Supersymmetry discovery at the LHC and beyond

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NmSuGra/CNMSSM focus:

Balazs, Carter PRD78 055001 (0808.0770)

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

Balazs, Carter JHEP03 016 (0906.5012)

Balazs, Carter, Farmer in preparation

The logic of discovering SUSY

Aristotelian logic	SUSY discovery
propositions : true or false	SUSY (S) & data (D) : true or false
assumption : $S = \text{true} \Rightarrow D = \text{true}$	SUSY true $\Rightarrow$ certain LHC data D
corollary 1 : $D = \text{false} \Rightarrow S = \text{false}$	data disagrees with S $\Rightarrow S = \text{false}$
corollary 2 : $D = \text{true} \Rightarrow S = ?$	certain LHC data $\Rightarrow$ SUSY ?

- Using this SUSY can be easily excluded but hardly discovered
- Easy to infer data from theory, but hard to go the other way
- We need a logic to infer the existence of SUSY from data

Bayesian inference

Bayesian inference

S = true $\Rightarrow$ D = true does NOT mean D = true $\Rightarrow$ S = true

In terms of conditional probabilities

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

Since the joint probabilities

$$\mathbb{P}(S\&D) = \mathbb{P}(S|D)\ \mathbb{P}(D) \quad \text{and} \quad \mathbb{P}(D\&S) = \mathbb{P}(D|S)\ \mathbb{P}(S)$$

are equal

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

Bayes' theorem

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

can be used to infer the probability of S for given D

SUSY discovery at the LHC

- New physics searches at the LHC start under the lamppost: super symmetry, extra-dimensions, little higgs, strong-dyn, etc.

- The LHC, together with low energy experiments and astrophysical observations, will decide the faith of these models

- How will this "decision" be made?

- One can only decide using a robust technique mapping experimental information to the theoretical Lagrangians

- Bayesian likelihood analysis of supersymmetric models

Outline

- Next-to-minimal SUSY model & supergravity
- Parameter extraction: Reverend Bayes
- Posterior probabilities: Fryer Occam
- LHC detectability and dark matter direct detection

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

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

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 → sign(μ)

$$\mathcal{L}_{soft}^{MSSM} = y_u\, A_0\, H_u \cdot \tilde{Q}\, \tilde{U} - y_d\, A_0\, H_d \cdot \tilde{Q}\, \tilde{D} - y_e\, A_0\, H_d \cdot \tilde{L}\, \tilde{E} + \mu\, B\, \tilde{H}_u \cdot \tilde{H}_d +$$

$$hc. + \frac{1}{2}\, M_0^2\, \tilde{\psi}_j^\dagger\, \tilde{\psi}_j + M_{1/2}\, \tilde{\lambda}_i^*\, \tilde{\lambda}_i$$

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}, 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 prec. 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 μ, hierarchy & fine-tuning problems is: Higgs sector

  extending the EWSB sector of the MSSM, problems alleviated

  in (n,N,S,U)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 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 dim. para.s

Parameter extraction

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

LHC measures a set of data $D = \{d_1, \ldots, d_m\}$

The probability of the parameters acquiring values P is

$$\mathbb{P}(P \mid D) = \frac{\mathbb{L}(D \mid P)\, \mathbb{p}(P)}{\mathbb{E}(D)}$$

- $\mathbb{P}(P|D)$ posterior probability distribution – this is what we want
- $\mathbb{L}(D|P)$ likelihood function – this is what we know
- $\mathbb{p}(P)$ prior – D independent info on P
- $\mathbb{E}(D)$ evidence – here only plays the role of normalization

Likelihood function

$$\mathbb{L}(D|P) = \prod_i \frac{e^{-\chi_i^2/2}}{\sqrt{2\pi}\,\sigma_i} \quad \text{where} \quad \chi_i^2 = \frac{(d_i - t_i(p_i))^2}{\sigma_{i,exp}^2 + \sigma_{i,the}^2} \quad 1 < i < m_{data}$$

- the likelihood is normalized

$$\int \mathbb{L}(D|P)\, dD = 1 \qquad \text{where } dD = \prod_j d d_j$$

Prior

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

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

- for under-constrained fits the prior dependence can be large

  but prior dependence diminishes with increasing amount of data

- the prior distribution is normalized

$$\int \mathbb{p}(P)\, dP = 1 \qquad \text{where } dP = \prod_j d p_j$$

Marginalization and evidence

- 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 inferred probability distributions of the parameters

