The fully relativistic correlation function for galaxy surveys

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Outline

Background and motivation

Applications

Results

Conclusions
Galaxy clustering in short

- what galaxy surveys measure:
  1. the energy (frequency) of a photon emitted by a galaxy at redshift $z$
  2. the direction $\hat{n}$ in the sky from which this photon originated

- given that at some redshift $z$ we detect on average $\langle N \rangle$ galaxies, we define the number counts “overdensity” as:

$$\Delta(z, \hat{n}) \equiv \frac{N(z, \hat{n}) - \langle N(z) \rangle}{\langle N(z) \rangle}$$

- we can split the contributions to the overdensity as follows:

$$\Delta = \Delta^{\text{den}} + \Delta^{\text{rsd}} + \Delta^{\text{lensing}} + \Delta^{\text{rel}}$$

- largest contributions to 2 point function of $\Delta$ come from $\Delta^{\text{den}}$ and $\Delta^{\text{rsd}}$, but $\Delta^{\text{lensing}}$ may be important on large scales
Future galaxy surveys

- DESI, Euclid, SKA, LSST - higher precision and larger survey volumes than ever before
- usual theoretical estimators: $P(k, z_1, z_2)$, $C_\ell(z_1, z_2)$, $\xi(\theta, z_1, z_2)$
  - $P(k)$ - easiest to compute theoretically and observationally, is not gauge invariant, challenging to include integrated effects
  - $C_\ell$ - easy to compute theoretically, gauge invariant, suitable for photometric surveys, needs many thin redshift bins for optimal information, not easy to extract growth rate $f$
  - $\xi$ - gauge invariant, easy to get growth rate $f$, mostly easy to compute, suitable for spectroscopic surveys, covariance is not diagonal and is challenging to include integrated effects in it
- codes: CAMB [$P(k), C_\ell$], CLASS [$P(k), C_\ell$], COFFE$^1[\xi]$

$^1$https://www.github.com/JCGoran/coffe/
Applications

- goal: estimate impact of lensing and rel. effects on future spectroscopic surveys
- method used: Fisher matrix analysis
- surveys considered: SKA II, DESI
- estimator: multipoles of 2 point correlation function, $\xi_L(\bar{z}, r)$
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Signal-to-noise (SNR) ratio

we define

\[ \xi_{\text{total}} = \xi_{\text{std}} + A \xi_{\text{effect}} \]

where effect \( \in \{ \text{lensing, rel.} \} \), and

\[ \xi_{\text{std}} \equiv \langle (\Delta_{\text{den}} + \Delta_{\text{rsd}})(\Delta_{\text{den}} + \Delta_{\text{rsd}}) \rangle_{\Omega} \]

define SNR \( \equiv \sqrt{F} \), where \( F \) denotes the Fisher matrix, and

\( A \) is the only free parameter
Signal-to-noise (SNR) ratio (cont.)

Figure: SNR of lensing for SKA II on linear (left) and logarithmic (right) scales

- Lensing has quite a large cumulative SNR ($\sim 10$), while for DESI it appears to be negligible.
- Rel. effects negligible for both ($\sim 0.35$ for SKA II, $\sim 0.65$ for DESI).
Cosmological parameters - constraints and bias

Table: Parameters used for the Fisher matrix analysis as well as their fiducial values

<table>
<thead>
<tr>
<th>name</th>
<th>$\omega_{cdm}$</th>
<th>$\omega_b$</th>
<th>$h$</th>
<th>$n_s$</th>
<th>$\log_{10}(10^{10} A_s)$</th>
<th>$b_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_i$</td>
<td>0.1186</td>
<td>0.02226</td>
<td>0.6781</td>
<td>0.9677</td>
<td>3.062</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Cosmological parameters - constraints and bias (cont.)

Figure: Contour plot of ΛCDM parameters used for the Fisher matrix analysis for SKA II
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Cosmological parameters - constraints and bias (cont.)

Table: SKA II, 8 bin configuration, no lensing in parameter constraints

<table>
<thead>
<tr>
<th>parameter</th>
<th>$b_0$</th>
<th>$\Omega_b$</th>
<th>$\Omega_{cdm}$</th>
<th>$h$</th>
<th>$n_s$</th>
<th>$\ln 10^{10} A_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\theta_i)/\theta_i$ (%)</td>
<td>0.36</td>
<td>1.31</td>
<td>0.37</td>
<td>1.25</td>
<td>1.04</td>
<td>0.69</td>
</tr>
<tr>
<td>$\Delta(\theta_i)/\sigma(\theta_i)$</td>
<td>-0.072</td>
<td>0.32</td>
<td>-0.19</td>
<td>0.19</td>
<td>-0.6</td>
<td>-0.14</td>
</tr>
</tbody>
</table>

