High-Scale Supersymmetry from Sgoldstino Inflation

C. Pallis

FACULTY OF ENGINEERING
ARISTOTLE UNIVERSITY OF THESSALONIKI

Based on:

- C.P., *Eur. Phys. J. C* **86**, *023523 (2012)* [arXiv:2211.05067].
- C.P., *Phys. Lett. B* **843**, *138018 (2023)* [arXiv:2302.12214].

Outline

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Super-Higgs Mechanism

- Within Global **Supersymmetry** (**SUSY**), The Scalar Potential of a **Gauge-Singlet** Field Z is Positive Semi-Definite,

$$V_{\rm SUSY} = |F_Z|^2 \ \text{With} \ F_Z = \partial_Z W$$

Where $W = W(Z)$ is an Holomorphic Function Named **Superpotential**. Spontaneous SUSY Breaking Occurs when

$$\langle F_Z\rangle \neq 0 \ \rightsquigarrow \ \langle V_{\rm SUSY}\rangle^{1/4} > 0 \ \text{where} \ V_{\rm SUSY}{}^{1/4} \simeq \langle F_Z\rangle^{1/2} \gg 1\ {\rm TeV} \gg \Lambda_{\rm CC} \simeq 1\ {\rm meV} \ \ !?$$

Which Is **Phenomenologically Unacceptable**. It is Accompanied With the Presence of A Massless Fermion Named **Goldstino**.

- In Contrast, Within Local-SUSY – i.e. **Supergraviity** (**SUGRA**) – The F-term Scalar Potential is Given by

$$V_{\rm SUGRA} = e^G\left(G^{ZZ^*}G_ZG_{Z^*} - 3\right) \ \text{Where}\ G := K + \ln|W|^2 \ \text{is the } \textbf{Kähler -Invariant Function} \ (\text{We Use } m_{\rm P} = 1).$$

$K = K(Z, Z^*)$ the Kähler Potential. Also $G_{ZZ^*} = K_{ZZ^*} = \partial_Z\partial_{Z^*}K$ is the **Kähler Metric** and $K^{ZZ^*} = K^{-1}_{ZZ^*}$.

- SUSY is Broken Again When $\langle F^Z\rangle \neq 0$ Where $F^Z = e^{G/2}K^{ZZ^*}G_{Z^*}$ Which May Occur With $\langle V_{\rm SUGRA}\rangle \simeq 0$.

This Effect is Accompanied With the Absorption Of The Goldstino By The **Gravitino**, $\widetilde{G}$, Which Acquires Mass:

$$m_{3/2} = \langle e^{G/2}\rangle = \langle e^{K/2}W\rangle = \langle G_{ZZ^*}F^Z\bar{F}^{Z^*} - V_{\rm SUGRA}\rangle^{1/2}/\sqrt{3} \quad :\textbf{“Super-Higgs” Mechanism}.$$

Minkowski Vacua In No-scale SUGRA

- Within **No-Scale**[1] SUGRA, SUSY Is Broken With Naturally $V_{\rm SUGRA} = 0$ **Along A Flat Direction**.
- To **Systematize** The Model Construction, We Use As Input K and **Determine** W so as $V_{\rm SUGRA} = 0$. Namely,

$$V_{\rm SUGRA} = e^G\left(G^{ZZ^*}G_ZG_{Z^*} - 3\right) = e^K\left(g_K^{-1}\left|\partial_Z W + WK_Z\right|^2 - 3|W|^2\right), \ \text{Where}\ g_K^{-1} = K^{-1}_{ZZ^*} = K^{ZZ^*}$$

- If We Assume That The Direction $Z = Z^*$ is Stable, We Are Able to **Solve the Equation** $V_{\rm SUGRA} = 0$ w.r.t $W = W_0(Z)$ i.e.,

$$g_K^{-1}\left(W_0' + W_0K_Z\right)^2 = 3W_0^2 \ \Rightarrow\ \frac{dW_0}{dZW_0} = \pm\sqrt{3g_K} - K_Z \ \Rightarrow\ W_0^{\pm} = m\exp\left(\pm\int dZ\sqrt{3g_K} - \int dZK_Z\right) \ \text{With}\ ' = d/dZ.$$

[1] E. Cremmer, S. Ferrara, C. Kounnas and D.V. Nanopoulos (1983).

Synergy Between W and K

- E.g., If we Select
  - $K = -3\ln(T + T^*)$ We Obtain the **Traditional** Form $W_0^- = m$ in the No-Scale SUGRA But Also $W_0^+ = 8mT^3$;
  - $K = |Z|^2$, then $W_0^\pm = me^{\pm\sqrt{3}Z - Z^2/2}$. Therefore We can Obtain A No-Scale Model Even With **Flat!** Geometry
- The Models can be Extended to Support **de Sitter** (**dS**) Vacua. In this Case $\langle V_{\rm SUGRA}\rangle$ **May Account** For the **Dark Energy** (**DE**). No External Mechanism For Vacuum Uplifting is Required.
- If we Consider The Following Linear Combination[2] of $W_0^\pm$

$$W_\Lambda = W_0^+ - C_\Lambda W_0^- \quad \text{which Yields} \quad V_\Lambda = e^K\left(g_K^{-1}\left(W'_\Lambda + W_\Lambda K_Z\right)^2 - 3W_\Lambda^2\right) = 12e^K C_\Lambda W_0^- W_0^+ = 12m^2 C_\Lambda.$$

