Including relativistic and primordial Non-Gaussianity contributions in cosmological simulations by modifying the initial condition

500 Mpc/h

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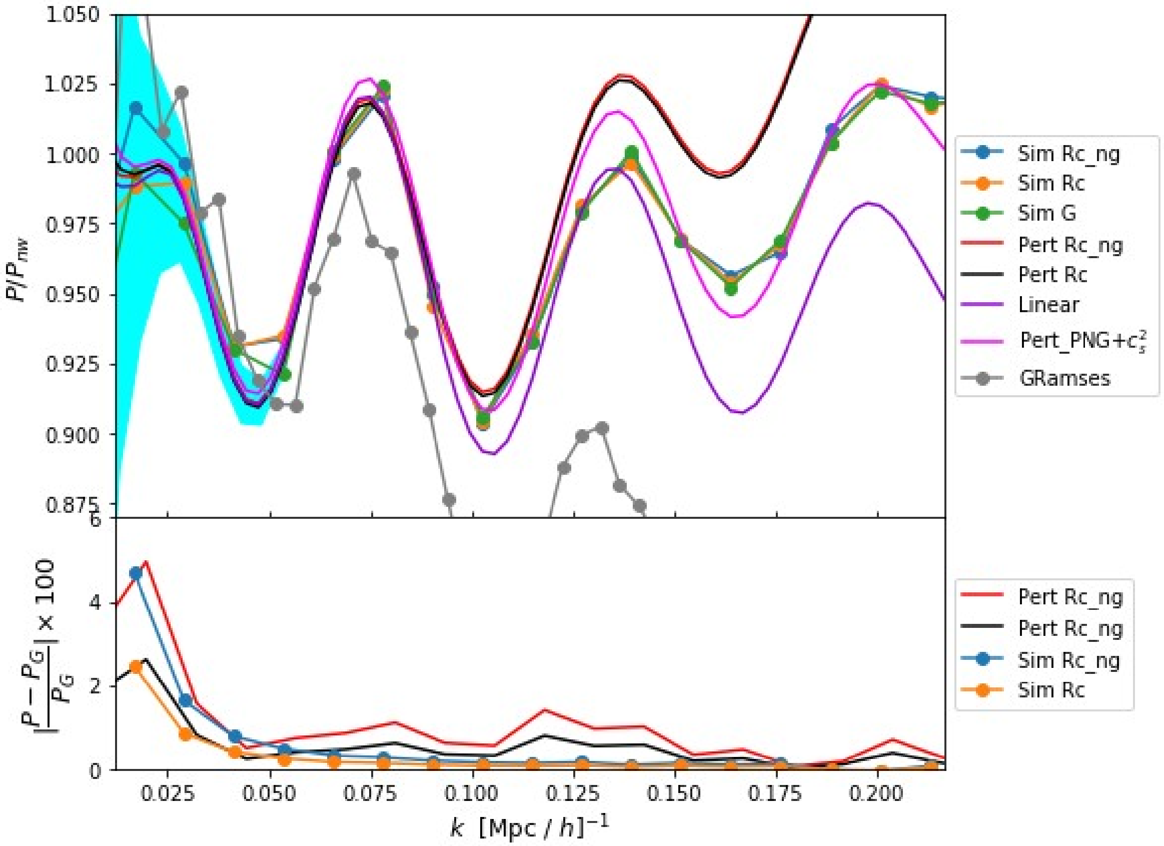
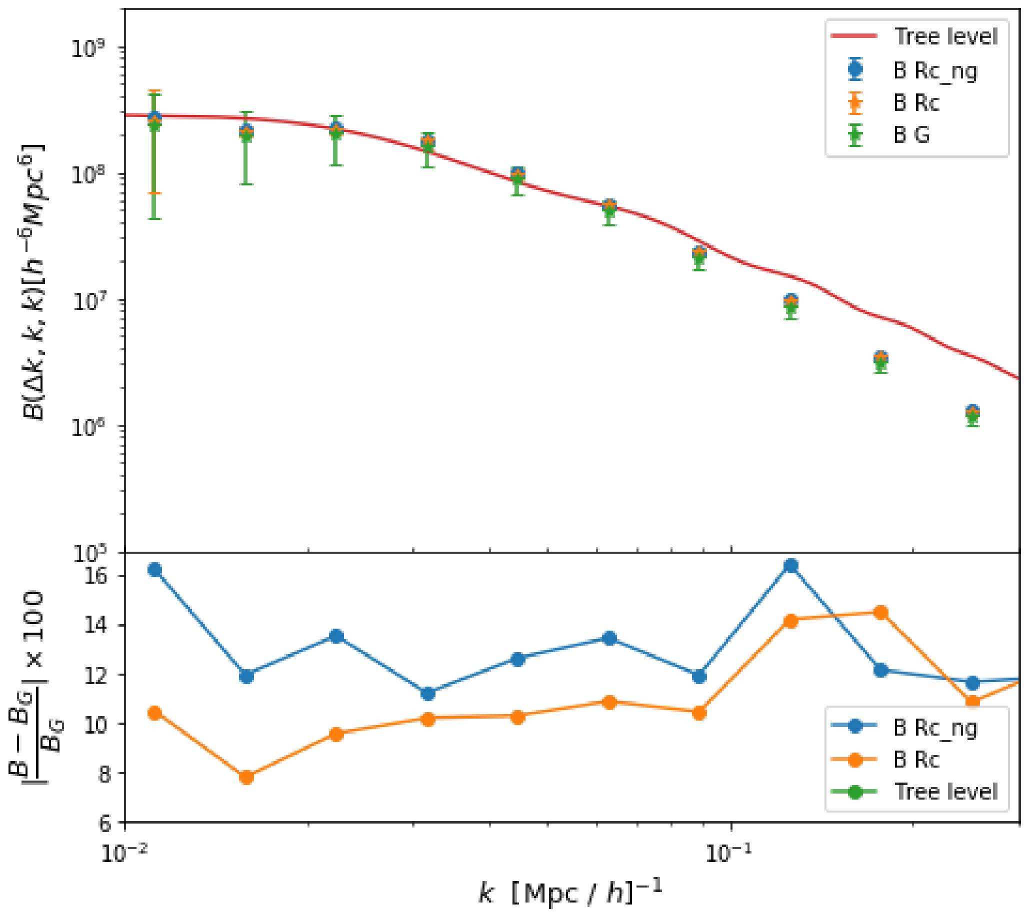
What is this all about…

