F-TERM HYBRID INFLATION, METASTABLE COSMIC STRINGS & LOW REHEATING

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OUTLINE

- OBSERVATIONS, COSMIC DEFECTS & INFLATION
- MODELING FHI & SUSY BREAKING
- INFLATION & POST-INFLATION
- METASTABLE COSMIC STRINGS
- CONCLUSIONS

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I. OBSERVATIONS, COSMIC DEFECTS & INFLATION

A. *Pulsar Timing Array* (PTA) Data (2024) and Metastable *Cosmic Strings* (CSs)

- The discovery of a ***gravitational wave*** (**GW**) background around the nanohertz frequencies announced from several PTA experiments most notably the ***NANOGrav 15-years results*** (**NG15**) provide a novel tool in exploring the structure of **early universe**.
- The observations can be interpreted by **gravitational radiation** emitted by topologically **unstable** superheavy **CSs** which may be formed during the *spontaneous symmetry breaking* (**SSB**) chains of *Grand Unified Theories* (**GUTs**) down to the *Standard Model* (**SM**) gauge group, $\mathbb{G}_{\rm SM}$
- Of particular attention is the **metastable** CSs which arise from a sequence of SSB of the form

$$\mathbb{G} \xrightarrow[\text{MM}]{\langle \text{adj}(\mathbb{G})\rangle} \mathbb{G}_{\rm int} \times U(1) \xrightarrow[\text{CSs}]{} \mathbb{G}_{\rm f} \;\text{ with }\; \pi_1(\mathbb{G}/\mathbb{G}_{\rm int}) = I \;\text{ and }\; \pi_1(\mathbb{G}/\mathbb{G}_{\rm f}) = I.$$

Where **MM** stands for *Magnetic Monopoles,* **adj** for adjoint rep & π_n for homotopy class of order n.

W. Buchmuller, V. Domcke and K. Schmitz

- The **simplest way** to implement such a SSB in a realistic particle model is to **identify**

$$\mathbb{G} = SU(2)_{\rm R} \times U(1)_{B-L} \;\text{ and }\; \mathbb{G}_{\rm int} \times U(1) = U(1)_{\rm R} \times U(1)_{B-L}$$

- If we embed $\mathbb{G}$ in the **Left-Right** gauge group $\mathbb{G}_{\rm LR} := SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)_{B-L}$

Then $\mathbb{G}_{\rm int} \times U(1)$ can be specified as $\mathbb{G}_{\rm L1R} := SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm R} \times U(1)_{B-L}$ & $\mathbb{G}_{\rm f}$ with $\mathbb{G}_{\rm SM}$

- Since the production of MM is **cosmologically catastrophic**, these are to be **inflated away**.

B. Introducing *F-term hybrid inflation* (FHI)

- A well-motivated inflationary model, which may **dilute** MM, and is **naturally followed** by a **GUT** phase transition which may **lead** to the formation of CSs is FHI.

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

- Therefore, we consider the **implementation** of FHI within $\mathbb{G}_{\rm L1R} := SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm R} \times U(1)_{B-L}$
- For a **reliable approach** to FHI soft *Supersymmetry* (**SUSY**)-breaking terms and *Supergravity* (**SUGRA**) **corrections** have to be taken into account together with the *radiative corrections* (**RCs**) employed in the **original version** of the model.

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

- **Both former** 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 mecha-nism of the (visible) *inflationary sector* (**IS**) and the *hidden sector* (**HS**) a mildly violated ***R* symmetry**.

C. Final Form of the Proposed Scheme

$$\mathbb{G}_{\rm LR} \times U(1)_R \times U(1)_B \times {\rm SUGRA} \xrightarrow[\rm MM]{\langle(1,1,3,0)\rangle} \mathbb{G}_{\rm L1R} \times U(1)_R \times U(1)_B \times {\rm SUGRA}$$

$$- ({\rm FHI}) \xrightarrow[\langle Z\rangle,\ {\rm CSs}]{\langle\Phi\rangle = \langle\bar\Phi\rangle = M} \mathbb{G}_{\rm SM} \times \mathbb{Z}_2^R \times U(1)_B \times \not{\rm S}{\rm USY}$$

- FHI occurs **after** the MM formation but **before** that of CSs
- Do not **confuse** U(1) *R* symmetry with the gauge *U(1)*$_{\rm R}$ in $\mathbb{G}_{\rm L1R}$!

