Primordial Non-Gaussianity
in
Large Scale Structures

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This talk

- Many LSS surveys in the next 10 years. I'll have them in mind (e.g. Euclid, DESI, LSST, SPHEREx, …). No 21 cm.

- I could spend the next hour discussing all kinds of different models, their peculiar signature, and forecasting bounds with various experimental specs…

- …but the number of models of inflation surpasses even the number of galaxies detected in a futuristic (photometric) survey, so I won't.

- Instead I'll discuss *general lessons* we might be able to learn

- general = simple = elegant = a bunch of caveat and exceptions. Feel free to keep me honest

Primordial non-Gaussianity

- Primordial perturbations appear very simple: scalar, adiabatic, almost scale invariant and *Gaussian.*
- All we need are *two numbers*, As and ns

$$\langle\zeta(k)\zeta(k')\rangle \sim A_s \left(\frac{k}{k_*}\right)^{ns-1}$$

- I will discuss testing Gaussianity with LSS surveys

$$\zeta = \zeta_G + f_{NL}\zeta_G * \zeta_G + \mathcal{O}(\zeta_G^3)$$

The landscape

- Three PNG shapes: local, equilateral, other* [*Other = quasi-single field, features, oscillations, modification initial state, …]
- If we see actually any PNG we will all be drinking champagne and dancing naked on the roof of our respective institutions. Fun, but I won't discuss it further
- I'll focus on science goals that do not rely on "getting lucky": what do we learn in the *absence* of PNG detection?

The equilateral *up*-shot

- Equilateral PNG arises in single & multifield inflation by derivative interactions as modes cross Hubble (e.g. P(X), DBI, axion, …)

- Best understood within the EFT of inflation:

$$\mathcal{L}_{int} = \frac{\dot{\pi}_c (\partial \pi_c)^2}{\Lambda_1^2} + \frac{\dot{\pi}_c^3}{\Lambda_2^2} \Rightarrow f_{NL}^{eq} 10^{-5} \sim \left(\frac{H}{\Lambda_{1,2}} \right)^2$$

- Theoretical benchmark below which it's slow roll

$$\sigma \left(f_{NL}^{eq} \right) \simeq 1$$

The equilateral *down*-shot

- Primary observable: *galaxy bispectrum*
- Theoretical benchmark will *not* be reach in next 10+ years.
    - Already *perturbative matter non-linearities* put the lower bound (see Yvette's talk)

$$\sigma\left(f_{NL}^{eq}\right) \gtrsim 10$$

    - non-linear Bias makes things worse (cfr local PNG)
    - Redshift space list (RSD), systematics,…
- not much to do: hope for a detection and wait for 21 cm

The local *up*-shot

- Local PNG is *strictly forbidden* in single field inflation (so *no* scale dependent bias) [Pajer, Schmidt & Zaldarriaga 13; Dai, Schmidt & Pajer 15; de Putter, Dore & Green 15]

- Arises generically in *multifield inflation* from superHubble evolution (e.g. turns, no derivatives)

- Couples shortest scales with the largest

- “Generically”, in multifield one expects (see later)

$$|f_{NL}^{loc}| \gtrsim 1$$

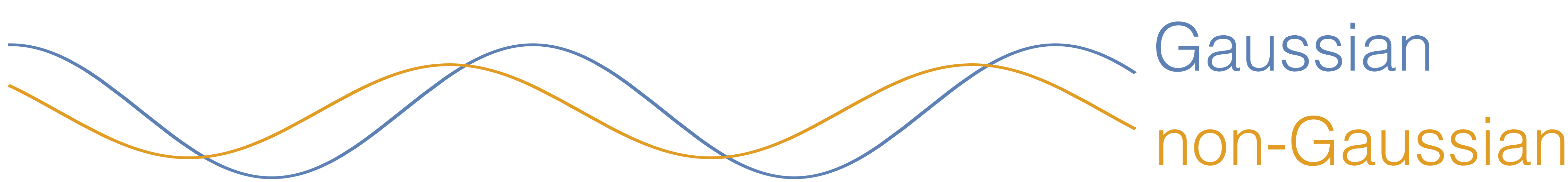
The local *up*-shot

- Primary observables: *galaxy spectrum and bispectrum*
- Theoretical benchmark is within reach!
  - *Scale dependent bias* boosts the signal
  - Local shape is *not generated by gravity*. Smaller effect of matter non-linearities

$$\sigma(f_{NL}^{loc}) \sim 1$$

Yes! (optimistic)

