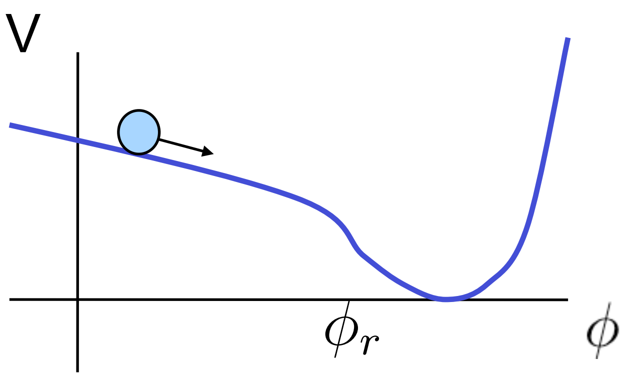
Leonardo Senatore (Stanford)

Supersymmetry in Inflation

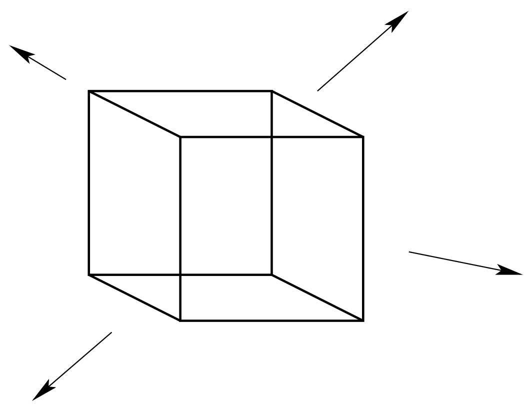
The usual theory of Inflation

- Inflation is usually described as a scalar field rolling on top of a flat potential

$$S=\int d^4x\sqrt{-g}\;\left[(\partial_\mu\phi)^2+V(\phi)\right]$$



- When potential is flat, universe expands as quasi de Sitter space



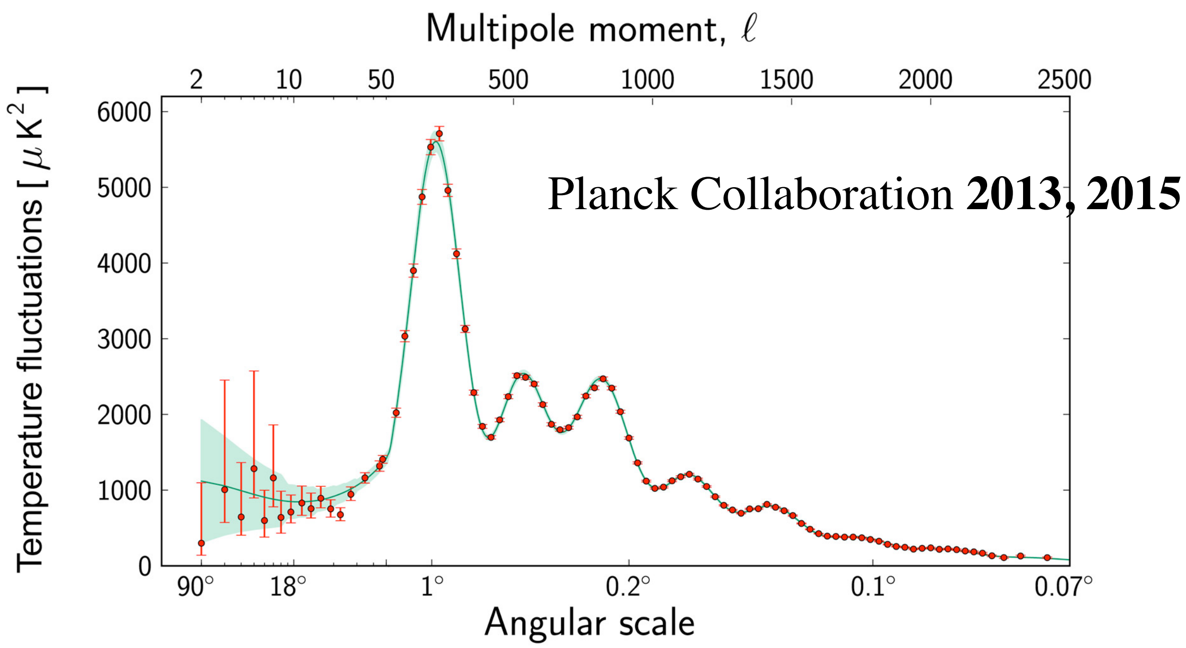
$$a(t)\sim e^{H\,t}$$

  - when inflaton reaches the bottom, inflation ends

What we have tested so far about Inflation

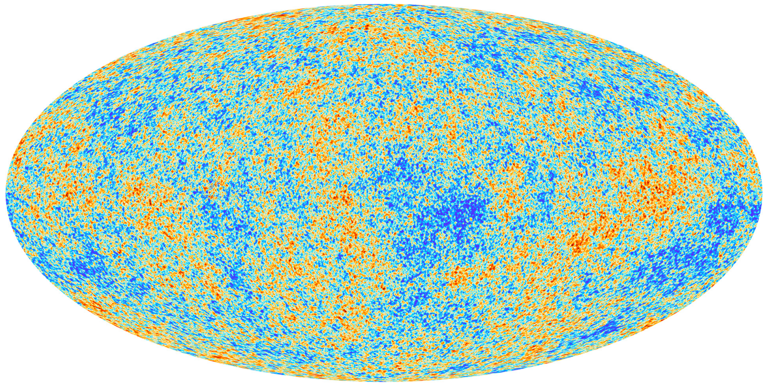
- The only observable we are testing from the background inflationary dynamics is

$$\Omega_K \lesssim 3 \times 10^{-3}$$



- All the rest, comes from the *fluctuations*
- For the fluctuations
  - they are primordial
  - they are scale invariant
  - they have a tilt $\quad n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$
  - they are quite gaussian

$$\mathrm{NG} \sim \frac{\langle \left(\frac{\delta T}{T}\right)^3 \rangle}{\langle \left(\frac{\delta T}{T}\right)^2 \rangle^{3/2}} \lesssim 10^{-3}$$

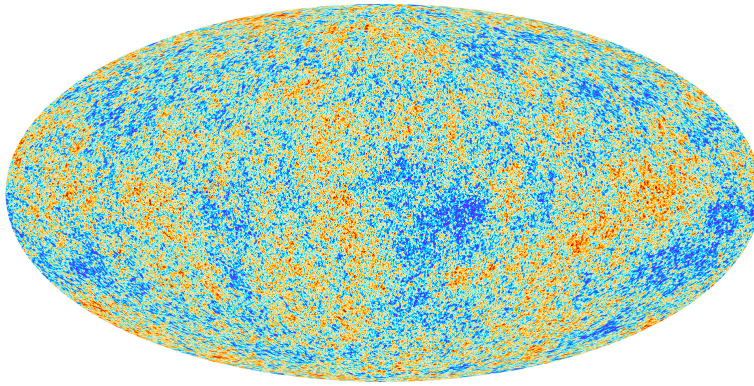


- Just 2 numbers
- Is this enough to conclude it is slow-roll Inflation? Indeed, there are other models
  - and in general, what is the dynamics of this inflaton?

What are we looking for

- Non-Gaussianities:
  - as much as the nature of interactions is revealed in scattering
  - so it is revealed in non-Gaussian correlations of primordial density fluctuations
- and for example, by their functional form, reveal the presence of additional light particles

