Novel LSS/CMB non-Gaussianities from Instabilities, Entropy Generation & Particle Creation During and After Inflation

Simons Foundation Modern Inflation group - b2fhms & Eva Silverstein+ & Dan Green+ & Matias & Liam & Raphael &..

Dick Bond @ Elmau 19 05 17

**varieties of primordial nonG and how to search for them: via Prominences**
**prominence-cluster expansion:** Everest, .., Mauna Kea/Loa - apply to the $\zeta$-super-web + fluctuation-field linear response

Prominences may be peaks, halos, void centres, etc. $X_c$ may be in real-space $x_c$, in k-space $k_c$ or in field-space $\chi_c$ or in coupling-space $g_c$.
during inflation intermittent prominence instabilities => entropy => nonG

$\Delta \zeta(\tau), \Delta \phi_{\parallel}(\tau), \Delta \phi_{\perp}(\tau)$ trajectory differences for $\Delta V = V_{\text{tot}} - V_{\text{reference}}$

standard linear stochastic feedback + nonlinear. a coarse-grain/ fine-grain split

$$\frac{d\zeta}{dt} = \sum_i \frac{\nabla \dot{\phi}_i \cdot \nabla \phi_i + \dot{\phi}_i \nabla^2 \phi_i}{3 \alpha^2 (\rho + P)}$$
During inflation - mass-spin memory in nonG nima, juan, 

\[ Nima + \frac{dV}{dt} \approx - \frac{2m^2}{\lambda^2} V \]
the true quadratic \(\zeta\)-Websky of the \(\zeta\)-scape

Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + BAO

\[ \Delta \phi/M_P < 0.09 \Delta \ln k \]

95%CL with \(k \sim H_\alpha\)

\(\Rightarrow\) little info on the \(V\)-surface over the observable range

Anomalies in CMB TT power: \(L \sim 20-30\) dip

\(\Rightarrow\) \(\zeta\)-k-dip \(\sim 2\sigma\)

\(\zeta\) spectra

\(< 1.3\% - 1.7\%\) isocurvature role

GW spectra

\(95\%\)CL with \(k \sim H_\alpha\)

\(\Rightarrow\) lots of room for large \(N \geq 2pt\)

\(\zeta\) \(\Rightarrow\) \(k\)-localized nonG during inflation

\(9\) e-folds

\(kd_{\text{rec}} \geq L\)
Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + BAO

\[ 10^{-4} \leq P_{\text{R,t}} \leq 10^0 \]

\[ 10^{10} \leq P_{\text{R,t}} \leq 10^2 \]

\[ \Delta \phi / M_p < 0.09 \Delta \ln k \]

Anomalies in CMB TT power: \( L \sim 20-30 \) dip

\[ \zeta - \text{dip} \approx 2 \sigma \]

95% CL with \( k \sim H_a \)

\[ \zeta - \text{surface over the observable range} \]

\[ \text{lots of room for large } N \geq 2 \text{ pt} \]

\[ \nu_s = 0.9669 \pm 0.00367 \text{ future} \pm 0.002 \text{ SO} \]

12-knot fit from \( k \sim .008 \) to .3 uniform \( n_s \) is perfect

\[ \Delta \nu_s / M_p < 0.09 \Delta \ln \nu_s \]

\[ \text{uniform } n_s \geq 0.9669 \pm 0.00367 \text{ future} \pm 0.002 \text{ SO} \]
the true quadratic $\zeta$-Websky of the $\zeta$-scape

Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + BAO

uniform $n_s=0.9669\pm.00367 \Rightarrow$ future $\pm.002$ SO

12-knot fit from $k\sim .008$ to .3 uniform $n_s$ is perfect
CMB TT power $L\sim 20-30$ dip $\Rightarrow$ $\zeta$-Spectrum $k$-dip $\sim 2\sigma$ $\ell_k \equiv kD_{\text{rec}}$