Power spectrum



Bispectrum



Basic equations

FLRW universe with curvature k=0 in LCDM

$$ds^2 = a^2(\tau)\left[-d\tau^2 + \gamma_{ij}(\boldsymbol{x},\tau)dx^i dx^j\right]$$

Einstein equations

$$\theta^{i\prime}_j + 2\mathcal{H}\theta^i_j + \theta\theta^i_j + \frac{1}{4}\left(\theta^k_l\theta^l_k - \theta^2\right)\delta^i_j + R^i_j - \frac{1}{4}R\delta^i_j = 0$$

$$\theta^2 - \theta^i_j\theta^j_i + 4\mathcal{H}\theta + R = 16\pi G a^2\bar{\rho}\delta$$

Continuity equation

$$\frac{\rho'}{\rho} = -\frac{1}{2}\gamma^{ij}\gamma'_{ij} - 3\mathcal{H}$$

Raychaudhuri equation (relativistic)

$$\theta' + \mathcal{H}\theta + \theta^i_j\theta^j_i + 4\pi G a^2\bar{\rho}\delta = 0$$

Newtonian and relativistic correspondance

Newtonian

$$\frac{d\delta_N}{d\tau} = -(1+\delta_N)\nabla^2\nu_N$$

$$\frac{d(\nabla^2\nu_N)}{d\tau} + \mathcal{H}\nabla^2\nu_N + \partial^i\partial_k\nu_N\partial^k + \partial_i\nu_N + 4\pi G a^2\bar{\rho}\delta_N = 0$$

$$\theta = \nabla^2\nu_N = \nabla^2\nu_l^{(1)}$$

$$\theta^i_k = \partial^i\partial_k\nu_N = \partial^i\partial_k\nu_l^{(1)}$$

Relativistic

$$\delta' = -(1+\delta)\theta$$

$$\theta' + \mathcal{H}\theta + \theta^i_j\theta^j_i + 4\pi G a^2\bar{\rho}\delta = 0$$

GR. Constrain equation

$$\theta^2 - \theta^i_j\theta^j_i + 4\mathcal{H}\theta + R = 16\pi G a^2\bar{\rho}\delta$$

