Minimal Supergravity Inflation without Slow Gravitino

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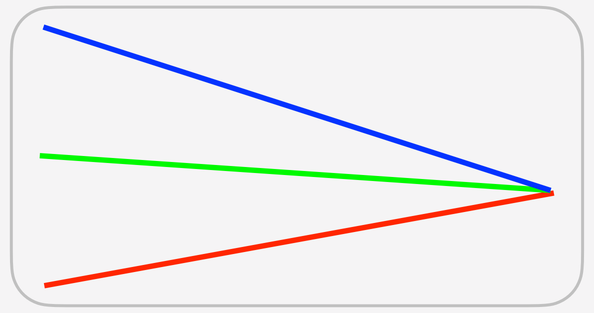
PASCOS 2021

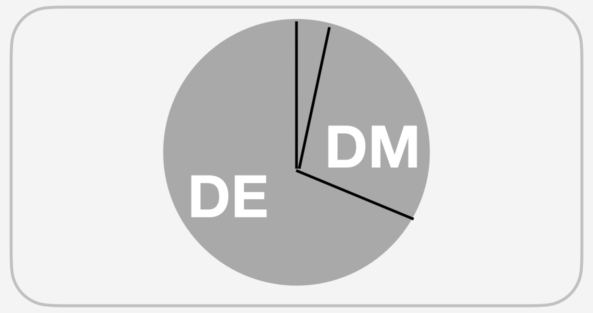
Broken SUSY in the Early Universe

- Supersymmetry (SUSY) may be a fundamental symmetry of the Nature.

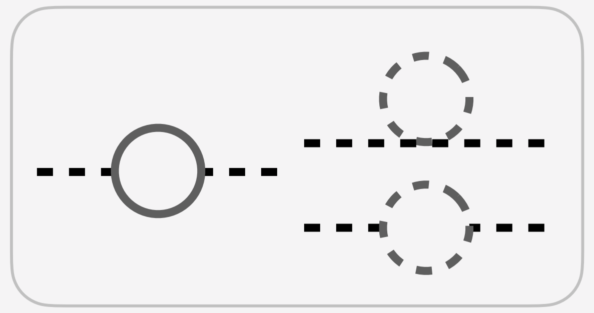
  Motivation:



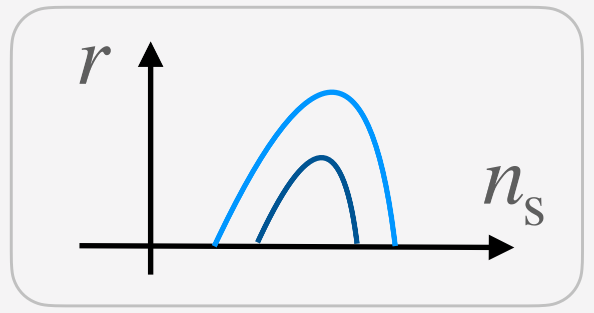
Coupling unification



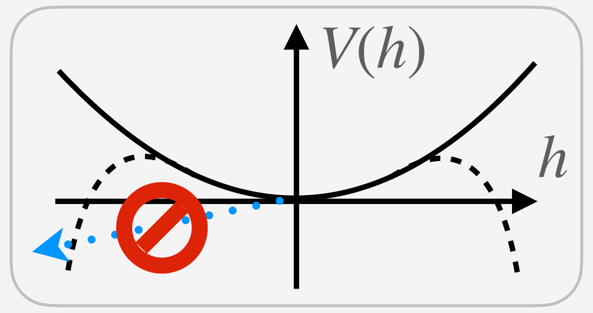
Dark matter



Hierarchy problem



Flat inflaton potential



Vacuum stability

Superstring theory

- It must be (spontaneously) broken in the cosmological background.

  Usually, the order parameters are $\langle F(\varphi)\rangle$, $\langle D(\varphi)\rangle$.

  In cosmology, kinetic energy $\langle\dot{\phi}^2\rangle$, Hubble expansion H, and temperature T can break SUSY.

- Generic fields receive SUSY breaking (Hubble-induced) mass of $\mathcal{O}(H)$.

  → Possibility for observational effects. "Cosmological Collider" [Arkani-Hamed, Maldacena, 1503.08043] etc.

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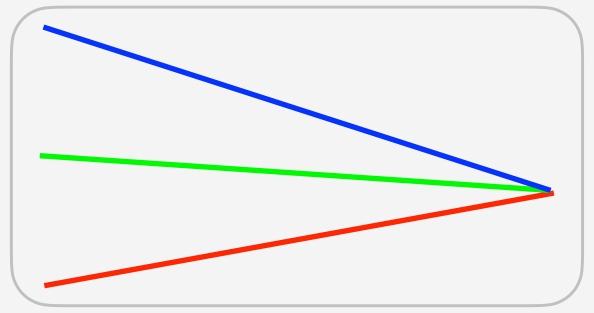

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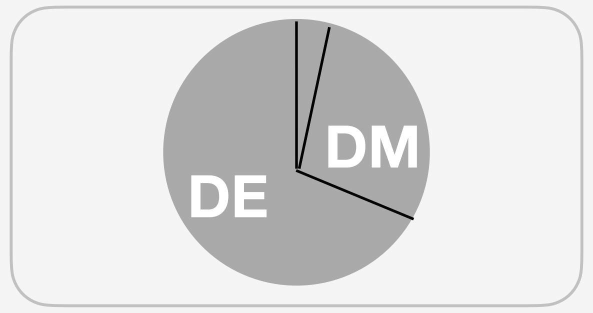

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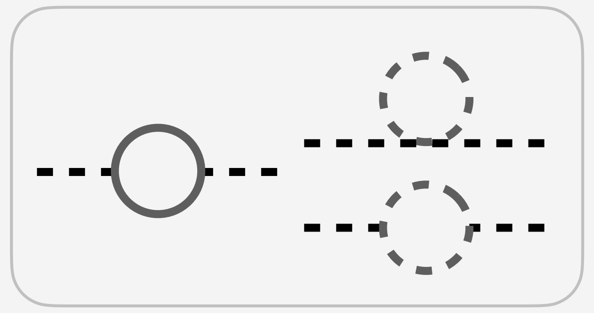

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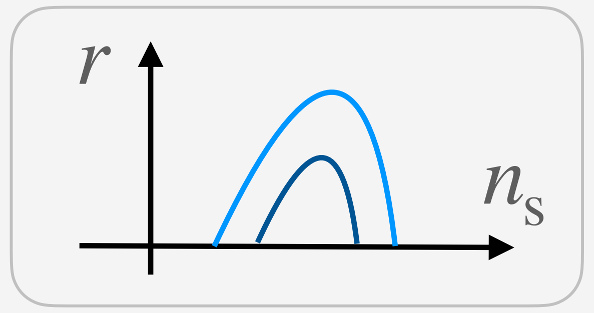

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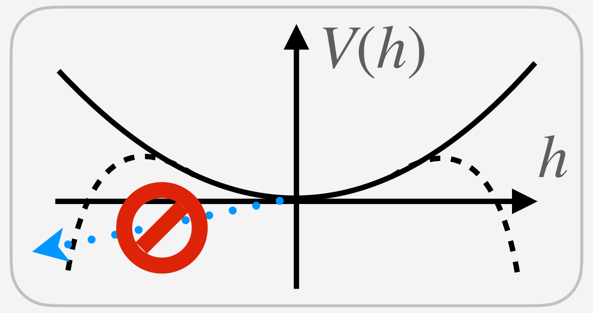

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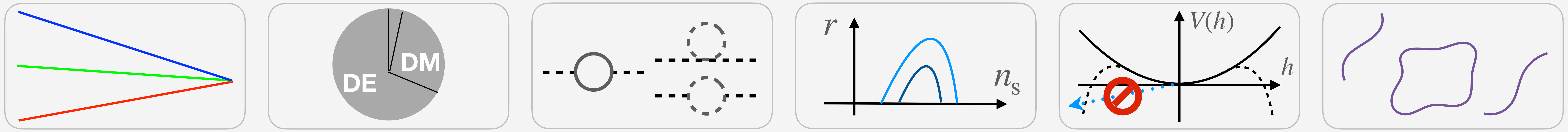

Coupling unification | Dark matter | Hierarchy problem | Flat inflaton potential | Vacuum stability | Superstring theory

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Decoupling & Non-Linear SUSY

- Fields much heavier than H decouple from inflationary dynamics.

  cf.) constraints on isocurvature perturbations

  e.g.) strong stabilization $\int \mathrm{d}^4\theta \frac{1}{\Lambda^2}|X|^4 \sim \frac{|F^X|^2}{\Lambda^2}|X|^2.$

For example,
[Lee, 1005.2735],
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  e.g.) nilpotent superfield X satisfying $X^2 = 0$.

$$X = x + \sqrt{2}\theta\chi^X + \theta\theta F^X$$

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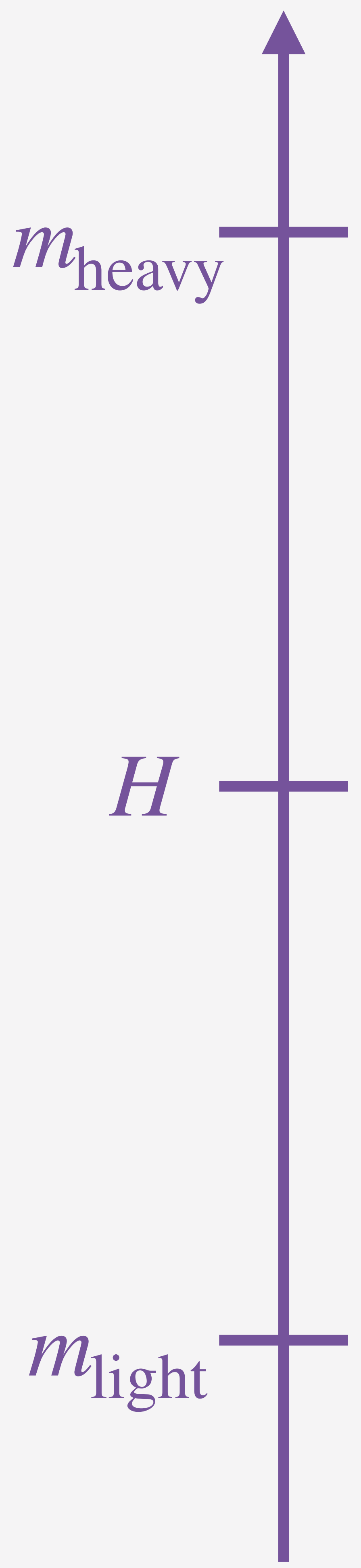

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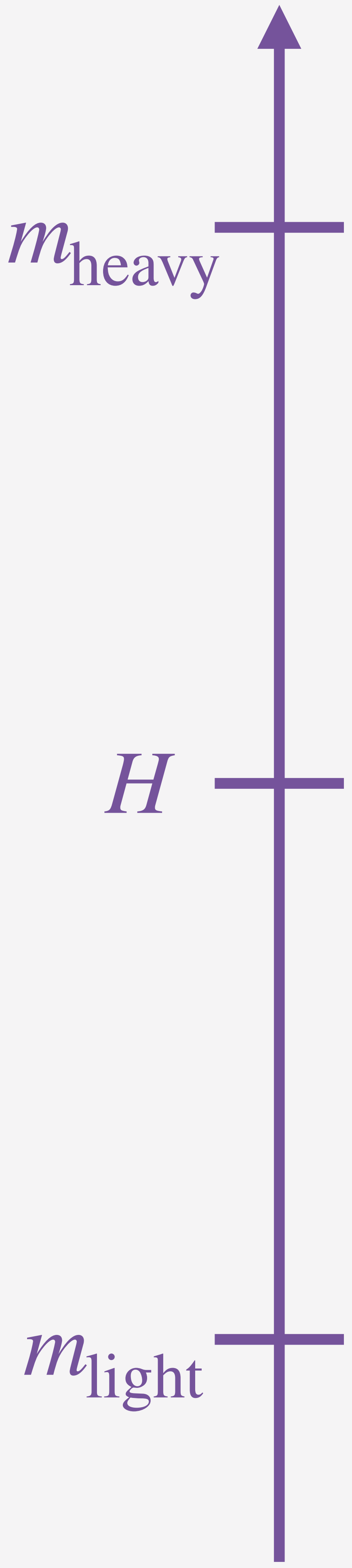

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Minimal Supergravity Inflation

[Ferrara, Kallosh, Thaler, 1512.00545],
[Carrasco, Kallosh, Linde, 1512.00546]

- Orthogonal nilpotent superfields X and T:

$$X^2 = X(T - \bar{T}) = 0$$

Stabilizer superfield $X = x + \sqrt{2}\theta\chi^X + \theta\theta F^X$

Inflaton superfield $T = t + \sqrt{2}\theta\chi^T + \theta\theta F^T$

- The only independent dynamical degrees of freedom are χ^X (stabilizino) and $\mathrm{Re}\, t$ (inflaton).

