Probing cosmology and dark energy with galaxy redshift surveys

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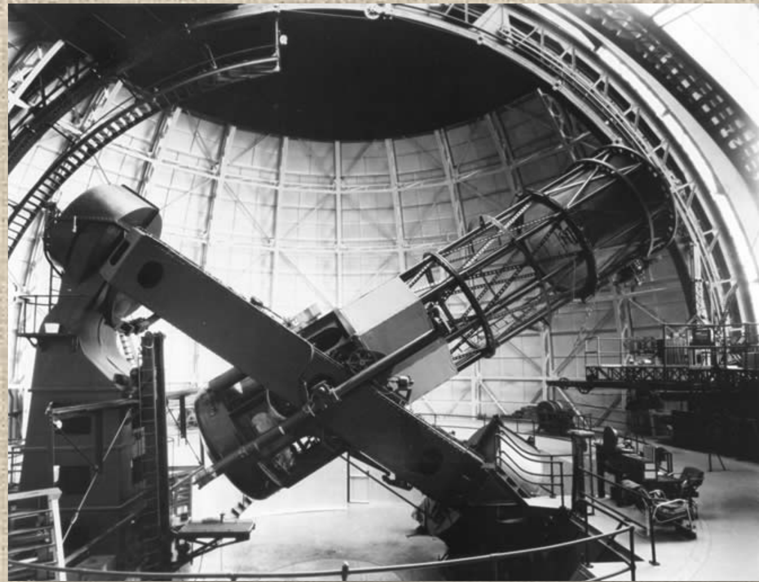
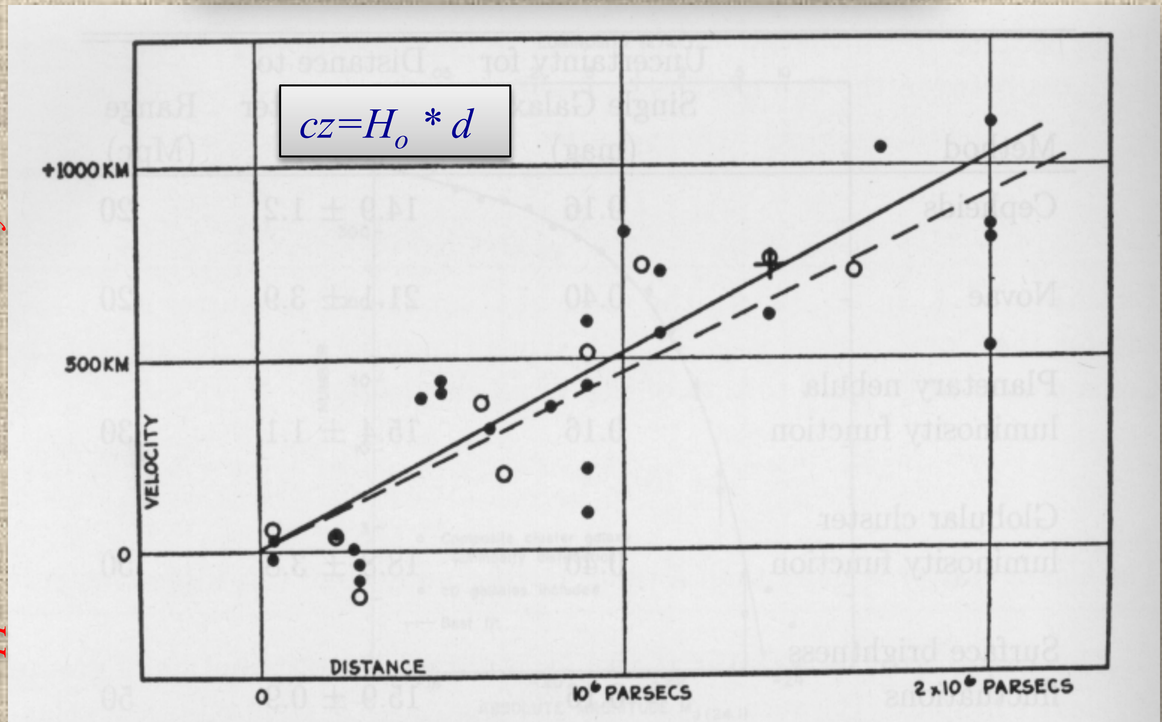
E. Hubble 1929



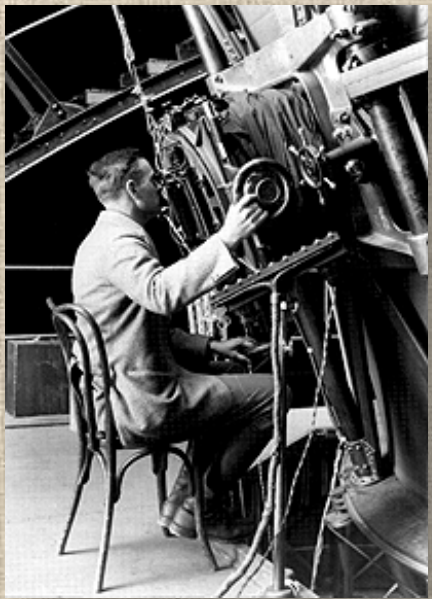
$cz=H_o * d$

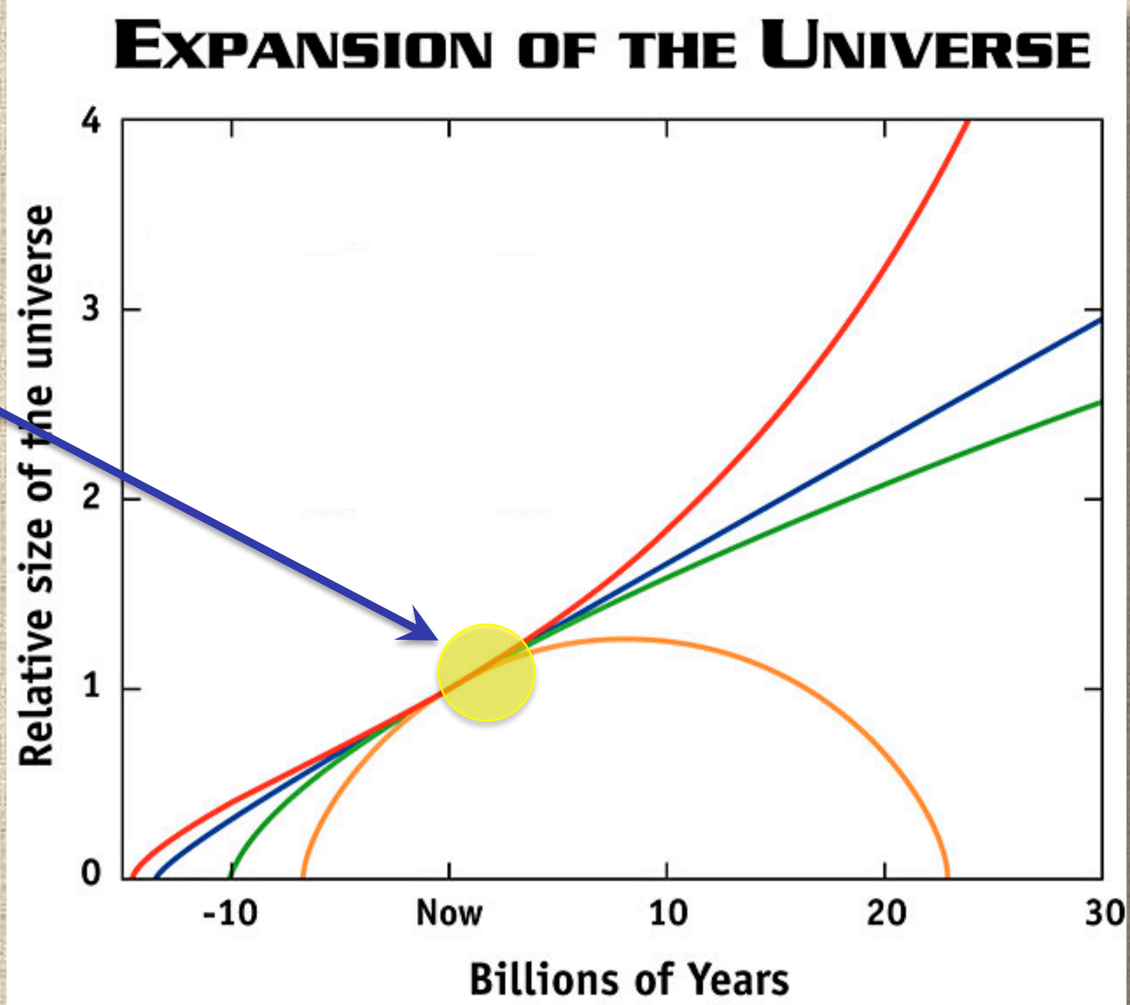
Apparent recession velocity $v=cz$



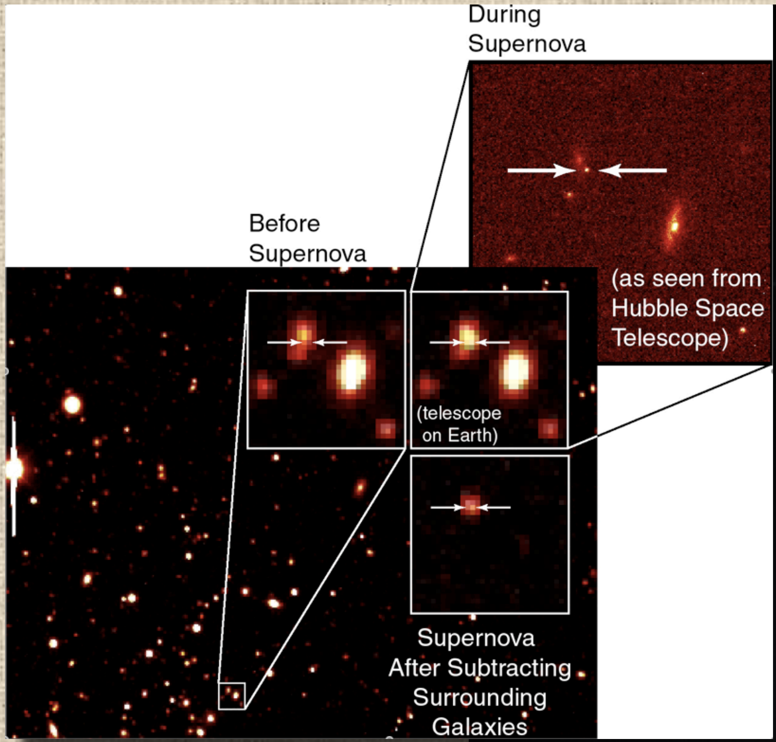
Distance

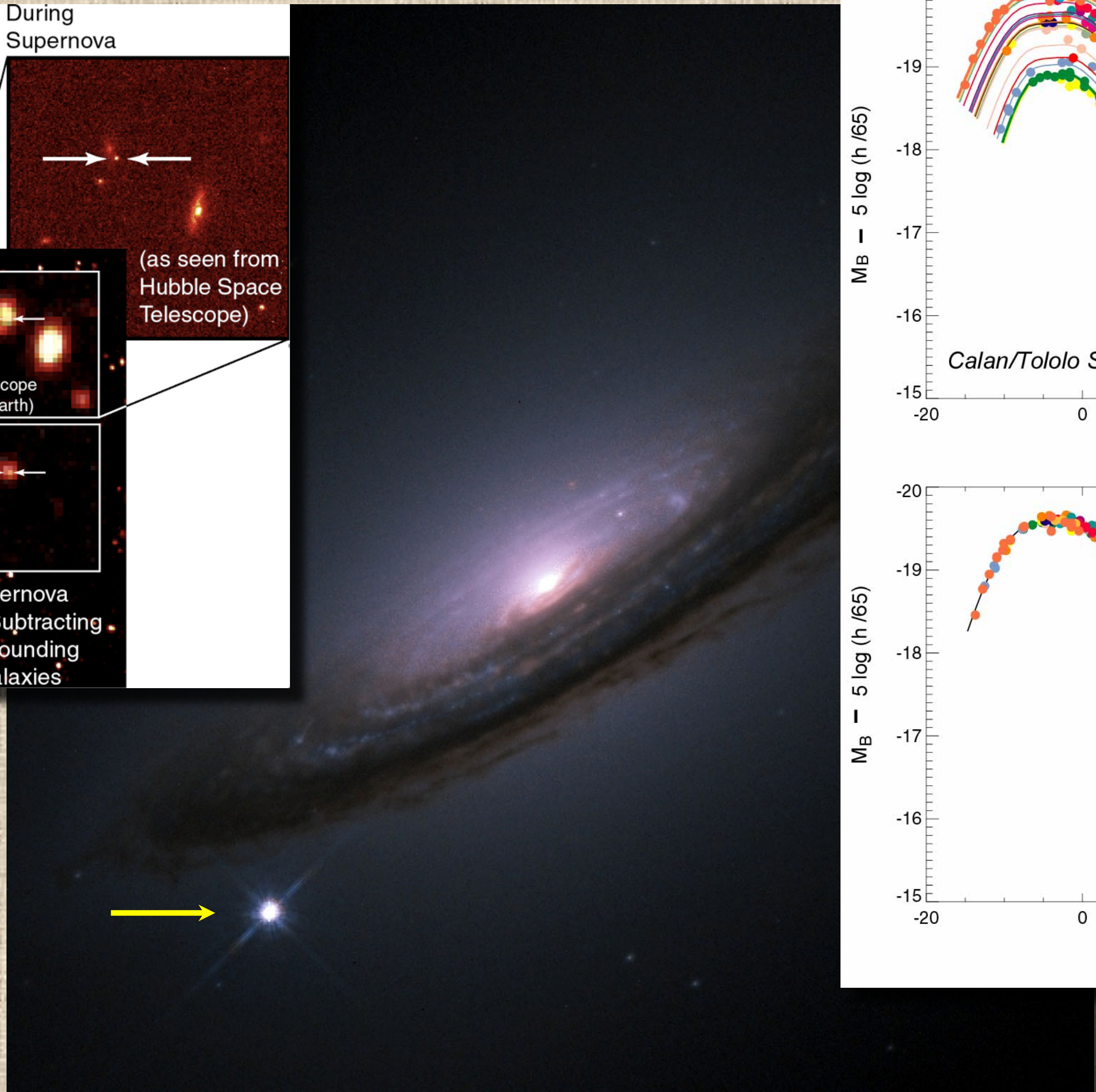
But, what is the past history of the expansion rate?

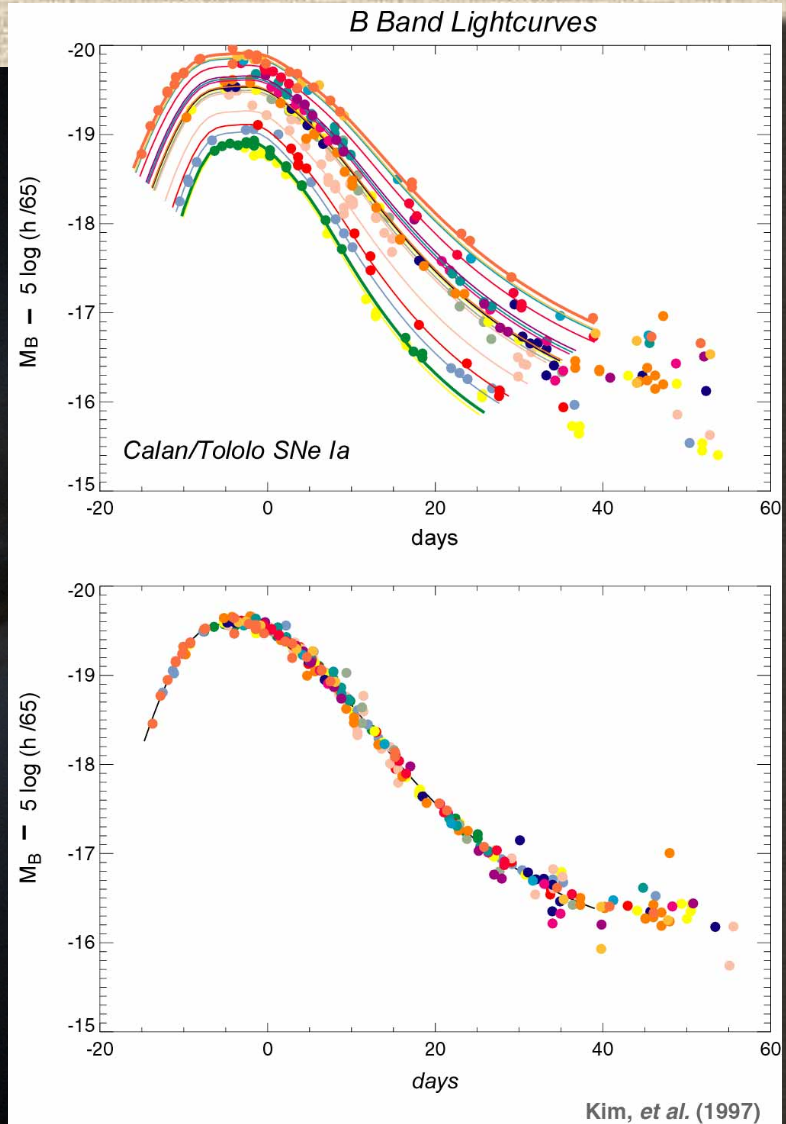




Beyond the Hubble law: Type-Ia supernovae as standard candles





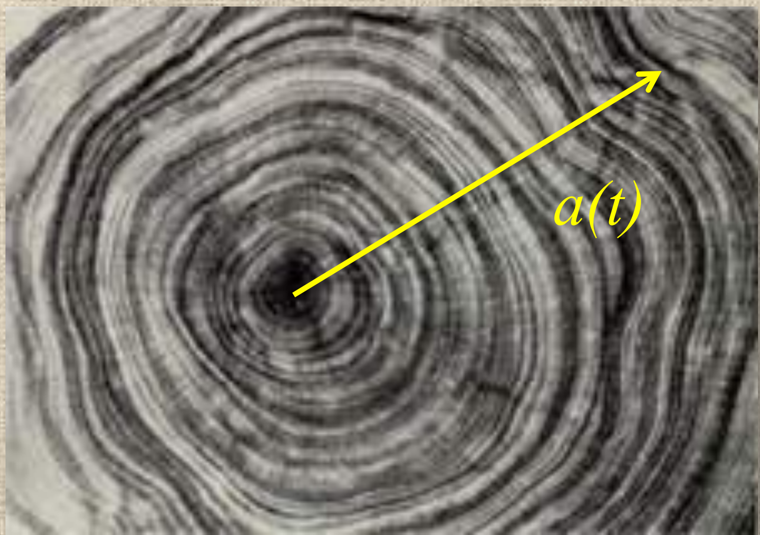


Perlmutter et al. 1999,
Riess et al. 1998

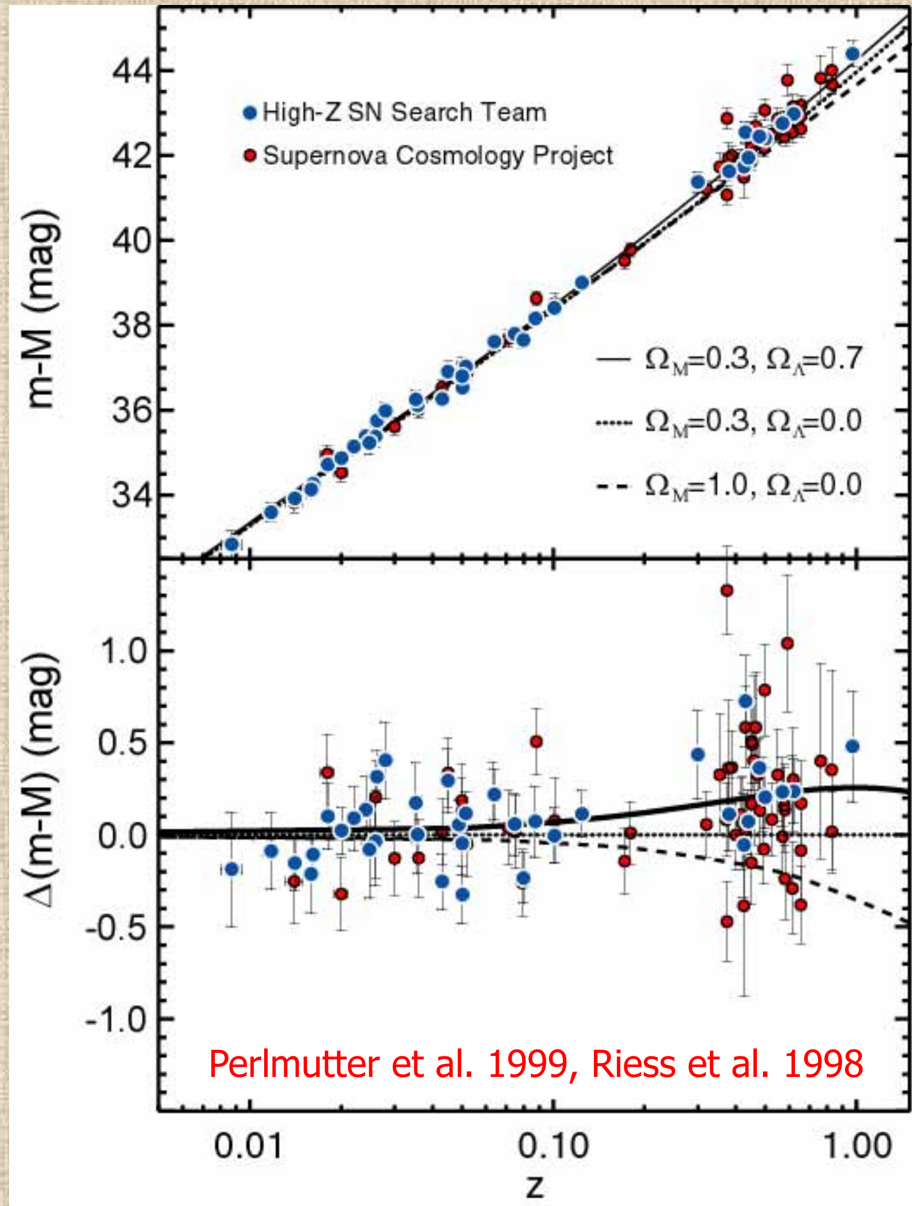
The "Hubble diagram" of Type Ia supernovae tells us that matter is not enough…