Perturbative and gradient expansion of the relativistic contribution

$$R = -4\nabla^2\zeta + (-2)[(\nabla\zeta)^2 - 4\zeta\nabla^2\zeta] + 2[2(\nabla\zeta)^2 - 4\zeta\nabla^2\zeta]\zeta$$

$$\zeta = \zeta^{(1)} + \frac{3}{5}f_{\rm NL}\zeta^{(1)2} + \frac{9}{25}g_{\rm NL}\zeta^{(1)3}$$

$$\begin{aligned} R \simeq & -4\nabla^2\zeta^{(1)} + \left(\nabla\zeta^{(1)}\right)^2\left[-2 - \frac{24}{5}f_{\rm NL}\right] + \zeta^{(1)}\nabla^2\zeta^{(1)}\left[-\frac{24}{5}f_{\rm NL} + 8\right] \\ & + \zeta^{(1)}\left(\nabla\zeta^{(1)}\right)^2\left[-\frac{216}{25}g_{\rm NL} + \frac{24}{5}f_{\rm NL} + 4\right] \\ & + \zeta^{(1)2}\nabla^2\zeta^{(1)}\left[-\frac{108}{25}g_{\rm NL} + \frac{72}{5}f_{\rm NL} - 8\right] + O(\zeta^{(1)4}) \quad . \end{aligned}$$

Modifications to 2LPTic

- **We modified the gravitational potential kernel in 2LPTic* code.**

- **These modifications are in Fourier space**

- **We included g_{NL}.**

- **This are the kernels added for relativistic contributions and PNG.**

$$\phi_{\rm ini} = \phi^{(1)} + \frac{1}{2}\phi^{(2)} + \frac{1}{6}\phi^{(3)}$$

$$\phi^{(2)} = -\frac{72}{625}\left[(\nabla\phi^{(1)})^2\left(\frac{5}{12} + f_{\rm NL}\right) + \phi^{(1)}\nabla^2\phi^{(1)}\left(\frac{5}{3} - f_{\rm NL}\right)\right]$$

$$\phi^{(3)} = -\frac{972}{15625}\left[2\phi^{(1)}(\nabla\phi^{(1)})^2\left(g_{\rm NL} - \frac{5}{9}f_{\rm NL} - \frac{25}{54}\right) + \phi^{(1)2}\nabla^2\phi^{(1)}\left(g_{\rm NL} - \frac{10}{3}f_{\rm NL} + \frac{50}{27}\right)\right]$$

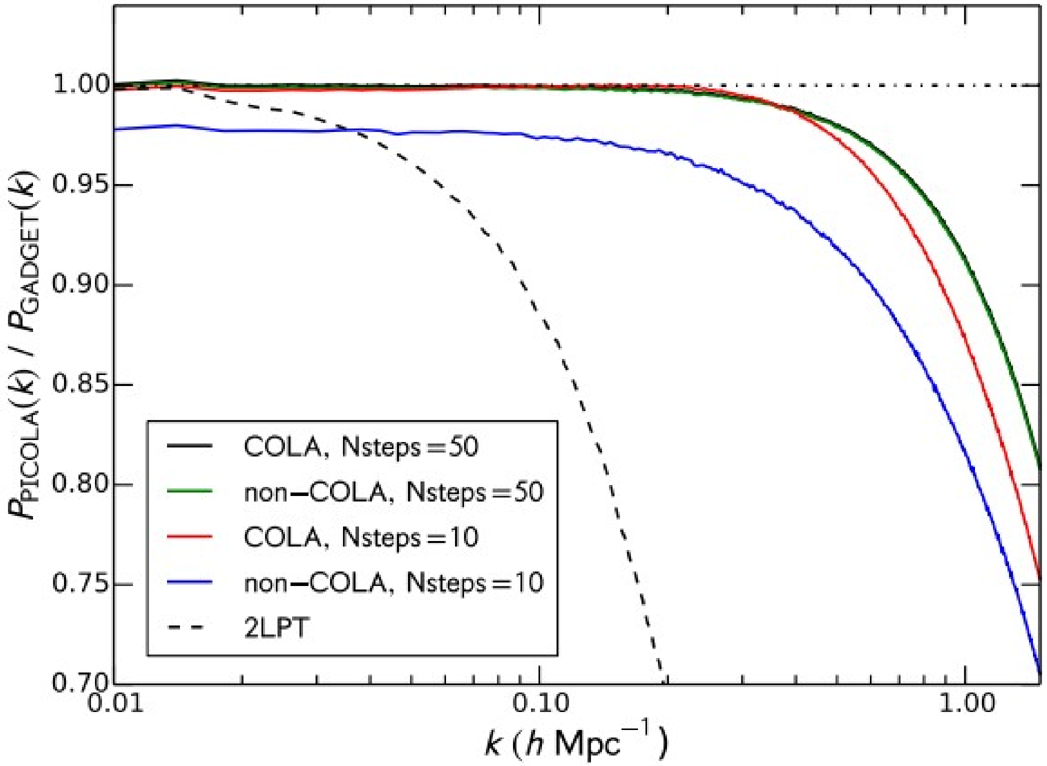
*M. Crocce, S. Pueblas, and R. Scoccimarro, 2LPTIC: 2nd-order Lagrangian Perturbation Theory Initial Conditions,

