NON-GAUSSIAN FLUCTUATIONS OF THE INFLATON AND CONSTANCY OF CORRELATIONS OF ζ OUTSIDE THE HORIZON

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- IN THE SIMPLEST COSMOLOGICAL MODELS, CURVATURE PERTURBATIONS ARE GENERATED BY FLUCTUATIONS IN THE INFLATON FIELD.

- THESE CURVATURE PERTURBATIONS THEN LEAD TO FLUCTUATIONS IN THE CMBR AND IN MATTER.

- CURVATURE PERTURBATIONS CAN BE DESCRIBED BY A VARIABLE ζ, AND CORRELATIONS OF ζ LEAD TO CORRELATIONS IN THE CMBR AND MATTER DISTRIBUTION.
- GAUSSIAN ($< \zeta \zeta >$ NON-TRIVIAL, 4PT ~ $(2 \text{ PT})^2$, ODD=0) NON-GAUSSIAN (ODD, OR NON-TRIVIAL EVEN)

NON-GAUSSIANITIES IN SINGLE FIELD INFLATION

- NON-GAUSSIANITIES IN THE CURVATURE PERTURBATION ζ CAN ARISE FROM

1) SELF INTERACTIONS OF THE INFLATON
2) NON-LINEARITIES IN COSMOLOGICAL PERTURBATION THEORY

3) PREHEATING, 4) NON-VACUUM QUANTUM STATE

USUALLY THE SELF INTERACTION CONTRIBUTION IS IGNORED.

SELF INTERACTION CONTRIBUTION

FOR EXAMPLE, CONSIDER CUBIC SELF INTERACTIONS, $\mu\,\phi^3$, WHERE ϕ IS THE INFLATON

- THE SELF INTERACTION CONTRIBUTION TO $<\hat{\zeta}^3>$ ~ $<(\delta\hat{\phi})^3>$ WHICH IS PROPORTIONAL TO μ, AND THUS TO THE SLOW ROLL PARAMETER $\xi \sim V'''$

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- THE SELF INTERACTION CONTRIBUTION TO $<\hat{\zeta}^3>$ ~ $<(\delta\hat{\phi})^3>$ WHICH IS PROPORTIONAL TO μ, AND THUS TO THE SLOW ROLL PARAMETER $\xi \sim V'''$
- IS PRESUMED SMALLER THAN TERMS PROPORTIONAL TO SLOW ROLL PARAMETERS $\varepsilon \sim V'^2$ AND $\eta \sim V''$, AND SO IGNORED. [MALDACENA 2003]

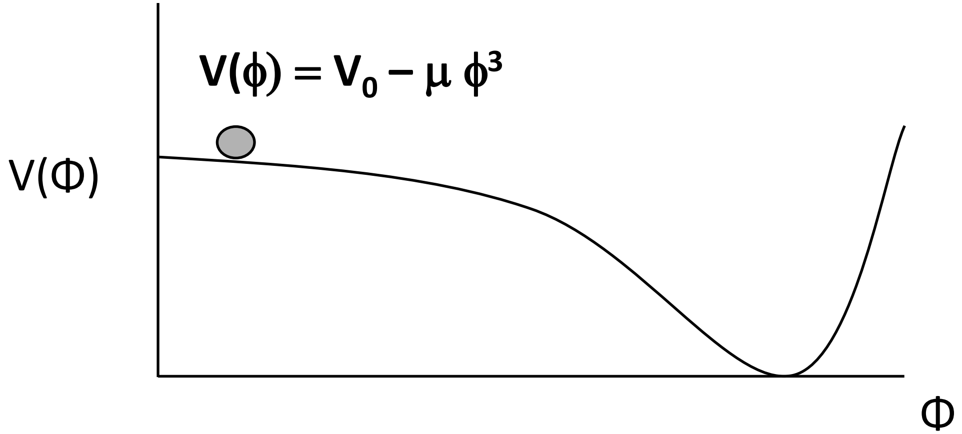
BUT .....