The physical spectrum:
(real) inflaton, (massive) gravitino, and graviton.

See also [Kahn, Roberts, Thaler, 1504.05958], [Dall'Agata, Farakos, 1512.02158], [Delacretaz, Gorbenko, Senatore, 1610.04227], [Cribiori et al., 1611.01490].

- The model is specified by

$$K(T, \bar{T}, X, \bar{X}) = \bar{X}X - \frac{1}{4}(T + \bar{T})^2,$$
$$W(T, X) = f(T)X + g(T).$$

- The scalar potential is

$$V(t) = |f(t)|^2 - 3|g(t)|^2.$$

Note that there is no $\partial g/\partial T$ term because of the constraint.

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Anomalous Production of Slow Gravitinos

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106], [Kolb, Long, Mcdonough, 2102.10113; 2103.10437]

Longitudinal gravitino Lagrangian

$$\mathscr{L} = -\frac{1}{2}\overline{\psi^\ell}\left(\gamma^0\partial_0 - \widehat{c}_{3/2}\left(\vec{\gamma}\cdot\vec{\nabla}\right) + a\,\widehat{m}_{3/2}\right)\psi^\ell$$

$$\widehat{c}_{3/2} \equiv \frac{p_{\mathrm{SB}} - \gamma^0 p_W}{\rho_{\mathrm{SB}}} \qquad \widehat{m}_{3/2} \equiv \frac{3Hp_W + m_{3/2}\left(\rho_{\mathrm{SB}} + 3p_{\mathrm{SB}}\right)}{2\rho_{\mathrm{SB}}}$$

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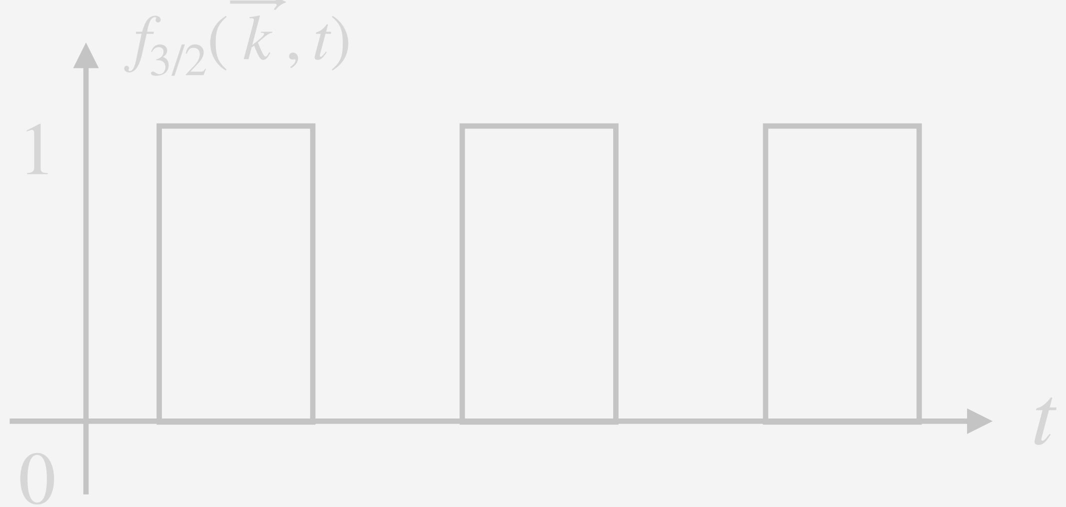
Inflaton potential & gravitino sound speed

For simplicity, we are assuming $p_W = 0$ so that $c_{3/2}$ is real.

Phase-space distribution (neglecting backreaction; $m_{3/2} \to 0$ limit)

$$f_{3/2}(\vec{k}, t) = \frac{1}{2}\left(1 + \mathrm{sgn}(c_{3/2}(t))\right)$$



Catastrophic gravitino production

$$a^3 n_{3/2} \sim 2\int_0^\Lambda \mathrm{d}k\,\frac{4\pi k^2}{(2\pi)^3} f_{3/2}(\vec{k}, t) \sim \Lambda^3$$

… or breakdown of the effective theory.

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[Kratzert, hep-th/0303260]
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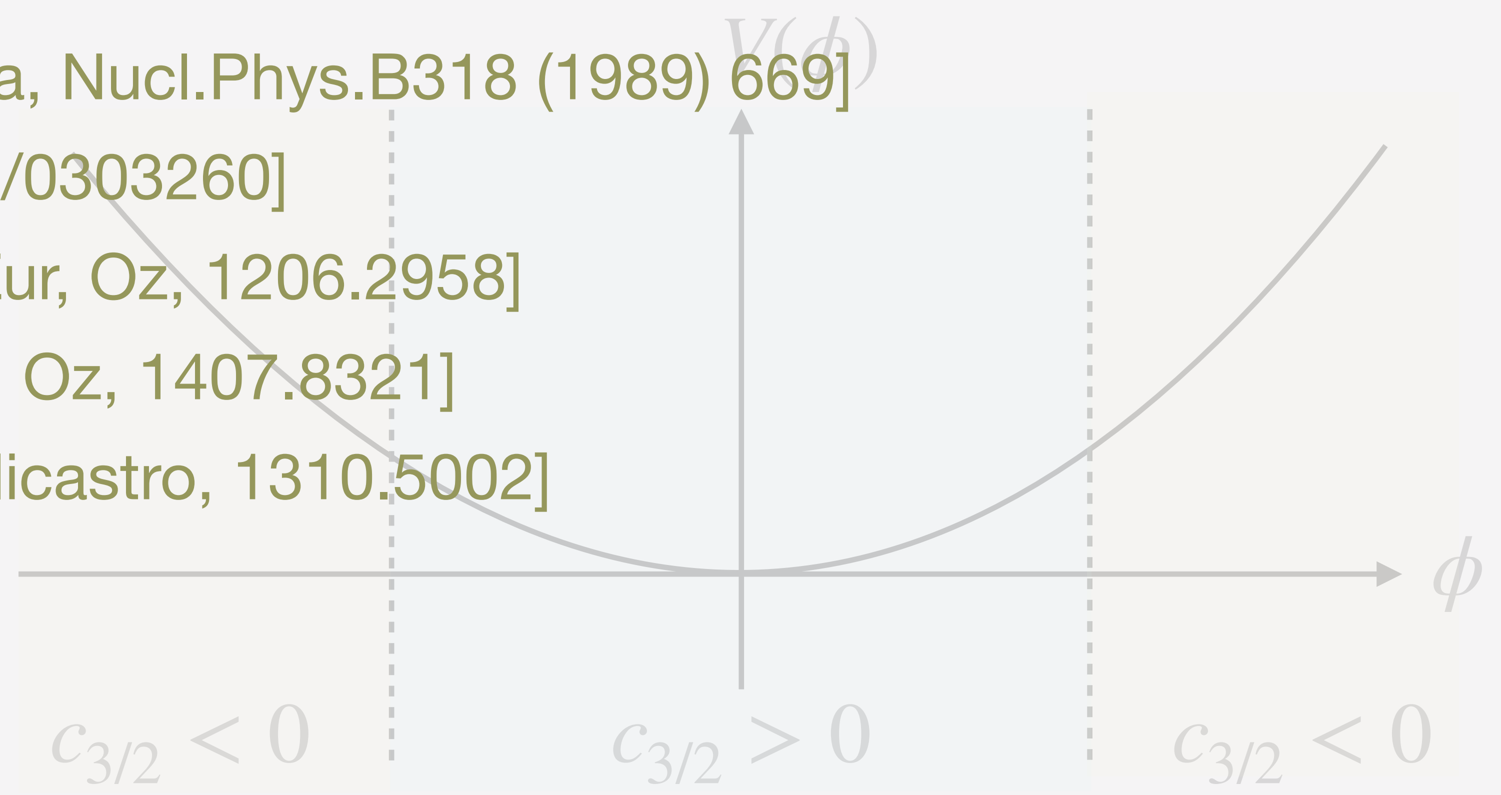

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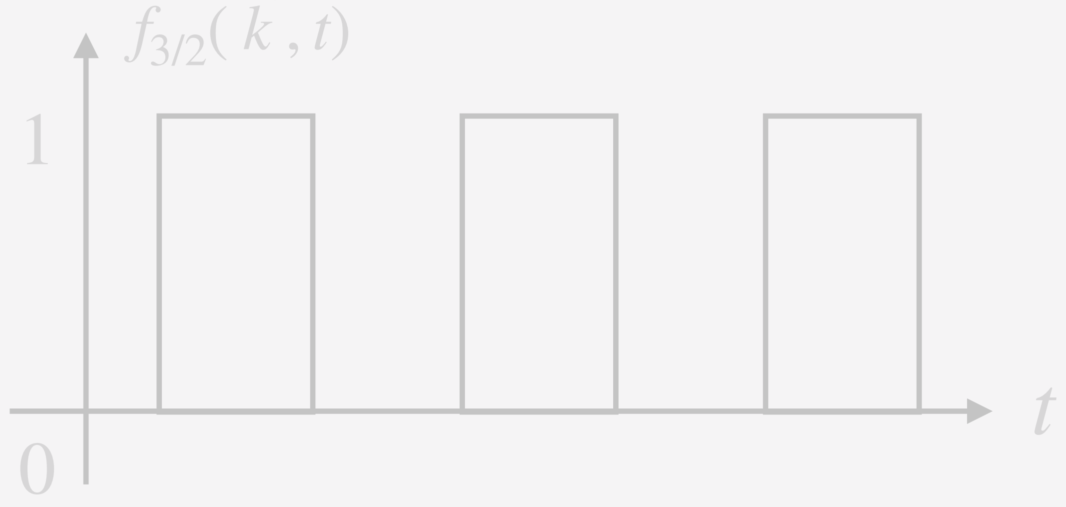