II. MODELING FHI & SUSY BREAKING
A. Particle Content

- The particle content of our model includes the **matter** superfields of the *Minimal SUSY SM* (**MSSM**) together with **right-handed neutrinos** and its **two Higgs** superfields.
- The implementation of **FHI** requires the introduction of other **three superfields:** the $\mathbb{G}_{\rm L1R}$ singlet Inflaton S and 2 Higgs fields: $\bar{\Phi}$ & Φ named **waterfall fields**.
- To establish connection with **SUSY breaking**, we also employ a $\mathbb{G}_{\rm L1R}$ 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 three **global symmetries.**
- **Prominent** role plays the ***R*** **symmetry** which guides us to the **construction** of the **superpotential** *W* and Kaehler potential *K.*

SUPER-FIELDS	REPRESENTATIONS UNDER $\mathbb{G}_{\rm L1R}$	GLOBAL SYMMETRIES R	B	L
MATTER SUPERFIELDS				
e_i^c	$(\mathbf{1},\mathbf{1},1/2,1)$	0	0	-1
ν_i^c	$(\mathbf{1},\mathbf{1},-1/2,1)$	0	0	-1
l_i	$(\mathbf{1},\mathbf{2},0,-1)$	0	0	1
u_i^c	$(\mathbf{3},\mathbf{1},-1/2,-1/3)$	0	$-1/3$	0
d_i^c	$(\mathbf{3},\mathbf{1},1/2,-1/3)$	0	$-1/3$	0
q_i	$(\bar{\mathbf{3}},\mathbf{2},0,1/3)$	0	$1/3$	0
HIGGS SUPERFIELDS				
H_d	$(\mathbf{1},\mathbf{2},-1/2,0)$	2	0	0
H_u	$(\mathbf{1},\mathbf{2},1/2,0)$	2	0	0
S	$(\mathbf{1},\mathbf{1},0,0)$	2	0	0
Φ	$(\mathbf{1},\mathbf{1},-1/2,1)$	0	0	-2
$\bar{\Phi}$	$(\mathbf{1},\mathbf{1},1/2,-1)$	0	0	2
GOLDSTINO SUPERFIELD				
Z	$(\mathbf{1},\mathbf{1},0,0)$	$2/\nu$	0	0

B. Superpotential, *W*

The superpotential of the model has the form $W = W_{\rm I} + W_{\rm H} + W_{\rm GH} + W_{\rm MSSM},$ 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, acquire 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**.
- $W_{\rm MSSM}$ contains the usual **terms** of MSSM (with Dirac neutrino masses) but **without** the *μ* term, i.e.

$$W_{\rm MSSM} = h_{ijD} d_i^c q_j H_d + h_{ijU} u_i^c q_j H_u + h_{ijE} e_i^c l_j H_d + h_{ij\nu} \nu_i^c l_j H_u.$$

C. Kaelher Potential, *K*

- The Kaelher potential includes the **terms** $K = K_{\rm I} + K_{\rm H} + K_{\mu} + |Y_\alpha|^2,$
- From which the **last one** is devoted to **MSSM** Matter and Higgs superfields. $Y_\alpha = q_i, l_i, d_i^c, u_i^c, e_i^c, \nu_i^c, H_d \text{ and } H_u.$
- **Canonical** kinetic terms are also adopted for the fields involved in FHI, i.e., $K_{\rm I} = |S|^2 + |\Phi|^2 + |\bar{\Phi}|^2$

- 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 avoid a **massless** *R* axion.

- In the **absence** of IS, vanishing potential energy density may be achieved if we impose the **condition**

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

- 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

$$K_\mu = \lambda_\mu \frac{Z^{*2\nu}}{m_{\rm P}^{2\nu}} H_u H_d + {\rm h.c.},$$

- The magnitudes of $\boldsymbol{\mu}$ **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** $\prod_\alpha U(1)_{Y^\alpha} \times U(1)_S \times (SU(1,1)/U(1))_Z$

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 $U(1)_R \, xU(1)_{B\text{-}L}$ **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.

E. SUSY and $\mathbb{G}_{L1R}$ BREAKING

- We can verify numerically that V_F is minimized at $\mathbb{G}_{L1R}$-breaking **vacuum** $|\langle\Phi\rangle| = |\langle\bar\Phi\rangle| = M$
- If we **parameterize** the two remaining $\mathbb{G}_{L1R}$- **singlet** superfields according to the descriptions

