Higgs versus Inflation in string theory

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MITP Workshop, Mainz
September, 2014

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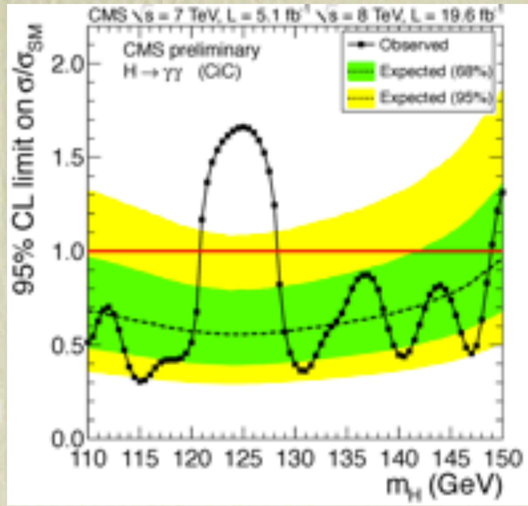
Fundamental scalars in physics:

- HIGGS EW masses
- INFLATON Cosmology
- (AXION CP ?)

Fundamental scalars in physics:

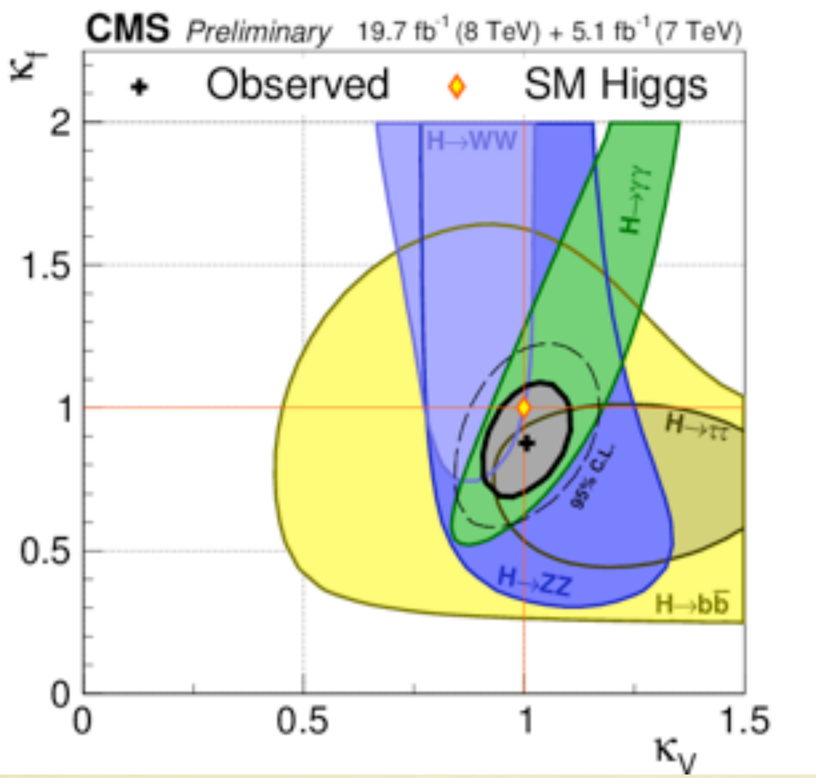


- HIGGS OBSERVED!!!
- INFLATON Cosmology
- (AXION CP ?)

- First elementary scalar ever seen in Physics

(Both SUSY and Strings predict elementary scalars !)

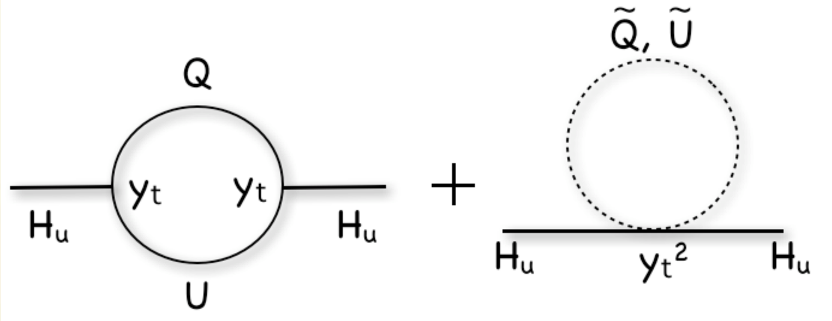
- Branching Ratios look also like SM (so far..)



No sign of new physics in the Higgs couplings..

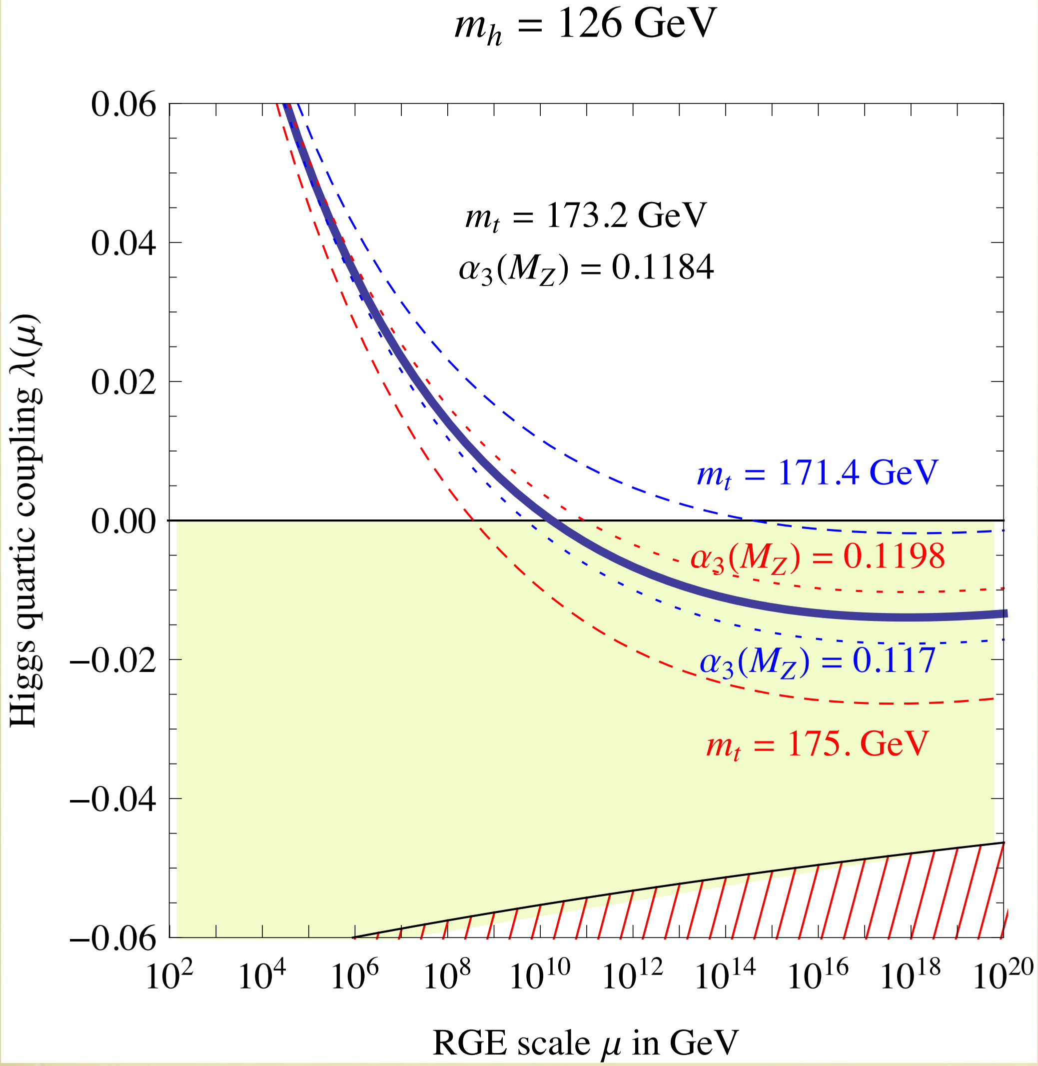
The SM Higgs problems get sharper:

- 1) The gauge hierarchy problem more explicit: the Higgs is there, light and weakly coupled. $Why\ \ m_{Higgs} \ll M_{Planck}$??



- 2) A new 'problem': the `Stability Problem´: the Higgs potential becomes unbounded well below the Planck scale....

Just-SM unlikely to survive all the way to Planck scale:



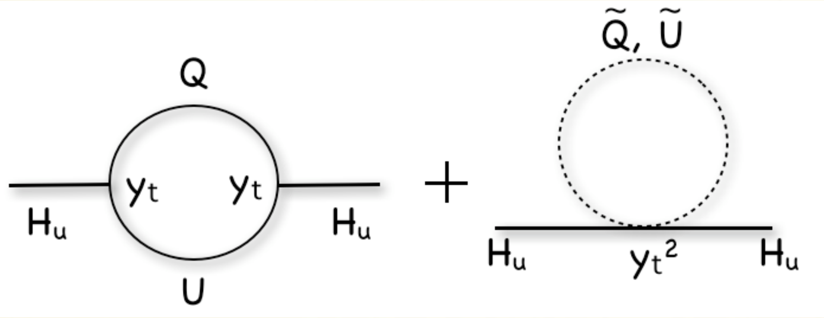
Elias-Miró et al. '12

- \`Stability Problem´: the Higgs potential unbounded well below the Planck scale....

Metastable

$at \simeq 10^{11} - 10^{14}\ GeV$

Low-energy SUSY?



$= 0$

- SUSY predicts $m_h \leq 130\ GeV$

In principle 126 GeV Higgs good news for SUSY

However... this value is a bit high....

... and no hints as yet of SUSY particles at LHC!

$$e.g.\ M_{\tilde{g}} = M_{\tilde{q}} \geq 1.7\ TeV\ !$$

(CMSSM)

High Scale SUSY breaking

Hall, Nomura '09, 13   Hebecker, and Weigand '12, '13 L. I., Marchesano, Regalado, Valenzuela arXiv:1206.2655

L. I. and Valenzuela 2013

- It is a simple solution to the stability problem

$$V \;=\; D^2 \;+\; F^2 \;\geq\; 0$$

- One assumes MSSM applies at scales

$$M_{ss} \;>\; 10^{11} - 10^{13}\; GeV$$

enough to stabilize the potential

- Additional motivation: SUSY is a fundamental symmetry of string theory and guarantees absence of tachyons in explicit compactifications

SUSY would be needed NOT to stabilize the hierarchy but to stabilize the SM vacuum

$$This\ would\ require\ M_{SS}\ \leq\ 10^{11} - 10^{13}\ GeV$$

$$(before\ \lambda\ becomes\ negative)$$

The solution of the hierachy problem would be then anthropic...

