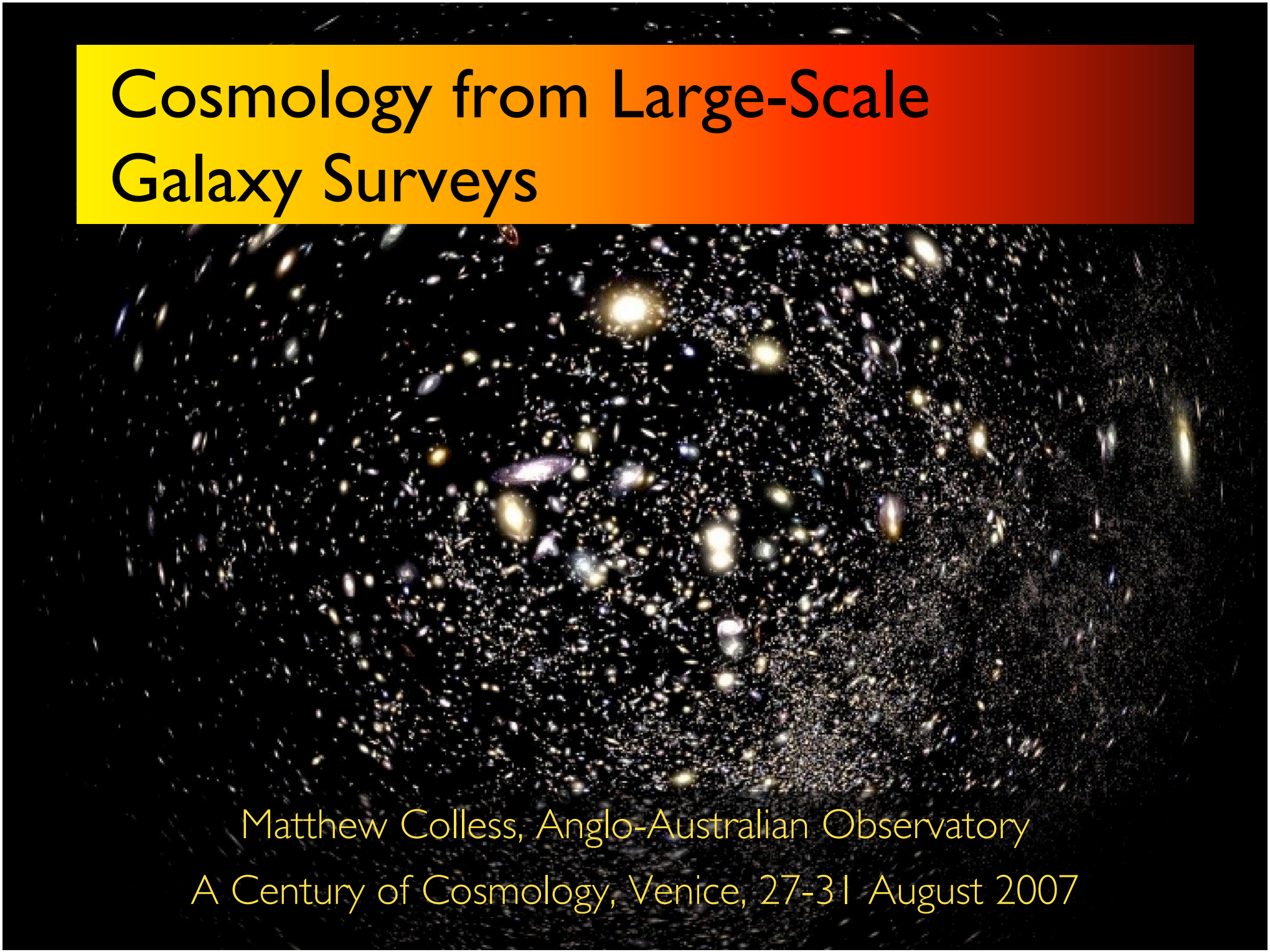
Cosmology from Large-Scale Galaxy Surveys



Matthew Colless, Anglo-Australian Observatory

A Century of Cosmology, Venice, 27-31 August 2007

A brief history of galaxy surveys

- Before 1980: Pre-history - first galaxy redshift surveys
  - Hubble, the expanding universe, and all that
- 1985-1995: Age of Discovery - large-scale structures
  - The CfA redshift survey and the iconic stick-figure
  - The development of multi-object spectrographs
  - Large (10^4) z-surveys - LDSS, Autofib, PSCz, LCRS…
- 1995-2005: Industrial Revolution - 'precision cosmology'
  - Massive (10^5) z-surveys - 2dFGRS, SDSS, 6dFGS, 2MRS…
  - Deep z-surveys - DEEP, VVDS, zCOSMOS…
- Present & future: Post-Modernism - death or glory?
  - Dark energy - holy grail? much ado about nothing?
  - BAO (10^6) surveys - WiggleZ, FASTsound, WFMOS…
  - Galaxy surveys with ELTs - baryon tomography…

