NmSuGra, LHC & dark matter

Csaba Balazs

Emerald Univercity, Land of OZ

Balazs, Carter PRD78 055001 (0808.0770)

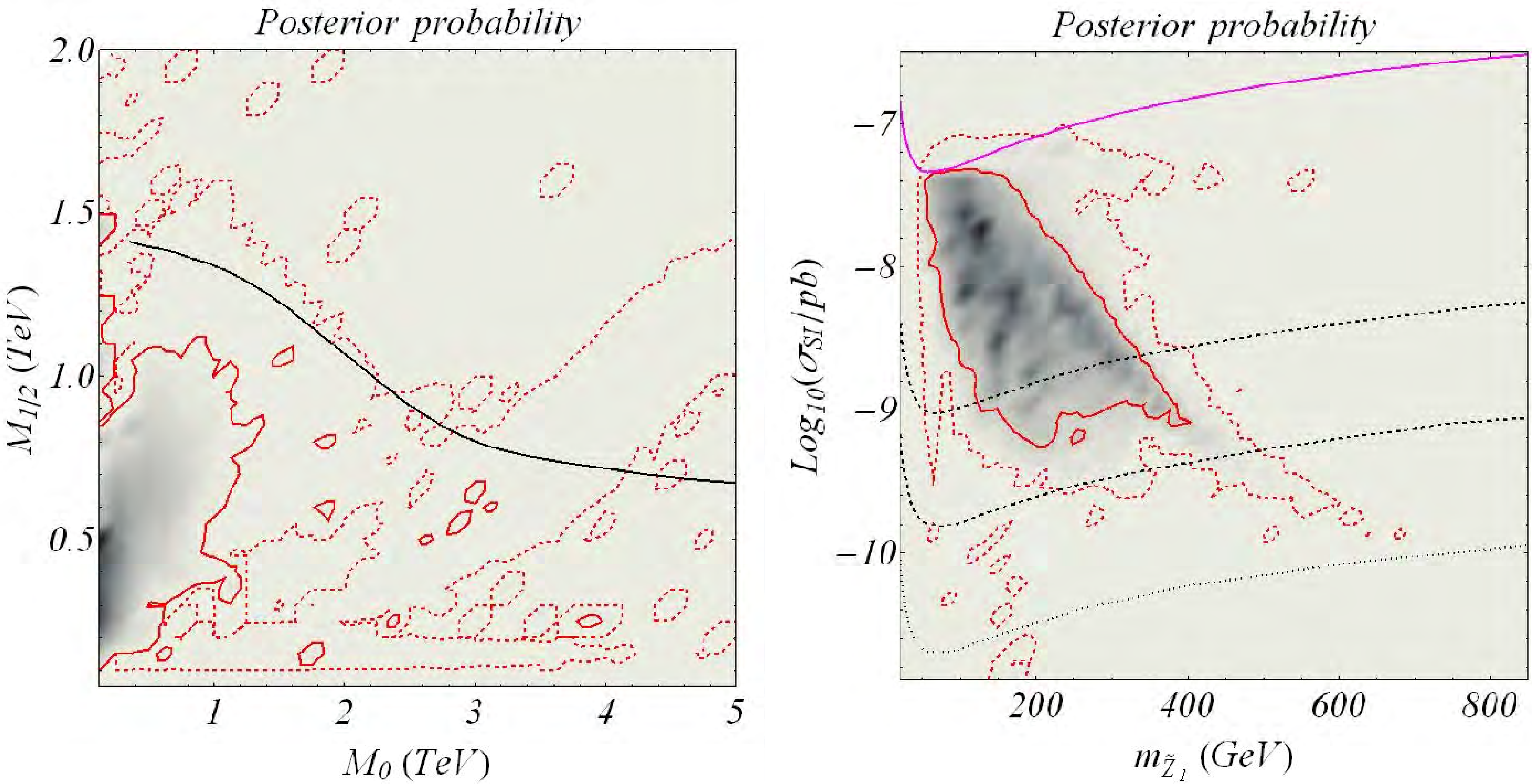
Lopez-Fogliani, Roszkowski, Ruiz de Austri, Varley PRD80 095013 (0906.4911)

Balazs, Carter JHEP03 016 (0906.5012)

The idea

- Constrain the simplest supersymmetric models using experiments
- Use smart statistics to obtain the maximal info about the model
- Determine future model detectability based on present data
- Confirm/rule out the simplest models (and repeat for nsimplest?)

The results (for NmSuGra)



- There's a beautiful complementarity between the LHC and direct dark matter detection experiments

Outline

- Next-to-minimal supersymmetric standard model
- Supergravity
- Parameter extraction: Reverend Bayes
- Posterior probabilities: Fryer Occam
- LHC detectability
- Dark matter direct detection

Supersymmetric models are robust

They explain the origin of

- naturalness: Higgsinos → Higgs mass protected by chiral symmetry
- (inertial) mass: SUSY breaking & radiative dynamics → EWSB
- light Higgs boson: $m_h^{tree} \lesssim m_Z$ & loop corrections → $m_h \lesssim 135$ GeV
- dark matter: conserved $R = (-1)^{3(B-L)+2S}$ → LSP is a stable WIMP
- baryonic matter: baryo- or lepto-genesis → $\overline{b}$aryon asymmetry
- gauge unification: sparticle loops → unification w/ $M_{GUT} \sim 10^{16}$ GeV
- gravity: gauged supersymmetry → supergravity
- and more experimental and theoretical puzzles unanswered by the standard models of particle & astrophysics

The Minimal Supersymmetric Standard Model (MSSM)

- Minimal particle content:

  standard fields → superfields

- Supersymmetry & gauge symmetry →

  all interactions

- Standard electroweak symmetry breaking →

  particle masses

- Model parameters are the same as in the standard model

  (with 2 Higgs doublets)

Superpotential

$$W_{MSSM} = y_u \hat{H}_u \cdot \hat{Q}\, \hat{U} - y_d \hat{H}_d \cdot \hat{Q}\, \hat{D} - y_e \hat{H}_d \cdot \hat{L}\, \hat{E} + \mu \hat{H}_u \cdot \hat{H}_d$$

The Minimal Supersymmetric Standard Model (MSSM)

- Minimal particle content:

  standard fields → superfields

- Supersymmetry & gauge symmetry →

  all interactions

- Standard electroweak symmetry breaking →

  particle masses

- Model parameters are the same as in the standard model

  (with 2 Higgs doublets)

Superpotential

$$W_{MSSM} = y_u \hat{H}_u \cdot \hat{Q}\,\hat{U} - y_d \hat{H}_d \cdot \hat{Q}\,\hat{D} - y_e \hat{H}_d \cdot \hat{L}\,\hat{E} + \mu \hat{H}_u \cdot \hat{H}_d$$

Supersymmetry ⇒ super-partner masses = particle masses

Supersymmetry breaking

However beautiful, attractive and smart SUSY is, she's broken!

