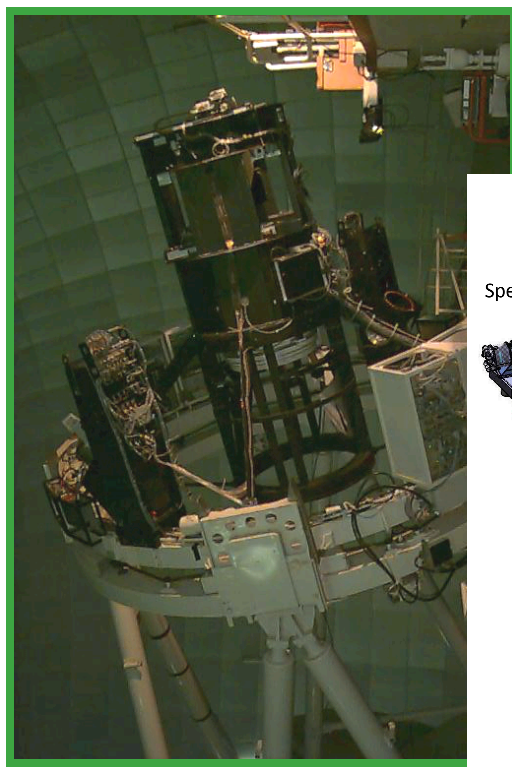
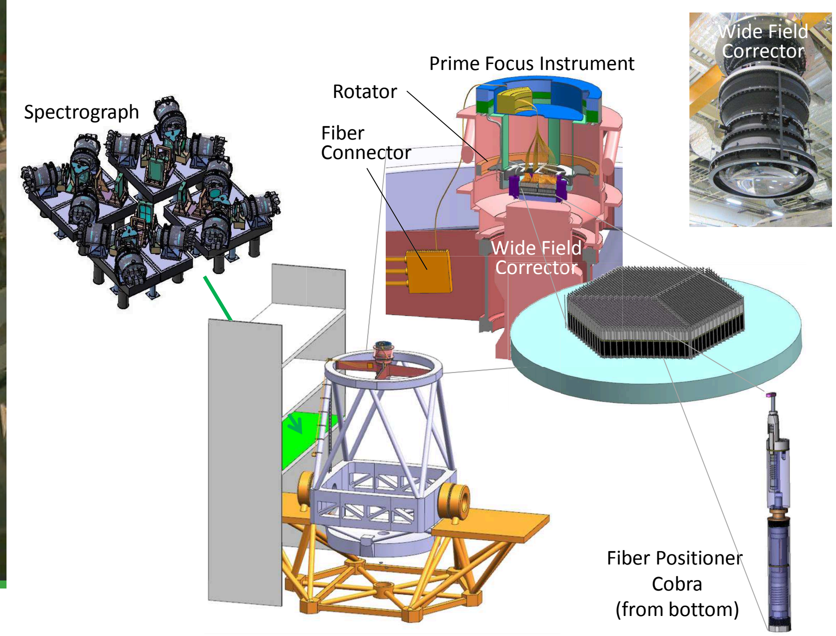
A Century of Redshift Surveys:
Past, Present & Future

Richard Ellis, Caltech





Origins of the Expanding Universe (1912-1932)

Sept 15 2012 Flagstaff, AZ

Technology Enables Discoveries (1980 – present)

Focus on the revolution of multiple object spectroscopy
which led to highly successful galaxy surveys

Multi-fiber spectroscopy has enabled large surveys of the local and intermediate redshift Universe driven by ambitious cosmological goals:

- is the Universe uniform on large scales?
- what is its mean mass density?
- the expansion history and growth of structure

Multi-slit technology on large telescopes with efficient optical and near-infrared detectors has probed faint galaxy properties seen over 95% of cosmic history addressing equally ambitious questions:

- how and when did galaxies form and assemble?
- can we locate the first generation of stars and galaxies?

NB: Personal choice of events – not intended to be complete

In the beginning (1980)…

THE ASTROPHYSICAL JOURNAL, 242:L69–L72, 1980 December 1

Hill

Angel

MULTIPLE OBJECT SPECTROSCOPY: THE MEDUSA SPECTROGRAPH

JOHN M. HILL, J. R. P. ANGEL, JOHN S. SCOTT, AND DELVIN LINDLEY
Steward Observatory, University of Arizona

AND

PAUL HINTZEN
NASA Goddard Space Flight Center
Received 1980 August 4; accepted 1980 August 28

ABSTRACT

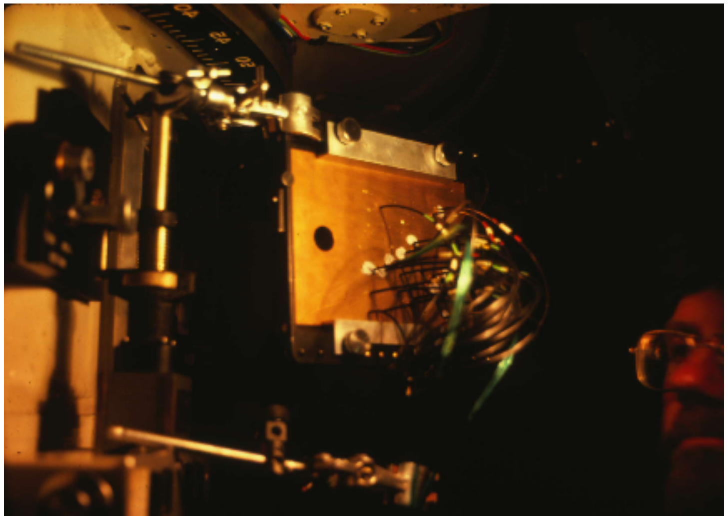
We have built and tested an instrument to obtain simultaneous spectra of many objects in the field of view of the Steward 90 inch (2.29 m) telescope. Short lengths of fused silica fiber 300 μm in diameter are used to bring the light from galaxy images at the Cassegrain focus into a line along the spectrograph slit. From a single exposure of the cluster Abell 1904, which has a redshift of ~20,000 km s^{-1}, we have determined the redshifts of 26 individual galaxies, each with a precision of ~100 km s^{-1}. The present device, while already giving a sixfold reduction in the mean telescope time per galaxy, has significant light losses because it is not ideally matched to the telescope. An instrument being designed for the prime focus will transmit light from each object as efficiently as a conventional spectrograph.
Subject headings: galaxies: redshifts — instruments

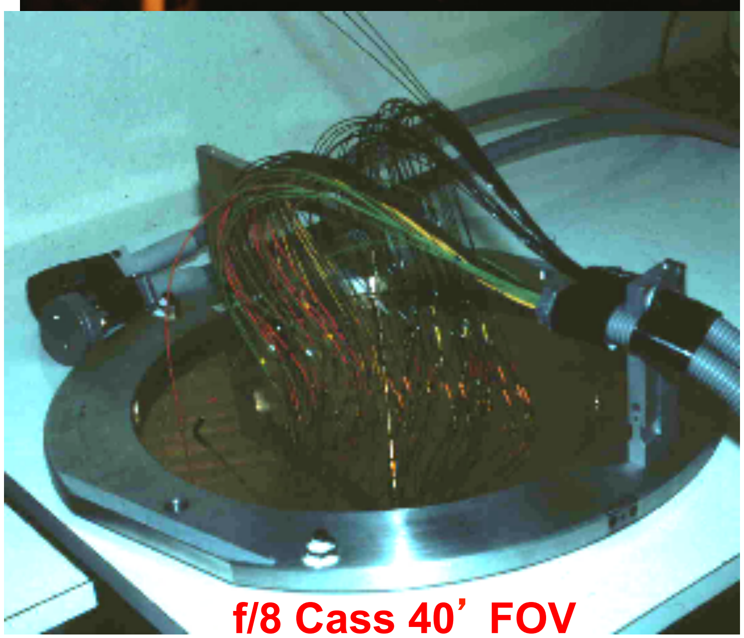
Anglo-Australian Telescope FOCAP

(Fibre Optic Coupled Aperture Plate)

Gray

Auxiliary f/8 Cass 12' FOV





f/8 Cass 40' FOV

Mon. Not. R. astr. Soc. (1984) **206**, 285–292

Multi-object spectroscopy using fibre optics at the Anglo-Austrialian telescope – an application to the IC 2082 galaxy cluster

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P. M. Gray *Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*
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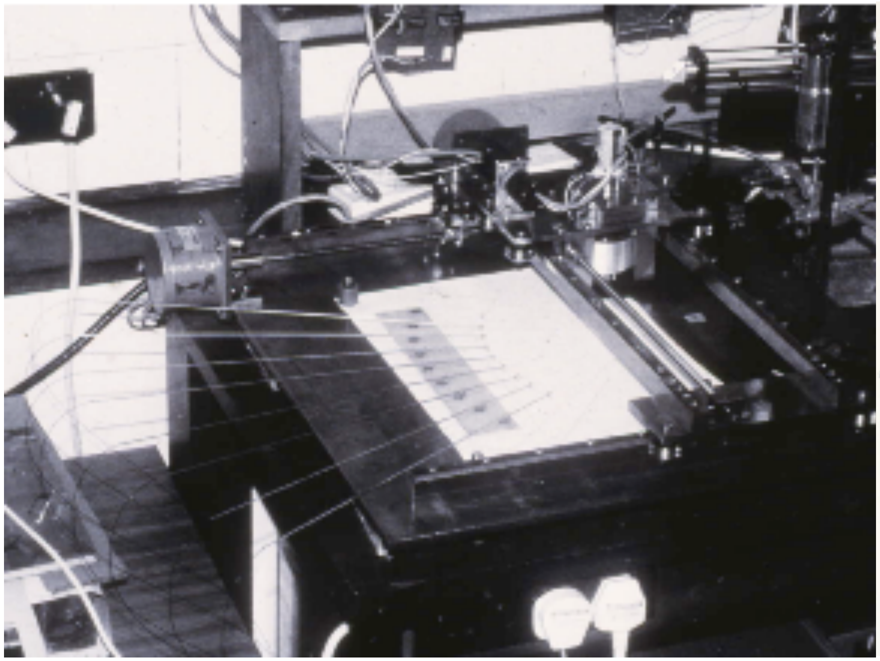
Received 1983 May 16; in original form 1983 January 27

Summary. We describe a multi-object fibre optic coupler we have developed for the Cassegrain focus of the Anglo-Australian telescope. The results of a test run on the southern cluster containing the dumb-bell galaxy IC 2082 are presented. Where comparisons with previous work can be made the radial velocities determined using the coupler show no signs of any systematic errors. The new results are briefly discussed in terms of earlier claims for galactic cannibalism in the cluster.

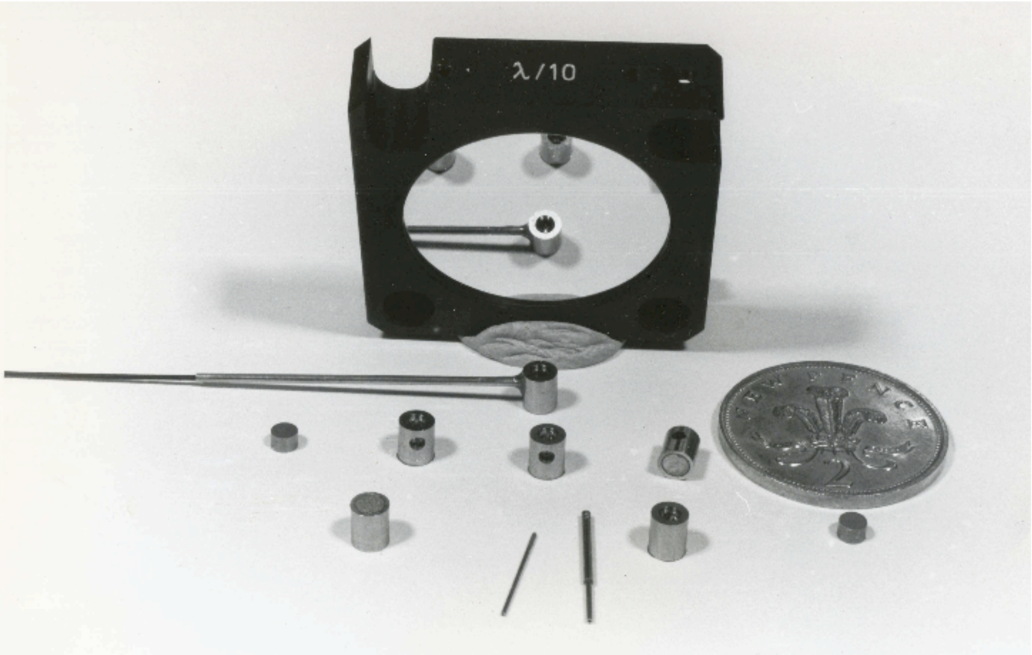
Automated Fiber Positioning

- FOCAP was a big success: 30% of all spectroscopic time!
- Aperture plates inflexible to target changes/atmospheric effects
- Automation ensures better placement, more uniform transmission
- Aug 1984: Parry et al proposes *prototype robotic positioner*
- May 1985: Autofib-1 commissioned in March 1987
- Total cost £20K + manpower

Parry

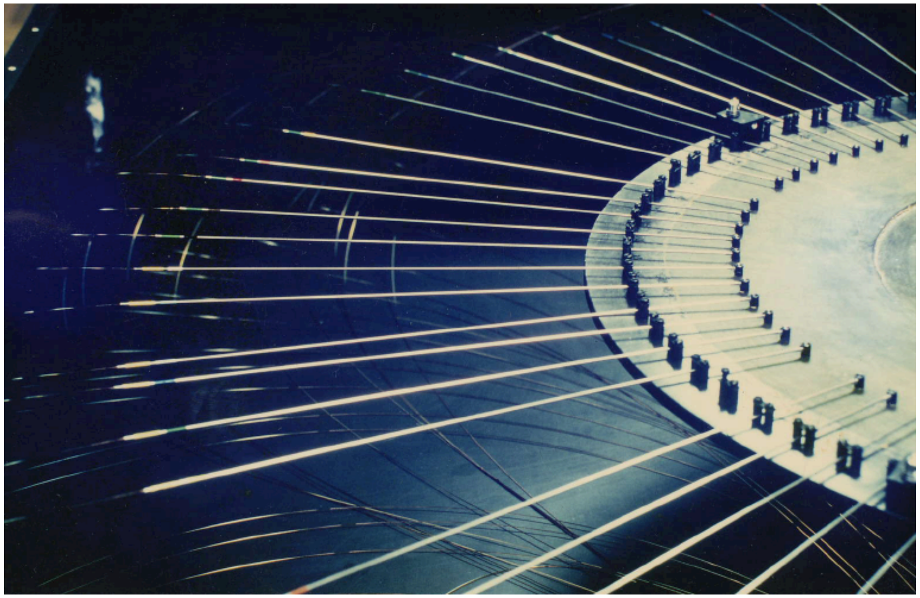


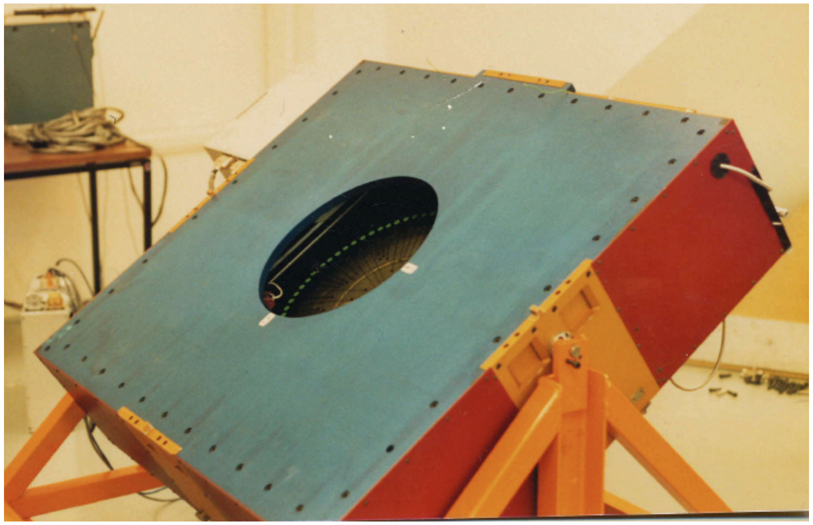
Laboratory protype (Durham U)



