

Title: TBA

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Abstract: TBA

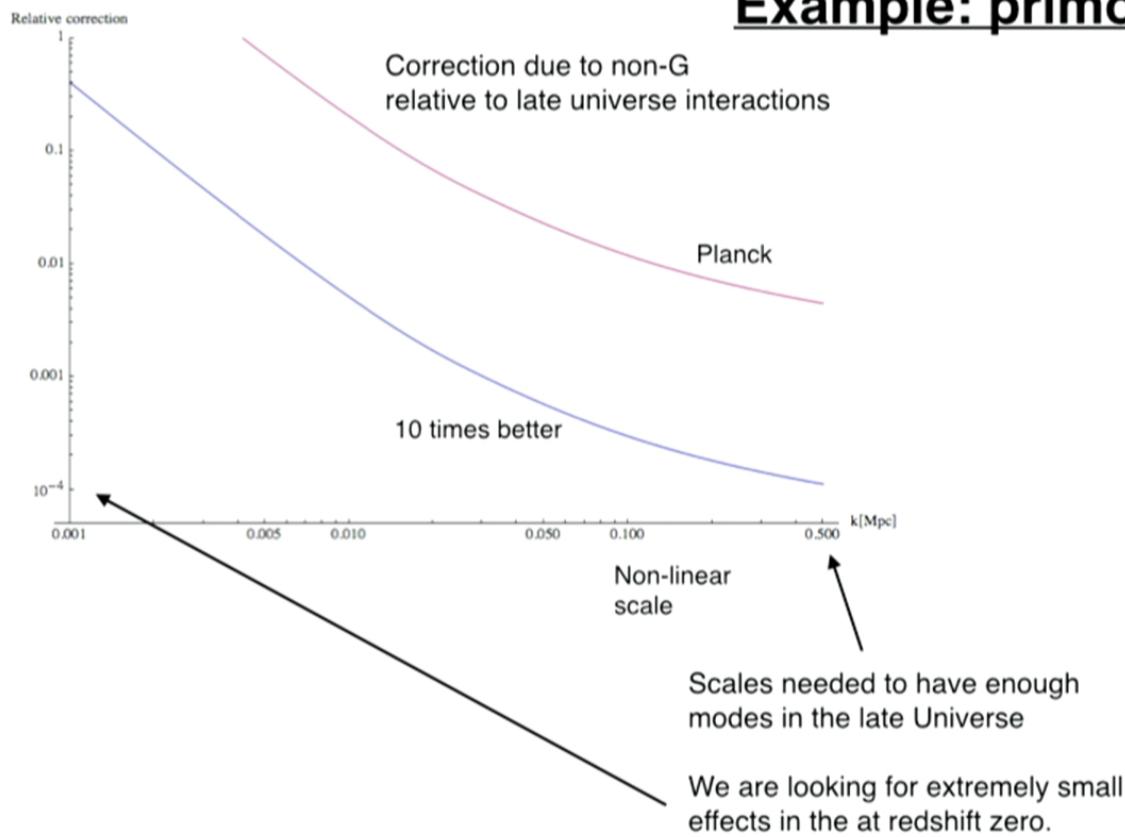
Recent results using the EFT of LSS

Tobias Baldauf, Mehrdad Mirbabayi, Marco Simonovic
Emmanuel Schaan

The need for accurate LSS predictions:

Physical effects already constrained by the CMB are now strongly constrained. Improvement can only be achieved by very powerful observation and theory.

Example: primordial non-G

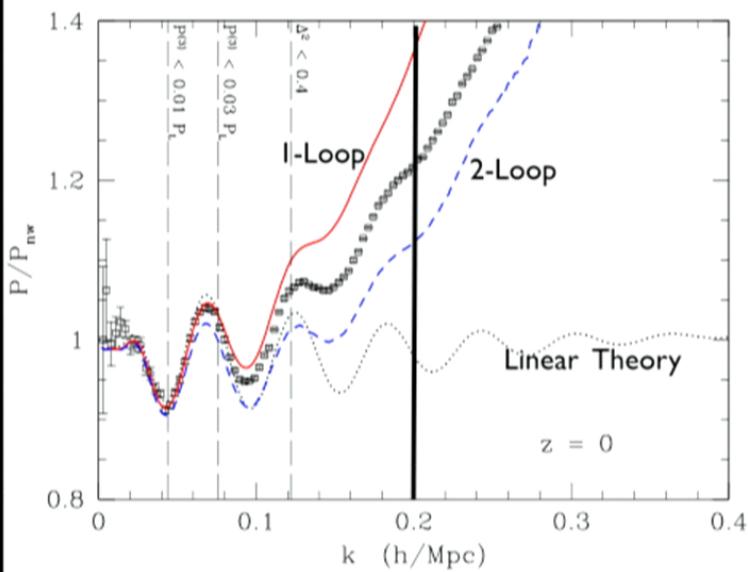


One has to go to high redshift: Primordial effects are fixed, density contrast goes down. More volume is available.

Neutrino masses and dark energy constraints also require sub percent precision.

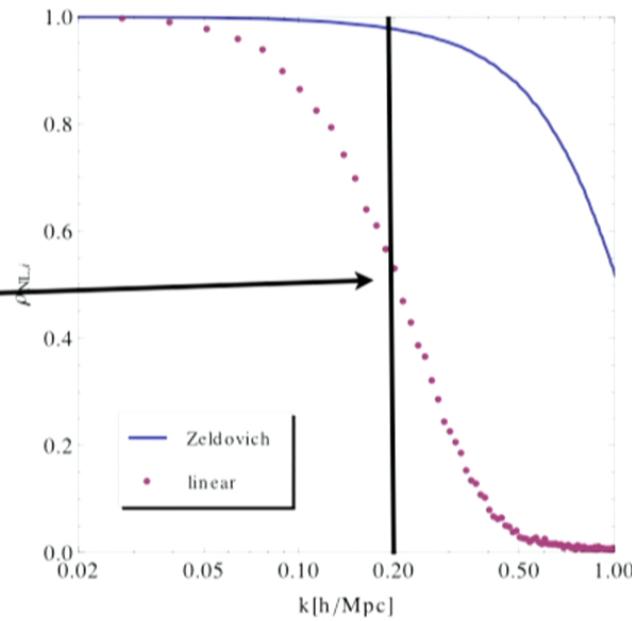
There are still open questions where even qualitative information would be important.

