F-TERM HYBRID INFLATION AND SUSY BREAKING

C. PALLIS

SCHOOL OF TECHNOLOGY

ARISTOTLE UNIVERSITY OF THESSALONIKI

GREECE

Based on:
G. LAZARIDES & C.P, *Phys.Rev. D **108**, no. 9, 095055 (2023)* [arXiv:2309.04848].

OUTLINE

- INTRODUCTION
- MODEL SET-UP
- SUPER- & GAUGE-SYMMETRY BREAKING
- INFLATION ANALYSIS
- SUSY-MASS SCALE
- CONCLUSIONS

Hellenic Foundation for Research & Innovation

Corfu2024 – Workshop on the Standard Model and Beyond

30 / 08 /2024

I. INTRODUCTION

A. Motivation

1. **Attractive Features of *F-term hybrid inflation* (FHI)**

G. Dvali, Q. Shafi, and R.K. Schaefer (1994); G. Lazarides,,R.K. Schaefer, and Q. Shafi (1997)

- It is based on a **renormalizable superpotential** uniquely determined by a **gauge** $\mathbb{G}$ & a **global** *U(1) R* symmetries;
- It does not require **fine tuned parameters** and **transplanckian** inflaton values;
- It can be naturally followed by a *Grand Unified Theory* (**GUT**) **phase transition** E.g we consider the following gauge groups:

$$\mathbb{G}_{B-L} := \mathbb{G}_{\rm SM} \times U(1)_{B-L}$$
$$\mathbb{G}_{\rm LR} := SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)_{B-L}$$
$$\mathbb{G}_{5_{\rm X}} := SU(5) \times U(1)_X$$

with $\mathbb{G}_{\rm SM}$ the gauge group of *Standard Model* (**SM**).

- As regards **topological defects,** only Cosmic Strings are formated after FHI in the first case.

2. **Possible Shortcomings**

- The **original** version of FHI, which employs only *radiative corrections* (**RCs**) in the inflationary potential is considered as **strongly disfavored** by the *Planck* data due to the **large scalar spectral index.**

N. Aghanim et al. [Planck Collaboration], (2018).

- This conclusion can be **evaded**, if we take in to account soft *Supersymmetry* (**SUSY**)-breaking terms and *Supergravity* (**SUGRA**) **corrections** with appropriate magnitude.

V.N. Senoguz and Q. Shafi (2005); C. P. and Q. Shafi (2013)

II. MODEL SET-UP

A. Particle Content

- **Both** corrections above are related to the adopted **SUSY breaking sector.**
- We here present a consistent **combination** of FHI and SUSY breaking using as a junction mechanism of the (visible) *inflationary sector* (**IS**) and the *hidden sector* (**HS**) a mildly violated ***R* symmetry**.

  - The implementation of FHI requires the introduction of **three fields**: the $\mathbb{G}$ singlet **Inflaton** S and two Higgs fields: $\bar{\Phi}$ and Φ (named also **waterfall** fields).
  - To establish connection with SUSY breaking, we also employ the $\mathbb{G}$ singlet superfield Z named **Goldstino.**
  - In the Table we can see the **representations and the charges** of the various fields under the gauge and the R symmetries.

SUPER-FIELDS	REPRESENTATIONS UNDER $\mathbb{G}$: $\mathbb{G}_{B-L}$	$\mathbb{G}_{LR}$	$\mathbb{G}_{5_X}$	R CHARGE
HIGGS SUPERFIELDS				
Φ	$(\mathbf{1},\mathbf{1},0,2)$	$(\mathbf{1},\mathbf{1},\mathbf{2},1)$	$(\mathbf{10},1)$	0
$\bar{\Phi}$	$(\mathbf{1},\mathbf{1},0,-2)$	$(\mathbf{1},\mathbf{1},\bar{\mathbf{2}},-1)$	$(\overline{\mathbf{10}},-1)$	0
S	$(\mathbf{1},\mathbf{1},0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	2
GOLDSTINO SUPERFIELDS				
Z	$(\mathbf{1},\mathbf{1},0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	$2/\nu$

B. Superpotential

The superpotential of the model has the form $W = W_{\rm I} + W_{\rm H} + W_{\rm GH} + W_{\rm Y},$ Where

- $W_{\rm I} = \kappa S\left(\bar\Phi\Phi - M^2\right)$ is related to **IS with** κ and M real input parameters **constrained** by FHI;
- $W_{\rm H} = m m_{\rm P}^2 (Z/m_{\rm P})^{\nu}$ is devoted to the **HS**. Here m is a **mass scale** related to SUSY breaking.

Also v is an exponent which may, in principle, acquires **any real value**, if $W_{\rm H}$ is considered as an **effective W** valid close to the non-zero <Z>. We take $v>0$ with $3/4 < \nu < 1.$

- $W_{\rm GH} = -\lambda m_{\rm P} (Z/m_{\rm P})^{\nu} \bar\Phi\Phi$ is an **unavoidable mixing term** of the two sectors which however plays an important role in the resolution of **DE problem**.
- $W_{\rm Y}$ contains the usual **trilinear terms** with Yukawa couplings (with Dirac neutrino masses)

$$W_{\rm Y} = h_{ijD} d_i^c Q_j H_d + h_{ijU} u_i^c Q_j H_u + h_{ijE} e_i^c L_j H_d + h_{ij\nu} \nu_i^c L_j H_u .$$

Written in terms of the well-known **Superfields of MSSM**.

