A large number of fast cosmological simulations for the revised WiggleZ BAO measurement

Jun Koda
Swinburne University of Technology
(Melbourne, Australia)

Collaborators: Eyal Kazin, Chris Blake (Swinburne)

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Outline

1. Revised WiggleZ BAO measurement

Kazin, JK, Blake & Padnabhan 2014 (arXiv:1401.0358)

— motivation for my simulations

- WiggleZ survey
- Baryon Acoustic Oscillations (BAO) in galaxy clustering
- “Reconstruction” technique

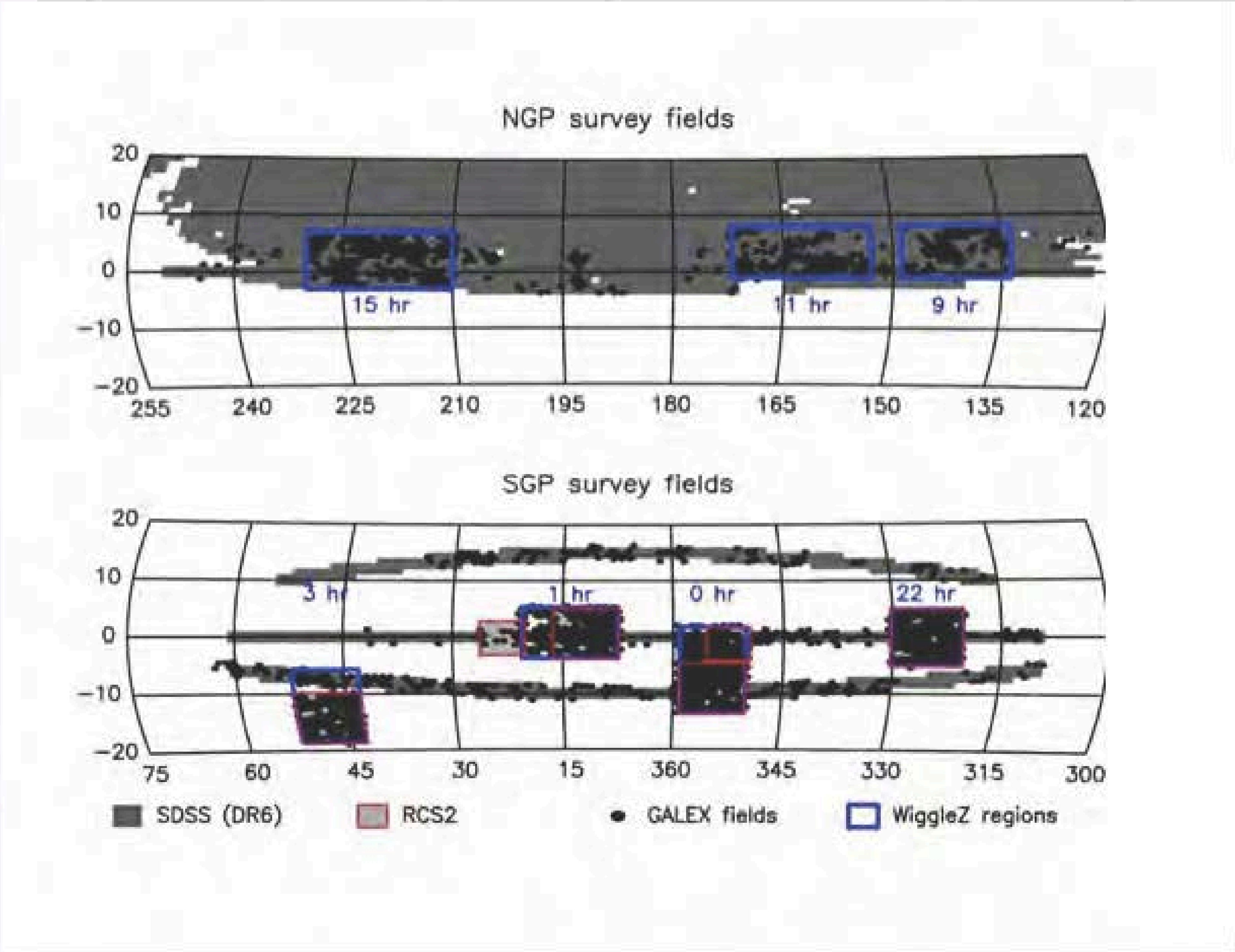
2. 3600 realizations of simulations

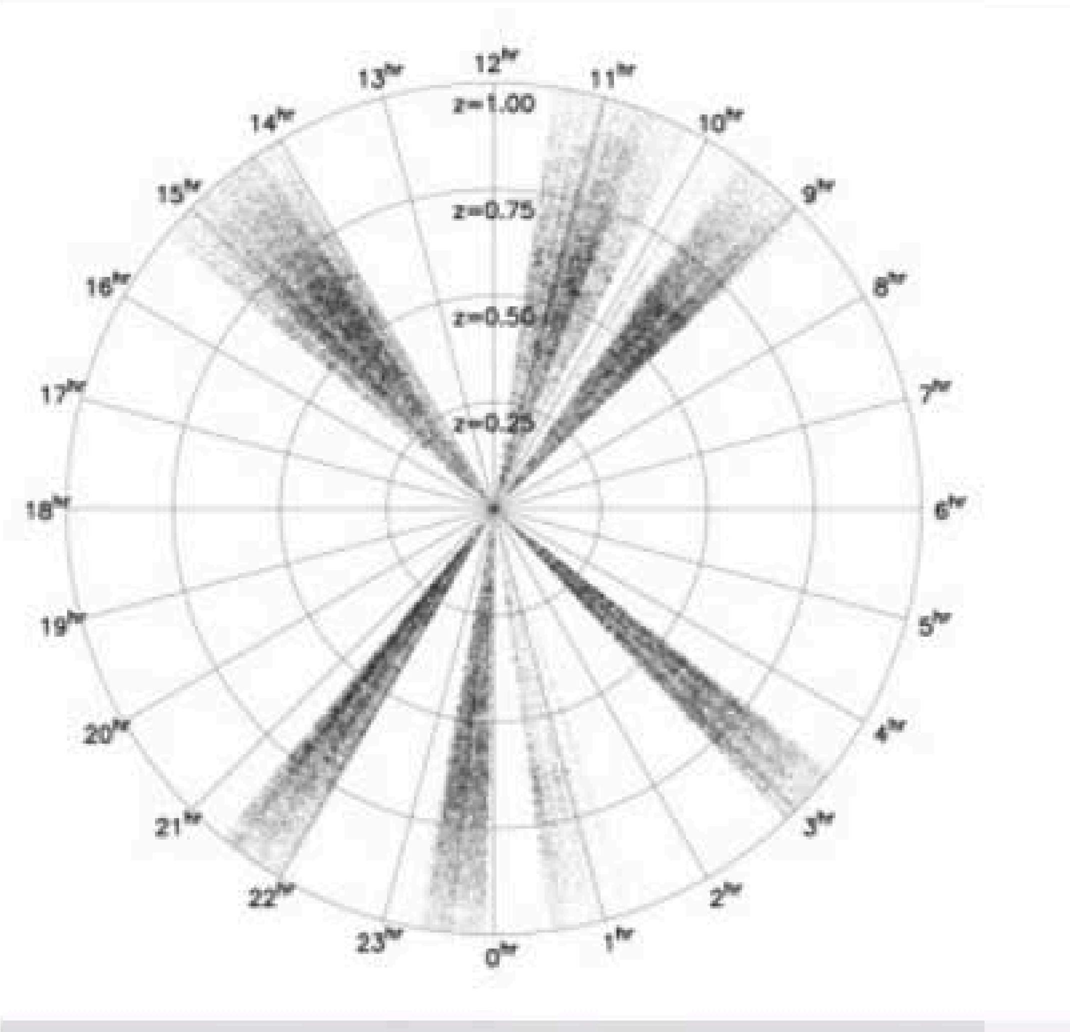
- Fast large-scale structure simulation methods
- 600 mocks for the WiggleZ survey (paper in prep)

The WiggleZ Dark Energy Survey

Drinkwater et al 2010, MNRAS **401** 1429

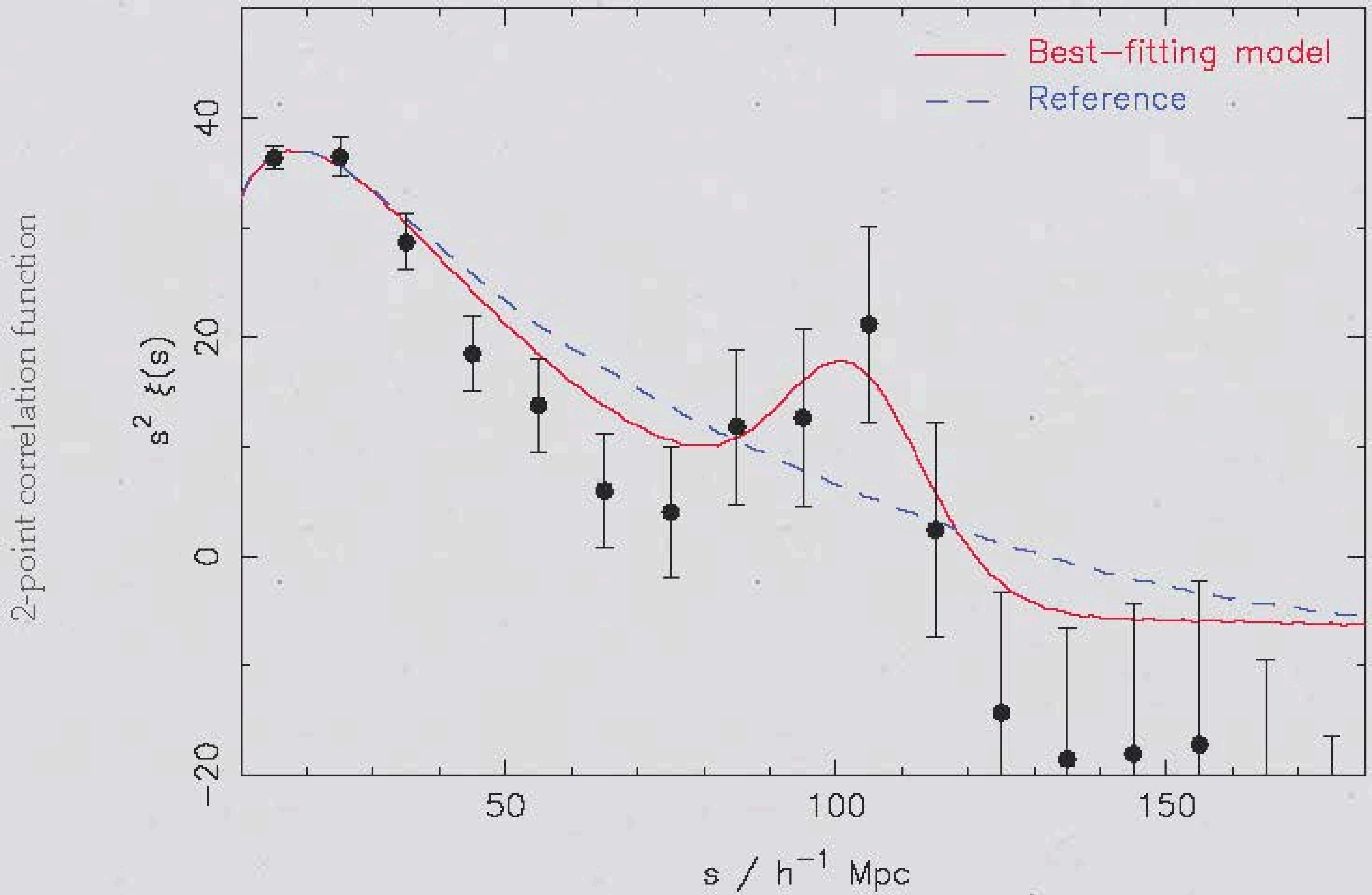
- Redshift range: $0.2 < z < 1.0$
- 1000 deg^2 in 6 regions, total volume 1 Gpc^3
- emission-line galaxies





Baryon Acoustic Oscillations (BAO)

A robust cosmological "standard ruler"

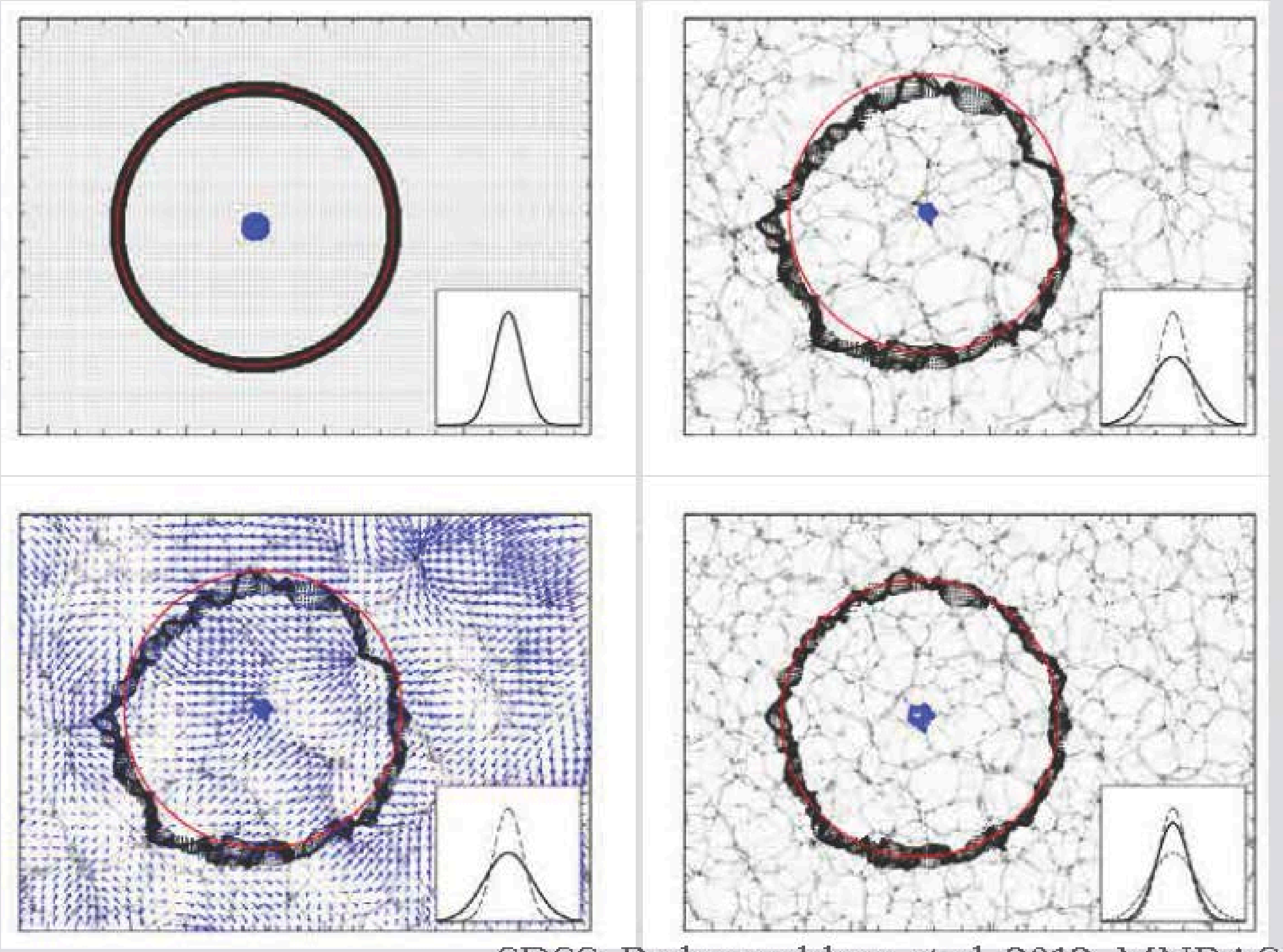


Blake et al 2011, MNRAS **415** 2892 (WiggleZ)