- Evidence implements Occam's razor

$$\mathbb{E}(D) = \int \mathbb{L}(D|P)\ \mathbb{p}(P)\ dP$$

where

$$\int \mathbb{p}(P)\ dP = 1$$

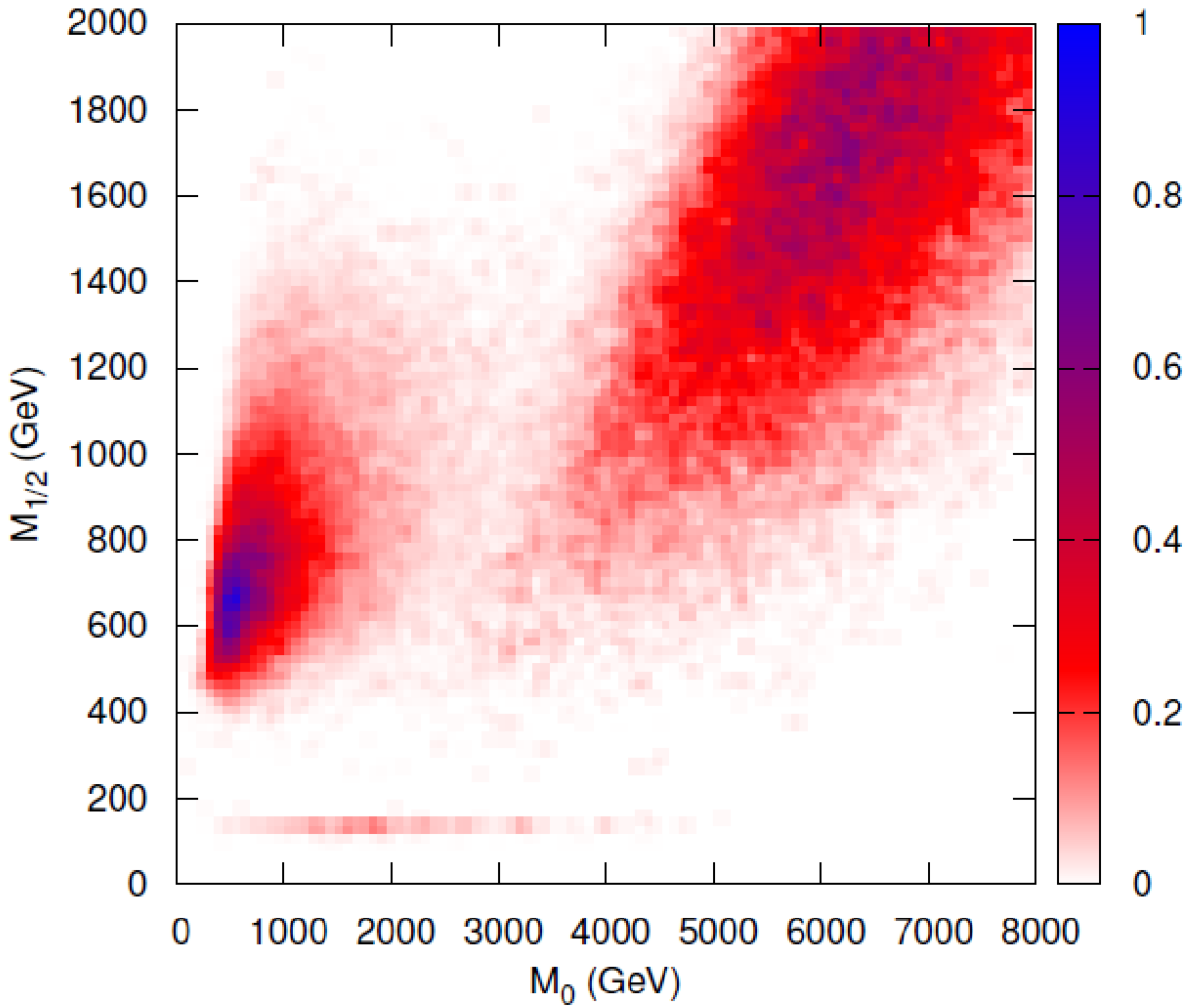
- A model with fewer parameters or smaller para-space has a higher prior leading to a higher evidence (assuming same likelihood)