- We select conveniently the R charges to **avoid** the presence in W of the **bilinear (*μ*) term** of the electroweak Higgs Superfields which **takes the forms**:

$$H_{\rm B} = \begin{cases} H_u H_d & \text{for } \mathbb{G} = \mathbb{G}_{B-L}, \\ h\!\!\!h^2 & \text{for } \mathbb{G} = \mathbb{G}_{\rm LR}, \\ \bar{\mathbf{5}}_h \mathbf{5}_h & \text{for } \mathbb{G} = \mathbb{G}_{5_{\rm X}}. \end{cases}$$

SUPER-FIELDS	REPRESENTATIONS UNDER $\mathbb{G}$: $\mathbb{G}_{B-L}$	$\mathbb{G}_{\rm LR}$	$\mathbb{G}_{5_{\rm X}}$	R CHARGE
H_u	$(\mathbf{1},\mathbf{2},1/2,0)$			2
H_d	$(\mathbf{1},\mathbf{2},-1/2,0)$			2
$h\!\!\!h$		$(\mathbf{1},\mathbf{2},\mathbf{2},0)$		2
$\mathbf{5}_h$			$(\mathbf{5},2)$	2
$\bar{\mathbf{5}}_h$			$(\bar{\mathbf{5}},-2)$	2

C. Kaelher Potential

- The Kaelher potential inclues the **terms**
- From which **the last** one is devoted to **MSSM** Matter and Higgs **superfields**.
- **Canonical kinetic** terms are also adopted for the fields involved in **FHI**, i.e.,

$$K = K_{\rm I} + K_{\rm H} + K_{\mu} + |Y_\alpha|^2,$$

$$Y_\alpha = Q, L, d^c, u^c, e^c, N^c, H_d \text{ and } H_u,$$

$$K_{\rm I} = |S|^2 + |\Phi|^2 + |\bar\Phi|^2$$

- For the **Goldstino** superfield we employ the following part of *K*

$$K_{\rm H} = N m_{\rm P}^2 \ln\left(1 + \frac{|Z|^2 - k^2 Z_-^4/m_{\rm P}^2}{N m_{\rm P}^2}\right),$$

With $Z_\pm = Z \pm Z^*$.

and *k ~ 0.1* **violates mildly** *R* symmetry assisting us to obtain **mass** for the *R* axion.

- In the **absence** of IS, $<V_{\rm H}(|Z|)>=0$ **without tuning** may be achieved if we impose **the condition**

$$N = \frac{4\nu^2}{3-4\nu} \text{ with } \frac{3}{4} < \nu < \frac{3}{2} \text{ for } N<0 \text{ and } \nu < \frac{3}{4} \text{ for } N>0.$$

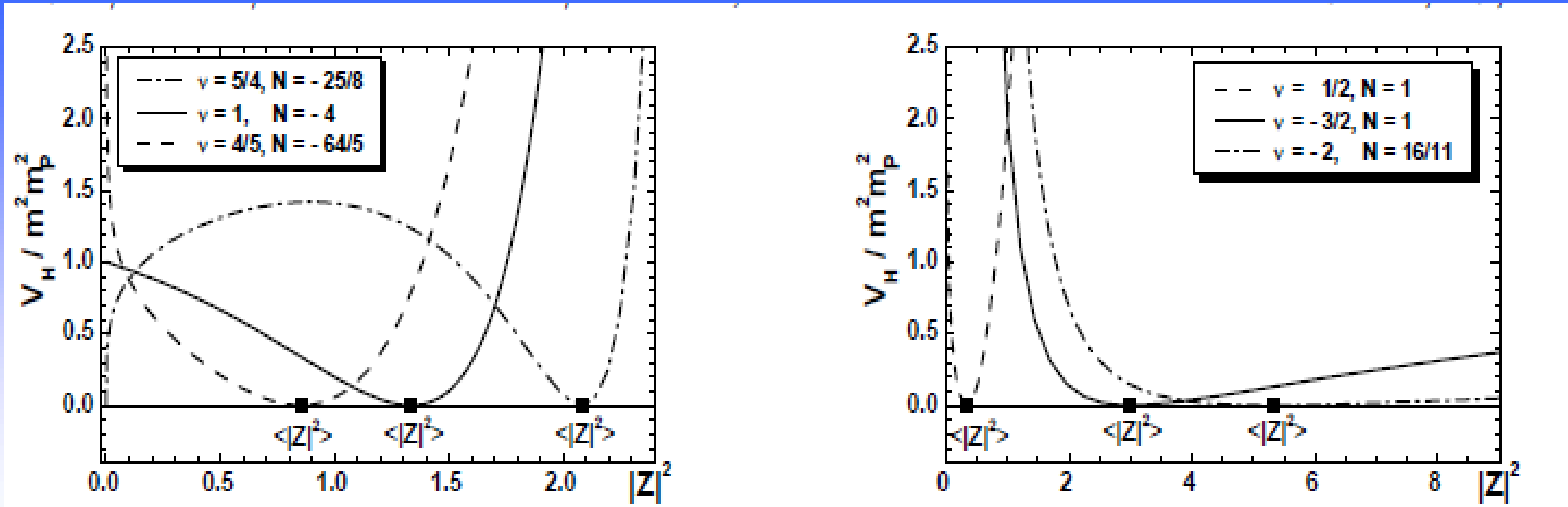
- Under this condition, the **HS SUGRA Potential,** $V_{\rm H}(|Z|)$, includes a trinomial which is **perfect square**

$$V_{\rm H} = \left(\frac{m m_{\rm P}}{4\nu}\right)^2 \left(1 + \frac{|Z|^2}{N m_{\rm P}}\right)^N \left(\frac{|Z|}{m_{\rm P}}\right)^{2(\nu-1)} \left(3\frac{|Z|^2}{m_{\rm P}^2} - 4\nu^2\right)^2.$$

and therefore we obtain a technically natural **Minkowski vacuum for** $<|Z|> = 2\nu m_P/3^{1/2}$.

