Cosmology from galaxy clustering: the VIPERS perspective

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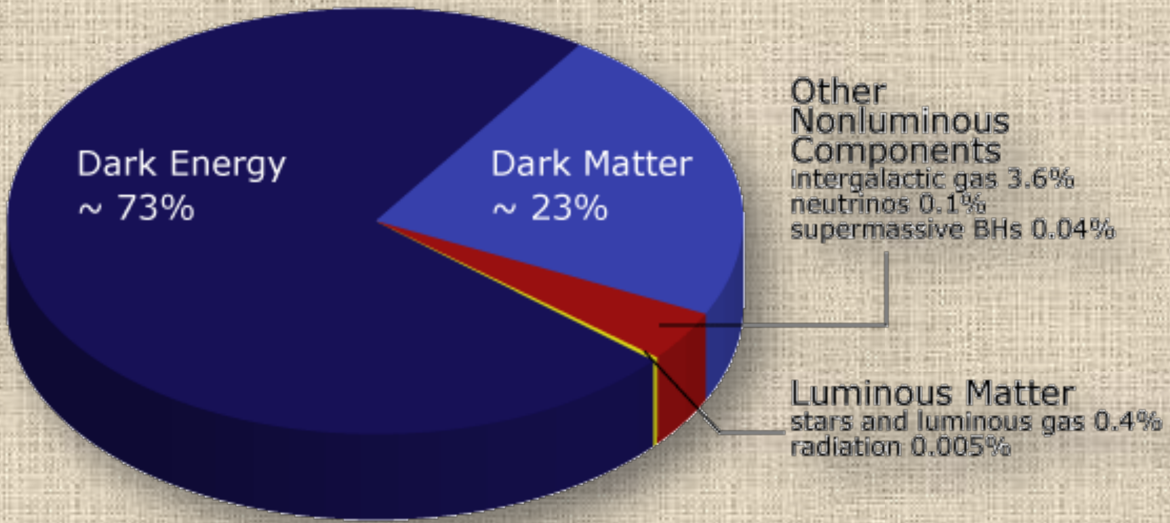
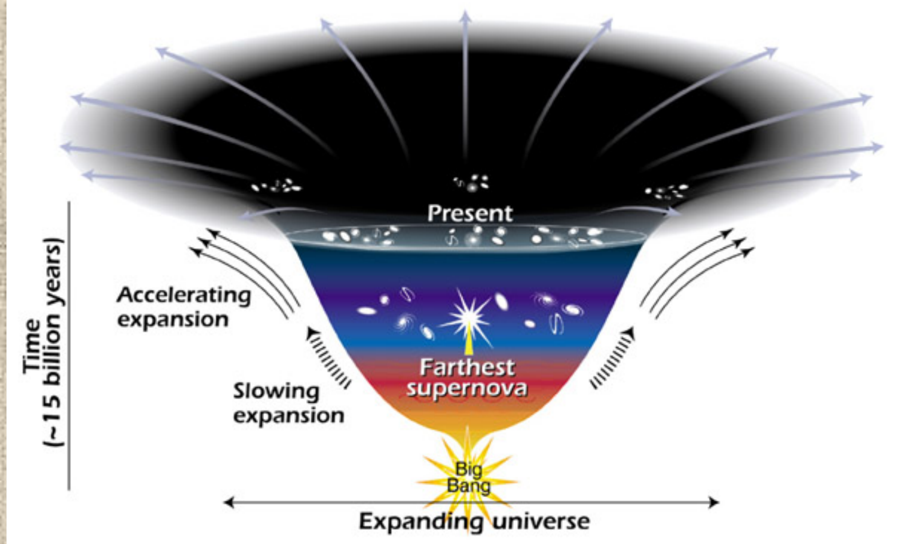
The "cosmic pizza" of the 21st century: but who ordered it?

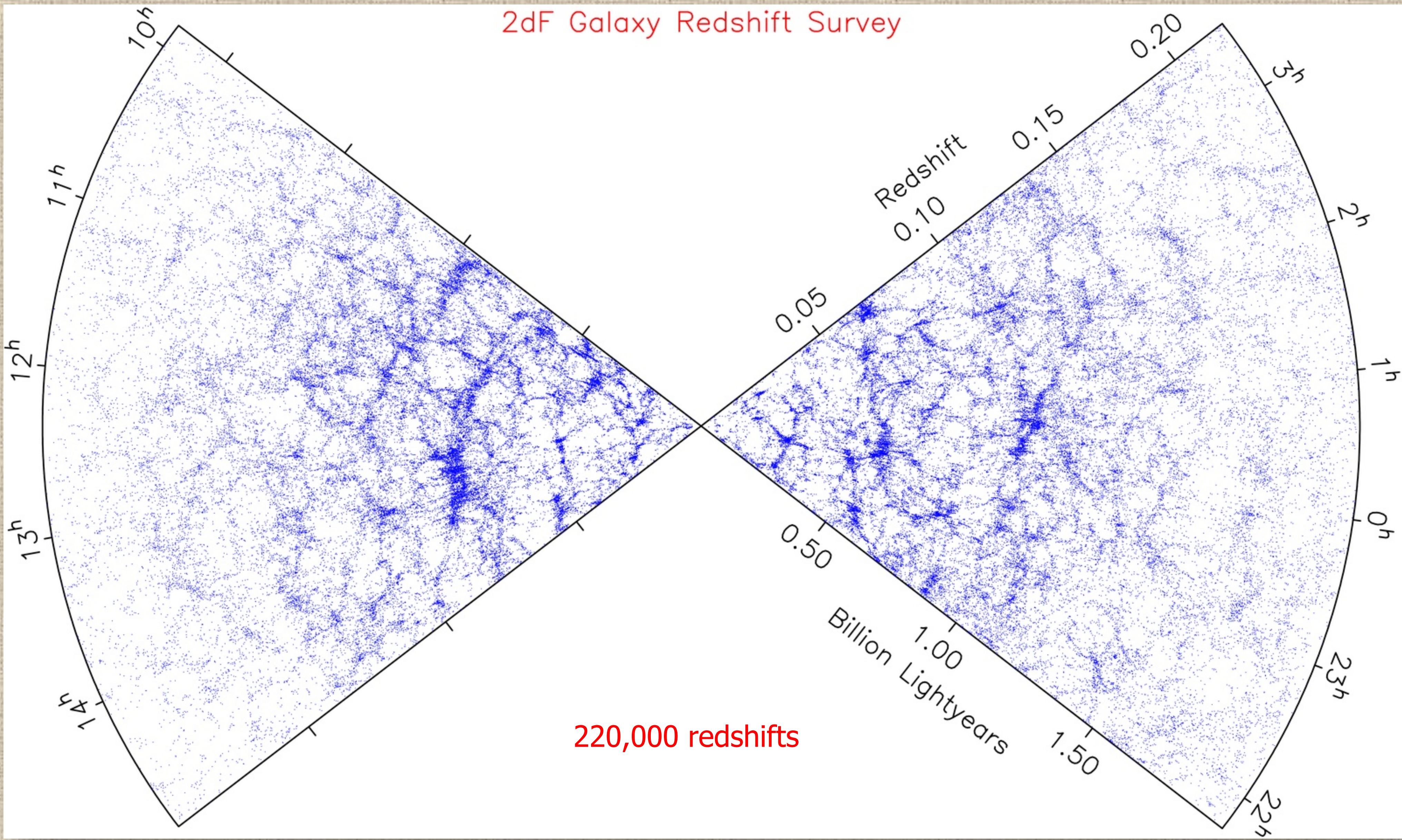


2011 Nobel Prize



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

Large-scale structure at z<0.2



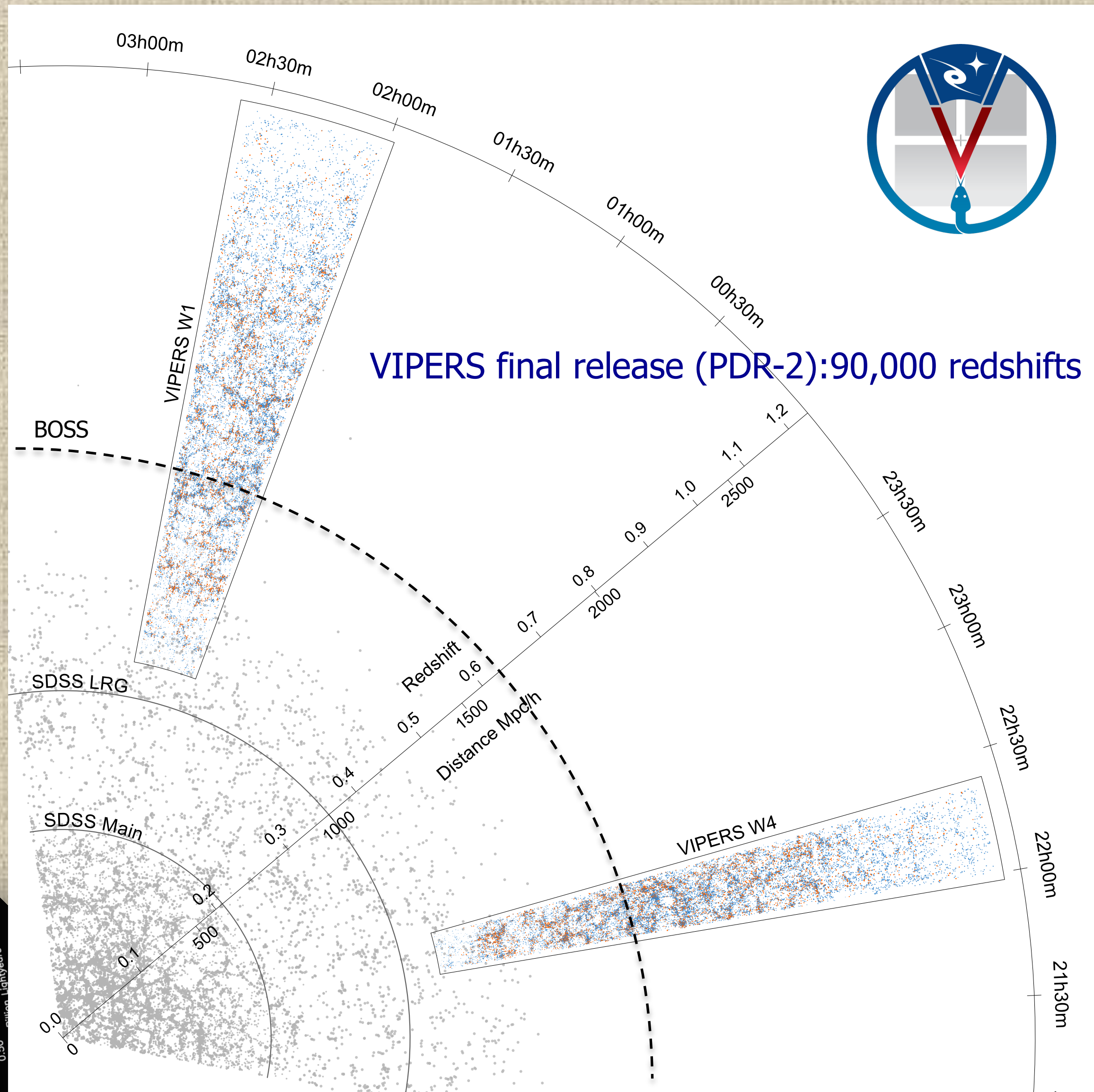
Galaxy redshift surveys: a major pillar of the cosmological model…

State of the art:

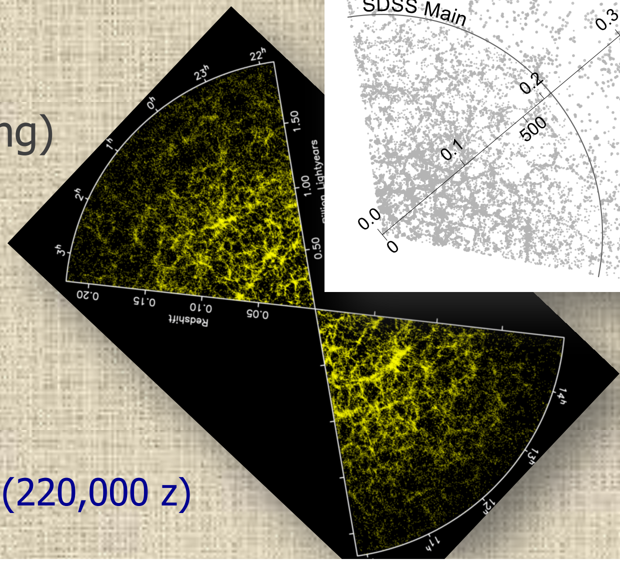
- SDSS-III BOSS (e.g. Alam+ 2016)
- WiggleZ (Blake+ 2014)
- **VIPERS** (Guzzo+2014, Scodeggio+ 2017)

Future:

- SDSS-IV eBOSS (ongoing)
- DESI (2019-)
- **Euclid** (2020-)

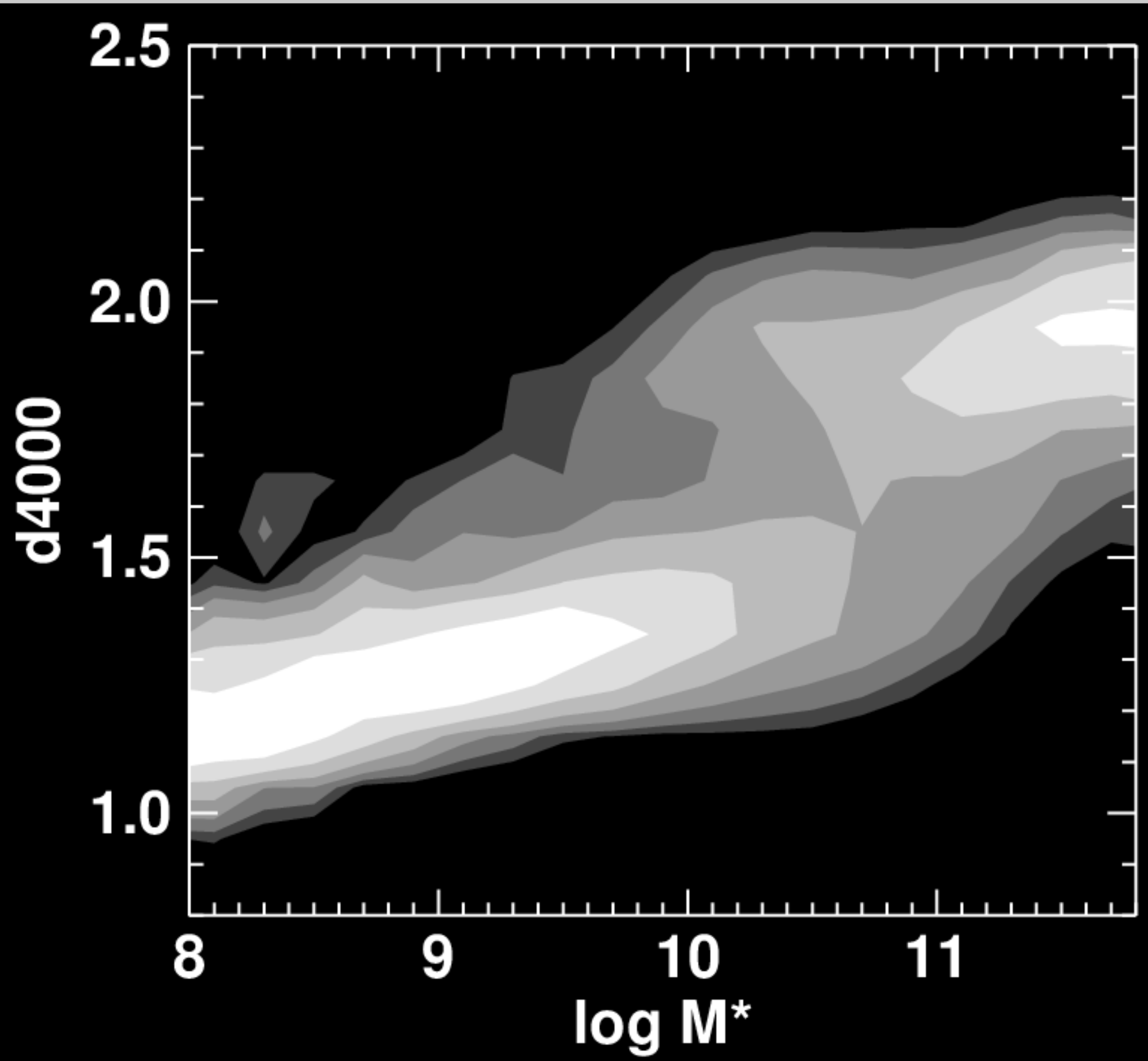


(arXiv 1611.07048)



2dFGRS (220,000 z)

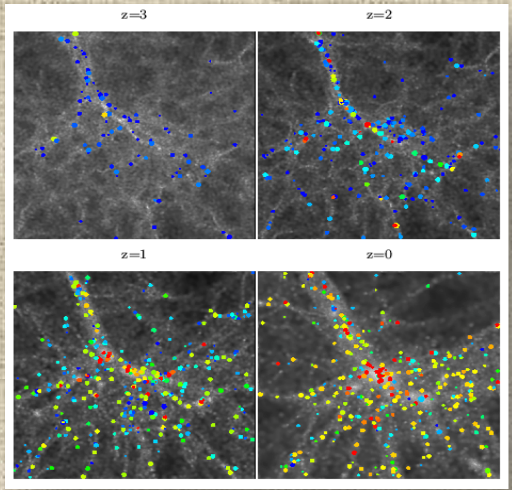
Let’s keep in mind that SDSS/2dFGRS did much more…



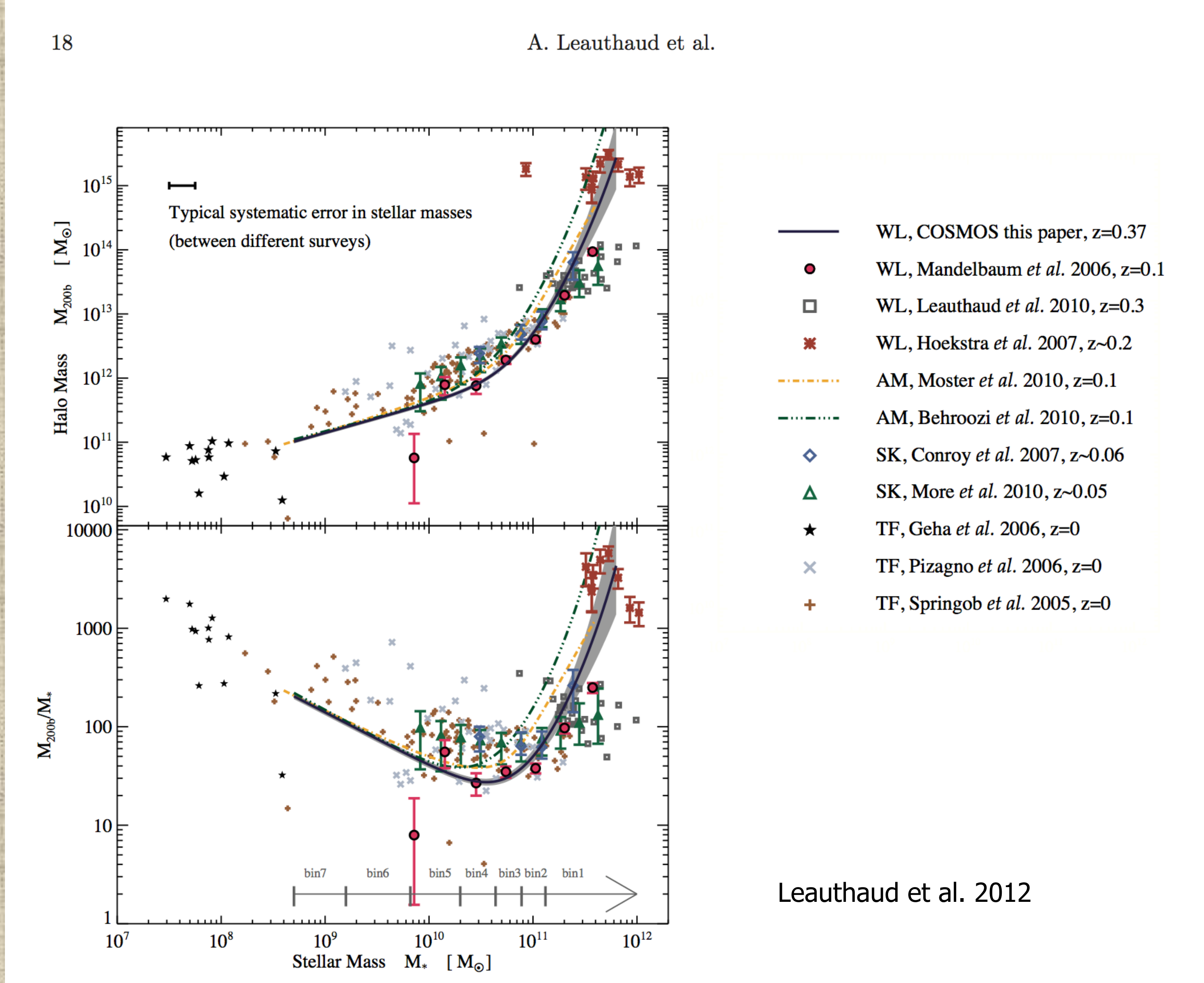
Z<0.2: SDSS (Kauffman+)