Fiber end (SmCo magnets & 90° prisms)

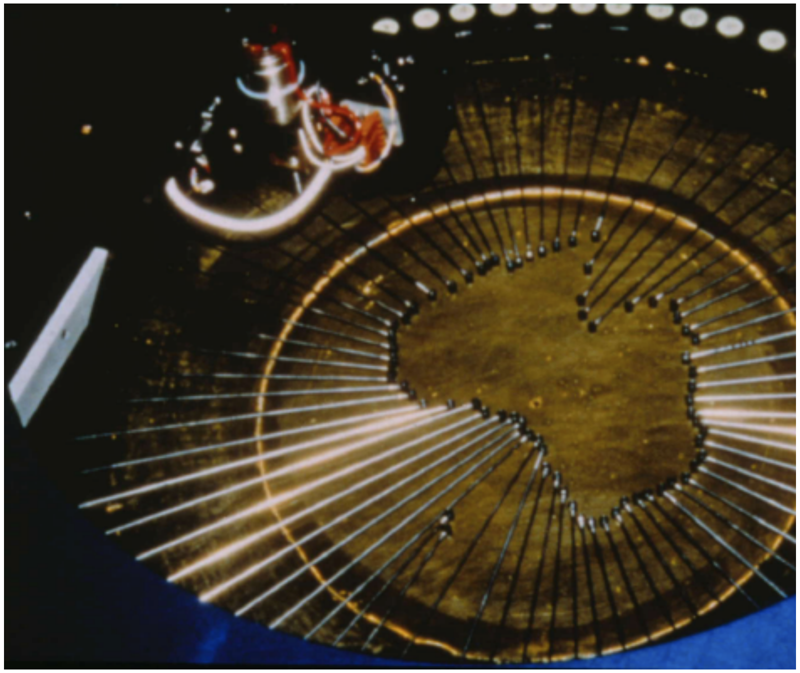
Autofib-1 @ AAT (1986 – 1994)



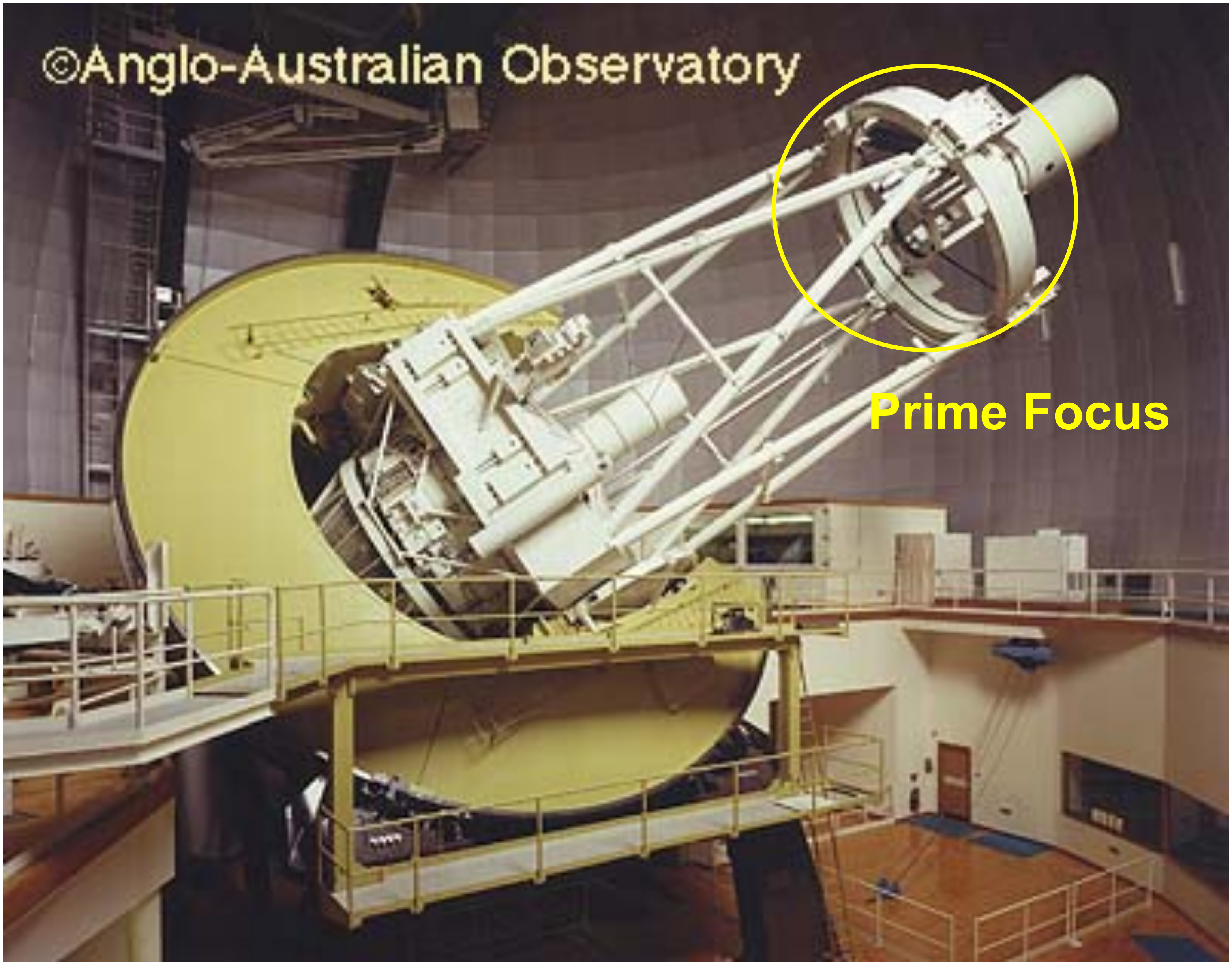


The Autofib concept (Parry) was pioneering and rapidly became the standard robotic option. It led to enquiries for cloned versions from:

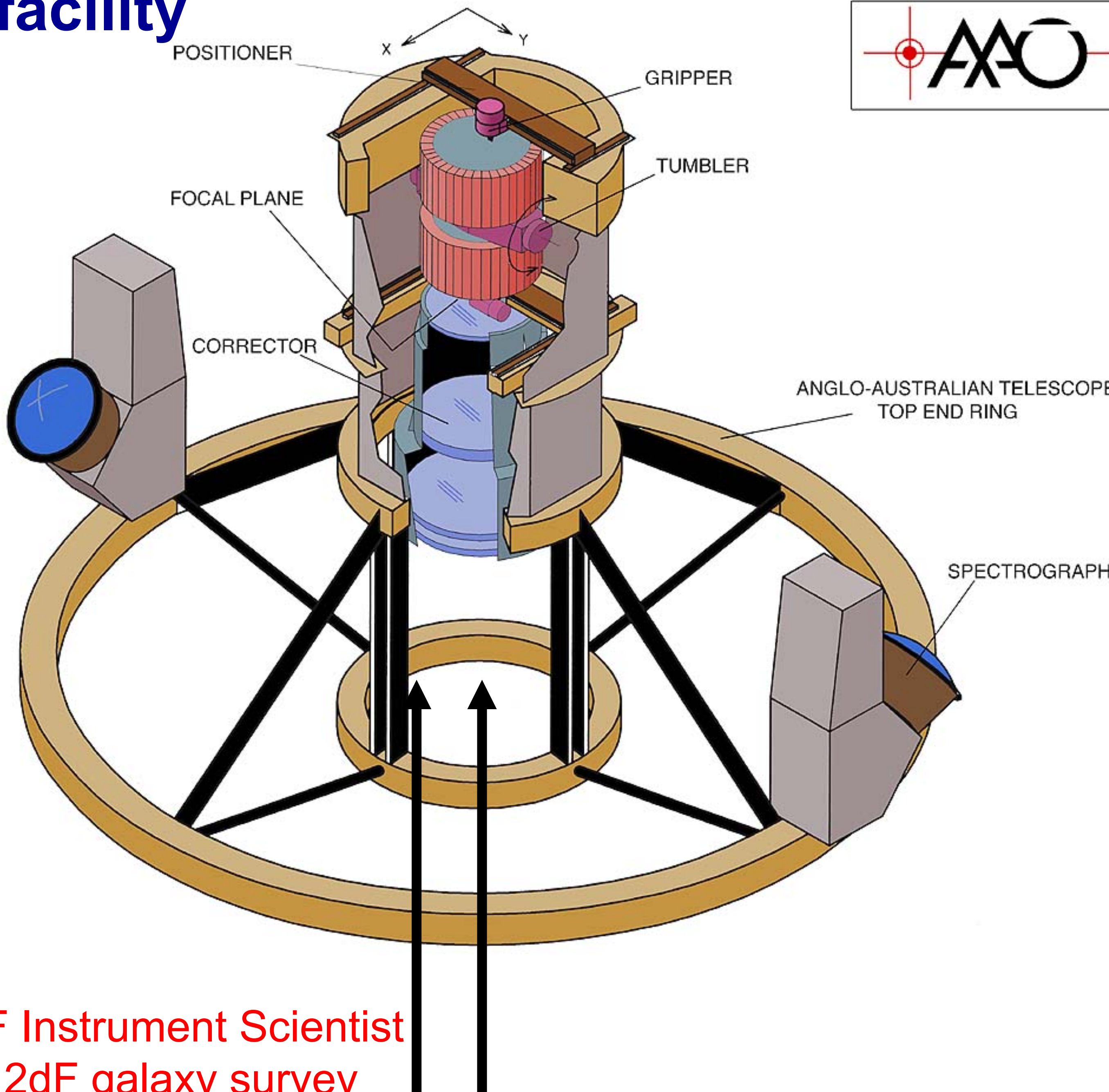
UH 2.2m, MDM 2.4m, CFHT 3.5m, ESO, NOAO & China (but not SDSS!)



The 2 degree Field (2dF) Project (1994 -)

