Pioneering Advancements in Modelling the Galaxy 3-point correlation function

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Sestri Levante, Italy
Understanding the Galaxy/Matter Connection in the Era of Large Surveys

In collaboration with: M. Moresco, A. Veropalumbo, A. Farina, E. Branchini and the Euclid Galaxy Clustering Higher-Order Work Package

Different twins: 3PCF vs Bispectrum
Mind the gap!

Configuration space

Estimator:

- Traditionally computationally expensive, now feasible due to the Spherical Harmonics decomposition estimator (Slepian&Eisenstein2017)
- survey geometry can be easily considered

Modelling: lack of modelling respect to Fourier space

Fourier space

Estimator: survey geometry affects observation requiring a window function to model mode coupling

Modelling: accessible modelling for power spectrum and bispectrum

Our goal is filling the gap!

Different twins: 3PCF vs Bispectrum
Mind the gap!

Configuration space

Estimator:

- Traditionally computationally expensive, now feasible due to the Spherical Harmonics decomposition estimator (Slepian&Eisenstein2017)
- survey geometry can be easily considered

Modelling: lack of modelling respect to Fourier space

1) Not yet accessing to non-template **cosmological parameters**

2) Not yet accessing to **small-scale modelling**

Our goal is filling the gap!

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1. **First cosmological parameters constraints from a joint 2-point and 3-point correlation functions analysis**

Filling the gap..
State of the art

State of the art:

- Modelling approaches pivot on **mapping the bispectrum to the three-point correlation** function by inverse Fourier transform (Slepian et al, 2017, Umeh et al, 2021, Guidi et al, 2023)

- 3PCF (joint with 2PCF) analyses have been recently addressed for **template fitting**, full shape (Veropalumbo et al, 2021, Veropalumbo et al, 2022, Farina et al, 2024, Pugno et al, 2024) and BAO scale (Gaztanaga et al, 2009, Moresco et al, 2021, Sugiyama et al, 2021)

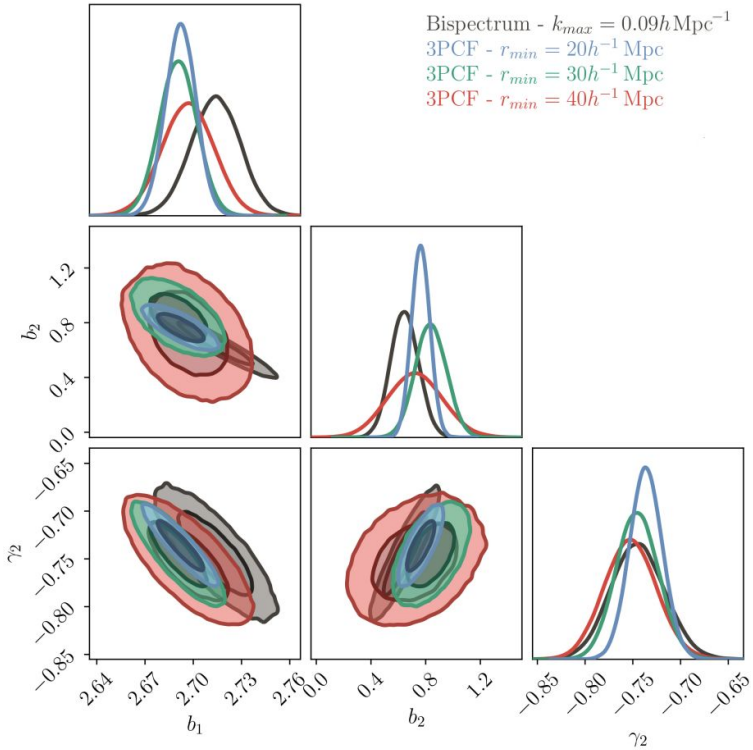

Figure 1: an example of bias template fitting on real space from Veropalumbo et al, 2022

Filling the gap..
The emulator

Our goal is the golden goal: going to cosmological parameter analyses, historically not feasible due to the high computational cost of the modelling

How do we achieve the golden goal?

First emulator based for 3PCF (and 2PCF) purposes, based on a *PyTorch* architecture:

1. Established model pipelines used to generate the training and testing set
2. Testing the emulated prediction considering a given covariance for a given scientific case

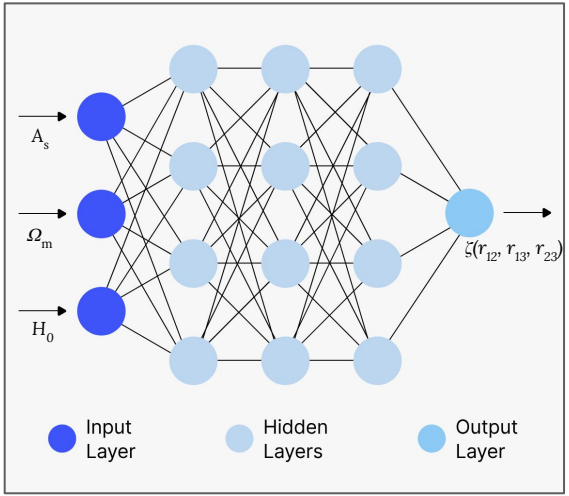

Figure 2: visual representation of the 3PCF emulation strategy

Pioneering Advancements in Modelling the Galaxy 3-point correlation function

1. **First cosmological parameters constraints from a joint 2-point and 3-point correlation functions analysis**

1.1 Application to Euclid *Flagship* Simulation

Application to *Euclid Flagship* simulation:
A joint 2PCF + 3PCF: breaking the degeneracies of bias parameters

Euclid Preparation Paper
(*Higher-Order Work Package, KP-GC-5-Paper 2*)

