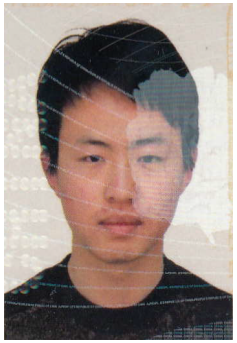
BAO and cosmic voids



LIANG Yu

APC
7 Janvier 2016
Charling Tao
CPPM, France
and THCA, Tsinghua U.

ZHAO Cheng

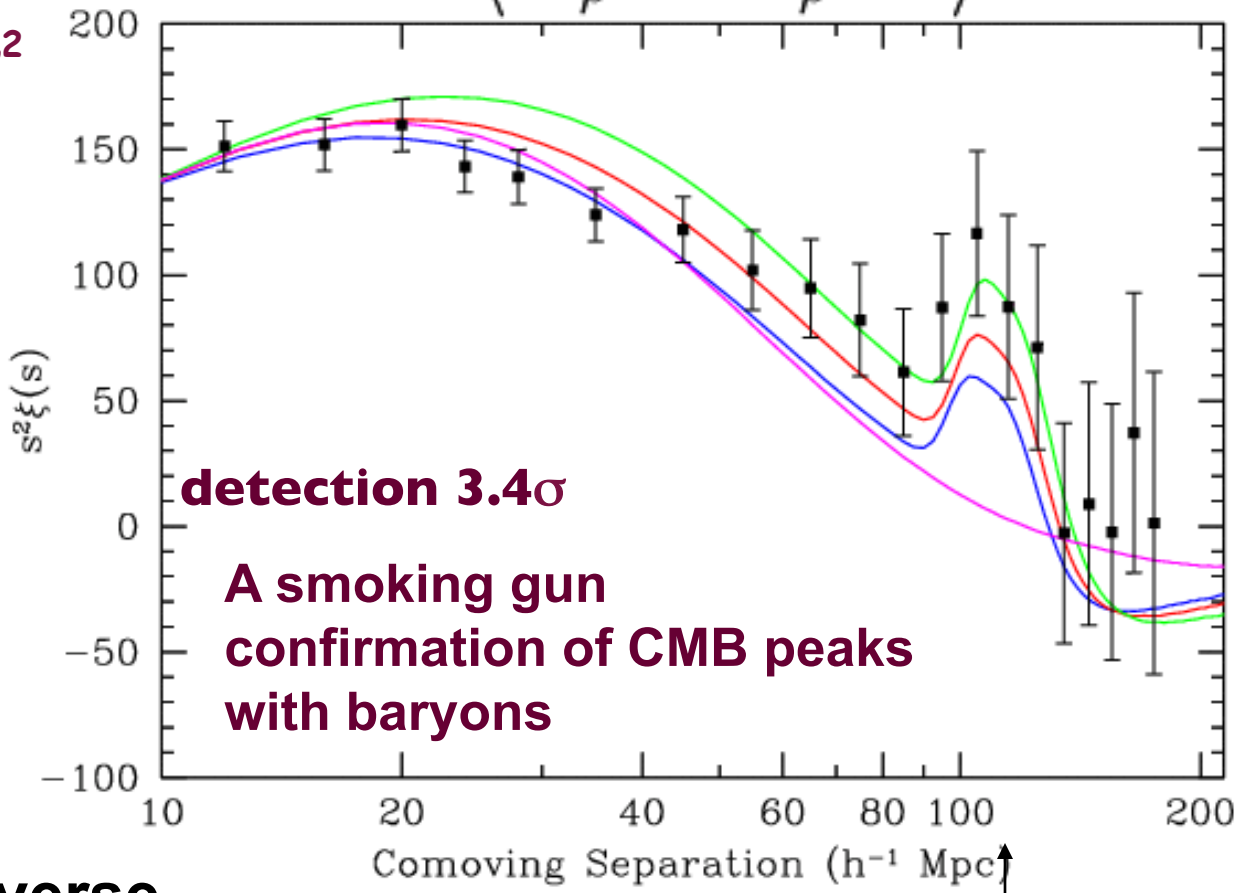
+ Postdocs : Francisco-Shu KITAURA, Albert Chia-Hsun CHUANG (Berlin)

10 years ago

Baryon Acoustic Oscillations : SDSS Luminous Red Galaxies Correlations

Eisenstein et al. 2005
46,700 LRGs 3816 deg^2
0.16<z<0.47
0.72h^{-3}Gpc^3

$$\xi(r) = \left\langle \frac{\delta\rho(\mathbf{x}_0)}{\rho} \frac{\delta\rho(\mathbf{x}_0+\mathbf{r})}{\rho} \right\rangle$$



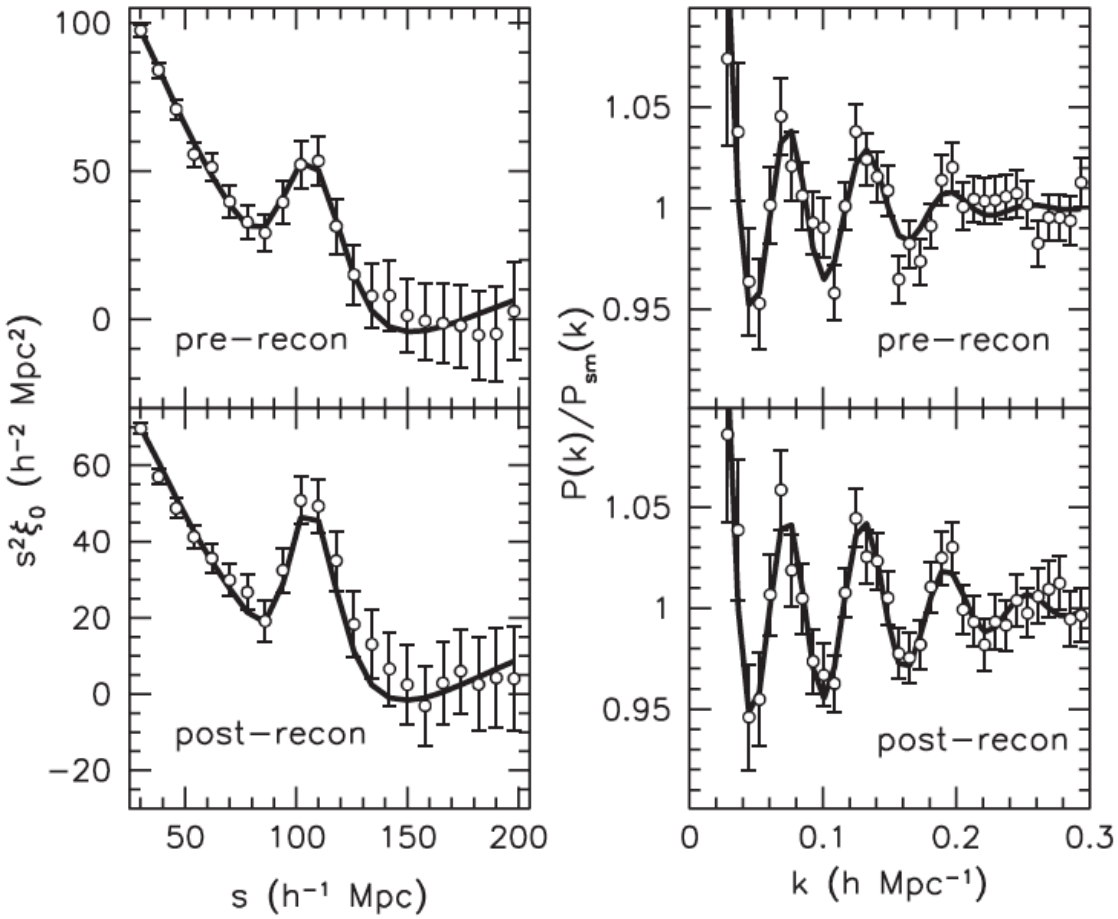
Hypothesis: flat Universe

$$\lambda_s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a+a_{eq})^{1/2}} da \quad = 150 \text{ Mpc}$$

Precise Determination
Ω_M

BAO Correlation functions and Power spectra of SDSSIII-BOSS (DR11- soon DR12) with LRG: 2015 status

Anderson et al. 2014



With LRG, reconstruction needed to recover more linear correlation!

>7σ effect

➔ **Best combinational Probe today for DE (with CMB) > SNIa**

BAO observations

- SDSS Quasars / Lyman alpha ➔ High redshift information
- Clusters Hong Tao et al. arxiv 1511.00392 BAO with SDSS BOSS DR12 clusters 3.9 sigma

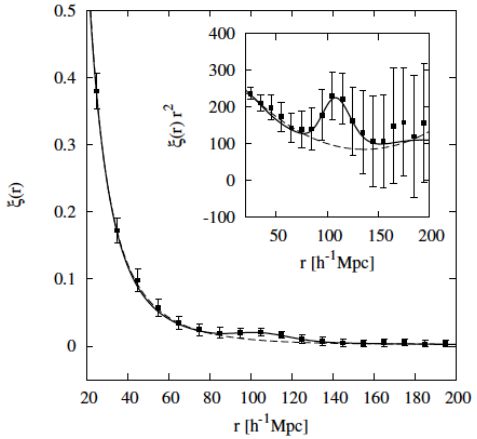


FIG. 4.— Correlation function of 79,091 clusters plotted by black squares with error bars. The solid line and dashed line indicate the best-fit ΛCDM model with and without acoustic feature. In the inset $\xi(r)r^2$ is plotted to show the BAO feature more clearly.

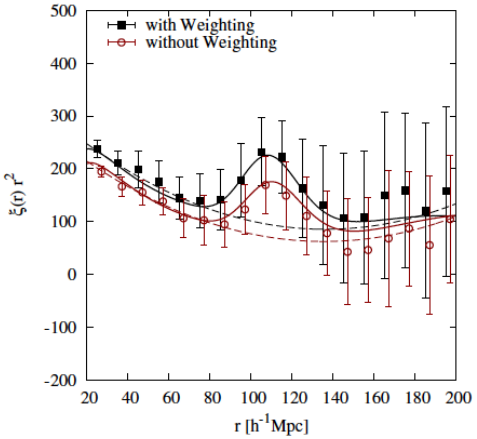


FIG. 5.— The correlation functions of the whole sample with (squares) and without (circles, shifted to right by 2 h^{-1}Mpc for clarity) weights during the calculations. The solid line is the best-fit ΛCDM model curve with acoustic feature, the dashed lines show the best-fit model curve without acoustic feature.

