Report of the first year
Research Fellow [(profilo: settore scientifico disciplinare FIS/05 - Astronomia e astrofisica) ai sensi dell’art. 24 comma 3 lettera a) della Legge 30 dicembre 2010, n. 240]

Daniele Bertacca

Riunione ASI/COSMOS - Pre-RA4 Meeting
Milano 5-6 March 2019

Dipartimento di Fisica e Astronomia Galileo Galilei
Università degli Studi di Padova

Cosmic Orbital and Suborbital Microwave ObservationS

The main topic of this year has been the study of the Universe on large scales, which is one of the major science cases for the next-generation cosmological and gravitational waves experiments.

During the first year I devoted my work to open new projects (e.g. Science Working Group of the Euclid Consortium) and new science collaborations in several experiments [e.g. in LISA Cosmology Group and Cosmology Group in GWIC 3G Science Team (related on ET)].

In the next slides I will discuss all tasks and works that I have performed during this year.

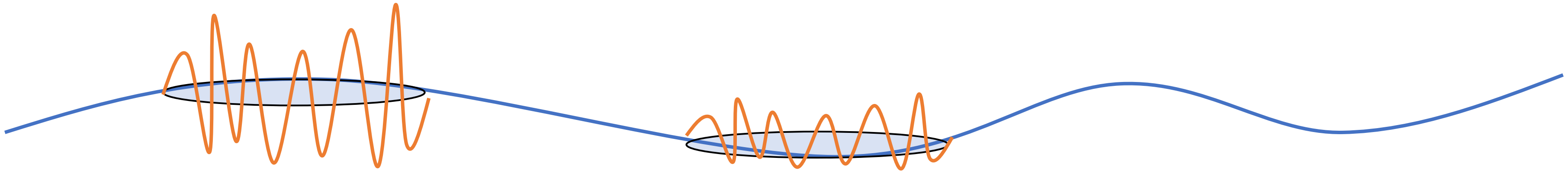
List of Publications

- D. J. Bacon et al. [SKA Collaboration], "Cosmology with Phase 1 of the Square Kilometre Array: Red Book 2018: Technical specifications and performance forecasts," Submitted to: Publ. Astron. Soc. Austral., arXiv:1811.02743.
- M. Hashim, C. Giocoli, M. Baldi, D. Bertacca and R. Maartens, "Cosmic Degeneracies III: N-body Simulations of Interacting Dark Energy with Non-Gaussian Initial Conditions," Mon. Not. Roy. Astron. Soc. 481 (2018) 2933 arXiv:1806.02356
- **K. Koyama, O. Umeh, R. Maartens and D. Bertacca, "The observed galaxy Bispectrum from single-field inflation in the squeezed limit," JCAP 1807 (2018) no.07, 050, arXiv:1805.09189.**

Consistency relation

The effect of long-wavelength modes on short-wavelengths modes can be regarded as a coordinate transformation in a patch where short-wavelength modes live

Large-scale modulation of small-scale power (Separate Universe approach):



J. M. Maldacena, JHEP **05**, 013 (2003), arXiv:astro-ph/0210603 [astro-ph].
N. Bartolo, S. Matarrese, and A. Riotto, Phys. Rev. **D64**, 123504 (2001), arXiv:astro-ph/0107502 [astro-ph].
P. Valageas, Phys. Rev. **D89**, 083534 (2014), arXiv:1311.1236 [astro-ph.CO].
L. Senatore and M. Zaldarriaga, JCAP **1208**, 001 (2012), arXiv:1203.6884 [astro-ph.CO].
S. Weinberg, Phys. Rev. **D67**, 123504 (2003), arXiv:astro-ph/0302326 [astro-ph].
E. Pajer, F. Schmidt, and M. Zaldarriaga, Phys. Rev. **D88**, 083502 (2013), arXiv:1305.0824 [astro-ph.CO].
P. Creminelli, J. Gleyzes, L. Hui, M. Simonović, and F. Vernizzi, JCAP **1406**, 009 (2014), arXiv:1312.6074 [astro-ph.CO].
P. Creminelli, J. Gleyzes, M. Simonović, and F. Vernizzi, JCAP **1402**, 051 (2014), arXiv:1311.0290 [astro-ph.CO].
P. Creminelli, J. Norea, M. Simonović, and F. Vernizzi, JCAP **1312**, 025 (2013), arXiv:1309.3557 [astro-ph.CO].
A. Kehagias, H. Perrier, and A. Riotto, Mod. Phys. Lett. **A29**, 1450152 (2014), arXiv:1311.5524 [astro-ph.CO].
A. Kehagias, J. Norea, H. Perrier, and A. Riotto, Nucl. Phys. **B883**, 83 (2014), arXiv:1311.0786 [astro-ph.CO].
A. Kehagias and A. Riotto, Nucl. Phys. **B873**, 514 (2013), arXiv:1302.0130 [astro-ph.CO].
A. Kehagias, A. M. Dizgah, J. Norea, H. Perrier, and A. Riotto, JCAP **1508**, 018 (2015), arXiv:1503.04467 [astro-ph.CO].

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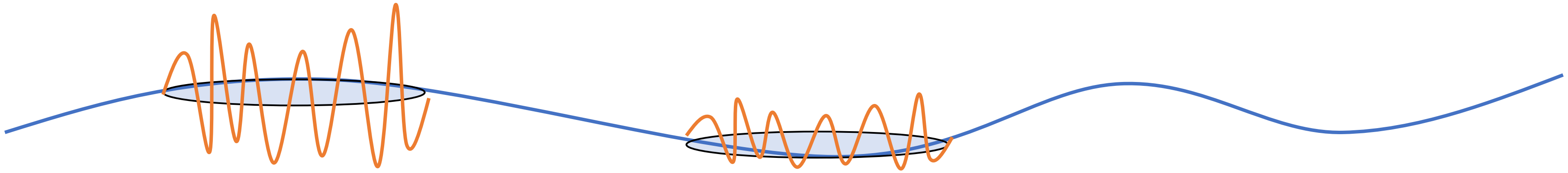

In the squeezed limit, where one of the three modes has a wavelength much longer than the other two, a simple analytical result can be obtained by using the **consistency relation**

This may introduce a correlation between long and short modes, leading to a nonzero squeezed-limit bispectrum.

We use this technique to derive the observed fluctuation of the number counts and confirm the validity of the full second-order [e.g. Bertacca et a. (2014a,b), Bertacca (2015)] results in the squeezed limit.

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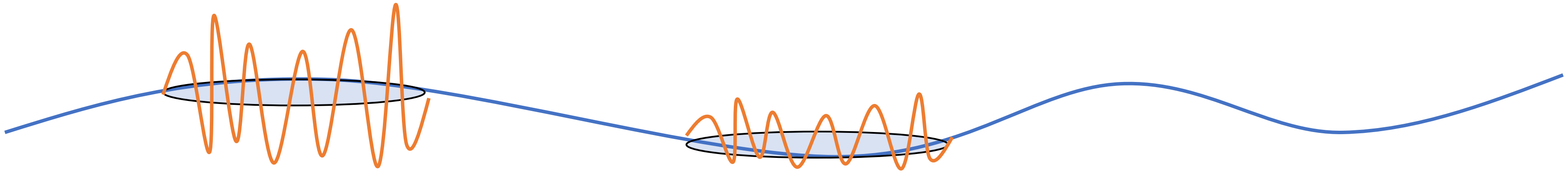

Example:

Dalal et al. (2008)
Matarrese & Verde (2008)
Slosar et al. (2008)

Newtonian potential a local function of ***Gaussian random field***

$$\Phi(x) = \phi_G(x) + f_{NL} \left(\phi_G^2(x) - \langle \phi_G^2 \rangle \right)$$

Split Gaussian field into long (L) and short (s) wavelengths $\phi_G(X+x) = \phi_L(X) + \phi_s(x)$

two-point function on small scales for given ϕ_L

$$\langle \Phi(x_1)\, \Phi(x_2) \rangle_L = (1+4 f_{NL}\, \phi_L) \langle \phi_s(x_1)\, \phi_s(x_2) \rangle + \ldots$$

i.e., ***inhomogeneous modulation of small-scale power***

$$\boldsymbol{P(k, X) \to [1 + 4 f_{NL}\, \phi_L(X)]\, P_s(k)}$$

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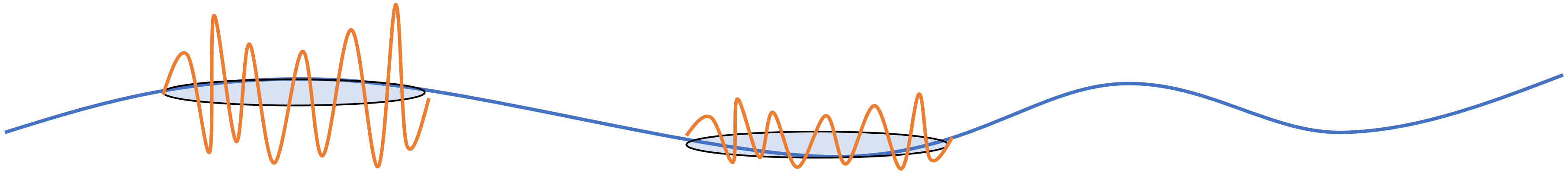