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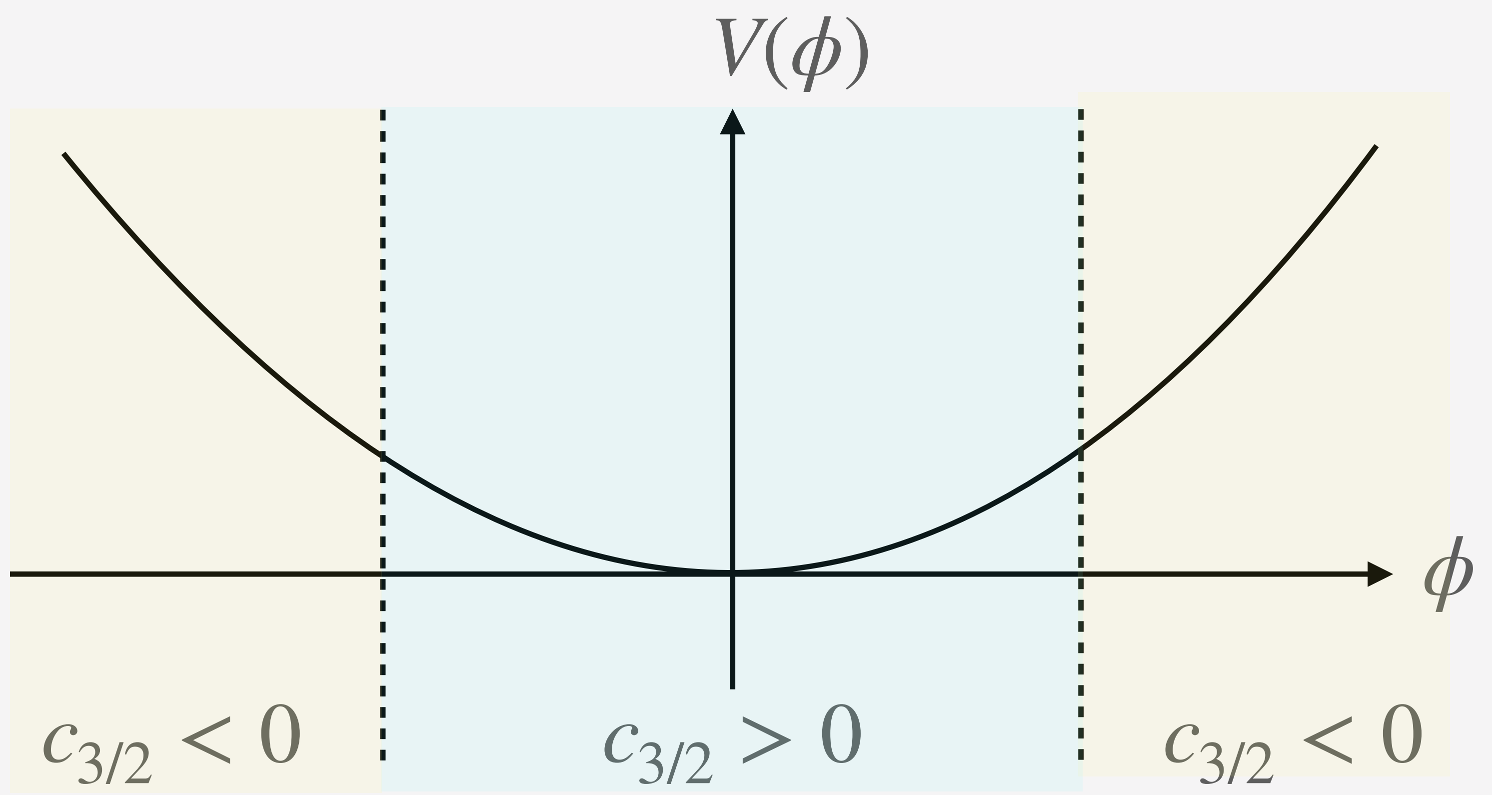

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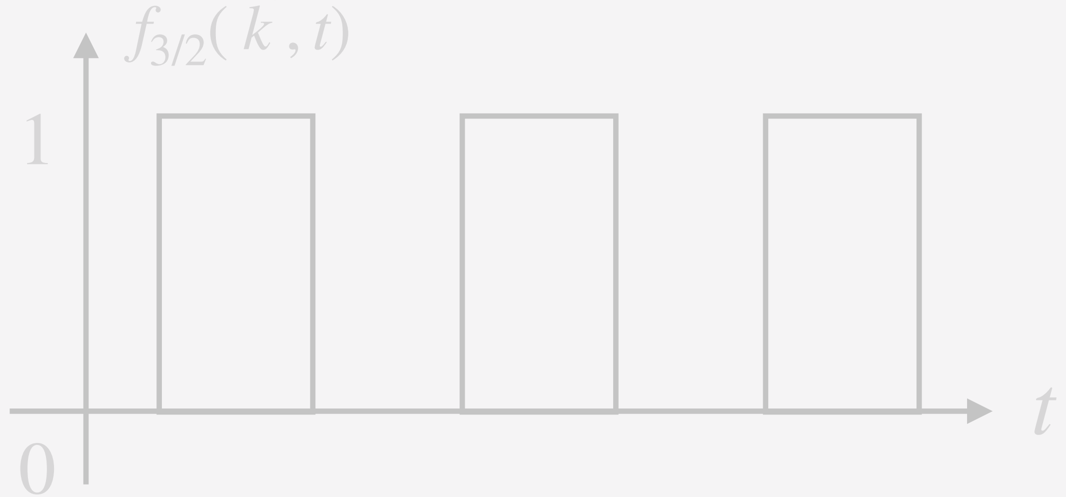

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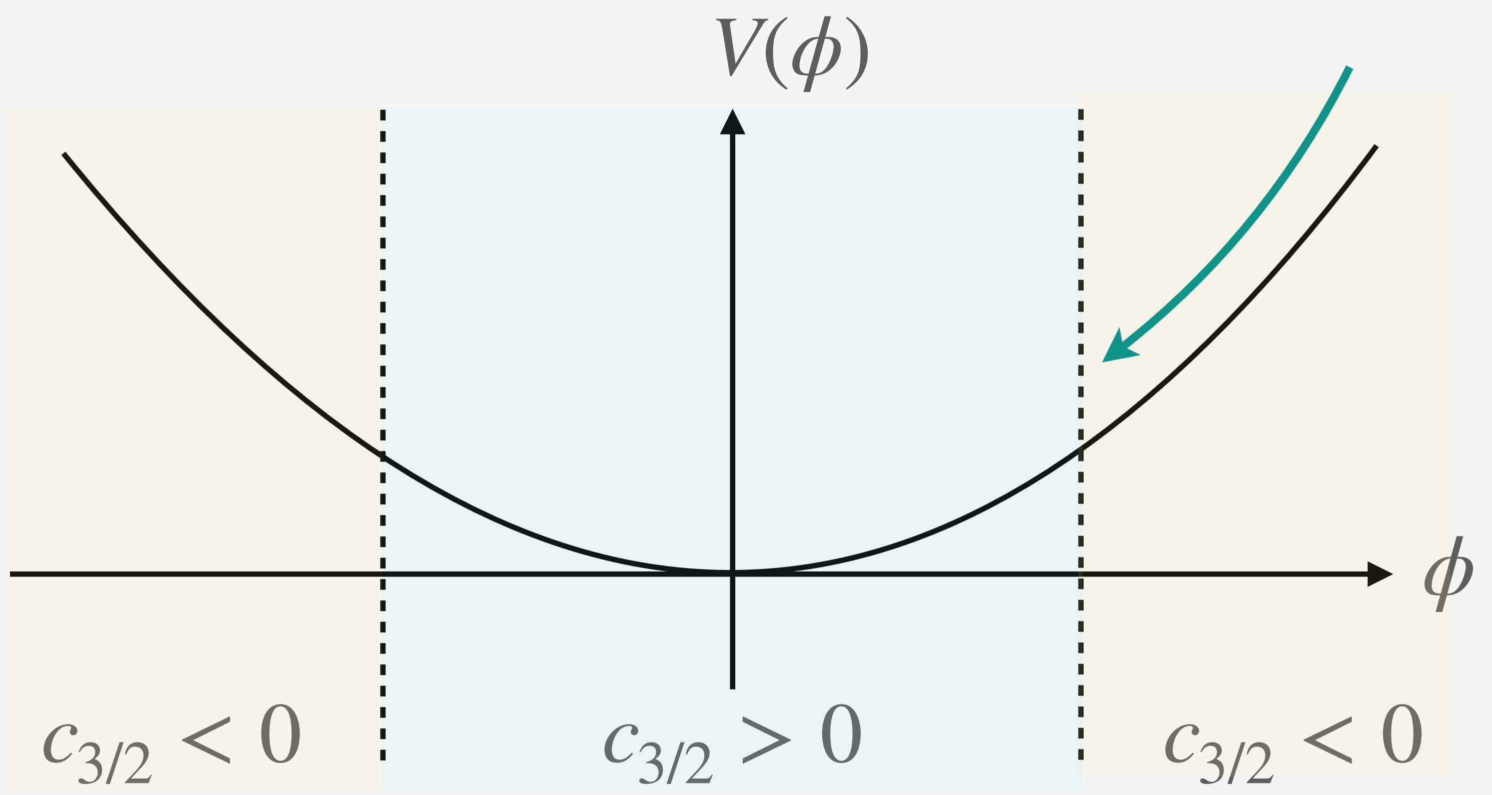

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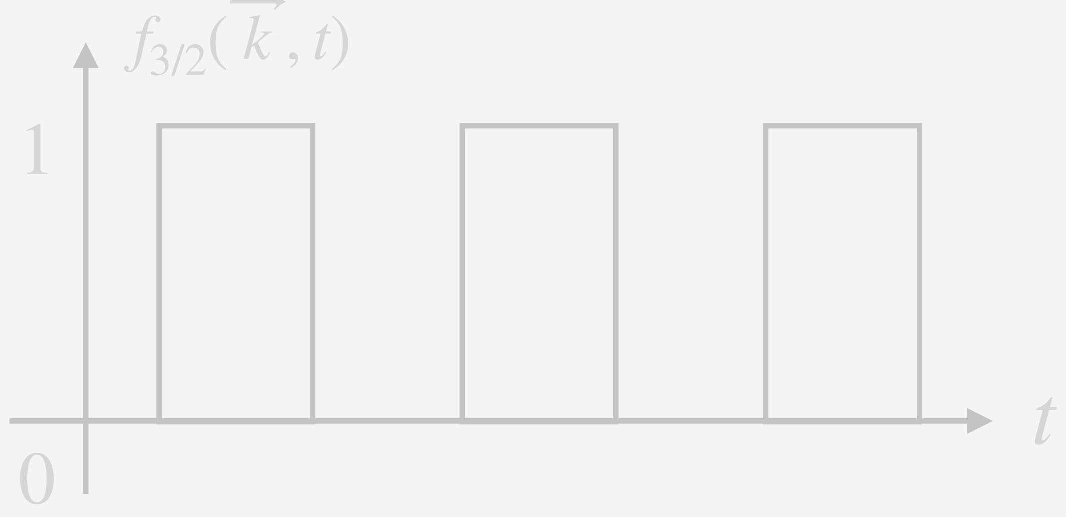

Catastrophic gravitino production

$$a^3 n_{3/2} \sim 2\int_0^\Lambda \mathrm{d}k\,\frac{4\pi k^2}{(2\pi)^3} f_{3/2}(\vec{k}, t) \sim \Lambda^3$$

… or breakdown of the effective theory.