- V_Λ may be Identified With The Present DE Energy Density by **Finely Tuning** C_Λ As Follows

$$V_\Lambda = \Omega_\Lambda \rho_{c0} = 10^{-120} \;\; \rightarrow \;\; C_\Lambda \simeq 10^{-108} \;\; \text{for } m \simeq 10^{-6}$$

- Possible **Shortcoming**: Although Quite Appealing, no-Scale SUGRA Yields a Completely Flat $V_{\rm SUGRA}$, i.e.

$$V_{\rm SUGRA} = V'_{\rm SUGRA} = V''_{\rm SUGRA} = 0$$

And So $m_{3/2}$ & Soft SUSY-Breaking Terms Remain **Undetermined** and A Massless Mode Arises in The Spectrum.
- To Cure that, we May Include in K A **Stabilization (Higher Order) Term**

$$-k^2 Z_{\rm v}^4 \quad \text{With} \quad Z_{\rm v} = Z + Z^* - \sqrt{2}{\rm v}$$

Which Selects the Vacuum $(\langle z\rangle, \langle\bar z\rangle) = ({\rm v}, 0)$ from the Flat Direction. It also Provides the Real Component of sgoldstino With **Mass** – Its Presence in **Natural** According to 't Hooft Argument Since The Symmetry Of the Model is Enhanced for $k \to 0$.

[2] J. Ellis et al. (2018, 2019); C. Pallis (2023).

Uni-Modular no-Scale Models

- Applying the Method Above Several no-Scale Models Can be Achieved **Varying** the Kähler Geometry[3].

Catalogue of Some Uni-Modular no-Scale SUGRA Models

	K	$W_0^{\pm}/m$	W_Λ/m	Kähler Geometry
1	$-N\ln\left(T+T^*+k^2T_{\rm v}^4/N\right)$, $T_{\rm v}=T+T^*-\sqrt{2}{\rm v}$	$(2T)^{n_\mp}$, Where $n_\pm=(N\pm\sqrt{3N})/2^{(\dagger)}$	$(2T)^{n_+}C_T^-$, Where $C_T^-=1-C_\Lambda(2T)^{-\sqrt{3N}}$	$SU(1,1)/U(1)$ Half-Plane Coordinates
2	$-N\ln\left(1-\|Z\|^2+k^2Z_{\rm v}^4/N\right)$, $Z_{\rm v}=Z+Z^*-\sqrt{2}{\rm v}$	$v_-^{-N/2}u_-^{\pm1}$, Where $v_-=1-Z^2/N$, $u_-=e^{\sqrt{3N}{\rm atnh}(Z/N)}$	$v_-u_-C_{u-}^-$, Where $C_{u-}^-=1-C_\Lambda u_-^{-2}$; ${\rm atnh}:={\rm arctanh}$	$SU(1,1)/U(1)$ Poincaré Disc Coordinates
3	$+N\ln\left(1+\|Z\|^2-k^2Z_{\rm v}^4/N\right)$, $Z_{\rm v}$ as Above	$v_+^{-N/2}u_+^{\pm1}$, Where $v_+=1+Z^2/N$, $u_+=e^{\sqrt{3N}{\rm atn}(Z/N)}$	$v_+u_+C_{u+}^-$, Where $C_{u+}^-=1-C_\Lambda u_+^{-2}$; ${\rm atn}={\rm arctan}$	$SU(2)/U(1)$ Compact Geometry
4	$\|Z\|^2-k^2Z_{\rm v}^4$, $Z_{\rm v}$ as Above	$wf^{\pm1}$, Where $w=e^{-Z^2/2}$ and $f=e^{\sqrt{3}Z}$	wfC_f^-, Where $C_f^-=1-C_\Lambda f^{-2}$	$U(1)$ Flat Geometry

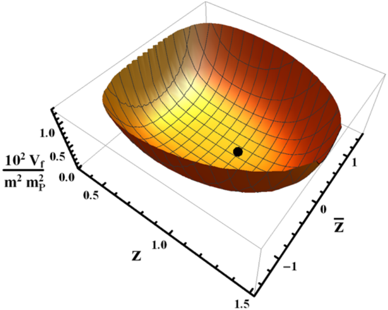
$^{(\dagger)}$: For $N=3$ we Obtain $n_+=3$ and $n_-=0$ and so, The Well-Known No-Scale Models Have the Ingredients[4]

$$K=-3\ln(T+T^*)\ \text{and}\ W_\Lambda=8mT^3C_T^-\ \text{where}\ C_T^-=1-C_\Lambda(2T)^{-3}$$

- Similar Models Can be Constructed for **More Than One** Modulus With **Mixed** Geometries[3].

[3] C. Pallis (2023); [4] J.R. Ellis, C. Kounnas and D.V. Nanopoulos (1984); J. Ellis et al. (2018, 2019).

