Redshift distortions as observational test of cosmic acceleration

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GGI, Firenze, 4th march 2009

Cosmic acceleration: a story with two sides …

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

Cosmic acceleration: a story with two sides …

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

Add dark energy
==> w(z)

Cosmic acceleration: a story with two sides …

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

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

Modify gravity theory

The equation of state is not the end of the story…

In fact, cosmic acceleration can be explained not only by an additional dark energy fluid but also by changing the theory of gravity as done in $f(R)$ theories [e.g.Copeland et al. 2006], multi-dimensional “braneworld” models [Dvali et al. 2000], back-reaction of super/sub-horizon perturbation [e.g. Kolb, Matarrese and Riotto 2006], or also by invoking non-minimal coupling between Dark Matter and Dark Energy [e.g. Di Porto & Amendola 2008].

--> Can we distinguish true dark energy from modified gravity, observationally?

Most of these models are degenerate, in the sense that they predict the same expansion history $H(z)$ as Dark Energy models.

How can we break this degeneracy ?

Beyond the cosmological principle: the inhomogeneous universe.

Cosmic structures grow via gravitational instability from small fluctuations in the primordial mass density field. The growth of density fluctuations $\delta=\delta\rho/\rho$ in the expanding Universe, for low-amplitude perturbations, this is described as

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

Which, in the linear regime, has a growing solution: $\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$

from which we define a *growth rate* $f = \frac{d\ln D}{d\ln a}$

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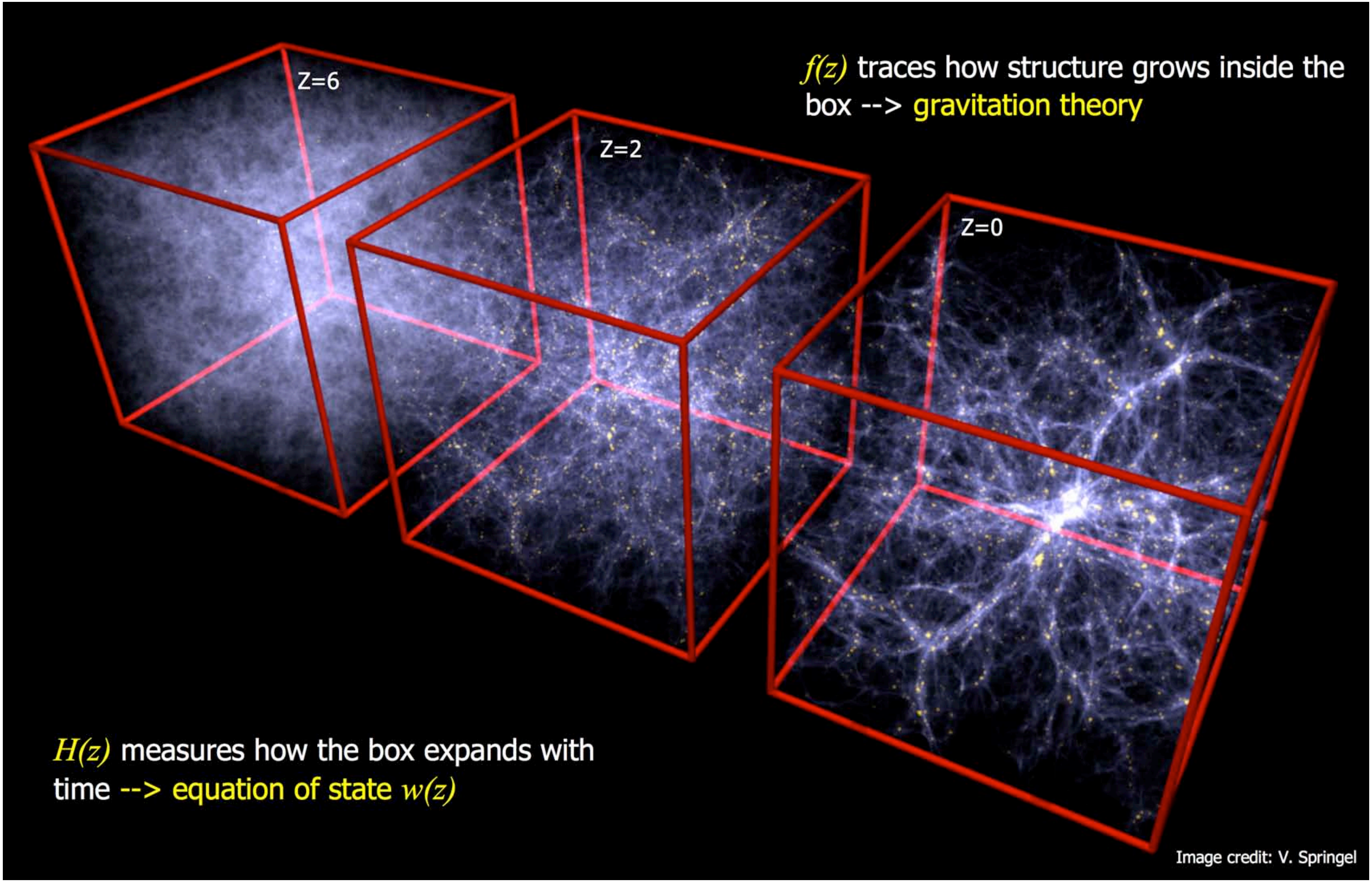
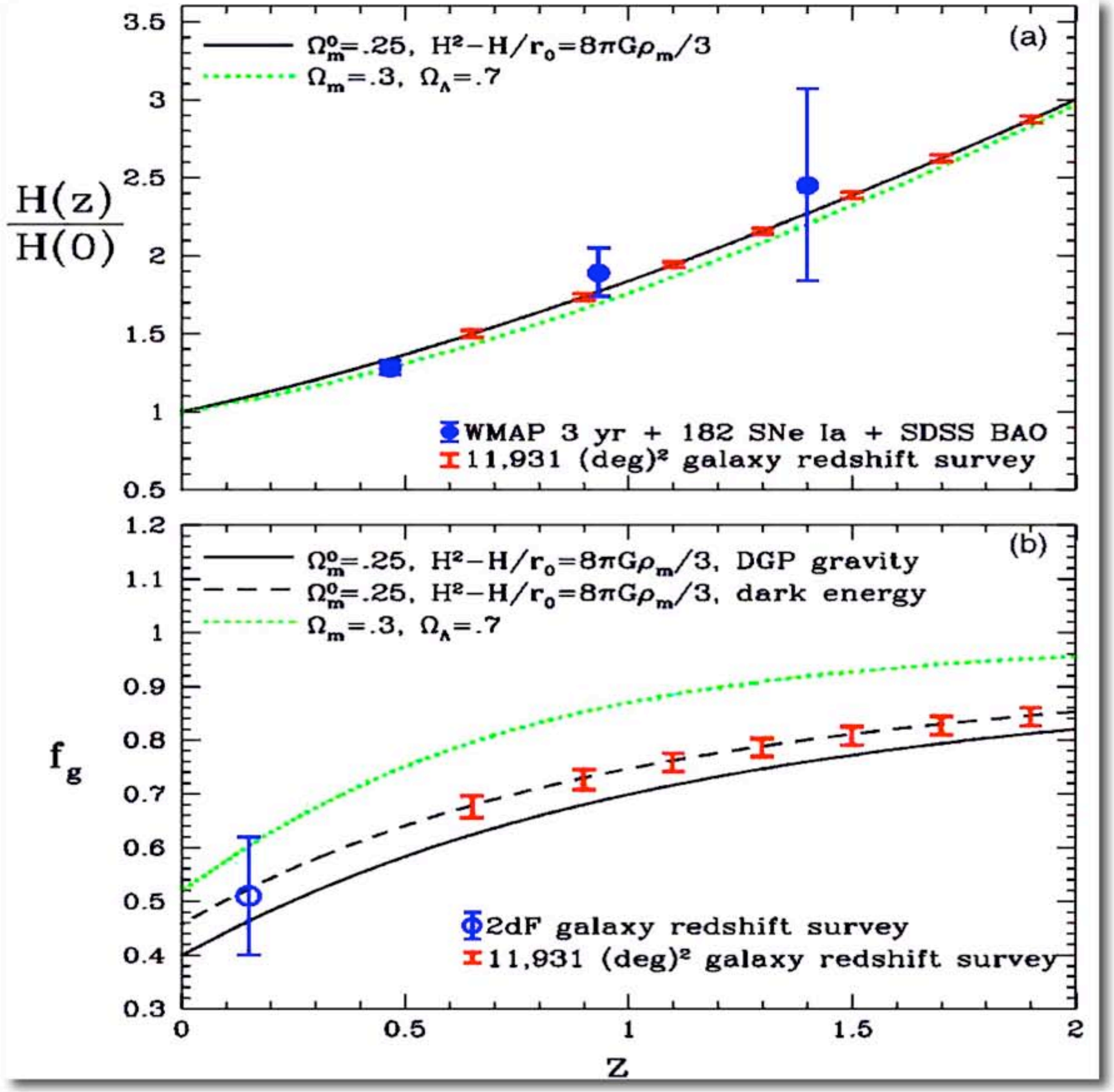
→ The growth equation (and thus the growth rate) depends not only on the expansion history $H(t)$ (and thus on w) but also on the underlying gravity theory (e.g. Linder 2005).



Z=6
Z=2
Z=0
f(z) traces how structure grows inside the box --> gravitation theory
H(z) measures how the box expands with time --> equation of state w(z)
Image credit: V. Springel

Measurements of the growth rate *f(z)* as a function of redshift (time) break the degeneracy between models with same effective expansion history [thus same *w(z)*], but completely different physics

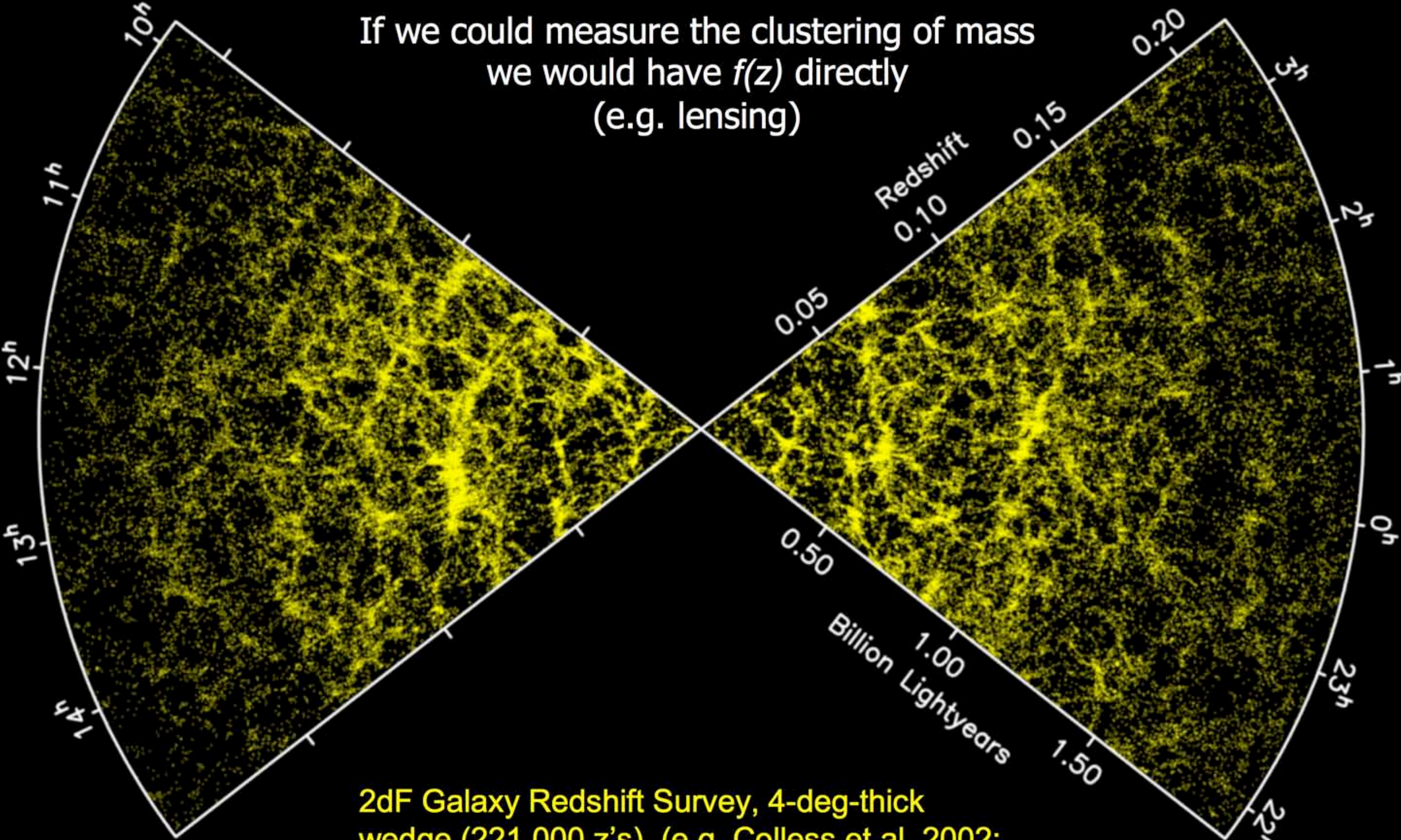


Wang 2008

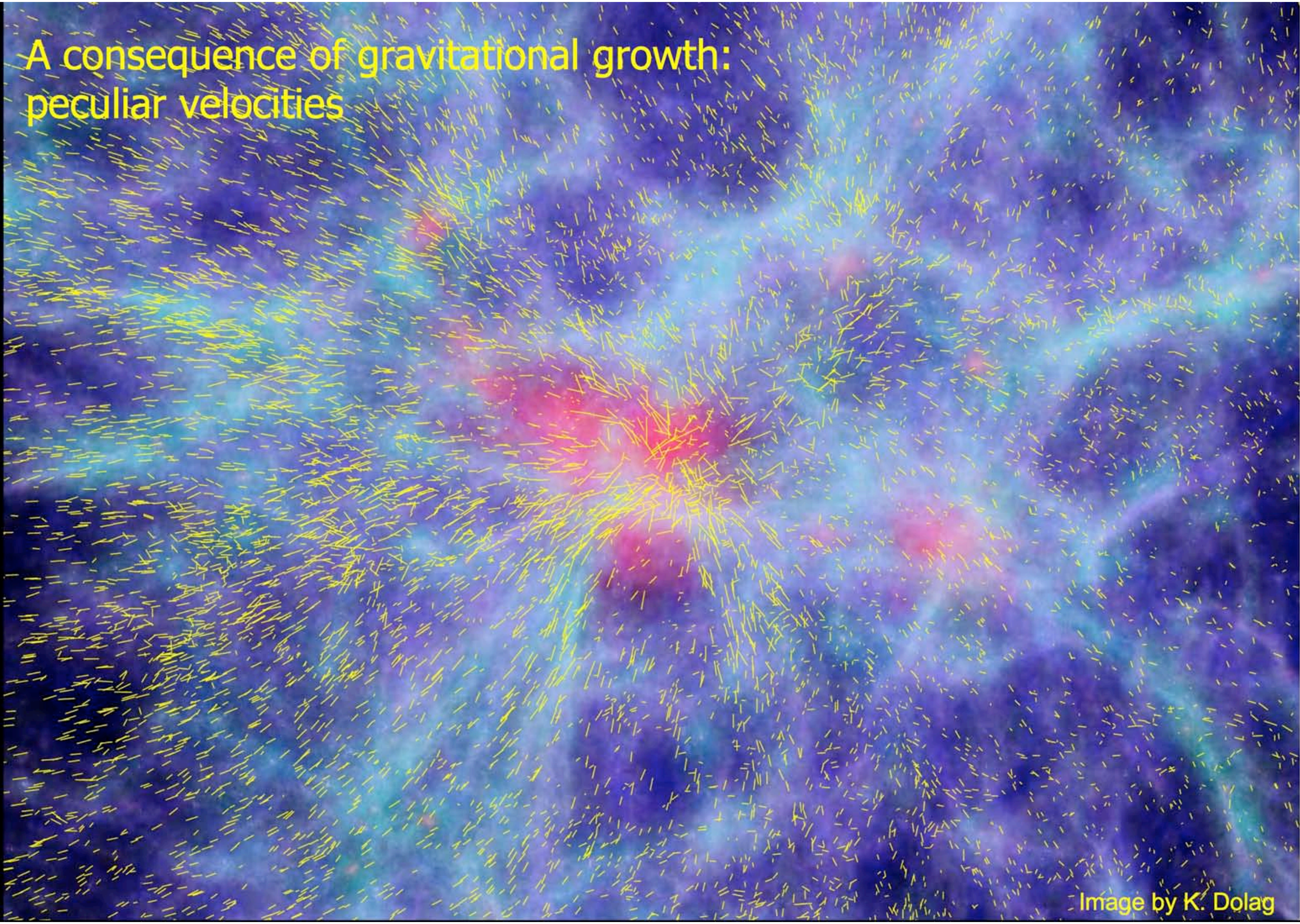
How do we measure *f(z)*?

f(z) is imprinted in the observed large-scale structure of the Universe

If we could measure the clustering of mass
we would have *f(z)* directly
(e.g. lensing)



