Interplay between Inflation and Super-Symmetry Breaking

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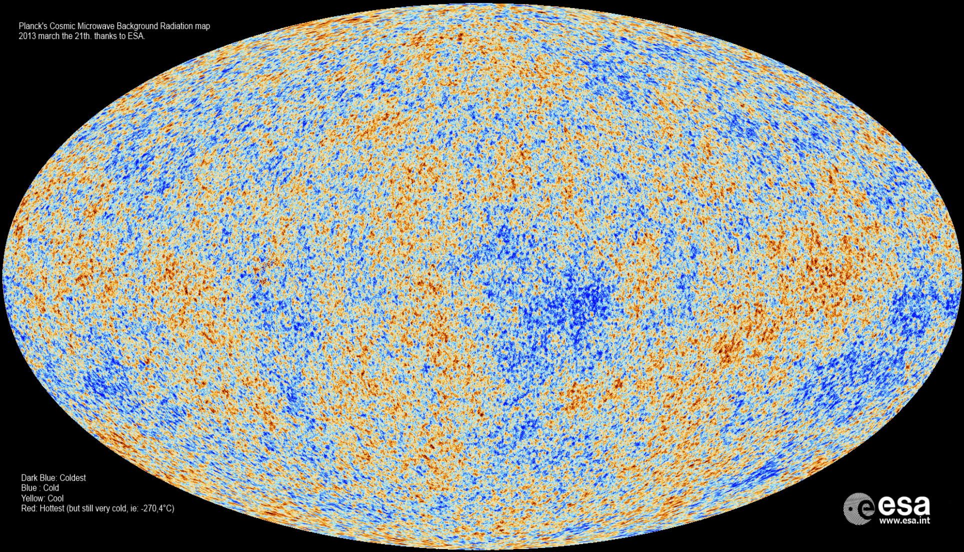
PAI Meeting : *June 2016*

Planck's Cosmic Microwave Background Radiation map
2013 march the 21th. thanks to ESA.



Dark Blue: Coldest
Blue : Cold
Yellow: Cool
Red: Hottest (but still very cold, ie: -270,4°C)

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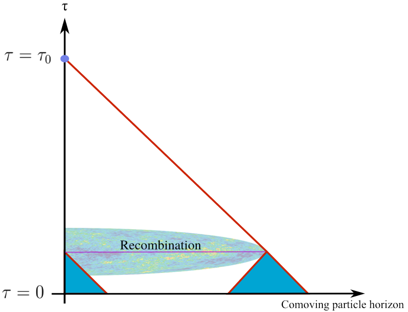
- **Horizon Problem :** Need $\delta\epsilon/\epsilon \sim 10^{-4}$ on 10^{84} initial patches!



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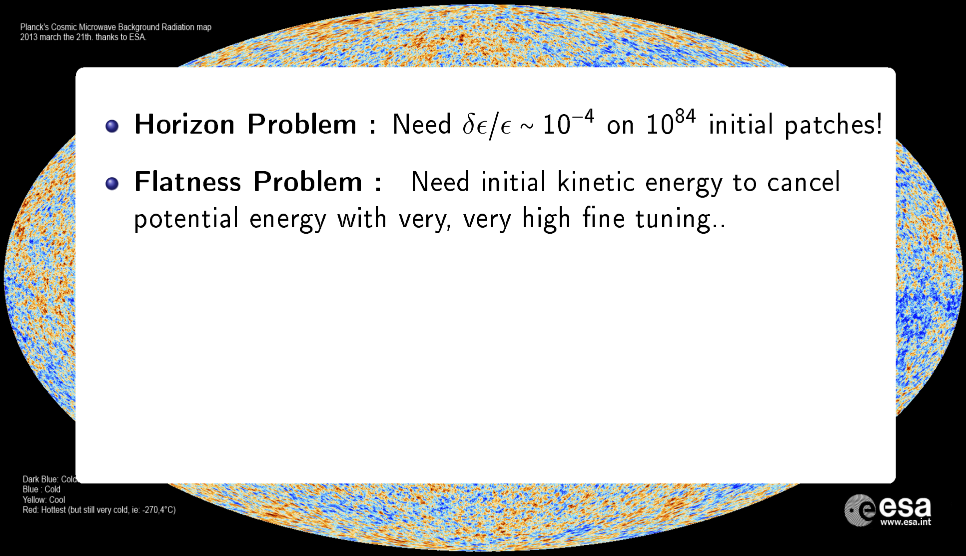