- Arguably, *multifield leads generically to $f_{NL}=O(1)$*
- Pert's along single-field inflationary trajectory are Gaussian because of slow-roll
- Other isocurvature directions are arbitrary, so produce non-Gauss pert's
- Turning trajectories, (modulated) reheating and curvaton mechanism convert iso into adiabatic



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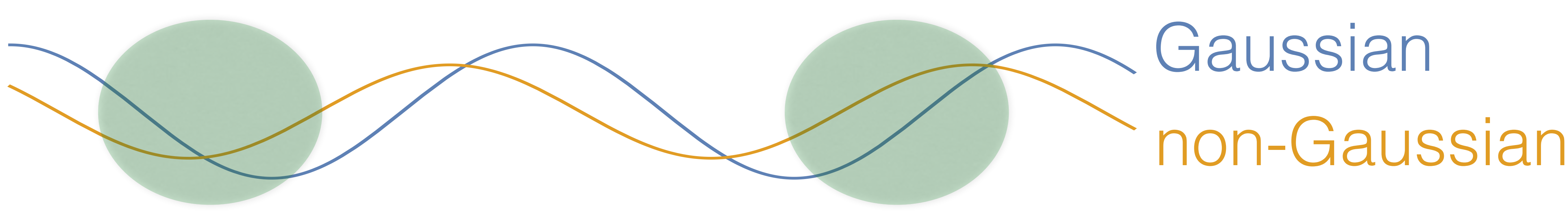

The (optimistic) slogan

The legacy of PNG studies in LSS in the next 10 years will be

1. ***<u>Establishing the origin of the adiabatic mode</u>***

2. and/or get lucky and see something

The (pessimistic) slogan

The legacy of PNG studies in LSS in the next 10 years will be

1. ***<u>...</u>***

2. and/or get lucky and see something

Adiabatic perturbations

- primordial pert's are adiabatic to few % [Planck]

$$\left(\frac{\delta\rho}{\bar\rho+\bar p}\right)_{DM}=\left(\frac{\delta\rho}{\bar\rho+\bar p}\right)_{b}=\left(\frac{\delta\rho}{\bar\rho+\bar p}\right)_{\gamma}=\left(\frac{\delta\rho}{\bar\rho+\bar p}\right)_{\nu}=\dots$$

- Where does this adiabaticity come from?

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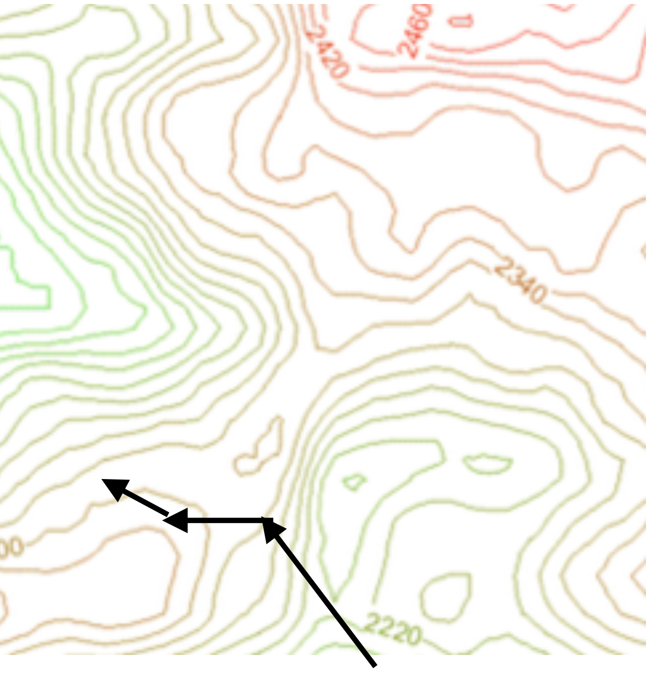
- Where does this adiabaticity come from?