Experimental input

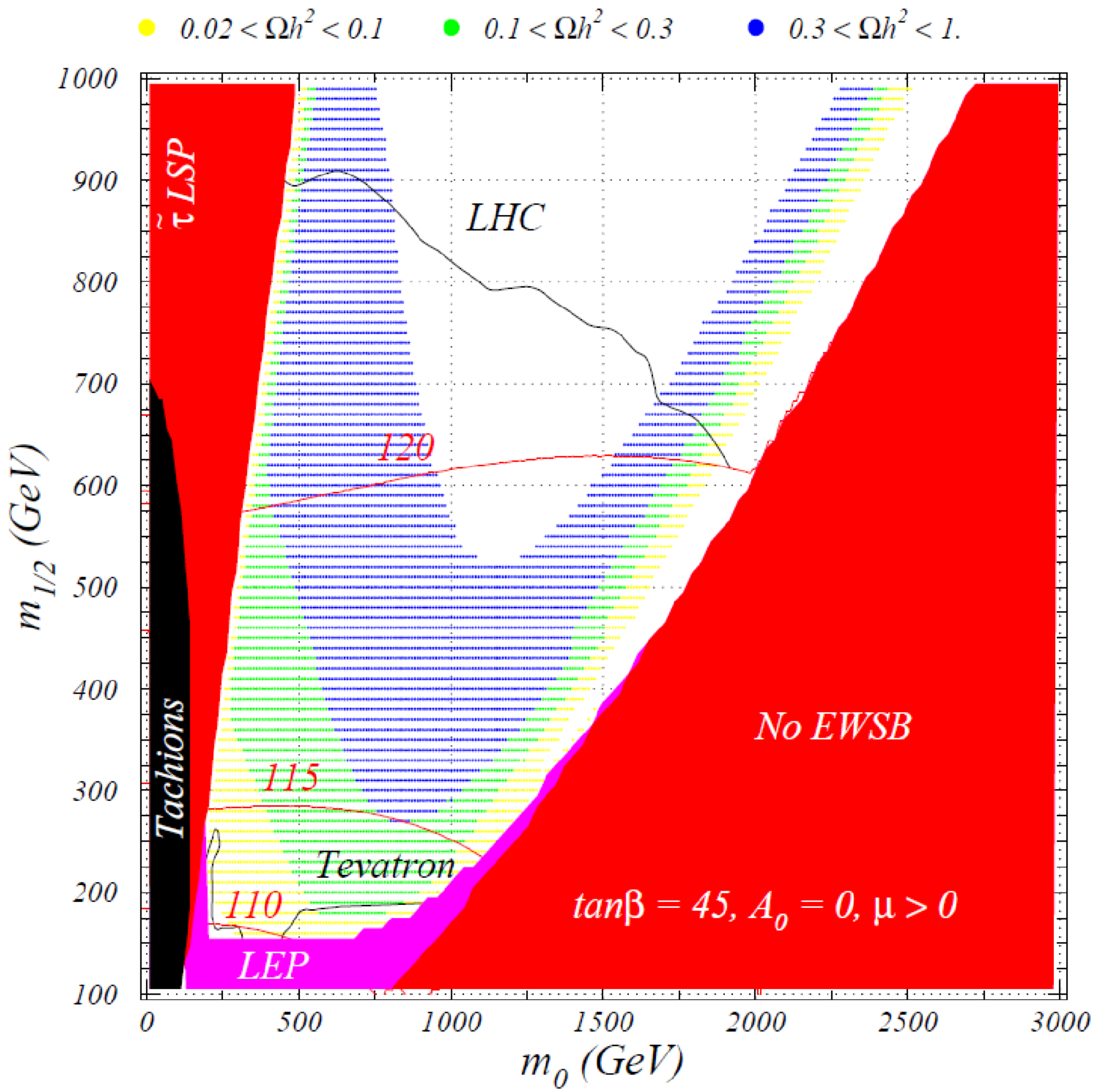
Experimental data, constraining supersymmetry, available today

- LEP — lower limits on spartner, Higgs masses & cross sect.s
  (dozens of bounds - 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 maps: marginalized posteriors for input para