This technique for computing the squeezed-limit bispectrum comes with a warning in the case of Gaussian initial conditions, e.g. in a single-field inflation model:

- If we use the global coordinates, then we inadvertently include gauge modes (or gauge 'artifacts') in the consistency relation.
- In a single-field inflation model, these gauge modes can be removed by using local coordinates
- In this way, we find the correct result for the bispectrum — the removal of the gauge modes leads to a vanishing squeezed-limit bispectrum (in a single-field inflation model)

Koyama et al + DB JCAP 1807 (2018) no.07, 050

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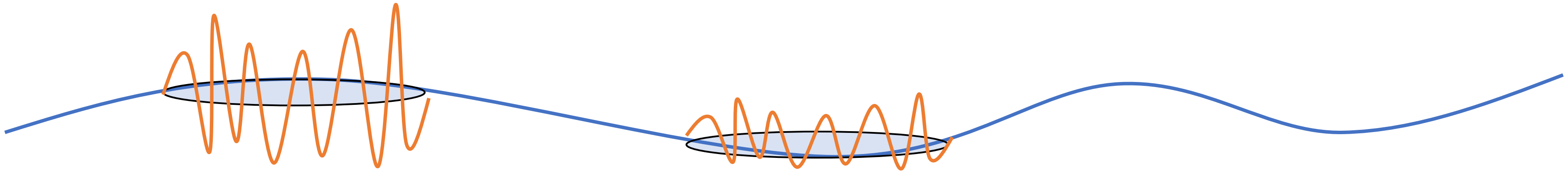
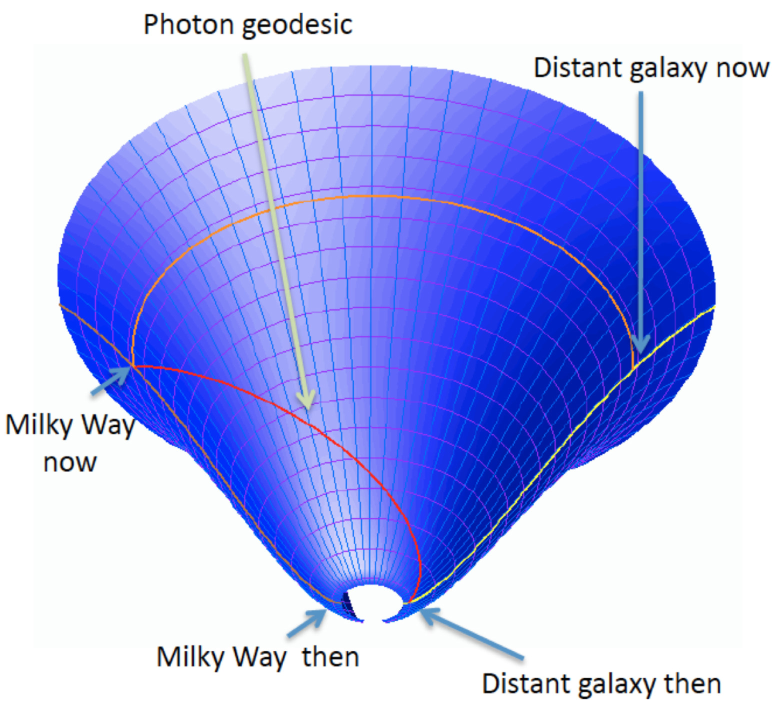


When the light-cone effects are taken into account, the squeezed-limit bispectrum is no longer zero, since the ultra-large scale relativistic effects correlate separated patches.

(However, it is still crucial to remove the gauge modes in second-order perturbations, in order to satisfy the consistency relation in observational coordinates.)

GALAXY CLUSTERING IN GENERAL RELATIVITY

- The standard approach to modeling galaxy clustering is based on the "Newtonian framework"
- It naturally breaks down on large scales, where relativistic (projection) effects become significant.



Observed galaxy density perturbation Δ_g

$$N_{\rm tot} = \int \sqrt{-g}\; n_{\rm phy}\; \varepsilon_{abcd}\; u^d\; \frac{\partial x^a}{\partial z_{\rm obs}} \frac{\partial x^b}{\partial \theta_{\rm obs}} \frac{\partial x^c}{\partial \phi_{\rm obs}}\; dz_{\rm obs}\; d\theta_{\rm obs}\; d\phi_{\rm obs}$$

manifestly gauge-invariant!

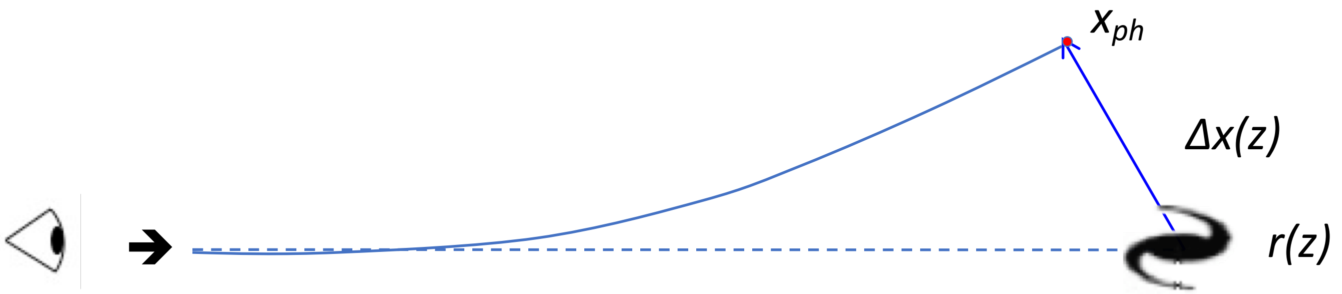
Observed galaxy density perturbation Δ_g

- The relativistic description of galaxy clustering can be derived from the fact that the number $dN_g^{\rm obs}$ of observed galaxies in a small volume is conserved:

$$dN_g^{\rm obs} = n_g^{\rm obs} dV_{\rm obs} = n_g^{\rm phy} dV_{\rm phy}$$

$n_g^{\rm obs}$ is the observed galaxy number density

$dV_{\rm obs}(z) = \dfrac{r^2(z)}{H(z)} \sin\theta \, dz \, d\theta \, d\phi$ is the observed volume element described by the observed galaxy position (θ, ϕ) on the sky and the observed redshift z



Observed galaxy density perturbation Δ_g

- The relation between observed and physical number density

$$a^3(\tilde{z})\tilde{n}_g(\tilde{\boldsymbol{x}},\tilde{z}) = a^3(\bar{z})n_g(\boldsymbol{x},\bar{z})\left[1+\delta V - 3\delta z - Q\delta L\right]_{(\tilde{\boldsymbol{x}},\tilde{z})} \qquad Q(\tilde{z}) \equiv -\frac{\partial \ln \bar{n}_g(\tilde{z},>L)}{\partial \ln L}$$

δV : volume perturbation $\qquad$ δL : luminosity perturbation

- Observed galaxy number density contrast

$$\tilde{n}_g(\tilde{\boldsymbol{x}},\tilde{z}) = \bar{n}_g(\tilde{z})\left[1+\Delta_g(\tilde{\boldsymbol{x}},\tilde{z})\right] \qquad a^3(\bar{z})n_g(\boldsymbol{x},\bar{z}) = a^3(\tilde{z})\bar{n}_g(\tilde{z})\left[1+b_e(\tilde{z})\delta z\right]\left[1+\delta_g(\boldsymbol{x},\bar{z})\right]$$

$$1+\Delta_g(\tilde{\boldsymbol{x}},\tilde{z}) = \left[1+\delta_g(\boldsymbol{x},\bar{z})\right]\left[1+(b_e-3)\delta z - Q\,\delta L + \delta V\right]$$

Yoo 1009.3021, Challinor & Lewis 1105.5292, Jeong, Schmidt, Hirata arXiv:1107.5427

Observed galaxy density perturbation Δ_g

- Volume and luminosity perturbations are gauge invariant

$$ds^2 = a^2(\eta)\Big[-(1+2\Phi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\Big]$$

$$\delta L = -2\Phi + 2\Big(1 - \frac{1}{\mathcal{H}\chi}\Big)(-\Phi + \partial_{\|}v + 2I) - \frac{2}{\chi}T - 2\kappa,$$

$$\delta V = -4\Phi + \frac{1}{\mathcal{H}}\Phi' + \Big(\frac{\mathcal{H}'}{\mathcal{H}} + \frac{2}{\chi\mathcal{H}}\Big)\Phi + \Big(-3 + \frac{\mathcal{H}'}{\mathcal{H}} + \frac{2}{\chi\mathcal{H}}\Big)(-\partial_{\|}v - 2I) - \frac{2}{\chi}T - 2\kappa$$

