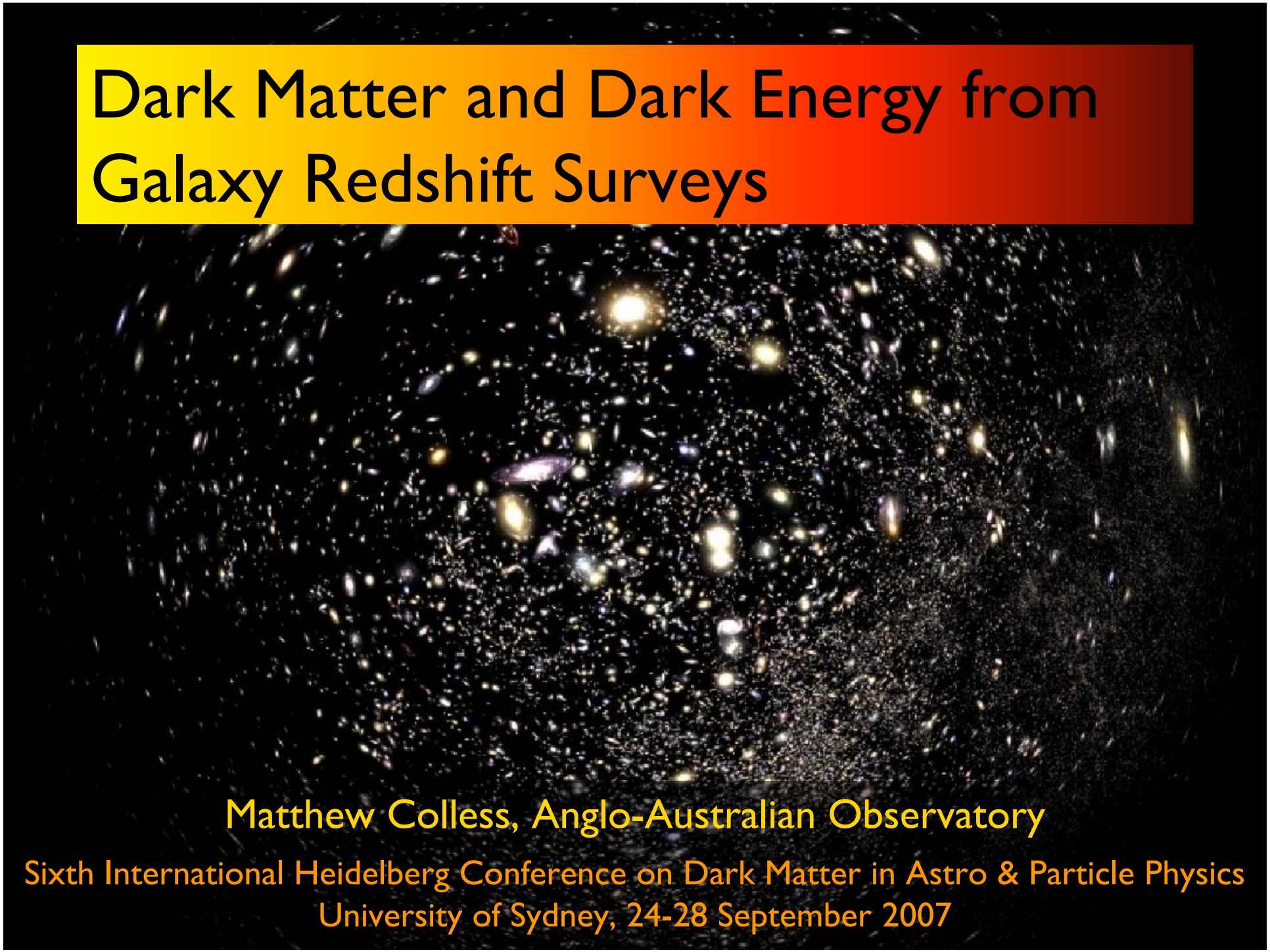
Dark Matter and Dark Energy from Galaxy Redshift Surveys



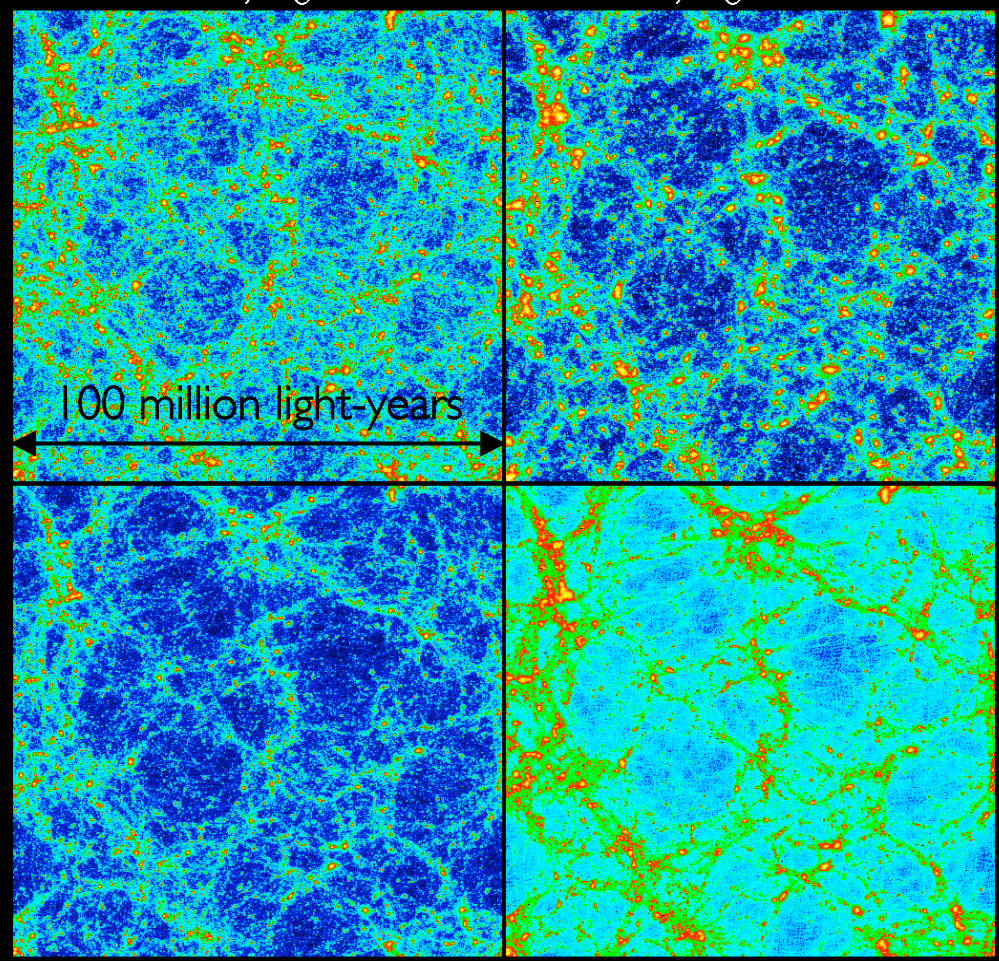
Matthew Colless, Anglo-Australian Observatory

Sixth International Heidelberg Conference on Dark Matter in Astro & Particle Physics
University of Sydney, 24-28 September 2007

