Polonyi Inflation

Dynamical Supersymmetry Breaking and Late-Time *R* Symmetry Breaking as the Origin of Cosmic Inflation

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Kai Schmitz

Postdoc in the Particle and Astroparticle Physics Division at

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Based on *arXiv:1604.04911 [hep-ph]*.

In collaboration with Tsutomu T. Yanagida (IPMU).

PASCOS 2016
XIIth Rencontres du Vietnam, ICISE, Quy Nhon, Vietnam
Parallel Session V: Inflation and Alternatives | July 12, 2016

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Inflation and Supersymmetry Breaking Unified ▪

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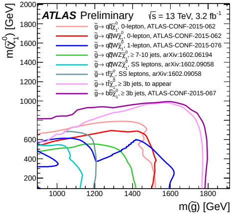
Status of inflation and low-scale SUSY in 2016

Inflation

- Plethora of models in the literature.
- Particle physics origin rather unclear.

Supersymmetry



- No SUSY signals at the LHC, so far.
- $m_h \simeq 125\,\mathrm{GeV}$ calls for large $\tilde{t}$ loops.

This talk: Link b/w inflation and supersymmetry. Answer to the question: *Why inflation?*

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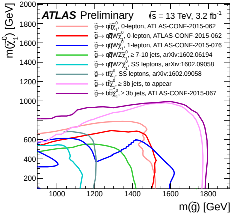

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Let go of SUSY as a solution to the hierarchy problem:

- R parity $\rightarrow$ stable LSP $\rightarrow$ dark matter.
- Unification at $\Lambda_{\mathrm{GUT}} \sim 10^{16}\,\mathrm{GeV}$.
- UV completion in string theory.

- Soft masses of $\mathcal{O}(10)\,\mathrm{TeV}$ or larger.
- No gravitino / Polonyi problems.
- Mediation: solely via gravity (PGM, ...)

High-scale SUSY breaking as the origin of inflation

Another intriguing possibility in high-scale supersymmetry:

- Spontaneous ~~SUSY~~ results in a nonzero contribution to the vacuum energy density:

$$\langle V\rangle = \Lambda_{\mathrm{SUSY}}^4\,, \quad \Lambda_{\mathrm{SUSY}}^2 \sim \langle F\rangle \text{ or } \langle D\rangle$$

Our idea: If Λ_{SUSY} large enough, $\Lambda_{\mathrm{SUSY}}^4$ may be the vacuum energy driving inflation!

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Consider SUSY breaking via nonzero F-terms:

[O'Raifeartaigh '75]

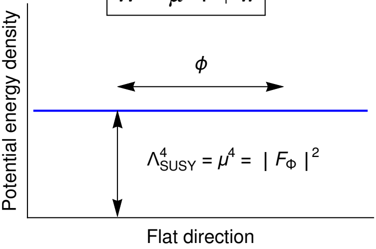
- Nonzero vacuum energy density $\Lambda^4_{\mathrm{SUSY}}$.
- In global SUSY, flat direction at tree level.
  [Ray '06] [Shih '08]
- Flatness of the potential protected by SUSY nonrenormalization theorem.
  [Grisaru, Siegel & Rocek '79] [Seiberg '93]

Our goal: Realize successful inflation in the Polonyi model. → Polonyi inflation!

Simplest example: the Polonyi model

[Polonyi '78]

$$\boxed{W = \mu^2 \Phi + w}$$



Late-time R symmetry breaking

Things are of course not as simple: SUGRA corrections typically spoil slow-roll inflation.

- In SUGRA, the cosmological constant (CC) needs to vanish in the true vacuum:

$$\boxed{\langle V \rangle = |\langle F \rangle|^2 - 3\, e^{\langle K \rangle}\, |\langle W \rangle|^2 \overset{!}{=} 0}$$

- E.g., in the Polonyi model, constant in the superpotential: $w \rightarrow w_0 = \left(2 - \sqrt{3}\right) \mu^2$.

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1. Assume unbroken *R* symmetry in the sector responsible for $w_0 \Rightarrow w = 0$ initially.
2. Assume SUSY and *R* symmetry are broken dynamically at times t_{SUSY} and t_R.
3. Assume there is no other sources of inflation present in the theory.