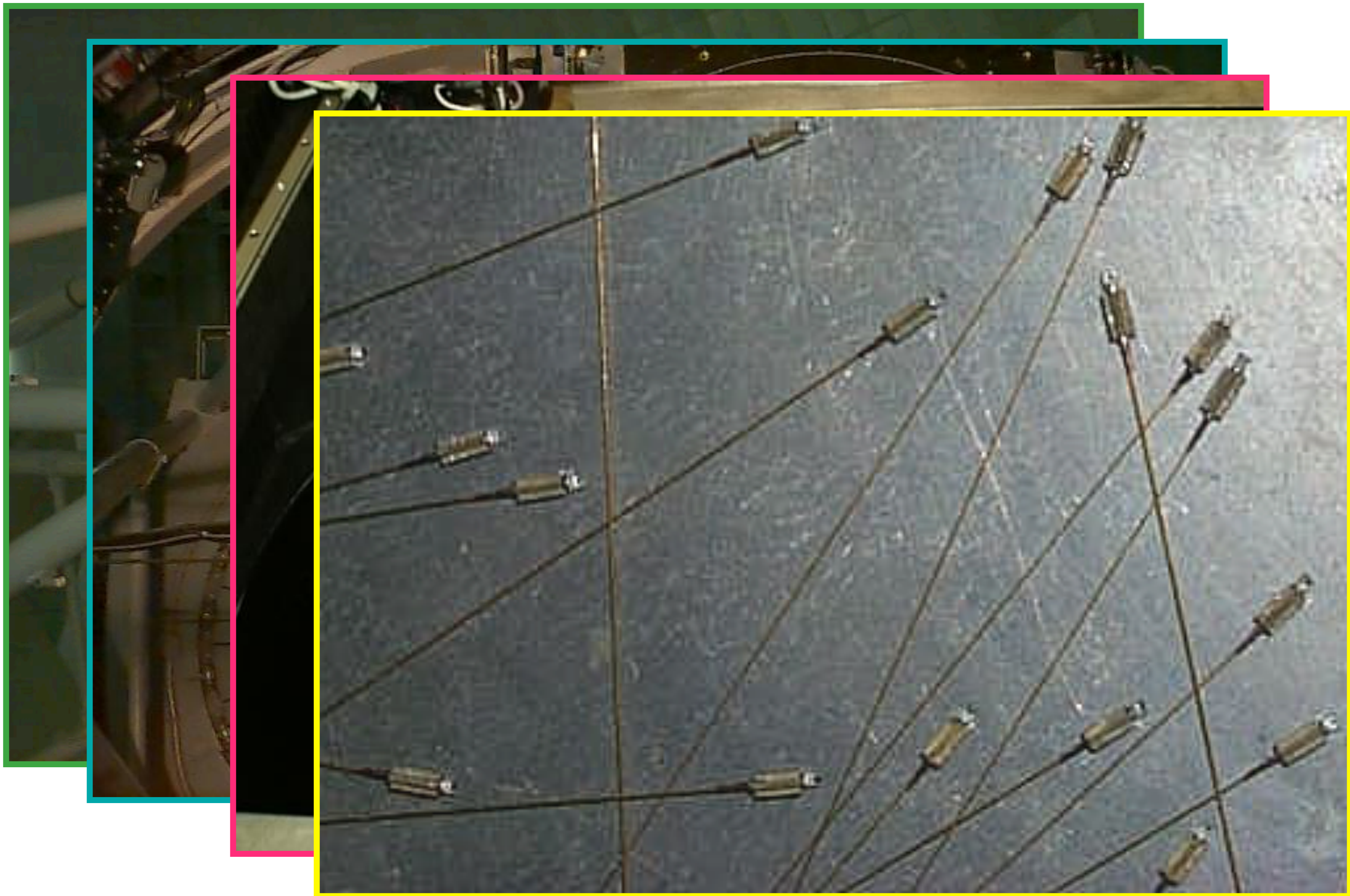


The 2dF facility

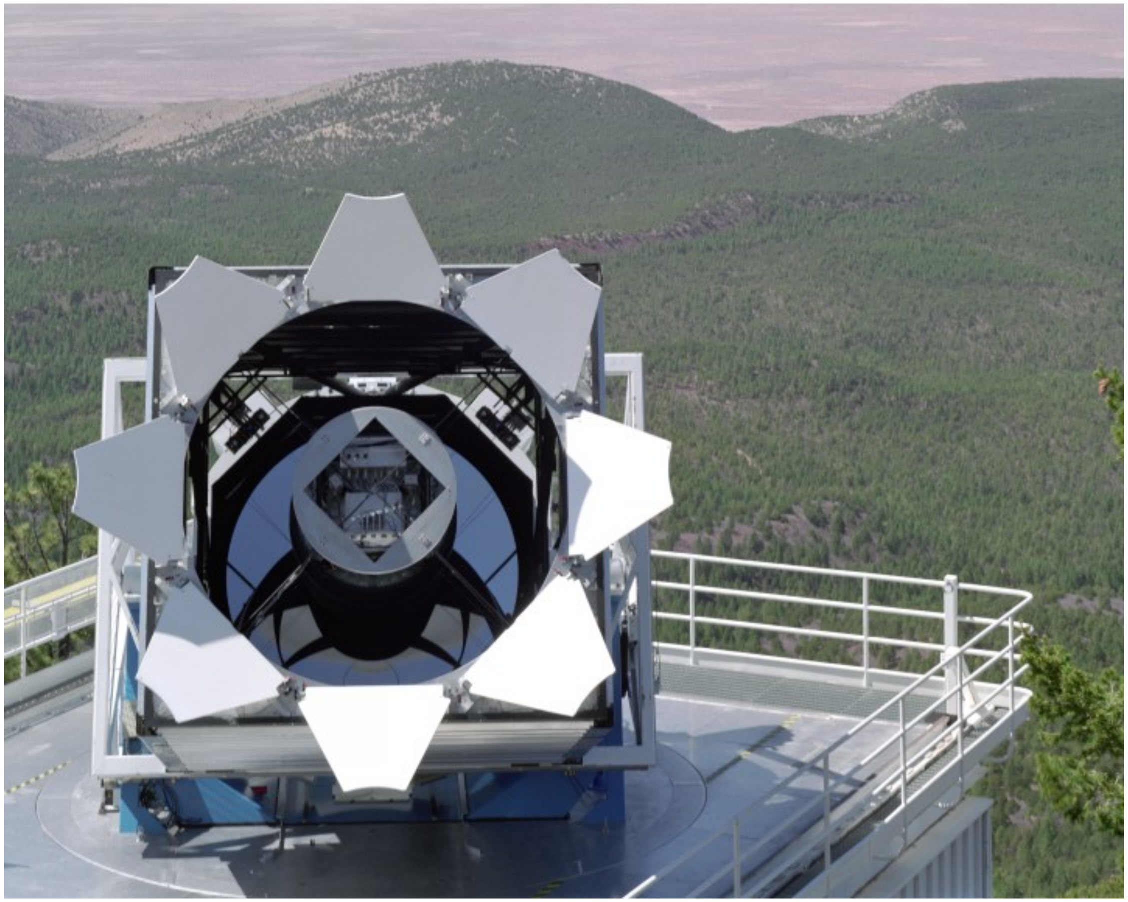


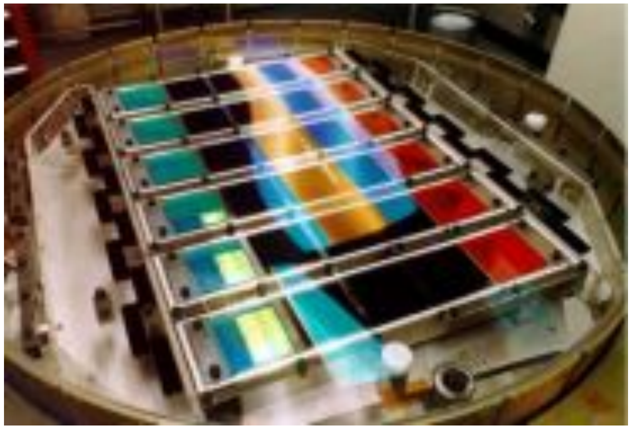
Glazebrook: 2dF Instrument Scientist
Peacock: UK PI 2dF galaxy survey

2dF on the AAT



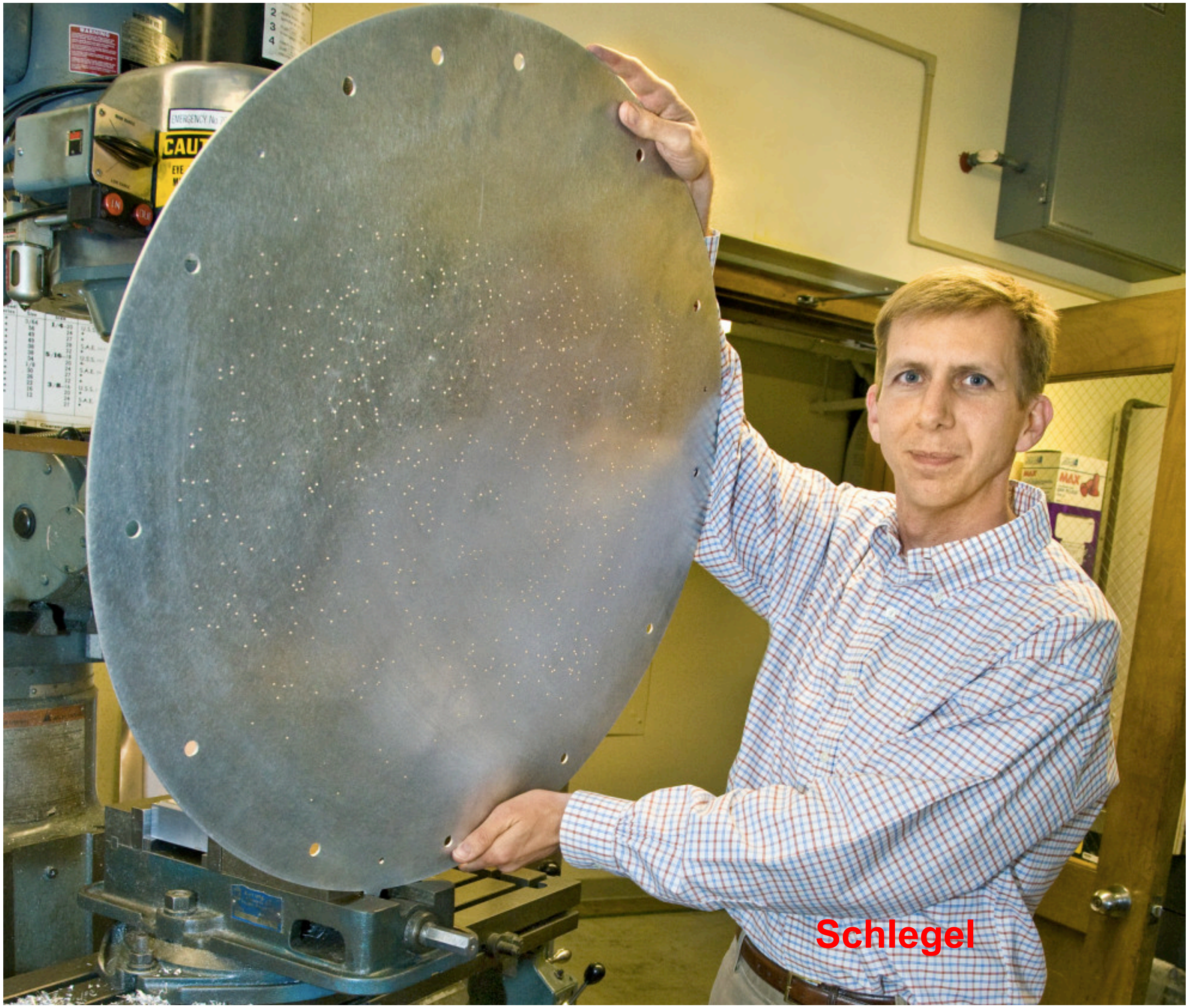
Sloan Digital Sky Survey





Remarkable contrast in technical, sociological and financial aspects between SDSS and 2dF

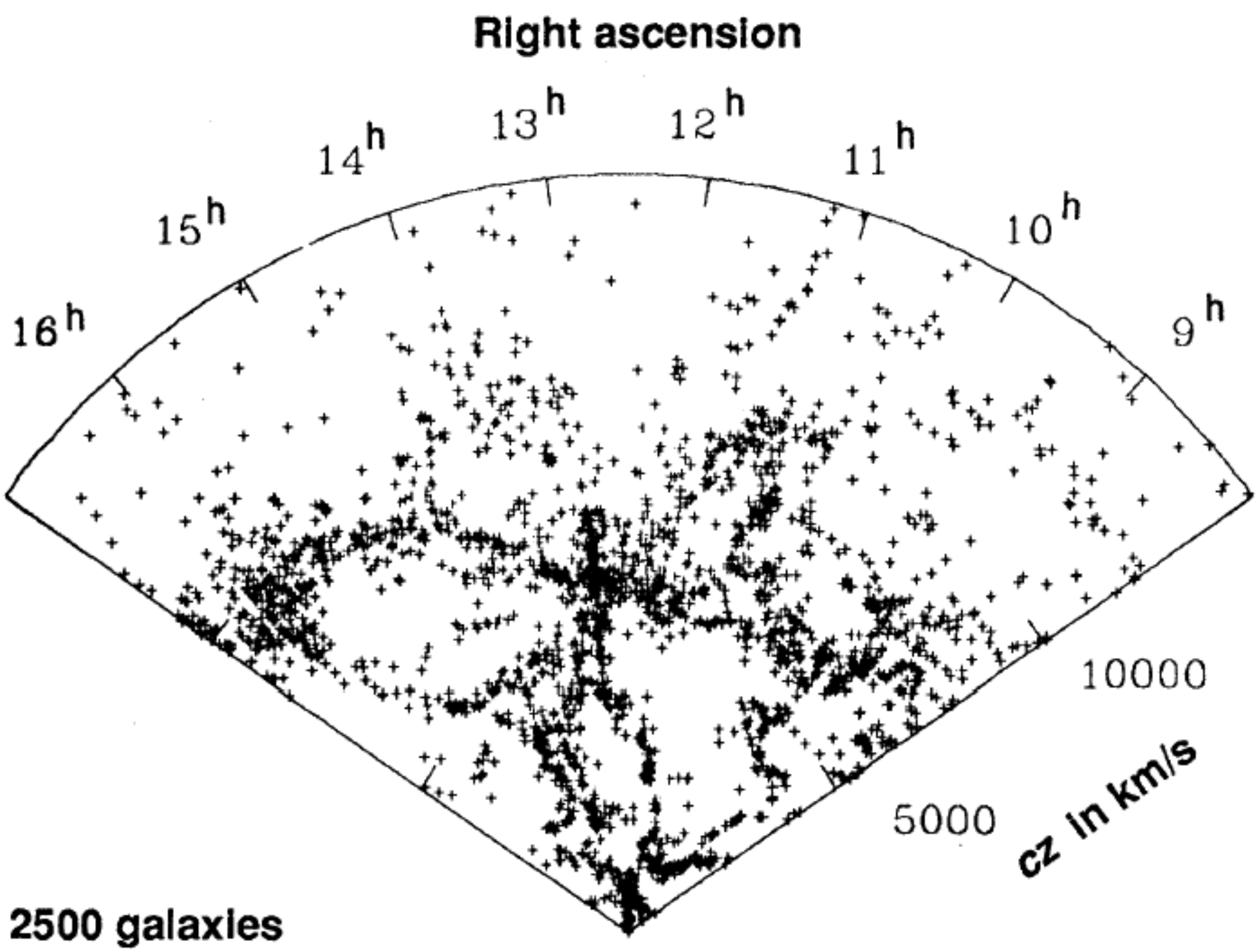
SDSS Aperture Plate



Discoveries with Multi-fiber Galaxy Surveys

- Is the Universe homogeneous on large scales?
- What is the mean mass density of the Universe? Is it suficient to halt the cosmic expansion
- What is the expansion history and ultimate fate of the Universe?

The Great Wall - “Largest Known Structure”



Geller & Huchra (1990) Science 246, 897

Las Campanas Redshift Survey

Pioneering multi-fiber survey at the 2.5m Du Pont telescope charted galaxy distribution to 50,000 km/s (c.f. 10,000 km/s in CfA survey)

