On constraning cosmology at the level of the field with a bootstrap approach

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A summary of the problem

The context of LSS cosmology:

- We want to extract the most information, test new models and discover/constrain new physics
- Cosmological inference on LSS is based on correlators of the galaxy density field $\delta_g(\vec{x})$ ($P + B$)
- Correlators suffer from many degeneracies (bias relation) and become impractical beyond 2-point (covariances, higher order correlators)
- The alternative: use the field itself, it contains all the information and has minimal amounts of degeneracies

REFERENCES:

Babić, Schmidt, Tucci 24 [2407.01524v1]

Nguyen+ 24 [2403.03220v3]

Stadler, Schmidt, Reinecke 23 [2303.09876v1]

This work

Outline:

- Data is the dark matter density field from N-body simulations + Poissonian shot noise as a proxy for galaxy density
- Perturbative forward model (from initial conditions to late time) within the “LSS bootstrap” approach
- Define a likelihood (gaussian in first approximation), and sample a posterior through MCMC

REFERENCES:

Kostić+22 [2212.07875v2]
Schmidt 20 [2009.14176v3]
Cabass 20 [2007.14988v2]
Schmidt+ 20 [2004.06707v2]

Forward model: bootstrap

Non-linearities (kernels) of the field constrained by symmetries and conservation laws (MODEL INDEPENDENT):

- Rotational and translational invariance
- Mass conservation (bias relation when dropped)
- Scale independence (no physical scales)
- Extended Galilean Invariance

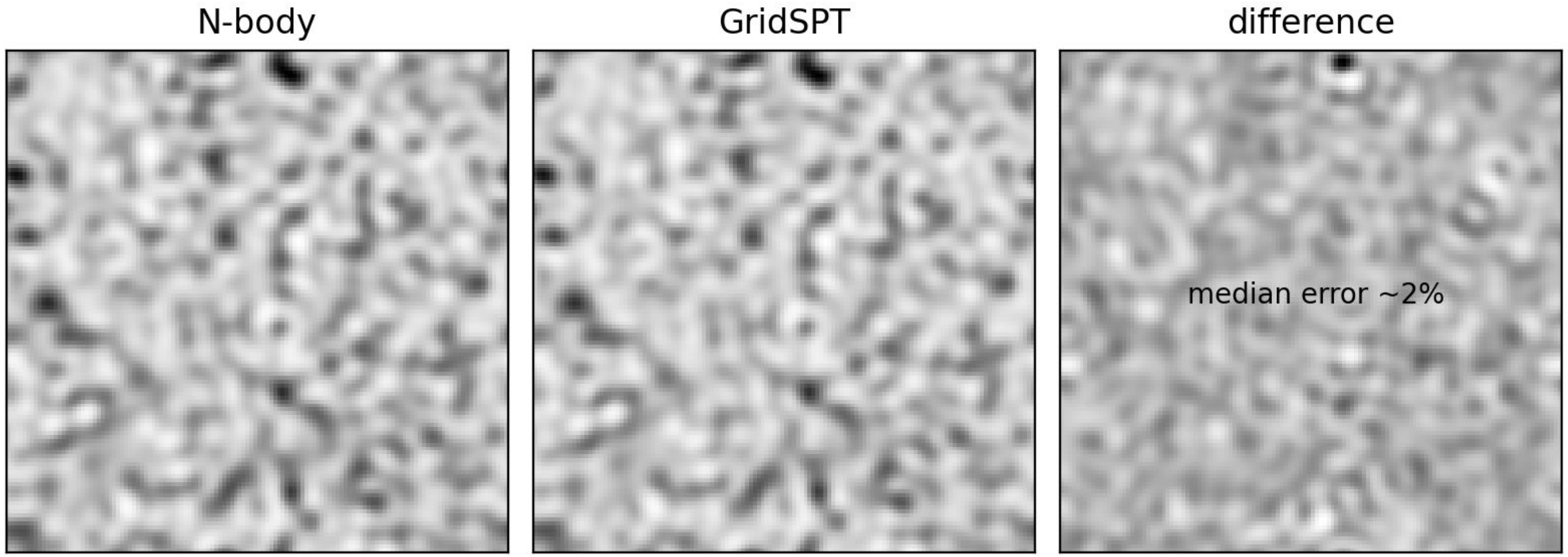
Extra degrees of freedom in the kernels (get fixed when choosing EOMs)