$\Delta \phi/M_P<0.09 \Delta \ln k$ 95%CL with $k\sim H_0$

$\Rightarrow$ little info on the V-surface over the observable range

Anomalies in CMB TT power: $L\sim 20-30$ dip $\Rightarrow$ $\zeta$-$k$-dip $\sim 2\sigma$

derive $V(\phi)$, $H(\alpha)$, $\varepsilon(\alpha)$

$kd_{\text{rec}} \gtrsim L$

$\Delta \phi/M_P<0.09 \Delta \ln k$

$95\%CL$ with $k\sim H_0$

$\Rightarrow$ lots of room for large $N\geq 2pt$

$\zeta \Rightarrow$ $k$-localized nonG during inflation

uniform $n_s r<0.061$

9 e-folds

GW spectra

$<1.3\%-1.7\%$ isocurvature role

TT, TE, EE + lensing + BK15 + BAO
**Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + BAO**

uniform $n_s = 0.9669 \pm 0.00367 \Rightarrow$ future $\pm 0.002$ SO

12-knot fit from $k \sim 0.008$ to 0.3 uniform $n_s$ is perfect

**Δφ/M_P < 0.09 Δlnk**
95% CL with $k \sim H_a$

$\Rightarrow$ little info on the V-surface over the observable range

**Δζ**

**TT, TE, EE + lensing + BK15 BB + BAO**

**Anomalies in CMB TT power: L ~ 20-30 dip**

$\Rightarrow \ ζ$-k-dip $\sim 2σ$

**GW spectra**

future 2σ($r$)
SO 0.006
S4 0.001
Litebird 0.002

uniform $n_s < 0.061$

**future 2σ(r)**

**GW spectra**

< 1.3% - 1.7% isocurvature role

$k d_{rec} \geq L$

**k-localized nonG during inflation**

Anomalies in CMB TT

$\Rightarrow ζ$-k-dip $\sim 2σ$

**GW spectra**

future 2σ($r$)

**GW spectra**

< 1.3% - 1.7% isocurvature role

$k d_{rec} \geq L$

**k-localized nonG during inflation**

Derive $V(\phi)$

$H(α)$

$ε(α)$

**future 2σ(r)**

SO 0.006
S4 0.001
Litebird 0.002

uniform $n_s < 0.061$
varieties of primordial nonG and how to search for them

perturbative: nonG part strongly correlated with dominant Gaussian part
see Planck 2015/2018 nonG for exhaustive study and current constraints - both with T+Epol but 18 better
local fnl* - current limit cf. fnl target < 1. & equilateral orthogonal

Planck2018 IX arxiv_1905.05697
nonG 3-point-correlation-pattern measure
f_{nl}: -0.9 ± 5.1 local for Newton potential
=> f_{NL} =-0.46 ± 3.0 for phonons/3-curvature
-f_{nl}: 26 ± 47 equilateral
-38 ± 24 orthogonal
cf. Planck2015
nonG 3-point-correlation-pattern measure
f_{nl}: 2.7 ± 5.8 local for Newton potential
=> f_{NL} =0.6 ± 3.5 for phonons/3-curvature
-f_{nl}: 42.3 ± 75.2 equilateral
-25.3 ± 39.2 orthogonal

beyond Planck2015/2018 nonG: some nonG probes in Planck 2015/2018 VII Isotropy & Statistics. main result is no strong evidence, anomalies Kolmogorov-Sinai test on n(T and E Prominences at 2 scales) OK
outside horizon (very): via stochastic inflation - huge nonG from feedback via diffusion sb90/91 semi-eternal

BBM numerical pseudo-spectral codes to correct stochastic inflation, all weakly nonlinear terms included.
all highly nonlinear terms included (post-inflation heating)
B2FHMS+C can ensemble-measure everything, N-pt, coherences!

k-localized nonG: wide open. role of instabilities during inflation to make k-localized zeta-bursts. could even make PBHs.

chain together instabilities - oscillations in power and 3-point. monodromy silverstein+ & Planck 2018 IX
- random inflaton forcing => lognormal random walks with coherence green+
explore higher N-points ⇒ anomalous tails silverstein+ approach
nonG from heating: 1 cm comoving scale ⇒ to be in observable LSS/CMB bands need modulation, but
that is natural if there are light fields (heavy fields damp power) matias

but if uncorrelated quadratic nonG suppressed by at least ~ ε^2

<ζ_{NL}|χ_{cg}+χ_{h}>~ β(χ_{h}) χ_{cg} + f(χ_{h}) χ_{cg}^2 + f_{NL}^{equiv} = f [β Pχ/Pζ,inf]^2 & Pχ/Pζ ≈ ε
B2FH target regime:
- secondary ballistic instability
- heating
- low-k modulation of nonG $k>(Ha)_{eoi}$
- relate to particle creation