NON-GAUSSIANITIES IN SINGLE FIELD INFLATION

1. FOR MANY MODELS (NEW INFLATION, SMALL FIELD NATURAL INFLATION AND RUNNING MASS INFLATION), $\xi >> \varepsilon$.

   FOR EXAMPLE, NEW INFLATION $V(\phi) = V_0 - \mu\,\phi^3$.

$$\epsilon \equiv \frac{1}{2}\left(\frac{V'}{V}\right)^2 M_P^2 \sim \frac{\mu^2\phi^2}{H^4}\frac{\phi^2}{M_P^2} \qquad \xi \equiv \frac{V'V'''}{V^2}M_P^4 \sim \frac{\mu^2\phi^2}{H^4}$$



NON-GAUSSIANITIES IN SINGLE FIELD INFLATION

1. FOR MANY MODELS (NEW INFLATION, SMALL FIELD NATURAL INFLATION AND RUNNING MASS INFLATION), $\xi >> \varepsilon$.

2. THE SELF INTERACTION CONTRIBUTION IS ACTUALLY $\sim \xi N_e$. THIS IS COMPARABLE TO η.

   (N_e (t) is the number of e-foldings since horizon exit, and increases from 0 to 60 by the end of inflation for our current horizon scale).

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2. THE SELF INTERACTION CONTRIBUTION IS ACTUALLY ~ ξN_e . THIS IS COMPARABLE TO η.

   THEREFORE SELF INTERACTIONS SHOULD NOT BE IGNORED OUTRIGHT

[MALDACENA 2003 - CHAOTIC]

DO SELF INTERACTIONS IMPLY GROWTH OUTSIDE THE HORIZON ?

- BUT A CONTRIBUTION TO $<\hat{\zeta}(k)^3> \sim N_e(t)$ IMPLIES THAT THE 3-POINT FUNCTION IS GROWING AFTER HORIZON EXIT ! THIS IS CONTRARY TO ONE'S EXPECTATIONS.

IS THE CALCULATION OF THE INFLATON SELF INTERACTION CONTRIBUTION TO $<\hat{\zeta}^3>$ INCORRECT?

- IT HAS BEEN DONE INDEPENDENTLY BY FALK, RR, SREDNICKI (1993), ZALDARRIAGA (2004), BERNARDEAU, BRUNIER, UZAN (2004) AND SEERY, MALIK, LYTH(2008) IN DIFFERENT CONTEXTS.

DO SELF INTERACTIONS IMPLY GROWTH OUTSIDE THE HORIZON ?

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- IT HAS BEEN DONE INDEPENDENTLY BY FALK ET AL (1993), ZALDARRIAGA (2004), BERNARDEAU ET AL (2004) AND SEERY ET AL (2008) IN DIFFERENT CONTEXTS.

- LET US RE-EXAMINE THE ARGUMENT THAT CORRELATIONS OF THE CURVATURE PERTURBATION $\zeta(k)$ ARE CONSTANT OUTSIDE THE HORIZON.

- $\zeta(k)$, THE CURVATURE PERTURBATION ON UNIFORM DENSITY SLICES, WAS FIRST INTRODUCED BY BARDEEN, STEINHARDT, TURNER
- GENERALISED BY SALOPEK, BOND TO STUDY NON-GAUSSIANITIES IN THE CURVATURE PERTURBATION
- IN THE LITERATURE, THE FUNCTION $\zeta(k)$ IS SHOWN TO BE CONSTANT OUTSIDE THE HORIZON.

[SALOPEK, BOND; LYTH, WANDS; RIGOPOULOS, SHELLARD; MALIK, WANDS; LYTH, MALIK, SASAKI; LANGLOIS, VERNIZZI]

- IN THE LITERATURE, THE FUNCTION $\zeta(k)$ IS SHOWN TO BE CONSTANT OUTSIDE THE HORIZON.

  CLASSICAL

  WHAT DOES THIS IMPLY FOR QUANTUM n-POINT FUNCTIONS OF $\hat{\zeta}(k)$?