- The shape of $V_{\rm H}(|Z|)$, for some **``magic pairs“** of (v, N) is shown in the plots.

C.P (2018,2020)



- Here we focus on the values $3/4 < \nu < 1$ and so $K_{\rm H}$ parameterizes the

hyperbolic Kaehler manifold $(SU(1,1)/U(1))_Z$ In the limit k->0.

- K_μ generates the ***μ* term** of MSSM adapting conveniently the **Giudice-Masiero** mechanism

$$K_\mu = \lambda_\mu \left(Z^{*2\nu}/m_{\rm P}^{2\nu}\right) H_{\rm B} + {\rm h.c.},$$

- The magnitudes of ***μ* parameter** and of the common soft **SUSY-breaking mass** $\widetilde{m}$ are

$$|\mu| = \lambda_\mu \left(\frac{4\nu^2}{3}\right)^\nu (5-4\nu) m_{3/2} \ \text{ and } \ \widetilde{m} = m_{3/2} \simeq 2^\nu 3^{-\nu/2} |\nu|^\nu m\omega^{N/2}.$$

- The total *K* enjoys the **enhanced symmetry** $\prod_\alpha U(1)_{Y^\alpha} \times U(1)_S \times (SU(1,1)/U(1))_Z$

In the **moduli space**, which assists us to **exclude** possible mixing terms allowed by the *R* symmetry.

D. SUGRA Potential, V_{SUGRA}

- With given W and K, we can derive V_{SUGRA} which includes contributions from **F and D terms.**
- The part of V_{SUGRA} due to **F terms** is $V_{\rm F} = e^{K/m_{\rm P}^2}\left(K^{\alpha\bar\beta}D_\alpha W D_{\bar\beta}W^* - 3|W|^2/m_{\rm P}^2\right),$

- Where the **Kaelher covariant derivative** is $D_\alpha W = \partial_{X^\alpha}W + W\partial_{X^\alpha}K/m_{\rm P}^2$

With $X^\alpha = S, Z, \Phi, \bar\Phi$

- The **Kaehler metric** $K_{\alpha\bar\beta} = \partial_{X^\alpha}\partial_{X^{*\bar\beta}}K$ and its **inverse** is defined as $K^{\bar\beta\alpha}K_{\alpha\bar\gamma} = \delta^{\bar\beta}_{\bar\gamma}$

- Since we have **no mixing** between the fields in *K*, we obtain a **diagonal metric** and the form of $V_{\rm F}$ is

$$V_{\rm F} = e^{\frac{K}{m_{\rm P}^2}}\left(|v_S|^2 + |v_\Phi|^2 + |v_{\bar\Phi}|^2 + K^{-1}_{ZZ^*}|v_Z|^2 - 3|v_W|^2\right),$$

where the contributions are obtained by **expanding** V_F .

G. Lazarides and C.Pallis (2023)

- The part of V_{SUGRA} due to $\mathbb{G}$ **D terms** with the matter superfields placed at zero is

$$V_{\rm D} = \frac{g^2}{2}\left(|\Phi|^2 - |\bar\Phi|^2\right)^2$$

- It vanishes along the **D-flat direction** $|\bar\Phi| = |\Phi|$ which is used as **inflationary trajectory** including the **vacuum of the theory.**

II. SUSY and $\mathbb{G}$ BREAKING

- We can verify numerically that $V_{\rm F}$ is minimized at $\mathbb{G}$ **-- breaking vacuum** $|\langle\Phi\rangle| = |\langle\bar\Phi\rangle| = M$
- If we **parameterize** the two remaining $\mathbb{G}$ **- singlet** superfields according to the descriptions

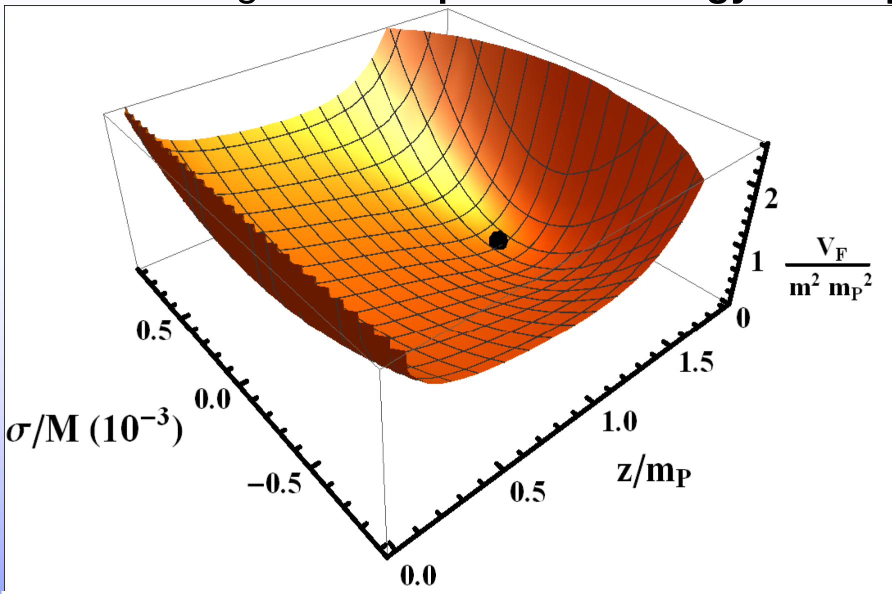
$$Z = (z + i\theta)/\sqrt{2} \text{ and } S = \sigma\, e^{i\theta_S/m_{\rm P}}/\sqrt{2}$$