2dF Galaxy Redshift Survey, 4-deg-thick
wedge (221,000 z's), (e.g. Colless et al. 2002;
Cole et al. 2005)


A consequence of gravitational growth:
peculiar velocities
Image by K. Dolag

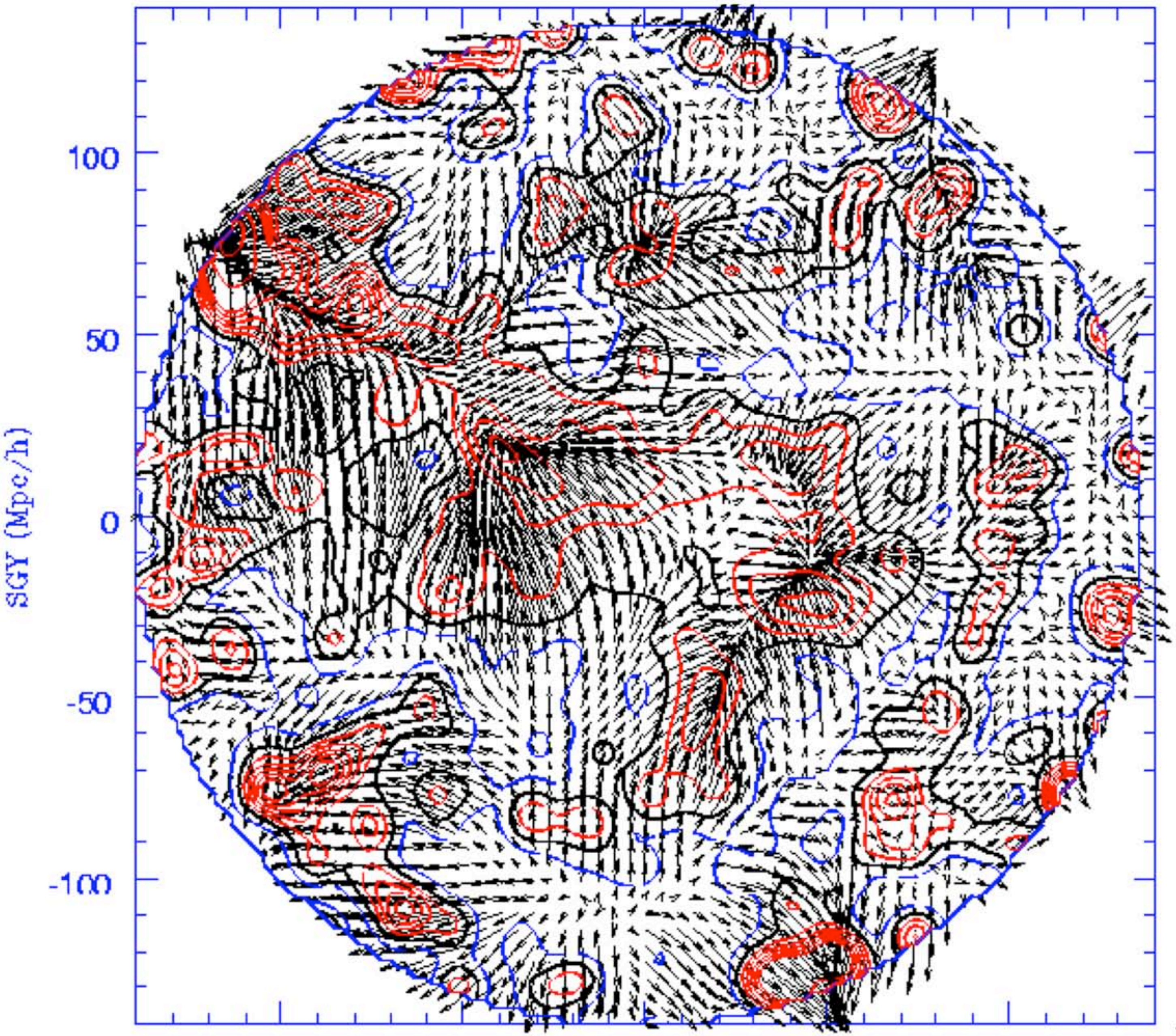
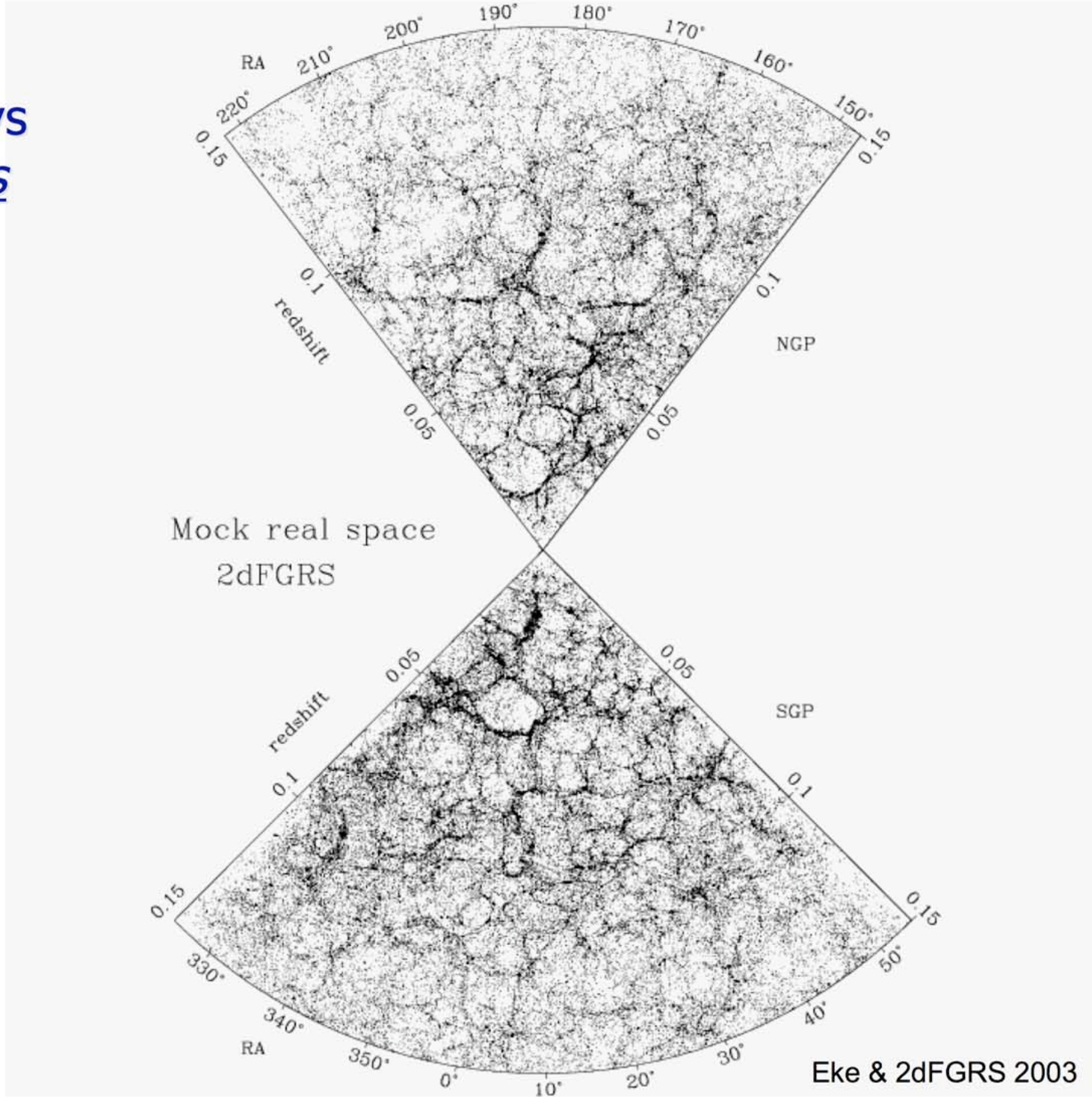


Image credit:

E. Branchini et al. 1999

Peculiar velocities manifest themselves in galaxy surveys as *redshift-space distortions*

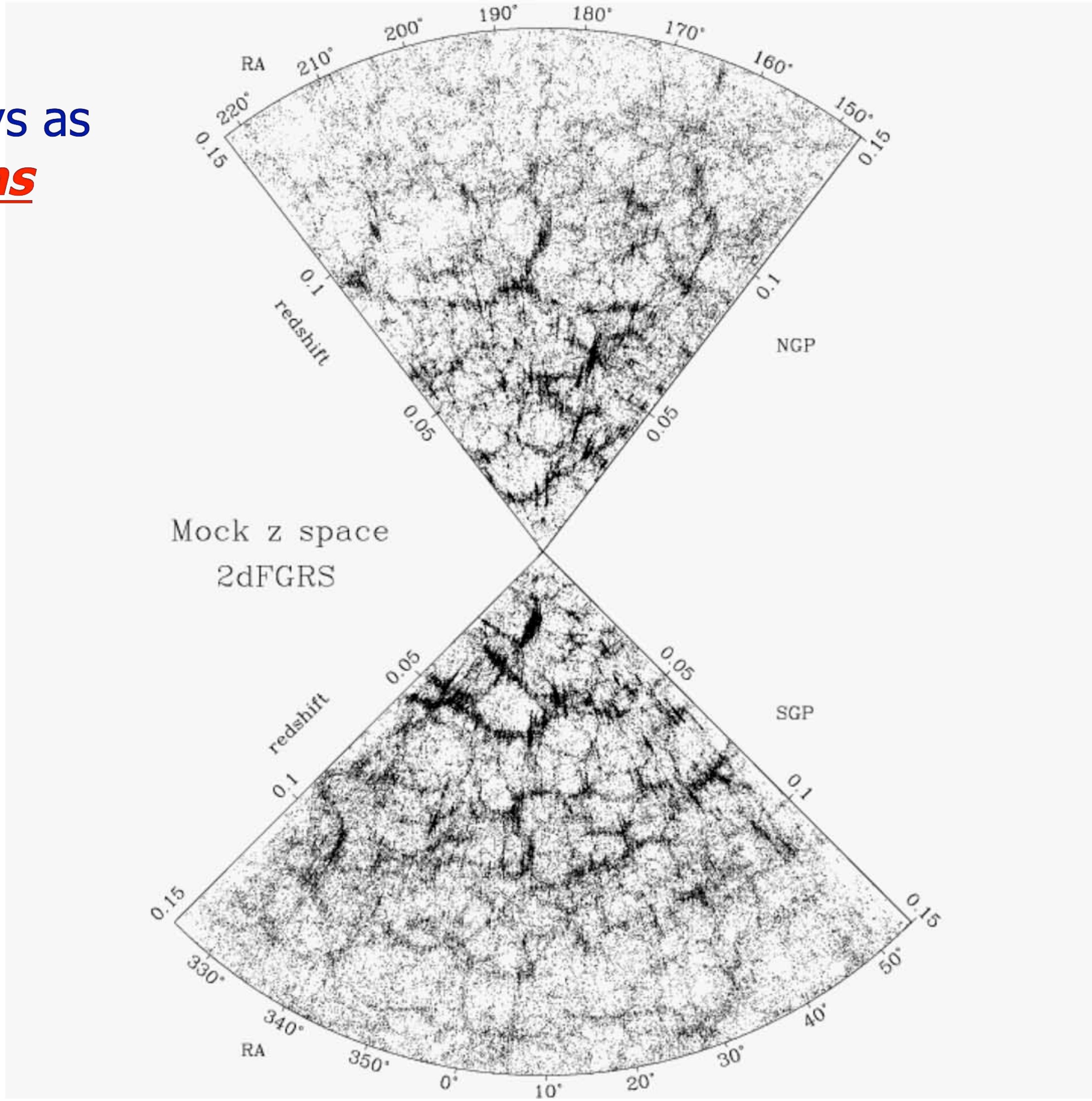
real space



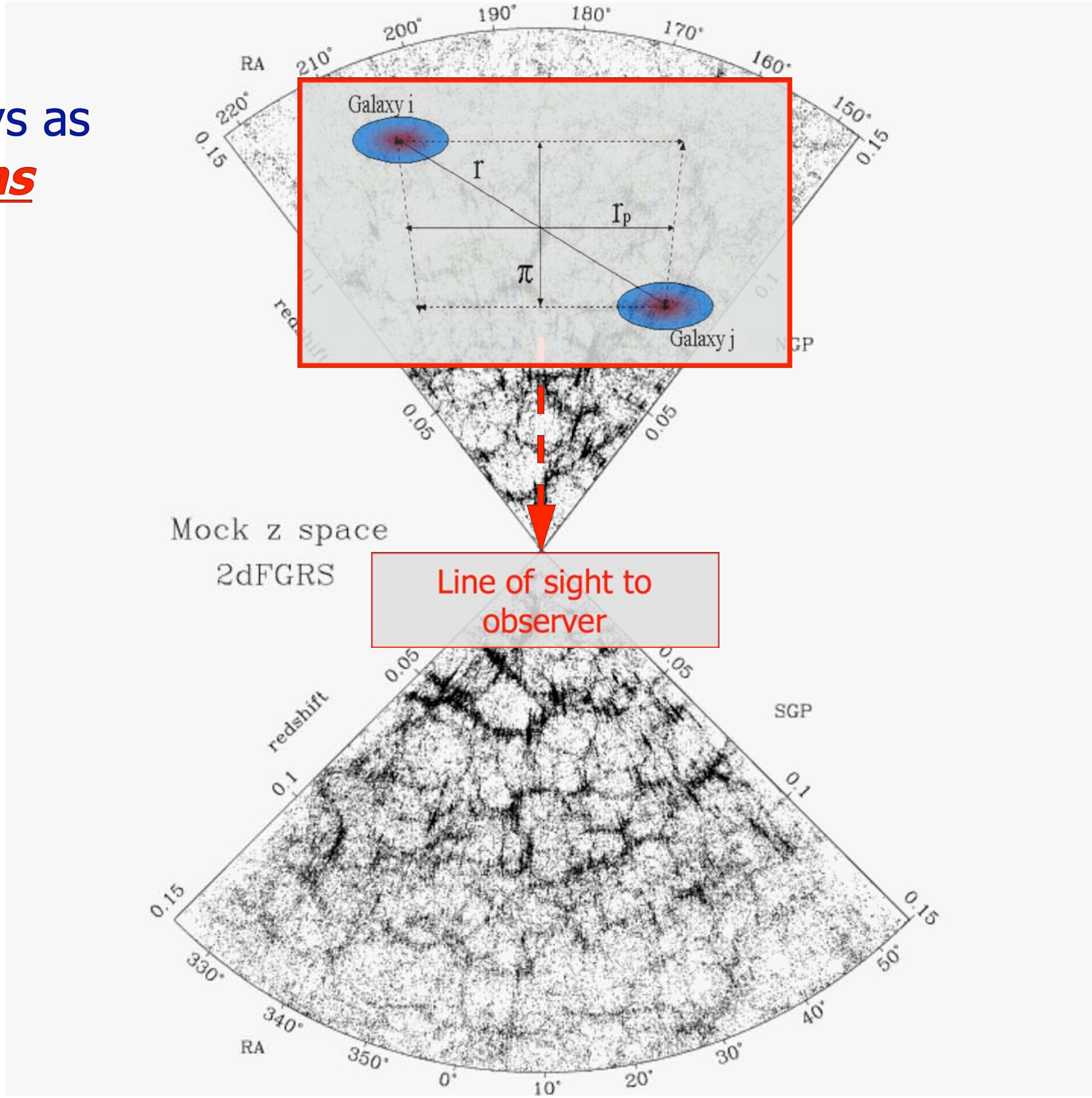
Eke & 2dFGRS 2003

Peculiar velocities manifest themselves in galaxy surveys as ***redshift-space distortions***

redshift space

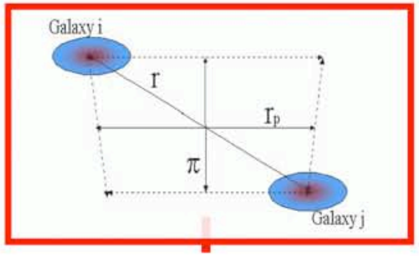


Peculiar velocities manifest themselves in galaxy surveys as ***redshift-space distortions***