- 4 comoving redshift snapshots, **58 $h^{-3}Gpc^{-3}$ comoving volume**
- **Real space** measurements (2PCF and 3PCF)
- **Adding 3PCF significantly improves the constraining power**

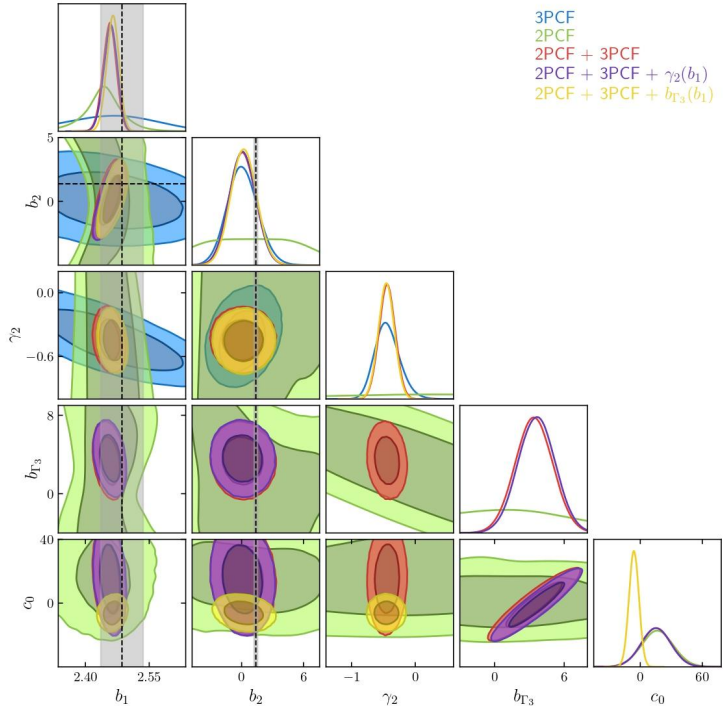

Figure 3: Bias constraints from 2PCF, 3PCF and the joint 2PCF+3PCF at **z = 0.9**, r^{2PCF}_{min} = 25 Mpc/h, r_{max} , r^{3PCF}_{min} = 40 Mpc/h, η_{min} = 3, r_{max} = 140 Mpc/h.

Application to *Euclid Flagship* simulation:
A joint 2PCF + 3PCF: breaking the degeneracies of cosmological parameters

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- **First real space joint 2+3 modelling pipeline addressing cosmological parameters + bias**

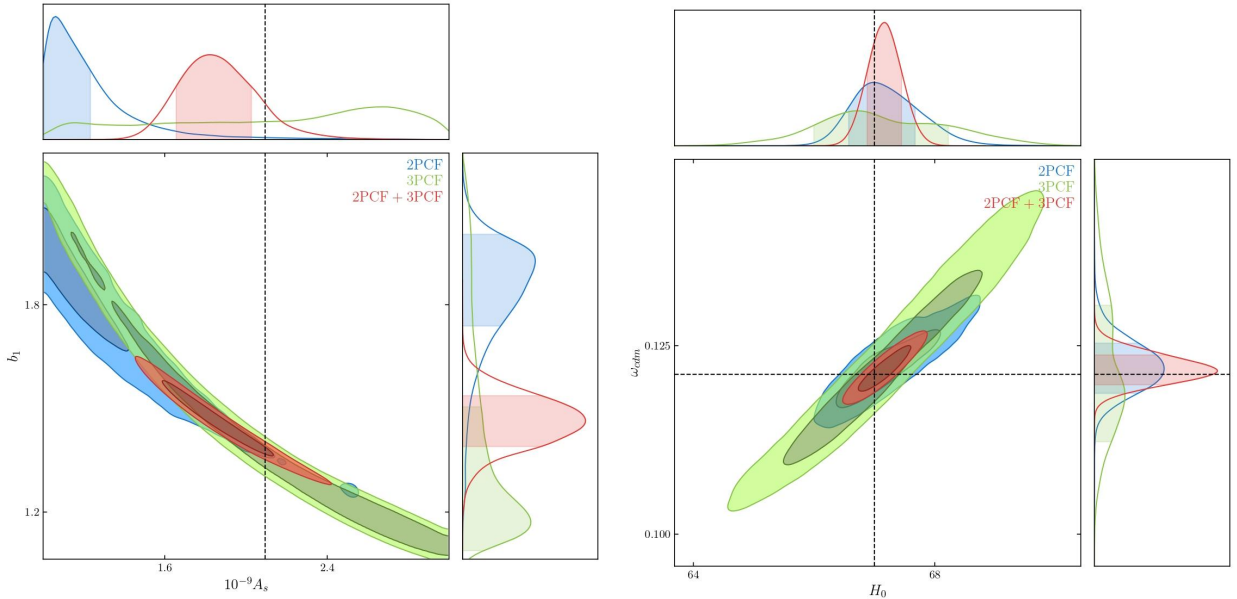

Figure 4: Cosmological and linear bias constraints 2PCF, 3PCF and the joint 2PCF+3PCF at **z = 0.9.** r^{2PCF}_{min} = 25 Mpc/h, r_{max} , r^{3PCF}_{min} = 30 Mpc/h, η_{min} = 3, r_{max} = 140 Mpc/h.