AAO

FOCAP

LDSS

Autofib

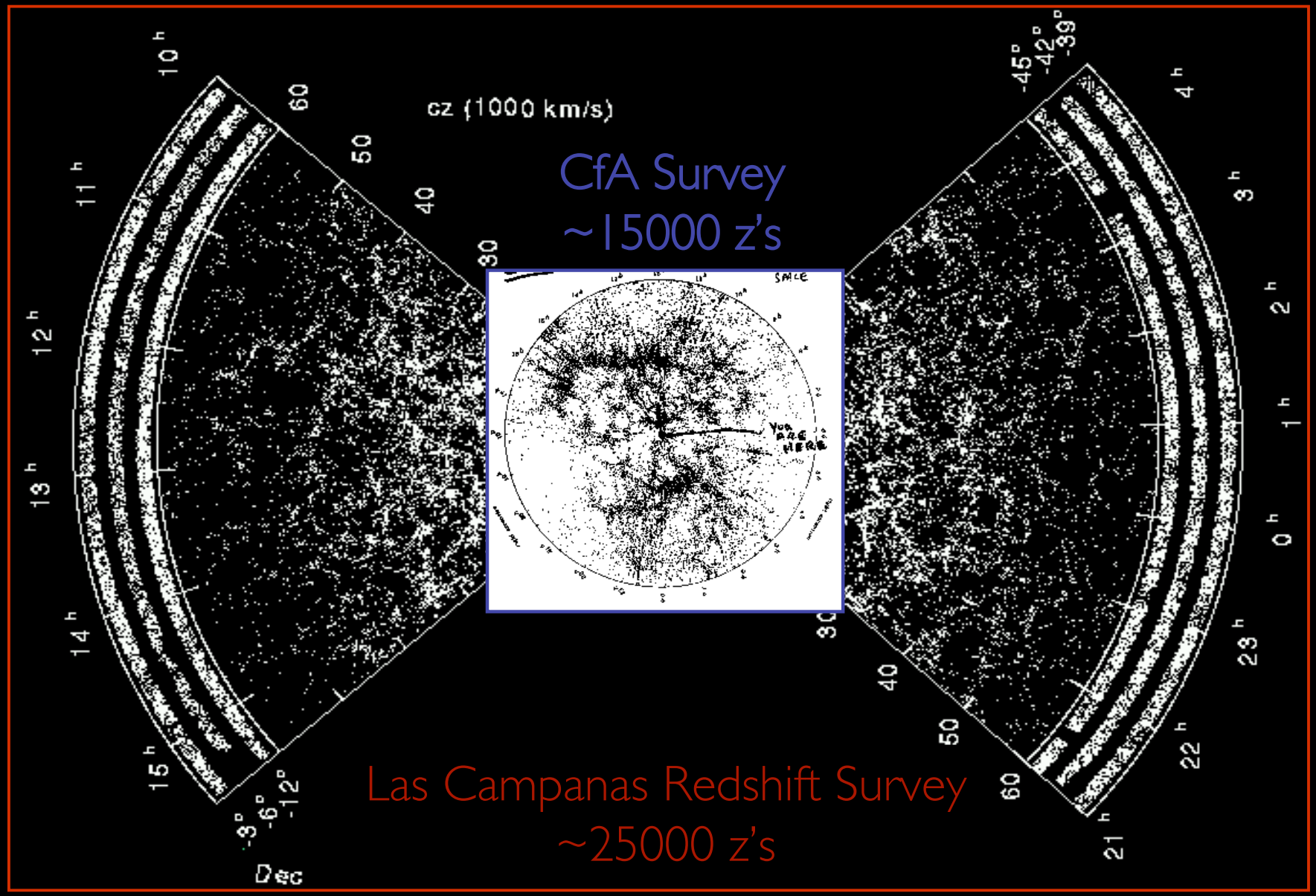
2dF

6dF

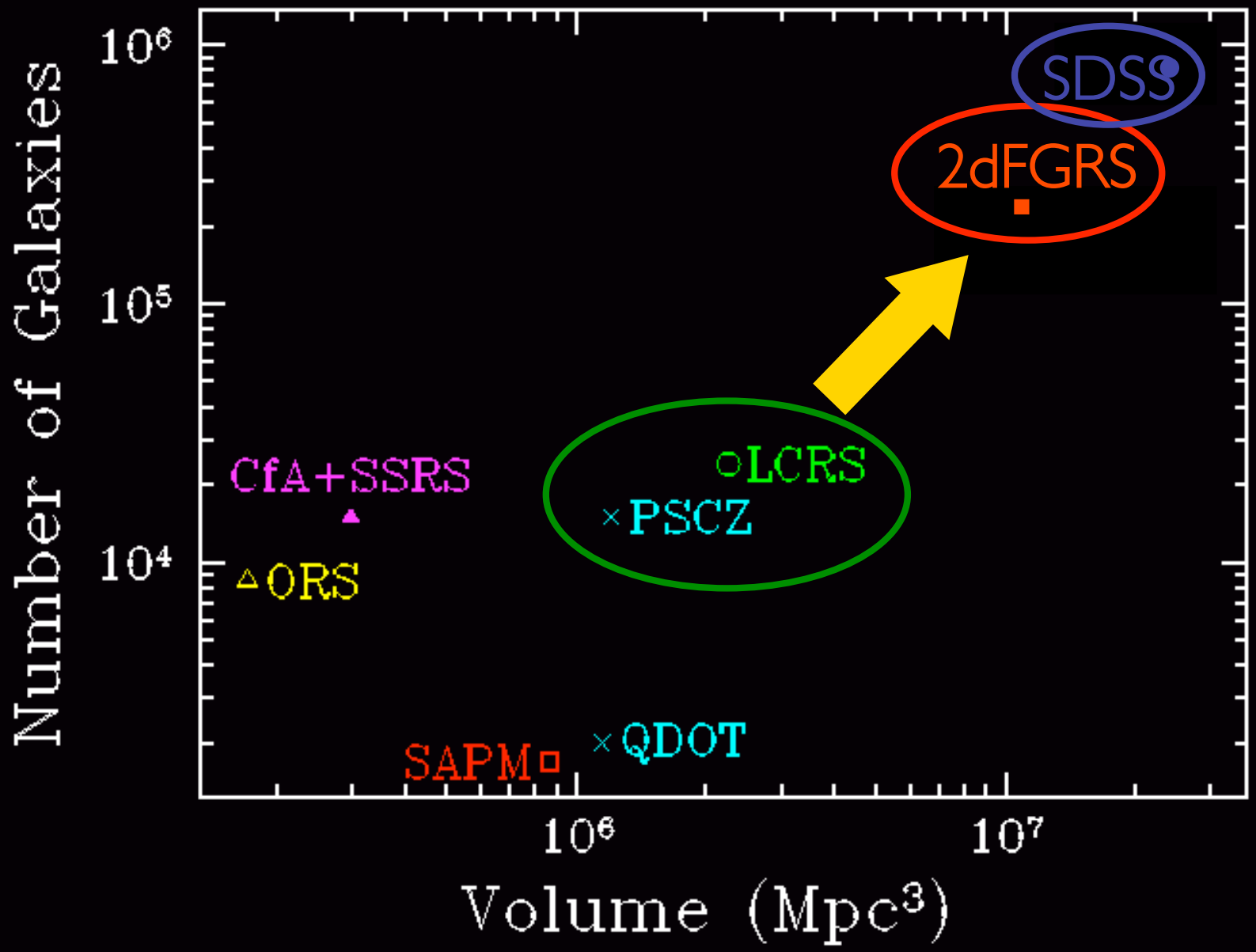
AAΩ

WFMOS

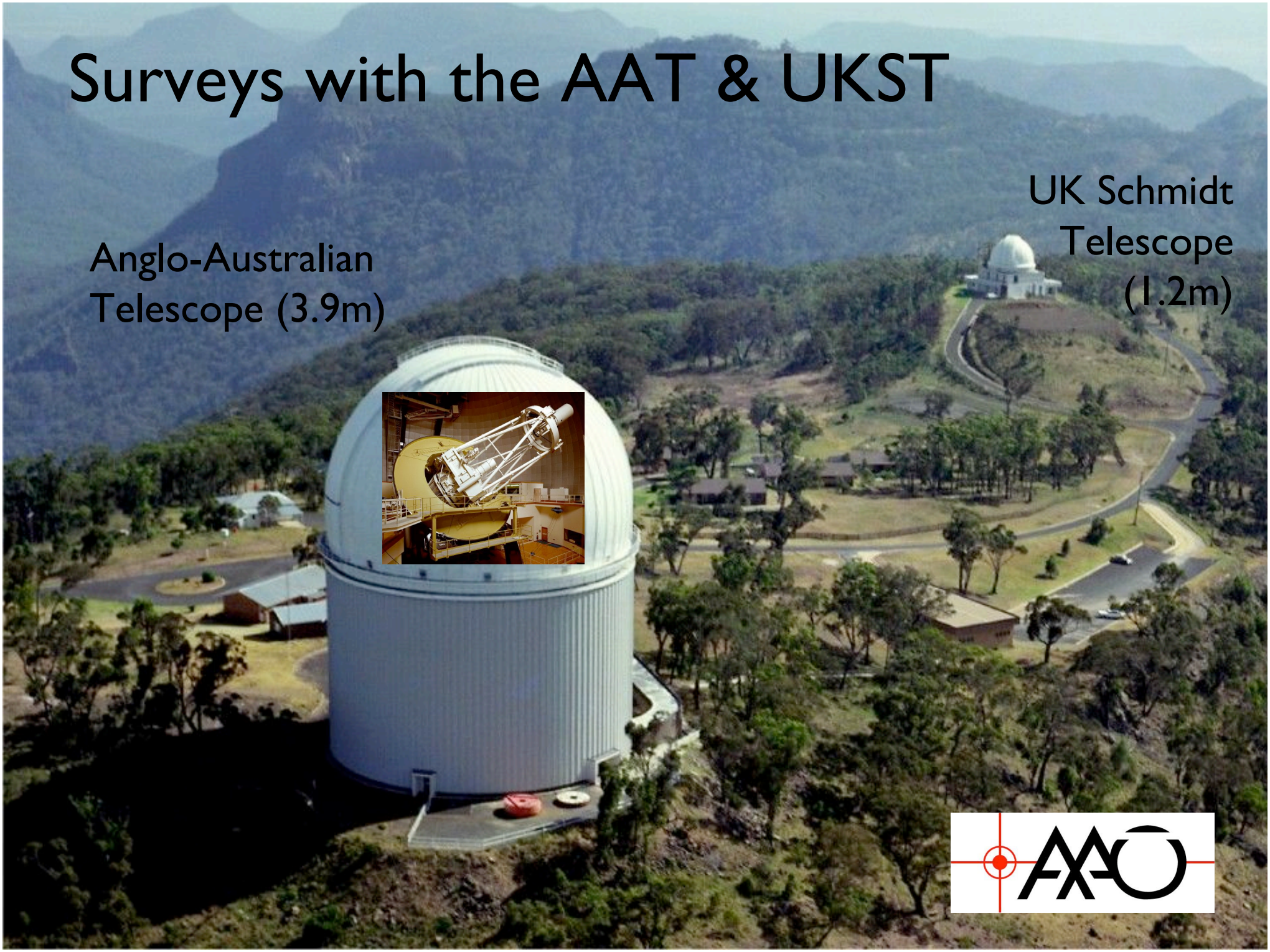
State of the art ~1997



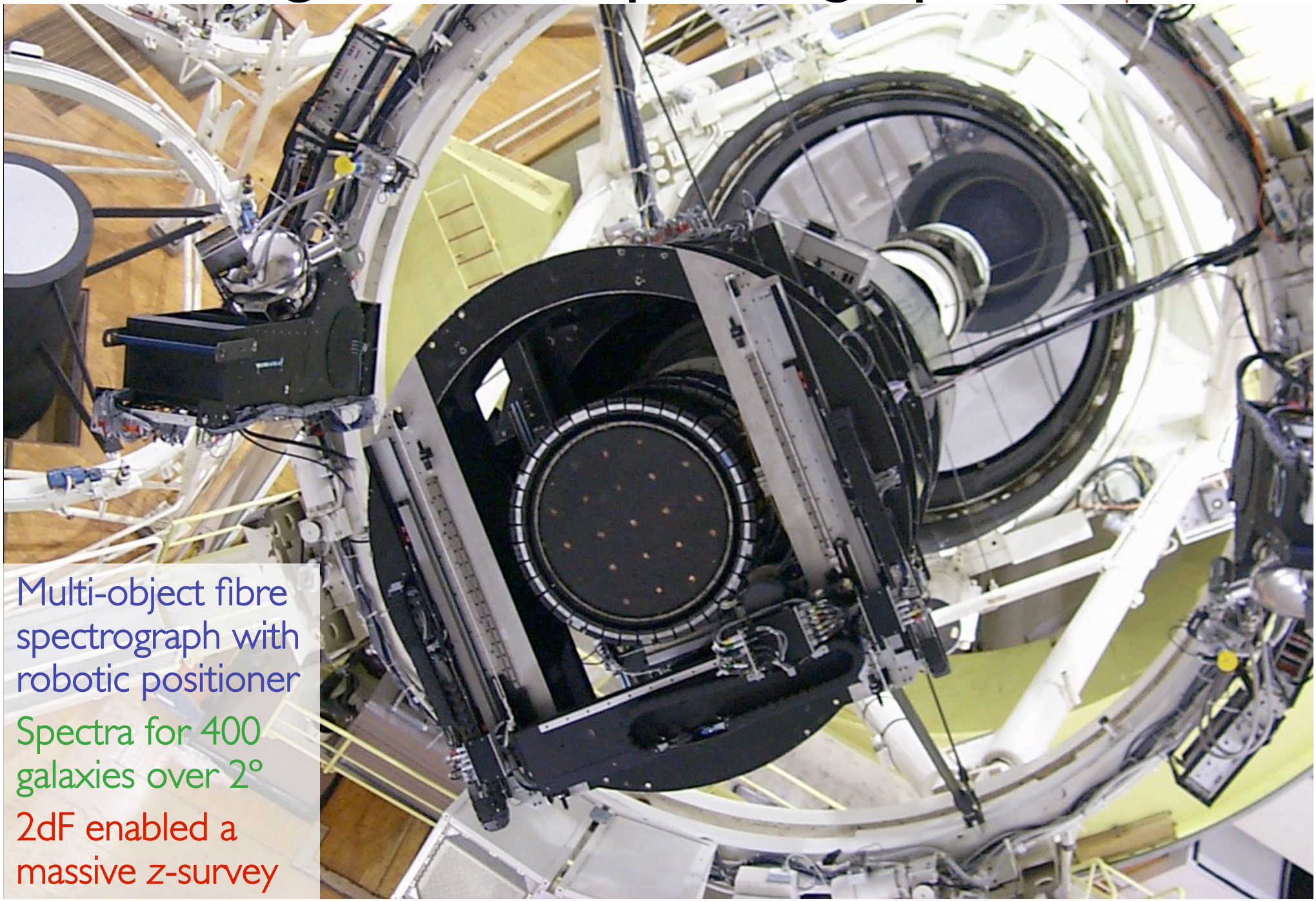
Evolution of Redshift Surveys



Surveys with the AAT & UKST



The 2-degree Field Spectrograph

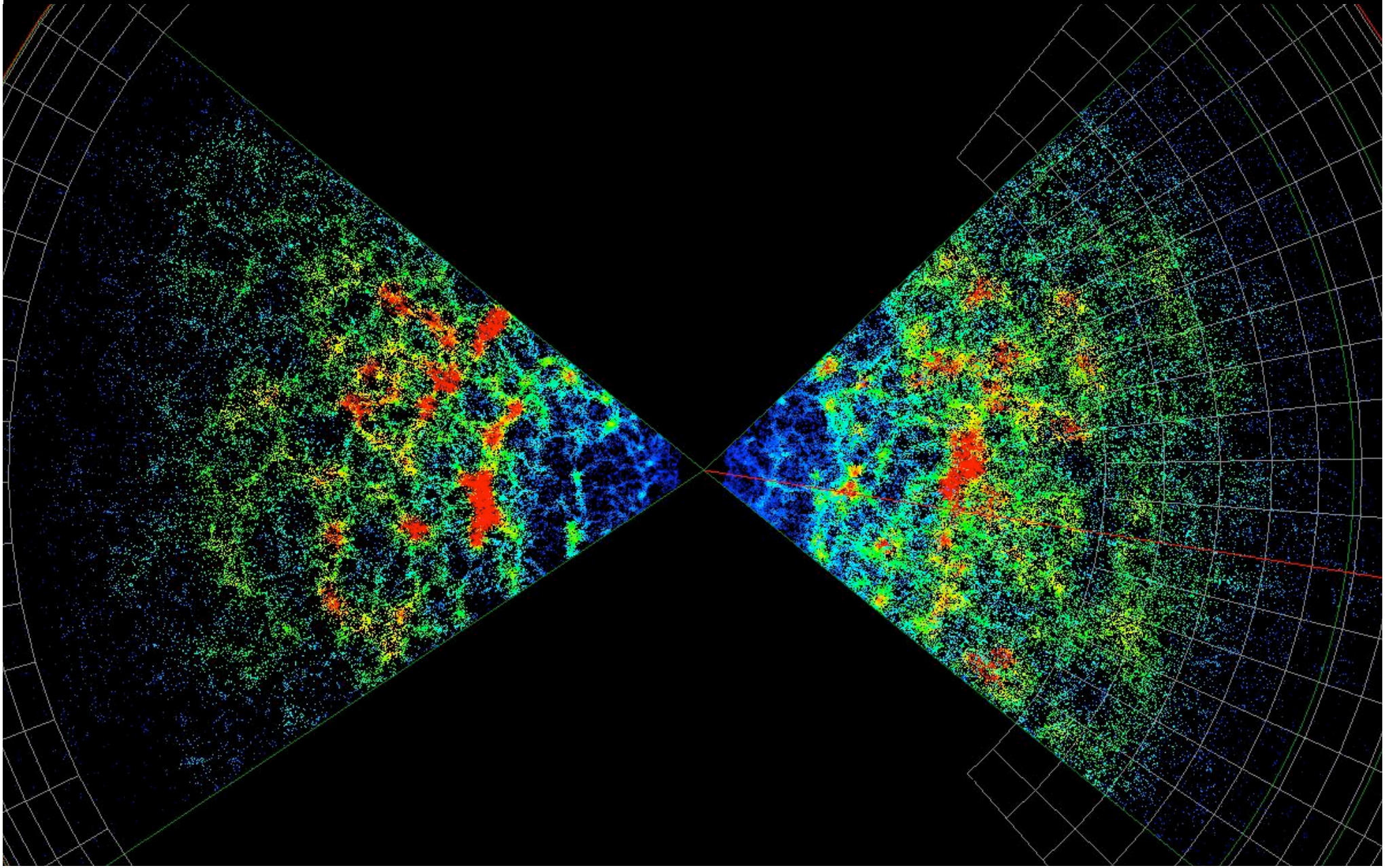


Multi-object fibre spectrograph with robotic positioner

Spectra for 400 galaxies over 2°

2dF enabled a massive *z*-survey

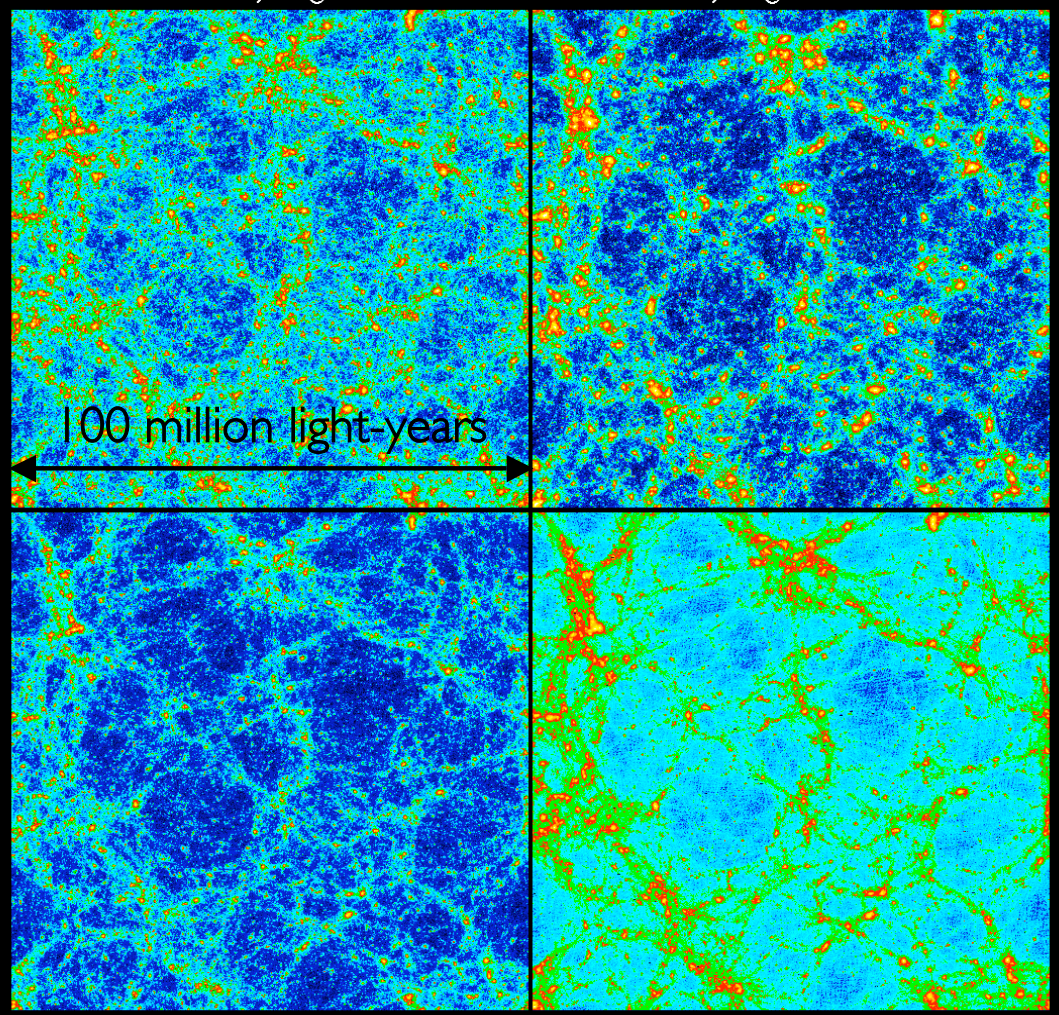
The 2dFGRS map of 221000 galaxies



Large-Scale Structure in Model Universes

- The large-scale structure of the galaxy distribution, on scales from millions to billions of light-years, depends on…
  - the amounts of the various constituents of the universe (baryonic matter, dark matter, dark energy etc.)
  - the recipe for how galaxies are formed (when, where, and with what bias relative to the dark matter)
- The rich structure of the galaxy distribution encodes much physics and many parameters

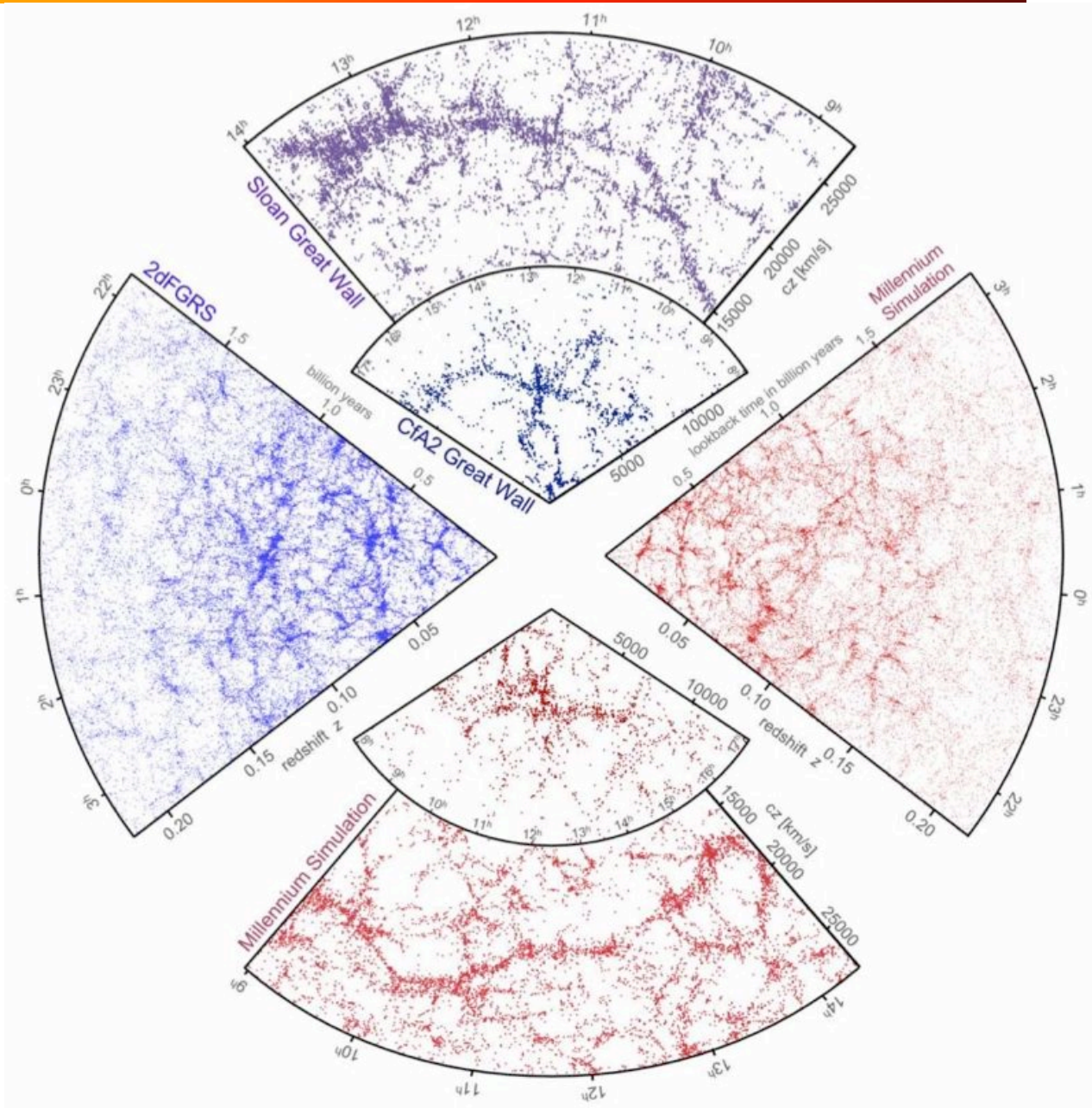
Model Comparison, 16.7 Million Particles



