

Inflaton @ LHC

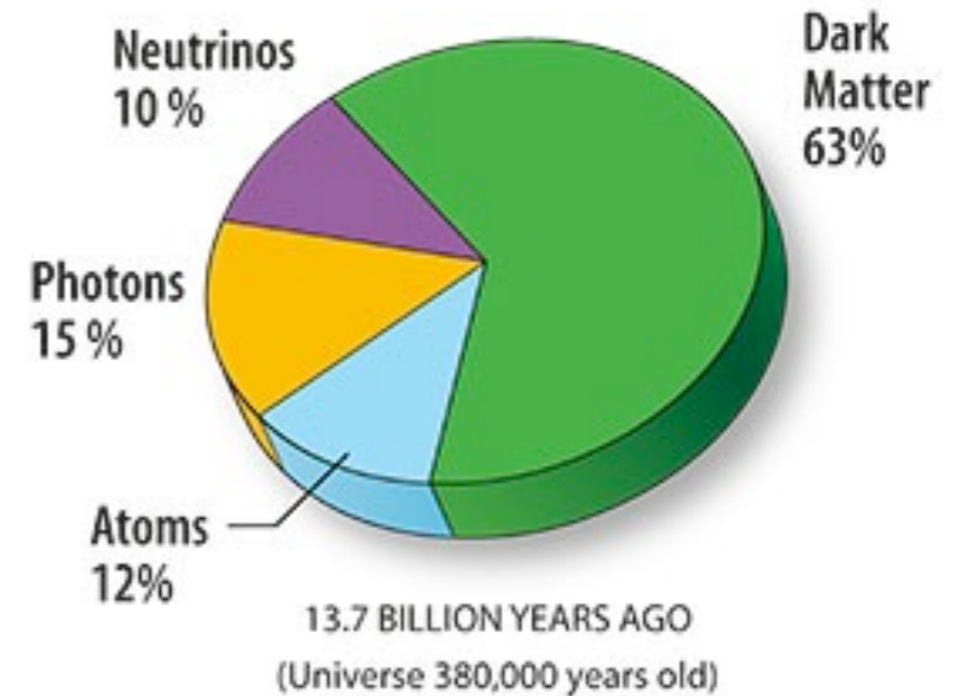
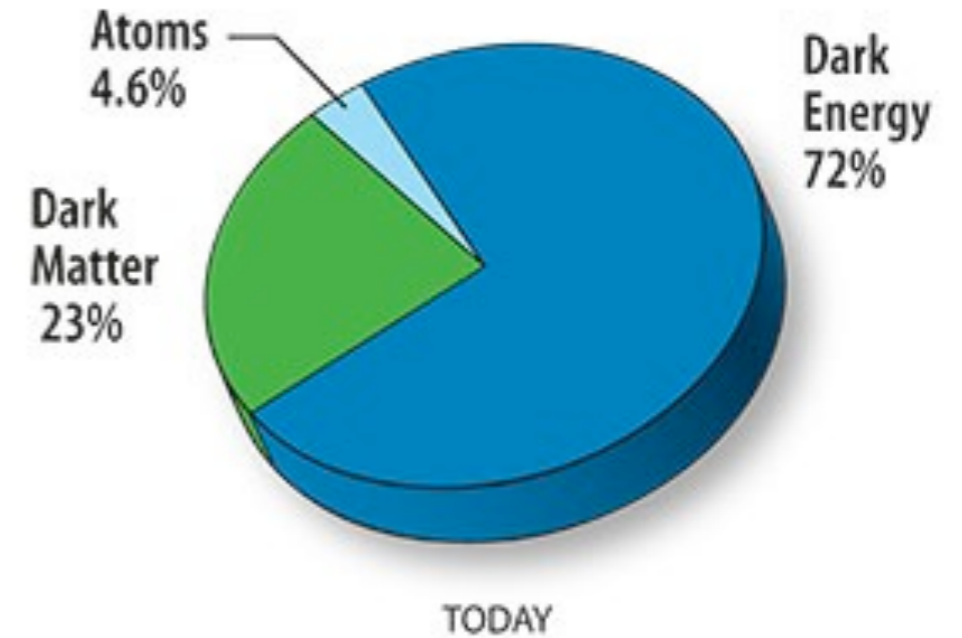
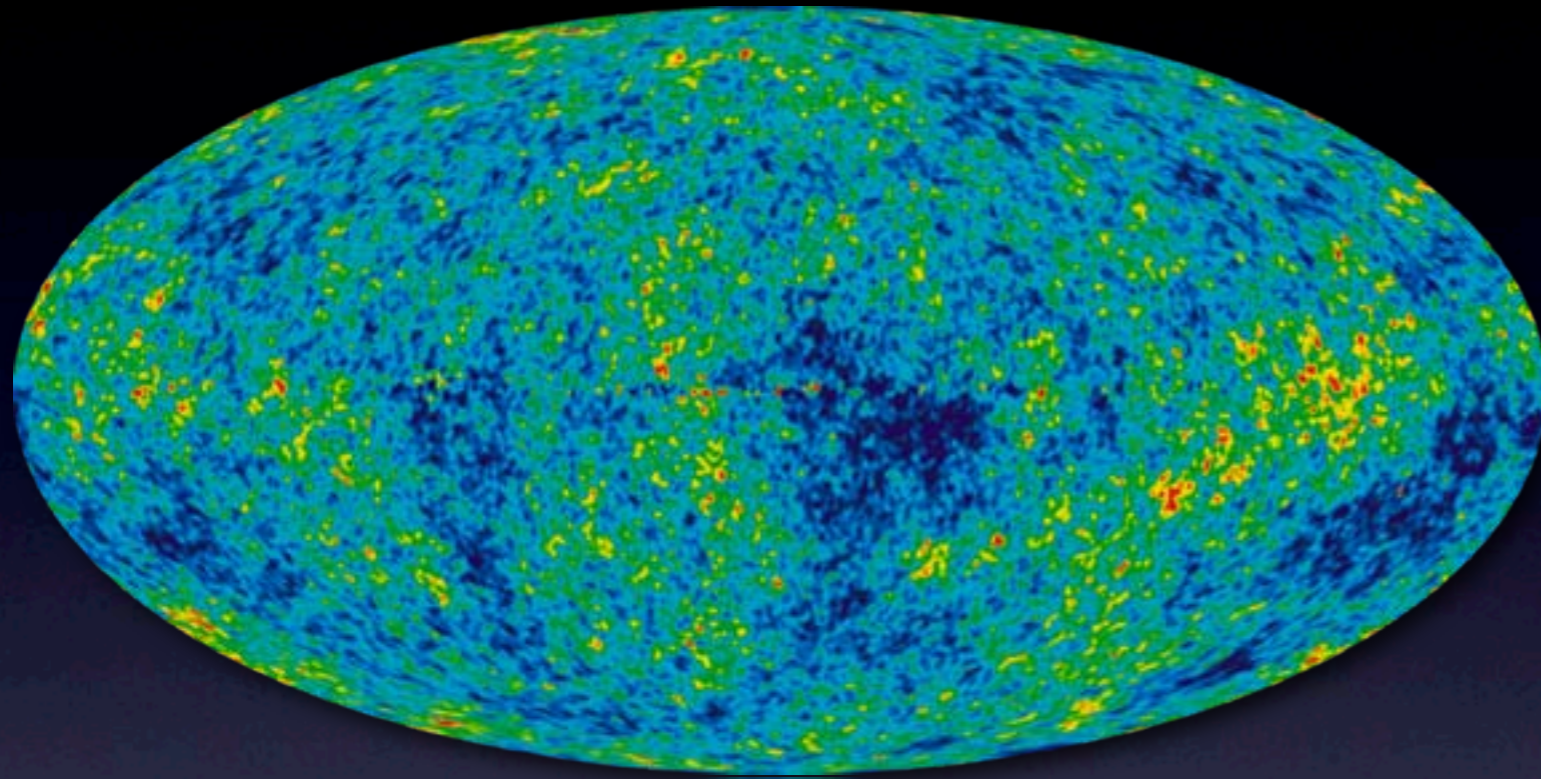
Anupam Mazumdar

Lancaster University



***Can we understand it in a
consistent framework ?***

Fluctuations in CMB



Creation of Matter

Ever Changing models of Inflation

1980 **R*R, OLD, NEW, CHAOTIC, EXTENDED, SOFT, BRANS-DICKE, SUSY, SUGRA, THERMAL, EXPONENTIAL, DOUBLE, ...**

HYBRID, MUTATED HYBRID, INVERTED

1990 **HYBRID, F-TERM, D-TERM, K-TERM, TOPOLOGICAL, ASSISTED,**

N-FLATION, BRANE, BRANE-CHAOTIC/

2000 **HYBRID, TACHYONIC, DBI, RACE-TRACK, HILL-TOP, FAST-ROLL, P-TERM, F+D-TERM, EXTENDED-HIGGS, CYCLIC, ...**

Ever Changing models of Inflation

1980 **R*R, OLD, NEW, CHAOTIC, EXTENDED, SOFT, BRANS-DICKE, SUSY, SUGRA, THERMAL, EXPONENTIAL, DOUBLE, ...**

HYBRID, MUTATED HYBRID, INVERTED

1990 **HYBRID, F-TERM, D-TERM, K-TERM, TOPOLOGICAL, ASSISTED,**

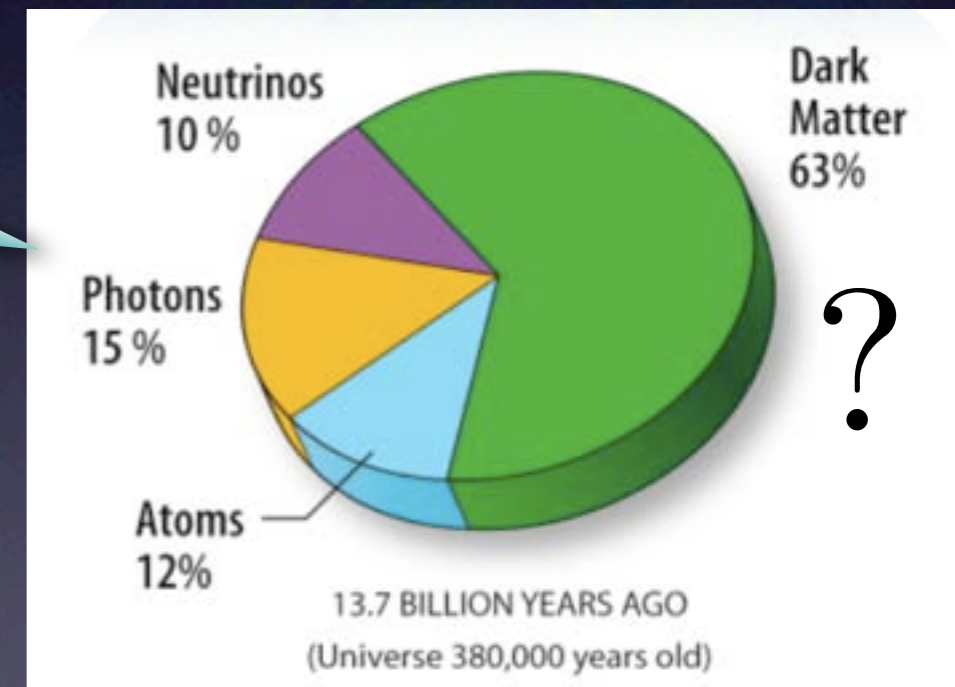
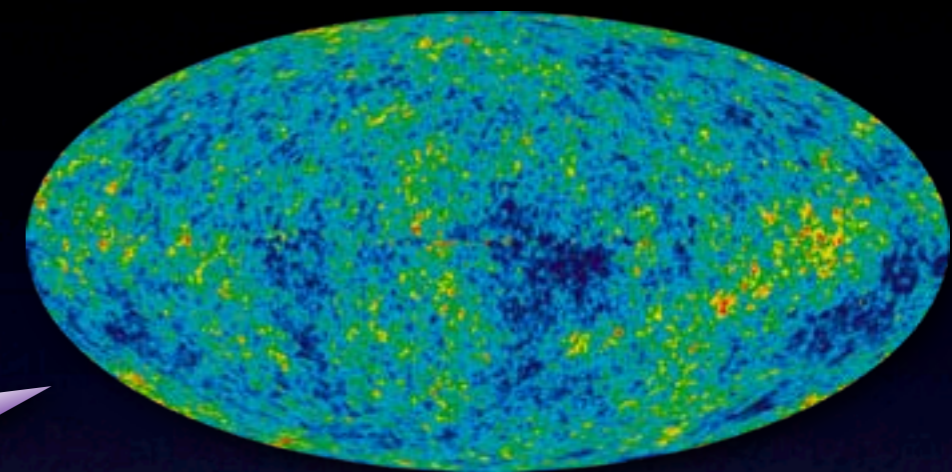
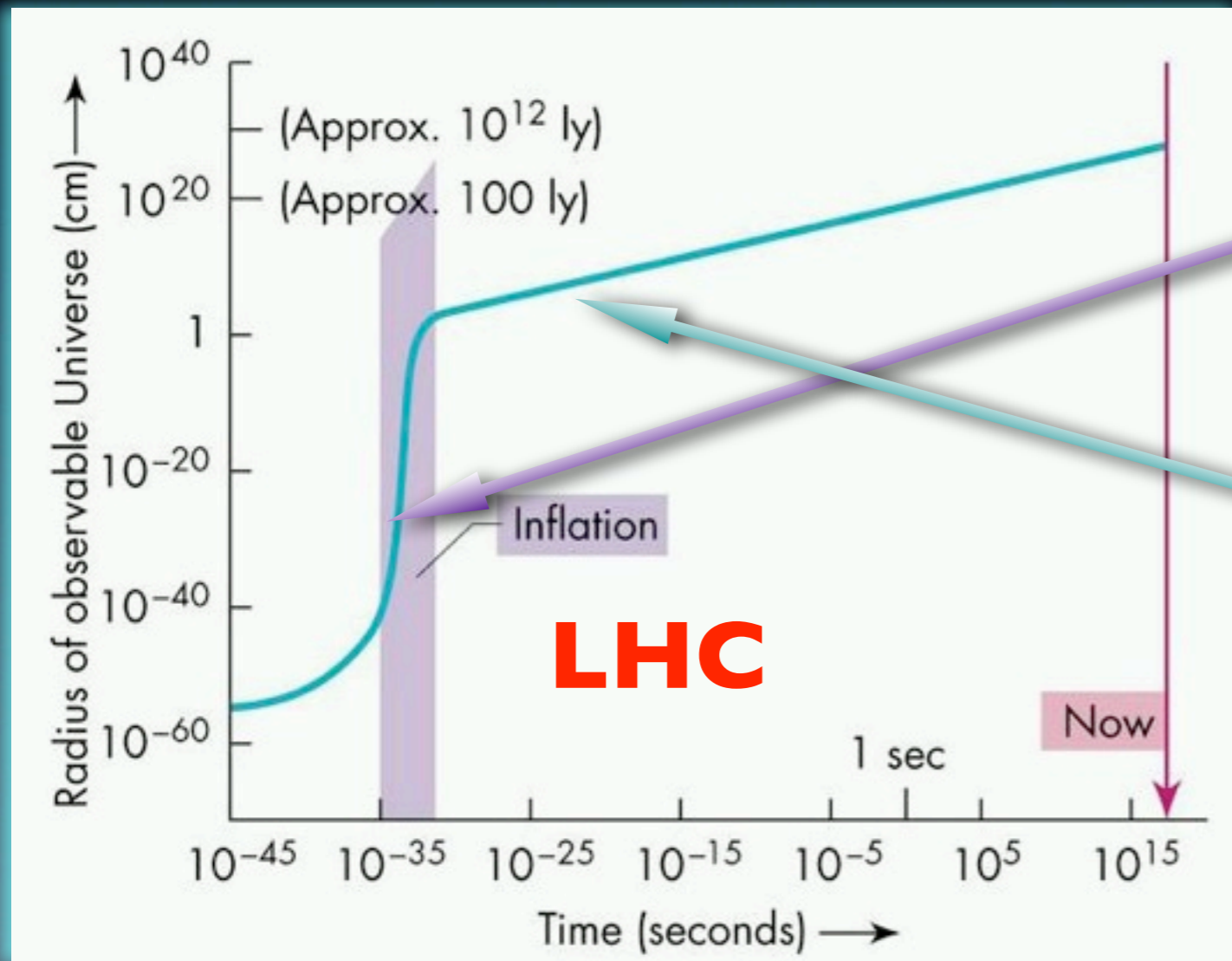
N-FLATION, BRANE, BRANE-CHAOTIC/