One of the simplest: minimal supergravity motivated model mSuGra

universality at M_{GUT}

- spin 0 (spartner) masses → M_0
- spin 1/2 (gaugino) masses → $M_{1/2}$
- all tri-linear couplings → A_0
- vacuum expectation values → $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
- electroweak symmetry breaking ⇒ μ^2 → $\text{sign}(\mu)$

$$\mathcal{L}_{soft}^{MSSM} = y_u A_0 H_u \cdot \tilde{Q}\, \tilde{U} - y_d A_0 H_d \cdot \tilde{Q}\, \tilde{D} - y_e A_0 H_d \cdot \tilde{L}\, \tilde{E} + \mu B H_u \cdot H_d + hc + \\ + M_{1/2} \tilde{\lambda}_i^* \tilde{\lambda}_i + \frac{1}{2} M_0^2 \tilde{\psi}_j^\dagger \tilde{\psi}_j$$

Problems with the MSSM

- μ problem

  $W_{MSSM} \supset \mu \hat{H}_u \cdot \hat{H}_d$ unnatural ← EW size for μ is not justified

- Little hierarchy problem

  SUSY stabilizes M_{EW}, by protecting m_h against $O(M_P)$ fluctuations

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

  Δm_h small if $m_{SUSY} \sim m_t$ ↔ EW precision data → $m_{SUSY} \sim O(1\ \text{TeV})$

- Electroweak fine-tuning problem

  $\max_i\left(\frac{1}{m_Z}\frac{dm_Z}{dp_i}\right)$ large in most constrained MSSM scenarios

- Dark matter fine-tuning problem

  $\max_i\left(\frac{1}{\Omega}\frac{d\Omega}{dp_i}\right)$ large in most constrained MSSM scenarios

Singlet extensions of the MSSM

- Root of the μ, hierarchy & fine-tuning problems is the Higgs sector

  extending the EWSB sector of the MSSM, problems are alleviated

  in the (n,N,S)MSSM the $W \supset \mu \hat{H}_u \cdot \hat{H}_d$ dynamically generated by

$$W \supset \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d$$

  all these fields (H_i and S) acquire vev.s at the weak scale

  little hierarchy and fine-tunings are also alleviated

- Next-to-minimal MSSM: $W_{NMSSM} = W_{MSSM,Y} + \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \frac{\kappa}{3} \hat{S}^3$

  mSuGra → universality fixes all NMSSM parameters, but λ

  5 free parameters:

$$M_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \lambda$$

Single parameter extension of mSuGra solving several MSSM problems

NmSuGra para count

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

solve domain wall problem

Next-to-minimal MSSM: $W_{NMSSM} = W_{MSSM} + \lambda \hat{S}\, \hat{H}_1 \cdot \hat{H}_2 + \frac{\kappa}{3} \hat{S}^3$

New parameters $\langle S \rangle$, λ, κ, A_λ, A_κ, m_S

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

9 parameters left M_0, $M_{1/2}$, A_0, $\langle H_1 \rangle$, $\langle H_2 \rangle$, $\langle S \rangle$, λ, κ, m_S

3 minimization eq. & $v^2 = \langle H_1 \rangle^2 + \langle H_2 \rangle^2$ eliminates 4 para &

$\tan\beta = \langle H_1 \rangle / \langle H_2 \rangle$, $\mu = \lambda \langle S \rangle$ exchanges β and μ with 2 para →

5 free parameters:

$$M_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \lambda$$

- Single parameter extension of mSuGra - no new dimensionful para.s

The logic of science: How NOT to discover SUSY

A SUSY model parametrized by $P = \{p_1, \ldots, p_n\}$

predicts an experimental outcome $D = \{d_1, \ldots, d_n\}$

Assume that the LHC measures the predicted D!

Ask the simplest question: Has SUSY been discovered?

It's (very-very) tempting to answer: Yes!

The logic of science: How NOT to discover SUSY

A SUSY model parametrized by $P = \{p_1, \ldots, p_n\}$

predicts an experimental outcome $D = \{d_1, \ldots, d_n\}$

Assume that the LHC measures the predicted D!

Ask the simplest question: Has SUSY been discovered?

In reality the answer is: No! Because

$$P \Rightarrow D \quad \text{does NOT imply} \quad D \Rightarrow P$$

or in terms of conditional probabilities

$$\mathbb{P}(P|D) \neq \mathbb{P}(D|P)$$

where $\mathbb{P}(P|D)$ is a measure of the plausibility that P is true given D

How to extract parameters

The correct relation between conditional probabilities is Bayes theorem:

$$\mathbb{P}(P|D)\ \mathbb{P}(D) = \mathbb{P}(D|P)\ \mathbb{P}(P)$$

- $\mathbb{P}(P|D)$ posterior distribution – this is what we want to know
- $\mathbb{P}(D)$ evidence – here only plays the role of normalization
- $\mathbb{P}(D|P)$ likelihood function – probability that D is measured given P

$$\mathbb{P}(D|P) = \prod_i \exp(-\chi_i^2/2)/\sqrt{2\pi}\,\sigma_i$$

$$\chi_i^2 = (d_i - t_i(p_i))^2/(\sigma_{i,exp}^2 + \sigma_{i,the}^2) \qquad i=1...N_{data\ points}$$

- $\mathbb{P}(P)$ prior, describes the a-priori (D independent) distribution of P

  for para extraction have been shown to be close to Jeffrey's

Posterior distributions

- Marginalized posteriors

$$\mathbb{P}(p_i|D) = \int \mathbb{P}(P|D)\, \prod_{j\neq i} dp_j \qquad i, j = 1, \ldots, N_{parameters}$$

$$\mathbb{P}(p_i,p_j|D) = \int \mathbb{P}(P|D)\, \prod_{k\neq i,j} dp_k \qquad i, j, k = 1, \ldots, N_{parameters}$$

are probability distributions of the parameters

- Marginalization implements Occam's razor

$$\mathbb{P}(p_i|D) = \int \mathbb{P}(P|D)\, \prod_{j\neq i} dp_j = \int \mathbb{P}(D|P)\, \mathbb{P}(P)/\mathbb{P}(D)\, \prod_{j\neq i} dp_j$$

where

$$1 = \int \mathbb{P}(D|P)\, \mathbb{P}(P)/\mathbb{P}(D)\, \prod_j dp_j \quad \text{and} \quad 1 = \int \mathbb{P}(P)\, \prod_j dp_j$$