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

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



$\log(Distance\ d_L)$



Redshift of spectral lines

… i.e. that the *expansion history* $H(z)$ given by the Friedmann equation:

$$\boxed{H^2(z) = H_0^2\{\Omega_m(1+z)^3 + \cancel{\Omega_k(1+z)^2} + \cancel{\Omega_\gamma(1+z)^4} + \Omega_x(1+z)^{3(1+w_x)}\}}$$

Matter **Curvature** **Radiation** **Generic component**

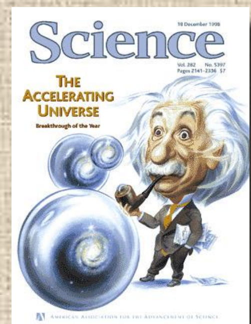
$$\left(H \equiv \frac{\dot{a}}{a}; \quad w_x \equiv \frac{p_x}{\rho_x c^2}; \quad \Omega_i \equiv \frac{\rho_i}{\rho_c}\right)$$

best matches observations when we add an extra component with *equation of state* $w_x = p/c^2\rho = -1$ corresponding to a cosmological constant Λ with energy density parameter today $\Omega_\Lambda \sim 3\Omega_m$

$$\boxed{H^2(z) = H_0^2\{\Omega_m(1+z)^3 + \Omega_\Lambda\}}$$

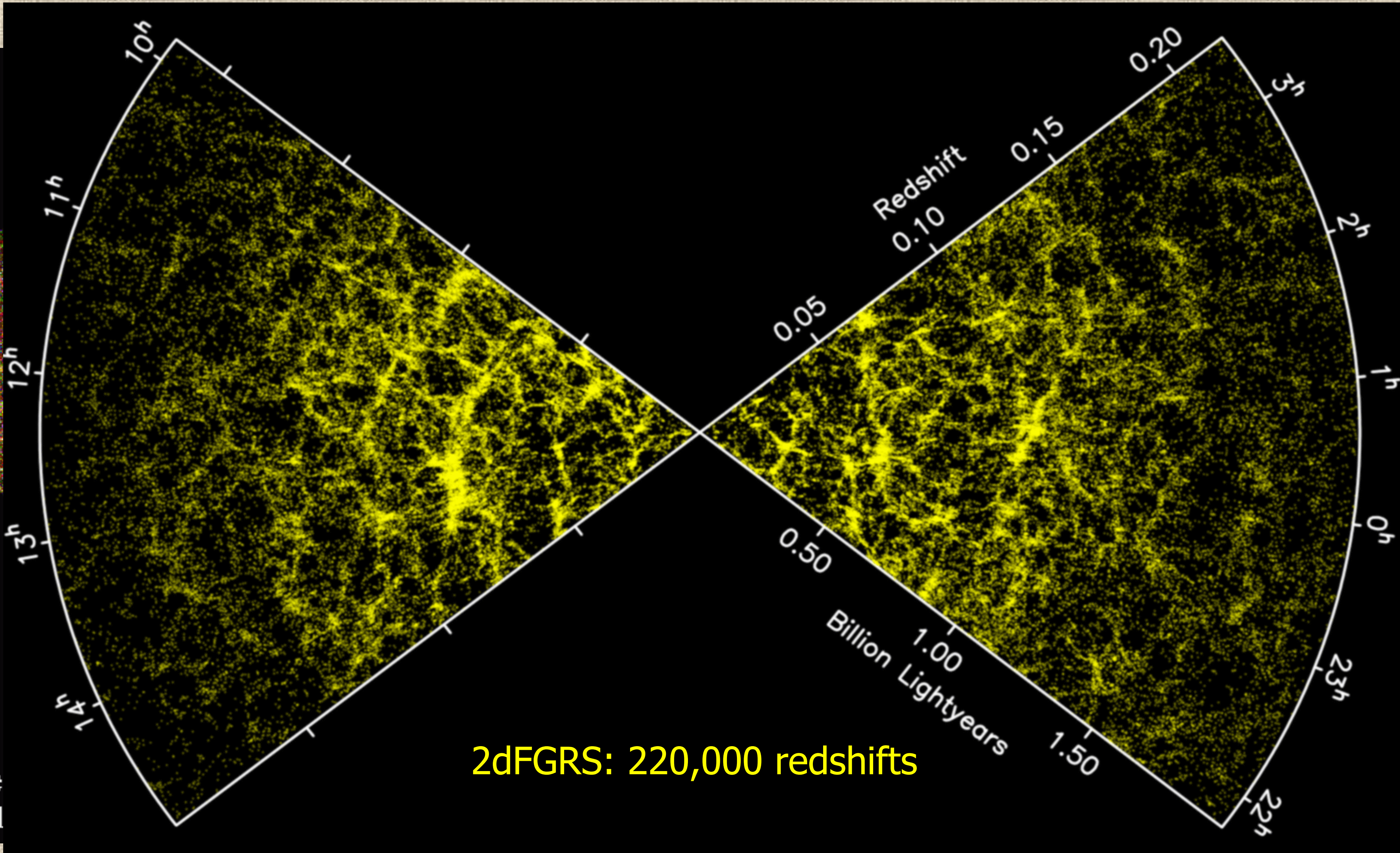
And thus the second equation

$$\boxed{\frac{\ddot{a}}{a} = -\frac{H_0^2}{2}(\Omega_m - 2\Omega_\Lambda)}$$



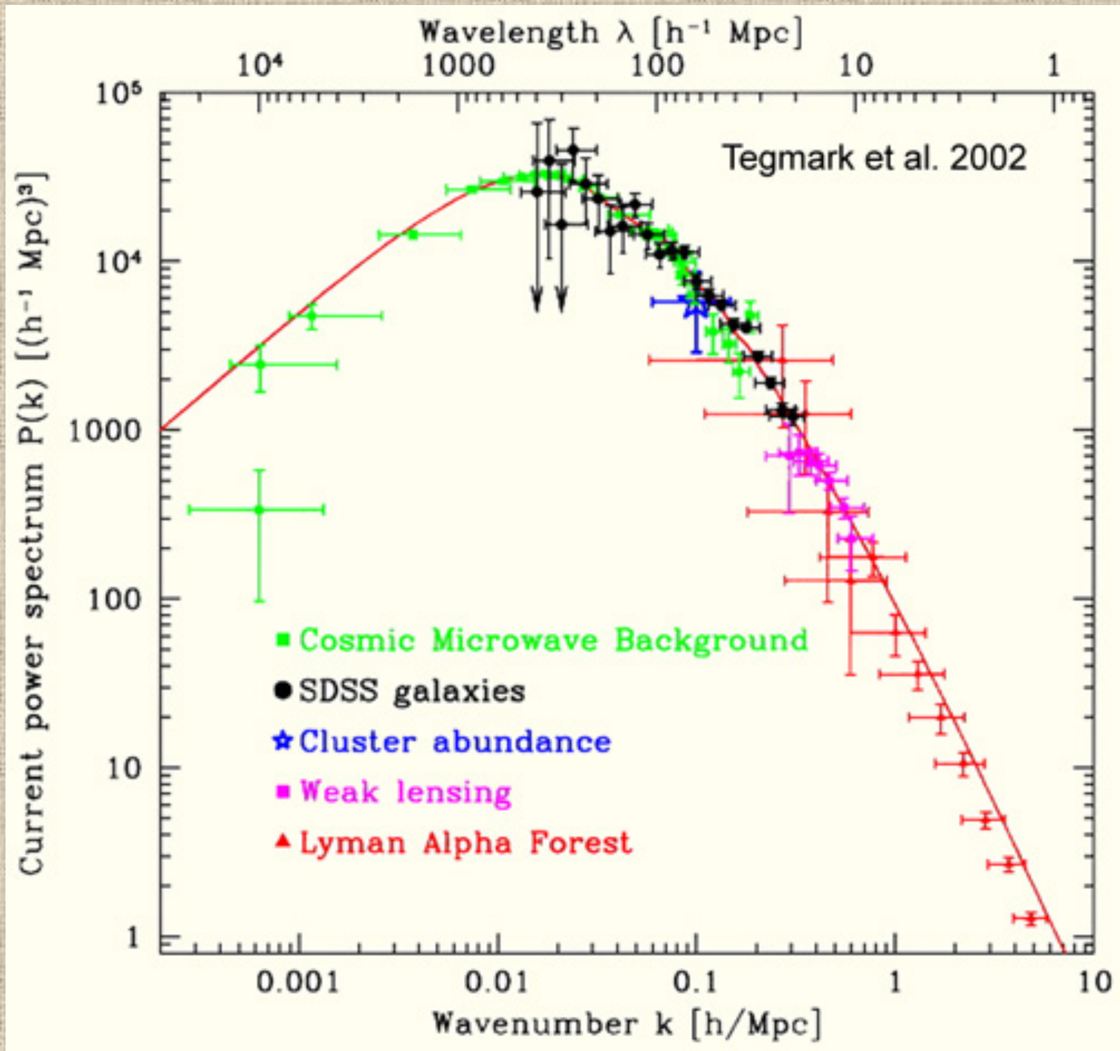
→ IMPLIES ACCELERATION OF THE EXPANSION (as soon as $\Omega_\Lambda > \Omega_m/2$)

Galaxy redshift surveys: reconstructing the 3D structure of the Universe



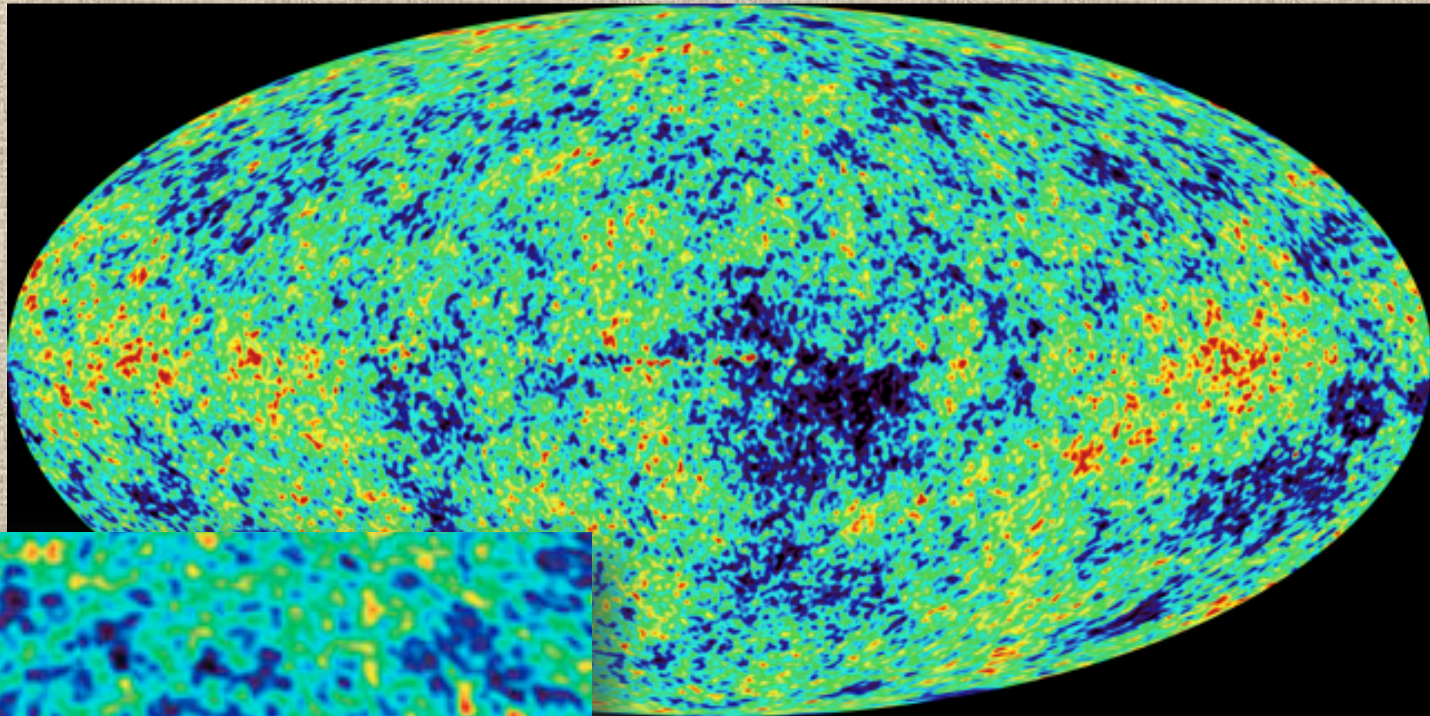
2dFGRS: 220,000 redshifts

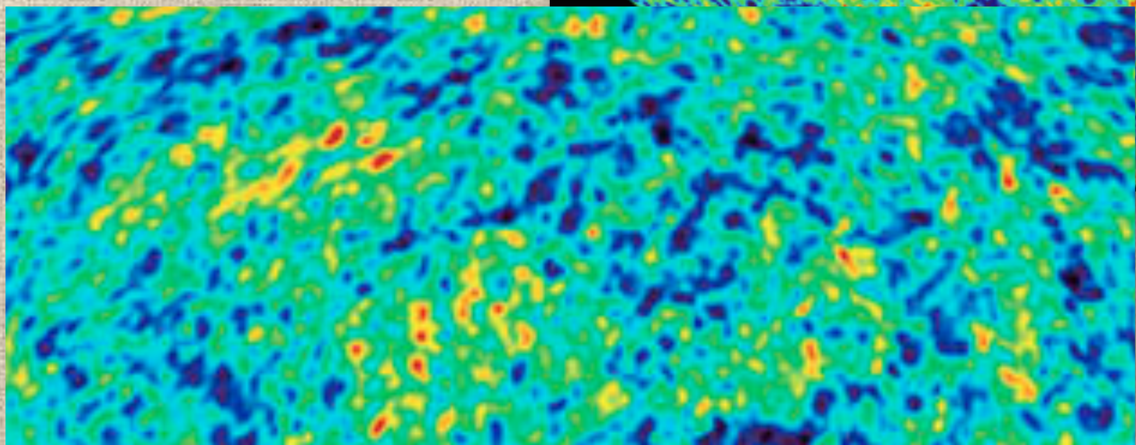
The clustering power spectrum: scale-dependence of inhomogeneities



Inhomogeneities in the Cosmic Microwave Background

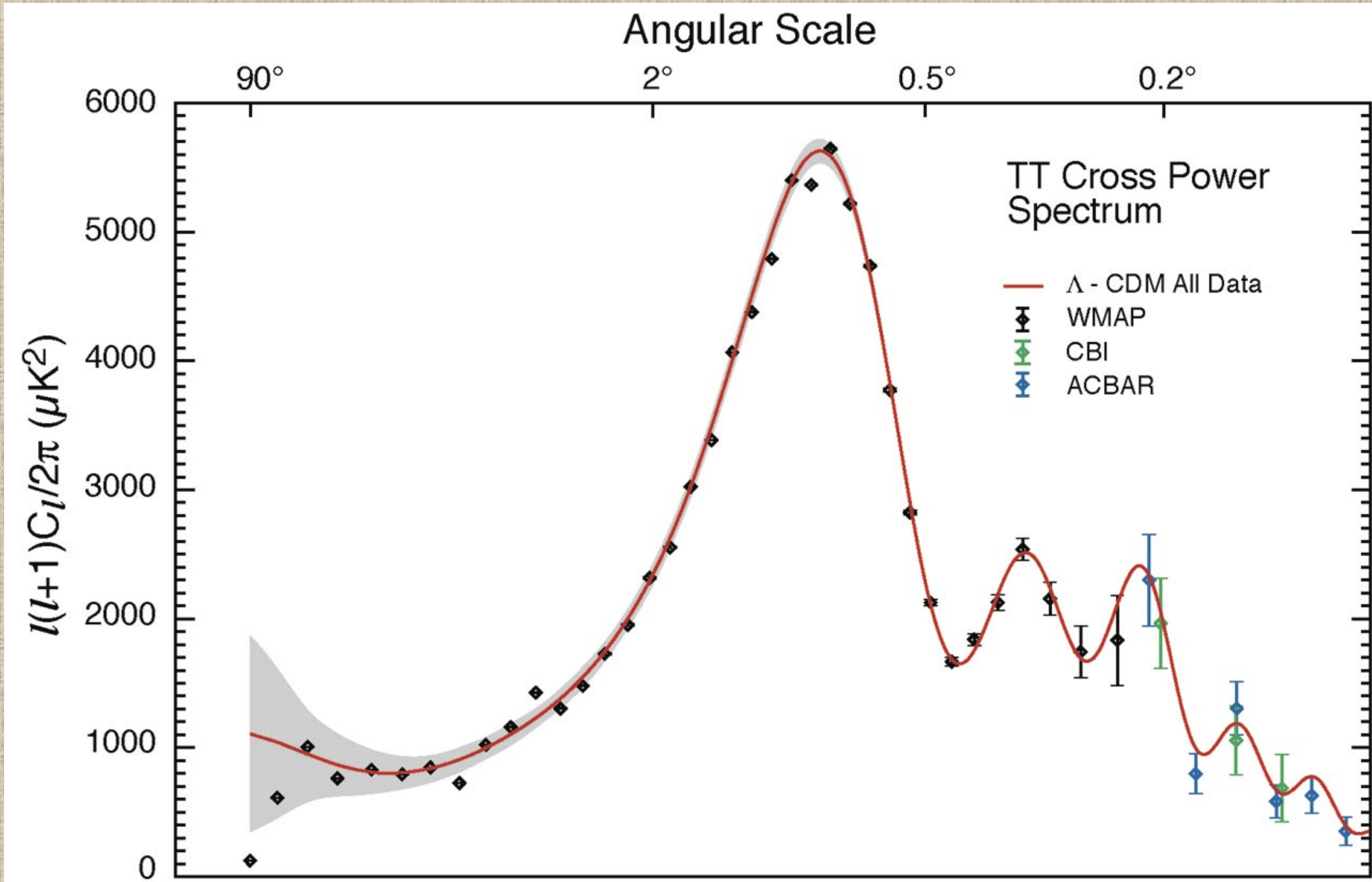
(WMAP, e.g. Bennett et al. 2003, Dunkley et al. 2009, Komatsu et al. 2009)





