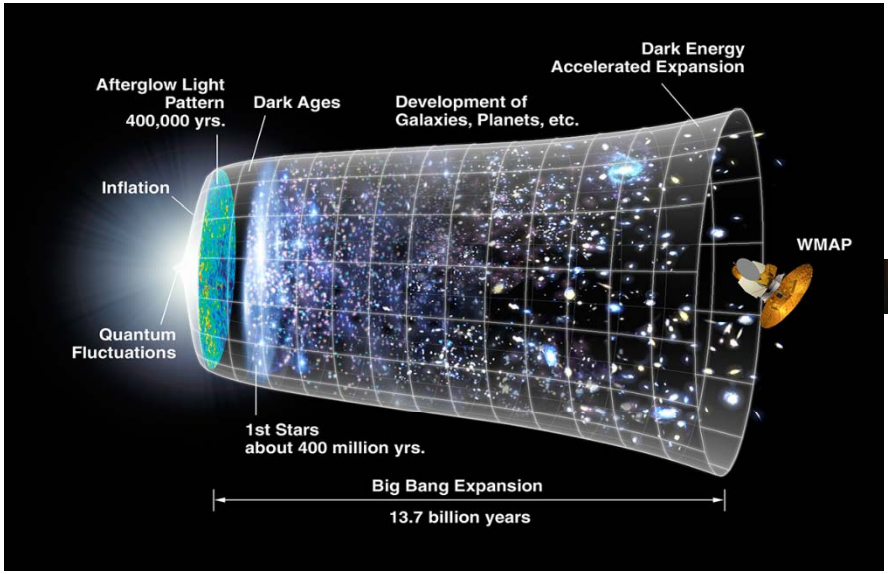
Inflation and the LHC



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Santa Fe 2010 Summer Workshop
“LHC: From Here to Where? ”
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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

Nojiri, Polesello, Tovey JHEP 0603, 063 (2005)
Baltz, Battaglia, Peskin, Wizanski PRD 74, 103521 (2006)
Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback PRL 100, 231802 (2008)

How about other connections between LHC & cosmology?

Standard Cosmological Model: **LCDM**
\+ **Inflation** (the best paradigm of the early universe cosmology)

Some connection between the models and TeV scale physics must exist.

Example: Probing TeV scale leptogenesis at the LHC
Blanchet, Chacko, Granor, Mohapatra arXiv:0904.2174

Lets focus on inflation.

LHC connection suggests low scale models of inflation
Key: Embedding inflation in TeV scale physics

Most direct connection:
Inflation driven by the visible sector

Example:
MSSM inflation

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

One can

- Directly probe the physics of inflation at colliders
- Use particle physics to constrain inflation parameters
- Reliably describe post-inflationary processes

Less direct:

Inflation driven by the SUSY breaking sector

Example:

Kahler modulus inflation

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

One can probe

- Predictions of inflation for sparticle masses
- New particles required for a successful post-inflation

R.A., Dutta, Sinha   arXiv:1005.2804

Inflation: a period of superluminal expansion o the universe.

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

Assumptions:
Canonical kinetic terms, minimal coupling to gravity

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

H : Hubble expansion rate

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

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

Slow-roll 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 <u>isotropy</u> and <u>flatness</u> problems of the big-bang model.

Observable: Density fluctuations (CMB temperature anisotropy).

$$\delta_H = \frac{1}{5\pi} \frac{1}{\sqrt{2\varepsilon}} \frac{H_{\inf}}{M_P} \qquad n_s = 1 + 2\eta - 6\varepsilon$$

Amplitude

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

Scalar spectral index

0.963 ± 0.024 (WMAP7)

Slow-roll inflation possible for $H_{\inf} \leq 10^{13}\ GeV$.

In low-scale inflation $H_{\inf} << 10^{13}\ GeV$.

Then generating correct δ_H requires that:

$$|\varepsilon| << 1$$

$$\Rightarrow n_s \approx 1 + 2\eta \Rightarrow$$

$$|\eta| << 1$$

The second condition naturally satisfied near a point of inflection.

Inflection point inflation provides a suitable framework for low scale models.

Inflation in MSSM:

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

Can MSSM lead to inflation?

Naive answer is “no”:
slow-roll conditions not satisfied for TeV scale masses and known Yukawa couplings.

BUT:
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 are two flat directions:

$$\varphi = \frac{\tilde{u}_i^{\alpha} + \tilde{d}_j^{\beta} + \tilde{d}_k^{\gamma}}{\sqrt{3}} \qquad\qquad \varphi = \frac{\tilde{L}_i^{a} + \tilde{L}_j^{b} + \tilde{e}_k}{\sqrt{3}}$$

$$\alpha \neq \beta \neq \gamma, j \neq k \qquad\qquad a \neq b, i \neq j \neq k$$

$$1 \leq i, j \leq 3 \quad 1 \leq \alpha, \beta, \gamma \leq 3 \quad 1 \leq a, b \leq 2$$

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

Lifted by SUSY breaking and higher order superpotential terms:

