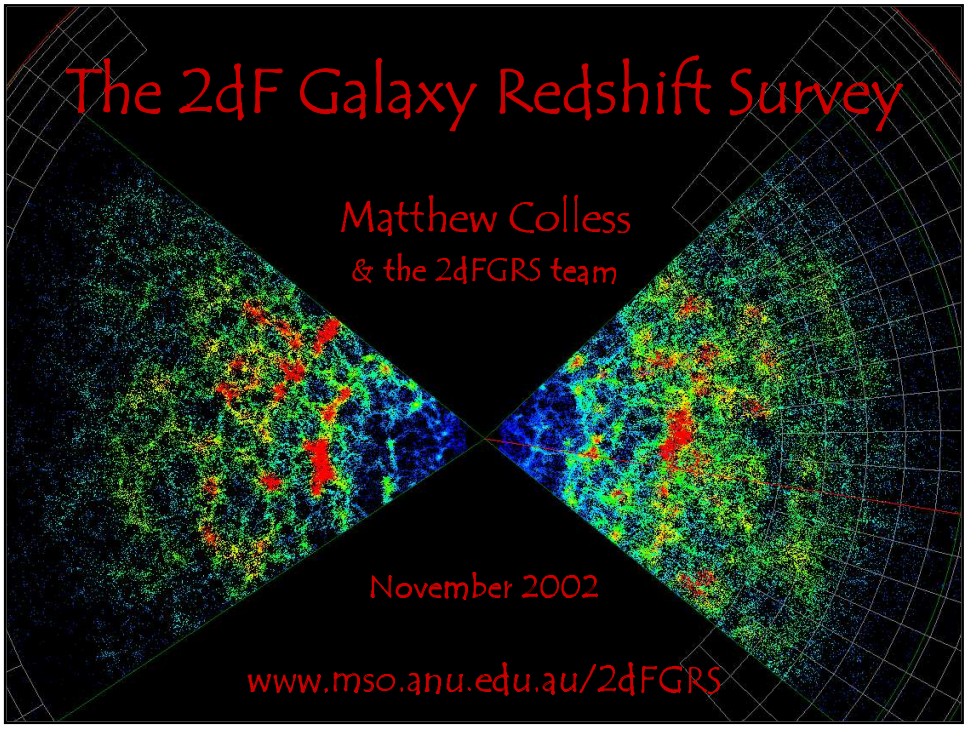
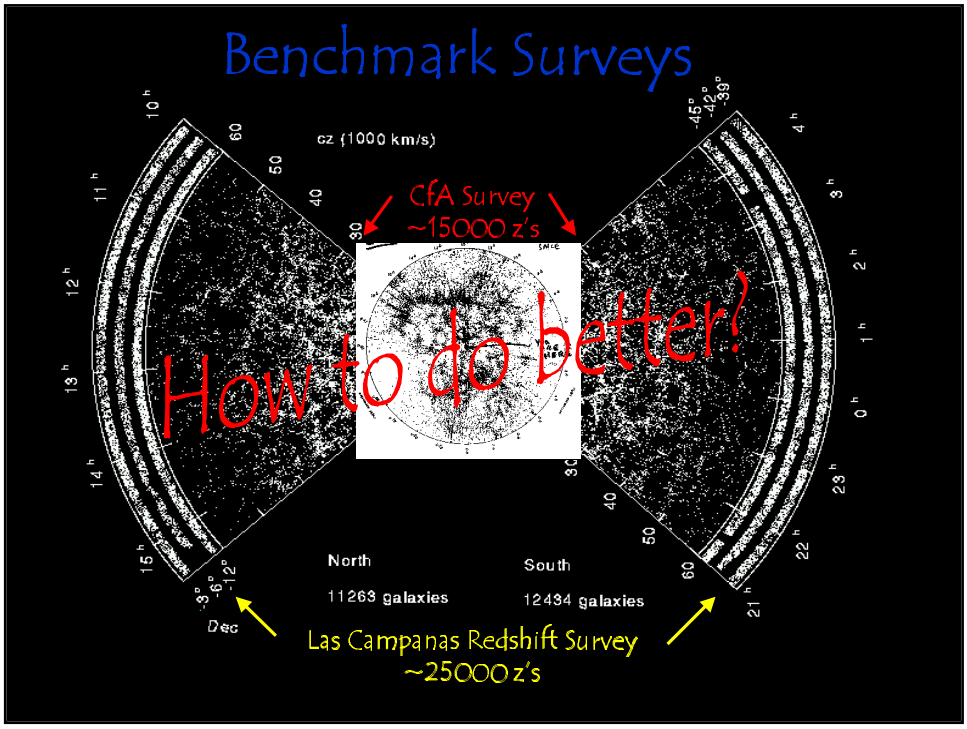
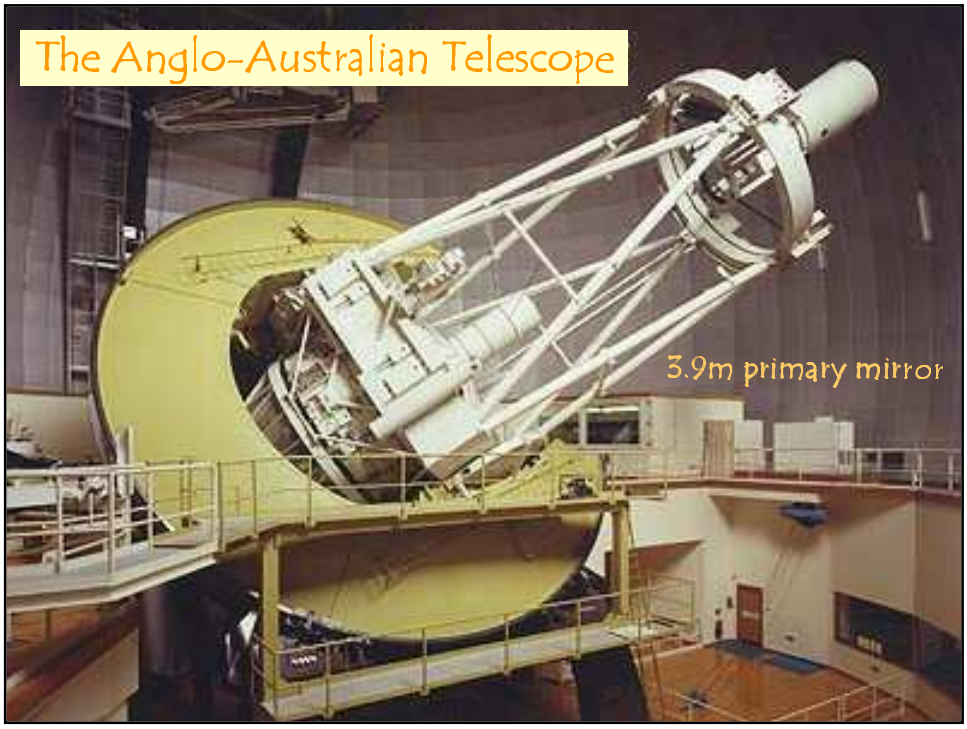


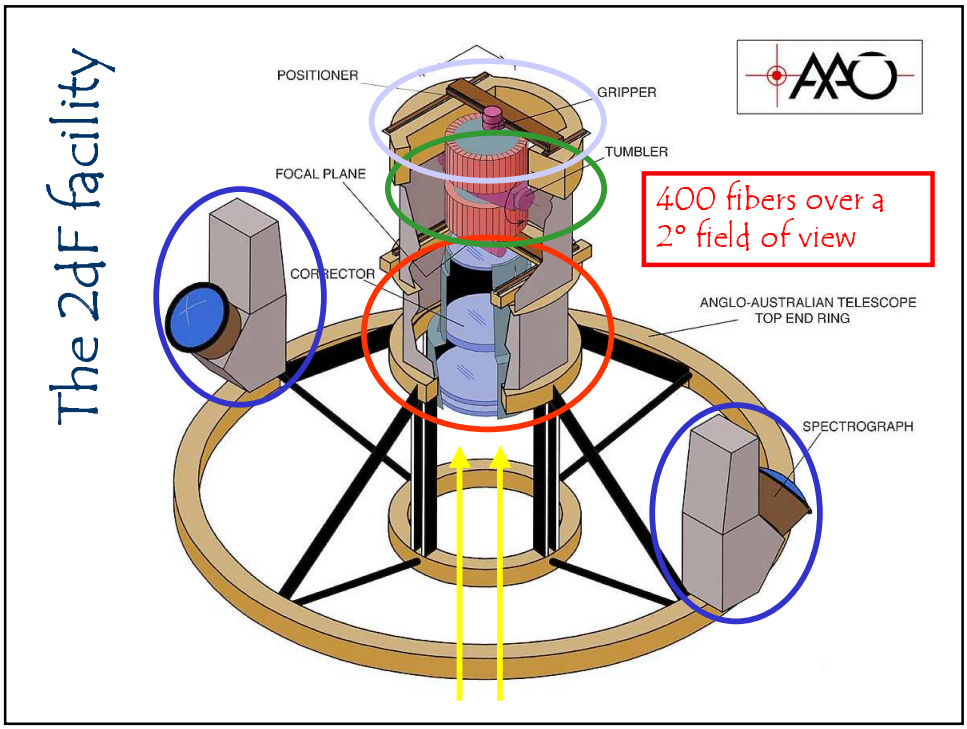
The 2dFGRS Team

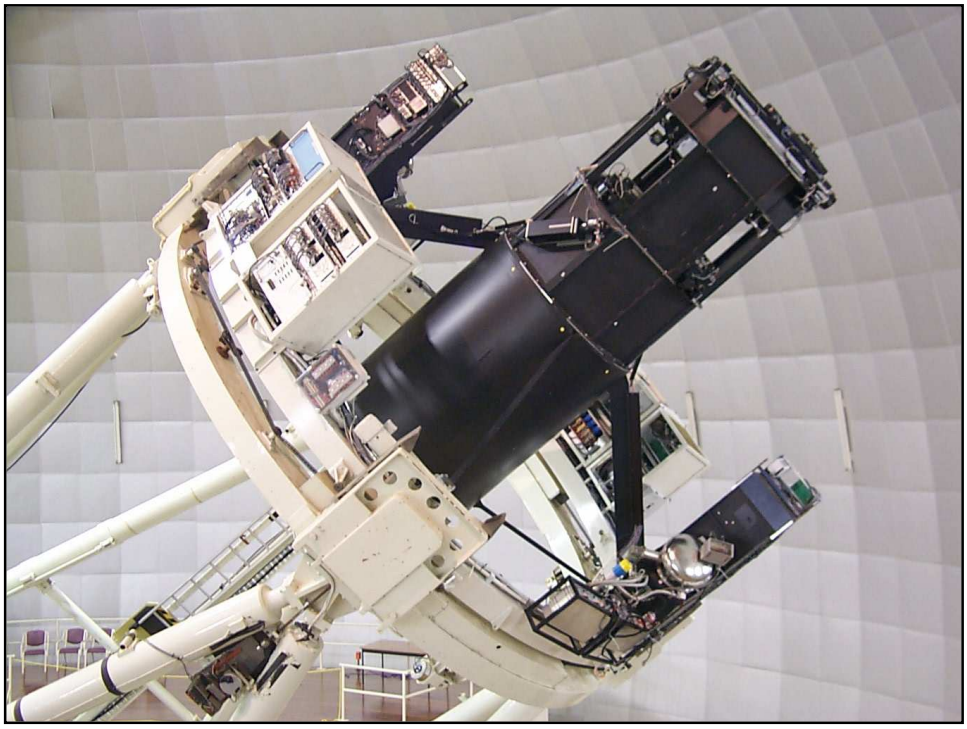
Ivan Baldry	Nick Cross	Ofer Lahav
Carlton Baugh	Gavin Dalton	Ian Lewis
Claus Beisbart	Roberto De Propris	Stuart Lumsden
Joss Bland-Hawthorn	Simon Driver	Steve Maddox (PI)
Terry Bridges	George Efstathiou	Darren Madgwick
Sarah Bridle	Richard Ellis	Peder Norberg
Russell Cannon	Carlos Frenk	John Peacock (PI)
Shaun Cole	Karl Glazebrook	Will Percival
Matthew Colless (PI)	Ed Hawkins	Bruce Peterson
Chris Collins	Carole Jackson	Will Sutherland
Warrick Couch	Bryn Jones	Keith Taylor

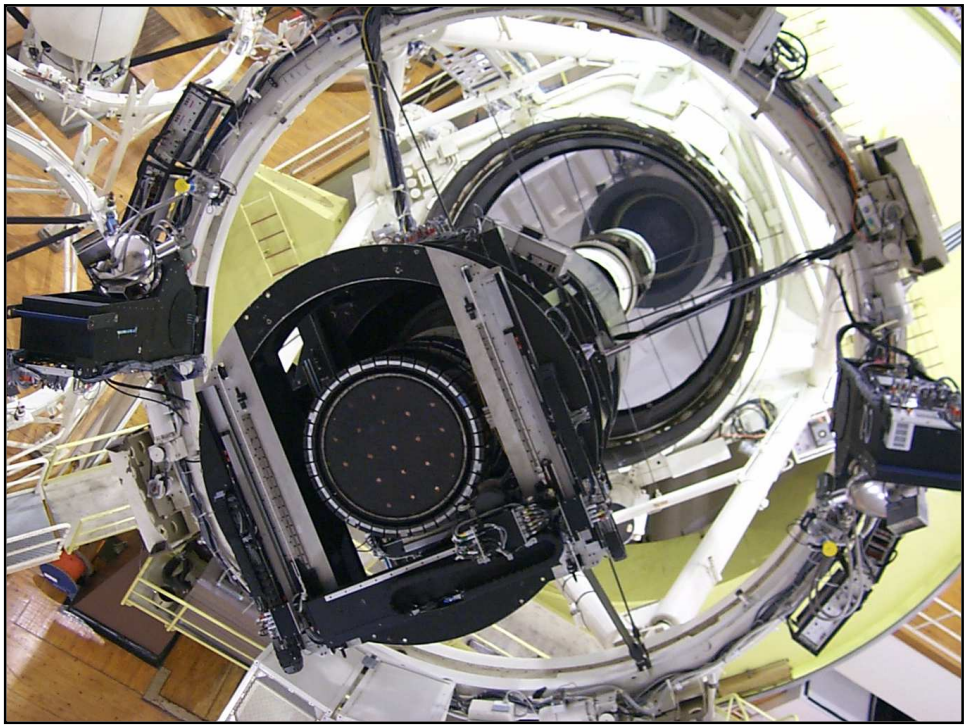

Benchmark Surveys
cz (1000 km/s)
CfA Survey
~15000 z's
How to do better?
North
11263 galaxies
South
12434 galaxies
Las Campanas Redshift Survey
~25000 z's
Dec