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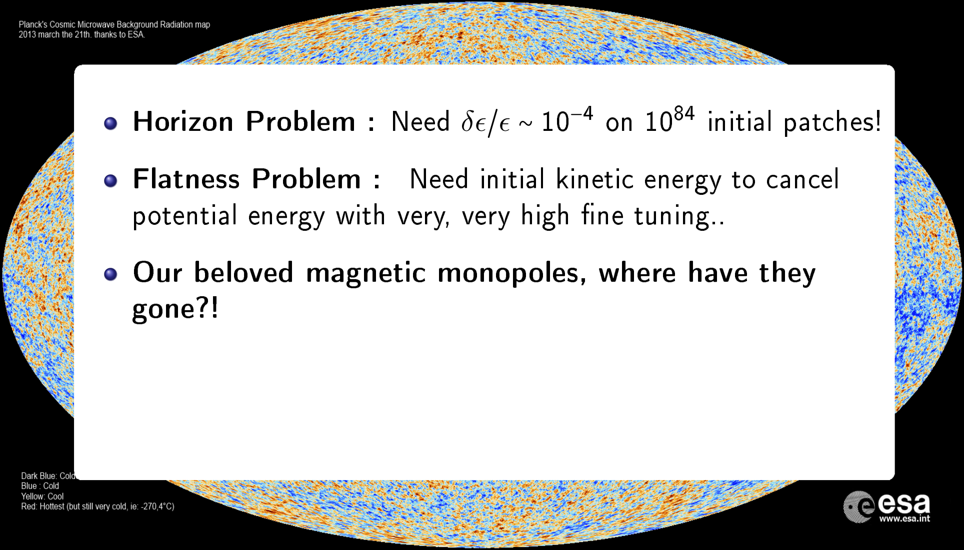

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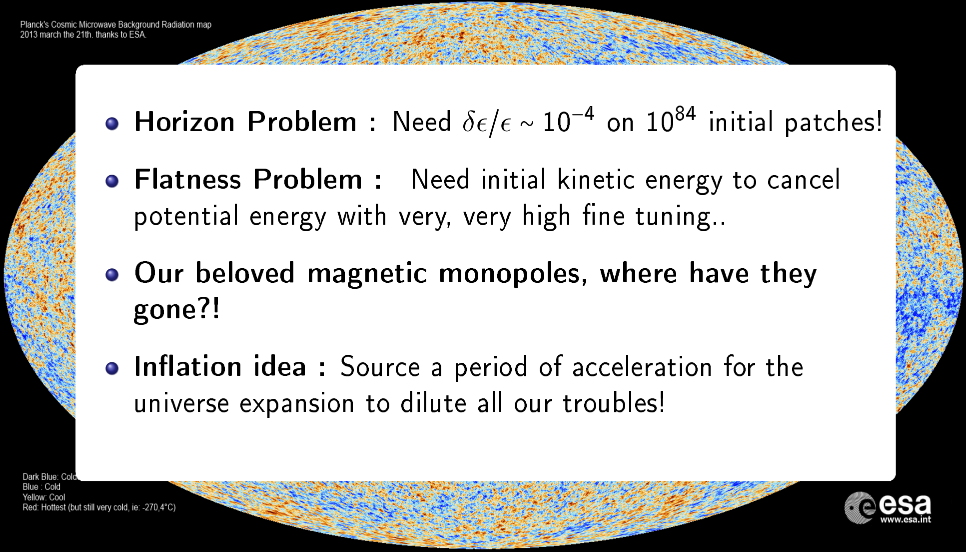

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- **Our beloved magnetic monopoles, where have they gone?!**
- **Inflation idea :** Source a period of acceleration for the universe expansion to dilute all our troubles!

"Mainstream" Single field Inflation

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right)$$

Spacetime dynamics : $\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0$

with

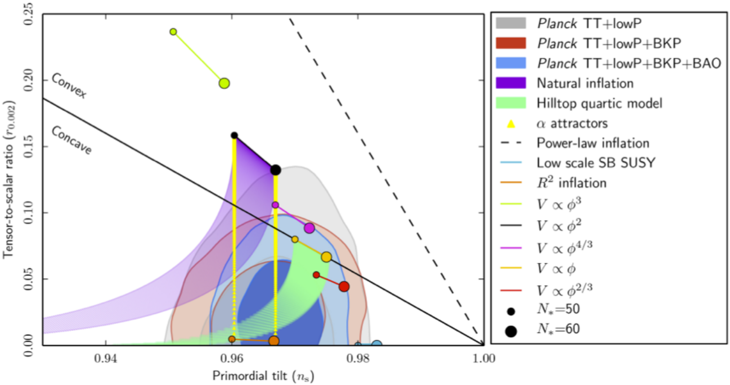
$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\varphi}^2 + V(\varphi)\right)$$

