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Saha Theory Workshop: Cosmology at the interface

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Constraining $\mathcal{N}=1$ supergravity inflationary framework with non-minimal Kähler operators

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Abstract: In this paper we will illustrate how to constrain unavoidable Kähler corrections for $\mathcal{N}=1$ supergravity (SUGRA) inflation from the recent Planck data. We will show that the non-renormalizable Kähler operators will induce in general non-minimal kinetic term for the inflaton field, and two types of SUGRA corrections in the potential — the *Hubble-induced mass* (c_H), and the *Hubble-induced A-term* (a_H) correction. The entire SUGRA inflationary framework can now be constrained from (i) the *speed of sound*, c_s, and (ii) from the upper bound on the *tensor to scalar ratio*, $r_\star$. We will illustrate this by considering a heavy scalar degree of freedom at a scale, M_s, and a light inflationary field which is responsible for a slow-roll inflation. We will compute the corrections to the kinetic term and the potential for the light field explicitly. As an example, we will consider a visible sector inflationary model of inflation where inflation occurs at the point of *inflection*, which can match the density perturbations for the cosmic microwave background radiation, and also explain why the universe is filled with the Standard Model degrees of freedom. We will scan the parameter space of the non-renormalizable Kähler operators, which we find them to be order $\mathcal{O}(1)$, consistent with physical arguments. While the scale of heavy physics is found to be bounded by the tensor-to scalar ratio, and the speed of sound, $\mathcal{O}\left(10^{11} \leq M_s \leq 10^{16}\right)$ GeV, for $0.02 \leq c_s \leq 1$ and $10^{-22} \leq r_\star \leq 0.12$.

Keywords: Cosmology of Theories beyond the SM, Supersymmetric Effective Theories, Supergravity Models

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Constraining $\mathcal{N}=1$ supergravity inflation with non-minimal Kähler operators using δN formalism

Sayantan Choudhury

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E-mail: sayanphysicsisi@gmail.com

Abstract: In this paper I provide a general framework based on δN formalism to study the features of unavoidable higher dimensional non-renormalizable Kähler operators for $\mathcal{N}=1$ supergravity (SUGRA) during primordial inflation from the combined constraint on non-Gaussianity, sound speed and CMB dipolar asymmetry as obtained from the recent Planck data. In particular I study the nonlinear evolution of cosmological perturbations on large scales which enables us to compute the curvature perturbation, ζ, without solving the exact perturbed field equations. Further I compute the non-Gaussian parameters f_{NL} , τ_{NL} and g_{NL} for local type of non-Gaussianities and CMB dipolar asymmetry parameter, A_{CMB}, using the δN formalism for a generic class of sub-Planckian models induced by the Hubble-induced corrections for a minimal supersymmetric D-flat direction where inflation occurs at the point of inflection within the visible sector. Hence by using multi parameter scan I constrain the non-minimal couplings appearing in non-renormalizable Kähler operators within, $\mathcal{O}(1)$, for the speed of sound, $0.02 \leq c_s \leq 1$, and tensor to scalar, $10^{-22} \leq r_\star \leq 0.12$. Finally applying all of these constraints I will fix the lower as well as the upper bound of the non-Gaussian parameters within, $\mathcal{O}(1-5) \leq f_{NL} \leq 8.5$, $\mathcal{O}(75-150) \leq \tau_{NL} \leq 2800$ and $\mathcal{O}(17.4-34.7) \leq g_{NL} \leq 648.2$, and CMB dipolar asymmetry parameter within the range, $0.05 \leq A_{CMB} \leq 0.09$.

Keywords: Cosmology of Theories beyond the SM, Supersymmetric Effective Theories, Supergravity Models

ArXiv ePrint: 1402.1251

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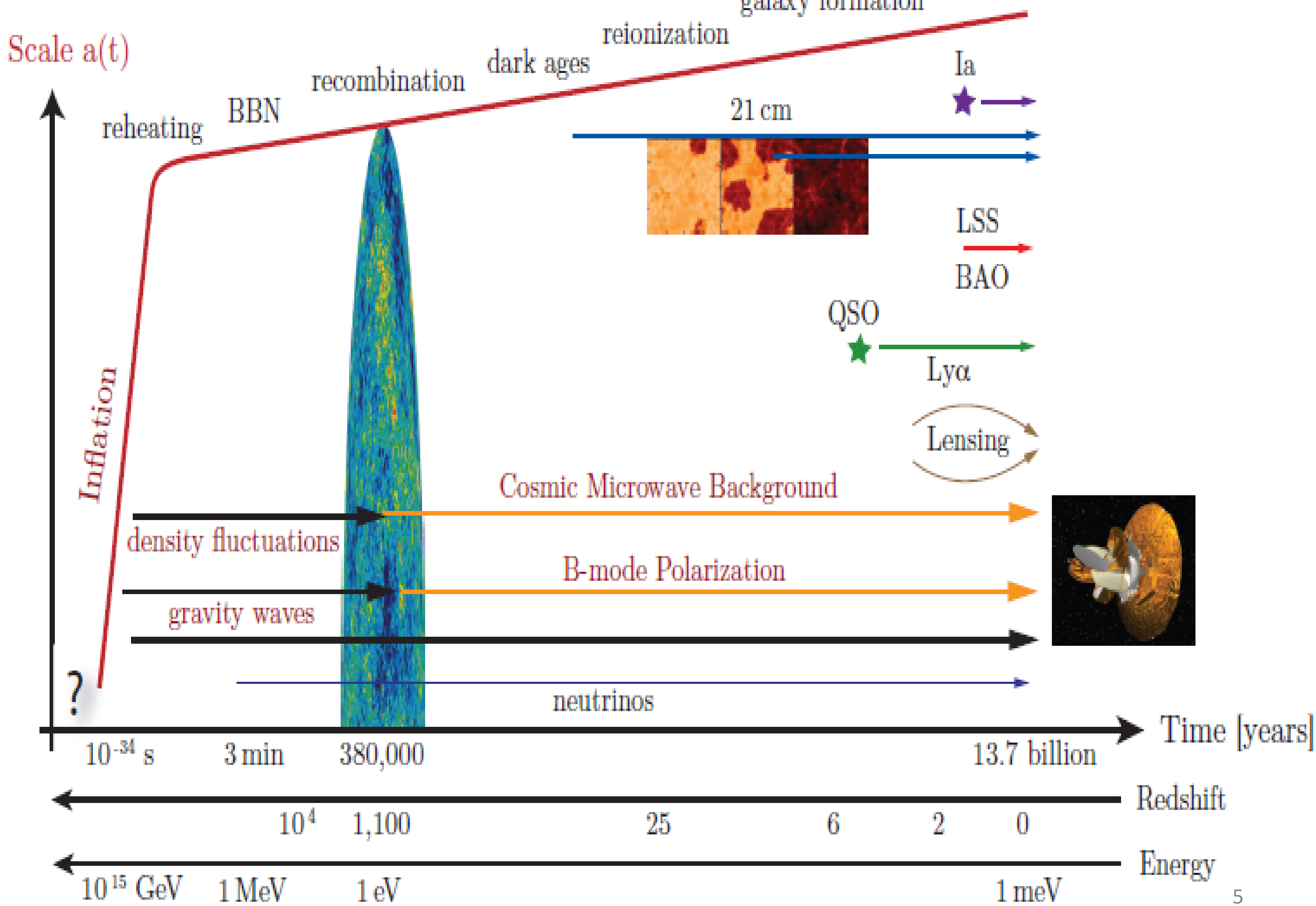
doi:10.1007/JHEP04(2014)105

JHEP04(2014)105

Outline of talk

- EFT Redux.
- The EFT setup for N=1 SUGRA.
- Non-minimal interactions in N=1 SUGRA.
- Gauge invariant inflatons.
- Primordial non-Gaussianity using δN formalism.
- Model (MSSM) constraints.
- Bottom lines and future prospects.

Baumann,arXiv:0907.5424



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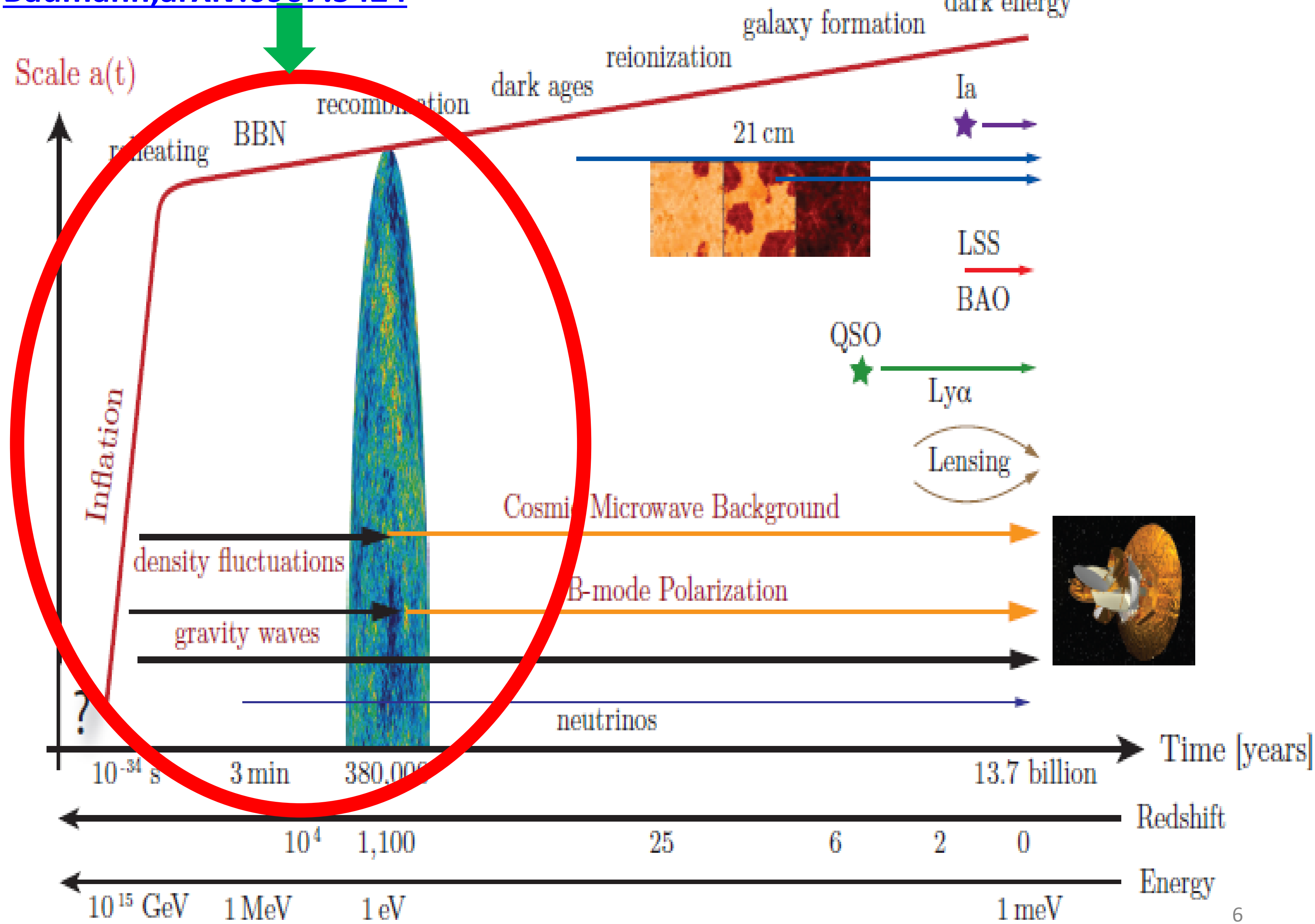

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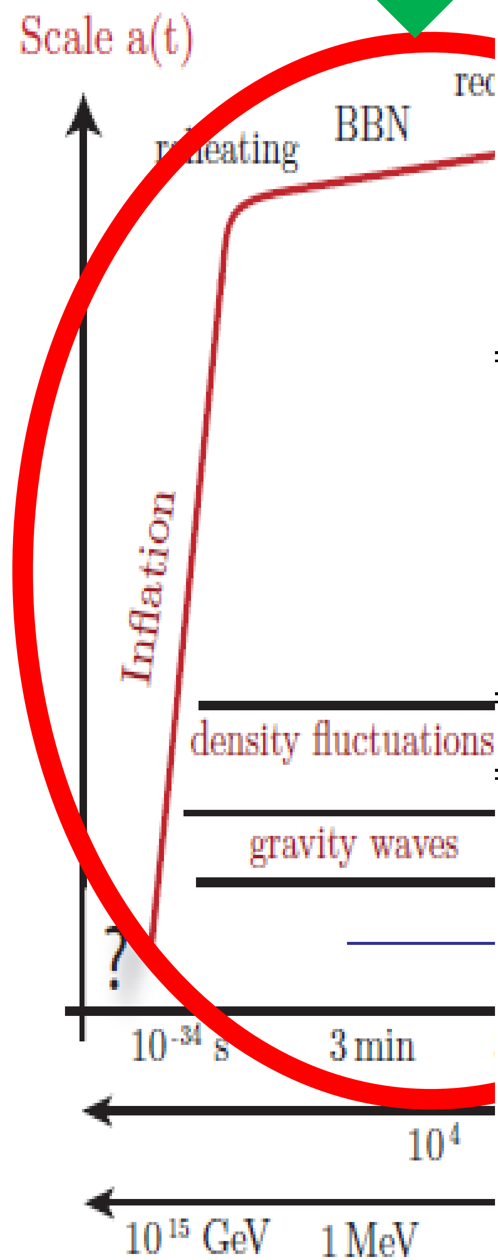
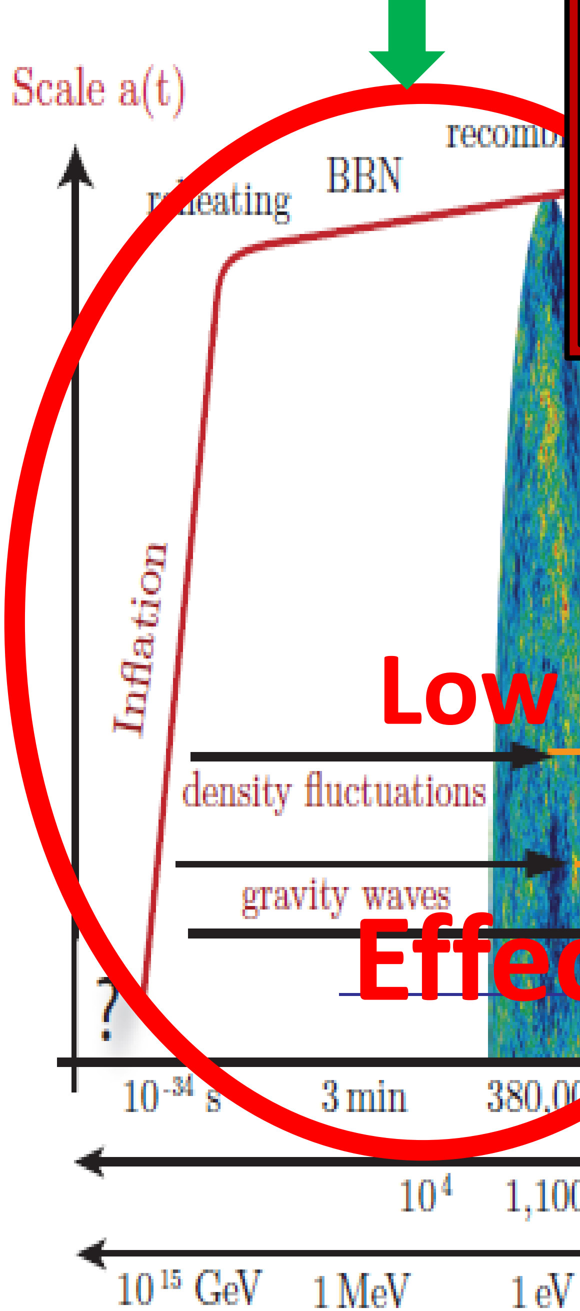