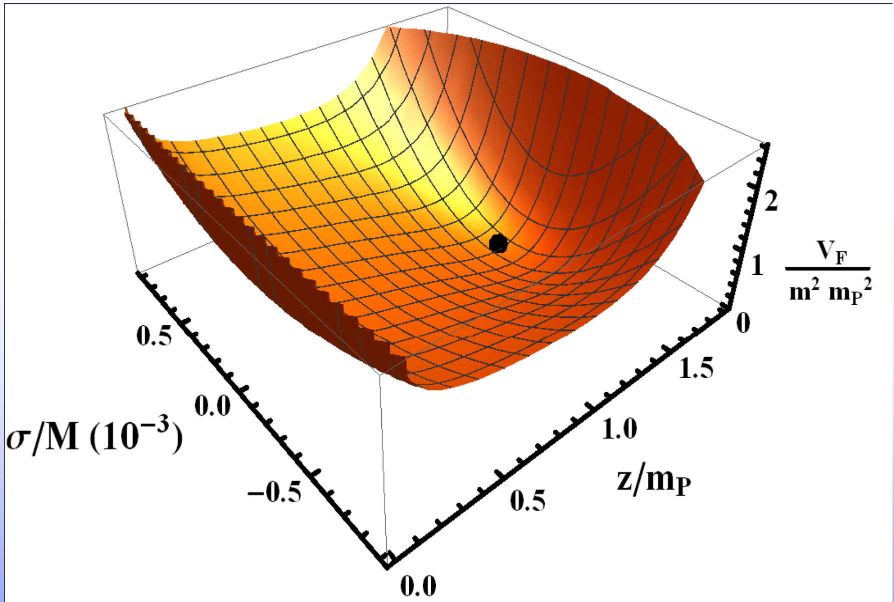
$$Z = (z + i\theta)/\sqrt{2} \text{ and } S = \sigma\, e^{i\theta_S/m_{\rm P}}/\sqrt{2}$$

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 constant **potential energy density** turns out to be

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



With $\omega = e^{\langle K_{\rm H}\rangle/N m_{\rm P}^2} \simeq 2(3-2\nu)/3$, **Mildly 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 representative **inputs** (ν=7/8 & k=0.1) we obtain

FHI Related Parameters

κ	$M/10^{15}$GeV	m/PeV	a_S/TeV
$5\cdot10^{-4}$	1.4	0.5	2.63

Particle Mass Spectrum At the Vacuum (1 PeV = 10^6 GeV)

$m_{\rm I}/10^{12}$ GeV	$\widetilde{m} = m_{3/2}$/PeV	m_z/PeV	m_θ/PeV
1.8	0.9	1.3	0.8

III. INFLATION AND POST-INFLATION

- In the **global SUSY**, FHI takes place for *S*>> *M* along a F- & 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

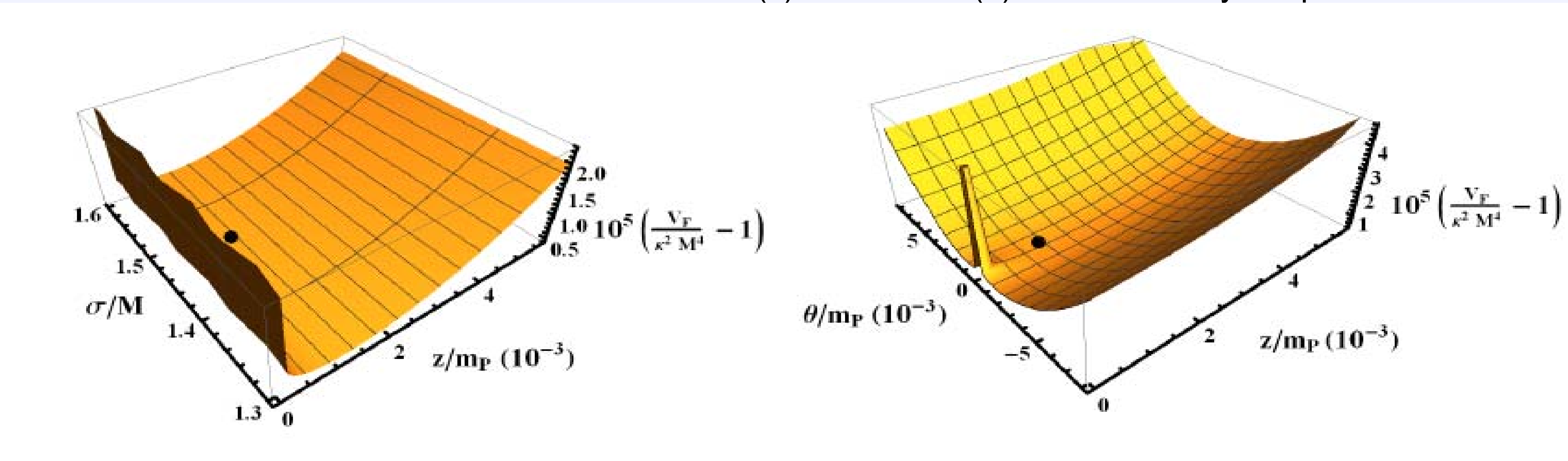
$$V_{\rm F}(z) = e^{\frac{K_{\rm H}}{m_{\rm P}^2}}\left(\kappa^2 M^4 + m^2 \frac{z^{2(\nu-1)}(8\nu^2 m_{\rm P}^2 - 3z^2)^2}{2^{5+\nu}\nu^2 m_{\rm P}^{2\nu}}\right)$$

