Probing angular dependent primordial non-Gaussianity with Intrinsic Galaxy Alignments

Nagoya Univ.
Kazuhiro Kogai

Collaborators: Kazuyuki Akitsu, Fabian Schmidt, Yuko Urakawa
(Kavli IPMU) (MPA) (Bielefeld Univ.)
Motivation

The statistical observable $\langle \zeta^2 \rangle, \langle \zeta^3 \rangle, \ldots$ or $\langle \delta^2 \rangle, \langle \delta^3 \rangle, \ldots$

Inflation
- Very high energy epoch
- Origin of density fluctuation

If there are higher energy particles, they left the imprint on the primordial fluctuation?

Unknown high energy physics

LHC experiment
$10^5$ GeV

$H_{\text{Inf}} \lesssim 10^{13-14}$ GeV

$M_{\text{Pl}}$ $10^{18}$ GeV
Squeezed Bispectrum template

\[ B_\Phi(k_L, k_S) \sim \sum_{s=0,2,\ldots} A_s P_s(k_L \cdot k_S) f_s \left( \frac{k_L}{k_S} \right) P_\Phi(k_L) P_\Phi(k_S) \left[ 1 + \mathcal{O} \left( \frac{k_L^2}{k_S^2} \right) \right] \]

- e.g., Legendre Polynomial: \( P_s(k_L \cdot k_S) \)
- Scale dependence: \( f_s \left( \frac{k_L}{k_S} \right) \)
- \( s = 0 \quad \text{Const.} \)
- \( s \geq 2 \quad \propto \cos^s \theta \)
- \( \propto \left( \frac{k_L}{k_S} \right)^{3/2} \)

Arkani-Hamed & Maldacena ('15)
Lee et al. ('16)
Scale-dependent bias

Galaxy bias

Observables follow the biased predictables.

\[ \delta_n \ \text{ (number density fluctuation)} = b \delta_m \ \text{ (matter density fluctuation)} \]

On the large scale, the galaxy distribution is expected to follow the long mode of the matter density fluctuation.

When the fluctuation follows the Gaussian distribution, each mode is independent.

If there is the primordial non-Gaussianity (PNG), the bias has scale dependent.

\[ \delta_n \sim b\delta_m + b_{\text{NG}} f_{\text{NL}} \Phi_L \]
Galaxy alignment

On the imaging survey, galaxy shapes are observed.

**Galaxy shape components**

- Gravitational lensing effect
- Intrinsic shape

**Linear alignment model**

Intrinsic galaxy shape align along the tidal field on the large scale.

\[
g_{ij}(x) = bK_{ij}(x)
\]

\[
K_{ij} \equiv \left[ \frac{\partial^2\delta(x)}{\partial x^2} \right]_{TL}
\]

Catelan et al. ('00)
Scale-dependent bias

Akitsu et al. (20)

Galaxy bias

w/o PDF

w/ PDF

$P_{\text{bii}}(k) \sim [(h^{\text{-1} \text{Mpc})^3}]$

$B_\phi \propto A_\phi P_{\phi}(k_s)P_{\phi}(k_1)$

s=0

PNG(s = 0)

s=2

PNG(s = 2)

$P_{EE}(k) \sim [(h^{\text{-1} \text{Mpc})^3}]$

$B_\phi \propto A_\phi \delta_2(k_1 \cdot k_s)P_{\phi}(k_s)P_{\phi}(k_1)$

position
Galaxy shape moment

Galaxy Image

Galaxy shape moment function

Definition

\[ g_{i_1 i_2 \cdots i_n}(x, \tau) \equiv \frac{1}{B(x, \tau)R_{\tau}^n} \int_{y \leq R_\tau} d^3 y \, y_{i_1} y_{i_2} \cdots y_{i_n} B(x + y, \tau) \]

Projection on the sky

Projected shape moment

\[ I_{i_1 i_2 \cdots i_n}(x, \tau) = \mathcal{P}_{i_1}^{j_1} \mathcal{P}_{i_2}^{j_2} \cdots \mathcal{P}_{i_n}^{j_n} g_{j_1 j_2 \cdots j_n}(x, \tau) \]
The bias expansion for galaxy shapes

\[ g_{i_1i_2\ldots i_n} \equiv \left\{ \delta, K_{ij}, \text{(higher derivative terms)} \right\} \]