2000 **HYBRID, TACHYONIC, DBI, RACE-TRACK, HILL-TOP, FAST-ROLL, P-TERM, F+D-TERM, EXTENDED-HIGGS, CYCLIC, ...**

**None of these models
actually work**

Challenge: Inflation **MUST** create radiation & perturbations

NO Hidden Radiation



After inflation

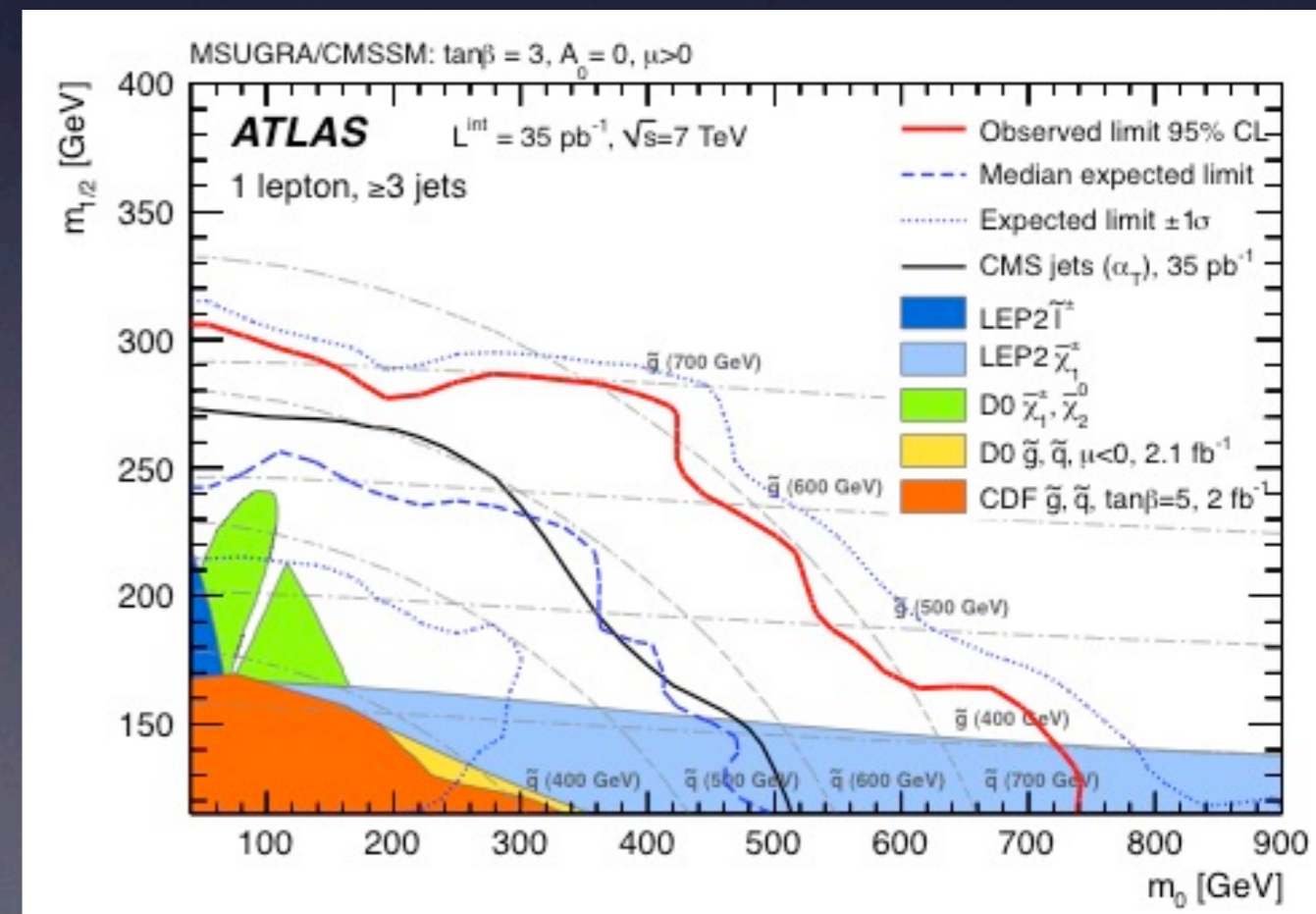
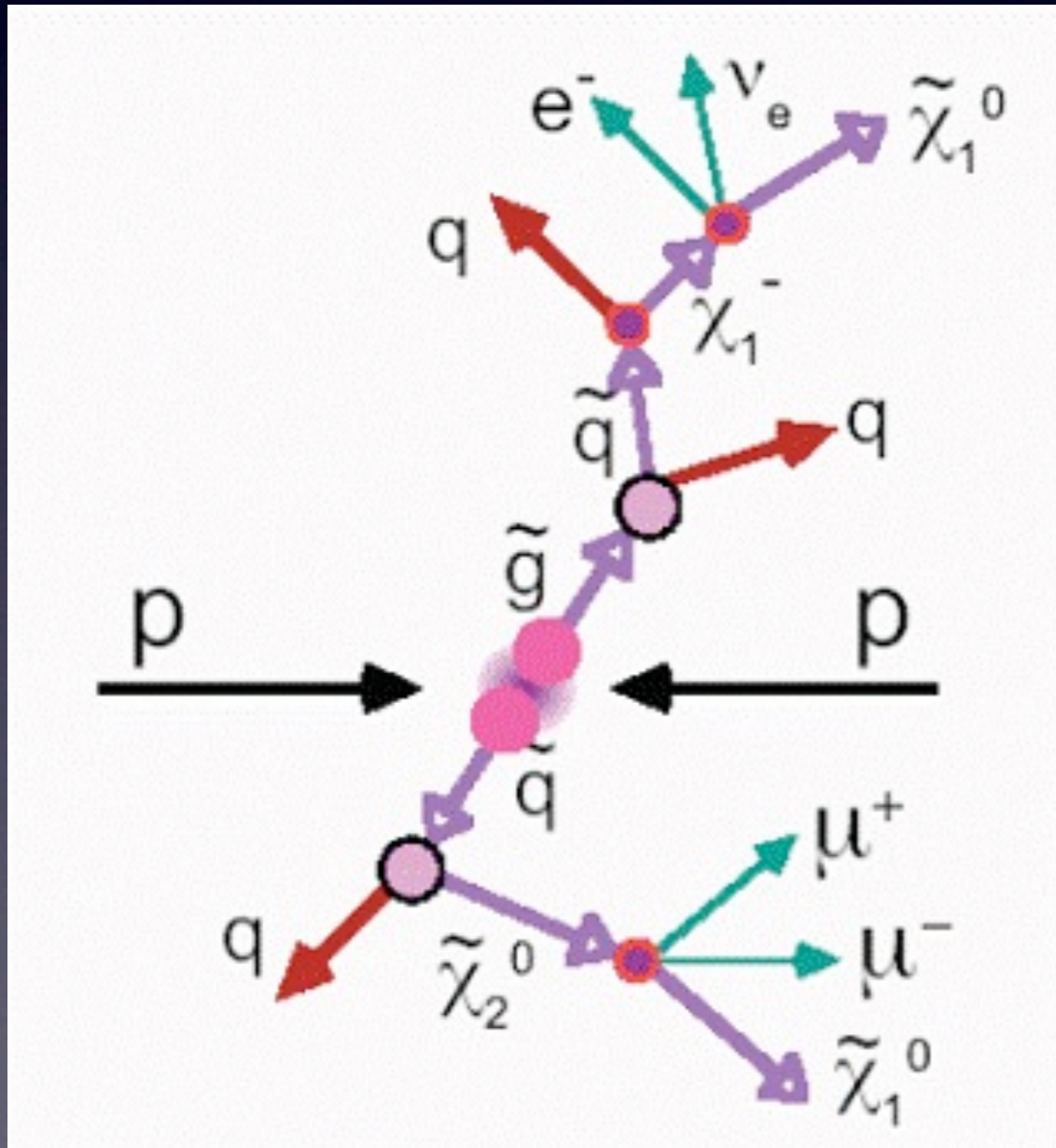
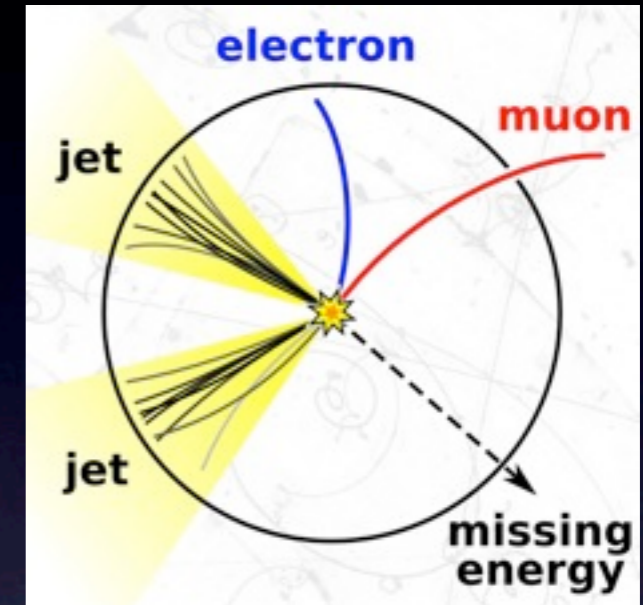
The Inflaton Vacuum cannot be arbitrary

