Title: On the Statistics of Biased Tracers and BAO in the Effective Field Theory of Large Scale Structures

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Abstract: <p>With the completion of the Planck satellite, in order to continue collecting cosmological information it is
important to gain a precise understanding of the formation of Large Scale Structures (LSS) of the universe.
The Effective Field Theory of LSS (EFTofLSS) offers a consistent theoretical framework that aims to develop
an analytic understanding of LSS at long distances, where inhomogeneities are small. We present the recent
developments in the field covering topics of biased tracers in the EFTofLSS including the effects of baryonic
physics and primordial non-Gaussianities, finding that new bias coefficients are required. We discuss the EFT
framework for dark matter clustering in Lagrangian formalism and present its consequences on baryon acoustic
oscillations (BAO). We present analytic results and compare them with the output of N-body simulations.</p>

On the Statistics of Biased Tracers and BAO in the Effective Field Theory of Large Scale Structures

Zvonimir Vlah

Stanford University & SLAC

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- Introduction to LSS
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- Adding Non-Gaussianities and baryonic effects
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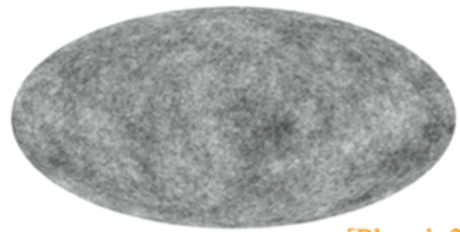
Structure Formation and Evolution

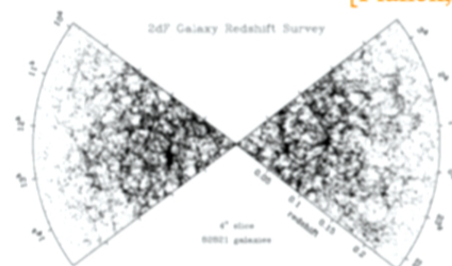
CMB: $\Delta\rho/\rho \sim 10^{-6}$ — z=1100

LSS: $\Delta\rho/\rho \sim 10^{0}$ — z=2

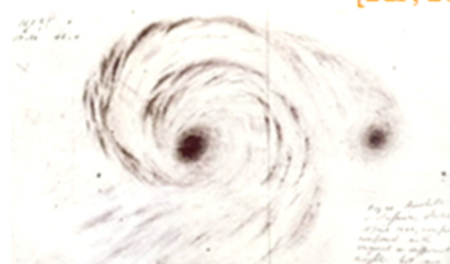
Galaxies: $\Delta\rho/\rho \sim 10^{6}$ — z=0



[Planck,2013]



[2dF, 2002]



[Parsons, 1845]

LSS: motivations and observations

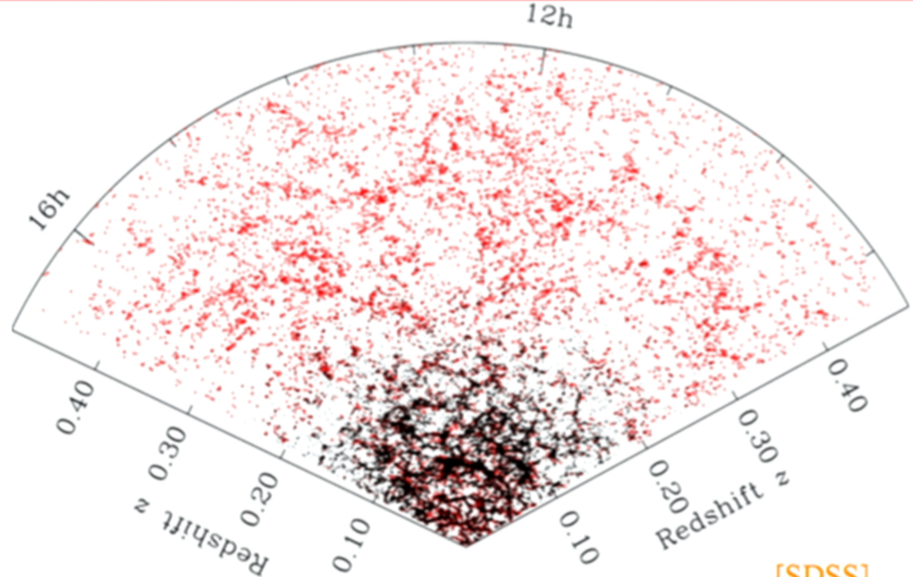
Theoretical motivations:

- Inflation - origin of structures
- Expansion history
- Composition of the universe
- Nature of dark energy and dark matter
- Neutrino mass and number of species
- Test of GR and modifications of gravity

Current and future observations:

- SDSS and SDSS3/4: Sloan Digital Sky Survey
- BOSS: the Baryon Oscillation Spectroscopic Survey
- DES: the Dark Energy Survey
- LSST: the large synoptic survey telescope.
- Euclid: the ESA mission to map the geometry of the dark Universe
- DESI: Dark Energy Spectroscopic Instrument
- SPHEREx: An All-Sky Spectral Survey

Galaxy clustering

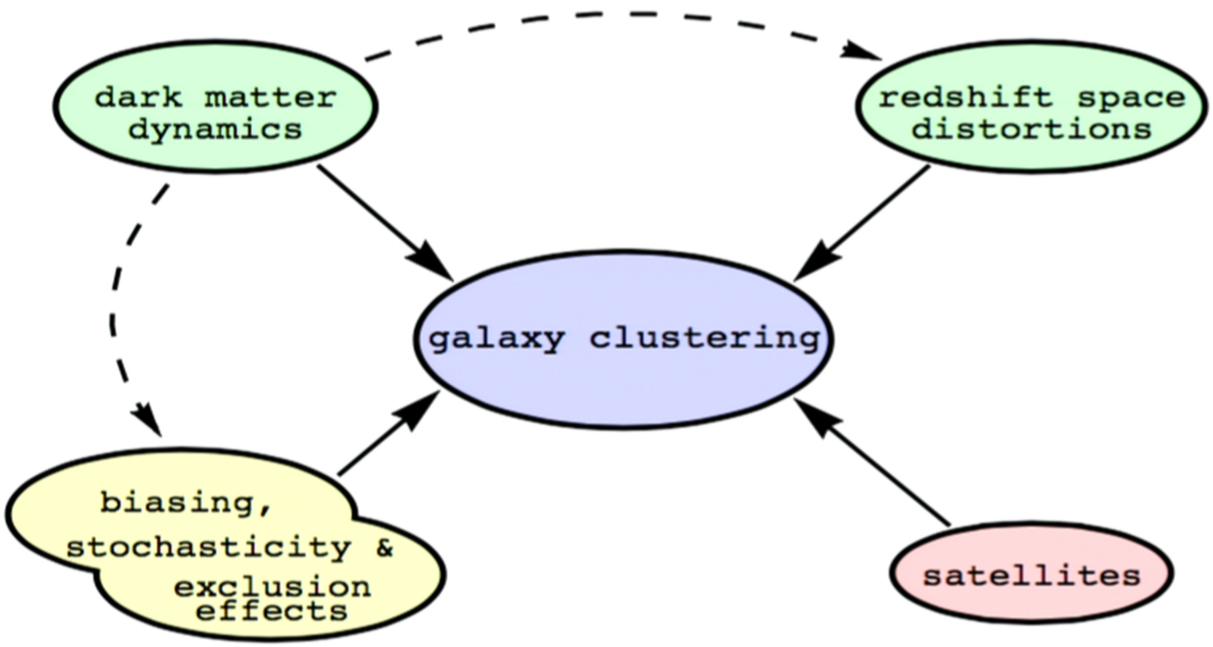


[SDSS]

- Measured 3*D* distribution ⇒much more modes than projected quantities (shear from weak lensing, etc.)
- Redshift surveys measure: θ, φ, redshift z

  overdensity: $\delta = (n - \bar{n})/\bar{n}$,
  power spectrum: $P(k) \sim \langle \delta(\mathbf{k}) | \delta(\mathbf{k}) \rangle$

Galaxy clustering scheme



+ others: baryons, assembly bias, neutrinos, GR effects ...