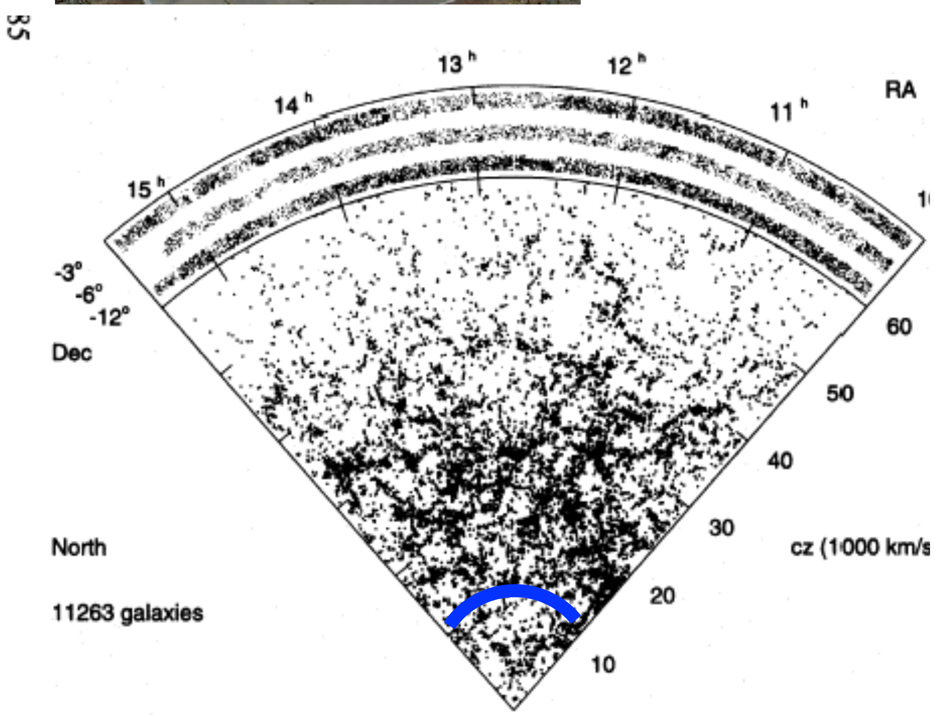


FIG. 8g

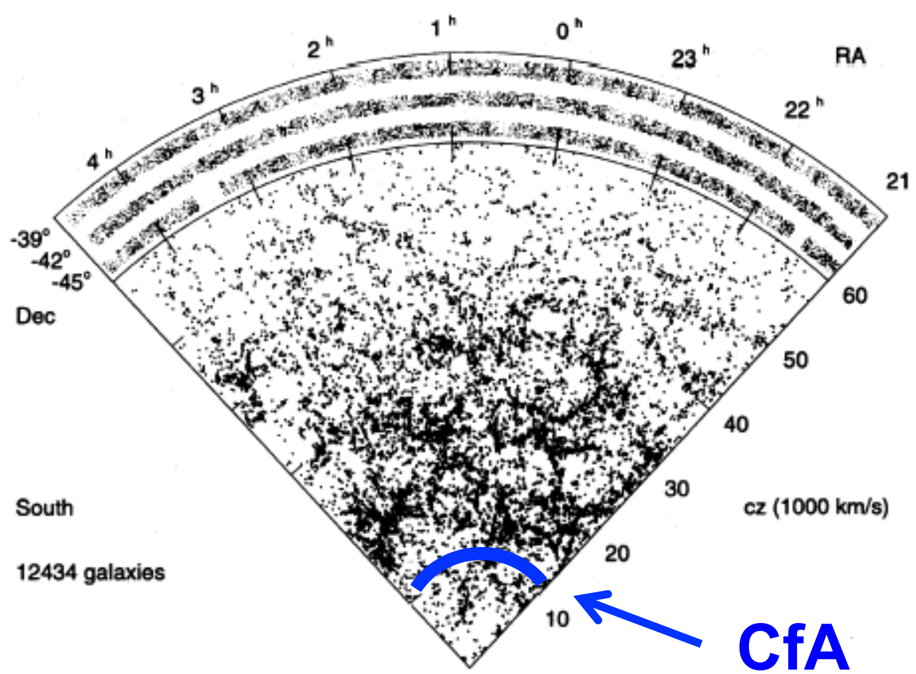
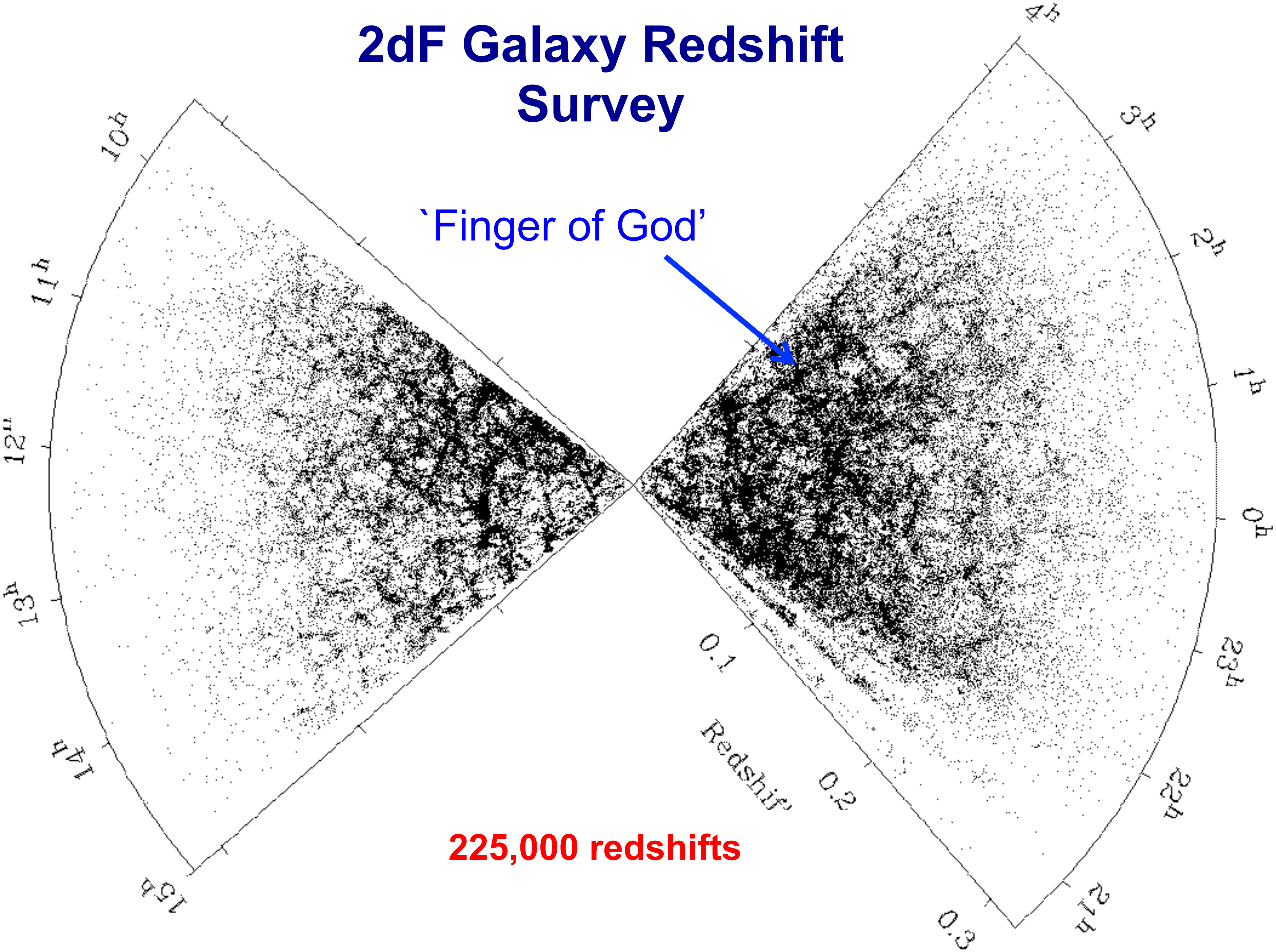


FIG. 8h

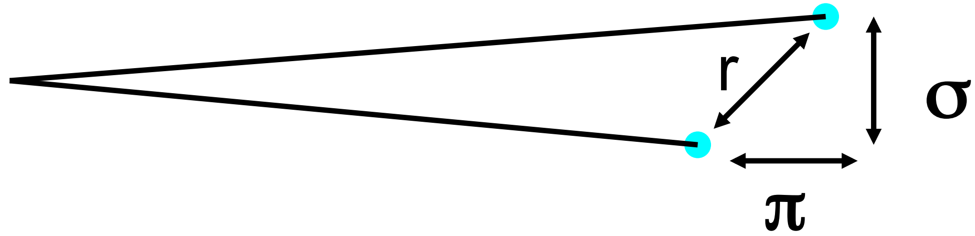
26412 gals R <17.7

Shectman et al 1996 Ap J 470, 172

2dF Galaxy Redshift Survey



2dF redshift space distortions



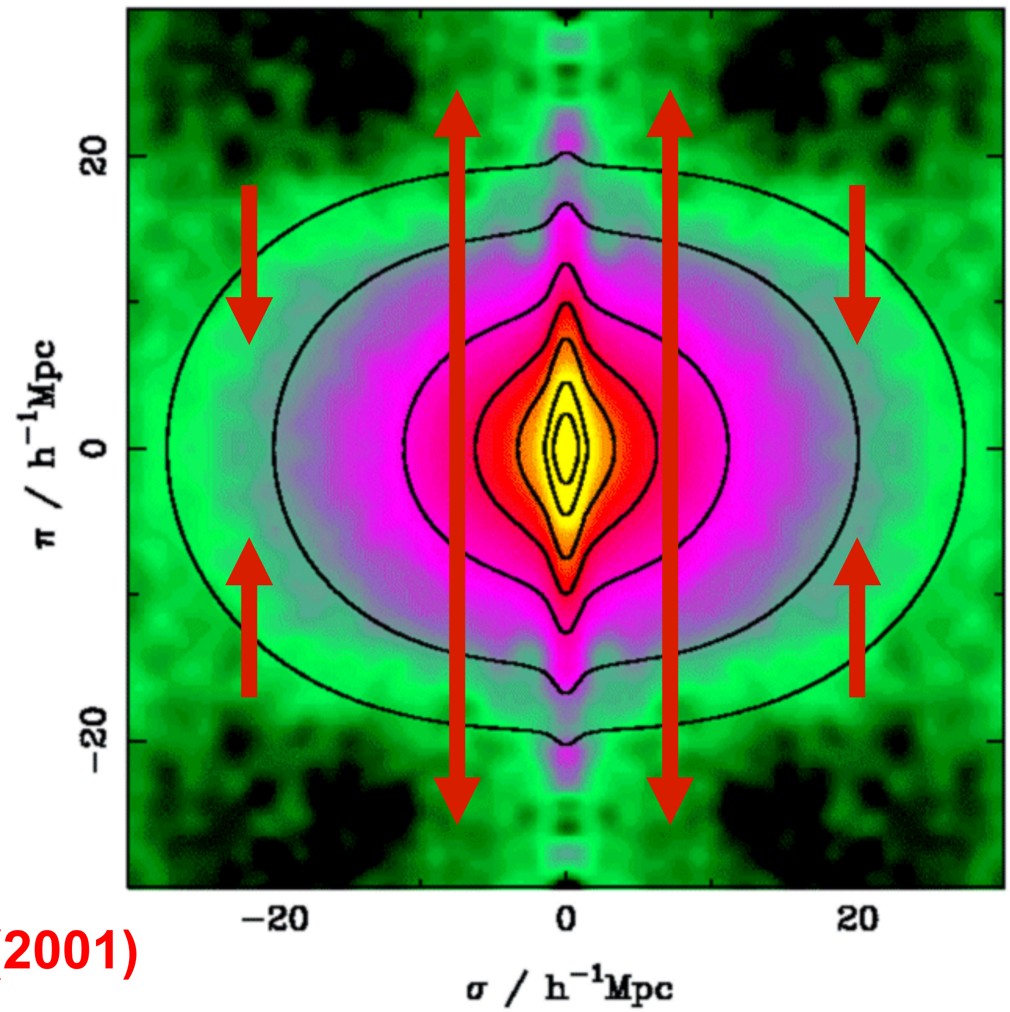
Galaxy distribution is distorted by peculiar velocities of galaxies induced by their mutual gravitational attraction

Offers a way to statistically measure the mean density of gravitating matter (dark + visible)

First applied in Peebles (1979) and Bean et al (1983).

In 2dF survey:

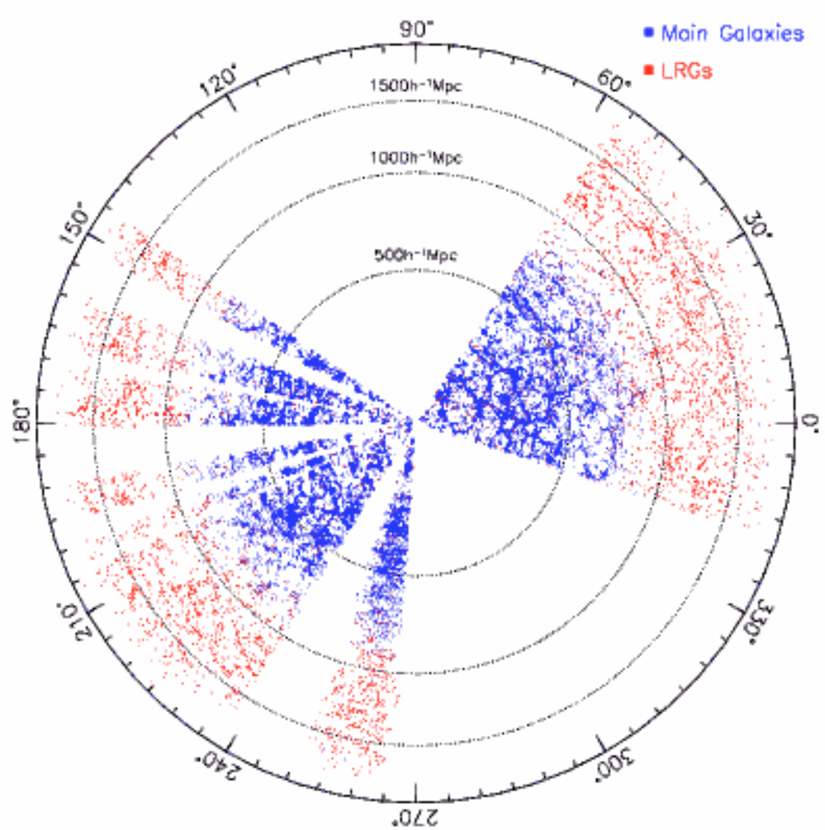
→ Ω ~ 0.25, insufficient to halt the cosmic expansion

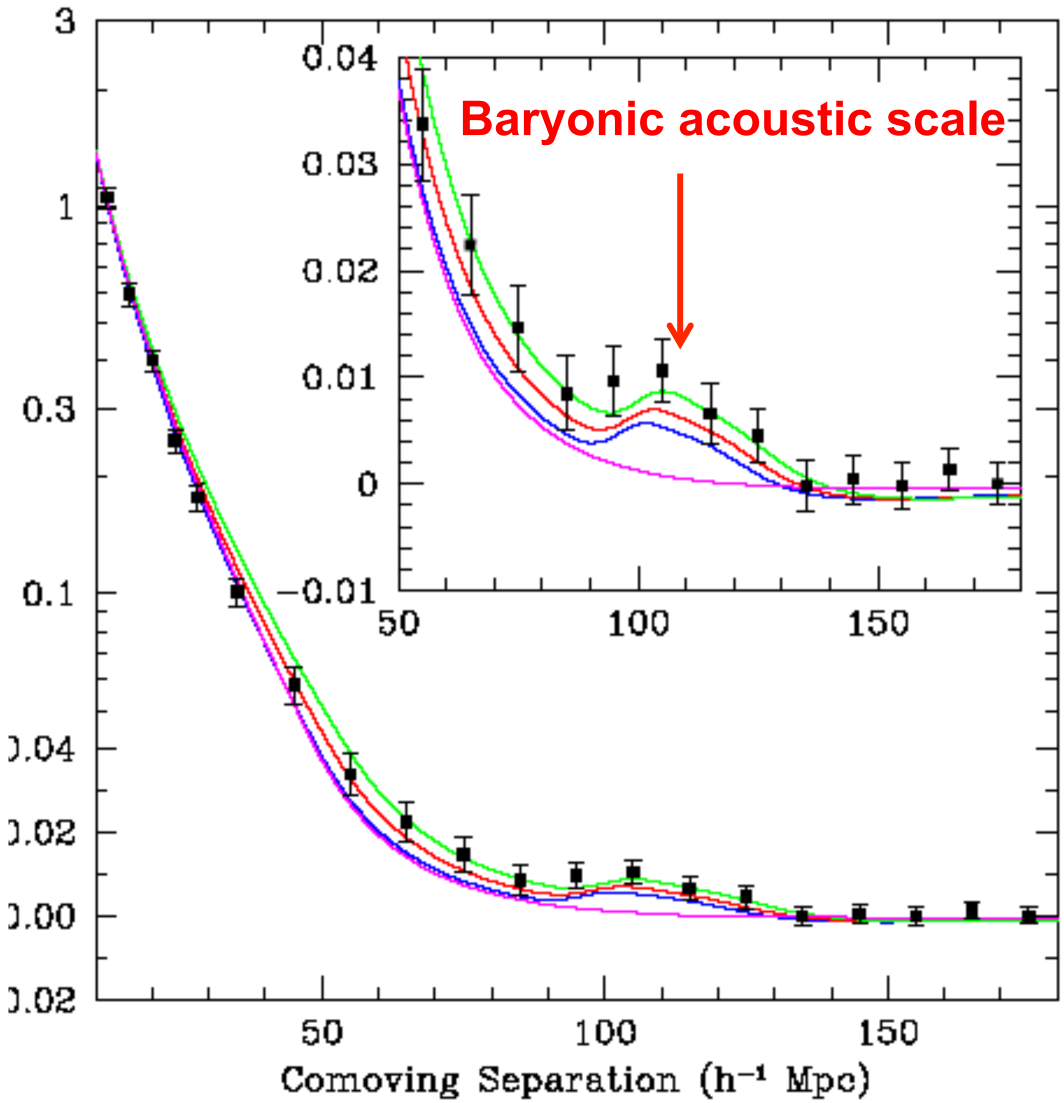


Peacock et al, Nature, 410, 169 (2001)

