STUDYING INFLATION WITH LARGE SCALE STRUCTURES:

LIFE ON THE NON-GAUSSIANITY FRONTIER

Olivier Doré
JPL/Caltech

with

Roland de Putter (Caltech),
Jérôme Gleyzes (JPL/Caltech),
Daniel Green (UCB),
and the SPHEREx Team

arXiv:1612.05248, 1612.0366, 1610.00785, 1504.05935
THE (REALLY, REALLY) BIG PICTURE

Credit: SPHEREx Team
DRIVING QUESTIONS

• What is primordial non-Gaussianity? Why measuring primordial non-Gaussianity with large scale structures?

• How well do we need to measure primordial non-Gaussianity? What can a measurement with $\sigma(f_{NL}) \sim 1$ tell us about multi-field inflation?

• What survey does it take to make measure $\sigma(f_{NL}) \sim 1$?

• A possible implementation, the SPHEREx mission
CONSTRAINING INFLATION WITH THE CMB - I

Planck 2015
CONSTRAINING INFLATION WITH THE CMB - I

Planck 2015. XX
• Measuring the skewness of this map ($\sim f_{NL}$) is extremely interesting

Planck 2015
CMB CONSTRAINTS ON PRIMORDIAL NON-GAUSSIANITY

\[ \Phi = \Phi_G + f_{NL}^{loc} \Phi_G^2 \]

- Measuring \( f_{NL} \) is a unique probe of inflation:
  - Probes interactions in the primordial Lagrangian
  - Distinguishes between single field and multi-field inflation

- Current limit using Planck (T+P) bispectrum:
  - \( f_{NL} = 0.8 \pm 5 \) (68%)

- Future limits with a perfect CMB experiment (T+P, l<3000):
  - \( f_{NL} \lesssim 2 \) (68%)
PRIMORDIAL NON-GAUSSIANITY INTRODUCES MODE COUPLING

$$\Phi = \Phi_G + f_{NL}^{loc} \Phi_G^2$$

• Peak-background split insights:

$$\Phi = \Phi_{Long} + \Phi_{Short}$$

$$\Phi = \Phi_{Long} + f_{NL}^{loc} \Phi_{Long} \Phi_{Short} + f_{NL}^{loc} \Phi_{Short}^2 + \ldots$$
PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

\[ \Phi_{\text{Long}} \]

\[ \Phi_{\text{Short}} \]

\[ f_{NL} = 0 \]

No mode coupling

\[ \delta_{\text{galaxy}} = b \, \delta_{\text{matter}} \]

Galaxy bias (linear)
PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

\[ \Phi_{\text{Short}} \]

\[ \Phi_{\text{Long}} \]

\[ \delta_{\text{galaxy}} = b \delta_{\text{matter}} + c f_{NL} \Phi_{\text{Long}} = (b + \Delta(b)) \delta_{\text{matter}} \]

\[ \Delta(b) \propto (b - 1) \frac{f_{NL}}{k^2} \]

Mode coupling introduced

Scale dependent galaxy bias

\[ f_{NL} \neq 0 \]
PRIMORDIAL NON-GAUSSIANITY AND BIASING

Dalal, OD, Huterer, Shirokov 07

Olivier Doré
NORDITA - Advances in theoretical cosmology in light of data - July 2017
CURRENT CONSTRAINTS WITH GALAXY SURVEYS

- Best current constraints using SDSS photometric quasar sample:
  \[ -49 < f_{NL} < 31 \] (95 % CL)
  ➞ Systematic limited

Leidstedt & Peiris 2014
Leidstedt, Peiris & Roth 2014
Giannantonio et al. 2014
Ross et al. 2013
SINGLE FIELD INFLATION PREDICTION

- No mode coupling

- Single field consistency relation

\[ f_{NL}^{\text{loc}} = -\frac{5}{4}(n_s - 1) \approx 0 \]

Maldacena 2003,
Creminelli & Zaldarriaga 2004
de Putter, Green, OD 16
SINGLE FIELD INFLATION
MULTI-FIELD INFLATION

• To study what a $f_{\text{NL}}$ measurement can teach us, we focus on a subset of two-field models:
  ➡ $\Phi$, an “inflaton” field, dominates background and curvature perturbations at Horizon exit.
  ➡ $\chi$, a “spectator” field, subdominant at Horizon exit but contributes to final curvature perturbation production later.
  ➡ Natural extension of single field inflation.