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

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

- 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:

- $C_{\rm SSB} = m_{\rm I3/2}^2\sigma^2/2V_{\rm I0} - {\rm a}_S\,\sigma/\sqrt{2V_{\rm I0}}$ is the contribution from the **soft SUSY-breaking effects,** where the **tadpole parameter** is given in terms of $\langle z\rangle_{\rm I}$

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

As we see, **observations constrain** $a_S \sim$ TeV, and since $\langle z\rangle_{\rm I}/m_{\rm P} \sim 10^{-3}$ **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

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

- $C_{\rm RC} = \frac{\kappa^2}{128\pi^2}\left(8\ln\frac{\kappa^2M^2}{Q^2} + f_{\rm RC}\left(\frac{\sigma}{M}\right)\right)$ is the contribution from **1-loop RCs** which include the function $f_{\rm RC}(x)$ with

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

- 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, a $\mathbb{G}_{\rm L1R}$ **phase transition**. It leads to the **formation** of CSs.

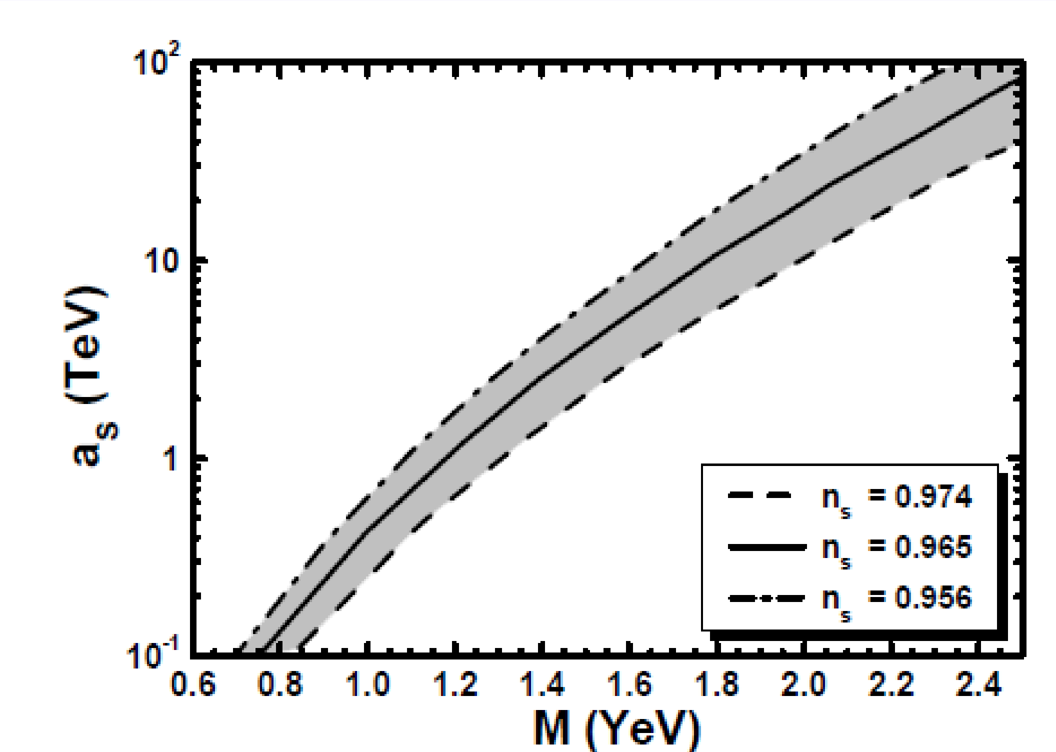
C. Inflationary Requirements

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

$$N_{I\star} = \int_{\sigma_f}^{\sigma_\star} \frac{d\sigma}{m_P^2} \frac{V_I}{V_I'} \simeq 19.4 + \frac{2}{3} \ln \frac{V_{I0}^{1/4}}{1\ \mathrm{GeV}} + \frac{1}{3} \ln \frac{T_{rh}}{1\ \mathrm{GeV}}$$