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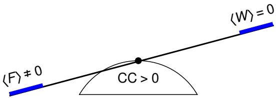
$t_{\rm SUSY} < t_R$



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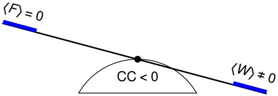

- dS, $\mathrm{CC} > 0$, exponential expansion
- AdS, $\mathrm{CC} < 0$, finite spatial extent

Universes (feat. ~~SUSY~~ and $\mathrm{CC} = 0$) that are habitable to life are bound to experience inflation & late-time *R* symmetry breaking! ⇒ Reason for inflation in our cosmic past!

Ingredients for successful Polonyi inflation

❶ Unbroken R symmetry in the sector responsible for the generation of $w \subset W$:

- Assume discrete, anomaly-free R symmetry: Z_N^R
  [Krauss & Wilczek '89] [Ibanez & Ross '91; '92] [Banks & Dine '92] [Ibanez '93]
- Best candidate: Z_4^R, also allows to solve the μ problem in the MSSM.
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❷ Strong gauge dynamics accounting for μ and w in the Polonyi superpotential:

- UV completion in the context of strongly coupled supersymmetric gauge theories.
- No dimensionful input parameters. All mass scales generated via dim. transmutation:
  [Affleck, Dine & Seiberg '84; '84; '85]

$$\Lambda_{\rm SUSY} \equiv \Lambda_{\rm inf} \sim \Lambda$$

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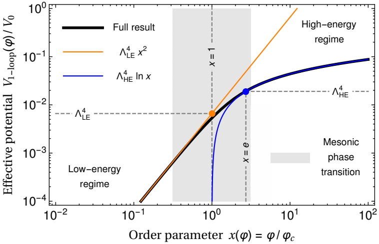
Our work: Minimal example of successful Polonyi inflation & late-time R symmetry breaking

- IYIT model of dynamical SUSY breaking to generate $V_{\rm inf} \sim \mu^4$.
- R symmetry breaking via gaugino condensation in a pure $SU(2)$ gauge theory.
- Small inflaton value triggers mass deformation of the R symmetry breaking sector.

Dynamical UV completion of the Polonyi model

Low-energy effective regime of the IYIT model



- $SU(2)$ theory $+$ 4 quarks, 6 singlets.
- Effective superpotential at low energies

$$W_{\text{eff}} \simeq \kappa_\Phi \Phi \left[v^2 - \frac{1}{2}\left(X^n\right)^2\right] + m_n S_n X^n + \cdots$$

- $m_a \geq \kappa_\Phi v \;\Rightarrow$ Keep vacuum energy after inflation! $\Rightarrow$ No topological defects!
- Plus radiative & gravitational corrections.

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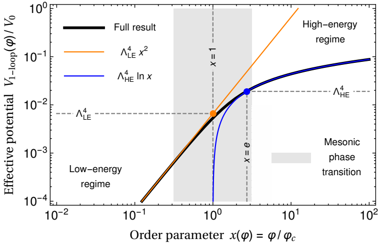

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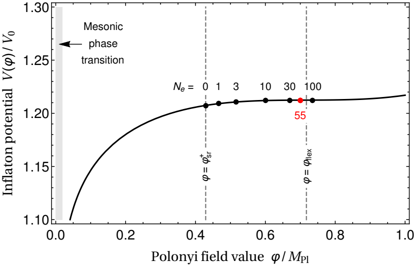
R symmetry breaking via gaugino condensation at small inflaton field values

- $SU(2)$ theory $+$ 4 quarks coupled to a singlet “waterfall” field, $W \supset P\, Q^i Q^i$.
- Render the field P unstable towards the end of inflation, $W \supset \alpha\, Y \left(v_P^2 - P^2\right) + \beta\, Y^3$.
- Choose α such that $m_P^2 = -\alpha^2 v_P^2 + 3\, H^2\left(\varphi\right)$ only becomes negative at late times.
- R symmetry breaking sector turns into pure SYM, $W \supset w \sim \langle P \rangle\, \tilde{\Lambda}^2$.

SUSY breaking scale: $\mu^2 \sim \kappa_\Phi v^2 \sim \kappa_\Phi \Lambda^2$. R symmetry breaking constant: $w \sim \langle P \rangle\, \tilde{\Lambda}^2$.