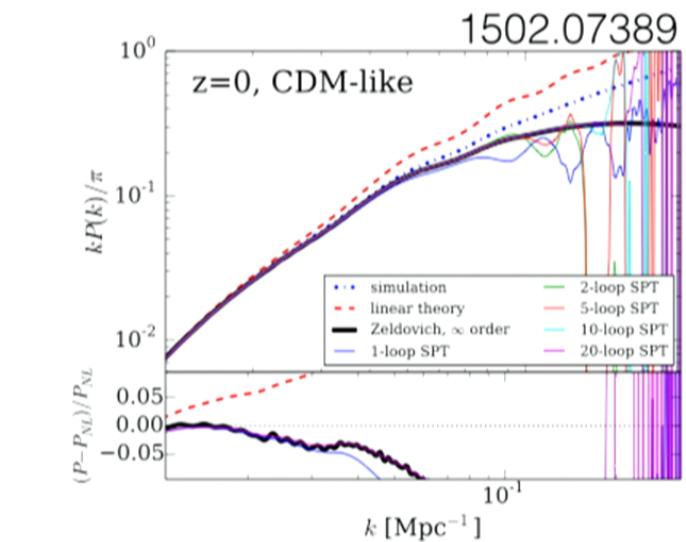
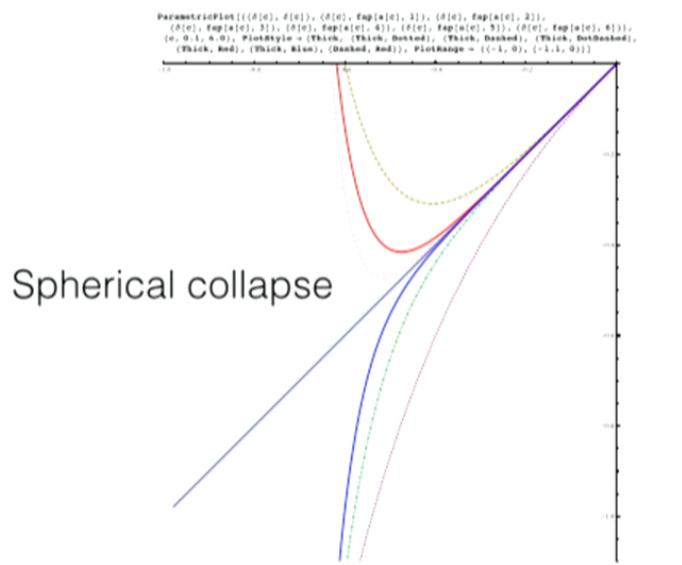
Carlson et al 0905.0479



At this scale the part of the density field
not correlated with the 2LPT solution is
only 1%

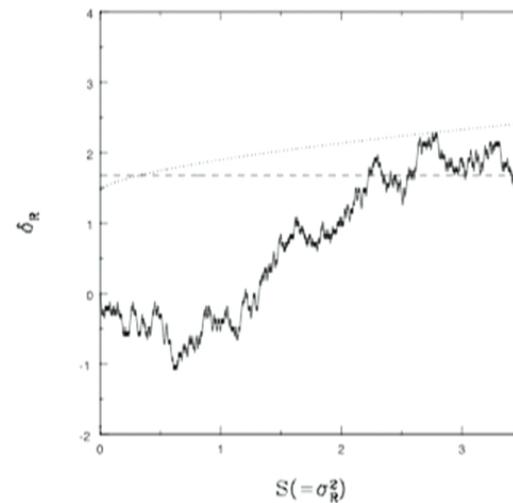
Standard Perturbation Theory





Convergence in the UV

It is not a matter of adding terms, being able to sum all the series. On small scales PT does not converge to the right answer.



UV sensitivity gets worse as you increase the order

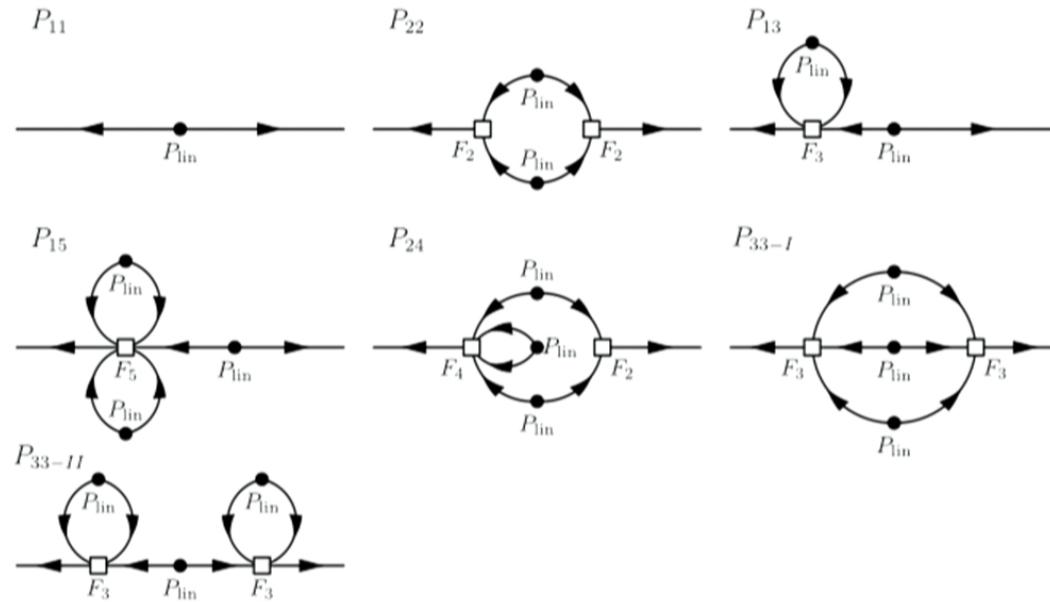
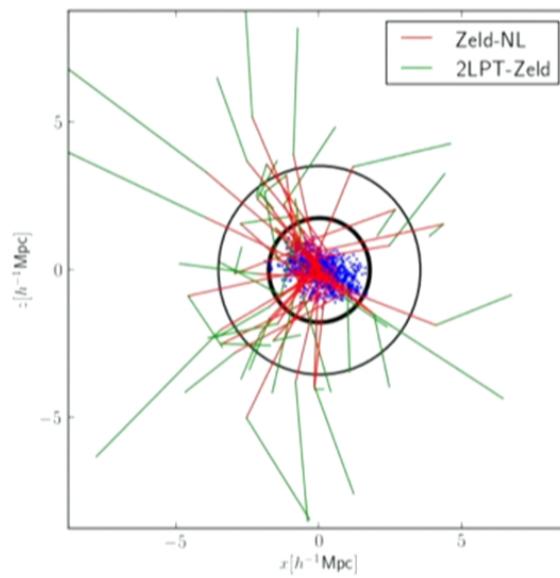
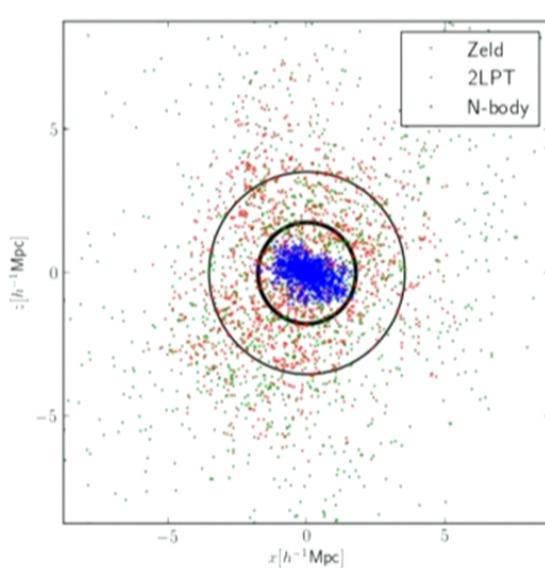
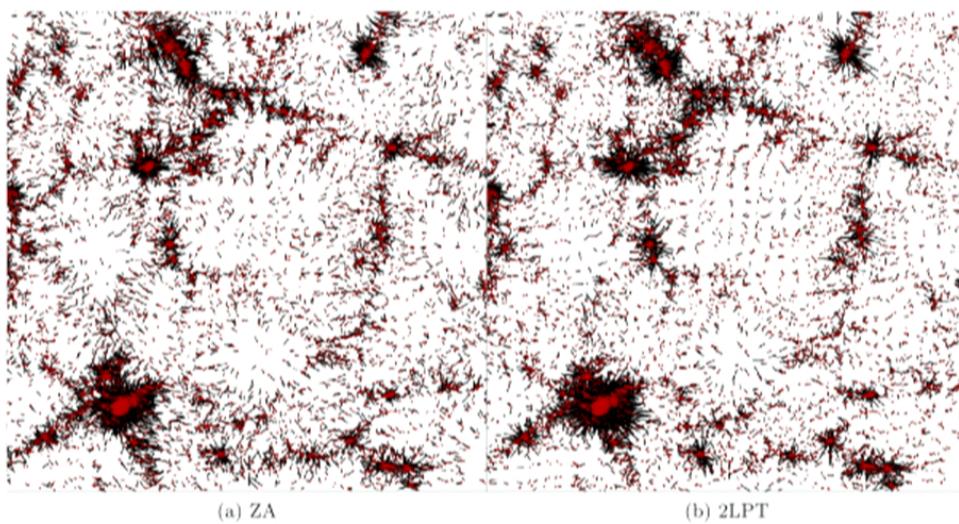


FIG. 1. Diagrams for the tree level, one- and two-loop expressions of the SPT power spectrum.