Most genereal MSSM Higgs masses:

$$\left(\begin{array}{ccc} H_u & , & H_d^* \end{array} \right) \left(\begin{array}{cc} m_{H_u}^2 & m_3^2 \\ m_3^2 & m_{H_d}^2 \end{array} \right) \left(\begin{array}{c} H_u^* \\ H_d \end{array} \right)$$

$$For\ \underset{\text{(fine-tuning)}}{m_{H_u}^2 m_{H_d}^2 = m_3^4} \ \simeq (10^{11} - 10^{13}\ GeV)^4 \ \ :$$

$$h \ = \ sin\beta H_u - cos\beta H_d^* \ , \ massless \rightarrow SM \ doublet$$

$$H \ = \ cos\beta H_u + sin\beta H_d^* \ , \ massive, m_H \simeq 10^{11} - 10^{13} GeV$$

$$tan\beta = |m_{H_d}/m_{H_u}|$$

$$at\ Q \simeq 10^{11} - 10^{13} GeV\ :$$

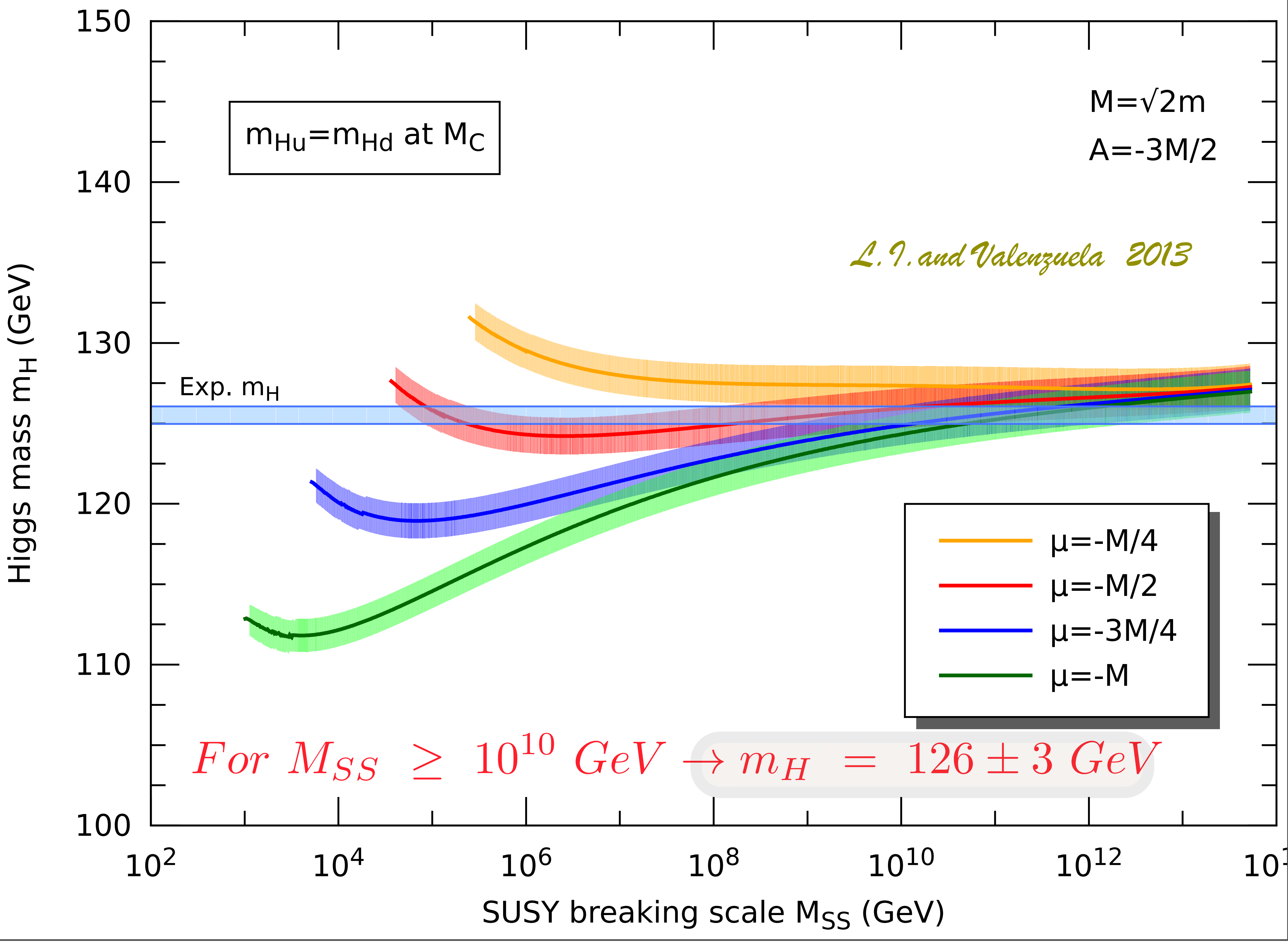
$$V \ = \ m_H^2|H|^2 \ + \ \frac{g_1^2+g_2^2}{8} cos^2 2\beta \left(|h|^2 - |H|^2\right)^2$$

SM Higgs

$$For\ cos2\beta \simeq 0\ (tan\beta \simeq 1)\ :$$

$$\boxed{\underset{\text{(massless)}}{h} \ = \ H_u - H_d^* \ \ ; \ \underset{\text{(massive)}}{H} \ = \ H_u + H_d^*}$$

$$V_h(Q) \ \simeq \ 0 \longrightarrow m_h^0(Q_{EW}) = \boxed{126 \pm 3\ GeV}$$



L.I. and Valenzuela 2013

$$For\ M_{SS}\ \geq\ 10^{10}\ GeV \rightarrow m_H\ =\ 126 \pm 3\ GeV$$

Observed Higgs mass indicates:

$$tan\beta = |m_{H_d}/m_{H_u}| \simeq 1 \ at \ Q \simeq 10^{11} - 10^{13} GeV$$

$$\longrightarrow \left(\begin{array}{cc} H_u \ , & H_d^* \end{array} \right) \left(\begin{array}{cc} m^2 & m^2 \\ m^2 & m^2 \end{array} \right) \left(\begin{array}{c} H_u^* \\ H_d \end{array} \right)$$

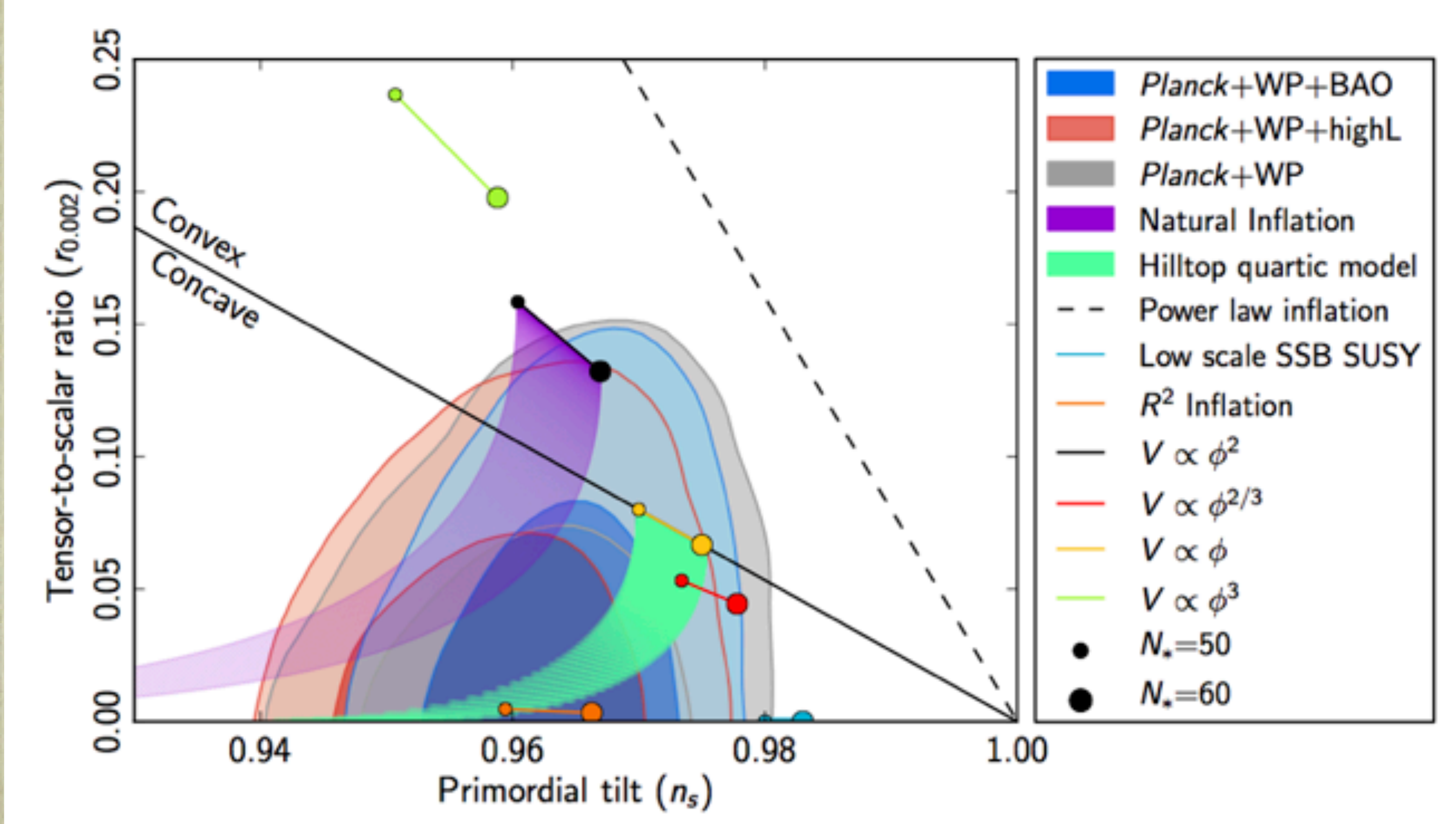
Suggests looking for SUSY-breaking sources leading to this kind of structure...

