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Halo/Galaxy bispectrum with Equilateral-type Primordial non-Gaussianities

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Phys. Rev. D 91, 123521 (arXiv: 1504.05505 [astro-ph.CO])

Phys. Rev. D 94, 043532 (arXiv: 1605.07348 [astro-ph.CO])

Inflation

Inflation- extremely rapid expansion of the early universe

- Solving problems of big-bang cosmology

  (Flatness problem, Horizon problem, Unwanted relics,…)

- Providing origin of the structures in the Universe

$$\zeta = -\frac{H}{\dot{\phi}}\delta\phi$$

(curvature perturbation) (inflaton fluctuation)

Almost scale invariant, adiabatic and Gaussian primordial density fluctuations

We can get information of high energy physics by detailed observational results related with inflation

Constraints from primordial power spectrum

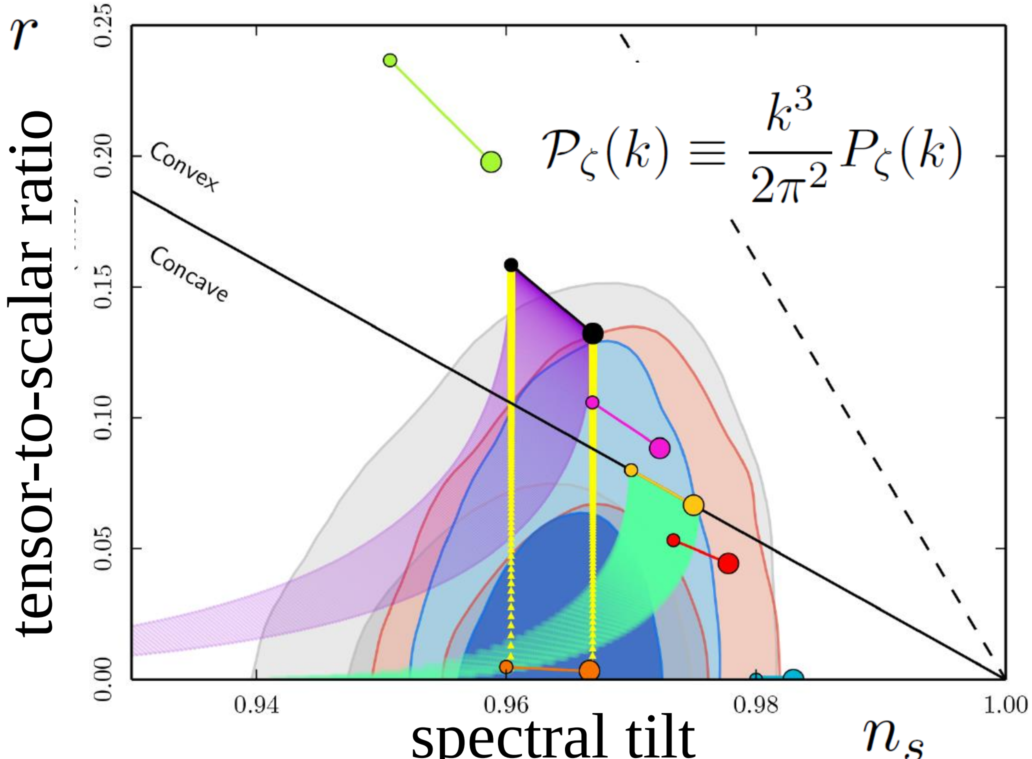
- Primordial power spectrum

$$\langle \zeta_{\mathbf{k}} \zeta_{\mathbf{k}'} \rangle = (2\pi)^3 \delta(\mathbf{k}+\mathbf{k}') P_\zeta(k) \qquad \mathcal{P}_\zeta(k) \equiv \frac{k^3}{2\pi^2} P_\zeta(k) \qquad \mathcal{P}_\zeta = \frac{1}{8\pi^2 M_{\rm Pl}^2} \frac{H^2}{\epsilon}$$

well approximated by $n_s - 1 = \dfrac{d \ln \mathcal{P}_\zeta(k)}{d \ln k}$

- Constraints from Planck (CMB)

Ade et al `15



For standard single-field slow-roll inflation models

$$\begin{cases} n_s - 1 \simeq -2\epsilon - \eta \\ r \equiv \dfrac{\mathcal{P}_h}{\mathcal{P}_\zeta} = 16\epsilon \end{cases}$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \qquad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon}$$

Primordial non-Gaussianity (PNG)

