High-Scale Supersymmetry and Inflation Unified.

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Based on

- *Polonyi Inflation*, K. S. and Tsutomu T. Yanagida (Kavli IPMU, Tokyo), arXiv:1604.04911 [hep-ph].
- *A Unified Model of D-term Inflation*, Valerie Domcke (APC, Paris) and K. S., arXiv:1702.02173 [hep-ph].

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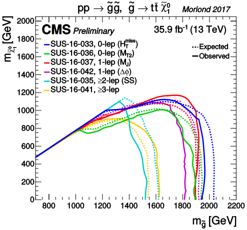
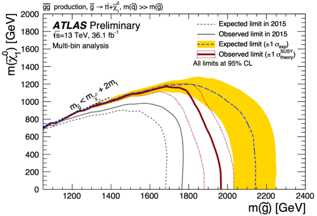
Supersymmetry: low-scale versus high-scale

[Talk by Tkaczyk on Monday]



[Talk by Diaconu on Tuesday]



Virtues of low-scale supersymmetry:

1. Solution to the (big) hierarchy problem.
2. R parity $\rightarrow$ stable LSP $\rightarrow$ dark matter.
3. Gauge unification at $\Lambda_{\mathrm{GUT}} \sim 10^{16}\,\mathrm{GeV}$.
4. UV completion of the SM in string theory.

TeV-scale SUSY under increasing pressure:

1. So far, no evidence for SUSY at the LHC.
2. Higgs mass $m_h \simeq 125\,\mathrm{GeV}$ calls for large radiative corrections from (s)top loops,
   [Okada, Yamaguchi, Yanagida '91] [Ellis, Ridolfi, Zwirner '91]

$$m_h^2 < m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2\,m_t^2} + \cdots\right]$$

Low-scale SUSY no longer everybody's darling. Fermi scale instead outcome of other dynamics: *compositeness*, *conformal symmetry*, *relaxion*, *clockwork*, ... [Many talks at this conference]

Dynamical SUSY breaking as the origin of inflation

WHAT IF ...

... SUSY is not responsible for stabilizing the EW scale? Imagine $m_{\rm soft} \gtrsim \mathcal{O}(10)\,\mathrm{TeV}$.

- No more gravitino / Polonyi problems in cosmology. Less tension from $\cancel{CP}$ & FCNCs.
- Trivial mediation to the visible sector: solely via gravitational interactions (PGM, ...).

Prospect: Simpler models + less pheno constraints + keep virtues except for naturalness!

[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]

Dynamical SUSY breaking as the origin of inflation

THEN: Intriguing new possibility! Inflation driven by ~~SUSY~~ vacuum energy $\Lambda^4_{\mathrm{SUSY}}$.

$$\boxed{\left\langle V_{\mathrm{SUGRA}} \right\rangle = \Lambda^4_{\mathrm{SUSY}} - 3\, e^{\langle K \rangle} \left\langle |W|^2 \right\rangle = \mathrm{CC} \simeq 0\,, \quad \Lambda^4_{\mathrm{SUSY}} = \left\langle |F|^2 \right\rangle + \frac{1}{2} \left\langle D^2 \right\rangle}$$

- Our idea: If $\Lambda^4_{\mathrm{SUSY}}$ large enough, $\Lambda^4_{\mathrm{SUSY}}$ may be the vacuum energy driving inflation!
- Goal: Inflation from *dynamical SUSY breaking*! No dimensionful input parameters.

IYIT model of dynamical SUSY breaking [Izawa & Yanagida '96; Intriligator & Thomas '96]

Break SUSY dynamically in a hidden sector to obtain $\langle F \rangle$ and $\langle D \rangle$ suitable for inflation.

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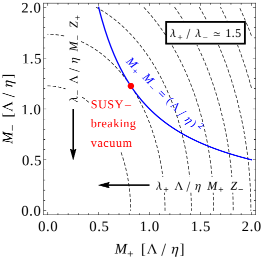

Hidden sector: Strongly coupled $SU(2)$ with four quarks Ψ^i.