Anomalous Production of Slow Gravitinos

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106], [Kolb, Long, Mcdonough, 2102.10113; 2103.10437]

Longitudinal gravitino Lagrangian

$$\mathscr{L} = -\frac{1}{2}\overline{\psi^\ell}\left(\gamma^0\partial_0 + \widehat{c}_{3/2}\left(\vec{\gamma}\cdot\vec{\nabla}\right) + a\,\widehat{m}_{3/2}\right)\psi^\ell$$

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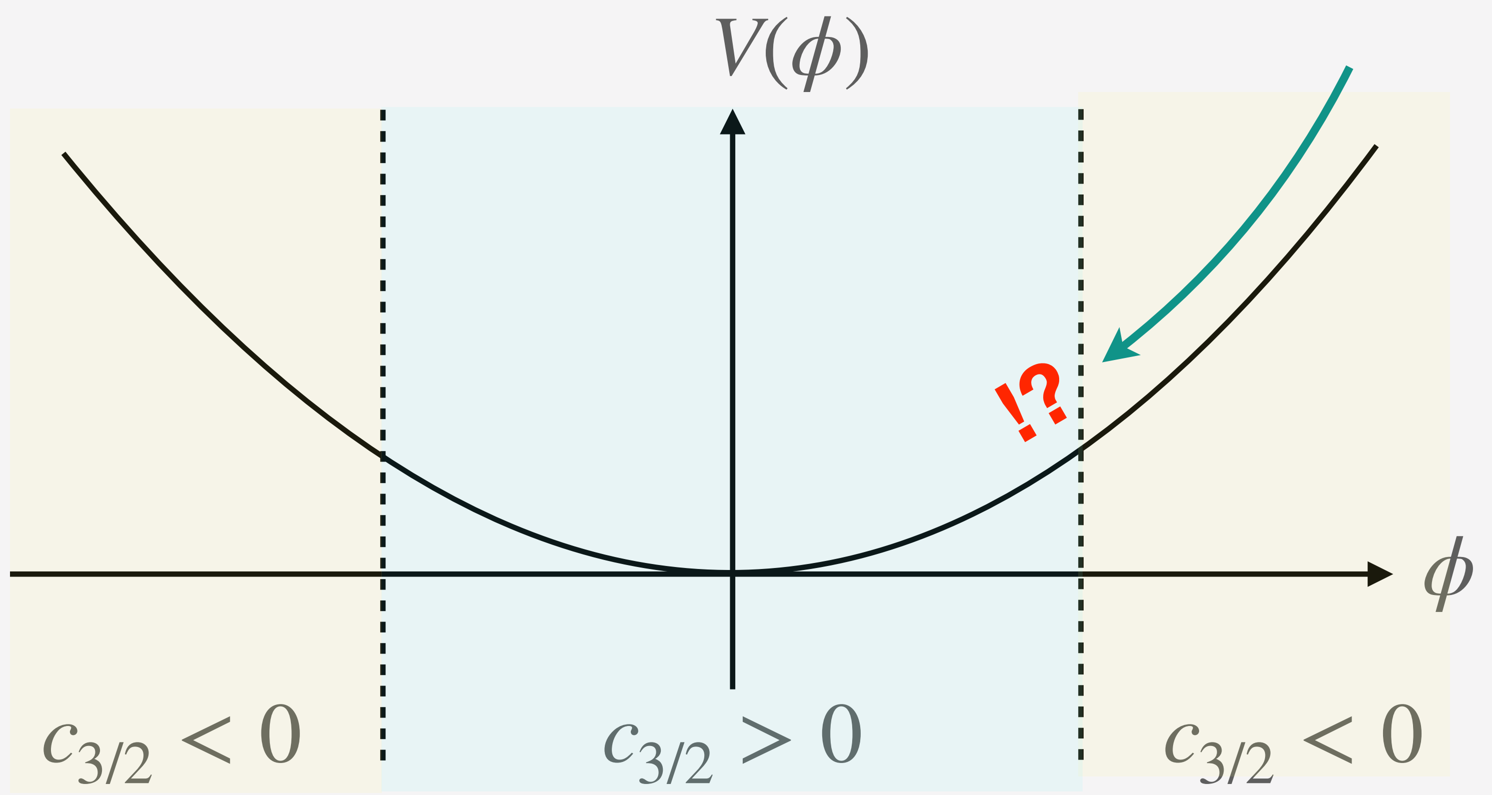

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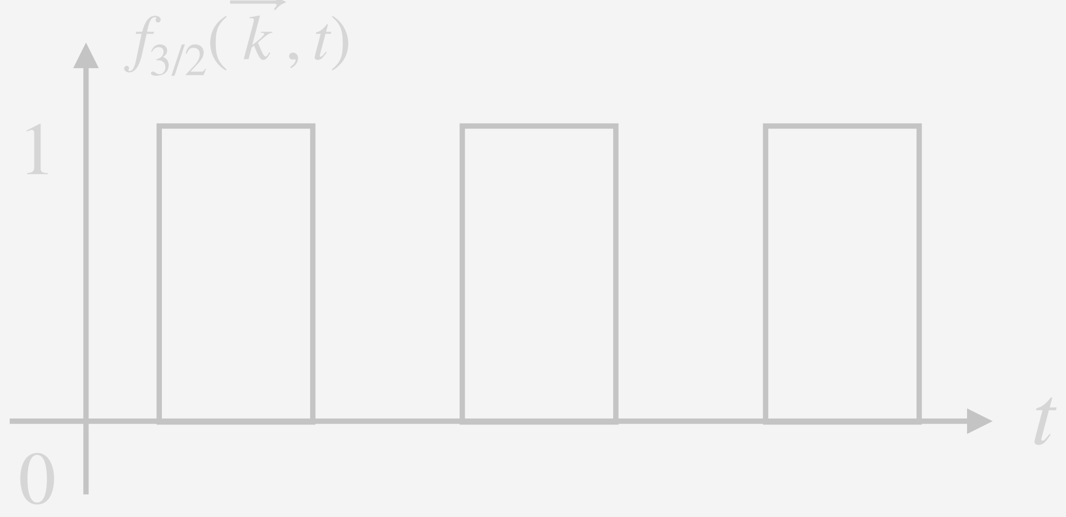

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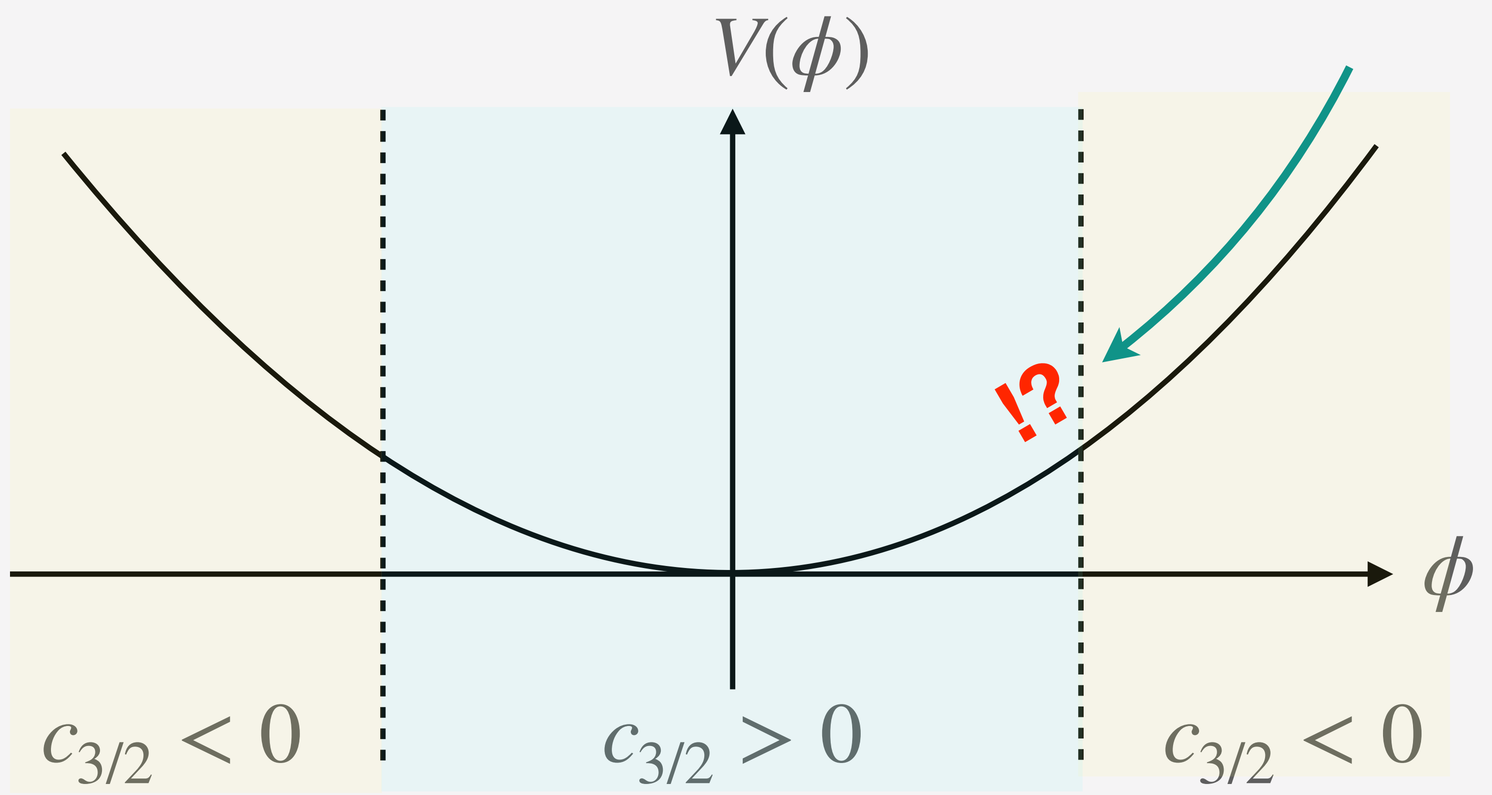

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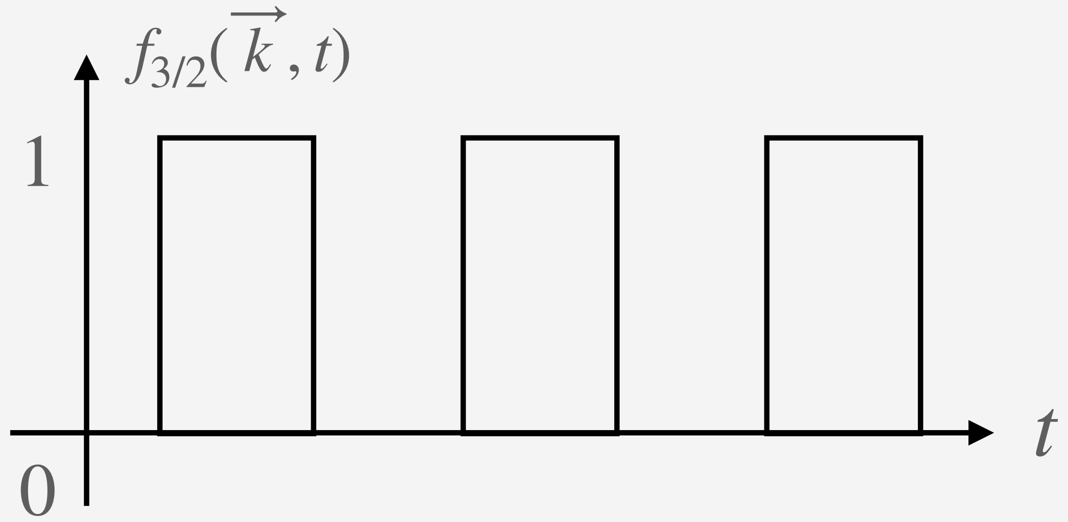