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A joint 2PCF + 3PCF: breaking the degeneracies of cosmological parameters

Euclid Preparation Paper
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- **First real space joint 2+3 modelling pipeline addressing cosmological parameters + bias**
- 2PCF + 3PCF: the lower the redshift, the better the constraining power

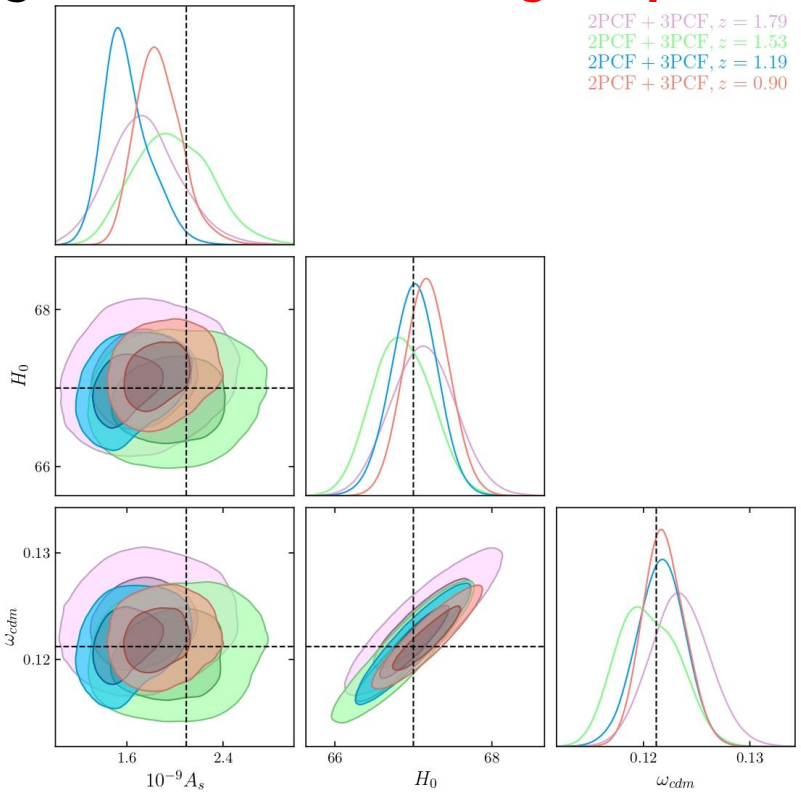

Figure 5: Cosmological constraints from a joint 2PCF + 3PCF analysis at z. r^{2PCF}_{min} = 25 Mpc/h, r_{max} , r^{3PCF}_{min} = 30 Mpc/h, η_{min} = 3, r_{max} = 140 Mpc/h.

Application to *Euclid Flagship* simulation:
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Take away messages:

1) First preliminary results indicate **2+3** analyses perform consistently as **P+B** results

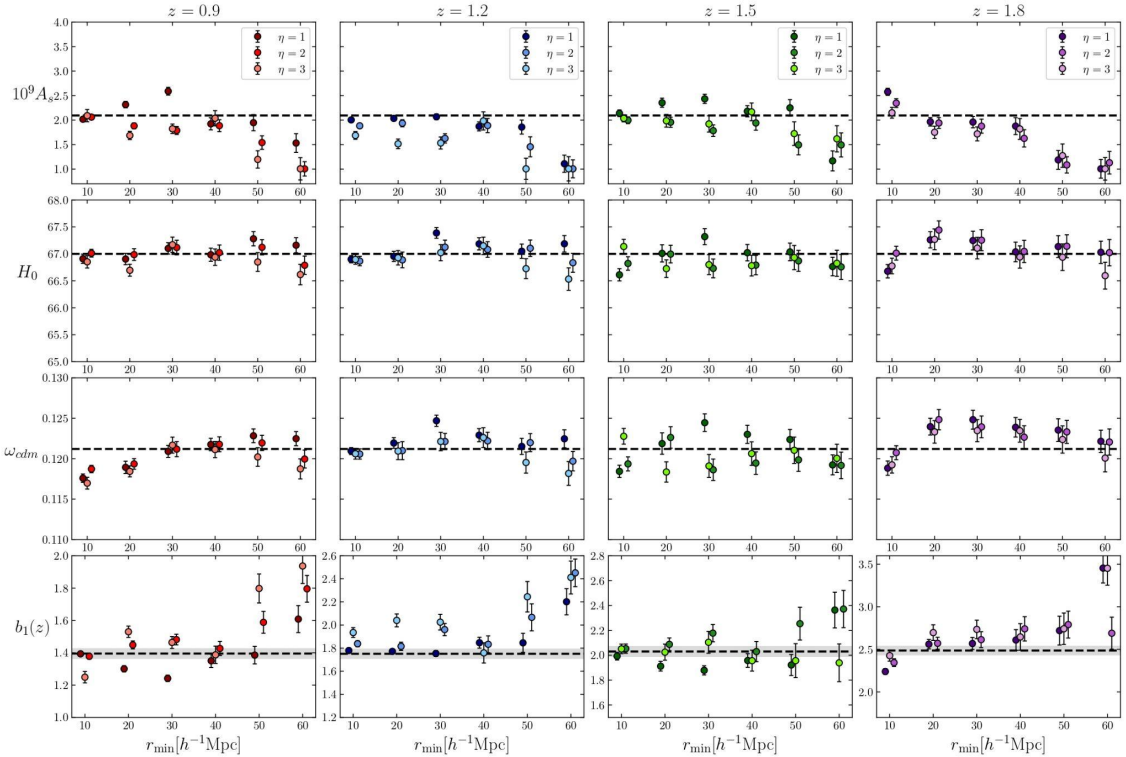

Figure 6: Cosmological and linear bias constraints from a joint 2PCF + 3PCF analysis as a function of r_{min}

Application to *Euclid Flagship* simulation:
A joint 2PCF + 3PCF: breaking the degeneracies of cosmological parameters