Clustering of SDSS red galaxies

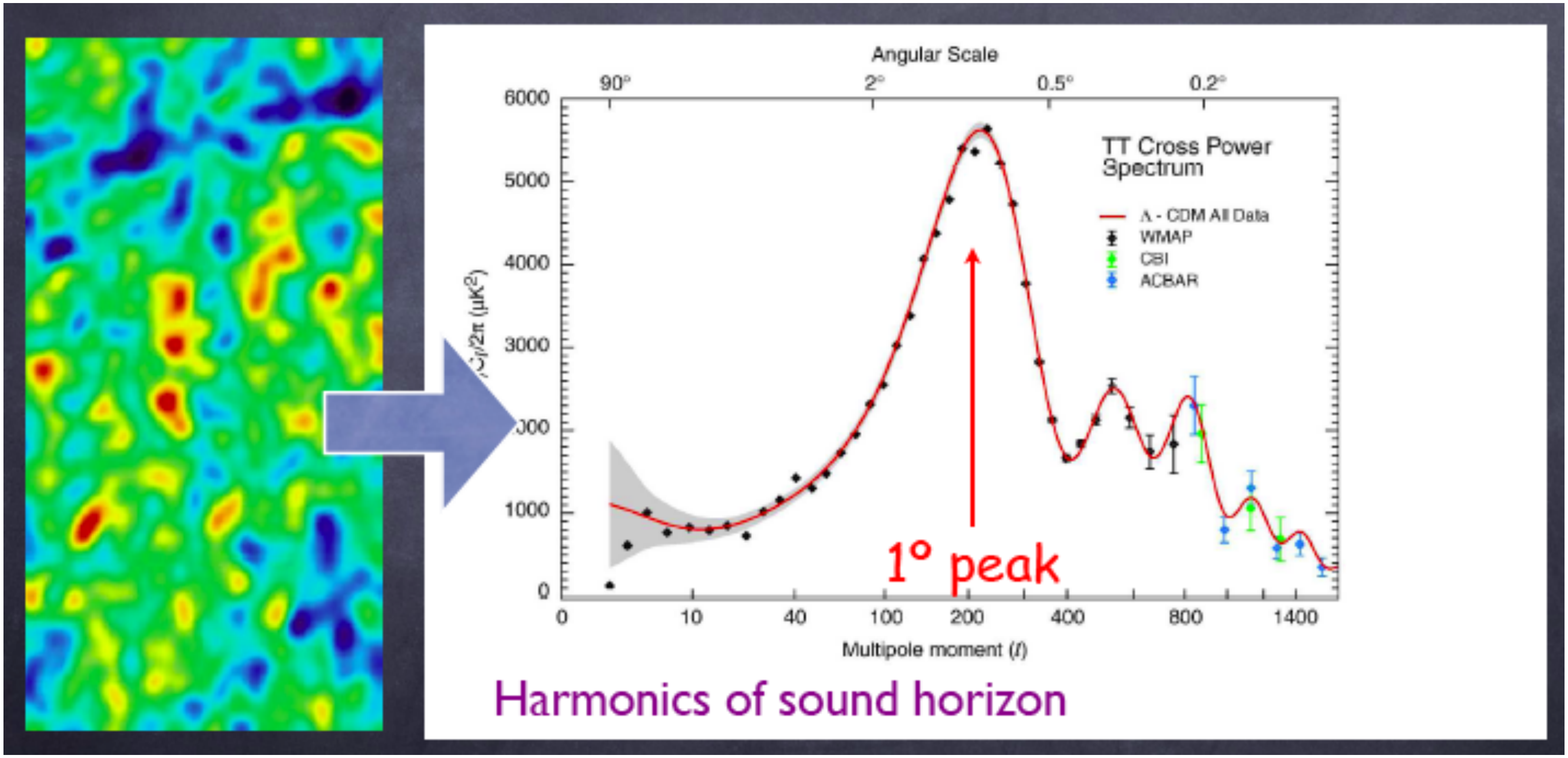
SDSS (and 2dF) discovered a coherent pattern in the distribution of galaxies on very large scales (120 Mpc)





Eisenstein et al (2005) Ap J 633, 560; also Cole et al (2005) MNRAS 362, 505

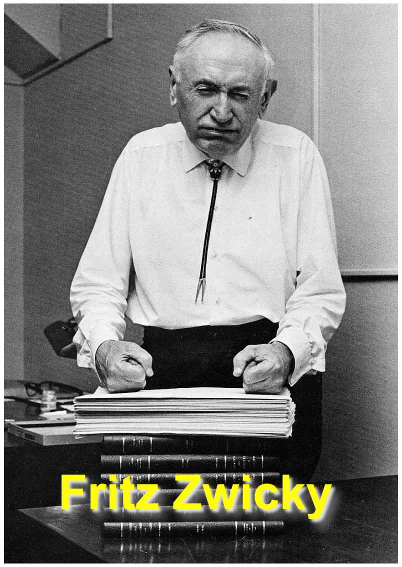
Origin of the Baryonic Acoustic Scale

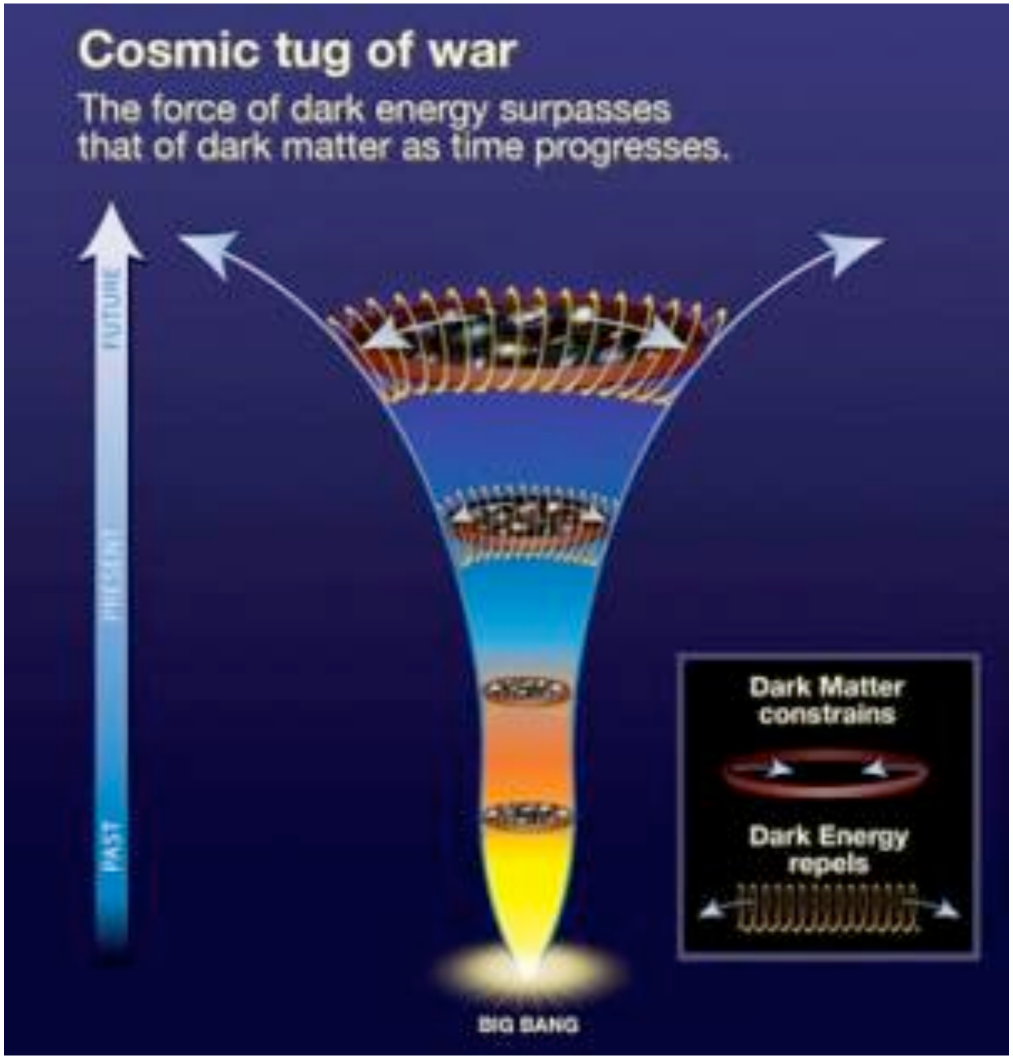


Relic of primary acoustic peak seen in cosmic microwave background radiation which has freely expanded with Universe since it was 300,000 yrs old. Its measurement at various look-back times offers a way to directly trace the history of the expansion

Predicted theoretically by Peebles & Yu 1970; Sunyaev & Zel'dovich 1970

Dark Matter vs Dark Energy





Extensive deep galaxy surveys would provide an empirical measure of the expansion history (independent of any theoretical formalism)

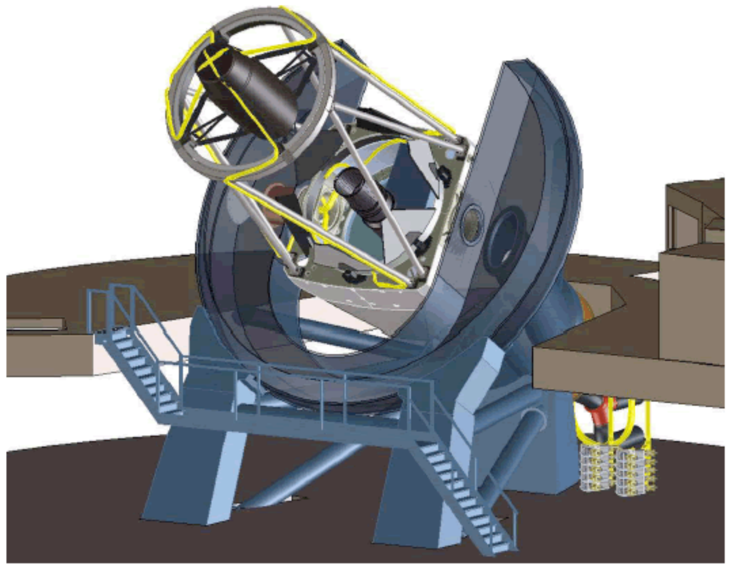
Next Generation Galaxy Surveys

4MOST

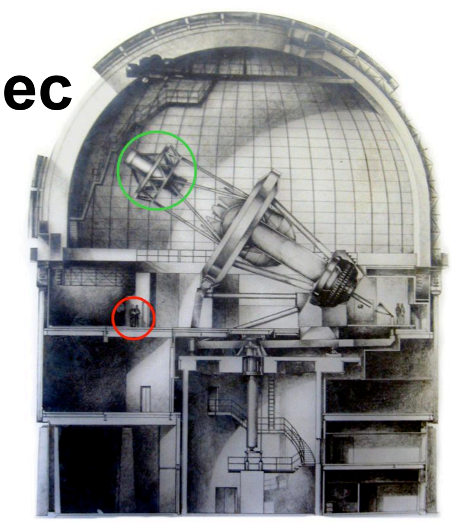
4-meter Multi Object Spectroscopic Telescope

Proposal for a Conceptual Design Study for ESO

BigBOSS



DESpec

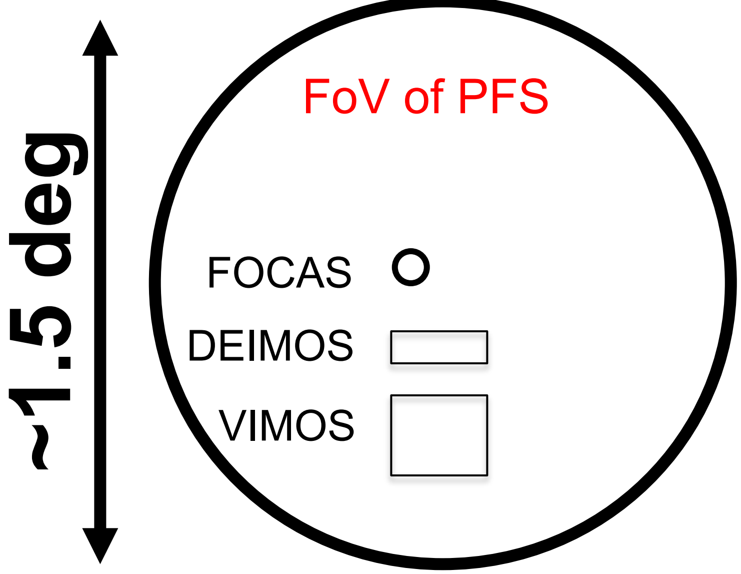


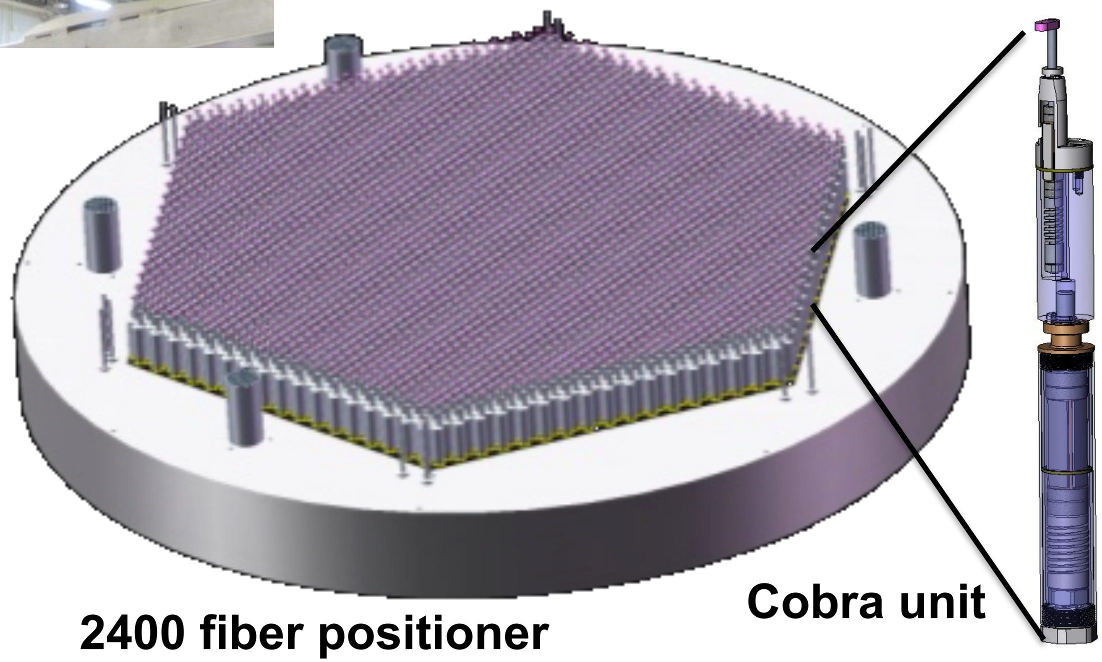
A new generation of massively-multiplexed spectroscopic surveys motivated by the need to measure the baryonic acoustic scale over the past 10 billion years.