BAO measurement in galaxy clustering: Cole et al. 2005 (2dF), Eisenstein et al. 2005 (SDSS)

"Reconstruction"

sharper peak → better BAO peak determination

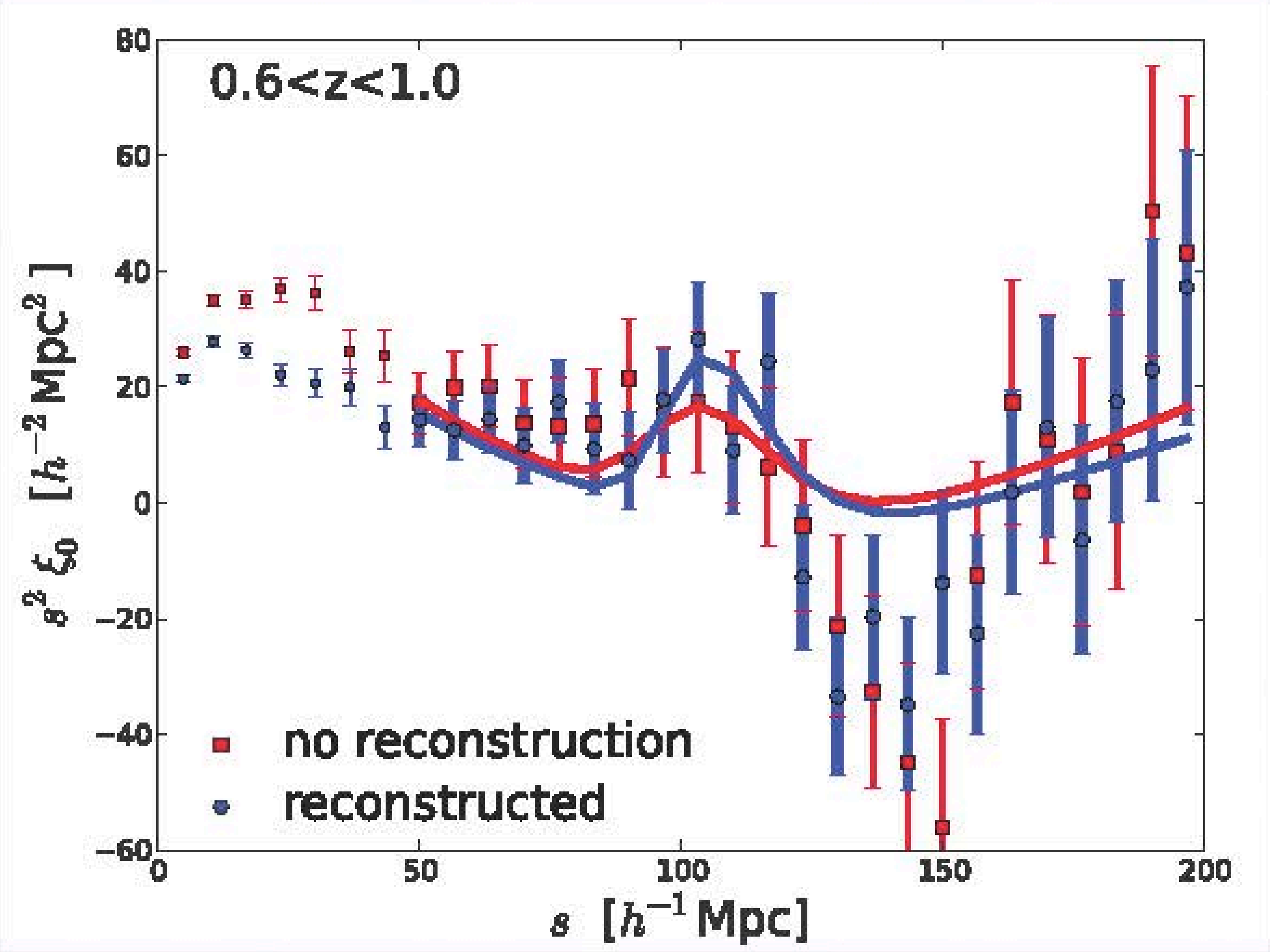


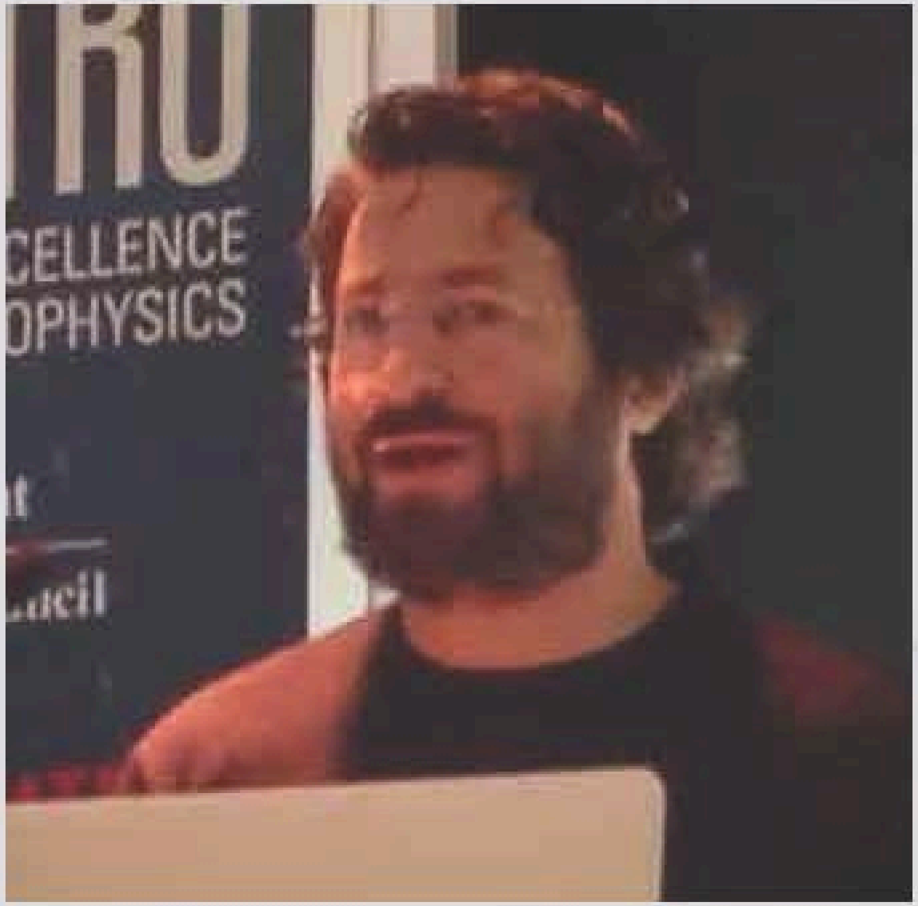
SDSS: Padmanabhan et al, 2012, MNRAS **427** 2132

Theoretical idea: Eisenstein et al, 2007, ApJ **664** 679

WiggleZ BAO with reconstruction

Kazin, JK, Blake & Padnabhan 2014 (arXiv:1401.0358)

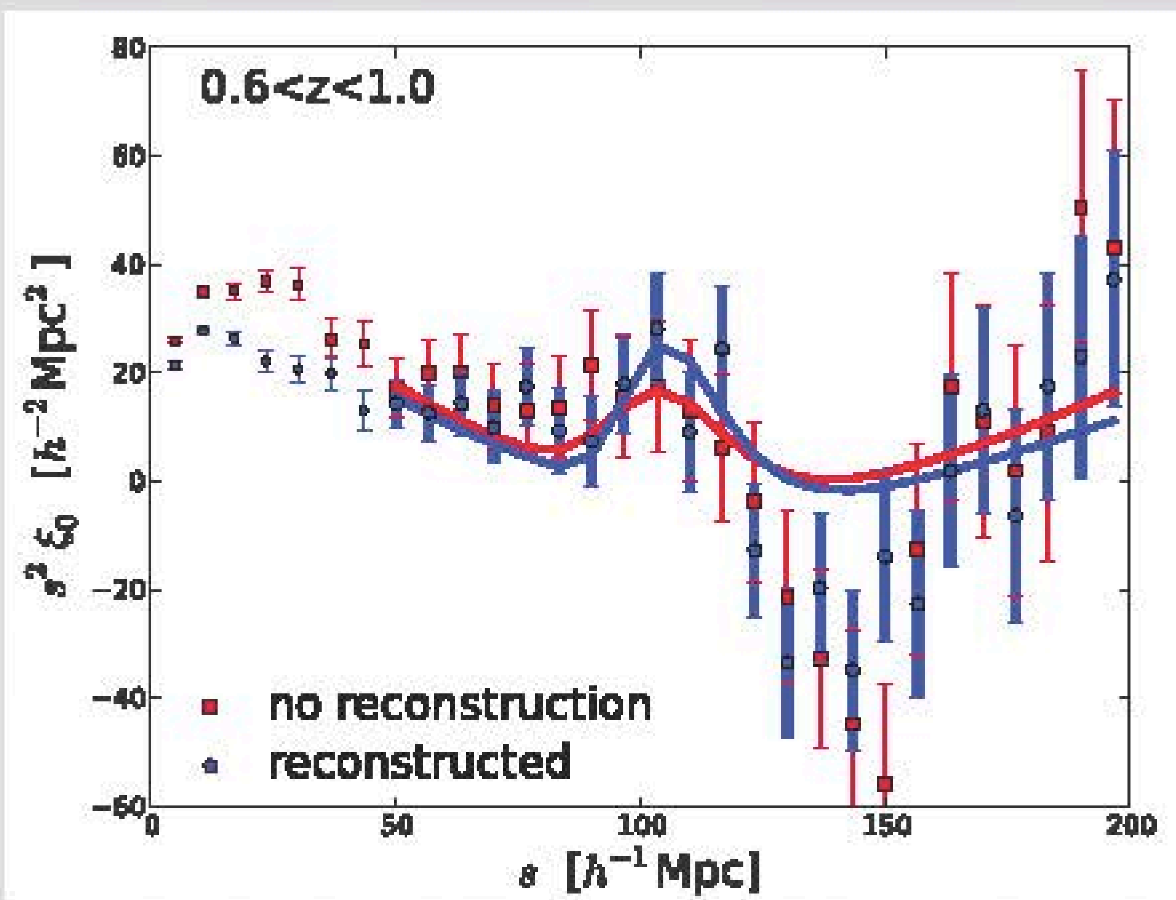


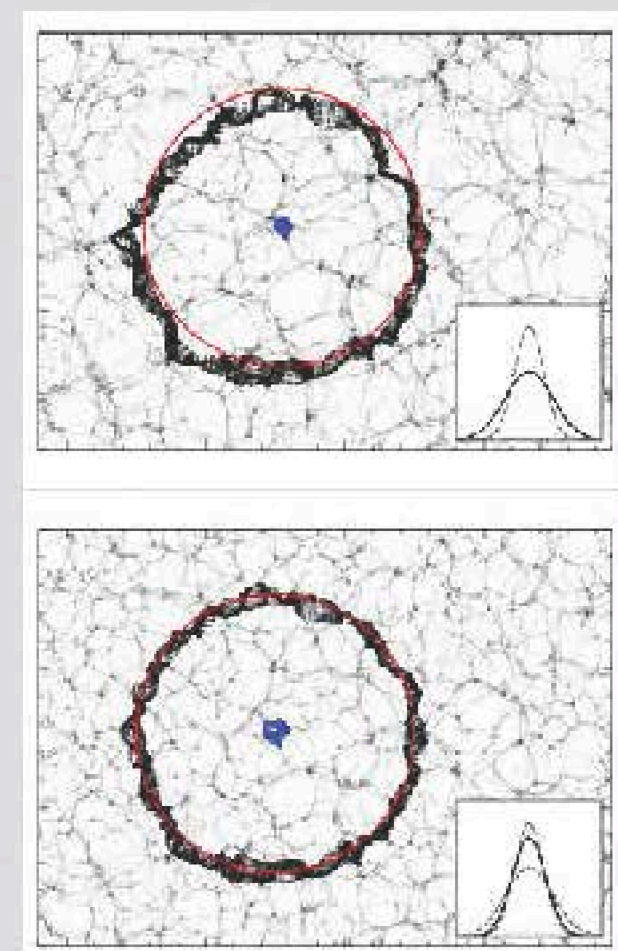


Motivation for my many simulations

Question:

How do we know the uncertainties (covariance matrix) of the 2-point correlation function, especially after reconstruction?





Motivation for my many simulations

Question:

How do we know the uncertainties (covariance matrix) of the 2-point correlation function, especially after reconstruction data process?