Stability of the Vacuum



- For The No-Scale Model With **Flat** Geometry if we decompose Z as $Z = (z + i\bar{z})/\sqrt{2}$, We see that The SUSY-Breaking dS Vacuum Lies at

$$\langle z\rangle = \mathrm{v} \;\; \text{and} \;\; \langle\bar{z}\rangle = 0 \;\; \text{with} \;\; \langle V_\Lambda\rangle = 12C_\Lambda m^2$$

- The (Dimensionless) SUGRA Potential $10^2 V_\mathrm{f}/m^2 m_\mathrm{P}^2$ Is Plotted As A Function Of z and $\bar{z}$ For The **Following Inputs**

m/m_P	$C_\Lambda/10^{-92}$	k	v/m_P
$5\cdot 10^{-13}$	1.4	0.3	1

m_z	$m_{\bar{z}}$	$m_{3/2}$	(in GeV)
612	340	170	

- To Check the **Stability of the Vacuum**, We Derive The Mass Spectrum. We need $k \neq 0$ & $N > 3$ For **Hyperbolic** Geometry.

Particle Mass Spectrum At the Vacuum

Case	Mass Of Sgoldstino		$m_{3/2}$	Restriction
	Real	Imaginary		
1	$24k\mathrm{v}^{3/2}m_{3/2}$	$2(1-3/N)^{1/2}m_{3/2}$	$m(\sqrt{2}\mathrm{v})^{\sqrt{3N}/2}$	$N > 3$
2	$12k\langle v_-\rangle^{3/2}m_{3/2}$	$2(1-3/N)^{1/2}m_{3/2}$	$m\langle u_-\rangle$	$N > 3$
3	$12k\langle v_+\rangle^{3/2}m_{3/2}$	$2(1+3/N)^{1/2}m_{3/2}$	$m\langle u_+\rangle$	-
4	$12km_{3/2}$	$2m_{3/2}$	$me^{\sqrt{3/2}\mathrm{v}}$	-

Combining DE With an Inflection Point

• We Aspire to **Identify z** (Real Component of the Sgoldstino) With the **Inflaton**. Checking Several Possibilities We Found Out That This Aim Can Be Accomplished for A Model[5] Similar to Case 1, for $T = 1/2 + Z/2$. I.e.,

$$K = -N\ln\Omega \quad \text{with} \quad \Omega = 1 - (Z + Z^*)/2 + k^2 Z_{\rm v}^4 \quad \text{and} \quad Z_{\rm v} = Z + Z^* - 2{\rm v},$$

• K Enjoys a Symmetry Related to a **Subset** of $U(1,1)$ Without to Define Specific Kähler Manifold[6].

Repeating Our Procedure Which Yields dS Vacua Within No-Scale SUGRA, we Find that K may be Associated with

$$W_\Lambda = m\omega^{n_+} C_\omega^- \quad \text{with} \quad n_+ = (N + \sqrt{3N})/2,\ \omega = \Omega(Z = Z^*, k = 0) = 1 - Z \quad \text{and} \quad C_\omega^- = 1 - C_\Lambda \omega^{-\sqrt{3N}}$$

Where m is An Arbitrary Mass Scale Which Is Constrained to **Values 10^{-7}** from the Normalization of $A_{\rm s}$ – see Below.

• The exponents n_+ in W_Λ may, in Principle, Acquire Any Real Value, If We Consider W_Λ As An **Effective** Superpotential.

• When $N/3 > 1$ is a Perfect Square, **Integer** $n_\pm$ Values May Arise Too. E.g.,

For $N = 12, 27$ and 48 We Obtain $(n_-, n_+) = (3, 9), (9, 18)$ and $(18, 30)$.

• The Resulting **SUGRA Potential** is

$$V_\Lambda = m^2\Omega^{-N}\omega^{2n_+}\left(|U/2\omega|^2 - 3|C_\omega^-|^2\right), \quad \text{where} \quad U = \frac{\sqrt{2N}}{J\Omega}\left(\left(\sqrt{3}C_\omega^+ + \sqrt{N}C_\omega^-\right)\Omega + 2\sqrt{N}C_\omega^-\Omega_{,Z}\,\omega\right)$$

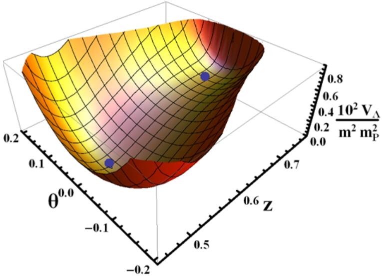
• The Canonical Normalized **Components** Of The Complex Scalar Field $Z = ze^{i\theta}$ are

$$\frac{d\widehat{z}}{dz} = \sqrt{2K_{ZZ^*}} = J \quad \text{and} \quad \widehat{\theta} = Jz\theta, \quad \text{where} \quad J = \sqrt{2N}\left(\frac{\Omega_{,Z}^2}{\Omega^2} - \frac{\Omega_{,ZZ^*}}{\Omega}\right)^{1/2} \quad \text{with} \quad \Omega_{,Z} = -1/2 + 4k^2 Z_{\rm v}^3 \quad \text{and} \quad \Omega_{,ZZ^*} = 12k^2 Z_{\rm v}^2.$$

[5] C. Pallis, PLB (2023).

[6] C. Pallis, EPJC (2022).

