Connections between colliders and cosmology in the nMSSM

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

What comes next? - The nMSSM, colliders and cosmology

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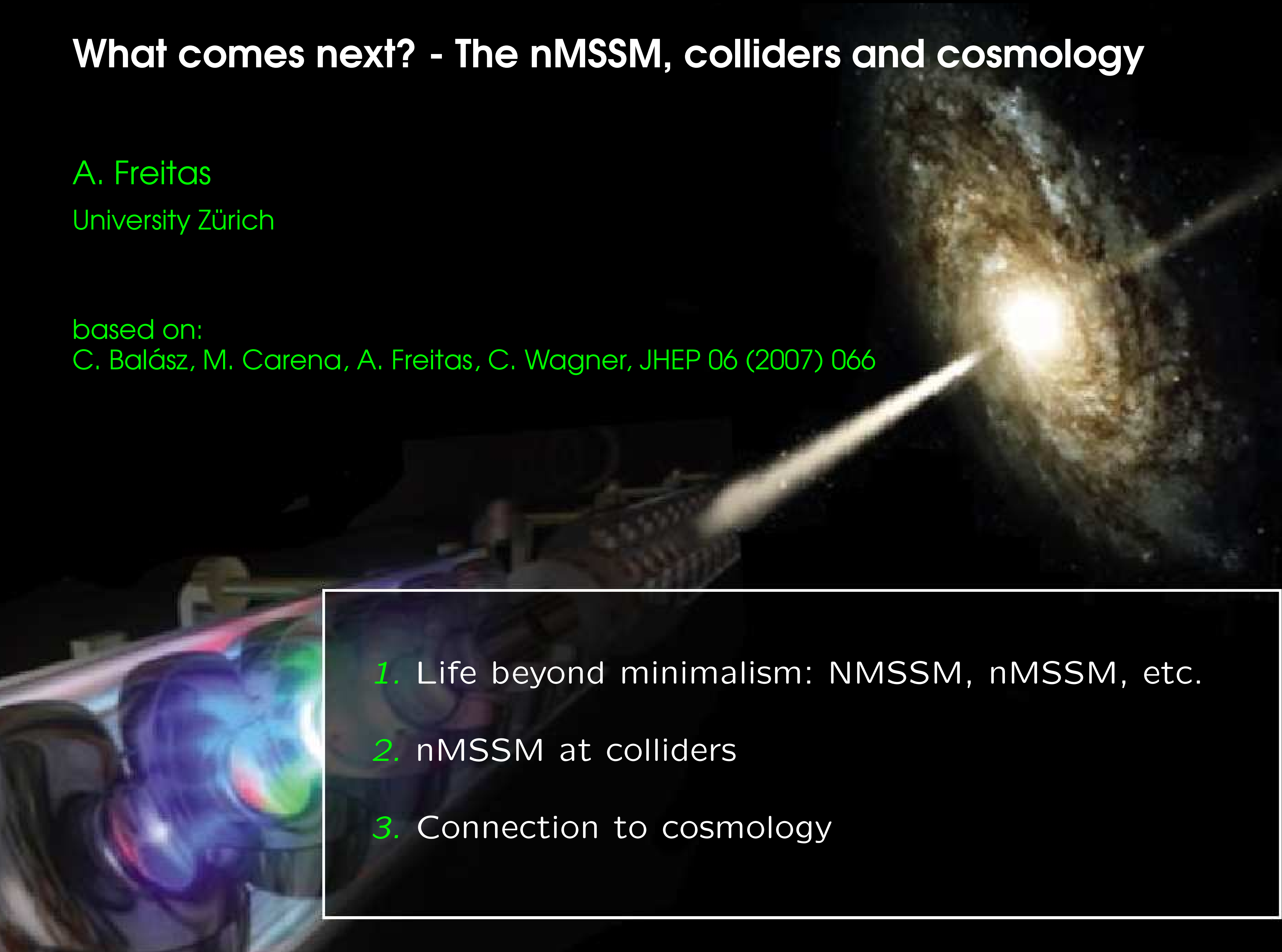
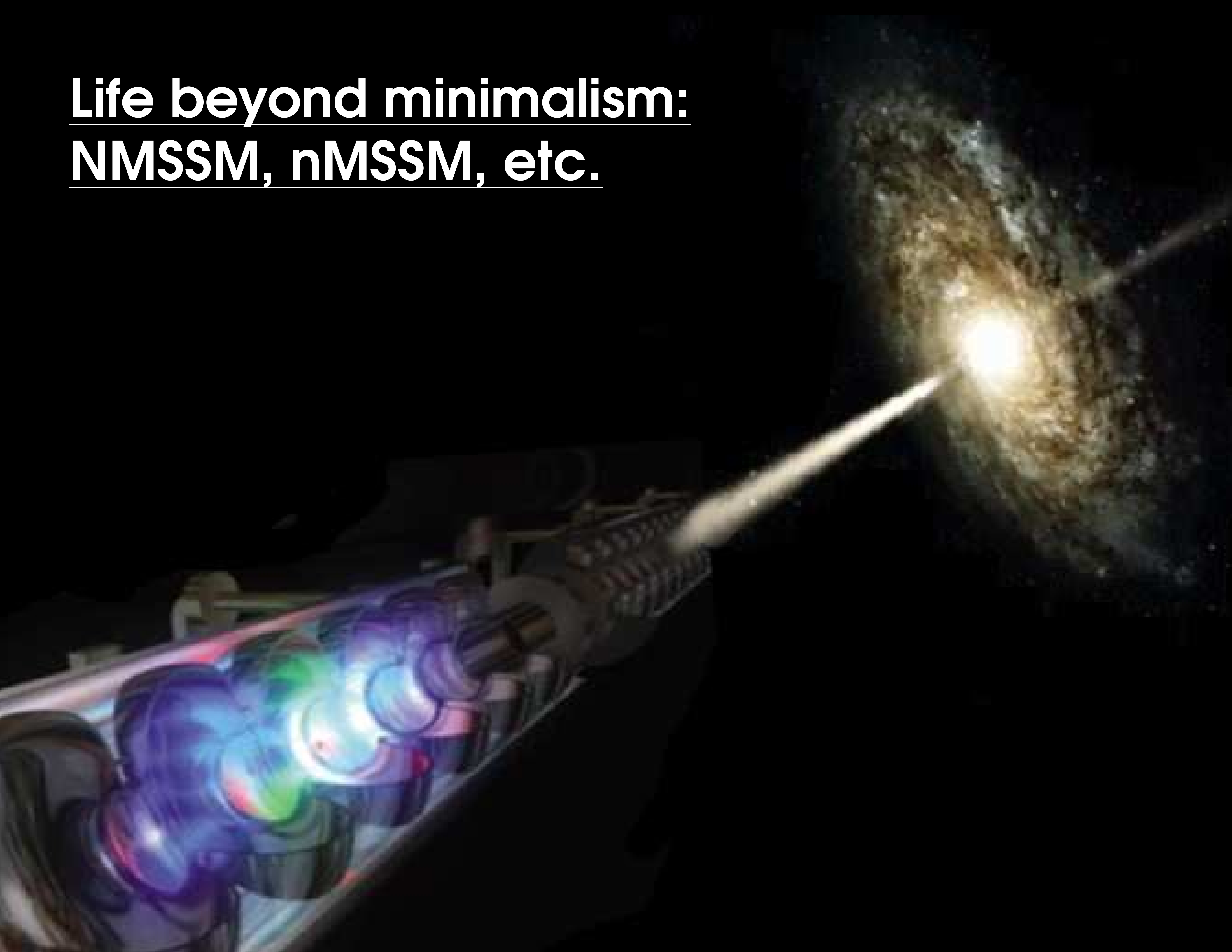