We find that their *vacuum expectation values* (**vevs**) lie at the directions:

$$\langle z\rangle = 2\sqrt{2/3}|\nu|m_{\rm P} \qquad \langle\sigma\rangle \simeq 0 \qquad \langle\theta\rangle = 0 \text{ and } \langle\theta_S/m_{\rm P}\rangle = \pi.$$

The resulting constant **potential energy density** is

$$\langle V_{\rm F}\rangle = \left(\frac{16\nu^4}{9}\right)^{\nu}\left(\frac{\lambda M^2 - m m_{\rm P}}{\kappa m_{\rm P}^2}\right)^2 \omega^N \times \left(\lambda(M^2 + m_{\rm P}^2) - m m_{\rm P}\right)^2,$$



With $\omega = e^{\langle K_{\rm H}\rangle/N m_{\rm P}^2} \simeq 2(3-2\nu)/3,$ **Tuning**

$$\lambda \sim m/m_{\rm P} \simeq 10^{-12}$$

we can obtain a post-inflationary **de Sitter vacuum** which corresponds to the current **DE** energy density.

- For $\mathbb{G} = \mathbb{G}_{\rm LR},$ *v*=7/8 & *k*=0.1 in K we obtain

Model Parameters				
$\mathbb{G}$	$\kappa/10^{-4}$	$M/{\rm YeV}$	$m/{\rm PeV}$	$\alpha_s/{\rm TeV}$
$\mathbb{G}_{\rm LR}$	5	1.9	1.15	6.7

Particle Mass Spectrum				
$\mathbb{G}$	$m_{\rm I}/{\rm ZeV}$	$m_z/{\rm PeV}$	$m_\theta/{\rm PeV}$	$m_{3/2}/{\rm PeV}$
$\mathbb{G}_{\rm LR}$	2.4	2.9	1.8	2

III. INFLATION ANALYSIS

In the **global** SUSY, FHI takes place for *S>> M* along a F- and D- **flat direction** of the SUSY potential

.

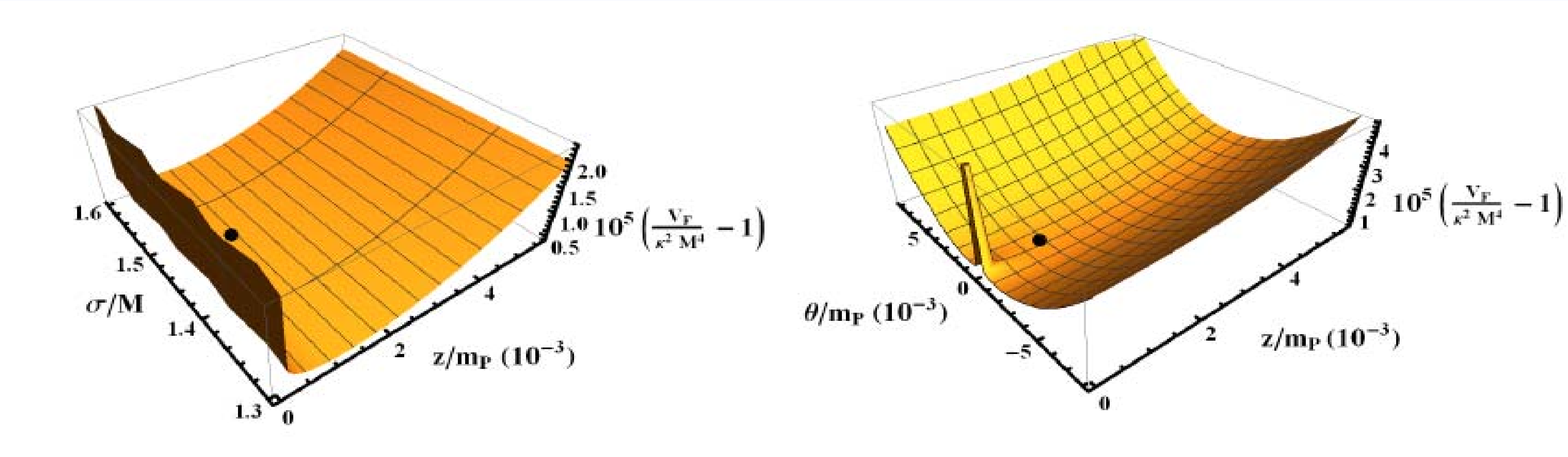
$$\bar\Phi = \Phi = 0,$$ where $$V_{\rm SUSY}\left(\Phi = 0\right) \equiv V_{\rm I0} = \kappa^2 M^4$$

A. Goldstino Stabilization

- In the **present context**, the expression of $V_{\rm F}$ along the **inflationary trajectory** above is
- $$V_{\rm F}(z) = e^{\frac{\kappa_{\rm H}}{m_{\rm P}^2}}\left(\kappa^2 M^4 + m^2 \frac{z^{2(\nu-1)}(8\nu^2 m_{\rm P}^2 - 3z^2)^2}{2^{5+\nu}\nu^2 m_{\rm P}^{2\nu}}\right)$$ With the v-N condition imposed
- Minimizing it for *v<1* we find that *z & θ are* **well stabilized** during FHI to the following values:

$\langle\theta\rangle_I = 0$ & $$\langle z\rangle_{\rm I} \simeq \left(\sqrt{3}\times 2^{\nu/2-1} H_{\rm I}/m\nu\sqrt{1-\nu}\right)^{1/(\nu-2)} m_{\rm P},$$ ~ 10^{-3} m_P

