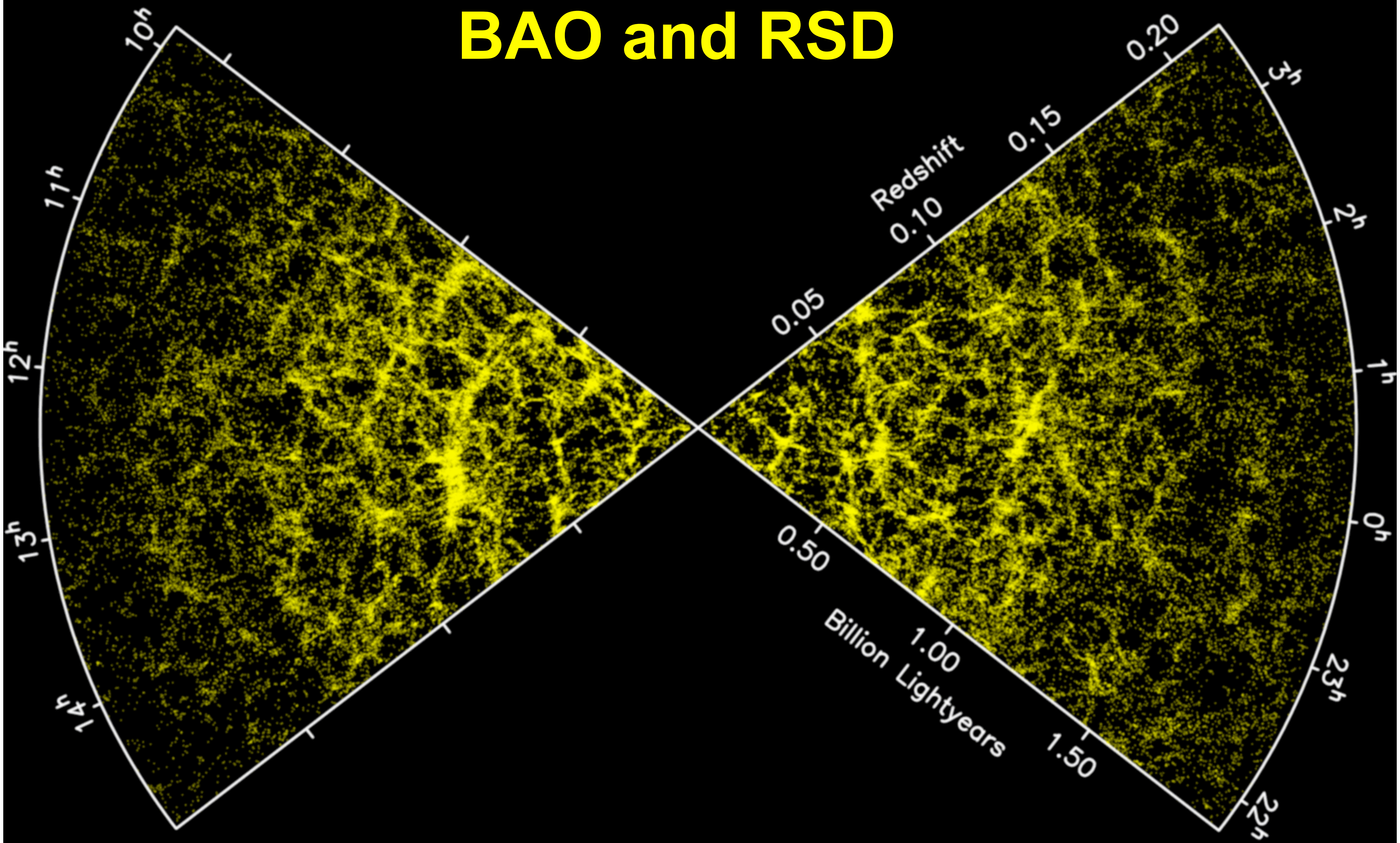
Measuring the Dark Universe: BAO and RSD

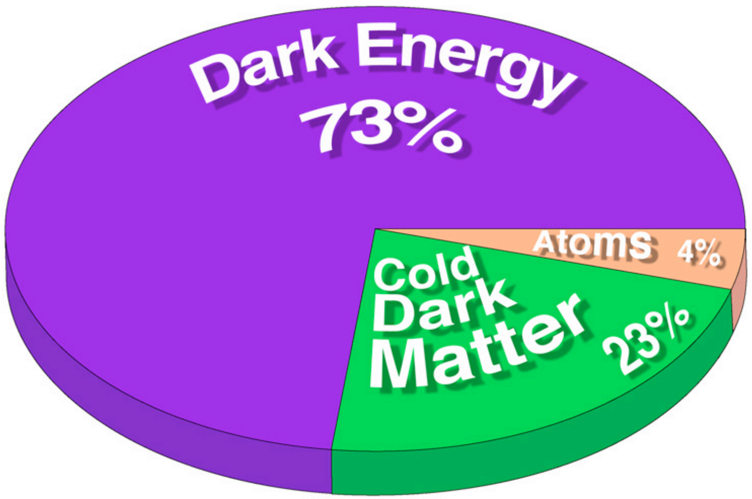


John Peacock

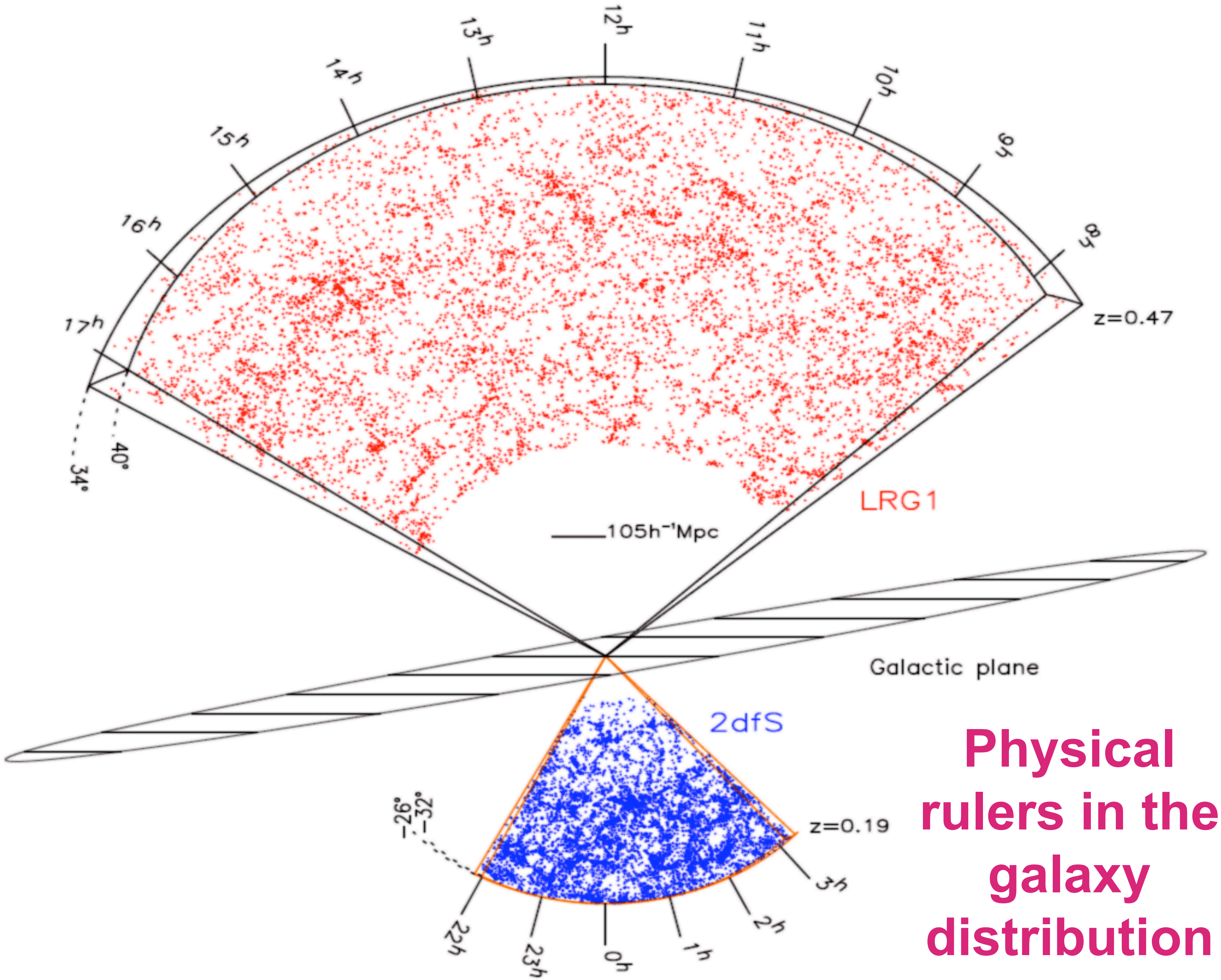
Oxford FMOS Workshop

23 June 2009

Outline



- A few basics
- Methodological issues
- Forthcoming surveys



Physical rulers in the galaxy distribution

Weighing the universe with horizons

(1) Matter-radiation horizon:

$123\ (\Omega_m h^2 / 0.13)^{-1}$ Mpc

(2) Acoustic horizon at last scattering :