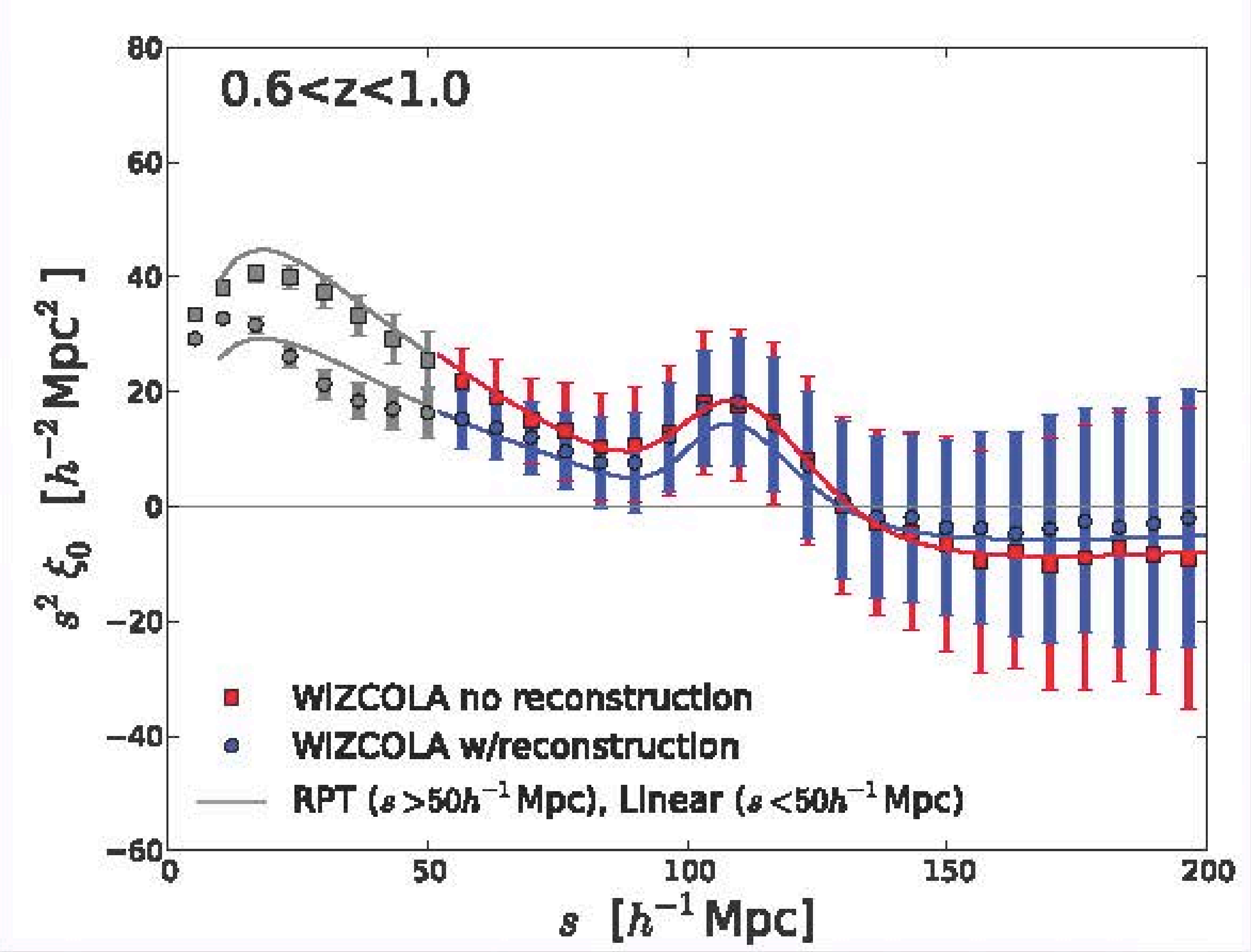
Answer:

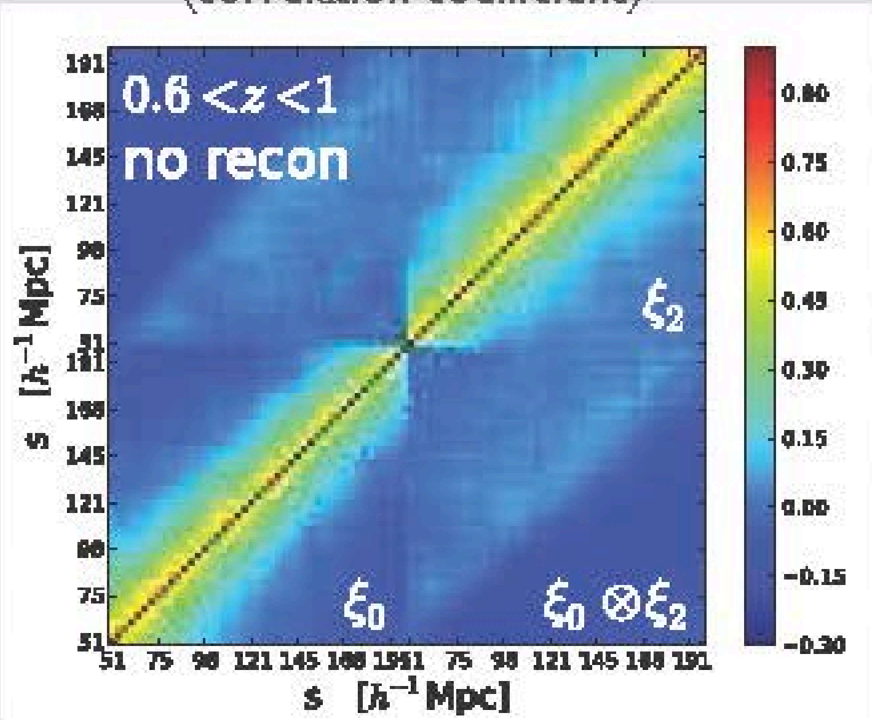
Do all the data analysis procedure for *many many* mock galaxy catalogues, and compute the covariance matrix with mocks

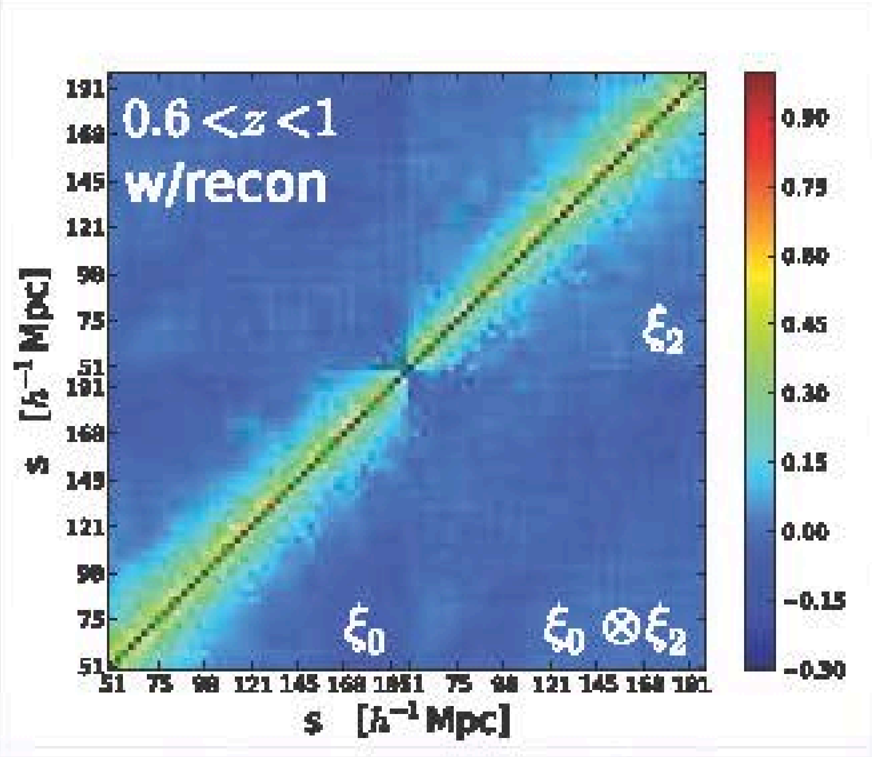
Covariance matrix

Error bars and covariance matrix from 600 mock galaxy catalogue

(correlation coefficient)

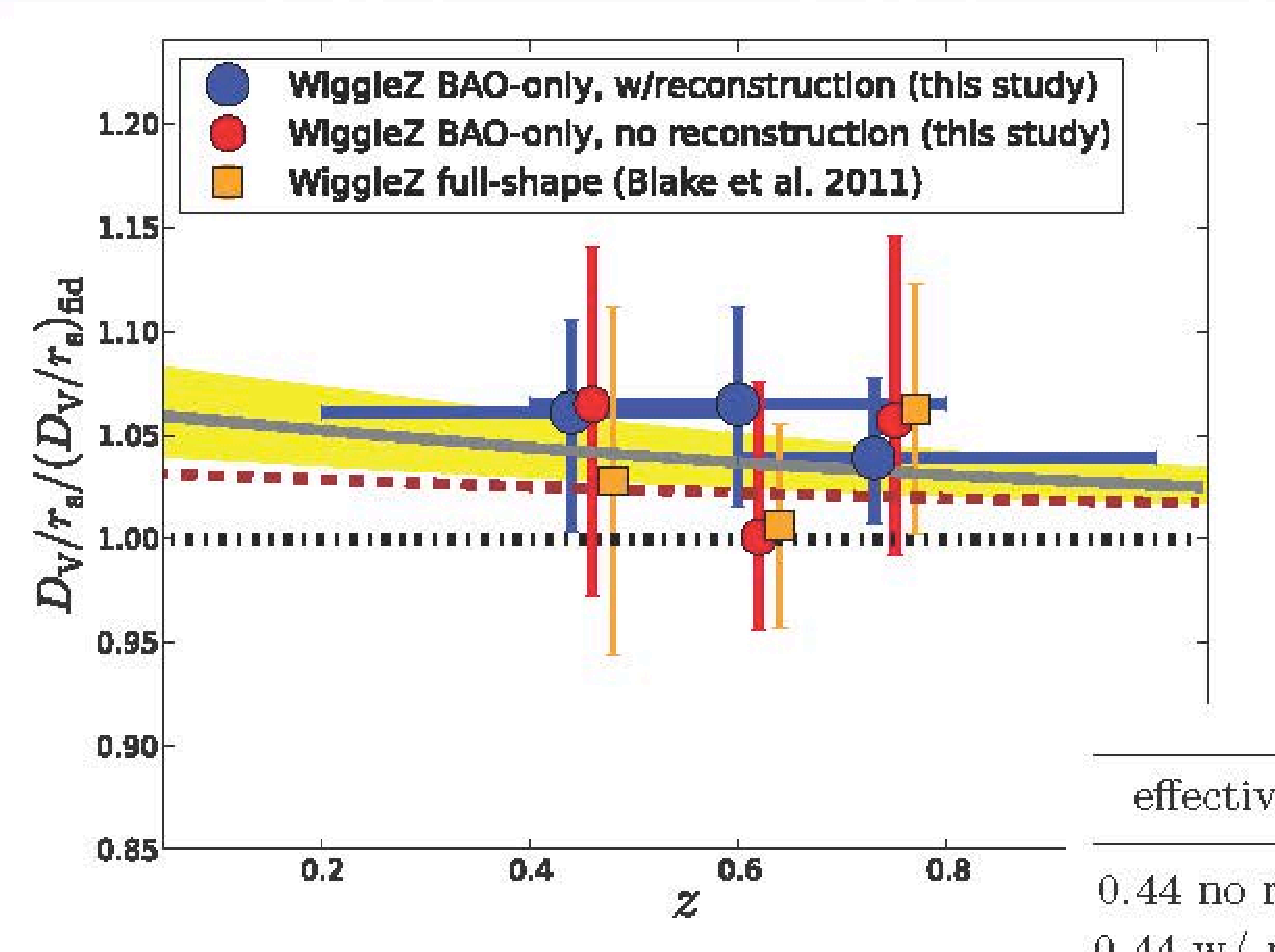






Kazin et al 2014

Cosmology result



$$D_V(z) = \left(\frac{cz(1+z)^2 D_A^2}{H} \right)^{1/3},$$

effective z	data $D_V\ (r_s^{\mathrm{fid}}/r_s)$ [Mpc]
0.44 no recon	1723^{+122}_{-151}
0.44 w/ recon	$\mathbf{1716^{+73}_{-93}}$
0.60 no recon	2087^{+156}_{-95}
0.60 w/ recon	$\mathbf{2221^{+97}_{-104}}$
0.73 no recon	2560^{+215}_{-157}
0.73 w/ recon	$\mathbf{2516^{+94}_{-78}}$

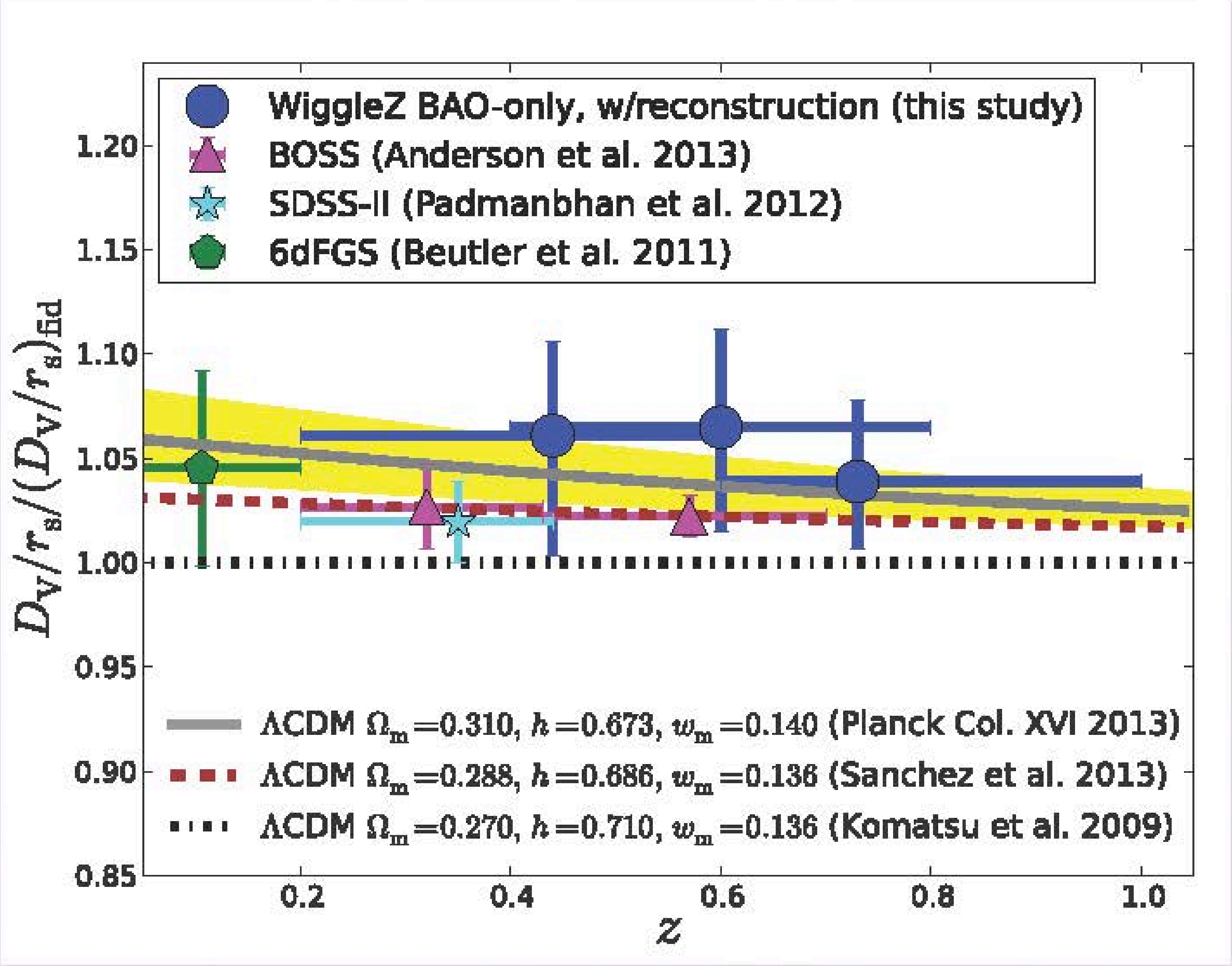
1/2 error bar for 0.6 < z < 1.0 bin

— still consistent with standard ΛCDM (Planck)