Scalar potential driving inflation

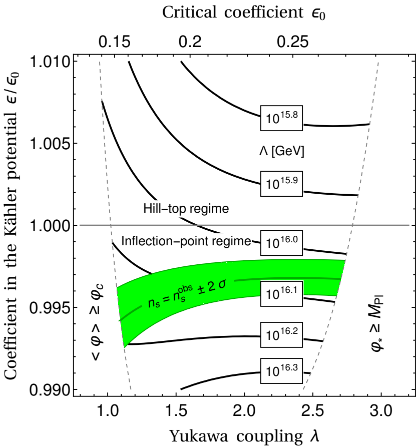
$$\boxed{V(\varphi) = \mu^4 \left[1 - \frac{\varepsilon}{2}\left(\frac{\varphi}{M_{\rm Pl}}\right)^2 + \frac{1}{8}\left(1 - \frac{7\varepsilon}{2} + \frac{8\varepsilon^2}{3}\right)\left(\frac{\varphi}{M_{\rm Pl}}\right)^4 + \cdots\right] + \frac{6\,m^4}{16\pi^2}\ln\frac{\varphi}{\varphi_c}}$$



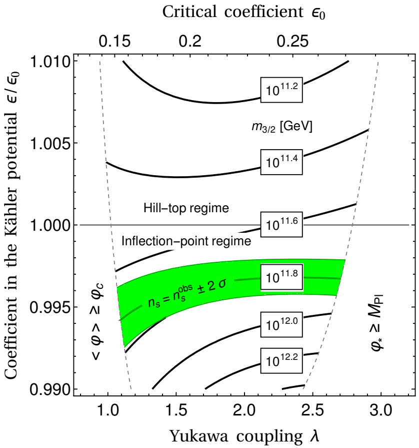
- Potential of FHI: incl. SUGRA and loop corrections, in the limit $m_{3/2} = 0$.
  [Bastero-Gil, King, Shafi '07]
- No tadpole term (no odd powers), no dependence on complex phase.
  [Buchmüller, Covi & Delpine '00]
- Usual slow-roll bound $m_{3/2} \lesssim 10^{-3} H$ does not apply. In fact, $m_{3/2} \simeq H$.
  [Buchmüller, Domcke, Kamada & K.S. '14]

Dynamical realization of F-term hybrid inflation minus all its shortcomings!

Inflationary CMB observables



Dynamical scale $\Lambda \sim 10^{16}\,\mathrm{GeV}$



Gravitino mass $m_{3/2} \sim 10^{12}\,\mathrm{GeV}$

- $A_s^{\rm obs} \simeq 2 \times 10^{-9}$ and $n_s^{\rm obs} \simeq 0.968$ for natural parameter values: $\lambda \simeq 2$ and $\varepsilon \simeq 0.2$.
- Similarity / equivalence of scales: $\Lambda \sim \Lambda_{\rm GUT}$ and $H \simeq m_{3/2}$. $\Rightarrow$ $r \sim 10^{-5} \cdots 10^{-4}$.

Dark matter, baryogenesis and electroweak vacuum stability

Thermally produced winos with a fine-tuned mass as dark matter:

- Assume anthropic selection of a fine-tuned wino mass. AMSB $+$ Higgsino loops:
  [Ibe, Matsumoto & Yanagida '12] [Hall, Nomura & Shirai '13]

$$M_{\rm wino} \sim 3\,\mathrm{TeV}$$

- Nonthermal relics reach thermal equilibrium. Simple solution to the Polonyi problem!
- Our prediction: neutral/charged winos only sparticles at low energies (detectable!).

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Reheating via gravitino decay:

- Polonyi inflation is followed by a phase of gravitino domination (nonrelativistic matter).
  [Jeong & Takahashi '13]
- Reheating temperature not a free parameter, but fixed by $m_{3/2} = m_{3/2}\left(A_s^{\mathrm{obs}}\right)$,

$$T_{\mathrm{rh}} \simeq 0.4\sqrt{\Gamma_{3/2}\,M_{\mathrm{Pl}}} \sim 10^8\,\mathrm{GeV}\,, \qquad \Gamma_{3/2} = \frac{193}{384\pi}\,\frac{m_{3/2}^3}{M_{\mathrm{Pl}}^2}$$

- Thermal leptogenesis plus moderate resonance effects or nonthermal leptogenesis.
  [Fukugita & Yanagida '86] [Pilaftsis '97; Pilaftsis & Underwood '04] [Lazarides & Q. Shafi '91]

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Vacuum stability: SUSY prevents $\lambda_h < 0$ as long as $m_{\rm soft} \lesssim 10^{12\cdots13}\,\mathrm{GeV}$. Coincidence!?

