Alternatives to inflation

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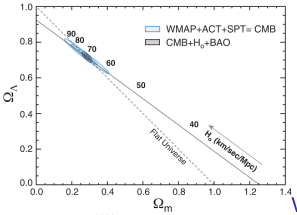
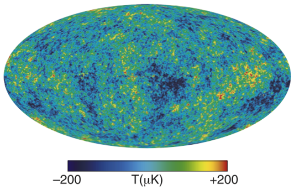
Cosmological puzzles

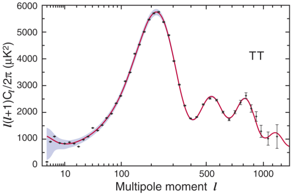
On the largest scales, we observe the universe to be

- Flat
- Homogeneous
- Isotropic





WMAP9 1212.5225



Further, we observe a spectrum of perturbations in the CMB which is correlated on super-horizon scales and nearly scale-invariant and gaussian

Handles on early universe physics

- Homogeniety and flatness of the background solution
  - We'll see how this is achieved both in inflation and in alternatives
- Temperature anisotropies $\longrightarrow$ nearly scale-invariant
  - The field responsible has to be nearly gaussian (not strongly self-interacting)
- Non-gaussianities of perturbations
  - Typically alternatives involve multiple field $\rightsquigarrow$ different non-gaussian signatures
- Gravitational waves
  - Inflation $\rightsquigarrow$ a scale-invariant spectrum of gravitational waves
  - Alternatives $\rightsquigarrow$ no appreciable excitation of gravitational waves

Flatness and homogeneity

The Friedmann equation reads:

$$3H^2 M_{\rm Pl}^2 = \frac{k}{a^2} + \frac{C_{\rm matter}}{a^3} + \frac{C_{\rm radiation}}{a^4} + \frac{C_{\rm anisotropy}}{a^6} + \ldots + \frac{C}{a^{3(1+w)}}$$

- For an expanding universe, curvature ($\sim 1/a^2$) is the most dangerous, but a smooth component with $w < -1/3$ will win $\implies$ accelerated expansion: inflation

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- For an expanding universe, curvature ($\sim 1/a^2$) is the most dangerous, but a smooth component with $w < -1/3$ will win $\implies$ accelerated expansion: inflation
- Another logical possibility: if the universe is contracting before the big bang, the most dangerous term is now anisotropy ($\sim 1/a^6$). A component with $w > 1$ will win out $\implies$ slow contraction
  Gratton, Khoury, Steinhardt & Turok astro-ph/0301395
  - Since w is very large, the background evolves slowly $\implies$ negligible gravitational waves

Null Energy Condition

At some point, all alternatives have to violate the Null Energy Condition

$$T_{\mu\nu}n^\mu n^\nu \geq 0 \overset{\text{fluid}}{\Longrightarrow} \rho + P \geq 0$$

- $M_{\rm Pl}^2 \dot{H} = -\frac{1}{2}(\rho + P)$; To have $\dot{H} > 0$, have to violate the NEC
- Whether or not this is possible is an open question — typically theories which violate the NEC exhibit pathologies
- No-go theorem: For $\mathcal{L} = \mathcal{L}(\phi, \partial\phi)$, violating the NEC introduces instabilities Dubovsky, Gregoire, Nicolis, Rattazzi 0512260