$147\ (\Omega_m h^2 / 0.13)^{-0.25} (\Omega_b h^2 / 0.024)^{-0.08}$ Mpc

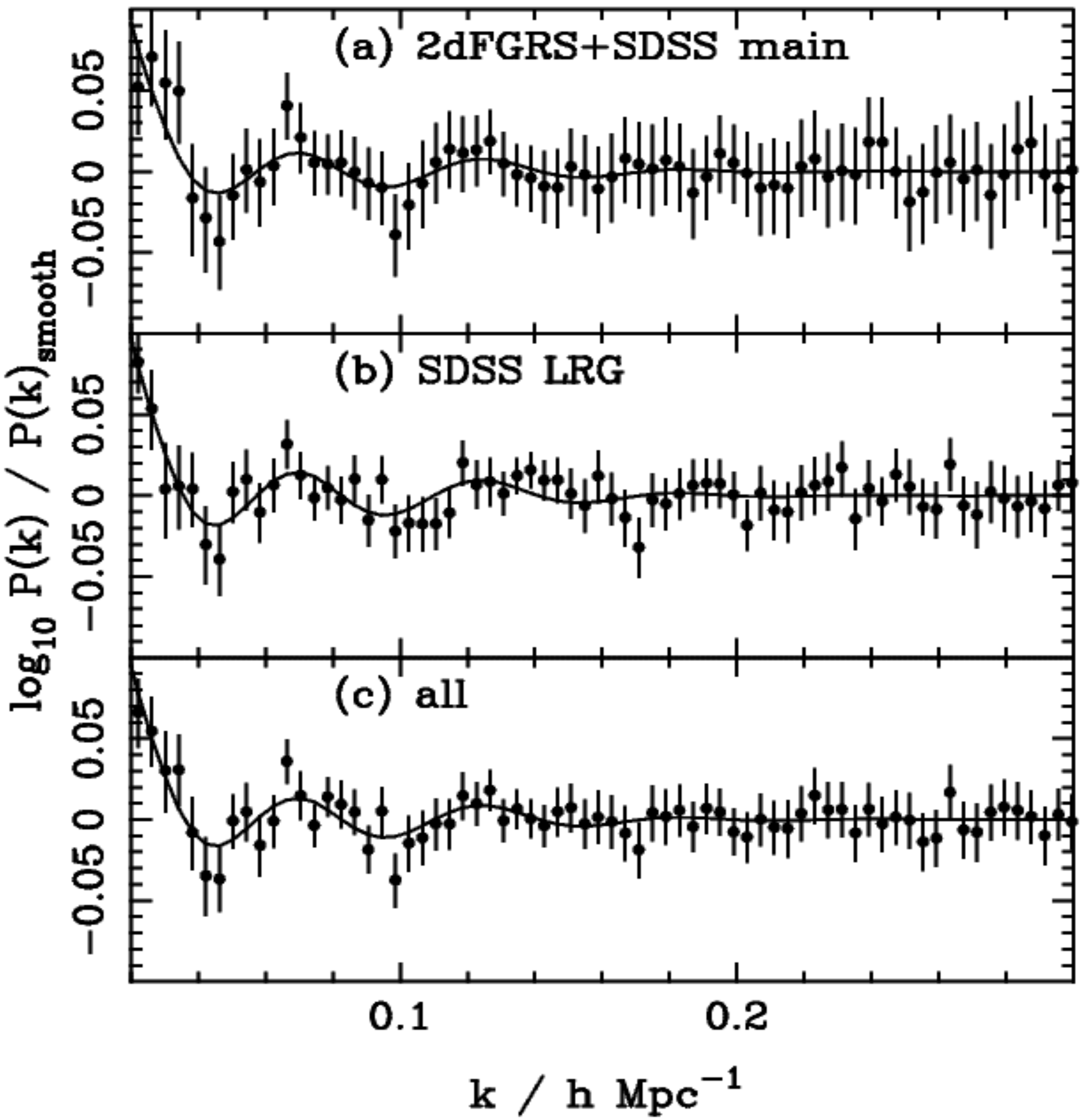
Acoustic horizon can be seen in CMB and baryon wiggles:

Use to probe distance-z relation

$$D(z) = \frac{c}{H_0} \int_0^z \frac{dz}{[(1-\Omega_m)(1+z)^{3+3w} + \Omega_m (1+z)^3]^{1/2}}$$

can measure w for vacuum ($P/\rho c^2$)

BAO: state of the art



Percival et al. 2007 arXiv: SDSS + 2dFGRS

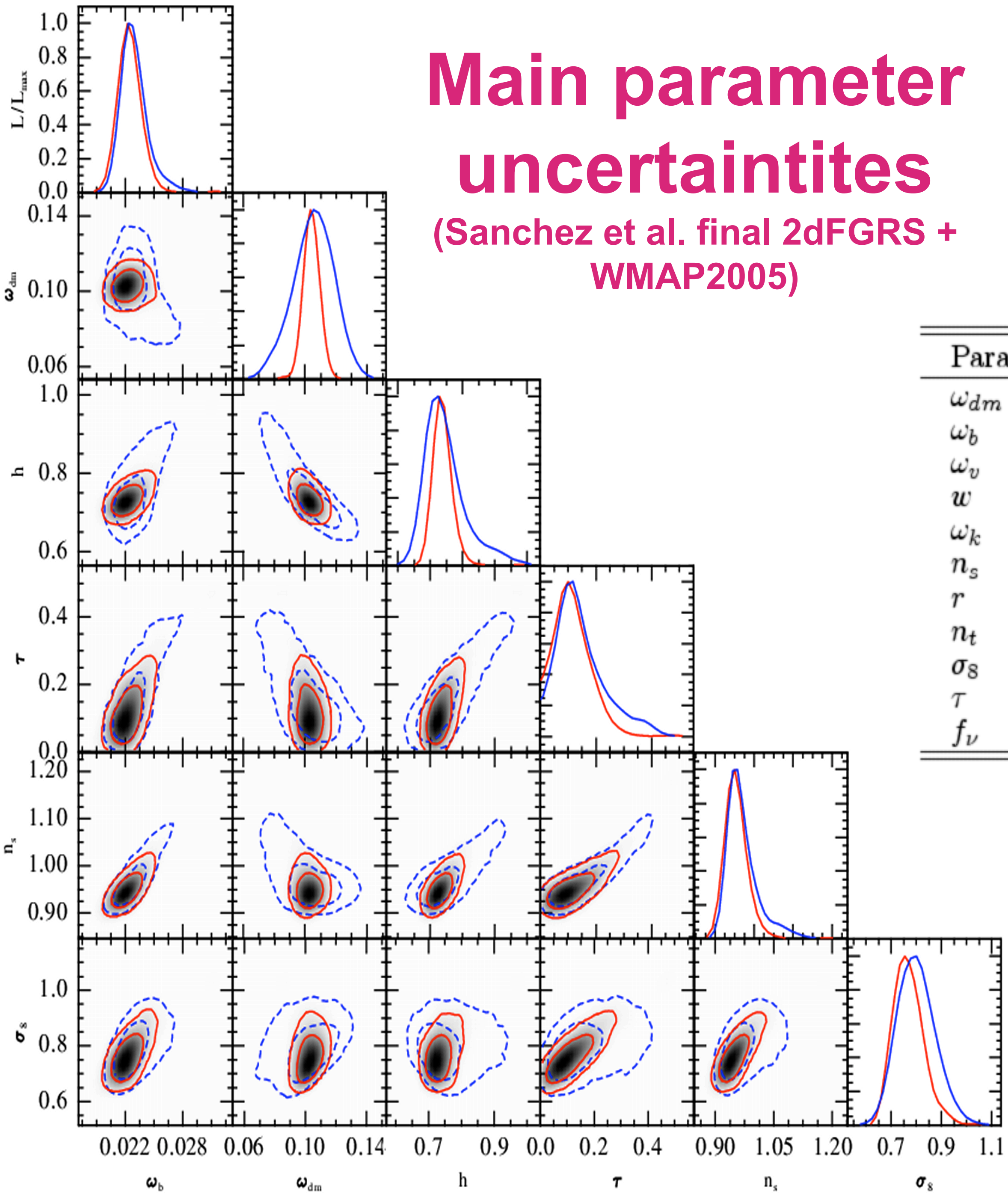
590,000 G's at <z> = 0.2

78,000 LRG's at <z> = 0.35

Measuring acoustic scale to 2%

Main parameter uncertaintites

(Sanchez et al. final 2dFGRS + WMAP2005)



Standard LCDM model has no remaining strong parameter degeneracies

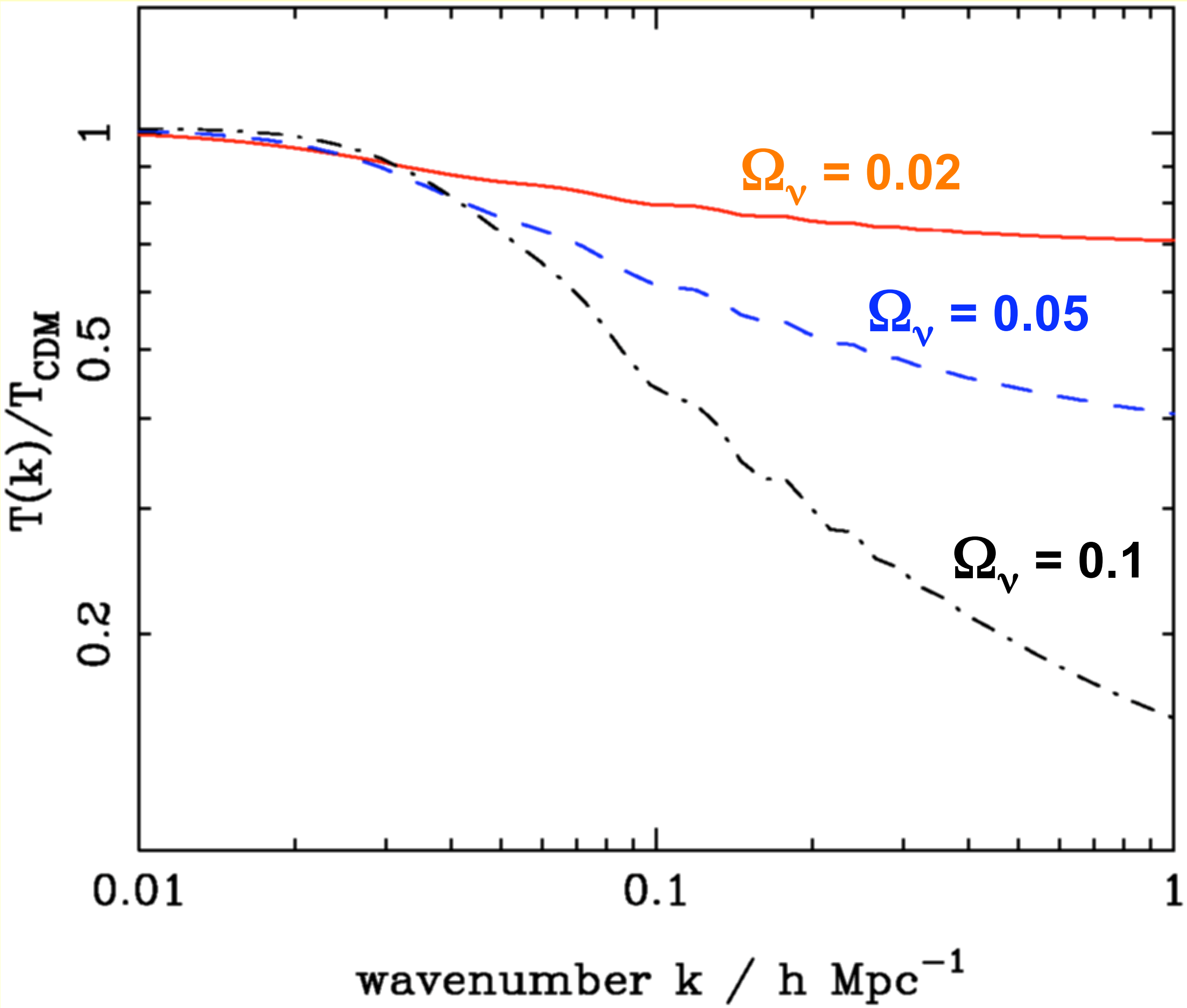
Parameter	Meaning
ω_{dm}	Physical density of dark matter
ω_b	Physical density of baryons
ω_v	Physical density of vacuum
w	Equation of state of vacuum
ω_k	Curvature 'density'
n_s	Scalar spectral index
r	Tensor-to-scalar ratio
n_t	Tensor spectral index
σ_8	Spectrum normalization
τ	Optical depth from reionization
f_ν	Neutrino mass fraction

