Proposal submitted to ARC in July 2006

Strong support from LBL and many other institutions.

They own the telescope

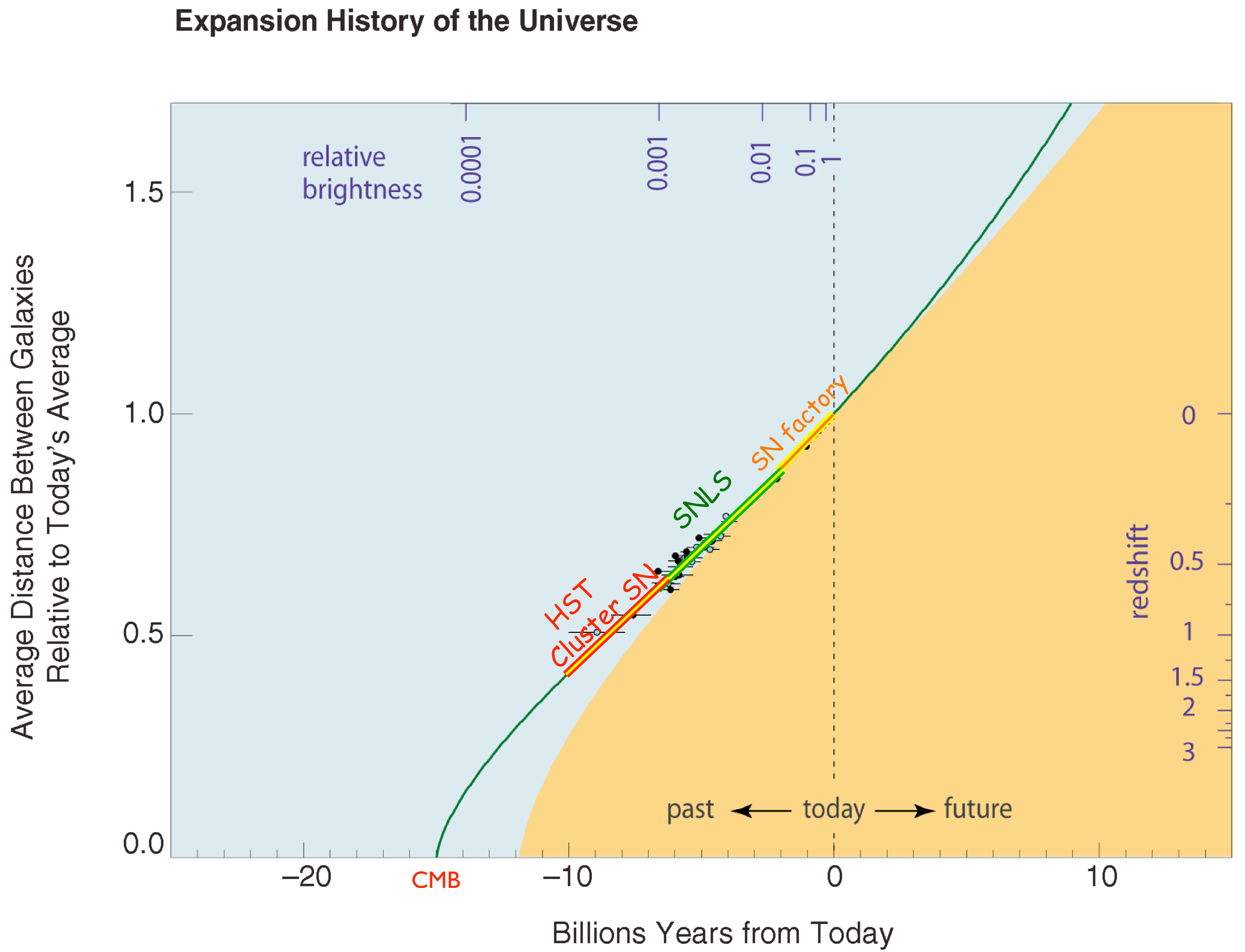
Refining the Distance Scale to 1% with the ARC 2.5-m Telescope

David Schlegel[1], Daniel Eisenstein[2], James Annis[3], Neta Bahcall[4], Bruce Bassett[5], Chuck Bennett[6], Michael Blanton[7], Francisco Javier Castander[8], Masataka Fukugita[9], James Gunn[4], Pat Hall[10], Tim Heckman[5], Wayne Hu[13], Zeljko Ivezic[11], Benjamin Koester[12,13], Jill Knapp[4], Guinever Kauffmann[14], Robert Lupton[4], Rachel Mandelbaum[4], Patrick McDonald[15], Robert Nichol[16], Nikhil Padmanabhan[1,4], Saul Perlmutter[1], Gordon Richards[6], Adam Riess[6,17], Natalie Roe[1], Connie Rockosi[18], Roman Scoccimarro[7], David Spergel[4], Michael Strauss[4], Nao Suzuki[1], Alex Szalay[6], Istvan Szapudi[19], Max Tegmark[20], David Weinberg[21], Martin White[1], Simon White[14], Idit Zehavi[22]

