Advances in few selected topics of perturbative LSS

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done in collaboration with:

- Martin White (Berkeley),
- Elisa Chisari (Oxford), Fabian Schmidt (MPA),
- Tomohiro Fujita (Kyoto, Geneva),
- Patrick McDonald (LBNL)
Agenda

What I would like to talk about:

- Redshift space distortions - categorization of few different approaches
- New look at the statistics of biased tracers - “Monkey bias“
- Clustering of shapes - applications to intrinsic alignments
- Lagrangian dynamics & stream crossing - statistical field theory attire
Early conclusions

Key messages:

- We have developed a new RSD framework based on the Fourier space cumulant expansion - highlight of differences and advantages.
- FoG are incorporated naturally - expressions are algebraic.
- New and simplified bias framework - we rely only on symmetries & equiv. principle.
- We use decomposition into spherical tensors to construct the bias/EFT of shapes - applications to intrinsic alignments.
- General framework - worked out full sky correlators.
- Consistently included shell crossing into the perturbative Lagrangian scheme.
- Connection to EFT-PT via low-\(k\) expansion - EFT parameter matching.
Redshift space distortions - Fourier space cluster expansion

with: Martin White (Berkeley)
I. Redshift space distortions - intro

Real space:

Redshift space:

Object position in redshift-space:
\[ s = x - f u_z(x) \hat{z}, \quad u_z \equiv -v_z/(fH) \]

Density in redshift-space:
\[ \delta_s(k) = \int_x (1 + \delta(x)) e^{ik \cdot x} \exp \left( -ifk_z u_z(x) \right) \]
I. Subjective overview of the RSD approaches

RSD power spectrum:

\[ P_s(k) = \int d^3r \ e^{ik\cdot r} \mathcal{M}(k_{\parallel} \hat{z}, r) = \int d^3r \ e^{ik\cdot r} \mathcal{M}(J = k\cdot R, r), \]

where \( r = x_2 - x_1 \) and

\[ 1 + \mathcal{M}(J, r) = \langle (1 + \delta(x))(1 + \delta(x'))e^{iJ\cdot \Delta u} \rangle, \]

is the pairwise velocity generating function, with \( \Delta u = u_2 - u_1 \).

Approaches:

▶ Streaming model: configuration space cumulant expansion, \( \mathcal{M} \rightarrow \ln \mathcal{M} \).
  [Peebles, White, ...]

▶ Velocity moment expansion: \( \mathcal{M} \) expanded in moment correlators.
  [SPT, Seljak&McDonald, ...]

▶ Smoothing kernel: cumulant expansion or individual contributions in \( \mathcal{M} \).
  [Scoccimarro, TNS ...]

▶ Direct Lagrangian approach: \( \mathcal{M} \) is transformed into Lagrangian coordinates.
  [Matsubara, White ...]
I. Fifth strategy - Fourier space cluster expansion

- a note on cumulant expansion / cluster expansion / cluster decomposition in general

**Config. space cumulant expansion:**

\[ Z(J, r) = \ln \left[ 1 + \mathcal{M}(J, r) \right] \]

where

\[ C_{i_1 \ldots i_n}^{(n)}(r) = (-i)^n \partial Z(J, r) / \partial J_{i_1} \ldots \partial J_{i_n} \bigg|_{J=0} \]

are the cumulants of the (density weighted) velocities, \( \Delta u \).

But we can work also in **Fourier space**

\[ \widetilde{Z}(J, k) = \ln \left[ 1 + \widetilde{\mathcal{M}}(J, k) \right] \]

which gives the Fourier space cumulants \( \widetilde{C}_{i_1 \ldots i_n}^{(n)}(k) \).

The nontrivial difference arises since \( \ln x \) and FT do not commute!

Redshift space power spectrum:

\[ \Delta_s^2(k) = \left[ 1 + \Delta^2(k) \right] \exp \left[ \sum_{n=1}^{\infty} \frac{i^n}{n!} k_{i_1} \ldots k_{i_n} \widetilde{C}_{i_1 \ldots i_n}^{(n)}(k) \right] - 1, \]

where \( \Delta^2 = \frac{k^3}{2\pi^2} P \).