Kazin et al 2014

Cosmology result

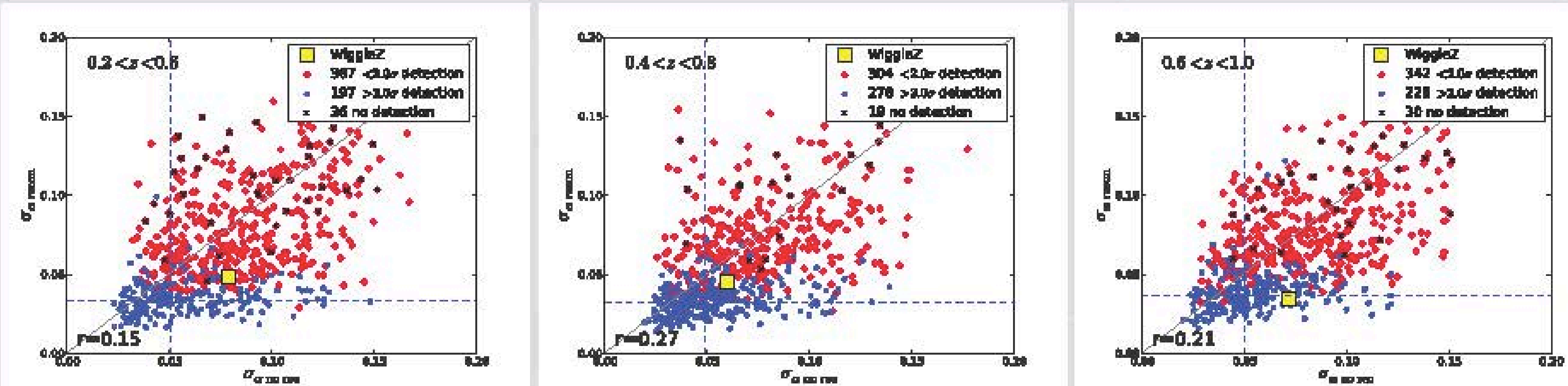
comparison with other BAO measurements



Kazin et al 2014

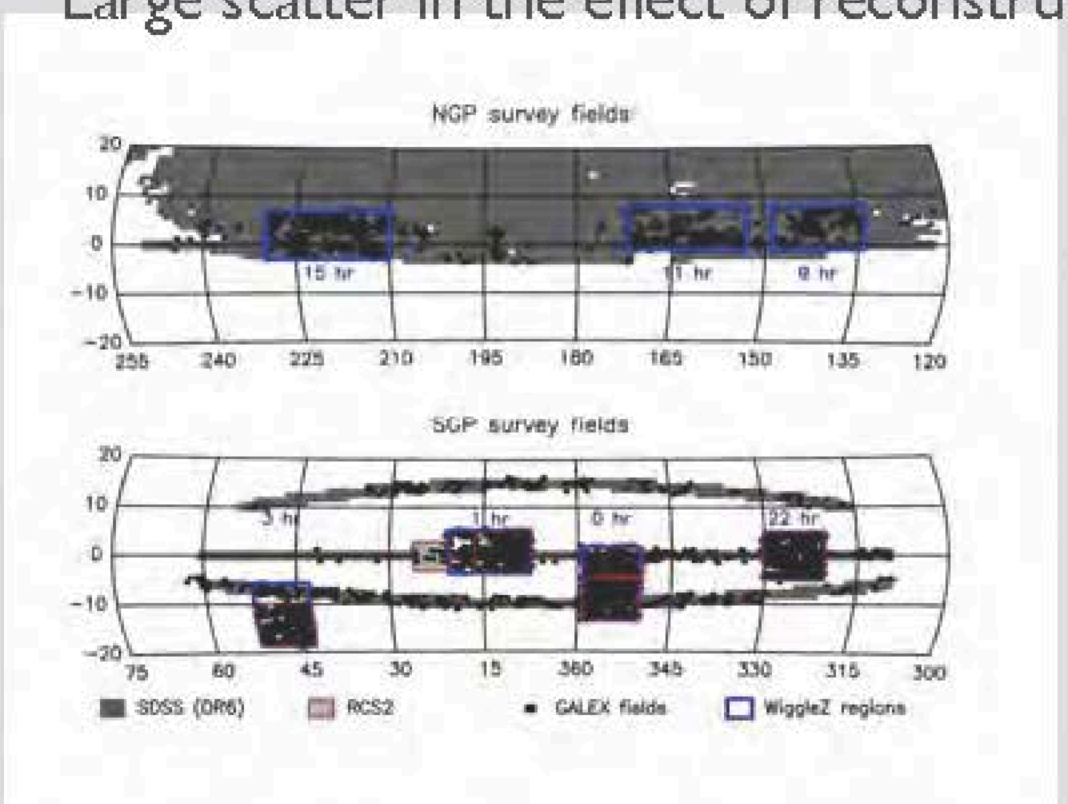
Precision before and after reconstruction

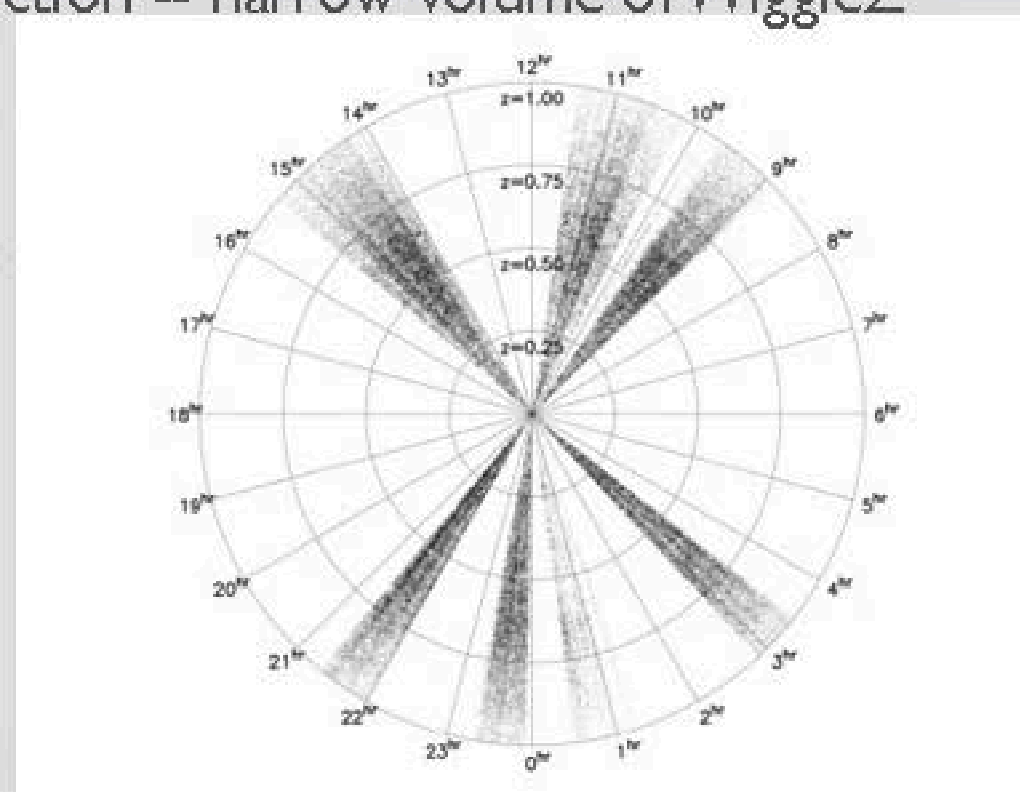
Uncertainty in $\alpha \equiv (D_{\mathrm{V}}/r_{\mathrm{s}})/(D_{\mathrm{V}}/r_{\mathrm{s}})_{\mathrm{fid}}$



Kazin et al 2014

Large scatter in the effect of reconstruction -- narrow volume of WiggleZ





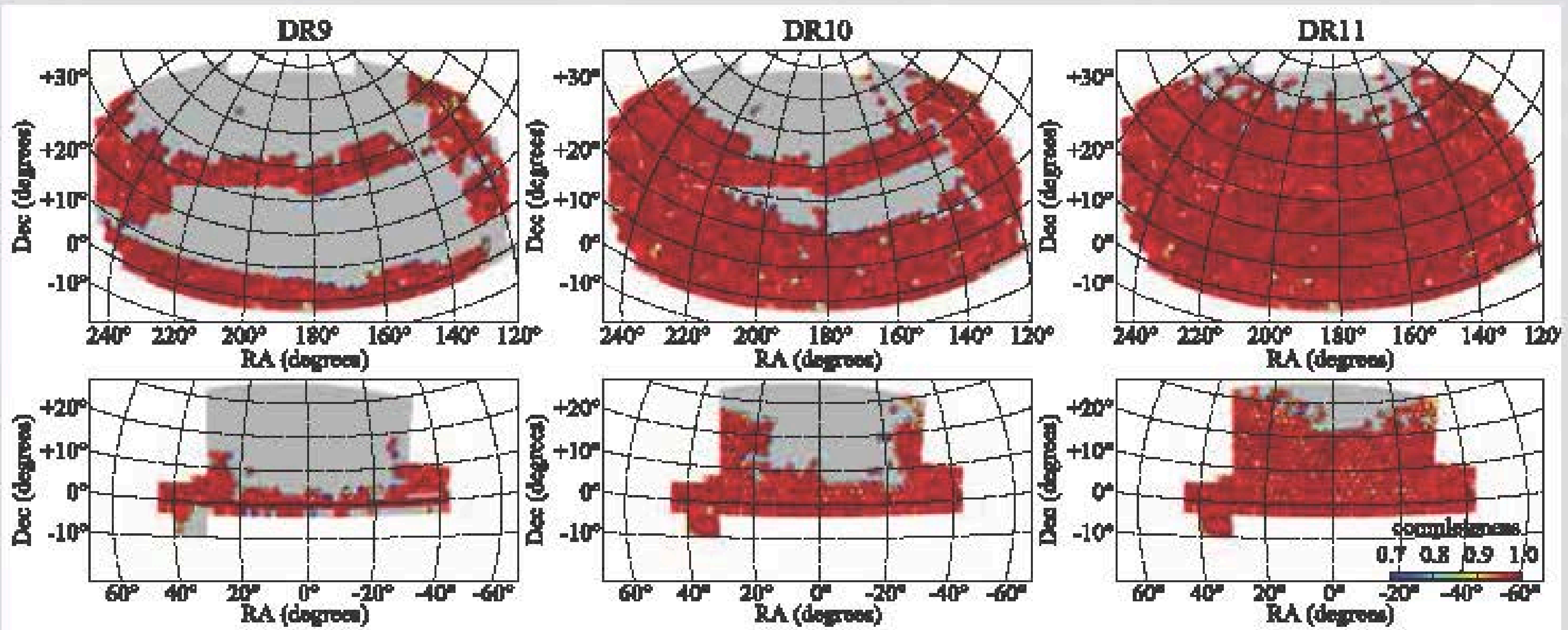
Precision before and after reconstruction

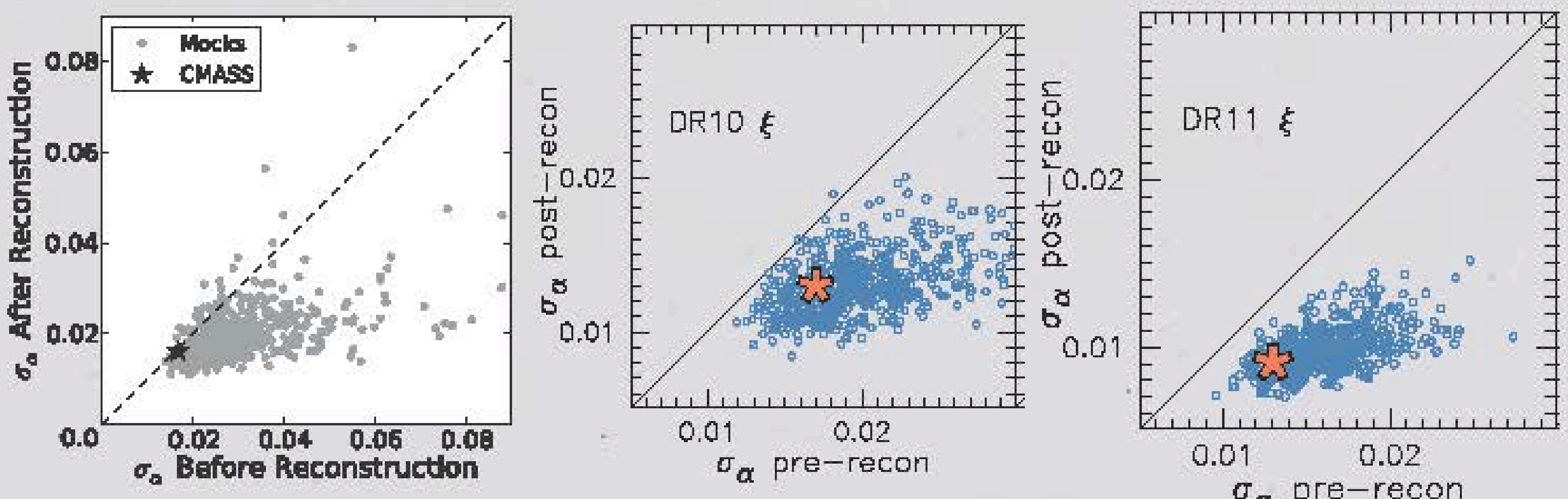
Table 2. Significance of detection of the baryonic acoustic feature