REFERENCES:
Marinucci, Pardede, Pietroni 24 [2405.08413v1]
D'Amico+ 21 [2109.09573v2]
Fujita, Vlah 20 [2003.10114v2]

Forward model: implementation

GridSPT (Taruya, Nishimichi, Jeong 21 [2109.06734v1])

$$\begin{pmatrix}\delta_n\\ \theta_n\end{pmatrix} = \frac{2}{(2n+3)(n-1)}\begin{pmatrix} n+\frac{1}{2} & 1\\ \frac{3}{2} & n\end{pmatrix}\sum_{m=1}^{n-1}\begin{pmatrix}\vec{\nabla}\delta_m\cdot\vec{u}_{n-m}+\delta_m\theta_{n-m}\\ \frac{1}{2}\Delta(\vec{u}_m\cdot\vec{u}_{n-m})\end{pmatrix};$$



3rd order, 1 Gpc box, Ng=128, z=1, kmax=0.12

Real space likelihood and results

GridSPT + 2nd order bootstrap + 3rd order UV counterterms:

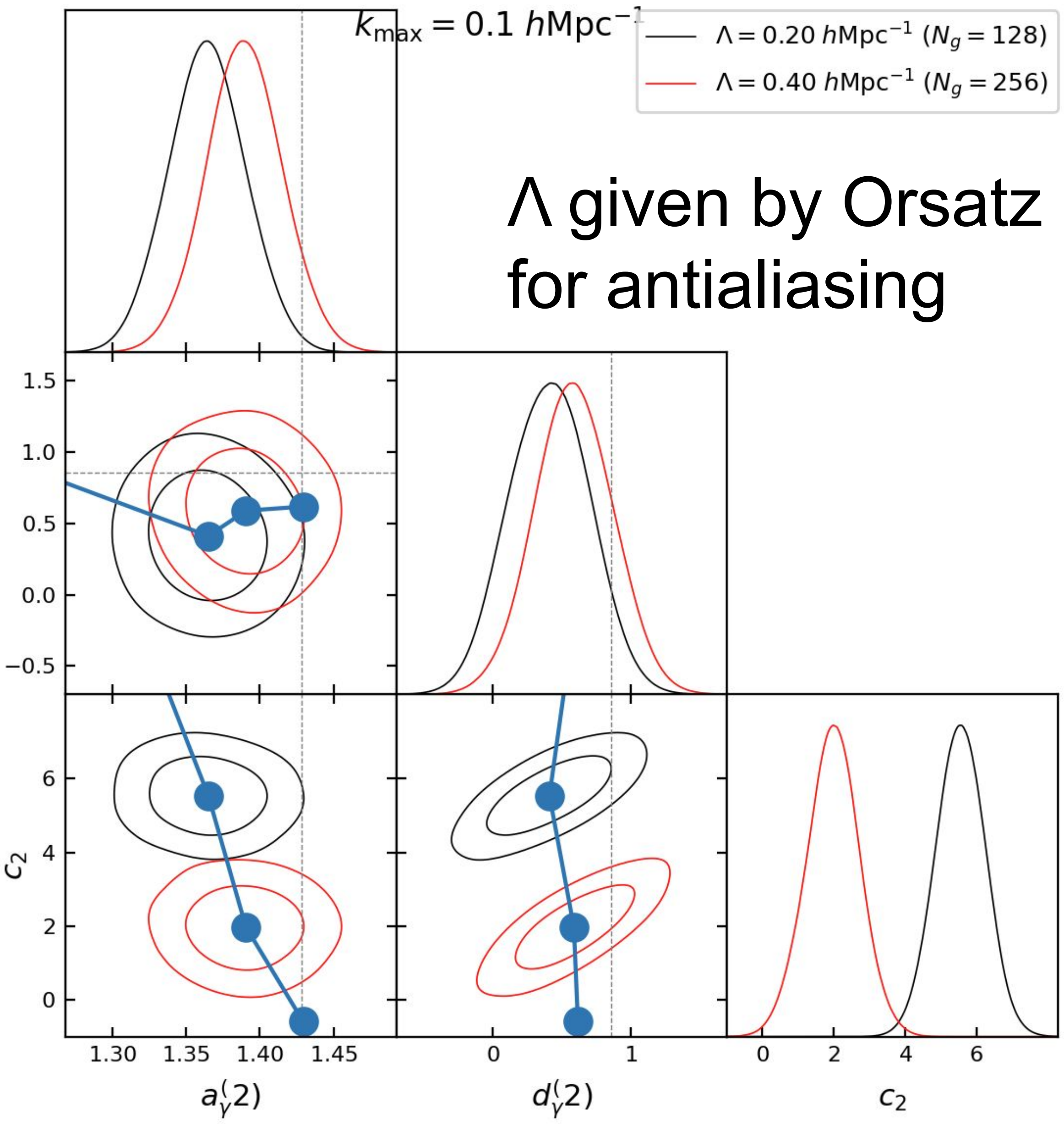
$$\begin{pmatrix}\delta_2\\ \theta_2\end{pmatrix} = \begin{pmatrix}\frac{a_\gamma^{(2)}}{2} & 1-\frac{a_\gamma^{(2)}}{2}\\ \frac{d_\gamma^{(2)}}{2} & 1-\frac{d_\gamma^{(2)}}{2}\end{pmatrix}\begin{pmatrix}\vec{\nabla}\delta_1\cdot\vec{u}_1+\delta_1\theta_1\\ \frac{1}{2}\Delta u_1^2\end{pmatrix}$$

