Alternatives After Planck

Justin Khoury (U. Penn)
Why explore alternatives?
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“Inflation is so compelling, why spend your time searching for an alternative?”
Why explore alternatives?

“Inflation is so compelling, why spend your time searching for an alternative?”

Because it is good science

- Science thrives on competition
- Sky is given to us once
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“Inflation fits data so well, aren’t you convinced?”

Data tells us that perturbations were imprinted at last scattering, and described by nearly scale invariant and gaussian statistics

i.e. pretty generic
“OK I’m willing to be open-minded, but threshold should be high.”
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Fully agree...

- This is not the 80’s “wild west” anymore
- Inflation is rooted in symmetries, so should alternatives
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But let’s keep in mind:

- Newborn theories are ugly (except to their parents)
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Fully agree...

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But let’s keep in mind:

- Newborn theories are ugly (except to their parents)
- Any alternative will almost certainly require a violation of the Null Energy Condition (i.e., a “bounce”)
  - Possible in string theory?
  - Predictions should be insensitive to details of bounce physics
Impact of Planck

\[ f_{\text{local}}^{NL} = 2.7 \pm 5.8 \]

- Alternatives rely on multiple fields
  - can have significant \( f_{\text{NL}} \)
- But answer is model-dependent

Will see examples where \( f_{\text{NL}} \) is naturally \( \sim O(1) \)
Impact of Planck

\[ f_{\text{local}}^{NL} = 2.7 \pm 5.8 \]

- Alternatives rely on multiple fields
  \[ \implies \text{can have significant } f_{NL} \]

- But answer is model-dependent

  Will see examples where \( f_{NL} \) is naturally \( \sim O(1) \)

- Robust prediction of (almost all) alternatives:
  Negligible primordial gravity waves
Could scale invariance observed in CMB/LSS have originated from conformal invariance in early universe?
Conformal Scenarios

Rubakov (2009); Creminelli, Nicolis & Trincherini (2010); Hinterbichler & Khoury (2011); Hinterbichler, Khoury & Joyce (2012)

- Non-inflationary scenario, takes place before the big bang
- Space-time is nearly static, i.e. $\simeq$ flat, Minkowski space
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**Minkowski space**

- 4 space-time translations
- 6 Lorentz transformations
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**Minkowski space**

- 4 space-time translations
- 6 Lorentz transformations
- + conformal symmetries:
  - 1 dilation
  - 4 special conformal transf’ns

\[= 15 \text{ symmetries} \ (so(4, 2))\]
Simplest Example
Rubakov (2009); Craps, Hertog & Turok (2007); Hinterbichler & Khoury, 1106.1428

\[ V(\phi) = -\frac{\lambda}{4} \phi^4 \]

\( \lambda > 0 \implies \text{asymptotically free} \)
Simplest Example
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\[ V(\phi) = -\frac{\lambda}{4} \phi^4 \]

\( \lambda > 0 \implies \text{asymptotically free} \)

As time goes on, \( \phi \) rolls off:

\[ E = \frac{1}{2} \phi^2 - \frac{\lambda}{4} \phi^4 \]

Particular solution is \( E = 0 \):

\[ \phi(t) = \frac{\sqrt{2}}{\sqrt{\lambda}(-t)} \quad -\infty < t < 0 \]

This is an attractor: Growing mode = time shift.
\[ \phi(t) = \frac{\sqrt{2}}{\sqrt{\lambda(-t)}} \]

Preserves dilation
\[
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Preserves dilation

15 original symmetries

\(so(4, 2)\)

\[\rightarrow\]

10 unbroken symmetries

\(so(4, 1)\)

(de Sitter symmetries)
\[ \phi(t) = \frac{\sqrt{2}}{\sqrt{\lambda}(-t)} \]

Preserves dilation

15 original symmetries \( so(4, 2) \)

\[ \Rightarrow \]

10 unbroken symmetries \( so(4, 1) \)

(de Sitter symmetries)

Angular field acquires scale invariant spectrum:

\[ \mathcal{L}_\theta = -\frac{1}{2} \phi^2 (\partial \theta)^2 \sim \frac{1}{t^2} (\partial \theta)^2 + \ldots \]

Like massless field in de Sitter
Other Realizations

\[ \phi_I(t) \sim \frac{1}{(-t)^{\Delta_I}} \]

\[ \Delta_I = \text{conformal weight} \]

\[ \implies \text{so}(4, 2) \rightarrow \text{so}(4, 1) \]

Galilean Genesis
Creminelli, Nicolis & Trincherini (2010)

Universe is slowly expanding from asymptotically static past.

Brane-world (DBI) realizations
Hinterbichler & Khoury (2011);
Hinterbichler, Joyce, Khoury & Miller (2012)
As usual in spontaneous symmetry breaking, much of the physics derives from symmetry breaking pattern,

\[ so(4, 2) \rightarrow so(4, 1) \]

irrespective of underlying microphysical theory.
Write down most general theory, irrespective of particular model.
Coset Construction

\[ \text{so}(4, 2) \rightarrow \text{so}(4, 1) \]

Write down most general theory, irrespective of particular model.

