A stringy way of generating cosmological structure

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The inflating curvaton

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2. STRING AXION WITH ANOMALY-MEDIATED SUSY for curvaton potential

Highly predictive — MAY be ruled out by LHC or detection of tensor. Otherwise WILL be ruled out or confirmed by measurement of running of spectral index.

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HOW DID THIS $\zeta(\mathbf{x})$ ORIGINATE?

ζ in a nutshell

Definition: smooth metric on super-horizon scale, choose uniform-ρ slicing and comoving threading, then

$$\zeta \equiv \delta[\ln a(\mathbf{x}, t)]$$

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Energy conservation $dE = -pd\mathcal{V}$:

$$\dot{\rho}(t) = -3\frac{\partial(\ln a(\mathbf{x}, t))}{\partial t}\left[\rho(t) + P(\mathbf{x}, t)\right]$$

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True for matter domination, radiation domination and single-field inflation.

Two formulas for ζ

FIRST ORDER:

$$\zeta(\mathbf{x},t) = H\delta t = -H\frac{\delta\rho(\mathbf{x},t)}{\dot\rho(t)}$$

with $\delta\rho$ defined on slice of uniform a (“flat slice”).

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EXACT:

$$\zeta(\mathbf{x},t) \equiv \delta[\ln a(\mathbf{x},t)] = \delta[\ln(a(\mathbf{x},t)/a(t))] \equiv \delta N(\mathbf{x},t)$$

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First-order is good if non-gaussianity is above second-order level. For $f_{\rm NL}$ this means $|f_{\rm NL}| \gg 1$.

To get a simple result WE USE FIRST-ORDER.

Our potential

$$V(\phi, \sigma) = V(\phi) + V(\sigma)$$

INFLATON POTENTIAL:

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CURVATON POTENTIAL:

$$V(\sigma) = V_0 \left(1 + \cos \frac{\pi \sigma}{\sigma_0} \right)$$

with

$$\sigma_0 \sim M_{\rm P}, \qquad m \equiv \sqrt{V_0} \pi / \sigma_0 \sim 100 \, \text{TeV}$$

(It's a string axion with anomaly-mediated susy breaking.)

Inflating curvaton scenario

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- Inflation with $V(\phi) \quad (V(\sigma) \ll V(\phi) and |V'(\sigma)| \ll |V'(\phi)|)$.
  - Curvaton field σ acquires classical gaussian perturbation $\delta\sigma(\mathbf{x}, t)$ as each scale leaves the horizon, $\mathcal{P}_{\delta\sigma} = (H/2\pi)^2$.
- At this stage $\zeta \simeq \zeta_\phi(\mathbf{x}) = -H\delta\phi/\dot{V}$ and we choose H small enough for it to be negligible.

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- At this stage $\zeta \simeq \zeta_\phi(\mathbf{x}) = -H\delta\phi/\dot{V}$ and we choose H small enough for it to be negligible.
- Inflation ends giving matter and/or radiation $\rho_\phi(t) \gg V(\sigma)$.
  - $\sigma(\mathbf{x}, t)$ rolls slowly down its potential.

Inflating curvaton scenario (continued)

- When $V(\sigma)$ dominates energy density, few e-folds more inflation.
- We choose parameters so that interval between the two inflations is short enough that the (large) cosmological scales stay outside horizon.
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- Near start of second inflation, $\delta\sigma$ causes increase of ζ. On cosmological scales we get the observed $\zeta(\mathbf{x})$.
- Second inflation ends when $V(\sigma)$ steepens and σ oscillates.
  - Eventual decay of σ produces standard Hot Big Bang.

The calculation

We use standard techniques:

- Einstein gravity
- Flat spacetime field theory
  - Equivalence principle embeds it in curved spacetime
- No particles before horizon exit
  - Practically mandatory for inflation to have begun.
- Vacuum fluctuation of fields set to zero before horizon exit.
  - A way of handling ultraviolet divergence.

Prediction for spectral index

$$n(k) - 1 = 2\eta_\sigma - 2\epsilon \equiv \frac{2M_{\rm P}^2}{V}\frac{d^2V(\sigma)}{d\sigma^2} + 2\frac{\dot{H}}{H^2}$$

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We need $|\eta_\sigma| \ll 1$ during SECOND inflation so it's nearly zero at horizon exit. Hence

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Observation requires $n - 1 \simeq -0.03$

So we need $N_1(k) \simeq 14p = 14$ (recall $V(\phi) \propto \phi^p$)

Prediction for running

$$n' \equiv \frac{dn(k)}{d\ln k} = \frac{4(1-n)^2}{p} = 4(1-n)^2$$

WILL EVENTUALLY BE VERIFIED OR RULED OUT!

A quick aside

Standard cosmology after second inflation needs

$$\simeq N_1 - \ln(10^{-5} M_\mathrm{P}/H_1)/2 + N_2 \simeq 50$$

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Going further we could allow $p = 4$, indeed any p, but no justification for them and running might be too small to measure.

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Note: for generic curvaton-type model (no second inflation) we need $14p \simeq 50$, eg. $p = 4$. (Unless $n - 1 \simeq 2\eta_\sigma$.)

More predictions

1. TENSOR FRACTION We're assuming ζ_ϕ negligible:

$$s \equiv \mathcal{P}_{\zeta_\phi}/\mathcal{P}_\zeta \ll 1$$

Hence tensor fraction is

$$r = 16s\epsilon = 8s(1-n) \simeq 0.24s \ll 0.24$$

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2. LOCAL NON-GAUSSIANITY

Our calculation gives $f_{\rm NL} \sim -1$ which would eventually be seen. But second order correction to $f_{\rm NL}$ will be ~ 1.

Need 2nd order or δN to get accurate prediction for $f_{\rm NL}$.

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Observation of pure monodromy tensor fraction $r \simeq 0.08$ will rule out the model. (And confirm pure monodromy if also $n - 1 \simeq -0.020$.) So will observation of any bigger tensor fraction.

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OTHERWISE IT'S IN GREAT SHAPE FOR MANY YEARS —

TILL n' IS MEASURED.