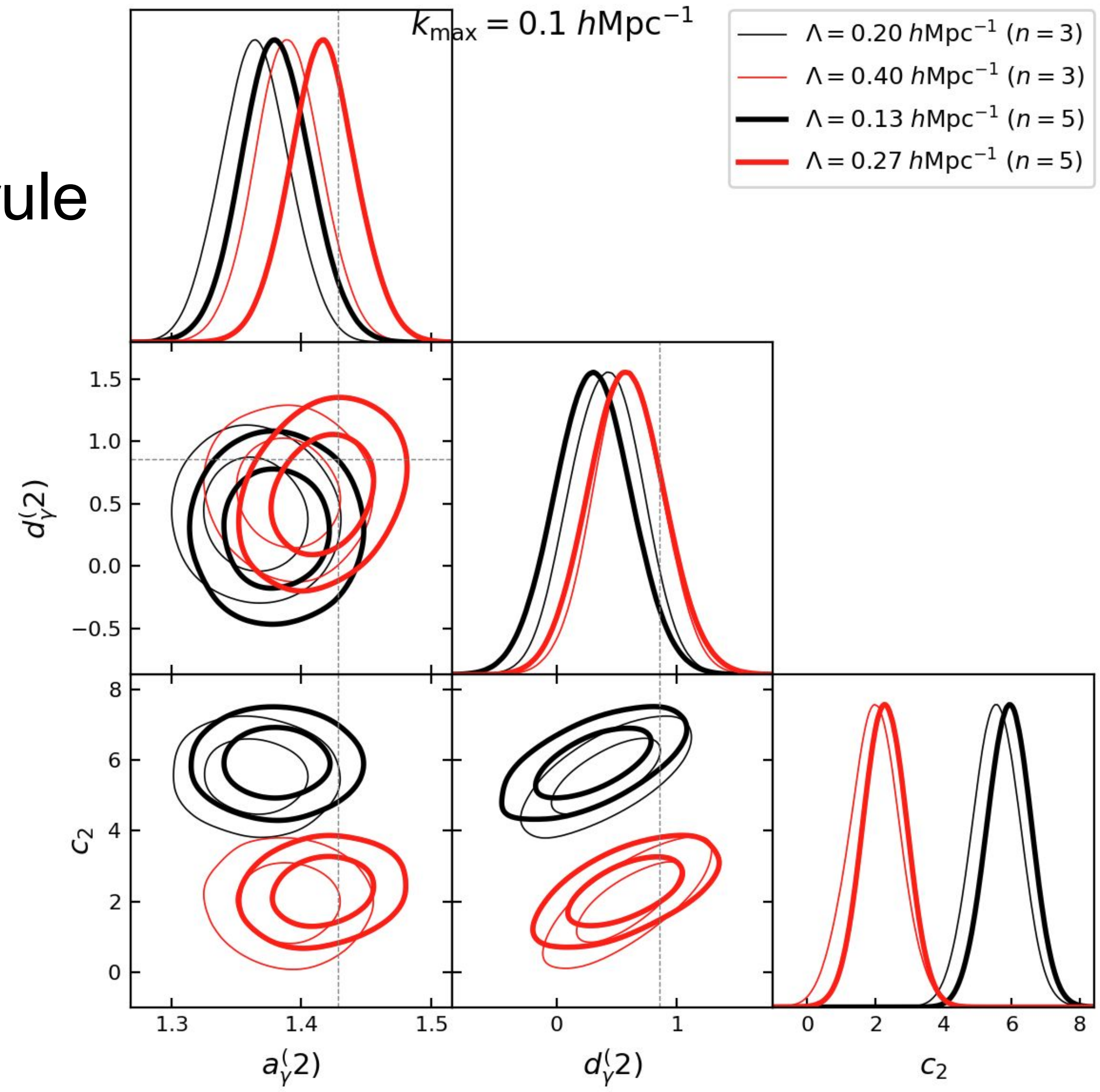
$$\begin{pmatrix}\delta_3\\ \theta_3\end{pmatrix} = \mathrm{GridSPT}\big|_{n=3} + c_2\begin{pmatrix}1\\ 0\end{pmatrix}\Delta\delta_1$$