Statistical properties of the galaxy population to high precision

We need to understand galaxies, to do cosmology…



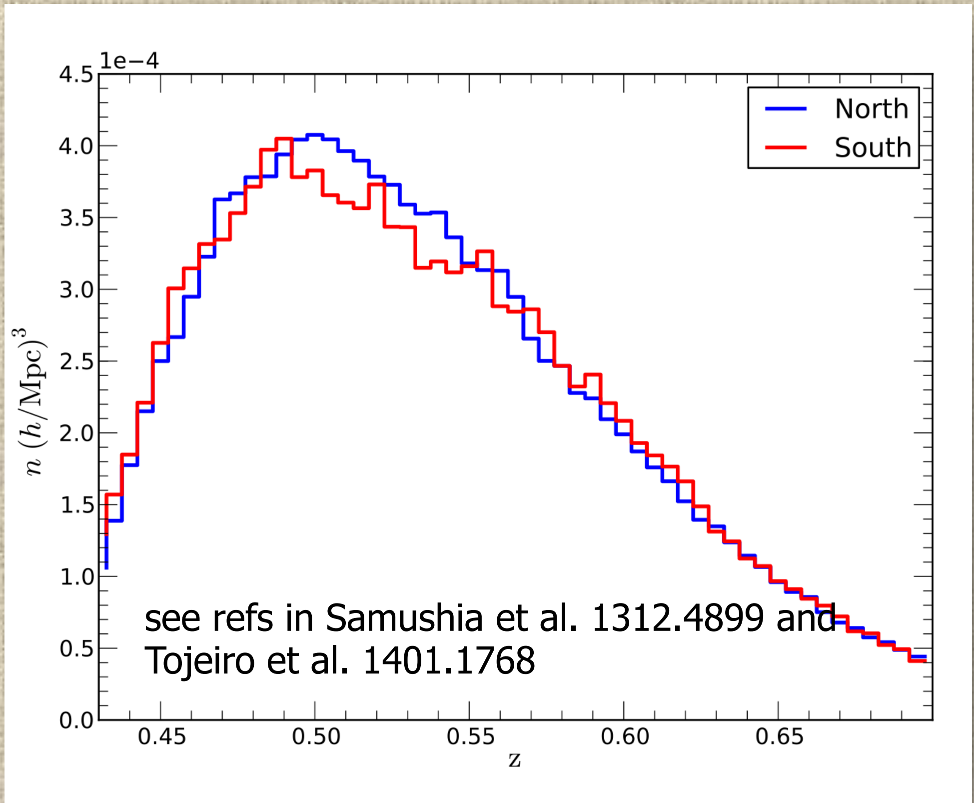
Kauffman & Diaferio 1998

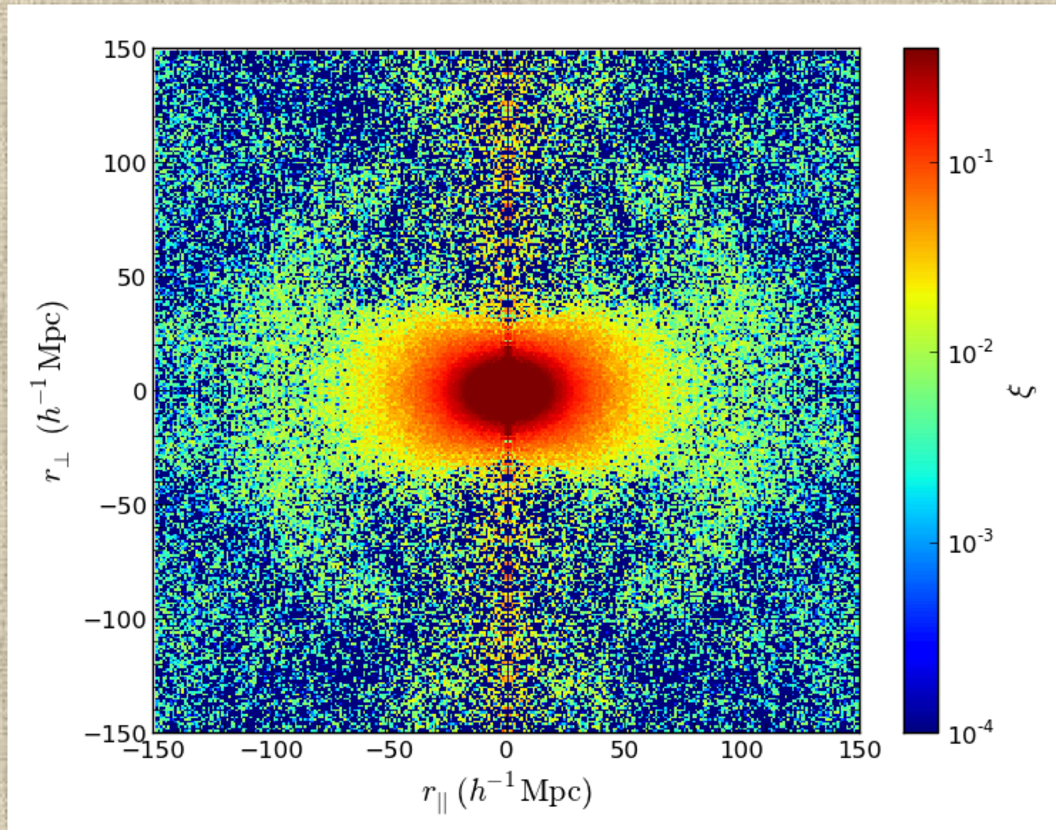


Leauthaud et al. 2012

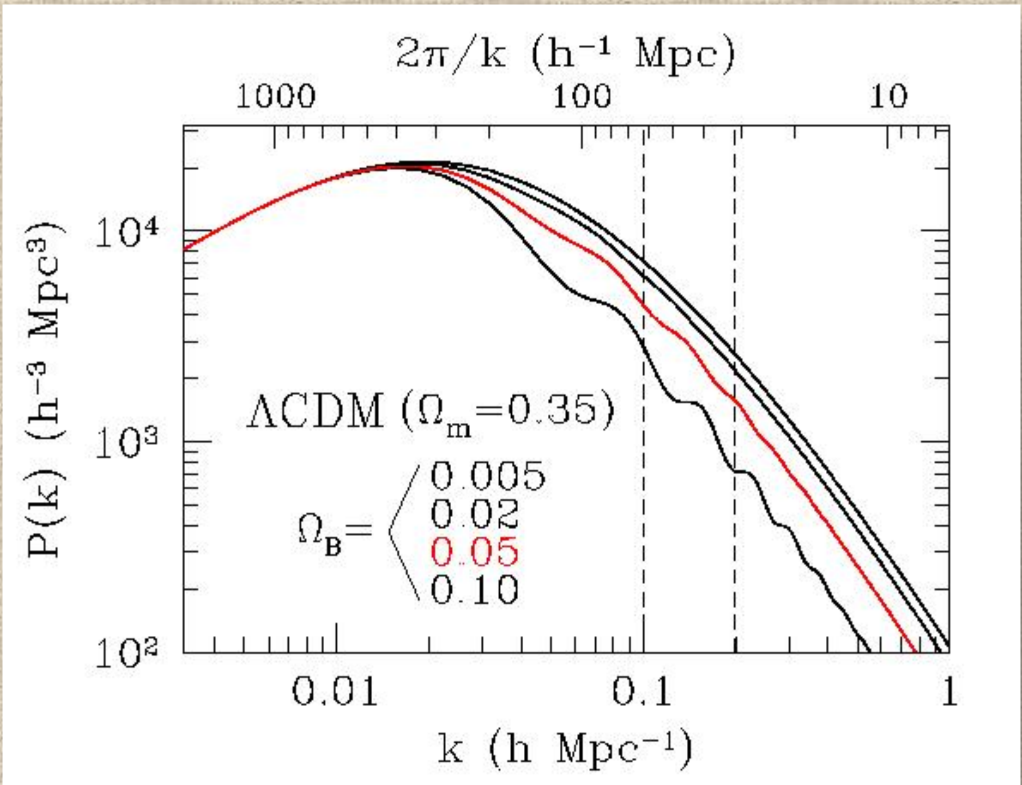
Pushing to higher z with a sparse population: e.g. **BOSS**

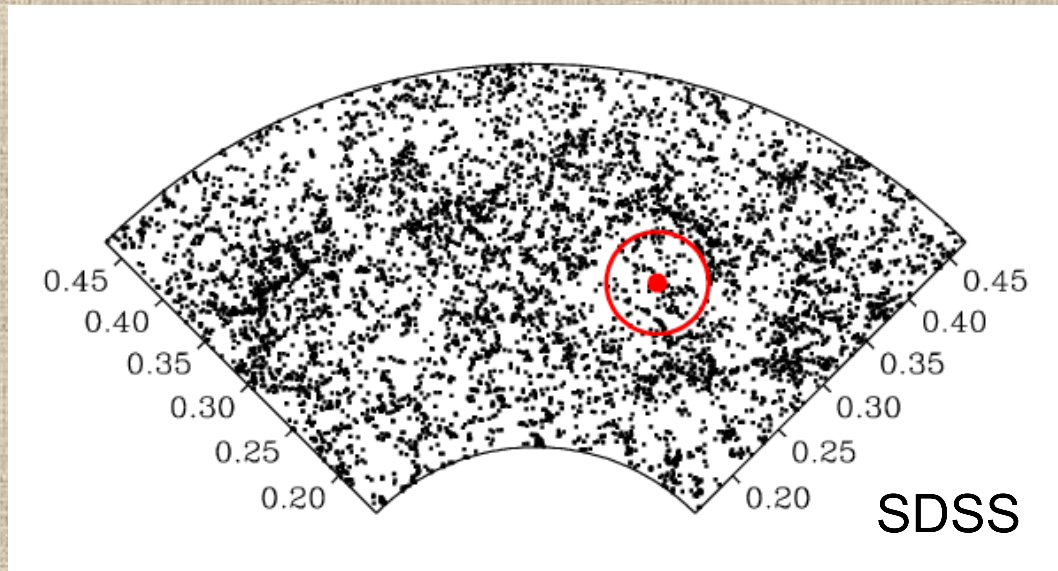
- **Area=8500 deg^2 , Volume~6 h^{-3} Gpc, Ngal = 690,000**
- **"CMASS" LRG-like col-col selection, "loosely selecting constant mass galaxies"**
- **Low-density tracers**
- **Optimized for BAO, not for P(k) shape information (selection function)**
- **Excellent (a posteriori) for Redshift Space Distortions thanks to huge volume**





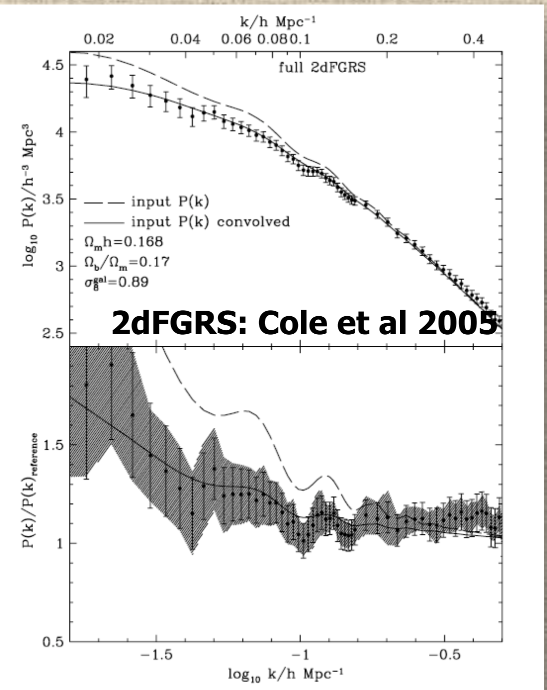
Baryonic Acoustic Oscillations: a standard ruler to measure H(z)





D. Eisenstein 2007

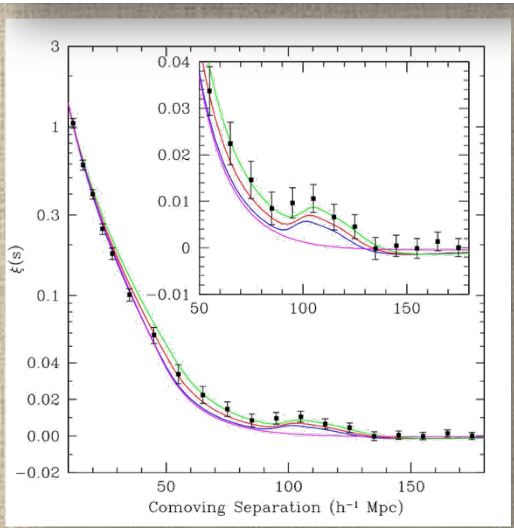
BAO in galaxy redshift surveys



2dFGRS: Cole et al 2005

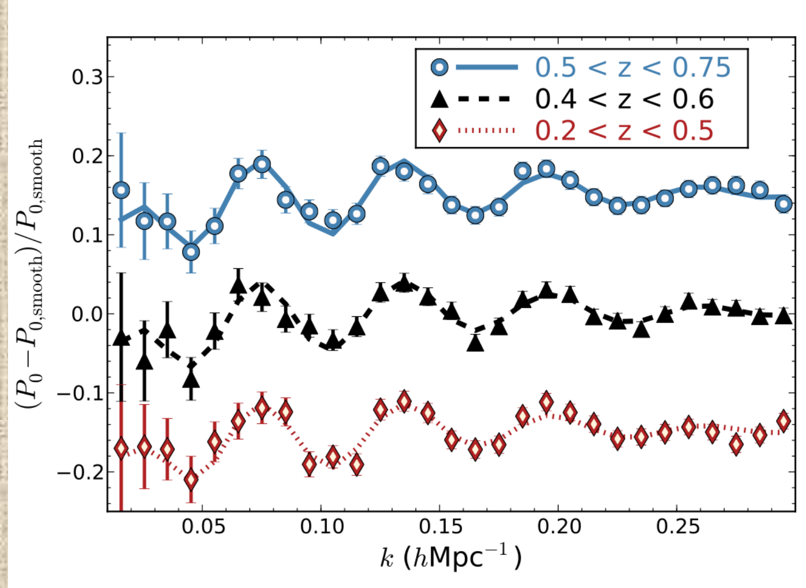
Fourier Space (wiggles):

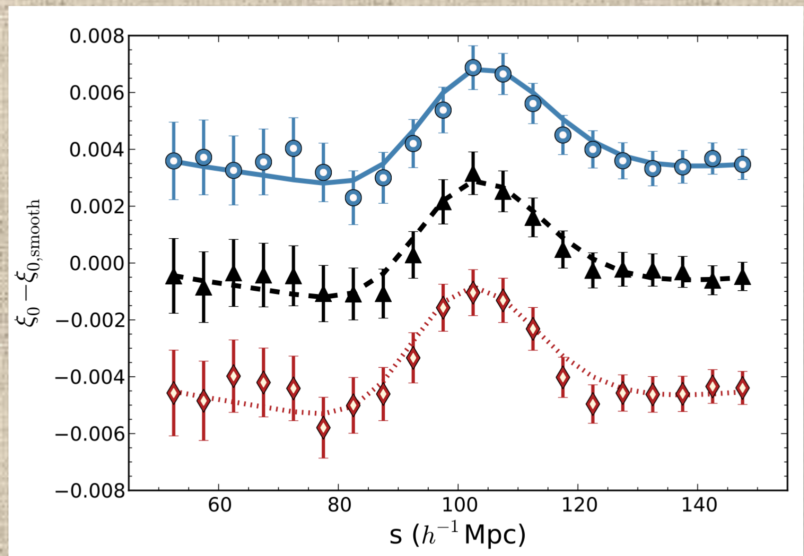
Configuration Space (BAO peak):



SDSS: Eisenstein et al 2005

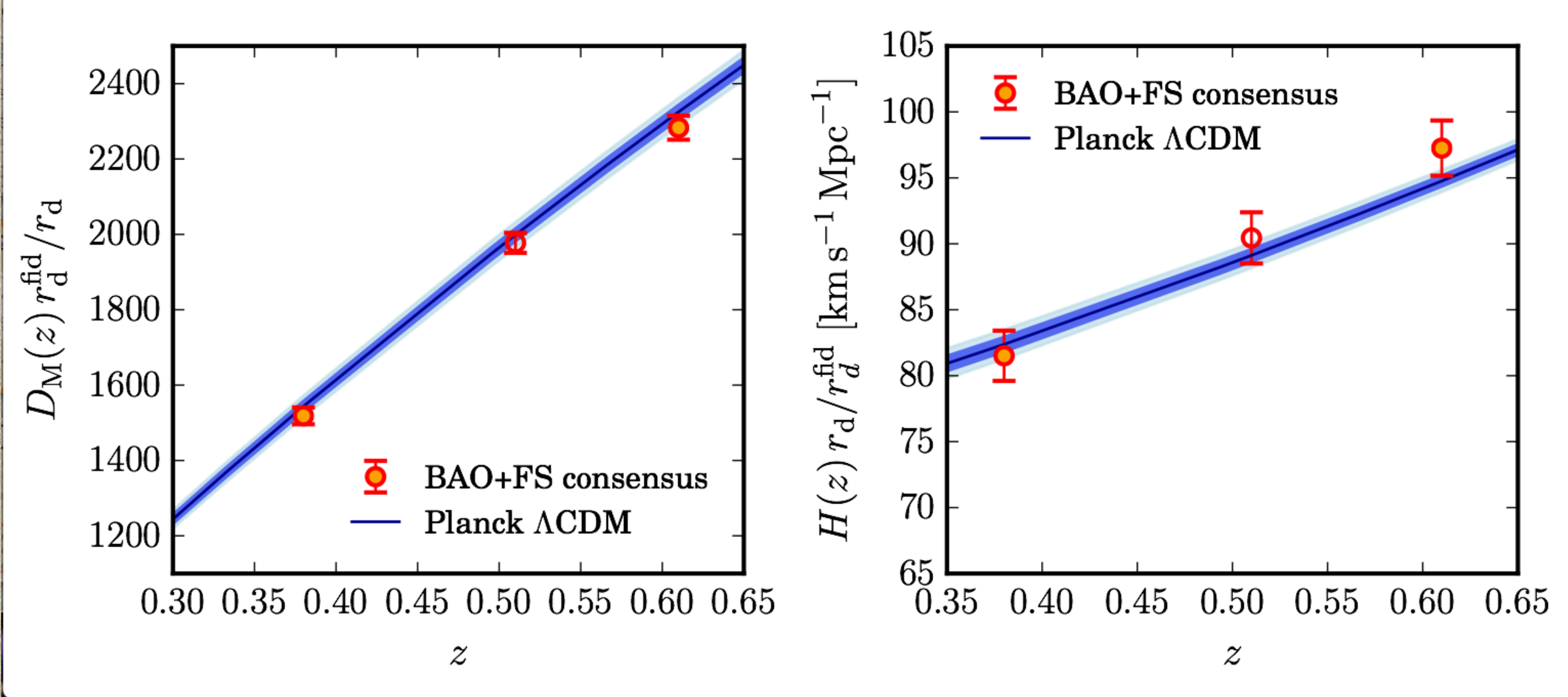
2016: Final measurement from BOSS-DR12





(BOSS Collaboration 2016, arXiv:1607.03155)

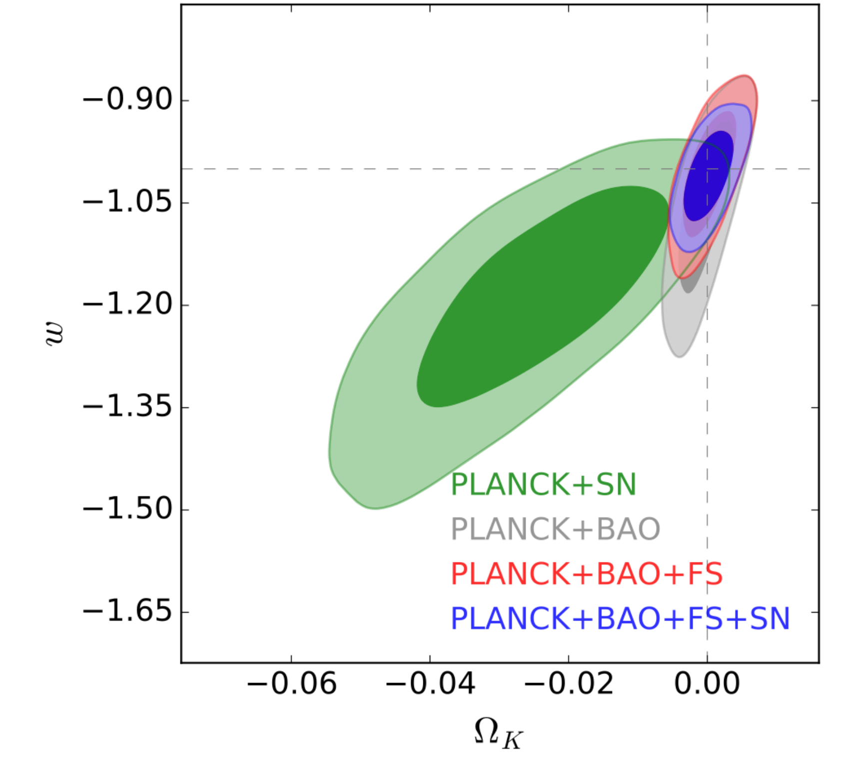
Probe expansion history with BAO

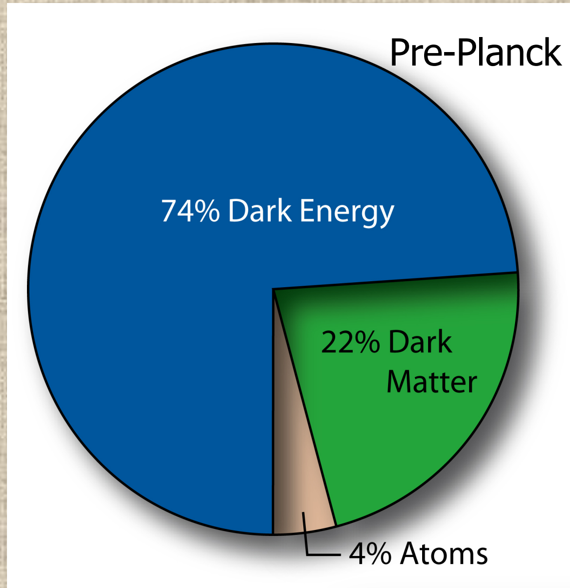


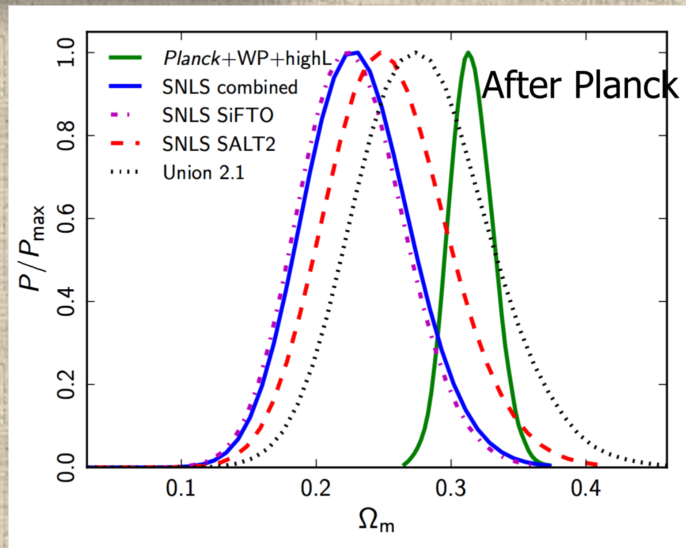
(BOSS Collaboration 2016)