Example of particle trajectories



- PT does not converge to the right answer on small scales
- Loops receive contributions from small scale momenta which are wrong
- The problem becomes progressively worse at higher loops (how bad is diagram dependent)
- The problem should not be so bad because things stick together
- There are non-perturbative effects

How to fix this?

Keep track of where the effects of the small scales show up.
Will have to introduce some free parameters (counter terms)

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Analogy: Scale dependence of the bias

$$\delta_g \approx b\delta_m + \dots \propto \nabla^2\phi + \dots$$

A. Slosar, C. Hirata, U. Seljak, S. Ho, and N. Padmanabhan (2008)

$b_\phi \phi$ Cannot be generated

Data set	f_{NL}
Photometric LRG	$63^{+54+101+145}_{-85-131-388}$
Photometric LRG (0-4)	$-34^{+115+215+300}_{-194-375-444}$
Spectroscopic LRG	$70^{+74+139+202}_{-83-191-371}$
ISW	$105^{+647+755+933}_{-137-1157-128}$
QSO	$8^{+26+47+65}_{-37-77-102}$
QSO ($b=1/D$)	$8^{+28+49+69}_{-38-81-111}$
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QSO merger	$12^{+30+58+102}_{-44-94-138}$
Combined	$28^{+23+42+65}_{-23-57-93}$
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One could think of the SPT results as a biased version of the true density. The EFT tells you the functional form of the biasing parameter.

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Lagrangian Perturbation theory

$$\nabla^2 \Phi_g = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta$$

$$\begin{aligned}\mathbf{x}(\mathbf{q}, \tau) &= \mathbf{q} + \mathbf{s}(\mathbf{q}, \tau) \\ \frac{d^2 \mathbf{s}}{d\tau^2} + \mathcal{H} \frac{d\mathbf{s}}{d\tau} &= -\nabla \Phi_g(\mathbf{q} + \mathbf{s}, \tau) \quad \text{Linear equation} \\ 1 + \delta(\mathbf{x}, \tau) &= \int d^3 q \, \delta^D(\mathbf{x} - \mathbf{q} - \mathbf{s}(\mathbf{q}, \tau)) = \det^{-1}(\delta_{ij} + \partial_i s_j)|_{\mathbf{x}=\mathbf{q}+\mathbf{s}}\end{aligned}$$

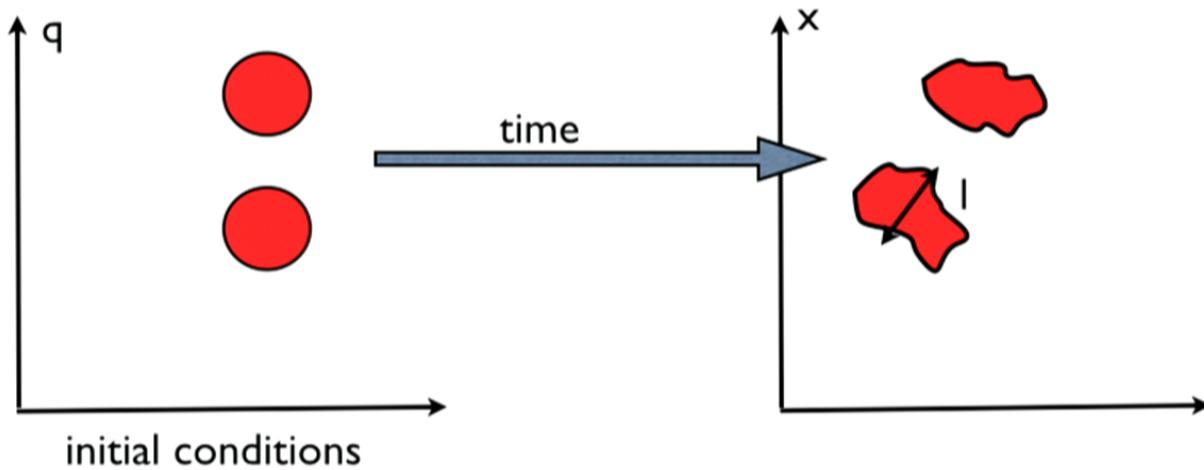
Has a quadratic plus a cubic vertex + coordinate transformation

$$\mathbf{s} = \nabla \phi + \nabla \times \boldsymbol{\omega}$$

$$\left\{ \begin{array}{l} \phi^{(n)} \equiv \frac{D^n}{n!} \int \frac{d^3 p_1 \dots d^3 p_n}{(2\pi)^{3n}} (2\pi)^3 \delta^D(p_{1..n} - \mathbf{k}) L_n(p_1, \dots, p_n) \delta_0(p_1) \dots \delta_0(p_n) \\ \boldsymbol{\omega}^{(n)} \equiv \frac{D^n}{n!} \int \frac{d^3 p_1 \dots d^3 p_n}{(2\pi)^{3n}} (2\pi)^3 \delta^D(p_{1..n} - \mathbf{k}) T_n(p_1, \dots, p_n) \delta_0(p_1) \dots \delta_0(p_n). \end{array} \right.$$

To obtain perturbative solution one takes divergence with respect to the x coordinate of the equation of motion for the particles and then has to account for the change of coordinates to obtain an equation in q coordinates. The resulting equation has quadratic and cubic vertices.

The EFT in Lagrangian space



Finite size effects in the interaction. At the lowest order basically just the quadrupole moment.

Derivative expansion, powers of $k l$. This expansion is different than the expansion in δ . Both are necessary in perturbation theory.

One needs to learn how to determine how many terms one should keep. This depends on the shape of the power spectrum.

Testing the EFT without cosmic variance

Transfer functions:

	a_1	a_2	a_3	a_4	a_5
tree	11				
1-loop	13	22			
2-loop	15	24	33		
3-loop	17	26	35	44	
4-loop	19	28	37	46	55

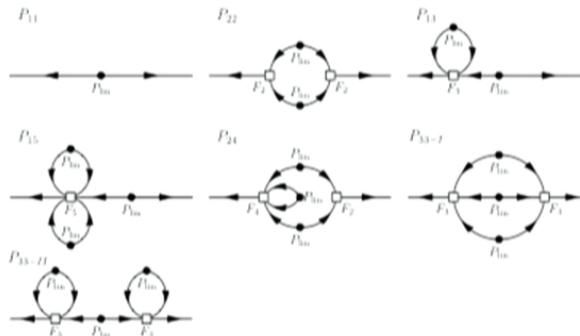


FIG. 1. Diagrams for the tree level, one- and two-loop expressions of the SPT power spectrum.

$$\phi_{\text{ntLPT}}(\mathbf{k}) = a_1(k)\phi^{(1)}(\mathbf{k}) + \dots + a_n(k)\phi^{(n)}(\mathbf{k}).$$

$$\phi_{\text{1-loop EFT}} = (1 + \alpha k^2) \phi^{(1)} + \phi^{(2)} + \phi^{(3)}$$

