a highly strained & stressed state in the universe at large (very, very), randomly simple in our Hubble patch, and highly entangled in the small to medium scale.
Dick Bond CITA & CIFAR: Aspects of Inflation $\zeta$-Phenomenology

SuperWeb: a highly strained & stressed state at large (very), randomly simple in our Hubble patch, and (now) highly entangled in the small to medium scale.

Quantum tunnels = bubbly-U

Topography of the $\zeta$-scape = entropy-scape

Phonons

Gravitons

$\zeta$-maps / trajectories

Dark Energy / modified gravity Trajectories

$\sim e^{\pm}$

Post-inflation Matter & Entropy

Our horizon

$\sim e^{-7}$

$\sim e^{0}$

$\sim e^{-67}$

$\sim e^{-127}$

$\sim e^{-132}$

$\sim e^{-170}$

Stochastic Inflation

$\sim e^{-10}$

$\sim e^{-5}$

$\sim e^{-0.5}$

$\sim e^{-0}$

$\sim e^{0.5}$

$\sim e^{5}$

$\sim e^{10}$
ζ & entropy & adiabatic trajectories

stochastic “coarse grain” S

ballistics caustics corrugated shock-in-time

⇒ S intermittent nonG

CMB: std inflaton ζ + subdominant uncorrelated ζ from modulated preheating

LSS tSZ: Gaussian std

LSS tSZ: Gaussian std + subdominant uncorrelated ζ

BBFH, b+braden+frolov+huang

ABSB+FH, alvarez+b+stein+frolov+huang
the Super-WEB aka the primordial 3-curvature web aka the phonon/isotropic strain = volume deformation web

\[ \ln \rho(x,t)/\langle \rho \rangle |_\nu \]

\[ \ln V/\langle V \rangle |_\rho = 3 \ln a(x,t)/\langle a \rangle |_\rho \]

\[ d\zeta \sim T dS / 3(E+PV) \]

\[ \zeta(x,t) = \int (dE+pdV)/E/\langle 3(1+p/\rho) \rangle(t) \]

\[ \zeta(x,t) = \ln \rho(x,t)/\langle 3(1+p/\rho) \rangle(t) + \int (1+p/\rho)(x,t) \ln a(x,t)/\langle 1+p/\rho \rangle(t) \]

or: \[ \zeta(x,t) = \ln \rho(x,t)/\rho_b / 3(1+p_b/\rho_b) + \ln a(x,t)/a_b \]

gradient / Morse flow + stochastic jitter, simple Hamilton principle function \( S \sim H(\phi_b) \)
along coarse-grain trajectories \( d\zeta = d\ln \rho/\rho_b / 3(1+p/\rho) + d\ln a/a_b = [d \bar{\zeta}](fg\rightarrow cg) \)
early preheating: gradient / Morse flow, complicated Hamilton principle function \( S \)
ballistic / caustic phase => \( \Delta S \) nonlinear \( \zeta \) lattice sims

cf. late-time density web ~ strain web - \( \ln \rho/\langle \rho \rangle = \text{Trace } \ln e^{-j} = \ln V/\langle V \rangle |_\rho \)
cold \( <p/\rho> \sim 0 \Rightarrow \zeta(x,t|cdm) \) conserved before shell crossing (preheating)
Reconstructing the Early Universe

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

\[ \zeta_{NL} = \ln\left( \frac{\rho a^{3(1+w)}}{3(1+w)} \right) \leq dE + pdV \sim d\text{Entropy} \]

linear map

caution: not de-lensed

phonons / strain

sb89, bb15

40 arcmin fwhm

visibility mask
Beyond the Standard Model of cosmology? \( S_M^c = \text{tilted } \Lambda \text{CDM} + r \left( \zeta, h^+_x \right) \)

\( BSM_c = S_M^c + \text{primordial anomalies} \)

\( \langle \zeta | T, E\text{-pol} \rangle \)

octupole/quadrupole alignment

dipole modulation/ asymmetry direction

the rare cold spot

GUTA = Grand Unified Theory of Anomalies? TBD

intermittent?