Large-Scale Structure and Cosmology

- 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

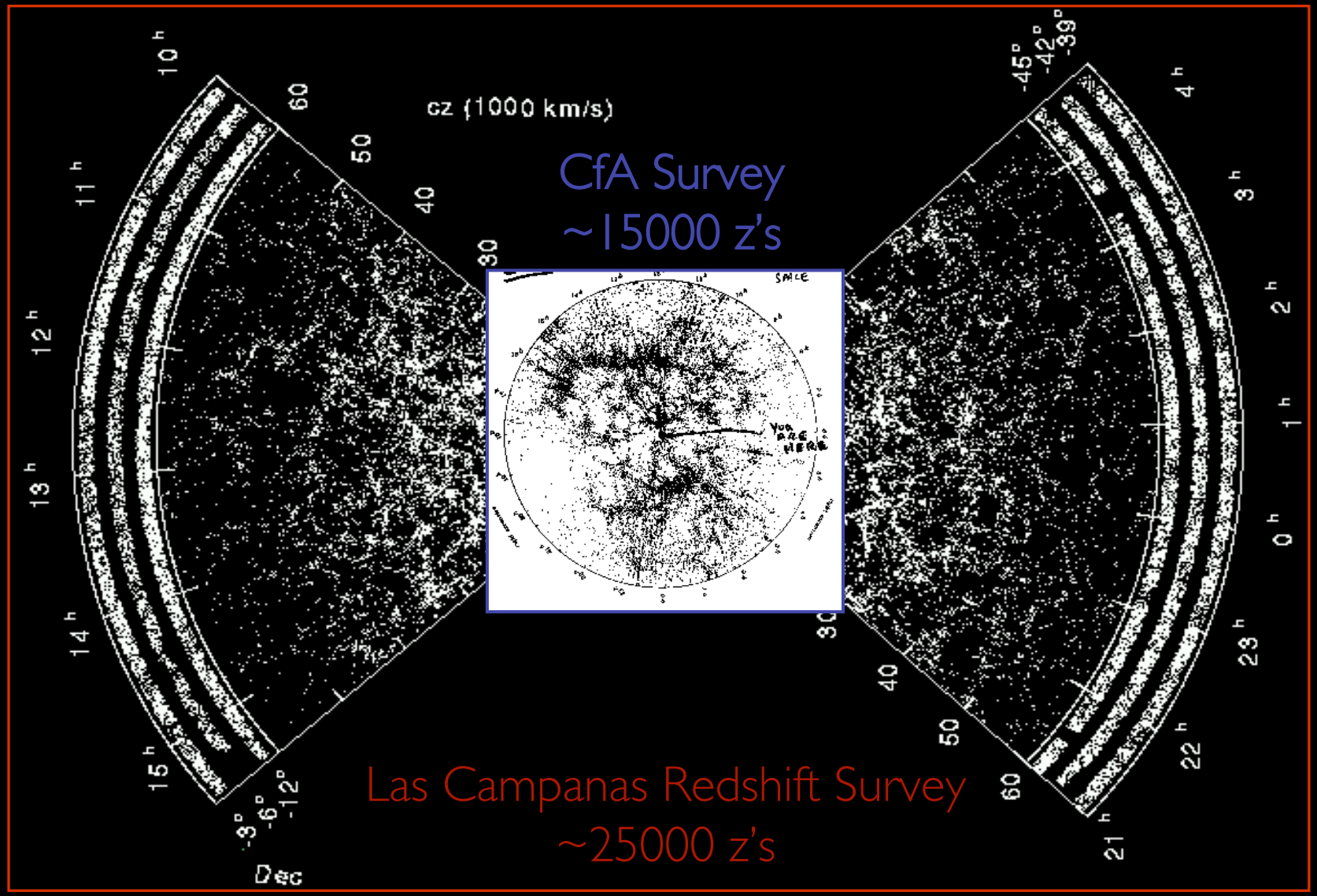


Warren *et al.*, Los Alamos

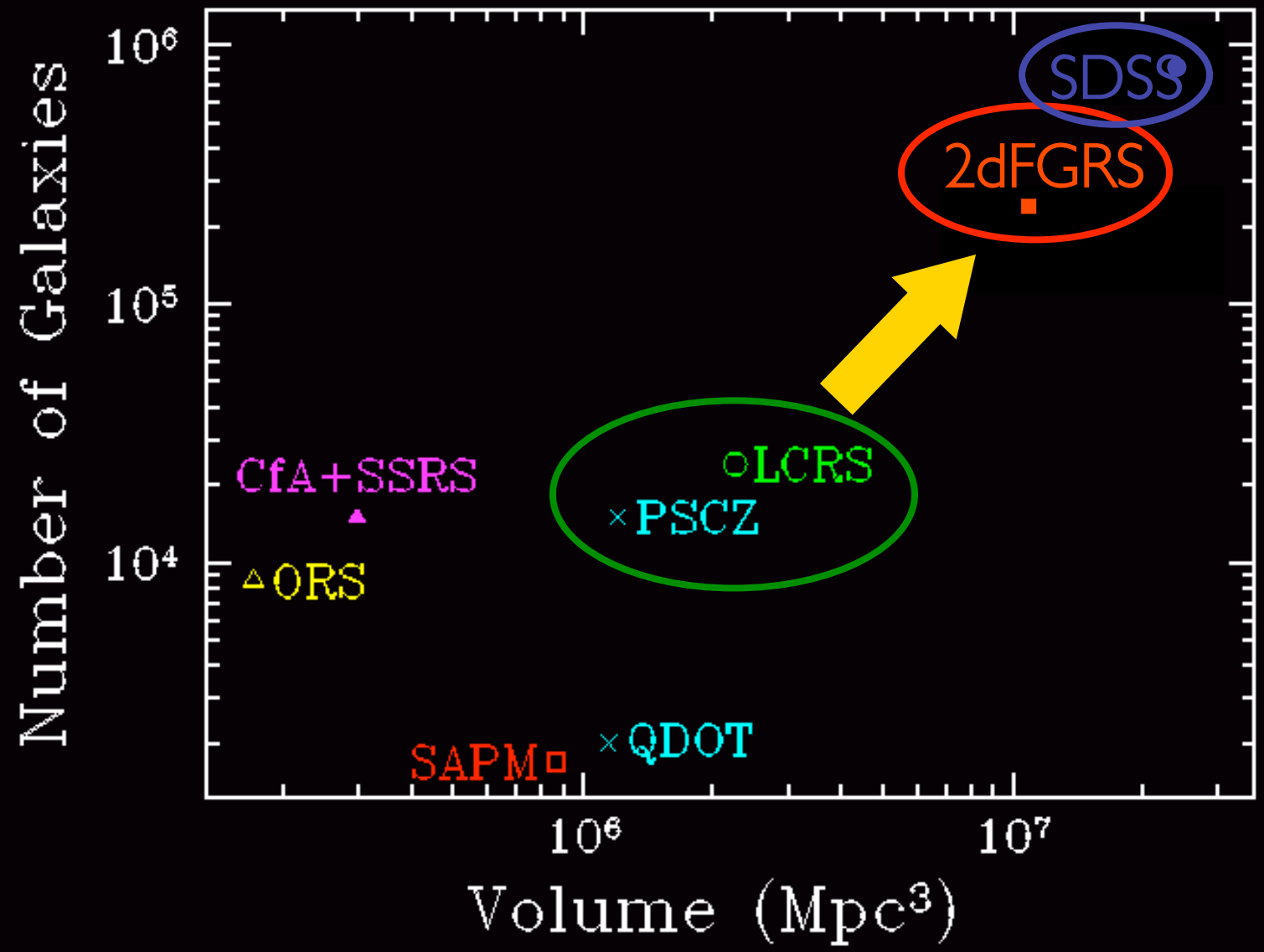
A brief history of galaxy surveys

- 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…
  - Matter densities - total, dark, baryonic and neutrino
  - 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…

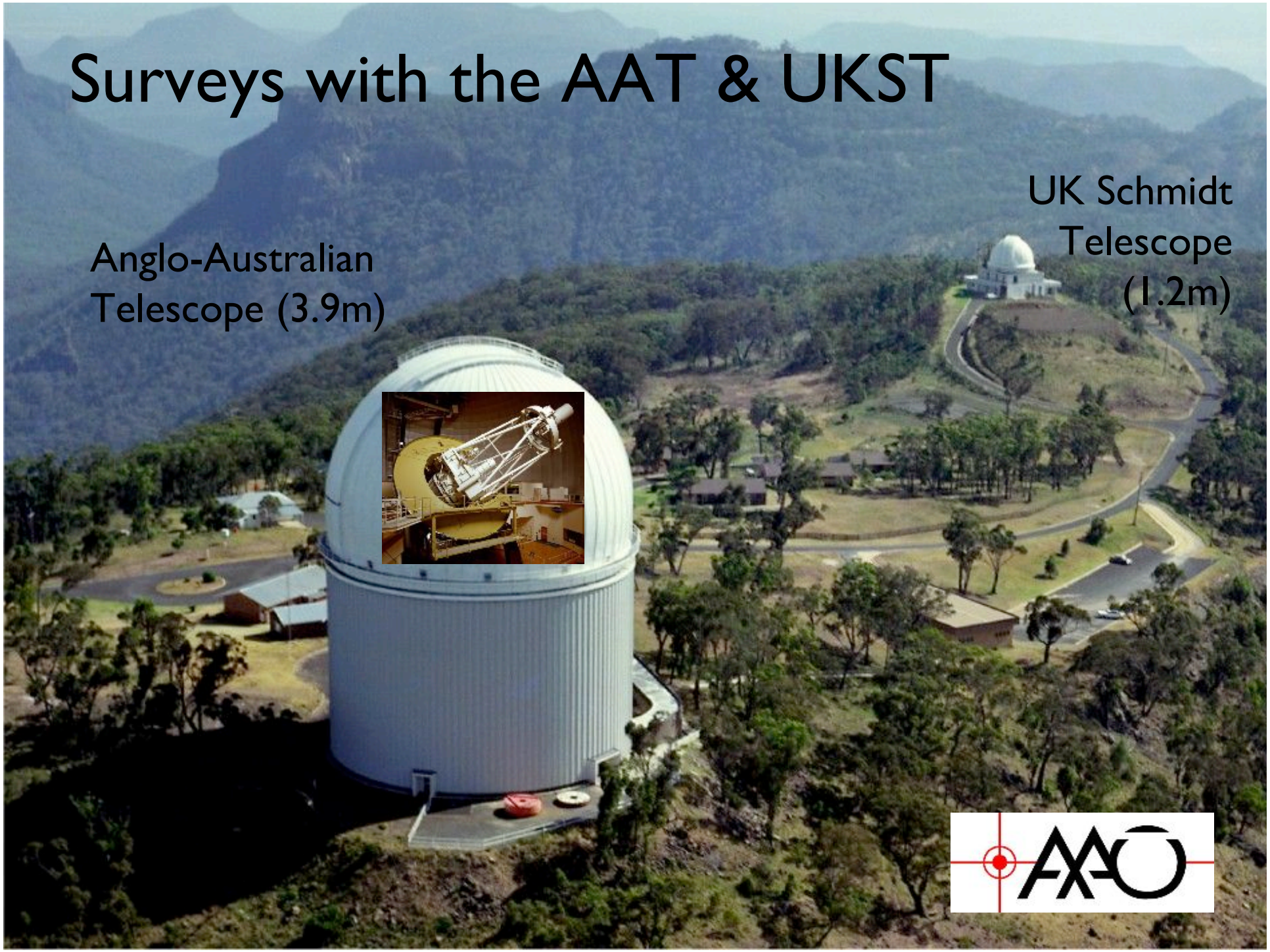
State of the art ~1997



Evolution of Redshift Surveys



Surveys with the AAT & UKST



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…
  - Matter densities - total, dark, baryonic and neutrino
  - 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…