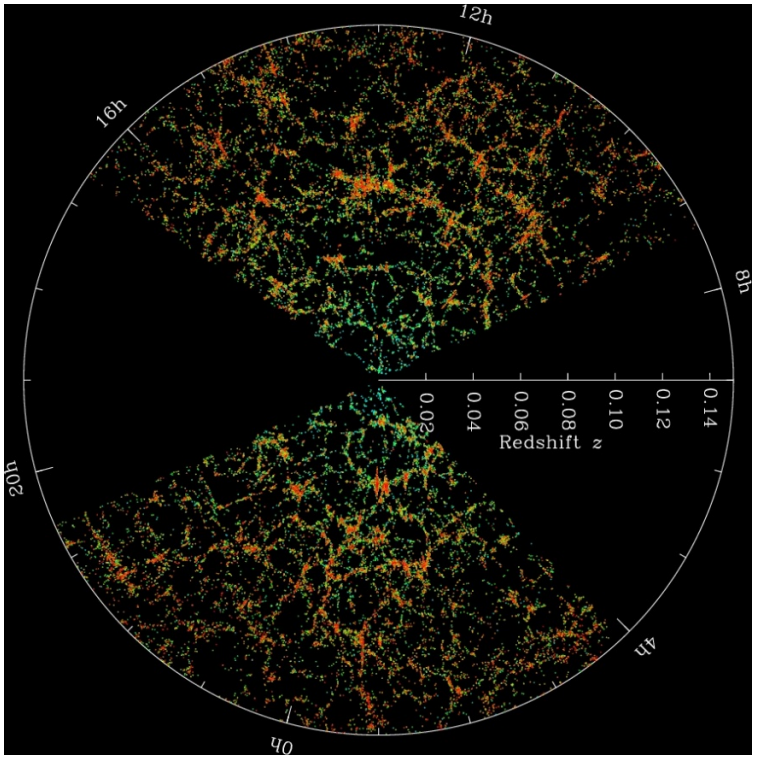
- What about voids?

BAO with Voids?

- What are voids? Empty or low density regions in the Cosmic Web !

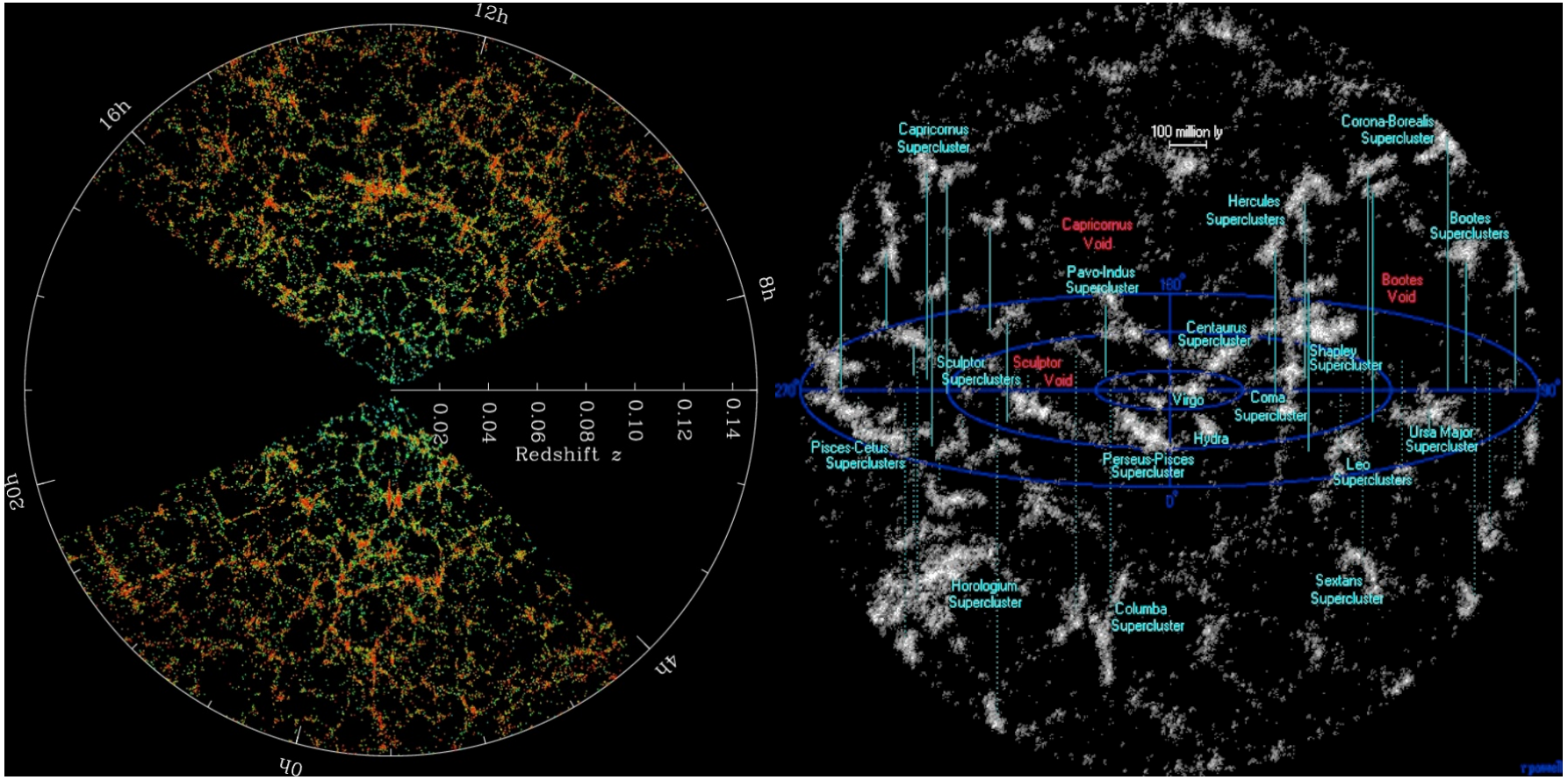
- Interesting : less gravity effects

- Less non-linear?
- More sensitive to alternative gravity?



Data in redshift space from sdss3.org

Cosmic Web: Knots, Filaments, Sheets and Voids

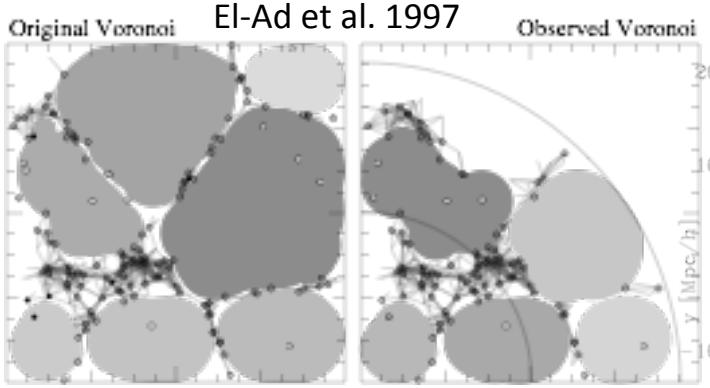


Data in redshift space from sdss3.org

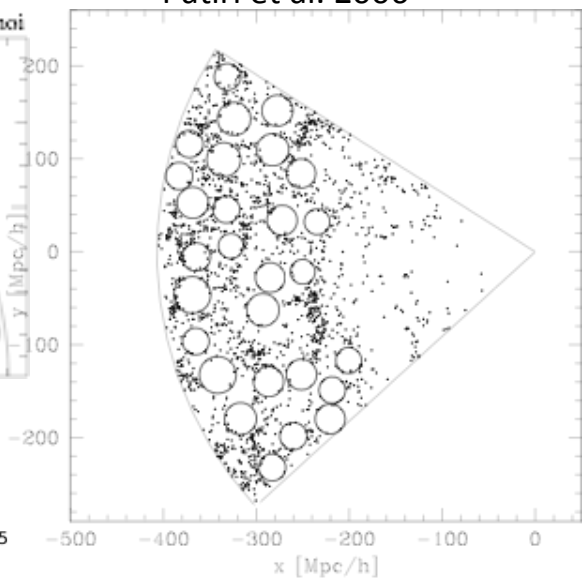
Data in real space from 6dF

Void finders: Many definitions!

