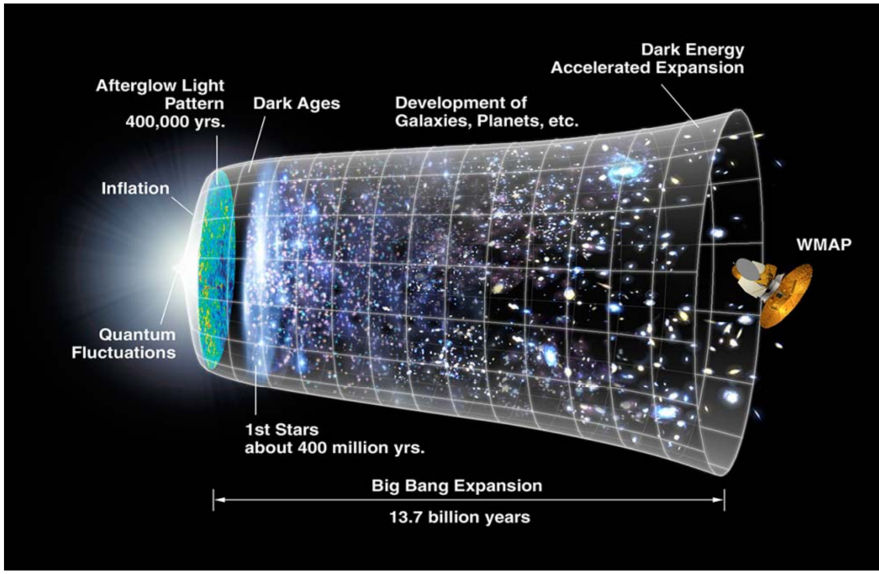
MSSM Inflation and the LHC



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University of New Mexico

GGI mini-Workshop on “LHC and Dark Mattetr”

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Outline:

- Introduction
- Inflation in MSSM
- Properties, predictions, and parameter space
- Cosmology/phenomenology complementarity
- LHC role
- Summary

Introduction:

LHC-Cosmology connection studied in the context of WIMP dark matter:

- See the WIMP (missing energy) and measure its mass
- Make measurements and identify a point in the dark matter allowed region for a given model (e.g., mSUGRA)
- Measure as many parameters as possible, and calculate thermal relic density

How about other connections between LHC & cosmology?

Inflation? (Baryogenesis?)

Some connection between physics of inflation
(or baryogenesis) and TeV scale physics must exist.

Example: Probing TeV scale leptogenesis at the LHC

Blanchet, Chacko, Granor, Mohapatra arXiv:0904.2174

Key: Embedding inflation in TeV scale physics

Most direct connection:

Inflation driven by the visible sector

R.A., Enqvist, Garcia-Bellido, Mazumdar PRL 97, 191304 (2006)

Less direct:

Inflation driven by the SUSY breaking sector

R.A., Dutta, Sinha PRD 81, 083538 (2010)

Inflation in MSSM:

Inflation: a period of superluminal expansion o the universe.

It is driven by a scalar field ϕ (inflaton):

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \qquad\qquad H^2 = \frac{V(\phi)}{3M_P^2}$$

H : Hubble expansion rate

Assumptions:
<u>Canonical kinetic terms</u>, <u>minimal coupling to gravity</u>

Inflation occurs in the slow-roll regime $|\varepsilon|, |\eta| << 1$:

$$\varepsilon \equiv \frac{1}{2} M_P^2 \left(\frac{V'}{V} \right)^2 \qquad\qquad \eta \equiv M_P^2 \frac{V''}{V}$$

Inflation occurs within a field range (ϕ_i, ϕ_e) :

$$\frac{a_e}{a_i} = \exp(N_{tot}) \qquad N_{tot} = \frac{1}{M_P^2}\int_{\phi_i}^{\phi_e} \frac{V}{V'} d\phi$$

a : Scale factor of the universe

$N_{tot} \geq N_{COBE} \approx (30-60)$ needed to explain the isotropy and flatness problems of the big-bang model.

Observable: Density fluctuations (CMB temperature anisotropy).

$$\delta_H = \frac{1}{5\pi}\frac{H^2}{\dot{\phi}} \qquad n_s = 1 + 2\eta - 6\varepsilon$$

Amplitude

$\approx 1.9 \times 10^{-5}$ (COBE)

Scalar spectral index

0.963 ± 0.024 (WMAP7)

MSSM has many scalar fields (Higgses, squarks, sleptons).

Can MSSM lead to inflation?

Answer (naive):
No, slow-roll conditions not satisfied.

Hopeless effort?

NO!

Potential can be made sufficiently flat along various directions in the field space.

Two such directions can lead to successful inflation.

R.A., Enqvist, Garcia-Bellido, Mazumdar PRL 97, 191304 (2006)
R.A., Enqvist, Garcia-Bellido, Jokinen, Mazumdar JCAP 0706, 019 (2007)

Inflaton candidates in MSSM:

$$\varphi = \frac{\tilde{u} + \tilde{d} + \tilde{d}}{\sqrt{3}} \qquad\qquad \varphi = \frac{\tilde{L} + \tilde{L} + \tilde{e}}{\sqrt{3}}$$

(family, color, and weak isospin indices omitted)

Flat directions: $V(\varphi) = 0$ in MSSM with unbroken SUSY.

SUSY breaking+
Higher order terms:

Dine, Randall, Thomas NPB 458, 291 (1996)

$$V(\varphi) = \frac{1}{2} m_\phi^2 \phi^2 + A\lambda \cos(6\theta) \frac{\phi^6}{M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$$

$$\varphi = \frac{\phi}{\sqrt{2}} \exp(i\theta) \qquad\qquad m_\phi, A \sim O(TeV)$$

soft mass A-term

Minimizing the potential along θ :