Volume	$\sqrt{\Delta\chi^2}$	$\chi^2_{\rm phys}$, $\chi^2_{\rm nw}$	Expected (All mocks)	Expected ($> 2\sigma$ subsample)
$\Delta z^{\rm Near}$ no recon	0.5	18.0, 18.3	1.4±0.8 (600)	2.0±0.8 (197)
$\Delta z^{\rm Near}$ w/ recon	1.3	24.3, 26.0	1.6±0.9 (600)	2.4±0.5 (197)
$\Delta z^{\rm Mid}$ no recon	2.1	20.5, 25.1	1.7±0.9 (600)	2.1±0.8 (278)
$\Delta z^{\rm Mid}$ w/ recon	2.1	9.1, 13.5	1.9±0.9 (600)	2.6±0.6 (278)
$\Delta z^{\rm Far}$ no recon	2.0	24.3, 28.5	1.5±0.8 (600)	2.0±0.7 (228)
$\Delta z^{\rm Far}$ w/ recon	2.9	24.0, 32.4	1.7±0.8 (600)	2.5±0.5 (228)

Precision before and after reconstruction

in BOSS





Anderson et al. 2012, MNRAS 427 3435 (DR9), 2013 arXiv:1312.4877 (DR11)

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2. <u>3600 realizations of simulations</u>

- Fast large-scale structure simulation methods
- 600 mocks for the WiggleZ survey (paper in prep)

Simulation requirements

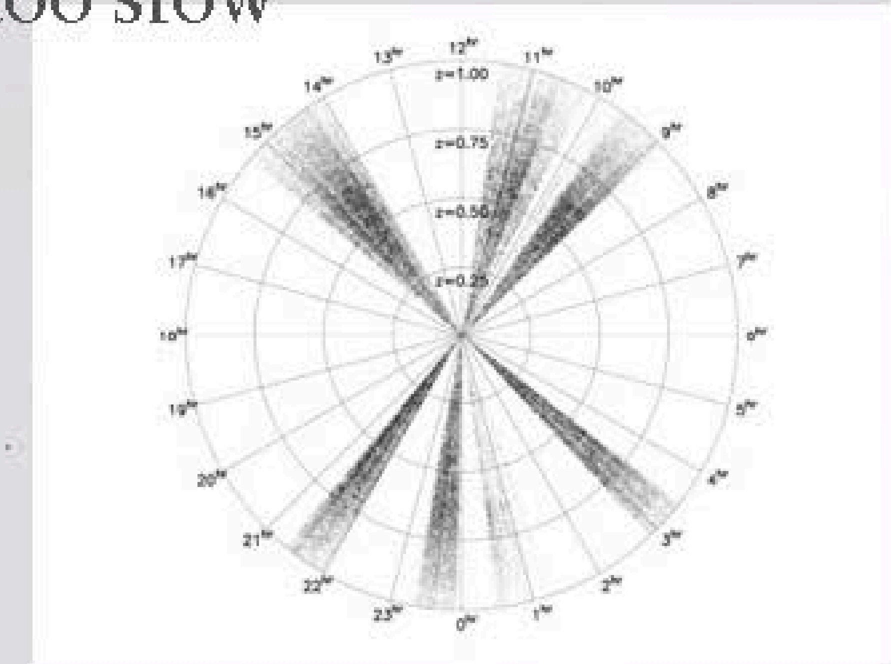
- 600 mock catalogues for each of 6 WiggleZ regions

  → **3600** independent simulations

- at least 600^3 $(h^{-1}\,\mathrm{Mpc})^3$ simulation volume

- needs to resolve $10^{12}\,M_\odot$ haloes → 1296^3 particles

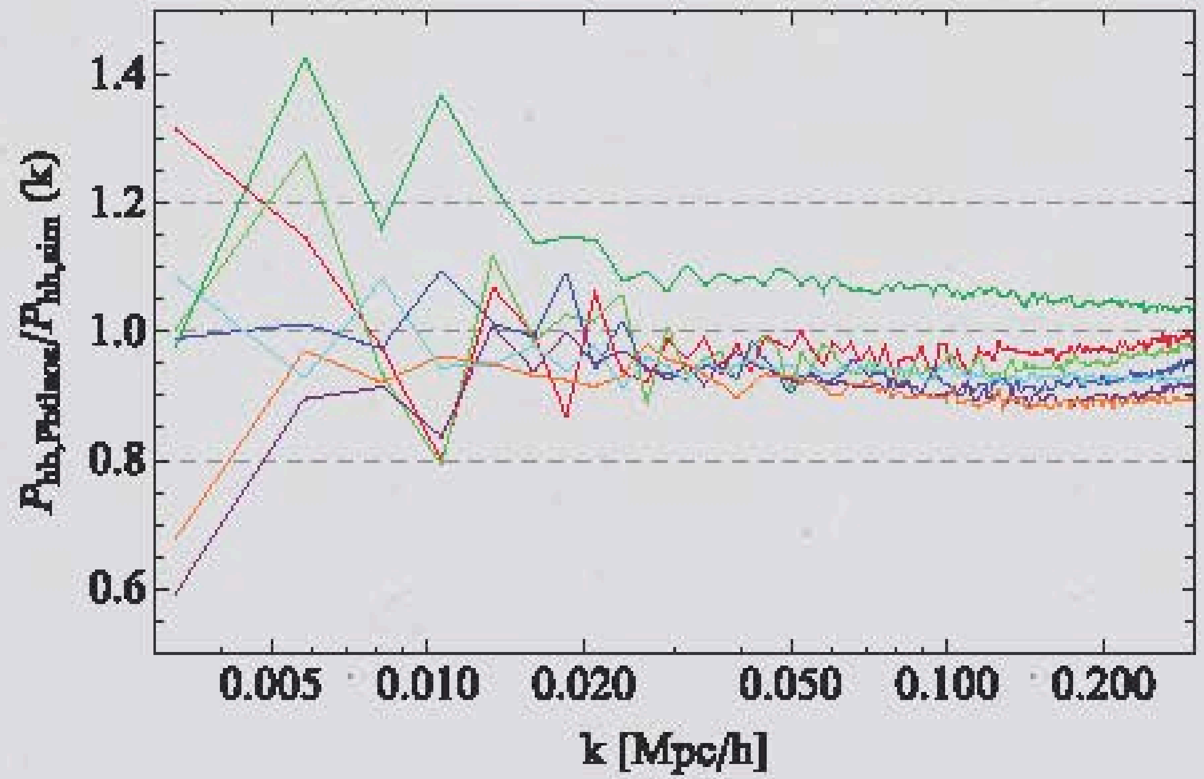
✱ But conventional N-body simulations are too slow



2LPT (PTHalos for BOSS)

Manera et al. 2013 MNRAS **428** 1036 (BOSS)

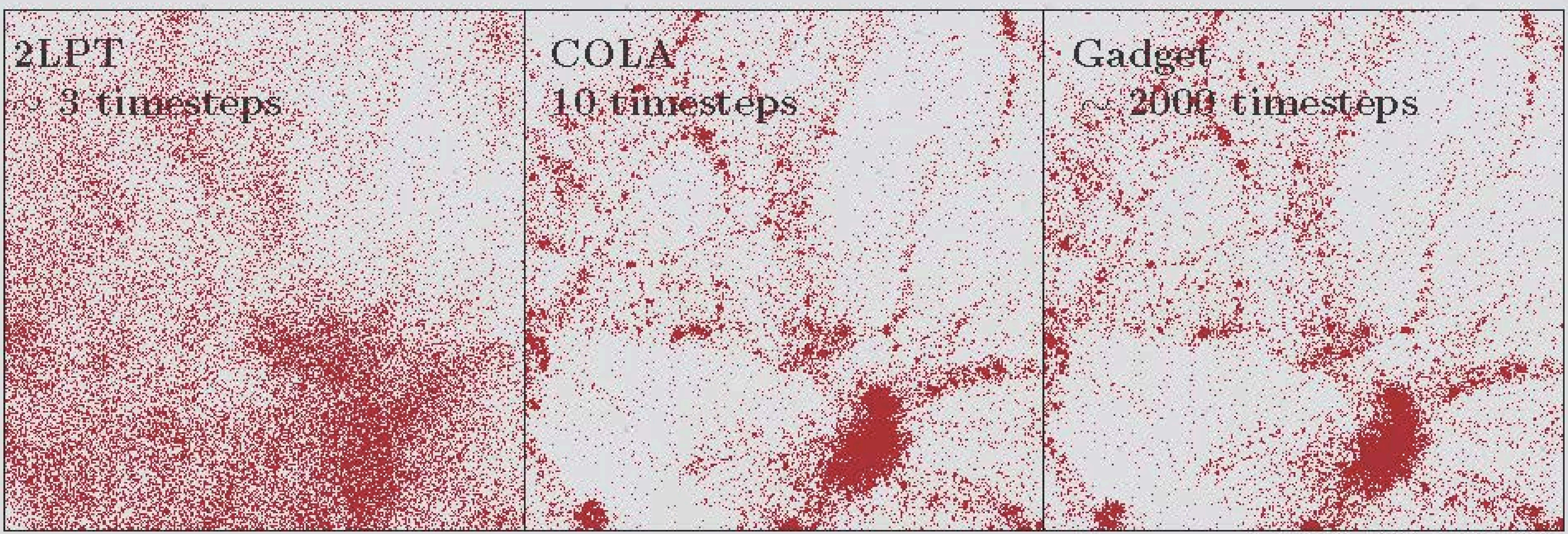
- 2nd order Lagrangian perturbation theory
- Usually for simulation initial conditions (e.g. $z \sim 50$)
- BOSS uses 2LPT instead of N-body for mocks (PTHalos)
  - ☑ Works for CMASS sample ($\sim 10^{13}$ solar mass, bias ~2)



✻ But I couldn't find PTHaloes for WiggleZ (low bias galaxies b ~ 1.1)

COLA 10-timestep simulation

2LPT + Particle Mesh (PM) force correction



Tassev et al. 2013 JCAP **06** 36

2LPT (*left*): very fast but resolves high-mass haloes only $\sim 10^{13}\,M_\odot$

COLA (*middle*): acceleration: $a_{COLA} = a_{PM} - a_{2LPT}$

Leap-frog "kick": $v_{COLA} \mathrel{+}= a_{COLA}\,\Delta t$

Leap-frog "drift": $x \mathrel{+}= \Delta\psi_{2LPT} + v_{COLA}\,\Delta t$

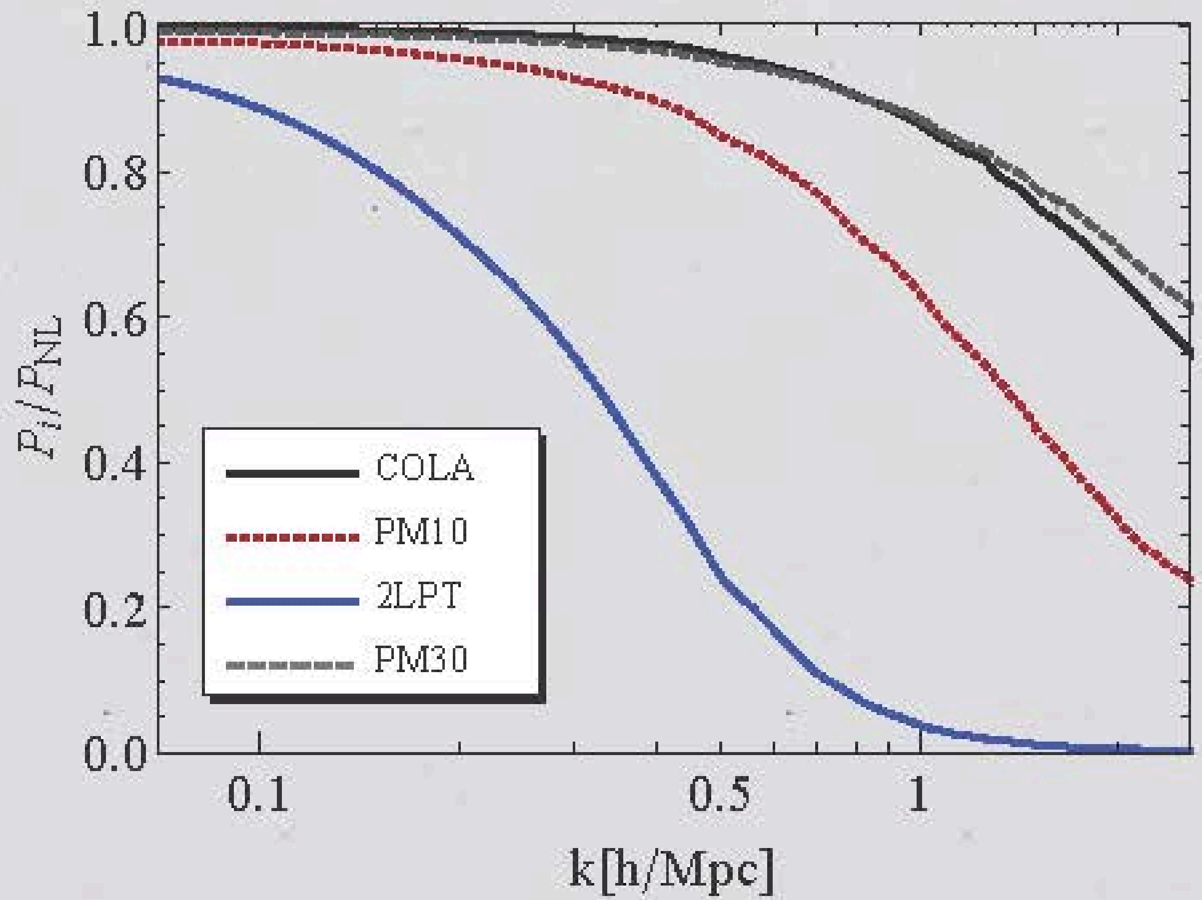
COLA 10-timestep simulation

Tassev et al. 2013 JCAP **06** 36

- Accurate matter power spectrum
- Good halo mass ~ 5% accuracy for COLA

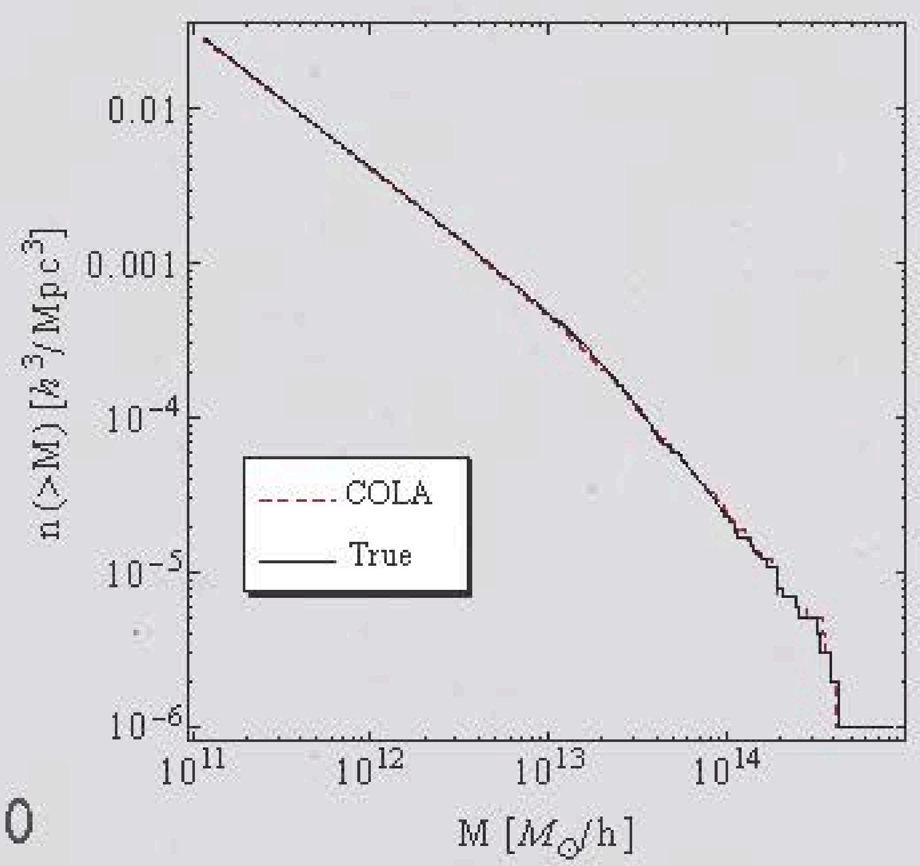
  30 % error for conventional 10-timestep Particle Mesh (PM)
- 10 COLA timesteps ~ 30 PM timesteps
- More than 100 times faster than usual simulations

