Towards the observed galaxy bispectrum

in the weak field approximation

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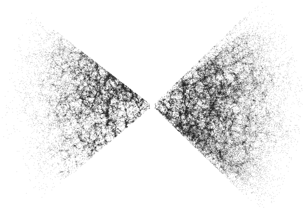
Based on : L.C, R.Gannouji, J.Noreña, C.Stahl (2018) arXiv:1811.05452,
J.Calles, L.C, J.Noreña, C.Stahl (2019) arXiv:1912.13034



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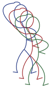
Inflation and primordial non-gaussianity

Inflation provides a mechanism to generate primordial perturbations which are the seed to structure formation.

Single field inflation?

Initial conditions: Gaussian, adiabatic and almost scale invariant.

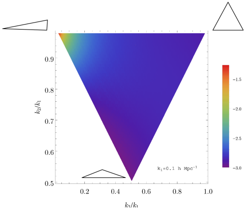
Multi-field inflation? Exotic Mechanism?



Predict large non-Gaussianity.

We are interested in the Bispectrum $B(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$

- Local shape: $k_1 \ll k_2 \sim k_3$ f_{NL}^{local}
- Equilateral shape $k_1 \sim k_2 \sim k_3$ f_{NL}^{equi}
- Folded triangles $k_1 + k_2 \sim k_3$ f_{NL}^{folded}



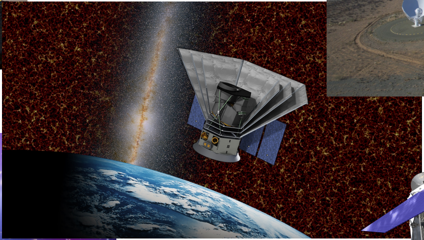
Meerburg.et.al.(2019) arXiv:1903.04409

We are in the era of precision cosmology.

The Large Synoptic Survey Telescope

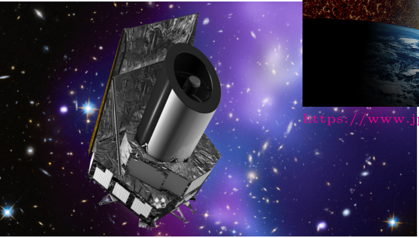
https://www.lsst.org/lsst

Spherex

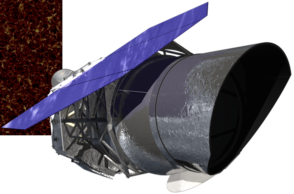


https://www.jpl.nasa.gov/missions/spherex/

Square Kilometre Array
https://www.skatelescope.org/



Euclid http://sci.esa.int/euclid/



Wide Field Infrared Survey Telescope
https://wfirst.gsfc.nasa.gov/index.html

Dark matter perturbations

Dark matter is considered as a barotropic irrotational perfect fluid

$$T_{\mu\nu} = \bar{\rho}\,(1+\delta)\,u_\mu u_\nu$$

Perturbed FLRW metric

$$ds^2 = -\,(1+2\phi)\,dt^2 + 2\omega_i dt dx^i + a(t)^2\left[(1-2\psi)\,\delta_{ij} + \gamma_{ij}\right] dx^i dx^j$$

$$\omega_i = \partial_i \omega + w_i \Longrightarrow \partial_i w_i = 0, \qquad \gamma_{ii} = \partial_i \gamma_{ij} = 0$$

- Weak field approximation:

$$\phi \sim \psi \sim \omega \sim \left(\frac{H^2}{\nabla^2}\right) = \mathcal{O}(\epsilon) \ll 1, \qquad w_i \sim \mathcal{O}(\epsilon^{3/2}), \quad \gamma_{ij} \sim \mathcal{O}(\epsilon^2)$$

- Gravitational field and velocity are small at small scales

$$\psi \sim \frac{H^2}{\nabla^2} \sim 10^{-5}, \qquad u^i \sim \frac{H}{\nabla} \sim 10^{-3}$$

Fluid Equations

Continuity equation

$$\dot{\delta} + \theta = -\partial_i \left(\delta u^i\right) + S_\delta \left[\psi, \delta, u^i\right]$$

Mass conservation

Euler equation

$$\dot{\theta} + 2H\theta + \tfrac{3}{2}H^2\delta = \partial_j \left(u^i \partial_j u^i\right) + S_\theta \left[\psi, \delta, u^i\right]$$

Momentum conservation

Einstein equations

$$\nabla^2\psi = \tfrac{5}{2}H^2\delta + S_\psi[\psi, \delta, \theta] \qquad \nabla^2 w_i = S_w[\psi, \delta, \theta]$$