Ok... but how well does all this work?
I. Fifth strategy - Fourier space cluster expansion

- a note on cumulant expansion / cluster expansion / cluster decomposition in general

**Config. space cumulant expansion:** \( \mathcal{Z}(J, r) = \ln \left[ 1 + \mathcal{M}(J, r) \right] \) where

\[
\mathcal{C}_{i_1 \ldots i_n}^{(n)}(r) = (-i)^n \frac{\partial \mathcal{Z}(J, r)}{\partial J_{i_1} \ldots \partial J_{i_n}} \bigg|_{J=0}
\]

are the cumulants of the (density weighted) velocities, \( \Delta u \).

But we can work also in Fourier space \( \tilde{\mathcal{Z}}(J, k) = \ln \left[ 1 + \tilde{\mathcal{M}}(J, k) \right] \), which gives the Fourier space cumulants \( \tilde{\mathcal{C}}_{i_1 \ldots i_n}^{(n)}(k) \).

**The nontrivial difference arises since \( \ln x \) and FT do not commute!**

Redshift space power spectrum, log for:

\[
\ln \frac{1 + \Delta_s^2(k, \nu)}{1 + \Delta^2(k)} = i(\nu k) \tilde{\mathcal{C}}_{n}^{(1)}(k, \nu) - \frac{(\nu k)^2}{2} \tilde{\mathcal{C}}_{n}^{(2)}(k, \nu) + \cdots,
\]

where \( \Delta^2 = \frac{k^3}{2\pi^2} P \).

Ok... but how well does all this work?
I. Zeldovich approx. - as an controlled environment

RSD in Zeldovich approx. : \( \psi \rightarrow \psi_s = \psi + (\hat{n} \cdot \dot{\psi})\hat{n}/H \)

- a robust environment to test these different approaches
- more robust for range of scales than sims, we can go to arbitrary moments

Zeldovich power spectrum (using \( R_{ij} = \delta^K_{ij} + f\hat{n}_i\hat{n}_j \)):

\[
P_s(k) = \int_q e^{ik \cdot q} \exp \left( -\frac{1}{2} k_i k_j R_{in} R_{jm} \langle \Delta_n^L \Delta_m^L \rangle \right).
\]

[z.v.&White, ’18]
I. Zeldovich approx. - convergence results

\[ P_s(k, \nu) \]

\[ \xi_s(r, \nu) \]

Topics in perturbative LSS

Redshift space distortions
I. Bispectrum - Fourier cluster expansion framework

Velocity generating fnc. can be generalized to get RSD \( n \)-point functions. For bispectrum:

\[
\widetilde{M}_{abc}^{\alpha}(J_1, J_2; k_1, k_2) = \frac{k_1^3 k_2^3}{4\pi^4} \int_{r_1, r_2} e^{i k_1 \cdot r_1 + i k_2 \cdot r_2} \left\langle (1 + \delta_a)(1 + \delta_b')(1 + \delta_c'')e^{i J_1 \cdot \Delta u_{ac} + i J_2 \cdot \Delta u_{bc}} \right\rangle.
\]

- RSD for higher \( n \)-pt. function is a quite difficult in the three canonical approaches
- In velocity moment expansion approach:

\[
B_{s}^{abc}(k_1, k_2) = \sum_{n,m=0}^{\infty} \frac{i^{n+m}}{n!m!} k_{1,i_1} \ldots k_{1,i_n} k_{2,j_1} \ldots k_{2,j_m} \widetilde{\Xi}_{i_1 \ldots i_n; j_1 \ldots j_m}(k_1, k_2)
\]

In Fourier cluster expansion framework the algebraic structure of the velocity cumulants is preserved

\[
1 + \Delta^2_{s,abc} = \left[ 1 + \Delta^2_{abc} \right] \exp \left[ \sum_{n+m=1}^{\infty} \frac{i^{n+m}}{n!m!} k_{1,i_1} \ldots k_{1,i_n} k_{2,j_1} \ldots k_{2,j_m} \widetilde{C}_{i_1 \ldots i_n; j_1 \ldots j_m}^{(n+m)}(k_1, k_2) \right].
\]