\( > 4.5\sigma \)

\( < 1\% \)

L~20

LSS void?
ζ-Maps of the Early Universe

A map is an ensemble = mean-map + fluctuation-maps, encoding correlated errors.

Maps = (radical) compressions of the time ordered information ToI onto a parameterized space \( q^A \): Linear maps, Quadratic maps (power), cosmic parameter maps.

\[ \text{Prob}(q|\text{Data, Th prior}) \Rightarrow <q^A|D,Th>, <\Delta q^A\Delta q^B|D,Th>,.. \text{ or } q_{\text{maxL}} \]

TOPOGRAPHY & CARTOGRAPHY of our Hubble-patch aka our bit of the universe

reconstructing \( \zeta = \ln a(x,t) @\text{uniform density} \), aka primordial scalar curvature \((^3R = -4)^3\Delta \ln a\)

Wiener-filtered \( \zeta \) maps make \( \zeta_{\text{LM}}(\chi), \chi = |x| \) instead of \( \zeta(x) \)

\[ T_{\text{LM}c,s} / E_{\text{LM}c,s} = \int e^{\zeta T/E}_{L\chi c,s} \zeta_{\text{LM}c,s}(\chi) \, d\chi, \text{ susceptibility } e \text{ depends on cosmic parameters} \]

\[ \Rightarrow \text{Linear response} \quad \zeta_{\text{LM}c,s}(\chi) = e^{*}\xi^T_{L\chi c,s} T_{\text{LM}c,s} + e^{*}\xi^E_{L\chi c,s} E_{\text{LM}c,s} + \delta \zeta_{\text{LM}c,s} \]

susceptibility of \( \zeta \) to \( T/E \): \( e^{*}\xi^{T/E}_{L\chi} \) interpolates \( T/E \) to \( \zeta \), if no info relax to \( \delta \zeta \)

project \( \zeta \) to minimize fluctuations: \[ \int \text{visibility(distance)} \left( <\zeta | \text{Temp, E pol}> + \delta \zeta \right) \]
allowed fluctuations are less noisy with E pol (extra mode/LM)

caution: not de-lensed, but the Wiener filter does partially de-lens
the unexplorable \( \zeta \)-scape, explore with landscape++ ideas our Hubble Bit will reveal all?

- Colour code Effective Noise
  \[ \left[ \frac{C_\zeta_L(T\text{-constrained})}{C_\zeta_L(\text{free})} \right]^{1/2} \]

- The vast CMB-un-illuminate \( \zeta_{LM}(d) \)

- **CMB** \( \sim 10,000,000 \ T/E \) modes of \( t\Lambda \text{CDM} \)
  \( \approx 500 \) modes of anomaly
  \( \approx 100 \) modes reionization history

- Explorables with CMB & Xcorr

- **DECOUPLING**

- Differential Visibility

- LENSing

- **CMB modes**
  \( \sim f_{\text{sky}} L_{\text{max}}^2 \)
  **LSS tomography**
  \( X k_{\text{max}} d_{\text{max}} \)

- **S/N**
  \[ [S/N]^T_L(\chi) = \frac{\rho}{\sqrt{1 - \rho^2}}; \rho \equiv \frac{C_L^{TT}(\chi)}{\sqrt{C_L^{TT} C_L^{EE}(\chi, \chi)}} \]
Reconstructing the Early Universe

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

\[ \zeta_{NL} = \ln \left( \frac{\rho a^{3(1+w)}}{3(1+w)} \right) \leq dE + pdV \sim d\text{Entropy} \]

\[ \text{phonons / strain} \]

linear map

\[ \zeta | T, E : \]

caution: not de-lensed

20x20 sq deg
20 arcmin fwhm

visibility mask
allowed fluctuations are less noisy with E pol (extra mode/LM)

caution: not de-lensed, but the Wiener filter does partially de-lens
SIMPLICITY
at $a \sim e^{-7} \sim 1/1100$ =>

stacked linear map aka
mean-field map

stacked

< $\zeta_{d\nu} \mid \zeta_{d\nu-pk}$>

20857 patches on $\zeta$ maxima, random orientation, threshold $\nu=0$

Planck2015 early U structure map
reveals primordial sound waves in matter
=> learn contents & structure at 380000 yr, $a \sim e^{-7}$