Cosmic (quasi) concordance

(BOSS Collaboration 2016, arXiv:1607.03155)







(Planck Collaboration 2013, paper XVI)

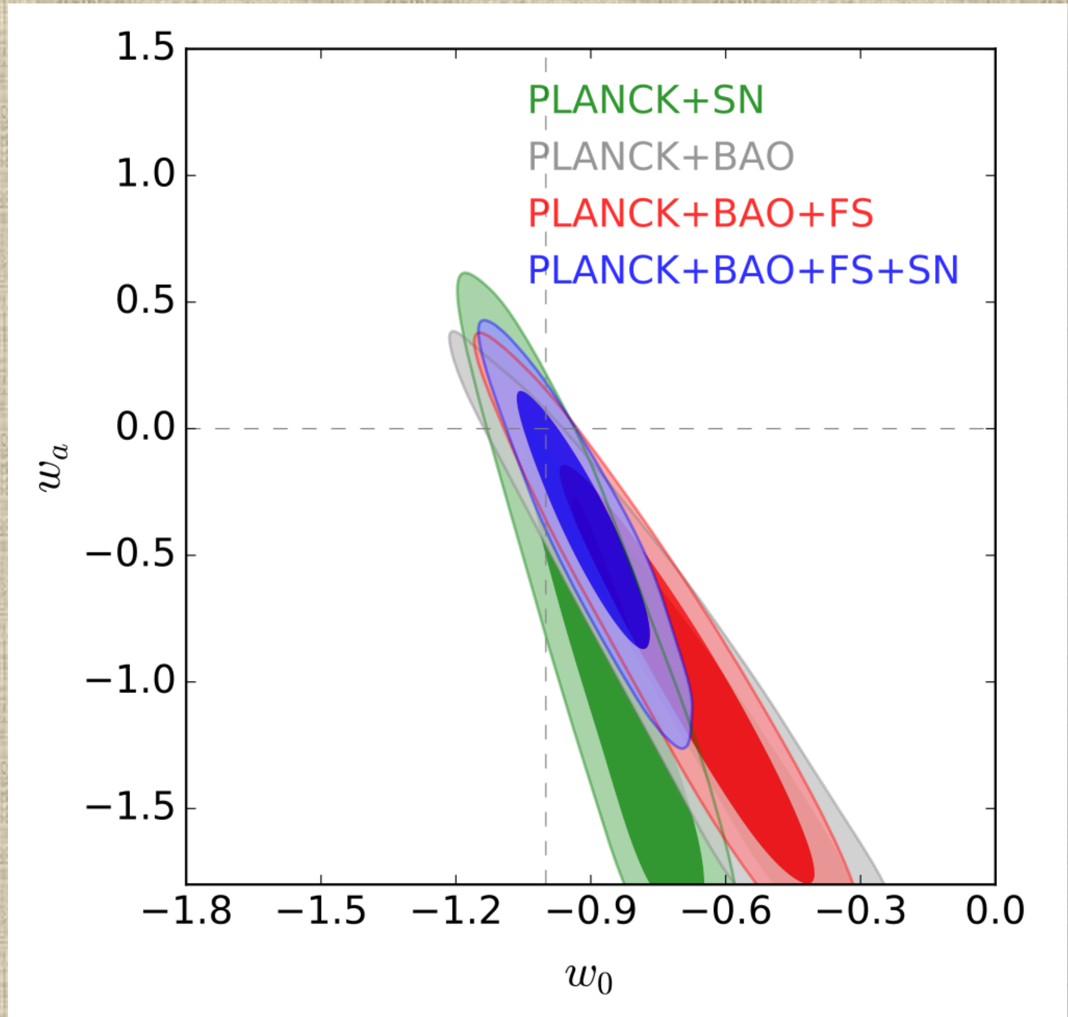
If leaving ***w*** as a free parameter (here with curvature), ***w=-1*** (cosmological constant) remains favoured

Λ is too small and fine-tuned: an evolving equation of state $w(a)$?

Parameterizing our ignorance:

$$w(a) = w_0 + w_a(1 - a)$$

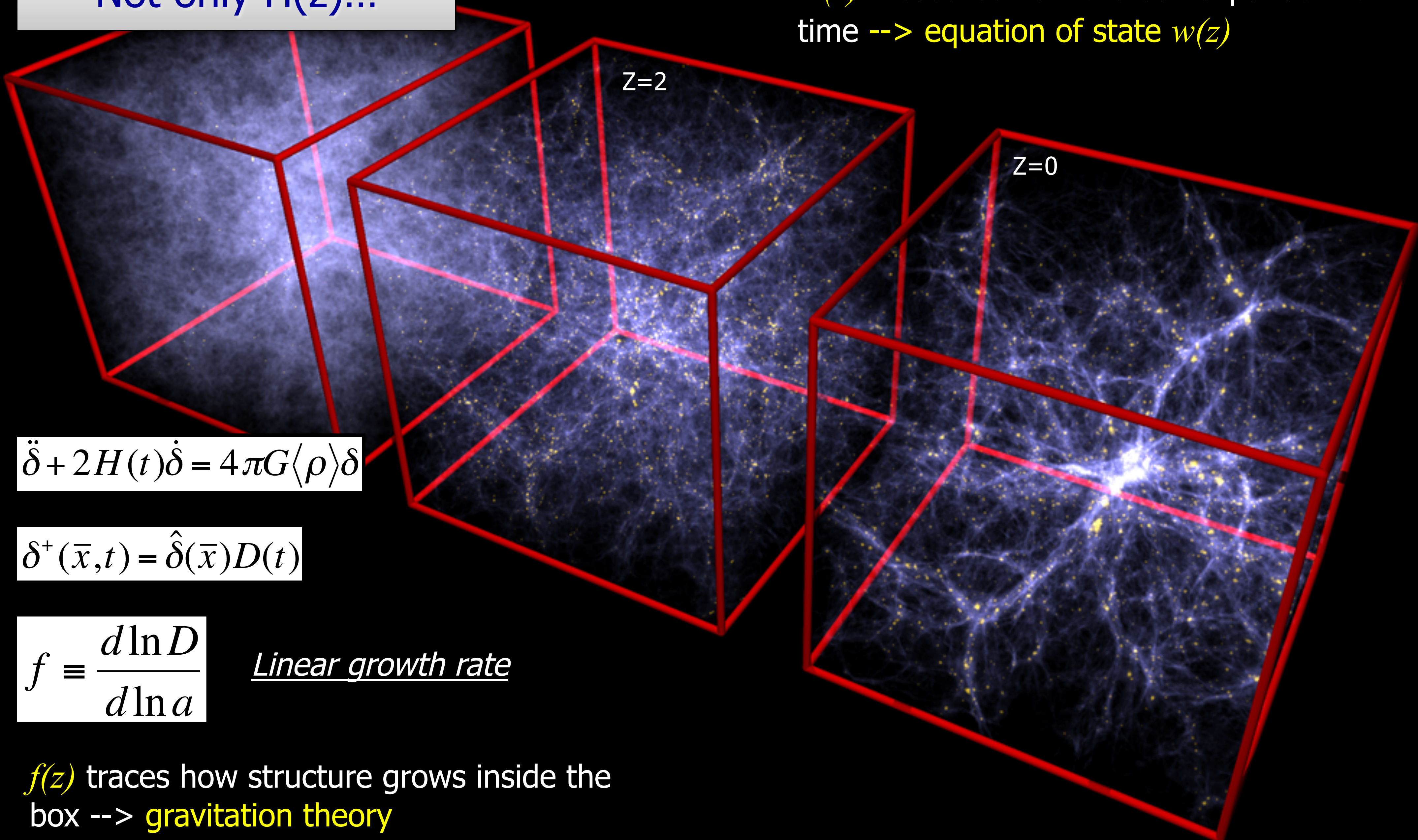
[a = scale factor of the Universe = $(1+z)^{-1}$]



(BOSS Collaboration 2016, arXiv:1607.03155)

Not only H(z)…

H(z) measures how the box expands with time --> equation of state *w(z)*



$$\ddot{\delta} + 2H(t)\dot{\delta} = 4\pi G\langle\rho\rangle\delta$$

$$\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$$

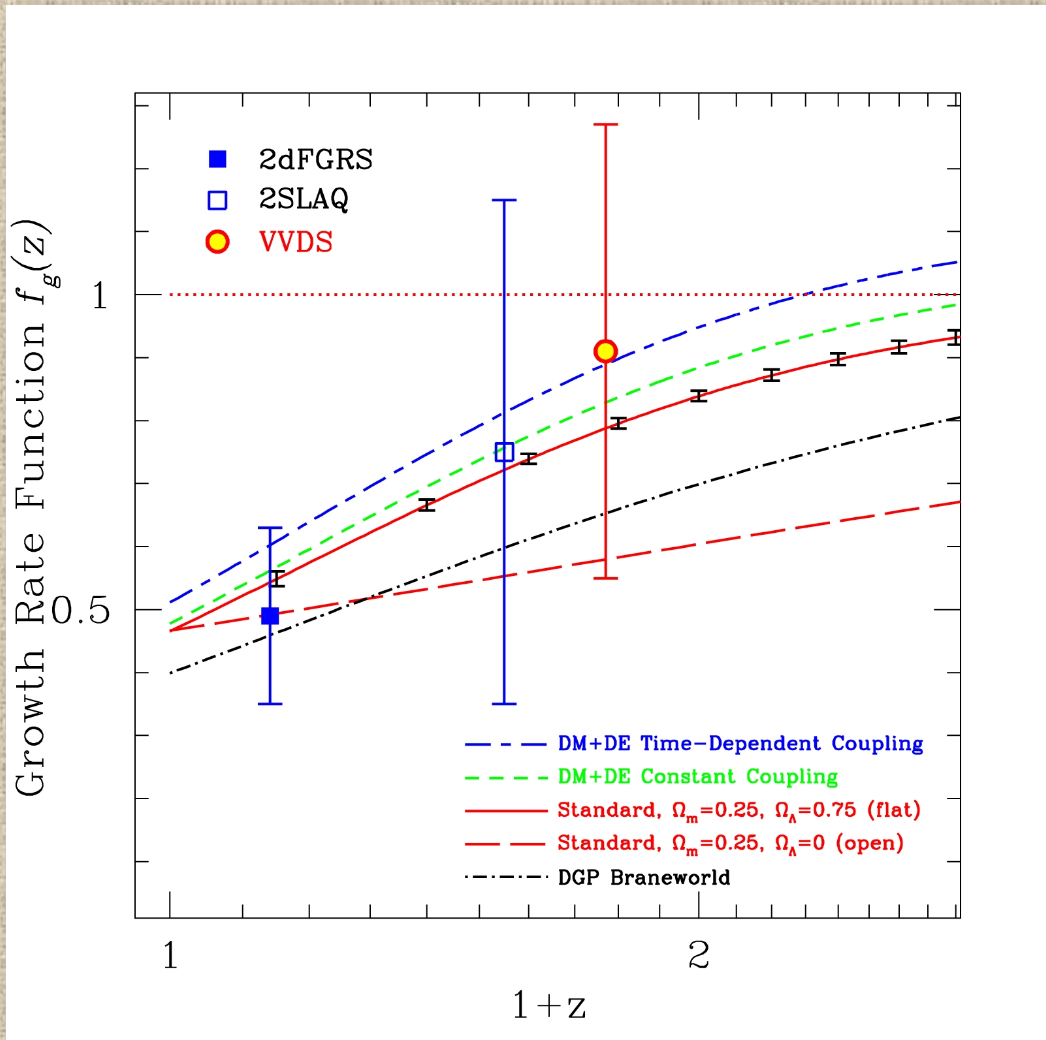
$$f \equiv \frac{d\ln D}{d\ln a}$$

Linear growth rate

f(z) traces how structure grows inside the box --> gravitation theory

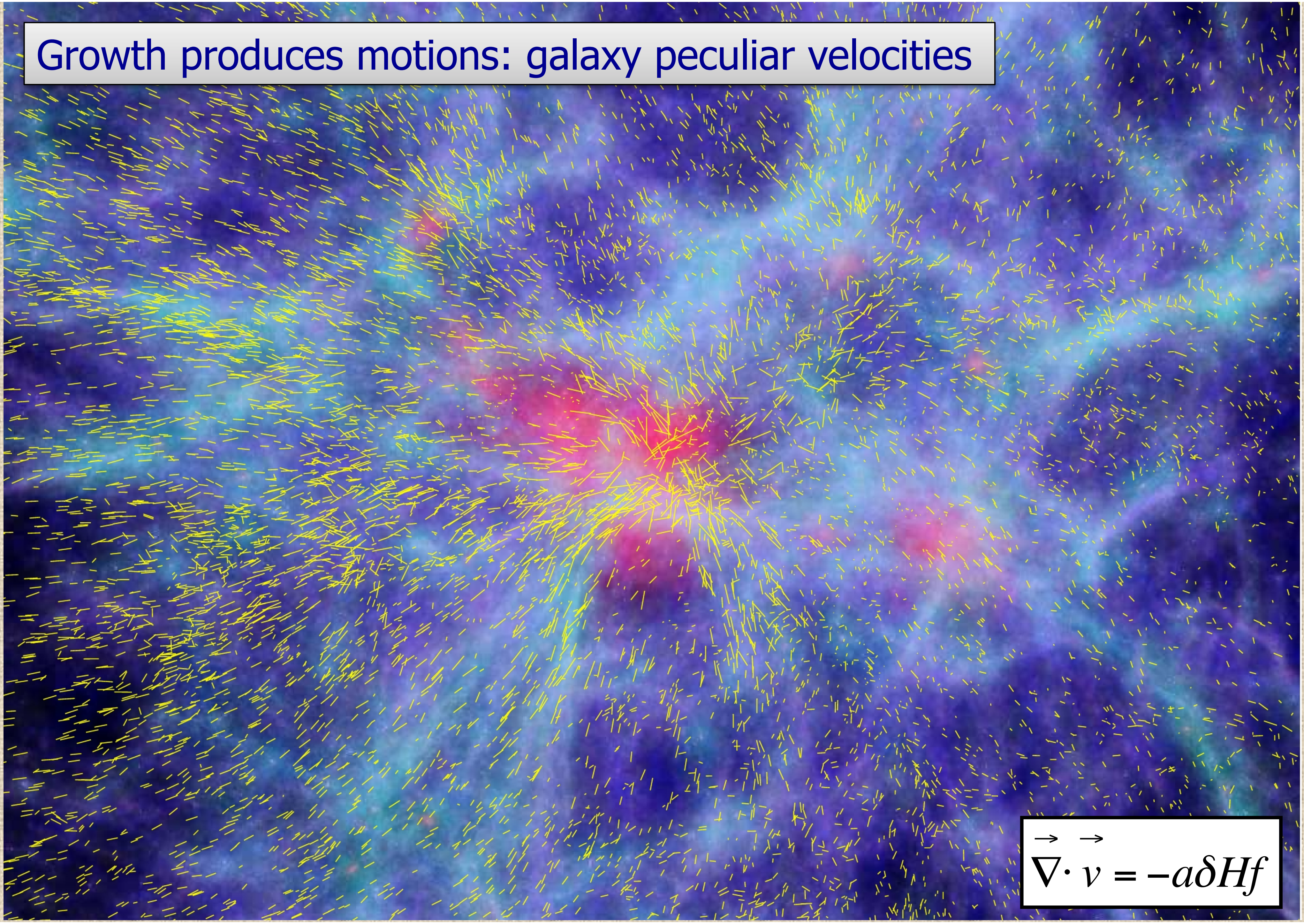
Springel et al.