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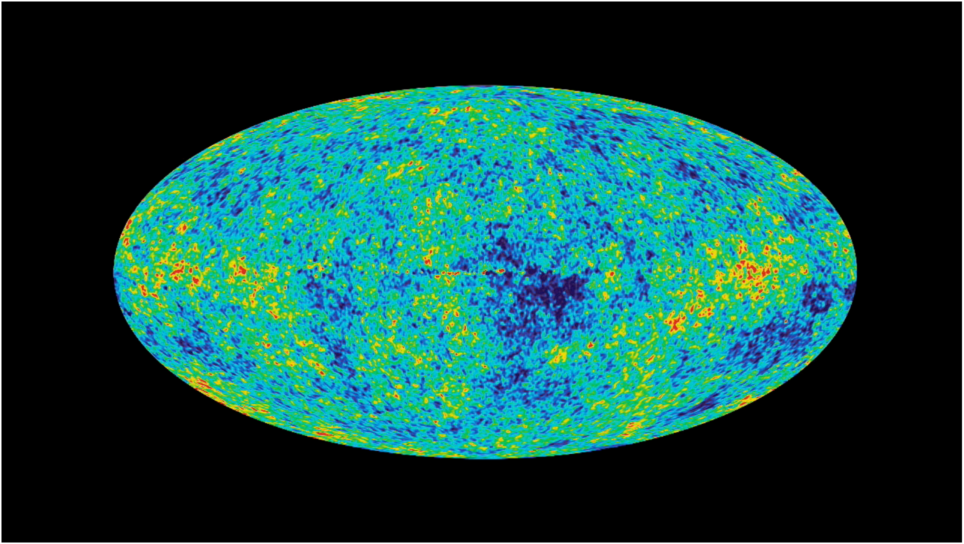
- No-go theorem: For $\mathcal{L} = \mathcal{L}(\phi, \partial\phi)$, violating the NEC introduces instabilities Dubovsky, Gregoire, Nicolis, Rattazzi 0512260
- Possible way out: consider theories where $\partial^2\phi$ is important

  Arkani-Hamed, Cheng, Luty, Mukohyama 0312099; Nicolis, Rattazzi, Trincherini 0912.4258; Creminelli, Nicolis, Trincherini 1007.0027; Hinterbichler, AJ, Khoury, Miller 1212.3607

Anisotropy



NASA/WMAP Science Team

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$$\text{observations} \implies P_\zeta(k) \propto k^3 \langle \zeta_k \zeta_{-k} \rangle \sim k^{2(n_s-1)}$$

$$n_s = 0.967 \pm 0.14 \quad \text{WMAP7}$$

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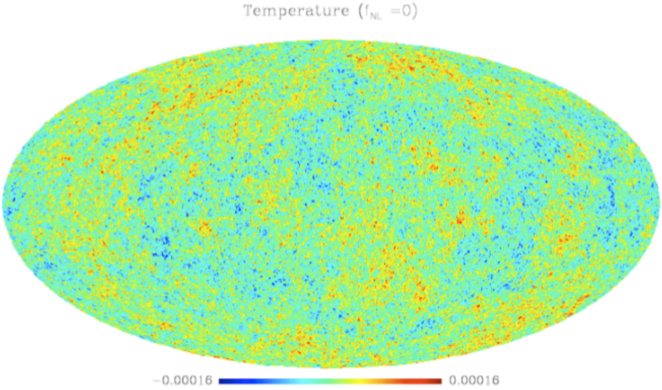
- Approximately gaussian
  - this says roughly that higher-point correlations are small compared to the two-point function

Non-gaussianites

$f_{NL} = 0$

$$f_{NL} \equiv -\frac{\left\langle \frac{\delta T}{T} \frac{\delta T}{T} \frac{\delta T}{T} \right\rangle}{\left\langle \frac{\delta T}{T} \frac{\delta T}{T} \right\rangle^2}$$



Liguori et al. 0708.3786

- Constraints
  - WMAP: $-10 < f_{NL} < 74$
  - Galaxy surveys: $-29 < f_{NL} < 69$
  - Planck: $\Delta f_{NL} \sim 5$

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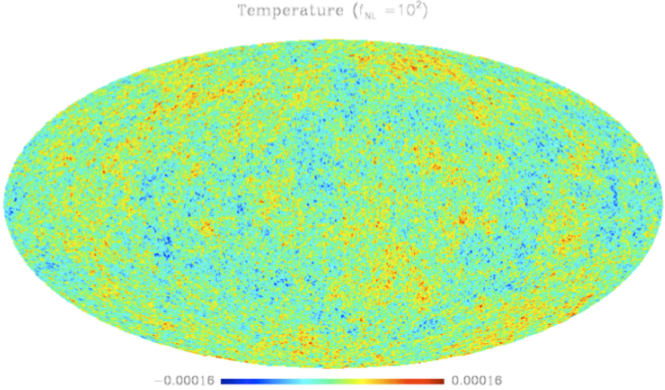