=> infer the sound structure far far earlier $a \sim e^{-67-60}$

2$^+$ numbers

stacked

< $\zeta_{d\nu} \mid$ oriented $\zeta_{d\nu-pk}$>

20854 patches on $\zeta$ maxima, oriented, threshold $\nu=0$

$\zeta$ stacks of P13 & WMAP9 look similar
simulations look very similar

BFH, b+frolov+huang
quadratic map of the $\zeta$-scape even more (radical) compression in quadratic space, using Planck likelihood rather than linear ($\langle \zeta | \text{Temp, E pol} \rangle + \delta \zeta$) maps, e.g., onto 12 bands in k-space (LM projection) => a quadratic map, fully includes lensing & BB from BKP

the exploration of the $L=20-30$ anomaly will improve in Planck2017 + BICEP/KECK2017 + Spider 201x

uniform $n_s=0.968$

P15+LSS best fit

superb 12-knot fit $k \sim 0.008$ to 0.3

$r < 0.11$ 95%CL cf.

$r < 0.09$ uniform $n_s$

9 e-folds

$k d_{\text{rec}} \gtrsim L$

$\ell_k \equiv k D_{\text{rec}}$

EE ($L > 30$) looks similar => a quadratic map, fully includes lensing & BB from BKP

Grand Unified $\zeta$ Spectra

Grand Unified GW Spectra

PlanckTT lowP BAO (+JLA+HSTlow), $z_{\text{re}} > 6$
trajectories of $\mathcal{D}_{\ell}^{TT,L}$
cf. Planck 2014 Commander Low L spectrum with Blackwell-Rao errors

12 knots, cubic spline

running of $P_\zeta$
$\equiv 3$ Chebyshev modes
$\Rightarrow$ very stiff
$\Rightarrow$ not what the data wants
Lower $\tau \Rightarrow$ shape similar to running at low $L$
similar response on $\mathcal{D}_{TT,L}$
for constrained & free $r$
modified by $\tau$ freedom

running of $P_\zeta$
NOT wanted

the down-up-down tendency
is here to stay,
2014-2022-...
Inflaton \( V(\phi) \)-maps = \( 3M_p^2 H^2 (1-\epsilon/3) \) HJ eqn, \( d\phi/M_p/d\ln a = \pm \sqrt{2\epsilon} \)

Along the gradient / Morse flow

\[
\ln \langle V(\phi) \mid r \rangle \text{ BKP}
\]

\[
\ln(\delta V(\phi) + \langle V(\phi) \mid r \rangle \text{ BKP})
\]

IR heating region is far off => many ways to extrapolate

TT+BKP+low-z, 12 knots

UV region far off => many ways to extrapolate

r to +0.02 Spider forecast

r to +0.003 AdvACTpol forecast w/ fgnds
Planck 2015+BKP+LSS

\[ \varepsilon = \frac{3(1+w)}{2} \]

\[ \approx r(k)/16 \]

\[ \approx \mathcal{P}_{GW}/\mathcal{P}_\zeta \]

\[ \ell_k \equiv kD_{\text{rec}} \]

\[ \varepsilon(\ln H_a) = -\frac{d\ln \rho}{d\ln a}/2 \]

\[ \delta \varepsilon + \langle \varepsilon | r \text{ float} \rangle \]

\[ \langle \varepsilon | r \text{ float} \rangle \]

\[ H_a \sim k \]

\[ 9 \text{ e-folds} \]

\[ -n_t \approx r/8 \approx 2\varepsilon(k) \]

\[ 1-n_s \approx 2\varepsilon + \frac{d\ln \varepsilon}{d\ln H_a} \]
Will any Anomalies in the CMB or Tensions with the CMB turn into BSMc Subdominant Physics?