- Primordial bispectrum

amplitude & shape

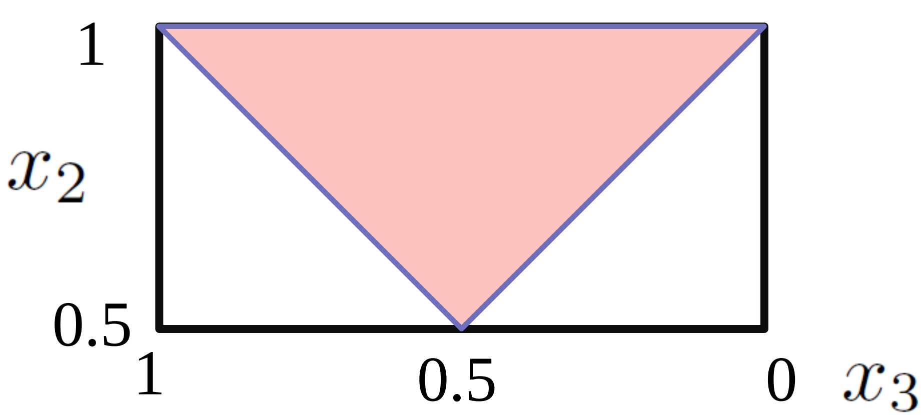
$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle \equiv (2\pi)^3 \delta(\sum_{\mathbf{i}} \mathbf{k_i}) \left[(2\pi)^4 \frac{S(k_1, k_2, k_3)}{(k_1 k_2 k_3)^2} \mathcal{P}_\zeta^2 \right]$$

wavevectors $\mathbf{k_i}$ form a triangle in Fourier space

Usually $S \sim \mathcal{O}(\epsilon)$, but some models can give large S

- Shape-dependence of bispectrum

In most models, S depends only on $x_2 \equiv k_2/k_1$ and $x_3 \equiv k_3/k_1$



For $k_3 \leq k_2 \leq k_1$

Allowed region is

$$1 \geq x_2 \geq x_3$$

$$1 \leq x_2 + x_3$$

Intrinsic non-linearity of inflaton fluctuation

- Expansion of the action

$$g_{\mu\nu}(t,x) = \bar{g}_{\mu\nu}(t) + \delta g_{\mu\nu}(t,x) \qquad \phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$$

$$\Rightarrow \quad S = \bar{S} + S^{(2)}(\delta g_{\mu\nu}, \delta\phi) + \underline{S^{(3)}(\delta g_{\mu\nu}, \delta\phi) + \cdots}$$

interactions of inflaton fluctuation

- In-in formalism Calzetta and Hu `87, Weinberg `05

The expectation value of an observable $O(t)$

$$\langle in|O(t)|in\rangle = \langle 0| \left[\bar{T} \exp\left(i \int_{-\infty}^{t} \underline{H_I(t')} dt' \right) \right] O^I(t) \left[T \exp\left(-i \int_{-\infty}^{t} \underline{H_I(t'')} dt'' \right) \right] |0\rangle$$

interaction Hamiltonian

At leading order $\Rightarrow$ $\langle O(t) \rangle = 2 \,\mathrm{Re} \left[-i \int_{-\infty}^{t} dt' \langle 0| O^I(t) H_I(t') |0\rangle \right]$

Single-field k-inflation

- Model

Armendariz-Picon et al. `99

$$\mathcal{L} = P(X,\phi) \qquad \text{with} \qquad X = -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

cf. $\mathcal{L} = X - V(\phi)$ for a canonical scalar field

- Linear fluctuations (leading order in slow-varying)

Garriga, Mukhanov `99

$$\mathcal{P}_\zeta(k) \equiv \frac{k^3}{2\pi^2}P_\zeta(k) = \left(\frac{H^2}{8\pi^2\epsilon \underline{c_s}}\right)_* \qquad c_s^2 = \frac{P_{,X}}{P_{,X}+2XP_{,XX}}$$

sound speed

- Third-order action

Chen, Huang, Kachru, Shiu `07

$$S^{(3)} = \int dtd^3xa^3\epsilon\left[\left(\frac{1}{c_s^2}-1\right)\left(\zeta\frac{(\partial\zeta)^2}{a^2}-\frac{3}{c_s^2}\zeta\dot{\zeta}^2\right)+\left(\frac{1}{c_s^2}-1-\frac{2\lambda}{\Sigma}\right)\frac{1}{Hc_s^2}\dot{\zeta}^3\right]$$

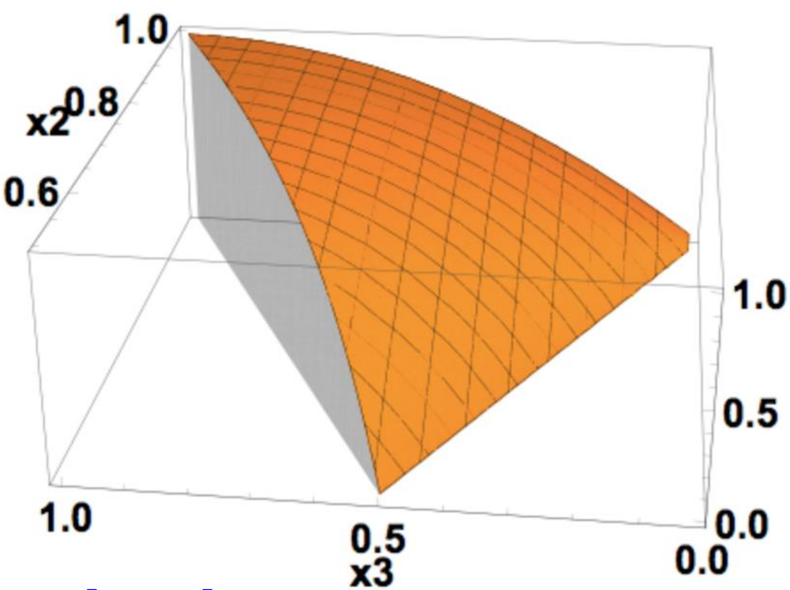
$$\Sigma = XP_{,X}+2X^2P_{,XX} \qquad \lambda = X^2P_{,XX}+\frac{2}{3}X^3P_{,XXX}$$