Matter power spectrum



z = 0

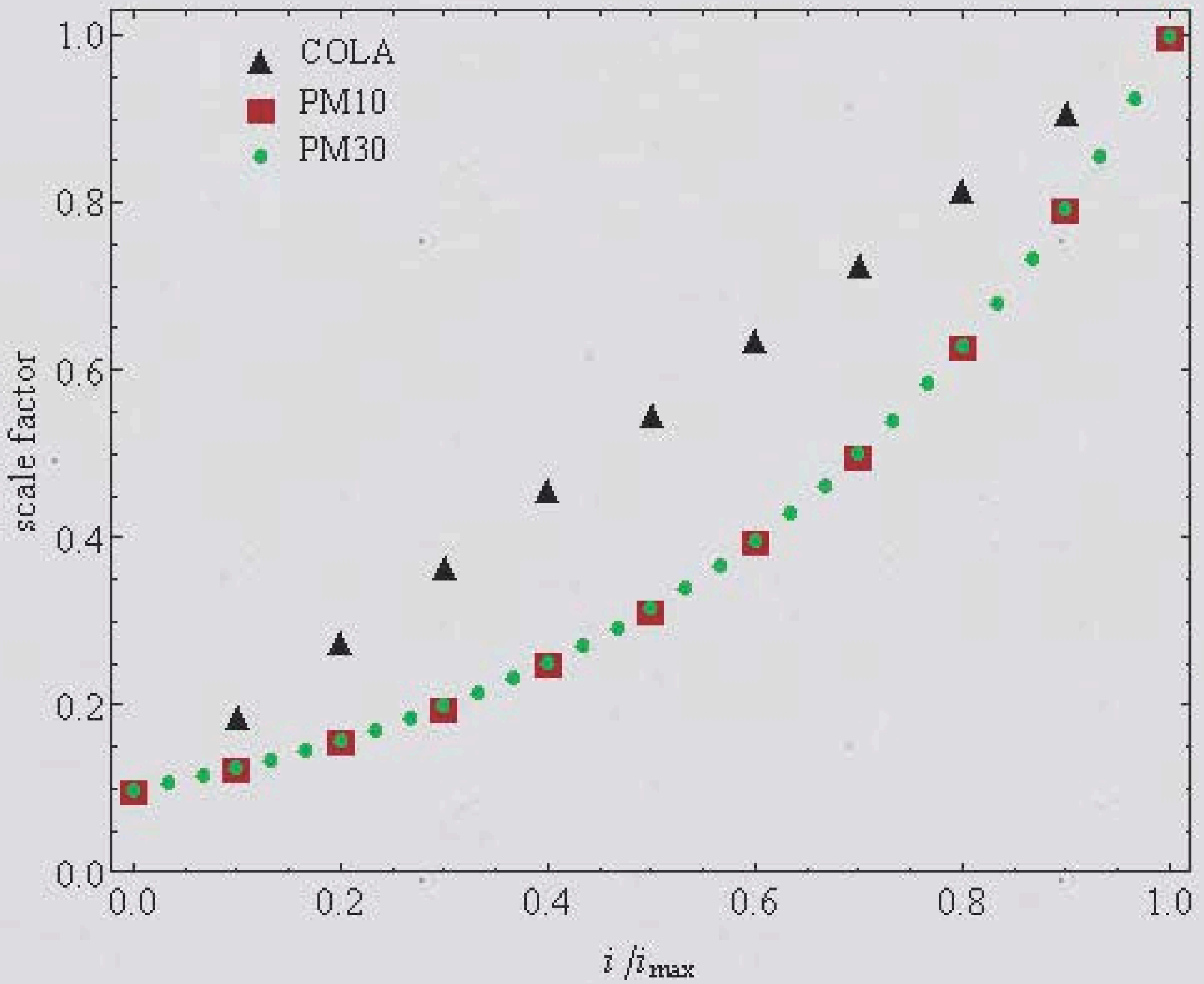
Mass function



Timestep distribution

COLA can use large timestep in quasi-linear regime (high z)

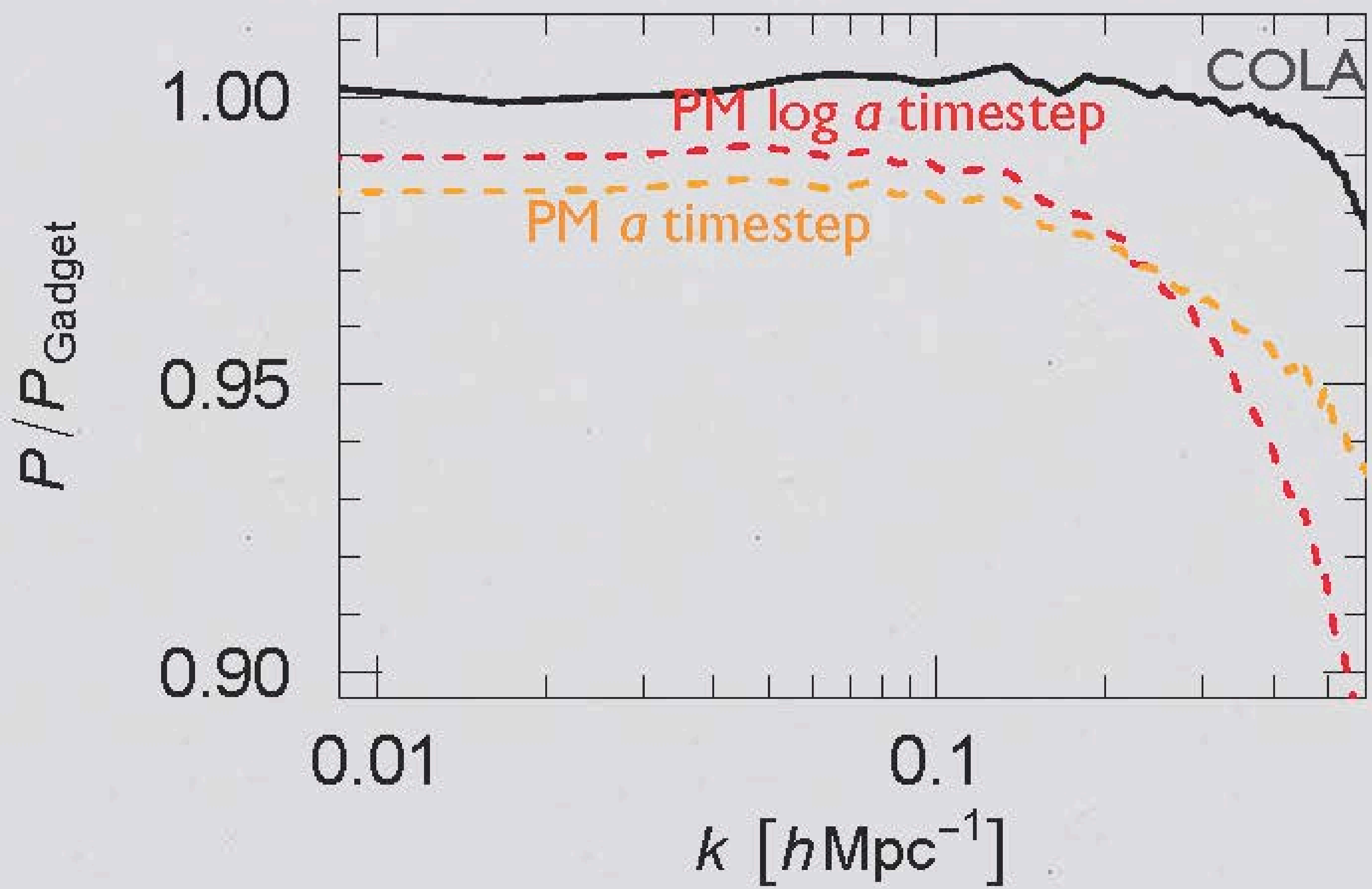
- PM — equally spaced in log a [$\Delta a \propto a$ or $\Delta t \propto H(a)^{-1}$]
- COLA - equally spaced in a



Large PM timestep at low z is causing halo mass error

Tassev et al. 2013 JCAP **06** 36

Timestep distribution



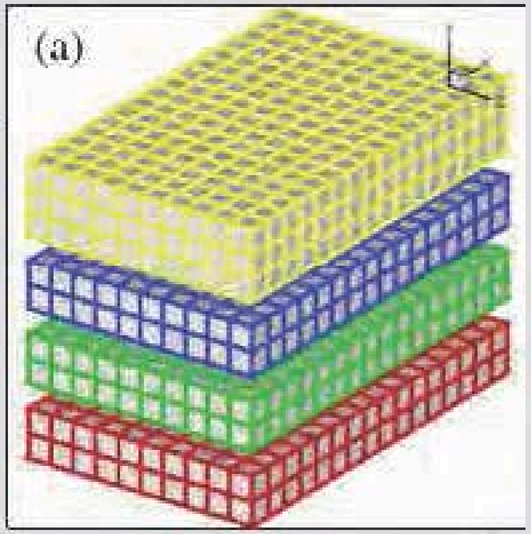
1-2 % error in large scale growth factor with 10-step PM, COLA is much better

Timestep equally spaced in log a gives slightly better growth factor for PM

Wiz-COLA simulation (my work)

- Parallelized the serial COLA code by Tassev et al.

  Simple slab decomposition with FFTW library



- Integrated the on-the-fly halo finder (FoF)

  (No disk space for post processing)

- Writes snapshots at given redshifts z= 0.44, 0.6, and 0.73
- Used 216 cores at SwinSTAR (RAM requirement)
- 15 minutes/simulation → 200,000 core hours in total

figure: http://www.2decomp.org/

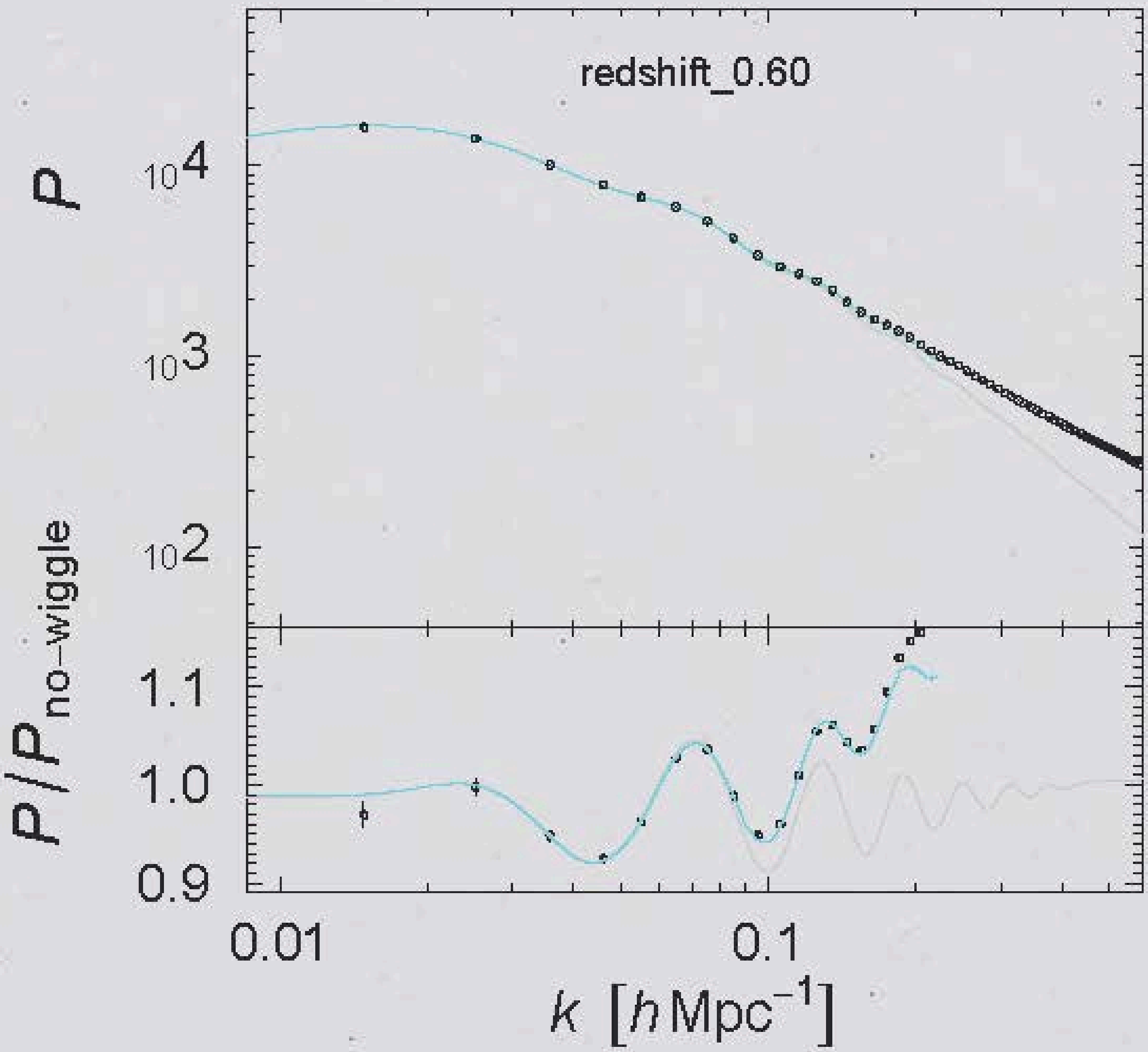
Details of computation time

	[sec]	
Init	4.2	0.7%
2LPT	15.6	**2.8%**
COLA	450.3	**79.3%**
FFT	392.1	**69.1%**
assign	9.7	1.7%
force_mesh	15.5	2.7%
pforce	19.2	3.4%
check	3.3	0.6%
communication	6.7	**1.2%**
evolve	2.2	0.4%
Snapshot analysis	97.5	17.2%
communication	6.0	1.1%
kd_build	8.3	1.5%
kd_link	22.4	4.0%
interpolate	5.4	0.1%
serial linking	40.5	7.1%
smalldata	19.7	3.5%

