Model-independent information



- Poor precision $\sim$ 60%
  (LEP constraints do not leave much room)

nMSSM at ILC

- Two (invisible) scalar Higgs bosons S_1 and S_2 can be found and measured through $e^+e^- \to Z\,S_k$
Branching fraction give estimate of Higgs selfcoupling λ

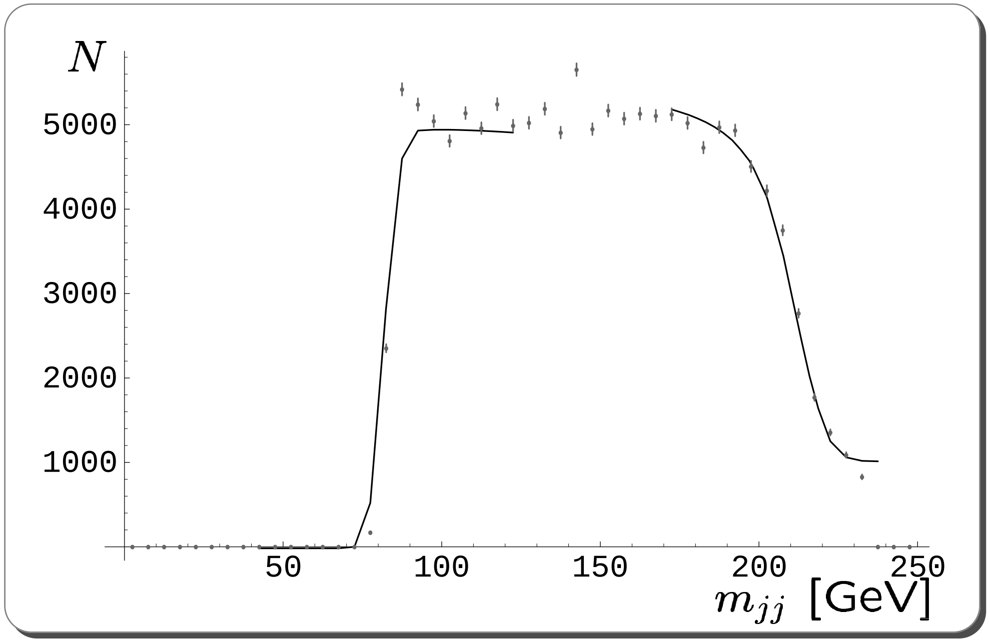
- Many SUSY particles could be discovered at 500 GeV ILC

- Reduction of SM backgrounds possible with few cuts

- Sparticle mass determination from kinematic edges

Ex.: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \quad \tilde{\chi}_1^+ \to W^+\tilde{\chi}_1^0 \to jj\,\tilde{\chi}_1^0$

$$E_{\text{min,max}} = \frac{1}{4m^2_{\tilde{\chi}_1^\pm}}\Big[(m^2_{\tilde{\chi}_1^\pm} - m^2_{\tilde{\chi}_1^0} + M^2_{\text{W}})\sqrt{s} \mp \sqrt{\lambda(m^2_{\tilde{\chi}_1^\pm}, m^2_{\tilde{\chi}_1^0}, M^2_{\text{W}})(s - 4m^2_{\tilde{\chi}_1^\pm})}\Big]$$



nMSSM at ILC

- At ILC with $\sqrt{s} = 500$ GeV charginos and neutralinos can be precisely measured (similar to MSSM)

	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$
m	33	107	182	278	165	320 GeV
δm	0.4	1.2	5	3.5	0.05	5.5 GeV

Discovery of two neutralino states with $m_{\tilde{\chi}_{1,2}^0} \ll m_{\tilde{\chi}_1^\pm}$ immediately tells $>$ MSSM

- Allows extraction of fundamental parameters and test of CDM and baryogenesis hypotheses