Growth rate of structure probes modified gravity



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

Growth produces motions: galaxy peculiar velocities

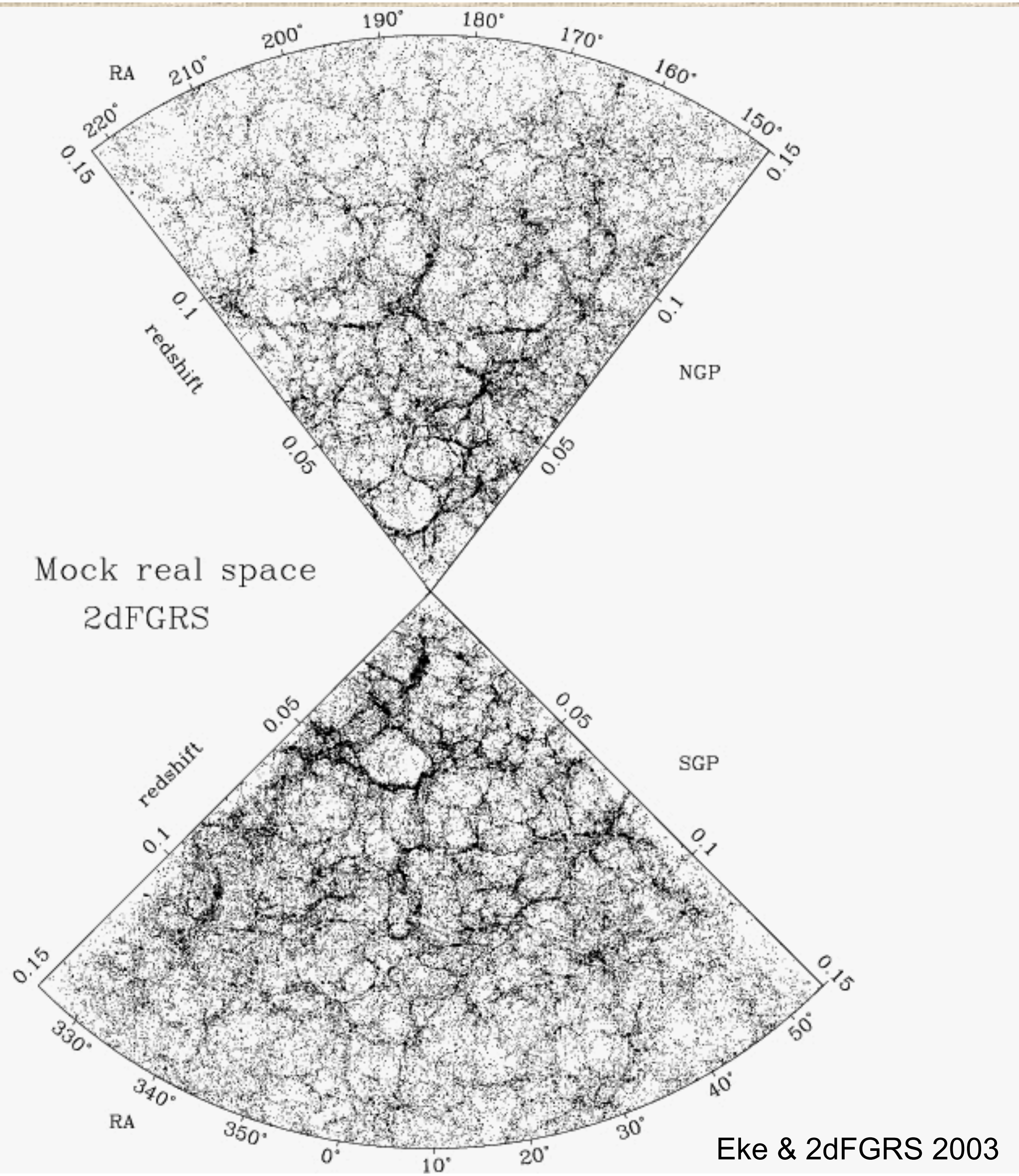


$$\vec{\nabla} \cdot \vec{v} = -a\delta H f$$

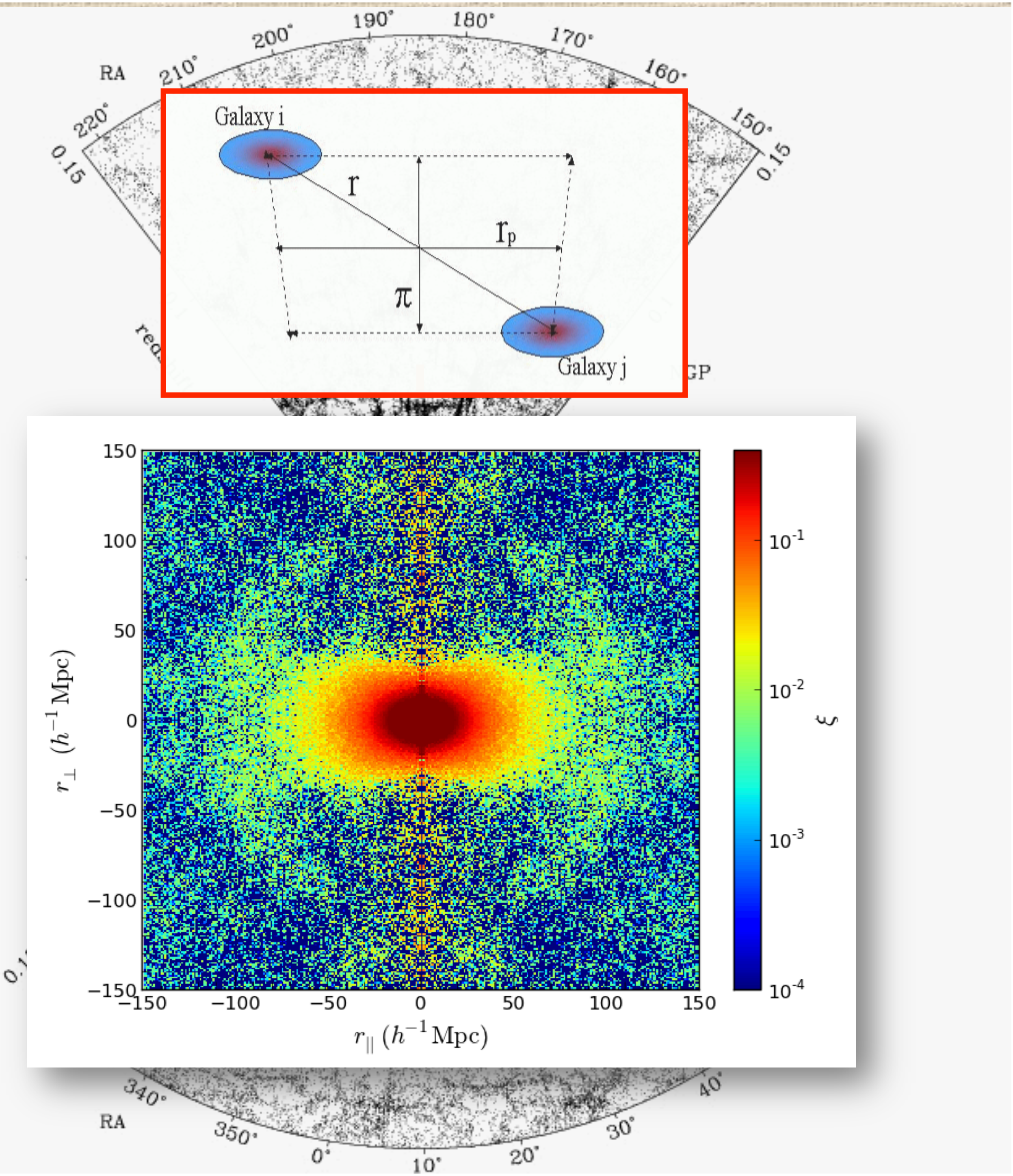
Growth produces peculiar velocities, which manifest themselves in galaxy redshift surveys as *redshift-space distortions*

real space

(Kaiser 1987)



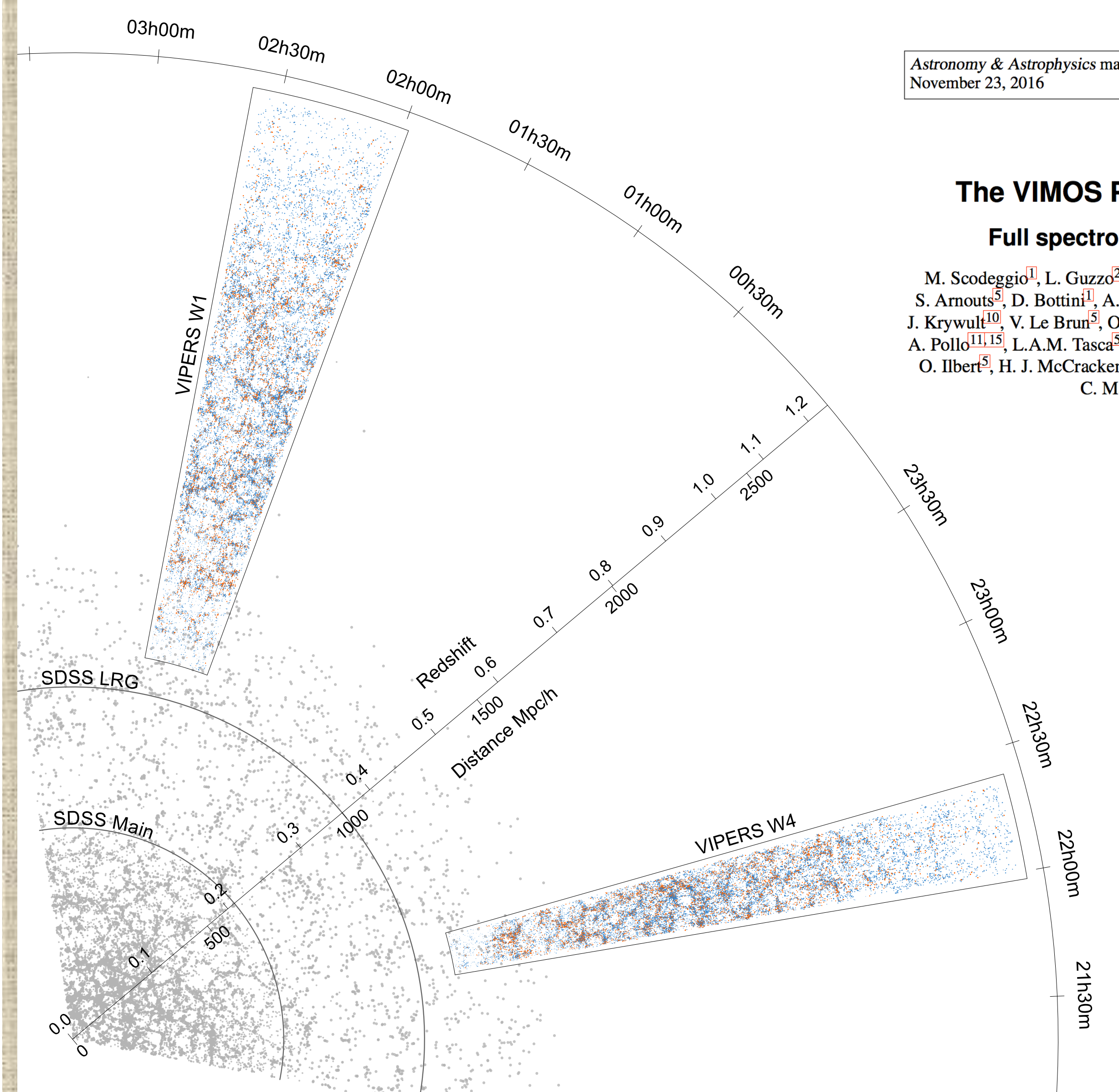
Growth produces peculiar velocities, which manifest themselves in galaxy redshift surveys as *redshift-space distortions*



redshift space

(Kaiser 1987)

VIPERS in the context of modern LSS surveys



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)

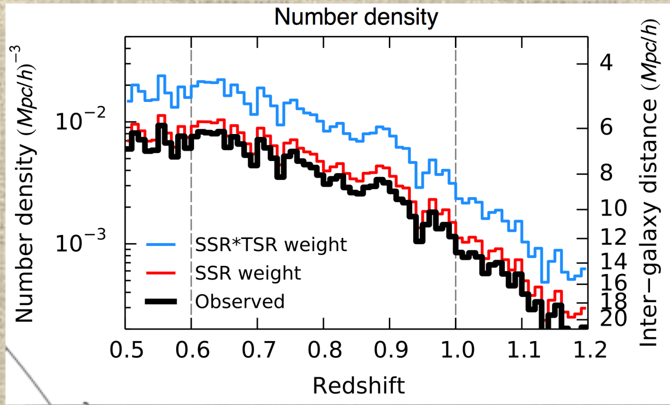
M. Scodeggio[1], L. Guzzo[2,3], B. Garilli[1], B. R. Granett[2,3], M. Bolzonella[4], S. de la Torre[5], U. Abbas[6], C. Adami[5], S. Arnouts[5], D. Bottini[1], A. Cappi[4,7], J. Coupon[8], O. Cucciati[9,4], I. Davidzon[5,4], P. Franzetti[1], A. Fritz[1], A. Iovino[2], J. Krywult[10], V. Le Brun[5], O. 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

- **Probes 0.4<z<1.2, with volume and density comparable to z=0 reference surveys (~2dFGRS)**
- **~24 deg^2**, **I_{AB}<22.5, z>0.5 color-color pre-selection** (+ accurate star-galaxy separation)
- **Volume: 5 x 10^7 h^{-3} Mpc^3, ~10^4 redshifts**
- **47% sampling**
- **<n> ~ 5 x 10^{-3} h^3 Mpc^{-3}**

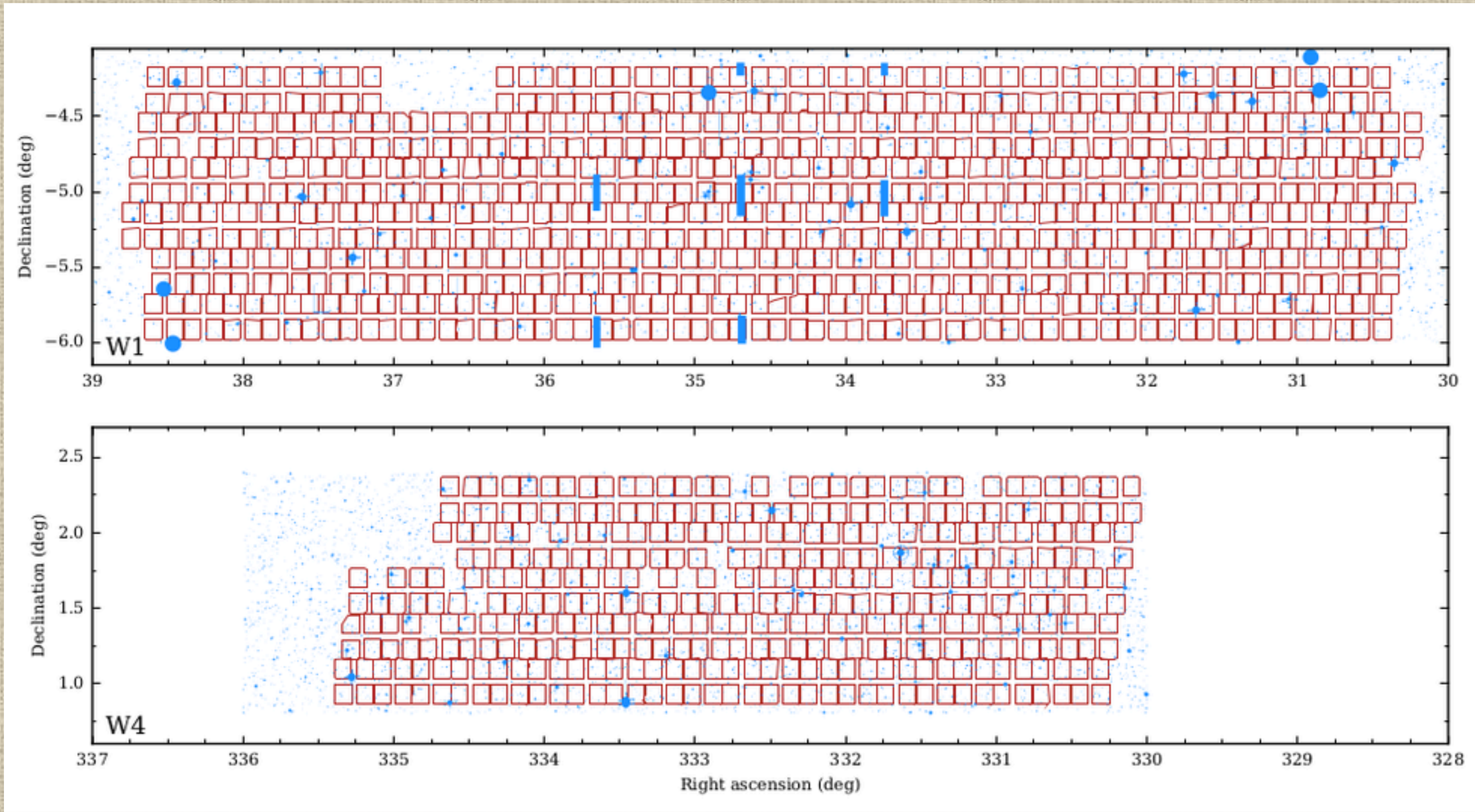


- **CFHTLS Wide** (W1 and W4 fields, ~16 + 8 deg^2) 5-band accurate photometry and high-quality images
- **VIPERS Multi-Lambda Survey** (Arnouts+, Moutard+2016a,b): revised CFHTLS ugriz + extra UV & NIR (http://cesam.lam.fr/vipers-mls/)
- VIMOS @ VLT, LR Red grism, **45 min exposure**
- Mosaic of **288 pointings**, **440.5 hours** (55 VLT night-equivalent) → **2008-2015**
- Expected # was 100,000 spectra; observed 97,414 in total

VIPERS Team

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

Survey layout and photometric/spectroscopic masks



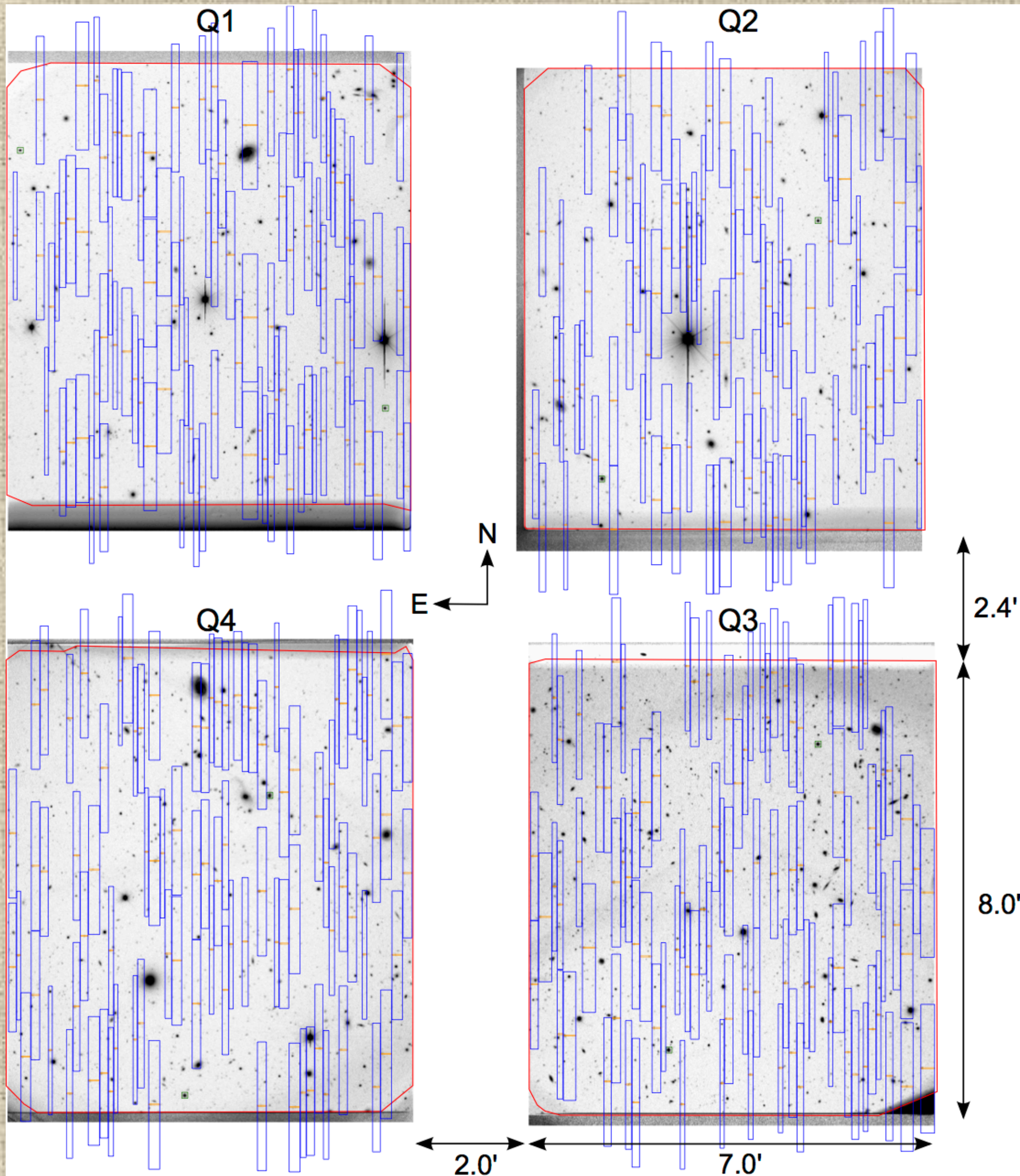
→ This and other ancillary information also released with PDR-2

(mask reconstruction by Ben Granett)

VIPERS single-shot footprint on the sky

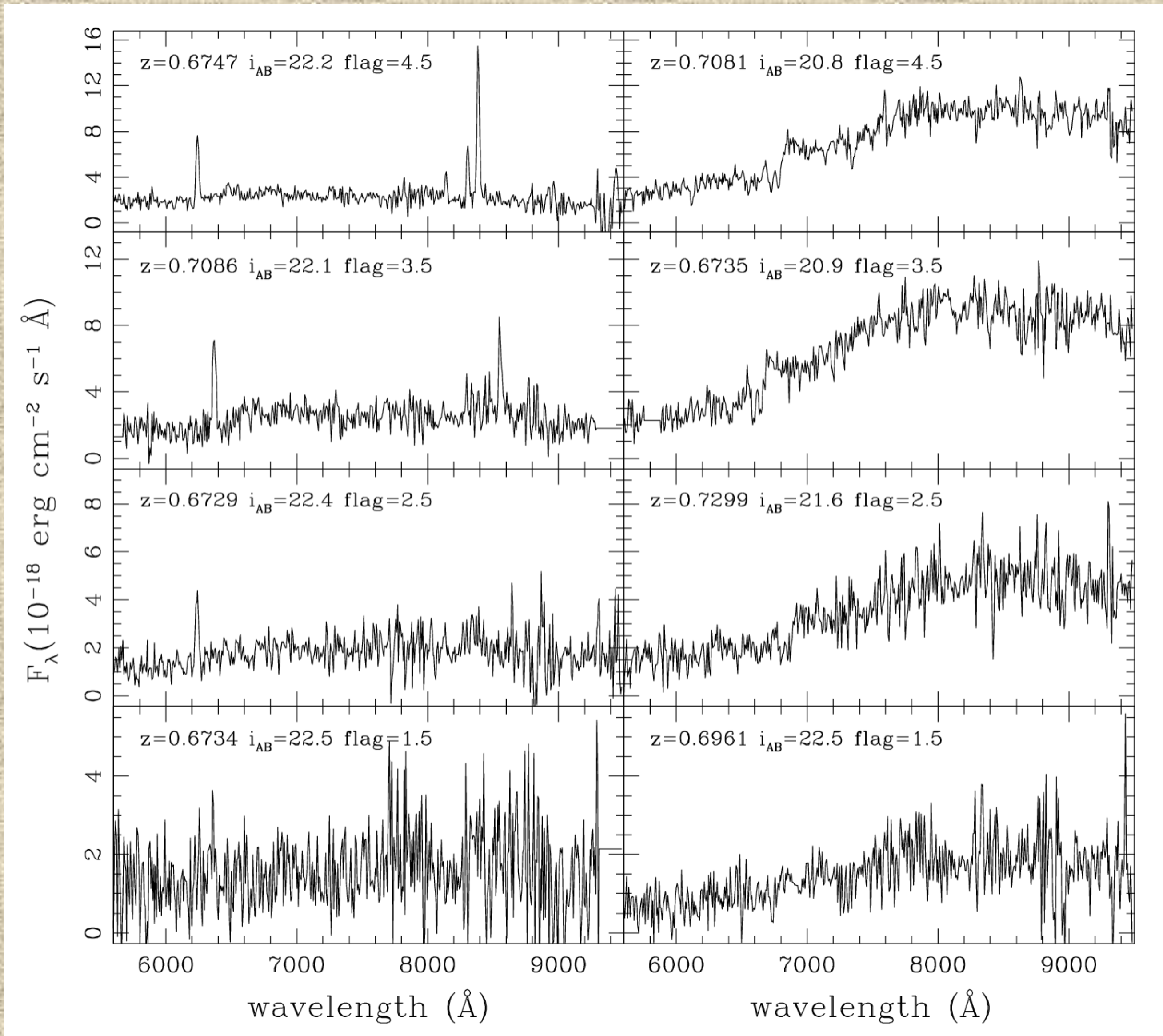
- **On average, 360 spectra observed per VIMOS pointing, given VIPERS target sample surface density and clustering**

- **VIPERS strategy yields mean spatial density <n>~10^{-2} h^{3} Mpc^{-3} within the range of interest**