Analogous structure valid for \( n \)-pt functions
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In Fourier cluster expansion framework the algebraic structure of the velocity cumulants is preserved

$$\ln \frac{1 + \Delta^2_{s,abc}}{1 + \Delta^2_{abc}} = \sum_{n+m=1}^{\infty} \frac{i^{n+m}}{n!m!} k_{1,i_1} \ldots k_{1,i_n} k_{2,j_1} \ldots k_{2,j_m} \Delta^{(n+m)}_{i_1 \ldots i_n; j_1 \ldots j_n}(k_1, k_2).$$

Analogous structure valid for $n$–pt functions
We have developed an LSS analysis framework: [z.v. et. al., ’15, ’16, z.v.&White, ’18]
- in application together with the Lagrangian EFT, bias

Codes that can be applied to real world data:
- power spectrum, correlation function
  - link: github.com/martinjameswhite/CLEFT_GSM

Robust understanding of the BAO:
- did not have time to address here (see e.g. [Ding et. al., ’17])
  - application to reconstruction (in prep. [Chen et. al., ’19])

Applied in the BOSS collaboration, as well as DESI in the future;
- something else?
“Monkey bias” - a new look at the statistics of biased tracers

with: Tomohiro Fujita (Kyoto, Geneva)
II. Non-linear dynamics and galaxy bias

- **Eulerian bias**: relates final dark matter (d.m.) density field and the final halo density field

\[ \delta_g(x) = c_0^e \delta(x) + c_2^e \delta^2(x) + c_3^e s^2(x) + \ldots + c_k^e \frac{\partial^2}{k^2} \delta(x) + \text{"stochastic"} + \ldots \]

- **Lagrangian bias**: relates initial d.m. density field and the proto-halo density field

\[ \delta_g(q) = c_0^\ell \delta_L(q) + c_2^\ell \delta_L^2(q) + c_3^\ell s_L^2(q) + \ldots + c_k^\ell \frac{\partial^2}{k^2} \delta_L(q) + \text{"stochastic"} + \ldots, \]

[Matsubara, ’11]
II. Monkey (bias) business

A new key idea:

1. construct a bias of operators out of linear density - as a Monkey would,
2. impose symmetries afterwards - application of consistency relations

\[ \langle \delta^g_k(\eta)\delta^g_{q_1}(\eta_1) \ldots \delta^g_{q_n}(\eta_n) \rangle' \sim P_g(k, \eta) \sum_{\alpha} c_{\alpha}(\eta, \eta_{\alpha}) \frac{k \cdot q_{\alpha}}{k^2} \langle \delta^g_{q_1}(\eta_1) \ldots \delta^g_{q_n}(\eta_n) \rangle', \text{ as } k \to 0. \]

[Peloso&Pietroni, ’13, Kehagias&Riotto, ’13, …]

Please check out Tomo’s poster to hear the whole fascinating story!
II. Monkey (bias) business

A new key idea:

1. Construct a bias of operators out of linear density - as a Monkey would,
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\]

[Peloso&Pietroni, ’13, Kehagias&Riotto, ’13,…]

Please check out Tomo’s poster to hear the whole fascinating story!
Clustering of shapes - applications to full-sky intrinsic alignment correlators

with: Elisa Chisari (Oxford), Fabian Schmidt (MPA)
Effective field theory of biasing

Alternatively we can be similarly expand density of tracers as

\[ \delta_t(x) = \sum_O c_o O_t(x), \]

where we list operators \( O_h \):

(1) \( \text{tr} [\Pi^{[1]}] \),

(2) \( \text{tr} [(\Pi^{[1]})^2], \left( \text{tr} [\Pi^{[1]}] \right)^2 \),

(3) \( \text{tr} [(\Pi^{[1]})^3], \text{tr} [(\Pi^{[1]})^2] \text{tr} [\Pi^{[1]}], \left( \text{tr} [\Pi^{[1]}] \right)^3, \text{tr} [\Pi^{[1]} \Pi^{[2]}] \).

where \( \Pi^{[1]}_{ij} (k) = \frac{k_i k_j}{k^2} \delta_m (k) \), with derivative operators

\[ R^2 \nabla^2 \text{tr} [\Pi^{[1]}], \ldots. \]