- The galaxy bias is naturally defined in the comoving-synchronous gauge

(= the rest frame of dark matter)

$$\delta z = -\Phi + \partial_{\|}v + 2I - \mathcal{H}v$$

Newtonian

$$\Delta_g = \boxed{\delta_g - \frac{1}{\mathcal{H}}\partial_{\|}^2 v} - \mathcal{H}(b_e - 3)v + \Big[b_e - \frac{\mathcal{H}'}{\mathcal{H}} - 2Q - 2\frac{(1-Q)}{\chi\mathcal{H}}\Big](-\Phi + \partial_{\|}v) + (-1+2Q)\Phi + \frac{1}{\mathcal{H}}\Phi'$$

(we ignored integral terms for simplicity)

$T = -2\int_0^{\chi} d\hat{\chi}\Phi,$ is the (Shapiro) time-delay term

$I = -\int_0^{\chi} d\hat{\chi}\Phi',$ is the integrated Sachs-Wolfe (ISW) effect at first order;

$\kappa = \int_0^{\chi} d\hat{\chi}\Big[(\chi - \hat{\chi})\frac{\hat{\chi}}{\chi}\nabla_{\perp}^2\Phi\Big]$ is the weak-lensing convergence term;

Observed galaxy density perturbation Δ_g

- The effect of long modes

$$1 + \left[\Delta_{gS}\right]_L(\tilde{\boldsymbol{x}}, \tilde{z}) = \left[1 + \Delta_{gS}(\boldsymbol{x}, \bar{z})\right]\left[1 + (b_e - 3)\delta z_L - Q\,\delta L_L + \delta V_L\right]$$

$$1 + \tilde{z} = (1 + \bar{z})(1 + \delta z_L), \quad \boldsymbol{x} = \tilde{\boldsymbol{x}} + \Delta \boldsymbol{x}_L$$

- To first order in long modes $\quad \Delta x^i = n^i \Delta x_{\|} + \Delta x^i_{\perp} \quad \partial_{\|} = n^i \dfrac{\partial}{\partial x^i}, \qquad \partial_{\perp i} = \dfrac{\partial}{\partial x^i} - n_i \partial_{\|}$

$$\begin{aligned}\left[\Delta^{(2)}_{gS}\right]_L = \Delta_{gS}&\left[(b_e - 3)\delta z_L - Q\,\delta L_L + \delta V_L\right] \\ &- (1+z)\delta z_L \frac{\partial}{\partial z}\Delta_{gS} + \Delta x_{L\|}\partial_{\|}\Delta_{gS} + \Delta x^i_{L\perp}\partial_{\perp i}\Delta_{gS} + \delta L_L \frac{\partial}{\partial L}\Delta_{gS}\end{aligned}$$

$$\Delta x_{\|} = -\frac{1}{\mathcal{H}}(-\Phi + \partial_{\|} v + 2I) - T - \partial_{\|}\xi, \qquad \xi = \int d\eta'\ v(\eta')$$

$$\Delta x^i_{\perp} = -2\int_0^{\chi} d\chi' \left[(\chi - \chi')\frac{\chi'}{\chi}\partial^i_{\perp}\Phi\right] - \partial^i_{\perp}\xi$$