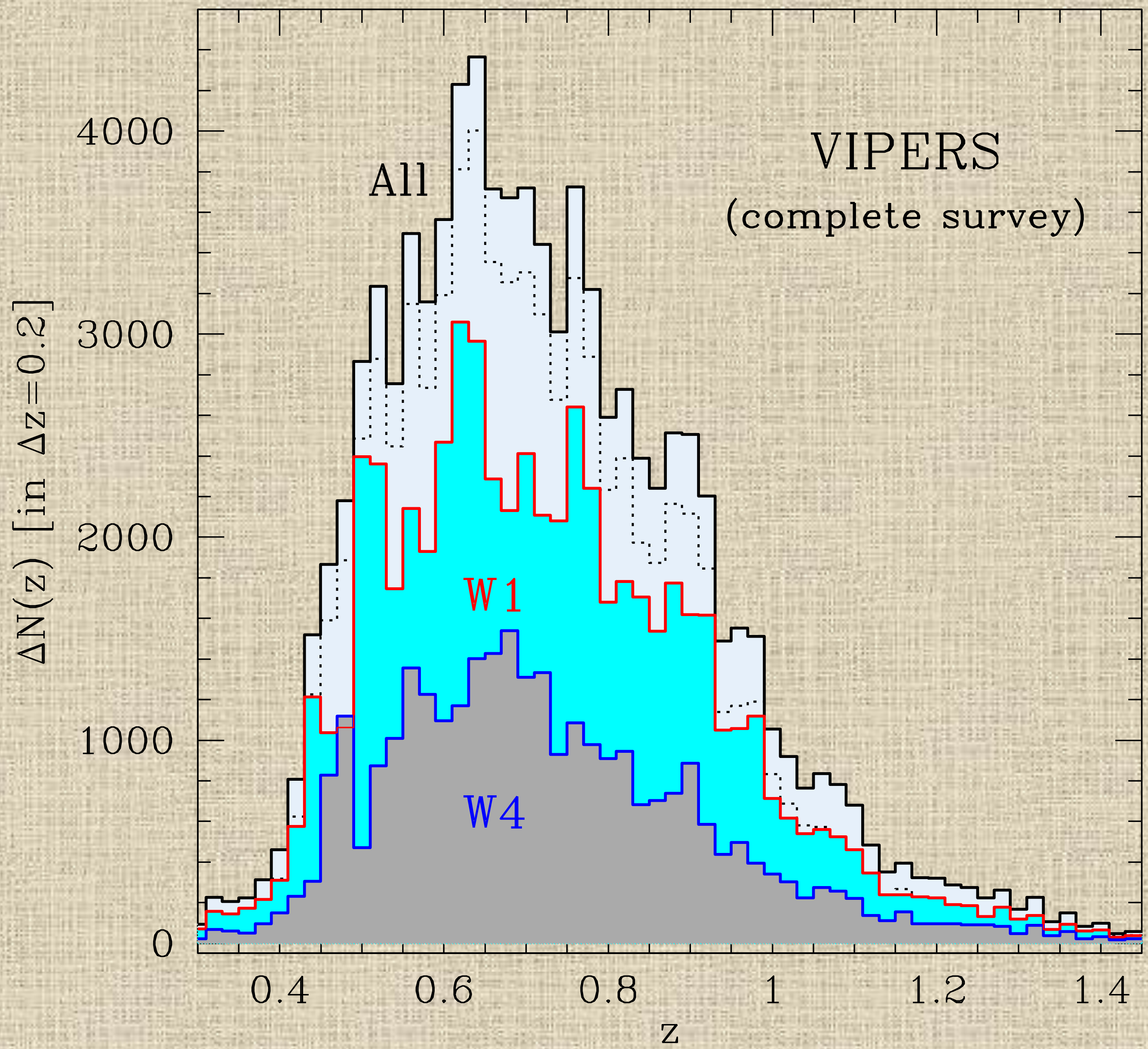
VIPERS spectra

- **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



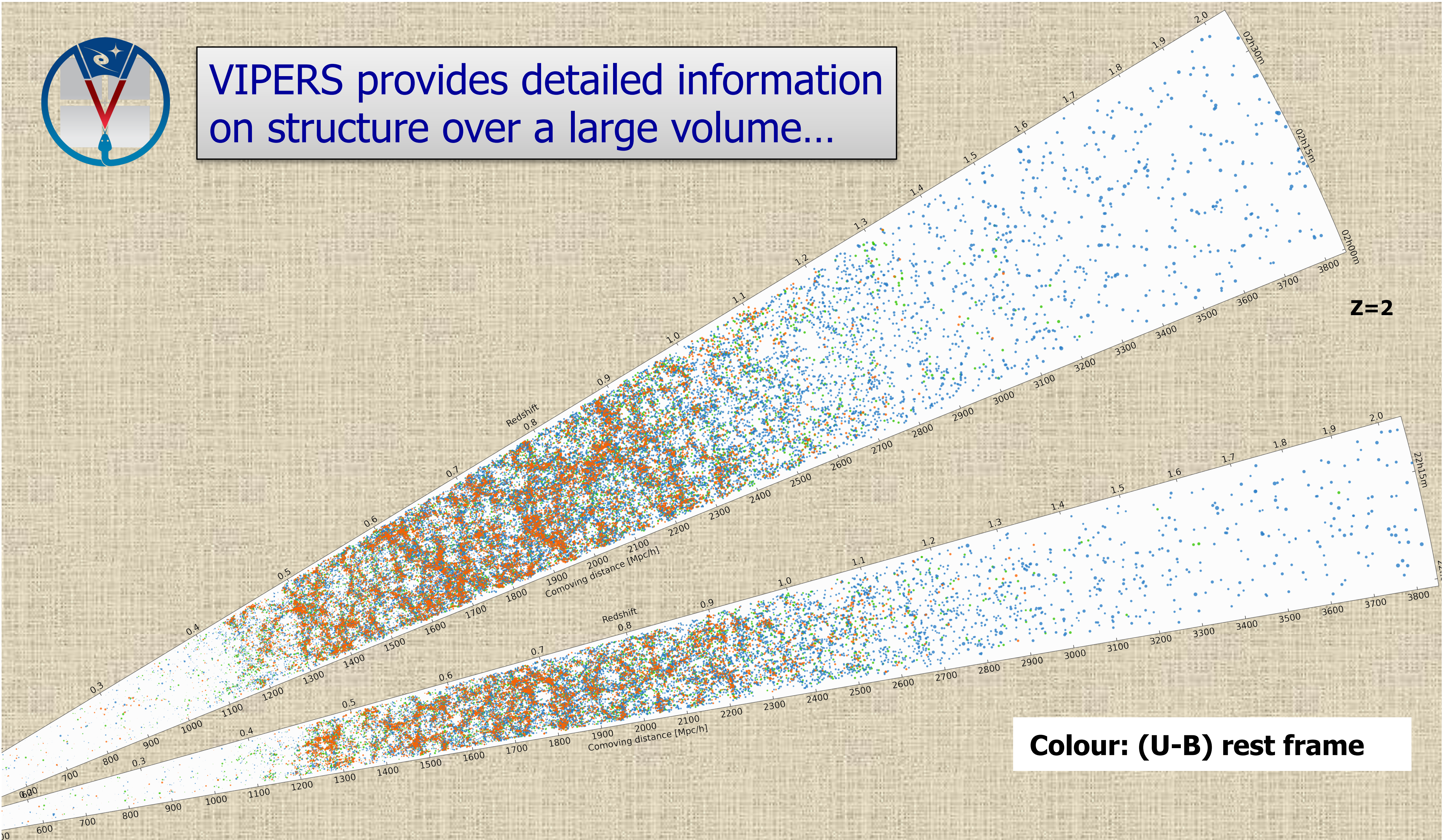
(Scodeggio+ 2016)

PDR-2 redshift distribution



(Scodeggio+ 2016)

VIPERS provides detailed information on structure over a large volume…



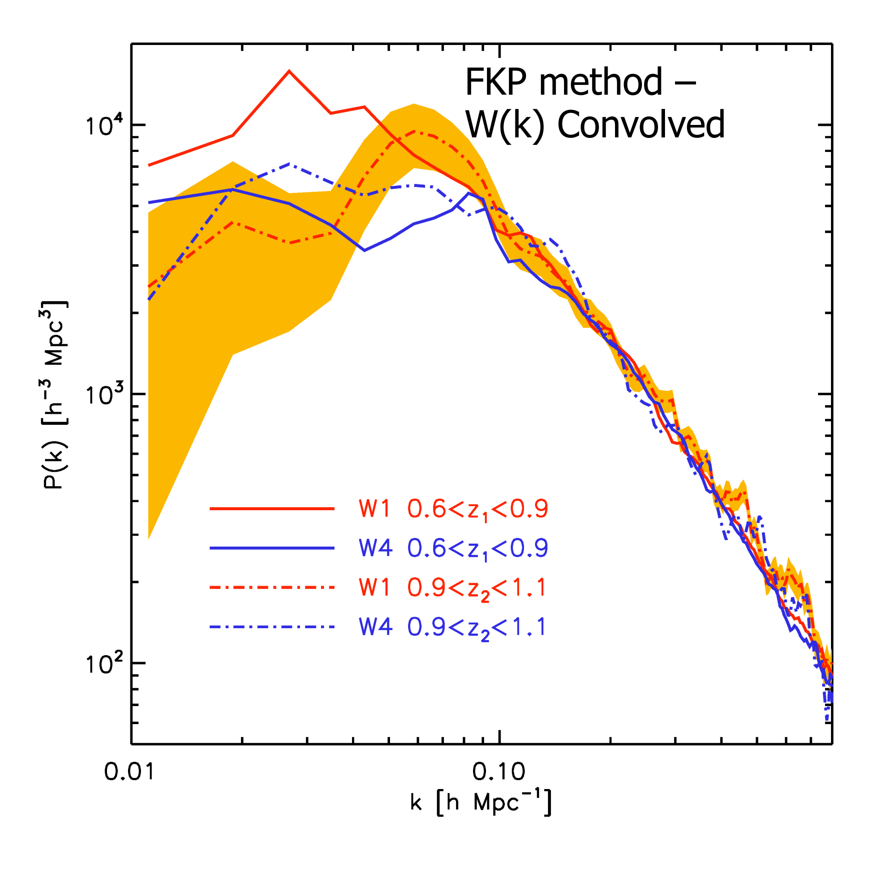
Z=2

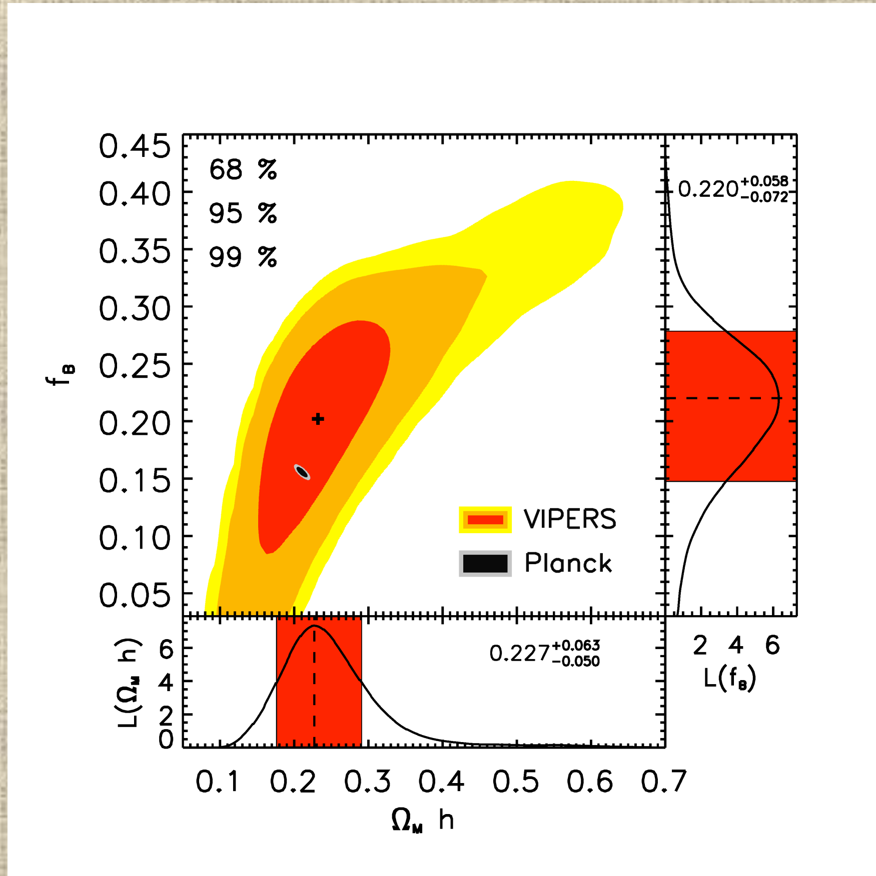
Colour: (U-B) rest frame

(artwork by Ben Granett)

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

(S. Rota PhD thesis, & Rota, Granett+ 1611.07044)



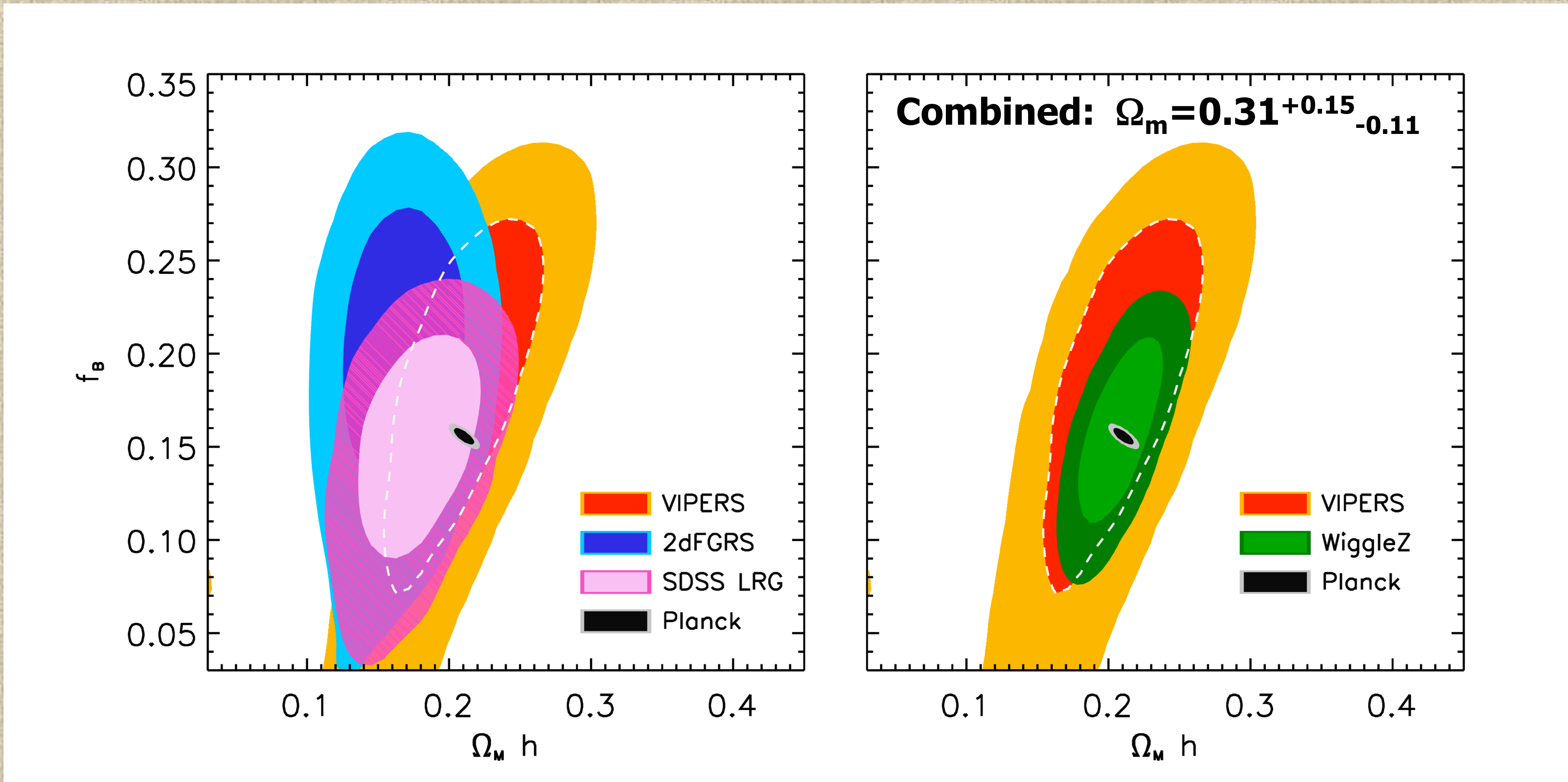


• Very careful tests of window function and nonlinear effects

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

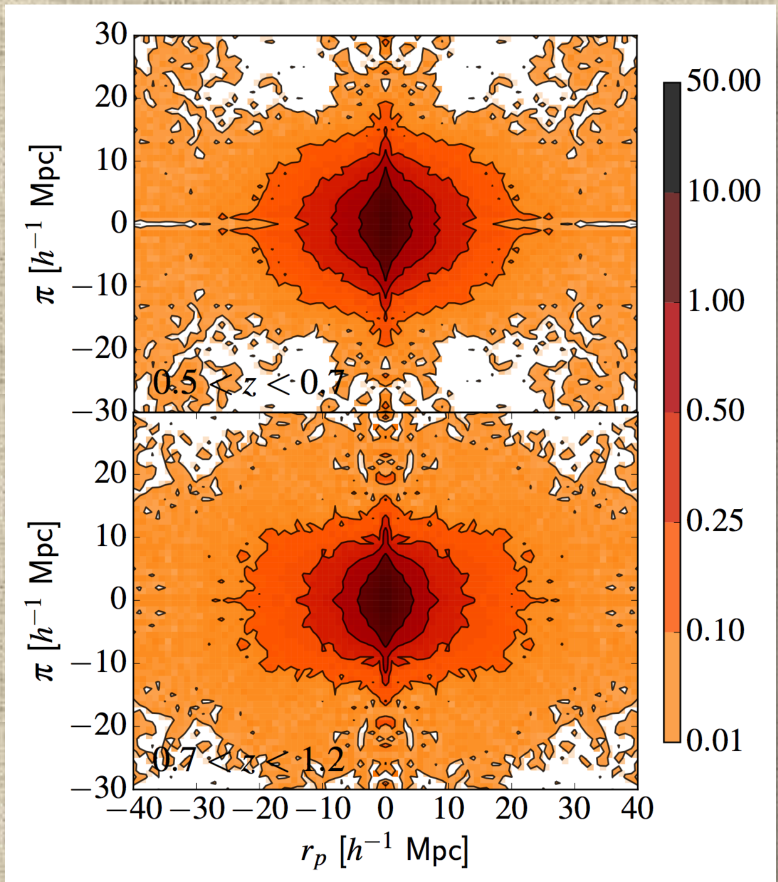
The power spectrum of the galaxy distribution at z=0.5-1.1

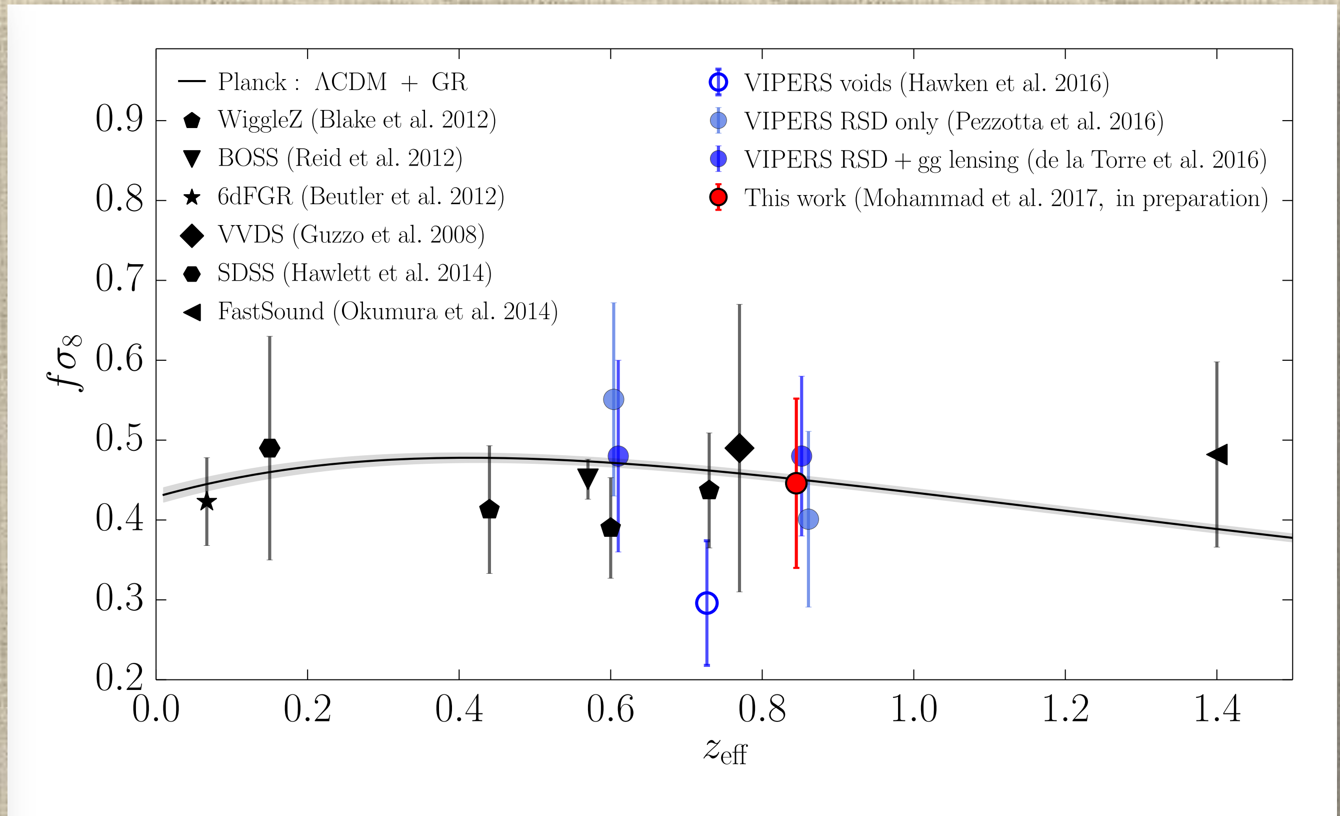
- Highest redshift where P(k) has been measured using galaxy distribution
- Consistency test of LCMD at about half Hubble time, straddling Planck and local values
- **Ellipses move towards Planck moving to higher z ?**



