# DEIMOS First Science Results: The DEEP2 Redshift Survey

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# The DEEP2 Collaboration

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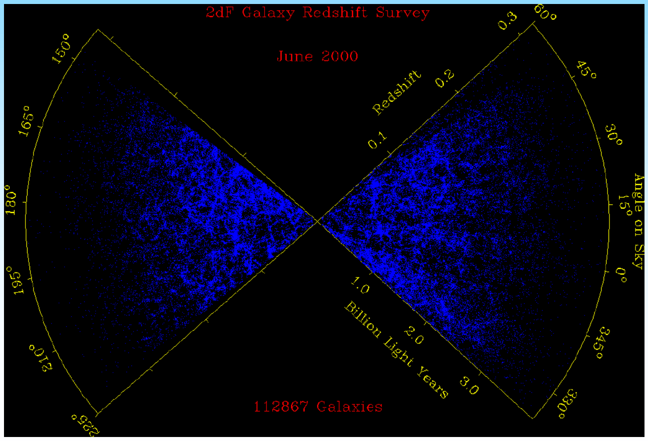
## How was the Universe different when half its current age?

A new generation of redshift surveys (Sloan, 2dF) are making comprehensive studies of the local Universe possible - **but how did it reach the current state**?

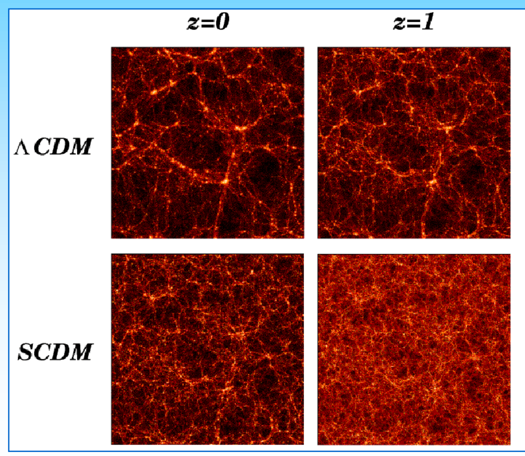



## **Redshift Surveys** have been vital to our understanding of the Universe

- The original CfA1 Survey revealed the highly biased, filamentary nature of the galaxy distribution, motivating some of the first numerical simulations of LSS
  - *Measured ~2000 redshifts at a rate of ~25/clear night, using a 1.5m telescope*
- Surveys more than 10 times as large have been completed since (e.g. LCRS)
  - *Provide strong constraints on $\xi(r)$ and higher order correlations, galaxy luminosity functions, properties of galaxies, etc.*
- Huge surveys are currently underway: e.g. SDSS and 2DF-GRS
  - *Will provide definitive measures of statistics of the local ($z < 0.2$) galaxy distribution, of great interest for testing cosmological models (e.g. via power spectrum constraints)*
  - *Detailed studies of galaxy properties, weak lensing, etc.*

## Surveys of distant galaxies can constrain both galaxy formation and cosmology...

- The evolution of large-scale structure is strongly dependent on the underlying cosmology.
- By comparing the universe at high redshift to what is seen by large local surveys, many unique cosmological tests can be performed; while simultaneously the evolution of galaxies may be studied!




## Scientific Goals of the DEEP2 Redshift Survey

1) Characterize the properties of galaxies (colors, sizes, linewidths, luminosities, etc.) at $z$~1 for comparison to $z$~0
2) Study the clustering statistics (2- and 3-pt. correlations) of galaxies as a function of their properties, illuminating the nature of the galaxy bias
3) Measure the small-scale "thermal" motions of galaxies at $z$~1, providing a measure of $\Omega_m$ and galaxy bias
4) Determine the apparent velocity functions of galaxies and clusters at high redshift, providing constraints on fundamental cosmological parameters

## Two surveys in one

**1-Hour Survey (1HS)**

- 3.5 sq. degrees
- ~65,000 targets
- >50,000 redshifts
- $\sim 6 \cdot 10^6\, h^{-3}$ Mpc$^3$
- 90 Keck nights
- One-hour exposures
- $R_{AB} \leq 24.1$ mag
- Linewidths for ~ 70%

**3-Hour Survey (3HS)**

- deeper over a smaller area
- ~7000 targets
- >5000 redshifts
- $\sim 10^5\, h^{-3}$ Mpc$^3$
- 30 Keck nights
- Three-hour exposures
- $R_{AB} \leq 24.5$ mag
- Linewidths for ~ 70%

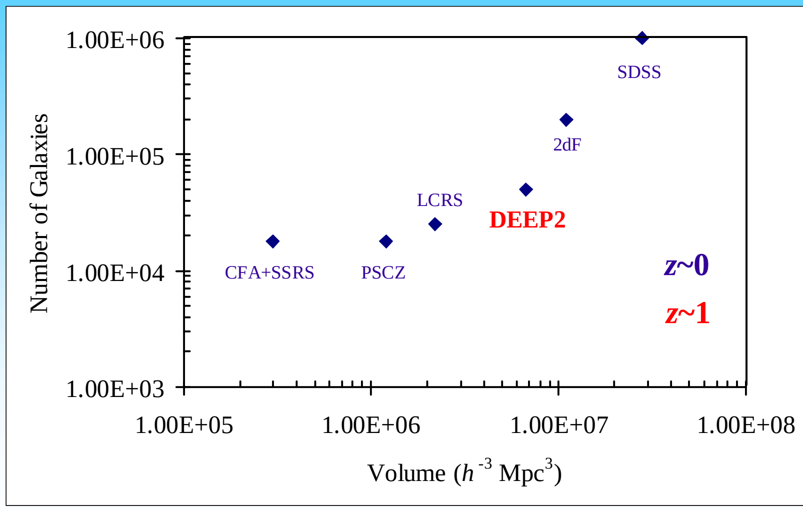
**Keck access: 80 nights of UC time and 40 nights of Caltech time over a 3-year period**

**Observing season: April-October**

## The DEEP2 1HS in brief

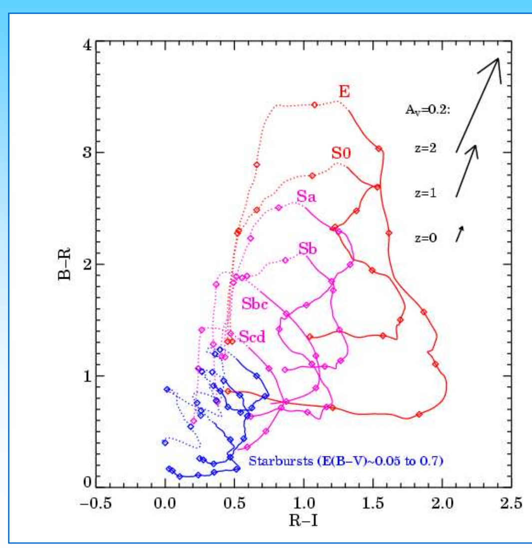
- **4 Fields:** 14 17 +52 30 (includes Groth Survey Strip)
  16 52 +34 55 (zone of very low extinction)
  23 30 +00 00 (on deep SDSS strip)
  02 30 +00 00 (on deep SDSS strip)
- **Field dimensions:** 30’ by 120’ (15’ × 120’ for Groth field)
- **Primary Redshift Range:** $z$=0.75-1.4, preselected using *BRI* photometry to eliminate objects with $z$<0.75
- **Comoving Volume:** ~20×80×1000 $h^{-3}$ Mpc$^3$ per field (LCDM)
- **Grating and Spectra:** 1200 l/mm: ~6500-9100 Å
  [OII] 3727Å doublet visible for 0.7<$z$<1.4
- **Resolution:** 1.0” slit: FWHM=1.7Å ≈ 68 km/s

## Comparison between DEEP2 1HS and local surveys




## CFHT *BRI* photometry is quite effective for selecting objects with $z>0.7$

- Plotted at right are the trajectories galaxies observed at $z=0$ would take in our color-color space as a function of redshift. Diamonds are plotted every 0.2 in $z$; the transition from $z<0.7$ to $z>0.7$ is marked by the change from dotted to solid lines.
- A simple curve (nearly parallel to the reddening vector) can be used to distinguish low-redshift from high-redshift objects. If we do not apply such a color cut, half the galaxies we observe would be at $z<0.7$ (and our sample would be much more dilute as a result).



# Survey strategy

Imaging: We have obtained deep CFHT 12k imaging in three bands (*BRI*) to allow photometric pre-selection of targets with $z>0.75$; otherwise, the majority of objects observed would be at lower $z$. The imaging is complete and fully reduced.

