# Guaranteed discovery of dark matter in NmSuGra

- NmSuGra
- Likelihood
- Discovery

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# MSSM

Explains the origin of

- dark matter: conserved $R = (-1)^{3(B-L)+2S} \rightarrow$ stable, neutral WIMP LSP
- baryons: GUT-, lepto-, baryogenesis → baryon-antibaryon asymmetry
- mass: SUSY breaking & radiative dynamics → electroweak symmetry breaking
- spin: fermionic superspace component → spin degree of freedom
- naturalness: Higgsinos → Higgs mass protected by chiral symmetry
- light Higgs: $m_h^{tree} \lesssim m_Z$ & loop corrections → $m_h \lesssim 135$ GeV
- gauge unification: sparticle loops → unification at $M_{GUT} \sim 10^{16}$ GeV
- gravity: gauged supersymmetry → supergravity

and more.

But ...

# Problems with MSSM

"Supersymmetry solves the hierarchy problem by protecting the Higgs mass from large quantum fluctuations." ...

## $\mu$ problem

- $W \supset \mu \hat{H}_1.\hat{H}_2$ unnatural $\leftarrow$ $\mu$ not protected against quantum fluctuations

## Electroweak fine-tuning (little hierarchy) problem

- tension between a light $h^0$ and LEP limits on spartner ($\tilde{t}$) masses: electroweak precision data demand $m_h$ close to 114.4 GeV, but

$$m_h = \cos^2(2\beta)\, m_Z^2 + m_{EW}^2 \left( \log\left( \frac{m_{SUSY}^2}{m_t^2} \right) + \frac{X_t{}^2}{m_{SUSY}^2} \left( 1 - \frac{X_t{}^2}{12\, m_{SUSY}^2} \right) \right)$$

$$m_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}, \quad X_t = A_t - \mu \cot(\beta)$$

## Dark matter fine-tuning problem

- $f \sim \max_i\left(\frac{1}{\Omega} \frac{d\Omega}{dP_i}\right)$ large in most constrained MSSM scenarios

--- list your own problems with the MSSM here ---

# Singlet extensions of the MSSM

Easy to fix these MSSM problems while keeping positive features intact!

The root of the $\mu$ and fine-tuning problems is the Higgs sector

- extending the EWSB sector of the MSSM, these problems are alleviated
- in the (n,N,S)MSSM the $W \supset \mu \hat{H}_1.\hat{H}_2$ dynamically generated by

$$W \supset \lambda \hat{S} \hat{H}_1.\hat{H}_2$$

- no dimensionful parameters are present in the superpotential
- all these fields ($H_i$ and $S$) acquire a vev.s at the weak scale
- electroweak fine tuning can also be alleviated
- caveat: new dimensionful soft parameters associated with the singlet

  it can be argued that the $\mu$ problem is only deferred to SUSY breaking

# NmSuGra

Discreet symmetries of super- & Kahler potentials: $Z_3 \times Z_2^{MP}$

solve domain wall problem

Superpotential $\quad W = W_{MSSM} + \lambda \hat{S} \hat{H}_1.\hat{H}_2 + \frac{\kappa}{3} \hat{S}^3$ $\quad$ Next-to-minimal MSSM

Scalar potential $\quad V = V_{MSSM} + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_1.H_2 + \frac{\kappa}{3} A_\kappa S^3 + h.c.\right)$

New parameters $\quad \langle S \rangle, \lambda, \kappa, A_\lambda, A_\kappa, m_S$

SUSY breaking $\quad$ mSuGra $\rightarrow$ universality: fixes $A_\kappa = A_\lambda = A_0$

All parameters $\quad M_0, M_{1/2}, A_0, \langle H_1 \rangle, \langle H_2 \rangle, \langle S \rangle, \lambda, \kappa, m_S$

3 minimization eq. and $v^2 = \langle H_1 \rangle^2 + \langle H_2 \rangle^2 \rightarrow$

five free parameters and a sign:

$$M_0, M_{1/2}, A_0, \tan\beta, \lambda, \text{sign}(\mu)$$

A single parameter extension of mSuGra, without new dimensionful parameters

# Likelihood

Experiments limit $M_0$, $M_{1/2}$, $A_0$, $\tan\beta$, $\lambda$, sign($\mu$)