(Rota, Granett+ 1611.07044)

Testing gravity with redshift-space distortions

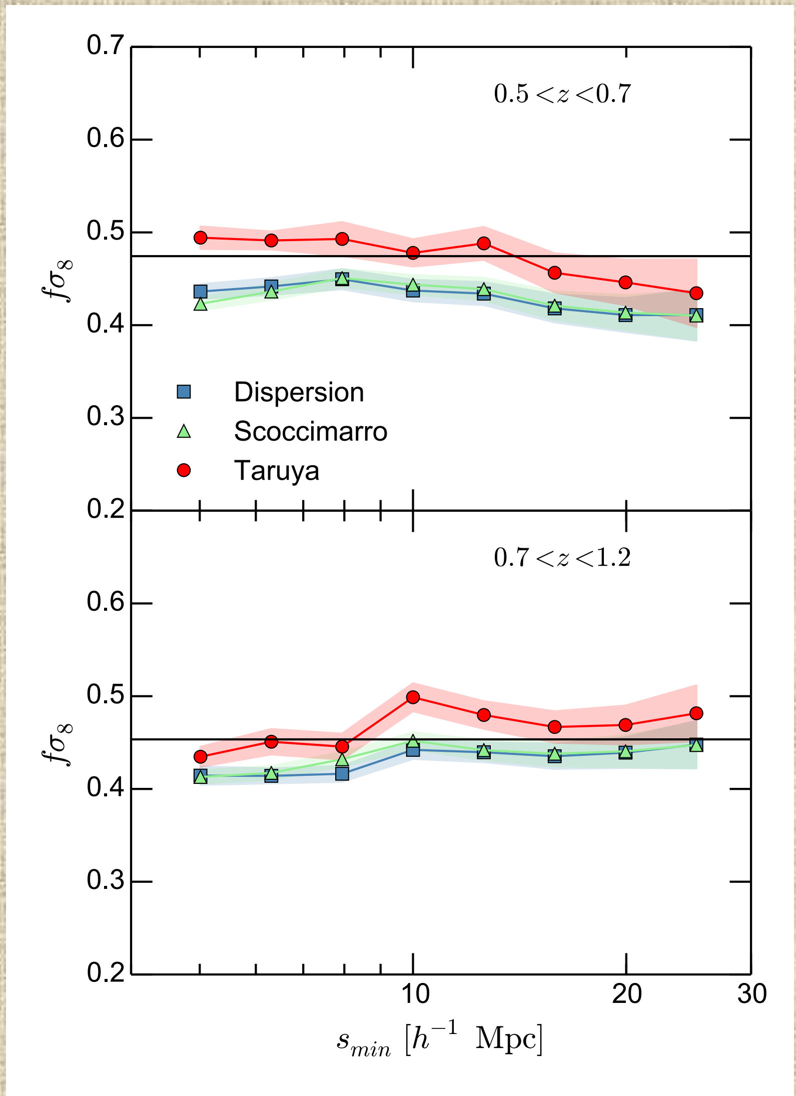


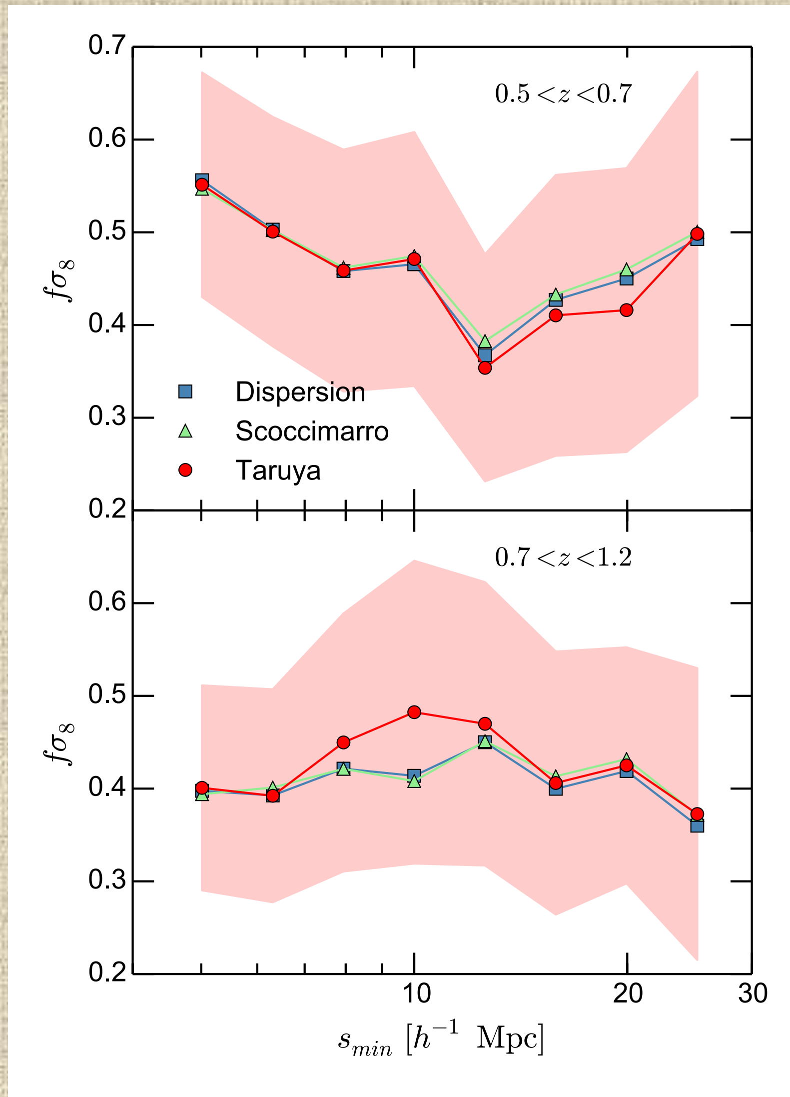


VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2017; Wilson 2017)

Refine nonlinear modelling

(Pezzotta+ 1612.05645; Bel et al., in preparation)



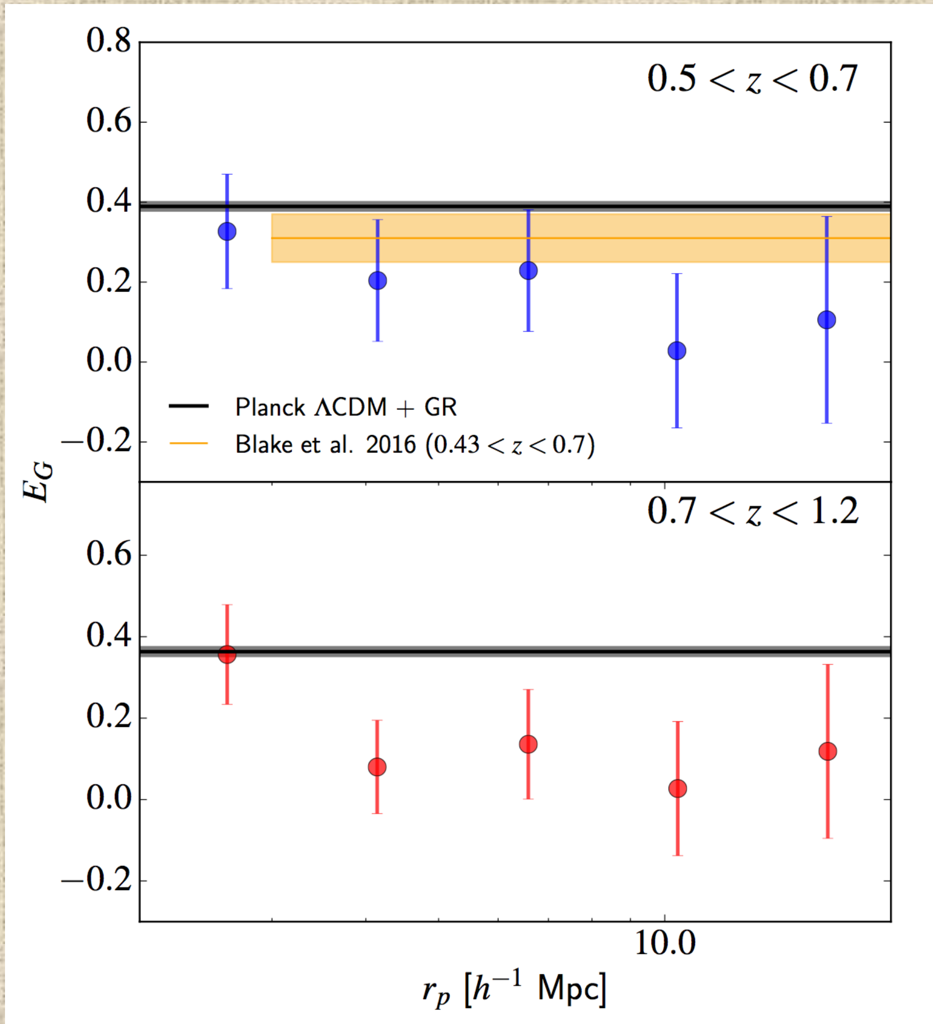


→ **Using new improved fitting formulae for velocity divergence / density power spectra (Bel et al. in prep.)**

→ **(See also Bianchi et al. 2014, 2016)**

Combine galaxy clustering and weak lensing

- Test for modified gravity combining CFHTLens imaging with VIPERS final data release PDR-2 (de la Torre + VIPERS Team 2017): **Slip parameter**



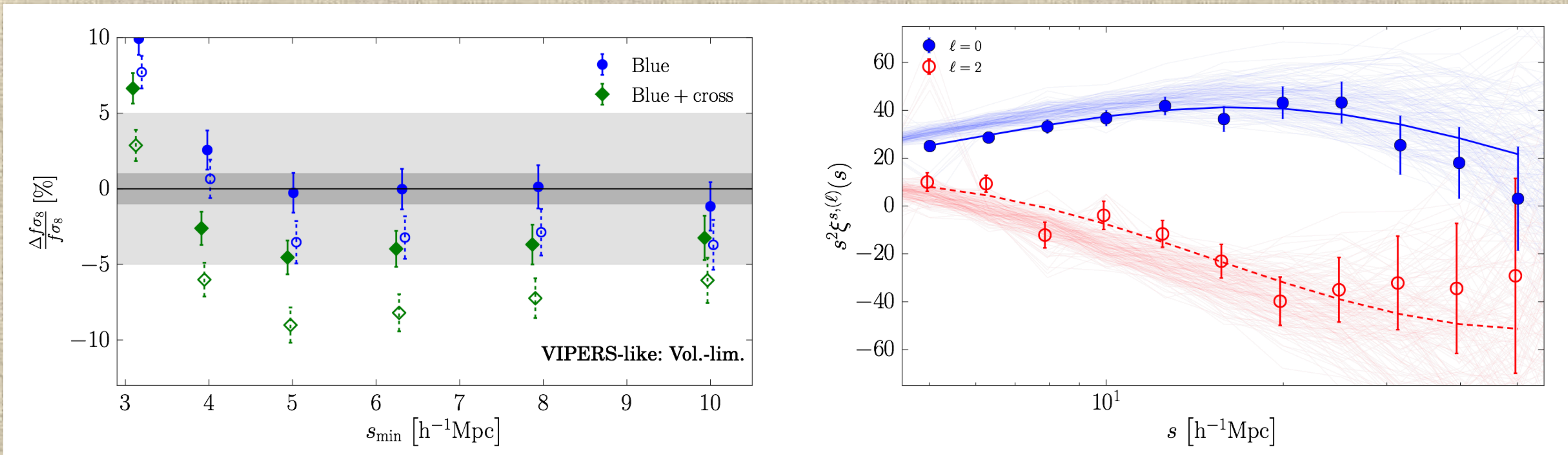
Complementarity of galaxy clustering and weak gravitational lensing: control systematic effects

(proof of concept for Euclid)

(see also Zhang et al. 2007; Reyes et al. 2009)

Optimise galaxy tracers to minimise modelling systematics

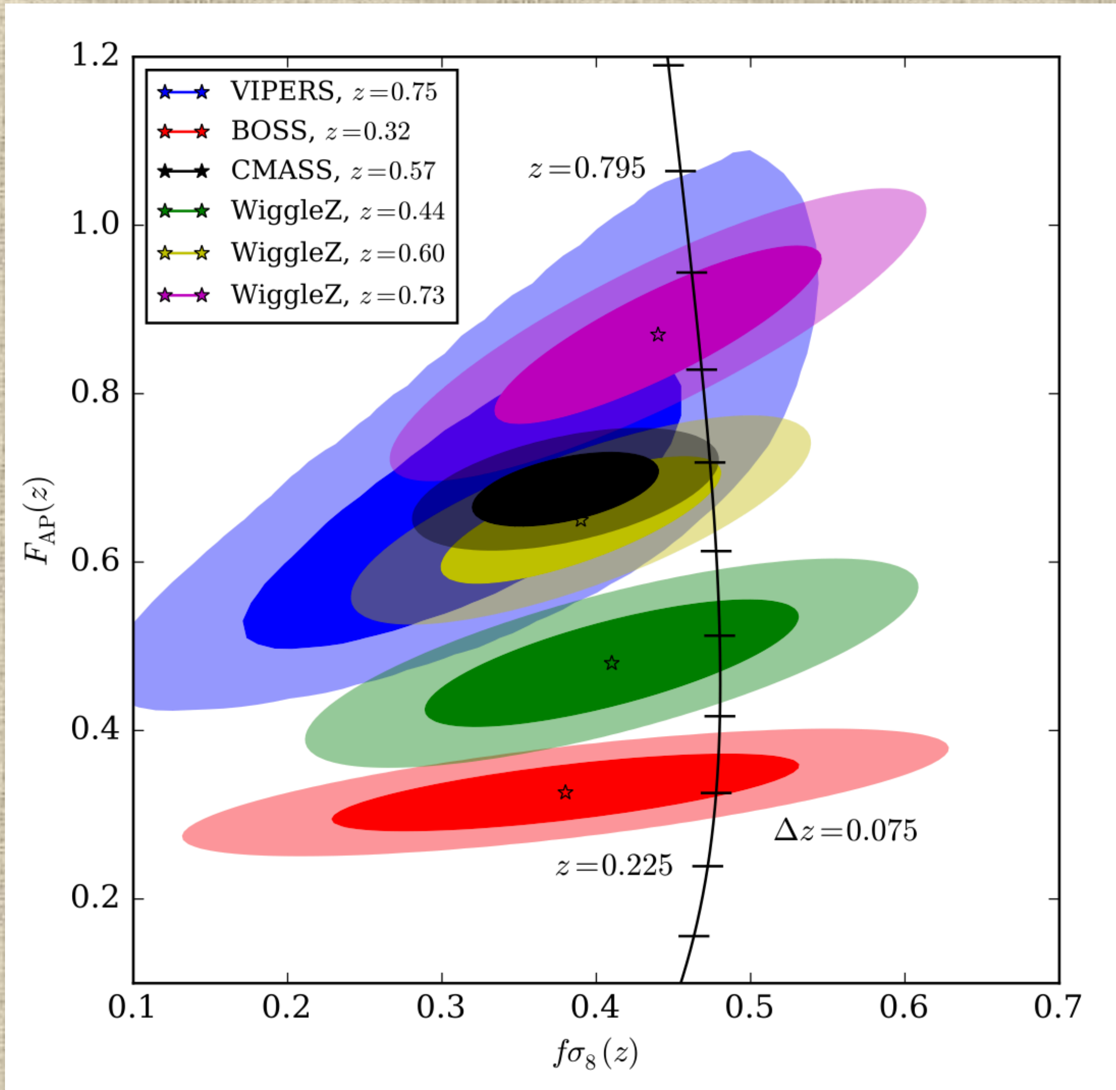
(Mohammad, Granett, Guzzo+ VIPERS, in preparation)



→ Blue luminous galaxies minimise weight of satellites

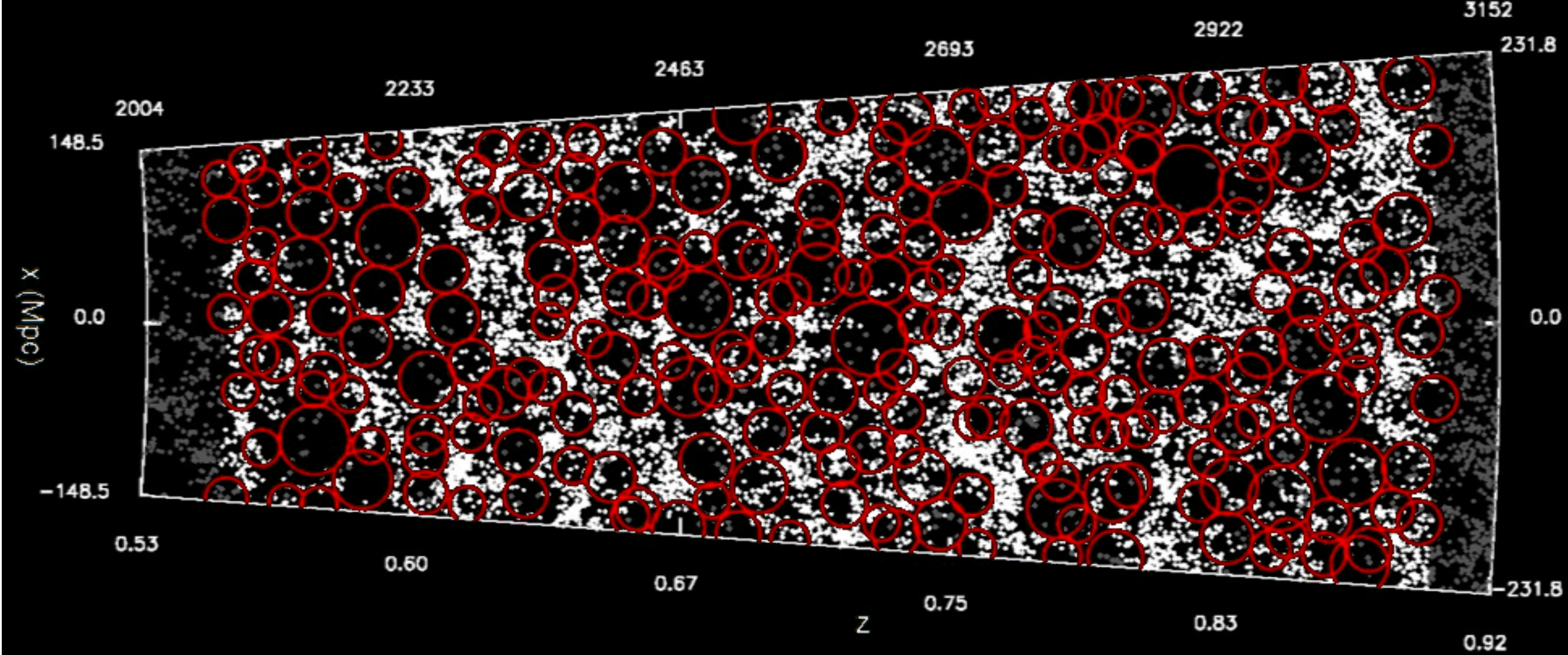
RSD-AP simultaneous fit (from clipped density field)

(Wilson, Peacock + VIPERS, in preparation)



