First detection of BAO peak in the three-point correlation function of galaxy clusters

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Overview

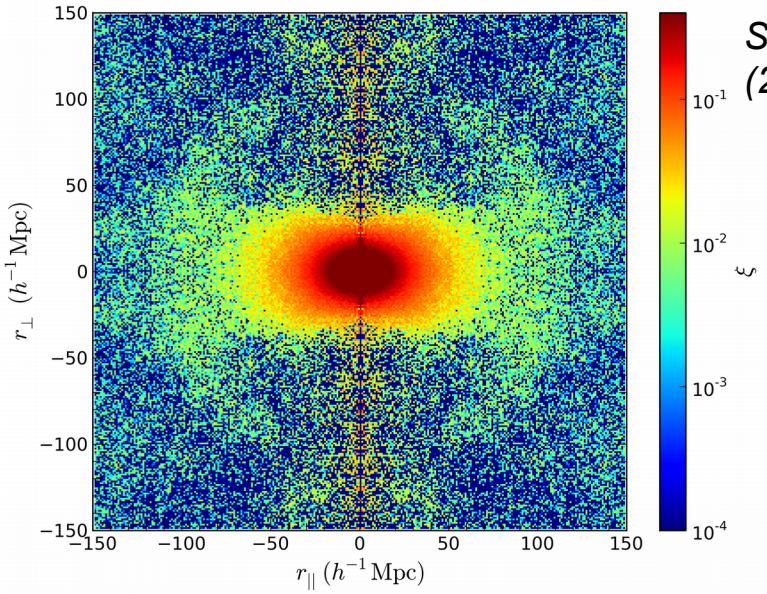
General overview and motivation of 3PCF

Some applications

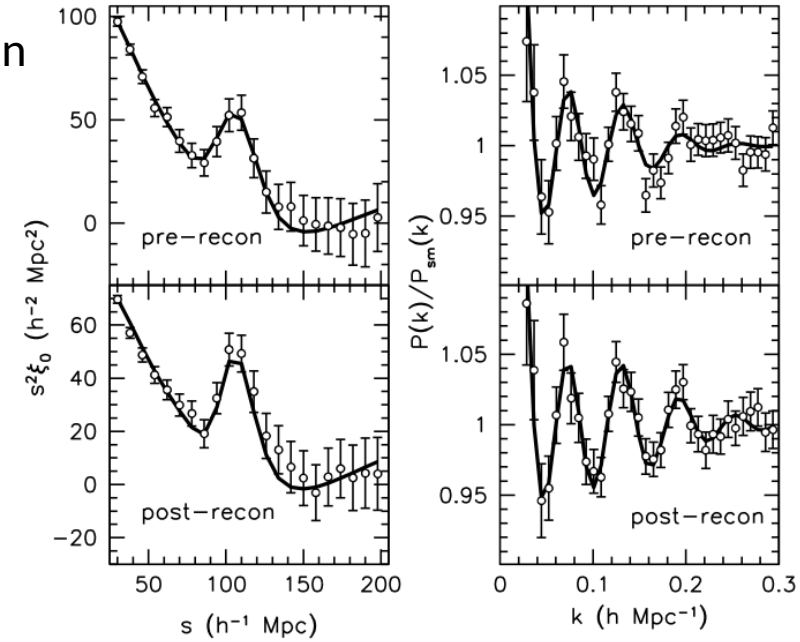
Detecting the BAO signal in the 3PCF of galaxy clusters

Galaxy clustering and cosmology

Galaxy correlation functions encode fundamental information for cosmology
- BAO
- RSD



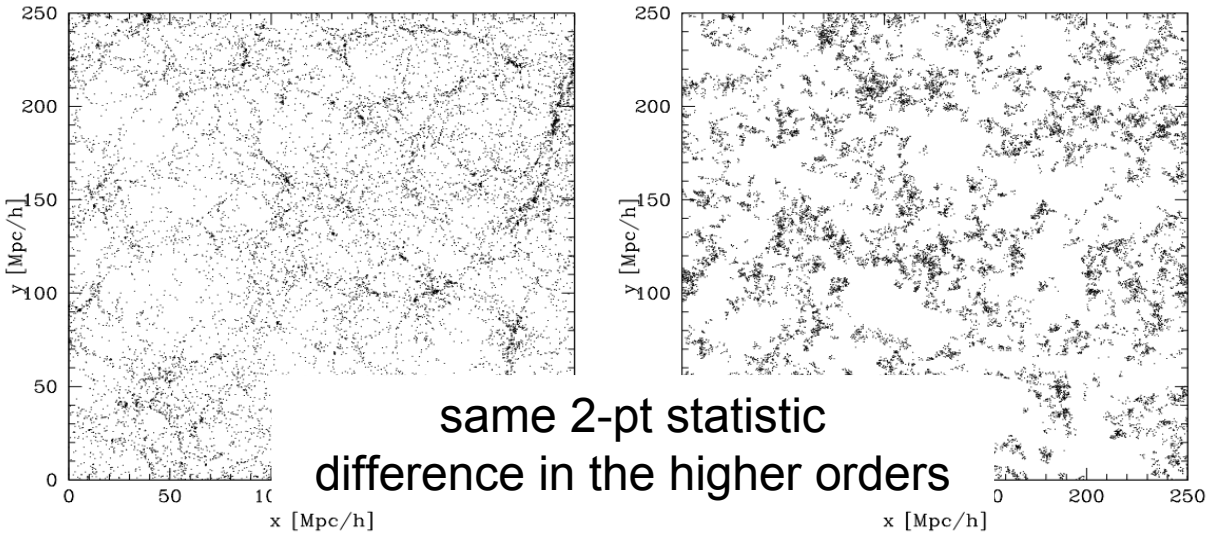
Samushia et al. (2013)



Anderson et al. (2014)

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

… but the Universe is just
not like that!

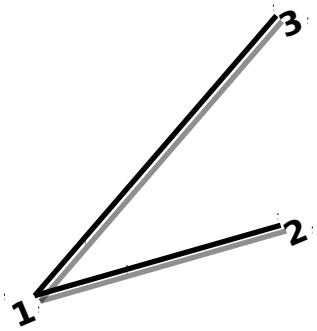


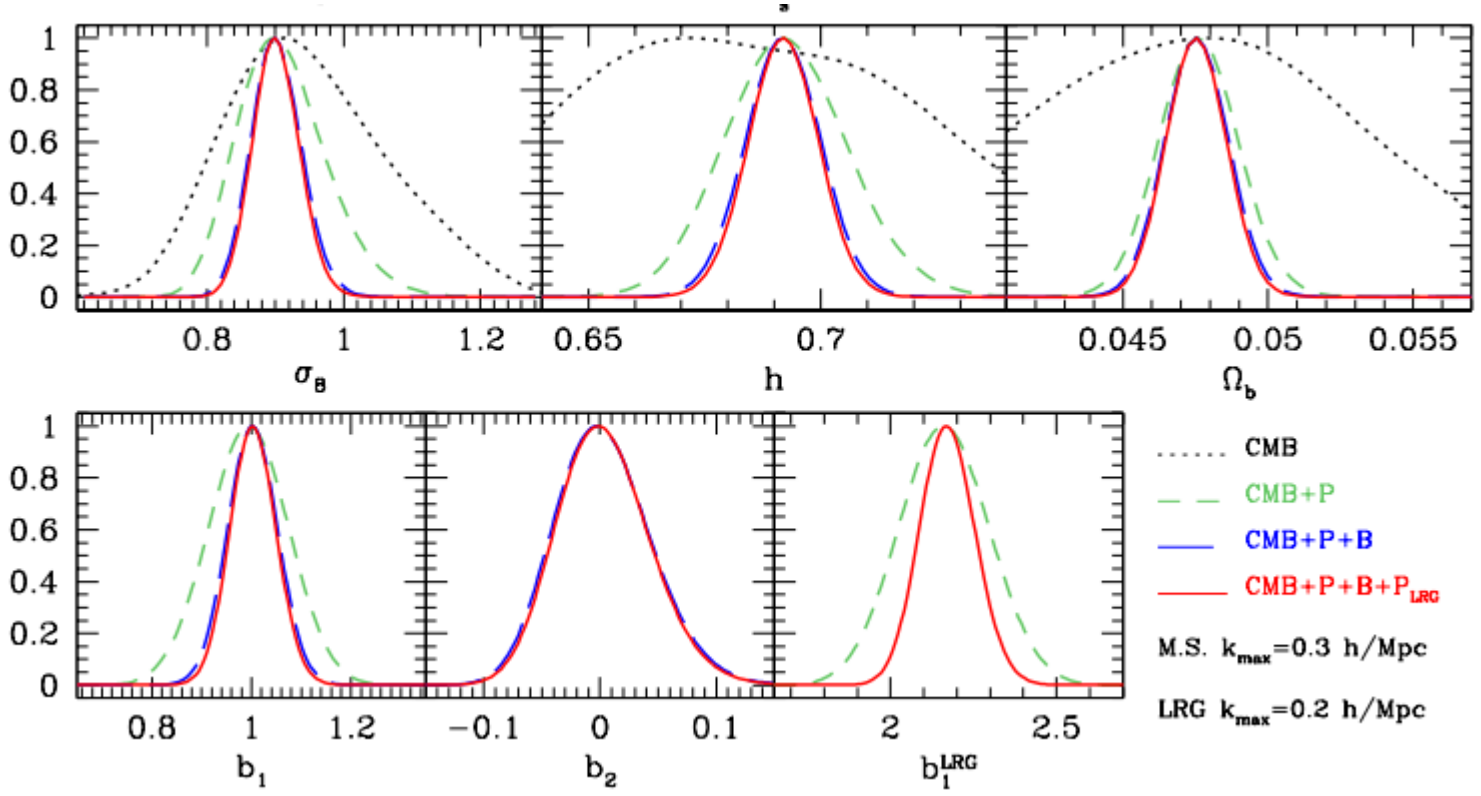
same 2-pt statistic
difference in the higher orders

Sefusatti & Scoccimarro (2005)

Why moving to higher orders?

- first significant order to detect non-Gaussian signals
- exploit additional information
- can probe both scale (as the 2PCF) and **shape (unlike the 2PCF)**
- in combination with the 2PCF **can break the degeneracy between bias and σ_8**
  => cosmological constraints
- improve constraints on parameters in combination with CMB and 2PCF



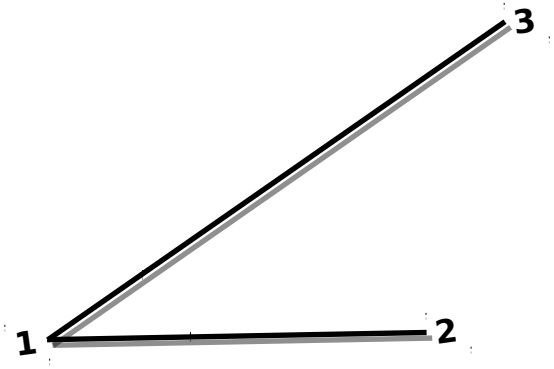


Sefusatti et al. (2006)

3-point functions: a (partial) review

Probability of finding triplets in configurations (3PCF) or Fourier space (bispectrum Bk)

$$P = \left[1 + \xi(r_{12}) + \xi(r_{23}) + \xi(r_{31}) + \zeta(r_{12}, r_{23}, r_{31})\right] \times \bar{n}^3 dV_1 dV_2 dV_3$$



Bispectrum

- estimators
  standard, skew, integrated, modal, … see Regan (2017)
- measurements on simulations
  e.g. PTHalos (Sefusatti et al. 2006), DeMNUNI (Ruggeri et al. 2017), DEUS-PUR (Chan&Blot, 2017), but many more...
- measurements on data
  CfA Redshift Survey (Baumgart&Fry, 1991), IRAS (Feldman et al., 2001, Scoccimarro et al., 2001), 2dFGRS (Verde el al., 2002), SDSS-LRGs (Gil-Marin et al. 2015a,b), SDSS-BOSS (Gil-Marin et al. 2016), but many more...
- modelization easier in Fourier space

3PCF

- estimators
  Szapudi & Szalay (1998), Slepian & Eisenstein (2015)
- measurements on simulations
  CODECS (Moresco et al. 2014), (DeMNUNI), DEUS-PUR (Hoffmann et al. 2018)
- measurements on data
  SDSS (Kayo et al., 2004, Nichol et al. 2006, McBride et al., 2011), 2dFGRS (Jing & Borner 2004,Pan & Szapudi 2005), SDSS-LRGs (Marin et a. 2011), SDSS-BOSS (Slepian et al. 2017), Wigglez (Marin et al. 2013), VIPERS (Moresco et al. 2016)
- modelization more difficult
  mixing of small- and large-scales modes

Much more mature and explored field

Many aspects still to be explored!