L-PICOLA vs. Gadget

- **L-PICOLA has shown good agreement with GADGET-2 at large scales.**

- **The number of steps is crucial to achive the desired accuracy.**

Comparison of LPICOLA and 2LPT with GADGET-2*



*C. Howlett, M. Manera, and W. J. Percival, (2015)

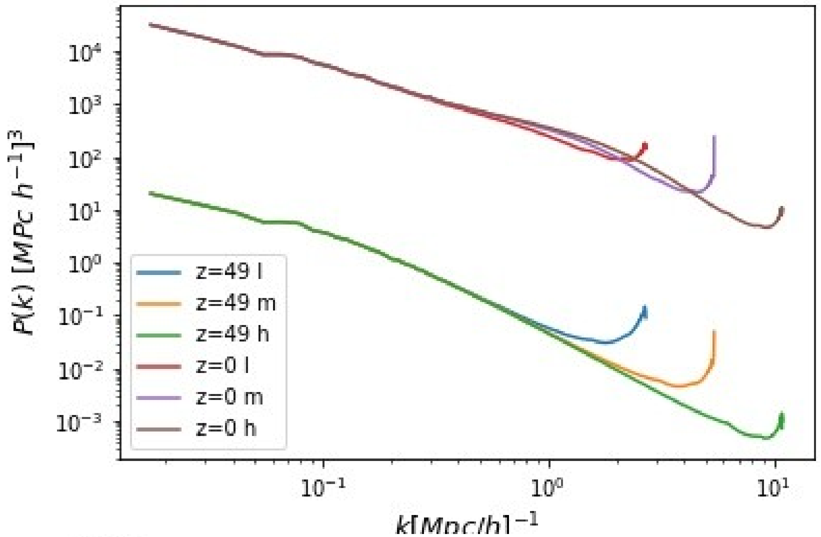
Spurious numerical effects in simulations

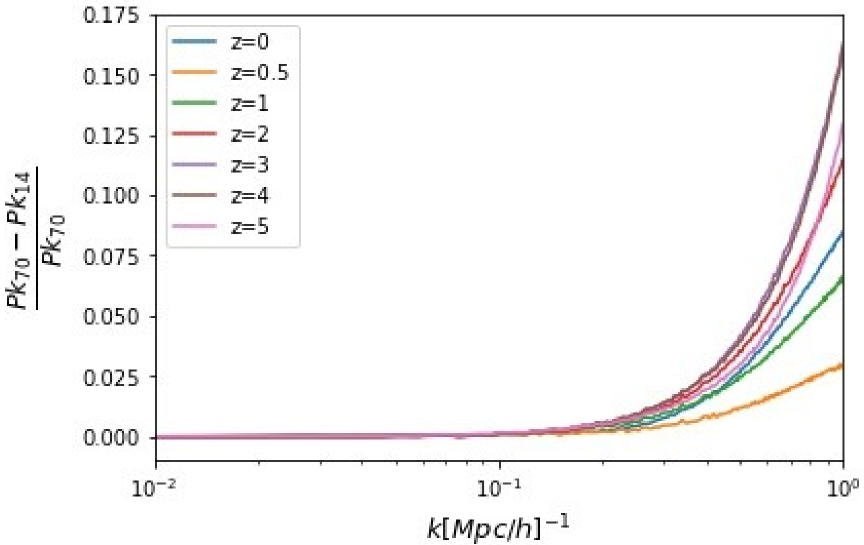
- **We made simulations at different resolution to show the effects on the power spectrum.**