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

$$W \supseteq \lambda \frac{\varphi^6}{6M_P^3}$$

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

$$\varphi=\frac{\phi}{\sqrt{2}}\exp(i\theta)$$

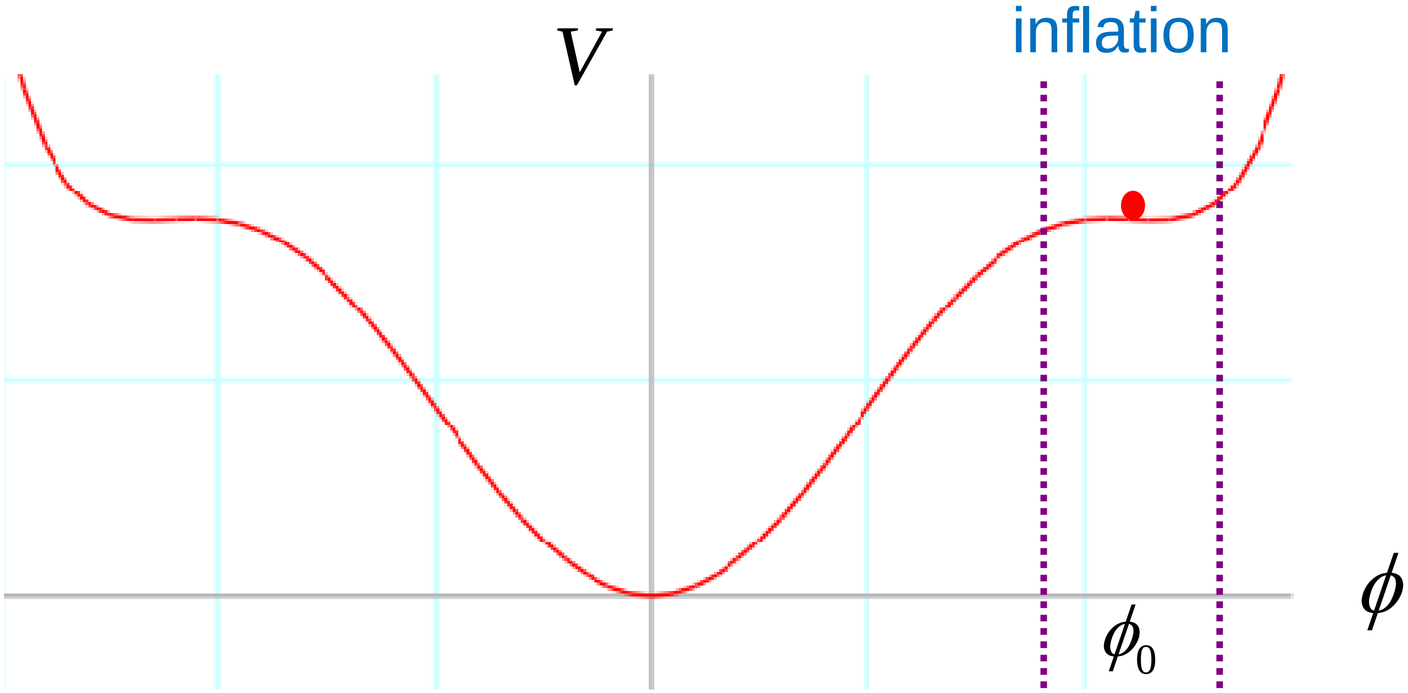
$$m_{\phi}, A\sim O(TeV)$$

soft mass A-term

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

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

$$\alpha<<1\Rightarrow\ \phi_{0}\cong\left(\frac{m_{\phi}M_{P}^{3}}{\sqrt{10\lambda}}\right)^{\frac{1}{4}}$$ is a point of inflection



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

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

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

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)

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

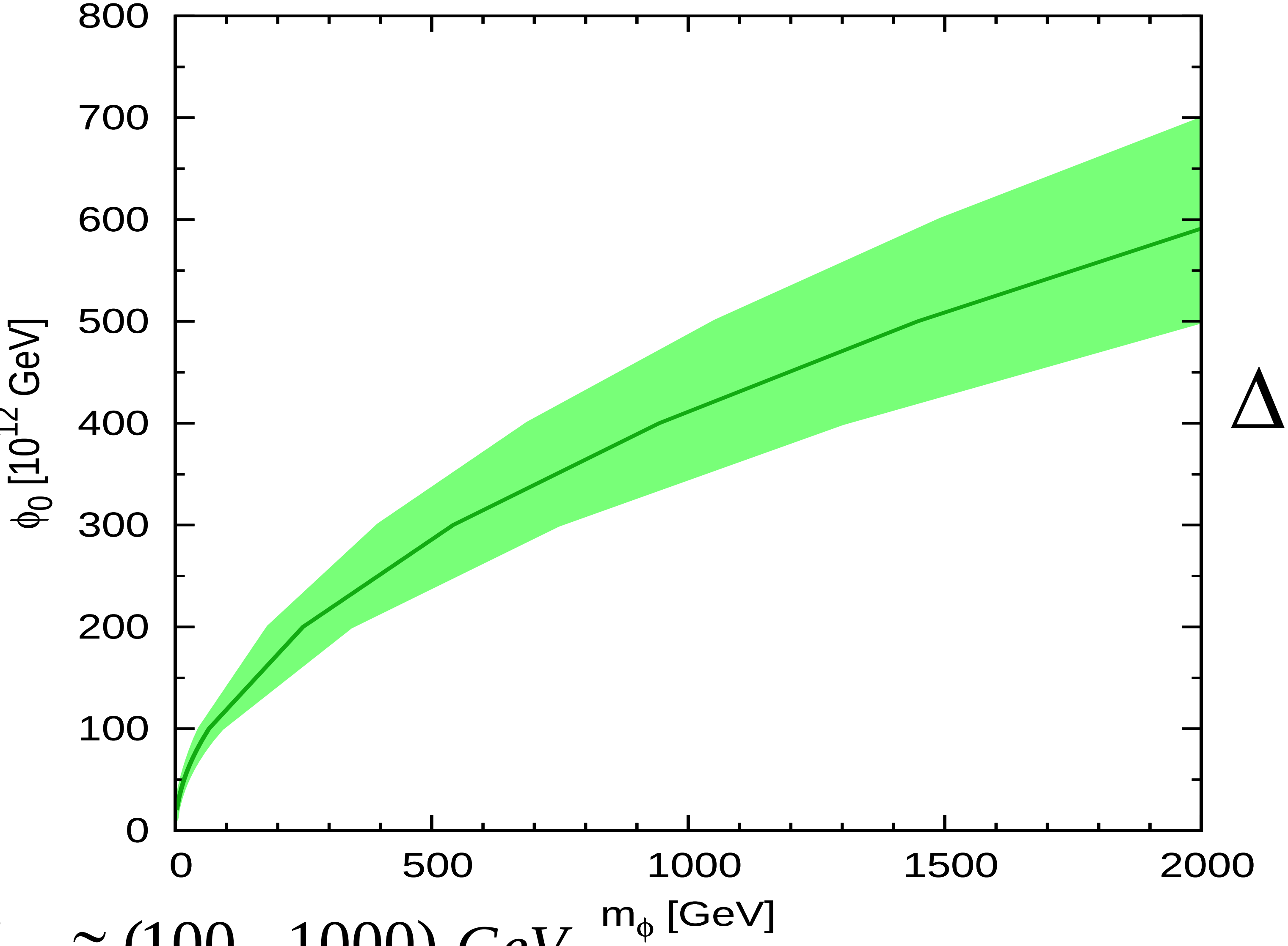
$$n_s = 1 - 4\Delta \cot\left[N_{COBE}\Delta\right]$$