Parameter	WMAP + 2dFGRS
σ_8	$0.737^{+0.036}_{-0.036}$
τ	$0.083^{+0.028}_{-0.028}$
n_s	$0.948^{+0.015}_{-0.015}$
ω_b	$0.0222^{+0.0007}_{-0.0007}$
ω_m	$0.126^{+0.005}_{-0.005}$
h	$0.733^{+0.020}_{-0.021}$
$\Rightarrow \Omega_m$	$0.236^{+0.020}_{-0.020}$

Additional questions

- What is the DM?
- If a relic particle, what is the mass?
- What can we say about neutrino mass?
- Is the vacuum energy a cosmological constant?

Effect of massive neutrinos

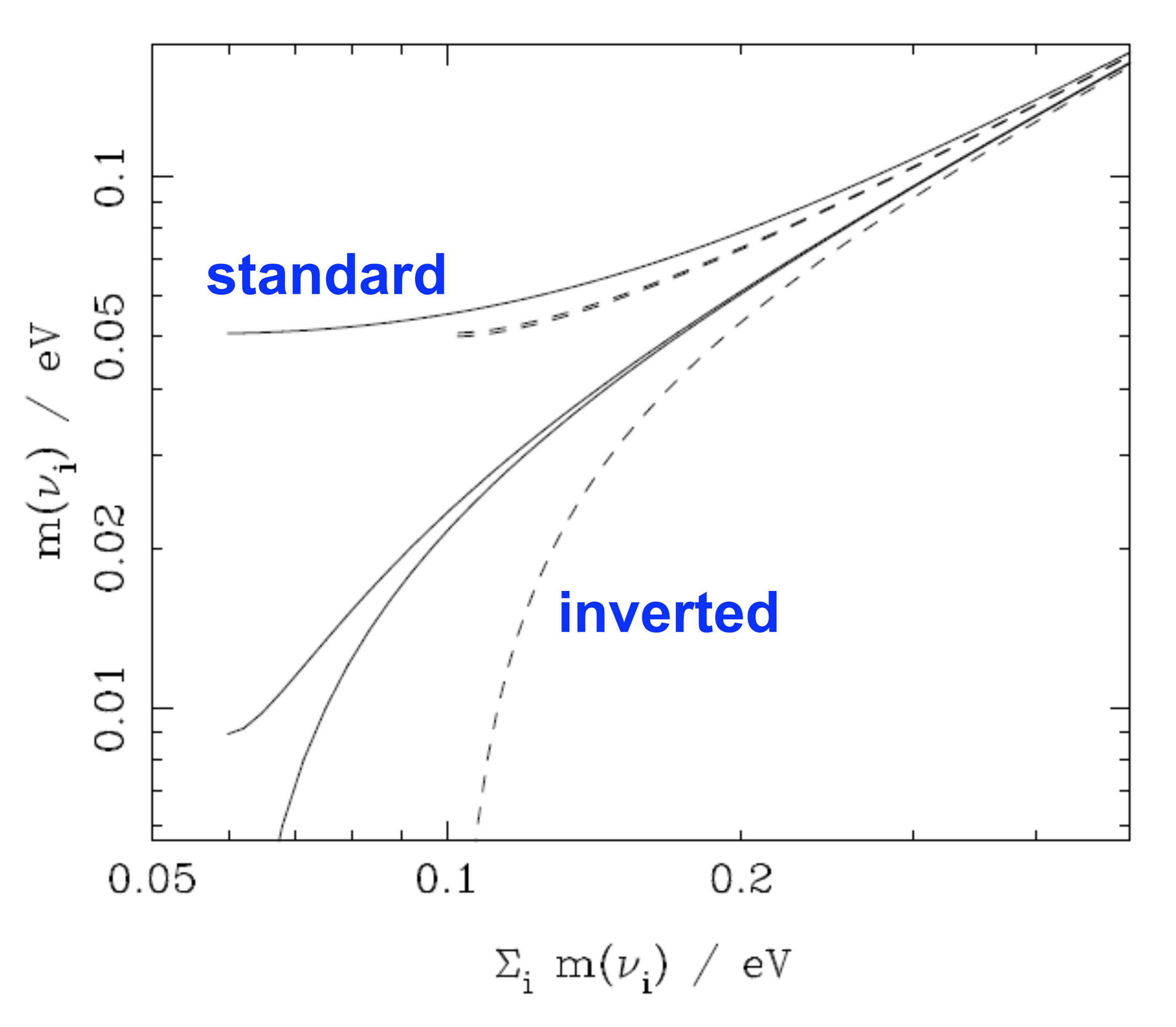


Free-stream length:
80 $(M/eV)^{-1}$ Mpc

$(\Omega_m h^2 = M / 93.5\ eV)$

M ~ 1 eV causes lower power at almost all scales, or a bump at the largest scales

Discriminating neutrino hierarchies



Limit total neutrino density from (a) Shape change in P(k) (b) reduction in small-scale growth

$\Sigma m_\nu < 0.6$ eV (WMAP++)

Should reduce to < 0.2 for ~ 10^7 redshift surveys: chance of detecting background

Sensitivity to the vacuum

Vacuum affects H(z):

$H^2(z) = H^2_0 \; [\, \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_V (1+z)^{3(1+w)} \,]$

matter radiation vacuum

Alters D(z) via $r = \int c\, dz / H(z)$

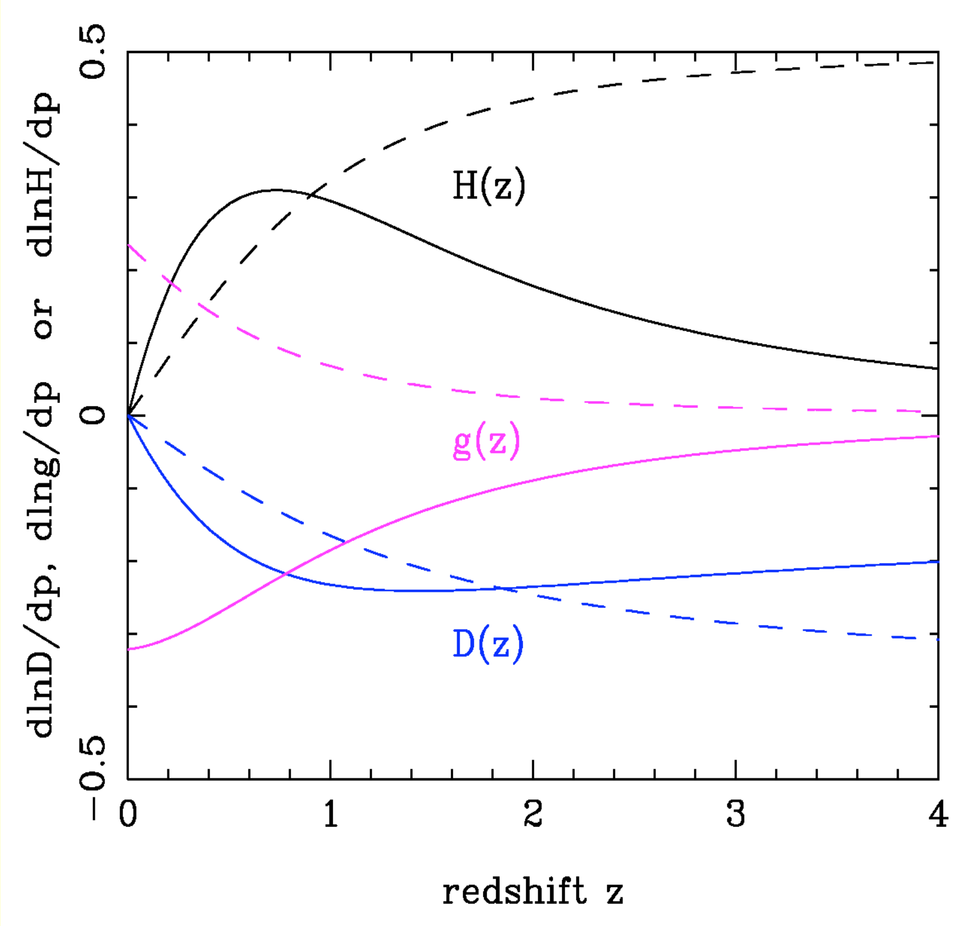
And growth via 2H $d\delta/dt$ term in growth equation