	Time	Energy
Planck Epoch?	$< 10^{-43}$ s	10^{18} GeV
String Scale?	$\gtrsim 10^{-43}$ s	$\lesssim 10^{18}$ GeV
Grand Unification?	$\sim 10^{-36}$ s	10^{15} GeV
Inflation?	$\gtrsim 10^{-34}$ s	$\lesssim 10^{15}$ GeV
SUSY Breaking?	$< 10^{-10}$ s	> 1 TeV
Baryogenesis?	$< 10^{-10}$ s	> 1 TeV
Electroweak Unification	10^{-10} s	1 TeV
Quark-Hadron Transition	10^{-4} s	10^{2} MeV
Nucleon Freeze-Out	0.01 s	10 MeV
Neutrino Decoupling	1 s	1 MeV
BBN	3 min	0.1 MeV
Matter-Radiation Equality	10^{4} yrs	1 eV
Recombination	10^{5} yrs	0.1 eV
Dark Ages	$10^{5} - 10^{8}$ yrs	
Reionization	10^{8} yrs	
Galaxy Formation	$\sim 6 \times 10^{8}$ yrs	
Dark Energy	$\sim 10^{9}$ yrs	
Solar System	8×10^{9} yrs	
Albert Einstein born	14×10^{9} yrs	1 meV

Baumann,arXiv:0907.5424



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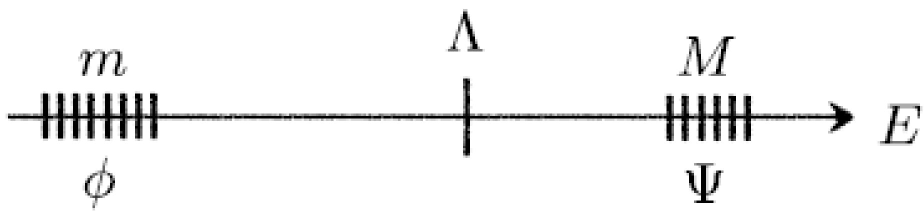
Low Energy version of Superstring Theory

Effective Theory prescription of N=1 Supergravity

Constructing EFTs from the Top Down

"integrating out"

EFT Redux



If the full theory is known (and computable), we can integrate out the heavy fields to get an effective theory for the light fields :

$$e^{iS_{\rm eff}[\phi]} = \int \mathcal{D}\Psi \; e^{iS[\phi,\Psi]}$$

Let me illustrate this in a toy model:

$$\mathcal{L}[\phi,\Psi] = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda\phi^4$$
$$-\frac{1}{2}(\partial\Psi)^2 - \frac{1}{2}M^2\Psi^2 - \frac{1}{4}g\,\phi^2\Psi^2$$

Light visible sector

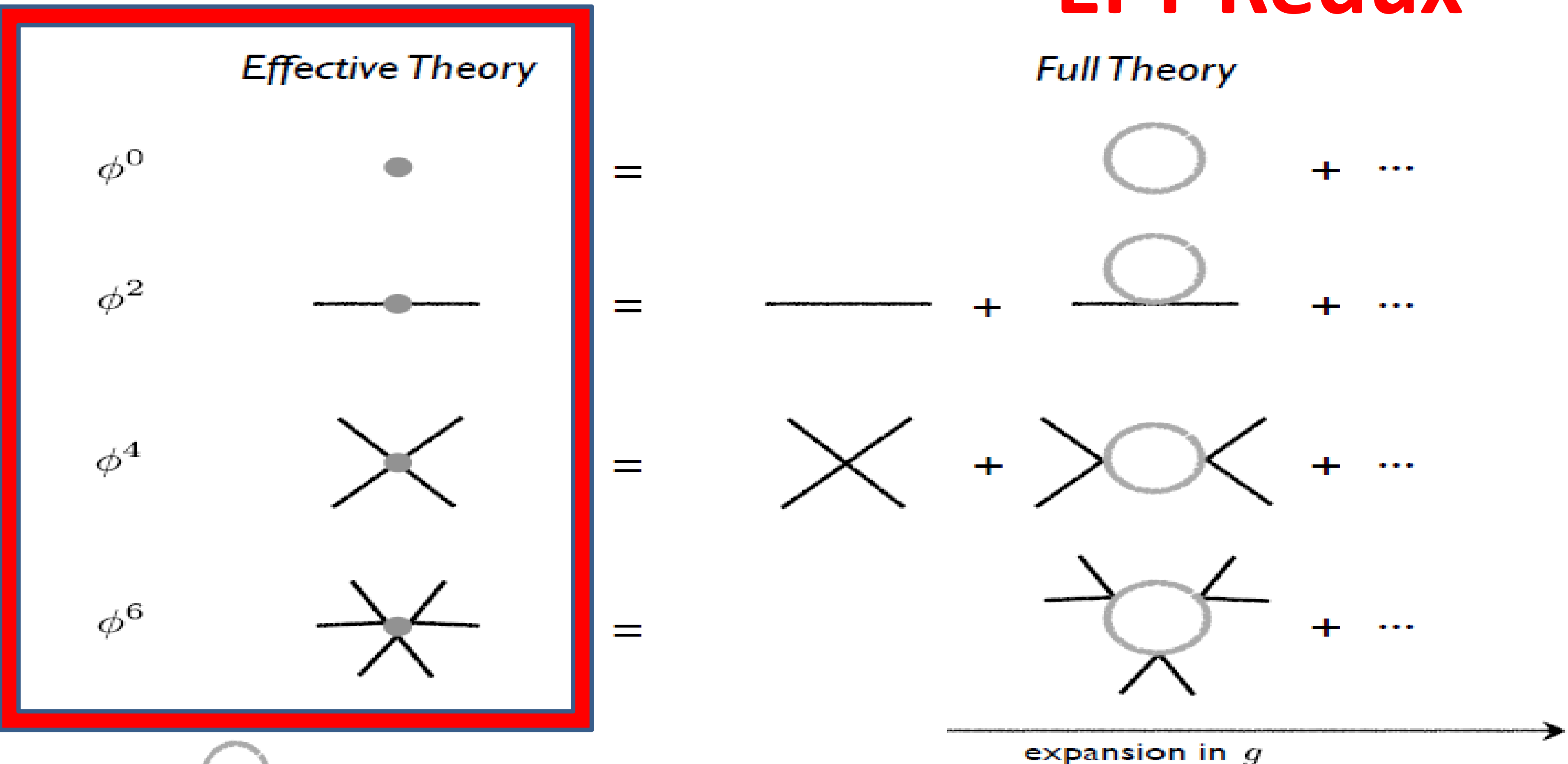
Heavy hidden sector

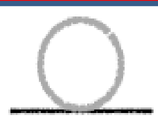
UV-coupling

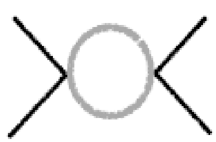
Constructing EFTs from the Top Down

matching

EFT Redux



$\Delta m^2 =$  $= \frac{g}{32\pi^2}\left(\Lambda^2 - M^2 \log\left(\frac{\Lambda^2}{\mu^2}\right)\right)$

$\Delta\lambda =$  $= -\frac{3g^2}{32\pi^2}\log\left(\frac{\Lambda^2}{\mu^2}\right)$

Renormalization of IR couplings

$$\mathcal{L}_{\rm eff}[\phi] = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_{\rm R}^2\phi^2 - \frac{1}{4!}\lambda_{\rm R}\phi^4$$

renormalizable

$$-\sum_{i=1}^{\infty}\left(\frac{c_i}{M^{2i}}\phi^{4+2i} + \frac{d_i}{M^{2i}}(\partial\phi)^2\phi^{2i} + \cdots\right)$$

non-renormalizable

expansion in $(E/M)^{2i}$

EFT Redux

Only a finite number of operators are relevant to describe observations with finite precision.

Baumann & McAllister, arXiv:1404.2601,1304.5226

renormalizable

operator

$$\mathcal{L}_{\rm eff}[\phi] = \mathcal{L}_0[\phi] + \sum_i c_i \frac{\mathcal{O}_i[\phi]}{\Lambda^{\delta_i - 4}}$$

Wilson coefficient

dimension

cutoff

Welcome to SUPER-WORLD

SUSY(SM +SSM)

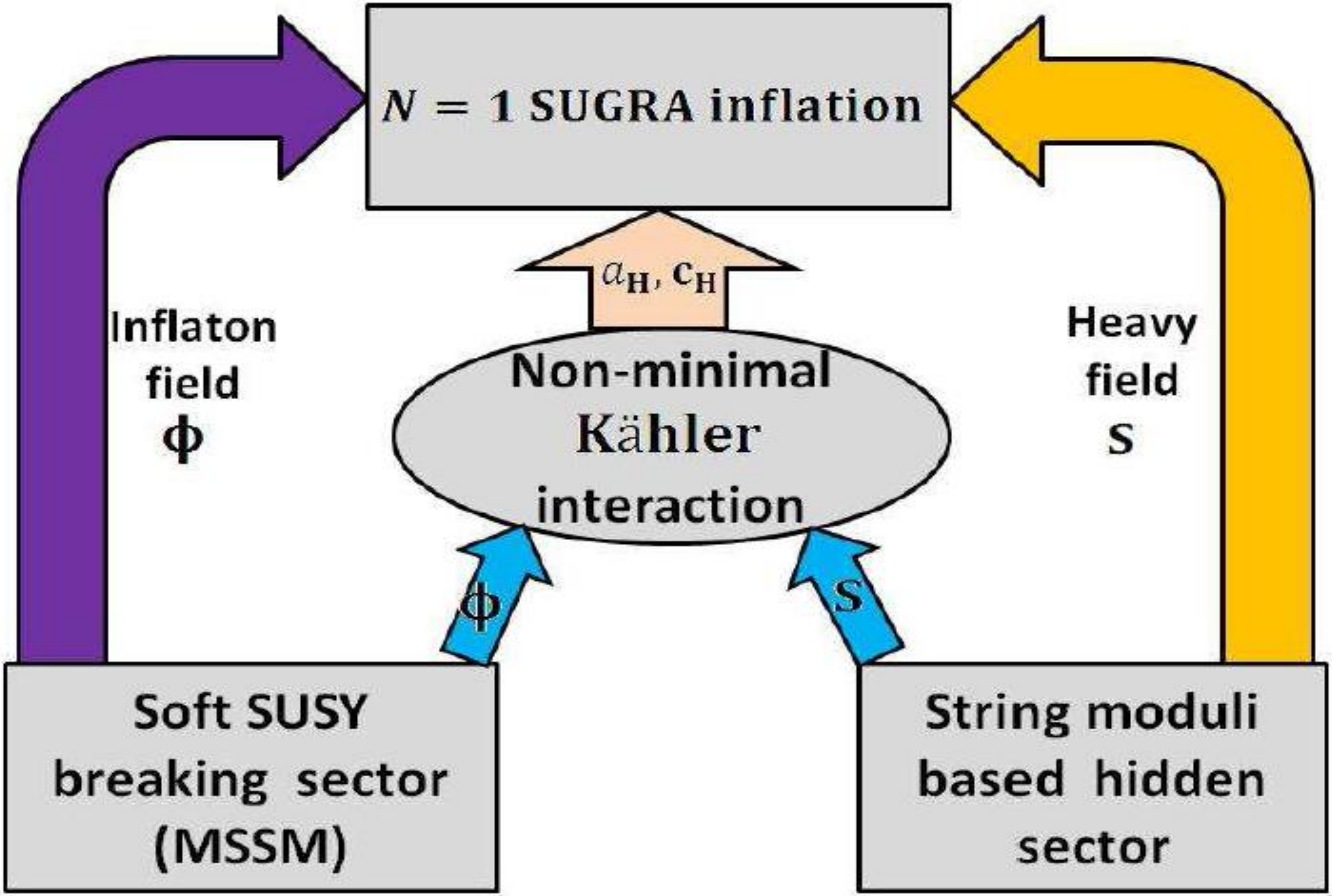
MSSM

+

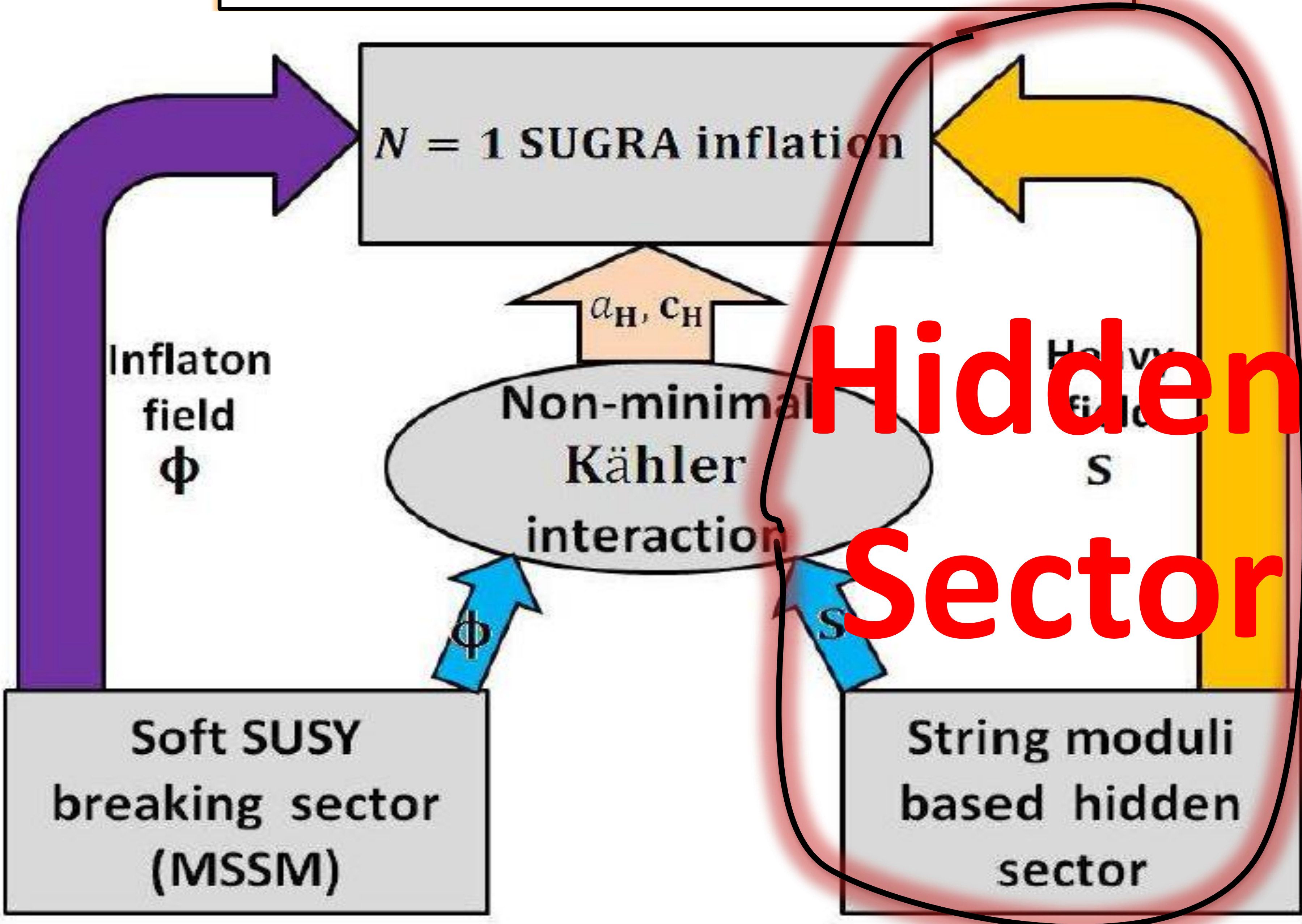
GRAVITY (GRAVITON+ GRAVITINO)