- Low-energy EFT in terms of composite mesons M^{ij}.
- Add singlet fields to lift flat directions in moduli space.
- Conflict between SUSY masses and nonperturbative constraint $\Rightarrow$ SUSY spontaneously broken!

$$\boxed{\Lambda_{\rm SUSY}^4 = \left\langle \left|F\right|^2 \right\rangle \sim \lambda^2 \Lambda^4}$$

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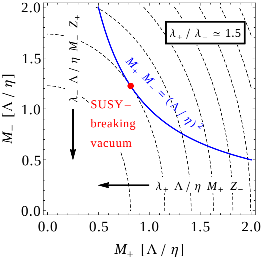

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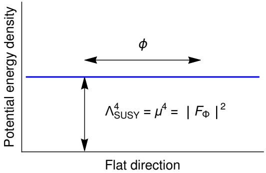
Effective Polonyi model at low energies: $W_{\rm eff} = \mu^2 \Phi$

- Φ tree-level flat direction in global SUSY. [Ray '06; Shih '08]
- IYIT Yukawa couplings $\rightarrow$ log corrections at one loop.

Intriguing possibility: Polonyi inflation! Use Φ as inflaton.



Polonyi inflation and late-time R symmetry breaking

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

Further model ingredients:

1. Corrections to a canonical Kähler potential,

$$K = |\Phi|^2 + \frac{\varepsilon}{4}\frac{|\Phi|^4}{M_{\rm Pl}^2}$$

2. No constant superpotential during inflation!
Generate at end of inflation to tune $\mathrm{CC} \rightarrow 0$,

$$W_{\rm eff} = \mu^2\,\Phi + w\,, \quad w = \begin{cases} 0 & \varphi \gg \varphi_c \\ w_0 & \varphi \ll \varphi_c \end{cases}$$

E.g., trigger gaugino condensation in another hidden sector at small inflaton field values.

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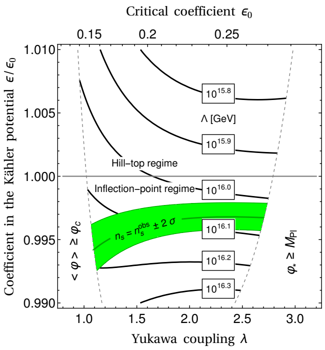
Successful F-term inflation in the Polonyi potential

- Energy density $\mu^4 = |F_\Phi|^2$ not only responsible for ~~SUSY~~ in the MSSM, but also for inflation!
- Same potential as in F-term hybrid inflation, incl. SUGRA corrections, but in the limit $m_{3/2} \to 0$.
- No tadpole, no waterfall transition, no cosmic strings. Worry-free UV completion of FHI!

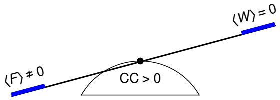


$A_s = A_s^{\rm obs}$ requires a dynamical scale $\Lambda \sim 10^{16}\,\mathrm{GeV}$!

- "Prediction"of GUT scale $\Lambda_{\rm GUT}$ from $A_s^{\rm obs}$.
- Soft scalar masses $m_0 \sim m_{3/2} \sim 10^{12}\,\mathrm{GeV}$.

D-term inflation in the gauged IYIT model

Polonyi inflation – the big picture:



- F-term SUSY breaking prior to R symmetry breaking ⇒ Dynamical *reason* for inflation!
- Late-time R symmetry breaking is possible; requires concerted interplay of parameters.

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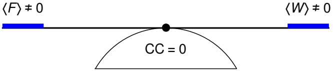

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D-term inflation in the gauged IYIT model

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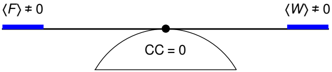

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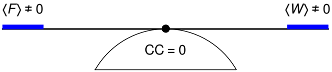

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1. IYIT sector exhibits global flavor symmetry $U(1)_A$. Opportunity to obtain $\langle D \rangle \neq 0$.
2. Promote to weakly gauged local symmetry. Then, dynamically generated FI term
   [Fayet & Iliopoulos '74] [Domcke, K. S., Yanagida '15]

$$\boxed{V_D = \frac{1}{2}\, g^2 q_0^2\, \xi^2\,, \quad \xi = \langle M_- \rangle^2 - \langle M_+ \rangle^2}$$

D-term inflation in the gauged IYIT model

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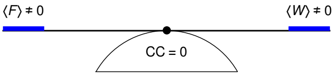

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3. Add new inflation sector: inflaton singlet S and charged waterfall fields Φ and $\bar{\Phi}$,
[Binetruy & Dvali '96] [Halyo '96]

$$W_{\rm inf} = \kappa S \Phi\bar{\Phi}\,, \quad V_D = \frac{1}{2}\, g^2 \left[q_0\, \xi - q\left(\left|\Phi\right|^2 - \left|\bar{\Phi}\right|^2\right)\right]^2$$

New possibility: SUSY breaking results in dynamical FI term, which drives inflation!