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

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

Allowed parameter space to generate acceptable perturbations:

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



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

$$H_{\text{inf}} \cong (100-1000)\ GeV$$

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 is connected to low energy masses via RGEs.

R.A., Dutta, Mazumdar PRD 75, 075018 (2007)

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

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

However A, λ have no bearing for phenomenology. Their only role is to give rise to successful inflation.

How to determine the parameters experimentally?

$$\phi = \frac{\tilde{u} + \tilde{d} + \tilde{d}}{\sqrt{3}}$$

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

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

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

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

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

The condition for successful inflation can be met dynamically due to RGEs.

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

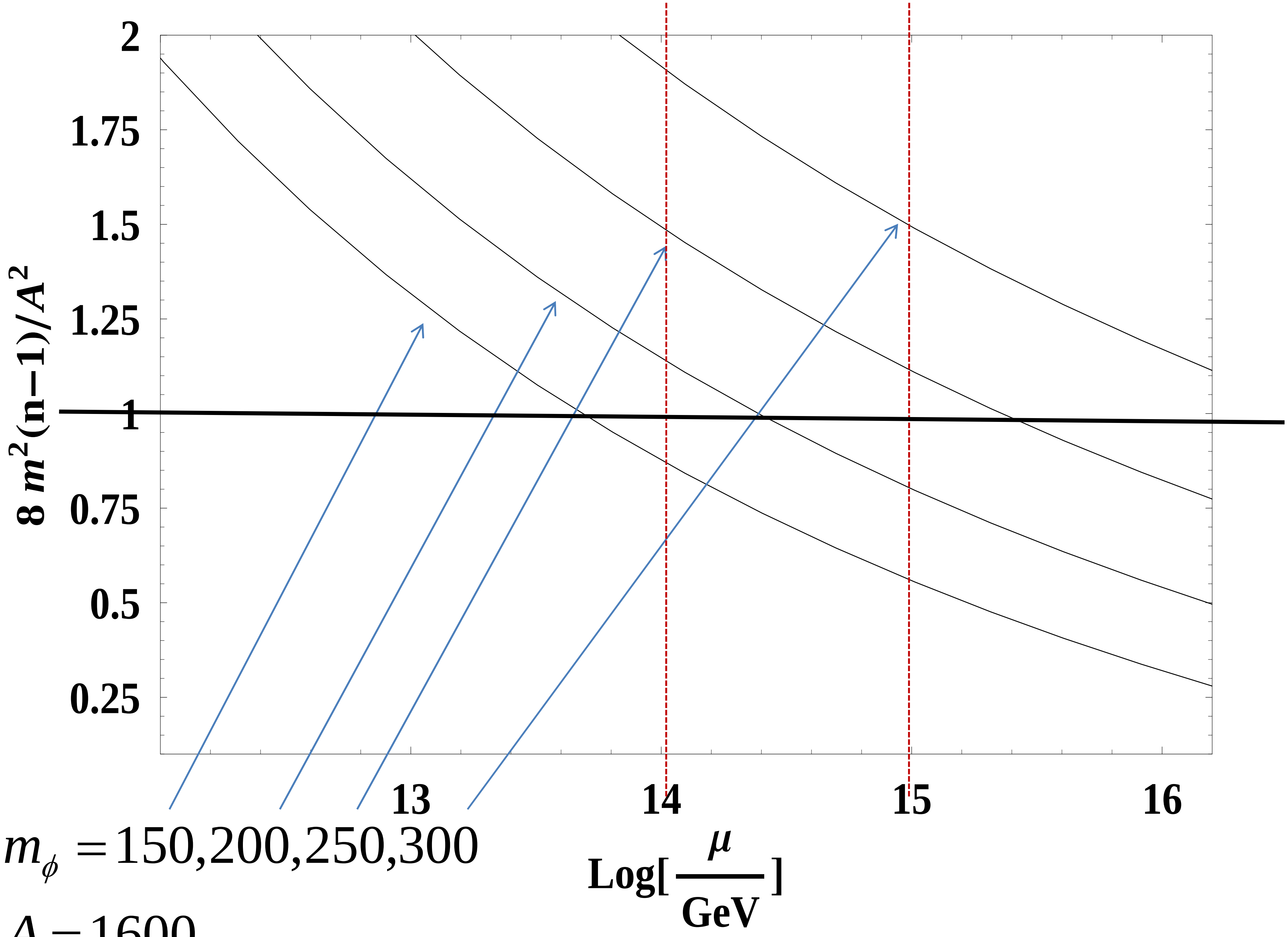
α is scale-dependent, hence VEV-dependent.

$\alpha = 0$ obtained within the phenomenologically interesting range $10^{14} - 10^{15}\, GeV$ for a wide range of input values.