- **Preliminary: W1 field only**

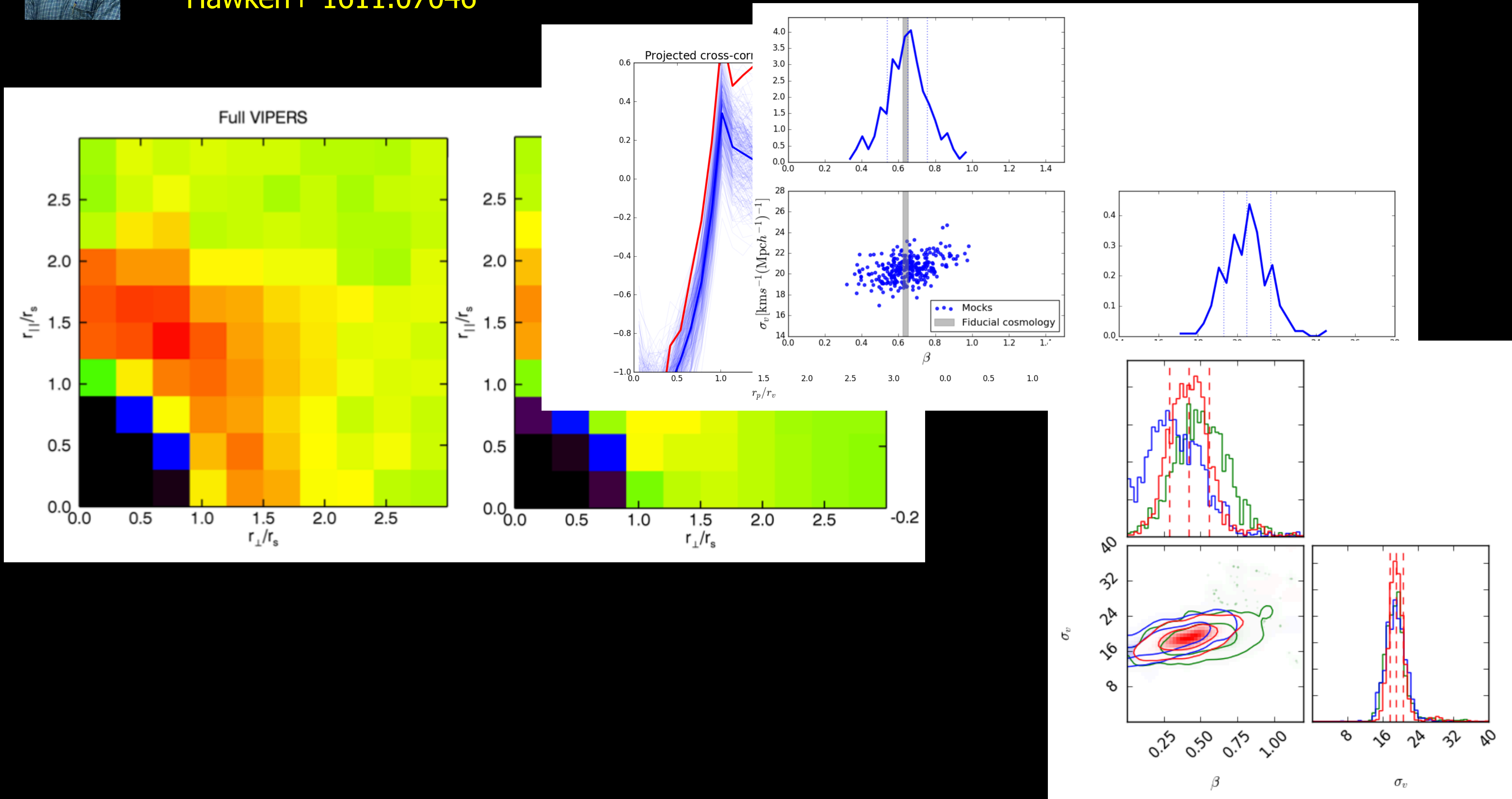
Use cosmic voids



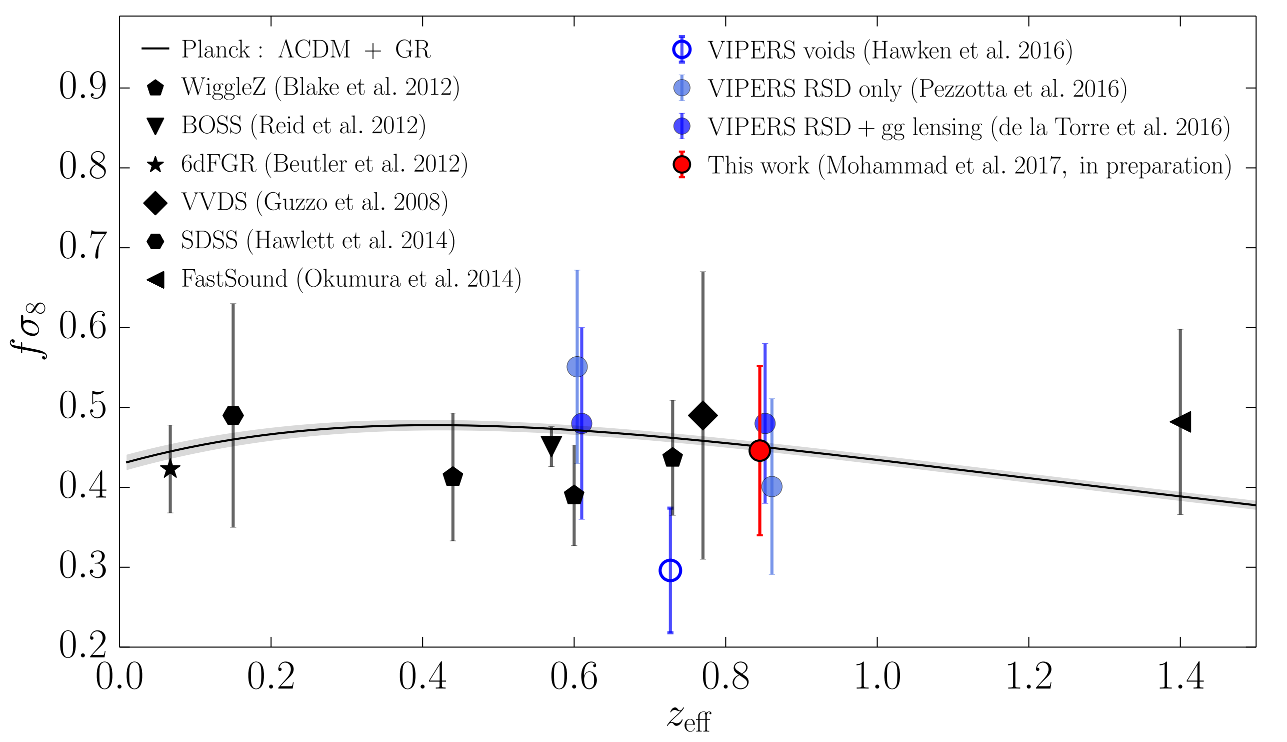
- Micheletti, Iovino+ 2015: void search and PDR-1 catalogue
- Hawken+2017: growth rate from galaxy outflows with PDR-2 void catalogue
- BOTH COSMOLOGY AND GALAXY EVOLUTION

Cosmic voids

Hawken+ 1611.07046



Testing gravity with redshift-space distortions



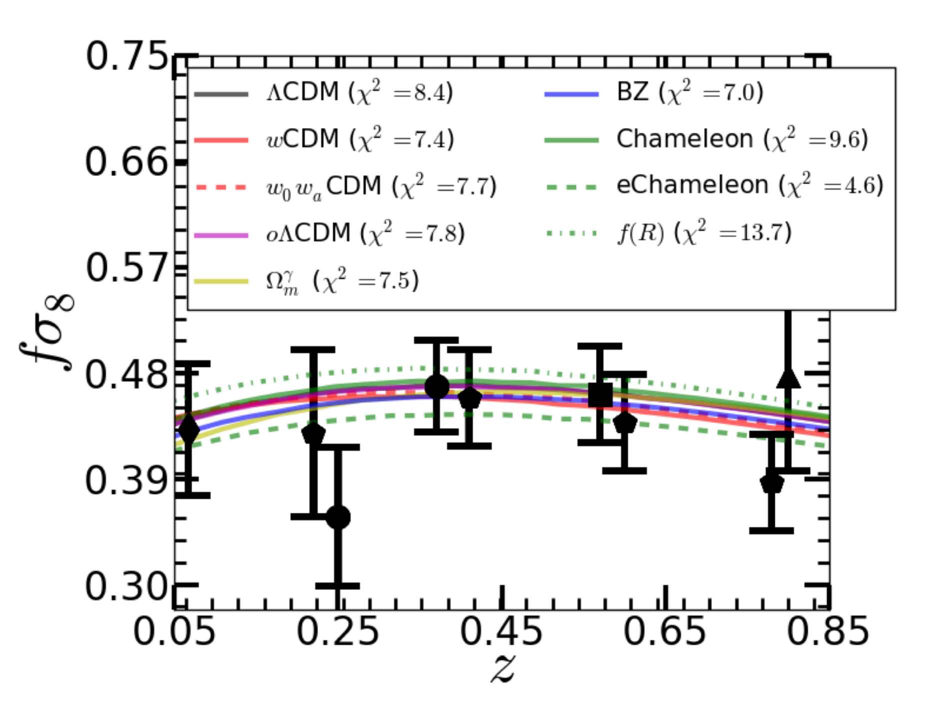
- RSD in configuration space with accurate nonlinear modelling (de la Torre+ 2013; Pezzotta+ 2017)
- RSD & Galaxy-Galaxy lensing (de la Torre+ 2017)
- RSD around galaxy voids (Hawken+ arXiv:1611.07046
- RSD in configuration space using sub-populations (Mohammad+ 2017)
- RSD from linearised density field in Fourier space (Wilson+ 2017)

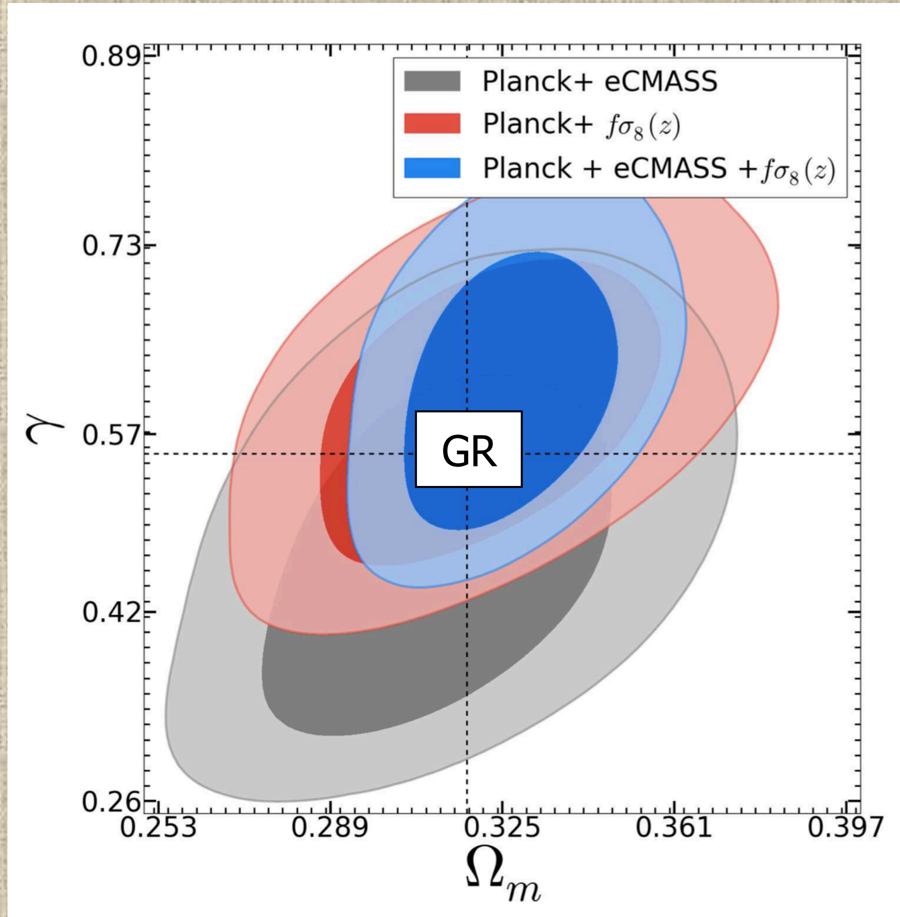
→ These different "angles" are made possible by unique combination of (a) large volume; (b) dense sampling; (c) broad selection function

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

Testing gravity with redshift-space distortions

(Alam, Ho & Silvestri 2016)





The future: **do it all at once**, e.g. Wiener-filter reconstruction of the density field

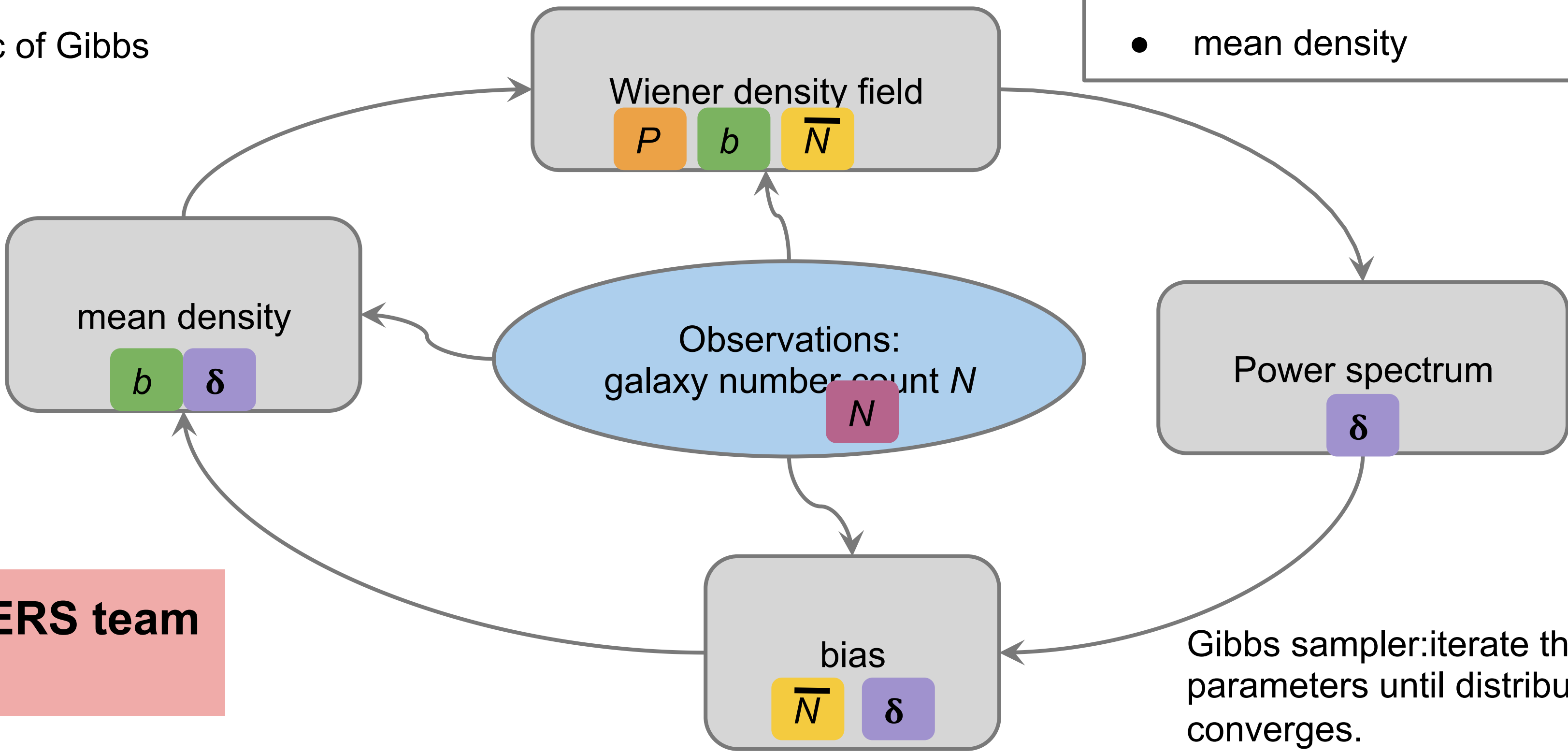
Bayesian technique

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

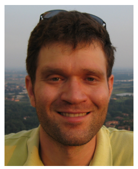
Dependencies

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

Schematic of Gibbs sampler:

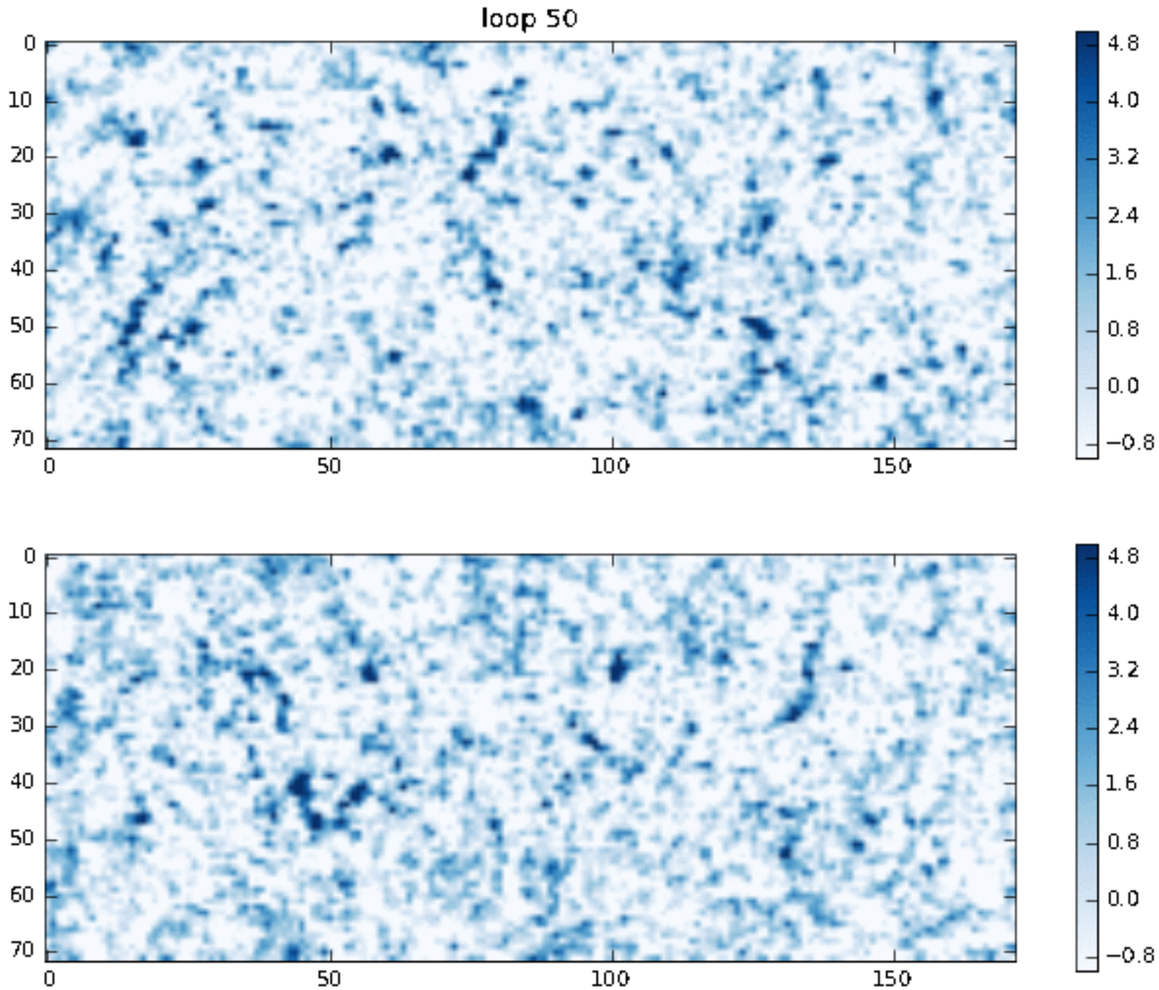


Gibbs sampler:iterate through parameters until distribution converges.



