The Local Hole revealed by galaxy counts and redshifts

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Overview

- At what scale does the Universe become homogeneous?
- How do we go about measuring the galaxy distribution
- Evidence for a local under-density ('Local Hole')

Evidence for Homogeneity

- **Theory/Simulation: 200-300 h-1Mpc structures expected/possible (Watson et al 2013, Park et al 2013, Yadav et al 2010).**
- **Many different observational approaches; Fractal Scale, Number Dipoles, Flux Dipoles, Bulk Flows ...**
- **200-300 h-1Mpc structures reported to exist (Gott et al 2005: Sloan Great Wall, Murphy et al 2011).**

Number Counts

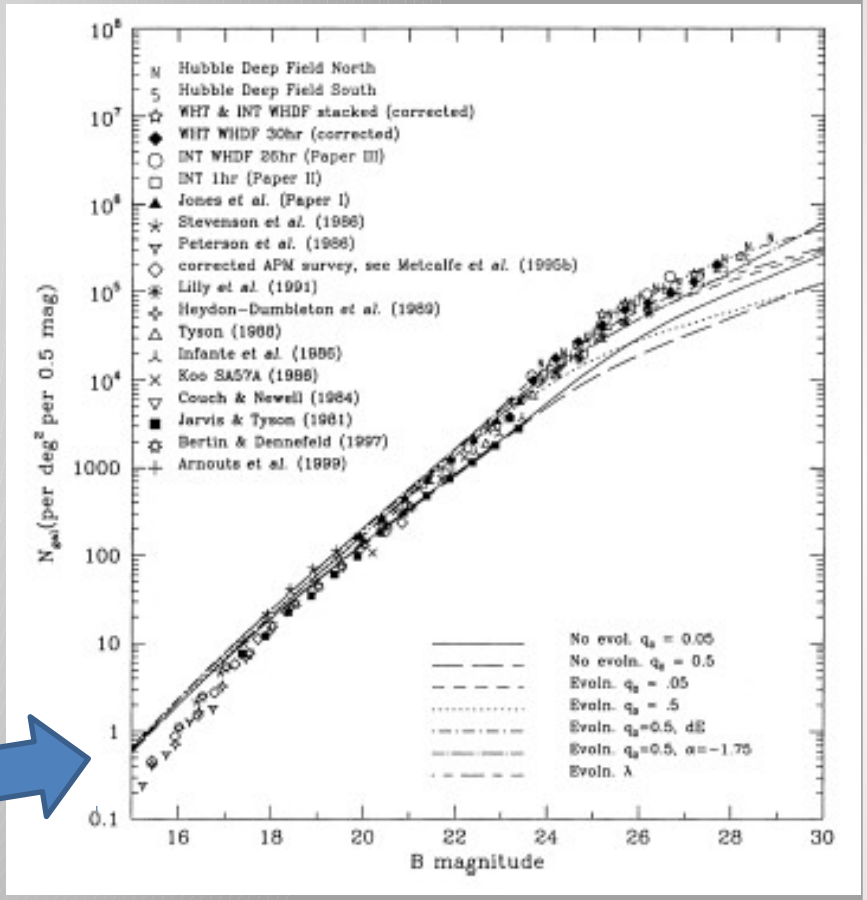
- Counts of galaxies -
- No first order dependence on Cosmology

- But depend on;
- Galaxy clustering (what we're looking for)
- Galaxy evolution (density/luminosity).
- Luminosity Function

$$n(m)\Delta m = \int_0^\infty 4\pi r(z)^2 \frac{dr}{dz} dz \int_{M(m_b,z)}^{M(m_f,z)} \Phi(M) dM,$$

Metcalfe et al 2001., 2006

- Simple phenomenological models (PLE) fit well between 18<B<28.
- But, fit is worse at B<18, slope too steep.
- Two explanations
  - Local Galaxy Evolution
  - Local Under-density:

