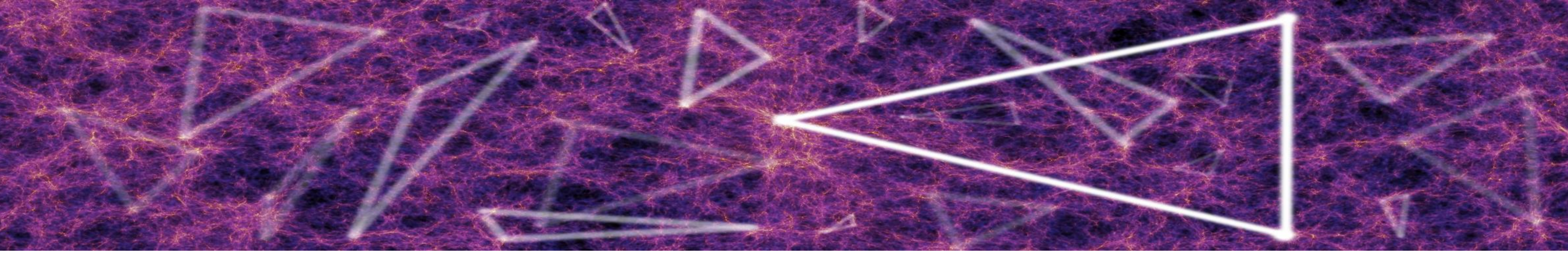

New frontiers for the 3PCF

Michele Moresco

Dipartimento di Fisica e Astronomia “Augusto RIghi” – Università di Bologna

in collaboration with

M. Guidi, N. Principi, K. Nagainis, A. Labate (UniBo), A. Veropalumbo, A. Farina (INAF OABr, INFN-Genova), B. Granett, I Risso (INAF OABr)

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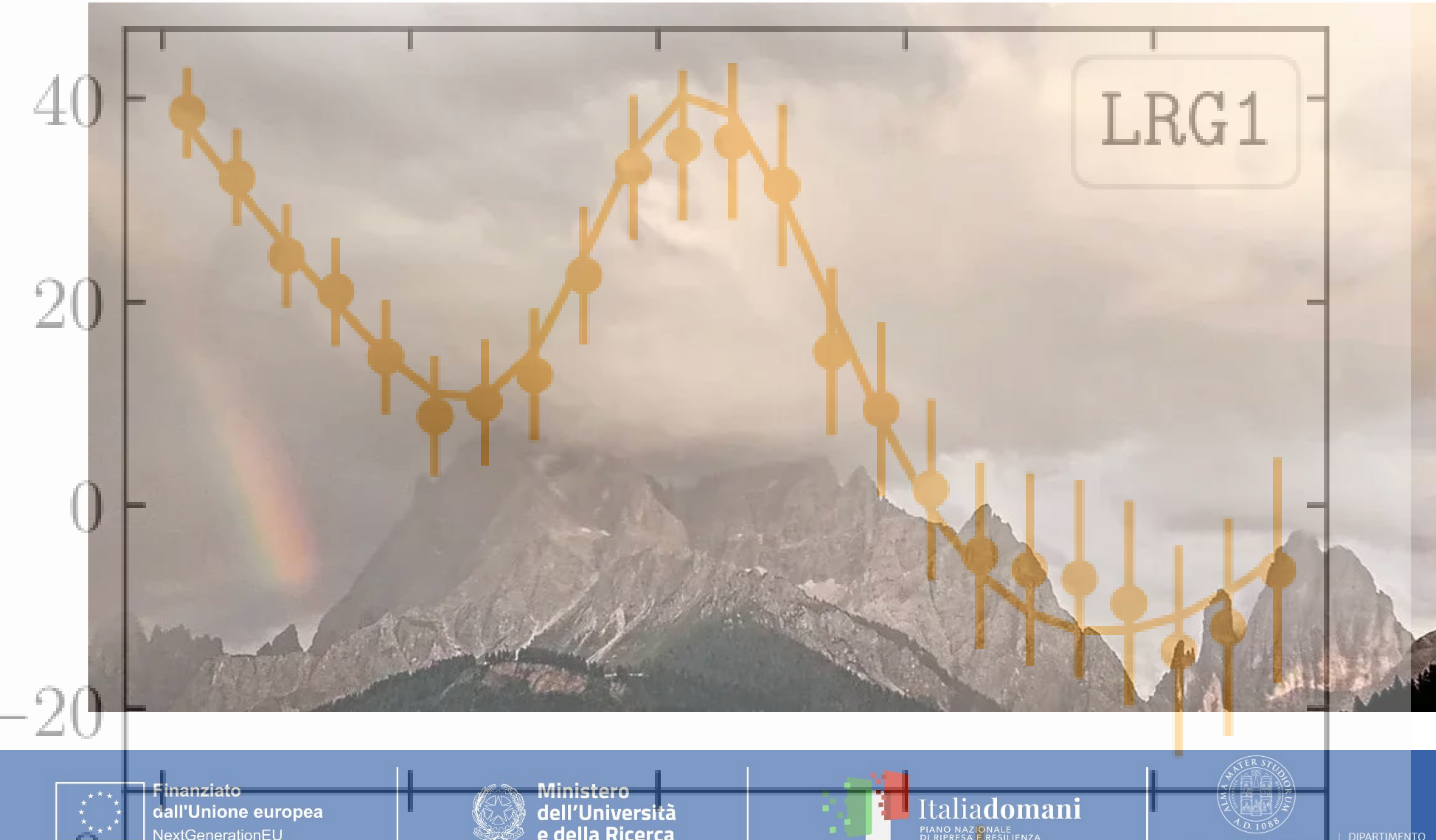
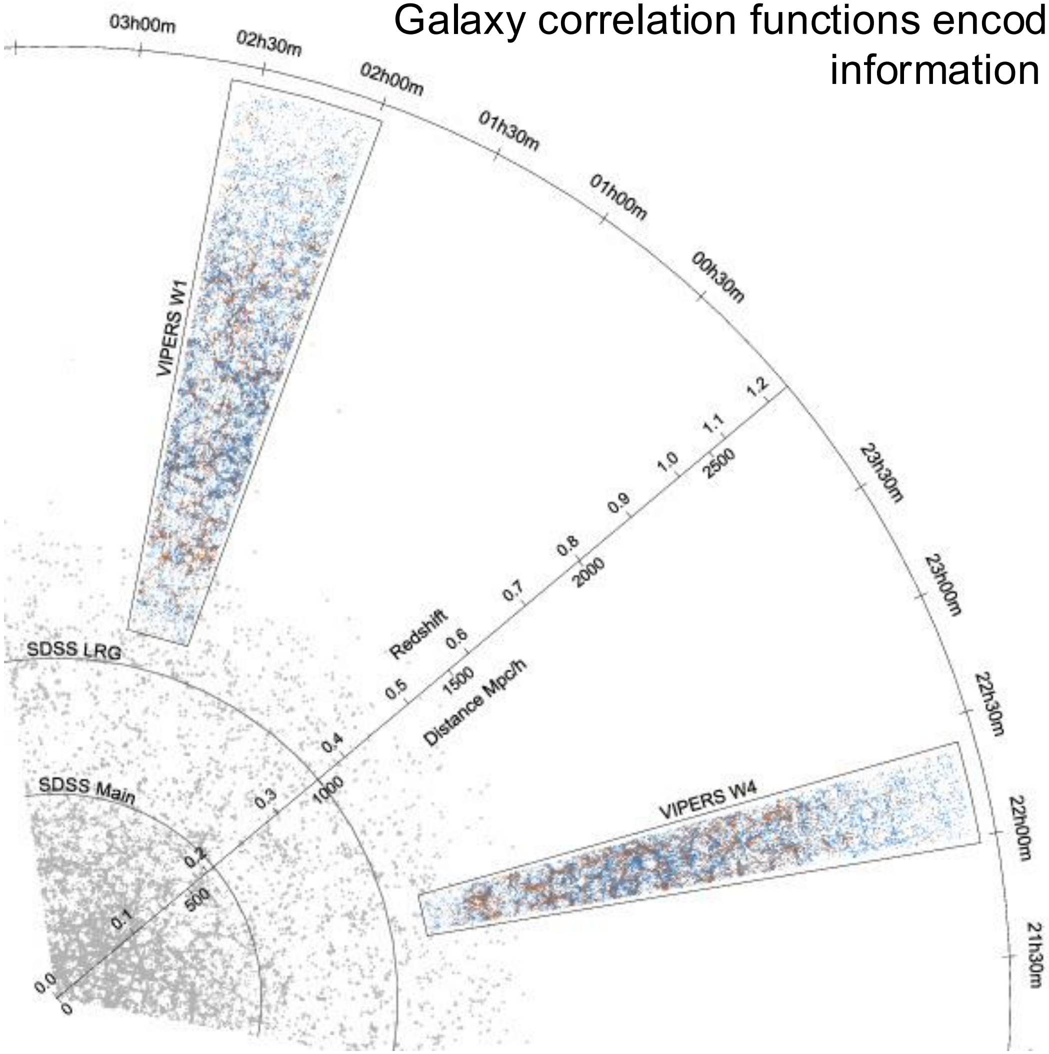
First observational spectrum in Sexten

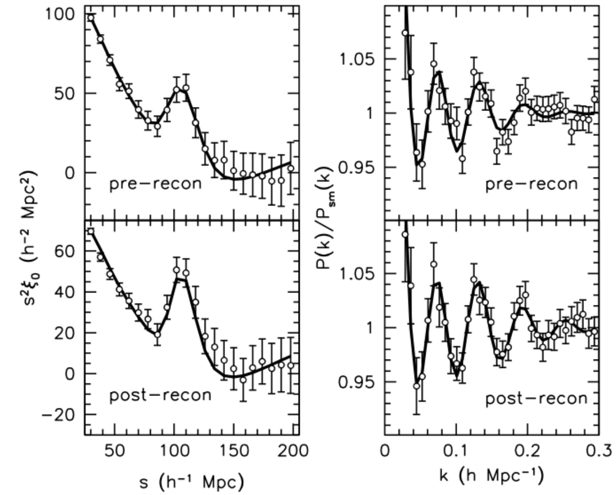


The importance of including higher-orders



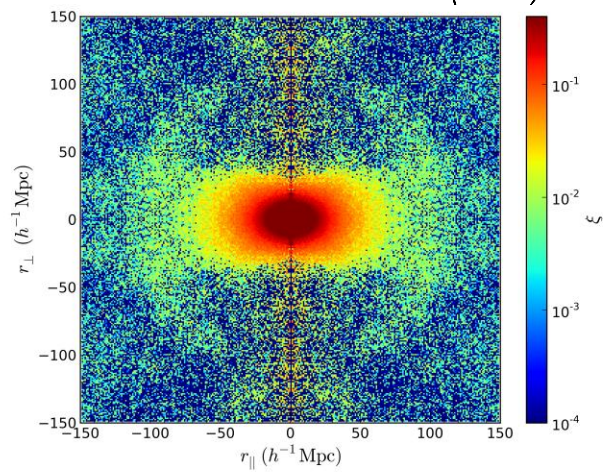
Galaxy correlation functions encode fundamental information for cosmology

- BAO
- RSD



Anderson et al. (2014)

Samushia et al. (2013)



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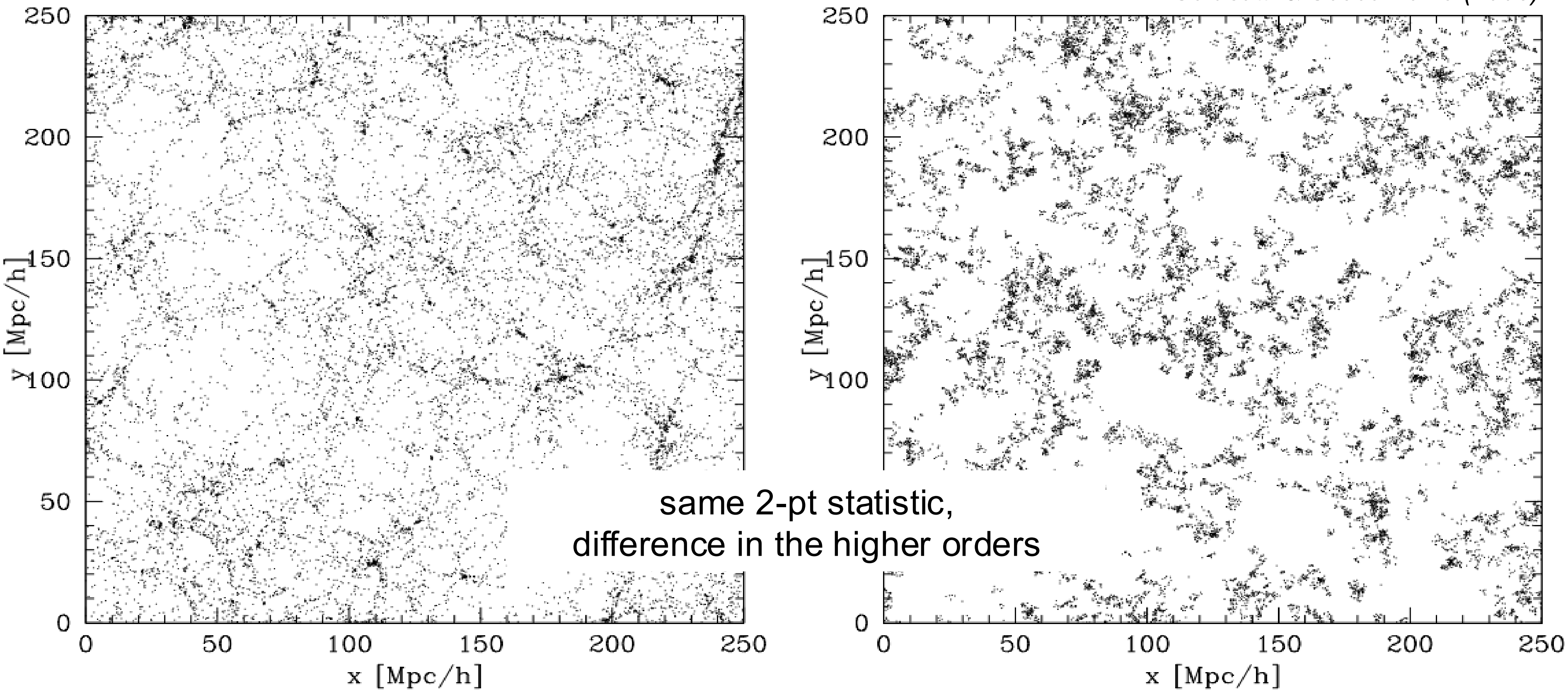
The importance of including higher-orders

For a Gaussian Random Field, 2PCF (and/or Pk) would be enough (mean and variance)

… but the Universe is just not like that!

