Understanding cosmic acceleration with galaxy redshift surveys

Luigi (Gigi) Guzzo
INAF - Osservatorio di Brera, Milano

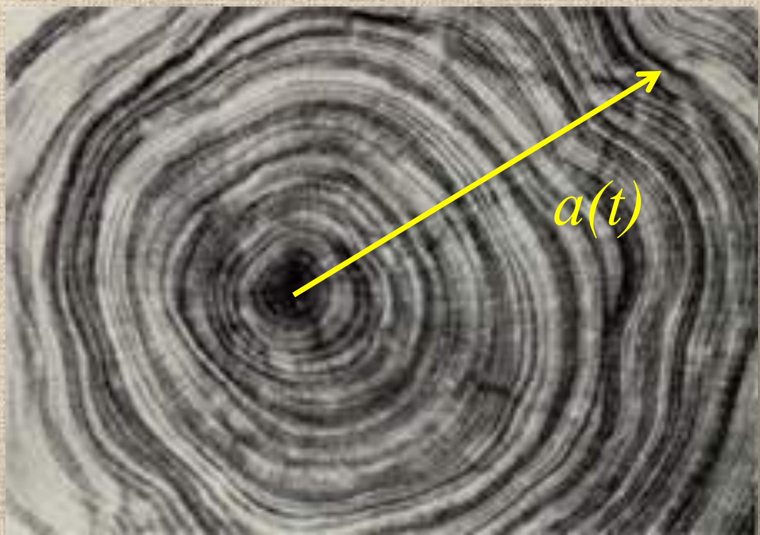
Outline

- Cosmic acceleration: the big puzzle
- Galaxy clustering: a key probe of the cosmological model
- Redshift-space distortions (RSD) an old tool for a new context
- Improving the data: the VIPERS project at ESO
- Improving the modelling: RSD in the precision cosmology era, forecasts and systematic errors
- A glimpse of the distant future: Euclid

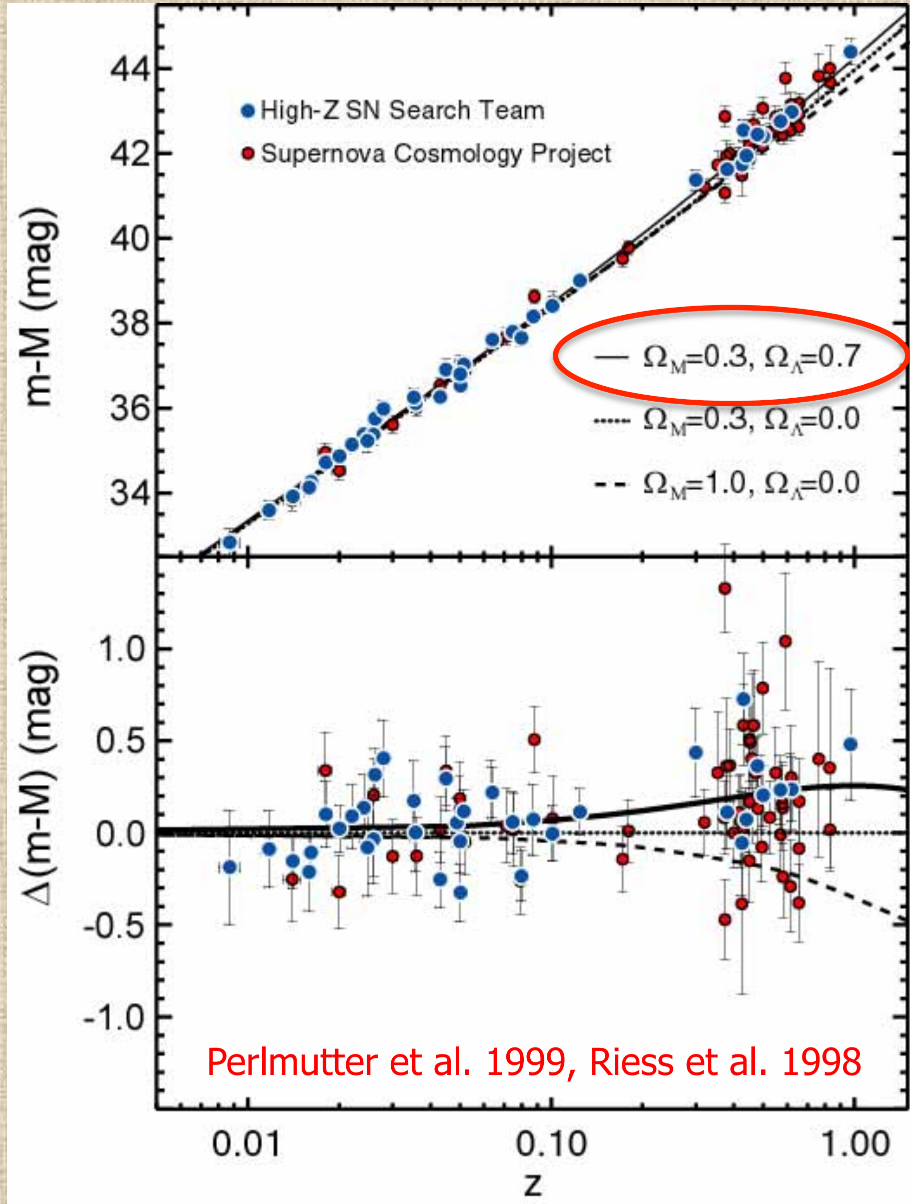
The "Hubble diagram" of Type Ia supernovae tells us that matter is not enough…

$$d_L = (1+z)\int_0^z \frac{c\, dz'}{H(z',\Omega_m,\Omega_\Lambda)}$$

$$H \equiv \frac{\dot{a}}{a}$$

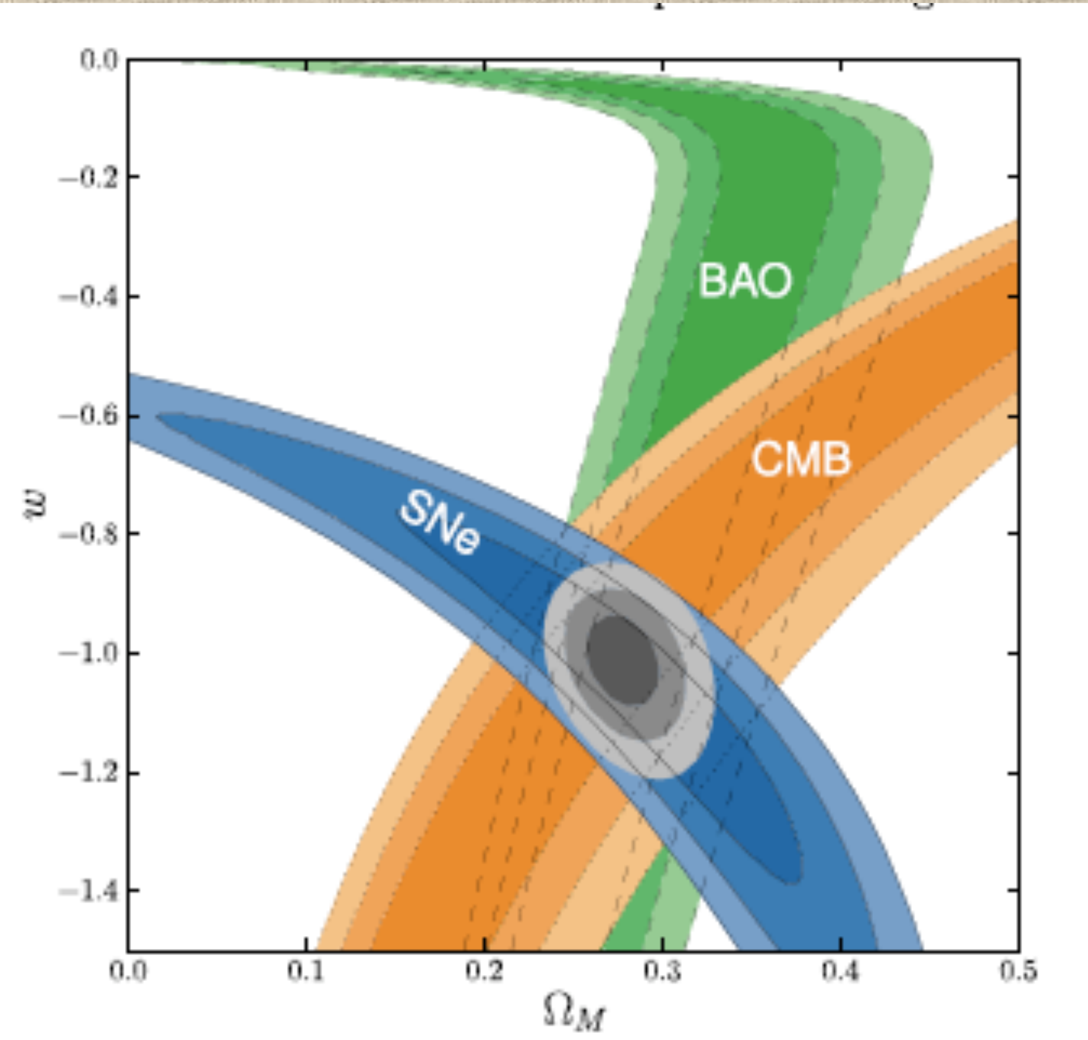


log(Distance d_L)

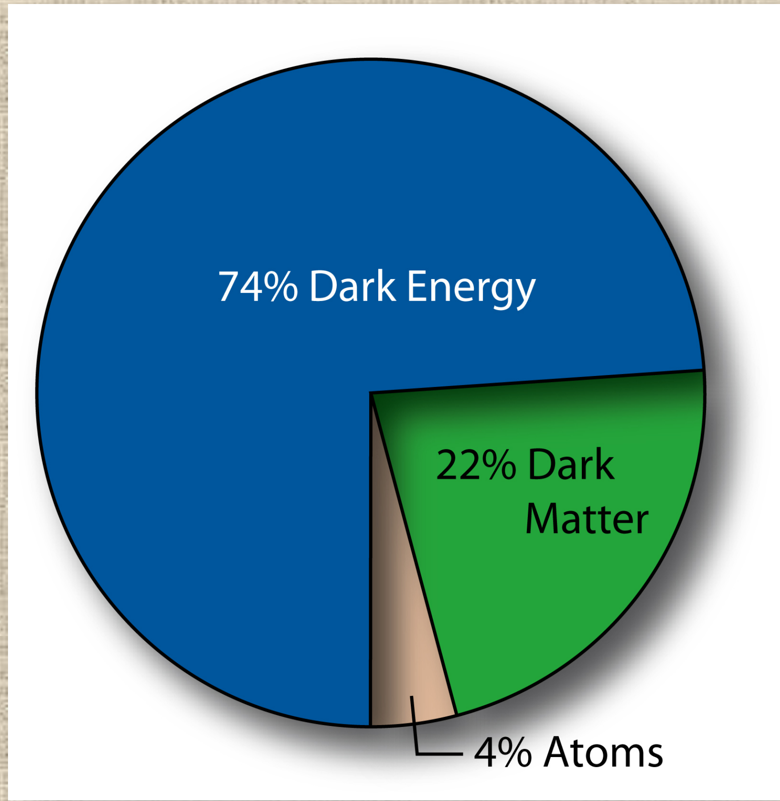


Redshift of spectral lines

Cosmic concordance: a w=-1 Universe?



Amanullah et al. 2010 (Union supernovae)



However, lambda (or dark energy) is not the end of the story…

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

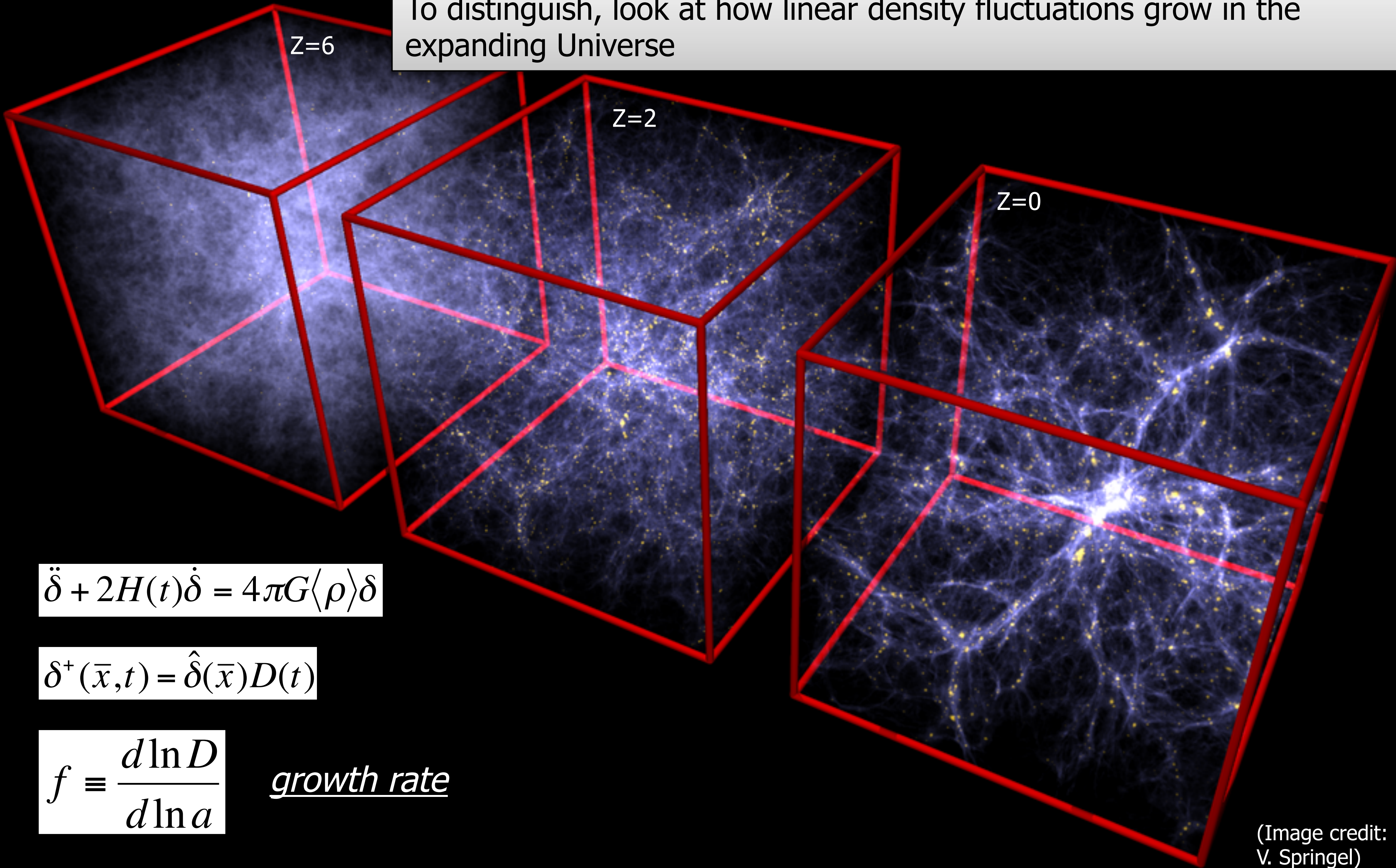
?

Modify gravity theory [e.g. ***R* → *f(R)***]

Add dark energy

"…the Force be with you"

To distinguish, look at how linear density fluctuations grow in the expanding Universe



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

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

$$f \equiv \frac{d\ln D}{d\ln a}$$ *growth rate*

(Image credit: V. Springel)

• The growth equation (and thus the growth rate) depends not only on the expansion history $H(z)$ (and thus on $w(z)$) but also on the gravitation theory

• Measuring $f(z)$ we can break the degeneracy between models with same effective $H(z)$, but completely different physics (unless DE clusters, Kunz & Sapone 2007)

For a wide variety of models:

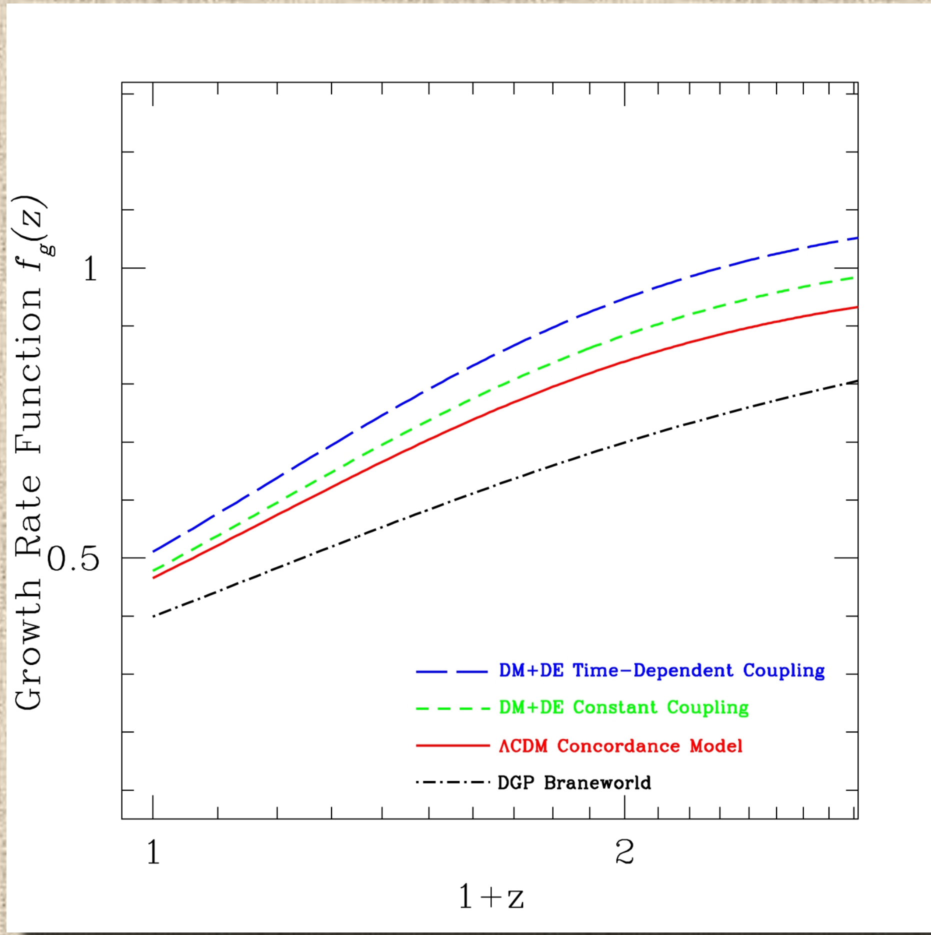
$$f(z) = [\Omega_m(z)]^\gamma$$

(Peebles 1980, Wang & Steinhardt 1998, Amendola et al. 2005, Linder 2005)

e.g.

$\gamma=0.55$ for standard Λ

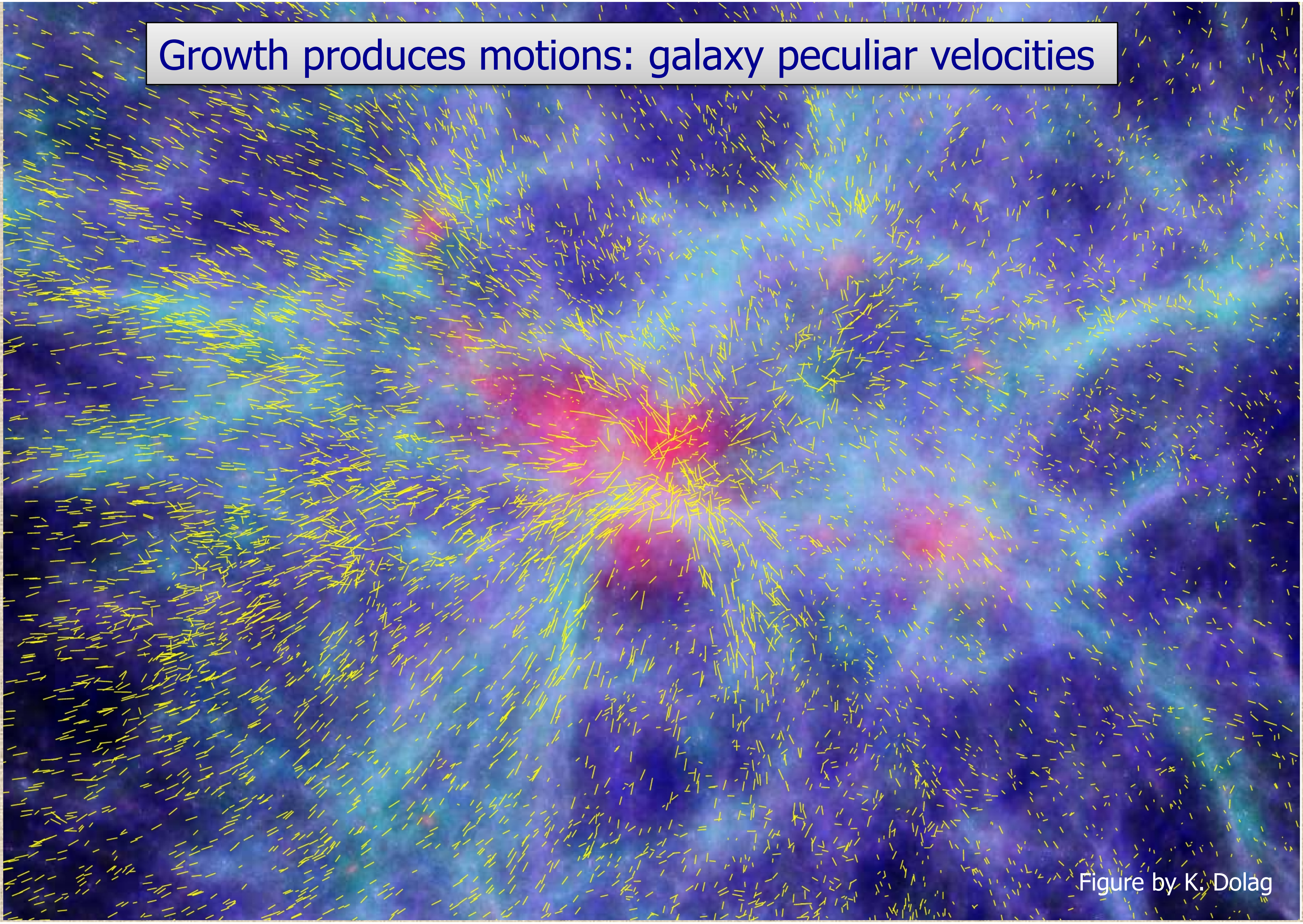
$\gamma=0.68$ for DGP braneworld



How do we measure $f(z)$?