- Separation between Newtonian result and relativistic (corrections suppressed by $\epsilon = \frac{H^2}{\nabla^2}$):

$$\delta = \delta_N + \delta_R, \qquad u^i = u^i_N + \left(u^i_R + u^i_T\right), \qquad \theta = \partial_i u^i$$

Matter perturbation dynamics

- Evolution equation for matter perturbations.

$$\ddot{\delta}(t, \boldsymbol{k}) + 2H\dot{\delta}(t, \boldsymbol{k}) - \frac{3}{2}H^2\delta(t, \boldsymbol{k}) = S(t, \boldsymbol{k})[\psi, \delta, u^i]$$

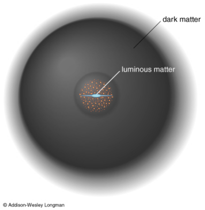
- Solving with standard perturbation theory, $\delta \ll 1$ and $\theta \ll 1$

The solution to fluid equations is an expansion in powers of the linear density perturbation

$$\delta(t, \boldsymbol{k}) = \sum_{n=1}^{\infty} a^n(t) \int_{\boldsymbol{k}_1 \cdots \boldsymbol{k}_n} (2\pi)^3 \delta_D(\boldsymbol{k} - \boldsymbol{k}_{1\cdots n}) \left[F_n\left(\boldsymbol{k}_1, \cdots, \boldsymbol{k}_n\right) + a^2(t) H^2(t) F_n^R(\boldsymbol{k}_1, \cdots, \boldsymbol{k}_n)\right] \delta_\ell\left(\boldsymbol{k}_1\right) \cdots \delta_\ell\left(\boldsymbol{k}_n\right)$$

- During matter domination $H^2 \sim \frac{1}{a^3}$

Galaxy Bias



Galaxies move with dark matter fluid

Neglect bias velocity.

Galaxy formation is a local processes.

- Matter density contrast.
- The extrinsic curvature of the constant-time hypersurfaces.

At a very early time $a_* \Longrightarrow$ Adiabatic initial conditions

$$\delta_g(a_*) = \sum_{n=1}^{4} \frac{b_n^*}{n! a_*^n} \delta^n + \sum_{n=2}^{4} \frac{b_{s^n}^*}{a_*^n} (S^n) + \frac{b_{\delta s^2}^*}{a_*^3} (S^2)\delta + \frac{b_{\delta^2 s^2}^*}{a_*^4} (S^2)\delta^2 + \frac{b_{\delta s^3}^*}{a_*^4} (S^3)\delta + \frac{b_{(s^2)^2}^*}{a_*^4} (S^2)^2$$

$$S^i{}_j \equiv (K^\ell{}_\ell \delta^i_j / 3 - K^i{}_j)/H^2$$

Galaxy bias evolution

Conserved number of galaxies

$$\dot{\delta}_g + \theta = -\partial_i \left(\delta_g u^i\right) + S_{\delta_g}\left[\psi, \delta_g, u^i\right]$$

At first order:

$$\delta_g(\eta_*) = b_1^* \delta_\ell \Longrightarrow \delta_g^{(1)} = a\delta_\ell \left(1 + \frac{b_1^*}{a}\right)$$

Eulerian Galaxy bias up to fourth order in perturbations

$$\delta_g(\boldsymbol{k}, a) = \delta(\boldsymbol{k}, a) + \sum_{n=1}^{\infty} a^n \int_{\boldsymbol{k}_1 \cdots \boldsymbol{k}_n} \delta_D(\boldsymbol{k} - \boldsymbol{k}_{1\ldots n}) \sum_{\mathcal{O}} b_{\mathcal{O}}^{\mathcal{L}} M_n^{\mathcal{O}}(\boldsymbol{k}_1, \cdots, \boldsymbol{k}_n, a) \delta_\ell(\boldsymbol{k}_1) \cdots \delta_\ell(\boldsymbol{k}_n)$$

$$M_n^{\mathcal{O}}(\boldsymbol{k}, \eta) = M_n^{\mathcal{O},N}(\boldsymbol{k}) + a^2 H^2 M_n^{\mathcal{O},R}(\boldsymbol{k})$$

Renormalization of the bias operators

The bias solution $\delta_g = \delta + \mathcal{O}$ generates correlations functions which have UV divergences coming from the composed operators $\mathcal{O}$.