Effects of w are:

(1) **Small (need D to 1% for w to 5%)**

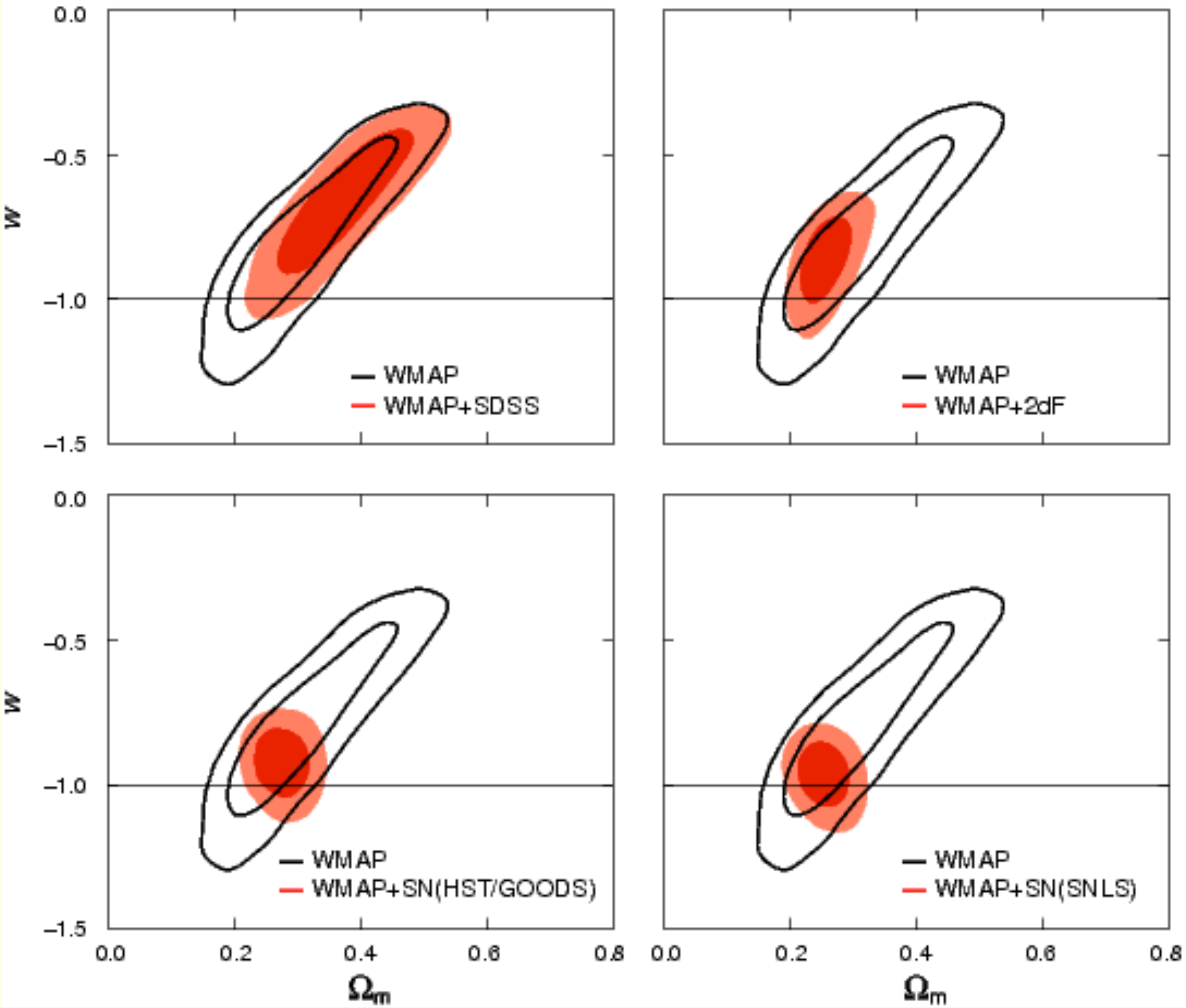
Rule of 5

(2) **Degenerate with changes in Ω_m**



To measure w to a few %, we need to have independent data on Ω_m and to be able to control systematics to ~ parts in 1000

The vacuum: current knowledge



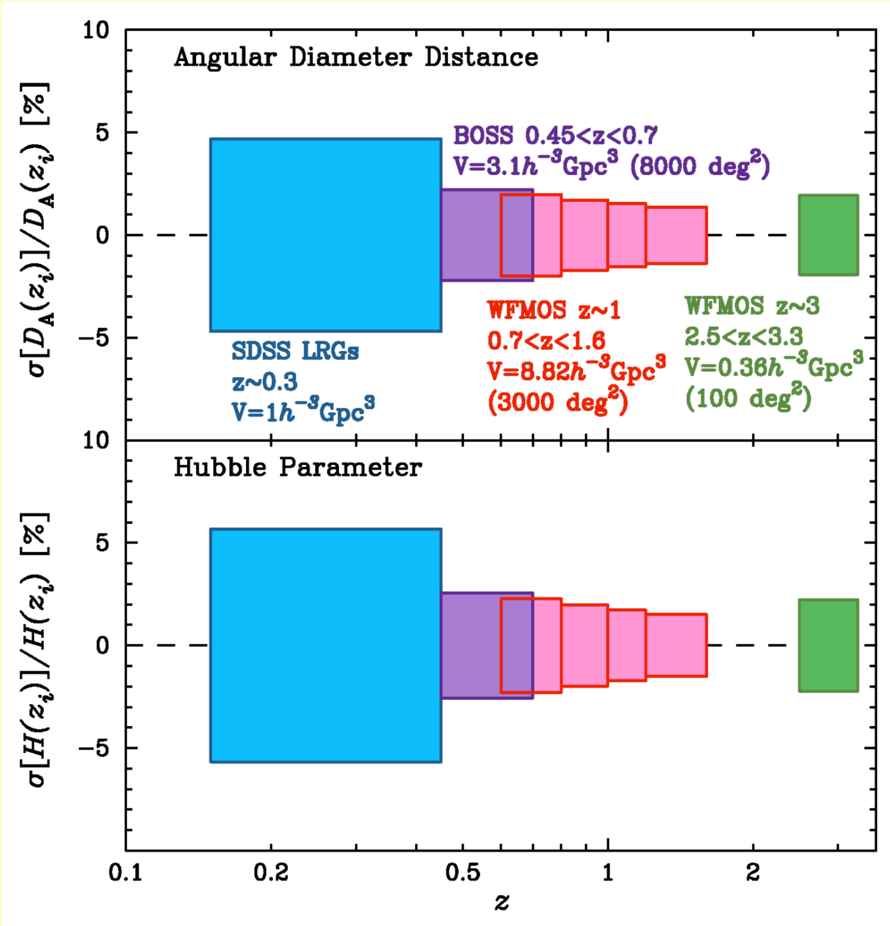
Combined:

$$w = -0.926^{+0.051}_{-0.075}$$

Fractional error on BAO scale

% error = $(V / 5\ h^{-3}\ Gpc^3)^{-1/2}$ x $(k_{max} / 0.2\ h\ Mpc^{-1})^{-1/2}$ x $(1+1/nP)/2$

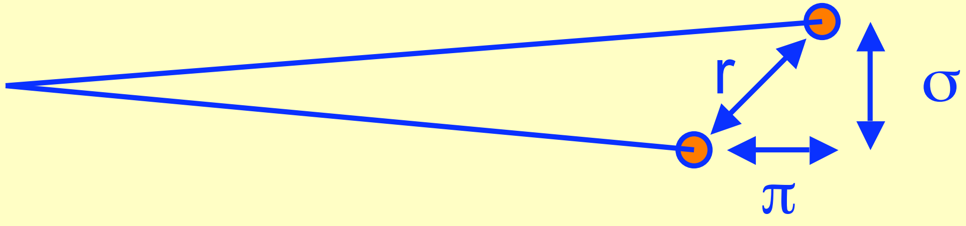
- Error from balancing cosmic variance & shot noise
- Assumes typical P=2500 $(h^{-1}Mpc)^3$ ⇒ $n_{optimal}$ = 4 x10^{-4} $(h^{-1}Mpc)^{-3}$. Similar clustering for many high-z tracers
- Uses only wiggle signature – not full P(k). Can do factor ~ 3 better but requires optimism about modelling bias