- **There are non-physical signal that appears due to numerical effects.**

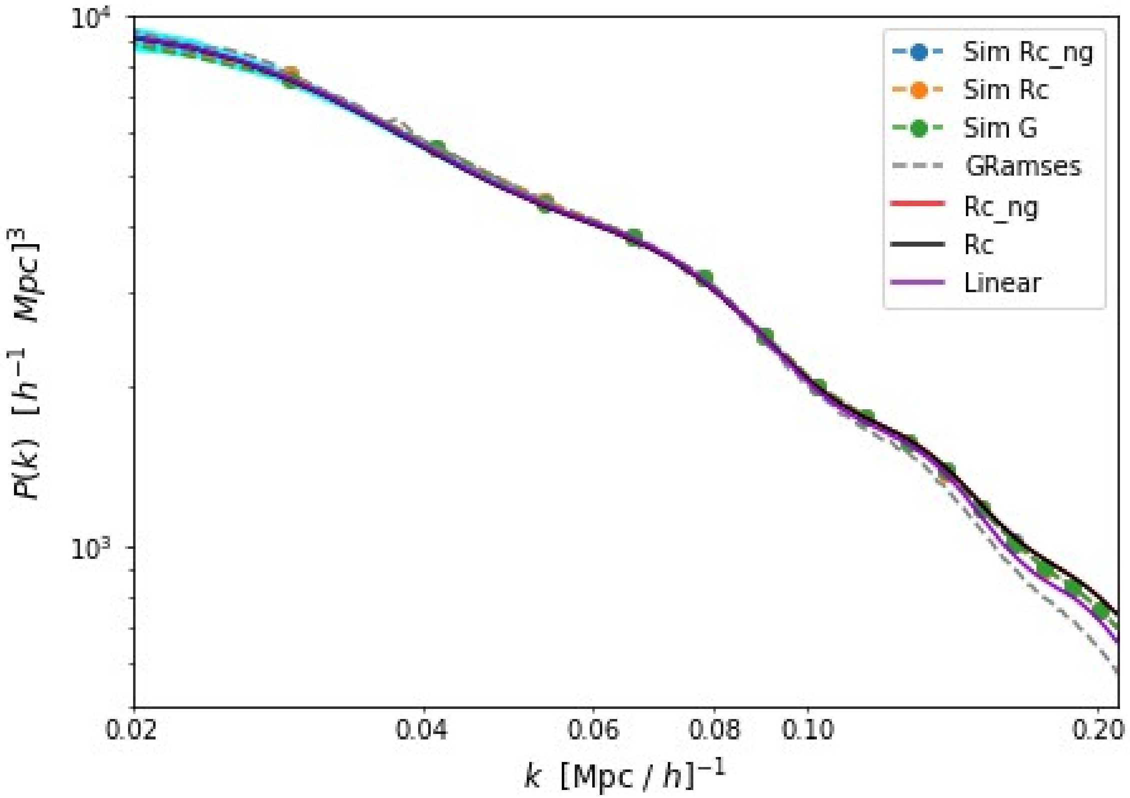
- **The figure shows that at lower redshift with low resolutions some of the amplitude of the power is lost.**

- **Also the number of steps becomes more relevant at lower redshift because of the lack of detail captured with fewer steps.**