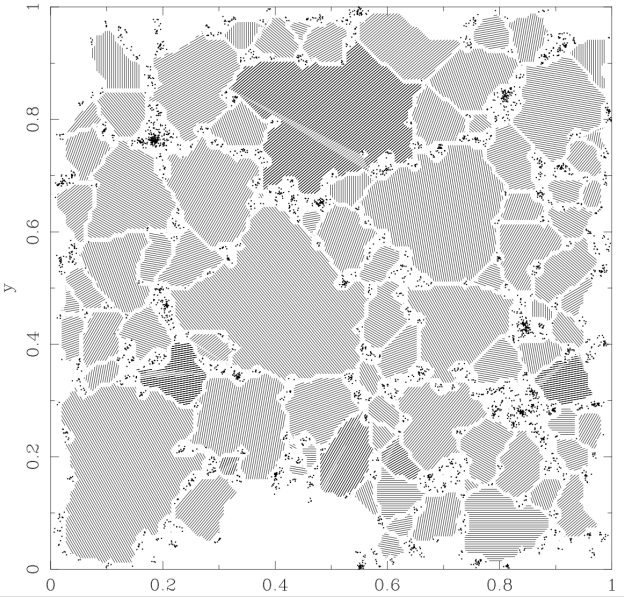
El-Ad et al. 1997



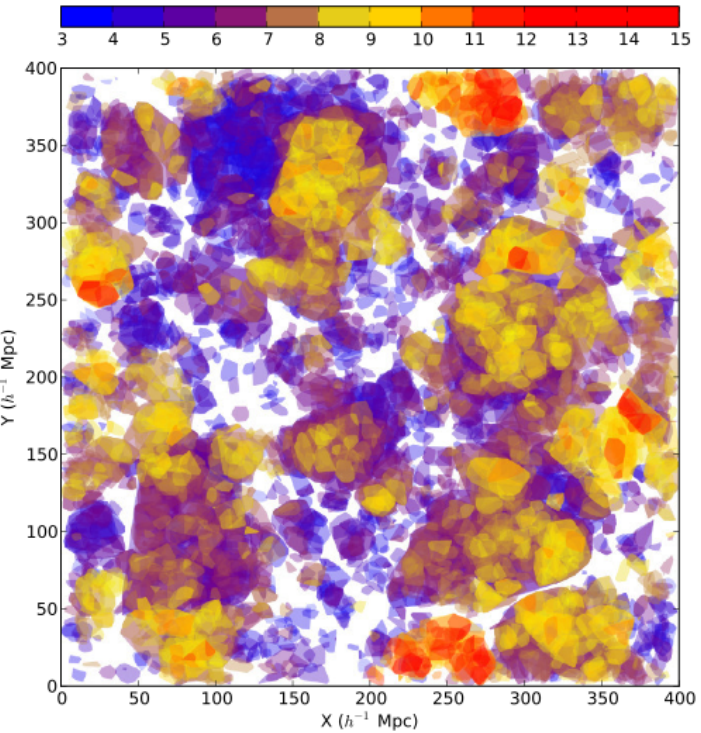
Patiri et al. 2006



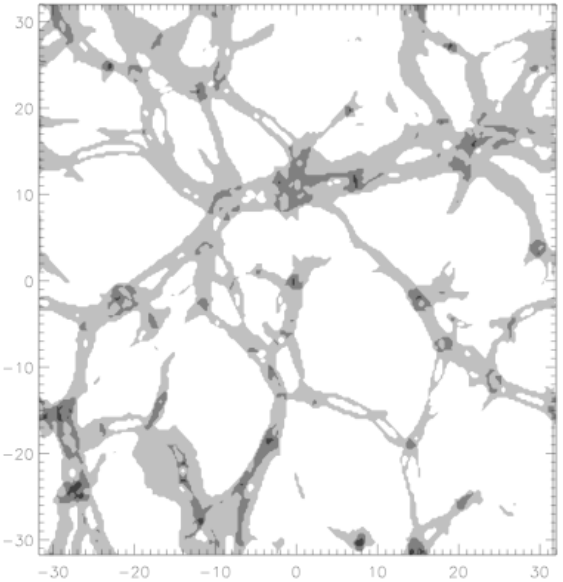
Aikio et al. 1998



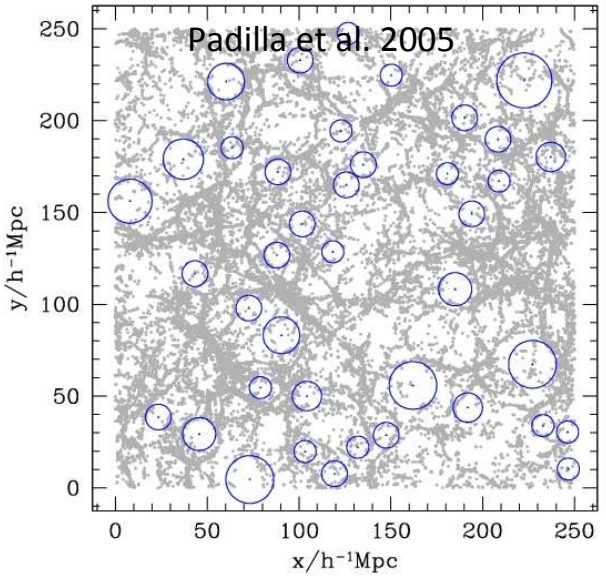
Lavaux et al. 2012



Hoffman et al. 2012



Padilla et al. 2005



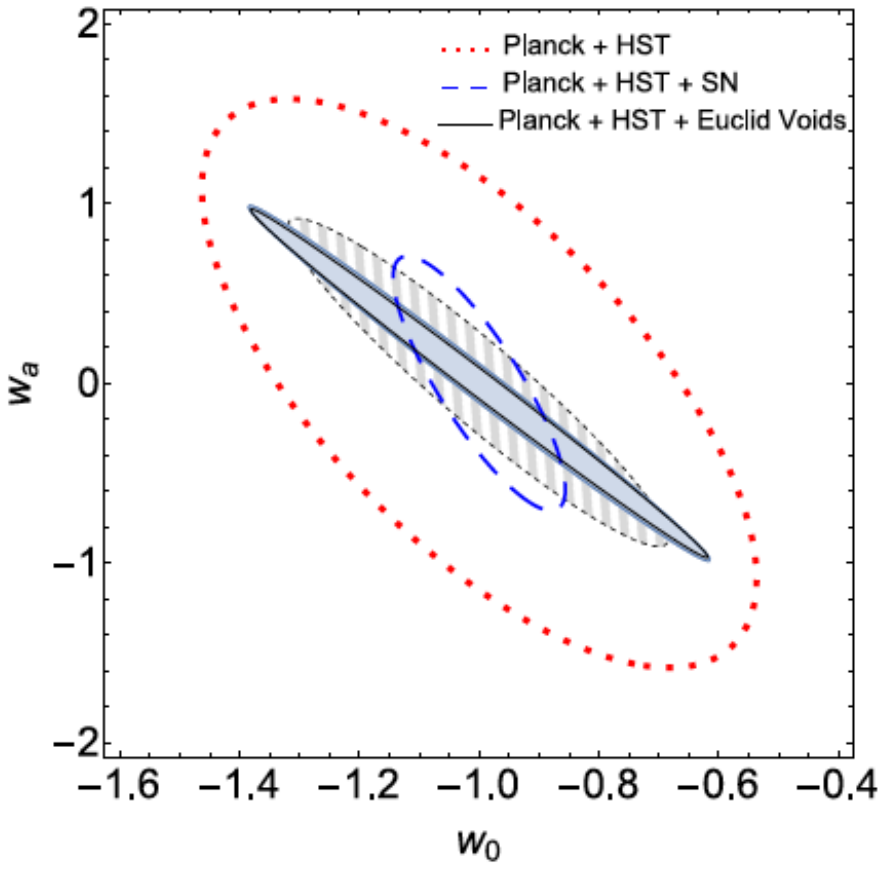
Voids as a probe of cosmology

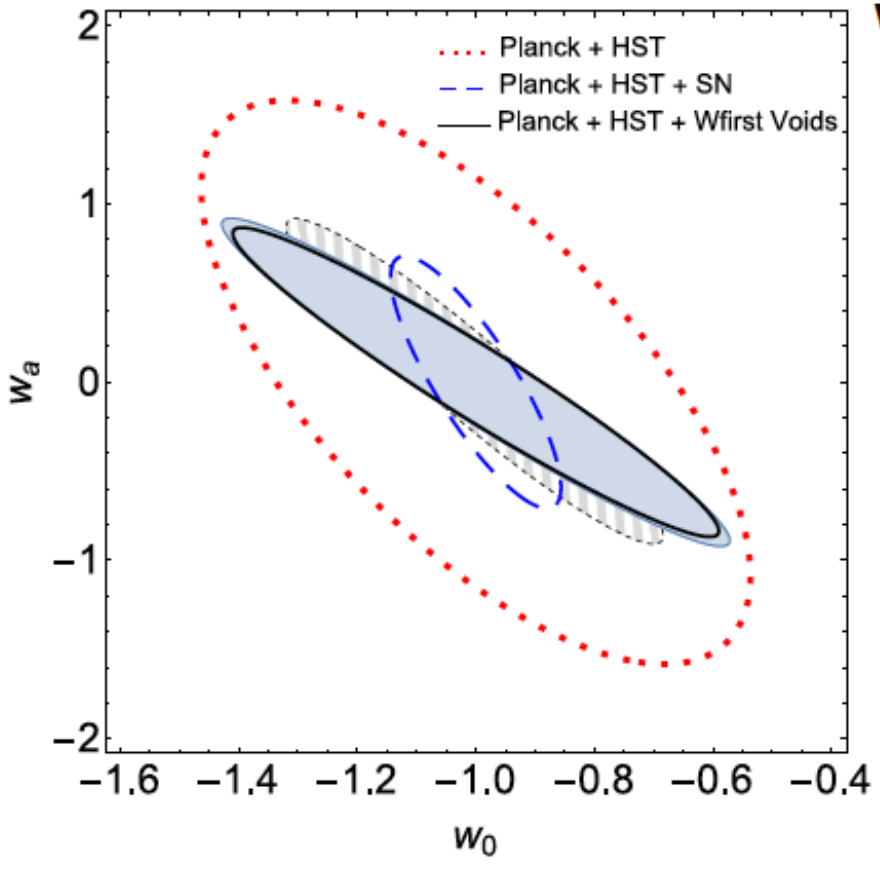
Voids suffer less non-linear gravitational effects, and are closer to the initial density field than high-dense tracers.

- Cosmic structure formation
- Cosmological parameter constraints
- Nature of dark energy and alternative gravity theories
- Primordial non-Gaussianities
- Alcock-Paczynski test (cf Sutter et al. with VIDE, Alice Pisani et al 2015…)
- Baryonic Acoustic Oscillations (BAO)
- …

Comparing future surveys

EUCLID





WFIRST

From Alice Pisani's presentation in Aix-en Provence 2015
Drifting through the Cosmic Web 10th Marseille worskhop on cosmology

arXiv:1503.07690 (Pisani, Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata 2015)

OUR WORK

New void Finder: DIVE

Delaunay trIangulation Void findEr

by Zhao Cheng

based on Delaunay Triangulation

New void definition

use 4-LRG or halos as tracers

\+ DT ➔ tetrahedrons

\+ Take the centres of circumspheres

\+ Take **all** spheres (including overlapping ones)

LSS mock and observed SDSS data

3 papers out 1 month ago!

- 1. arXiv:1511.04299 DIVE in the cosmic web: voids with Delaunay Triangulation from discrete matter tracer distributions, Cheng Zhao, Charling Tao, Yu Liang, Francisco-Shu Kitaura, Chia-Hsun Chuang

- 2. arXiv:1511.04391 Measuring Baryon Acoustic Oscillations from the clustering of voids, Yu Liang, Cheng Zhao, Chia-Hsun Chuang, Francisco-Shu Kitaura, Charling Tao

- 3. arXiv:1511.04405 Signatures of the primordial Universe from its emptiness

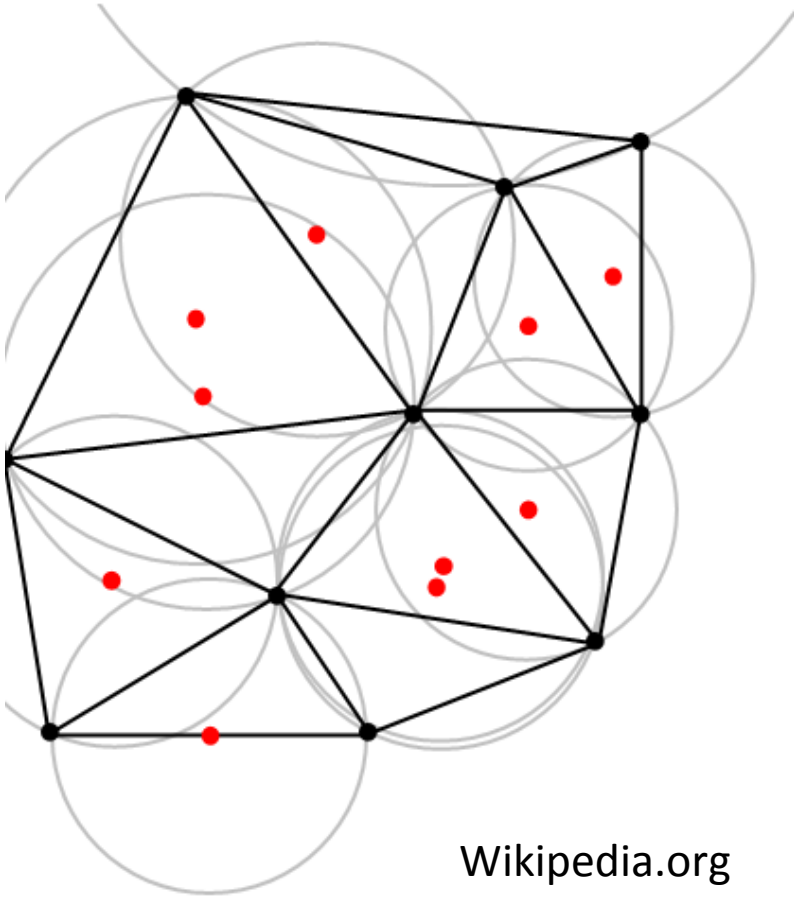
Francisco-Shu Kitaura, Chia-Hsun Chuang, Yu Liang, Cheng Zhao, Charling Tao,

+SDSS: Sergio Rodriguez-Torres, Daniel J. Eisenstein, Hector Gil-Marin, Jean-Paul Kneib, Cameron McBride, Will Percival, Ashley J. Ross, Ariel G. Sanchez, Jeremy Tinker, Rita Tojeiro, Mariana Vargas-Magana, Gong-Bo Zhao

Delaunay Triangulation

A Delaunay triangulation for a set P of points in a plane is a triangulation (subdivision into triangles) DT(P) such that no point in P is inside the circumcircle of any triangle in DT(P).