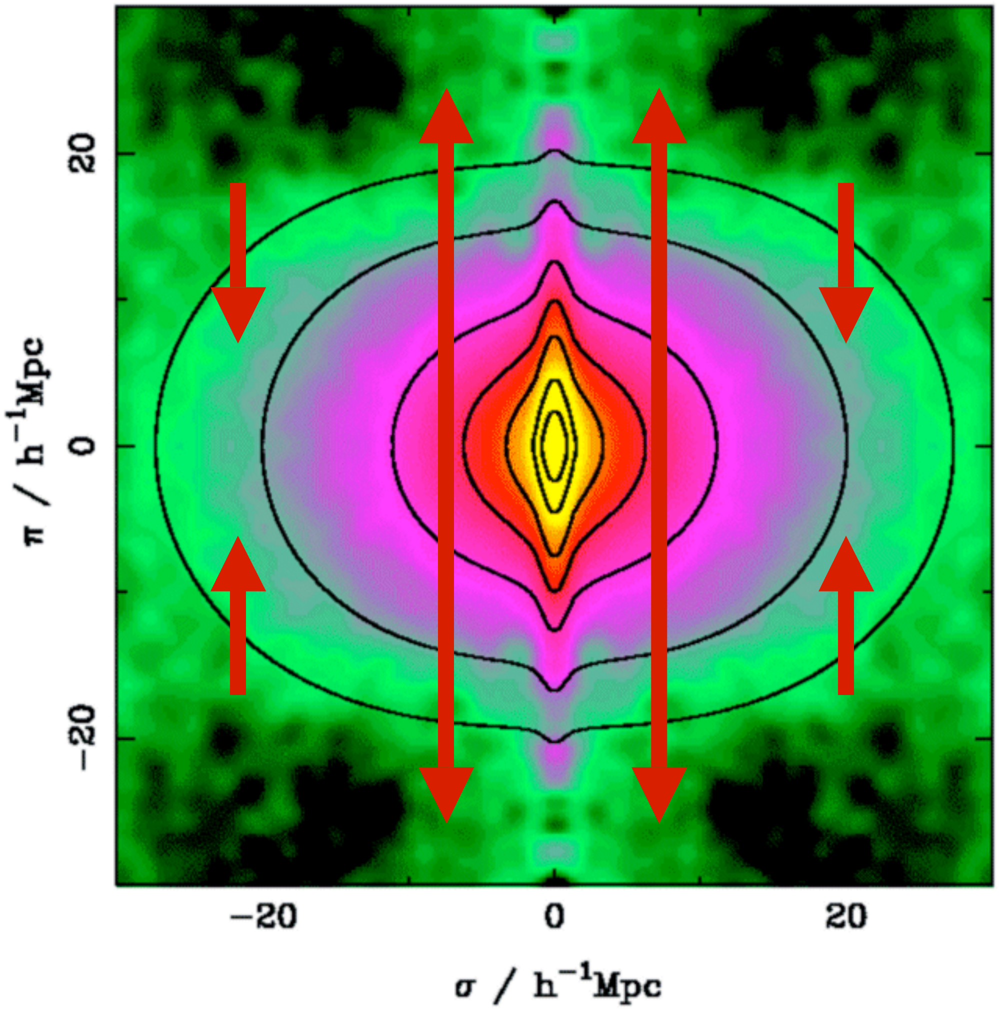
Density growth and modified gravity

- Peculiar velocities come from $f(a)=d \ln \delta / d \ln a$
- Peebles approximation: $f(a)=d \ln \delta / d \ln a \simeq \Omega_m^{0.6}$
- Roughly independent of Λ (and, indeed, w)
- But DE could be an illusion, indicating failure of Einstein gravity. Density fluctuations perform differently to global a(t) as probe
- Linder parameterization: $f(a)=d \ln \delta / d \ln a \simeq \Omega_m^{\gamma}$
- Interesting values 0.5 – 0.8

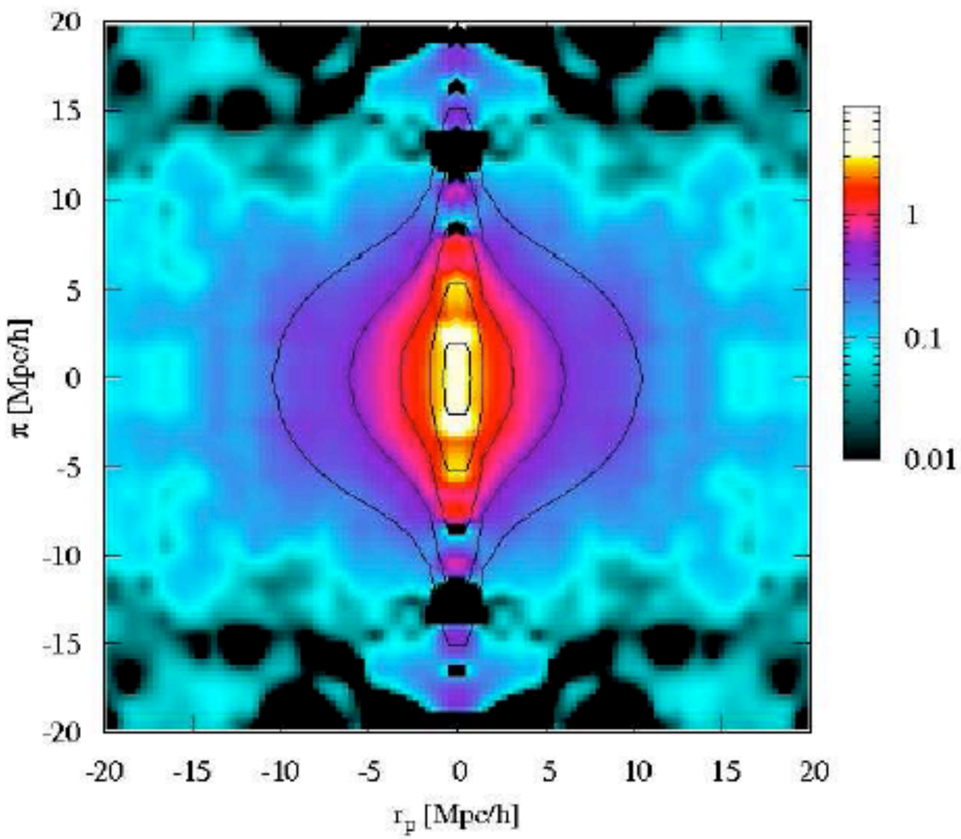
Redshift-Space Distortions

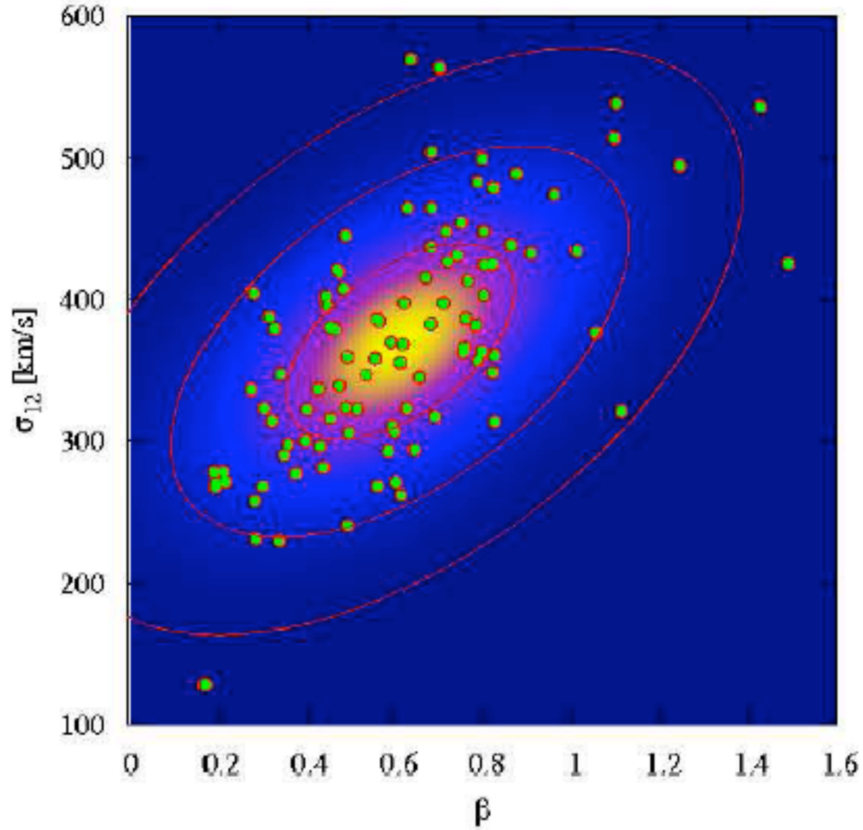


- RSD due to peculiar velocities are quantified by correlation fn $\xi(\sigma,\pi)$.
- Two effects visible:
  - Small separations on sky: 'Finger-of-God';
  - Large separations on sky: flattening along line of sight.
- Measure $\beta = f(a) / b$



VVDS redshift-space distortions





10k z's: Guzzo et al. Nature 2008

VImos Public Extragalactic Redshift Survey

- New ESO VLT programme
- P.I. Guzzo (Milan)
- 24 deg^2 to $I_{AB} < 22.5$ in CFHTLS fields
- 100k targets at $z > 0.5$, >50% sampling
- 440 VLT hours

- Main aim is to probe modified gravity via RSD

RSD Precision

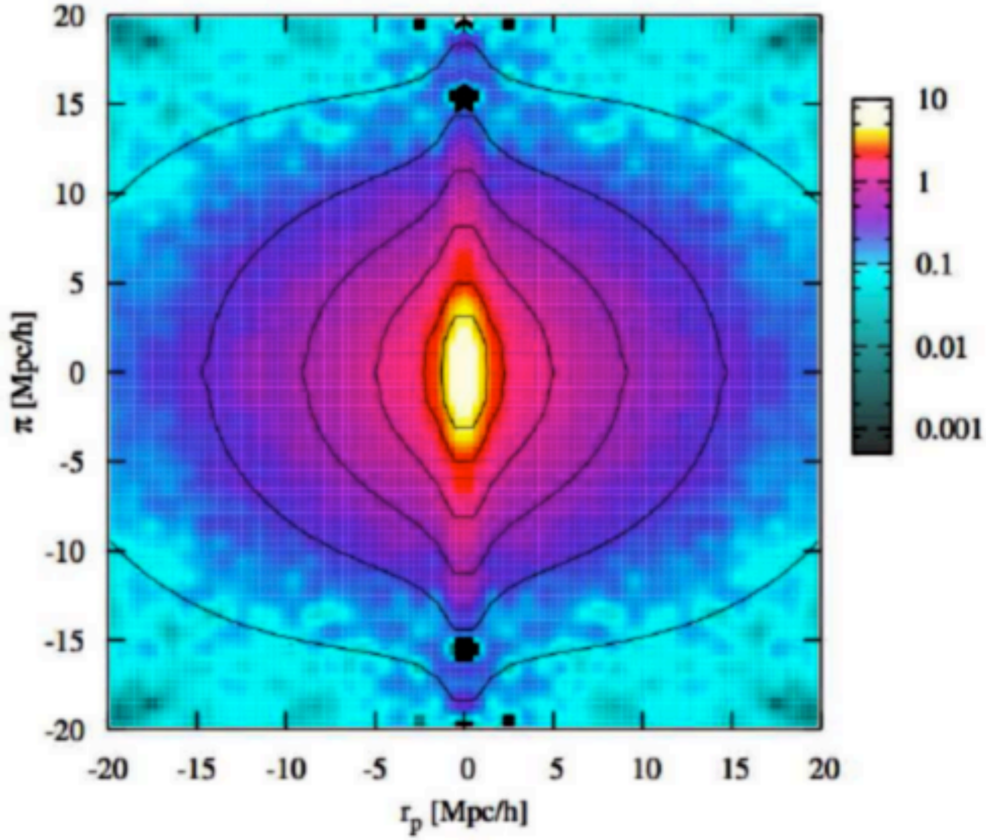
% error in β = (V / 20 h^{-3} Gpc^3)$^{-1/2}$ x (n / 4x10^{-4} h^3 Mpc^{-3})$^{-0.44}$