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p}\cdot\nabla f - am\nabla\phi\cdot\nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

Integral moments of the distribution function:

mass density field & mean streaming velocity field

$$\rho(\mathbf{x}) = ma^{-3}\int d^3p\, f(\boldsymbol{x},\boldsymbol{p}), \qquad v_i(\mathbf{x}) = \frac{\int d^3p\, \frac{p_i}{am} f(\boldsymbol{x},\boldsymbol{p})}{\int d^3p\, f(\boldsymbol{x},\boldsymbol{p})},$$

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

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and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

Eulerian framework - fluid approximation:

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$
$$\frac{\partial v_i}{\partial \tau} + \mathcal{H}v_i + \mathbf{v} \cdot \nabla v_i = -\nabla_i\phi - \frac{1}{\rho}\nabla_i(\rho\sigma_{ij}),$$

where σ_{ij} is the velocity dispersion.

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p} \cdot \nabla f - am\nabla\phi \cdot \nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

EFT approach introduces a tress tensor for the long-distance fluid:

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$
$$\frac{\partial v_i}{\partial \tau} + \mathcal{H}v_i + \mathbf{v} \cdot \nabla v_i = -\nabla_i\phi - \frac{1}{\rho}\nabla_j(\tau_{ij}),$$

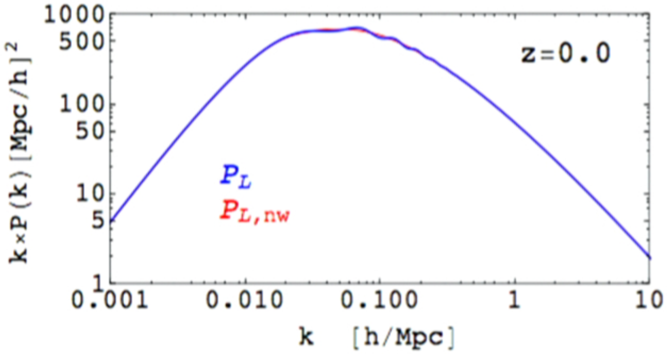
with given as $\tau_{ij} = p_0\delta_{ij} + c_s^2\delta\rho\delta_{ij} + O(\partial^2\delta, \ldots)$
-derived by smoothing the short scales in the fluid with
the smoothing filter $W(\Lambda)$.

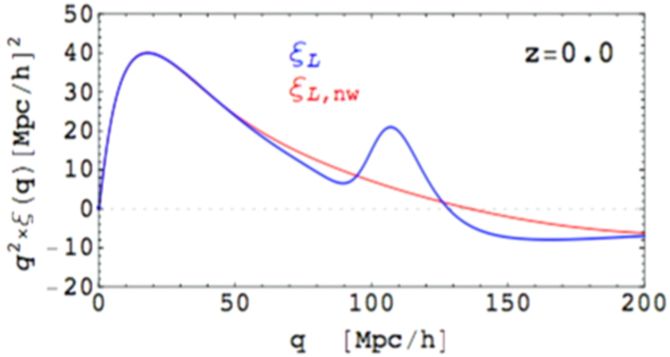
[Baumann et al 2010, Carrasco et al 2012]

Linear power spectrum, correlation function & BAO

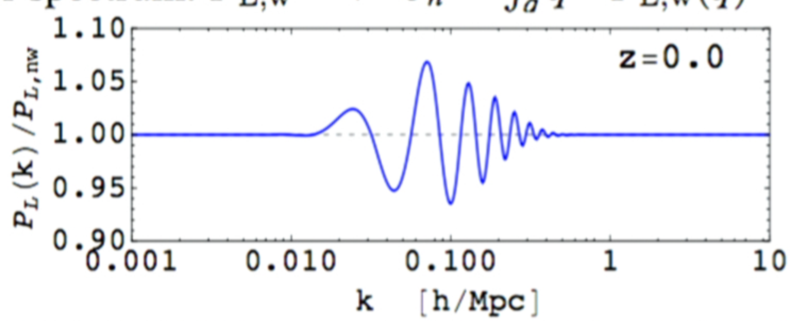
Linear power spectrum $P_{\rm L}$: obtained form Boltzmann codes (CAMB, Class). Formally we can divide it into smooth part $P_{\rm L,nw}$ and wiggle part $P_{\rm L,w}$ so that:

$$P_{\rm L} = P_{\rm L,nw} + P_{\rm L,w}$$





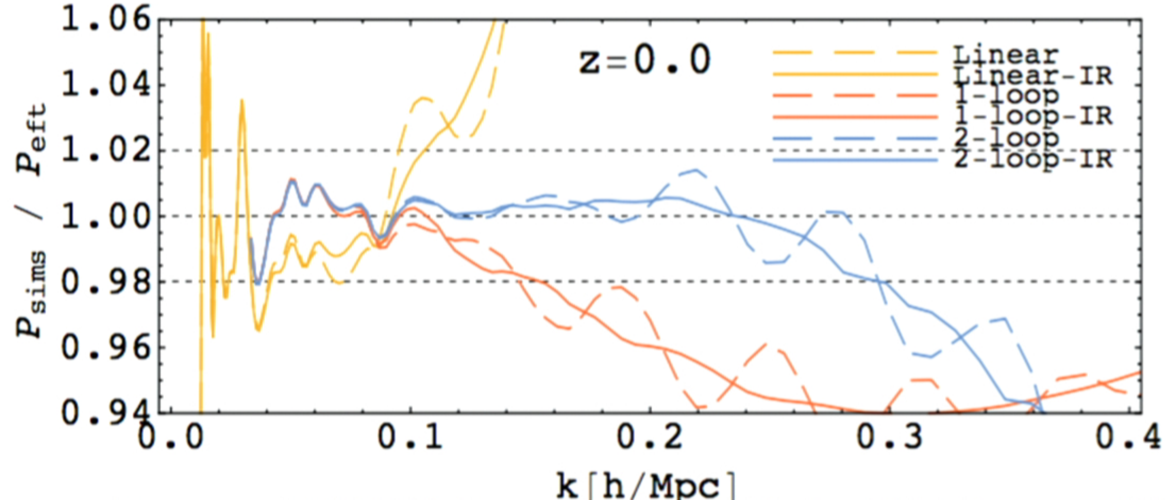
Wiggle power spectrum: $P_{\rm L,w} \quad \rightarrow \quad \sigma_n = \int_q q^{-n} P_{\rm L,w}(q) = 0$ for $n = \{0, 2\}$.