Slow roll conditions :

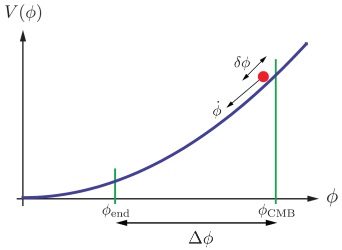
$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \quad \text{and} \quad \eta = \left|\frac{V''}{V}\right| \ll 1$$

Single field Inflation : Observables

- Tensor-to-scalar ratio : $r = 16\epsilon$
- Spectral index : $n_s = 1 - 6\epsilon + 2\eta$



Experimentally : $r \lesssim 0.1$ (Planck) and $n_s \sim 0.965$



Chaotic Inflation : $V(\phi) = m^2\phi^2$

Lyth Bound : $\frac{\Delta\phi}{M_P} = \mathcal{O}(1) \times \left(\frac{r}{0.01}\right)^{1/2}$

$r \sim 0.1 \Rightarrow \Delta\phi \sim 10 M_P$

$\hookrightarrow$ Need a UV theory of gravitation...

Supergravity Set up

Need to embed Inflation in a Supergravity framework

Scalar potential : $V = e^K \left[D_\alpha W \overline{D^\alpha W} - 3|W|^2 \right],$

η–Problem : $V \sim e^{|\phi|^2}$ much too steep for slow rolling...

Idea : Provide a shift symmetry for ϕ in the Kähler :
i.e. Inv. under $\phi \to \phi + ic$

Naive attempt : $K = \frac{1}{2}\left(\phi + \bar{\phi}\right)^2$ and $W = \frac{1}{2} m\phi^2$

$\hookrightarrow V = \frac{1}{2} m^2 \varphi^2 - \frac{3}{16} m^2 \varphi^4 \Rightarrow$ Unbounded from below for $\varphi \sim \mathcal{O}(1)$

Supergravity set up

Simplest attempt : Add a stabilizer field S

$$W = mS\phi$$
$$K = \frac{1}{2}(\phi + \bar{\phi})^2 + |S|^2 - \xi|S|^4$$

- ξ : needed to stabilize S, arising through raditative corrections
- *Inflaton* : $\varphi \equiv \sqrt{2} \cdot Im(\phi)$

Integrating out S gives effectively : $V_{eff}(\varphi) = \frac{m^2}{2}\varphi^2$