Sefusatti & Scoccimarro (2005)



same 2-pt statistic,
difference in the higher orders

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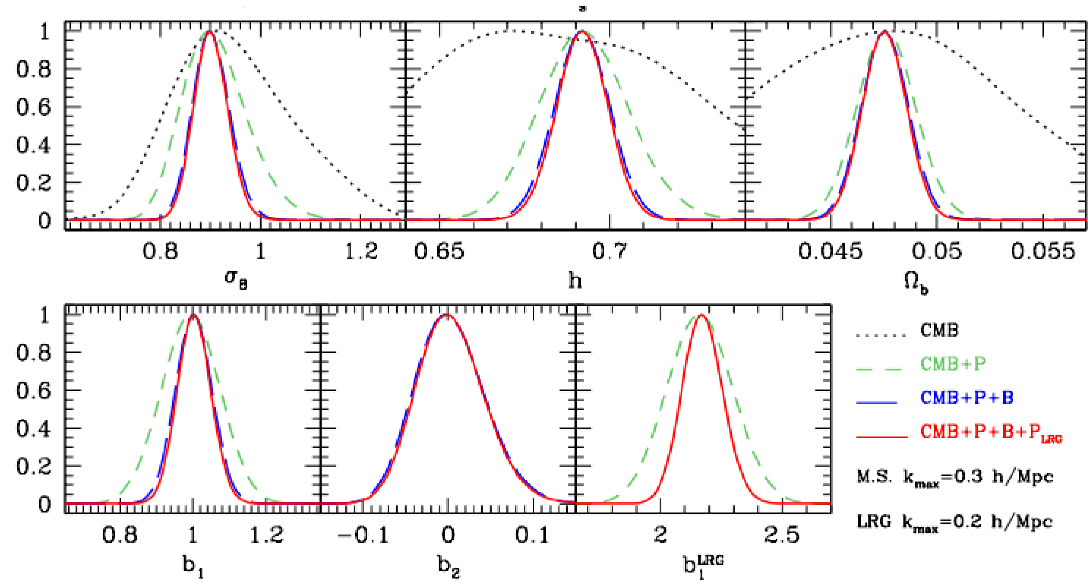
The gain and price to move to higher orders

PROs

- first significant order to detect non-Gaussian signals
- can probe both scale (as the 2PCF) and **shape (unlike the 2PCF)**
- in combination with the 2PCF **can break the degeneracy between bias and s_8**
- improve constraints on parameters in combination with other probes
- exploit additional information: **fundamental for future surveys** (Euclid, …)

CONs

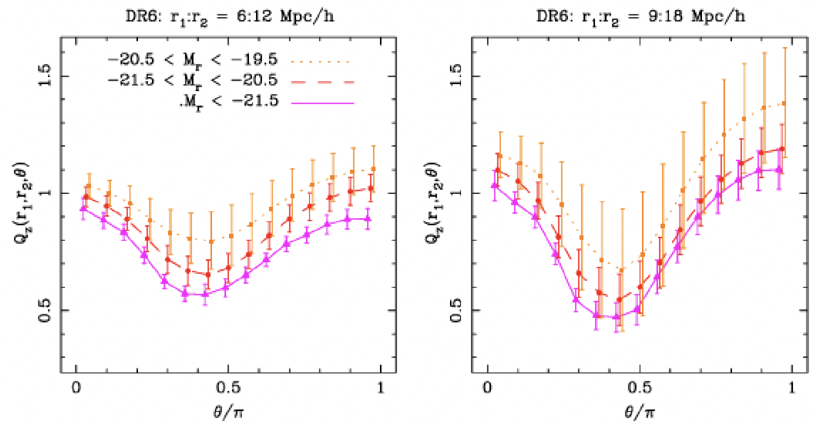
- scales as $O(N^3)$ (at least nominally)
- difficult to model (both theoretically and computationally)
- quite unexplored field (at least in configuration space)



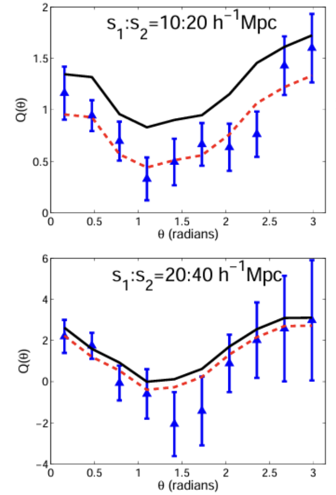
Sefusatti et al. (2006)

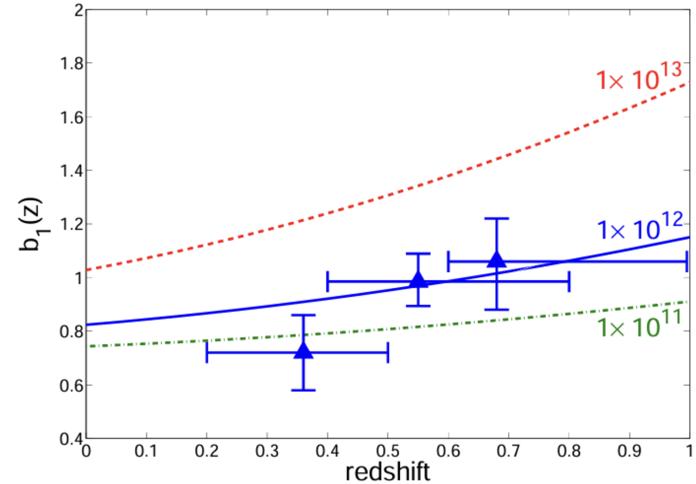
Quite novel field (in configuration space)

Mc Bride et al. (2011)

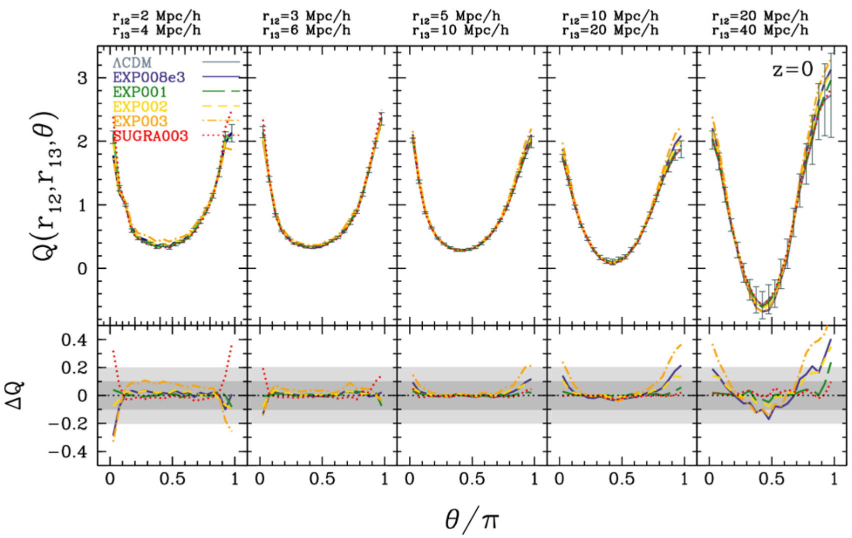


Marin et al. (2013)

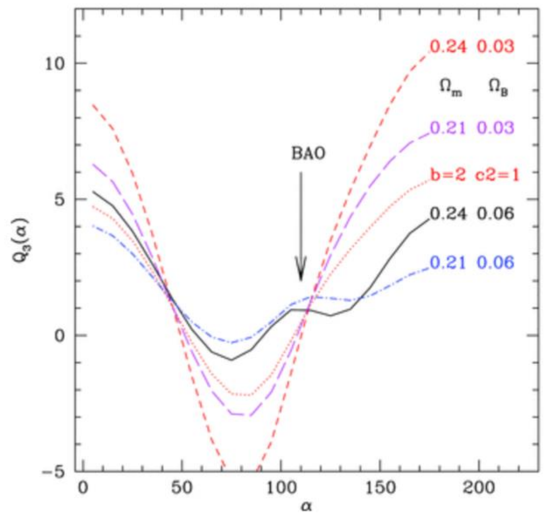




Moresco et al. (2013)



Gaztanaga et al. (2009)



Bottlenecks
- Computation time
- Modelling
- Covariance

State of the art (pre-2015)

3PCF analysis

Measurements
- Direct counting (linked-list, KDE-tree, ...)
- Spherical Harmonics Decomposition
- ?

Modelling
- Isotropic and anisotropic 3PCF
- Template fit and full-shape
- Beyond tree-level

Covariance
- Theoretical covariance
- From simulations
- Alterntive methods?

Speeding up modelling
- Emulators
- ?

Bayesian analysis
- 3PCF
- Reduced 3PCF
- 2PCF+3PCF
- 3PCF+B(k)
- ?

Parameter constraints
- Bias parameters (b1, b2, bt)
- Cosmological parameters, BAO
- Neutrinos, PNG
- ?

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State of the art (pre-2015)

3PCF analysis

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- 2PCF+
- 3PCF+
- ?

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- ?

A (possibly incomplete) list of improvements

New algorithms and covariance
- *SHD, theoretical covariance (Slepian et al. 2015, 2017)*
- *Impact of covariance (Veropalumbo et al. 2022)*

Modelling
- *Anisotropic 3PCF (Slepian et al. 2017, Sugiyama et al. 2019, Farina et al. 2025)*
- *Sub-leading order with FFTLog (Guidi et al. 2023)*
- *Full-shape (Guidi et al. 2025)*

BAO detection
- *Galaxies (Slepian et al. 2017)*
- *Clusters (Moresco et al. 2021)*

Analysis
- *2PCF+3PCF (Veropalumbo et al. 2021, Guidi et al. 2025)*

... and many others...

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State of the art (now)

3PCF analysis

Measurements
- Direct counting (linked-list, KDE-tree, ...)
- Spherical Harmonics Decomposition
- ?

Modelling
- Isotropic and anisotropic 3PCF
- Template fit and full-shape
- Beyond tree-level

Covariance
- Theoretical covariance
- From simulations
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- ?

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How to move forward?

- Computational improvements vs approximations: direct counting, spherical harmonics decomposition, what else?
- Improvements in codes? GPU?
- Modelling at the level of multiples vs resummed 3PCF vs reduced 3PCF?
- Push models to small scales?
- Models beyond tree-level: is it feasible? How much gain?
- Improving covariance?
- Configuration + Fourier space?
- **Modelling 3PCF in the analysis of real data** (**Euclid**, DESI, ...)
- **3PCF to provide constraints beyond standard** (**neutrinos**, PNG, ...)

- Others?