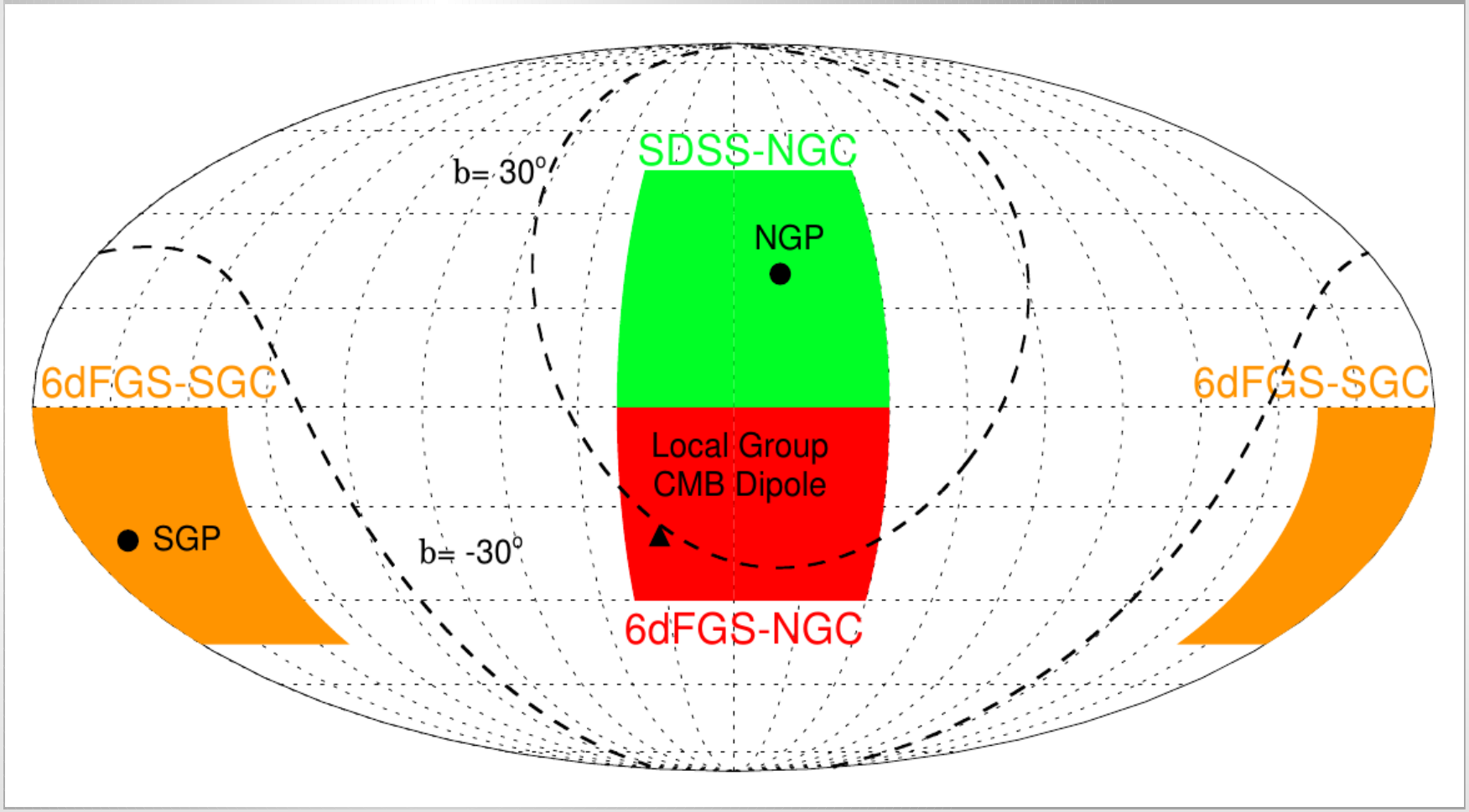


Data

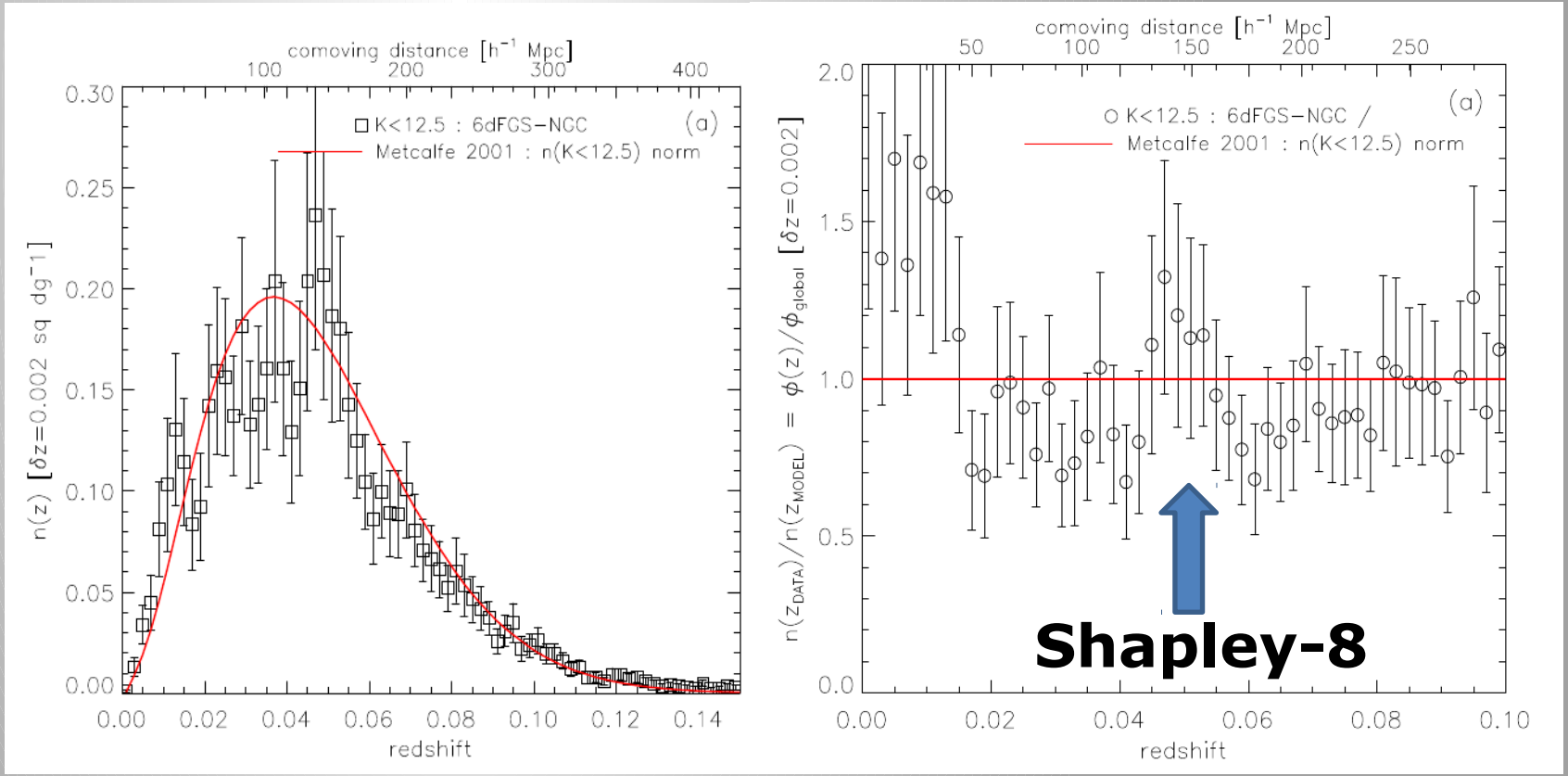
Survey	z_{median}	Mag limit	Area (deg^2)
6dFGS	0.053	$K_{\mathrm{s}} < 12.5$	17000
SDSS-MAIN	0.108	$r < 17.61$	8500
GAMA	0.18	$r < 19.24$	150
2MASS	-	$K_{\mathrm{s}} < 13.5$	$\sim$ Full Sky
SDSS-MAIN	-	$r < 22.04$	8500