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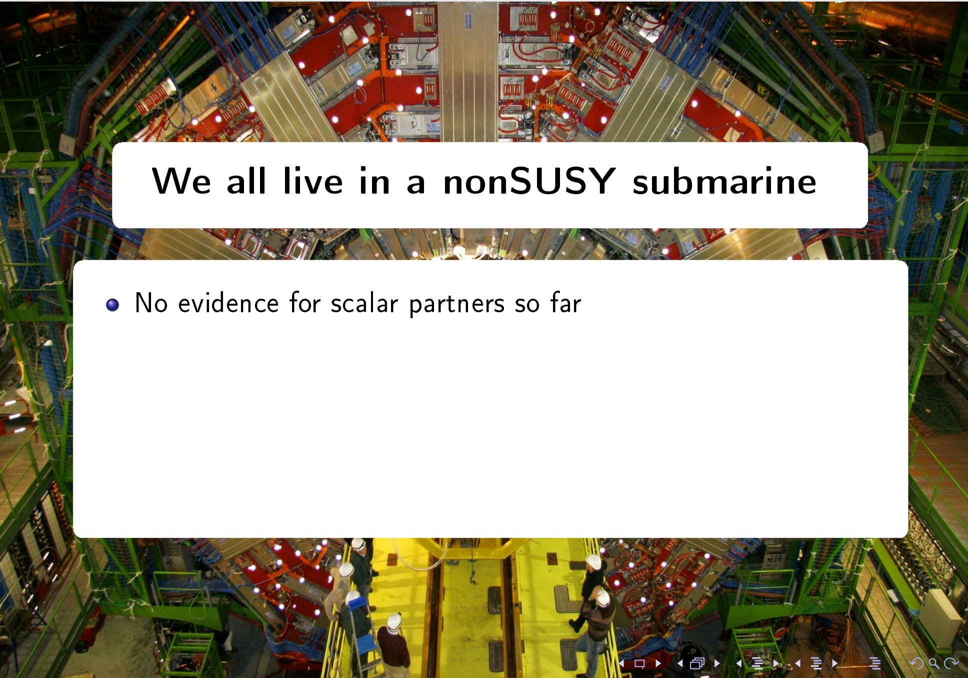
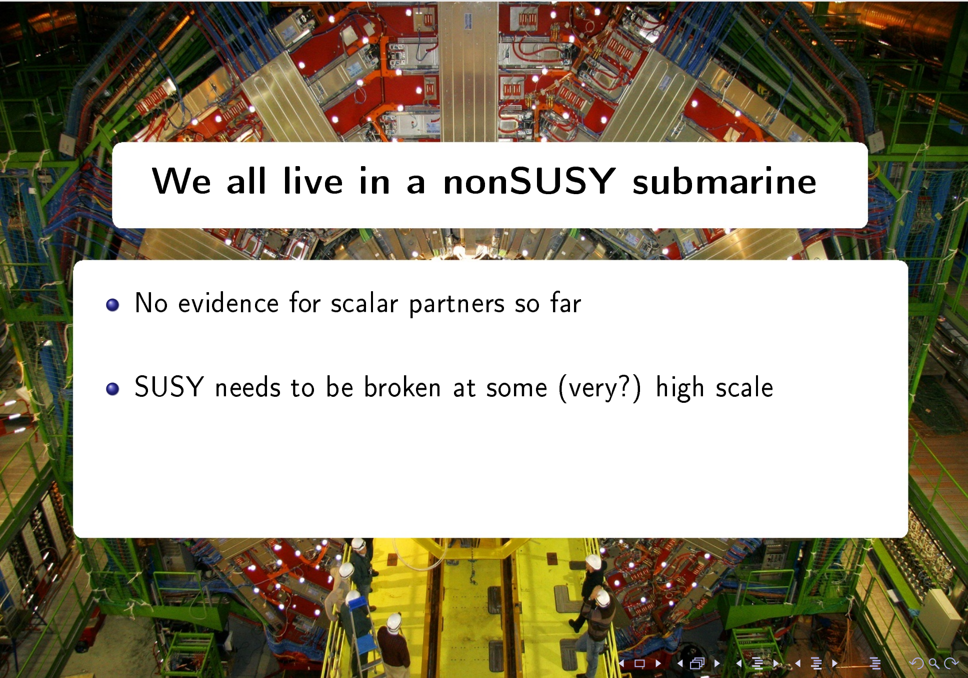
With additional fields, problems can be solved.

We all live in a nonSUSY submarine



We all live in a nonSUSY submarine

- No evidence for scalar partners so far



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- SUSY needs to be broken at some (very?) high scale
- Can inflation trigger SUSY breaking?

SUSY Breaking

How to break SUSY **at the end of Inflation?**

~~SUSY~~ sector		**Inflation sector**
Polonyi field	**O'Raifeartaigh**	**Chaotic**
$W \supset fX$	$W = fX + mS\phi + \frac{h}{2}S^2X$	$W = mS\phi$ + Shift sym.

Idea : Build explicit models $\longrightarrow$ ~~SUSY~~ + Inflation

+ Impose effective chaotic inflation

[W. Buchmüller, E. Dudas, **L.H.**, C. Wieck '14]

Inflaton + Polonyi field

$$\begin{cases} W &= mS\phi + fX + W_0 \\ K &= \frac{1}{2}(\phi+\bar{\phi})^2 + S\bar{S} + X\bar{X} - \xi_1 (X\bar{X})^2 - \xi_2 (S\bar{S})^2 \end{cases}$$

$$V = e^K \left\{ |mS + (\phi+\bar{\phi})W|^2 + K^{-1}_{S\bar{S}} |m\phi + K_S W|^2 + K^{-1}_{X\bar{X}} |f + K_X W|^2 - 3|W|^2 \right\}$$