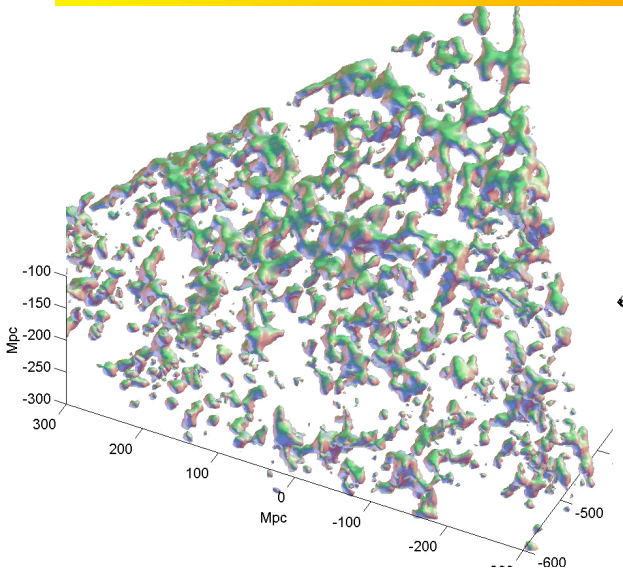
Warren *et al.*, Los Alamos

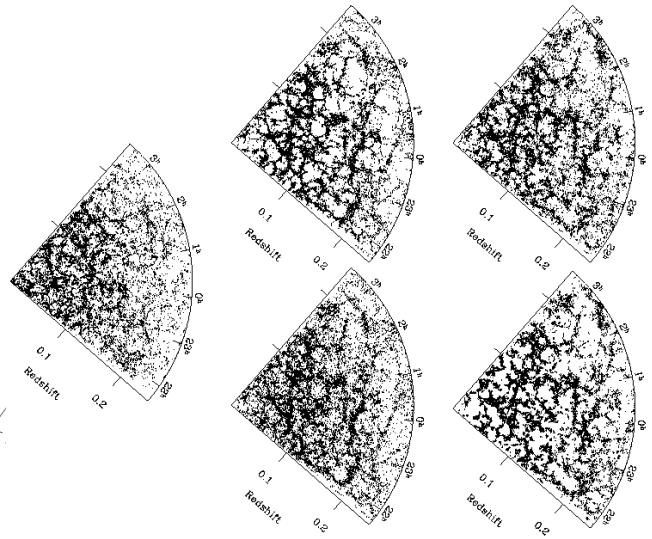
Surveys versus simulations

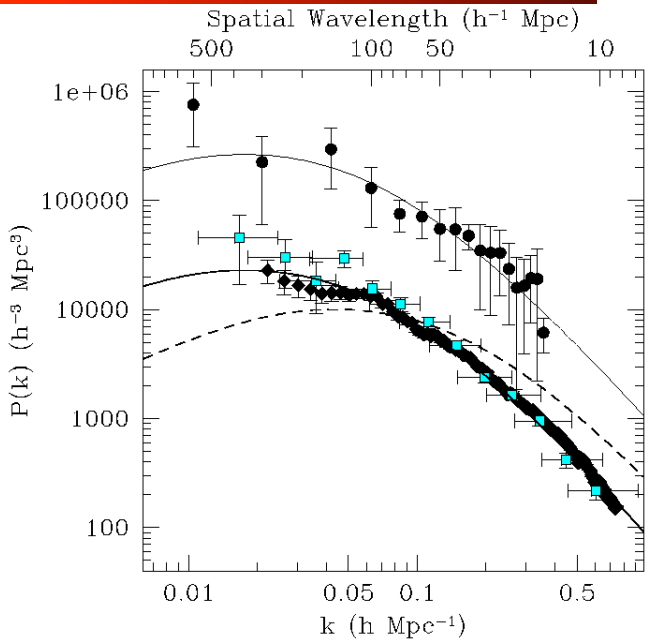
- Comparison of slices from CfA2, 2dFGRS and SDSS surveys on different scales, all compared to equivalent slices, selected for their similarity, from the Millennium Simulation (Springel, Frenk & White 2006)

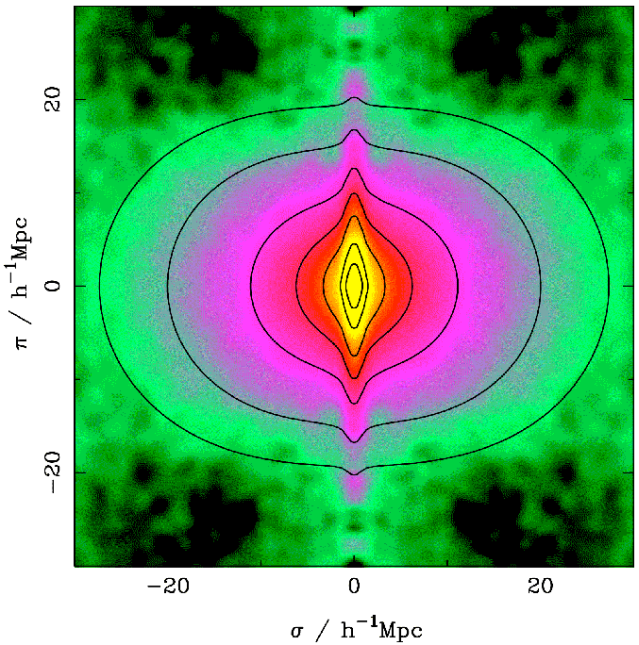


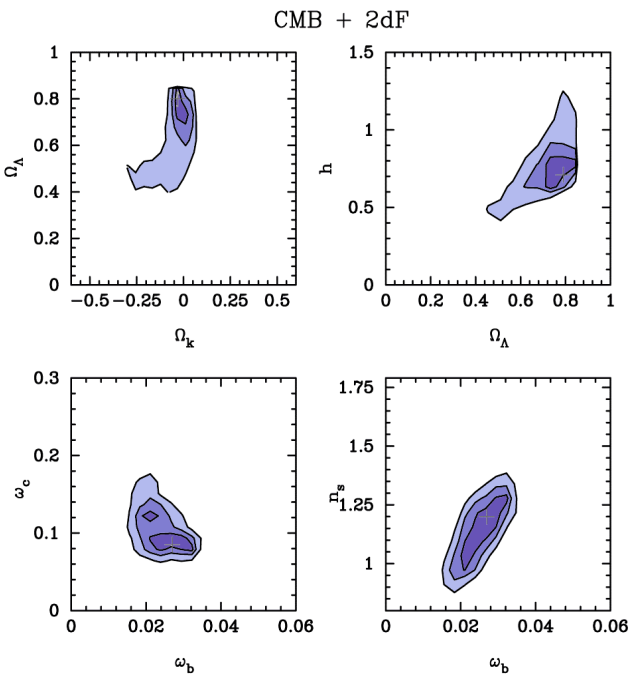
2dFGRS structure & cosmology results

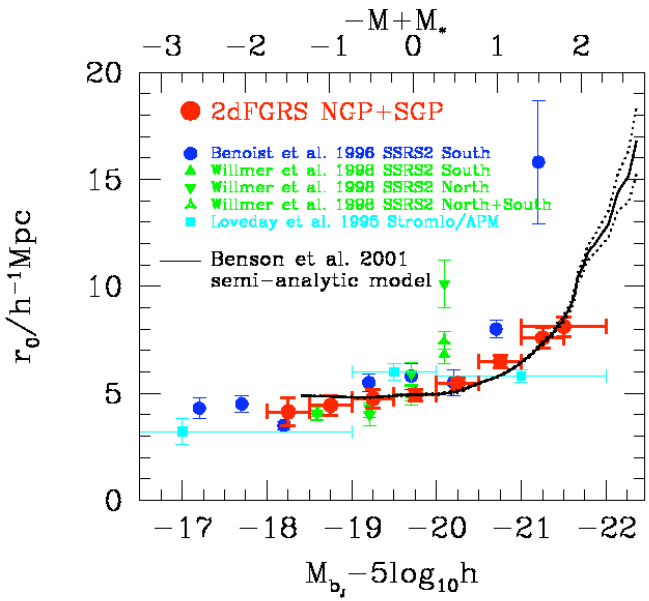






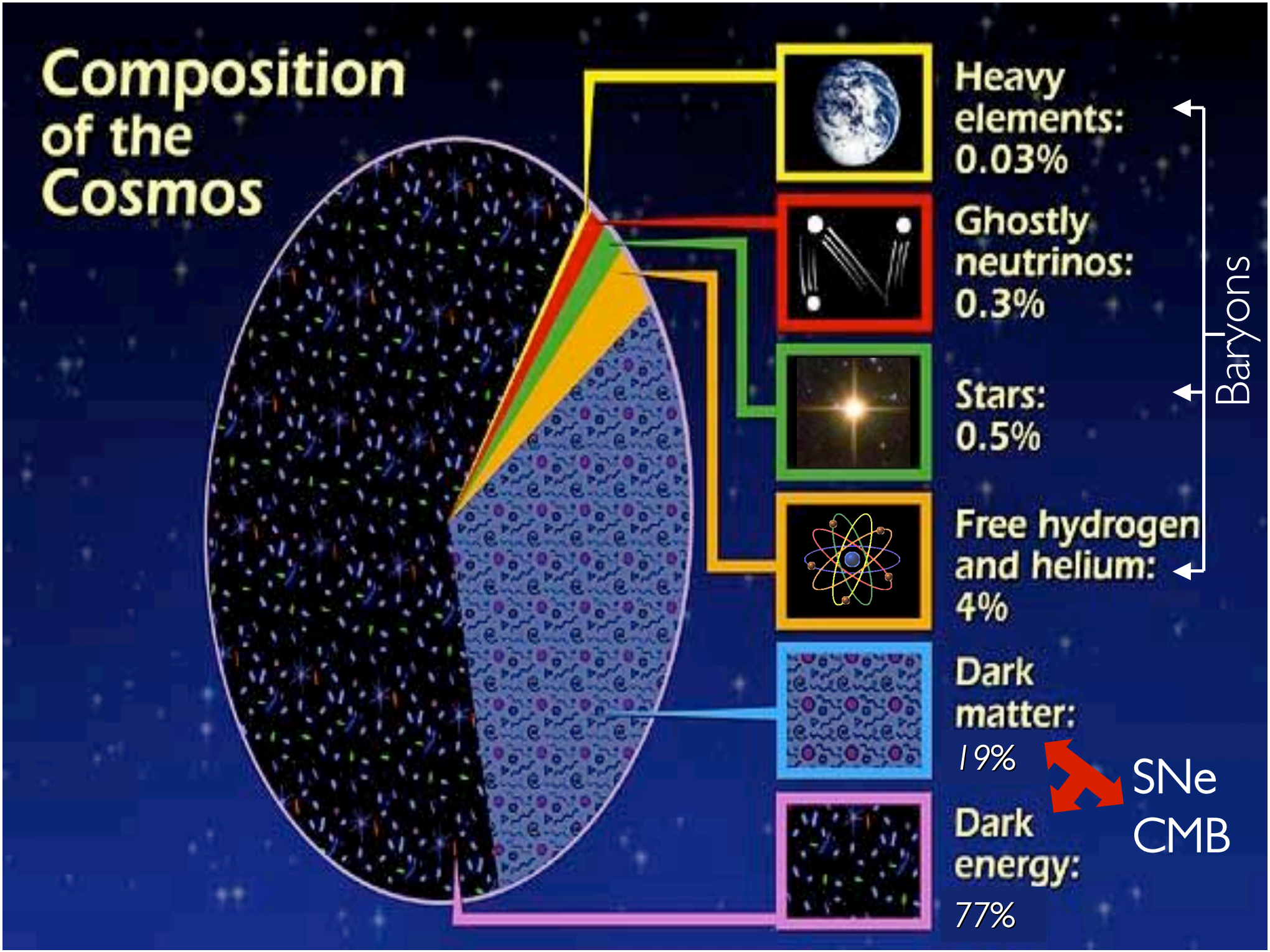






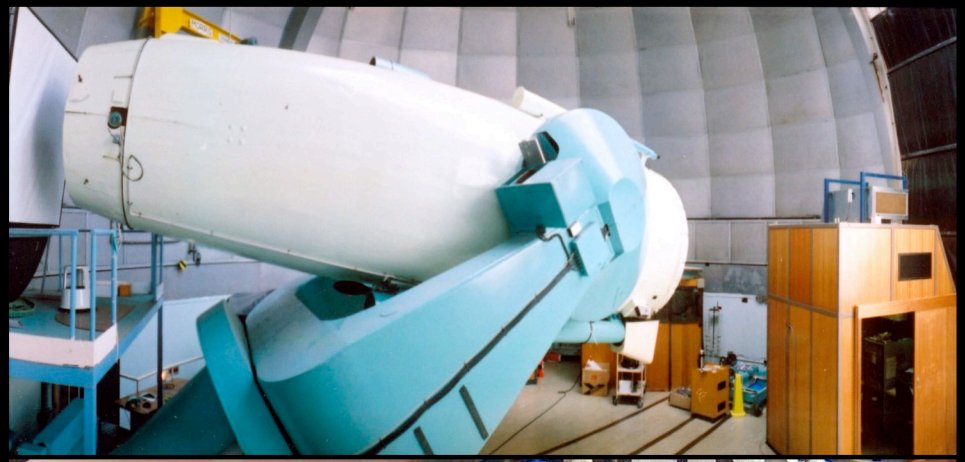
2dFGRS structure & cosmology results

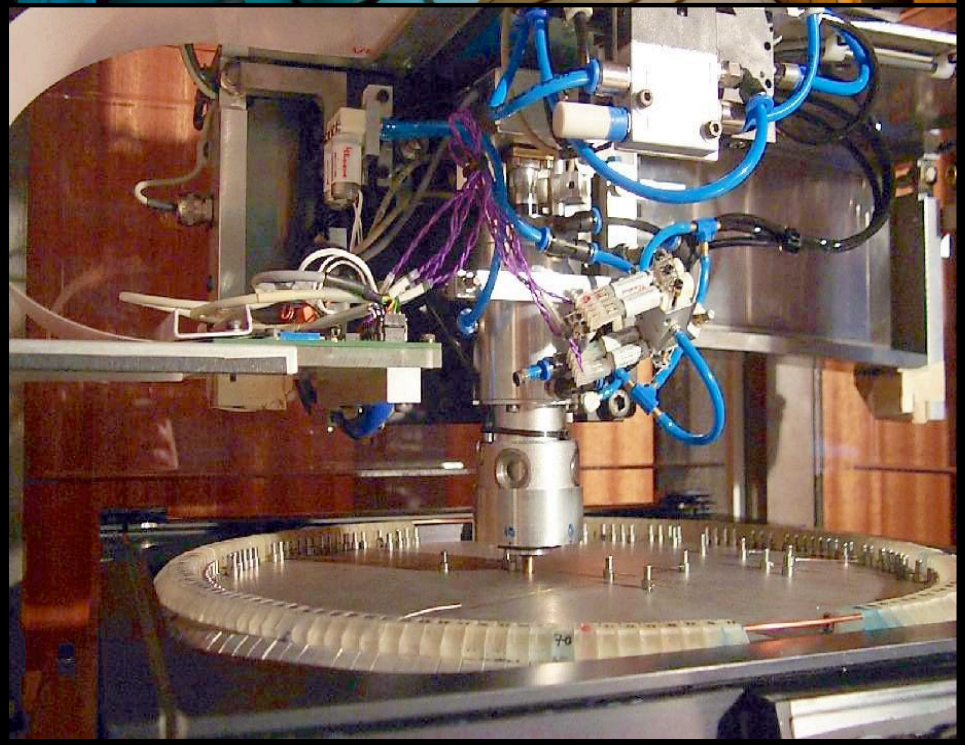
- The large-scale structure of the galaxy distribution is reliable and precisely determined on size scales from 1 Mpc to 200 Mpc
- The properties of the galaxy distribution confirm that the large-scale structure grows by gravitational instability…
  - ⇒ consistent with quantum fluctuations emerging from Big Bang being amplified by gravity into galaxies/clusters/superclusters
- The total density of all types of matter in the universe is $\Omega_M = 0.23$
  - ⇒ there is only 23% of critical density needed for a flat universe
- The total density in ordinary matter is $\Omega_B = 0.04$
  - ⇒ baryons are 19% and CDM is 81% of all matter in the universe
- Neutrinos make up less than 13% of all the matter in the universe
  - ⇒ the total mass of the 3 neutrino species is less than 0.7 eV
- First detection of baryon acoustic oscillations (simultaneous with SDSS)


Composition of the Cosmos
Heavy elements: 0.03%
Ghostly neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: 19%
Dark energy: 77%
Baryons
SNe
CMB