Interpretation of results

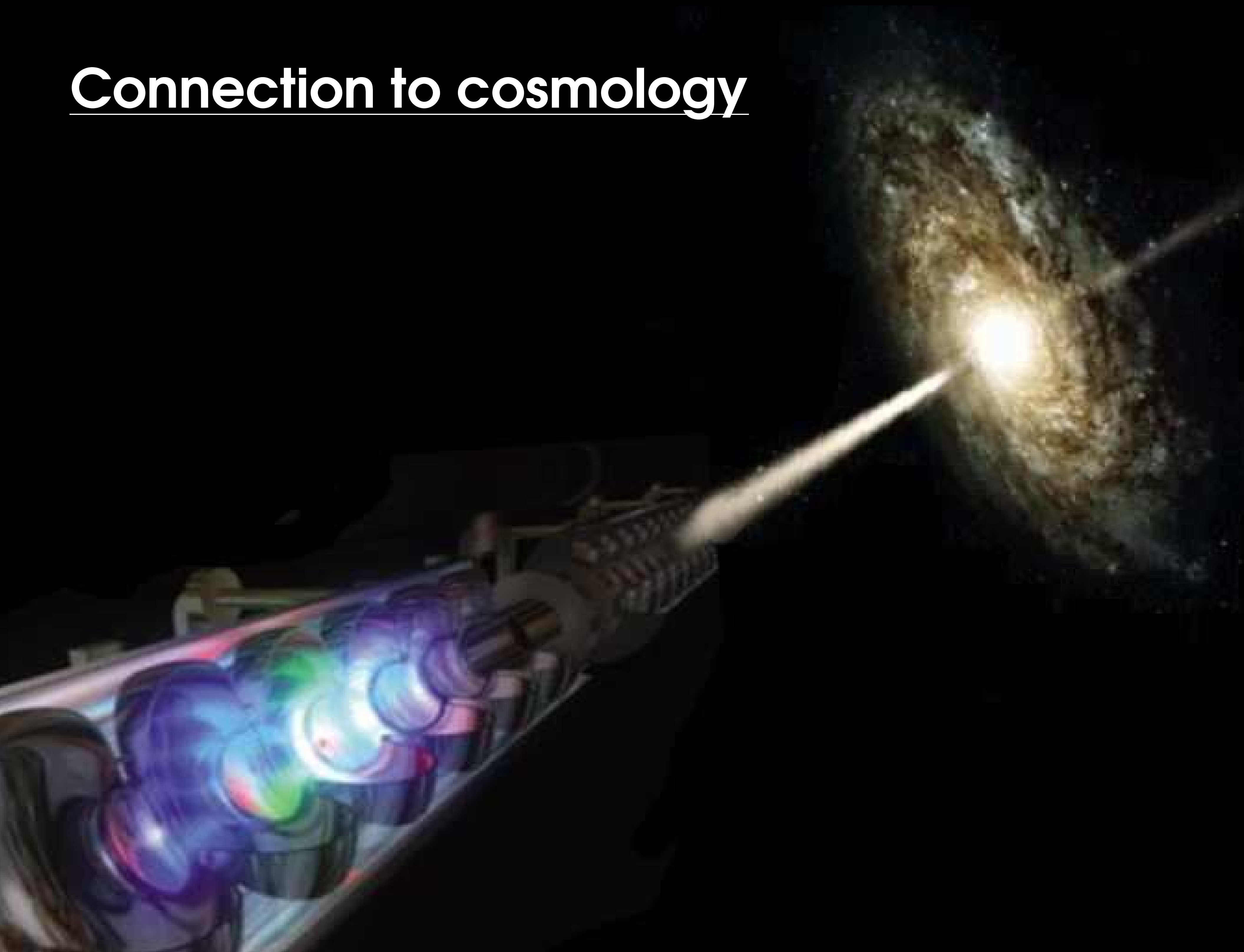
Fundamental parameters from neutralino/chargino maesurements:

$$
\begin{array}{lll}
M_1 = (122.5 \pm 1.3)\ \text{GeV}, & |\kappa| < 2.0\ \text{GeV}, & m_{\tilde{\nu}_e} > 5\ \text{TeV}, \\
M_2 = (245.0 \pm 0.7)\ \text{GeV}, & \tan\beta = 1.7 \pm 0.09, & m_{\tilde{e}_R} > 1\ \text{TeV}. \\
|\lambda| = 0.619 \pm 0.007, & |\phi_M| < 0.32, & \\
v_s = (-384 \pm 4.8)\ \text{GeV}, & &
\end{array}
$$