Delaunay Triangulation is unique in non-degenerate case (no 4 points on the same circle).



Wikipedia.org

Applications of Delaunay Triangulation in cosmology

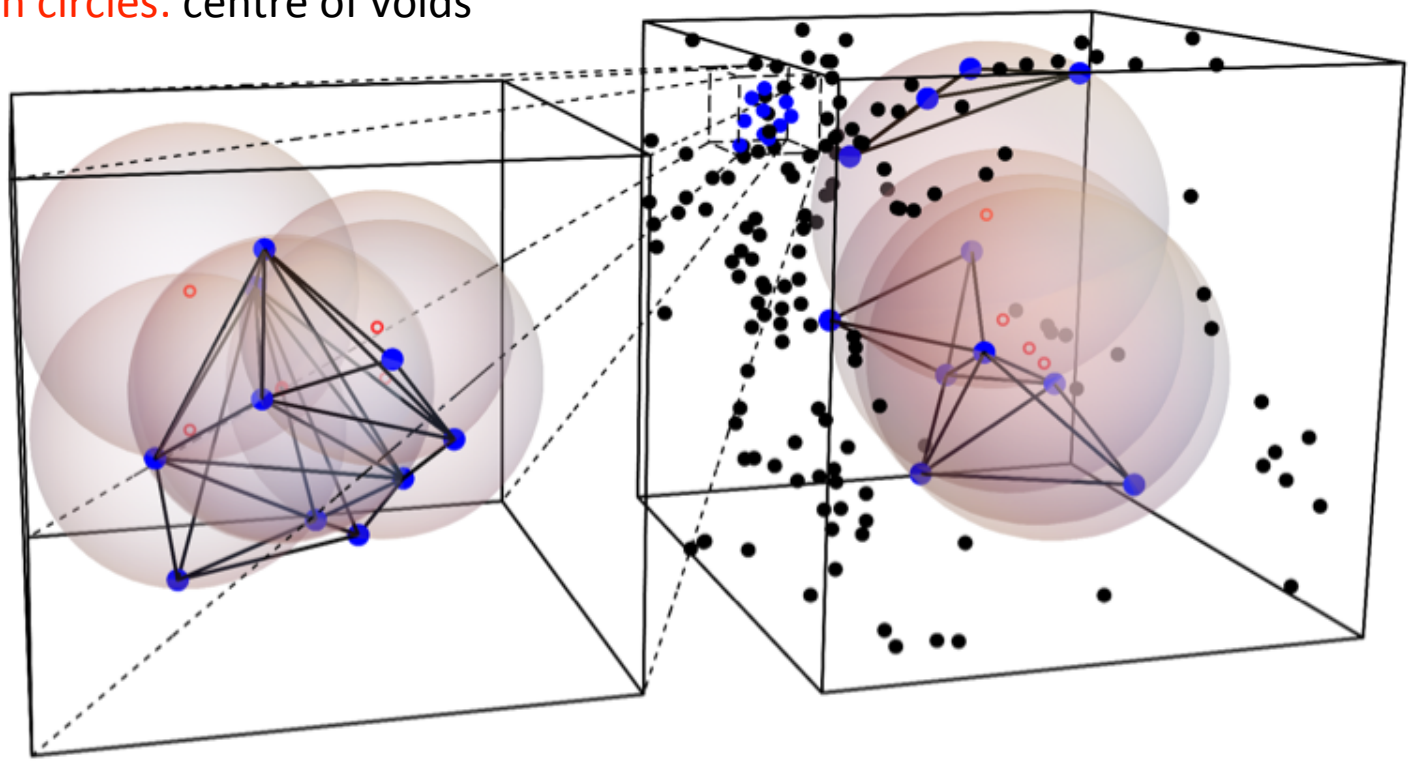
- Reconstruction (interpolation) of a continuous field from discrete samples:
  - Density field (DTFE, Delaunay Tessellation Field Estimator, Schapp & van de Waygaert 2000)
  - Velocity field (Bernardeau 1996)
- Cluster finder (Marinoni et al. 2002)
- Topology of cosmic web (van de Weygaert et al. 2011)

DIVE: Delaunay trlangulation Void findEr

- Definition: circumspheres of tetrahedrons defined by Delaunay Triangulation in 3-D space. (All the empty spheres defined by four haloes/galaxies)
- Advantage:
  - Parameter-free
  - Fast: ~ 10 min for over 5 million haloes
  - Robust: applicable to arbitrary shapes of domains

Visualisation of DT voids

Points: haloes
Open circles: centre of voids



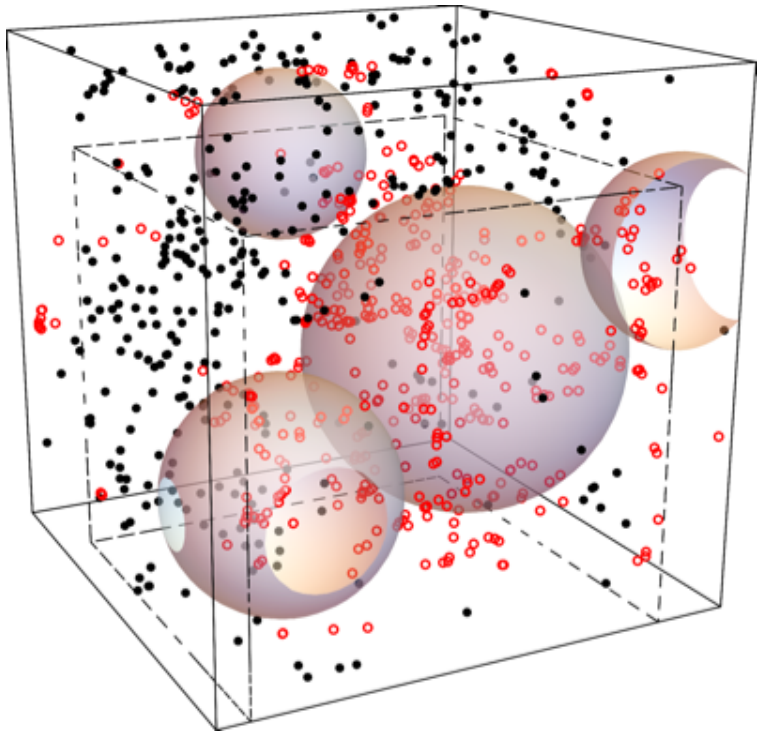
Box size:
- left: $12^3\ h^{-3}\ \mathrm{Mpc}^3$
- right: $80^3\ h^{-3}\ \mathrm{Mpc}^3$

Void radius:
- left: $R \leq 4\ h^{-1}\ \mathrm{Mpc}$
- right: $R \in [16,17]\ h^{-1}\ \mathrm{Mpc}$

DIVE: Disjoint voids

Sort and remove.

Same as the void definition of Patiri et al. 2006



Box size: 100^3 h^{-3} Mpc^3
Void radius: $R \geq 17$ h^{-1} Mpc

DT void properties

1. arXiv:1511.04299 DIVE in the cosmic web: voids with Delaunay Triangulation from discrete matter tracer distributions, Cheng Zhao, Charling Tao, Yu Liang, Francisco-Shu Kitaura, Chia-Hsun Chuang

1) Not very different from voids from other void finders:
- volume function
- Number function
- Void density profile
- Overlapping fraction

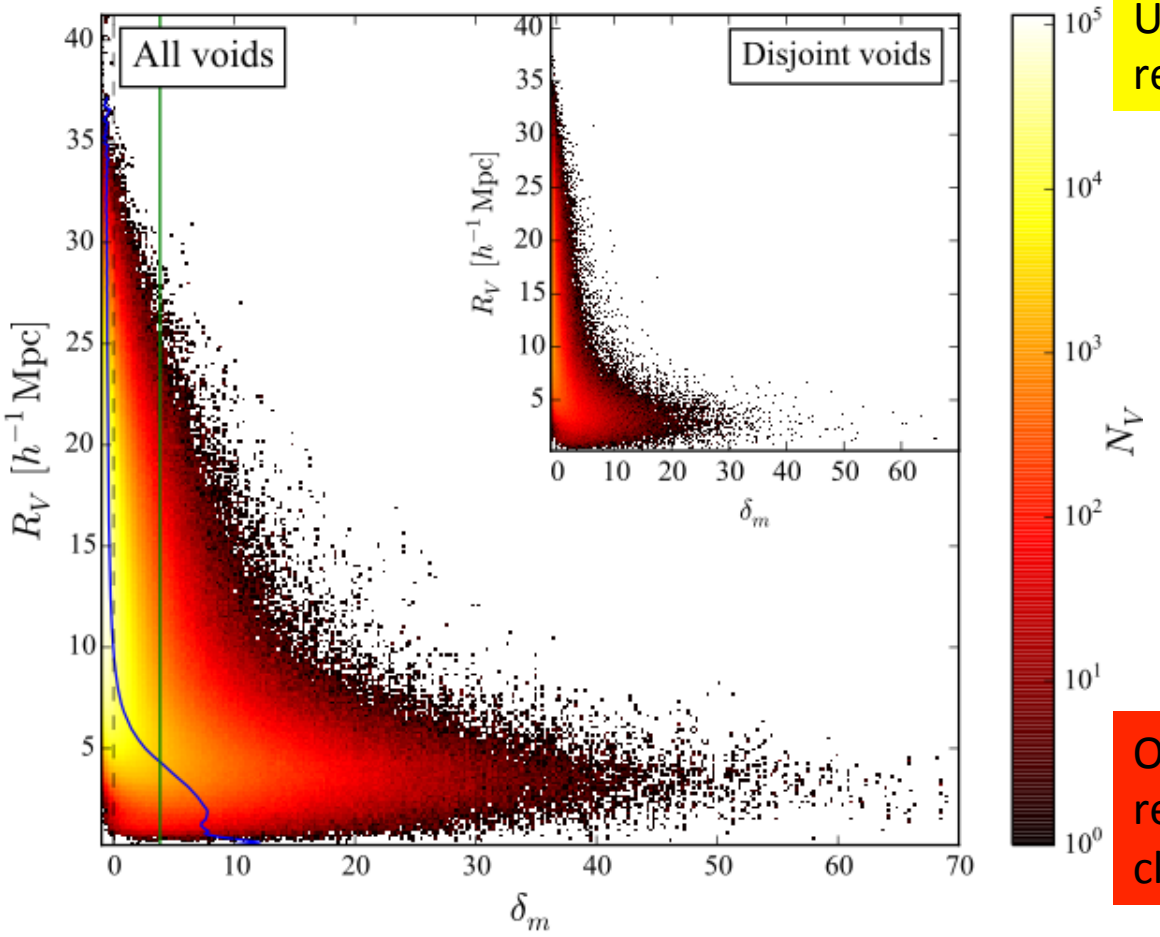
2) 2 populations distinguished by circumsphere radius ~ 16 Mpc/h
- voids in clouds (small spheres) not underdense spheres
- voids in voids (large spheres) underdense spheres