EFT of N=… SUGRA in 4D

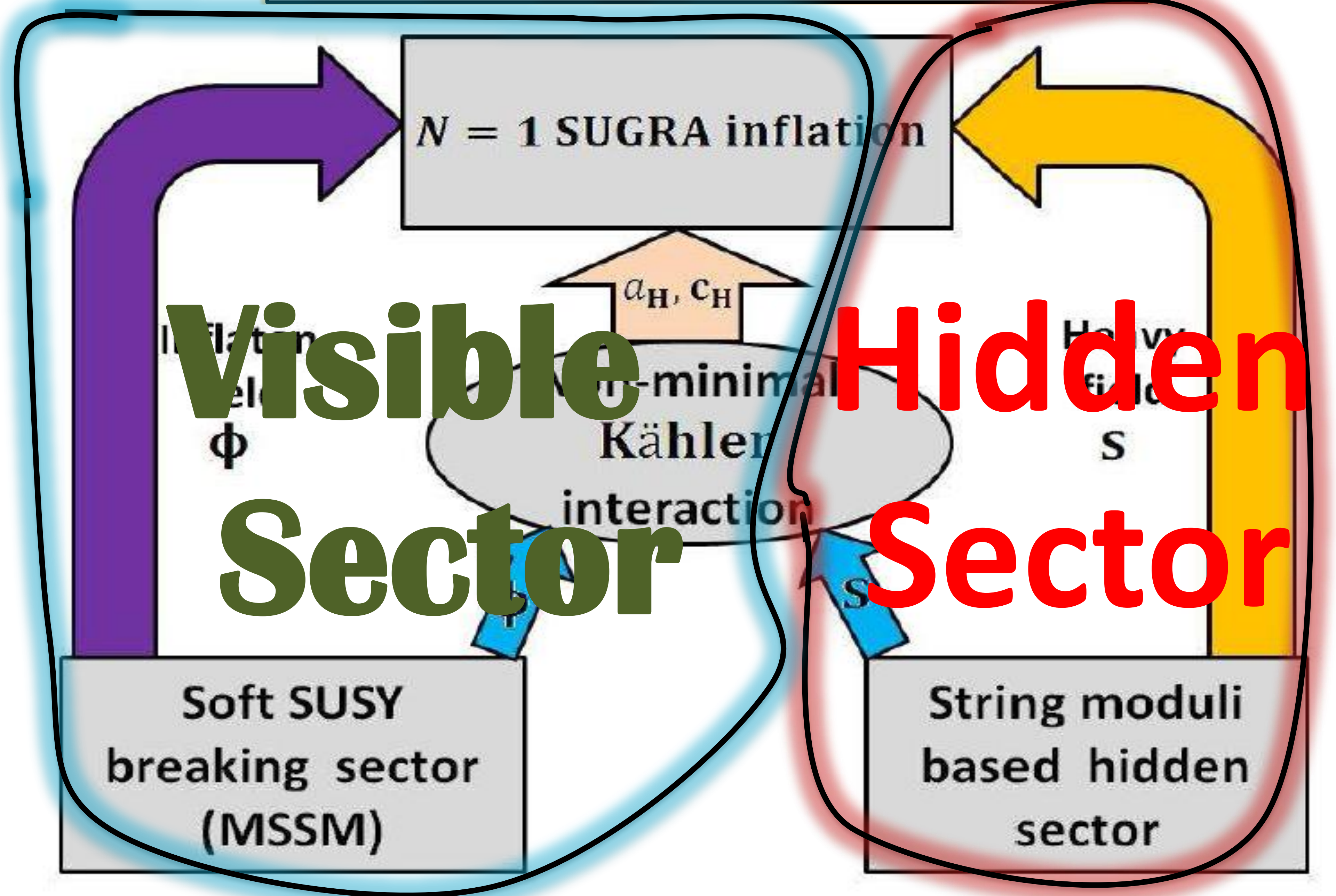
The EFT setup for N=1 SUGRA



The EFT setup for N=1 SUGRA



The EFT setup for N=1 SUGRA



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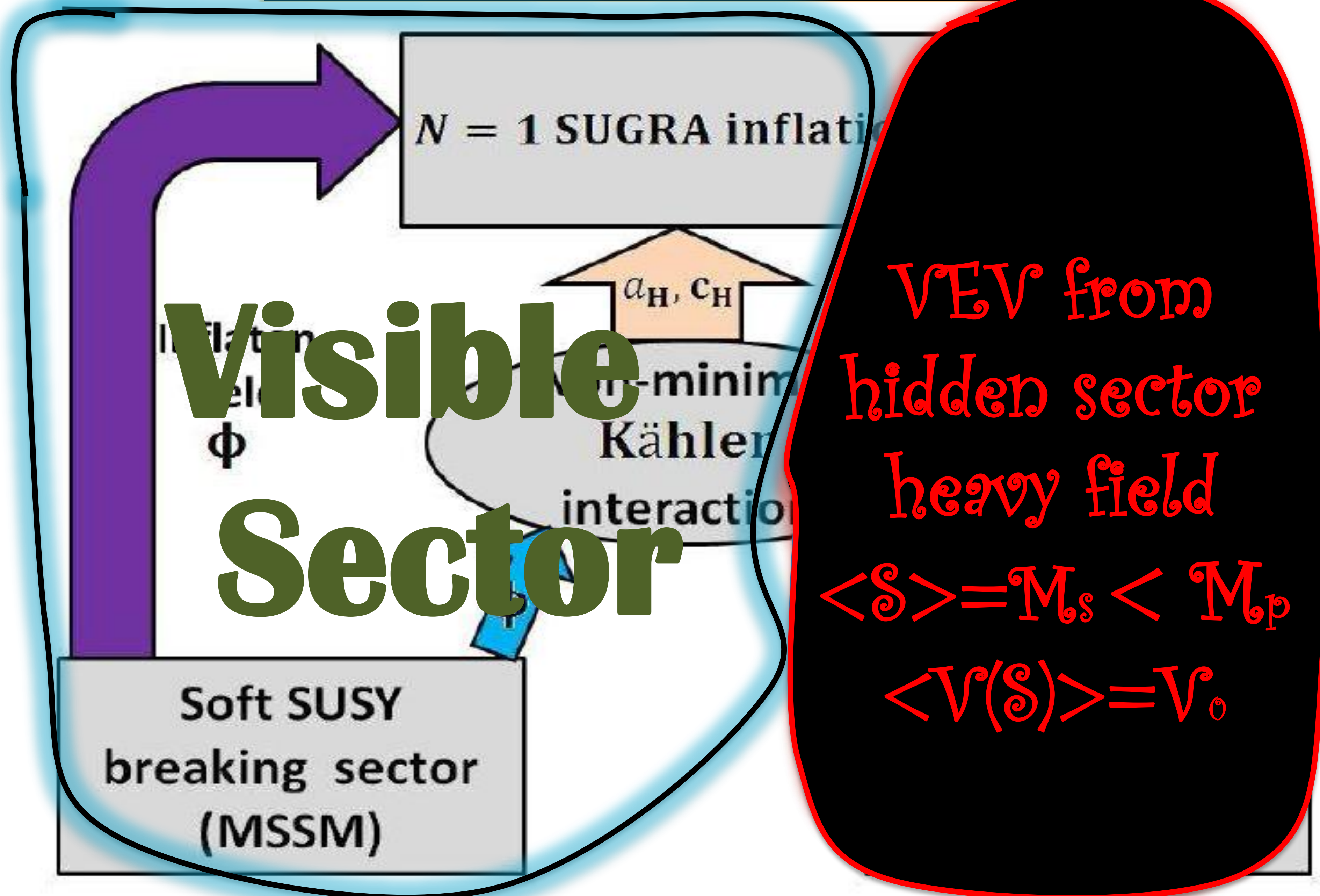


The EFT setup for N=1 SUGRA

Theory from visible sector in N=1 SUGRA:

$V_{vis} = V_m + V_H$

MSSM flat Direction contents (udd, LLe, NH_uL ......)

VEV from hidden sector heavy field

$<S> = M_s < M_p$

$<V(S)> = V_0$

The EFT setup for N=1 SUGRA

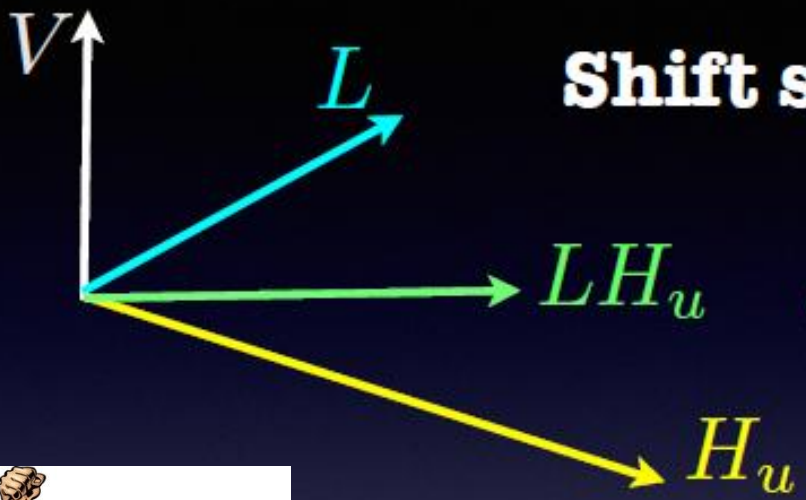
Theory from visible sector

Effective Theory of N=1 SUGRA

$$V_{EFT} = V_{vis} + V_0 = V_m + V_H + V_0$$

$$V(\phi) = V(s) + (m_\phi^2 + c_H H(t)^2)|\phi|^2 + \left(A\frac{\lambda\phi^n}{nM_p^{n-3}} + a_H H(t)\frac{\lambda\phi^n}{nM_p^{n-3}} + h.c. \right) + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}}$$

SUSY Flat directions

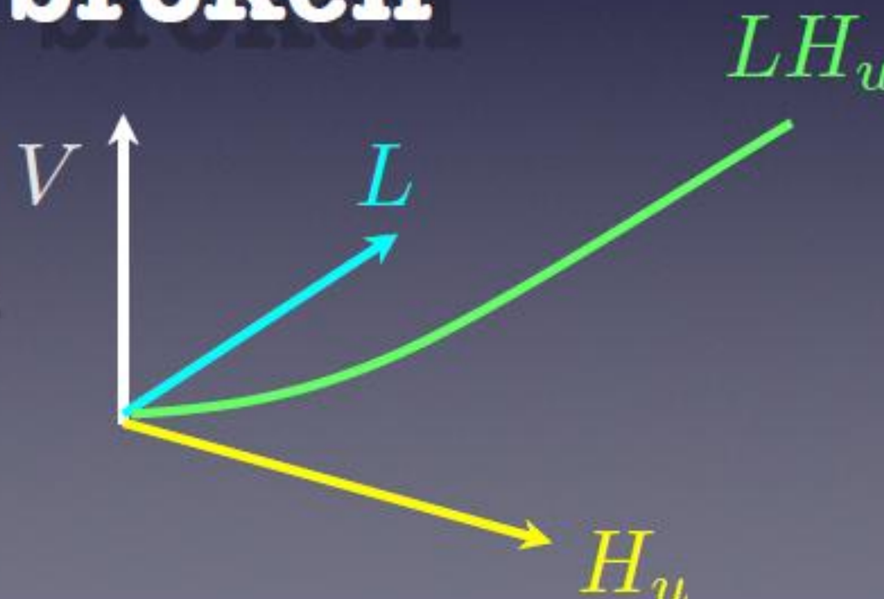


Shift symmetry

as a Gauge Invariant operator minimises the Potential

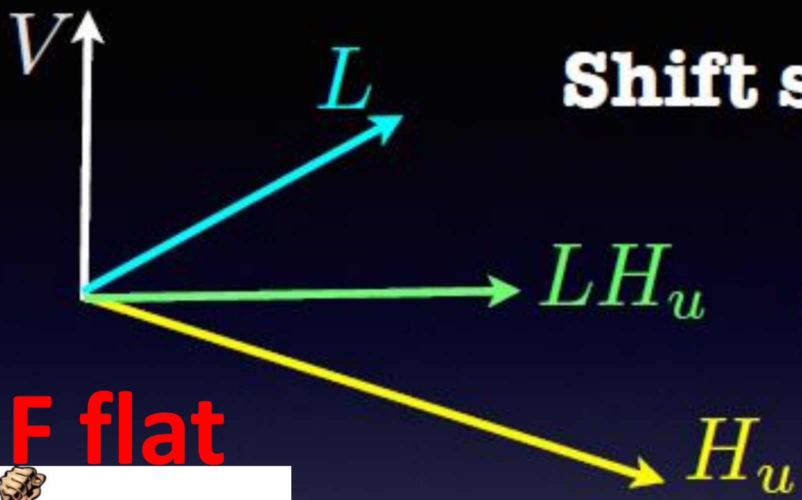
SUSY is broken

Shift symmetry is broken



Enqvist, Mazumdar, Phys. Rept. (2004)

SUSY Flat directions

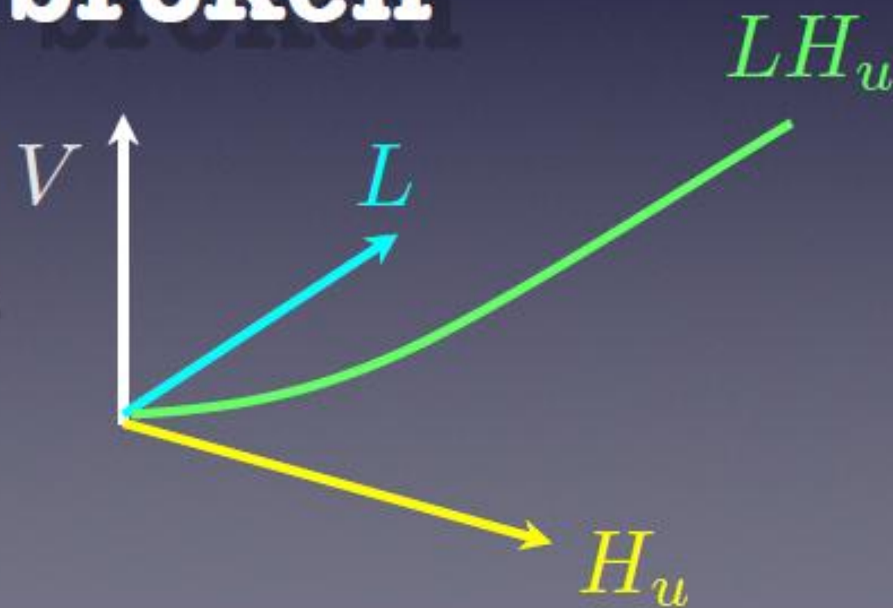


Shift symmetry

as a Gauge Invariant operator minimises the Potential

F flat

SUSY is broken



Shift symmetry is broken

Enqvist, Mazumdar, Phys. Rept. (2004)

IASSNS-HEP-95/85
UM-TH-95-25
hep-ph/9510370

arXiv:hep-ph/9510370v2 25 Mar 1996

Flat directions in the scalar potential of the supersymmetric standard model

Tony Gherghetta[1], Chris Kolda[2] and Stephen P. Martin[1]

[1] *Randall Physics Laboratory, University of Michigan, Ann Arbor MI 48109*

[2] *School of Natural Sciences, Institute for Advanced Study, Princeton NJ 08540*

ABSTRACT: The scalar potential of the Minimal Supersymmetric Standard Model (MSSM) is nearly flat along many directions in field space. We provide a catalog of the flat directions of the renormalizable and supersymmetry-preserving part of the scalar potential of the MSSM, using the correspondence between flat directions and gauge-invariant polynomials of chiral superfields. We then study how these flat directions are lifted by non-renormalizable terms in the superpotential, with special attention given to the subtleties associated with the family index structure. Several flat directions are lifted only by supersymmetry-breaking effects and by supersymmetric terms in the scalar potential of surprisingly high dimensionality.