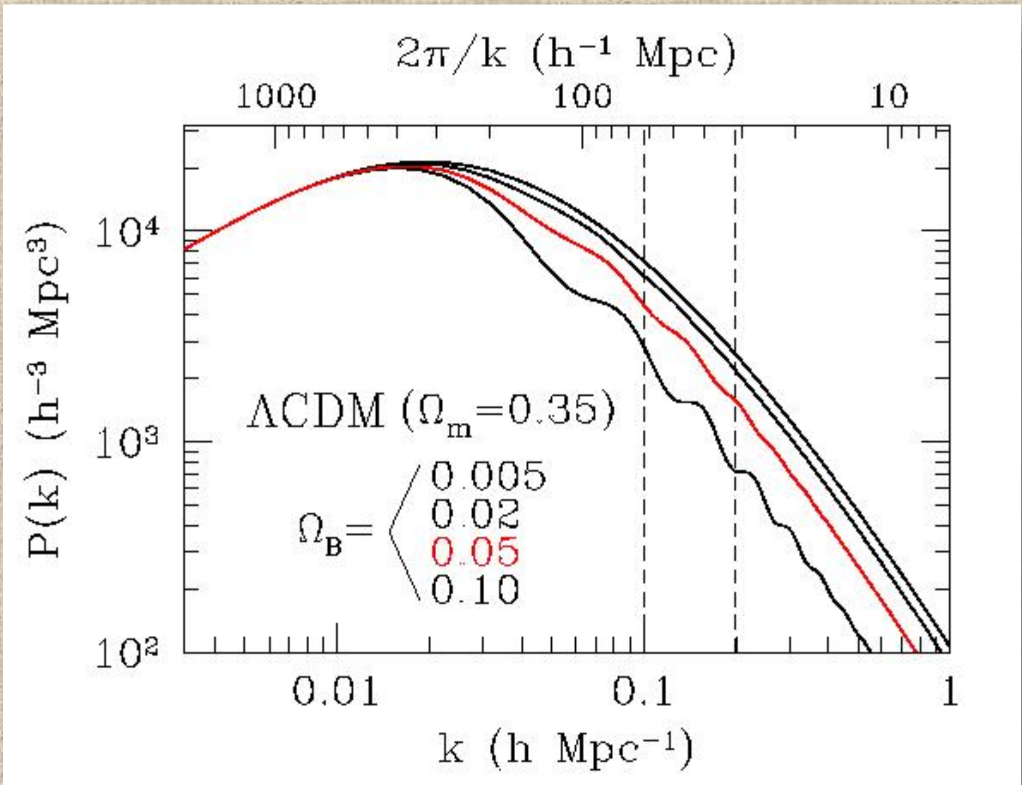
Fluctuations on all scales, however, one characteristic angular scale

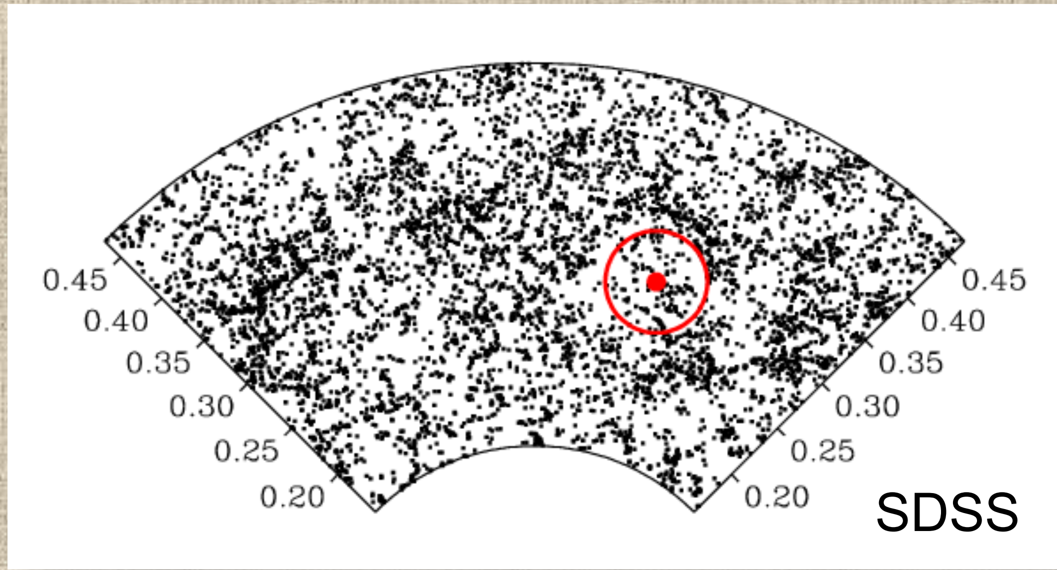
Acoustic Oscillations in the CMB



e.g. Komatsu et al. 2009 WMAP.

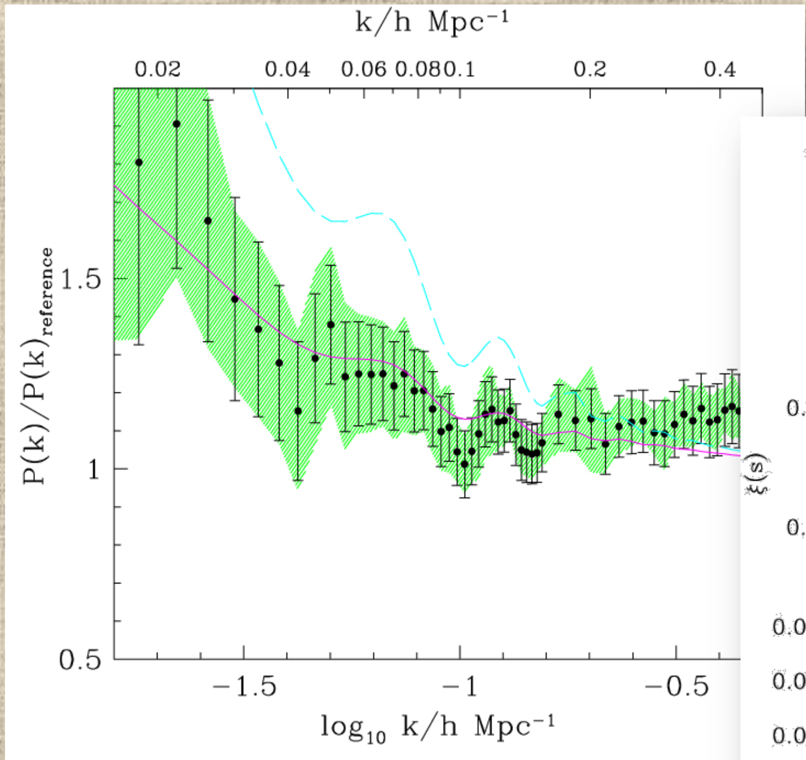
Baryonic Acoustic Oscillations imprint in the galaxy distribution



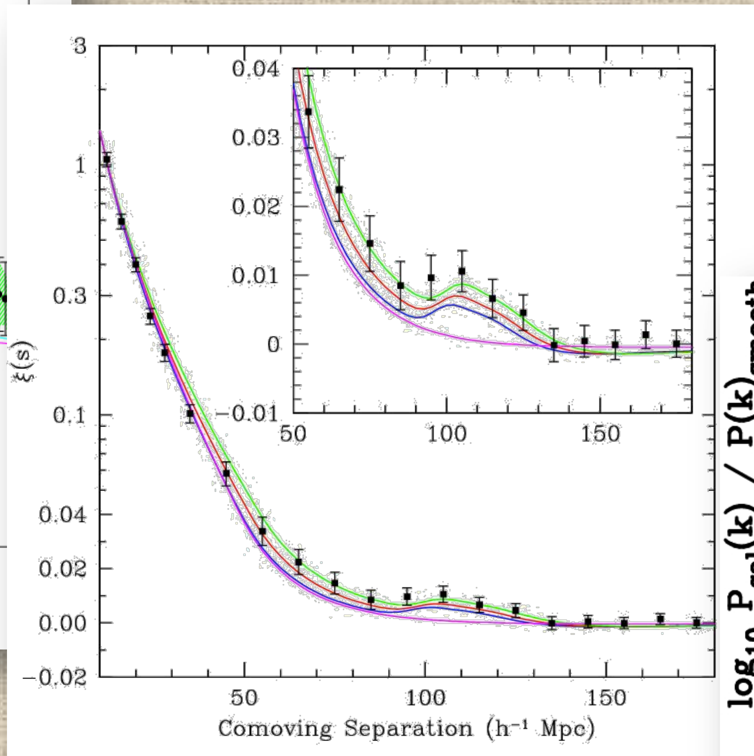


D. Eisenstein 2007

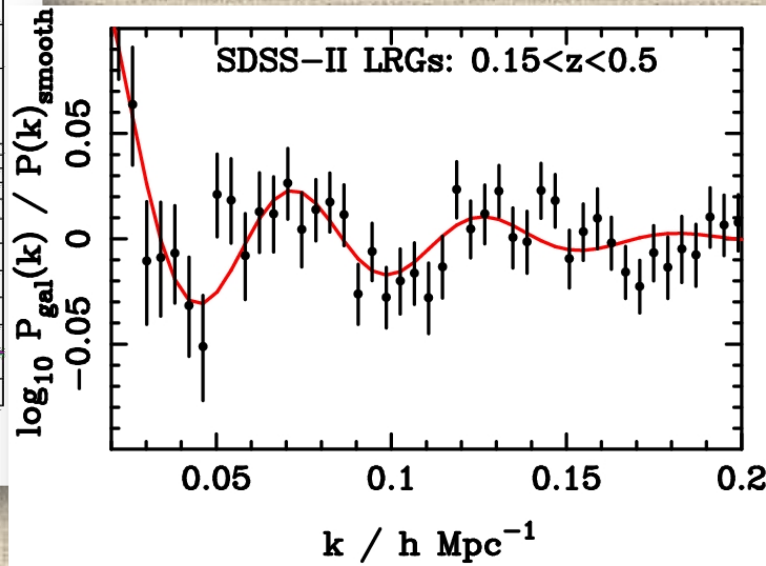
BAO detections from spectroscopic samples



2dFGRS: Cole et al 2005, MNRAS, 362, 505

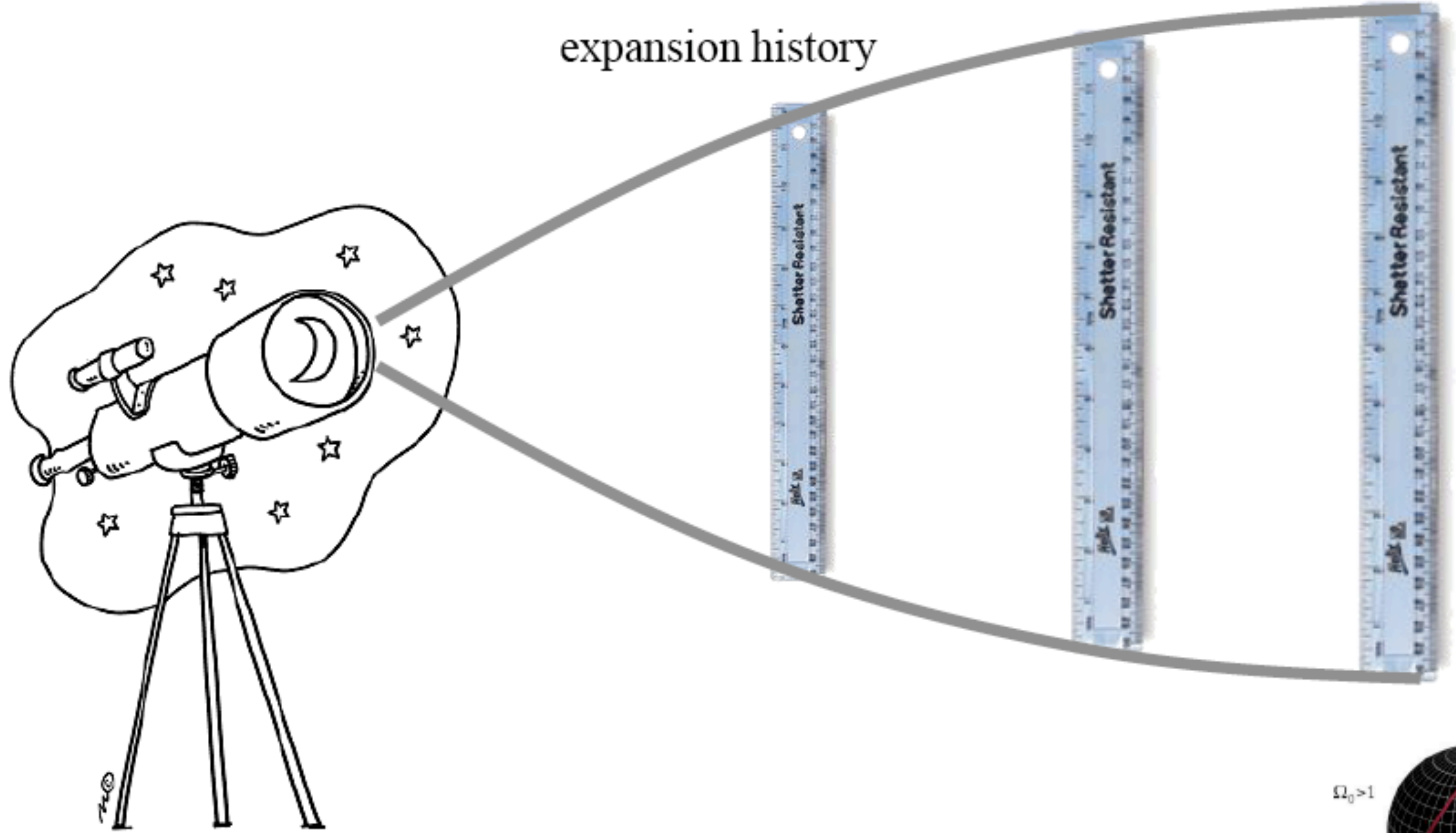


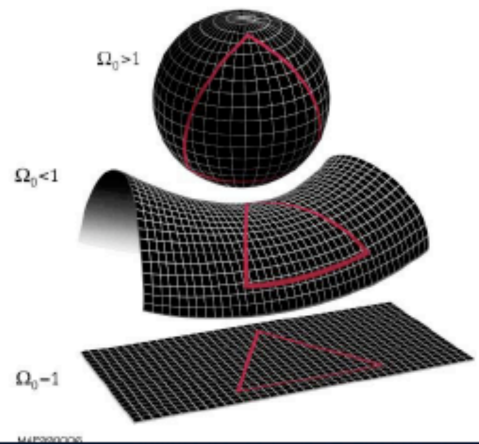
SDSS-LRG: Eisenstein et al 2005, ApJ, 633, 560



SDSS2-DR7: Percival et al 2010, MNRAS, 401, 2148

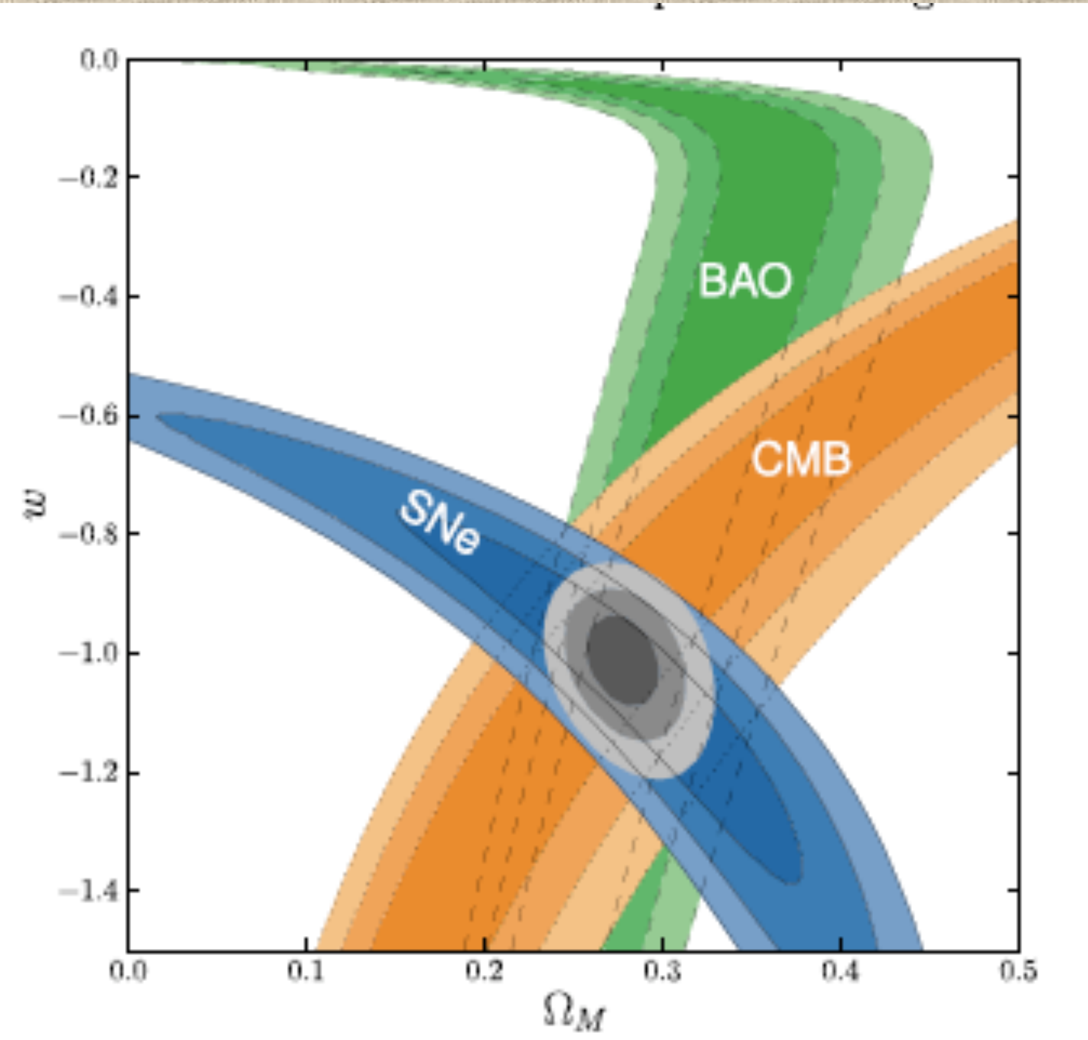
Baryonic Acoustic Oscillations: measure H(z) from redshift surveys



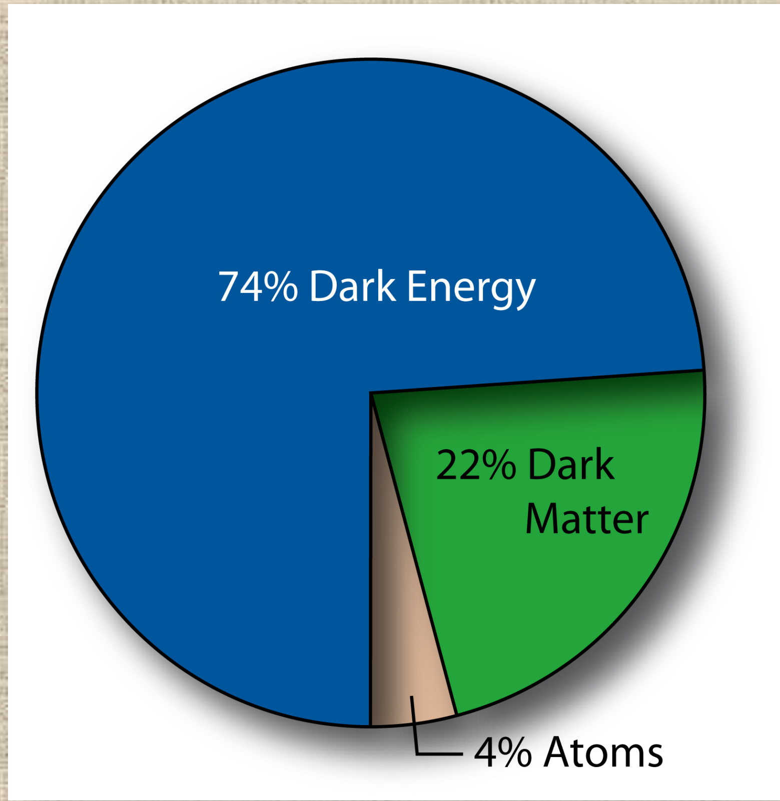


Give $D_A(z)$ and $H(z)$: see Percival et al. arXiv:0907.1660 for most recent application to SDSS and 2dFGRS

Cosmic concordance: a w=-1 Universe?