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

$$\sqrt{A_s} = \frac{1}{2\sqrt{3}\,\pi m_P^3} \frac{V_I^{3/2}(\sigma_\star)}{|V_I'(\sigma_\star)|} \simeq 4.588 \times 10^{-5}$$



- The **scalar spectral index** n_s, its **running** α_s and the **scalar-to-tensor ratio** r must be in agreement with *Planck* data, i. e.,

$$n_s = 0.967 \pm 0.0074 \quad \text{and} \quad r \lesssim 0.032,$$

With $|\alpha_s| \ll 0.01$.

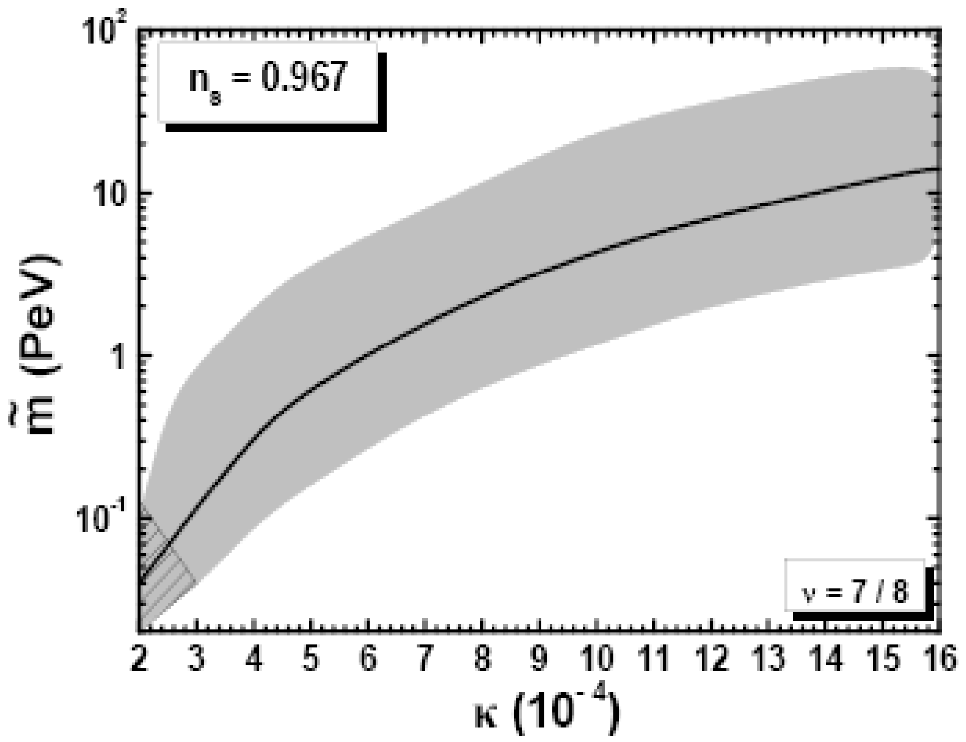
- Imposing the requirements above we delineate the **allowed gray region** in the *M*-a_S plane. The **central** n_s is obtained along the **solid** black line.

$$0.7 \lesssim M/\mathrm{YeV} \lesssim 2.56 \ \text{and}\ 0.1 \lesssim a_S/\mathrm{TeV} \lesssim 100$$

D. SUSY-Mass Scale

- Thanks to the $a_S - m_{3/2}$ **connection**, the model offers a **prediction** for the range of $\widetilde{m}$
- Varying *v* and *μ* within their possible respective margins (0.75-1) and (1-3) $\widetilde{m}$ we obtain the gray shaded region in the $\kappa - \widetilde{m}$ Plane. The solid line is obtained for v=7/8.
- We have therefore a **clear prediction** for which lies at the PeV region

$$0.34 \lesssim \widetilde{m}/\mathrm{PeV} \lesssim 13.6$$



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

E. Bagnaschi, G.F. Giudice, P. Slavich and A. Strumia (2014)

- The hanched region is **excluded** due to *Big Bang Nucleosynthesis* (**BBN**) .
- To avoid any **disturbance** of the successful predictions of **BBN** we require

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

Where B_h is the **hadronic** branching ratio.

E. Post-Inflationary Evolution

- Soon after FHI, *z* and IS enter into an **oscillatory phase** about their **minima** and eventually decay.