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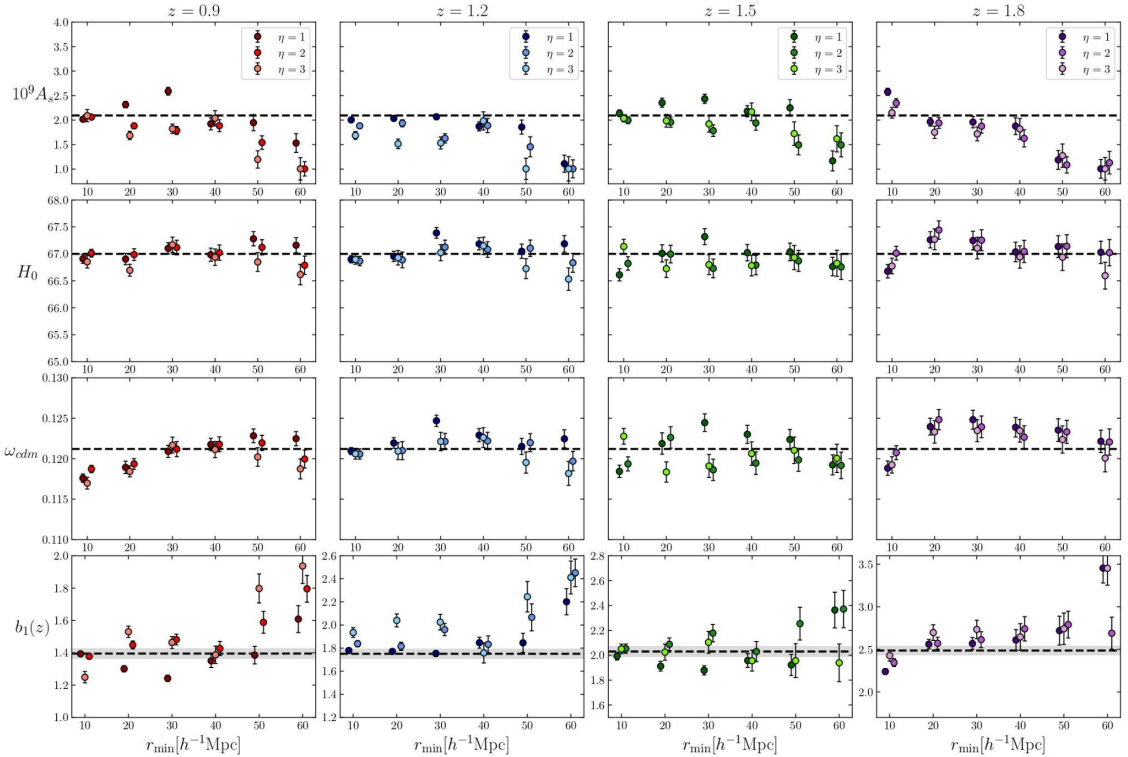
Take away messages:

1) First preliminary results indicate 2+3 analyses perform consistently as P+B results

2) Minimum scales for constraining cosmological parameters are **consistent with template fitting and methodological studies** (Veropalumbo et al, 2022)



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Application to *Euclid Flagship* simulation:
A joint 2PCF + 3PCF: breaking the degeneracies of cosmological parameters

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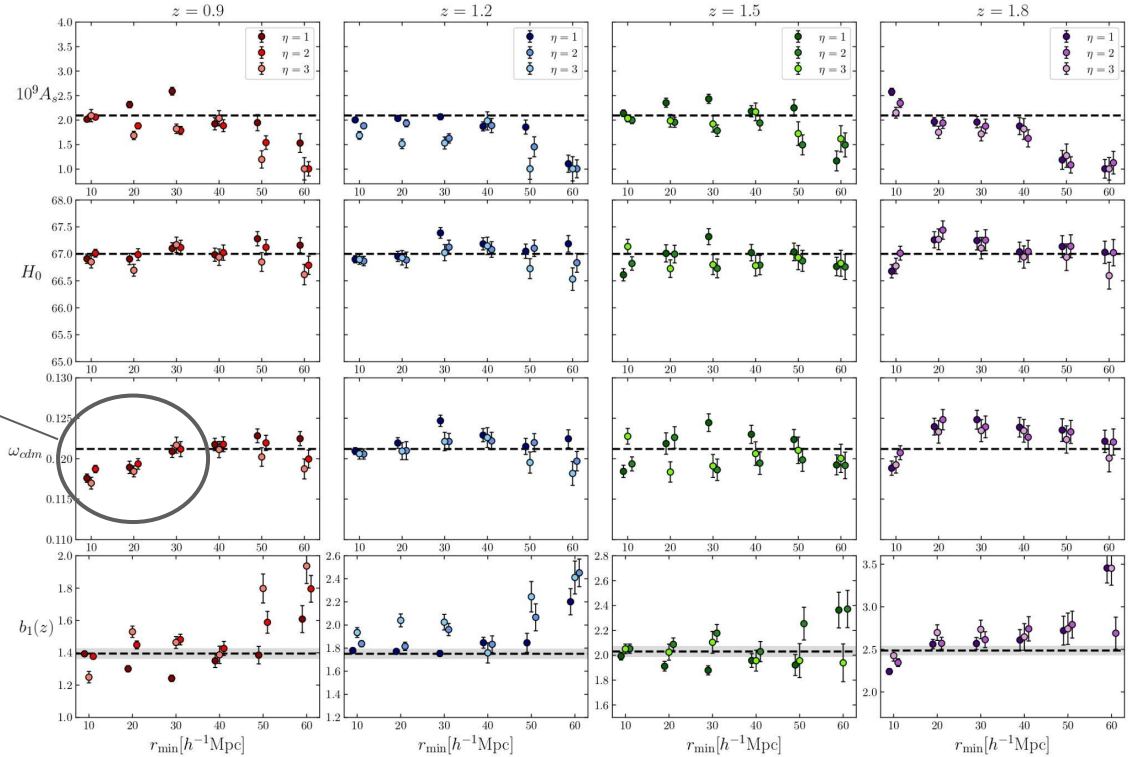
In the very-small scale regime, 2pcf + 3pcf models fail short to be predictive