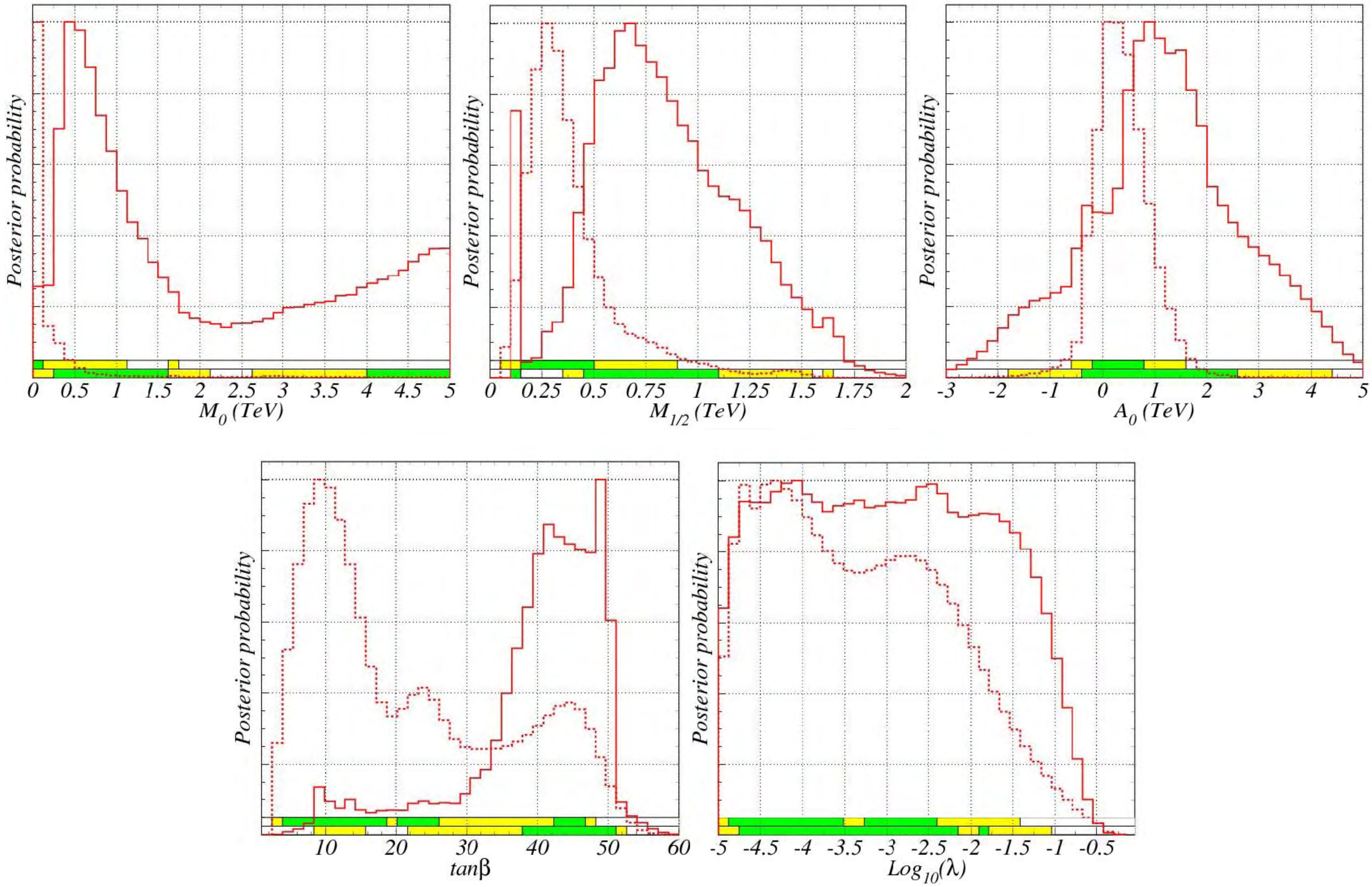
A model with a fewer parameters has a higher prior density leading to a higher posterior (assuming same likelihood)

Experimental input

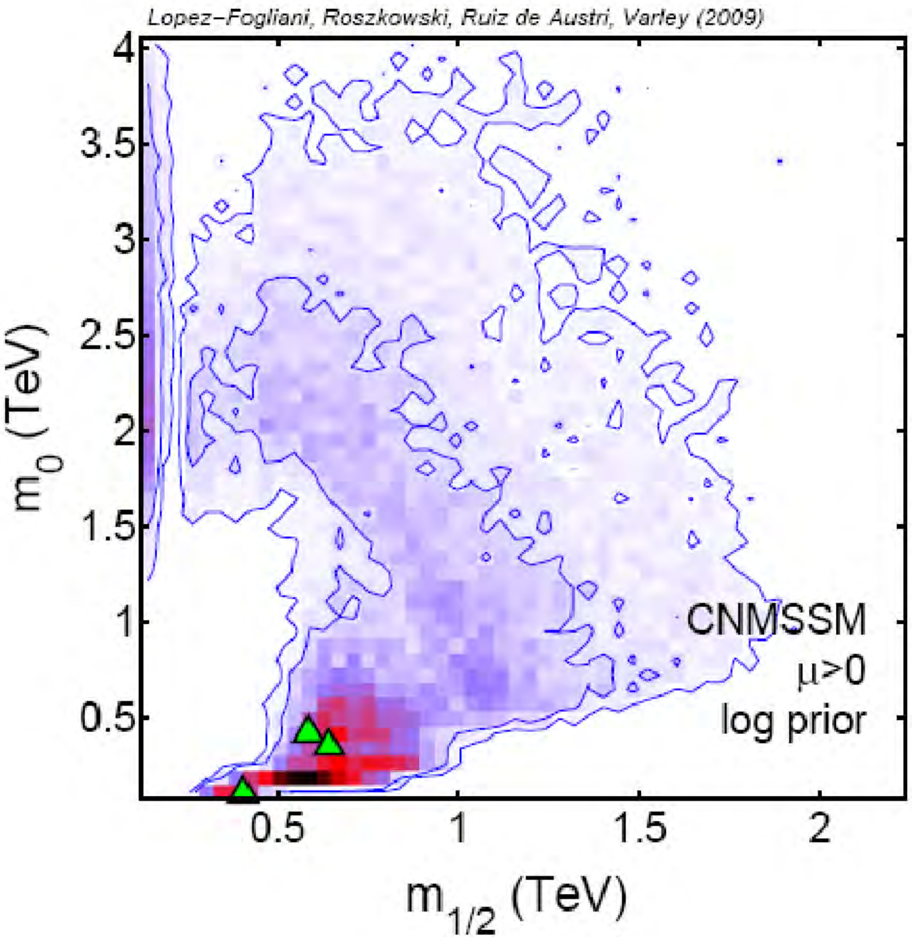
Experimental data, constraining supersymmetry, available today

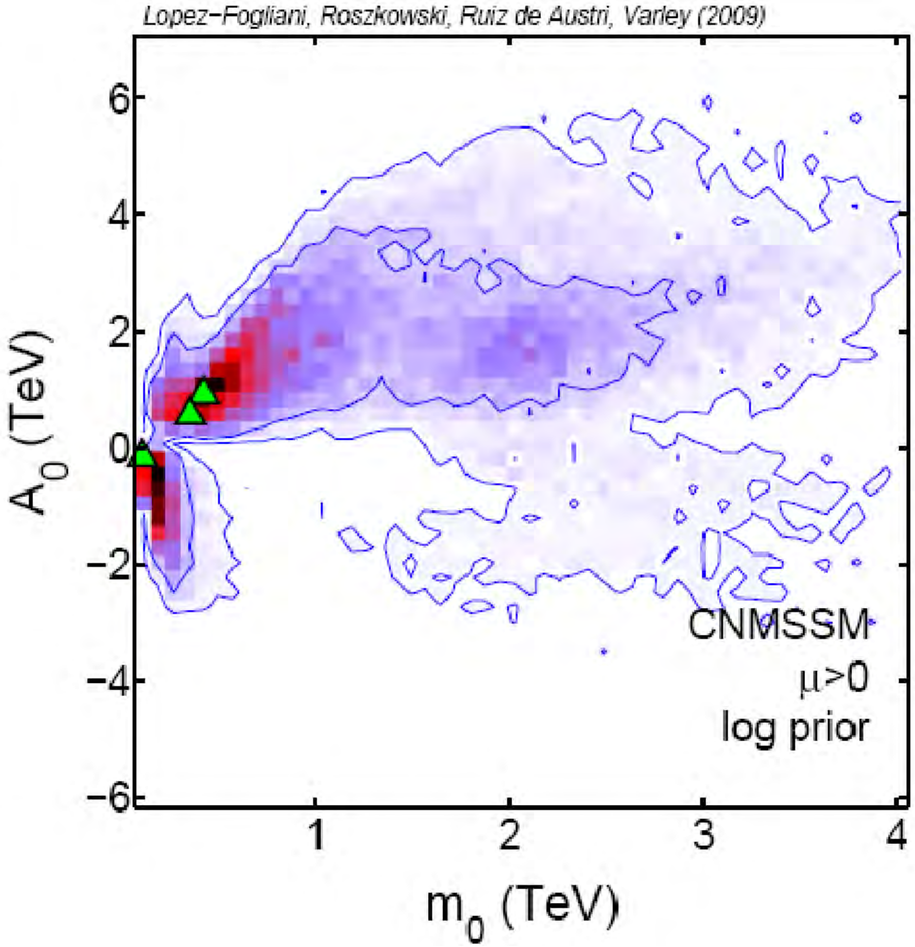
- LEP — lower limits on spartner, Higgs masses & cross sections (dozens of upper limits - most restrictive m_h, $m_{\tilde{W}_1}$, $m_{\tilde{Z}_1}$)
- Tevatron — as for LEP & upper limit on $Br(B_s \to l^+ l^-)$
- b fact. — $Br(b \to s \gamma)$, $Br(B^+ \to l^+ \nu_l)$, ΔM_d, ΔM_s, ...
- g_μ-2 — anomalous magnetic moment of muon
  plays strong role: constraining high M_0 and $M_{1/2}$
- WMAP — WIMP abundance upper limit
  very important: excluding significant para-space
- CDMS/Xe — WIMP-proton elastic recoil