Mazumdar, Rocher, 1001.0993 Phys. Rept. (2010), AM, arXiv: 1106.5408

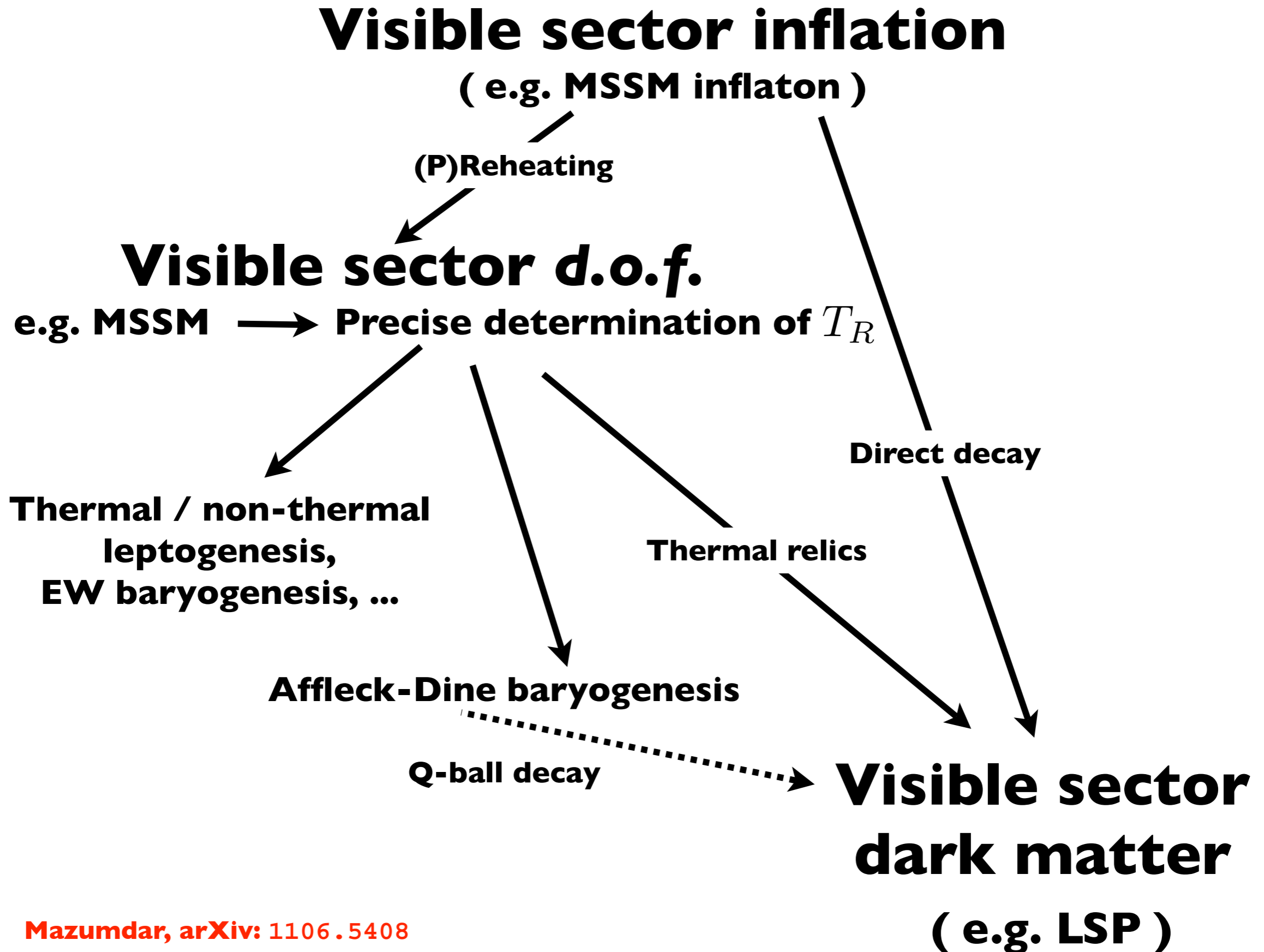
Low scale SUSY

A consistent Framework, **Testability**

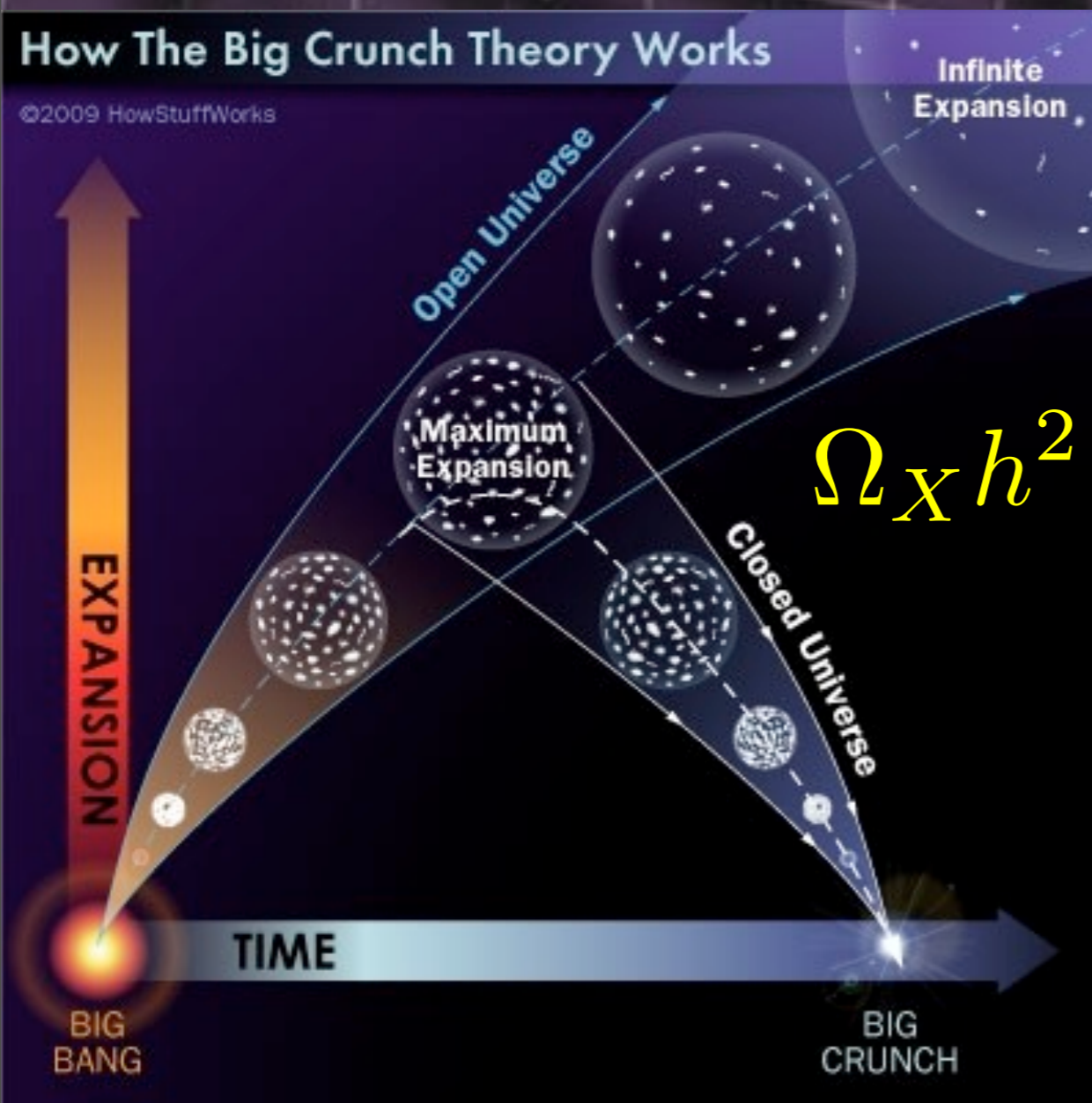
WIMP, e.g. LSP with R-Parity



A consistent set-up



Alarming Phenomena: Dark Matter Dominance



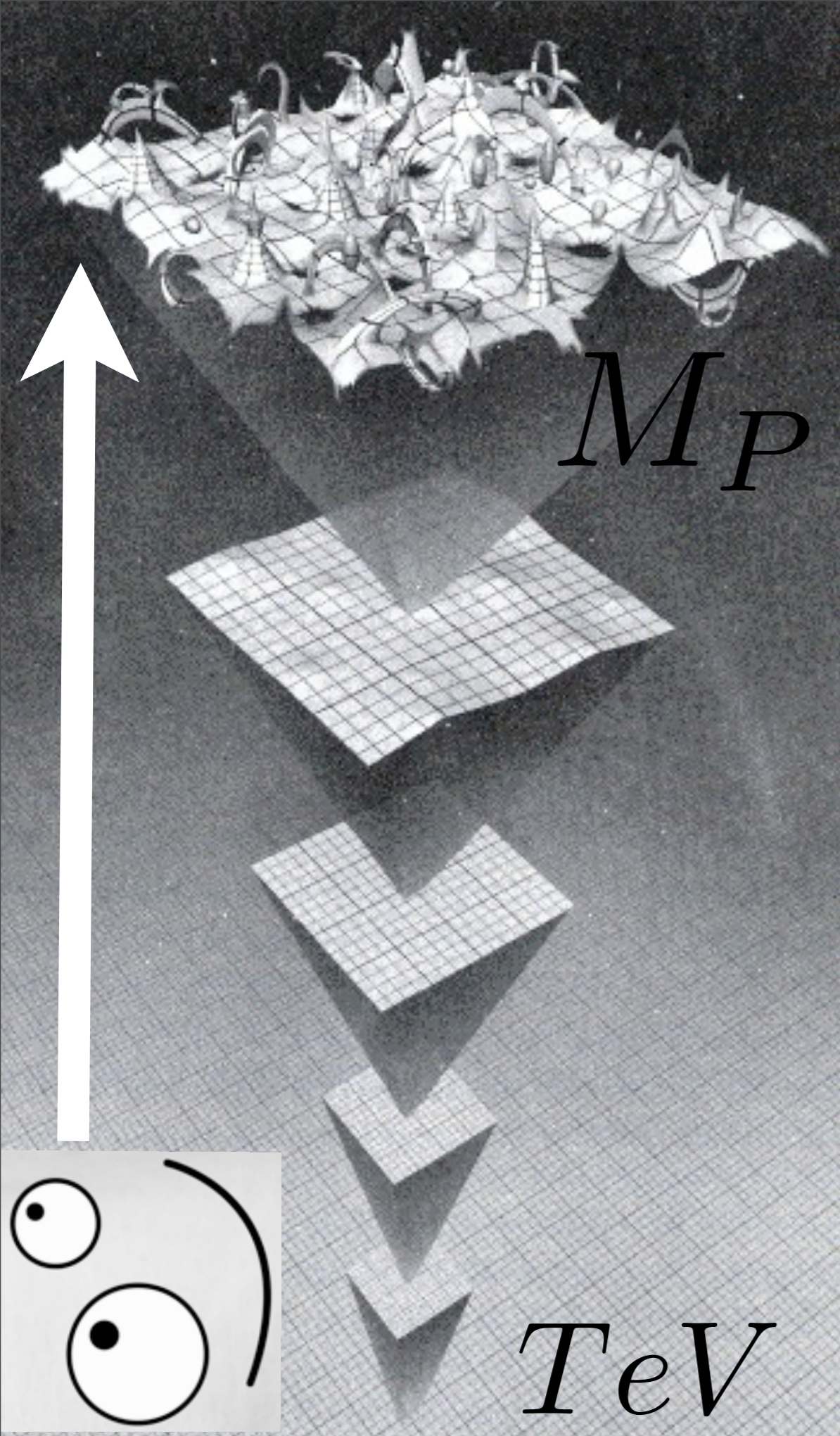
Instant collapse of the universe

$$\Omega_X h^2 \approx 10^{17} \left(\frac{T_R}{10^9 \text{ GeV}} \right) \frac{\rho_X}{\rho_{inf}}$$

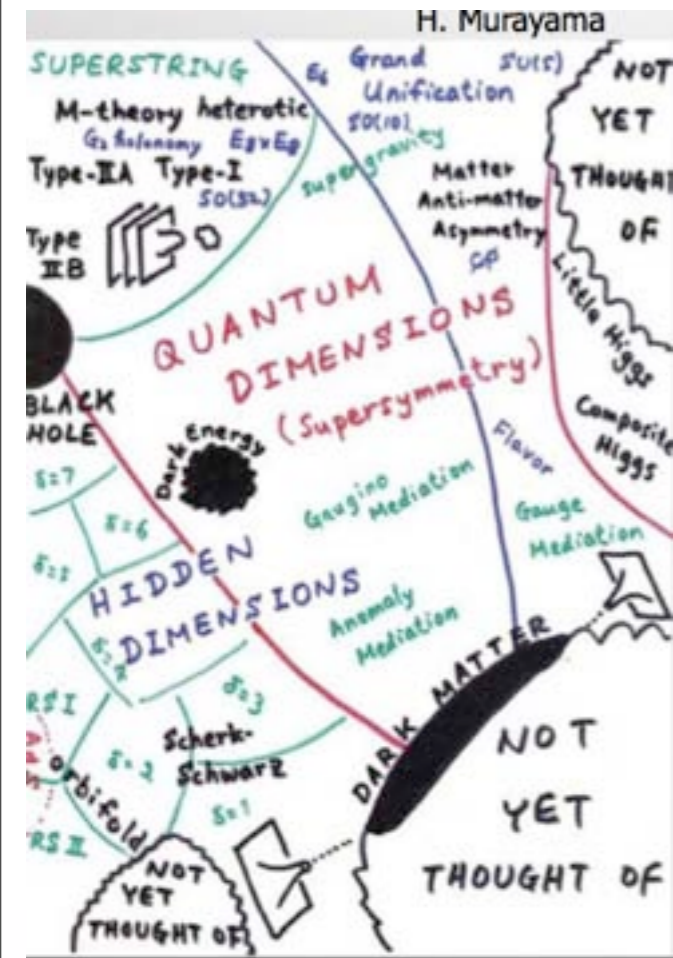
Solution: Thermal/kinetic decoupling of dark matter

Kolb (1998), Kofman (2004), Frey & AM (2004),
Mazumdar (2011)

Beauty of Effective Field Theory



Beyond Standard Model



SUSY extensions of SM

Landscape



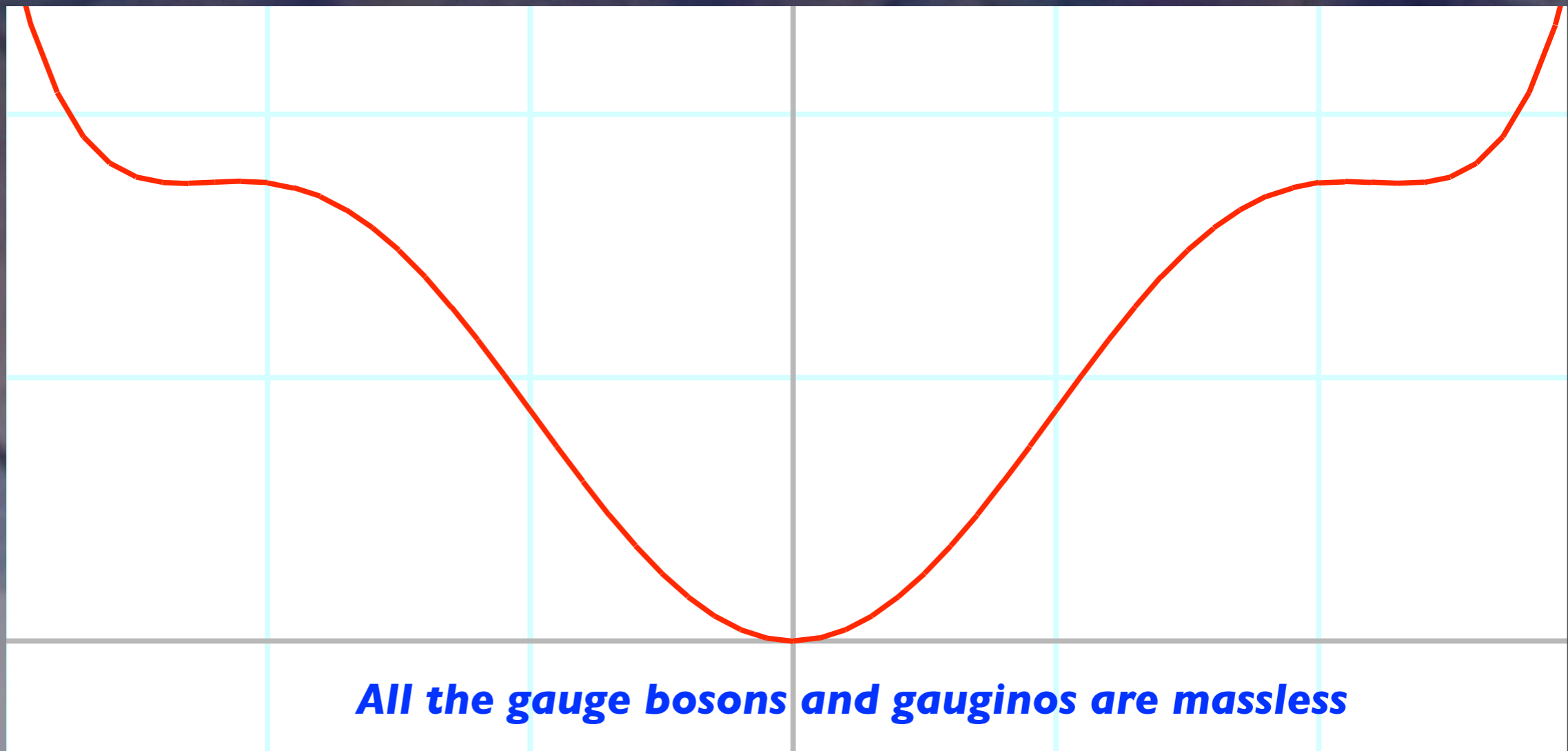
How do we know which is the right vacuum?



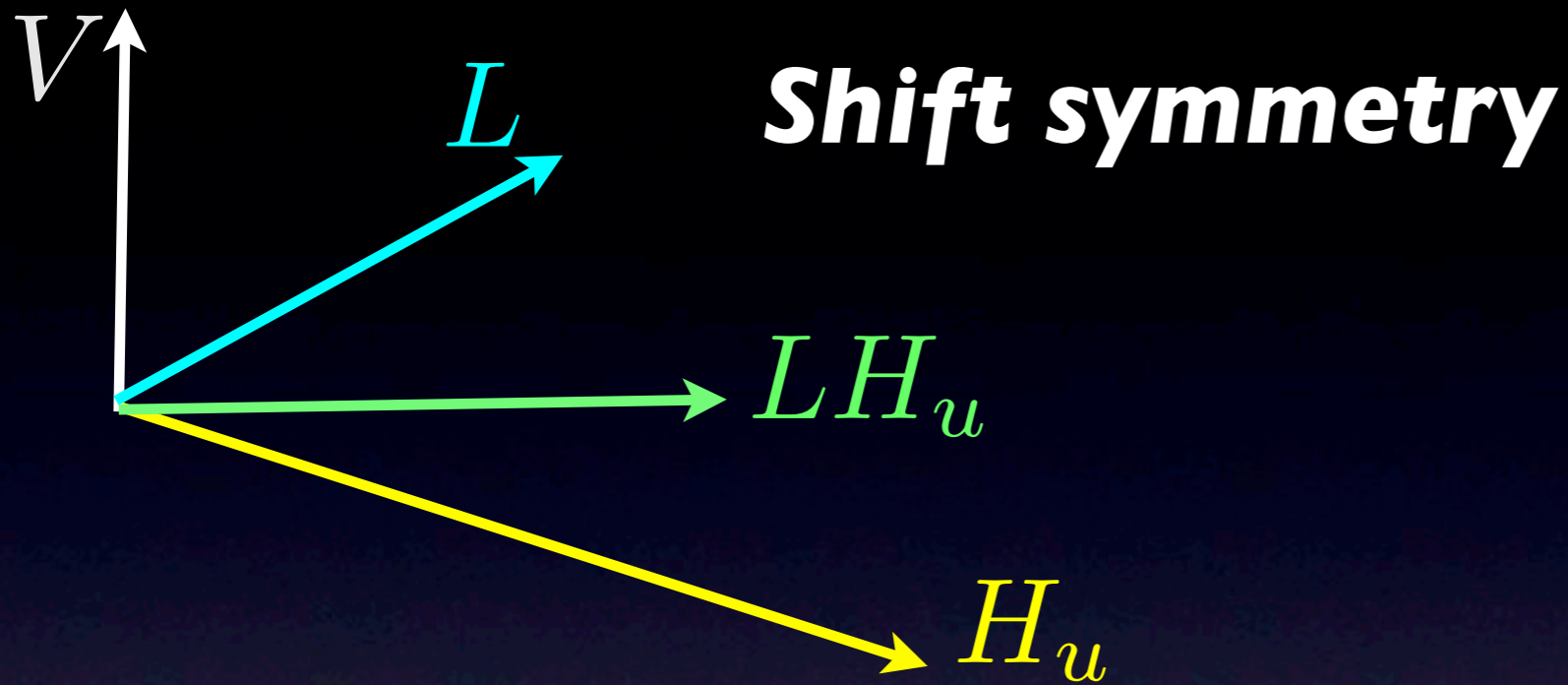
**LAST 50-60 efoldings of
Inflation must end in our own vacuum !**

Point of enhanced gauge symmetry

@ TeV scale: $SU(3)_c \times SU(2)_l \times U(1)_Y$

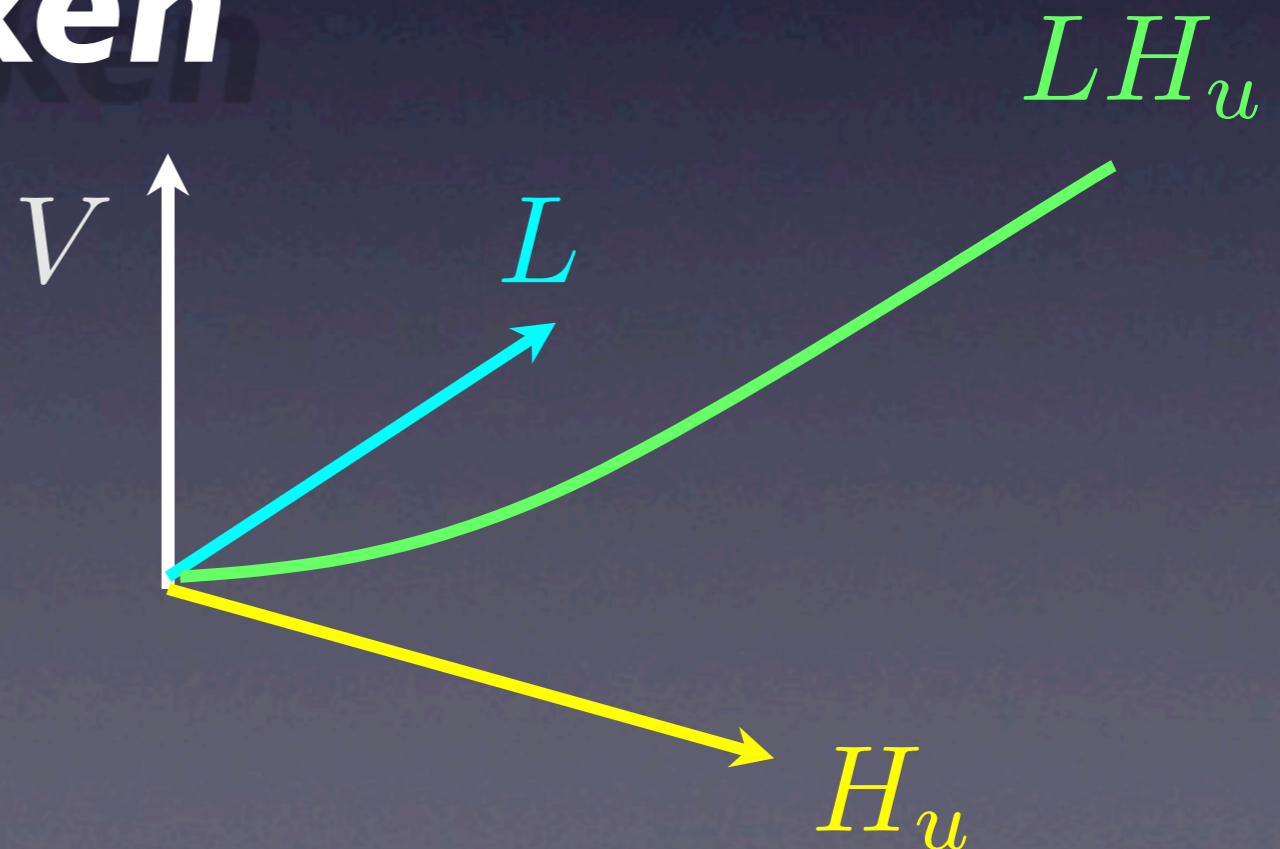


Power of SUSY



SUSY is broken

Shift symmetry is broken



MSSM Inflavons

Allahverdi, Enqvist, Bellido, AM, (PRL, 2006, hep-ph/0605035),
 (JCAP, 2007, hep-ph/0610134),
 Allahverdi, Dutta, AM (PRL 2007, 0708.3983)