This scale must coincide with an inflection point:

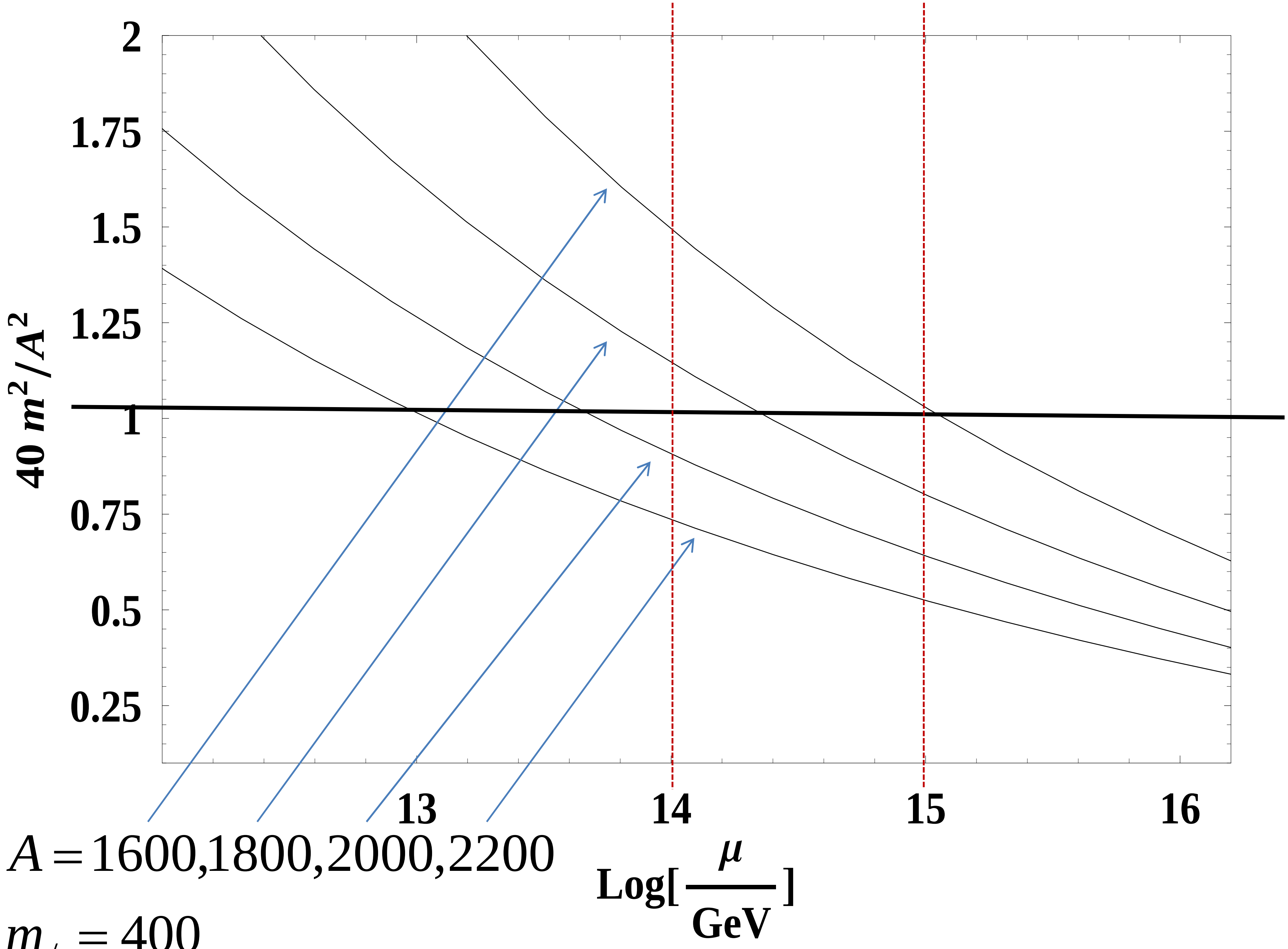
$$\phi_0 \cong \left(\frac{m_\phi M_P^3}{\sqrt{10\lambda}} \right)^{\frac{1}{4}}$$

This condition will fix the value of λ very precisely.