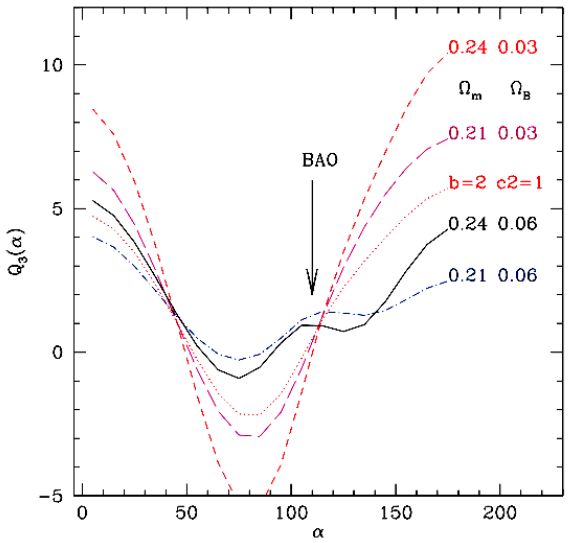
Status of the art

- dependence on **color, luminosity and stellar mass**
  e.g. Jing & Borner 2004, Kayo et al. 2004, McBride et al. 2011, Guo et al. 2014, Moresco et al. (2016)
- cosmology-independent measure of **galaxy bias**
  e.g. McBride et al. (2011), Marin et al. (2011), Marin et al. (2013)
- study **different estimators**
  e.g. Slepian & Eisenstein (2015a,b)

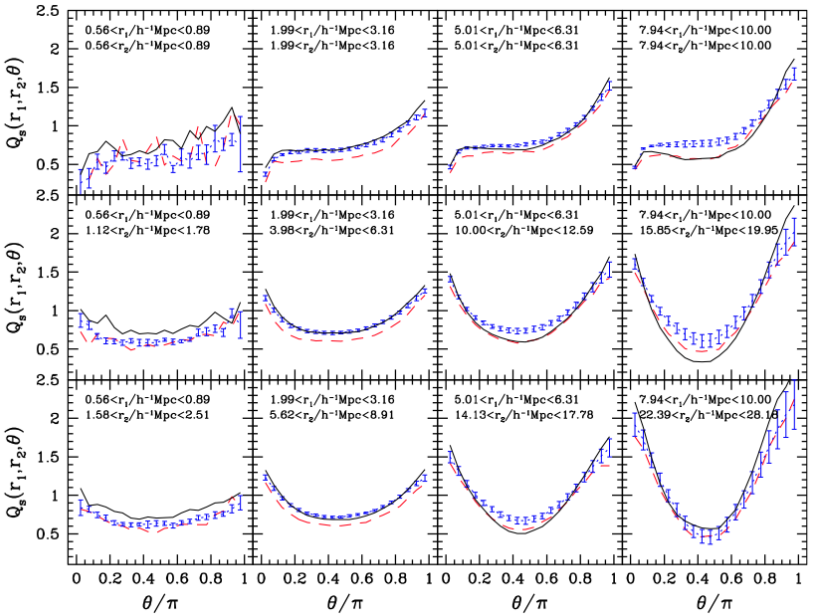
significant work on galaxy evolution

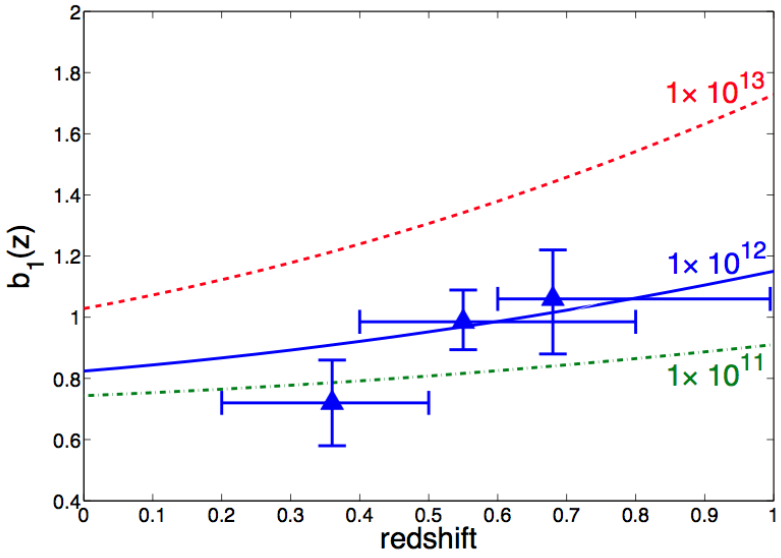
- disentangle **different cosmologies and neutrino masses**
  e.g. Moresco et al. (2014)
- **BAO detection**
  e.g. Gaztanaga et al. (2009), Slepian et al. (2016)

Gaztanaga et al. (2009)



Guo et al. (2014)





Marin et al. (2013)

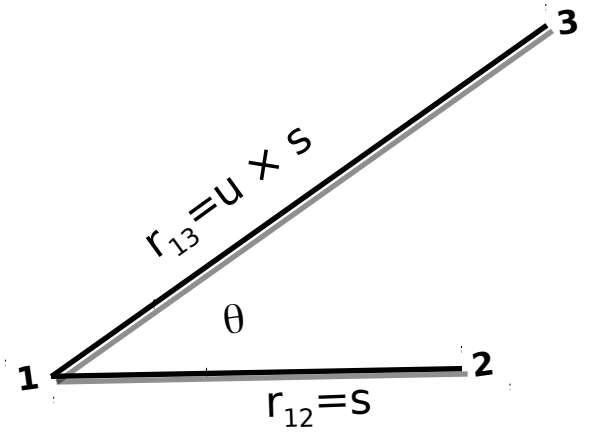
Definition and estimators

3PCF estimator
Szapudi & Szalay (1998)

$$\zeta = \frac{DDD - 3DDR + 3DRR - RRR}{RRR}$$

data catalog

random catalog



$r_{12} = s$
$r_{13} = u \times s$
$r_{23} = s \times (1 + u^2 - 2 \times u \times \cos\theta)^{1/2}$

binning $\Delta r_{ij}/r_{ij} = \text{cost}$

Marin et al. (2011)

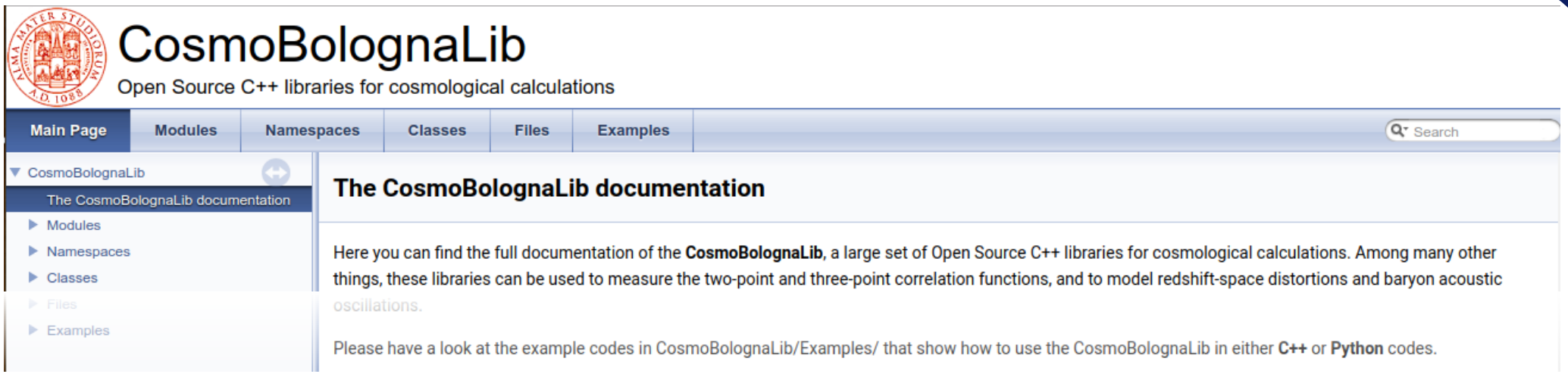
2PCF estimator
Landy & Szalay (1993)

$$\xi = \frac{DD - 2DR + RR}{RR}$$

connected 3PCF $\quad \zeta(r_{12}, r_{13}, \theta) \quad \propto b^3 \sigma_8^4$

reduced 3PCF $\quad Q(r_{12}, r_{13}, \theta) = \dfrac{\zeta(r_{12}, r_{13}, \theta)}{\xi(r_{12})\xi(r_{23}) + \xi(r_{23})\xi(r_{31}) + \xi(r_{31})\xi(r_{12})} \quad \propto b^{-1}$

The code: CosmoBolognaLib



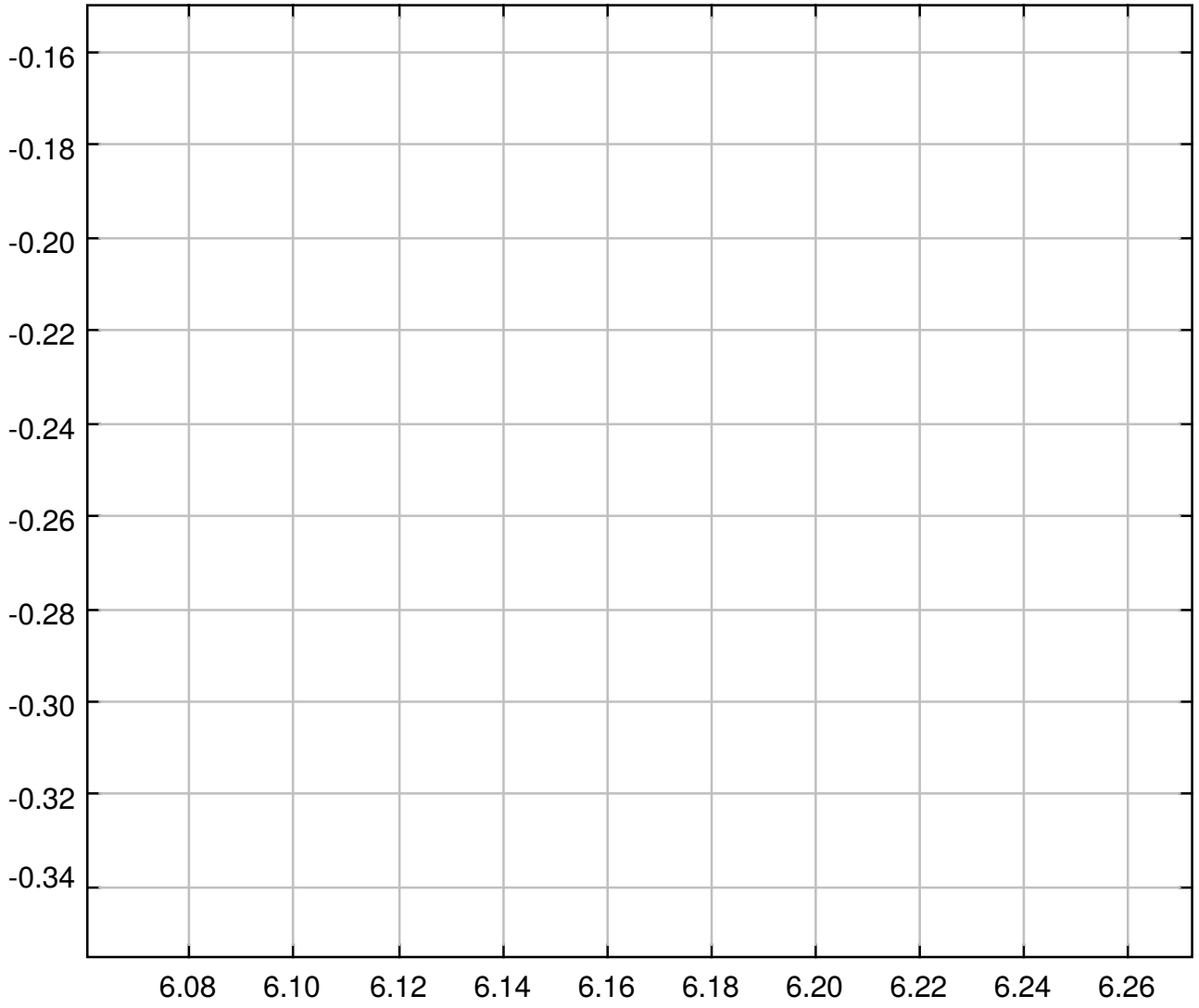
C++ and python libraries for cosmological calculation

Code. https://github.com/federicomarulli/CosmoBolognaLib
Doc. http://apps.difa.unibo.it/files/people/federico.marulli3/CosmoBolognaLib/Doc/html/index.html
Ref. Marulli, Veropalumbo & Moresco (2016, arXiv:1511.00012)