- IN THE LITERATURE, THE FUNCTION $\zeta(k)$ IS SHOWN TO BE CONSTANT OUTSIDE THE HORIZON. CLASSICAL

  WHAT DOES THIS IMPLY FOR QUANTUM n-POINT

  FUNCTIONS OF $\hat{\zeta}(k)$?

  THE 2-POINT FUNCTION

  $$< \hat{\zeta}(k_1)\, \hat{\zeta}(k_2) > = (2\pi)^3\ |\zeta(k_1)|^2\ \delta^3\,(\mathbf{k_1} - \mathbf{k_2})$$

  IS CONSTANT AFTER HORIZON EXIT. (LOOPS ~ $N_e(t)$)

  [WEINBERG 2006]

- **WHAT ABOUT HIGHER POINT FUNCTIONS ?**

CONSTANCY CONDITION FOR ζ(k) 3-POINT FUNCTION

TO OBTAIN $<\hat{\zeta}^n>$ USE THE IN-IN FORMALISM TO OBTAIN CORRELATIONS AS A FUNCTION OF TIME

$$\langle\hat{\zeta}(t)^n\rangle = \sum_{N=0}^{\infty} i^N \int_{t_0}^{t} dt_N \int_{t_0}^{t_N} dt_{N-1} \cdots \int_{t_0}^{t_2} dt_1$$

$$\times \left\langle \left[\hat{H}_I(t_1), \left[\hat{H}_I(t_2), \cdots \left[\hat{H}_I(t_N), \hat{\zeta}_I^n(t)\right] \cdots\right]\right]\right\rangle$$

$\hat{H}_I$ IS THE INTERACTION HAMILTONIAN

$\hat{\zeta}_I$ = INTERACTION PICTURE, $<\ldots> = {}_{in}<0|\ldots|0>_{in}$

$$\langle\hat{\zeta}(t)^3\rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\zeta}_I(t)^3\right]\right\rangle$$

LOWEST ORDER

CONSTANCY CONDITION FOR ζ(k) 3-POINT FUNCTION

$$\langle \hat{\zeta}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\zeta}_I(t)^3 \right] \right\rangle$$

- FOR < $\hat{\zeta}(t)^3$ > TO BE CONSTANT AFTER HORIZON EXIT THE CONTRIBUTION TO THE INTEGRAL FOR t AFTER HORIZON EXIT SHOULD BE SUPPRESSED.

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- WEINBERG (2008) SHOWED THIS WAS SO, BUT .. FOR GAUSSIAN INFLATON FLUCTUATIONS, I.E., IGNORING SELF INTERACTIONS OF THE INFLATON.

CONSTANCY CONDITION FOR ζ(k) 3-POINT FUNCTION

- ζ IS CLASSICAL AND CONSTANCY OUTSIDE THE HORIZON IMPLIES CORRELATIONS ALSO CONSTANT OUTSIDE THE HORIZON

- WEINBERG (2006) ARGUES THAT PERTURBATIONS OUTSIDE HORIZON CLASSICAL IN THE SENSE THAT

$$[\hat{\zeta}, \hat{\zeta}], \quad [\hat{\zeta}, \dot{\hat{\zeta}}] \to 0 \qquad \text{for large } t$$

n-POINT FUNCTIONS OF CAN GROW AS (ln a) OR POWERS OF (ln a), BUT NOT POWERS OF a.

$(\ln a) = N_e$

CONSTANCY CONDITION FOR ζ(k) 3-POINT FUNCTION

- WE INVESTIGATE WHETHER THE 3-POINT FUNCTION IS CONSTANT OUTSIDE THE HORIZON, IN LIGHT OF THE TIME DEPENDENT CONTRIBUTION PROPORTIONAL TO N_e FROM INFLATON SELF INTERACTIONS

CALCULATION OF THE 3-POINT FUNCTION OF $\zeta(k)$ AND f_{NL}

- WE CALCULATE $<(\hat{\delta\phi})^3>$ IN THE $\delta\phi \neq 0$ GAUGE, USING THE CANONICAL FORMALISM FOR CUBIC NEW INFLATION $V(\phi) = V_0 - \mu\,\phi^3$.