Vacuum Stability & Particle Spectrum



- The SUSY-Breaking **Vacuum** is

$$\langle z\rangle = \mathrm{v} \ \ \text{and} \ \ \langle\theta\rangle = 0 \ \ \text{with} \ \ \langle V_\Lambda\rangle = 12 C_\Lambda m^2$$

- For $z = z_0 > \mathrm{v}$ an **Inflection Point** Arises Letting Open The Possibility Of An Inflationary Stage.
- We Show $10^2 V_\Lambda / m^2 m_P^2$ As A Function Of z and θ For

Following Inputs

m/m_P	$C_\Lambda/10^{-108}$	$k/0.1$	v/m_P
$5.6\cdot10^{-7}$	2.5	4.0167291	0.5
N	n_+	n_-	
12	9	3	

- The dS Vacuum Lies at $(\langle z\rangle, \theta) = (0.5, 0)$ Whereas the Inflection Point is located at $(z_0, \theta) \simeq (0.71, 0)$.

- The Vacuum Above is **Stable** Against Fluctuations Of The Various Excitations for $N > 3$ Which Assures $m_\theta^2 > 0$. Indeed, We find

$$m_z \simeq 48 m_{3/2} k N^{-1/2} \langle\omega\rangle^{3/2} \ \ \text{and} \ \ m_\theta \simeq 2 m_{3/2}\left(1-(3/N)\right)^{1/2} \ \ \text{with} \ \ m_{3/2} = m\langle\omega\rangle^{\sqrt{3N}/2} \ \ \text{for} \ \ N > 3.$$

Particle Mass Spectrum in EeV$(1\ \mathrm{EeV} = 10^9\ \mathrm{GeV})$

m/EeV	m_z/EeV	m_θ/EeV	$m_{3/2}/\mathrm{EeV}$
1344	319	281	162

Observable and Hidden Sectors

• The SUSY Breaking Occurred At The Vacuum Can Be **Transmitted** To The Visible World If We Specify a Low energy Reference Model. We Adopt MSSM (i.e. **Minimal SUSY Standard Model**).

• The **Total** Superpotential, $W_{\Lambda\rm O}$, and Kähler Potential $K_{\Lambda\rm O}$ Include Two Contributions

$$W_{\Lambda\rm O} = W_\Lambda(Z) + W_{\rm MSSM}(\Phi_\alpha) \ \text{ and } \ K_{1\Lambda\rm O} = K(Z) + \textstyle\sum_\alpha|\Phi_\alpha|^2 \ \text{ or } \ K_{2\Lambda\rm O} = K(Z) + N_{\rm O}\ln\left(1 + \sum_\alpha|\Phi_\alpha|^2/N_{\rm O}\right)$$

Where $N_{\rm O}$ May Remain Unspecified.

• $W_{\rm MSSM}$ Has The Well-Known Form Written In Short As

$$W_{\rm MSSM} = h_{\alpha\beta\gamma}\Phi_\alpha\Phi_\beta\Phi_\gamma/6 + \mu H_u H_d, \ \text{ with } \ \Phi_\alpha = Q, L, d^c, u^c, e^c, H_d \ \text{ and } \ H_u,$$

and non-vanishing h's $h_{\alpha\beta\gamma} = h_D, h_U$ and h_E for $(\alpha,\beta,\gamma) = (Q, H_d, d^c), (Q, H_u, u^c)$ and (L, H_d, e^c).

• Expanding The **Total** $V_{\rm SUGRA}$ for Low Values of Φ_α We Arrive at The Low Energy Potential Which Can Be Written As

$$V_{\rm SSB} = \widetilde{m}^2|\Phi_\alpha|^2 + \left(\frac{1}{6}A\widehat{h}_{\alpha\beta\gamma}\Phi_\alpha\Phi_\beta\Phi_\gamma + B\widehat{\mu}H_uH_d + \text{h.c.}\right) \ \text{ with } \ (\widehat{h}_{\alpha\beta\gamma},\widehat{\mu}) = \langle\omega\rangle^{-N/2}(h_{\alpha\beta\gamma},\mu),$$

Where **The Soft SUSY-Breaking Parameters** are found to be[7]

$$\widetilde{m} = m_{3/2}, \ \ |A| = F^Z\partial_Z K \simeq \sqrt{3N}m_{3/2} \ \text{ and } \ |B| = \langle F^Z\partial_Z K - m_{3/2}\rangle \simeq (1+\sqrt{3N})m_{3/2}$$

. • For **the Gauginos** of MSSM we May Select The **Gauge-Kinetic Function** As

$$f_{\rm a} = \lambda_a Z \ \text{ Which Results to Following Masses } \ |M_{\rm a}| = \sqrt{3/N}\lambda_a\langle\omega\rangle/\text{v}m_{3/2}$$

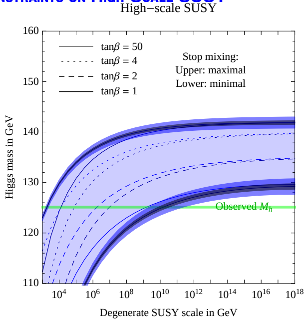
with Free λ_a and $\text{a} = 1, 2, 3$ Runs Over The Factors Of The Gauge Group of MSSM, $U(1)_Y$, $SU(2)_{\rm L}$ and $SU(3)_{\rm c}$.