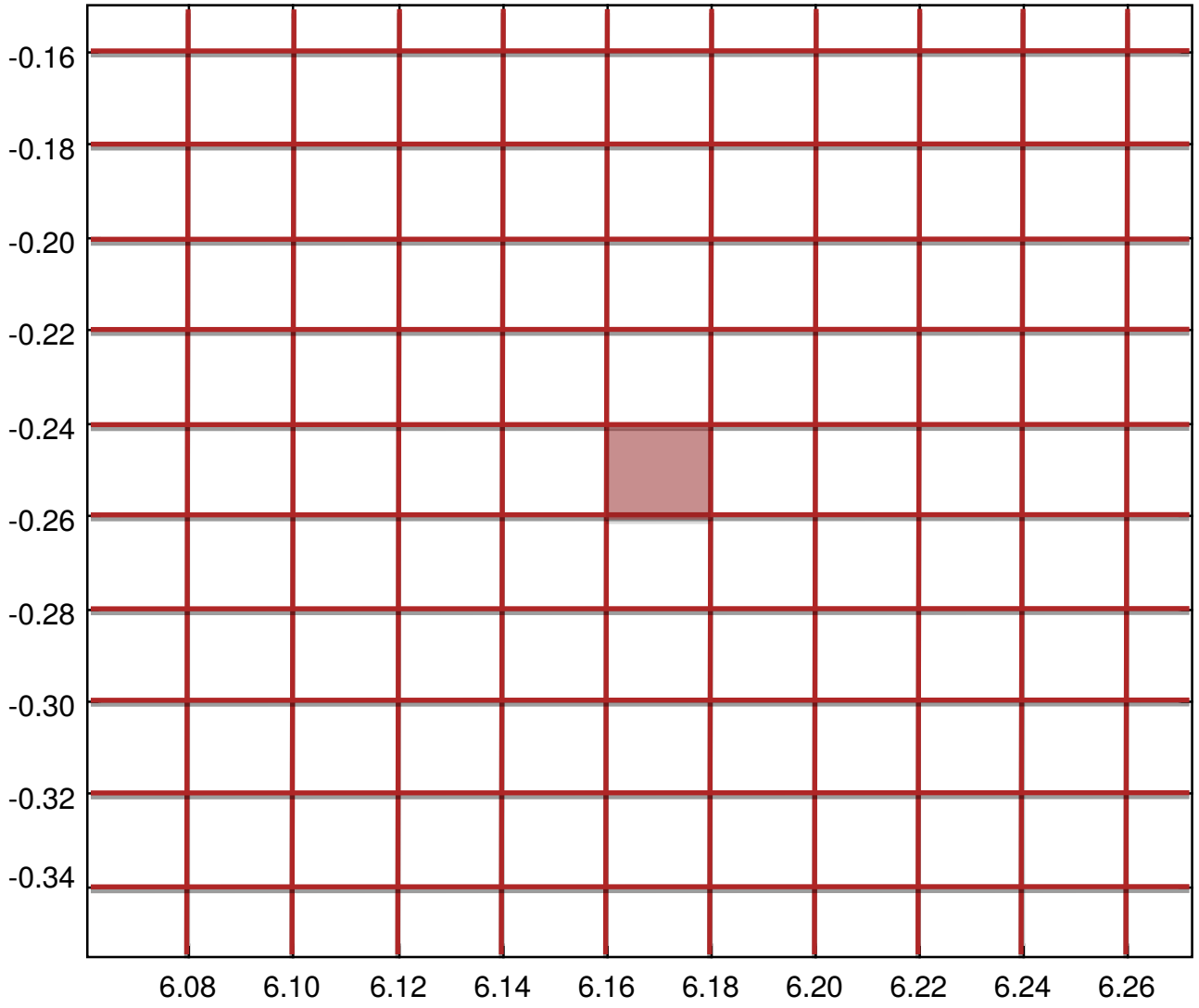
Extensive 2PCF measurements and modelling. For the 3PCF:

- measure the connected ζ and reduced 3PCF Q in different configurations
- implement a double chain-mesh technique
- binning as a function of θ or r
- errors with integrated JK and/or BS
- modelization of both ζ and Q
- MCMC adopting the stretch move ensemble sampler (Goodman & Weare, 2010)