A close link between inflation and dynamical SUSY breaking

Observation: High-scale SUSY offers the possibility to unify SUSY breaking and inflation!

- Expansion driven by $\Lambda_{\rm SUSY}^4$, pseudoflat Polonyi direction acts as the inflaton field.

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Implications: Polonyi inflation, similar to F-term hybrid inflation in the limit $m_{3/2} = 0$.

- No tadpole term in the inflaton potential, no topological defects, no bound on $m_{3/2}$.

$$H \simeq m_{3/2} \quad \Rightarrow \quad m_{3/2} \simeq \frac{\pi}{\sqrt{2}} \sqrt{r\, A_s^{\mathrm{obs}}} \sim 10^{12}\,\mathrm{GeV} \left(\frac{r}{10^{-4}}\right)^{1/2}$$

- Suppose anthropic selection of A_s^{obs}. $\Rightarrow$ Explanation for large SUSY-breaking scale.
- Wino LSP (DM, only sparticles at low energies), leptogenesis, EW vacuum stability.

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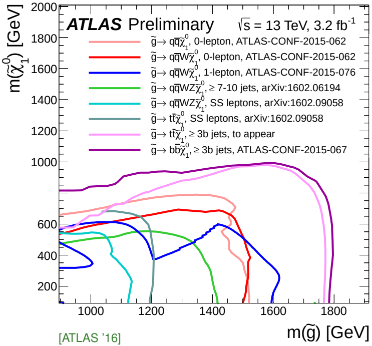
Next steps: Seek alternative UV completions of the Polonyi model, $W = \mu^2\Phi + w$. More comprehensive study of reheating and low-energy phenomenology. $\Rightarrow$ Lots of work to do!

Thank you for your attention!

Supplementary Material

Status of supersymmetry in early 2016



[ATLAS '16]

Low-scale supersymmetry under pressure:

- No SUSY signals at the LHC, so far.
- SM Higgs boson mass of a 125 GeV calls for large stop loop corrections.

No need to give up on SUSY altogether:

- *R* parity $\to$ stable LSP $\to$ dark matter.
- Gauge unification at $\Lambda_{\mathrm{GUT}} \sim 10^{16}\,\mathrm{GeV}$.
- UV completion of the SM in string theory.

What if we let go of the notion that SUSY is responsible for stabilizing the EW scale?

- Allow for soft sparticle masses of $\mathcal{O}(10)\,\mathrm{TeV}$ and larger.
- No more gravitino / Polonyi problems in cosmology. Less tension from $\not{CP}$ & FCNCs.
- Simple mediation to the visible sector: solely via gravitational interactions (PGM).

[Giudice, Luty, Murayama & Rattazzi '98] [Wells '03; '05] [Arkani-Hamed & Dimopoulos '05] [Ibe, Moroi & Yanagida '07; Ibe & Yanagida '12] [Arkani-Hamed, Gupta, Kaplan, Weiner & Zorawski '12] [Hall & Nomura '12] [Arvanitaki, Craig, Dimopoulos & Villadoro '13]

Our starting point for a realistic model of Polonyi inflation

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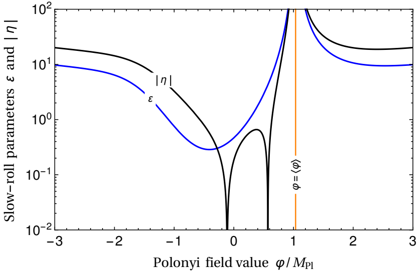
Program: Find UV completion of the Polonyi model, identify flat tree-level direction in global SUSY, study inflationary potential in dependence of *gravitational and radiative corrections*.