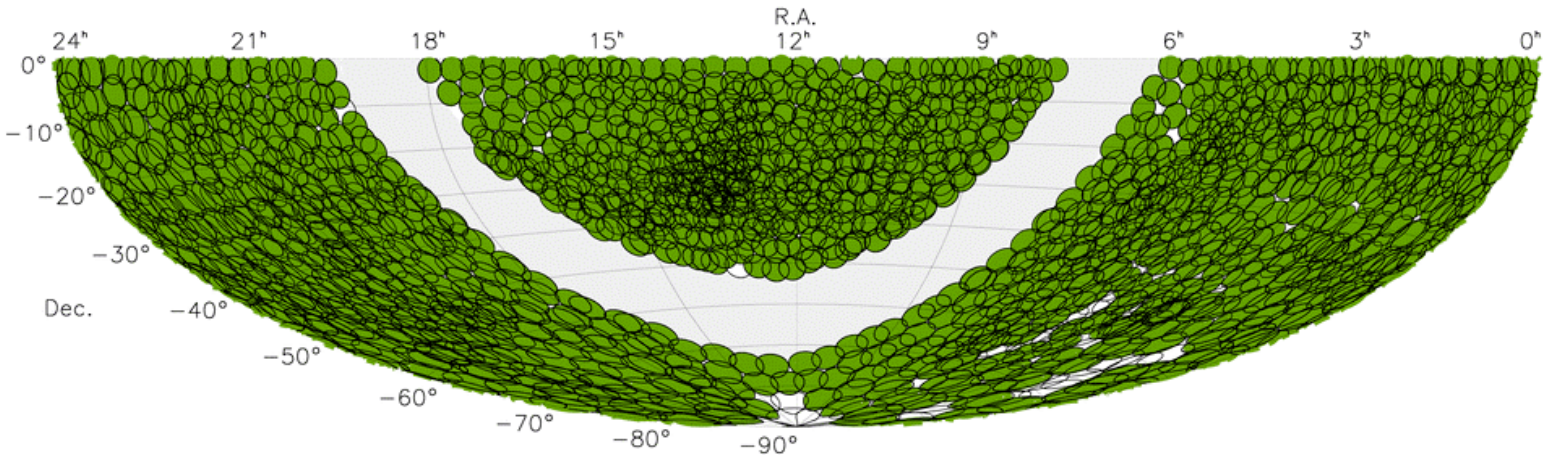
The 6dF Galaxy Survey

- A redshift & peculiar velocity survey of galaxies in the local universe
- Covers southern sky with |b|>10°
- Primary galaxy sample selected from 2MASS with K_{tot}<12.75
- Also H<13.0, J<13.75 (2MASS) and r<15.6, b<16.75 (SuperCosmos)
- 11 other samples: radio, X-ray, IRAS
- Peculiar velocity survey uses FP for 15,000 bright early-type galaxies
- Observations obtained May 2001 to Jan 2006 using 6dF spectrograph on the UK Schmidt Telescope
- Database:137k spectra, 124k galaxy redshifts over 80% of southern sky
- Final data release Aug 2007

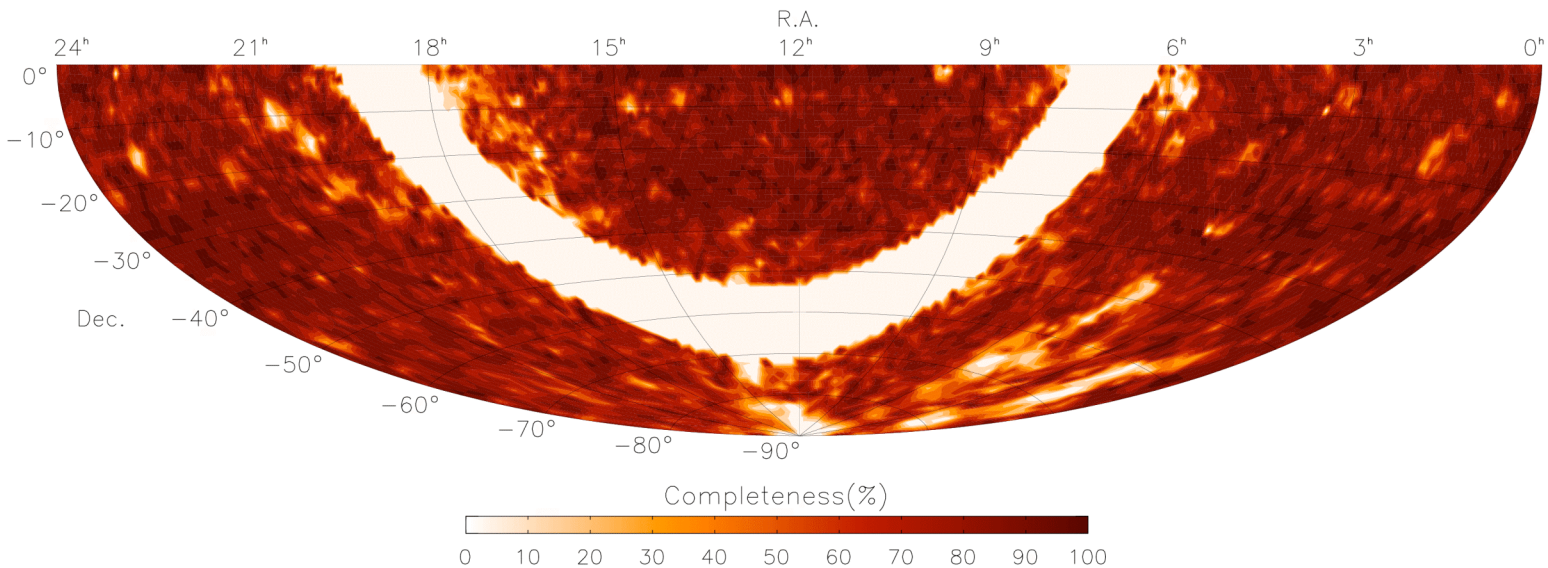




Sky coverage & redshift completeness



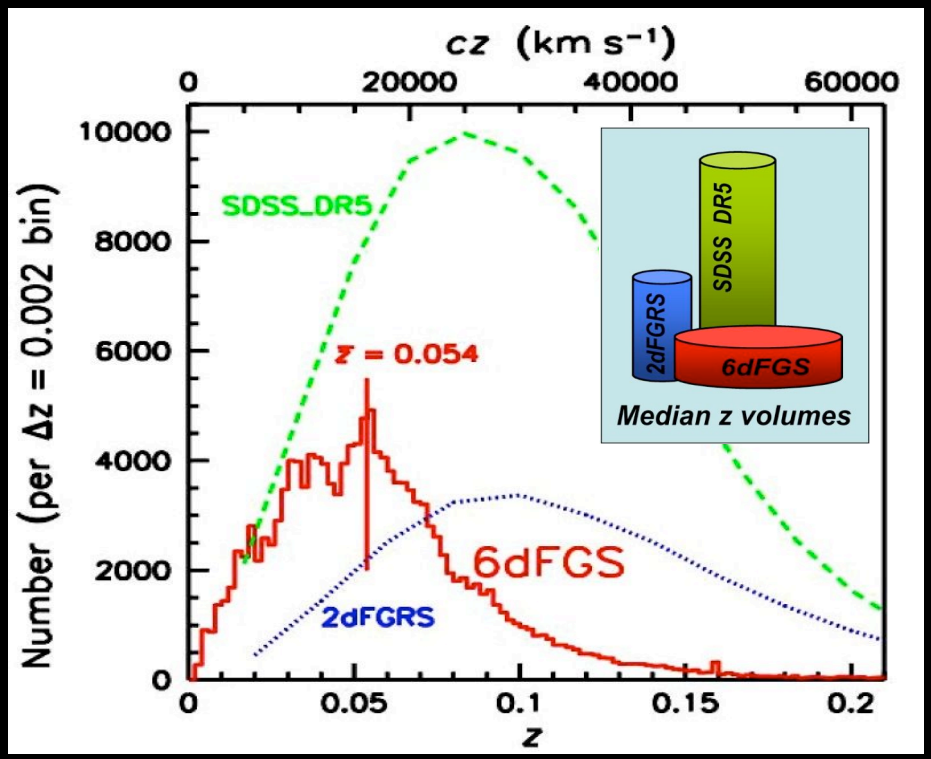
Observed 1464/1598 fields; 92% of the southern sky with |b|>10°

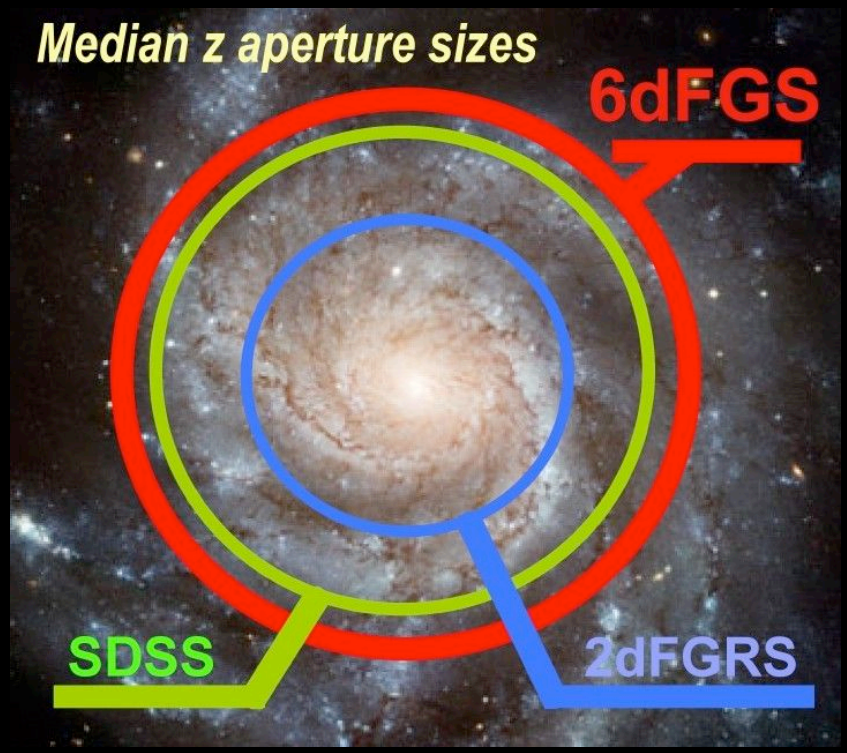


Mean redshift completeness for the K-band primary sample is 88%

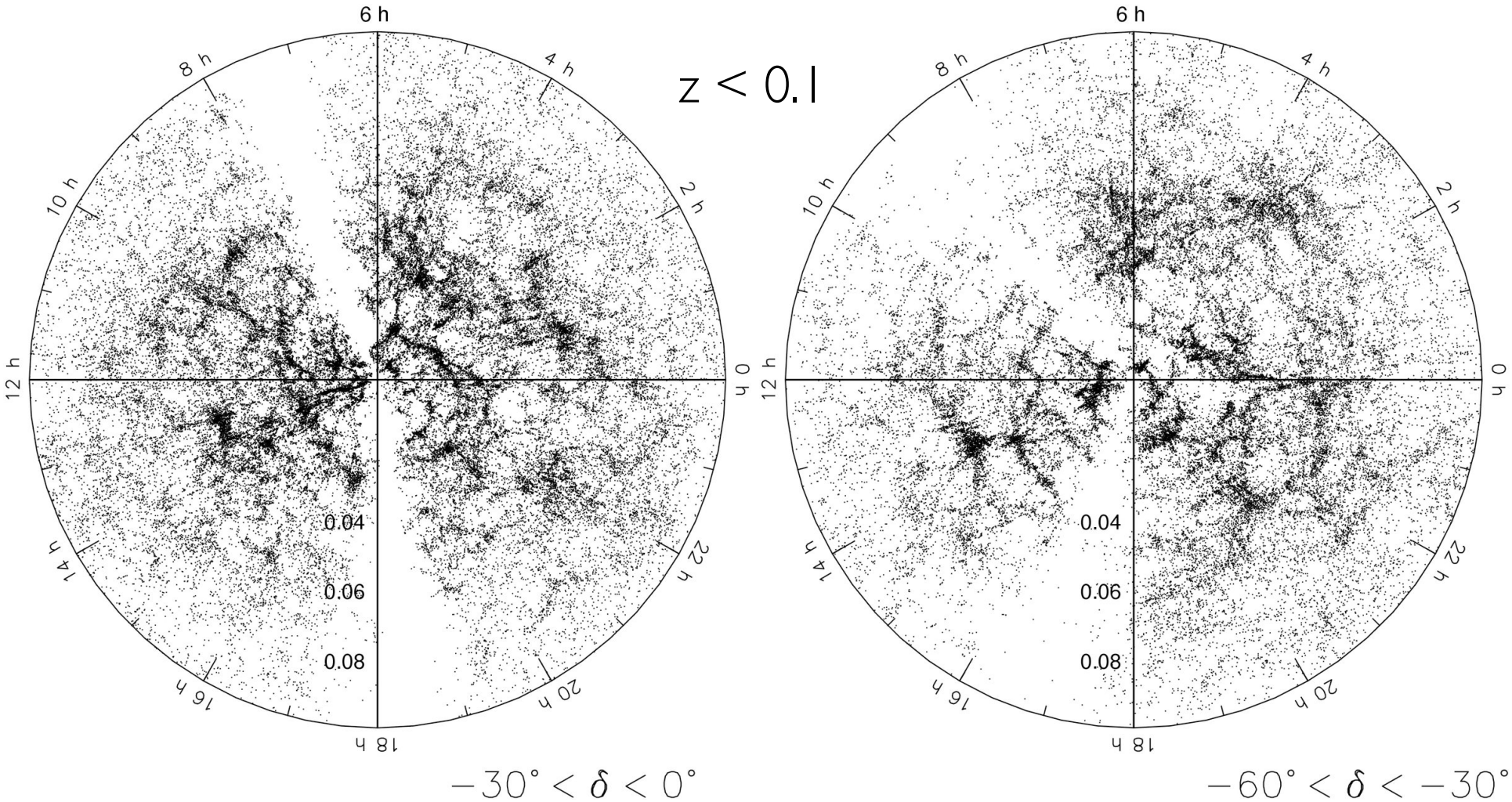
Comparison with other z-surveys

- Comparing the 6dFGS to the 2dFGRS and SDSS…
  - 6dFGS galaxy sample is NIR selected rather than optically-selected
  - 6dFGS surveys <z>=0.05 local universe (cf. 2dFGRS/SDSS <z>=0.1)
  - 6dFGS volume is comparable to the 2dFGRS, but 3x smaller than SDSS
  - Large fibres, so aperture effects are less for 6dFGS than 2dFGRS/SDSS