Probability distributions for input para

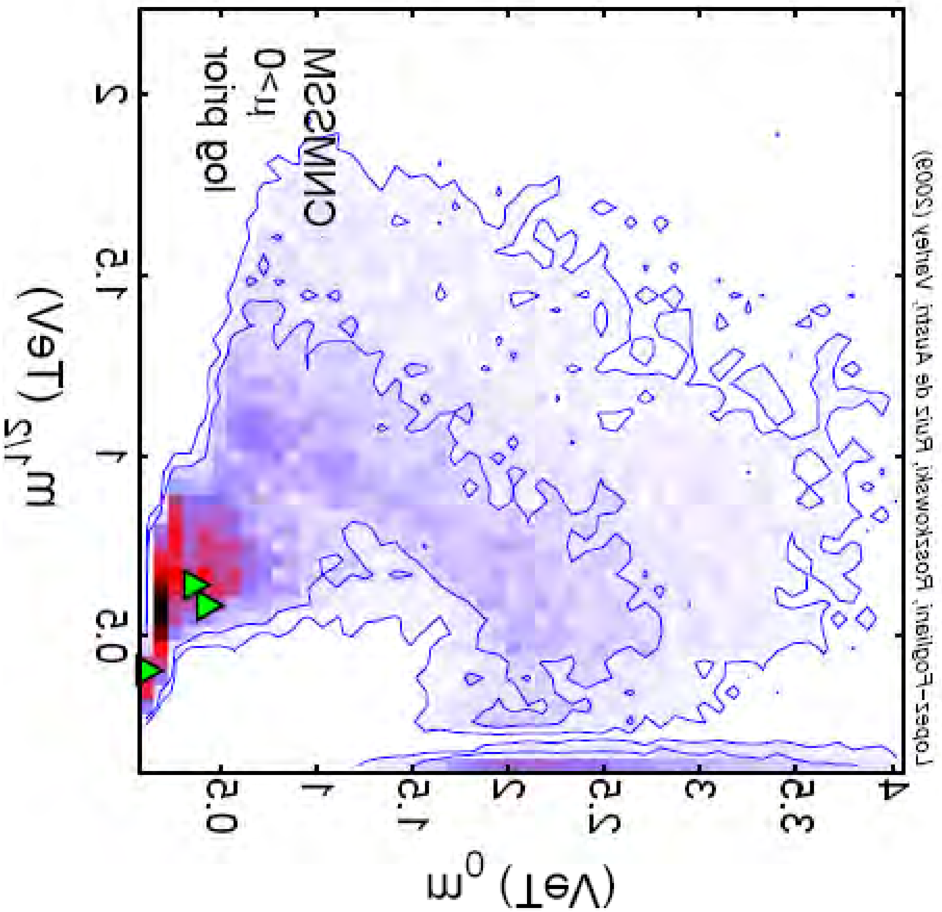


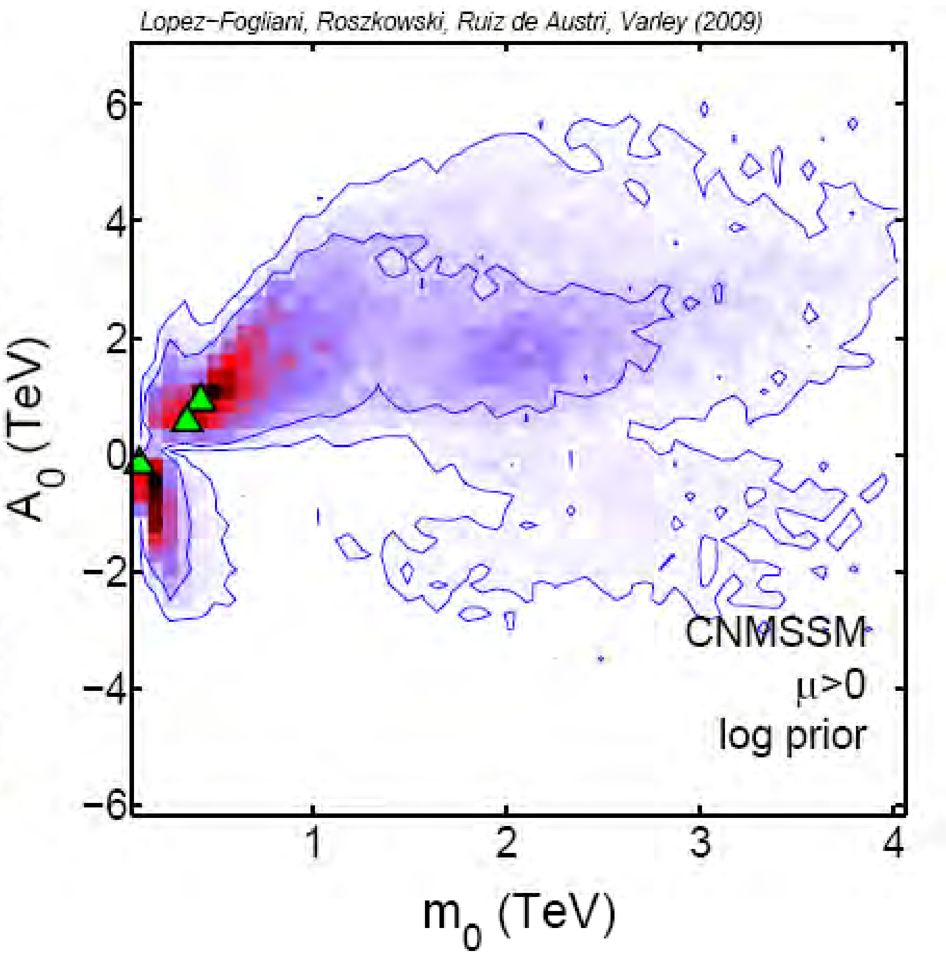
Probability maps for input para





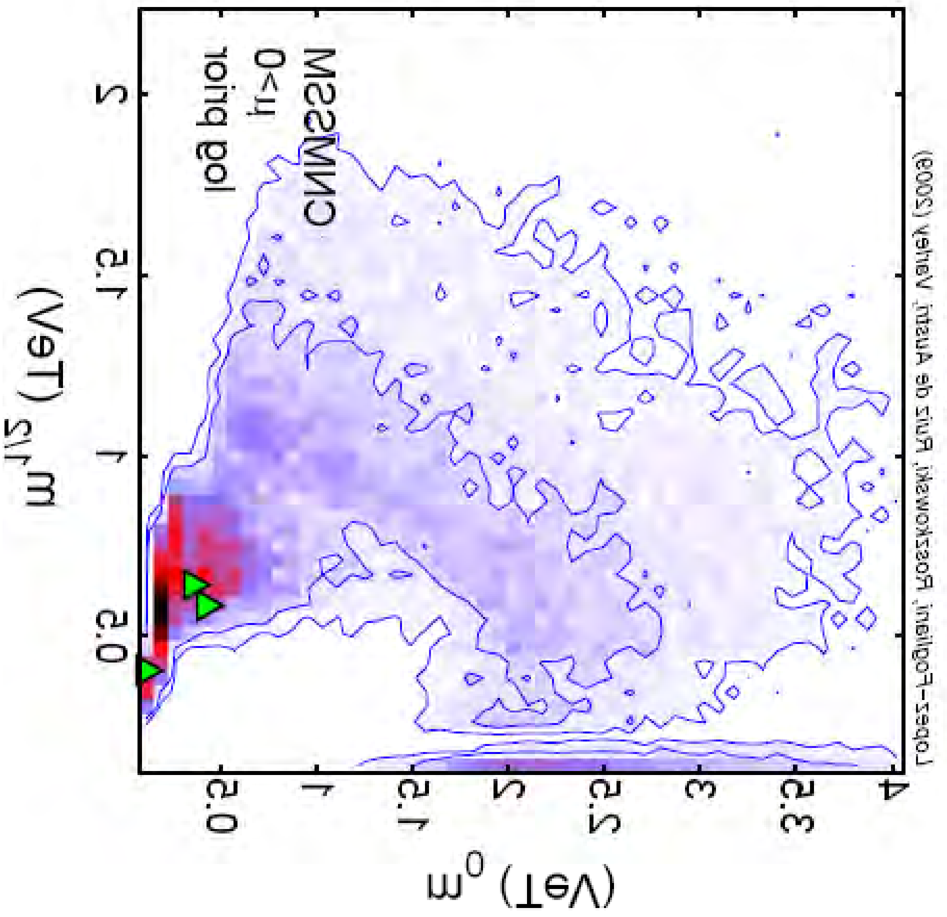