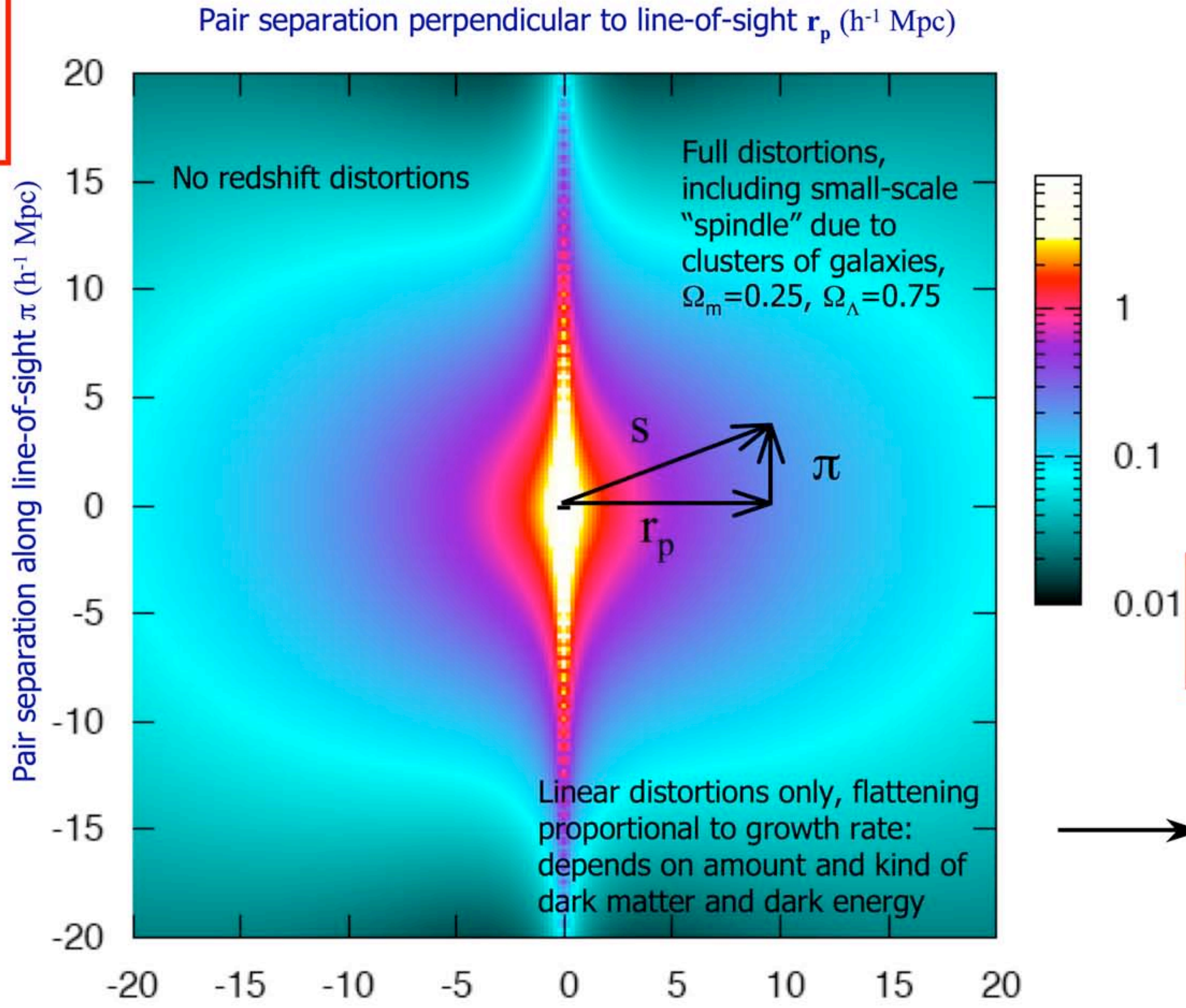


redshift space

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



Line of sight to observer



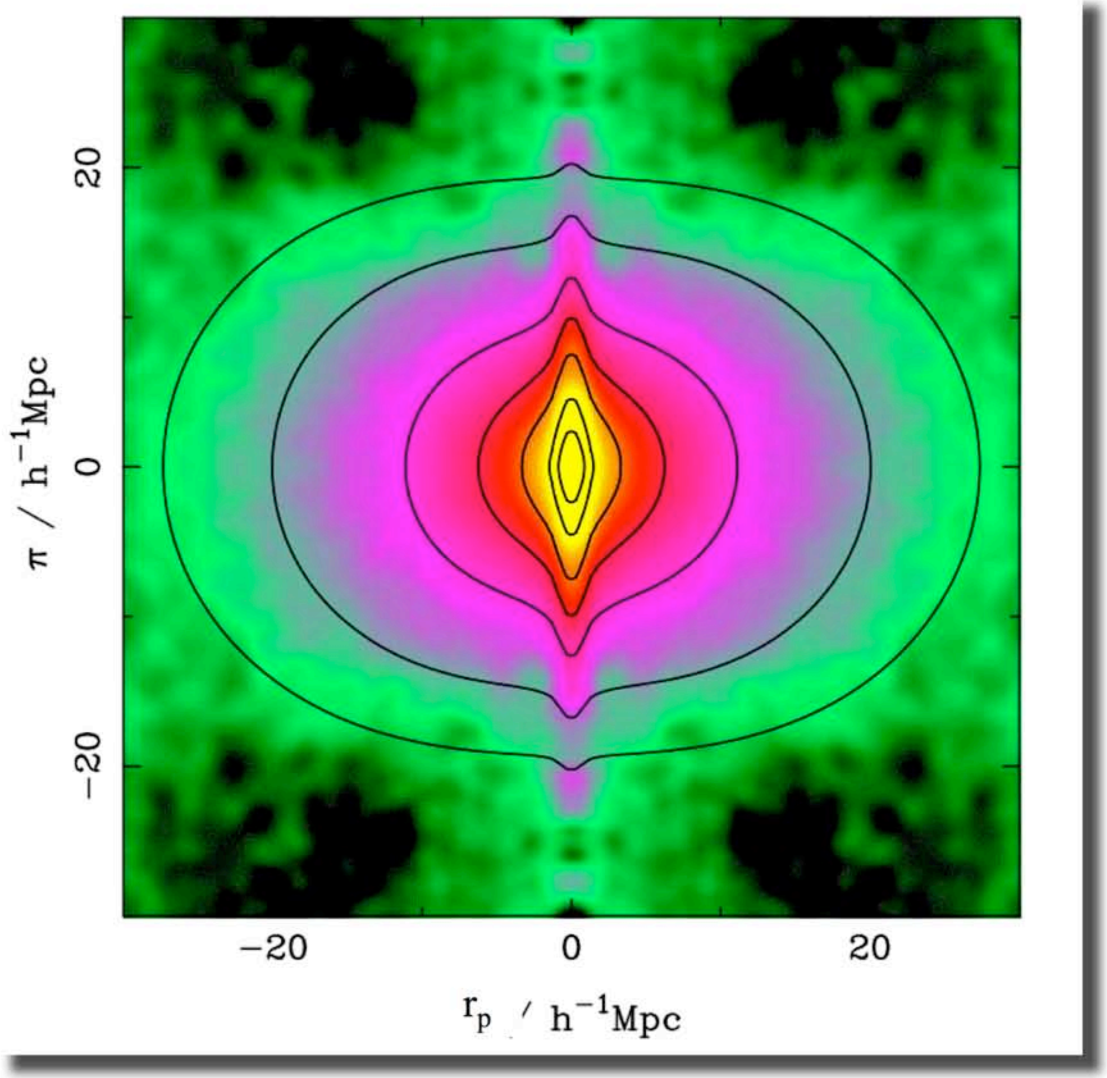
$f = b_L\,\beta$

Compression parameter β

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

2dFGRS, z~0.1

Peacock et al. 2001,
Hawkins et al. 2003



Compression parameter β =0.49±0.09

$$f = b_L \beta$$

→ USE REDSHIFT-SPACE DISTORTIONS AT DIFFERENT REDSHIFTS TO TRACE $f(z)$

A program to understand accuracy of mesurements of $f(z)$ from z-distortions: How well can we measure β from real surveys?

(with Branchini, Guzzo, Marulli & Pierleoni – M. Pierleoni, 2006, Master Thesis, Univ. of Bologna; Branchini et al. 2009, in preparation).

Use numerical simulations to test:

1. Performances of different estimators (multipole ratios, Q-statistics, direct fit) under realistic deep-survey conditions
2. Details of distortion model: which $\xi(r)$? (power-law, de-projected, theoretical model?)
3. Biases due to non-linear distortions (fitting range, small-scale weight, sparse sampling)
4. Role of geometrical distortions (Alcock-Paczynski effect)
5. Application to real data: VVDS-Wide → fully realistic mock samples (including survey selection, observing strategy, realistic Poisson noise and cosmic variance) – with Blaizot, Meneux et al.

→ Well-calibrated scaling formula for error on β as a function of survey parameters

How is actually β measured from the observed $\xi(r_p,\pi)$?

A natural way for this circularly (a)symmetric problem is to decompose $\xi(s)$ in spherical harmonics (e.g. Hamilton 1997)

$$\xi(r_p,\pi) = \xi_0(s)P_0(\mu) + \xi_2(s)P_2(\mu) + \xi_4(s)P_4(\mu)$$

where P_n are *Legendre polynomials* and the moments $\xi_n(s)$ are given by

$$\xi_0(s) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right)\xi(r)\,,$$

$$\xi_2(s) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2\right)\left[\xi(r) - \bar{\xi}(r)\right]\,,$$

$$\xi_4(s) = \frac{8}{35}\beta^2\left[\xi(r) + \frac{5}{2}\bar{\xi}(r) - \frac{7}{2}\,\bar{\bar{\xi}}(r)\right]\,;$$

$$\bar{\xi}(r) \equiv 3r^{-3}\int_0^r \xi(r')r'^2 dr'\,,$$

$$\bar{\bar{\xi}}(r) \equiv 5r^{-5}\int_0^r \xi(r')r'^4 dr'\,.$$

In general, β can be extracted in different ways from combinations of the moments or using the full relationship:

a) Ratio of redshift to real-space functions

$$\frac{\xi(s)}{\xi(r)} = \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right)$$

b) Quadrupole to monopole ratio [requires power-law assumption for ξ(r)]

$$\frac{\xi_2(s)}{\xi_0(s)} = \frac{\gamma - 3}{\gamma} \frac{\frac{4}{3}\beta + \frac{4}{7}\beta^2}{1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2} .$$

c) Q-statistics [totally independent from functional form of ξ(r)]

$$Q(s) = \frac{\frac{4}{3}\beta + \frac{4}{7}\beta^2}{1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2} = \frac{\xi(s)}{\xi_0(s) - \frac{3}{s^3}\int_0^s \xi_0(s')s'^2 ds}$$

d) Full model in terms of moments of ξ(r) and Legendre polynomials

These tests show that under our typical observing conditions the best (least biased) results are obtained through a fit the **full 2D model,** constructed as the convolution of the linearly-distorted $\xi_L(s)$

$$\xi_L(r_p,\pi) = \xi_0(s)P_0(\mu) + \xi_2(s)P_2(\mu) + \xi_4(s)P_4(\mu)$$

with the distribution of non-linear pairwise velocities, well described by an exponential (Peebles 1980)

$$f(v) = \left(\sigma_{12}\sqrt{2}\right)^{-1} \exp\left\{-\sqrt{2}|v|/\sigma_{12}\right\}$$

The overall model for $\xi(r_p,\pi)$ is thus given by

$$\xi(r_p,\pi) = \int_{-\infty}^{\infty} \xi_L\left[r_p, \pi - \frac{v(1+z)}{H(z)}\right] f(v)dv$$

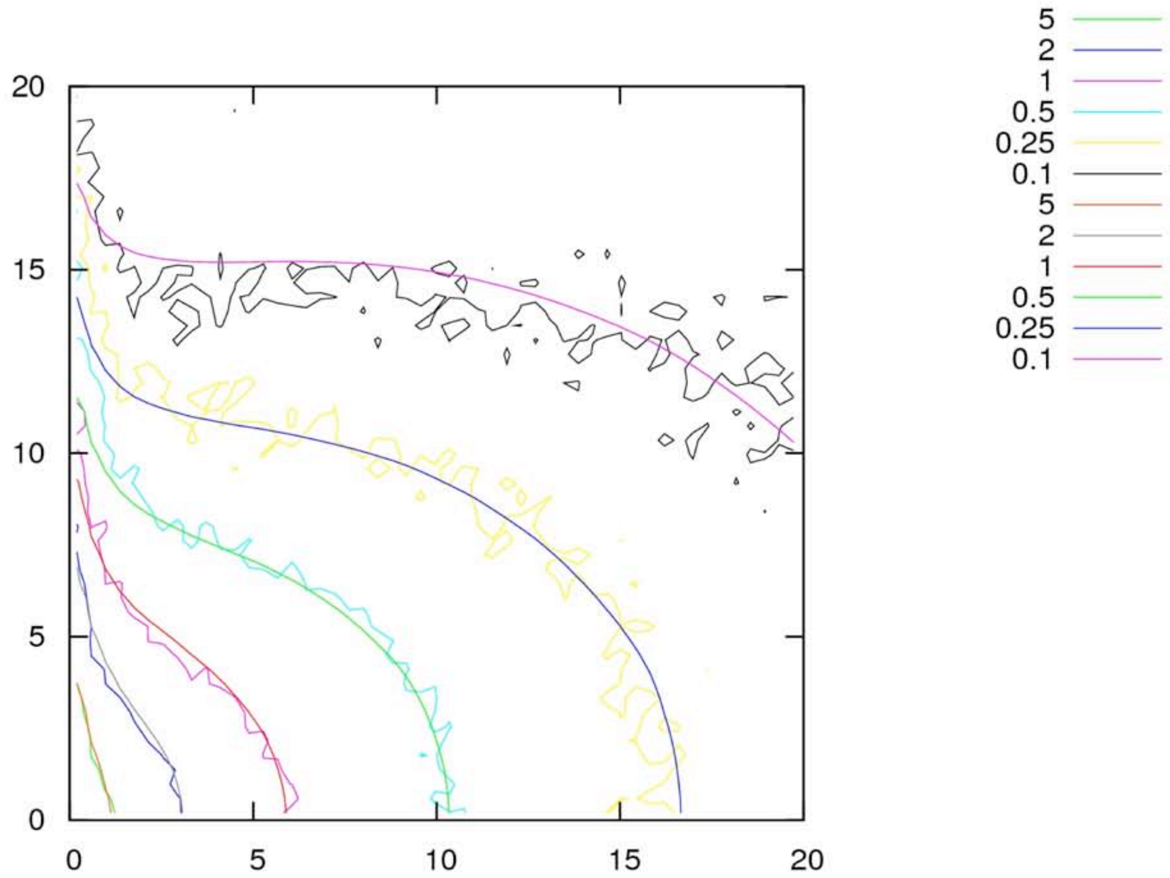
Here the real-space $\xi(r)$ is obtained from the projected (distortion-free) function

$$w_p(r_p) \equiv 2\int_0^{\infty} \xi(r_p,\pi)d\pi$$

as

$$\xi(r) = \frac{1}{\pi}\int_0^{\infty} \frac{dw_p}{dr_p} \frac{dr_p}{\left(r_p^2 - r^2\right)}$$

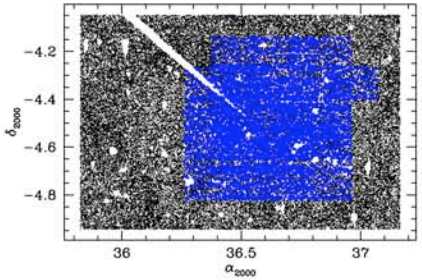
Fit of observed $\xi(r_p,\pi)$ with full redshift-distortion model



CAN WE MEASURE THE GROWTH RATE AT LARGE REDSHIFTS? THE VVDS SURVEY

The VVDS (Le Fevre et al. 2005, 2006) has so far produced a large series of results on galaxy evolution and small-scale clustering from its *Deep* part to I_{AB}=24 (F02 field). The *VVDS-Wide* survey was conceived to complementarily sample LSS at z~1 on scales >> 10/h Mpc. Here blue points correspond to measured redshifts.