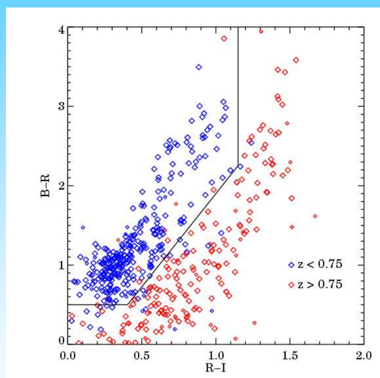
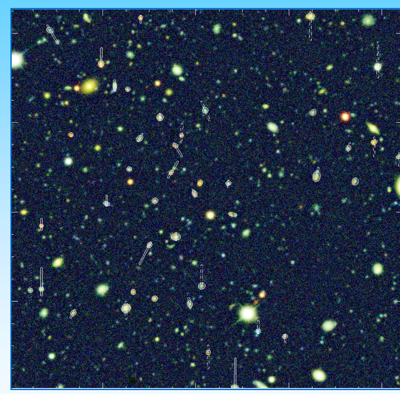


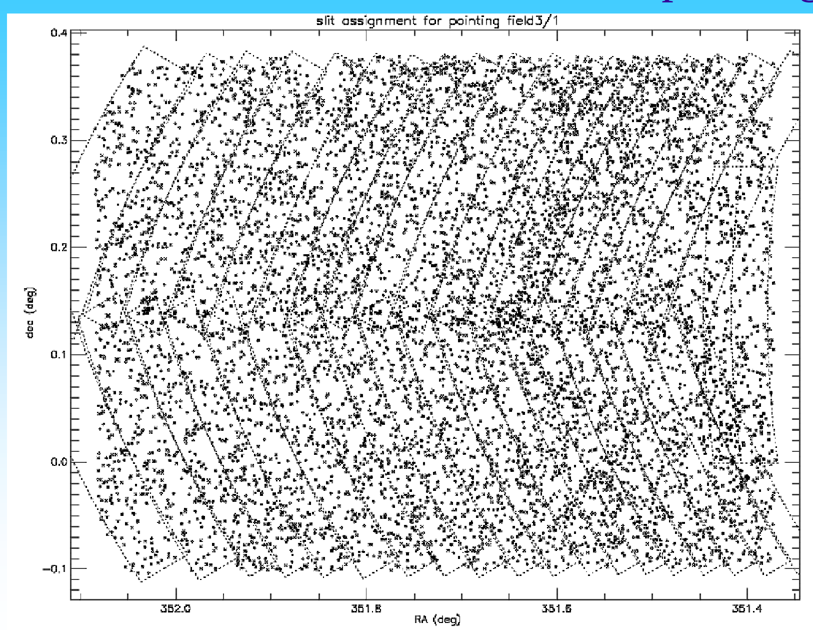

Photo-z preselection of targets



A 200″ × 200″ *BRI* image from one of our fields

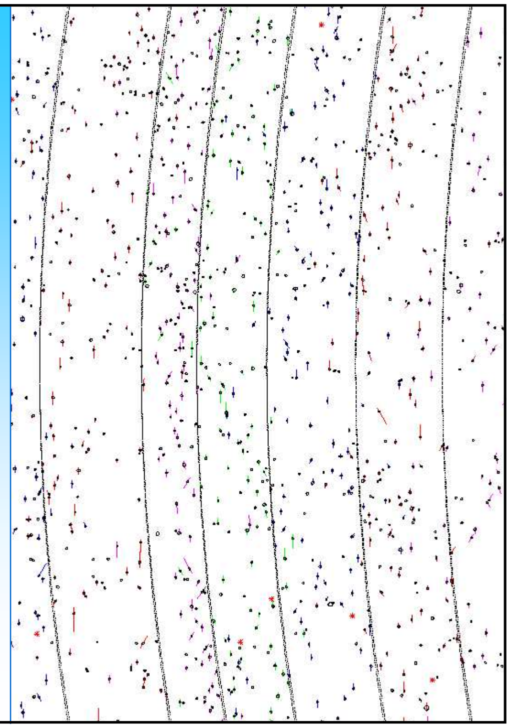
Spectroscopy: Using custom-milled slitmasks with DEIMOS we are obtaining spectra of ~120 targets at a time. A total of 480 slitmasks will be required for the 1-hour survey.

# Masks tiled across a 42’x28’ CFHT pointing



## Multipass target selection

- On a given mask, we cannot allow spectra from different objects to overlap - so tend to undersample dense regions (clusters!)
- To ameliorate this, we overlap successive masks on the sky with an adaptive tiling, giving galaxies excluded by neighbors extra chances to be observed in secondary passes
- In the figure to right, the first-pass region of each mask is drawn, and the objects are color-coded by mask. Most objects on each mask are in its primary region, but a few may be found outside.
- ~70% of all selected objects observed



## Coordinated observations in Groth field

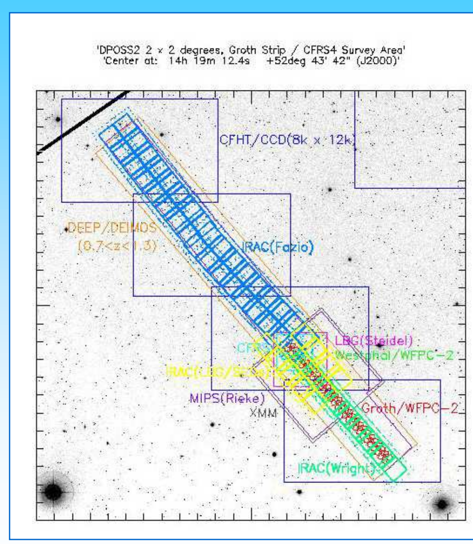
The Groth field is particularly convenient for observation from space. Many complementary observations in this field exist (e.g. XMM, HST WFPC2) or are planned (Chandra, GALEX, HST ACS, SIRTF IRAC and MIPS, S-Z, VLA).

Effectively, we will have already performed the follow-up spectroscopy these observations require with DEEP2!