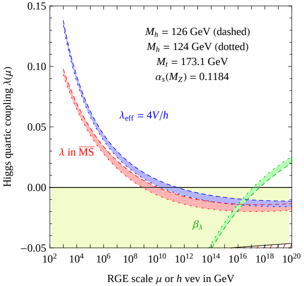
Particle Mass Spectrum in EeV(1 EeV $= 10^9$ GeV)

m/EeV	$\widehat{\mu}$/EeV	$\widetilde{m}$/EeV	$\lvert A\rvert$/EeV	$\lvert B\rvert$/EeV	$\lvert M_{\rm a}\rvert$/EeV
1344	81	162	1024	1200	81.1

[7] *A. Brignole, L.E. Ibáñez and C. Muñoz (1997).*

Constraints on High-Scale SUSY





- Scenarios with Large **SUSY Mass Scale** $\widetilde{m}$, Although Not Directly Accessible At The LHC, can Be Probed Via The Measured Value of the **Higgs Boson Mass**. In the Context of **High-Scale SUSY**, Taking Into Account the 1σ Variation of

$$m_t = (173.34 \pm 0.76)\ \text{GeV},\ \ a_3(M_Z) = 0.1184 \pm 0.0007,\ \ \text{and}\ \ m_h = (125.15 \pm 0.25)\ \text{GeV}.$$

The Following $\widetilde{m}$ Limits Can be Imposed[8]: $3 \cdot 10^3 \lesssim \widetilde{m}/\text{GeV} \lesssim 3 \cdot 10^{11}$,

for Degenerate Sparticle Spectrum, $\widetilde{m}/3 \leq \mu \leq 3\widetilde{m}$, $1 \leq \tan\beta \leq 50$ and Varying the $\tilde{t}_{1,2}$ mixing.

- Our Model Prefers $3 \lesssim \widetilde{m}/\text{EeV} \lesssim 300$ And So Low $\tan\beta$ Values And Minimal Stop Mixing.
- The **Stability Of The Electroweak Vacuum** Up To The $m_{\rm P}$ Is Automatically Assured Within This Framework[8].

[8] *G.F. Giudice and A. Strumia (2014);* [8] *G. Degrassi et al. (2012)*

Localization of the Inflection Point

- The **Inflationary Potential** $V_{\rm I} = V_{\rm I}(z)$ is Obtained from $V_\Lambda(Z)$ Setting $Z = ze^{i\theta}$ With $\theta = 0$ and $C_\Lambda \simeq 0$. I.e.,

$$V_{\rm I} = m^2\Omega^{-N}\omega^{2n_+}\left(|U/2\omega|^2 - 3\right) \text{ with } U = \frac{\sqrt{2N}}{J\Omega}\left(\left(\sqrt{3}+\sqrt{N}\right)\Omega + 2\sqrt{N}\Omega_{,Z}\omega\right),\ \ \omega = 1 - z \text{ and } \Omega_{,Z} = 24k^2(z-\mathrm{v})^2 - 1/2.$$

- To Localize The Position Of The **Inflection Point**, We Impose The Conditions

$$V_{\rm I}'(z) = V_{\rm I}''(z) = 0 \text{ for } \mathrm{v} < z < 1, \text{ where } ' := d/dz.$$

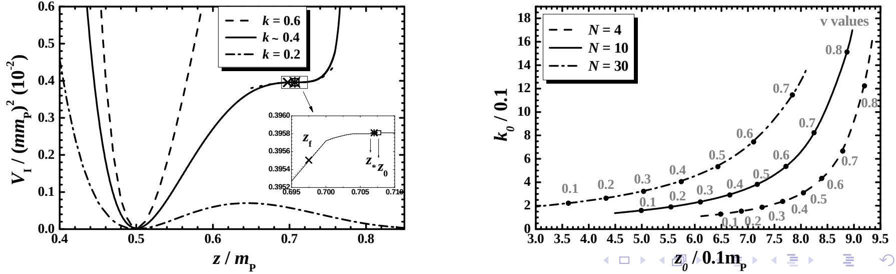
- For Every Selected v and N and Independently From m and C_Λ These Conditions yield **Inflection Point** (k_0, z_0) .
- E.g., For $N = 12$ & $\mathrm{v} = 0.5$ We Find $(k_0, z_0) = (0.40166971, 0.707433)$.

No Inflection Point Exists for $k = 0.2$ and $k = 0.6$.

- E.g., For $N = 4, 10$ and 30 (Dashed, Solid And Dot-Dashed Line Respectively) We Show the Inflection Points (z_0, k_0).

Along each Line We Show The Variation of v in grey.

- Therefore, the Presence Of Inflection Point is A **Systematic Feature** Of the Model.



Approaching the Inflationary Dynamics

- Due to the Complicate Form of $V_{\rm I}$, we Limit Ourselves In Expanding Numerically of $V_{\rm I}$ and J about $z = z_0$,

$$V_{\rm I} \simeq v_0 + v_1\delta z + v_2\delta z^2 + v_3\delta z^3 \ \text{and}\ J \simeq J_0,\ \text{Where}\ \delta z = z - z_0,\ v_0 = V_{\rm I}(z_0)\ \text{and}\ J_0 = J(z_0)$$

Expansion Parameters

$v_0/(m m_{\rm P})^2$	$v_1/(m m_{\rm P})^2$	$v_2/(m m_{\rm P})^2$	$v_3/(m m_{\rm P})^2$	J_0
$3.9\cdot10^{-3}$	$1.5\cdot10^{-6}$	$-2.1\cdot10^{-6}$	2.2	5.4

- Since $v_1 = V_{\rm I}'(z_0)$ & $v_2 = V_{\rm I}''(z_0)/2 \ll v_0, v_3$ we **Neglect** Terms With v_1^2, v_2^2 and v_1v_2

- The **Slow-Roll Parameters** Read $\epsilon = \left(\frac{V_{{\rm I},\widehat z}}{\sqrt{2}V_{\rm I}}\right)^2 \simeq \frac{v_1 + \delta z(2v_2 + 3\delta z v_3)}{\sqrt{2}J_0v_0}$ and $\eta = \frac{V_{{\rm I},\widehat z\widehat z}}{V_{\rm I}} \simeq \frac{2(v_2 + 3\delta z v_3)}{J_0^2v_0}$.