1. Life beyond minimalism: NMSSM, nMSSM, etc.
2. nMSSM at colliders
3. Connection to cosmology

Life beyond minimalism: NMSSM, nMSSM, etc.



MSSM with additional singlet

$$W = \lambda \, \widehat{S} \widehat{H}_1 \cdot \widehat{H}_2 + \kappa \, \widehat{S}^3 + m_{\mathrm{N}} \, \widehat{S}^3 + m_{12}^2 / \lambda \, \widehat{S} + \text{ Yukawa terms}$$

- Solve μ-problem:

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

- Evade LEP-Higgs bounds

λ coupling allows heavier CP-even Higgs masses than MSSM

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

- Strong 1st order electroweak phase transition

Triple-Higgs coupling λ already at tree-level

Electroweak Baryogenesis

Sakharov conditions:

	SM	**NMSSM**
Baryon number violation	Non-perturbative sphaleron processes	
C and CP violation	CKM phase $\to$ too small	Soft SUSY breaking e.g. gaugino masses M_i
Non-equilibrium	Strong electroweak phase transition only for $M_{\mathrm{H}} \lesssim 40$ GeV	also for $M_{\mathrm{H}} > 100$ GeV due to Higgs self-coupl.

NMSSM vs. nMSSM

Panagiotakopoulos, Tamvakis '99

$$W = \lambda \, \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \kappa \, \hat{S}^3 + m_{\rm N} \, \hat{S}^3 + m_{12}^2/\lambda \, \hat{S} + \text{ Yukawa terms}$$

NMSSM	nMSSM
$\mathbb{Z}_3 \subset U(1)_{\rm PQ}$ symmetry	$\mathbb{Z}_5^{\rm R}$ or $\mathbb{Z}_7^{\rm R}$ symmetry
$m_{\rm N} = 0$, $m_{12} = 0$	$m_{\rm N} = 0$, $\kappa = 0$
	m_{12} at higher loop order
Domain walls from $\langle S \rangle$	Subgroups of $U(1)_{\rm PQ}$ broken by m_{12}

- New parameters in nMSSM compared to MSSM:

Superpotential	SUSY breaking	Higgs states
λ	a_λ	
m_{12}	t_s	$m_{12} \to M_{\rm A}$
	m_s^2	$m_s \to v_s = \langle S \rangle$

Dark matter and nMSSM

With **R-parity** conservation LSP becomes stable

In nMSSM LSP is lightest neutralino $\tilde{\chi}_1^0$
$\longrightarrow$ good **dark matter** candidate

- In nMSSM $\tilde{\chi}_1^0$ is mainly singlino and $m_{\tilde{\chi}_1^0} < M_Z$

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

- $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling suppressed $\longrightarrow$ Evade LEP1 bounds

- For $m_{\tilde{\chi}_1^0} \sim M_Z/2$: efficient annihilation through Z resonance
  $\longrightarrow$ Good agreement with observed Ω_{CDM}

nMSSM and baryogenesis

Menon, Morrissey, Wagner '04

Lightest neutralino $\tilde{\chi}_1^0$ is mainly singlino and $m_{\tilde{\chi}_1^0} \ll M_Z$