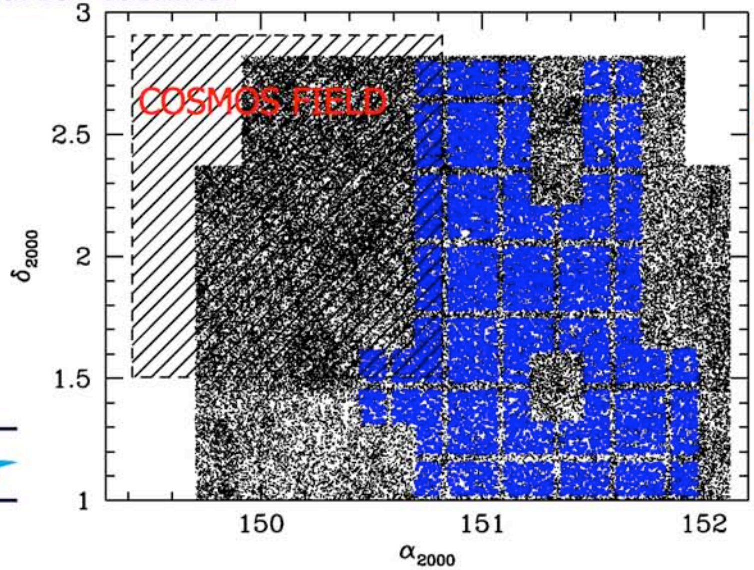
F02-Deep



~11,000 spectra (I_{AB}<24)

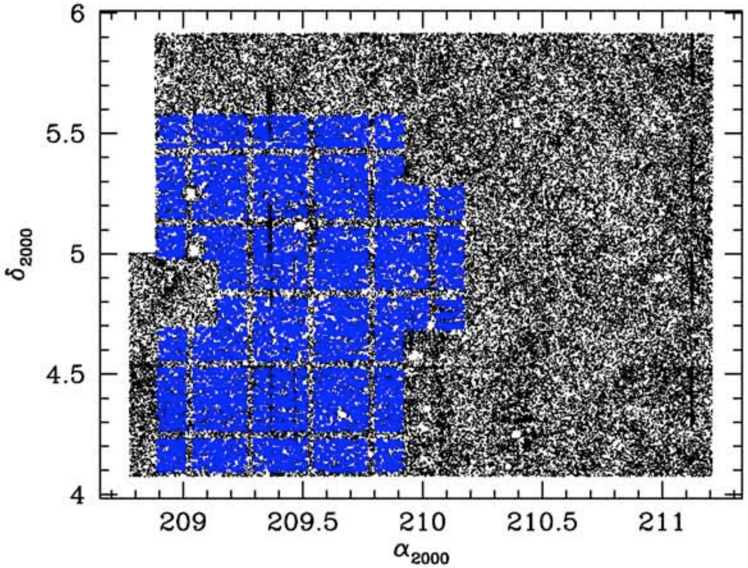
8322 z's over ~0.5 deg²

F10-Wide



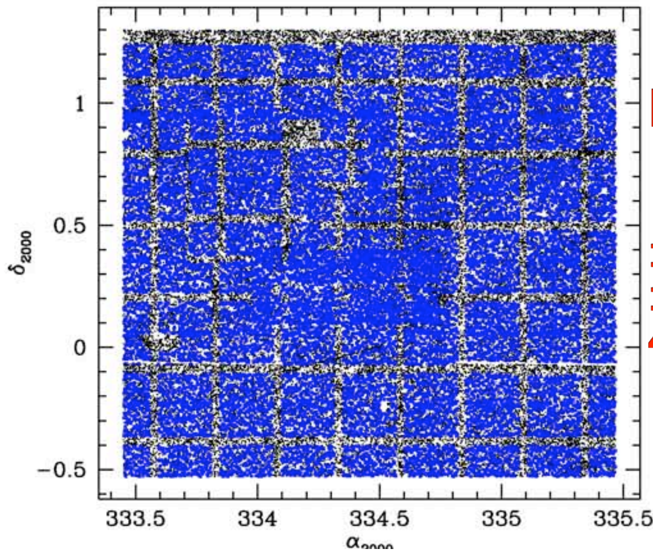
5984 spectra

F14-Wide



8455 spectra

F22-Wide



15,000 spectra
11,400 z's
4 deg²

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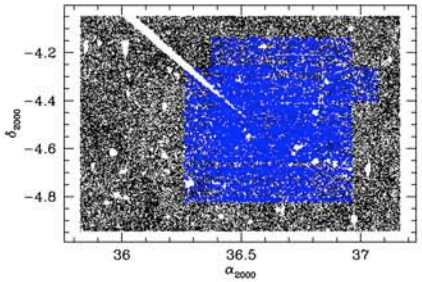
F02-Deep



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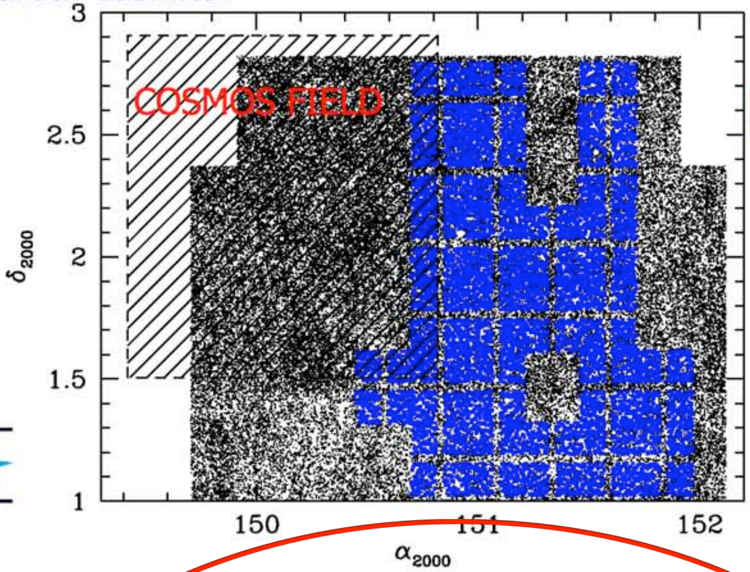
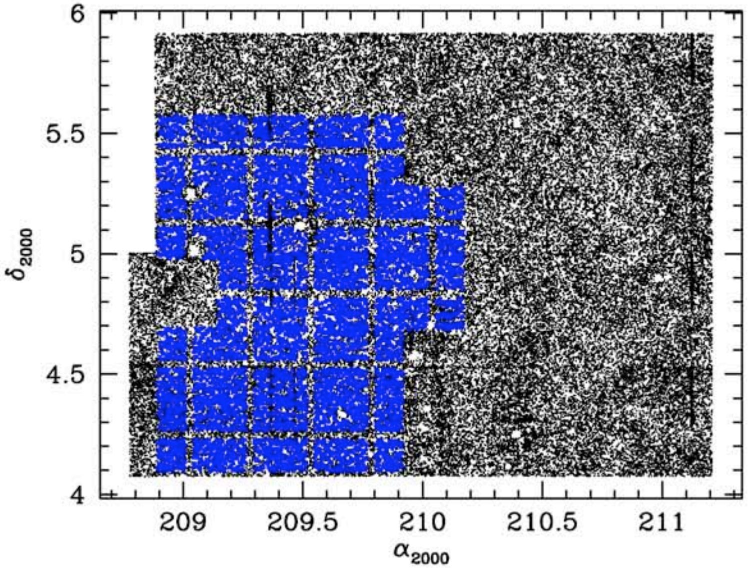


F10-Wide

5984 spectra

F14-Wide



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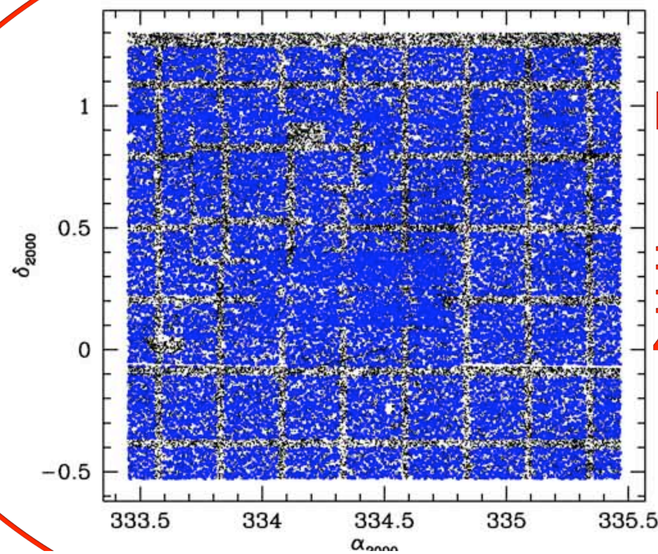
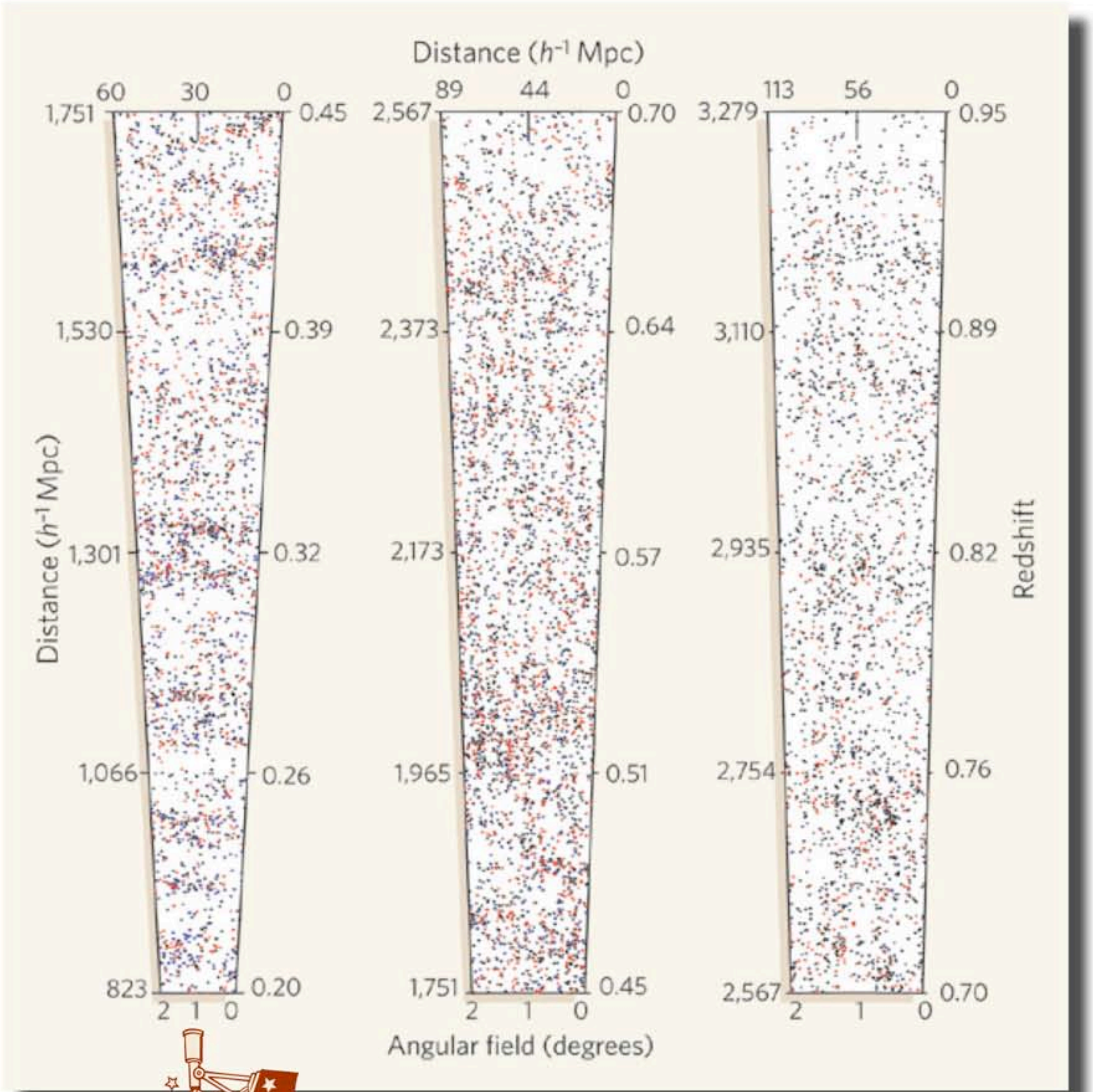


F22-Wide

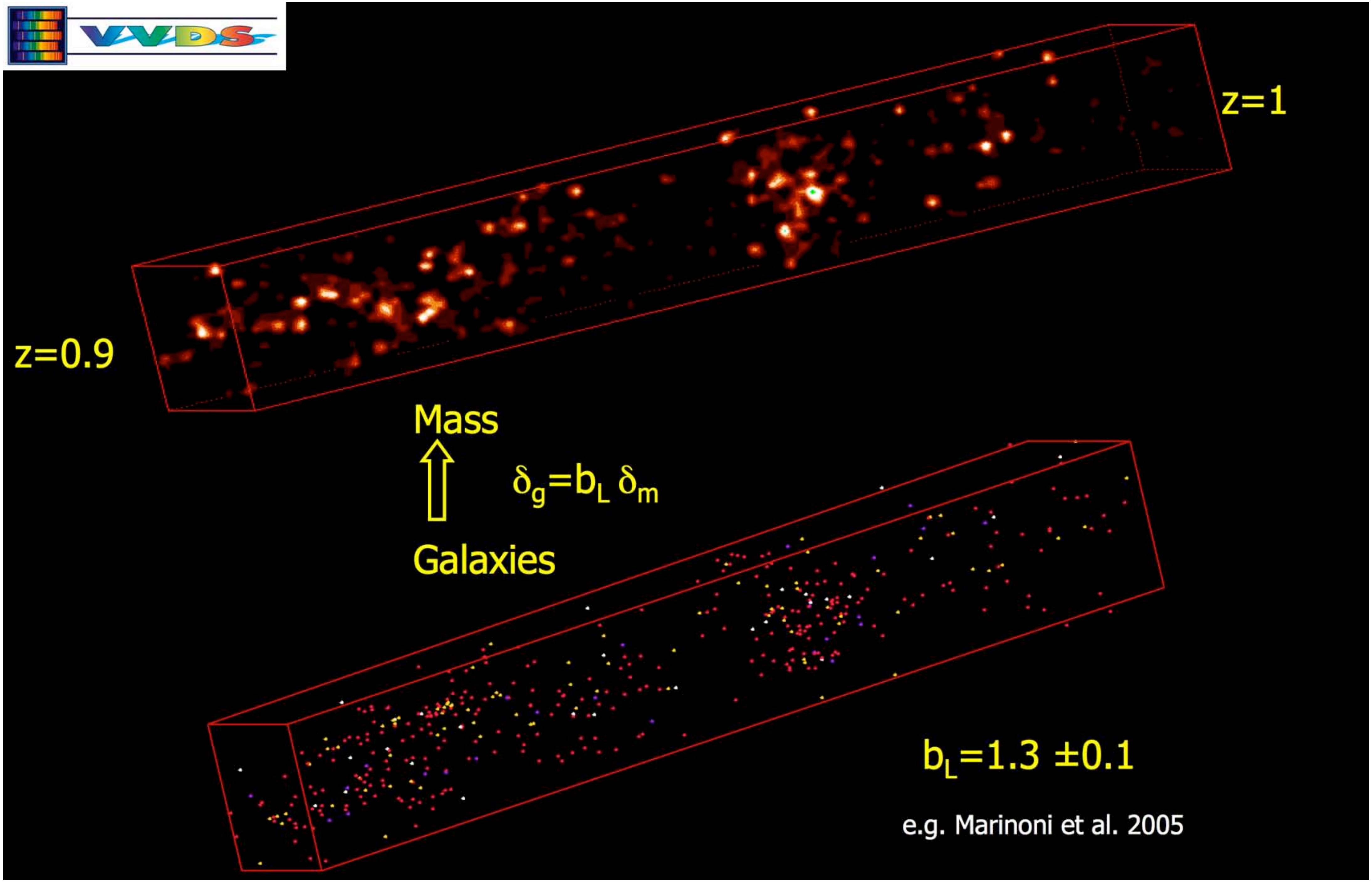
15,000 spectra
11,400 z's
4 deg²

VVDS-Wide F22 field: 10,000 redshifts to z~1.2



Fully public

(Garilli et al. 2008, A&A 486, 683)



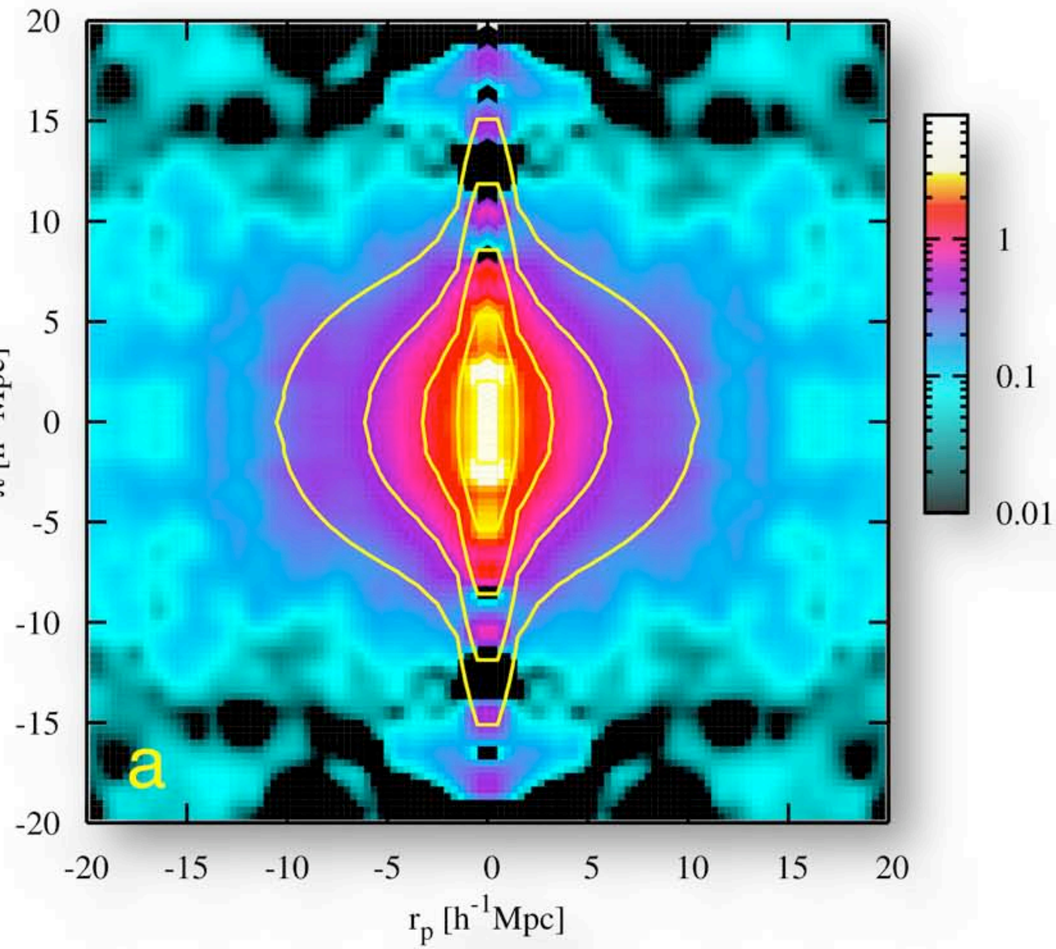
VVDS
z=1
z=0.9
Mass
$\delta_g = b_L \, \delta_m$
Galaxies
$b_L = 1.3 \pm 0.1$
e.g. Marinoni et al. 2005