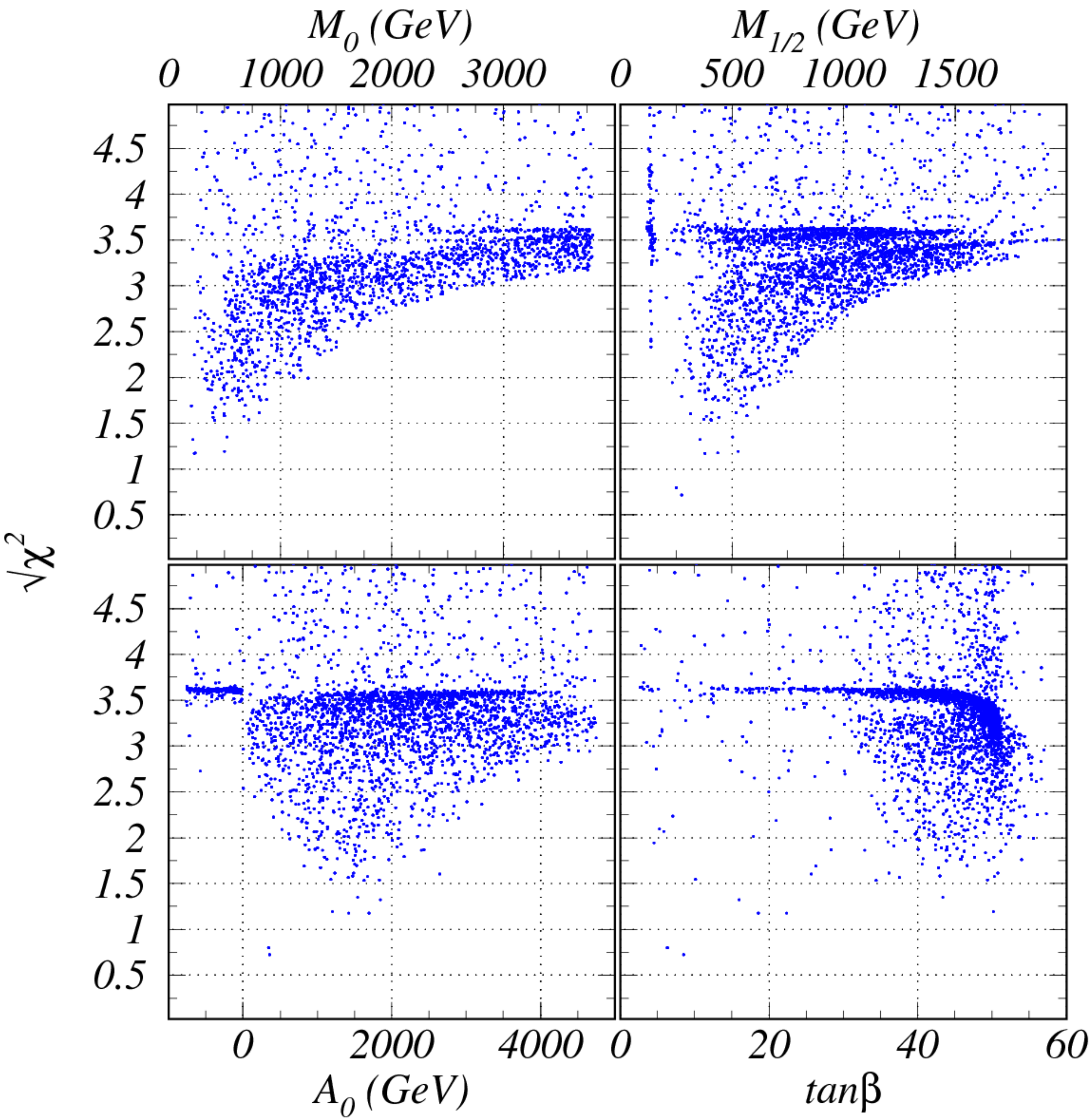
To quantify experimental constraints use the exponent of the likelihood function:

$$\sqrt{\chi^2} = \left( \sum_{i=1}^{7} \left( \frac{m_i^{experiment} - m_i^{NmSuGra}}{\sigma_i} \right)^2 \right)^{1/2}$$

i runs over:

- LEP — chargino & Higgs mass
- Tevatron — $Br(B_s \to l^+ l^-)$
- HFAG — $Br(b \to s\gamma)$
- g-2 — anomalous magnetic moment of $\mu$
- WMAP — neutralino relic abundance
- CDMS — spin-independent neutralino-proton elastic recoil

# Likelihood



M0 (GeV)
0
1000
2000
3000
M1/2 (GeV)
0
500
1000
1500
√χ2
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2000
4000
A0 (GeV)
0
20
40
60
tanβ

# Likelihood: role of $g_\mu$-2

$\chi^2$ is dominated by the muon anomalous magnetic moment of $a_\mu$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 29.5 \pm 8.8 \times 10^{-10} \qquad 3.4\ \sigma \text{ discrepancy}$$

Largest theoretical uncertainty comes from hadronic vacuum polarization (HVP)

- optical theorem: HVP contribution $\leftrightarrow \sigma(e^+e^- \to \text{hadrons})$
- $\sigma(e^+e^- \to \text{hadrons})$ is measured

The HVP contribution can also be calculated using $\tau$ decay data

In the past there was a significant discrepancy between the e+e- → hadrons
- and $\tau$ decay based data

Most recent calculations of the HVP contribution are in very good agreement
- isospin-breaking corrections reduce the difference between these two sets of data (lowering the $\tau$-based determination), and a new analysis of the pion form factor claims that the $\tau$ and $e^+e^-$ data are consistent