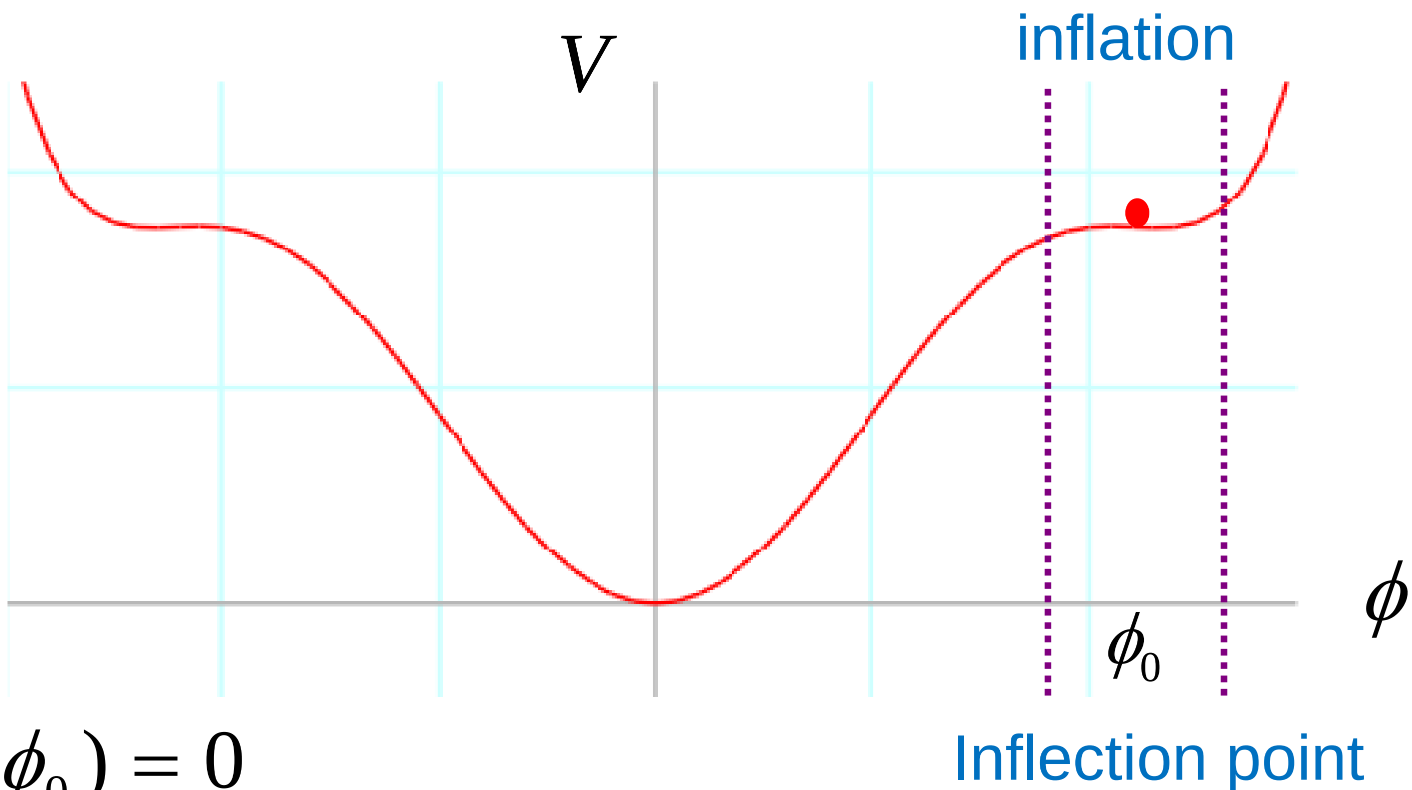
$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - A\lambda \frac{\phi^6}{M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$$

A point of inflection ϕ_0 exists in the potential:

$$\phi_0 \cong \left(\frac{m_\phi M_P^3}{\sqrt{10}\lambda} \right)^{\frac{1}{4}}$$

Provided that:

$$\frac{A^2}{40\, m_\phi^2} \equiv 1 + 4\alpha^2 \qquad (\alpha << 1)$$



$$V''(\phi_0) = 0$$

$$V'(\phi_0) = 4\alpha^2 m_\phi^2 \phi_0$$

$$V(\phi_0) = \frac{4}{15} m_\phi^2 \phi_0^2$$

Properties, Predictions, and Parameter Space:

Density perturbations:

Bueno-Sanchez, Dimopoulos, Lyth   JCAP 0701, 015 (2007)

R.A., Enqvist, Garcia-Bellido, Jokinen, Mazumdar   JCAP 0706, 019 (2007)

$$\delta_H \approx \frac{8}{\sqrt{5}\pi} \frac{m_\phi M_P}{\phi_0^2} \frac{1}{\Delta^2} \sin^2\left[N_{COBE}\Delta\right]$$

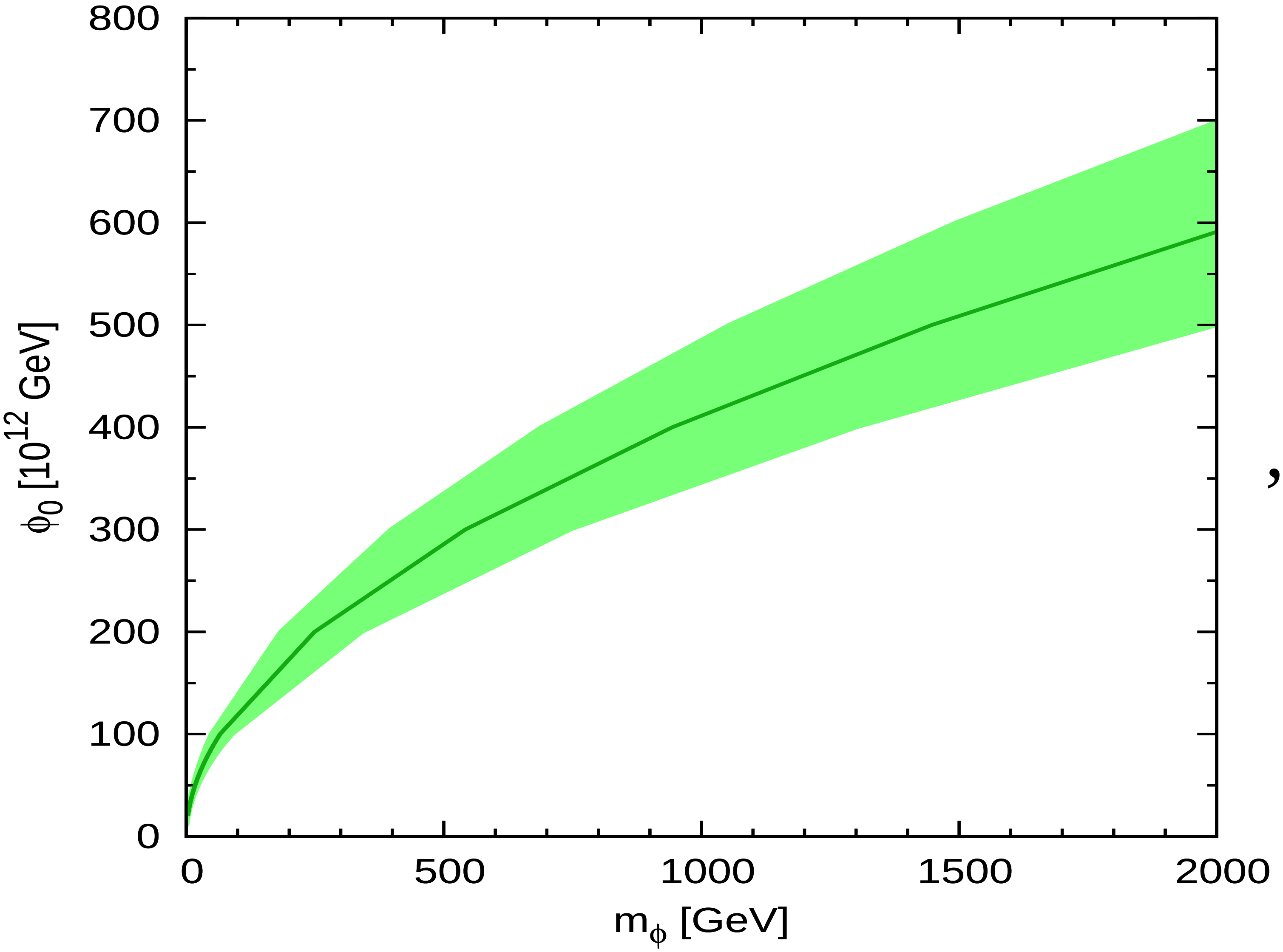
$$n_s = 1 - 4\Delta \cot\left[N_{COBE}\Delta\right]$$