A valuable probe of dark energy (in addition to other measures)

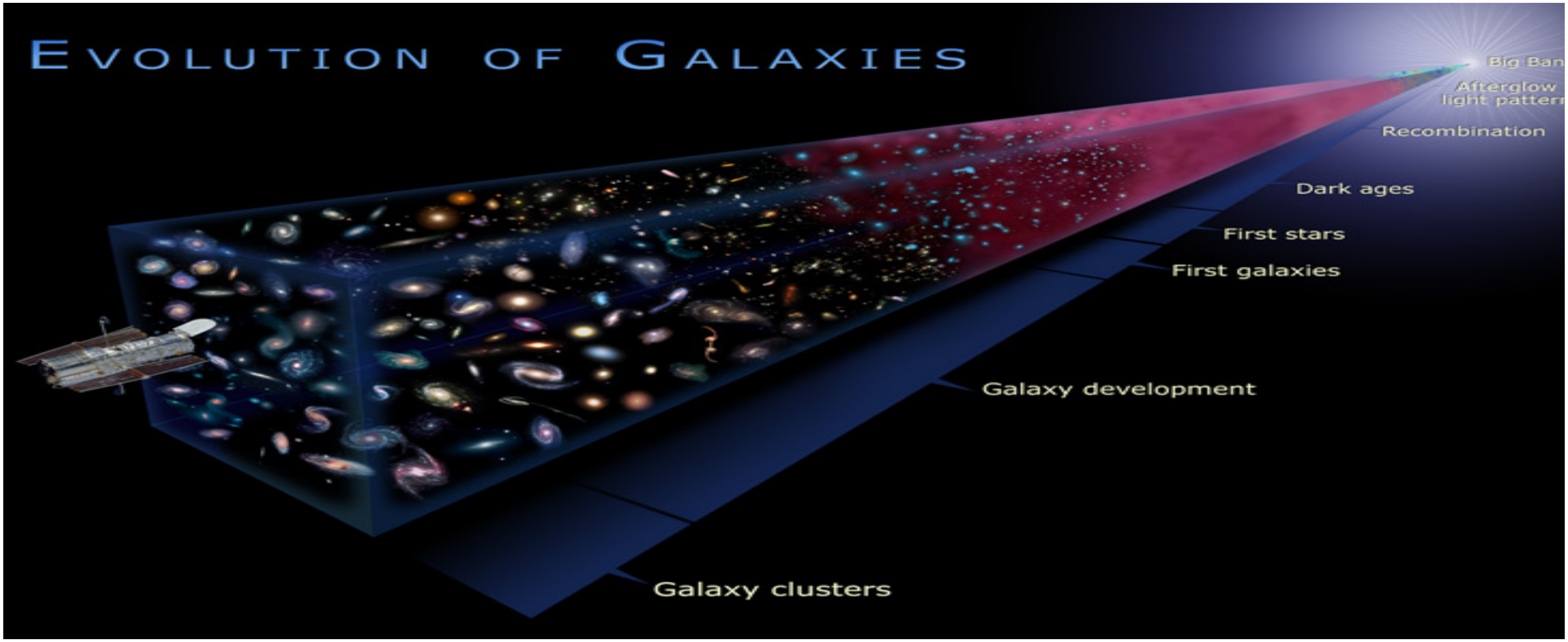
Subaru Prime Focus Spectrograph (PFS)

PFS is a collaboration between Caltech/JPL, Princeton, JHU and Japan) addressing the expansion history over the past 10 billion years through measures of the baryonic acoustic scale at various `look-back times'. A survey of 4 million galaxies to z~2.4 is proposed (2017-2022)



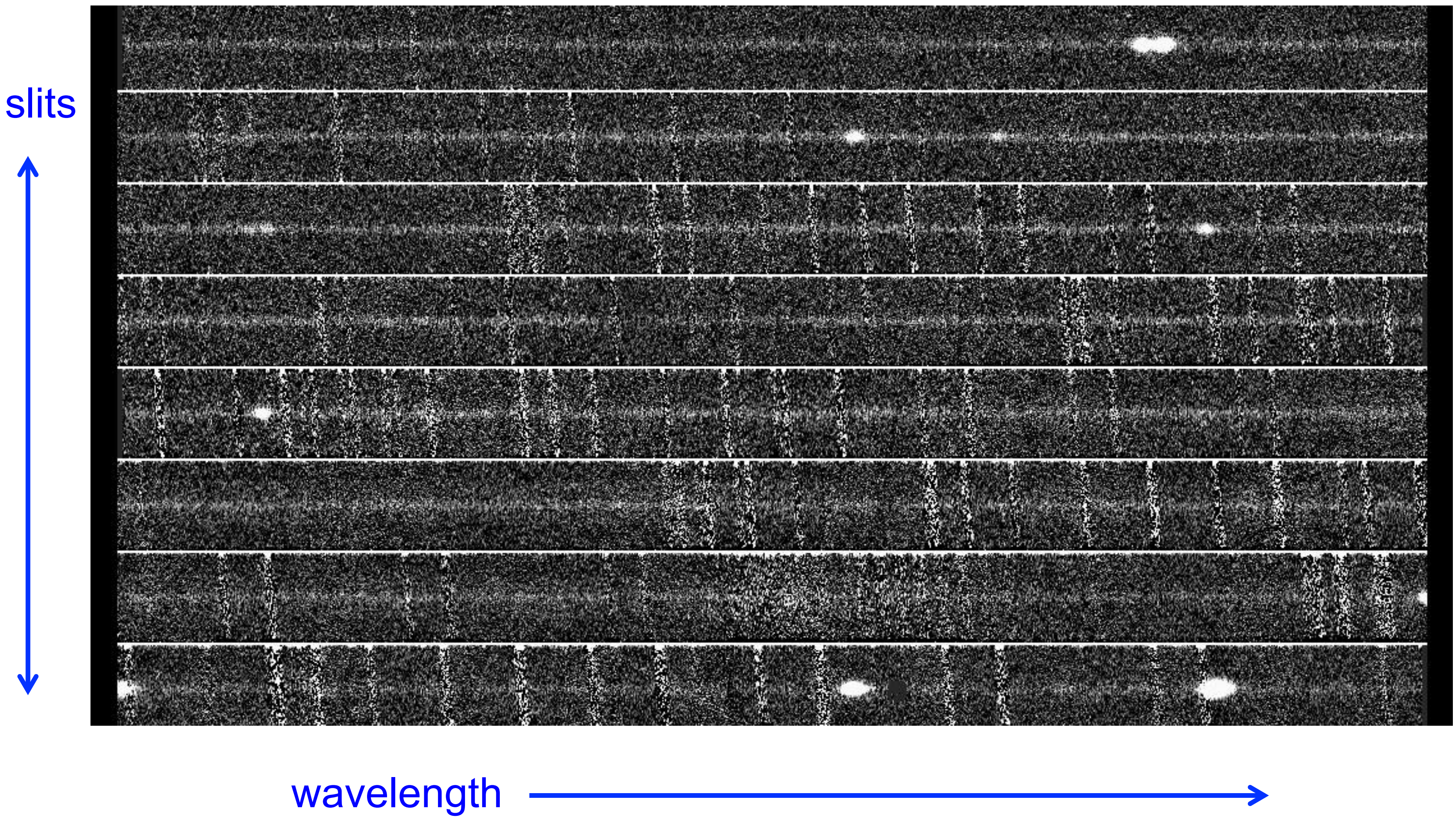


Multi-Slit Technologies: Looking Back in Time



Galaxy redshift surveys have also been influential in charting the ***evolving properties of galaxies over cosmic time*** – determining the mass assembly history, origin of the Hubble sequence of morphological types and searching for the earlier systems

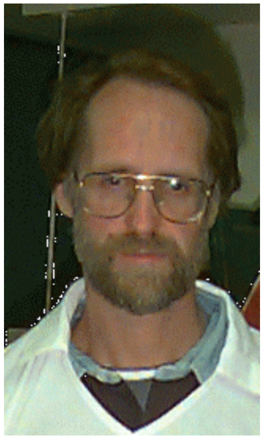
Advantages of Multi-slit Spectroscopy



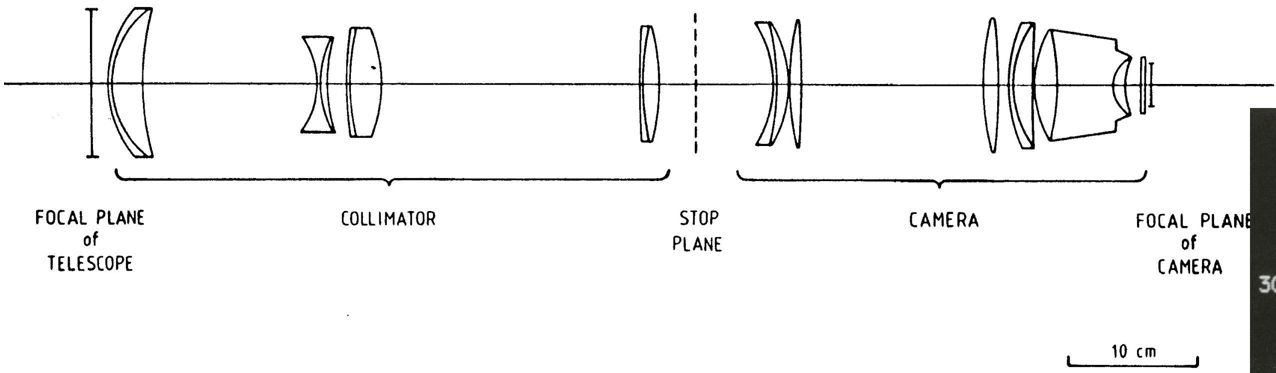
With a 2-D detector each `mini-slit' produces a spectrum of the galaxy and an adjacent portion of the night sky. The initial challenge was the limited field of view c.f. fiber-fed spectrographs

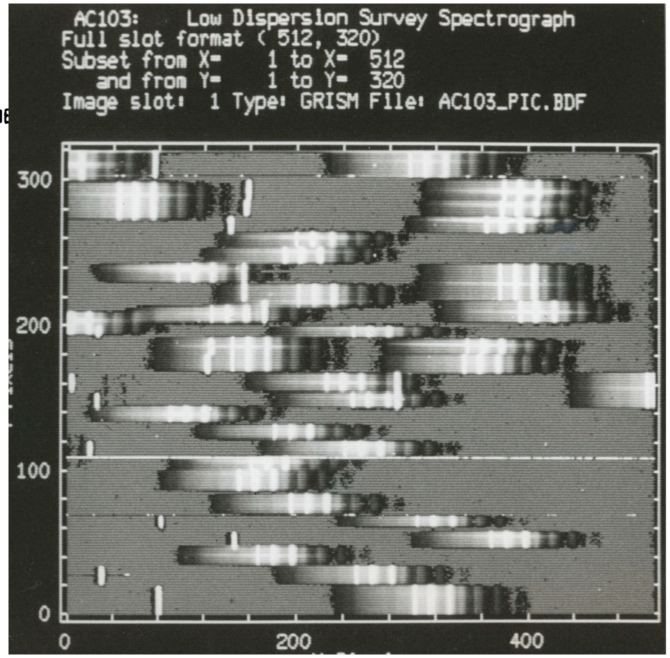
Low Dispersion Survey Spectrograph (LDSS-1)

- Revolutionary optical design by C.G. Wynne gives ***<u>12.3 arcmin FOV</u>***
- Mar 1984: Keith Taylor as Project Scientist
- Optics fabrication delayed due to difficulties with fragile glass FK54
- May 1986: commissioned at AAT
- LDSS-2 commissioned at WHT (now at Magellan)



Taylor





Whereas fiber spectrographs reached to m~21.5, multi-slit spectrographs on 4m telescopes (Cryocam, LDSS-1/2, EFOSC, EMMI) reached to m~24 due to improved sky subtraction.