# Dark matter

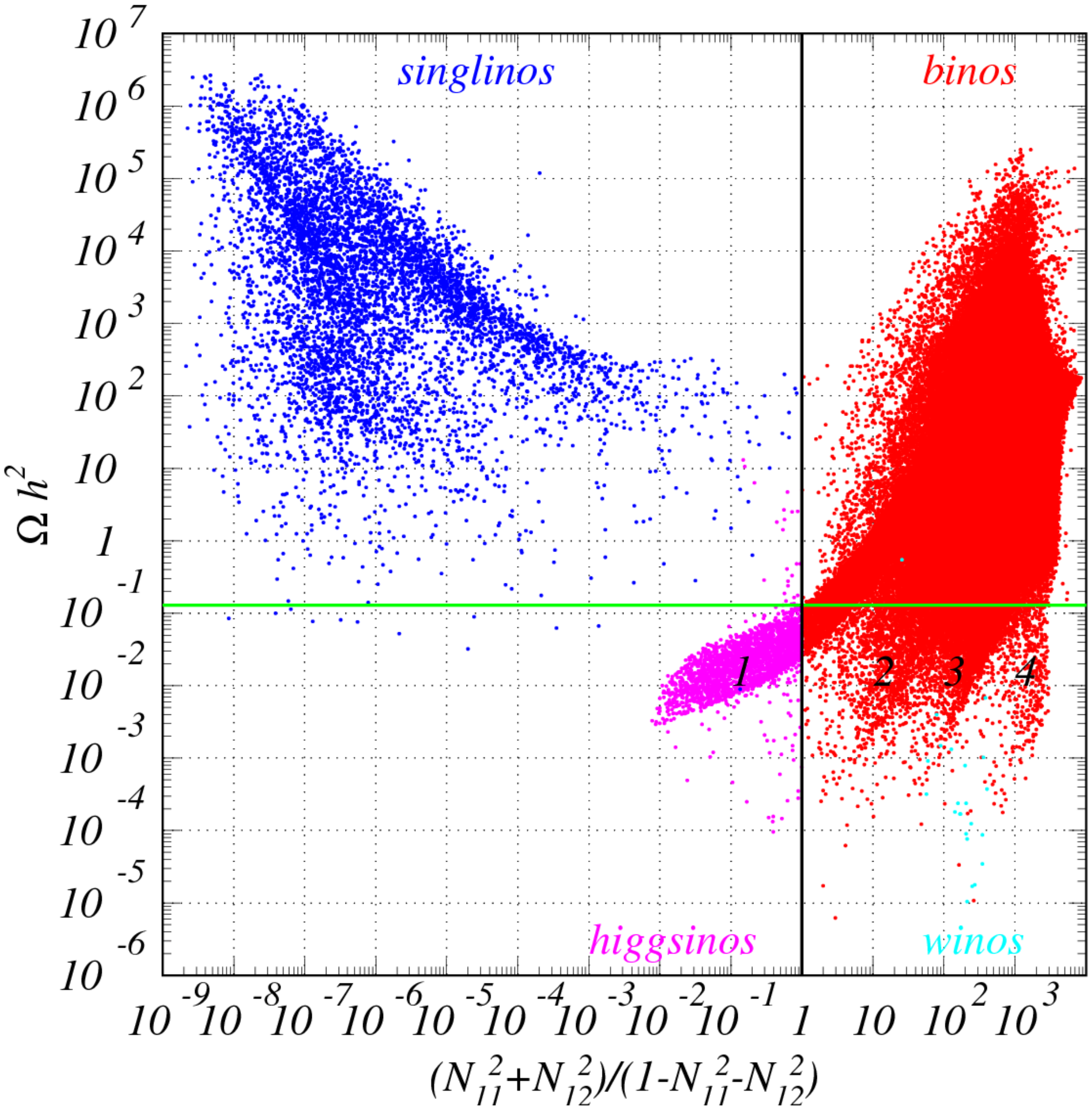
The LSP is the lightest neutralino

$$\tilde{Z}_1 = N_{11}\,\tilde{B} + N_{12}\,\tilde{W}_3 + N_{13}\,\tilde{H}_1 + N_{14}\,\tilde{H}_2 + N_{15}\,\tilde{S}$$

- $\tilde{Z}_1$ is mostly bino-like as in mSuGra, but all type of dark matter occurs: bino-, wino-, higgsino- and singlino-like dark matter

- All the familiar neutralino (co-)annihilation mechanisms are found:
  bulk region,
  focus point type region (1),
  Higgs resonances (via all five neutral Higgses 2),
  stau co-annihilation (3),
  stop co-annihilation (4).

# Dark matter



singlinos
binos
higgsinos
winos
1
2
3
4
$\Omega h^2$
$(N_{11}^2+N_{12}^2)/(1-N_{11}^2-N_{12}^2)$

# Discovery

A given NmSuGra model point is discoverable at

- LEP if $m_{h^0} < 114.4$ GeV or $m_{\tilde{W}_1} < 103.5$ GeV

  $m_{h^0}$ limit is relaxed for non-SM-like Higgses

- LHC if $m_{\tilde{g}} < 1.75$ TeV or $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} < 2$ TeV