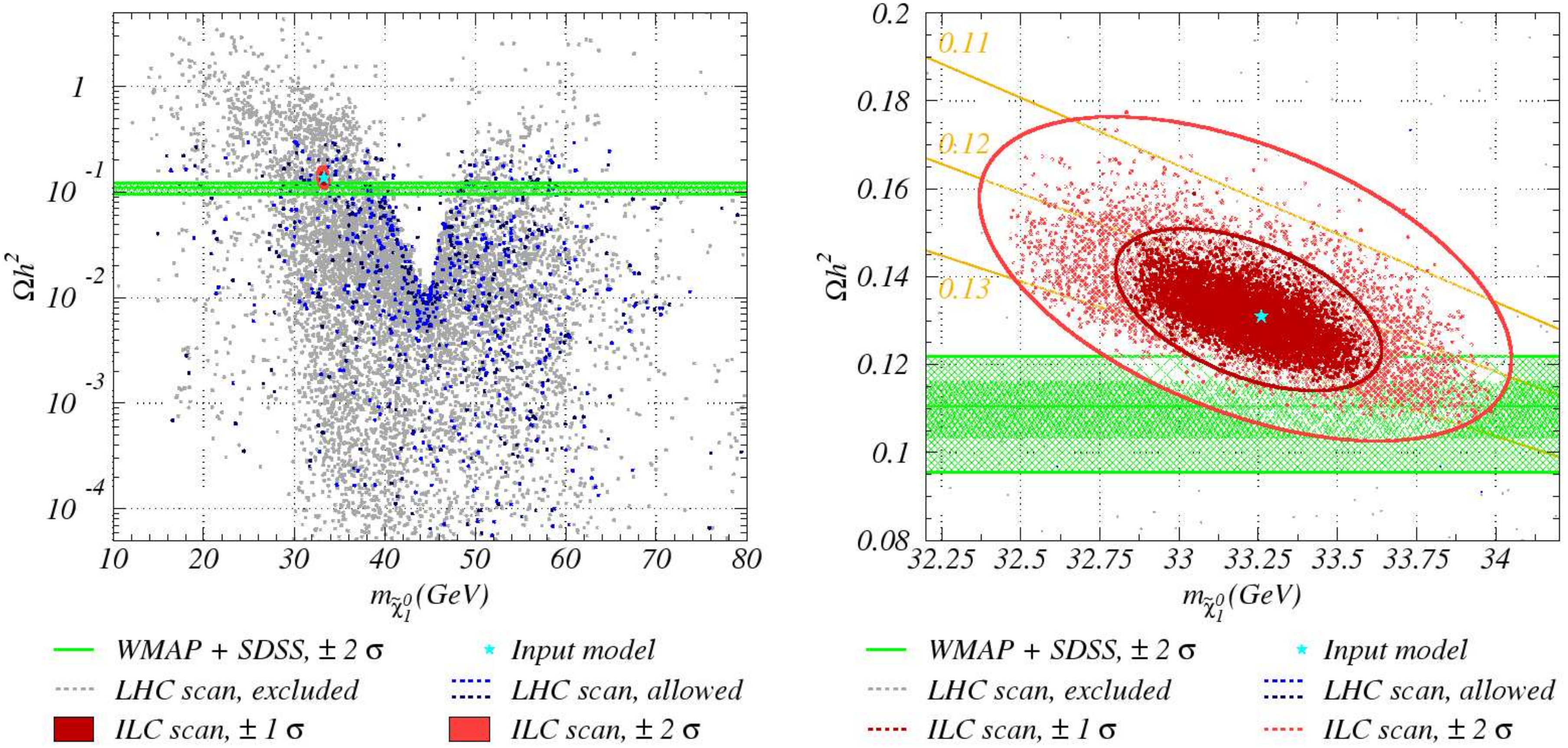
- Higgs triple coupling can be measured precisely
- Absence of cubic singlet self-coupling can be tested
  (nMSSM ↔ NMSSM)

