Measuring the Universe with galaxy clustering and motions

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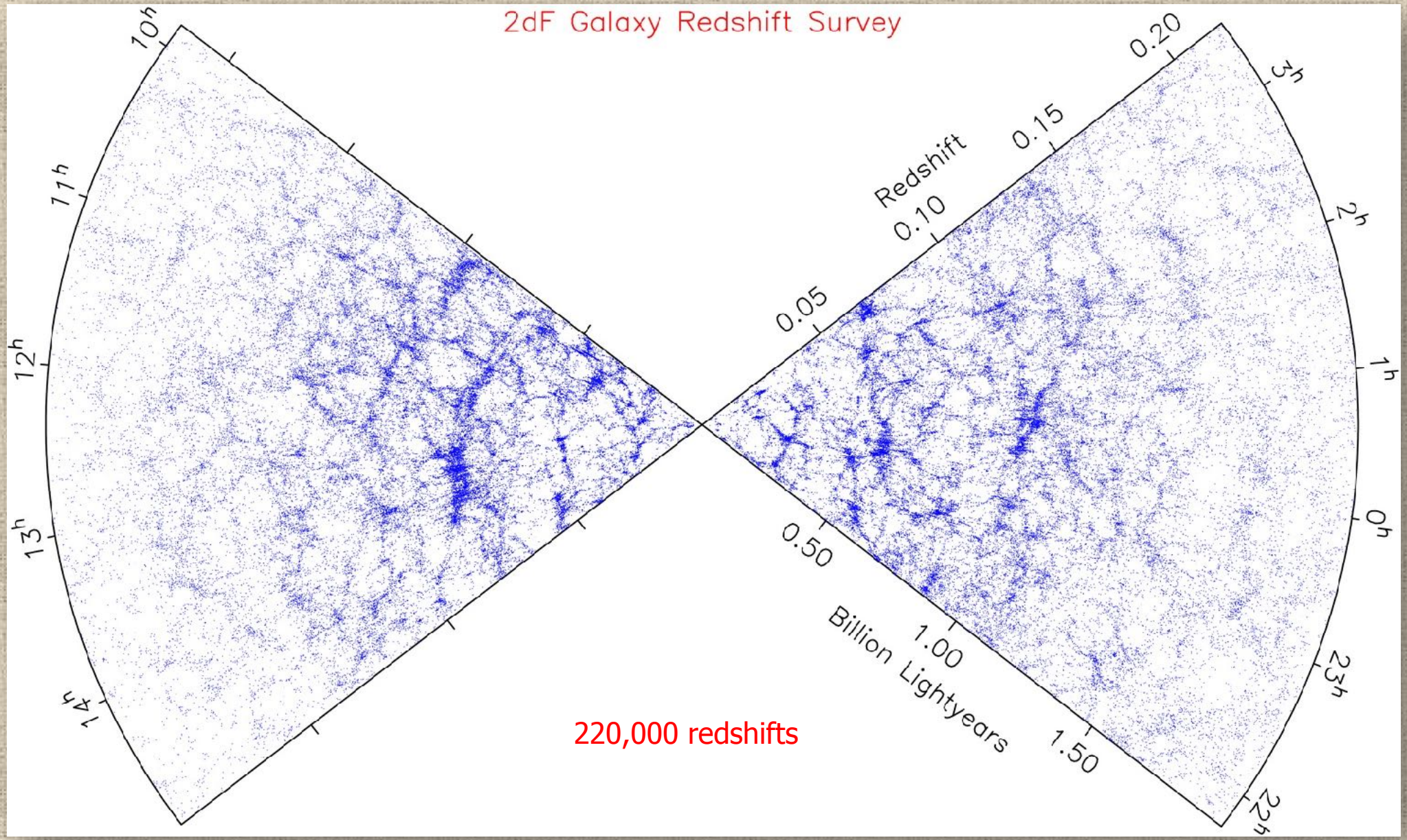
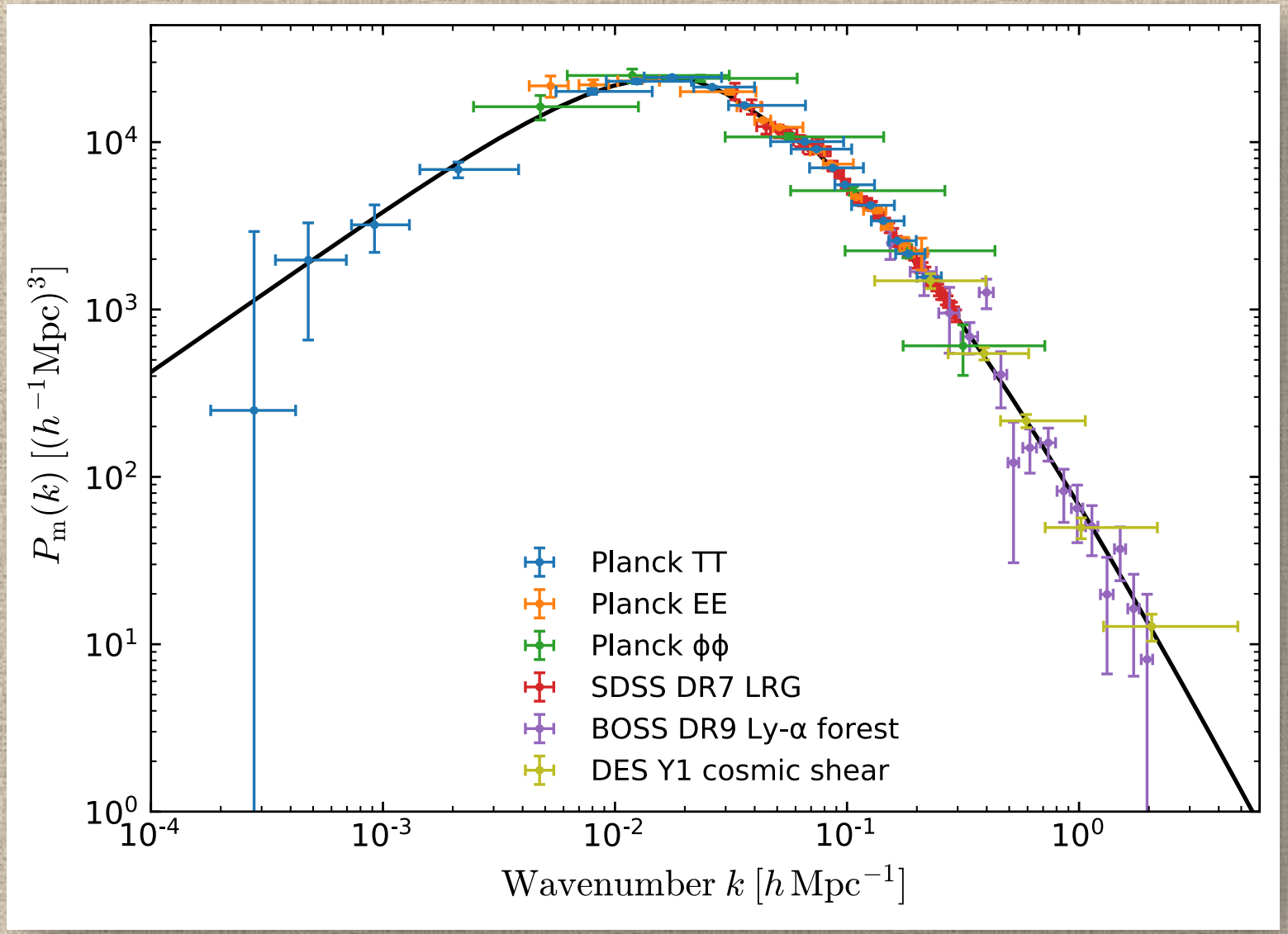
Large-scale structure at z<0.2: a pillar of the standard cosmological model

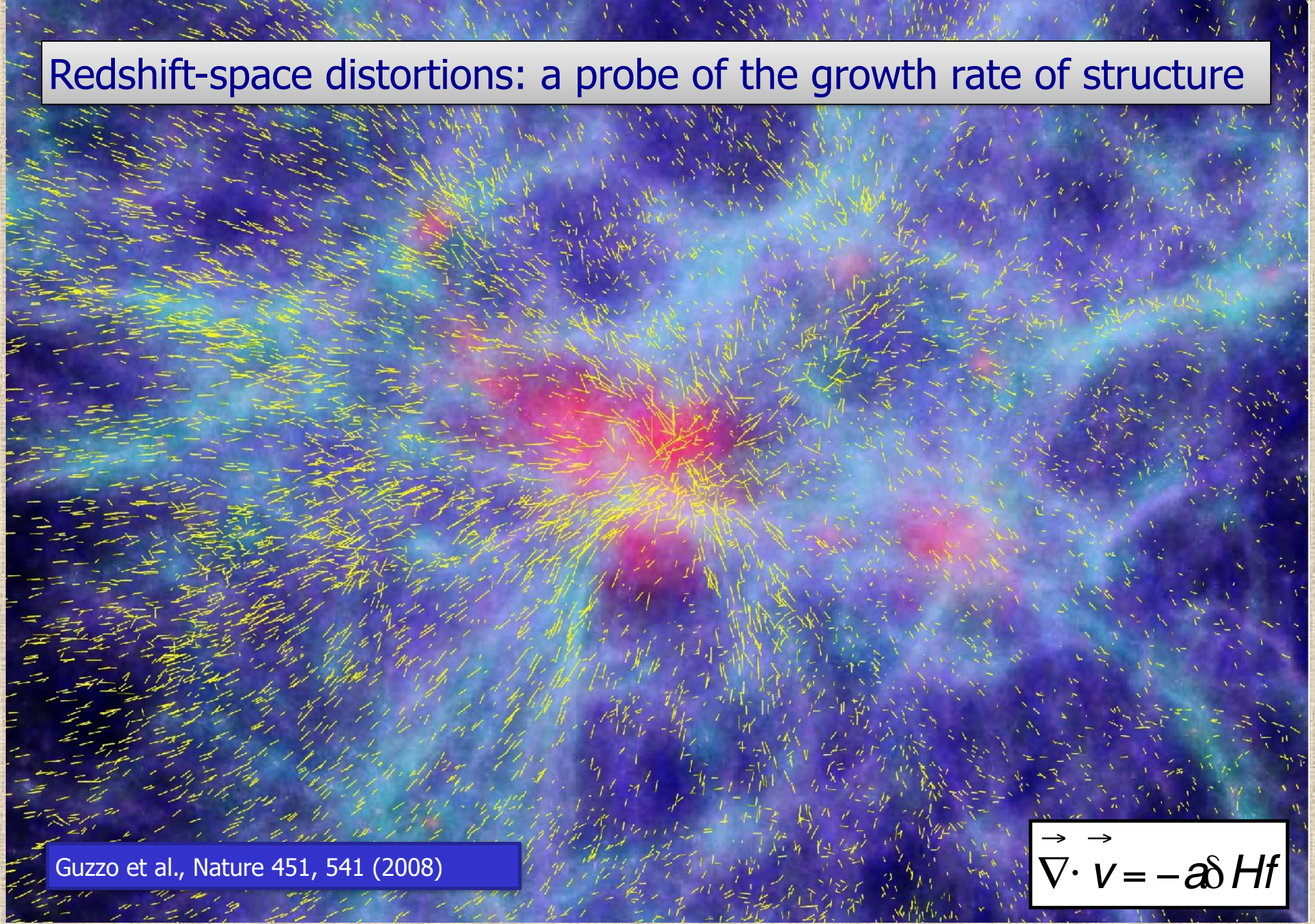


The power spectrum of density fluctuations



Planck 2018 - I

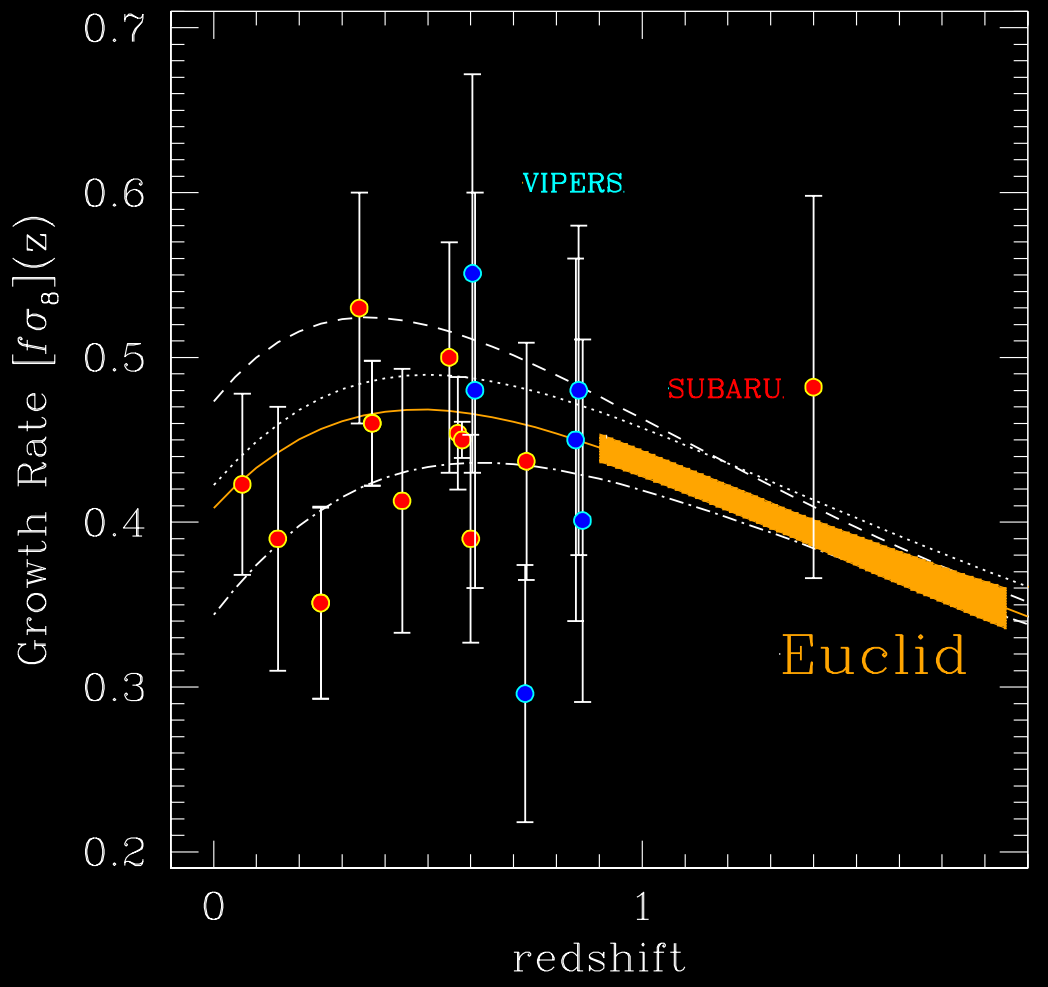
Redshift-space distortions: a probe of the growth rate of structure



Guzzo et al., Nature 451, 541 (2008)

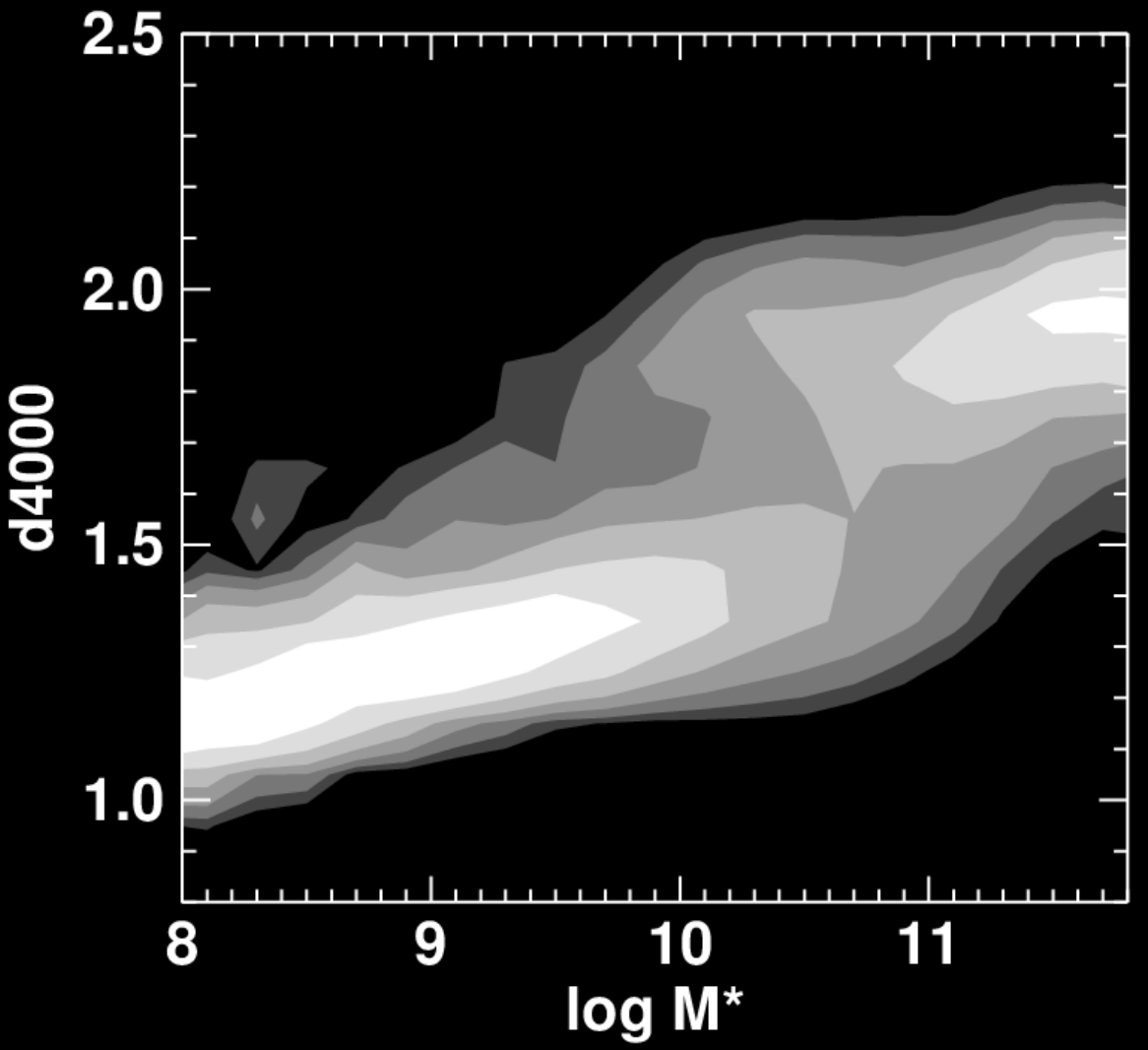
$$\vec{\nabla}\cdot\vec{v} = -a\delta Hf$$