Goldstone action: \[ \phi = \phi(t) + \pi \]

\[
\mathcal{L}_\pi = M_0^2 \left( -\frac{1}{2} e^{2\pi (\partial \pi)^2} - H^2 e^{2\pi} + \frac{H^2}{2} e^{4\pi} \right) + M_1 \left( (\Box \pi)^2 + 2\Box \pi (\partial \pi)^2 + (\partial \pi)^4 - 4H^2 (\partial \pi)^2 \right) + M_2 \left( (\partial \pi)^4 + 2\Box \pi (\partial \pi)^2 + 6H^2 (\partial \pi)^2 \right) + \ldots
\]

Other fields in the ballgame:

\[
\mathcal{L}_\chi = -\frac{M^2}{\chi} e^{2\pi (\partial \chi)^2} + e^{4\pi} V(\chi) + a_1 (\partial \chi)^4 + a_2 (\Box \chi)^2 + \ldots
\]
By symmetries,

\[ \rho_{\text{CFT}} \simeq 0 ; \quad P_{\text{CFT}} \simeq \frac{\beta}{t^4} \]
Cosmology

By symmetries,

\[
\rho_{\text{CFT}} \approx 0 ; \quad P_{\text{CFT}} \approx \frac{\beta}{t^4}
\]

Solve Einstein's eqns:

\[
\dot{H} = -\frac{1}{2M_{\text{Pl}}^2} (\rho_{\text{CFT}} + P_{\text{CFT}})
\]

\[
H(t) \approx \frac{\beta}{6t^3 M_{\text{Pl}}^2}
\]

\[
a(t) \approx 1 - \frac{\beta}{12t^2 M_{\text{Pl}}^2}
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Nearly static universe
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Nearly static universe

Universe becomes increasingly flat and homogeneous:

(Akin to ekpyrotic cosmologies Gratton, Khoury, Steinhardt & Turok (2003))

\[ 3H^2 M_{\text{Pl}}^2 = -\frac{3K}{a^2} + \frac{C_{\text{mat}}}{a^3} + \frac{C_{\text{rad}}}{a^4} + \frac{C_{\text{aniso}}}{a^6} + \ldots + \rho_{\text{CFT}} \]
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\[ \simeq \text{const.} \]
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\[ H(t) \approx \frac{\beta}{6t^3 M_{\text{Pl}}^2} \]

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\[ \approx \text{const.} \]

\[ \sim \frac{1}{t^6 M_{\text{Pl}}^2} \]
Correlation fcns are $so(4, 1)$ invariant (i.e. conformally inv.)

e.g. $\langle \chi(x, \tau) \chi(x', \tau) \rangle \sim |x - x'|^{-2\Delta}$

Any field with $\Delta \ll 1$ acquires nearly scale invariant spectrum
Symmetries and Consistency Relations
Greminelli, Joyce, Khoury & Simonovic, 1212.3329

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  Any field with $\Delta \ll 1$ acquires nearly scale invariant spectrum

- Prediction for $f_{NL}$ is model-dependent

  Rubakov’s model: $\langle \theta \theta \theta \rangle = 0$

  Contribution to $f_{NL}$ comes from conversion

  $\theta \rightarrow \frac{\delta \rho}{\rho}$

  e.g. Modulated reheating with $\Gamma \ll H$:

  $f_{NL} = 3$

  Zaldarriaga (2003)
Have additional **consistency relations** (Ward identities) from the **5 broken symmetries** $so(4, 2) \rightarrow so(4, 1)$.

\[
\lim_{\vec{q} \rightarrow 0} \frac{1}{P_\pi(q)} \langle \pi(\vec{q}) \mathcal{O}(\vec{k}_a) \rangle = - \left( 1 + \frac{1}{N} \sum_a \vec{q} \cdot \frac{\partial}{\partial \vec{k}_a} + \frac{q^2}{6N} \sum_a \frac{\partial^2}{\partial k_{a}^2} \right) t \frac{\partial}{\partial t} \langle \mathcal{O}(k_a) \rangle
\]
Model-independent predictions

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\]

Goldstone spectrum is very red:

\[
q^3 P_{\pi}(q) = \frac{A^2_\pi}{q^2 t^2}
\]
Observational Signatures

Creminelli, Joyce, Khoury & Simonovic, 1212.3329

Soft internal lines: Libanov, Mironov & Rubakov (2011)

\[
\langle \chi_{\vec{k}_1} \chi_{\vec{k}_2} \chi_{\vec{k}_3} \chi_{\vec{k}_4} \rangle_{q \to 0} = \frac{1}{P_\pi(q)} \langle \pi \bar{q} \chi_{\vec{k}_1} \chi_{\vec{k}_2} \rangle_{q \to 0} \langle \pi \bar{q} \chi_{\vec{k}_3} \chi_{\vec{k}_4} \rangle_{q \to 0}
\]

\[
\sim \frac{1}{q} \left( 3(\hat{k}_1 \cdot \hat{q})^2 - 1 \right) \left( 3(\hat{k}_3 \cdot \hat{q})^2 - 1 \right).
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(Vanishes as \( q^2 \) in inflation)
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Loop contribution:

\[ \tau_{NL} \sim \log \frac{q}{\Lambda} \]