We use Vega magnitudes and redshifts in the local group frame

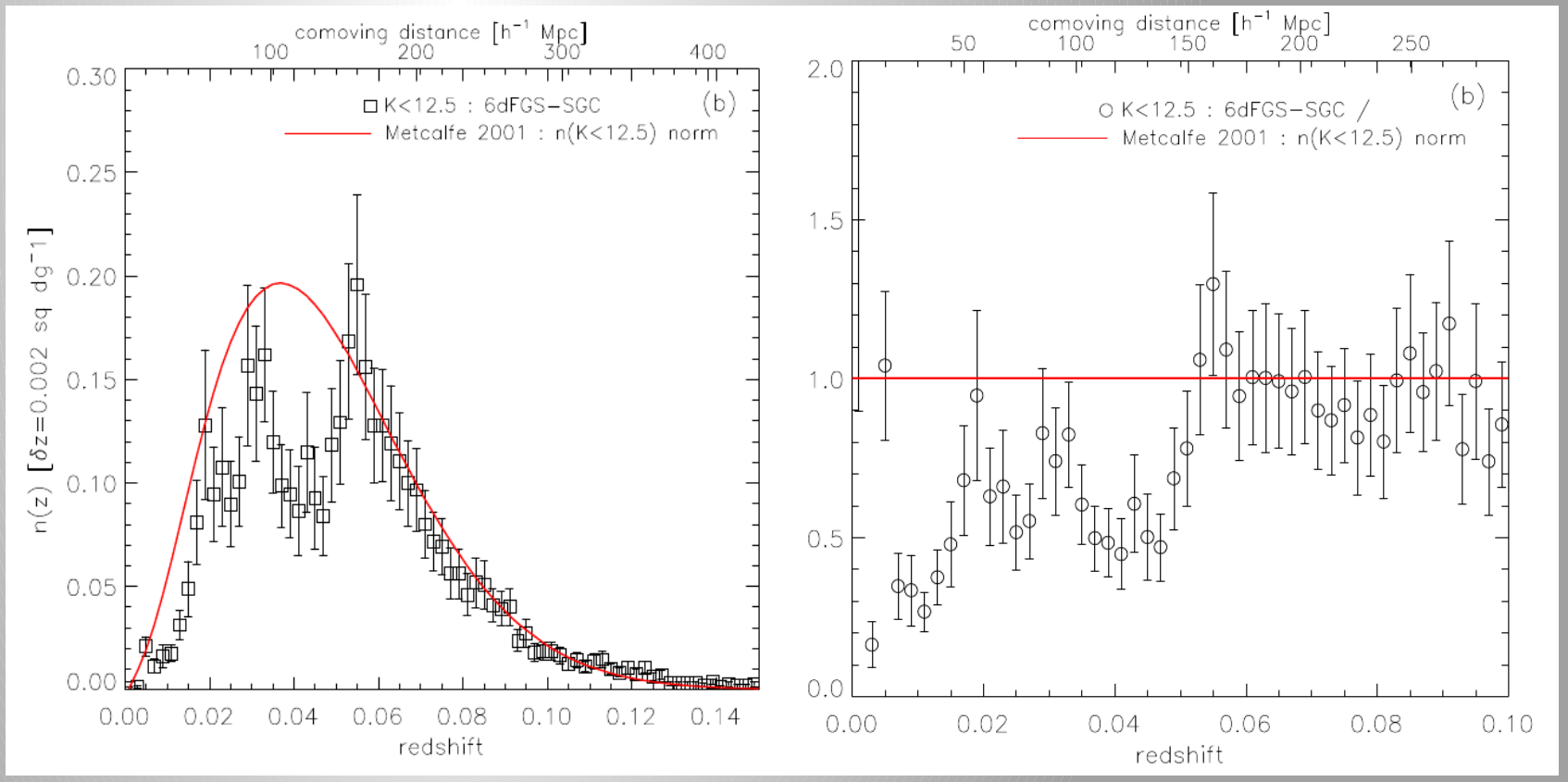
Target Fields



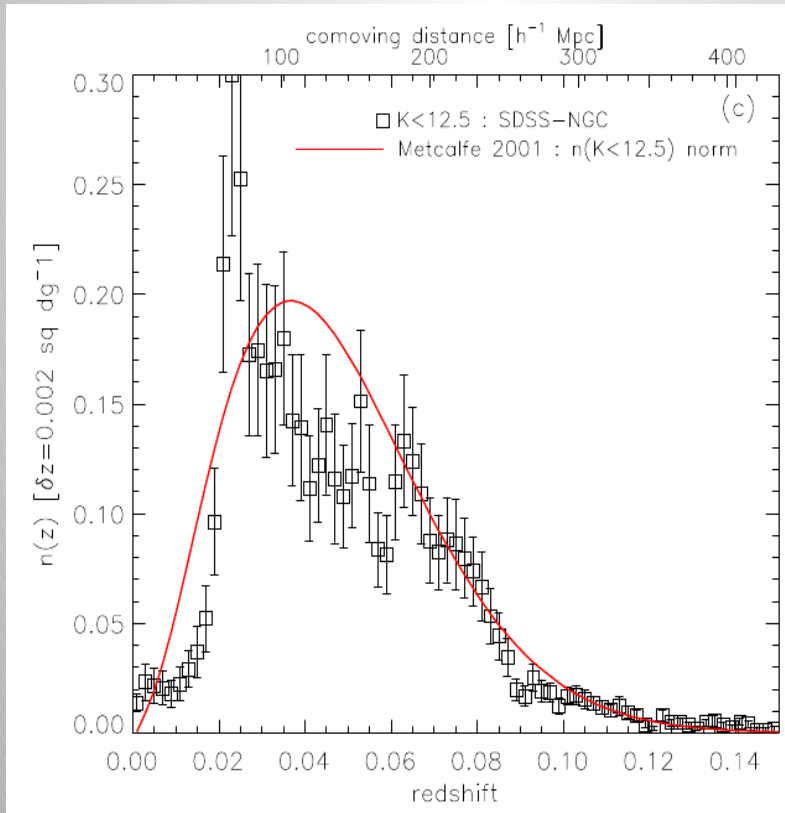
n(z): 6DF-GALACTIC NORTH

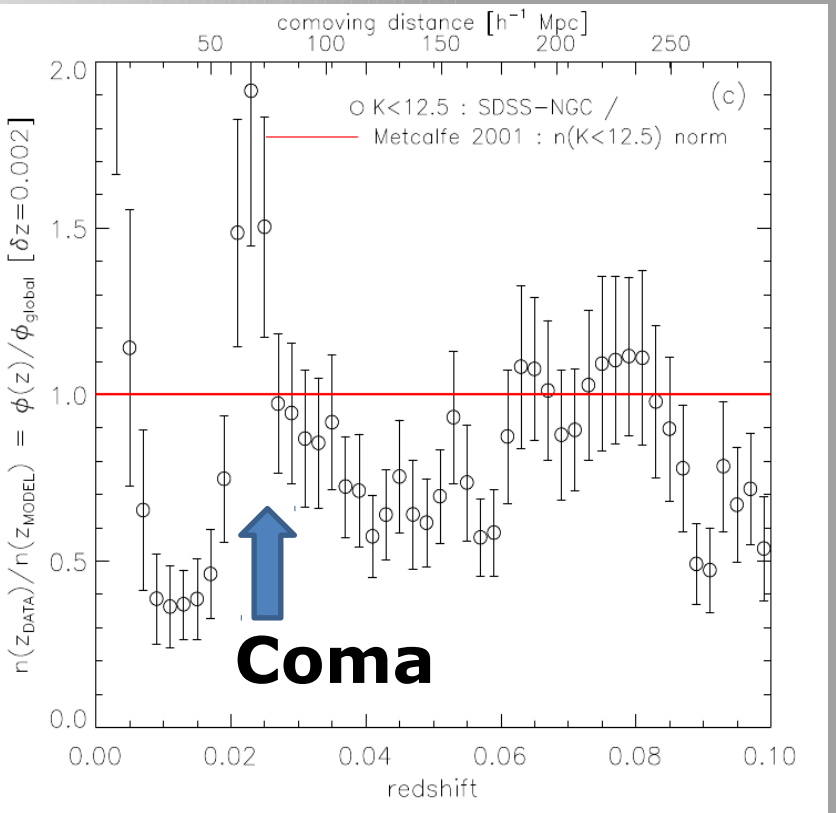


n(z): 6DF-GALACTIC SOUTH



n(z): SDSS-GALACTIC NORTH

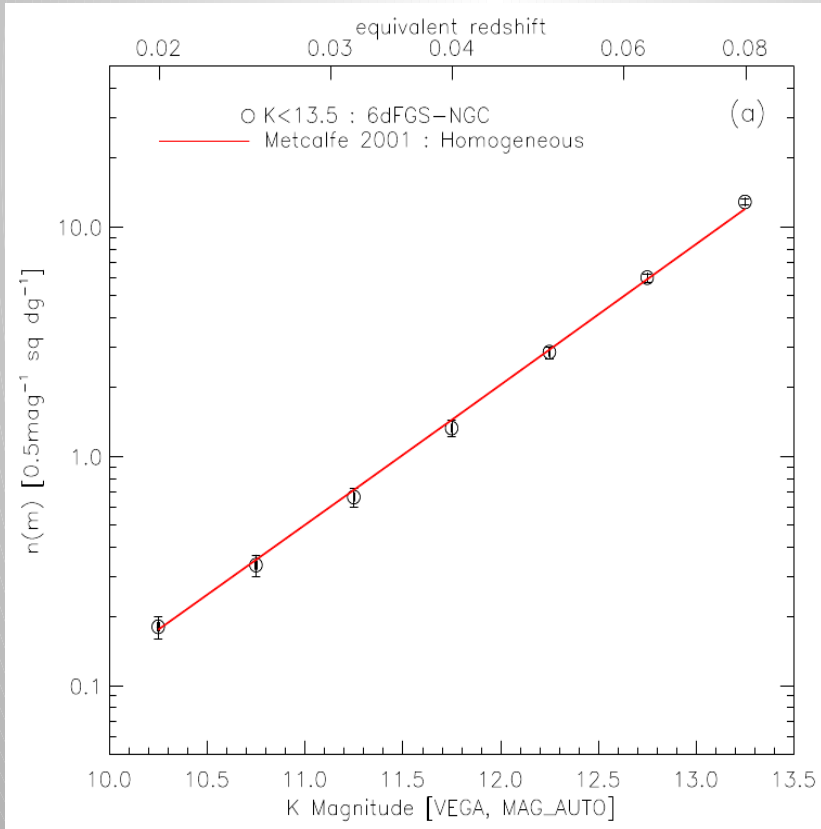