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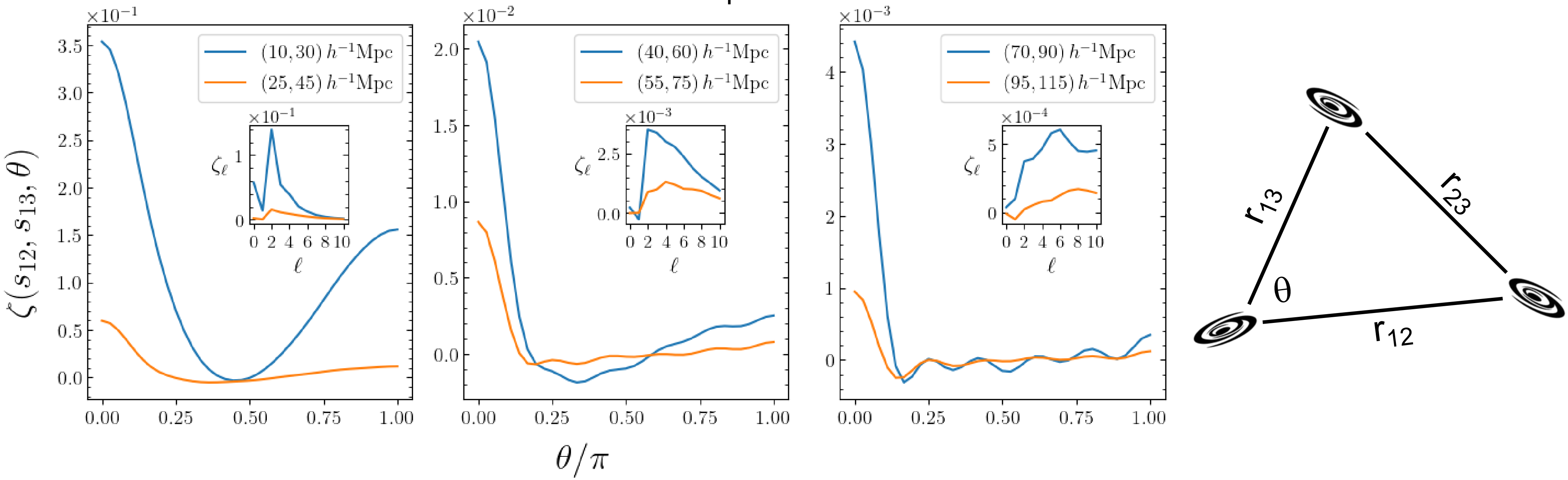
The three-point correlation function

3PCF: $\hat{\zeta}(r_{12}, r_{13}, \theta)$

reduced 3PCF: $$Q(r_{12}, r_{13}, r_{23}) \equiv \frac{\zeta(r_{12}, r_{13}, r_{23})}{\xi_0(r_{12})\xi_0(r_{13}) + \xi_0(r_{13})\xi_0(r_{23}) + \xi_0(r_{23})\xi_0(r_{12})}$$

quasi-isosceles



The impact of redshift interlopers on the 3PCF

and how to deal with it

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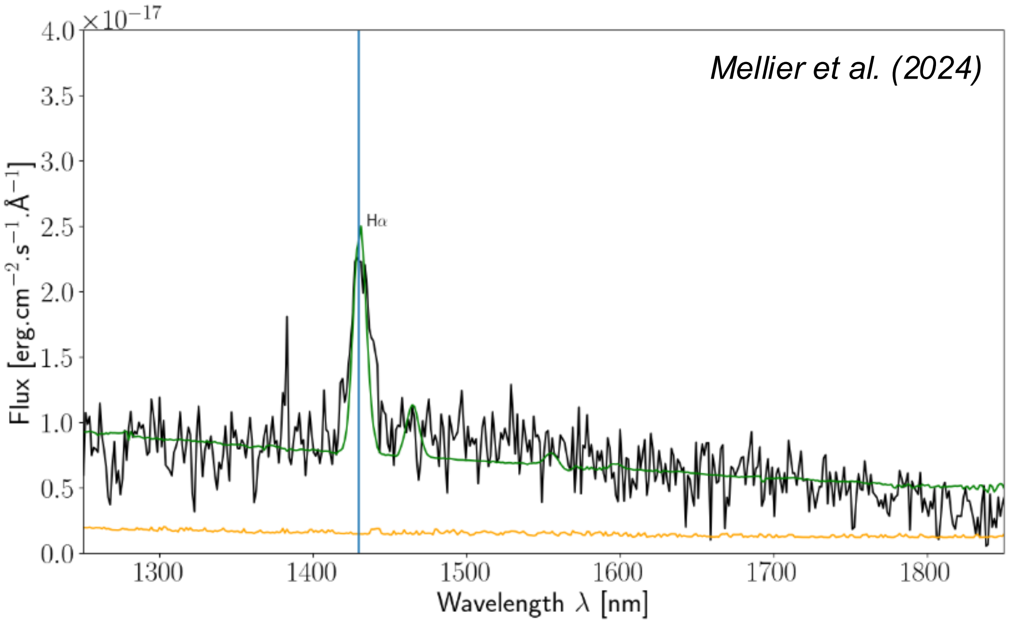
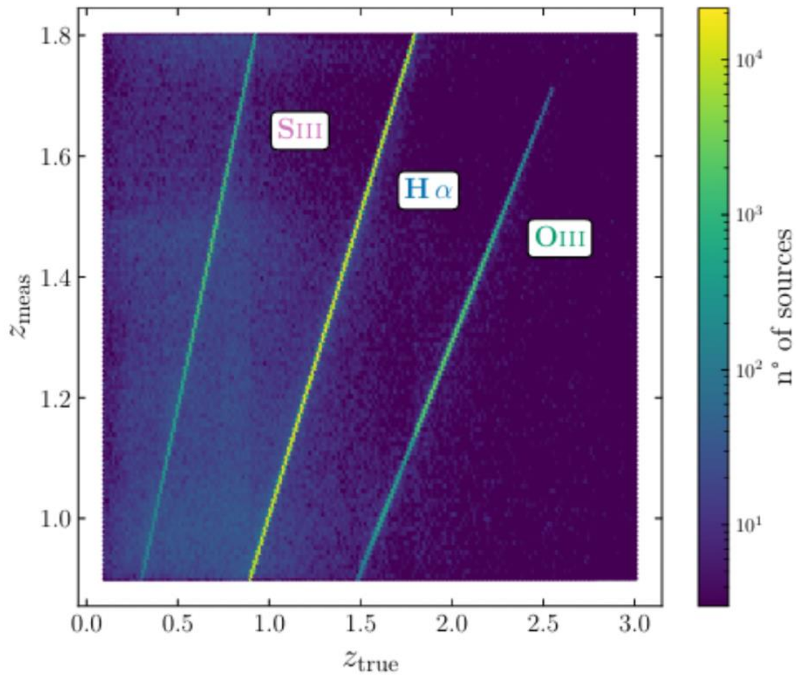
The issue of redshift interlopers

The spectroscopic part of the Euclid ESA mission will base the determination of redshifts on Hα emitters. In many cases, spectra will show only one line. While the spectroscopic pipeline is developed to minimize as much as possibile the contamination, **line interlopers** and **noise interlopers** may be present in the sample.



Risso et al. (2025)



Different redshift intervals, different contaminations

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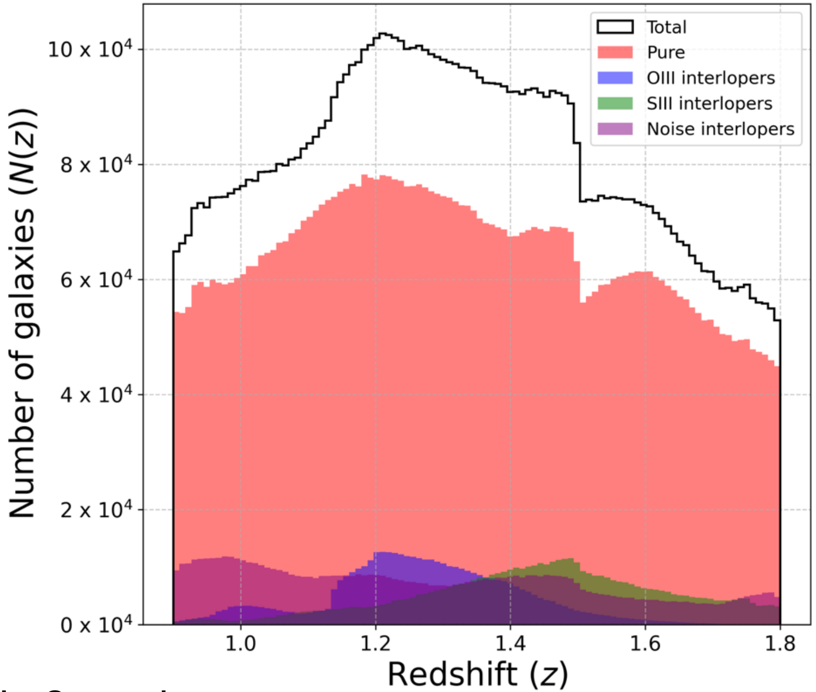
Euclid Large Mocks

To assess their impact, mocks have been created reproducing the expected behaviour of contaminants in Euclid samples (see Risso et al. 2025)

- 1000 Euclid mock samples
- Area: 2763 square degrees (similar to Euclid Data Release 1)
- Flux limit = 10^{-16} erg/s/cm^2 (1/2 of Euclid nominal limit)
- Redshift from the probabilistic model in Granett et al. (2025, in prep), calibrated on:
  - spectra simulated with fastSpec (Granett et al. 2025 in prep)
  - redshift derived with the official Euclid pipeline (Le Brun et al. 2025)

Risso et al. (2025)

	$z \in [0.9, 1.1]$	$z \in [1.1, 1.3]$	$z \in [1.3, 1.5]$	$z \in [1.5, 1.8]$
O III	0.03	0.12	0.09	0.01
S III	0.01	0.03	0.08	0.07
noise	0.12	0.08	0.08	0.06



Analysis performed as cross-check also on Euclid Flagship 2 mocks

New cross 3PCF estimators

Work by Nicola Principi, with M. Moresco, F. Marulli, A. Veropalumbo

fraction of i-th sample — autocorrelation 3PCF — bicross 3PCF — tricross 3PCF

$$\hat{\zeta}_{tot} = \sum_i f_i^3 \frac{R_iR_iR_i}{R_{tot}R_{tot}R_{tot}}\hat{\zeta}_i + 3\left[\sum_{i\neq j, i<j}\left(f_i^2 f_j \frac{R_iR_iR_j}{R_{tot}R_{tot}R_{tot}}\hat{\zeta}_{iij} + f_i f_j^2 \frac{R_iR_jR_j}{R_{tot}R_{tot}R_{tot}}\hat{\zeta}_{ijj}\right)\right] + 6\sum_{i\neq j\neq k, i<j<k} f_i f_j f_k \frac{R_iR_jR_k}{R_{tot}R_{tot}R_{tot}}\hat{\zeta}_{ijk}.$$

$$\hat{\zeta}_i = \frac{D_iD_iD_i - 3D_iD_iR_i + 3D_iR_iR_i - R_iR_iR_i}{R_iR_iR_i},$$

$$\hat{\zeta}_{iij} = \frac{D_iD_iD_j - D_iD_iR_j - 2D_iR_iD_j + 2D_iR_iR_j + R_iR_iD_j - R_iR_iR_j}{R_iR_iR_j},$$

$$\hat{\zeta}_{ijj} = \frac{D_iD_jD_j + D_iR_jR_j - 2D_iD_jR_j + 2R_iD_jR_j - R_iD_jD_j - R_iR_jR_j}{R_iR_jR_j},$$

$$\hat{\zeta}_{ijk} = \frac{D_iD_jD_k - D_iR_jD_k - D_iD_jR_k - R_iD_jD_k + R_iR_jD_k + R_iD_jR_k + D_iR_jR_k - R_iR_jR_k}{R_iR_jR_k}$$