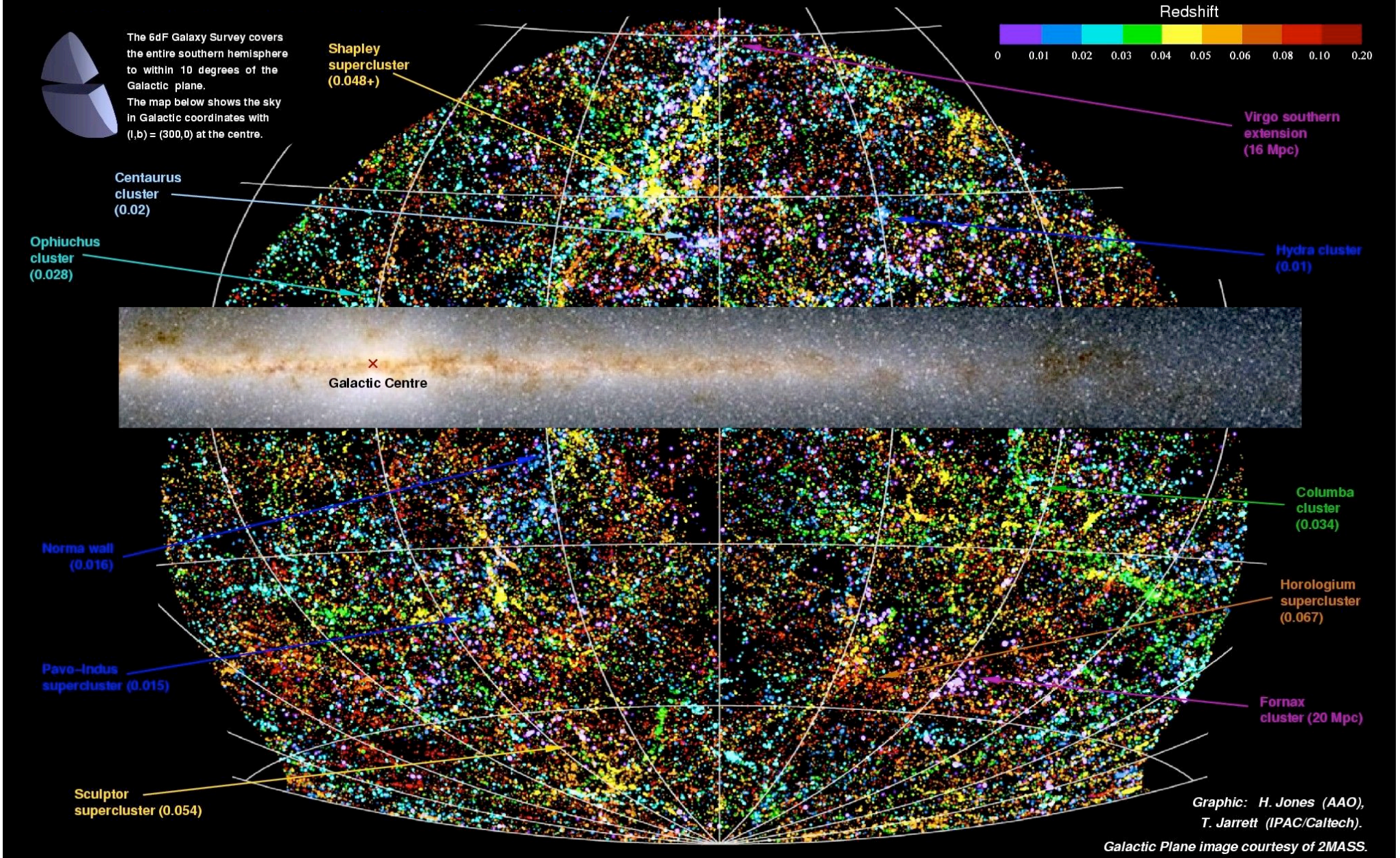




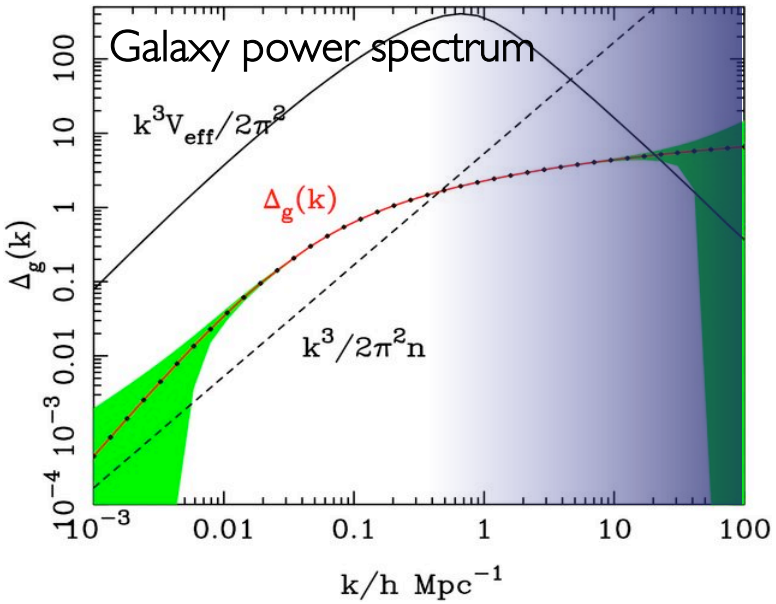
6dFGS redshift space maps

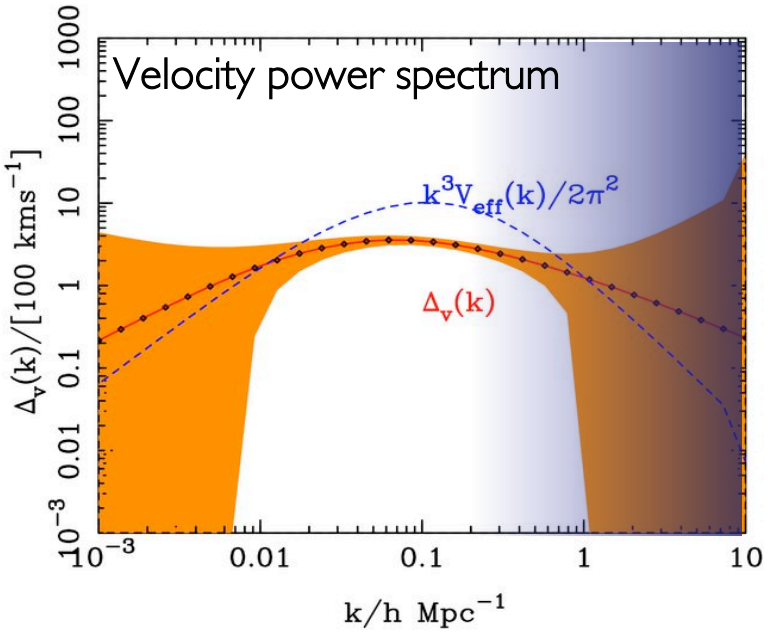


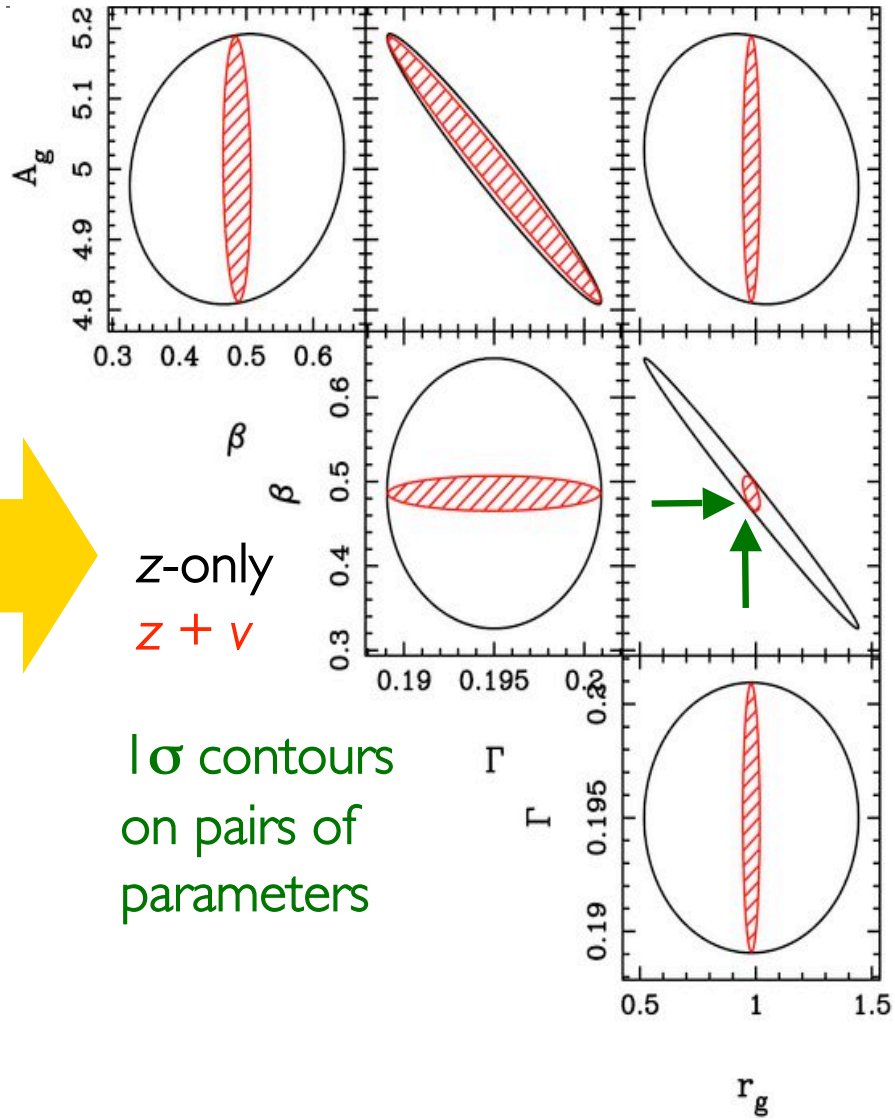
The 6dFGS view of the local universe



6dFGS power spectra and constraints







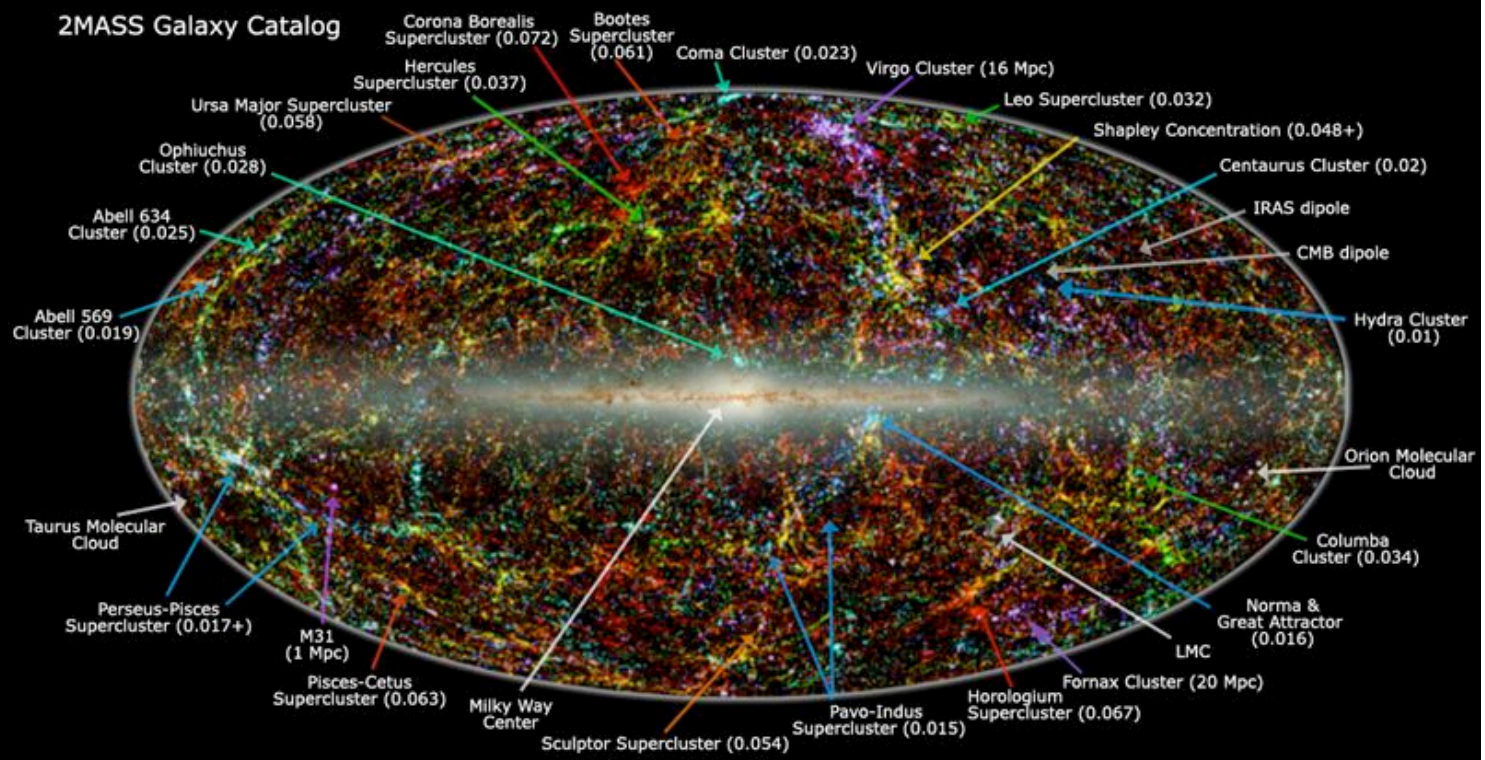
z-only

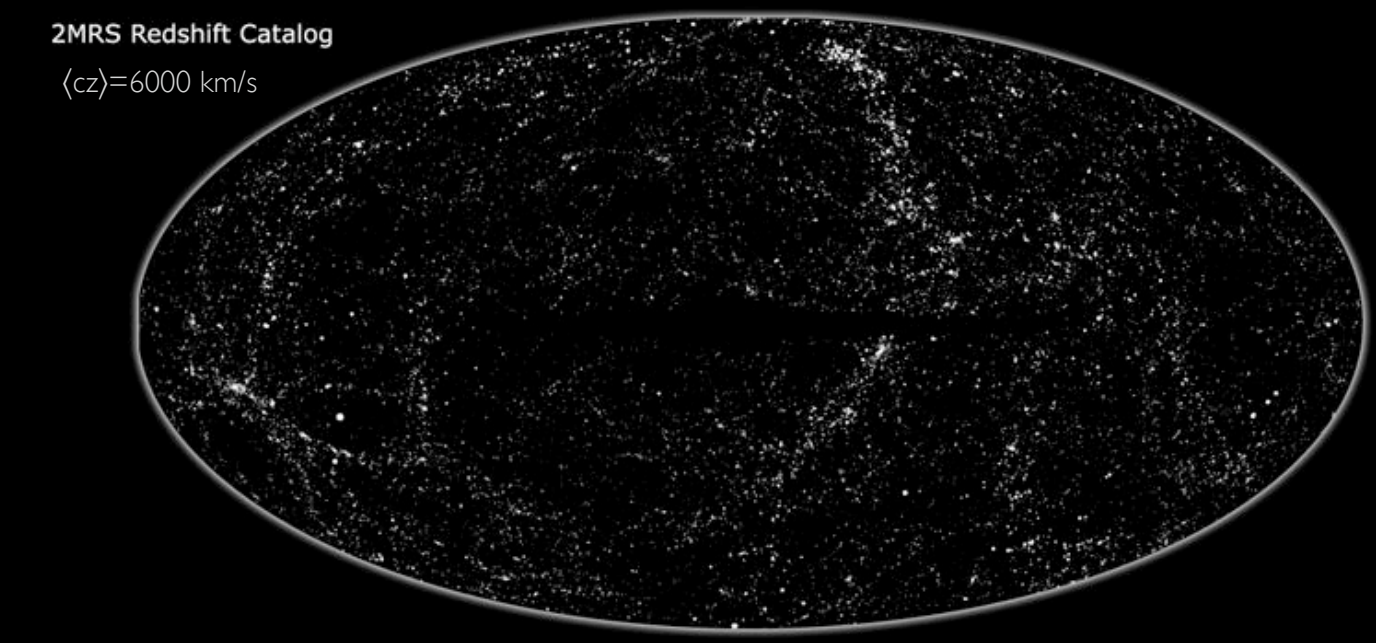
z + *v*

1σ contours on pairs of parameters

2MASS Redshift Survey

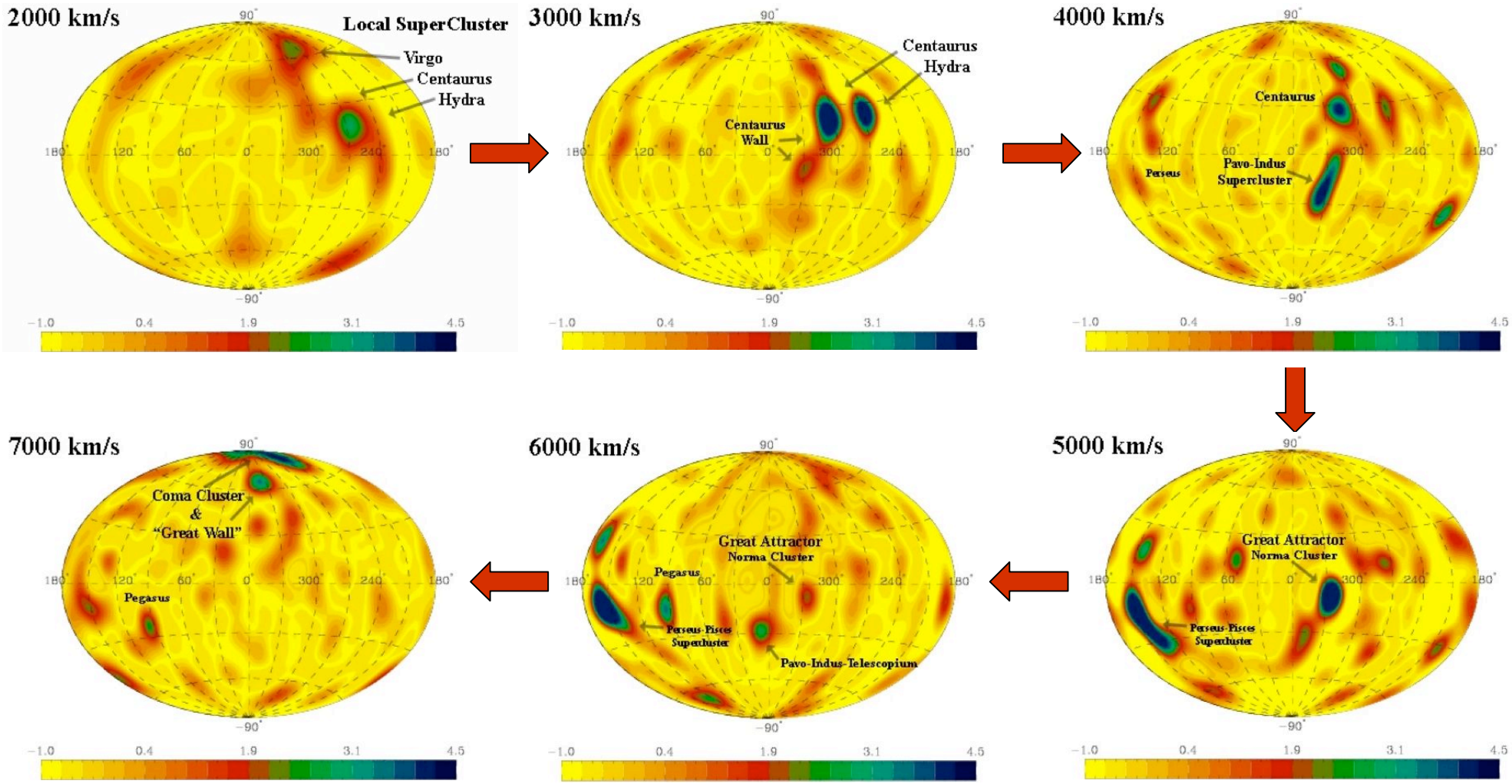
- All-sky *z*-survey to K_s=11.25 (limit is 1.5 mag brighter than 6dFGS)
- 93% complete with z's from Arecibo, Green Bank and FLWO 1.5m in North and 6dFGS and CTIO in South
- 2MRS contains 23,000 galaxies and is densest all-sky *z*-survey to date





Erdogdu et al., 2006, MNRAS, 368, 151

Local density field reconstruction

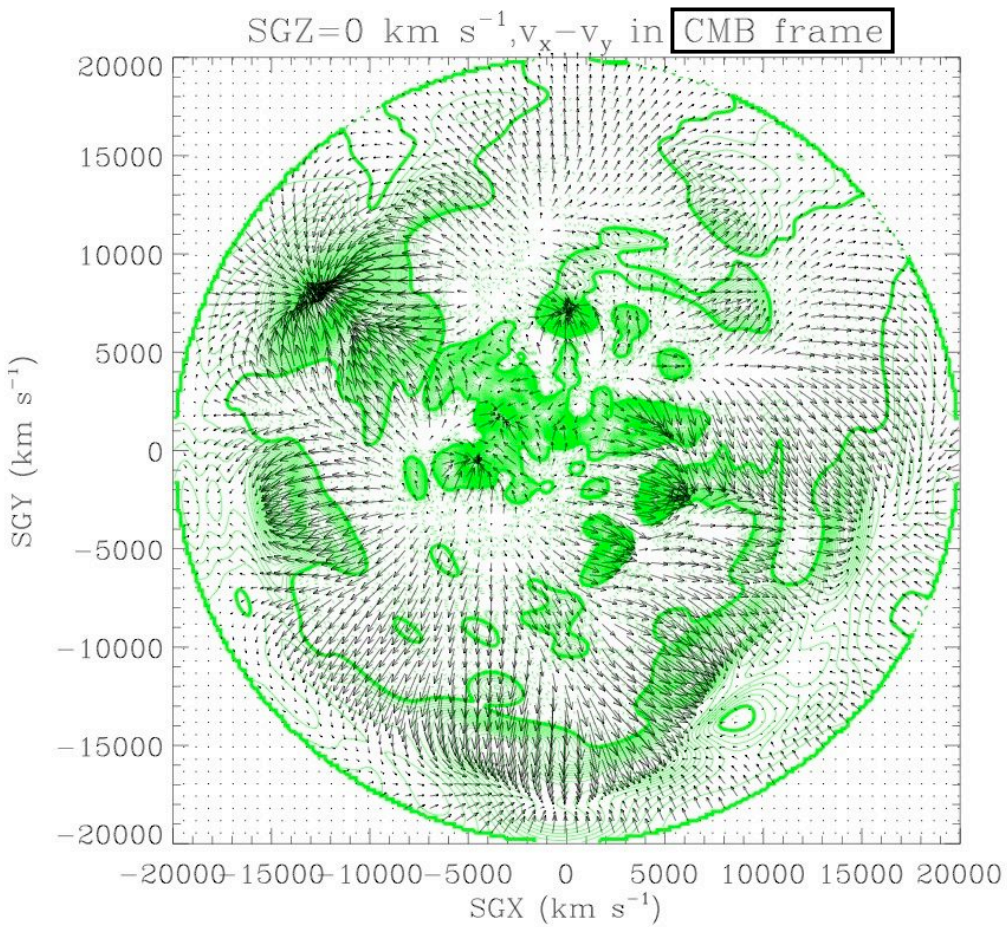


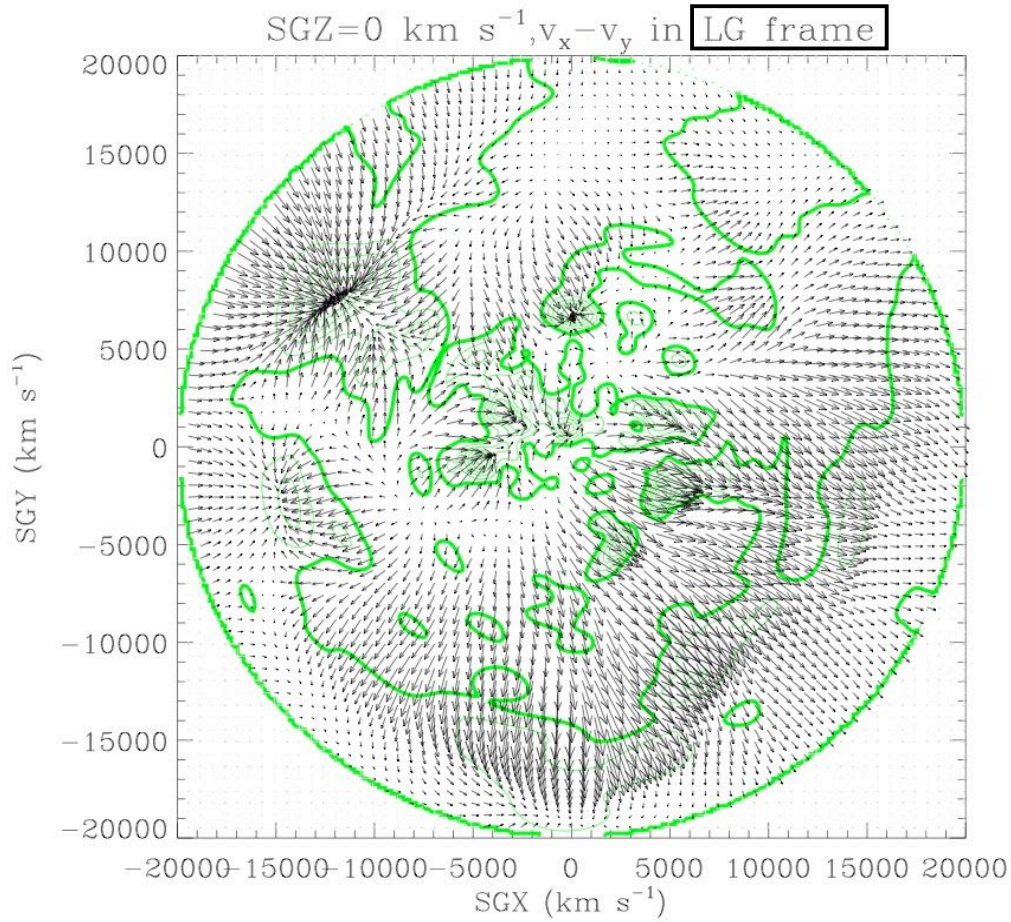
2MRS density field reconstruction by Fourier-Bessel decomposition and Wiener filtering

Erdogdu et al., 2006, MNRAS, 373, 45

Predicted local velocity field

- The linear velocity field in the Supergalactic Plane as predicted from the reconstructed 2MRS density field (assuming β=0.5)

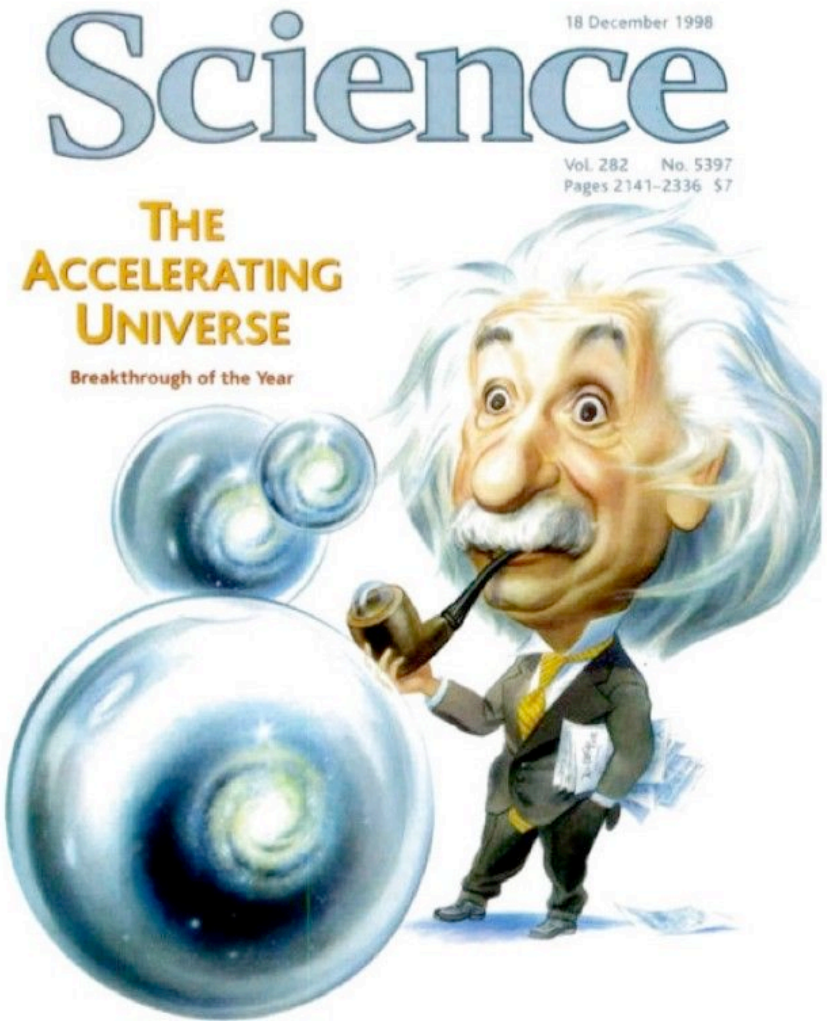




Erdogdu et al., 2006, MNRAS, 373, 45

Dark energy from geometry

- The geometry of the universe can be measured at very early times from CMB, and at later times by a variety of methods:
  - ‘Standard candle’ provided by supernovae
  - ‘Standard scale’ from gravitational lensing
  - Growth of density perturbations in clusters
  - ‘Standard ruler’ of baryon acoustic oscillations (BAO) in the galaxy distribution



- The geometry of the universe is governed by the equation of state, knowledge of which reveals the nature of the dark energy

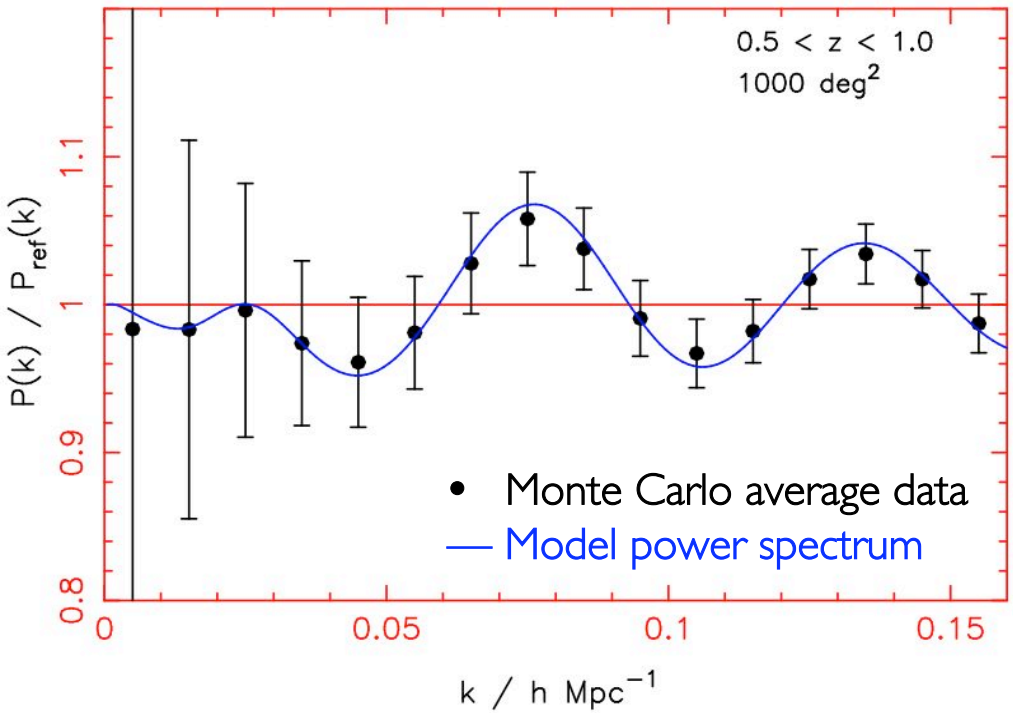
The WiggleZ BAO survey

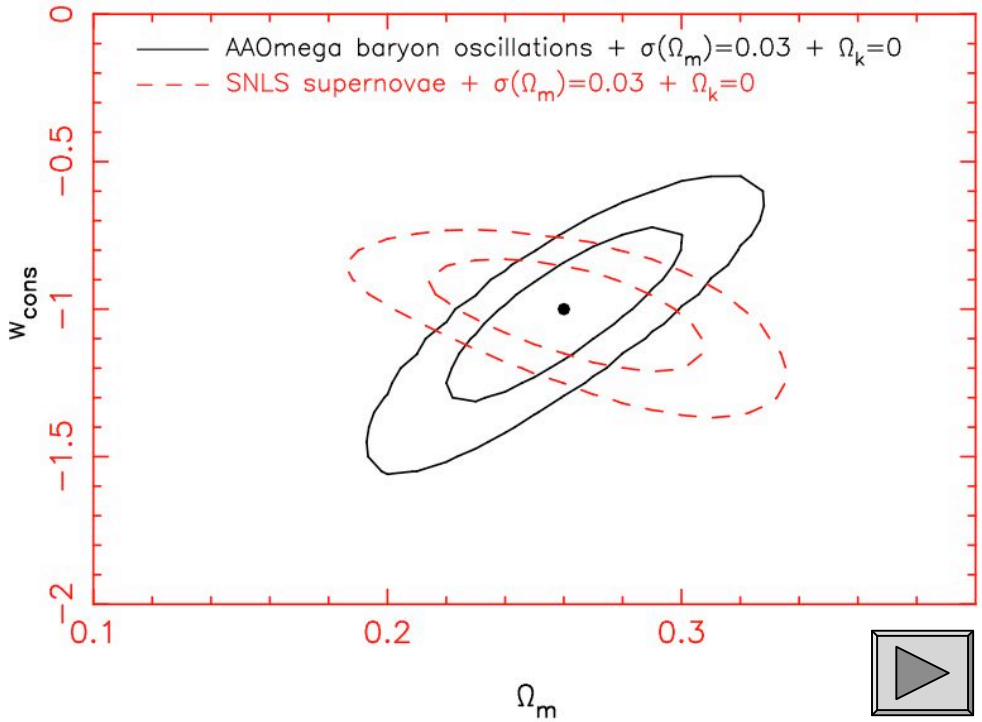
- Science goals…
  - Primary: first *z*-survey measure of BAO scale at *z*~1; aim for ~2% precision to constrain *w* to ~10% and test for evolution
  - Secondary: study properties of star-forming galaxies at *z*~1
- Observing plan…
  - Targets: 400,000 b~1 galaxies (200,000 with z>0.5) over 1000 deg^2
  - Sample: from GALEX + SDSS/RCS; FUV-NUV colour selects Lyman break at *z*>0.7; NUV-r selects emission line galaxies
  - Observations: using AAOmega spectrograph with 2dF on AAT
  - Status: ~80,000 redshifts to date; aim to complete in 2009
- WiggleZ team…
  - Australia: Drinkwater, Jurek, Pimbblet (UQ); Blake, Couch, Forbes, Glazebrook, Brough, Jones, Barnes (Swinburne); Woods (UNSW); Croom (Sydney); Pracy (ANU); Colless, Sharp (AAO); USA: Forster, Madore, Martin, Small (GALEX); Canada: Gilbank, Gladders, Yee (RCS2)