Growth rate from RSD



LG (2017), Euclid forecast based on Galaxy Clustering WG Interim Review Report

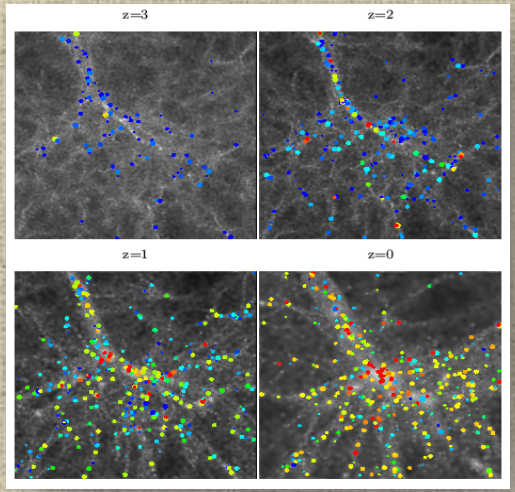
SDSS/2dFGRS: much more than point distributions in z space…



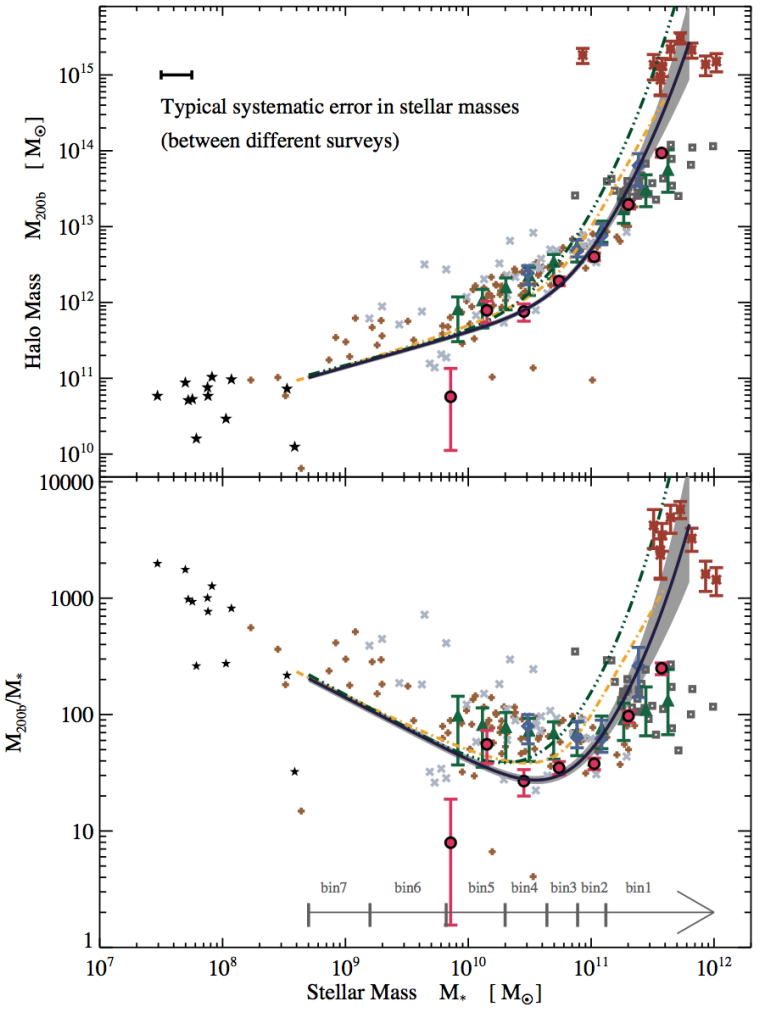
Statistical properties of the galaxy population to high precision

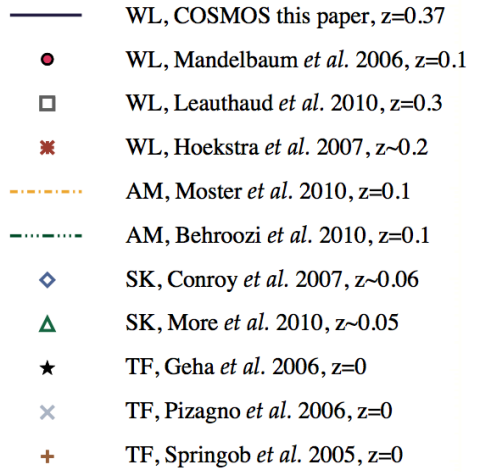
Z<0.2: SDSS (Kauffman+)

We need to understand galaxies, to do cosmology...



Kauffman & Diaferio 1998





Leauthaud et al. 2012

What I will talk about

1. The VIPERS survey at ESO VLT: structure and galaxy evolution back in time

2. Improve RSD measurements: better models and/or better galaxies?

3. Forward modelling galaxy clustering and RSD

→ Aim at z~1, with **volume and density** comparable to 2dFGRS and SDSS, sampling the **full galaxy population with their physical and structural properties**

VIMOS @ VLT fills unique niche in density-area observing space

At VIPERS depth: ~100 gal/quadrant →
400/224 gal/arcmin^2 ~ **6000 gal/deg^2**

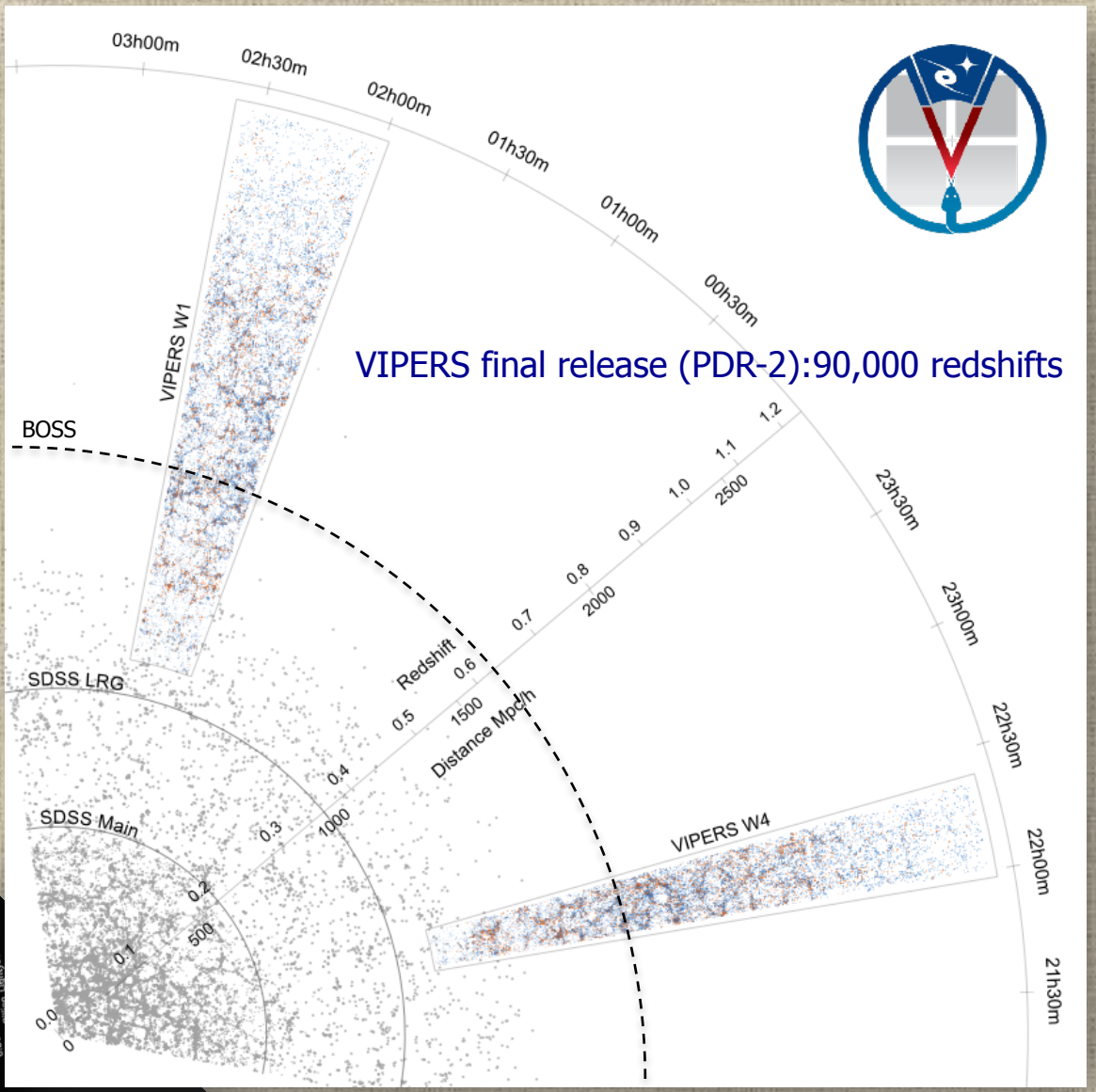
VIPERS in the context of modern LSS surveys

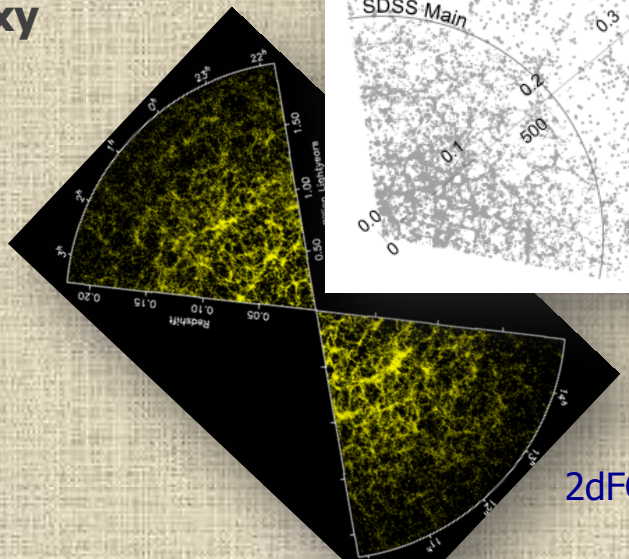
State of the art:

- SDSS-III BOSS (e.g. Alam+ 2016)
- WiggleZ (Blake+ 2014)
- **VIPERS** (Guzzo+2014, Scodeggio+ 2017)
- SDSS-IV eBOSS (ongoing)
- BOSS and WiggleZ have **huge volume,** but are **very sparse** and **not probing full galaxy population**

Future:

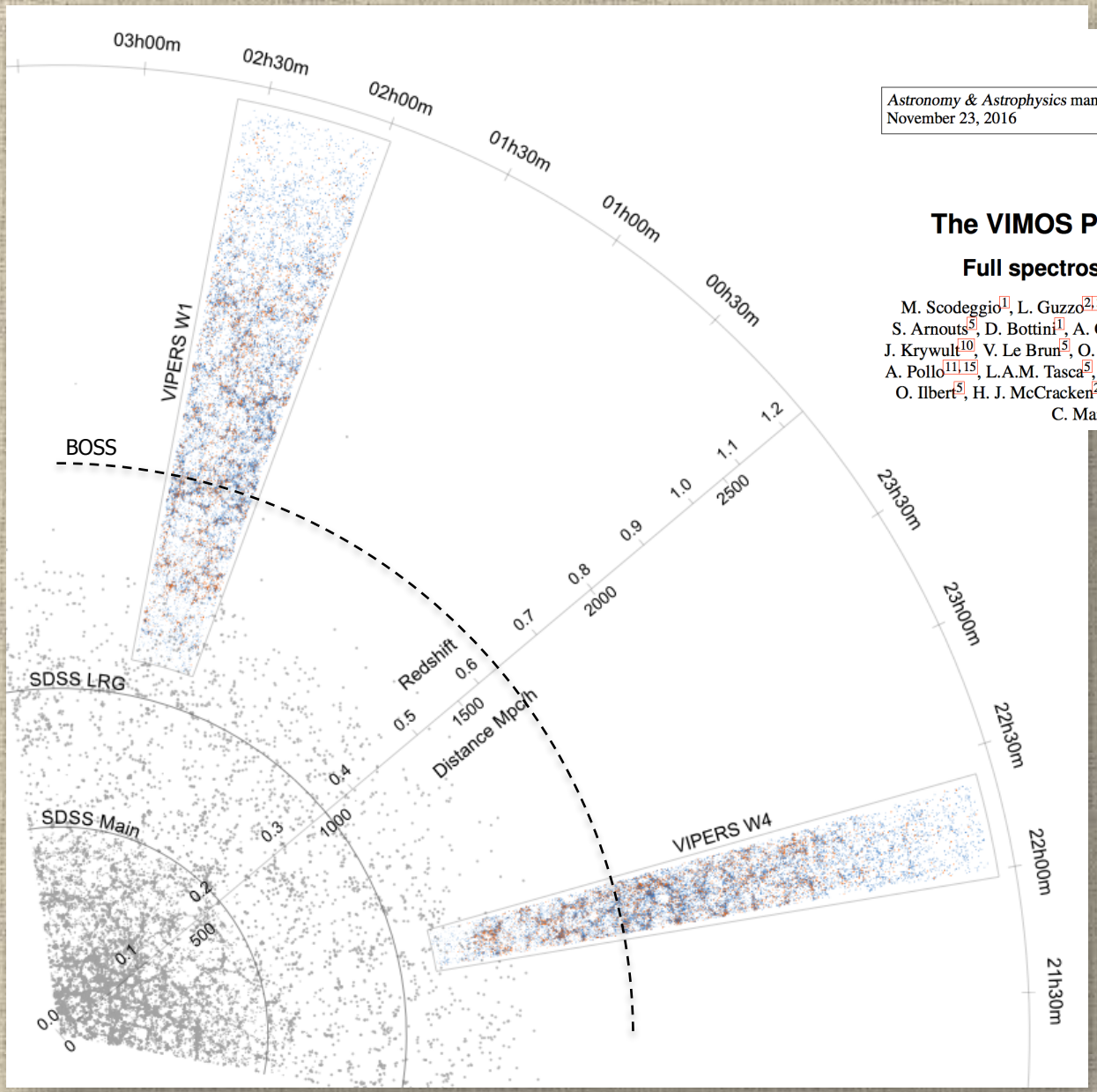
- DESI (2020-)
- **Euclid** (2021-)





2dFGRS (220,000 z)

VIPERS brings SDSS-like concept to z~1



Astronomy & Astrophysics manuscript no. scodeggio_PDR2_v2.5
November 23, 2016

The VIMOS Public Extragalactic Redshift Survey (VIPERS)⋆

Full spectroscopic data and auxiliary information release (PDR-2)

M. Scodeggio[1], L. Guzzo[2,3], B. Garilli[1], B. R. Granett[2,3], M. Bolzonella[4], S. de la Torre[5], U. Abbas[6], C. Adami[5], S. Arnouts[5], D. Bottini[1], A. Cappi[4,7], J. Coupon[8], O. Cucciati[9,4], I. Davidzon[5,4], P. Franzetti[1], A. Fritz[1], A. Iovino[2], J. Krywult[10], V. Le Brun[5], O. Le Fèvre[5], D. Maccagni[1], K. Małek[11], A. Marchetti[1], F. Marulli[9,12,4], M. Polletta[1,13,14], A. Pollo[11,15], L.A.M. Tasca[5], R. Tojeiro[16], D. Vergani[17], A. Zanichelli[18], J. Bel[19], E. Branchini[20,21,22], G. De Lucia[23], O. Ilbert[5], H. J. McCracken[24], T. Moutard[25,5], J. A. Peacock[26], G. Zamorani[4], A. Burden[27], M. Fumana[1], E. Jullo[5], C. Marinoni[19,28], Y. Mellier[24], L. Moscardini[9,12,4], and W. J. Percival[27]

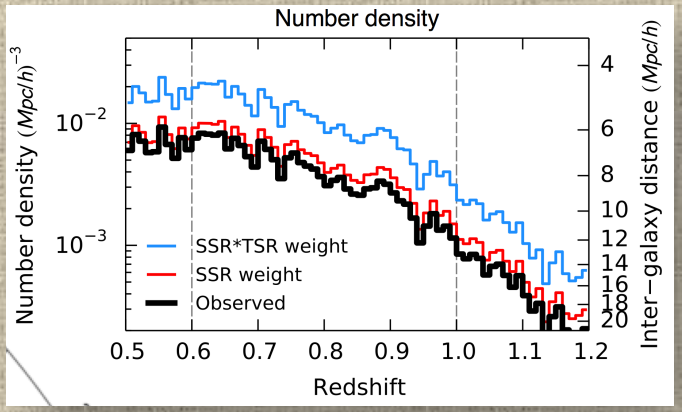
Table 2. The VIPERS PDR-2 spectroscopic sample

Sample	Number
Spectroscopically observed	97,414
— Main survey targets	94,335
— Serendipitous targets	1,478
— AGN candidates (not part of main survey)	1,601
Measured redshifts	**Number**
All measured	91,507
Main survey, all targets	89,022
— galaxies	86,775
— stars	2,247
Flag ≥ 2 main survey, all targets	78,586
Flag ≥ 2 main survey, galaxies	76,552

VIPERS fact sheet

- **~24 deg², I_{AB}<22.5, z>0.5 color-color pre-selection** (+ accurate star-galaxy separation)
- VIMOS @ VLT, LR Red grism, **45 min exposure**
- Mosaic of **288 pointings**, **440.5 hours** (55 VLT night-equivalent) → **2008-2015**

- **97,414 redshifts**, with **47% sampling**
- **Volume: 5 x 10^7 h^{-3} Mpc^3 (~2dFGRS)**
- **<n> ~ 5 x 10^{-3} h^3 Mpc^{-3}**