$$\langle \delta T(\vec{x}_1) \delta T(\vec{x}_2) \delta T(\vec{x}_3) \rangle$$

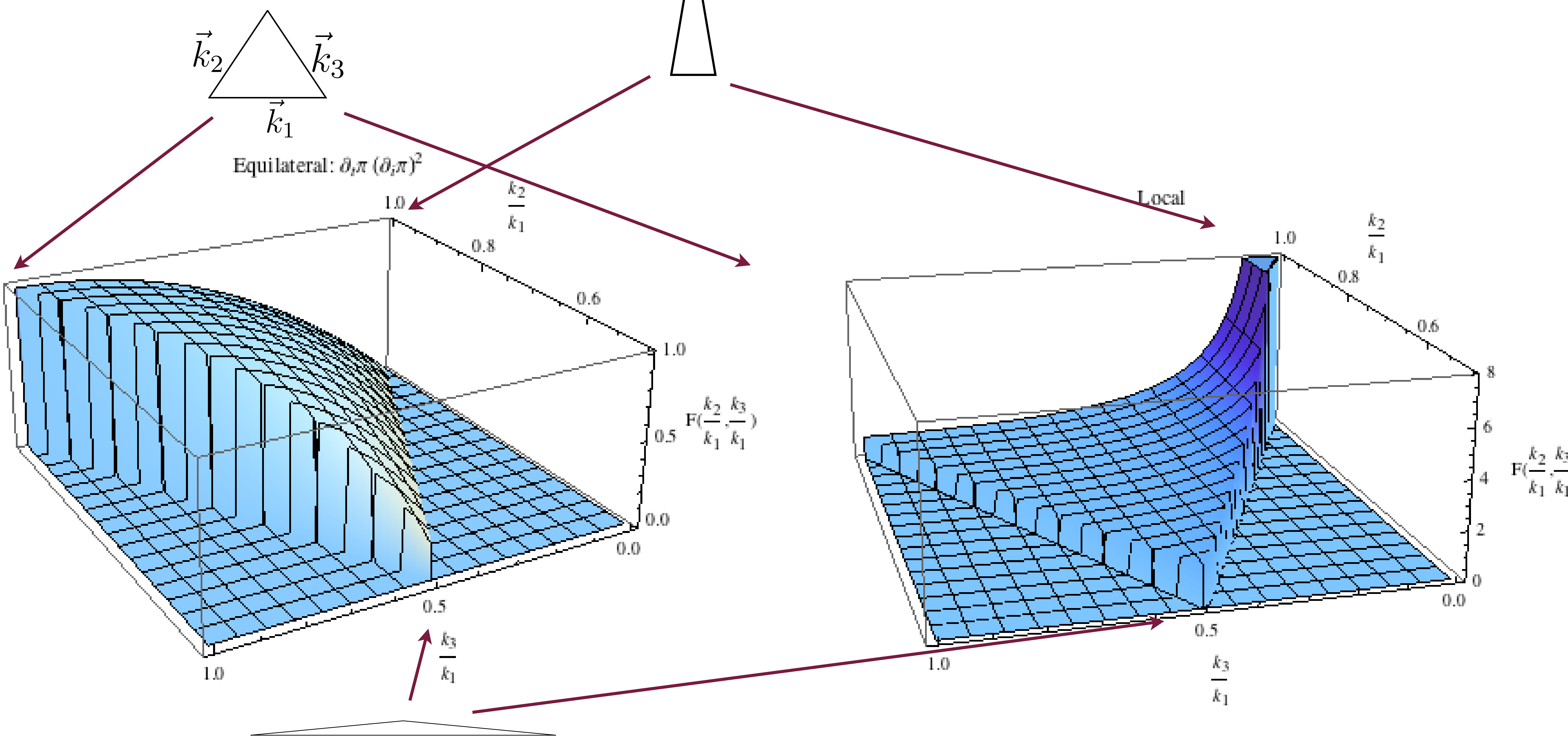


  – as do poles in ordinary scattering amplitudes
  - EFT of Inflation and Multifield Inflation

    with Cheung, Creminelli, Fitzpatrick, Kaplan **2008**
    with Zaldarriaga **2010**
  - quasi single field inflation Chen and Wang **2010**
  - cosmological collider Arkani-Hamed and Maldacena **2016**

Example: 3-point function

$$\langle \left(\frac{\delta T}{T}\right)_{\vec{k}_1} \left(\frac{\delta T}{T}\right)_{\vec{k}_2} \left(\frac{\delta T}{T}\right)_{\vec{k}_3} \rangle \sim \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\; f_{\rm NL}\; F\left(\frac{k_2}{k_1}, \frac{k_3}{k_1}\right)$$



A function of two variables: like a scattering amplitude, very non-trivial.

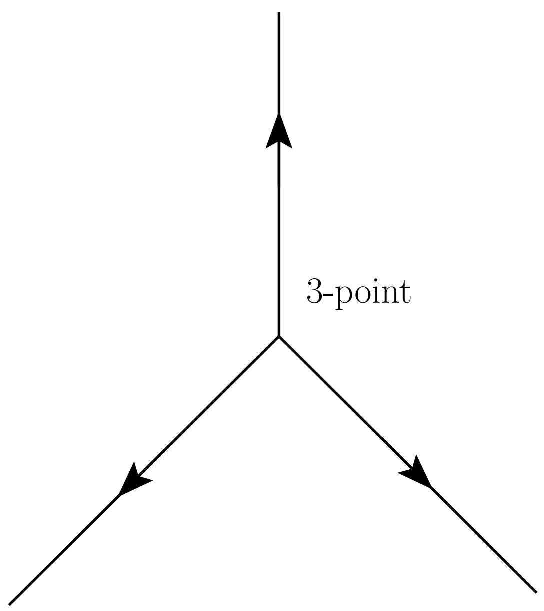
Presence of signal in squeezed limit $\Longrightarrow$ additional fields

Maldacena, Creminelli, Zaldarriaga, Senatore, Khoury, Hui, ….

☹ ~No detection ☹

Komastu, Spergel, Wandelt **Ast.J. 2005**
With Creminelli, Nicolis, Tegmark and Zaldarriaga, **JCAP2006**
With Creminelli, Tegmark and Zaldarriaga, **JCAP2007**
With Smith and Zaldarriaga, **JCAP2009**
JCAP2010

Optimal analysis of Planck data are ~ compatible with Gaussianity



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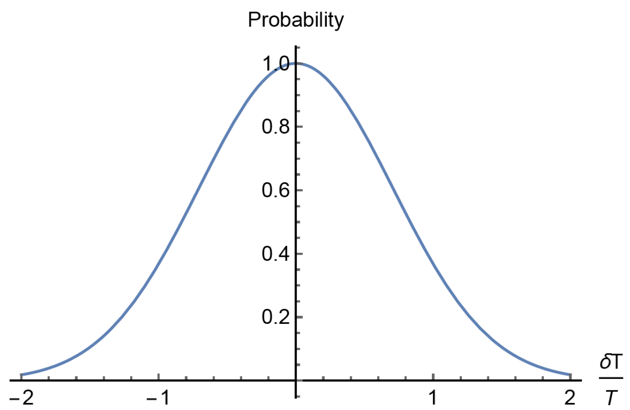
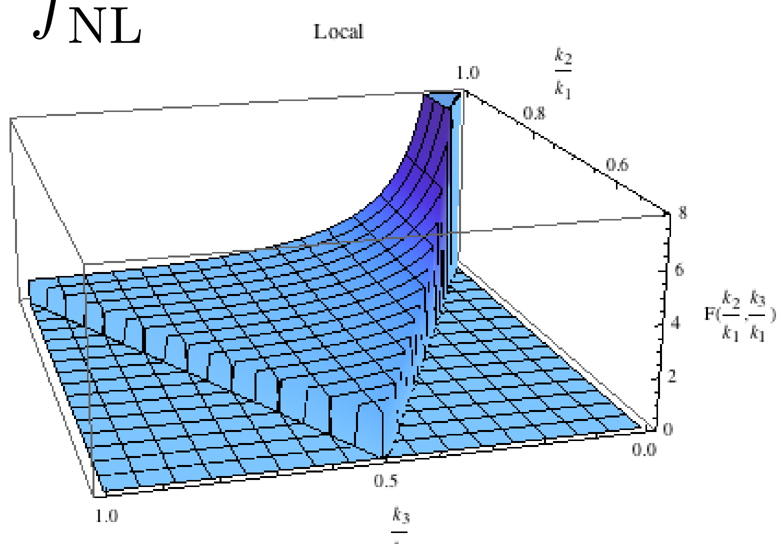
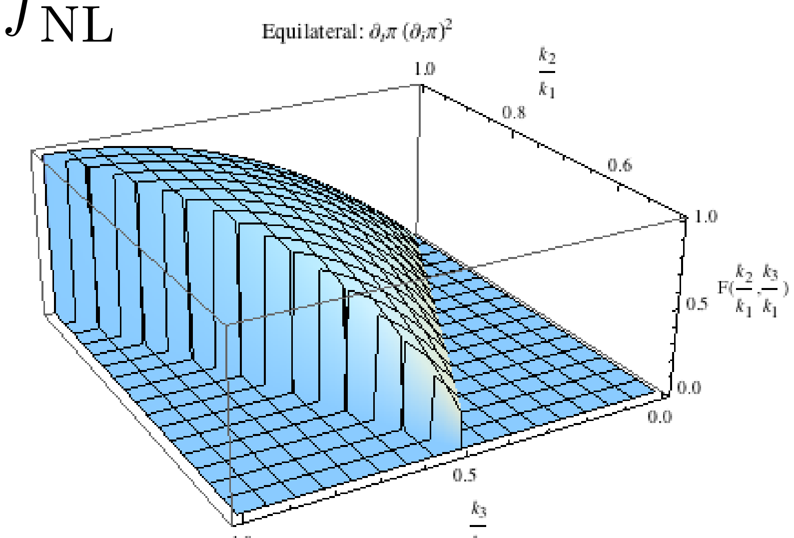
WMAP team
Planck team