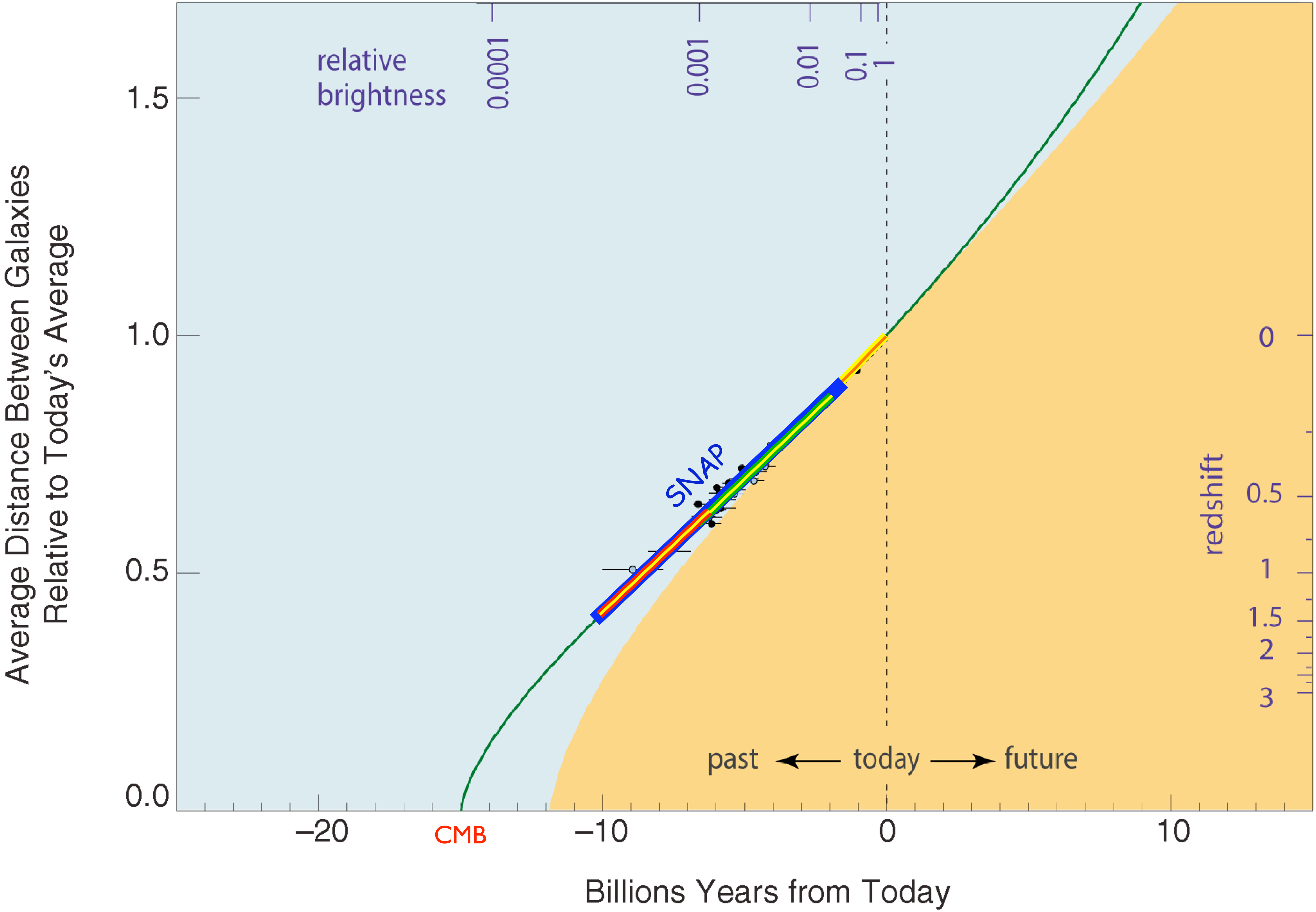
[1] *Lawrence Berkeley National Laboratory*, [2] *University of Arizona*, [3] *Fermi National Accelerator Laboratory*, [4] *Princeton University*, [5] *University of Cape Town*, [6] *Johns Hopkins University*, [7] *New York University*, [8] *Institut d'Estudis Espacials de Catalunya*, [9] *University of Tokyo*, [10] *York University*, [11] *University of Washington*, [12] *University of Michigan*, [13] *University of Chicago*, [14] *Max Planck Institut für Astrophysik*, [15] *Canadian Institute for Theoretical Astrophysics*, [16] *University of Portsmouth*, [17] *Space Telescope Science Institute*, [18] *University of California at Santa Cruz*, [19] *University of Hawaii*, [20] *Massachusetts Institute of Technology*, [21] *The Ohio State University*, [22] *Case Western Reserve University*