$$N_{COBE} \approx 66.9 + \frac{1}{4}\ln\left(\frac{V(\phi_0)}{M_P^4}\right)$$

$$\Delta \equiv 30\alpha \;\; N_{COBE}\left(\frac{M_P}{\phi_0}\right)^2 \qquad \qquad \frac{A^2}{40\, m_\phi^2} \equiv 1 + 4\alpha^2$$

Allowed parameter space to generate acceptable perturbations:

$$(\delta_H \approx 1.9\times 10^{-5}, n_s = 0.963 \pm 0.024)$$



$$, \Delta \leq 10^{-6}$$

Important properties:

1) n_s within <u>the whole range</u> allowed by WMAP can be generated (unlike other models of inflation).

2) Creation of matter after inflation is guaranteed, and can be treated reliably (inflaton is a linear combination of sparticles).

3) CMB data alone cannot pinpoint the inflaton parameters (unlike other models of inflation).

Two observables: δ_H, n_s
Three parameters: m_ϕ, A, λ (can be traded for m_ϕ, ϕ_0, Δ)

<u>Other experiments required to fix inflaton parameters</u>

Cosmology/Phenomenology Complementarity:

The inflaton mass can be connected to low energy masses or input masses via RGEs.

$$\phi = \frac{\tilde{u} + \tilde{d} + \tilde{d}}{\sqrt{3}} \qquad \Rightarrow m_\phi^2 = \frac{m_{\tilde{u}}^2 + m_{\tilde{d}}^2 + m_{\tilde{d}}^2}{3}$$

$$\phi = \frac{\tilde{L} + \tilde{L} + \tilde{e}}{\sqrt{3}} \qquad \Rightarrow m_\phi^2 = \frac{m_{\tilde{L}}^2 + m_{\tilde{L}}^2 + m_{\tilde{e}}^2}{3}$$

M_1, M_2, M_3 : gaugino masses

g_1, g_2, g_3 : gauge couplings

$$\phi = \frac{\tilde{u} + \tilde{d} + \tilde{d}}{\sqrt{3}}:$$ R.A., Dutta, Mazumdar PRD 75, 075018 (2007)

$$\mu \frac{dm_\phi^2}{d\mu} = -\frac{1}{6\pi^2}\left(4M_3^2 g_3^2 + \frac{2}{5}M_1^2 g_1^2\right)$$

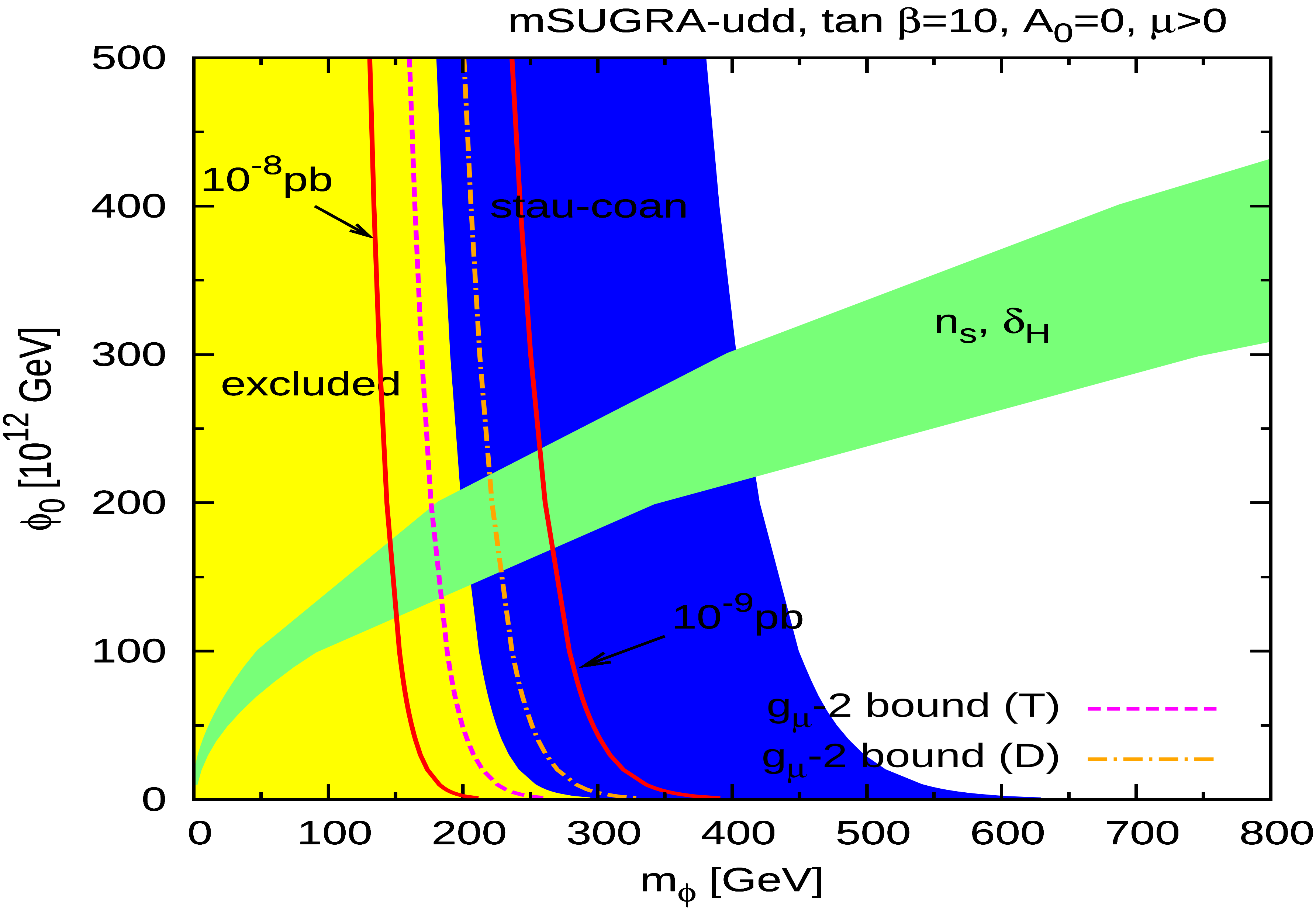
$$\mu \frac{dA}{d\mu} = -\frac{1}{4\pi^2}\left(\frac{16}{3}M_3 g_3^2 + \frac{8}{5}M_1 g_1^2\right)$$