We will see later that certain classes of string compactifications lead to this structure

Inflation and strings

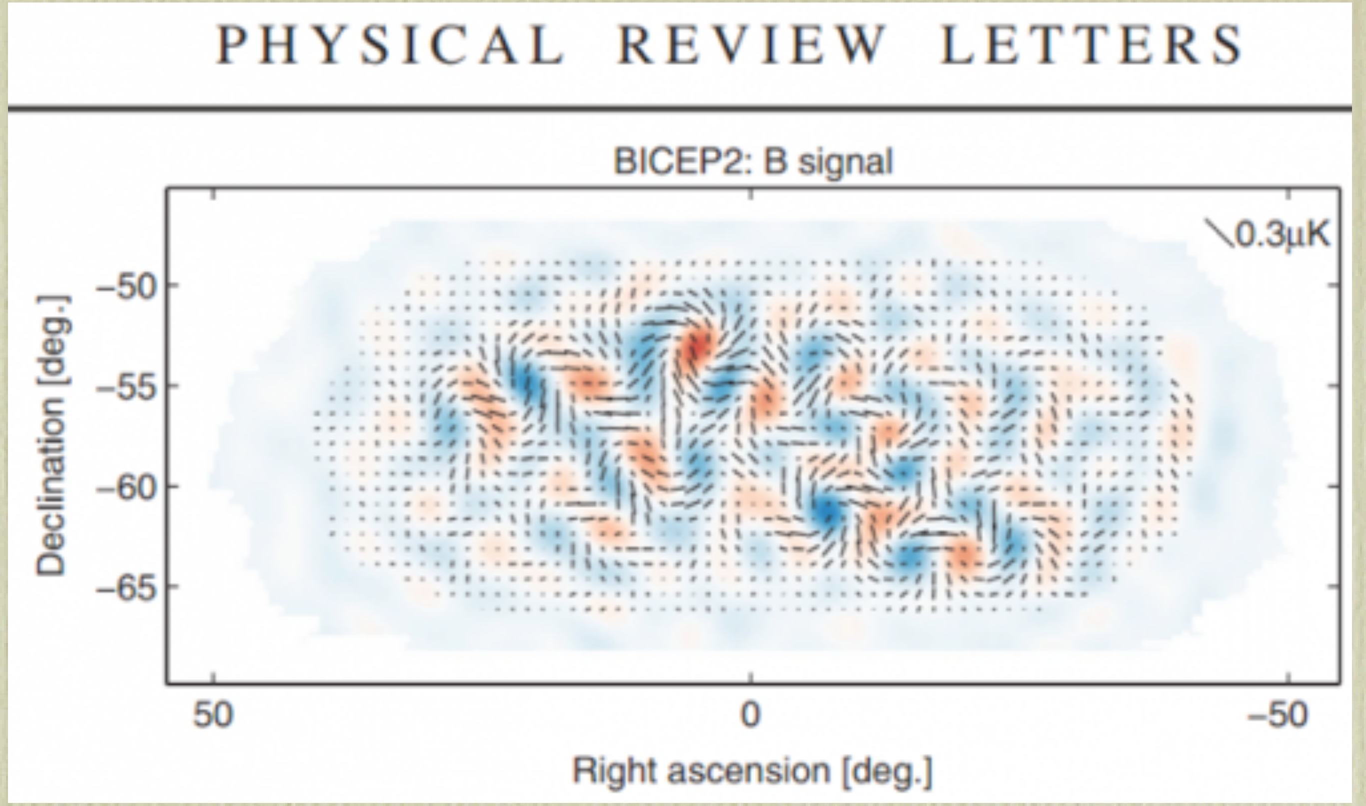
Inflation before March 17-th 2014

Planck:



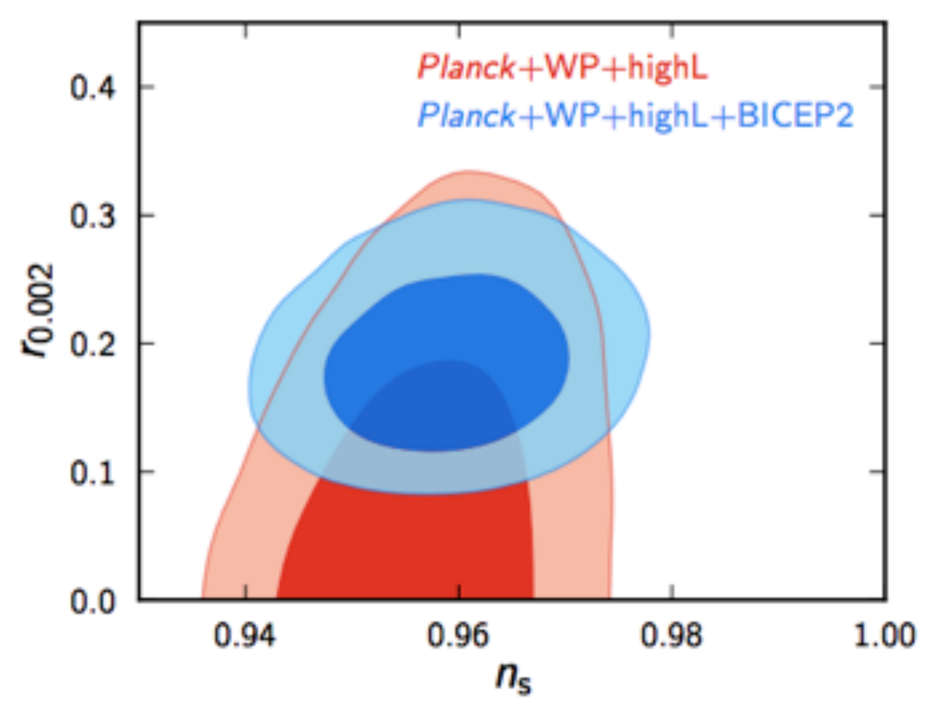
$\phi^n \ , \ n \geq 2 \ close \ to \ exclusion \ldots$

BICEP2

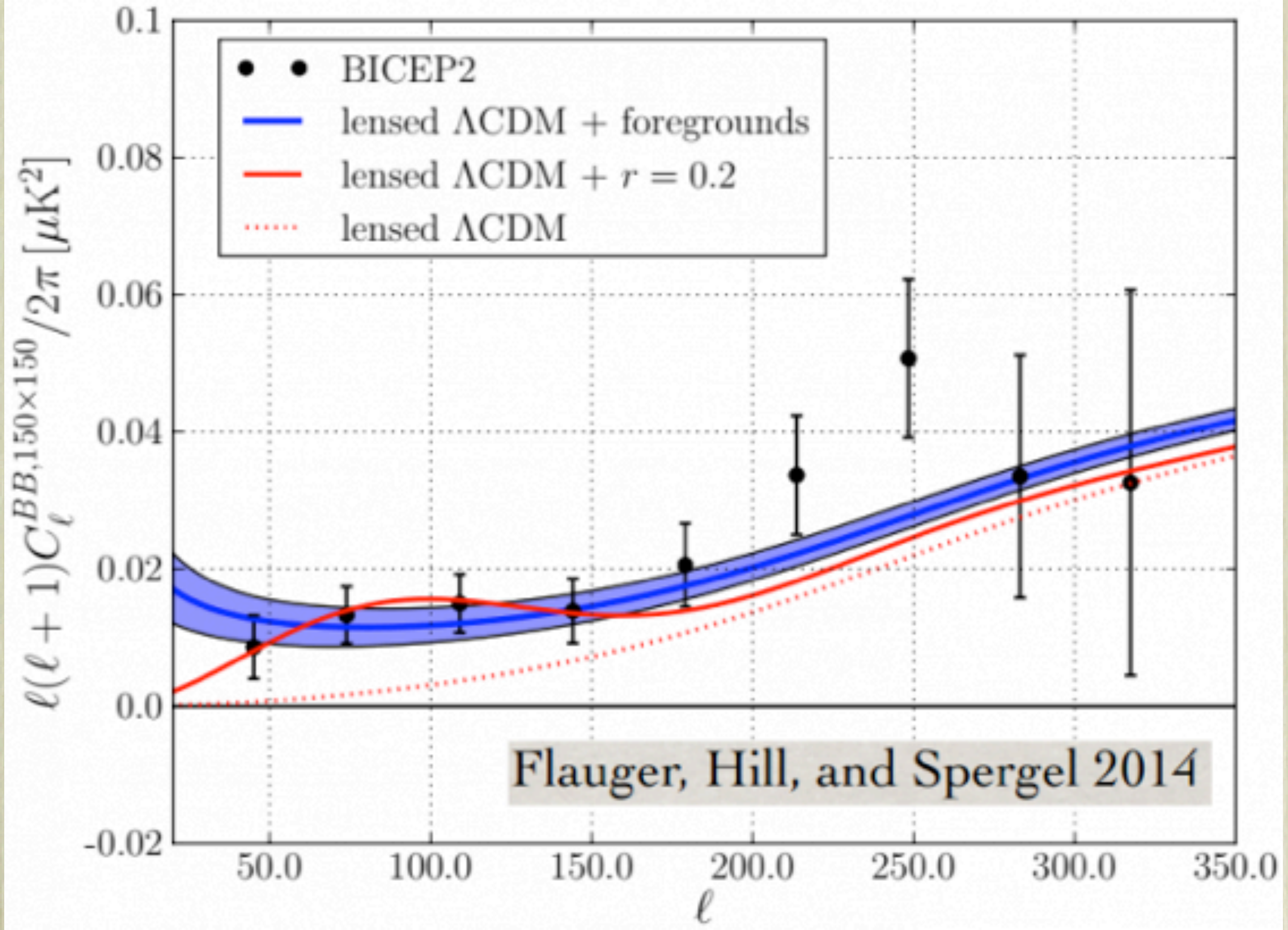


Primordial
B-modes

$$r = 0.1 - 0.2$$



But the dust still has to settle....