Kehagias et.al. 1503.04467, Koyama et.al. 1805.09189

2nd order results

see Bertacca 1409.2024

$$
\begin{aligned}
\Delta_g^{(2)} = {} & \delta_g^{(2)} + \Big[b_e - 2\mathcal{Q} - \frac{\mathcal{H}'}{\mathcal{H}^2} - (1-\mathcal{Q})\frac{2}{\bar\chi\mathcal{H}}\Big]\Delta\ln a^{(2)} - (1-\mathcal{Q})\Big(2\Psi^{(2)} + \frac{1}{2}\hat h_\parallel^{(2)}\Big) - (1-\mathcal{Q})\frac{2}{\bar\chi}T^{(2)} - 2(1-\mathcal{Q})\kappa^{(2)} \\
& + \Phi^{(2)} + \frac{1}{\mathcal{H}}\Psi^{(2)\prime} - \frac{1}{2\mathcal{H}}\hat h_\parallel^{(2)\prime} - \frac{1}{\mathcal{H}}\partial_\parallel^2 v^{(2)} - \frac{1}{\mathcal{H}}\partial_\parallel \hat v_\parallel^{(2)} + 2(-1+2\mathcal{Q})\Phi\delta_g^{(1)} - \frac{2}{\mathcal{H}}\delta_g^{(1)}\partial_\parallel^2 v + \frac{2}{\mathcal{H}}\delta_g^{(1)}\Phi' + \frac{2}{\mathcal{H}}\Big(2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\Phi\Phi' \\
& + \Big(-5 + 4\mathcal{Q} + 4\mathcal{Q}^2 - 4\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Phi^2 + (\partial_\parallel v)^2 - \frac{2}{\mathcal{H}}\Big(1 + 2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\Phi\partial_\parallel^2 v + \frac{2}{\mathcal{H}^2}(\Phi')^2 + \frac{2}{\mathcal{H}^2}\big(\partial_\parallel^2 v\big)^2 - \frac{2}{\mathcal{H}}\Phi\partial_\parallel\Phi \\
& + \frac{2}{\mathcal{H}^2}\partial_\parallel v\partial_\parallel^2\Phi + \frac{4}{\mathcal{H}}\partial_\parallel v\partial_\parallel\Phi - \frac{2}{\mathcal{H}^2}\Phi\partial_\parallel^3 v + \frac{2}{\mathcal{H}^2}\Phi\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar\chi} - \frac{2}{\mathcal{H}^2}\partial_\parallel v\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar\chi} + \frac{2}{\mathcal{H}}\Big(1 + \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\partial_\parallel v\partial_\parallel^2 v - \frac{2}{\mathcal{H}^2}\Phi\partial_\parallel^2\Phi \\
& + \frac{2}{\mathcal{H}}\Big(1 - \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\partial_\parallel v\Phi' - \frac{4}{\mathcal{H}^2}\partial_\parallel^2 v\Phi' + \frac{2}{\mathcal{H}^2}\partial_\parallel v\partial_\parallel^3 v + \frac{2}{\mathcal{H}}\partial_{\perp i}v\partial_\perp^i\Phi - \frac{4}{\mathcal{H}}\partial_{\perp i}v\partial_\perp^i\partial_\parallel v + \Big(-1 + \frac{4}{\bar\chi\mathcal{H}}\Big)\partial_{\perp i}v\partial_\perp^i v \\
& + \Big\{\Big[-2b_e - 4\mathcal{Q} + 4b_e\mathcal{Q} - 8\mathcal{Q}^2 + 8\frac{\partial\mathcal{Q}}{\partial\ln\bar L} + 4\frac{\partial\mathcal{Q}}{\partial\ln\bar a} + 2\frac{\mathcal{H}'}{\mathcal{H}^2}(1-2\mathcal{Q}) + \frac{4}{\bar\chi\mathcal{H}}\Big(-1 + \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Big]\Phi \\
& + 2\Big[b_e - 2\mathcal{Q} - \frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{2}{\bar\chi\mathcal{H}}(1-\mathcal{Q})\Big]\delta_g^{(1)} - \frac{2}{\mathcal{H}}\frac{\mathrm{d}\delta_g^{(1)}}{\mathrm{d}\bar\chi} + \frac{2}{\mathcal{H}}\Big[-b_e + 2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2}{\bar\chi\mathcal{H}}(1-\mathcal{Q})\Big]\partial_\parallel^2 v \\
& + \frac{2}{\mathcal{H}}\Big[-2 + b_e - \frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{2}{\bar\chi\mathcal{H}}(1-\mathcal{Q})\Big]\Phi' - \frac{4}{\mathcal{H}}\mathcal{Q}\partial_\parallel\Phi + 4\Big[-\Big(b_e - b_e\mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L} - \frac{\partial\mathcal{Q}}{\partial\ln\bar a}\Big) + \frac{\mathcal{H}'}{\mathcal{H}^2}(1-\mathcal{Q}) \\
& + \frac{1}{\bar\chi\mathcal{H}}\Big(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Big]\Big(\frac{1}{\bar\chi}T^{(1)} + \kappa^{(1)}\Big)\Big\}\Delta\ln a^{(1)} + \Big\{-b_e + b_e^2 + \frac{\partial b_e}{\partial\ln\bar a} + 6\mathcal{Q} - 4\mathcal{Q}b_e + 4\mathcal{Q}^2 \\
& - 4\frac{\partial\mathcal{Q}}{\partial\ln\bar L} - 4\frac{\partial\mathcal{Q}}{\partial\ln\bar a} + (1 - 2b_e + 4\mathcal{Q})\frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{\mathcal{H}''}{\mathcal{H}^3} + 3\Big(\frac{\mathcal{H}'}{\mathcal{H}^2}\Big)^2 + \frac{6}{\bar\chi}\frac{\mathcal{H}'}{\mathcal{H}^3}(1-\mathcal{Q}) + \frac{2}{\bar\chi^2\mathcal{H}^2}\Big(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big) \\
& + \frac{2}{\bar\chi\mathcal{H}}\Big[1 - 2b_e - \mathcal{Q} + 2b_e\mathcal{Q} - 4\mathcal{Q}^2 + 4\frac{\partial\mathcal{Q}}{\partial\ln\bar L} + 2\frac{\partial\mathcal{Q}}{\partial\ln\bar a}\Big]\Big\}\big(\Delta\ln a^{(1)}\big)^2 + 4\Big[+\frac{1}{\mathcal{H}}\Big(1 - \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\Phi' + \frac{1}{\mathcal{H}}\partial_\parallel\Phi \\
& + \frac{1}{\mathcal{H}}\Big(1 + \frac{\mathcal{H}'}{\mathcal{H}^2}\Big)\partial_\parallel^2 v + \frac{1}{\mathcal{H}^2}\partial_\parallel^2\Phi + \frac{1}{\mathcal{H}^2}\partial_\parallel^3 v - \frac{1}{\mathcal{H}^2}\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar\chi}\Big]I^{(1)} + \Big[-\frac{4}{\bar\chi}(1-\mathcal{Q})\delta_g^{(1)} - 2\partial_\parallel\delta_g^{(1)} - \frac{4}{\bar\chi\mathcal{H}}(1-\mathcal{Q})\Phi' \\
& + \frac{4}{\bar\chi}\Big(-1 + \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Phi + 2(1-2\mathcal{Q})\partial_\parallel\Phi + \frac{4}{\bar\chi\mathcal{H}}(1-\mathcal{Q})\partial_\parallel^2 v + \frac{2}{\mathcal{H}}\partial_\parallel^3 v - \frac{2}{\mathcal{H}}\partial_\parallel\Phi'\Big]T^{(1)} + \Big(1 - \mathcal{Q} + 2\mathcal{Q}^2 \\
& - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Big[\frac{2}{\bar\chi^2}\big(T^{(1)}\big)^2 + \frac{4}{\bar\chi}T^{(1)}\kappa^{(1)}\Big] + 4\Big[-\Big(1 - \mathcal{Q} - 2\mathcal{Q}^2 + 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\Phi + \frac{1}{\mathcal{H}}(1-\mathcal{Q})\partial_\parallel^2 v - \frac{1}{\mathcal{H}}(1-\mathcal{Q})\Phi' \\
& - (1-\mathcal{Q})\delta_g^{(1)}\Big]\kappa^{(1)} + (1-\mathcal{Q})\vartheta_{ij}^{(1)}\vartheta^{ij(1)} + 2\Big(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar L}\Big)\big(\kappa^{(1)}\big)^2 - 2(1-\mathcal{Q})\big|\gamma^{(1)}\big|^2 + 4\Big[\frac{\bar\chi}{\mathcal{H}}\Big(\partial_{\perp i}\Phi' \\
& - \partial_{\perp i}\partial_\parallel^2 v\Big) + \bar\chi\partial_{\perp i}\delta_g^{(1)} + \bar\chi\partial_{\perp i}\Phi - 2\bar\chi(1-\mathcal{Q})\partial_{\perp i}\Phi + \frac{1}{\mathcal{H}}(1-\mathcal{Q})\partial_{\perp i}\Delta\ln a^{(1)}\Big]S_\perp^{i(1)} - 4(1-\mathcal{Q})S_\perp^{i(1)}S_\perp^{j(1)}\delta_{ij} \\
& + 2\Big[\frac{2}{\bar\chi\mathcal{H}}\partial_{\perp i}v - \frac{\bar\chi}{\mathcal{H}}\partial_{\perp i}\Phi' + \frac{\bar\chi}{\mathcal{H}}\partial_{\perp i}\partial_\parallel^2 v - \frac{2}{\mathcal{H}}\partial_{\perp i}\partial_\parallel v - \bar\chi\partial_{\perp i}\delta_g^{(1)} - \bar\chi\partial_{\perp i}\Phi + 2\bar\chi(1-\mathcal{Q})\partial_{\perp i}\Phi\Big]\partial_\perp^i T^{(1)} \\
& + 4\mathcal{Q}^{(1)}\Big[\Phi - \Big(1 - \frac{1}{\bar\chi\mathcal{H}}\Big)\Delta\ln a^{(1)} + \frac{1}{\bar\chi}T^{(1)} + \kappa^{(1)}\Big] + 8(1-\mathcal{Q})\Big\{\int_0^{\bar\chi}\mathrm{d}\tilde\chi\Big[-\Phi\tilde\partial_{\perp m}S_\perp^{m(1)} + \Big(\frac{\mathrm{d}\Phi}{\mathrm{d}\tilde\chi} - \frac{1}{\tilde\chi}\Phi\Big)\kappa^{(1)}\Big] \\
& - \frac{1}{\bar\chi}\int_0^{\bar\chi}\mathrm{d}\tilde\chi\Big(\Phi^2 + \Phi' T^{(1)} + 2\Phi\kappa^{(1)} + \tilde\chi\tilde\partial_{\perp i}\Phi\partial_\perp^i T^{(1)}\Big) + \frac{1}{\bar\chi}\int_0^{\bar\chi}\mathrm{d}\tilde\chi\,(\bar\chi - \tilde\chi)\Big[-2\Phi\tilde\partial_{\perp m}S_\perp^{m(1)} + 2\Big(\frac{\mathrm{d}\Phi}{\mathrm{d}\tilde\chi} - \frac{1}{\tilde\chi}\Phi\Big)\kappa^{(1)}\Big]\Big\} \\
& - (1-\mathcal{Q})\big(24\Phi_o v_{\parallel o} + v_{\perp k\, o}v_{\perp o}^k\big) - 8(1-\mathcal{Q})v_{\parallel o}\Big(\frac{1}{\bar\chi}T^{(1)} + 3\int_0^{\bar\chi}\frac{\mathrm{d}\tilde\chi}{\tilde\chi}\Phi\Big) + 2\big(\Phi_o - v_{\parallel o}\big)\Big[\Big(\frac{\mathcal{H}'}{\mathcal{H}^3} + \frac{1}{\mathcal{H}}\Big)\partial_\parallel^2 v \\
& + \Big(-\frac{\mathcal{H}'}{\mathcal{H}^3} + \frac{1}{\mathcal{H}}\Big)\Phi' + \frac{1}{\mathcal{H}^2}\partial_\parallel^2\Phi + \frac{1}{\mathcal{H}^2}\partial_\parallel^3 v + \frac{1}{\mathcal{H}}\partial_\parallel\Phi - \frac{1}{\mathcal{H}^2}\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar\chi}\Big] + v_{\perp o}^i\Big[-2\bar\chi\partial_{\perp i}\Phi + 2\frac{\bar\chi}{\mathcal{H}}\partial_{\perp i}\big(-\Phi' + \partial_\parallel^2 v\big) - 2\bar\chi\partial_{\perp i}\delta_g^{(1)}\Big] \\
& + (1-\mathcal{Q})v_{\perp i\, o}\Big[4S_\perp^i - \frac{2}{\mathcal{H}}\partial_\perp^i\Delta\ln a^{(1)} + 4\bar\chi\partial_\perp^i\Phi\Big].
\end{aligned}
\tag{100}
$$

Including all redshift effects: lensing distortions from convergence and shear, and contributions from velocities, Sachs-Wolfe, integrated SW, magnification and time-delay terms.

See also D.B. et al.(2014a,b), Yoo & Zaldarriaga (2014), Di Dio et al (2014,2015)

Koyama et al + DB JCAP 1807 (2018) no.07, 050

Consistency relation

- Squeezed limit contribution from spatial dilatation in 2nd perturbations

  - This is generated by a spatial dilatation on an equal-time slice, which is not observables

    (Local physics should not be affected by long modes in a single field inflation model. The coupling between long and short modes disappears if perturbations are evaluated at a fixed physical scale, see Pajer et.al. 1305.0824, de Putter et.al. 1504.00351, Dai et.al. 1504.00351, Bartolo et.al. 1506.00915)

  - The effect of long modes needs to be calculated directly for what we actually observe and it is included in the observed position of galaxies $\boldsymbol{x} = \tilde{\boldsymbol{x}} + \Delta \boldsymbol{x}_L$ and the volume, luminosity and redshift perturbations in the consistency relation
  - This "projection effect" is included in the second order projection terms

With these corrections, 2nd order results satisfy the consistency relation

Squeezed limit bispectrum

Koyama et al + DB JCAP 1807 (2018) no.07, 050

We derive the expression for the observed galaxy bispectrum in the squeezed limit and compute the effective local non-Gaussianity due to general relativistic light cone effects

- Bispectrum from single-field inflation

$$\langle \Delta_g(\mathbf{k}_1)\Delta_g(\mathbf{k}_2)\Delta_g(\mathbf{k}_3)\rangle = (2\pi)^3 B_g(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)$$

$$\boldsymbol{k}_2 = -\boldsymbol{k}_1 \equiv -\boldsymbol{k}_S, \quad \boldsymbol{k}_3 \equiv \boldsymbol{k}_L, \quad k_1 = k_2 = k_S \gg k_3 = k_L, \quad \boldsymbol{k}_L \cdot \boldsymbol{k}_S = 0,$$