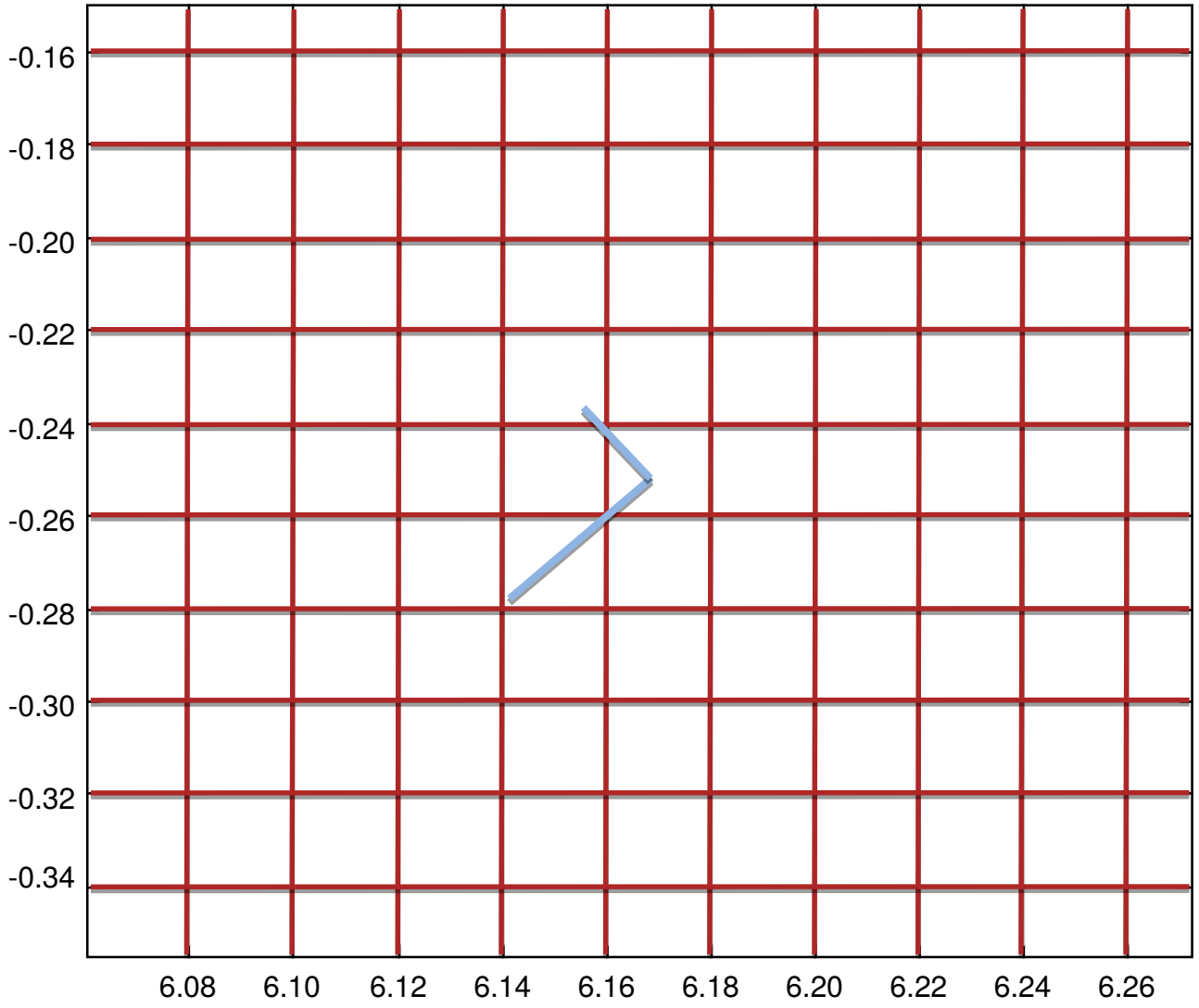
Chain-mesh approach



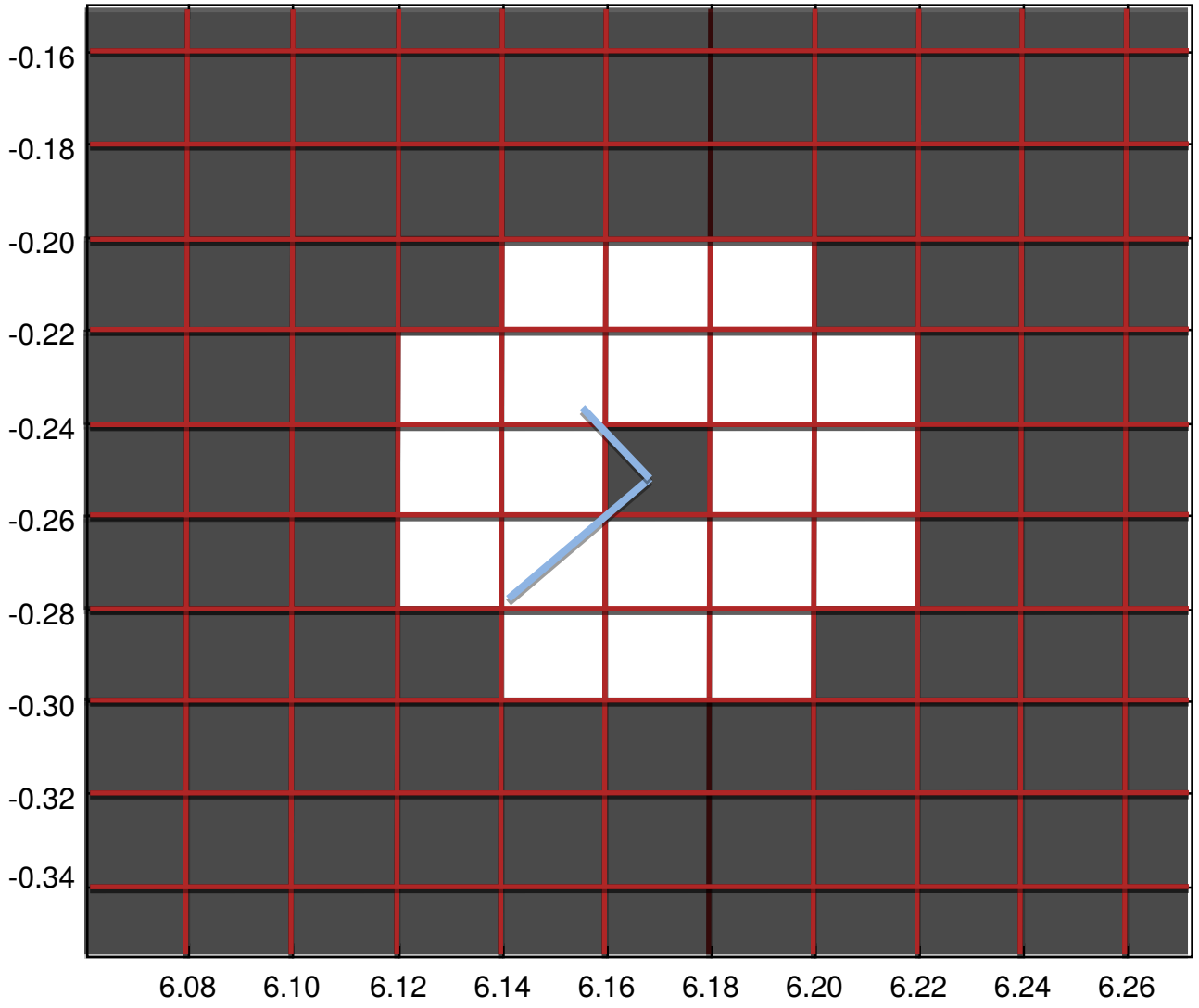
Chain-mesh approach



Chain-mesh approach



Chain-mesh approach



Some application of the 3PCF

Exploring 3PCF in simulations

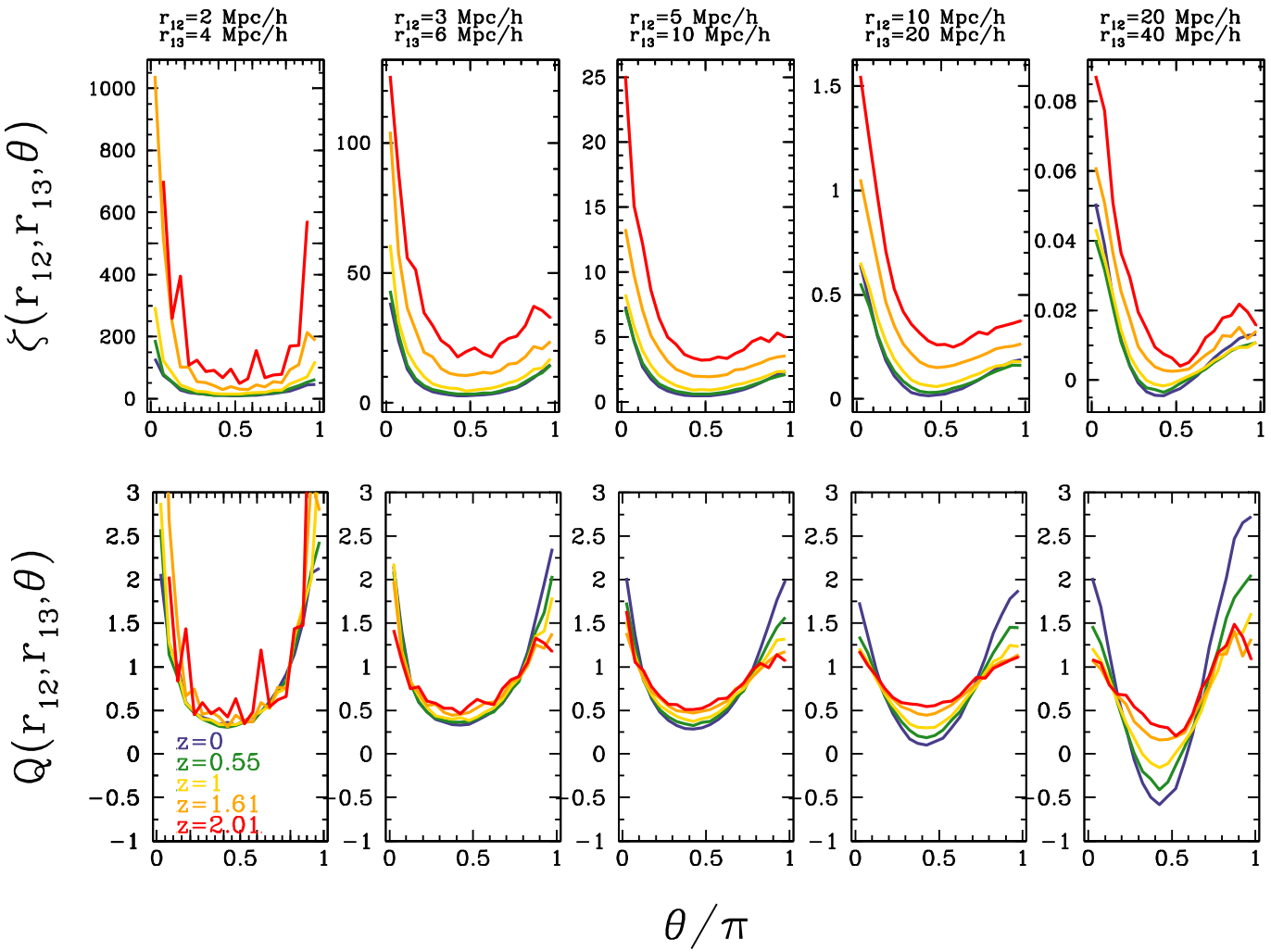
CODECS simulations
Baldi (2012)

5 cDE models + LCDM(WMAP7yr),
$N_p=2x1024^3$, $L_{box}=1$ Gpc/h,
$M_p=5.84x10^{10}$ M_{sun}/h

interacting dark energy cosmologies + LCDM

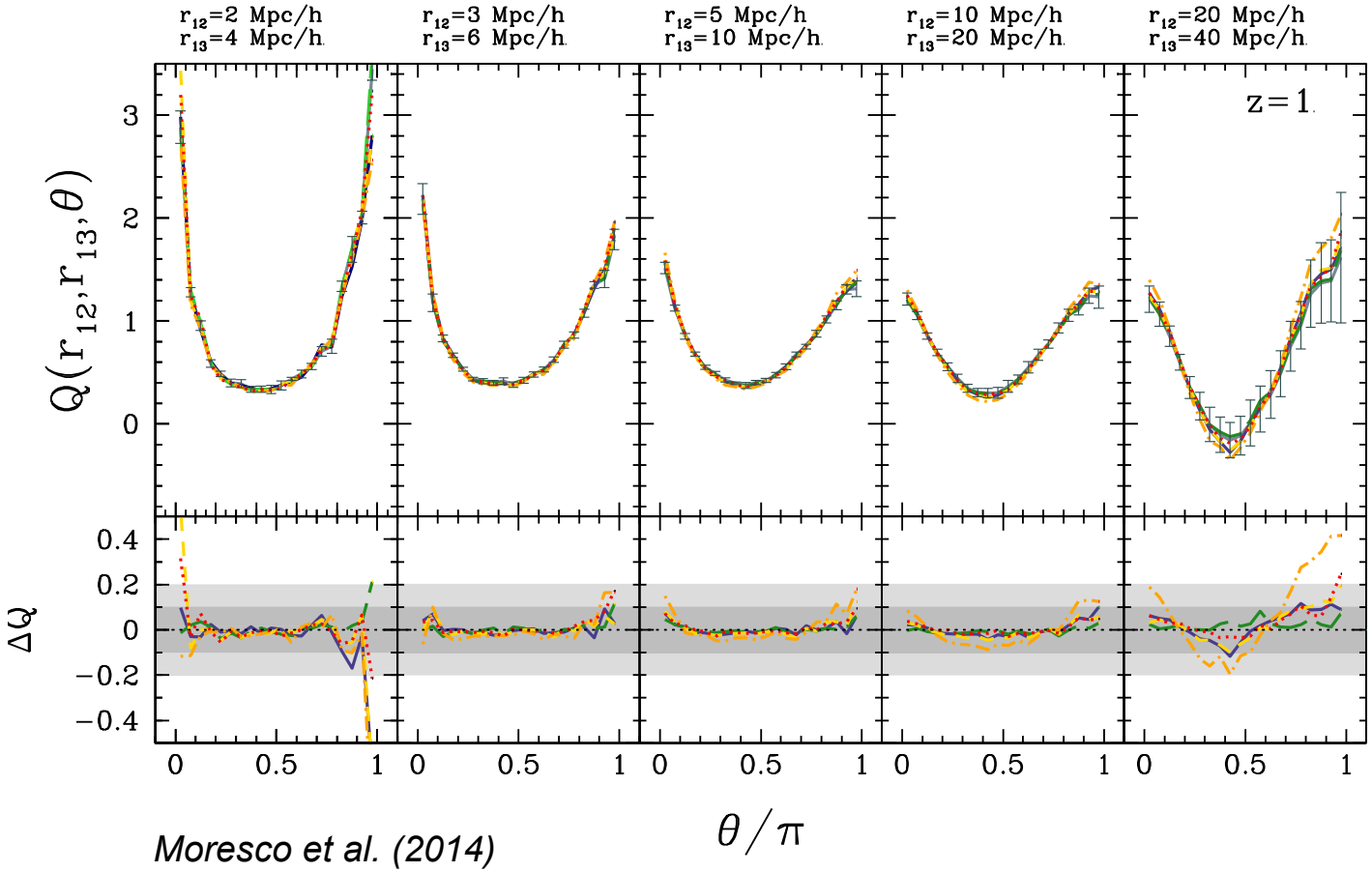
5 different redshifts analyzed
5 scales

- confirm the transition from the U-shape to V-shape
- witnessing the build-up filaments with redshift



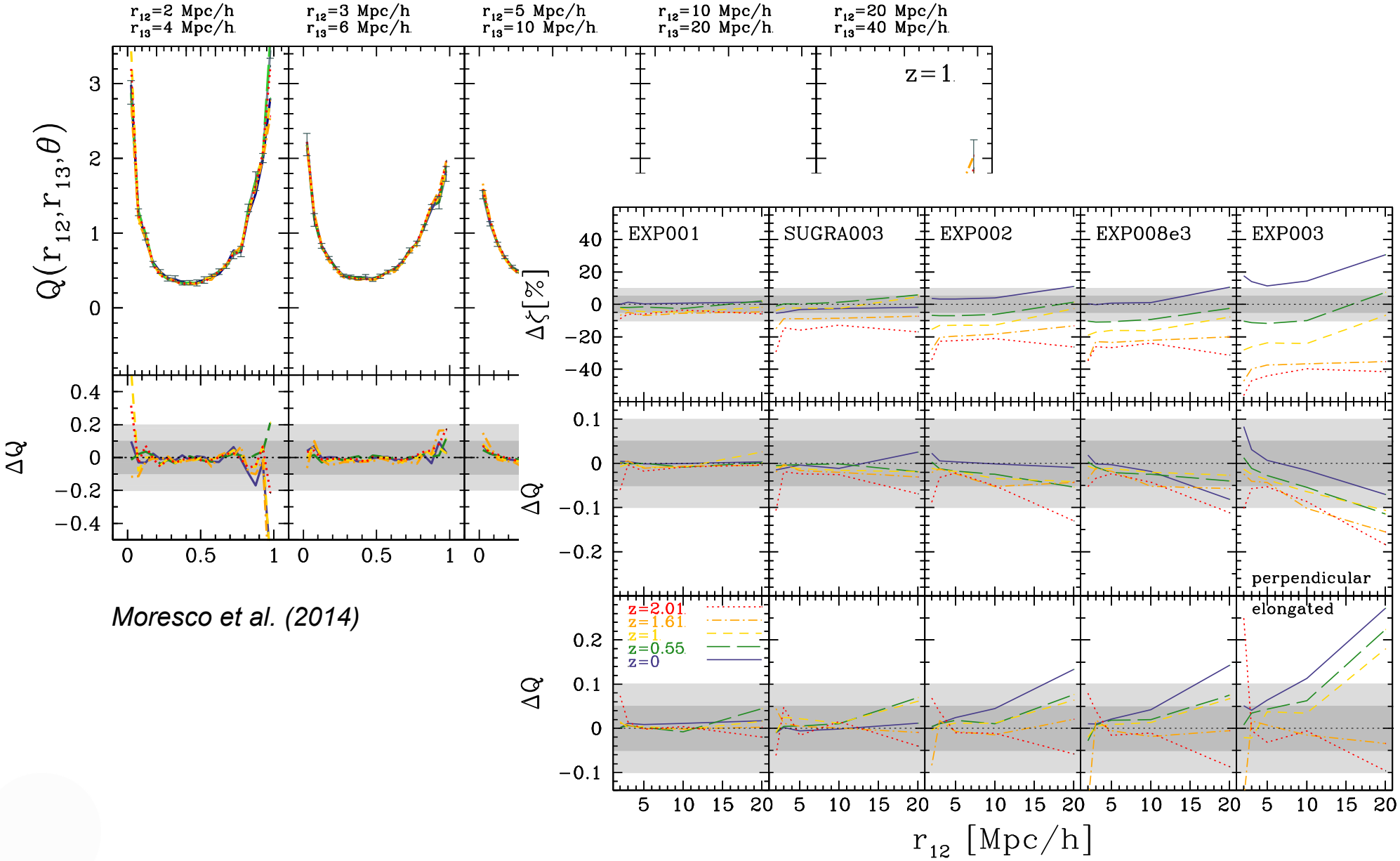
Moresco et al. (2014)

Disentangling ΛCDM with 3PCF



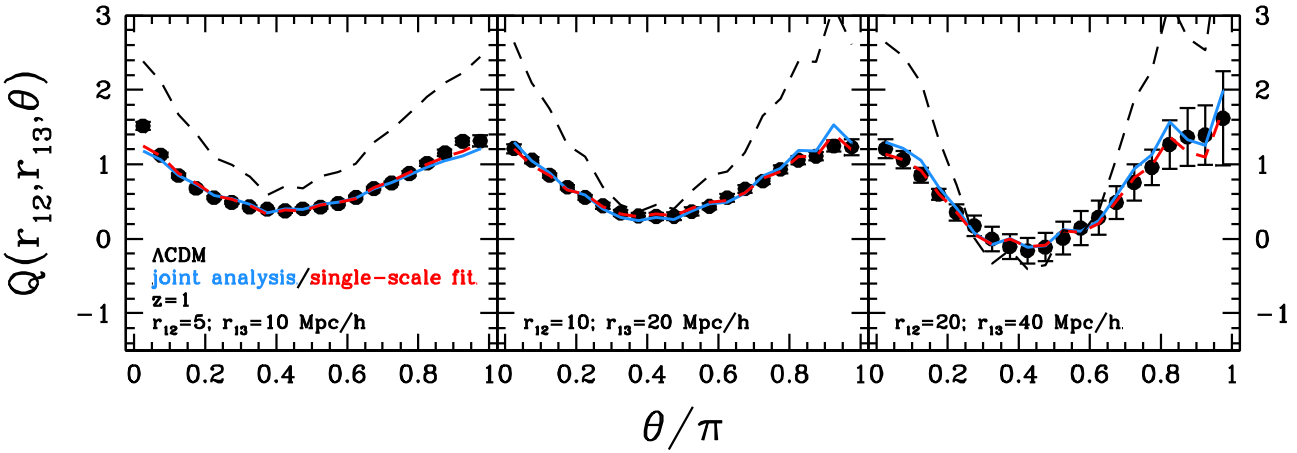
Moresco et al. (2014)

Disentangling ΛCDM with 3PCF



Moresco et al. (2014)