	B-L	Always lifted by W_{renorm} ?
LH_u	-1	
$H_u H_d$	0	
udd	-1	
LLe	-1	
$Q_u L$	-1	
$Q_u H_u$	0	✓
$Q_d H_d$	0	✓
$LH_d e$	0	✓
QQQL	0	
$Q_u Q_d$	0	
$Q_u L e$	0	
uude	0	
QQQH _d	1	✓
$Q_u H_d e$	1	✓
dddLL	-3	
uuuee	1	
$Q_u Q_u e$	1	
QQQQ _u	1	
dddLH _d	-2	✓
uudQdH _u	-1	✓
$(QQQ)_4 LLH_u$	-1	✓
$(QQQ)_4 LH_u H_d$	0	✓
$(QQQ)_4 H_u H_d H_d$	1	✓
$(QQQ)_4 LLLe$	-1	
uudQdQd	-1	
$(QQQ)_4 LLH_d e$	0	✓
$(QQQ)_4 LH_d H_d e$	1	✓
$(QQQ)_4 H_d H_d H_d e$	2	✓

$$u_1 d_2 d_3$$

$$d_2^\beta = \frac{1}{\sqrt{3}} \phi \quad u_1^\alpha = \frac{1}{\sqrt{3}} \phi$$

$$d_3^\gamma = \frac{1}{\sqrt{3}} \phi$$

$$L_1 L_2 e_3$$

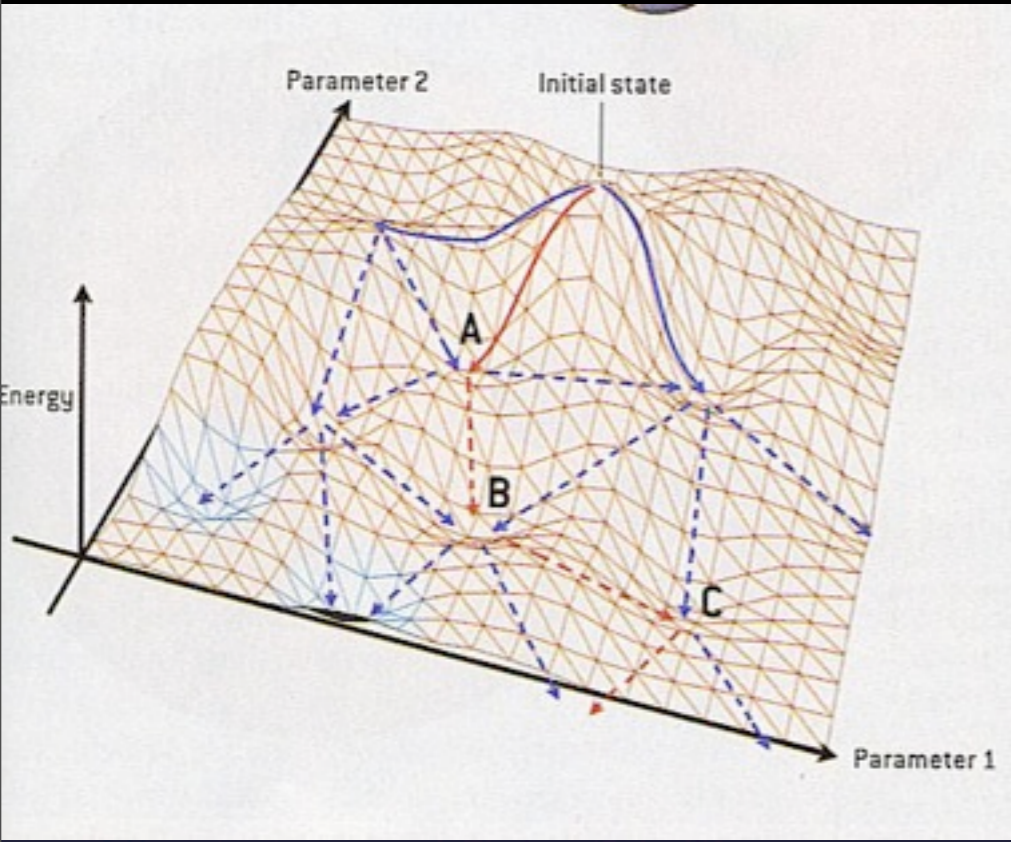
$$L_1^a = \frac{1}{\sqrt{3}} \begin{pmatrix} 0 \\ \phi \end{pmatrix} \quad L_2^b = \frac{1}{\sqrt{3}} \begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

$$e_3 = \frac{1}{\sqrt{3}} \phi$$

$$H_u H_d$$

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix} \quad H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}$$

Catastrophe Theory



$$W = \sum_n \frac{\lambda_n}{n} \frac{\Phi^n}{M_P^{n-3}}$$

$$V(\phi) = |f(\phi)|^2, \quad f(\phi) \equiv \frac{dW(\phi)}{d\phi}$$

$$f(\phi) = \lambda_1 \phi^2 + \lambda_2 \frac{\phi^5}{M_P^3} + \lambda_3 \frac{\phi^8}{M_P^6}$$

$$V'(\phi) = f'(\phi)f^*(\phi) + h.c. = 0 @ \phi = (0, a^{1/3}, b^{1/3})M_P$$

$$\text{If } a = b \Rightarrow \frac{\partial V}{\partial \phi} = \frac{\partial V}{\partial \phi^*} = \frac{\partial^2 V}{\partial \phi^2} = \frac{\partial^2 V}{\partial \phi^{*2}} = 0$$

$$\lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n \leq 1 \text{ for } \phi \leq M_P$$

MSSM Landscape

False vacua, Saddle points, Inflection points,

Mazumdar, Nadathur, 1107.4078 [hep-ph],

Allahverdi, Downes, Dutta, 1106.5004 [hep-th]

MSSM Inflaton:

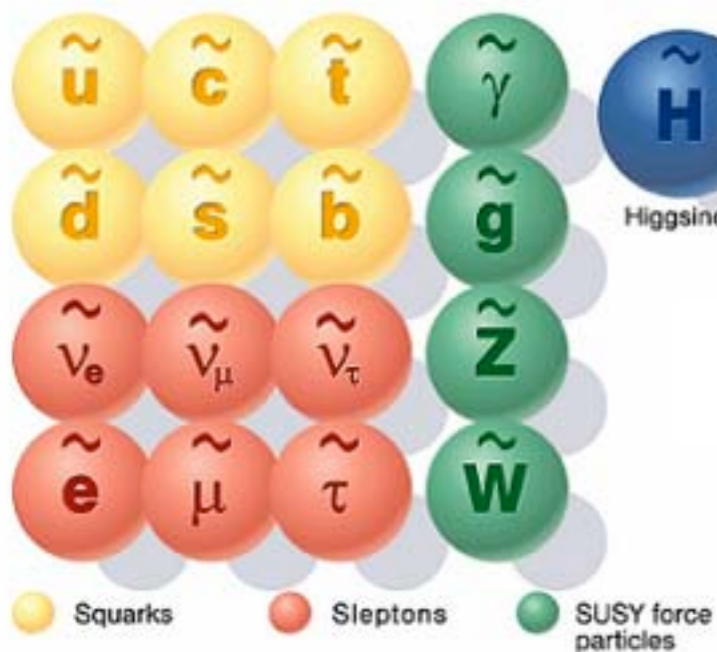
Highly constrained model of Inflation

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

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

$$V = \frac{1}{2}m^2\phi^2 - A\frac{\phi^6}{M_P^3} + \frac{\phi^{10}}{M_P^4}$$

SUSY particles

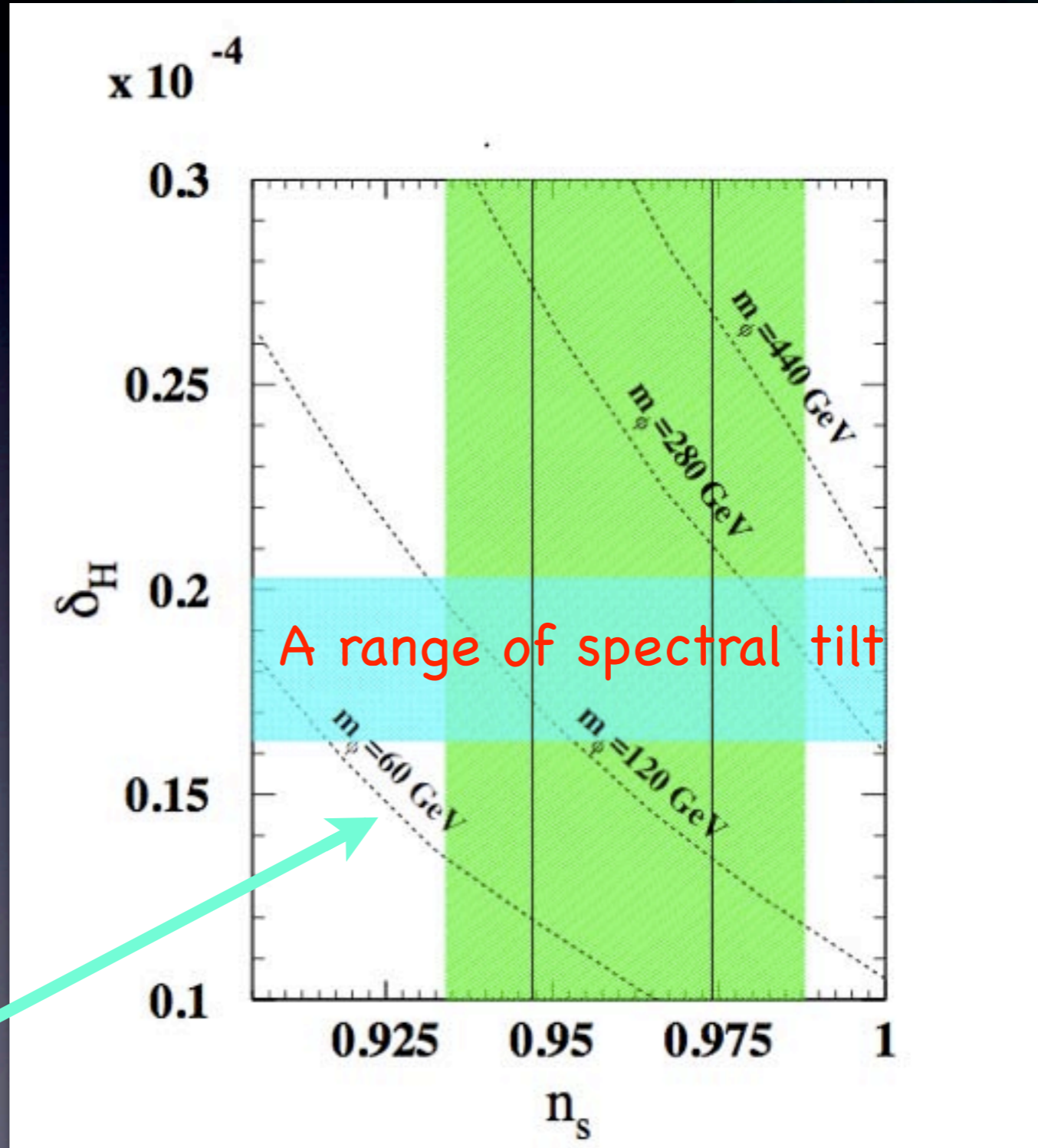
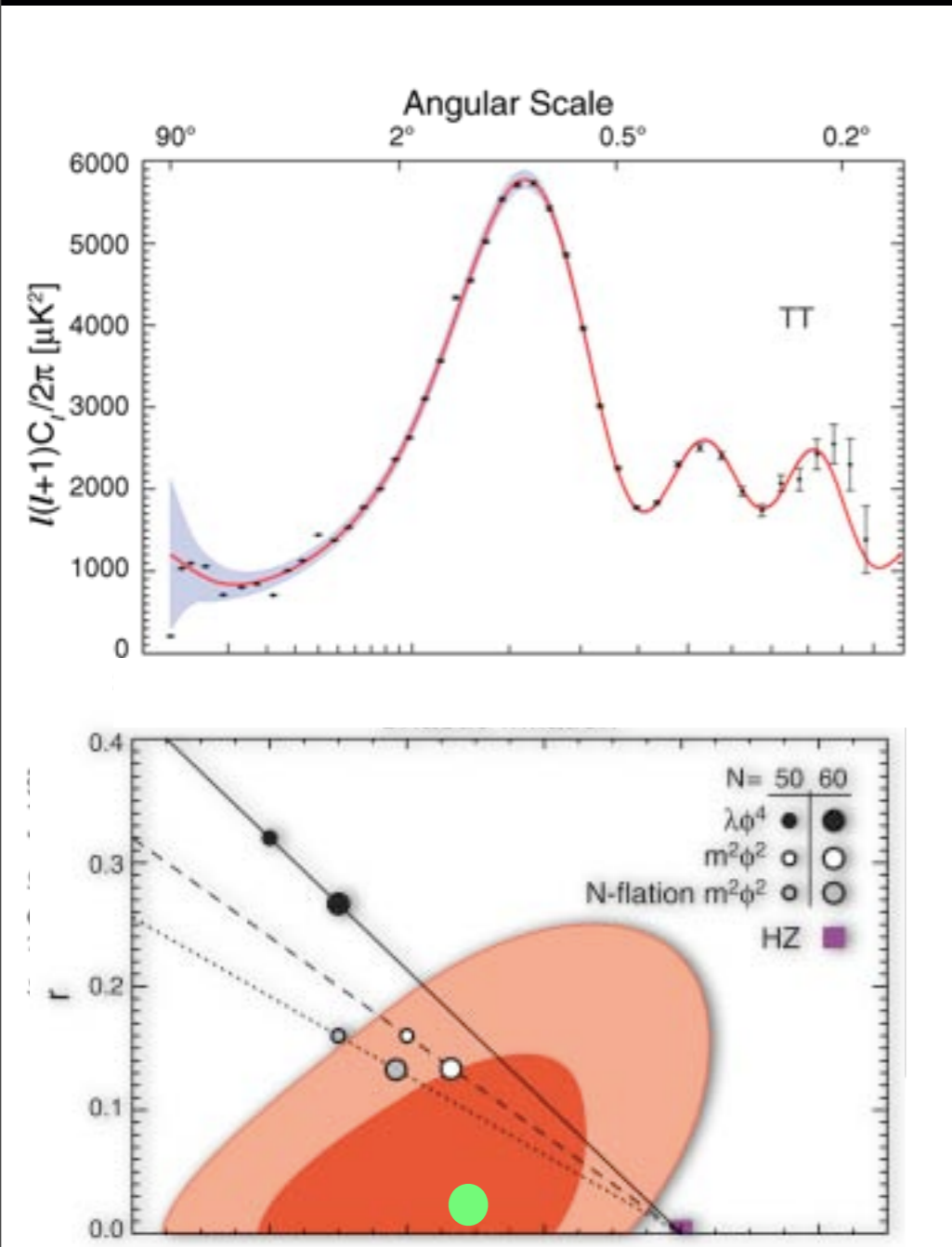
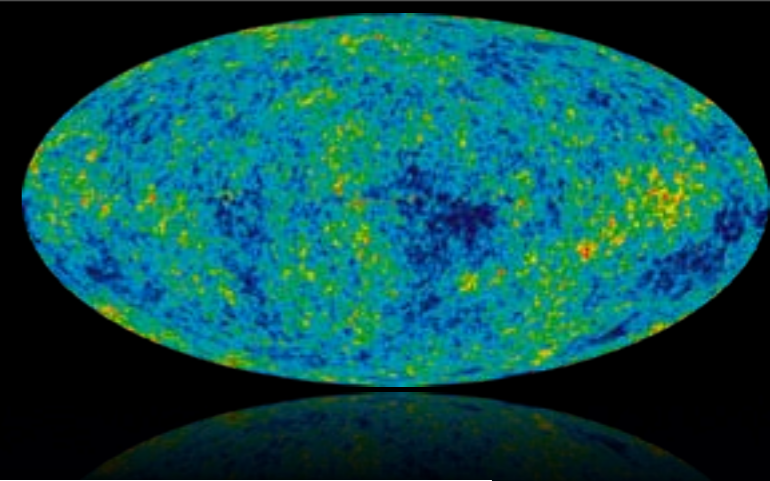