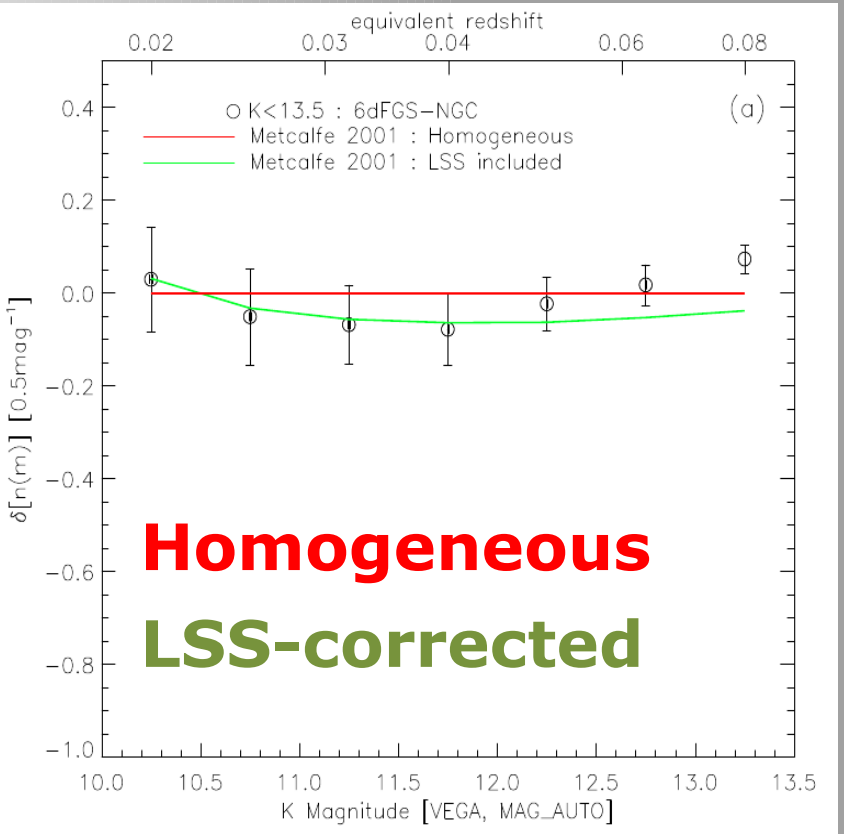


Summarising n(z) - < 150h-1Mpc

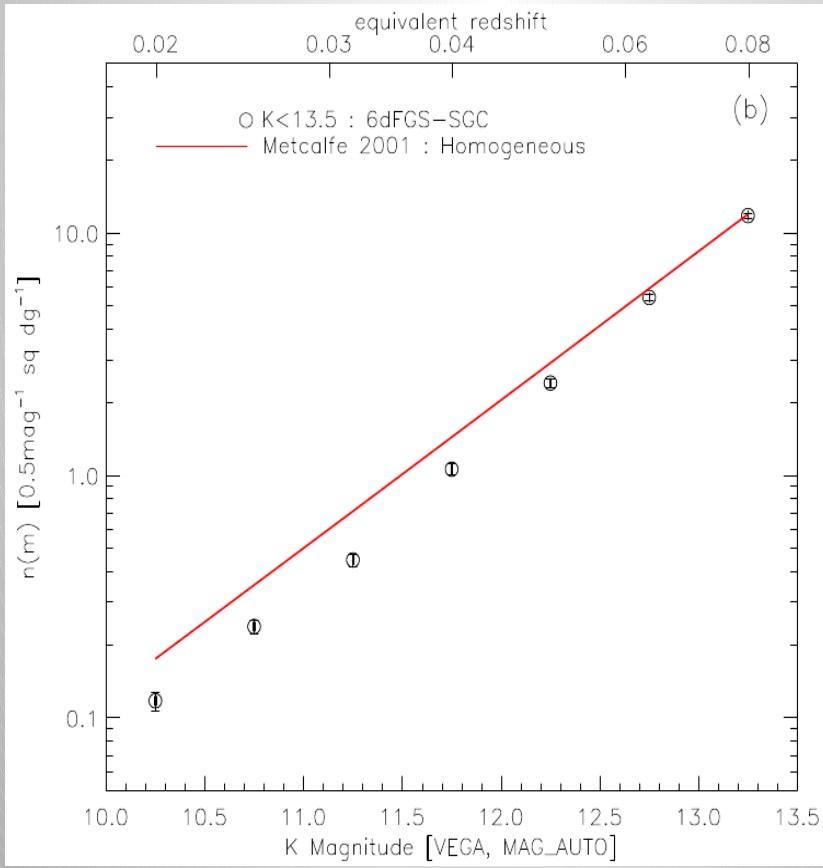
- **40±5% under-density over Southern Galactic cap**
- **14±5% under-density over 6DF-Northern Galactic cap**
- **Less significant under-density over SDSS-Northern Galactic cap, 4±10%**
- **Weighted average: 15±3% under-density overall**