4 new classes and 19 new functions implemented in the CosmoBolognaLib suite

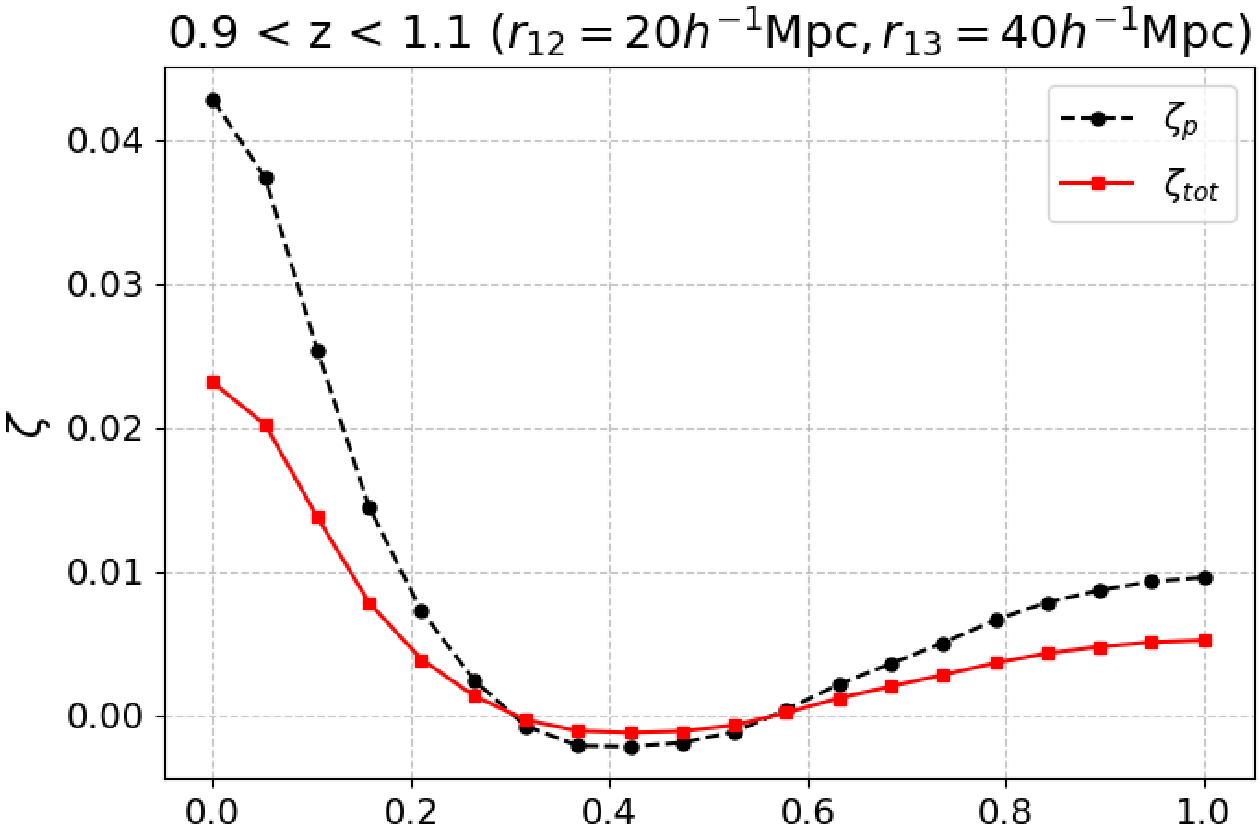
CosmoBolognaLib

Autocorrelations and cross-correlations

Work by Nicola Principi, with M. Moresco, F. Marulli, A. Veropalumbo

Analysis on Flagship 2 catalog

Global effect: **damping of the signal**



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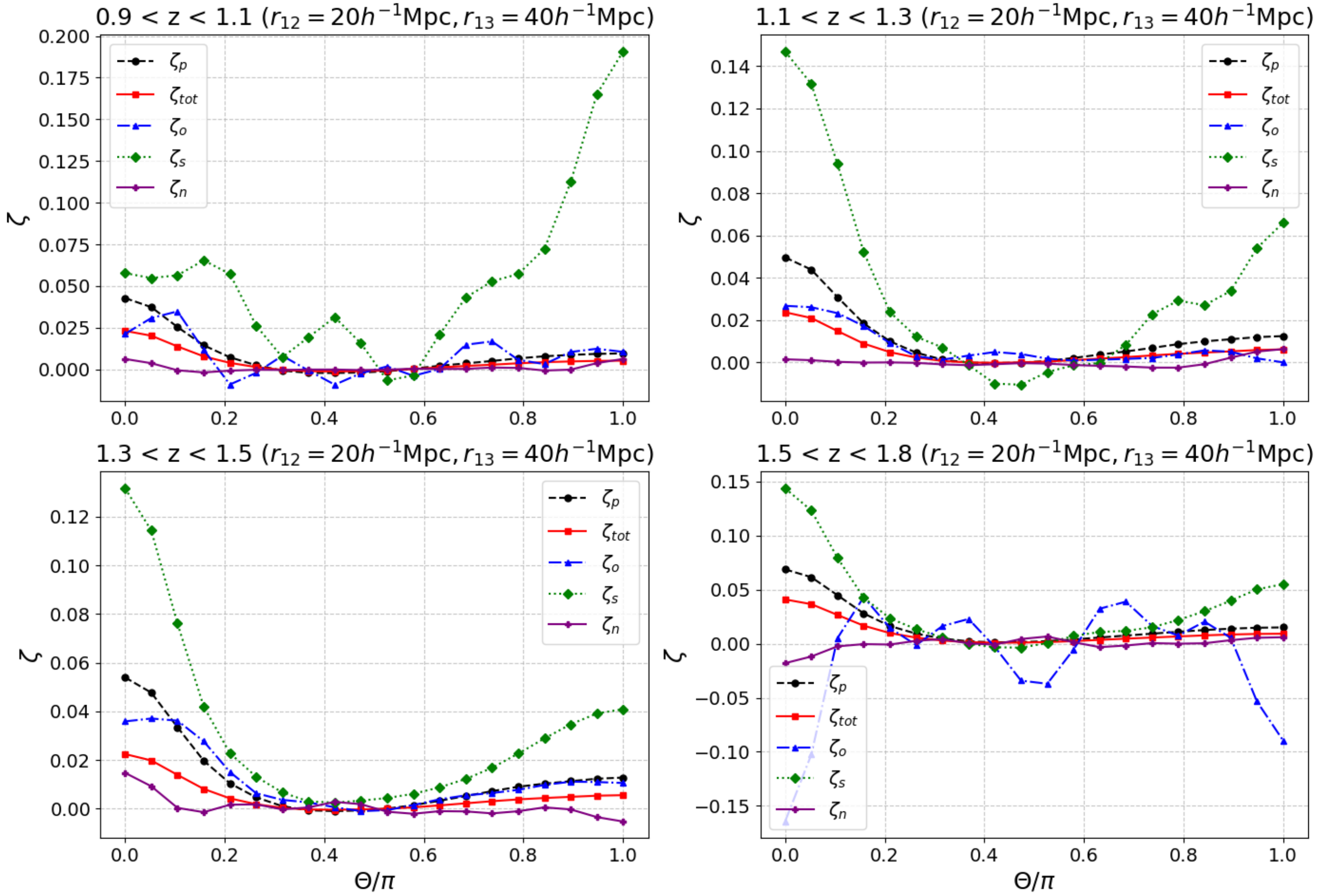

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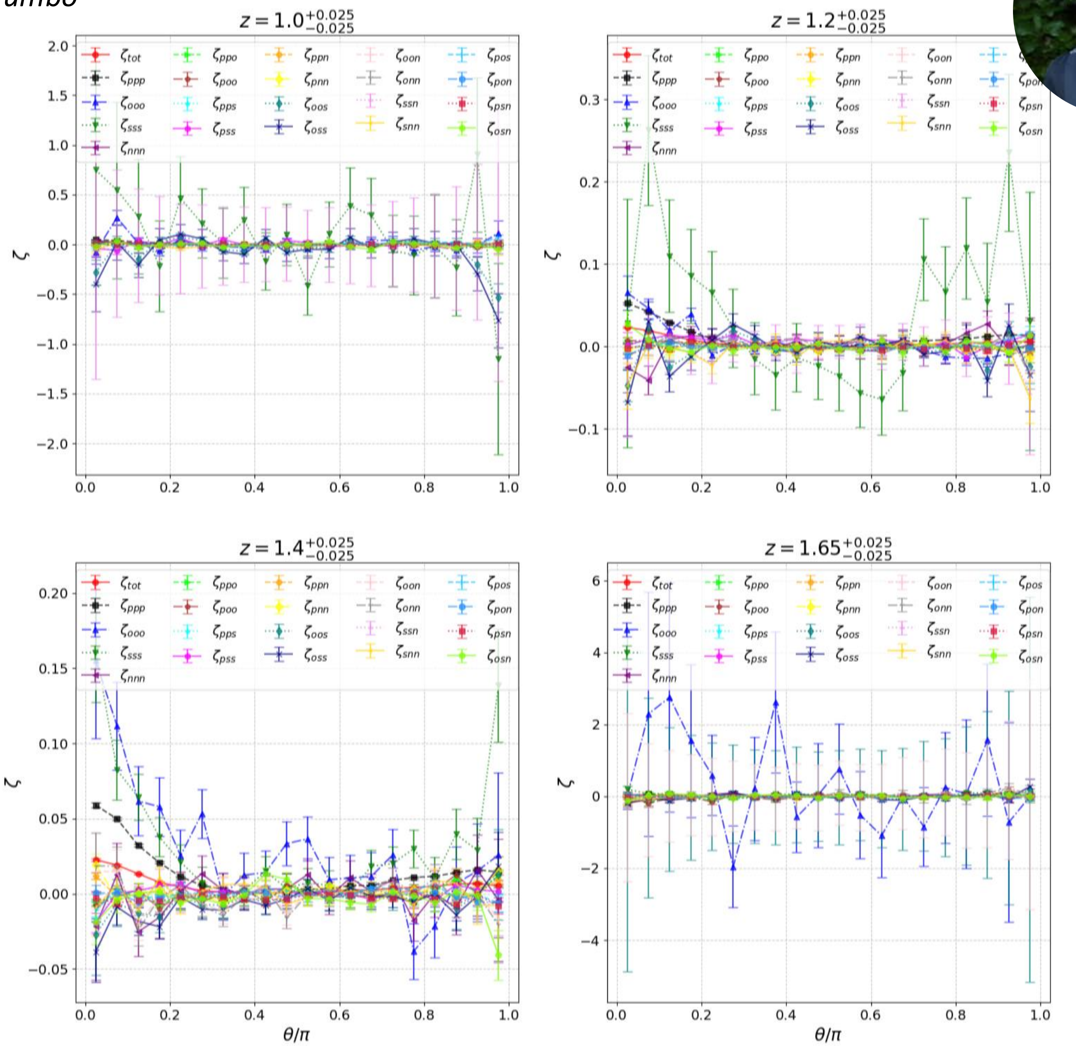

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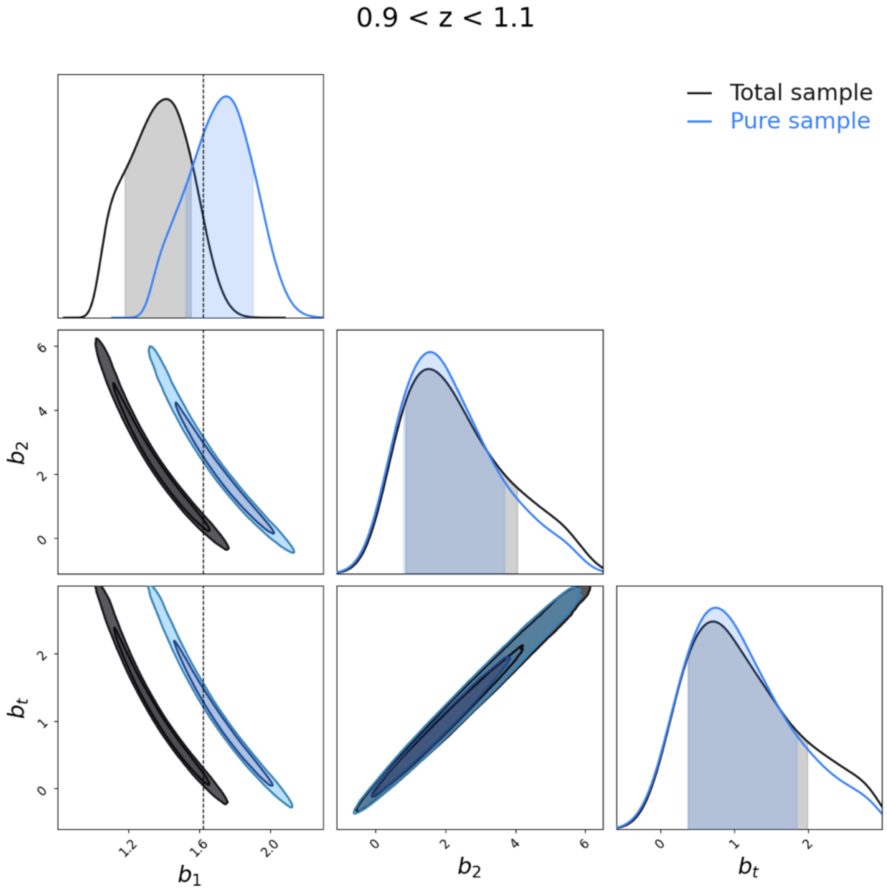
Impact of interlopers on the 3PCF

Work by Nicola Principi, with M. Moresco, F. Marulli, A. Veropalumbo

Analysis on Euclid Large Mocks



Direct analysis:

Offset in b_1, but not in b_2 and b_t

Could be due to a simple offset between contaminated and pure 3PCF

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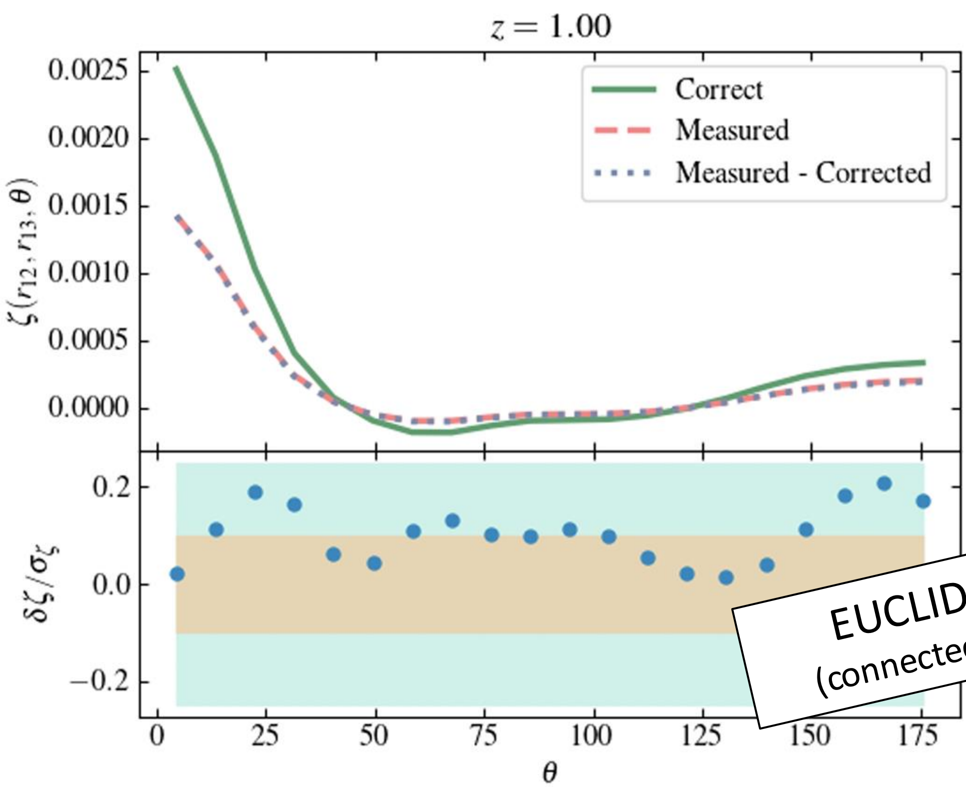
Can we retrieve the expected signal?