- constraints on the sub-percent level for some parameters
- bias for standard $\Lambda$CDM parameters smaller than 1σ for all parameters
- DESI - constraints between 0.8% and 3.5%, bias negligible
Measuring the growth function

- we now assume that the ΛCDM parameters are fixed, and want to know what’s the accuracy with which we can constrain the parameters \( \tilde{b}(z) \equiv \sigma_8 D_1(z)b(z) \) and \( \tilde{f}(z) \equiv \sigma_8 D_1(z)f(z) \) in each redshift bin
- Reasoning - the \( L = 0, 2, 4 \) multipoles of the correlation function, neglecting wide-angle effects, are proportional to:

\[
\xi_L \sim D_1^2 \alpha \beta P(k)
\]

where \( \alpha, \beta \in \{b, f\} \), so we can rewrite \( \xi_L \) completely in terms of \( \tilde{f} \) and \( \tilde{b} \), with fiducial values taken to be those of ΛCDM
Results for $\tilde{f}$

Figure: Value and constraints for $\tilde{f}$ (blue), as well as the values offset by the bias (orange) for SKA II, 8 bin configuration.
Results for \( \tilde{b} \)

**Figure:** Value and constraints for \( \tilde{b} \) (blue), as well as the values offset by the bias (orange) for SKA II, 8 bin configuration. Note that for \( z > 0.5 \) the errors are smaller than the line thickness.
### Tables

**Table:** SKA II, 8 bin configuration: the values of the parameters $\tilde{b}_i$ and $\tilde{f}_i$, their constraints, and shifts when neglecting the lensing contribution to the correlation function.

<table>
<thead>
<tr>
<th>$\bar{z}_i$</th>
<th>$\tilde{b}_i$</th>
<th>$\sigma_{\theta}(\tilde{b}_i)(%)$</th>
<th>$\Delta \frac{\sigma}{\sigma}(\tilde{b}_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>0.52</td>
<td>2.22</td>
<td>-0.02</td>
</tr>
<tr>
<td>0.35</td>
<td>0.54</td>
<td>1.08</td>
<td>-0.01</td>
</tr>
<tr>
<td>0.48</td>
<td>0.56</td>
<td>0.77</td>
<td>0.01</td>
</tr>
<tr>
<td>0.66</td>
<td>0.59</td>
<td>0.50</td>
<td>0.07</td>
</tr>
<tr>
<td>0.92</td>
<td>0.65</td>
<td>0.22</td>
<td>0.36</td>
</tr>
<tr>
<td>1.23</td>
<td>0.73</td>
<td>0.21</td>
<td>1.17</td>
</tr>
<tr>
<td>1.54</td>
<td>0.83</td>
<td>0.25</td>
<td>2.45</td>
</tr>
<tr>
<td>1.85</td>
<td>0.96</td>
<td>0.29</td>
<td>3.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\bar{z}_i$</th>
<th>$\tilde{f}_i$</th>
<th>$\sigma_{\theta}(\tilde{f}_i)(%)$</th>
<th>$\Delta \frac{\sigma}{\sigma}(\tilde{f}_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>0.47</td>
<td>1.97</td>
<td>0.02</td>
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<td>-0.01</td>
</tr>
<tr>
<td>0.66</td>
<td>0.47</td>
<td>0.72</td>
<td>-0.06</td>
</tr>
<tr>
<td>0.92</td>
<td>0.45</td>
<td>0.48</td>
<td>-0.30</td>
</tr>
<tr>
<td>1.23</td>
<td>0.41</td>
<td>0.71</td>
<td>-0.95</td>
</tr>
<tr>
<td>1.54</td>
<td>0.38</td>
<td>1.38</td>
<td>-1.94</td>
</tr>
<tr>
<td>1.85</td>
<td>0.35</td>
<td>3.16</td>
<td>-2.40</td>
</tr>
</tbody>
</table>

- **bias** **significant** for SKA II, negligible for DESI
Conclusions and remarks

Questions answered:

- Will relativistic effects be detectable in the 2PCF for single tracers of future spectroscopic surveys? **Probably not**
- Does lensing have an impact on constraints on standard cosmological parameters? **Not much**
- Does neglecting lensing induce a bias in the values of standard cosmological parameters? **Yes, but less than 1σ**
- Does neglecting lensing induce a bias when measuring $\tilde{f}$ and $\tilde{b}$? **Yes, up to 3σ**

Future work:

1. combining spectroscopic and photometric surveys → impact on bias and constraints (talk by Francesca tomorrow!)
2. nonlinear effects neglected in analysis → does it increase or decrease the signal?
3. analysis for Euclid (when we get the specs)
Fin