The primordial curvature perturbation

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Plan of the talk

1. Statistical properties of the primordial curvature perturbation. Generation from scalar field perturbations.

2. Statistical anisotropy from vector field contributions.

LSS — our window on early universe

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  - CMB anisotropy + galaxy distribution and bulk flow

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- Can predict LSS in terms of primordial curvature perturbation $\zeta(\mathbf{x})$ existing at $T \sim 1$ MeV.
  - So $\zeta(\mathbf{x})$ is an observable.
- Other effects $< 10\%$, probably $\simeq 0$
  - tensor perturbation, cosmic strings, textures, isocurvature (matter or ν) perturbation.

Defining the curvature perturbation ζ

No restriction to first order cosmological perturbation theory

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- Perturbed universe:

$$g_{ij} = a^2(t)e^{2\zeta(\mathbf{x},t)}\gamma_{ij}(\mathbf{x},t), \qquad ||\gamma|| = 1, \qquad \langle\zeta\rangle = 0. \tag{1}$$

threading comoving, slicing uniform energy density$\rho(t)$

- Local scale factor $a(\mathbf{x},t) \equiv a(t)e^{\zeta(\mathbf{x},t)}$, volume $d\mathcal{V} \propto a^3(\mathbf{x},t)$.

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threading comoving, slicing uniform energy density $\rho(t)$ (0)

- Local scale factor $a(\mathbf{x},t) \equiv a(t)e^{\zeta(\mathbf{x},t)}$, volume $d\mathcal{V} \propto a^3(\mathbf{x},t)$.
- Derivation of δN formula

$$\dot\zeta = \frac{\dot a(\mathbf{x},t)}{a(\mathbf{x},t)} - \frac{\dot a(t)}{a(t)}, \qquad N(\mathbf{x},t,t_1) \equiv \int_{t_1}^{t} dt \frac{\dot a(\mathbf{x},t)}{a(\mathbf{x},t)}$$

$$\boxed{\zeta(\mathbf{x},t) - \zeta(\mathbf{x},t_1) = \delta N(\mathbf{x},t,t_1)}$$

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- Smooth ρ and P on scale L. Local energy continuity equation

$$\dot{\rho}(t) = -\frac{\dot{a}(\mathbf{x},t)}{a(\mathbf{x},t)} \left(\rho(t) + P(t) + \delta P_{\rm nad} \right)$$

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  where $\delta P_{\rm nad}$ is pressure perturbation on uniform ρ slicing.
- If $P(\rho)$ is unique $\dot{\zeta} = 0$.
- So $\dot{\zeta} = 0$ for matter domination and for radiation domination.

Setting the initial condition for LSS

Consider the epoch $\boxed{T \sim 10^{-1}\,\text{MeV}}$.

- Universe is radiation dominated and ζ has time-independent value $\zeta(\mathbf{x})$.
- LSS probes scales (inverse wavenumbers) $e^{-15} H_0^{-1} \lesssim k^{-1} \lesssim H_0^{-1}$.
- These 'cosmological scales' are outside horizon at $T \sim 10^{-1}$ MeV.
- Assume adiabatic initial condition: $\delta\rho_\gamma = \delta\rho_\nu = \delta\rho_{\rm B} = \delta\rho_{\rm CDM} = 0$ on the slicing of uniform ρ.
- Then $\zeta(\mathbf{x})$ determines subsequent evolution of all perturbations (except tensor mode).

Spectrum $\mathcal{P}_\zeta(k,t)$

- Work in box $\gg$ scales of interest.
- Assume $\langle\zeta(\mathbf{x})\zeta(\mathbf{x}')\rangle$ translation invariant
  - $\langle\rangle$ is average over box location

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- Define $\mathcal{P}_\zeta(\mathbf{k})$: $\langle\zeta_{\mathbf{k}}\zeta_{\mathbf{k}'}\rangle \equiv (2\pi)^3\delta^3(\mathbf{k}+\mathbf{k}')(\pi^2/k^3)\mathcal{P}_\zeta(\mathbf{k})$
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- Mean-square (volume average) is

$$\langle\zeta^2\rangle = \int \frac{dk}{k}\mathcal{P}_\zeta(k)$$

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  - Assuming statistical isotropy, $B_\zeta = B_\zeta(k, k', k'')$.

$$f_{\rm NL}(k, k', k'') \equiv \frac{5}{6} \frac{B_\zeta(k, k', k'')}{\frac{k^3}{2\pi^2} \frac{k'^3}{2\pi^2} \mathcal{P}_\zeta(k) \mathcal{P}_\zeta(k') + \text{cyclic perms}}$$

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- Curvaton-type models for origin of ζ predict

$$\zeta(\mathbf{x}) = g(\mathbf{x}) + \frac{3}{5} f_{\rm NL} \left[g^2(\mathbf{x}) - \langle g^2 \rangle \right]$$

with g gaussian and $f_{\rm NL}$ constant.