Linear power spectrum, correlation function & BAO

$$P_{\text{EFT-1-loop}} = P_{11} + P_{\text{1-loop}} - 2(2\pi)c^2_{s(1)}\frac{k^2}{k^2_{\text{NL}}}P_{11}$$

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2(2\pi)c^2_{s(1)}\frac{k^2}{k^2_{\text{NL}}}(P_{11} + P_{\text{1-loop}}) + \text{c.t.}$$



[Carrasco et al, 2012/2013, Senatore et al 2014, Baldauf et al 2015, Foreman et al 2015]

- Well defined/convergent expansion in k/k_{NL} (one parameter).
- IR resummation (Lagrangian approach) - BAO peak! [Senatore et al, 2014]
- Six c. t. for two-loop - approximate degeneracy! [Zaldarriaga et al, 2015]

Contents

- Lagrangian dynamics and EFT

[1506.05264]

with:
Martin White, Alejandro Aviles (Berkeley)

Lagrangian dynamics and EFT

Fluid element at position $\boldsymbol{q}$ at time t_0, moves due to gravity: Lagrangian displacement field $\boldsymbol{x}(\boldsymbol{q},t) = \boldsymbol{q} + \psi(\boldsymbol{q},t)$.
Density field at any time is given by

$$1 + \delta(\boldsymbol{x}) = \int_q \delta_D\left[\boldsymbol{x} - \boldsymbol{q} - \psi(\boldsymbol{q})\right] \quad \Rightarrow \quad \delta(\boldsymbol{k}) = \int_q e^{i\boldsymbol{k}\cdot\boldsymbol{q}}\left(e^{i\boldsymbol{k}\cdot\psi(\boldsymbol{q})} - 1\right)$$

The evolution of ψ is governed by $\partial_t^2\psi + 2H\partial_t\psi = -\nabla\phi(\boldsymbol{q}+\psi)$.
Integrating out short modes (using filter $W_R(\boldsymbol{q},\boldsymbol{q}')$) system is splitting tnto $L-$long and $S-$short wavelength modes, e.g.

$$\psi_L(\boldsymbol{q}) = \int_q W_R(\boldsymbol{q},\boldsymbol{q}')\psi(\boldsymbol{q}'), \quad \psi_S(\boldsymbol{q},\boldsymbol{q}') = \psi(\boldsymbol{q}') - \psi_L(\boldsymbol{q}).$$

This defines δ_L as the long-scale component of the density perturbation corresponding to ψ_L and also Φ_L as the gravitational potential $\nabla^2\Phi_L \sim \delta_L$.
E.o.m. for long displacement:

$$\ddot{\psi}_L + \mathcal{H}\dot{\psi}_L = -\nabla\Phi_L(\boldsymbol{q} + \psi_L(\boldsymbol{q})) + \boldsymbol{a}_S\left(\boldsymbol{q}, \psi_L(\boldsymbol{q})\right),$$

and $\boldsymbol{a}_S(\boldsymbol{q}) = -\nabla\Phi_S(\boldsymbol{q}+\psi_L(\boldsymbol{q})) - \frac{1}{2}Q_L^{ij}(\boldsymbol{q})\nabla\nabla_i\nabla_j\Phi_L(\boldsymbol{q}+\psi_L(\boldsymbol{q})) + \ldots,$
Similar formalism was also derived in [Porto et al, 2014]

Lagrangian dynamics and EFT

The correlation function and power spectrum can now be defined through the cumulants of the displacement, e.g.

$$P(k) = \int_q e^{i\boldsymbol{q}\cdot\boldsymbol{k}} \left[\left\langle e^{i\boldsymbol{k}\cdot\boldsymbol{\Delta}} \right\rangle - 1 \right] .$$

For one loop power spectrum results, keeping linear modes resumed:

$$P(k) = \int_q e^{i\boldsymbol{k}\cdot\boldsymbol{q} - (1/2)k_i k_j A_{ij}^{\text{lin}}} \left[1 - \frac{1}{2} k_i k_j A_{ij}^{\text{lpt+eft}} + \frac{i}{6} k_i k_j k_k W_{ijk}^{\text{lpt+eft}} + \cdots \right]$$

where $A_{ij}(\boldsymbol{q}) = 2\left\langle \Psi_i(\boldsymbol{0})\Psi_j(\boldsymbol{0}) \right\rangle - 2\left\langle \Psi_i(\boldsymbol{q}_1)\Psi_j(\boldsymbol{q}_2) \right\rangle$.
Final results equivalent to the Eulerian scheme.
Allows for the insight in the counter term structure and IR resummation schemes (in particular one leads to the scheme in [Senatore&Zaldarriaga, 2014]).

PS and transfer function approach

Transfer function

$$\tilde{T}_{\rm 1LPT}(k) = \frac{\langle \delta_{\rm 1LPT} \delta_{\rm dm} \rangle}{\langle \delta_{\rm 1LPT} \delta_{\rm 1LPT} \rangle},$$

with 1LPT and dark matter density perturbations in Fourier space. Cross-correlation coefficient

$$r^2_{\rm 1LPT} = \frac{\langle \delta_{\rm 1LPT} \delta_{\rm dm} \rangle^2}{\langle \delta_{\rm 1LPT} \delta_{\rm 1LPT} \rangle \langle \delta_{\rm dm} \delta_{\rm dm} \rangle}.$$

The corresponding stochastic power $P_J(k)$ is defined as

$$P_J(k) = \left[1 - r^2_{\rm 1LPT}(k)\right] P_{\rm dm}(k).$$

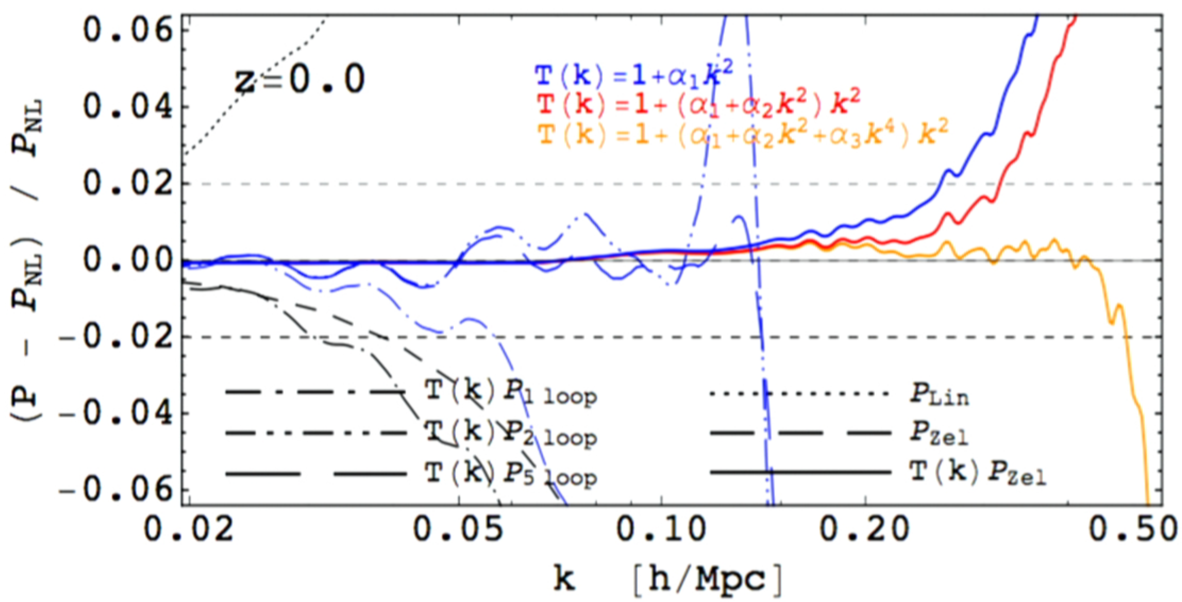
Non-perturbative effects on the power spectrum then it is simpler to define,

$$\frac{P_{\rm dm}(k)}{P_{\rm 1LPT}(k)} \equiv T^2_{\rm 1LPT}(k) = 1 + \alpha_{\rm 1LPT}(k) k^2 \equiv \left(1 + \sum_{i=1}^{\infty} \alpha_{i,{\rm 1LPT}} k^{2i}\right).$$

Note that $T(k)$ includes stochasticity and there is no guarantee that it can be expanded in terms of even powers of k, although we expect that at low k the leading term is $\alpha_{1,1LPT} k^2$.