Definition of multifield inflation

- Consider inflation with many (scalar) fields
- Assume gradient flow. At any point in field space compute efolds N(Φ) until the adiabatic attractor is reached
- On superHubble scales, delta-N formalism gives

$$\zeta = \delta N = \frac{\partial N}{\partial \phi^I}\,\delta\phi^I + \dots$$

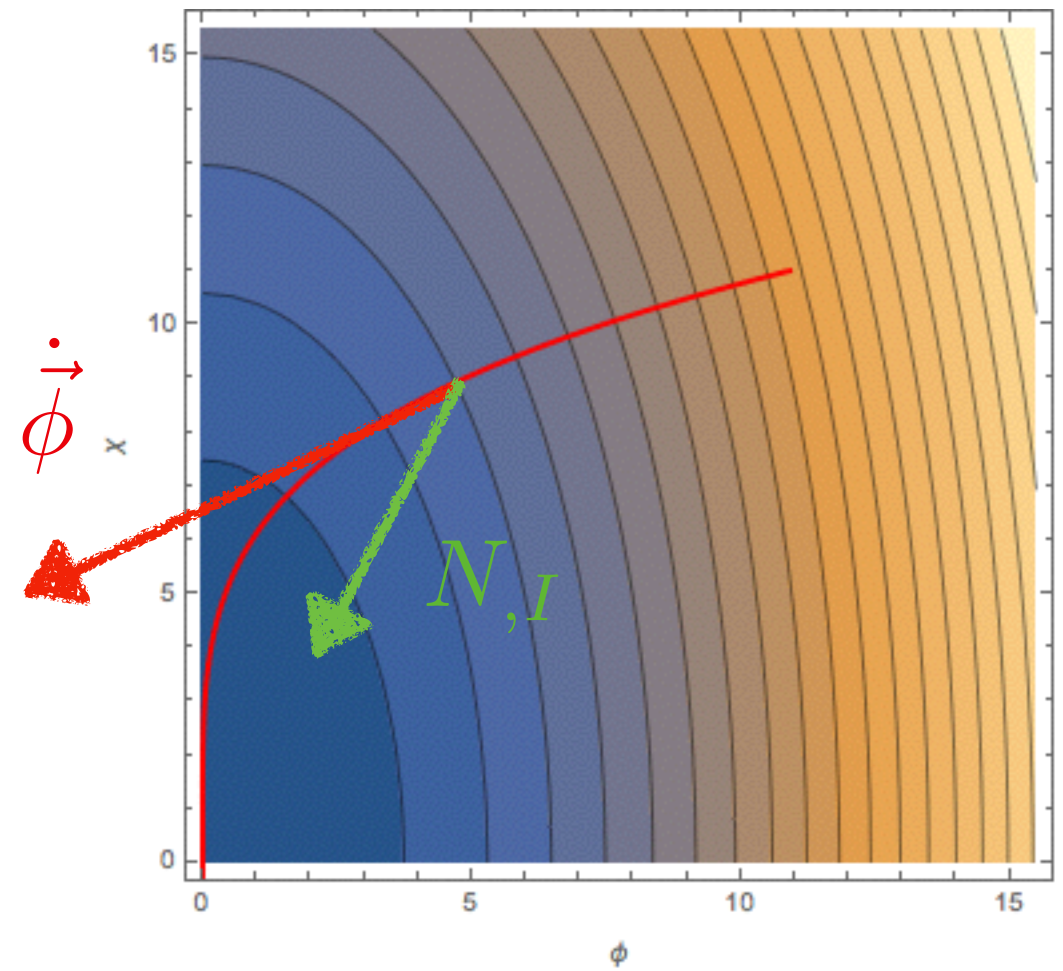
- observed pert's from the gradient of N(Φ)

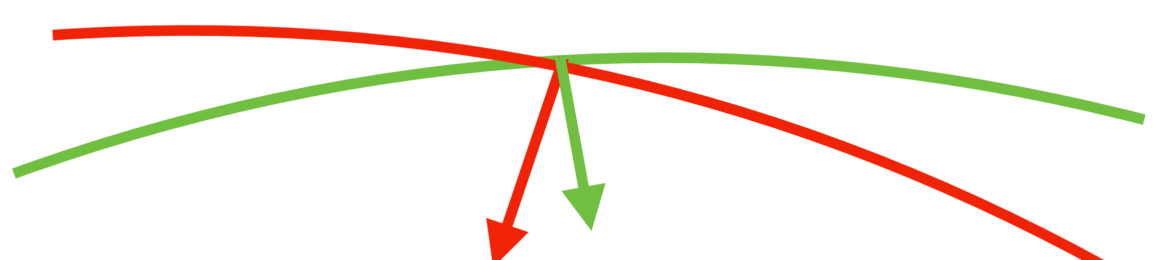


Constant N lines

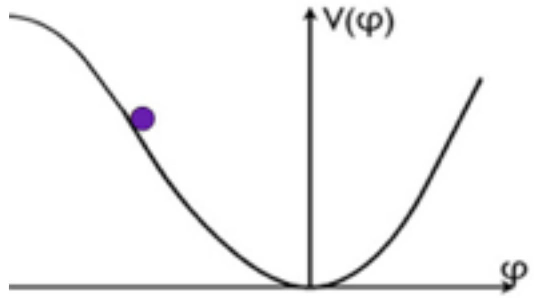
Definition of multi-field

- consider constant V surfaces normal to the gradient $V_{,\Phi}$
- In effective single field, the gradients of V and N are parallel