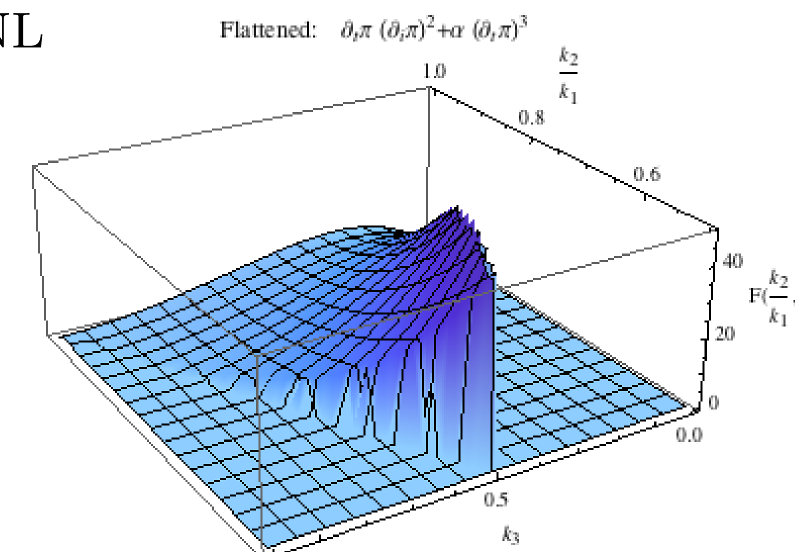
$f_{\mathrm{NL}}^{\mathrm{loc.}}$



$f_{\mathrm{NL}}^{\mathrm{equil.}}$



$f_{\mathrm{NL}}^{\mathrm{flat}}$



The Normal approach

– The normal approach to Inflation, and also to Supersymmetric Inflation is

  – first: find a background solution that gives rise to an inflationary spacetime (a quasi de-Sitter space)

  – second: study the fluctuations

- For SUGRA, huge literature with very-large number of authors
- This usually gives rise to a very-rich, but also quire-obscure long expressions

  – that make it to unclear to explore the physics in generality

  – confusion about particle content and signature (ex: additional light scalar field)

The EFT approach

- We will instead focus on what is observable, that is the theory of the fluctuations.
- We will take the point of view that Inflation is a period where time-translations are spontaneously broken. This leads us to the so-called EFT of Inflation, where the inflationary fluctuations are described by the associated Goldstone boson.
  - This approach has several practical advantages
    - by focusing on the theory of the obs., it makes connection to obs. very easy.
    - for the same reason, the description is very general
      - does not rely on our capabilities to describe the background solution
    - ….
- We wish now to ask *what happens if the fundamental description of Nature is supersymmetric*, and explore the resulting phenomenological consequences
- Since gravity is clearly important, we will be lead into the world of Supergravity
  - this is a notoriously complicated subject, so that mainly specialists work on it.
  - we will instead make it quite simple (we hope)

Review of Bosonic EFT of Inflation

with Cheung, Creminelli, Fitzpatrick, Kaplan **2008**

– Gravity is the theory of a massless spin-2 particles. To have a local, Lorentz invariant description, we impose the particular gauge invariance called diff. invariance.

– In the EFT of Infl., motivated by the presence of a physical clock, we assume that there is not invariance under time diffs., $t \quad \to t - \xi^0$, but only under time-dependent spatial diffs.: $x^i \quad \to \quad x^i - \xi^i(t, \vec{x})$.

– We write down the most general Lagrangian respecting this smaller gauge invariance, using the metric operator:

$$S_{\rm EFTofI}[g] = \int d^4x\, \sqrt{-g}\, \mathcal{L}\left[R_{\mu\nu\rho\sigma}, g^{\mu\nu}, K_{\mu\nu}, \nabla_\mu, t\right]_{\rm upper\ zero\ uncontracted} =$$

$$= \int d^4x\, \sqrt{-g}\, \{M_{\rm Pl}^2 R$$

$$+M_{\rm Pl}^2 \dot{H}(t) g^{00} + M_{\rm Pl}^2 (H(t)^2 + \dot{H}(t)) + M(t)^4 \left(g^{00}+1\right)^2 + \ldots + \bar{M}(t)^3 \left(g^{00}+1\right) \delta K + \ldots \}$$

Review of Bosonic EFT of Inflation

– It is useful to reintroduce non-linearly-realized time-diff. invariance by the Stuckelberg trick: we perform a broken gauge transformation, and promote the parameter of the transformation to a field:

$$g^{00} \quad \to \quad \hat{g}^{00}[g,\pi] = \partial_\mu(t+\pi)\partial_\nu(t+\pi)g^{\mu\nu}$$

– and we declare that $\pi \quad \to \quad \pi + \xi^0, \quad \text{as} \quad t \quad \to \quad t - \xi^0$

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– and we declare that $\pi \quad \to \quad \pi + \xi^0, \quad \text{as} \quad t \quad \to \quad t - \xi^0$

– We call $\hat{g} = g + \delta_\pi^{\text{diff.}} g + \ldots$ a *dressed* field.

– Under a time diff., it transforms as if under a spatial diff. (in this case it is a scalar)

– If we build a Lagrangian out of dressed fields and invariant under the linearly realized gauge invariance, then the Lagrangian is automatically invariant under the non-linearly realized ones (CCWZ construction for gauge invariances). So:

$$S_{\text{EFTofI}}[g,\pi] = \int d^4x\,\sqrt{-g}\,\Big\{M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H}(\hat{t})\hat{g}^{00}[g_{\mu\nu},\pi] + M_{\rm Pl}^2 (H(\hat{t})^2 + \dot{H}(\hat{t}))$$
$$+ M(\hat{t})^4 \left(\hat{g}^{00}[g_{\mu\nu},\pi]+1\right)^2 + \ldots + \bar{M}(\hat{t})^3 \left(\hat{g}^{00}[g_{\mu\nu},\pi]+1\right)\delta\hat{K}[g_{\mu\nu},\pi] + \ldots\Big\}\ ,$$

Why this was useful?

– Why this non-linearly-realized gauge invariance is useful? If the terms that are not automatically invariant are relevant, then there is an interval of energies where the Goldstone boson π is decoupled from the metric $g_{\mu\nu}$, while playing an particular role in the dynamics (the most strongly interacting field). In the high energy, therefore

$$S_{\rm EFTofI}[g,\pi]=\int d^4x\,\sqrt{-g}\,\Big\{M_{\rm Pl}^2R+M_{\rm Pl}^2\dot H(\hat t)\hat g^{00}[g_{\mu\nu},\pi]+M_{\rm Pl}^2(H(\hat t)^2+\dot H(\hat t))$$
$$+M(\hat t)^4\left(\hat g^{00}[g_{\mu\nu},\pi]+1\right)^2+\ldots+\bar M(\hat t)^3\left(\hat g^{00}[g_{\mu\nu},\pi]+1\right)\delta\hat K[g_{\mu\nu},\pi]+\ldots\Big\}\ ,$$

$$\Downarrow$$

$$\int d^4x\,\sqrt{-g}\,\left[\dot H M_{\rm Pl}^2\,(\partial\pi)^2+M_2^4\left(\dot\pi^2+\dot\pi(\partial\pi)^2+(\partial\pi)^4\right)+\ldots\right]$$

– This is the decoupling regime. For inflation, this happens for $E^2\gtrsim E_{\rm mix}^2\sim\dot H$

– which is useful because in inflation we care of $E^2\sim H^2\gg\dot H$

Non-linearly-realized Gauge Invariances

–Recipe to construct a Lagrangian invariant under a non-linearly realized invariance:

– Write the Lagrangian invariant only under the linearly-realized gauge invariance,

– Interpret the fields as a dressed fields, i.e. as combinations of the original fields and the Goldstones (i.e. perform a Stuckelberg transformation).

– If situation allows so, go to the decoupling limit, and dynamical description is simplified.

–We are now going to repeat the same steps for SUGRA

– but we will face additional subtleties.

SUGRA

– As General Relativity is the theory of a massless spin-2 particle (the graviton), SUGRA is the theory of a massless spin-2 particles (the graviton) and a massless spin-3/2 particle (the gravitino). So, we will deal with these two fields.