A consistent model of D-term inflation

$$\boxed{V(\sigma) \simeq \left(-\frac{3\,M_{\mathrm{Pl}}^2}{\Omega(\sigma)}\right)^2 \left[\frac{1}{2}g^2 q_0^2\,\xi^2 - \frac{\chi}{3}\,\mu^4 \left(\frac{\sigma}{M_{\mathrm{Pl}}}\right)^2\right] + \frac{\Delta m_J^4(\sigma)}{16\pi^2}\ln\frac{\sigma}{\sigma_c}}$$

Further model ingredients:

1. Work in Jordan-frame supergravity with canonically normalized kinetic terms:
   [Ferrara, Kallosh, Linde, Marrani, van Proeyen '10; '11] [FKL, Porrati '13]

   $$-\frac{\Omega}{6}R = \left[\frac{M_{\mathrm{Pl}}^2}{2} - \frac{1}{6}\left(F + \Phi^\dagger\Phi + \cdots\right)\right]R$$

   Inflaton sector sequesters from ~~SUSY~~ sector. No SUGRA eta problem. Waterfall fields can become unstable at the end of inflation.

2. Slightly broken shift symmetry in σ direction:
   [Kawasaki, Yamaguchi, Yanagida '00]

   $$F = \frac{\chi}{2}\left(S + S^\dagger\right)^2 - \frac{(1-\chi)}{2}\left(S - S^\dagger\right)^2$$

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Implications and applications

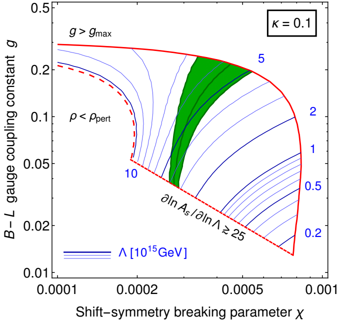
- No hard dimensionful input scale. ~~SUSY~~ at a very high scale. Recover once again $\Lambda_{\rm GUT}$.

$$\frac{m_{3/2}}{5\times 10^{12}\,\mathrm{GeV}} \sim \left(\frac{\sqrt{\xi}}{5\times 10^{15}\,\mathrm{GeV}}\right)^{5/2}$$

- Identify $U(1)_A$ with $U(1)_{B-L}$ and couple waterfall field Φ to right-handed neutrinos,
  [Buchmüller, K. S., Vertongen '10; Buchmüller, Domcke, K. S. '12]

$$W \supset \frac{1}{2}\, h_i\, \Phi\, N_i N_i$$

- Employ in the two-field relaxion mechanism.
  [Evans, Gherghetta, Nagata, Peloso '17]



Experimental signatures beyond inflation

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

- Pure gravity mediation: anomaly-mediated gaugino masses $m_{3/2}/16\pi^2 \sim 10^{10}\,\mathrm{GeV}$.
  [Dine & MacIntire '92] [Giudice, Luty, Murayama & Rattazzi '98] [Randall & Sundrum '99] [Bagger, Moroi & Poppitz '00]
- LSP (wino) overproduction during reheating in gravitino decay: $\psi_{3/2} \rightarrow \cdots \rightarrow \mathrm{LSP}$.
  [Moroi & Randall '00] [Kawasaki, Takahashi & Yanagida '06] [Buchmüller, Domcke & K. S. '12]
- Assume anthropic selection of a fine-tuned wino mass. AMSB $+$ Higgsino loops:
  [Ibe, Matsumoto & Yanagida '12] [Hall, Nomura & Shirai '13]

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

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

Experimental signatures beyond inflation

Gravitational waves from inflation, reheating, etc.

- GWs from inflation typically very weak. GWs from reheating model-dependent.
- Drastically enhanced if inflaton exhibits an axion-like coupling to gauge fields,
  [Cook & Sorbo '12] [Barnaby, Pajer, Peloso '12] [Domcke, Pieroni, Binetruy '16]

$$\boxed{\mathscr{L}_{\mathrm{eff}} \supset \frac{\varphi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}}$$

- Fits well together with the inflaton shift symmetry in the case of D-term inflation.

Take-Home Messages

Questions: Embedding of inflation into particle physics? Role of SUSY in nature?