To the halo bias



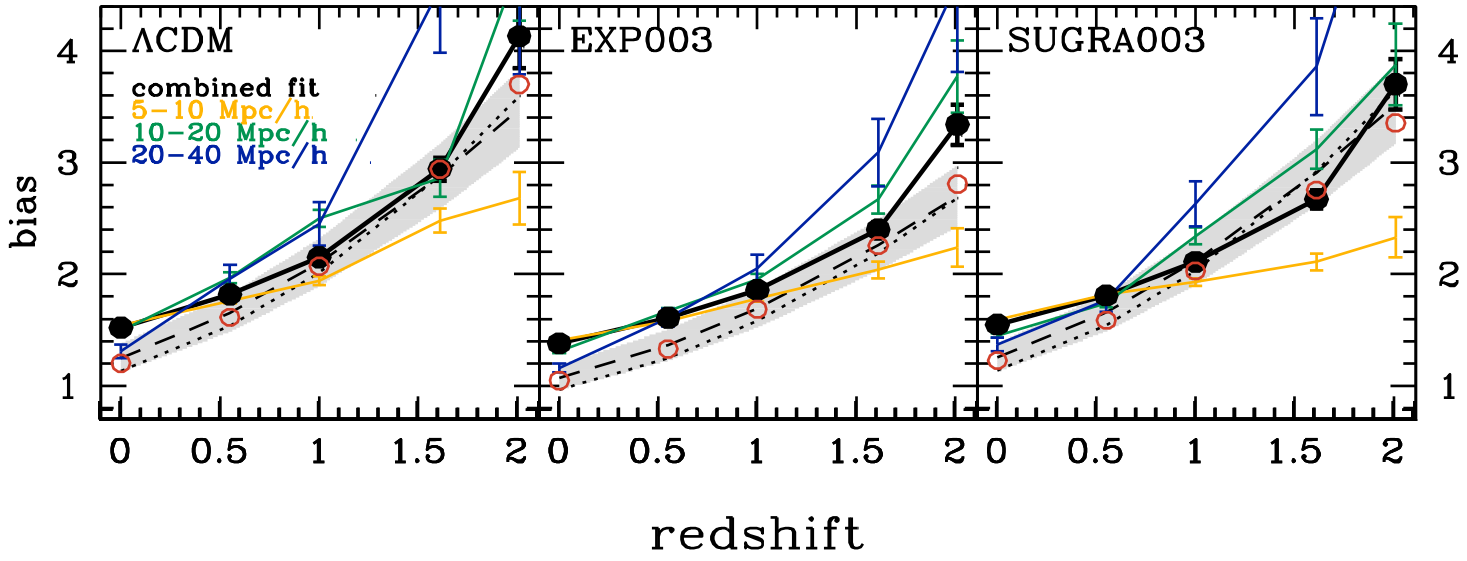
- possibility to use 3PCF to **discriminate** between standard and non-standard cosmologies
- **cosmology-independent** bias

N.B.

- To be included non-local bias term e.g. see Bel et al. (2015)

$$Q_h = \frac{1}{b_1}\left(Q_{dm} + \frac{b_2}{b_1}\right)$$

local bias model



A sneak peak on neutrino masses

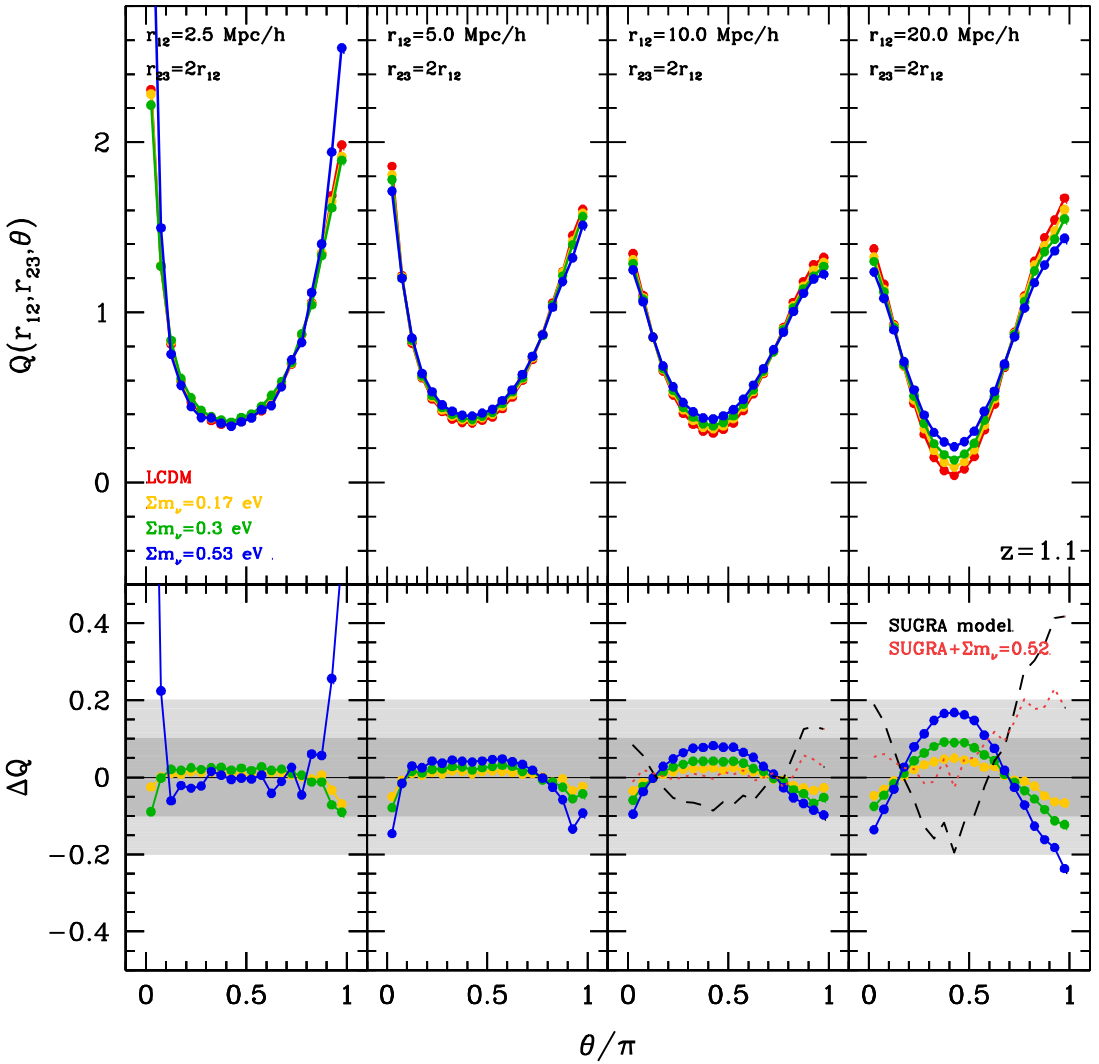
DEMNUNI simulations
Carbone et al. (2016)

3 neutrino masses + LCDM (Planck13)
N_p=2x2048^3 (nu included), L_{box}=2 Gpc/h
M_p= 8.27x10^{10} M_{sun}/h, 62 snaps with z_{in}=99

the largest cosmological simulation with massive neutrinos, suited for both galaxy clustering and lensing Euclid analysis

5 redshifts analyzed, 4 scales

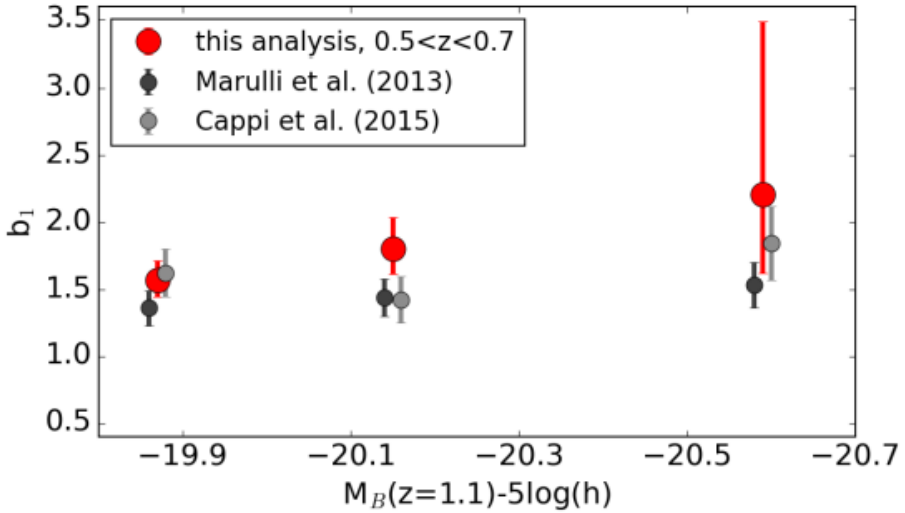
- first 3PCF with massive neutrino cosmologies
- using higher-order correlation functions to constrain neutrino masses

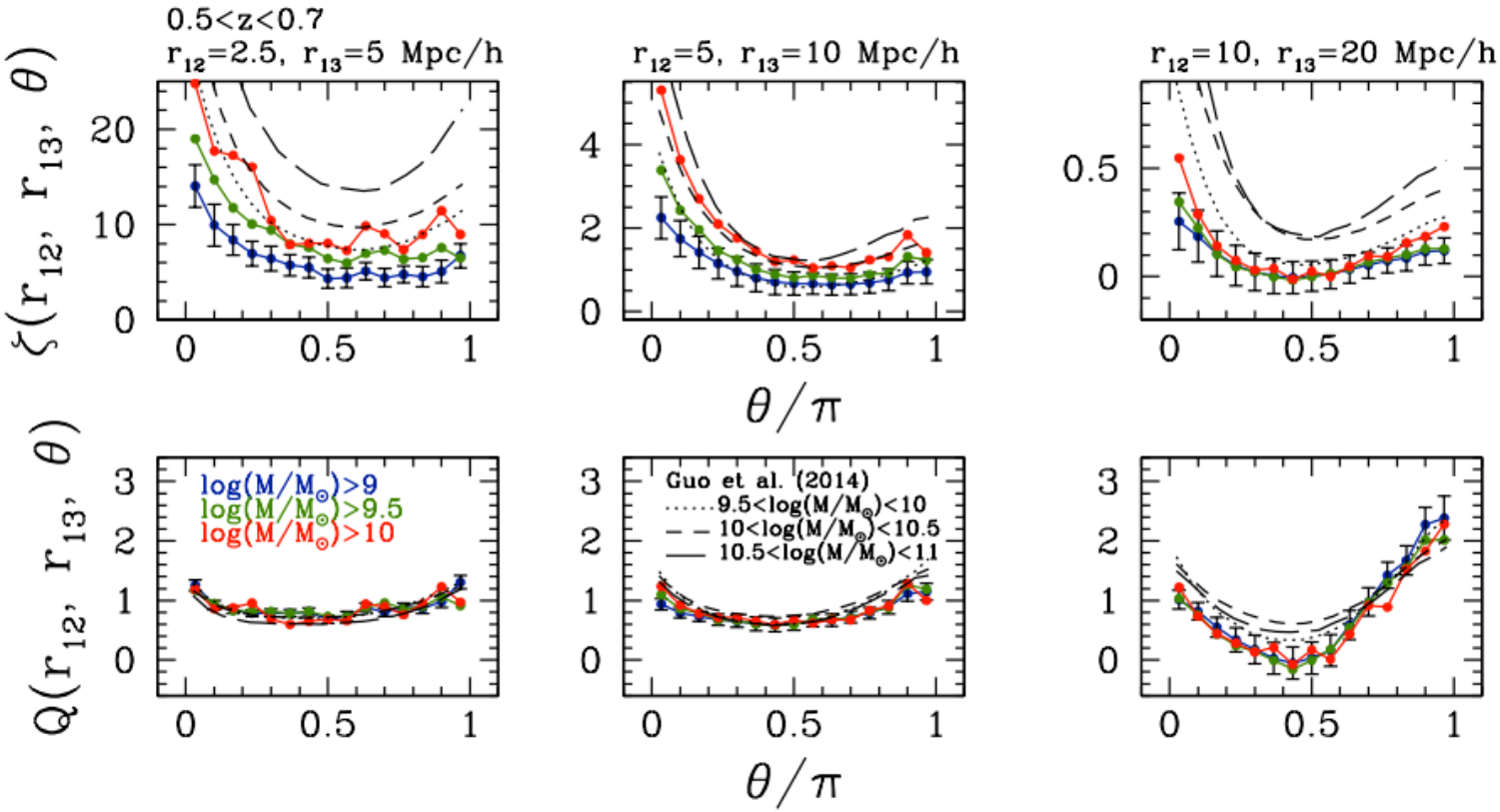


3PCF measurements in VIPERS

VIPERS survey
Guzzo et al. (2014)

spectroscopic survey of ~100000 galaxies at 0.5<z<1.1, 3 redshift bins, 5 magnitude bins and 4 stellar mass bins, 3 scales (r_{12}=2.5, 5, 10 Mpc/h)





Moresco et al. (2017)

BAO signal detection in the 3PCF of galaxy clusters

The BOSS cluster catalog

Original catalog from Wen et al. (2012)