B-mode power spectrum

Slow roll inflation

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \quad , \quad \eta = M_p^2\frac{|V''|}{V} \ll 1$$

Perturbations:

$$Scalar\ spectral\ index: \quad n_s - 1 = 2\eta - 6\epsilon$$

$$tensor/scalar\ ratio: \ r = 16\epsilon$$

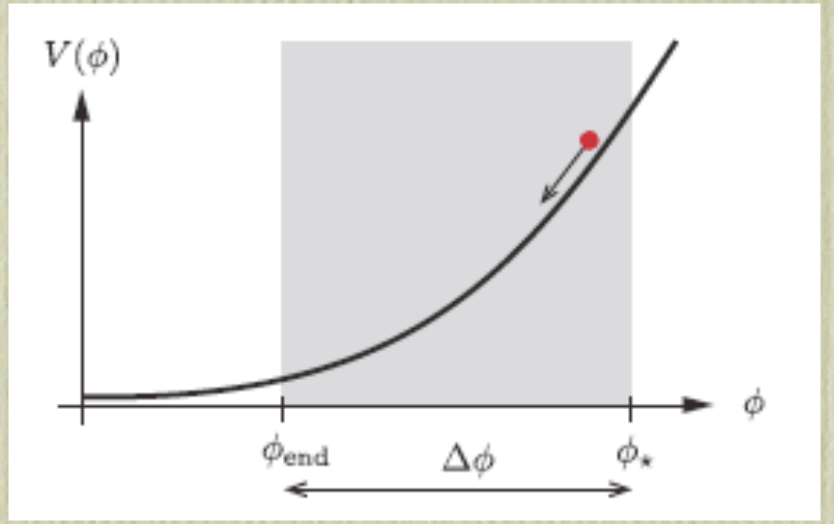
$$Number\ e-folds: \quad N_* = \frac{1}{M_p}\int_{\phi_{end}}^{\phi_*}\frac{d\phi}{\sqrt{2\epsilon}}$$

Lyth bound: $$\frac{\Delta\phi}{M_p} \geq 0.25\left(\frac{r}{0.01}\right)^{1/2}$$

Large r requires trans-Planckian inflaton excursions

Simplest large r: Chaotic Inflation

Linde 88



(Bauman McAllister book)

$$V(\phi) \ = \ \mu^{4-p}\phi^p$$

$$N_* \simeq \frac{1}{2p}\left(\frac{\phi_*}{M_p}\right)^2 \rightarrow trans - Planckian$$

$$n_s - 1 \ = \ - \ \frac{(2+p)}{2N_*} \quad , \quad r = \frac{4p}{N_*}$$

If BICEP2 correct:

$$V^{1/4} \simeq \left(\frac{r}{0.01}\right)^{1/4} \times 10^{16}\ GeV \simeq 10^{16} GeV$$

$$H_I \simeq \left(\frac{r}{0.20}\right)^{1/2} \times 10^{14}\ GeV$$

$$m_I \simeq 10^{13}\ GeV$$

If BICEP2 correct:

$$V^{1/4} \simeq \left(\frac{r}{0.01}\right)^{1/4} \times 10^{16}\ GeV \simeq 10^{16} GeV$$

$$H_I \simeq \left(\frac{r}{0.20}\right)^{1/2} \times 10^{14}\ GeV$$

$$m_I \simeq 10^{13}\ GeV$$

L.I. and Valenzuela hep-ph/1403.6081

Related to SUSY-breaking scale?

(I call SUSY breaking scale the size of the SOFT TERMS)

10^{13}	10^{14}	10^{16}	10^{18}	10^{19}
m_I	H_I	$V^{1/4}$	M_p	ϕ_*

NEED:

1) *Stable* $m_I \ll M_p$ ($m_I \ll H_I$ *if SUSY*) : η *problem*

2) *Large* $\phi_* \gg M_p$ *possible*

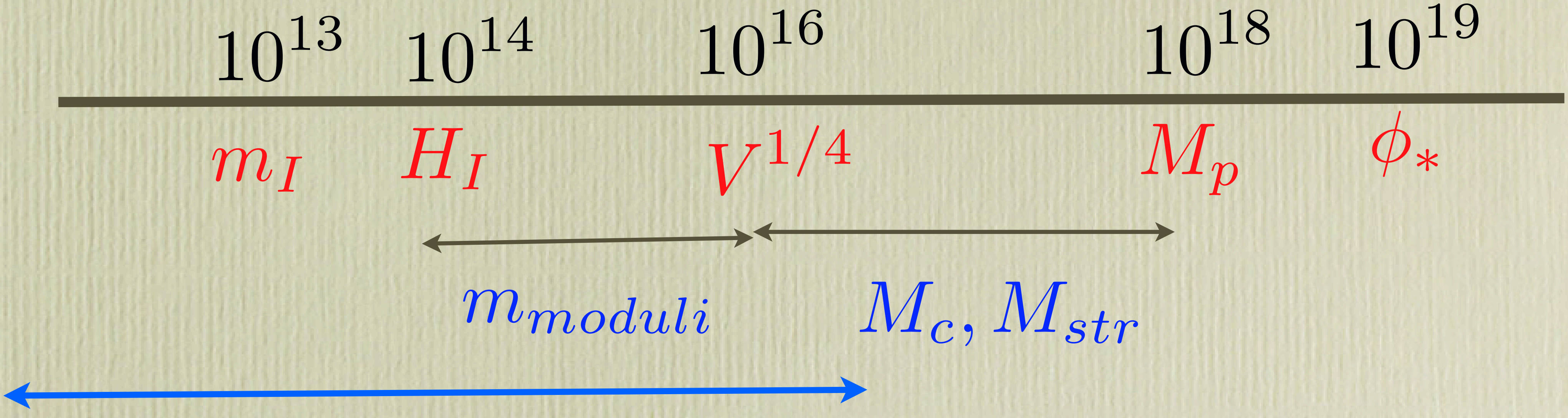
3) *Corrections under control for* $\phi_* \gg M_p$

1), 3) $\longrightarrow$ *shift symmetry* :

$$\phi \longrightarrow \phi + c$$

2) $\rightarrow$ *periodic inflaton field*

Scales in string large inflaton



10^{13} 10^{14} 10^{16} 10^{18} 10^{19}

m_I H_I $V^{1/4}$ M_p ϕ_*

m_{moduli} M_c, M_{str}

$D = 4$ *field theory ok*

$\phi_* \simeq 10 M_p$ *ok, as long as* $V(\phi)^{1/4} \leq M_c, M_{str}$

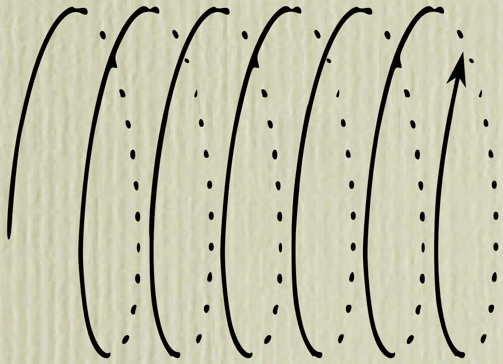
Disclaimer: we will assume that moduli are fixed somehow well above inflaton mass

R. Blumenhagen talk on friday

Large field inflation in string theory:

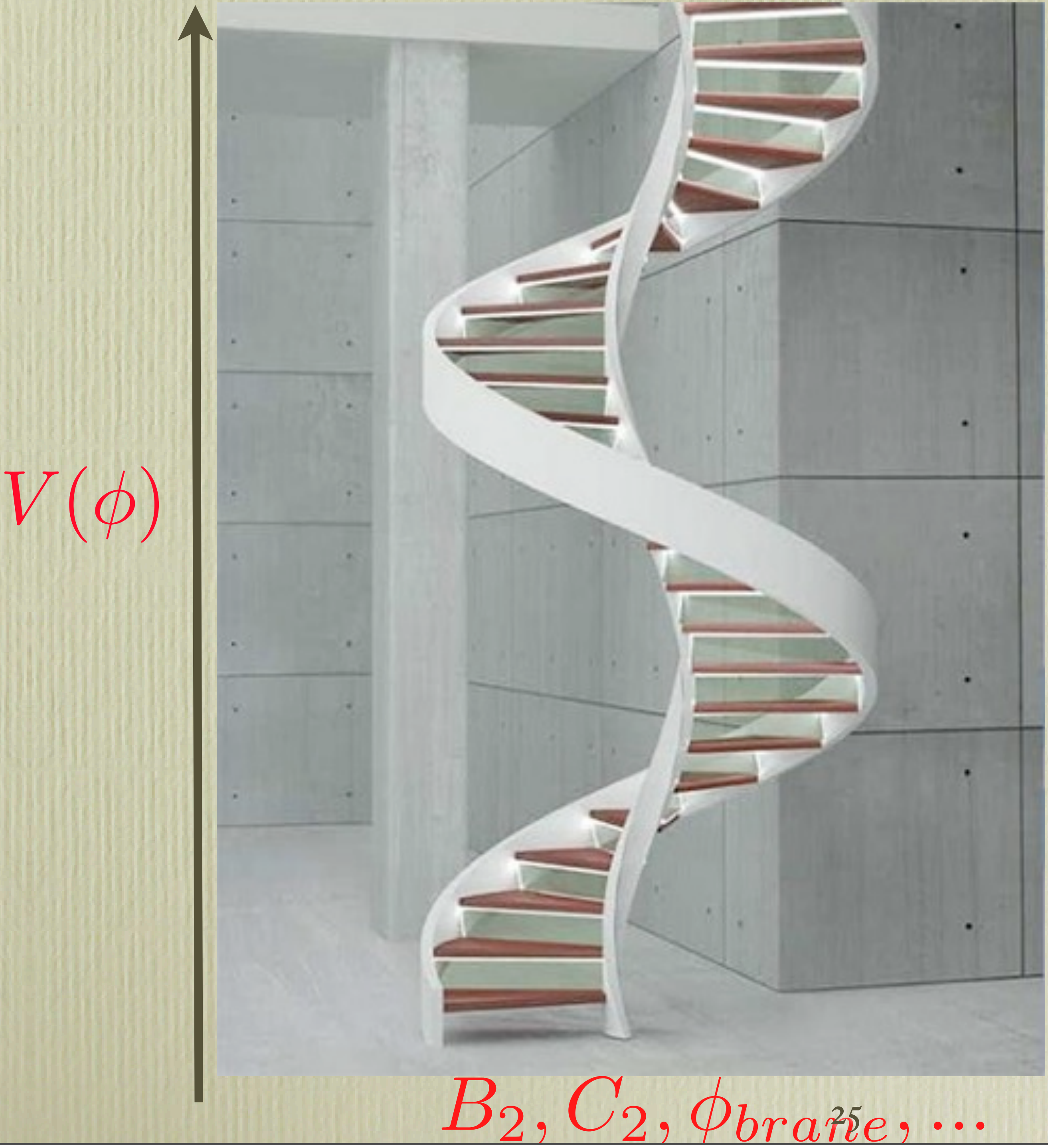
- Inflaton identified with either an axion, a Wilson line or a D-brane position

- Periodicity in those fields allows for large trans-Planckian excursions without exciting heavy KK or string states



- Gauge symmetries of those fields make potentials stable against corrections to the potential.