$$
M_{\tilde{\chi}^0} = \begin{pmatrix}
M_1 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\
0 & M_2 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\
\mathcal{O}(v) & \mathcal{O}(v) & 0 & \boldsymbol{\lambda} v_s & \mathcal{O}(v) \\
\mathcal{O}(v) & \mathcal{O}(v) & \boldsymbol{\lambda} v_s & 0 & \mathcal{O}(v) \\
0 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & \boldsymbol{\kappa}
\end{pmatrix}
$$

Connection to cosmology

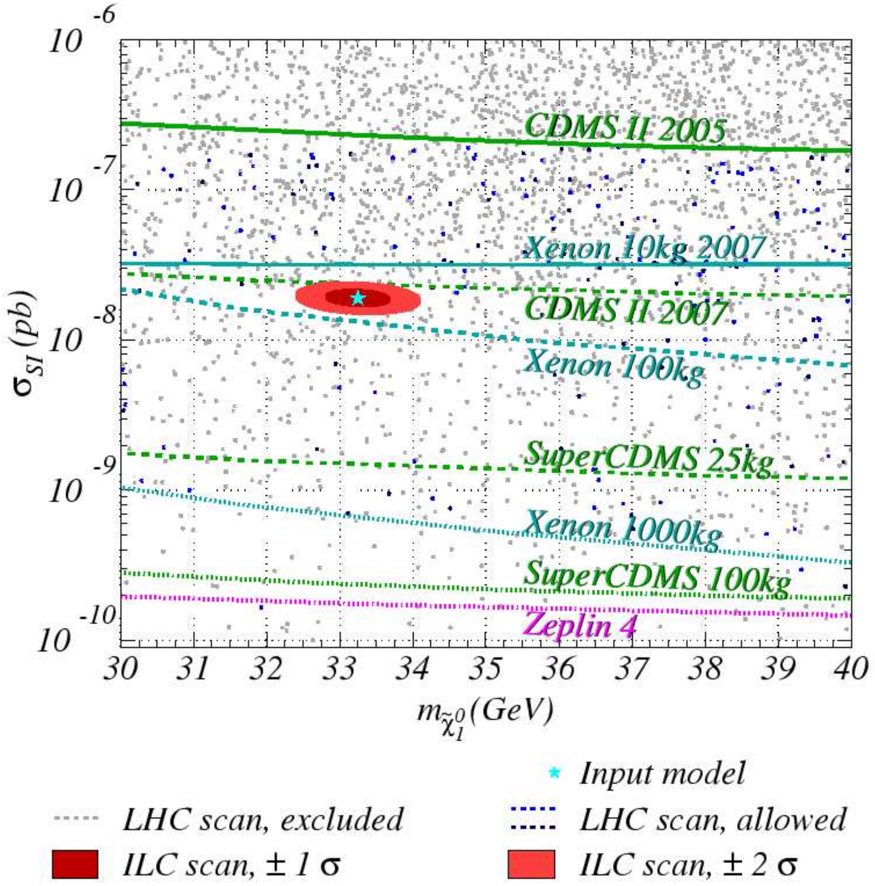


Dark matter density projection from simulation



- LHC does not tell much
- ILC allows computation with precision comparable to WMAP