$$A \approx \sqrt{40}m_\phi \sim 100 \text{ GeV}$$

Electroweak symmetry is restored

$$\phi_0 = 10^{14} \text{ GeV}$$

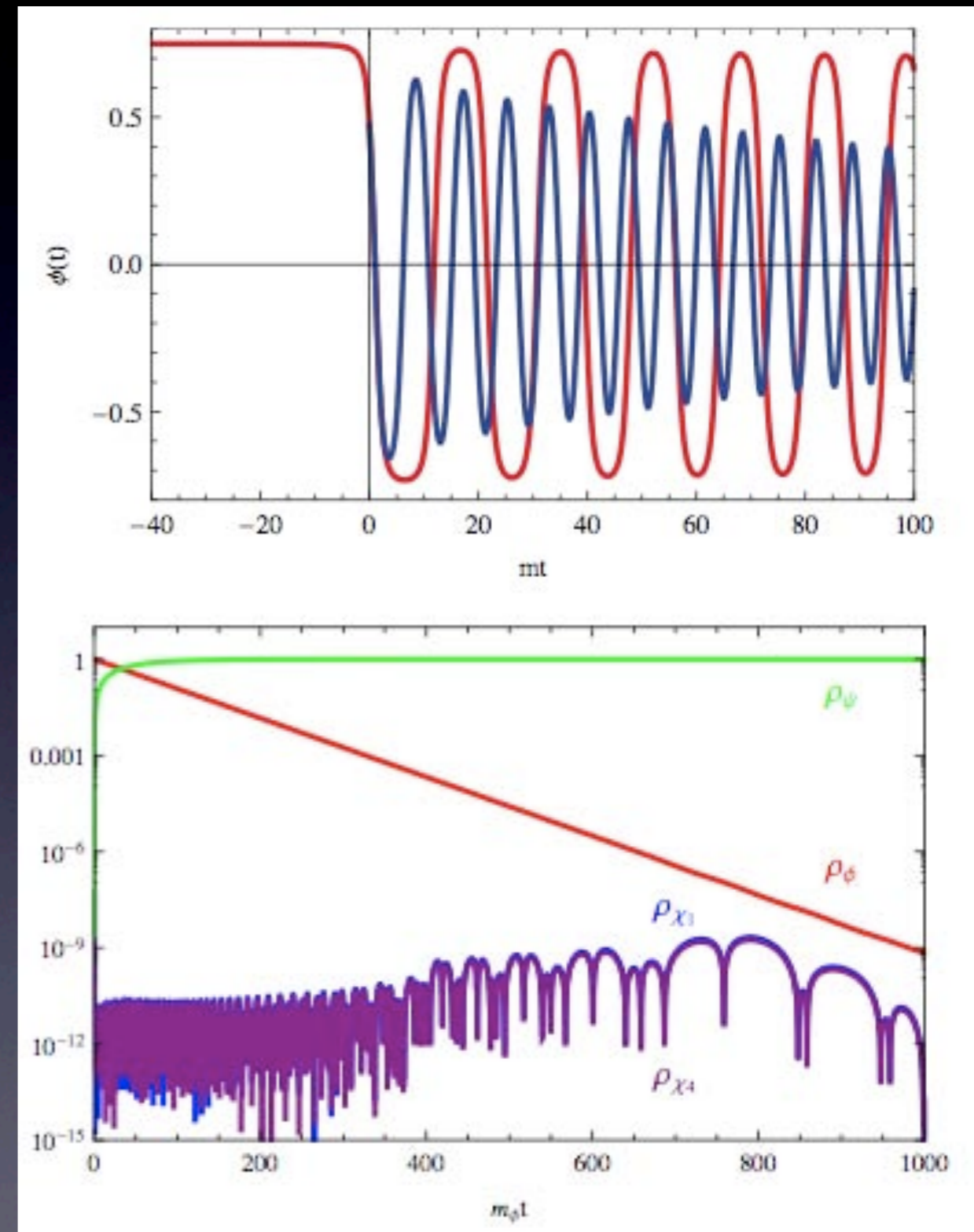
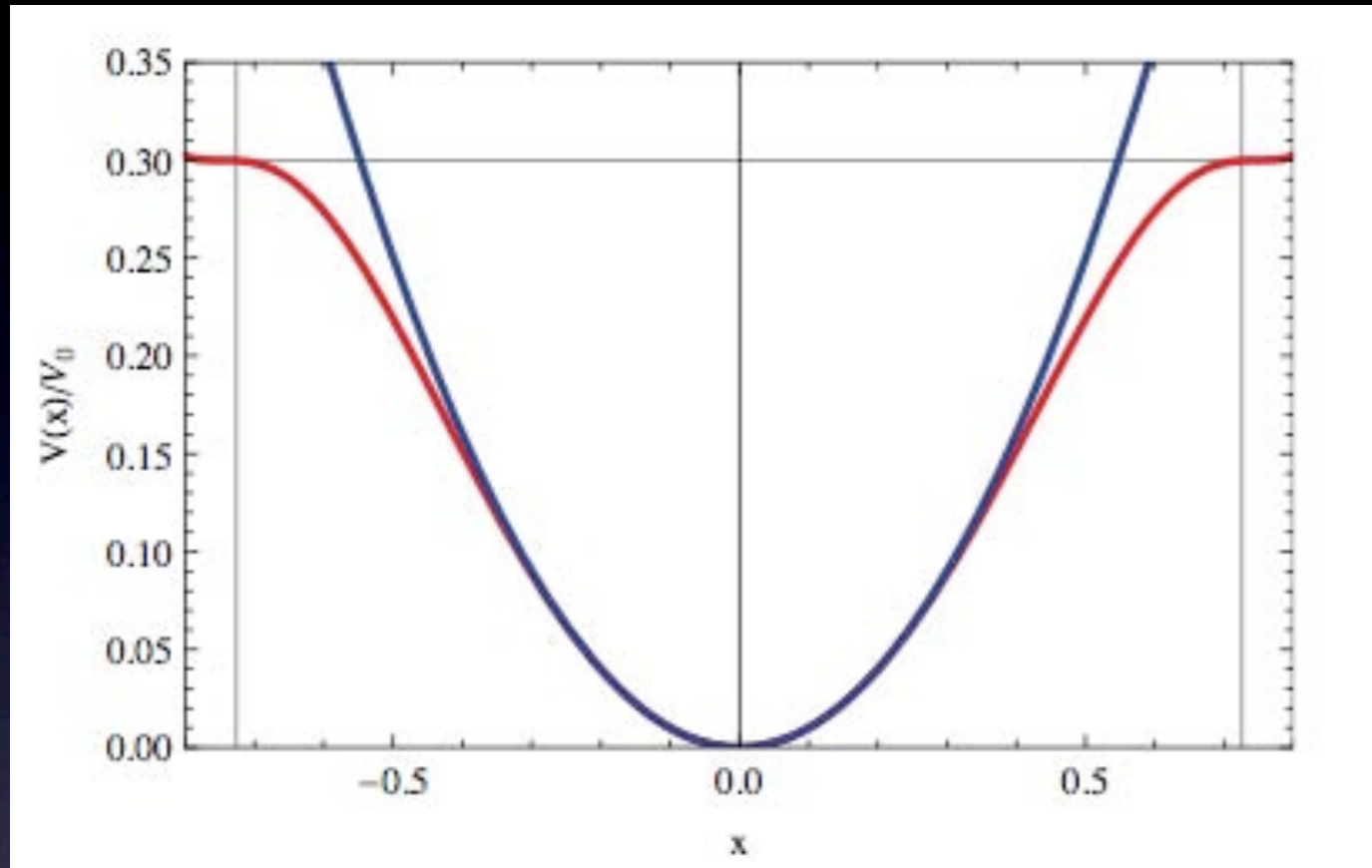
MSSM Inflation: Predictions for CMB + LHC



LHC

Creating SM quarks, leptons, & all

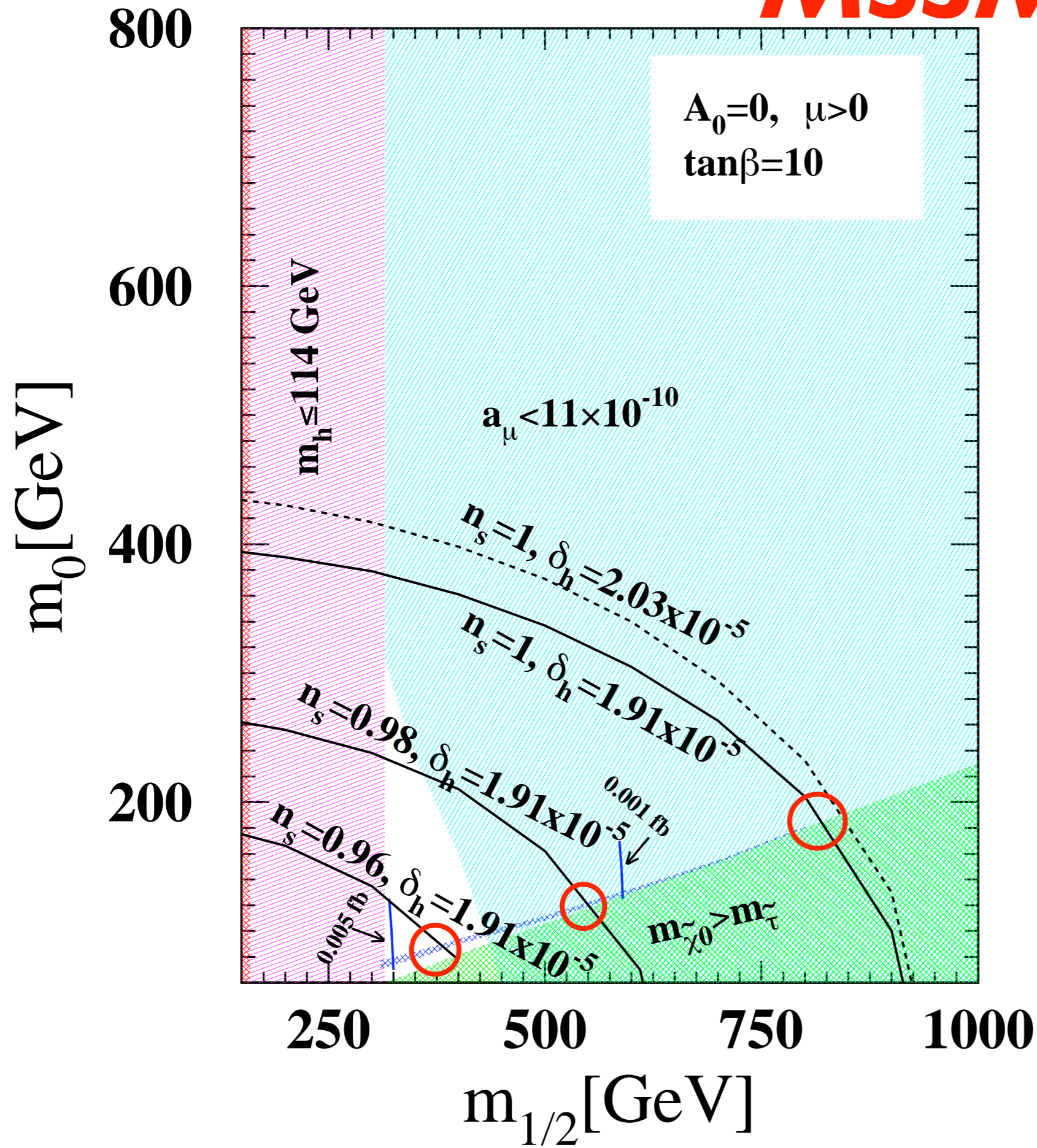
First ever state-of-the art calculation



$$T_R \sim 3 \times 10^8 \text{ GeV}$$

Allahverdi, Ferrantelli, Garcia-Bellido, Mazumdar, arXiv:1103.2123, Phys. Rev. D (2011)