Monodromy inflation

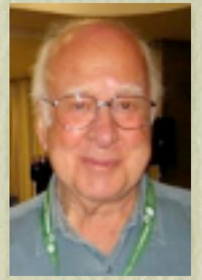


Silverstein, Westphal 08;
McAllister, Silverstein, Westphal
Kaloper, Sorbo 08
Gur-Ari, 13

Marchesano, Shiu, Uranga , 14
Palti, Weigand 14
Hebecker, Kraus, Witkowwski 14
Blumenhagen 14
....

Alternative: two axions

Kim, Nilles, Peloso , 04
Kappl, Krippendorf, Nilles , 14
Ben-Dayan, Pedro, Westphal, '14



Higgs-otic inflation

L.I. and Valenzuela arXiv-ph/1403.6081; th/1404.5235

L.I.Marchesano and Valenzuela 2014, to appear

Higgs inflation?

- Atractive: having a light SM $m_h = 126\ GeV \ll M_p$ is already an amazing miracle.

- Having an additional inflaton scalar with mass $m_I = 10^{13}\ GeV \ll M_p$ is an additional miracle. Can we relate both miracles?

- In the SM this identification is complicated. Present implementations lead to non-minimal gravity $\int |h|^2 R$ and to small r.

Bezrukov, Shaposhnikov '07

- The SUSY-SM case looks more promising.

For large SUSY breaking we saw:

$$V_h(M_{ss}) \simeq 0 \quad , \qquad V_H(M_{ss}) \simeq m^2|H|^2$$

Chaotic inflation with H the inflaton?

- Large inflaton excursions and stability required:

Look for a string implementation with some sort of monodromy inflation with H = Wilson line or D-brane position

L.I. and Valenzuela arXiv-th/1404.5235   L.I. Marchesano and Valenzuela 2014, to appear

Higgs MSSM fields in string compactifications

Possible both in Type II orientifolds and Heterotic

A SM toy model with D7-branes at singularities

L.I. Valenzuela 14

6 D7-branes at $(\mathbf{C^2} \times \mathbf{T^2})/Z_4$

$(z_1, z_2, z_3) \to (\alpha z_1, \alpha z_2, \alpha^2 z_3)$

$\gamma = diag(\alpha \mathbf{1_3}, \alpha^2 \mathbf{1_2}, \mathbf{1})$

$\alpha = exp(i2\pi/4)$

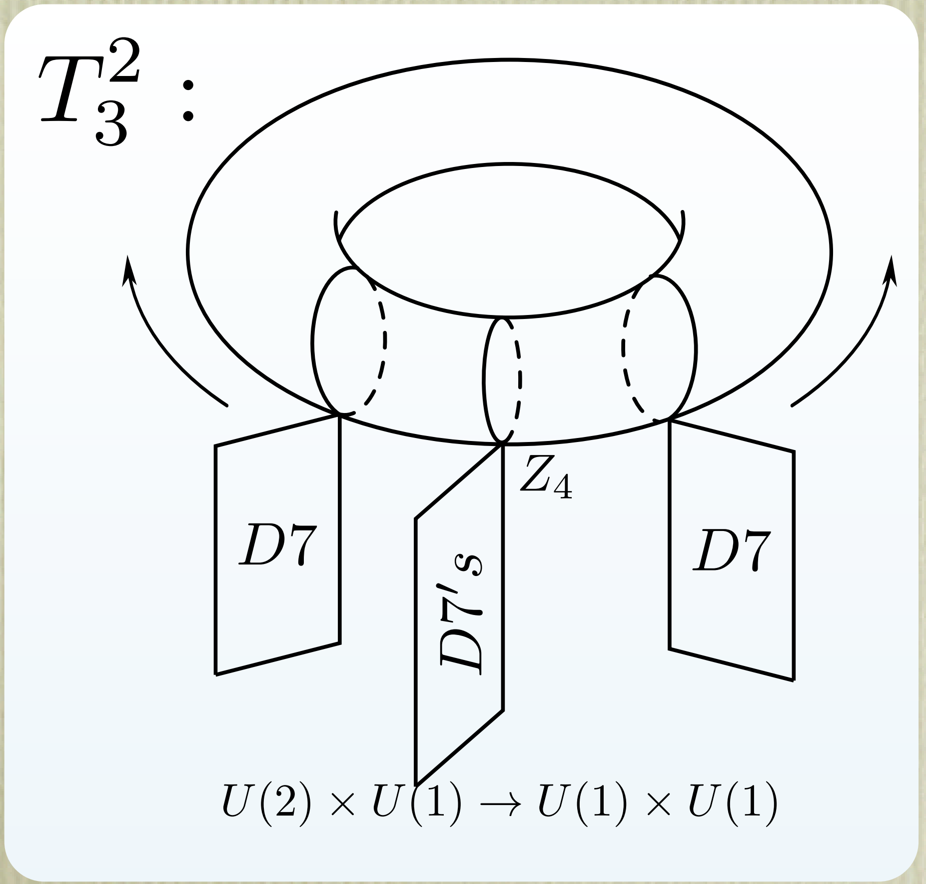
Gauge group: $U(3) \times U(2) \times U(1)$

Matter fields: $2(3,\overline{2}) \; + \; 2(1,\overline{3}) \; + \; \underbrace{(1,2) + (1,\overline{2})}$

vector pair: $\mathrm{H_u}$, $\mathrm{H_d}$

↑

$in\ 3-d\ complex\ plane$



$U(2) \times U(1) \to U(1) \times U(1)$

One U(2)-brane + U(1)-brane can leave the singularity in opposite directions in 3-d torus

$SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)$

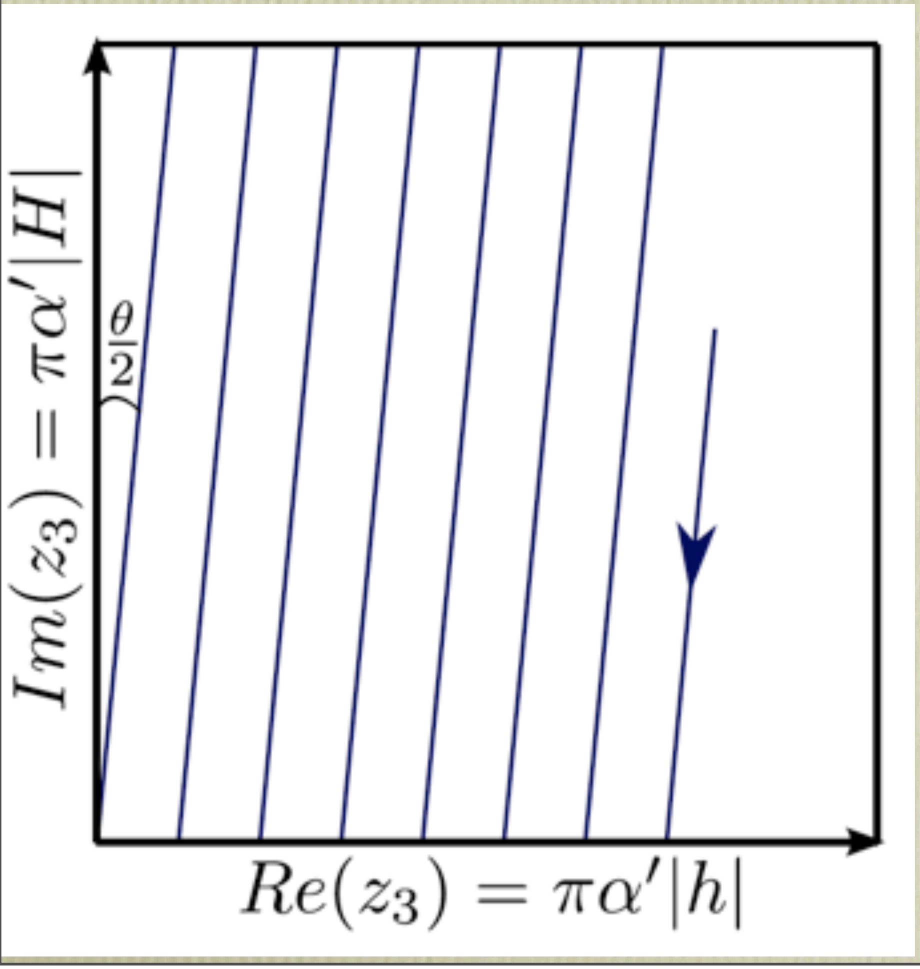
Inflaton breaks SM gauge symmetry

D-flat: $H_u = \sigma \ , \ H_d = \sigma e^{i\theta}$ $\sigma, \theta \in \mathbf{R}$

$$H = |H_u + H_d^*| = 2\sigma cos\frac{\theta}{2}$$

$$h = |H_u - H_d^*| = 2\sigma \ sin\frac{\theta}{2}$$

- Position on T_3^2 :