AAO

FOCAP

LDSS

Autofib

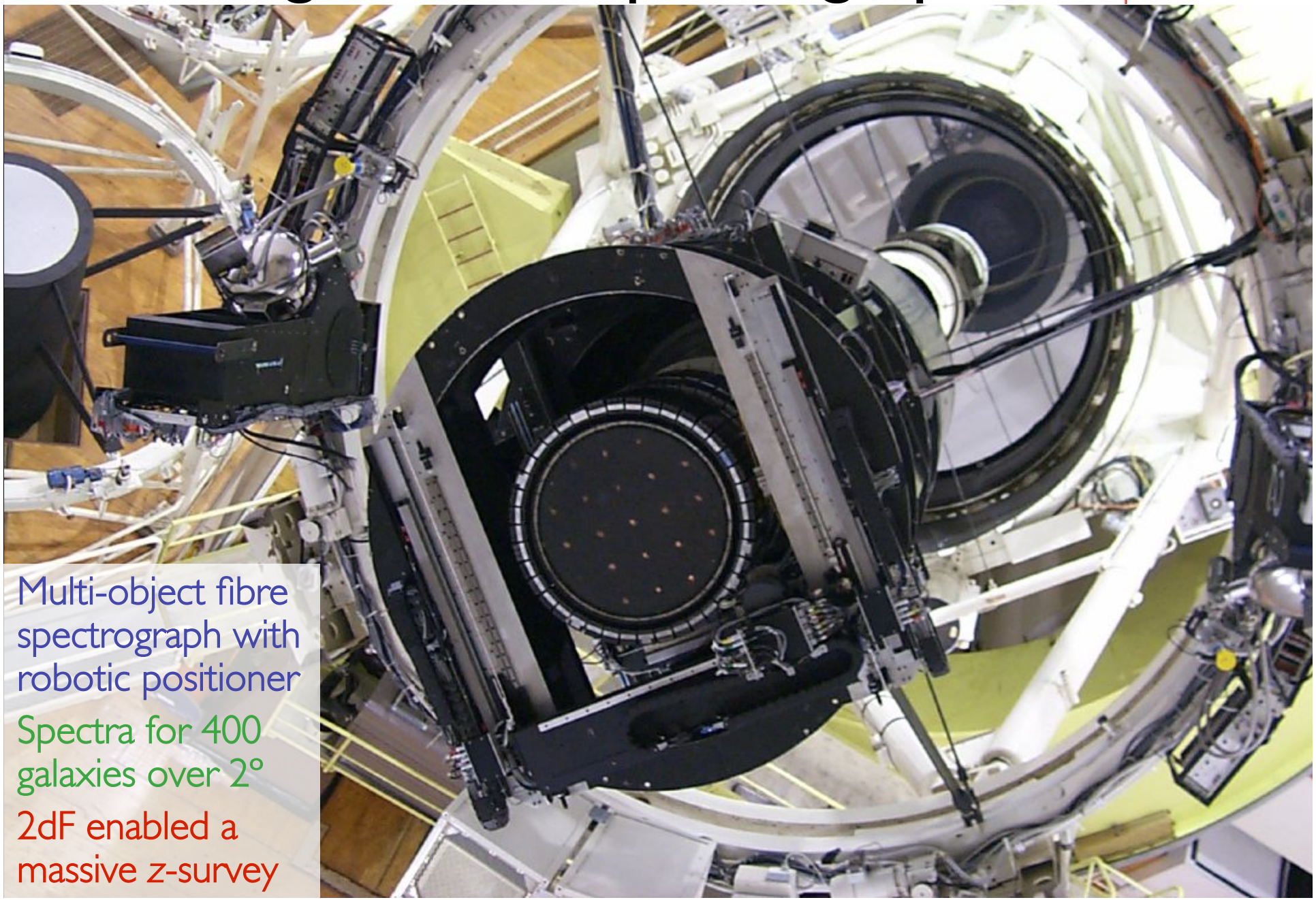
2dF

6dF

AAΩ

WFMOS

The 2-degree Field Spectrograph

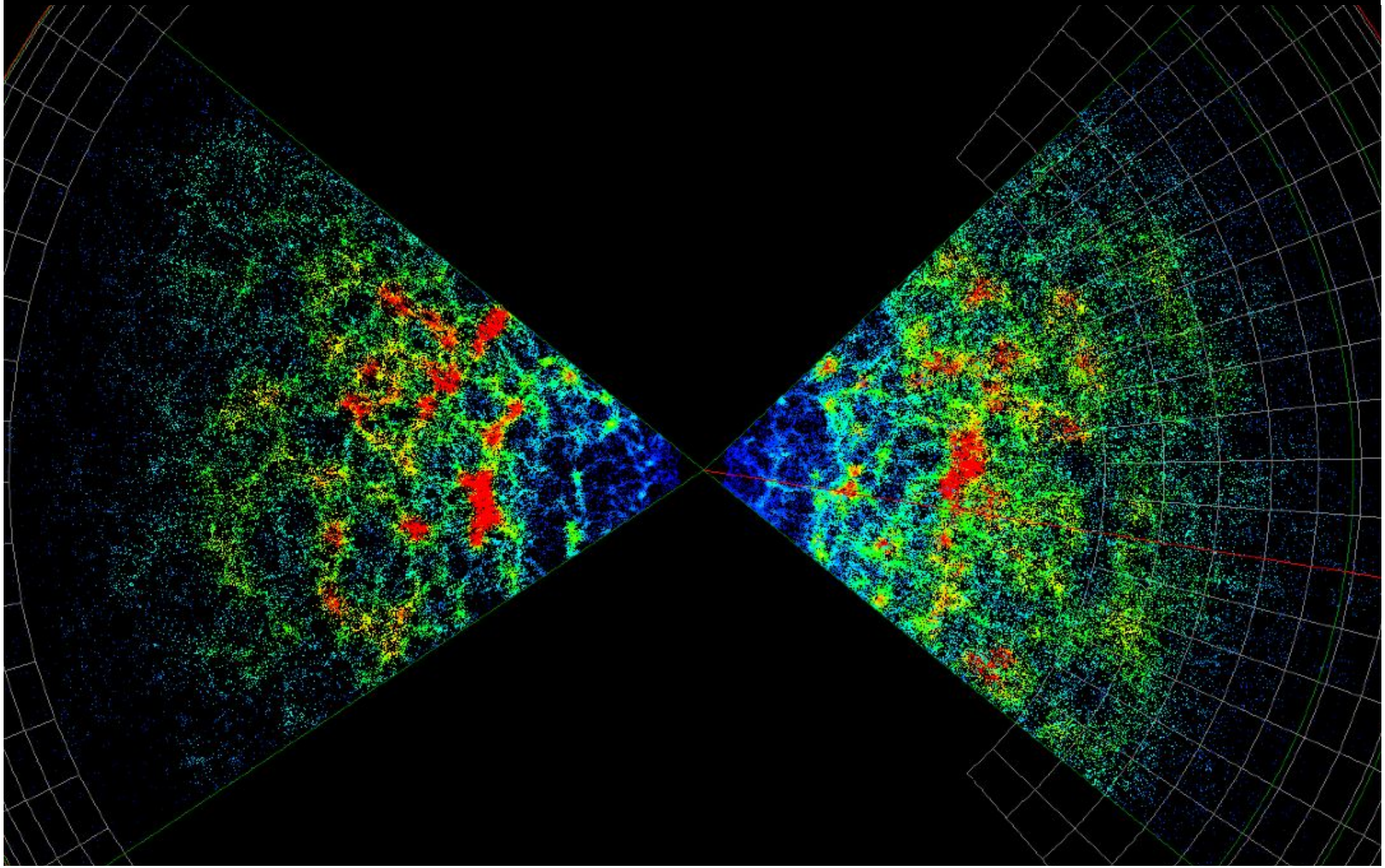


Multi-object fibre spectrograph with robotic positioner

Spectra for 400 galaxies over 2°

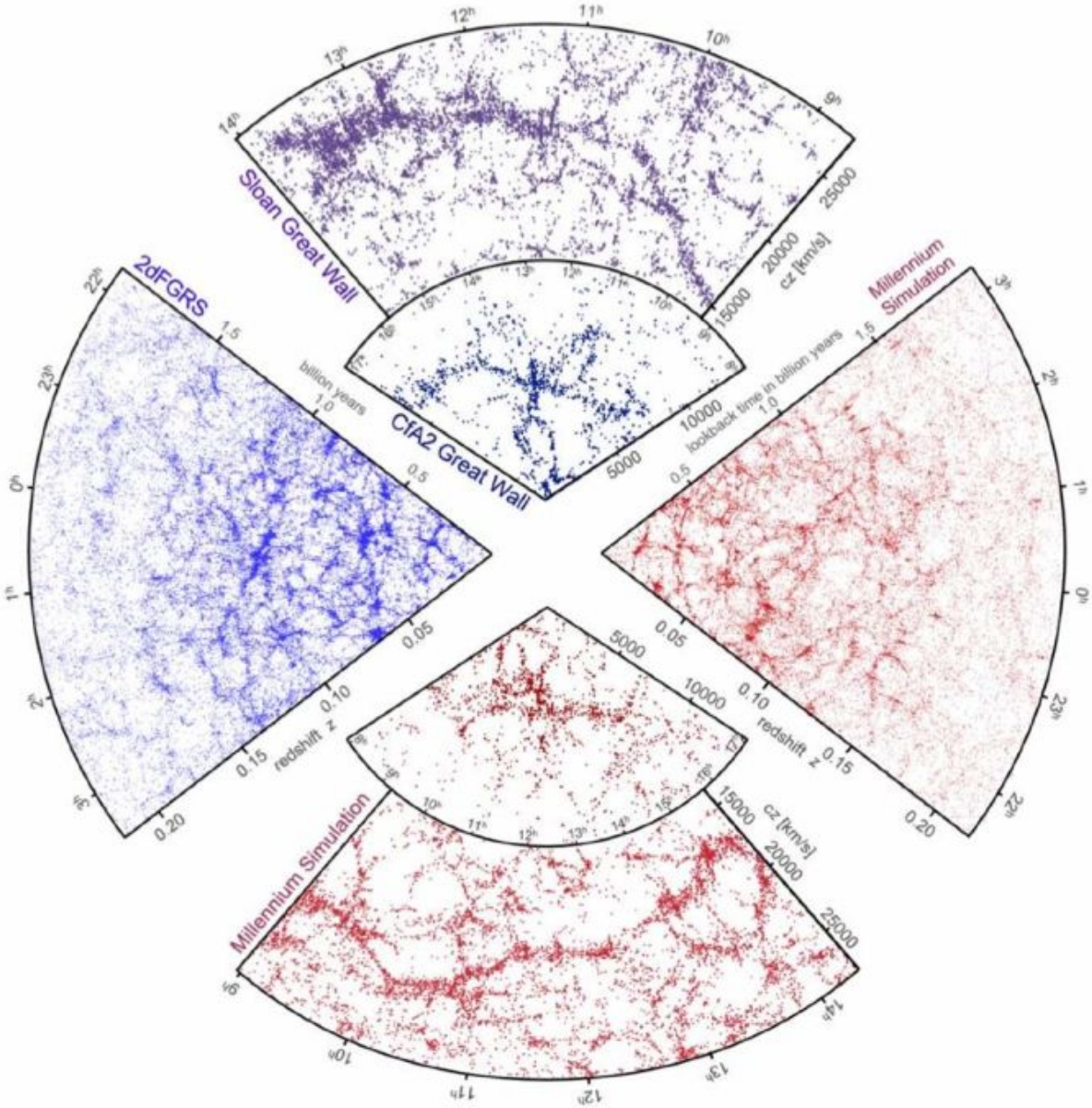
2dF enabled a massive z-survey

The 2dFGRS map of 221000 galaxies

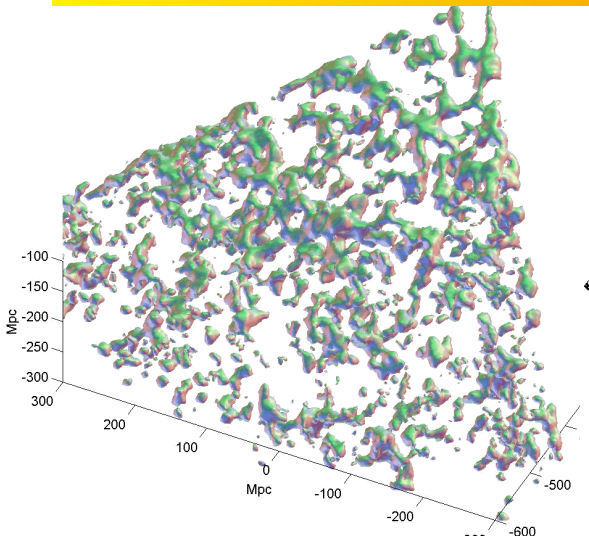


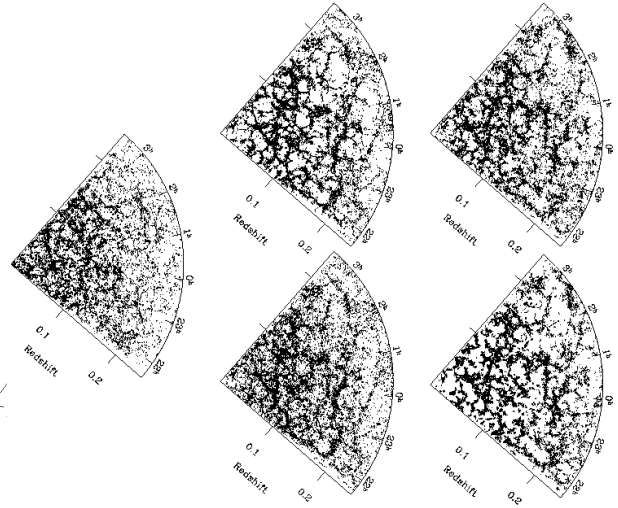
Surveys versus simulations

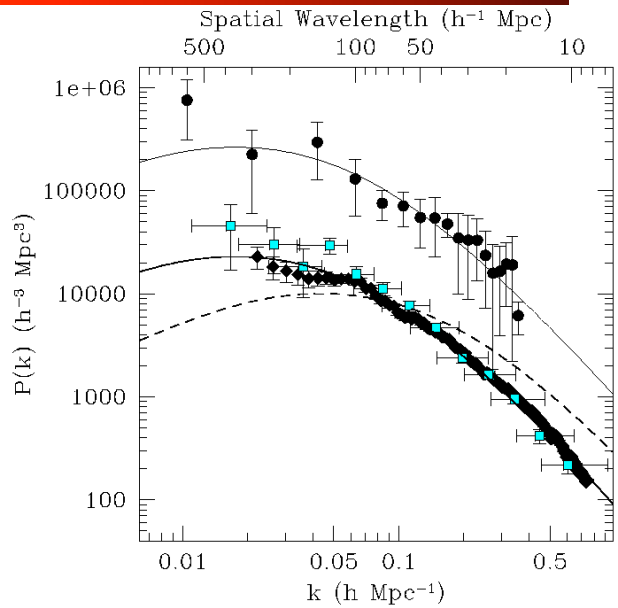
- Comparison of slices from CfA2, 2dFGRS and SDSS surveys on different scales, all compared to equivalent slices, selected for their similarity, from the Millennium Simulation (Springel, Frenk & White 2006)