Why loop corrections? Inflation in the bare Polonyi model

Study viability of inflation in the original Polonyi model for different choices of K and w:



Superpotential:

$$W = \mu^2 \Phi + w$$

Kähler potential (the usual suspects):

$$K_{\rm can} = |\Phi|^2 + \frac{\varepsilon}{4} |\Phi|^4 + \cdots$$

$$K_{\rm shi}^{\pm} = \pm \frac{1}{2} \left(\Phi \pm \Phi^\dagger\right)^2 \mp \frac{\varepsilon}{2} \left(\Phi \mp \Phi^\dagger\right)^2 + \cdots$$

	$K_{\rm can}$ $(\varepsilon \leq 0)$	$K_{\rm can}$ $(\varepsilon > 0)$	$K_{\rm shi}^{\pm}$ $(\varepsilon = 0)$	$K_{\rm shi}^{+}$ $(\varepsilon \neq 0)$	$K_{\rm shi}^{-}$ $(\varepsilon \neq 0)$
$w = w_0$	$\cancel{SR}$	$\cancel{SR}$	$V \to -\infty$	$\langle V \rangle < 0$	$\cancel{SR}$
$w = 0$	$n_s \geq 1$	$w \to w_0$?	$V \to -\infty$	$\langle V \rangle < 0$	$\langle V \rangle < 0$

Conclusion: Inflation not feasible in the bare Polonyi model. Need radiative corrections!

[Ovrut & Steinhardt '83]

Dynamical SUSY breaking in the IYIT model

[Izawa & Yanagida '96]
[Intriligator & Thomas '96]

IYIT model: Simplest vector-like model of dynamical SUSY breaking. Use to generate μ!

- Strongly coupled $SU(2)$ SUSY gauge theory with 4 fundamental quark fields Ψ^i.
- At low energies, quantum moduli space of degenerate SUSY vacua, spanned by

$$M^{ij} \simeq \frac{1}{4\pi}\frac{1}{\Lambda}\left\langle \Psi^i \Psi^j \right\rangle , \qquad M^{ij} = -M^{ji} , \qquad \mathrm{Pf}\left(M^{ij}\right) \simeq \frac{\Lambda^2}{16\pi^2}$$

- 6 gauge-invariant composite flat directions ("mesons") subject to deformed constraint.

Dynamical SUSY breaking in the IYIT model

[Izawa & Yanagida '96]
[Intriligator & Thomas '96]

IYIT model: Simplest vector-like model of dynamical SUSY breaking. Use to generate μ!

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Break SUSY by introducing appropriate tree-level couplings to 6 singlet fields Z_{ij} in W_{tree}:

$$W_{\mathrm{IYIT}}^{\mathrm{tree}} = \frac{1}{4}\lambda_{ij}^{kl} Z_{kl} \Psi^i \Psi^j \quad \rightarrow \quad W_{\mathrm{IYIT}}^{\mathrm{eff}} \simeq \frac{1}{16\pi}\lambda_{ij}^{kl} \Lambda Z_{kl} M^{ij}$$

- Lifts the flat directions in moduli space. $\mathrm{Pf}(M) \neq 0$ no longer compatible with $V = 0$.
- SUSY broken à la O'Raifeartaigh by nonvanishing singlet F-terms, $F_Z \sim \lambda \left\langle M \right\rangle \neq 0$.

Next: Perform some magic and derive the superpotential of hybrid inflation from $W_{\mathrm{IYIT}}^{\mathrm{eff}}$.

F-term hybrid inflation with massive waterfall fields

[Copeland, Liddle, Lyth, Stewart & Wands '94] [Dvali, Shafi & Schaefer '94] [Dimopoulos, Dvali & Rattazzi '97] [Izawa '98]

$$W_{\rm IYIT}^{\rm eff} \simeq \frac{1}{16\pi}\lambda_{ij}^{kl}\Lambda Z_{kl}M^{ij} \rightarrow \kappa_\Phi \Phi\left[v^2 - \frac{1}{2}\left(\Xi^0\right)^2 - \frac{1}{2}\left(X^n\right)^2\right] + m_0\,\Sigma\,\Xi^0 + m_n\,S_n\,X^n + \cdots$$

---

❶ Transform singlet and meson fields Z_{kl} and M^{ij} from $SU(4)$ to $SO(6)$ basis:

- Global $SU(4)$ flavor symmetry if $\lambda_{ij}^{kl} = \lambda\,\delta_i^k\,\delta_j^l$. Antisymmetric tensors $Z_{kl}, M^{ij} \sim$ **6** of $SU(4)$.
- $SU(4) \cong SO(6)$ $\Rightarrow$ Switch to vectors $S_a, X^a \sim$ **6** of $SO(6)$ $\Rightarrow$ $W_{\rm IYIT}^{\rm eff} \simeq \lambda_a/4\pi\ S_a\,X^a$.