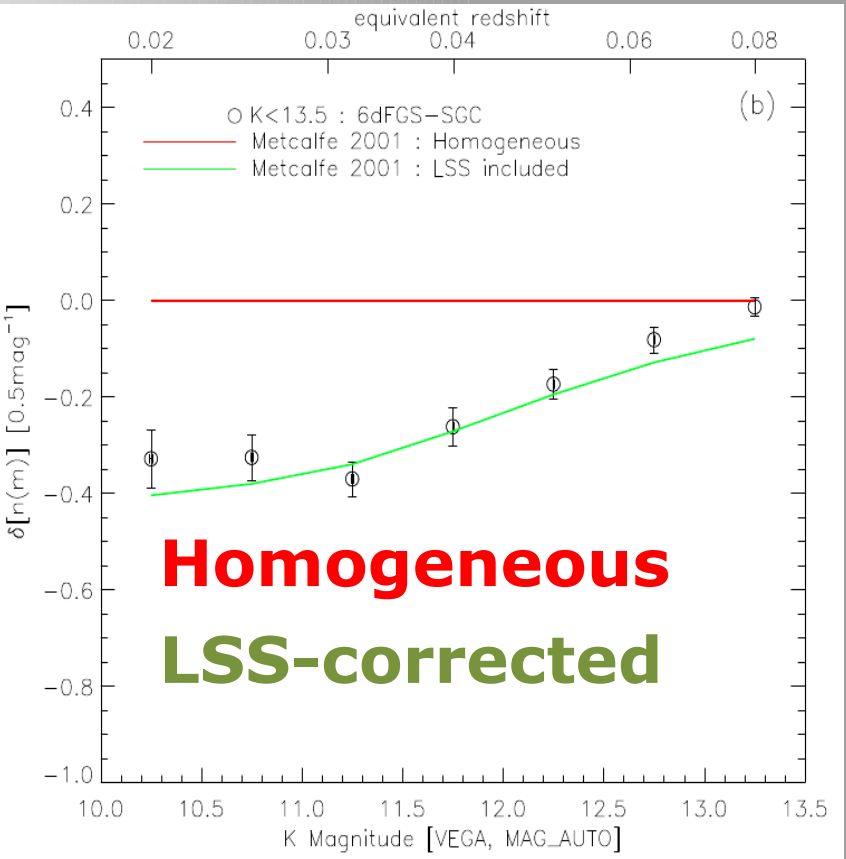
n(m): 6DF-GALACTIC NORTH



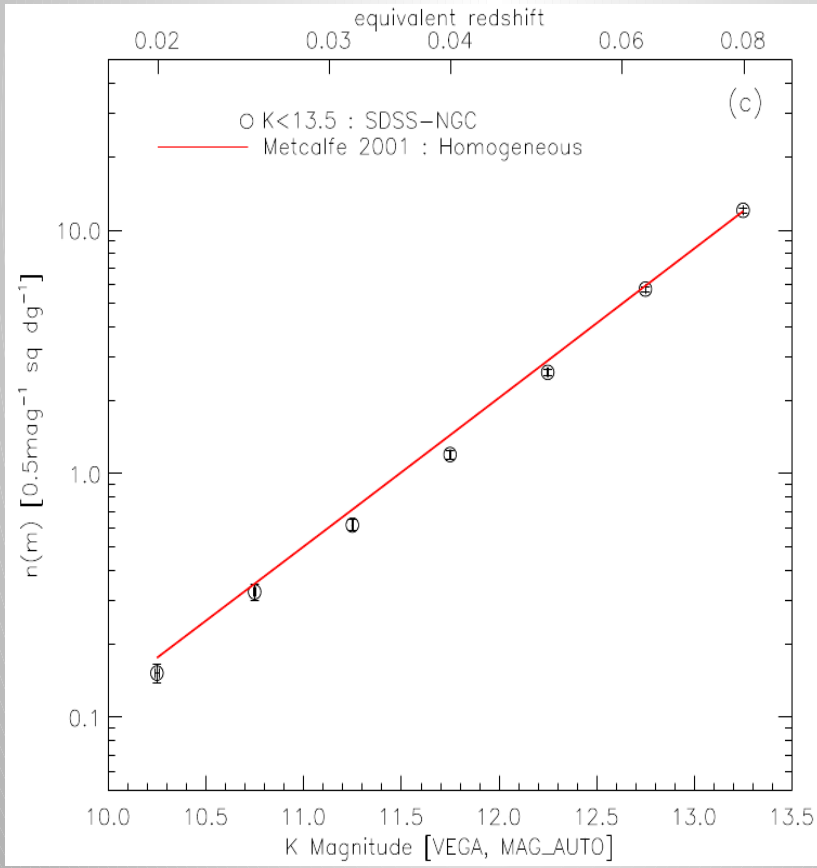


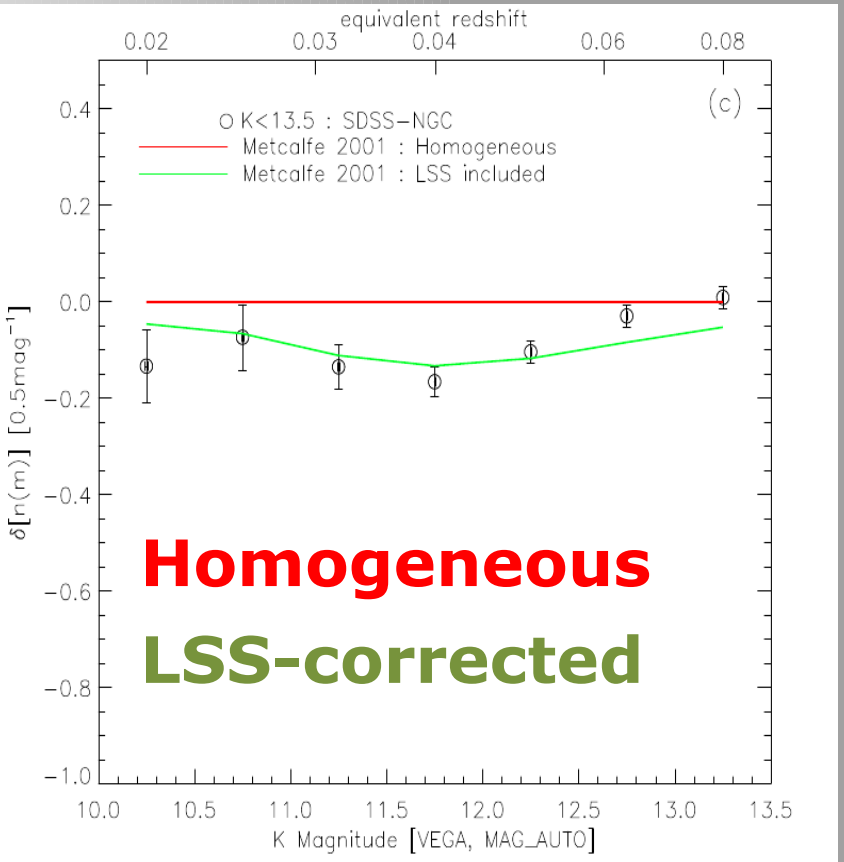
n(m): 6DF-GALACTIC SOUTH





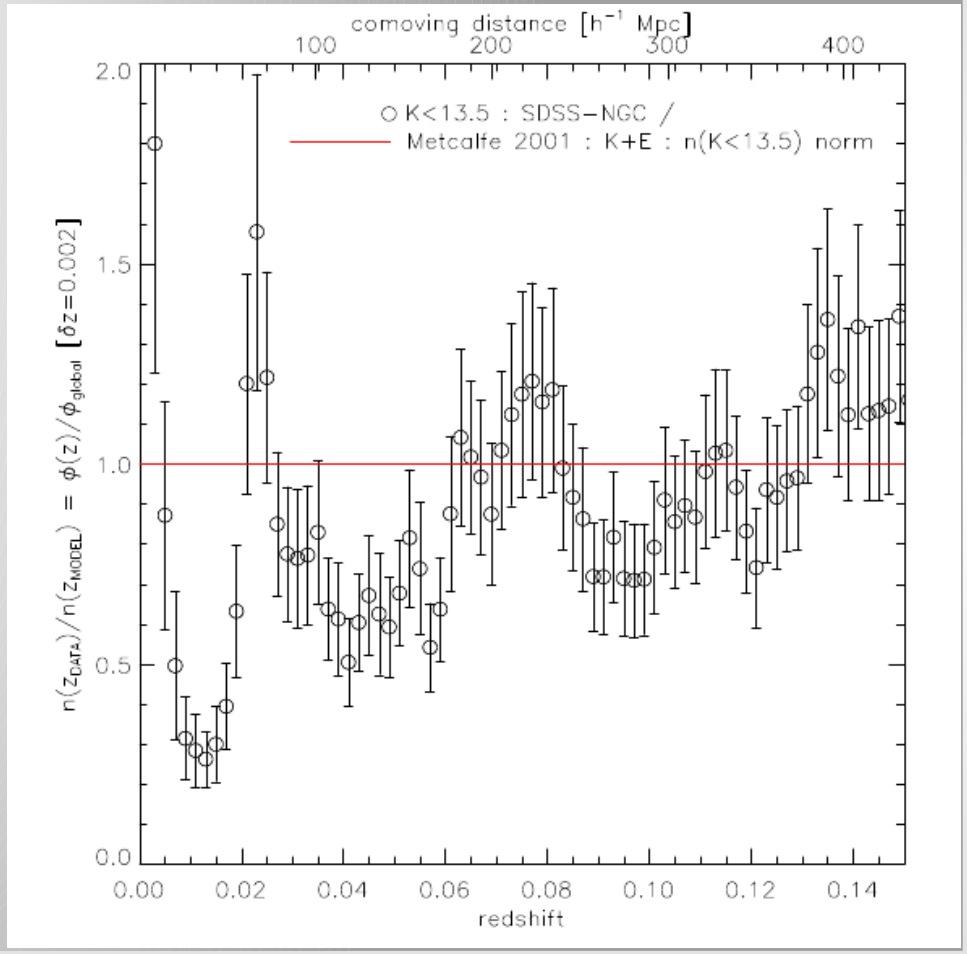
n(m): SDSS-GALACTIC NORTH





Summarising n(z) - < 300h-1Mpc

- Deeper redshifts in SDSS-NGC region.
- Suggests under-density deeper than 150h-1 Mpc → 300h-1Mpc
- Density contrast of 12±3% to z<0.1



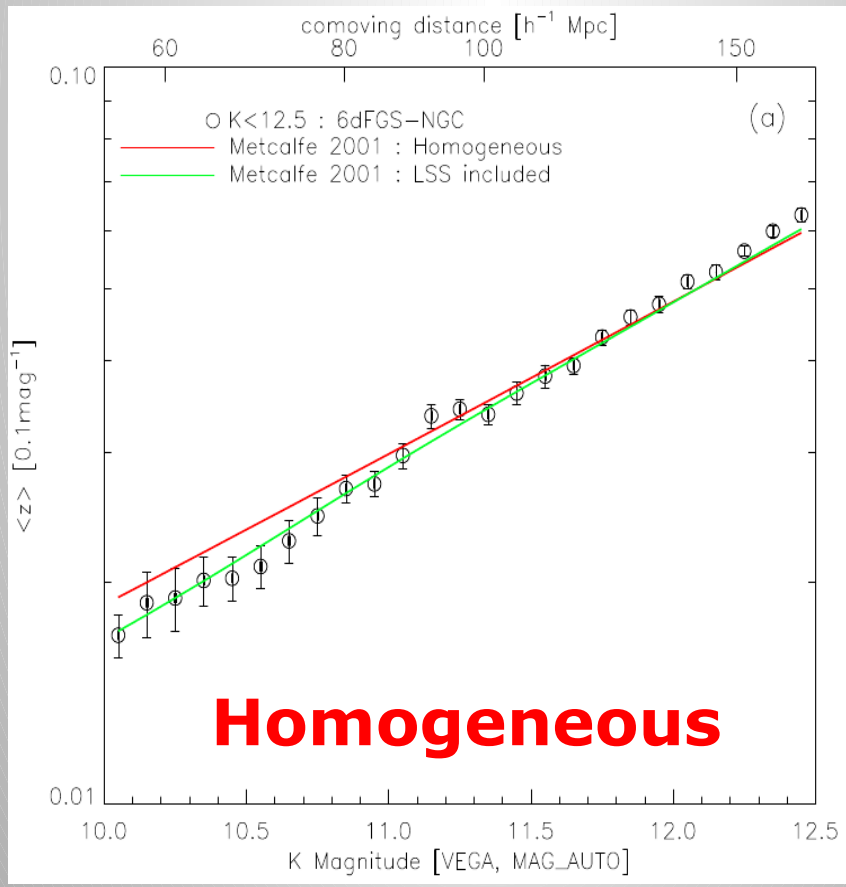
What is <z(m)>?