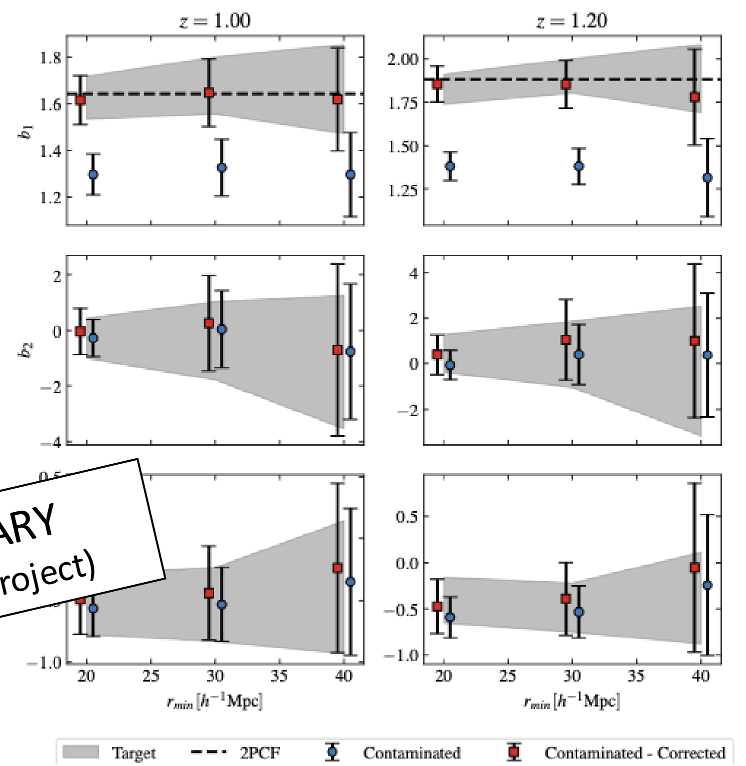
Work by A. Veropalumbo, Nicola Principi, M. Moresco, F. Marulli

Analysis on Euclid Large Mocks

$$\zeta_m = (1 - f_i)\,\frac{R_C R_C R_C}{R_m R_m R_m}\,\zeta_C + cross.corr.$$

Accounting for the leading term provide a very good approximation, with baseline contamination (f_i~20%)





EUCLID PRELIMINARY
(connected to HOS Key Project)

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3PCF as a tool to constrain neutrino masses

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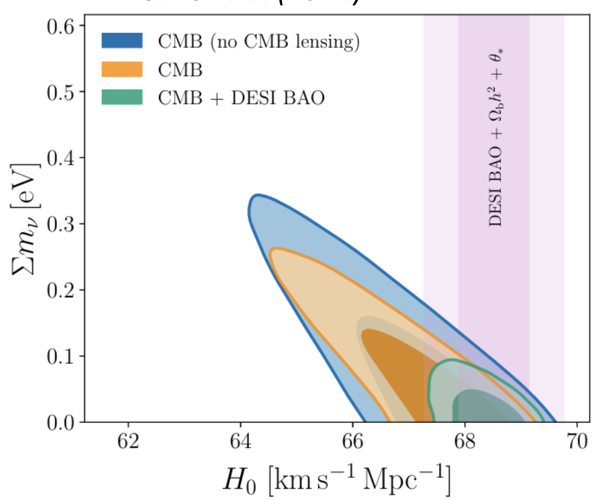
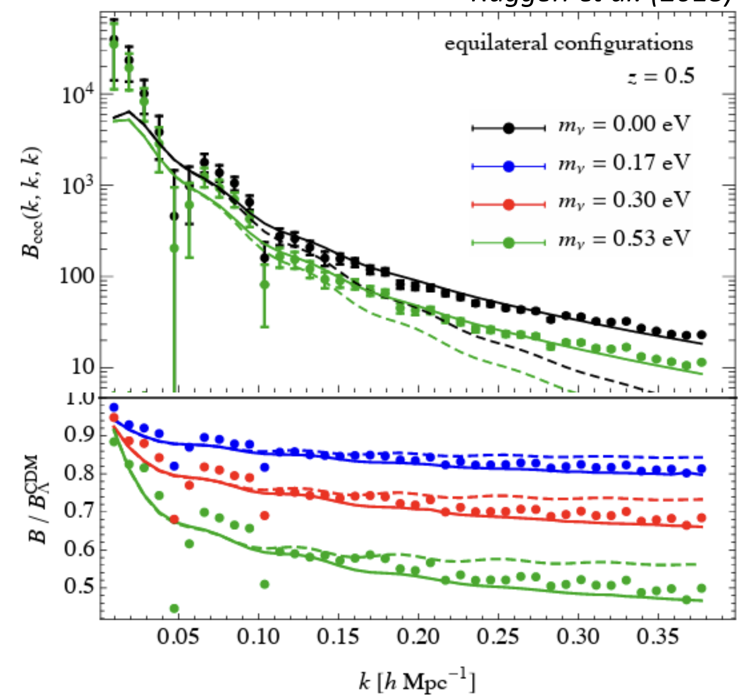
The effects of neutrinos on clustering

Not a novel topic, exploited extensively at 2-point level and in combination with other probes

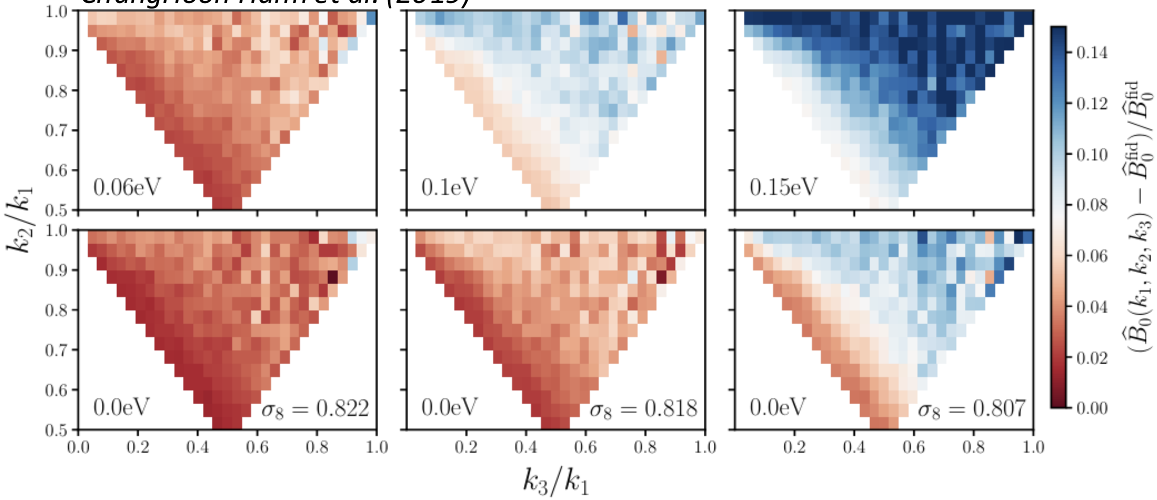
DESI 2024 VI (2024)



Ruggeri et al. (2018)



ChangHoon Hahn et al. (2019)



More recently, expanded also at higher-order
(but only for the bispetrum)

Never attempted fot the 3PCF

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The Quijote simulations

Work by A. Labate, M. Moresco, M. Guidi

Data sample: Quijote simulations
Villaescusa-Navarro et al., 2020

- 2000 fiducial simulations (for the covariance)
- 500 fiducial simulations (for control sample)
- 500 x 2 neutrino simulations
- 500 x 2 s8 simulations

Name	M_ν (eV)	σ_8	Realizations	Simulations	ICs	$N_c^{1/3}$	$N_\nu^{1/3}$
fiducial	0	0.834	2000	standard	2LPT	512	0
fiducial	0	0.834	500	paired fixed	2LPT	512	0
fiducial_ZA	0	0.834	500	standard	ZA	512	0
Mnu_ppp	0.4	0.834	500	standard	ZA	512	512
Mnu_pp	0.2	0.834	500	standard	ZA	512	512
Mnu_p	0.1	0.834	500	standard	ZA	512	512
s8_p	0	0.849	500	paired fixed	2LPT	512	0
s8_m	0	0.819	500	paired fixed	2LPT	512	0

Measurements (with MeasCorr):
- 2PCF from 1<r [Mpc/h]<150
- 3PCF from 2.5<r [Mpc/h]<147.5 up to l=10
  - Zeta multipoles
  - Zeta resummed (both single and all scales)
  - Reduced 3PCF (both single and all scales)

$$\hat{\zeta}(r_{12}, r_{13}, \theta) = \sum_{\ell=0}^{\ell_{\max}} \bar{\hat{\zeta}}_\ell(r_{12}, r_{13}) P_\ell(\cos\theta)$$

$$Q(r_{12}, r_{13}, r_{23}) \equiv \frac{\zeta(r_{12}, r_{13}, r_{23})}{\xi_0(r_{12})\xi_0(r_{13}) + \xi_0(r_{13})\xi_0(r_{23}) + \xi_0(r_{23})\xi_0(r_{12})}$$

independent of s8

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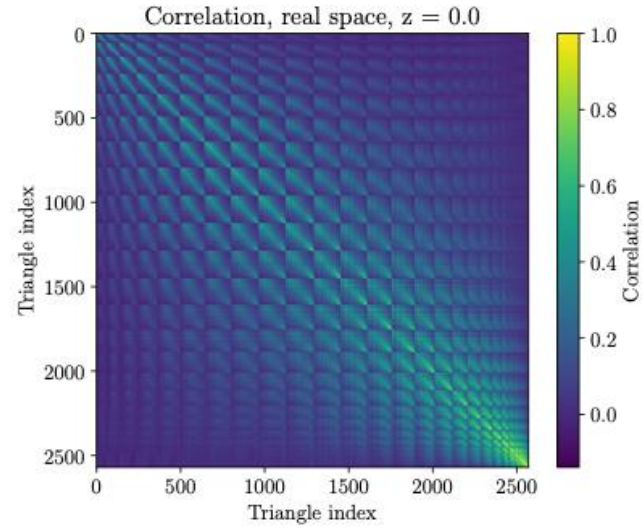
fiducial	0	0.834	500	paired fixed	2LPT	512	0
fiducial_ZA	0	0.834	500	standard	ZA	512	0
Mnu_ppp	0.4	0.834	500	standard	ZA	512	512
Mnu_pp	0.2	0.834	500	standard	ZA	512	512
Mnu_p	0.1	0.834	500	standard	ZA	512	512
s8_p	0	0.849	500	paired fixed	2LPT	512	0
s8_m	0	0.819	500	paired fixed	2LPT	512	0

Measurements (with MeasCorr):
- 2PCF from 1<r [Mpc/h]<150
- 3PCF from 2.5<r [Mpc/h]<147.5 up to l=10
  - Zeta multipoles
  - Zeta resummed (both single and all scales)
  - Reduced 3PCF (both single and all scales)



Covariance estimated for all these datasets (rescaled for a volume of 10 h^{-3} Gpc^3)

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DIPARTIMENTO DI FISICA E ASTRONOMIA "AUGUSTO RIGHI"

The Quijote simulations

Work by A. Labate, M. Moresco, M. Guidi

Data sample: Quijote simulations
Villaescusa-Navarro et al., 2020

- 2000 fiducial simulations (for the covariance)
- 500 fiducial simulations (for control sample)
- 500 x 2 neutrino simulations
- 500 x 2 s8 simulations