- The stabilization of both modes -- *R* **saxion** (*z*) and **axion** (*θ*) -- is verified by the plots below



B. Inflationary Potential

▪ The low but non-vanishing value $\langle z\rangle_{\rm I}$ gives rise to **soft SUSY-breaking terms and SUGRA corrections** to the **inflationary potential** which may be cast in the form: $V_{\rm I} \simeq V_{\rm I0}\left(1 + C_{\rm RC} + C_{\rm SSB} + C_{\rm SUGRA}\right),$

where the **individual contributions** are specified as follows:

- $C_{\rm SSB} = m_{{\rm I}3/2}^2\sigma^2/2V_{\rm I0} - {\rm a}_S\,\sigma/\sqrt{2V_{\rm I0}}$ is the contribution from the **soft SUSY-breaking** effects,

with **a adpole parameter** $${\rm a}_S = 2^{1-\nu/2} m \frac{\langle z\rangle_{\rm I}^\nu}{m_{\rm P}^\nu}\left(1 + \frac{\langle z\rangle_{\rm I}^2}{2N m_{\rm P}^2}\right)\left(2 - \nu - \frac{3\langle z\rangle_{\rm I}^2}{8\nu m_{\rm P}^2}\right)$$

As we see, **observations constrain** $a_S \sim$ TeV, and since $\langle z\rangle_I/m_P \sim 10^{-3}$ **we obtain** $m = m_{3/2} = \widetilde{m} \sim 1$ PeV.

- $C_{\rm SUGRA} = c_{2\nu}\frac{\sigma^2}{2m_{\rm P}^2} + c_{4\nu}\frac{\sigma^4}{4m_{\rm P}^4},$ is the pure **SUGRA correction** where the relevant coefficients are

$$c_{2\nu} = \langle z\rangle_{\rm I}^2/2m_{\rm P}^2 \ \text{ and } \ c_{4\nu} = (1 + \langle z\rangle_{\rm I}^2/m_{\rm P}^2)/2.$$

- $$C_{\rm RC} = \frac{{\rm N}_{\mathbb{G}}\kappa^2}{128\pi^2}\left(8\ln\frac{\kappa^2M^2}{Q^2} + f_{\rm RC}\left(\frac{\sigma}{M}\right)\right) \ \text{ with } \ {\rm N}_{\mathbb{G}} = \begin{cases} 1 & \text{for } \mathbb{G} = \mathbb{G}_{B-L}, \\ 2 & \text{for } \mathbb{G} = \mathbb{G}_{\rm LR}, \\ 10 & \text{for } \mathbb{G} = \mathbb{G}_{5_{\rm X}}. \end{cases}$$

Is the contribution from **1-loop RCs** includes the function

$$f_{\rm RC}(x) = 8x^2\tanh^{-1}\left(2/x^2\right) - 4(\ln 4 - x^4\ln x) + (4 + x^4)\ln(x^4 - 4)$$

▪ For $x<2^{1/2}$, one effective mass of the particle spectrum becomes **negative,** causing a destabilization of the waterfall fields from 0 and triggering, thereby, the $\mathbb{G}$ **phase transition.**

C. Inflationary Requirements

- The **number of e-foldings** have to be enough to resolve the problems of the Standard Big Bang, i.e.,

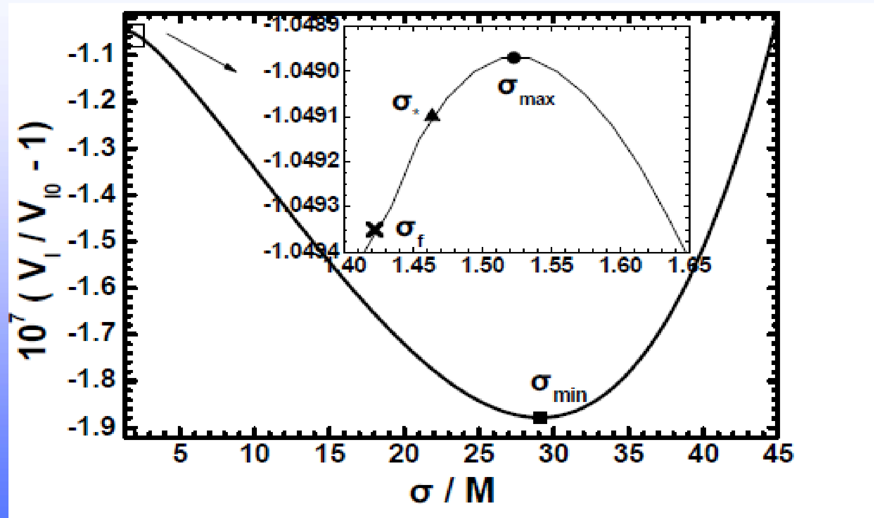
$$N_{\rm I\star} = \int_{\sigma_{\rm f}}^{\sigma_\star} \frac{d\sigma}{m_{\rm P}^2}\,\frac{V_{\rm I}}{V_{\rm I}'} \simeq 19.4 + \frac{2}{3}\ln\frac{V_{\rm I0}^{1/4}}{1~{\rm GeV}} + \frac{1}{3}\ln\frac{T_{\rm rh}}{1~{\rm GeV}}$$

▪ The amplitude A_s of the **power spectrum** of the curvature perturbation generated by σ during FHI and ıs calculated at k_*=0.05/Mpc as a function of σ_* must be consistent with the data, i.e.,

$$\sqrt{A_{\rm s}} = \frac{1}{2\sqrt{3}\,\pi m_{\rm P}^3}\,\frac{V_{\rm I}^{3/2}(\sigma_\star)}{|V_{\rm I}'(\sigma_\star)|} \simeq 4.588\times 10^{-5}$$

The **scalar spectral index** n_s, its **running**, α_s and the **scalar-to-tensor** ratio *r* must be n agreement with *Planck* data, i. e., $n_{\rm s} = 0.967 \pm 0.0074$ and $r \leq 0.032$, With $|\alpha_s|$<<0.01.