Probability maps for input para

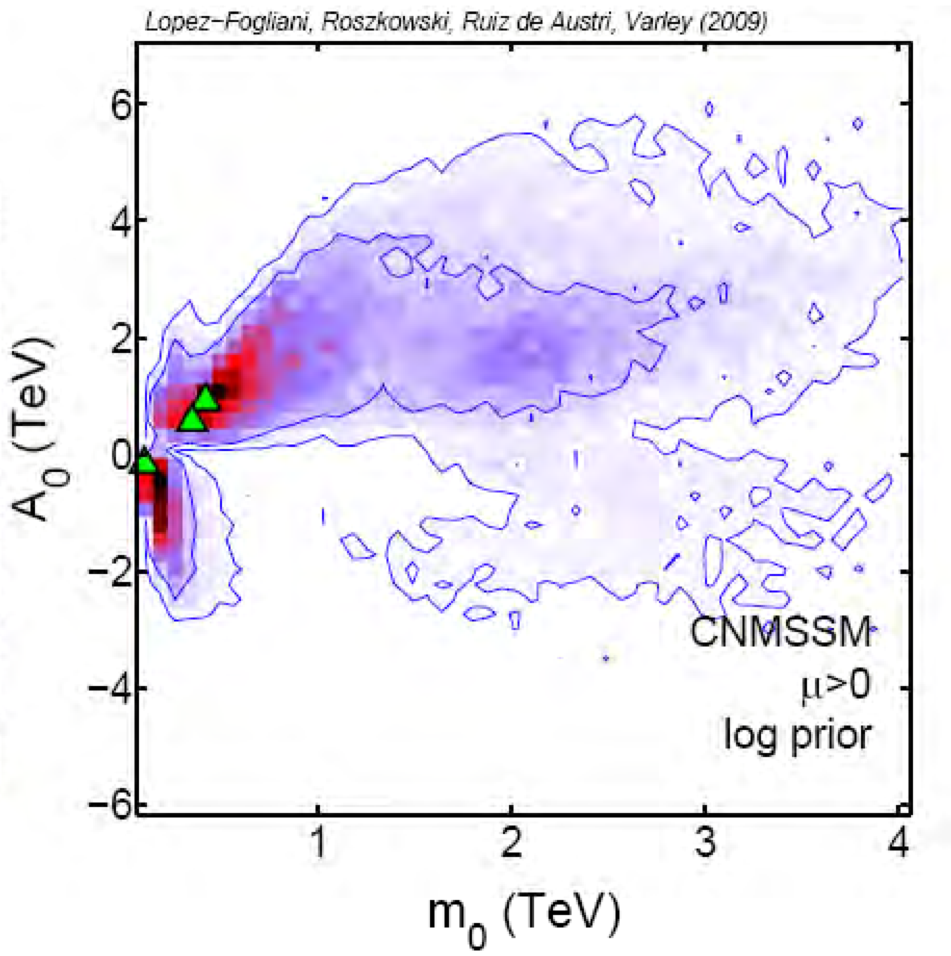




- mSuGra features can be identified: $\tilde{\tau}$ coann., h funnels, FP, ...

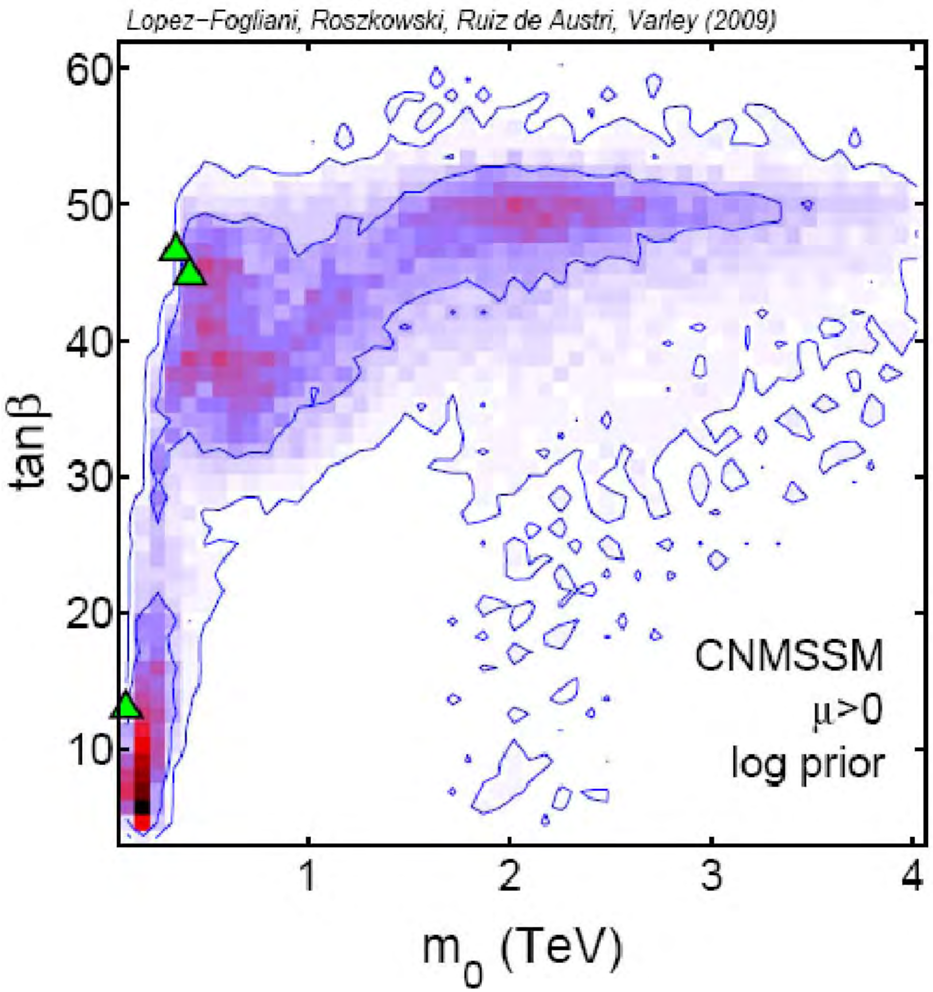
An old mSuGra movie ...