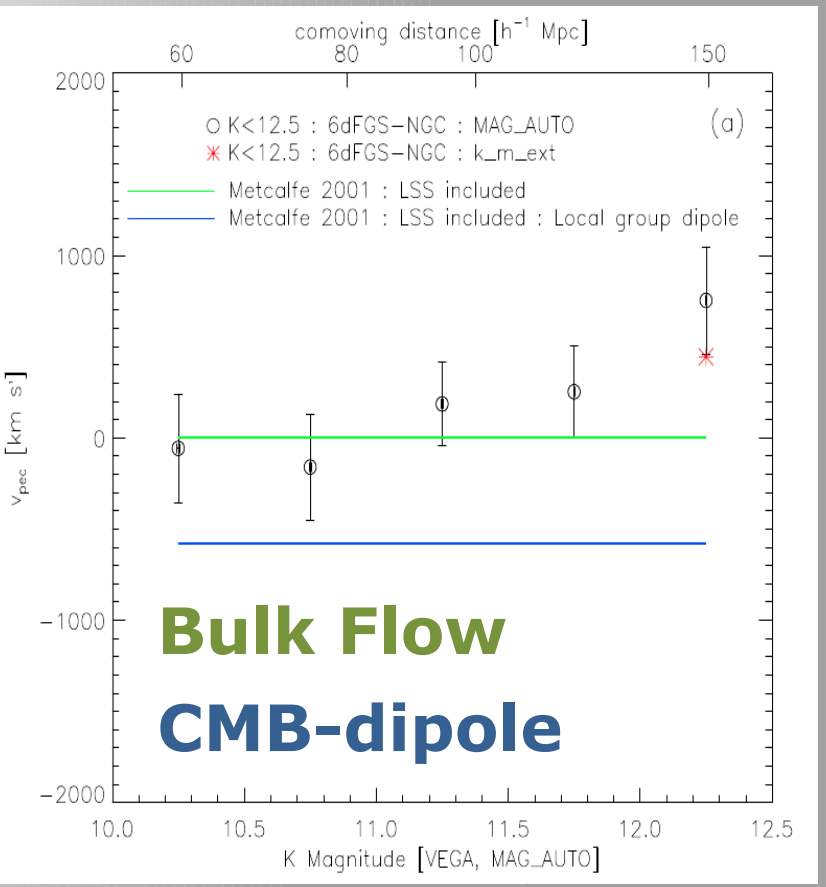
- Mean redshift in an apparent magnitude bin [m,m+δm]

$$\overline{z}(m) \propto 10^{0.2pm}.$$

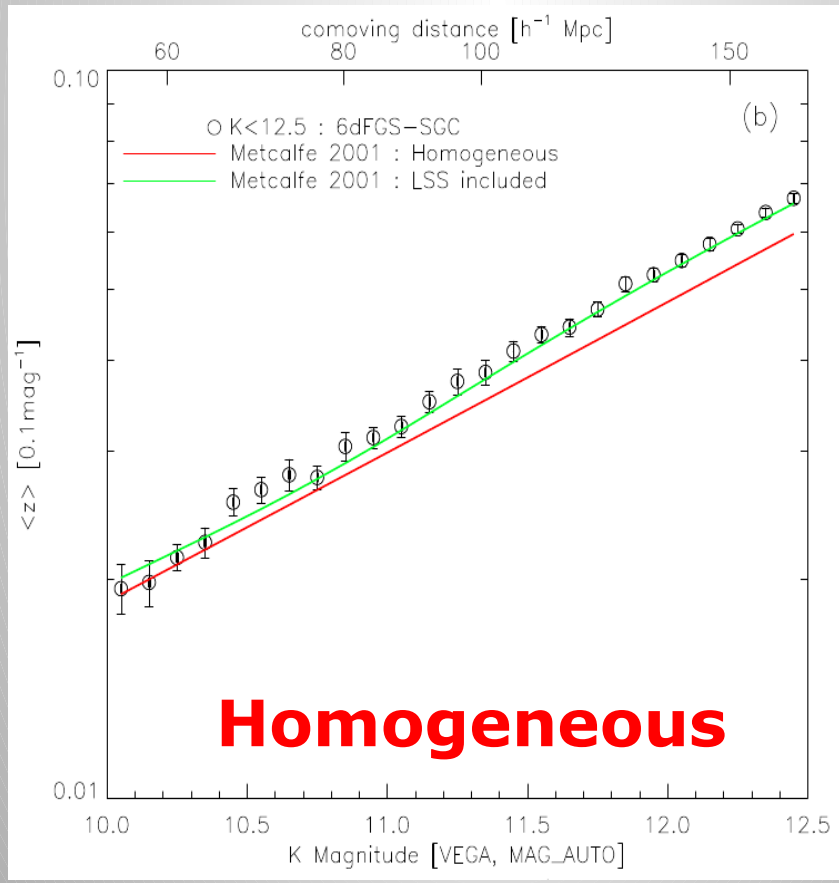
- Soneira 1979, Hubble's Law implies p=1.
- Effectively using the Luminosity function as a standard candle
- Can probe over/under-density in mass, not just galaxies.