Non-linear Representation of SUGRA algebra

with Delacretaz and Gorbenko **JHEP2017**

SUGRA algebra

– Since we deal with curved spacetime and spinors, we introduce local lorentz invariance

$$g_{\mu\nu} = \eta_{ab} e^a_\mu e^b_\nu$$

– $\text{SUGRA} \sim \text{diff.} \ \times \ (\text{local lorentz}) \ \times \ (\text{local SUSY})$

– The defining representation of the SUSY transformation is given by the action on the gravity multiplet: $\{e^a_\mu, \psi_\mu, m, b_\mu\}$:

$$\delta_\epsilon e^a_\mu = i\psi_\mu \sigma^a \bar{\epsilon} + \text{c.c.}\,,$$

$$\delta_\epsilon \psi_\mu = -2D_\mu \epsilon - K^{ab}_\mu \sigma_{ab}\epsilon + i\left[m\sigma_\mu \bar{\epsilon} + b_\mu \epsilon + \frac{1}{3} b^\nu (\sigma_\mu \bar{\sigma}_\nu \epsilon)\right]\,,$$

$$K \sim \psi\psi$$

$$\omega^{ab}_\mu = e^b{}_\nu \nabla_\mu e^{a\nu}$$

$$\delta_\epsilon m = -\frac{1}{3}\epsilon\left(\sigma^\mu \bar{\sigma}^\nu \psi_{\mu\nu} + i b^\mu \psi_\mu - 3i\sigma^\mu \bar{\psi}_\mu m\right)\,,$$

$$\delta_\epsilon b^a = \frac{3}{8}(\bar{\psi}_{\mu\nu}\bar{\sigma}^a \sigma^\mu \bar{\sigma}^\nu \epsilon) - \frac{1}{8}(\bar{\psi}_{\mu\nu}\bar{\sigma}^\mu \sigma^\nu \bar{\sigma}^a \epsilon) - \frac{3i}{2} m^* (\epsilon \psi^a)$$
$$- \frac{i}{8} b_c (\epsilon \sigma^c \bar{\sigma}^a \sigma^\mu \bar{\psi}_\mu) + \frac{i}{4} b^a (\epsilon \sigma^\mu \bar{\psi}_\mu) + \frac{i}{8} b^c (\bar{\psi}_\mu \bar{\sigma}^a \sigma_c \bar{\sigma}^\mu \epsilon) + \text{c.c.}\,,$$

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– from which we deduce the SUGRA algebra:

$$[\delta_{\epsilon'}, \delta_\epsilon] = \left(\delta^{\text{diff}}_y + \delta^L_\Lambda + \delta_{\hat{\epsilon}}\right)\,,$$

$$[\delta_\epsilon, \delta^{\text{diff}}_\xi] = \delta_{\xi^\mu \partial_\mu \epsilon}\,,$$

$$[\delta_\epsilon, \delta^L_\Lambda] = \delta_{\frac{1}{2}\Lambda^{ab}\sigma_{ab}\epsilon}\,,$$

with

$$y^\mu = -2i(\epsilon' \sigma^\mu \bar{\epsilon} - \epsilon \sigma^\mu \bar{\epsilon}')\,,$$

$$\Lambda^{ab} = y^\mu \left(\omega^{ab}_\mu(e) + K^{ab}_\mu\right) - \left[4m\bar{\epsilon}\bar{\sigma}^{ab}\bar{\epsilon}' + \frac{2}{3}\epsilon\sigma^{[a} \not{b} \sigma^{b]}\bar{\epsilon}' + \text{c.c.}\right]\,,$$

$$\hat{\epsilon} = \psi_\mu y^\mu / 2\,,$$

Notice: algebra is field dependent!

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$$\hat{\epsilon} = \psi_\mu y^\mu / 2\,,$$

Notice: algebra is field dependent!

The Goldstino and a minimal Multiplet

– We are interested in the case of non-linear realization of time translations

  – Since $\{Q, \bar{Q}\} = P^\mu \sigma_\mu$, also SUSY is non-linearly realized

– We have to introduce a Goldstino λ., which transforms as

$$\delta_\epsilon \lambda = -\epsilon + i(\lambda\sigma^\mu\bar{\epsilon} - \epsilon\sigma^\mu\bar{\lambda})\left(-\frac{1}{2}(\psi_\mu + \delta_\lambda\psi_\mu) + \frac{i}{3} m\sigma_\mu\bar{\lambda}\right) + (\lambda\epsilon)\left(2m^*\lambda - \frac{4}{3}\not{b}\bar{\lambda}\right) + (4\text{ ferm.})\epsilon\,,$$

– Thanks to the Goldstino, we can construct SUGRA-dressed fields.

– If a is a field transforming in some representation of a group G, where H is the linearly-realized subgroup, we can define a *dressed* field

$$A = D_G\left[e^{\lambda(x)\cdot Q}\right] \circ a \sim a + \delta_\lambda a + \ldots$$

  – which transforms under a general G transformation, as under H

    – from $g\, e^{-\lambda\cdot Q} = e^{-\lambda'\cdot Q}\, h(\lambda, a, g) \;\to\; e^{\lambda'\cdot Q} = h(\lambda, a, g) e^{\lambda\cdot Q} g^{-1}$

$$A \;\to\; A' = D_G\left[e^{\lambda'(x')\cdot Q}\right] \circ a' = D_G\left[h(\lambda, g, \psi)\, e^{\lambda(x)\cdot Q}\, g^{-1} g\right] \circ a = D_G\left[h(\lambda, g, \psi)\right] \circ A$$

    – again, this is the slightly-generalized CCWZ construction (see footnotes).

– In particular the dressed $\{e^a_\mu, \psi_\mu, m, b_\mu\}$ transforms in a reducible rep. of diffs. now.

Eliminating the auxiliary fields

– It is a well-known nuisance the presence of the auxiliary fields in SUSY/SUGRA.

– Their presence is dictated by enforcing an equal number of off-shell bosonic and fermionic DOF, and by common lore that `the algebra does not close without them'.

– But when SUGRA is non-linearly realized, boson-fermion degeneracy does not need to hold. So, can we do without the auxiliary fields?!

– In fact, if A is the dressed gravity supermultiplet, we can set to zero the dressed auxiliary fields $M = 0\,, \qquad B_\mu = 0$: this is a SUSY inv. constraint.

– This amounts to expressing the original aux. fields in terms of the dynamical ones:

$$m = \frac{2}{3}(\lambda \sigma^{\mu\nu} \psi_{\mu\nu}) + \ldots\,, \qquad b^a = -\frac{3}{8}(\bar{\psi}_{\mu\nu} \bar{\sigma}^a \sigma^\mu \bar{\sigma}^\nu \lambda) + \frac{1}{8}(\bar{\psi}_{\mu\nu} \bar{\sigma}^\mu \sigma^\nu \bar{\sigma}^a \lambda) + \text{c.c.} + \ldots\,,$$

– we just got rid of the aux. fields:

- – we constructed a smaller multiplet $\{e, \psi, \lambda\}$ that realizes SUGRA off-shell
- – Subtlety: the algebra does not change upon substituting the aux. fields with these

– This construction was never done before in SUGRA, but was done for SUSY by Rocek (as we found out after the construction).

Eliminating the auxiliary fields

– Intuitively, thanks to the Goldstino, we can construct operators out of it that, under SUSY, transform exactly as m & b_μ ; so, we can replace m & b_μ .

– This removal of the aux. fields is different than common procedures where one `integrates out' the auxiliary fields (for example, see Friedmann).

- In this case the induced transformations rules for the fields are Lagrangian dependent (while for us are *Lagrangian independent*)
- The algebra closes only on-shell (while for us it closes *off-shell*)

– We indeed have defined a new multiplet realizing SUGRA off-shell: $\{e, \psi, \lambda\}$

Eliminating the auxiliary fields

– For later purposes, we field-redefine the gravitino

– Subtlety: field redefinitions do not change the algebra

– and here is our minimal SUGRA multiplet:

$$\delta_\epsilon e^a_\mu = i\left(\psi'_\mu - i m^*_{3/2}\bar{\lambda}\bar{\sigma}_\mu\right)\sigma^a\bar{\epsilon} + \text{c.c.} + (3\ \text{fermion})\cdot\epsilon\,,$$

$$\delta_\epsilon \psi'_\mu = -2\mathcal{D}_\mu\epsilon + (2\ \text{fermion})\cdot\epsilon\,,$$

$$\delta_\epsilon\lambda = -\epsilon + i(\lambda\sigma^\mu\bar{\epsilon} - \epsilon\sigma^\mu\bar{\lambda})(\mathcal{D}_\mu\lambda - \frac{1}{2}\psi'_\mu) + (4\ \text{ferm.})\epsilon$$

– where $\mathcal{D}_\mu\epsilon$ is a generalized covariant derivative we will define later

– for maximally symmetric spacetimes, it is $\mathcal{D}_\mu\lambda = D_\mu\lambda - \frac{i}{2}m^*_{3/2}\sigma_\mu\bar{\lambda}$

– and the field redefinition is $\psi'_\mu = \psi_\mu - i\,m^*_{3/2}\sigma_\mu\bar{\lambda}$

Construction of the Action:
the Supersymmetric Effective Field Theory of Inflation

with Delacretaz and Gorbenko **JHEP2017**

Constructing the Action

– We are now ready to construct the action for the Supersymmetric EFT of Inflation

– We repeat the steps of the bosonic theory:

  – In terms of symmetries, this is the action where we have a graviton and a gravitino (no auxiliary fields), and the only gauge invariance is $x^i \quad \to \quad x^i - \xi^i(t,\vec{x})$