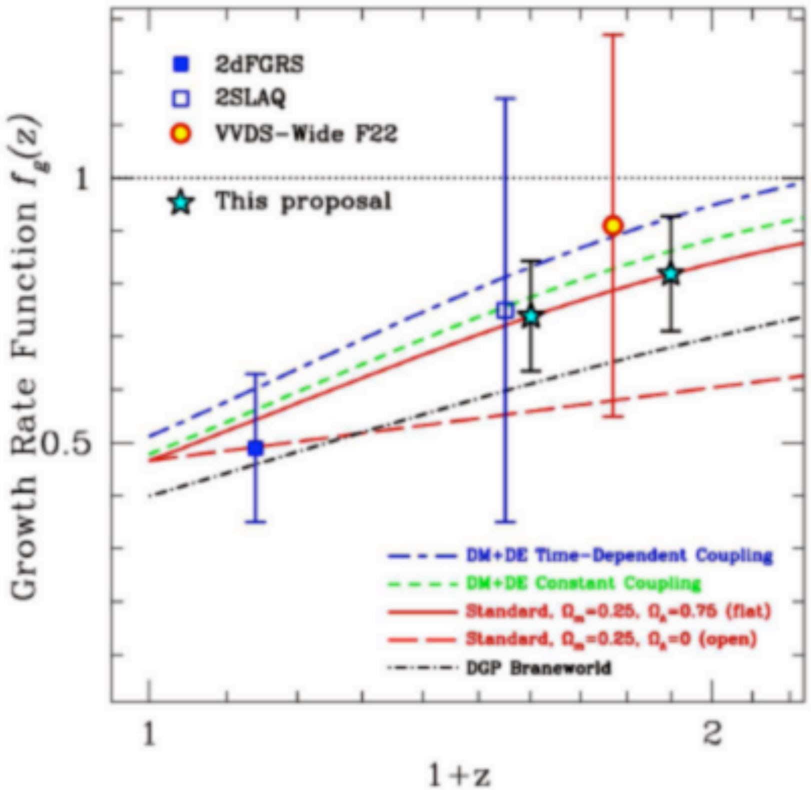
Guzzo et al. 2007; see White & Percival for more accurate Fisher-matrix estimates

Would probably expect a function of V_{eff}:

$$V_{\rm eff} = V \left(\frac{1+nP}{nP} \right)^2$$

RSD predictions for VIPERS

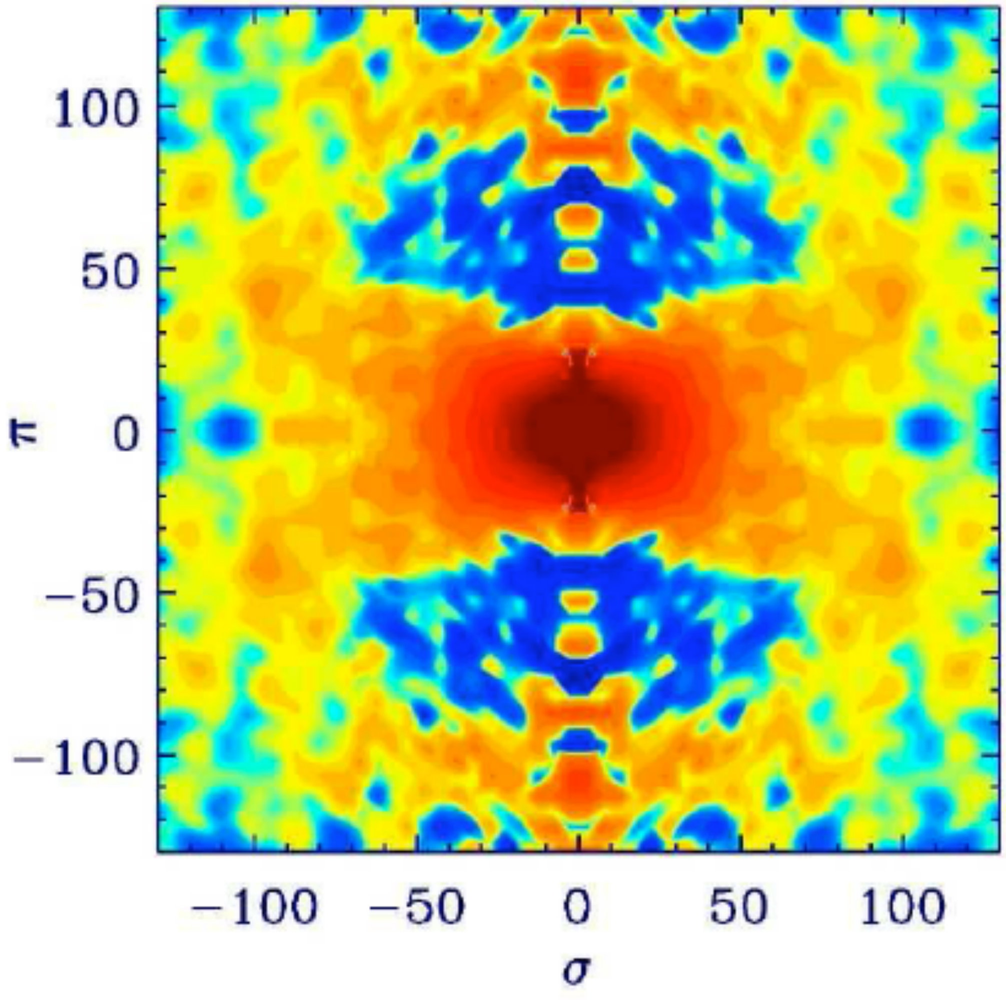




Approved 400h VLT programme: 100k z’s over 3 years: predict $\Delta\ f_g$ = 0.1 in 2 bins

Combining BAO and RSD

SDSS LRG Redshift-space 2D ξ(σ,π)
Gaztanaga et al. 0807.3551

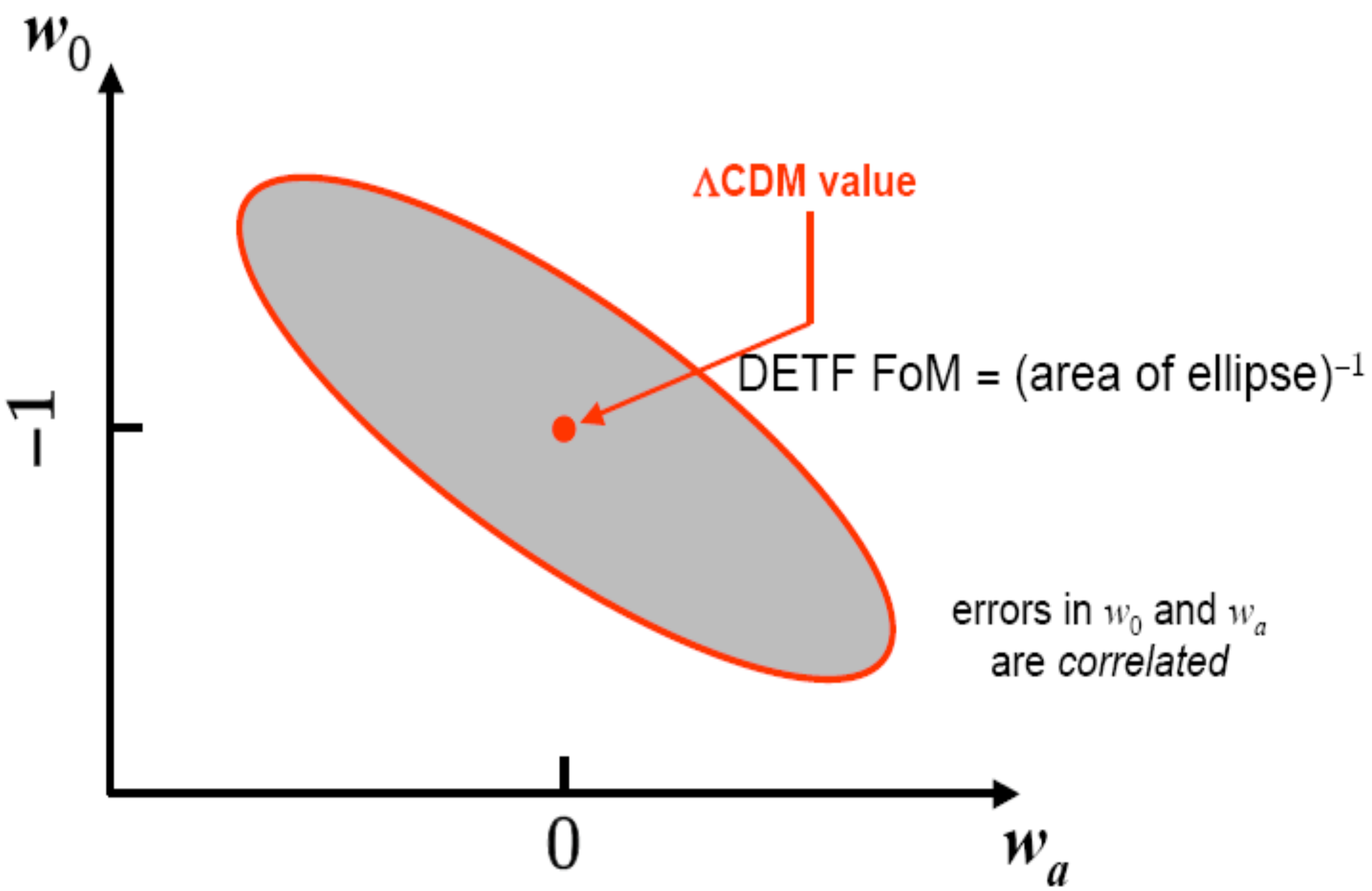


Note Kaiser flattening has little affect on BAO ring

DETF figure of merit

$w(a) = w_0 + w_a(1 - a)$: $w = w_0$ today & $w = w_0 + w_a$ in the far past

Marginalize over all other parameters and find uncertainties in w_0 and w_a



2008: add higher order w(a) variations plus quote error on γ

Pivot redshifts

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

If observe degeneracy $w_0 = A + Bw_a$,

$\Rightarrow w = A + (B+1-a)w_a = w_p + (a_p-a)w_a$

$\Rightarrow z_{pivot} = 1/(1+B) - 1 \Rightarrow$ FoM = $[\sigma(w_p)\sigma(w_a)]^{-1}$