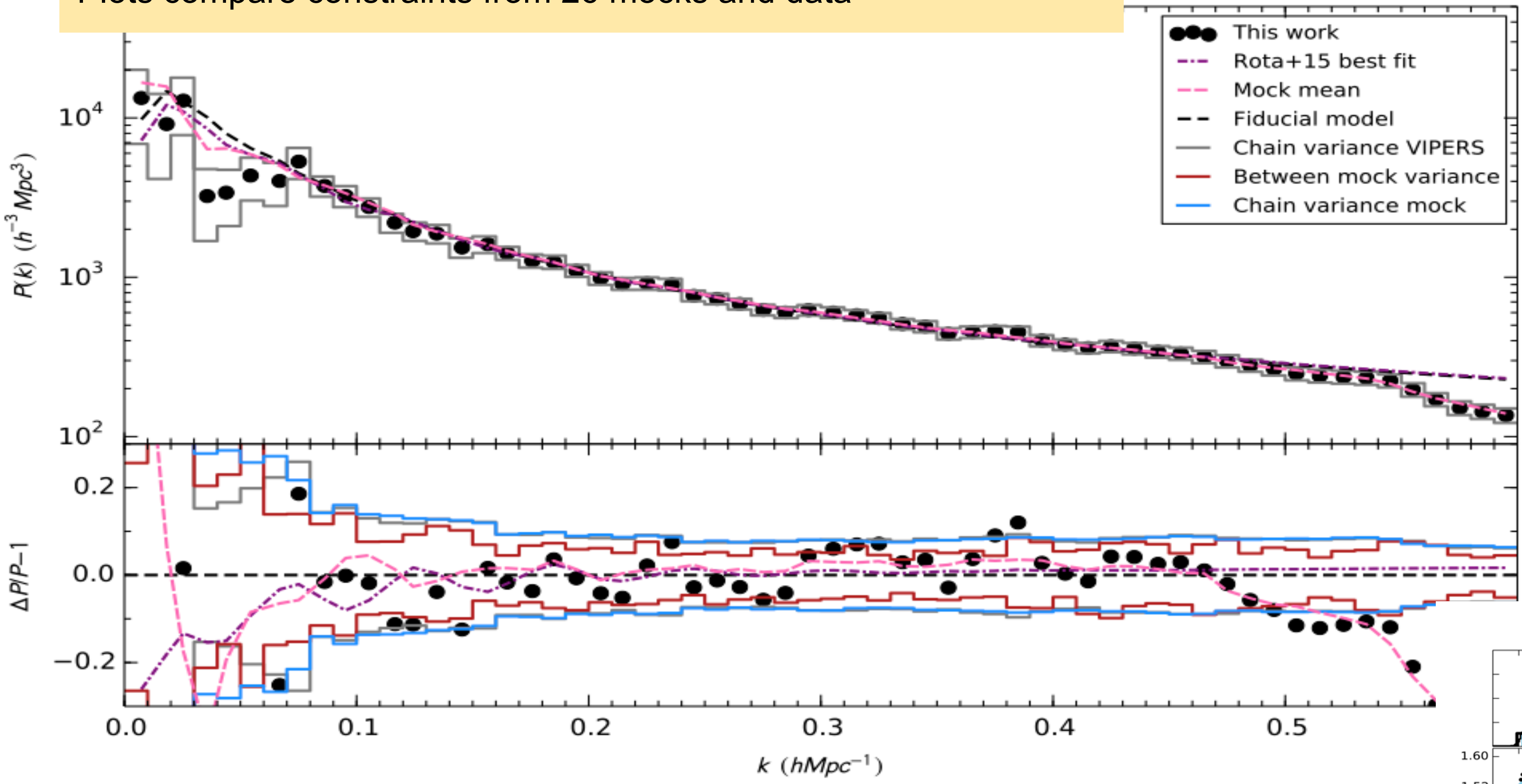
Granett+VIPERS team 1505.06337

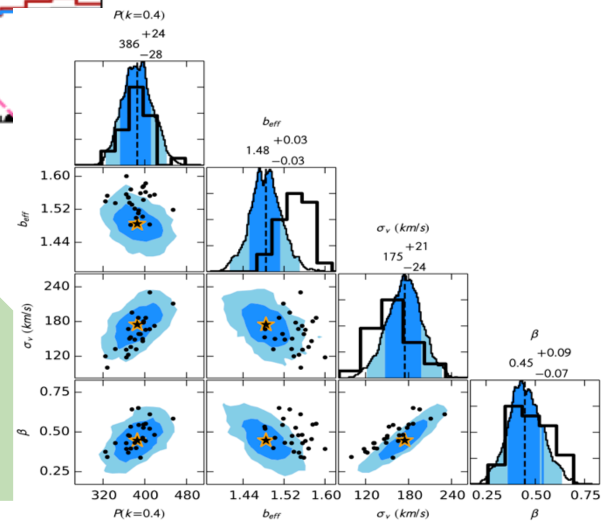
Wiener-filter reconstruction of the density field



Results: Power spectrum and RSD parameters

Plots compare constraints from 26 mocks and data





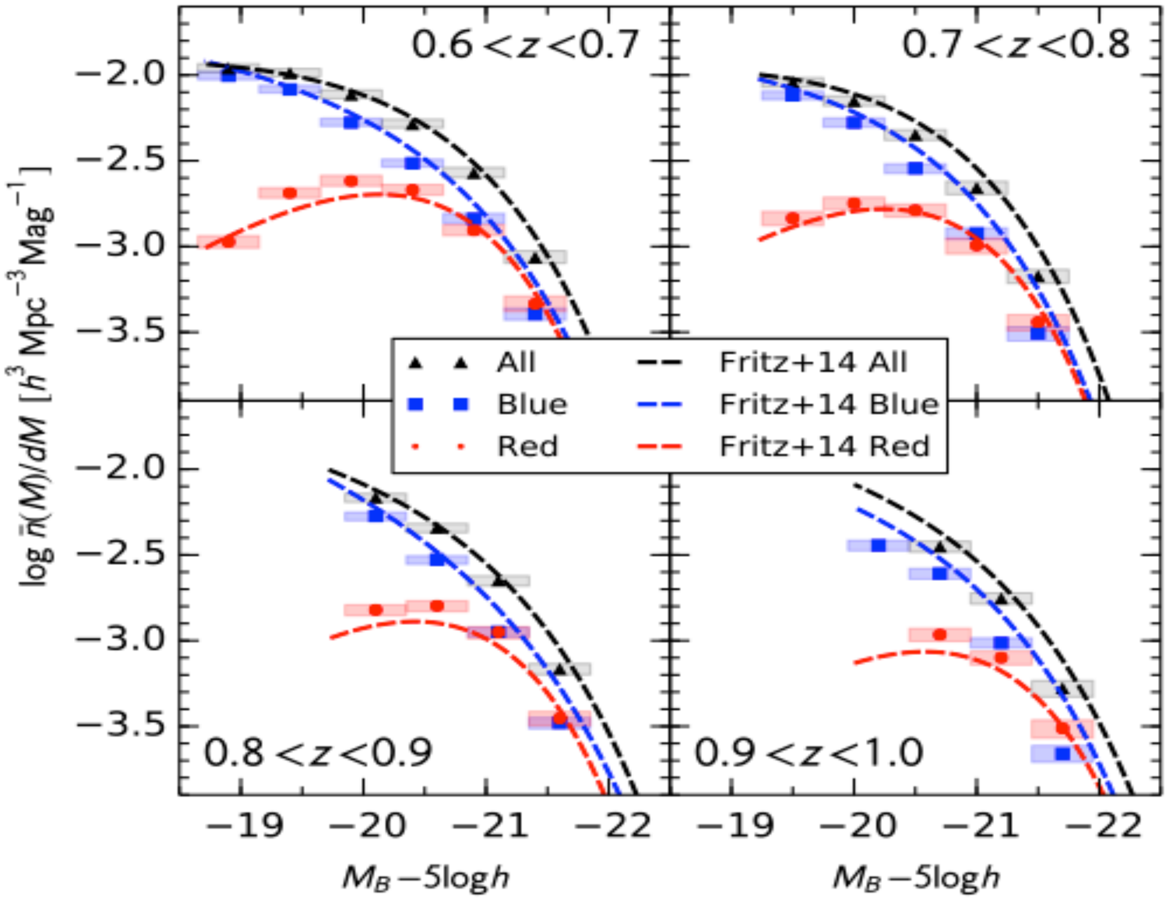
Recovered value for beta and growth rate are consistent with previous VIPERS analyses

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

Results: number density and luminosity function

- Comparison of n(z,L) with Fritz et al

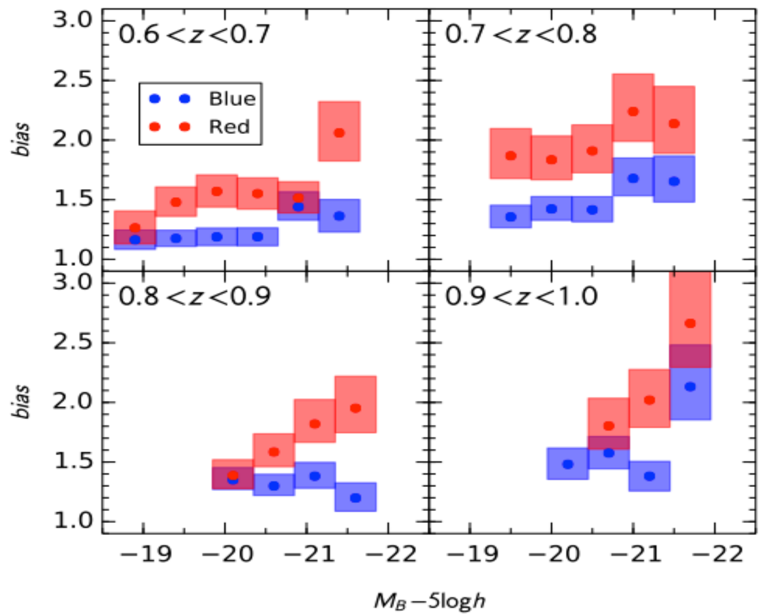
- Bayesian estimator accounts for correlations between galaxy bias and luminosity
  (a difference with STY estimator)

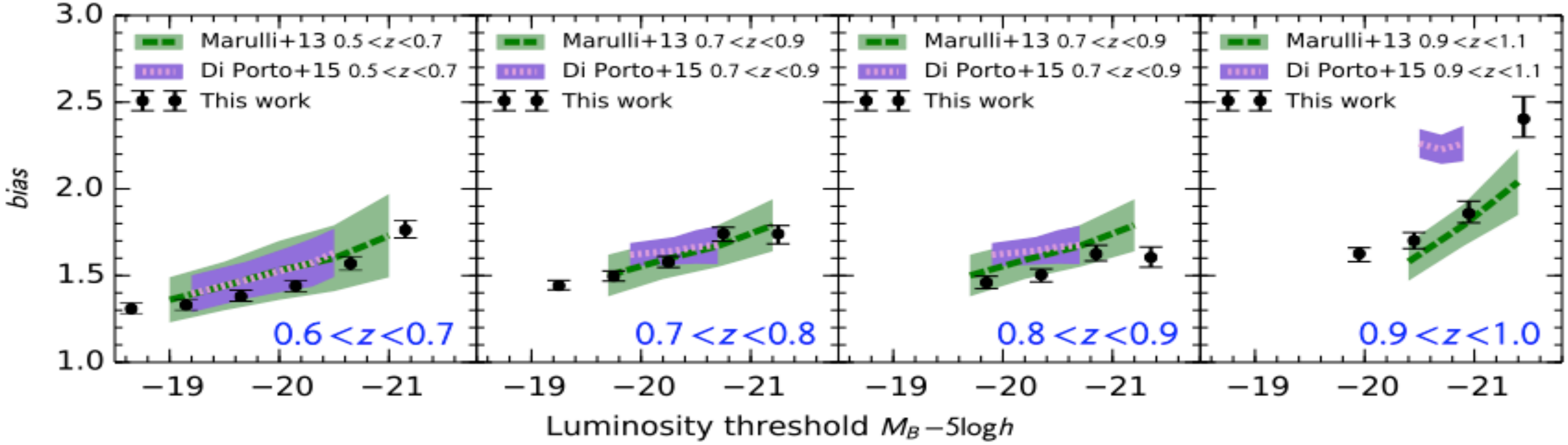


Granett+VIPERS team (2015)
http://arxiv.org/abs/1505.06337

Results: galaxy bias

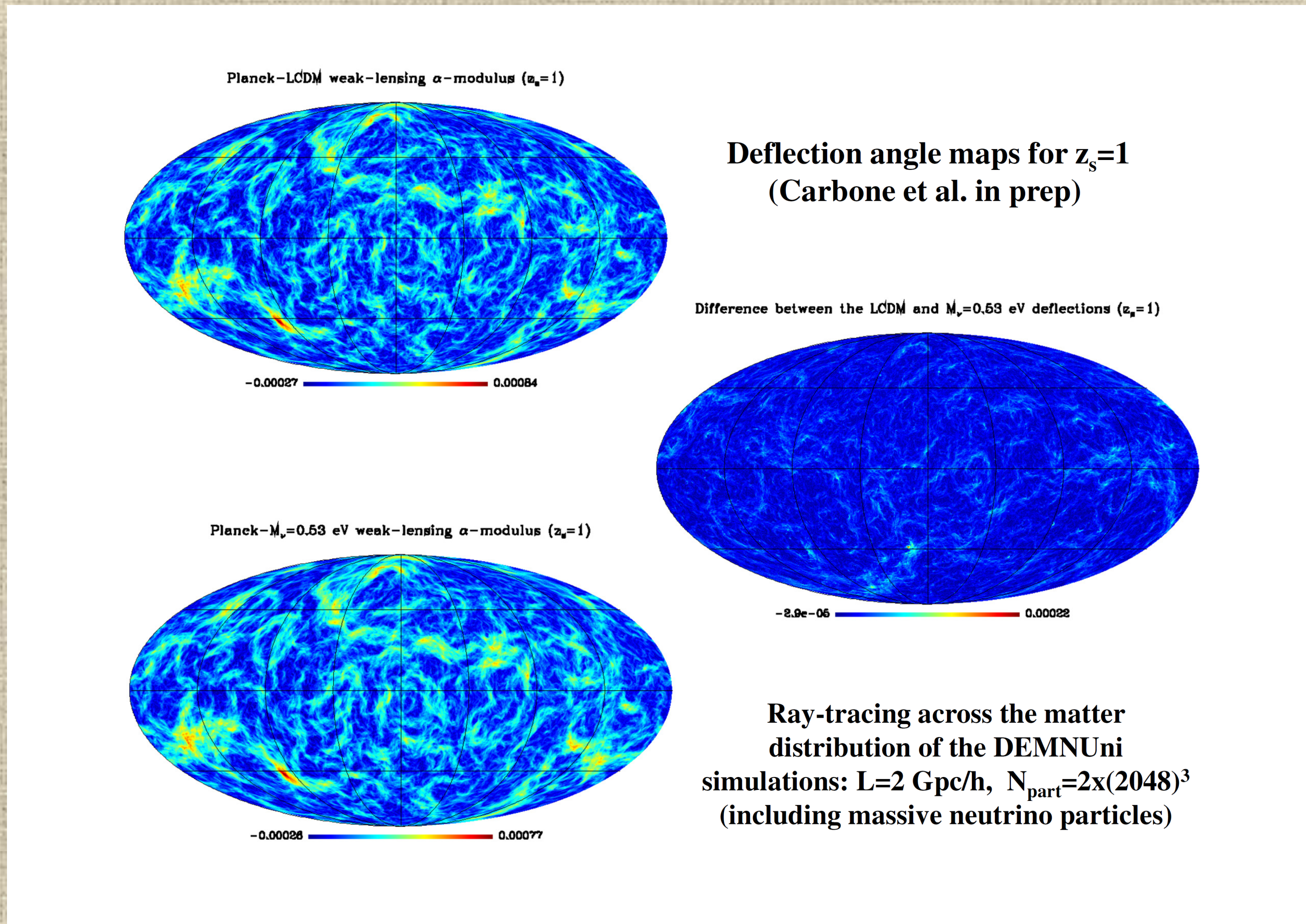
- ***Color dependence shows red/blue bimodality***
- ***Luminosity dependence in agreement with previous VIPERS analyses.***





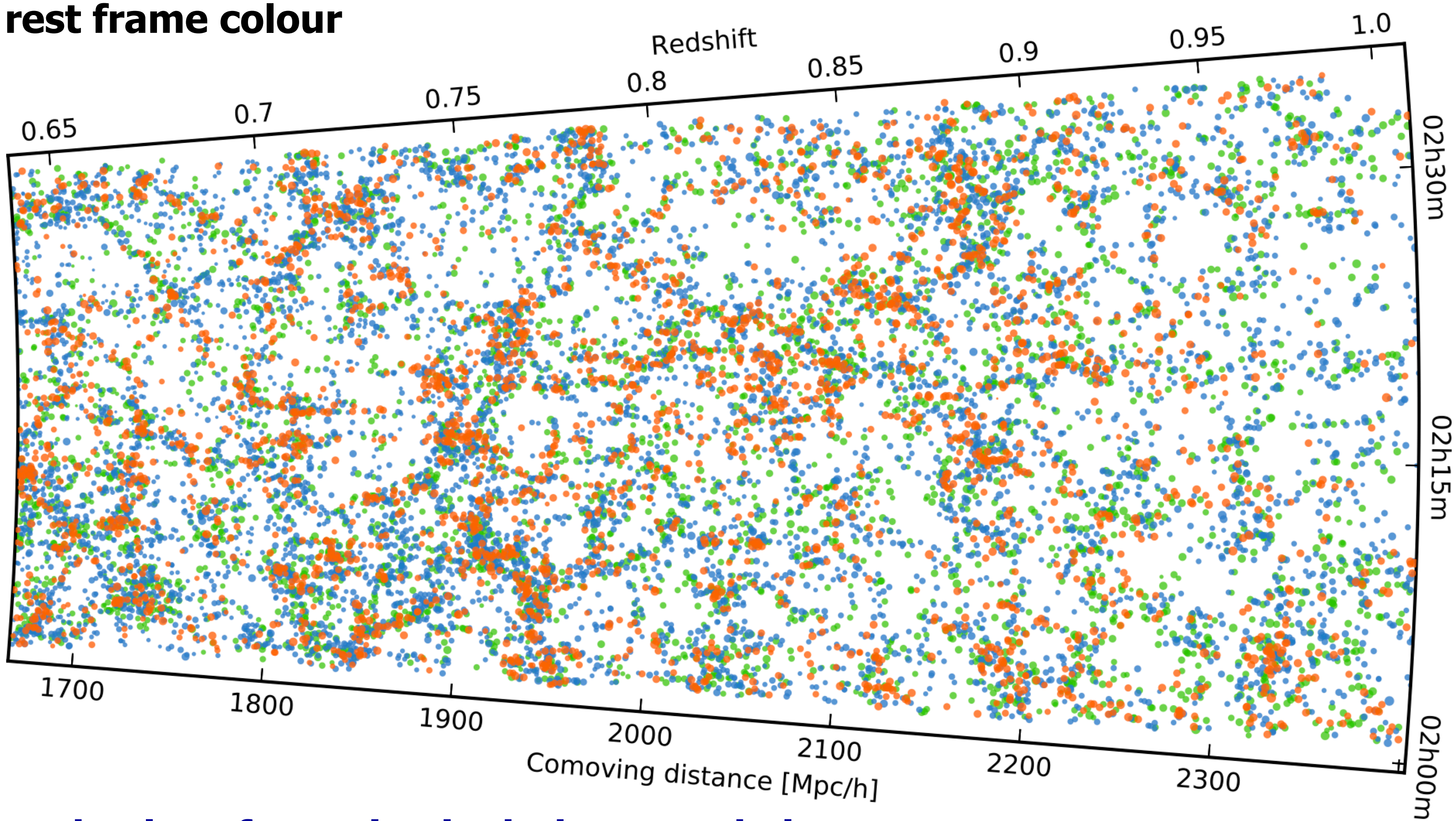
Caveats: (1) account for all existing (known) components: **neutrinos**

Carbone et al., DEMNUni simulations, largest existing n-body simulations including massive neutrino component (Carbone et al. 2016). Need particular care in setting initial conditions (Zennaro+ arXiv:1605.05283)



Caveats: (2) Improve modelling and understanding of galaxies…

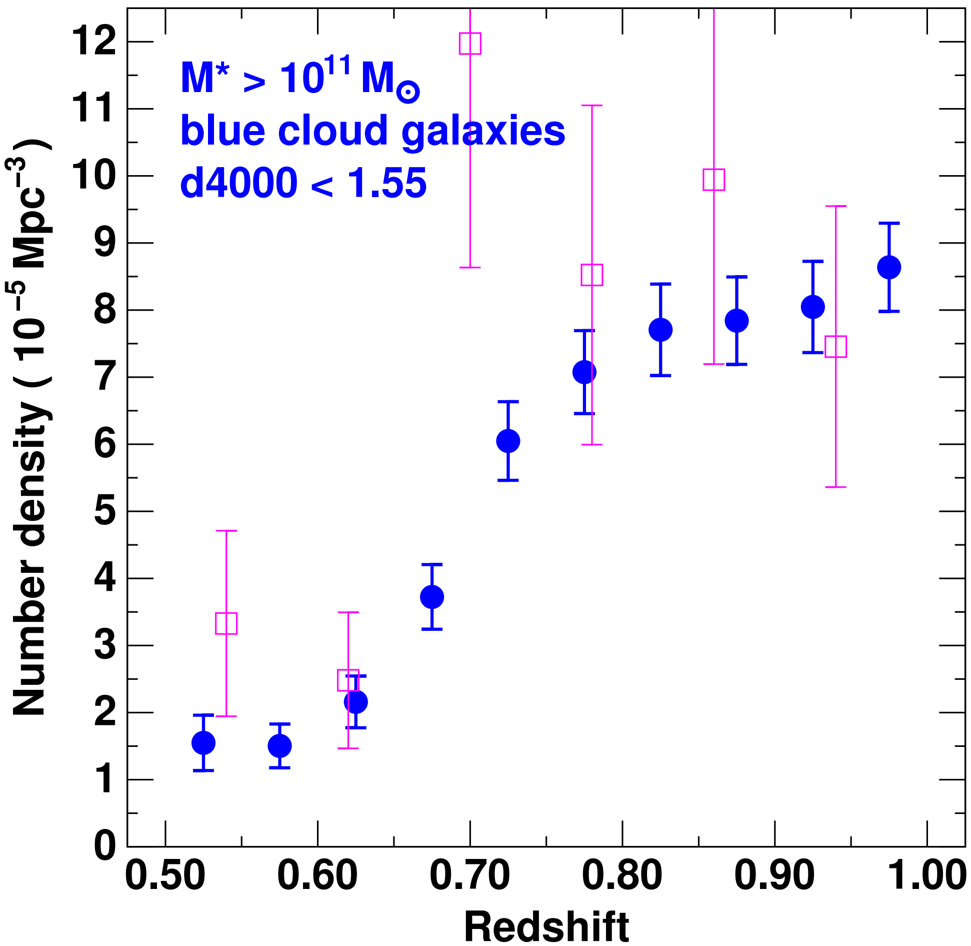
VIPERS galaxies encoded using (U-B) rest frame colour



- **Understand galaxy formation in dark matter halos**
- **Understand *galaxy bias:* use galaxies properly to precisely infer cosmological parameters**

VIPERS traces the raise of star formation in massive objects back in time

Haines+ 1611.07050



<n> of massive star-forming galaxies

Take home messages

A brilliant future ahead for cosmology with galaxy surveys: by 2030 we'll have >50 million redshifts measured, over huge volumes down to z=2 (Euclid, DESI, but also SKA, etc). <u>This makes systematic errors the real limit</u>

OBSERVATIONAL BIASES

- e.g. Low SNR slitless spectra (Euclid): confusion, completeness, purity → all these can be position dependent on the sky!
- Observational mask, uneven exposures, etc
- **Do not plan galaxy surveys just for cosmology! Leave door open for new techniques (e.g. voids, requiring high sampling), or selection of optimal sub-samples of galaxies**

MODELLING

- How do my galaxy tracers sample the dark-matter distribution? DM-baryon connection (**bias)**
- We like it linear, however reality is **non-linear** if we want to maximise signal
- We work in **redshift space**: we have turned this to our advantage, yet need to keep improving RSD models (e.g. de la Torre & Guzzo 2012, Bianchi et al. 2014, 2016)
- **Modelling is easier if we choose the right galaxy population (Mohammad+ 2017)**
- We are working at 1% precision. Need to include all ingredients → **neutrinos!** (e.g. Carbone+ 2017)