Glazebrook et al. , astro-ph/0701876

BAO precision and constraints on *w*

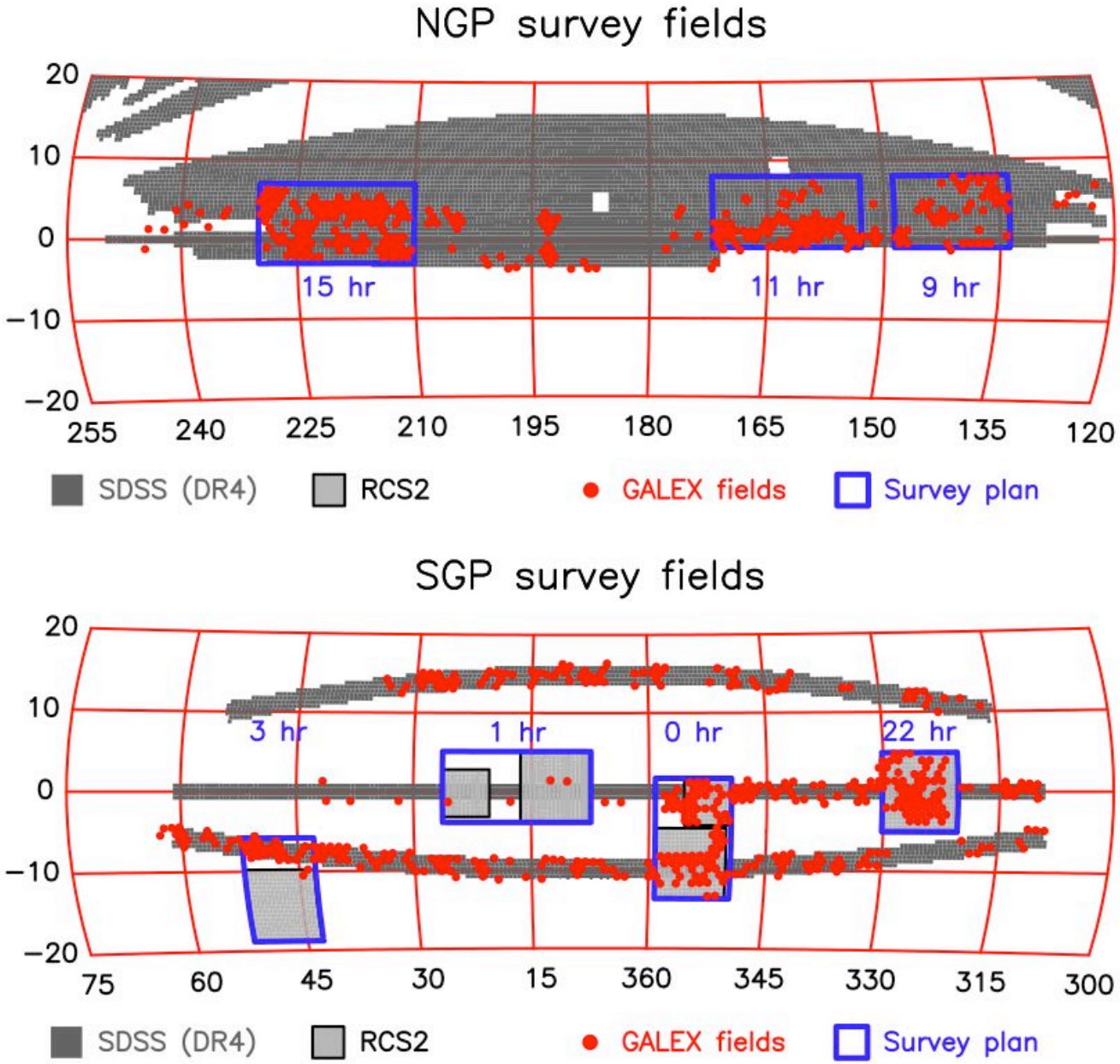
- Simulations of WiggleZ BAO measurement compared to model power spectrum ⇒ expect ~2% precision on standard ruler scale
- Measure $H(z)$ and $D_A(z)$ at z~0.7, use priors on Ω_M and H_0 (CMB gives $\Omega_M h^2$), reconstruct density field ⇒ 2.7% on H, 1.8% on D_A
- Equation of state precision ⇒ 10% on w_0 (similar to SNe surveys but complementary in having a different method & different degeneracies)





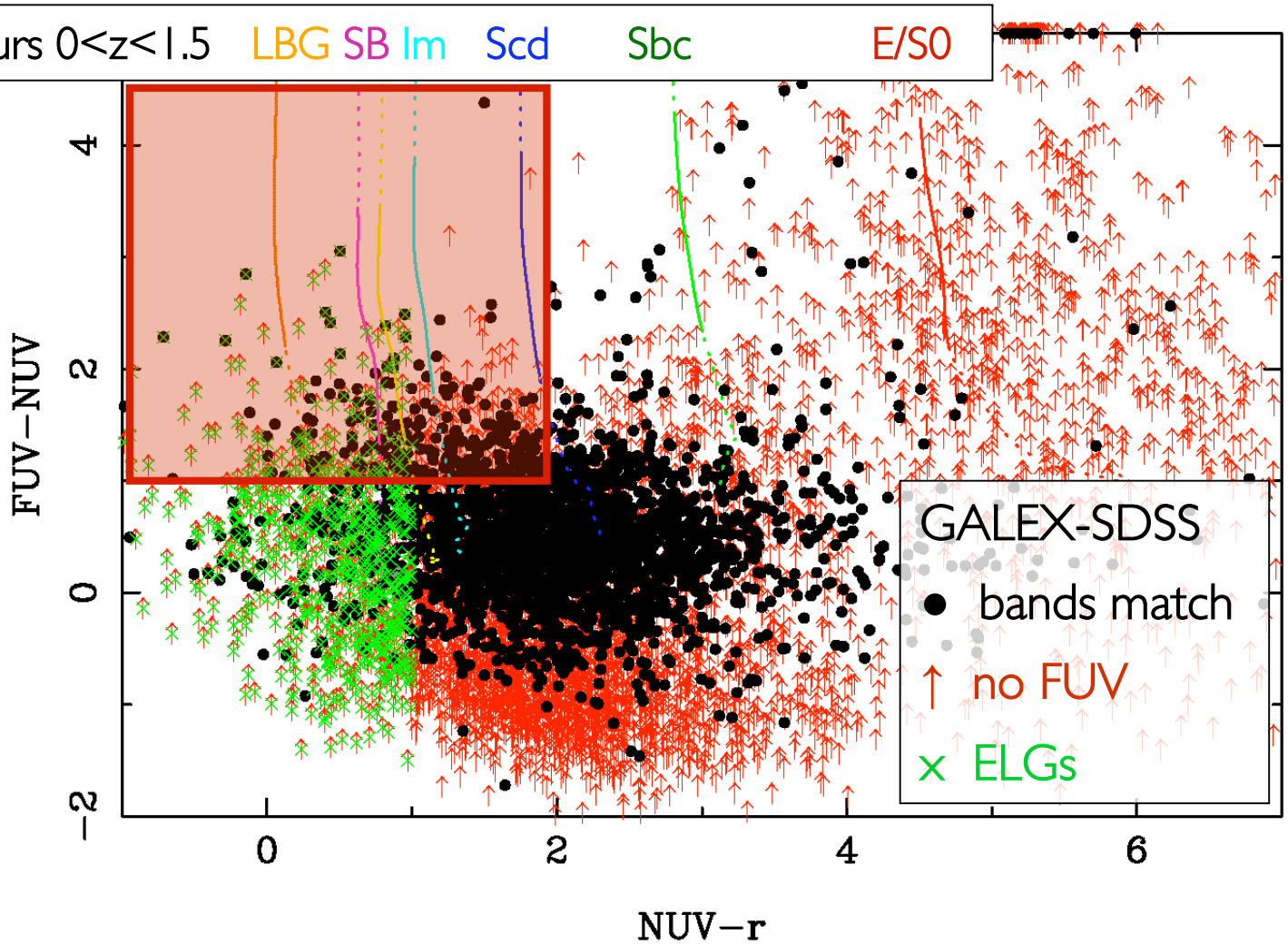
WiggleZ fields and target selection

- Total survey area of ~1000 deg^2, made up of 7 equatorial fields, each of 100-200 deg^2 (>9° on a side, >2-3x BAO scale at z>0.5)
- Targets selected using combination of UV (GALEX) and optical (SDSS/RCS2) colours
- Selection criteria pick emission-line galaxies at *z*~0.7 (>200 of the ~400 targets per deg^2)
- Allocated 220 nights on AAT over 2006-9



UV-optical selection criteria

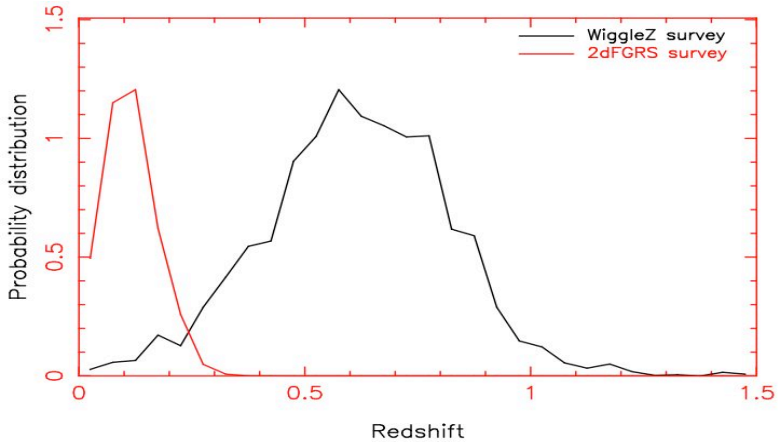
- Galaxies with NUV < 22.8 and 20.0 < r < 22.5
- FUV-NUV >1 or no FUV detection ⇒ z > 0.5
- NUV-r < 2 ⇒ blue star-forming galaxies, strong emission lines
- g-r/r-i colour cut reduces number of z<0.5 galaxies

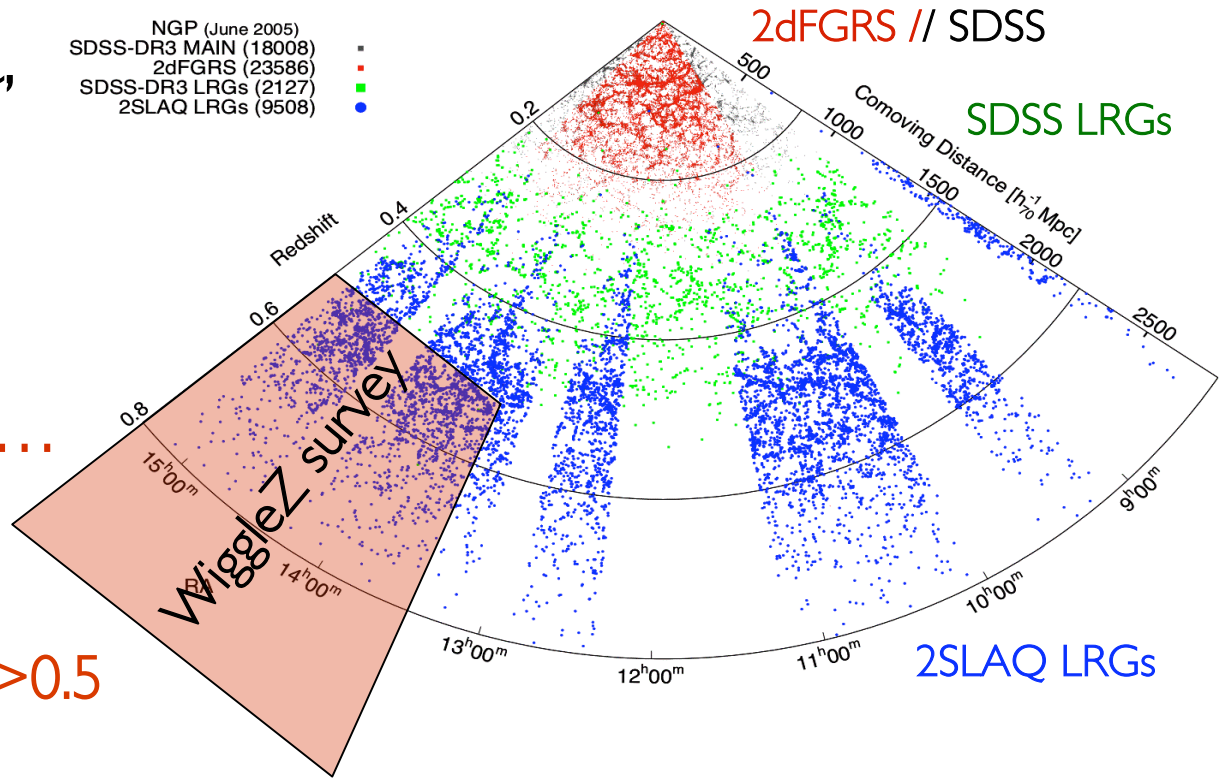


- Emission-line galaxies marginally preferred to luminous red galaxies: bias factor smaller but easier to redshift (shorter exposures, more robust in poor conditions)