Likelihood:

$$\mathcal{L}(\delta\,|\,\vec{\alpha}) \propto \exp\left[-\frac{\bar{n}}{2L^3}\sum_{k<k_{\max}}\left(\delta_{\vec{k}}-\delta_{\vec{k}}^{\mathrm{PT}}(\vec{\alpha})\right)^2\right]$$

Λ given by Orsatz rule for antialiasing





Redshift space results

Redshift space GridSPT (bootstrap+UV):

$$\delta_1^{(\mathrm{S})} = D_1$$

$$\delta_2^{(\mathrm{S})} = D_2 + f\tilde{\nabla}_z\Big(D_1 u_{z,1}\Big),$$

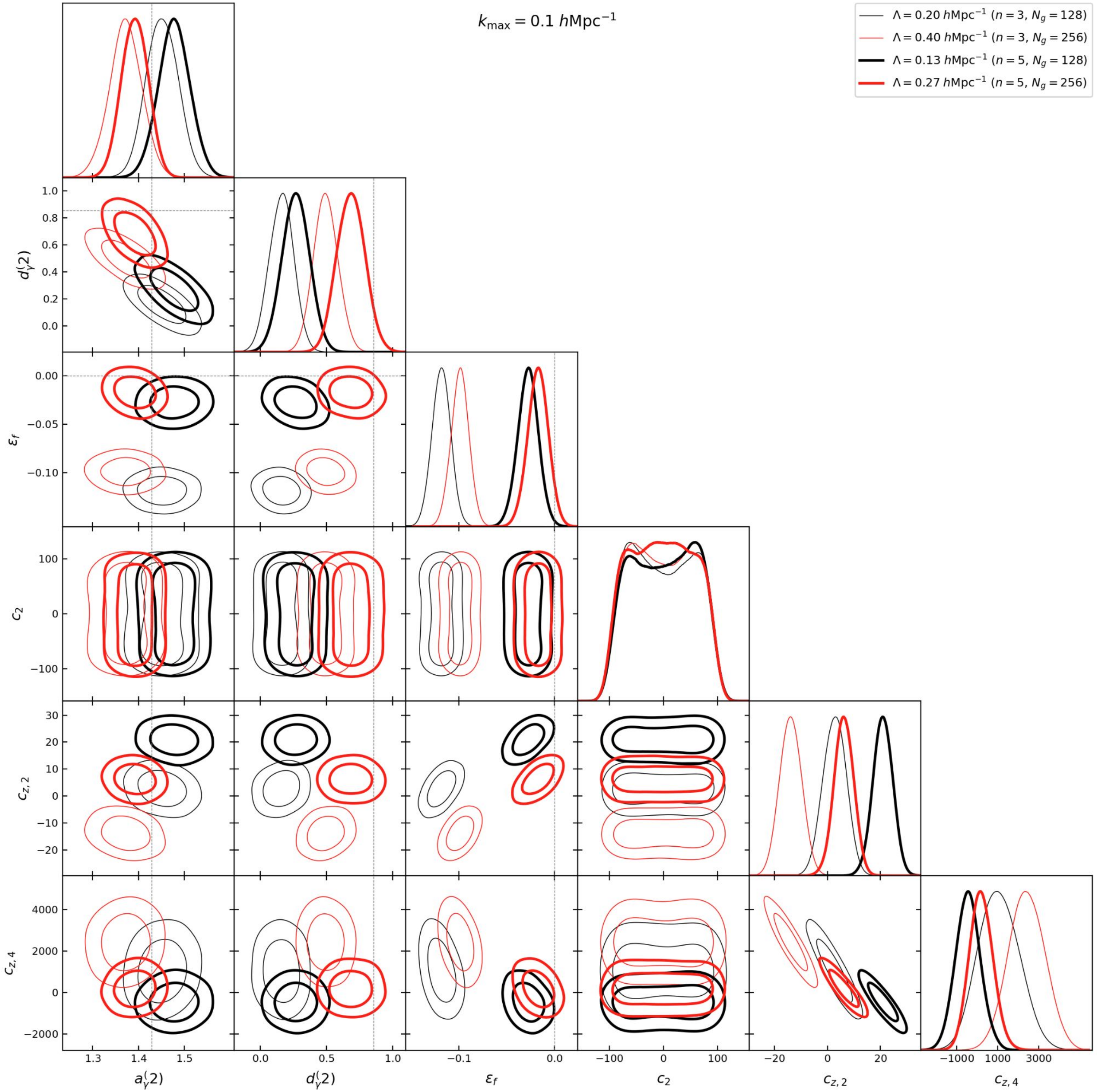
$$D_n \equiv \delta_n + f\tilde{\nabla}_z u_{z,n}.$$