1. High-scale SUSY does not address the hierarchy problem; but offers new perspective on the interplay between SUSY breaking and cosmic inflation.
   - Inflation may be driven by F term or D term associated with SUSY breaking.
2. Models of dynamical SUSY breaking (e.g., the IYIT model) result in effective Polonyi models. May give rise to F-term hybrid inflation $\rightarrow$ *Polonyi inflation*.
   - Minimal and viable model; but requires *late-time R symmetry breaking*.
3. IYIT model coupled to Jordan-frame supergravity allows to realize D-term inflation in accord with all theoretical and phenomenological constraints.
   - Gauged flavor symmetry. Unifies SUSY breaking, inflation, and $B-L$ breaking!

Possible answer: Inflation and SUSY breaking may have single dynamical origin!

- DM signal at low energies. Further signatures from GWs, reheating, ...

Thank you for your attention!

Supplementary Material

IYIT Model of Dynamical SUSY Breaking [Izawa & Yanagida '96; Intriligator & Thomas '96]

Simplest realization of DSB in vector-like gauge theories: $Sp(N)$ with $N_f = N+1$ flavors.

- Supersymmetric gauge theory that becomes strongly coupled at *dynamical scale* Λ.

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❶ Flat moduli space at low energies [Seiberg '94; Luty '98]

- $Sp(1) \cong SU(2)$ with 4 fundamental quarks Ψ^i.
- Low-energy EFT in terms of composite mesons,

$$M^{ij} \sim \frac{1}{\Lambda}\left\langle \Psi^i \Psi^j \right\rangle , \quad \mathrm{Pf}\left(M^{ij}\right) \sim \Lambda^2$$

- Instanton-induced (deformed) moduli constraint.

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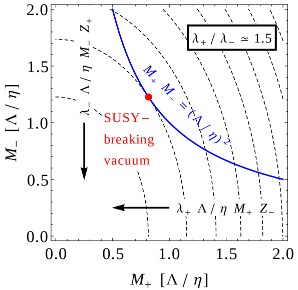
❷ Lift flat directions by means of Yukawa interactions

- Coupling to singlets in tree-level superpotential,

$$W_{\text{tree}} = \lambda_{ij}\, Z_{ij}\, \Psi^i \Psi^j \;\rightarrow\; W_{\text{eff}} \sim \lambda_{ij}\, \Lambda\, Z_{ij}\, M^{ij}$$

- Global axial $U(1)_A$ associated with Ψ^i rotation,

$$\left[\Psi^{1,2}\right] = +q_0 \,, \quad \left[\Psi^{3,4}\right] = -q_0$$



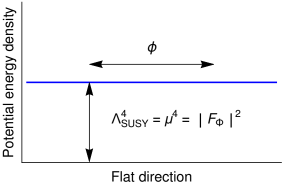
❸ Yukawa couplings such that

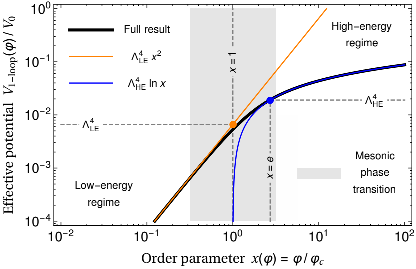
- $\left|F_{Z_\pm}\right| = \lambda_\pm \Lambda \left\langle M_\pm \right\rangle \neq 0$
- F-term SUSY breaking.
- $\left\langle M_\pm \right\rangle \neq 0$ breaks $U(1)_A$.

Effective Polonyi model

Superpotential at low energies: $W_{\rm eff} = \mu^2\,\Phi + \cdots$

- SUSY-breaking Polonyi field $\Phi = \left(Z_+ + Z_-\right)/\sqrt{2}$.
- In global SUSY, tree-level flat direction. [Ray '06; Shih '08]
- F-term SUSY-breaking scale $\mu^2 = \sqrt{2}\sqrt{\lambda_+\lambda_-}\,\Lambda^2$.





Radiative corrections:

- Yukawa couplings to quarks/mesons induce effective one-loop potential:

$$V_{\rm CW} \sim \begin{cases} m_{\rm eff}^2\,\varphi^2 & ;\ \varphi \ll \varphi_c \\ m^4/16\pi^2 \ln\varphi/\varphi_c & ;\ \varphi \gg \varphi_c \end{cases}$$

- Strong stabilization around the origin.
- Log corrections at large field values.