$$\cos\theta \equiv \frac{\dot\phi^I N_{,I}}{|\dot\phi^I|\,|N_{,I}|}$$



Two paradigms

Single field inflation

- Only one (light) field has super-Hubble scale pert's
- These freeze and re-enter at late times
- Pert's *are born* adiabatic
- Weinberg's adiabatic mode

Multi-field inflation

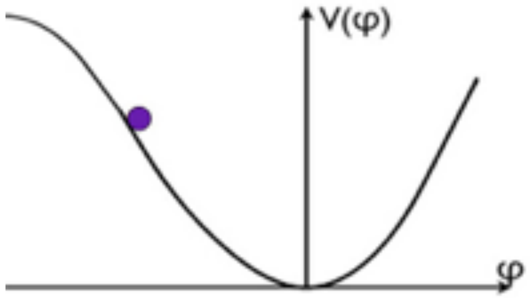
- Many fields are perturbed on super-Hubble scales
- Sub-Hubble *thermalization* (no conserved charges) erases isocurvature pert's

$$n_i \sim e^{-E_i/T} \;\rightarrow\; \delta n_i \sim \delta T$$

- Pert's *become* adiabatic

Adiabatic modes à la Weinberg

- Weinberg's argument mimics the proof of massless Goldstone bosons
- Consider classical GR perturbations around FLRW
- Fix the gauge *at finite momentum* (pert's vanish at infinity), e.g. Newton gauge (cosmological pert. theory)
- Apply a large diff. By diff-invariance it must generate a new solution that does not vanish at infinity (zero momentum)
- Two (non-decaying) solutions survive to finite momentum: the adiabatic mode and gravitational waves
- *If there is only one scalar mode, it is the adiabatic mode*



Single vs multi-field

A few observables can rule out single field:

- isocurvature perturbations
- local non-Gaussianity

But can we rule out the multi-field paradigm?

- Computing multi-field predictions requires understanding: inflation, reheating, coupling to SM physics and thermalization

Yes! (optimist)

- Curvaton scenario: additional curvaton field with sizable superHubble pert's. Irrelevant during inflation, but dominates at late time, converting into adiabatic perturbations

$$f_{NL}^{loc} = \left(1 - \cos\theta^2\right)^2 \left[\frac{5}{4A}\left(1 - \frac{gg''}{g'^2}\right) - \frac{5}{3} - \frac{5A}{6}\right]$$

- *Generically* needs thermalization (no cons. charges) to obtain the late time adiabatic mode

No! (pessimist)

- There are simple multifield models that produce no local PNG, e.g.

$$V = \frac{1}{2} m_1^2 \phi_1^2 + \frac{1}{2} m_2^2 \phi_2^2$$

- More more complicated models [Byrnes, Choi '10, …]
- In the limit of very many fields could invoke central limit theorem and get Gaussian pert's from many non-Gaussian fields

No! (pessimistic)

- (Pessimistic) $f_{NL} < O(1)$ is not sufficient. What's next?
- Single field consistency relations:
  - Tensors: $r = 8\, n_t \cos\theta^2$
  - Scalars (new): $f_{NL}^{equi.} = \alpha_s$
- Both extremely challenging to test observationally

Simple scalings

- Data suggest the simple relation [Mukhanov 13; Roest 13; Creminelli 14; Zavala 14; Gobbetti, EP, Roest 15]

$$1 - n_s = \frac{2}{N}$$

- In single field this can easily happen (e.g. chaotic inflation or Starobinski)
- In multifield, even tuning the potential, the region of initial condition that satisfy 1/N has measure zero [EP in progress]
- In multifield, 1/N requires (more) *tuning of the potential AND of the initial conditions*
- observation of running $-2/N^2=6\ 10^{-4}$ would *rule out multifield*
- This is the sensitivity of SPHEREx

Conclusions

- The major science goal of PNG study with LSS will be
  - establish the origin of the adiabatic mode (single field or multifield paradigm?)
  - get lucky and see some PNG
- We studied how to DM evolve with PNG (Drian van der Woude)
- We forecasted PNG limits accounting for theory noise (Yvette Welling)