**Therefore in this field, we will:**

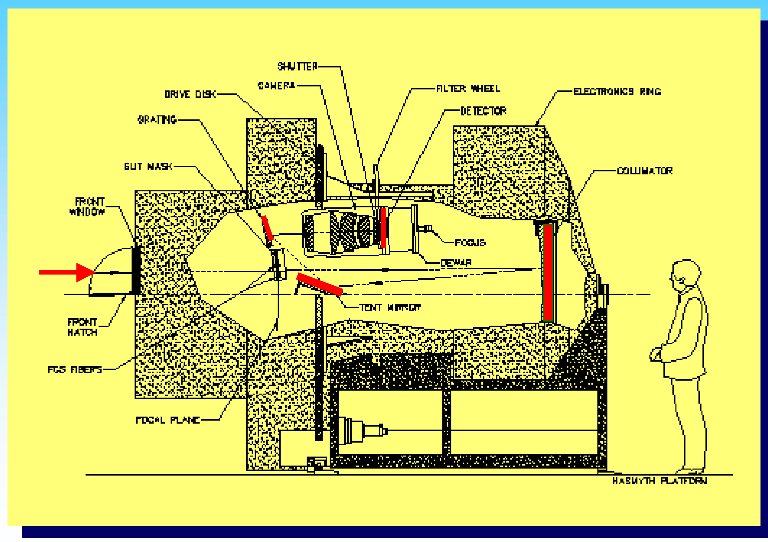
**- apply no photo-z cut**

**- survey a 15’ × 120’ region, spacing masks twice as densely as other fields**

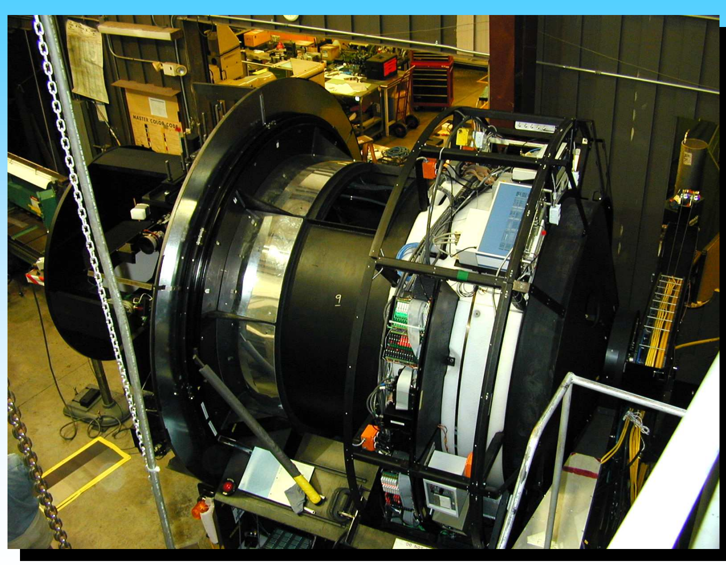


## DEIMOS Structural Overview

Deep Imaging Multi-Object Spectrograph



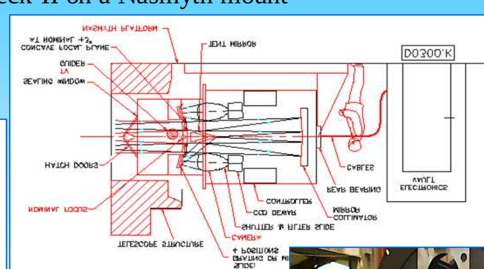

## During Assembly

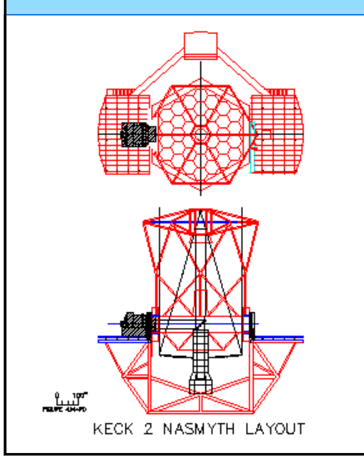


## At the Nasmyth Focus at Keck

## The DEIMOS Spectrograph (Deep Imaging Multi-Object Spectrograph)

- Recently installed at Keck-II on a Nasmyth mount
- S. Faber, PI
- 10 tons!



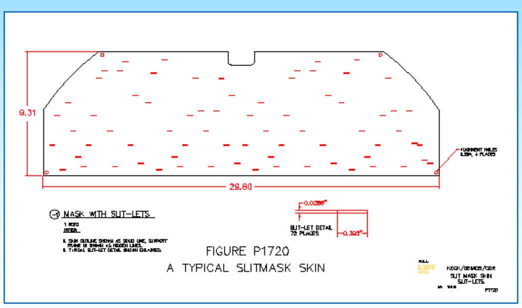

## DEIMOS characteristics

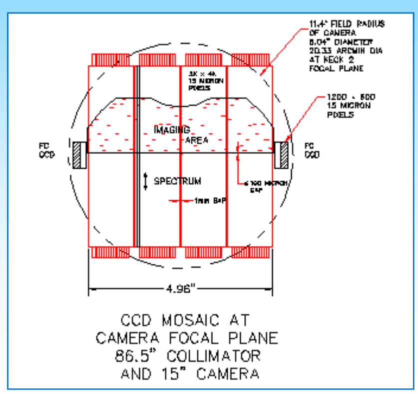
- Multi-object capability via custom-milled slitmasks, over up to a $16' \times 5'$ field (imaging over same field size)
- $8k \times 8k$ detector array made up of 8 MIT-Lincoln Labs high-resistivity CCDs
  - 50% QE to beyond 9500Å, fringing low
- Active flexure compensation network to keep pixel-to-wavelength registration constant (vital for flat-fielding & sky subtraction in the near-IR).
- Resolution ~5000 can be achieved over a ~300 nm wavelength range (with 1200 line/mm grating)

## DEIMOS slit masks and detector

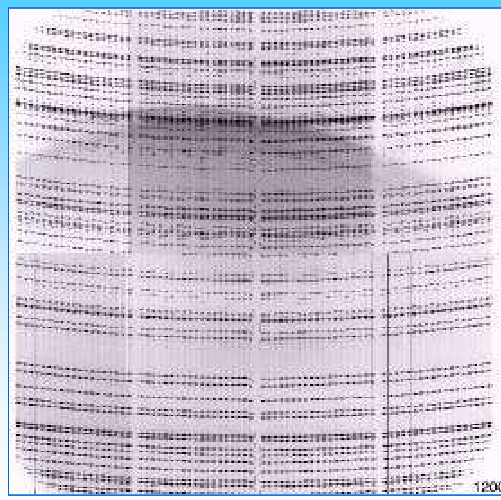
•Slit masks are curved to match the focal plane and imaged onto an array of $2k \times 4k$ CCDs

•Readout time for full array (150 MB!) is 40 seconds (16 amplifier mode)



## DEIMOS has been tested thoroughly in the lab...




HgNeArKrXe arc through a slitmask

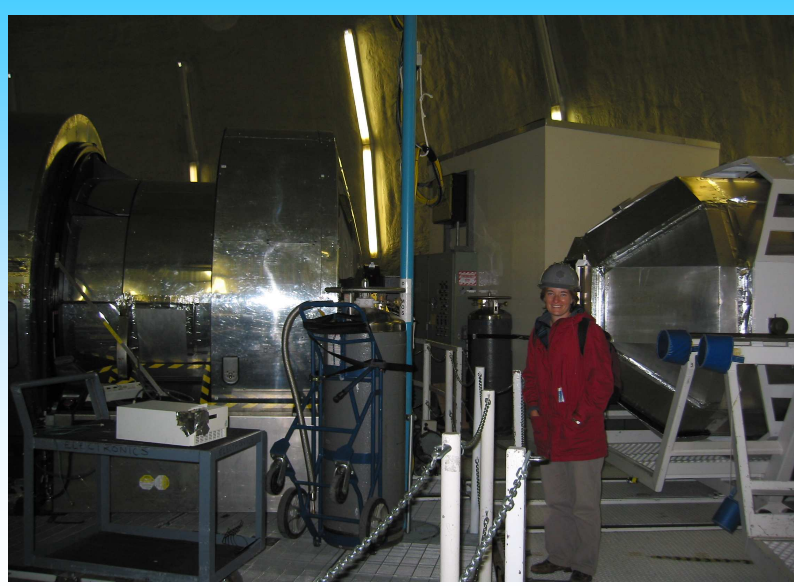
## DEIMOS was delivered to Keck this winter...

## Travelling via ship. . .

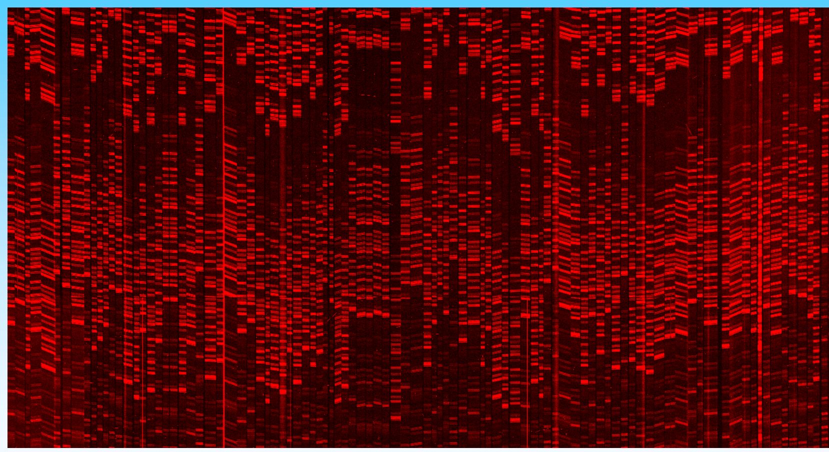

## and truck. . .

## and crane...

## The DEIMOS Spectrograph



## First spectroscopy of DEEP2 masks



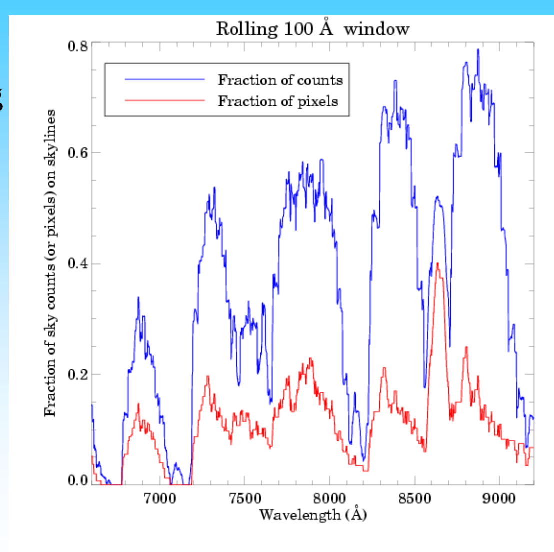
Each slitmask has ~120 objects over an 8k x8k array. The average slit length is ~5” with a gap of 0.5” between slits. We tilt slits up to 30 degrees to trace the long axis of a galaxy.