The signature of linear growth at z~1

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

Maximum likelihood fit of $\xi(r_p,\pi)$ with Kaiser-Hamilton distortion model gives

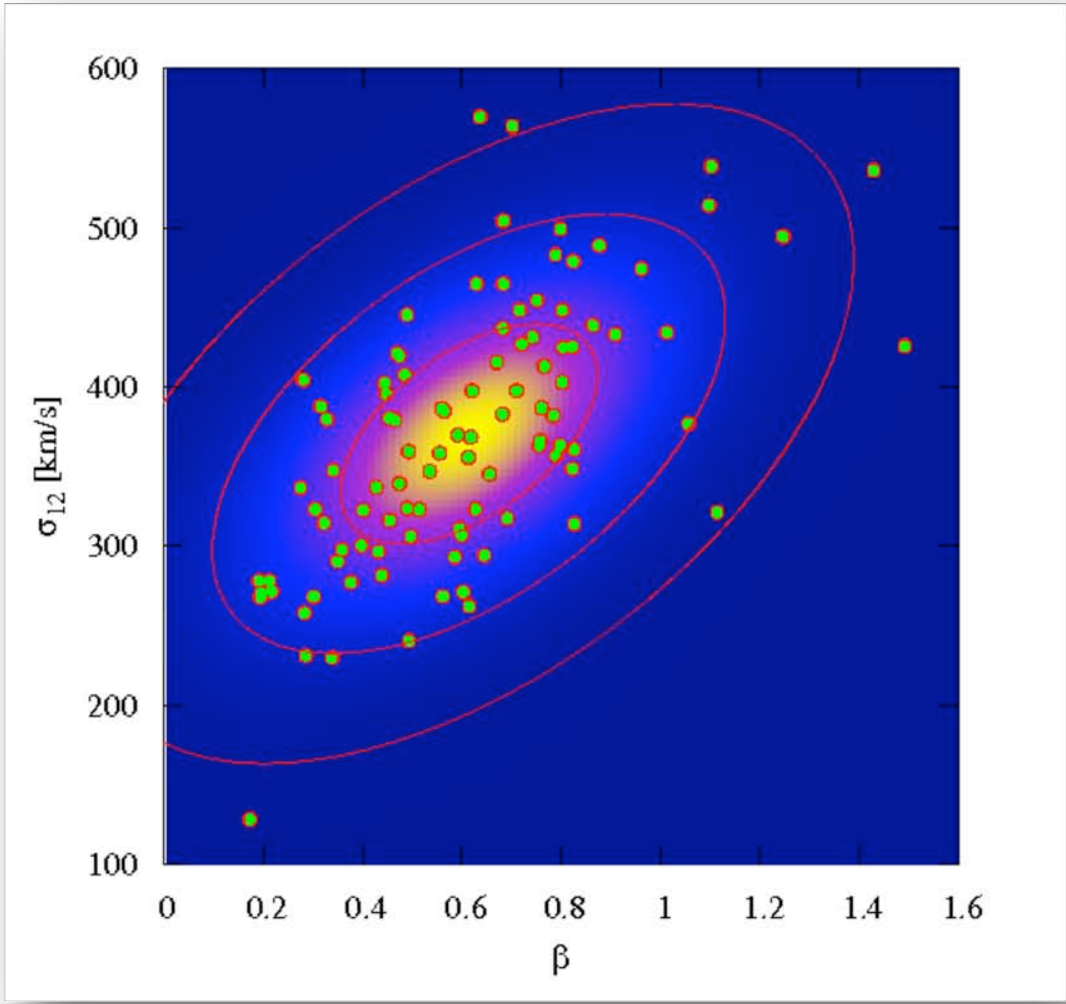
β=0.70±0.26



Guzzo, Pierleoni, Meneux, et al. 2008, Nature 451, 541

Error from realistic mock experiments (VVDS-Wide F22 field)

Distribution of the two free parameters (β and σ_{12}) from 100 realizations of 4 deg^2 F22 mock "light cones" built from Millennium Run + semi-analytic (Guzzo et al., Nature, Supplementary Information)



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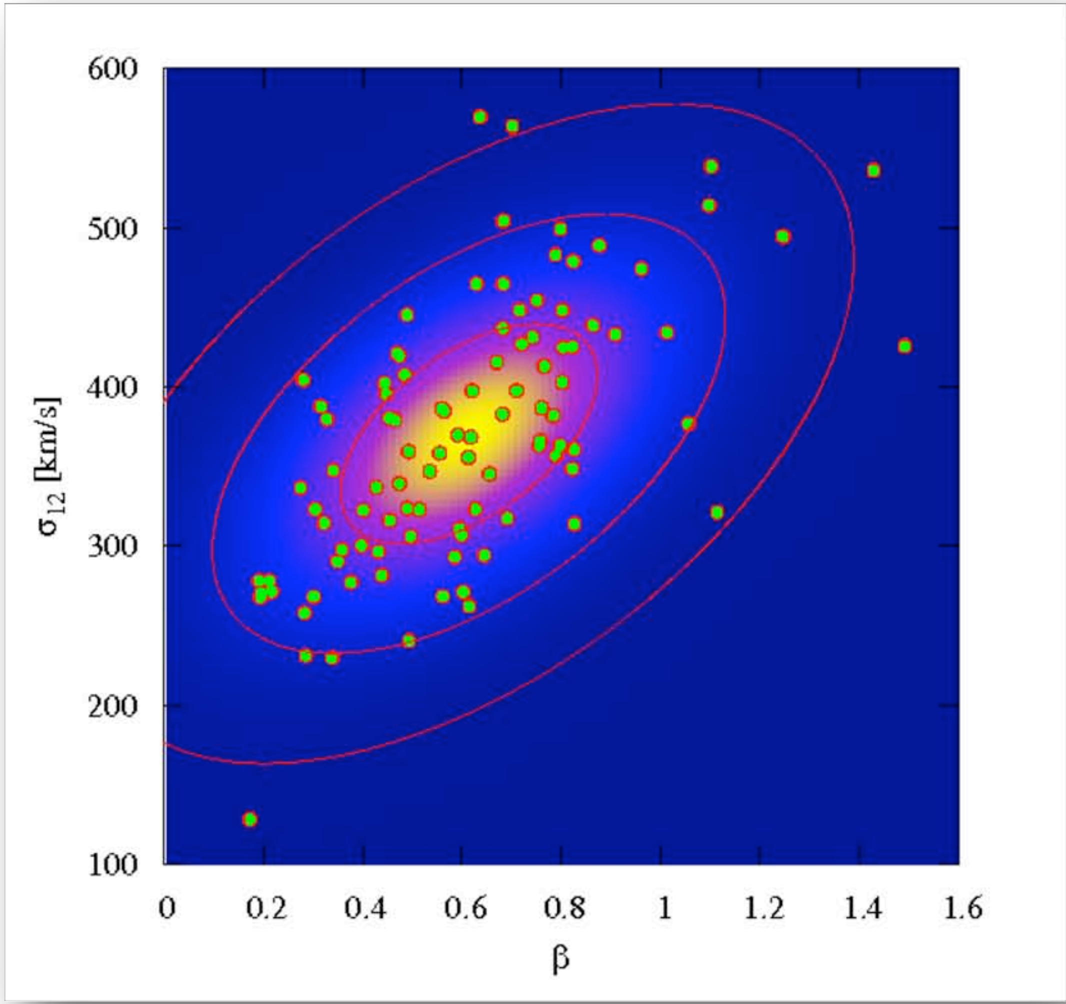
-NO SIGNIFICANT SYSTEMATIC ERROR (at this statistical accuracy): we recover the value of Ω_M known from the simulation within 3% (Ω_M= 0.628 vs Ω_M=0.649 expected at the effective z=0.77) → also test of effect of b(z) evolution within redshift bin



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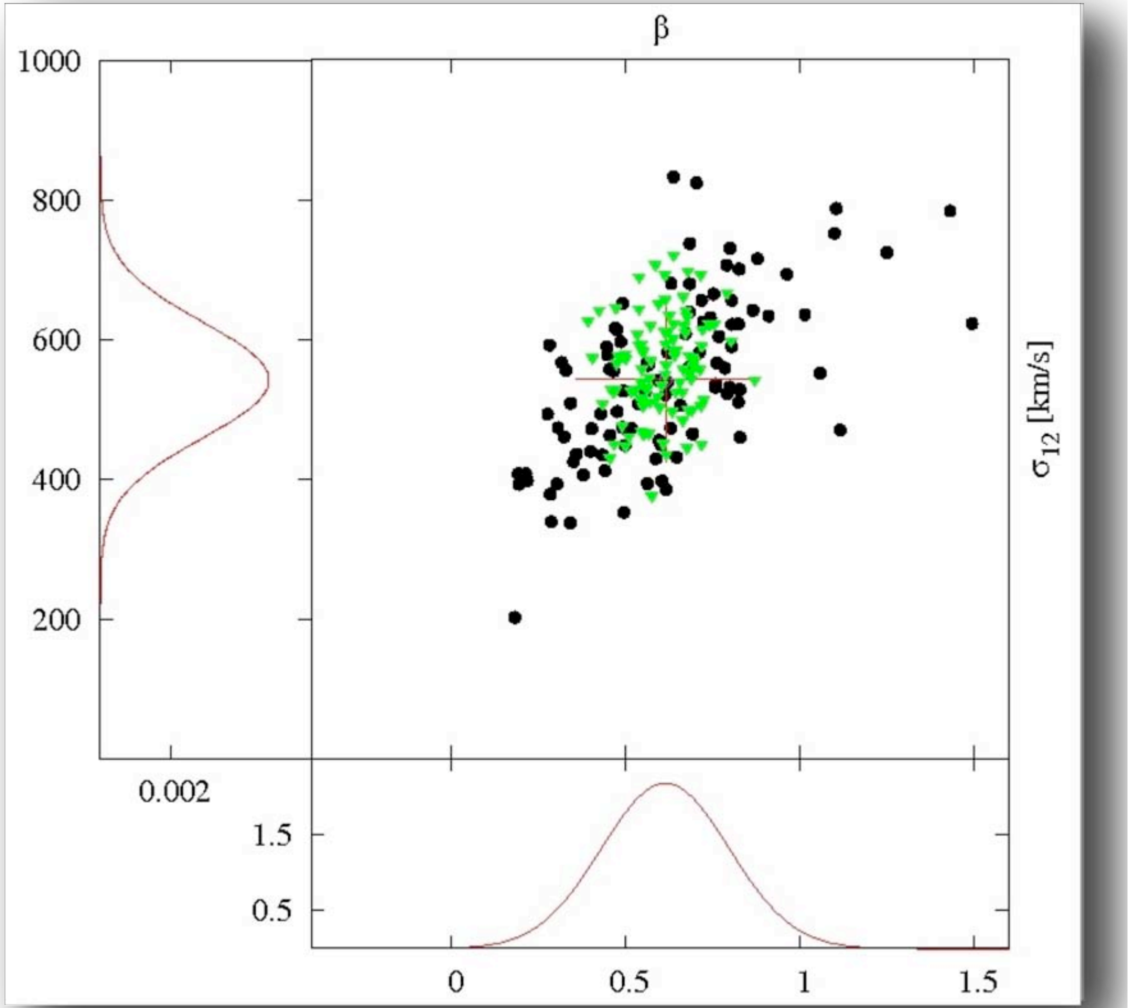
- SCATTER DOMINATED BY:

→ COSMIC VARIANCE AMONG THE FIELDS

→ UNCERTAINTY ON THE REAL-SPACE CORRELATION FUNCTION USED IN THE MODEL FOR $\xi(r_p,\pi)$: green points are obtained by using the "known" a priori $\xi(r)$ from the simulation, giving an error which is a factor of 3 smaller

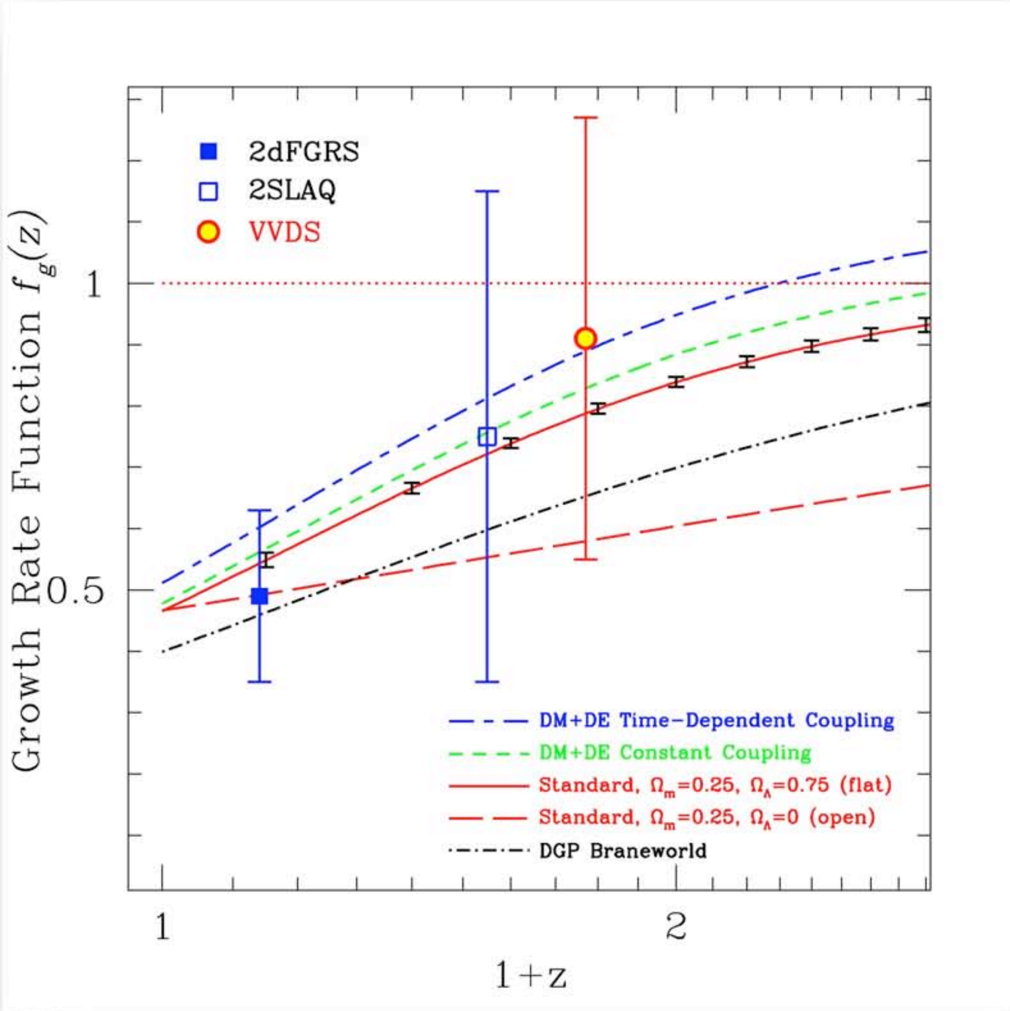


Evolution of the growth rate of large-structure from redshift distortions

$$f = b_L \beta$$

Bias estimated from:

- 2dFGRS: higher-order clustering
- 2SLAQ: combination of AP effect and clustering evolution
- VVDS: self-consistent inversion method (Sigad, Branchini & Dekel 2000; Marinoni et al. 2005); essentially based on WMAP3 σ_8 normalization



VVDS-Wide @ z=0.77:

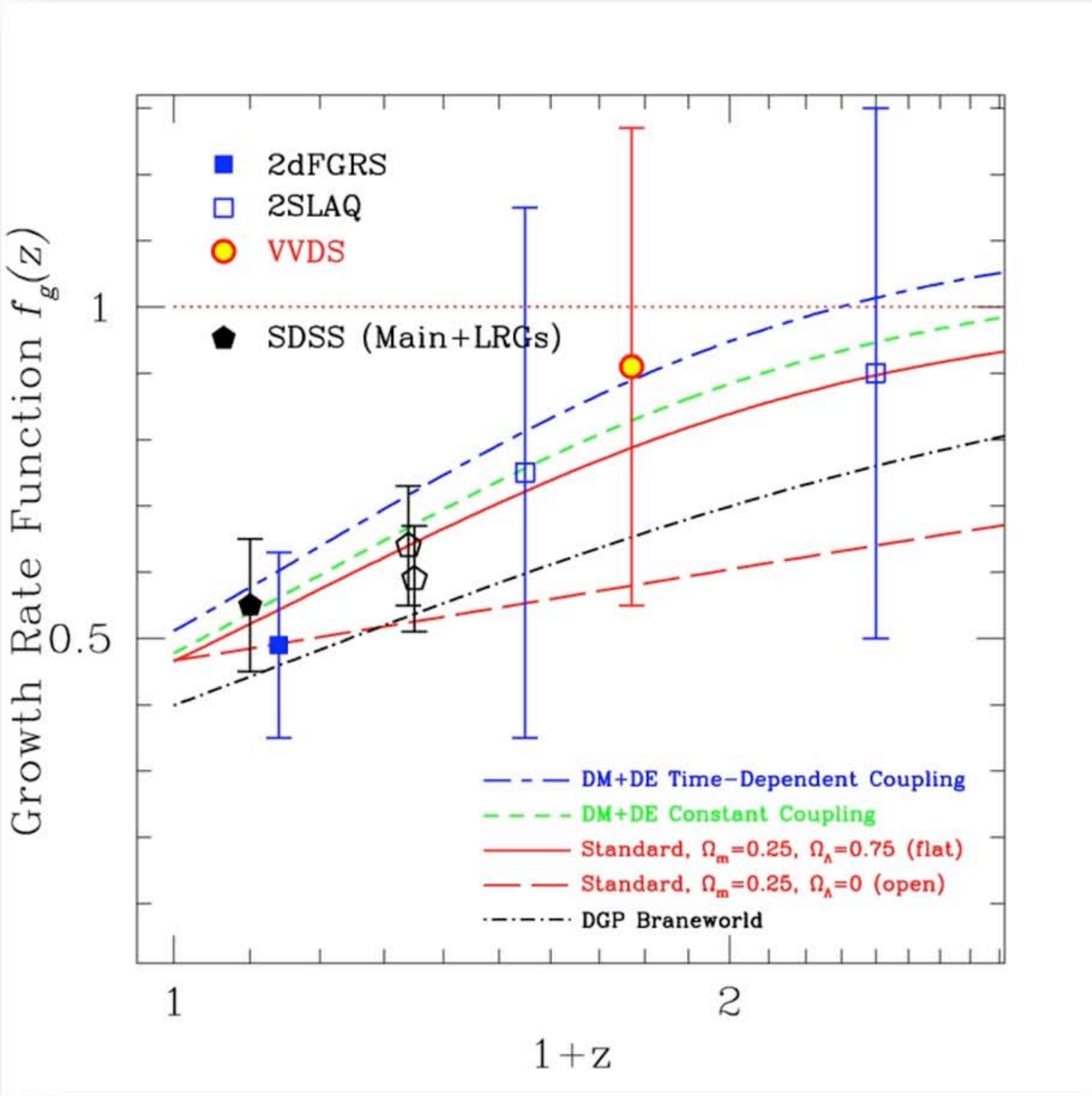
$f = 0.91 \pm 0.36$

Guzzo et al. 2008

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

Populating the f(z) diagram

- 2dFGRS: Hawkins+ 2003
- SDSS main: computed from Tegmark+ 2005
- SDSS-LRG: Tegmark+ 2007, Cabre & Gaztanaga 2009 (see also Yamamoto+ 2008)
- 2SLAQ: Ross+ 2007 (gal), da Angela+ 2007 (QSO)

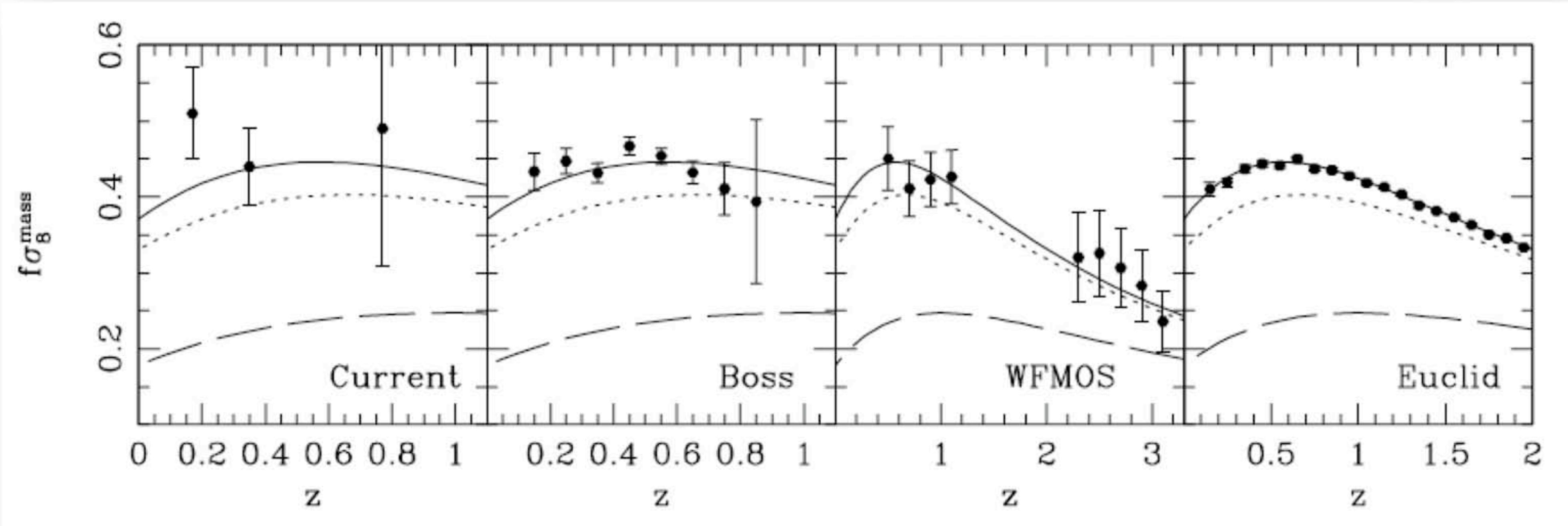


Is galaxy bias a problem? Probably not

- Yeong-Song & Percival arXiv:0807.0810

All observables

$$f = b\beta \approx \frac{\sigma_8^{gal}}{\sigma_8^{mass}}\beta \quad \rightarrow \quad F(z) = f(z)\sigma_8^{mass}(z) = \sigma_8^{gal}(z)\beta(z)$$



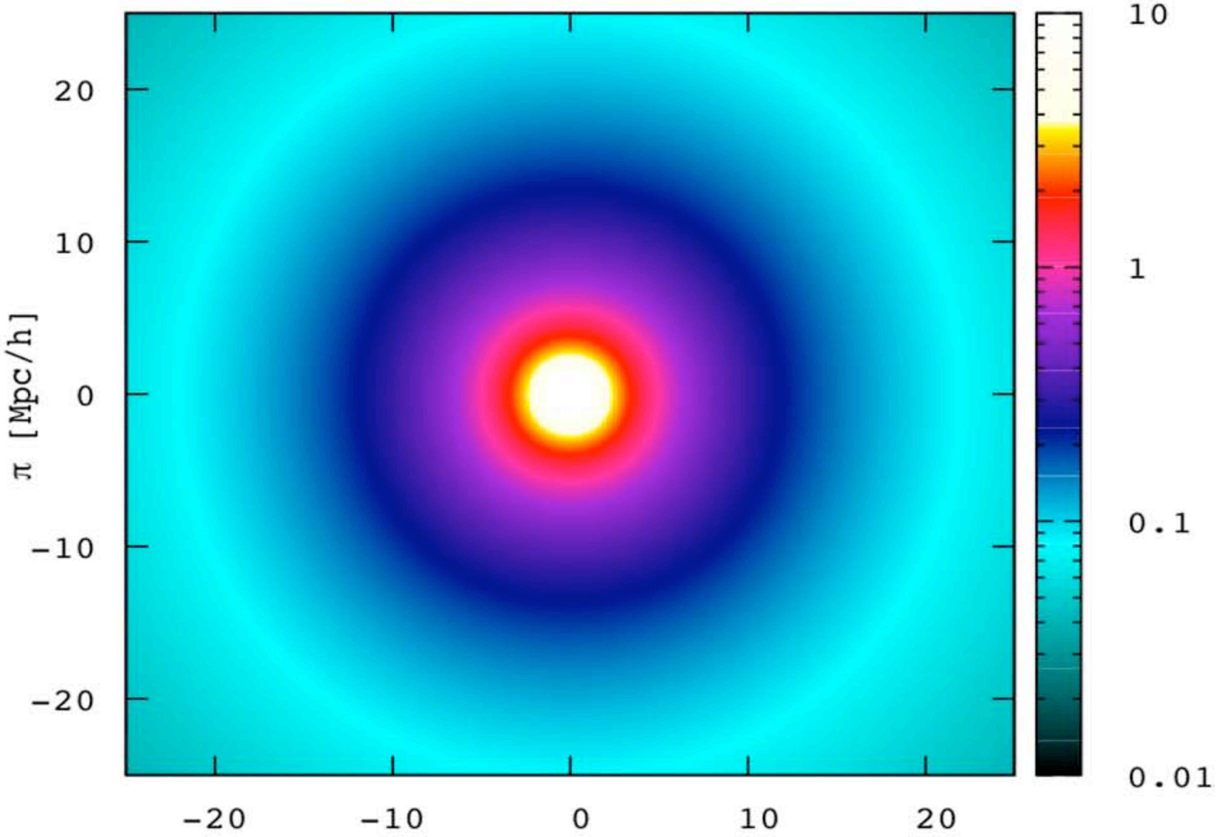
- Percival and White arXiv:0808.0003

Geometrical distortions

Additional distortions are introduced by adopting an incorrect cosmological model to obtain distances from measured redshifts

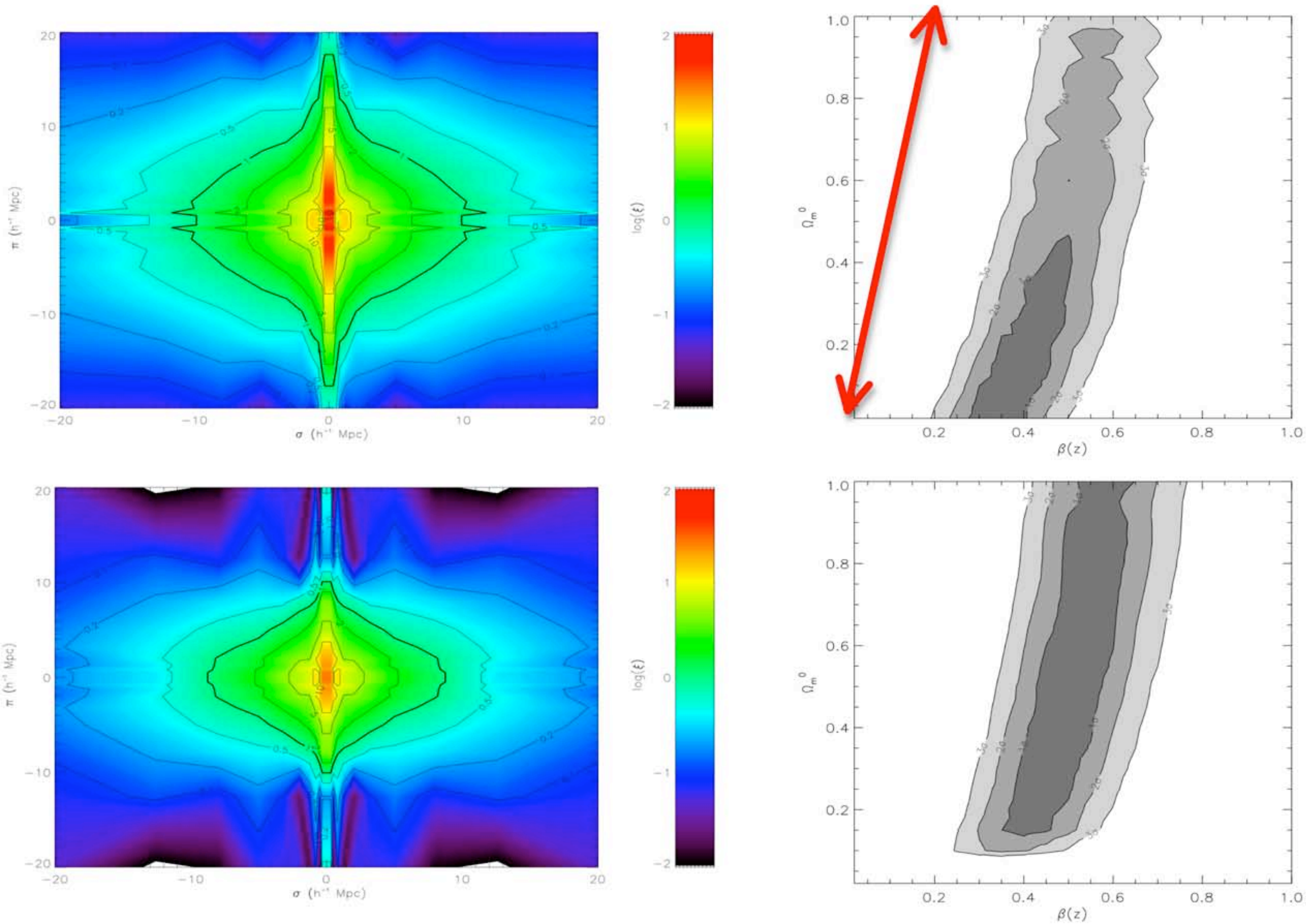
$$\Delta\pi \propto \frac{c}{1+z}$$

$$\Delta r_p = H(z) D_A(z) \Delta\theta$$



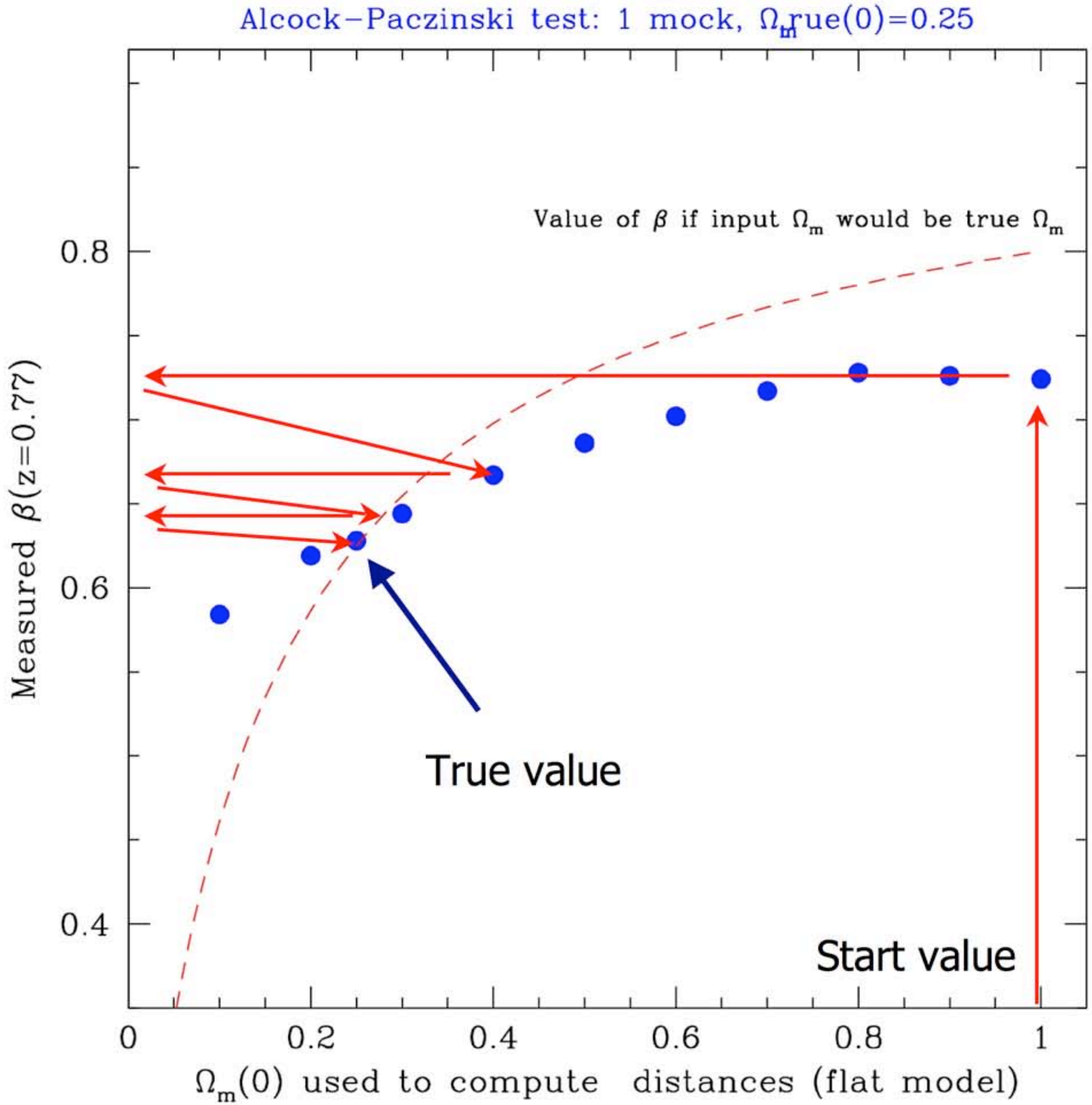
At low redshifts such distortions are small but can, in principle, be separated from genuine dynamical distortions

2dF-SDSS LRG and QSO Survey (Ross et al. 2008)