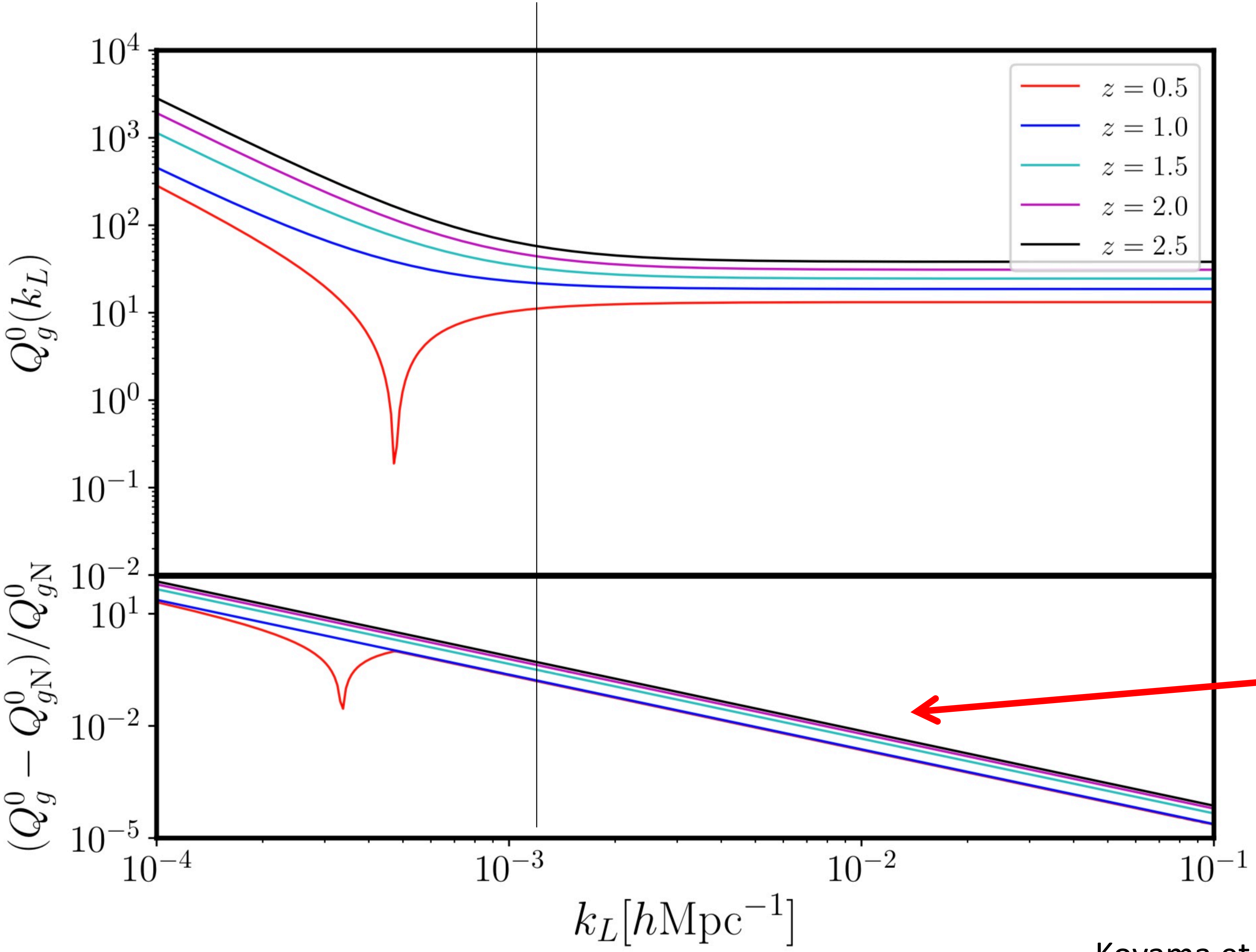
$$\mu_S \equiv \mu_1 = -\mu_2, \qquad \mu_L \equiv \mu_3 = \sqrt{1-\mu_S^2}\cos\phi\,,$$

$$B_g^0(k_L,k_S) = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_{-1}^{1} d\mu_S\, B_g(k_L,k_S,\mu_S,\phi) = \left(\mathcal{B}_0 + \frac{\mathcal{B}_2}{k_L^2} + \frac{\mathcal{B}_4}{k_L^4}\right)P(k_S)P(k_L)$$

- Bispectrum from primordial non-G (in Newtonian)

$$B_{g\mathrm{N}}^0(k_L,k_S)\Big|_{f_{\mathrm{NL}}} = \left(\mathcal{B}_{\mathrm{N}0} + f_{\mathrm{NL}}\frac{\mathcal{B}_{\mathrm{N}2}}{k_L^2} + f_{\mathrm{NL}}^2\frac{\mathcal{B}_{\mathrm{N}4}}{k_L^4}\right)P(k_S)P(k_L)$$

The reduced relativistic galaxy bispectrum in the squeezed limit

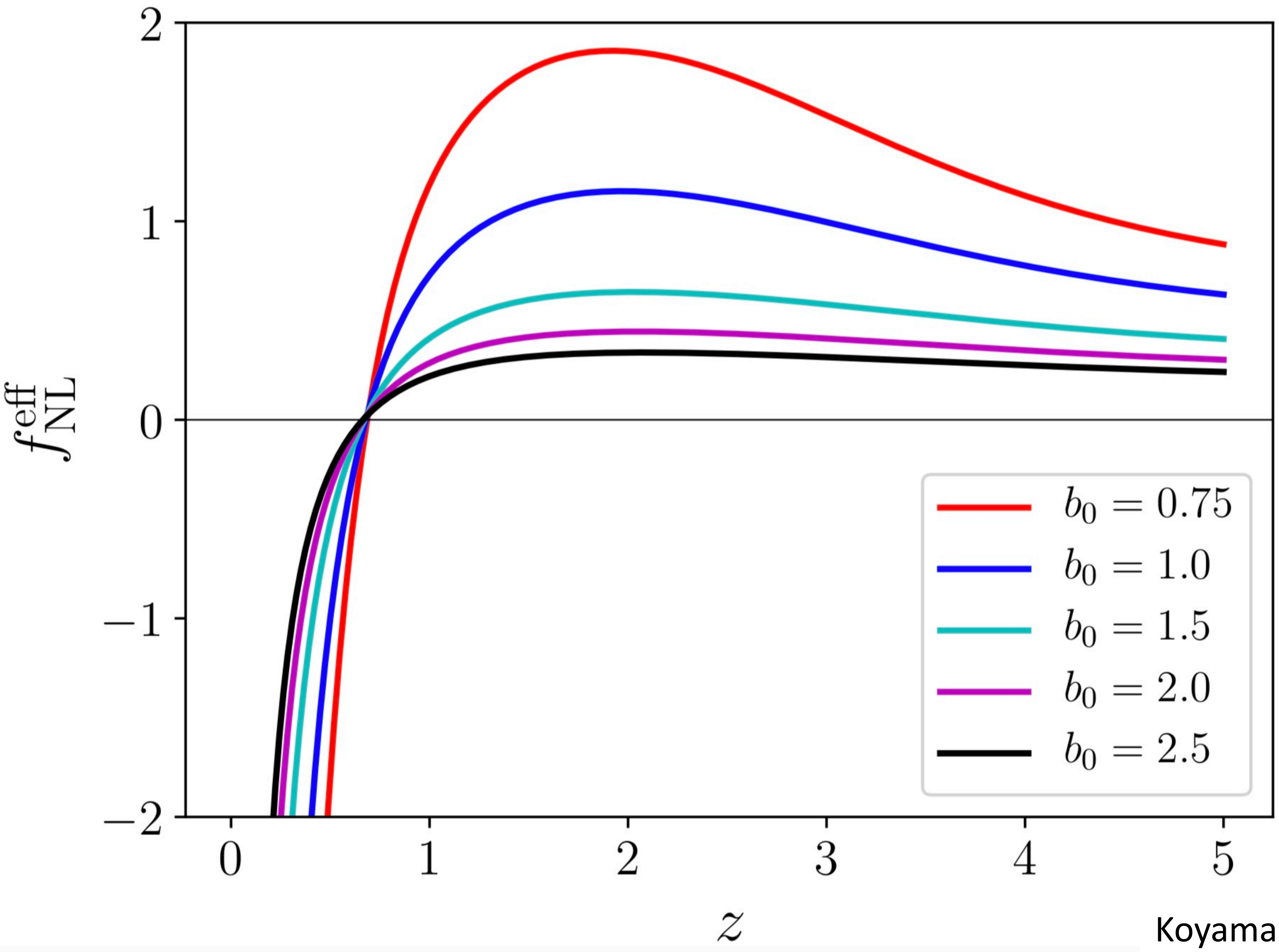


$$Q_g^0 = \frac{B_g^0(kSkL)}{P(k_s)P(k_L)}$$

The fractional difference relative to the Newtonian Q_{gN}^0

Koyama et al + DB JCAP 1807 (2018) no.07, 050.

Redshift dependence of the effective non-Gaussianity



$$f_{\rm NL}^{\rm eff} = \frac{\mathcal{B}_2}{\mathcal{B}_{\rm N2}}.$$

Koyama et al + DB JCAP 1807 (2018) no.07, 050.