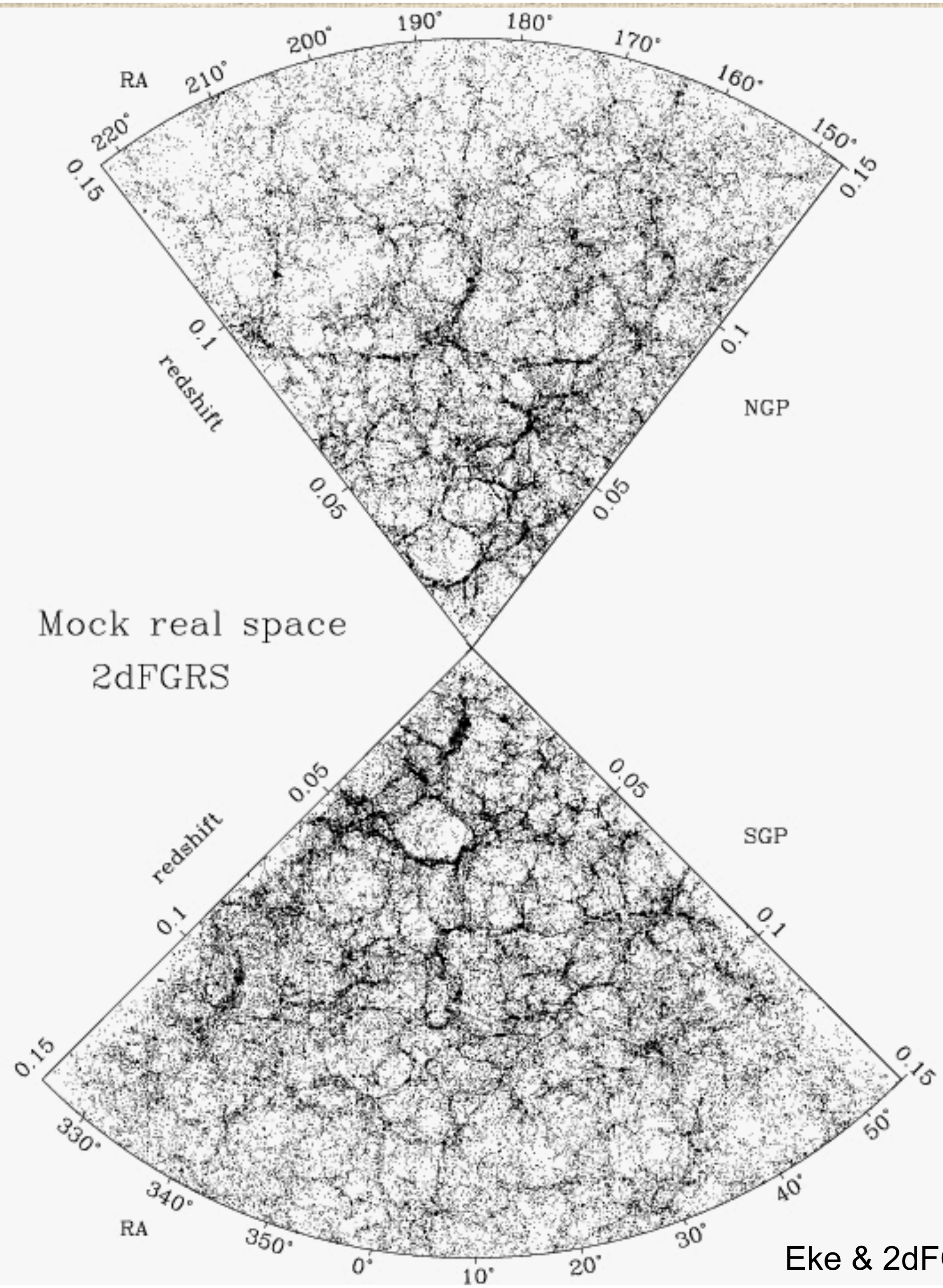
DGP: Lue et al. 2004; DM+DE models: Di Porto & Amendola 2007

Growth produces motions: galaxy peculiar velocities



In galaxy redshift surveys peculiar velocities manifest themselves as *redshift-space distortions* (Kaiser 1987)

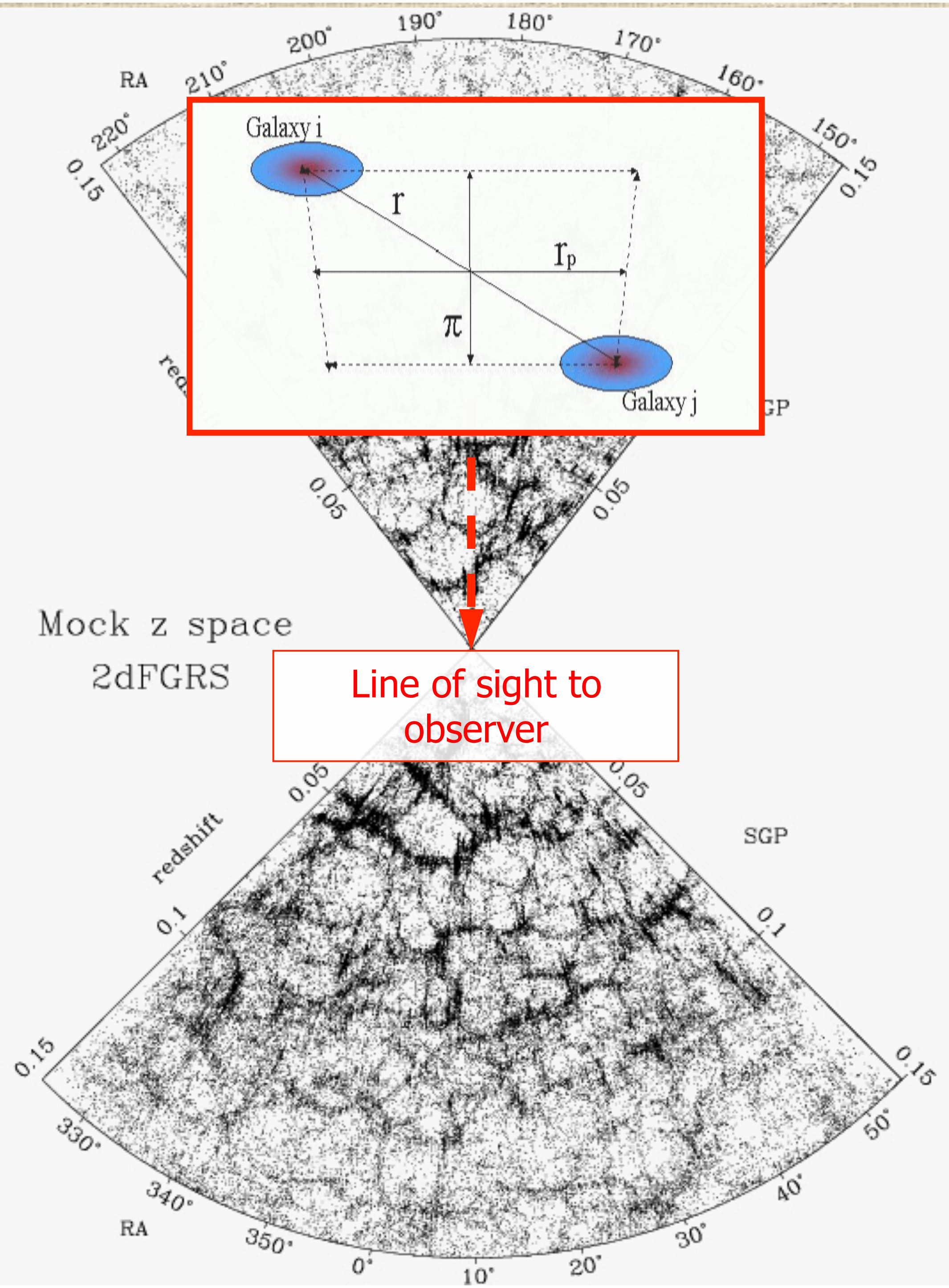
real space



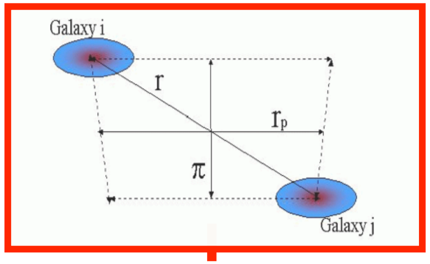
Eke & 2dFGRS 2003

In galaxy redshift surveys peculiar velocities manifest themselves as *redshift-space distortions* (Kaiser 1987)

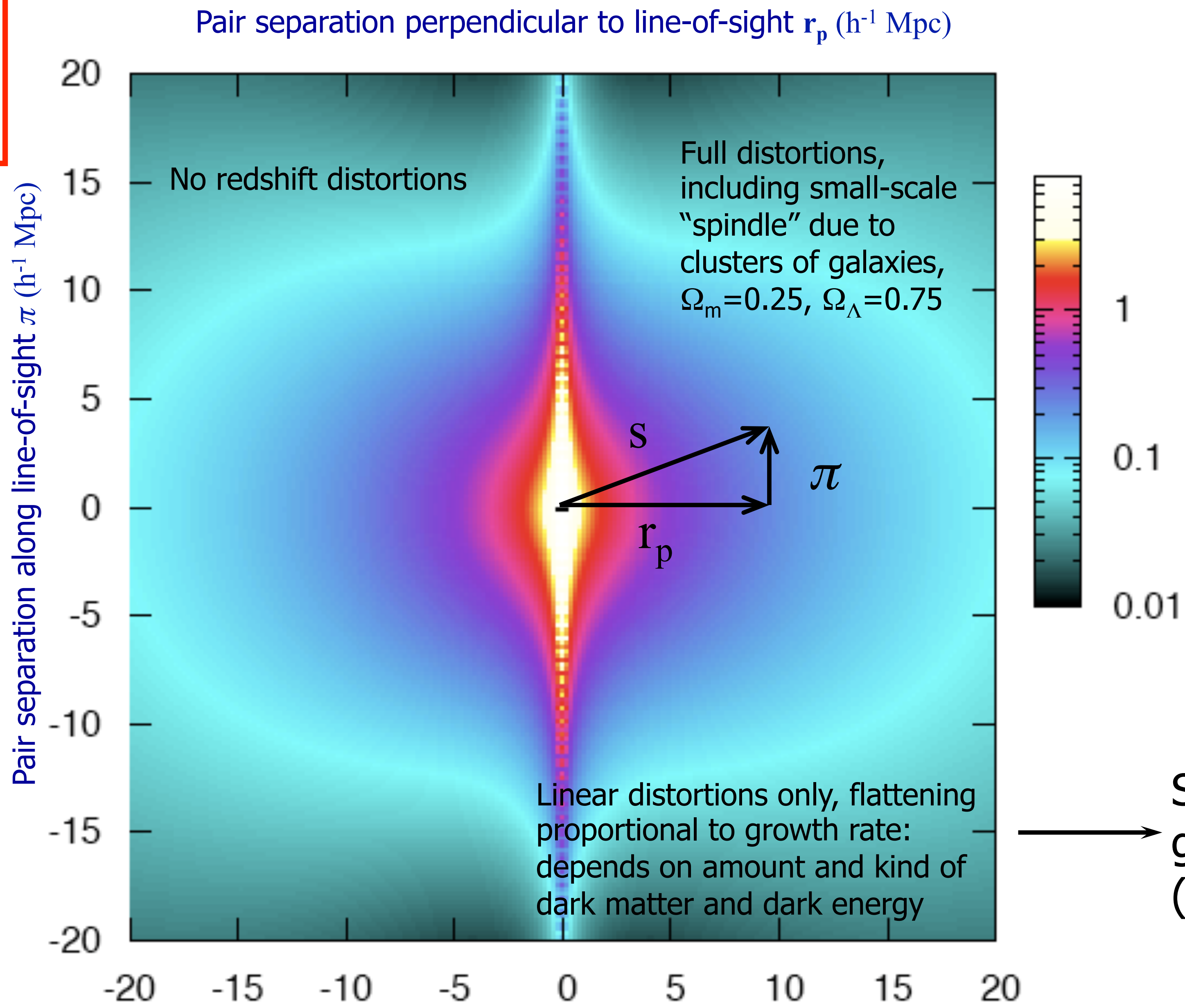
redshift space



Redshift-space galaxy-galaxy correlation function $\xi(r_p,\pi)$



Line of sight
to observer



$f = b_L\,\beta$

Specific
growth rate β
(Kaiser 1987)

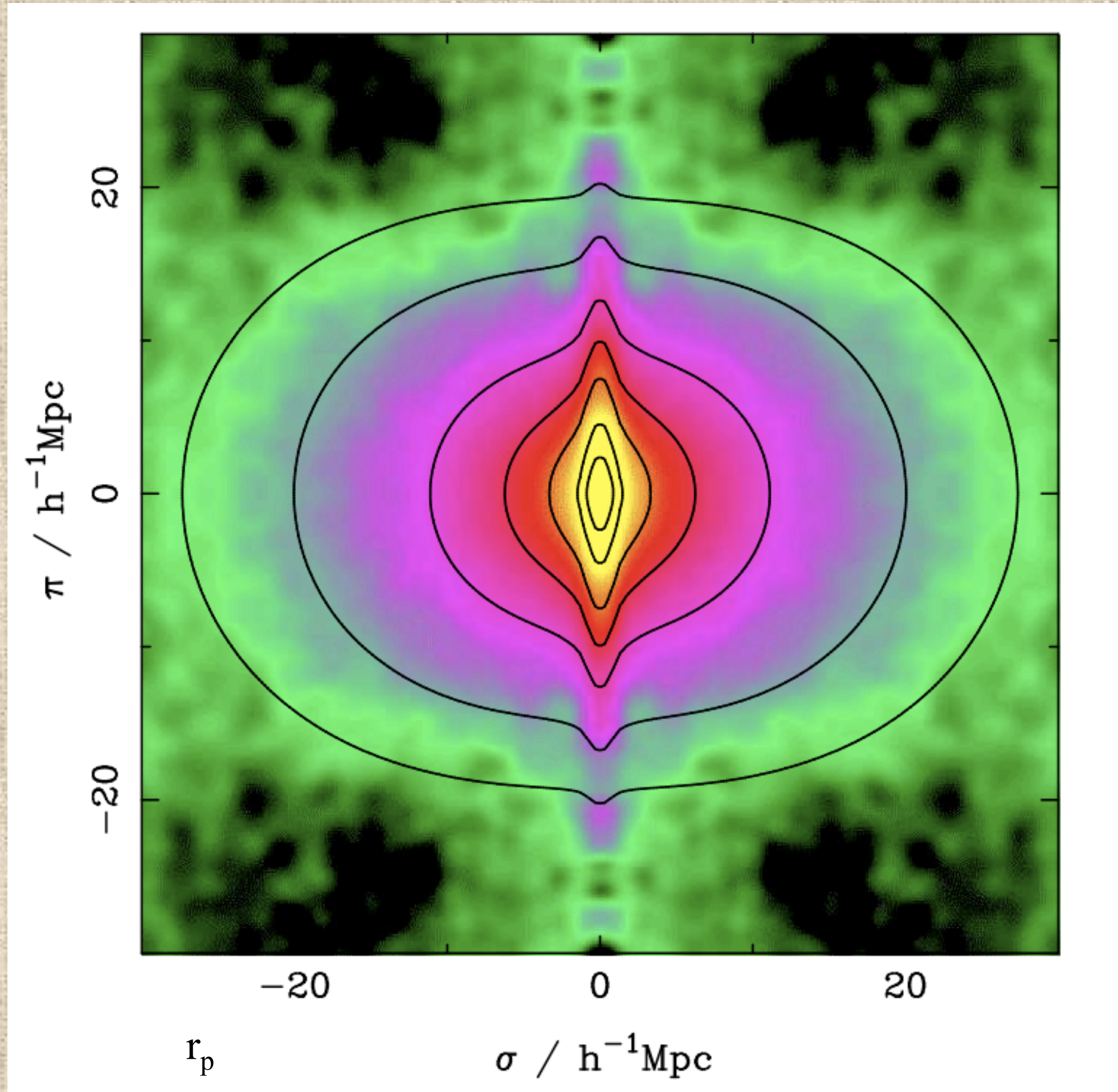
A well established effect at z~0

• E.g. 2dFGRS, z~0.1, Peacock et al. 2001, Hawkins et al. 2003

$$\beta = 0.49 \pm 0.09$$

• Essentially used to obtain an estimate of Ω_M once the bias is known or derived (e.g. from the bi-spectrum, Verde et al. 2001):

$$\beta \approx \frac{\Omega_M^{0.55}}{b_L}$$



(Defiinitive 2dFGRS measurement: Hawkins et al. 2003)

…which becomes even more interesting in the context of DE

Vol 451|31 January 2008|doi:10.1038/nature06555 nature

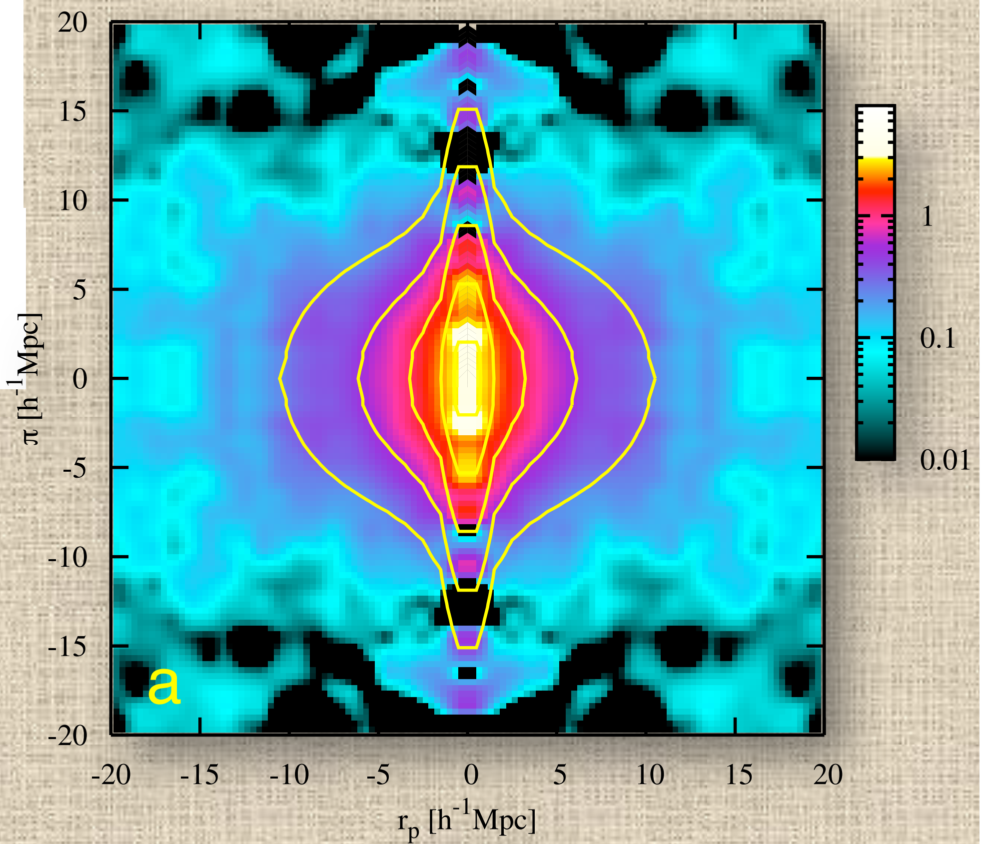
LETTERS

A test of the nature of cosmic acceleration using galaxy redshift distortions

L. Guzzo[1,2,3,4], M. Pierleoni[3], B. Meneux[5], E. Branchini[6], O. Le Fèvre[7], C. Marinoni[8], B. Garilli[5], J. Blaizot[3], G. De Lucia[3], A. Pollo[7,9], H. J. McCracken[10,11], D. Bottini[5], V. Le Brun[7], D. Maccagni[5], J. P. Picat[12], R. Scaramella[13,14], M. Scodeggio[5], L. Tresse[7], G. Vettolani[13], A. Zanichelli[13], C. Adami[7], S. Arnouts[7], S. Bardelli[15], M. Bolzonella[15], A. Bongiorno[16], A. Cappi[15], S. Charlot[10], P. Ciliegi[15], T. Contini[12], O. Cucciati[1,17], S. de la Torre[7], K. Dolag[3], S. Foucaud[18], P. Franzetti[5], I. Gavignaud[19], O. Ilbert[20], A. Iovino[1], F. Lamareille[15], B. Marano[16], A. Mazure[7], P. Memeo[5], R. Merighi[15], L. Moscardini[16,21], S. Paltani[22,23], R. Pellò[12], E. Perez-Montero[12], L. Pozzetti[15], M. Radovich[24], D. Vergani[5], G. Zamorani[15] & E. Zucca[15]