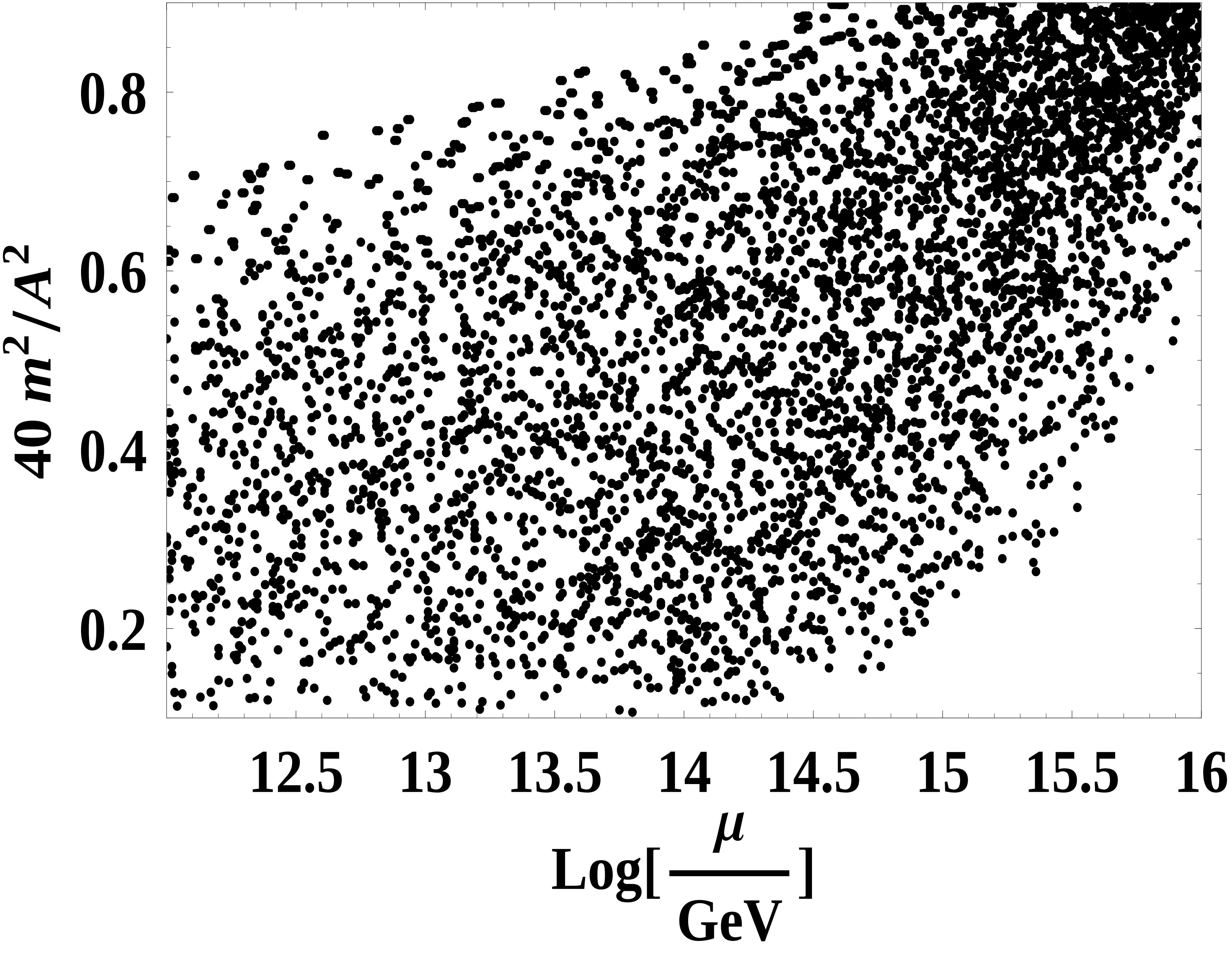
$m_\phi = 150, 200, 250, 300$

$A = 1600$

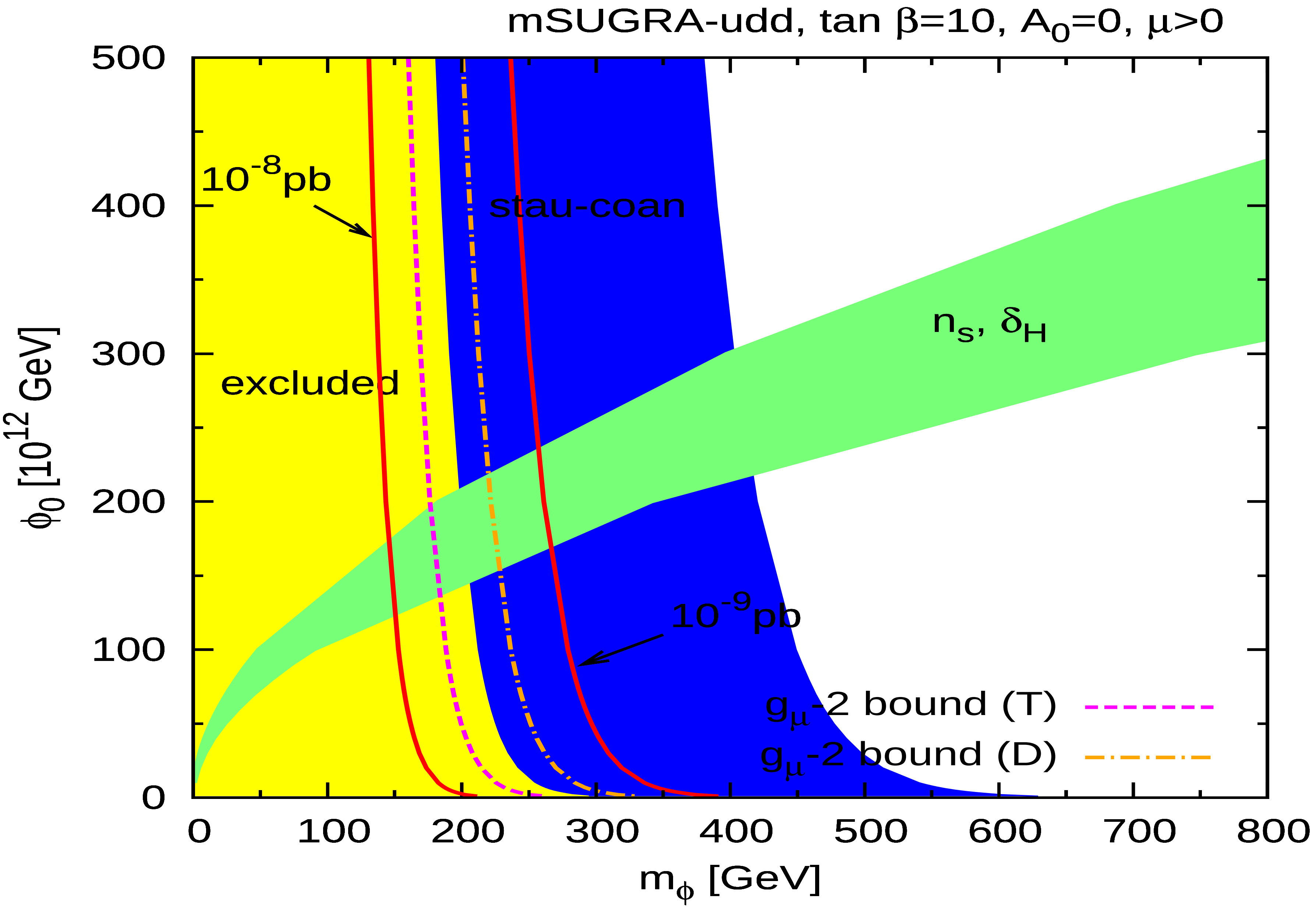


$A = 1600, 1800, 2000, 2200$

$m_\phi = 400$