Planck2015+LSS some tension released. still Ho tension but not bad agreement+a bright future
Galaxy Lensing tension persists, systematics? CMB lensing $A_L$
Cluster $\sigma_{8SZ}$ cf $\sigma_{8\text{primary}}$ tension relaxing, with large $KE_{\text{bulk}}/KE_{\text{thermal}}$ corrections, hydro expected tho
Beyond the Standard Model of cosmology? \( \text{SMc} = \text{tilted} \Lambda \text{CDM} + r (\zeta, h_x) \)

BSMc = SMc + primordial anomalies
\(~10,000,000 \ T/E \text{ modes} = t \Lambda \text{CDM}, \lesssim 500 \text{ modes of anomaly}\)

vast unexplored parts of the \( \zeta \)-scape CMB is 2D

hope to use 3D \( \text{LSS} \) tomography \( f_{\text{sky}} L_{\max}^2 k_{\max} d_{\max} \)

CMB TT power \( L \sim 20-30 \) dip =>

Grand Unified \( \zeta \)-Spectrum \( k \)-dip

hemisphere difference in TT power \( \sim 7\% \) at low resolution

zero-ish \( C(\theta) > 60^\circ \)

sigh, Mother Nature puts her Anomalies @ low \( L \) where sample variance obscures => tantalizing \( \sim 2\sigma \)'s?
if a GUTA then maybe \( >> 2\sigma \)?

GUTA = Grand Unified Theory of Anomalies? TBD intermittent?
looking at the CMB cold spot again as an anomaly example

$>4.5 \sigma < 1\% \ L \sim 20 \ ..... \ \text{LSS void?}$

B+Huang tried hard to make a GUTA = Grand Unified Theory of Anomalies? new ways of looking at the anomalies (comparing harmonic and real space in various ways) but no GUTA ... TBD
the rare cold spot
no cold spot
cold spot emerges between $L_s=6$ and $L_s=20$
cold spot prominent in the difference map $L_s=6$ to $L_s=20$
tantalizing that the cold spot is the same L-band range as the Lensed dip, but all of our tools have not teased out a relation

B+Hu 2015

e.g. low L constrained fields do not make a nice low-L cavity for the cold spot to be boosted up

cold spot statistics same as in P15 I & S, here in bands between \( L_s = 20 \) and \( L_s = 40 \)
how intermittency could amplify the cold spot to statistical correctness

from $>4.5\sigma$ Gaussian random field anomaly
Planck 2015 XVII nonG

\[ \xi_{T,E}(\delta \zeta) \]

intermittent nG from early U preheating sims - too small

5deg fwhm

also cf. quadratic nG:
correlated fNL
uncorrelated large fNL_{eff}

scan sims to get chance intermittent alignment to get a “cold spot”

5deg fwhm

intermittent nG from early U single spike sims - tunable amplitude, get the “cold spot”

40 arcmin fwhm

caution: not de-lensed
Single Gaussian Spike intermittent nonG Model. one of 32 random choices to yield chance cold spot constructive interference.
Single Gaussian Spike
intermittent nonG
Model: 3 parameters
caustics in ballistic orbits
caustics are ubiquitous: LSS/cosmic web & preheating
\[ V(\phi, \chi) = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} g^2 \phi^2 \chi^2 \]

\( V_{\text{eff}} \) is trajectory dependent.
The nonlinearly-arrested caustic structure of ballistic $k=0$ trajectories can be described by the potential $V(\phi, \chi) = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} g^2 \phi^2 \chi^2$. This is illustrated in the gigafigure of lattice simulations, which shows a computational tour de force.
arresting the caustic orbits via a shock in time, incoherent cf. coherent trajectory bundles

understanding the $\zeta$-spike structure, qualitatively YES and quantitatively MAYBE
nonG from large-scale modulations of the shock-in-times of preheating

entropy production
info-content in phonons

\[ \text{true thermal equilibrium far off} \]
& on to coupling to standard model degrees of freedom

\[ \zeta_{NL} = \ln (\rho a^{3(1+w)}) / 3(1+w) \]
adiabatic "invariant" = curvature fluctuations

\[ \delta \zeta_{NL\text{shock}} (g(\sigma(x))) \Rightarrow \text{modulated non-G} \]

\[ V(\phi, \chi) = \frac{1}{2} m^2 \phi^2 + \frac{1}{2} g_{\text{eff}}(\sigma)^2 \phi^2 \chi^2 \]

\[ \delta \zeta_{NL\text{shock}}(\chi_i(x) | g^2/\lambda)) \Rightarrow \text{NonG cold spots} ++ \]