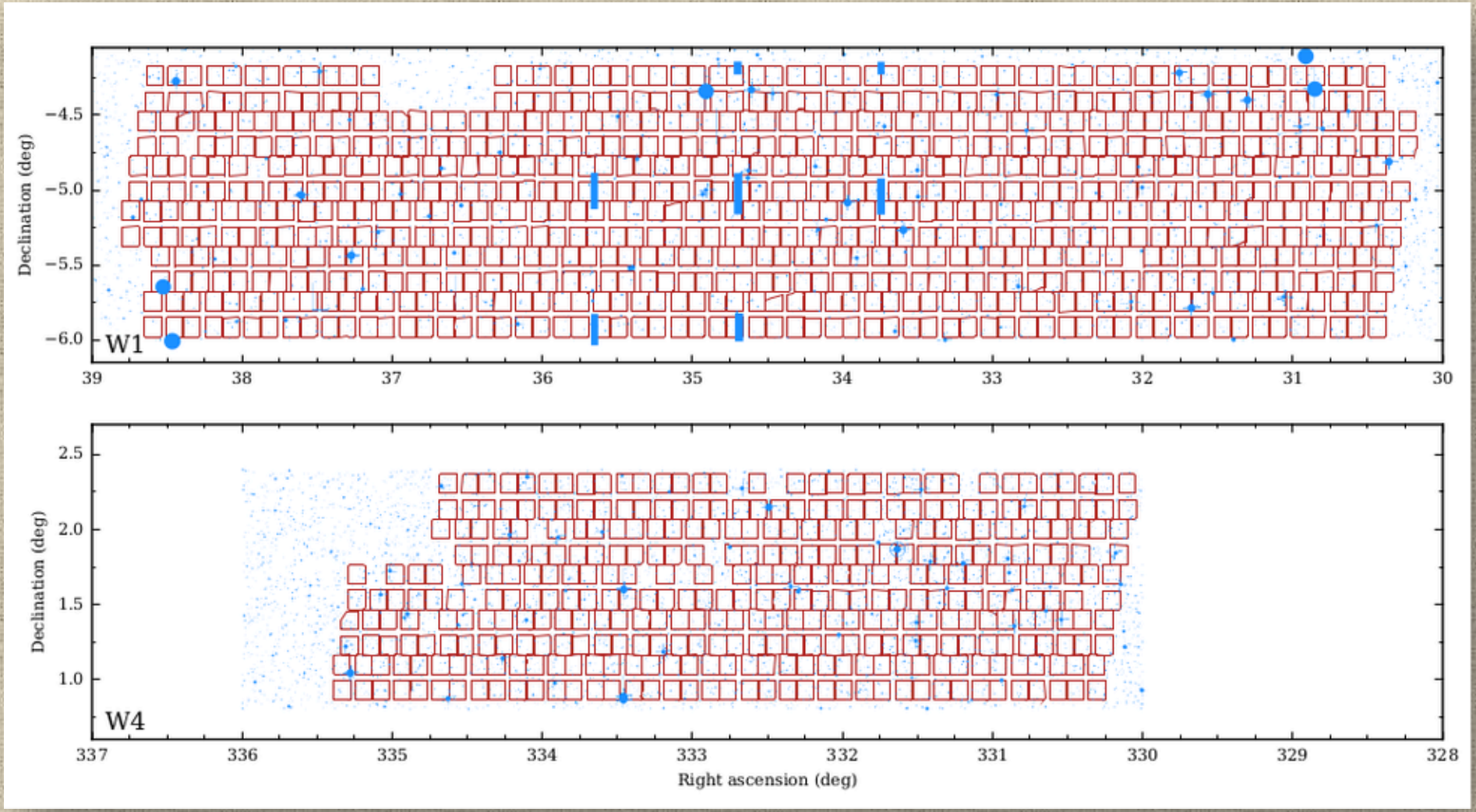
- **CFHTLS Wide** (W1 and W4 fields, ~16 + 8 deg²) **5-band accurate photometry** and **high-quality images**
- **VIPERS Multi-Lambda Survey** (Arnouts+, Moutard+2016a,b): revised CFHTLS **ugriz** + extra **UV & NIR** (**http://cesam.lam.fr/vipers-mls/**)
- —> **photometric and structural properties for most galaxies**

VIPERS Team

(see http://vipers.inaf.it)

- **MILANO OAB (Project Office)**: L. Guzzo (P.I.), B. Granett, J. Bel, A. Iovino, S. Rota, U. Abbas (Turin), A. Hawken, F. Mohammad, A. Pezzotta
- **MILANO IASF (Data Reduction Centre)**: B. Garilli, M. Scodeggio, A. Fritz, D. Bottini, P. Franzetti, A. Gargiulo, D. Maccagni, A. Marchetti, M. Polletta, [L. Paioro]
- **BOLOGNA**: M. Bolzonella, O. Cucciati, A. Cappi, F. Marulli, L. Moscardini, D. Vergani, G. Zamorani, A. Zanichelli, E. Branchini (Rome), G. De Lucia (Trieste)
- **MARSEILLE**: S. de la Torre, O. Le Fevre, C. Adami, Y. Davidzon, V. Le Brun, L. Tasca, C. Marinoni, T. Moutard, E. Jullo
- **WARSAW**: A. Pollo, J. Krywult (Kielce), K. Malek, O. Solarz, M. Siudek
- **EDINBURGH**: J. Peacock, M. Wilson
- **PARIS (TERAPIX)**: H. McCracken, Y. Mellier, J. Coupon (Geneva)
- **PORTSMOUTH**: W. Percival, R. Tojeiro (St.Andrews), A. Burden (Yale), R. Nichol
- **[GARCHING MPE]**: [S. Phleps], [M. Schlagenhaufer], [B. Meneux]

Survey layout and photometric/spectroscopic masks

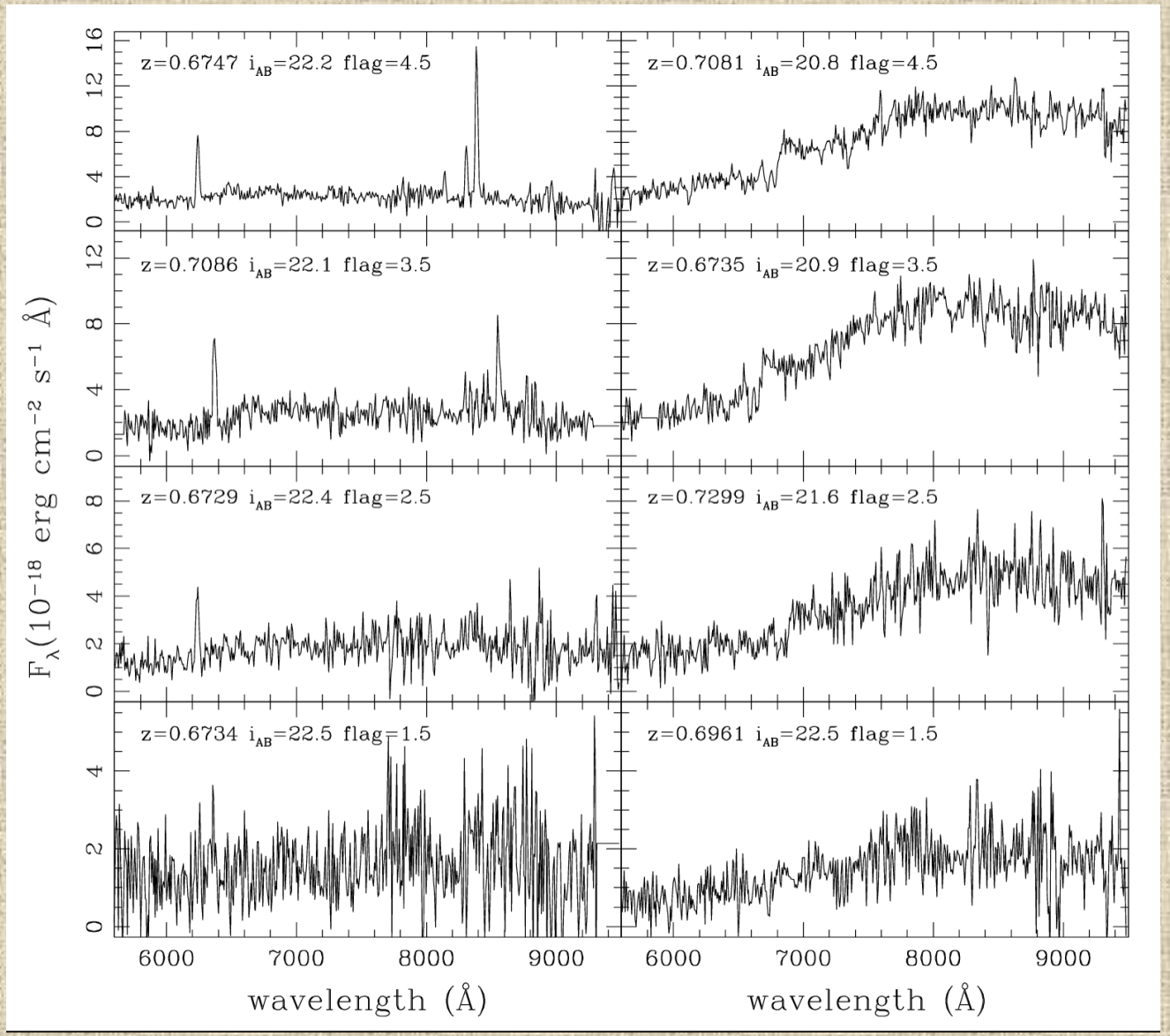


→ This and other ancillary information also released with PDR-2

(mask reconstruction by Ben Granett)

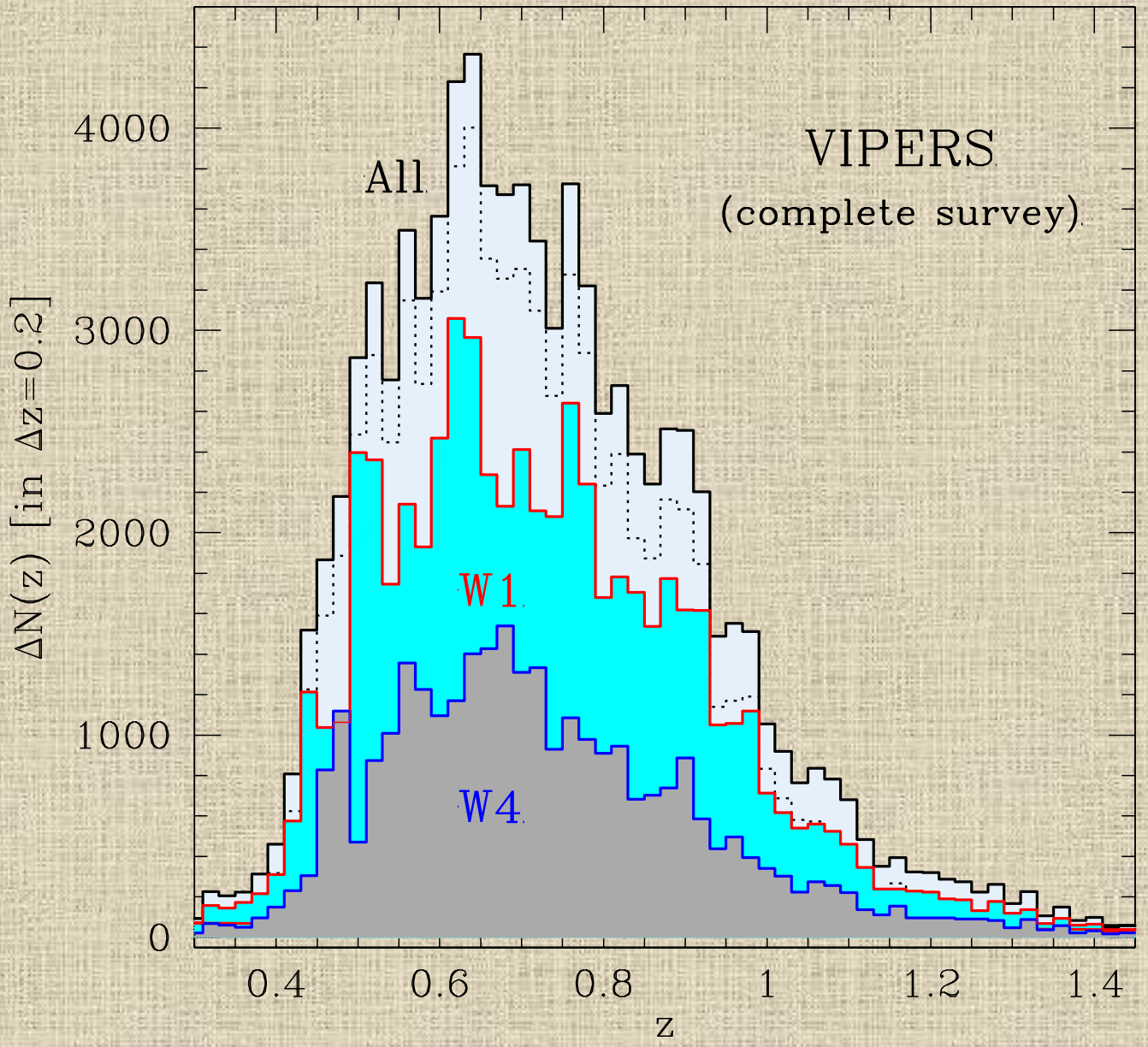
VIPERS spectra

- **R=220 at mid-range**
- **λ= 5500 – 9500 A**
- **σ_z = 0.00054(1+z)**
- **Spectral indices and line fluxes** (e.g. D4000, [OII]3727), available for large fraction of sample



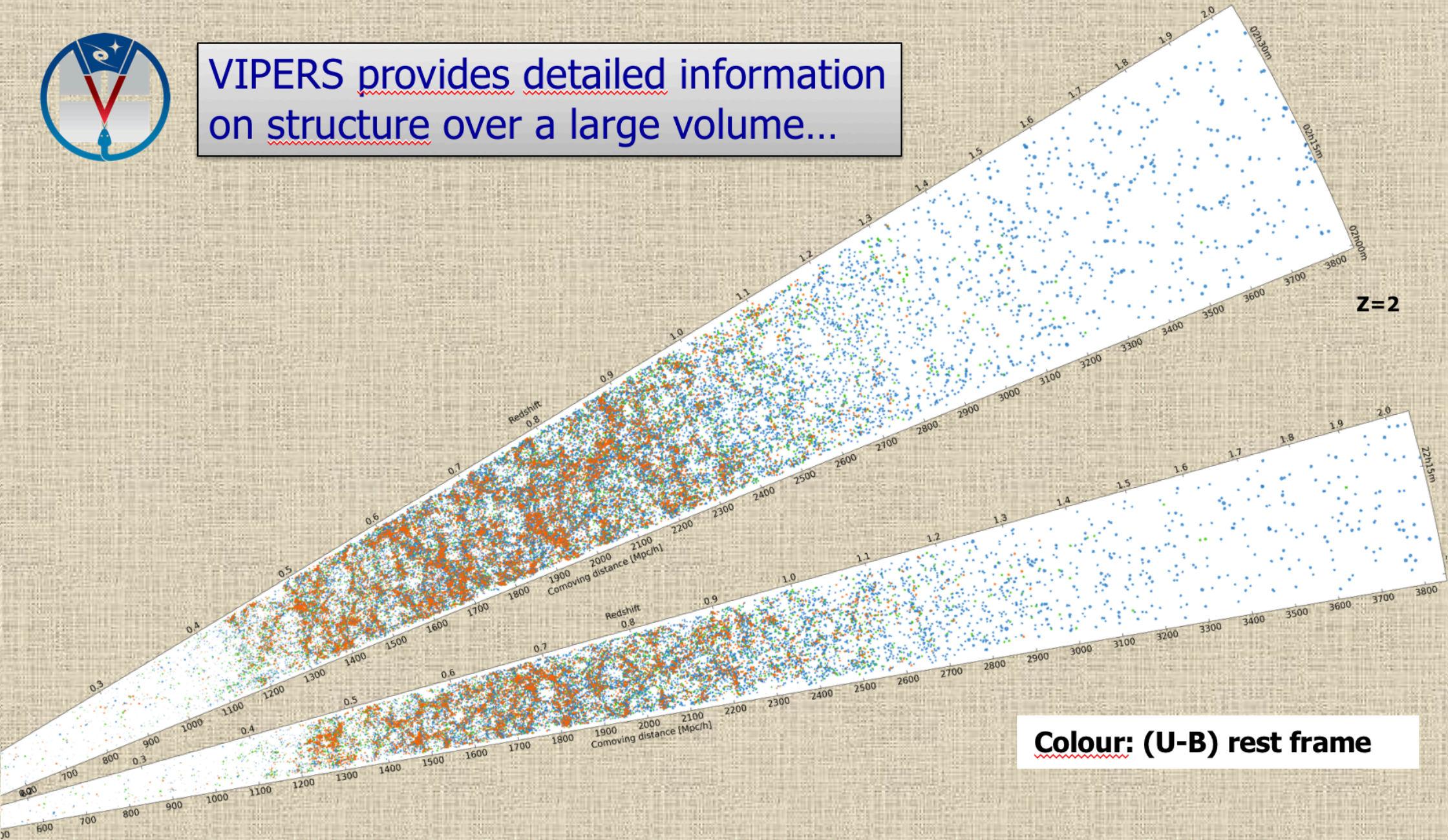
(Scodeggio+ 2018)

Redshift distribution



(Scodeggio+ 2017)