• Fraction of the primordial curvature perturbation contributed by $\chi$ is quantified $R$
  ➡ $R \approx 0$: Inflaton dominated regime
  ➡ $R \approx 1$: Spectator dominated regime

\[
R \equiv \frac{\mathcal{P}_{\xi|\chi}}{\mathcal{P}_\xi} = \frac{N_{\chi*}^2}{N_{\phi*}^2 + N_{\chi*}^2}
\]
\begin{align*}
W(\Phi, \chi) &= U(\Phi) + V(\chi) \\
U(\phi) &= \frac{1}{2} m^2 \phi^2 \\
V(\chi) &= \frac{1}{2} V_0 \left[ 1 + \cos \left( \frac{2\pi \chi}{f} \right) \right] \\
V(\chi) &= \frac{1}{2} m^2 \chi^2
\end{align*}

- **U potential is not critical to \( f_{\text{NL}} \):**

- **We consider three cases for \( V \):**
  - (Quadratic-) Axion in the Horizon crossing approximation
  - Modulated reheating
  - \ldots

\textit{de Putter, Gleyzes, OD 16}
POSTERIOR DISTRIBUTION OF FNL GIVEN PLANCK

Quadratic-Axion Potential

Modulated Reheating

de Putter, Gleyzes, OD 16
INSIGHTS TO BE GAINED FROM FNL MEASUREMENTS

Quadratic-Axion Potential

f~ axion decay constant

Modulated Reheating

Inflation decay rate and its dependence on X

de Putter, Gleyzes, OD 16
OBSERVATIONAL PROSPECTS

Modulated Reheating

de Putter, Gleyzes, OD 16
COMPLEMENTARITY BETWEEN THE PNG PROGRAM AND THE B-MODE PROGRAM

Curvaton Model

de Putter, Gleyzes, OD 16
QUANTIFYING PRIMORDIAL NON-GAUSSIANITY DISCOVERY POTENTIAL

- Assuming spectator field dominance ($R > 0.9$)

- Quadratic-Axion:

  ➡ With Planck $f_{NL}$: $P(|f_{NL}| > 1) = 58\%$

  ➡ Without Planck $f_{NL}$: $P (|f_{NL}| > 1 (10)) = 63 (6)\%$

- Modulated reheating

  ➡ With Planck $f_{NL}$: $P(|f_{NL}| > 1) = 72\%$

  ➡ Without Planck $f_{NL}$: $P (|f_{NL}| > 1 (10)) = 92 (60)\%$

$de$ $Putter$, $Gleyzes$, $OD$ $16$

$Strong$ $discovery$ $potential$

$Planck$ $already$ $reduced$ $the$ $parameter$ $space$ $but$ $more$ $to$ $cover$
CONSTRaining EQuILATERAL NG with GALAXY SURVEYS

Gleyzes, de Putter, Green, OD 16
• QSF models lead to a scale dependent $f_{\text{NL}}$ term
• It becomes degenerate with non-linear bias
GALAXY CLUSTERING ON ULTRA-LARGE SCALES: WHAT DOES IT TAKE TO REACH $\sigma(f_{NL}) \sim 1$?

- Effective survey volume:
  - $V = \text{many } 100's (h^{-1} \text{ Gpc})^3$ for $\sigma(f_{NL}) \sim 1$

- Redshift accuracy:
  - High redshift accuracy NOT needed ($\sigma(z)/(1+z) \sim 0.1$)

- Systematic error control (0.2% rms $\delta n/n$ per dex in $k$ ($\sim 2 \text{ mmag}$)):
  - Galactic extinction
  - Stellar density
  - Atmosphere
  - Redshift calibration errors
  - …
SPHEREx: An All-Sky Spectral Survey

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

A high throughput, low-resolution near-infrared spectrometer.
SPHEREX: AN ALL-SKY SPECTRAL SURVEY

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

A high throughput, low-resolution near-infrared spectrometer.