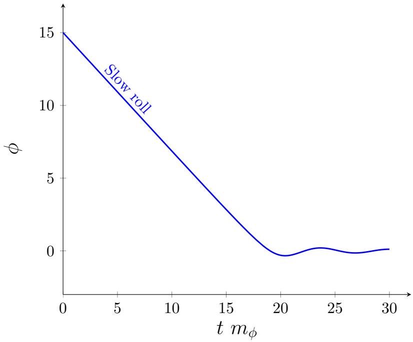
- **End of Inflation**

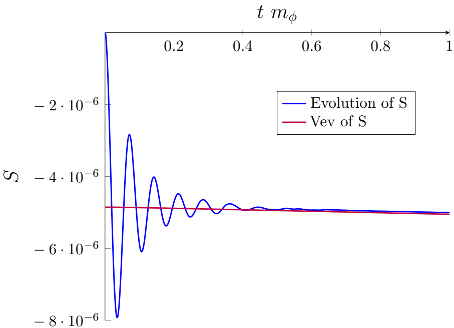
  $\langle\phi\rangle = \langle S \rangle = 0\,, \qquad \langle X \rangle \simeq \frac{1}{2\sqrt{3}\xi_1}$ and $m_{3/2} \simeq W_0 \simeq \frac{f}{\sqrt{3}}$

- **During Inflation**

$$\sqrt{2}\cdot Im(S) \equiv \chi \simeq -\frac{2mW_0\varphi}{f^2 - 2W_0^2 + m^2 + 2m^2\varphi^2\xi_2}$$

Inflaton + Polonyi field





$m = 6 \times 10^{-6},\ f = 10^{-8}$, and $\xi_1 = \xi_2 = 10$

Which dependance in f?

$\hookrightarrow$ Integrate out heavy fields (Stabilizer & Polonyi) to their vevs

$$V_{eff}(\varphi) = f^2 - 3W_0^2 + \frac{1}{2}m^2\varphi^2\left(1 - \frac{4W_0^2}{f^2 - 2W_0^2 + m^2 + 2m^2\varphi^2\xi_2}\right)$$

Bound on the gravitino mass

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⚠ **High values of f $\longrightarrow$ negativity of the potential!**

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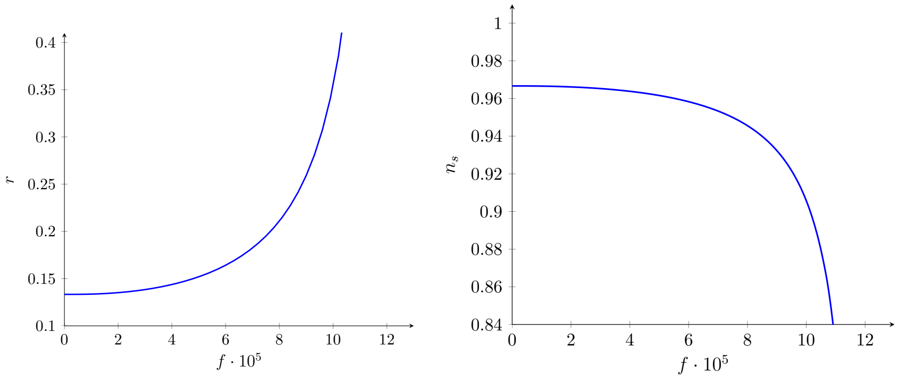
High values of $f \longrightarrow$ negativity of the potential!

- Case $f < m$: $W_0 \simeq \frac{f}{\sqrt{3}}$
- Case $f > m$: $W_0 \simeq \frac{f}{\sqrt{3}}$ + corrections

Anyway, problems expected at least for $m^2 \lesssim m_{3/2}^2 \lesssim \frac{2m^2}{3}\varphi^2\xi_2$

Bound on the gravitino mass

Observables



$$m = 6 \times 10^{-6} \text{ and } \xi_1 = \xi_2 = 10$$

$$m_{3/2} \lesssim H$$

Extended scenario

Can we circumvent the bound?

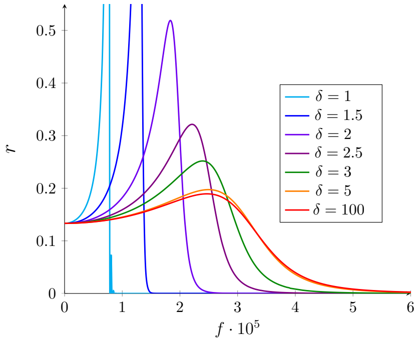
$$\begin{cases} W &= mS\phi + MX\phi + fX + W_0 \\ K &= \frac{1}{2}(\phi+\bar{\phi})^2 + S\bar{S} + X\bar{X} - \xi_1 (X\bar{X})^2 \end{cases}$$