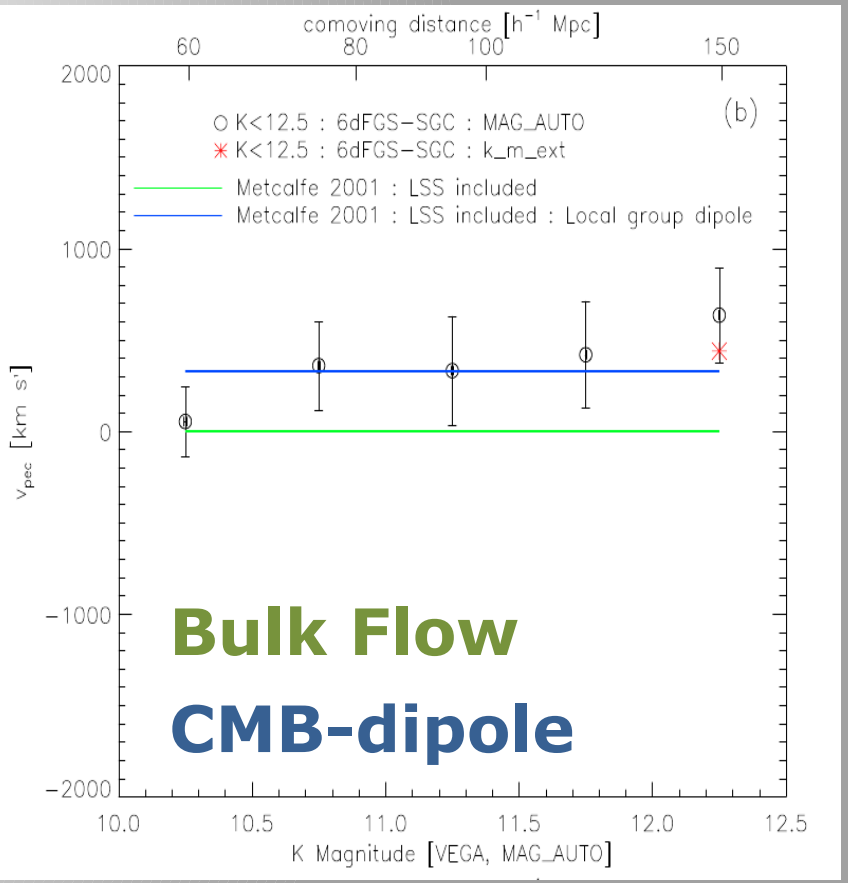
<z(m)>: 6DF-GALACTIC NORTH



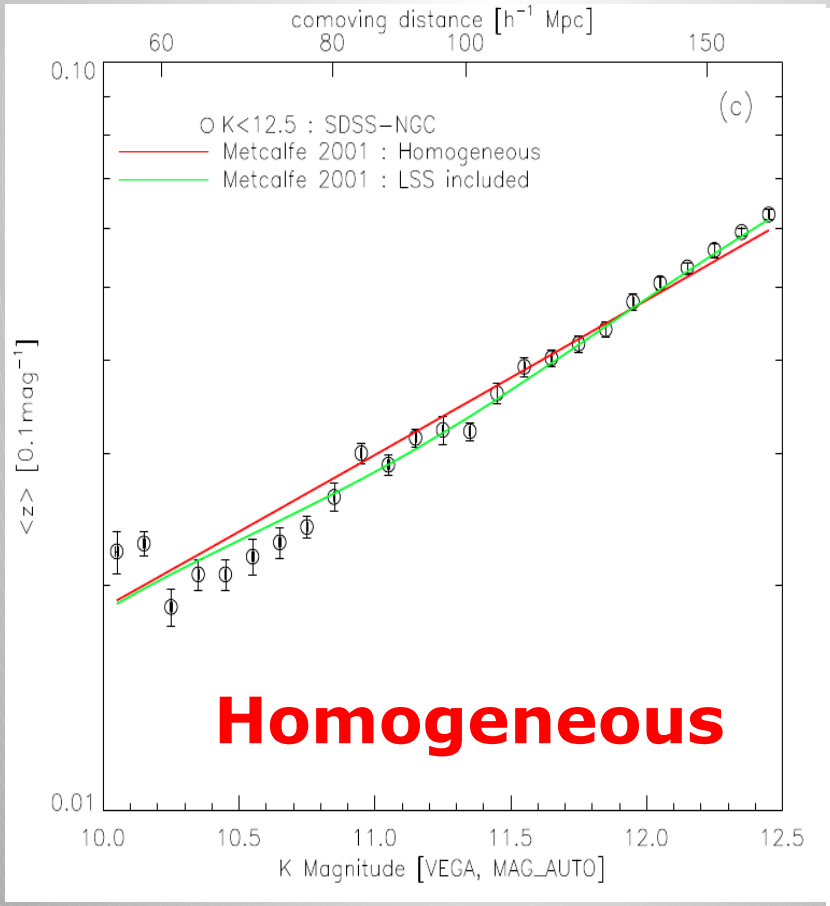


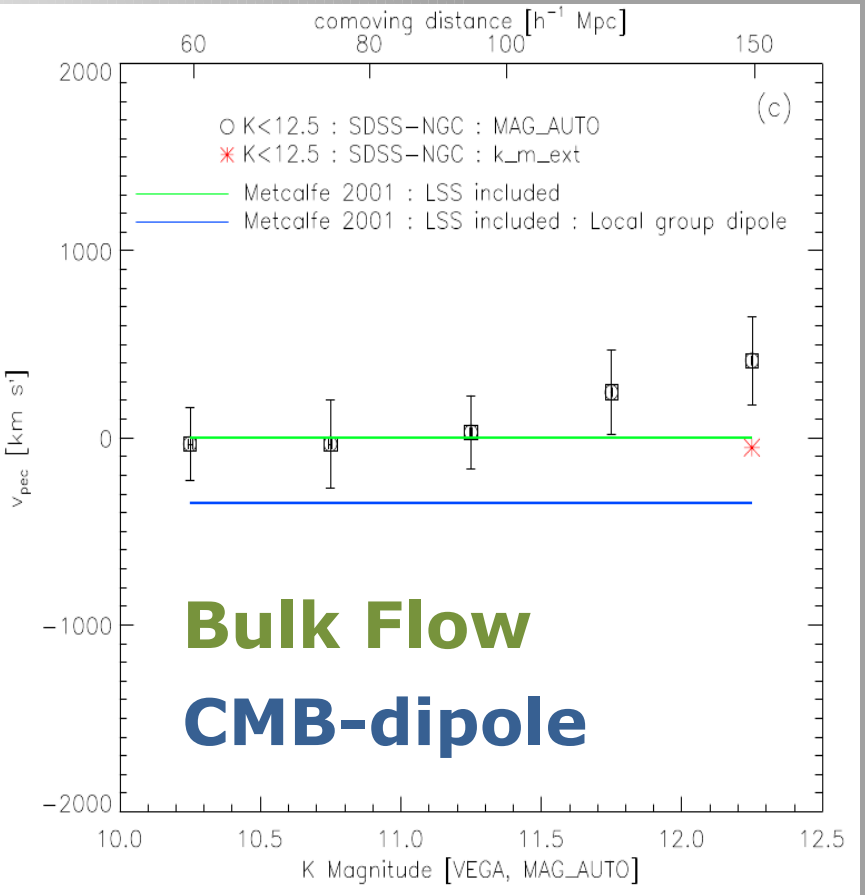
<z(m)>: 6DF-GALACTIC SOUTH





<z(m)>: SDSS-GALACTIC NORTH





Summarising <z(m)>

- LSS corrected models improve fit to <z(m)>
- Bulk motion preferred in 2 of 3 regions (green line better fit than blue)
- Overall, no convergence to CMB dipole in volume surveyed to K<12.5 (~150h-1Mpc)
- May also be consistent with a faster local expansion (data rises above green line).

Faster Expansions

- **5% tension between local and CMB (global) measurements of H0**
- **Sits well with a local under-density. This would drive a faster expansion (i.e: higher local H0).**
- **Spherical, linear prediction δg~15% → δH0/H0 ~2-3%.**
- **Bigger |δg|, bigger δH0/H0**

$$\delta H_0/H_0 = -\frac{1}{3}\Omega_m^{0.6}/b \times \delta\rho_g/\rho_g$$

But what about systematics ...

- **Magnitude System**
  - Magnitude scale error is needed to explain steep n(m)
  - Minor difference between 2MASS magnitudes and deeper Loveday et al 2002 system. We correct for this.

- **K corrections and Galaxy Evolution**
  - Used a range of corrections (BZ models)
  - K band results robust to K+E.

But what about systematics ...

- **Star-Galaxy Separation**
  - >99% for 2MASS K<12.8
- **Photometric Incompleteness**
  - >97.5 for 2MASS K<13.5
- **Spectroscopic Incompleteness**
  - folded into modelling

- **Metcalfe et al 2001 LF checks out after applying ML methods to these samples (Shanks and Whitbourn in prep.)**

Summary

- **Detected 40±5% underdensity over ~3500 sq deg of Southern Galactic cap out to 150h-1Mpc.**
- **Less significant under-densities detected in two other similar sized regions (14±5%, 4±10%). Overall, 15±3% underdensity.**
- **Bulk flow preferred for LSS-corrected<z(m)> residuals → Dipole not converged within 150h-1Mpc**
- **Tentative evidence using deeper SDSS samples that under-density extends to 300 h-1Mpc (smaller delta)**

Any Questions … ?

CMB and Homogeneity

- CMB isotropic to ~1 parts in 105
- → z=0 Density contrast: $\delta\rho/\rho \sim \pm 0.06$

- Sound horizon scales rs~100h-1 Mpc
- Acoustic scale ℓa~210h-1 Mpc

- Roughly expect at most ±30% over/under-densities on r~200h-1 Mpc scales.

Luminosity Functions ...

- **Metcalfe et al 2001 Luminosity function is significantly different from other literature LF's.**
- **Significantly steeper alpha, higher normalisation**
- **Goes to the heart of the matter, so we've re-measured luminosity function of our samples.**

- **Approx equivalent LF found (upcoming paper ± finishing a thesis).**
- **Approx equivalent shape density profiles.**

Luminosity Function Normalisation.