Clustering in 1D

1D case studied recently in: [McQuinn&White, 2015]



Extensions to 3D: models

Define one-loop SPT-EFT parameter $\alpha_{\rm SPT,1-loop}(k)$

$$P_{\rm dm}(k) = D_+^2 P_L(k)\left[1 + \alpha_{\rm SPT,1-loop}(k)k^2\right] + D_+^4 P_{\rm SPT,1-loop},$$

Two loop results:

[Carrasco et al, 2012]

$$P_{\rm dm}(k) = \left(1 + \alpha_{\rm SPT,1-loop}(k)k^2\right)P_{\rm L}(k) + \left(1 + \alpha_{\rm SPT,1-loop}(k)k^2\right)P_{\rm SPT,1-loop}(k) + \left(P_{\rm SPT,2-loop}(k) - k^2\sigma^2_{\rm SPT,2loop}P_{\rm L}(k)\right)$$

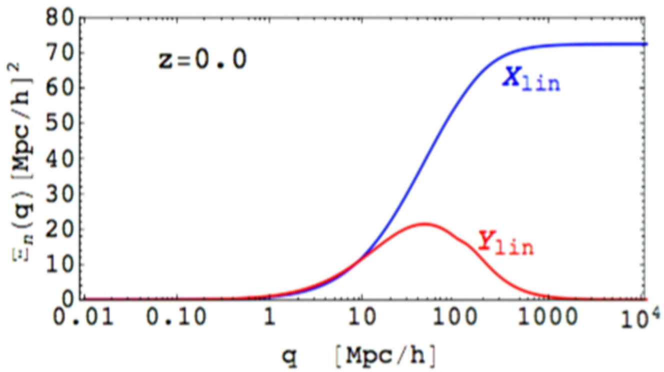
Hybrid model:

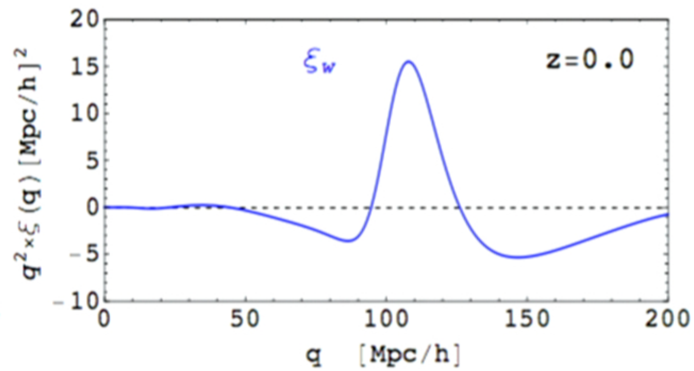
$$P_{\rm dm}(k) = P_{\rm 1LPT}(k)\left(1 + \alpha_{\rm 1LPT,1-loop}(k)k^2\right) + \left(P_{\rm SPT,1-loop}(k) - P_{\rm 1LPT,1-loop}(k)\right)_{IR}$$

Resummation of IR modes: simple scheme

Separating the wiggle and non-wiggle part $A^{ij}_{\rm L}(\boldsymbol{q}) = A^{ij}_{\rm L,nw}(\boldsymbol{q}) + A^{ij}_{\rm L,w}(\boldsymbol{q})$;

$$P = P_{\rm nw} + \int_q e^{i\boldsymbol{k}\cdot\boldsymbol{q} - (1/2)k_i k_j A^{ij}_{\rm L,nw}} \left[-\frac{k_i k_j}{2} A^{ij}_{\rm L,w} + \cdots \right] \simeq P_{\rm nw} + e^{-k^2\Sigma^2} P_{\rm L,w} + \ldots$$





IR-SPT resummation model:

$$P_{\rm dm}(k) = P_{\rm nw,L}(k) + P_{\rm nw,SPT,1-loop}(k) + \alpha_{\rm SPT,1-loop,IR}(k) k^2 P_{\rm nw,L}(k)$$
$$+ e^{-k^2\Sigma^2} \Big(\Delta P_{\rm w,SPT,1-loop}(k) + \left(1 + (\alpha_{\rm SPT,1-loop,IR} + \Sigma^2)k^2\right) \Delta P_{\rm w,L}(k) \Big).$$

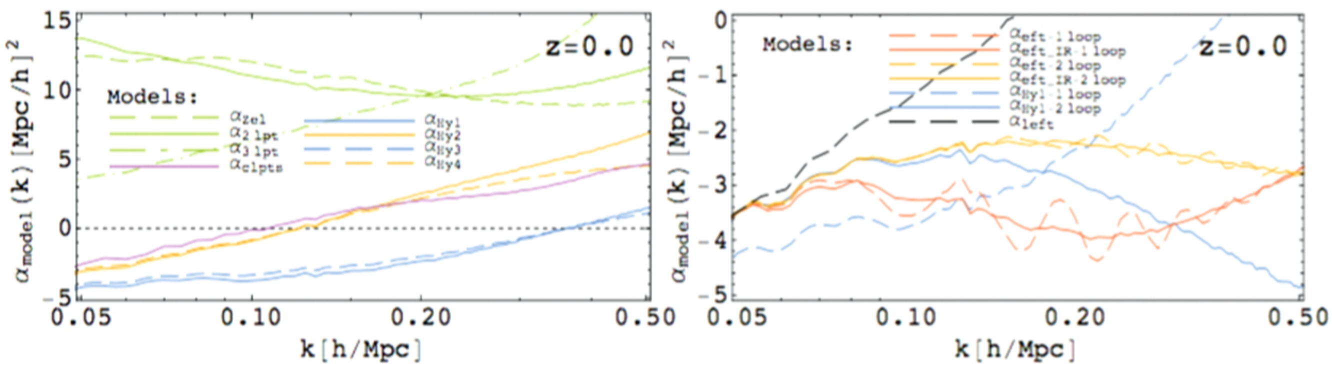
Alternative derivation in: [Baldauf et al, 2015]