Amanullah et al. 2010 (Union supernovae)



DOES THEN UNDERSTANDING COSMIC ACCELERATION SIMPLY MEAN FINDING WHETHER $w=w(z)$?

Not only: we need to look at both sides of the story…

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

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

Add dark energy

"…the Force be with you"

So, the equation of state is not the end of the story…

Cosmic acceleration can also be explained by modifying the theory of gravity [as e.g. in *f(R)* theories, Capozziello et al. 2005, or in multi-dimensional "braneworld" models, Dvali et al. (DGP) 2000].

→ How to distinguish between these two options, observationally?

Growth of linear density fluctuations $\delta=\delta\rho/\rho$ in the expanding Universe (in GR):

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

which has a growing solution:

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

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

growth rate

→ 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 gravitation theory (e.g. Lue et al. 2004)

→ [N.B. There is also a third possibility, i.e. that we are not applying GR correctly to the inhomogeneous Universe , e.g. Buchert 2008, GeRGr, 40, 467] *(Backreaction)*]

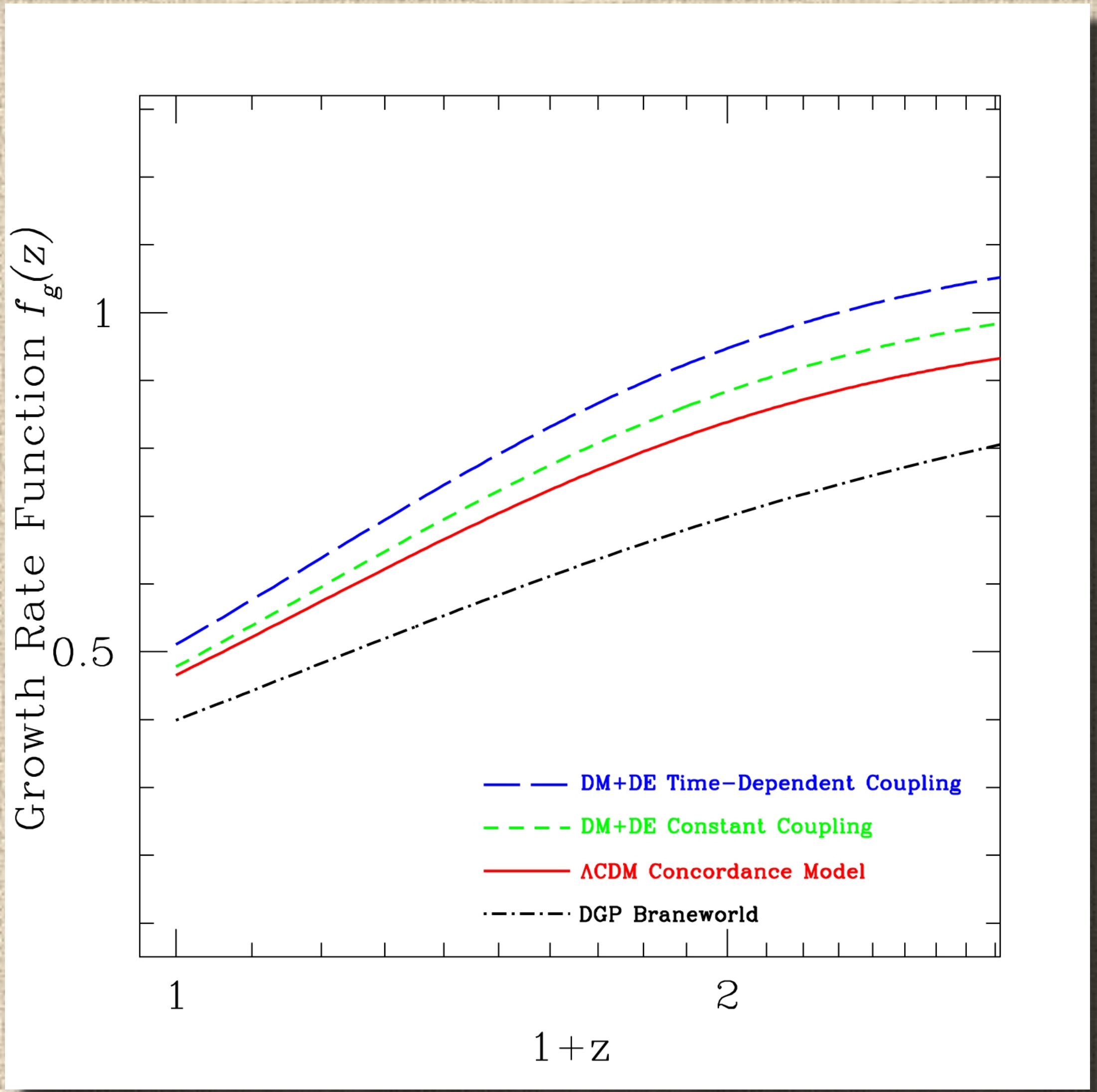
Measurements of the growth rate evolution $f(z)$ break the degeneracy between models with same effective expansion history [thus same $w(z)$], but completely different physics (however, see Kunz & Sapone 2007)

For a wide variety of models

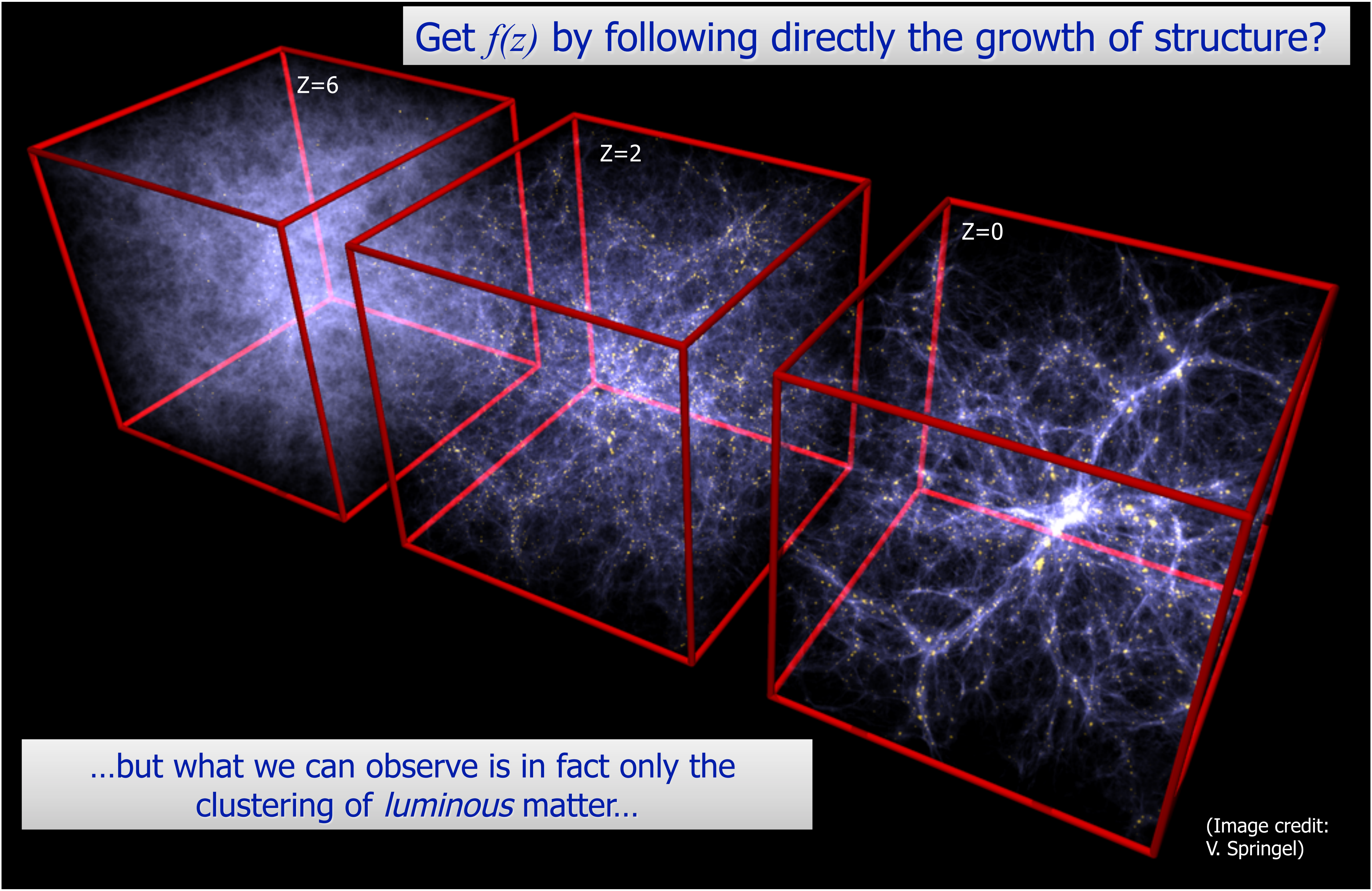
$$f(z)=[\Omega_m(z)]^{\gamma}$$

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

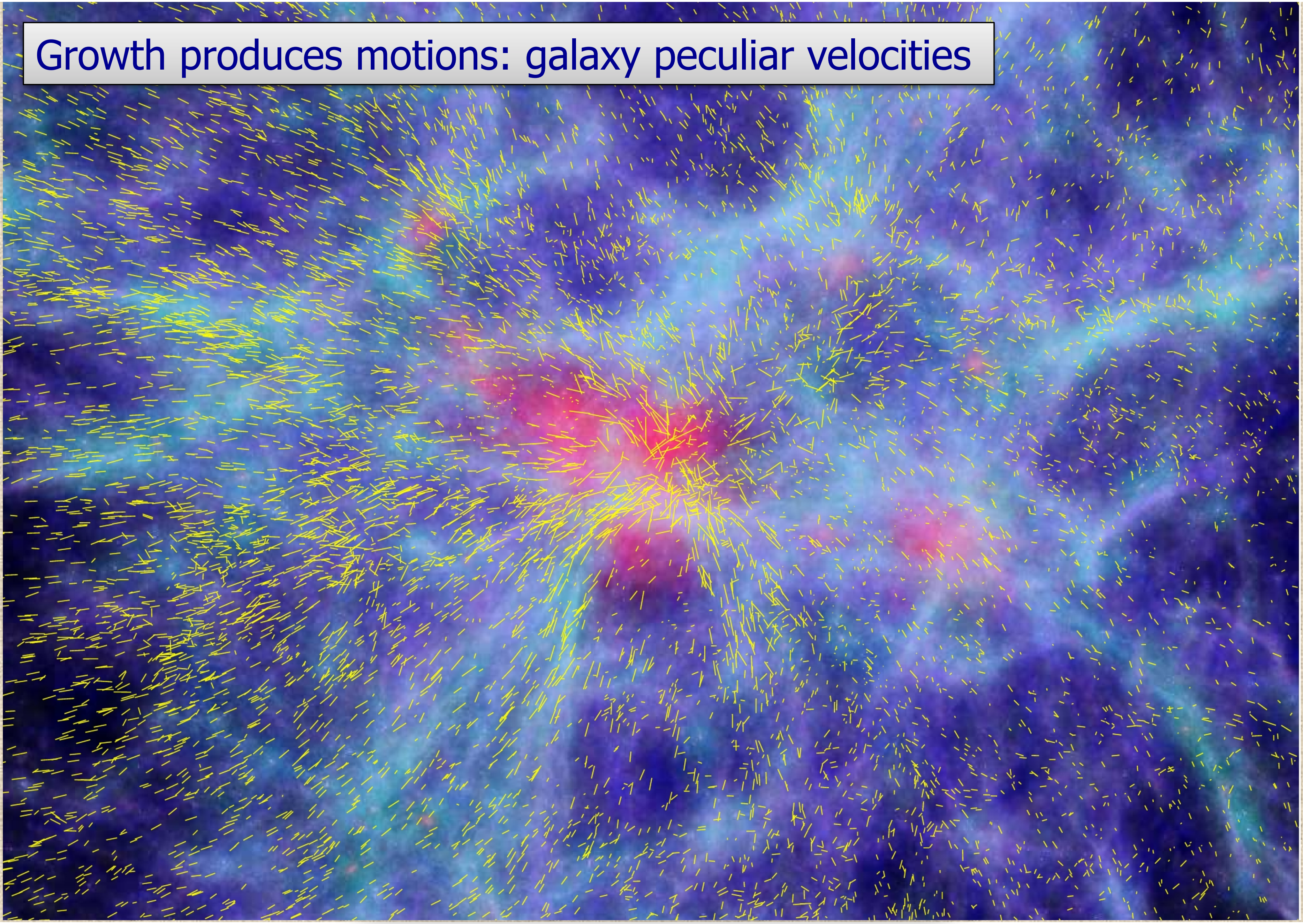
e.g.
γ=0.55 for standard Λ
γ=0.68 for DGP braneworld



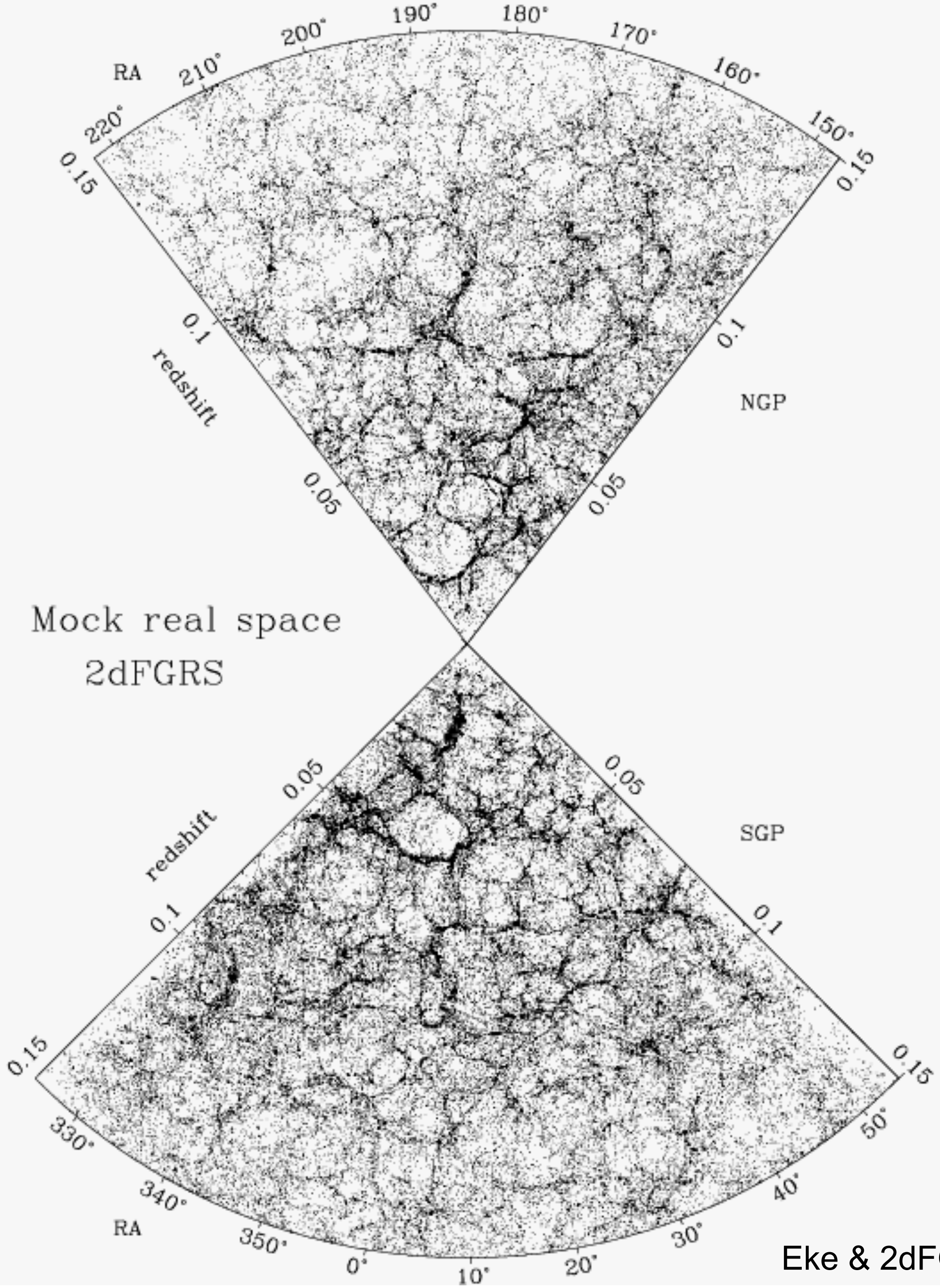
How do we measure $f(z)$?