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❷ Include deformed moduli constraint using a Lagrange multiplier field T:

$$W_{\mathrm{eff}}^{\mathrm{dyn}} \simeq 4\pi T\left[\mathrm{Pf}\left(M^{ij}\right) - \Lambda^2/16\pi^2\right], \quad \mathrm{Pf}\left(M^{ij}\right) = \frac{1}{2}\left(X^a\right)^2$$

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$$X^0 = \left\langle X^0 \right\rangle + \Xi^0, \quad \left\langle X^0 \right\rangle = f(\lambda)\,\Lambda/4\pi, \quad \langle T \rangle = g(\lambda)\,\langle S_0 \rangle$$

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❹ Diagonalize the mass matrix of the SUSY-breaking fields S_0 and T:

$$\left(\Phi\;\Sigma\right)^T = R(\beta)\cdot\left(S_0\;\;T\right)^T\,, \quad \tan\beta = g\left(\lambda\right)$$

$$v \sim \Lambda/4\pi\,, \quad \kappa_\Phi \sim \lambda_0\,, \quad m_0 = m/\sin\beta\,, \quad m = \kappa_\Phi v = \lambda_0/4\pi\;\Lambda\,, \quad m_n = \lambda_n/4\pi\;\Lambda$$

Low-energy effective theory

$$\boxed{W_{\mathrm{IYIT}}^{\mathrm{eff}} \simeq \kappa_\Phi \Phi \left[v^2 - \frac{1}{2}\left(\Xi^0\right)^2 - \frac{1}{2}\left(X^n\right)^2\right] + m_0\, \Sigma\, \Xi^0 + m_n\, S_n\, X^n + \cdots}$$

- Polonyi field Φ: linear combination of the IYIT singlet S_0 & the Lagrange multiplier T.
- Mesons Ξ^0, X^n: $SO(6)$ multiplet of *would-be* waterfall fields with masses m_0, m_n.
- $m_a \geq m = \kappa_\Phi v$ $\Rightarrow$ Keep vacuum energy density after inflation! $\Rightarrow$ No top. defects!

Low-energy effective theory below the meson mass thresholds $m_a \sim \Lambda$:

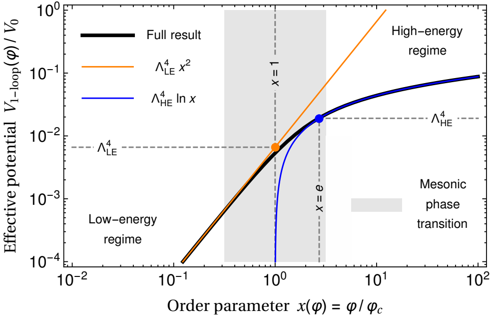
$$W_{\mathrm{IYIT}}^{\mathrm{eff}} \simeq \mu^2 \Phi \quad , \qquad \mu = \kappa_\Phi^{1/2} v \sim \lambda^{1/2}/4\pi\, \Lambda$$

Dynamical UV completion of half the Polonyi model!

- Complex Polonyi scalar $\phi \subset \Phi$: flat tree-level direction in global SUSY.
- Dynamically generated SUSY-breaking scale: $\mu \sim \lambda^{1/2}/4\pi\, \Lambda$.

However: Now Φ couples to massive matter fields $\Rightarrow$ Radiative corrections!

Radiative corrections from massive meson loops



Inflaton-dependent mass:

$$\phi = \frac{\varphi}{\sqrt{2}}\, e^{i\theta}\,, \quad M(\varphi) = \frac{\kappa_\Phi\, \varphi}{\sqrt{2}}$$

Critical field value:

$$M(\varphi_c) = \Lambda\,, \quad \varphi_c = \sqrt{2}\,\frac{\Lambda}{\kappa_\Phi}$$

Order parameter:

$$x(\varphi) = \frac{\varphi}{\varphi_c} = \frac{M(\varphi)}{\Lambda}$$

$$V_{1-\text{loop}}(\varphi) = \begin{cases} \frac{1}{2}\, m_{\rm eff}^2\, \varphi^2 & ; \quad \varphi \ll \varphi_c \qquad \text{(effective mass around the origin)} \\ \frac{6\, m^4}{16\pi^2} \ln \varphi/\varphi_c & ; \quad \varphi \gg \varphi_c \qquad \text{(usual log corrections as in FHI)} \end{cases}$$

- ϕ stabilized around the origin by strong dynamics: $m_{\rm eff}^2 \sim N_{\rm eff}(\lambda_n)\, \frac{\kappa_\Phi^2}{16\pi^2}\, m^2$.
  [Chacko, Luty & Ponton '98]
- Harmless confinement transition at $\varphi \sim \varphi_c$: quark/gluons → mesons, $SU(2) \to \mathbb{1}$.