VIPERS provides detailed information on structure over a large volume…

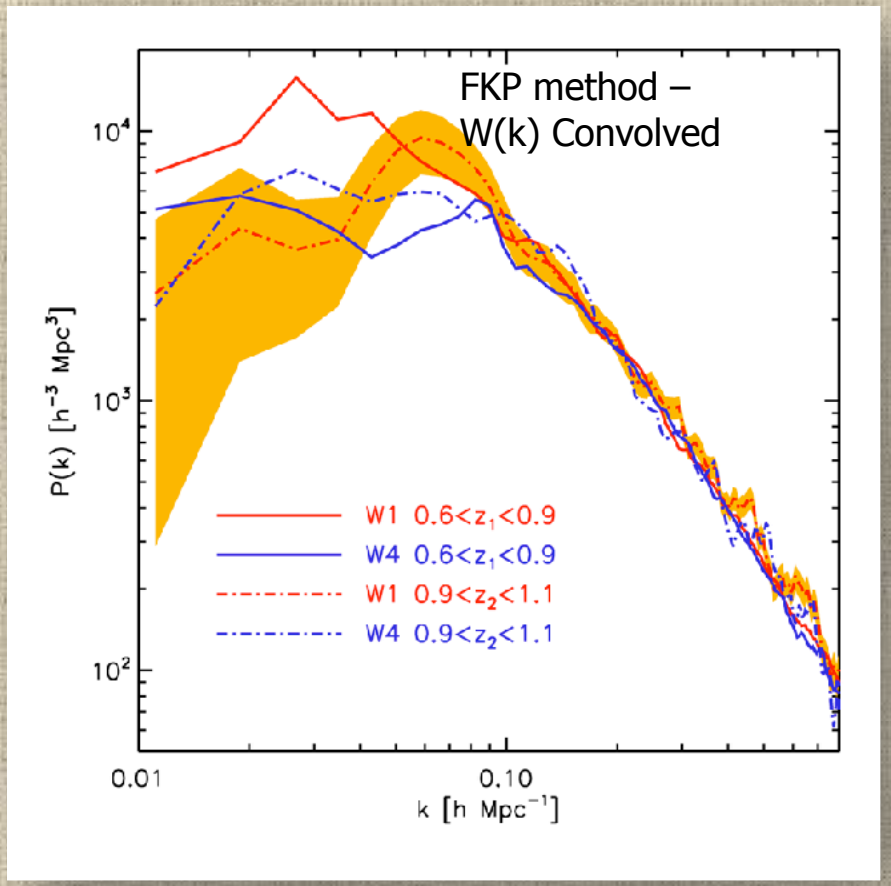


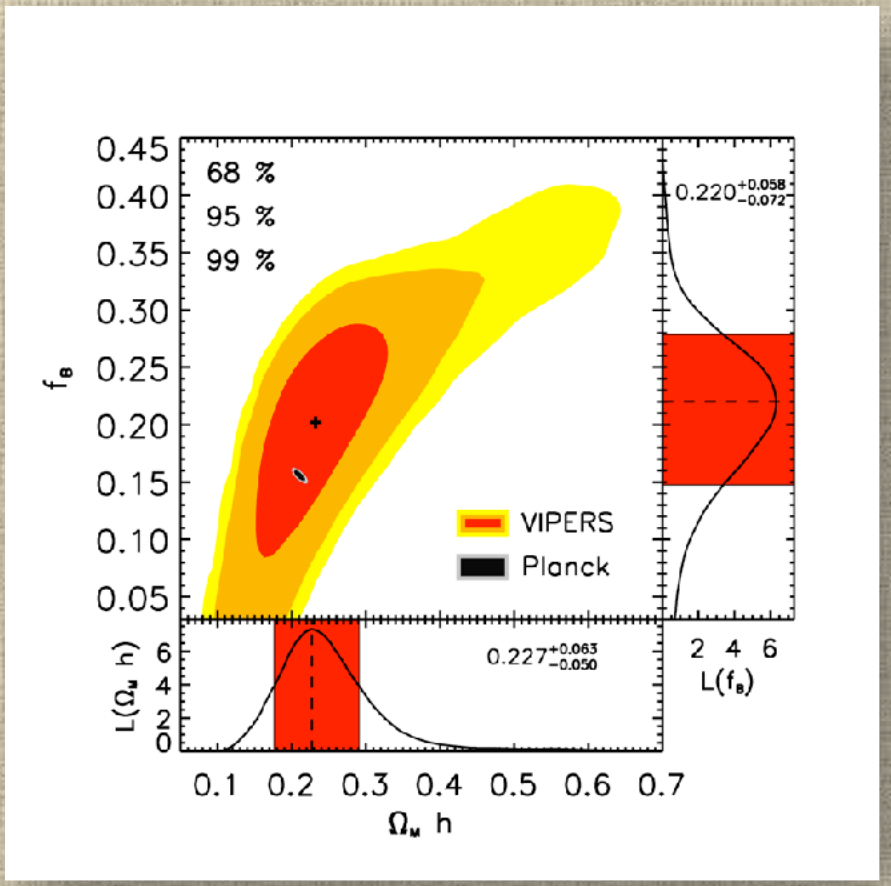
Colour: (U-B) rest frame

(artwork by Ben Granett)

The power spectrum of the galaxy distribution at z=0.5-1.1

(S. Rota PhD thesis; Rota, Granett+ 2017 (1611.07044)





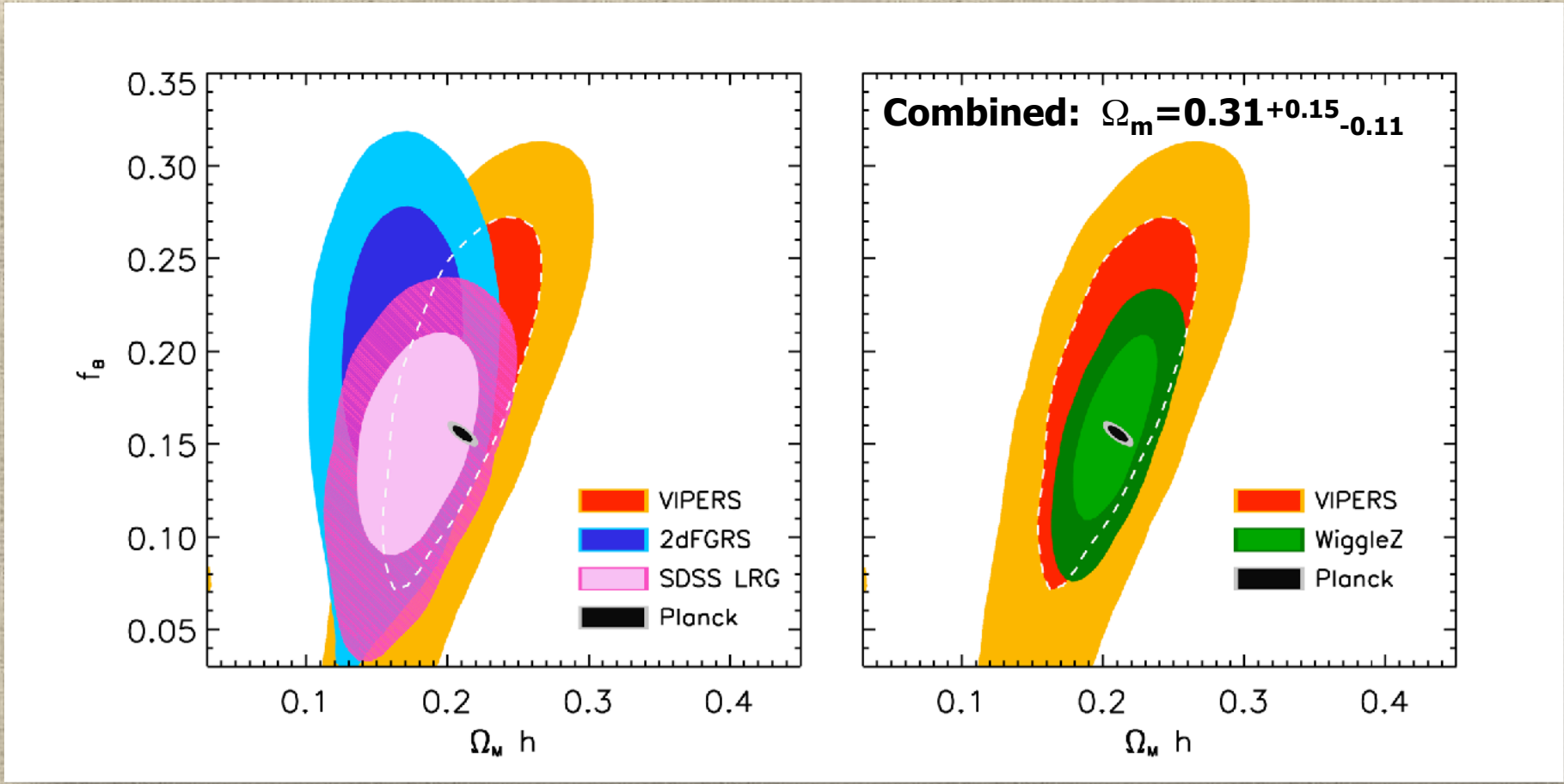
- Needs careful treatment of window function and nonlinear effects

- Joint likelihood of 4 independent estimates: 2 redshift bins in 2 fields (W1 and W4)

The power spectrum of the galaxy distribution at z=0.5-1.1

- **Highest redshift at which P(k) measured from galaxy distribution**
- **Consistency test of ΛCMD at about half Hubble time, straddling Planck and local data**

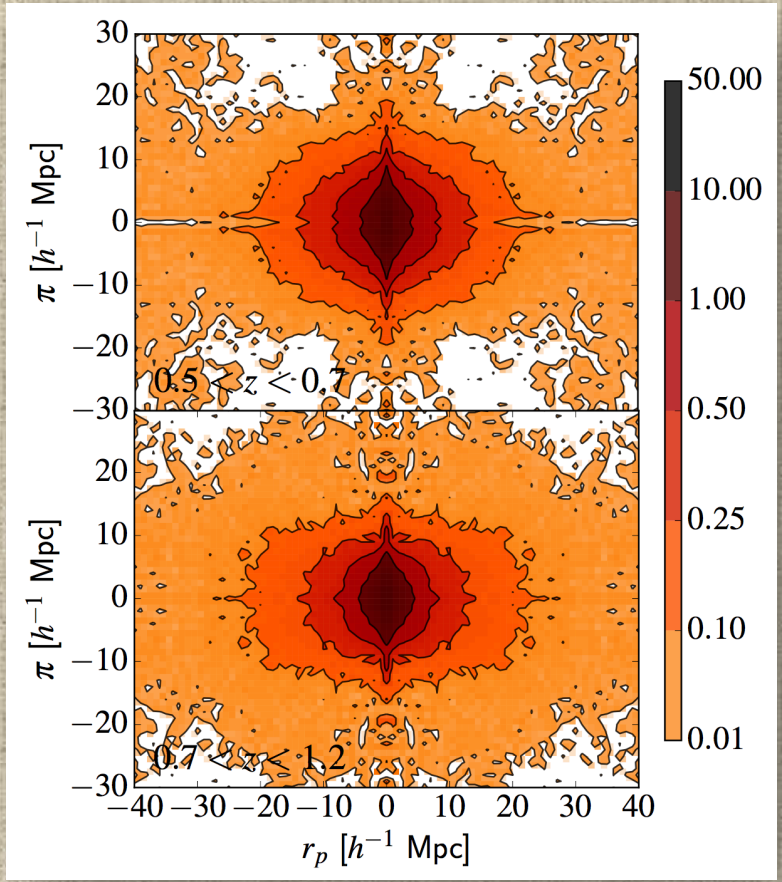
→ Ellipses move towards Planck moving to higher z ?

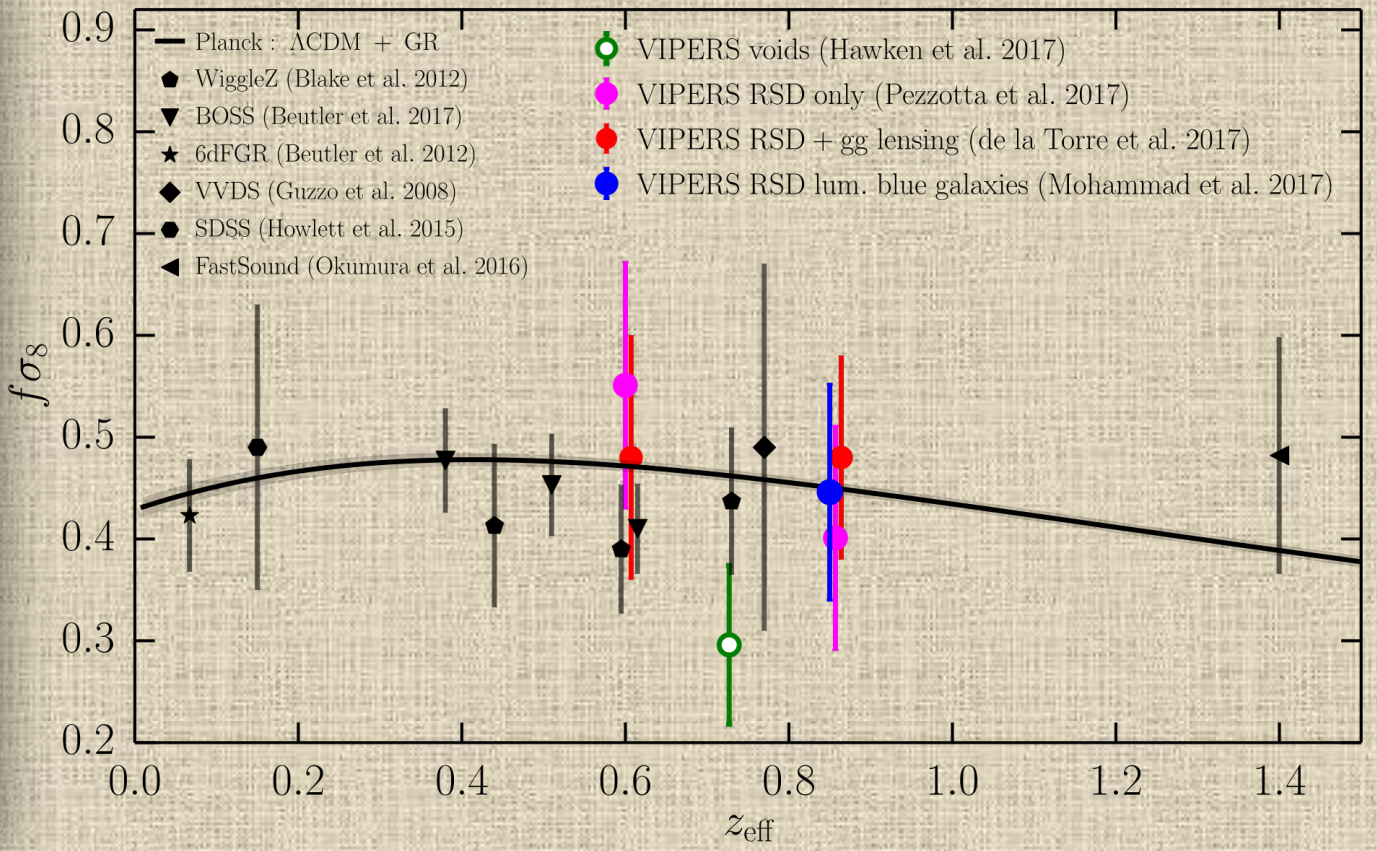


(Rota+ 2017; arXiv:1611.07044)

erc DARK LIGHT

Complementary RSD measurements with VIPERS





VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2018)

Reducing systematic errors in RSD measurements

1. Improve non-linear modelling

2. Optimise the tracers of the velocity field

3. Reverse perspective: forward model the full non-linear RSD

Reducing systematic errors in RSD measurements

1. **Improve non-linear modelling**
2. Optimise the tracers of the velocity field
3. Reverse perspective: forward model the full non-linear RSD

1. Improve nonlinear modelling

- **Improved "dispersion models":** Scoccimarro (2004); Taruya+ TNS (2010)

$$P^s(k,\mu) = D(k\mu\sigma_{12})\Big(b^2 P_{\delta\delta}(k) + 2fb\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + \\ + C_A(k,\mu,f,b) + C_B(k\,u,f,b)\Big), \qquad \text{(TNS)}$$

- Widely applied (e.g Blake+ 2014; Beutler+ 2016)
- Adopted in VIPERS (Pezzotta+ 2017, de la Torre 2013, 2017; Mohammad+ 2018), with improved features and performances:
  - Use non-linear $P_{\delta\delta}$ from HALOFIT rather than linear one as in original prescription
  - Use new fitting formulae for $\mathbf{P}_{\delta\Theta}$ and $\mathbf{P}_{\Theta\Theta}$ derived from simulations (Bel et al., arXiv: 1809.09338), which properly account for redshift and cosmology dependence, improving over Jennings+ 2011
- Note: many other modelling developments over past decade, as e.g. using the streaming model, e.g. Reid & White 2011; Bianchi+2015; 2016; Uhlemann+ 2016 or distribution function approach, e.g. Okumura+ 2015, Hand+ 2017, and several others. Only a few of these got at the level of being applicable to real galaxy data, though.

Refined nonlinear modelling: mock tests

(Pezzotta+ 2017, arXiv:1612.05645)

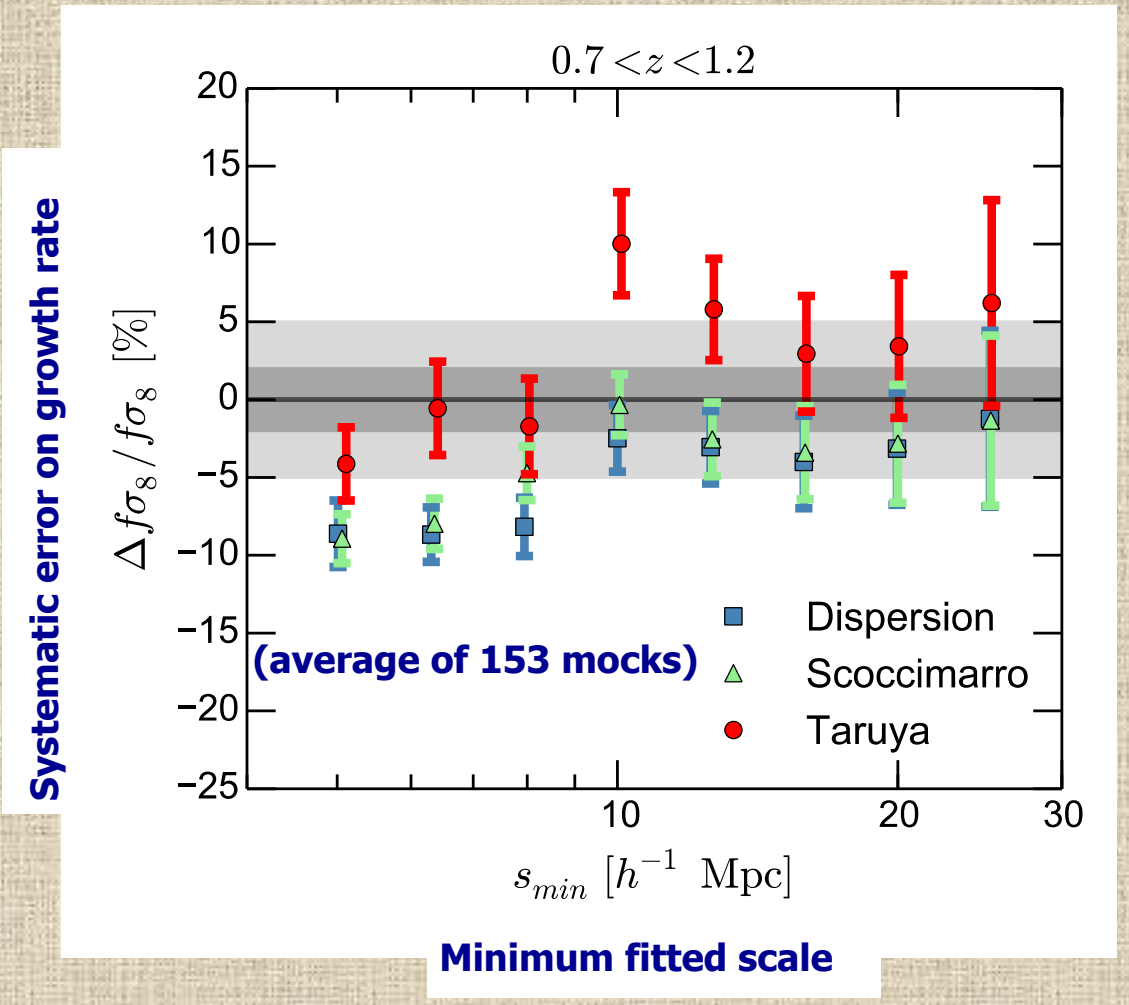
→ Using new fitting formulae for velocity divergence / density power spectra ($P_{\delta\theta}$, $P_{\theta\theta}$) - **Bel et al. arXiv:1809.09338**