Tool for computing SUSY flat directions

Gauge invariant Inflatons

	B−L	Always lifted by W_{renorm}?
LH_u	−1	
H_uH_d	0	
udd	−1	
LLe	−1	
QdL	−1	
QuH_u	0	√
QdH_d	0	√
LH_de	0	√
QQQL	0	
QuQd	0	
QuLe	0	
uude	0	
$QQQH_d$	1	√
QuH_de	1	√
dddLL	−3	
uuuee	1	
QuQue	1	
QQQQu	1	
$dddLH_d$	−2	√
$uudQdH_u$	−1	√
$(QQQ)_4LLH_u$	−1	√
$(QQQ)_4LH_uH_d$	0	√
$(QQQ)_4H_uH_dH_d$	1	√
$(QQQ)_4LLLe$	−1	
uudQdQd	−1	
$(QQQ)_4LLH_de$	0	√
$(QQQ)_4LH_dH_de$	1	√
$(QQQ)_4H_dH_dH_de$	2	√

$SU(3) \times SU(2)_l \times U(1)_Y$

$u_1 d_2 d_3$ $\quad d_2^\beta = \frac{1}{\sqrt{3}}\phi \quad u_1^\alpha = \frac{1}{\sqrt{3}}\phi \quad d_3^\gamma = \frac{1}{\sqrt{3}}\phi$

$L_1 L_2 e_3$ $\quad L_1^a = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \quad L_2^b = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \quad e_3 = \frac{1}{\sqrt{3}}\phi$

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

$SU(3) \times SU(2)_l \times U(1)_Y \times U(1)_{B-L}$

$N H_u L$ $\quad N = \frac{1}{\sqrt{3}}\phi \quad H_u = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \quad L = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$

Allahverdi, Enqvist, Bellido, AM, (PRL, 2006), (JCAP, 2007), Allahverdi, Kusenko, AM, JCAP (2007), Allahverdi, Dutta, AM (PRL 2007), Chatterjee, AM, JCAP (2011)

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LLe	−1	
QdL	−1	
QuH_u	0	√
QdH_d	0	√
[illegible]e	[illegible]	√
QQQL	0	[illegible]
[illegible]	0	[illegible]
QuLe	[illegible]	[illegible]
uude	0	
$QQQH_d$	1	√
QuH_de	1	√
dddLL	[illegible]	[illegible]
[illegible]	1	[illegible]
[illegible]	1	[illegible]
QQQQu	1	
$dddLH_d$	−2	√
$uudQdH_u$	−1	√
$(QQQ)_4LLH_u$	−1	√
$(QQQ)_4LH_uH_d$	0	√
$(QQQ)_4H_uH_dH_d$	1	√
$(QQQ)_4LLLe$	−1	
uudQdQd	−1	
$(QQQ)_4LLH_de$	0	√
$(QQQ)_4LH_dH_de$	1	√
$(QQQ)_4H_dH_dH_de$	2	√

300 such combinations……

$$SU(3) \times SU(2)_l \times U(1)_Y$$

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

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QuLe	0	
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$SU(3) \times SU(2)_l \times U(1)_Y$

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

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Non-minimal interactions in N=1 SUGRA

$$e^{K(\phi,\phi^\dagger)/M_p^2}V(s)$$

$$(D_S W(s))K^{s\bar{s}}(D_{\bar{S}}W^*(s^\dagger))$$

$$W_\phi K^{\phi\bar{\phi}}K_{\bar{\phi}}\frac{W^*(s^\dagger)}{M_p^2}+h.c.$$

$$-\frac{3}{M_p^2}W^*(s^\dagger)W(\phi)+h.c.$$

$$K_\phi K^{\phi\bar{\phi}}K_{\bar{\phi}}\frac{|W(s)|^2}{M_p^4}$$

$$K_s\frac{W(\phi)}{M_p^2}K^{s\bar{s}}\left(D_{\bar{S}}W^*(s^\dagger)\right)+h.c.$$

$$K_\phi K^{\phi\bar{s}}D_{\bar{s}}W^*(s^\dagger)\frac{W(s)}{M_p^2}+h.c.$$

$$W_\phi K^{\phi\bar{s}}\left(D_{\bar{S}}W^*(s^\dagger)\right)+h.c.$$

Gauge invariant Inflatons

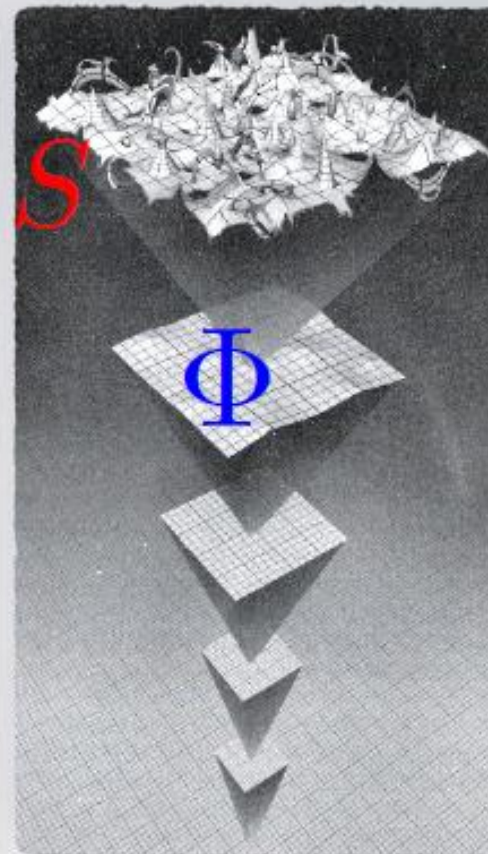
$$W = W(\Phi) + W(S)\,, \quad \Phi = \text{Light}\,, \; S = \text{Heavy}$$
$$= \frac{\lambda \Phi^n}{n M_p^{n-3}} + \frac{M_s}{2} S^2\,, \qquad \phi = \frac{\tilde{u} + \tilde{d} + \tilde{d}}{\sqrt{3}}, \qquad \phi = \frac{\tilde{L} + \tilde{L} + \tilde{e}}{\sqrt{3}}$$

$$K = s^\dagger s + \phi^\dagger \phi + \delta K\,,$$

where *gauge invariant* Kähler corrections:

$$\delta K = f(\phi^\dagger \phi, s^\dagger s),\; f(s^\dagger \phi\phi),\; f(s^\dagger s^\dagger \phi\phi),\; f(s\phi^\dagger\phi)$$

$$V = e^{K(\Phi_i^\dagger, \Phi_i)/M_p^2}\left[(D_{\Phi_i} W(\Phi)) K^{\Phi_i \bar{\Phi}_j} (D_{\bar{\Phi}_j} W^*(\Phi^\dagger)) - 3\frac{|W(\Phi)|^2}{M_p^2}\,,\right]$$



$$V_{total} = M_s^4 + c_H H^2 |\phi|^2 + \left(a_H H \frac{\lambda \phi^n}{n M_p^{n-3}} + h.c.\right) + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}}$$

EFT potential structure (for MSSM) in N=1 SUGRA.

$$\mathcal{L}_{\rm Kin} = \left(1 + \frac{a|s|^2}{M_p^2}\right)\left(\partial_\mu \phi\right)\left(\partial^\mu \phi^\dagger\right) + \frac{a}{M_p^2}\left\{\phi^\dagger s \left(\partial_\mu \phi\right)\left(\partial^\mu s^\dagger\right) + \phi s^\dagger \left(\partial_\mu s\right)\left(\partial^\mu \phi^\dagger\right)\right\} + \left(1 + \frac{a|\phi|^2}{M_p^2}\right)\left(\partial_\mu s\right)\left(\partial^\mu s^\dagger\right)$$

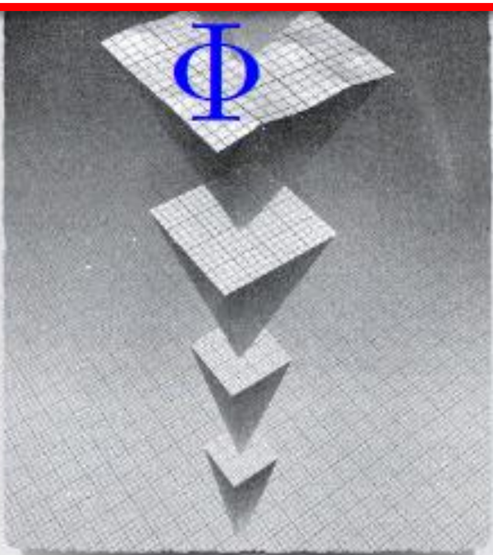
$$V(s) + \left(m_\phi^2 + 3(1-a)H^2\right)|\phi|^2 - \frac{A\phi^n}{nM_p^{n-3}} - \left(1 + a\frac{|s|^2}{M_p^2}\right)\left(1 - \frac{3}{n}\right)\frac{s^2}{M_p^2}\frac{\lambda M_s \phi^n}{M_p^{n-3}} - \left(1 - a\frac{|s|^2}{M_p^2}\right)\left(a - \frac{1}{n}\right)\frac{(s^\dagger)^2}{M_p^2}\frac{\lambda M_s \phi^n}{M_p^{n-3}} + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + \text{h.c.}$$

$$K = s^\dagger s + \phi^\dagger \phi + \delta K\,,$$

where *gauge invariant* Kähler corrections:

$$\delta K = f(\phi^\dagger \phi, s^\dagger s),\ f(s^\dagger \phi\phi),\ f(s^\dagger s^\dagger \phi\phi),\ f(s\phi^\dagger \phi)$$

$$V = e^{K(\Phi_i^\dagger, \Phi_i)/M_p^2}\left[(D_{\Phi_i}W(\Phi))K^{\Phi_i\bar{\Phi}_j}(D_{\bar{\Phi}_j}W^*(\Phi^\dagger)) - 3\frac{|W(\Phi)|^2}{M_p^2},\right]$$



$$V_{total} = M_s^4 + c_H H^2|\phi|^2 + \left(a_H H\frac{\lambda\phi^n}{nM_p^{n-3}} + h.c.\right) + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}}$$

EFT potential structure (for MSSM) in N=1 SUGRA.

$$\mathcal{L}_{\rm Kin} = (\partial_\mu \phi)(\partial^\mu \phi^\dagger) + (\partial_\mu s)\left(\partial^\mu s^\dagger\right) + \frac{b\phi}{2M_p}(\partial_\mu \phi)\left(\partial^\mu s^\dagger\right) + \frac{b\phi^\dagger}{2M_p}(\partial_\mu s)\left(\partial^\mu \phi^\dagger\right)$$

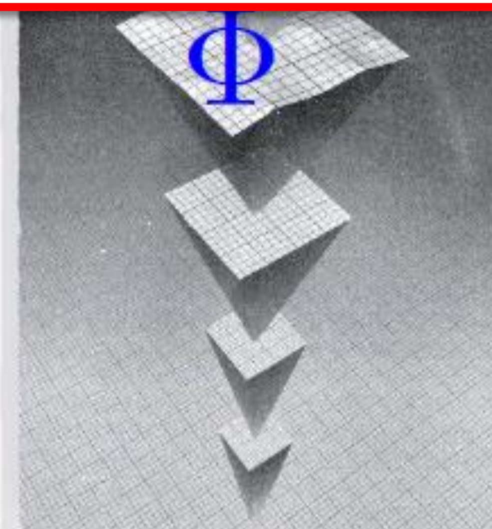
$$V(s) + \left(m_\phi^2 + 3\left(1+b^2\right)H^2\right)|\phi|^2 - A\frac{\phi^n}{nM_p^{n-3}} - \left\{\left(1-\frac{3}{n}\right)\phi + \frac{b\phi^\dagger s}{nM_p}\right\}\frac{\lambda\phi^{n-1}M_s s^2}{M_p^{n-1}} - \left(\frac{s^\dagger\phi}{M_p} - bn\phi^\dagger\right)\frac{2M_s\lambda\phi^{n-1}s^\dagger}{nM_p^{n-2}} - \frac{bM_s s^2}{2M_p^2}\left(\frac{2M_s s}{M_p} - \frac{M_s s^2 s^\dagger}{M_p^3}\right)\phi\phi - \frac{4M_s^2 b|s|^2 s^\dagger}{M_p^3}\phi\phi + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + \text{h.c.}$$

$$K = s^\dagger s + \phi^\dagger\phi + \delta K\,,$$

where *gauge invariant* Kähler corrections:

$$\delta K = f(\phi^\dagger\phi, s^\dagger s),\ f(s^\dagger\phi\phi),\ f(s^\dagger s^\dagger\phi\phi),\ f(s\phi^\dagger\phi)$$

$$V = e^{K(\Phi_i^\dagger,\Phi_i)/M_p^2}\left[(D_{\Phi_i}W(\Phi))K^{\Phi_i\bar\Phi_j}(D_{\bar\Phi_j}W^*(\Phi^\dagger)) - 3\frac{|W(\Phi)|^2}{M_p^2}\,,\right]$$



$$V_{total} = M_s^4 + c_H H^2|\phi|^2 + \left(a_H H\frac{\lambda\phi^n}{nM_p^{n-3}} + h.c.\right) + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}}$$