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

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

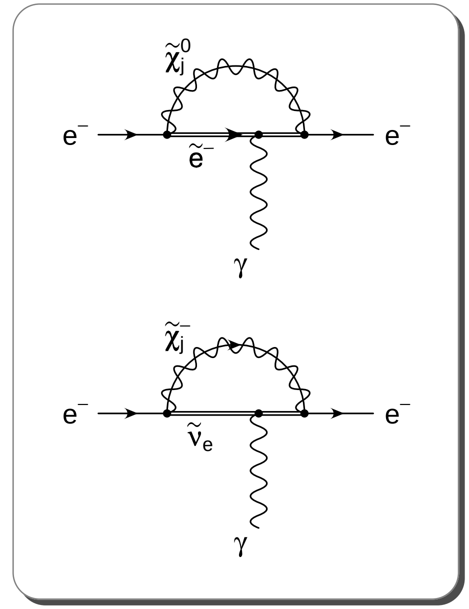
Typical parameter point:

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

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

Spectrum

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



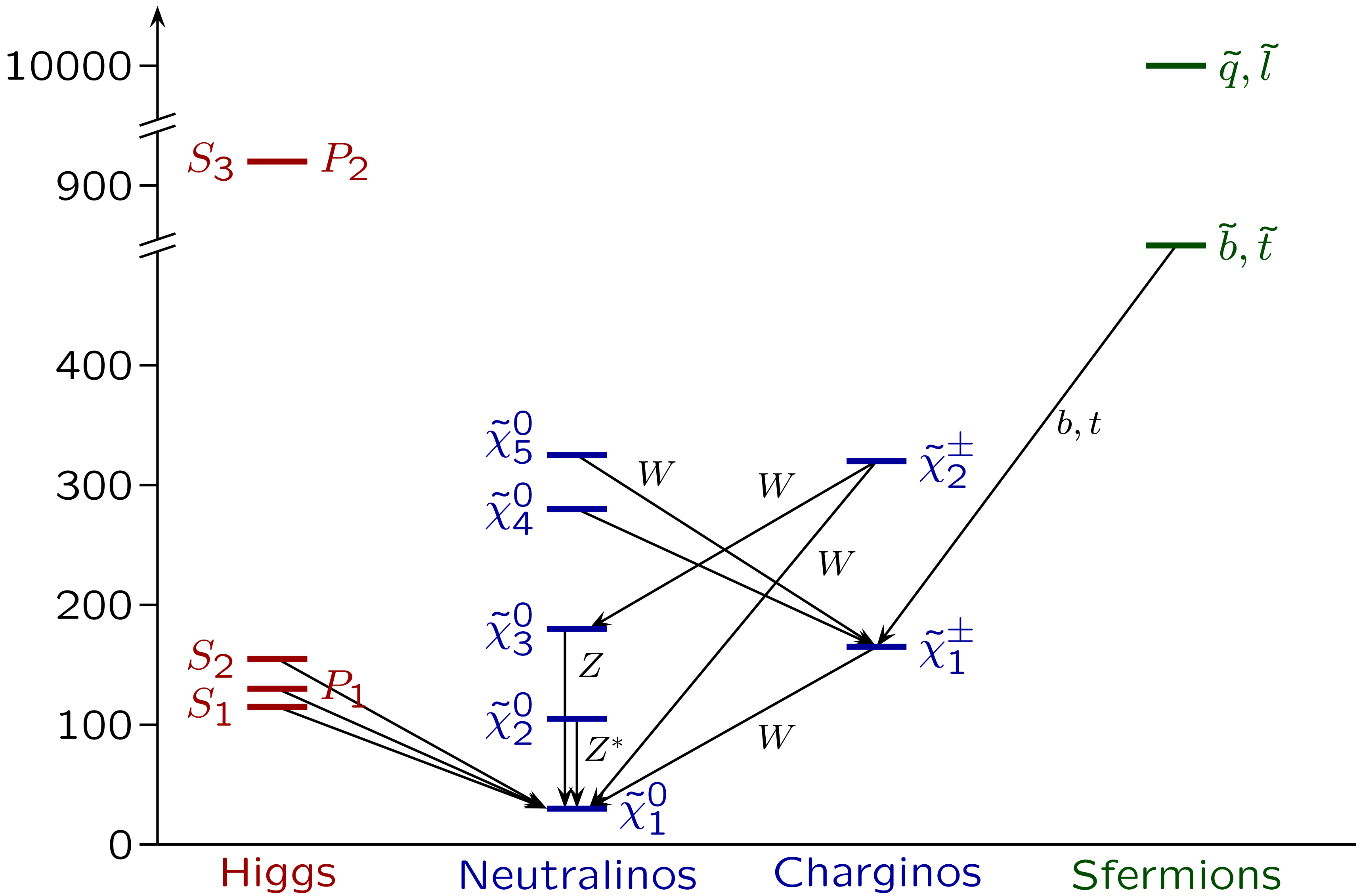
- 3rd generation sfermions at ~ 500 GeV
  for baryogenesis and Higgs naturalness