Projects in preparation

Projects in preparation (1):

- Using LIGER method [see Mon. Not. Roy. Astron. Soc. 471 (2017)], in collaboration with Prof. Cristiano Porciani from Bonn University, I have two projects:

  i) We are studying the lensing effects and contaminations in the galaxy Power Spectrum (i.e. assuming flat-sky/plane parallel approximation),

  ii) We are working on a good estimator for wide-angle effects.

- In collaboration with Prof. Alessio Notari from Barcelona University, we are analyzing the systematic and GR effects on muon g−2 experiments.

Projects in preparation (2): (GWs works)

- In LISA cosmology working group, we are testing modified gravity at cosmological distances with LISA standard sirens.
- In collaboration with Prof. Sabino Matarrese, Dr. Angelo Ricciardone, I am analysing the Stochastic Gravitational Wave Power Spectrum using the observed quantities which are gauge invariant.
- In collaboration with Prof. Sabino Matarrese, Dr. Angelo Ricciardone, I am computing for the first time the Bispectrum for the Stochastic Gravitational Wave.

Projects in preparation (3): (Other reviews)

Large-scale galaxy clustering: a review

Alvise Raccanelli[a,*], Daniele Bertacca[b], Will J. Percival[c], Alexander S. Szalay[d]

[a] *ICC, University of Barcelona, Marti i Franques 1, Barcelona, 08028, Spain*
[b] *Argelander-Institut für Astronomie der Universität Bonn, D-53121 Bonn, Germany*
[c] *Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada*
[d] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218*

We are writing a review for the Physic Report Journal.

Until now we wrote around 185 pages. We hope to finish soon!

Projects in preparation (3): (Other reviews)

Alvise Ra… S. Szalay[d]

[a] IC… Spain

[b] Argelar… Germany

[c] Perimeter… oo, ON N2L

[d] Departme… Charles St.,

Abstract

We present a review on large-scale galaxy clustering, including the physical effects governing it and how it can be used to test cosmological models. We focus on large scales where the density field is linear and the effect of astrophysical modelling is minimal. After a review of the basics and the derivation of the standard formalism, we discuss the more recent developments, namely the inclusion of geometry and ultra-large scale effects. Measuring galaxy clustering accurately represents one of the main targets of forthcoming and planned cosmological galaxy surveys; we recollect measurements obtained so far, and discuss the precision in theoretical modeling needed to obtain the desired accuracy for future experiments. Furthermore, we investigate generalizations to deviations from General Relativity and primordial non-Gaussianity. We conclude with an outlook on future experiments and the theoretical improvements that are still needed.

We a…

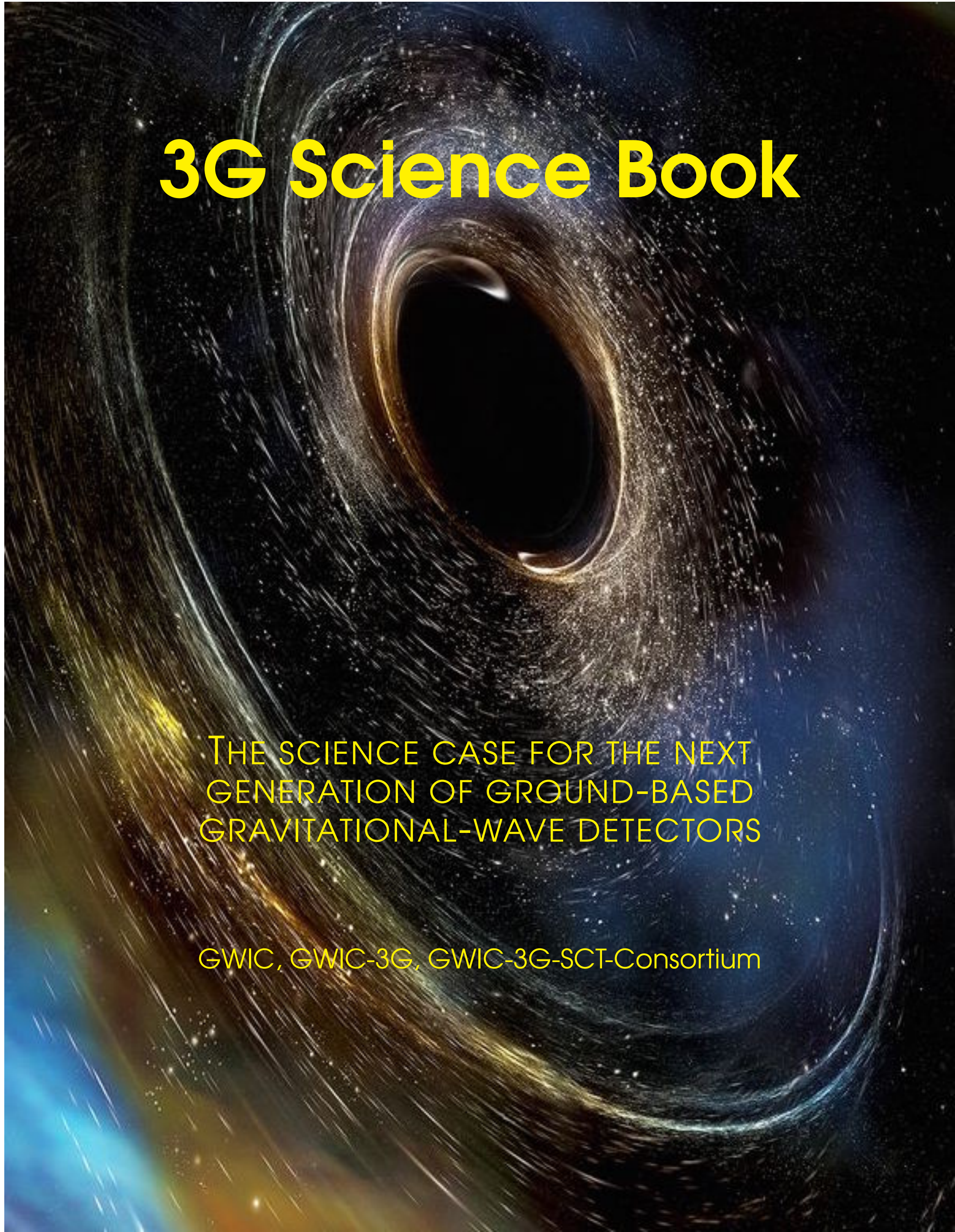
Until… n!

Projects in preparation (4):

I am a coauthor of the white book for 3G GW Science Collaboration.

This document was produced by the GWIC 3G Committee, the GWIC 3G Science Case Team and the International 3G Science Team Consortium

We wrote around 223 pages.



Projects in preparation (5):

- I am finalizing the following paper: ‘‘Generalisation of the Kaiser Rocket effect in general relativity in the wide-angle galaxy 2-point correlation function’’.

Bertacca in prep.

Dipole terms in the wide-angle galaxy two-point correlation:

- We are not observing the galaxy catalogs in the CMB rest frame. The motion of our galaxy is related on the peculiar velocity of the Local Group (LG), $v_r(\mathbf{0})$ [Juszkwwicz, Vittorio, Wise (1989), Lahav Kaiser Hoffman (1989)]
- Using the continuity equation and assuming the linear theory we can write the velocity field in the following way:

$$v_r(\mathbf{0}) = \frac{1}{H_0}\hat{\mathbf{r}} \cdot \mathbf{v}(\mathbf{0}) = \frac{f_0}{4\pi} \int_{V^{\mathcal{R}}} \mathrm{d}^3\mathbf{r}' \; \frac{\hat{\mathbf{r}} \cdot \hat{\mathbf{r}'}}{{r'}^2} \delta_{\mathrm{m}}^{\mathcal{R}}(\mathbf{r}')$$

(It guarantees that the peculiar velocities of the galaxies in the LG frame are small with respect to the distances r)

Bertacca in prep.

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- An important effect that we have to take into account is the impact of the rocket effect or also called *Kaiser rocket effect* [Kaiser (1987)]

$$W_r(r)\left(2 + \frac{\partial \ln \bar{n}_{\mathrm{g}}(r)}{\partial \ln r}\right)$$

- Signature of the *rocket effect* becomes very important if we consider the reconstructed LG motion at radii larger than $100h^{-1}$ Mpc, for example see [Nusser, Davis, and Branchini (2014)].

Bertacca in prep.

Relativistic (projection) effects

- The relativistic description of galaxy clustering can be derived from the fact that the number dN_g^{obs} of observed galaxies in a small volume is conserved:

$$dN_g^{\mathrm{obs}} = n_g^{\mathrm{obs}} dV_{\mathrm{obs}} = n_g^{\mathrm{phy}} dV_{\mathrm{phy}}$$

1) $dV_{\mathrm{phy}} \neq dV_{\mathrm{obs}}$ due to the distortion between these two volume elements: **the volume effect**, i.e. **the redshift-space distortions, the gravitational lensing**

2) Evolution bias b_e takes into account that the comoving number density of galaxies in the sample changes with redshift.