$$P_{\delta\theta}(k) = \left(P_{\delta\delta}(k)P^{lin}(k)e^{-k/k^*}\right)^{\frac{1}{2}}$$

$$P_{\theta\theta}(k) = P^{lin}(k)e^{-k/k^*},$$

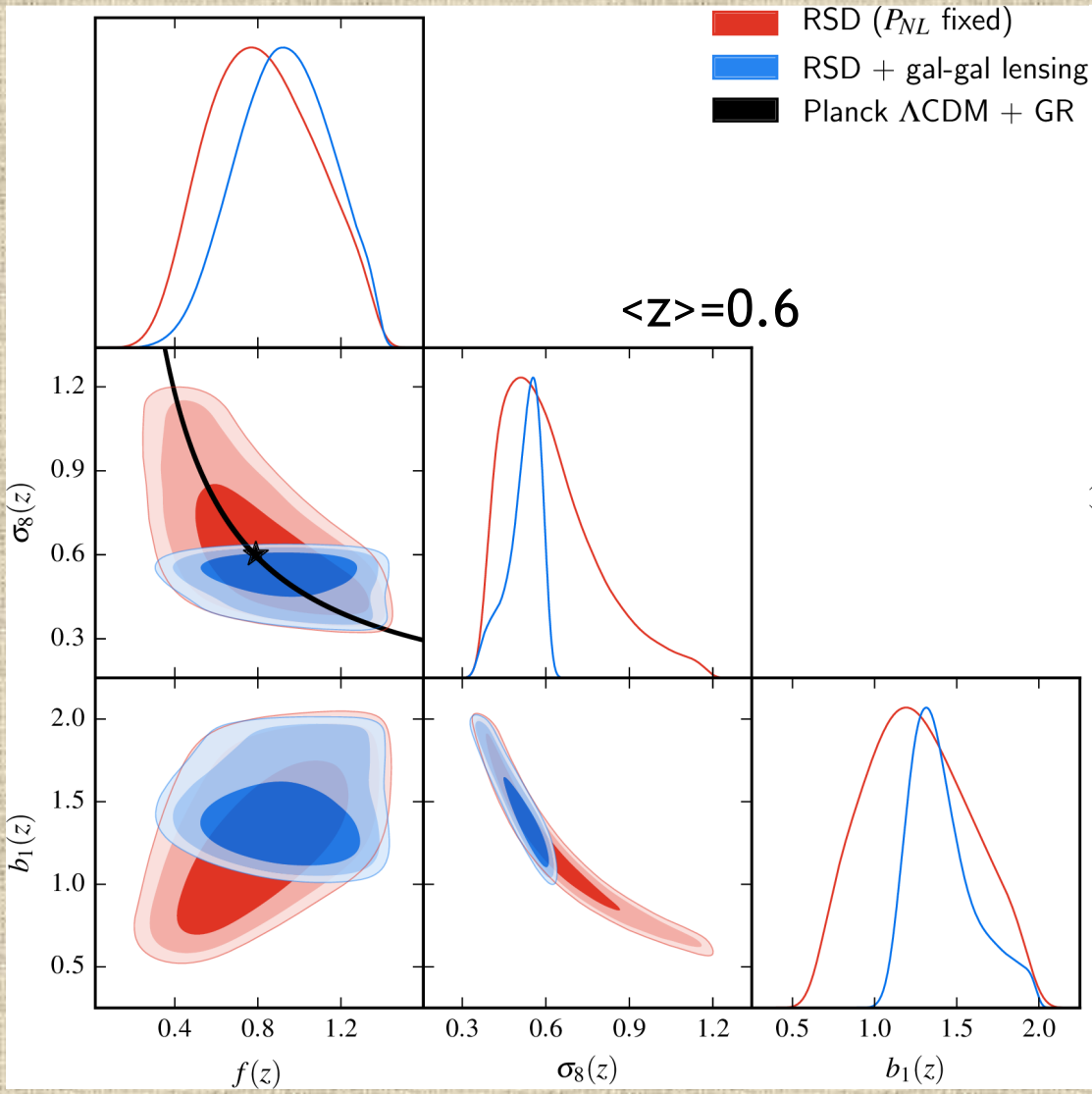
$$\frac{1}{k^*} = p_1\sigma_8^{p_2}$$

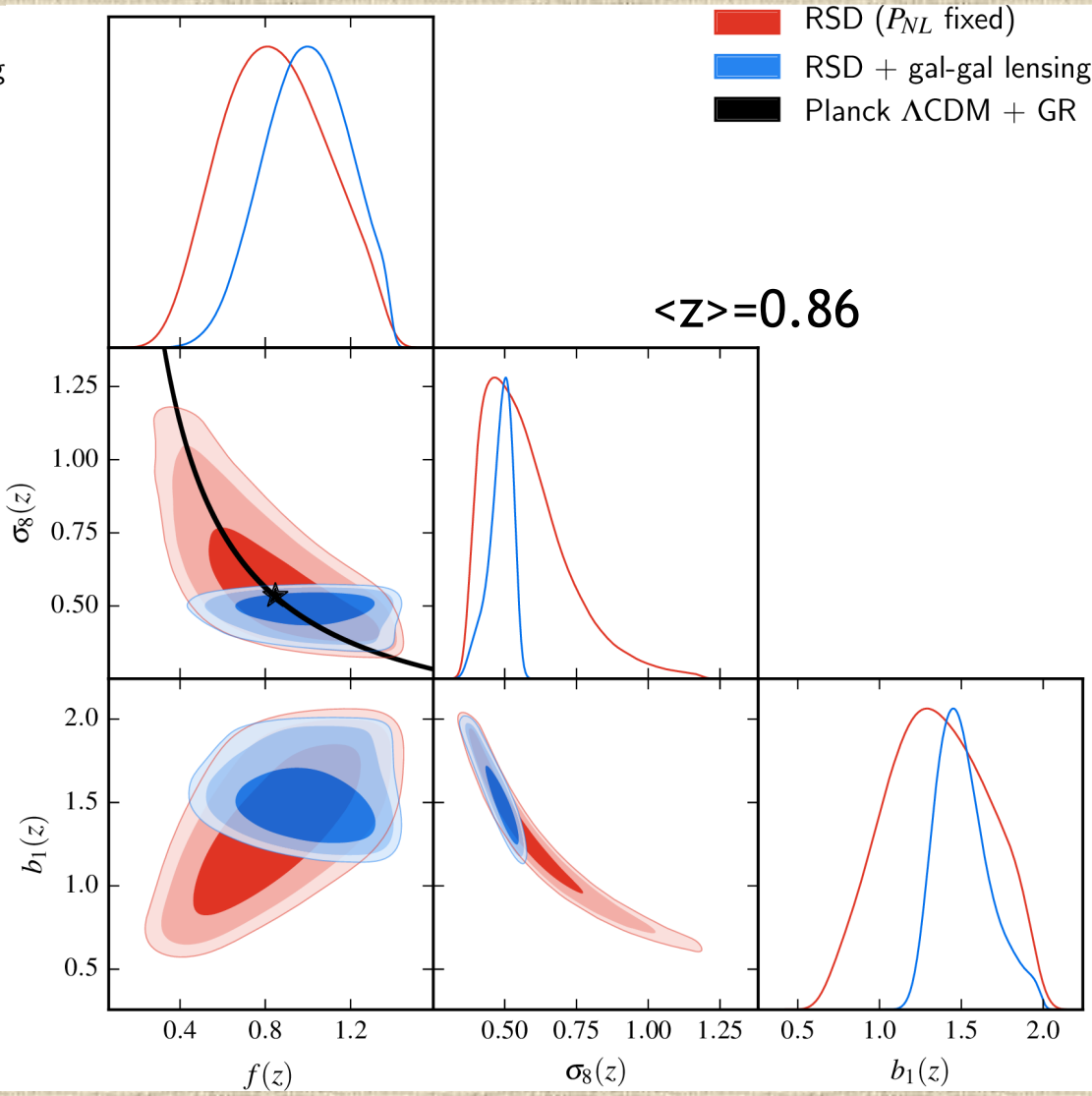
- p1,p2 only free parameters in the fit



Taruya TNS model on VIPERS data adding CFHTLS weak lensing

(de la Torre+ 2017, arXiv:1612.05647; Pezzotta+ 2017, arXiv:1612.05645)





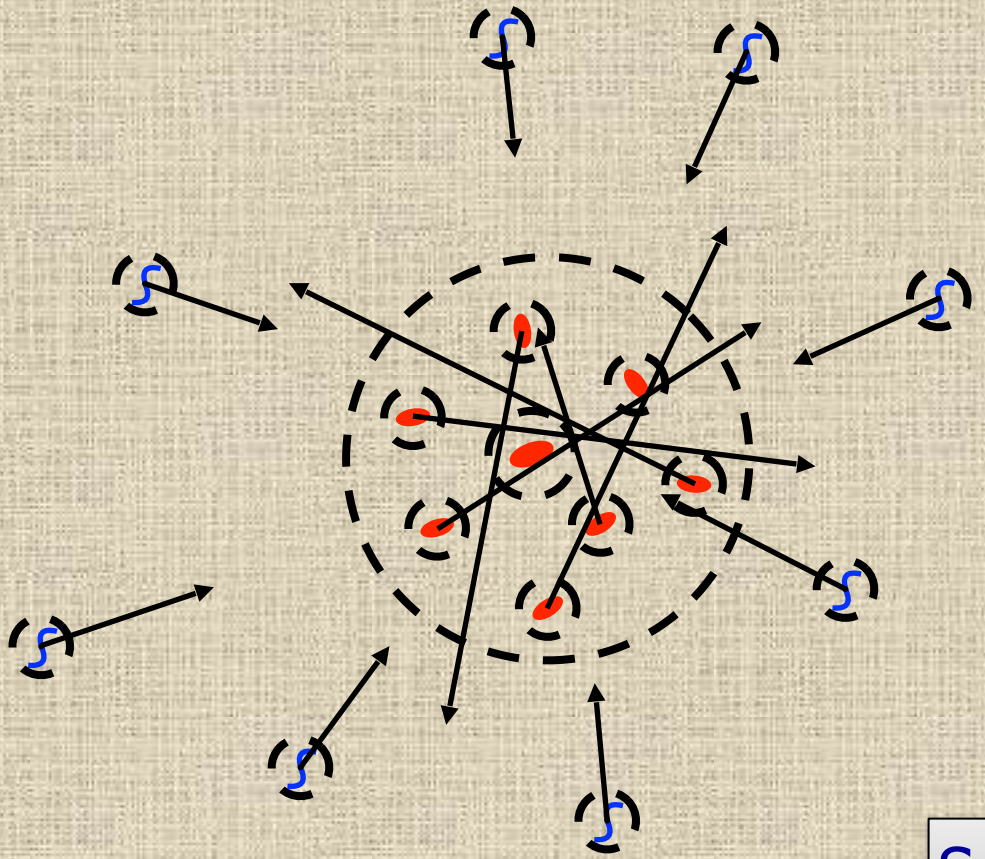
Reducing systematic errors in RSD measurements

1. Improve non-linear modelling

2. Optimise the tracers of the velocity field

3. Reverse perspective: forward model the full non-linear RSD

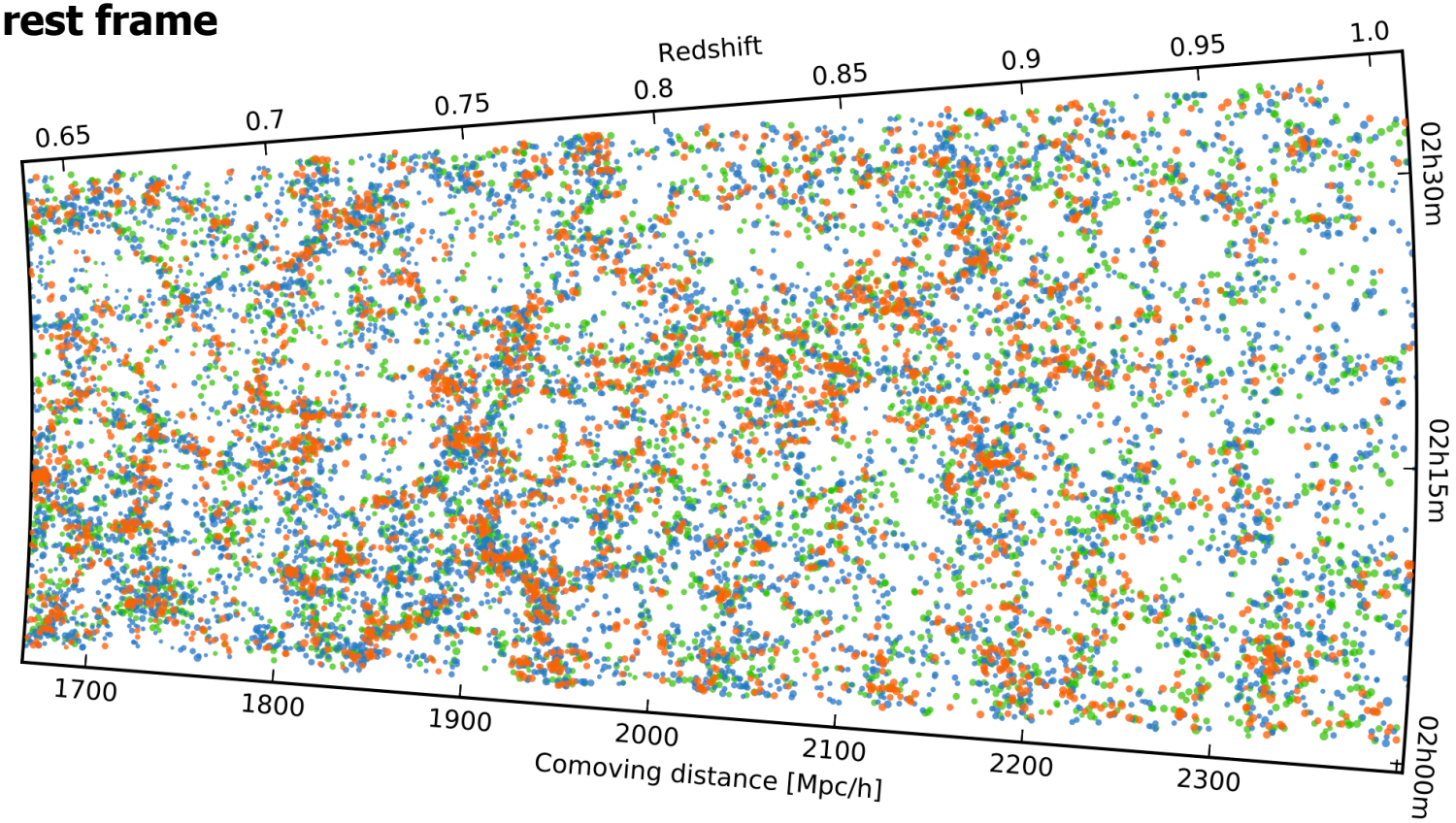
Different galaxies trace the velocity field differently…



Some may be easier to model…

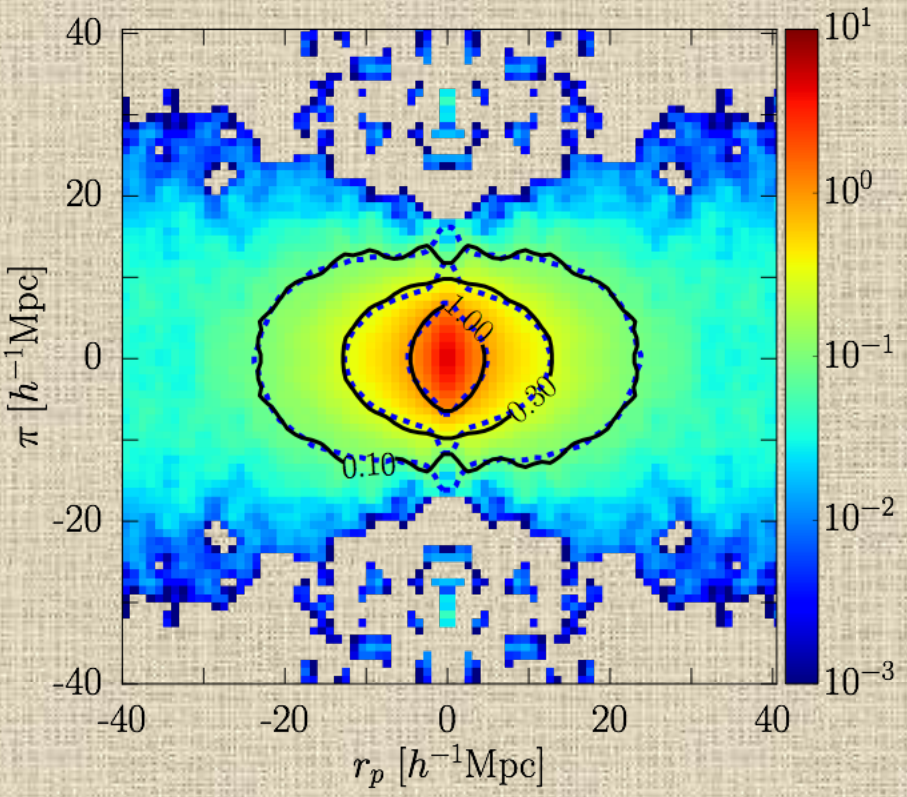
...as different populations trace structure differently