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Application to *Euclid Flagship* simulation:
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the greater the minimum scale and the lower the redshift, the stronger projection effect on A_s - b_1

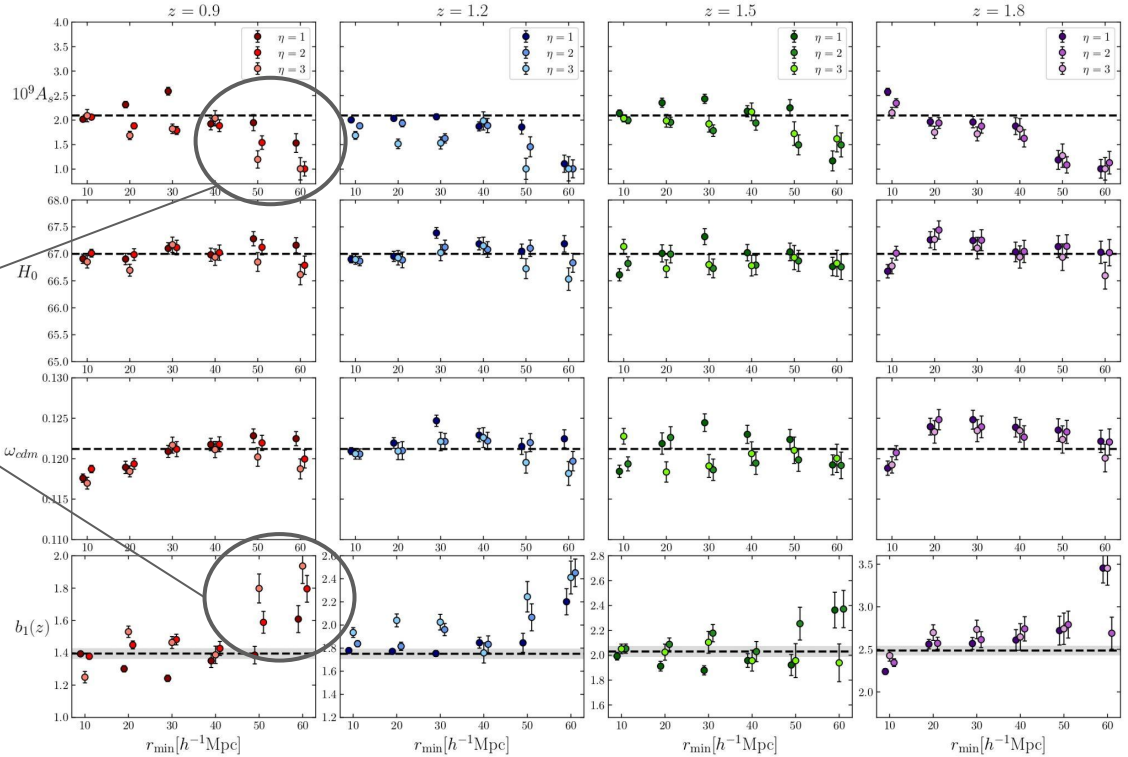
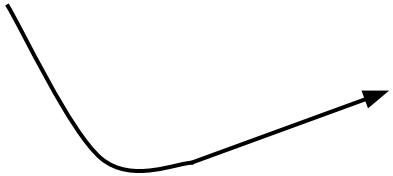


Figure 6: Cosmological and linear bias constraints from a joint 2PCF + 3PCF analysis as a function of r_{min}

2. A new model for the galaxy 3-point correlation function in the nonlinear regime

A new one-loop model for the galaxy 3PCF:
Recap from the one-loop matter case

- Goal? **Filling the gap** with Fourier space:
- Why? To increase the **number of triplets matched by the theory** to enhance statistical significance
- How? **One-loop** expansion of the **galaxy 3PCF**



*From (Guidi et al, 2023): the **one-loop** models for matter 3PCF (red and green) **outperform** the **tree-level** model for matter 3PCF in the small-scales regime*

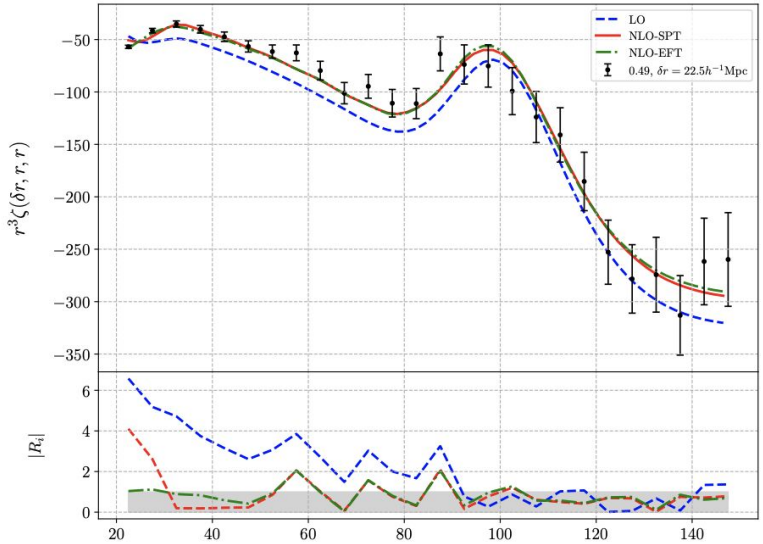


Figure 7: Different 3PCF tre-level/one-loop models of matter perturbations compared with measurements extracted from the DEMNUni simulations at z = 0.5

A new one-loop model for the galaxy 3PCF:
Modelling the very-smale scale regime in real-space

- Goal? **Filling the gap** with Fourier space:
- Why? To increase the **number of triplets matched by the theory** to enhance statistical significance
- How? **One-loop** expansion of the **galaxy 3PCF**