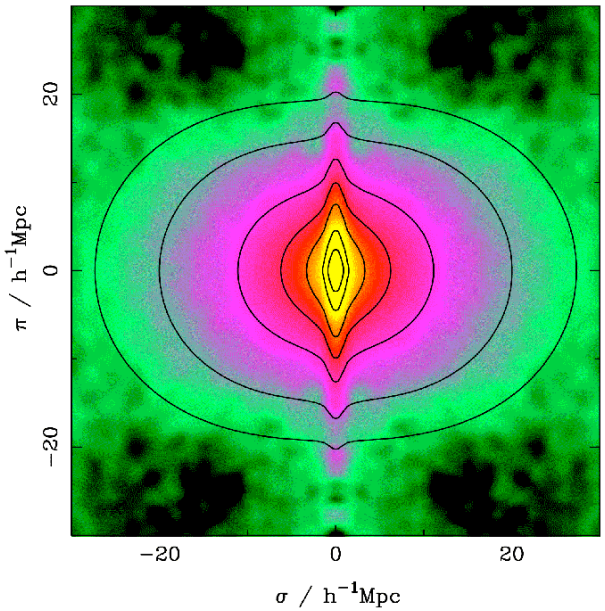


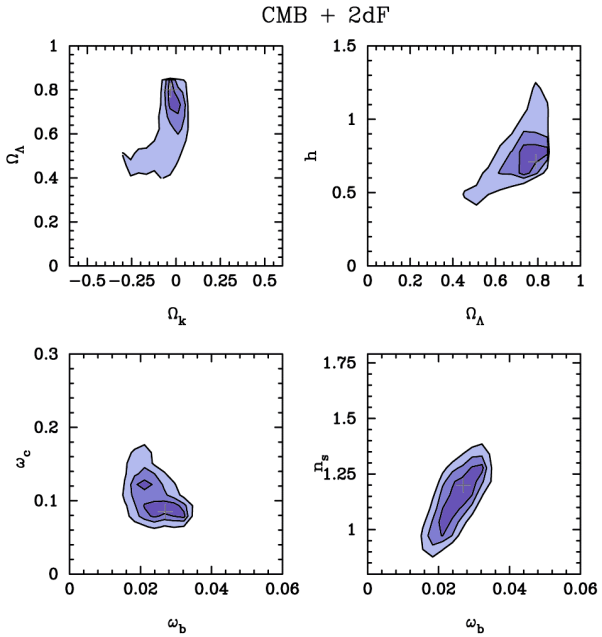
2dFGRS structure & cosmology results

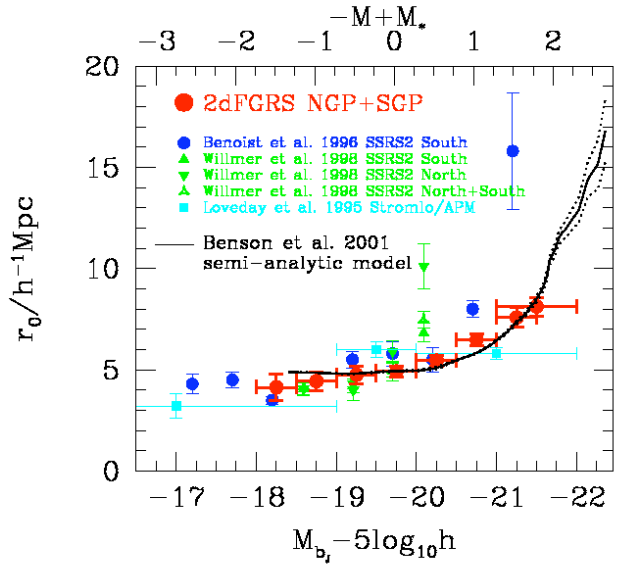






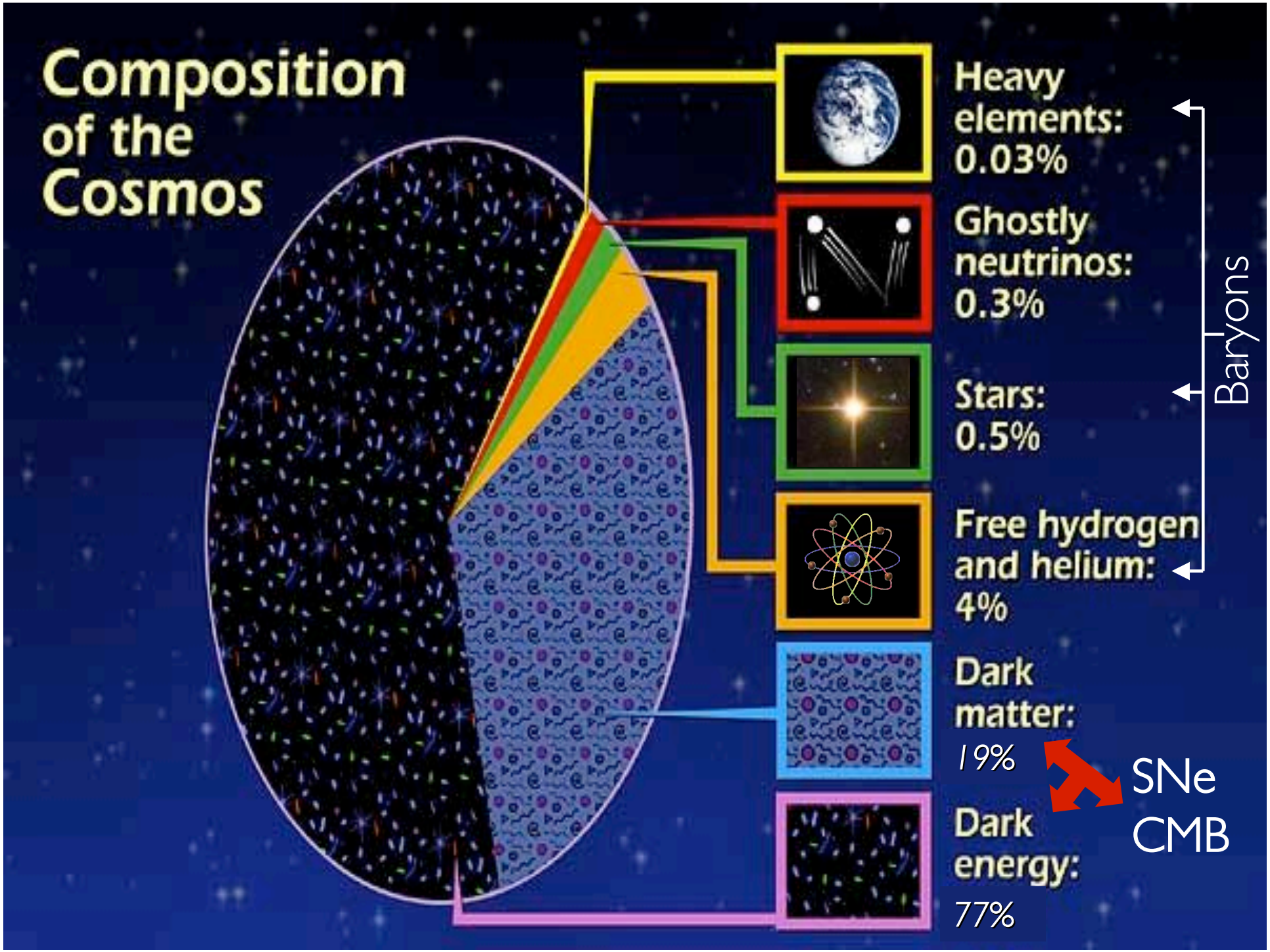






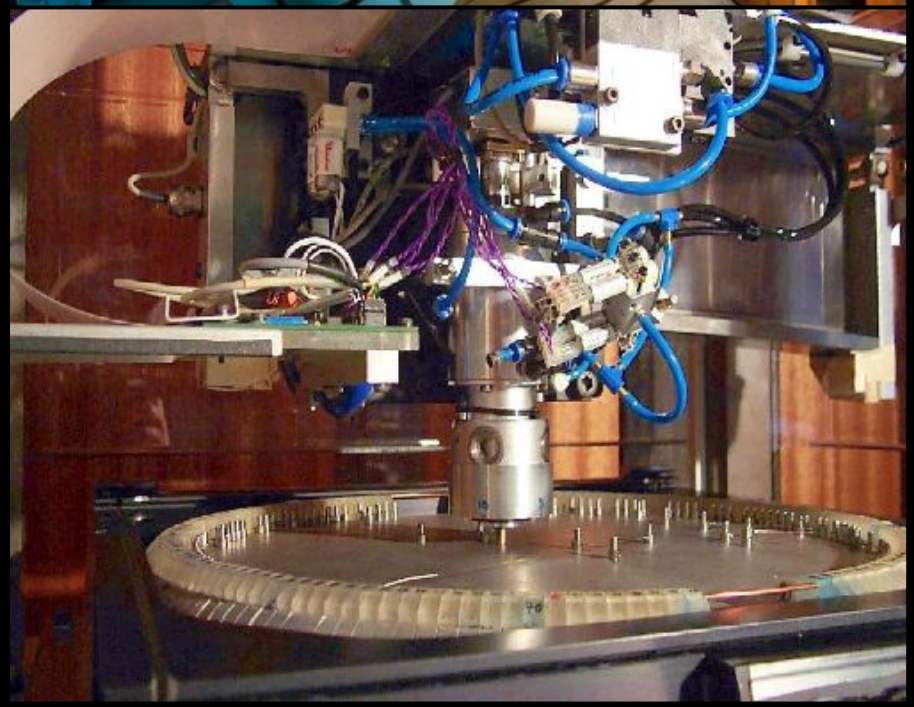
2dFGRS structure & cosmology results

- 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 $\mathbf{\Omega}_M = 0.23$
  - ⇒ there is only 23% of critical density needed for a flat universe
- The total density in ordinary matter is $\mathbf{\Omega}_B = 0.04$
  - ⇒ 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

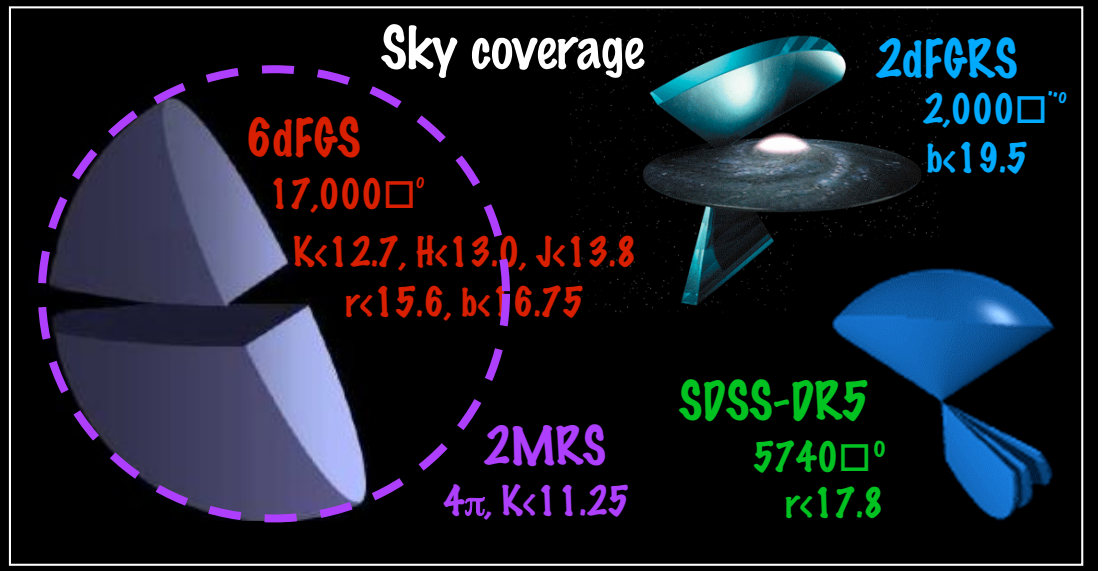
The 6dF Galaxy Survey

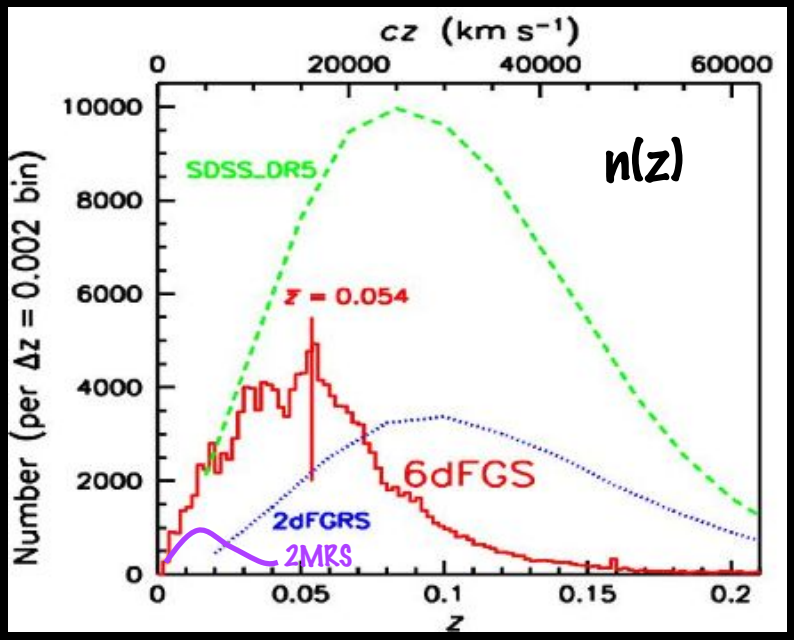
- A redshift & peculiar velocity survey of galaxies in the local universe
- Covers southern sky with |b|>10°
- Primary galaxy sample selected from 2MASS with K_{tot}<12.75
- Also H<13.0, J<13.75 (2MASS) and r<15.6, b<16.75 (SuperCosmos)
- Peculiar velocity survey uses the Fundamental Plane to get distances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