Equilateral-type primordial non-Gaussianity

・Shape of equilateral-type primordial bispectrum

Babichi, Creminelli, Zaldarriaga `04

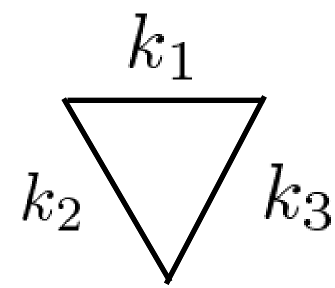
$$S^{k-\mathrm{inf}} \simeq S^{\mathrm{equil}} = \frac{9}{10} f_{\mathrm{NL}}^{\mathrm{equil}} \left[-\left(\frac{k_1^2}{k_2 k_3} + 2 \text{ perm.} \right) + \left(\frac{k_1}{k_2} + 5 \text{ perm.} \right) - 2 \right]$$



$$f_{\mathrm{NL}}^{\mathrm{equil}} = \mathcal{O}\left(\frac{1}{c_s^2}, \frac{\lambda}{\Sigma} \right)$$

Maximum in the equilateral limit

$k_1 \sim k_2 \sim k_3$



This shape emerges in more general higher-derivative scenarios

Ghost-inflation, Galileon-inflation, Horndeski theories,…

Equilateral-type primordial trispectrum

- Primordial trispectrum in k-inflation

ex.) Arroja, SM, Koyama, Tanaka `09

$$\frac{T_\zeta^{\dot\sigma^4}}{(2\pi^2\mathcal{P}_\zeta)^3} = \frac{221184}{25}\frac{g_{\rm NL}^{\dot\sigma^4}}{(\sum k_i)^5 k_1k_2k_3k_4}$$

$$\frac{T_\zeta^{\dot\sigma^2(\partial\sigma)^2}}{(2\pi^2\mathcal{P}_\zeta)^3} = -\frac{27648}{325}g_{\rm NL}^{\dot\sigma^2(\partial\sigma)^2}\left[\frac{k_1^2k_2^2(\mathbf{k}_3\cdot\mathbf{k}_4)}{(\sum k_i)^3\Pi k_i^3}\left(1+3\frac{(k_3+k_4)}{\sum k_i}+12\frac{k_3k_4}{(\sum k_i)^2}\right)+\text{perm.}\right]$$

$$\frac{T_\zeta^{(\partial\sigma)^4}}{(2\pi^2\mathcal{P}_\zeta)^3} = \frac{165888}{2575}g_{\rm NL}^{(\partial\sigma)^4}\frac{[(\mathbf{k}_1\cdot\mathbf{k}_2)(\mathbf{k}_3\cdot\mathbf{k}_4)+\text{perm.}]}{\sum k_i\Pi k_i}$$
$$\times\left(1+\frac{\sum_{i<j}k_ik_j}{(\sum k_i)^2}+3\frac{\Pi k_i}{(\sum k_i)^3}\sum\frac{1}{k_i}+12\frac{\Pi k_i}{(\sum k_i)^4}\right)$$

$$g_{\rm NL}^{\dot\sigma^4},\ g_{\rm NL}^{\dot\sigma^2(\partial\sigma)^2},\ g_{\rm NL}^{(\partial\sigma)^4} = \mathcal{O}\left(\frac{1}{c_s^4}\right)$$ written in terms of $P_{,X}$, $P_{,XX}$, $\cdots$

These shapes also appear in effective field theory of inflation

Senatore, Zaldarriaga `11

Primordial non-Gaussianities in the CMB

- CMB angular bispectrum

$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle \qquad \frac{\Delta T}{T}(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

The link between $a_{\ell m}$ and ζ is well known at linear order

- Constraints from Planck (68% CL) Ade et al `15

Equilateral-type

$$f_{\rm NL}^{\rm equil} = -4 \pm 43$$

$$g_{\rm NL}^{\dot{\sigma}^4} = (-0.2 \pm 1.7) \times 10^6 \qquad g_{\rm NL}^{(\partial\sigma)^4} = (-0.1 \pm 3.8) \times 10^5$$

local-type (generated by multi-field inflation)

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0 \qquad g_{\rm NL}^{\rm local} = (-9.0 \pm 7.7) \times 10^4$$

Perspectives

• The simplest single-field slow-roll models of inflation passed very stringent tests due to the lack of PNG

• The bounds on $f_{\rm NL}^{\rm equil}$ translate into a limit on c_s

$$c_s \geq 0.020 \quad (95\%\ \mathrm{CL})$$

Strong coupling scale in EFT $\Lambda_\star \sim \frac{1}{\sqrt{\zeta f_{\rm NL}^{\rm equil}}} H_{inf}$