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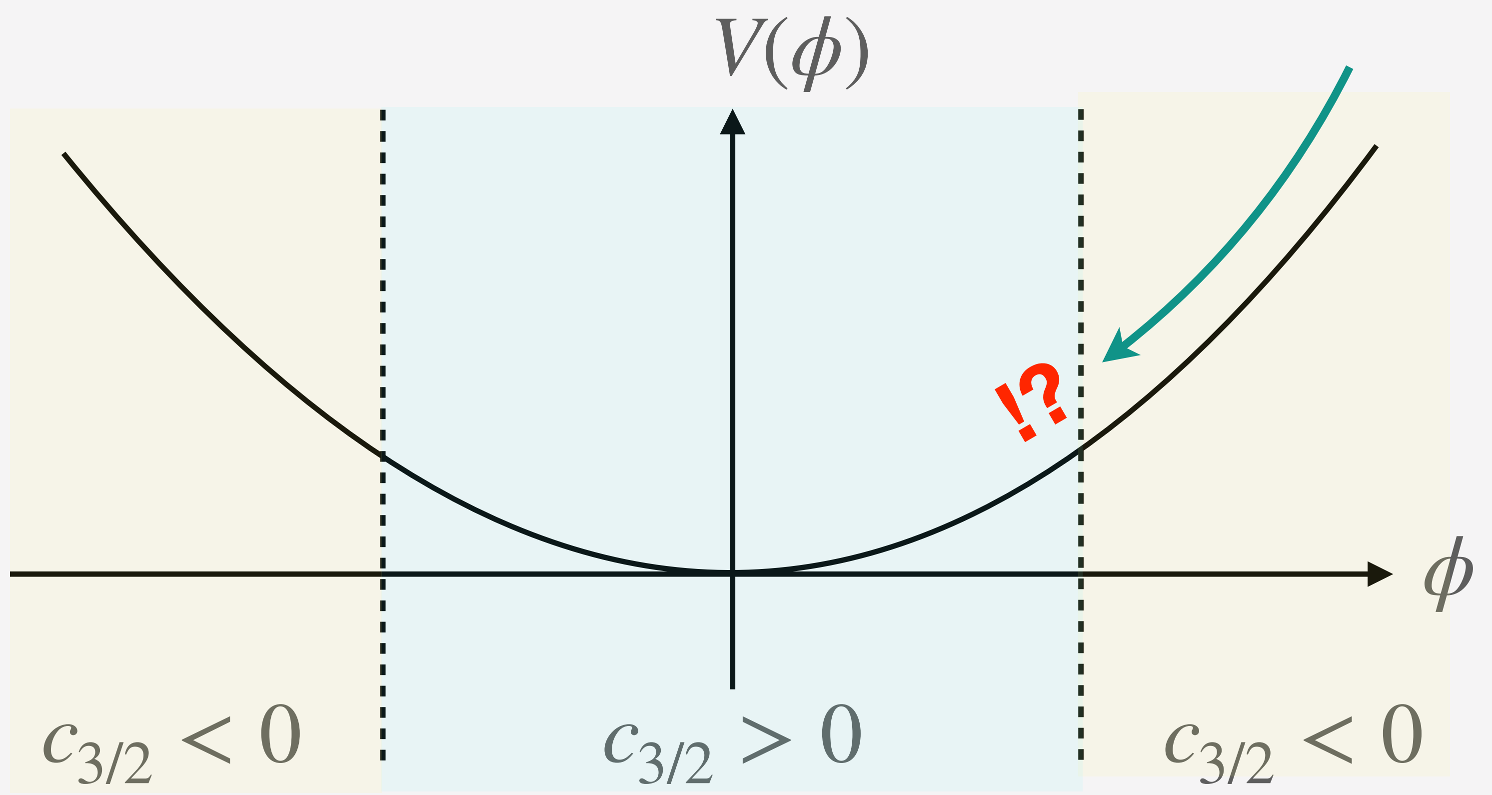

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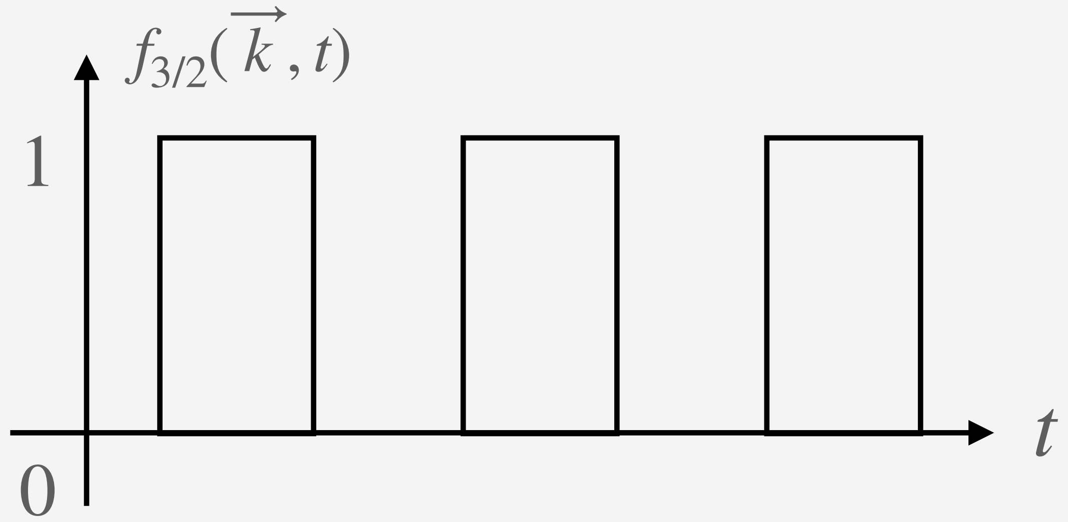

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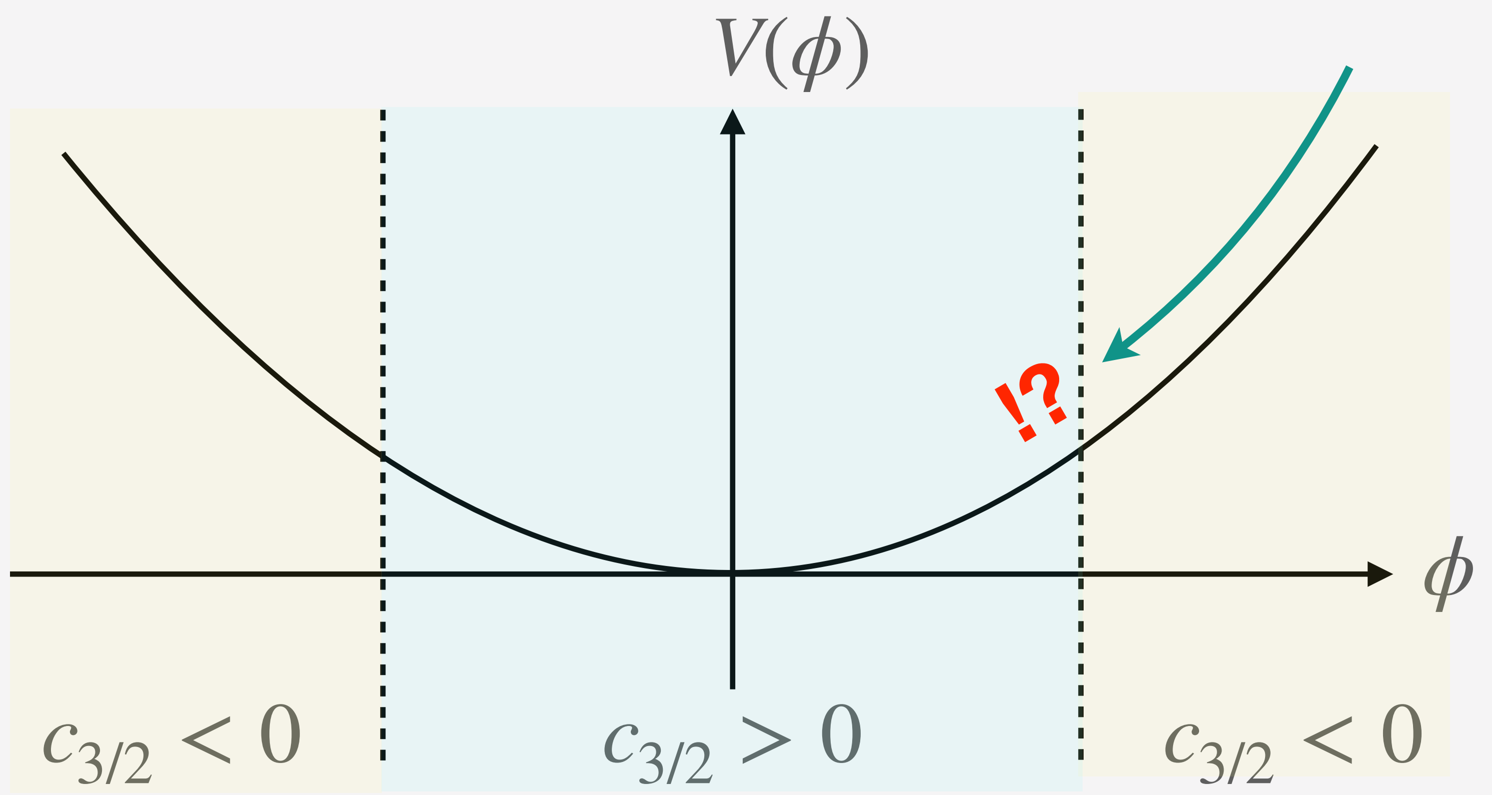

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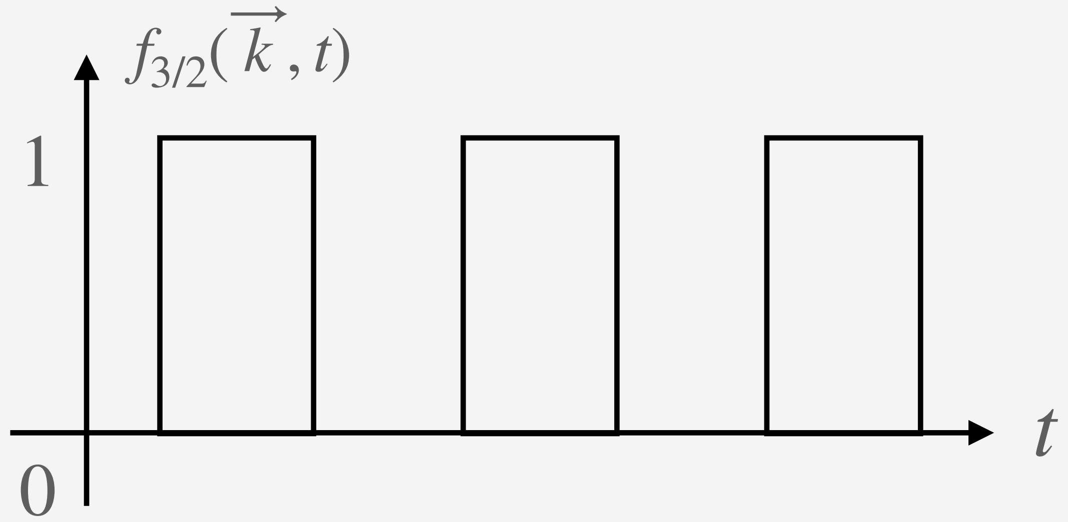

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… or breakdown of the effective theory.

In this talk, our aim is **not** to solve this issue.

Instead, we propose an alternative model for “Minimal Supergravity Inflation” without the issue.

Cubic Nilpotent Superfield Φ: $(\Phi - \bar{\Phi})^3 = 0$

[Aldabergenov, Chatrabhuti, Isono, 2103.11217]
See also [Kuzenko, 1712.09258],
[Komargodski, Seiberg, 0907.2441]

$$\Phi = \phi + \sqrt{2}\theta\chi^{\Phi} + \theta\theta F^{\Phi}$$

The global-SUSY solution of the constraint, $\mathrm{Im}\,\phi = \mathrm{Im}\,\phi(\chi^{\Phi}, F^{\Phi}, \mathrm{Re}\,\phi)$, is complicated.
See [Aldabergenov, Chatrabhuti, Isono, 2103.11217] for the explicit expression.

→ The solution in supergravity would be much complicated…

However, the solution in the unitary gauge, $\upsilon = \chi^{\Phi} = 0$, can be obtained easily.