## Advantages of working at high dispersion

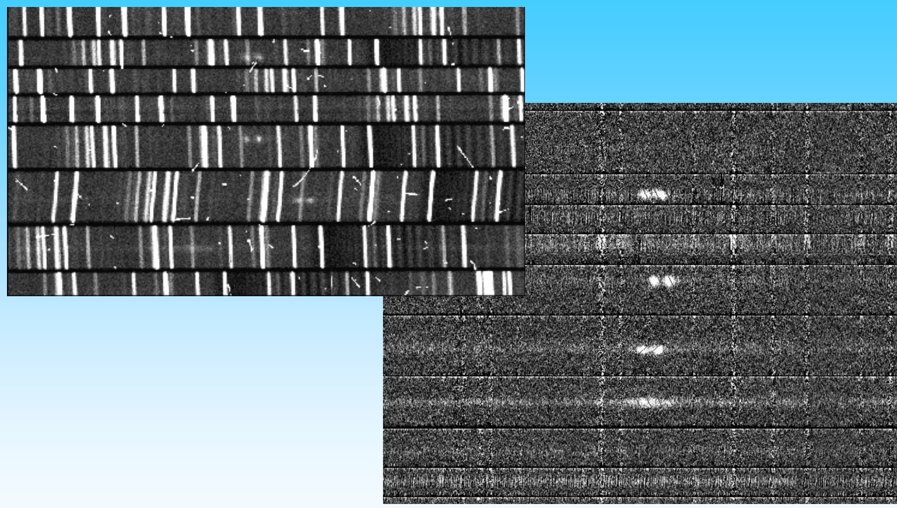
Blue curve: fraction of sky flux in zones coming from pixels with >2x continuum background, versus wavelength

Red curve: fraction of pixels with >2x background flux, with 1200 l/mm grating.

**Most pixels have low background– OH suppression by Inv-var weighted smoothing**

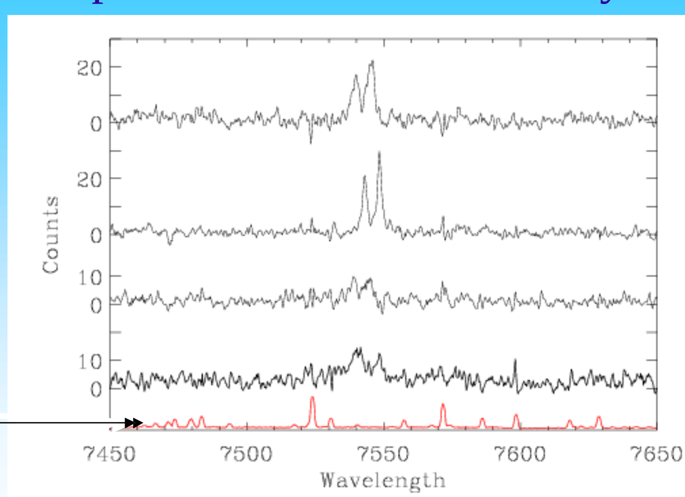


## A fully automated pipeline is already operational!



A few percent of one DEEP2 mask, rectified, flat-fielded, CR cleaned, wavelength-rectified, and sky subtracted. Note the resolved O[II] doublets. Shown is a small group of galaxies with velocity dispersion $\sigma \approx 250$ km/s at $z \sim 1$. Note the clean residuals of sky lines!

## 1-d spectral extraction and analysis

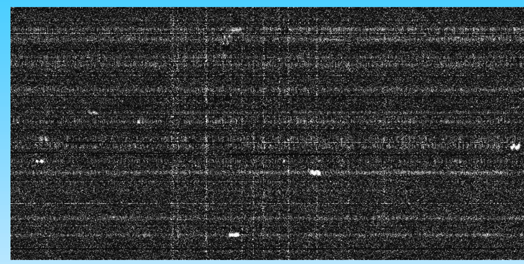


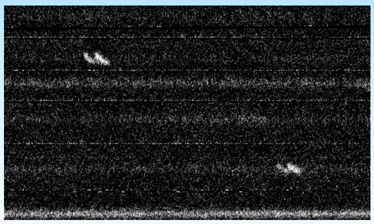

Sky

[O II] lines prominent in this modest galaxy group. Linewidth extraction and ratio will be straightforward

## DEIMOS reduced data

Right: A small percentage of one mask: an [OII] playground!





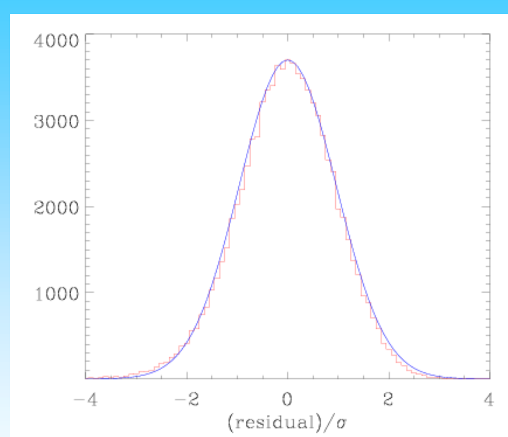
**Left: We will obtain thousands of well-resolved rotation curves**

**Below:** Analysis of a tilted slitlet; reduced data above, raw data below. We routinely achieve Poisson-limited sky subtraction in most cases.

## Poisson limited sky subtraction is routinely achieved on local sky subtraction

Plot shows residual of flux from b-spline sky model in region of sky emission lines, in units of local RMS.

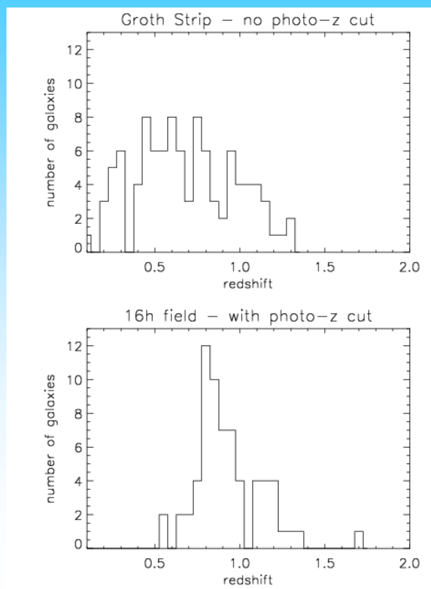
Smooth curve is gaussian, width 1.




*Work in progress to do non-local sky subtraction using narrower, sky-only slitlets, for the shortest slitlets where local sky subtraction is impossible.*

## From commissioning data, we have a successful test of the photo-z selection procedure

The redshift distributions in these 2 masks are consistent with expectations.




We will measure redshifts for ~75-80% of the sample

## Schedule of the DEEP2 Survey

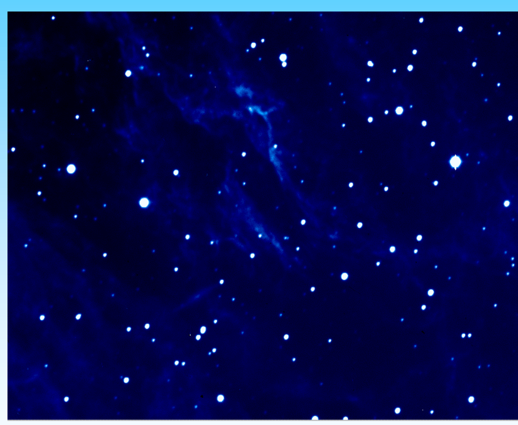
- DEIMOS is working amazingly well!
- Commisioning began June 2002 under clear skies and was extremely successful.
- DEEP2 observing campaign began in July 2002. So far we've had 7 clear nights, observed 53 masks, **>10% complete**!
- Observations complete late 2004 *(we hope)*
- Analysis complete late 2006

## Science Topics Using First Semester of Data

- Evolution of galaxy properties with redshift
  - Luminosity function, SFR evolution
  - Linewidth, galaxy color evolution
- Comparison with galaxy simulations
- Galaxy mergers and accretion
- **Scale-length of galaxy clustering**
- **Small-scale velocity dispersion – galaxy bias at z=1**
- Tully-Fisher properties at z=1
- High-z serendips

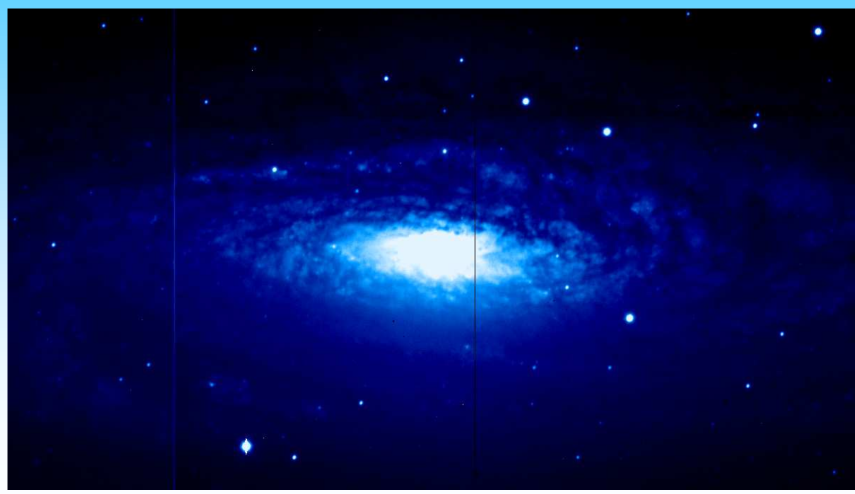
## First light: June 3, 2002

Our major requirements for DEEP2, accurate slitmask alignment and multiobject spectroscopy across a mask, were achieved on the first night of DEIMOS commissioning. Since then, we have performed a variety of tests over the 5½ nights allocated for June (including many required for commissioning DEIMOS as a facility instrument).