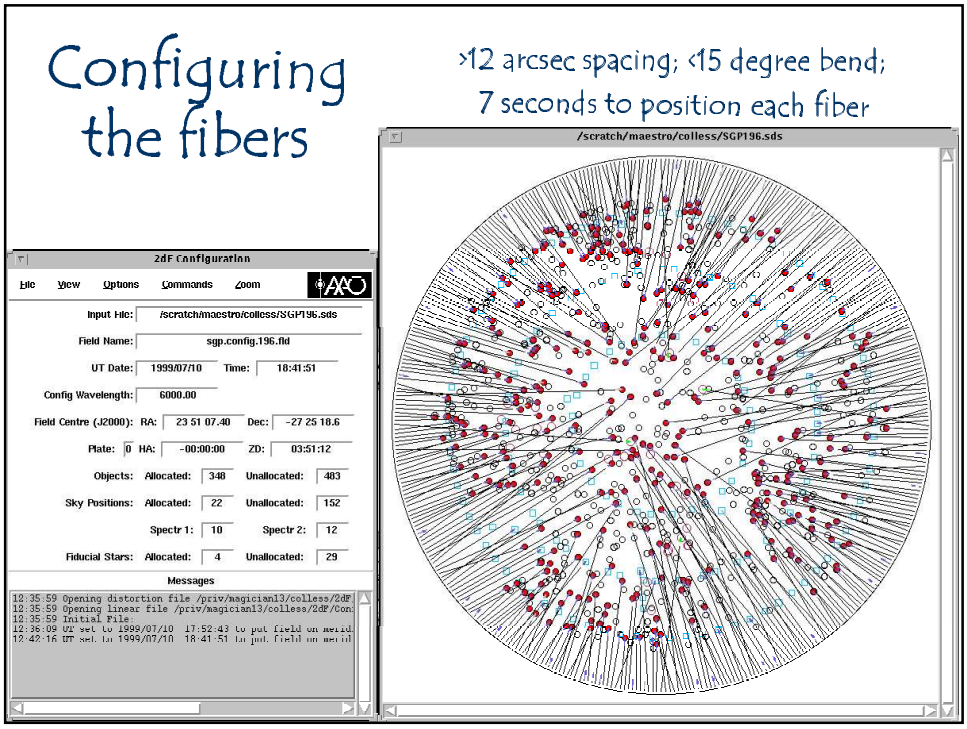

The UK Schmidt Telescope
The Anglo-Australian Telescope

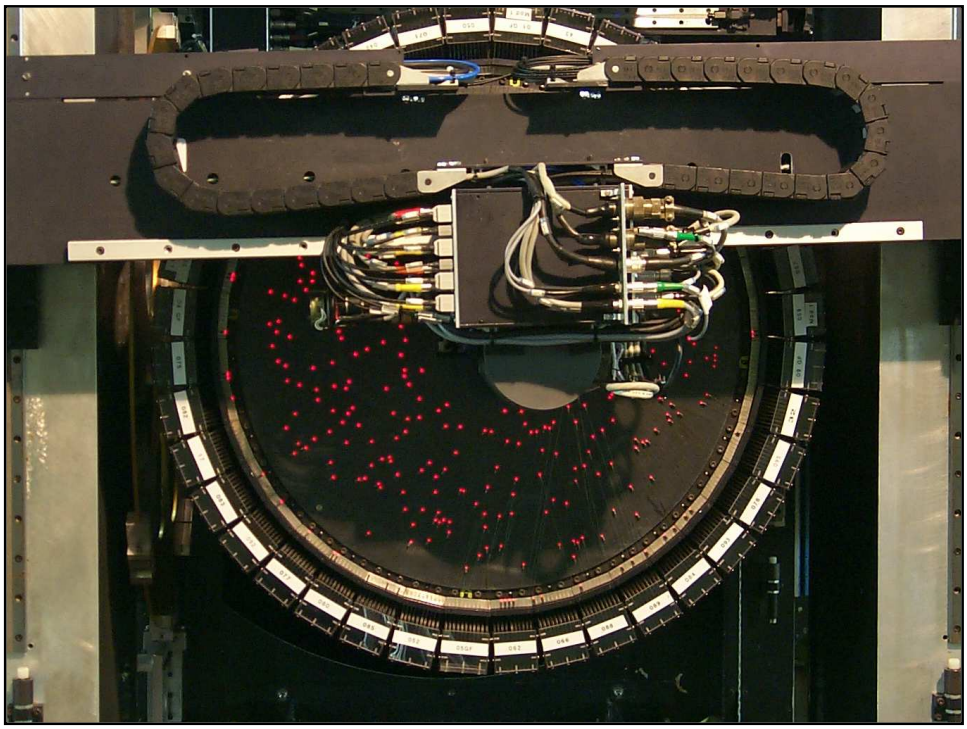

The Anglo-Australian Telescope
3.9m primary mirror

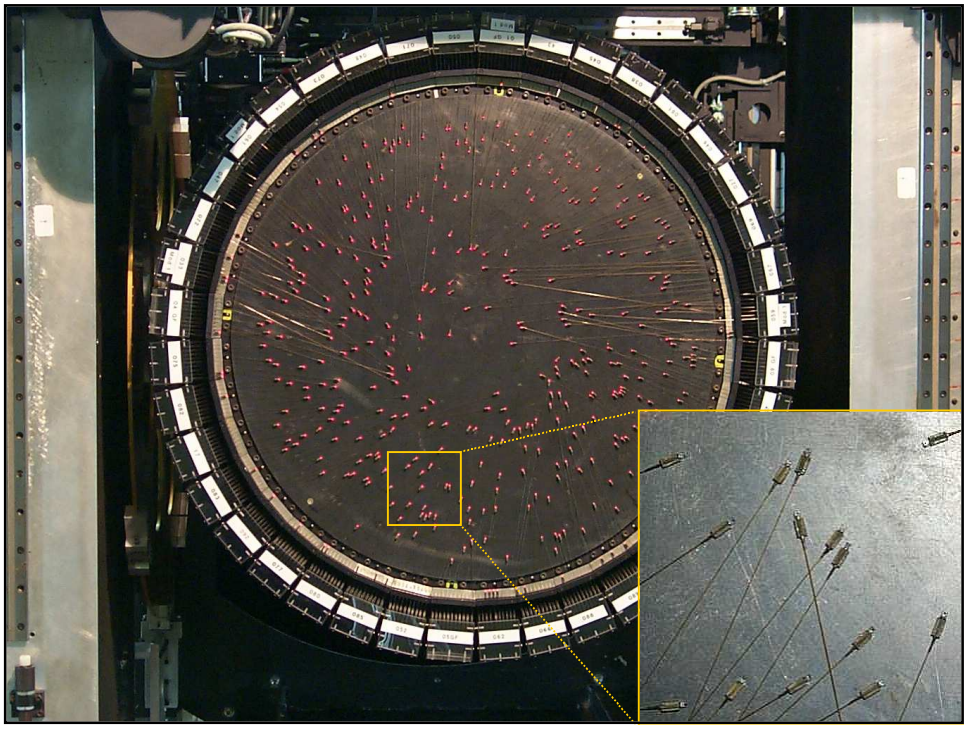

The 2dF facility
POSITIONER
GRIPPER
TUMBLER
FOCAL PLANE
CORRECTOR
400 fibers over a 2° field of view
ANGLO-AUSTRALIAN TELESCOPE TOP END RING
SPECTROGRAPH

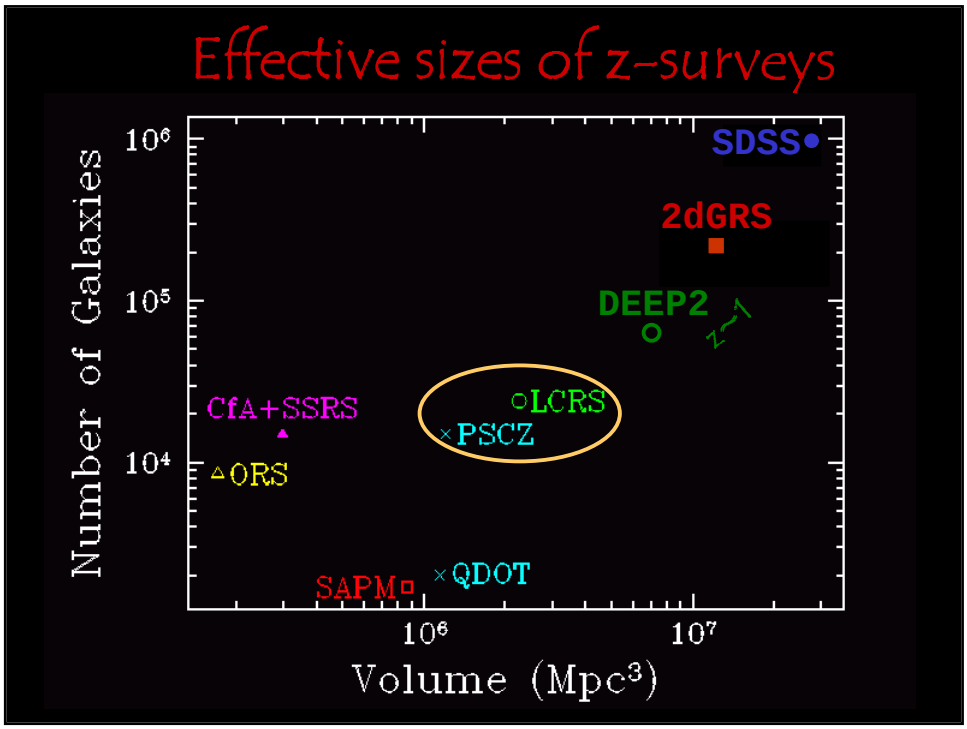


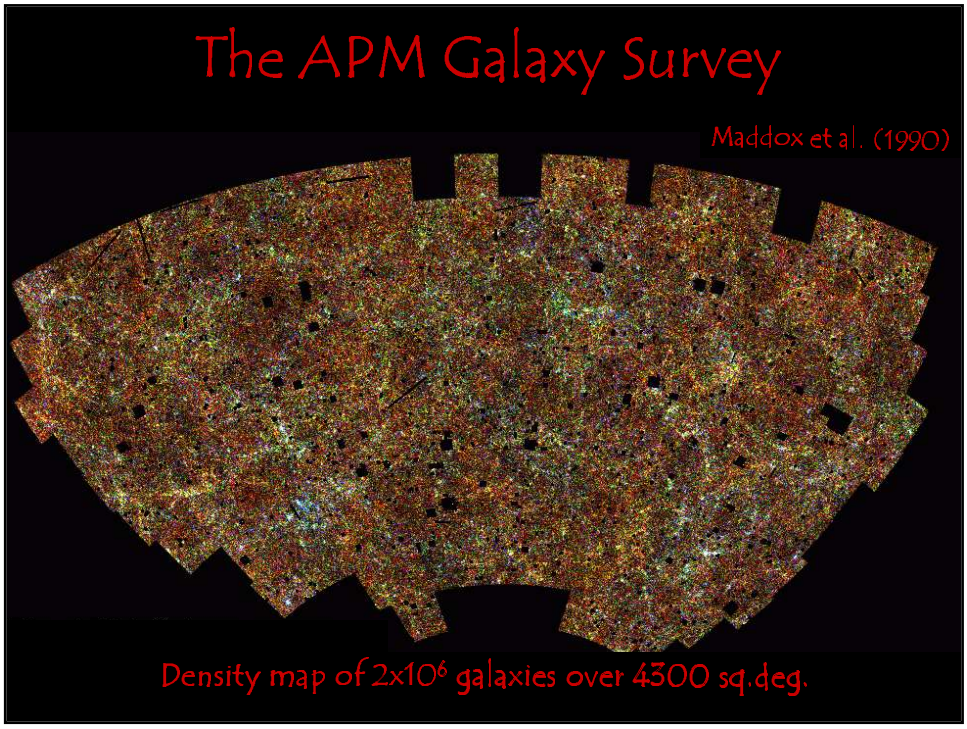


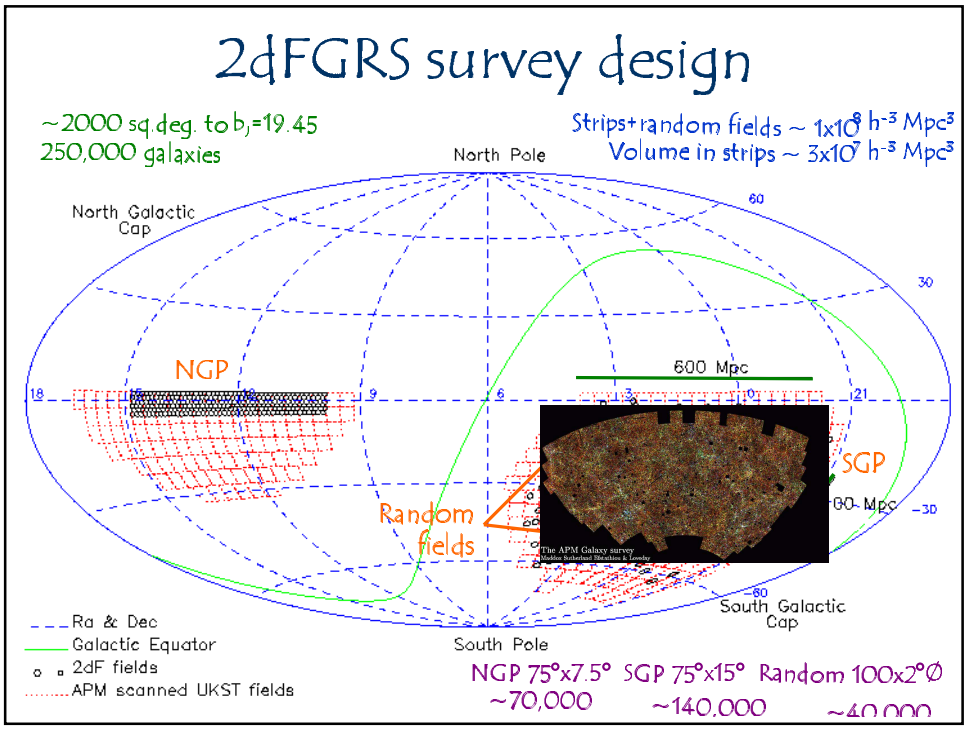

Configuring the fibers
>12 arcsec spacing; <15 degree bend;
7 seconds to position each fiber
/scratch/maestro/colless/SGP196.sds
2dF Configuration
File View Options Commands Zoom
Input File: /scratch/maestro/colless/SGP196.sds
Field Name: sgp.config.196.fld
UT Date: 1999/07/10 Time: 18:41:51
Config Wavelength: 6000.00
Field Centre (J2000): RA: 23 51 07.40 Dec: -27 25 10.6
Plate: 0 HA: -00:00:00 ZD: 03:51:12
Objects: Allocated: 348 Unallocated: 483
Sky Positions: Allocated: 22 Unallocated: 152
Spectr 1: 10 Spectr 2: 12
Fiducial Stars: Allocated: 4 Unallocated: 29
Messages