Dynamical UV completion of the Polonyi model (in global SUSY): $W = \mu^2\,\Phi + w_0$ [Polonyi '78]

- R-symmetry-breaking constant w_0, so as to tune the cosmological constant to zero.

Inflation in the effective Polonyi model

Aim: Realize inflation in the effective potential for the Polonyi field Φ.

- Main obstacle: Large μ implies large w_0. Gravitational corrections spoil slow-roll.
- Way out: Unbroken R symmetry in the sector responsible for $w_0 \Rightarrow w = 0$ initially.

Effective IYIT superpotential may be brought into the following form:

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

- $SO(5)$ realization of F-term hybrid inflation (FHI) with massive waterfall fields.
  [Copeland *et al.* '94] [Dvali, Shafi, Schaefer '94]
- Mesons X^n: $SO(5)$ multiplet of *would-be* waterfall fields with masses $m_n \geq \kappa_\Phi v$.
- Stabilized by $SO(5)$ multiplet of IYIT singlets S_n, even at the end of inflation.

Big picture: SUSY breaking prior to R symmetry breaking $\Rightarrow$ Reason for inflation!

- Assume *late-time R symmetry breaking*. w_0 only generated at the end of inflation.
- Until then, (FHI-like) *Polonyi inflation* driven by the SUSY-breaking Polonyi F term.

R symmetry breaking via gaugino condensation

Idea: Gaugino condensation in a strongly coupled pure SYM theory. Use to generate w_0!
[Veneziano & Yankielowicz '82]

- R-symmetry-breaking sector: SQCD with field-dependent masses, $W_R = P\, Q^i \bar{Q}^i$.
- $\langle P \rangle \gtrsim \tilde{\Lambda}$: Integrate out heavy quarks $\Rightarrow$ Pure SYM $\Rightarrow$ Gaugino condensation.

$$W_R^{\rm eff} \to w = \frac{N_c}{16\pi^2}\,\tilde{\Lambda}_{\rm eff}^3\,, \quad \tilde{\Lambda}_{\rm eff}^{3N_c} = \langle P \rangle^{N_f}\,\tilde{\Lambda}^{3N_c - N_f}$$

Application to the scenario of Polonyi inflation:

- Introduce waterfall superpotential, $W_P = \alpha\, Y \left(v_P^2 - \frac{1}{2} P^2\right) + \frac{\beta}{6} Y^3 + \cdots$
- Competition between tachyonic mass in global SUSY and Hubble-induced mass,

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

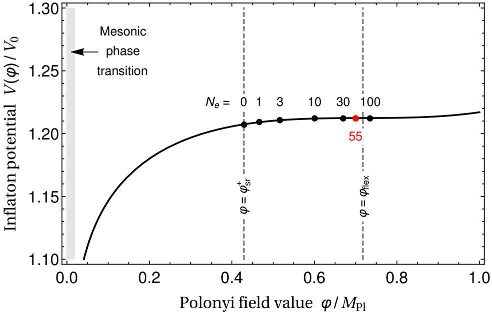
- Arrange parameters such that P becomes unstable only at small inflaton field values.

Waterfall transition in a separate sector $\Rightarrow$ Control over time of R symmetry breaking!

Scalar potential of Polonyi inflation

Ingredients: ① IYIT log corrections ② Near-canonical Kähler potential ③ $w = 0$ initially

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



Dynamics controlled by interplay b/t

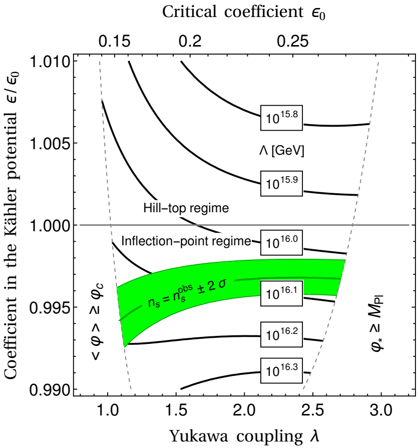
- Radiative log term
- SUGRA mass term

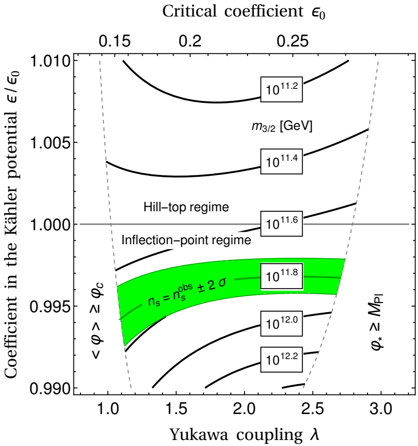
Saddle point for $\varepsilon = \varepsilon_0$