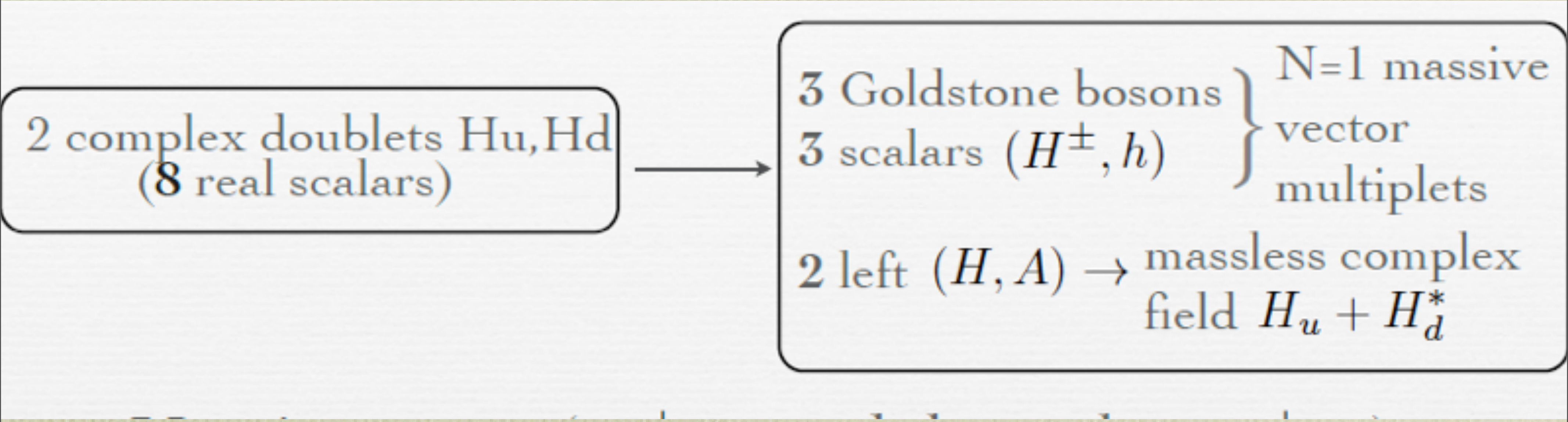


$$z_3 = \pi\alpha'\langle h + iH\rangle = \sigma e^{i\theta/2}$$

$\llcorner\!\!\rightarrow$ Inflaton

Counting of degrees of freedom:

$(for\ e.g.\ h=0)$



2 complex doublets Hu,Hd
(8 real scalars)

3 Goldstone bosons
3 scalars $(H^{\pm}, h)$
} N=1 massive vector multiplets

2 left $(H, A) \rightarrow$ massless complex field $H_u + H_d^*$

- Massive states ($W^{\pm}, Z$ and the scalars $H^{\pm}, h$)

Mass given by D7 distance to rest of U(2)xU(1) D7-branes

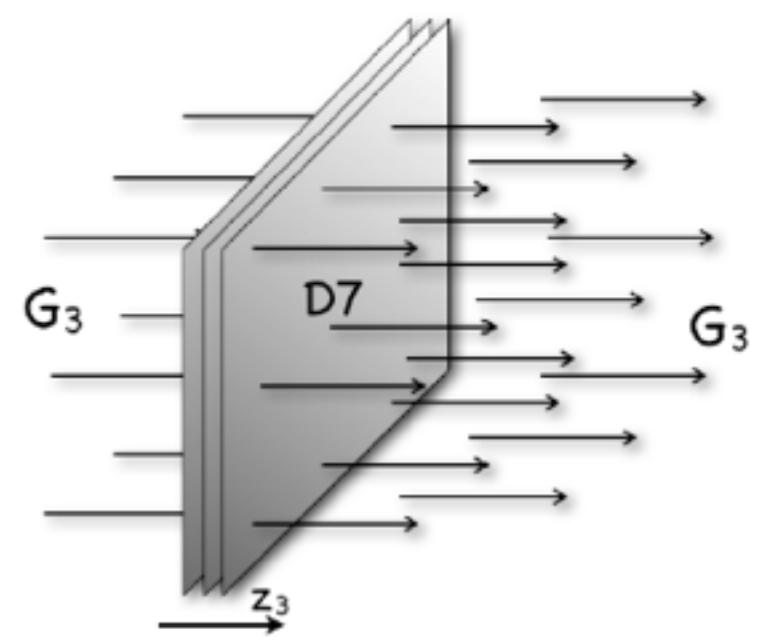
$$M^2 = \frac{1}{(2\pi\alpha')^2}(2\pi R_6 w + x)^2 \rightarrow M_{W,Z}^2 \simeq \frac{R^2}{(\alpha')^2}$$

even though one can have $$|H_u + H_d^*| \gg \frac{R}{\alpha'}$$

(may be trans-Planckian)

Addition of fluxes creates potential

$IIB\ closed\ string\ fluxes:$ $\quad G_3 = F_3 - iSH_3$



Imaginary self-dual closed string fluxes:

$G_{(0,3)}$ (non-SUSY) , $G_{(2,1)}$ (SUSY)

→ insert fluxes in DBI+CS action

L.I., Marchesano and Valenzuela 2014, to appear

Inflaton potential from D7 DBI+CS

$$S_{DBI} = -\mu_7 g_s^{-1} \mathrm{STr}\left(\int d^8\xi \sqrt{-det(P[E_{ab}] + \sigma' F_{ab})}\right)$$

$$S_{CS} = \mu_7 g_s \mathrm{STr}\left(\int d^8\xi P\left[-C_6 \wedge B_2 + C_8\right]\right)$$

$$E_{ab} = g_s^{1/2} G_{ab} - B_{ab} \quad ; \quad \sigma' = 2\pi\alpha' \quad ; \quad \mu_7 = (2\pi)^{-3}(\sigma')^{-4} g_s^{-1}$$

In the presence of fluxes : (*here only $G_{(0,3)}$ for simplicity*)

Pull-back:

$$B_{12} = \frac{g_s \sigma}{2i} G^*_{(0,3)} \Phi$$

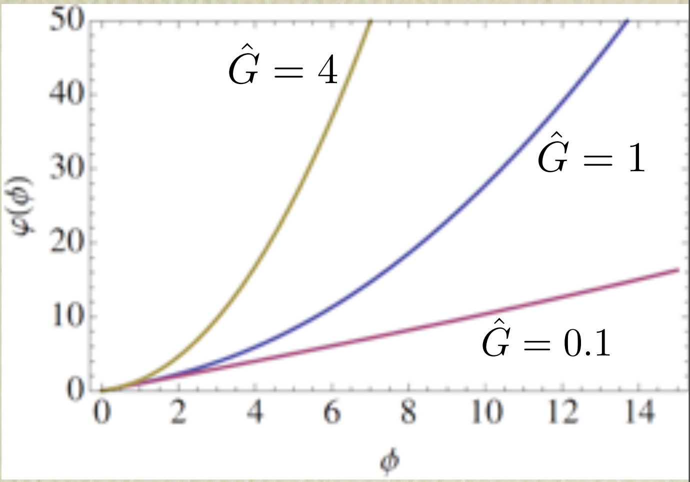
$$(C_6)_{12} = -\frac{\sigma}{2i} G^*_{(0,3)} \Phi$$

$$(C_8)_{1\bar{1}2\bar{2}} = \frac{g_s \sigma^2}{4} |G_{(0,3)}|^2 |\Phi|^2$$

$$\Phi = \begin{pmatrix} 0_3 & & \\ & 0_2 & H_u \\ & H_d & 0 \end{pmatrix}$$

$$S_{DBI} = -\mu_7 g_s STr \int d^8\xi \; \theta^{1/2}(\Phi) \left(1 + (\sigma')^2 \theta(\Phi) D_\mu \Phi D_\mu \bar{\Phi} + O(\partial^4)\right)$$

$$S_{CS} = -\mu_7 g_s STr \int d^8\xi \left(\frac{|\hat{G}_{(0,3)}|^2}{4} |\Phi|^2 \right)$$



$$where \; \theta(\Phi) = \left(1 + \frac{1}{4}|\hat{G}|^2|\Phi|^2\right)^2, \quad \hat{G} \equiv g_s^{1/2}\sigma' G_{(0,3)}$$

Canonical kinetic term needs redefinition:

$$canonical \;\; \varphi = \int^{\Phi} \theta^{1/4}(\Phi')d\Phi' = \frac{1}{4}|\Phi|\sqrt{4 + |\hat{G}|^2|\Phi|^2} + |\hat{G}|^{-1}\sinh^{-1}[|\hat{G}||\Phi|/2$$

$$V(\varphi) = \mu_7 g_s V_4 \left[\theta^{1/2}\left(\Phi(\varphi')\right) + \frac{1}{4}|\hat{G}|^2 \left|\Phi\left(\varphi'\right)\right|^2 - 1 \right]$$

DBI

CS

T_O

Inflaton potential:

$$V(\varphi) = \mu_7 g_s V_4 \left(\frac{1}{2}|\hat{G}|^2|\Phi(\varphi')|^2\right)$$

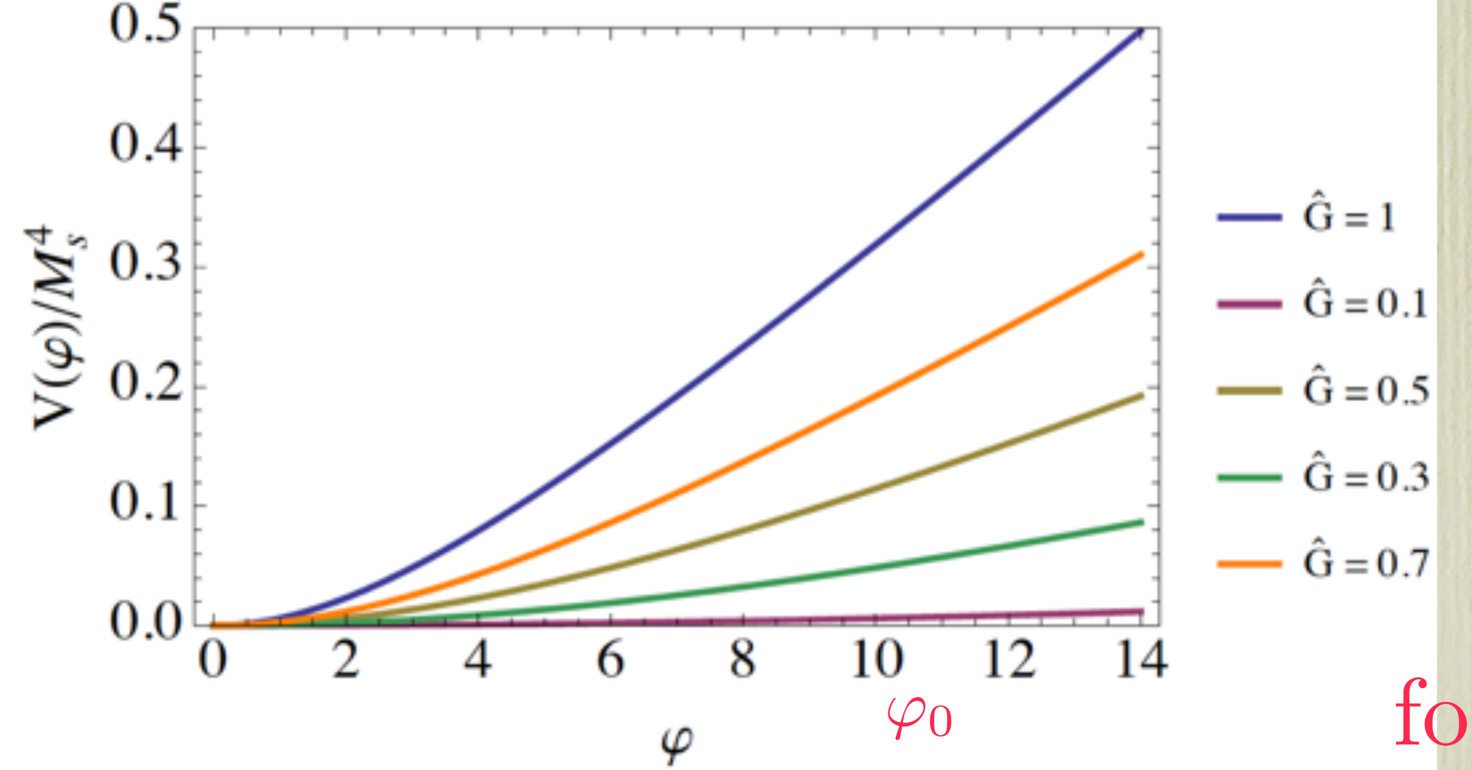
$\hat{G} \equiv g_s^{1/2}\sigma' G_{(0,3)}$