Embedding into supergravity

Canonical Kähler potential plus subdominant higher-dimensionful corrections:

$$K = \Phi^\dagger \Phi + \frac{\varepsilon}{4}\left(\Phi^\dagger \Phi\right)^2 + \cdots$$

- $|\Phi|^4$ not forbidden by any symmetry. Expected in low-energy EFT of quantum gravity.
- Introduces Hubble-induced mass: $m_\varphi^2 = -3\,\varepsilon\, H^2$ (accidental cancellation if $\varepsilon = 0$).
- Coefficient ε needs to be slightly suppressed to avoid the η problem in SUGRA.
  [Dine, Fischler, Nemeschansky '84] [Coughlan, Holman, Ramond, Ross '84]

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Total scalar potential for the real Polonyi field φ in the large-field regime:

$$\boxed{V(\varphi) = \mu^4 \left[1 - \frac{\varepsilon}{2}\left(\frac{\varphi}{M_\mathrm{Pl}}\right)^2 + \frac{1}{8}\left(1 - \frac{7\,\varepsilon}{2} + \frac{8\,\varepsilon^2}{3}\right)\left(\frac{\varphi}{M_\mathrm{Pl}}\right)^4 + \cdots\right] + \frac{6\,m^4}{16\pi^2} \ln \frac{\varphi}{\varphi_c}}$$

- Same potential as in FHI: incl. SUGRA and loop corrections, in the limit $m_{3/2} = 0$.
  [Bastero-Gil, King, Shafi '07]
- No tadpole term (no odd powers), no dependence on the complex phase $\theta = \arg\phi$.
  [Buchmüller, Covi & Delpine '00]
- Usual slow-roll bound $m_{3/2} \lesssim 10^{-3} H$ does not apply. In fact, $m_{3/2} \simeq H$ in our case.
  [Buchmüller, Domcke, Kamada & K.S. '14]
- No waterfall transition, no production of topological defects at the end of inflation.

Dynamical realization of F-term hybrid inflation minus all its shortcomings!

Gaugino condensation in a mass-deformed hidden sector

Simplest possibility for $\cancel{R}$: GC in a strongly coupled pure SYM theory. Use to generate w!
[Veneziano & Yankielowicz '82]

Introduce separate SQCD sector with field-dependent quark masses:

$$W_R = P\, Q^i \bar{Q}^i$$

- $\langle P \rangle = 0$: $SU(N_c)$ gauge theory with N_f massless flavors and quantum moduli space.
- $\langle P \rangle \gtrsim \tilde{\Lambda}$: Integrate out heavy quarks $\Rightarrow$ Pure SYM $\Rightarrow$ Gaugino condensation.
- Obtain gaugino condensation scale $\tilde{\Lambda}_{\text{eff}}$ from RGE matching at mass threshold $\langle P \rangle$,

$$W_R^{\text{eff}} = \frac{N_c}{16\pi^2}\,\tilde{\Lambda}_{\text{eff}}^3\,, \qquad \tilde{\Lambda}_{\text{eff}}^{3N_c} = \langle P \rangle^{N_f}\,\tilde{\Lambda}^{3N_c - N_f}\,, \qquad \tilde{\Lambda} = M_{\text{Pl}} \exp\left[-\frac{8\pi^2}{b}\,\frac{1}{\tilde{g}^2\left(M_{\text{Pl}}\right)}\right]$$

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Constant term in the superpotential:

$$\boxed{w = \frac{N_c}{16\pi^2} \langle P \rangle^{N_f/N_c} \tilde{\Lambda}^{3-N_f/N_c}}$$

- $U(1)_R \rightarrow Z_{2N_c}^R$ by $SU(N_c)$ instantons in SYM. $Z_{2N_c}^R \rightarrow Z_2^R$ by gaugino condensation.
- Simplest realization (consistent with Z_4^R): $N_c = N_f = 2$ (same as in the IYIT sector).
- w controlled by $\tilde{g}\left(M_{\mathrm{Pl}}\right)$. CC problem deferred to boundary conditions in the UV.