– series allows one to estimate the higher order (theory) errors
– coefficients - physics from the \( R_* \) scale - degeneracies
III. Effective field theory of biasing

Expansion of the field of galaxy shapes:

\[ g_{ij}(x) = \sum_{O} b_{O} O_{ij}(x). \]

where the list of operators (up to higher derivatives and stochastic contributions) is

1. \( \text{TF}[\Pi^{[1]}]_{ij}, \)
2. \( \text{TF}[\Pi^{[2]}]_{ij}, \text{TF}[(\Pi^{[1]})^{2}]_{ij}, \text{TF}[\Pi^{[1]}]_{ij} \text{tr}[\Pi^{[1]}], \)
3. \( \text{TF}[\Pi^{[3]}]_{ij}, \text{TF}[\Pi^{[1]}\Pi^{[2]}]_{ij}, \text{TF}[\Pi^{[2]}]_{ij} \text{tr}[\Pi^{[1]}], \text{TF}[(\Pi^{[1]})^{3}]_{ij}, \text{TF}[(\Pi^{[1]})^{2}]_{ij} \text{tr}[\Pi^{[1]}], \text{TF}[\Pi^{[1]}]_{ij} \left( \text{tr}[\Pi^{[1]}] \right)^{2} \ldots \)

Derivative operators relevant for leading power spectrum corrections

\[ R^{2} \nabla^{2} \text{TF}[\Pi^{[1]}]_{ij}. \]
III. Effective field theory of biasing

Expansion of the field of galaxy shapes:

\[ g_{ij}(x) = b_o O_{ij}(x) \]

where the list of operators (up to higher derivatives and stochastic contributions) is

1. \( \text{TF} [\Pi^{[1]}]_{ij} \)
2. \( \text{TF} [\Pi^{[2]}]_{ij}, \text{TF} [\Pi^{[1]}]_{ij} \text{tr} [\Pi^{[1]}] \)
3. \( \text{TF} [\Pi^{[3]}]_{ij}, \text{TF} [\Pi^{[2]}]_{ij} \text{tr} [\Pi^{[1]}], \text{TF} [\Pi^{[1]}]_{ij} (\text{tr} [\Pi^{[1]}])^2 \ldots \)

Derivative operators relevant for leading power spectrum corrections:

\[ \text{TF} [\Pi^{[1]}]_{ij} \]
III. One-loop perturbation theory

Perturbative form of the shear tensor field

\[
\Pi^t_{ij}(k) = \sum_{n=1}^{\infty} (2\pi)^3 \delta^D_{k-q_1n} \mathcal{K}^{(n)}_{ij,\text{bias}}(q_1, \ldots, q_n) \delta_L(q_1) \cdots \delta_L(q_n),
\]

where \(\mathcal{K}^{(n)}_{\text{bias}}\) are bias kernels (up to third order for one-loop).

PT results up to one-loop power spectrum

\[
P^{\text{one-loop}}_{ijlm} = P^{ab,\text{lin}}_{ijlm} + P^{(22)}_{ijlm} + P^{(13)}_{ijlm} + P^{(31)}_{ijlm},
\]

Linear, and loop (22), (13) contributions

\[
P^{\text{lin}}_{ijlm}(k) = \frac{k_i k_j k_l k_m}{k^4} c^{\Pi[1]} P_{\text{lin}}(k),
\]

\[
P^{(22)}_{ijlm}(k) = 2 \mathcal{K}^{(2)}_{ij}(q, k - q) \mathcal{K}^{(2)}_{lm}(q, k - q) P_{\text{lin}}(q) P_{\text{lin}}(|k - q|),
\]

\[
P^{(13)}_{ijlm}(k) = 3 c^{\Pi[1]} \frac{k_i k_j}{k^2} P_{\text{lin}}(k) \mathcal{K}^{(3)}_{lm,b}(k, q, -q) P_{\text{lin}}(q).
\]

Similar for bispectrum...
Symmetries and Spherical Tensors

Separation: “symmetries” + “dynamics”