- 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 $P_{1,2}$

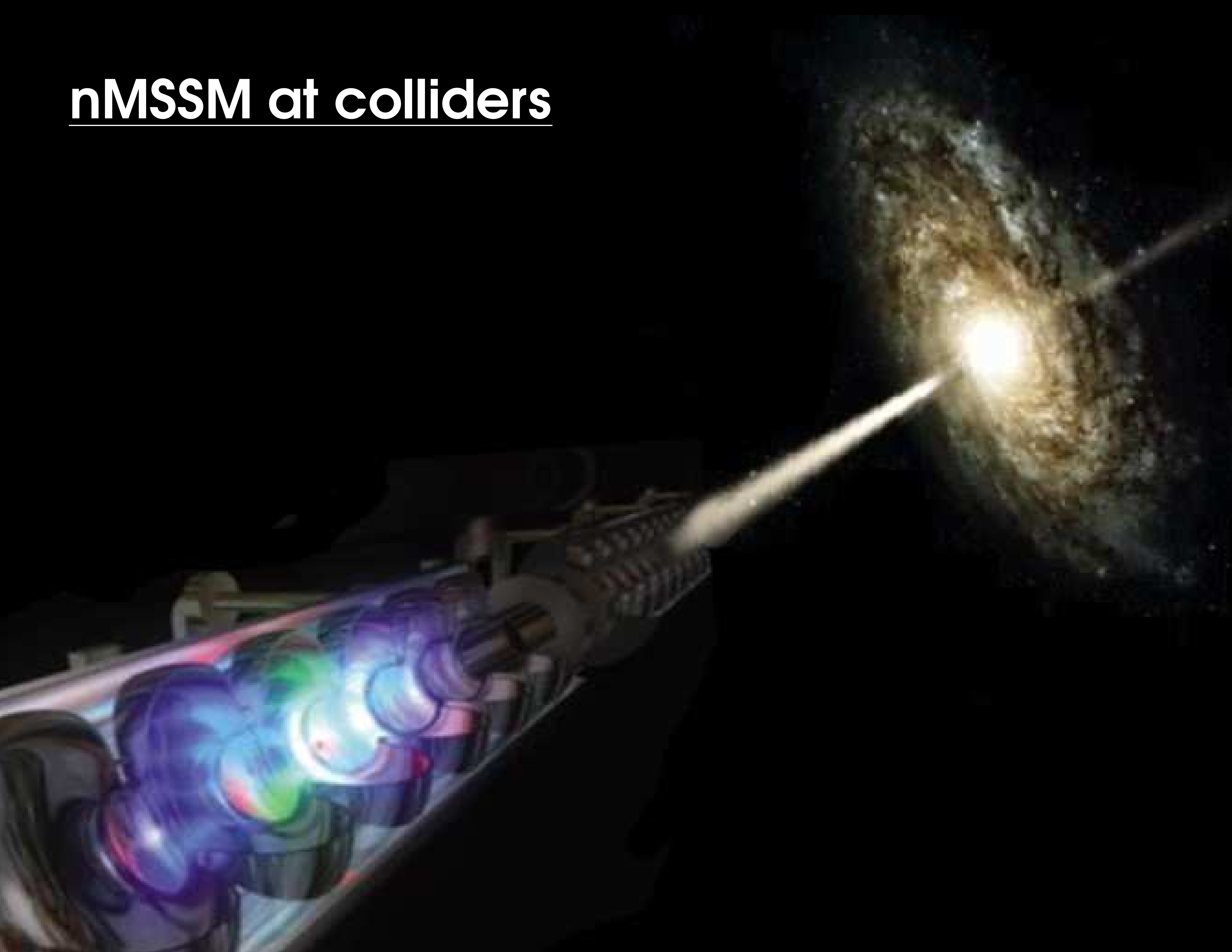
- Light Higgses have large coupling λ to singlet
  $\rightarrow$ BR$(S_1, S_2, P_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 90\%$

Spectrum



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

nMSSM at colliders



nMSSM at LHC

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

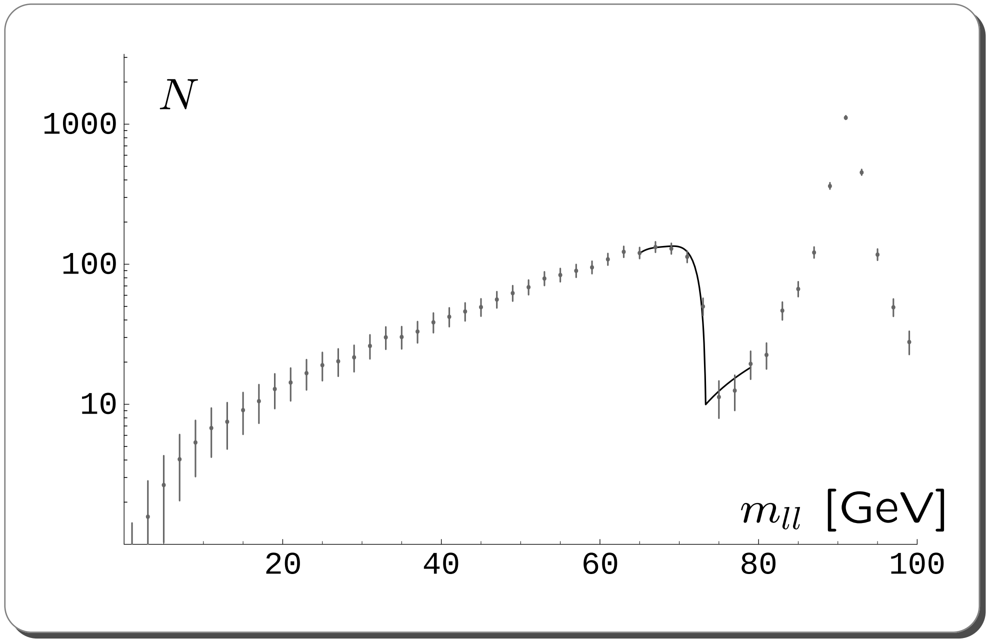
  Choudhury, Roy '94
  Eboli, Zeppenfeldt '00