Delaunay spheres and DM density

- Spheres classified by radius

Blue curve: Mean density of voids

Green line: Mean density of haloes



Underdense regions= VOIDS

Overdense regions= clusters

Clustering: power spectra

Large voids:

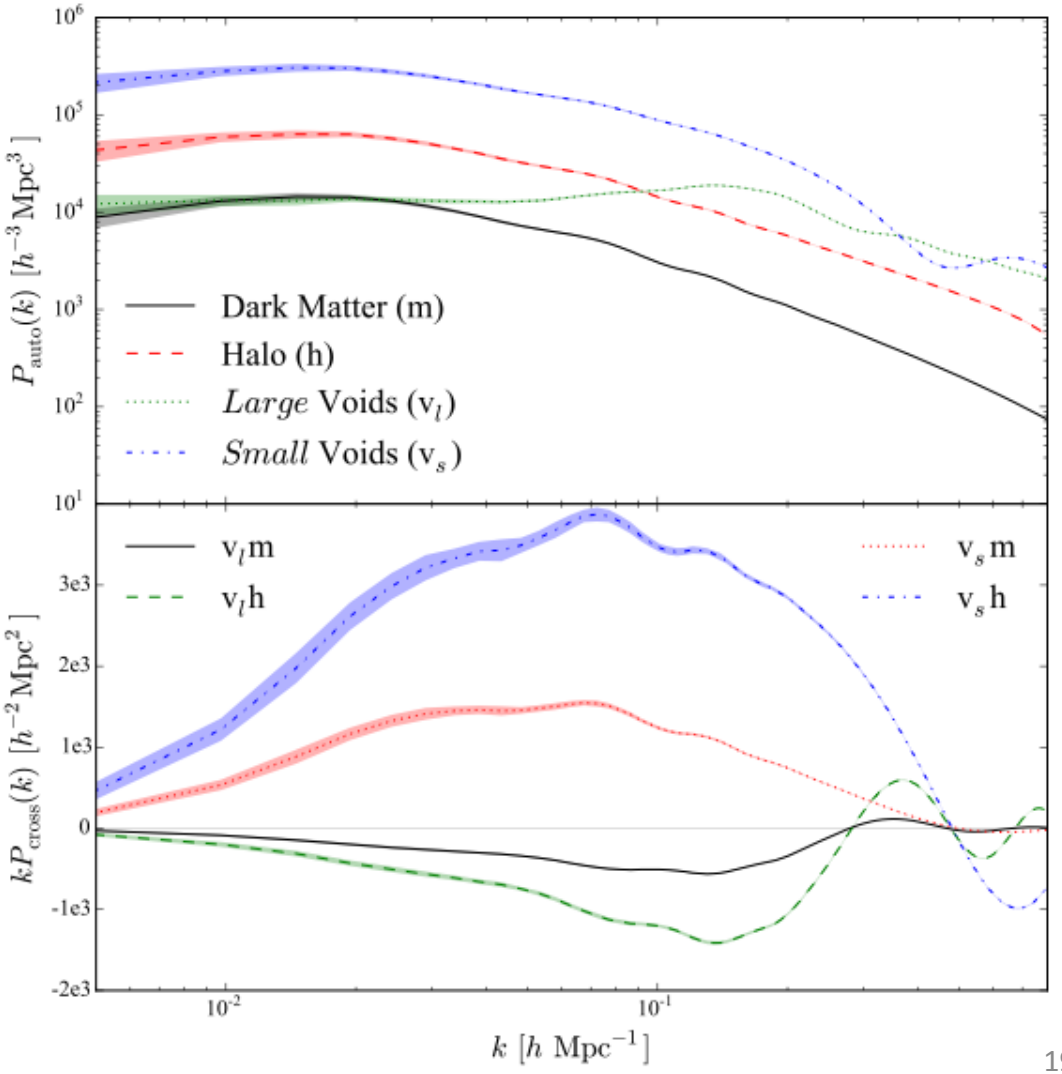
negative bias: real voids

Small voids:

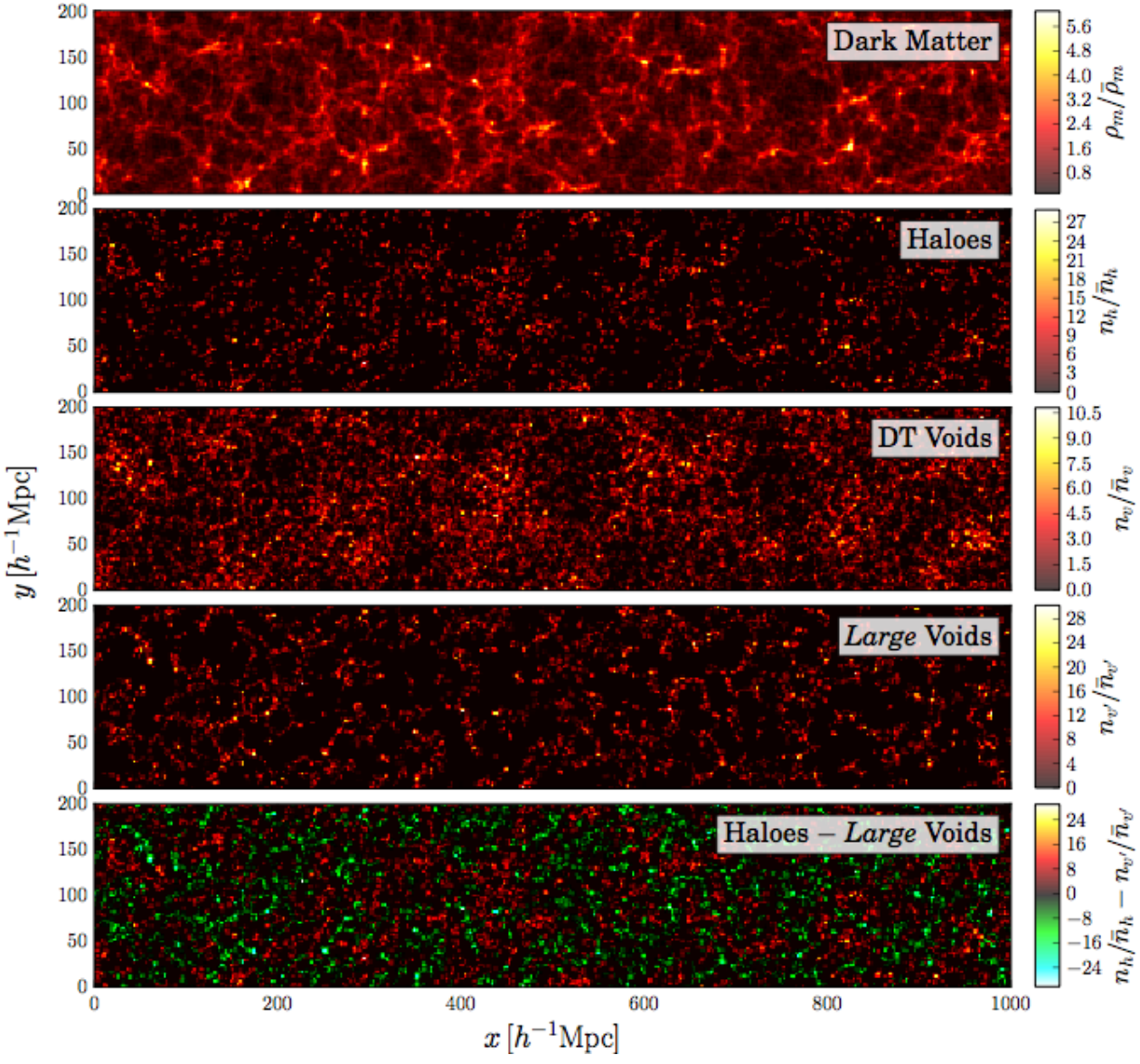
positive bias

➔ group of haloes

➔ not voids



Spatial distribution



Large voids complement haloes

Study of 2 Point Correlation functions

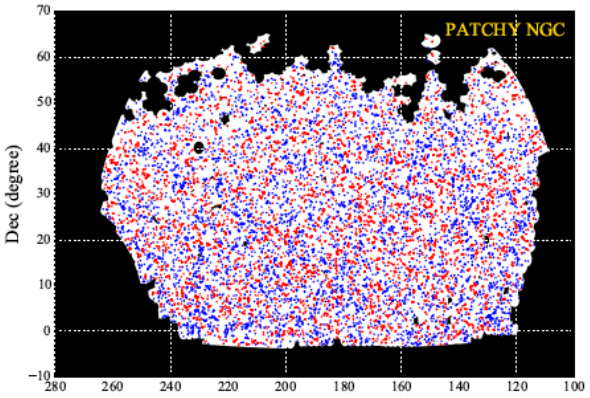
- fix the void selection with mocks: best S/N ratio before using observed data (blind analysis)

Mocks = simplified simulations ➔ covariance matrices

- Patchy mocks: Kitaura, Yepes, Prada 1307.3285 fastest + most precise mock generator calibrated on BigMultiDark Planck cosmology (cf Nifty paper: Chuang et al.... 2015) **Adopted in 2015 by BOSS !**

- Apply to galaxy catalogues (S. Rodriguez- Torres, in prep.) for SDSS DR11/DR12 statistics and covariance matrices computation: 1024 "lightcone mocks" public

- Apply to public DR11 data



Patchy Mocks

PerturbAtion Theory Catalogue generator of Halos and galaxY distributions

- generation of mock halo catalogues based on perturbation theory and nonlinear stochastic biasing

- Augmented Lagrangian Perturbation Theory (ALPT) ➔ a dark matter density field from Gaussian fluctuations and peculiar velocity field.