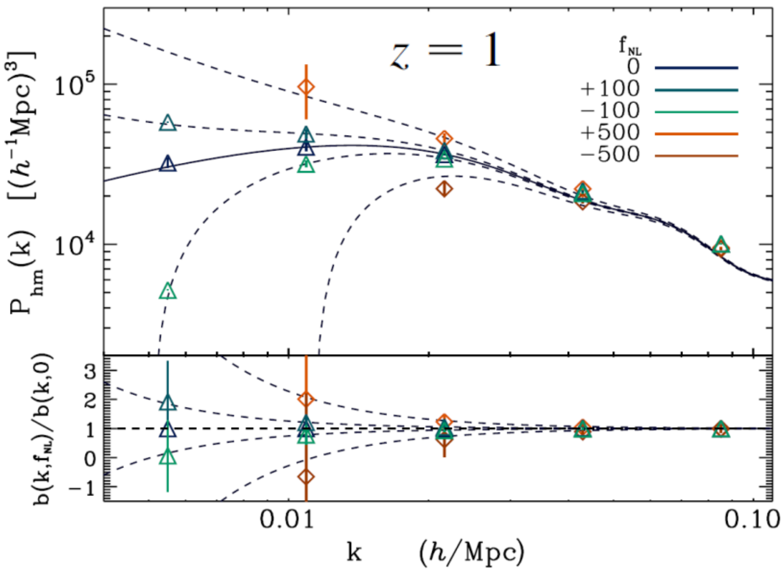
Unless $f_{\rm NL}^{\rm equil} \leq 1$, new physics appears much below $M_{\rm Pl}$

Baumann, Green `11

• $f_{\rm NL}^{\rm local}$ from multifield scenarios is very model-dependent
But large class of spectator models predicts $|f_{\rm NL}^{\rm local}| \geq \mathcal{O}(1)$

Constraints on local-type NG from LSS

Dalal et al `08



$$1.6 \times 10^{13} M_\odot < M < 3.2 \times 10^{13} M_\odot$$

Constraints on bispectrum

Giannatonio et al `13

$$-36 < f_{\mathrm{NL}}^{\mathrm{local}} < 45 \quad \text{(95\% CL)}$$

Future constraints:

Yamauchi et al `14

SKA (Square Km Array)

$|f_{NL}| < 0.1$?

Constraints on trispectrum

Desjacques and Seljak `10

$$\zeta(x) = \zeta_G(x) + \frac{9}{25} g_{\mathrm{NL}}^{\mathrm{local}} \zeta_G^3(x)$$

$$-3.5 \times 10^5 < g_{\mathrm{NL}}^{\mathrm{local}} < 8.2 \times 10^5 \quad \text{(95\% CL)}$$

How about equilateral-type NG ?

Integrated Perturbation Theory (iPT)

Matsubara `12, `13, Bernardeau et al `08

- Multi-point propagator of biased objects

$$\left\langle \frac{\delta^n \delta_X(\mathbf{k})}{\delta\delta_{\rm L}(\mathbf{k}_1)\delta\delta_{\rm L}(\mathbf{k}_2)\cdots\delta\delta_{\rm L}(\mathbf{k}_n)} \right\rangle = (2\pi)^{3-3n}\delta(\mathbf{k}_1+\mathbf{k}_2+\cdots+\mathbf{k}_n)\underline{\Gamma_X^{(n)}(\mathbf{k}_1,\mathbf{k}_2,\cdots,\mathbf{k}_n)}$$

Gravitational evolution

Lagrangian bias, ….

δ_X : number density field of the biased objects

$\delta_{\rm L}$: linear density field which is related with

primordial curvature perturbation ζ through

$$\delta_{\rm L}(k) = \mathcal{M}(k)\zeta(k);\ \mathcal{M}(k) = \frac{2}{3}\frac{D(z)}{D(z_*)(1+z_*)}\frac{k^2T(k)}{H_0^2\Omega_{\rm m0}}$$

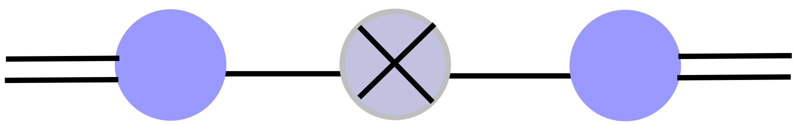
$D(a)$: growth factor $\qquad$ $T(k)$: transfer function

⇒ spectra of biased objects (Halo/Galaxy) systematically !!

Effects on Halo/galaxy power spectrum

- Diagrams for the power spectrum of the biased objects

P_0



$\Gamma_X^{(1)}(\mathbf{k})\, P_{\rm L}(k)\, \Gamma_X^{(1)}(-\mathbf{k})$

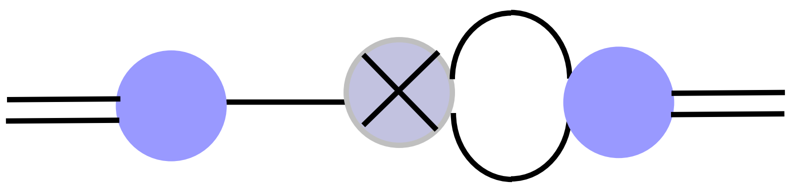
$\propto \mathcal{M}(k)^2 P_\zeta(k) \propto k$

large scale limit

$k \ll p$

typical scale of the biased objects

$P_{\rm bis}$



$\Gamma_X^{(1)}(\mathbf{k})\, B_{\rm L}(k, p, |\mathbf{p}+\mathbf{k}|)\, \Gamma_X^{(2)}(\mathbf{p}, -\mathbf{p}-\mathbf{k})$

large scale limit

$$\begin{cases} \propto \mathcal{M}(k) k^{-3} \propto k^{-1} & \text{for } B_\zeta^{\rm local} \\ \propto \mathcal{M}(k) k^{-1} \propto k & \text{for } B_\zeta^{\rm equil} \end{cases}$$

enhancement (for $B_\zeta^{\rm local}$)