$$\phi = \frac{\tilde{L} + \tilde{L} + \tilde{e}}{\sqrt{3}}:$$

$$\mu \frac{dm_\phi^2}{d\mu} = -\frac{1}{6\pi^2}\left(\frac{3}{2}M_2^2 g_2^2 + \frac{9}{10}M_1^2 g_1^2\right)$$

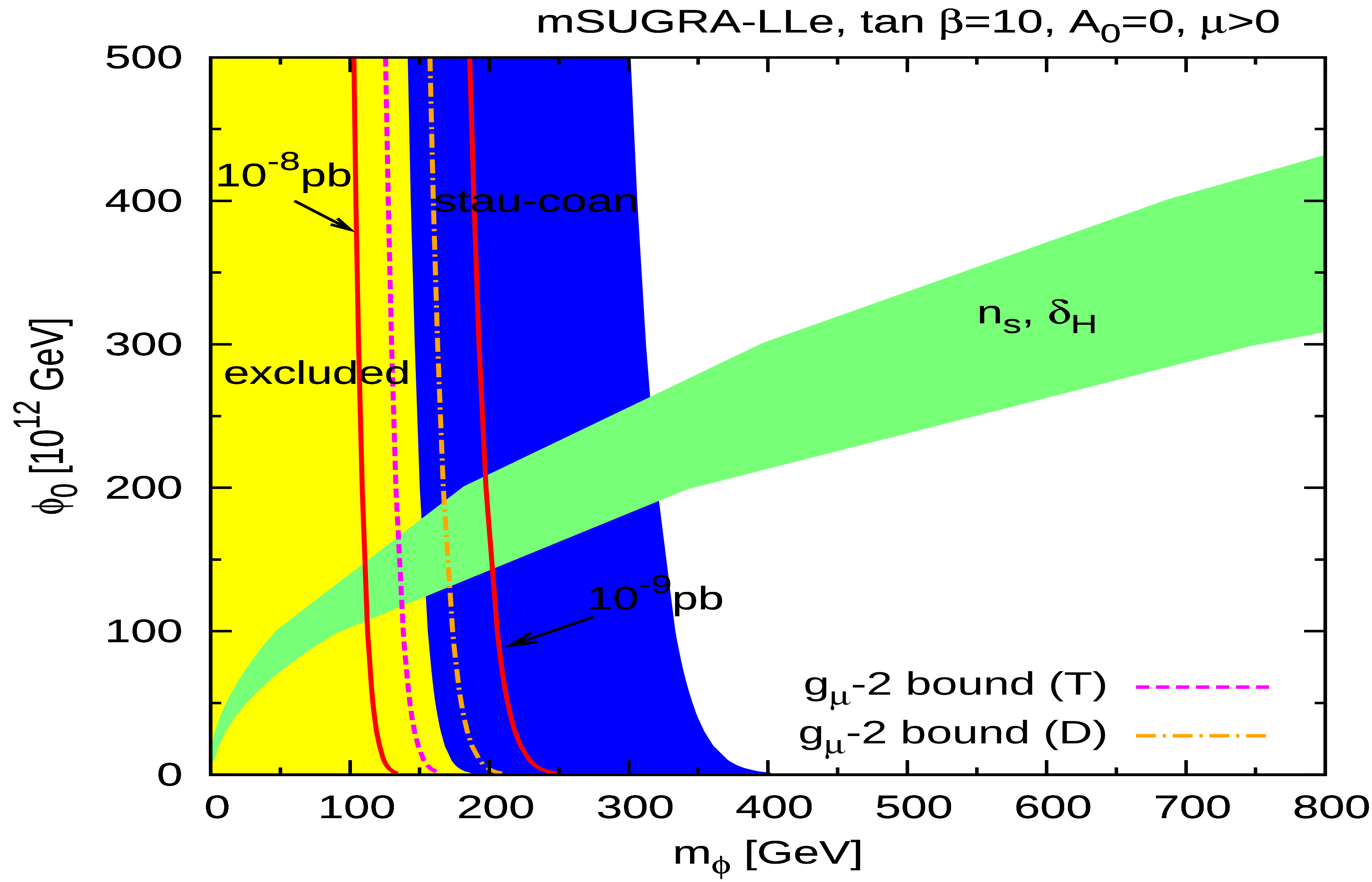
$$\mu \frac{dA}{d\mu} = -\frac{1}{4\pi^2}\left(\frac{3}{2}M_2 g_2^2 + \frac{9}{5}M_1 g_1^2\right)$$