568 sec per realization with 324 cores
Raijin supercomputer in NCI Australia

Wiz-COLA matter power spectrum

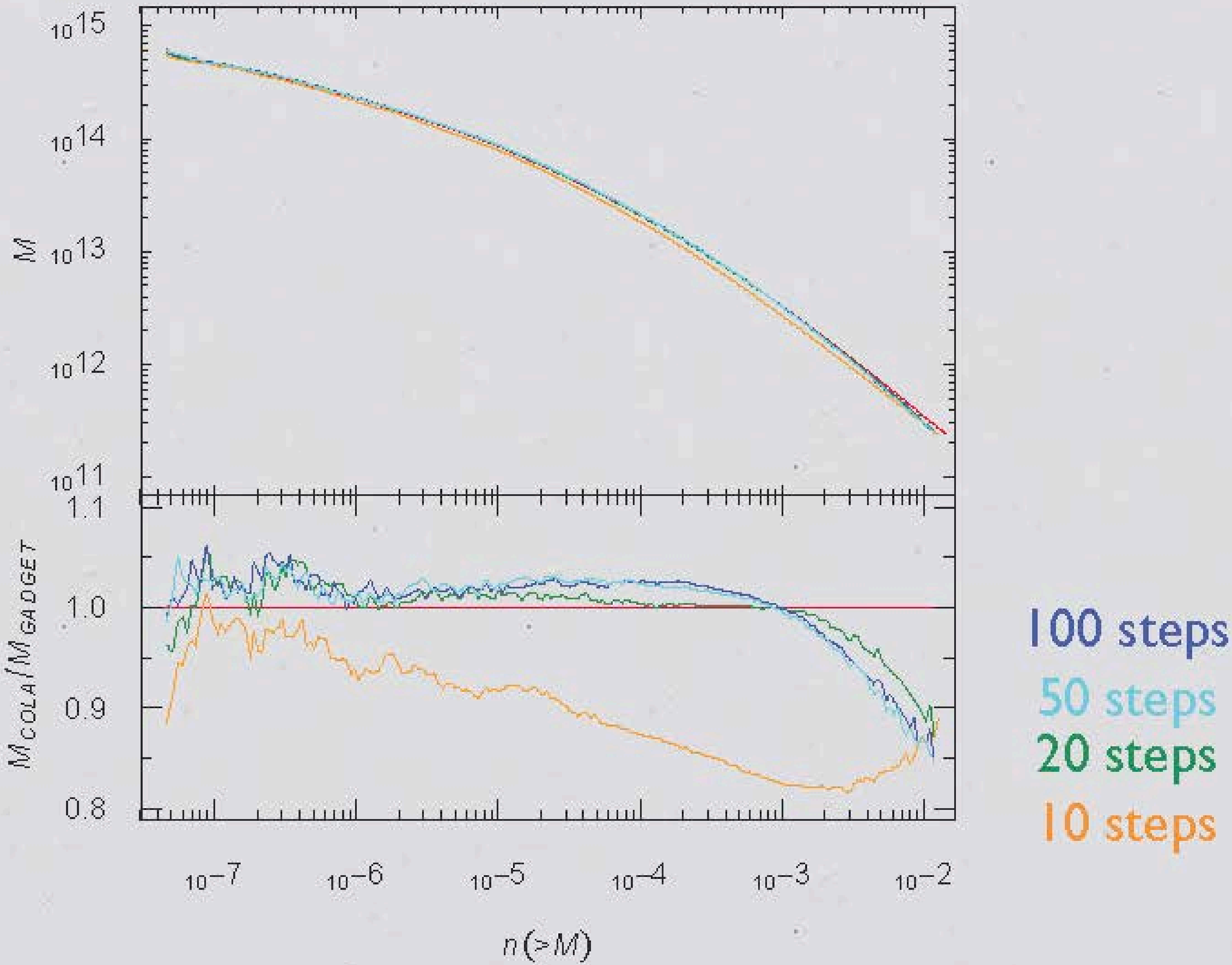
(preliminary. mean of 1800 realizations)



Blue line: MPTBREEZE Crooce et al. 2012 MNRAS **427** 2537

Mass function

(preliminary results)



- Mass resolution at low end is limited by force resolution not timestep

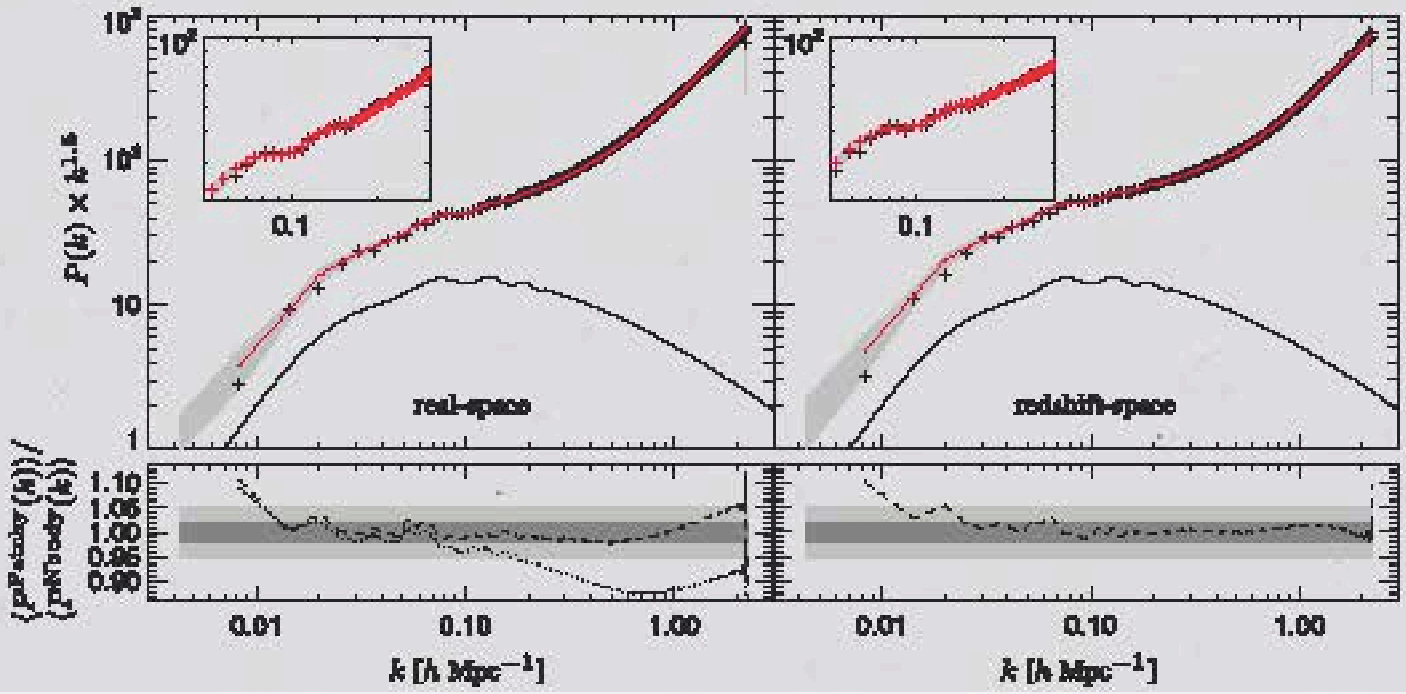
Halo mass should match better (work in progress)

Need to resolve haloes?

Price of resolving haloes is expensive -- FFT with ×3 finer grid.
New ideas are coming up to create halo catalogue without resolving.

- de la Torre & Peacock 2013, MNRAS **435** 743
- QPM (White et al. 2014, MNRAS **437** 2594)
- PATCHY (Kitaura et al 2014, MNRAS **439** 21)

1. Generate smooth density field using fast methods (2LPT, ALPT, PM)
2. Randomly "populates" **haloes** depending on the density field



Kitaura et al. 2014

Populates haloes with mock galaxies

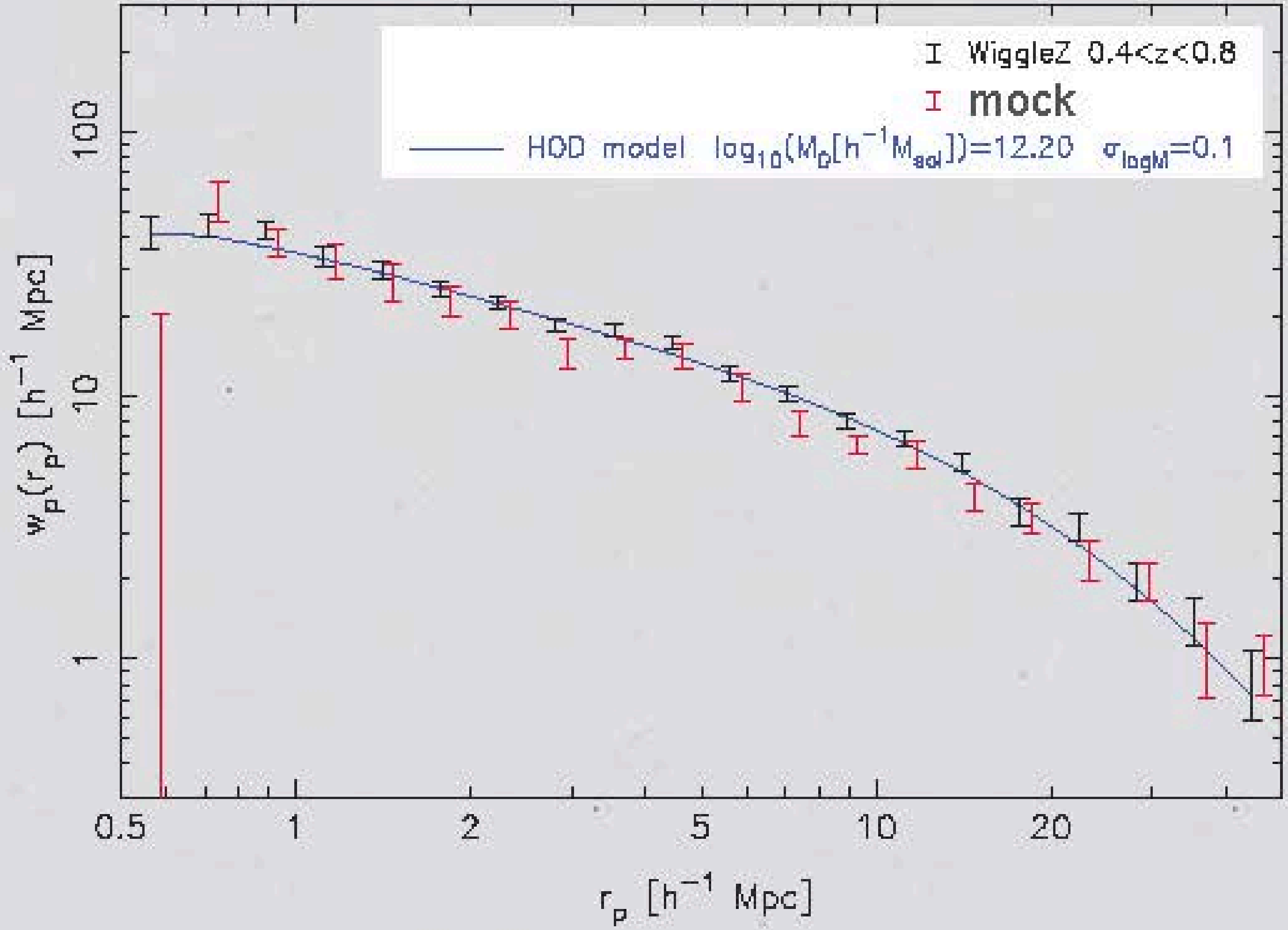
Making mock catalogue: step 1

Using a Gaussian Halo Occupation Distribution (HOD)

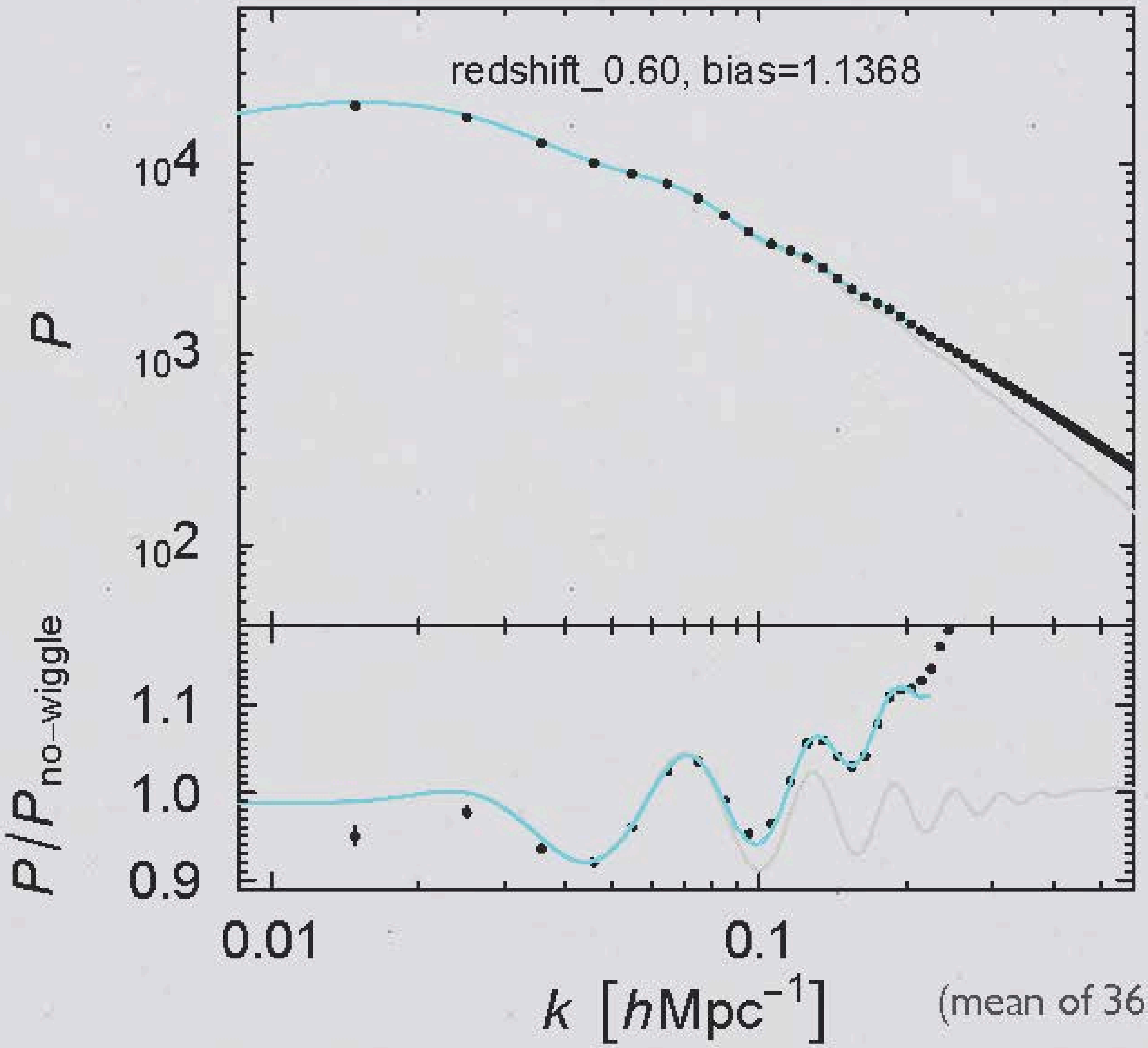
Probability that a halo of mass M hosts a WiggleZ galaxy is set to:

$$P = A \exp\left[-\frac{(\log M - \log M_0)^2}{2\sigma_M^2}\right]$$

- Assumed $\sigma = 0.1$
- $\log_{10} M_0 = 12.3$ (COLA halo mass)
- Satellite galaxies are not important in WiggleZ