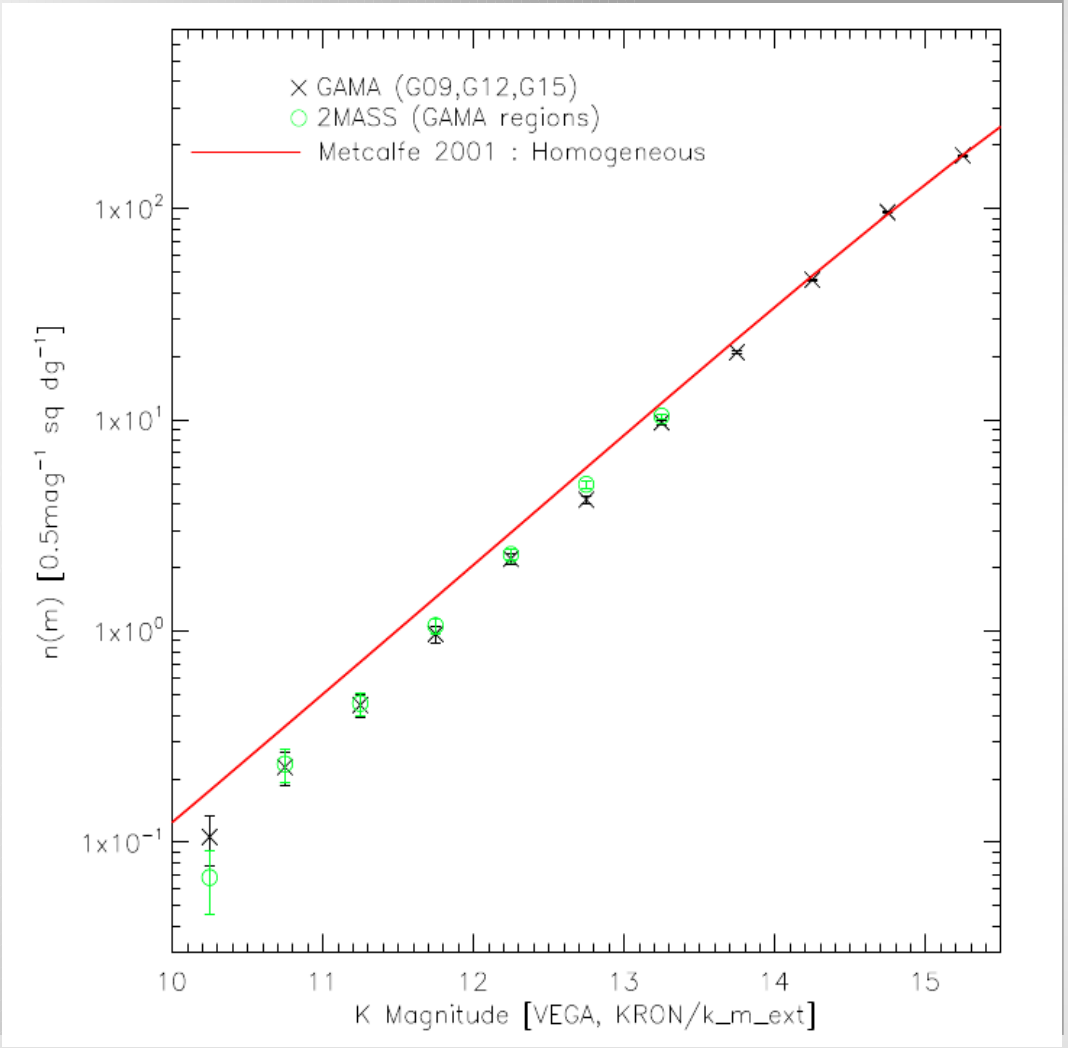
- **Standard method for inferring phistar is not valid if there are large scale over/under-densities (Davis & Huchra 1982).**

$$\bar{n} = \frac{\sum_{j=1}^{N_{\rm gal}} w(z_j)}{\int dV S(z) w(z)}, \quad w(z) = \frac{1}{1 + \bar{n} J_3 S(z)},$$

- **We therefore use number counts to set normalisation.**
- **Therefore studied deep K band → GAMA and deep r band → SDSS data**

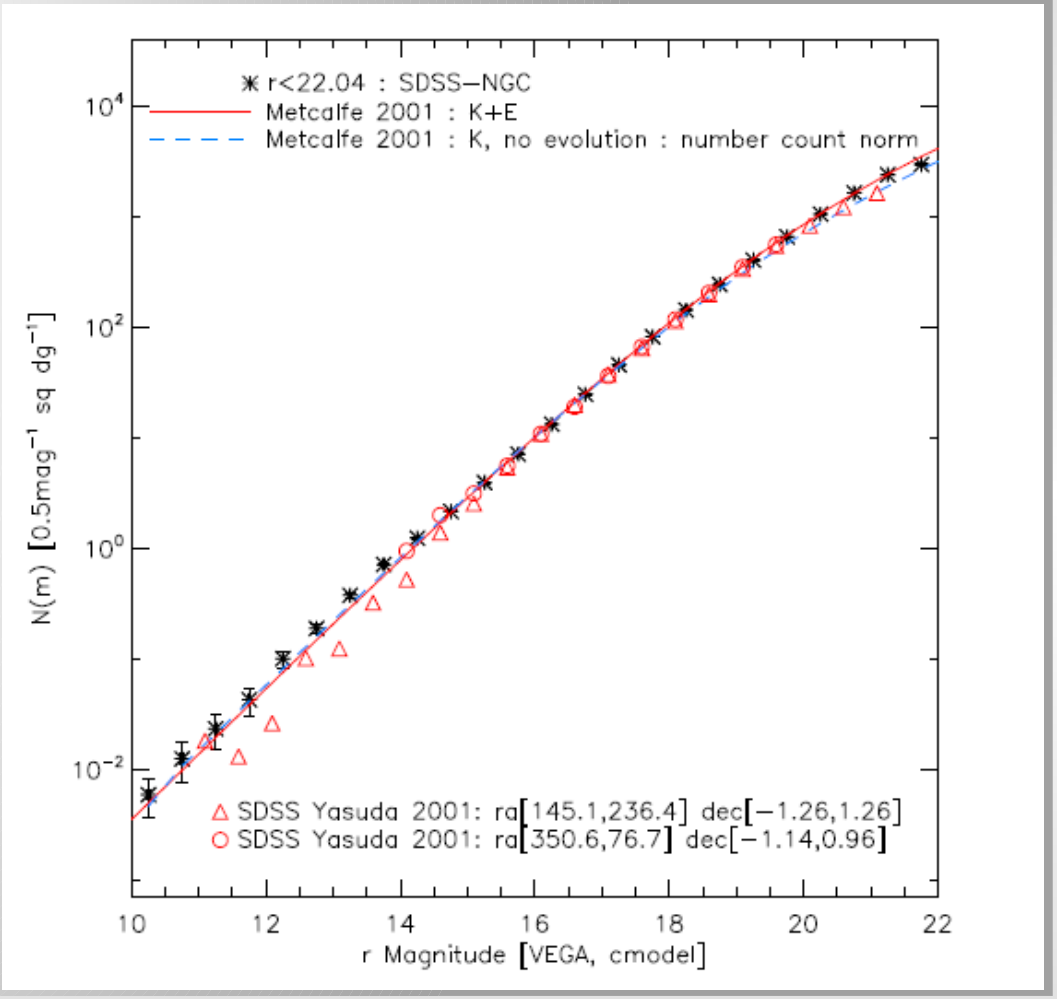
GAMA K counts.

- Good GAMA-2MASS agreement, supports magnitude scale
- Good GAMA-Metcalfe et al 2001 agreement, supports LF normalisation.



SDSS r counts

- Good agreement with early commissioning data counts, supports magnitude scale
- Good SDSS-Metcalfe et al 2001 agreement, supports LF normalisation.



Frith et al 2003., 2005a,2005b,2006a,2006b

- Studied 'Local Hole' via 2dFGRS, preliminary 2MASS and Calar-Alto H band data.
- Under-density δ~20% extending to 300 h-1Mpc scales
- 2.5-4σ anomaly with respect to a set of ΛCDM mocks.