Get $f(z)$ by following directly the growth of structure?
Z=6
Z=2
Z=0
…but what we can observe is in fact only the clustering of *luminous* matter…
(Image credit: V. Springel)

Growth produces motions: galaxy peculiar velocities



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

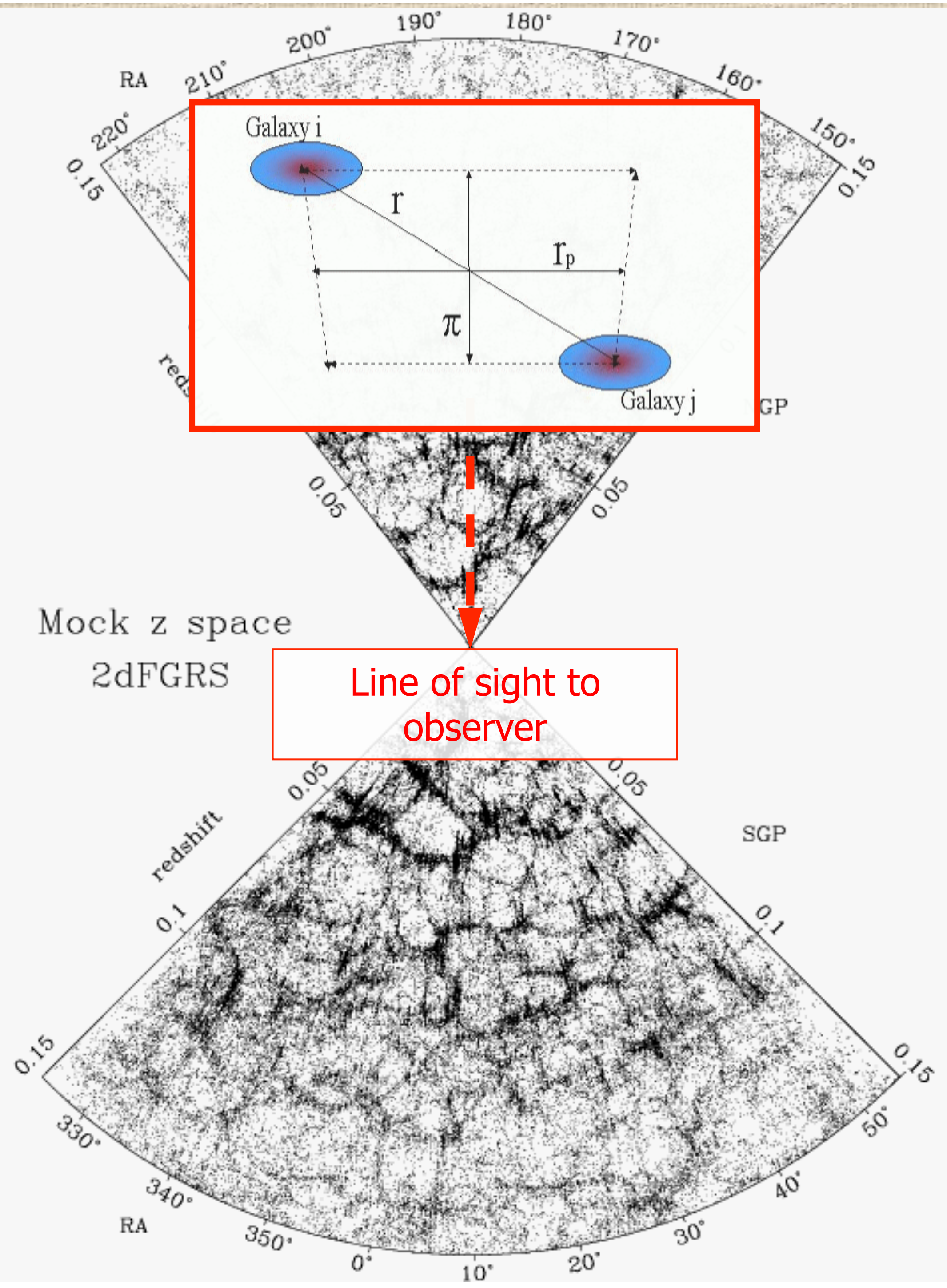


real space

(Kaiser 1987)

Eke & 2dFGRS 2003

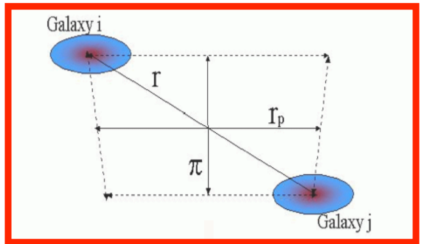
Peculiar velocities manifest themselves in galaxy redshift surveys as *redshift-space distortions*



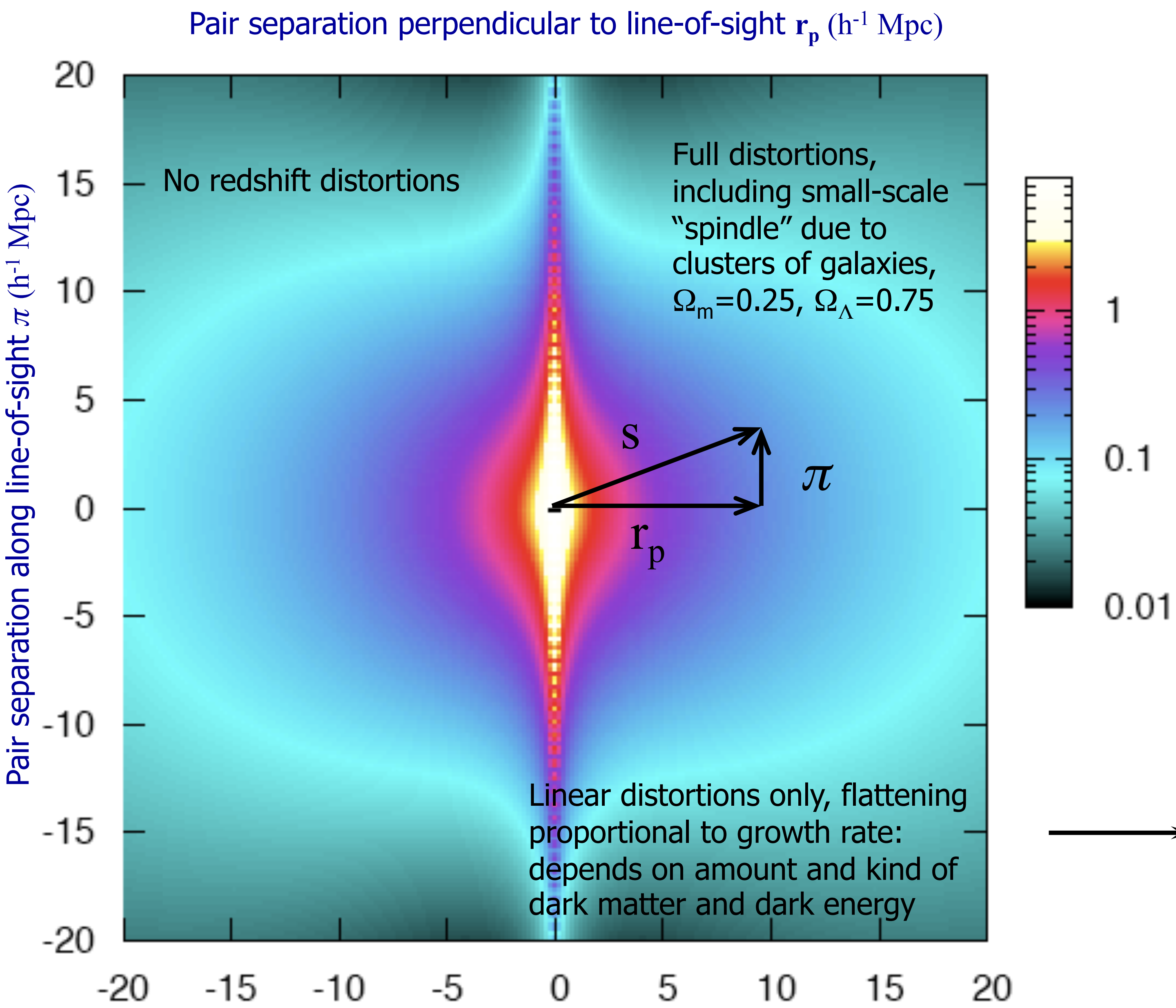
redshift space

(Kaiser 1987)

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



Line of sight to observer



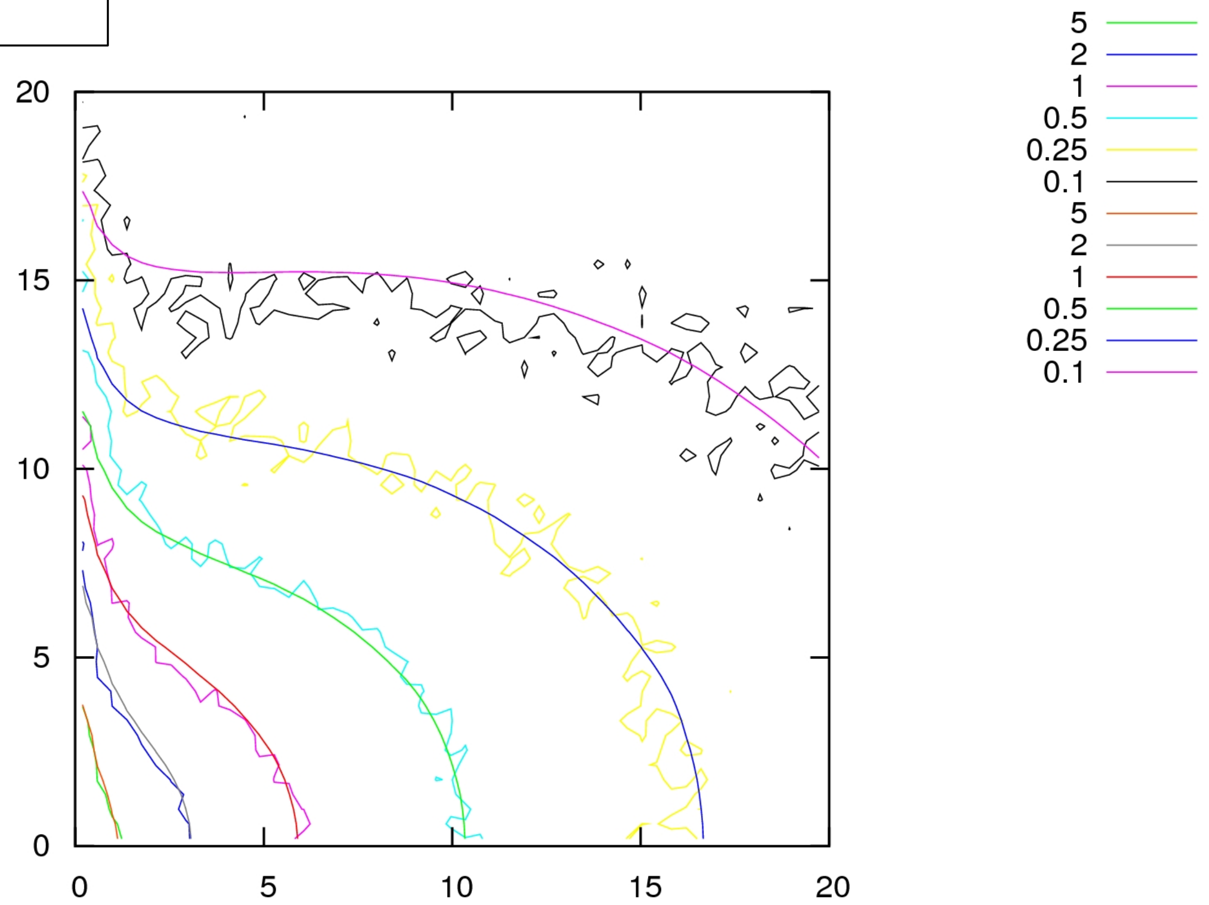
$f = b_L \beta$

Compression parameter β (Kaiser 1987)

Extract β through Kaiser/Hamilton linear redshift-distortion model

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

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



At z~0, e.g. from 2dFGRS Peacock et al. 2001, Hawkins et al. 2003

→Use redshift-space distortions to trace the growth of structure *f(z)* at different epochs

→Coupled to measurements of H(z) (from BAO or Supernovae), break the "*dark energy vs modified gravity*" degeneracy

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

See also parallel paper by Pengjie Zhang et al., Phys. Rev. Lett. 99, 141302 (2007), proposing combination of lensing and z-distortions

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]

Observations of distant supernovae indicate that the Universe is now in a phase of accelerated expansion[1,2] the physical cause of which is a mystery[3]. Formally, this requires the inclusion of a term acting as a negative pressure in the equations of cosmic expansion, accounting for about 75 per cent of the total energy density in the Universe. The simplest option for this 'dark energy' corresponds

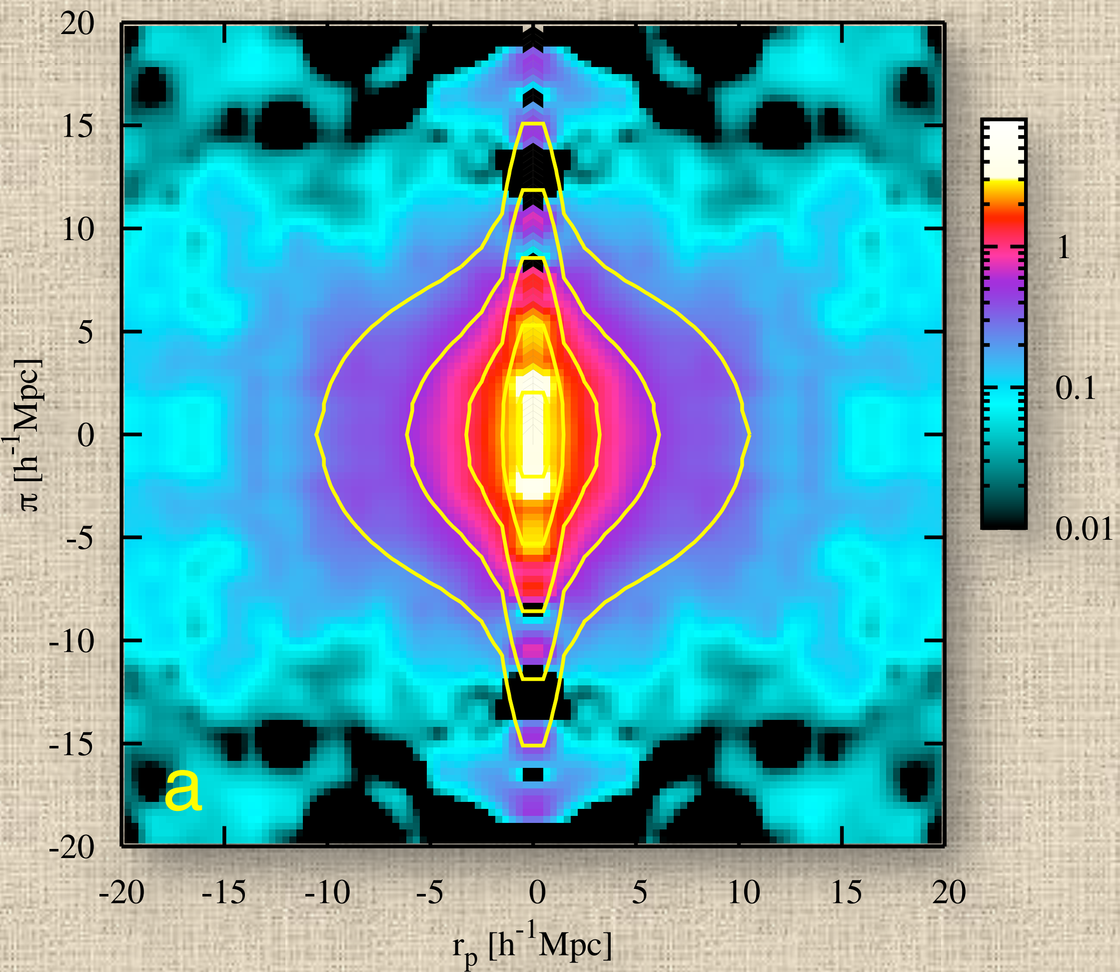
linear growth rate f that measures how rapidly structure is being assembled in the Universe as a function of cosmic time, or, equivalently, of the redshift. The redshift $z = \lambda_{meas}/\lambda_{emis} - 1$ of the radiation emitted by a distant object is a measure of the time of emission through its dependence on the cosmic scale factor $a(t)$, which is $1 + z = 1/a(t_{emis})$. $f(z)$ essentially depends on the value of the mass

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

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

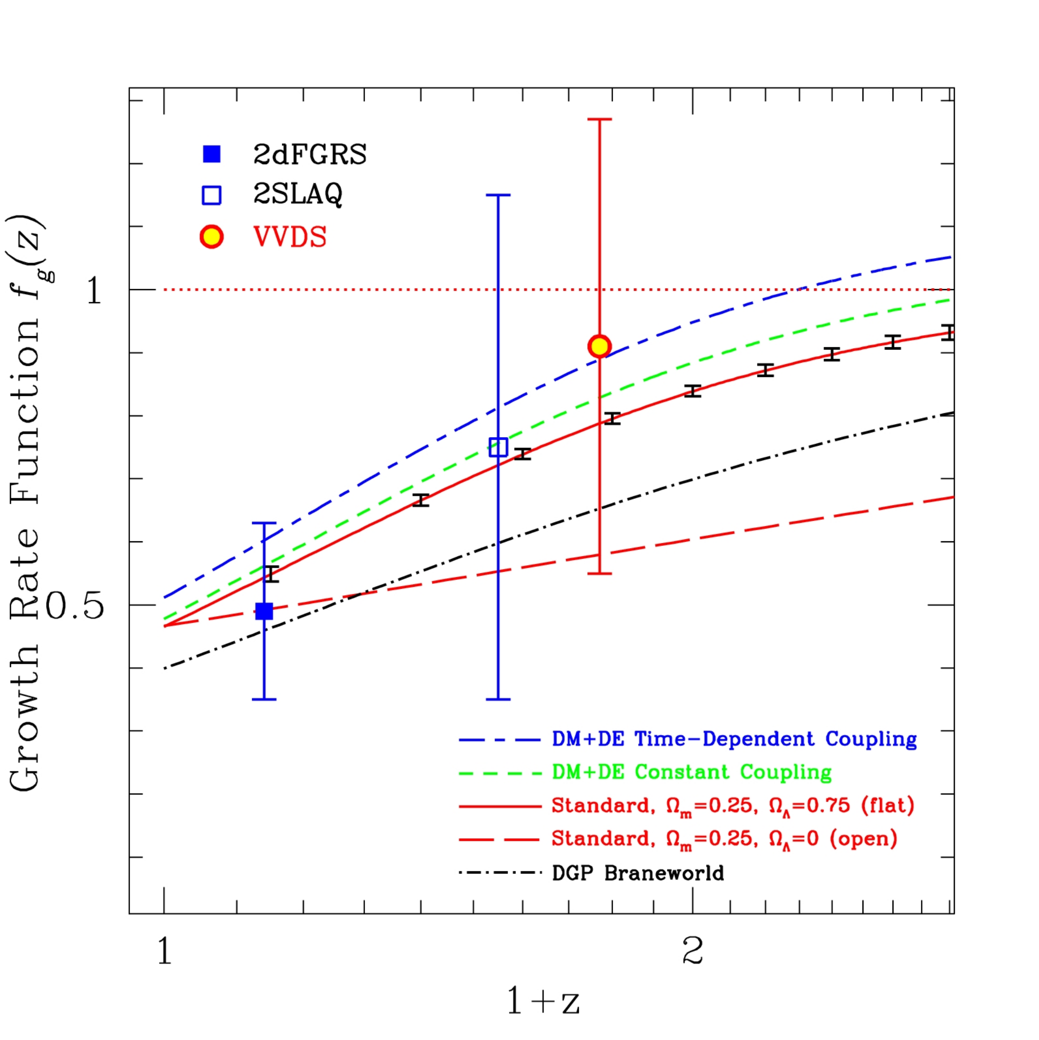
$\boxed{\beta=0.70\pm0.26}$



Guzzo et al. 2008, Nature 451, 541

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

$$f = b_L \beta$$



VVDS-Wide @ z=0.77:

$\boxed{f = 0.91 \pm 0.36}$

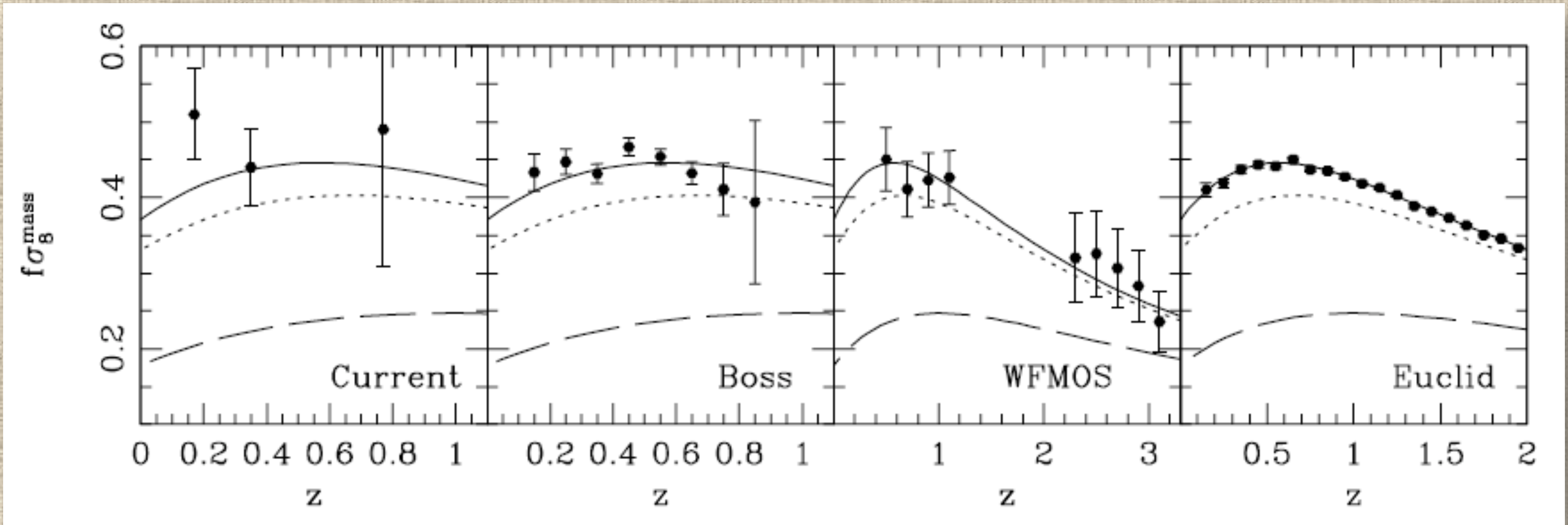
DGP: Lue et al. 2004; DM+DE models: Di Porto & Amendola 2007

What are redshift distortions probing in practice?