- The methodology pivots on computing the **one-loop galaxy bispectrum** (Eggemeier et al, 2019) and its Fourier Transform throught **2D-FFTLog** pipeline (**high computational cost!**)

Models	***Galaxy bias modelling: Parameter space***	***Computational strategy***
One-loop 2PCF	$\{b_1, b_{z1}, \gamma_{z1}, \gamma_{21}, c_0\}$	*1D-FFTLog + 1D loop FFT integrals*
Tree-level 3PCF	$\{b_1, b_{z1}, \gamma_{z1}\}$	*2D-FFTLog*
One-loop 3PCF **(new!)** ***46 bias triplets!***	$\{b_1, b_{z1}, \gamma_{z1}\}$ + 8 higher order bias params	*2D-FFTLog + 3D, 2D, 1D CUBA integrals (order of hours)* ***43 bias loop integrals!***

Table 1: recap of tree-level and one-loop models for the galaxy 2PCF and 3PCF

A new one-loop model for the galaxy 3PCF:
Testing real space one-loop galaxy bias 2PCF + 3PCF on *Minerva* simulation

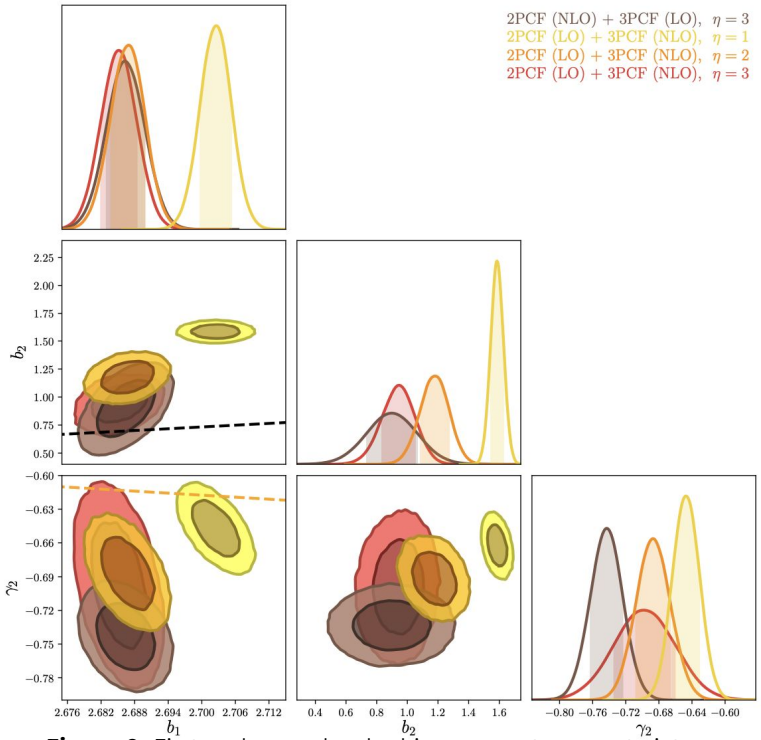
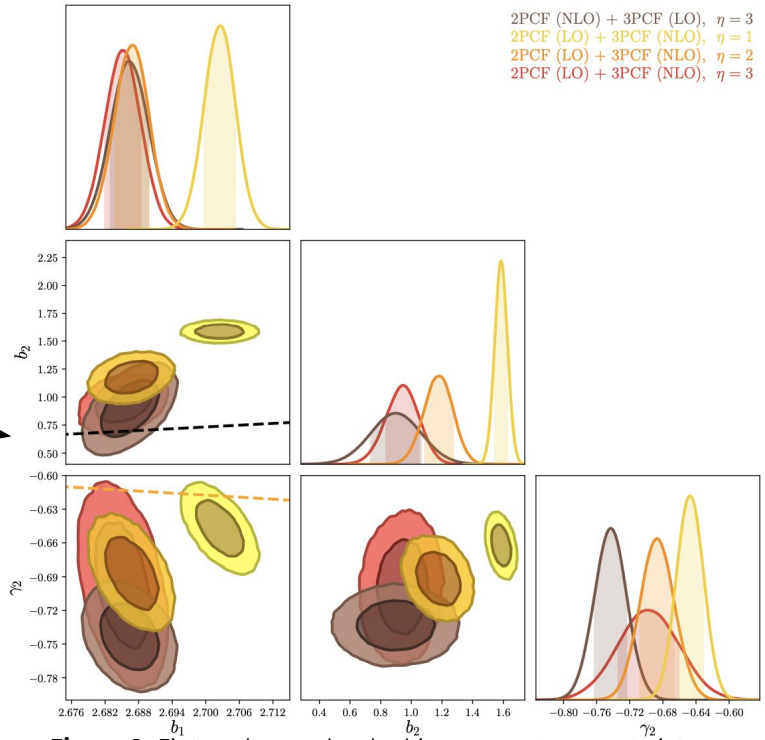


Figure 8: First and second order bias parameters constraints from a 2PCF + 3PCF analysis (see color coding). The dashed line represents known bias relations in the literature

A new one-loop model for the galaxy 3PCF:
Testing real space one-loop galaxy bias 2PCF + 3PCF on *Minerva* simulation

One-loop 3PCF models better agree with already established bias relations in the small scale regime