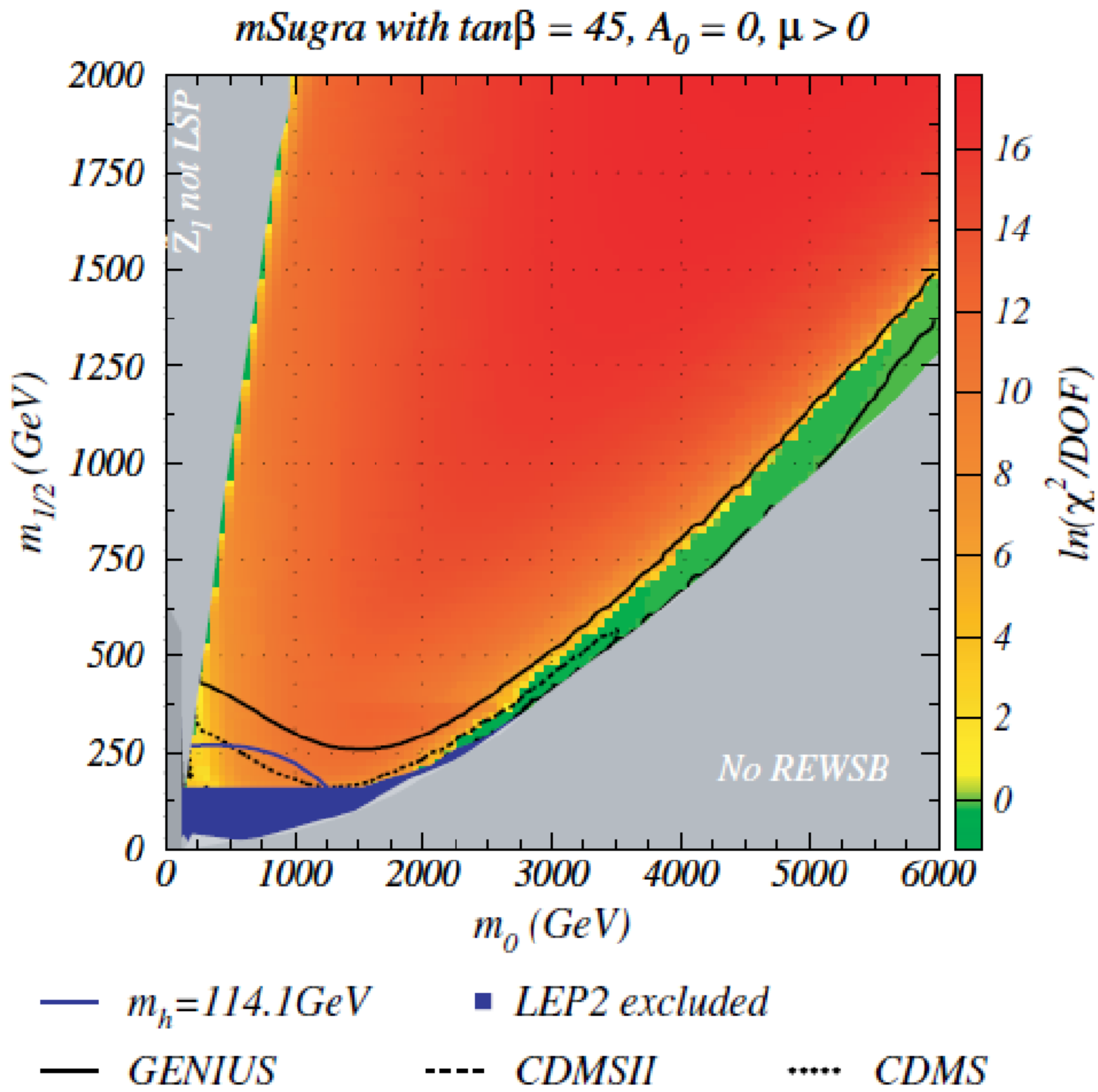


The old way of looking at things



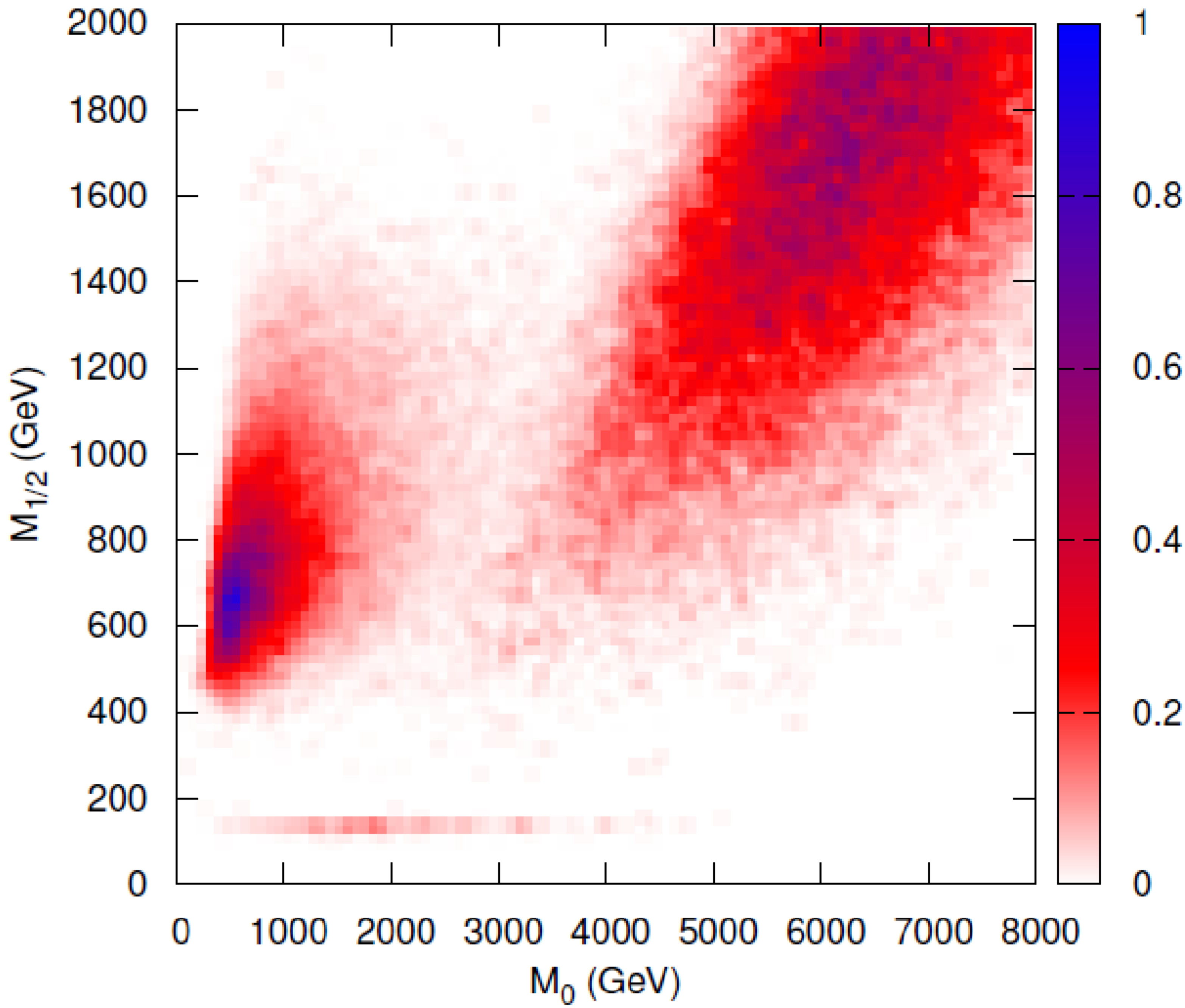
Baer, Balazs ca. 2002

The old way of looking at things

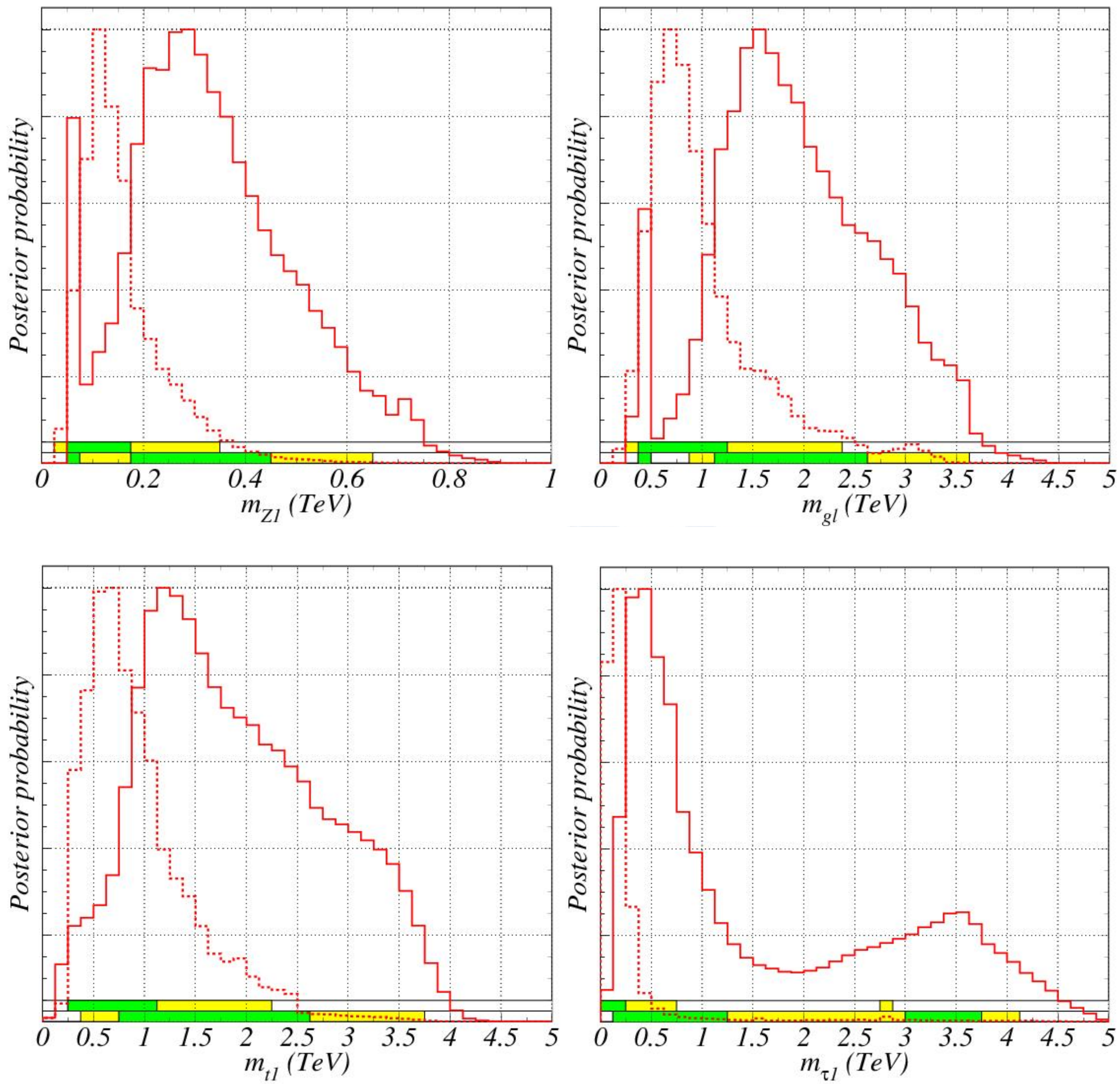