Spherical tensors: \( Y^{(\ell)}_{m}(\hat{k}') = \sum_{q=-\ell}^{\ell} \left( D^{(\ell)} \right)_{m}^{q} Y^{(\ell)}_{q}(\hat{k}) \)

Rank 0, 1, 2 form the orthogonal basis constructed from reps. of so(3):

- scalar: \( Y_{0} = 1 \),
- vector: \( Y_{i}^{(0)} = \hat{k}_{i}, \quad Y_{i}^{(\pm 1)} = e_{i}^{\pm} \),
- tensor: \( Y_{ij}^{(0)} = \hat{k}_{i}\hat{k}_{j} - \frac{1}{3} \delta_{ij}^{K}, \quad Y_{ij}^{(\pm 1)} = \hat{k}_{j}e_{i}^{\pm} + \hat{k}_{i}e_{j}^{\pm}, \quad Y_{ij}^{(\pm 2)} = e_{i}^{\pm}e_{j}^{\pm} \),

This gives the expansion

\[
\Pi_{ij}(k) = \frac{1}{3} \Pi_{0}^{(0)}(k) \delta_{ij}^{K} + \sum_{m=-2}^{2} \Pi_{2}^{(m)}(k) Y_{ij}^{(m)}
\]

This equivalent to the usual cosmological SVT decomposition.
3D correlators

Power spectra $P_{00}^{(0)}$, $P_{02}^{(0)}$, $P_{22}^{(0)}$, $P_{22}^{(1)}$ and $P_{22}^{(2)}$. 

Topics in perturbative LSS
III. Projections onto the sky: flat sky approximation

3D shape of galaxies get projected onto the sky:

\[ \gamma_{I,ij}(r,z) = \left( \mathcal{P}_{ik}(\hat{n}) \mathcal{P}_{jl}(\hat{n}) - \frac{1}{2} \mathcal{P}_{ij}(\hat{n}) \mathcal{P}_{kl}(\hat{n}) \right) g_{kl}(r,z), \]

where \( \mathcal{P}_{ij}(\hat{r}) \equiv \delta^K_{ij} - \hat{r}_i \hat{r}_j. \)

Integrating along the line of sight for photometric survey

\[ \hat{\gamma}_{I,ij}(\theta) = \int d\chi \, W(\chi) \gamma_{I,ij}(\chi \hat{n}, \chi \theta), \]

These rotation of the basis leads to the following spectra

\[ C_{\delta E}(\ell) = \int d\chi \, \frac{W^2(\chi)}{\chi^2} P^{(0)}_{02}(\ell/\chi), \]
\[ C_{\delta B}(\ell) = 0, \]
\[ C_{EE}(\ell) = \int d\chi \, \frac{W^2(\chi)}{\chi^2} \left( 2P^{(0)}_{22}(\ell/\chi) + P^{(2)}_{22}(\ell/\chi) \right), \]
\[ C_{BB}(\ell) = \int d\chi \, \frac{W^2(\chi)}{\chi^2} P^{(1)}_{22}(\ell/\chi), \]
\[ C_{EB}(\ell) = 0. \]
III. Projections onto the sky: full sky

Note that configuration space basis vectors are eigenfunctions of the projection operator $\mathcal{P}.m^{\pm} = m^{\pm}$ Thus projections are simple!

$$\hat{\gamma}_{\pm 2}(\hat{r}) = M_{ij}^{(\pm 2)*} \hat{\gamma}_{I,ij}(\hat{r}) = \int d\chi W(\chi) \gamma_{\pm 2}(\chi \hat{r}) = \int d\chi W(\chi) g_{\pm 2}(\chi \hat{r}).$$

that can be decomposed into spin weighted spherical harmonics

$$\hat{\gamma}_{\pm 2} = \sum_{lm} \pm \hat{\gamma}_{lm} Y_{l}^{(m)}$$

Full angle power spectrum is than given by

$$\langle X_{lm}^{*} X_{lm}' \rangle = (2\pi)^2 \delta_{ll'}^{K} \delta_{mm'}^{K} C_{l}^{XX'}.$$