Name	M_ν (eV)	σ_8	Realizations	Simulations	ICs	$N_c^{1/3}$	$N_\nu^{1/3}$
fiducial	0	0.834	2000	standard	2LPT	512	0
fiducial	0	0.834	500	paired fixed	2LPT	512	0
fiducial_ZA	0	0.834	500	standard	ZA	512	0
Mnu_ppp	0.4	0.834	500	standard	ZA	512	512
Mnu_pp	0.2	0.834	500	standard	ZA	512	512
Mnu_p	0.1	0.834	500	standard	ZA	512	512
s8_p	0	0.849	500	paired fixed	2LPT	512	0
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  - Zeta multipoles
  - Zeta resummed (both single and all scales)
  - Reduced 3PCF (both single and all scales)

$$\mathrm{DET}_i \equiv \frac{\hat{f}_i^{(\nu)} - \hat{f}_i^{(\mathrm{fiducial})}}{\sqrt{2}\,\sigma_{f,i}}.$$

$$\chi^2(r_{12}, r_{13}) \equiv \sum_{i,j=1}^{N_\theta} \left(\hat{f}^{(\nu)} - \hat{f}^{(\mathrm{fiducial})}\right)(r_{12}, r_{13}, \theta_i) \times \left[\hat{C}^{(\mathrm{single-sc.})}\right]^{-1}_{ij} \times \left(\hat{f}^{(\nu)} - \hat{f}^{(\mathrm{fiducial})}\right)(r_{12}, r_{13}, \theta_j),$$

Covariance estimated for all these datasets (rescaled for a volume of 10 h^{-3} Gpc^3)

Different estimators for the neutrino detectability

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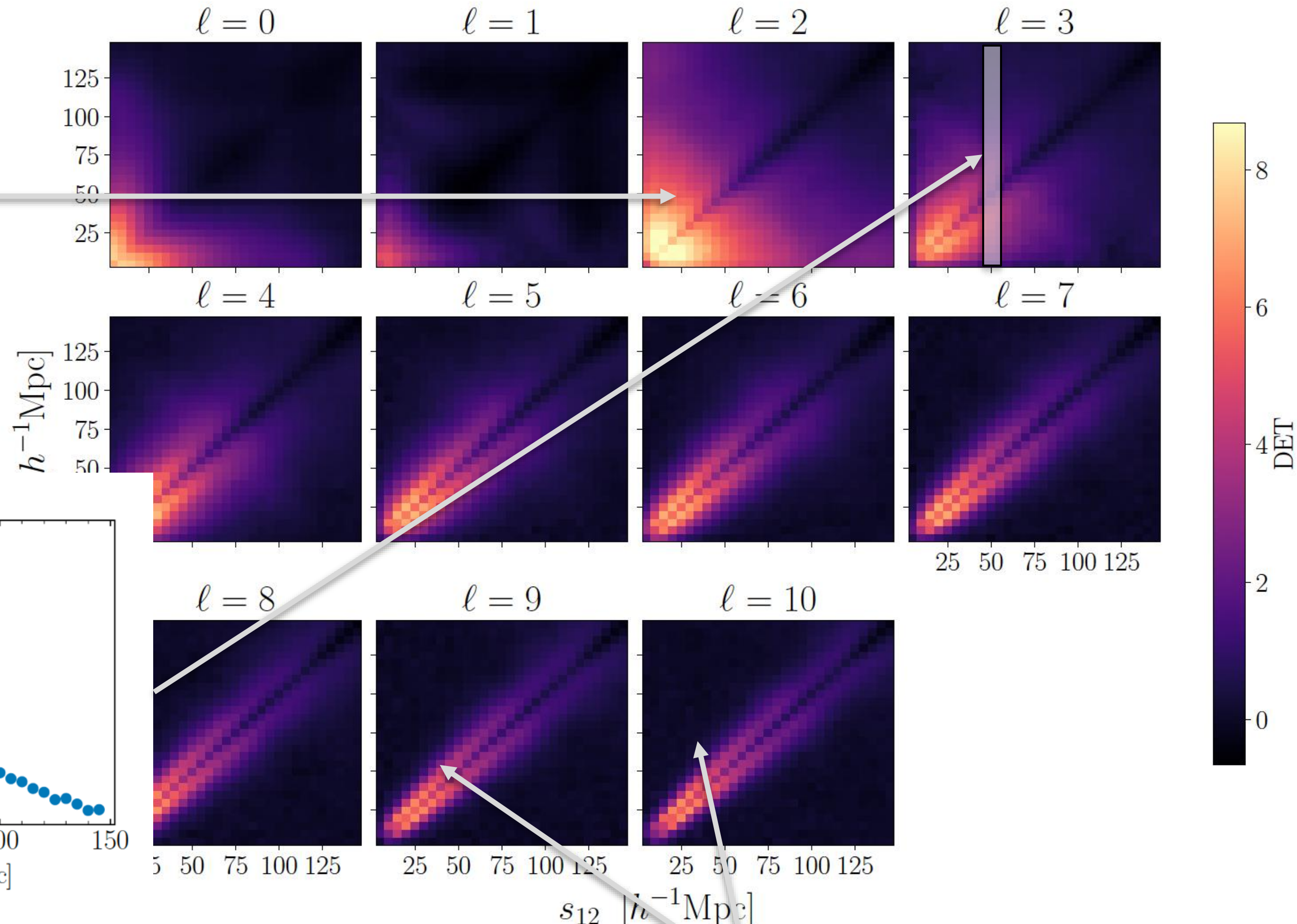
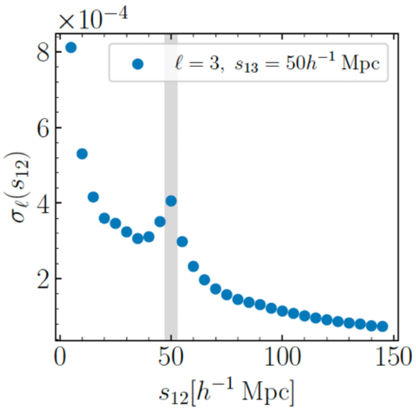
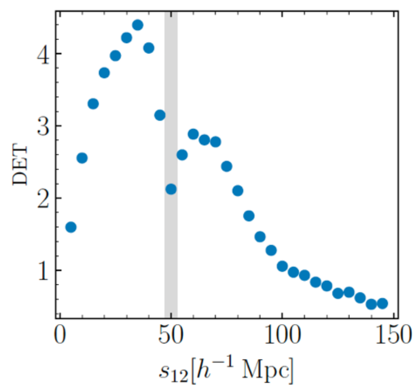
Effect of neutrinos on 3PCF multiples

Work by A. Labate, M. Moresco, M. Guidi

strong effect for l=2 multipoles







Low detectability in isosceles configurations due to increased error

Many multipoles needed to reconstruct quasi-isosceles configurations

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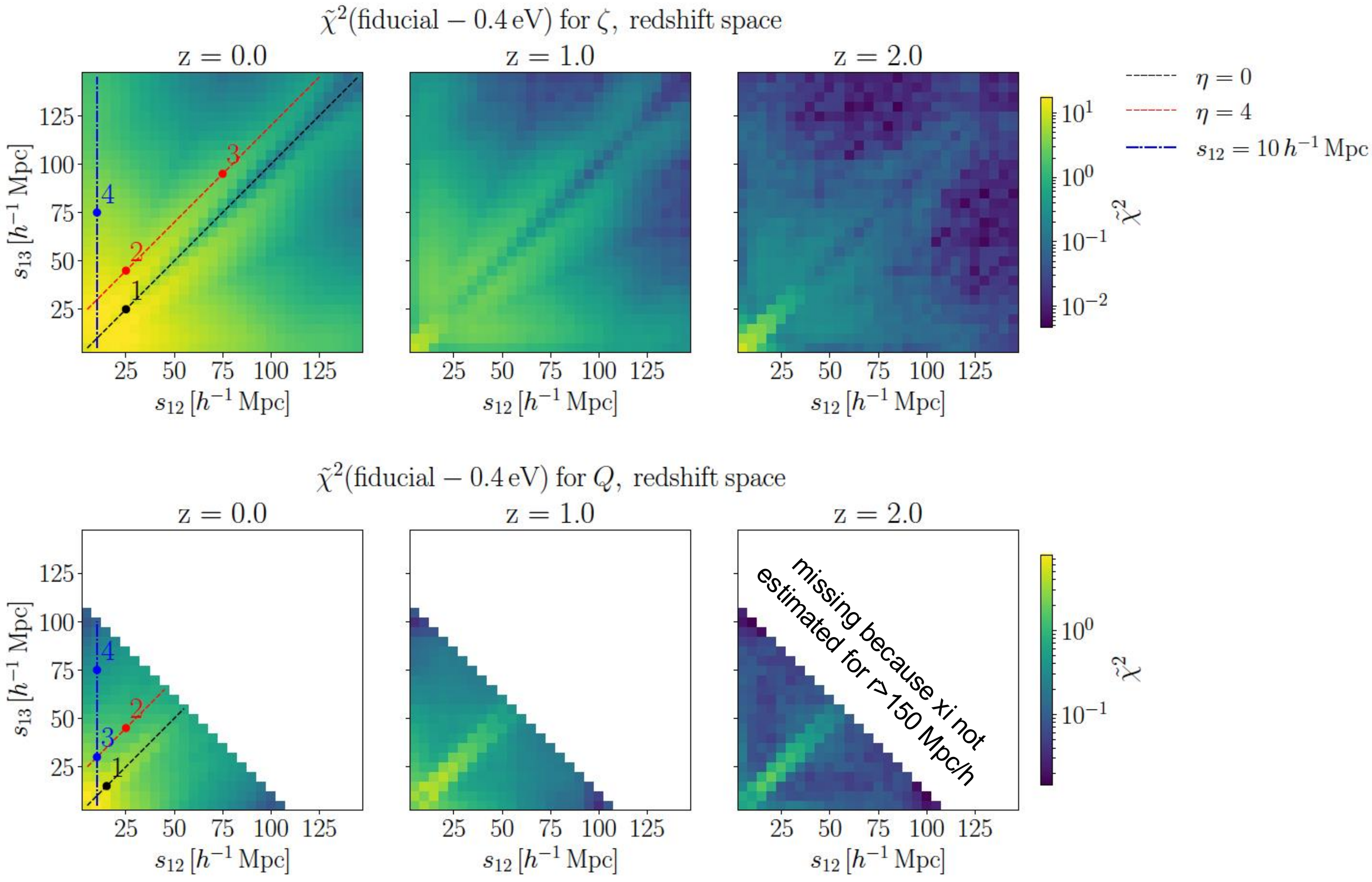
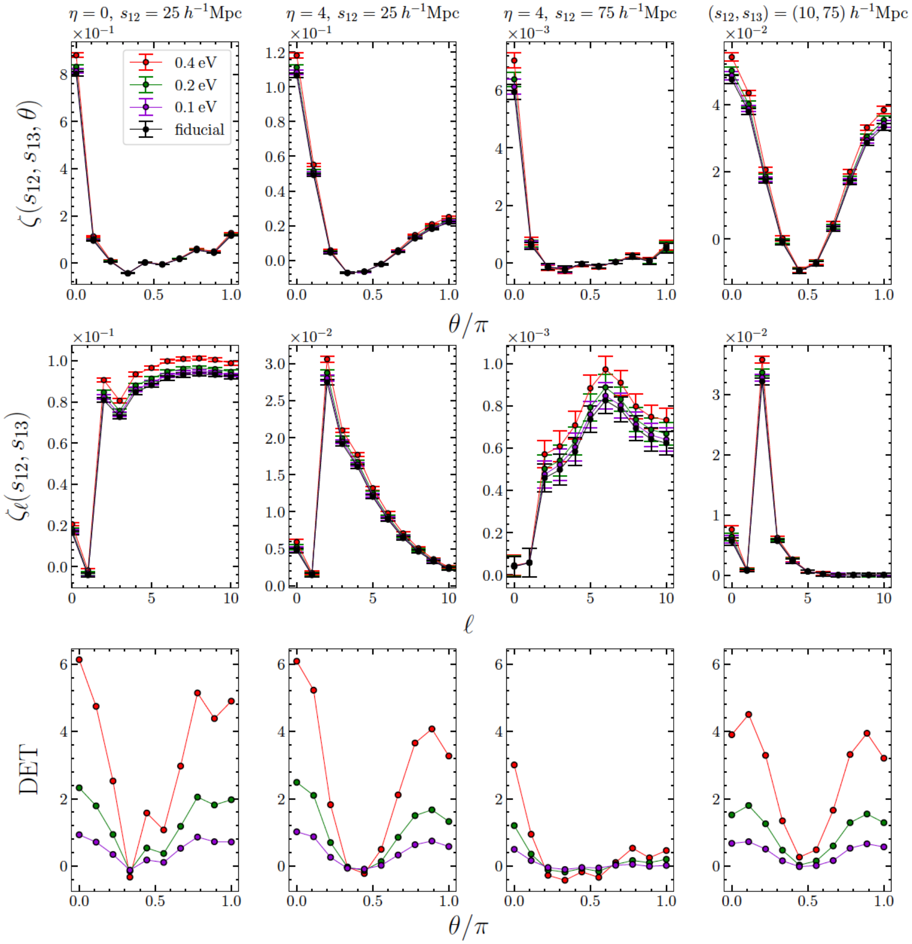