- Song & Percival 2009 (arXiv:0807.0810)

All from model (+CMB) *All observables*

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



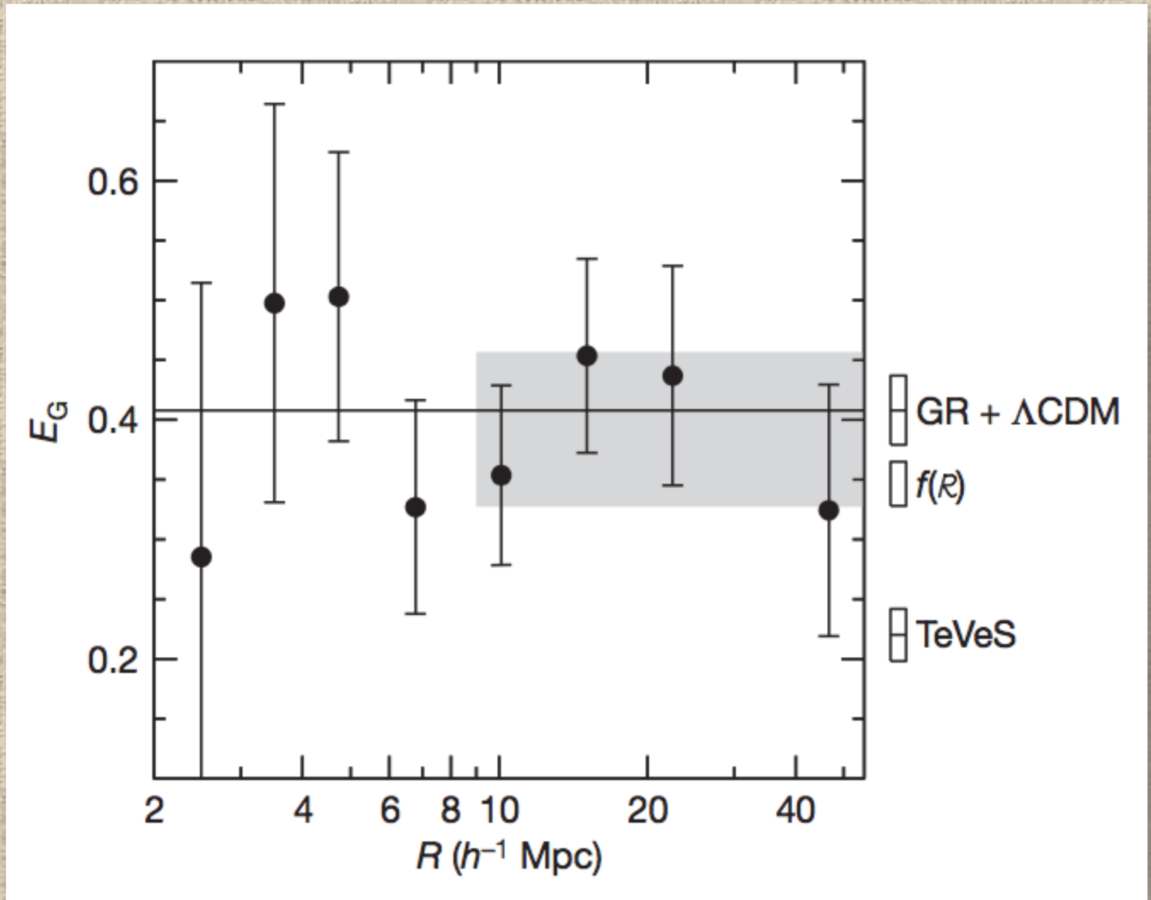
- Percival & White 2009 (arXiv:0808.0003); White, Song & Percival 2009

Variation on a theme: combine redshift distortions and lensing (P. Zhang method)

(Reyes et al. 2010, Nature, 464, 256)

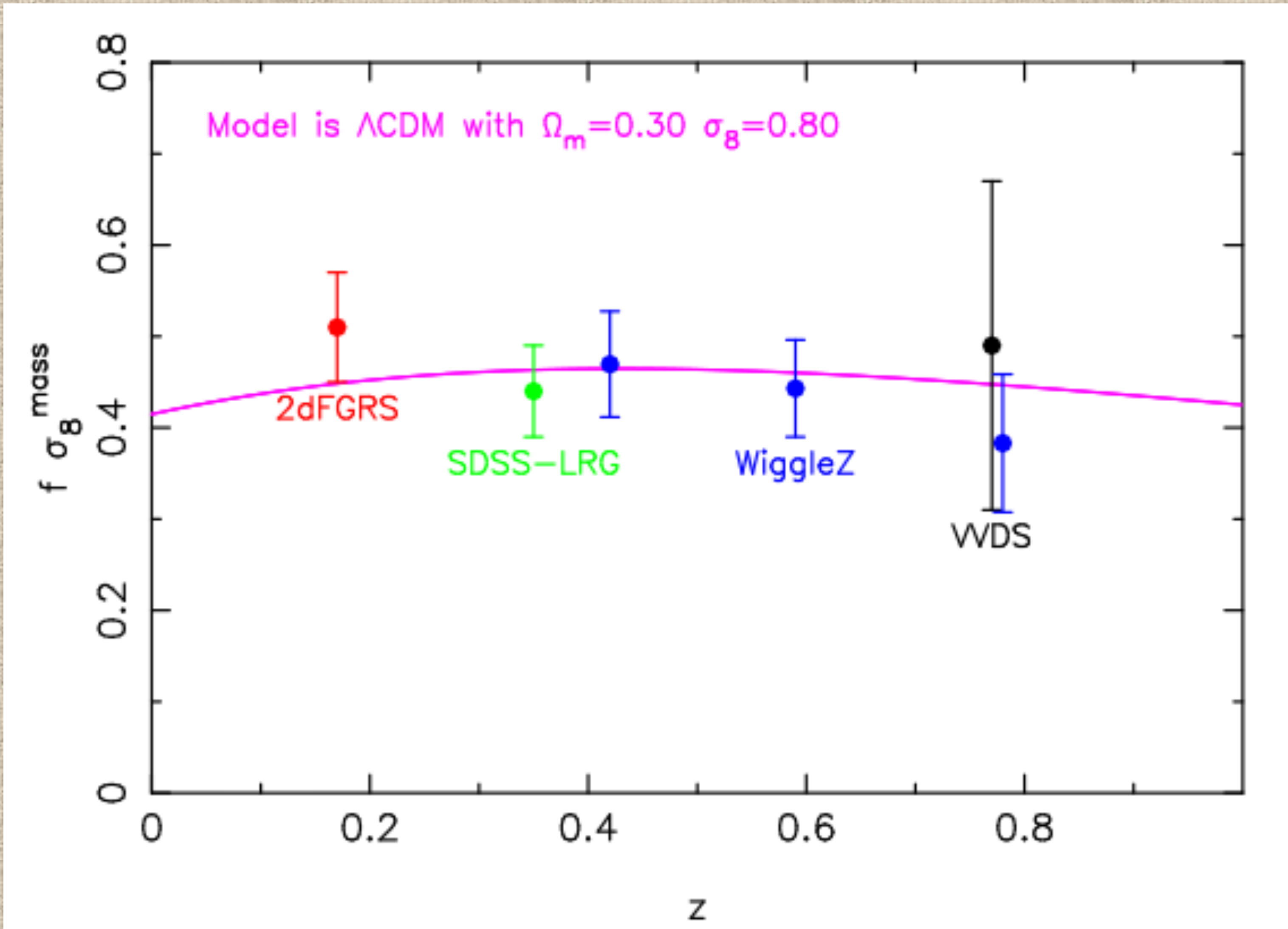
- Combine measurement of β with weak lensing to get rid of the bias, building the quantity

$$E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{gm}(R)}{\Upsilon_{gg}(R)}$$



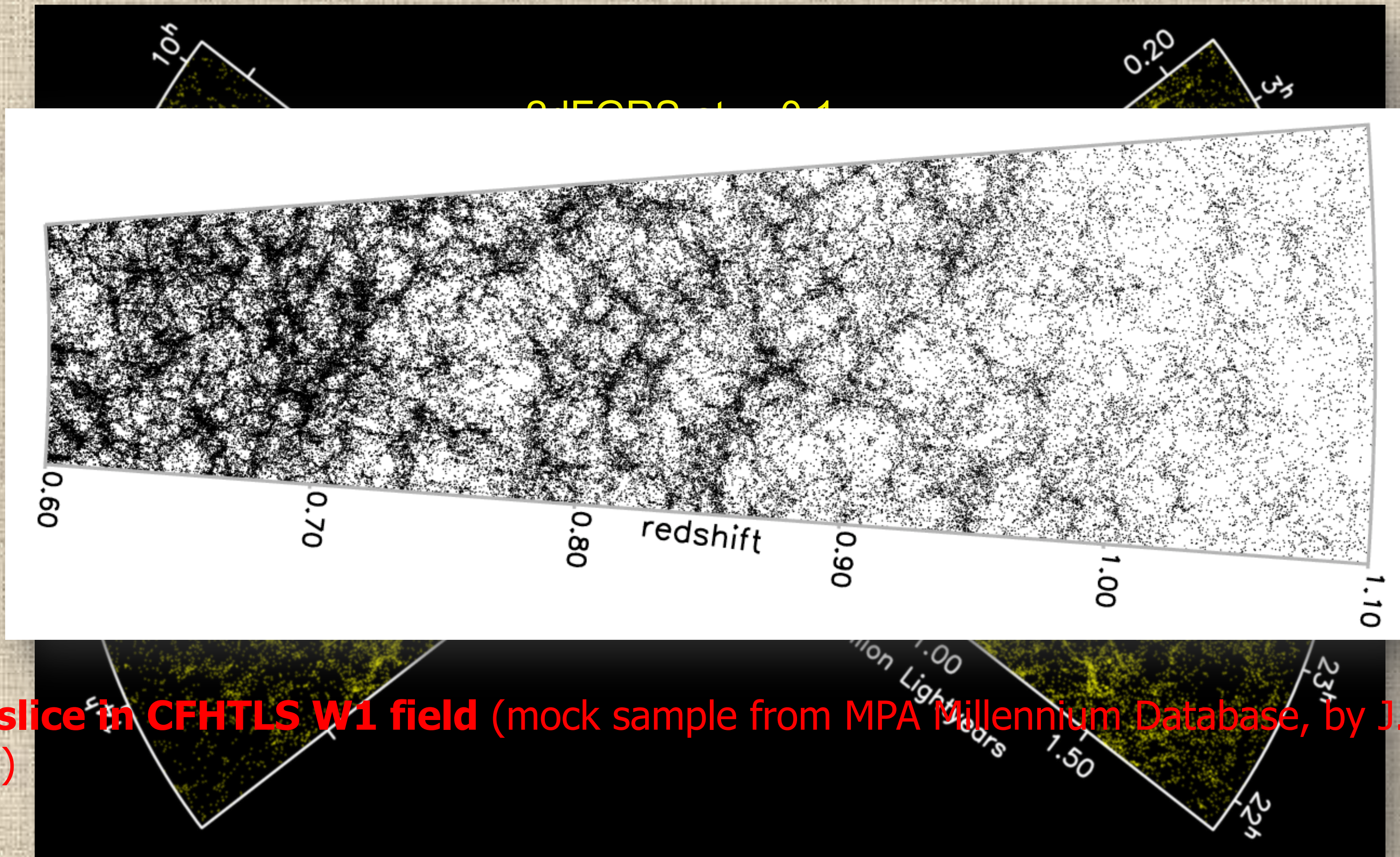
f(z) from redshift distortions, recent developments

Blake et al. 2010, arXiv:1003.5721



- WiggleZ survey, 56,000 redshifts 0.4<z<0.8 (aim at 200,000 gals)
- Main goal: BAOs
- Redshift distortions from P(k): **preliminary analysis** (e.g. f estimated for fixed Ω_m, which is sort of circular)
- Large volume, but very sparse sample
- UV-selected emission-line galaxies from GALEX: complex selection function

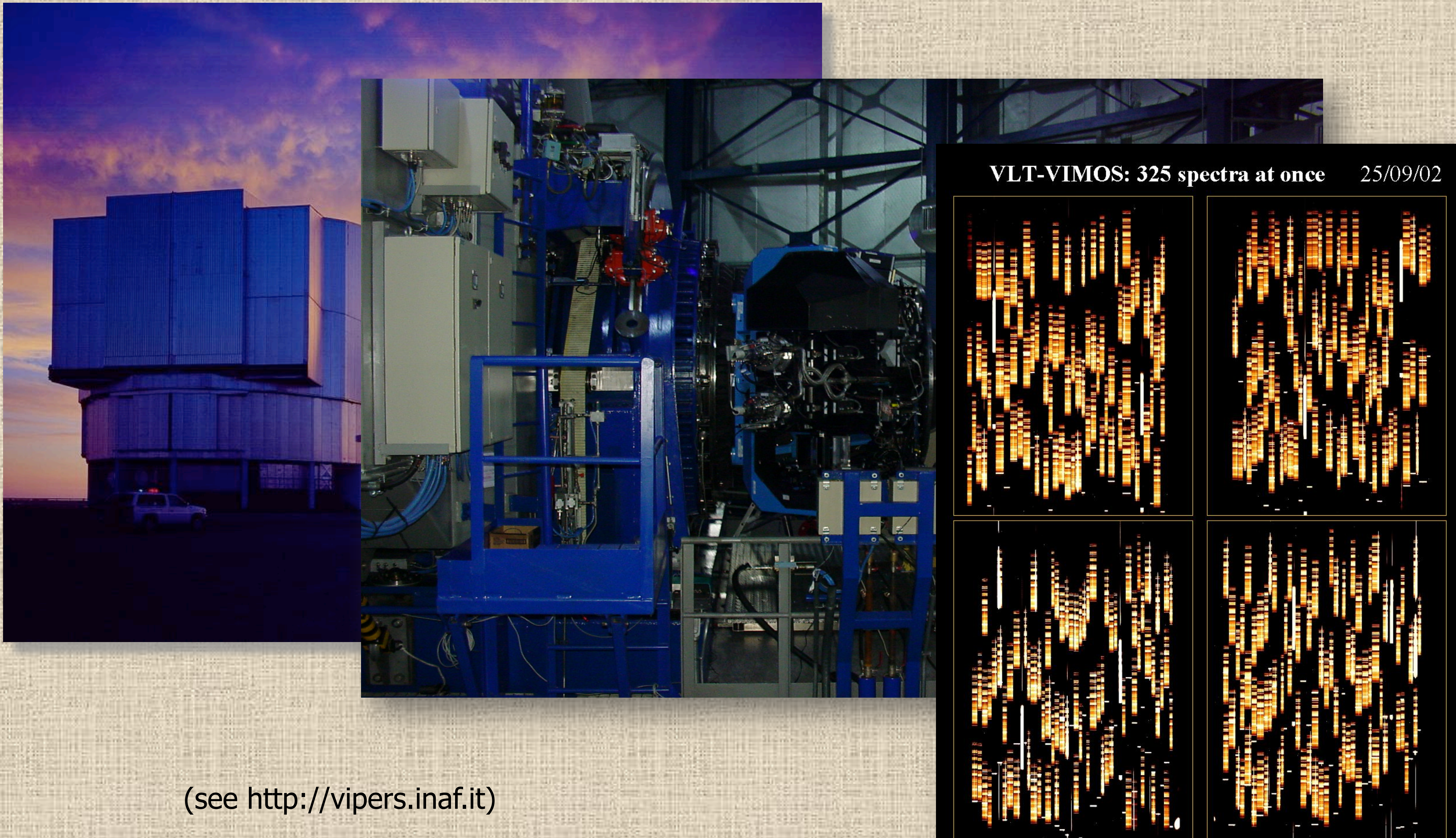
However, surveys like 2dFGRS provided a much more comprehensive view of large-scale structure and its relation to galaxies…



2x8 deg2 slice in CFHTLS W1 field (mock sample from MPA Millennium Database, by J. Blaizot & G. De Lucia)

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

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



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

VIPERS Team

- **MILANO OAB (PI)**: L. Guzzo, B. Granett, A. Iovino, U. Abbas (Turin), G. De Lucia (Trieste)
- **MILANO IASF (data reduction center)**: B. Garilli, M. Scodeggio, D. Bottini, P. Franzetti, D. Maccagni, L. Paioro, M. Polletta, L. Tasca
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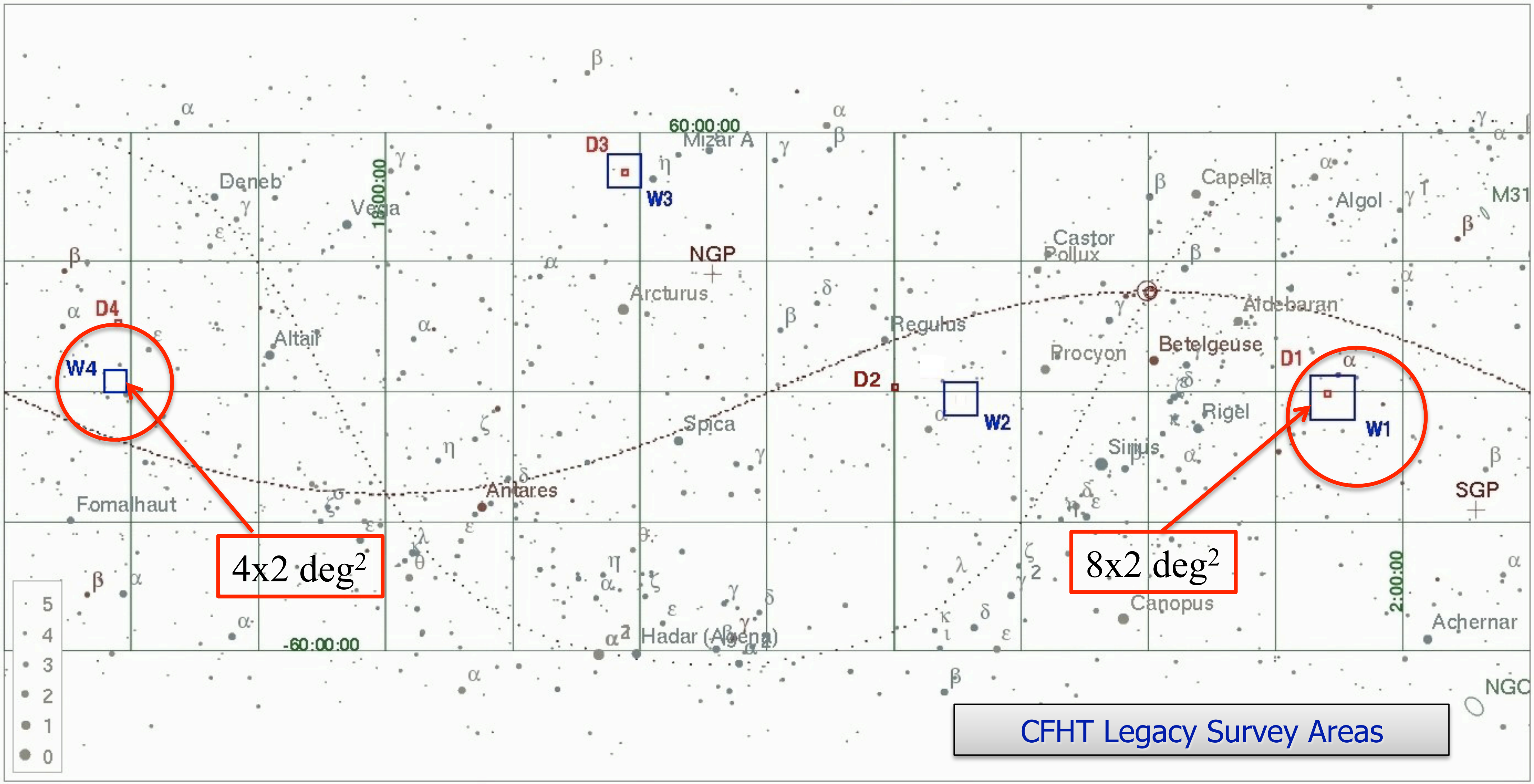
- **MARSEILLE**: O. Cucciati, O. Ilbert, O. Le Fevre, V. Le Brun, C. Adami, C. Marinoni, J. Bel, J. Blaizot (Lyon)
- **PARIS (TERAPIX CFHTLS center)**: H. McCracken, Y. Mellier, J. Coupon (Tokyo)
- **PORTSMOUTH**: W. Percival, R. Tojeiro, R. Nichol
- **WARSAW**: A. Pollo, J. Krywult, K. Malek