Leads to familiar E & B mode full sky form:

$$\langle s \hat{\gamma}_{\ell m} | s' \hat{\gamma}_{\ell' m'} \rangle = \delta_{\ell,\ell'}^{K} \delta_{m,m'}^{K} 4\pi \sum_{q=0}^{2} \int_{k} P_{22}^{(q)} (k) \left[ \int_{\chi_{1}} W_{1} J_{\ell,2}^{s},s' (\chi_{1}k) \right] \left[ \int_{\chi_{2}} W_{2} J_{\ell,2}^{s'},-q (\chi_{2}k) \right].$$
Lagrangian dynamics & stream crossing
- statistical field theory attire

with: Patrick McDonald (LBL)
### IV. Path integrals and going beyond shell crossing

- as we saw the Lagrangian framework includes shell crossing
- Lagrangian dynamics can be compactly written using

\[
L_0 \phi + \Delta_0(\phi) = \epsilon,
\]

where:

\[
\phi \equiv (\psi, \nu), \quad [L_0]_{i_2i_1} = \begin{pmatrix}
\frac{\partial}{\partial \eta_2} & -1 \\
-\frac{3}{2} & \frac{\partial}{\partial \eta_2} + \frac{1}{2}
\end{pmatrix}, \quad \Delta_0(\phi) = \frac{3}{2} \left( 0, \partial_x \partial_x^{-2} \delta + \psi \right).
\]

Statistics of interest given by generating function

\[
Z(j) \equiv \int d\epsilon \ e^{-\frac{1}{2} \epsilon N^{-1} \epsilon + j \phi[\epsilon]} \quad \text{and} \quad \langle \phi_{i_1} \phi_{i_2} \rangle = \frac{\partial^2}{\partial j_{i_1} \partial j_{i_2}} Z(j) \bigg|_{j=0},
\]

which after the variable change becomes

\[
Z(j) \equiv \int d\phi \ e^{-S(\phi) + j \phi},
\]

with \( S(\phi) = 1/2 \left[ L_0 \phi + \Delta_0(\phi) \right] N^{-1} \left[ L_0 \phi + \Delta_0(\phi) \right] \).

[McDonald&Vlah, ’17]
We can organize our perturbation theory as:

\begin{equation}
S = S_g + S_p,
\end{equation}

where then we do \( \exp(-S) = \exp(-S_g)(1 - S_p + S_p^2/2 + ...) \)

where we can choose what the ”Gaussian part” will be, i.e.

\begin{equation}
S_g = 1/2 \chi N \chi + i \chi [W^{-1} L_0] \phi = 1/2 \chi N \chi + i \chi L \phi
\end{equation}

and

\begin{equation}
S_p = i \chi \Delta_0(\phi) + i \chi [(1 - W^{-1}) L_0] \phi \equiv i \chi \Delta(\phi),
\end{equation}

where \( \chi \) is the auxiliary field from the Hubbard-Stratonovich transformation.

Perturbation theory result : \( Z_0(j) = Z_0(j) + Z_1(j) + \ldots \)

Leading order result: truncate Zel’dovich dynamics!!!

\begin{equation}
Z_0 = e^{\frac{1}{2} j \cdot C j} \quad \text{and} \quad P(k) = \int d^3q \ e^{i q \cdot k} e^{-\frac{1}{2} k_i k_j A_{ij}^{W}}
\end{equation}

higher orders more complicated, build in renormalization! [McDonald & Vlah, ’17]
IV. Path integrals and going beyond shell crossing

\( n = 0.5 \)

Significance and connection EFT formalism:

- no need of EFT free parameters, i.e. counter terms are predicted
- CMB lensing: direct information on baryonic and neutrinos physics
- reduction of degeneracy in galaxy bias coefficients
- possible connection to the EFT formalism by matching the \( k \to 0 \) limit
IV. Path integrals and going beyond shell crossing

\( n = 1.0 \)

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Concluding thoughts

To recapitulate:

- We have developed a new RSD framework based on the Fourier space cumulant expansion - highlight of differences and advantages.
- FoG are incorporated naturally - expressions are algebraic.
- New and simplified bias framework - we rely only on symmetries & equiv. principle.
- We use decomposition into spherical tensors to construct the bias/EFT of shapes - applications to intrinsic alignments.
- General framework - worked out full sky correlators.
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