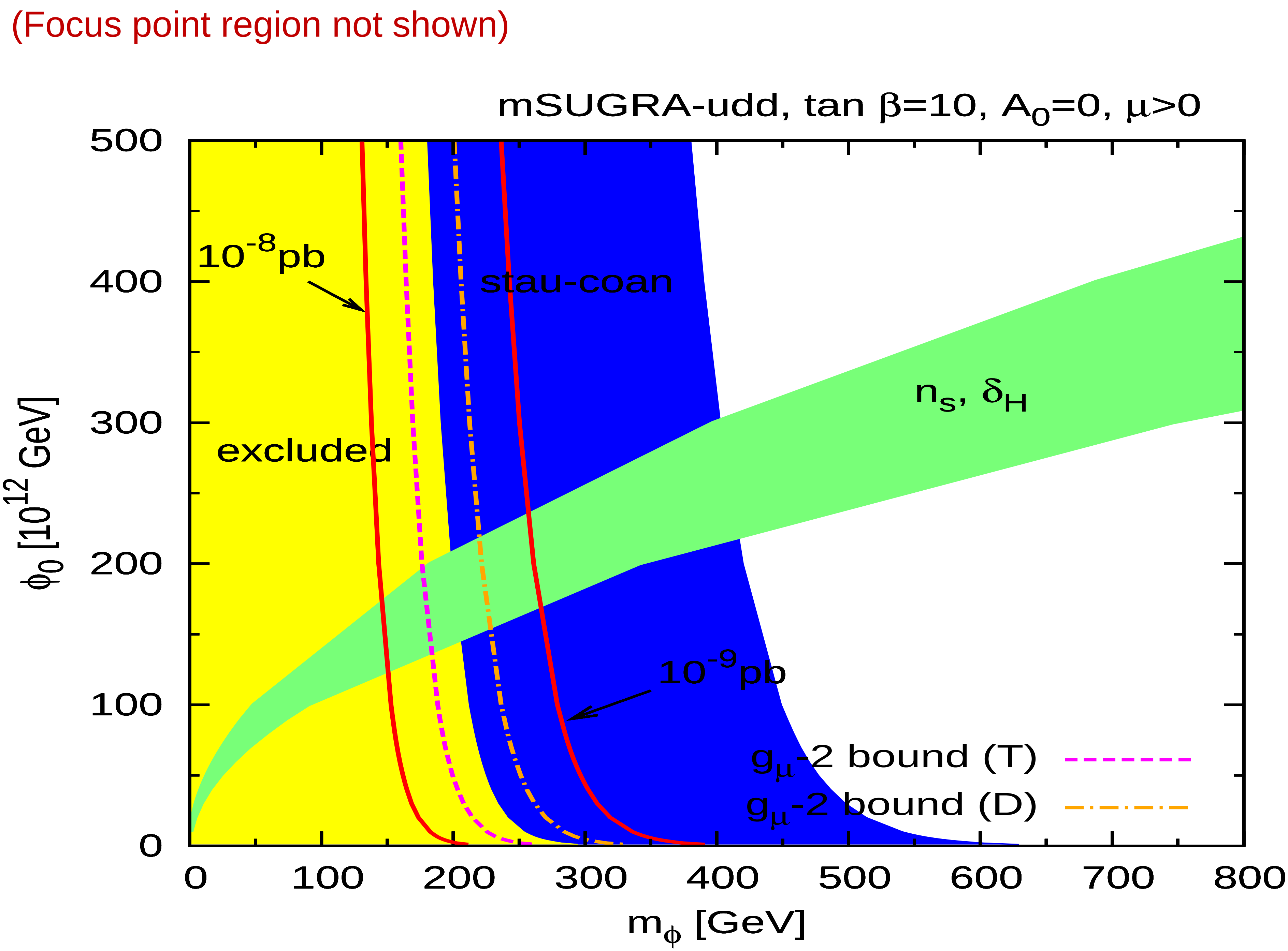
The RGEs can be used to map mSUGRA parameter space into $m_\phi - \phi_0$ plane: R.A., Dutta, Santoso arXiv:1004.2741