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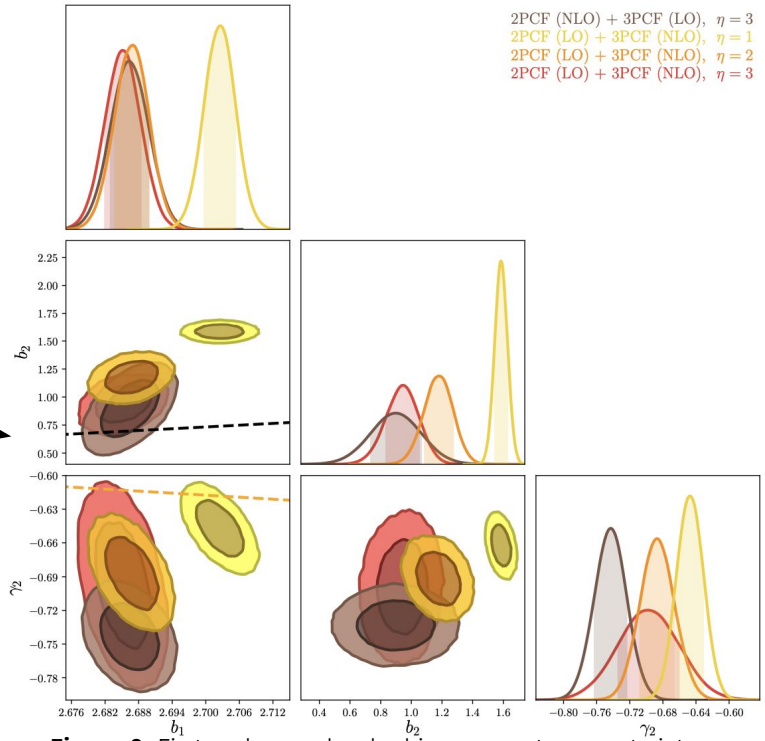
A new one-loop model for the galaxy 3PCF:
Testing real space one-loop galaxy bias 2PCF + 3PCF on *Minerva* simulation

Take away messages:

1) Next-to-leading order modelling of 3-point statistics introduce **additional bias parameters** affecting the constraining power

2) Modelling the nonlinear regime allows to **increase the number of triplets** matched by models, increasing the statistics

One-loop 3PCF models better agree with already established bias relations in the small scale regime



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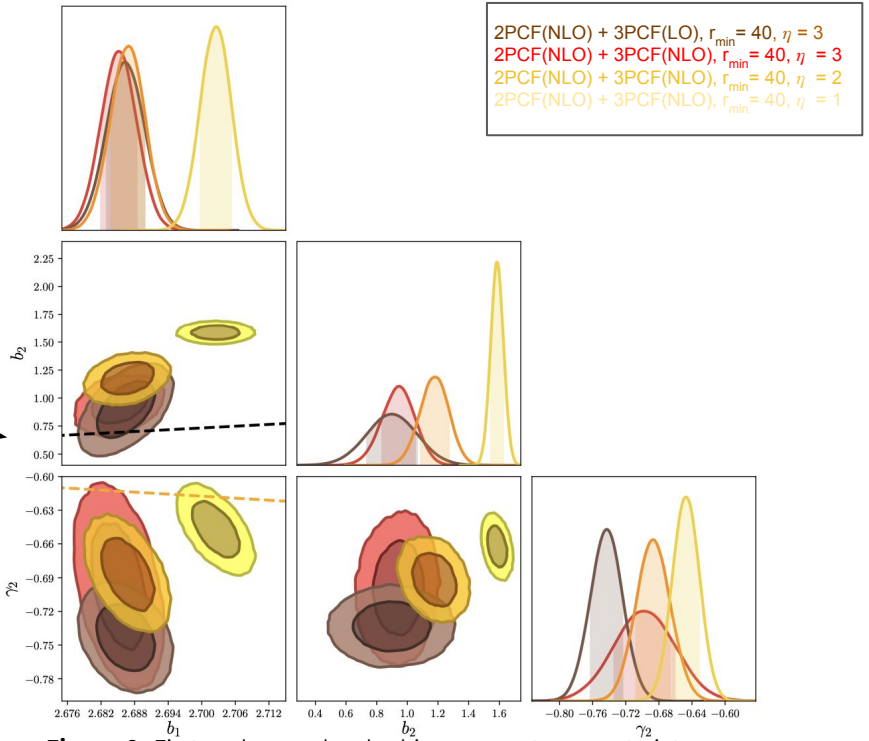
A new one-loop model for the galaxy 3PCF:
Testing real space one-loop galaxy bias 2PCF + 3PCF on *Minerva* simulation

Pro: access to the η small-scale regime!

Cons: high computational cost!

One-loop 3PCF models better agree with already established bias relations in the small scale regime



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Recap:

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Recap:

1) Filling the gap with Fourier space: **First cosmological parameters constraints from a full-shape fit real-space 2PCF + 3PCF ✅**

Pioneering Advancements in Modelling the Galaxy 3-point correlation function

Recap:

1) Filling the gap with Fourier space: First cosmological parameters constraints from a full-shape real-space 2PCF + 3PCF fit ✅

2) Filling the gap with Fourier space: **joint analysis of one-loop galaxy bias from 2PCF + 3PCF** ➡️SOON

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Ongoing and future activities:

1) Cosmological parameter constraints from a redshift space 2PCF + 3PCF analysis on real data

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Ongoing and future activities:

1) Cosmological parameter constraints from a 2PCF + 3PCF analysis from real data

2) Modelling of the peculiar velocity - density - density 3-point correlation function: goal of constraining the growth factor within a 2+3 analysis

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Thanks!