Stochastic bias, \( \mu \)-distortion of CMB
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Anisotropy: Realization-dependent from super-Hubble \( \pi \) mode

Libanov & Rubakov (2010)

\[
\langle \chi_{k} \chi_{-k} \rangle_{\pi \hat{q}} = \langle \chi_{k} \chi_{-k} \rangle \left( 1 + c_1 \frac{A_\pi}{2\pi} \frac{H_0}{k} \left( 3 \cos^2 \theta - 1 \right) + c_2 \frac{3A_\pi^2}{4\pi^2} \cos^2 \theta \log \frac{H_0}{\Lambda} \right)
\]
Inflation
Single-field inflation: consistency relations

\[ \lim_{\vec{q} \to 0} \langle \zeta_{\vec{q}} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle = -(n_s - 1) \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle \]

Maldacena (2002); Creminelli & Zaldarriaga (2004); Cheung, Fitzpatrick, Kaplan & Senatore (2007)
Single-field inflation: consistency relations

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\]

Maldacena (2002); Creminelli & Zaldarriaga (2004); Cheung, Fitzpatrick, Kaplan & Senatore (2007)

- **Holds in all single-field models, under the following assumptions:**
  - background is attractor
  - adiabatic (Bunch-Davies) vacuum

- **Measuring (primordial) 3-point function in this limit**

  \[ f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8 \]
Generalized inflationary consistency relations
Hinterbichler, Hui and Khoury, 1304.5527

Single-field inflation constrained by infinite number of symmetries, corresponding to an infinite number of consistency relations:

\[
\lim_{q \to 0} \frac{\partial^n}{\partial q^n} \left(\frac{1}{P_\zeta(q)} \langle \zeta(q) \mathcal{O}(k_a) \rangle + \frac{1}{P_\gamma(q)} \langle \gamma(q) \mathcal{O}(k_a) \rangle\right) \sim \frac{\partial^n}{\partial k_a^n} \langle \mathcal{O}(k_a) \rangle
\]

- \( q^0 \) and \( q \) behavior completely fixed
- \( q^n, n \geq 2 \), behavior partially fixed
- These are physical statements (i.e., can be violated)
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\]

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- These are physical statements (i.e., can be violated)

Master consistency relation

Berezhiani and Khoury, 1309.4461

Spatial diffeomorphisms imply the Slavnov-Taylor identity:

\[
\frac{1}{3} q_i \Gamma^{\zeta \zeta \zeta} (\vec{q}, \vec{p}, -\vec{q} - \vec{p}) + 2 q^j \Gamma^{\gamma \zeta \zeta}_{ij} (\vec{q}, \vec{p}, -\vec{q} - \vec{p}) = q_i \Gamma_\zeta (p) - p_i \left( \Gamma_\zeta (|\vec{q} + \vec{p}|) - \Gamma_\zeta (p) \right)
\]
The Ultimate Smoking Gun

Inflation:
- Rapid background expansion
- All light fields are excited, including gravitational waves

\[ \implies \text{scale invariant primordial gravity waves} \]

Conformal Scenario (and Ekpyrotic):
- Very slow contraction/expansion
- Graviton modes not appreciably excited

Brustein, Gasperini, Giovannini & Veneziano (1995)
Khoury, Ovrut, Steinhardt and Turok (2001)

Detection of primordial gravity waves, e.g. through CMB polarization, would rule out pre-big bang scenarios.
Null Energy Condition

\[ T_{\mu\nu}n^\mu n^\nu \geq 0 \implies \rho + P \geq 0 \]

\( n^\mu = \text{null vector} \)

Assuming spatially flat universe,

\[ \therefore \quad M_{P_1}^2 \dot{H} = -\frac{1}{2} (\rho + P) \leq 0 \]

Forbids smooth bounce from contraction \((H < 0)\) to expansion \((H > 0)\)

Violating NEC generally comes hand in hand with various pathologies:

- Ghosts (wrong-sign kinetic term)
- Gradient instabilities
- Superluminality
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<th>Galileon</th>
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Conclusions

Conformal scenario:

- Quasi-static universe
- Scale invariance from conformal invariance

Predictions:

- Slightly anisotropic $P_\zeta(k)$
- $f_{NL}$ model-dependent (as small as $f_{NL} = 3$)
- Signature contributions to $\langle \zeta \zeta \zeta \zeta \rangle$
- No primordial tensors

Requires NEC

Can it be realized in a well-behaved, relativistic QFT?