\[ V_{\text{eff}} \text{ is dynamical} \]

unconventional local non-G: no scale built into \( V \);
perturbative isocon-based \( f_{NL} \); rare event cold spots
nonG from large-scale modulations of the shock-in-times of preheating

entropy production
info-content in phonons
- \( \ln [\rho \ V/E] \)

\[ \zeta_{NL} = \ln \left( \rho \ a^{3(1+w)} \right) / 3(1+w) \]

adiabatic "invariant"
= curvature fluctuations

\[ \delta \zeta_{NL_{\text{shock}}} (g(\sigma(x))) \Rightarrow \text{modulated non-G} \]

\[ V(\phi,\chi) = 1/2 \ m^2 \phi^2 + 1/2 \ g_{\text{eff}}(\sigma)^2 \phi^2 \chi^2 \]

\[ \delta \zeta_{NL_{\text{shock}}} (\chi_i(x) | g^2/\lambda)) \Rightarrow \text{NonG cold spots ++} \]

\[ V(\phi,\chi) = 1/4 \ \lambda \phi^4 + 1/2 \ g^2 \phi^2 \chi^2 \]

\[ V_{\text{eff}} \text{ is dynamical} \quad \text{Bond, Braden, Frolov, Huang17} \]

unconventional local non-G: no scale built into \( V \);
perturbative isocon-based \( f_{NL} \); rare event cold spots

\[ g_0 + g_1 \ \sigma/M_P, g_0 \exp[\gamma_1 \ \sigma/M_P], .. \]

\[ a = 60.1 \]
ballistic billiards \( k=0 \) mode phase space string evolution.

stopping criterion when coarse-grained entropy of field variables rises

\[ V = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} g^2 \phi^2 \chi^2 \]
caustics are ubiquitous
calculating ballistic evolution to caustics gives the spikes in good agreement with full nonlinear lattice simulations

\[ \frac{1}{\partial \ln a / \partial \chi_i(x)} \]

\( B2FH, b+braden+frolov+huang \)

nonG from post-inflation but pre-entropy generation ballistic trajectories can lead to pre-shock-in-time caustics and other phase space convergences in the deformations (!) Zeldovich map-ish

eg \( \partial \ln a / \partial \chi_i(x), \partial \ln a / \partial g(x) \Rightarrow P[\ln a(x), t_{\text{shock}} \mid \chi_i(x), g(x), t_{\text{end-of-inflation}}] \)
phase string growth in time
“parameter strain rate”
how modulated caustics in preheating could give observable intermittency
modulating the caustics on large scales & super-horizon scales via isocons
ULSS modulation beyond our Hubble patch

LSS modulation within our Hubble patch

preheating horizon scale < comoving cm

$$\delta \zeta_{NL_{\text{shock}}}(\chi_i(x) | g^2/\lambda)$$

=> NonG cold spots ++
how generic will caustic preheating be? structure around minima: filamentary potentials define channels multi-filaments may lead to caustics
modulating post-inflation entropy generation shocks via long range fields

$\chi(x)$

How generic is the intermittent caustic phenomenon? Holds for many basin potentials at the end of inflation. but not if rapid heating

or $g(\sigma(x))$

or...

$\phi$

inflaton

pre-heating patch (~1cm)

$\chi_{ini}=3.6 \times 10^{-7} M_p$

$filaments!$

$V(r,\theta)=\sum_M V_M(r) \cos(m\theta)$ pNGB, Roulette r~hole size

$3D \phi \chi \sigma$ fields $V(r,n)=\sum_{LM} V_{LM}(r)Y_{LM}(n)$

$V(\phi,\chi)=1/4 \lambda \phi^4 - 1/2 \xi \phi^2 R + 1/2 g^2 \phi^2 \chi^2$

conformally transformed potentials a la Higgs/R$^2$, modified kinetic terms, flattened potentials of all sorts
mocking heaven to explore 3D intermittency from modulating preheating, bubble collisions, etc.

a quest for the apparent breakdown of LSS homogeneity - but NOT
Mocking Heaven @ CITA Alvarez Bond Stein Battaglia ..