Renormalization condition

$$\lim_{\boldsymbol{q}_i \to 0} \left\langle [\mathcal{O}_{\boldsymbol{k}}]_\Lambda \, \delta^{(1)}_{\boldsymbol{q}_1} \cdots \delta^{(1)}_{\boldsymbol{q}_n} \right\rangle = \left\langle [\mathcal{O}_{\boldsymbol{k}}] \, \delta^{(1)}_{\boldsymbol{q}_1} \cdots \delta^{(1)}_{\boldsymbol{q}_n} \right\rangle_{\text{tree}}$$

Assassi, Baumann, Green, Zaldarriaga (2014)

Renormalization for the operator proportional to b_2^*

$$\frac{b_2^*}{2a_*^2} \left\langle \delta^2 \right\rangle = \frac{1}{2} b_2^* \int_{\boldsymbol{q}} P_L(q) = \frac{1}{2} b_2^* \sigma^2_\Lambda(q)$$

$$\frac{1}{2a^2} b_2^* \lim_{\boldsymbol{k}\to 0} \left\langle \delta_\ell(\boldsymbol{k}) \delta^2(-\boldsymbol{k}) \right\rangle' = \left(-\frac{5}{k^2} \sigma^2(\Lambda) - 5\sigma^2_{-2}(\Lambda) \right) b_2^* a^3 H_*^2 P(k)$$

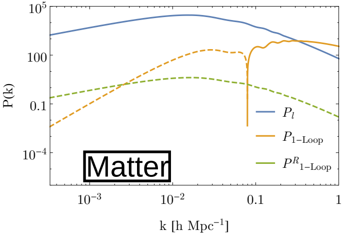
$$\left[\frac{1}{2a_*^2} b_2^* \delta^2 \right]_\Lambda = \frac{1}{2a_*^2} b_2^* \delta^2 - \frac{1}{2} b_2^* \sigma^2 + \frac{5}{k^2} b_2^* \sigma^2 \delta_\ell + 5 b_2^* a_*^3 H_*^2 \sigma^2_{-2} \delta_\ell$$

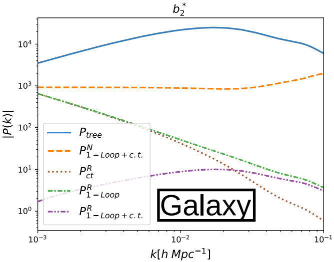
The comoving physical cutoff scale is modified by the presence of the long-wavelength perturbation $\sigma(\Lambda_{\text{phy}}) = \left(1 - \frac{10}{k^2} \delta_\ell\right)$. de Putter, Doré, Green (2015)

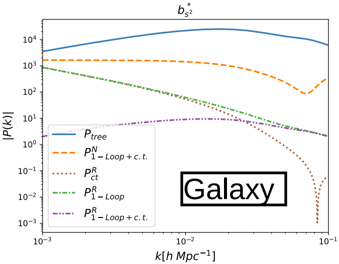
One-loop power spectrum

$$\langle \delta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2)\rangle = (2\pi)^3 \delta_D(\boldsymbol{k}_{12}) P(k_1)$$

$$P(k) = P_{11}(k) + P_{22}(k) + P_{13}(k)$$



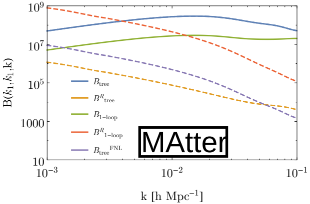




One-loop bispectrum

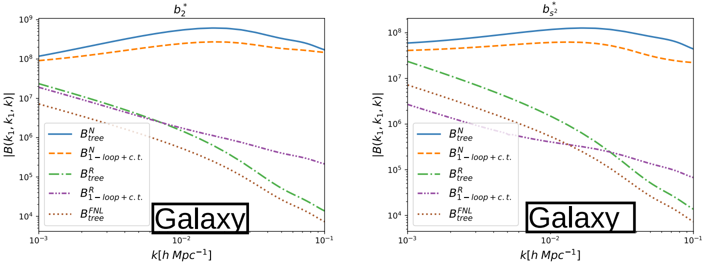
$$\langle \delta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2)\delta(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta_D(\boldsymbol{k}_{123})B(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$

$$B(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = B_{211} + B_{321} + B_{222} + B_{411}$$



Primordial non-Gaussianity of the local type

$$\psi_o = \psi_G + f_{NL}\psi_G^2 \Longrightarrow F_2^{NL}(\boldsymbol{k}_1,\boldsymbol{k}) \propto \frac{1}{\boldsymbol{k}_1^2\boldsymbol{k}^2}$$



$k_1 = 0.1\text{h/Mpc}$

Conclusions

- We compute evolution for matter and galaxy perturbations in a framework which is based on general relativity and is non-linear under the weak field approximation.
- Relativistic corrections to the bispectrum are degenerated with the primordial non-Gaussianity (PNG) of the local type.
- Relativistic corrections to the bispectrum have to be considered when comparing with observations in order to avoid misinterpreting them as PNG.

Work in progress

We are computing projections effects related with photon propagation.

- Photon geodesic
- Redshift perturbations. >Redshift space distortions.
- Volume perturbations. >Lensing.

J. Calles, L. Castiblanco, J. Noreña, and C. Stahl, "**Work in Progress**"

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