Since $\langle z\rangle \sim m_{\rm P}$ & $H_{z\rm I} \sim m_z$ the energy densities of *z*, and the total of the Universe, at the **onset** of oscillations

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

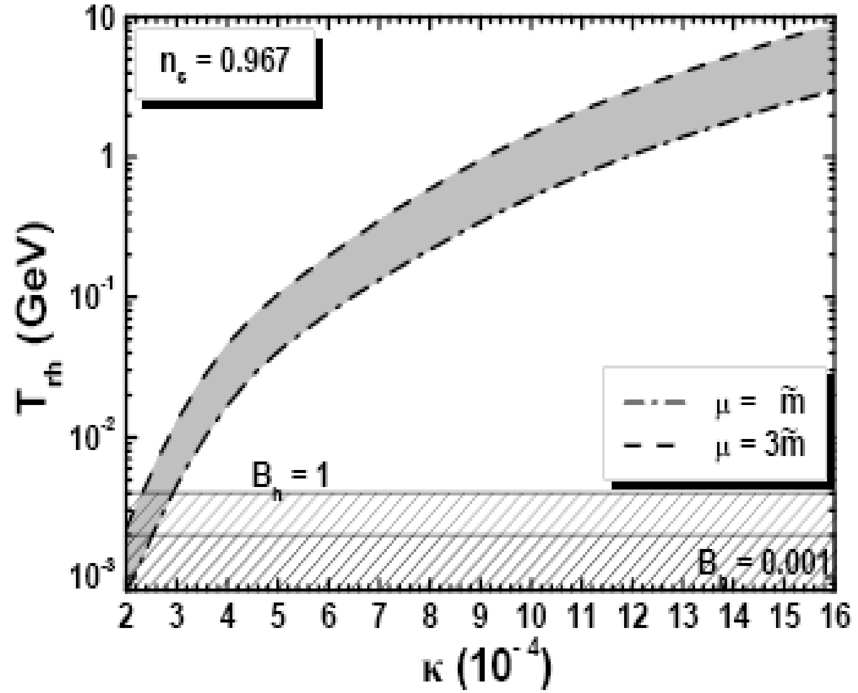
Are **equal**. Therefore, *z* **dominates** and reheats the universe at a **low** reheating temperature

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

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

- For *v=7/8* and **varying** *μ* in the range (1-3)$m_{3/2}$ we obtain the **gray strip** in the *κ*-T_{rh} plane. **BBN** constraint is satisfied in the major part of the graph with **maximal** T_{rh}=14 GeV.
- In order to protect our setting from a possible **non-thermal** overproduction of LSPs, we kinematically **block** the decay of *z* to $\widetilde{G}$ by demanding $m_z<2m_{3/2}$. This is easily **achieved for** *v*>3/4 since

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



III. METASTABLE COSMIC STRINGS

- Due to the **SSB** of $\mathbb{G}_{L1R}$ for $\sigma < \sigma_c = 2^{1/2}M$, CSs are **formatted.** Since these are topologically unstable, they can become **bounded** by MM pairs which **cut** & "**eat**" them before decay.

A. CS tension

- The **dimensionless tension** $G\mu_{cs}$ of the CSs mainly depends on M via the relation

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

Here $G=1/8\pi\, m_P^2$ is the Newton gravitational constant and $g\sim 0.7$ is the gauge coupling constant

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

- Since the CSs are **metastable,** due to the embedding of $U(1)_R \times U(1)_{B-L}$ into $\mathbb{G}_{\rm LR}$ we can explain the recent NG15 data, which requires $G\mu_{cs}$ to be **confined** at the margin

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

- The **metastability factor** r_{ms} (i.e., ratio of the monopole mass squared m_M to $\mu_{cs.}$) is estimated to be