(U-B) rest frame

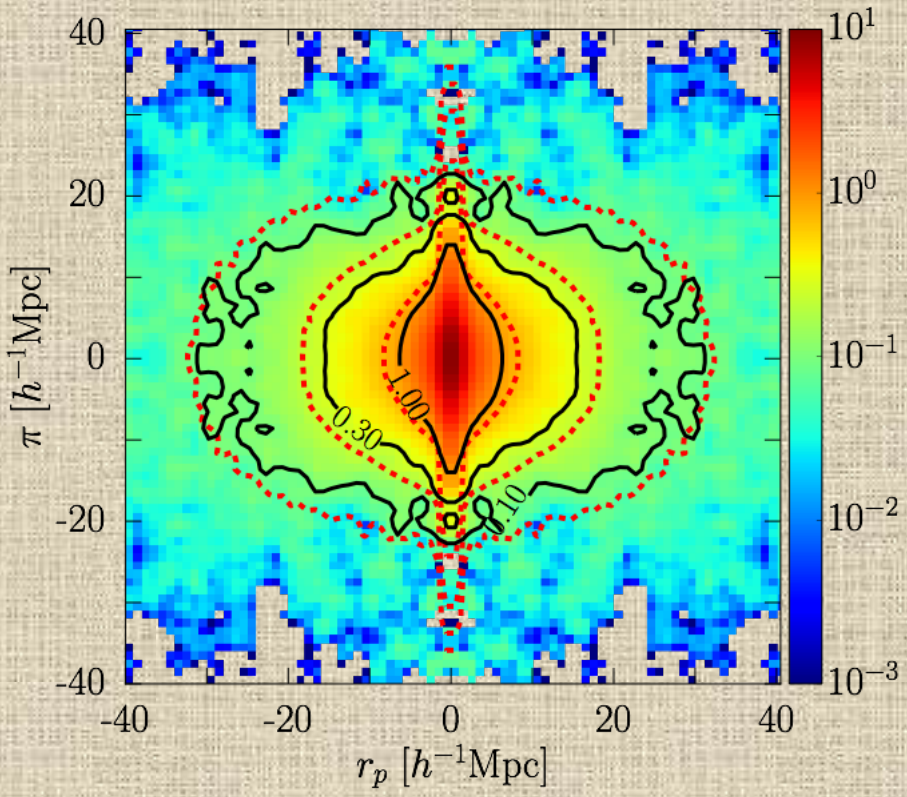


Redshift-space clustering of blue and red galaxies in VIPERS

Blue

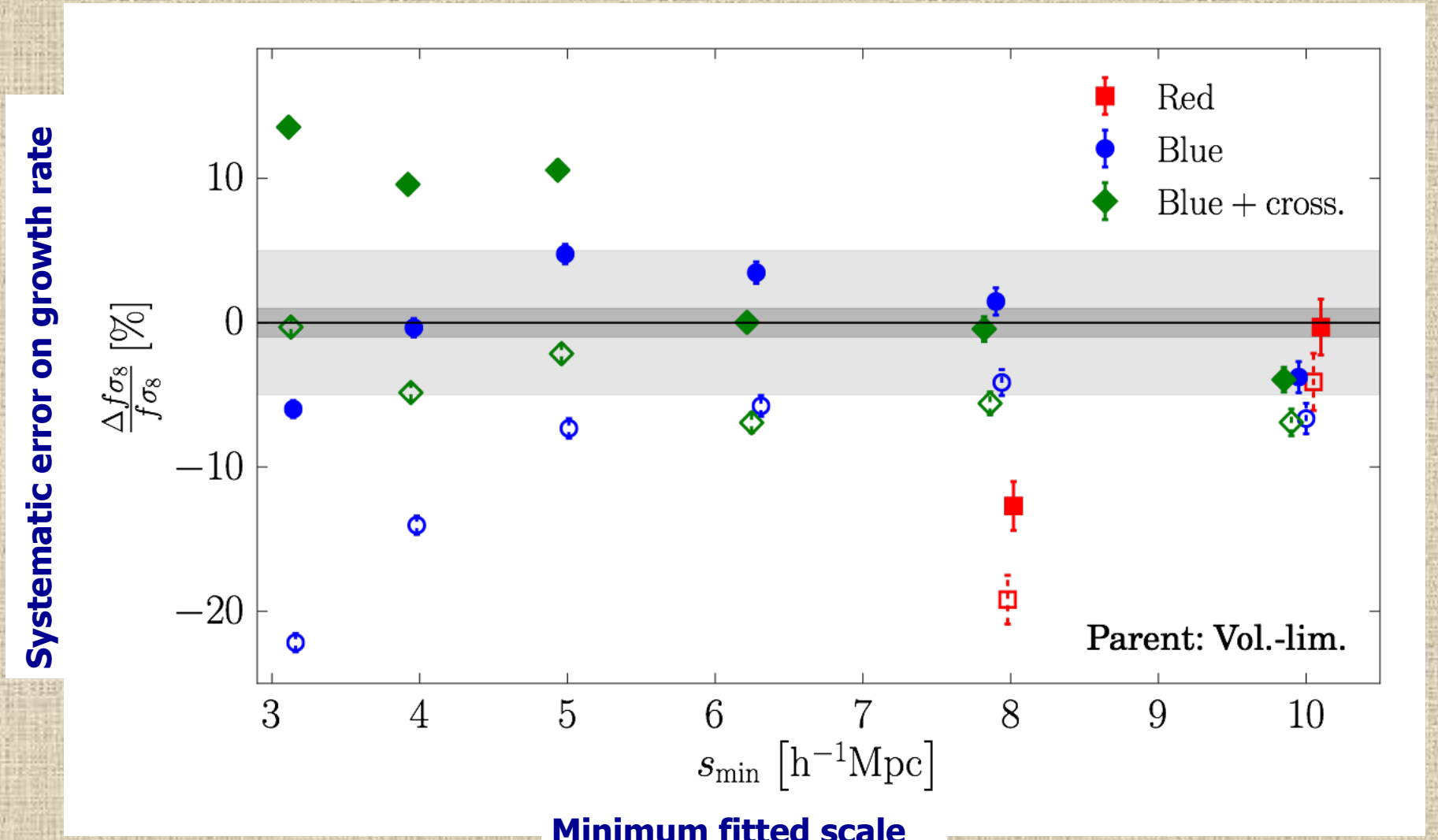


Red



(Mohammad+ 2018, arXiv:1708.00026)

VIPERS **volume-limited** mocks, using Scoccimarro model

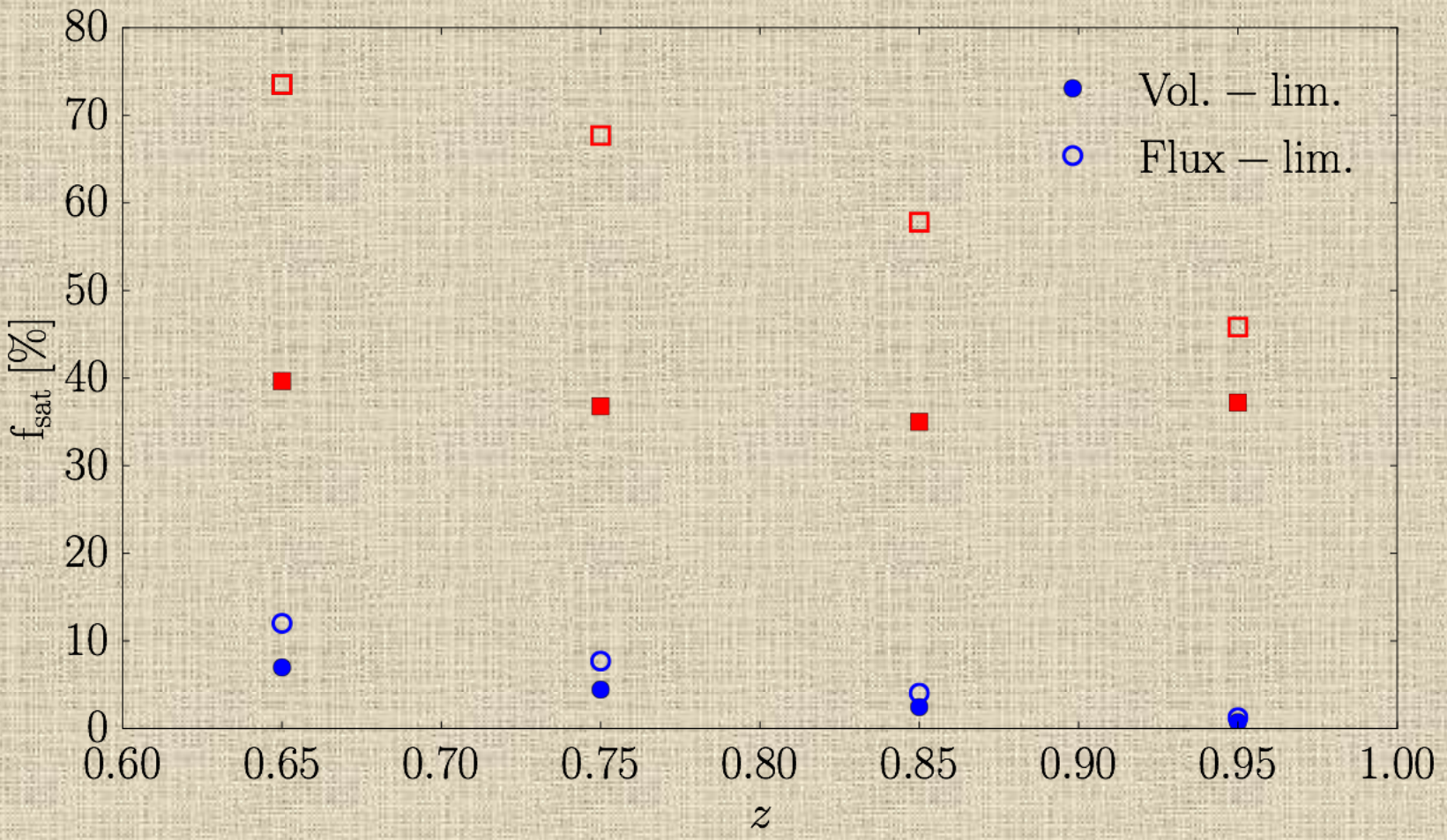


Systematic error on growth rate

Minimum fitted scale

(Mohammad+ 2018, arXiv:1708.00026)

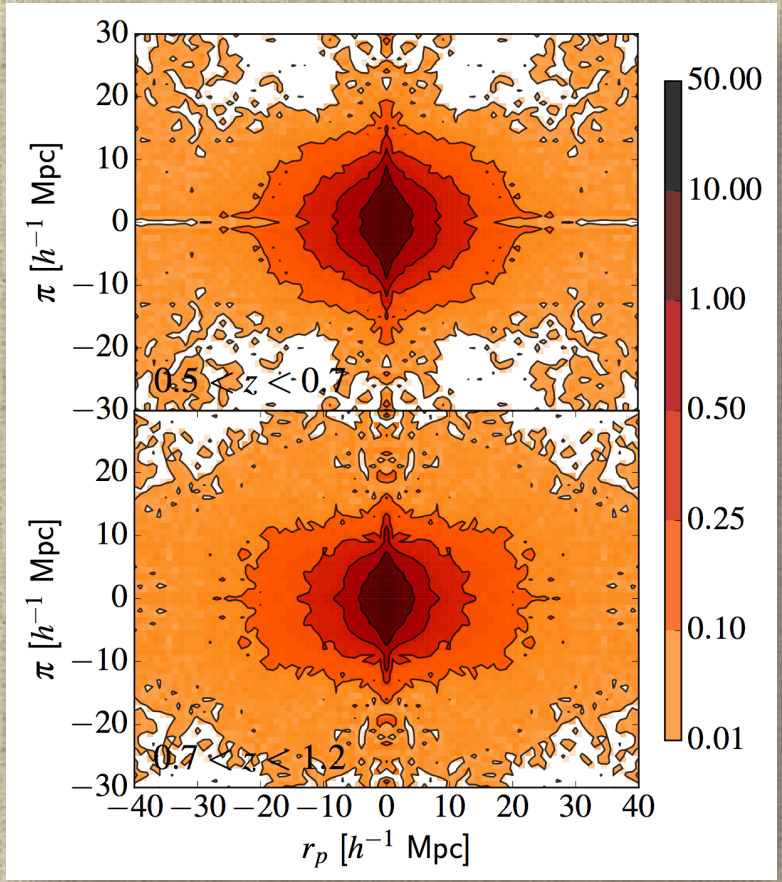
Satellites are the culprit...

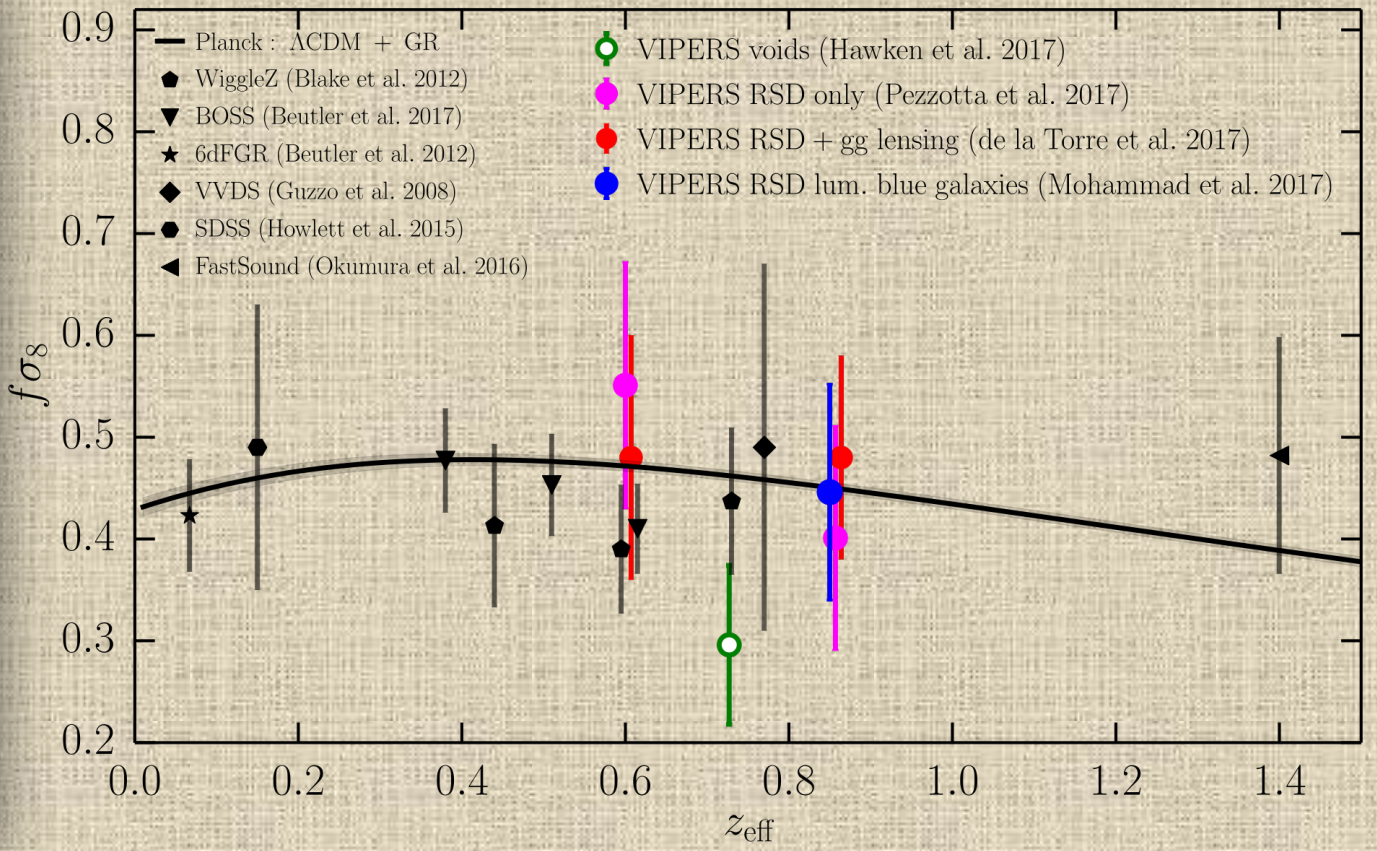


—> Realism of mocks is crucial (de la Torre et al. 2013)

(Mohammad+ 2018, arXiv:1708.00026)

Complementary RSD measurements with VIPERS

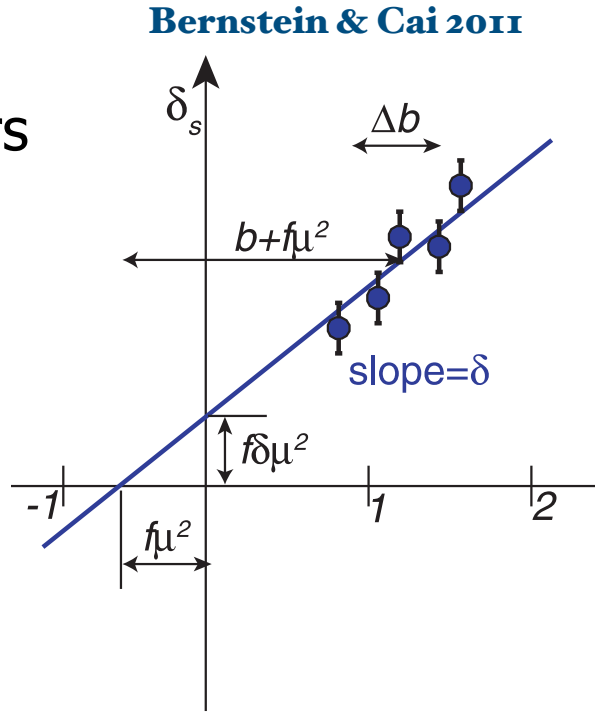




VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2018)

More in general: multi-tracer analyses

- The covariances between multiple tracers of the same volume can be used to measure relative bias without sample variance (McDonald & Seljak 2009)
- Applications: growth-rate, non-Gaussianity
- Gains depend on the spread in bias and are limited by shot noise
- ~20% improvement on growth rate from two galaxy populations in GAMA (Blake+2013)



$$\delta_1^s = (b_1 + f\mu^2)\delta_m + \epsilon_1$$
$$\delta_2^s = (b_2 + f\mu^2)\delta_m + \epsilon_2$$

(Slide by Ben Granett)

Reducing systematic errors in RSD measurements

1. Improve non-linear modelling

2. Optimise the tracers of the velocity field

3. Forward modelling (in general)

Cosmic Inference

Galaxy Counts N

Data Model $N = \bar{N}\,(1 + b\delta)$

Posterior

$$p(\delta|N,C) \propto |C|^{-1/2} e^{-\frac{1}{2}} \frac{\left(N-\bar{N}(1+b\delta)\right)^2}{\bar{N}} e^{-\frac{1}{2}\delta C^{-1}\delta^T}$$

Likelihood

Prior

Posterior of the density field with Gaussian likelihood and prior (Wiener filter)

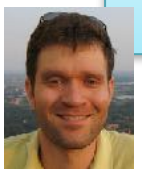
★ The Bayesian formalism shows how to optimally make use of available data.