(would-be) Nambu-Goldstone fermion: $\upsilon_{\mathrm{L}} \equiv e^{K/2} D_i W \chi^i_{\mathrm{L}} + g_{i\bar{j}} \partial_\mu \phi^i \gamma^\mu \chi^{\bar{j}}_{\mathrm{R}}$

more precise parametrization: $\Phi = \left(\phi + i\varphi, 0, -iF^{\Phi}, -F^{\Phi}, -i\partial_\mu(\phi + i\varphi), 0, 0\right)$

constraint: $0 = \dfrac{i}{8}(\Phi - \bar{\Phi})^3 = \left(\varphi^3, 0, -3\varphi^2 \mathrm{Re}\,F^{\Phi}, -3\varphi^2 \mathrm{Im}\,F^{\Phi}, -3\varphi^2 \partial_\mu \phi, 0, 3\varphi\left(-\partial^\mu\phi\partial_\mu\phi - \partial^\mu\varphi\partial_\mu\varphi + |F^{\Phi}|^2\right)\right)$

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Inflation

In terms of a cubic nilpotent superfield Φ, $(\Phi - \bar{\Phi})^3 = 0$,

Kähler potential can be expanded as follows.

$$K(\Phi, \bar{\Phi}) = K_0(\Phi + \bar{\Phi}) - iK_1(\Phi + \bar{\Phi})(\Phi - \bar{\Phi}) - \frac{1}{2}K_2(\Phi + \bar{\Phi})(\Phi - \bar{\Phi})^2$$

Superpotential is generic.

$$W(\Phi) = W(\Phi)$$

Shift symmetry in Kähler potential ($K_0, K_1, K_2 \simeq$ const.); soft explicit breaking in superpotential.

[Kawasaki, Yamaguchi, Yanagida, hep-ph/0004243], [Kallosh, Linde, 1008.3375], [Kallosh, Linde, Rube, 1011.5945]

For simplicity, let us take $K_0 = 0, K_1 = c,$ and $K_2 = 1$.

Scalar potential is

$$V = e^K(g^{\bar{\Phi}\Phi}|D_\Phi W|^2 - 3|W|^2)$$

$$= |W_\Phi|^2 + (c^2 - 3)|W|^2 + 2c\,\mathrm{Im}(W\bar{W}_{\bar{\Phi}}).$$

There are several methods to construct inflation potentials in supergravity with a single chiral superfield.

[Ketov, Terada, 1406.0252; 1408.6524; 1509.00953; 1606.02817], [Linde, 1504.00663], [Ferrara, Roest, 1608.03709]

See also [Goncharov, Linde, PLB 139 (1984) 27], [Izawa, Shinbara, 0710.1141], [Achucarro, Mooji, Ortz, Postma, 1203.1907], [Alvarez-Gaume, Gomez, Jimenez, 1001.0010; 1101.4948]

Example with $c = 0$

[Roest, Scalisi, 1503.07909]

$$W(\Phi) = W_0\left(e^{\sqrt{3}\Phi} - e^{-\sqrt{3}\Phi}\,\mathrm{Polynomial}\left(e^{-2\Phi/\sqrt{3\alpha}}\right)\right)$$

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In terms of a cubic nilpotent superfield Φ, $(\Phi - \bar{\Phi})^3 = 0$,

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Superpotential is generic.

$$W(\Phi) = W(\Phi)$$

Shift symmetry in Kähler potential ($K_0, K_1, K_2 \simeq$ const.); soft explicit breaking in superpotential.

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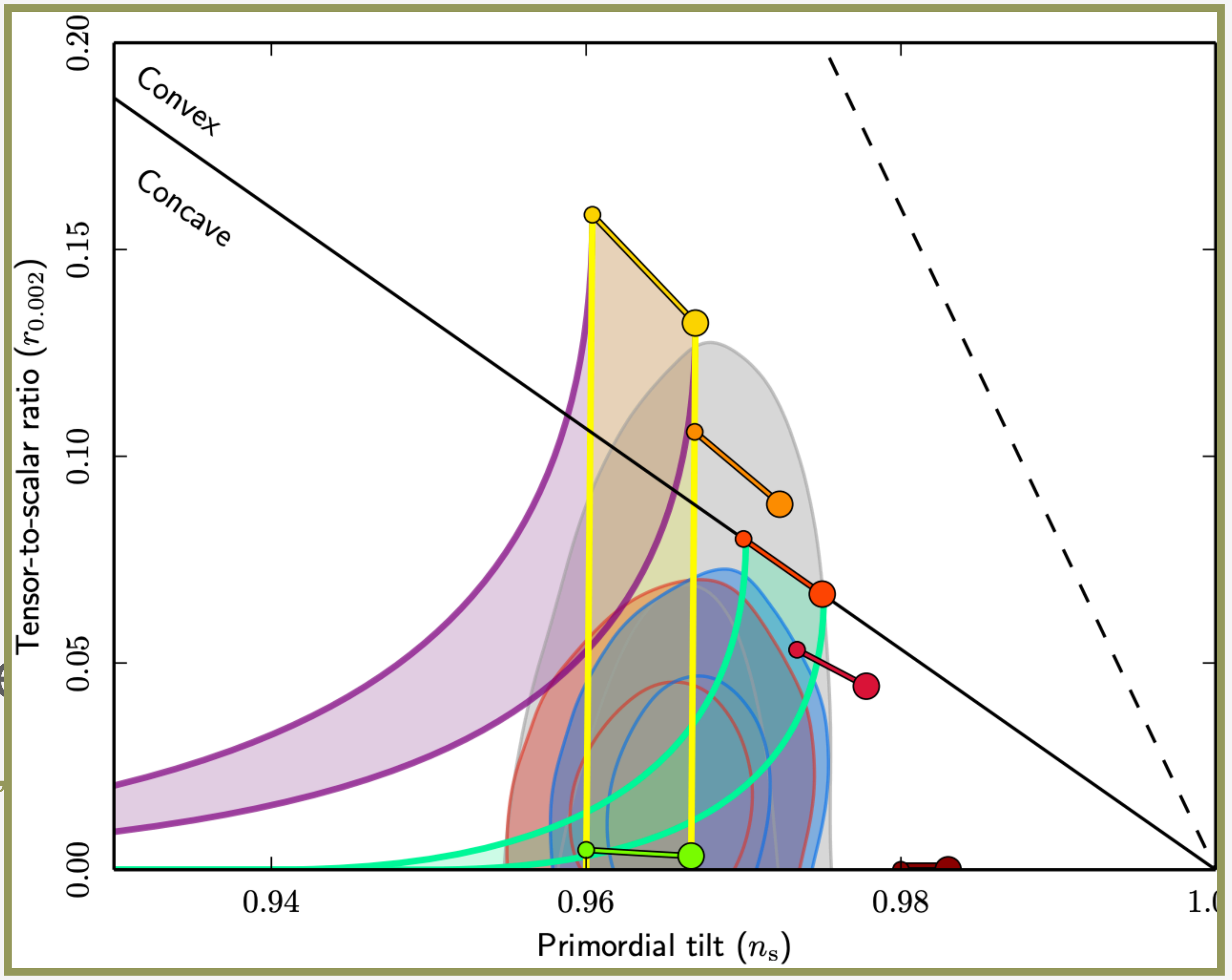
[Akrami et al., Planck 2018, Constraints on inflation]



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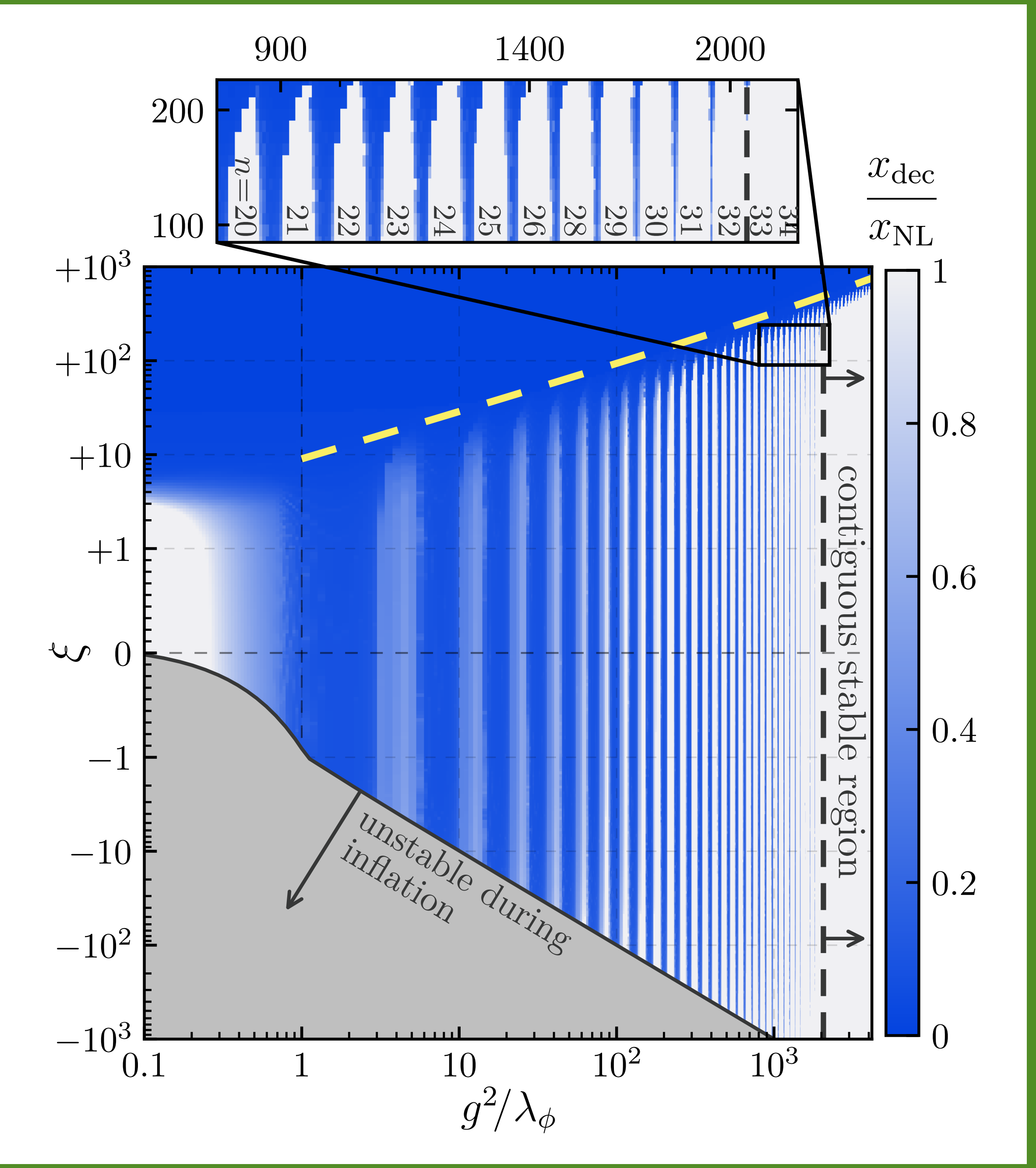
J. Kost, C.S. Shin, T. Terada

arXiv: 2105.06939 [hep-ph]

We forgot to submit the abstract by the PASCOS deadline...