132683 clusters from SDSS-DR8 photo. identified with FoF

$N_{200} > 8$, $M_{200} > 0.6 \times 10^{14} M_{sun}$

Cross-correlated with spec. info from SDSS-MGS, BOSS-LOWZ and BOSS-CMASS

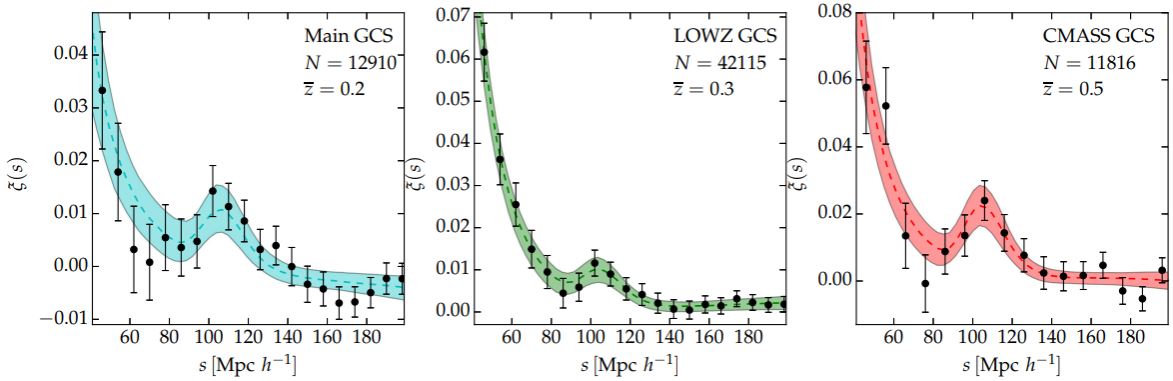
72563 clusters spec. identified (BCG)

<z> = 0.38

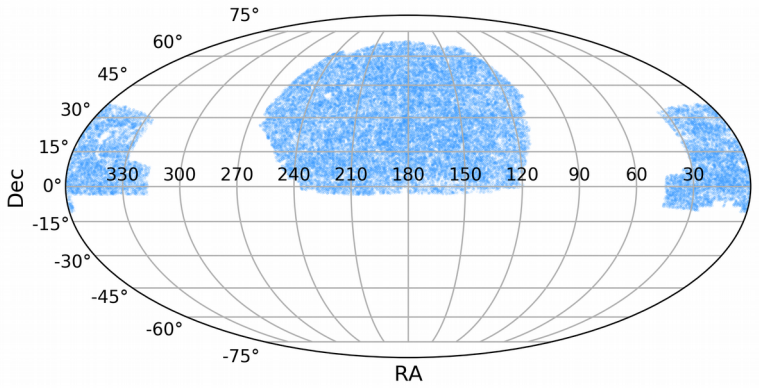
Smaller impact of non-linear distortions

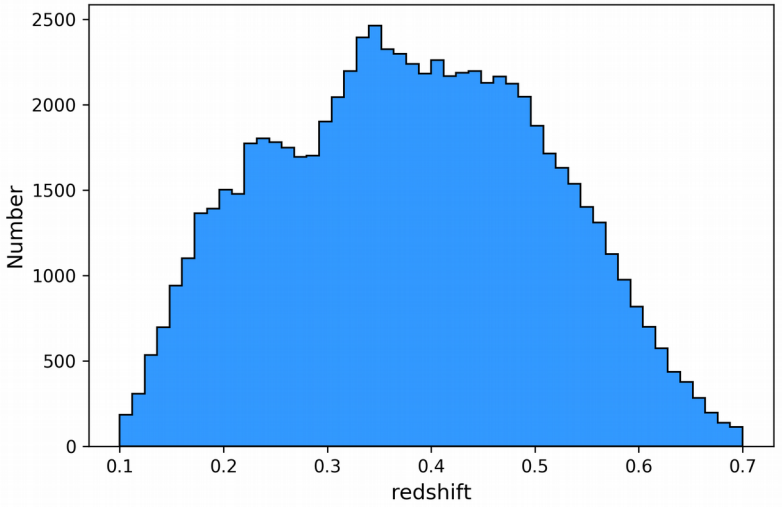
Neat detection of BAO peak in 2PCF

(Veropalumbo et al. 2016)



Veropalumbo et al. (2016)





Moresco et al. (in prep)

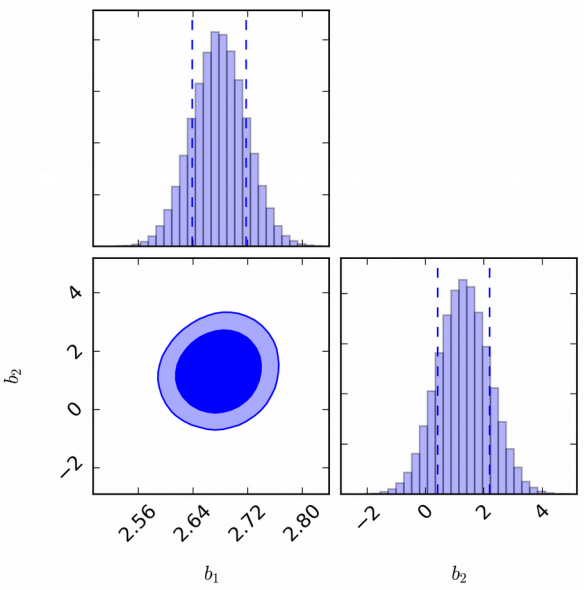
Constraining the bias parameter

- Measured connected and reduced 3PCF at different scales
- covariance matrix estimated with JK
- fit on Q (independent on σ_8)
- assumed a Gaussian prior on b_1 from 2PCF ($b_1 = 2.67 \pm 0.04$)

- local bias model: 1 free parameter (b_2)
- also test with non-local bias model

$$Q_g = \frac{1}{b_1}\left(Q_m + \frac{b_2}{b_1} + g_2 Q_{nl}\right)$$

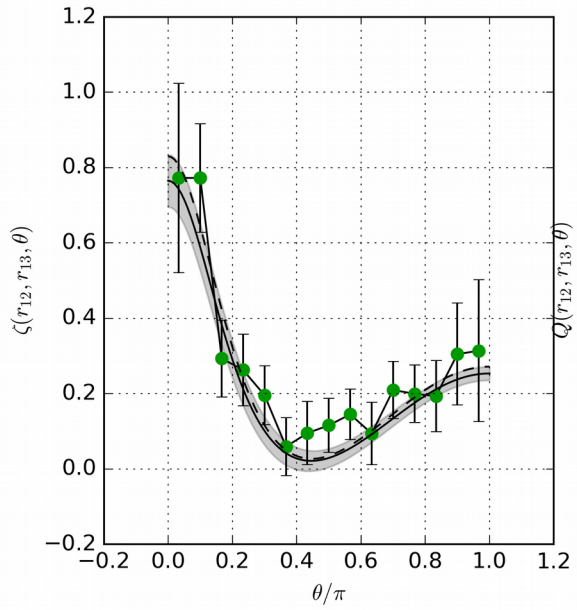
Bel et al. (2015)

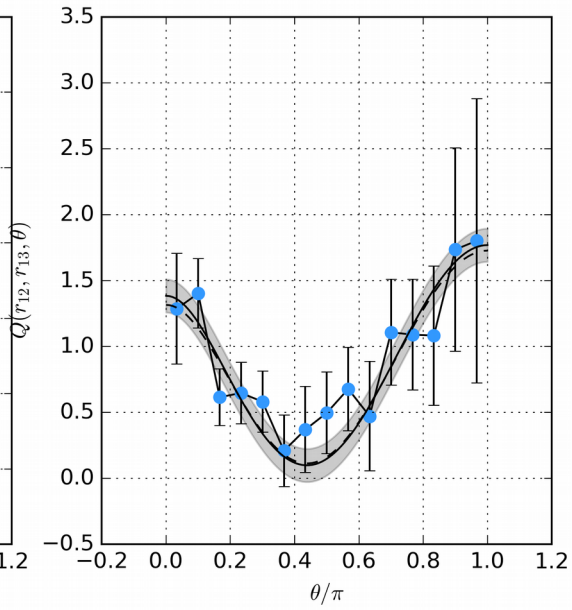


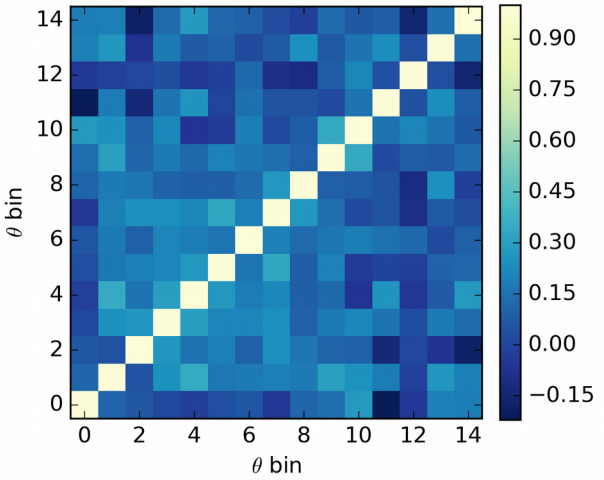
r_{13} probing scales [20-50] and [50-80] Mpc/h

$b_2 = 1.4 \pm 0.7$

Moresco et al. (in prep)







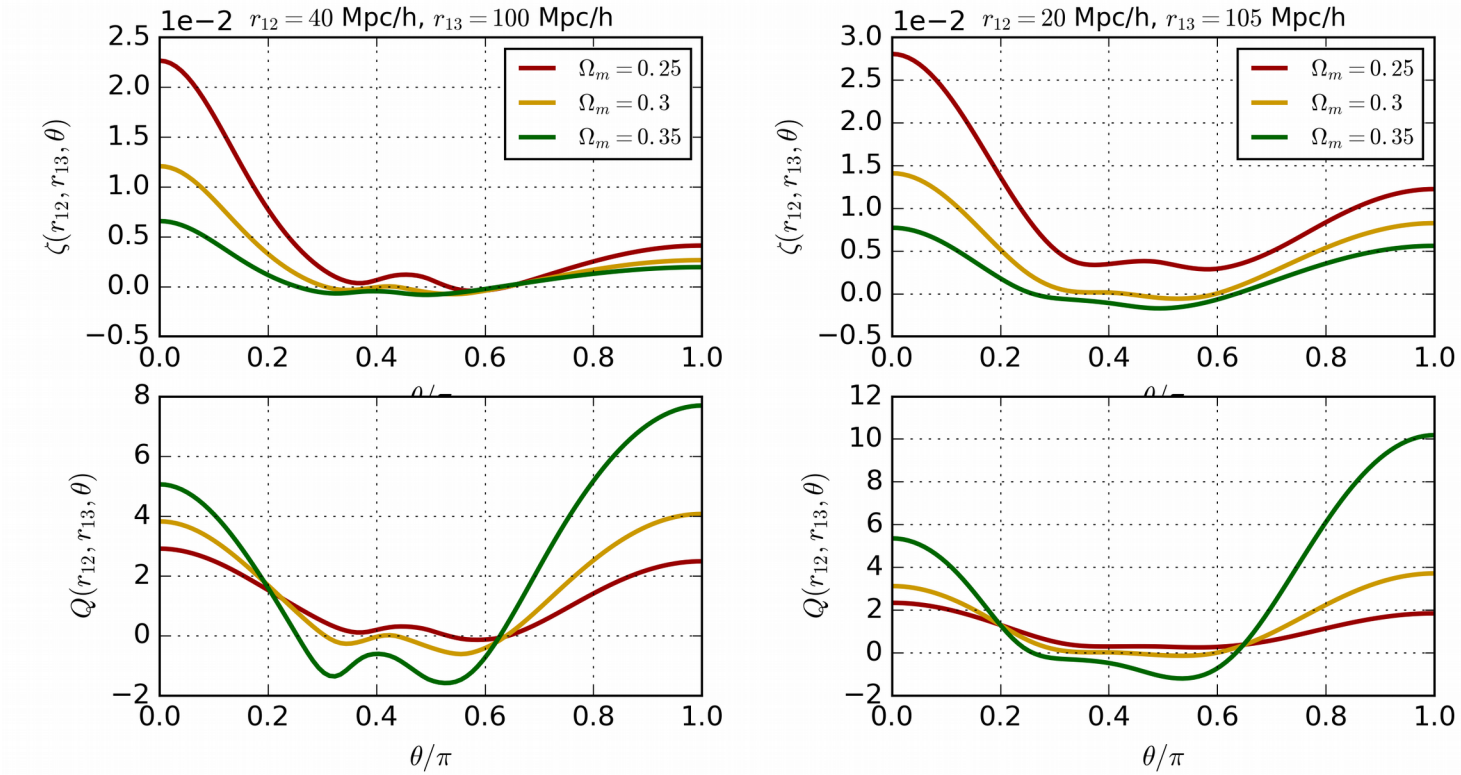
Detection of BAO peak 1/3

The BAO peak appear summed with the expected dip in the shape dependence of the 3PCF

smaller range of r_{23} ==> higher SNR ==> more dispersed signal (only a flattening)

larger range of r_{23} ==> lower SNR ==> more concentrated signal (but larger errors)