- The Realization Of IPI Is Delimited By The **Condition**

$$\max\{\epsilon(\widehat z), |\eta(\widehat z)|\} \leq 1,\ \text{Which is Saturated for}\ \delta z = \delta z_{\rm f}\ \text{found As Follows}\ \eta(\delta z_{\rm f}) \simeq 1 \ \Rightarrow\ \delta z_{\rm f} \simeq -(J_0^2v_0 + 2v_2)/6v_3 < 0.$$

Given that $J_0^2v_0 \gg v_2$, we Expect $\delta z_{\rm f} < 0$ or $z_{\rm f} < z_\star$.

- The **Number of e-Foldings** $N_\star$ That The Scale $k_\star = 0.05/{\rm Mpc}$ Experiences During IPI

$$N_\star = \int_{\widehat z_{\rm f}}^{\widehat z_\star} d\widehat z \frac{V_{\rm I}}{V_{{\rm I},\widehat z}} = \frac{f_{N\star} - f_{N{\rm f}}}{p_N} \ \text{where}\ p_N = \frac{\sqrt{3v_1v_3}}{J_0^2v_0}\ \text{and}\ f_N(z) = \arctan\frac{v_2 + 3zv_3}{\sqrt{3v_1v_3}}$$

Also $z_\star$ $[\widehat z_\star]$ is the Value of z $[\widehat z]$ When $k_\star$ Crosses The Inflationary Horizon and $f_{N\star} = f_N(\delta z_\star)$ and $f_{N{\rm f}} = f_N(\delta z_{\rm f})$.
Solving it w.r.t $\delta z_\star$ We Obtain

$$\delta z_\star \simeq -\frac{v_2}{3v_3} + \sqrt{\frac{v_1}{3v_3}}\tan\left(\frac{\sqrt{3}N_\star}{J_0^2v_0} + f_{N{\rm f}}\right) < 0.$$

Inflaton Decay – Reheating

- Soon After The End Of IPI, The (Canonically Normalized) **Sgoldstino**

$$\widehat{\delta z} = \langle J\rangle \delta z \quad \text{with} \quad \delta z = z - \mathrm{v} \quad \text{and} \quad \langle J\rangle = \sqrt{\frac{N}{2}\frac{1}{\langle\omega\rangle}}$$

Settles Into A Phase Of Damped Oscillations Abound The Minimum **Reheating** The Universe At A **Temperature**

$$T_{\rm rh} = \left(72/5\pi^2 g_{\rm rh*}\right)^{1/4} \Gamma_{\delta z}^{1/2} m_{\rm P}^{1/2} \quad \text{where } g_{\rm rh*} = 106.75 \text{ and } \Gamma_{\delta z} \simeq \Gamma_{3/2} + \Gamma_\theta + \Gamma_{\tilde h}$$

The Total **Decay Width**, $\Gamma_{\delta z}$, of $\widehat{\delta z}$ With The Individual Decay Widths Are Found To Be

$$(\Gamma_{3/2}, \Gamma_\theta, \Gamma_{\tilde h}) \simeq \left(\frac{\langle\omega\rangle^{-\sqrt{3N}} m_z^5}{96\pi m^2 m_{\rm P}^2}, \ \frac{m_z^3}{16N\pi \mathrm{v} m_{\rm P}}, \frac{N\widehat{\mu}^2 m_z}{16\pi m_{\rm P}^2}\right).$$

They Express Decay of $\widehat{\delta z}$ into **Gravitinos, Pseudo-Sgoldstinos And Higgsinos** via the μ Term Respectively. Thanks to the appearance of N in $\Gamma_{\tilde h}$, it Is Rather Enhanced For Large N's.

- Thanks to the High m_z and $\widehat{\mu}$ Values, no **Moduli Problem** Arises in this Context Since $T_{\rm rh} \sim 1\ \mathrm{PeV} \gg 1\ \mathrm{MeV}$.

Inflationary Requirements

- A **Successful** Inflationary Scenario **In Principle** Requires That
  - The **Number of e-foldings**, $N_\star$, that the Scale $k_\star = 0.05/\mathrm{Mpc}$ Underwent During IPI has to be Sufficient to Resolve the Horizon and Flatness Problems of Standard Big Bang;
  - The **Amplitude** $A_{\rm s}$ **of the Power Spectrum** of the Curvature Perturbations is To Be Consistent with ***Planck*** Data.

$$\text{In total, We Impose} \quad N_\star \simeq 61 + \ln\left(\pi v_0 T_{\rm rh}^2\right)^{1/6} \quad \text{and} \quad A_{\rm s} \simeq 2.1052 \cdot 10^{-9}$$

- The Combined Bicep2/*Keck Array* and *Planck* Results Require For The **Spectral Index** $n_{\rm s}$, its **Running**, $\alpha_{\rm s}$, and the **Tensor-To-Scalar** Ratio r, I.e., $n_{\rm s} = 0.9658 \pm 0.008$, $\alpha_{\rm s} = -0.0066 \pm 0.014$ and $r \lesssim 0.068$ at 95% c.l.