- **ALPT = 2LPT on large scales + spherical collapse model on smaller scales**

- Calibrated with Bound Density Maximum (BDM, including sub-halos) catalogues of BigMultiDark N-body simulation (klypin et al. 2014)

Fastest and most precise mock generator : cf Nifty paper: Chuang et al….2015

Adopted in 2015 by BOSS !

Our methodology

- We generate 100 Patchy mocks in real and redshift space boxes
- BOSS Luminous Red Galaxies properties:
  - number density around 3.5 10^{-4} $(Mpc/h)^{-3}$,
  - mean redshift of z about 0.56
  - cubical (box) volumes of 2.5 Gpc/h side.
- apply DTVoid on halo or galaxy catalogues ➔ Void catalogue
- compute the 2 pt CFs with the void catalogues

Computing 2pt CF

- For simulated boxes with periodic boundary conditions

Peebles & Hauser (1974) estimator,

$$\xi(s) = DD(s)/RR(s) - 1$$

DD=normalised pair counts

$$RR(s)\ \text{analytical} = 4\pi/3\ (s_{max}^3 - s_{min}^3)/2V \quad (V\ \text{volume})$$

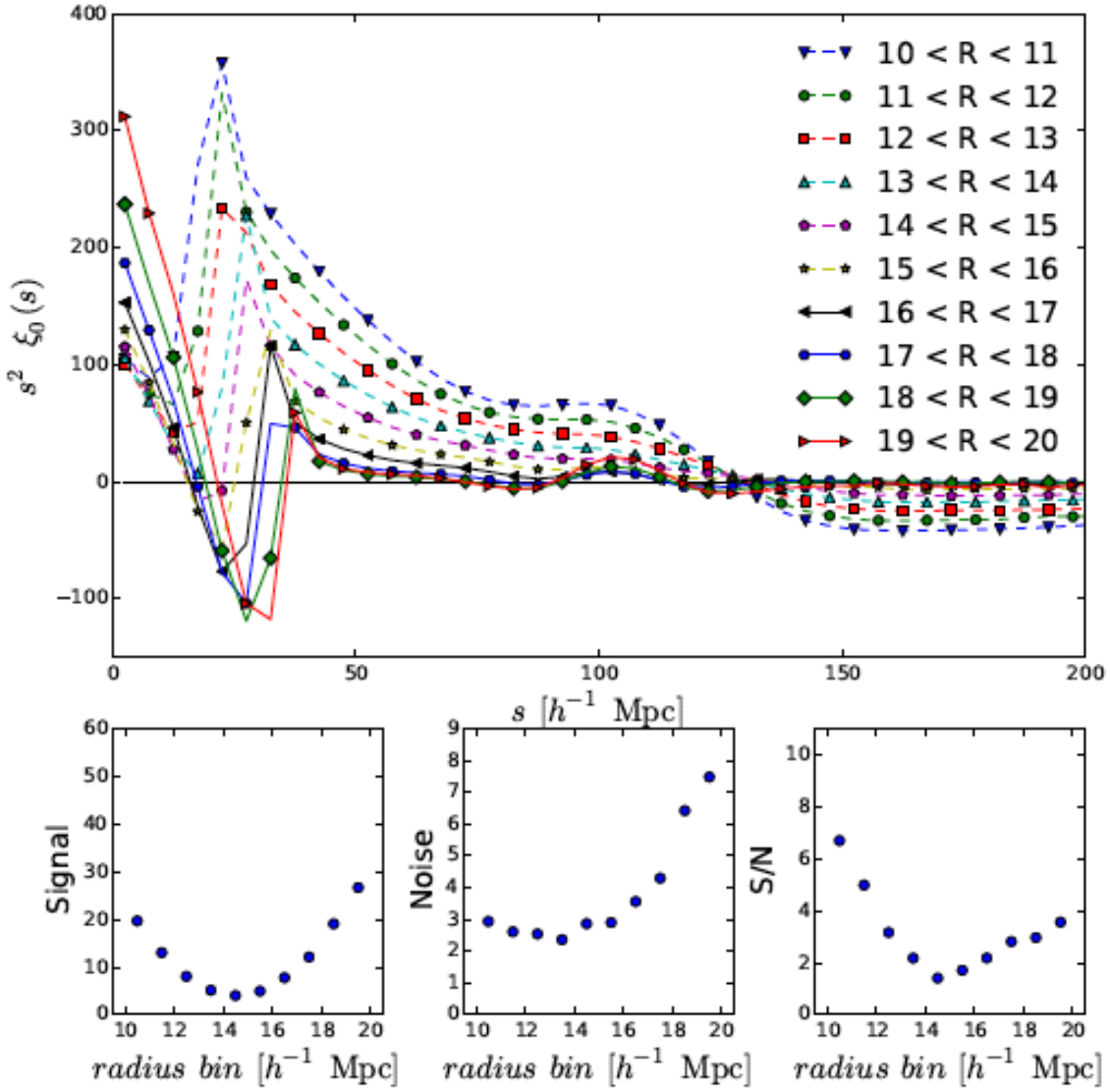
- For lightcone catalogues and data,

Landy & Szalay (1993) estimator