- $\varepsilon > \varepsilon_0$: Hill-top regime $\Rightarrow$ Fine-tuned initial conditions or inflaton stuck in false vacuum.
- $\varepsilon < \varepsilon_0$: Inflection-point regime

Expectation: $\varepsilon \sim \varepsilon_0$ maximizes # of e-folds. $\varepsilon < \varepsilon_0$ consistent with $\varphi_{\rm ini} \sim M_{\rm Pl}$. $\Rightarrow$ $\varepsilon \lesssim \varepsilon_0$

Predictions of Polonyi inflation



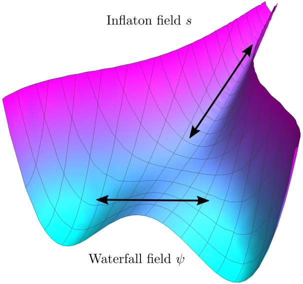


Dynamical scale $\Lambda \sim 10^{16}\,\mathrm{GeV}$

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

- Similarity / equivalence of scales: $\Lambda \sim \Lambda_{\rm GUT}$ and $H \simeq m_{3/2}$. $\Rightarrow$ $r \sim 10^{-5} \cdots 10^{-4}$.

Connection to spontaneous $B-L$ breaking



$$W_{\rm inf} = \kappa\, S\, \Psi \bar{\Psi}\,, \quad V_D = \frac{g^2}{2}\left[q_0\,\xi - q\left(|\psi|^2 - |\bar{\psi}|^2\right)\right]^2$$

Standard D-term inflation in a nutshell

[Binetruy & Dvali '96] [Halyo '96]

- In global SUSY, inflaton direction flat at tree level.
- Lifted by radiative log corrections (plus SUGRA).
- Waterfall transition at the end of inflation

$$\langle\psi\rangle = \left(q_0/q\,\xi\right)^{1/2} \text{ or } \langle\bar{\psi}\rangle = \left(-q_0/q\,\xi\right)^{1/2}$$

Identify waterfall transition with $B-L$ phase transition: $U(1)_A \rightarrow U(1)_{B-L}$

[Buchmüller, K. S., Vertongen '10; Buchmüller, Domcke, K. S. '12; Buchmüller, Domcke, Kamada, K. S. '13]

- Set $q = -2$ and choose $q_0\,\xi < 0$, so that ψ can couple to right-handed neutrinos

$$W \supset \frac{1}{2}\, c_{ij}\, \psi\, N_i N_j \quad \rightarrow \quad W \supset \frac{1}{2}\, M_{ij}\, N_i N_j\,, \quad M_{ij} = c_{ij}\,\langle\psi\rangle$$

- Breaks $B-L$ in the visible sector $\Rightarrow$ type-I seesaw mechanism and leptogenesis.
  [Minkowski '77] [Yanagida '79] [Gell-Mann, Ramond, Slansky '79] [Mohapatra & Senjanovic '80] [Fukugita & Yanagida '86]

Exciting possibility to unify the dynamics of SUSY breaking, inflation, and $B-L$ breaking!

Problems of standard D-term inflation

Standard D-term inflation is, however, plagued by several problems:

1. Coupling FI terms to SUGRA is a subtle story. Field-independent FI terms require exact global symmetries; field-dependent FI terms result in flat moduli directions.
[Binetruy *et al.* '04] [Komargodski & Seiberg '09; '10] [Dienes & Thomas '10] [Wieck & Winkler '14]

2. Other charged scalars (that do not couple to the inflaton) may eat up the FI term,
[Domcke, K. S. Yanagida '15] [Babu, K. S. Yanagida '16]

$$V_D = \frac{g^2}{2}\left[q_0\,\xi - q_i\left(\left|\tilde{q}_i\right|^2 - \left|\tilde{\bar{q}}_i\right|^2\right)\right]^2 \quad \Rightarrow \quad \langle\tilde{q}_i\rangle = \left(q_0/q_i\,\xi\right)^{1/2}$$