– We therefore have:

$$S_{\mathcal{S}\mathrm{EFTofI}} = S_{\mathrm{EFTofI}}[g] +$$

$$M_{\rm Pl}^2 \int d^4x\, e \left[\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu \bar{\sigma}_\nu D_\rho \psi_\sigma + m_{3/2}(\psi_\mu \sigma^{\mu\nu}\psi_\nu) + m_0(\psi_\mu \sigma^{\mu 0}\psi^0) + m_\star(\psi_\mu\psi^\mu + \psi^0\psi^0) + \text{c.c.} \right.$$

$$\left. + i\widetilde{m}_1(\bar{\psi}^0\bar{\sigma}^\mu\psi_\mu - \bar{\psi}_\mu\bar{\sigma}^\mu\psi^0) + i\widetilde{m}_2\varepsilon^{\mu\nu\lambda 0}(\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \ldots \right]$$

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$$\left. + i\tilde{m}_1(\bar{\psi}^0\bar{\sigma}^\mu\psi_\mu - \bar{\psi}_\mu\bar{\sigma}^\mu\psi^0) + i\tilde{m}_2\varepsilon^{\mu\nu\lambda 0}(\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \ldots \right]$$

– The presence of the gravitino *does not* precludes any term we could write in the non-SUSY EFT

– Notice also that $\quad S_{\text{EFTofI}} \supset \int d^4x\sqrt{-g}\,\Lambda \quad$: we can just write these terms

– we wrote mass terms and non-minimal couplings

Constructing the Action

$$S_{\mathcal{S}\text{EFTofI}} = S_{\text{EFTofI}}[g] +$$
$$M_{\text{Pl}}^2 \int d^4x\, e \Big[\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\bar{\sigma}_\nu D_\rho\psi_\sigma + m_{3/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu) + m_0(\psi_\mu\sigma^{\mu 0}\psi^0) + m_\star(\psi_\mu\psi^\mu + \psi^0\psi^0) + \text{c.c.}$$
$$+ i\widetilde{m}_1(\bar{\psi}^0\bar{\sigma}^\mu\psi_\mu - \bar{\psi}_\mu\bar{\sigma}^\mu\psi^0) + i\widetilde{m}_2\varepsilon^{\mu\nu\lambda 0}(\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \dots \Big]$$

– We wrote mass terms and non-minimal couplings $m'\text{s}$ & $\Lambda'\text{s}$

– All SUSY-breaking contributions (for ex from SM) go into $m'\text{s}$

– if $m'\text{s} \gg H$, we can integrate out the Gravitino and be left with the standard single field EFTofI

– cosmologically interesting only for $m'\text{s} \lesssim H$

Unitary gauge action

– Suggestively, put the kinetic terms in (apart for $m_\star$)

$$S_{\mathcal{S}\text{EFTofI}} = S_{\text{EFTofI}}[g] +$$

$$M_{\text{Pl}}^2 \int d^4x\, e \left[\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\bar{\sigma}_\nu D_\rho\psi_\sigma + m_{3/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu) + m_0(\psi_\mu\sigma^{\mu 0}\psi^0) + m_\star(\psi_\mu\psi^\mu + \psi^0\psi^0) + \text{c.c.}\right.$$
$$\left. + i\widetilde{m}_1(\bar{\psi}^0\bar{\sigma}^\mu\psi_\mu - \bar{\psi}_\mu\bar{\sigma}^\mu\psi^0) + i\widetilde{m}_2\varepsilon^{\mu\nu\lambda 0}(\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \ldots\right]$$

– can be written as

$$S^{(k)}_{\psi\psi} = \frac{1}{2}M_{\text{Pl}}^2 \int d^4x\, e\, \varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\bar{\sigma}_\nu\mathcal{D}_\rho\psi_\sigma + \text{c.c.}\,,$$

– where $\mathcal{D}_\mu\lambda = D_\mu\lambda - \frac{i}{2}\left[\left(m^*_{3/2} + \frac{1}{2}m^*_0 g^{00}\right)\sigma_\mu - m^*_0 t_\mu\sigma^0\right]\bar{\lambda} - \frac{i}{2}\left[2\widetilde{m}_2 t_\mu - i\widetilde{m}_1\sigma^0\bar{\sigma}_\mu\right]\lambda$

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$$S_{\mathcal{S}\mathrm{EFTofI}} = S_{\mathrm{EFTofI}}[g] +$$

$$M_{\rm Pl}^2 \int d^4x\, e \left[\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar\psi_\mu\bar\sigma_\nu D_\rho\psi_\sigma + m_{3/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu) + m_0(\psi_\mu\sigma^{\mu 0}\psi^0) + m_\star(\psi_\mu\psi^\mu + \psi^0\psi^0) + \text{c.c.}\right.$$

$$\left. + i\widetilde m_1(\bar\psi^0\bar\sigma^\mu\psi_\mu - \bar\psi_\mu\bar\sigma^\mu\psi^0) + i\widetilde m_2\varepsilon^{\mu\nu\lambda 0}(\bar\psi_\mu\bar\sigma_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \ldots\right]$$

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Reintroducing non-linear SUGRA

– With the same logic as before, but now with larger group, we can think of this action

$$S_{\mathcal{S}\mathrm{EFToI}} = S_{\mathrm{EFToI}}[g] +$$

$$M_{\rm Pl}^2 \int d^4x\, e \left[\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\bar{\sigma}_\nu D_\rho\psi_\sigma + m_{3/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu) + m_0(\psi_\mu\sigma^{\mu 0}\psi^0) + m_\star(\psi_\mu\psi^\mu + \psi^0\psi^0) + \text{c.c.}\right.$$

$$\left. + i\widetilde{m}_1(\bar{\psi}^0\bar{\sigma}^\mu\psi_\mu - \bar{\psi}_\mu\bar{\sigma}^\mu\psi^0) + i\widetilde{m}_2\varepsilon^{\mu\nu\lambda 0}(\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\lambda) + \delta g^{00}(m_{(3)}\psi_\mu\psi^\mu + \text{c.c.}) + \ldots\right]$$

– as written in terms of the dressed-fields. Then we get non-linearly realized SUGRA for free

$$g^{00} = \eta^{ab} e_a^0 e_b^0 \xrightarrow{\text{diff. Stück.}} \hat{g}^{00} = \eta^{ab} e_a^\mu e_b^\nu \partial_\mu(t+\pi)\partial_\nu(t+\pi)$$

$$\xrightarrow{\text{SUSY Stück.}} \hat{G}^{00} = \eta^{ab} E_a^\mu E_b^\nu \partial_\mu(t+\pi)\partial_\nu(t+\pi)\,,$$

$$E_\mu^a \equiv e_\mu^a + \delta_\lambda e_\mu^a + \ldots = e_\mu^a + i\left(\psi_\mu - D_\mu\lambda\right)\sigma^a\bar{\lambda} + \text{c.c.} + (4 \text{ fermion})\,,$$

$$\Psi_\mu \equiv \psi'_\mu + \delta_\lambda\psi'_\mu + \ldots = \psi'_\mu - 2\mathcal{D}_\mu\lambda + (3 \text{ fermion})\,,$$

– Notice, from CWZ construction, π transforms under SUSY as under a time-diff. (the symmetries `linearly' realized: i.e. realized before the introduction of the Goldstones):

$$\delta_\epsilon\pi = \frac{1}{2}(\delta_\xi^{\rm diff} + \delta_{\Lambda_\xi}^L)\pi + \ldots = \frac{1}{2}(\xi^0 + \xi^\mu\partial_\mu\pi) + \ldots = -i(\epsilon\sigma^0\bar{\lambda} - \lambda\sigma^0\bar{\epsilon}) - i(\epsilon\sigma^\mu\bar{\lambda} - \lambda\sigma^\mu\bar{\epsilon})\partial_\mu\pi + \ldots$$

Reintroducing non-linear SUGRA

– This action

$$S_{\mathcal{S}\mathrm{EFTofI}} = S_{\mathrm{EFTofI}}[g,\pi] + \frac{1}{2}M_{\mathrm{Pl}}^2 \int d^4x\, e\, \varepsilon^{\mu\nu\rho\sigma} \bar{\hat{\Psi}}_\mu \bar{\sigma}_\nu \hat{\mathcal{D}}_\rho \hat{\Psi}_\sigma + m_{(3)} \delta\hat{G}^{00} \hat{\Psi}_\mu \hat{\Psi}^\mu + \text{c.c.} + \ldots \;,$$

with $\hat{\Psi}_\mu(\psi,\lambda) = \psi_\mu + \mathcal{D}_\mu \lambda$

– is the most general action where time-diffs and SUSY are non-linearly realized.

– Several technical achievements:

- – automatically coupled to gravity (a well known difficulty is standard approaches)
- – no auxiliary fields
- – no superspace
- – no exponentials of Kahler potential in the potential
- – not many many fields
- – this is quite simple (to us)

– In particular: *no second scalar field* is needed (and therefore its presence cannot be claimed to be a signature of SUSY in Inflation, as apparently suggested in literature)

Decoupling Limit

– Reintroducing a non-linearly realized gauge invariance is useful only because of the decoupling limit (why otherwise bother ourselves with a redundancy!).