These can be measured without cosmic variance

$$\phi_{\text{ntLPT}}(\mathbf{k}) = a_1(k)\phi^{(1)}(\mathbf{k}) + \dots + a_n(k)\phi^{(n)}(\mathbf{k}) + \phi_{\text{stoch}}$$

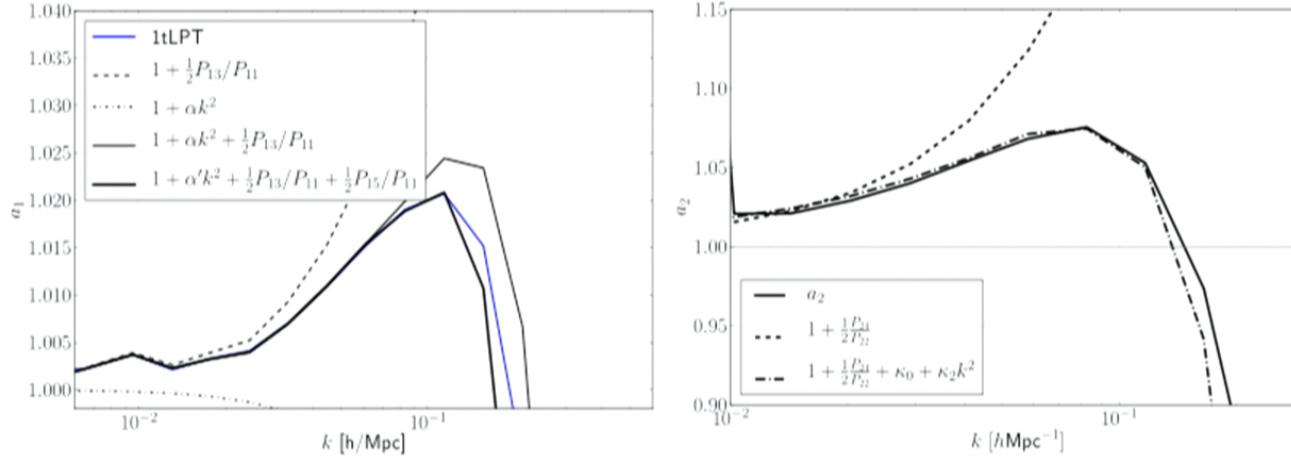
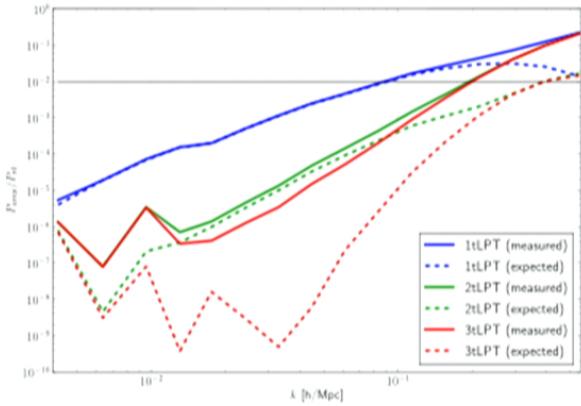
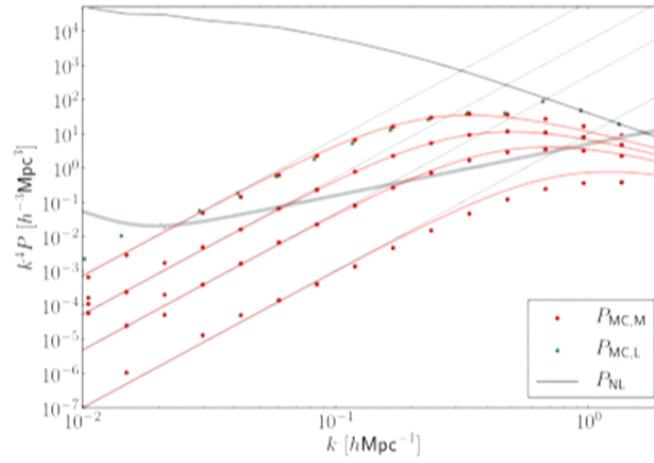


Figure 19. *Left panel:* Transfer function a_1^\perp of the 1tLPT model. Adding P_{15} modifies the value of α , as expected, and improves the agreement. *Right panel:* Transfer function a_2^\perp of the 1tLPT model. We clearly see a percent level deviation on the largest scales, that is accounted for by adding $P_{24}/P_{22}/2$ to the model for this term. The latter however over predicts the enhancement in the mildly non-linear regime, which is in turn fixed by the EFT counter terms $E_{2,i}$. As we pointed out before, they lead to k^0 and k^2 corrections through P_{22}/P_{22} .

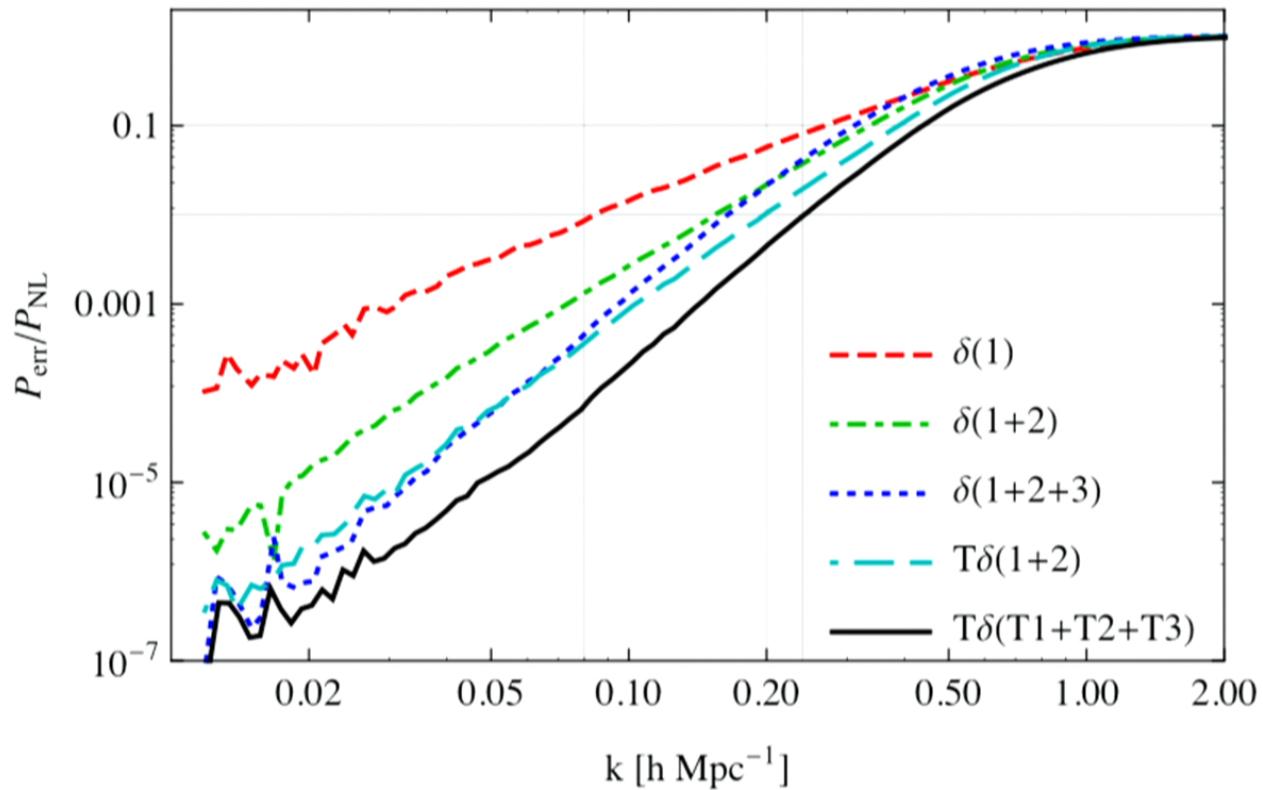
Stochastic term:



$$\sigma_{\text{stoch.,h}}^2 = \int dm \frac{dn}{dm} m \left(2R_{\text{vir}}(m) \right)^2 / \int dm \frac{dn}{dm} m$$



Eulerian results: What happens if we use the displacement to compute the density?