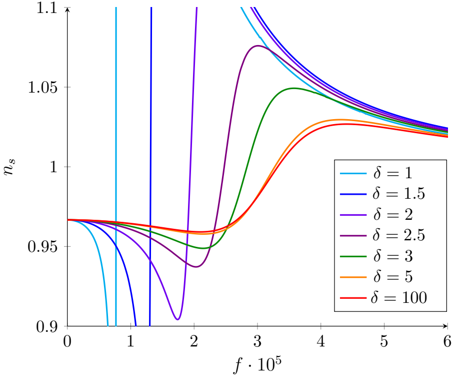
- Inflaton mass : $V = \frac{1}{2}m^2\varphi^2 \longrightarrow V = \frac{1}{2}(m^2+M^2)\varphi^2$
- gravitino mass becomes : $m_{3/2} \simeq W_0 \simeq \frac{m}{\sqrt{m^2+M^2}}\frac{f}{\sqrt{3}}$
- Effective Inflaton potential :

$$V(\varphi) = \frac{1}{2}(1+\delta^2)m^2\varphi^2\left(1 - \frac{8f^2}{f^2(2+8\delta^2+6\delta^4)+3m^2(1+\delta^2)^2(2+\delta^2\varphi^2)}\right) + f^2\left(1-\frac{1}{1+\delta^2}\right),$$

Extended scenario : gravitino bound

Observables





Best case : $\delta \sim 4 \Rightarrow m_{3/2} \lesssim 8 \times 10^{12}$ GeV $\ll H$

O'Raifeartaigh ?

Possible to combine inflation with an O'Raifeartaigh ~~SUSY~~ sector?

$$W = X(f + \frac{1}{2} h S^2) + mS\phi + W_0$$

$$K = \frac{1}{2}(\phi + \bar{\phi})^2 + S\bar{S} + X\bar{X}$$

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Problem : large cross terms $V \supset m\varphi X \bar{S} + \text{c.c.}$

$\longrightarrow$ Tachyonic masses : $m^2_{\text{tach}} \sim -m\varphi \sim -H$

O'Raifeartaigh ?

Issues?

- Add quartic terms for S and X with high ξ_1, ξ_2 coefficients

  $\longrightarrow$ not possible to achieve through loops... (string theory?)

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$$W = W_{\mathrm{O'R}}(\chi_i) + mS\phi$$

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- Completely decouple inflation from $\not{SUSY}$ sector

$$W = W_{\mathrm{O'R}}(\chi_i) + mS\phi$$

- Use Non-linear supersymmetry with goldstino superfield

$$X = \frac{\psi_X \psi_X}{2F_X} + \sqrt{2}\theta\psi_X + \theta^2 F_X \quad , \qquad X^2 = 0$$

$\longrightarrow$ Similar conclusion : $m_{3/2} \lesssim H$

[W. Buchmüller, E. Dudas, **L.H.** , C. Wieck '14]

Nilpotent Inflation

- A popular class of models : Nilpotent Inflation
  [Ferrara, Kallosh, Linde '14], [Dall'Agata, Zwirner '14],...

- Couple the inflaton to a Nilpotent Goldstino Superfield

$$W = f(\Phi)(1 + \sqrt{3}S)\,, \qquad S^2 = 0$$

$$\hookrightarrow V = \left|f'\right|^2 \qquad m_{3/2}^2 = |f|^2 \quad \left(\text{chaotic Inflation: } f(\Phi) = f_0 - \frac{m}{2}\Phi^2\right)$$

- Sgoldstino artificially decoupled (decoupling of the sgoldstino assumed to be released)

- Stabilizer technically eliminated 

- Nice Inflation scenario + ~~SUSY~~

Can we decouple explicitly the sgoldstino ?

Integrating out some heavy sector :

$$W = f(\Phi)(1+\sqrt{3}S) \qquad K = \frac{1}{2}(\Phi+\bar{\Phi})^2 + S\bar{S} - \frac{1}{\Lambda}(S\bar{S})^2$$

$$\hookrightarrow m_s^2 = \frac{m_{3/2}^2}{\Lambda^2}, \qquad \text{and} \quad V = V_0\left[1+\left(1-\frac{V_0}{4m_{3/2}^2}\right)\Lambda^2 + \mathcal{O}(\Lambda^4)\right]$$

- Limit $\Lambda \longrightarrow \infty$: m_s very small, large corrections
- Limit $\Lambda \longrightarrow 0$: m_s large (consistent with nilpotency), low mass of the UV sector : non consistent...