Method	z_{pivot}	
CMB	0.43	
BAO z=1	0.54	Difficult to get much baseline
BAO z=1+z=3	0.85	

Figures of merit

- DE is just a term in Friedmann: probing non-GR is at least as important as measuring w
- But most people are happy not to consider $\gamma(a)$; thus should avoid too much emphasis on variation in w
-
- $w = w_0 + w_a\,(1\text{-}a)$ is better regarded as measuring w_p. Rejection of w = – 1 less likely from poorly measured w_a
- PCA of w(a) interesting, but not a strong driver
- Suggests focus on $\gamma - w_p$ plane

Combining RSD and BAO

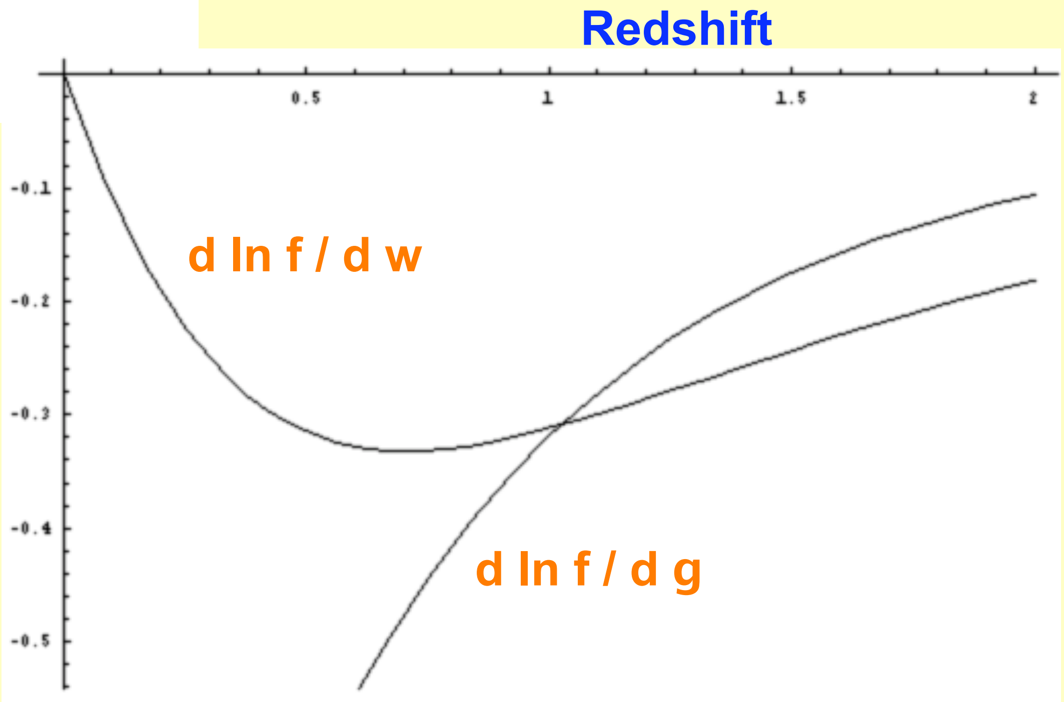
BAO depend on just w if matter content is known (assumed from CMB). RSD depend on both w and γ.

$$f \equiv \frac{d \ln \delta}{d \ln a} = \Omega_m(a)^\gamma \quad \Rightarrow$$

$$\frac{\partial \ln f}{\partial \gamma} = \ln \Omega_m(a)$$

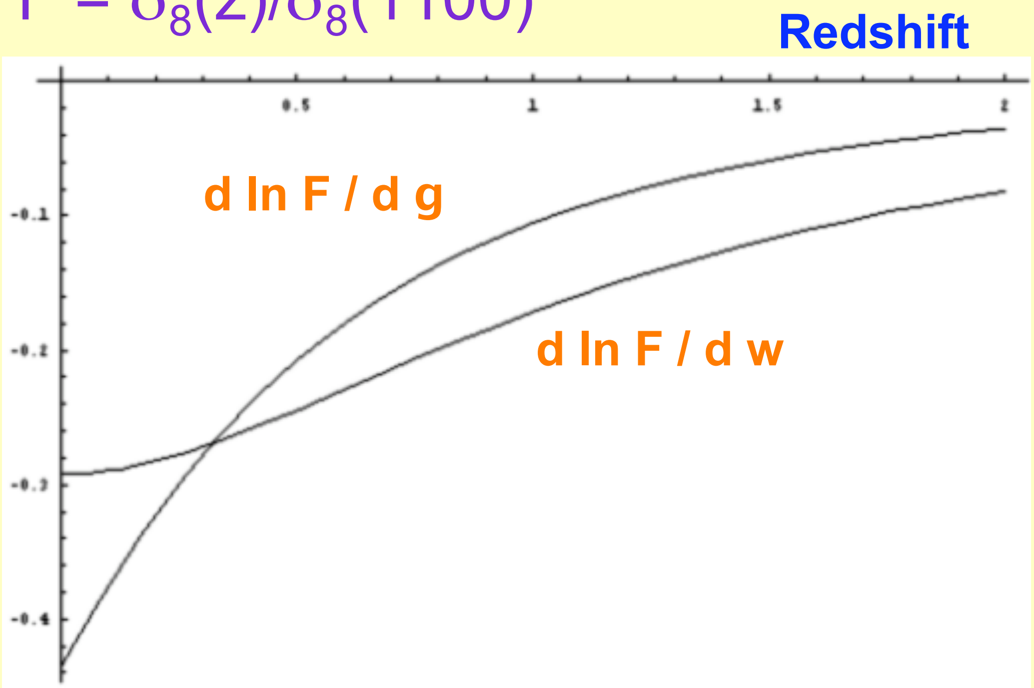
$$\frac{\partial \ln f}{\partial w} = \gamma \frac{\partial \ln \Omega_m(a)}{\partial w}$$

Both derivatives around -0.3 at z = 1



Observing f?

- But what we see directly is $\beta = f / b$
- One route to b is from higher-order correlations (cf. 2dFGRS) – but would we trust it?
- Safer to say $b = \sigma_{gal}/\sigma_8(z)$
- $\sigma_8(z=1100)$ is known from CMB
- $\Rightarrow$ observe f F, where $F = \sigma_8(z)/\sigma_8(1100)$

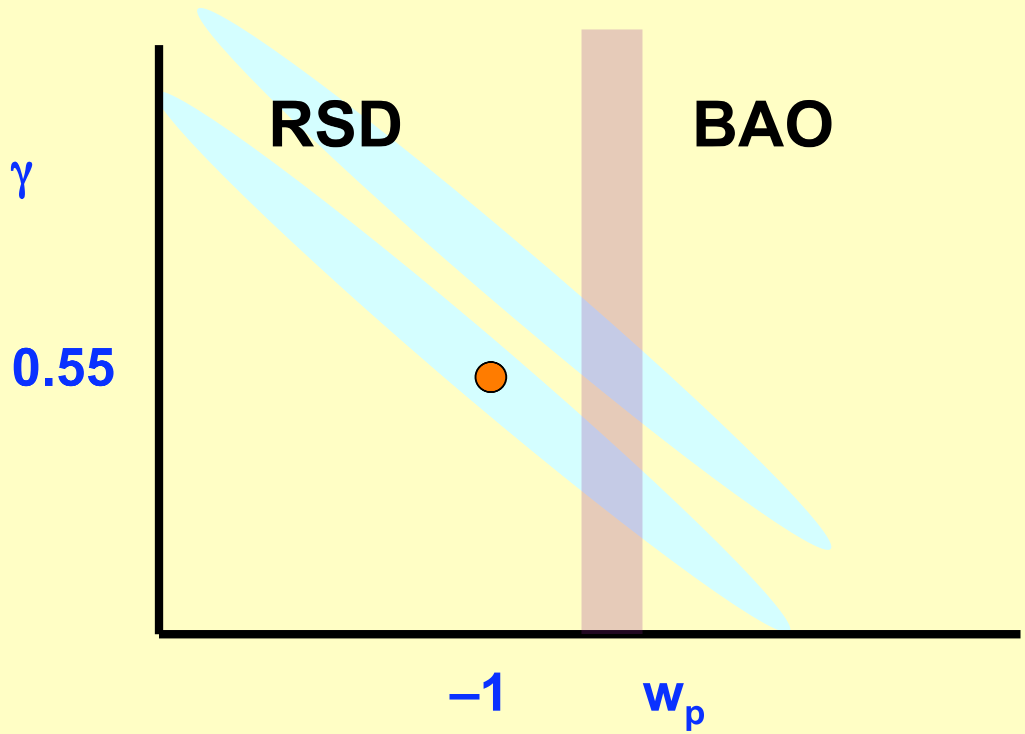


$d \ln F / d w = -0.2$

$d \ln F / d \gamma = -0.1$

at redshift z = 1

DE-gravity degeneracy



$\gamma - 2w = x1 \pm y1$

$w = x2 \pm y2$

Good to have both errors comparable.