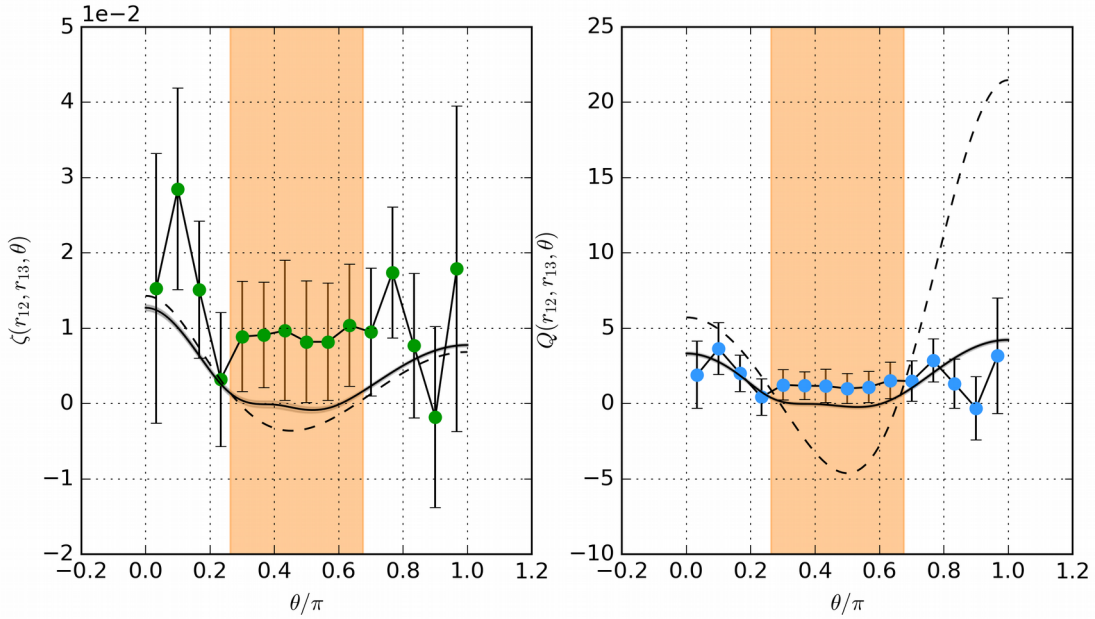
Different configurations explored for both cases, Q appears more sensitive



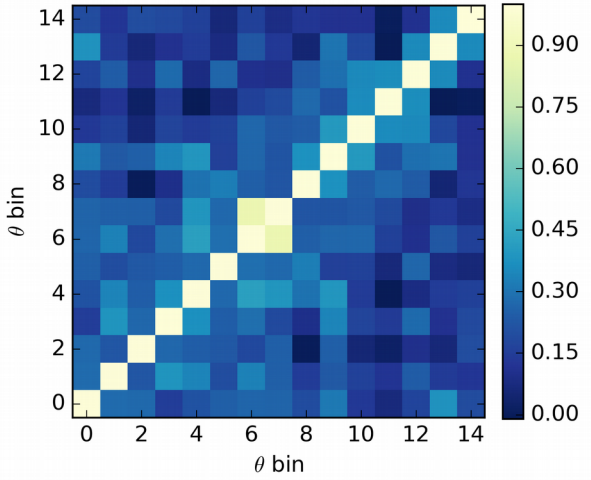
Moresco et al. (in prep)

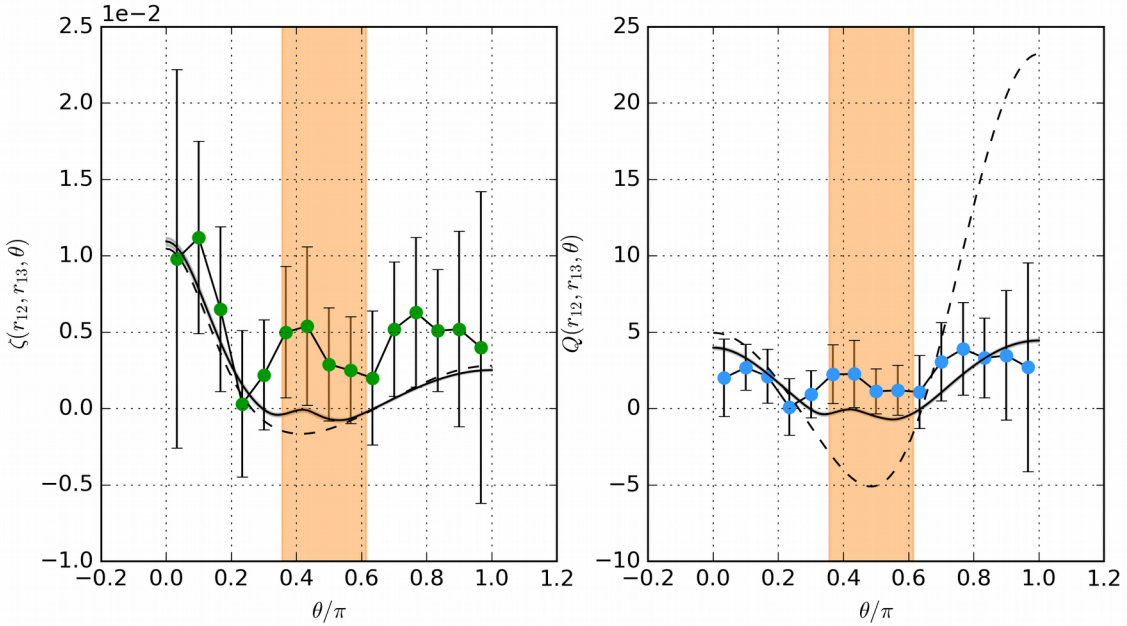
Detection of BAO peak 2/3

squeezing the BAO signal

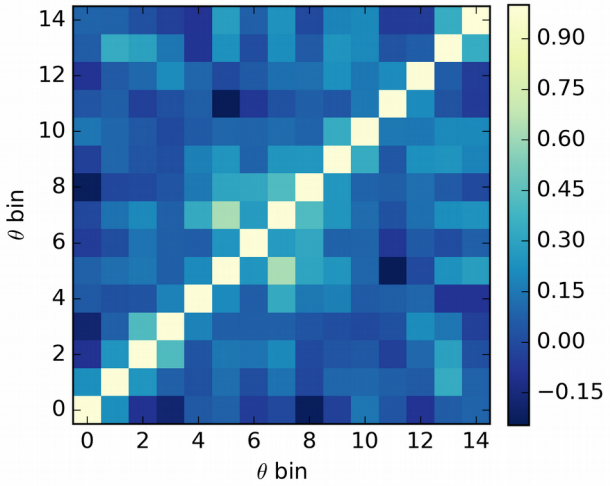


r_{12}=25, r_{23}=105, r_{13}=[80-130] Mpc/h





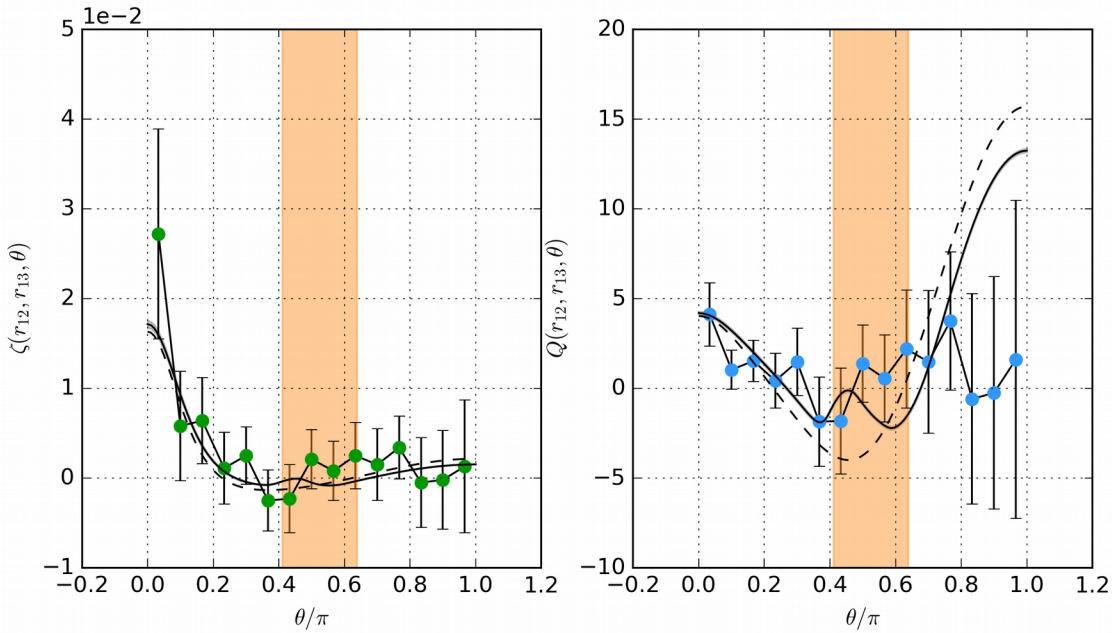
r_{12}=40, r_{23}=100, r_{13}=[60-140] Mpc/h



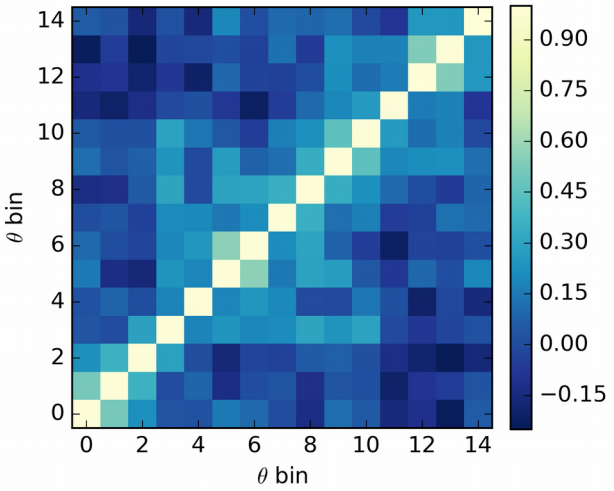
Moresco et al. (in prep)

Detection of BAO peak 3/3

squeezing the BAO signal



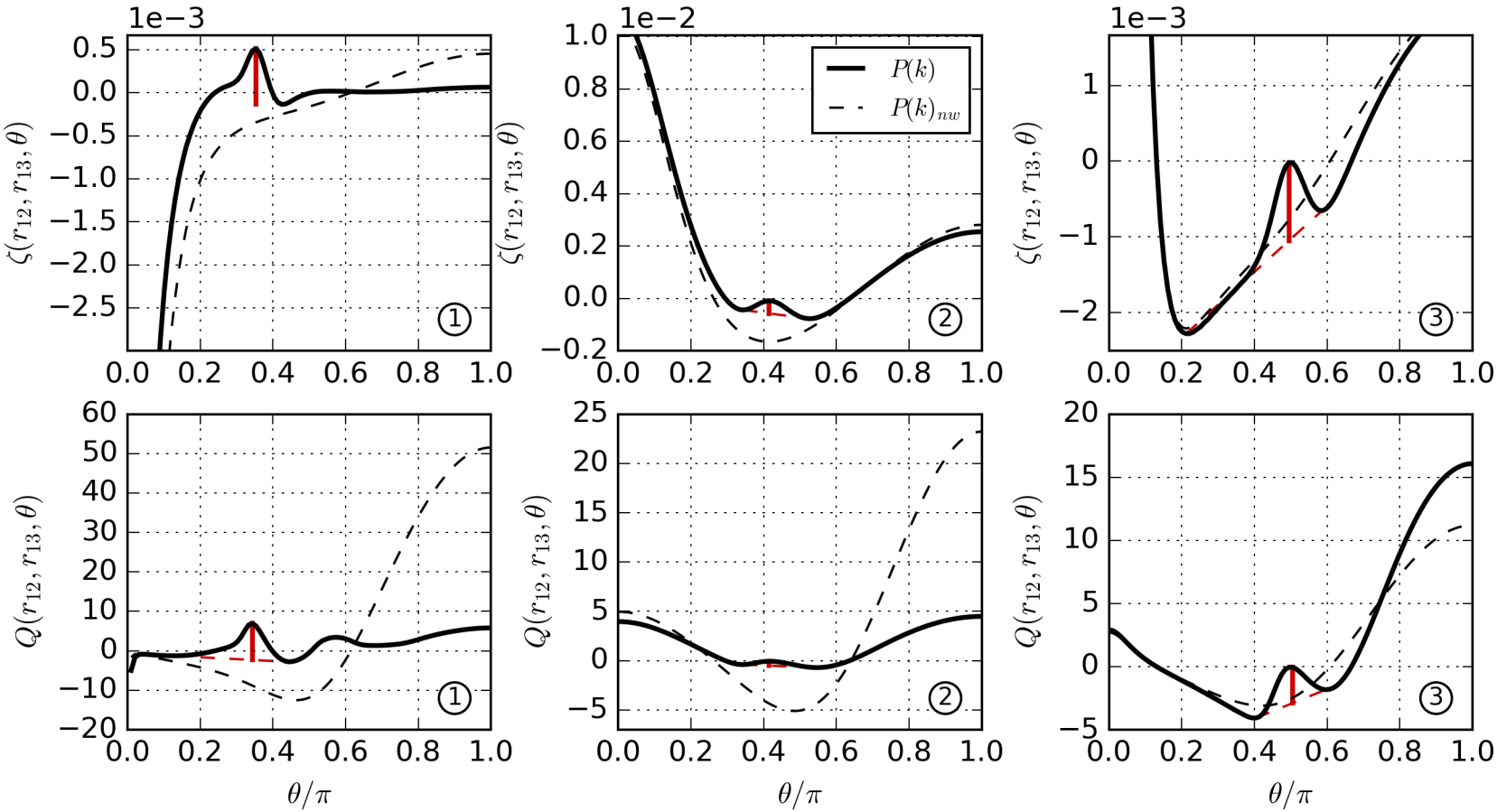
r_{12}=50, r_{23}=90, r_{13}=[40-140] Mpc/h



scales	$\Delta\chi^2$
r_{13}=[80-130] Mpc/h	90.5
r_{13}=[60-140] Mpc/h	39.4
r_{13}=[40-140] Mpc/h	3.9