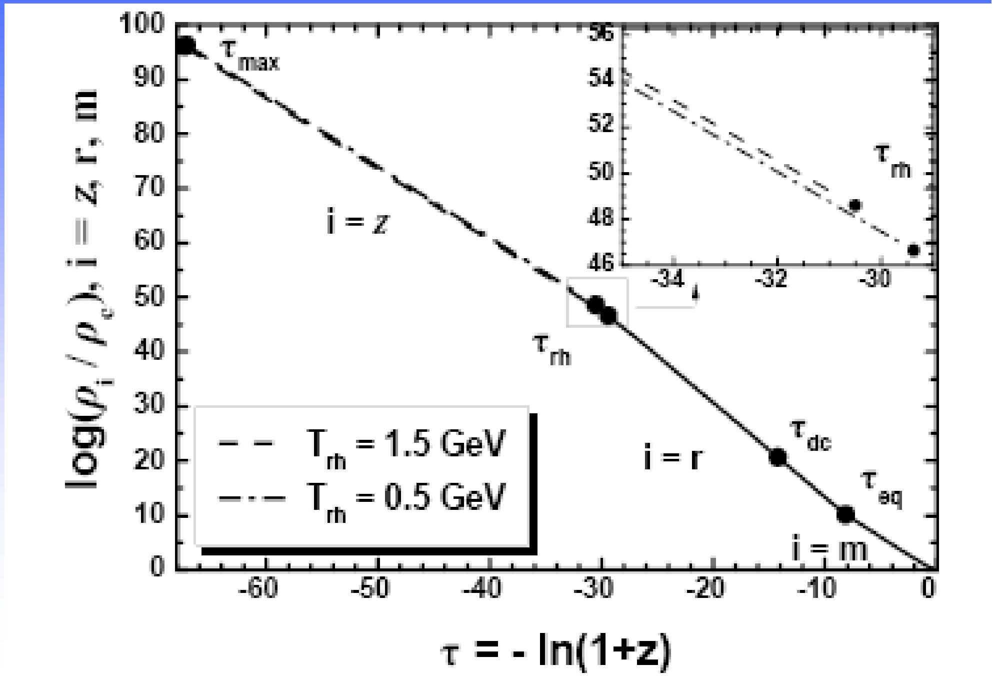
$$r_{\rm ms} \simeq m_{\rm M}^2/\mu_{\rm cs} \ \text{with} \ m_{\rm M} = 4\pi M_{W_R^\pm}/g^2 \ \text{and} \ M_{W_R^\pm} = \sqrt{2}g v_{\rm R}$$

- It may be used to determine the $SU(2)_R$-**Breaking** Scale, v_R E.g. For g=0.7 and $r_{ms}=8^2$, we obtain

$$1 \leq v_{\rm R}/{\rm YeV} \leq 2.86 \ \text{for} \ 0.9 \leq M/{\rm YeV} \leq 2.56$$

I.e., A proximity between v_R and M is required.

B. CSs' decay



- To obtain a more complete picture for the post-inflationary evolution we present the log **energy densities** ρ_i for i=
- z (**oscillations**),
- r (**radiation**) and
- m (**matter**)

as a function of the **logarithmic time**

$$\tau = -\ln(1+z)$$

for **two values** of T_{rh} is given in the figure.

- The reheating process is not instantaneous. The **maximal temperature** is obtained for $\tau_{max} \ll \tau_{rh}$
- In both cases, for $\sqrt{r_{\rm ms}}$ = 8 we obtain $\tau_{\rm dc} = -\ln\left((70/H_0)^{1/2}(\Gamma\Gamma_{\rm d}G\mu_{\rm cs})^{1/4}+1\right)$ < $\tau_{\rm eq}$

with $\Gamma_{\rm d} = 4G\mu_{\rm cs}m_{\rm P}^2 e^{-\pi r_{\rm ms}}$ the **decay rate per unit length** of CSs.