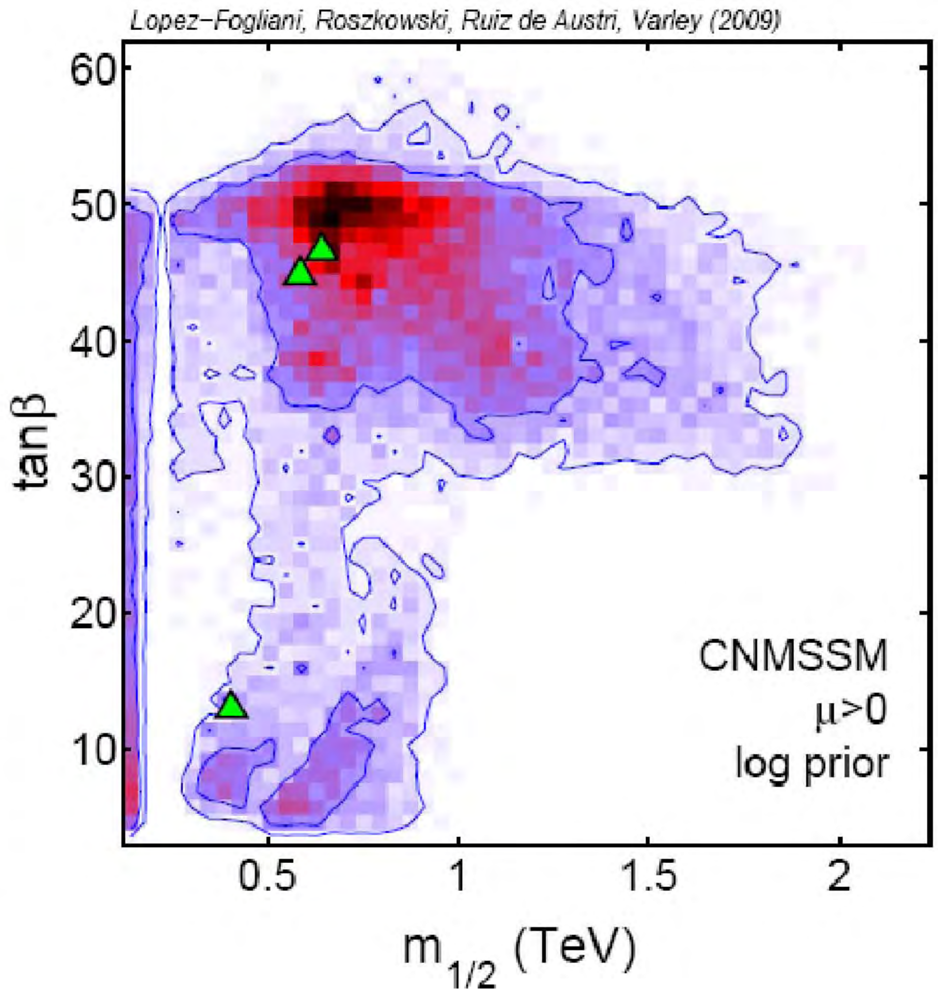




- mSuGra features: $\tilde{\tau}$ coann., h funnels, FP, ...

Probability maps for input para

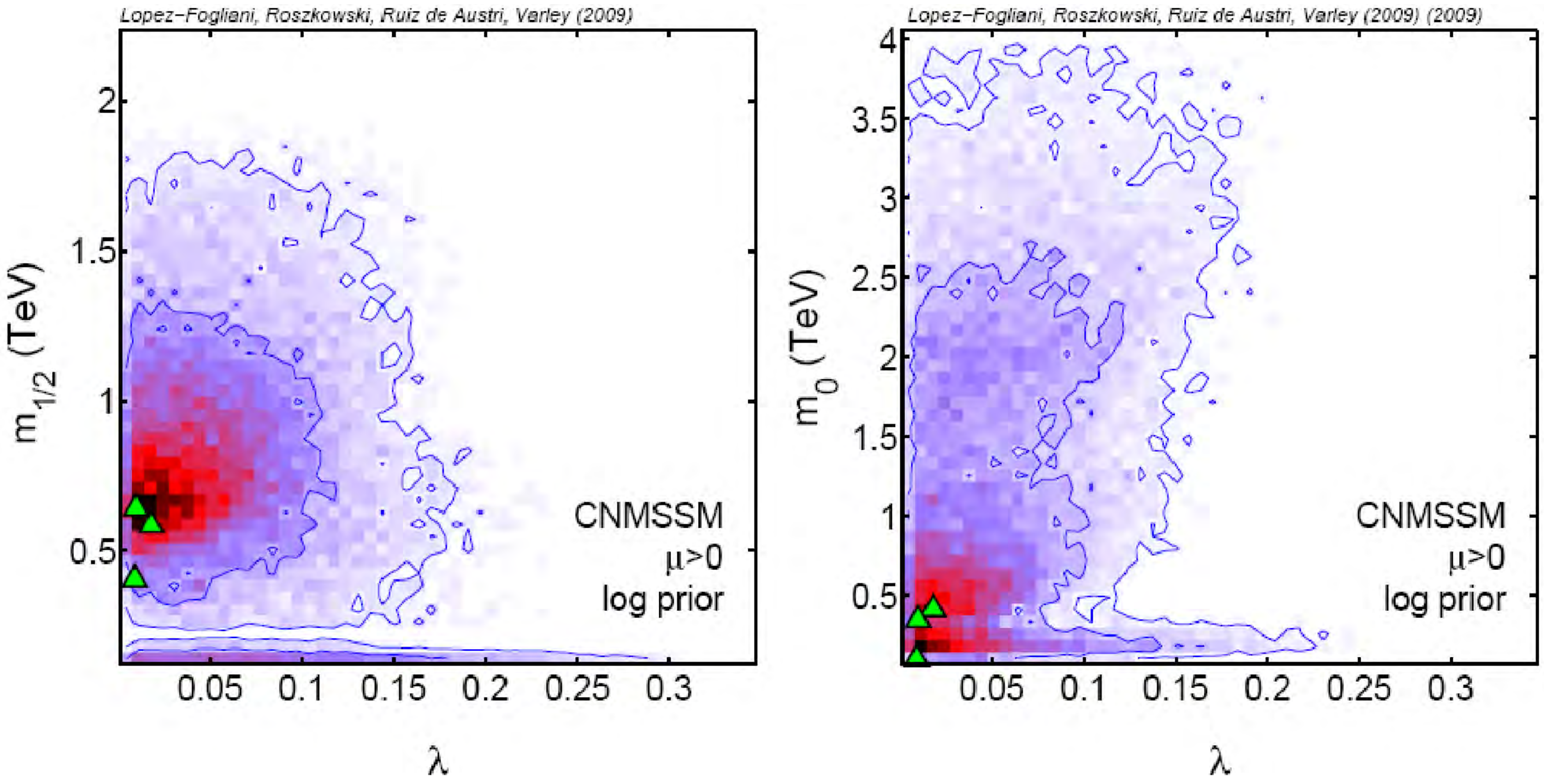




- mSuGra features can be identified: $\tilde{\tau}$ coann., h funnels, focus p, ...