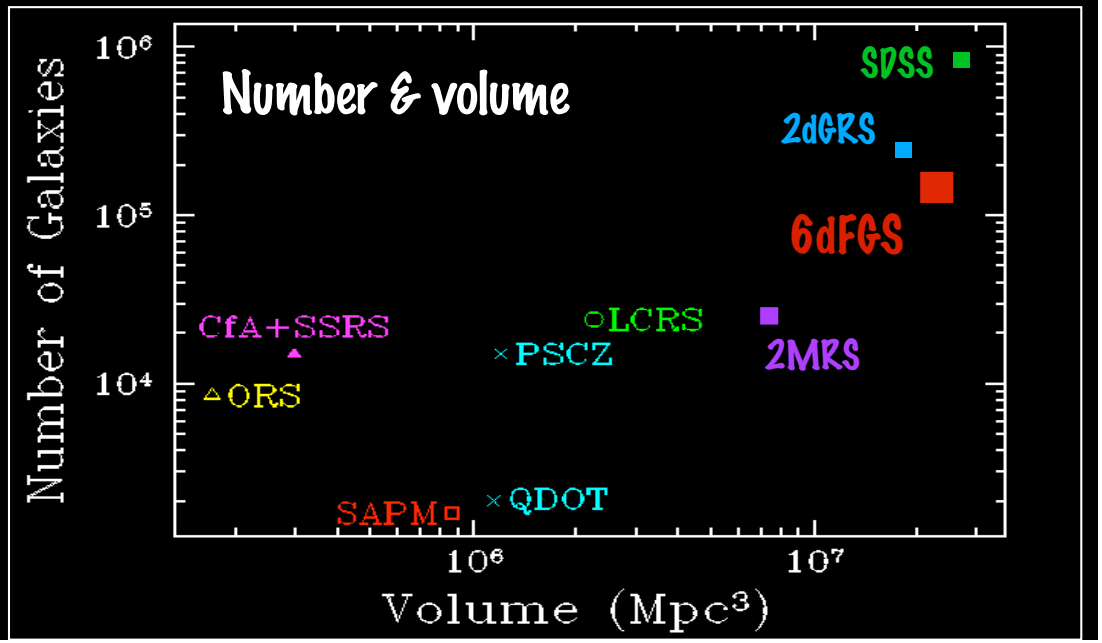


Comparison with other z-surveys

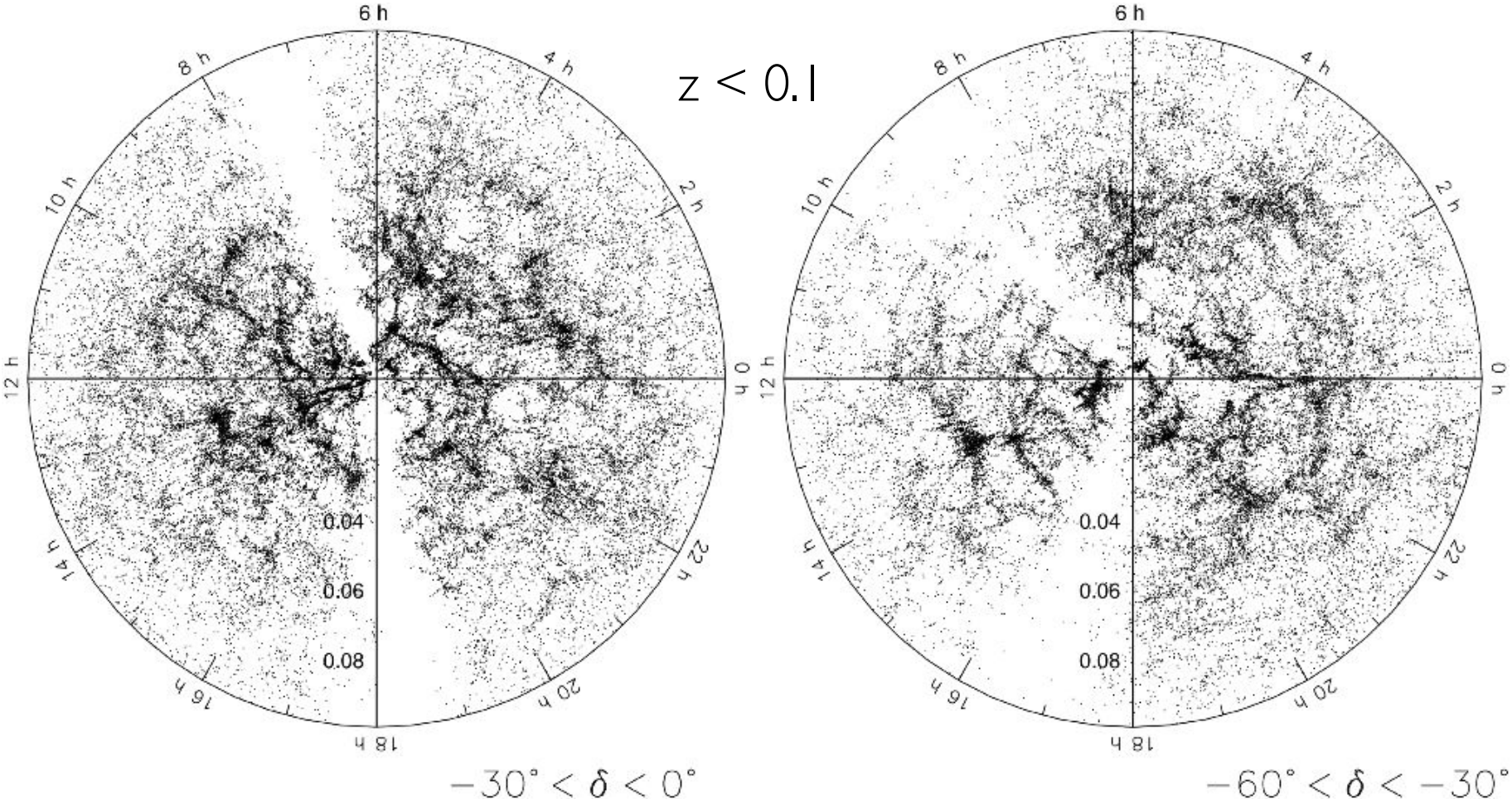
- 6dFGS galaxy sample is NIR selected rather than optically
- 6dFGS survey of local universe at z~0.05 (cf. 2dFGRS at z~0.1)
- 6dFGS volume is comparable to 2dFGRS (SDSS is 3x larger)