Again the EFT tells you constraints the shape of the transfer functions

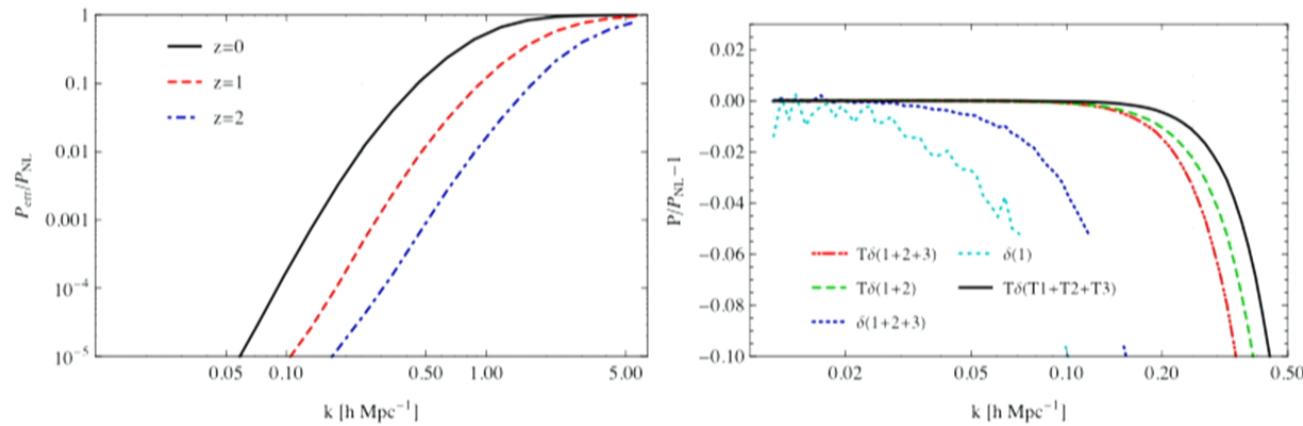
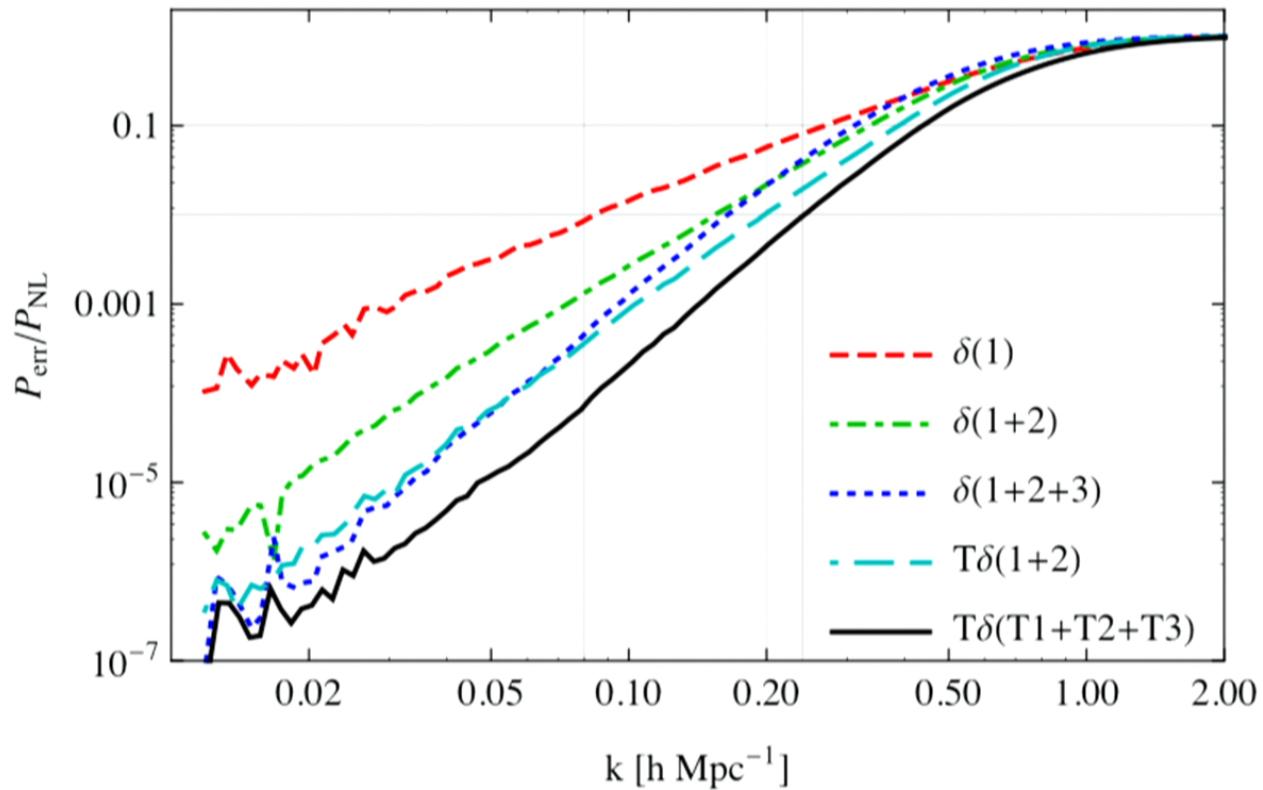


Figure 6. *Left panel:* Ratio of the best possible EFT power spectrum to the non-linear power spectrum as a function of redshift. We indicate the 1% and 10% accuracy lines and mark the crossing of the 1%-threshold by vertical lines, whose wavenumbers are given in Tab. 1. *Right panel:* Ratio of the perturbative model with and without transfer functions and the non-linear power spectrum at $z = 0$.

Eulerian results: What happens if we use the displacement to compute the density?