▪ To obtain these results for the latter quantities, we construct a **hilltop** inflationary path, i.e., $V_I(\sigma)$ **develops**



▪ A **maximal** value σ_{max} =1.52 *M;*

▪ A **minimal** value σ_{min} =29.1*M;*

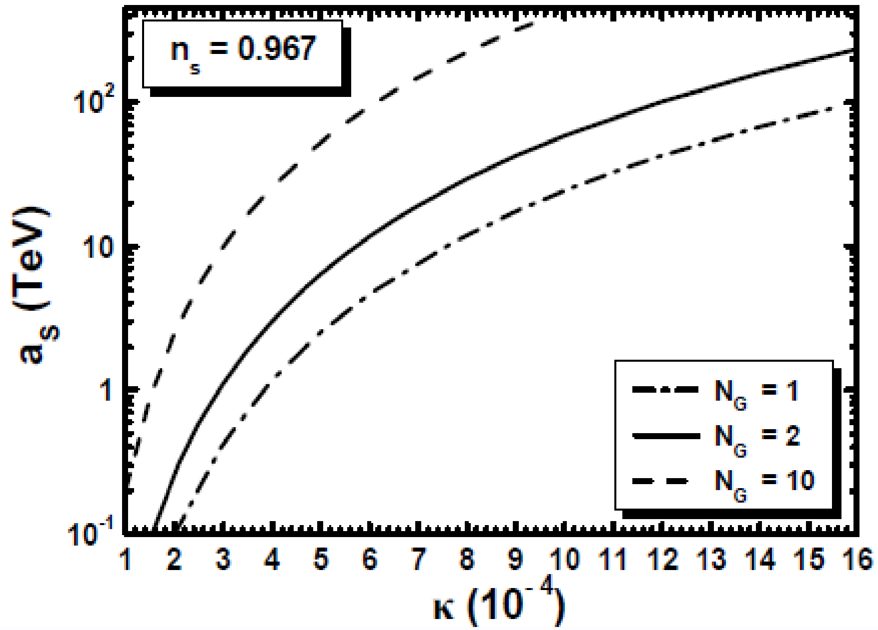
▪ At the **end of FHI** we have σ_c =1.41421 *M*.

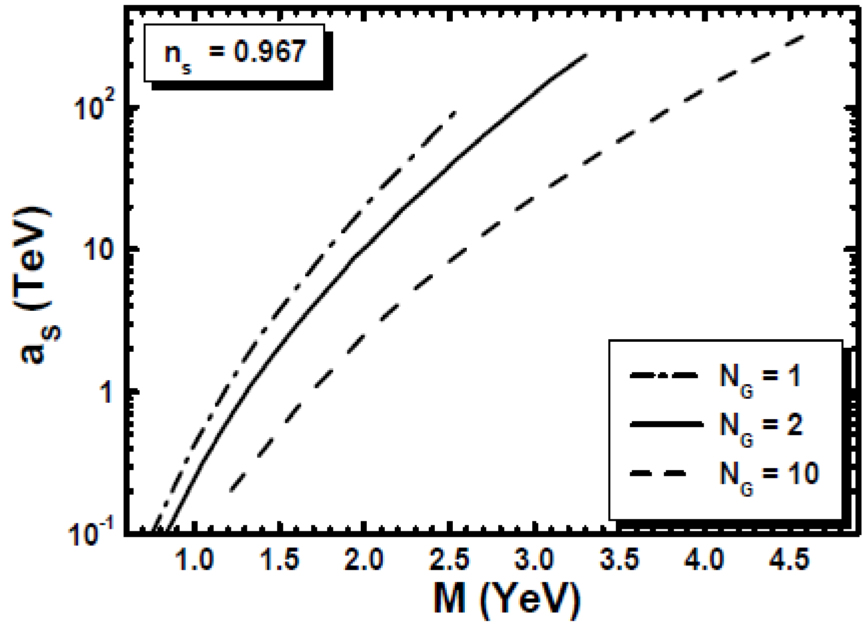
▪ At the horizon crossing of *k*$_*$*=0.05/Mpc*

$\sigma_c < \sigma_* = 1.4637\ M < \sigma_{max}$;

▪ These arrangements signal **some tuning** in the initial conditions.

D. Results





- **Imposing the constraints** above, we determine the allowed contours in the κ-a_S and M-a_S plane for the **central** n_s value and various N_G (or $\mathbb{G}$).
- We observe that **increasing** N_G, M and $\underline{a_S}$ **increase** with M~10^{15} GeV and a_S~10 TeV. Namely,

$$0.07 \lesssim M/\mathrm{YeV} \lesssim 2.56 \ \text{ and } \ 0.1 \lesssim a_S/\mathrm{TeV} \lesssim 100 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{B-L}$$
$$0.82 \lesssim M/\mathrm{YeV} \lesssim 3.7 \ \text{ and } \ 0.09 \lesssim a_S/\mathrm{TeV} \lesssim 234 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{\mathrm{LR}}$$
$$1.22 \lesssim M/\mathrm{YeV} \lesssim 4.77 \ \text{ and } \ 0.2 \lesssim a_S/\mathrm{TeV} \lesssim 460 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{5_X}.$$

- We also obtain **$|\alpha_s|$ ~ 10^{-4} and r ~ 10^{-12}** throughout our investigation.
- The required **tuning** in the initial conditions is estimated to be (0.5-20)% **increasing** with N_G .