- Neutralinos produced in stop/sbottom cascades

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

Mass measurements in invariant mass distributions

$\longrightarrow$ Good determination of mass differences



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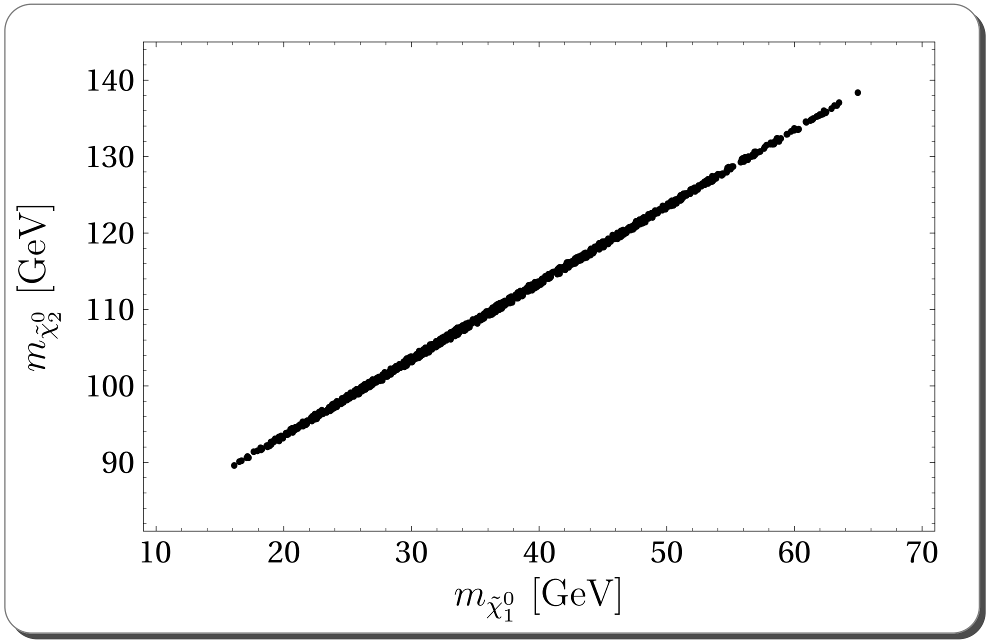
Mass measurements in invariant mass distributions

→ Good determination of mass differences

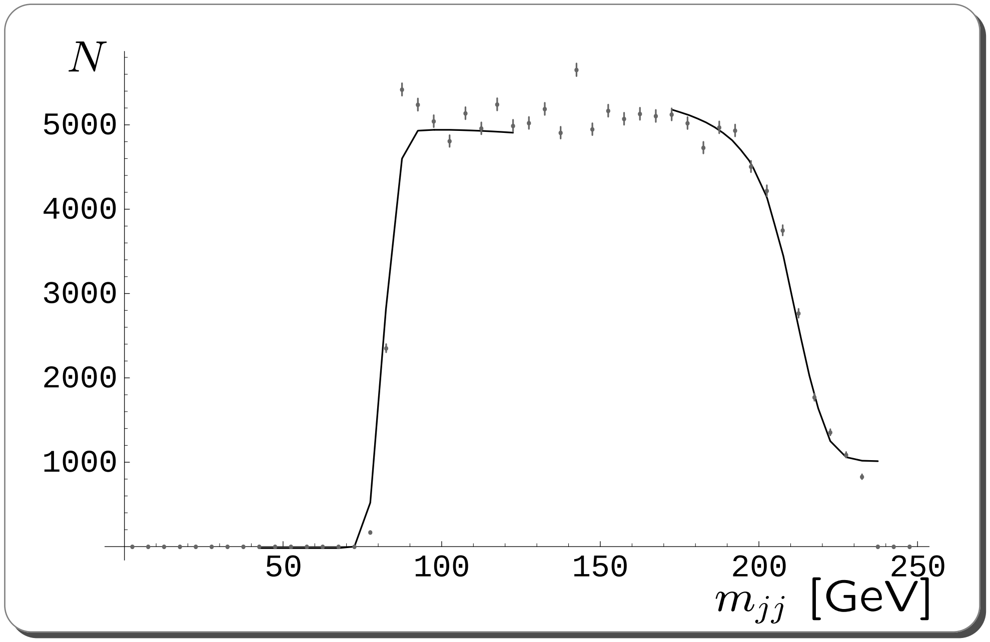
→ Poor determination of abolute masses

Typical errors for $m_{\tilde{\chi}^0_{1,2,3}}$:
20–30 GeV



nMSSM at ILC

- Many SUSY particles could be discovered at 500 GeV ILC
- Reduction of SM backgrounds possible with few cuts
- Kinematic edges in energy distributions allow sparticle mass measurement



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

nMSSM at ILC

- Two (invisible) scalar Higgs bosons S_1 and S_2 can be found and measured th rough $e^+e^- \to Z\,S_k$

- 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 prediction for CDM abundance and consistency-check for baryogenesis