Appendix

Cubic Nilpotent Superfield, in more detail

[Aldabergenov, Chatrabhuti, Isono, 2103.11217]

A chiral superfield $\mathbf{S}$ can be expanded as follows: $\mathbf{S} = S + \sqrt{2}\theta\chi + \theta\theta F, \qquad S = \phi + i\varphi.$

The constraint, $(S + \bar{S})^3 = 0$, is solved for the real part of the bosonic component, $\Sigma \equiv S + \bar{S}$.

$$\Sigma = \chi^2\beta + \bar{\chi}^2\bar{\beta} + \frac{2}{U}\chi\sigma^\mu\bar{\chi}\partial_\mu\varphi,$$

where $U \equiv 2(|F|^2 - \partial_\mu\varphi\partial^\mu\varphi)$, and β is defined as

$$\begin{aligned}\beta \equiv \frac{\bar{F}}{U} + \frac{i\bar{\chi}}{U^2}\left(\bar{F}\bar{\sigma}^\mu\partial_\mu\chi - \partial_\mu\varphi\partial^\mu\bar{\chi} + 2\partial_\mu\varphi\bar{\sigma}^{\mu\nu}\partial_\nu\chi\right) \\ -\frac{\bar{\chi}^2}{2U^3}\left(F\partial_\mu\bar{\chi}\bar{\sigma}^{\mu\nu}\partial_\nu\bar{\chi} + \bar{F}\partial_\mu\chi\sigma^{\mu\nu}\partial_\nu\chi + \partial_\mu\varphi\partial_\nu\chi\left(2\sigma^\mu\eta^{\nu\rho} - \sigma^\nu\eta^{\rho\mu} - \sigma^\rho\eta^{\mu\nu} - i\epsilon^{\mu\nu\rho\sigma}\sigma_\sigma\right)\partial_\rho\bar{\chi}\right).\end{aligned}$$

Proof of $|\hat{c}_{3/2}| = c$

$$|\hat{c}_{3/2}|^2 = \frac{p_{\rm SB}^2 + |p_W|^2}{\rho_{\rm SB}^2} = \frac{\left(\frac{1}{2}\dot{\phi}^2 - |F^\Phi|^2\right)^2 + \left|\sqrt{2}F^\Phi\dot{\phi}\right|^2}{\left(\frac{1}{2}\dot{\phi}^2 + |F^\Phi|^2\right)^2} = 1.$$

The gravitino sound speed equals the speed of light when the inflation sector is composed of a single chiral superfield. This fact is well known.

[Kallosh, Kofman, Linde, Van Proeyen, hep-th/9907124; hep-th/0006179]
[Giudice, Tkachev, Riotto, hep-ph/9907510; hep-ph/9911302]
See also [Nilles, Peloso, Sorbo, hep-ph/0102264; hep-th/0103202]
[Ema, Mukaida, Nakayama, Terada, 1609.04716]

Anomalous Gravitino Production, Details 1

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

Gravitino mode expansion (Dirac rep.)

$$\psi^{\ell} = \underbrace{\sum_h}_{\text{helicity sum}} \int \underbrace{\frac{d^3k}{(2\pi)^{3/2}} e^{i\vec{k}\cdot\vec{x}}}_{\text{Fourier transform}} \begin{pmatrix} u^{+}_{\vec{k},h}(t) \\ u^{-}_{\vec{k},h}(t) \end{pmatrix} \otimes \underbrace{\xi_{\vec{k},h}}_{\text{eigenvector of helicity}} \overbrace{\hat{b}_{\vec{k},h}}^{\text{annihilation op.}} + \text{H.c.}$$

Equation of motion for this

$$c_{3/2}u'' - c'_{3/2}u' + c_{3/2}\widetilde{\omega}^2_k u = 0$$

$$\widetilde{\omega}^2_k \equiv a^2\omega^2_k - ic_{3/2}(a\widehat{m}_{3/2}/c_{3/2})'$$

where $c_{3/2} \equiv (p_{\mathrm{SB}} + ip_W)/\rho_{\mathrm{SB}}$ and $\omega_k \equiv \sqrt{\widehat{m}^2_{3/2} + |c_{3/2}k/a|^2}$.

Let us begin with the simplest case: $g(\Phi) = m_{3/2}M_{\mathrm{P}}^2$ (const.). $\Rightarrow$ $p_W = 0$, and $c_{3/2} = c^*_{3/2} = w_{\mathrm{SB}}(= p_{\mathrm{SB}}/\rho_{\mathrm{SB}})$.

Further, let us consider the limit $m_{3/2} \to 0$ to allow an analytic solution:
(Of course, this limit restores SUSY, so we cannot take this limit literally.)

$$u(\eta) = \frac{1}{\sqrt{2}}\exp\left[ik\int_0^{\eta} \mathrm{d}\eta' c_{3/2}(\eta')\right]$$

The sign change of the sound speed switches the positive and negative frequency modes.

$$f_{3/2}(\vec{k};t) \equiv \frac{1}{2\omega_k(t)}\left(2\mathrm{Im}\left(u^{+*}_{\vec{k}}(t)\dot{u}^{+}_{\vec{k}}(t)\right) - \widehat{m}_{3/2}(t)\right) + \frac{1}{2} = \frac{1}{2}\left(1 + \mathrm{sgn}\left(c_{3/2}(t)\right)\right)$$

← Momentum independent!!

Anomalous Gravitino Production, Details 1

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

Gravitino mode expansion (Dirac rep.)

annihilation op.

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Restoring $m_{3/2}(\ll H)$ smears the sharp edge of $f_{3/2}$ and modulates the oscillation in a longer time scale $m_{3/2}^{-1}$.
Our orders-of-magnitude estimates and conclusions would not be affected.

The sign change of the sound speed switches the positive and negative frequency modes.

$$f_{3/2}(\vec{k};t) \equiv \frac{1}{2\omega_k(t)}\left(2\mathrm{Im}\left(u^{+*}_{\vec{k}}(t)\dot{u}^{+}_{\vec{k}}(t)\right) - \widehat{m}_{3/2}(t)\right) + \frac{1}{2} = \frac{1}{2}\left(1 + \mathrm{sgn}\left(c_{3/2}(t)\right)\right)$$

$\leftarrow$ Momentum independent!!

Anomalous Gravitino Production, Details 2

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

Dirac Sea filled up to $k \to \infty$!?

Possibilities

(A) The effective theory breaks down, and the linearized SUSY theory is needed.

(B) The particle production phenomenon is real, and it is valid up to some UV cutoff scale Λ.

(Expected) unitarity bound

$$\Lambda_{\mathrm{UB}} = \left(M_{\mathrm{P}}^2 \left(H^2 + m_{3/2}^2 \right) \right)^{1/4}$$

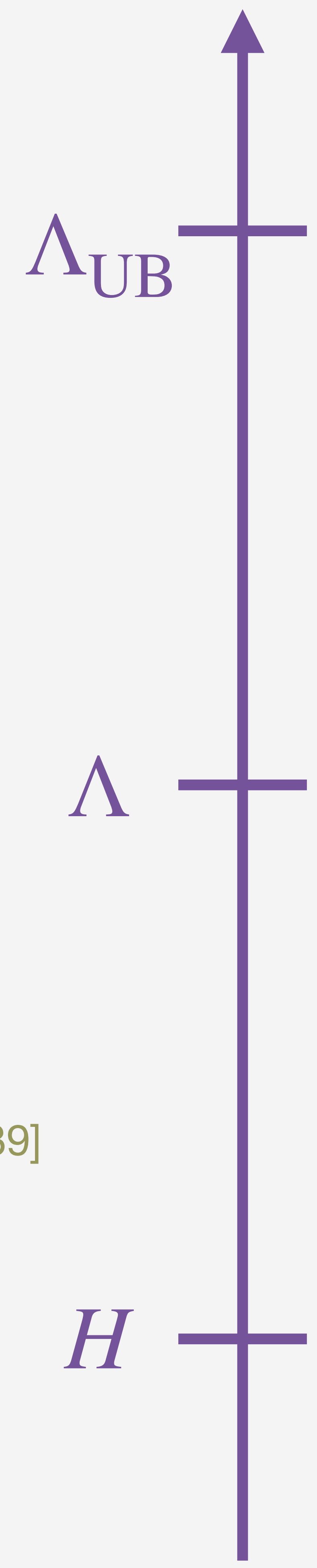
[Kallosh, Kofman, Linde, Van Proeyen, hep-th/0006179]
[Dall'Agata, Zwirner, 1411.2605]
[Ferrara, Kallosh, Thaler, 1512.00545]
[Kahn, Roberts, Thaler, 1504.05958]
[Carrasco, Kallosh, Linde, 1512.00546]
[Delacretaz, Gorbenko, Senatore, 1610.04227]
[Casalbuoni, De Curtis, Dominici, Feruglio, Gatto, Phys.Lett.B216 (1989) 325, erratum: PLB229 (1980) 439]

Gravitino number density

$$a^3 n_{3/2} \sim 2 \int_0^{\Lambda} dk \frac{4\pi k^2}{(2\pi)^3} f_{3/2}(\vec{k};t) \sim \Lambda^3$$

Gravitino energy density

$$\rho_{3/2} \sim a^{-4}\Lambda^4 \lesssim \Lambda_{\mathrm{UB}}^4 \sim 3H^2 M_{\mathrm{P}}^2 = \rho$$



A substantial fraction of the energy density is transferred to gravitinos.

Anomalous Gravitino Production, Details 3

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

Alternative understanding based on the standard technique of preheating

Field redefinition to remove the γ^0-dependence of the sound speed parameter: $\psi^\ell = e^{\theta\gamma^0}\tilde{\psi}^\ell$

Longitudinal gravitino Lagrangian

$$\mathscr{L} = -\frac{1}{2}\overline{\tilde{\psi}^\ell}\left(\gamma^0\partial_0 - |c_{3/2}|\left(\vec{\gamma}\cdot\vec{\nabla}\right) + a(\widehat{m}_{3/2} - \theta')\right)\tilde{\psi}^\ell$$

where $\tan 2\theta = -p_W/p_{SB}$. The effective mass oscillates like spikes.

Particle production is now understood as being caused by the non-adiabaticity of the oscillating mass.

Consider more general cases with $|g_\Phi| \neq 0$.

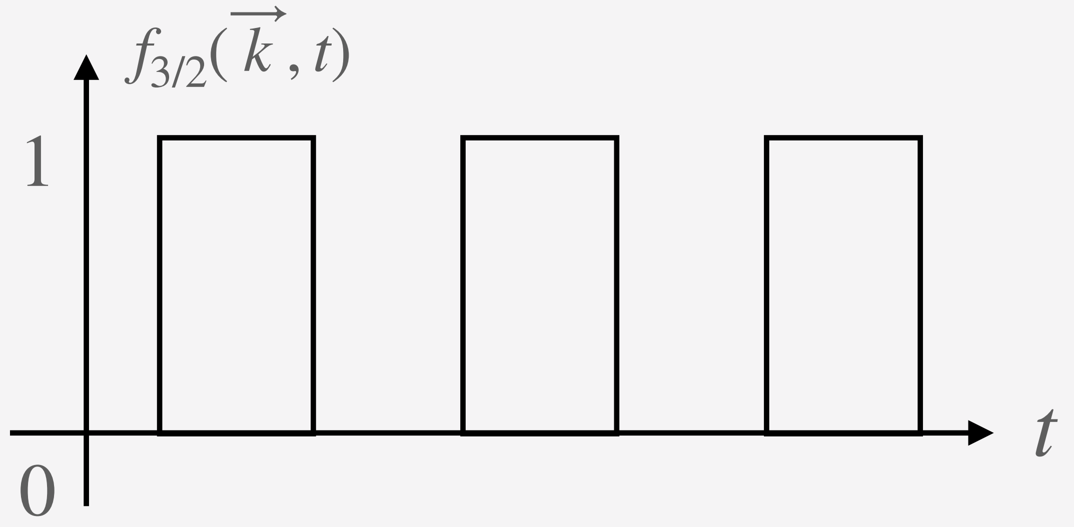
Gravitinos are produced up to $k_{\max} \sim \min\left[\Lambda, \frac{M_P^2 H^2 m_\phi}{|g_\Phi|^2}\right]$. However, "standard" gravitino problem remains.

Anomalous Gravitino Production, Details 4

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

Particle production and annihilation

by inflaton coherent oscillation



Even without assuming inflaton coherent oscillation,

(for simplicity, we here assume $p_W = 0$ and small $m_{3/2}$.)

$$c_{3/2} = w_{\mathrm{SB}} = \frac{p - 3m_{3/2}^2 M_{\mathrm{P}}^2}{\rho + 3m_{3/2}^2 M_{\mathrm{P}}^2}$$

Inflation $w = -1 (< 0)$ → **Radiation era** $w = 1/3 (> 0)$ → **Late time** $w = -1 (< 0)$

Gravitino production; Gravitino annihilation

… Can we hope that the produced gravitinos disappear?