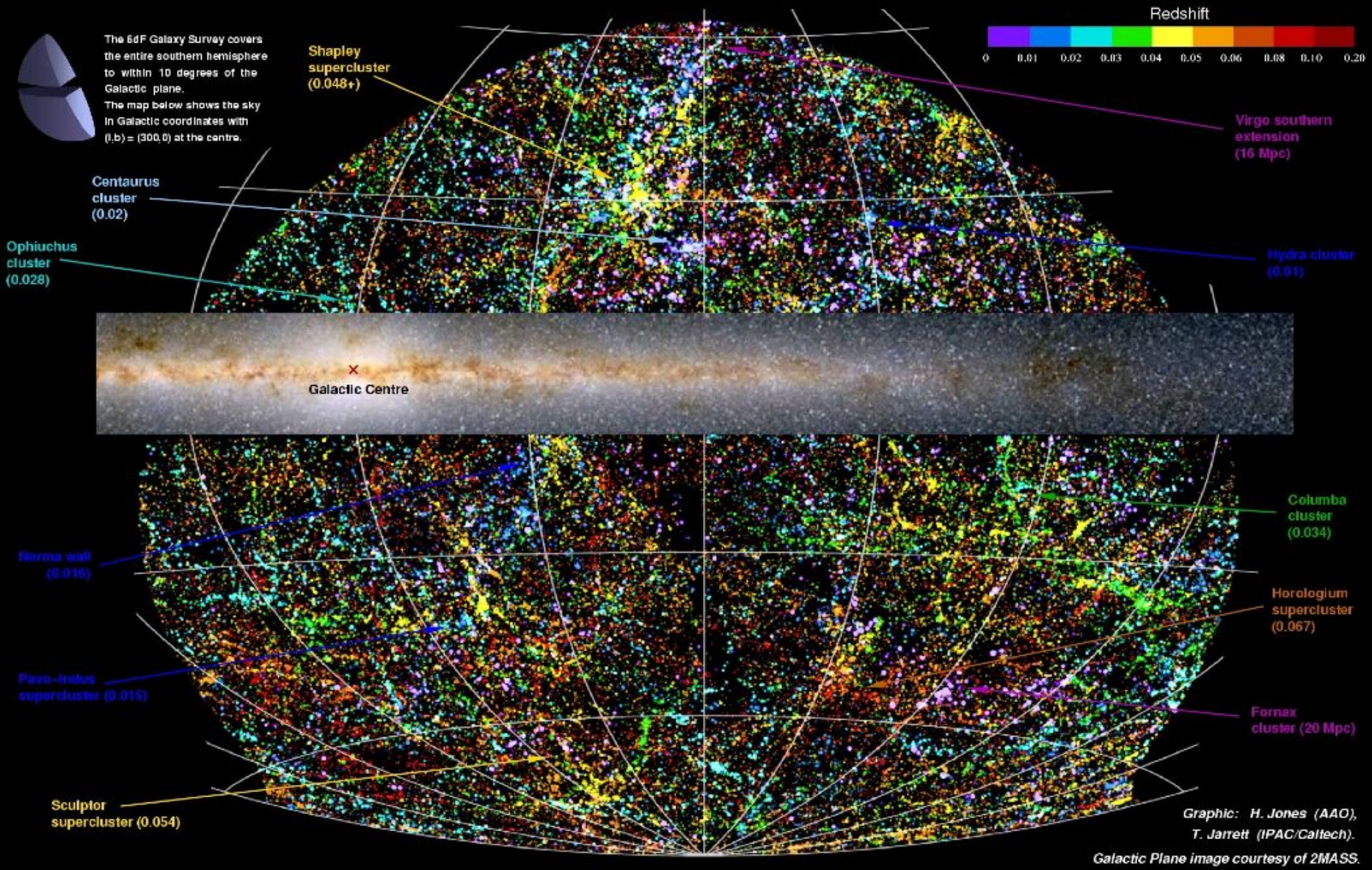




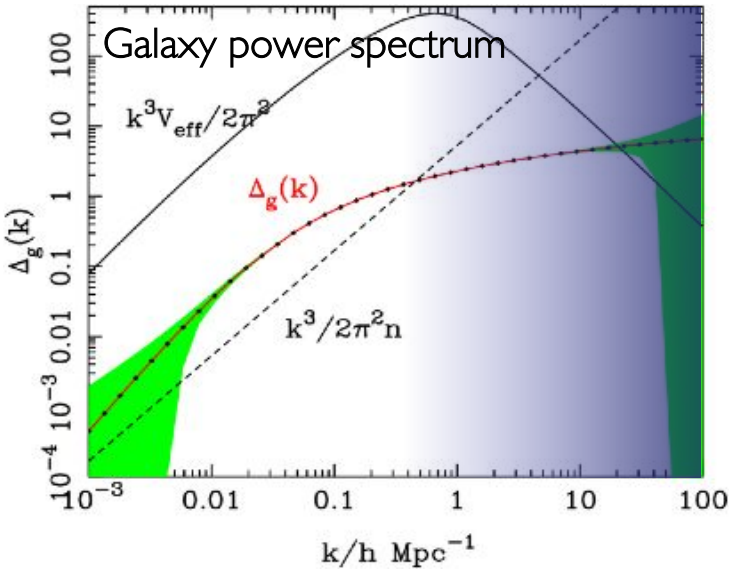
6dFGS redshift space maps

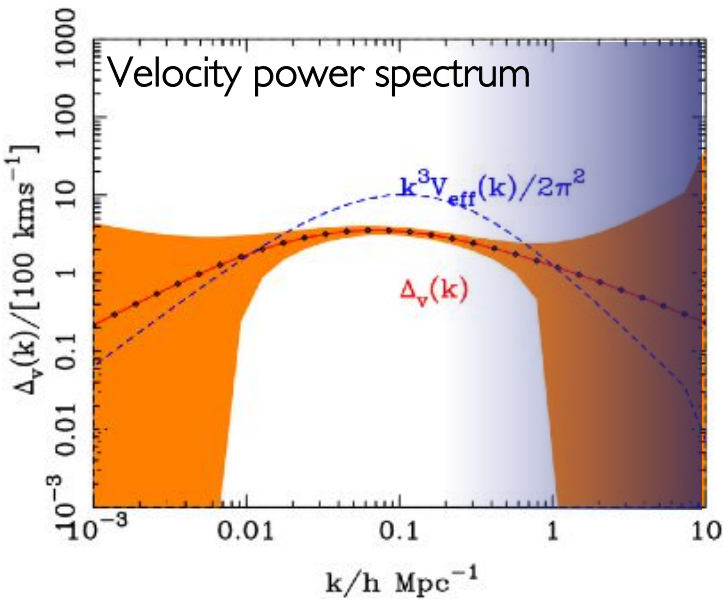


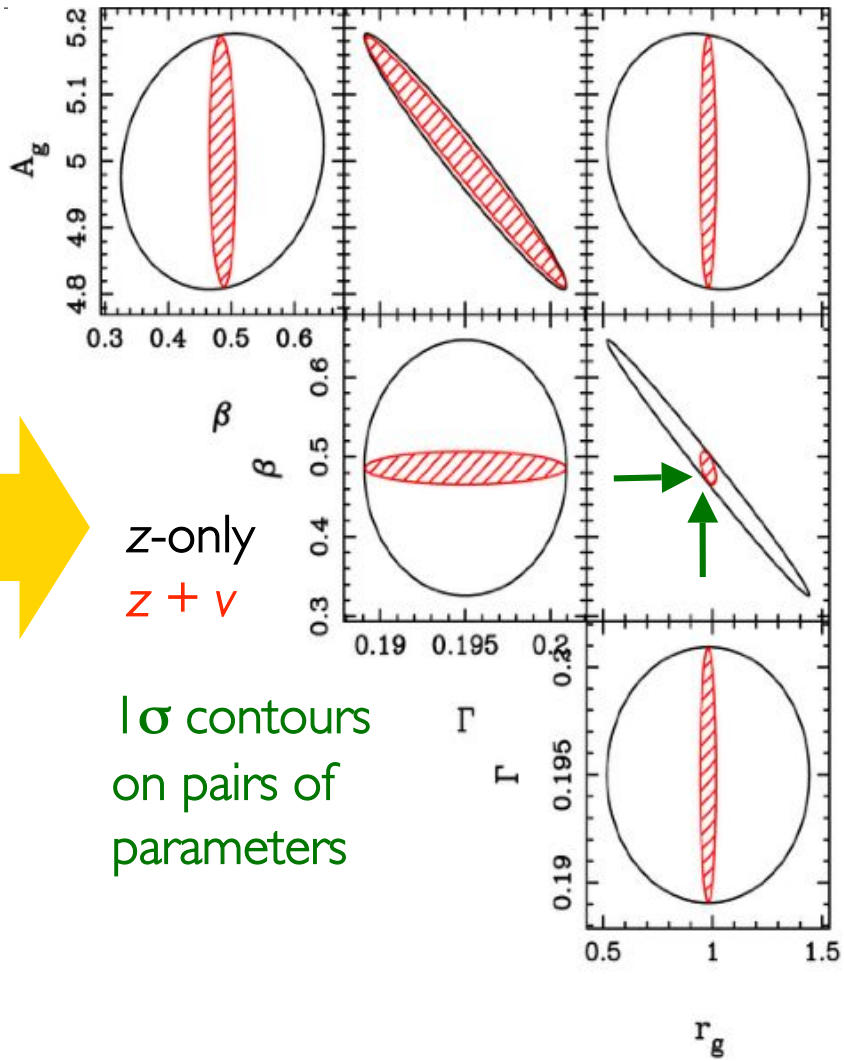
The 6dFGS view of the local universe



6dFGS power spectra and constraints







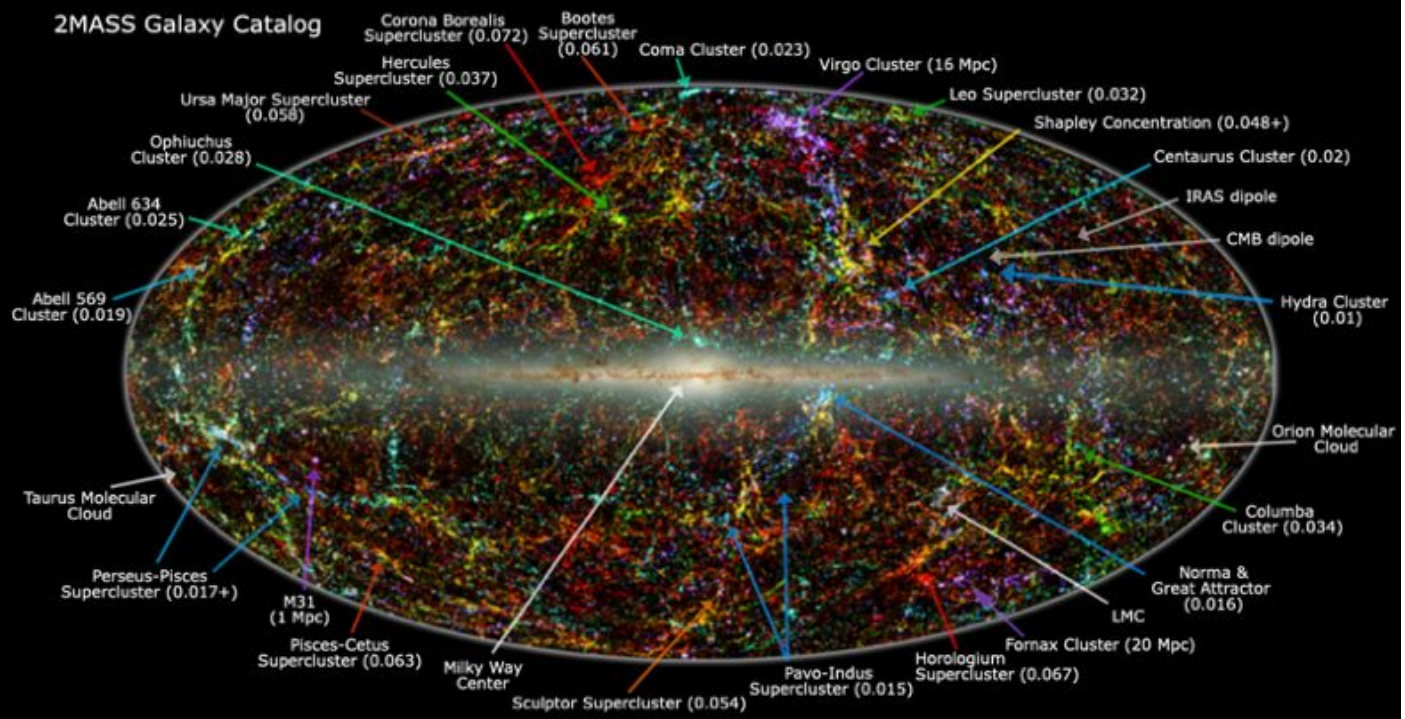
z-only

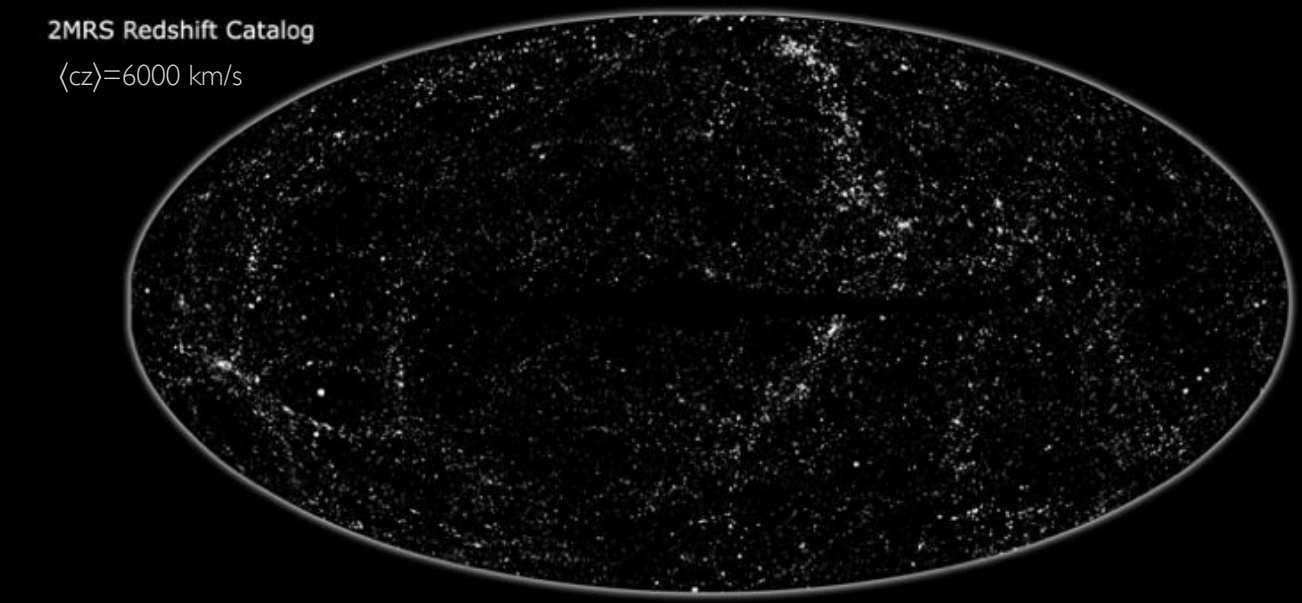
z + *v*

1σ contours on pairs of parameters

2MASS Redshift Survey

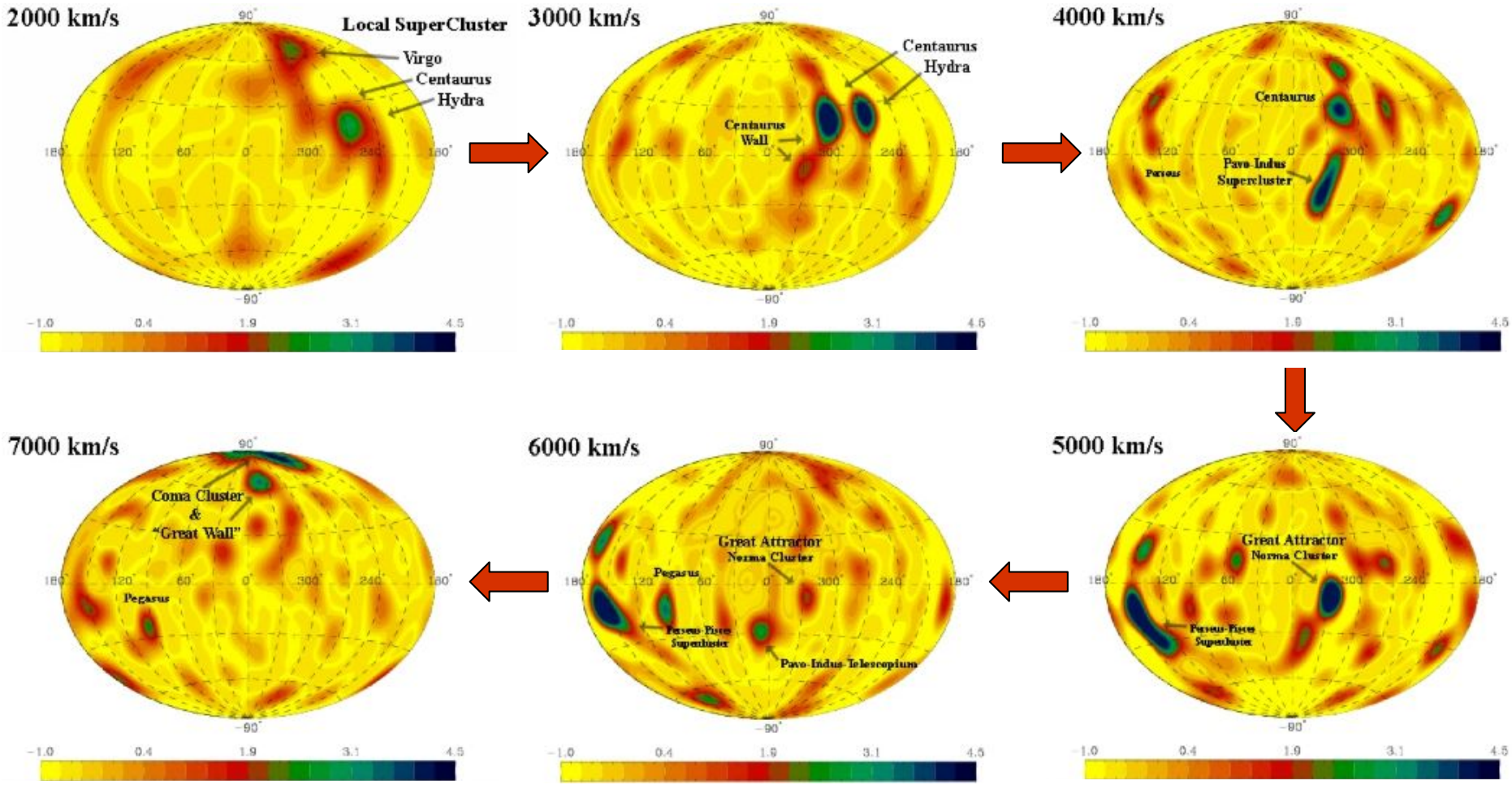
- All-sky *z*-survey to K_s=11.25 (limit is 1.5 mag brighter than 6dFGS)
- 93% complete with z's from Arecibo, Green Bank and FLWO 1.5m in North and 6dFGS and CTIO in South
- 2MRS contains 23,000 galaxies and is densest all-sky *z*-survey to date