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EFT of LSS directly in Eulerian space

$$\begin{aligned}\partial_\tau \delta + \partial_i [(1 + \delta) v^i] &= \partial_i u^i , \\ \partial_\tau v^i + \mathcal{H} v^i + \partial^i \phi + v^j \partial_j v^i &= -\frac{1}{a\rho} \partial_j \tau^{ij} \quad \delta = \delta_{(1)} + \delta_{(2)} + \delta_{(3)} + \delta_{(4)} + \delta_{(5)} + \dots \\ \triangle \phi &= \frac{3}{2} \mathcal{H}^2 \Omega_m \delta .\end{aligned}$$

$$\tau_\theta \equiv -\partial_i \left[\frac{1}{a\rho} \partial_j \tau^j \right] = \tau_\theta^{\text{det}} + \tau_\theta^{\text{stoch}} \quad \tau_\theta^{\text{det}} = \tau_\theta^{\text{det}} [\partial_i \partial_j \bar{\phi}].$$

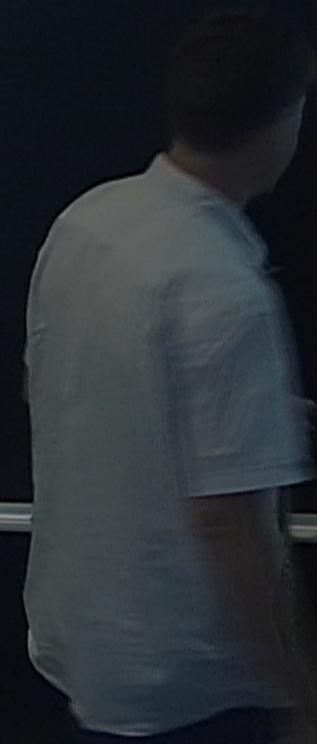
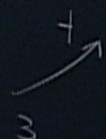
$$\tau_\theta^{\text{det}}|_{\text{LO}} = -d^2 \triangle \delta_{(1)} = -d^2 \triangle \triangle \bar{\phi}_{(1)}$$

$$\tau_\theta^{\text{det}}|_{\text{NLO}} = -d^2 \triangle [\delta_{(1)} + \delta_{(2)}] - e_1 \triangle \delta_{(1)}^2 - e_2 \triangle (s_{ij(1)} s_{(1)}^{ij}) - e_3 \partial_i s_{(1)}^{ij} \partial_j \delta_{(1)},$$

$$s_{ij} = \left(\partial_i \partial_j - \frac{1}{3} \delta_{ij}^{(\text{K})} \triangle \right) \bar{\phi}.$$

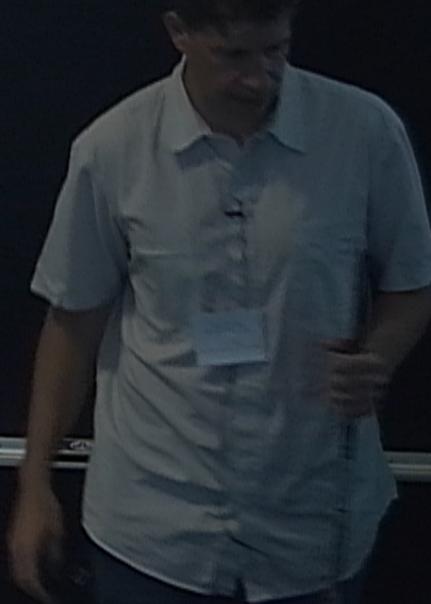
$$\tau^{\text{'}\prime} = \# \partial \partial_i \phi_i$$

$$S^{\prime \prime} \nabla^2 \phi_i$$

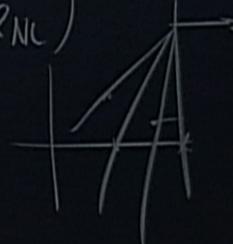


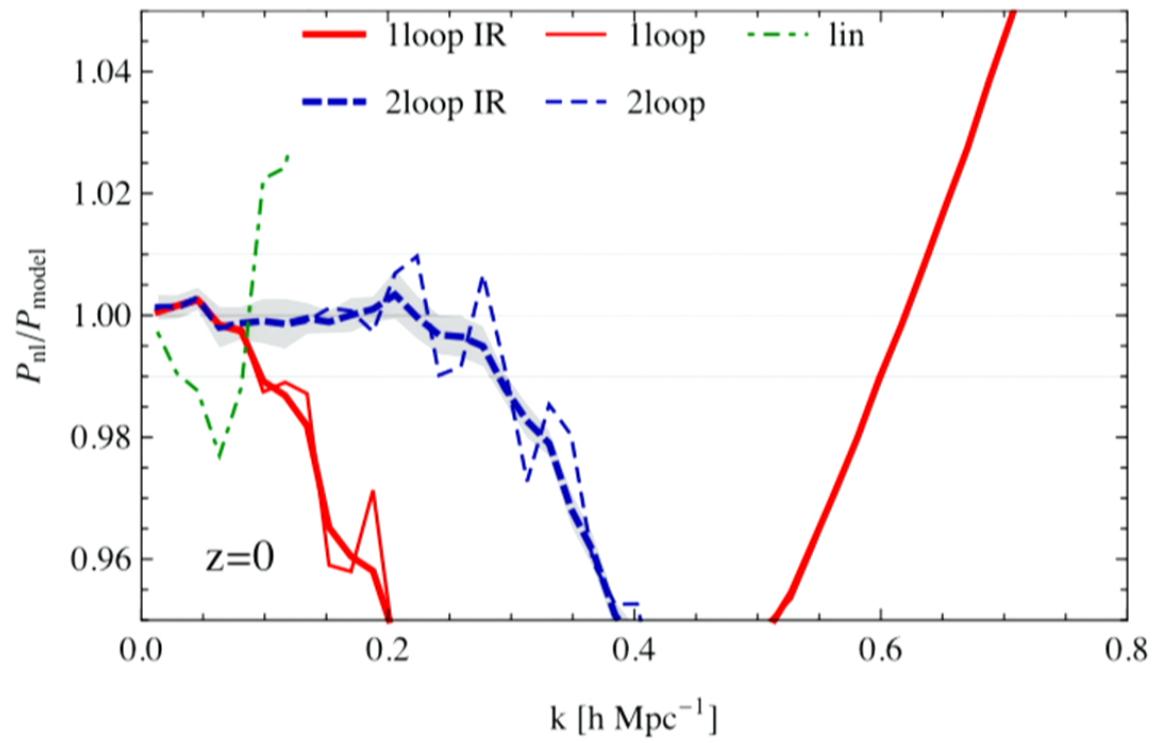
$$\tau^{\text{in}} = \frac{\# \partial \partial_i \phi_i}{\oint \nabla^2 \phi_i} > \frac{\ell k^2 P_{\text{in}}}{}$$