Extensions to 3D

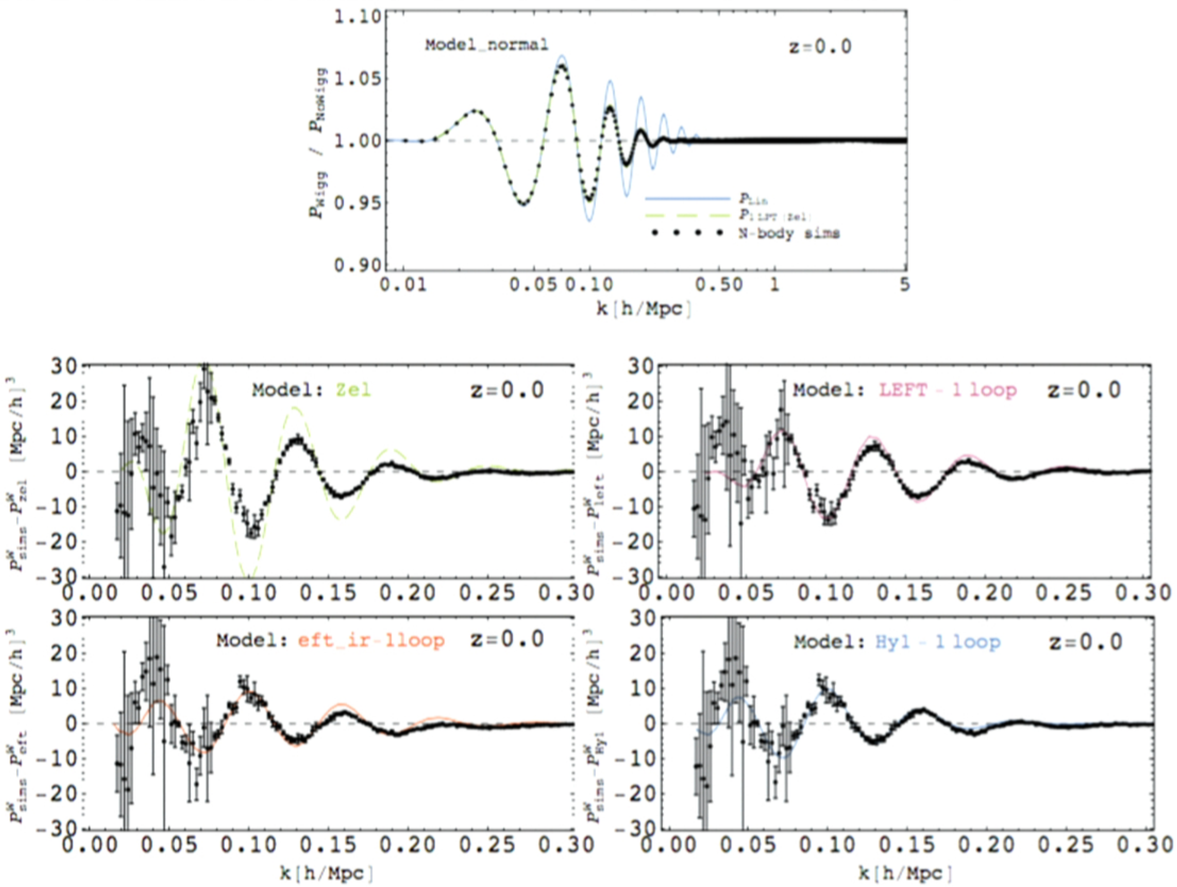
Positive corrections relative to 1LPT or 2LPT:

$$P_{\rm dm} = P_{\rm iLPT}\left(1 + \alpha_{\rm iLPT}(k)k^2\right),$$

Stochasticity for 2LPT suppressed. [Tassev et. al. 2011, Baldauf et. al. 2015]

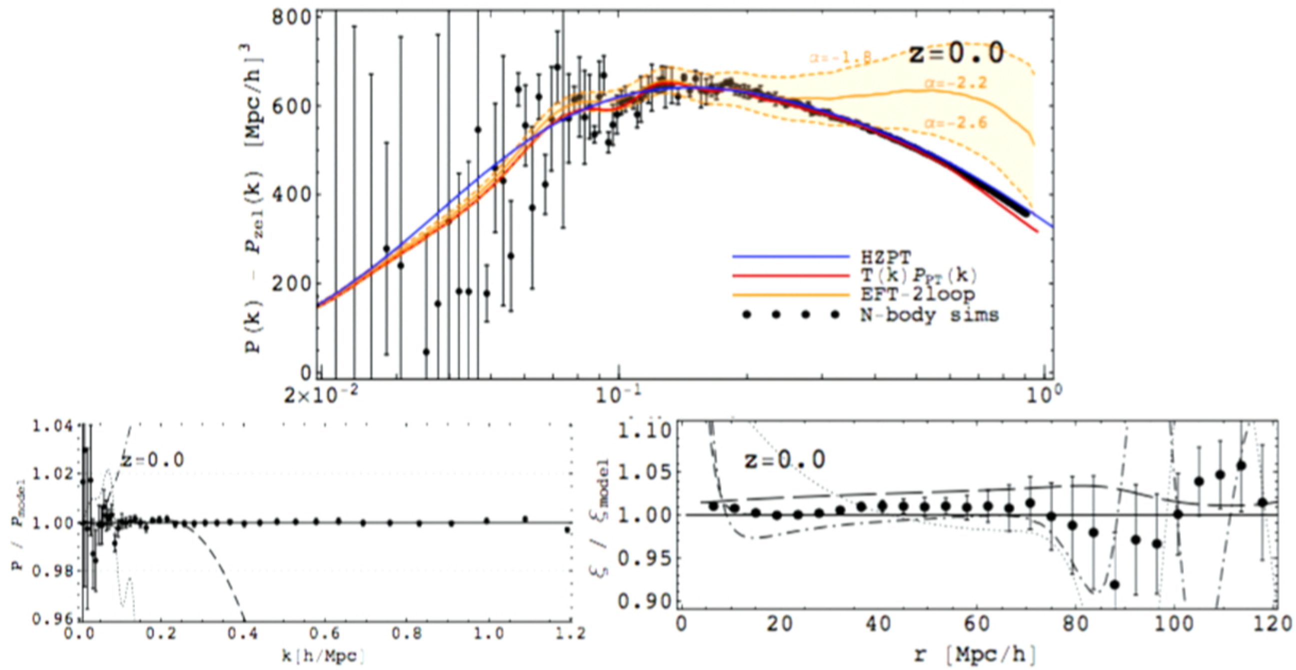


Wiggle residuals in our schemes: BAO



Interpreting the dark matter power spectrum

Halo-Zeldovich model : $P(k) = P_{Zel}(k) + P_{BB}(k)$

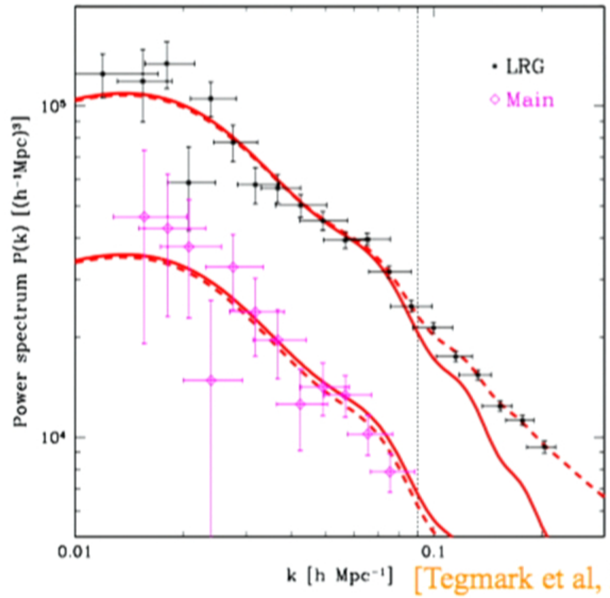


Matching of the large scale (low k) perturbative (EFT) results with the small scales Halo model offers description on wide range of scales.