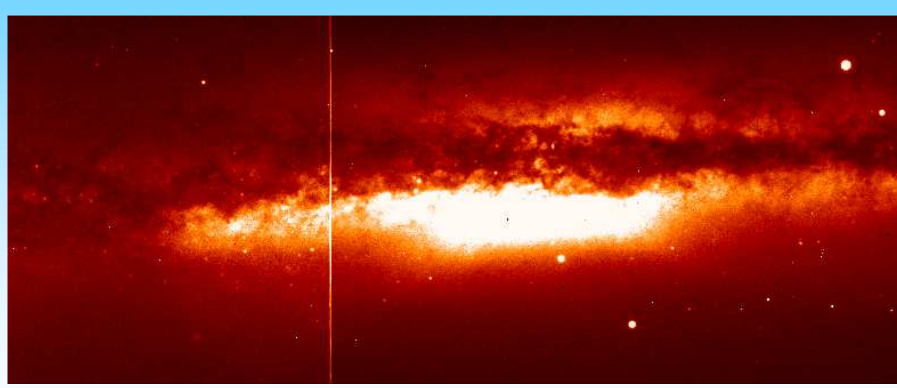


DEIMOS image of the Veil Nebula

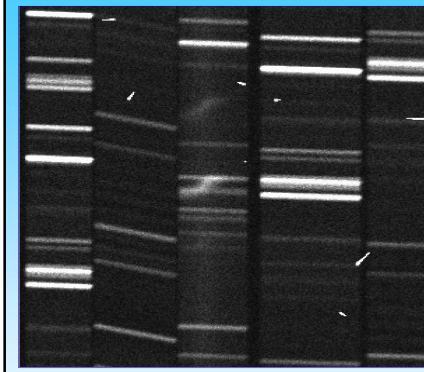
## Pretty pictures: NGC 7331



## Pretty pictures: NGC 3628

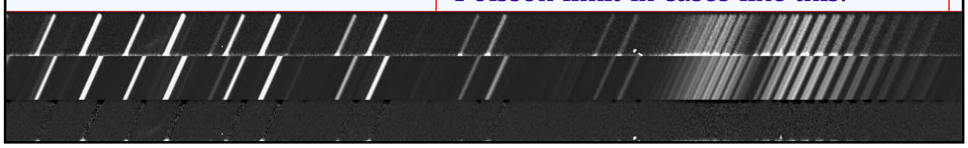


## DEIMOS reduction tools



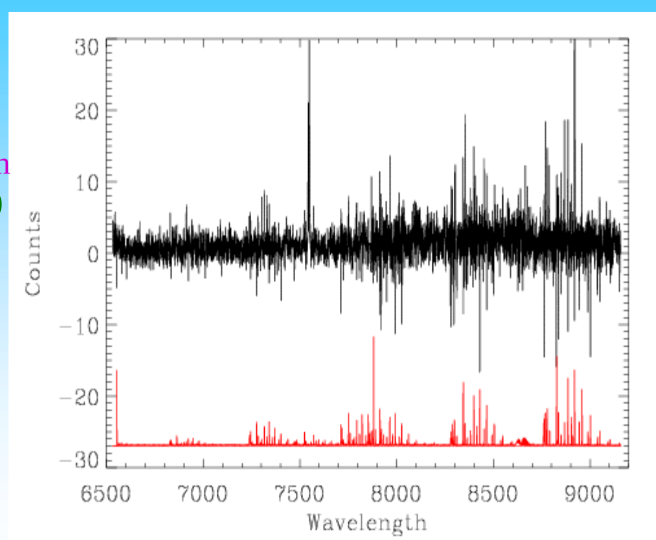
**Left:** Raw data from an unaligned DEIMOS slitmask, with serendip (detail). Some slitlets are tilted to allow rotation curve measurements; this poses unique challenges for automated sky subtraction.

**Below:** test analysis of one tilted slitlet. From top: raw data, b-spline model of the night sky lines, and rescaled residual. We already can achieve sky subtraction at close to the Poisson limit in cases like this.



## Typical extracted 1-d spectrum

Unsmoothed 1d spectrum (black) with background sky (red) offset and rescaled..



## DEEP2 and dark energy: The classical $dN/dz$ test

The apparent abundance per unit redshift and solid angle of a class of object depends on fundamental cosmological parameters :

$$dN/dz \sim n(z) \times D_C^2 / E(z)\, d\Omega \,,$$

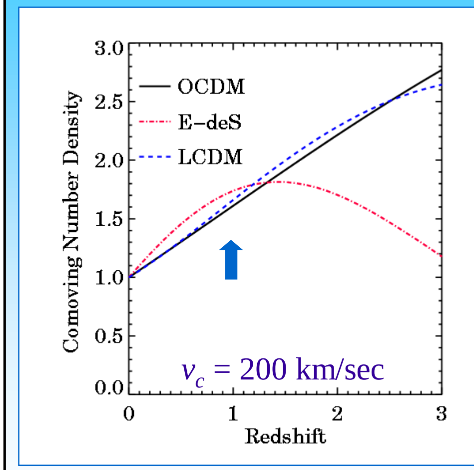
where $n(z)$ is its comoving number density, $E(z) \equiv H(z)/H_0 = (\Omega_m(1+z)^3 + \Omega_\Lambda + \ldots)^{1/2}$, and $D_C$ is the comoving distance to the redshift of interest, $\propto \int \frac{1}{E(z)} dz$ .

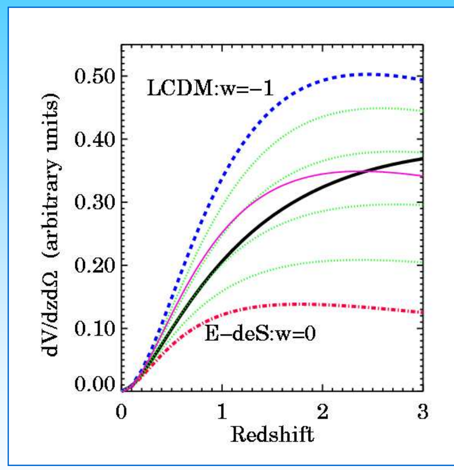
## From counts to cosmology

Two basic routes to cosmological parameters via *dN/dz* :

1) Study objects for which *n(z)* is independent of cosmological parameters
   - E.g. galaxies of fixed linewidth/rotation speed (equivalent to potential well depth of the dark matter halo) at *z*~1 normalized to *z*~0: cf. Newman & Davis 2000
2) Count objects whose comoving abundance *n(z)* is more sensitive to cosmology than the volume element
   - E.g. galaxy clusters of fixed mass/S-Z decrement/X-ray luminosity. . . **or velocity dispersion σ** ($v_c^2 \sim 2\sigma^2 \sim GM/r$).
     - $n(\sigma,z)$ is independent of $H_0$ and can be calculated directly in extended Press-Schechter formalisms, vs. e.g. $n(>L_X,z)$

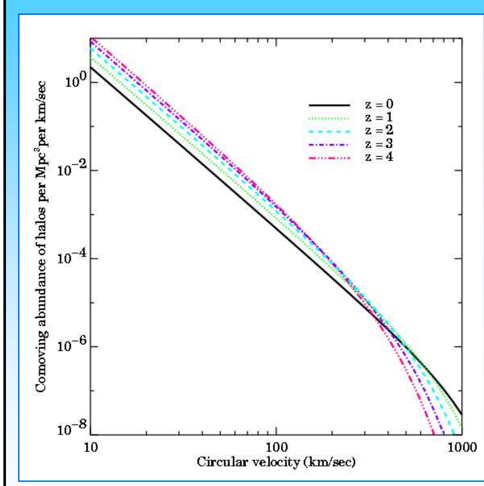
## $n(v_c,z)$ for galaxies is nearly cosmology-free




For halos on the scale of a typical galaxy, the ratio of the comoving number density at $z$=1 to today is identical to within a few percent!