EFT potential structure (for MSSM) in N=1 SUGRA.

$$\mathcal{L}_{\rm Kin} = (\partial_\mu \phi)\left(\partial^\mu \phi^\dagger\right) + (\partial_\mu s)\left(\partial^\mu s^\dagger\right) + \frac{cs^\dagger\phi}{4M_p^2}(\partial_\mu\phi)\left(\partial^\mu s^\dagger\right) + \frac{cs\phi^\dagger}{4M_p^2}(\partial_\mu s)\left(\partial^\mu\phi^\dagger\right)$$

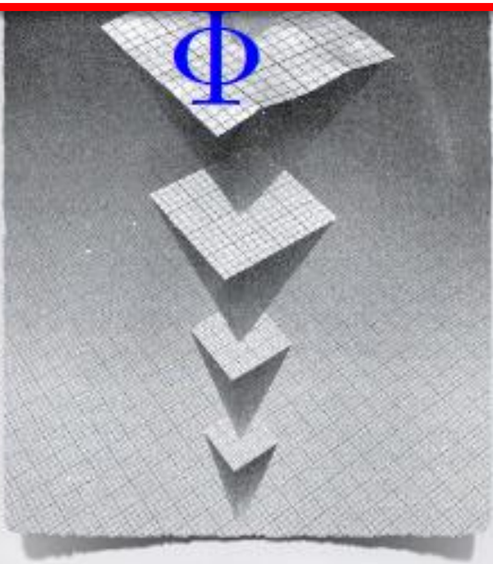
$$V(s) + \left(m_\phi^2 + 3H^2\right)|\phi|^2 - A\frac{\phi^n}{nM_p^{n-3}} - \left\{\left(1-\frac{3}{n}\right)\phi + \frac{c\phi^\dagger ss}{2M_p^2}\right\}\frac{\lambda\phi^{n-1}M_s s^2}{M_p^{n-1}} + \frac{cM_s^2 s^2 s^\dagger s\phi\phi}{M_p^4} - \frac{M_s^2 c|s|^2 s^\dagger s^\dagger}{M_p^4}\phi\phi + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} - \left(\frac{s^\dagger\phi}{M_p} - \frac{cn\phi^\dagger s}{M_p}\right)\frac{2M_s\lambda\phi^{n-1}s^\dagger}{nM_p^{n-2}} + \text{h.c.}$$

$$K = s^\dagger s + \phi^\dagger\phi + \delta K\,,$$

where *gauge invariant* Kähler corrections:

$$\delta K = f(\phi^\dagger\phi, s^\dagger s),\ f(s^\dagger\phi\phi),\ f(s^\dagger s^\dagger\phi\phi),\ f(s\phi^\dagger\phi)$$

$$V = e^{K(\Phi_i^\dagger,\Phi_i)/M_p^2}\left[(D_{\Phi_i}W(\Phi))K^{\Phi_i\bar{\Phi}_j}(D_{\bar{\Phi}_j}W^*(\Phi^\dagger)) - 3\frac{|W(\Phi)|^2}{M_p^2},\right]$$



$$V_{total} = M_s^4 + c_H H^2|\phi|^2 + \left(a_H H\frac{\lambda\phi^n}{nM_p^{n-3}} + h.c.\right) + \lambda^2\frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}}$$

EFT potential structure (for MSSM) in N=1 SUGRA.

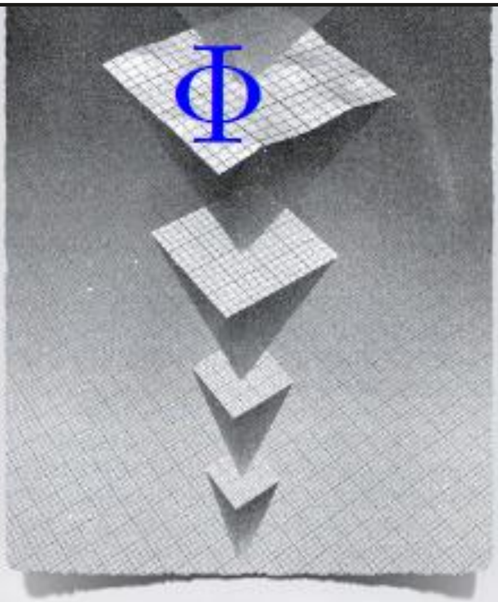
$\mathcal{L}_{\rm Kin} = \left(\frac{ds}{M_p} + \frac{ds^\dagger}{M_p} + 1\right)(\partial_\mu \phi)\left(\partial^\mu \phi^\dagger\right) + (\partial_\mu s)\left(\partial^\mu s^\dagger\right) + \frac{d\phi^\dagger}{M_p}(\partial_\mu \phi)\left(\partial^\mu s^\dagger\right) + \frac{d\phi}{M_p}(\partial_\mu s)\left(\partial^\mu \phi^\dagger\right)$	$V(s) + \left(m_\phi^2 + 3\left(1+d^2\right)H^2\right)\lvert\phi\rvert^2 - A\frac{\phi^n}{nM_p^{n-3}} - \left(1-\frac{3}{n}\right)\frac{\lambda\phi^n M_s s^2}{M_p^{n-1}} - \left(\frac{s^\dagger}{M_p} - d\right)\frac{2M_s\lambda\phi^n s^\dagger}{nM_p^{n-2}} + \lambda^2\frac{\lvert\phi\rvert^{2(n-1)}}{M_p^{2(n-3)}} + \text{h.c.}$

$$K = s^\dagger s + \phi^\dagger \phi + \delta K\,,$$

where *gauge invariant* Kähler corrections:

$$\delta K = f(\phi^\dagger\phi, s^\dagger s),\ f(s^\dagger\phi\phi),\ f(s^\dagger s^\dagger\phi\phi),\ f(s\phi^\dagger\phi)$$

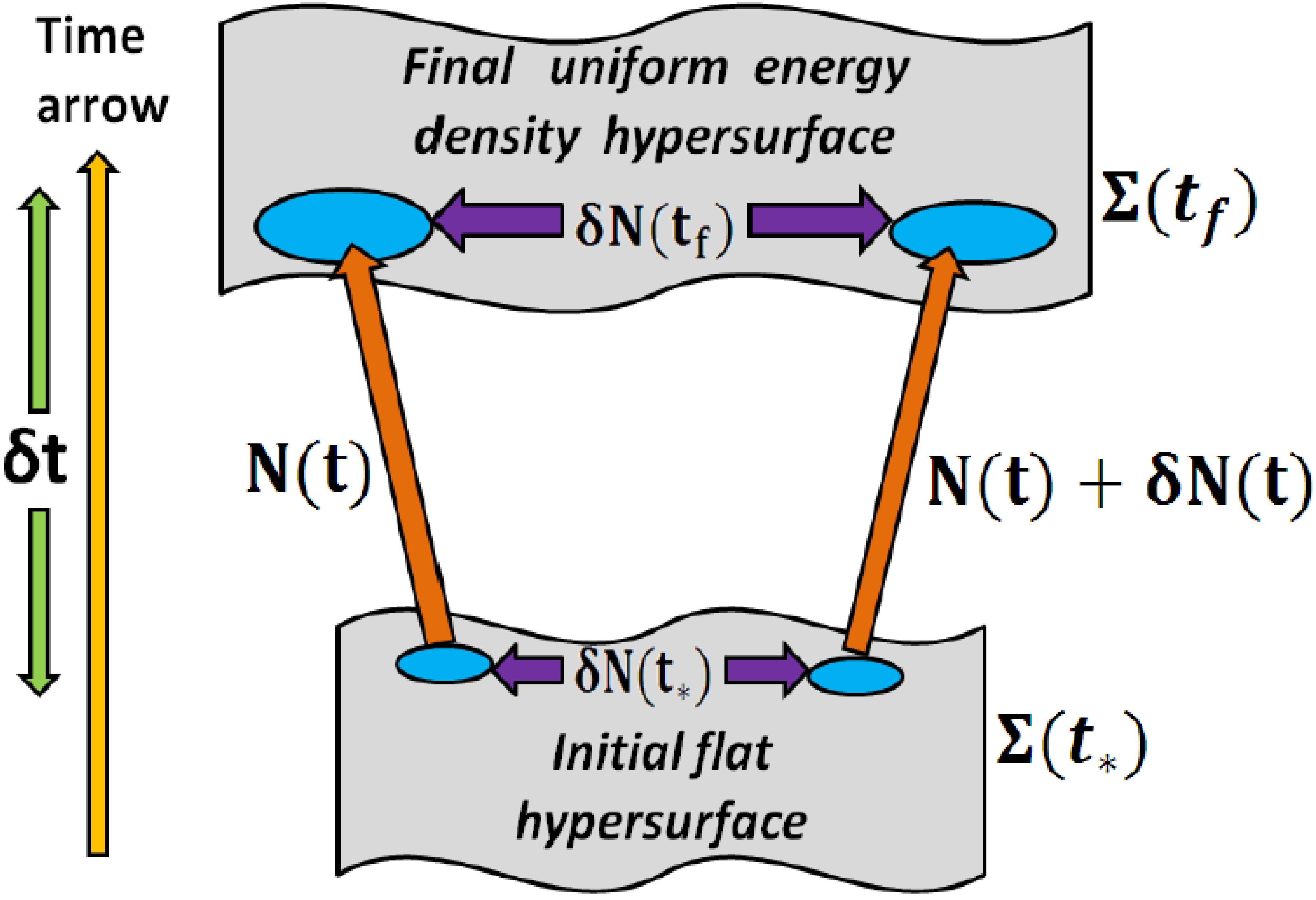
$$V = e^{K(\Phi_i^\dagger,\Phi_i)/M_p^2}\left[(D_{\Phi_i}W(\Phi))K^{\Phi_i\bar{\Phi}_j}(D_{\bar{\Phi}_j}W^*(\Phi^\dagger)) - 3\frac{\lvert W(\Phi)\rvert^2}{M_p^2},\right]$$



$$V_{total} = M_s^4 + c_H H^2\lvert\phi\rvert^2 + \left(a_H H\frac{\lambda\phi^n}{nM_p^{n-3}} + h.c.\right) + \lambda^2\frac{\lvert\phi\rvert^{2(n-1)}}{M_p^{2(n-3)}}$$

EFT potential structure (for MSSM) in N=1 SUGRA.

Primordial non-Gaussianity using δN formalism



Primordial non-Gaussianity using δN formalism

δN….?

- δN is a well accepted tool for computing PNG in classical regime via non linear evolution of cosmological perturbations on large scales.
- Provides fruitful technique to compute the expression for curvature perturbation without explicitly solving the perturbed field equations.
- Independent of any intrinsic NG generated at the scale of horizon crossing.

Primordial non-Gaussianity using δN formalism

$$\zeta = \delta N = N_{,\phi}\delta\phi + \frac{1}{2}N_{,\phi\phi}\delta\phi^2 + \frac{1}{6}N_{,\phi\phi\phi}\delta\phi^3 + \cdots$$

3 point correlation

$$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle = (2\pi)^7\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\left[\frac{3f_{NL}^{\rm local}}{10k_1^3k_2^3}P_s(k_1)P_s(k_2) + (k_2\leftrightarrow k_3) + (k_1\leftrightarrow k_3)\right]$$

4 point correlation

$$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\zeta_{\mathbf{k}_4}\rangle = (2\pi)^9\delta^4(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)\left[\frac{27g_{NL}^{\rm local}}{100}\sum_{i<j<p=1}^{3}\frac{P_s(k_i)P_s(k_j)P_s(k_p)}{(k_ik_jk_p)^3} + \frac{\tau_{NL}^{\rm local}}{8}\sum_{j<p,i\neq j,p=1}^{11}\frac{P_s(k_{ij})P_s(k_j)P_s(k_p)}{(k_{ij}k_jk_p)^3}\right]$$

Primordial non-Gaussianity using δN formalism

$$f_{NL}^{\rm local} = \frac{5}{6}\frac{N_{,\phi\phi}}{N_{,\phi}^2} + \cdots = \frac{5\vartheta}{6} + \cdots$$

$$\tau_{NL}^{\rm local} = \frac{N_{,\phi\phi}^2}{N_{,\phi}^4} + \cdots = \vartheta^2 + \cdots$$

$$g_{NL}^{\rm local} = \frac{25}{54}\frac{N_{,\phi\phi\phi}}{N_{,\phi}^3} + \cdots = \frac{25\vartheta^2}{108} + \cdots$$

$$\vartheta \approx \left[\eta_V\left(1+\frac{1}{c_s^2}\right)^2 + \epsilon_V\left(1-\frac{1}{c_s^4}\right)\right]$$

$$\mathcal{P}_S = \frac{V_\star}{24\pi^2 M_p^4 c_s \epsilon_V}$$

$$\mathcal{P}_T = \frac{2V_\star}{3\pi^2 M_p^4} c_s^{\frac{2\epsilon_V}{1-\epsilon_V}}$$

$$n_S - 1 = 2\eta_V - 6\epsilon_V - s$$

$$n_T = -2\epsilon_V$$

$$r_\star = 16\epsilon_V c_s^{\frac{1+\epsilon_V}{1-\epsilon_V}} = -8 n_T c_s^{\frac{1-\frac{n_T}{2}}{1+\frac{n_T}{2}}}$$

$$\epsilon_V = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \qquad \eta_V = M_p^2\left(\frac{V''}{V}\right)$$

$$s = \frac{\dot{c}_s}{Hc_s} = \sqrt{\frac{3}{V}}\frac{\dot{c}_s}{c_s}M_p$$

Scale of visible sector (inflation) and hidden sector

$$H \leq 9.241 \times 10^{13} \times \sqrt{\frac{r_*}{0.12}}\; c_s^{\frac{\epsilon_V}{\epsilon_V - 1}}\ \mathrm{GeV}\,,$$

$$\sqrt[4]{V_*} \leq 1.96 \times 10^{16} \times \sqrt[4]{\frac{r_*}{0.12}}\; c_s^{\frac{\epsilon_V}{2(\epsilon_V - 1)}}\ \mathrm{GeV}\,,$$

$$M_s \leq 1.77 \times 10^{16} \times \sqrt[4]{\frac{r_*}{0.12}}\; c_s^{\frac{\epsilon_V}{2(\epsilon_V - 1)}}\ \mathrm{GeV}\,.$$