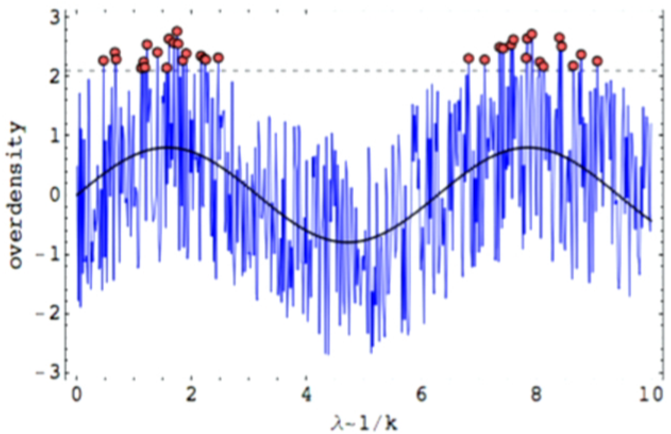
Galaxies and biasing of dark matter halos

Galaxies form at high density peaks of initial matter density:

rare peaks exhibit higher clustering!



[Tegmark et al, 2006]



- Tracer detriments the amplitude: $P_g(k) = b^2 P_m(k) + \ldots$
- Understanding bias is crucial for understanding the galaxy clustering

Earlier approaches to halo biasing

Local biasing model: halo field is a function of just DM density field

$$\delta_\mathrm{h} = c_\delta \delta + c_{\delta^2}\left(\delta^2 - \langle \delta^2 \rangle\right) + c_{\delta^3}\delta^3 + \ldots$$

[Fry & Gaztanaga, 1993]

Quasi-local (in space) relation of the halo density field to the dark matter

[McDonald & Roy 2008, Assassi et al, 2014]

$$\begin{aligned}\delta_\mathrm{h}(\mathbf{x}) &= c_\delta \delta(\mathbf{x}) + c_{\delta^2}\delta^2(\mathbf{x}) + c_{\delta^3}\delta^3(\mathbf{x}) \\ &+ c_{s^2} s^2(\mathbf{x}) + c_{\delta s^2}\delta(\mathbf{x}) s^2(\mathbf{x}) + c_\psi \psi(\mathbf{x}) + c_{st} s(\mathbf{x}) t(\mathbf{x}) + c_{s^3} s^3(\mathbf{x}) \\ &+ c_\epsilon \epsilon + \ldots,\end{aligned}$$

with effective ('Wilson') coefficients c_l and variables:

$$s_{ij}(\mathbf{x}) = \partial_i \partial_j \phi(\mathbf{x}) - \frac{1}{3}\delta^\mathrm{K}_{ij}\delta(\mathbf{x}), \qquad t_{ij}(\mathbf{x}) = \partial_i v_j - \frac{1}{3}\delta^\mathrm{K}_{ij}\theta(\mathbf{x}) - s_{ij}(\mathbf{x}),$$

$$\psi(\mathbf{x}) = [\theta(\mathbf{x}) - \delta(\mathbf{x})] - \frac{2}{7}s(\mathbf{x})^2 + \frac{4}{21}\delta(\mathbf{x})^2,$$

where ϕ is the gravitational potential, and white noise (stochasticity) ϵ.

Effective field theory of biasing

Non-local (time) and quasi-local (spece) relation of the halo density field to the dark matter

[Senatore 2014, Mirbabayi et al, 2014]

$$\delta_h(\boldsymbol{x},t) \simeq \int^t dt'\ H(t')\ \left[\bar{c}_\delta(t,t')\ :\delta(\boldsymbol{x}_{\rm fl},t'):\right.$$
$$+\ \bar{c}_{\delta^2}(t,t')\ :\delta(\boldsymbol{x}_{\rm fl},t')^2: +\bar{c}_{s^2}(t,t')\ :s^2(\boldsymbol{x}_{\rm fl},t'):$$
$$+\ \bar{c}_{\delta^3}(t,t')\ :\delta(\boldsymbol{x}_{\rm fl},t')^3: +\bar{c}_{\delta s^2}(t,t')\ :\delta(\boldsymbol{x}_{\rm fl},t')s^2(\boldsymbol{x}_{\rm fl},t'): + \dots$$
$$+\ \bar{c}_\epsilon(t,t')\ \epsilon(\boldsymbol{x}_{\rm fl},t') + \bar{c}_{\epsilon\delta}(t,t')\ :\epsilon(\boldsymbol{x}_{\rm fl},t')\delta(\boldsymbol{x}_{\rm fl},t'): + \dots$$
$$\left. +\bar{c}_{\partial^2\delta}(t,t')\ \frac{\partial^2_{x_{\rm fl}}}{k_M^2}\delta(\boldsymbol{x}_{\rm fl},t') + \dots \right]$$

Novice consideration of non-local in time formation, which depends on fields evaluated on past history on past path:

$$\boldsymbol{x}_{\rm fl}(\boldsymbol{x},\tau,\tau') = \boldsymbol{x} - \int_{\tau'}^{\tau} d\tau''\ \boldsymbol{v}(\tau'',\boldsymbol{x}_{\rm fl}(\boldsymbol{x},\tau,\tau''))$$

Alternative - all effects chaptered in Lagrangian approach.
Note: Assembly bias effects captured in the scheme.

Effective field theory of biasing

New physical scale $k_M \sim 2\pi \left(\frac{4Pi}{3}\frac{\rho_0}{M}\right)^{1/3}$, which can be different then k_{NL}.
We look at the correlations at $k \ll k_M$.

Each order in perturbation theory we get new bias coefficients:

$$\delta_{\rm h}(k,t) = c_{\delta,1}\left[\delta^{(1)}(k,t) + \text{flow terms}\right] + c_{\delta,2}\left[\delta^{(2)}(k,t) + \text{flow terms}\right] + \dots$$

Emergence of degeneracy: choice of most convenient basis

Turns out that at one loop 2-pt and tree level 3-pt function LIT and non-LIT are degenerate- this is no longer the case at higher loops or when 4-pt function is considered.

Effective field theory of biasing

Independent operators in the`Basis of Descendants':

$$\text{(1)st order: } \left\{ \mathbb{C}^{(1)}_{\delta,1} \right\}$$

$$\text{(2)nd order: } \left\{ \mathbb{C}^{(2)}_{\delta,1},\ \mathbb{C}^{(2)}_{\delta,2},\ \mathbb{C}^{(2)}_{\delta^2,1} \right\}$$

$$\text{(3)rd order: } \left\{ \mathbb{C}^{(3)}_{\delta,1},\ \mathbb{C}^{(3)}_{\delta,2},\ \mathbb{C}^{(3)}_{\delta,3},\ \mathbb{C}^{(3)}_{\delta^2,1},\ \mathbb{C}^{(3)}_{\delta^2,2},\ \mathbb{C}^{(3)}_{\delta^3,1},\mathbb{C}^{(3)}_{\delta,3_{c_s}}\ \mathbb{C}^{(3)}_{s^2,2} \right\}$$

$$\text{Stochastic: } \left\{ \mathbb{C}_{\epsilon},\ \mathbb{C}^{(1)}_{\delta\epsilon,1} \right\}$$

We compare $P^{1-\text{loop}}_{\text{hh}}$, $P^{1-\text{loop}}_{\text{hm}}$, $B^{\text{tree}}_{\text{hhh}}$, $B^{\text{tree}}_{\text{hhm}}$, $B^{\text{tree}}_{\text{hmm}}$ statistics
Renormalization! (takes care of short distance physics has at long distances of interest)
In practice, $\tilde{c}_{\delta,1}$ is a bare parameter, the sum of a finite part and a counterterm:

$$\tilde{c}_{\delta,1} = \tilde{c}_{\delta,1,\text{ finite}} + \tilde{c}_{\delta,1,\text{ counter}},$$

After renormalization we end up with using 7 finite bias parameters b_i (coefficients in EFT).