Direct detection



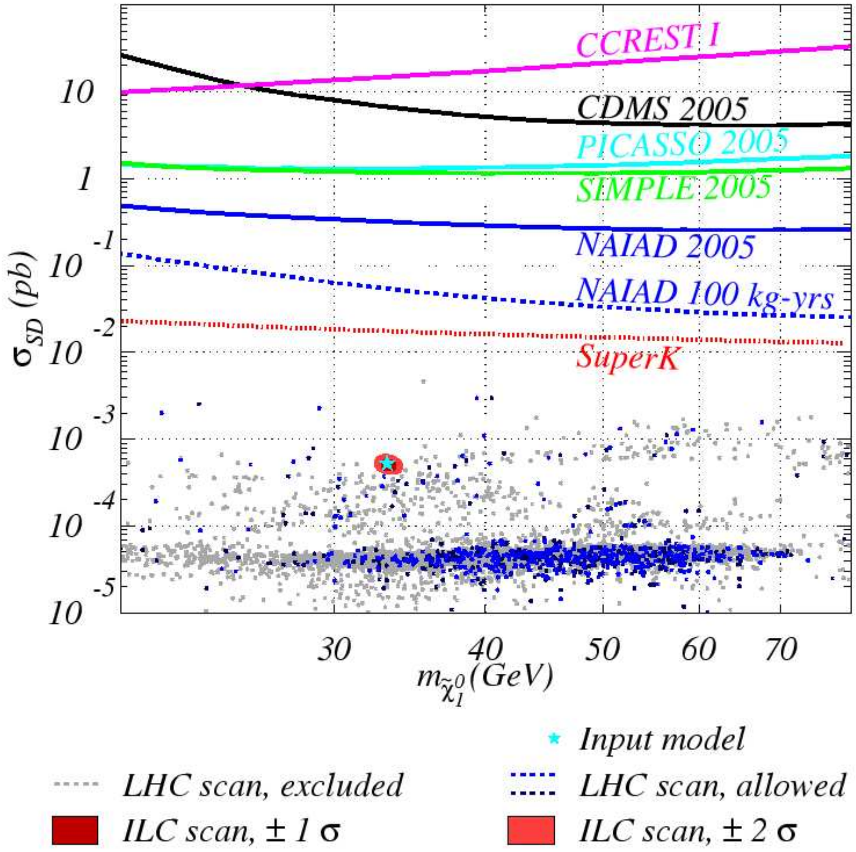
- Large singlino component of $\tilde{\chi}_1^0$:

  Spin-independent cross-section is sizeable due to singlet-Higgs coupling λ

  Spin-dependent cross-section is very small

- Next generation SI experiments can probe this scenario

Direct detection



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Testing electroweak baryogenesis

- Neutralino/chargino parameters allow to extract some parameters

- More information from Higgs masses:

  $M_{S1} = 115.2 \pm 0.13$ GeV, $M_{S2} = 156.6 \pm 0.19$ GeV

- Mass matrix of CP-even Higgs bosons gets large corrections:

$$M_S^2 = M_{S,\text{tree}}^2 + \Delta M_S^2$$

  Leading contributions from $t/\tilde{t}$ loops, e.g.

$$\Delta M_{S,11}^2 \approx \frac{3}{8\pi^2} \frac{m_\text{t}^4}{v^2} \log \frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_\text{t}^4}$$

  In general very complicated, depends on stop mixing, A_t

- Assumptions: $\delta m_{\tilde{t}} = 50$ GeV (no simulations for LHC available)
  $A_\text{t} \lesssim 500$ GeV (from small stop mass difference)

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Parameter	Input value	Expected constraints from ILC	Range preferred by baryogenesis
m_s	106.5 GeV	$88 < m_s < 122$	$50 \lesssim m_s \lesssim 200$
a_λ	373 GeV	$352 < a_\lambda < 390$	$300 \lesssim a_\lambda \lesssim 600$
$t_s^{1/3}$	157 GeV	$117 < t_s^{1/3} < 181$	$50 \lesssim t_s^{1/3} \lesssim 200$

- Constraints from experiment not very precise
  (mainly from loop corrections)
  but sufficient to test conditions for EWBG

Conclusions

- Baryogenesis and dark matter within the nMSSM lead to strong constraints on the parameters space
- This scenario will be testable at the LHC and ILC
- The LHC would be able to rule out EWBG in the nMSSM
- Precision measurements at the ILC can
  - distinguish nMSSM from MSSM
  - test the validity of SUSY dark matter accurately
  - explore the electroweak phase transistion quantitatively