[Dudas, **L.H.**, Wieck, Winkler '16]

A minimal UV model :

$$W = f(\Phi)(1 + \delta S) + \lambda S X^2 + M X Y \,,$$
$$K = \frac{1}{2}(\Phi + \overline{\Phi})^2 + |S|^2 + |X|^2 + |Y|^2 \,.$$

- Here : $\Lambda \sim M/\lambda^2$
- Heavy field sector : tachyonic directions if

$$M^2 \gtrsim \lambda m_{3/2}$$

- Backreaction on the potential under control only if

$$\Lambda \sim 0.1 M_p \Rightarrow m_s \sim \mathcal{O}(10) m_{32}$$

- Initial conditions fine tuned..
  [Dudas, **L.H.**, Wieck, Winkler '16]

Can (very)low-scale ~~SUSY~~ be incorporated in such set up?

- Using "naive" nilpotent inflation : Obviously yes.
- In UV complete scenario much more difficult since $m_s \sim 10 m_{32}$:

  Very low gravitino mass $\Rightarrow$ Low sgoldstino mass (not detected so far)

Idea :

$$m_s \approx \frac{m_{3/2}}{\Lambda} \Rightarrow \text{Make } \Lambda \text{ dynamical!}$$

⋆ During Inflation : $\Lambda(\phi) \approx 0.1 M_p$

⋆ End of Inflation : $\Lambda(0) = \Lambda_0 \ll \Lambda$

Coming soon : [Argurio, Coone, **L.H.**, Mariotti '16]

UV complete, dynamical scale $\Lambda(\phi)$

$$W = f(\Phi)(1+\delta S) + \lambda S X^2 + (M + g\Phi) XY\,,$$
$$K = \frac{1}{2}(\Phi + \overline{\Phi})^2 + |S|^2 + |X|^2 + |Y|^2\,.$$

During Inflation :

$$\Lambda_{eff} = \frac{2\sqrt{3}\pi M_{eff}}{\lambda^2}\,, \qquad \text{where} \qquad M_{eff}^2 \equiv M^2 + g^2\frac{\phi^2}{2}$$

and the UV scale at the end of inflation decreases until

$$\Lambda_0 = \frac{2\sqrt{3}\pi M}{\lambda^2}\,.$$

Can accomodate : $m_s \sim \mathrm{TeV}$, $m_{3/2} \gtrsim \mathrm{eV}$ and reasonable inflation observables.

Coming soon : [Argurio, Coone, **L.H.**, Mariotti '16]

Conclusion

- Interplay between Supersymmetry breaking and Inflation can be subtle to handle and leads to constraints on the gravitino mass
- Models **with** stabilizer fields require $m_{3/2} \ll H$
- Models **without** stabilizer fields require SUSY breaking and generically $m_{3/2} \gg H$

→ Soft breaking terms MUST drive Inflation!

- Nilpotent constraints difficult to render consistent with UV complete formulation without tuning
- UV complete models can though accomodate (very) low SUSY breaking

That's all folk!

Back up Slides

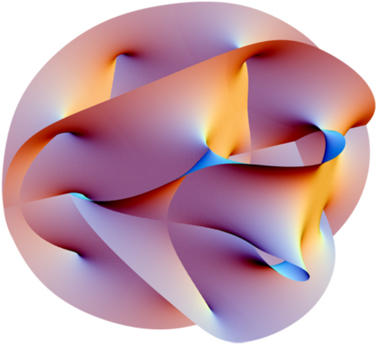
Bound on the gravitino mass

- Need to estimate ξ_1, ξ_2 :

  Heavy modes couplings $W_{\text{heavy}} \supset \lambda_1 S\psi_1^2 + \lambda_2 X\psi_2^2 + \text{mass terms}$

  $$K_{\text{1-loop}} \simeq S\bar{S}\left[1 - \frac{\lambda^2}{16\pi^2}\log\left(1 + \frac{\lambda^2 S\bar{S}}{M^2}\right)\right] \simeq S\bar{S} - \frac{\lambda^4}{16\pi^2 M^2}(S\bar{S})^2$$

  $$\lambda \sim \mathcal{O}(1) \text{ and } M \sim M_{GUT} \Rightarrow \xi_1, \xi_2 \sim \mathcal{O}(10) M_P^{-2}$$



A source of SUSY breaking :
Stabilized Moduli

Single field scenario:

$$V = \frac{1}{2} m^2 \varphi^2 - \frac{3}{16} m^2 \varphi^4$$

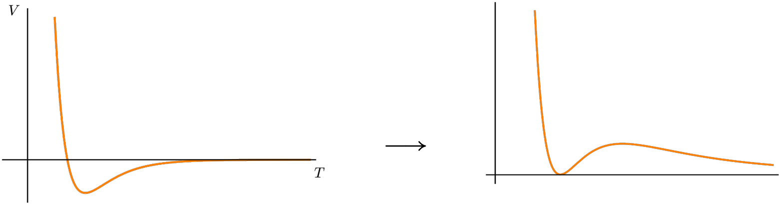
Can backreaction of moduli stabilization help?

