Field level BAO inference

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Summary

The Baryon Acoustic Oscillation BAO feature is damped by non-linear structure formation, which reduces the precision with which we can infer the BAO scale from standard galaxy clustering analysis methods. A variety of techniques, known as BAO reconstruction, have been proposed to mitigate this damping effect; however, in order to work, these methods need to make assumptions abut bias and cosmology as well as to rely on the compression functions. **In our study, we combine forward modeling with field-level inference** in the goal of extracting the size of BAO scale using HMC sampling. Unlike traditional methods, **field-level approach does not require reconstruction** and permits full information extraction without relying on n-point functions. To fully gauge the gain of this approach, we are conducting a thorough comparison with n-point functions analysis, employing both standard likelihood-based and simulation-based inference methods.

Goal

Asses how much information about the BAO scale we can access using the forward model and the EFT likelihood compared to:

- Power spectrum likelihood
- SBI methods (ongoing)
- Power spectrum likelihood + BAO reconstruction (ongoing)

Forward Model

The goal is to find a joint posterior for the initial density field, cosmological parameters, bias parameters and stochastic amplitudes whose four ingredients are:

- Prior for the initial conditions

$$\mathcal{P}(\hat{s}(x)) = \begin{cases} \delta_D(\hat{s} - \hat{s}_{true}), & \text{Fixed IC} \\ \mathcal{N}(0,1), & \text{Free IC} \end{cases}$$

- Forward model for matter and gravity: 2nd order LPT
- Deterministic bias model:
  - 2nd order Lagrangian bias

    $$O_L \in \left\{\delta, \left(\mathrm{tr}\left[M^{(1)}\right]\right)^2, \mathrm{tr}\left[M^{(1)}M^{(1)}\right], \nabla^2\delta\right\}$$

  - 2nd order Eulerian bias

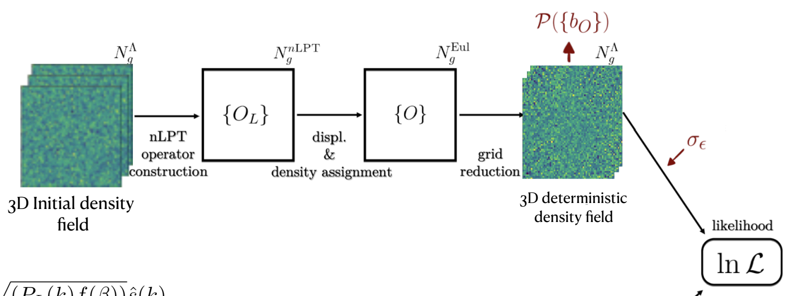
    $$O \in \{\delta, \delta^2, K^2, \nabla^2\delta\}$$

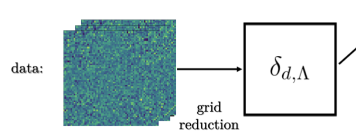
- EFT likelihood

$$\ln P(\delta_h|\delta_{\rm in},\{b_O\}) = -\frac{1}{2}\sum_{|k|<\Lambda}\left[\ln[2\pi\sigma_\varepsilon^2] + \frac{1}{\sigma_\varepsilon^2}\left|\delta_h(\mathbf{k}) - \delta_{h,\rm det}[\delta_{\rm in},\theta,\{b_O\}](\mathbf{k})\right|^2\right]$$

Posterior is constructed directly from the field allowing us to access the information directly without having to rely on compression functions.