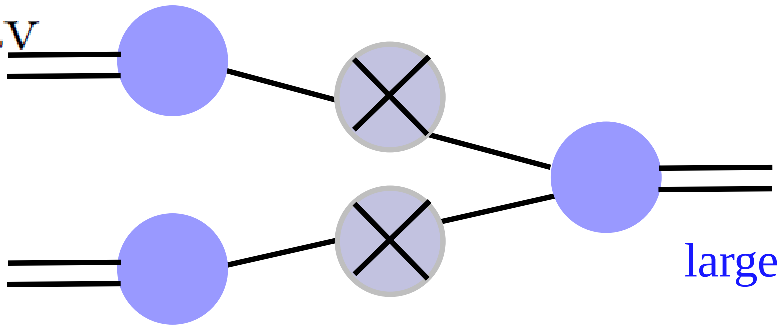
no enhancement (for $B_\zeta^{\rm equil}$)

Halo/galaxy bispectrum with equilateral PNG

- Diagrams for the bispectrum of the biased objects

SM, Yokoyama `15

$B_{\rm grav}$

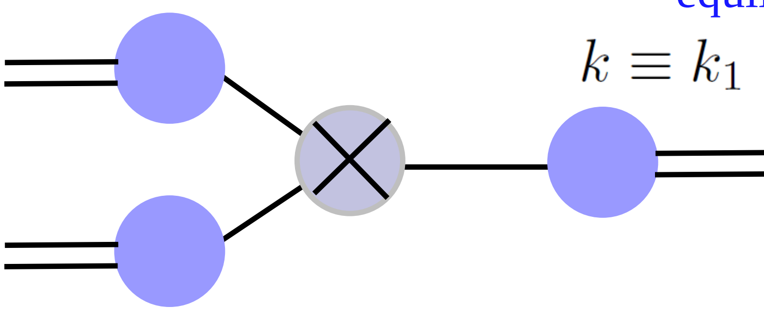


$\Longrightarrow \quad \propto \mathcal{M}(k)^4 P_\Phi(k)^2 \propto k^2$

large scale limit
&
equilateral config.