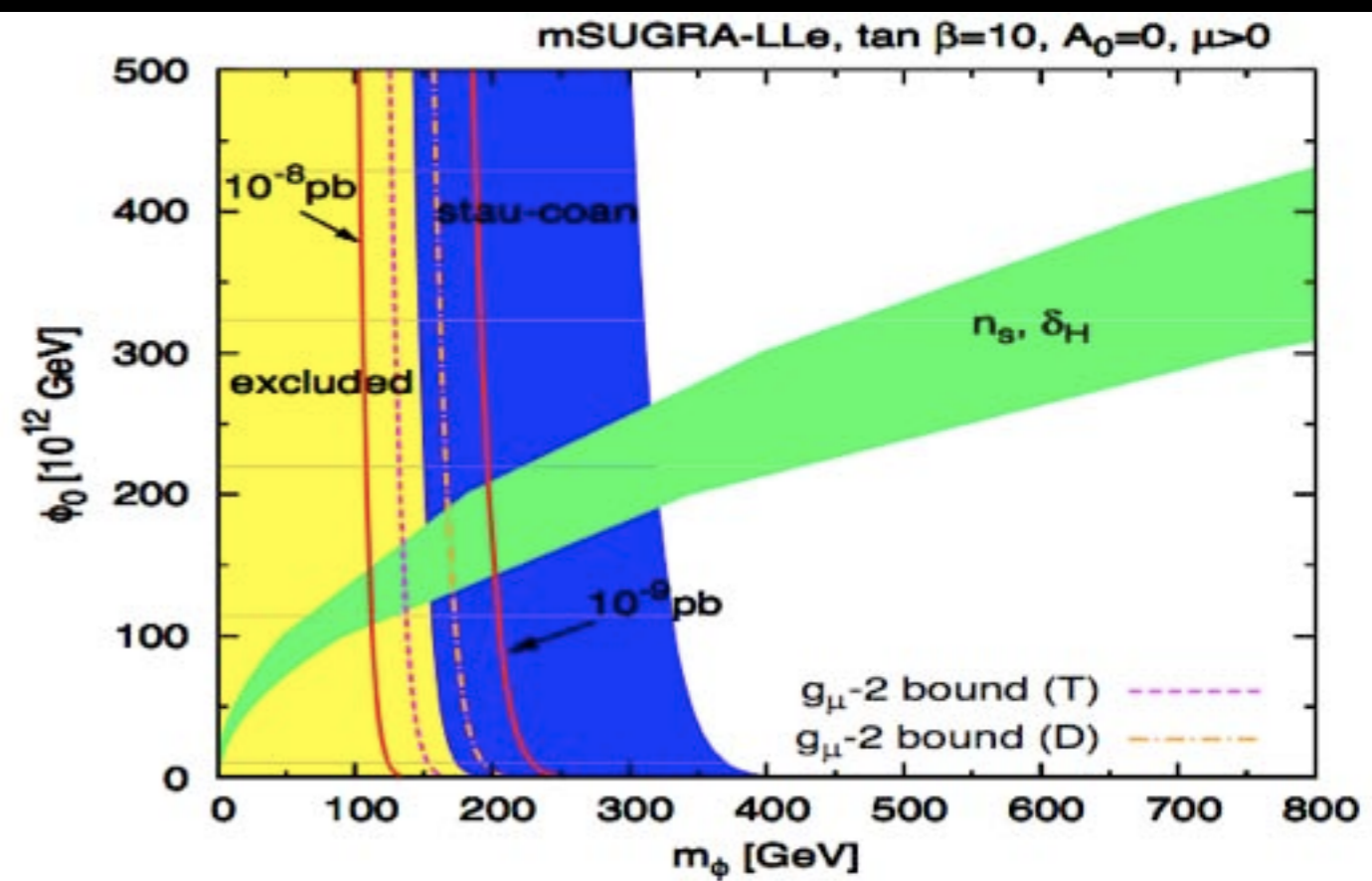
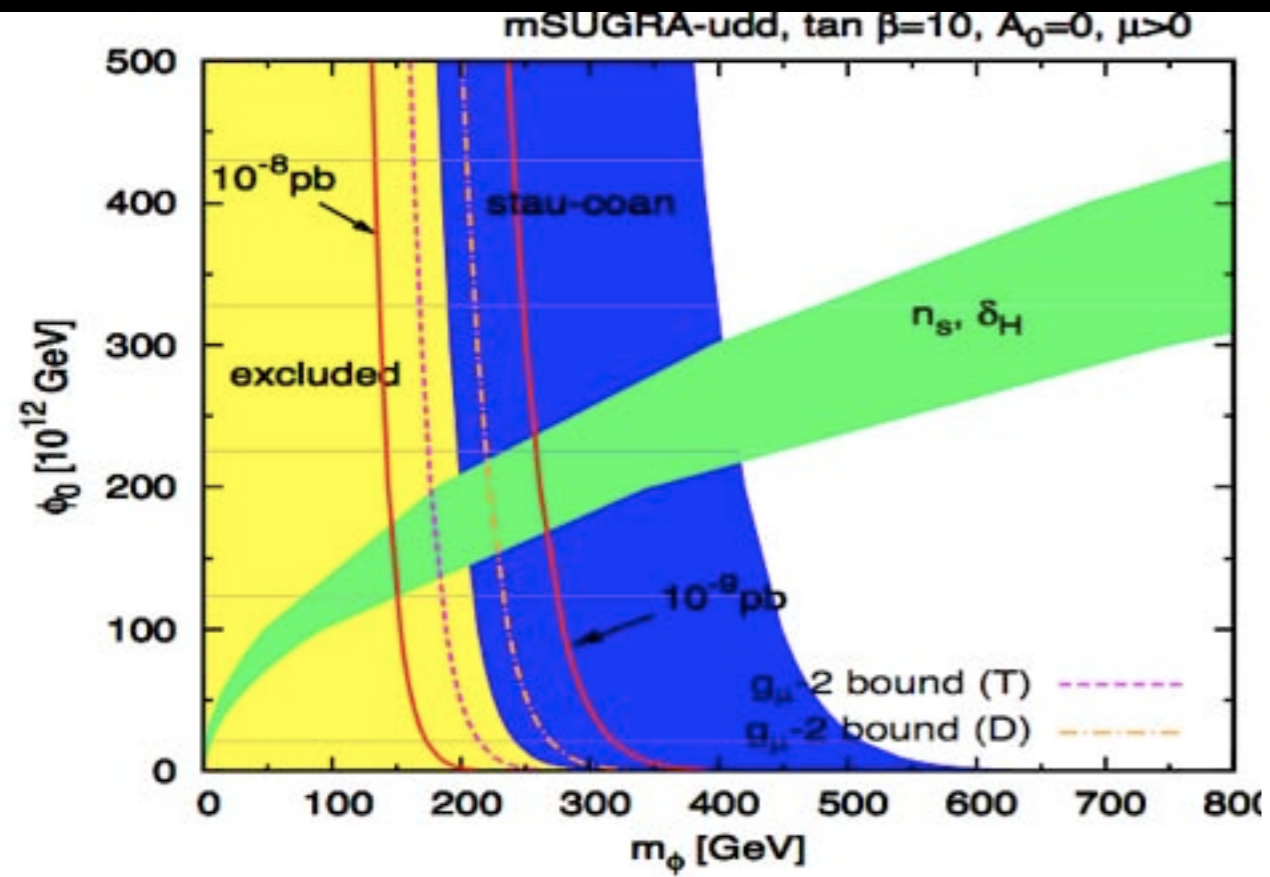
MSSM Inflation



**LSP Dark
Matter,
Inflation,
&
LHC**

Allahverdi, Dutta, Mazumdar
Phys. Rev. D (2007)

MSSM Inflation @ LHC



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

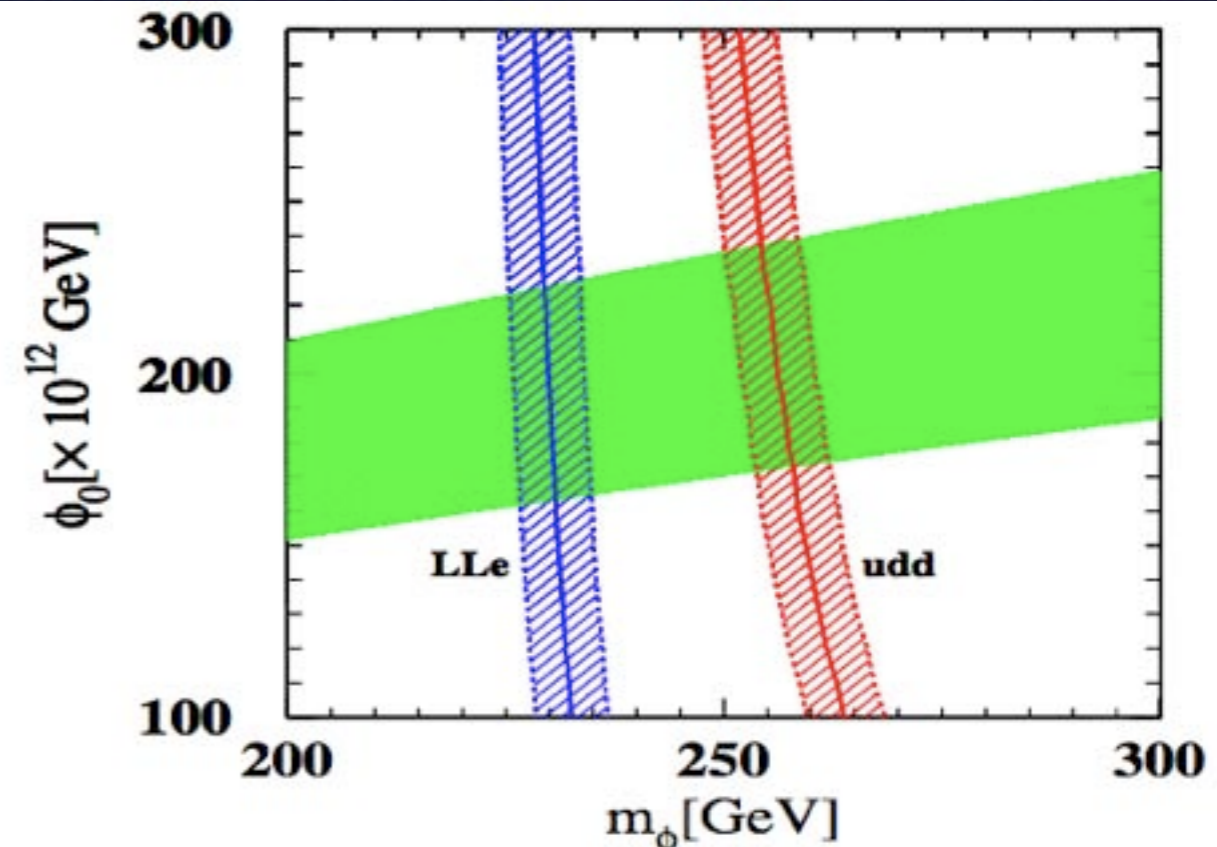
Consider a SUSY reference point in the co-annihilation region (all masses are in GeV):

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

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

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

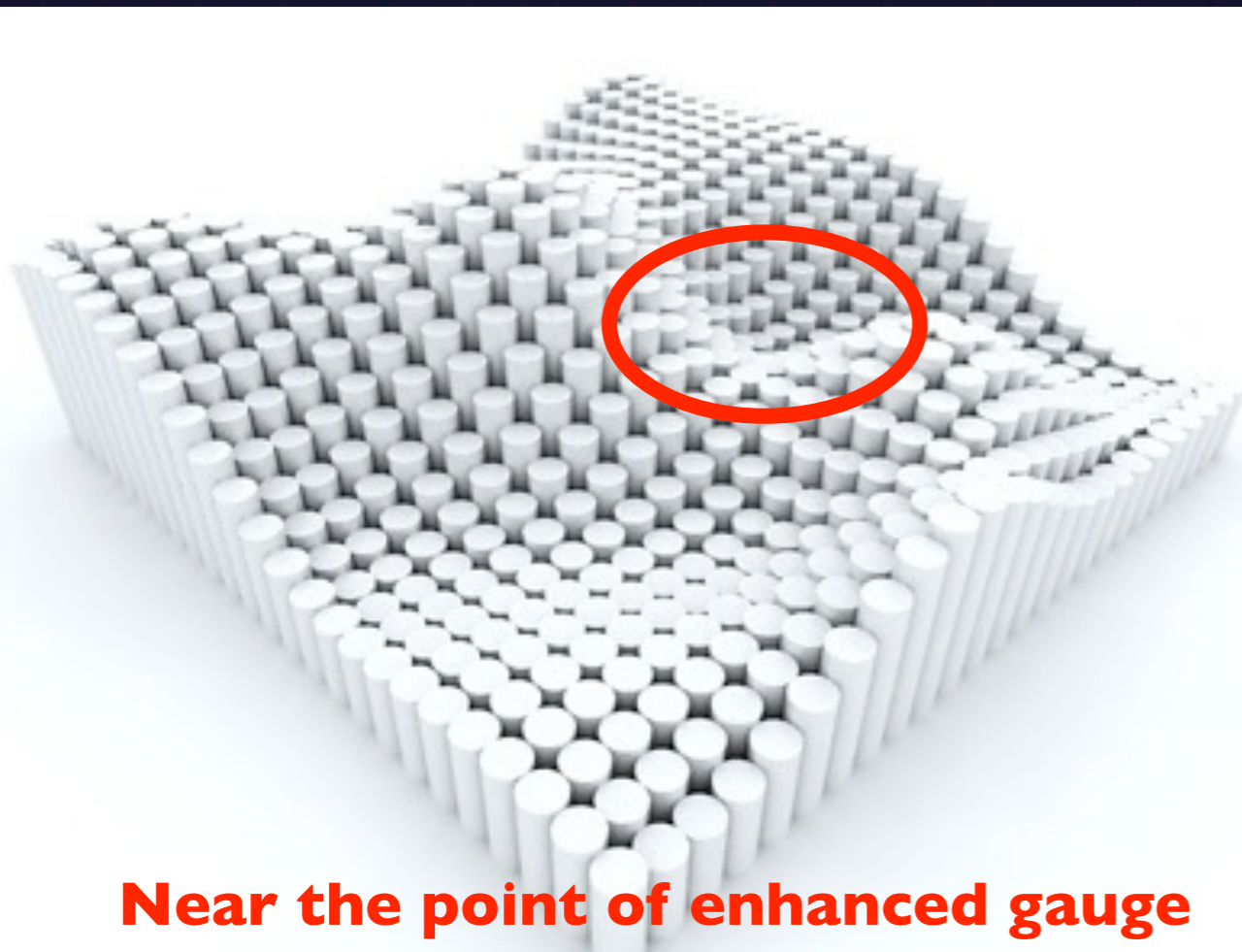
$$m_0 = 210 \pm 4, m_{1/2} = 350 \pm 4, \tan \beta = 40 \pm 1, A_0 = 0 \pm 16$$



Higgsiology

$$V(\varphi, \theta) = \frac{1}{2}m^2(\theta)\varphi^2 + (-1)^{k-1}2\lambda'_k\mu \cos[2(\theta - 1)]\varphi^{2k} \\ + 2\lambda'_k{}^2\varphi^{2(2k-1)}$$

$$m^2(\theta) = m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 - 2B\mu \cos(2\theta) \quad \lambda'_k = \frac{\lambda_k}{2^{(2k-1)}M_P^{2k-3}}$$