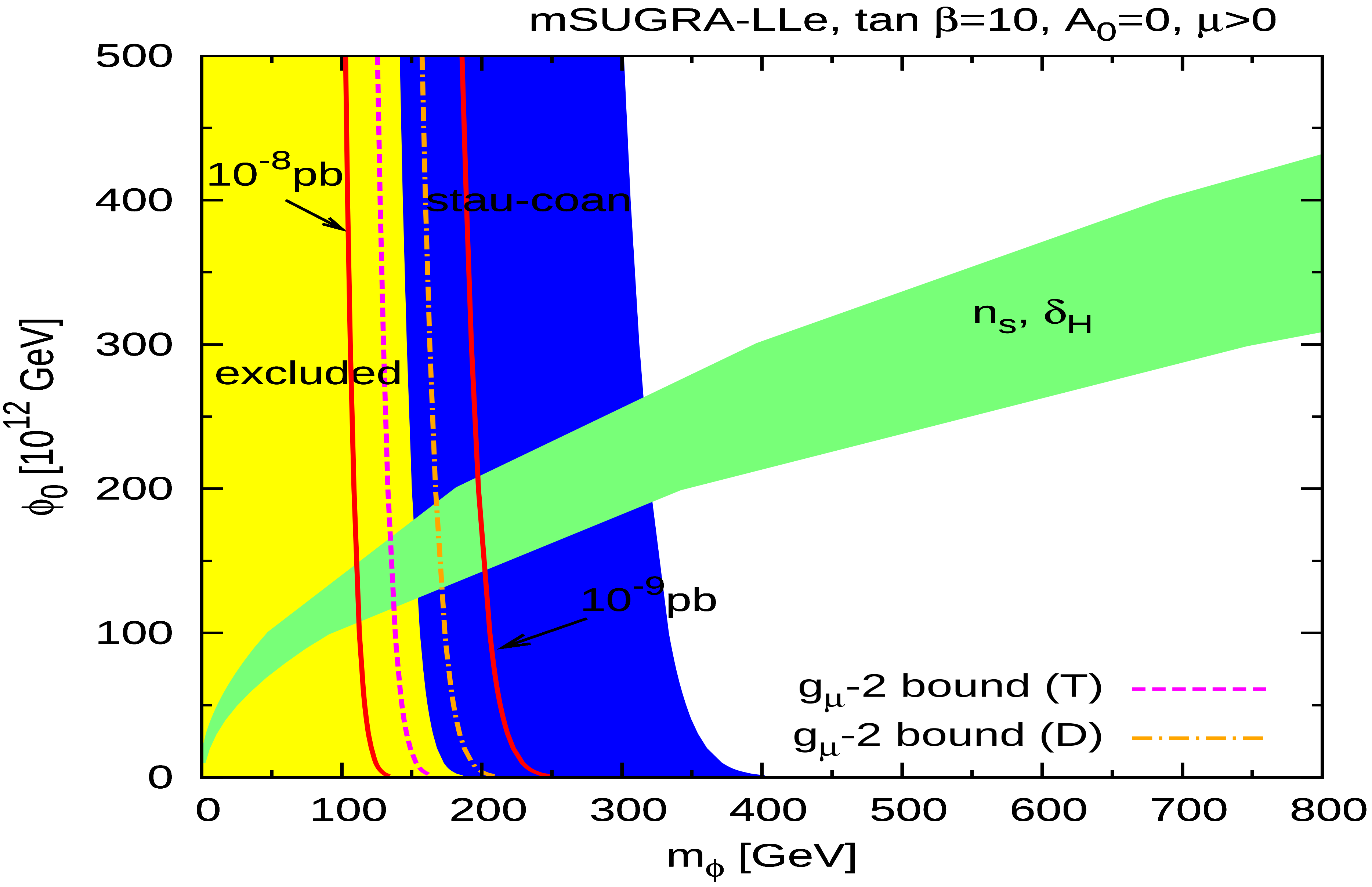

0.8
0.6
0.4
0.2
$40\, m^2/A^2$
12.5
13
13.5
14
14.5
15
15.5
16
$\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$