Probability maps for input para

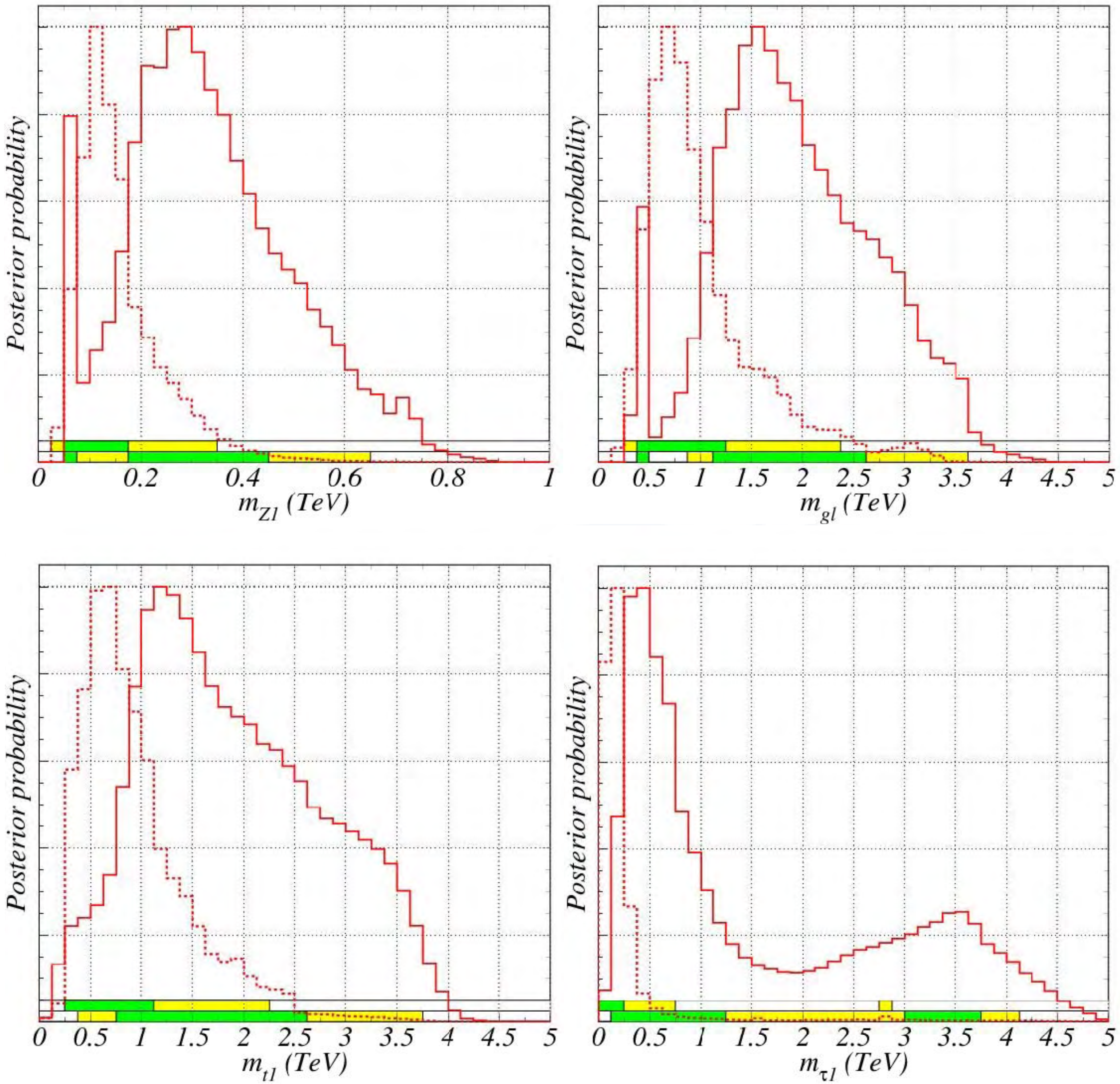
- Do we need this NmSuGra at all?



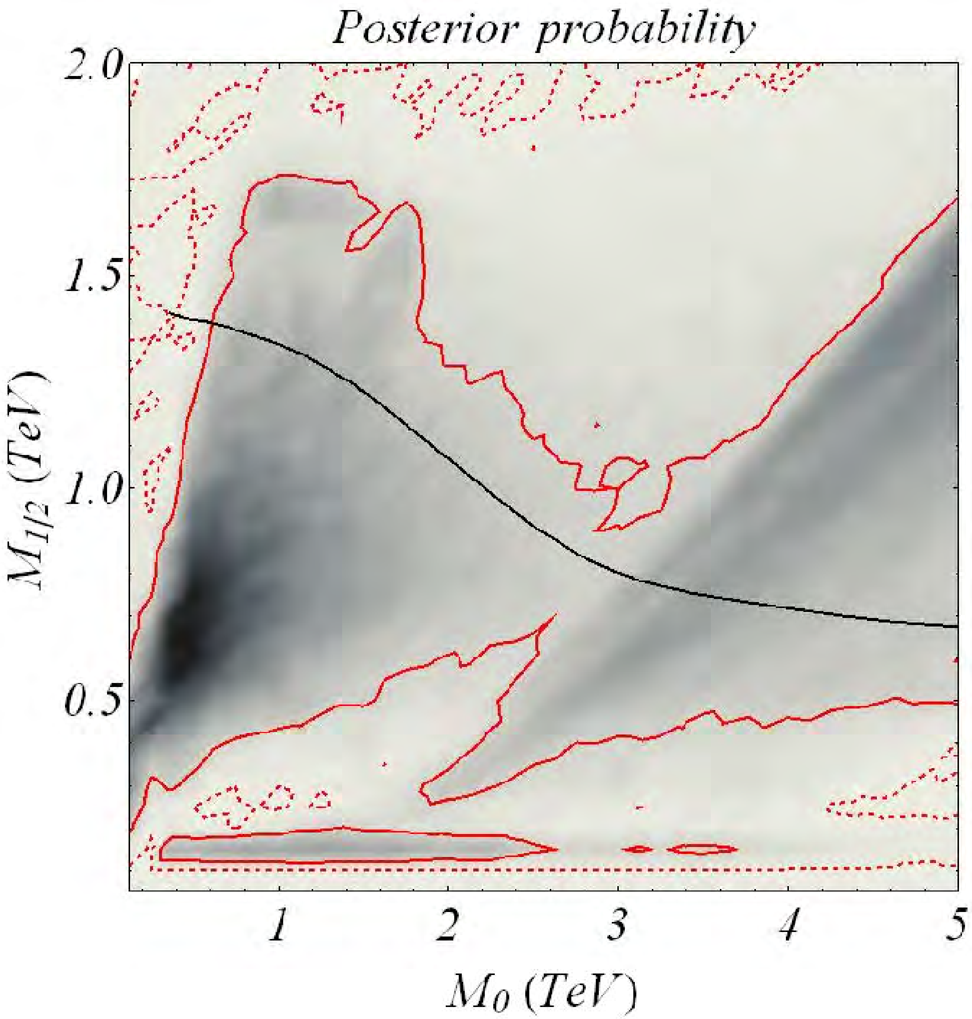
- Data prefer a small λ – just a small deviation from mSuGra!

  Is this a theoretical triumph or an experimental challenge?