Results

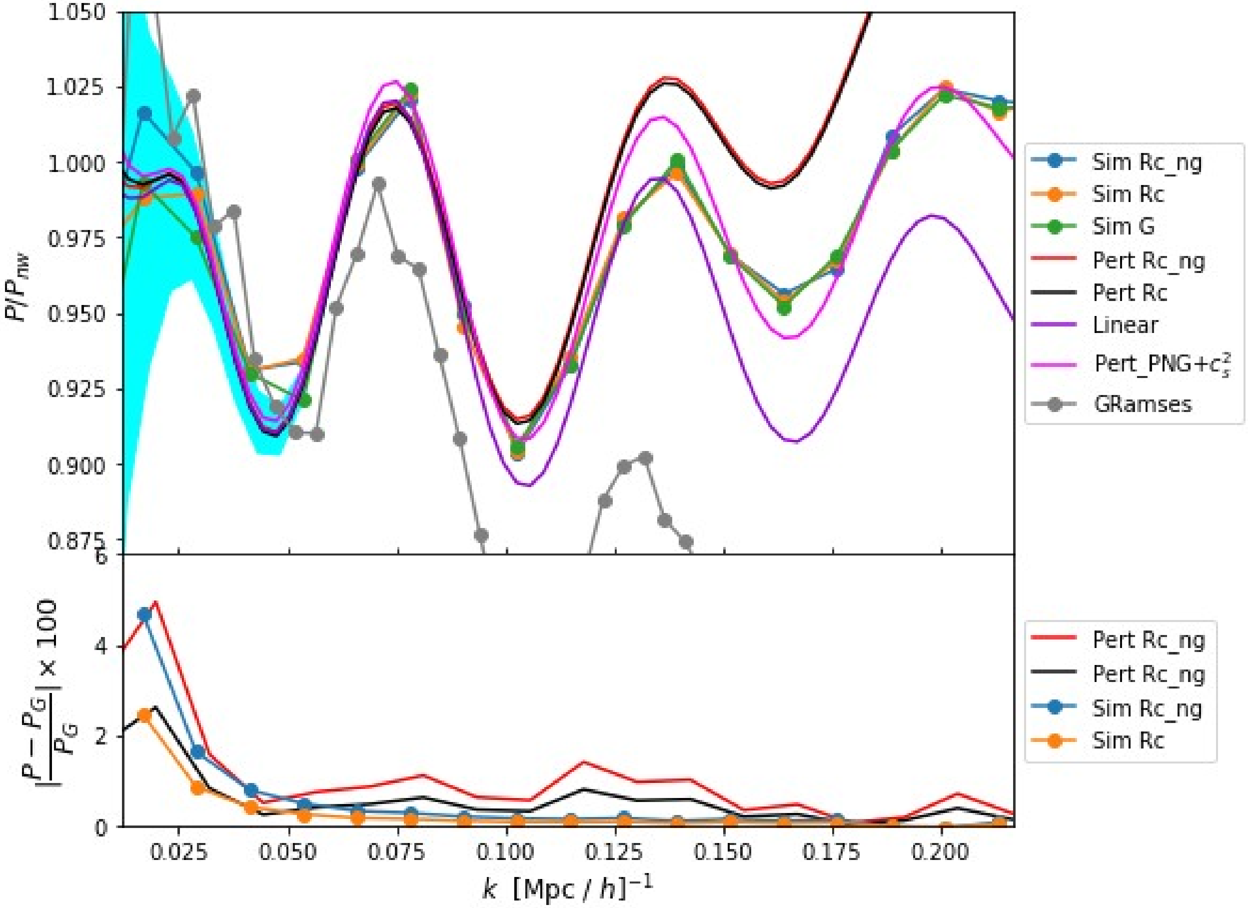


Ω_Λ	0.69
Ω_M	0.31
Ω_b	0.048
H_0	0.69
$f_{\rm NL}$	-4.2
$g_{\rm NL}$	-7e3
σ_8	0.8
n_s	0.96

- **We used Planck 2015 data displayed.**
- **We computed the power spectrum with Pylians* for relativistic contributions, relativistic with PNG contributions and Gaussian.**
- **We also plot full relativistic simulations with GRAMSES****
- **One loop EFT estimations were also computed for relativistic and relativistic with PNG contributions**

*F. Villaescusa-Navarro, Pylians:Python libraries for the analysis of numerical simulations
**C. Barrera-Hinojosa and B. Li, “GRAMSES: a new route to general relativistic N-body simulations in cosmology. Part I. Methodology and code description,”

Results



- **We computed the difference with no-wiggle power spectrum.**
- **The blue shadow corresponds to a Euclid-like observed area.**
- **The difference in the supression with GRAMSES is due to the counter term* as:**