Baer, Balazs ca. 2003

Probability maps: marginalized posteriors for input para

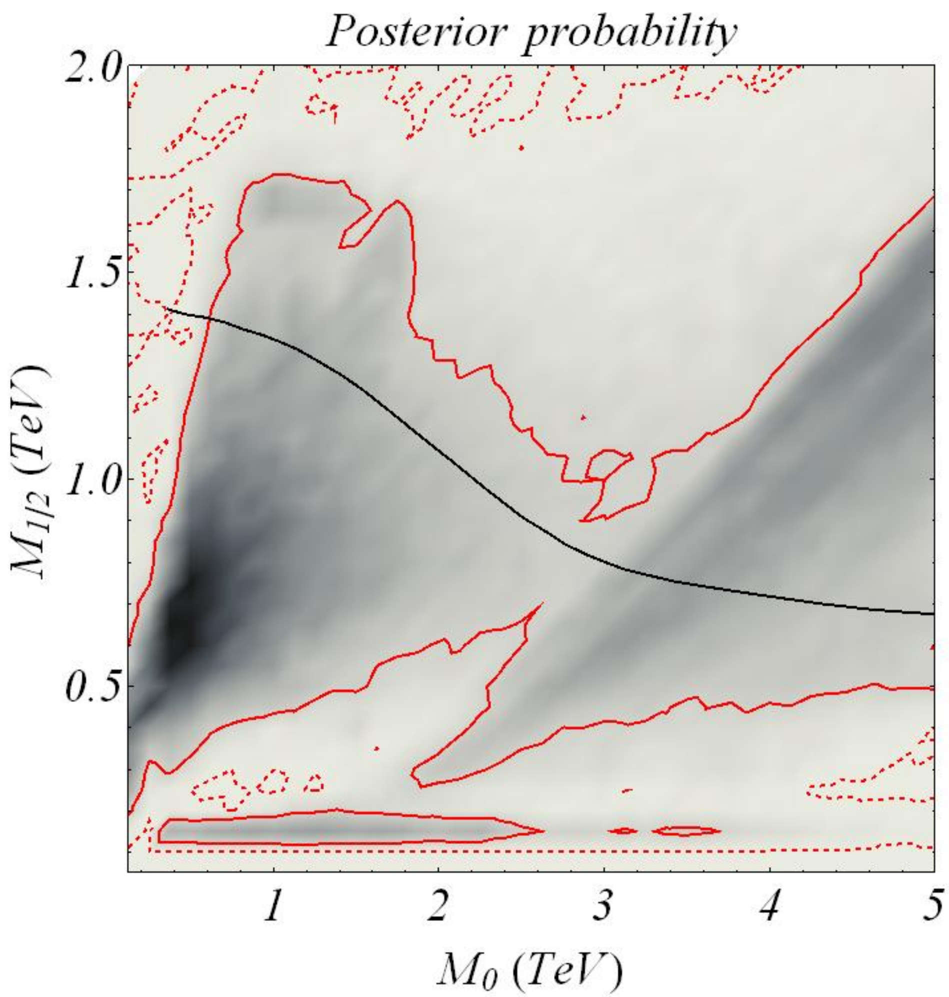


LHC detectability

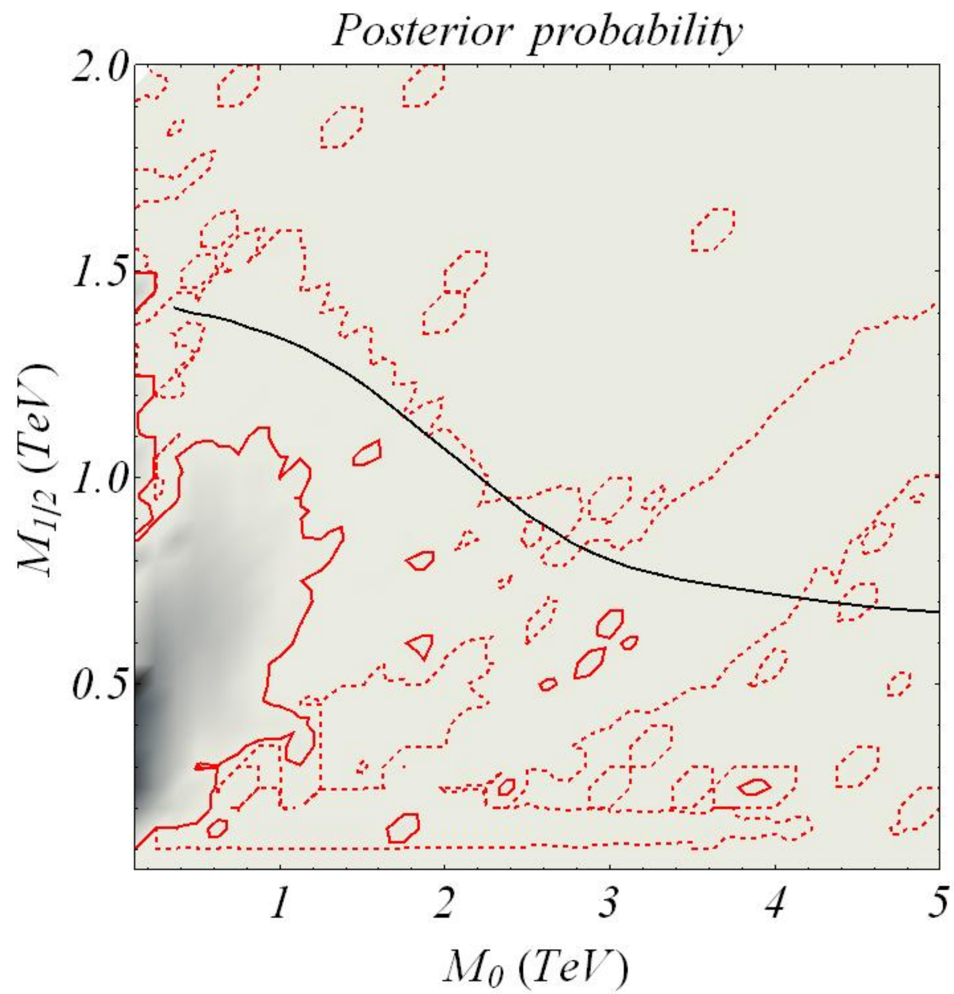


____ lin prior .... log prior

LHC reach