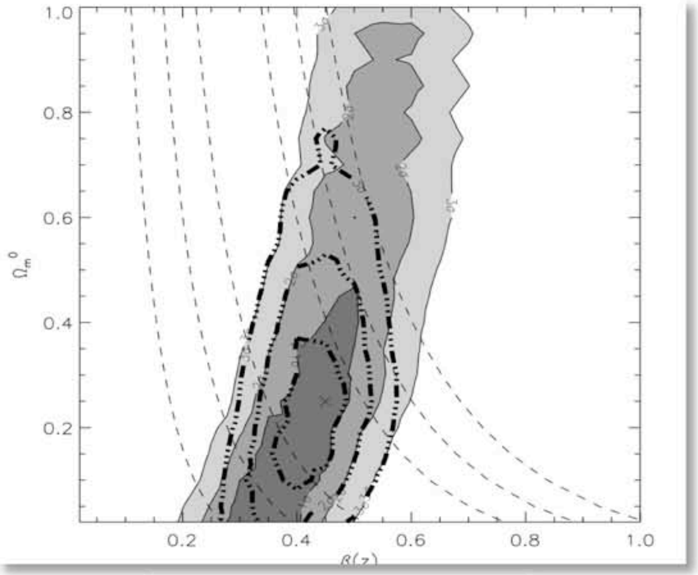
ΛCDM assumed

EdS assumed

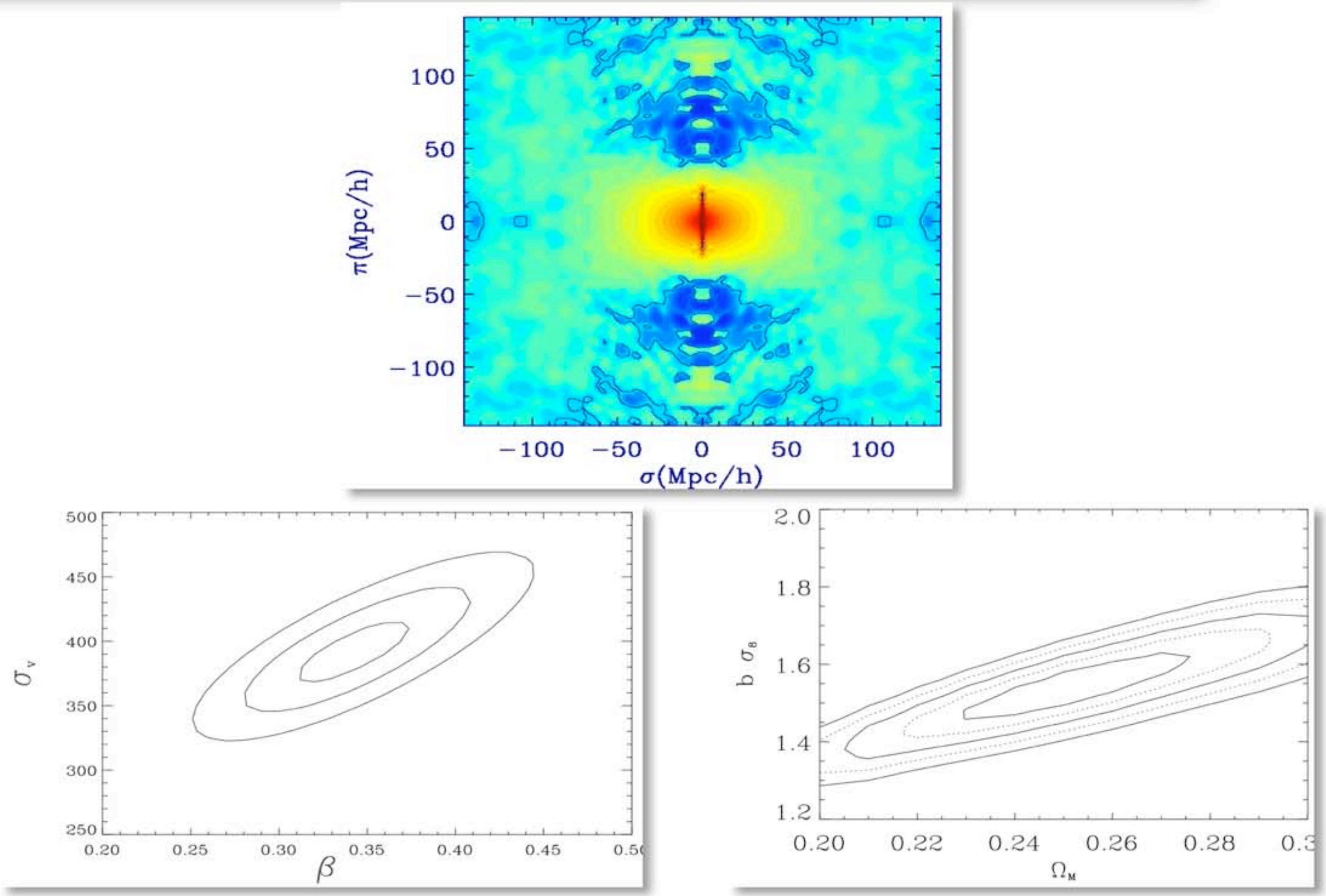


Alcock–Paczinski test: 1 mock, Ωtrue(0)=0.25
Value of β if input Ωm would be true Ωm
0.8
0.6
0.4
Measured β(z=0.77)
True value
Start value
0
0.2
0.4
0.6
0.8
1
Ωm(0) used to compute distances (flat model)

Additional hypotheses required to measure $f(\Omega_m)$ and b separately. E.g. clustering evolution



Ross et al. 2007



LRG – SDSS galaxies (DR6 release) Cabre' and Gaztanaga 2009

Which redshift surveys for the future?

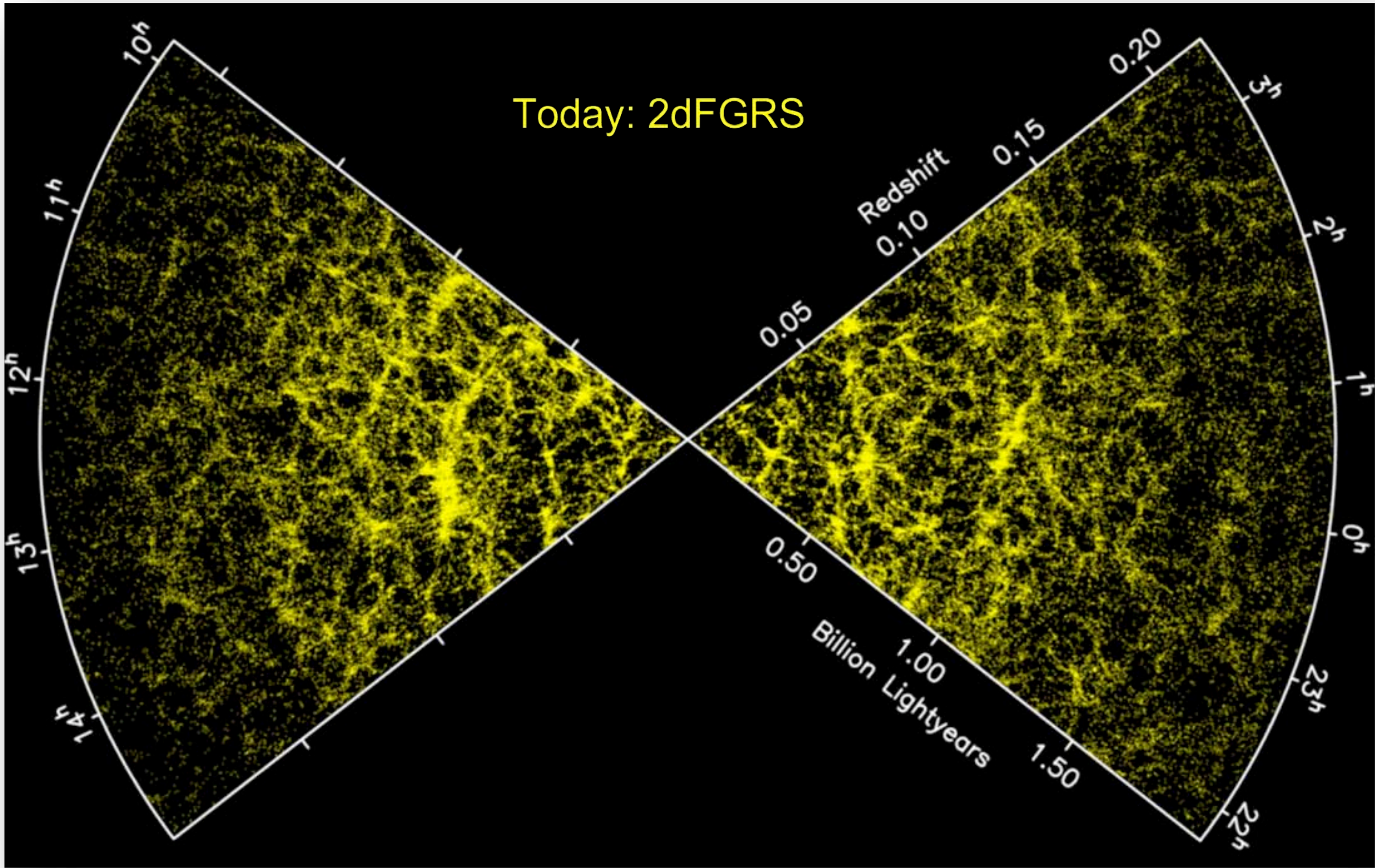
A) With (slightly refurbished?) VIMOS@VLT (IAB<22.5, ~1 hr integration, <n>~350 gal/pointing) :

A1) Short-term (<3-6 yrs): ~ 100,000 redshifts over ~24 deg^2 (Vol ~ 6 x 10^7 h^{-3} Mpc^3) - 400 hrs --> σ_β<10%

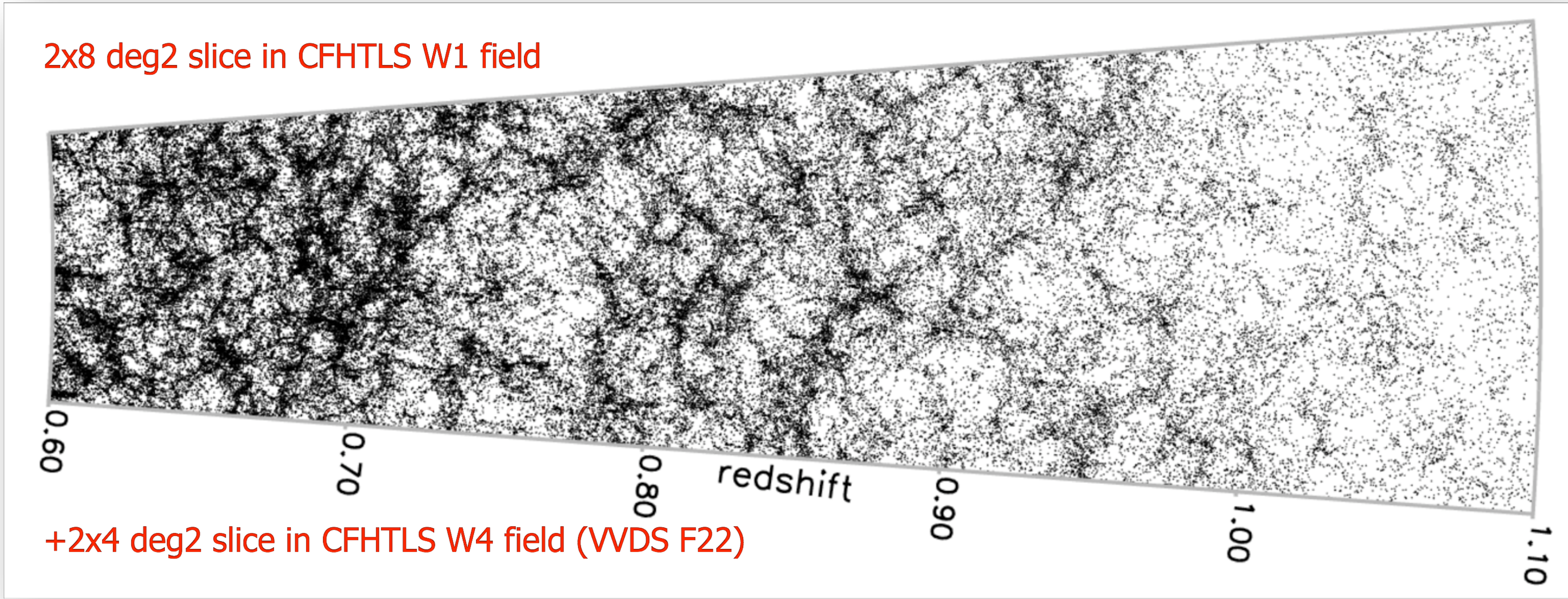
A2) Mid-term (<10 yrs): ~ 10^6 redshifts over ~400 deg^2 (Vol ~ 10^8 h^{-3} Mpc^3) - ~5000 hrs --> σ_β~3%

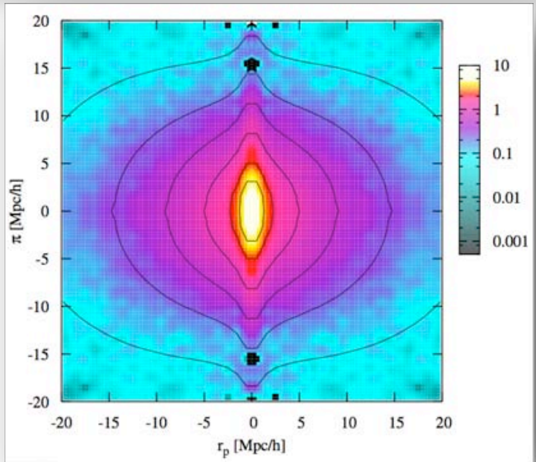
B) Long-term (<10 yrs), new Large Area MOS on VLT (~4000 fibres over ~1-2 deg^2 field - WFMOS-like) - not easy technically:
~ 5 x 10^6 redshifts over ~1000 deg^2. Do both galaxy-DM connections from same survey. Growth rate: σ_β~1%

C) Even longer term (~10 yrs), ultimate LSS survey: go in space and do IR spectroscopy to H=22-23 over whole sky (~20,000 deg^2): half billion redshifts to z~2 -- ESA Cosmic Vision "EUCLID" satellite.



Today: 2dFGRS
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50



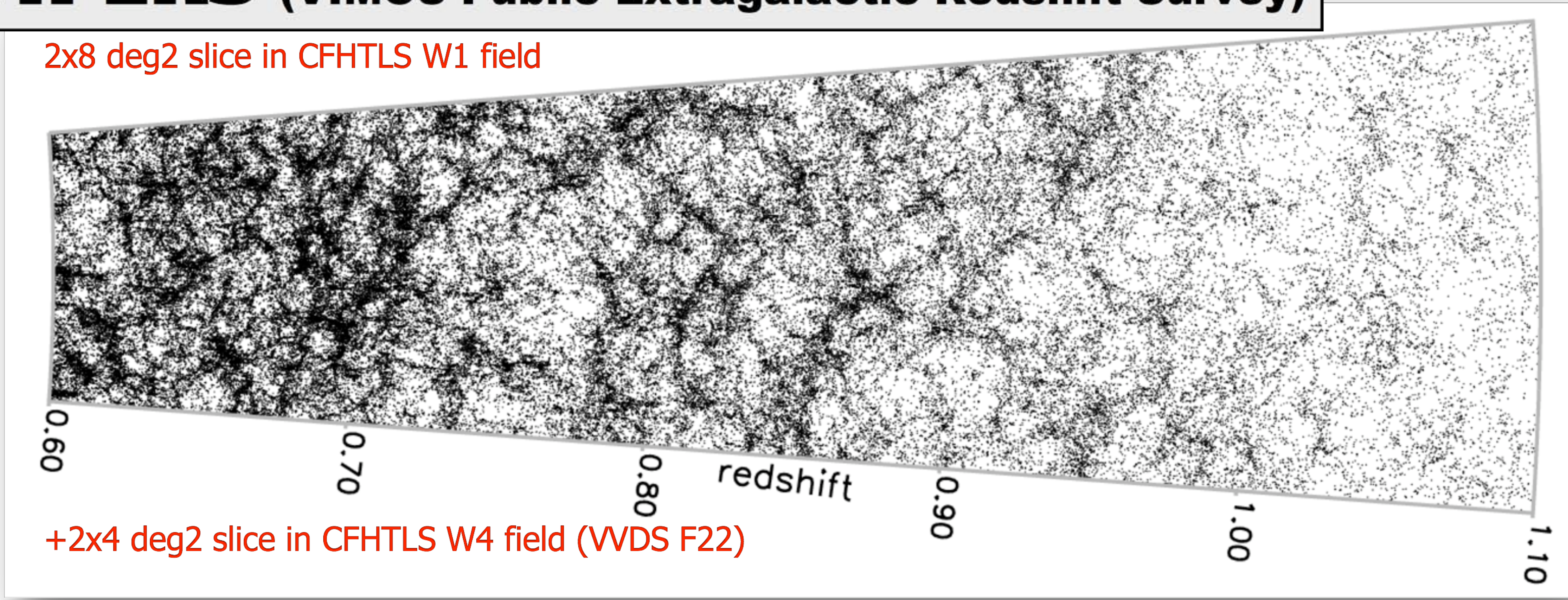


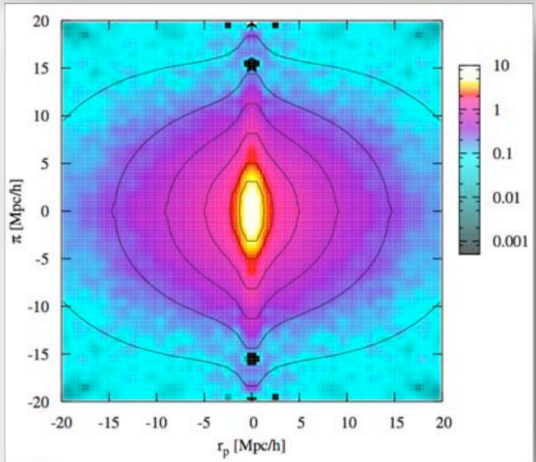
Tomorrow: New ESO Large Program

VLT-VIMOS, 24 deg^2, I_{AB}<22.5 & z>0.5 robust color/photo-z pre-selection: ~34% sampling, **100,000 redshifts**, 425 VLT hours. PI: Luigi Guzzo