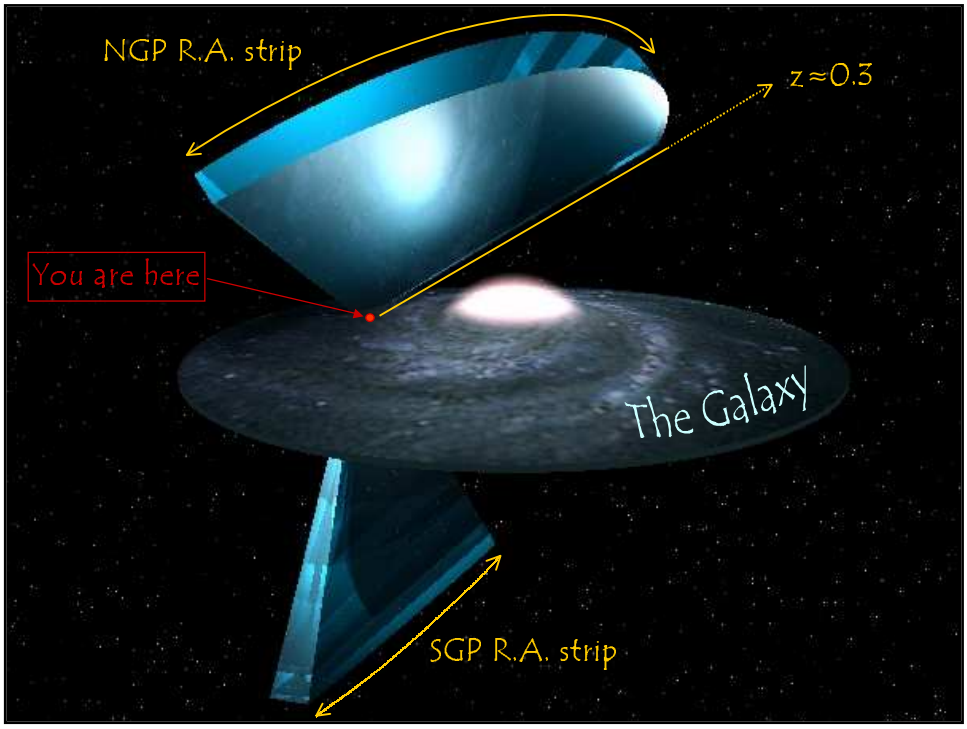


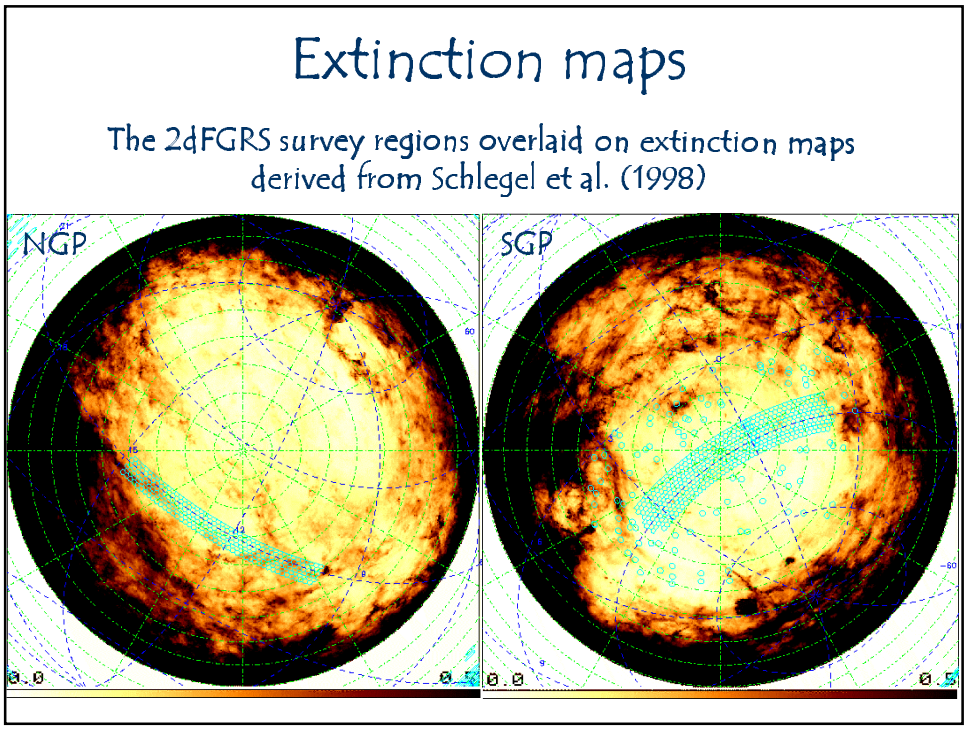


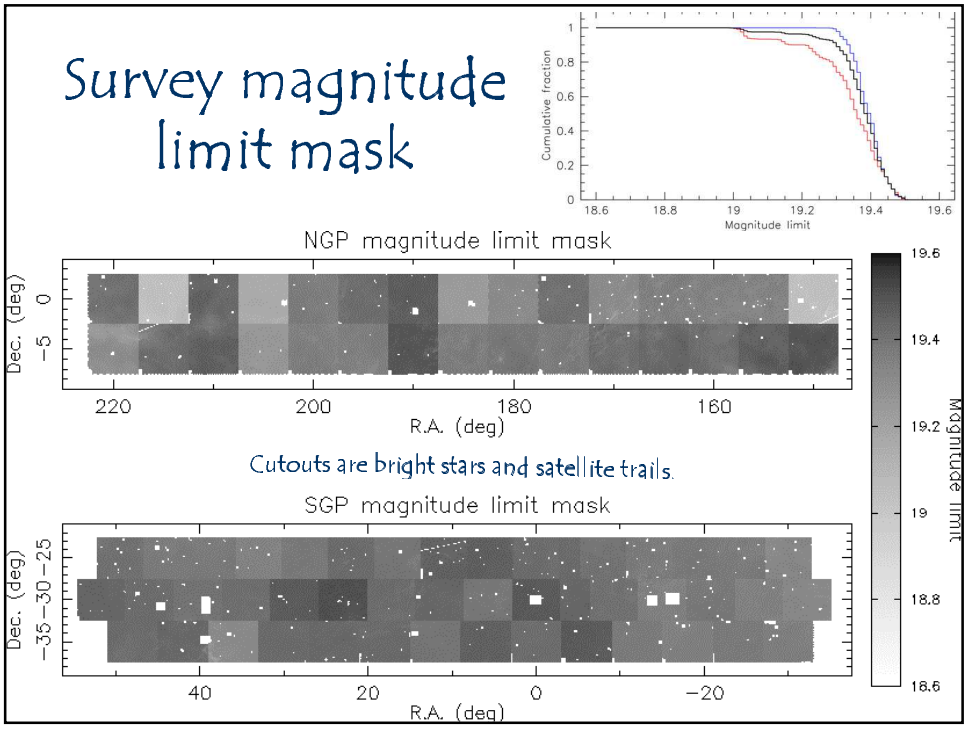

Effective sizes of z-surveys
Number of Galaxies
Volume (Mpc³)
10⁶
10⁵
10⁴
10⁶
10⁷
SDSS
2dGRS
DEEP2
z~1
CfA+SSRS
LCRS
PSCZ
ORS
SAPM
QDOT

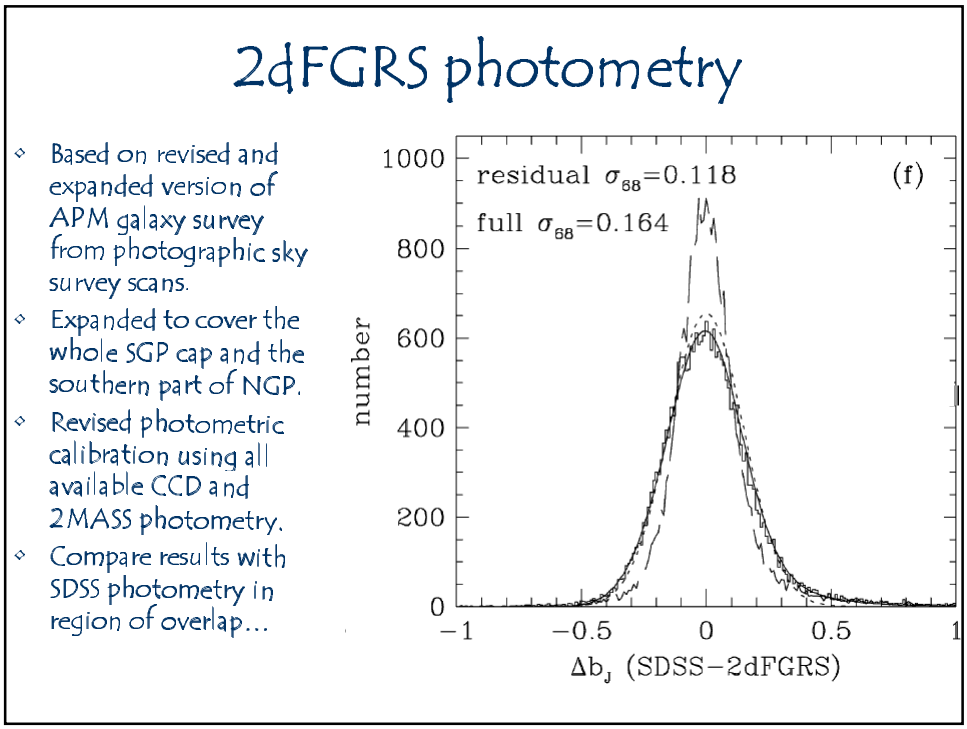

The APM Galaxy Survey
Maddox et al. (1990)
Density map of 2x10⁶ galaxies over 4300 sq.deg.

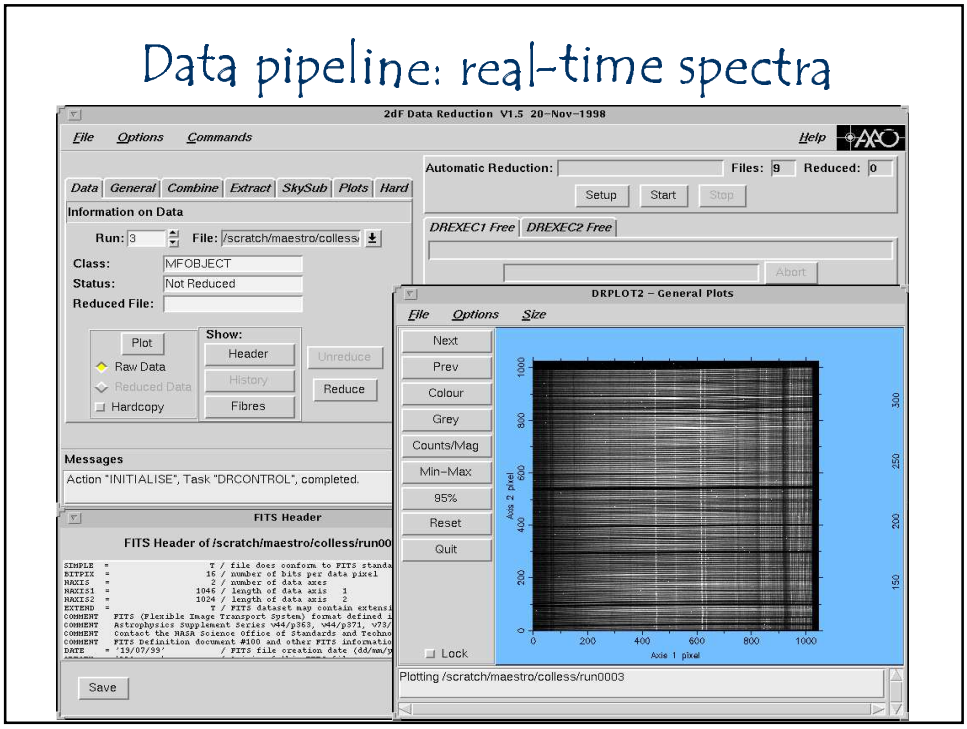

2dFGRS survey design
~2000 sq.deg. to b_J=19.45
250,000 galaxies
Strips+random fields ~ 1x10⁸ h⁻³ Mpc³
Volume in strips ~ 3x10⁷ h⁻³ Mpc³
North Pole
North Galactic Cap
NGP
600 Mpc
SGP
Random fields
South Galactic Cap
South Pole
Ra & Dec
Galactic Equator
2dF fields
APM scanned UKST fields
NGP 75°x7.5° SGP 75°x15° Random 100x2°Ø
~70,000 ~140,000 ~40,000

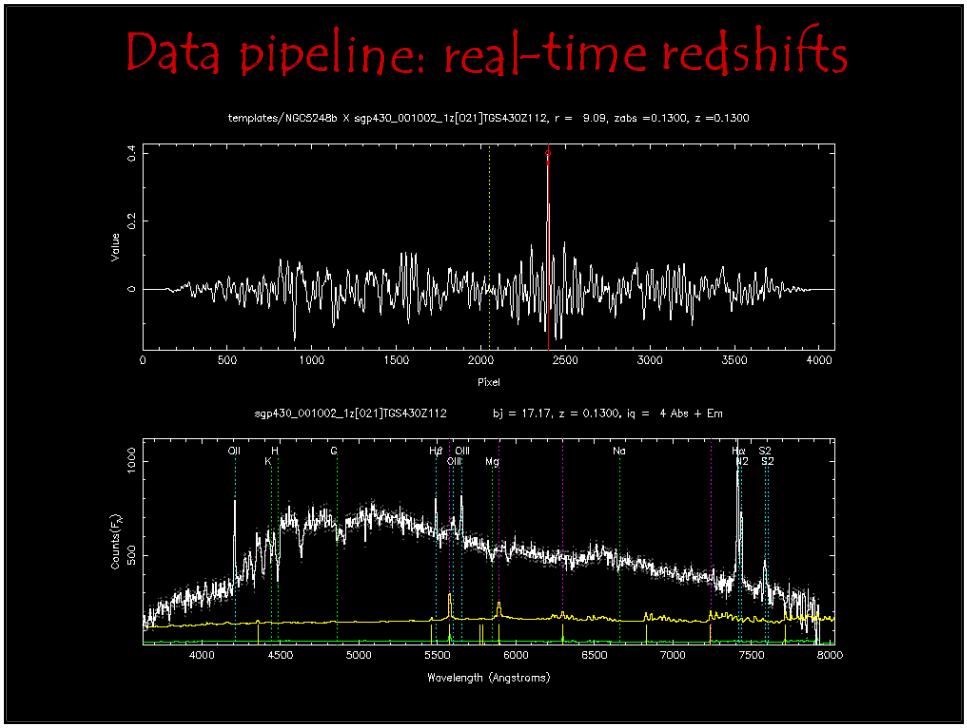

NGP R.A. strip
z≈0.3
You are here
The Galaxy
SGP R.A. strip


Extinction maps
The 2dFGRS survey regions overlaid on extinction maps
derived from Schlegel et al. (1998)
NGP
SGP


Survey magnitude limit mask
Cumulative fraction
Magnitude limit
NGP magnitude limit mask
Dec. (deg)
R.A. (deg)
Cutouts are bright stars and satellite trails.
SGP magnitude limit mask
Dec. (deg)
R.A. (deg)
Magnitude limit

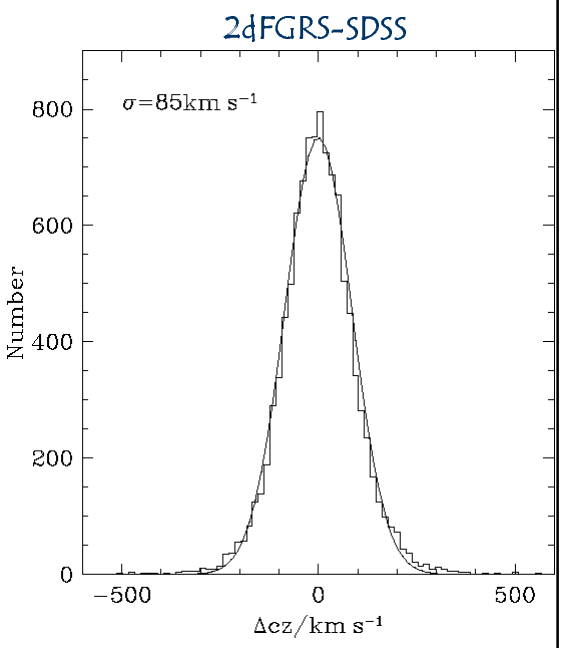

2dFGRS photometry
Based on revised and expanded version of APM galaxy survey from photographic sky survey scans.
Expanded to cover the whole SGP cap and the southern part of NGP.
Revised photometric calibration using all available CCD and 2MASS photometry.
Compare results with SDSS photometry in region of overlap…
residual σ_{68}=0.118
full σ_{68}=0.164
(f)
number
Δb_J (SDSS−2dFGRS)


Data pipeline: real-time spectra
2dF Data Reduction V1.5 20-Nov-1998
File Options Commands Help
Automatic Reduction: Files: 9 Reduced: 0
Setup Start Stop
Data General Combine Extract SkySub Plots Hard
Information on Data
Run: 3 File: /scratch/maestro/colless
Class: MFOBJECT
Status: Not Reduced
Reduced File:
DREXEC1 Free DREXEC2 Free
Abort
Plot
Raw Data
Reduced Data
Hardcopy
Show:
Header
History
Fibres
Unreduce
Reduce
Messages
Action "INITIALISE", Task "DRCONTROL", completed.
FITS Header
FITS Header of /scratch/maestro/colless/run00
Save
DRPLOT2 – General Plots
File Options Size
Next
Prev
Colour
Grey
Counts/Mag
Min-Max
95%
Reset
Quit
Lock
Axis 2 pixel
Axis 1 pixel
Plotting /scratch/maestro/colless/run0003


Data pipeline: real-time redshifts
templates/NGC5248b X sgp430_001002_1z[021]TGS430Z112, r = 9.09, zabs =0.1300, z =0.1300
Value
Pixel
sgp430_001002_1z[021]TGS430Z112 bj = 17.17, z = 0.1300, iq = 4 Abs + Em
OII
K
H
G
Hβ
OIII
OIII
Mg
Na
Hα
N2
S2
S2
Counts(Fλ)
Wavelength (Angstroms)