➡ Maximum posterior solution

➡ Monte Carlo sample

➡ Quadratic estimator

Example application to VIPERS: Wiener-filter density field reconstruction



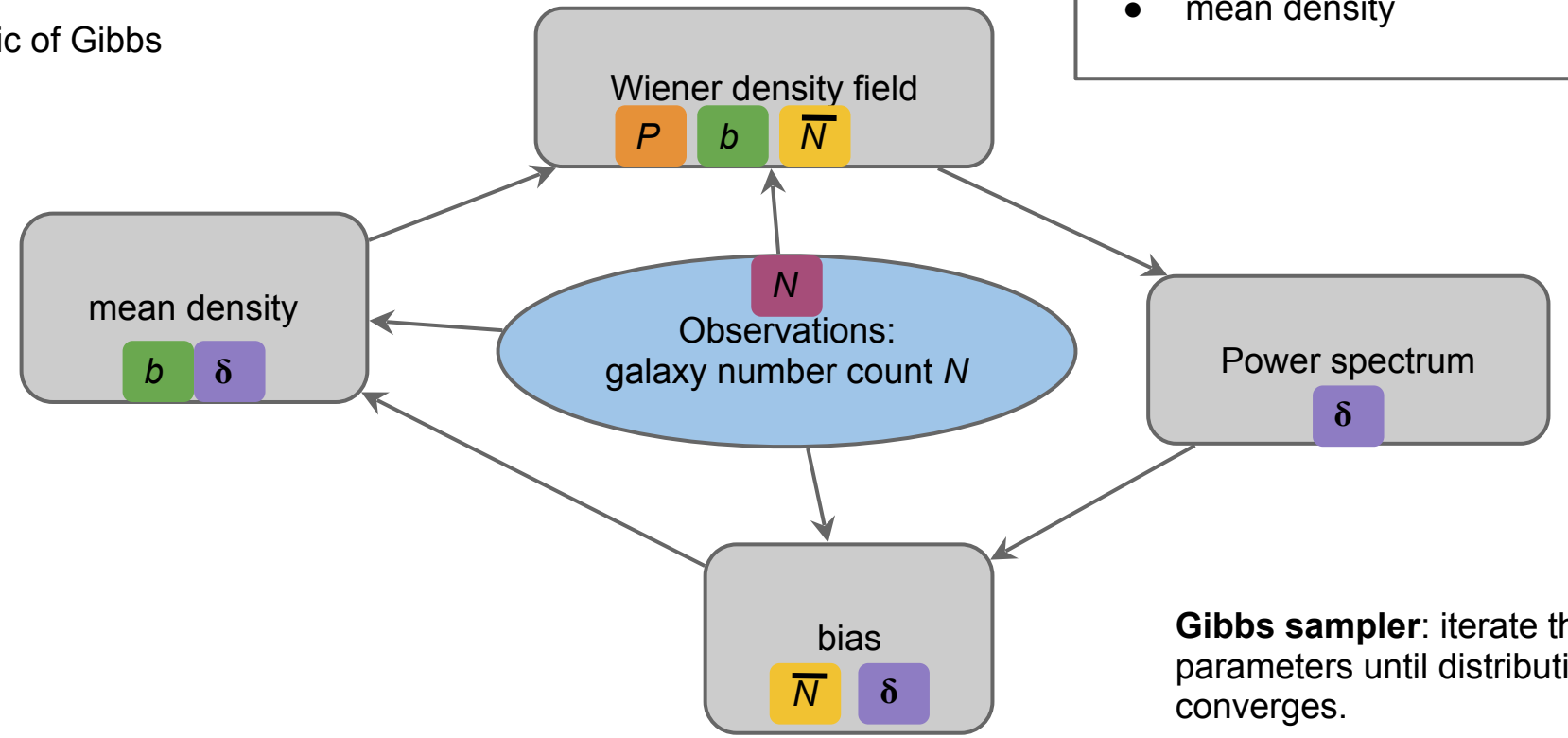
Granett+ 2015 (1505.06337)

- Markov Chain random walk through the parameter space gives the joint posterior probability distribution of the density field and galaxy statistics.

Dependencies

- Wiener density field — δ
- Power spectrum — P
- bias — b
- mean density — $\overline{N}$

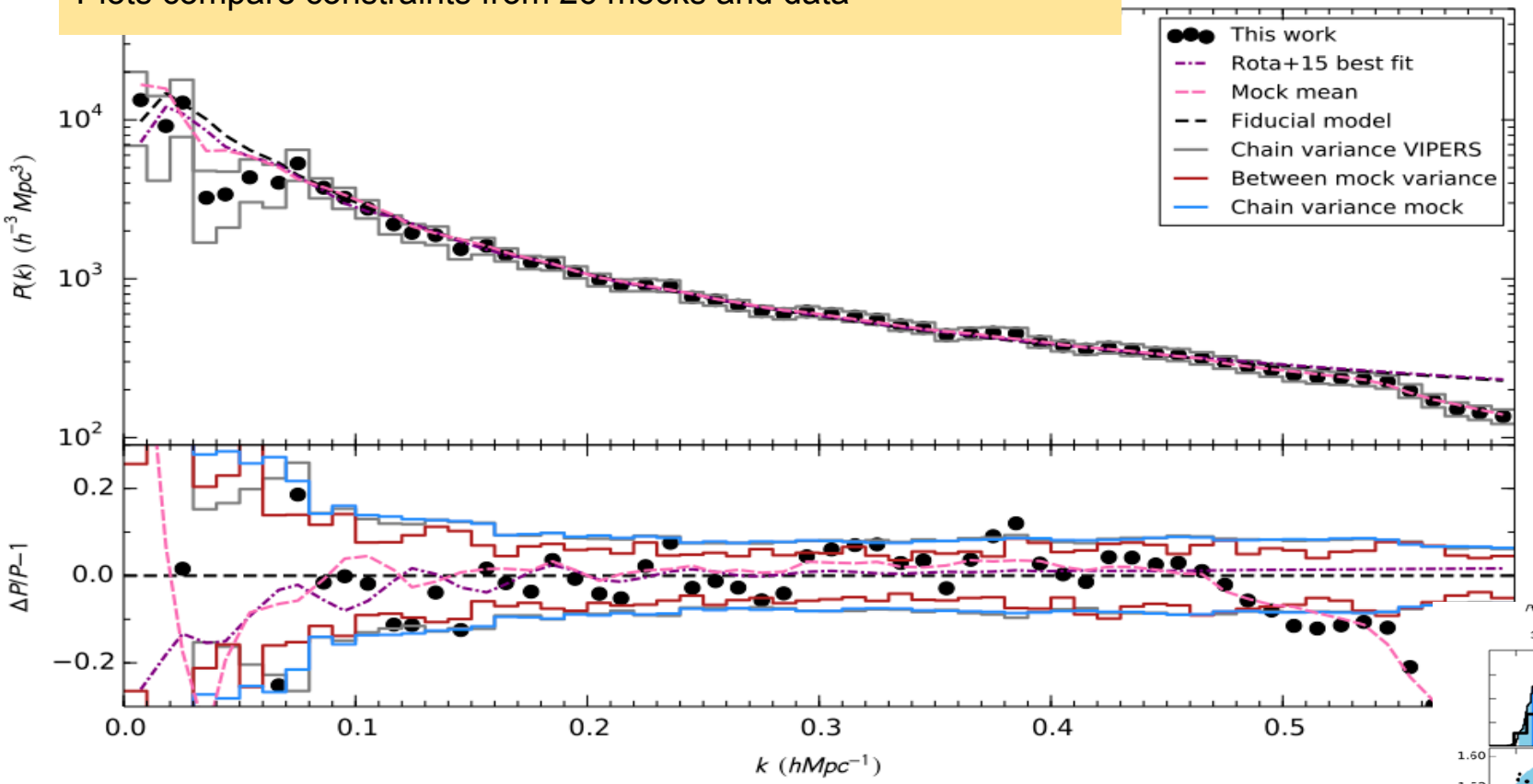
Schematic of Gibbs sampler:

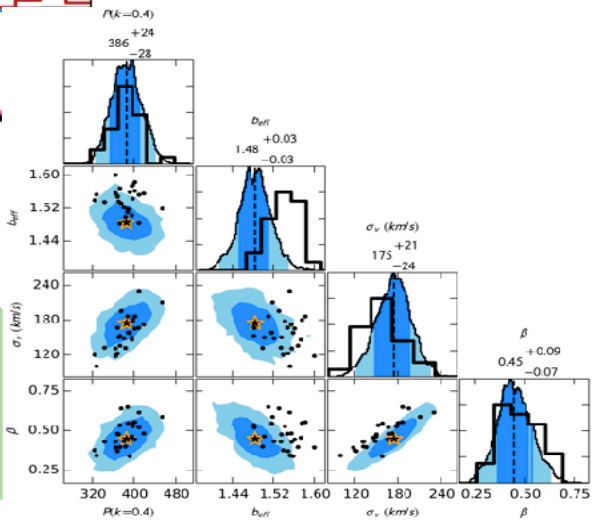


Gibbs sampler: iterate through parameters until distribution converges.

Output: e.g. statistics of density (matter) field, P(k) and RSD

Plots compare constraints from 26 mocks and data





Granett+VIPERS team (2015)
http://arxiv.org/abs/1505.06337

Recovered value for growth rate consistent with direct VIPERS analyses

Ongoing work (led by Ben Granett)

- VIPERS P(k) with Quadratic estimator (Granett+ in prep.), 50% improvement on error bars over FKP ?

- Wiener filter reconstruction of final VIPERS data, with improved density field model (Nicolas Estrada Msc thesis, just started)

- Exploring Jasche & Lavaux approach (Federico Tosone PhD project, just started)

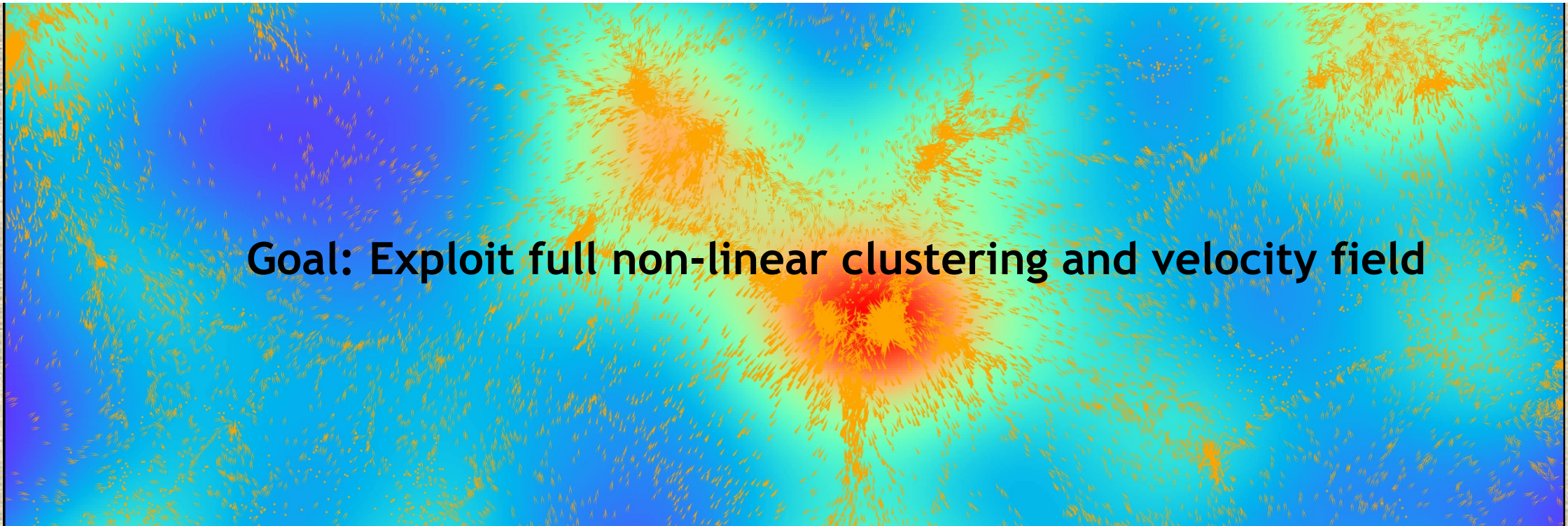
nature astronomy

LETTERS

https://doi.org/10.1038/s41550-018-0573-2

No evidence for modifications of gravity from galaxy motions on cosmological scales

Jian-hua He[1*], Luigi Guzzo[2,3,4], Baojiu Li[1] and Carlton M. Baugh[1]



Testing gravity with RSD through Sub-Halo Abundance Matching (SHAM)

INGREDIENTS

- **N-body simulations:**
  1. High-resolution (**9.6 x 10^7 M_{sun}/h)** **ΛCDM** simulation: Small Multi-Dark Planck (**MDPL**, Klypin+ 2016), **400/h Mpc box**
  2. State-of-the-art high-resolution (**1.5 x 10^8 M_{sun}/h)** simulation run with **Hu & Sawicki f(R) model**, with f_{Ro}=-10^{-6} and n=1 (Shi, Li+ 2015), **64/h Mpc box**
     - barely distinguishable from ΛCDM in terms of cluster number counts and WL signal - Schmidt+ 2009):
     - highest-resolution existing f(R) simulation **—> crucial for properly describing screening mechanism** (He+ 2015, PRL 115, 071306–071310)
- **Data:**
  1. SDSS "NYU Value Added Galaxy Catalogue" (NYU-VAGC - enhanced version of SDSS-DR7): **542,432 galaxies** to r=17.60 over 7732 deg^2, highly complete, includes extended
  2. SHAM performed on **volume-limited sub-samples** complete in stellar mass (re-estimated with 3 different methods)