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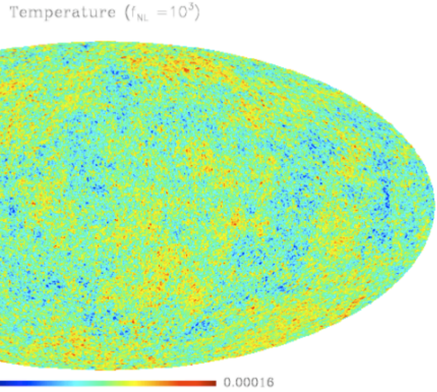

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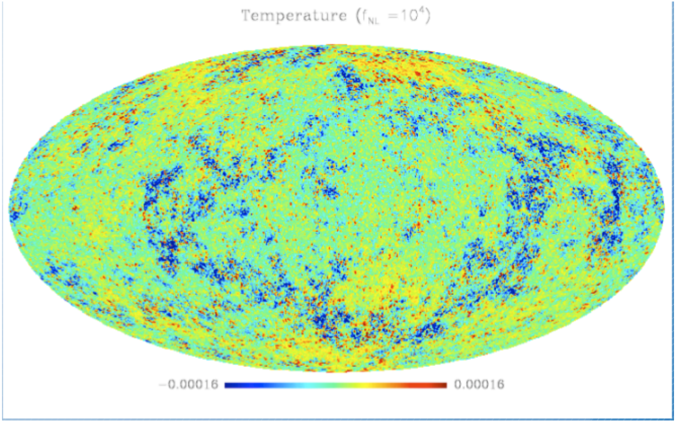

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Symmetries of inflation

- Inflation is a period of quasi-de Sitter expansion

$$\mathrm{d}s^2 \simeq -\mathrm{d}t^2 + e^{2Ht}\mathrm{d}\vec{x}^2$$

- Inflation ends $\implies$ there must be a clock telling it when to end! The level sets of this clock provide a preferred foliation of de Sitter space
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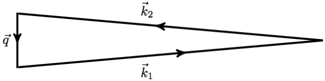
- Then, the scale-invariant spectrum of ζ is a consequence of the diagonal combination of a (broken) coordinate dilation and the shift symmetry of the field
- Spectator fields enjoy the full de Sitter isometries $\implies$ gravitational waves acquire scale-invariant spectrum Maldacena, Pimentel 1104.2846; Creminelli 1108.0874

Consistency relation



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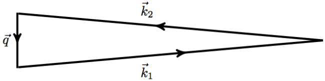

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- We can therefore infer the 3-point function where one of the modes is very soft ($q \ll k_1, k_2$) Maldacena 0210603; Creminelli & Zaldarriaga 0407059

$$\lim_{q\to 0} \frac{1}{P_\zeta(q)} \langle \zeta_q \zeta_{k_1} \zeta_{k_2} \rangle' = \left(3 + \vec{k}\cdot\vec{\partial}_k\right) \langle \zeta_{k_1} \zeta_{-k} \rangle' = (n_s - 1) \langle \zeta_{k_1} \zeta_{-k} \rangle'$$

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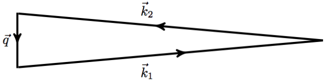

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  - Assumptions: the background is an attractor ($\zeta \to$ const.); there is a single clock; Bunch–Davies vacuum

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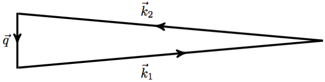

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In general, single-field alternatives will have different non-Gaussian signatures from inflationary models but, their squeezed limit is *also* constrained by the consistency relation:

Alternatives?

Khoury & Miller 1012.0846; AJ, Khoury 1107.3550;
Baumann, Senatore, Zaldarriaga; 1101.3320

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- Adiabatic ekpyrosis/expansion: $f_{NL} \sim \tau^{-4} \rightsquigarrow$ strong coupling issues

  Khoury, Steinhardt 0910.2230; AJ, Khoury 1104.4347

Alternatives?