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

- VVDS-Wide F22 field: 4 deg^2
- IAB<22.5
- 0.6<z<1.2 --> 5988 redshift
- Effective <z>=0.77



β=0.70±0.26 (@ z=0.77)

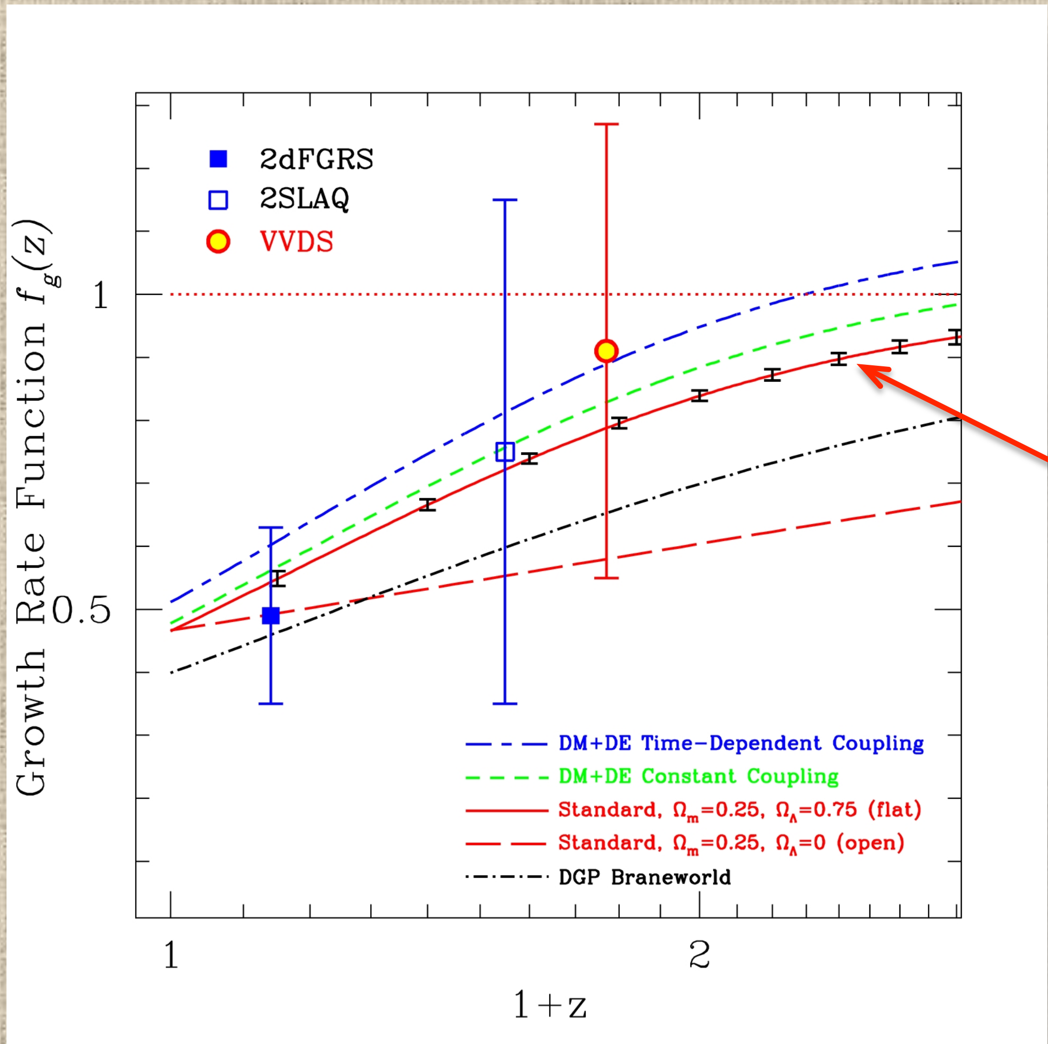
(see also Zhang et al., Phys. Rev. Lett. 99, 141302 (2007), proposing combination of lensing and z-distortions)

The signature of linear growth at z~1

VVDS-Wide @ z=0.77:

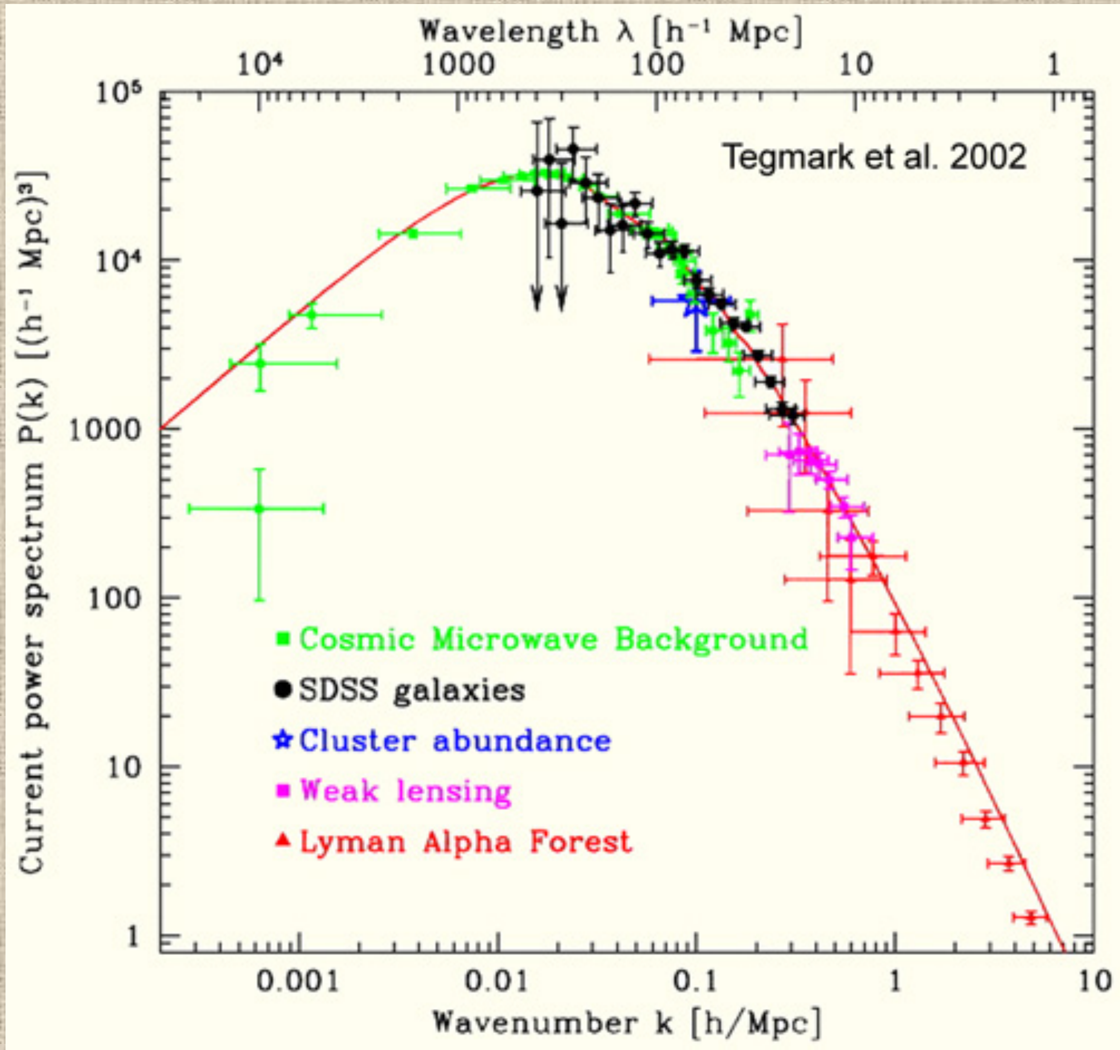
$$\boxed{f = b_L\, \beta = 0.91 \pm 0.36}$$

Where b_L=1.3±0.1 is measured combining VVDS and CMB (e.g. Marinoni et al. 2005)

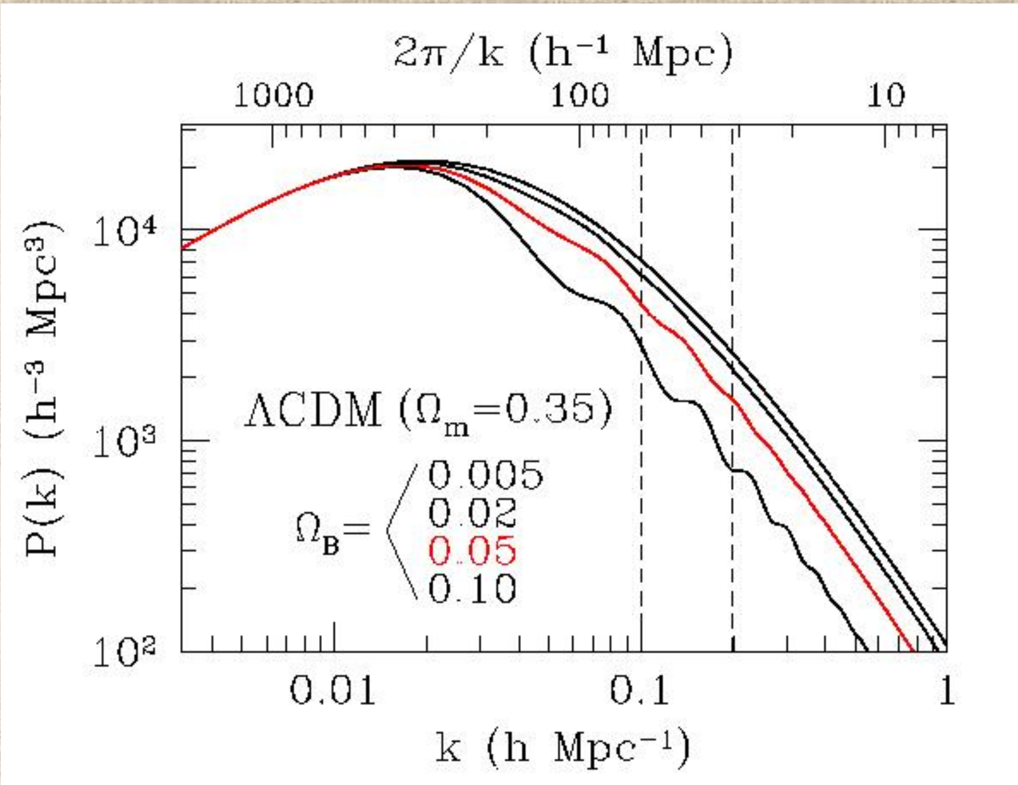


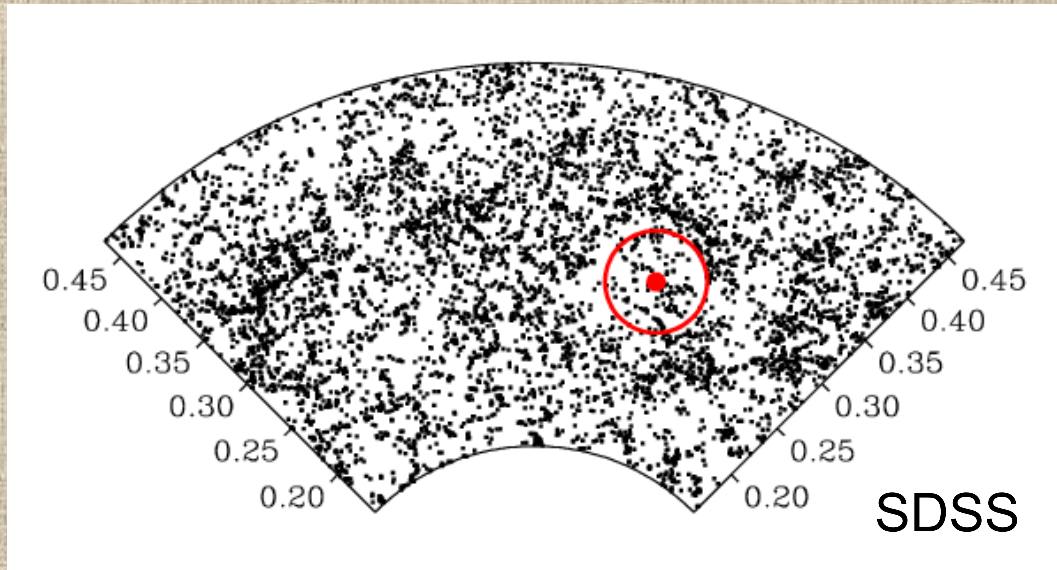
Guzzo et al. 2008, Nature 451, 541

Redshift surveys also measure H(z): the galaxy power spectrum as a standard ruler



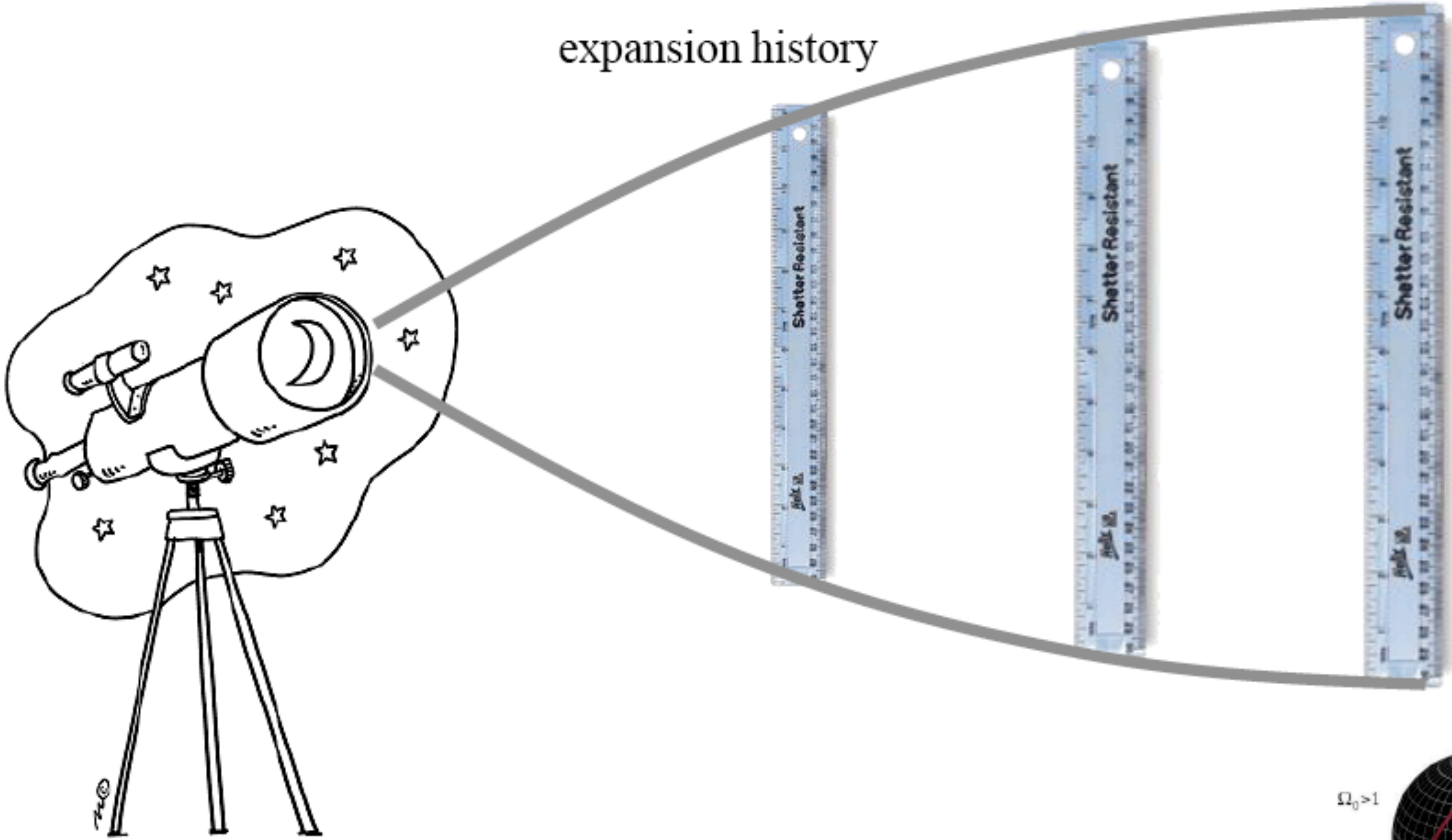
Baryonic Acoustic Oscillations (BAO) in the galaxy distribution



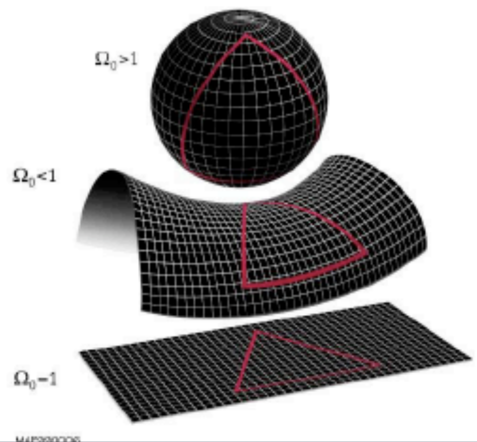


D. Eisenstein 2007

Baryonic Acoustic Oscillations: measure H(z) from redshift surveys



Give $D_A(z)$ and $H(z)$: see Percival et al. 2011 for most recent application to SDSS and 2dFGRS