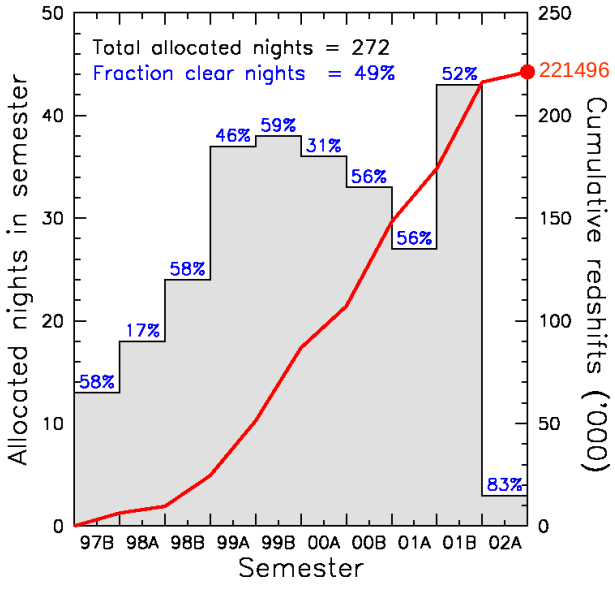
Redshifts

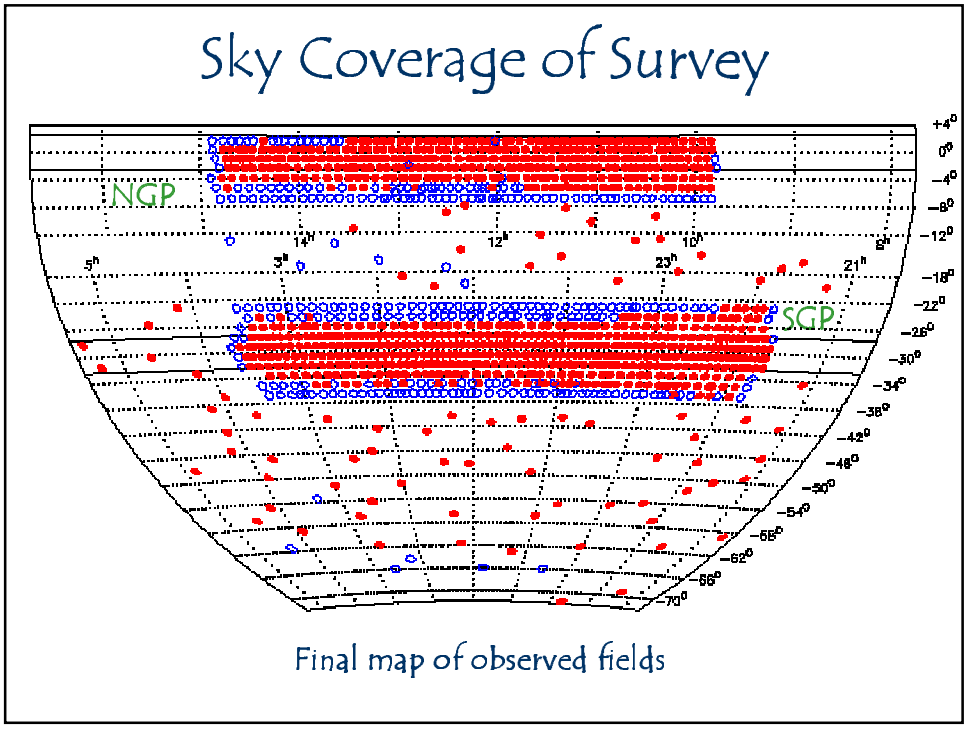
- Redshift yield per field:
  - median yield is 93%
  - 10% of fields have a yield less than 80%
  - 70% of fields have a yield more than 90%
- Redshift reliability: of 10763 z's in common with SDSS, only 1.0% differ by >600 km/s
- Redshift precision: for the remaining 99%, the rms Δcz is 85 km/s

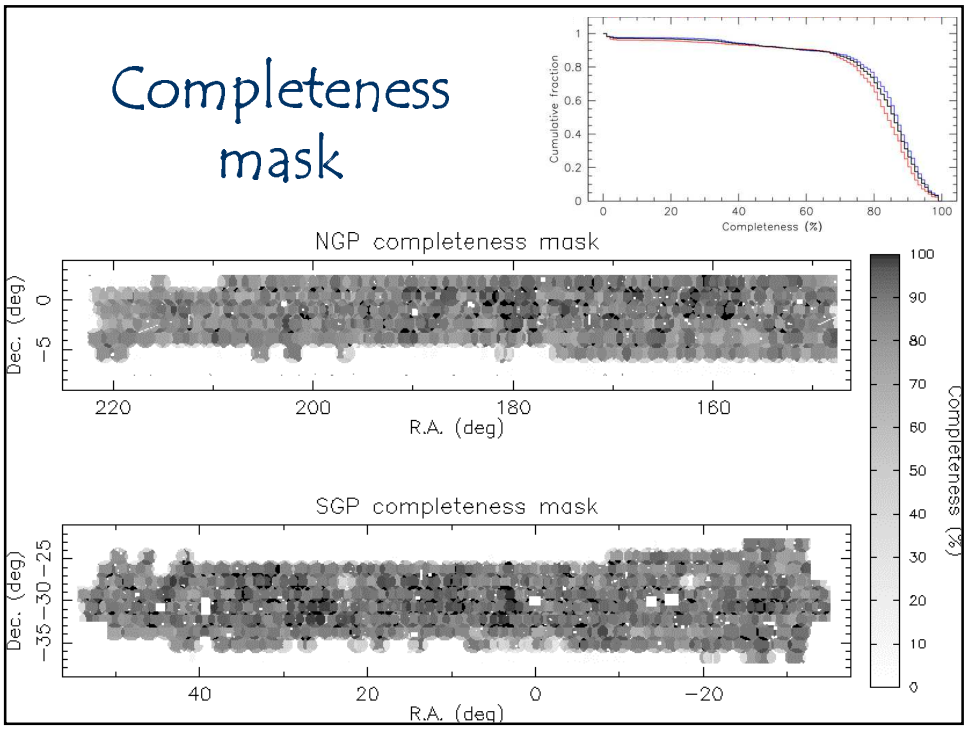


Final Status of Survey Observations

- Survey observations were completed on 11 April 2002.
- Survey took 272 nights over 5 years... but fraction of clear nights was only 49%!
- Measured 221,000 unique galaxy z's (also 14,000 stars and 180 QSOs).
- Total of 270,000 spectra (including repeat observations).

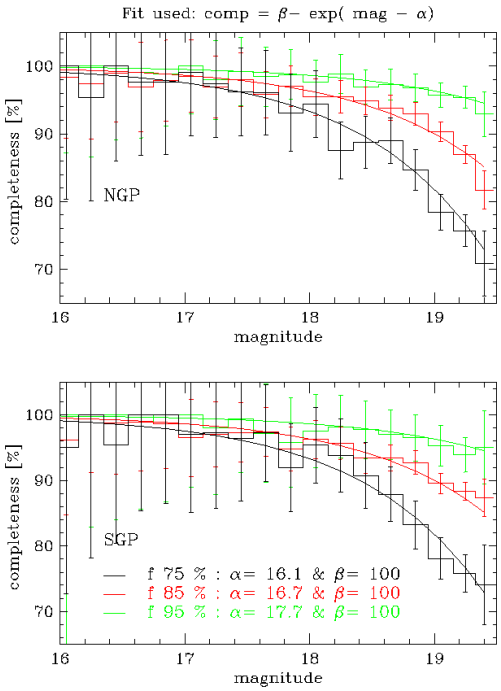



Sky Coverage of Survey
NGP
SGP
Final map of observed fields

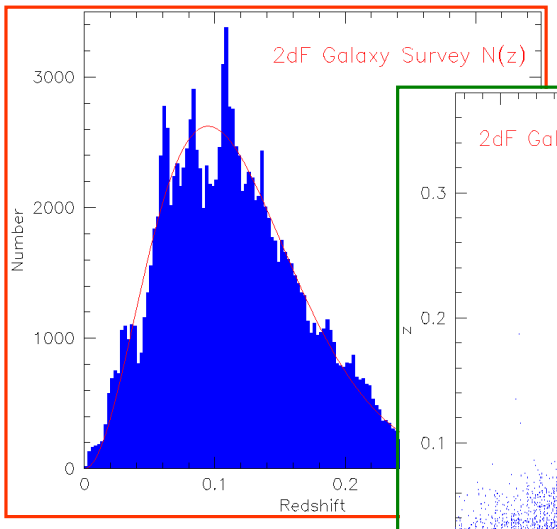

Completeness mask
Cumulative fraction
Completeness (%)
NGP completeness mask
Dec. (deg)
R.A. (deg)
SGP completeness mask
Completeness (%)

Completeness

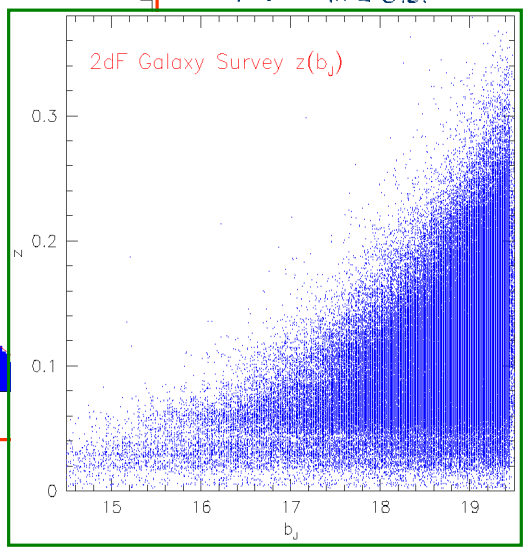
- Redshift completeness is >90% for b_J<19 but drops to 80-85% at b_J=19.45.
- Completeness is similar in NGP and SGP strips.
- Completeness as a function of magnitude varies with the overall completeness of the field.
- Selection function depends on (at least) overall completeness + magnitude.



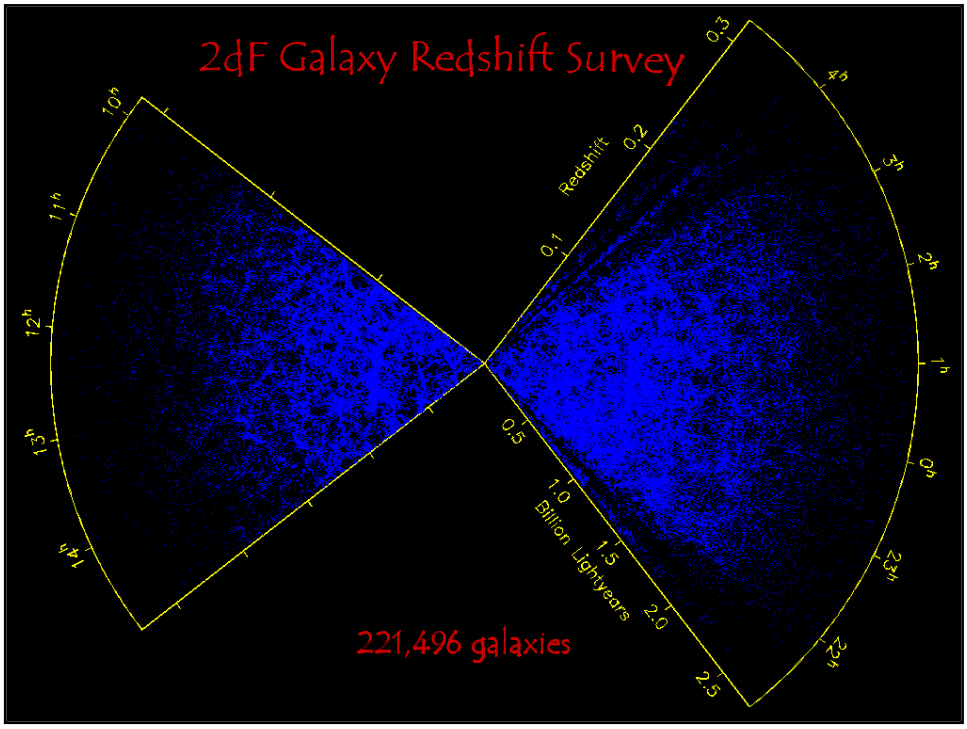
Redshift distribution

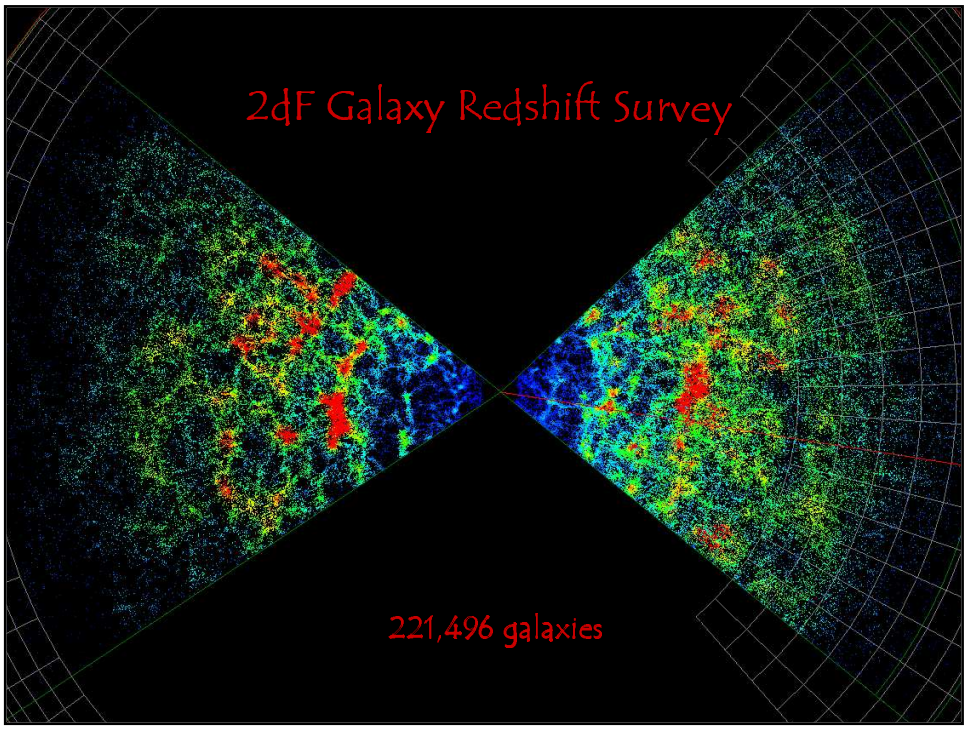


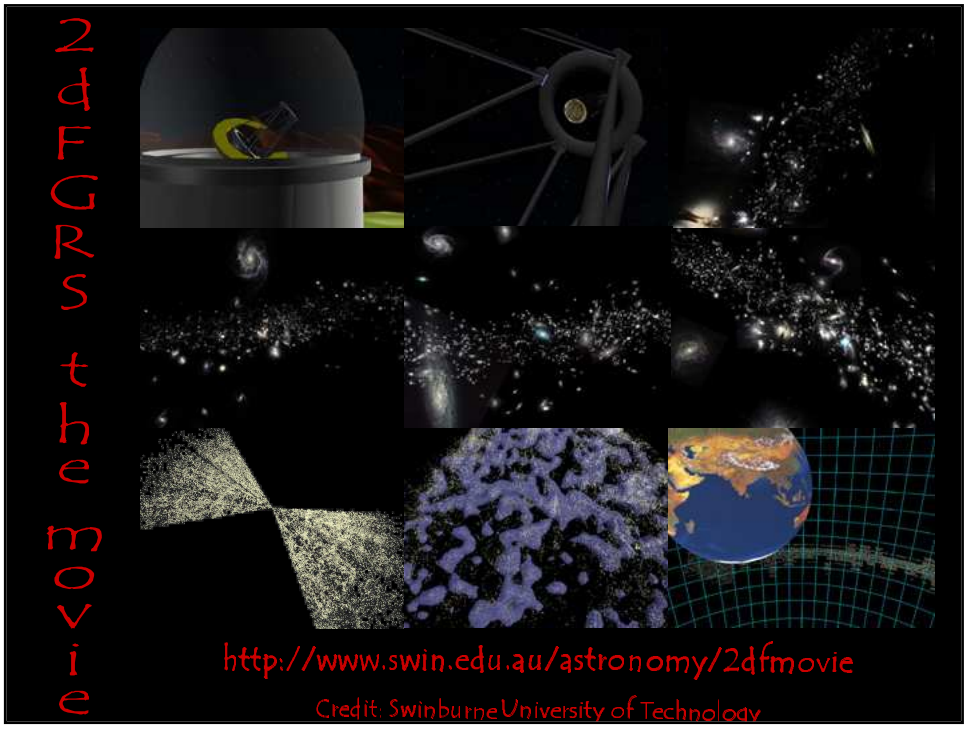
Median redshift <z>=0.11; almost all z<0.3.