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

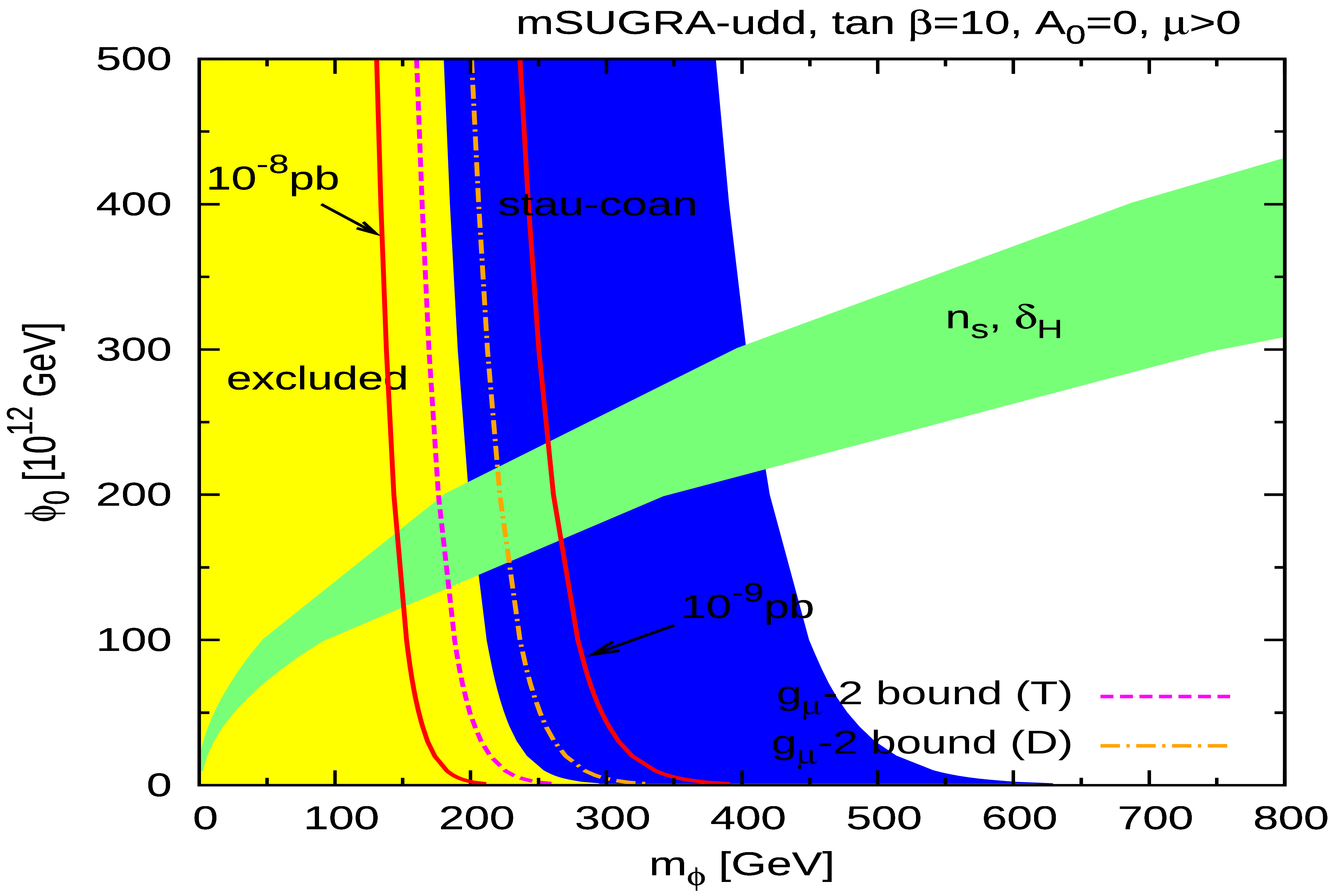


(T): Teubner, *et al* arXiv:1001.5401

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



(Focus point region not shown)



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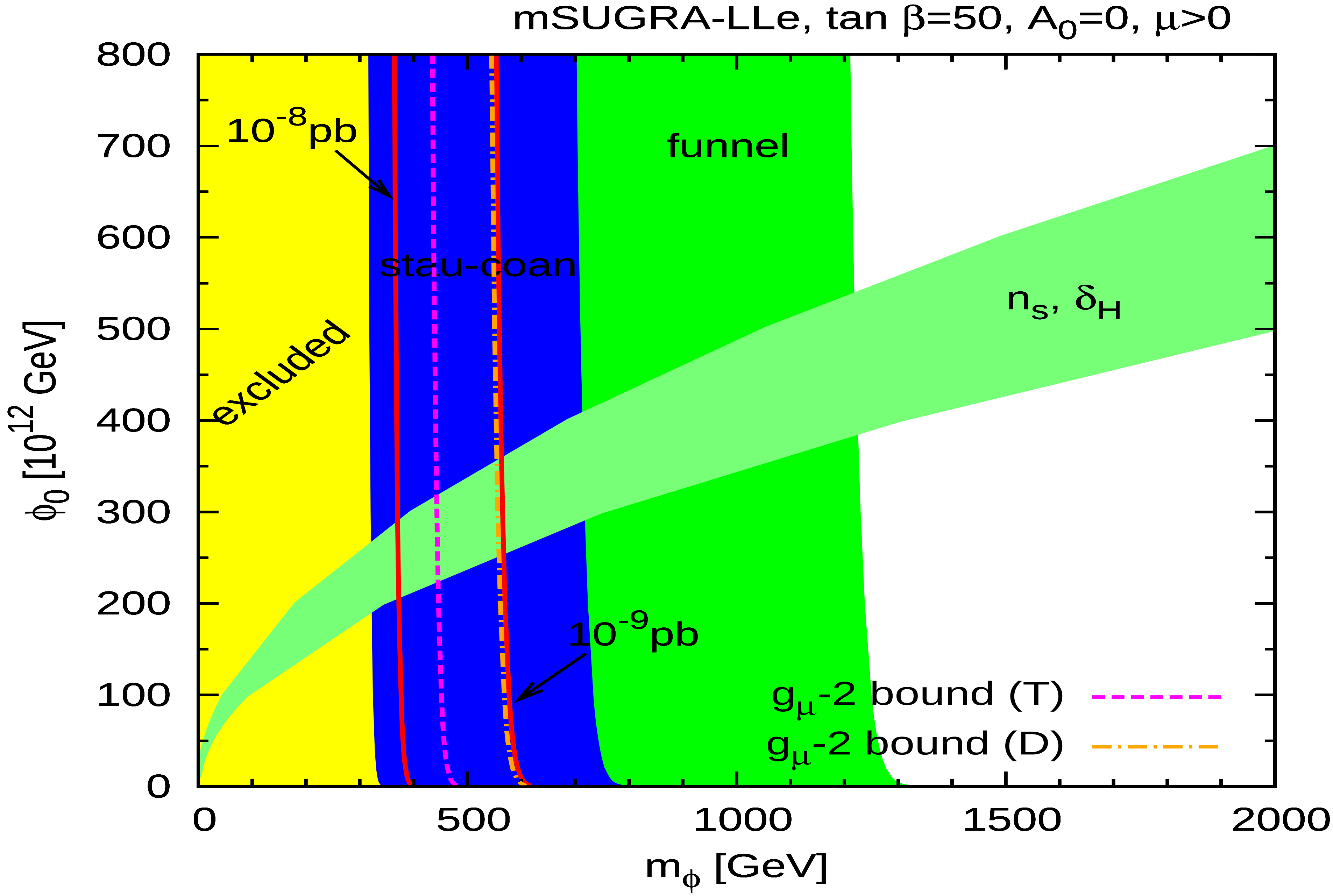