VIPERS in a nut-shell

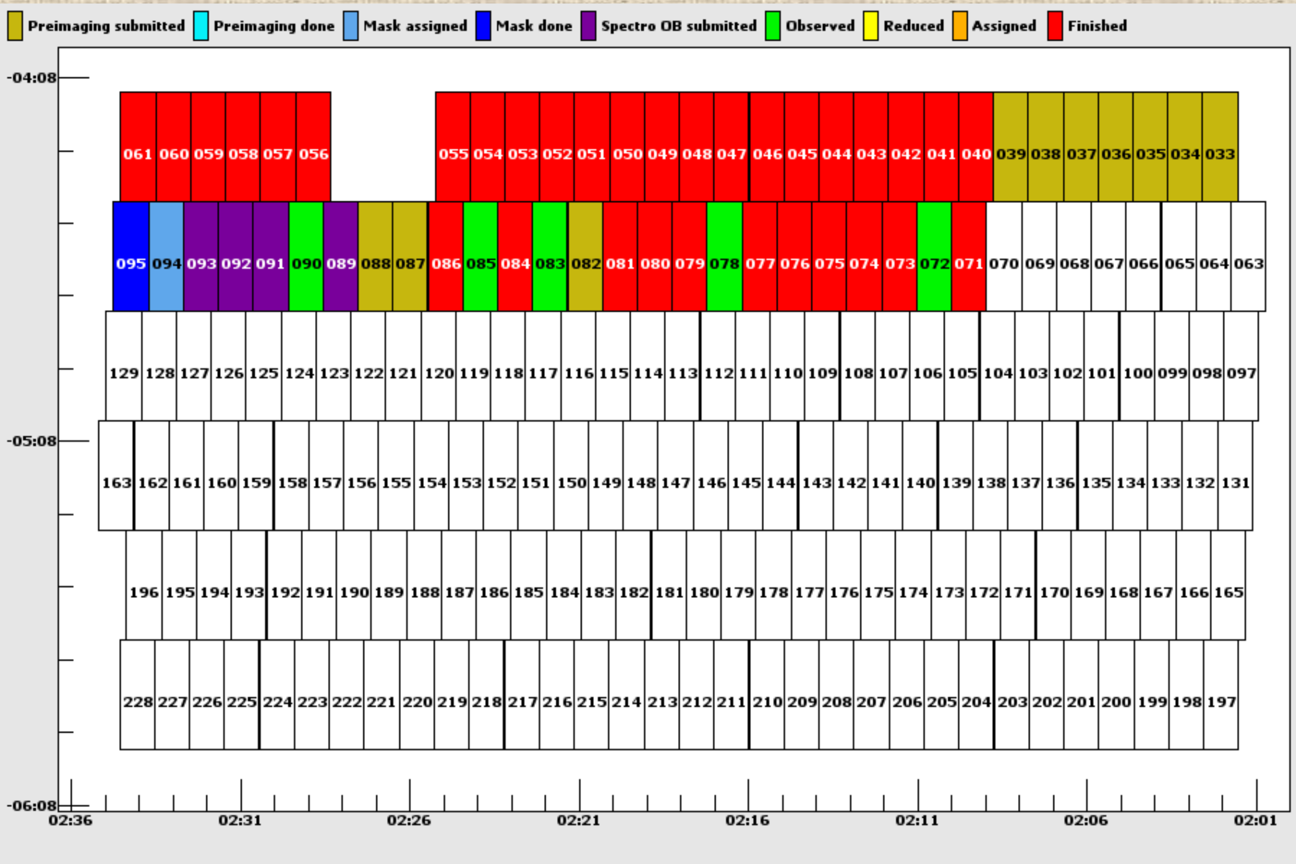
- 440.5 VLT hours
- ~24 deg^2 over W1 and W4 CFHTLS wide fields (~16 + 8)
- I_{AB}<22.5, LR Red grism, 45 min exp.
- 288 VIMOS pointings
- z>0.5 color-color pre-selection
- PSF + SED –based star-galaxy separation (AGN color recovery)
- **~100,000 redshifts, >40% sampling**
- **Density and volume comparable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

Location of VIPERS fields

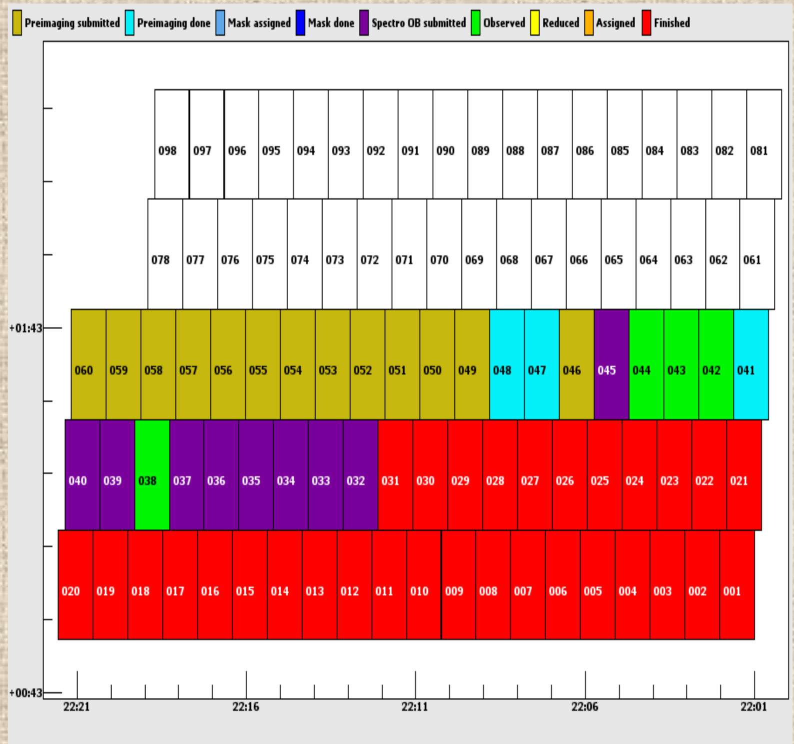


VIPERS coverage (as of today): ~24,000 spectra

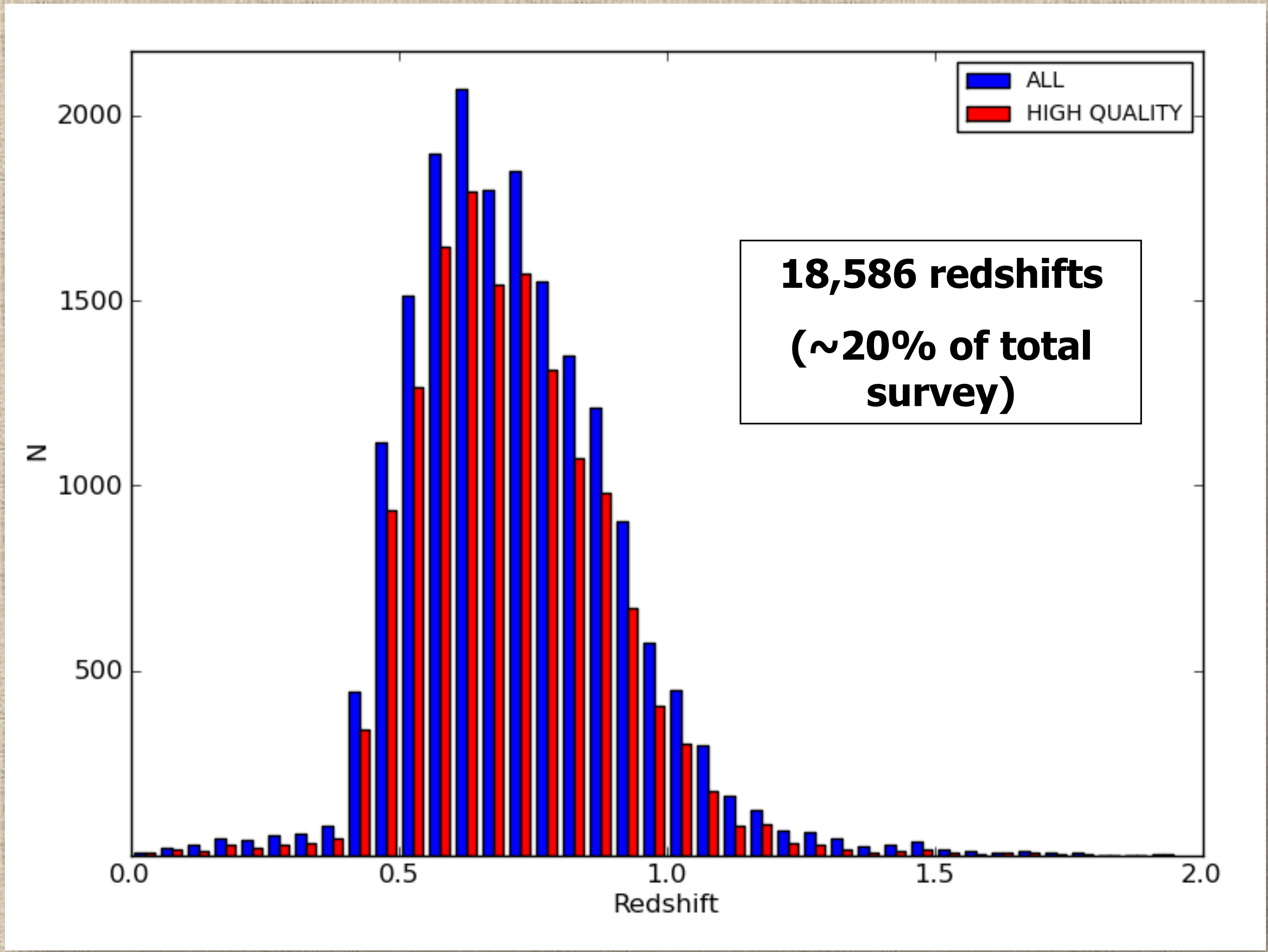
W1



W4

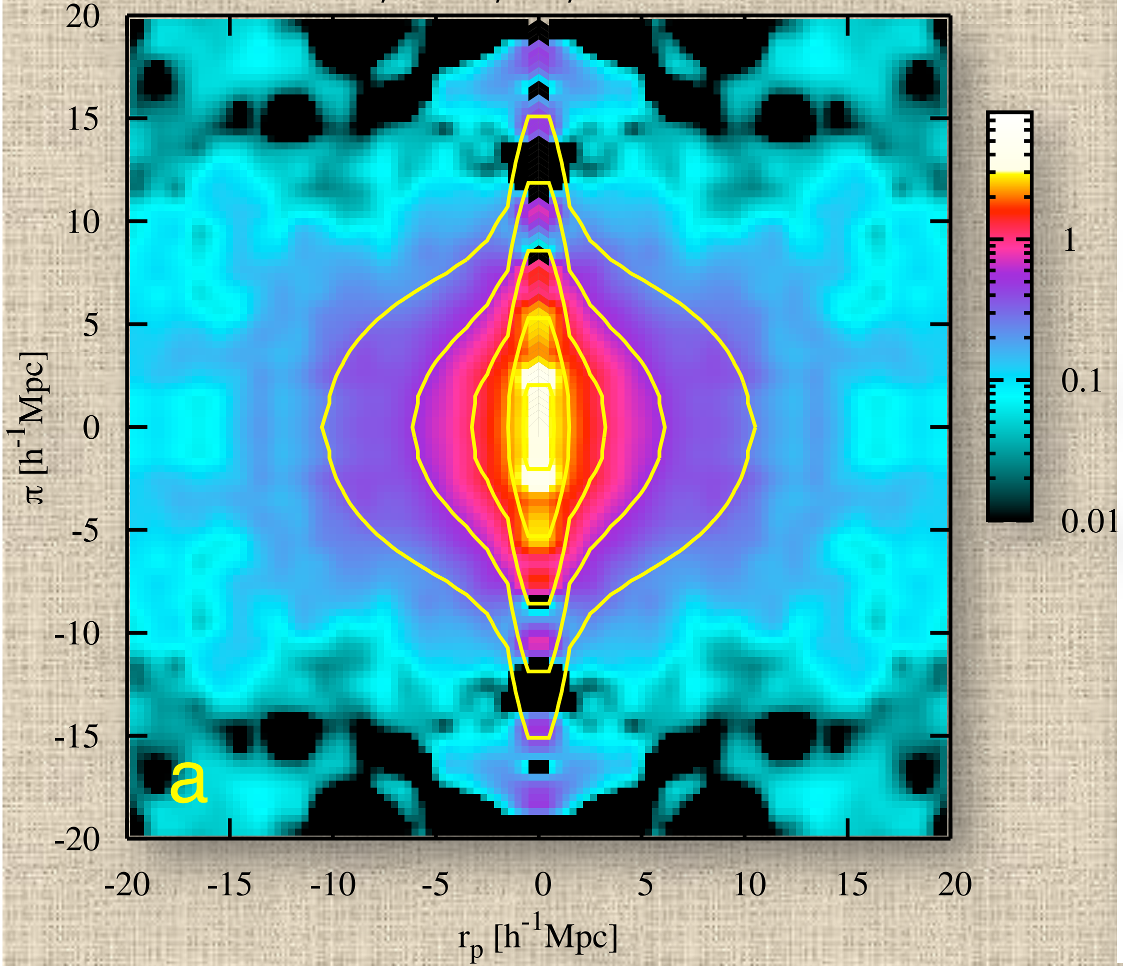


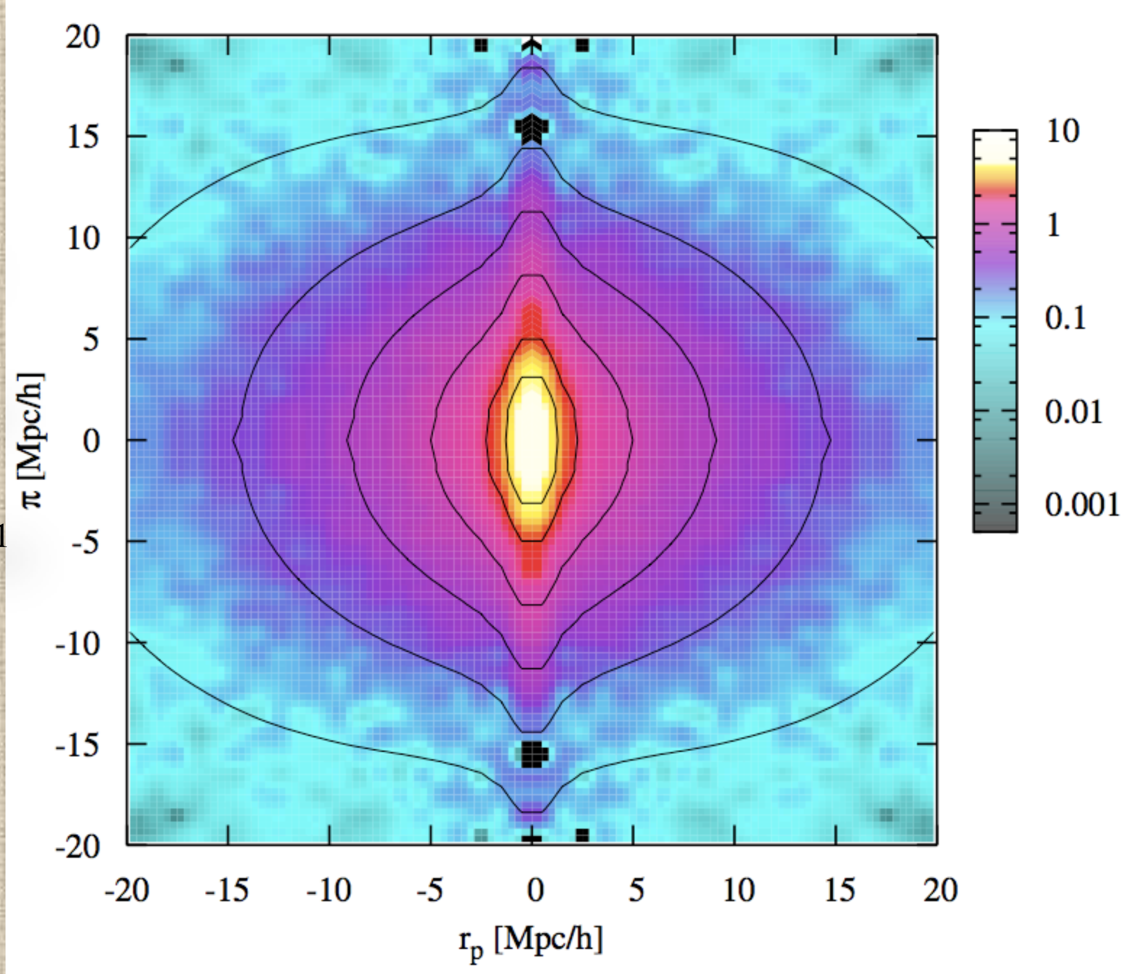
VIPERS redshift distribution (14 Jun 2010)



Expectations: growth rate from redshift-space distortions

Guzzo et al 2008, Nature, 451, 541

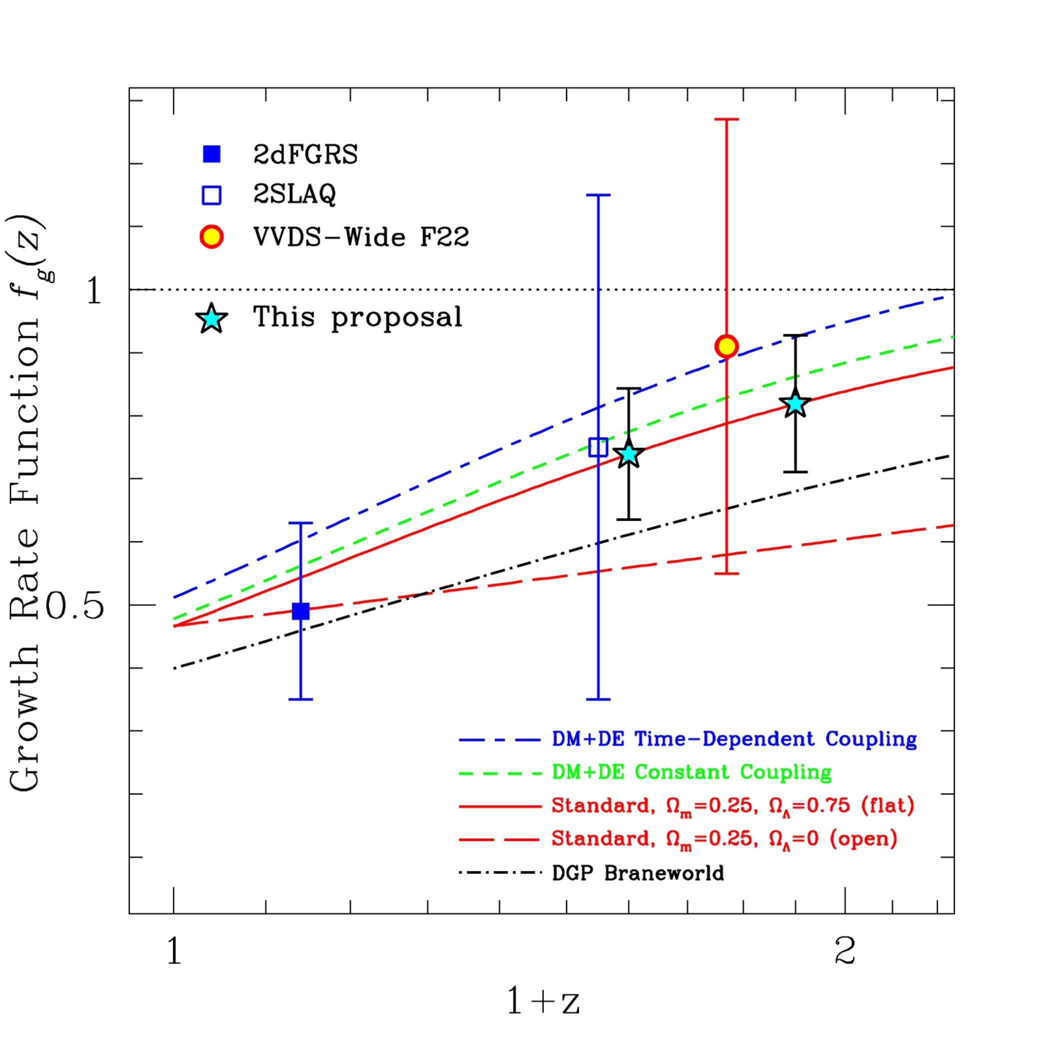




VVDS F22 (~6000 gals)