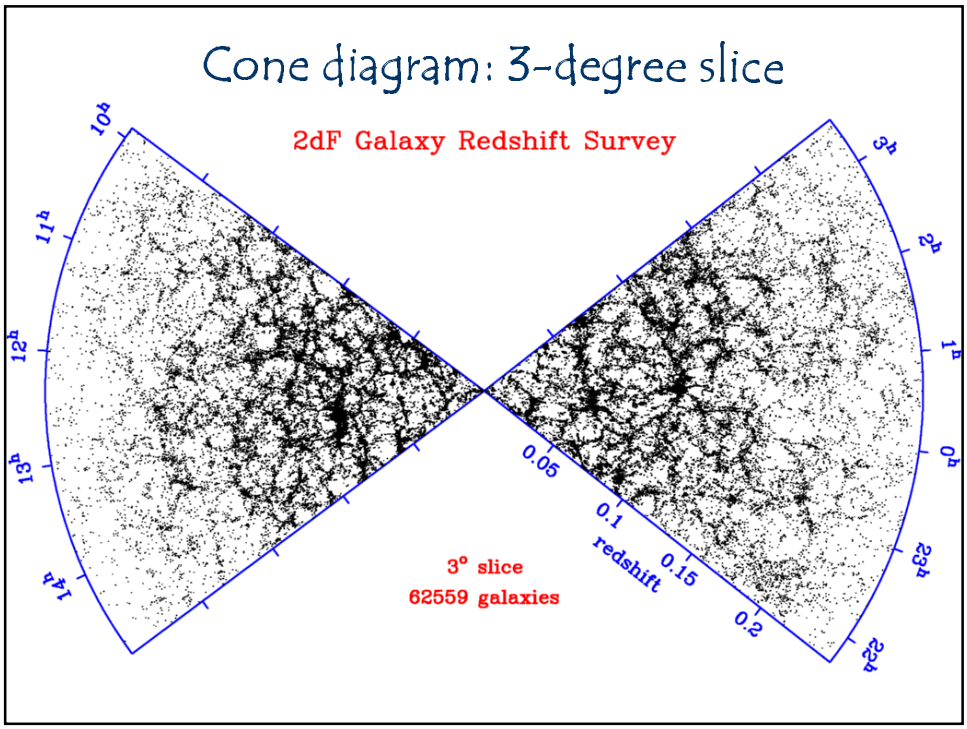


N(z) still shows significant clustering.

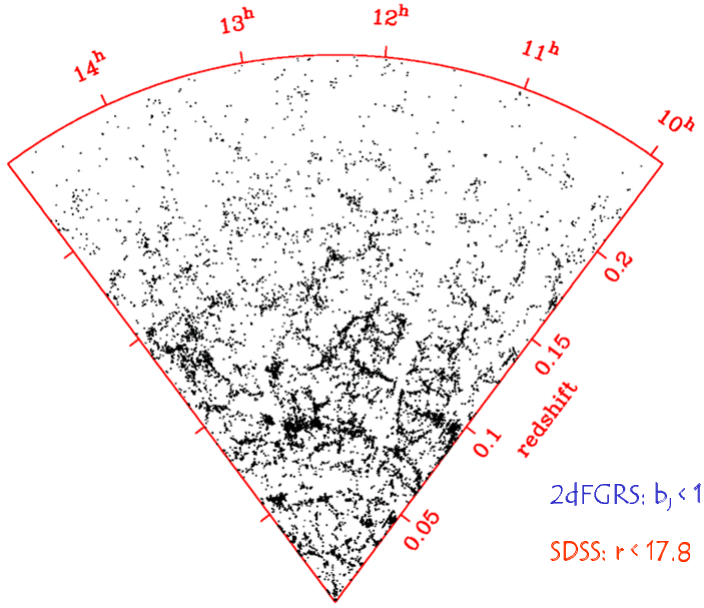

2dF Galaxy Redshift Survey
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h
221,496 galaxies


2dF Galaxy Redshift Survey
221,496 galaxies


2dFGRS the movie
http://www.swin.edu.au/astronomy/2dfmovie
Credit: Swinburne University of Technology

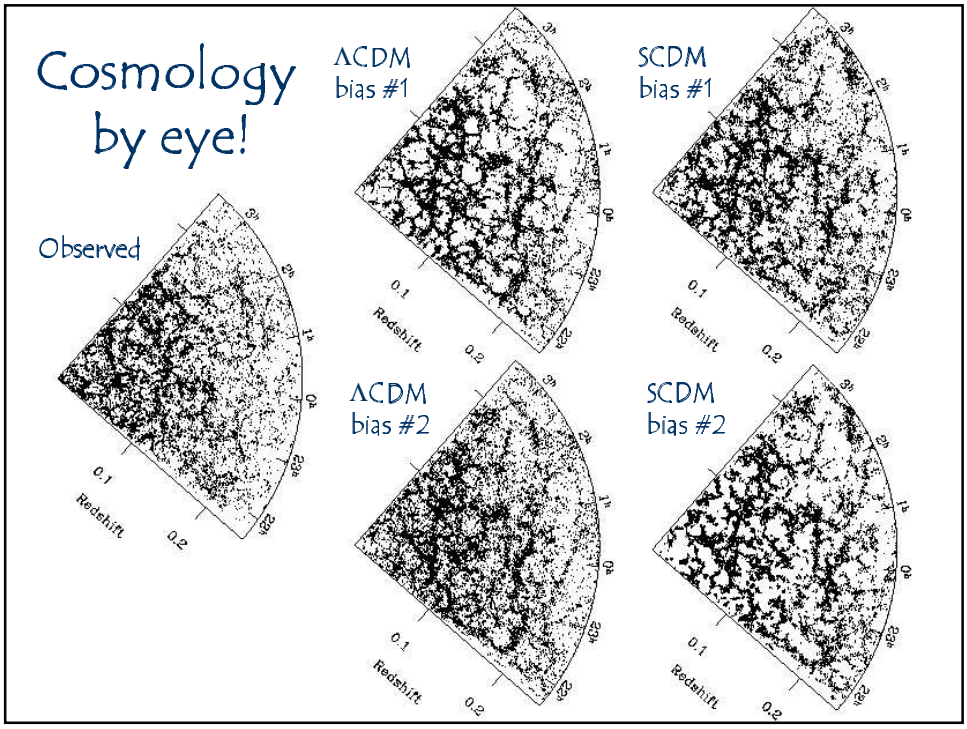

Cone diagram: 3-degree slice
2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
3° slice
62559 galaxies

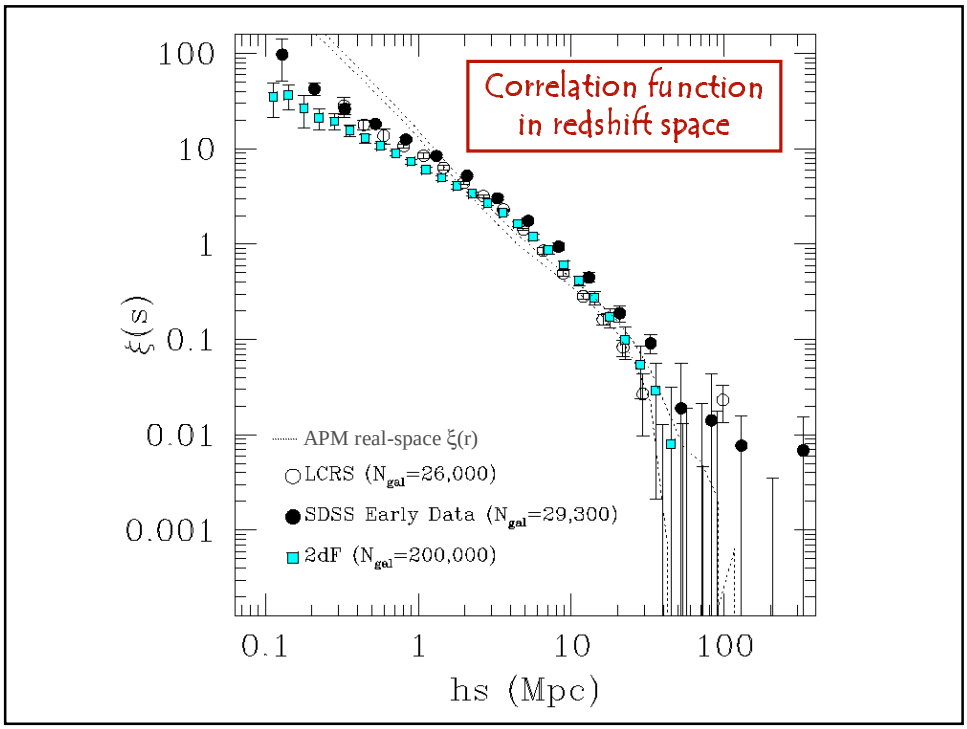
Fine detail: 2-deg NGP slices (1-deg steps)

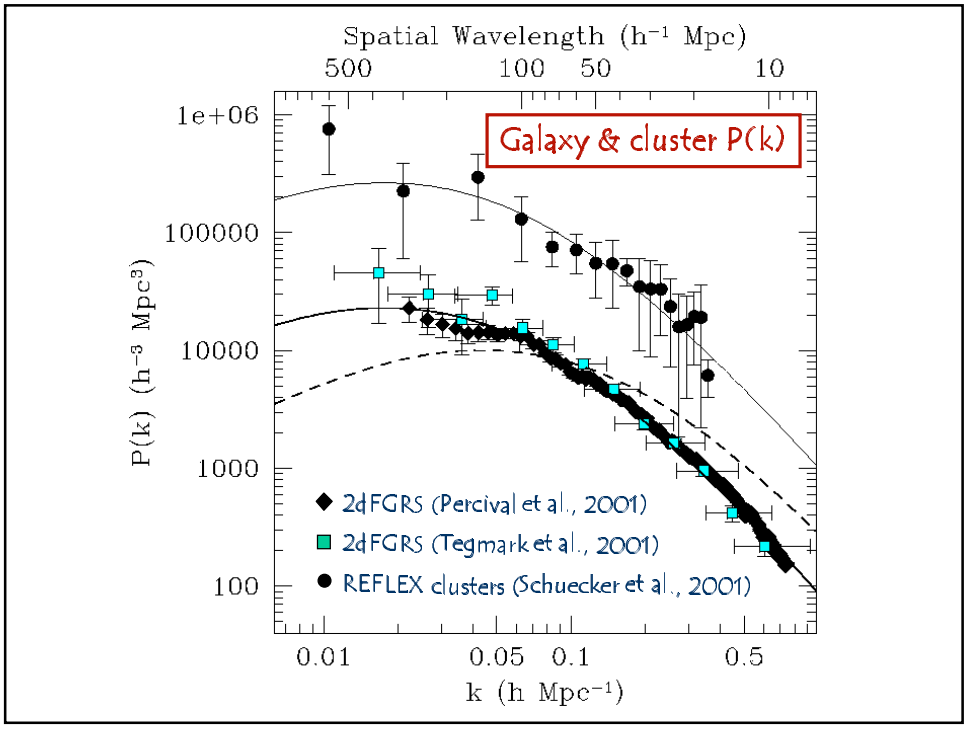


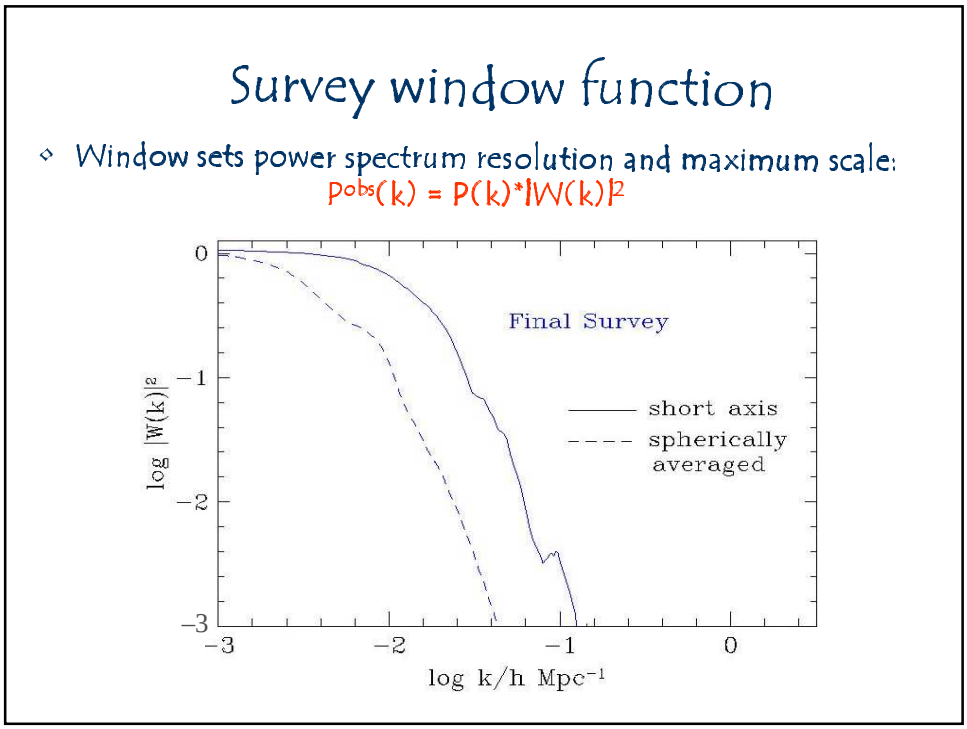
Structure + Cosmology Highlights

- A precise determination of the large-scale structure of the galaxy distribution on scales up to 600 h^{-1} Mpc.
- Unambiguous detection of coherent collapse on large scales, confirming structures grow via gravitational instability.
- The detection of acoustic oscillations in the distribution of galaxies due to baryon/photon coupling in the early universe.
- Measurements of Ω_m (the mean mass density) from both the power spectrum and redshift-space distortions: $\Omega_m = 0.30 \pm 0.06$
- A measurement of the baryon fraction from the acoustic oscillations in the power spectrum: $\Omega_b/\Omega_m = 0.17 \pm 0.06$
- First measurement of the galaxy bias parameter: $b^* = 0.96 \pm 0.08$
- A stronger upper limit on the neutrino fraction, $\Omega_\nu/\Omega_m < 0.13$, implying a limit on the mass of all neutrino species, $m_\nu < 1.8$ eV.


Cosmology by eye!
Observed
ΛCDM bias #1
SCDM bias #1
ΛCDM bias #2
SCDM bias #2
Redshift
0.1
0.2

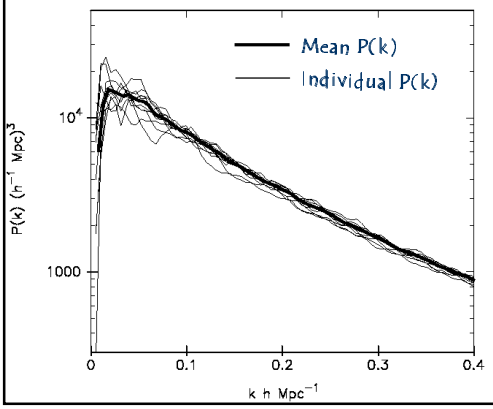

Correlation function in redshift space
APM real-space ξ(r)
LCRS (N_gal=26,000)
SDSS Early Data (N_gal=29,300)
2dF (N_gal=200,000)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
hs (Mpc)

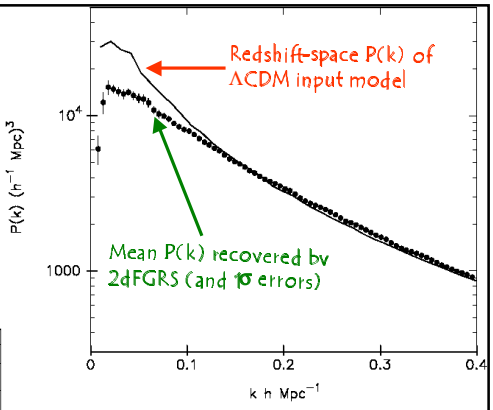

Spatial Wavelength (h⁻¹ Mpc)
500
100
50
10
1e+06
100000
10000
1000
100
P(k) (h⁻³ Mpc³)
Galaxy & cluster P(k)
2dFGRS (Percival et al., 2001)
2dFGRS (Tegmark et al., 2001)
REFLEX clusters (Schuecker et al., 2001)
0.01
0.05
0.1
0.5
k (h Mpc⁻¹)


Survey window function
Window sets power spectrum resolution and maximum scale:
Pobs(k) = P(k)*|W(k)|²
0
−1
−2
−3
log |W(k)|²
Final Survey
short axis
spherically averaged
−3
−2
−1
0
log k/h Mpc⁻¹

P(k) errors

- Systematic effects: effect on *mean* observed z-space P(k) is to depress power at small k (i.e. on large scales).





- Cosmic variance: spurious features in the recovered P(k) for *individual* realizations of the survey.