Inflationary Observables

- The **Normalization** of $A_{\rm s}$ Provides A **Value of m**, I.e.

$$A_{\rm s} = \frac{1}{12\pi^2}\frac{V_{\rm I}(\widehat{z_\star})^3}{V^2_{{\rm I},\widehat{z}}(\widehat{z_\star})} \simeq \frac{2\sqrt{3}\pi v_1}{J_0 v_0^{3/2}}\cos^2\left(p_N N_\star + f_{N{\rm f}}\right) \sim 2.1\cdot 10^{-9} \quad\Rightarrow\quad m\sim 10^{-7}m_{\rm P}\ \text{ or }\ 100\ {\rm EeV}.$$

- For The Remaining Inflationary Observables, We Obtain

$$n_{\rm s} = 1-6\epsilon_\star + 2\eta_\star \simeq 1+4p_N\tan\left(p_N N_\star + f_{N{\rm f}}\right),\ \ r = 16\epsilon_\star \simeq 8v_1^2\cos^{-4}\left(p_N N_\star + f_{N{\rm f}}\right)/J_0^2 v_0^2,$$

$$\alpha_{\rm s} = 2\left(4\eta_\star^2-(n_{\rm s}-1)^2\right)/3-2\xi_\star \simeq -4p_N\cos^{-2}\left(p_N N_\star + f_{N{\rm f}}\right),\ \ \text{with}\ \ \xi = V_{{\rm I},\widehat{z}}V_{{\rm I},\widehat{zzz}}/V_{\rm I}^2$$

and the Variables With Subscript $\star$ are Evaluated at $z = z_\star$.

Sample Values of Inflationary Parameters for $N = 12$, $\mathrm{v} = 0.5$ and $m = 5.6\cdot 10^{-7}$.

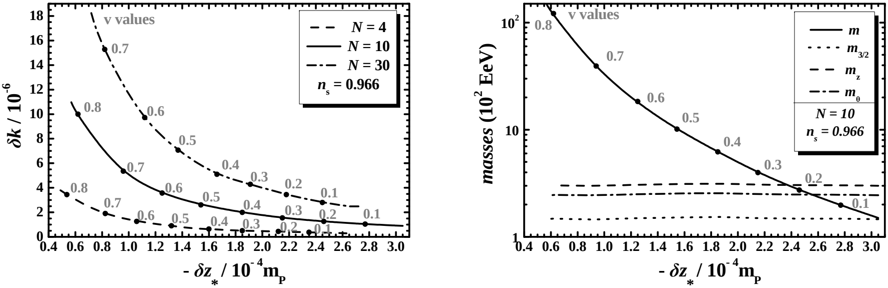
$k_0/0.1$	$z_0/0.1m_{\rm P}$	$\delta k/10^{-6}$	$\delta z_\star/10^{-4}m_{\rm P}$	
4.0166971	7.07433	3.20232	-1.5 {-1.1}	
$V_{\rm I\star}^{1/4}$/EeV	$H_{\rm I\star}$/EeV	$\delta z_{\rm f}/10^{-2}m_{\rm P}$		$m_{\theta{\rm I}\star}/H_{\rm I\star}$
$4.6\cdot 10^5$	49.5	-1.16 {-0.87}		5.1
$n_{\rm s}$	$r/10^{-8}$	$-\alpha_{\rm s}/10^{-3}$	$10^5 A_{\rm s}^{1/2}$	$N_\star$
0.966 {0.97}	4.8 {3.9}	3.3 {3.2}	4.59 {4.27}	46.5 {45}

- The Results Of Our Semianalytic Approach – displayed **in Curly Brackets** – are quite Close to the Numerical Ones.
- The **Semiclassical Approximation**, Used In Our Analysis, Is Perfectly Valid Since $V_{\rm I\star}^{1/4} \ll m_{\rm P}$.
- The **$\theta = 0$ Direction** Is Well Stabilized And Does Not Contribute To The Curvature Perturbation, Since For The Relevant Effective Mass $m_{\theta{\rm I}}$ we find $m^2_{\theta{\rm I}} > 0$ for $N > 3$ and $m_{\theta{\rm I}\star}/H_{\rm I\star} > 1$ where $H_{\rm I} = (V_{\rm I}/3)^{1/2}$.
- The **One-Loop Radiative Corrections**, $\Delta V_{\rm I}$, to $V_{\rm I}$ induced by $m_{\theta{\rm I}}$ Let Intact Our Inflationary Outputs.

Parameter Space Of the Model

- The **Free Parameters** of the model Are $m, N, \mathrm{v}, \delta k = k - k_0$ and $\delta z_\star = z_\star - z_0$ – Recall (k_0, z_0) is the Inflection Point.
- For Any Selected N and v, we Compute (k_0, z_0). Then Enforcing the $N_\star$ and A_s Requirements We Restrict δk and m Whereas the n_s Bounds Determines $\delta z_\star$ E.g., Increasing δk Decreases $N_\star$
- The Model's **Predictions** Regard α_s and r.