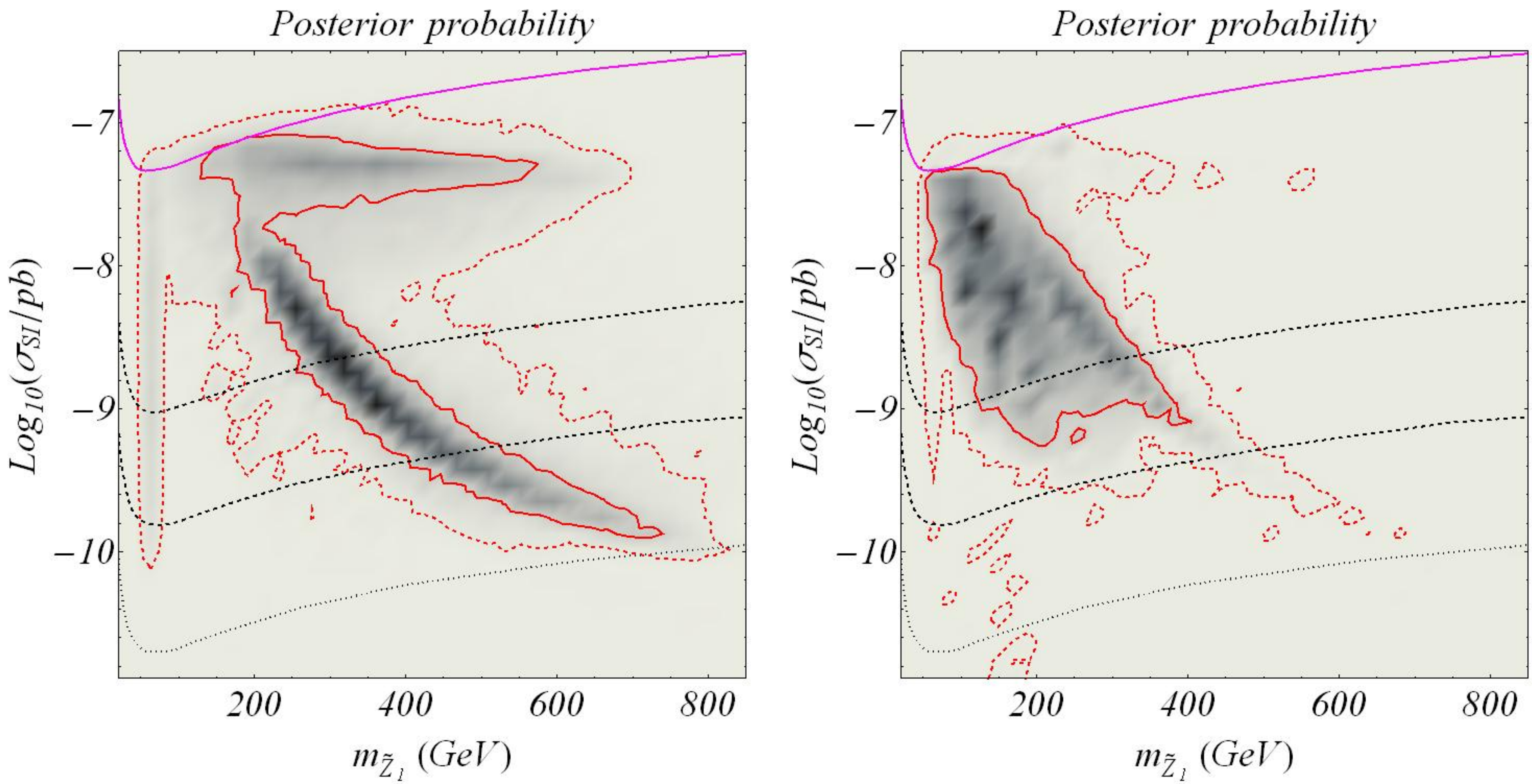
lin prior



log prior

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

CDMS/XENON future reach



lin prior   log prior

- Direct detection experiments complement the LHC well!

Summary

- We have limited experimental information impacting on SUSY
- Bayesian inference already guides us to discover SUSY
- (N)mSuGra can be discovered at the LHC except the full FP
- Direct detection experiments reach deep into the FP
- There's a complementarity between LHC and direct detection
- The LHC and near future underground dark matter searches are guaranteed to discover (N)mSuGra