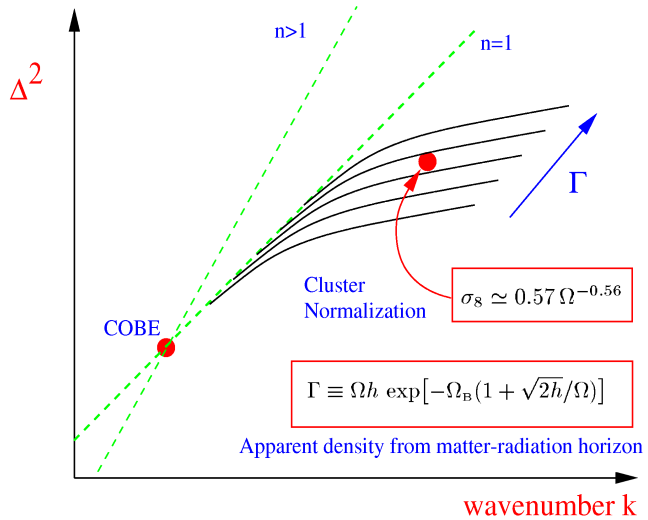
The CDM Power Spectrum

Fourier decomposition of density field

$$\delta(\mathbf{r}) \equiv \frac{\delta\rho}{\rho} = \sum_k \delta_k \, e^{-i\mathbf{k}\cdot\mathbf{r}}$$

Dimensionless power

$$\Delta^2(k) \equiv \frac{d\sigma^2}{d\ln k} \propto k^3 \, |\delta_k|^2 \propto k^{3+n} \, T_k^2$$

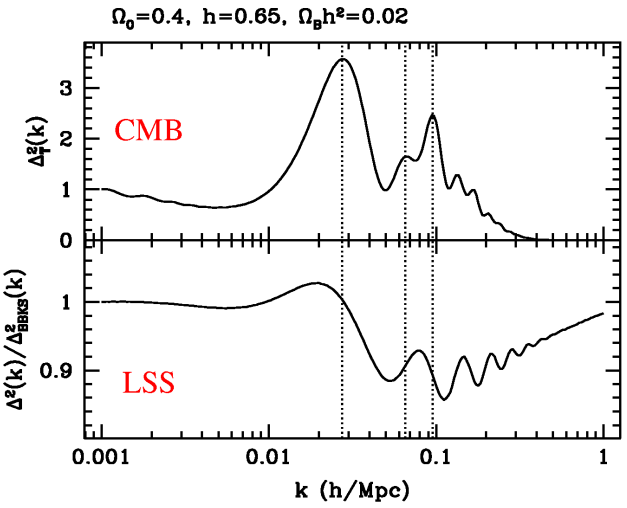


Fluctuations in the density grow as $\delta(a) = a\, f(\Omega[a])$

Scale of break in power spectrum relates to mean mass density Ω_m

In practice, get shape parameter Γ ($\approx \Omega_m h$)

Effect of baryons on P(k)

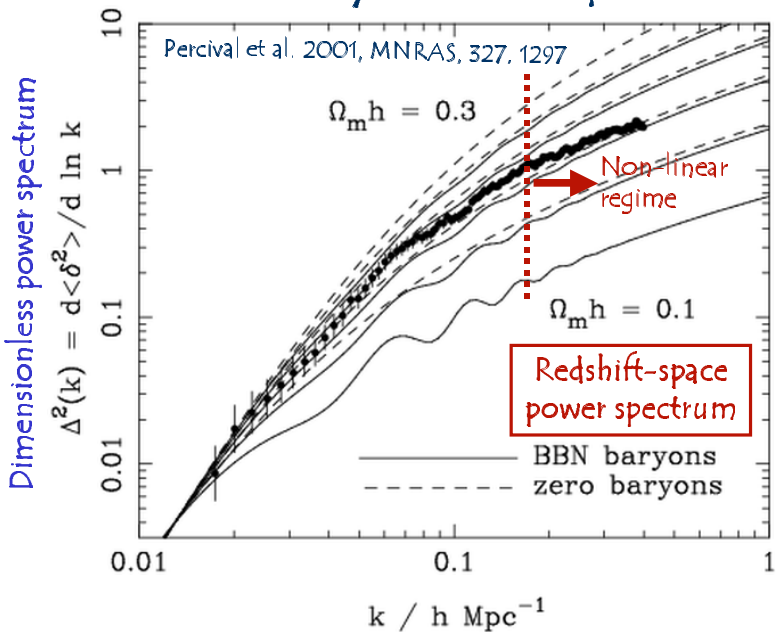


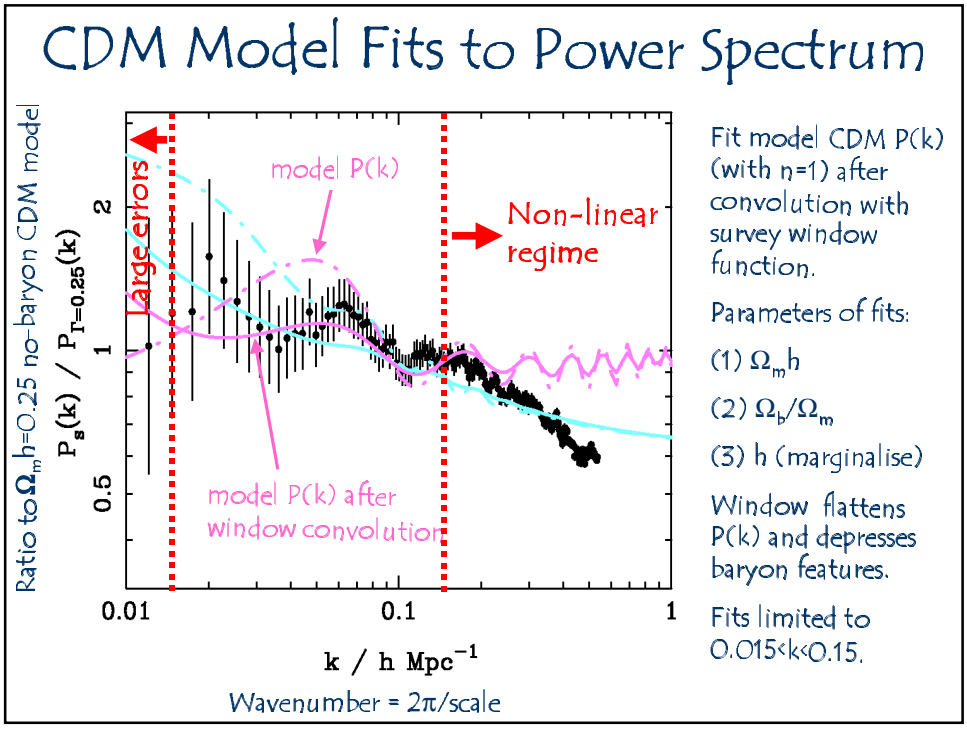
CMB and LSS out of phase:

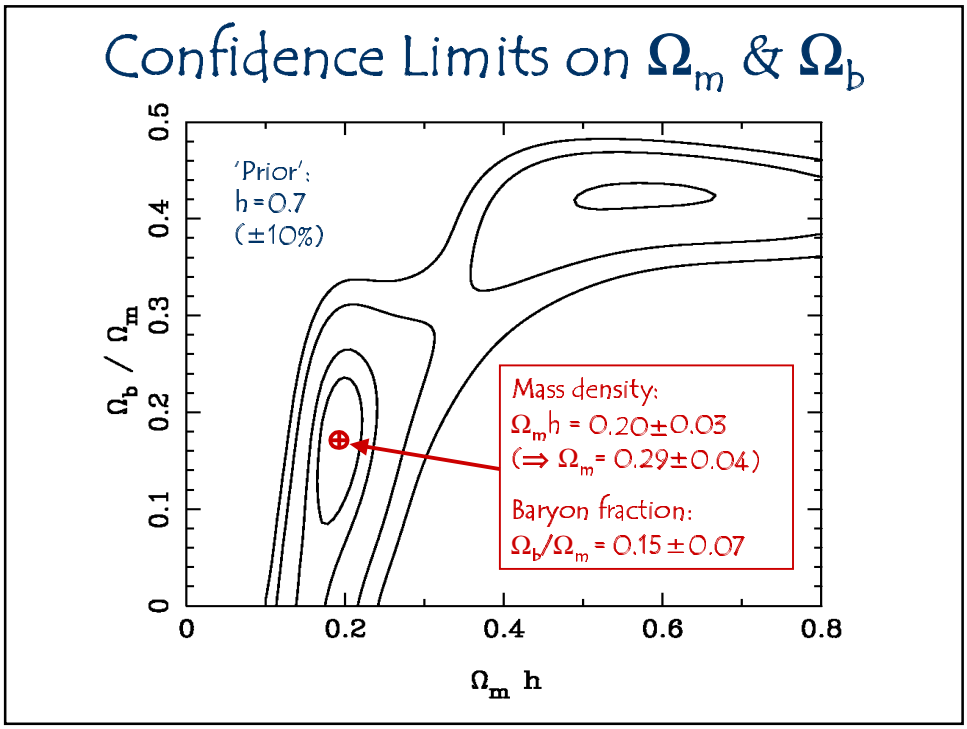
'velocity overshoot'

LSS amplitude smaller than CMB

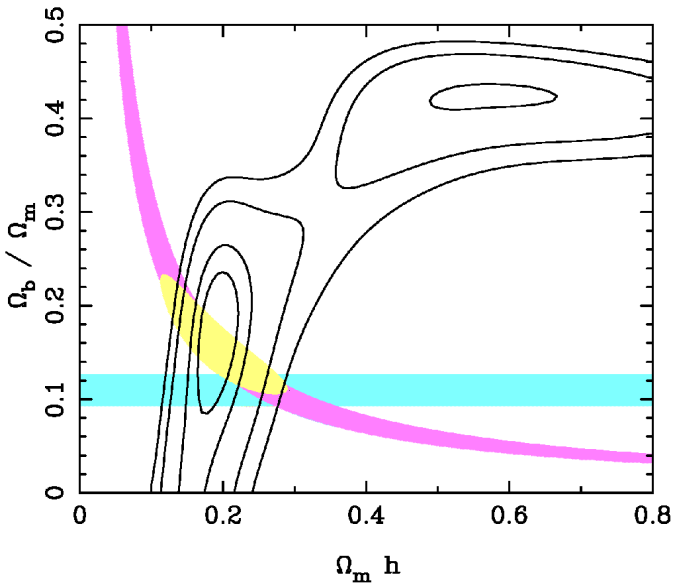
The Galaxy Power Spectrum




CDM Model Fits to Power Spectrum
Ratio to Ω_mh=0.25 no-baryon CDM model
$P_s(k) / P_{T=0.25}(k)$
Large errors
model P(k)
Non-linear regime
model P(k) after window convolution
0.01
0.1
1
0.5
1
2
k / h Mpc^{-1}
Wavenumber = 2π/scale
Fit model CDM P(k) (with n=1) after convolution with survey window function.
Parameters of fits:
(1) Ω_mh
(2) Ω_b/Ω_m
(3) h (marginalise)
Window flattens P(k) and depresses baryon features.
Fits limited to 0.015<k<0.15.


Confidence Limits on Ω_m & Ω_b
'Prior':
h=0.7
(±10%)
Mass density:
Ω_mh = 0.20±0.03
(⇒ Ω_m= 0.29±0.04)
Baryon fraction:
Ω_b/Ω_m = 0.15±0.07
Ω_b / Ω_m
0
0.1
0.2
0.3
0.4
0.5
0
0.2
0.4
0.6
0.8
Ω_m h

Consistency with Other Constraints

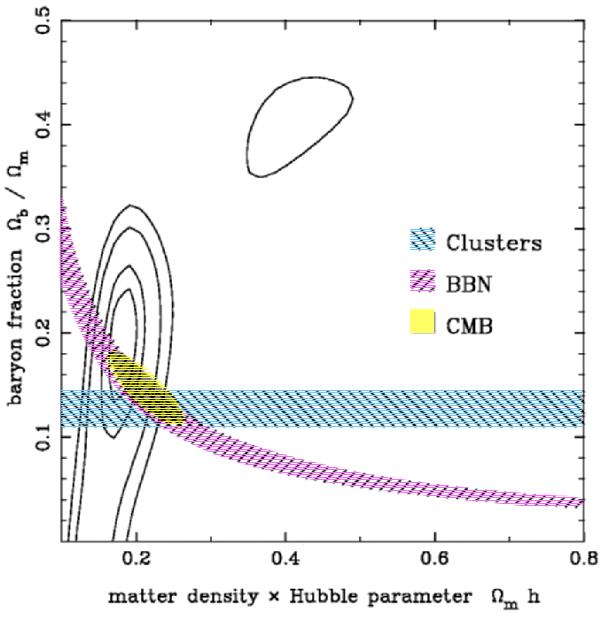


Cluster baryon fraction

Nucleo-synthesis

CMB anisotropies

Model fits: 2001 vs final



If no constraint on n:

$\Gamma = \Omega_m h = 0.20 \pm 0.03$

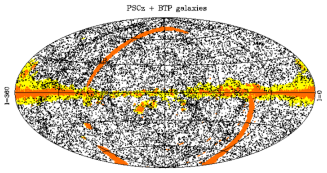
Baryon fraction = $\Omega_b/\Omega_m = 0.15 \pm 0.07$

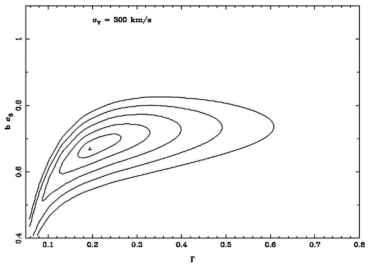
If require n=1:

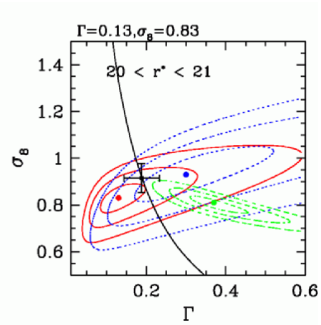
$\Gamma = \Omega_m h = 0.18 \pm 0.02$

Baryon fraction = $\Omega_b/\Omega_m = 0.17 \pm 0.06$

Comparison with other results





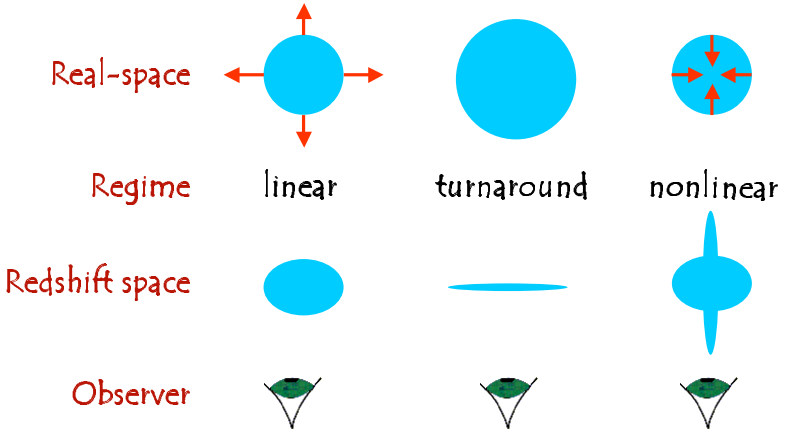


All-sky PSCz: $\Gamma = 0.20 \pm 0.05$ SDSS EDR: $\Gamma = 0.19 \pm 0.04$

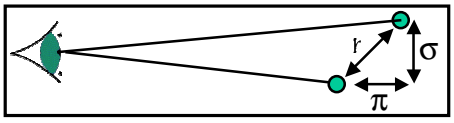
2dFGRS: $\Gamma = 0.20 \pm 0.03$

Redshift-Space Distortions

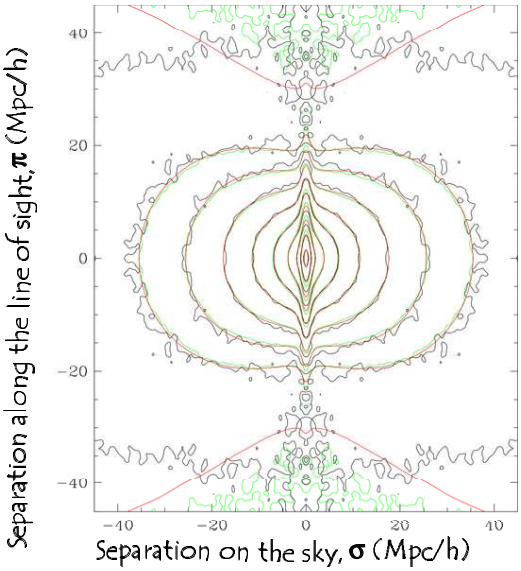
$z_{obs} = z_{true} + v_{pec}/c$ where $v_{pec} \propto \Omega^{0.6} \delta\rho/\rho = (\Omega^{0.6}/b)\, \delta n/n$ (bias)



Redshift-Space Correlation Function



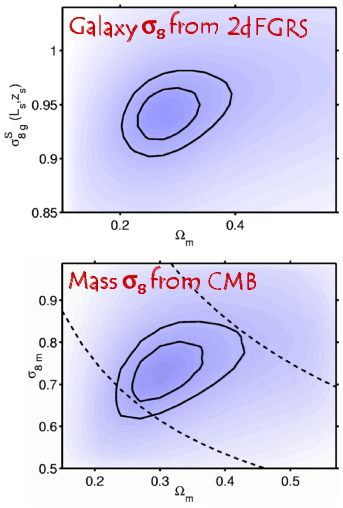
- Small σ ⇒ non-linear 'Finger-of-God' effect
- Large σ ⇒ flattening along line of sight due to coherent infall
- Fit to r = 8-25 h^{-1} Mpc gives (after correction for <z>=0.17, <L>=1.9L*) pair-wise vel. dispersion $\sigma_p = 385 \pm 50$ km/s and $\beta = \Omega^{0.6}/b = 0.49 \pm 0.08$
- For b ≈ 1 (cf. CMB) ⇒ $\Omega \approx 0.30 \pm 0.08$

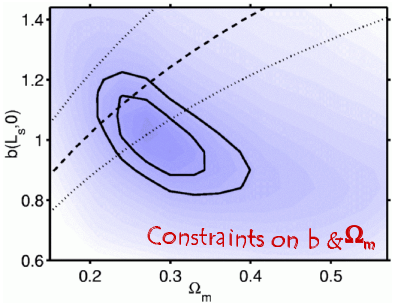


Measuring Bias I. - 2dFGRS + CMB

Do galaxies trace mass?