VIPERS (~100,000 gals)

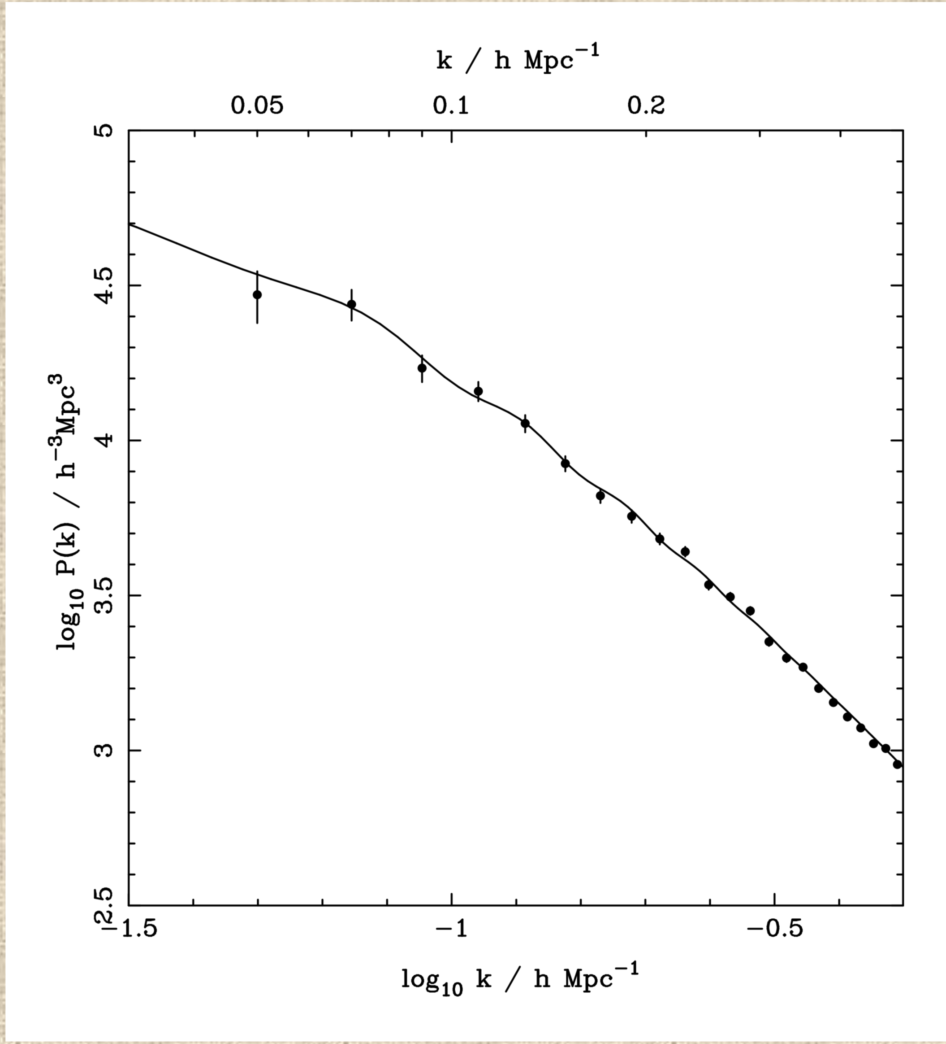
(Conservative) forecast on f(z) in two bins from VIPERS



- ~10% error using full population of galaxies
- However, specific advantage of VIPERS: high sampling (2 x 10^{-3} h^3 Mpc^{-3})
- It will allow us to select sub-samples with different bias (e.g. luminous early type galaxies)
- Combined 2-population estimate of β to possibly reduce cosmic variance can be (McDonald & Seljak, 2009, JCAP) → but apparently gain not so large as claimed (see Gil-Marin et al. 2010, arXiv: 1003.3238)
- If optimistic conclusion of McDonald and Seljak were verified, VIPERS would correspond to a sparser survey with 10 times larger volume, (Gil-Marin et al. suggest only ~3 times at best)

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

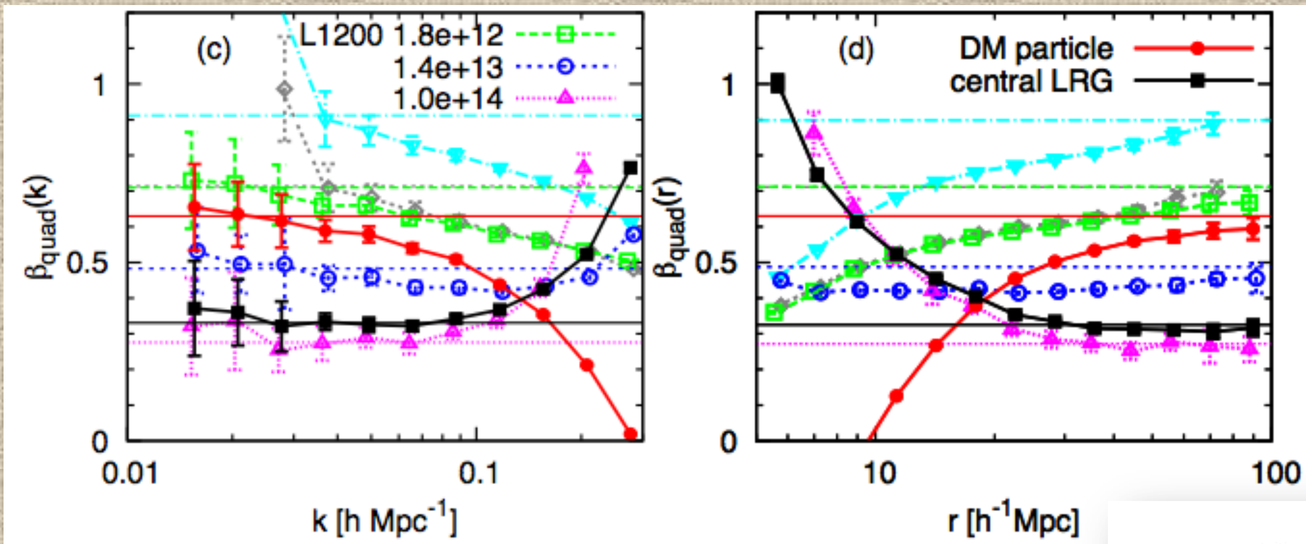
- Measure $\Omega_m h$ from shape of power spectrum
- BAO (baryon fraction, standard ruler?)
- z-space distortions
- neutrino mass?
- large-scale bias vs galaxy properties
- Comparable to 2dF P(k) at z~0.1: joint constraints will be very powerful
- …



(simulation by W. Percival)

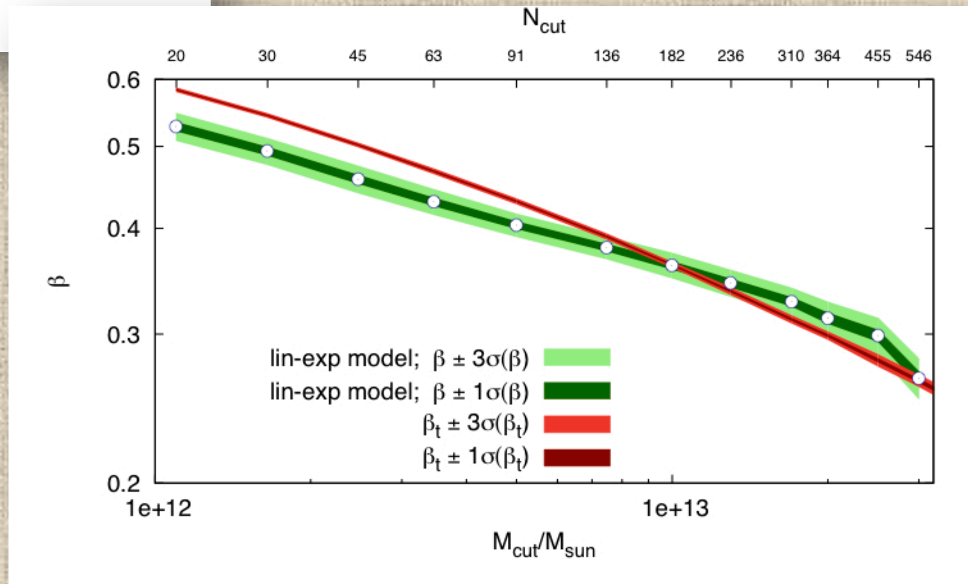
But, are we able to measure redshift distortions with "precision cosmology" accuracy?

Systematic errors in estimating β with linear model



Okumura & Jing 2010

- ~5-10% systematic underestimate of β for galaxy halos, using any method based on linear (Kaiser) model
- For some reason, trend is inverted for masses $>10^{13}$ M_{sun}



- D. Bianchi, 2009, Master Thesis, Univ. of Milan;
- Bianchi, LG et al. 2010, to be submitted to MNRAS

We need to improve the linear model

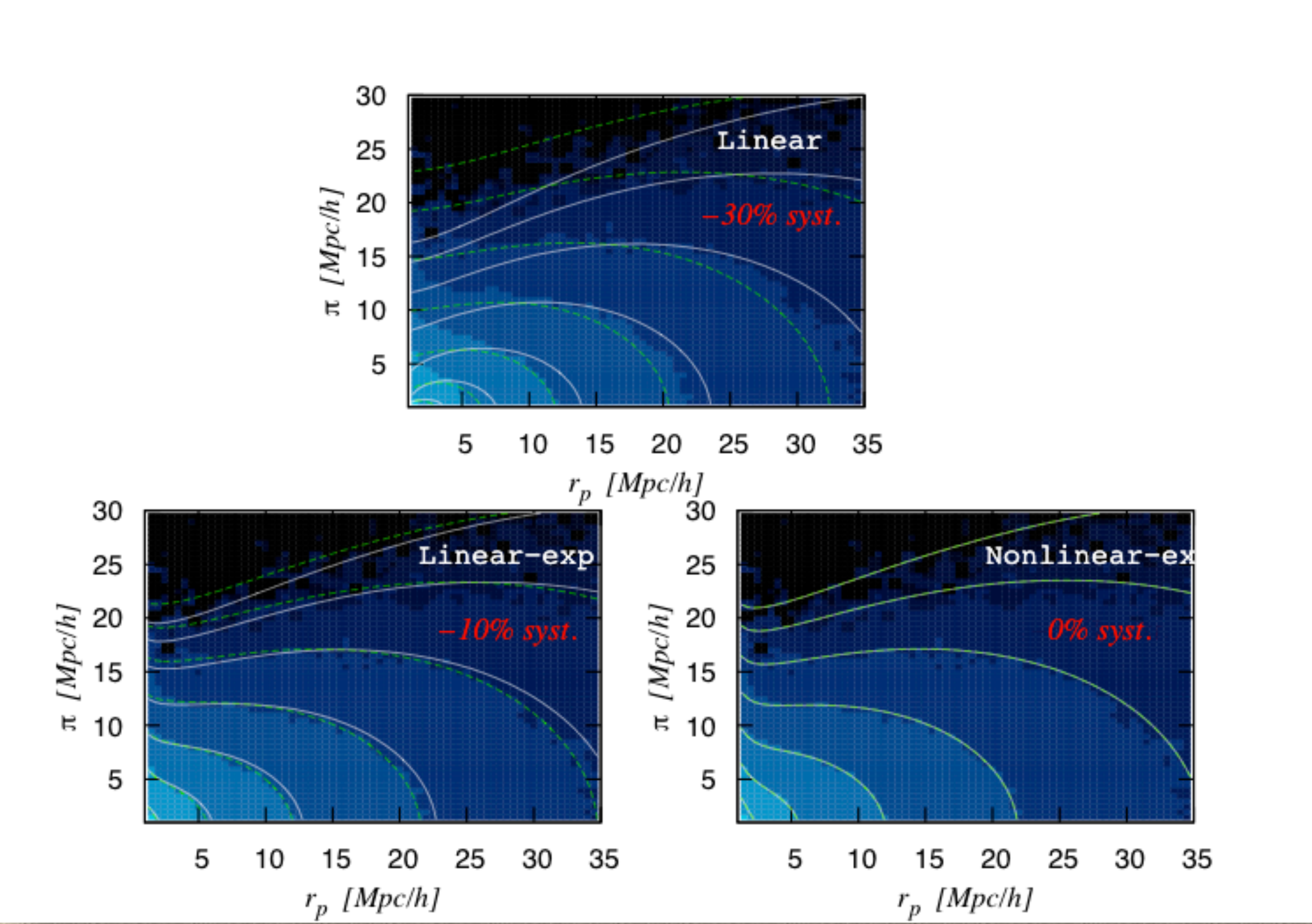
- **Nonlinear correction 1: need to go beyond linear Kaiser model (see talks by Song and Taruya)**
  - Main theoretical foundations go back to Scoccimarro (2004)
  - Not clear how to implement them in practice, though
  - Need to find a way to describe $P_{\theta\theta}(k)$ (e.g. Tegmark et al. 2002, poor constraints from data)
  - From n-body simulations (Jennings et al., 2010)
  - From Perturbation Theory (Crocce & Scoccimarro 2008)
  - From Improved PT (Taruya et al. 2010a, 2010b)
  - …
- **Nonlinear correction 2: Need to treat properly highly nonlinear regions (*Fingers of God*)**
  - Use Halo Occupation Distribution (HOD) models (e.g. Seljak 2001, Tinker et al. 2006, 2007). However, need to assume too many things that depend on cosmology
  - Use usual convolution with an exponential pairwise distribution function

Improving the linear model: practical examples (preliminary)

1) DARK MATTER PARTICLES

Durham BASICC DM large simulation (Angulo et al.): average and scatter from 27 sub-cubes

Nonlinear correction following Taruya et al., arXiv:1006.0699



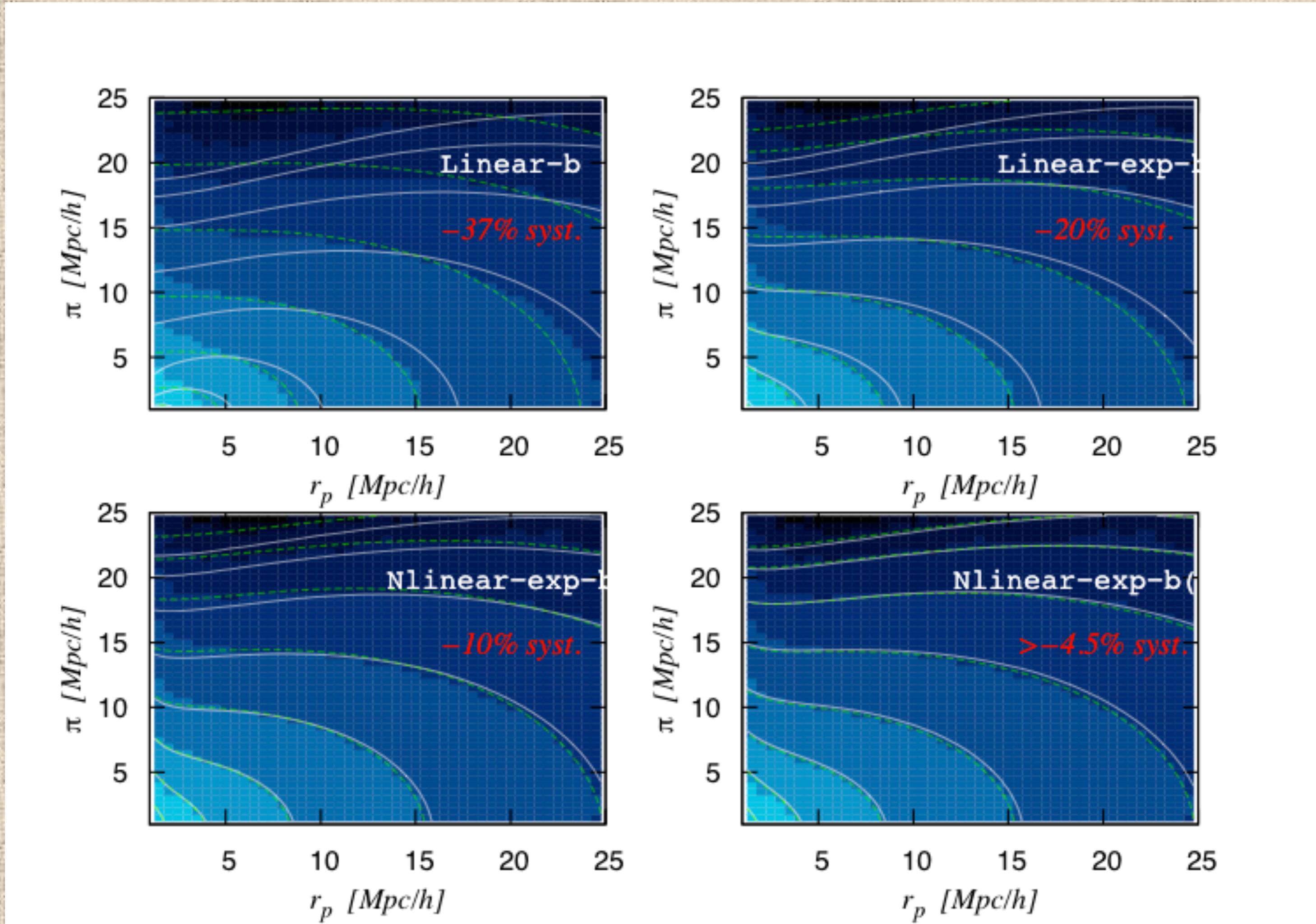
S. De la Torre, LG, et al., in prep.

Improving the linear model: practical examples (preliminary)

2) SEMI-ANALYTIC "GALAXIES"

100 mock surveys from Millennium run (Springel et al. 2005) + Munich semi-analytic models (De Lucia & Blaizot 2006): smaller volumes, but allow to test effect of bias

Nonlinear correction following Taruya et al., arXiv:1006.0699



S. De la Torre, LG, et al., in prep.

Summary

- Explaining the origin of cosmic acceleration is possibly the greatest existing problem in cosmology: it could lead to a profound revision of our standard model(s)
- 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 & modified gravity
- Redshift surveys carry additional enormous value on cosmology and galaxy formation: NOT SINGLE-GOAL EXPERIMENTS
- Last but not least, incommensurable discovery potential (just consider that <u>BAO were not amongst expected results from SDSS and 2dFGRS</u>)

1) Better data:

- Soon new results from ongoing redshift surveys as Wiggle-z (emission-line galaxies) and BOSS (Luminous Red Galaxies), watch out for VIPERS.
- Major interest by space agencies (ESA/NASA – see e.g. FoMSWG Report, arXiv:0901.0721): **EUCLID** plans to couple a massive (slitless) redshift survey with a high-resolution imaging survey, to combine galaxy clustering and weak lensing (launch 2018 if approved)

2) Better redshift-space distortion estimators:

- Models for redshift-space distortions need to go beyond Kaiser-Hamilton formalism, if we aim at precision cosmology
- Do simultaneous estimate of BAO and z-distortions (including Alcock-Paczynski)
- Significant effort and already promising results: need to improve tests to real data