Observables: $P_{\mathbf{hm}}, P_{\mathbf{hh}}, B_{\mathbf{hmm}}, B_{\mathbf{hhm}}, B_{\mathbf{hhh}}$

Example: Halo-Matter Power Spectrum (one loop)

$$
\begin{aligned}
P_{hm}(k) = \quad & b_{\delta,1}(t)\left(P_{11}(k) + 2\int_q F_s^{(2)}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q})\,\widehat{c}^{(2)}_{\delta,1,s}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q})\,P_{11}(q)P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)\right.\\
& \left. + 3P_{11}(k)\int_q \left(F_s^{(3)}(\boldsymbol{k},-\boldsymbol{q},\boldsymbol{q}) + \widehat{c}^{(3)}_{\delta,1,s}(\boldsymbol{k},-\boldsymbol{q},\boldsymbol{q})\right)P_{11}(q)\right)\\
& + b_{\delta,2}(t)\,2\int_q F_s^{(2)}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q})\left(F_s^{(2)}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q}) - \widehat{c}^{(2)}_{\delta,1,s}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q})\right)P_{11}(q)P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)\\
& + b_{\delta,3}(t)3P_{11}(k)\int_q \widehat{c}^{(3)}_{\delta,3,s}(\boldsymbol{k},-\boldsymbol{q},\boldsymbol{q})P_{11}(q)\\
& + b_{\delta^2}(t)2\int_q F_s^{(2)}(\boldsymbol{k}-\boldsymbol{q},\boldsymbol{q})P_{11}(q)P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)\\
& + \left(b_{c_s}(t)k_{\rm NL}^2/k_{\rm M}^2 - 2(2\pi)c^2_{s(1)}(t)b_{\delta,1}(t)\right)\frac{k^2}{k_{\rm NL}^2}P_{11}(k)
\end{aligned}
$$

...and similar expressions hold for: $P_{\rm hh}$, $B_{\rm hmm}$, $B_{\rm hhm}$, $B_{\rm hhh}$.

Error estimates and bias fits

Error bars of the theory are given by the higher loop estimates:

e.g. $\Delta P_{hm} \sim (2\pi)\, b_1 \left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}(k)$.

This determines the theory reach $k_{\rm max}$.

$k_{\rm max}$ [h/Mpc]	bin0	bin1
mm	0.22 – 0.31	0.22 – 0.31
hm	0.24 – 0.35	0.22 – 0.35
hh	0.19 – 0.32	0.17 – 0.30
mmm	0.14 – 0.22	0.14 – 0.22
hmm	0.13 – 0.22	0.13 – 0.22
hhm	0.13 – 0.22	0.13 – 0.22
hhh	0.13 – 0.21	0.13 – 0.21

Fits to N-body simulations:

bin_1: $k_{\rm min}$=0.04h/Mpc, $k_{\rm max}$=0.11h/Mpc						
hm	hh	hmm	hhm	hhh	χ^2	p
+	+	−	−	−	0.0372	1.000
+	+	+	−	−	0.662	0.9937
+	+	−	+	−	0.615	0.9982
+	+	−	−	+	0.730	0.9724
+	+	+	+	−	0.849	0.8911
+	+	+	−	+	0.846	0.8963
+	+	−	+	+	1.17	0.09115
+	+	+	+	+	1.13	0.1105

Most of the constraint comes form the 3-pt function.

Fits to 3-pt and 4-pt function would enable full predictivity for 2-pt function.

EFT of biased tracers: bias fits

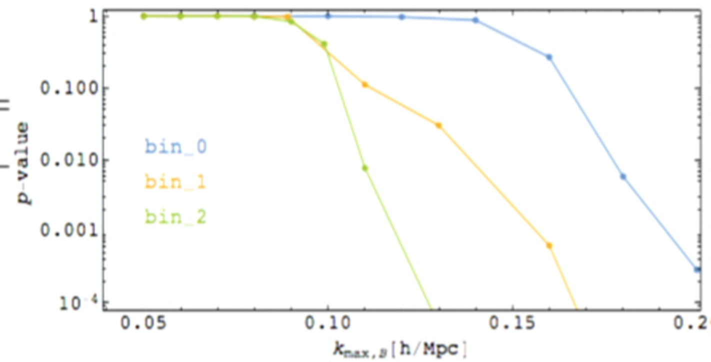
Error bars of the theory are given by the higher loop estimates:

e.g. $\Delta P_{hm} \sim (2\pi)\, b_1 \left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}(k)$.

This determines the theory reach $k_{\rm max}$.

	bin0	bin1
$b_{\delta,1}$	1.00 ± 0.01	1.32 ± 0.01
$b_{\delta,2}$	0.23 ± 0.01	0.52 ± 0.01
$b_{\delta,3}$	0.48 ± 0.12	0.66 ± 0.13
b_{δ^2}	0.28 ± 0.01	0.30 ± 0.01
b_{c_s}	0.72 ± 0.16	0.27 ± 0.17
$b_{\delta\epsilon}$	0.31 ± 0.08	0.76 ± 0.17
Const_ϵ	5697 ± 108	10821 ± 169

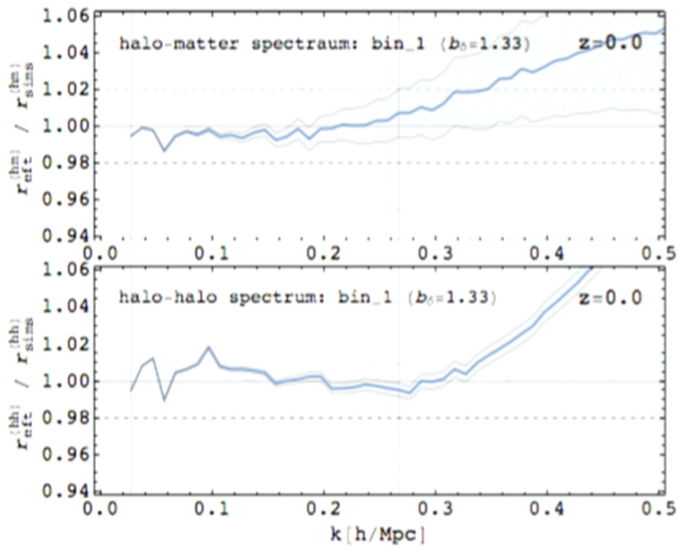
Characteristic sharp drop in the p-value after the maximal Bispectrum scale $k_{\rm max,B}$



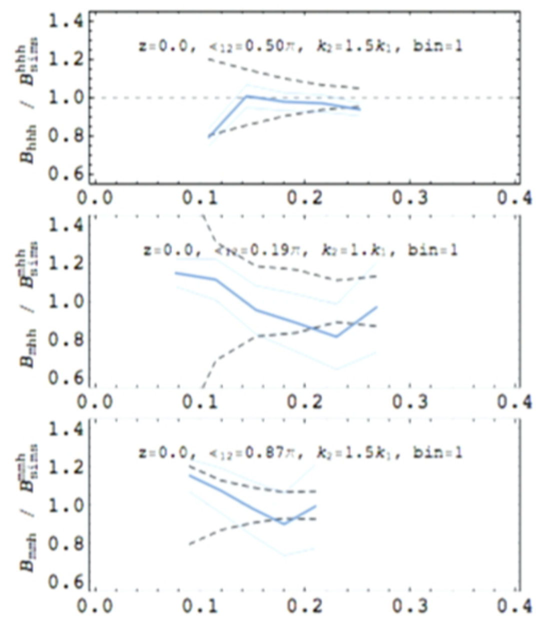
Within these scales EFT results fit the data well, and then fail after crossing this scales.