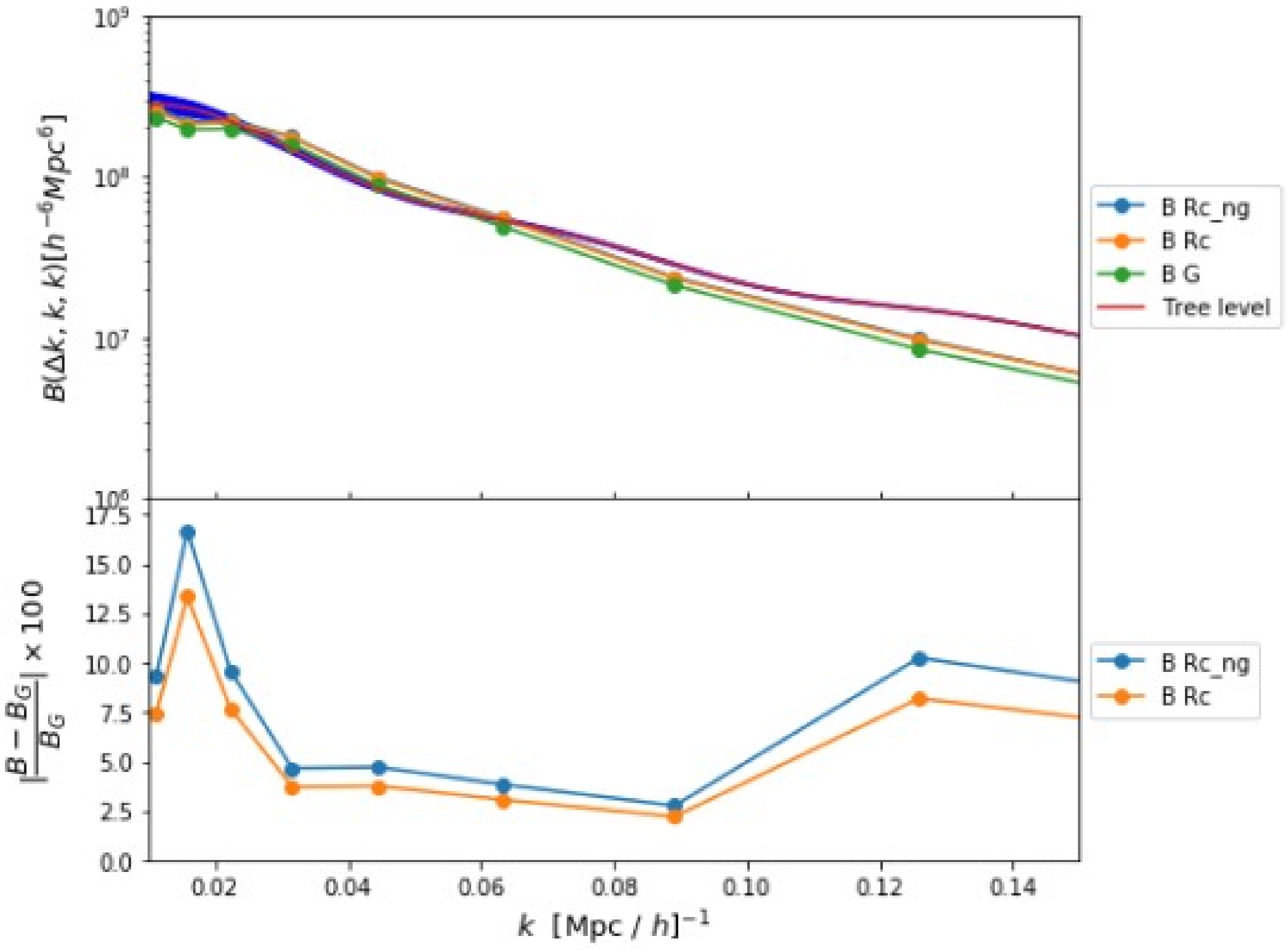
$$P_{ctr,1loop} \equiv -2k^2 c_s^2 P_{11}$$

- **PNG and relativistic contibutions difference up to 4.5% (fnl=-4.2 gnl=-7000) at k=0.025[Mpc/h]$^{-1}$**

*T. Baldauf, L. Mercolli, and M. Zaldarriaga, “Effective field theory of large scale structure at two loops: The apparent scale dependence of the speed of sound,”

Results

- **We computed the bispectrum with Pylians* and compare it with the Tree level bispectrum, where we found a maximum difference for relativistic contributions with PNG at large scales of 16%**