$$\xi(s) = (DD(s) - 2DR(s) + RR(s))/RR(s)$$

DD= data pair counts, RR= random pair counts

Void 2 point correlation functions with mocks

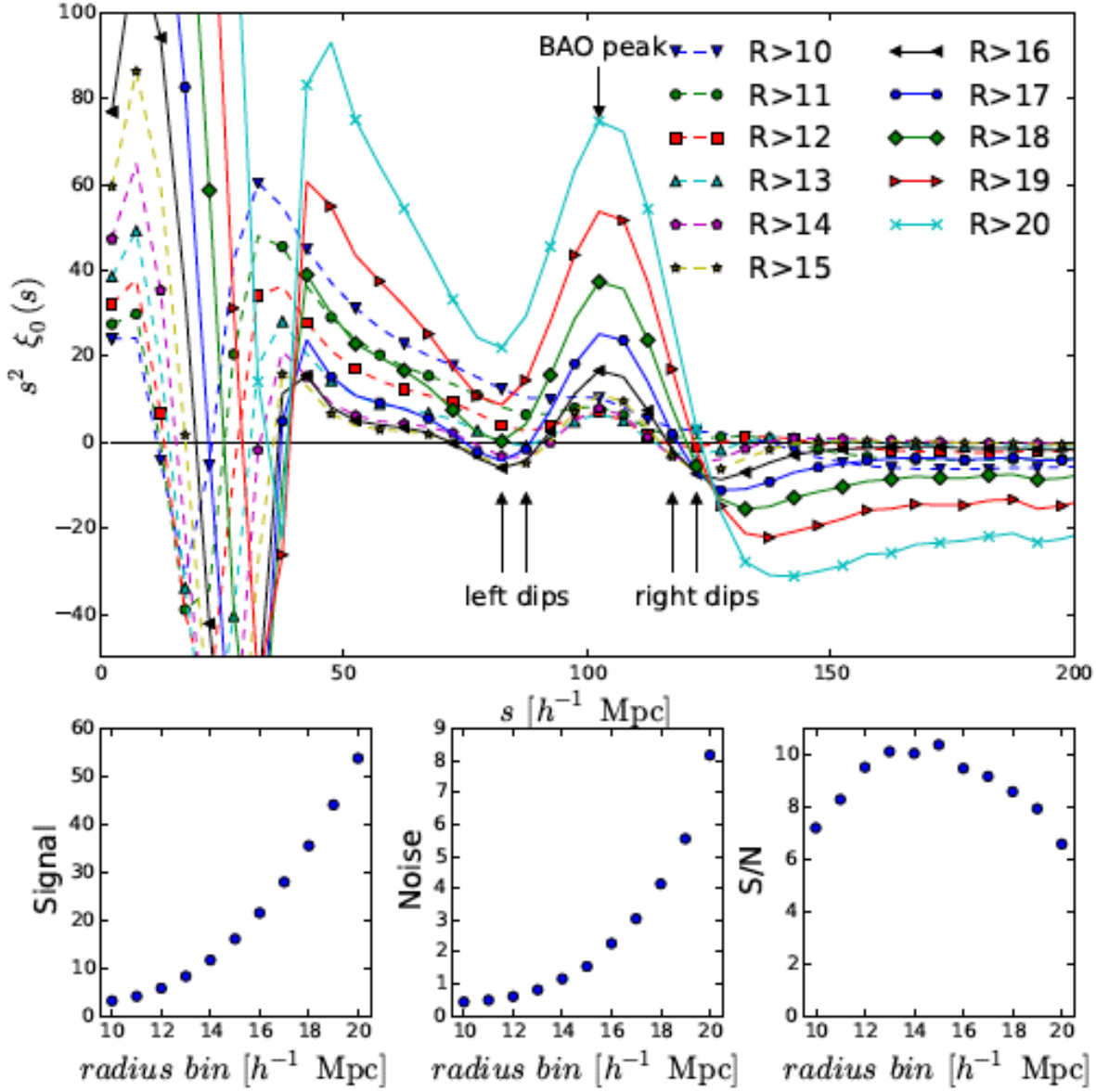


Box Patchy halo mocks
Real space- R bins

- peaks at 102.5 Mpc/h for all voids ➔ **BAO**

- Other peaks and throughs : positions depend on void radius

Study of Void 2 point correlation functions with mocks



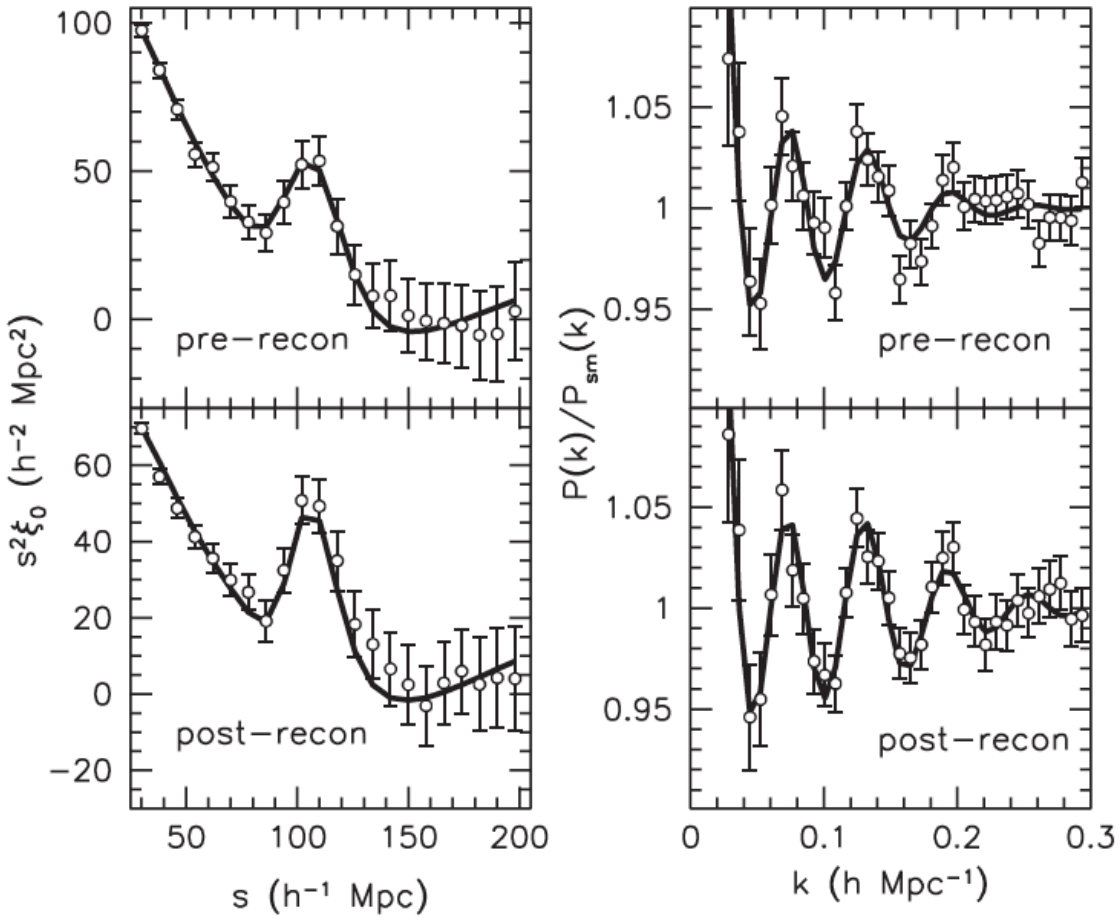
Box Patchy mocks
Real space for R cuts

- BAO peaks at 102.5 Mpc/h for all voids

Best S/N: R>16 Mpc/h

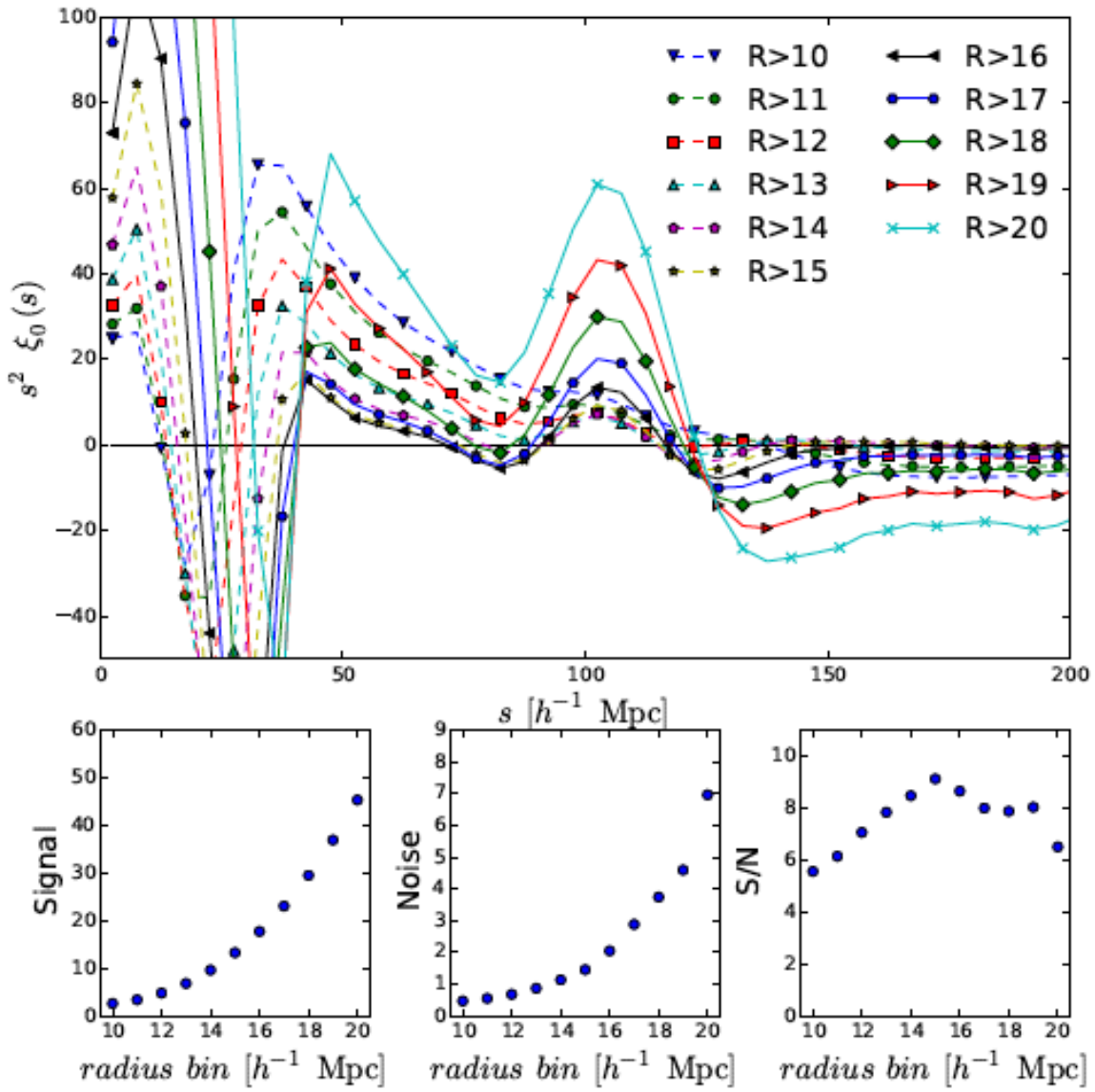
- Other peaks and throughs : positions depend on void radius

BAO Correlation functions and Power spectra of SDSSIII-BOSS (DR11- soon DR12) with LRG



Anderson et al. 2014 >7σ effect

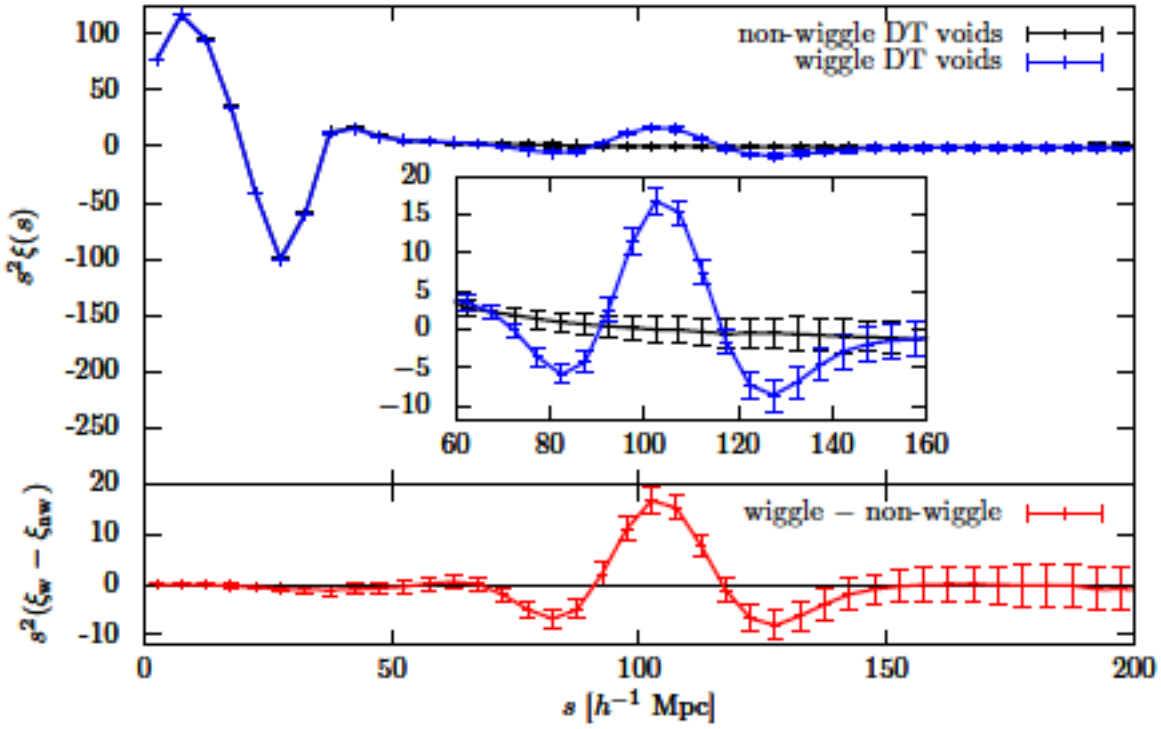
Void 2 point Correlation functions



Box Patchy mocks
Redshift space
(observed space is redshift space)

Not very different than real space!
➔ RSD effects are smaller/ different from Galaxies RSD

BAO detection with Our New voids from Patchy mock galaxy catalogues (simulations)