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

Local density field reconstruction

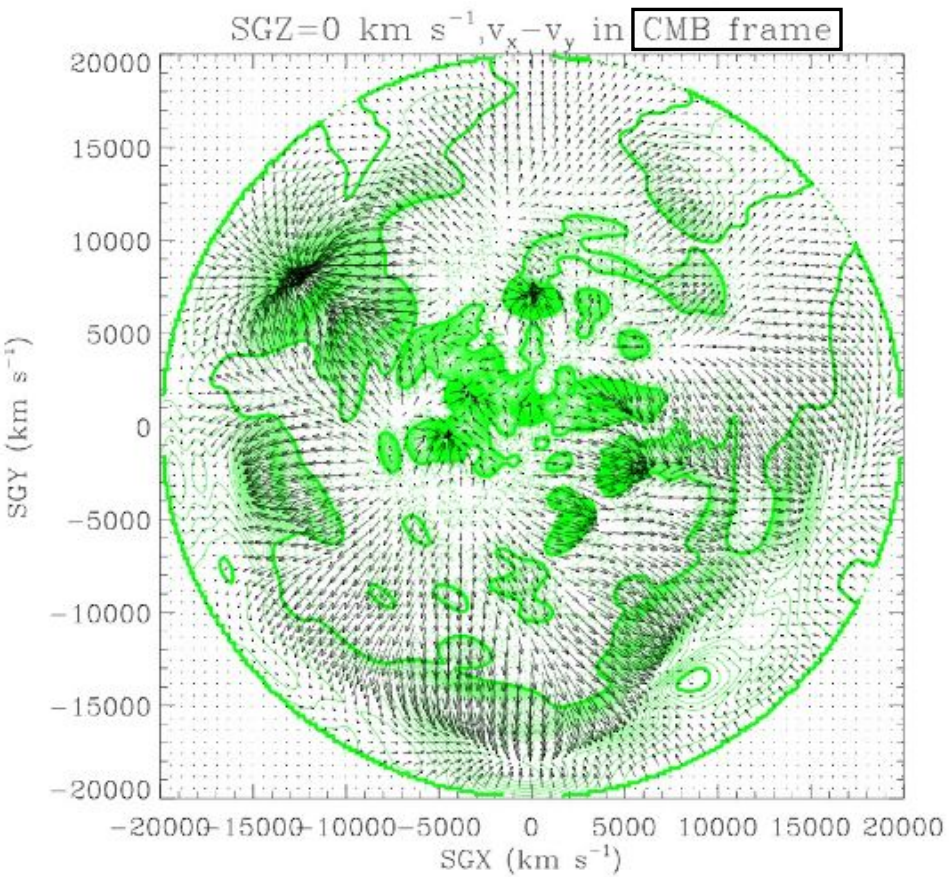


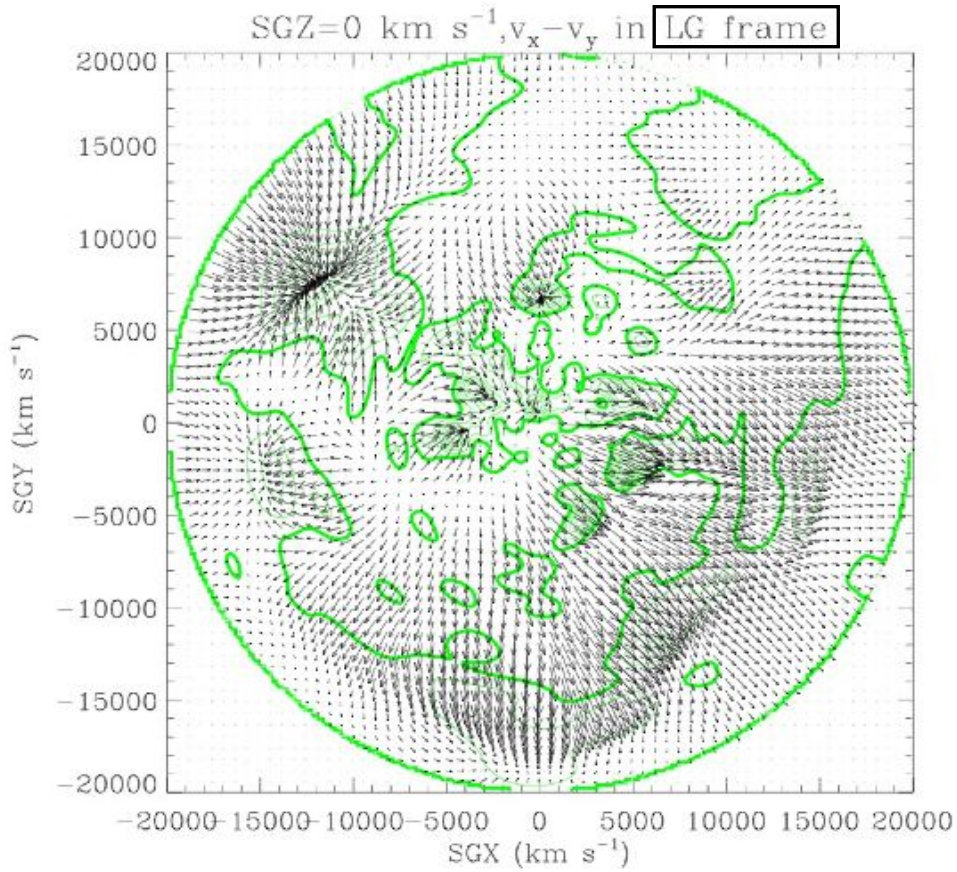
2MRS density field reconstruction by Fourier-Bessel decomposition and Wiener filtering

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 can illuminate the nature of the dark energy

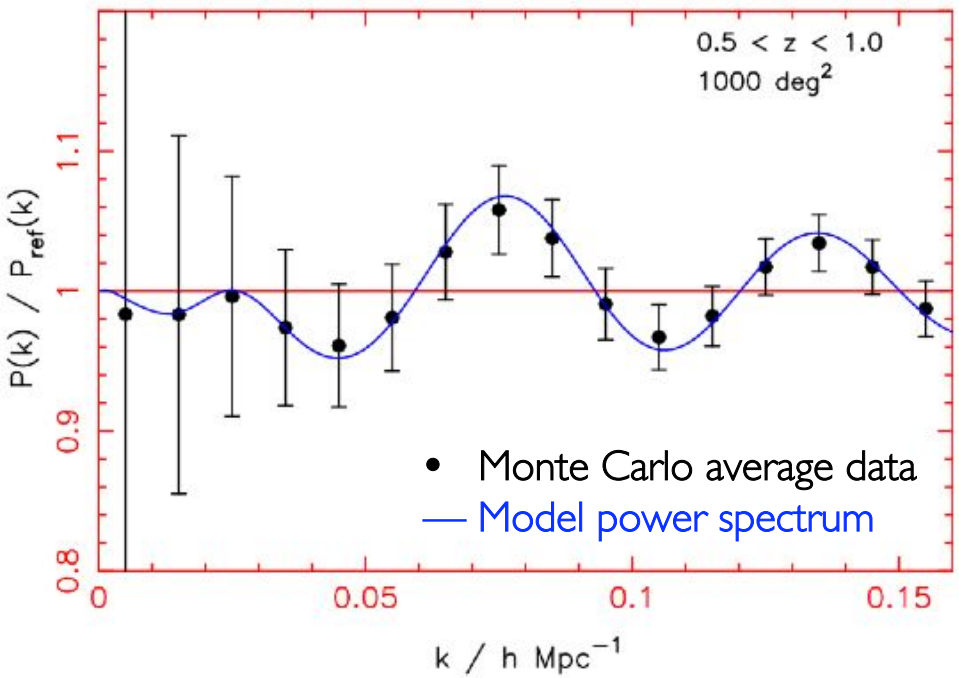
The WiggleZ BAO survey

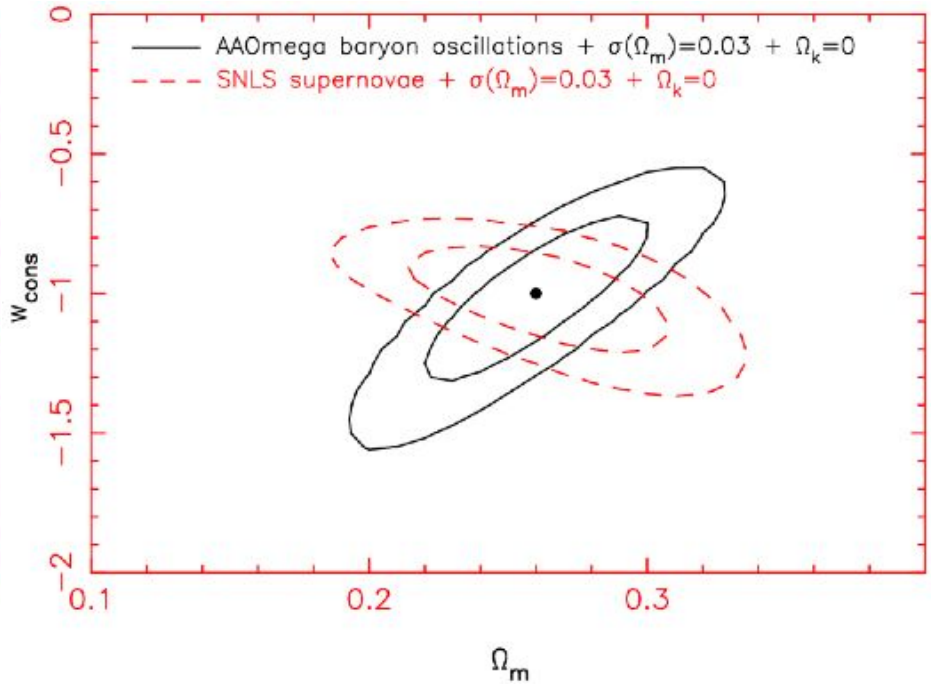
see Glazebrook et al. , astro-ph/0701876
and Chris Blake's talk later in this meeting

- 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)

BAO precision and constraints on *w*

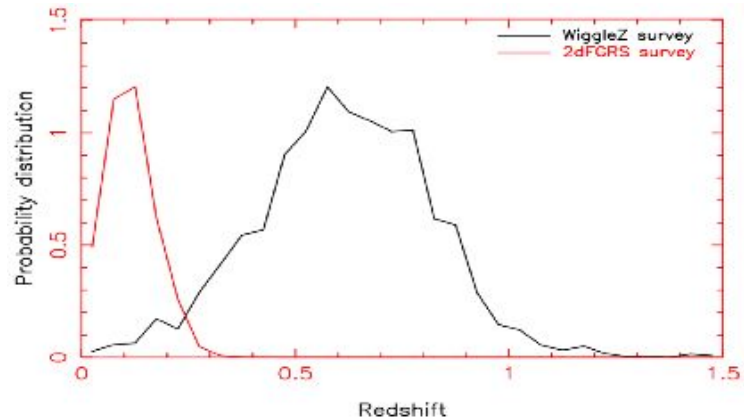
- Simulations of WiggleZ BAO measurement compared to model power spectrum ⇒ expect ~2% precision on standard ruler scale
- Measure $H(z)$ and $D_A(z)$ at z~0.7, use priors on Ω_M and H_0 (CMB gives $\Omega_M h^2$), reconstruct density field ⇒ 2.7% on H, 1.8% on D_A
- Equation of state precision ⇒ 10%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

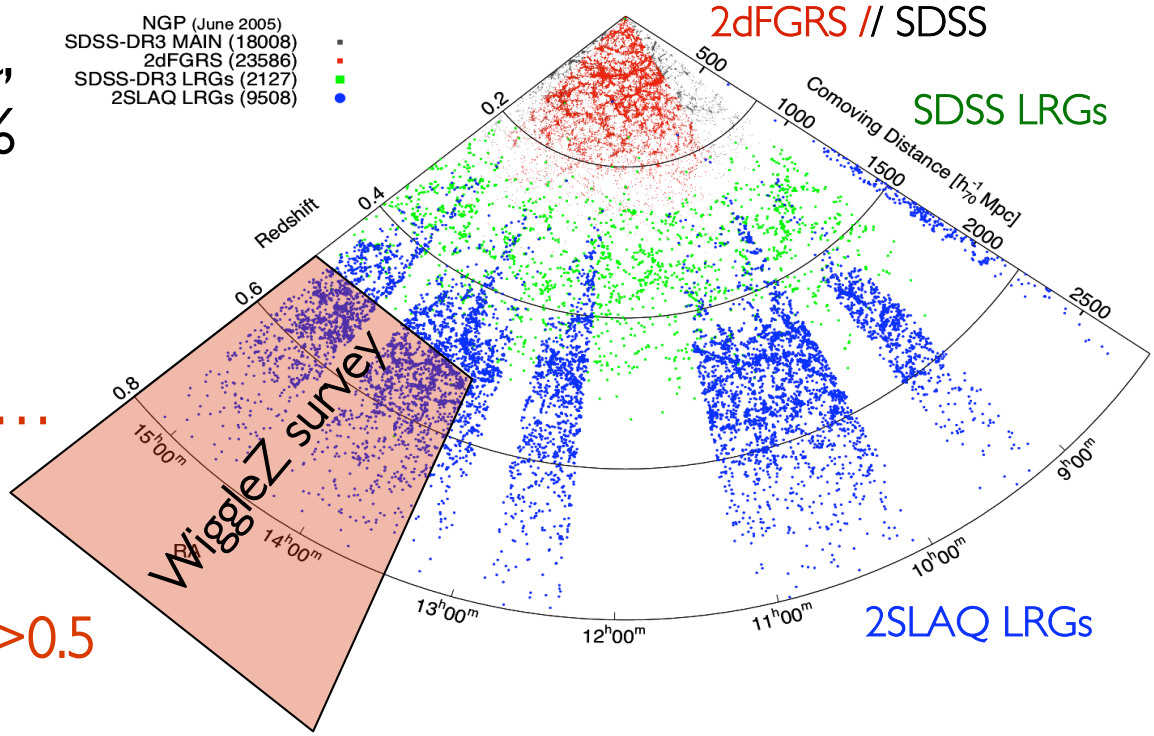




Status of WiggleZ survey

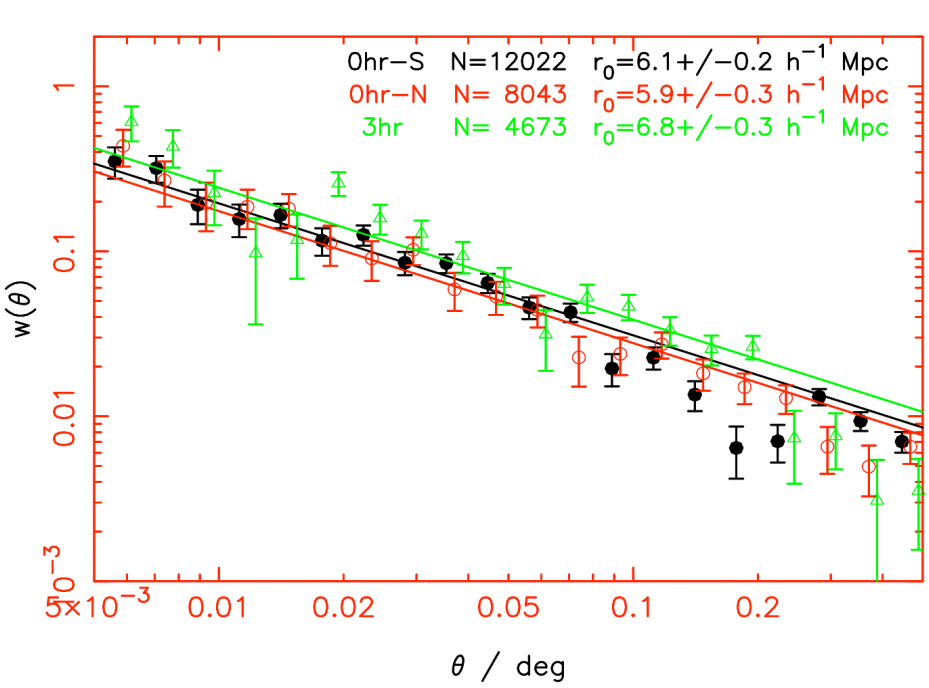
- Reaches z~1 in 1–hour exp. (cf. z~0.1 for 2dFGRS) due to ELG selection & efficiency of AAOmega spectrograph
- Redshift success rate ≈ 60%
- Tuning selection criteria, fraction at z>0.5 ≈ 75%
- Fraction of sample at z>0.5 ≈ 45%
- Final expected numbers…
  - ~300,000 spectra
  - ~200,000 redshifts
  - ~150,000 galaxies at z>0.5