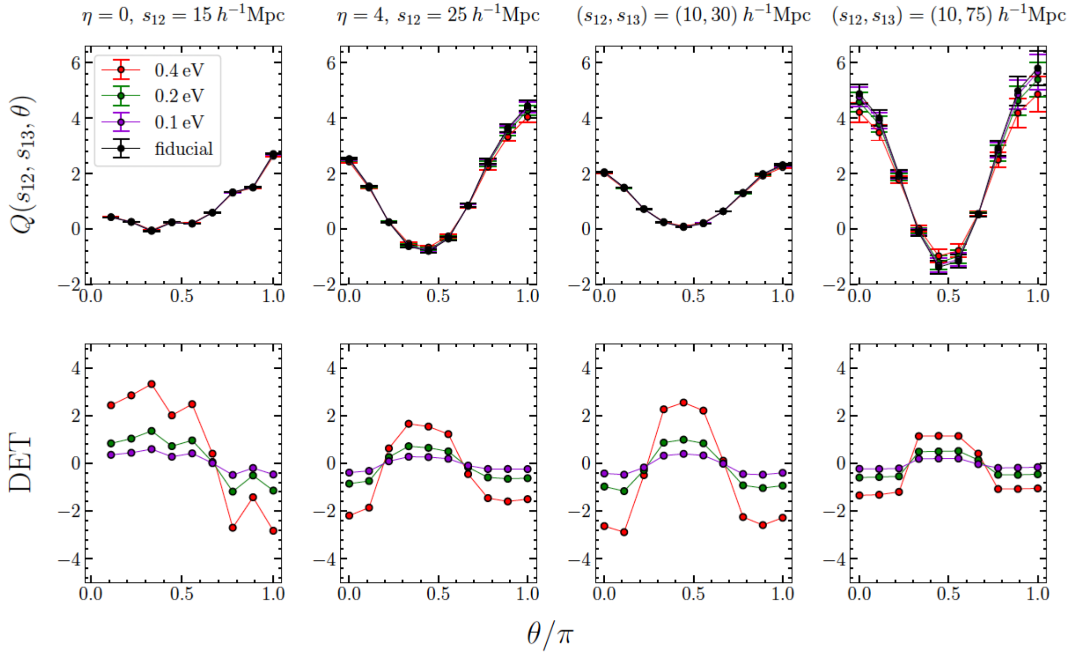
Effect of neutrinos on 3PCF

Work by A. Labate, M. Moresco, M. Guidi

3PCF



reduced 3PCF



- larger ls are needed to reconstruct quasi-isosceles configurations
- larger effect of neutrinos at smaller scales
- more significant impact for elongated configurations
- stronger effect on zeta

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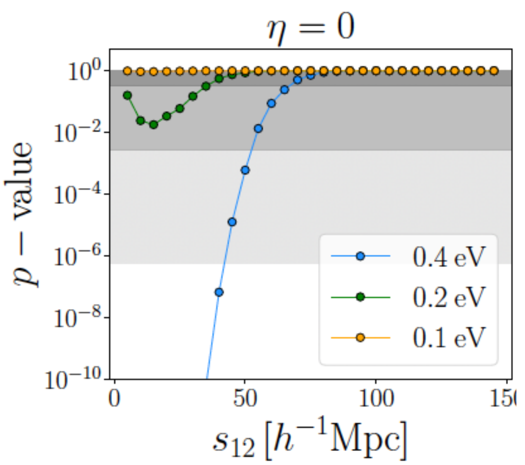
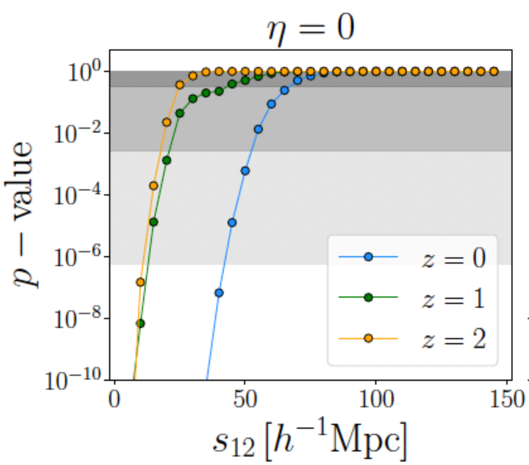
Quantifying the detectability

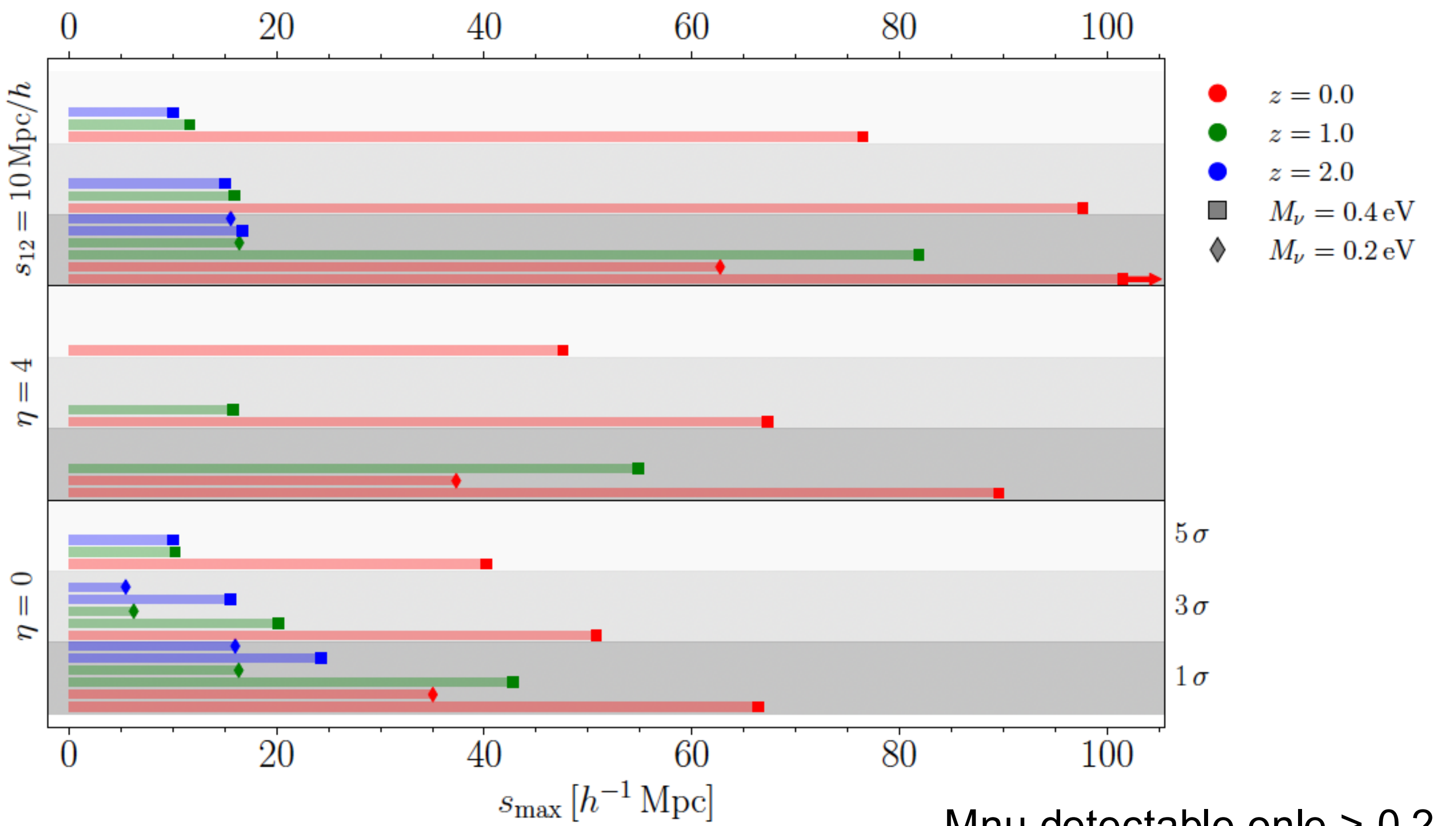
Work by A. Labate, M. Moresco, M. Guidi

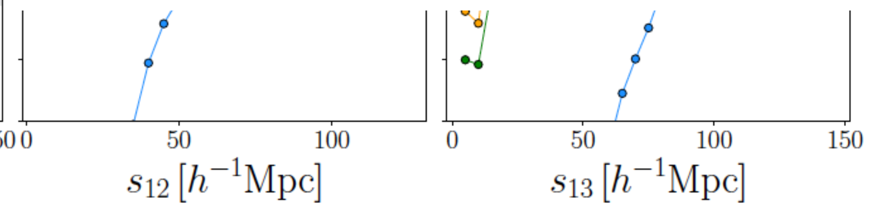
Mnu



z







- Mnu detectable onle > 0.2 eV with this volume
- the lower Mnu, the more is needed to go to lower scales

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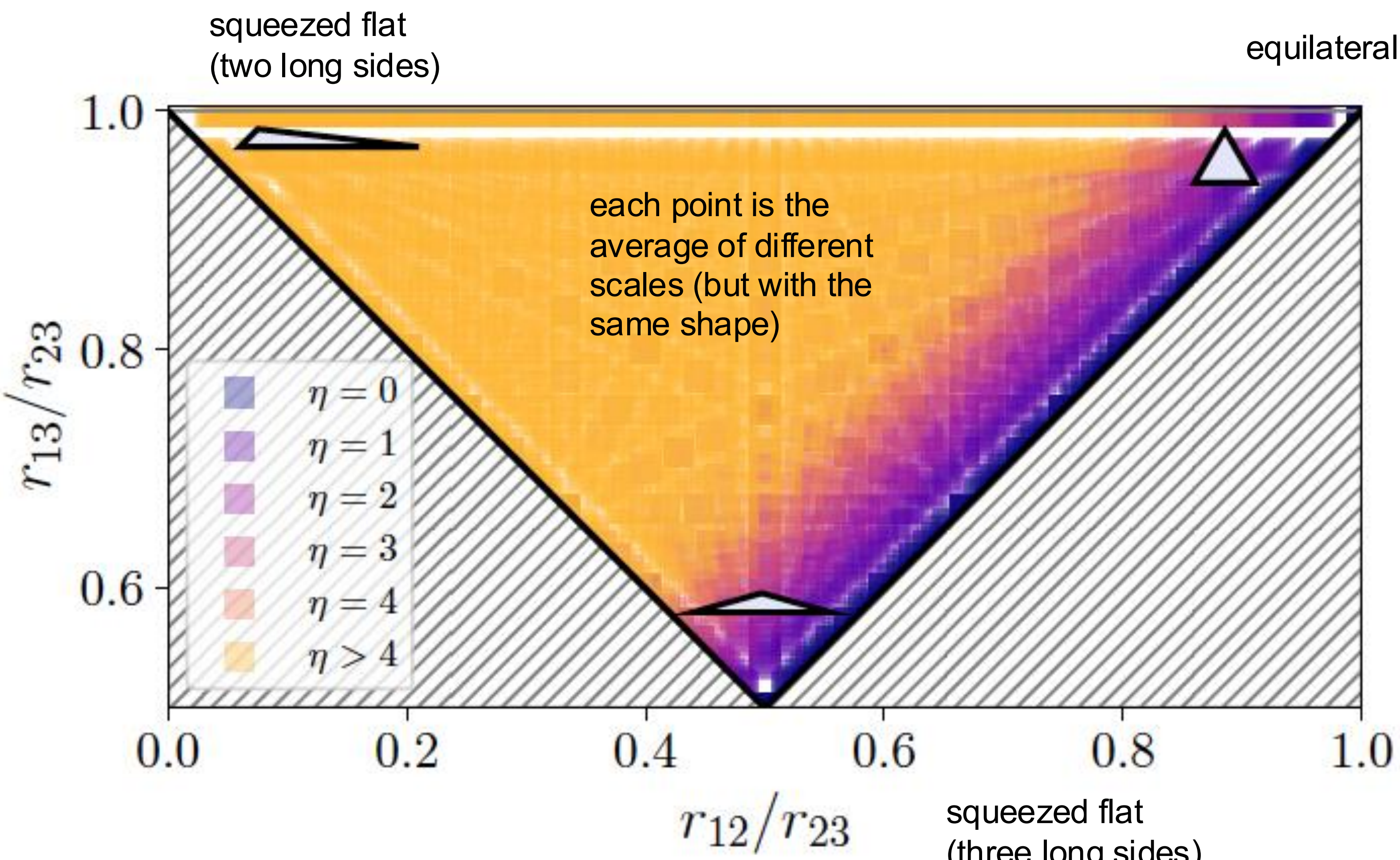
Which kind of configurations are better?

Work by A. Labate, M. Moresco, M. Guidi



Which kind of configurations are better?