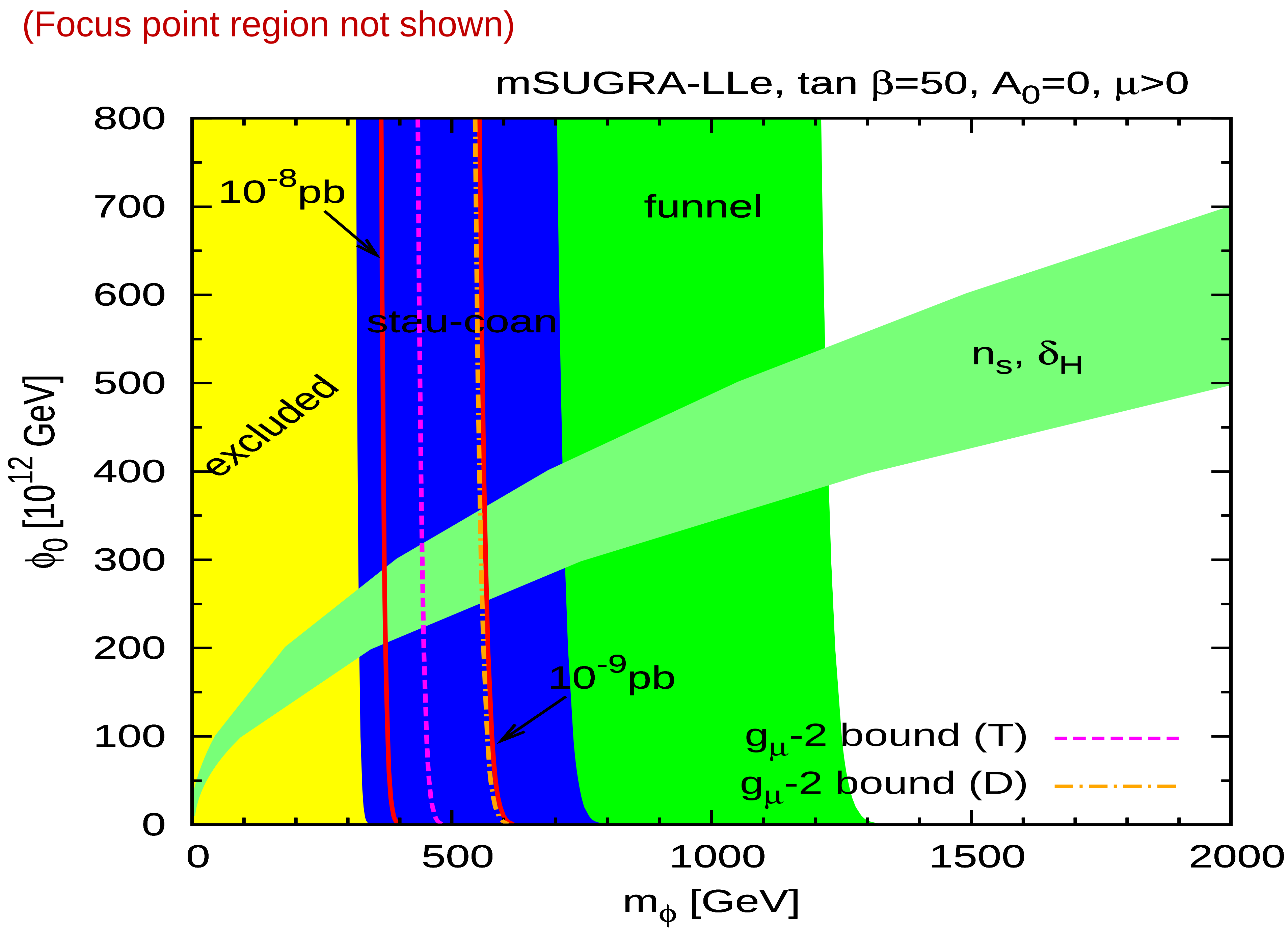
(T): Teubner, *et al* arXiv:1001.5401

(D): Davier, *et al* arXiv:1004.2741





(Focus point region not shown)
mSUGRA-udd, tan β=10, A0=0, μ>0
10-8pb
stau-coan
ns, δH
excluded
10-9pb
gμ-2 bound (T)
gμ-2 bound (D)
φ0 [10^12 GeV]
mφ [GeV]
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800



(Focus point region not shown)
mSUGRA-LLe, tan β=50, A0=0, μ>0
10-8pb
10-9pb
funnel
stau-coan
excluded
ns, δH
gμ-2 bound (T)
gμ-2 bound (D)
φ0 [10^12 GeV]
mφ [GeV]
0
100
200
300
400
500
600
700
800
0
500
1000
1500
2000

LHC Role:

Mass measurements at the LHC can also be used to constrain $m_\phi - \phi_0$ plane.

Consider a SUSY reference point in the co-annihilation region (all masses are in GeV):

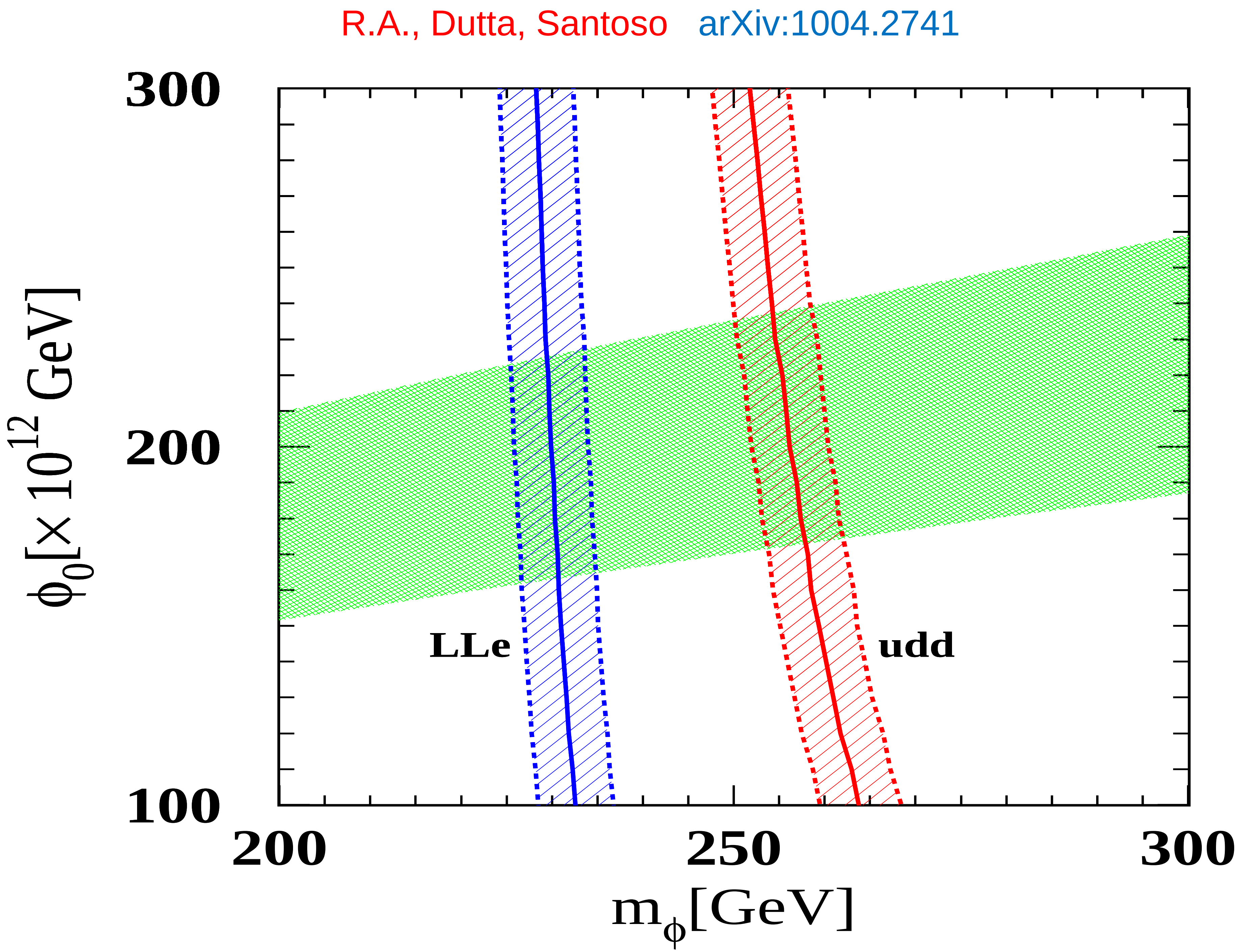
$$m_0 = 210, m_{1/2} = 350, \tan\beta = 40, A_0 = 0$$

$$\Rightarrow m_{\chi_1^0} = 140.7, m_{\tilde{\tau}_1} = 151.3, m_{\tilde{\tau}_2} = 329$$

With $10\ fb^{-1}$ of data, LHC can determine high energy parameters:

$$m_0 = 210 \pm 4, m_{1/2} = 350 \pm 4, \tan\beta = 40 \pm 1, A_0 = 0 \pm 16$$

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback PRL 100, 231802 (2006)


R.A., Dutta, Santoso arXiv:1004.2741
300
200
100
200
250
300
$\phi_0[\times 10^{12}$ GeV]
m_ϕ[GeV]
LLe
udd

General approach:

1) Find SUSY.