Suppression by the fluctuation to the powers of \((kR_s)\)

The bias expansion for the number density and the 2nd moment shape up to 2nd order

\[
\delta_n(x, \tau) = b^{(0)}_{\delta}(\tau)\delta(x, \tau) + \frac{1}{2} b^{(0)}_{\delta^2}(\tau)\delta^2(x, \tau) + \frac{1}{2} b^{(0)}_{K^2}(\tau)[K^2_{ij}](x, \tau) + \cdots ,
\]

\[
\tilde{g}_{ij}(x, \tau) = b^{(2)}_K(\tau)K_{ij}(x, \tau) + \frac{1}{2} b^{(2)}_{\delta K}(\tau)[\delta K_{ij}](x, \tau) + \frac{1}{2} b^{(2)}_{K^2}(\tau)[K_{ik}K^k_{j}]{_{\text{TL3}}}^{\text{sym}}(x, \tau) + \cdots ,
\]

The bias expansion for 4th moment shape up to 2nd order

\[
\tilde{g}_{ijkl}(x, \tau) = b^{(4)}_K[K_{ij}(x, \tau)K_{kl}(x, \tau)]{_{\text{TL3}}}^{\text{sym}}
\]

Note: Under no-mode coupling, the short mode statistics is encoded in the bias coefficients.
Galaxy shape func. w/ PNG

Squeezed Primordial Bispectrum

\[ B_{\Phi}(k_S, k_L) = \sum_{s=0,2,4,...} A_s P_s (\hat{k}_L \cdot \hat{k}_S) f_s \left( \frac{k_L}{k_S} \right) P_\Phi(k_L) P_\Phi(k_S) \]

Modulated Local potential power spectrum

\[ f(k_L/k_S) = g(k_L/k_p) h(k_p/k_S) \]

\[ P_\Phi(k_S; x|\Phi_L) = \left[ 1 + \sum_{s=0,2,4,...} h_s \left( \frac{k_p}{k_S} \right) [\hat{k}_S \cdots \hat{k}_s]^\text{TL3}_s \alpha_{L,i_1...i_s} \right] P_\Phi(k_S) \]

The modulated 4th moment galaxy shape function

\[ g_{ijkl}(\mathbf{k}) \sim b_{NG} A_4 g_4 \left( \frac{k}{k_p} \right) [\hat{k}_i \hat{k}_j \hat{k}_k \hat{k}_l]^\text{TL3}_s \Phi(\mathbf{k}) + b_{K^2}[K_{ij}K_{kl}]^\text{TL3, sym} \]
Angular power spectrum for 4th moment

Convert to the observable

(3D) Galaxy shape function

1. Projection on the sky
2. Integrate with respect to redshift (Assume LSST imaging survey)
3. Correlation under spherical harmonics decomposition

Angular power spectrum

\[ C_\ell^{(4,4)} = \frac{k}{k_p} \]

\[ g_4(k/k_p) = \frac{k}{k_p}^\Delta \quad (k_p = 1/\text{Mpc}) \]
Other contributions

How is weak lensing effect?

- Higher derivative to lensing potential (Linear WL)
- The loop effect derived from the projection on the sky (2D 1LOOP)
Detectability

Signal to noise ratio w/o shape noise

\[
[S/N]^2(z) \sim f_{\text{sky}} \sum_{l=4}^{l_{\text{max}}} (2l + 1) \left[ \frac{C^{(4,4)\text{PNG}}(l, z)}{C^{(4,4)\text{PNG}}(l, z) + C^{(4,4)\text{NL}}(l, z)} \right]^2
\]

\[g_4(k/k_p) = (k/k_p)^\Delta \quad (k_p = 1/[\text{Mpc}])\]

← The amplitude of \(b_{\text{NG}}^{(4)}A_4\) which is detectable with S/N = 5 at each redshift
Summary

• We investigated the response of galaxy shape moment to Angular dependent PNG. (especially, 4th moment galaxy shape case)
  →We found that the only angular dependent PNG corresponding to spin-4 was encoded in the 4th moment galaxy shape on the leading term.

• Since we do not know the response of the tidal field or the PNG to the higher moment galaxy shape (i.e. bias, shape noise), we have to investigate these by simulation etc.