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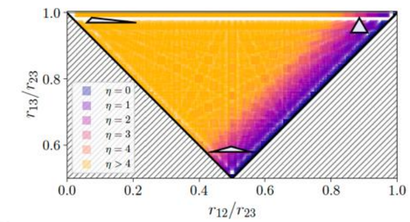
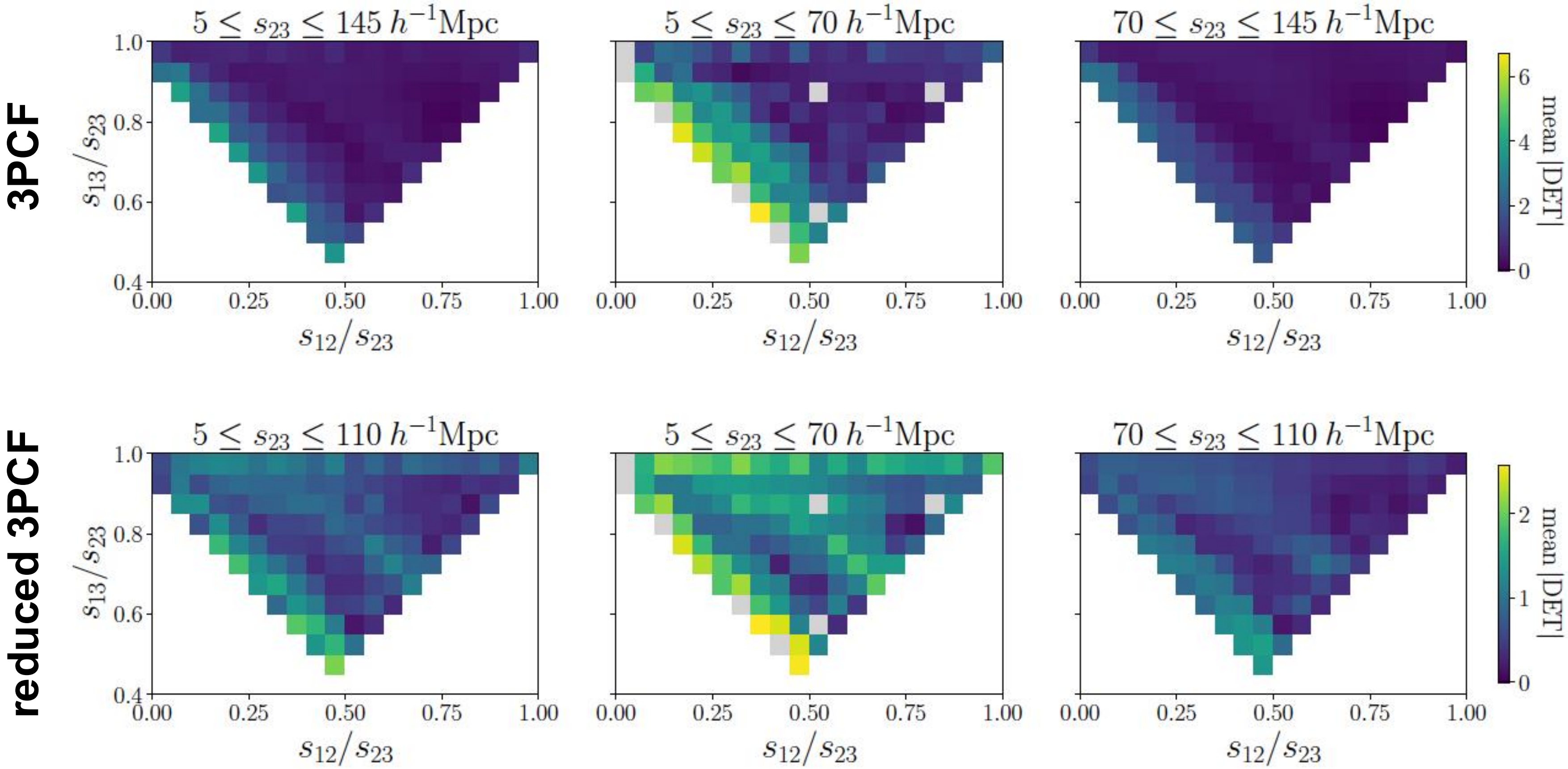
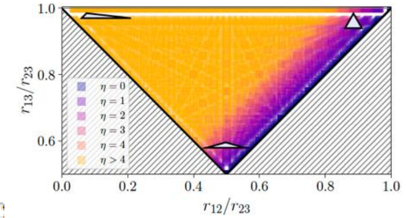


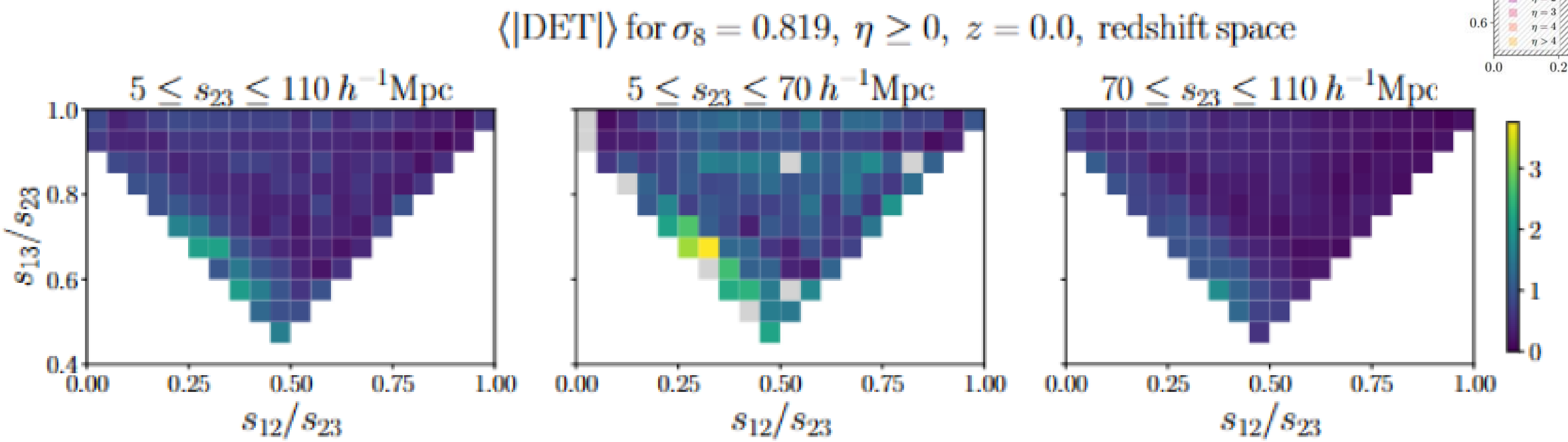


Are there degeneracies?

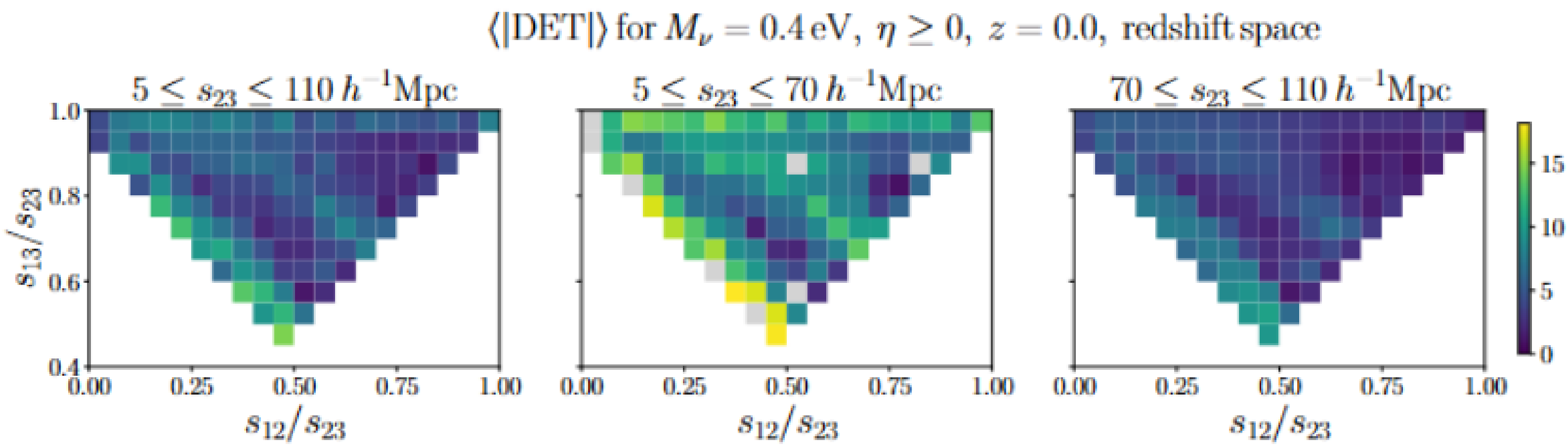
Work by A. Labate, M. Moresco, M. Guidi



3PCF s8



3PCF Mnu



Are there degeneracies?

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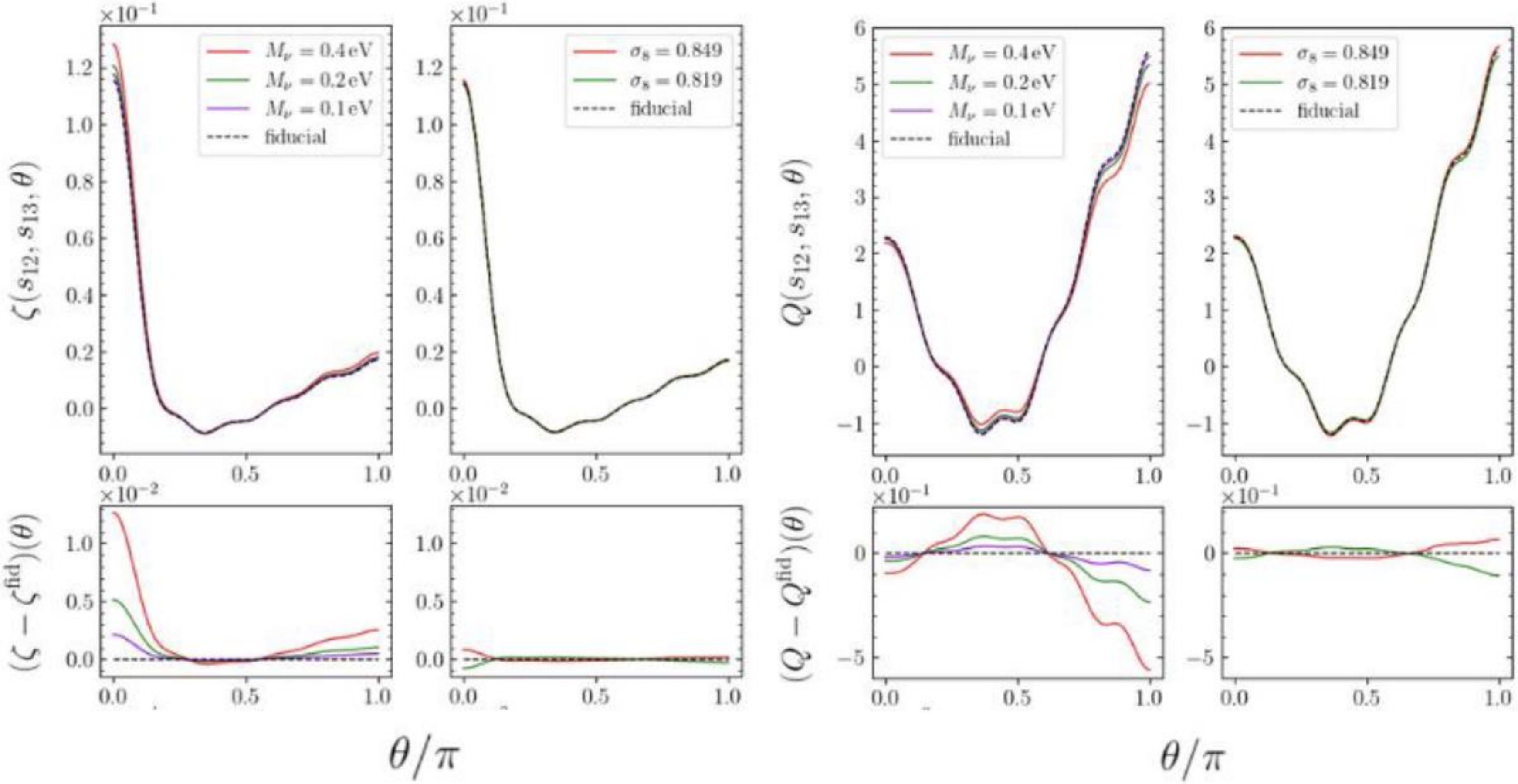

How to move forward?

- Computational improvements vs approximations: direct counting, spherical harmonics decomposition, what else?
- Improvements in codes? GPU?
- Modelling at the level of multiples vs resummed 3PCF vs reduced 3PCF?
- Push models to small scales?
- Models beyond tree-level: is it feasible? How much gain?
- Improving covariance?
- Configuration + Fourier space?
- Modelling 3PCF in the analysis of real data (Euclid, DESI, ...)
- 3PCF to provide constraints beyond standard (neutrinos, PNG, ...)

- Others?