## Behavior of $n(v_c,z)$

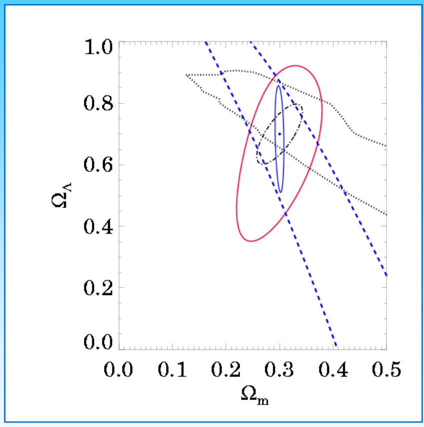


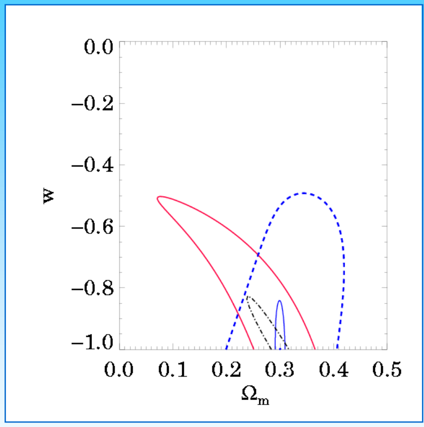

$\Omega_m$=0.3 ΛCDM

At low velocities, $n(v_c,z)$ (or equivalently $n(\sigma,z)$) exhibits simple power-law behavior; systematic effects cause deviations from this, making them identifiable and correctable.

We include the effects of cosmic variance in our calculations and have tested our ability to correct for incompleteness, baryonic infall, and measurement errors using Monte Carlo simulations.

## Comparison to SNAP & CMB constraints



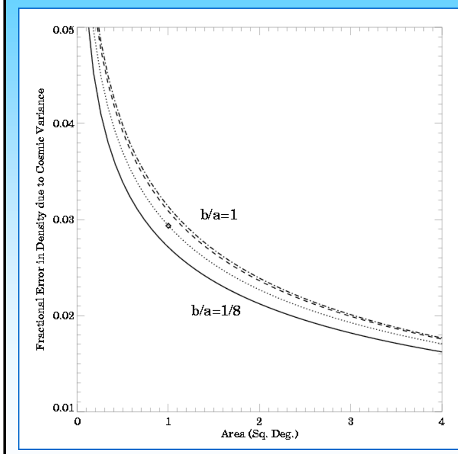




- **Solid Red**: DEEP2 galaxy *dN/dz*; **Solid/dashed blue**: optimistic/ traditional DEEP2 cluster *dN/dz*
- **Dotted black**: BOOMERANG/MAXIMA; **Dot-dash black**: SNAP (target statistical uncertainty)

## Conclusions

- **DEEP2 observations began July 5!**
- DEEP2, in combination with local surveys now underway (2dF, SDSS), will be able to provide a variety of constraints on galaxy formation and evolution as well as measurements of cosmological parameters.
- In all DEEP2 fields, it should be possible to compare velocity structure of clusters and massive groups vs. weak lensing mass vs. Sunyaev-Zel'dovich maps vs. galaxy types/richness, etc. (plus X-ray observations for most massive clusters in the Groth strip, at minimum). The integrated picture of clusters to *z*~1.2 provided should allow us to test for the sorts of systematic effects that may already dwarf statistical uncertainties.
- **Recent DEEP2 papers**:
  - **Galaxy dN/dz systematics: Newman & Davis 2002, ApJ, 564, 567**
  - **DEEP2 cluster dN/dz: Newman et al. 2002, PASP, 114, 29**
  - **Finding DEEP2 clusters: Marinoni et al. 2002, ApJ, submitted (astro-ph/0109163)**

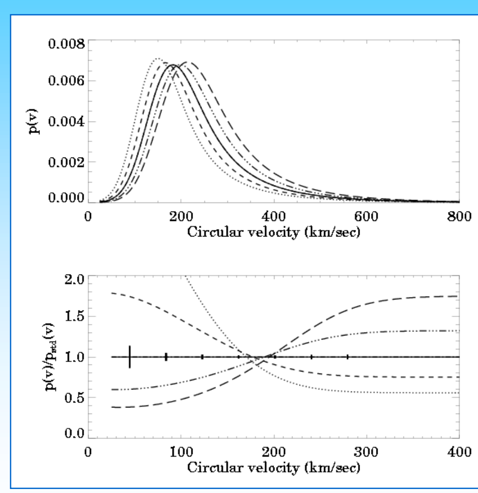
## Cosmic variance




Naively, we would expect errors in a measurement based on counting objects to be controlled by simple Poisson statistics. However, because the locations of galaxies or clusters are correlated, there are fewer independent elements, so fluctuations are greater; $\sigma$ ~2x Poisson for DEEP2 galaxies. Observing more fields or a wider area would reduce this.

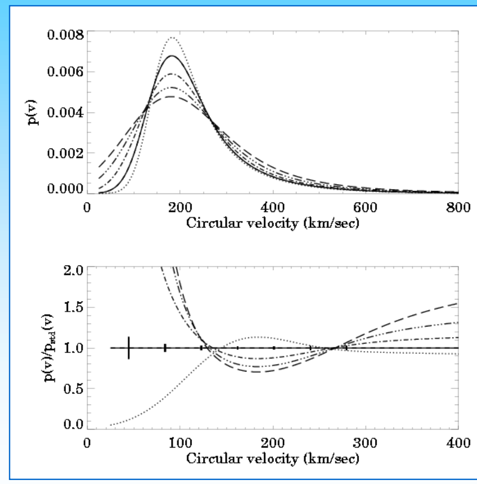
## Systematic effects: Incompleteness

- **Incompleteness** will radically change the observed velocity function from its intrinsic power-law to the form seen on the top right.
- However, as seen in the bottom right, the velocity at which incompleteness becomes important can be determined sensitively from the observed velocity function.
- Residual *dN/dz* error from incompleteness after correction (using observed velocity function): 1.4x Poisson



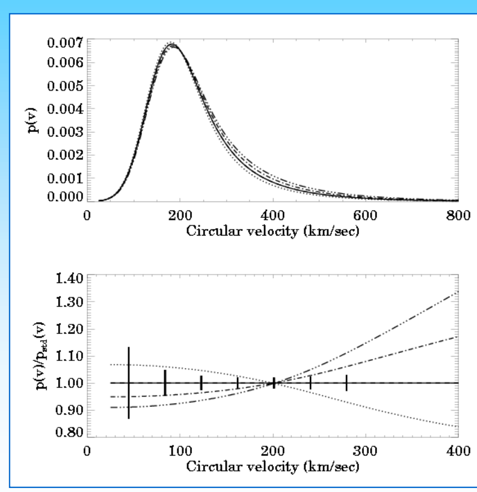
# Systematic effects: $\sigma_v$

- Any source of **random errors** between predicted and measured circular velocities will alter the observed velocity function
  - Measurement errors, variable distribution of gas in galaxies, etc.
- The signature on the velocity function is strong, and quite different from incompleteness
- Our Monte Carlo simulations indicate a residual *dN/dz* error after correction of only 20% Poisson



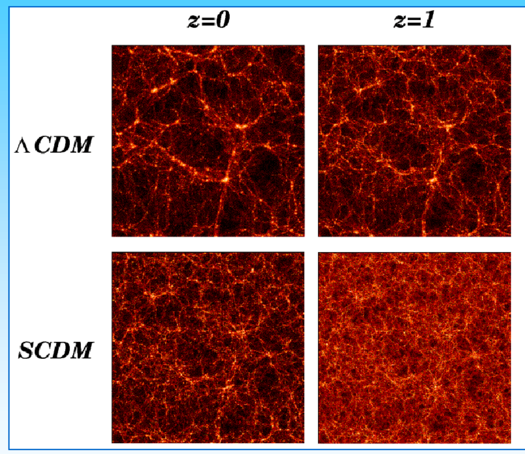

# Systematic effects: Baryonic Infall

- As galaxies collapse within dark matter halos, the halos adjust their structure, and thus their circular velocities, adiabatically in response. This process is generally referred to as "**baryonic infall**".
  - Effectively, a remapping of $n(v_c)$ to higher velocities
- The impact of baryonic infall on the velocity p.d.f. is subtle compared to its influence on a *dN/dz* measurement.
- We find that if the only constraint on baryonic infall comes from the observed $z$~1 velocity function, the residual *dN/dz* errors after correction will be 5x Poisson.