3. In ordinary gravity mediation, S acquires a SUGRA mass that easily spoils slow-roll,
[Dumitrescu, Komargodski, Sudano '10] [Kawamura '11]

$$m_S = m_{3/2} \sim \frac{F}{M_{\rm Pl}} \gg \frac{D}{M_{\rm Pl}} \sim H_{\rm inf}$$

4. In global SUSY, n_s deviates from the PLANCK best-fit value by about $2\,\sigma$,
[Binetruy & Dvali '96] [Halyo '96] [PLANCK '15]

$$n_s \simeq 1 - \frac{1}{N_e^*} \simeq 0.98 \quad \leftrightarrow \quad n_s^{\rm obs} \simeq 0.9677 \pm 0.0060$$

5. The waterfall transition is accompanied by the production of cosmic strings. CMB constraints on the cosmic string tension rule out large parts of the parameter space.
[Battye, Garbrecht, Moss '10] [PLANCK '15]

Jordan-frame supergravity

SUGRA corrections can be tamed in Jordan-frame supergravity

[Ferrara, Kallosh, Linde, Marrani, van Proeyen '10; '11] [Ferrara, Kallosh, Linde, Porrati '13]

- Matter fields couple nonminimally to gravity via the *frame function* $\Omega_{\rm tot}$,

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{6}\,\Omega_{\rm tot}\,R + \cdots\right], \quad \Omega_{\rm tot} = -3\,M_{\rm Pl}^2\,\exp\left[-\frac{K_{\rm tot}}{3\,M_{\rm Pl}^2}\right] = -3\,M_{\rm Pl}^2 + F_{\rm tot}$$

Assume partial sequestering in the *kinetic function* $F_{\rm tot}$

[Inoue, Kawasaki, Yamaguchi, Yanagida '92] [Randall & Sundrum '99] [Luty & Sundrum '02; '03] [Ibe, Izawa, Nakayama, Shinbara, Yanagida '06]

$$F_{\rm tot} = F_{\rm hid} + F_{\rm vis} + F_{\rm inf} + \frac{1}{M_*^2}\,F_{\rm hid}\,F_{\rm vis}\,, \quad F_{\rm inf} = \left|\Psi\right|^2 + \left|\bar{\Psi}\right|^2 + F\left(S\right)$$

- Canonical terms for the waterfall fields $\Rightarrow$ No dangerous SUGRA-induced masses.
- MSSM sfermions couple directly to the IYIT sector $\Rightarrow$ Stabilized during/after inflation.

Approximate shift symmetry along the inflaton direction

[Kawasaki, Yamaguchi, Yanagida '00]

$$F\left(S\right) = \frac{1}{2}\,\chi\left(S+S^\dagger\right)^2 - \frac{1}{2}\left(1-\chi\right)\left(S-S^\dagger\right)^2, \quad \chi \ll 1$$

- Canonical term yields Hubble-induced mass, $m_S^2 \sim H_{\rm inf}^2$. In our case: $m_S^2 \sim \chi\,m_{3/2}^2$.

A consistent realization of D-term inflation

Ingredients for a successful model of D-term inflation

1. FI term generated by dynamics of a strongly coupled supersymmetric gauge theory.
2. Jordan-frame supergravity with canonical kinetic terms for all matter fields.
3. Approximate shift symmetry in the kinetic function along the inflaton direction.

This remedies all shortcomings of standard D-term inflation

1. Field-dependent FI term, $\xi = \langle M_- \rangle^2 - \langle M_+ \rangle^2$. Modulus $\cong$ $B{-}L$ Goldstone multiplet.
2. MSSM sfermions stabilized thanks to direct coupling to the SUSY-breaking sector.
3. Sequestering $\Rightarrow$ slow-roll OK; waterfall fields become unstable at the end of inflaton.
4. $n_s \simeq n_s^{\mathrm{obs}}$, sensitive to amount of shift symmetry breaking, $V \supset -\chi\, m_{3/2}^2\, \varphi^2$.
5. $B{-}L$ broken before the end of inflation in the IYIT sector $\Rightarrow$ no cosmic strings!

Note: This solution of the cosmic string problem only works in the D-term scenario,

$$W = \kappa\, S \left(v^2 - \Psi\bar{\Psi}\right) , \quad V_D = \frac{g^2}{2} \left(q_0 \xi + \cdots\right)^2 , \quad [v] = 0 , \quad [\xi] \neq 0$$