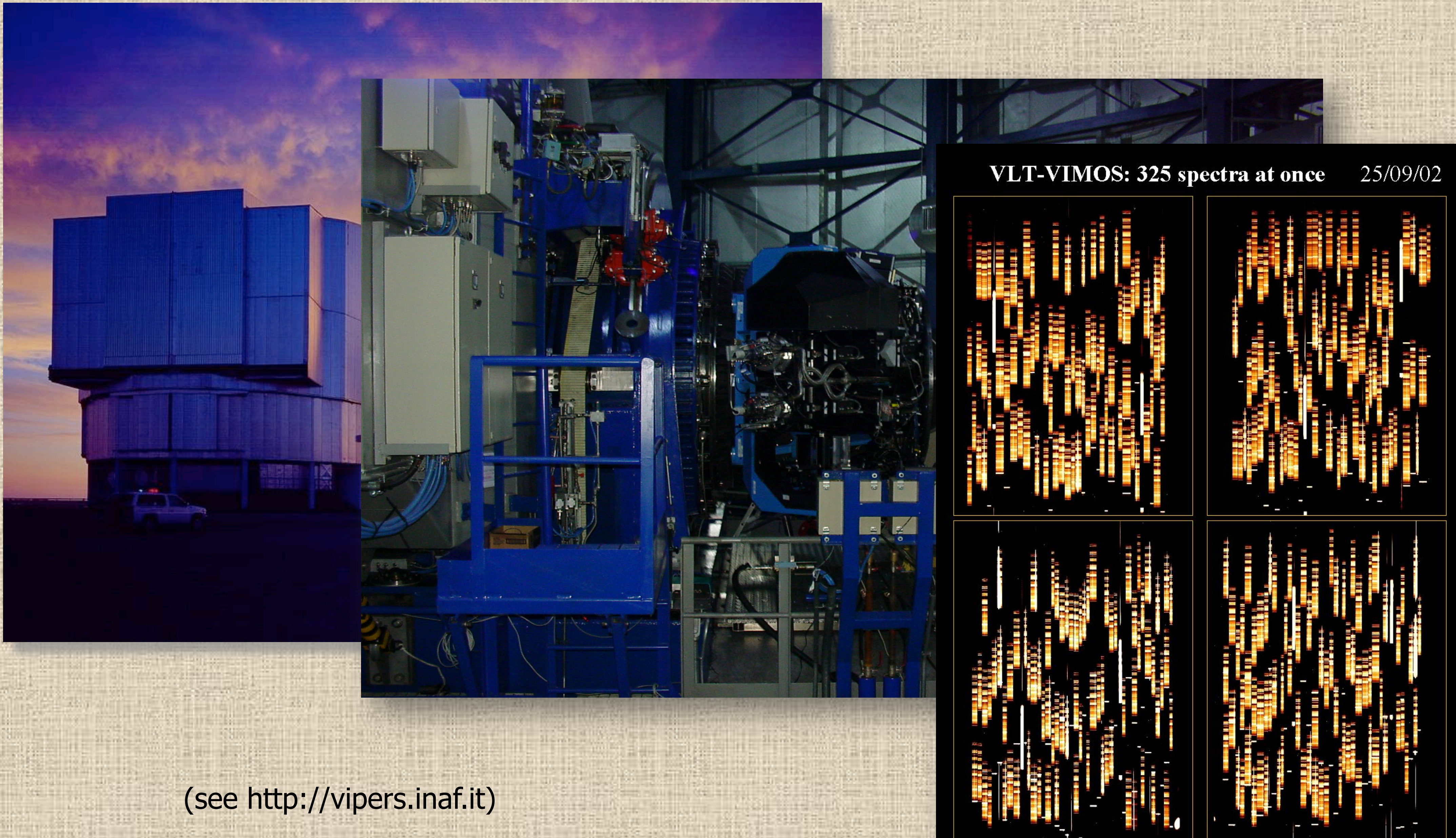


Waiting for Euclid…

VIPERS

VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

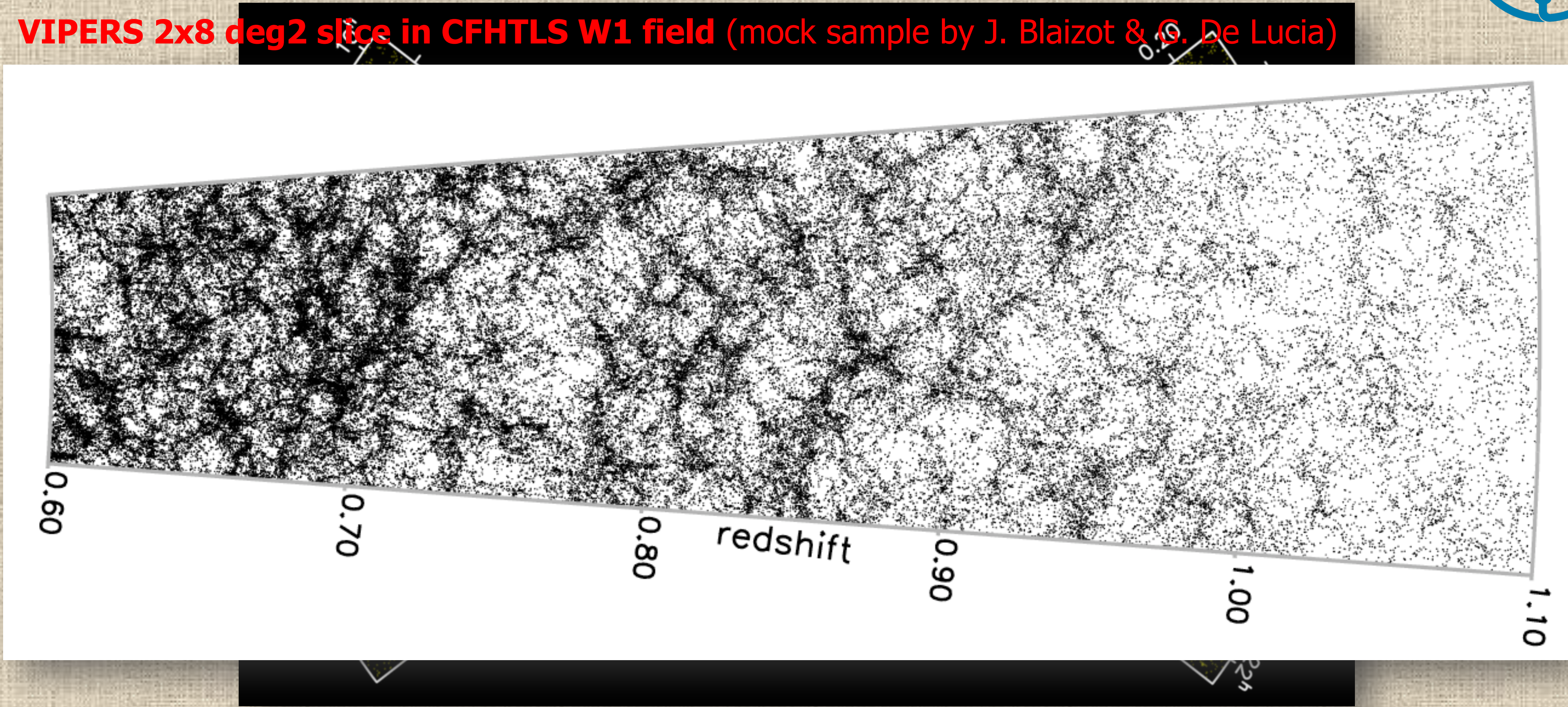
VIPERS: exploiting VIMOS Multi-Object Spectroscopy at the VLT (440 hours)



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

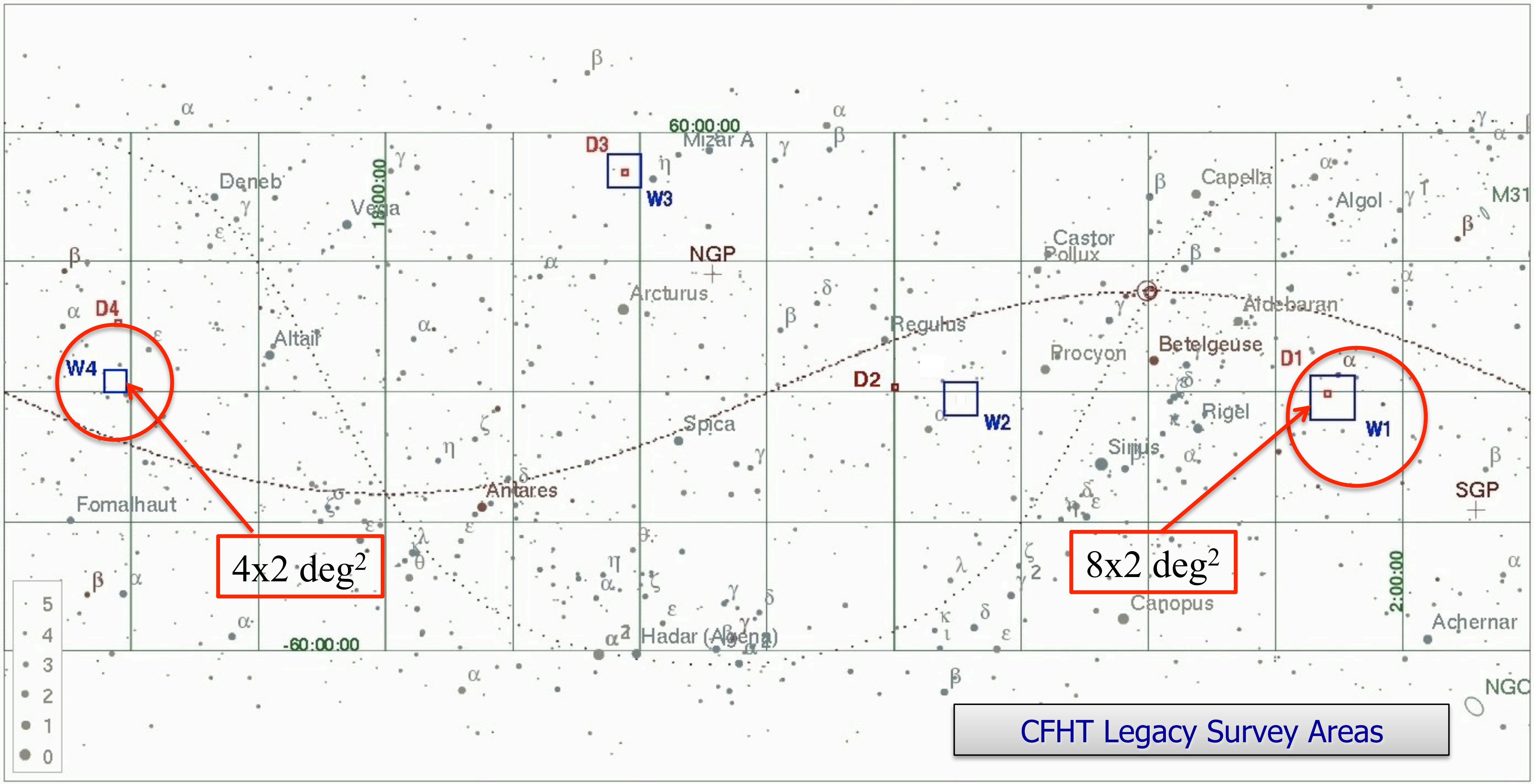
VIPERS: a 2dFGRS at 0.5<z<1.2

VIPERS 2x8 deg2 slice in CFHTLS W1 field (mock sample by J. Blaizot & G. De Lucia)



+2x4 deg2 slice in CFHTLS W4 field (VVDS F22)

Location of VIPERS fields



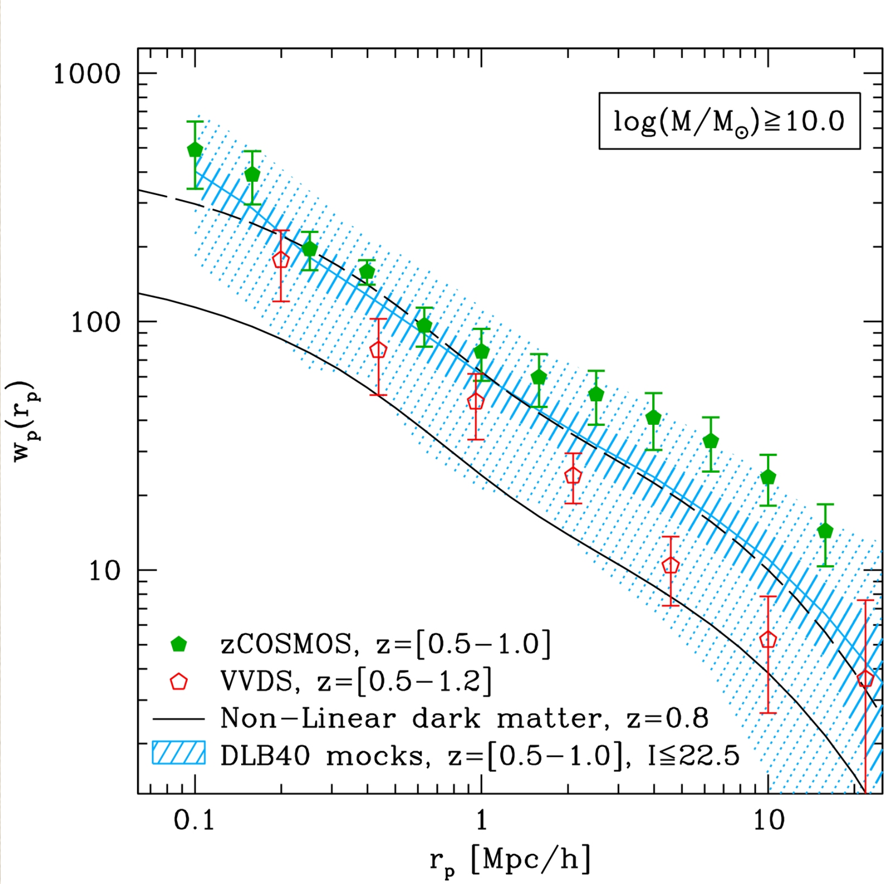
VIPERS in a nut-shell

- 440.5 VLT hours
- ~24 deg^2 over W1 and W4 CFHTLS wide fields (~16 + 8)
- I_{AB}<22.5, LR Red grism, 45 min exp.
- 288 VIMOS pointings
- z>0.5 color-color pre-selection
- PSF + SED –based star-galaxy separation (AGN color recovery)
- **~100,000 redshifts, >40% sampling**
- **Density and volume comparable to 2dFGRS, but at z~0.8**

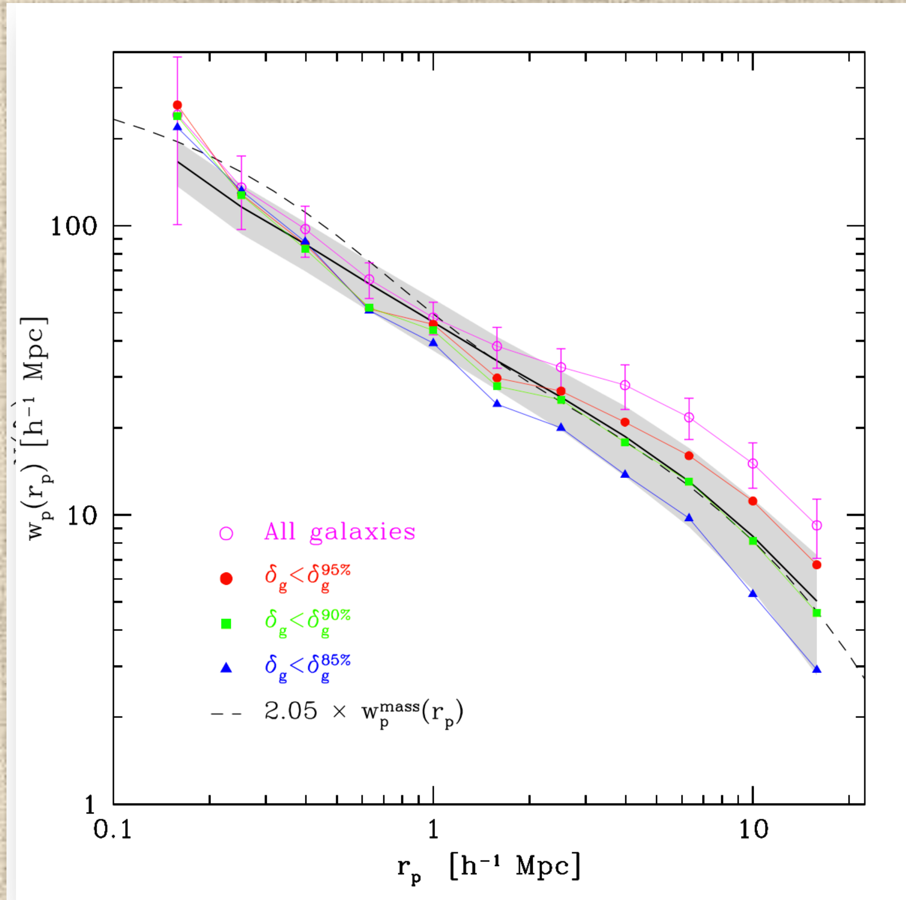
VIPERS broader scientific goals

- Growth rate from redshift-space distortions
- Galaxy clustering at z~1 with comparable precision to z~0:
  - Evolution of $\xi(r)$ and $P(k)$ (Ω_m, Ω_b at z~1)
  - Dependence on galaxy properties
  - Galaxy-DM relations (HOD modeling)
- Galaxy biasing
- Massive clusters and super-clusters of galaxies (large volume)
- Evolution of galaxy colors and environmental effects (good sampling)
- Bright/massive/rare galaxies and the galaxy luminosity and stellar mass functions (large volume)
- Evolution of AGN's
- Weak-lensing (photo-z calibration, combination with CFHTLenS)
- Multi-wavelength properties (SWIRE, XMM-XXL, UDS)

Small volumes and low statistics at z>0.5: strong variance



Meneux, LG & ZCOSMOS Collaboration, 2009



De la Torre, LG & ZCOSMOS Collaboration, 2010, MNRAS, 409, 867

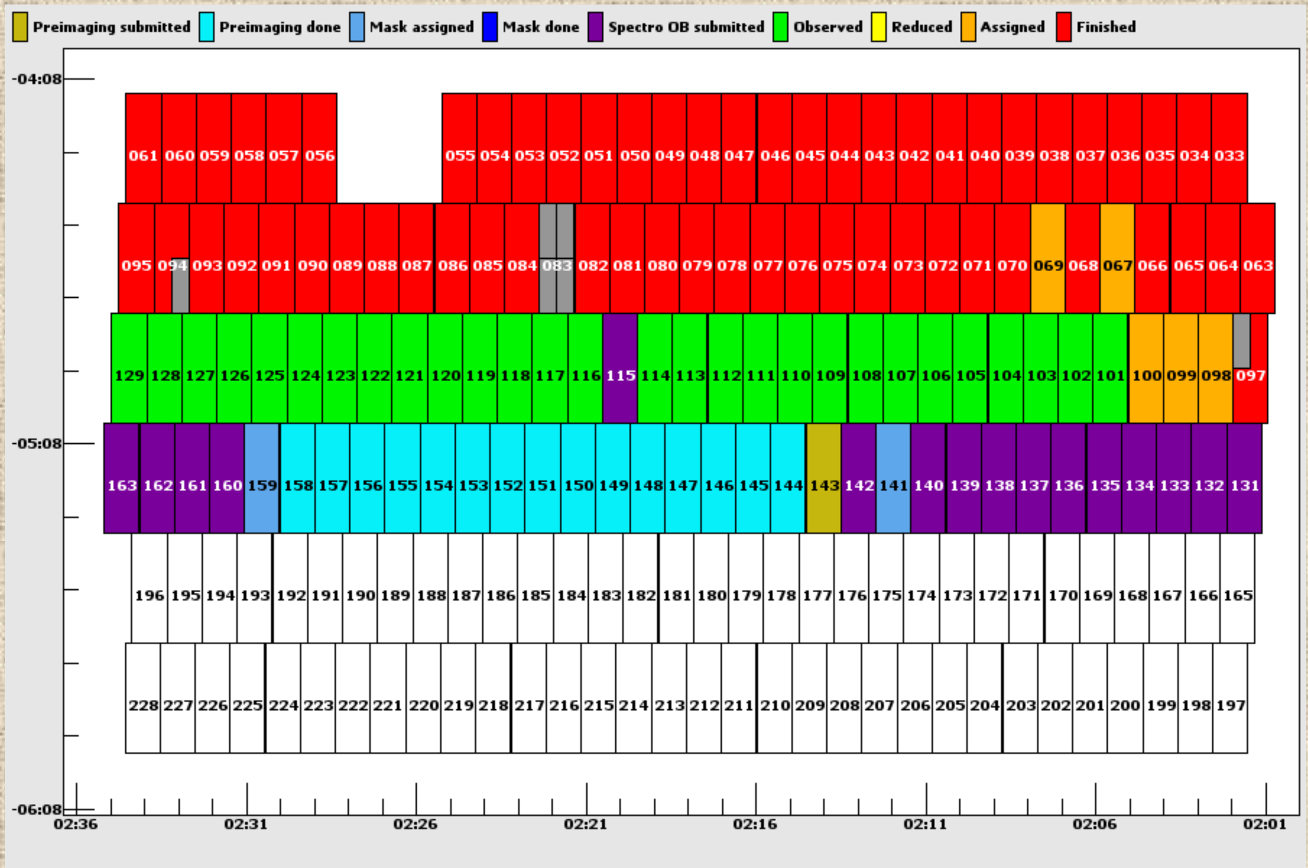
→ Enviromental dependence of clustering in hierarchical models (Abbas & Sheth 2005)