Waterfall transition at small inflaton field values

How to use this mechanism of *R* symmetry breaking in the context of Polonyi inflation?

- The field P is stabilized during inflation by its Hubble-induced mass, $m_p^2 \propto H^2$.
- Why unstable at small field values? Introduce waterfall superpotential for the field P,

$$\boxed{W_P = \alpha Y \left(v_P^2 - \frac{1}{2} P^2\right) + \frac{\beta}{6} Y^3 + \cdots}$$

- α, β dimensionless coefficients; v_P mass scale, maybe also of dynamical origin.
- Z_2 parity: $[Y] = +1$, $[P] = -1$. Assume suppressed parity-breaking operators.

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Mass eigenstates in global supersymmetry:

$$m_{p^\pm}^2 = \pm\,\alpha^2 v_P^2\,, \qquad m_{y^\pm}^2 = \pm\,\alpha\beta\, v_P^2$$

- Choose α such that $-\alpha^2 v_P^2$ exceeds the Hubble-induced mass only after inflation.
- If α too small / large, inflation never ends / never takes place. ⇒ Anthropic selection?

Our novel approach: Waterfall transition in a separate sector. ⇒ Control over t_R!

(De)stabilization of the waterfall field P

Total mass of the waterfall scalar p^- in supergravity:

$$m_{p^-}^2(\varphi) = -\alpha^2 v_P^2 + \frac{V(\varphi)}{M_{\rm Pl}^2} + \Delta m^2(\varphi)$$

- Choose $\alpha \simeq \mu^2/v_P/M_{\rm Pl}$, so that p^- becomes unstable close to $\varphi = 0$.
- During inflation, additional stabilization similarly as in standard F-term hybrid inflation,

$$\langle Y\rangle = \frac{|F_Y|}{m_{y^+}^2}\frac{\mu^2\varphi}{\sqrt{2}M_{\rm Pl}^2}\,, \qquad |F_Y| = \alpha v_P^2\,, \qquad \Delta m^2(\varphi) \supset \alpha\langle Y\rangle$$

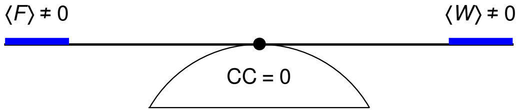
Size and gradient of $m_{p^-}^2(\varphi)$ as a function of φ sensitive to noncanonical Kähler potential,

$$K_{\rm mix} = \varepsilon_P\frac{|\Phi|^2|P|^2}{M_*^2}\,, \qquad \frac{V(\varphi)}{M_{\rm Pl}^2} \to \left(1 - \varepsilon_P\frac{M_{\rm Pl}^2}{M_*^2}\right)\frac{V(\varphi)}{M_{\rm Pl}^2}$$

- Only means of communication between the SUSY and R symmetry-breaking sectors.
- Arrange parameters such that $\left|m_{p^-}\right| \gtrsim H$ before and after the waterfall transition.

Induced R symmetry-breaking phase transition at late times as a pure SUGRA effect!

Tuning the cosmological constant to zero



SUSY-breaking sector:

$$W \simeq \mu^2 \Phi$$

Required constant in the superpotential:

$$w_0 \simeq \frac{\mu^2 M_{\rm Pl}}{\sqrt{3}}$$

R symmetry-breaking sector:

$$W \simeq \frac{1}{8\pi^2} \left< P \right> \tilde{\Lambda}^2$$

Actual constant in the superpotential:

$$w \simeq \frac{1}{8\pi^2} \frac{6\sqrt{2}}{7} v_P \tilde{\Lambda}^2$$

Match these results by tuning the dynamical scale $\tilde{\Lambda}$ in the *R* symmetry-breaking sector:

$$\boxed{w \rightarrow w_0 \quad \Rightarrow \quad \tilde{\Lambda} \rightarrow \left(\frac{8\pi^2}{\sqrt{3}} \frac{7}{6\sqrt{2}} \frac{\mu^2 M_{\rm Pl}}{v_P} \right)^{1/2}}$$

Then, late-time *R* symmetry breaking after inflation resulting in $\mathrm{CC} = 0$!