Observation of ζ on cosmological scales

- Statistical inhomogeneity and anisotropy $\lesssim 10\%$
- Tensor fraction $r \lesssim 10^{-1}$
- $\mathcal{P}_\zeta \simeq (5 \times 10^{-5})^2$
- Assuming $r \lesssim 10^{-2}$

$$n - 1 \equiv \frac{d \ln \mathcal{P}_\zeta}{d \ln k} = -0.04 \pm 0.015$$

- Running

$$|\frac{dn}{d \ln k}| \lesssim 10^{-2}$$

- Non-gaussian fraction $\mathcal{P}_\zeta{}^{-1/2} f_{\rm NL} \lesssim 10^{-2}$

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- Vacuum fluctuation of any light ($|m|^2 \ll H^2$) scalar field ϕ with canonical kinetic term is converted at horizon exit to classical perturbation $\delta\phi_{\mathbf{k}}(t)$.
- For exponential and isotropic inflation $\mathcal{P}_{\delta\phi}(k,t) \simeq (H/2\pi)^2$.

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- Vacuum fluctuation of any light ($|m|^2 \ll H^2$) $\boxed{\text{scalar}}$ field ϕ with canonical kinetic term is converted at horizon exit to classical perturbation $\delta\phi_{\mathbf{k}}(t)$.
- For $\boxed{\text{exponential and isotropic inflation}}$ $\mathcal{P}_{\delta\phi}(k,t) \simeq (H/2\pi)^2$.
- Usual assumption: ζ generated from one (or more) of these perturbations.
- Prediction: $\boxed{\text{Statistical homogeneity and isotropy}}$.

Three paradigms for generating ζ

- ϕ is inflaton in single-field slow roll inflation.
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  - Negligible $f_{\rm NL}$ but expect observable n'
- ϕ is curvaton-type field effective only after inflation.
  - Expect observable $f_{\rm NL}$
- ϕ is inflaton in generic scalar field inflation.
  - Expect observable n' and in many cases observable $f_{\rm NL}$

Statistical anisotropy of the spectrum

Reality $\zeta^*_{\mathbf{k}} = \zeta_{-\mathbf{k}}$ requires $\mathcal{P}_\zeta(\mathbf{k}) = \mathcal{P}_\zeta(-\mathbf{k})$

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Simplest parameterisation with $\hat{\mathbf{n}}$ a preferred direction:

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WMAP gives $|g| < 10^{-1}$, PLANCK will give $|g| < 10^{-2}$ or detect.

Strongly decreasing $g(k)$ could explain axis of evil?

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- Scalar field perturbation generates ζ

Kanno/Soda/Watanabe 1010.5307, Emami/Firouzjahi/Movahed/Zarei 1010.5495

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- I'll just discuss second possibility

Calculating ζ_A

$$\delta \mathbf{A}(\mathbf{k}) = \sum_\lambda \mathbf{e}_\lambda(\hat{\mathbf{k}}) \delta A_\lambda(\mathbf{k}),$$

$\lambda = R,\ L$ or $\|$

If $\mathbf{A}$ gauge field, $A_\| = 0$

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$$\langle \delta A_\lambda(\mathbf{k}) \delta A^*_{\lambda'}(\mathbf{k}') \rangle = (2\pi)^2 \frac{2\pi^2}{k^3} \delta_{\lambda\lambda'} \delta(\mathbf{k} - \mathbf{k}') \boxed{\mathcal{P}_\lambda(k)}$$

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Calculate contribution of $\delta\mathbf{A}$ to ζ using δN formula

$$\begin{aligned} \zeta_A &= \delta N(\mathbf{A}) = \sum N_i \cdot \delta A_i + + \sum N_{ij} \delta A_i \delta A_j + \cdots \\ N_i &\equiv \partial N / \partial A_i, \qquad N_{ij} \equiv \partial^2 N / \partial A_i \partial A_j \end{aligned}$$

Scenario for creating ζ_A gives $N(\mathbf{A})$.