It is hard to imagine the exact cancellation because of the cosmic expansion.
Gravitinos are diluted with time-dependent Hubble factor, so the annihilation will be incomplete.

Anomalous Gravitino Production, Details 5

[Hasegawa, Mukaida, Nakayama, Terada, Yamada, 1701.03106]

What is the essence of the anomalous/catastrophic production?

In the standard case without constraints, the fermion gradient terms can be diagonalized:

$$\mathscr{L}_{\text{grad}} = -\frac{1}{2}\begin{pmatrix}\overline{\psi^\ell} & \overline{\upsilon_\perp}\end{pmatrix}\left(i\vec{\gamma}\cdot\vec{k}\right)\widehat{\mathscr{C}_{3/2}}\begin{pmatrix}\psi^\ell \\ \upsilon_\perp\end{pmatrix}$$

For multi-(super)fields, $|\hat{c}_{3/2}|^2 \neq 1$, in general.

[Kallosh, Kofman, Linde, Van Proeyen, hep-th/9907124; hep-th/0006179]
[Giudice, Tkachev, Riotto, hep-ph/9907510; hep-ph/9911302]
[Nilles, Peloso, Sorbo, hep-ph/0102264; hep-th/0103202]
[Ema, Mukaida, Nakayama, Terada, 1609.04716]
[Dudas, Garcia, Mambrini, Olive, Peloso, Verner, 2104.03749]
[Antoniadis, Benakli, Ke, 2105.03784]

$$\widehat{\mathscr{C}_{3/2}} = \begin{pmatrix} -\hat{c}^\dagger_{3/2} & \alpha_i e^{-2\gamma^0\theta_i}\widetilde{O}_{iJ} \\ \widetilde{O}^{\mathrm{T}}_{Ii}\alpha_i e^{-2\gamma^0\theta_i} & \widetilde{O}^{\mathrm{T}}_{Ii} e^{-2\gamma^0\theta_i}\widetilde{O}_{iJ}\end{pmatrix}$$

The whole matrix satisfies $|\widehat{\mathscr{C}_{3/2}}|^2 = 1$ and can be diagonalized into the unit matrix.

The anomalous/catastrophic gravitino production can be interpreted as
the brute-force intervention to the diagonalization process by the constraints.
→ Inflatino (or other relevant fermions) should not be removed from the spectrum.

Gravitino Abundance

Partial decay rate (for $m_{3/2} \ll m_\phi$)

$$\Gamma(\phi \to \psi_{3/2}\psi_{3/2}) \simeq \frac{m_\phi^5}{96\pi m_{3/2}^2 M_P^2}$$

It can easily lead to a gravitino-dominated Universe!

Gravitino yield

$$Y_{3/2} \equiv \frac{n_{3/2}}{s} = \frac{3T_R}{2m_\phi}\mathrm{Br}(\phi \to \psi_{3/2}\psi_{3/2})$$

$$= \frac{m_\phi^4}{64\pi m_{3/2}^2 T_R M_P}\left(\frac{90}{\pi^2 g_*(T_R)}\right)^{1/2}$$

$$= 4.4 \times 10^{-5}\left(\frac{m_\phi}{10^{12}\,\mathrm{GeV}}\right)^4\left(\frac{m_{3/2}}{10^{11}\,\mathrm{GeV}}\right)^{-2}\left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)^{-1}\left(\frac{g_*}{200}\right)^{-1/2}$$

← Suppose the branching fraction is small.
We have also neglected a possible dilution effect during gravitinos are relativistic and after the end of the production at $H \sim m_{3/2}$ for simplicity.

Some possibilities to avoid the gravitino problem:

(1) Reheating by gravitino decay.
(2) Kinematically too heavy gravitinos.
(3) Entropy production.
(4) R-parity violation.

Inflation Model: Example 1

[Roest, Scalisi, 1503.07909]

Kähler potential $K(\Phi, \bar{\Phi}) = -\frac{1}{2}\left(\Phi - \bar{\Phi}\right)^2$ Superpotential $W(\Phi) = W_0\left(e^{\sqrt{3}\Phi} - e^{-\sqrt{3}\Phi}F\left(e^{-\frac{2\Phi}{\sqrt{3\alpha}}}\right)\right)$

where $\alpha, W_0 > 0$ as a convention, and $F(x) \equiv \sum_{n=0}^{\infty} f_n x^n$ is a real holomorphic function ($f_n \in \mathbb{R}$).

We impose 3 conditions (parametrization):

(1) The origin of the field is a stationary point (minimum) $V'(0) = 0$.

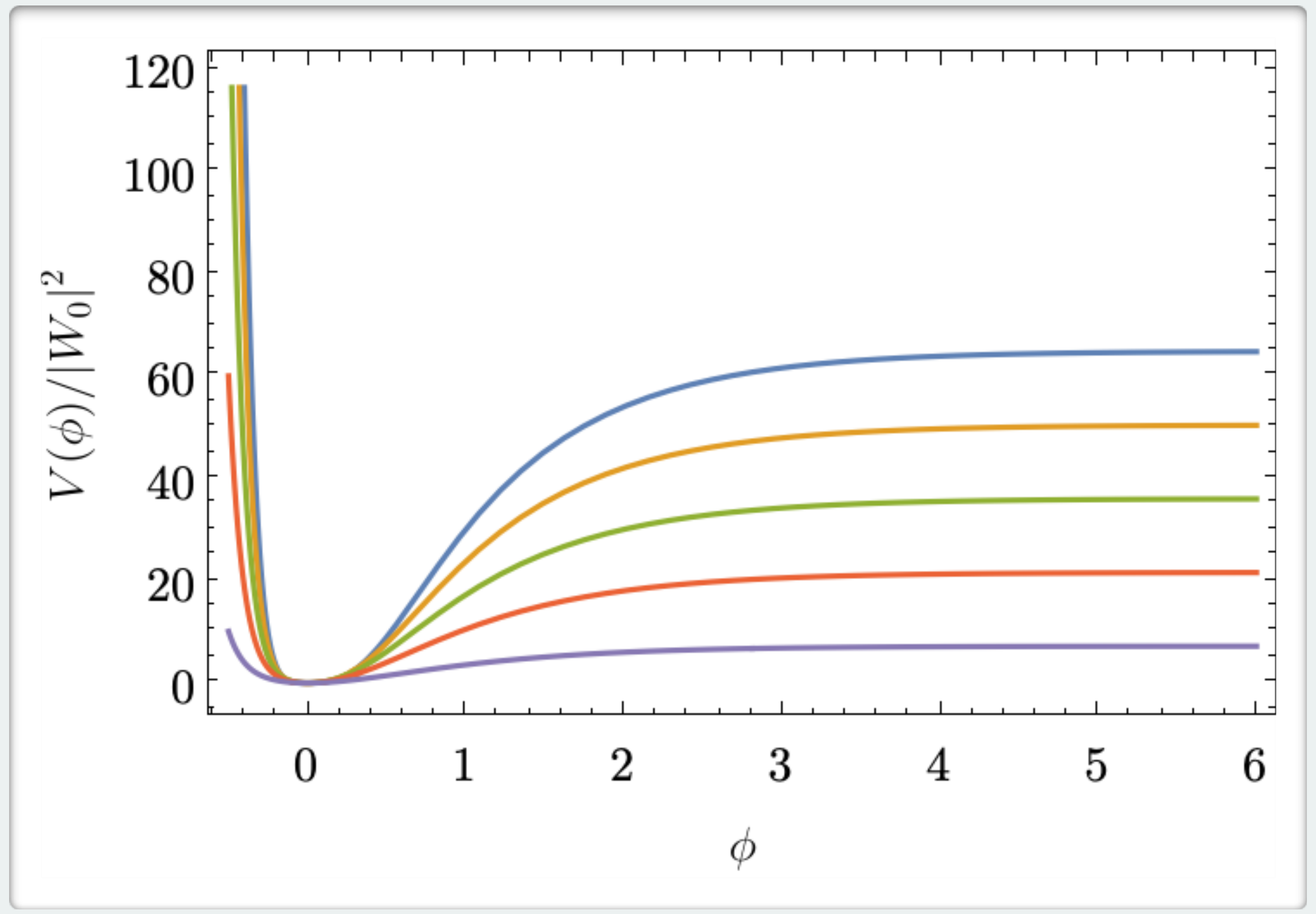
(2) The small cosmological constant $V(0) = \Lambda$.

(3) The tunable SUSY breaking parameter $F(1) = 1 - \delta$.

Truncating at $n = 2$, f_0, f_1, and f_2 can be solved in terms of α, δ, and Λ.

Inflaton mass in terms of gravitino mass and cosmological constant

$$m_\phi^2 = \frac{4(2 + 9\sqrt{\alpha} + 9\alpha)}{3\alpha\delta}\left((2-\delta)m_{3/2}\sqrt{3(3m_{3/2}^2 + \Lambda)} - \delta(3m_{3/2}^2 + \Lambda)\right)$$



Examples of the scalar potential.
δ = 0.1, 0.3, 0.5, 0.7, and 0.9 from top to bottom.
$\alpha = 4/9$ and $\Lambda = 0$.

The gravitino is heavier than the inflaton for $\delta \simeq 1$ and for $\delta \lesssim -8\alpha^{-1}(2 + 9\sqrt{\alpha} + 9\alpha)$.

Inflation Model: Example 2

[Ketov, Terada, 1406.0252]

Kähler potential $K(\Phi,\bar{\Phi}) = -ic(\Phi-\bar{\Phi}) - \frac{1}{2}\left(\Phi-\bar{\Phi}\right)^2$

Superpotential $W(\Phi) = \mu\left(b - e^{-\sqrt{2}a\Phi}\right)$

where c, μ, and a are real, but $b = b_{\mathrm{R}} + ib_{\mathrm{I}}$ is complex.

Scalar potential

$$V = \mu^2\left((c^2-3)\left(b_{\mathrm{R}} - e^{-a\phi}\right)^2 + \left(cb_{\mathrm{I}} - \sqrt{2}ae^{-a\phi}\right)^2 - 3b_{\mathrm{I}}^2\right)$$

VEV of the inflaton

$$e^{-a\phi} = \frac{(c^2-3)b_{\mathrm{R}} - \sqrt{2}acb_{\mathrm{I}}}{c^2+2a^2-3}$$

Inflaton mass

$$m_\phi^2 = \frac{2a^2\mu^2\left((c^2-3)b_{\mathrm{R}} - \sqrt{2}acb_{\mathrm{I}}\right)^2}{c^2+2a^2-3}$$

Gravitino mass

$$|m_{3/2}|^2 = \mu^2\left|\frac{a\left(2ab_{\mathrm{R}} + \sqrt{2}cb_{\mathrm{I}}\right)}{c^2+2a^2-3} + ib_{\mathrm{I}}\right|^2$$

We can require that the form of the potential is $V = \dfrac{m_\phi^2}{2a^2}(1-e^{-a\phi})^2 + \Lambda$ and solve for b_{R} and b_{I}.

Inflaton decay into gravitinos is kinematically forbidden for $0 < c^2 - 3 \lesssim \mathcal{O}(1)$.

same as α-attractors, generalizing Starobinsky model and Higgs inflation.

Gravitino and Swampland

Some Swampland conjectures about gravitinos were proposed recently.
These are not the topic of this talk.

Gravitino Swampland conjecture [Kolb, Long, Mcdonough, 2102.10113; 2103.10437]

Gravitino sound speed should not vanish.

Gravitino mass conjecture [Cribiori, Lust, Scalisi, 2104.08288]
Gravitino distance conjecture [Castellano, Font, Herraez, Ibáñez, 2104.10181]

The limit of vanishing gravitino mass corresponds to an infinite distance.
An infinite tower of states become light in the limit, and the EFT breaks down.