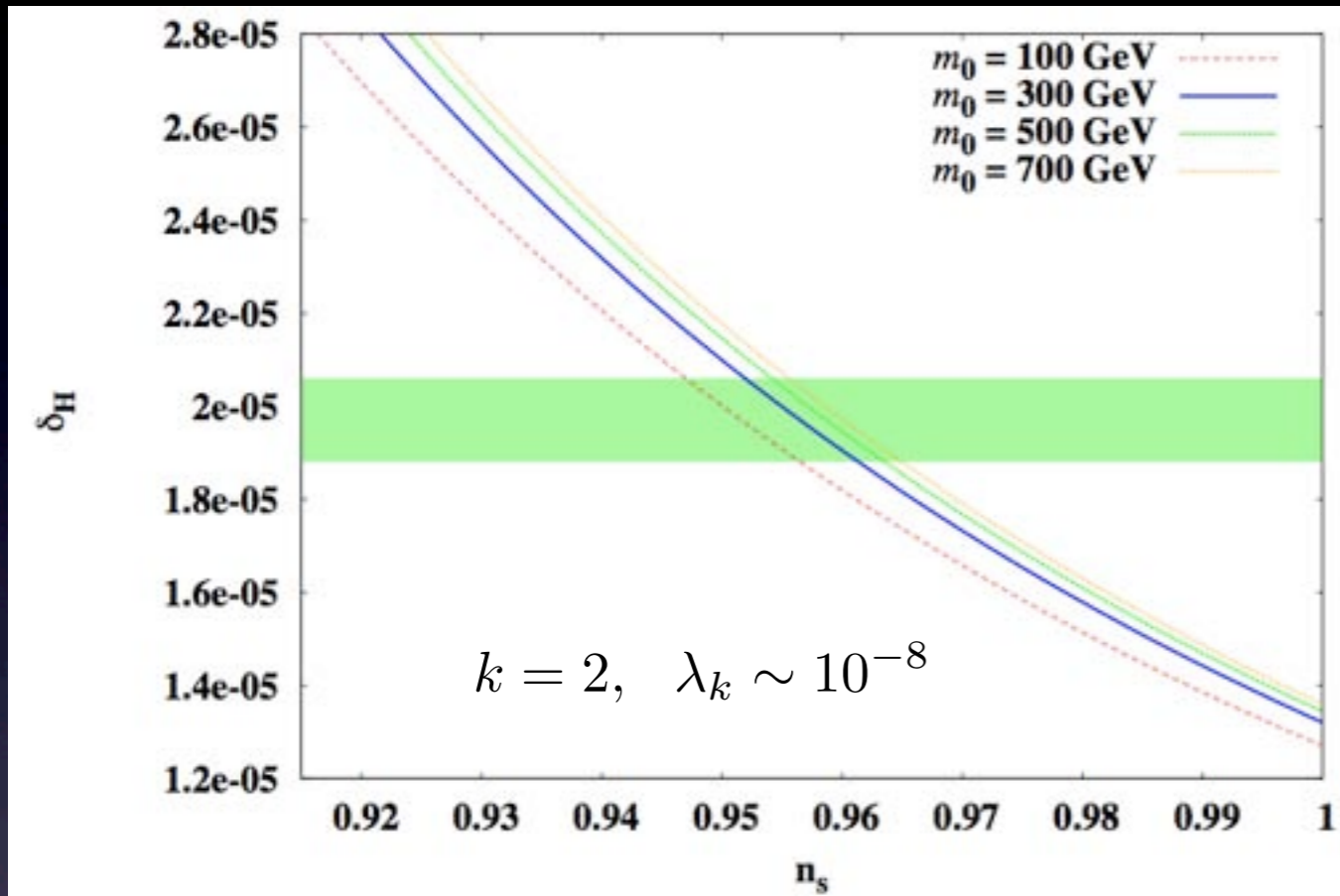


Near the point of enhanced gauge symmetry

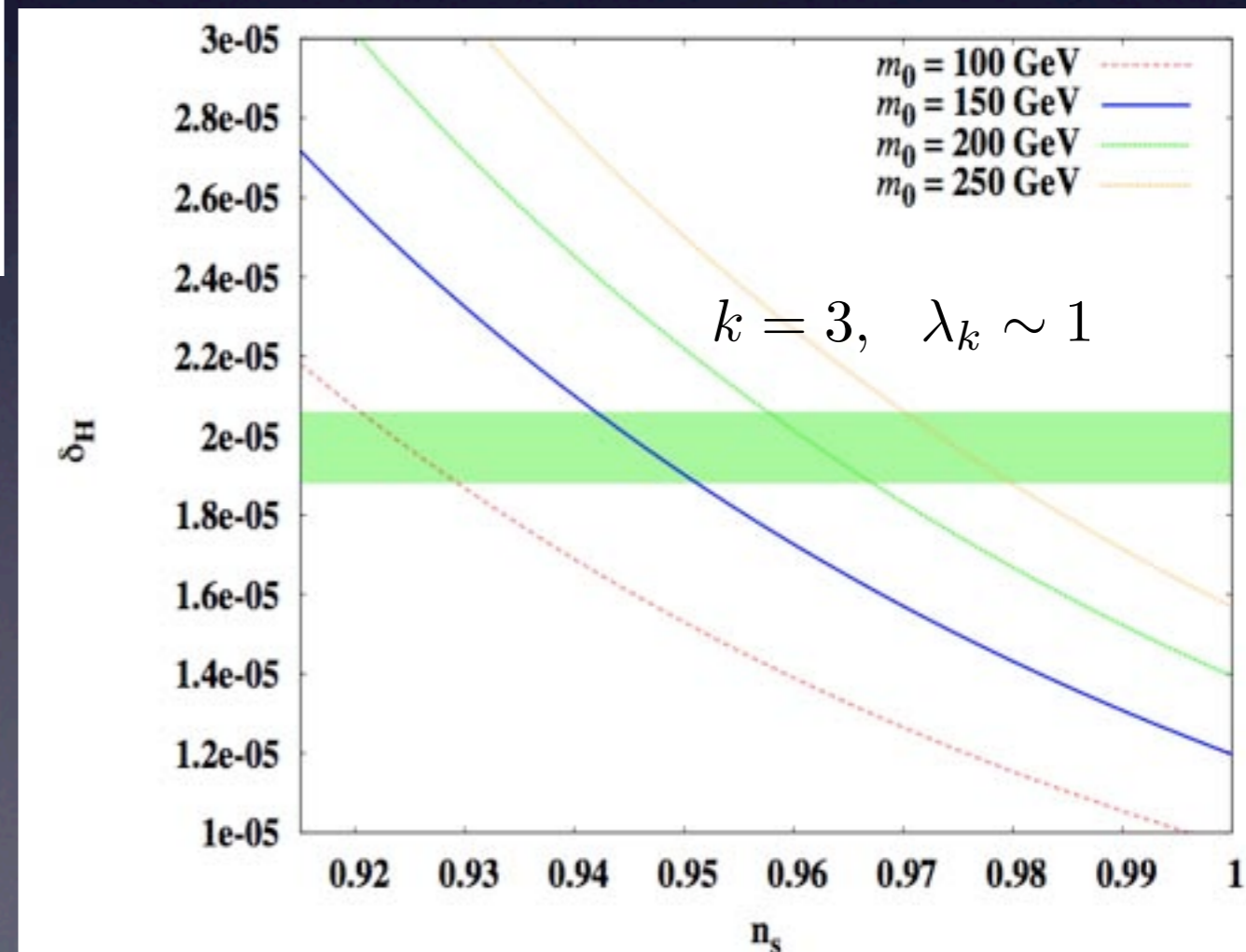
**Where would
Inflation
occur?**

$$\theta = \{0, \pm\pi/2\}$$

CMB + LHC Constraints

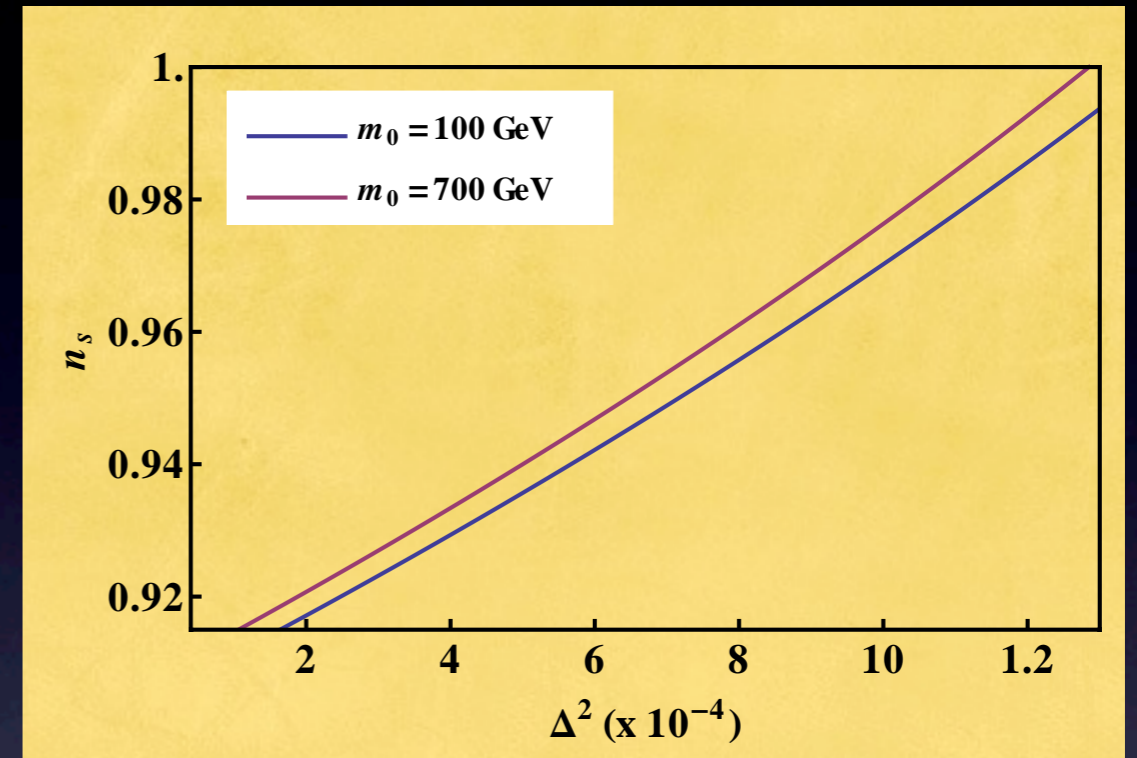
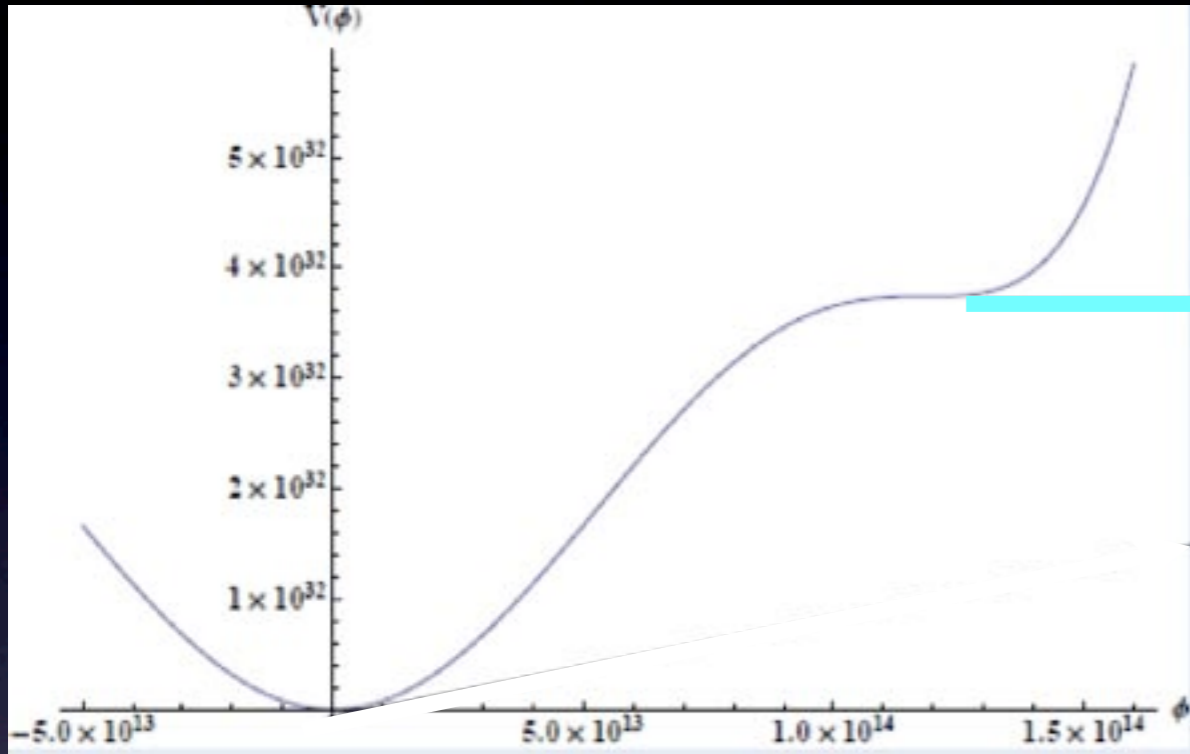


$$m_0^2 = m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 - 2B\mu$$



Mazumdar, Chatterjee, 1103.5758 [hep-ph]

Tuned Higgses @ High VeVs



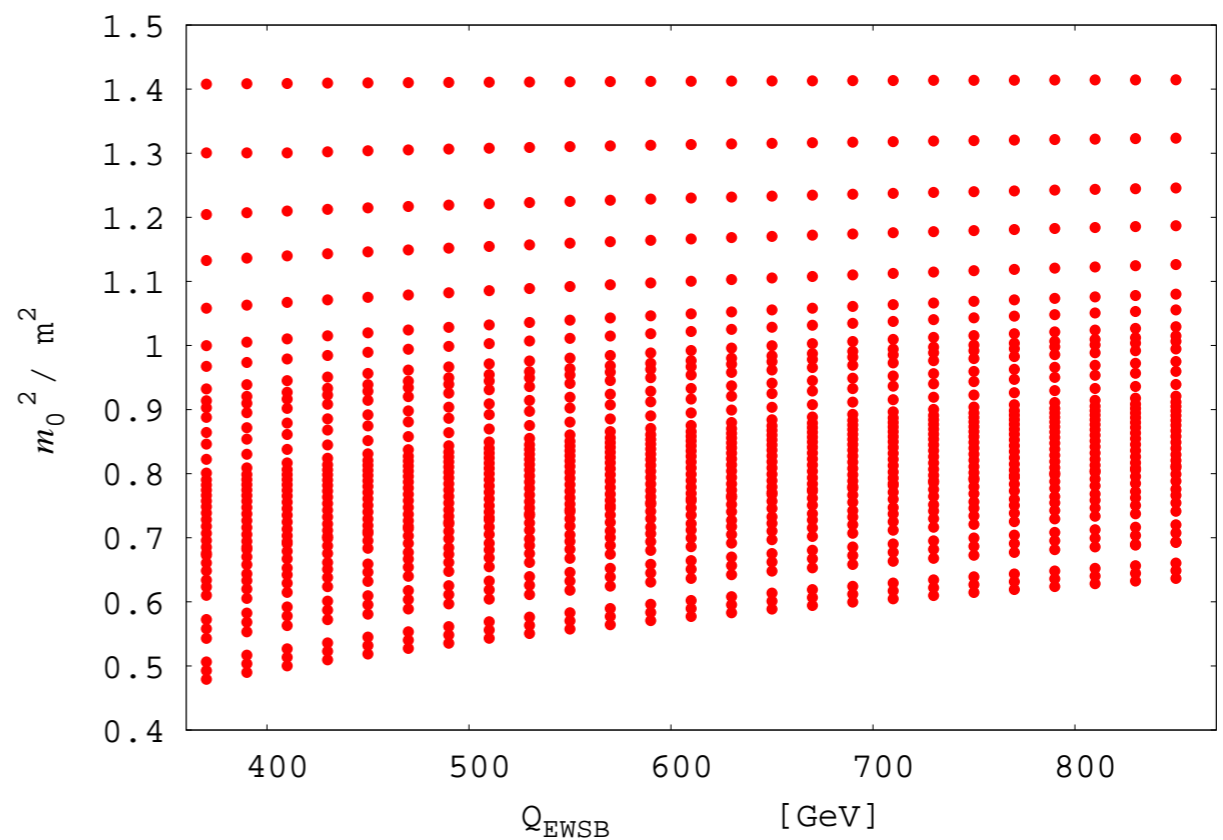
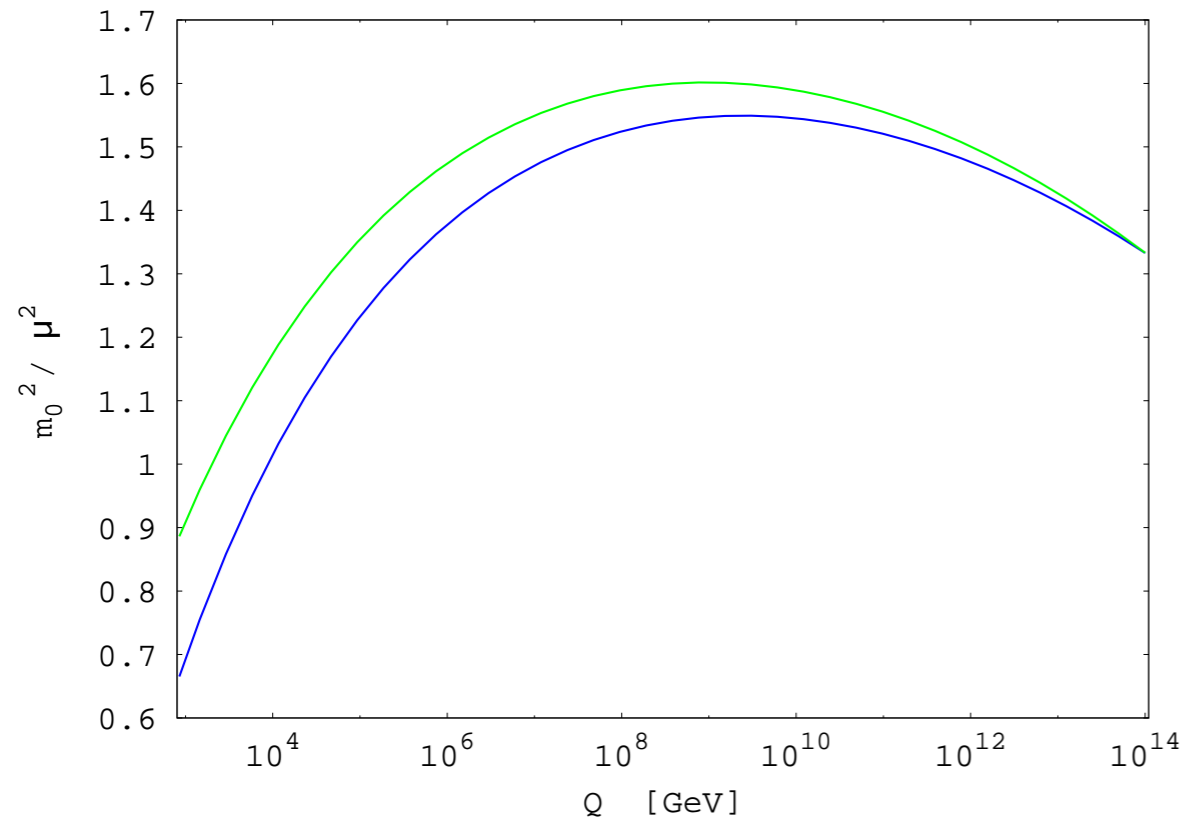
$$\Delta^2 = 32k^2(2k-1)^2\lambda^2\mathcal{N}_{COBE}^2\left(\frac{M_P}{\varphi_0}\right)^4 \quad k=3, \quad \lambda_k \sim 1$$

$$\Delta^2 \sim 10^{-3} \longrightarrow \alpha \sim 10^{-11}$$

$$m_0^2 = m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 - 2B\mu$$

Tuning between m_0 & μ

What happens to the tuning @ TeV scale ?