$$\delta_3^{(\mathrm{S})} = D_3 + f\tilde{\nabla}_z\Big(D_1 u_{z,2} + D_2 u_{z,1}\Big) + \frac{f^2}{2!}\tilde{\nabla}_z^2\Big(D_1 u_{z,1}^2\Big)$$

+ 3rd order angle dependent counterterms:

$$c_{z,2} f(1+\varepsilon_f)\mu^2\Delta\delta_1 \qquad c_{z,4} f^4(1+\varepsilon_f)^4\mu^4\left(1+f(1+\varepsilon_f)\mu^2\right)\Delta^2\delta_1$$

$$(f \equiv f_{\Lambda\mathrm{CDM}})$$



$k_{\rm max} = 0.1\ h{\rm Mpc}^{-1}$
$\Lambda = 0.20\ h{\rm Mpc}^{-1}$ ($n = 3$, $N_g = 128$)
$\Lambda = 0.40\ h{\rm Mpc}^{-1}$ ($n = 3$, $N_g = 256$)
$\Lambda = 0.13\ h{\rm Mpc}^{-1}$ ($n = 5$, $N_g = 128$)
$\Lambda = 0.27\ h{\rm Mpc}^{-1}$ ($n = 5$, $N_g = 256$)
$a_\gamma^{(2)}$
$d_\gamma^{(2)}$
ϵ_f
c_2
$c_{z,2}$
$c_{z,4}$

Future developments

- Understand the running and find ways to correct for it
- Also see what this implies for the cosmological parameters
- Perform MCMC with much finer grids (possible in the case of bootstrap)
- Hamiltonian MC (Julia GridSPT) to marginalize over ICs
- Compare with $P + B$

About running on bootstrap and counterterm (real space, WIP):

The running can actually be computed explicitly for bootstrap parameters and counterterms: they act similarly as bias parameters in the perturbative expansions (factors x fields).

Take the derivative of the likelihood wrt the Λ-dependent parameter to 0 (to trace the maximum), $a_\gamma^{(2)}$ and c_2 will be co-dependent and so will run together as Λ changes

# ng	ag2	c_2
64	1.2212762932584806	20.28538993651349
128	1.3571428571428283	0.024750000000000022
256	1.3892006054156556	2.5069942207809537
512	1.4281154551674966	-0.07416138676181436

About running on bootstrap and counterterm (real space, WIP):

If the instead of using the N-body as data in the likelihood, we perform the same calculations with PT with a large Λ, we find that $a_\gamma^{(2)}$ doesn't run, but c_2 does.

# ng	ag2	c_2
64	1.421875	0.02438672
128	1.4296875	0.02424805
256	1.42849312	0.17251358
512	1.42857143	0.