- WE THEN RELATE $\hat{\zeta}(k,t)$ TO $\delta\phi(k,t)$. AND CALCULATE $<\hat{\zeta}^3(t)>$, AND THE NON-GAUSSIANITY PARAMETER f_{NL}.

- t IS ARBITRARY, UNLIKE IN THE δN FORMALISM WHERE t ~ TIME OF HORIZON EXIT SO AS TO STUDY POSSIBLE GROWTH AFTER HORIZON EXIT

CALCULATION OF THE 3-POINT FUNCTION OF $\zeta(k)$ AND f_{NL}

$< (\hat{\delta\phi})^3 >$ IN THE $\delta\phi \neq 0$ GAUGE, FOR CUBIC NEW INFLATION $V(\phi) = V_0 - \mu\, \phi^3$.

$$\langle \hat{\varphi}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3 \right] \right\rangle$$

$$\varphi \equiv \delta\phi \text{ AND } \phi(x,t) = \phi(t) + \varphi(x,t)$$

TO OBTAIN H_I WITH CUBIC INTERACTION TERMS

$$S[\varphi, \dot{\varphi}] = S_2 + S_3$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

< $(\hat{\delta\phi})^3$ > IN THE $\delta\phi \neq 0$ GAUGE, FOR CUBIC NEW INFLATION $V(\phi) = V_0 - \mu\, \phi^3$.

$$\langle \hat{\varphi}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3 \right] \right\rangle \qquad \varphi \equiv \delta\phi$$

$$S_3 = \int dt\, d^3x\, a^3 \left[-\frac{\dot{\varphi}}{4H} \varphi \dot{\varphi}^2 - \frac{1}{a^2} \frac{\dot{\phi}}{4H} \varphi (\partial_i \varphi)^2 + \frac{\dot{\phi}}{2H} \partial_i \varphi (\partial_i^{-1} \dot{\varphi}) \dot{\varphi} - \frac{1}{6} V'''(\phi) \varphi^3 \right]$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle\hat{\varphi}(t)^3\rangle = i\int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3\right]\right\rangle$$

$$1.\ H_I = \frac{\dot{\varphi}}{4H}\varphi\dot{\varphi}^2$$

$$I_1 = -2 \times \frac{1}{4}\frac{H^3(\tau)}{\prod_i(2k_i^3)}(2\pi)^3\delta^3\Big(\sum_i \vec{k}_i\Big)\dot{\phi}(\tau)\left[\frac{k_2^2k_3^2}{k_t} + \frac{k_1k_2^2k_3^2}{k_t^2} + \text{perm}\right]$$

τ IS THE CONFORMAL TIME

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle \hat{\varphi}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3 \right] \right\rangle$$

$$2.\ H_I = \frac{1}{a^2} \frac{\dot{\phi}}{4H} \varphi (\partial_i \varphi)^2$$

$$\begin{aligned} I_2 &= -2 \frac{1}{4} \frac{H^3(\tau)}{\prod_i (2k_i^3)} (2\pi)^3 \delta^3 (\sum_i \vec{k_i}) \dot{\phi}(\tau) (\vec{k_2} \cdot \vec{k_3}) \\ &\quad \times \left[-k_t + \sum_{i \neq j} \frac{k_i k_j}{k_t} + \frac{k_1 k_2 k_3}{k_t^2} + \text{perm} \right] \end{aligned}$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle \hat{\varphi}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3 \right] \right\rangle$$

$$3.\ H_I = -\frac{\dot{\phi}}{2H} \partial_i \varphi (\partial_i^{-1} \dot{\varphi}) \dot{\varphi}$$