– Let us open up our Lagrangian. The $\epsilon^{\mu\nu\rho\sigma}$ forces cancellations and we get:

$$\frac{1}{e}(\mathcal{L}^{(k)}_{\psi\psi}+\mathcal{L}^{(k)}_{\psi\lambda}+\mathcal{L}^{(k)}_{\lambda\lambda}) = M_{\rm Pl}^2\,\varepsilon^{\mu\nu\rho\sigma}\left(\frac{1}{2}\bar{\psi}_\mu\bar{\sigma}_\nu\hat{\mathcal{D}}_\rho\psi_\sigma - \bar{\psi}_\mu\bar{\sigma}_\nu[\hat{\mathcal{D}}_\rho,\hat{\mathcal{D}}_\sigma]\lambda + \hat{\mathcal{D}}_\mu\bar{\lambda}\bar{\sigma}_\nu[\hat{\mathcal{D}}_\rho,\hat{\mathcal{D}}_\sigma]\lambda\right) + \text{c.c.}\,,$$

– This action has manifest decoupling as $[\mathcal{D},\mathcal{D}]\,\lambda \sim \left(H^2+m^2\right)\lambda$ (no derivatives!)

Curvature

– Schematically:

$$S \sim \int d^4x\sqrt{-g}\,\left[M_{\rm Pl}^2\,\psi\partial\psi + (H^2+m^2)M_{\rm Pl}^2\,\lambda\partial\lambda + (H^2+m^2)M_{\rm Pl}^2\,\psi\lambda\right]$$

– The wavefunction of the Goldstino is $\gtrsim M_{\rm Pl}^2\,H^2$ as dS breaks SUSY

– The decoupling energy is at least as big as $E \gg E_{\rm mix} \sim H$ (as dS breaks SUSY)

– This means that for inflation, the mixing with the gravitino is crucial (a lot of literature on SUSY inflation neglects coupling to gravity (due to usual difficulties). Not clear what can be saved of those results). Here, coupling to gravity is *trivial*.

Non-triviality of Decoupling

$$S_{\mathcal{S}\mathrm{EFTofI}} = S_{\mathrm{EFTofI}}[g,\pi] + \frac{1}{2}M_{\mathrm{Pl}}^2 \int d^4x\, e\, \varepsilon^{\mu\nu\rho\sigma}\bar{\hat{\Psi}}_\mu \bar{\sigma}_\nu \hat{\mathcal{D}}_\rho \hat{\Psi}_\sigma + m_{(3)}\delta \hat{G}^{00}\hat{\Psi}_\mu \hat{\Psi}^\mu + \mathrm{c.c.} + \ldots\ ,$$

- Obtaining decoupling was non trivial at all
  - First, we make a field redefinition $E \to e$, so that λ appears only where gravitino was present, as otherwise it would appear also in the bosonic sector
    - field redefinition do not change the algebra
  - Second, more importantly, for fermionic symmetries, decoupling *does not* occurs automatically by power counting

Subtlety with Decoupling Limit

– In bosonic theories, decoupling is trivial, as it is just dictated by power counting:

$$\hat{A} \sim A + \partial\pi \quad \Rightarrow \quad m^2(\partial\pi)^2 + m^2\pi\partial A \quad \Rightarrow \quad \text{Manifest decoupling}$$

– But for case spinorial symmetry:

$$\hat{\Psi} \sim \Psi + \partial\lambda \quad \Rightarrow \quad m_{3/2}\,\partial\lambda\partial\lambda + m_{3/2}\,\psi\partial\lambda \sim 0 + m_{3/2}\,\psi\partial\lambda$$

$$\Rightarrow \quad \text{Total mixing}$$

– We need to keep track of the subleading terms. So we redefined the gravitino so that it transform as $\Psi_\mu \sim \psi_\mu + \mathcal{D}_\mu\lambda \sim \psi_\mu + \partial_\mu\lambda + m_{3/2}\lambda$

– Simple reasons (in max symmetric spacetimes):

– We know that AdS with $\Lambda = -3M_{\rm Pl}^2|m_{3/2}|^2$ our gravitino transformation is linearly realized. Therefore the breaking must be proportional to $\Lambda/M_{\rm Pl}^2 - m_{3/2}^2$, which is a dimension-two parameter (instead of a dimension-one one), just like the curvature. Once it is dimension-two, we have guaranteed (*quadratic*) decoupling.

– Similar reason is somewhat true also in non-maximal symmetric case.

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Multifield Inflation

– Adding additional fields is trivial. Suppose you have an additional scalar field σ

– Write action in unitary gauge

$$S_{\mathcal{S}\text{multiEFTofI}} = S_{\mathcal{S}\text{EFTofI}} + S_{\widetilde{\text{multiEFTofI}}}$$
$$+ M_{\rm Pl}^2 \int d^4x\, e\, \left[c_{3/2,1}\dot\sigma(\psi_\mu\sigma^{\mu\nu}\psi_\nu) + \left(c_{0,1}\dot\sigma(\psi_\mu\sigma^{\mu 0}\psi^0) + \partial_\rho\sigma\left(c_{0,2}\psi_\mu\sigma^{\mu\rho}\psi^0 + c_{0,3}\psi_\mu\sigma^{\mu 0}\psi^\rho\right)\right)\right.$$
$$\left. + \left(c_{\star,1}\dot\sigma\psi_\mu\psi^\mu + c_{\star,2}\partial_\mu\sigma\psi^\mu\psi^0 + c_{\star,3}\dot\sigma\psi^0\psi^0\right) + \ldots + \text{c.c.}\right] \ .$$

– Write it in terms of dressed fields, but make the field redefinition so that

$$\sigma \to \Sigma =_{\rm red} \sigma$$

– In particular, knowledge of transformations of σ under the non-linearly realized group is *not* needed (again, CCWZ construction)

– Goldstino only present where gravitino is present

– it decouples

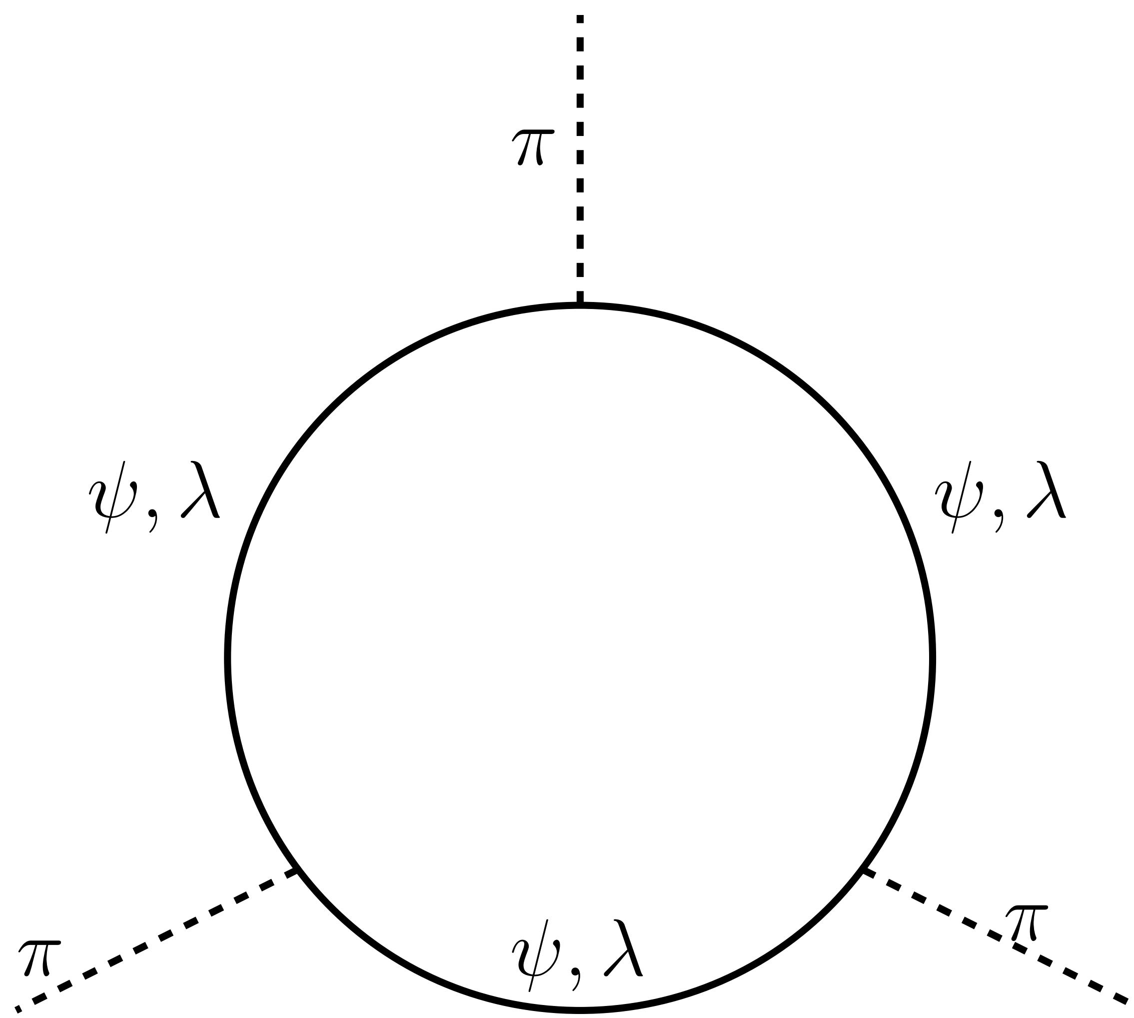
Phenomenology

Phenomenology

– Dispersion relation of Goldstino $\omega \sim c_\lambda k$, and $c_\lambda - 1 \sim \mathcal{O}(1)$