Void 2 point Correlation functions

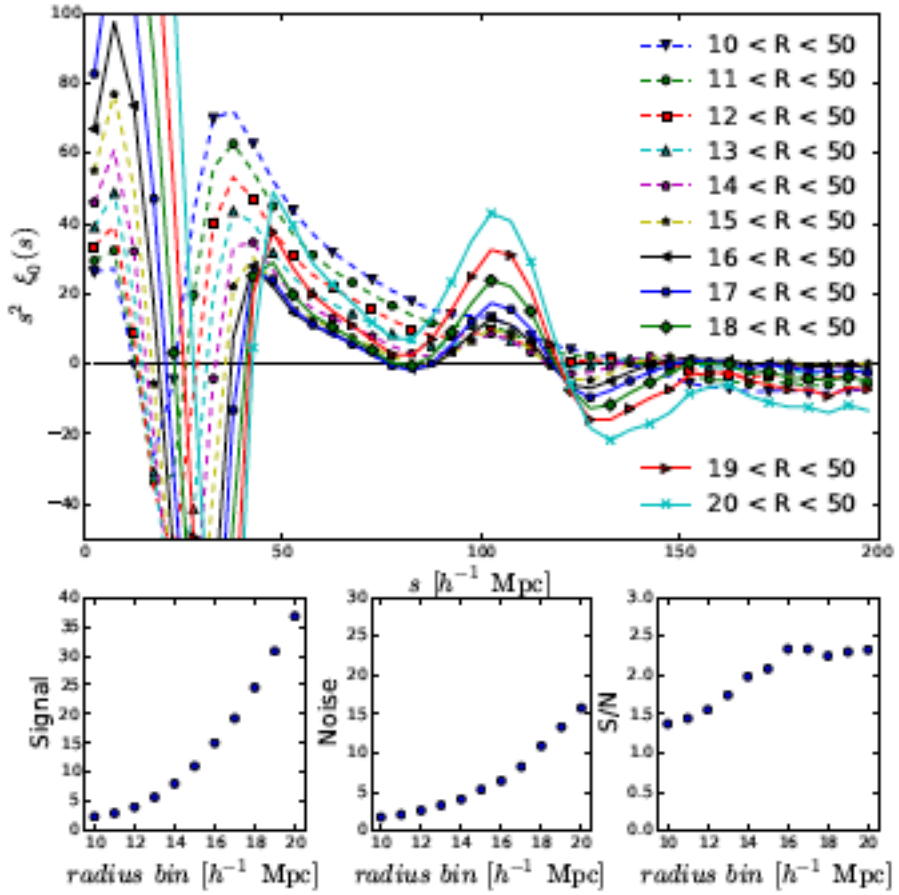
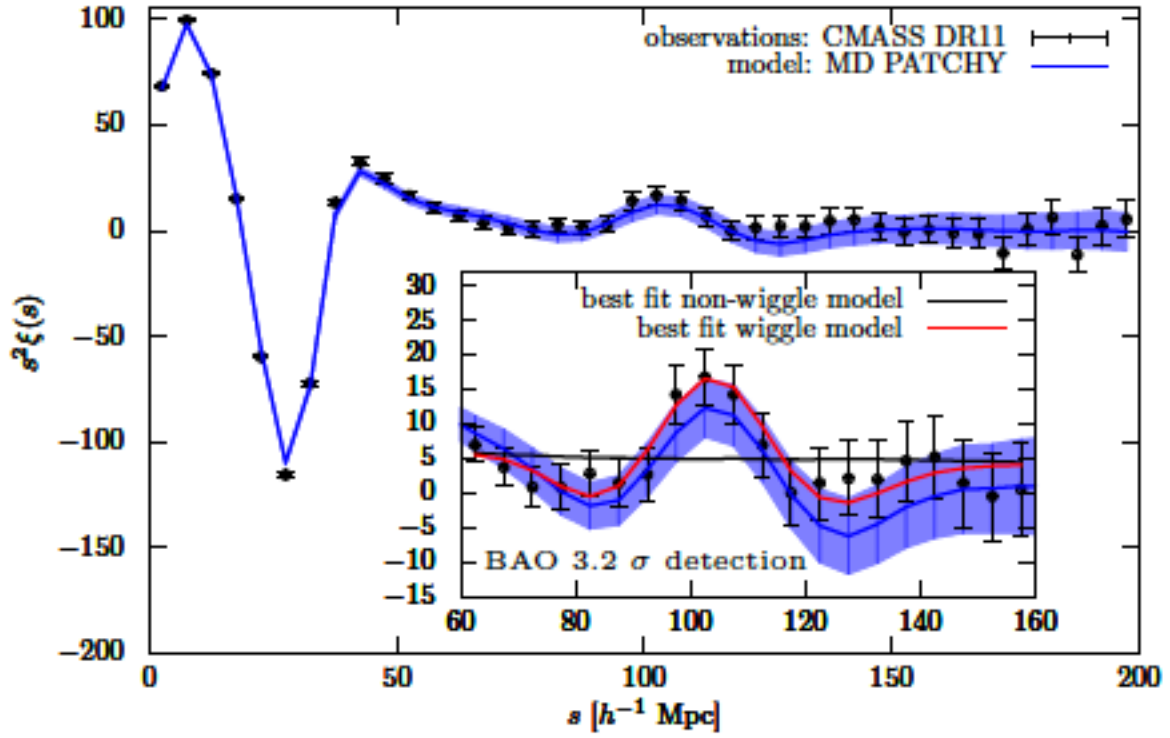


Figure 7. Correlation functions measured from the first 100 PATCHY CMASS-NGC void catalogues with R bins and $R > R_{\mathrm{cut}}$.

Patchy halo
Mocks + HAM
Rodriguez--Torres et al. 2015
➔ Simulated galaxy mocks
+ information on BOSS
systematics: masks, borders,…
“lightcone mocks”

Note : the low S/N

BAO detection with Our New voids from SDSSIII BOSS DR11 CMASS-North



Surprise

3.2 σ detection!

Positive cosmic Variance?

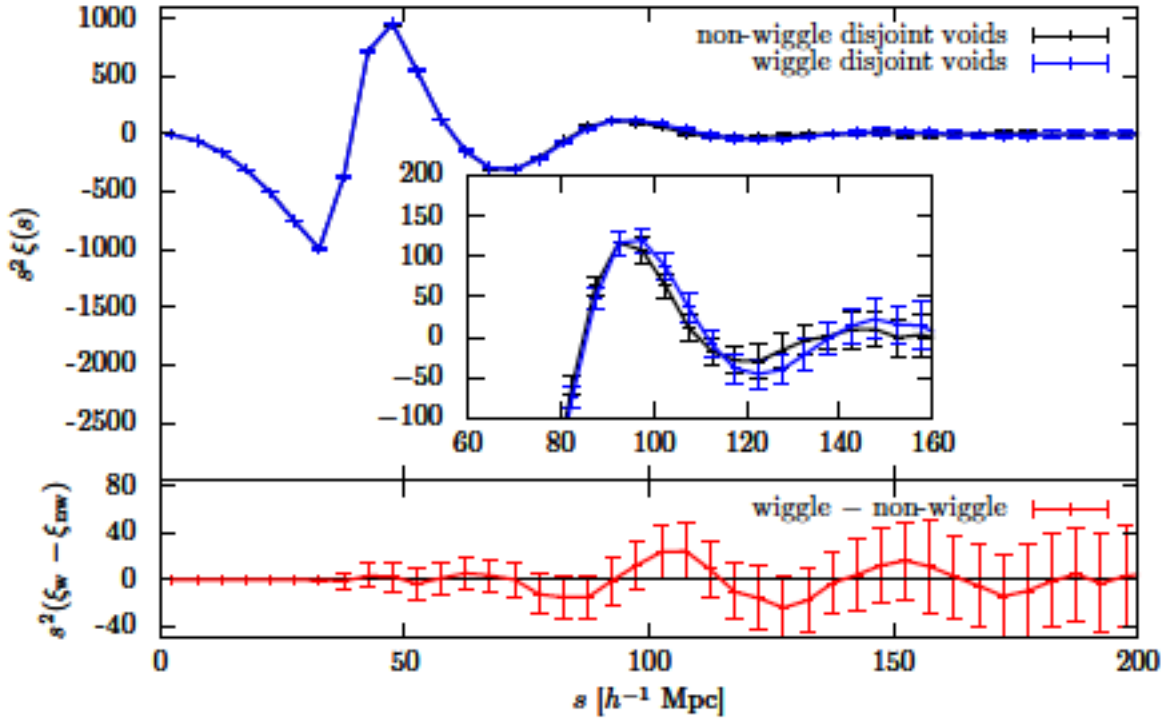
DR12 final complete BOSS study in preparation

No Baryon Acoustic Oscillations with disjoint Voids

- Take disjoint voids as people did before:

➔ Large oscillations in void-void Correlation functions due to hard spheres with large filling factors

➔ void statistics is low



No BAO with disjoint voids !
(previously used definitions)

Cosmology with Voids?
And application to EUCLID
in preparation

Voids and galaxies are correlated.

How to add voids in cosmology combination?

New information:

- Voids are correlated with galaxy 4pt statistics
- Void BAO peak is narrower than LRG BAO peak before reconstruction

Some Clustering Correlation analysis computing issues

- 1 Million CPU hours for void SDSS BOSS DR11 LRG analysis in 2 months
  - Mare Nostrum in Spain and Supermuc in Leibniz: fast return

- Test of Computing at CCIN2P3 : Thanks to Quentin LeBoulc'h and Ken Ganga
  - Report to Ken Ganga +…
  - Sep 2015: 2000 h in 5 days on 5 Mh available
  - Problem with queues: wait too long ➔ Spanish or German supercomputers

- **Extrapolation to EUCLID:** volume ~ 500 x BOSS
  - Need additional ressources/supercomputing machines !
  - Need code optimization/acceleration

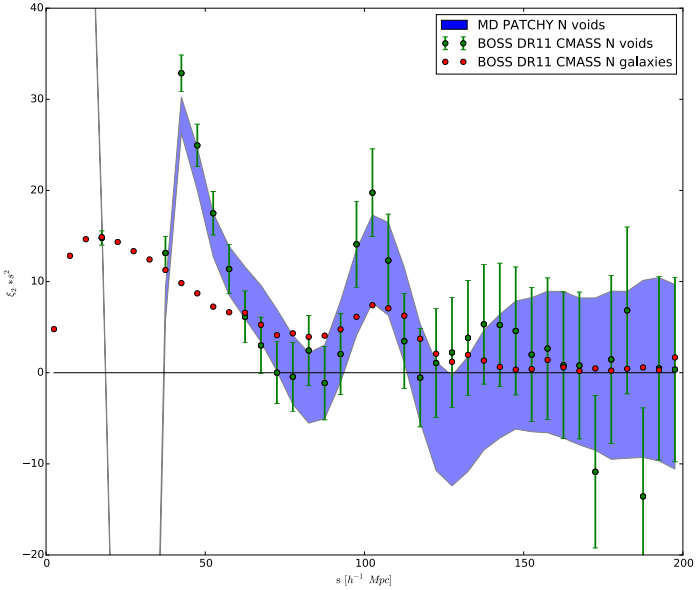
  - **How do we foresee computing for different science (SWG) analysis?**

  Setting up a control system and resource allocation system for requests
  (Cf Quentin + Ken)

Summary

Our **New void finder** by Zhao Cheng based on Delaunay Triangulation and void definition

➔ **> 3σ BAO detection with our New voids from SDSSIII BOSS DR11 CMASS-North data and mocks**



Cosmology with Void BAO: not an independent probe- correlation void-galaxy

New information : 4pt statistics

Better than Galaxy wrt non linear effects