Mon. Not. R. Astron. Soc. 273, 157–168 (1995)

LDSS-1/2 Redshift Survey

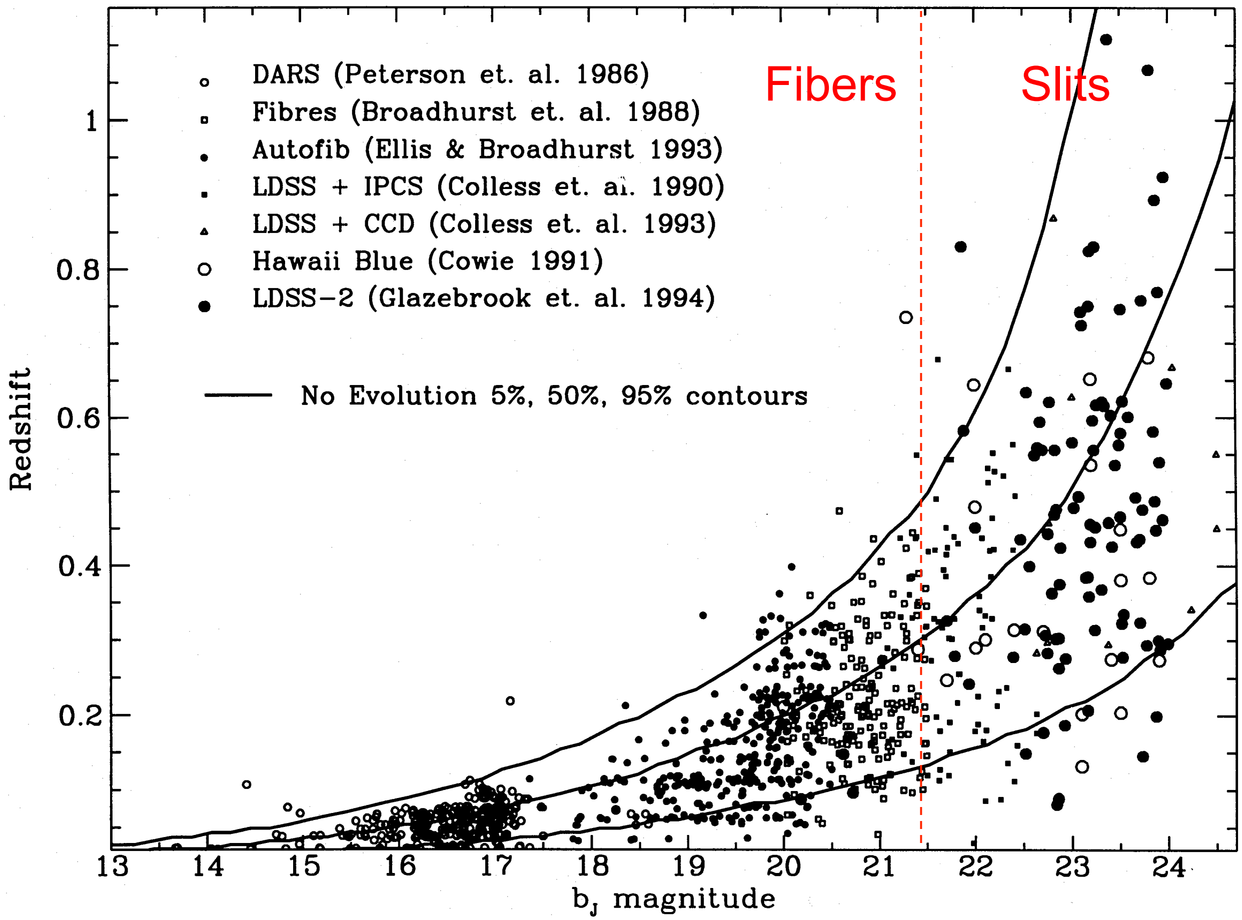
A faint galaxy redshift survey to $B = 24$

Karl Glazebrook,[1★] Richard Ellis,[2] Matthew Colless,[3] Tom Broadhurst,[4] Jeremy Allington-Smith[1] and Nial Tanvir[2]

[1] *Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE*
[2] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[3] *Mt. Stromlo and Siding Spring Observatories, Australian National University, Weston Creek, ACT 2611, Australia*
[4] *Department of Physics and Astronomy, The John Hopkins University, Baltimore, MD 21218, USA*

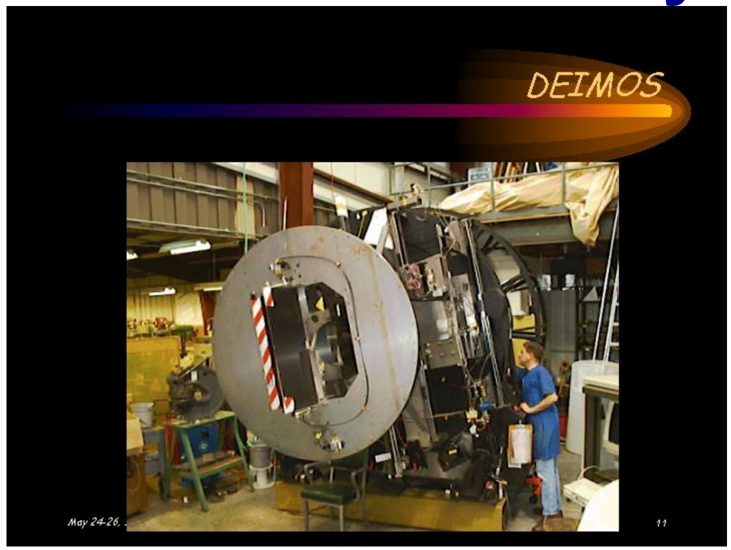
Colless

A succession of AAT surveys (fibers+slits) demonstrated galaxy evolution as a function of time and luminosity. Key to this result was the extension to z~1 from LDSS multi-slit data

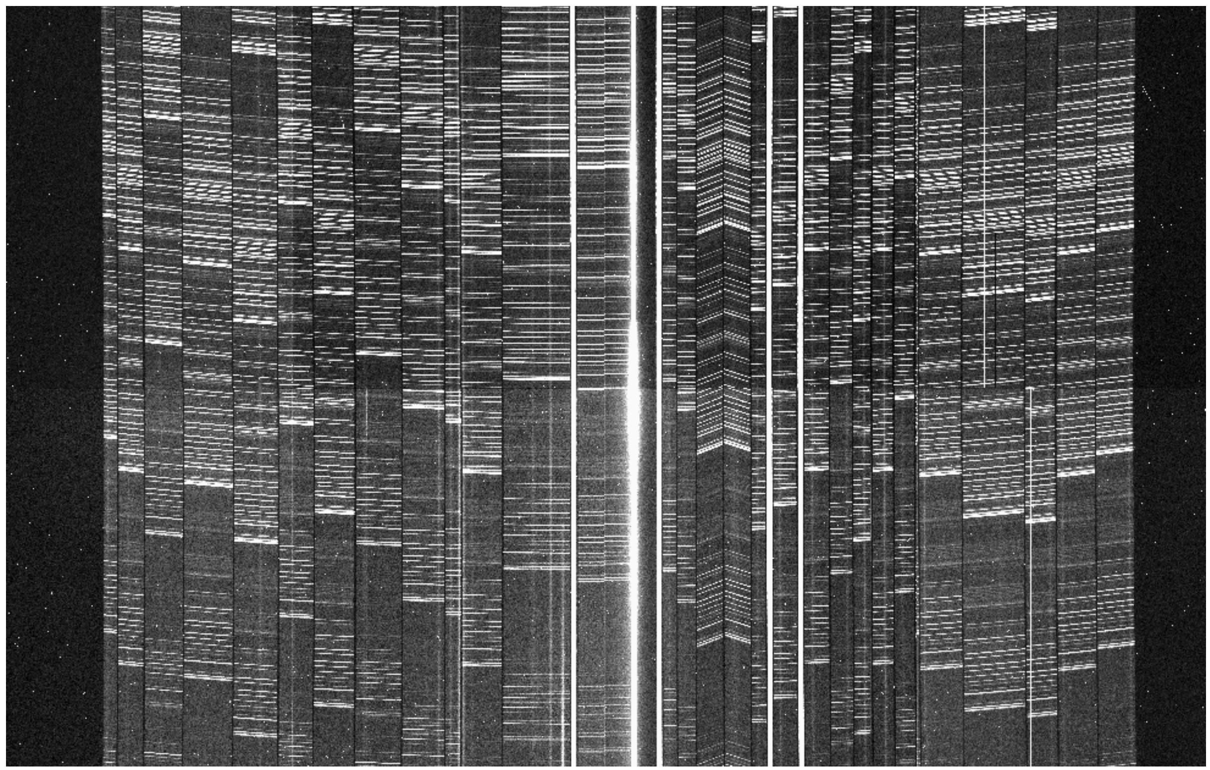


DEIMOS at Keck Observatory

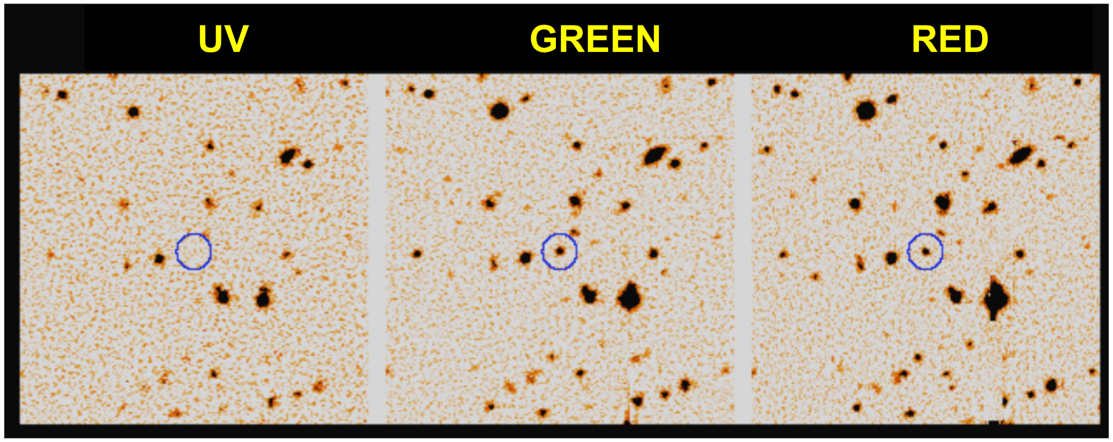
Faber



DEIMOS provided a large field (15 × 5 arcmin) via a mosaic of CCD detectors on a 10 meter aperture enabling surveys of ~30,000 faint galaxies to m~24 and a detailed understanding of galaxy evolution since z~1.5 (9 Gyr ago)



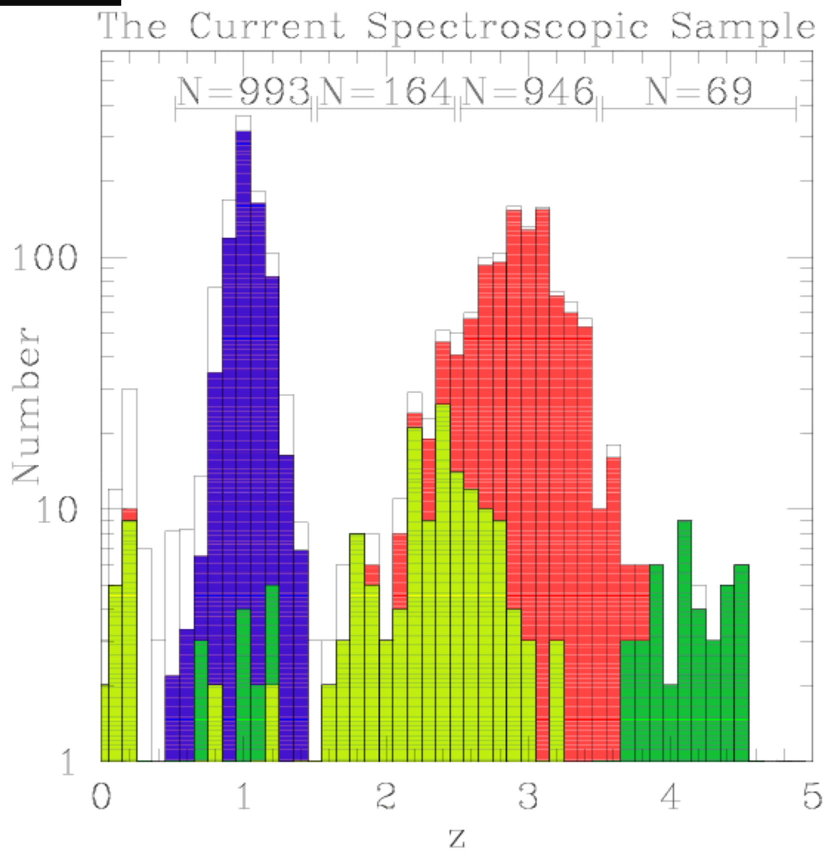
Star-forming galaxies at higher z



Steidel

Via a novel 2 color-selection technique, Steidel et al located the first convincing population of star-forming galaxies at redshift 3 (when the Universe was only 2 Gyr old – 15% of its present age).

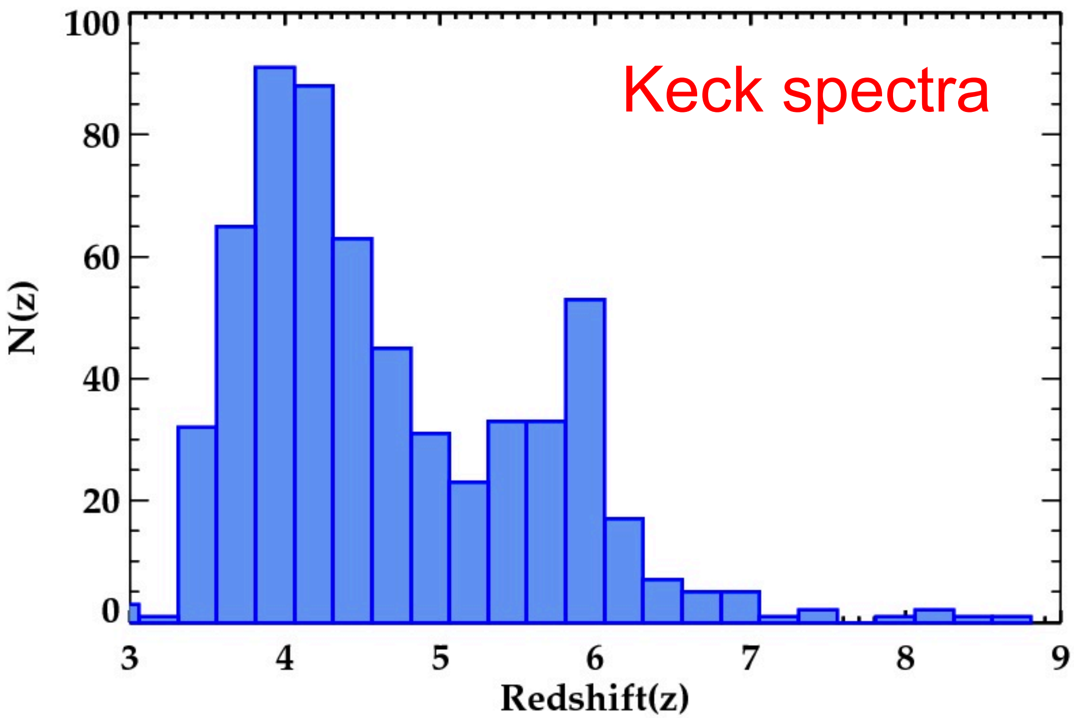
Over 1996-2003 they secured ~1000 redshifts at z~3