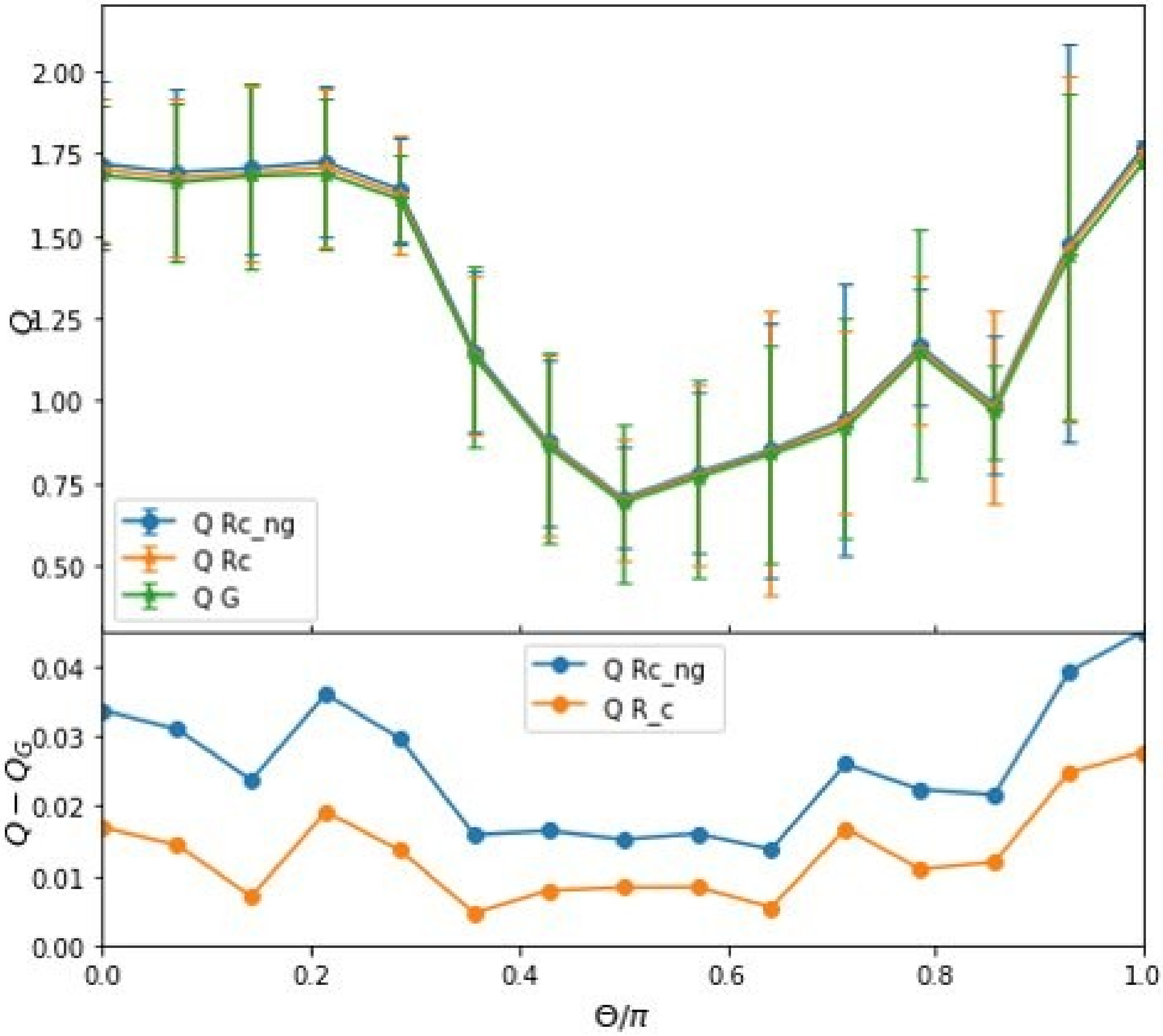


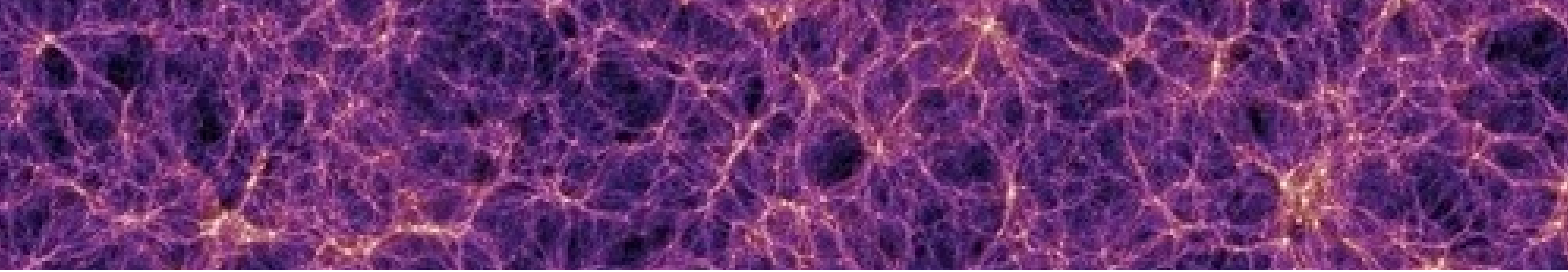
*F. Villaescusa-Navarro, Pylians:Python libraries for the analysis of numerical simulations

Results

- **We computed the reduced bispectrum were we observe a higher difference in the squeezed configuration.**

$$Q = \frac{B(k_1, k_2, k_3)}{P(k_1)P(k_2) + P(k_2)P(k_3) + P(k_3)P(k_1)}$$





Summary and future work

Relativistic contributions can be included as initial conditions in Newtonian N-body evolutions.

The non-Gaussianity and the relativistic corrections are manifest at high order statistics as the bispectrum.

We are currently looking at the effects on simulations with codes with adaptive mesh to identify effects at small scales. We are working in generating halo catalogs.

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