$k \equiv k_1 = k_2 = k_3 \ll p$

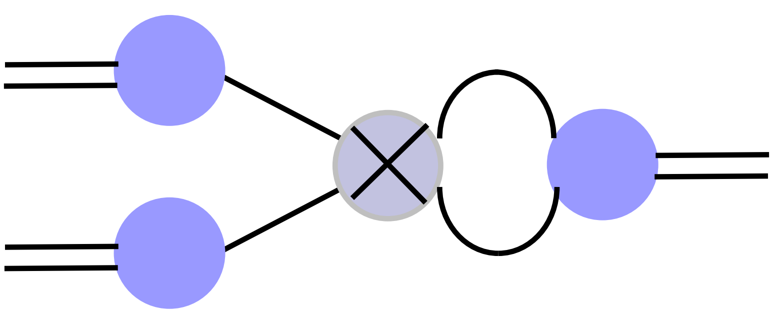
$B_{\rm bis}$



$\Longrightarrow \quad \propto \mathcal{M}(k)^3 P_\Phi(k)^2 \propto k^0$

with $f_{\rm NL}^{\rm equil}$

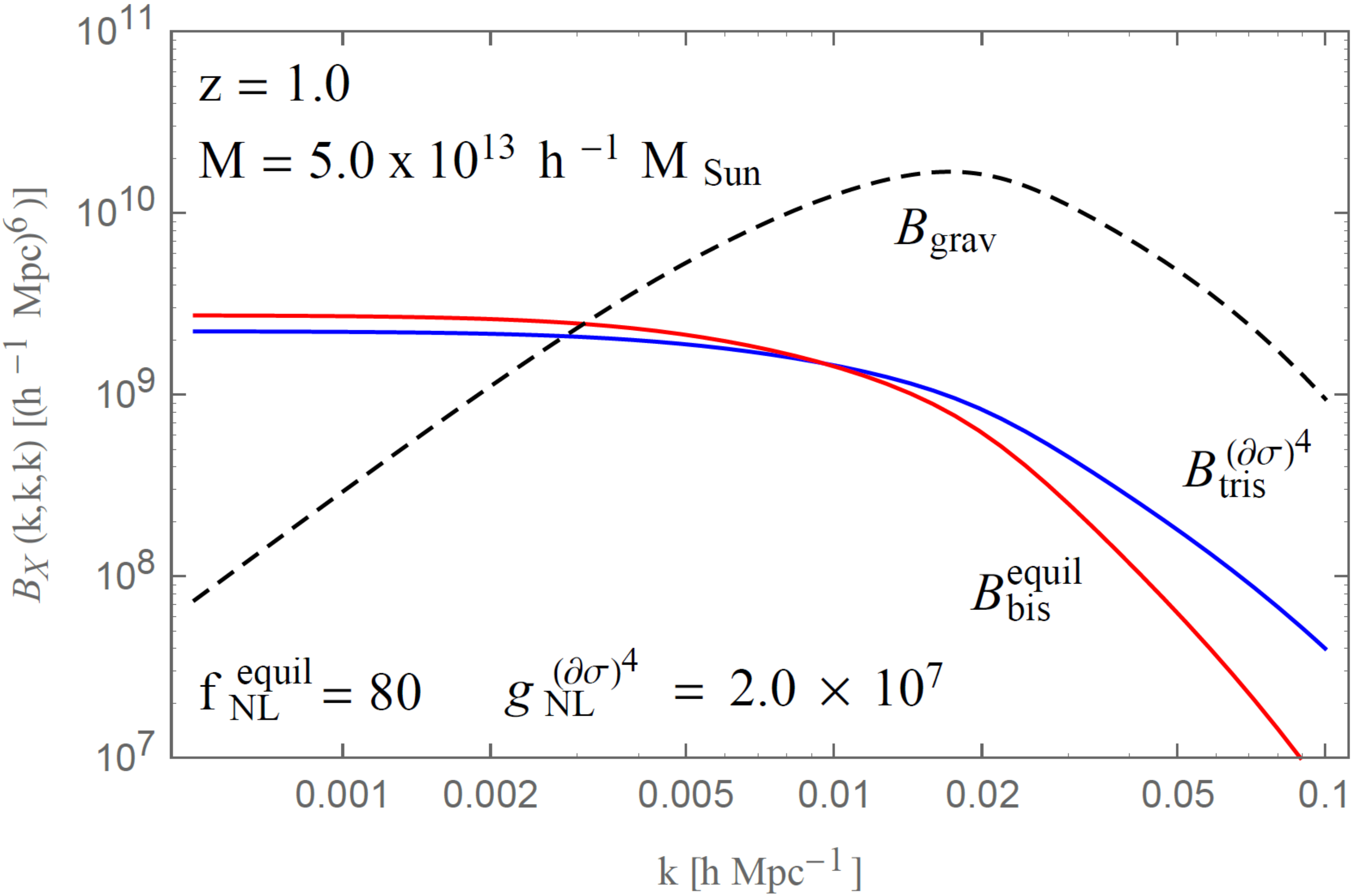
$B_{\rm tri}$



$\Longrightarrow \quad \propto \mathcal{M}(k)^2 k^{-4} \propto k^0$

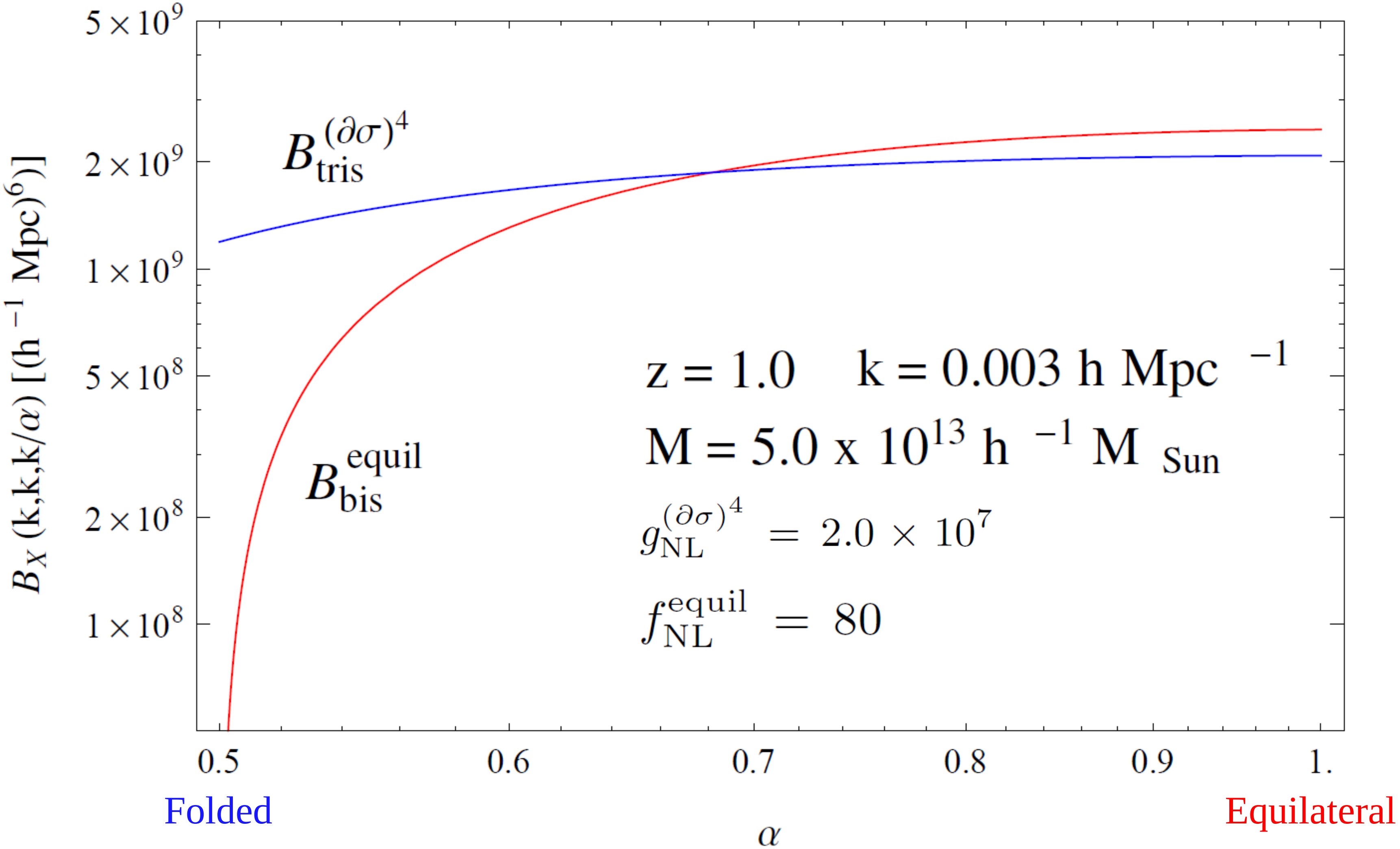
with $g_{\rm NL}^{(\partial\sigma)^4}$

Scale-dependence o halo/galaxy bispectrum



Halo/galaxy bispectrum with $g_{\rm NL}^{(\partial\sigma)^4}$ and $f_{\rm NL}^{\rm equil}$

isosceles configuration given by $k \equiv k_1 = k_2 = \alpha k_3$



Forecast constraints

Hashimoto, SM, Yokoyama `16

Can LSS obtain more severer constraints than CMB ?

▪Planned future surveys on LSS

	$f_{\rm sky}$	$z_{\rm m}$	$\bar{n}_{\rm s}$ [arcmin^{-2}]
HSC [21]	0.0375 (1,500 deg^2)	1.0	35