$$I_3 == 2\frac{1}{2} \frac{H^3(\tau)}{\prod_i (2k_i^3)} (2\pi)^3 \delta^3 (\sum_i \vec{k}_i) \dot{\phi}(\tau) (\vec{k}_1 \cdot \vec{k}_2) \left[\frac{k_3^2}{k_t} + \frac{k_1 k_3^2}{k_t^2} + \mathrm{perm} \right]$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle \hat{\varphi}(t)^3 \rangle = i \int_{t_0}^{t} dt' \left\langle \left[\hat{H}_I(t'), \hat{\varphi}_I(t)^3 \right] \right\rangle$$

$$4.\ H_I = \frac{1}{6} V'''(\phi) \varphi^3$$

$$I_4 = \frac{H^2 V'''}{4 \prod_i k_i^3} (2\pi)^3 \delta^3 \left(\sum_i \vec{k_i} \right) \times \left[-\frac{4}{9} k_t^3 + k_t \sum_{i<j} k_i k_j + \frac{1}{3} \left\{ \frac{1}{3} + \gamma + \ln |k_t \tau| \right\} \sum_i k_i^3 \right]$$

IS EULER’S CONSTANT = 0.577216

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle\hat{\varphi}(\vec{k}_1,t)\hat{\varphi}(\vec{k}_2,t)\hat{\varphi}(\vec{k}_3,t)\rangle = (2\pi)^3\delta(\vec{k}_1+\vec{k}_2+\vec{k}_3)$$

$$\times\left[\frac{H^2V'''}{4\prod_i k_i^3}\left(-\frac{4}{9}k_t^3+k_t\sum_{i<j}k_ik_j+\frac{1}{3}\left\{\frac{1}{3}+\gamma+\ln|k_t\tau|\right\}\sum_i k_i^3\right)\right.$$

$$\left.+\frac{H^4}{8\prod_i k_i^3}\frac{\dot{\phi}}{H}\left(\frac{1}{2}\sum_i k_i^3-\frac{4}{k_t}\sum_{i<j}k_i^2k_j^2-\frac{1}{2}\sum_{i\neq j}k_ik_j^2\right)\right]$$

$i,j=1,2,3,\ k_i=|\mathbf{k}_i|$ $\quad$ $k_t = \Sigma\, k_i$, k_i APPROX EQUAL

SEERY, LIDSEY (PI w/o SELF INTER), SEERY ET AL (HEIS. FIELD EQS)

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\zeta(\mathbf{k},t) = -\frac{1}{\sqrt{2\epsilon}}\varphi(\mathbf{k},t)$$
$$+\frac{1}{2}\left(1-\frac{\eta}{2\epsilon}\right)\int\frac{d^3q}{(2\pi)^3}\,\varphi(\mathbf{k}_1-\mathbf{q},t)\varphi(\mathbf{q},t)+\cdots$$

[GAUGE TRANSFORMATION - MALDACENA 2003]

$$\langle\hat{\zeta}(\mathbf{k_1},t,)\hat{\zeta}(\mathbf{k_2},t)\hat{\zeta}(\mathbf{k_3},t)\rangle = -\frac{1}{(2\epsilon)^{\frac{3}{2}}}\langle\hat{\varphi}(\mathbf{k_1},t)\hat{\varphi}(\mathbf{k_2},t)\hat{\varphi}(\mathbf{k_3},t)\rangle$$

$$+\frac{1}{2\epsilon}\frac{1}{2}\left(1-\frac{\eta}{2\epsilon}\right)\langle\hat{\varphi}(\mathbf{k}_1,t)\hat{\varphi}(\mathbf{k}_2,t)\int\frac{d^3q}{2\pi^3}\hat{\varphi}(\mathbf{k}_3-\mathbf{q},t)\hat{\varphi}(\mathbf{q},t)+\mathrm{perm}\rangle$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\langle \hat{\zeta}(\mathbf{k}_1, t)\hat{\zeta}(\mathbf{k}_2, t)\hat{\zeta}(\mathbf{k}_3, t)\rangle \equiv (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \frac{6}{5} f_{NL} \sum_{i<j} P_\zeta(k_i) P_\zeta(k_j)$$