B2M target regime:
- inflation instability
- primary correlated beyond stochastic inflation
- direct nonG around $\phi_p k_p H_{a_p}$
- $k$-localized nonG
- ubiquitous 2-point $k$-burst $P\zeta\zeta$
- get 3-point, 4-point bursts
- control parameters $\Rightarrow$ data-OK
- related to particle creation
- repetitive bursts?
- relation to trapped inflation …

Intermittent, secondary uncorrelated with primary $\zeta$-power more localized
$\Rightarrow$ controllable wrt data
higher order N-points evade Planck18 $f_{NL}$

apply to PBHs etc!! $\alpha=\ln(a)$

B+Braden+Frolov+Huang+Morrison
Intermittent Heating Non-Gaussian case

uncorrelated $\zeta_{GRF}$

prominences: $\zeta$-maxima in $\chi_{eo}$ field-space

$\chi_{eo}$

$\zeta$ for $g^2/\lambda=2$

$V(\phi, \chi) = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} g^2 \phi^2 \chi^2$

Chaotic Billiards: NonG from Parametric Resonance in Preheating

$\delta V = \delta v(x_0, y_0) \cdot 10^5$

Bond, Huang, Stein; Braden, Morrison, ...
Lensing of CIB COmap HImaps kSZ tSZ nonG sources through a nonG lens

\textit{Planck, AdvACT, SO, CMB-S4, CCATp, LITEBIRD}

\textit{optical/IR EUCLID, LSST, DES, DESI, SphereX, WFIRST,}

\textit{radio LIM CHIME, HIRAX, COMAP, CHORD, ... SKA}
Primordial Non-Gaussianity in CO example: the LCDM signal and 2 nonG difference maps - a movie

\[ f_{\text{nl}} = 10 \]

\[ \sigma_8 = 0.82 \]

In all cases

large scale => CHIME much larger volume is better
During inflation - instabilities => entropy => nonG

Numerical experiments of in-out states through localized ΔV. Chain together .. oscillating

Experiment χ-light

In states

Out states

Instability around $\phi_p k_p \alpha_p$

$$\frac{d\zeta}{dt} = \sum_i \frac{\nabla \dot{\phi}_i \cdot \nabla \phi_i + \dot{\phi}_i \nabla^2 \phi_i}{3a^2 (\rho + P)}$$

Bond+Braden+Morrison
$\zeta$-2pt-power

$\frac{d\langle \Delta \zeta^2 \rangle}{d \ln(\alpha)} \frac{d\langle \Delta \zeta_0^2 \rangle}{d \ln(\alpha)}$

$\alpha_p \quad \alpha = \ln(\alpha)$

$\frac{d\zeta}{dt} = \sum_i \frac{\nabla \dot{\phi}_i \cdot \nabla \phi_i + \dot{\phi}_i \nabla^2 \phi_i}{3a^2(\rho + P)}$
$\zeta$-3pt-power

big 3-point burst k-localized
also big 4-point burst ..

TBD coherence of N-point bursts in N-space ..
During inflation nonG: k-space bursts $\Rightarrow$ x-space bursts

Experiment $\chi$-light $\Delta V$ wide

$> 3\sigma$ $\zeta$-hot-spot dominance makes nonG (black)

Prominence
Cluster-expansion + fluctuations

Prominences: $\zeta$-hot-extrema in real-space lattice

cf. WMAP T-cold-spot $= \zeta$-hot-spot
During inflation nonG: k-space bursts $\Rightarrow$ x-space bursts

$> 3\sigma \, \zeta$-cold-spot + $\zeta$-hot makes nonG (black, white)

prominences:
$\zeta$-hot-cold extrema in real-space lattice

$\Delta \zeta$

prominence cluster-expansion + fluctuations

$\Delta \zeta_f$

cf. WMAP T-cold-spot = $\zeta$-hot-spot
During inflation - instabilities => entropy => non-\(G\) numerical experiments of in-out states through localized \(\Delta V\). Chain together .. oscillating around \(\phi_p k_p \alpha_p\)

Instability potential surface

Bond+Braden+Frolov+Morrison

\[
\frac{d\zeta}{dt} = \sum_i \frac{\nabla \phi_i \cdot \nabla \phi_i + \dot{\phi_i} \nabla^2 \phi_i}{3a^2 (\rho + P)}
\]

Trapped potential surface

Trapped inflation: same parameters, no instability

.. Kofman, Silverstein, Green, Barnaby, Huang, many more
During inflation nonG: k-space bursts $\Rightarrow$ x-space bursts