DES [22]	0.125 (5,000 deg^2)	0.5	12
LSST [23]	0.5 (20,000 deg^2)	1.5	100

sky coverage　　mean source redshift　　mean number density of source

Strategy

From integrated perturbation theory

Three-dimensional spectra: $B_{XYZ}(k_1, k_2, k_3)$, $X = \mathrm{h}$ or m

project on celestial sphere

$$\Delta_{\mathrm{h}}^{(2)}(\boldsymbol{\theta}) = \int_0^{\infty} dz\, W_{\mathrm{h}}(z) \delta_{\mathrm{h}}^{(3)}(\chi(z)\boldsymbol{\theta}, z),$$ halo

$$\kappa(\boldsymbol{\theta}) = \int_0^{\infty} dz\, W_{\kappa}(z) \delta_{\mathrm{m}}^{(3)}(\chi(z)\boldsymbol{\theta}, z)$$ matter (lensing)

Angular spectra: $B_{abc}(\ell_1, \ell_2, \ell_3)$, $a = \mathrm{h}$ or κ

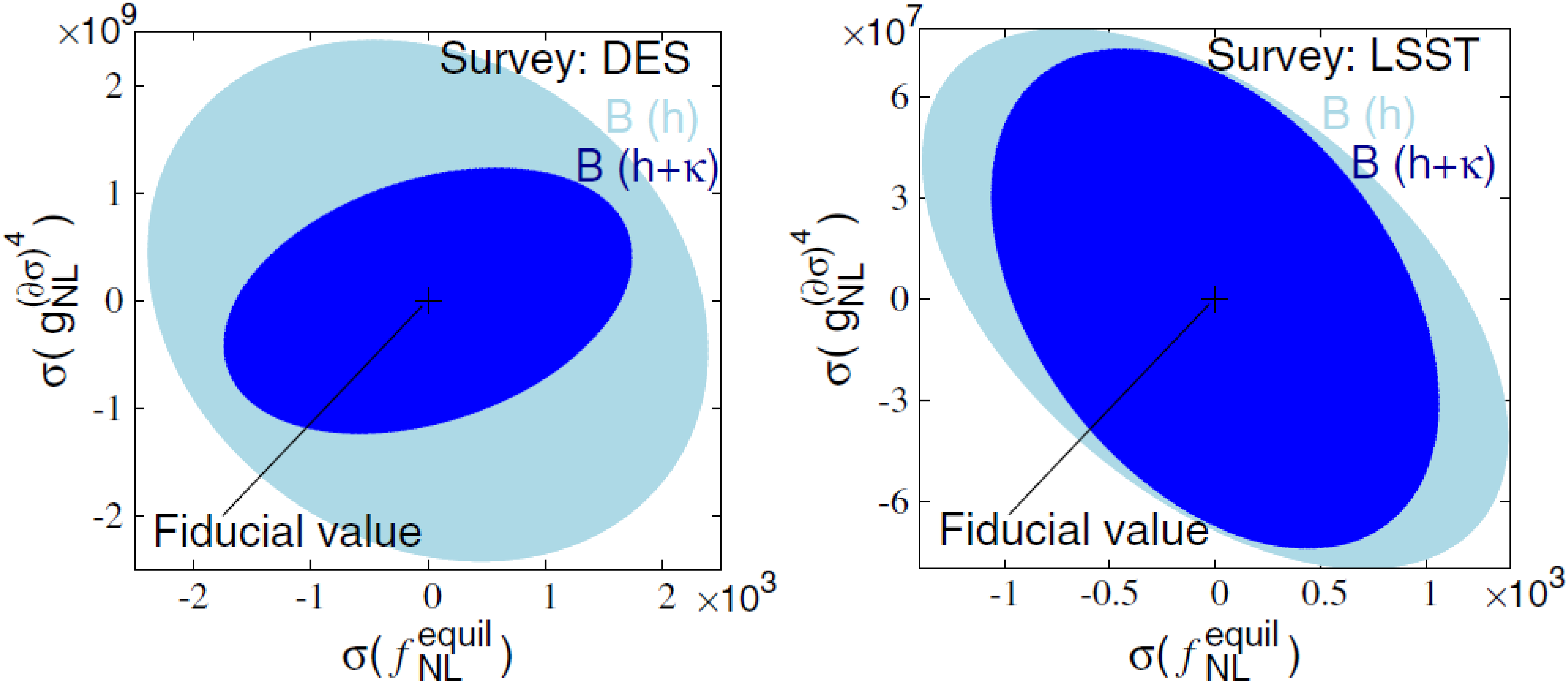
Fisher analysis $\mathrm{Cov}[B_{\mathrm{abc}}(\ell_i, \ell_j, \ell_k), B_{\mathrm{a'b'c'}}(\ell_l, \ell_m, \ell_n)]$