Therefore if we want scale invariant & Gaussian spectrum over broad range of modes, we have 3 options:

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- Unstable background
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  - Conformal mechanism $\Longleftarrow$

Conformal mechanism — scale invariance from conformal invariance

Inflation is rooted in symmetry ($so(4,1)$); worth thinking about alternatives also based on symmetries

- Conformal mechanism: At early times, the universe is described by a (nearly) CFT on (nearly) flat space
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  - 6 rotations/boosts
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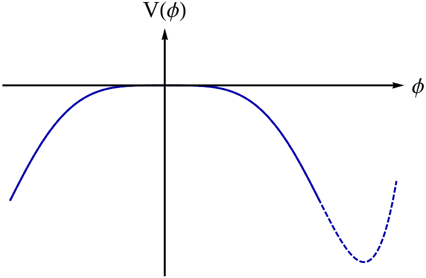
- Under general conditions, scale-invariance for spectator fields follows from symmetry breaking to the isometries of de Sitter
- Universe is driven to be homogeneous and flat ($|w| \gg 1$)

Negative quartic example — Hinterbichler, Khoury 1106.1428



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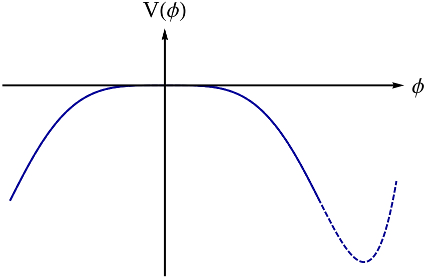

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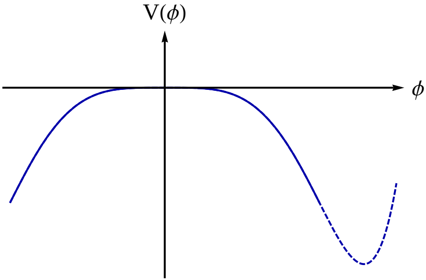
Classically conformally invariant

Consider coupling a massless field χ in the CFT

$$\mathcal{L}_\chi = -\frac{1}{2}\phi^2(\partial\chi)^2 \ .$$

This field couples to the effective metric $g^{\rm eff}_{\mu\nu} = \phi^2\eta_{\mu\nu}$

Negative quartic model cont.



The field rolls off:
$E = \frac{1}{2}\dot{\phi}^2 - \frac{\lambda}{4}\phi^4$

The solution with zero energy is an attractor
$\phi(t) = \sqrt{\frac{2}{\lambda}}\frac{1}{(-t)} \quad -\infty < t < 0$

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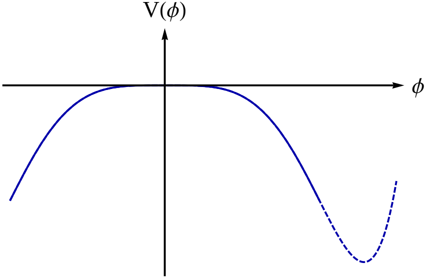

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- If one couples this to gravity, they find that the universe is very slowly contracting with equation of state

$$w = \frac{P}{\rho} \sim t^2 M_{\mathrm{Pl}}^2 \ ,$$

which is very large; the universe is therefore driven to be homogeneous, flat, isotropic

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- This profile breaks 5 of these symmetries (e.g. time translation symmetry); leaving us with 10
- These can be recombined into the isometries of de Sitter space $so(4,1)$

It is therefore not so surprising that certain fields will acquire a scale invariant spectrum

- Recall that χ coupled to the *effective* metric $\bar{\phi}^2\eta_{\mu\nu} \sim \frac{1}{t^2}\eta_{\mu\nu}$
  - This is the metric of de Sitter space!