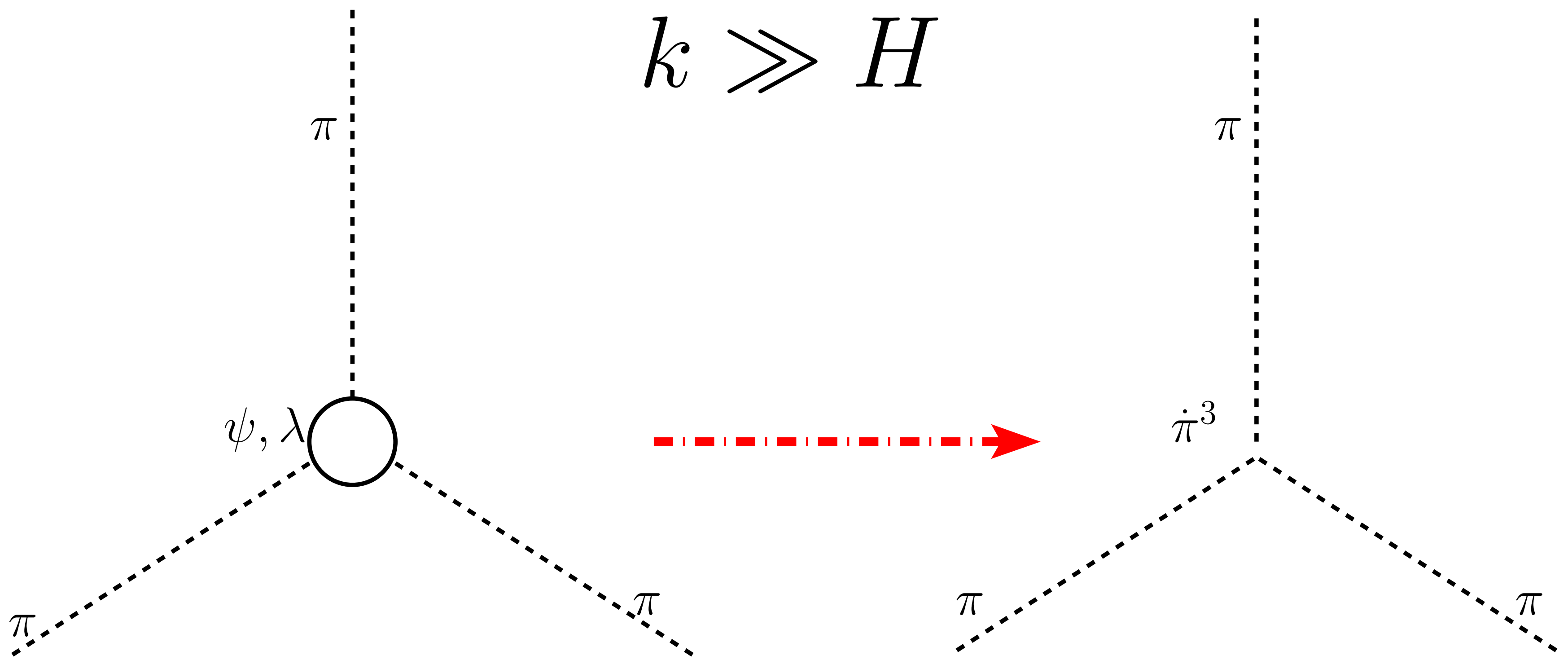
– Interactions: we do not see directly fermions, and their bilinears do not have in general scale invariant perturbations. But they can affect the fluctuations that we see, π , in a loop (and this effect will be scale invariant by its time-translation invariance).

– All our operators are irrelevant (i.e. non-renormalizable, but observationally relevant)



Phenomenology

– There are two contributions: $k \gg H$ and $k \lesssim H$



– This effect is degenerate with the effect from operators in the pure bosonic case (by renormalizability).

– Their size cannot be predicted by the EFT, as it is UV dependent; but upper bound is obtained by cutting off the loop at the unitarity bound.

– This gives $f_{\rm NL}^{\rm equil.,\, orthog.} \sim 1$, and even, for non minimal couplings, $f_{\rm NL}^{\rm equil.,orthog.} \gg 1$

Phenomenology

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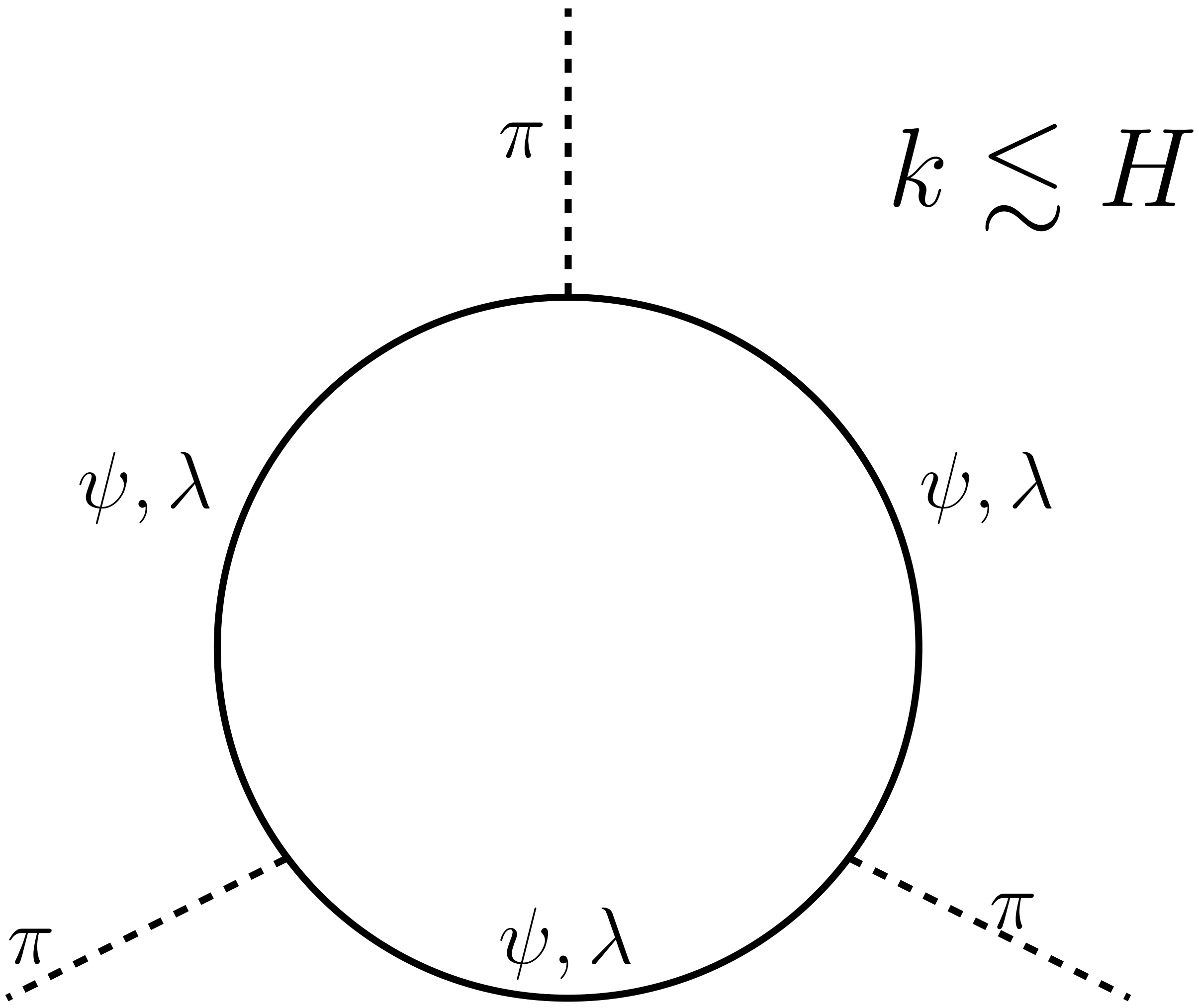


– This is a non-degenerate signal, a sort of *smoking gun* for SUSY

– Induce signal estimated to be very very small.