Interpretation of results

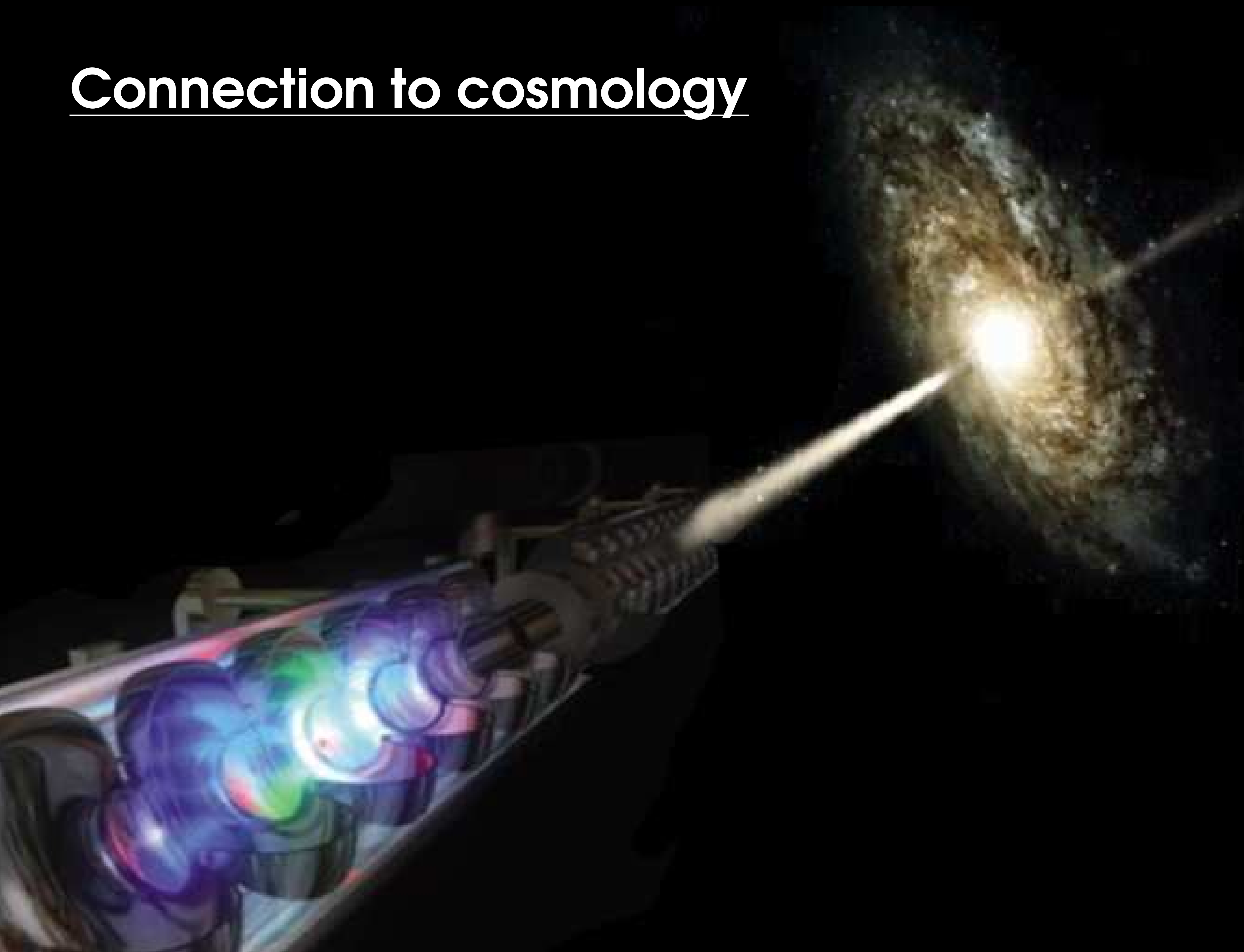
Fundamental parameters from neutralino/chargino maesurements:

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

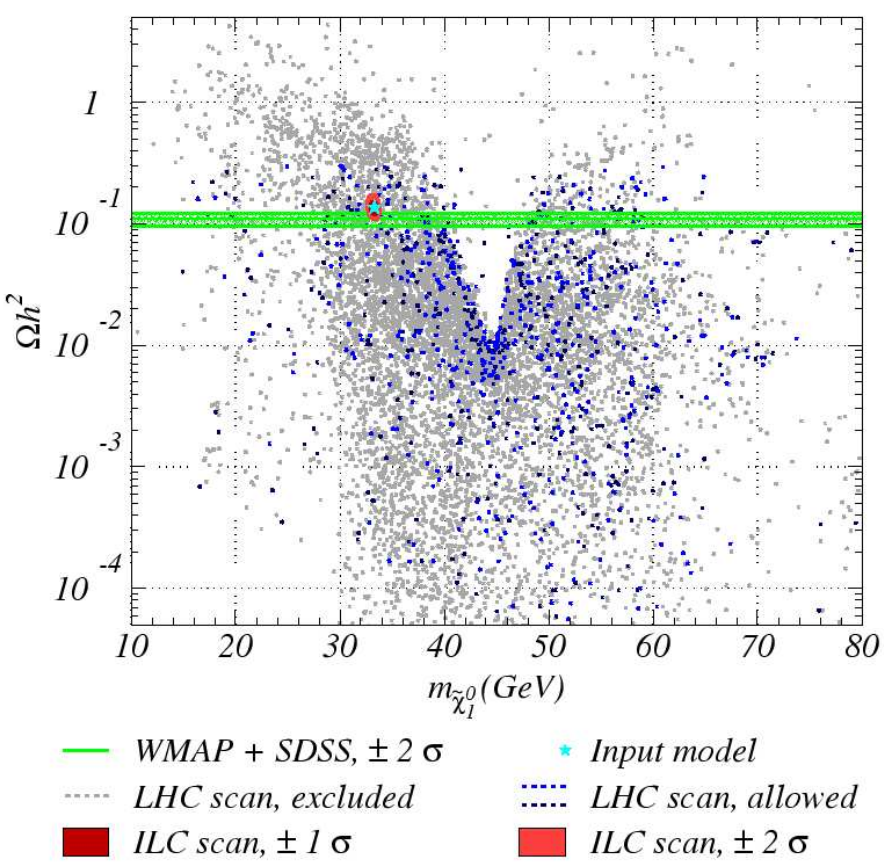
- Higgs triple coupling can be measured precisely
- Absence of cubic singlet self-coupling can be tested (nMSSM $\leftrightarrow$ NMSSM)