VIPERS Team

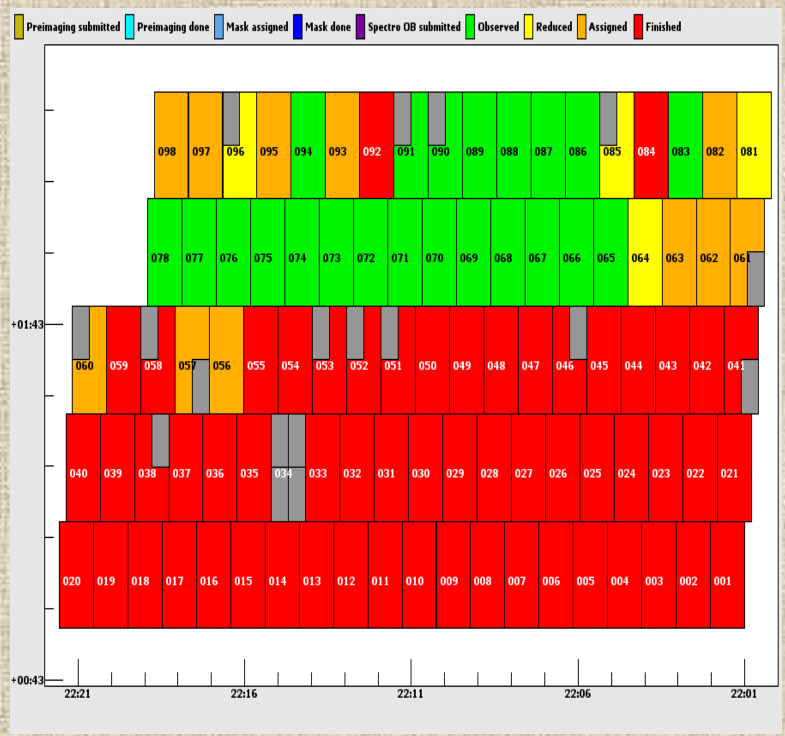
- **MILANO OAB (Project Office)**: L. Guzzo, B. Granett, A. Iovino, A. Marchetti, S. Rota, U. Abbas (Turin)
- **MILANO IASF (Data Reduction Centre)**: B. Garilli, M. Scodeggio, D. Bottini, A. Fritz, P. Franzetti, D. Maccagni, L. Paioro, M. Polletta
- **BOLOGNA**: M. Bolzonella, L. Moscardini, A. Cappi, Y. Davidzon, C. Di Porto, F. Marulli, D. Vergani, G. Zamorani, A. Zanichelli, E. Branchini (Rome)
- **EDINBURGH**: J. Peacock, S. de la Torre
- **GARCHING MPE**: S. Phleps, H. Schlagenhaufer, B. Meneux
- **MARSEILLE**: O. Le Fevre, C. Adami, J. Bel, V. Le Brun, L. Guennou, L. Tasca, C. Marinoni
- **PARIS (TERAPIX CFHTLS)**: H. McCracken, Y. Mellier, M. Volk, J. Coupon (Tokyo), J. Blaizot (Lyon)
- **TRIESTE**: G. De Lucia, O. Cucciati
- **PORTSMOUTH**: W. Percival, R. Tojeiro, R. Nichol, A. Burden
- **WARSAW**: A. Pollo, K. Malek, J. Krywult (Kielce)

VIPERS coverage (as of Dec 2011): ~55,000 spectra observed; ~35,000 redshifts reduced and validated (v2.0 internal release)

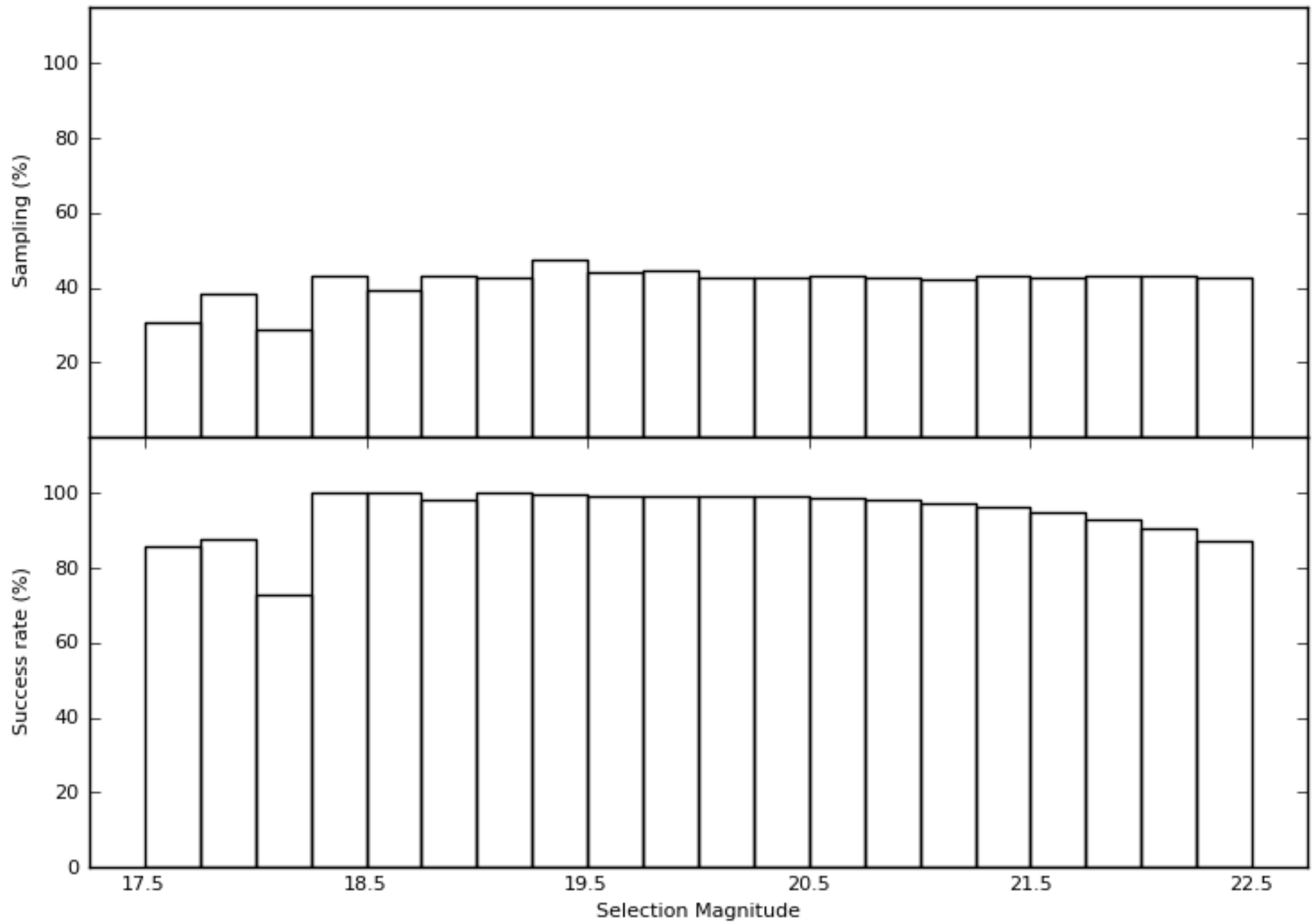
W1



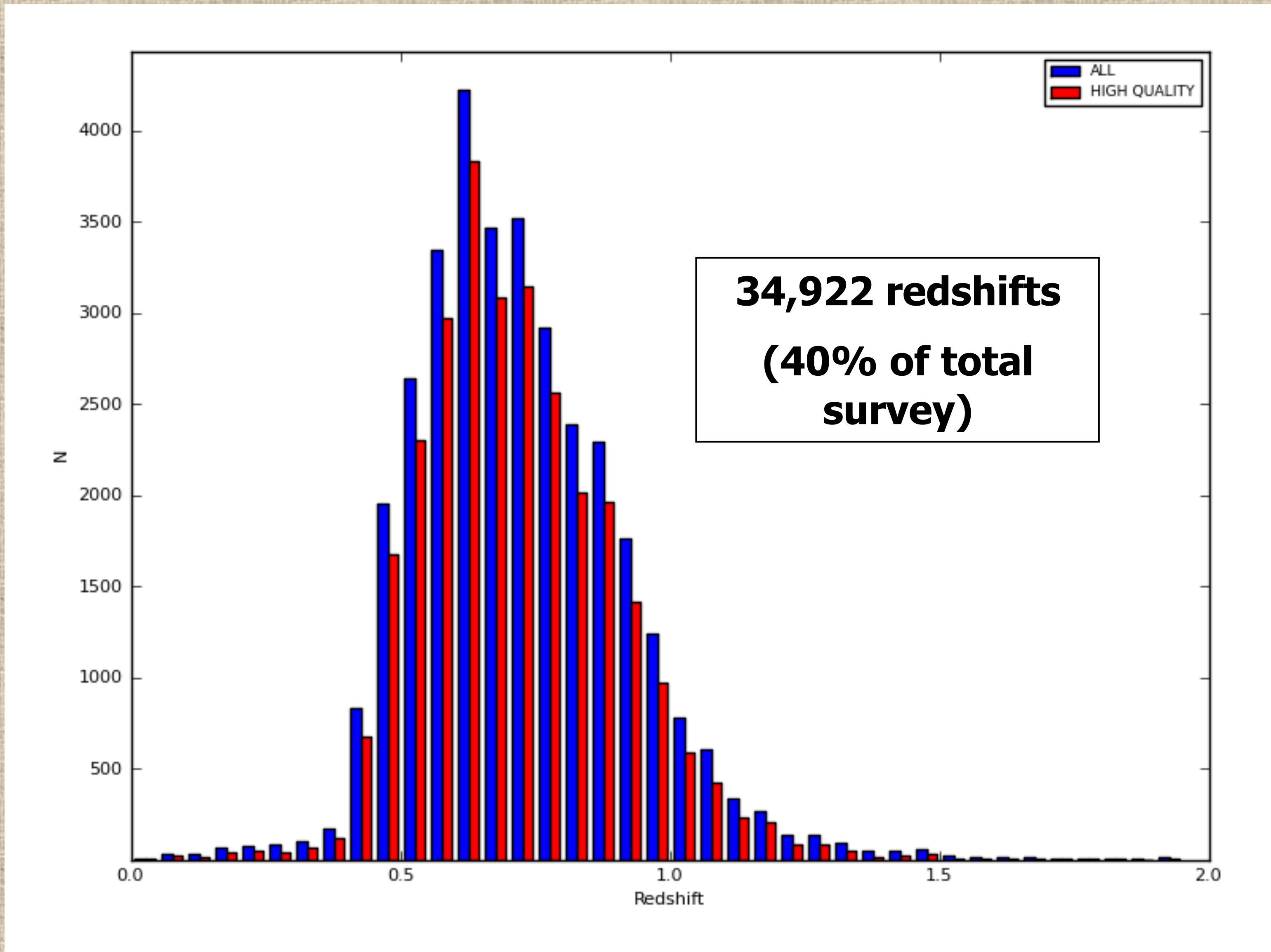
W4



Sampling rate and efficiency

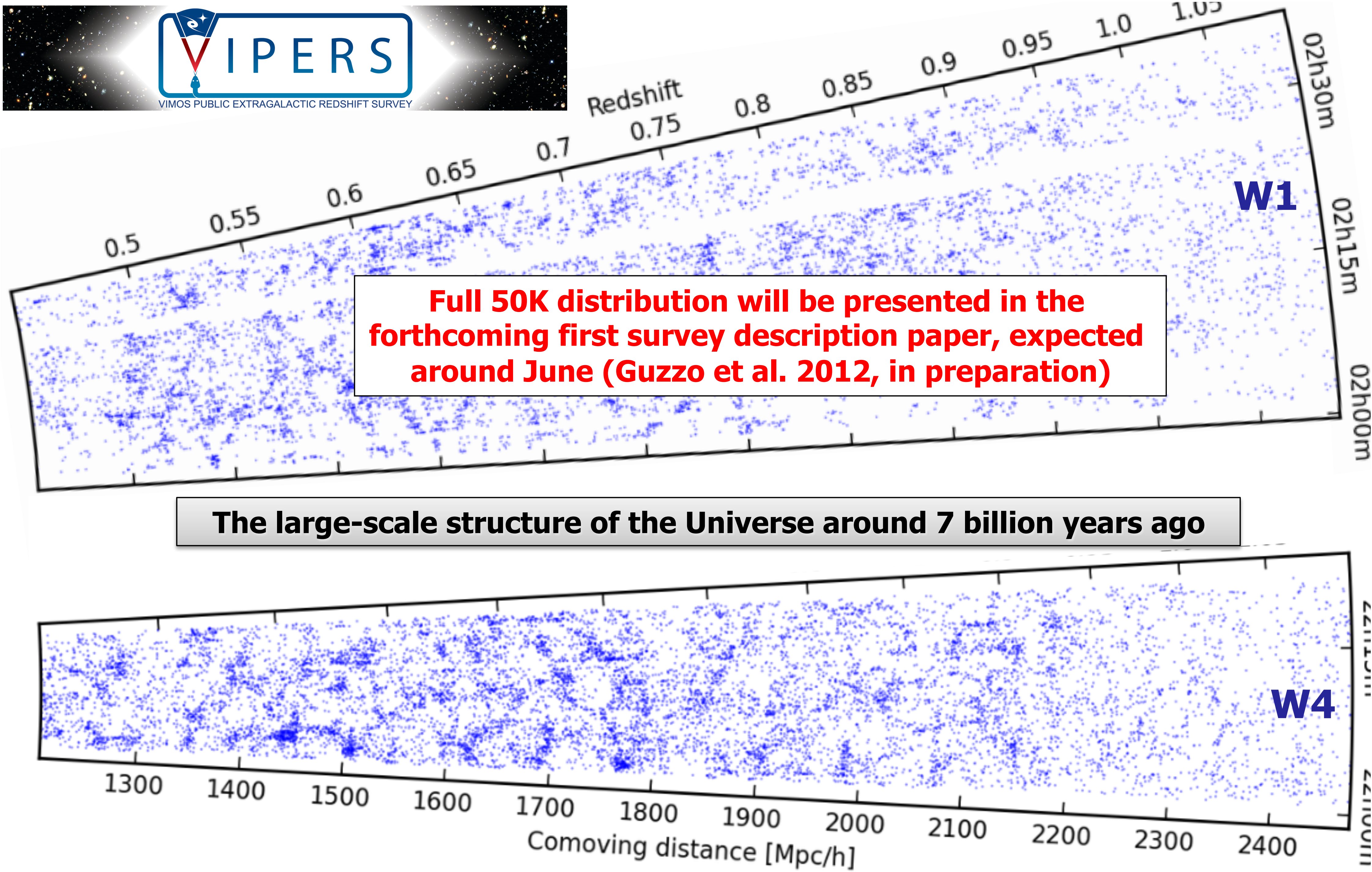


VIPERS redshift distribution



VIPERS

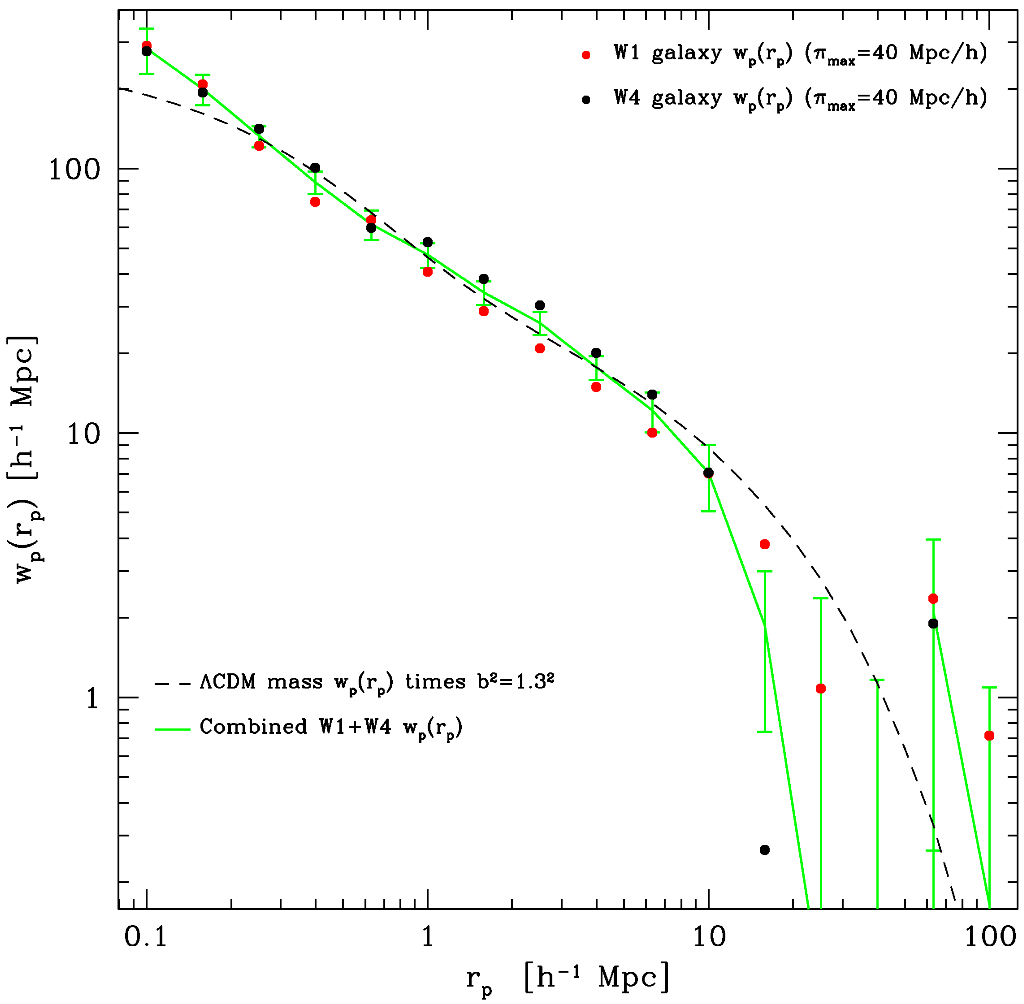
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY



Full 50K distribution will be presented in the forthcoming first survey description paper, expected around June (Guzzo et al. 2012, in preparation)

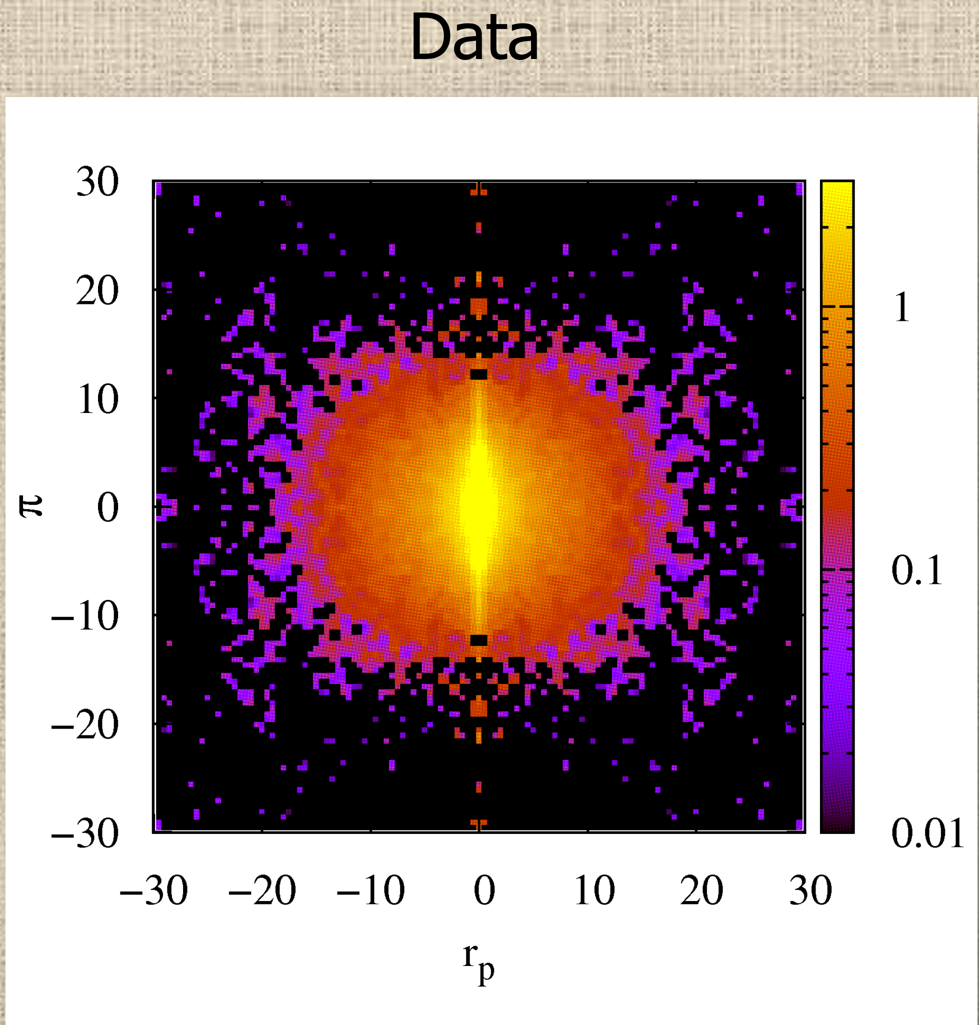
The large-scale structure of the Universe around 7 billion years ago