E. Cosmic Strings (CSs)

- If $\mathbb{G} = \mathbb{G}_{B-L}$, *B-L* CSs are formatted for $\sigma<2^{1/2} M$ due to the *B-L* **phase transition**.
- The **dimensionless tension** $G\mu_{cs}$ of the *B-L* CSs mainly depends on *M* via the relation

$$G\mu_{\rm cs} \simeq \frac{1}{2}\left(\frac{M}{m_{\rm P}}\right)^2 \epsilon_{\rm cs}(r_{\rm cs}) \text{ with } \epsilon_{\rm cs}(r_{\rm cs}) = \frac{2.4}{\ln(2/r_{\rm cs})} \text{ and } r_{\rm cs} = \kappa^2/8g^2 \leq 10^{-2}.$$

- For the **allowed *M* values** from the FHI stage we find: $5.9 \lesssim G\mu_{\rm cs}/10^{-9} \lesssim 83$
- If the CSs are **stable**, then these are:

1. **Acceptable** from *Planck* data which dictates $G\mu_{\rm cs} \lesssim 2.4 \times 10^{-7}$ at 95% c.l.

This is related to the CS contribution to the observed anisotropies of the Cosmic Microwave Background.

2. Completely **excluded** by the recent PTA bound: $G\mu_{\rm cs} \lesssim 2 \times 10^{-10}$ at 95% c.l.

- If the **CSs are metastable,** due to the embedding of $\mathbb{G}_{B-L}$ into a larger group, whose breaking

leads to magnetic monopoles **(MM)**, we can explain the recent **NANOGrav 15 yr** data, which requires $G\mu_{cs}$ to be confined at the margin

$10^{-8} \lesssim G\mu_{\rm cs} \lesssim 2 \times 10^{-7}$ for $8.2 \gtrsim \sqrt{r_{\rm ms}} \gtrsim 7.9$ for $M \gtrsim 9 \times 10^{14}$ GeV

The **metastability factor** r_{ms} (i.e., the ratio of the MM mass squared to μ_{cs}) is used as a **free parameter.**

It may give information for the **first step** of symmetry breaking E.g. $SO(10) \xrightarrow[\rm MM]{\langle 45\rangle} \mathbb{G}_{B-L} \xrightarrow[\rm CSs]{\langle 16\rangle, \langle\overline{16}\rangle} \mathbb{G}_{\rm SM}$

E. Post-Inflationary Evolution

- Soon after FHI, *z* and IS enter into an **oscillatory phase** about their minima and eventually decay **reheating** the Universe. Since $\langle z\rangle \sim m_{\rm P}$ the energy densities of *z*, ρ_z, and the that of the Universe, ρ_t,

$$\rho_{z\rm I} \sim m_z^2 \langle z\rangle^2 \ \text{and}\ \rho_{\rm t} = 3m_{\rm P}^2 H^2 \simeq 3m_{\rm P}^2 m_z^2$$

Are **equal**. Therefore, we expect that *z* will **dominate** and reheat the universe at a **low temeperature**

$$T_{\rm rh} = \left(72/5\pi^2 g_{\rm rh*}\right)^{1/4} \Gamma_{\delta z}^{1/2} m_{\rm P}^{1/2},$$ Where $\Gamma_{\delta z} \sim \lambda_\mu^2 m_z^3/m_{\rm P}^2$

the decay width $\Gamma_{\delta z}$ is dominated by the decay of *z* into *electroweak* higgs fields H_u & H_d via K_μ.

- To avoid any disturbance of the successful predictions of *Big Bang Nucleosynthesis* (**BBN**) we require

$$T_{\rm rh} \geq 4.1\ \text{MeV}\ \ \text{for}\ \ \text{B}_{\rm h}=1\ \ \text{and}\ \ T_{\rm rh} \geq 2.1\ \text{MeV}\ \ \text{for}\ \ \text{B}_{\rm h}=10^{-3}.$$

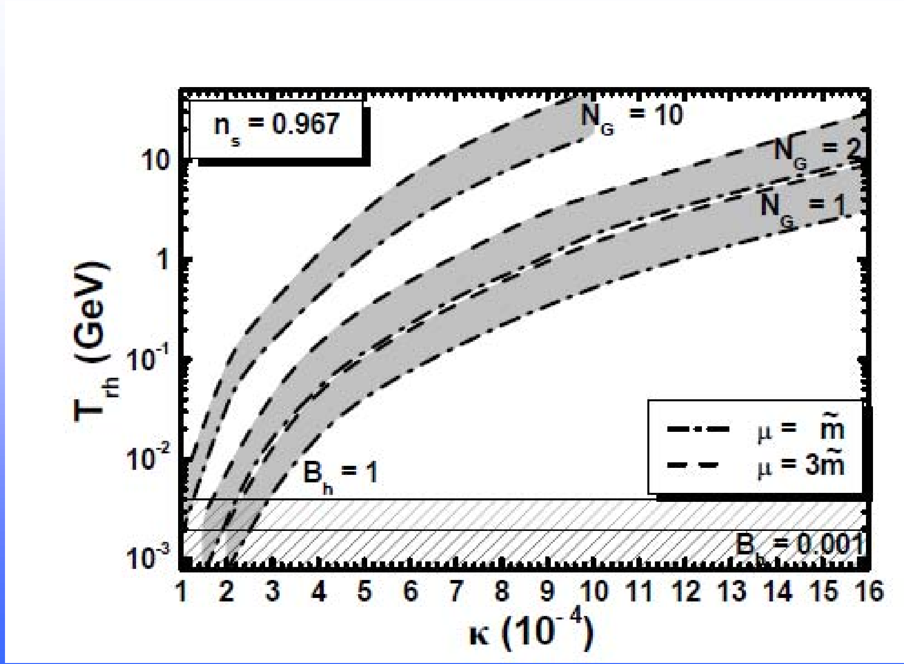
Where B_h is the hadronic branching ratio.