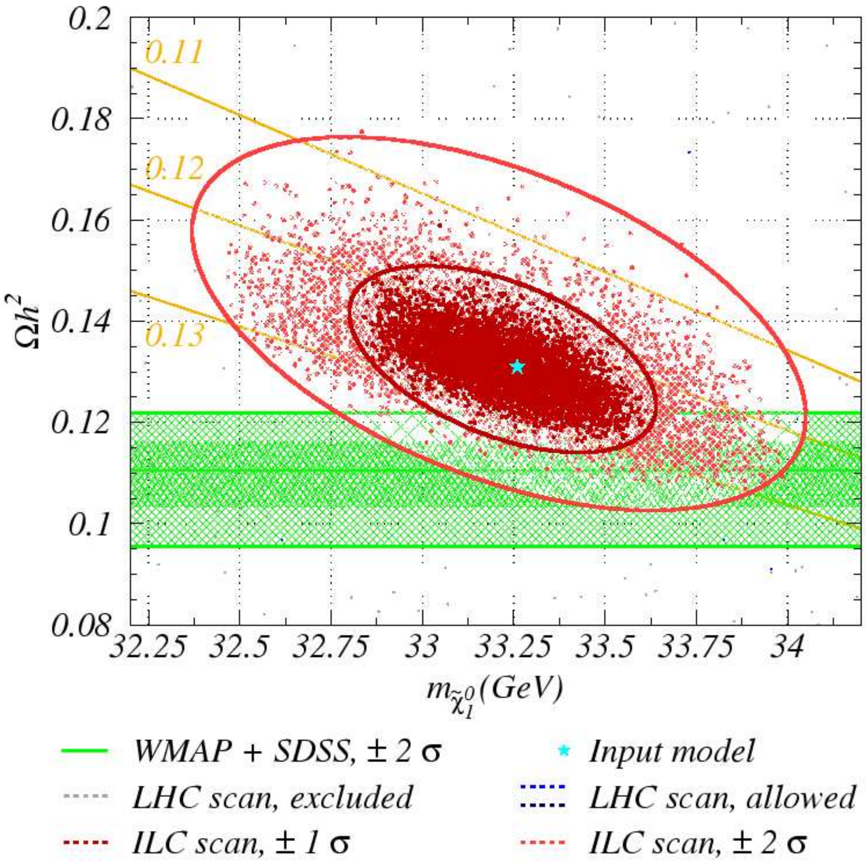
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\ 0 & M_2 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\ \mathcal{O}(v) & \mathcal{O}(v) & 0 & \boldsymbol{\lambda} v_s & \mathcal{O}(v) \\ \mathcal{O}(v) & \mathcal{O}(v) & \boldsymbol{\lambda} v_s & 0 & \mathcal{O}(v) \\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

Connection to cosmology



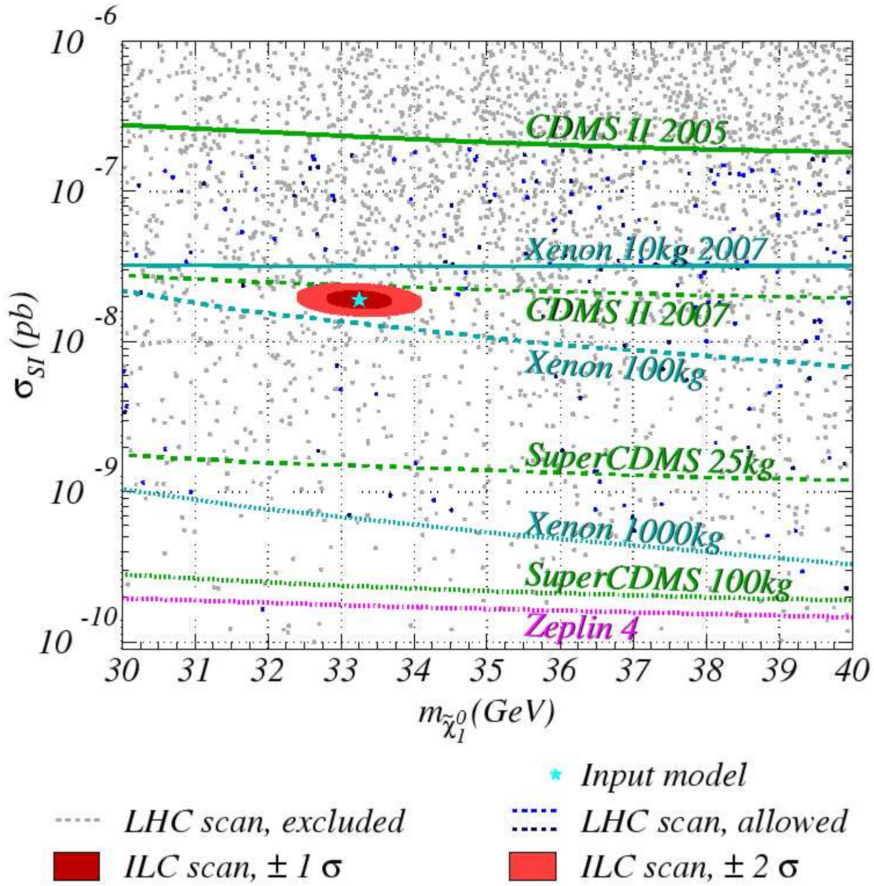
Dark matter density projection from simulation