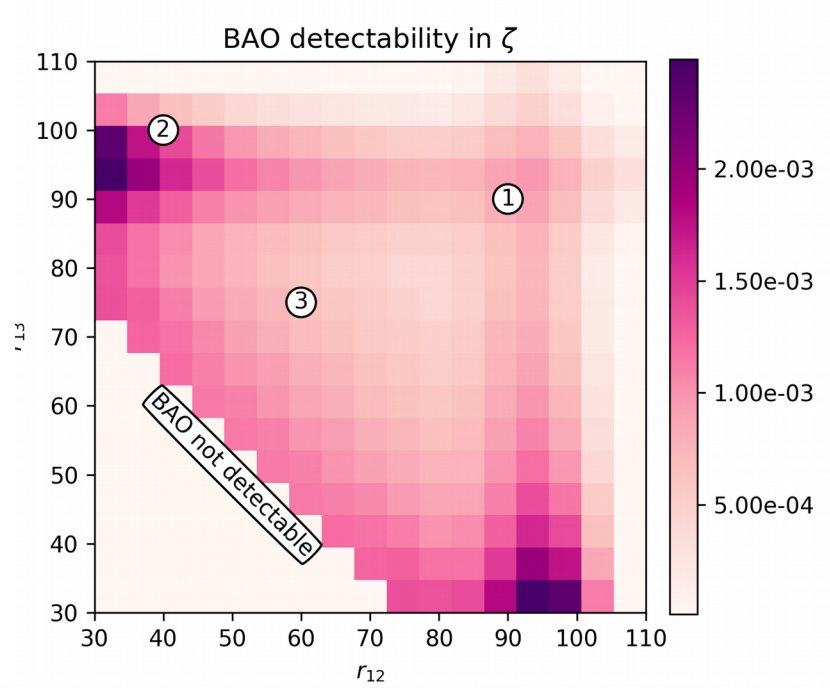
Moresco et al. (in prep)

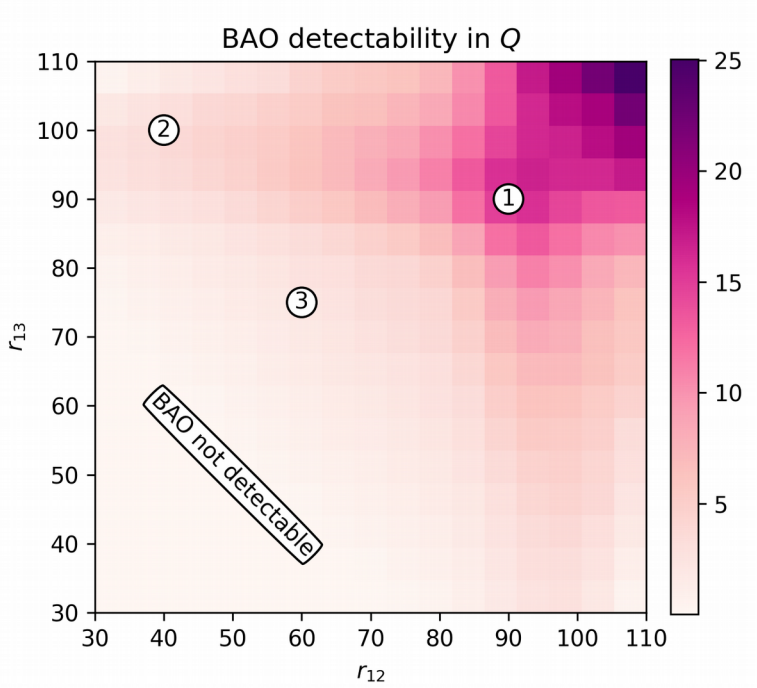
BAO detectability and SNR - definitions

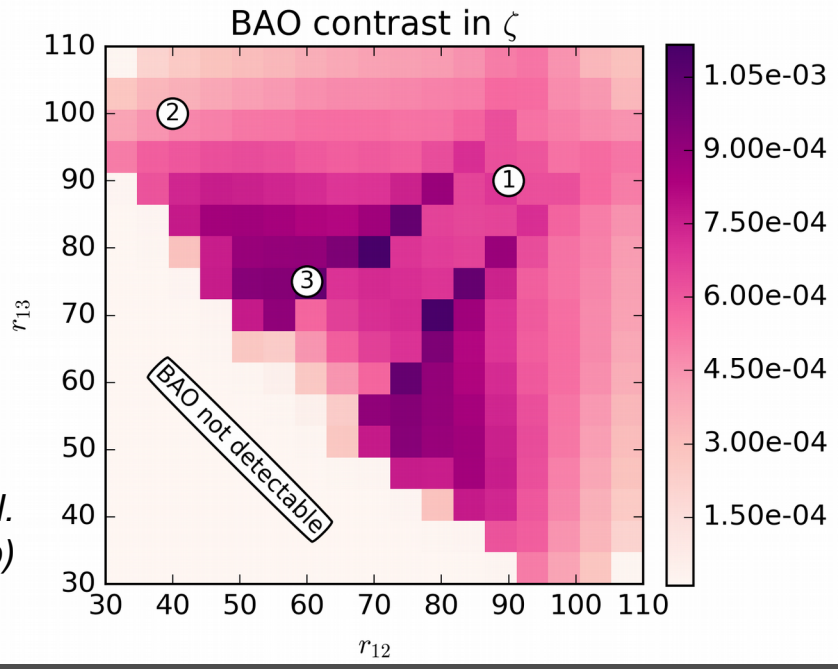


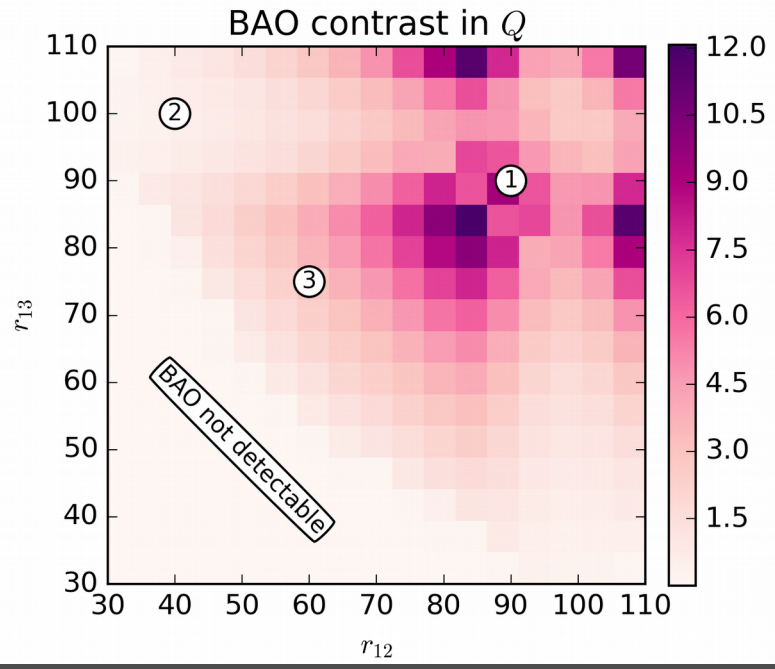
Moresco et al. (in prep)

BAO detectability



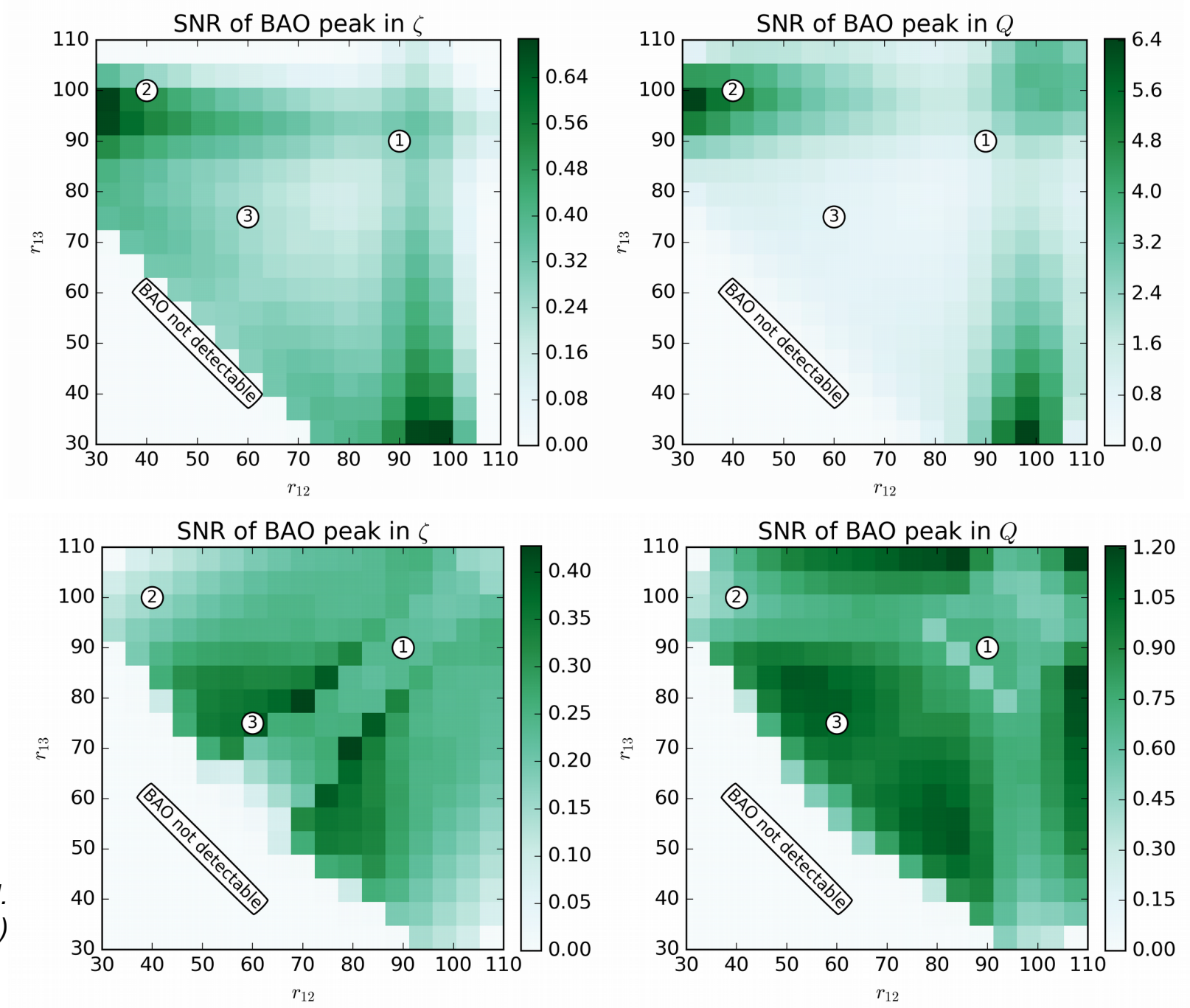






Moresco et al. (in prep)

BAO SNR



Moresco et al. (in prep)

Conclusions

- 3PCF measured at different scales on the largest (to date) SDSS cluster catalog

- On large scales (below BAO) obtained a measurement of non-linear bias
  $b_2 = 1.4 \pm 0.7$

- BAO may impact on 3PCF in different ways (squeezed/not squeezed, more peaked/flatter)

- significant detection of BAO signature in the 3PCF

- setup of a framework to identify the BAO signal in the 3PCF (both connected and reduced) with different approaches (BAO vs no BAO/BAO contrast)

- framework applicable to Euclid science case