$$P(\theta) = \int \mathcal{D}\delta_{in} P(\delta_h|\delta_{fwd}[\delta_{in},\theta]) P_{prior}(\delta_{in},\theta)$$





$$\delta_{in} = W_\Lambda(k)\sqrt{(P_L(k)f(\beta))}\hat{s}(k)$$

- We construct the initial density field by sampling the IC from the prior and multiplying it with a linear PS to add the cosmology. To ensure that only the modes under perturbative control are included, we apply a sharp-k filter.
- To change the size of the BAO in the initial density field, we multiply the linear PS with a function of a parameter $\beta = \frac{r_s}{r_{fid}}$, which is the ratio of the proposed BAO scale to the fiducial one

$$\delta_{\rm in}(k,\beta) = f(k,\beta)\delta_{\rm fid}(k)$$

Fixed IC

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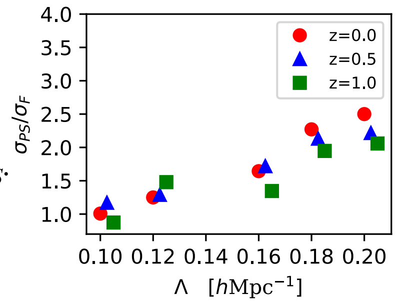
Data: Rest frame halo catalogs
Initial Conditions: Fixed to the values used to initialise the halo catalog
Inference: Profile likelihood
Likelihoods:

- EFT likelihood - input is the field δ_h found using the forward model
- PS likelihood - takes the power spectrum of δ_h
  - **no additional reconstruction performed**
  - Analytical covariance adjusted to fixed IC

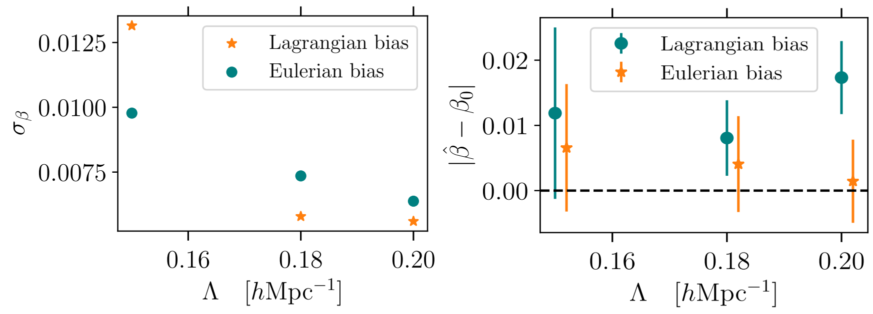
Results:
The size of the error bar for the EFT scale found using the EFT likelihood σ_F **is between 1.1 and 3.3 times smaller than the PS likelihood error bar** σ_{PS}.



Free initial conditions

• Field level

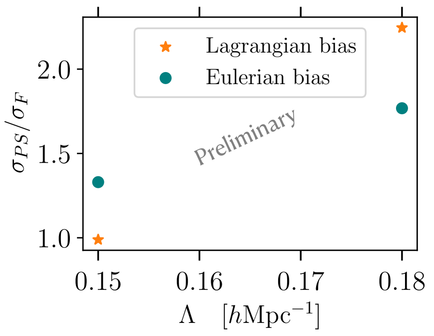
Data: Using LEFTfield, we generate mock data at a cut-off $\Lambda_0 = 0.3$. Mock is generated using 2nd order LPT and 2nd order Eulerian bias expansion. For the ground truth BAO scale size, we choose $\beta_0 = 0.98$
Initial Conditions: We assume a unit Gaussian prior with zero mean
Method: Performing inference at cut-offs smaller then Λ_0 using both 2nd order Lagrangian and Eulerian bias. For sampling cosmological parameter we use slice sampler and for initial conditions we use HMC sampler.



Results:
Using the HMC sampler allowed us to marginalise the posterior over the initial conditions and successfully perform the BAO scale inference despite the size of the parameter space for the initial conditions.
We notice that the error bar on the BAO scale is smoothly decreasing with increasing Λ as more k modes are being included in the likelihood and forward model. We also notice that the remaining systematic bias is consistently below 1% in the case of Eulerian bias.

• Comparing to PS likelihood

PS likelihood:
Input: Fwd model PS without additional reconstruction
Covariance: Free IC sample covariance
Inference: Profile likelihood



Preliminary Results: Error bar for the EFT scale found using the EFT likelihood σ_F seems to be up to 2.5 times smaller than the PS likelihood. We note that there was no additional reconstruction performed on the PS.