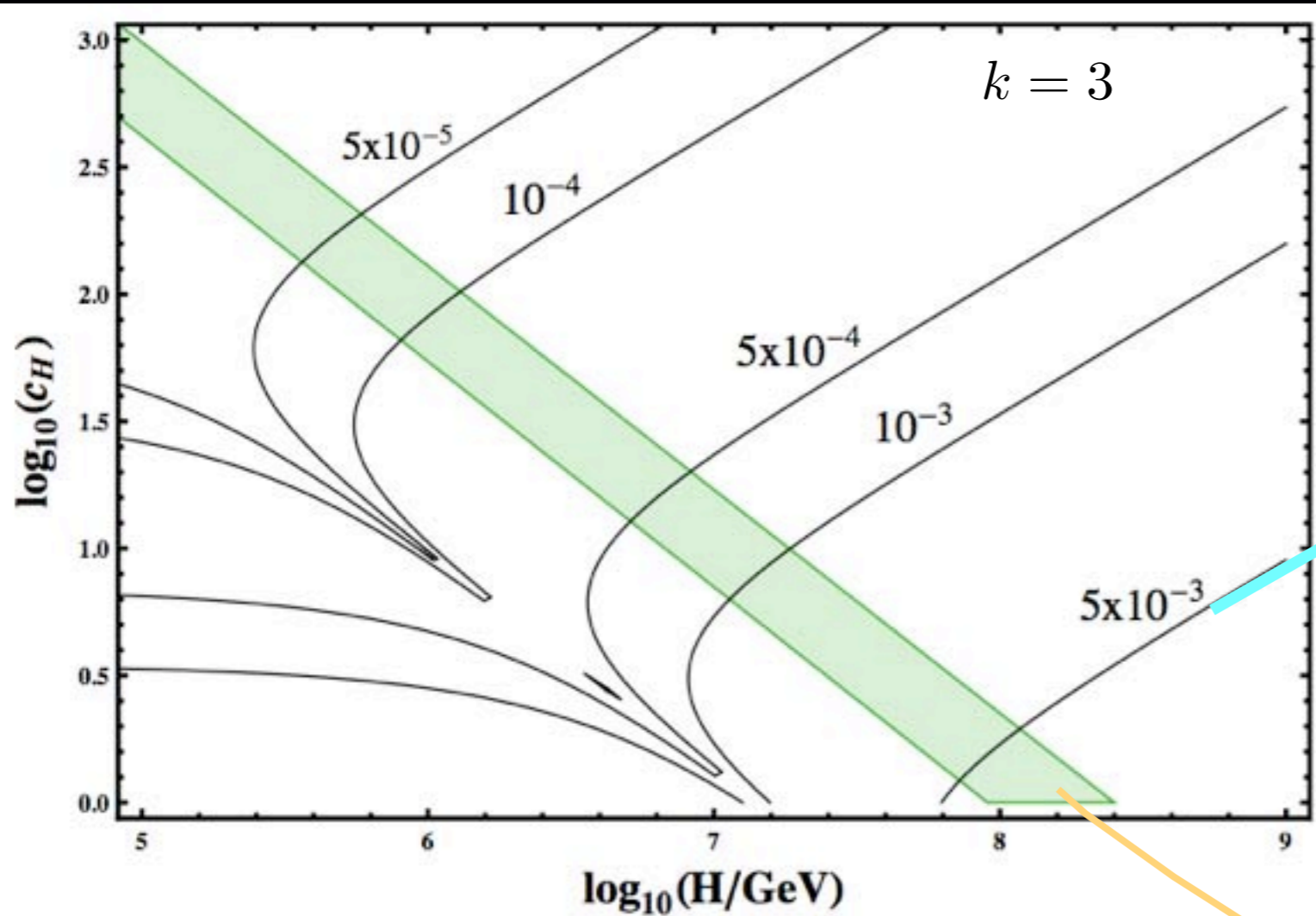
We can track the evolution via R-G flow from high scale to the observable scale

$$m_0^2 = \frac{k^2 [(-1)^{k-1} 2\mu + A]^2}{8k - 4} + \alpha^2$$

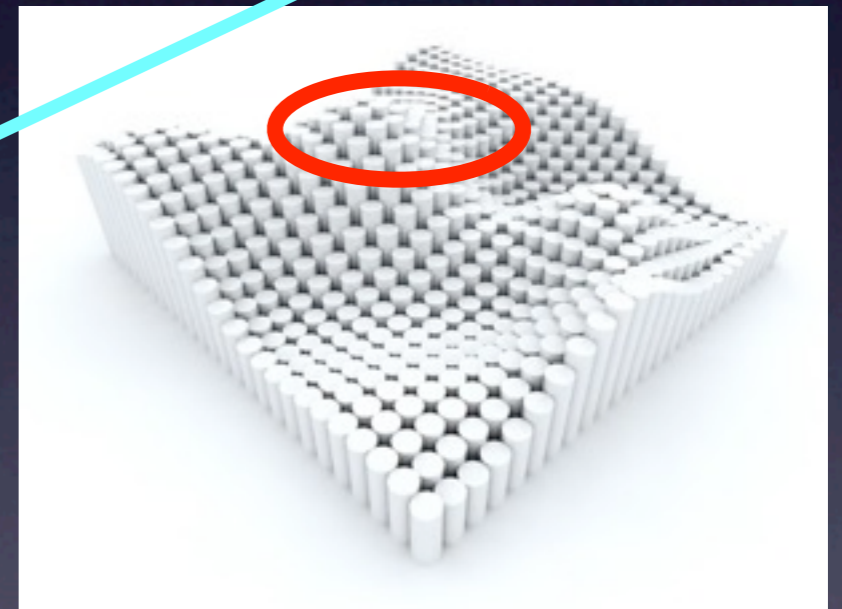
Fine tuning could come from many sources

Effects from Supergravity

$$V(\phi) = 3H^2 M_P^2 + \frac{c_H H^2}{2} \phi^2 - \frac{a_H H}{k M_P^{k-3}} \phi^k + \frac{\phi^{2(k-1)}}{M_P^{2(k-3)}}$$

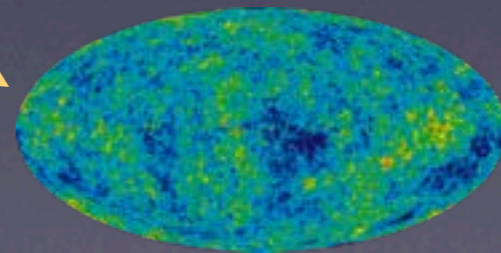


$$\frac{a_H^2}{8(k-1)c_H} = 1 - \frac{(k-2)^2}{4} \beta^2$$



$$W = W_{Hid} + W_{MSSM}$$

$$K = K_{hid} + K_{MSSM} + \delta k$$

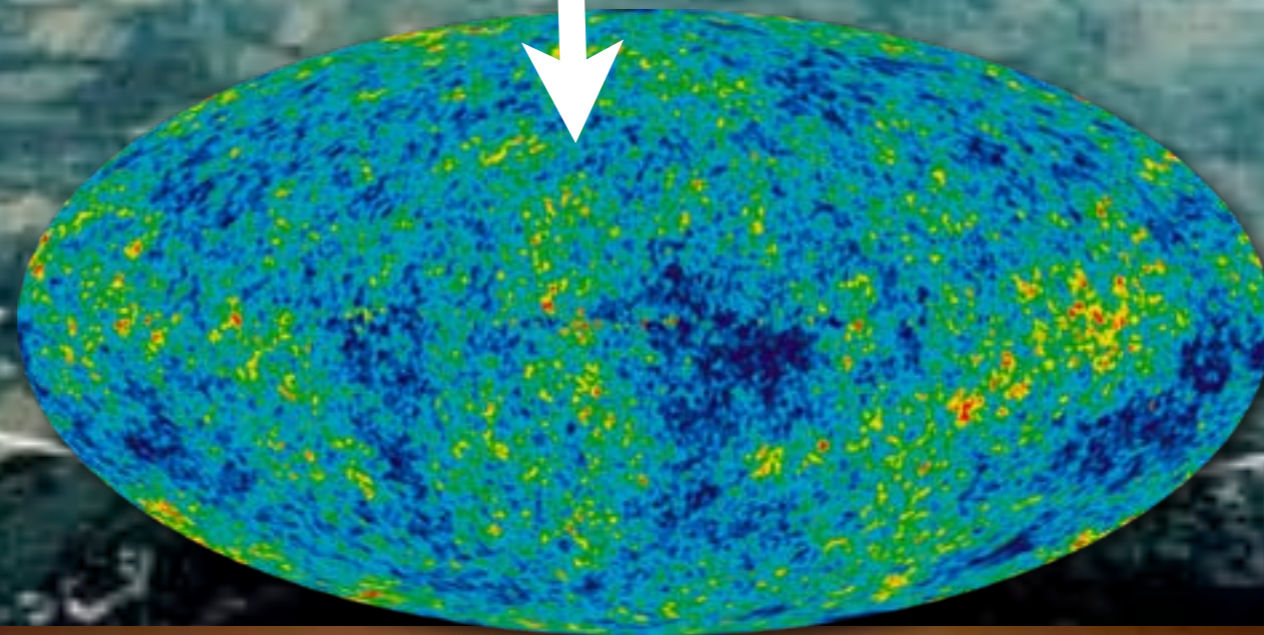


AM, Nadathur, Stephens, arXiv: 1105.0430

MSSM Inflation

Baryons

Dark matter

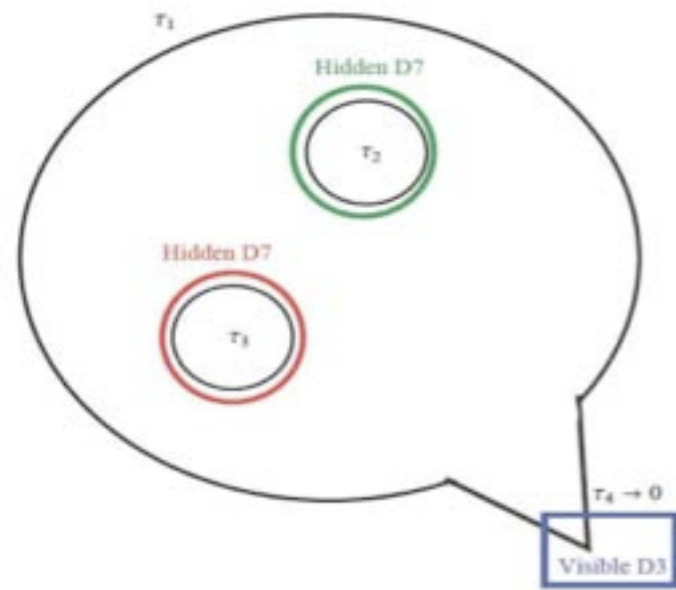
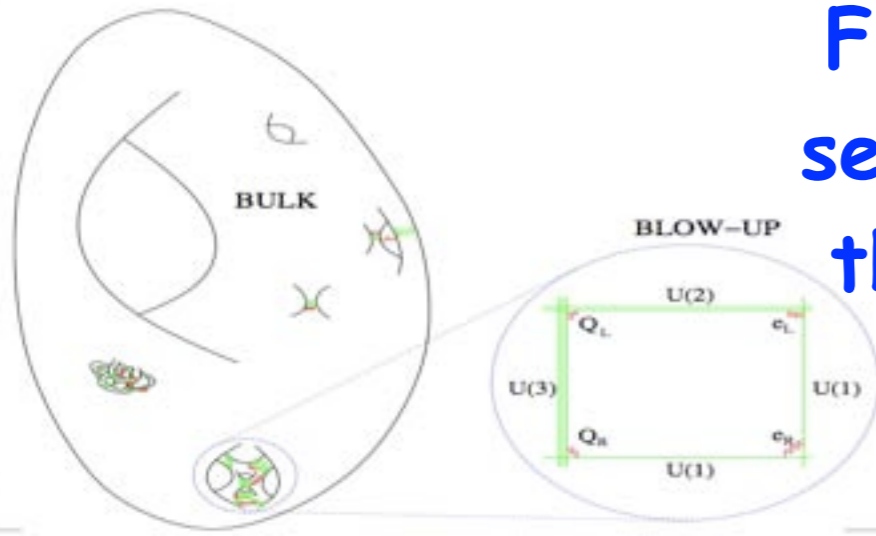
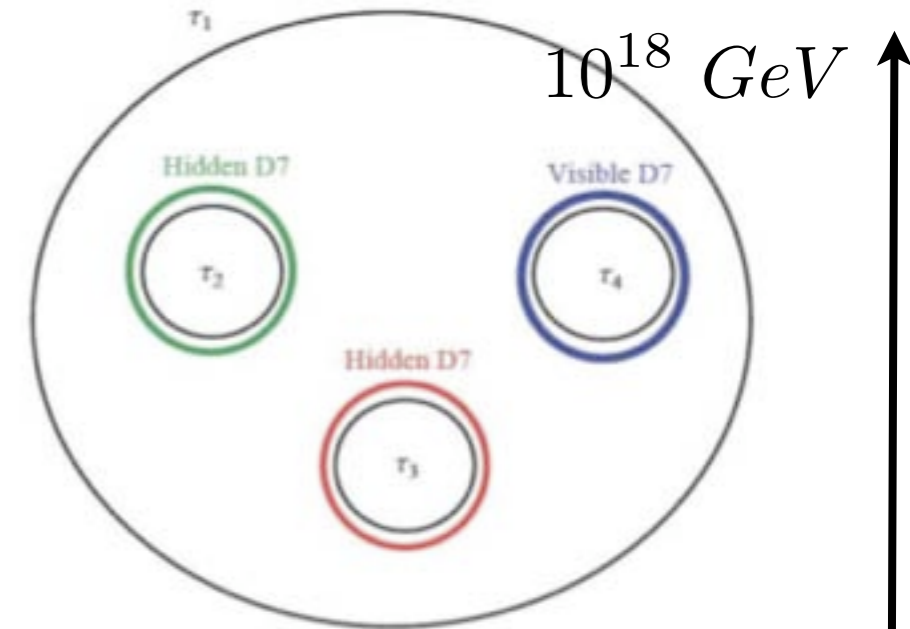


In search for SUSY

In search for Inflaton

Explicit example of Kahler modulus Inflaton in Large Volume Compactification

First example of hidden sector inflation where all the couplings are known



$$\delta\tau_1 \sim \mathcal{O}(\mathcal{V}^{2/3})\delta\phi_1 + \sum_{i=2}^4 \mathcal{O}(\mathcal{V}^{1/6})\delta\phi_i \sim \mathcal{O}(\mathcal{V}^{2/3})\delta\phi_1,$$

$$\delta\tau_2 \sim \mathcal{O}(1)\delta\phi_1 + \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_2 + \sum_{i=3}^4 \mathcal{O}(\mathcal{V}^{-1/2})\delta\phi_i \sim \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_2,$$

$$\delta\tau_3 \sim \mathcal{O}(1)\delta\phi_1 + \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_3 + \sum_{i=2,4} \mathcal{O}(\mathcal{V}^{-1/2})\delta\phi_i \sim \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_3,$$

$$\delta\tau_4 \sim \mathcal{O}(1)\delta\phi_1 + \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_4 + \sum_{i=2}^3 \mathcal{O}(\mathcal{V}^{-1/2})\delta\phi_i \sim \mathcal{O}(\mathcal{V}^{1/2})\delta\phi_4,$$

10^3 GeV

All the inflaton energy goes to Hidden Sectors

	$\delta\phi_1$	$\delta\phi_2$	$\delta\phi_3$	$\delta\phi_4$
$(F_{\mu\nu}^{(2)} F^{\mu\nu}_{(2)})$	$\frac{1}{M_P}$	$\frac{\mathcal{V}^{1/2}}{M_P}$	$\frac{1}{\mathcal{V}^{1/2} M_P}$	$\frac{1}{\mathcal{V}^{1/2} M_P}$
$(F_{\mu\nu}^{(3)} F^{\mu\nu}_{(3)})$	$\frac{1}{M_P}$	$\frac{1}{\mathcal{V}^{1/2} M_P}$	$\frac{\mathcal{V}^{1/2}}{M_P}$	$\frac{1}{\mathcal{V}^{1/2} M_P}$
$(F_{\mu\nu}^{(4)} F^{\mu\nu}_{(4)})$	$\frac{1}{M_P}$	$\frac{\mathcal{V}^{1/2}}{M_P}$	$\frac{1}{\mathcal{V}^{1/2} M_P}$	$\frac{\mathcal{V}^{1/2}}{M_P}$

Cicoli, Mazumdar: 1005.5076