Good case for FoM based on joint area of confidence ellipsoid in this plane

But remember Alcock-Paczynski

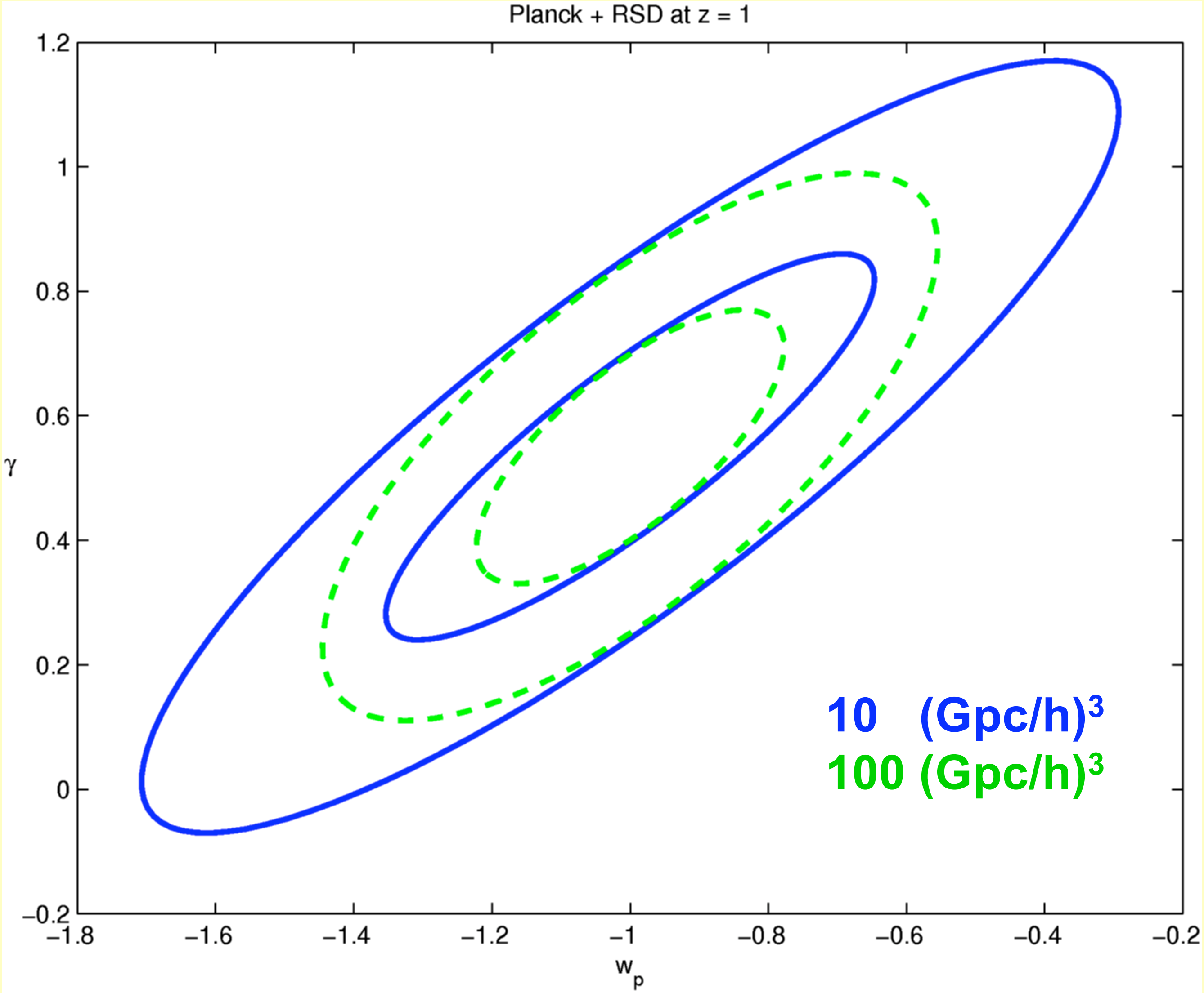
Observe correlations in angular and redshift directions

Conversion to distance involves ratio of D(z) and dD/dz: thus geometrical flattening by F = D / (dD/dz) compared to assumed value

- Alcock & Paczynski (1979): clustering is isotropic, so this gives us Λ etc.
- Suto & Matsubara (1996); Ballinger, JP & Heavens (1996): degeneracy between RSD and geometry

$$\beta_{\rm eff} = 0.5(F - 1)$$

Allowing for Alcock-Paczynski



Fergus Simpson + JAP:

Overall uncertainty in γ can be 3 x figure for w=-1

Cumulative data expected in near term

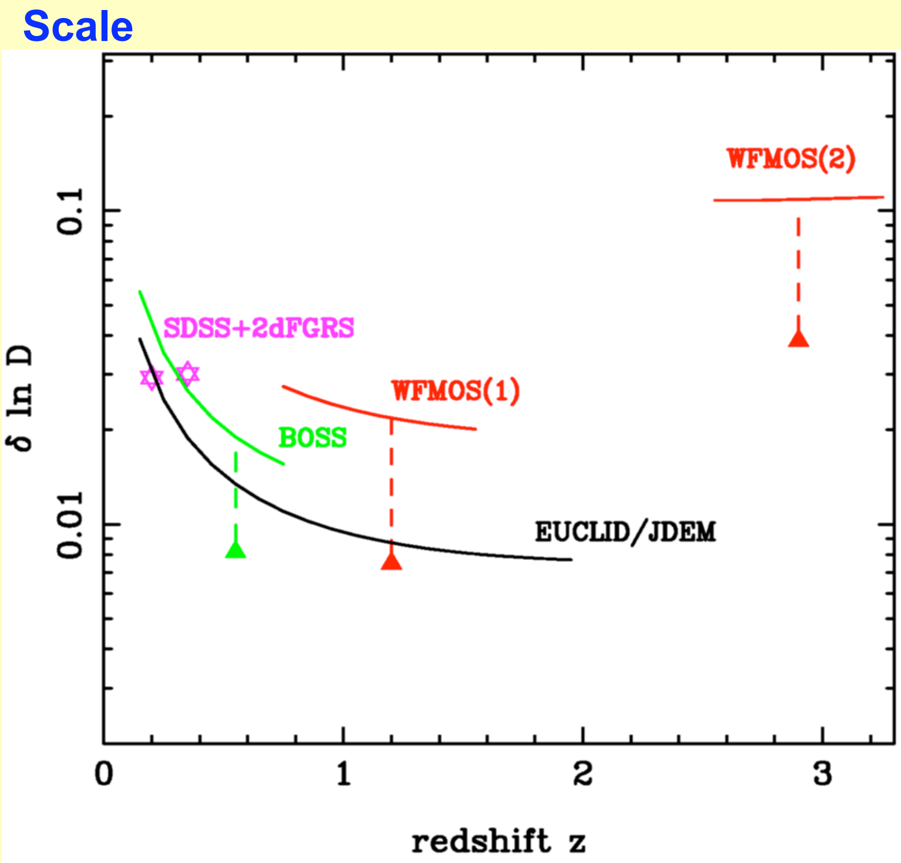
Name	Telescope	N(z) / 10^6	Dates	Status
SDSS/2dFGRS	SDSS/AAT	0.8	Now	Done (low z)
WiggleZ	AAT(AAOmega)	0.4	2007-2010	Running
FastSound	Subaru(FMOS)	0.6	2009-2012	Proposal
BOSS	SDSS	1.5	2009-2014	Funded
HETDEX	HET(VIRUS)	1	2010-2013	Part funded
WFMOS	Subaru	4	2014-2017	???
BigBOSS	Kitt Peak 4m	30	2015-2025	Proposal

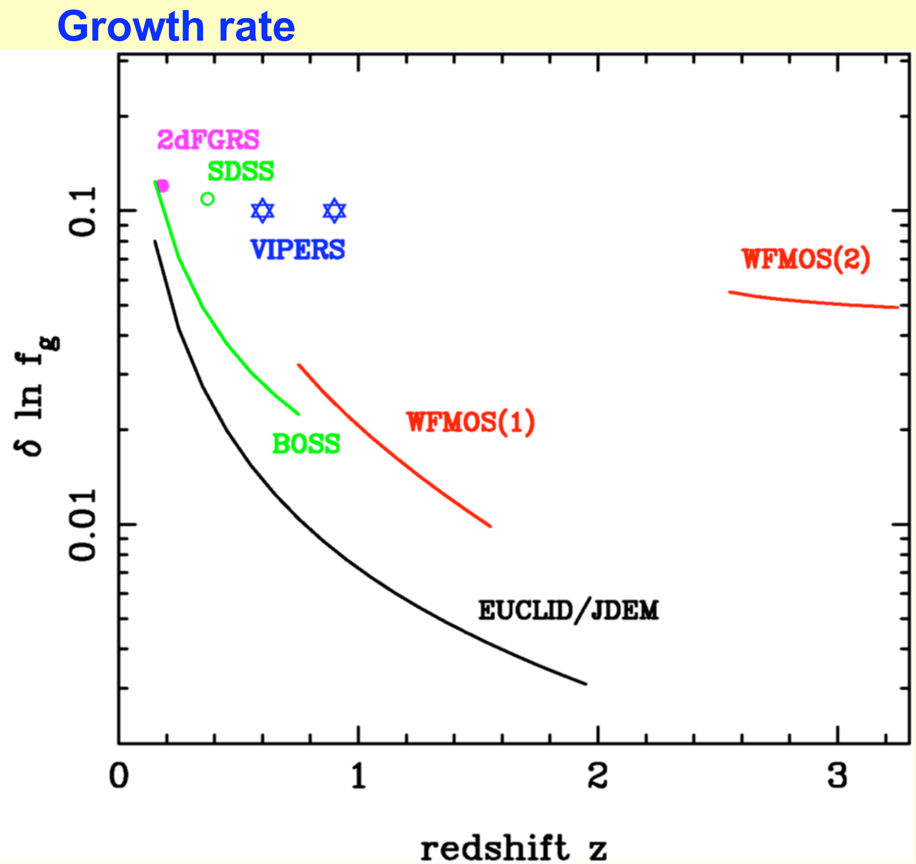
Most data will come at z ~ 1 (U-band bottleneck for LBGs)

Σ WiggleZ/BOSS = 2-3m by ~2012 (~5% on w)

Photo-z surveys similar but poorer precision on this timescale

Euclid/JDEM Context





Precision in band of width Δz = 0.1. Triangles show average over all bands

WFMOS proposal: 5,000,000 at z=1, 100,000 at z=3: minimum level to match or exceed VIPERS but at higher z. Also attractive level for FMOS, especially if we can achieve a large redshift baseline wrt BOSS