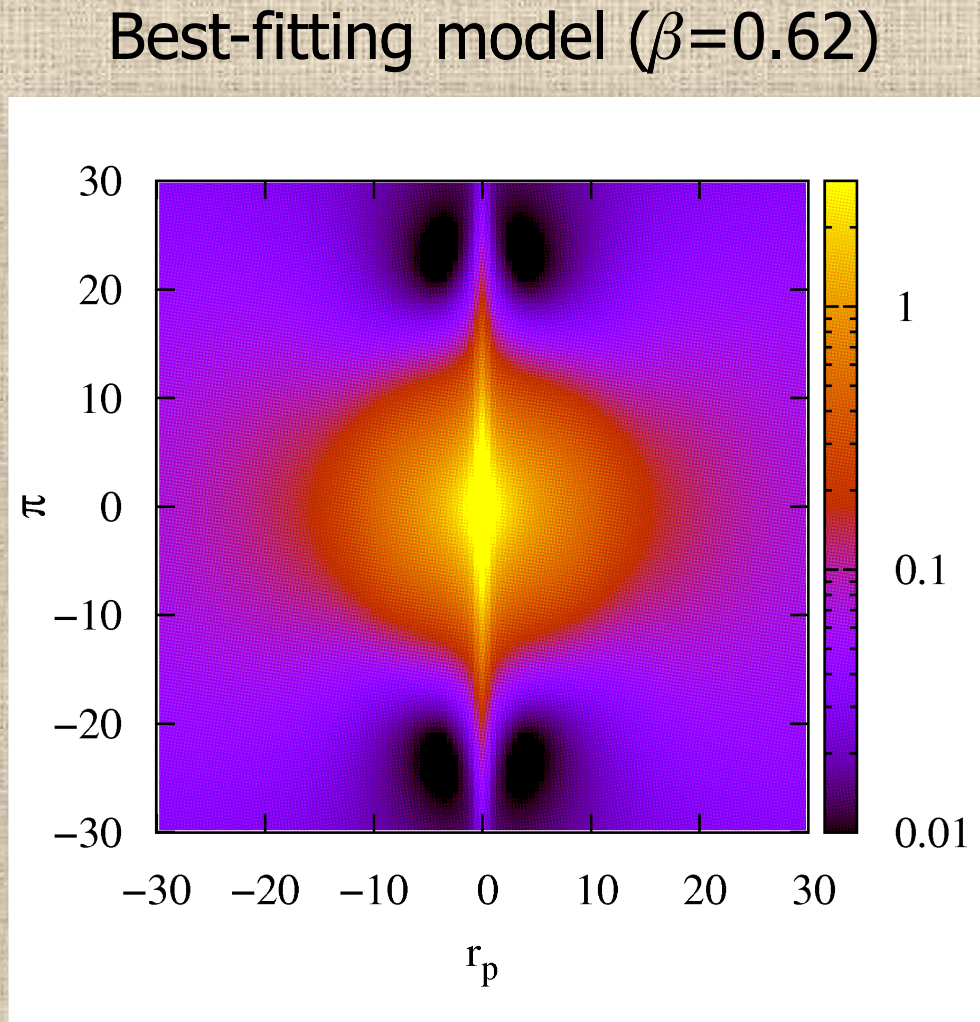
Projected correlation function wp(rp) from early ~12,000 high-quality VIPERS redshifts



- Remarkably small difference of clustering (amplitude and shape) between the two fields
- Well-defined correlation function on $0.1<r_p<\sim 15$ scales
- Galaxy bias b~1.35 (assuming ΛCDM)

Early $\xi(r_p,\pi)$ from first ~12,000 high-quality VIPERS redshifts at 0.5<z<1

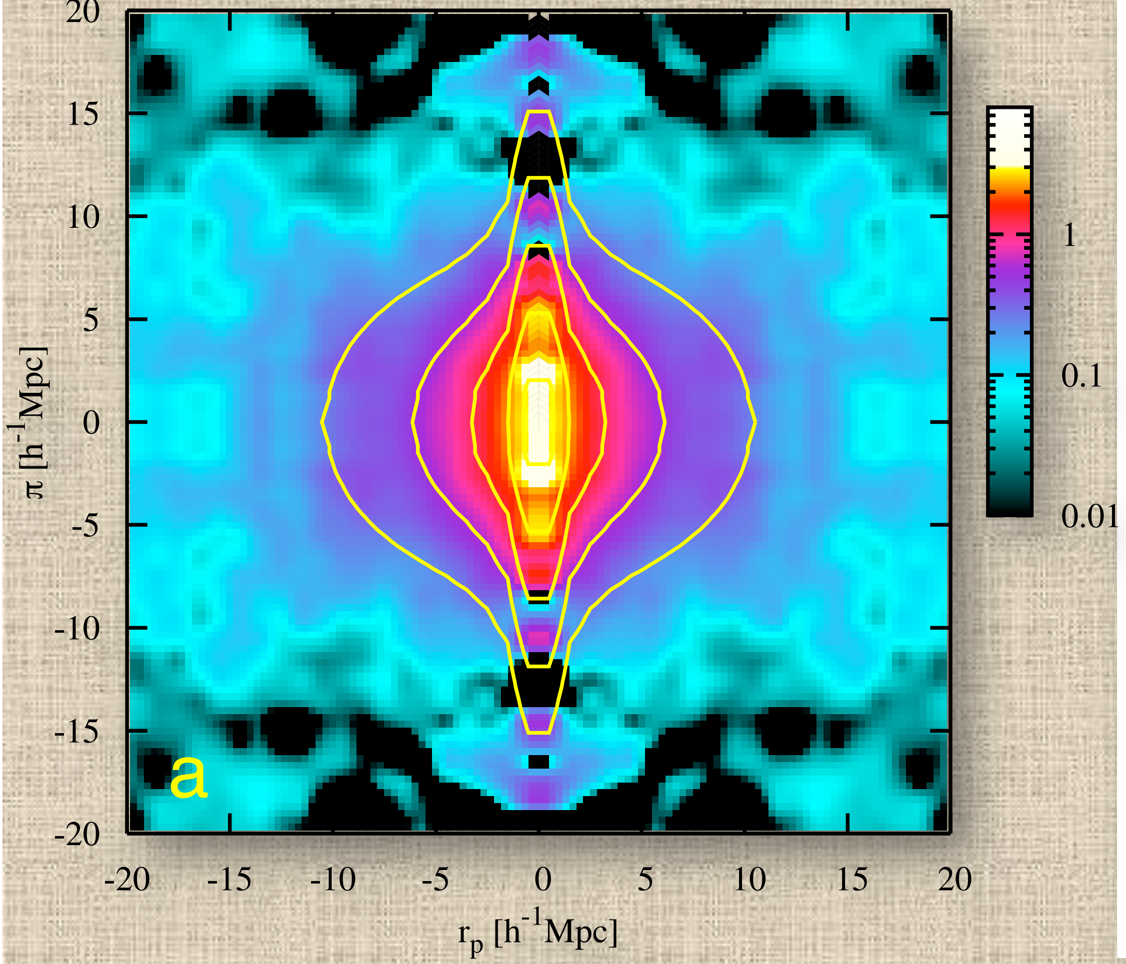


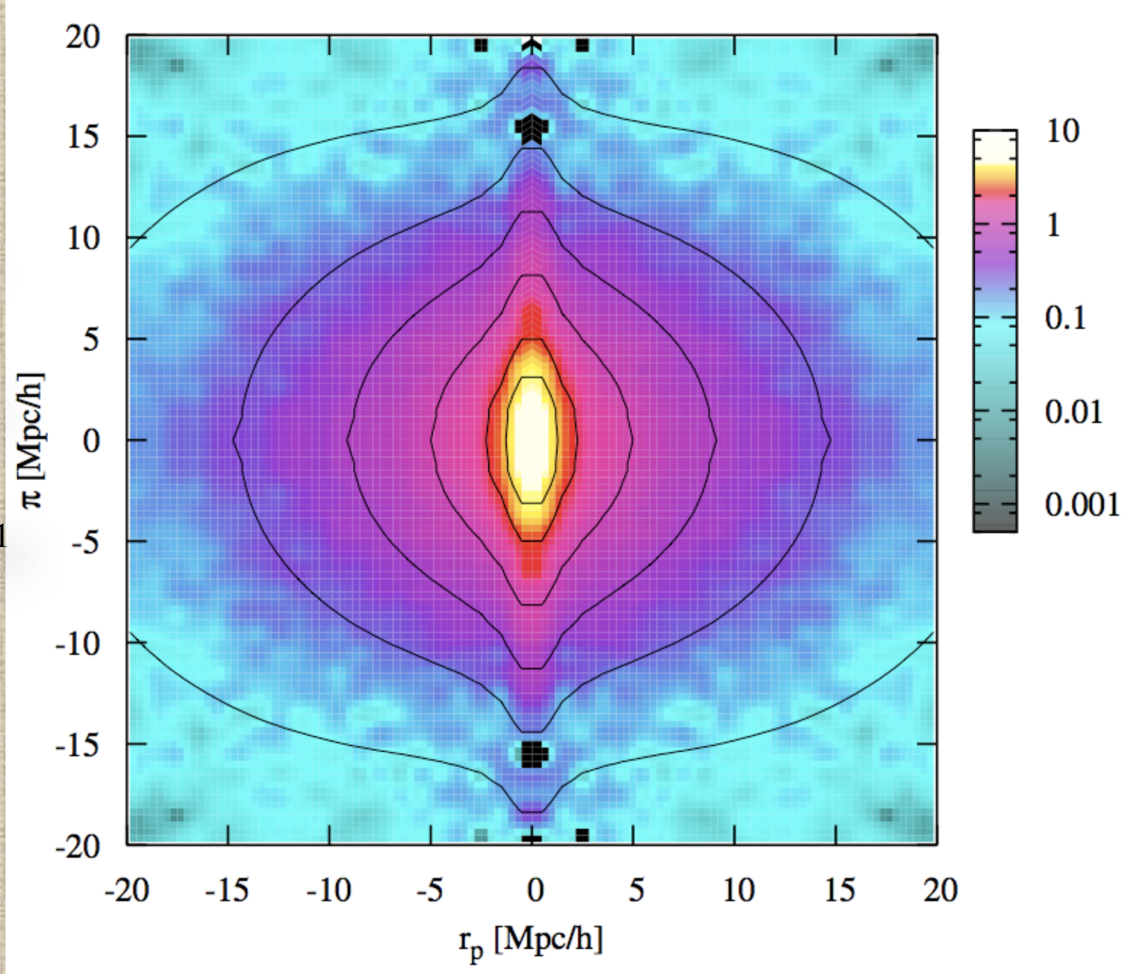


2 parameter fit of the full shape of $\xi(r_p,\pi)$ on $0<r_p<20$ scale (S. de la Torre, & the VIPERS Collaboration)

Expectations from fully completed survey

Guzzo et al 2008, Nature, 451, 541

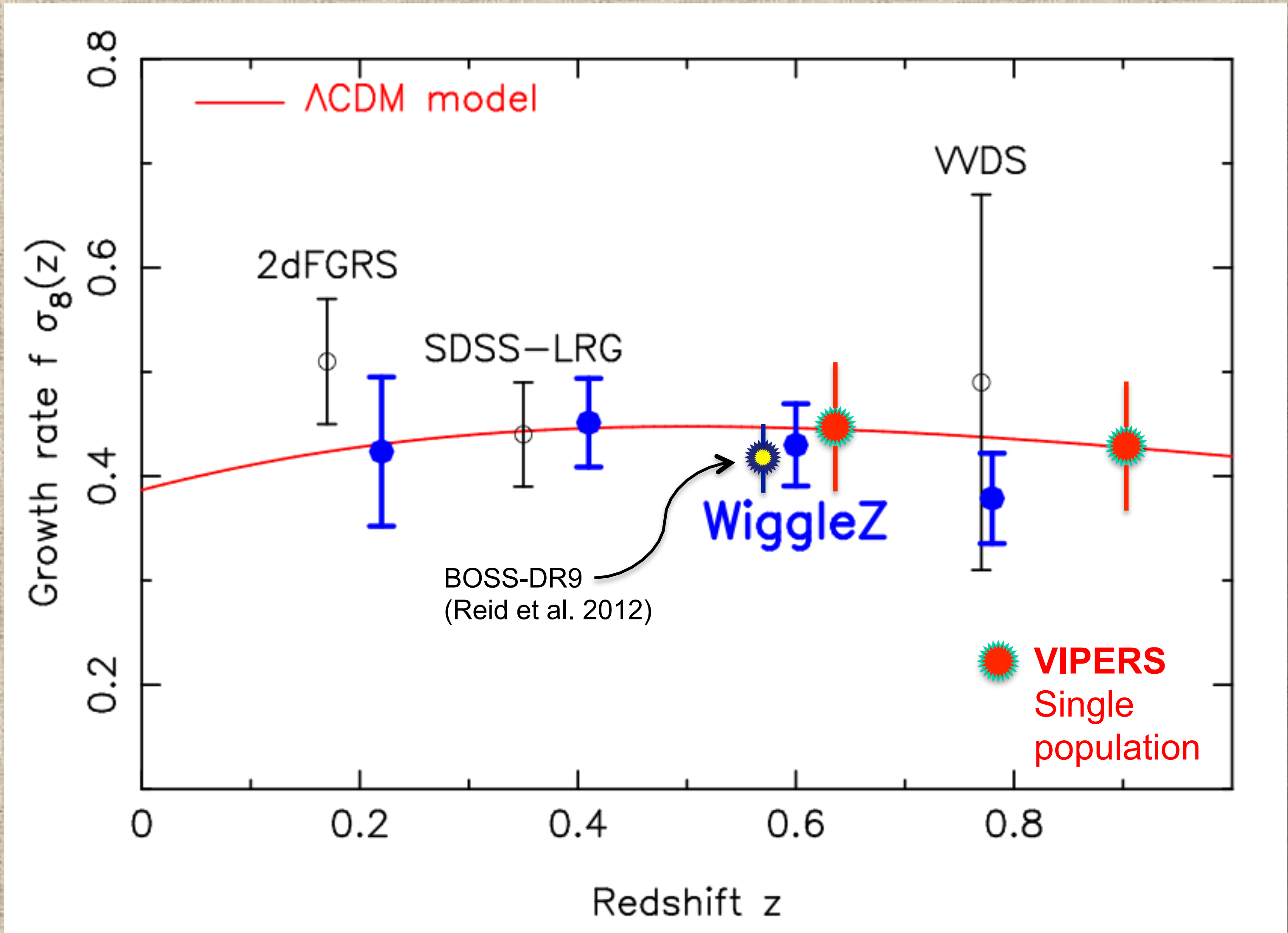




VVDS F22 (~6000 gals)

VIPERS (~100,000 gals)

BAO-designed surveys can also measure RSD well

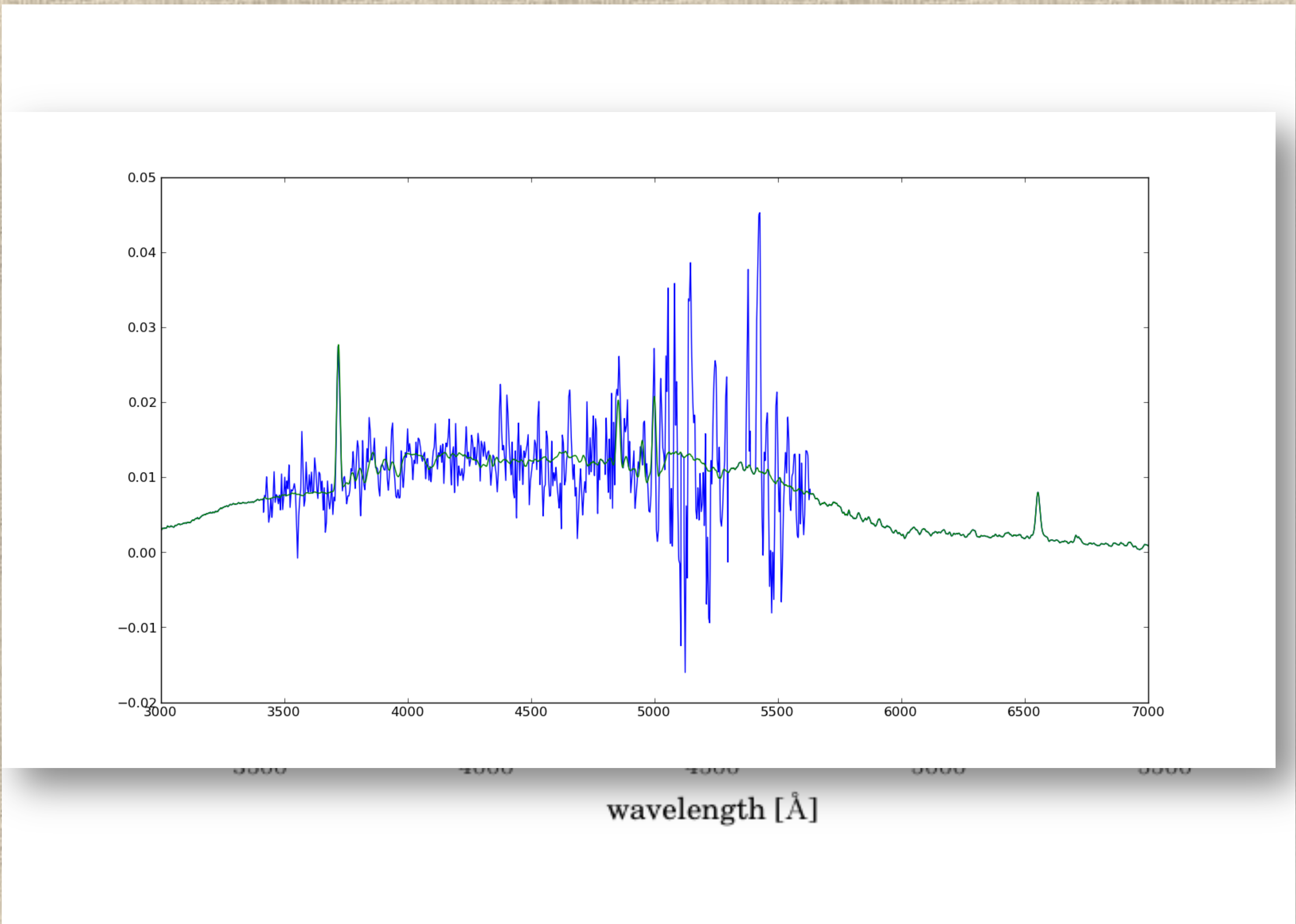


- WiggleZ: ~152,000 gals over 5000 deg^2 (Blake et al. 2011, arXiv:1104.2948)

- SDSS-III BOSS DR9: ~265,000 galaxies over 3275 deg^2 (see series of BOSS papers on astro-ph)

- VIPERS will measure β with multiple populations and reduce cosmic variance (McDonald & Seljak, 2009, JCAP; but see Gil-Marin et al. 2010, arXiv:1003.3238), while testing systematic effects

How to define sub-populations: PCA spectral classification

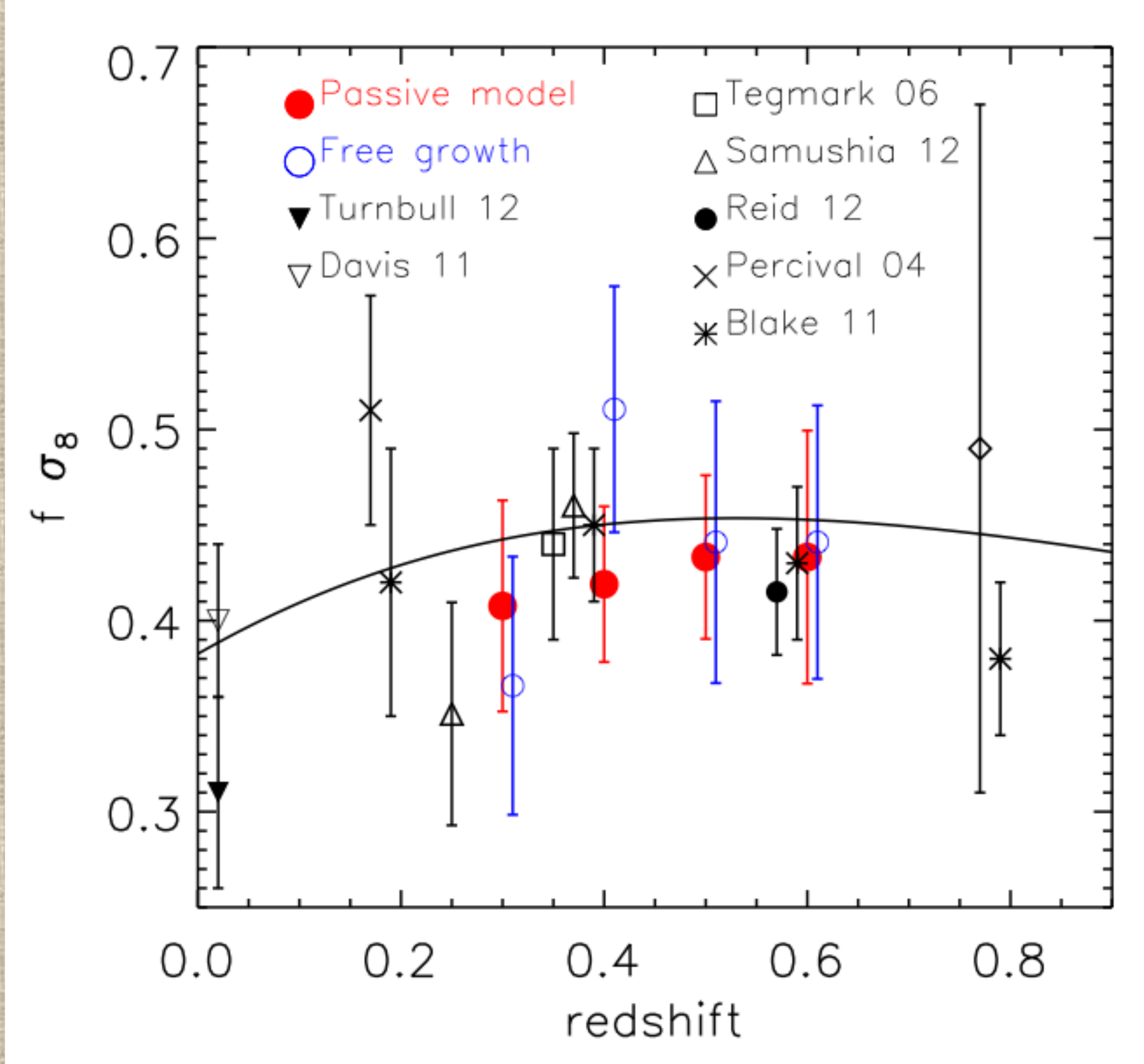


- Classify quantitatively sub-populations of galaxies (e.g. LRG-like)
- Build well-defined sub-sample for cosmological analysis (e.g. a la McDonald & Seljak 2010)
- "Repair" damaged spectra
- Consistently compare clustering/evolution with z~0 samples

A. Marchetti (PhD project), B. Granett & LG

The current status (update to a week ago), including new ways to measure f(z)

1. From redshift distortions
2. From peculiar velocities at low redshift (Hudson & Turnbull 2012, astro-ph)
3. From a direct estimate of the growth of structure using passive galaxies as tracers (Tojeiro et al. 2012)



(from Tojeiro & BOSS Collaboration 2012)

What are redshift distortions probing in practice?