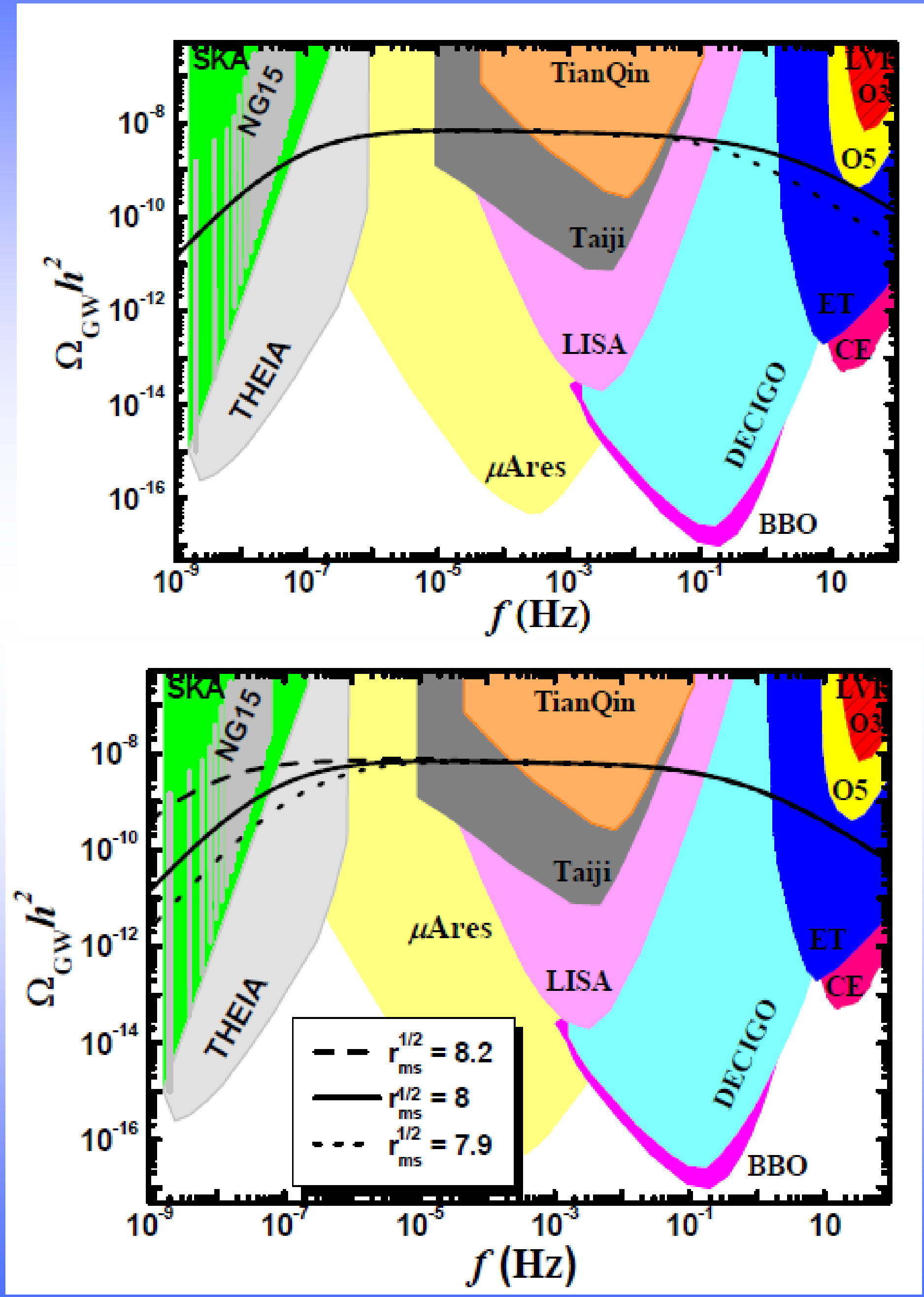
- It is computed using as **inputs** *v*=7/8 (*N*=-49/8) and $\kappa = 0.001$ and $a_S = 25.8$ TeV

resulting to $M = 2.2\times10^{15}$ GeV and $G\mu_{\rm cs} = 6\times10^{-8}$

C. GWs from CSs' decay

- With the **same inputs** we compute the emitted GW background $\Omega_{\rm GW} h^2$ as a function of the frequencies for T_{rh} = 0.43 GeV (**dotted line**) and T_{rh} = 3.5 GeV (**solid line**). We see that the achieved curves **explain** rather well the **NG15.**

- $\Omega_{\rm GW} h^2$ **Increases** with $\sqrt{r_{\rm ms}}$ for **constant** T_{rh}=1.2 GeV.



- The **long-lasting matter domination** obtained because of the z oscillations leads to a **suppression** of $\Omega_{\rm GW} h^2$ at frequencies f>0.1 Hz. Thanks to this effect our results are comfortably consistent with **LIGO-Virgo-KAGRA** data too.

$$\Omega_{\rm GW} h^2(f_{\rm LVK}) \lesssim 7.8 \cdot 10^{-9} \;\; \text{for} \;\; f_{\rm LVK} = 25 \text{ Hz}.$$

- The **sensitivities** of various other experiments are also shown.

V. CONCLUSIONS

- We analyzed the production of **metastable** CSs in the context of a model which incorporates **FHI and SUSY breaking** consistently with an **approximate *R* symmetry.**

- The model offers the following interesting **achievements**:

1. Observationally **acceptable** FHI adjusting the **tadpole parameter** and the $\mathbb{G}_{L1R}$ **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 explanation of the **NG15** via the decay of the CSs

- The model does not address the following **open issues**: Due to the low $\mathbf{T_{rh}}$

1. **Baryogenesis** is made difficult. Some possibilities which may work is **Affleck-Dine** or take advantage from the **non-thermal decay of Sgoldstino** with some modified version of MSSM.
2. The abundance of the **Lightest Neutralino** may be **inadequate** to account for the CDM problem. Non-thermal contribution from **gravitino decay** is possible.

THANK YOU !