Assume $\delta n/n = b\,\delta\rho/\rho$ (b=linear bias). Then $P_{gal}(k)=b^2 P_m(k)$, so can get the bias parameter by comparing the relative normalizations (σ_8) of the mass PS from CMB (linearly evolved to z=0) and the galaxy PS from 2dFGRS.

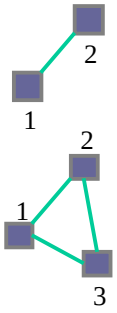




Lahav et al., 2001, MNRAS, 333, 961

$b^* = b(L^*) = 0.96 \pm 0.08$

Measuring Bias II. – The Bispectrum



Two-point correlations:

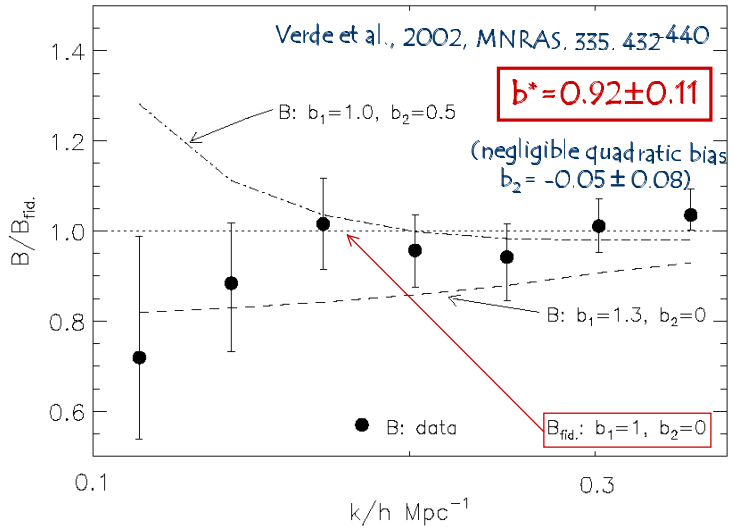
$\langle \delta_1 \delta_2 \rangle = \xi$: FT = P(k) power spectrum

Three-point correlations:

$\langle \delta_1 \delta_2 \delta_3 \rangle = \zeta$: FT = $B(k_1, k_2, k_3)$ bispectrum

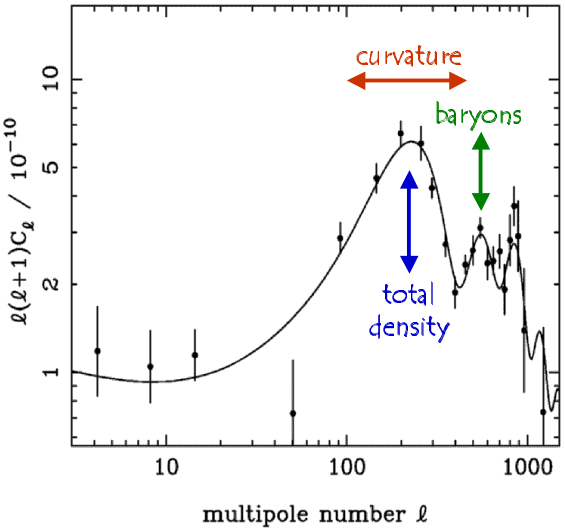
- bispectrum ≡ 0 for Gaussian field (large-scale/linear regime)
- on small scales, it is a measure of non-linear structure
- assume local non-linear bias: $\delta_g = b_1 \delta_m + b_2 (\delta_m)^2$
- non-linear bias can mimic some aspects of structure (e.g. skewness)
- but full bispectrum contains shape info - bias doesn't form filaments
- the shape of the bispectrum depends on the bias parameter

Bias from the 2dFGRS bispectrum



Combining results for β and b $\Rightarrow \Omega_m = 0.27 \pm 0.06$ purely from 2dFGRS

Relation to CMB results

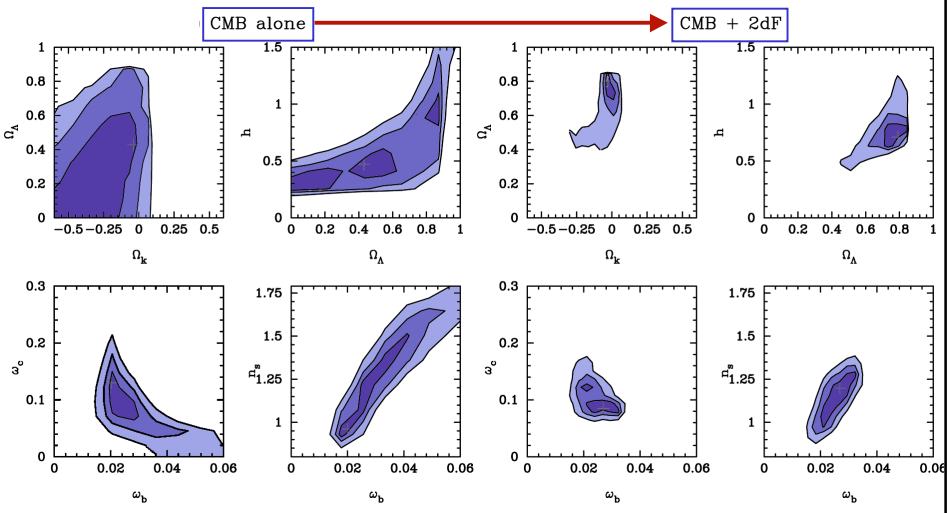


Combining LSS & CMB breaks degeneracies:

(a) LSS measures $\Omega_m h$ only if power index n is known

(b) CMB measures n and $\Omega_m h^3$ only if curvature is known

Cosmology from 2dFGRS + CMB



Combining LSS and CMB greatly improves constraints on fundamental parameters

2dFGRS+CMB fits – general

Efstathiou et al., 2002, MNRAS, 330, L29

	Fit A CMB alone + tensor	Fit B CMB + 2dFGRS no tensor	Fit C CMB + 2dFGRS + tensor	Fit D CMB + 2dFGRS + BBN + tensor	Approximate $\pm 2\sigma$ parameter ranges: Fit A CMB alone + tensor	Fit C CMB + 2dFGRS + tensor	Fit D CMB + 2dFGRS + BBN + tensor
ω_b	0.020	0.021	0.027	0.020	0.016–0.045	0.018–0.034	0.018–0.022
ω_c	0.13	0.12	0.085	0.10	0.03–0.18	0.07–0.13	0.08–0.13
n_s	0.96	1.00	1.20	1.04	0.89–1.49	0.95–1.31	0.95–1.16
Ω_k	−0.04	0.001	−0.030	−0.013	−0.68–0.06	−0.05–0.04	−0.05–0.04
Ω_Λ	0.43	0.71	0.80	0.73	<0.88	0.65–0.85	0.65–0.80
τ_{opt}	0	0	0	0	<0.5	<0.5	<0.5
n_t		–	−0.10	0.13			
$\bar{r}$	0	–	0.60	0.20	<0.98	<0.87	<0.82
r_{10}	0	–	1.24	0.26			
ω_b/ω_m	0.14	0.15	0.24	0.17	0.10–0.40	0.13–0.28	0.13–0.22
$\Omega_m h$		0.21	0.16	0.19		0.12–0.22	0.16–0.21
h		0.69	0.71	0.66		0.60–0.86	0.61–0.84

- Ω_M = 0.27 (±0.07)
- Ω_Λ = 0.73 (±0.04)
- Ω_b/Ω_M = 0.17 (±0.03)
- H_0 = 66 (+9,-3) km/s/Mpc
- σ_8 = 0.61–0.72

2dFGRS+CMB fits – flat cosmology

Percival et al., 2002, MNRAS, in press (astro-ph/0206256)

parameter	results: scalar only CMB	results: scalar only CMB+2dFGRS	results: with tensor component CMB	results: with tensor component CMB+2dFGRS
$\Omega_b h^2$	0.0205 ± 0.0022	0.0210 ± 0.0021	0.0229 ± 0.0031	0.0226 ± 0.0025
$\Omega_c h^2$	0.118 ± 0.022	0.1151 ± 0.0091	0.100 ± 0.023	0.1096 ± 0.0092
h	0.64 ± 0.10	0.665 ± 0.047	0.75 ± 0.13	0.700 ± 0.053
n_s	0.950 ± 0.044	0.963 ± 0.042	1.040 ± 0.084	1.033 ± 0.066
n_t	–	–	0.09 ± 0.16	0.09 ± 0.16
r	–	–	0.32 ± 0.23	0.32 ± 0.22
Ω_m	0.38 ± 0.18	0.313 ± 0.055	0.25 ± 0.15	0.275 ± 0.050
$\Omega_m h$	0.226 ± 0.069	0.206 ± 0.023	0.174 ± 0.063	0.190 ± 0.022
$\Omega_m h^2$	0.139 ± 0.022	0.1361 ± 0.0096	0.123 ± 0.022	0.1322 ± 0.0093
Ω_b/Ω_m	0.152 ± 0.031	0.155 ± 0.016	0.193 ± 0.048	0.172 ± 0.021

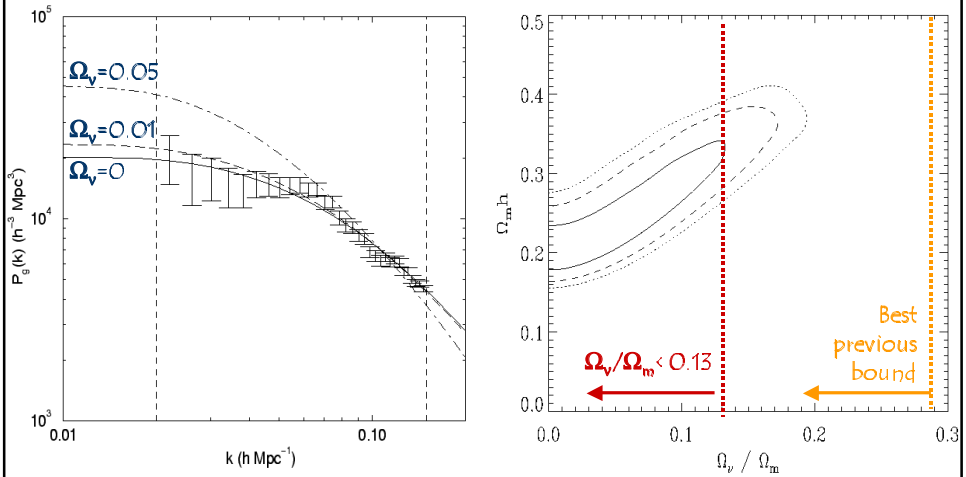
Fits assume Ω_k=0 and use CMB + 2dFGRS only (no priors)

Preferred model is scalar-dominated and almost scale-invariant

Constraints on the neutrino mass

P(k) gives an upper limit on the total mass of all ν species:

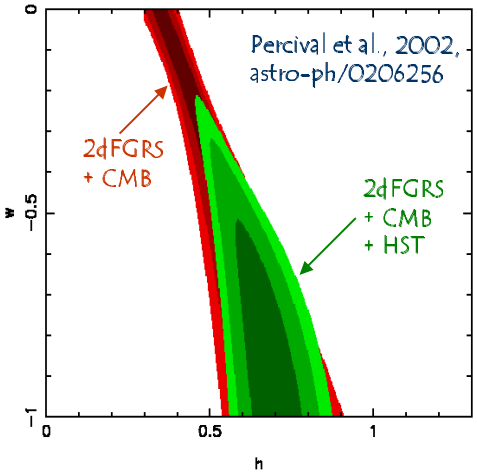
$\Omega_\nu/\Omega_m < 0.13 \Rightarrow m_{\nu,tot} < 1.8$ eV (95% confidence)



Elgaroy et al., 2002, Phys.Rev.Lett., 89, 061301

The dark energy equation of state

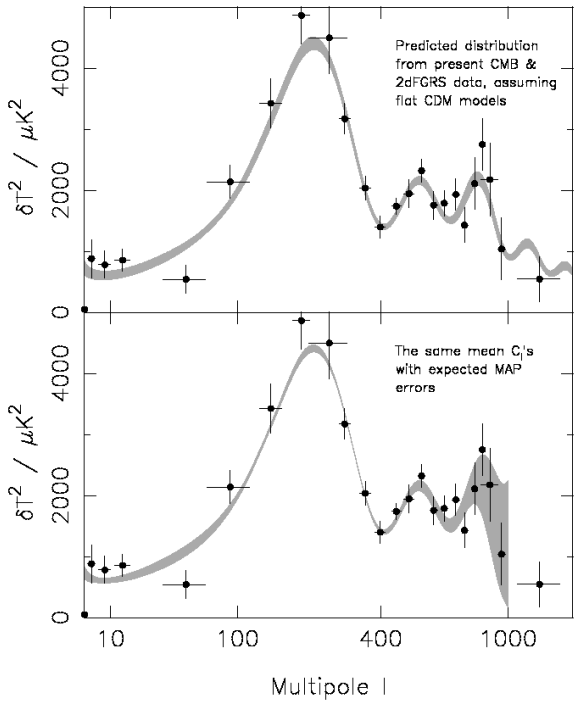
- Dark energy equation of state: $w(z) \equiv p/\rho$
  - generally, $\rho(z) \propto (1+z)^n$ with $n \equiv 3(1+w)$;
  - cosmological constant has $w = -1$ and $n = 0$.
- The combined constraint on $\langle w \rangle$, assuming a flat universe, from the CMB and 2dFGRS power spectra plus the HST key project H_0, is:
  $\langle w \rangle \leq -0.52$ (95% c.l.)



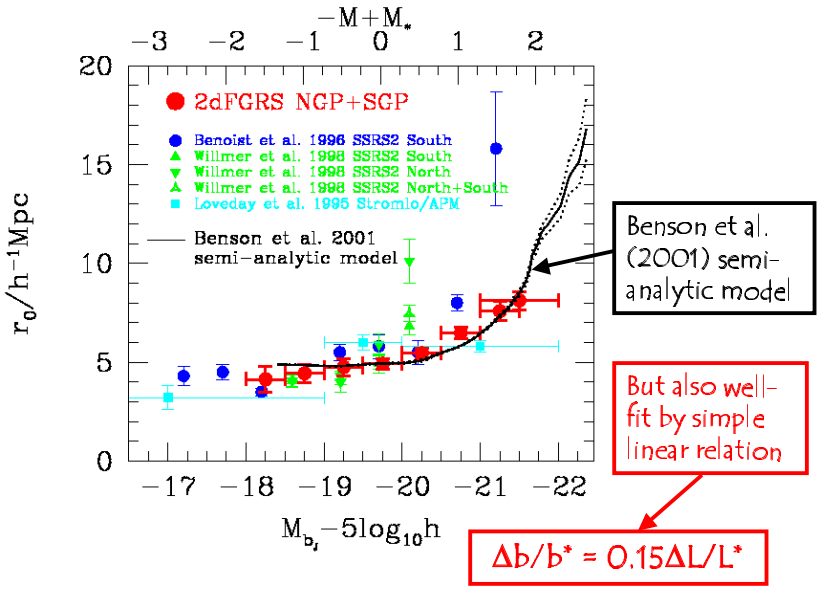
- The main contribution of the 2dFGRS to this limit is via its constraint on Ω_m.