- Song & Percival 2009

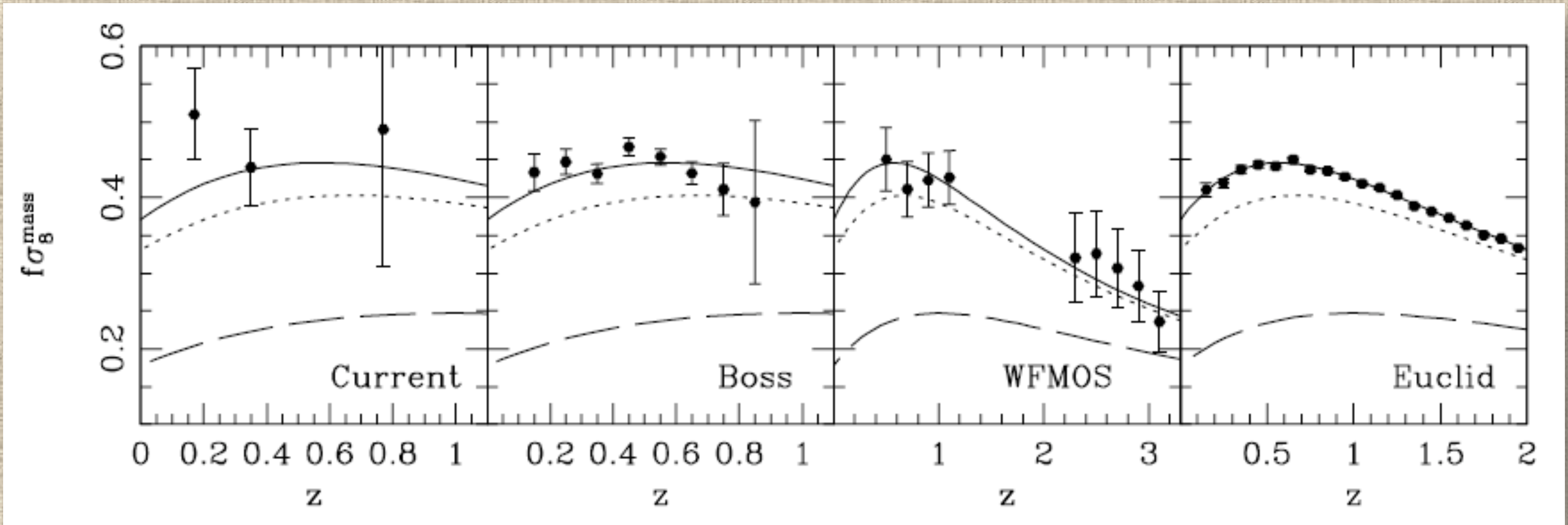
$$f = b\beta \approx \frac{\sigma_8^{gal}}{\sigma_8^{mass}}\beta$$

➔

All from model (+CMB)

All observables

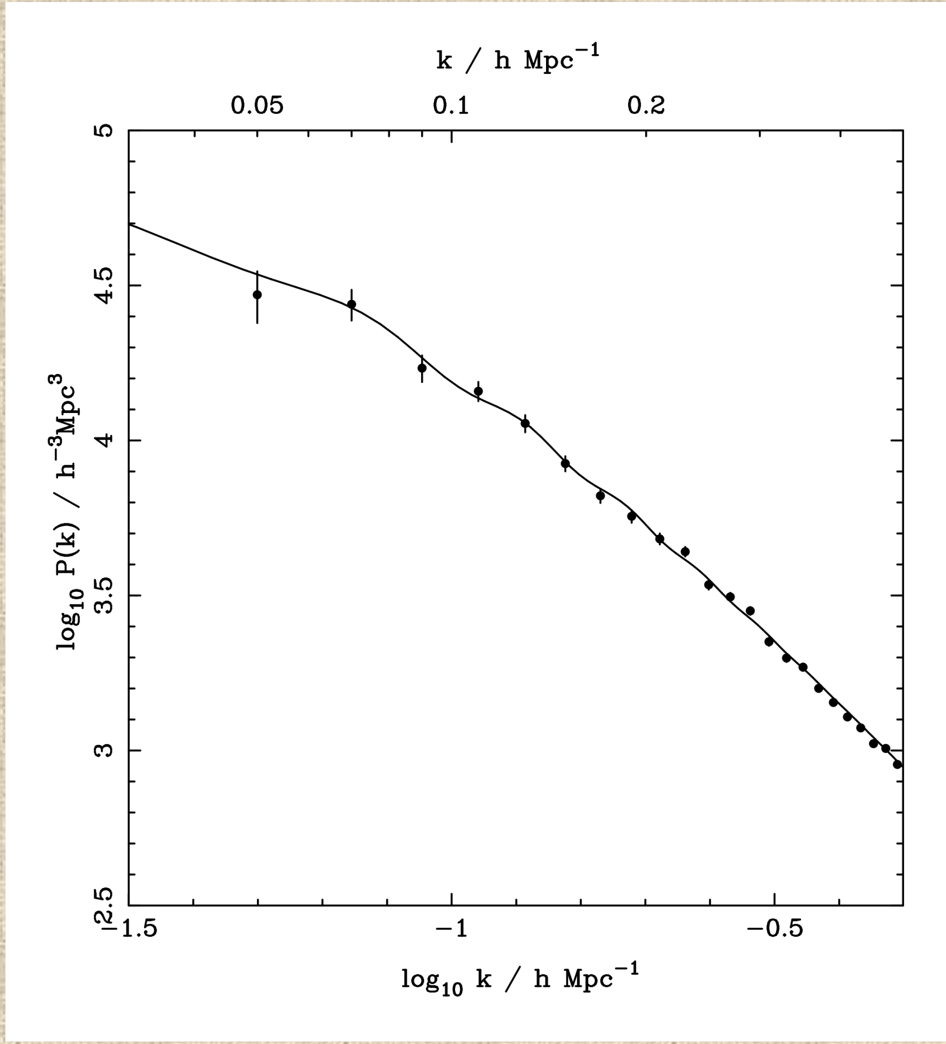
$$F(z) = f(z)\sigma_8^{mass}(z) = \sigma_8^{gal}(z)\beta(z)$$



- Percival & White 2009; White, Song & Percival 2009

Expected P(k) at <z>~0.8 from VIPERS

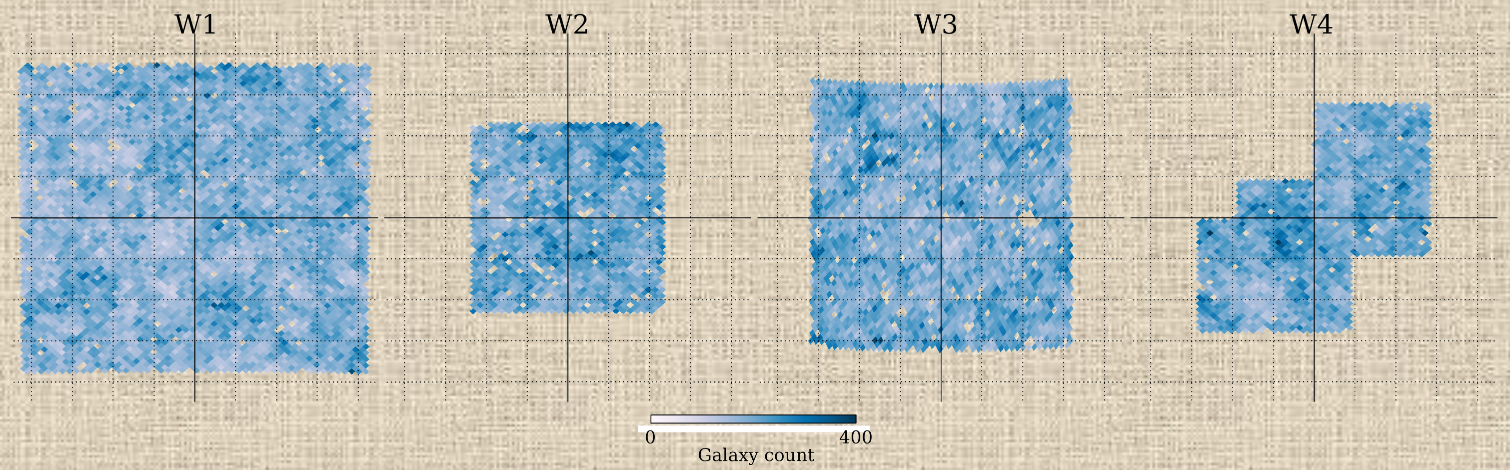
- Measure $\Omega_m h$ from shape of power spectrum
- BAO (baryon fraction, standard ruler? → Reconstruction – see Padmanabhan 2012)
- z-space distortions
- neutrino mass?
- large-scale bias vs galaxy properties
- …



(simulation by W. Percival)

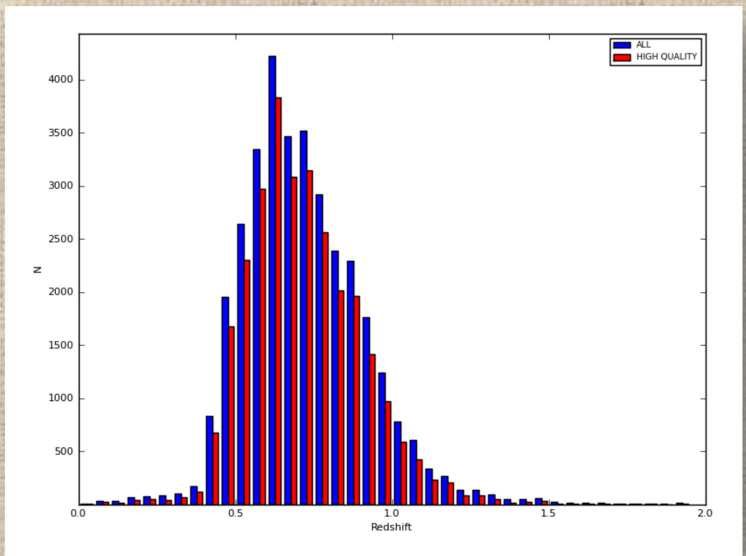
Early results using VIPERS: real-space galaxy P(k) at <z>~0.8 from the full CFHTLS-Wide data, "sliced" using VIPERS N(z) and color selection

B. Granett & VIPERS Team, MNRAS, in press, **arXiv 1112.0008**



CFHTLS-Wide:

- ~140 deg^2
- 5-bands (ugriz)
- 2.1 million galaxies



- VIPERS mag/color criteria work very well in selecting 0.5<z<1.2
- Characterize VIPERS parent sub-catalogue
- Accurate N(z) crucial for de-projection: provided by VIPERS
- Exploits currently largest available volume of CFHTLS-Wide areas
- Recent Cl angular Thomas

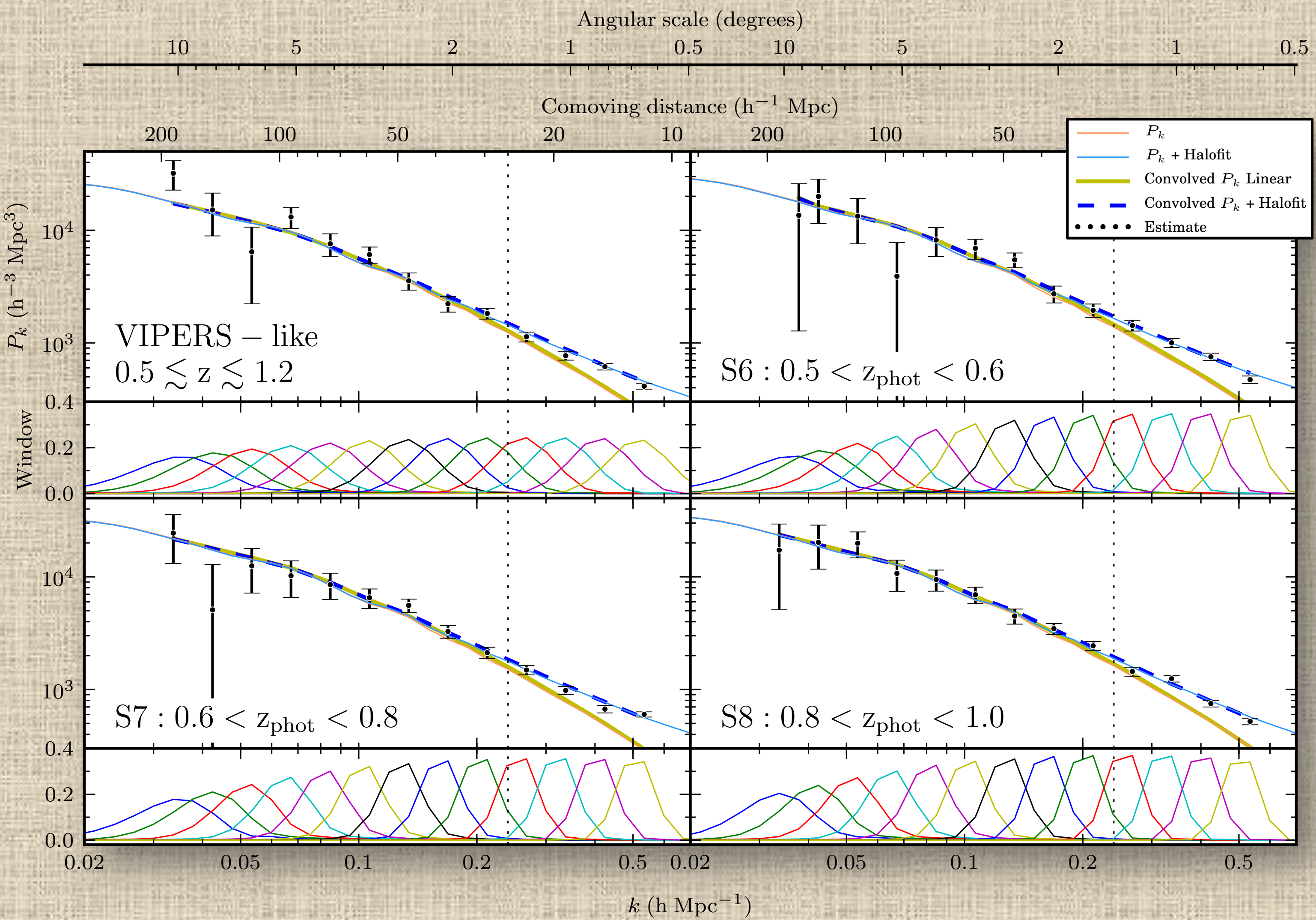
Real space P(k) at z~0.7 from CFHTLS-Wide + VIPERS N(z)

W1+W2+W3+W4

1) Cl spectrum using Tegmark 1997 quadratic estimator

2) Deconvolved following Efstathiou & Moody 2001

Complementary to recent Cl estimate at z~0.5 from SDSS LRGs (Thomas, Abdalla & Lahav 2011)



B. Granett, LG & VIPERS Team, MNRAS, in press - arXiv 1112.0008

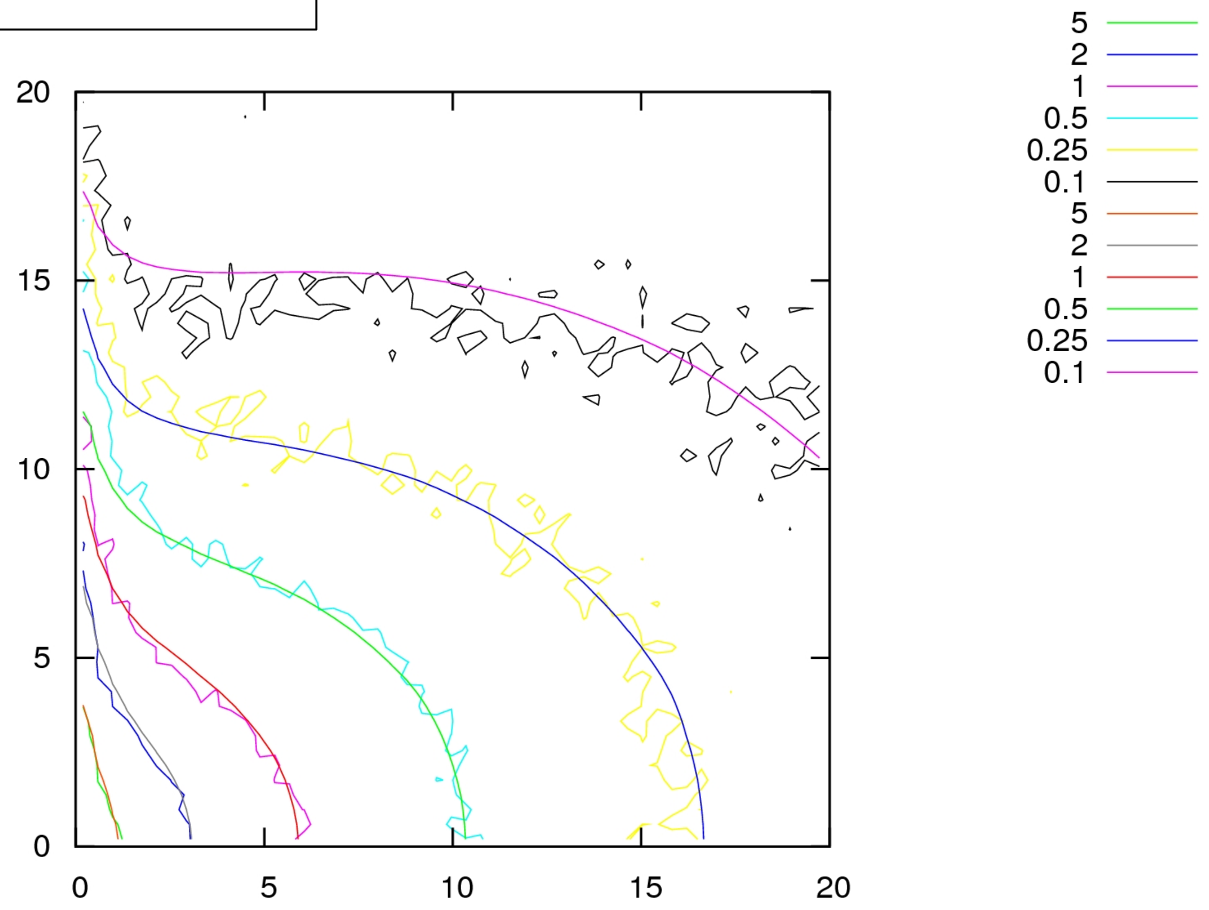
Xia, Granett, Viel et al., submitted to MNRAS: constraints on neutrino masses (preprint on arXiv)