Field excursion in MSSM within N=1 SUGRA

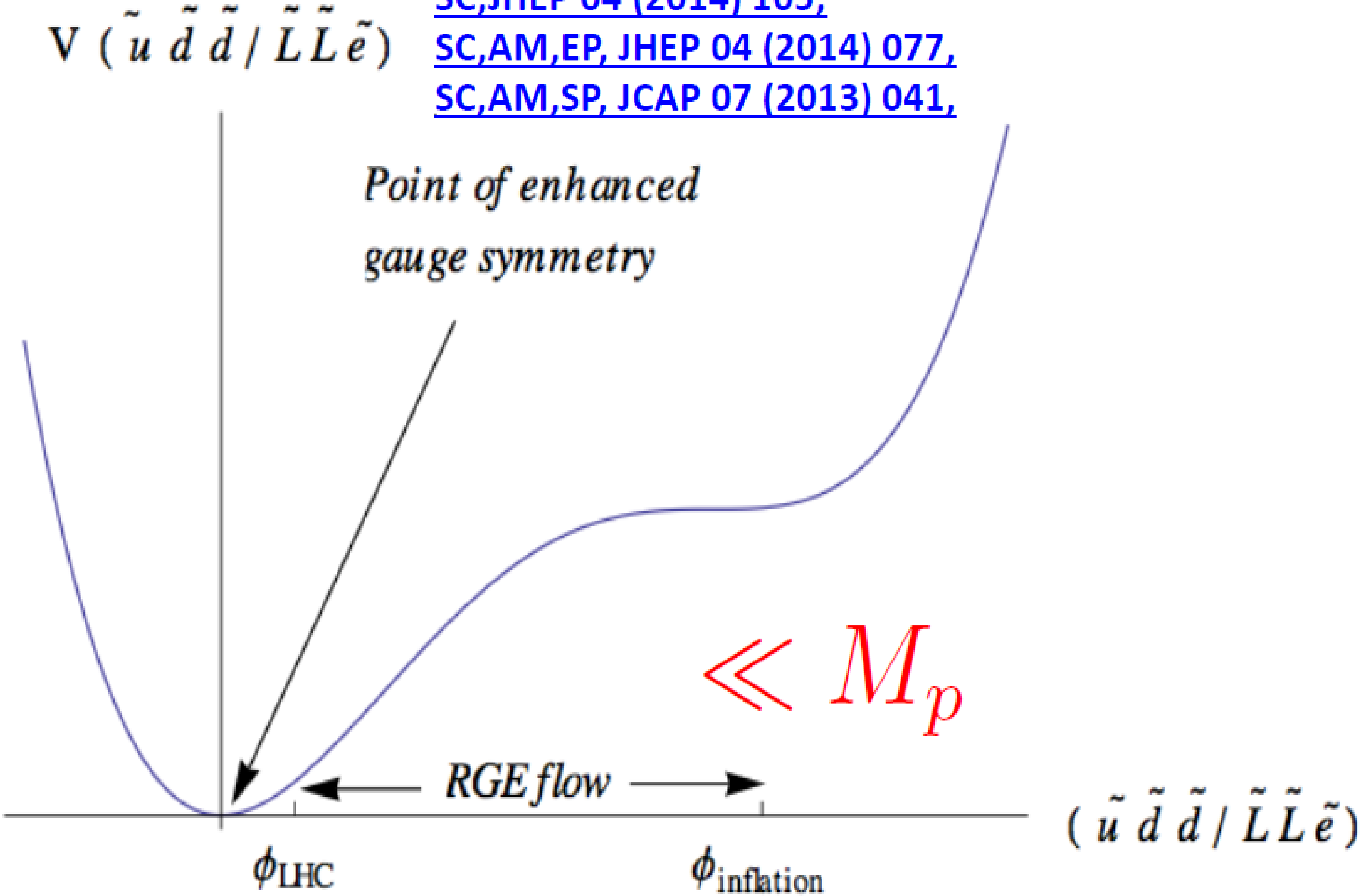
$$\frac{|\Delta\phi|}{M_p} \approx \frac{3}{25\sqrt{c_s}}\sqrt{\frac{r_*}{0.12}}\left|\left\{\frac{3}{400}\left(\frac{r_*}{0.12}\right) - \frac{\eta_V(k_\star)}{2} - \frac{1}{2}\right\}\right|$$

Reheating temperature

$$T_{rh} = \left(\frac{30}{\pi^2 g_\star}\right)^{\frac{1}{4}} \sqrt[4]{V_\star} \leq 6.654 \times 10^{15} \sqrt[4]{\frac{r_\star}{0.12}}\, c_s^{\frac{\epsilon_V}{2(\epsilon_V - 1)}}\ \mathrm{GeV}$$

Model (MSSM) constraints

SC, JHEP 04 (2014) 105,
SC, AM, EP, JHEP 04 (2014) 077,
SC, AM, SP, JCAP 07 (2013) 041,



Model (MSSM) constraints

$$V(\phi) = \alpha + \beta(\phi - \phi_0) + \gamma(\phi - \phi_0)^3 + \kappa(\phi - \phi_0)^4 + \cdots$$

Point of inflection

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

$$\alpha = V(\phi_0) = V(s) + \left(\frac{(n-2)^2}{n(n-1)} + \frac{(n-2)^2}{n}\delta^2\right) c_H H^2 \phi_0^2 + \mathcal{O}(\delta^4),$$

$$\beta = V'(\phi_0) = 2\left(\frac{n-2}{2}\right)^2 \delta^2 c_H H^2 \phi_0 + \mathcal{O}(\delta^4),$$

$$\gamma = \frac{V'''(\phi_0)}{3!} = \frac{c_H H^2}{\phi_0}\left(4(n-2)^2 - \frac{(n-1)(n-2)^3}{2}\delta^2\right) + \mathcal{O}(\delta^4),$$

$$\kappa = \frac{V''''(\phi_0)}{4!}$$

$$= \frac{c_H H^2}{\phi_0^2}\left(12(n-2)^3 - \frac{(n-1)(n-2)(n-3)(7n^2 - 27n + 26)}{2}\delta^2\right)$$

$$\frac{a_H^2}{8(n-1)c_H} = 1 - \left(\frac{n-2}{2}\right)^2 \delta^2$$

$$\phi_0 = \left(\sqrt{\frac{c_H}{(n-1)}} H M_p^{n-3}\right)^{1/n-2} + \mathcal{O}(\delta^2)$$

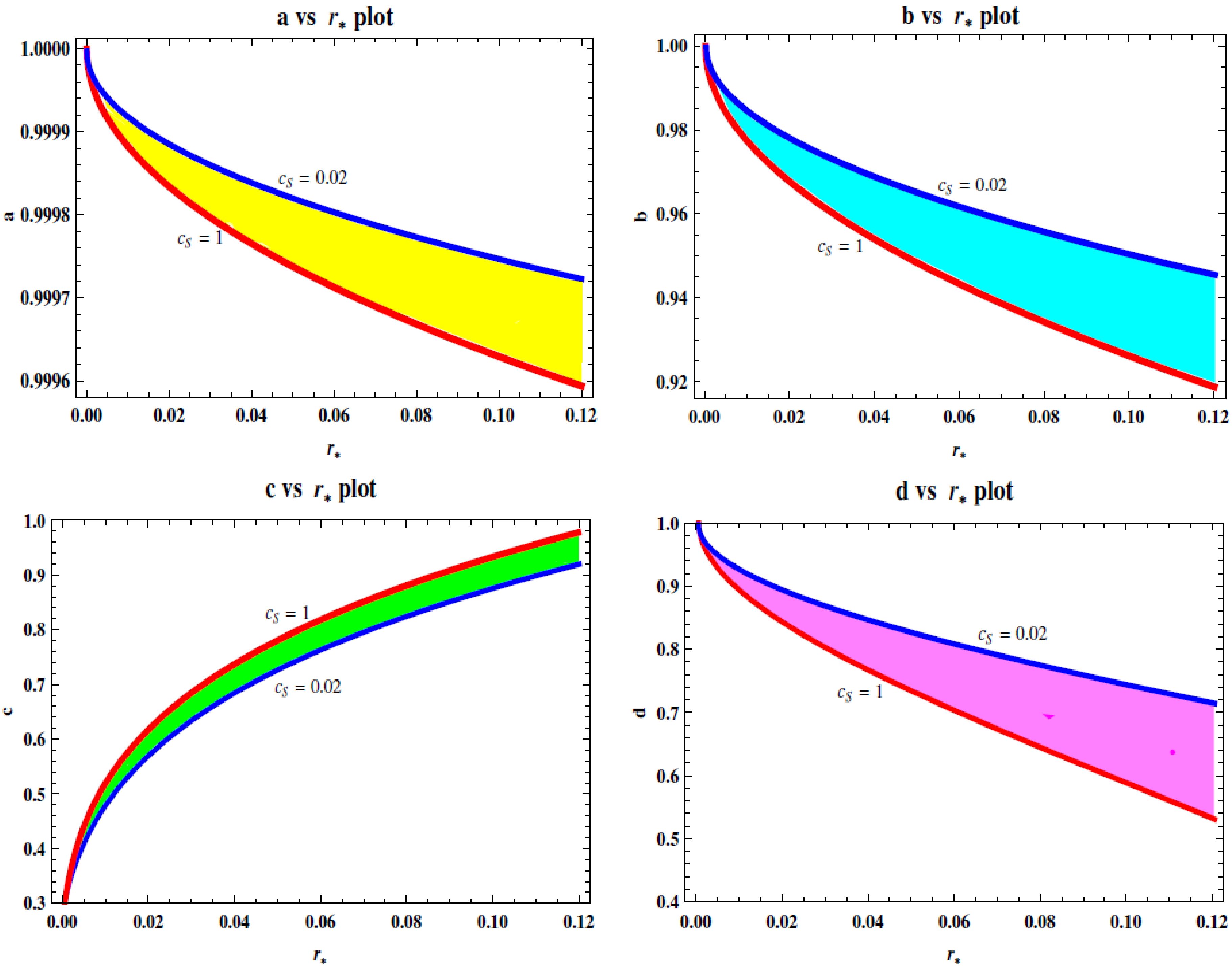
Model (MSSM) constraints

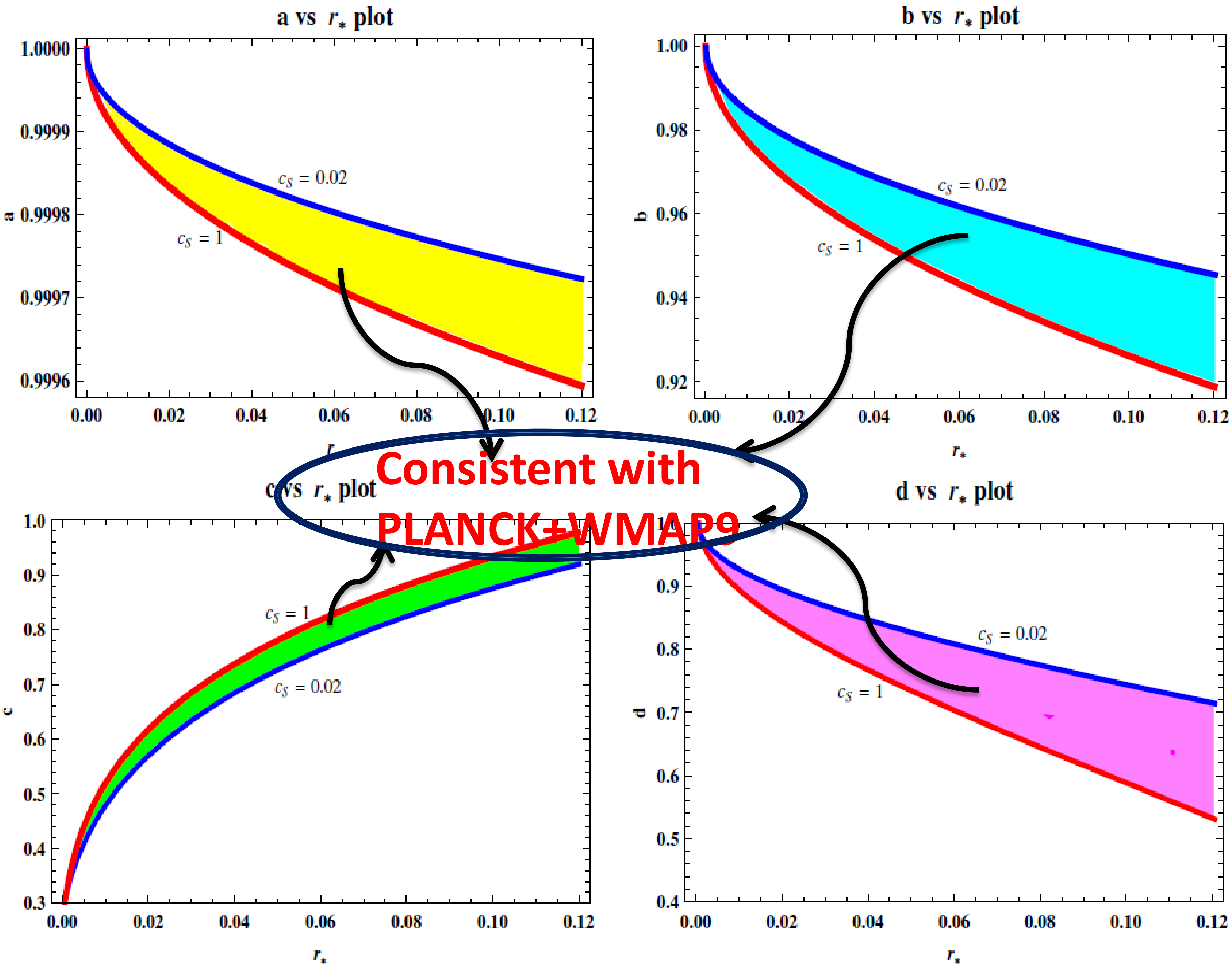
$$c_H \sim \mathcal{O}(10 - 10^{-6})$$
$$a_H \sim \mathcal{O}(30 - 10^{-3})$$
$$\phi_0 \sim \mathcal{O}(10^{14} - 10^{17})\ \text{GeV}$$
$$a \sim \mathcal{O}(1 - 0.99)\,,$$
$$b \sim \mathcal{O}(1 - 0.92)\,,$$
$$c \sim \mathcal{O}(0.3 - 1)\,,$$
$$d \sim \mathcal{O}(1 - 0.5)\,.$$
$$M_s \sim \mathcal{O}(9.50 \times 10^{10} - 1.77 \times 10^{16})\ \text{GeV}$$