→ **e_β~8% in two redshift bins**

VIPERS (VIMOS Public Extragalactic Redshift Survey)





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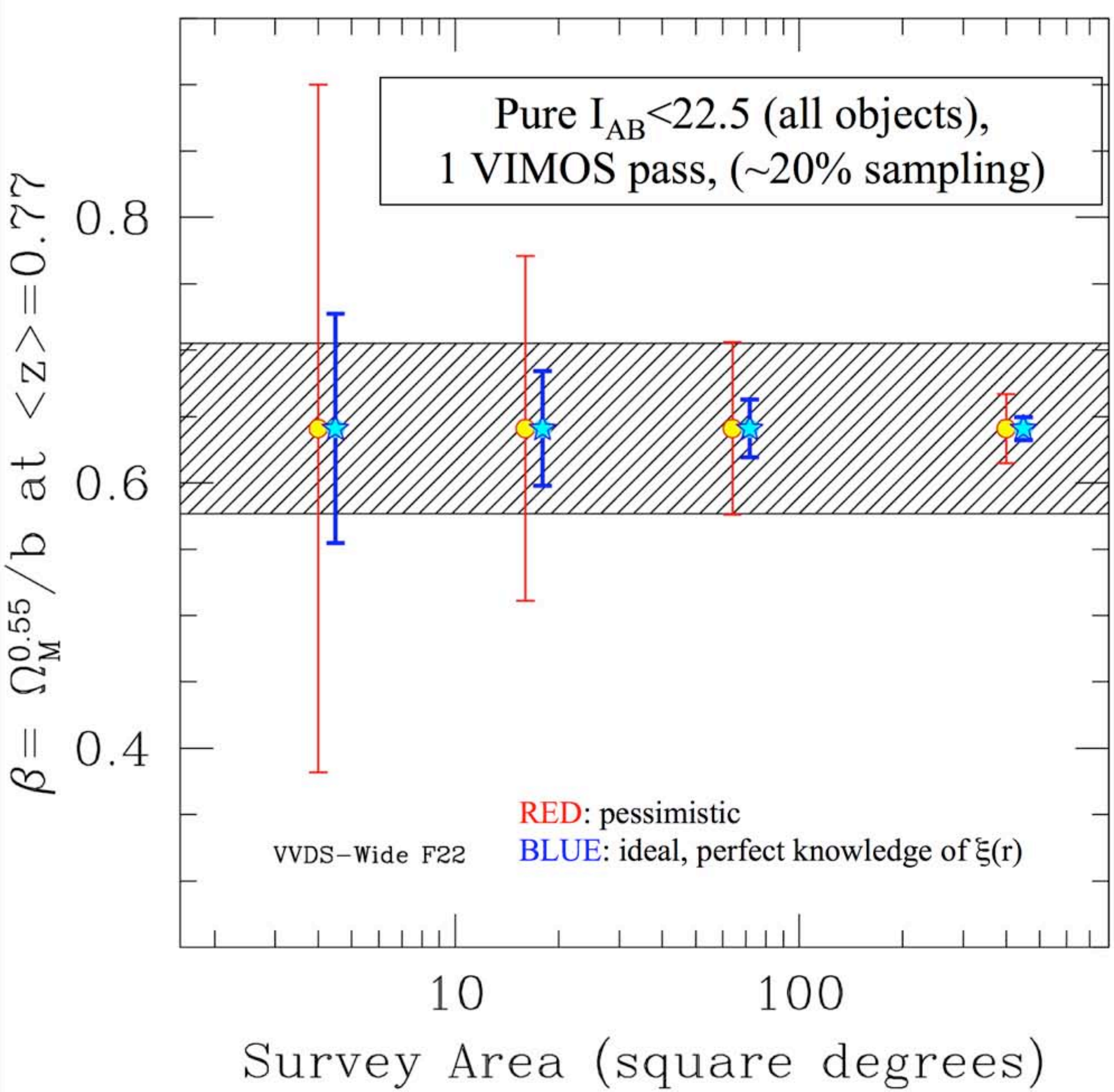
Behaviour of rms error with survey size/sampling, from mock surveys experiments:

$\sigma_\beta \sim 1/(<n>^{0.44} Vol^{0.5})$

→ volume increase slightly more important than density/sampling increase (as more or less expected, but non trivial, given need of measuring accurately underlying spatial correlation function)



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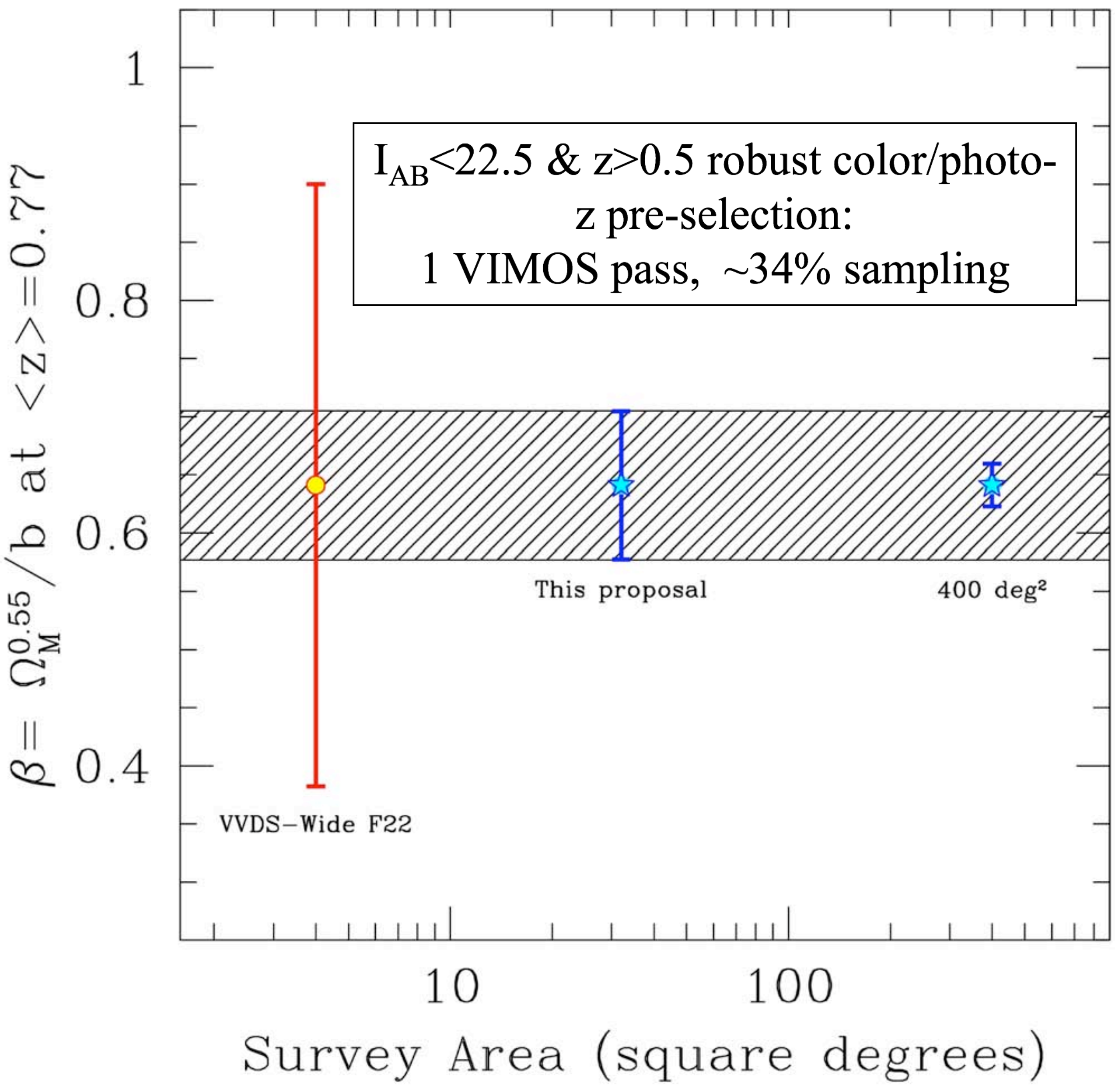
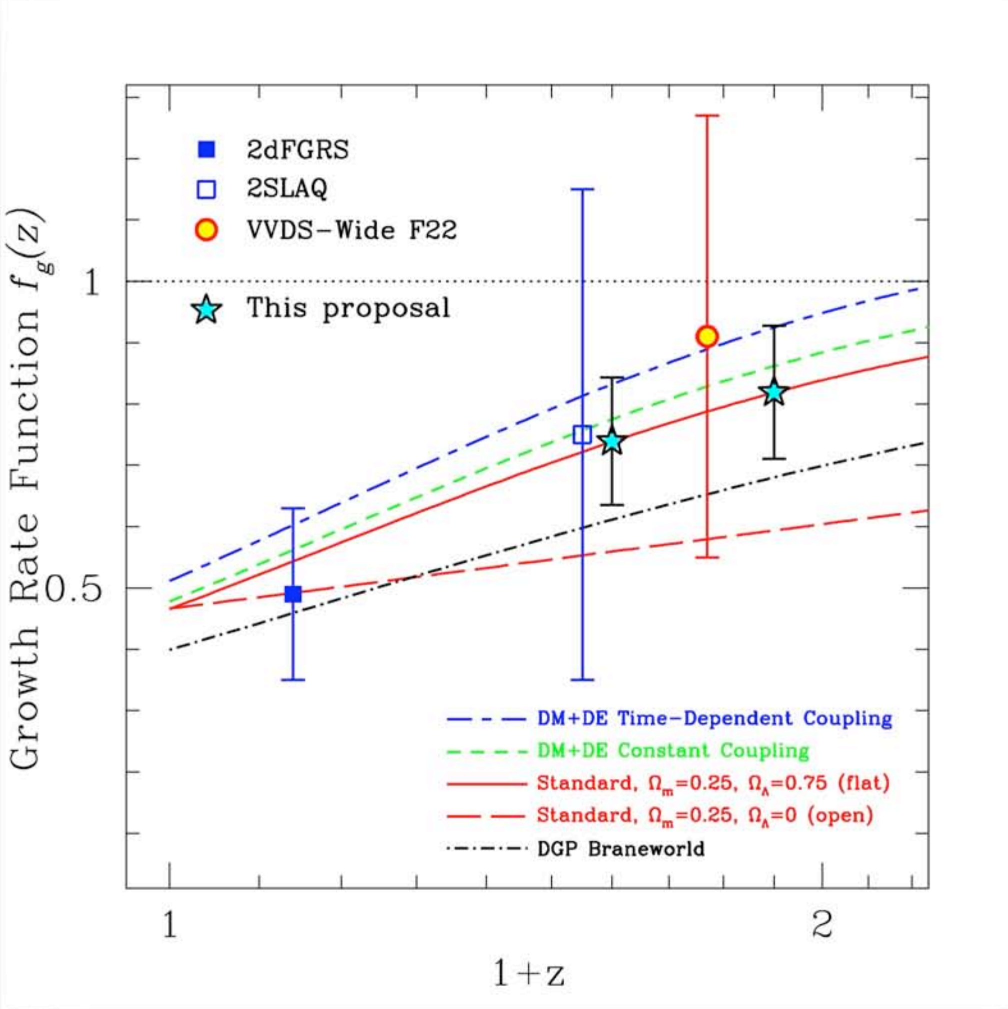
$\sigma_\beta \sim 1/(\langle n \rangle^{0.44}\ Vol^{\ 0.5})$

→ volume increase slightly more important than density/sampling increase (as more or less expected, but non trivial, given need of measuring accurately underlying spatial correlation function)

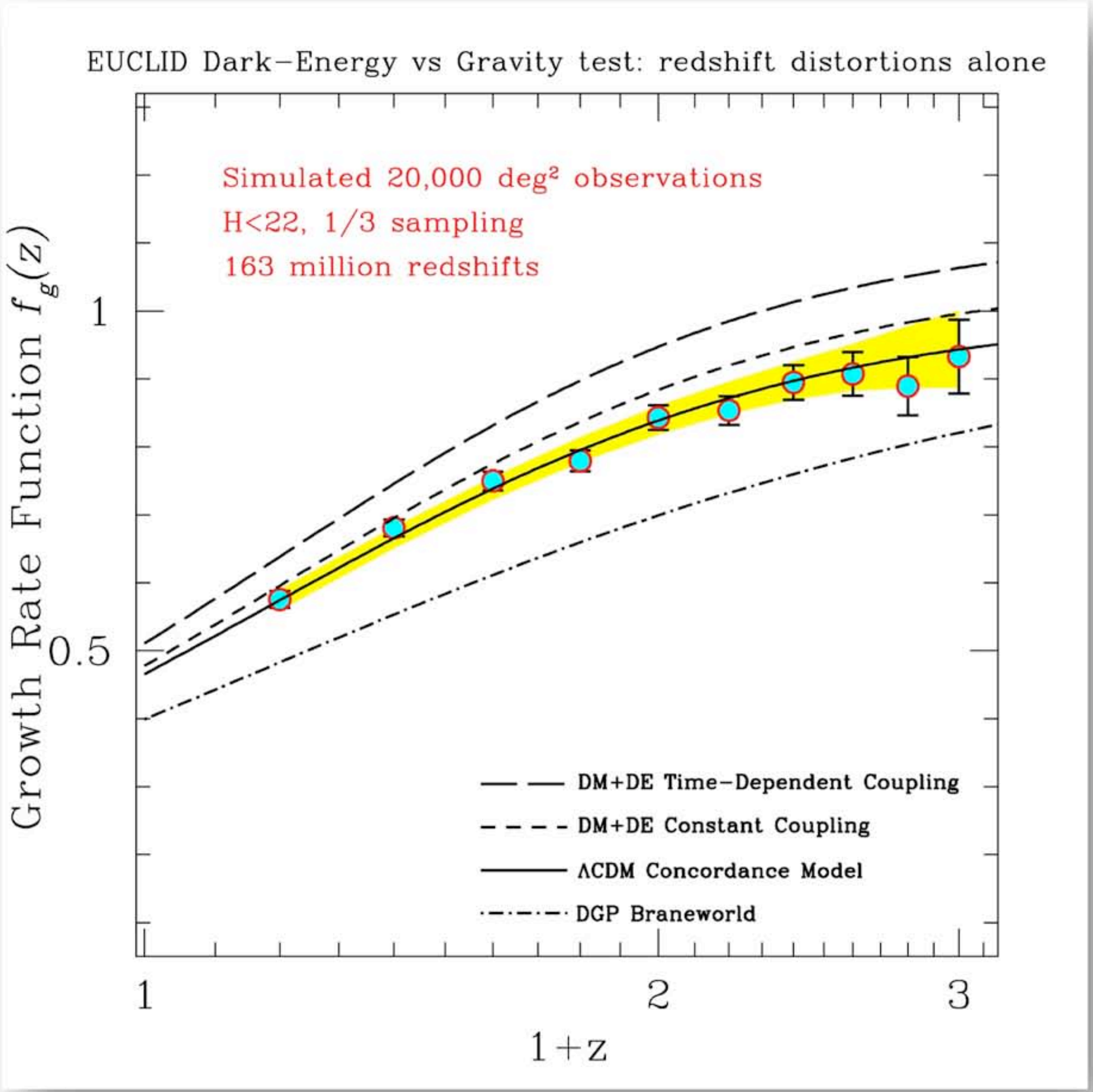
→ Maximize sampling within z range of interest (z>0.5) by using accurate multi-band color information (available over larger and larger areas, e.g. CFHTLS)



(Conservative) forecast on f(z) in two bins from VIPERS



Expected accuracy from redshift-space distortions for a Euclid-like survey



A possible future:

EUCLID, a satellite proposed for ESA Cosmic Vision
PI's: A. Cimatti (Bologna) & A. Refregier (Paris):
--> SUCCESFULLY PASSED 1st SELECTION

see the talks by A. Cimatti and A. Refregier

To summarize:

→*We need to measure both $f(z)$ and $H(z)$ to break the degeneracy between models that predict exactly the same expansion history [and thus identical $w(z)$], but are based on completely different physics*

→*A discrepancy between the measured growth rate and that predicted (assuming General Relativity) from $H(z)$ would be a smoking gun for new gravitational physics*

→*We have shown that measurements of redshift-space distortions at different z's open a new window on this problem: current error bars on $f(z)$ are large, but perspectives extremely promising (Branchini et al. 2009)*

→*This indicates that massive redshift surveys of galaxies will continue to be a primary tool for understanding our Universe over the next decade*