Galaxy Power Spectrum (mock mean)



(mean of 3600 realizations)

Simulation box remapping

Carlson & White 2010 ApJS **190** 311

Making mock catalogue: step 2

$(600\ h^{-1}\ \mathrm{Mpc})^3$ box

$\rightarrow 1039h^{-1}\mathrm{Mpc} \times 490h^{-1}\mathrm{Mpc} \times 424h^{-1}\mathrm{Mpc}$

$\sqrt{3}$ (for $0.2 < z < 0.6$)

$\rightarrow 849h^{-1}\mathrm{Mpc} \times 735h^{-1}\mathrm{Mpc} \times 346h^{-1}\mathrm{Mpc}$

$\sqrt{2}$ (for $0.4 < z < 0.8$ and $0.6 < z < 1.0$)

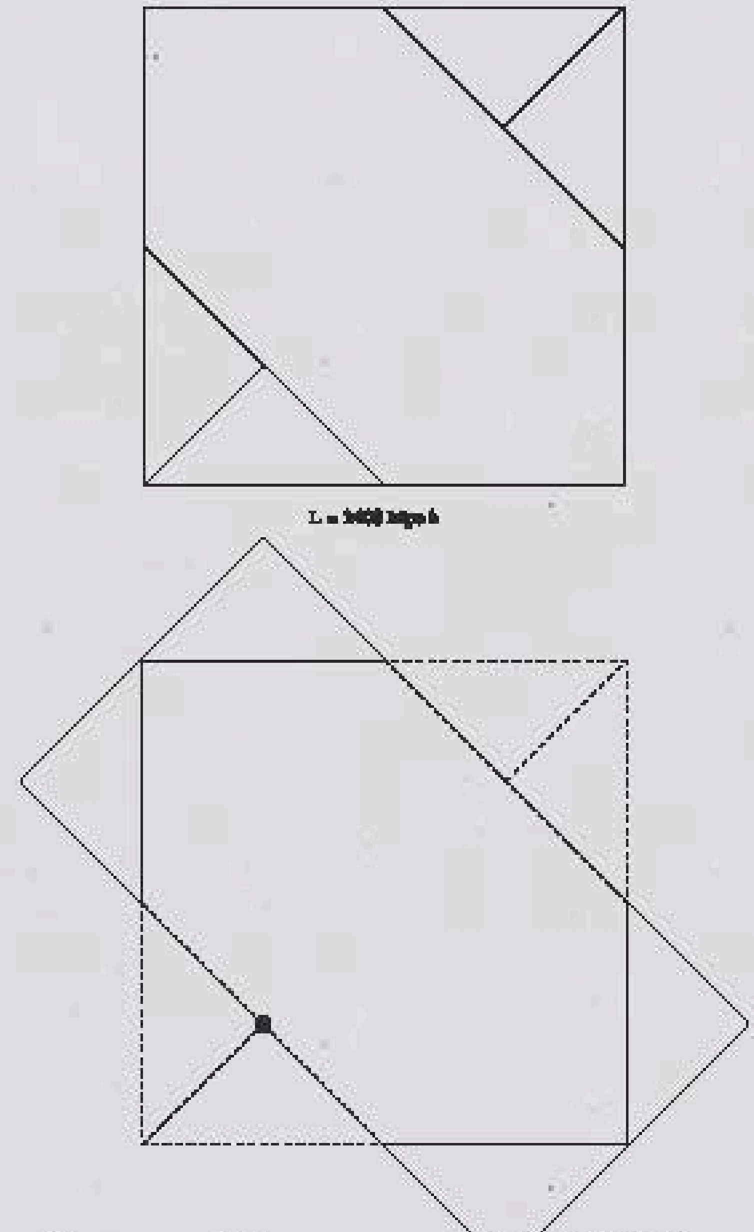
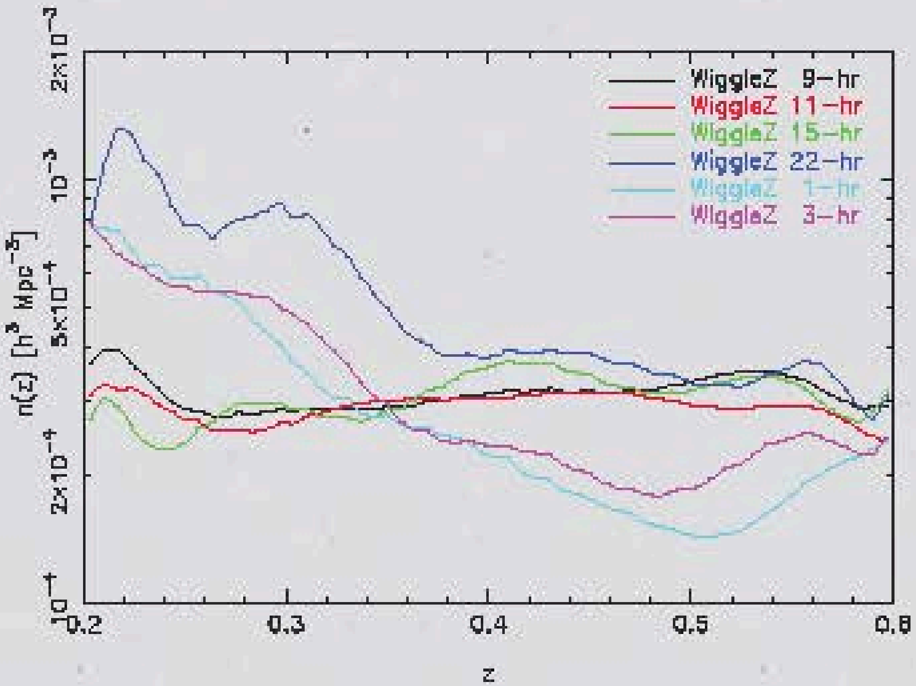
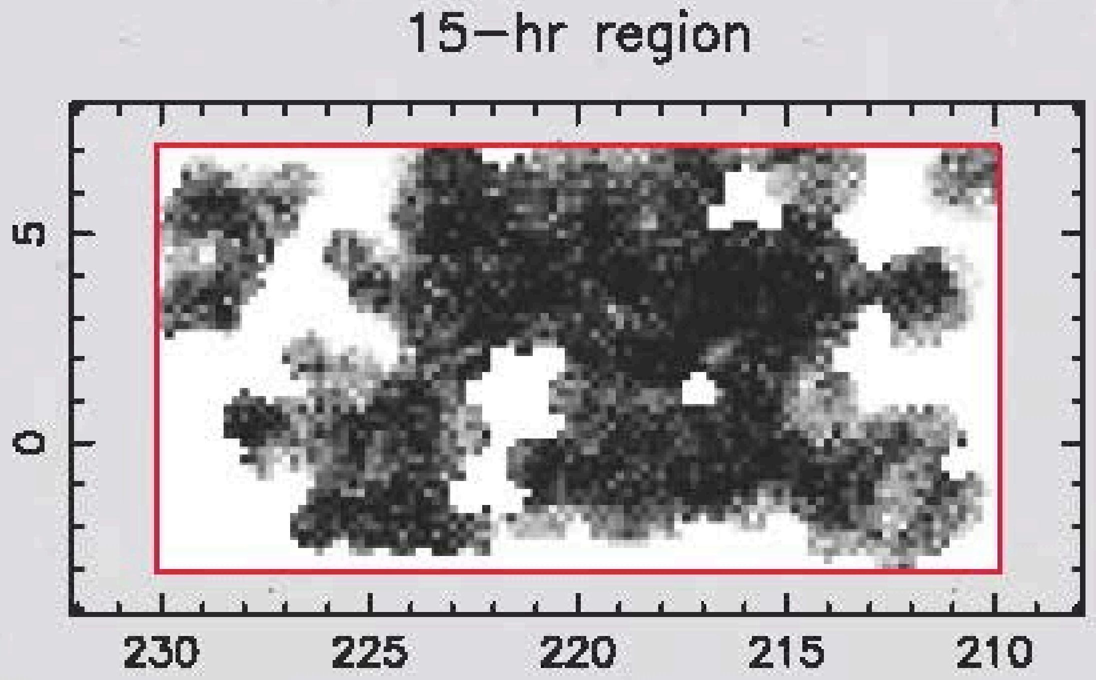


figure: Manera et al. 2013

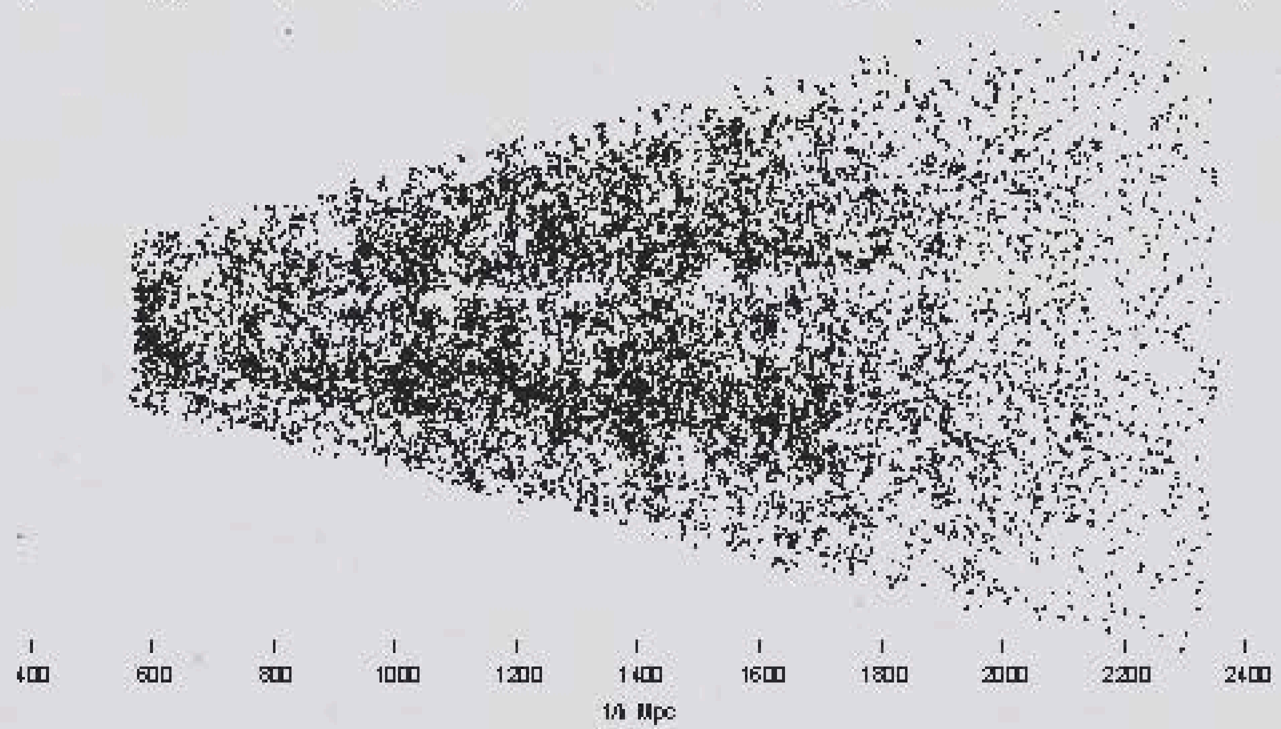
Apply selection function

Making mock catalogue: step 3



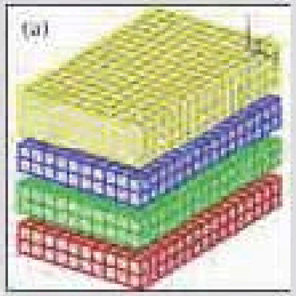


number density × angular completeness (Blake et al 2010, MNRAS **406** 803)



Future of many mock galaxies

- Demand of many fast simulation is growing
  - TAIPAN – larger volume BAO for 1% Hubble constant H_0
  - ASKAP/WALLABY -- higher mass resolution
  - eBOSS – wants mocks better than PTHalo
  - Euclid, SKA – requires both resolution and volume
- Better parallelization needed for my code for larger simulation
  - slab decomposition of FFTW is not ideal



- No need to resolve haloes?
  - Comparison project in July at Madrid (Knebe et al. http://popia.ft.uam.es/nIFTyCosmology/)

Summary

- 3600 simulations for low-bias mock galaxies catalogues
  - Complicated data analysis technique (reconstruction) requires many realizations of simulations for error evaluation
  - Parallelized COLA simulation code
  - Ran with 1296^3 particles in a 600 h^{-1} Mpc box
  - Resolves 10^{12} h^{-1} solar mass halos with10 time steps, $(3\times1296)^3$ PM grids
  - With reasonable computational resource 216 cores, 200k hours for 3600 simulations
- Revised WiggleZ BAO measurement (Kazin et al. 2014)
  - improved the distance by a factor of 2 in $0.6 < z < 1.0$ (luckily)
  - consistent with the standard ΛCDM
- Many other ideas without resolving haloes.
  - I'm interested in the requirements / requests from observers here