Effective density field in f(R) gravity

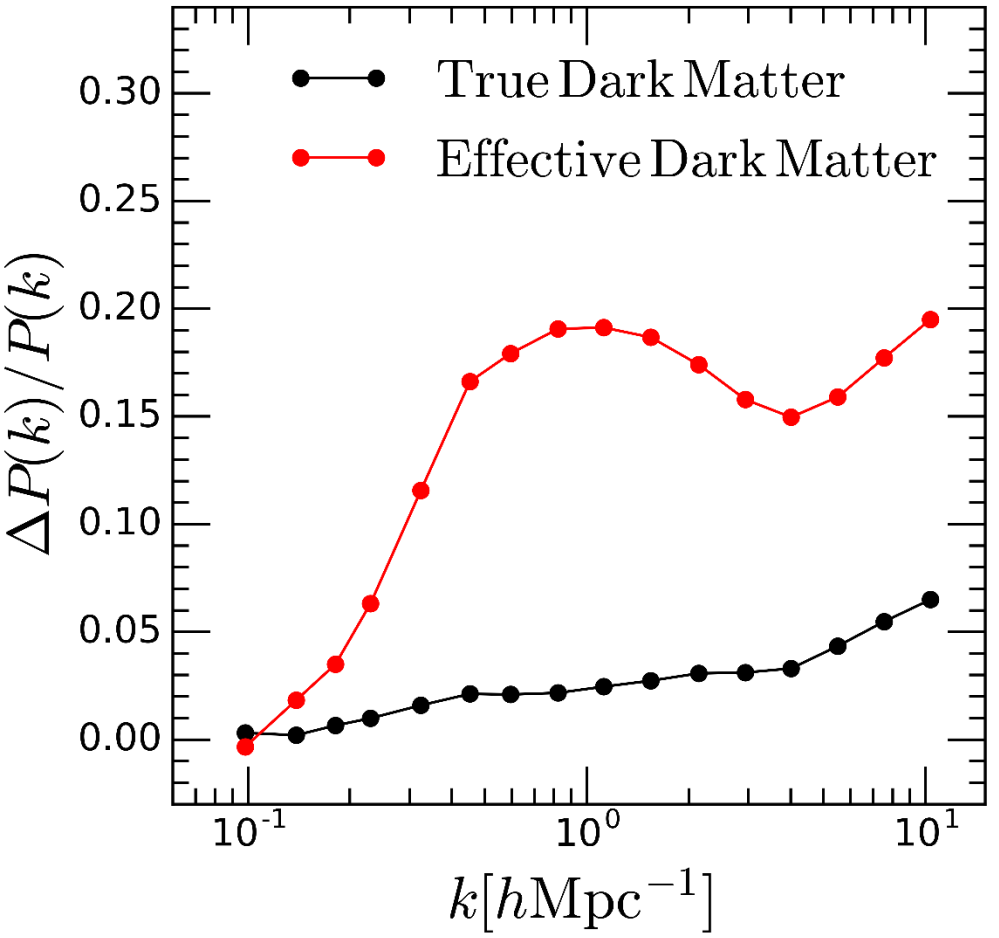
Dynamical Mass

$$\Phi_+ = \frac{\psi + \phi}{2} = 4\pi G \delta \rho_{eff}$$

Lensing Mass

$$\Phi_- = \frac{\psi - \phi}{2} = 4\pi G \delta \rho_m$$

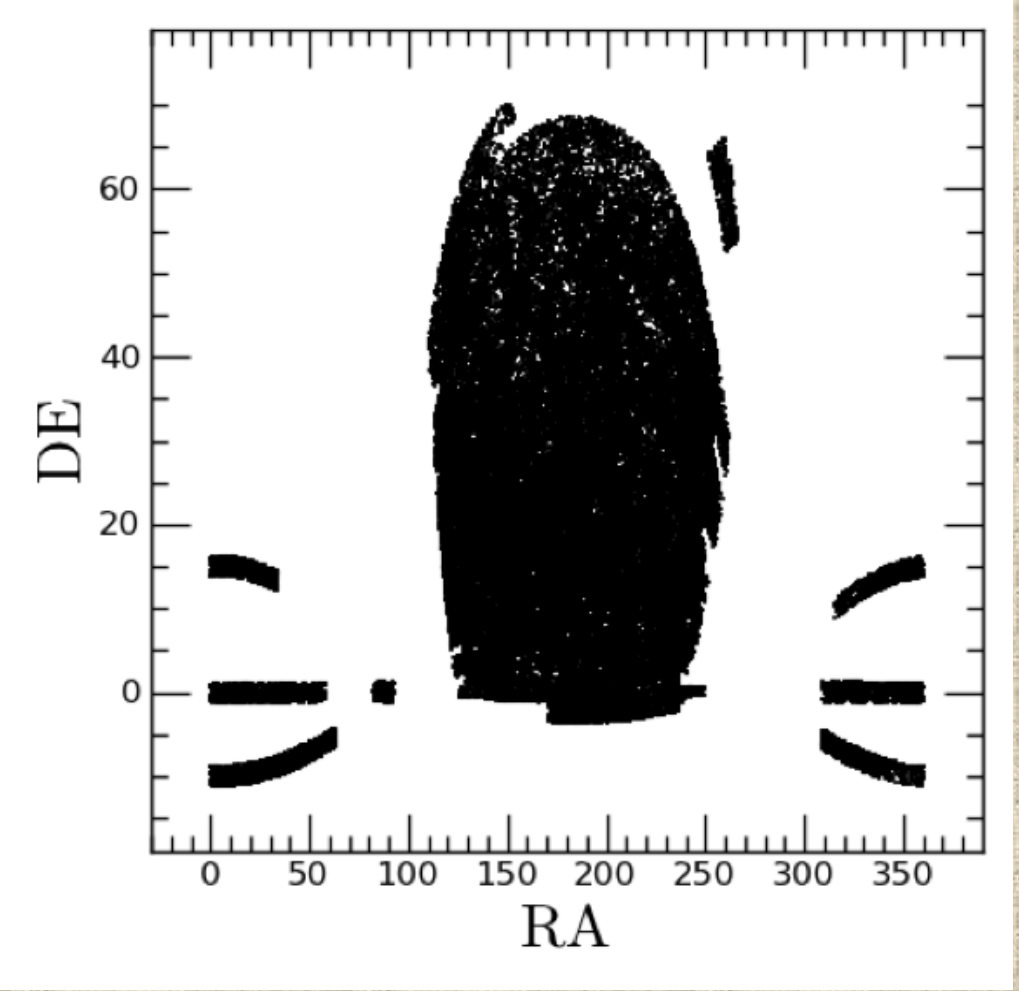
$$f_{R0} = -10^{-6}$$



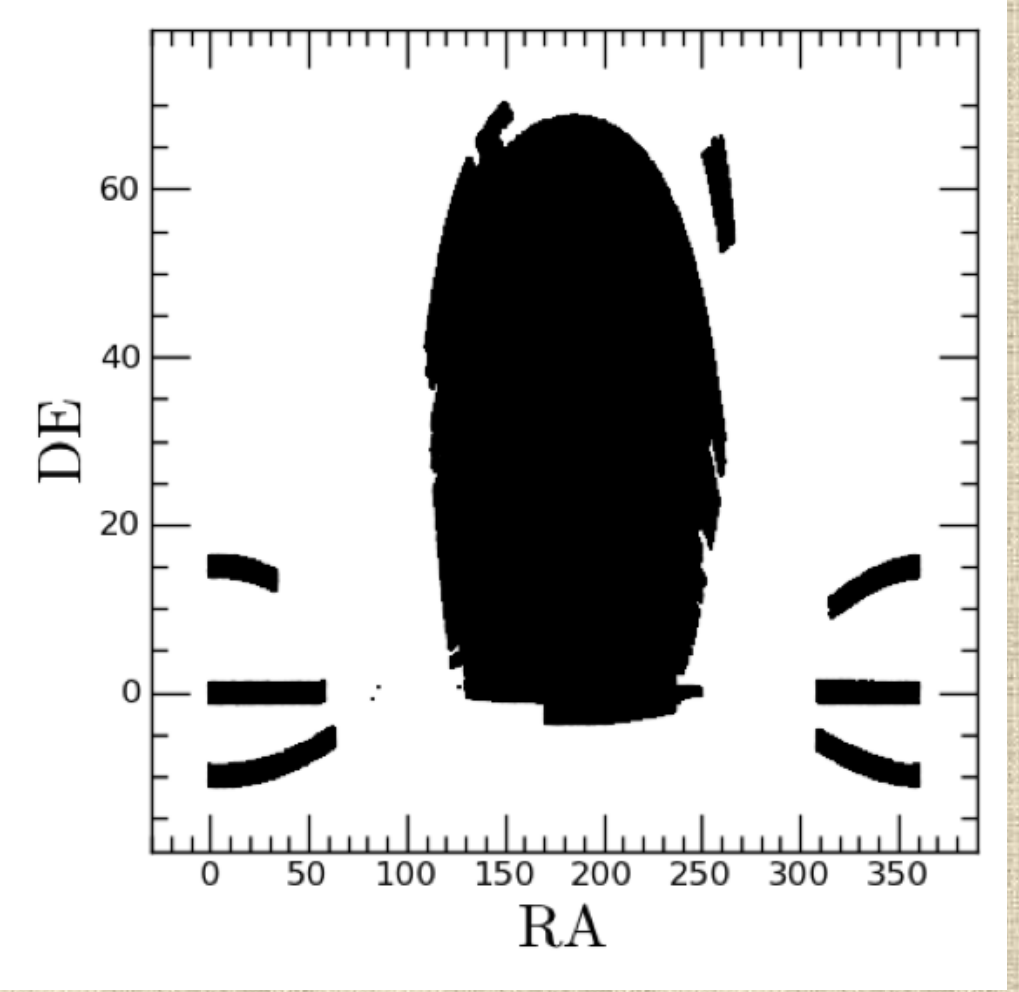
Jianhua He et al PRD 2015

SHAM SDSS-like mocks

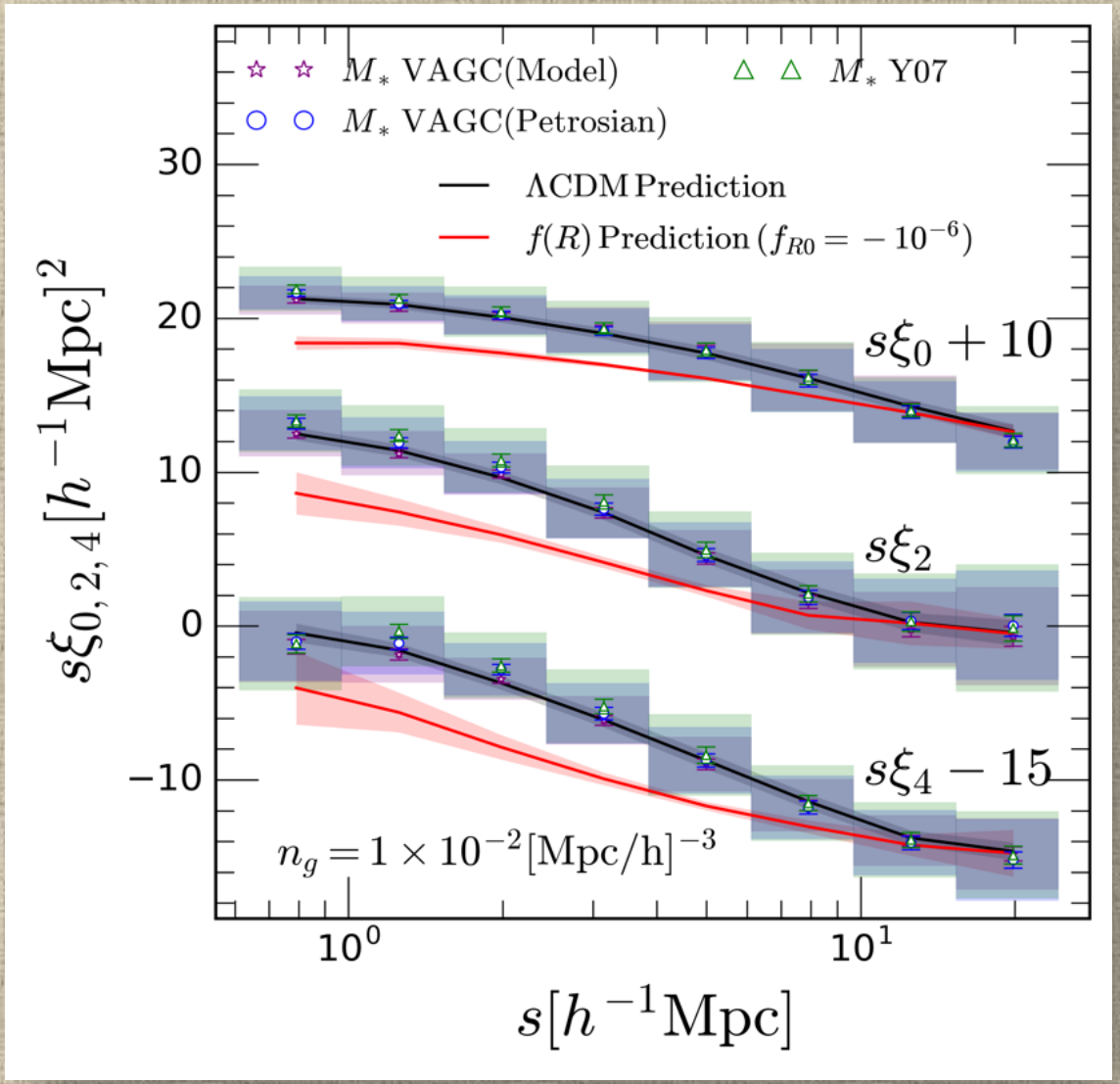
SHAM mock



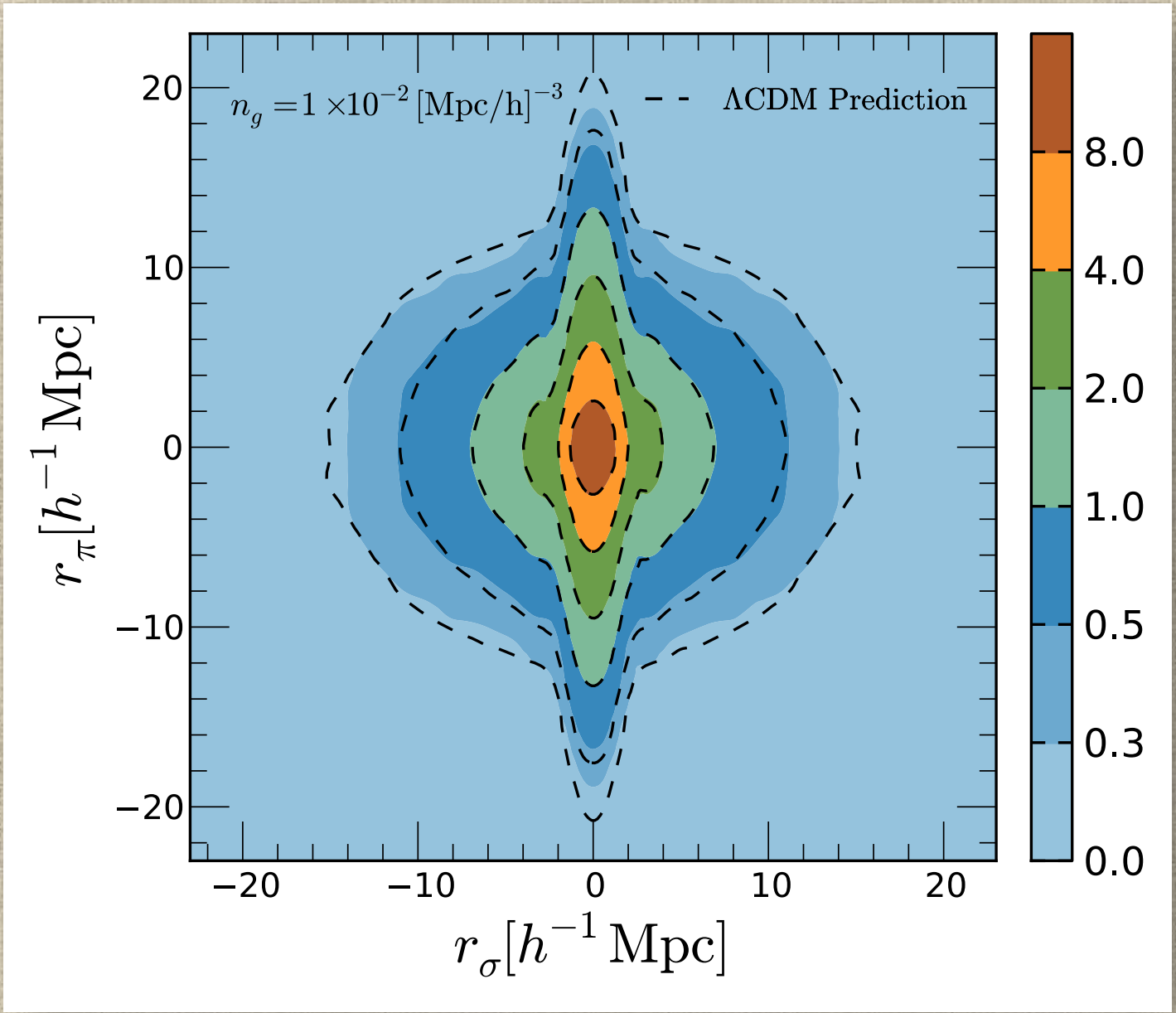
SDSS Data



Results


M_* VAGC(Model)
M_* VAGC(Petrosian)
M_* Y07
ΛCDM Prediction
$f(R)$ Prediction ($f_{R0} = -10^{-6}$)
$s\xi_0 + 10$
$s\xi_2$
$s\xi_4 - 15$
$n_g = 1 \times 10^{-2}[\mathrm{Mpc/h}]^{-3}$
$s\xi_{0,2,4}[h^{-1}\mathrm{Mpc}]^2$
$s[h^{-1}\mathrm{Mpc}]$
30
20
10
0
−10
10^0
10^1

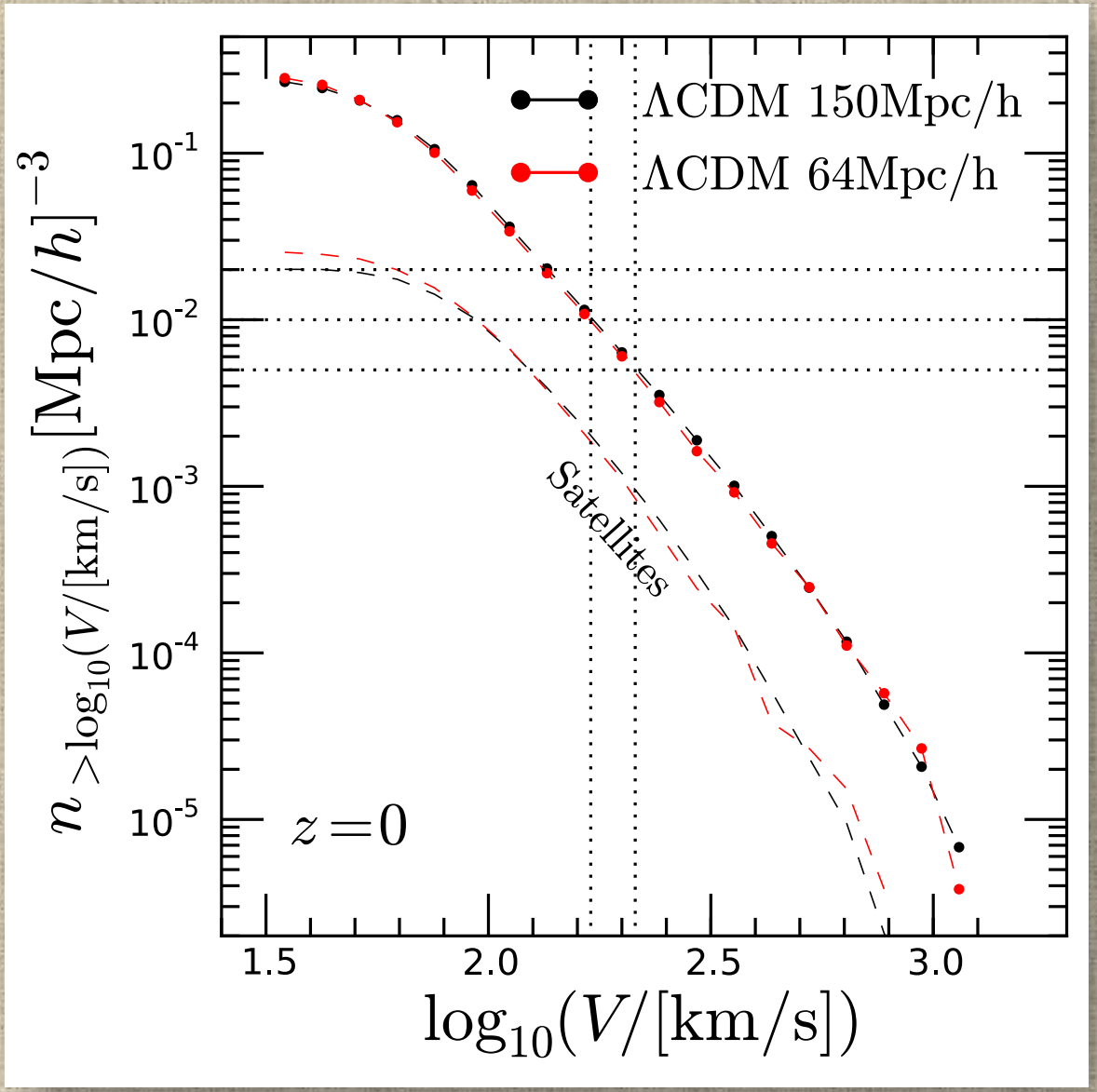
Results


$n_g = 1 \times 10^{-2}\,[\mathrm{Mpc/h}]^{-3}$
ΛCDM Prediction
20
10
0
−10
−20
$r_\pi[h^{-1}\,\mathrm{Mpc}]$
−20
−10
0
10
20
$r_\sigma[h^{-1}\,\mathrm{Mpc}]$
8.0
4.0
2.0
1.0
0.5
0.3
0.0

A number of potential issues tested (see Supplementary Info)

- Impact of galaxy stellar mass SED-fitting estimates: 3 different methods
- Robustness wrt to SHAM implementation: measured clustering is stable when high-density galaxy samples are used (uncertainties and variations at high-end do not modify significantly rank order wrt clustering properties)
- Numerical stability of SHAM (changing n-body codes and halo finder)
- Lack of long-wavelength modes in small-box f(R) simulation: correction scheme
- Survey geometry and wide-angle effects (different simulation boxes)
- Fiber collisions
- Key to stable clustering of matched SHAM mocks is stellar-mass selection of galaxy sample and its fairly high mean density, which minimises effect of rank-order changes on measured clustering
- Unknowns?

Box size impact on halo mass function



Summary

- **VIPERS results provide an olistic view of large-large-scale structure and galaxy evolution, allowing to place galaxy types in their LSS context**
- **Consistent RSD results with different techniques**
- **Proper choice of galaxy tracers allows minimising systematic uncertainties: not all galaxies are equally good to do cosmology!**
- **Importance of galaxy surveys with broad selection function**
- **Forward modelling approaches allow us to make full use of multiple tracers and extended information in surveys**

- **A SHAM mock catalogue properly built from a ΛCDM simulation provides impressive match to redshift-space clustering of a corresponding stellar mass - selected galaxies in the SDSS, with no fine-fine-tuning at all**
- **Analogous SHAM analysis in a mild f(R) cosmology deviates significantly from the observations**
- **GR is alive and kicking, also on large scales**
- **Forward modelling based on numerical simulations is the future**