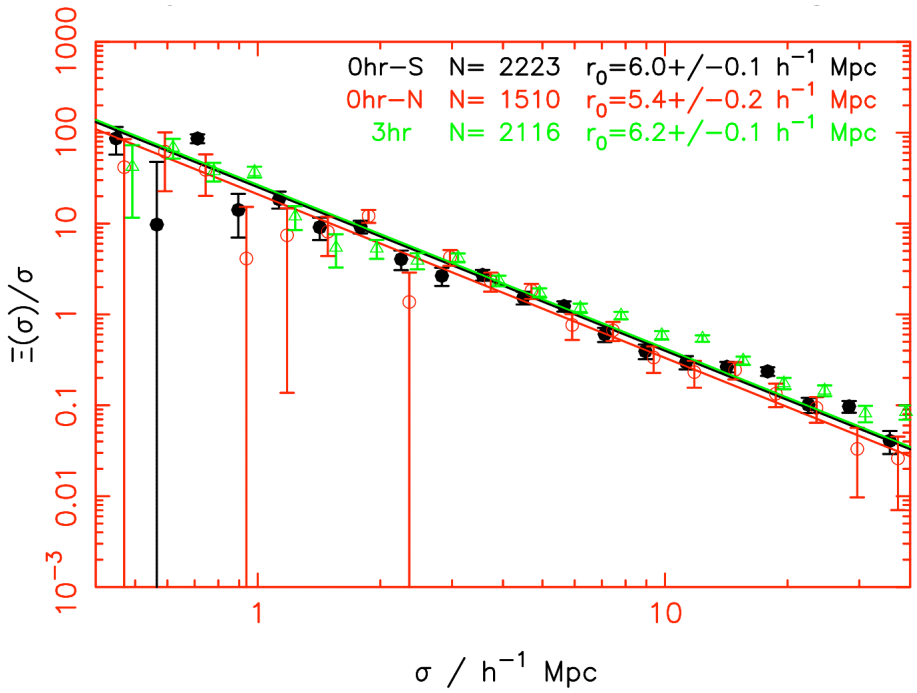




Small-scale clustering

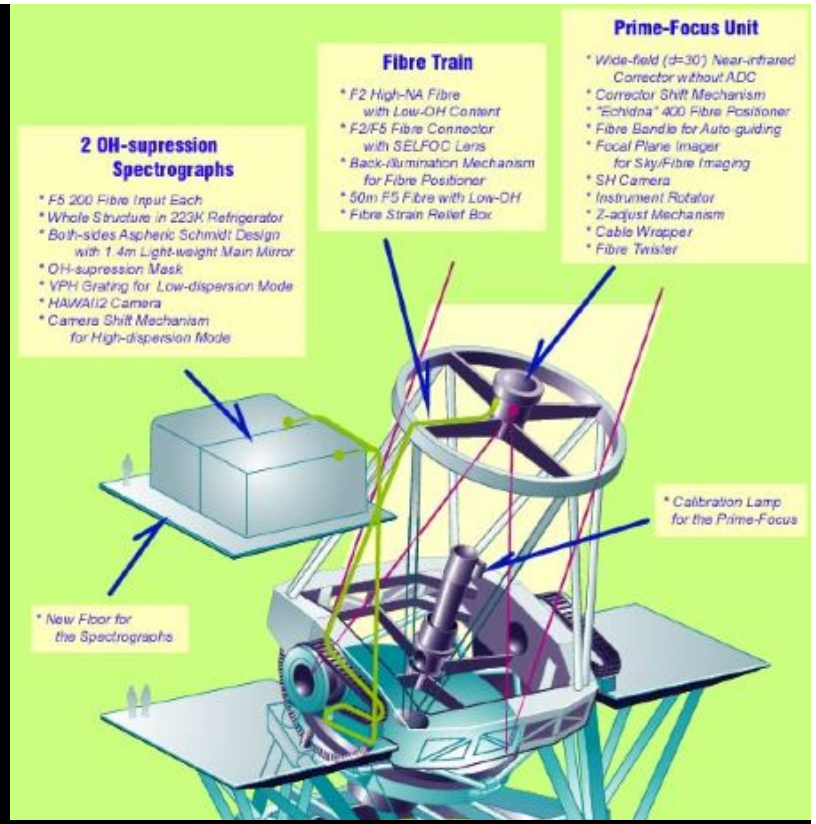
- Preliminary clustering measurement stronger than assumed…
  - Proposal was 400 redshifts/deg^2 at z>0.5 for sample with b=1.0
  - Clustering length now measured to be 6 Mpc/h ⇒ b=1.4
  - Equivalent survey with b=1.4 requires 200 redshifts/deg^2 at z>0.5
  - Thus the revised target is a survey of 200,000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



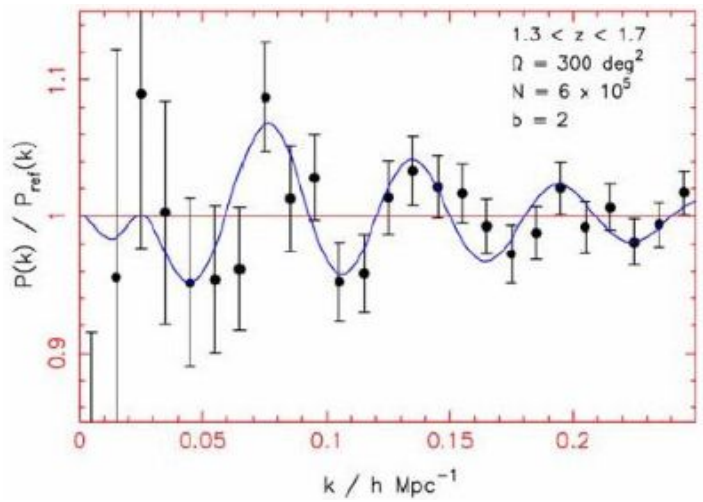


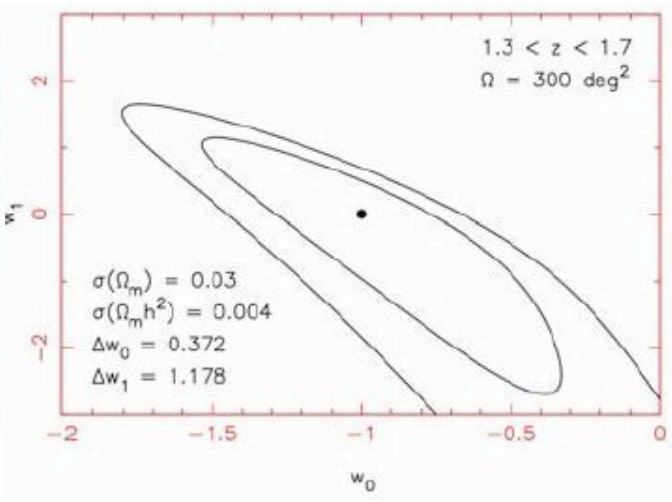
FastSound survey

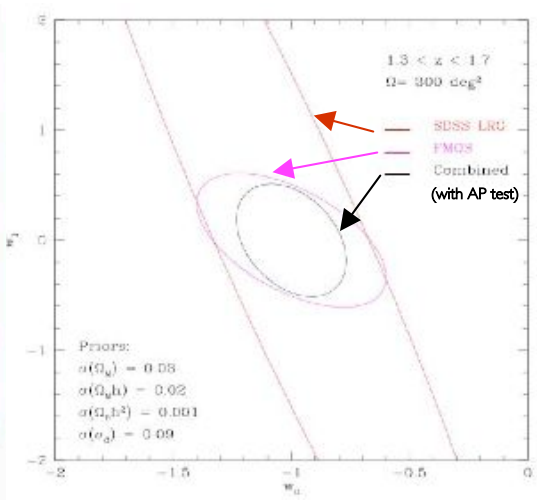
- Proposed z>1 BAO survey using FMOS/Subaru NIR spectroscopy…
  - FMOS: 400-fibre J+H OH-suppressed NIR spectrograph, first light in Feb 08
  - ~600,000 Hα galaxies in 'redshift desert' at z~1.0–1.7 over ~300 deg^2 (~1 Gpc^3) ⇒ O(100) nights on Subaru
  - Unique redshift range for BAO survey, good precision,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



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

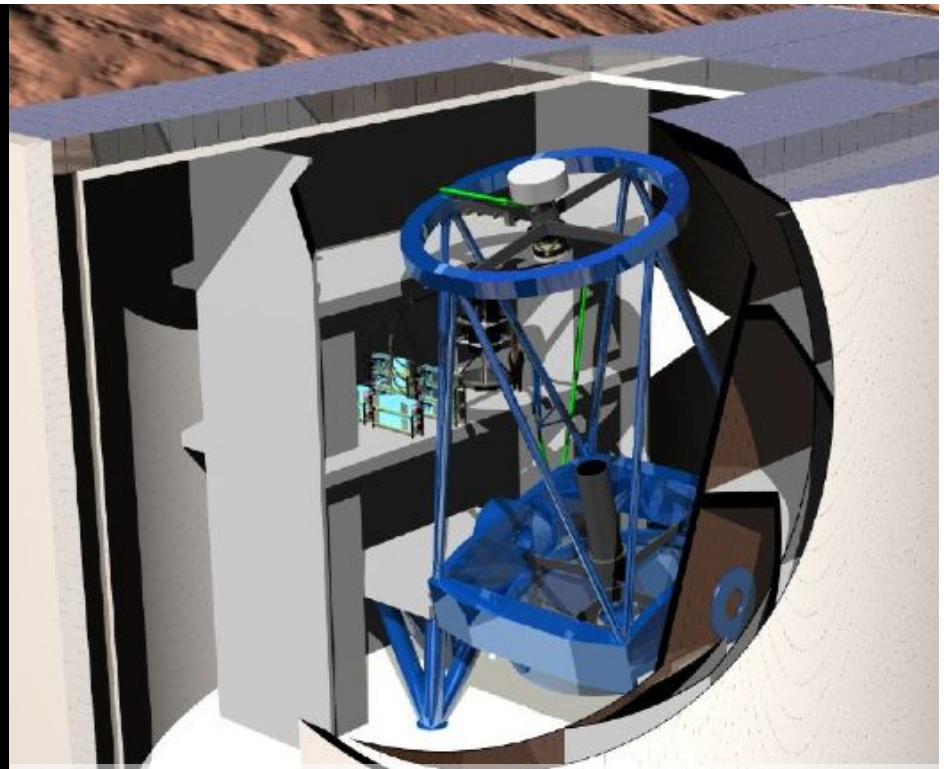




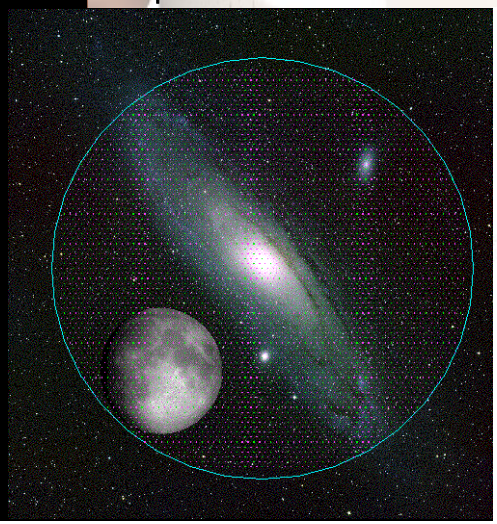


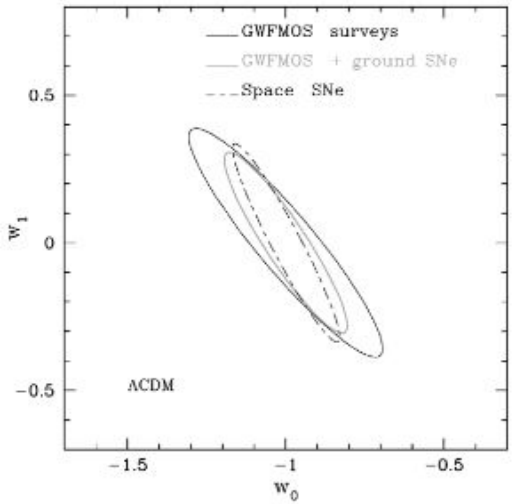
WFMOS survey

- 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 $\delta w_0 \sim 3\text{-}8\%$; $\delta w_1 \sim 20\text{-}25\%$
  - 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