$\varphi = \sigma$

(take here $\theta \simeq 0$)

$\mu_7 g_s V_4 \simeq 0.005 g_s M_s^4$ $\quad$ $\hat{G} \simeq \frac{0.1 \sim 1}{M_p}$

$x_6 \simeq \pi\alpha'|H_u + H_d^*|$ $\quad$ *for large* $|\varphi|$: $\quad \frac{1}{4}|\hat{G}|^2|\Phi(\varphi)|^2 \to |\varphi|$



almost linear
for large inflaton

Tensor to scalar perturbations ratio

$$\epsilon = \frac{m_p^2}{2}\left(\frac{V'}{V}\right)^2 \quad ; \quad \eta = m_p^2 \frac{V''}{V} \qquad N = \frac{1}{m_p}\int_{\varphi_{end}}^{\varphi_0} \frac{1}{\sqrt{2\epsilon}}$$

$$r = 16\epsilon|_{\varphi=\varphi_0} \quad , \quad n_s = -6\epsilon + 2\eta + 1$$

$$\Delta\varphi = \varphi_0 - \varphi_{end}$$

$$\varphi_{end} \simeq M_p$$

For $|\hat{G}| = 1/m_p \; , \; M_{ss} \simeq 5 \times 10^{12} \; GeV$:

For 60 e-folds → $\varphi_0 = 13.1 m_p \rightarrow r = 0.078 \; , \; n_s = 0.973$

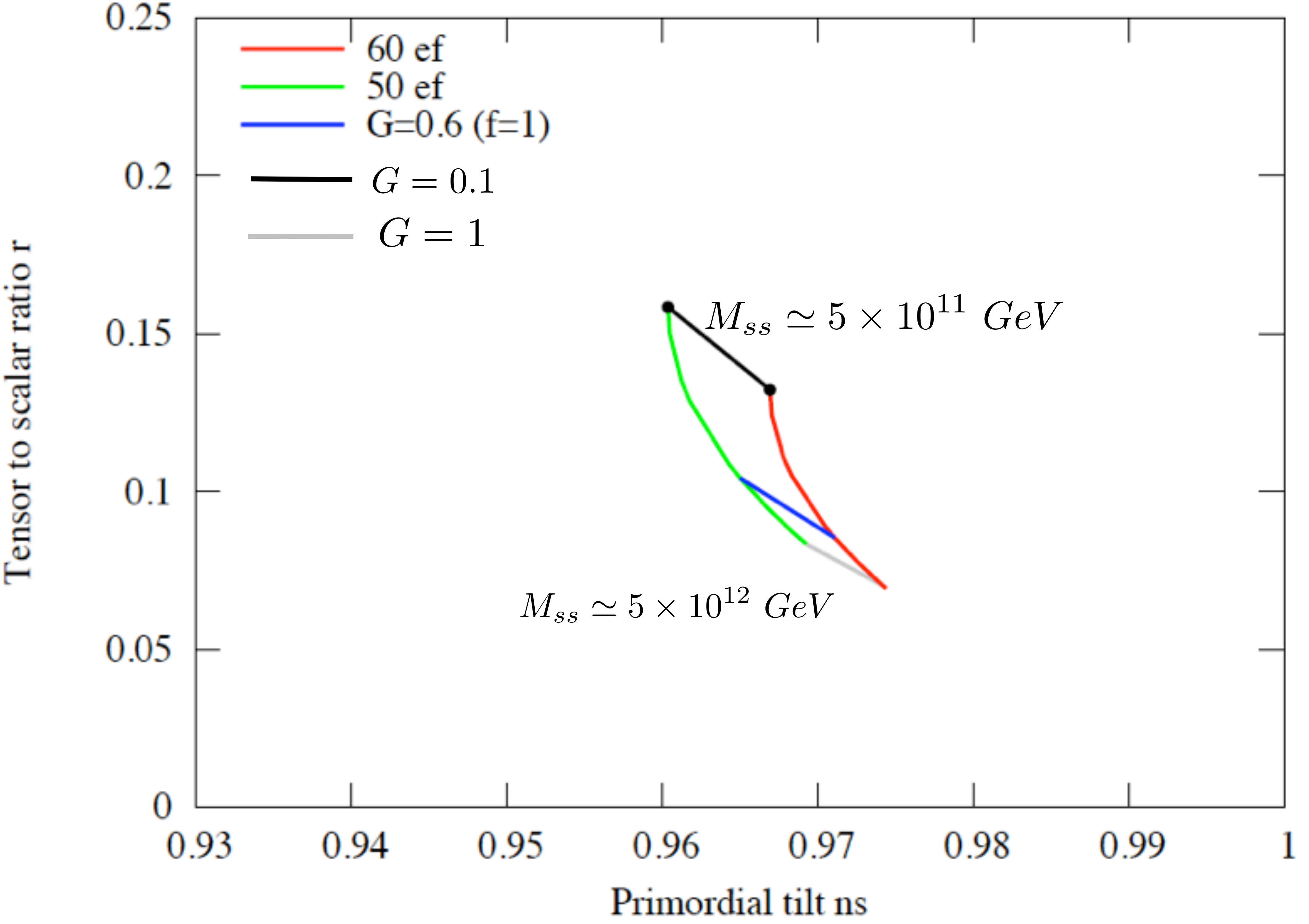
For 50 e-folds → $\varphi_0 = 12.1 m_p \rightarrow r = 0.095 \; , \; n_s = 0.967$

For $|\hat{G}| = 0.1/m_p \; , \; M_{ss} \simeq 5 \times 10^{11} \; GeV$:

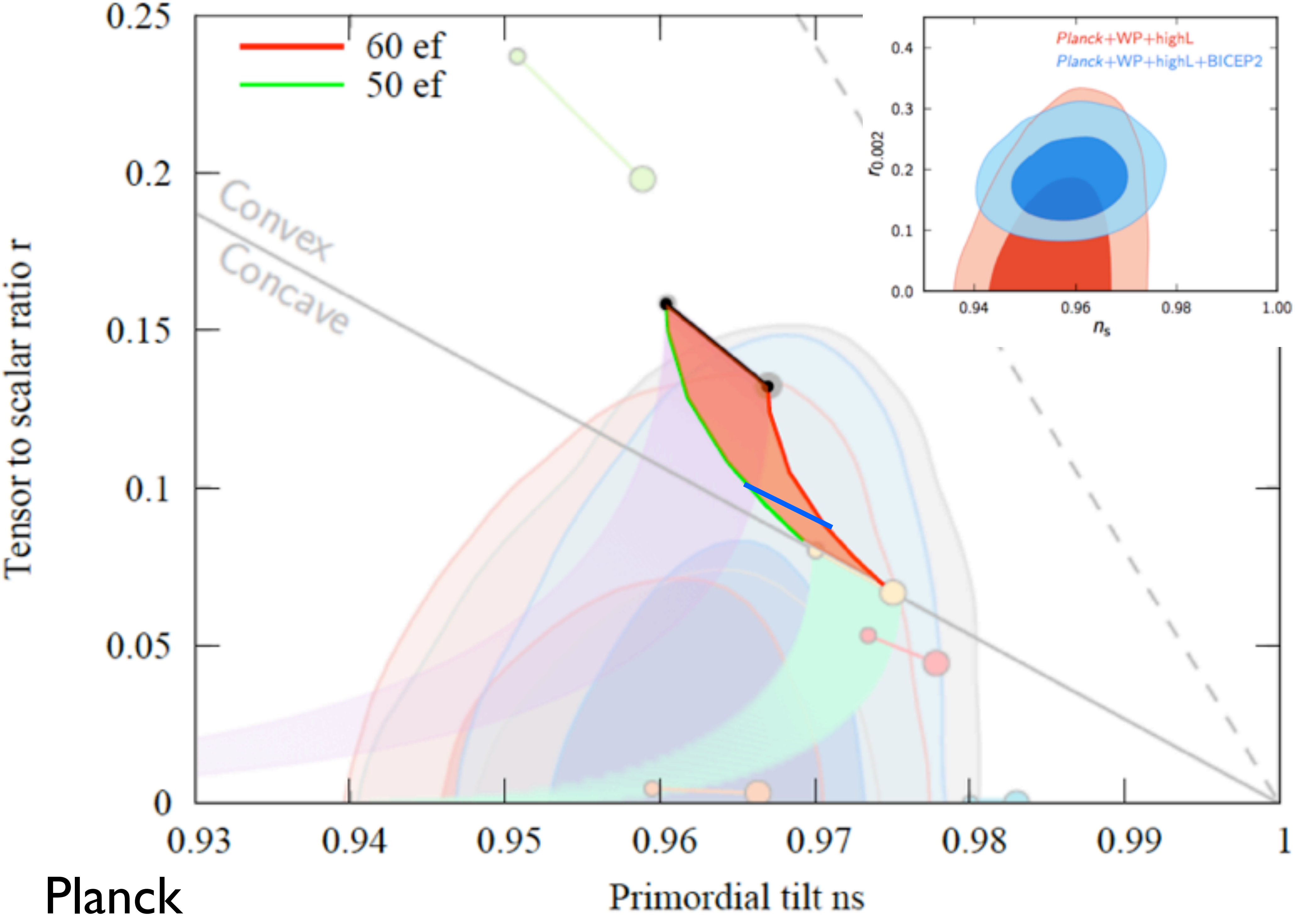
For 60 e-folds → $\varphi_0 = 15.4 m_p \rightarrow r = 0.124 \; , \; n_s = 0.967$