LHC Role:

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):

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

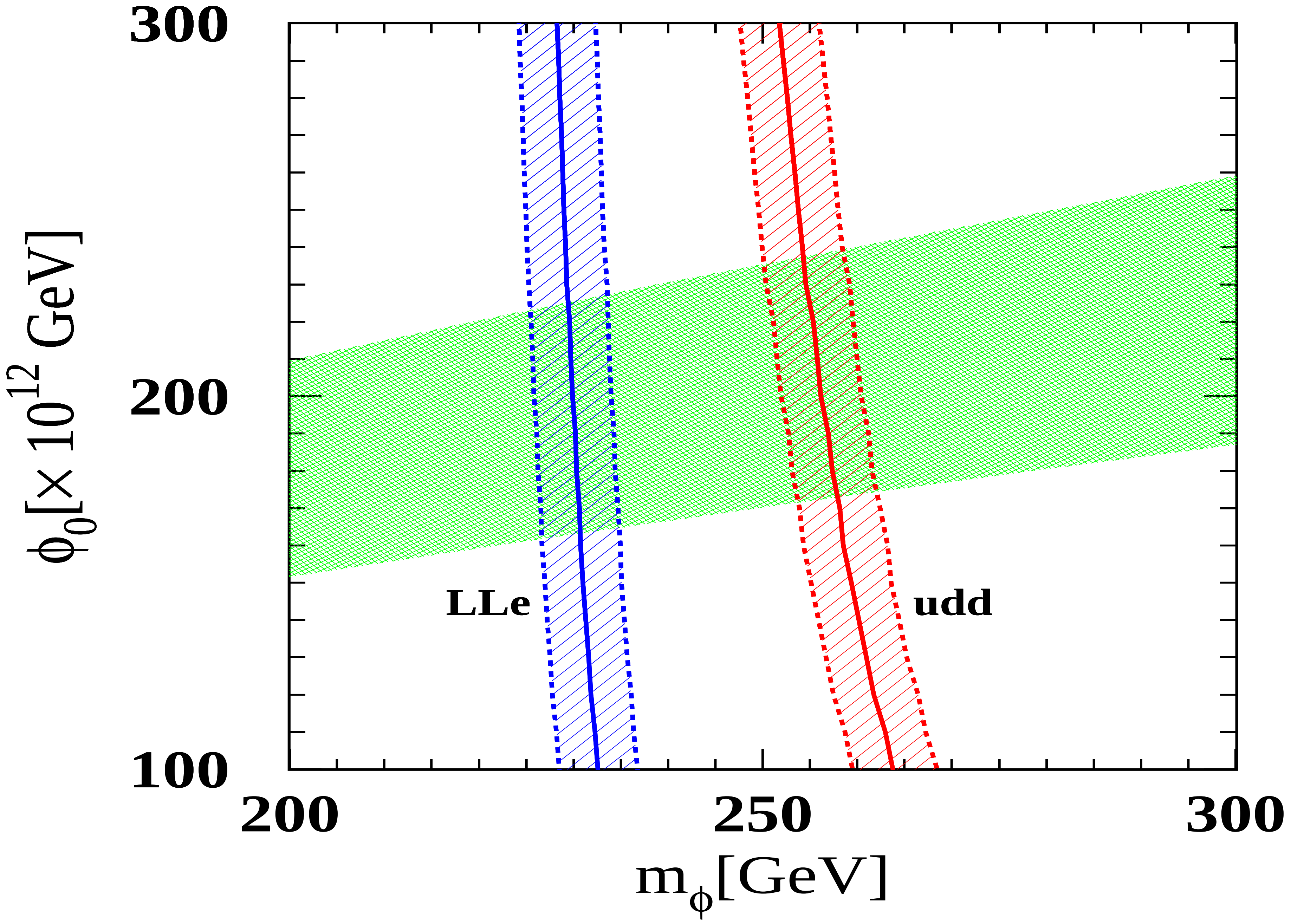
$$\Rightarrow m_{\chi_1^0} = 140.7, m_{\tilde{\tau}_1} = 151.3, m_{\tilde{\tau}_2} = 329$$

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



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 .

Provides information about the underlying physics that induces higher order term, SUSY breaking sector

Inflation from SUSY Breaking Sector:

Kahler modulus inflation within a KKLT set up:

$$W = W_{flux} + Ae^{-a\sigma} + Be^{-b\sigma}$$

$$V = V_F + \delta V \quad , \quad \delta V = \frac{C}{\sigma^2}$$

Inflection point can be found, resulting in a low-scale inflation driven by σ :

$$H_{\inf} \sim m_{3/2} \sim 50\ TeV \quad , \quad m_\sigma \sim 3000\ TeV$$

This model gives rise to mirage mediation of SUSY breaking to the observable sector.

Predictions for LHC:

Successful inflation implies that:

- Gaugino masses receive comparable contributions from modulus and anomaly mediation.

- Scalar masses mainly come from anomaly mediation.

Reheat temperature is very low in the model

$T_R \sim 200\ MeV$ (challenge for baryogenesis)

Successful baryogenesis with R.A., Dutta, Sinha arXiv:1005.2804

- TeV scale color triplet fields

Summary:

- LHC-inflation connection possible for a realistic embedding of inflation within TeV scale physics.

- Inflation can be realized within MSSM. The underlying parameters cannot be determined from CMB measurements alone. Particle physics experiments are also needed to pinpoint the parameters.

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

- Inflation can be driven by the SUSY breaking sector. Predicted sparticle masses, and new colored fields required for baryogenesis, can be probed at the LHC.