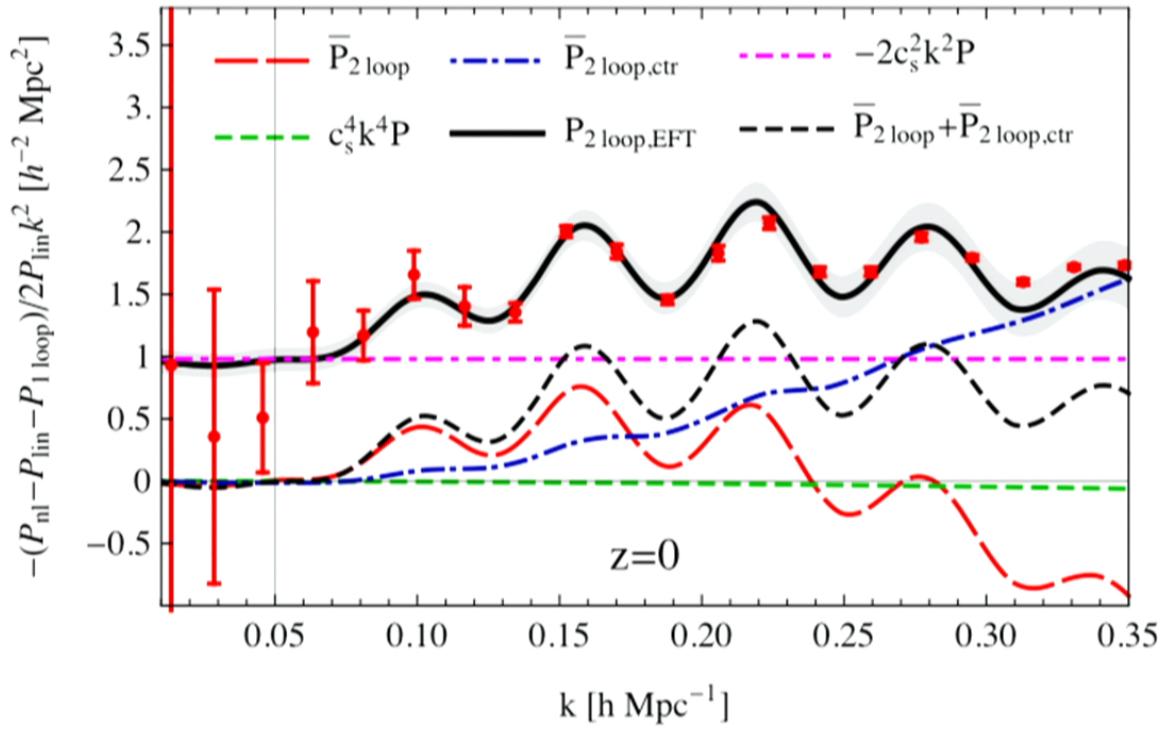
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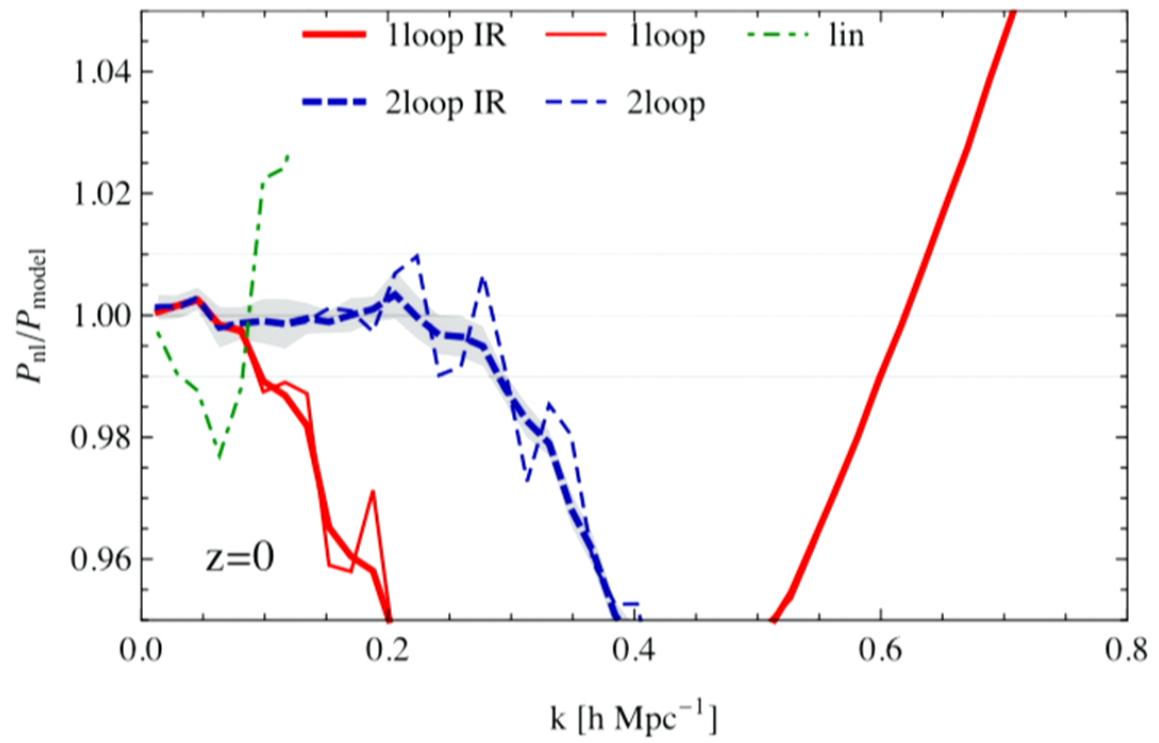


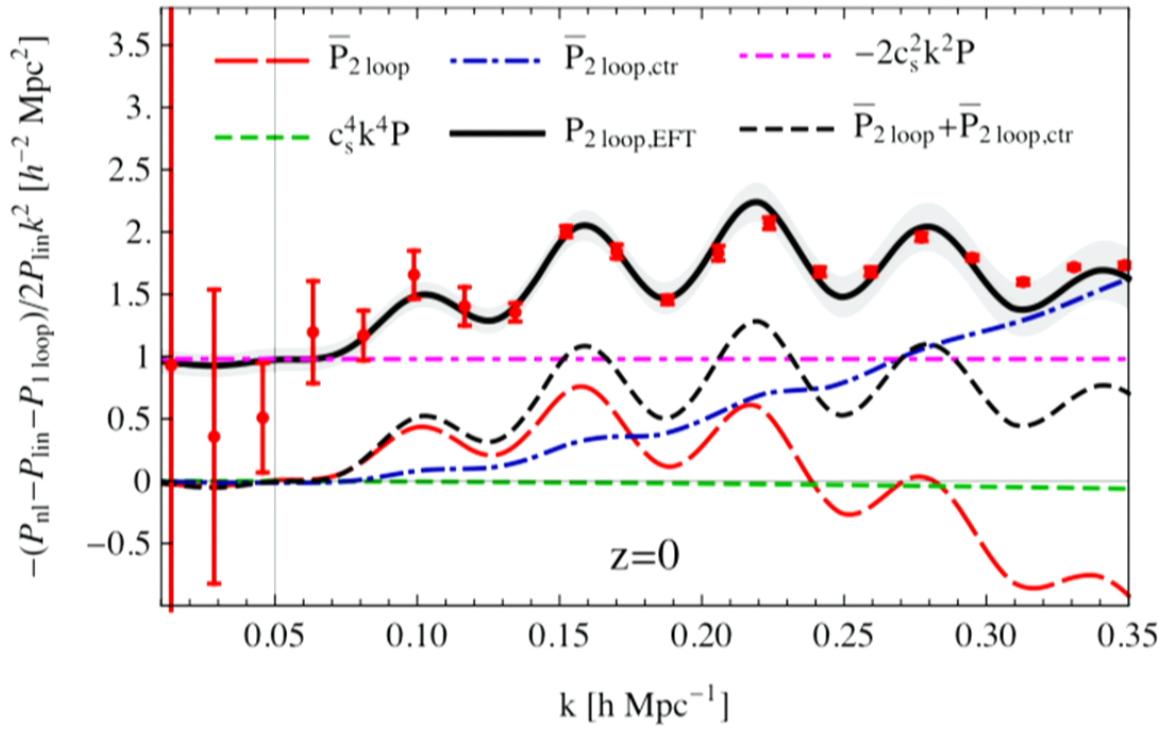
$$\tau^{(1)} = \frac{\# \partial\partial \phi}{\delta^2 \nabla^2 \phi} > \frac{c k^2 P_2(k)}{}$$