$$i, j = 1, 2, 3, \ \ k_i = |\mathbf{k}_i|$$

CURVATURE POWER SPECTRUM $\quad P_\zeta(k) = \frac{1}{2\epsilon} \frac{H^2}{2k^3}$

$$\langle \hat{\zeta}(\mathbf{k})\hat{\zeta}(\mathbf{k}')\rangle = (2\pi)^3 \delta^3(\mathbf{k} + \mathbf{k}') P_\zeta(k)$$

$$\left[(k^3/2\pi^2) P_\zeta(k) \right]^{\frac{1}{2}} = 5 \times 10^{-5}$$

CALCULATION OF THE 3-POINT FUNCTION OF ζ(k) AND f_{NL}

$$\frac{6}{5} f_{\rm NL}(k_1, k_2, k_3, t) = \underline{\xi} \left[\frac{1}{3} + \gamma - \underline{\mathbf{N_e}} + \frac{3}{\sum_i k_i^3} \left(k_t \sum_{i<j} k_i k_j - \frac{4}{9} k_t^3 \right) \right]$$

$$+ \frac{3}{2}\epsilon - \underline{\eta} + \frac{\epsilon}{\sum_i k_i^3} \left(\frac{4}{k_t} \sum_{i<j} k_i^2 k_j^2 + \frac{1}{2} \sum_{i \neq j} k_i k_j^2 \right)$$

$k_t = \Sigma\, k_i$, k_i APPROX EQUAL

FOR $n_s = 0.96$, **$\eta = -0.02$**. $\xi = 0.5\,\eta^2$. **$\xi N_e = 0.012$, $\varepsilon \ll \xi N_e$**

SO THE SELF INTERACTION CONTRIBUTION ~ ξ SHOULD NOT BE IGNORED OUTRIGHT

d f_{NL} /dt

- f_{NL} IS A FUNCTION OF OF $N_e(t) = H\,(t - t_{exit})$, AND $\varepsilon(t)$, $\eta(t)$, $\xi(t)$.

- DOMINANT CONTRIBUTION TO f_{NL} IS

$$f_{\rm NL} \approx \frac{5}{6}\left[-\xi N_e - \eta\right]$$

$$\frac{d}{dt} f_{\rm NL} \approx \frac{5}{6}\,\frac{d}{dt}\left[-\xi N_e - \eta\right]$$

d f_{NL} /dt

- f_{NL} IS A FUNCTION OF OF $N_e(t) = H\,(t - t_{exit})$, AND ε(t), η(t), ξ(t).

$$\frac{d}{dt} f_{\rm NL} \approx \frac{5}{6}\frac{d}{dt}[-\xi N_e - \eta]$$

$$\frac{d\eta}{dt} \simeq [\,2\epsilon\eta - \xi\,]\,H \quad \text{AND} \quad \frac{d\xi}{dt} \simeq [\,4\epsilon\xi - \eta\xi\,]\,H$$

$$\begin{aligned} \frac{d}{dt} f_{\rm NL} &= 5/6\,[-\xi H + \xi H] \\ &= 0 \end{aligned}$$

SIMILAR TO SEERY, MALIK, LYTH (2008)

$d\, f_{NL} /dt = 0$

TIME EVOLUTION OF f_{NL} DUE TO SELF INTERACTIONS IS CANCELLED BY CONTRIBUTION OF OTHER TERMS FROM COSMOLOGICAL PERT. THEORY.

THUS THE TOTAL 3-POINT FUNCTION OF ζ DOES NOT GROW OUTSIDE THE HORIZON.

CONCLUSION

- THE ARGUMENT THAT ONE SHOULD IGNORE THE CONTRIBUTION OF SELF INTERACTIONS TO f_{NL} HAS BEEN RE-EXAMINED

- GROWS OUTSIDE THE HORIZON ~ N_e

- WE CALCULATE $< \hat{\zeta}^3 (t) >$ TO STUDY SUPERHORIZON EVOLUTION

- GROWTH DUE TO SELF INTERACTIONS IS CANCELLED BY GROWTH IN OTHER TERMS IN f_{NL}

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THANK YOU