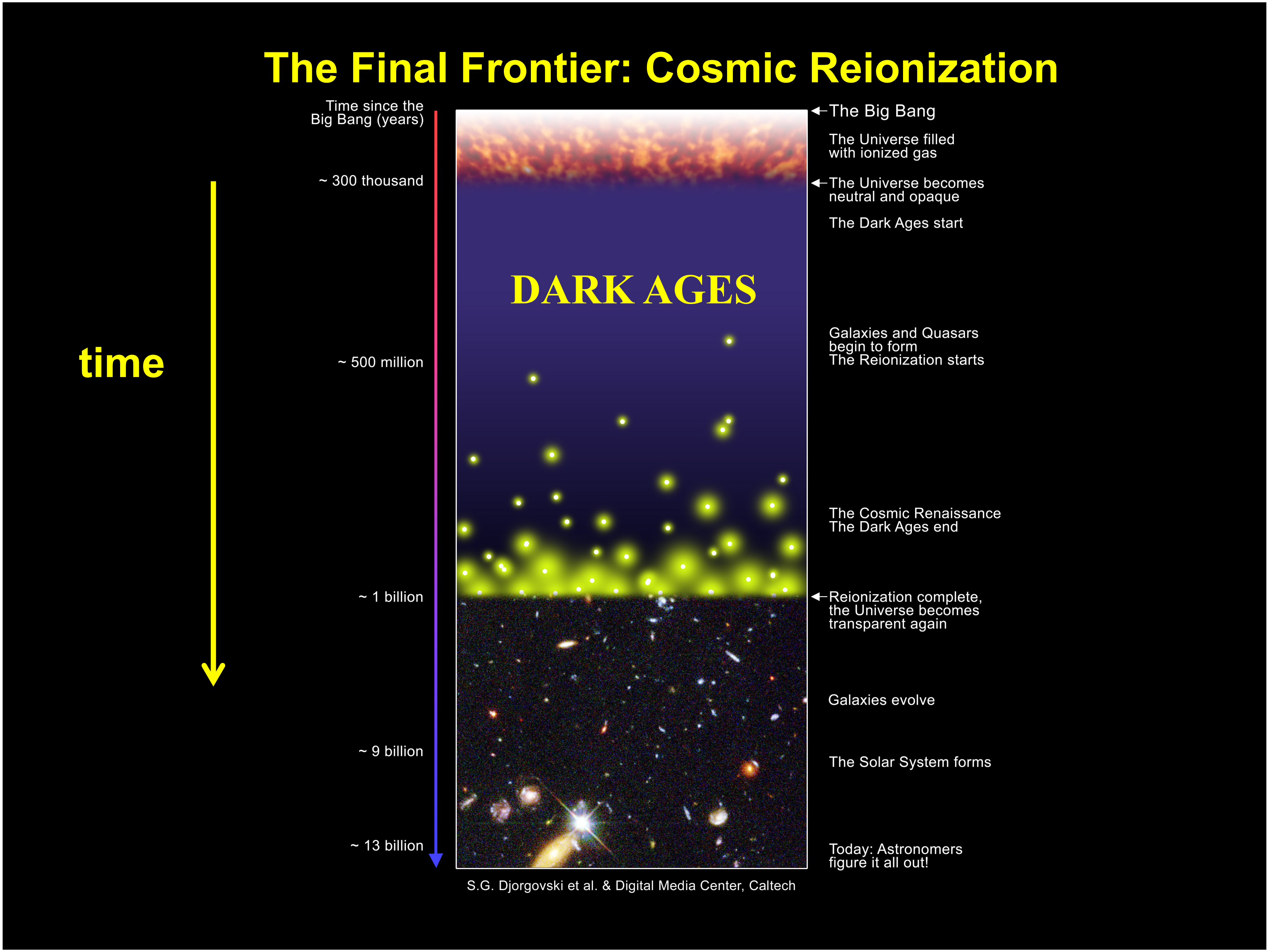
Steidel et al 1999 Ap J 462, L17
Steidel et al 1999 Ap J 519, 1
Steidel et al 2003 Ap J 592 728

Stark

From a selection of over 3000 targets from Hubble Space Telescope imaging, Keck has now secured spectra for almost 1000 galaxies over 3<z<7 to m~27, many involving 2 night exposures

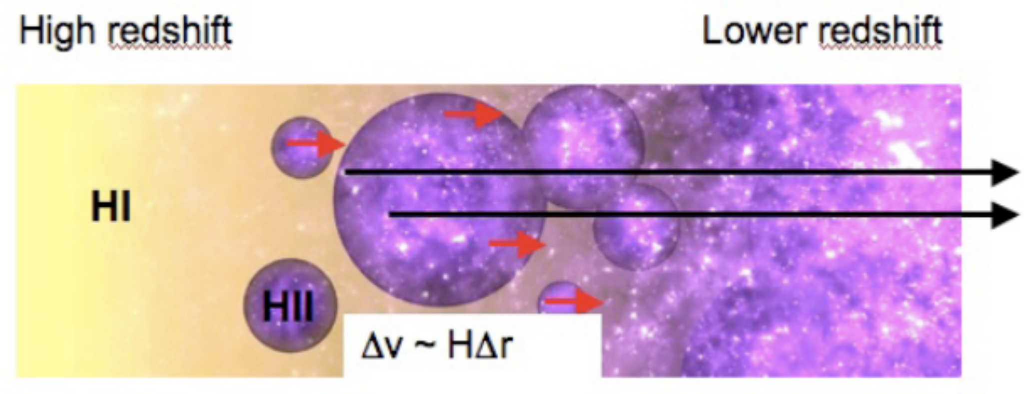


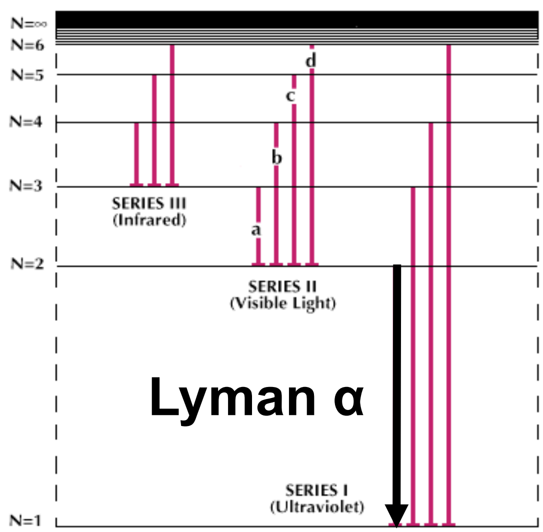
Stark et al 2010 MNRAS 408, 1628; Stark et al 2011 Ap J 728, L2


The Final Frontier: Cosmic Reionization
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
time
DARK AGES
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

When did Reionization End?

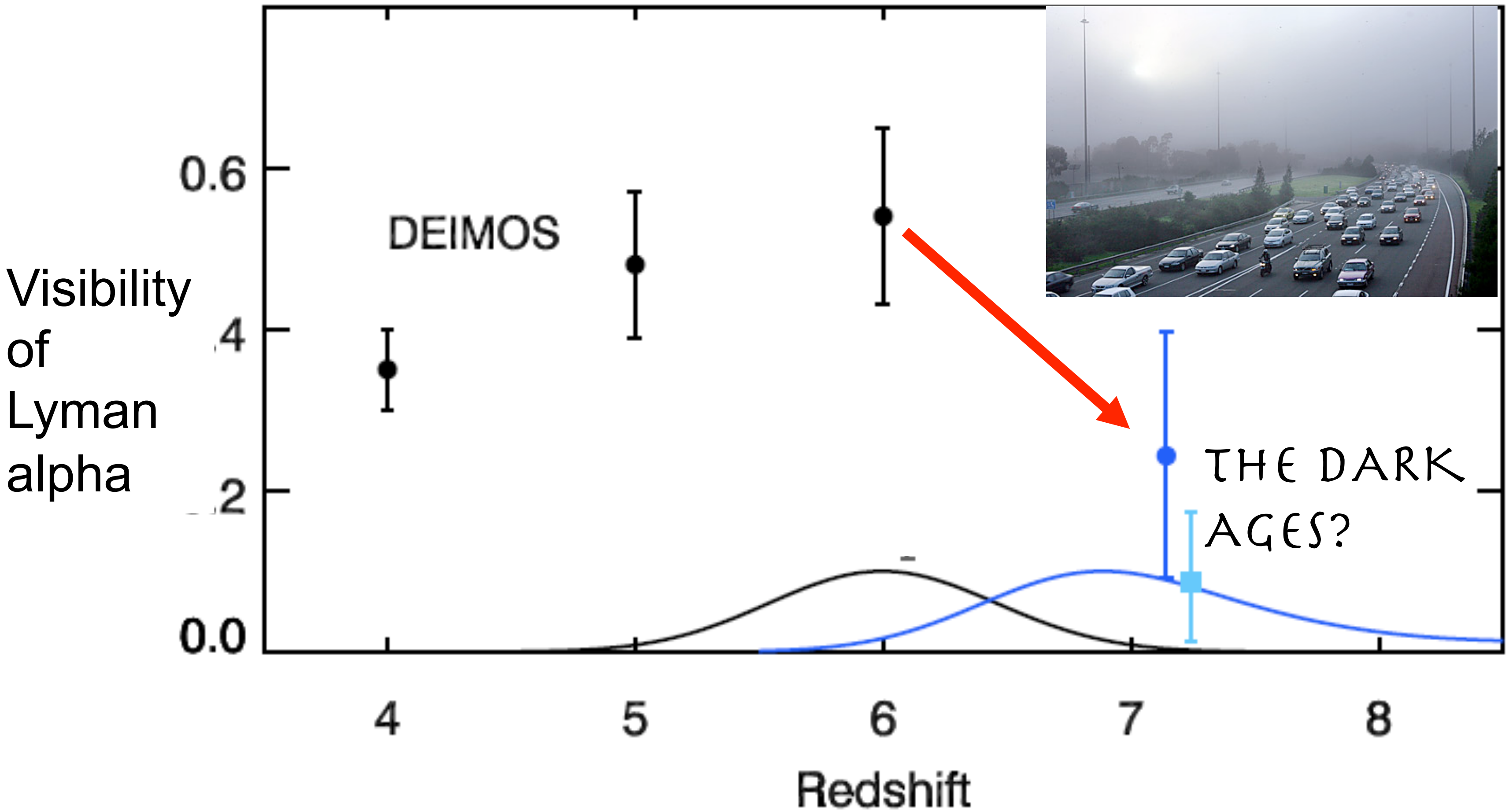
- Lyman α spectrum line is scattered by hydrogen along the line of sight and thus can trace its presence
- `Dark Ages' acts as fog obscuring the line emission from young galaxies
- A drop in the visibility of line may indicate the Dark Ages





Energy Levels of Hydrogen

Sudden Drop in Lyman Alpha Emission

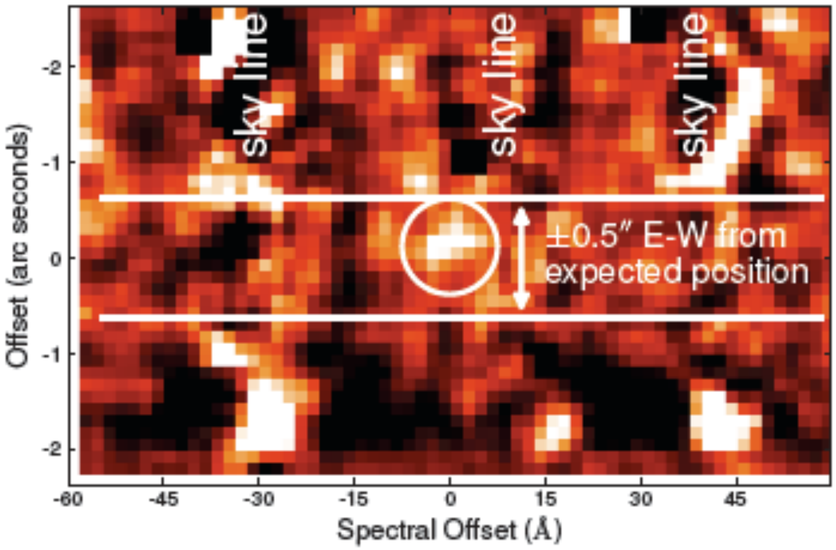


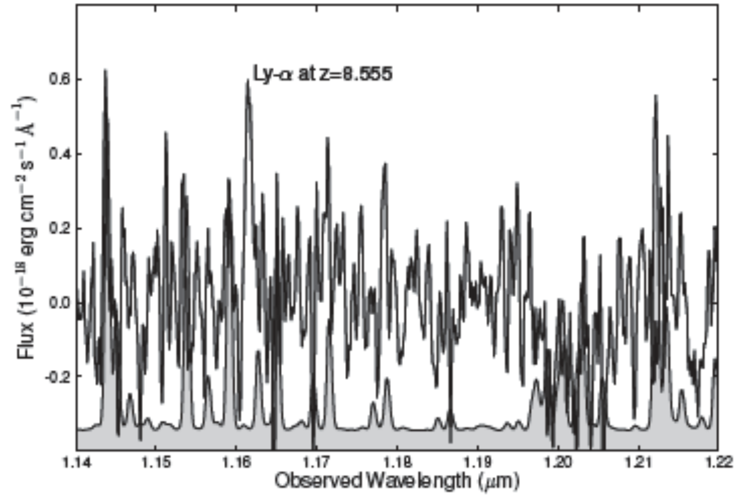
The decline in the visibility of Lyman alpha emission beyond redshift 7 may indicate we have entered the Dark Ages

Schenker et al Ap J 744, 179 (2012)

Controversies remain: a z=8.55 galaxy?

UDFy-38135539 = HUDF-YD3



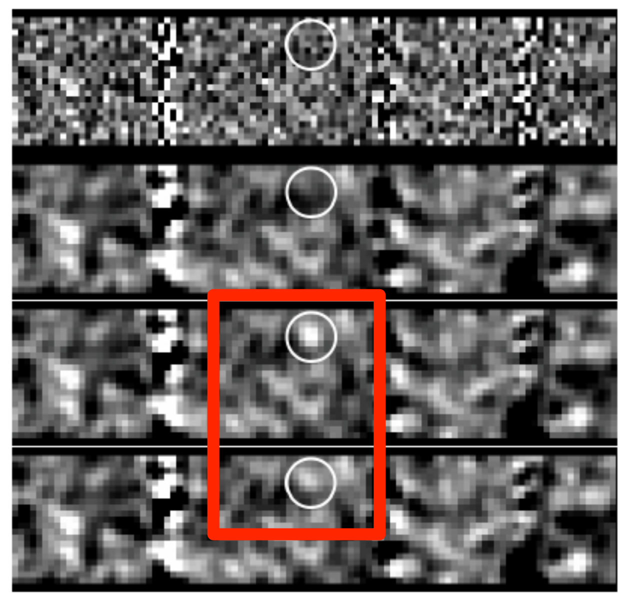


Lehnert et al (2010) VLT
SINFONI 14.8 hours R~2000
Claims 6.0σ detection

Bunker et al (2012) VLT X-Shooter
5 hours R~5100
Expected 3.5-4.5σ detection
but sees nothing

data

simulation



Spectroscopy at the frontier…

A warning from an independent commentator…

DAVE BARRY

Over the years I have been harshly critical of the scientific community for wasting time researching things nobody cares about, such as the universe. I don't know about you, but I'm tired of reading newspaper stories like this:

"Using a giant telescope, astronomers at the prestigious Crudwinkle Observatory have observed a teensy light smudge that they say is a humongous galaxy cluster 17 jillion light years away, which would make it the farthest-away thing that astronomers have discovered this week. However, astronomers at the rival Fendleman Observatory charged that what the Crudwinkle scientists discovered is actually mayonnaise on the lens. Both groups of astronomers say they plan to use these new findings to obtain even larger telescopes."

Next Generation Telescopes

A new generation of 30-40m class telescopes are being considered that will exploit adaptive optics and enhanced instruments to provide a much clearer view of the early Universe. Spectroscopy will remain the main tool of these facilities