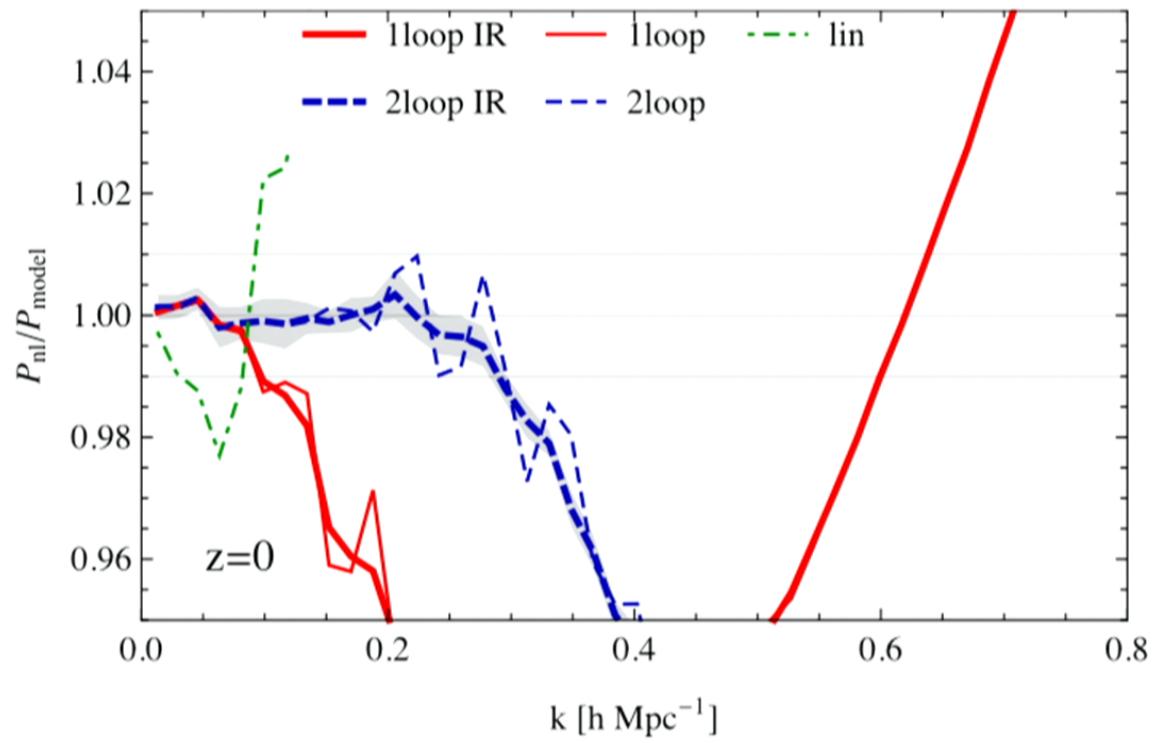
$$z \nearrow \partial\partial \phi \quad \left(\frac{R}{R_{NL}}\right)^{\#}$$


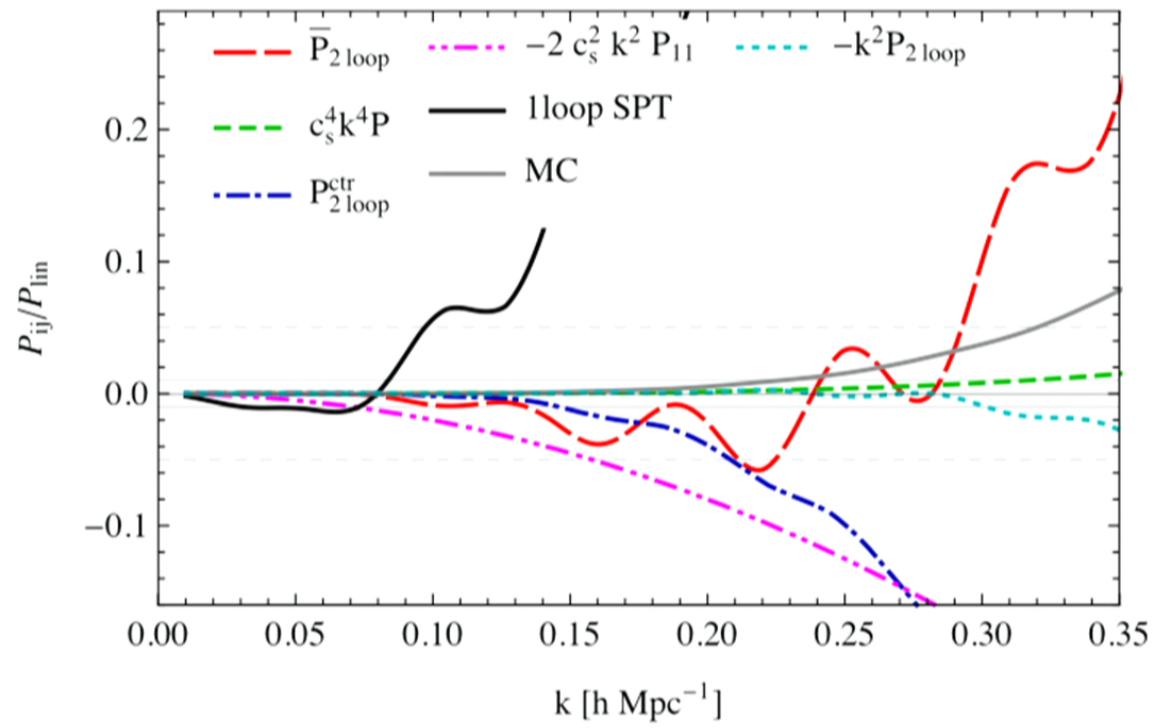


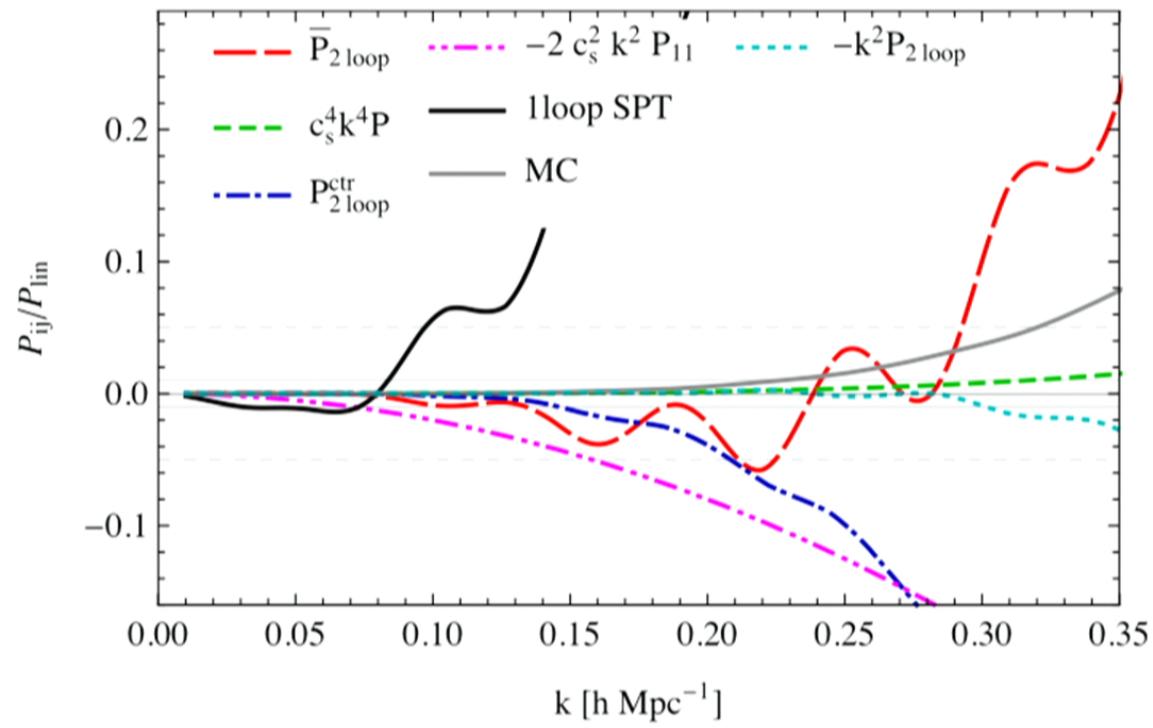












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