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Backup: Application to *Euclid* simulation:
first cosmological constraints from a 2+3 analysis

- Emulation performance has been validated comparison differences between emulated predictions and the testing set
- The chosen metric exhibits good emulation performance

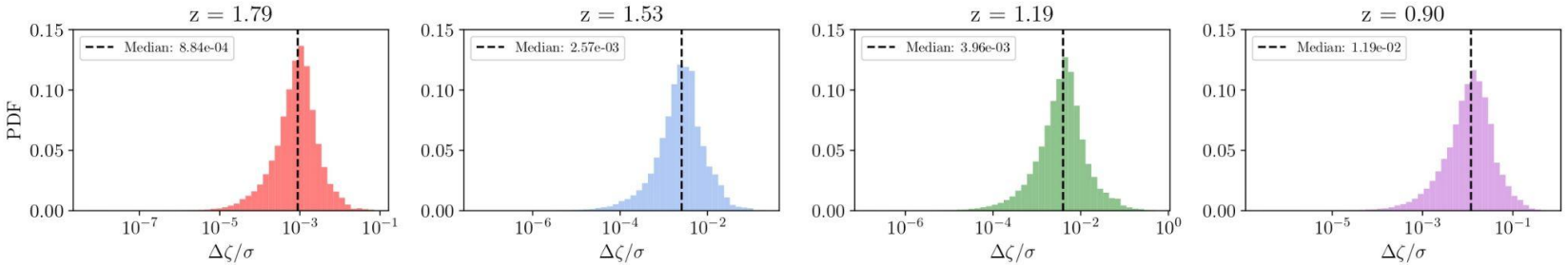

Figure 9: PDF of difference between emulated predictions and testing sets

Backup: Application to *Euclid* simulation:
first cosmological constraints from a 2+3 analysis

Euclid Preparation Paper
(*Higher-Order Work Package*, *KP-GC-5-Paper 2*)

- Euclid simulation box: four comoving redshift snapshots, **58 $h^{-3}Gpc^{-3}$ comoving volume**
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- **First real space joint 2+3 modelling pipeline addressing cosmological parameters + bias**

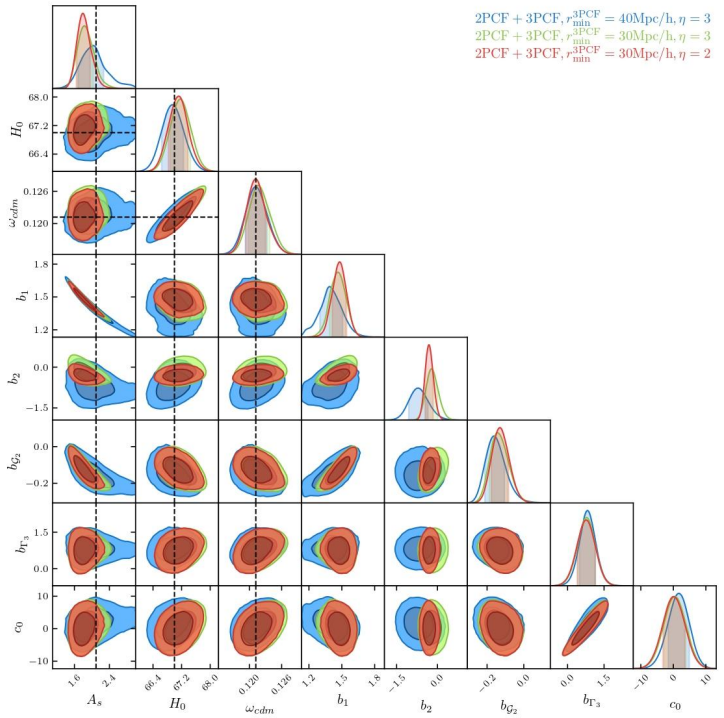

Figure 10: constraints on cosmological and bias parameters from a joint two- and three-point corelation functions analysis a **z = 0.9** snapshot, r_{min} for the 2PCF being fixed to 25 Mpc/h, r_{max} for the 2PCF and 3PCF being fixed to 140 Mpc/h. Different colours represent different minimum triangle configurations

Backup: Application to *Euclid* simulation:
first cosmological constraints from a 2+3 analysis adopting bias relation

Euclid Preparation Paper
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- Euclid simulation box: four comoving redshift snapshots, **58 $h^{-3}Gpc^{-3}$ comoving volume**
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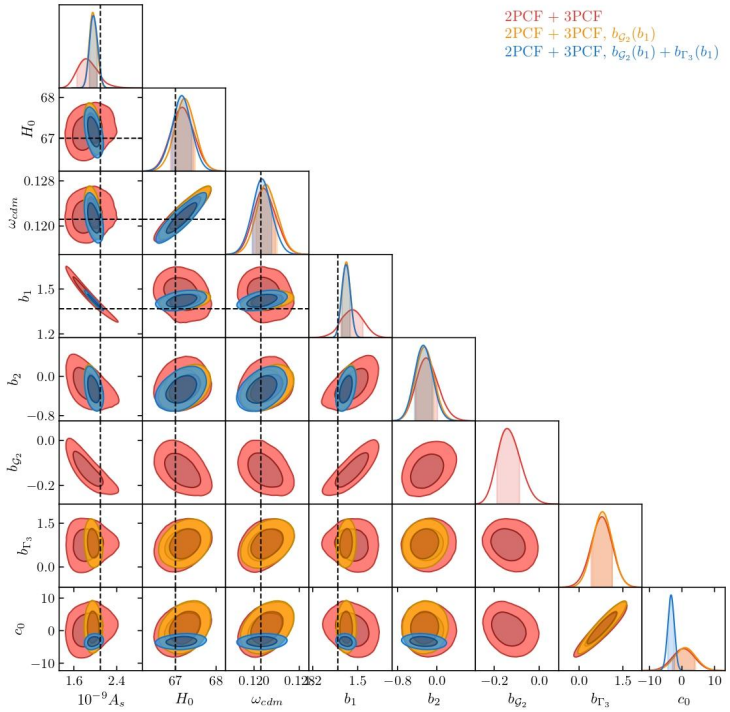

Figure 11: constraints on cosmological and bias parameters from a joint two- and three-point correlation functions analysis a **z = 0.9** snapshot, r_{min} for the 2PCF being fixed to 25 Mpc/h, r_{max} for the 2PCF and 3PCF being fixed to 140 Mpc/h. Different colours represent different minimum triangle configurations