Moduli stabilization

- String Theory compactification on a 6D manifold
- Non perturbative corrections to the superpotential allow to stabilize moduli, e.g.

$$\text{e.g.}\quad W = W_0 + Ae^{-aT}, \qquad K = -3\ln(T+\bar{T}) \qquad \text{[KKLT, '03]}$$

- Uplift required to pull up the cosmological constant



Various options : F-term, D-term, anti-branes,...

Moduli stabilization

- If coupled to Inflation : Need $m_{3/2} > H_{inf}$ for the modulus to remain stabilized [Kallosh, Linde '04]

- Alternatively, add a second non perturbative term (Racetrack)

$$W = W_0 + Ae^{-aT} + Be^{-bT} \,, \qquad \text{[Kallosh, Linde '04]}$$

$\longrightarrow$ Tune parameters to stay in a supersymmetric vacuum

$$\langle D_T W \rangle = \langle W \rangle = 0$$

$\hookrightarrow$ No constraint from Inflation

- Supersymmetric stabilization : Corrections to the potential suppressed for heavy moduli [Buchmüller,Dudas,LH,Wieck '14]

- SUSY breaking $\rightarrow$ non-decoupling effects

$$V = \frac{1}{2}\tilde{m}^2\varphi^2 + \frac{c}{2}\tilde{m}m_{3/2}\varphi^2 - \frac{3}{16}\tilde{m}^2\varphi^4 + \ldots .$$

$\rightarrow$ Soft breaking terms can save Inflation for large $m_{3/2}$!

- General formulation of the effective potential

- Investigate this option through several models : KKLT, Kähler uplifting, Large Volume Scenario

Case with Stabilizer

$$K = K_0(T_\alpha, \overline{T}_{\bar{\alpha}}) + \frac{1}{2}K_1(T_\alpha, \overline{T}_{\bar{\alpha}})(\phi + \bar{\phi})^2 + k(|S|^2)\,,$$
$$W = W_{\rm mod}(T_\alpha) + mS\phi\,.$$

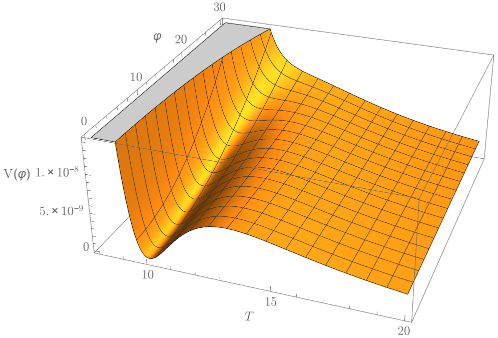
$$m_{3/2} << \tilde{m}$$

Case without Stabilizer

$$K = K_0(T_\alpha, \overline{T}_{\bar{\alpha}}) + \frac{1}{2}K_1(T_\alpha, \overline{T}_{\bar{\alpha}})(\phi + \bar{\phi})^2\,,$$
$$W = W_{\rm mod}(T_\alpha) + \frac{1}{2}m\phi^2\,.$$

$\Rightarrow$ Corrections to V can possibly solve the problem...
[Buchmüller,Dudas,LH,Westphal, Winkler, Wieck '14]

KKLT



$$V(\varphi) = \frac{1}{2}m^2\varphi^2 + \frac{3}{2}m m_{3/2}\varphi^2 - \frac{3}{16}m^2\varphi^4 + \dots \longrightarrow \boxed{m_{3/2} \gtrsim H}$$

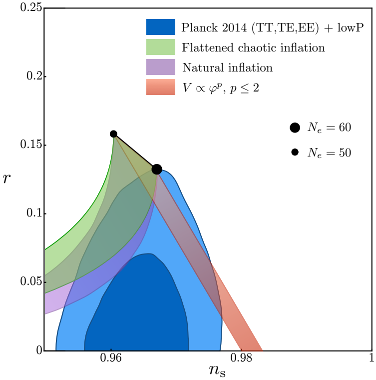
supersymmetric mass term

dangerous term, still there...

- In all scenarios : Generic form of the potential

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2 \left(1 - \frac{\varphi^2}{\varphi_c^2}\right)$$

$\longrightarrow$ Monomial flattening vs Polynomial flattening



[Buchmüller,Dudas,LH,Westphal, Winkler, Wieck '14]