Generalities — Hinterbichler, AJ & Khoury 1202.6056

I've showed you a particular realization, but most of the physics follows solely from symmetry breaking pattern

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

Generalities — Hinterbichler, AJ & Khoury 1202.6056

I've showed you a particular realization, but most of the physics follows solely from symmetry breaking pattern

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and for spectator fields

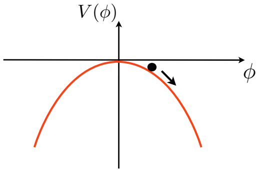
$$\mathcal{L}_\chi = -\frac{M_\chi^2}{2}e^{2\pi}(\partial\chi)^2 + e^{4\pi}V(\chi) + a_1(\partial\chi)^4 + \ldots$$

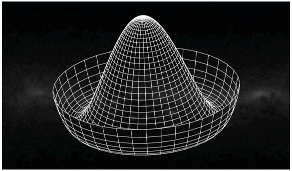
When χ is massless, it acquires a scale-invariant spectrum

Realizations

There are various realizations of this mechanism

Negative ϕ^4, $U(1)$ model

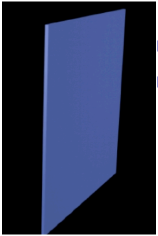




Craps, Hertog, Turok 0712.4180;
Rubakov 0906.3693;

Hinterbichler, Khoury 1106.1428

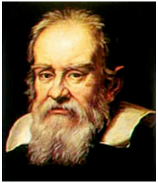
DBI braneworlds



Hinterbichler, Khoury 1106.1428;

Hinterbichler, AJ, Khoury, Miller 1212.3607

Galilean Genesis



Creminelli, Nicolis, Trincherini 1007.0027;

Creminelli, Hinterbichler, Khoury, Nicolis, Trincherini 1209.3768

Distinguishing from inflation? - Creminelli, AJ, Khoury & Simonović 1212.3329

This model has $so(4,1)$ symmetry, which is the same as a spectator field in inflation,

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$$\langle \chi(\vec{x}_1, t_1)\chi(\vec{x}_2, t)\rangle \sim |\vec{x}_1 - \vec{x}_2|^{-2\Delta}$$

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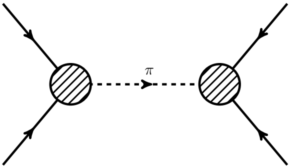
But this also has *additional* symmetries, because it came from an $so(4,2)$ invariant action

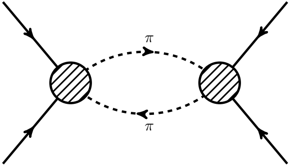
- These additional symmetries have corresponding Ward identities, which constrain correlation functions in a way different from inflation
$$\lim_{q\to 0}\frac{1}{P_\pi(q)}\langle\pi_{\vec{q}}\phi_{\vec{k}_1}\ldots\phi_{\vec{k}_N}\rangle' = -\left(1+\frac{1}{N}q_i\sum_a\partial_{k_{ai}}+\frac{1}{6N}\vec{q}^2\sum_a\partial^2_{k_a}\right)\frac{\mathrm{d}}{\mathrm{d}\log t}\langle\phi_{\vec{k}_1}\ldots\phi_{\vec{k}_N}\rangle'$$

4pt function from symmetry - Creminelli, AJ, Khoury & Simonović 1212.3329

There are two distinct contributions to the 4-point function, coming from exchanging either one or two soft goldstone fields. The predicted shapes are model-independent



$$\sim \frac{1}{q k_1^4 k_3^4}\left(3(\hat{k}_1\cdot q)^2-1\right)\left(3(\hat{k}_2\cdot q)^2-1\right)$$



$$\sim \frac{1}{q^3 k_1^3 k_2^3}$$

Notice that the loop's contribution is of τ_{NL} form, which is relevant for the stochastic scale-dependent bias or μ-distortion

Summary

- We have several probes of the early universe
  - Homogeneity, flatness and isotropy $\rightsquigarrow$ $w < -1/3$ or $|w| \gg 1$
  - Scale-invariant & Gaussian perturbations $\rightsquigarrow$ alternatives with multiple fields
  - Gravitational waves — inflation predicts them, alternatives do not
- Inflation is a theory deeply rooted in symmetry, therefore alternatives should have similarly deep symmetry principles
- Conformal mechanism is an alternative to inflation based upon breaking $so(4,2) \to so(4,1)$
- Non-linearly realized conformal symmetry imposes additional constraints on correlation functions relative to inflation