Halo PS & BIS results (bin 1)

Comparison to N-body simulations: Power Spectrum fitted up to $k < 0.26\text{Mpc}/h$ and Bispectrum up to $k < 0.11\text{Mpc}/h$



Comparison to N-body simulations: Power Spectrum fitted up to $k < 0.26\text{Mpc}/h$ and Bispectrum up to $k < 0.11\text{Mpc}/h$



Adding Non-Gaussianities

We assume that non-G. correlations are present only in the initial conditions and effect can be described by the squeezed limit, $k_L \ll k_S$ of correlation functions.

After horizon re-rentry, but still early enough to neglect all gravitational non-linearities, the primordial density fluctuation are given by

$$\delta^{(1)}(\boldsymbol{k}_S, t_{\rm in}) \simeq \delta_g(\boldsymbol{k}_S) + f_{\rm NL}\tilde{\phi}(\boldsymbol{k}_L, t_{\rm in})\delta_g(\boldsymbol{k}_S - \boldsymbol{k}_L, t_{\rm in}) \,,$$

where $\tilde{\phi}(\boldsymbol{k}_L, t_{\rm in}) = \frac{3}{2}\frac{H_0^2\,\Omega_m}{D(t_{\rm in})}\frac{1}{k_S^2\,T(k)}\left(\frac{k_L}{k_S}\right)^{\alpha}\delta_g(\boldsymbol{k}_L, t_{\rm in})$ and where $T(k)$ is the transfer function.

In the presence of primordial non-Gaussianities, additional components:

$$\delta_h(\boldsymbol{x}, t) \simeq f_{\rm nl}\,\tilde{\phi}(\boldsymbol{x}_{\rm fl}(t, t_{\rm in}), t_{\rm in}) \int^t dt'\, H(t') \left[\bar{c}^{\,\tilde{\phi}}(t, t') + \bar{c}^{\,\tilde{\phi}}_{\partial^2\phi}(t, t')\,\frac{\partial^2\phi(\boldsymbol{x}_{\rm fl}, t')}{H(t')^2} + \ldots\right]$$
$$+ f_{\rm nl}^2\,\tilde{\phi}(\boldsymbol{x}_{\rm fl}(t, t_{\rm in}), t_{\rm in})^2 \int^t dt'\, H(t') \left[\bar{c}^{\,\tilde{\phi}^2}(t, t') + \bar{c}^{\,\tilde{\phi}^2}_{\partial^2\phi}(t, t')\,\frac{\partial^2\phi(\boldsymbol{x}_{\rm fl}, t')}{H(t')^2} + \ldots\right] + \ldots$$

Recently also studied in: [Assassi et al, 2015]

Adding baryonic effects

- baryon effects (on DM) in EFT framework recently studied [Lewandowski et al, 2014]
- baryons at large distances described as additional fluid component (short distance physics is encoded in an effective stress tensor)

$$\delta_h(\boldsymbol{x},t) \simeq \int^t dt'\, H(t') \left[\bar{c}_{\partial^2\phi}(t,t')\, \frac{\partial^2\phi(\boldsymbol{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\delta_b}(t,t')\, w_b\, \delta_b(\boldsymbol{x}_{{\rm fl}\,b}) \right.$$
$$+ \bar{c}_{\partial_i v_c^i}(t,t')\, w_c\, \frac{\partial_i v_c^i(\boldsymbol{x}_{{\rm fl}\,c},t')}{H(t')} + \bar{c}_{\partial_i v_b^i}(t,t')\, w_b\, \frac{\partial_i v_b^i(\boldsymbol{x}_{{\rm fl}\,b},t')}{H(t')}$$
$$+ \bar{c}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\, \frac{\partial_i\partial_j\phi(\boldsymbol{x}_{\rm fl},t')}{H(t')^2}\, \frac{\partial^i\partial^j\phi(\boldsymbol{x}_{\rm fl},t')}{H(t')^2} + \dots$$
$$+ \bar{c}_{\epsilon_c}(t,t')\, w_c\, \epsilon_c(\boldsymbol{x}_{{\rm fl}\,c},t') + \bar{c}_{\epsilon_b}(t,t')\, w_b\, \epsilon_b(\boldsymbol{x}_{{\rm fl}\,b},t')$$
$$\left. + \bar{c}_{\epsilon_c\partial^2\phi}(t,t')\, w_c\, \epsilon_c(\boldsymbol{x}_{{\rm fl}\,c},t')\, \frac{\partial^2\phi(\boldsymbol{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\epsilon_b\partial^2\phi}(t,t')\, w_b\, \epsilon_b(\boldsymbol{x}_{{\rm fl}\,b},t')\, \frac{\partial^2\phi(\boldsymbol{x}_{\rm fl},t')}{H(t')^2} \dots \right]$$

where $\boldsymbol{x}_{\rm fl}$ is defined by Poisson equation and:

$$\boldsymbol{x}_{{\rm fl}\,b}(\boldsymbol{x},\tau,\tau') = \boldsymbol{x} - \int_{\tau'}^{\tau} d\tau''\, \boldsymbol{v}_b(\tau'', \boldsymbol{x}_{\rm fl}(\boldsymbol{x},\tau,\tau'')) , \quad \boldsymbol{x}_{{\rm fl}\,c}(\boldsymbol{x},\tau,\tau') = \boldsymbol{x} - \int_{\tau'}^{\tau} d\tau''\, \boldsymbol{v}_c(\tau'', \boldsymbol{x}_{\rm fl}(\boldsymbol{x},\tau,\tau''))$$

Summary

Part I:

- Lagrangian framework offers physical insight in LSS, application is e.g. IR resumption
- Transfer function framework offers a approximate outlook to dark matter nonlinear clustering.
- All constructed models can predict various wiggle shapes.
- Matching of EFT schemes at low k and Halo model at high k offers good prescription for describing a wide range of scales.

Part II:

- EFT gives a consistent expansion in $(k/k_{\rm NL})^2$, and for halos also in $(k/k_{\rm M})^2$, nonlocal effect in time and space included
- EFT approach is well suited for galaxy clustering (one-loop power spectra $k \sim 0.25h/\mathrm{Mpc}$, tree level bispectra $k \sim 0.1 - 0.15h/\mathrm{Mpc}$)
- Consistent description of five different observables ($P_{\rm hm}$, $P_{\rm hh}$, $B_{\rm hmm}$, $B_{\rm hhm}$, $B_{\rm hhh}$) with seven bias parameters.

Summary

Outlook:

- Higher loops calculations in order to extend the k_{max}, and higher statistics (e.g. 4-pt function - great potential)
- Calculation of observables taking into account baryons, non-Gaussianities and RSD …
- Generalization of the formalism in order include GR effects (become important as surveys grow).