## The $J_3$ ratio test

- $\xi(r)$, the two-point correlation function of galaxies, represents the excess probability that one galaxy will be found near another.
- The volume integral of $\xi$, typically labeled "$J_3$", provides a measure of the total amount of large-scale structure; i.e., it quantifies the differences between the pictures at right.
- For the dark matter, the ratio $J_3(z=1)/J_3(z=0)$ depends on cosmology (via the growth factor $D$ and the angular size distance $d_A$) but not $H_0$ (as $d_A \propto h^{-1}$).
- To interpret the measurement, we have to determine the amount of bias in the galaxy distribution compared to matter. **This will be possible with DEEP2**.

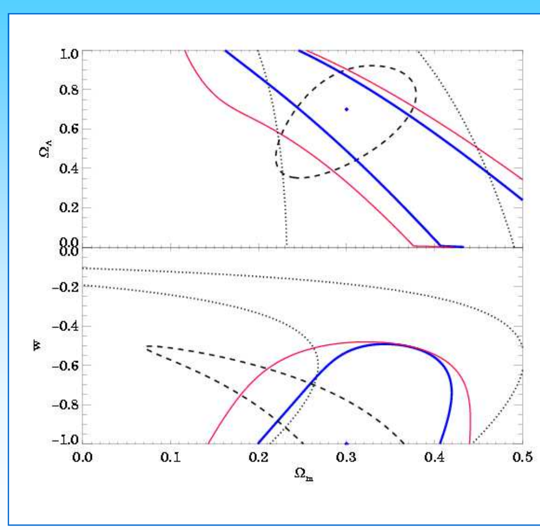



$$\frac{J_3(z)}{J_3(0)} \propto (hd_A)^{3-\gamma}\left(\frac{D(z)}{D(0)}\frac{b(0)}{b(z)}\right)^2$$

## Constraints on cosmological parameters

95% constraints for an $\Omega_m$=0.3 LCDM model:

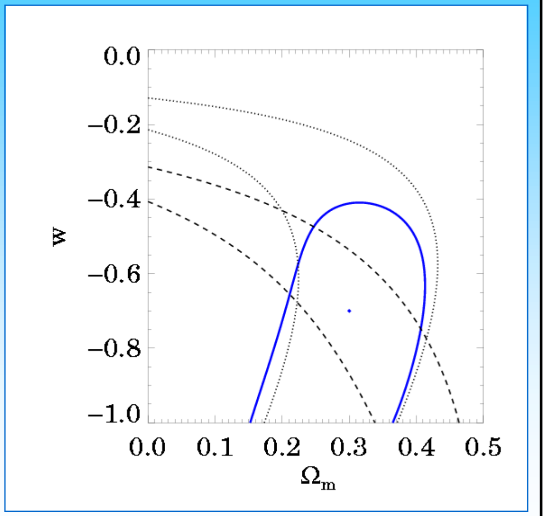
- **black, dashed**: *dN/dz* for DEEP2 galaxies
- **black, dotted**: $J_3$ ratio (68% constraint)
- **red, solid**: $dN(>\sigma)/dz$ for DEEP2 clusters
- **blue, solid** : $dN/d\sigma\, dz$ for DEEP2 clusters



## Constraints for $w \neq -1$

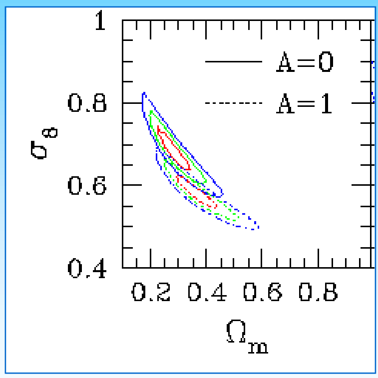
95% constraints for a $w$=-0.7 model:

- **black, dashed**: *dN/dz* for DEEP2 galaxies
- **black, dotted**: $J_3$ ratio (68% constraint)
- **blue, solid** : *dN/dσ dz* for DEEP2 clusters



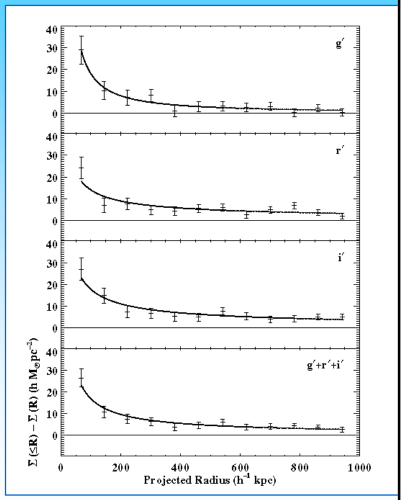

## Improved cluster methods: $\sigma_8$

- To predict the abundance of clusters in a cosmological model, we need to know the amplitude of density fluctuations, typically parameterized by $\sigma_8$ (the typical fractional fluctuation of the matter density in an 8 Mpc sphere).
- Past techniques used X-ray observations of local clusters to constrain a degenerate combination of $\sigma_8$ and $\Omega_m$, but not either one directly. Furthermore, systematic errors in the methods may persist (~35% discrepancies between some recent measurements)



## Improved cluster methods: $\sigma_8$

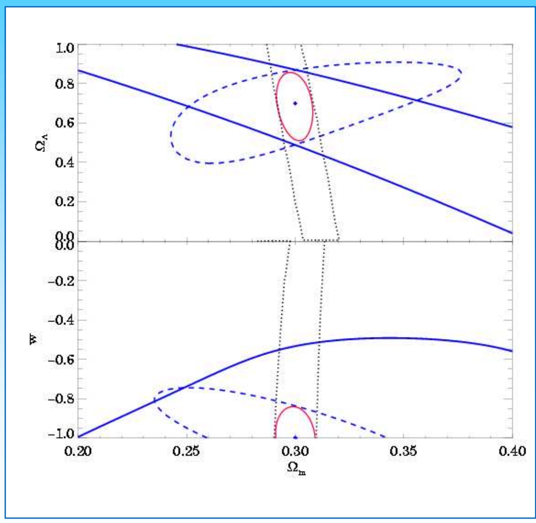
Weak lensing measurements around galaxies in the SDSS spectroscopic sample are already sufficient to allow the measurement of the mass distribution around typical galaxies. With $10^6$ objects in the sample instead of tens of thousands, it will be possible to do this as a function of galaxy properties, etc. By combining this information with the observed distribution of galaxies, it will be possible to calculate $\sigma_8$ directly (rather than a degenerate combination with other parameters).




## Improved cluster methods, *w*=-1

With measurements of $\sigma_8$ of the mass that do not come from *z*~0 clusters, we can do better:

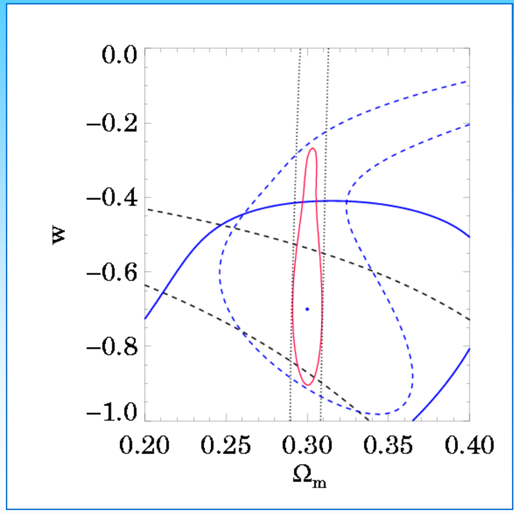
- **blue, solid** : *z*~1 *dN/dσ dz,* traditional $\sigma_8$ method
- **blue, dashed**: *z*~1cluster *dN/dσ dz,* $\sigma_8$ fixed
- **black, dotted**: *z*~0 cluster *dN/dσ,* $\sigma_8$ fixed
- **red, solid**: combined constraint, $\sigma_8$ fixed ("optimistic")



# Improved cluster methods, *w*≠ -1

It is still difficult to constrain *w*=-0.7 models:

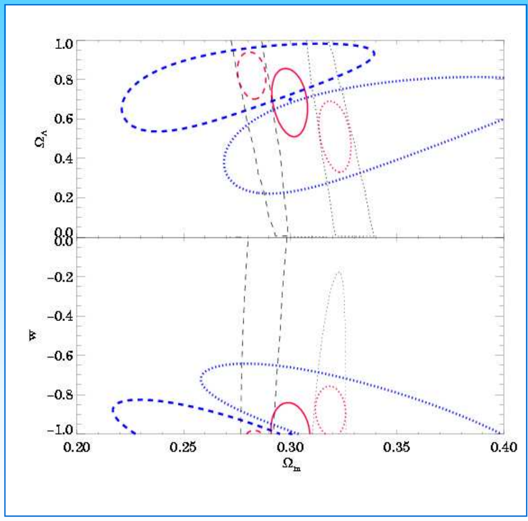
- **blue, solid** : *z*~1 *dN/dσ dz*, traditional $\sigma_8$ method
- **black, dashed**: *dN/dz* for DEEP2 galaxies
- **blue, dashed**: *z*~1 *dN/dσ dz*, $\sigma_8$ fixed
- **black, dotted**: *z*~0 *dN/dσ*, $\sigma_8$ fixed
- **red, solid**: combined constraint, $\sigma_8$ fixed ("optimistic")




# Results of an error in $\sigma_8$

Near-future methods for measuring $\sigma_8$ independent of $\Omega_m$ will still have finite error.