For 50 e-folds → $\varphi_0 = 14.1 m_p \rightarrow r = 0.150 \; , \; n_s = 0.961$

L.I.Marchesano and Valenzuela 2014, to appear



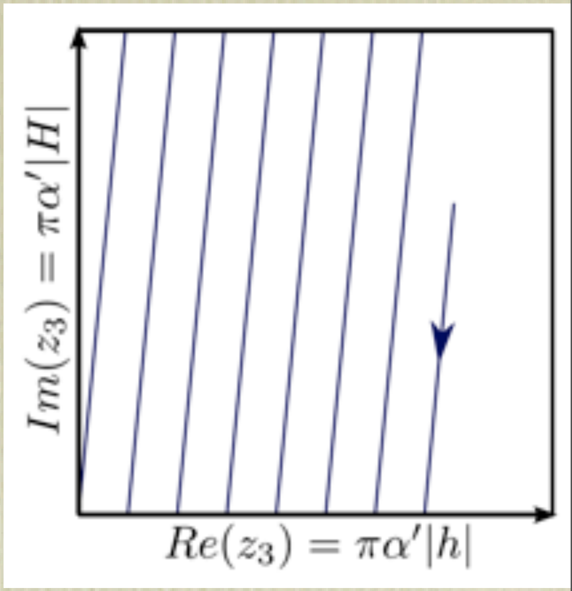
L.I.Marchesano and Valenzuela 2014, to appear



Planck

End of inflation:

$\langle\varphi\rangle = \langle H\rangle = 0\ (SU(2)\times U(1)\ restablished)$



Inflaton: $H = H_u + H_d^* \rightarrow m_H^2 \simeq \frac{g_s}{2}|G|^2$

SM Higgs: $h = H_u - H_d^* \rightarrow m_h^2 \simeq 0$

Now h is the lightest field and will play the role of the SM Higgs
(The massive Higgs states decouple at low energies)

$$V_{SM} = m_h^2 h^2 + \frac{g^2+g_1^2}{8} cos^2 2\beta|h|^4$$

$\rightarrow \lambda_{SM} \simeq 0$ at $10^{11} - 10^{13}\ GeV$ $\rightarrow m_h(EW) \simeq 126\ GeV$

Reheating:

$$T_R \simeq \sqrt{\Gamma_\varphi M_p} \simeq g\sqrt{m_\varphi M_p} \simeq 10^{11} GeV$$

(allow for leptogenesis)

A supergravity description

$$K_H \;=\; -log[(S+S^*)(U_3+U_3^*)\;-\;\frac{\alpha'}{2}(H_u+H_d^*)(H_u^*+H_d)\,]$$

$$W = W_0 + \mu H_u H_d + W_f$$

$$After\ SUSY\ breaking:\ V(H_u+H_d^*)$$

For $\mu = 0$ and only $F_T \neq 0$:

$$V \simeq \frac{|F_T|^2}{M_p}|H_u + H_d^*|^2$$

(to leading order in α')

L.Cardoso et al; Antoniadis et al '94

Structure of Kahler potential essentially dictated by

$$SL(2,Z)\ duality\ symetries:$$

$$U_3 \to \frac{1}{U_3}\ ;\ S \to S - \frac{H_u H_d}{2U_3}\ ;\ H_u \to \frac{H_u}{iU_3}\ ;\ H_d \to \frac{H_d}{iU_3}$$

$\longrightarrow$ $K_H \to K_H - log|U_3|^2$ Kahler transformation

The Kahler potential is NOT invariant, the potential IS

$$\to expect\ \alpha'\ corrections:\ V^n(H_u + H_d^*)$$

Consistent with what we obtained from DBI+CS expansion

- The $\eta - \mathrm{problem}$ and the Higgs fine-tuning problem not independent. Need inflaton mass of order $10^{13}\ \mathrm{GeV}$ to stabilize the SM potential

- Large inflaton from multiple winding around a one-cycle. Common in string theory.

- Generic: flattening of potential for large inflaton: N=1 SUGRA leading effective action may be not sufficient. On the other hand DBI+CS exact in α'

- A complete analysis would require a complete global model with all moduli fixed.

- Typical danger in monodromy inflation models are induced RR-tadpoles:

$$\int_{D7} C_4 \wedge B \wedge B \to \int_{D7} C_4 \text{ tadpole}$$

turns out to be cancelled by term from

$$\int_{D=10} C_4 \wedge H_3 \wedge F_3$$

- Generalize to other geometries (e.g cycles on Riemann surfaces)

Conclusions

- The observed Higgs mass leads to an unstable vacuum at $10^{10} - 10^{13}$ GeV

- $\mathrm{SUSY\ at}\ 10^{10} - 10^{13}\ \mathrm{GeV}$ stabilizes the potential and consistent with $m_H \simeq 126\ GeV$

- Minimality suggests to study whether the SUSY Higgs sector with SUSY broken at $M_{ss} \simeq 10^{10} - 10^{13}\ GeV$ can give rise to inflation.
- We find a massive MSSM Higgs field H may be identified with an inflaton

- Higgs/Inflaton may be realized as a D7-brane position moving over a 2-torus (also as W.L. in Type II and Heterotic)

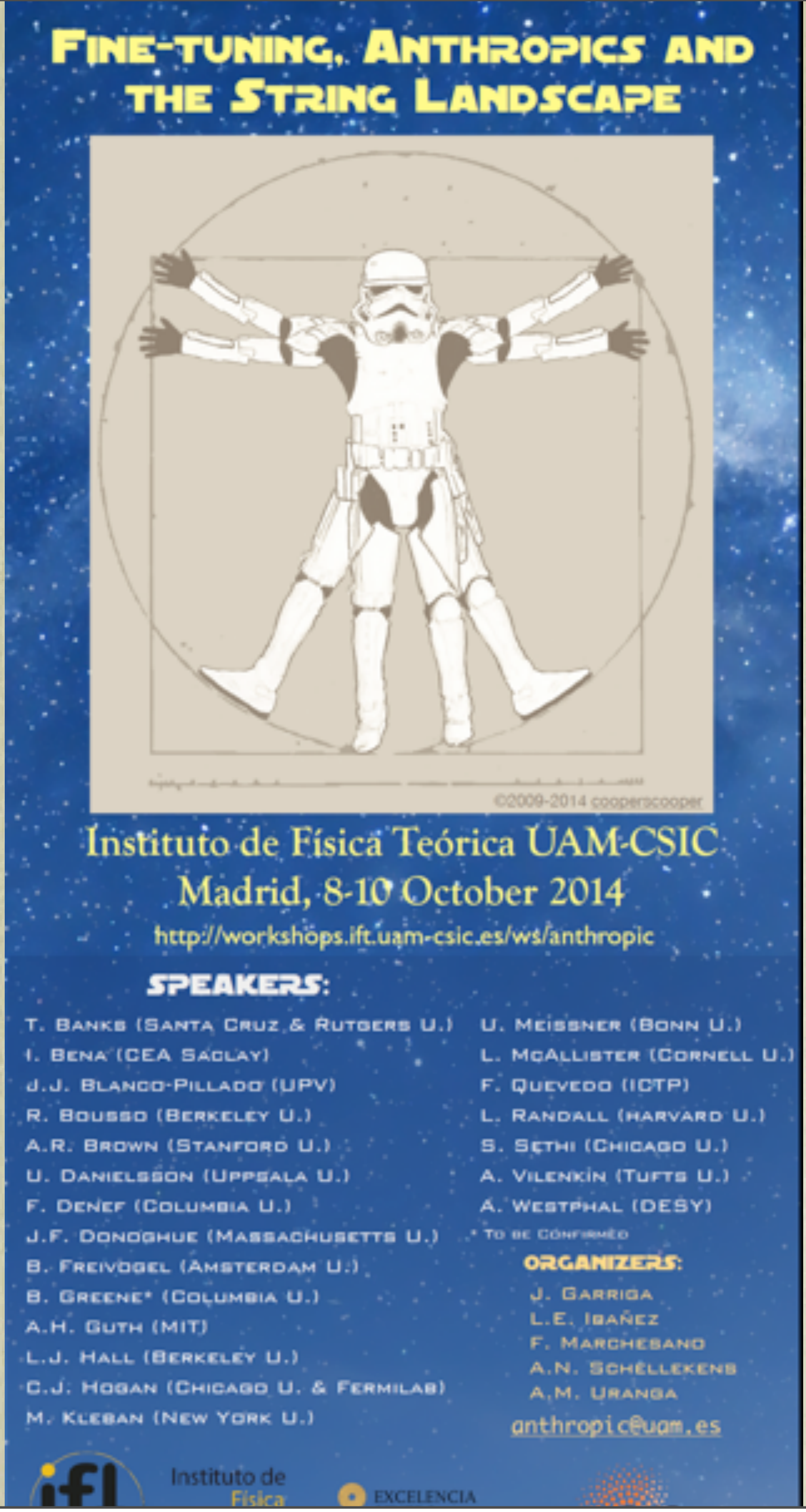
- ISD fluxes induce a potential which may be obtained from the DBI+CS action

- Leads to a variant of chaotic inflation with a leading linear behavior at large Higgs vev: Higgs-otic inflation?

- One obtains: $r \simeq 0.078 - 0.15 \ , \ n_s \simeq 0.97 - 096$ which hopefully will soon be tested!

Thank you !!

8 – 10 October 2014



Fine-tuning, Anthropics and the String Landscape

Instituto de Física Teórica UAM-CSIC
Madrid, 8-10 October 2014
http://workshops.ift.uam-csic.es/ws/anthropic

Speakers:

- T. Banks (Santa Cruz & Rutgers U.)
- I. Bena (CEA Saclay)
- J.J. Blanco-Pillado (UPV)
- R. Bousso (Berkeley U.)
- A.R. Brown (Stanford U.)
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- B. Freivogel (Amsterdam U.)
- B. Greene* (Columbia U.)
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- A. Vilenkin (Tufts U.)
- A. Westphal (DESY)

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