Peak Patch Full Sky Models for Planck, AdvACT, SO, CMB-S4, CCATp, CHIME, HIRAX, SKA, COMAP, EUCLID, LSST, …

need End to End mocks, fully correlated to draw out: BSMc, DE/modG, Mnu, nonG (correlated, uncorrelated, intermittent),…

Planck 2015 XII: Full Focal Plane Sims (Nov): FFP8 ensemble of 10K EndtoEnd mission realizations in 1M maps. instrument noise + CMB + PSM + .. (25M NERSC CPU hrs)
Compton Scattering (Sunyaev-Zeldovich) Simulations for ACT, Planck, Simons Obs & CMB Stage 4 Cluster Observations
Using high res Gas Hydro Sims

0.00 < z < 1.25
8Gpc, 4096^3 Box

HI Intensity Mapping simulations of CHIME / HIRAX ..
z=0.8-2.5, ~(8 Gpc)^3
Compton Scattering (Sunyaev-Zeldovich) Simulations for ACT, Planck, Simons Obs & CMB Stage 4 Cluster Observations

Using high res Gas Hydro Sims

0.00 < z < 1.25
8Gpc, 4096³ Box

HI Intensity Mapping simulations of CHIME / HIRAX ..
z=0.8-2.5, ~ (8 Gpc)³

Gaussian

6 deg

δT_b [μK]

δ = 0.81, ν = 784.11, δν = 0.39
Compton Scattering (Sunyaev-Zeldovich) Simulations for ACT, Planck, Simons Obs 
& CMB Stage 4 Cluster Observations Using high res Gas Hydro Sims

0.00 < z < 1.25
8Gpc, 4096^3 Box

tSZ

HI

HI Intensity Mapping simulations of CHIME / HIRAX .. 
z=0.8-2.5, ~ (8 Gpc)^3

0.1 < z < 1.25
8Gpc, 4096^3 Box

0.81, ν = 784.11, δv = 0.39

f_{NL} = 25

correlated Quadratic nonG

6 deg

ABS&B+FH, alvarez+b+stein+frolov+huang
Compton Scattering (Sunyaev-Zeldovich) Simulations for ACT, Planck, Simons Obs & CMB Stage 4 Cluster Observations

Using high res Gas Hydro Sims

$0.00 < z < 1.25$
8Gpc, $4096^3$ Box

HI Intensity Mapping simulations of CHIME / HIRAX .. $z=0.8-2.5$, $\sim(8 \text{ Gpc})^3$

$z=0.81, \nu =784.11, \delta \nu =0.39$

Gaussian Spike

uncorrelated modulated preheating intermittent nonG

$\delta T_b [\mu \text{K}]$

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

$\nu^2 T_b$
this is a very quantitative exercise
e.g., response of BAO and biasing of halos to forms of nonG - correlated cf. uncorrelated, intermittent cf. perturbative
e.g., search for rare superBIAS events > supercluster-scale
intermittent nG from early U single spike

Positive Curvature: Overabundance of Negative Extrema
cf. fit to N-body results: without any tuning it comes out from peak patches naturally

\( P_{hh}(k) = b_1^2 \left[ 1 + b_2^2 k^2 \right] P_{\text{lin}}(k) \)
highly nonlinear field evolutions happened (EoI, bubble collisions)!

*amusing subdominant patterns do arise!*

lead to observable rare-event CMB/LSS anomalies?

light isocons cf. heavy isocons, the heavy can lighten up = original SBB nG
isocon modulators, coupling(isocon) modulators, isocon tunneling, isocon oscillons, isocon short-lived fuzzy-strings, + very long-lived strings

or just to weak constraints on multifield potentials,
>horizon fields, nucleation rates, etc.

*a 2-number $A_s$-$n_s$ early universe so far*

intermittency frustration: statistical variance is large cf. 2-3 parameter search

CMB restricts us to a projected 2D $\zeta$-scape to reconstruct phonon/isotropic-strain power, the future may look much the same as now for $\zeta$=>potential $V(\phi)$$\Rightarrow$acceleration $\varepsilon(a)$

we mock the LSS future *end-to-end to probe the* mode-rich 3D $\zeta$-scape