2) Measure as many masses as possible (sparticles, gauginos).

3) Use RGEs to extrapolate the inflaton mass to high scales.

4) Narrow down the allowed region in $m_\phi - \phi_0$ plane.

5) Use this to find λ, A .

(Information about the underlying physics giving rise to higher order term, SUSY breaking sector?)

Summary:

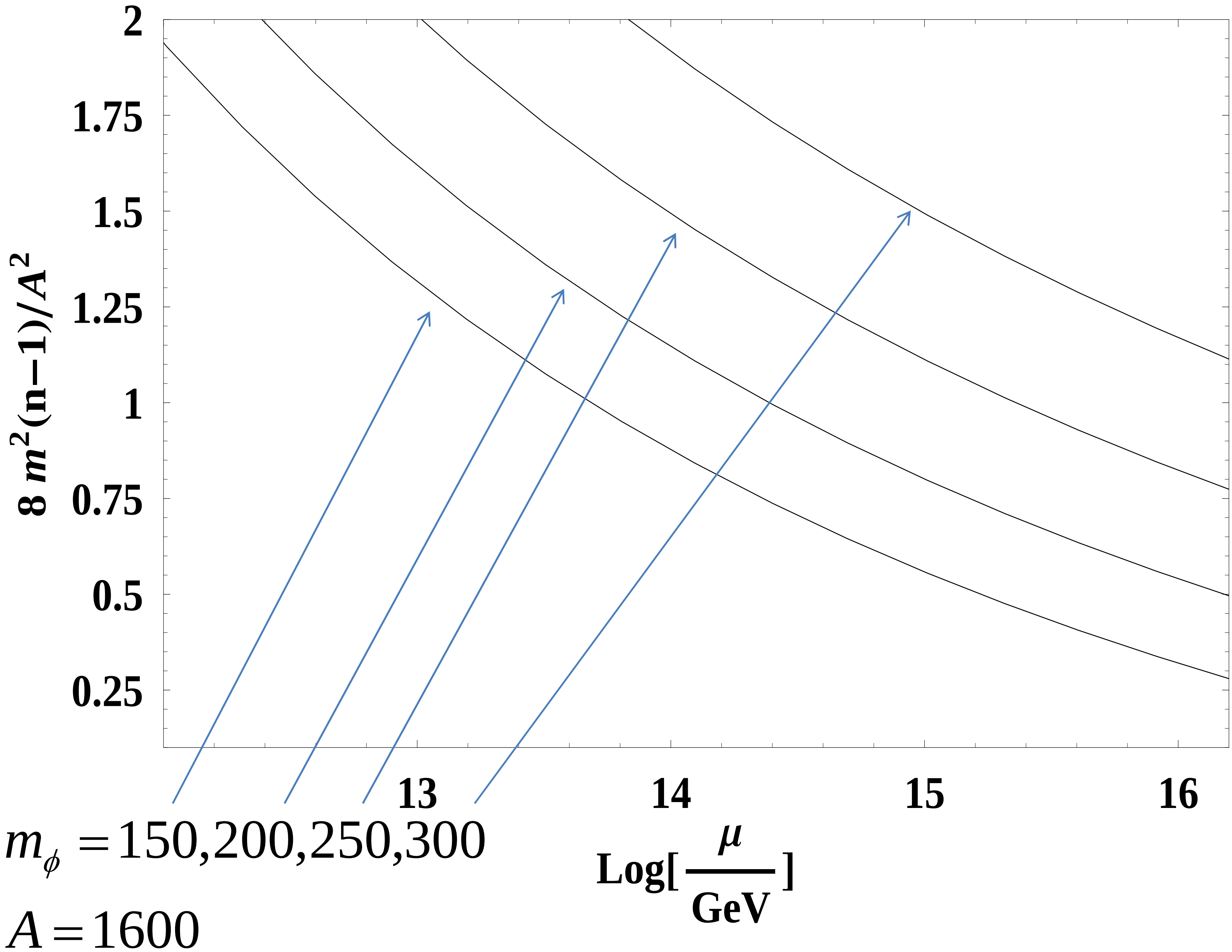
- MSSM can lead to inflation, provides the first example of LHC-inflation connection.

- MSSM inflation has three underlying parameters. CMB measurements alone cannot pinpoint them.

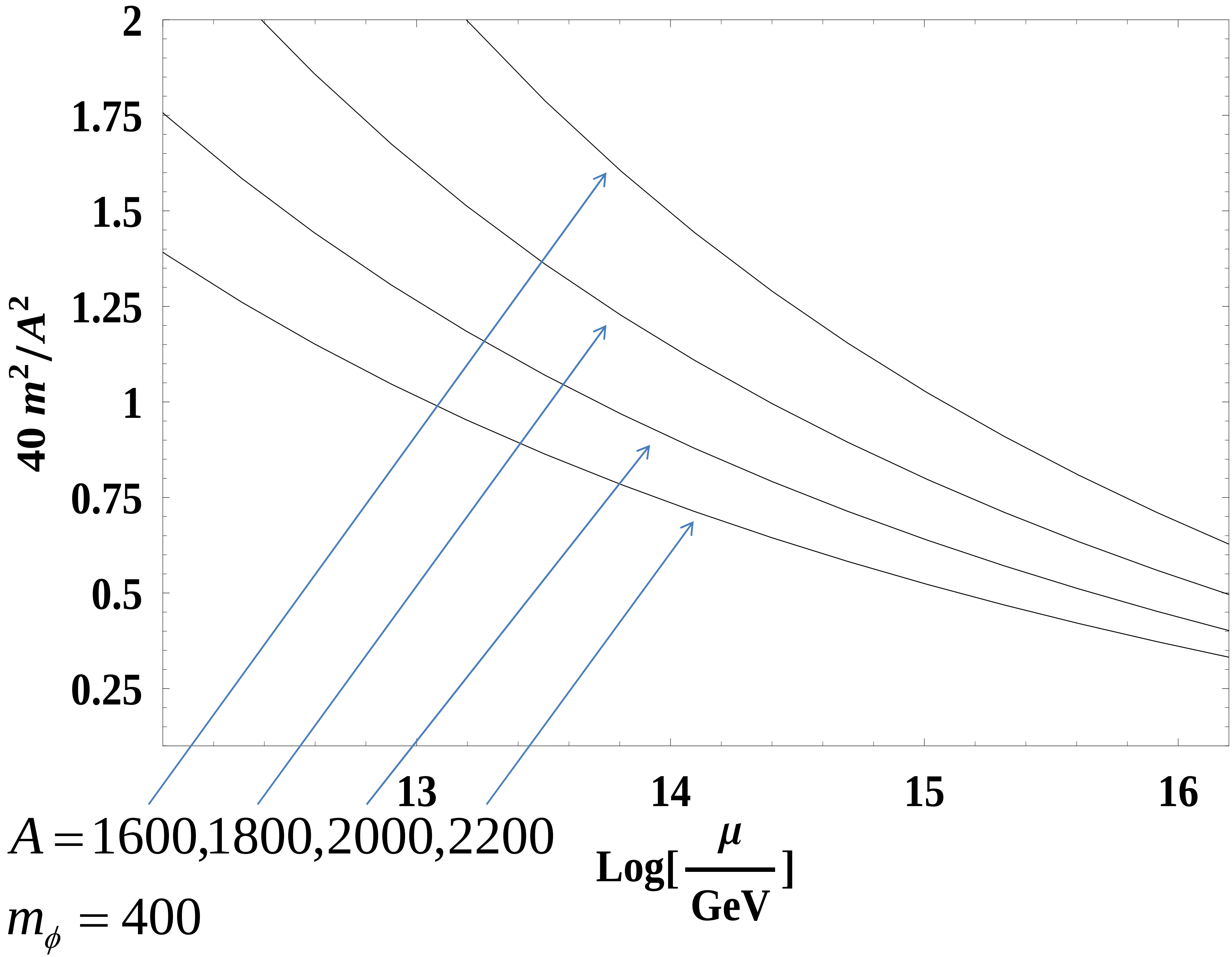
- Particle physics experiments are needed to determine the parameters.