$$F_{\alpha\beta} = \sum_{\ell_i=\ell_{\min}}^{\ell_{\max}} \frac{\partial \boldsymbol{B}_i(\boldsymbol{p})}{\partial p_\alpha} (\mathrm{Cov}^B)_{ij}^{-1} \frac{\partial \boldsymbol{B}_j(\boldsymbol{p})}{\partial p_\beta} \bigg|_{\boldsymbol{p}=\boldsymbol{p}_0}, \quad \boldsymbol{B}_i = \begin{pmatrix} (B_{\mathrm{hhh}})_i \\ (B_{\mathrm{hh}\kappa})_i \\ (B_{\mathrm{h}\kappa\kappa})_i \end{pmatrix},$$

weight function and covariance matrix depend on surveys

- Expected constraints on f_{NL}^{equil} , g_{NL}^{equil}

$(1/F_{\alpha\alpha})^{1/2}$, $([F]_{\alpha\alpha}^{-1})^{1/2}$



Survey: DES
B (h)
B (h+κ)
Fiducial value
$\sigma(g_{NL}^{(\partial\sigma)^4})$
$\times 10^9$
$\sigma(f_{NL}^{equil})$
$\times 10^3$
Survey: LSST
B (h)
B (h+κ)
Fiducial value
$\sigma(g_{NL}^{(\partial\sigma)^4})$
$\times 10^7$
$\sigma(f_{NL}^{equil})$
$\times 10^3$

Forecast results (1σ errors)

Survey		B_{hhh}	$B_{hhh}+B_{hh\kappa}+B_{h\kappa\kappa}$
HSC	$\sigma(f_{\rm NL}^{\rm equil})$	$3.2\times10^3\,(2.9\times10^3)$	$2.3\times10^3\,(2.1\times10^3)$
	$\sigma(g_{\rm NL}^{(\partial\sigma)^4})$	$3.2\times10^8\,(2.9\times10^8)$	$2.9\times10^8\,(2.7\times10^8)$
DES	$\sigma(f_{\rm NL}^{\rm equil})$	$1.6\times10^3\,(1.6\times10^3)$	$1.1\times10^3\,(1.1\times10^3)$
	$\sigma(g_{\rm NL}^{(\partial\sigma)^4})$	$1.6\times10^9\,(1.7\times10^9)$	$8.2\times10^8\,(7.7\times10^8)$
LSST	$\sigma(f_{\rm NL}^{\rm equil})$	$9.2\times10^2\,(8.0\times10^2)$	$7.0\times10^2\,(6.4\times10^2)$
	$\sigma(g_{\rm NL}^{(\partial\sigma)^4})$	$5.3\times10^7\,(4.6\times10^7)$	$4.9\times10^7\,(4.4\times10^7)$

cf. $\sigma\left(f_{\rm NL}^{\rm equil}\right)=43$, $\sigma\left(g_{\rm NL}^{(\partial\sigma)^4}\right)=1.3\times10^6$

for Planck

Summary and Discussions

• Equilateral-type PNG has information on intrinsic nonlinearity of inflaton and is helpful to distinguish inflation models

• Currently, from CMB , no significant PNG is observed and the simplest single-field slow-roll inflation models are consistent

• From halo/galaxy bispectrum, we can constrain $f_{\rm NL}^{\rm equil}$, but constraints from LSS are looser than that from CMB

•We can constrain $f_{\rm NL}^{\rm equil}$ more from information of small scales if we specify nonlinear and nonlocal bias (Gleyzes et al `16)