Spectrum of ζ_A

Define $\mathcal{P}_\perp = (\mathcal{P}_R + \mathcal{P}_L)/2$ and $(\mathbf{N}_A)_i \equiv N_i$ [D/K/D/R]

$$\mathcal{P}_{\zeta_A} = N_A^2 \mathcal{P}_\perp \left[1 + \hat{\mathbf{N}}_A \cdot \hat{\mathbf{k}} \left(\frac{\mathcal{P}_\| - \mathcal{P}_\perp}{\mathcal{P}_\perp} \right) \right].$$

If $\mathbf{A}$ is a gauge field $\mathcal{P}_\| = 0$, anyhow expect $\mathcal{P}_\| \neq \mathcal{P}_\perp$. So small anisotropy needs

Vector contribution to ζ is small

Bispectrum of ζ_A

(D/K/L/R) Define $\mathcal{P}_- \equiv \frac{1}{2}(\mathcal{P}_R - \mathcal{P}_L)$

$$B_{\zeta_A} = \sum_{ijnm} N_i N_n N_{jm} \left(P_{ij}(\mathbf{k}) P_{nm}(\mathbf{k}') + \text{cyclic perms.}\right)$$

$$P_{ij}(\mathbf{k}) \equiv \frac{2\pi^2}{k^3}\left[\left(\delta_{ij} - \hat{k}_i\hat{k}_j\right) + p\hat{k}_i\hat{k}_j + iq\epsilon_{ijk}\hat{k}_k\right]\mathcal{P}_\perp(k)$$

$$p \equiv \mathcal{P}_\parallel / \mathcal{P}_\perp, \qquad q \equiv \mathcal{P}_- / \mathcal{P}_\perp$$

Analogue of ‘local’ bispectrum generated by *scalar* field perturbation.

No fit to observation yet done.

PLANCK team please note!

Non-canonical gauge kinetic function

Application: generate ζ at end of inflation S. Yokoyama/Soda 0805.4265

During exponential inflation take

$$S = -\frac{1}{4}\int d\eta d^3x\sqrt{-g}f^2(\chi(\eta))F_{\mu\nu}F^{\mu\nu}$$

Scalar field χ assumed to give $f \propto a^\alpha$.

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Gauge invariance gives $\mathcal{P}_{\|} = 0$.

$$\mathcal{P}_{\perp}(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{k}{k_{\rm end}}\right)^{3-2|\alpha+\frac{1}{2}|}$$

Flat spectrum for $\alpha \simeq -2$ or $+1$.

$\frac{1}{6}RA^2$ coupling to gravity

Application: vector curvaton model

K. Dimopoulos hep-ph/0607229; D/K/L/R 0809.1055

$$S = \int d\eta d^3x \sqrt{-g} \left[\frac{1}{2} M_{\mathrm{P}}^2 R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \left(m^2 + \frac{R}{6} \right) B_\mu B^\mu \right]$$

$$F_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu,$$

physical field $A_\mu = B_\mu / a(\eta)$

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Use it during exponential inflation when $R = 12H^2$.

$$\mathcal{P}_+(k) = \left(\frac{H}{2\pi}\right)\left(\frac{k}{k_{\rm end}}\right)^{2m^2/3H^2}, \qquad \mathcal{P}_{||}(k) = 2\mathcal{P}_+(k)$$

Flat spectrum for $m = 0$.

Vector inflation

Golovnev/Mukhanov/Vanchurin 0802.2068, D/K/DHL/R.

- Uses $\frac{1}{6}RA^2$ interaction with many vector fields.
- Random orientation gives almost isotropic inflation.
- Anisotropy of ζ_A is small so don't need scalar fields! D/K/L/R
- Except for anisotropy, prediction same as for ϕ^2 chaotic inflation.
- Tensor with statistical anisotropy is the smoking gun.

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- Could use it with non-canonical kinetic term.
- Statistical anisotropy could be small, no need for scalar fields.
- But gauge interaction might generate too much non-gaussianity.
- Existing studies incomplete

Bartolo/Dimastrogiovanni/Matarrese/Riotto 0906.4944, 0909.5621.

Concluding remarks

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Thanks for listening!