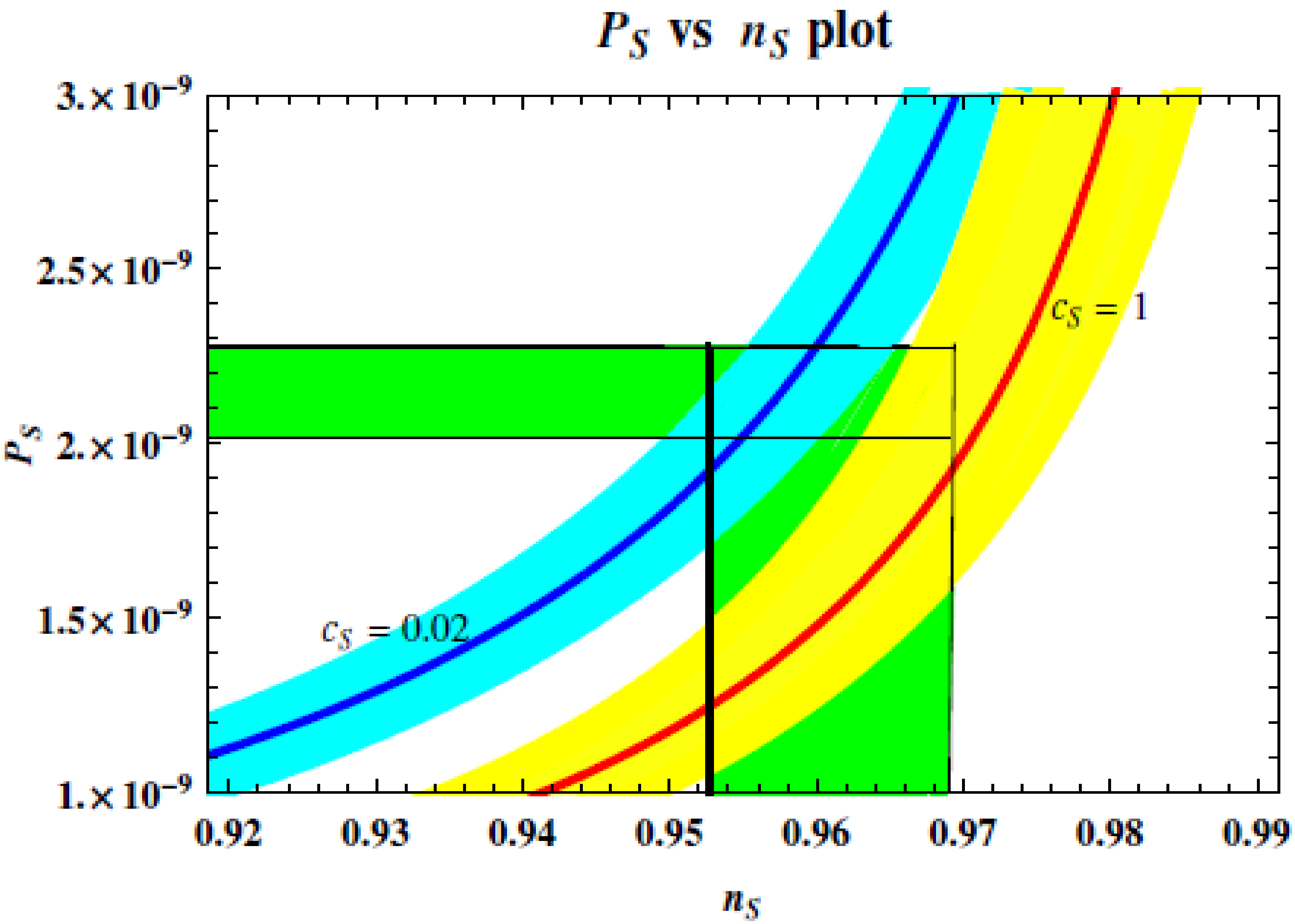
Model (MSSM) parameters

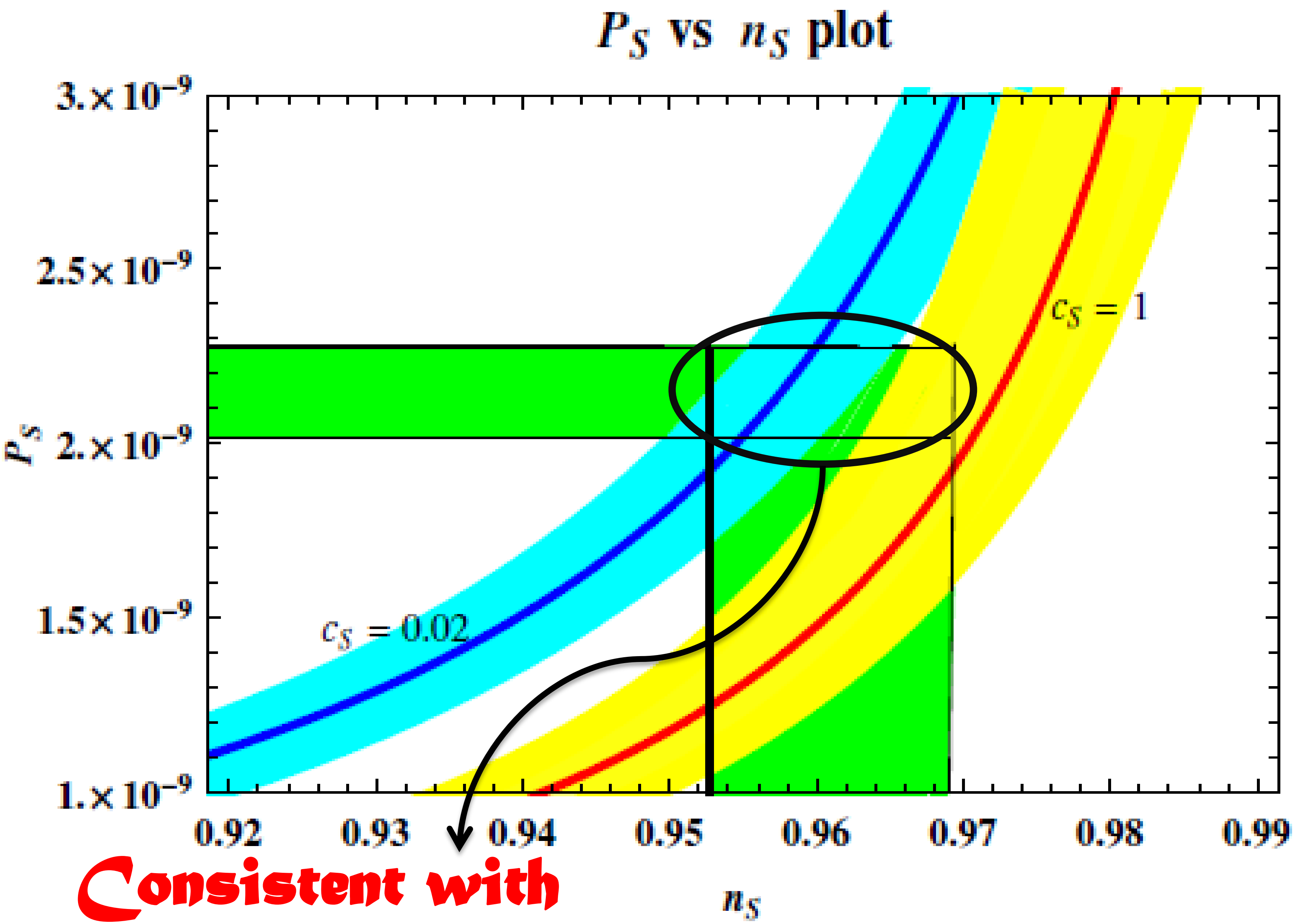
Inflationary Observables from MSSM

$$2.092 \times 10^{-9} < P_S < 2.297 \times 10^{-9}$$
$$0.02 \le c_s \le 1 \qquad 0.958 < n_S < 0.963$$
$$10^{-22} < r_\star < 0.12$$
$$\mathcal{O}(1 - 5) \le f_{NL} \le 8.5$$
$$\mathcal{O}(75 - 150) \le \tau_{NL} \le 2800$$
$$\mathcal{O}(17.4 - 34.7) \le g_{NL} \le 648.2$$

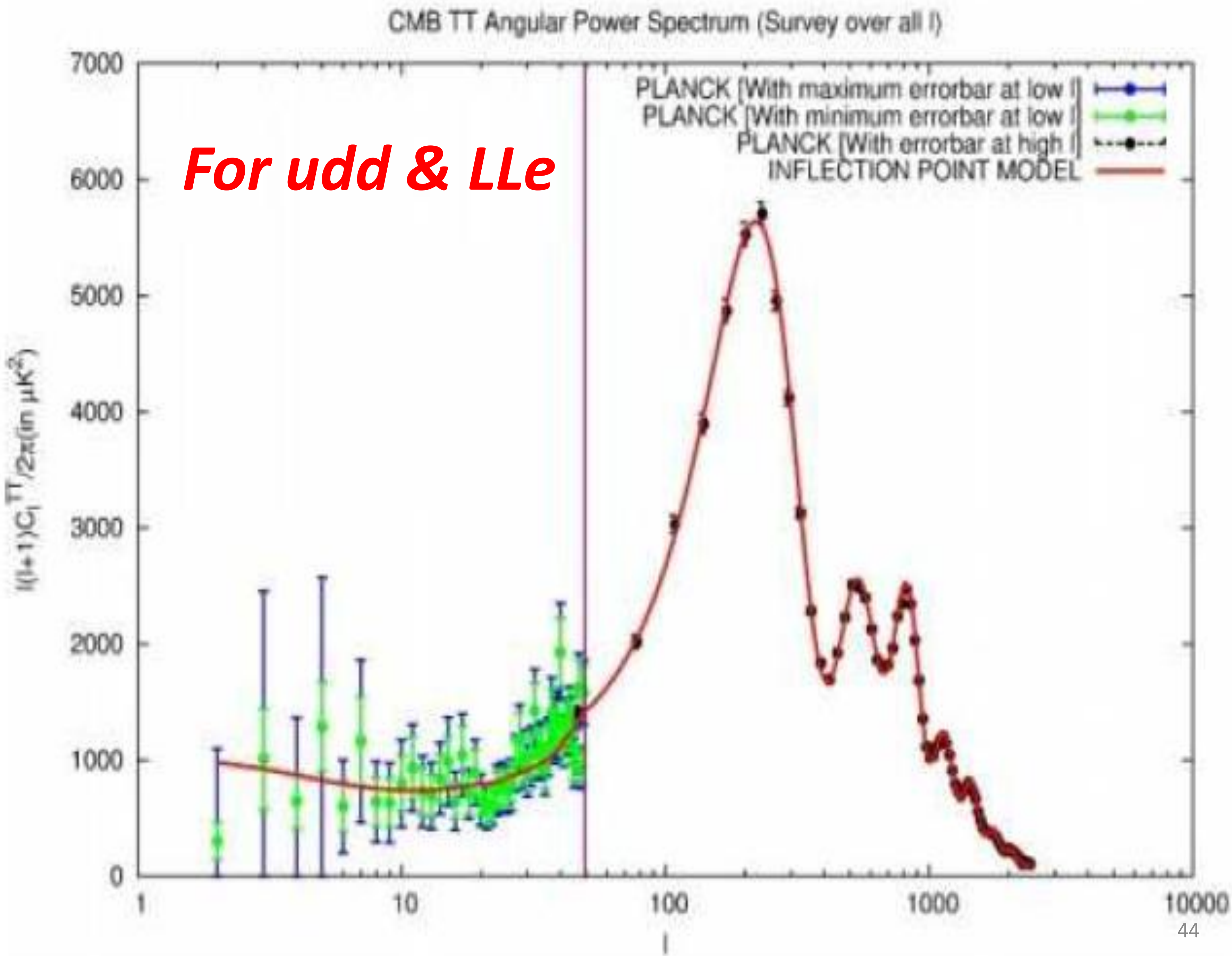

a vs r* plot
a
r*
cS = 0.02
cS = 1
1.0000
0.9999
0.9998
0.9997
0.9996
0.00
0.02
0.04
0.06
0.08
0.10
0.12
b vs r* plot
b
r*
cS = 0.02
cS = 1
1.00
0.98
0.96
0.94
0.92
c vs r* plot
c
r*
cS = 1
cS = 0.02
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
d vs r* plot
d
r*
cS = 0.02
cS = 1

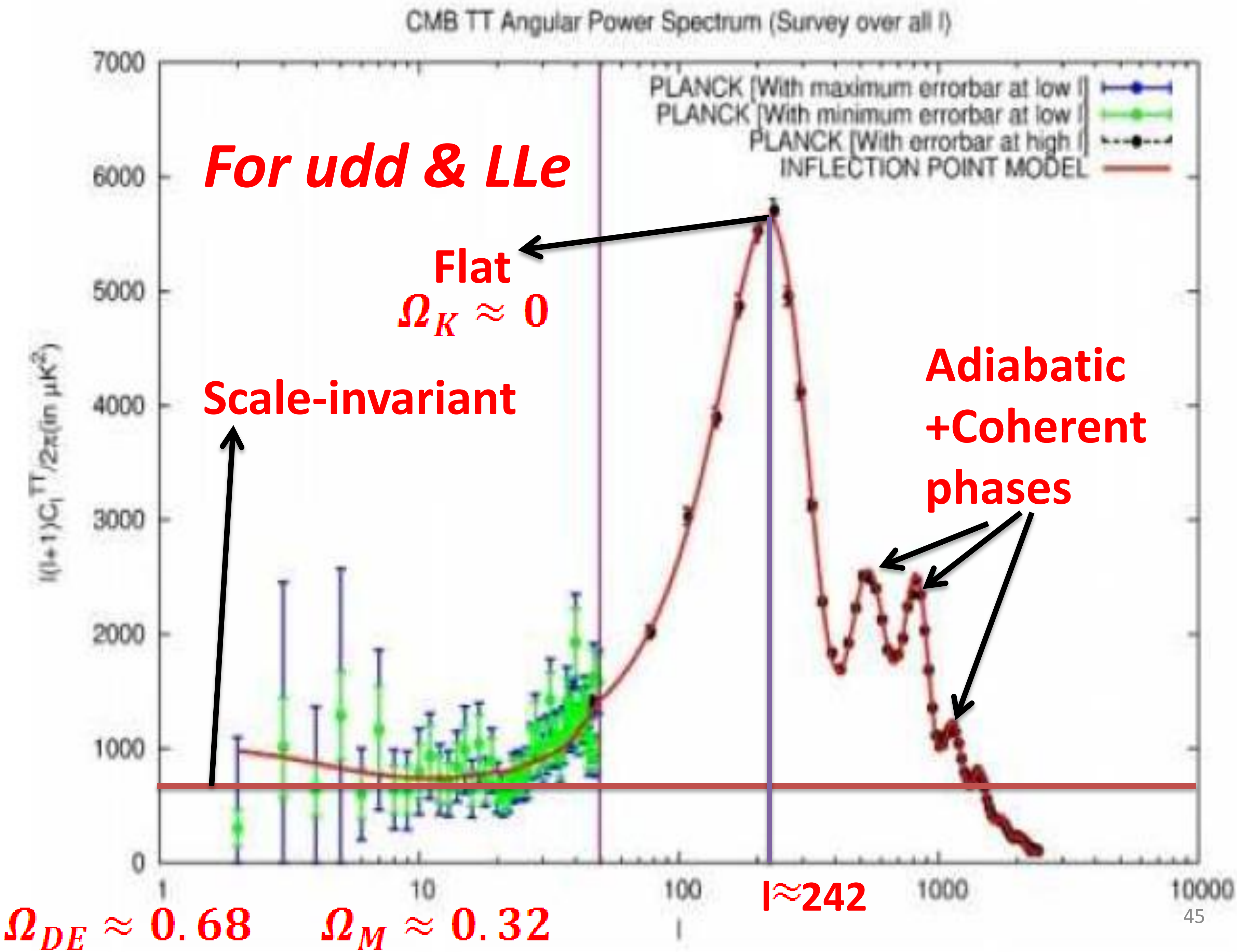

a vs r_* plot
b vs r_* plot
c vs r_* plot
d vs r_* plot
$c_S = 0.02$
$c_S = 1$
r_*
Consistent with PLANCK+WMAP9