1. Allowed Contours Fixing n_s to Its Central Value & Varying v for Selected N's

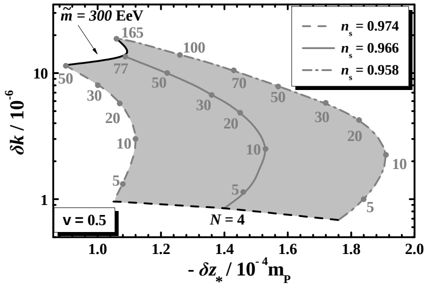


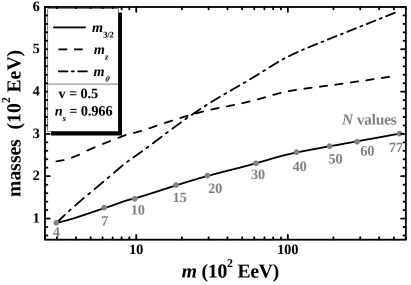
- As N & v Increase The **Tuning** w.r.t δk Reduces.
- For $N = 10$ we Find The Following **Ranges** Of Parameters

$$0.01 \lesssim \mathrm{v} \lesssim 0.815, \quad 15 \lesssim m/10\,\mathrm{EeV} \lesssim 1470 \quad \text{and} \quad (m_{3/2}, m_z, m_\theta) \simeq (150, 300, 250)\,\mathrm{EeV}$$

Whereas the Inflationary **Predictions** Are $\alpha_\mathrm{s} \simeq -3 \cdot 10^{-3}$ and $r \simeq 5 \cdot 10^{-8}$ For $T_\mathrm{rh} \simeq 1.75$ PeV and $N_\star \simeq 46.5$

2. Allowed Region Fixing v = 0.5 & Varying n_s and N





- The Variation of N is Shown Along Each Line.
- The Allowed Region Is Bounded by n_s Bounds, $N > 3$ and $\widetilde{m} < 300$ EeV. Increasing $|\delta z_\star|$, Decreases n_s With Fixed δk.
- Fixing $n_s \simeq 0.966$, we Obtain The Gray Solid Line, Along Which We Obtain

$$3 \lesssim \frac{m}{1\ \mathrm{EeV}} \lesssim 55600, \ \ 8.9 \lesssim \frac{m_{3/2}}{10\ \mathrm{EeV}} \lesssim 30, \ \ 2.3 \lesssim \frac{m_z}{100\ \mathrm{EeV}} \lesssim 4.4, \ \ \text{and} \ \ 8.9 \lesssim \frac{m_\theta}{10\ \mathrm{EeV}} \lesssim 59.$$

- The Required $N_\star \simeq (45.5 - 46.7)$ Corresponds to $T_{\rm rh} \simeq (4 - 20)$ PeV and $w = 0$.
- The Obtained $\alpha_s \simeq -(3.1 - 3.2) \cdot 10^{-3}$ Might Be **Detectable** In Future[10]
- The **Needed Tuning** Though Is **Milder** Than That Needed Within The Conventional MSSM IPI[11]

[10] J.B. Muñoz et al. (2017); [11] R. Allahverdi, K. Enqvist, J. Garcia-Bellido and A. Mazumdar (2017); J.C. Bueno Sanchez, K. Dimopoulos and D.H. Lyth (2006).

Summary

- We Proposed a SUGRA Model With Just **One** Singlet Chiral Superfield That Manages to Offer at Once:
  - **Tiny Cosmological Constant** In The Low-Energy Vacuum at the Cost Of A Fine Tuned Parameter;
  - **Inflection-Point Inflation** Resulting To An Adjustable $n_{\rm s}$, a Small r and a Sizable $\alpha_{\rm s} \sim -10^{-3}$;
  - **Spontaneous SUSY Breaking** at the Scale $\widetilde{m} \sim 100~{\rm EeV}$, Which Is Consistent With The Higgs Boson Mass Measured at LHC within High-Scale SUSY.

Perspectives

- It Would Be Interesting To Investigate:
  - The Generation of Primordial **Black Holes** Which **Is Currently Under Debate**[12] During an **Ultra Slow-Roll Phase**[13]. Here We Did Not Address The Question Of How z reaches z_0. Since $z_\star < z_0$, We Assumed That The Slow-Roll Approximation Offers A Reliable Description Of IPI. This is True if z Lies Initially Near z_0 With A Small Enough Kinetic Energy Density.
  - The Candidacy of Intermediate-Scale Lightest Neutralino With Mass $M_1 \sim {\rm EeV}$ in the Interval $T_{\rm rh} < M_1 < T_{\max}$ As a Cold Dark Matter Candidate Adapting the Production Mechanism Of WIMPZILLAS[14].
  - Whether The Model can be Reconciled With The **String Swampland**[15] After Including one More Superfield[16].

Thank You!

[12] J. Kristiano and J. Yokoyama (2022); cf. A. Riotto (2023) – See also talk of Prof. S. Ketov.
[13] C. Germani and T. Prokopec (2017); J. Garcia-Bellido and E. Ruiz Morales (2016); K. Dimopoulos (2017).
[14] D.J.H. Chung, E.W. Kolb and A. Riotto (1998).
[15] C. Vafa (2005); [16] I.M. Rasulian, M. Torabian and L. Velasco-Sevilla (2021).