  this is based on detailed mSuGra analysis

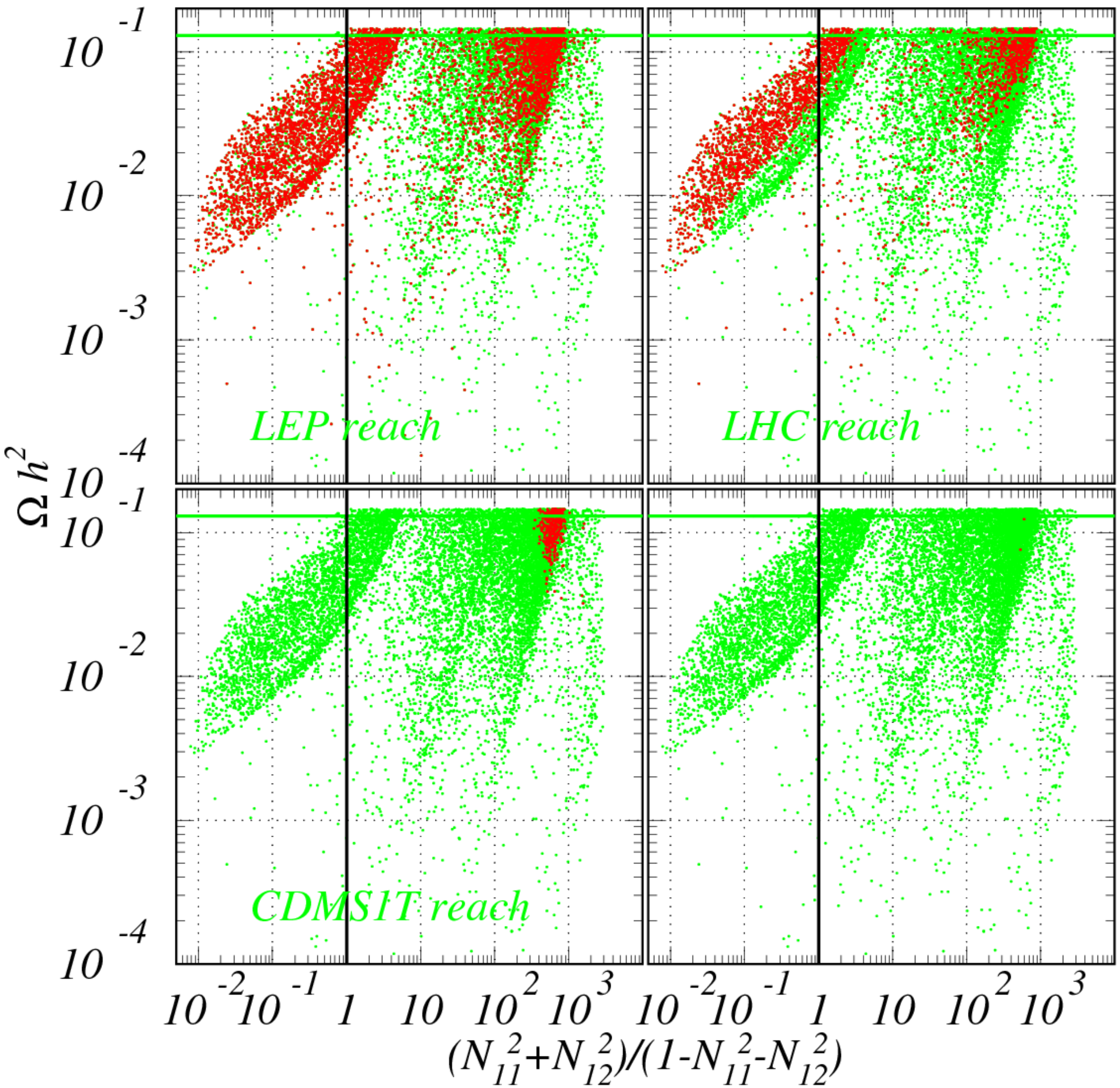
- CDMS1T if $\sigma^{SI}_{p\tilde{Z}_1}(m_{\tilde{Z}_1})$ is larger than the estimated 1 ton CDMS limit

Assuming this, the bulk of the NmSuGra para-space is discoverable!

The remaining para-space is disfavored at more than 99 % confidence level

- this is dominated by $g_\mu - 2$

# Discovery



LEP reach
LHC reach
CDMS1T reach
$\Omega h^2$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-2}$ $10^{-1}$ 1 10 $10^2$ $10^3$
$(N_{11}^2+N_{12}^2)/(1-N_{11}^2-N_{12}^2)$

# Summary

- Supersymmetry offers solutions to challenging cosmological problems: dark matter, matter-antimatter asymmetry, inflation, etc.
- The MSSM suffers from a number of problems which are alleviated by the addition of a singlet and universality at the GUT scale → NmSuGra
- Present experiments prefer moderate values of the dimensionful NmSuGra parameters $M_0$, $M_{1/2}$, and $|A_0|$
- If $M_0$, $M_{1/2}$, and $|A_0|$ are indeed moderate, then the LHC and a ton equivalent of CDMS is guaranteed to discover NmSuGra under the condition that the g-2 discrepancy prevails

  If the g-2 discrepancy goes away, new experimental techniques will be needed to fully explore the NmSuGra parameter space

DSU 2009

Melbourne, Australia

The Dark Side of the Universe on the Other Side of the Globe

Co-organized by Monash University and University of Melbourne

Planned time: June 1-5 2009

Planned venue: University of Melbourne

Welcome to the southern hemisphere!

The End