- For *v=7/8* and varying *μ* in the range (1-3)$m_{3/2}$ we find

$$T_{\rm rh}^{\max} \simeq \begin{cases} 14\ \text{GeV} & \text{for}\ \mathbb{G}=\mathbb{G}_{B-L}, \\ 33\ \text{GeV} & \text{for}\ \mathbb{G}=\mathbb{G}_{\rm LR}, \\ 49\ \text{GeV} & \text{for}\ \mathbb{G}=\mathbb{G}_{5_{\rm X}}. \end{cases}$$

In order to avoid **non-thermal overproduction** of **LSPs**, we kinematically block the decay of *z* to $\widetilde{G}$ by demanding $m_z<2m_{3/2}$, i.e., *v>3/4* since

$$m_z \simeq \frac{3\omega}{2\nu} m_{3/2}$$ with $$\omega = 2(3-2\nu)/3$$

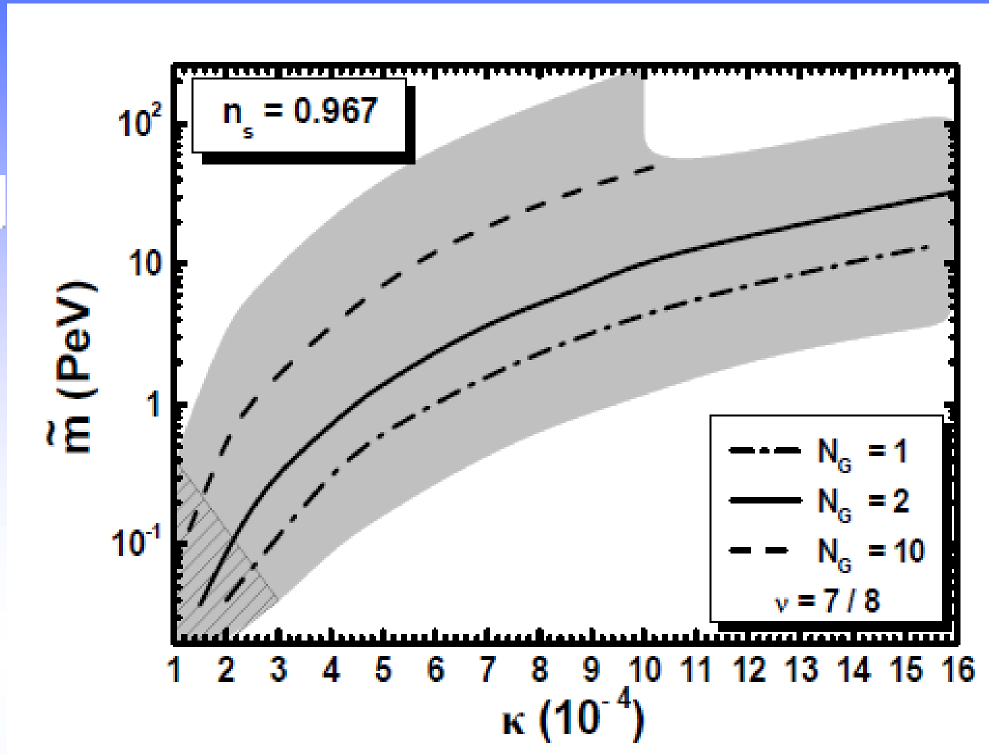


IV. SUSY MASS SCALE

- **Allowing *v* and *μ* vary** within their possible respective margins (0.75-1) and (1-3) $\widetilde{m}$ we obtain the gray **shaded region** in the plane $\kappa - \widetilde{m}$. The lines are obtained for v=7/8 and various $\mathbb{G}$
- Therefore the SUSY mass scale lies at

$$0.34 \lesssim \widetilde{m}/\mathrm{PeV} \lesssim 13.6 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{B-L},$$
$$0.21 \lesssim \widetilde{m}/\mathrm{PeV} \lesssim 32.9 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{\rm LR},$$
$$0.58 \lesssim \widetilde{m}/\mathrm{PeV} \lesssim 46.8 \ \text{ for } \ \mathbb{G} = \mathbb{G}_{5_{\rm X}}.$$

- These are consistent with the **Higgs boson mass** discovered in LHC within the **high-scale SUSY**.



V. CONCLUSIONS

- We analyzed the realization of **FHI and SUSY breaking** in the context of a model which is consistent with an **approximate *R* symmetry**. The model offers the following interesting **achievements**:

1. Observationally **acceptable** FHI adjusting the **tadpole parameter** and the $\mathbb{G}$ **breaking scale**;
2. A **prediction** of the **SUSY-mass scale** which turns out to be of the order of **PeV**;
3. Generation of the ***μ* term** of MSSM with $|\mu| \sim m_{3/2}$;
4. An interpretation of the **DE problem** without extensive tuning.
5. Compatibility of T_{rh} with **BBN**;
6. An explaination of the **NANOGrav 15 years** data via the decay of metastable *B-L* CSs if $\mathbb{G} = \mathbb{G}_{B-L}$.