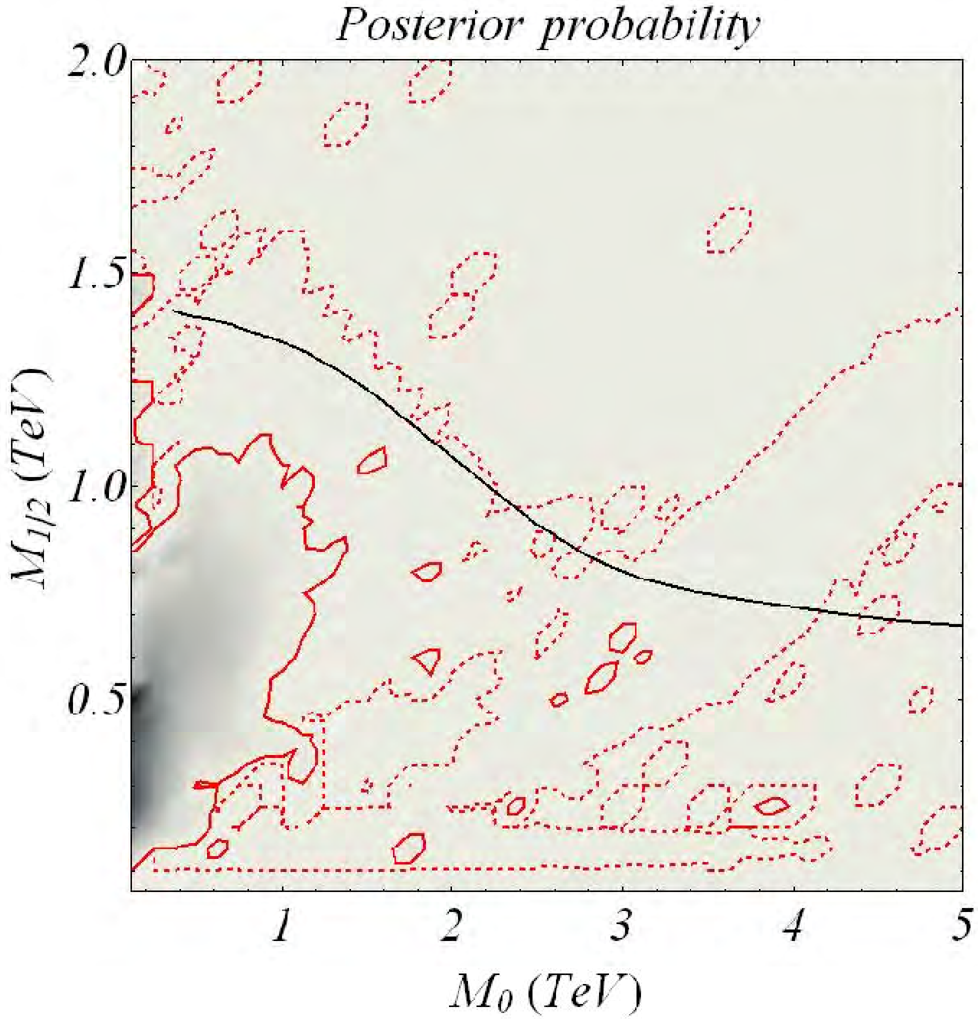
LHC detectability



LHC reach



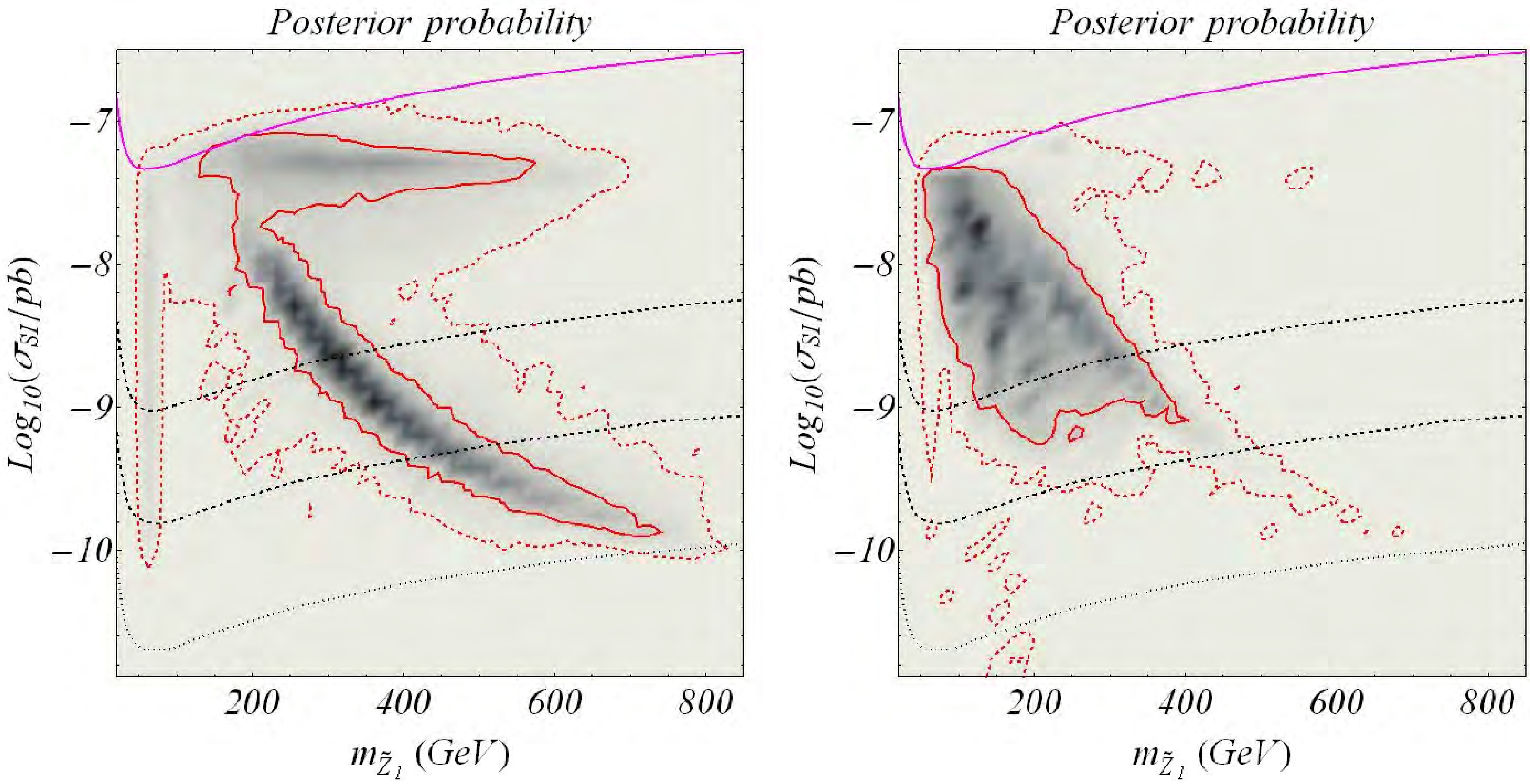
lin prior



log prior

- Part of the focus point is out of the LHC reach!

CDMS reach



lin prior — log prior

- Direct detection experiments complement the LHC well!

Summary

- NmSuGra phenomenology is very similar to that of mSuGra
- (N)mSuGra can be discovered at the LHC except the full FP
- Direct detection experiments reach deep into the FP
- The LHC and near future underground dark matter searches are guaranteed to discover (N)mSuGra
- There's a beautiful complementarity between the LHC and direct dark matter detection experiments

The End