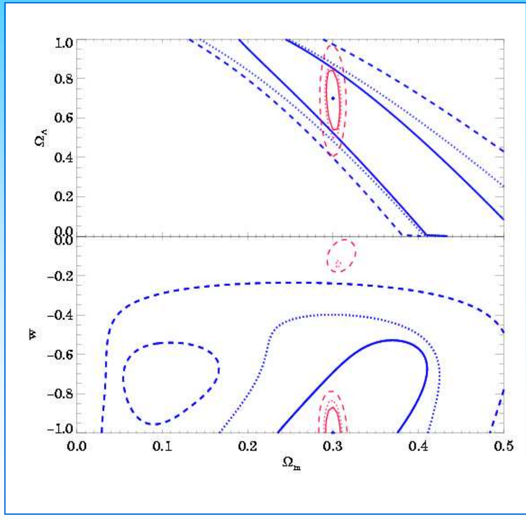
Here we show the results if a value of $\sigma_8$ too large by 5% (**dashed curves**) or too small by 5% (**dotted curves**) has been assumed in analysis.



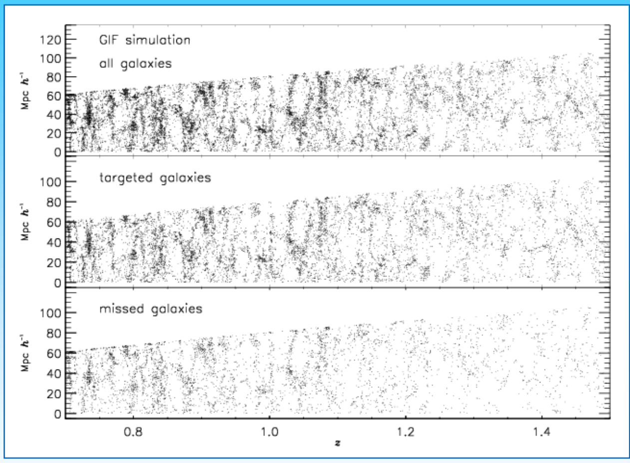
## Dependence of constraints on minimum σ

The preceding plots assumed we can identify all clusters down to 400 km $s^{-1}$ dispersion. What if we do better or worse?

- **red**: optimistic $\sigma_8$
- **blue**: traditional $\sigma_8$
- **solid, dot, dashed**: 300, 500, 700 km $s^{-1}$ limits
- Optimistic scenario not very affected; degenerate solutions excluded by other tests




## How well will we do? DEEP2 simulations

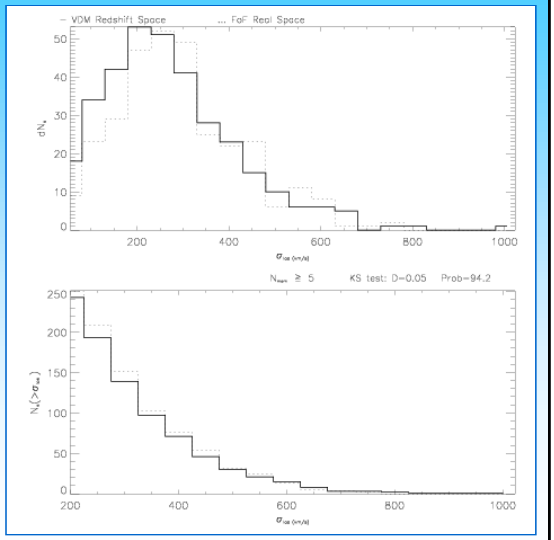



**Courtesy A. Coil**

**Targeted** objects were included when our slitlet assignment algorithm is performed on a mock DEEP2 survey created from an N-body simulation; **missed** objects were not selected

# Recovery of $n(\sigma)$

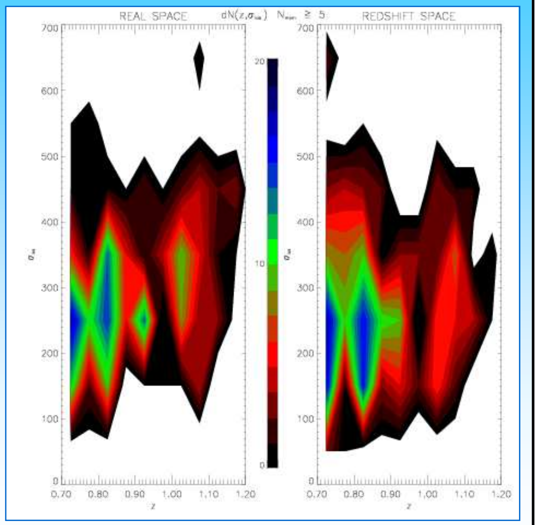
- We have developed a new method for detecting clusters of galaxies in a redshift survey based upon the Voronoi-Delaunay partition.
- When applied to the mock catalog of galaxies assigned slitlets, this algorithm yields a distribution of cluster velocity dispersions indistinguishable from the actual distribution in the underlying simulation down to ~300 km $s^{-1}$ !!!




Courtesy C. Marinoni

# Recovery of $n(\sigma,z)$

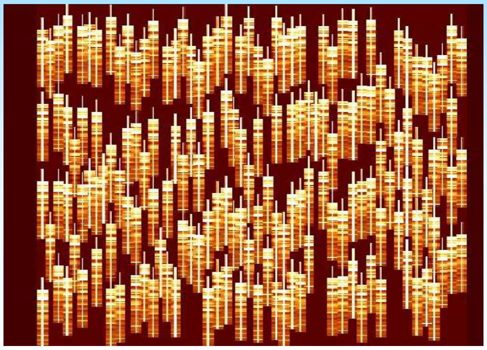
- Although the properties of each individual cluster (velocity dispersion, etc.) cannot be measured perfectly from a small number of members, the statistical properties of the sample as a whole are preserved.
- Reconstruction of the cluster population should not cause significant systematic errors in the cluster *dN/dz* test!




Courtesy C. Marinoni

## Another deep redshift survey: The VLT/VIRMOS Project

- 50,000 galaxies to $I_{AB} < 24$ (1.2 sq. deg)
- $10^5$ galaxy redshifts with $I_{AB} < 22.5$ (9 sq. deg)
- 800 simultaneous slitlets (4 barreled instrument)
- Resolution R~ 180-2520 – short spectra, multiple spectra/row
- 100+ nights on VLT-3 - **Observations start 2002 ?**



## Comparison of DEEP2 to VLT/VIRMOS

| *category* | **DEEP2** | **VLT/VIMOS** |
|---|---|---|
| Survey size | 65000+6500 | 130,000+50,000+3000 |
| Multiplexing | 120-140 galaxies | 750 galaxies |
| Resolution $R=\lambda/\Delta\lambda$ | ~ 5000 | 200 - 2500 |
| Wavelength range | ~2600 Å | ~2500 Å |
| Magnitude Limit | $I_{AB} < 23.5 – 24.5$ | $I_{AB} < 22.5 – 24$ |
| Redshift Range | $0.7 < z < 1.4$ | $0<z<?$<br>>50% with $z<0.7$ |
| 0-order Summary | LCRS at *z~1* | CFRS for the 21st century |

## Advantages of DEEP2 over VLT/VIRMOS

- Higher resolution:
  - Provides more precise redshifts and allows secure *z* measurements from the [OII] doublet alone
  - Permits us to measure linewidths/rotation curves
  - Reduces contamination by night skylines
  - Necessary for many of our science goals: e.g. T-F type relations, studies of bias (e.g. via redshift-space distortions), measurement of thermal motions, determining velocity dispersions of clusters, the *dN/dz* test… None of these will be possible with low-resolution VLT/VIRMOS data.
- Photometric cut for $z$>0.7 will eliminate ~50% of all galaxies with $I_{AB}$< 23.5 from target list, yielding denser sampling at $z \sim 1$

## Advantages of VLT/VIRMOS over DEEP2

- Greater multiplexing, larger team
- Larger area on sky covered – better control over cosmic variance
- Full coverage from $z$=0 to $z$>1
- More objects total in sample
- Guaranteed access to IR Multi-Object Spectrograph
  - Objects with $z$>1.4, $H\alpha$ at $z$~1, etc.