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

Direct detection



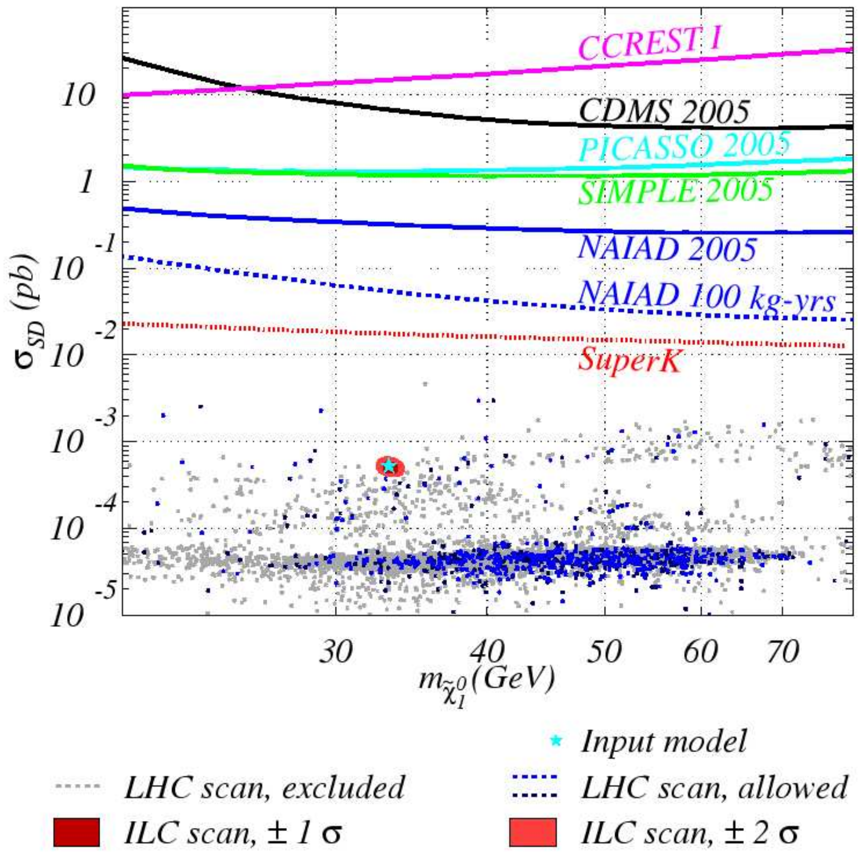
- Large singlino component of $\tilde{\chi}_1^0$:

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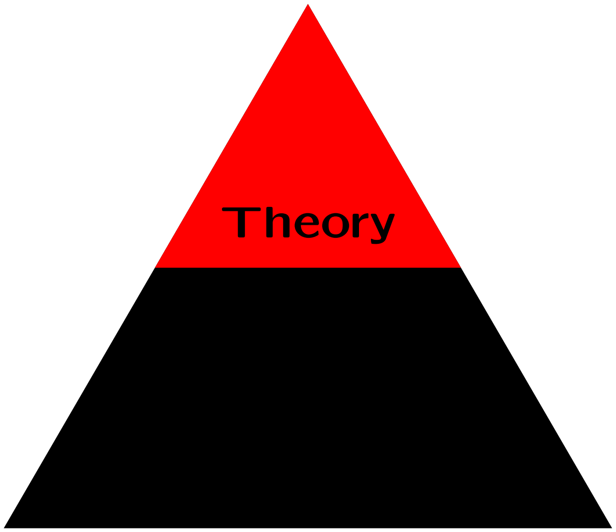
Parameter	Input value	Expected constraints from ILC	Range preferred by baryogenesis
m_s	106.5 GeV	$88 < m_s < 122$	$50 \lesssim m_s \lesssim 200$
a_λ	373 GeV	$352 < a_\lambda < 390$	$300 \lesssim a_\lambda \lesssim 600$
$t_s^{1/3}$	157 GeV	$117 < t_s^{1/3} < 181$	$50 \lesssim t_s^{1/3} \lesssim 200$

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

Conclusions

- The nMSSM is an appealing framework for
  - Explaining the origin of matter and dark matter
  - Solving the μ problem
  - Avoiding fine-tuning in the Higgs sector



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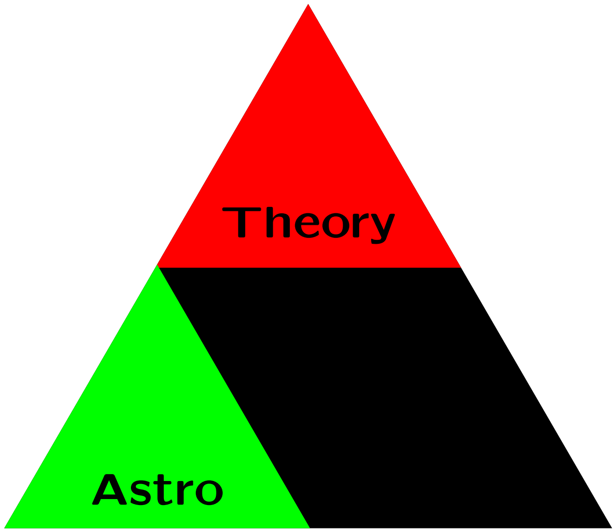

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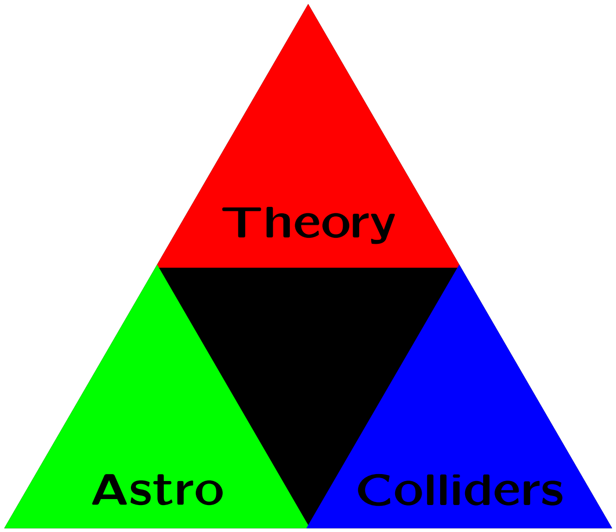
  - The validity of SUSY dark matter
  - The ingredients for baryogenesis



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