SPHEREEx Dataset:

For every 6.2” pixel over the entire sky:

- R=40 spectra spanning (0.75 \( \mu \text{m} < \lambda < 4.18 \mu \text{m} \)).
- R=150 spectra (4.18 \( \mu \text{m} < \lambda < 5.0 \mu \text{m} \)).

O.D., Bock et al., arXiv:1412.4872
THREE MAJOR SCIENTIFIC THEMES

• How did the Universe begin?
  ➡ Probing Inflation with the 3D clustering of galaxies.
    • Survey the z<1.5 Universe to fundamental limits to measure signatures of inflation (non-Gaussianity, primordial power spectrum shape) and dark energy.
    • Complement Euclid & WFIRST which survey smaller area at z>1.

• How did Galaxies begin?
  ➡ Measure the extra-galactic background light (EBL) to probe the epoch of reionization (EOR).

• What are the Condition for Life Outside the Solar System?
  ➡ Measure broad ice absorption features in stellar spectra to explain how interstellar ices bring water and organic molecules into proto-planetary systems.
SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE

<table>
<thead>
<tr>
<th>Category</th>
<th>Detected</th>
<th>Med. Accuracy z’s</th>
<th>High Accuracy z’s</th>
<th>Clusters</th>
</tr>
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<tbody>
<tr>
<td>Galaxies</td>
<td>&gt; 1 billion</td>
<td>&gt; 100 million</td>
<td>10 million</td>
<td>25,000</td>
</tr>
<tr>
<td>Main Seq. Spectra</td>
<td>&gt; 100 million</td>
<td>Dust-forming 10,000</td>
<td>Brown Dwarfs &gt; 400</td>
<td>Cataclysms &gt; 1,000</td>
</tr>
<tr>
<td>Stars</td>
<td>&gt; 1 million</td>
<td>Quasars z &gt; 7 1 - 300?</td>
<td>Asteroid Spectra 10,000</td>
<td>Galactic Line Maps PAH, HI, H₂</td>
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<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td>COBE IRAS GALEX WMAP Planck WISE</td>
</tr>
</tbody>
</table>

All-Sky surveys demonstrate high scientific returns with a lasting data legacy used across astronomy.
• **SPHEREx improves non-Gaussianity accuracy by >10**
  ➔ Improves $\Delta f_{NL} \sim 5$ accuracy today to $\Delta f_{NL} < 0.5$

• Discriminates between models
  ➔ Single-field inflation $f_{NL} \ll 1$
  ➔ Multi-field inflation $f_{NL} \gtrsim 1$

• **SPHEREx improves non-Gaussianity accuracy by >10**
  ➔ SPHEREx produces a unique 3-D galaxy survey
  ➔ Optimized for large scales to study inflation
  ➔ Two independent tests of non-Gaussianity Improves
CONCLUDING ANSWERS

• What is primordial non-Gaussianity? Why measuring primordial non-Gaussianity with large scale structures?
  ➡ Primordial non-Gaussianity can discriminate multi-field and single field inflation and rule out single field inflation
  ➡ LSS are needed as CMB is near cosmic variance limit

• How well do we need to measure primordial non-Gaussianity? What can a measurement with $\sigma(\fnl) \sim 1$ tell us about multi-field inflation?
  ➡ $\sigma(\fnl) \sim 1$ is a natural theoretical target
  ➡ Primordial non-Gaussianity can constrain the inflation Lagrangian

• What survey does it take to make measure $\sigma(\fnl) \sim 1$?
  ➡ Large effective volume, moderate redshift accuracy, exquisite control of systematics on large scales

• A possible implementation, the SPHEREx mission
FIN