Improving the tool: RSD in the precision cosmology era

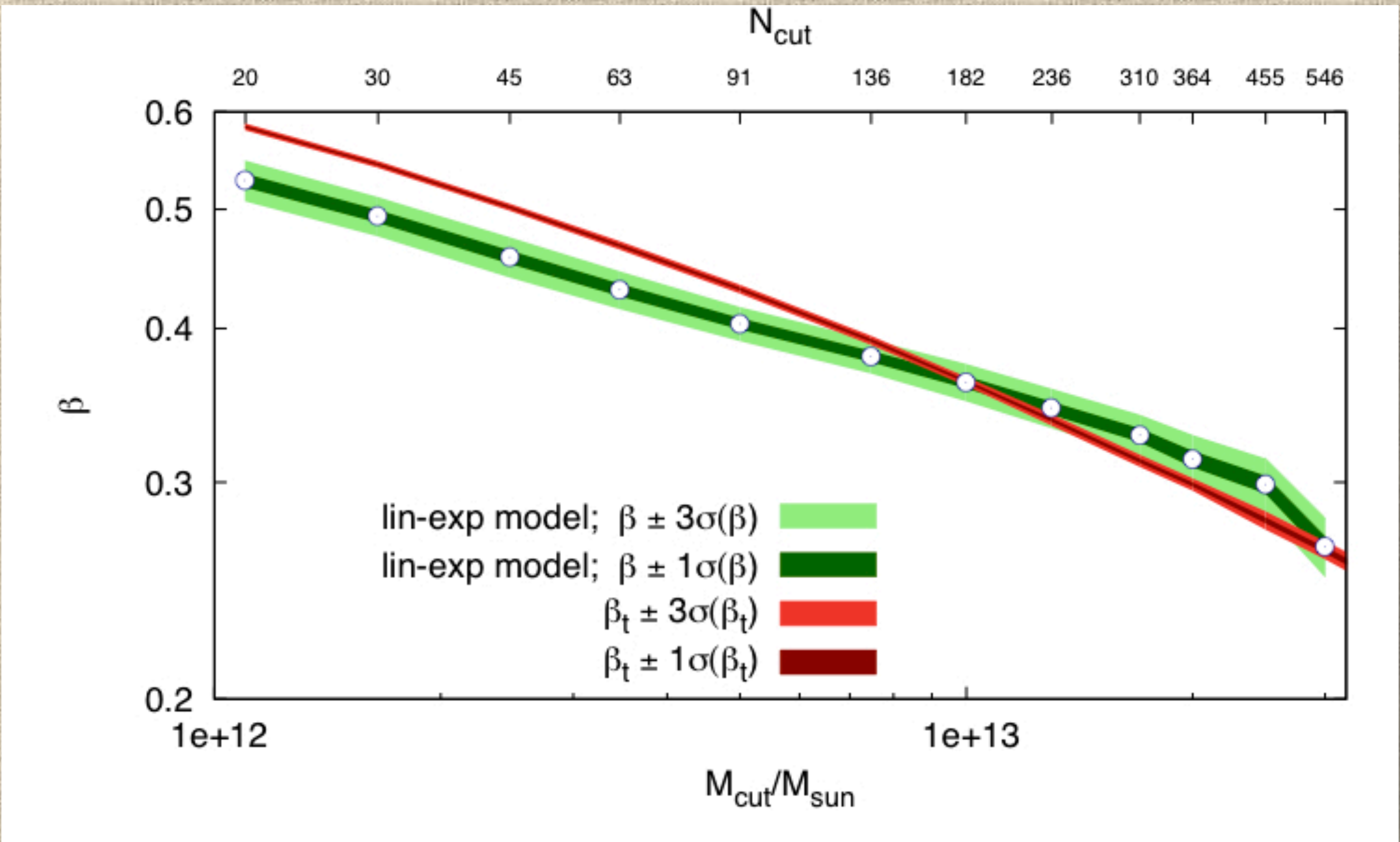
Kaiser/Hamilton linear redshift-distortion model

$$P(k_{||}, k_{\perp}) = P(k)\left(1 + \beta\mu^2\right)^2 D(k\mu\sigma_p).$$

$$D(k\mu\sigma_p) = \frac{1}{1 + (k\mu\sigma_p)^2/2}$$



Systematic errors in estimating β with classical linear model + exponential correction



Bianchi, LG, Branchini et al. 2012, arXiv:1203.1545

- Based on BASICC simulation halo catalogues (Angulo et al): 3 billion particles in a 1340 h^{-1} Mpc side box
- RESULT: ~5-10% systematic underestimate
- Hints that larger-mass halos do perform better (e.g. LRGs)
- See also Okumura & Jing 2011 using ratios of moments and Kwan et al. 2011
- Calls for improved description of RSD
- Much work ongoing (e.g. Kwan et al. 2011, Reid & White 2012, …)

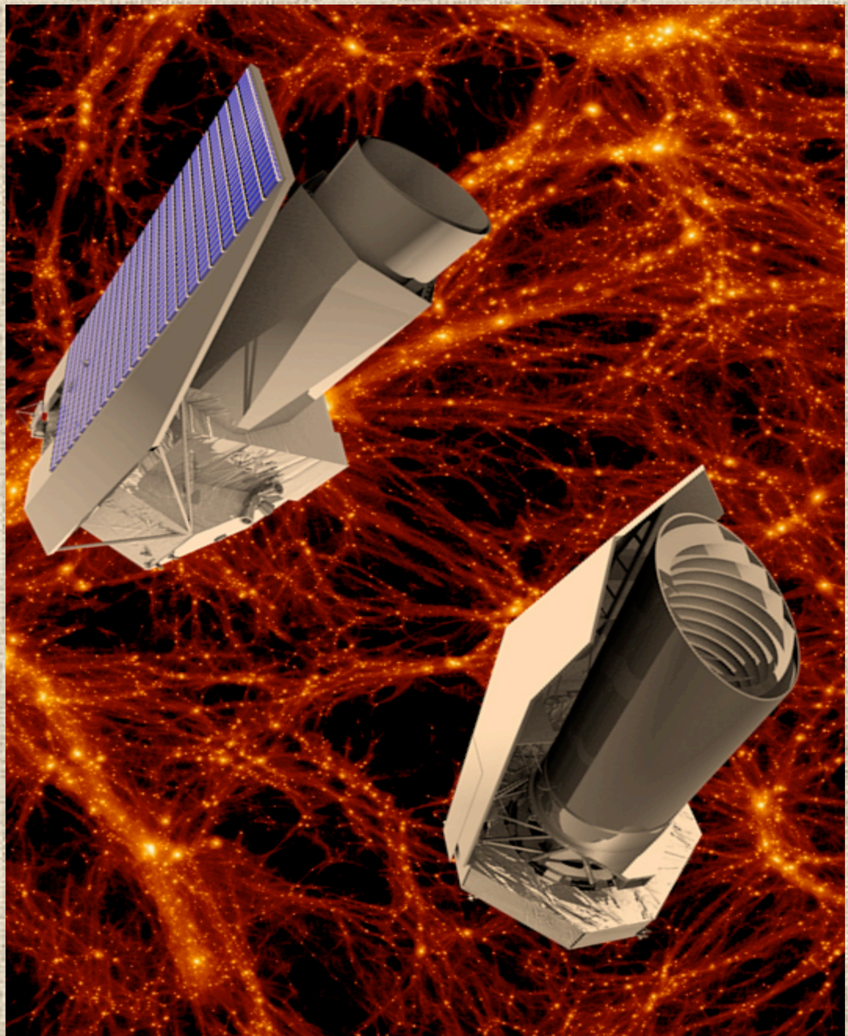
DARKLIGHT

- *"ILLUMINATING DARK ENERGY WITH THE NEXT GENERATION OF COSMOLOGICAL REDSHIFT SURVEYS"*
- **ERC Advanced Research grant, 5 years, 1.72 Meuro**
- **5 postdoc + 3 PhD positions**
- **Starting 1 May 2012**

- Improve modelling and estimators of clustering and redshift distortions, preparring for precision cosmology
- Apply them to ongoing new surveys (e.g. VIPERS)
- Combine with other probes of LSS (clusters of galaxies) and CMB measurements (Planck)

→ PREPARE FOR EUCLID…

EUCLID, an all-sky imaging and spectroscopic survey from space



APPROVED ON OCTOBER 4 FOR LAUNCH IN 2019

One satellite, two dark-energy probes:

- **Weak lensing**
- **Galaxy clustering**
- EUCLID Consortium now lead by Y. Mellier
- Merge of two earlier proposals: DUNE (A. Refregier) and SPACE (A. Cimatti)

→**NOTE: EUCLID IS NOT TWO SATELLITES !!!!**
☺

Euclid will image the

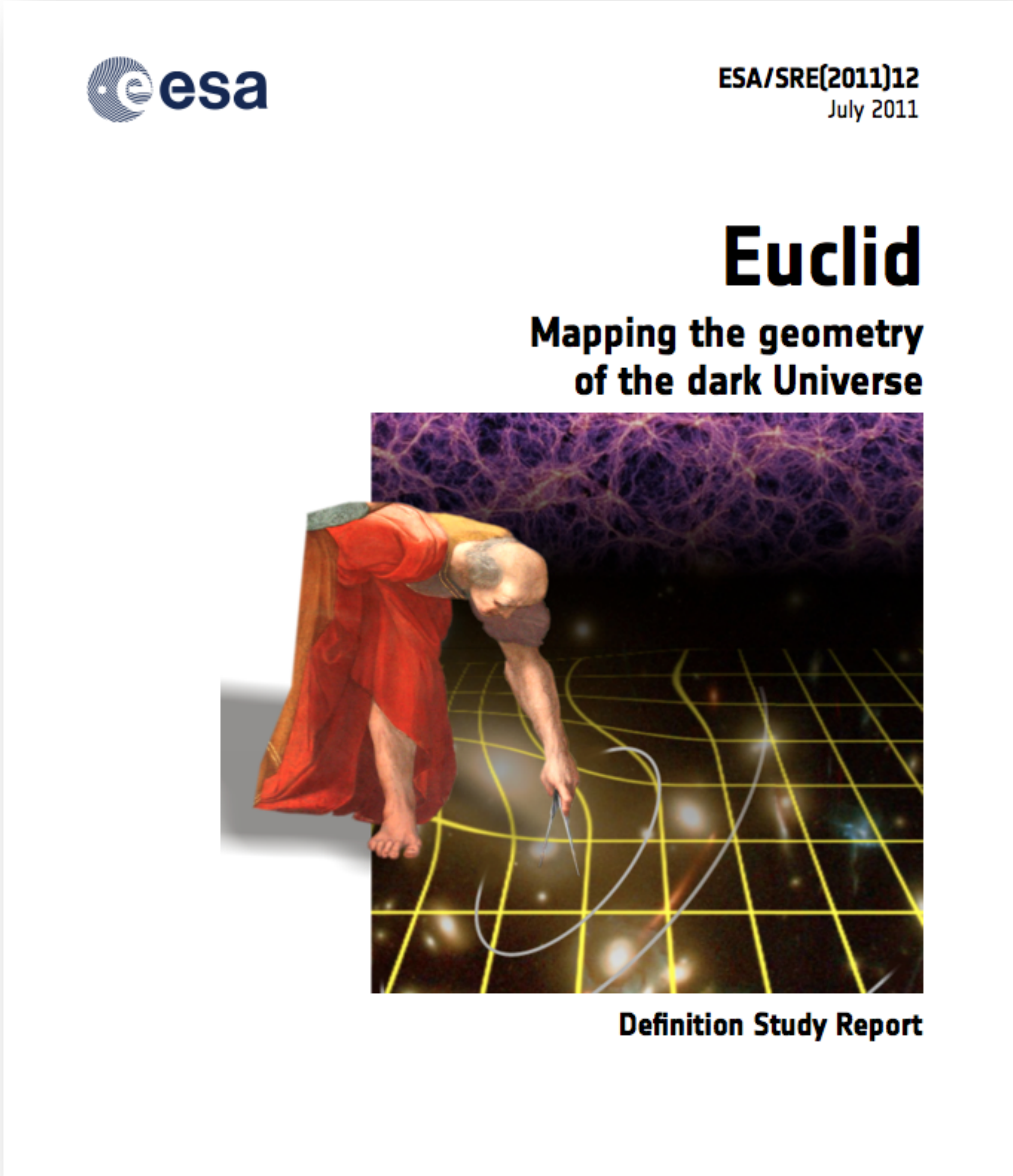
- best 1/3 of the sky (15000 deg^2)
- similar resolution at HST in optical
- NIR imaging in 3 filters
- Images for 2×10^9 galaxies

and carry out an unprecedented redshift survey with

- NIR spectra for 5×10^7 galaxies ($0.7<z<2$)

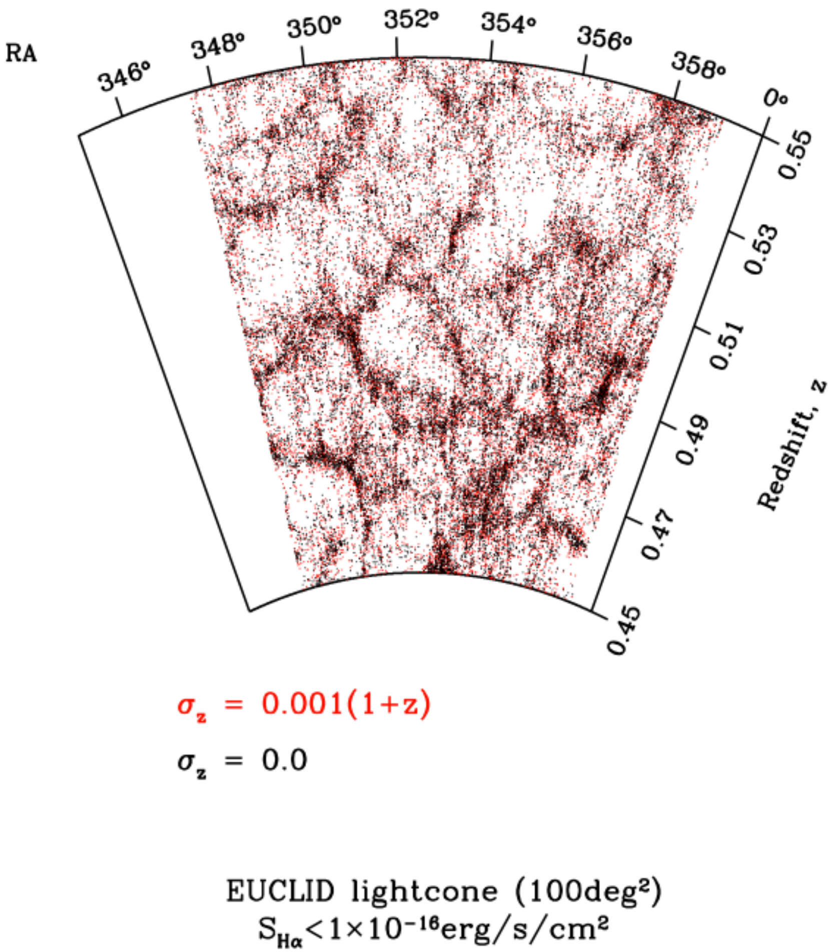
The Euclid "Red Book"

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#

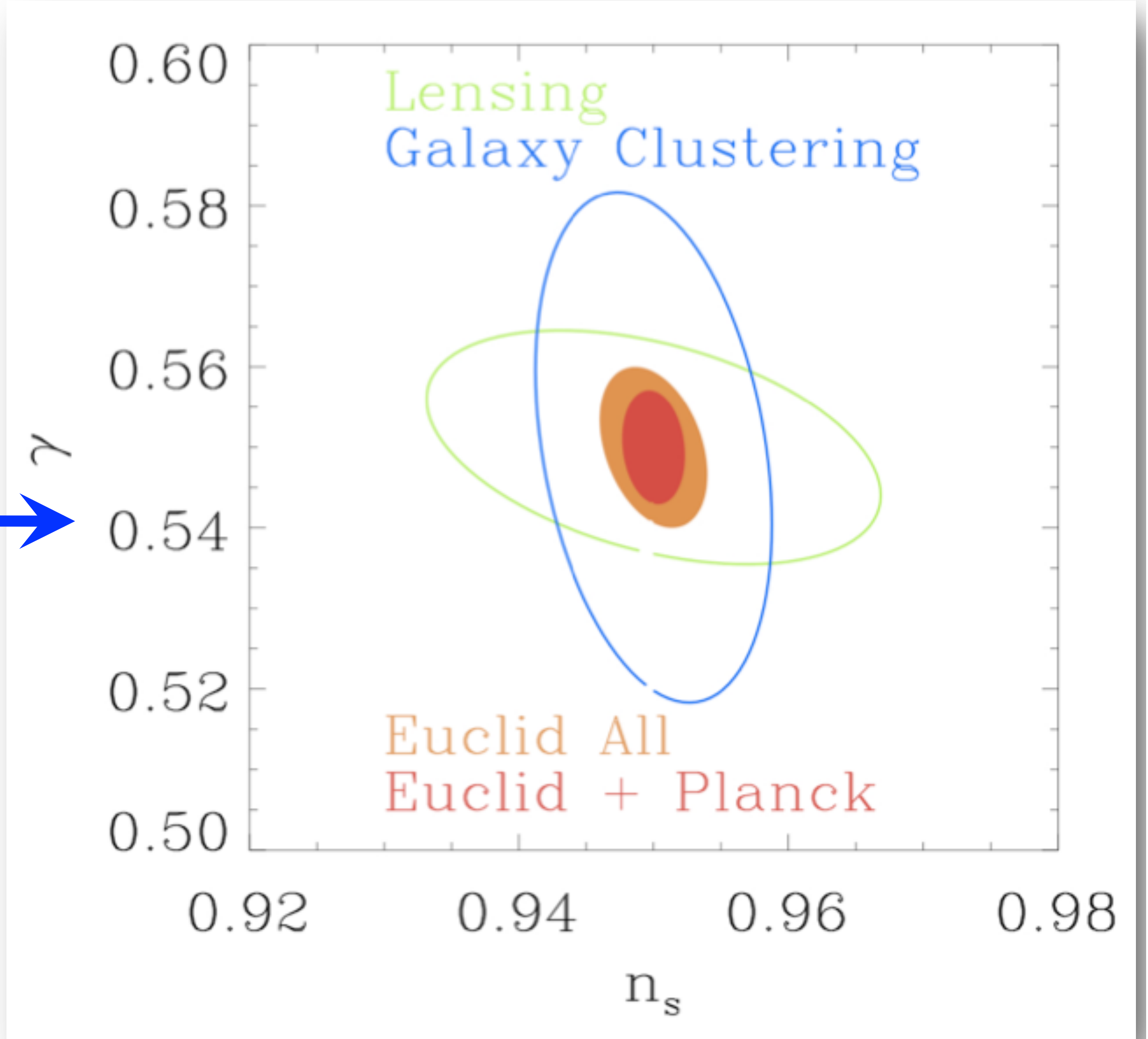


Growth with Euclid: RSD

- Redshift-space distortions map motions due to structure growth



(sims from Durham group)



Summary

- Explaining the origin of cosmic acceleration is plausibly the most compelling problem in cosmology: did Einstein have the last word on gravity?
- A brilliant future for galaxy redshift surveys: measure both w(z) and f(z) using BAOs/P(k) and z-distortions (plus clusters…) → test dark energy vs modified gravity
- A renaissance for redshift-space distortions: not considered in this context before 2008, now accepted as standard "dark energy probe" (EUCLID)

1) RSD: Improving the data

- Exciting z-distortions results from WiggleZ and BOSS, originally fully focused on BAO
- VIPERS: a 2dFGRS at z~0.8, ~100,000 highly-sampled redshifts; early measurement of real-space P(k) in combination with CFHTLS
- EUCLID is approved and plans to couple a massive (slitless) redshift survey with a high-resolution imaging survey, to combine galaxy clustering and weak lensing (launch 2019)

2) RSD: Improving the estimators

- Need to go beyond Kaiser-Hamilton formalism, if we aim at precision cosmology on f(z)
- Do simultaneous estimate of BAO and z-distortions (including Alcock-Paczynski, see Simpson & Peacock 2010)
- A lot of work ongoing in the community, exciting times ahead
- **DARKLIGHT**: an ERC-supported program to bring estimators to the level of the new data