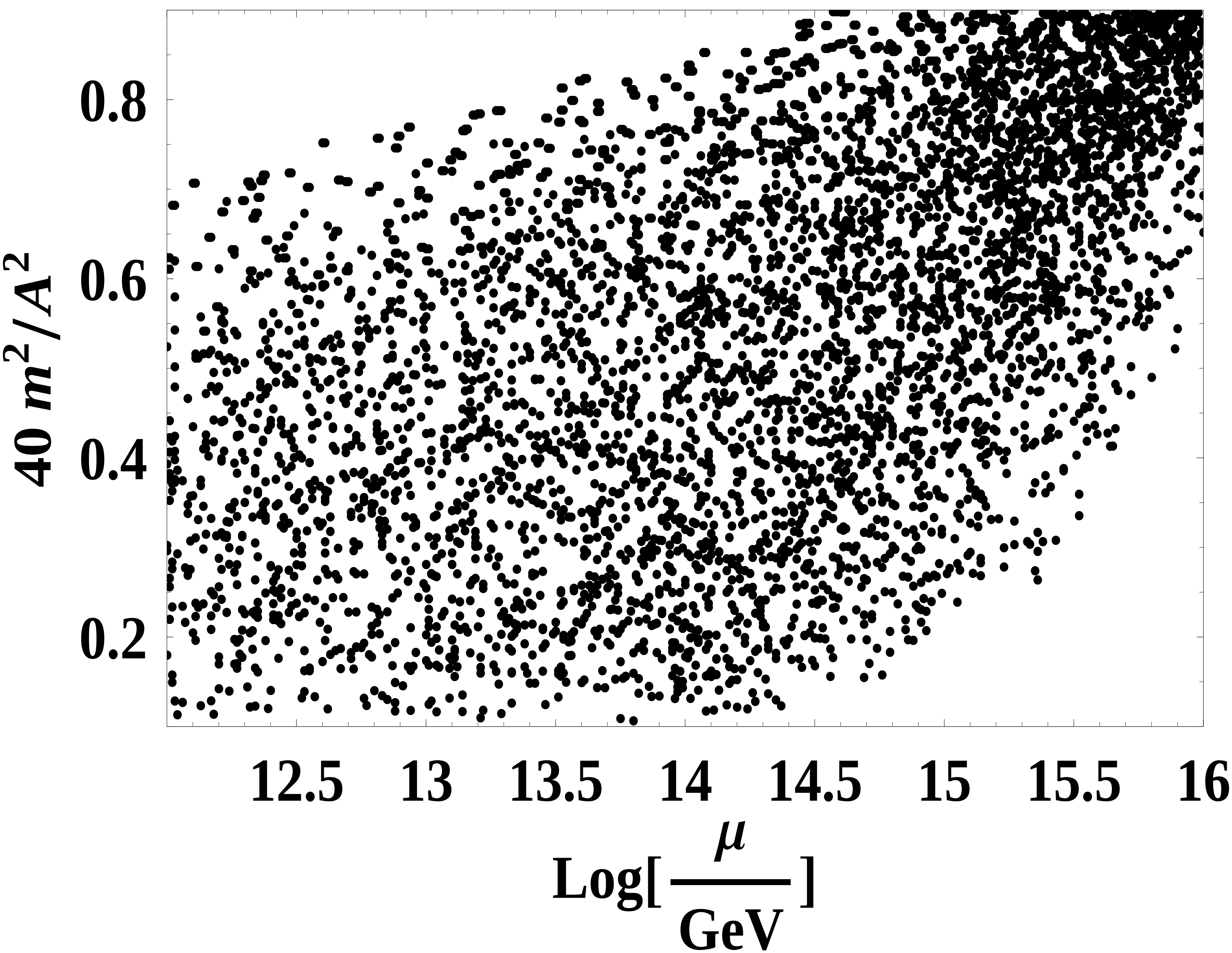
- Dark matter plus muon $g-2$ can significantly narrow down the allowed parameter space.

- Mass measurements at the LHC are important. Combined LHC/ILC and PLANCK data can lead to precise determination of the parameters.



2
1.75
1.5
1.25
1
0.75
0.5
0.25
$8\, m^2(\mathrm{n}-1)/A^2$
13
14
15
16
$\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$
$m_\phi = 150, 200, 250, 300$
$A = 1600$


2
1.75
1.5
1.25
1
0.75
0.5
0.25
$40\ m^2/A^2$
13
14
15
16
$\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$
$A = 1600, 1800, 2000, 2200$
$m_\phi = 400$



0.8
0.6
0.4
0.2
$40\ m^2/A^2$
12.5
13
13.5
14
14.5
15
15.5
16
$\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$