The CMB power spectrum

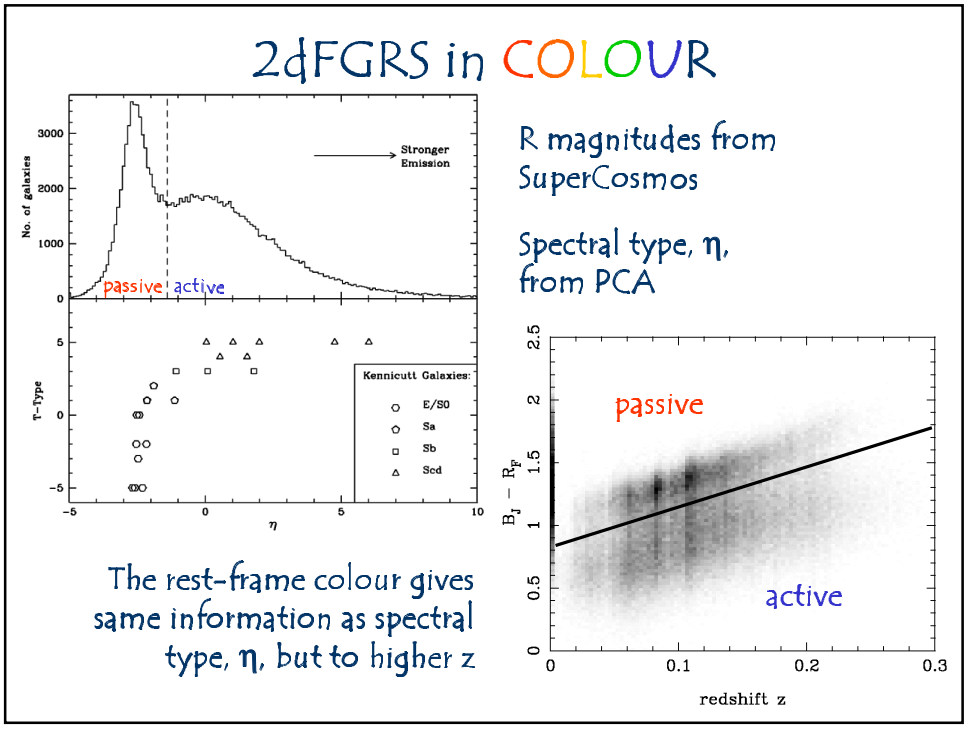
- Can 'predict' the CMB angular power spectrum from the best-fit model based on present CMB and 2dFGRS data (for a flat universe)
- Can also predict the CMB spectrum as measured by MAP (given the expected MAP errors)

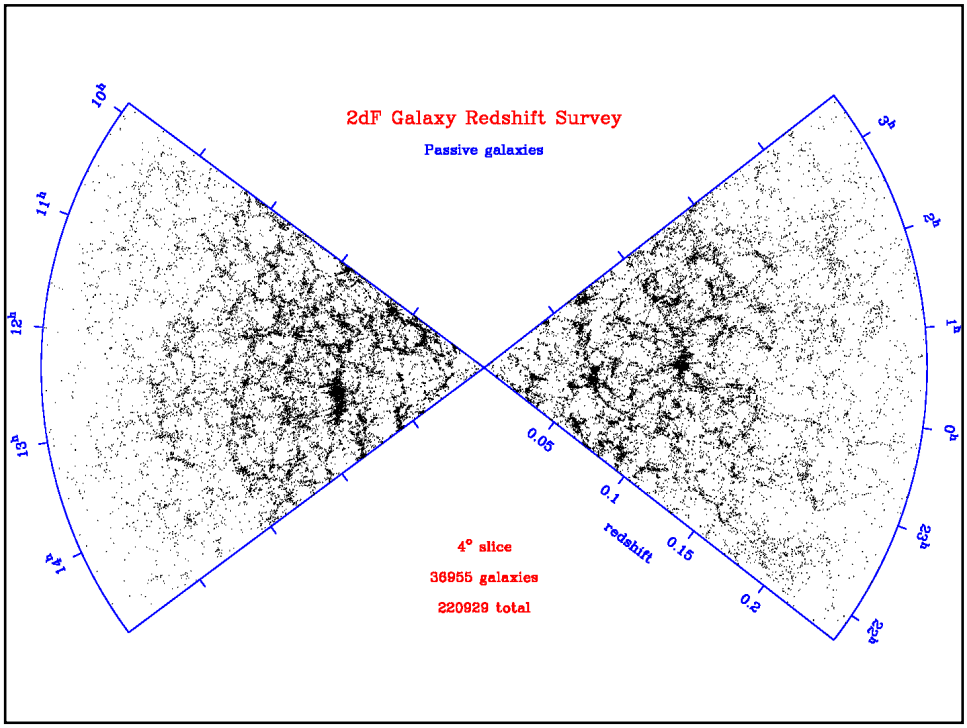


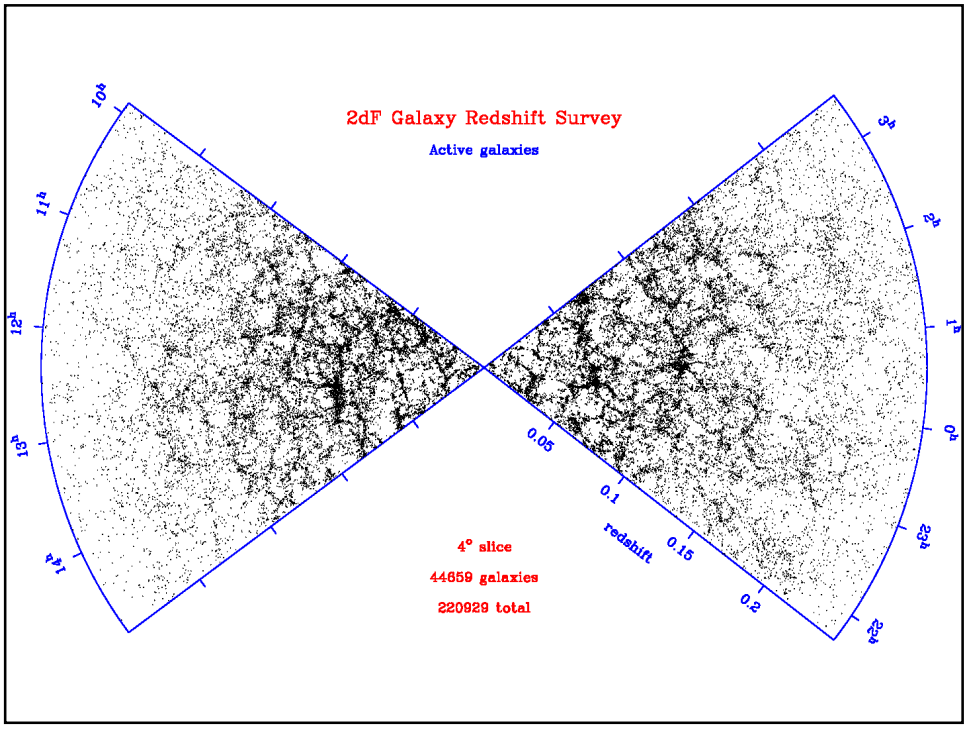
Clustering/bias vary with Luminosity

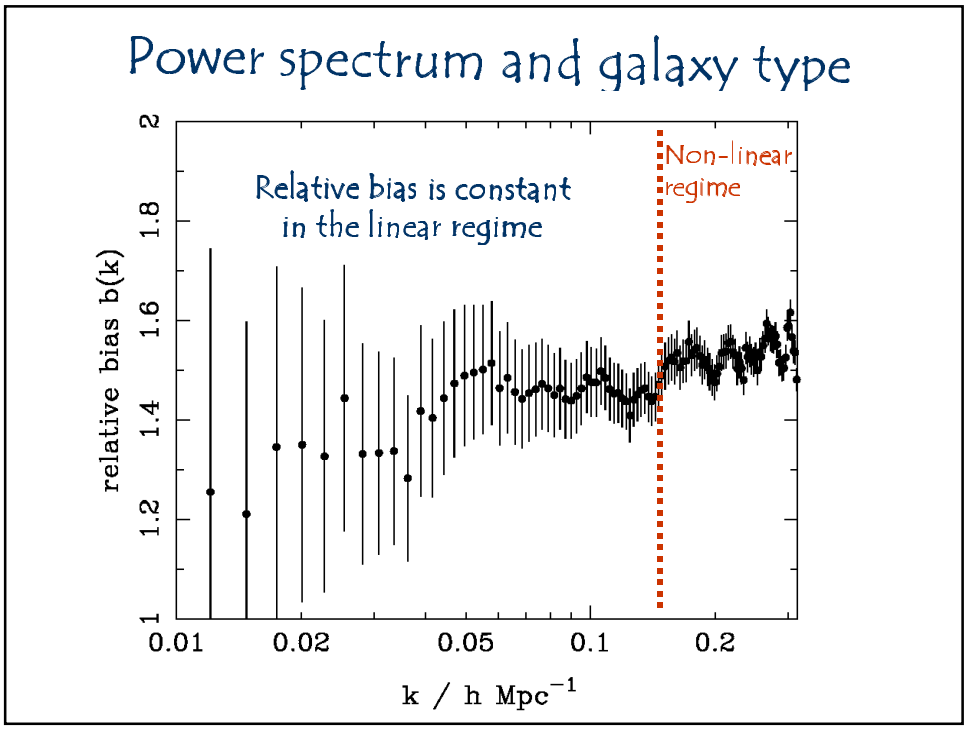


Norberg et al. (the 2dFGRS team) 2001, astro-ph/0105500

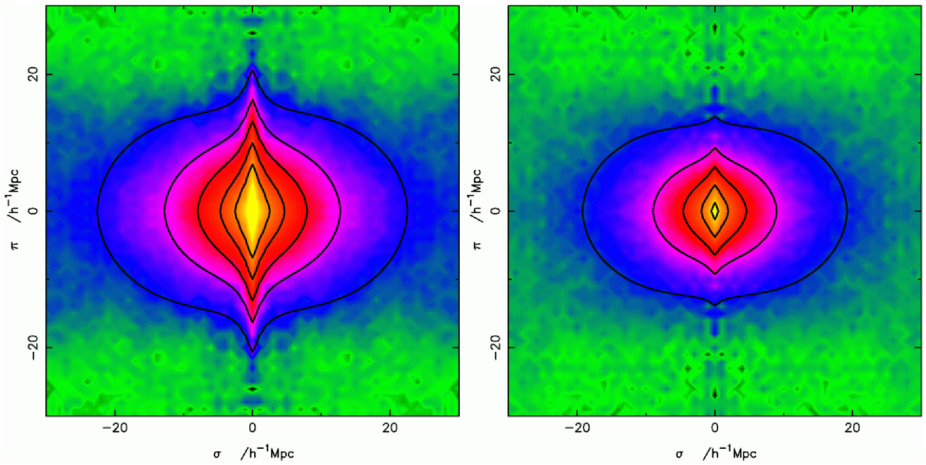

2dFGRS in COLOUR
Stronger Emission
No. of galaxies
passive
active
T-Type
η
Kennicutt Galaxies:
E/S0
Sa
Sb
Scd
R magnitudes from SuperCosmos
Spectral type, η, from PCA
The rest-frame colour gives same information as spectral type, η, but to higher z
passive
active
$B_J - R_F$
redshift z


2dF Galaxy Redshift Survey
Passive galaxies
4° slice
36955 galaxies
220929 total
redshift


2dF Galaxy Redshift Survey
Active galaxies
4° slice
44659 galaxies
220929 total
redshift
0.05
0.1
0.15
0.2


Power spectrum and galaxy type
Relative bias is constant
in the linear regime
Non-linear
regime
relative bias b(k)
1
1.2
1.4
1.6
1.8
2
0.01
0.02
0.05
0.1
0.2
k / h Mpc^{-1}

Redshift-space distortions and galaxy type



Passive:

$\beta = \Omega^{0.6}/b = 0.46 \pm 0.13$

$\sigma_p = 618 \pm 50$ km s^{-1}

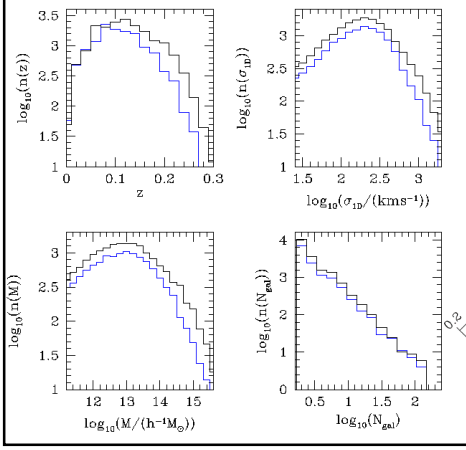
Active:

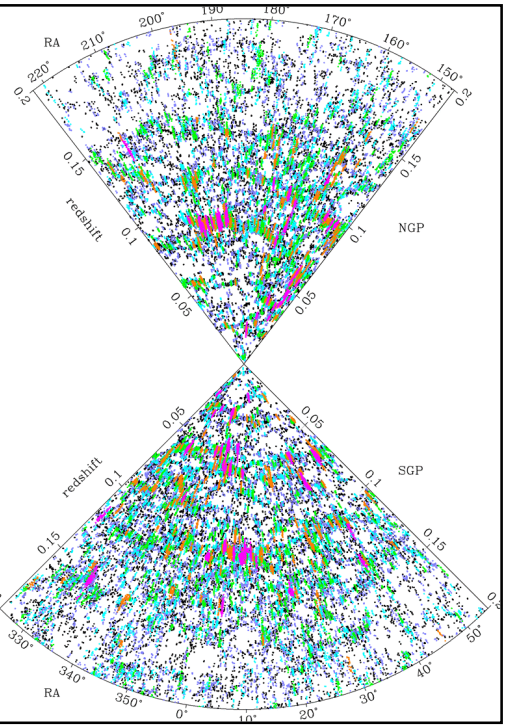
$\beta = \Omega^{0.6}/b = 0.54 \pm 0.15$

$\sigma_p = 418 \pm 50$ km s^{-1}

Groups & Clusters

- Work in progress on identifying the groups and clusters from the 3D position-velocity maps, and measuring their properties.

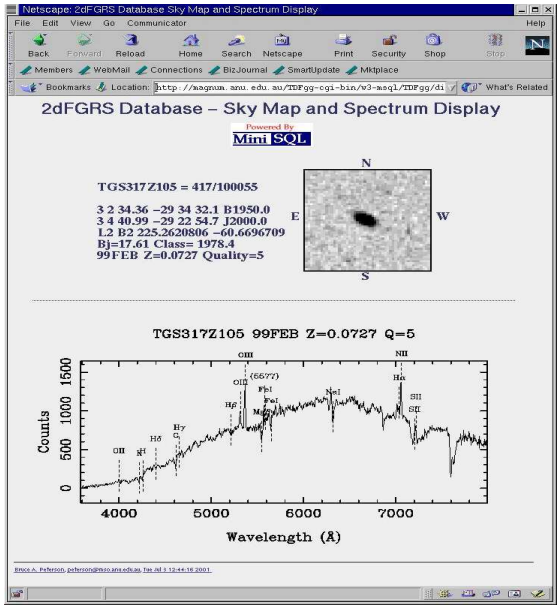




2dFGRS database

Major data products:

- photometric catalogue (improved & extended APM catalogue);
- spectroscopic catalogue (redshifts, principal components, spectral types, line indices, velocity dispersions…);
- database of spectra and images for all objects.



Public release of full final 2dFGRS data set is slated for June 2003

http://www.mso.anu.edu.au/2dFGRS