Signatures of the Early Universe in the BAO Spectrum

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Based on work with:
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Daniel Green, Mariana Vargas-Magaña, Anže Slosar, Christophe Yêche

Origins of the Universe, Simons Foundation, New York, September 2018
Big Bang

Inflation?

Standard Evolution?

Cosmic Microwave Background

Large-Scale Structure

Very Early Universe

Early Universe

Observable Universe
Big Bang

Very Early Universe

Early Universe

Observable Universe

Features?

Cosmic Neutrinos?

Standard Evolution?

Cosmic Microwave Background

Large-Scale Structure

Inflation?

BAO Spectrum

Inflation?

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Standard Evolution?
Why Consider Large-Scale Structure?

- Additional observational information.
- Complementary to cosmic microwave background observations.
- More observable modes: 2d (CMB) versus 3d (LSS).
- More statistical power (in principle).
- Accessibility of smaller scales (in principle).
- Vast observational effort in next few years: DES, DESI, LSST, Euclid, WFIRST, ...

→ Another window onto our universe!
LSS Interests in the Inflation Group

- Dick Bond
  - Pushing perturbative approaches (e.g. EFT of LSS).
- Jonathan Braden
  - Developing nonperturbative tools.
- Andrei Frolov
  - Simulating structure formation.
- Daniel Green
  - Cross-correlating different probes (e.g. the CMB).
- Moritz Münchmeyer
  - Employing known observables in novel ways.
- Leonardo Senatore
  - Uncovering new observables.
- Benjamin Wallisch
- Matias Zaldarriaga
  - ...

● Dick Bond
● Jonathan Braden
● Andrei Frolov
● Daniel Green
● Moritz Münchmeyer
● Leonardo Senatore
● Benjamin Wallisch
● Matias Zaldarriaga
Matter Power Spectrum

\[ P(k, t = t_0) \] [\( h^{-3} \text{Mpc}^3 \)]

- **Galaxy clustering**
- **CMB**
- **Lyman-\( \alpha \)**
- **CMB lensing**
- **Clusters**
- **Weak lensing**

- **linear** (reconstructed)
- **nonlinear**
Spectrum of Baryon Acoustic Oscillations

\[ P(k) = P^{nw}(k) + P^w(k) \]

- Captures the cosmic sound waves (cf. CMB anisotropies).
- Sensitive to effects on the cosmological evolution.
- Sensitive to changes in the primordial initial conditions.
- Gravitational nonlinearities under theoretical control.

BOSS (2016)
Spectrum of Baryon Acoustic Oscillations

So far, the following information is essentially extracted from the BAO spectrum:

- BAO scale/frequency.

However, there is more information stored in this observable!

Examples:

- Free-streaming nature of neutrinos,
- Features in the primordial spectrum.
Neutrinos in the BAO Spectrum

D. Baumann, D. Green and BW
arXiv:1712.08067 (JCAP 2018)

D. Baumann, F. Beutler, R. Flauger, D. Green, M. Vargas-Magaña, A. Slosar, BW and C. Yèche
arXiv:1803.10741
Cosmic Neutrinos

- 41% of the radiation density in the universe:
  → Leave gravitational imprint,
  → Can detect their energy density.

- Free-streaming since their decoupling at $T \sim 1\,\text{MeV}$.

- Free-streaming neutrinos overtake the photons and pull them ahead of the sound horizon:

\[
\rho_r = \left[1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] \rho_{\gamma}
\]

\[
N_{\text{eff}}^{SM} = 3.046
\]

Eisenstein, Seo and White (2007)
Phase Shift

This corresponds to a phase shift in the photon perturbations:

$$\delta_\gamma(\vec{k}) \approx A(\vec{k}) \cos(kr_s + \phi)$$

The same coherent shift can be seen in the BAO spectrum:

The phase is immune to the effects of nonlinear gravitational evolution.

Baumann, Green & BW (2018)

Baumann, Green & Zaldarriaga (2017)

Bashinsky & Seljak (2003)

Follin, Knox, Millea & Pan (2015)

Detected in Planck data!
Generalized BAO Analysis

Proposal to adapt the standard BAO analysis:

\[ P^w(k) \sim A(k) \sin(kr_s/\alpha + \beta f(k)) \]

Baumann, Green & BW (2018)
The neutrino-induced phase shift can be measured in the BOSS DR12 dataset:

This is a proof of principle for directly extracting information on neutrinos (and other light relics) from galaxy clustering data.

Future observations will greatly improve on this first measurement.

$\beta = 2.05 \pm 0.81$

$\beta > 0$ at $> 99\%$ c.l.

(CMB prior from Planck 2015)
Features in the BAO Spectrum

F. Beutler, M. Biagetti, D. Green, A. Slosar and BW
arXiv:181X.XXXXX
Features in the Primordial Power Spectrum

Several inflationary (and other) models of the very early universe predict features in the primordial power spectrum:

\[ P_\zeta(k) = P_{\zeta,0}(k) + \Delta P_\zeta(k), \quad P_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3} \left( \frac{k}{k_*} \right)^{n_s-1}, \]

such as

- linearly-spaced oscillatory features:
  \[ \frac{\Delta P_\zeta(k)}{P_{\zeta,0}} = A_{\text{lin}} \sin(\omega_{\text{lin}} k + \phi_{\text{lin}}), \]

- logarithmically-spaced oscillatory features:
  \[ \frac{\Delta P_\zeta(k)}{P_{\zeta,0}} = A_{\text{log}} \sin(\omega_{\text{log}} \log(k/k_*) + \phi_{\text{log}}). \]
Nonlinear Damping of the BAO Spectrum

\[ P^w(k) \sim P^w_{\text{lin}}(k) e^{-\frac{1}{2} k^2 \Sigma_{\text{BAO}}^2} + P_{\text{lin}}(k) \Delta P_\zeta(k) e^{-\frac{1}{2} k^2 \Sigma_f(k)^2} \]

The additional nonlinear damping \( \Sigma_f(k) \) can be obtained similar to \( \Sigma_{\text{BAO}} \):

– Compute the leading soft-mode contribution to \( P^w_{1-\text{loop}}(k) \),
– Resum this contribution to all orders.

At BOSS sensitivity, it suffices to use \( \Sigma_f(k) \approx \Sigma_{\text{BAO}} \).
Upper limits can be obtained from the BOSS DR12 dataset:

→ Feature amplitudes are limited to $\mathcal{O}(1\%)$ relative to the primordial amplitude (at 2$\sigma$).
→ Competitive with current CMB constraints in available frequency range.

Beutler, Biagetti, ..., BW (in prep.)
Conclusions

• Large-scale structure observations will provide a treasure trove of information.

• The BAO spectrum can be robustly employed beyond its current use.
  – New observable for the early universe.

• Neutrino-induced phase shift measured in the BAO spectrum.
  – Non-trivial confirmation of the standard model.
  – First application of the BAO signal beyond the standard ruler.

• Constraints on primordial feature models from the BAO spectrum are possible.
  – Effect of nonlinearities on the spectrum can be computed.
  – First application of the BAO signal to primordial physics.
Thank you!

Neutrino-Induced Phase Shift

Constraints on Primordial Features

arXiv:1712.08067; 1803.10741

arXiv:181X.XXXXX

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