Conclusions on the Supersymmetric EFTofI

– We have explored the role of Supersymmetry in Inflation

– Its non-linear realization has allowed for a series of *tremendous simplifications* that make the construction of the general EFT rather straightforward. In unitary gauge:

  – no auxiliary fields, no superspace, no superpotential, no conformal compensator

  – coupling to gravity made trivial

– After a careful field redefinition, we have reintroduced a Goldstino that decouples at H

  – inflationary predictions cannot in general be made without including the gravitino

  – *no need of additional light scalar fields*: π & λ are enough to realize SUGRA

  – Goldstino appears only in association with the gravitino: there is *no constraint on purely bosonic* terms

– Phenomenology:

  –further motivation for large purely bosonic operators (large non-Gaussianities)

    –if something known as the EFT of Large-Scale Structure, we might have enough data to see them.

Extra

Reheating

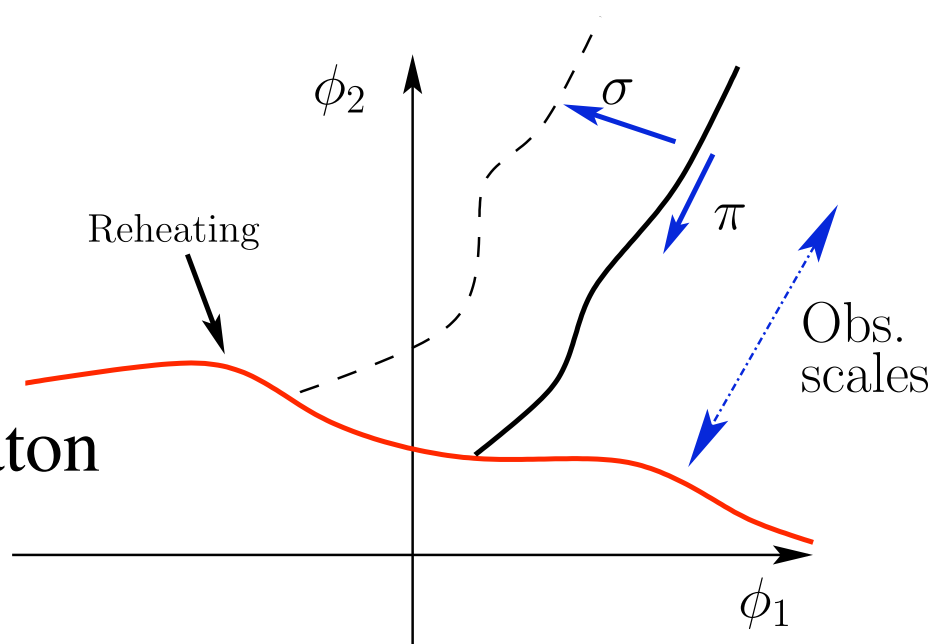
– We did a lot of field redefinitions. Field redefinitions matter for in-in correlation functions for observables in cosmology.

– But the additional fields could have contributed anyway to perturbations by affecting reheating.

– Luckily, this contribution occurs only when modes are outside of the horizon and gradients can be neglected. The expression is therefore very simple: it is local:

$$\zeta(\vec{x},t_{\rm rh}) = \zeta_{\rm bosonic}\left(\hat{g}_{\alpha\beta}(e(\vec{x},t_{\rm rh}),\pi(\vec{x},t_{\rm rh}))\right) \\ +a_1\,\hat{\psi}_\mu\left(e(\vec{x},t_{\rm rh}),\pi(\vec{x},t_{\rm rh})\right)\,\hat{\psi}^\mu\left(e(\vec{x},t_{\rm rh}),\pi(\vec{x},t_{\rm rh})\right) \\ +a_2\,\hat{\psi}^0\left(e(\vec{x},t_{\rm rh}),\pi(\vec{x},t_{\rm rh}))\right)\,\hat{\psi}^0\left(e(\vec{x},t_{\rm rh}),\pi(\vec{x},t_{\rm rh})\right)+\ldots\ ,$$

– where $\zeta_{\rm bosonic} = -H\pi + \ldots,$



– analogous to what was done in the EFT of multifield inflaton

with Zaldarriaga,
JHEP2012

Maximally Symmetric Case

Constructing the Action

–For clarity, let us give again the results in the case we break only SUSY (time-diffs are unbroken)

$$S_{\rm dS}[e,\psi]=S_{\rm S\bar{G}}+S_{m_{3/2}}-\int d^4x\, e\,\Lambda\,,$$

$$S_{\rm S\bar{G}}[e,\psi]=\frac{1}{2}M_{\rm Pl}^2\int d^4x\, e\left[-R+\varepsilon^{\mu\nu\rho\sigma}(\bar{\psi}_\mu\bar{\sigma}_\nu D_\rho\psi_\sigma+{\rm c.c.})\right]$$

$$S_{m_{3/2}}=M_{\rm Pl}^2\int d^4x\, e\, m_{3/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu)+{\rm c.c.}\,.$$

Constructing the Action

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$$S_{\rm dS}[e,\psi] = S_{\rm \bar{SG}} + S_{m_{3/2}} - \int d^4x\, e\, \Lambda\,,$$

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$$S_{m_{3/2}} = M_{\rm Pl}^2 \int d^4x\, e\, m_{3/2}(\psi_\mu \sigma^{\mu\nu}\psi_\nu) + {\rm c.c.}\,.$$

–Tadpole cancellation

- notice that there is no field taking a vev and originating a cosmological constant

Constructing the Action

– We can combine the above action as

$$S_{\rm dS}[e,\psi] = S_{\rm S\bar{G}} + S_{m_{3/2}} - \int d^4x\, e\, \Lambda\,,$$

$$S_{\rm S\bar{G}} + S_{m_{3/2}} = \frac{1}{2}M_{\rm Pl}^2 \int d^4x\, e\left[-R + \varepsilon^{\mu\nu\rho\sigma}(\bar{\psi}_\mu \bar{\sigma}_\nu \mathcal{D}_\rho \psi_\sigma + {\rm c.c.})\right]\,.$$

– Where $\mathcal{D}_\mu \lambda = D_\mu \lambda - \frac{i}{2} m^*_{3/2} \sigma_\mu \bar{\lambda}\,,$

Reintroducing non-linear SUGRA

– We can think of this action

$$S_{\rm S\bar{G}} + S_{m_{3/2}} = \frac{1}{2} M_{\rm Pl}^2 \int d^4x\, e \left[-R + \varepsilon^{\mu\nu\rho\sigma} (\bar{\psi}_\mu \bar{\sigma}_\nu \mathcal{D}_\rho \psi_\sigma + \text{c.c.}) \right] .$$

– as written in terms of dressed fields, and then the action is automatically invariant under non-linearly-realized SUGRA: $\Psi_\mu = \psi - 2\mathcal{D}_\mu \lambda + (3\,\text{fermions})$,

– Subtlety: since the importance of the Goldstino is to describe the helicity-1/2 state *within* the gravitino, we field-redefine the vielbein, so that the fundamental vielbein is the dressed one: $e \to E \to e$

- We obtain:

$$\frac{1}{e}(\mathcal{L}_{\psi\psi} + \mathcal{L}_{\psi\lambda} + \mathcal{L}_{\lambda\lambda}) =$$

$$M_{\rm Pl}^2\, \varepsilon^{\mu\nu\rho\sigma} \left(\frac{1}{2} \bar{\psi}_\mu \bar{\sigma}_\nu \mathcal{D}_\rho \psi_\sigma - \bar{\psi}_\mu \bar{\sigma}_\nu [\mathcal{D}_\rho, \mathcal{D}_\sigma] \lambda + \mathcal{D}_\mu \bar{\lambda} \bar{\sigma}_\nu [\mathcal{D}_\rho, \mathcal{D}_\sigma] \lambda \right) + \text{c.c.}\,.$$

Reintroducing non-linear SUGRA

– SUGRA-action:

$$\frac{1}{e}(\mathcal{L}_{\psi\psi} + \mathcal{L}_{\psi\lambda} + \mathcal{L}_{\lambda\lambda}) =$$

$$M_{\rm Pl}^2\, \varepsilon^{\mu\nu\rho\sigma} \left(\frac{1}{2}\bar{\psi}_\mu \bar{\sigma}_\nu \mathcal{D}_\rho \psi_\sigma - \bar{\psi}_\mu \bar{\sigma}_\nu [\mathcal{D}_\rho, \mathcal{D}_\sigma]\lambda + \mathcal{D}_\mu \bar{\lambda} \bar{\sigma}_\nu [\mathcal{D}_\rho, \mathcal{D}_\sigma]\lambda \right) + \text{c.c.}\,.$$

– Focus on $$[\mathcal{D}_\mu, \mathcal{D}_\nu]\lambda = \left(\frac{1}{2} R_{\mu\nu\alpha\beta} - |m_{3/2}|^2 g_{\mu\alpha} g_{\nu\beta} \right) \sigma^{\alpha\beta} \lambda\,.$$

– Manifest decoupling.

– Kinetic term has to be proportional to deviation from AdS SUGRA.

  – so, decoupling is guaranteed to happen, but for the right Gravitino field