$\Delta \zeta$-heavy $\Delta V$ wide

$> 3\sigma \; \zeta$-hot-spot dominance makes nonG (black)

Prominences: $\zeta$-hot-extrema in real-space lattice

Prominence cluster-expansion + fluctuations

cf. WMAP T-cold-spot $= \zeta$-hot-spot

$\Delta \zeta_f$
during inflation nonG:
k-space bursts $\Rightarrow$ x-space bursts

$\Delta \zeta$-heavy $\Delta V$ narrow

$> 3\sigma \zeta$-cold-spot $+ \zeta$-hot
makes nonG (black, white)

prominence cluster-expansion $+$ fluctuations

prominences:
$\zeta$-hot-cold extrema in real-space lattice

cf. WMAP $T$-cold-spot
$= \zeta$-hot-spot
Planck 2018 VII Isotropy & Statistics E-polarization normal in the T-anomalies

A&A accepted in Mar, press release then ArXiv

consistent with \( \langle E|T \rangle + \delta E_{\text{fluc}} \)

many non-template nonG tests on CMB T/E, e.g., peak tests, stacking test, Gaussian OK

standard inflaton Gaussian + intermittent nonG early U preheating lattice sims

T-cold-spot as \( \zeta \)-hot-spot from heating
Beyond the Standard Model of cosmology?

\( T \)-anomalies @ low L \( \Rightarrow \) \( \zeta \)-anomalies @ low L

Sample variance limited \( \sim 2\sigma \)’s

\( <\zeta | T,E-pol> \)

**CMB** \( \sim 10,000,000 \) T/E modes of \( t\Lambda CDM \)

\( \cong 500 \) modes of anomaly

\( \cong 100 \) modes reionization history

\( CMB \) modes \( \sim f_{sky} L_{\max}^2 \)

\( LSS \Rightarrow \) tomography

\( X k_{\max} d_{\max} \)

\( >4.5\sigma \)

\( <1\% \)

L\( \sim 20 \)

LSS void?
WebSky reveals *early universe phonons*.

**ζ- TOPOGRAPHY & CARTOGRAPHY**

=> @a ~$1/10^{55}$ only 2 numbers
more: r? $n_s(k)$? nonGaussian; isocons

only partial de-lens

Planck 2018
15 arcmin fwhm

random sound loudness $P_\zeta(k_p)$+ bass/treble $n_s = 0.967 \pm 0.004$ 8.8σ from 1

visibility mask

$\int d \text{visibility}(\text{distance}) \ <\zeta | \text{Temp, E pol}>$

bond + huang 2015 ⇒ 2019
\[ \langle \zeta | \text{Temp, E pol} \rangle \] WebSky reveals early universe phonons

\[ \zeta \] - TOPOGRAPHY & CARTOGRAPHY

=> @a \sim 1/10^{55} \ only 2 numbers
more: r? \( n_s(k) \)? nonGaussian; isocons

linear map

only partial de-lens

Planck 2018
15 arcmin fwhm

random sound loudness \( P_{\zeta}(k_p) \) + bass/treble \( n_s \) = 0.967\pm0.004
8.8\sigma from 1

visibility mask

\[ \int d \text{visibility(distance)} \] \[ \langle \zeta | \text{Temp, E pol} \rangle \] 

bond + huang 2015 => 2019
real $\zeta$-WebSkys mean field

visibility mask

real $\zeta$-WebSkys with fluctuations

zoom in, higher res: 20 arcmin fwhm

20x20 sq deg

real $\zeta$-WebSkys stacked to damp fluctuations

$<\zeta | \zeta pk > | dv$

similar to -Gravitational Potential WebSkys

oriented stacks, etc.

bond + frolov + huang 2019
Novel LSS/CMB non-Gaussianities from Instabilities, Entropy Generation & Particle Creation During and After Inflation

simulate ensembles in early U inflation & through to End-to-End tests of CMB+LSS experiments - augments analytics, measure local response functions for analytics

Dick Bond @ Elmau 19 05 17

varieties of primordial nonG and how to search for them: via Prominences

\[ \zeta(x,t) = \int_{\text{field-path}} \frac{(dE+pdV)}{(E+pV)} \sim dS/\beta(E+pV) = \text{Trace } \alpha^i_j + \int_{\text{path}} d\ln \rho_{Ec} / (1+w_c) \]
END of Bond's time