Status of WiggleZ survey

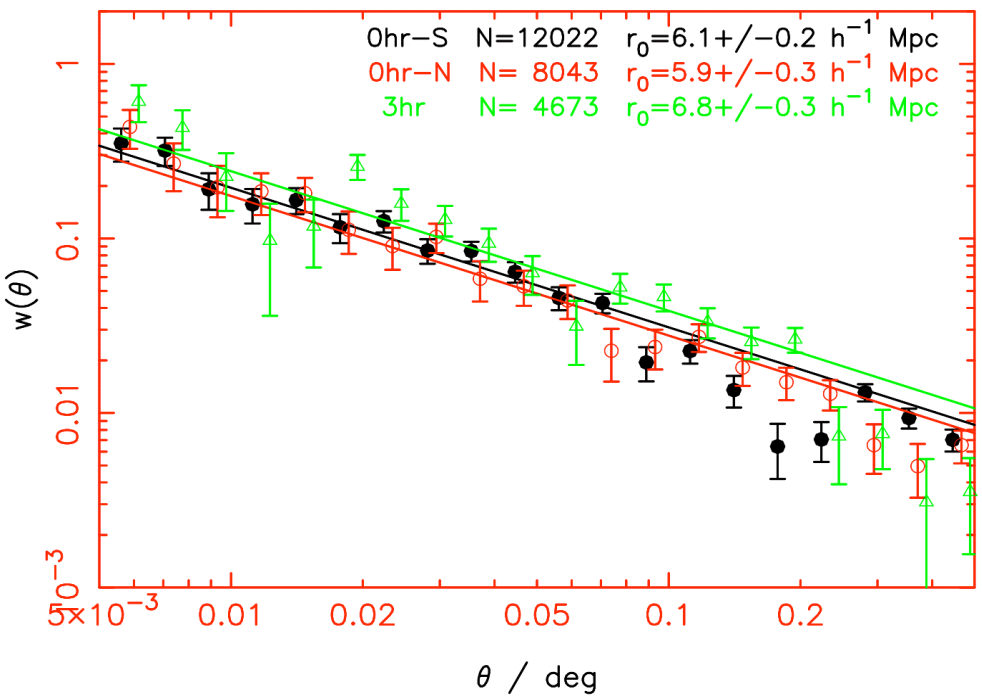
- Reaches z~1 in 1–hour exp. (cf. z~0.1 for 2dFGRS) due to ELG selection & efficiency of AAOmega spectrograph
- Redshift success rate ≈ 60%
- Tuning selection criteria, fraction at z>0.5 ≈ 75%
- Fraction of sample at z>0.5 ≈ 45%
- Final expected numbers…
  - ~350,000 spectra
  - ~210,000 redshifts
  - ~160,000 galaxies at z>0.5

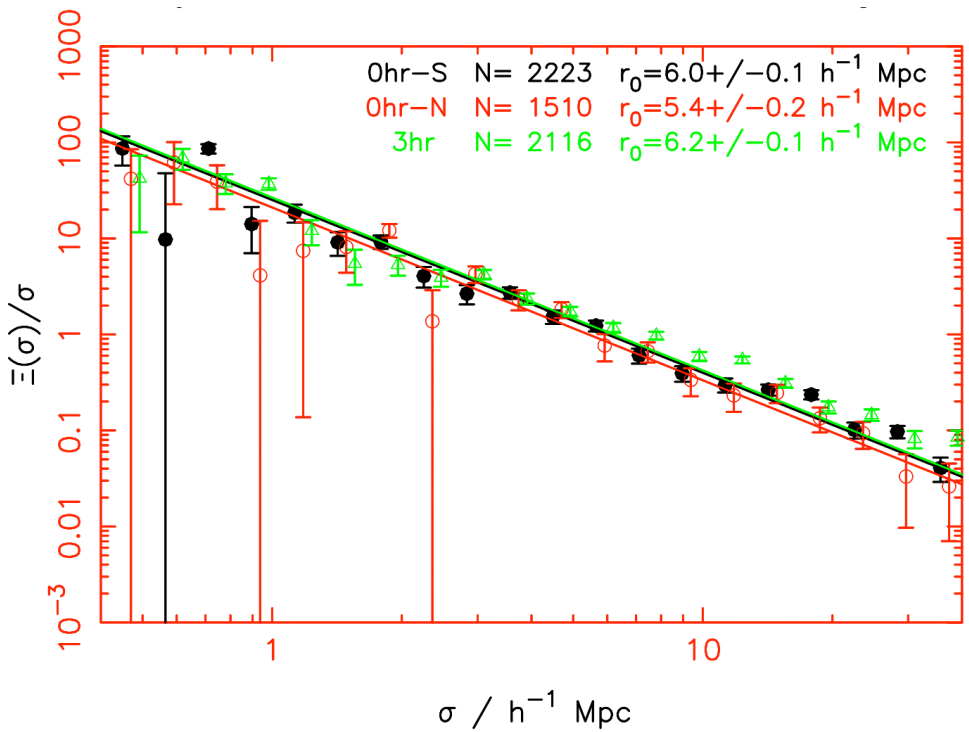




Small-scale clustering

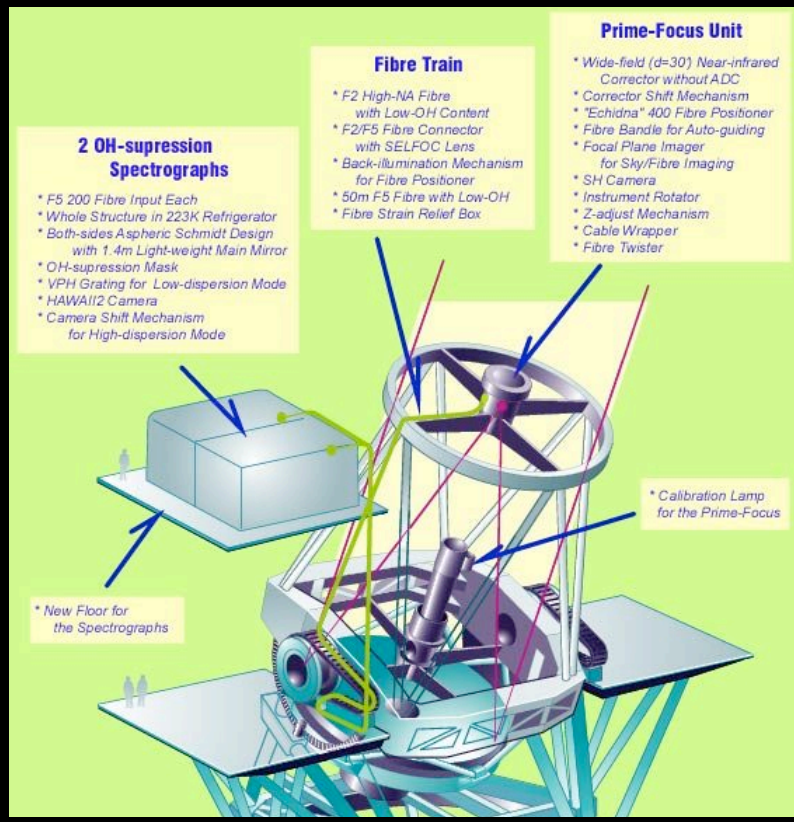
- Preliminary clustering measurement stronger than assumed…
  - Proposal was 400 redshifts/deg^2 at z>0.5 for sample with b=1.0
  - Clustering length now measured to be 6 Mpc/h ⇒ b=1.4
  - Equivalent survey for b=1.4 is 200 redshifts/deg^2 at z>0.5
  - Thus the revised target is a survey of 200,000 z>0.5 galaxies
  - Higher bias therefore largely compensates for lower efficiency



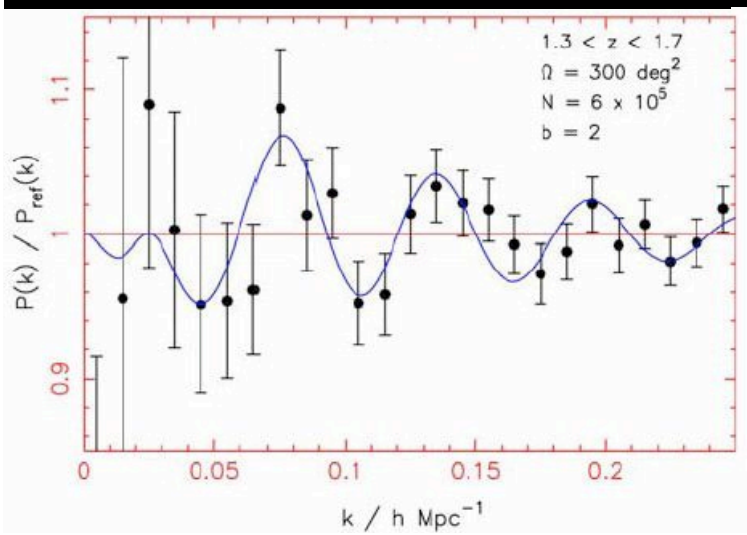


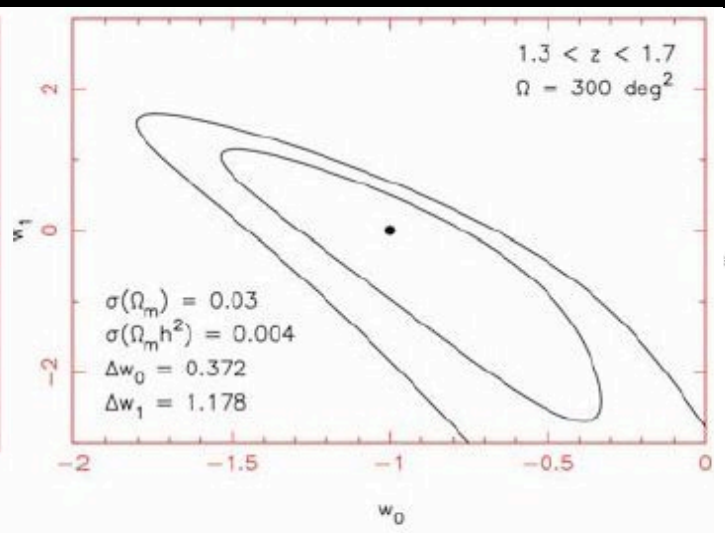
FastSound survey

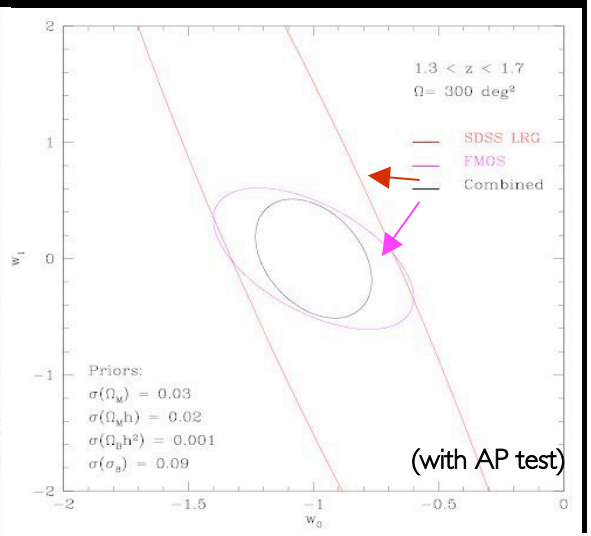
- Proposed z>1 BAO survey using FMOS/Subaru NIR spectroscopy…
  - FMOS: 400-fibre J+H OH-suppressed NIR spect., commissioning in Feb 08
  - ~600,000 Hα galaxies in 'redshift desert' at z~1.0–1.7 over ~300 deg^2 (~1 Gpc^3) ⇒ O(100) nights on Subaru
  - Unique redshift range for BAO survey, good precision, lots of ancillary science
  - Japan/UK/Australia team of 40+ people



Totani et al., 2006, in *Cosmology with wide-field photometric and spectroscopic galaxy surveys*

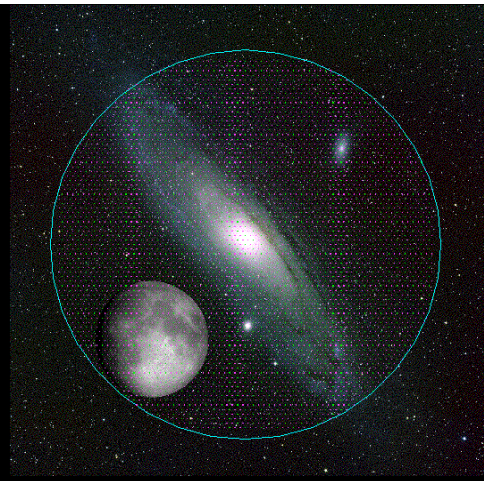


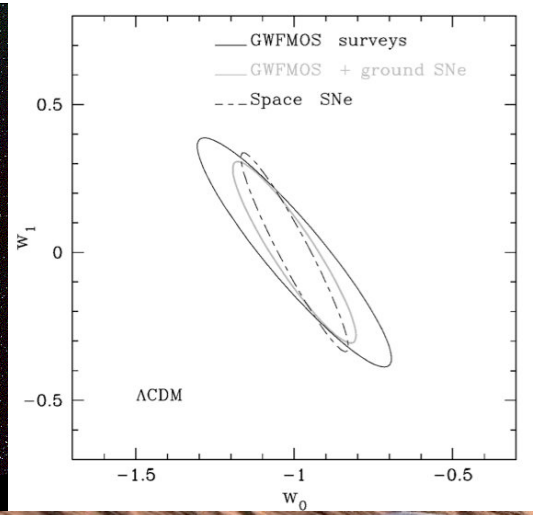


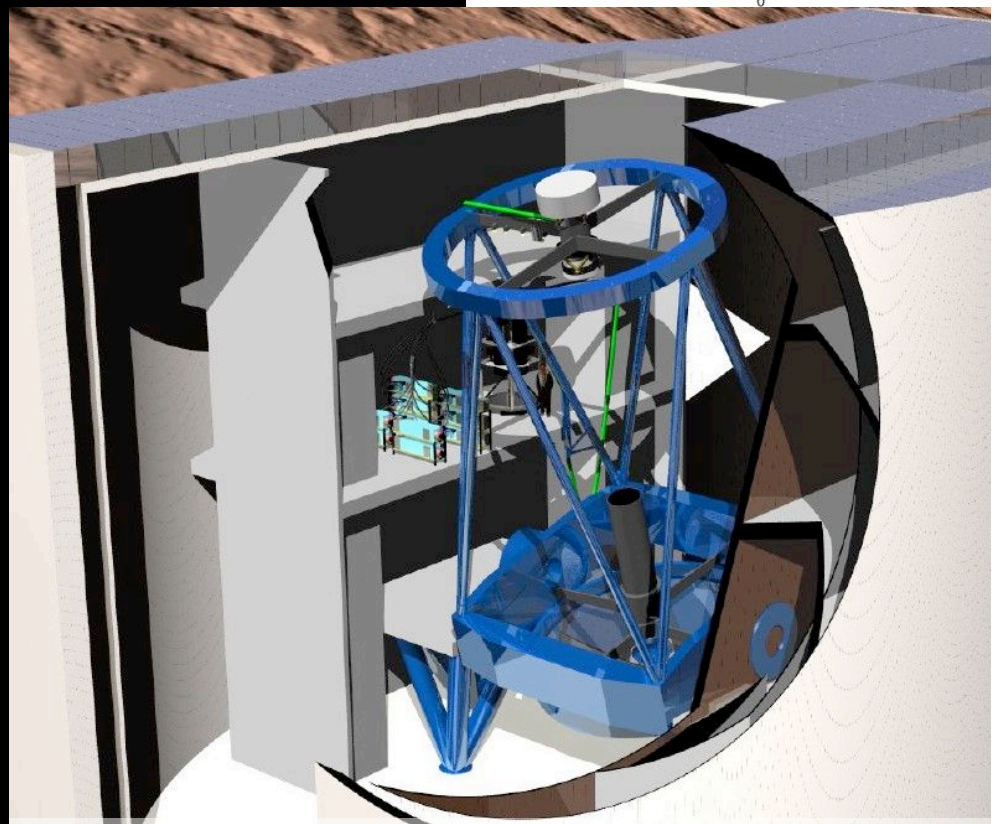


WFMOS survey

- Wide-Field Multi-Object Spectrograph for an 8-m telescope (Subaru/Gemini)
  - 1.5 degree field
  - 4000 optical fibres
  - 5 years to build
- Survey of >1,000,000 z~1 galaxies to measure BAO
  - Survey takes ~3 years
  - Combined with CMB / SNe / lensing methods, could achieve precision of δw_0~few% & δw_1~10%
  - Also possible z~3 survey







Colless (2005) & Glazebrook (2005), both in *Probing the Dark Universe with Subaru and Gemini*, http://www.noao.edu/meetings/subaru

Once and future galaxy surveys

- Wide-field spectroscopy and redshift surveys will continue to be powerful tools for large-scale structure and cosmology
- The combined 6dF redshift + velocity survey will better constrain fundamental parameters (such as β and r_g) and so provide new insights on the relative distributions of luminous and dark matter
- Current (WiggleZ) and future (FASTsound, WFMOS) redshift surveys will trace the evolution of galaxies & large-scale structure, measuring precisely the evolving geometry of the universe
- Combined with CMB, SNe and weak lensing, BAO surveys will determine the evolution of the equation of state with few-% precision and strongly constrain the nature of the dark energy
- Future ELT surveys will map the 3D distribution of baryons down to galaxy scales out to the epoch of formation of the first galaxies