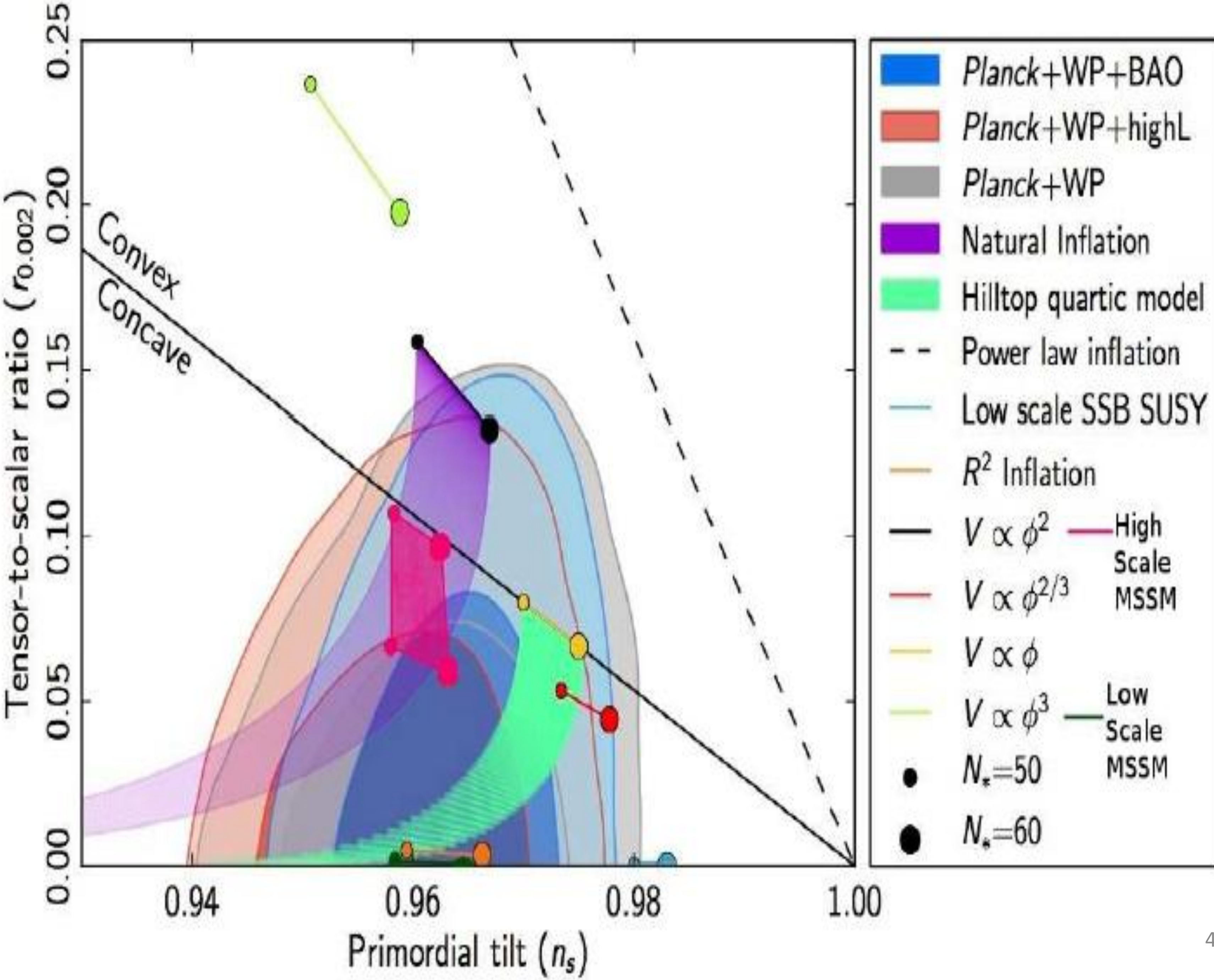

P_S vs n_S plot
$3.\times 10^{-9}$
2.5×10^{-9}
$2.\times 10^{-9}$
1.5×10^{-9}
$1.\times 10^{-9}$
P_S
$c_S = 1$
$c_S = 0.02$
0.92
0.93
0.94
0.95
0.96
0.97
0.98
0.99
n_S

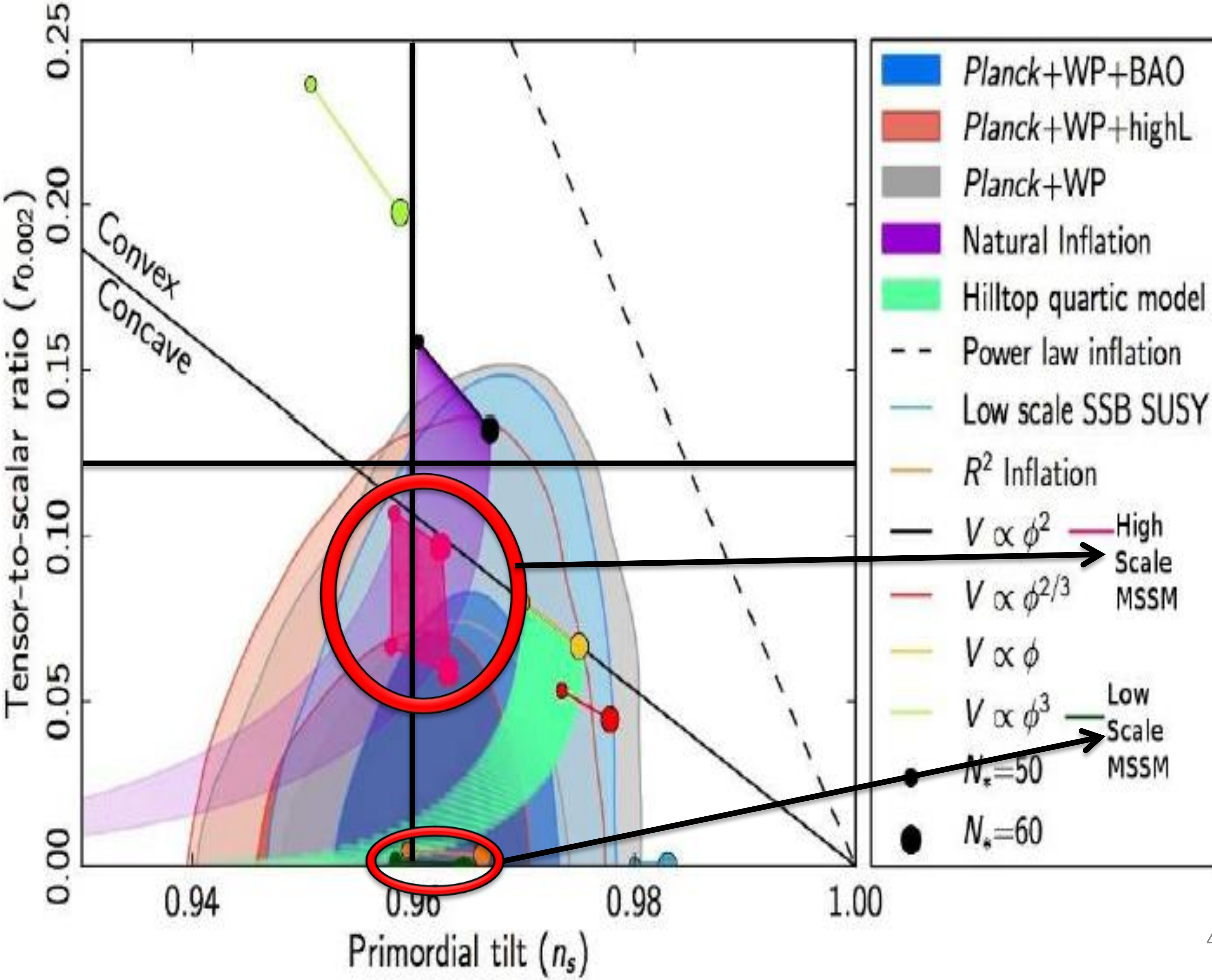


Consistent with PLANCK+WAP9


CMB TT Angular Power Spectrum (Survey over all l)
For udd & LLe
PLANCK [With maximum errorbar at low l]
PLANCK [With minimum errorbar at low l]
PLANCK [With errorbar at high l]
INFLECTION POINT MODEL
l(l+1)C_l^TT/2π(in μK^2)
l
7000
6000
5000
4000
3000
2000
1000
0
1
10
100
1000
10000


CMB TT Angular Power Spectrum (Survey over all l)
PLANCK [With maximum errorbar at low l]
PLANCK [With minimum errorbar at low l]
PLANCK [With errorbar at high l]
INFLECTION POINT MODEL
For udd & LLe
Flat
$\Omega_K \approx 0$
Scale-invariant
Adiabatic
+Coherent
phases
$l(l+1)C_l^{TT}/2\pi$ (in μK^2)
7000
6000
5000
4000
3000
2000
1000
0
1
10
100
1000
10000
l
l≈242
$\Omega_{DE} \approx 0.68$
$\Omega_M \approx 0.32$


Planck+WP+BAO
Planck+WP+highL
Planck+WP
Natural Inflation
Hilltop quartic model
Power law inflation
Low scale SSB SUSY
R^2 Inflation
$V \propto \phi^2$
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^3$
High Scale MSSM
Low Scale MSSM
N_*=50
N_*=60
Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00


Planck+WP+BAO
Planck+WP+highL
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Natural Inflation
Hilltop quartic model
Power law inflation
Low scale SSB SUSY
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High Scale MSSM
Low Scale MSSM
Convex
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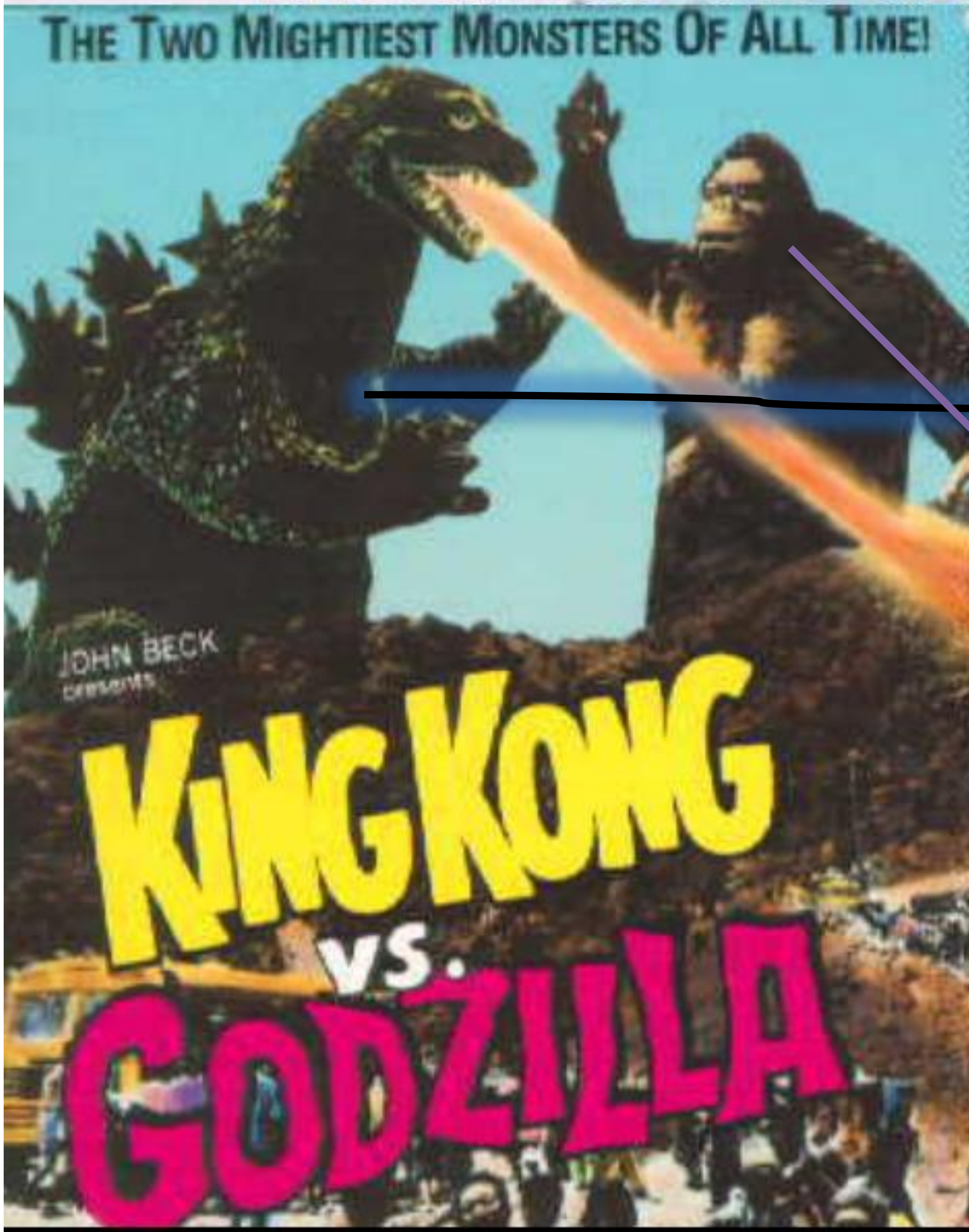
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

How to obtain Large 'r'



Super vs Sub Planckian Inflation ?

In MSSM with Non-minimal PSO

Sub-Plankian Inflation

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Observable gravitational waves from inflation with small field excursions

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Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Low & high scale MSSM inflation, gravitational waves and constraints from Planck

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An accurate bound on tensor-to-scalar ratio and the scale of inflation

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Bound on largest $r \lesssim 0.1$ from sub-Planckian excursions of inflaton

[O] 15 Sep 2014

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$$V = V_0 + A\phi^2 - B\phi^6 + C\phi^{10}$$

Sub-Plankian Inflation

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Observable gravitational waves from inflation with small field excursions

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Low & high scale MSSM inflation, gravitational waves and constraints from Planck

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$$V = V_0 + A\phi^2 - B\phi^6 + C\phi^{10}$$

$$\Delta \phi \le M_p$$

Super vs Sub Planckian Inflation ?

Checked for udd, LLe,NH_uL, H_uH_d.

Sub

EFT works well for (v)MSSM

Checked for udd, LLe, NH_uL, H_uH_d.

Sub

Bottom lines

- **High scale models of MSSM inflation within N=1 SUGRA are favoured after Planck.**
- **Validity of EFT prescription in N=1 SUGRA within MSSM requires non-minimal kahler interactions.**
- **Sub-Planckian VEV and field excursion can be generated in presence of PSO for udd,LLe, H_uH_d, NH_uL flat directions for MSSM.**
- **Non-minimal setup put stringent constraint on PNG parameters.**
- **Also put constraint on Reheating temperature .**

Future prospects

- Dark matter +baryogenesis in presence of non-minimal PSO???
- Reconstruction of EFT within N=1 SUGRA sector using observed data (Planck)???
- (UV-IR) behaviour of MSSM in presence of higher curvature corrections???
- Origin of non-minimal corrections in N=1 SUGRA???
- Source of hidden sector and its uniqueness??? Only stringy origin???
- Embedding of MSSM within N=1 SUGRA from superstring theory ???
- Sensitivity of EFT couplings at UV end???

MSSM collaborators…..

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Supratik Pal

Ernestas Pukartas

Lingfei Wang

Thanks for your time……