3) Magnification bias $\mathcal{Q}$: lensing magnification alters the observed number density of galaxies.

Bertacca in prep.

Dipole terms in the wide-angle galaxy two-point correlation:

Generalisation of the Kaiser rocket effect in GR

In GR, the rocket effect contains new terms that depends also on the magnification bias and the expansion rate:

$$\Delta_{v_\| o} = b(z)\omega_o(z) \int \frac{d^3k}{(2\pi)^3} \frac{\mathcal{P}_1(\hat{\mathbf{k}} \cdot \mathbf{n})}{ik} \delta(\mathbf{k}, 0)$$

where

$$\omega_o(z) = -\frac{H_0 f_0}{b(z)} \left[3 - b_e(z) - \frac{3}{2}\Omega_{\rm m}(z) + \frac{2(1+z)}{\chi(z)H(z)} \left(1 - \mathcal{Q}(z)\right) \right]$$

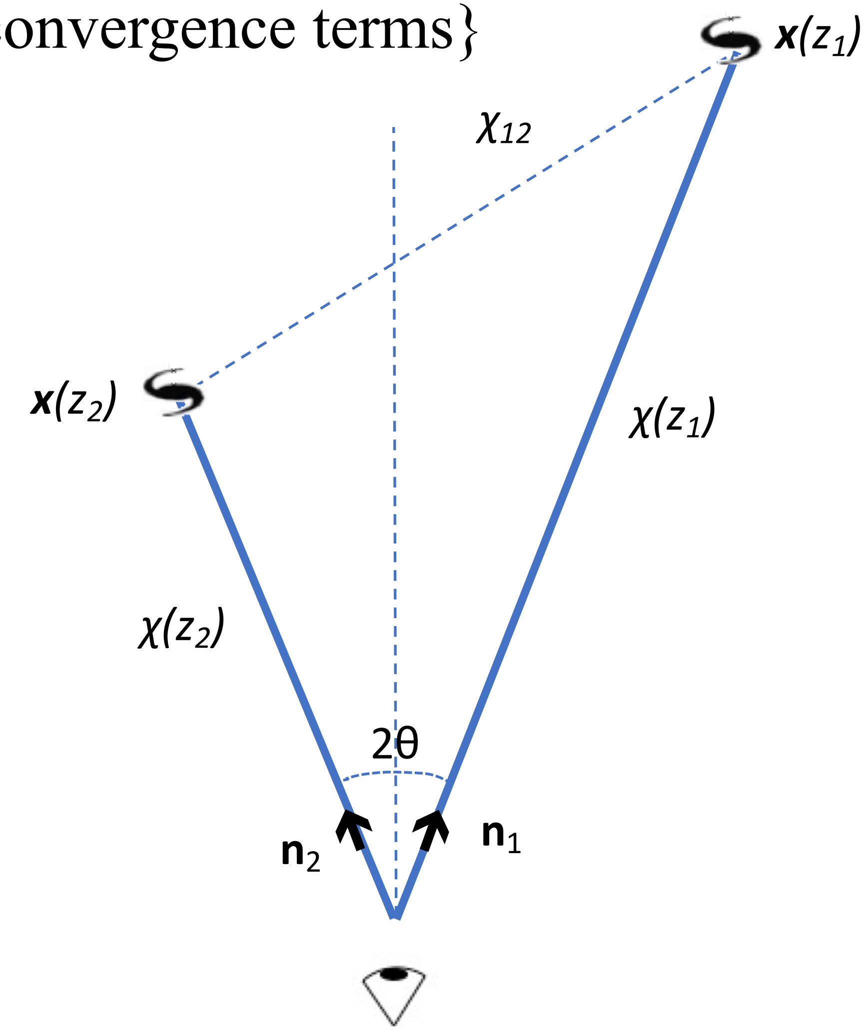
Then we need to understand if this effect is really relevant and/or the same order of GR and wide-angle contributions. See Scaccabarozzi, Yoo & Biern (2018), and Bertacca in prep. (2019).

Bertacca in prep.

Observed galaxy correlation

$$\xi_{\text{total}}(\mathbf{n}_1, z_1, \mathbf{n}_2, z_2) = \sum_{AB} \langle \Delta_A(\mathbf{n}_1, z_1) \Delta_B(\mathbf{n}_2, z_2) \rangle = \sum_{lm} C_l(z_1, z_2) Y_{lm}(\mathbf{n}_1) Y^*_{lm}(\mathbf{n}_2)$$

where {A, B} = {local, integrated, convergence terms}



$$\mathbf{x}_1 = \chi_1 \mathbf{n}_1$$

$$\mathbf{x}_2 = \chi_2 \mathbf{n}_2$$

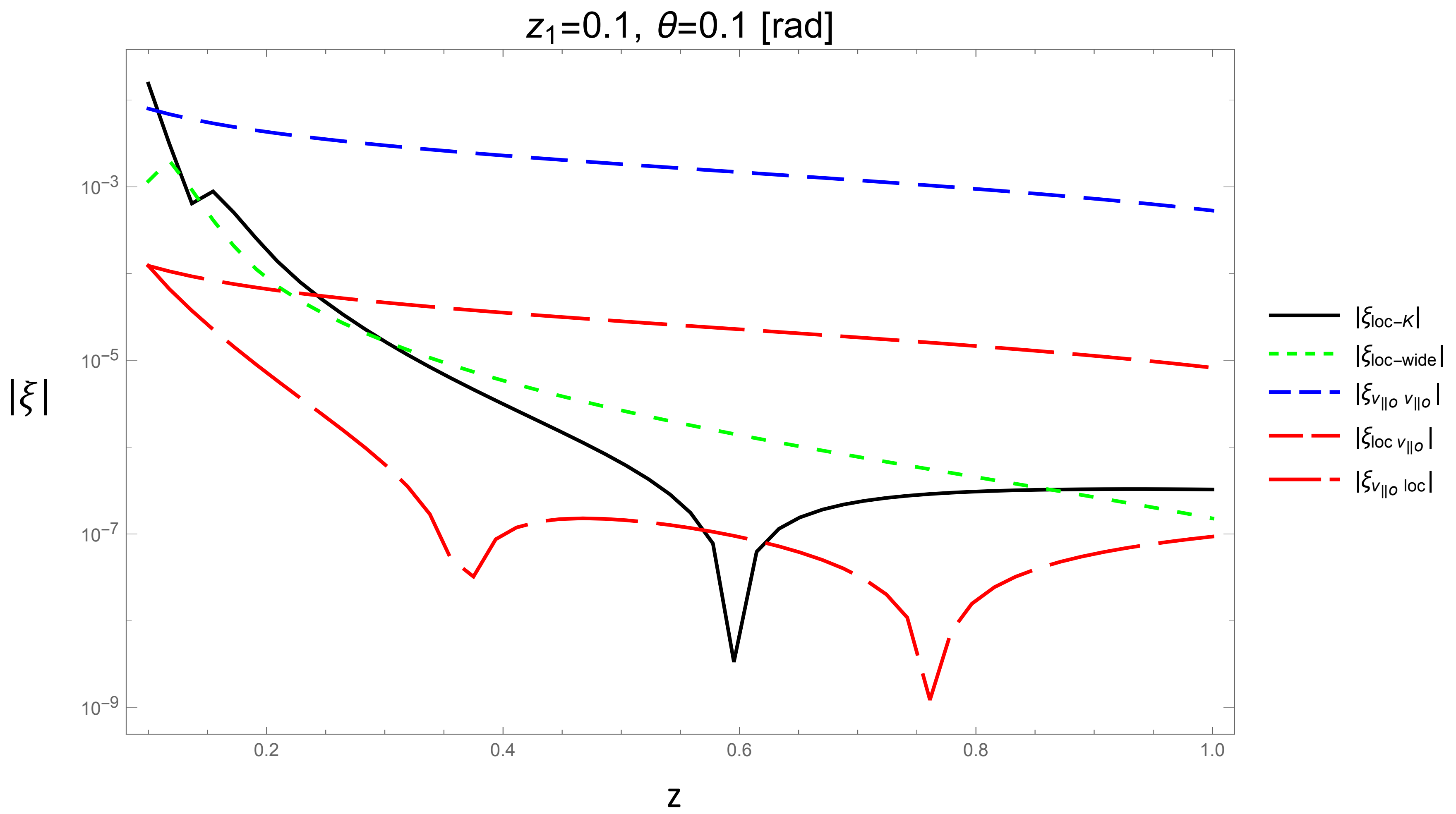
$$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2 \equiv \chi_{12} \mathbf{n}_{12}$$

$$\mathbf{n}_1 \bullet \mathbf{n}_2 = \cos(2\theta)$$

Bertacca et al 2012
Raccanelli (+ Bertacca) et al 2013, 2014, 2015, 2016

Dipole terms in the wide-angle galaxy two-point correlation:

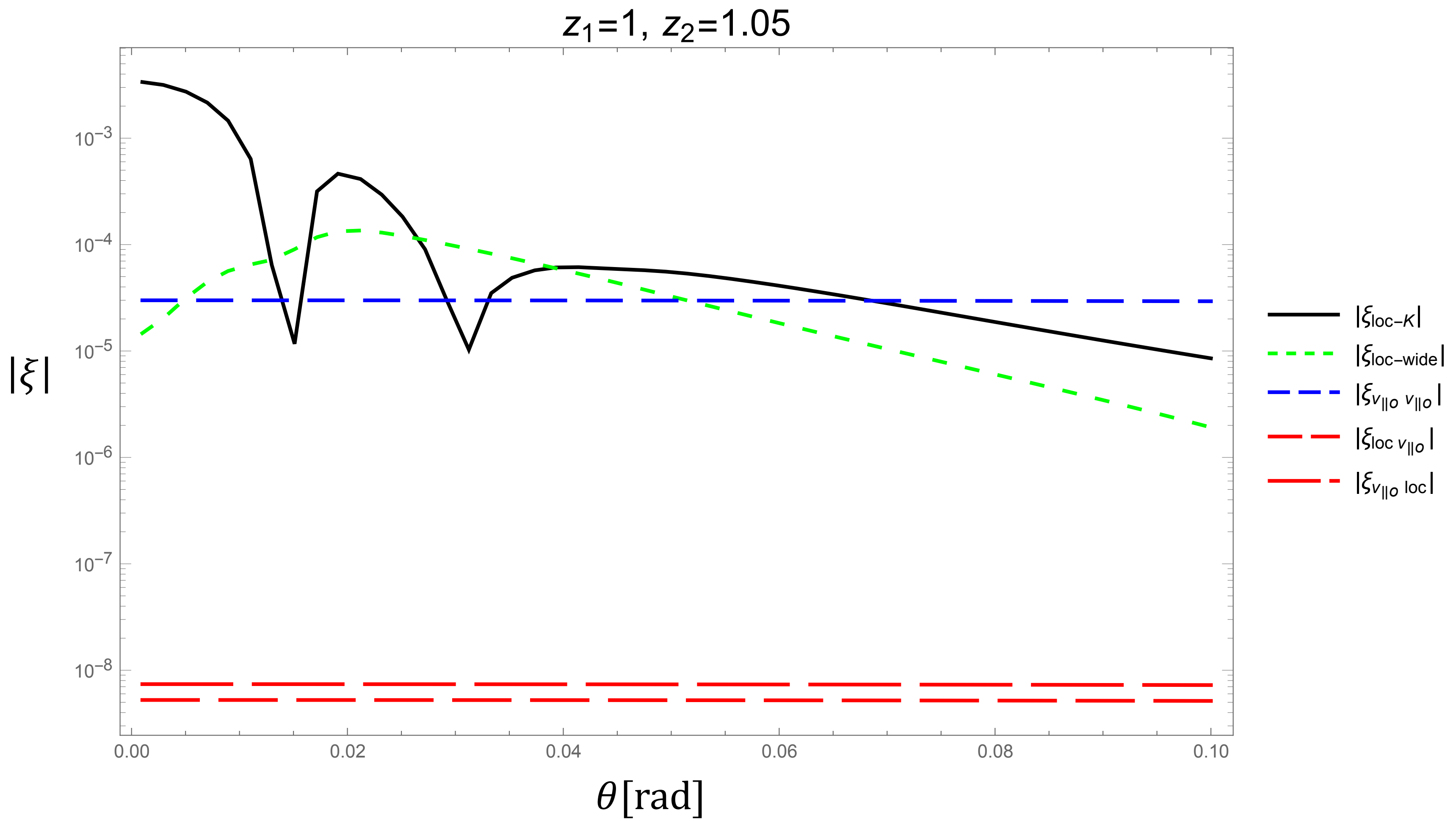
Generalisation of the Kaiser rocket effect in GR



Bertacca in prep.

Dipole terms in the wide-angle galaxy two-point correlation:

Generalisation of the Kaiser rocket effect in GR



Bertacca in prep.

New Membership in National and International Collaborations

- GWIC 3G Science Team - 3GSCT Cosmology Group. (2018-present)
- Member of High-order stats Science Working Group for the Euclid Consortium. (May 2018 - present)
- LISA Cosmology Group. (2018-present)
- Member of Galaxy Clustering Science Working Group for the Euclid Consortium. (November 2018-present)
- Member of Euclid Science Working Group CMBXC (which deals with cross-correlations between Euclid fields and CMB related fields as measured by Planck and other probes). (November 2018-present)
- Member of ASI/COSMOS network for Cosmic Microwave Background research. (March 2018-present)

Workshop and Conference Organization

- Scientific Organizing Committee of the workshop: “The vacuum of the Universe 2018: from cosmology to particle physics”, the Institut de Ciències del Cosmos Barcelona (Spain), 4 - 6 June 2018. The workshop is devoted to “CMB Anomalies and Tensions”. http://icc.ub.edu/congress/Vacuum2018/

- Scientific Organising Committee of the workshop: “General Relativistic effects in cosmological large-scale structure”, in Sesto Pusteria (Italy) on 16-20 July 2018. http://www.sexten-cfa.eu/en/conferences/2018/details/105-gr-effects-in-cosmological-lss.html

- Scientific Organising Committee of the “1st International PhD School on Physics of the Universe – Multi-Messenger Astrophysics”, Asiago Astronomical Observatory (Italy), 14 -23 January 2020 https://agenda.infn.it/event/17979/

Supervision/Teaching/ Thesis Committee

- From November 2018 to now, I am a co-supervisor of the MSc student Alice Garoffolo from Milan University.

- From June 2018 to Now, I am a co-supervisor of the MSc student Claudia Caputo.

- From April 2018 to Now, I supervise MSc student Monica Pagliaroli.

- Academic year 2018/2019. Title of the course: “Modern Physics” for postgraduate study course for MPhil degree in Mathematics at the University of Padua.

- During 2018, I was the internal examiner of a MSc thesis: the name of MSc student is Mrs. Alba Kalaja.

Conference and Workshop contributions as invited speaker

- Euclid and beyond: the many faces of modern cosmology Euclid and beyond: the many faces of modern cosmology, 11-13 February 2019 CNR Sala convegni, Pl.e Aldo Moro 7, Rome, Italy
  Title of the talk: “Light cone effects in the wide-angle galaxy 2-point correlation function”
- Euclid Galaxy Clustering - Weak Lensing SWG joint meeting, December 3-6 2018, Milan, Italy
  Title of the talk: “The LIGER method: light-cone using GR”
- Cosmology 2018 in Dubrovnik, 22-27 October 2018, Dubrovnik, Croatia
  Title of the talk: “The LIGER method: light-cone using GR”
- Workshop: “General Relativistic effects in cosmological large-scale structure”, Sesto Pusteria (Italy), 20 July 2018, Italy.
  Title of the talk: “Relativistic wide-angle galaxy Power Spectrum and Bispectrum on the light-cone: All-sky analysis”
- Workshop: “incontro Padova-Trento” on Gravitational Waves, 25 June 2018, Padua, Italy.
  Title of the talk: “Cosmology with Gravitational Waves”.
- Venice Cosmology Workshop 2018: The Island. A workshop to discuss the future of cosmology, 4-7 June 2018, Venice, Italy.
  Title of the talk: Discussion on “LSS Theory”.
- CosmoBack “From inhomogeneous gravity to cosmological back-reaction: Theoretical opportunity? Observational evidence?” 28-31 May 2018, Marseille, France.
  Title of the talks:

  1) “Relativistic wide-angle galaxy Power Spectrum and Bispectrum on the light-cone: All-sky analysis”
  2) “LIGER (LIght cones using GEneral Relativity) method”

- Conference “UniVersum 2018”, 13 April 2018, Bologna, Italy.
  Title of the talk: “Relativistic wide-angle galaxy power spectrum and bispectrum on the light-cone”

Other Schools, Meetings and Conferences attended

- Euclid consortium Meeting 14 February 2019 CNR “Sala convegni”, Pl.e Aldo Moro 7, Roma, Italy
- Workshop “CMB and Large-Scale Structure of the Universe?” - Nicola Vittorio’s 65th birthday, January 21-22 2019, Villa Mondragone, Monte Porzio Catone, Rome, Italy
- 6th workshop of the LISA Cosmology Working Group, Universidad Autonoma de Madrid, January 14-18 2019, Madrid, Spain
- Workshop: “Fundamental Physics with LISA”, November 12th-14th, 2018, Firenze, Italy.
- Third-Generation Science-Case Consortium Meeting, Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam (Germany), October 1-2, 2018.
- Cosmology Journal Club from March 2018 to now.
- SKA Cosmology SWG meeting, Turin (Italy), 13th - 14th Sept 2018.
- COSMOS meeting on Astroparticle and Fundamental Physics with the CMB, Ferrara (Italy), 26th - 27th June 2018.
- Annual meeting of the Euclid Theory Working Group, Institut Henri Poincaré, Paris (France), 16th - 18th April 2018.
- Annual meeting of the Euclid IST-forecast, Institut Henri Poincaré, Paris (France), 18th - 20th April 2018.
- The international GRAvitational-wave Science & technology Symposium (GRASS 2018), on March 1st and 2nd, 2018, Padova (Italy).

Thank You