ABSTRACT

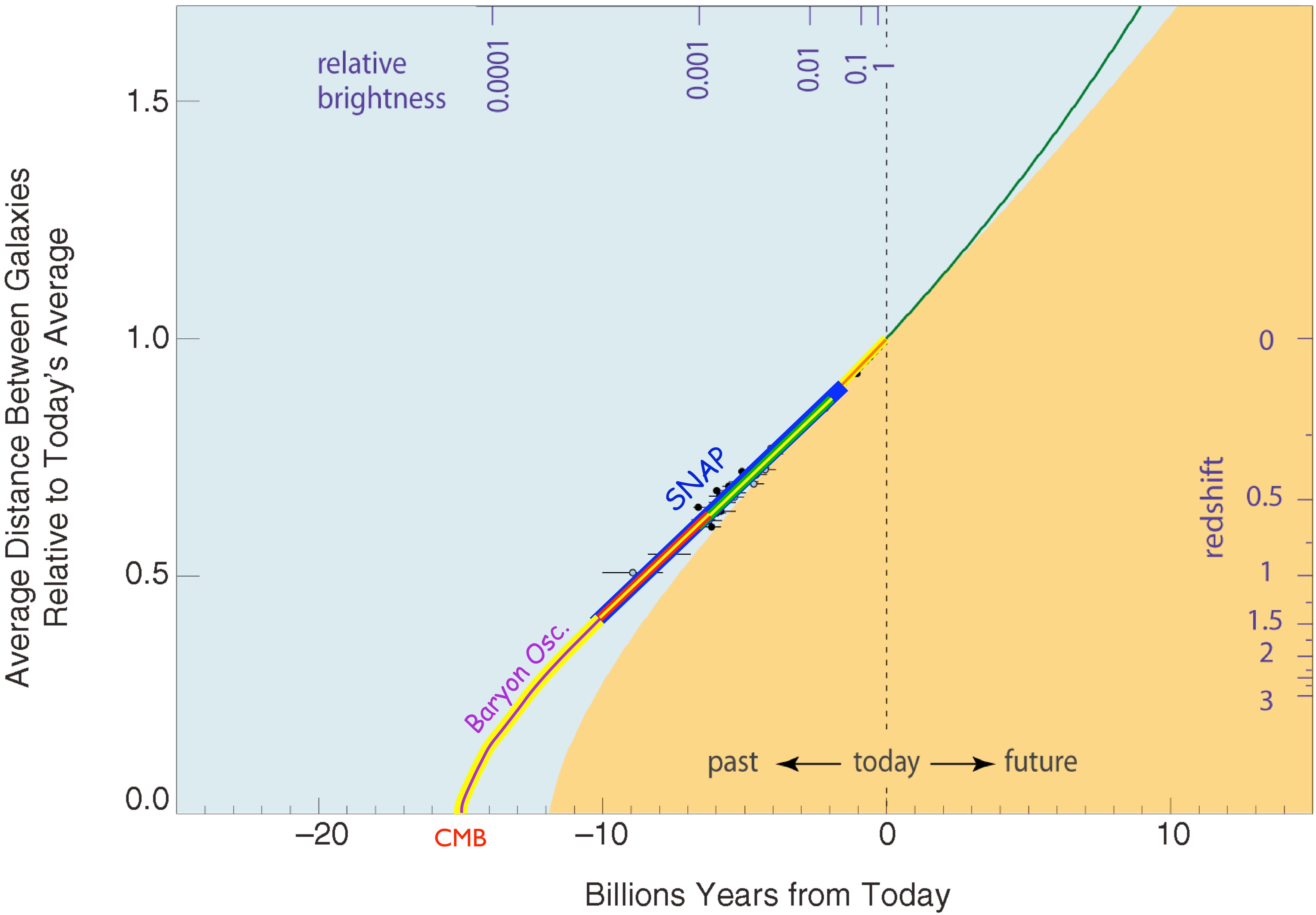
We propose to use the SDSS facility post-2008 to conduct the largest spectroscopic survey to date of cosmological large-scale structure. The survey is designed to use the baryon acoustic oscillation phenomenon to make significant improvements in our measurements of the cosmic distance scale and hence the acceleration of the expansion rate of the Universe. The primary goal is a survey of Luminous Red Galaxies (LRGs) out to $z \approx 0.7$ over 10,000 square degrees, aimed at the measurement of the baryon acoustic peak in the large-scale galaxy correlations.


Expansion History of the Universe
relative brightness
0.0001
0.001
0.01
0.1
1
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
0
0.5
1
1.5
2
3
redshift
HST Cluster SN
SNLS
SN factory
past
today
future
–20
CMB
–10
0
10
Billions Years from Today

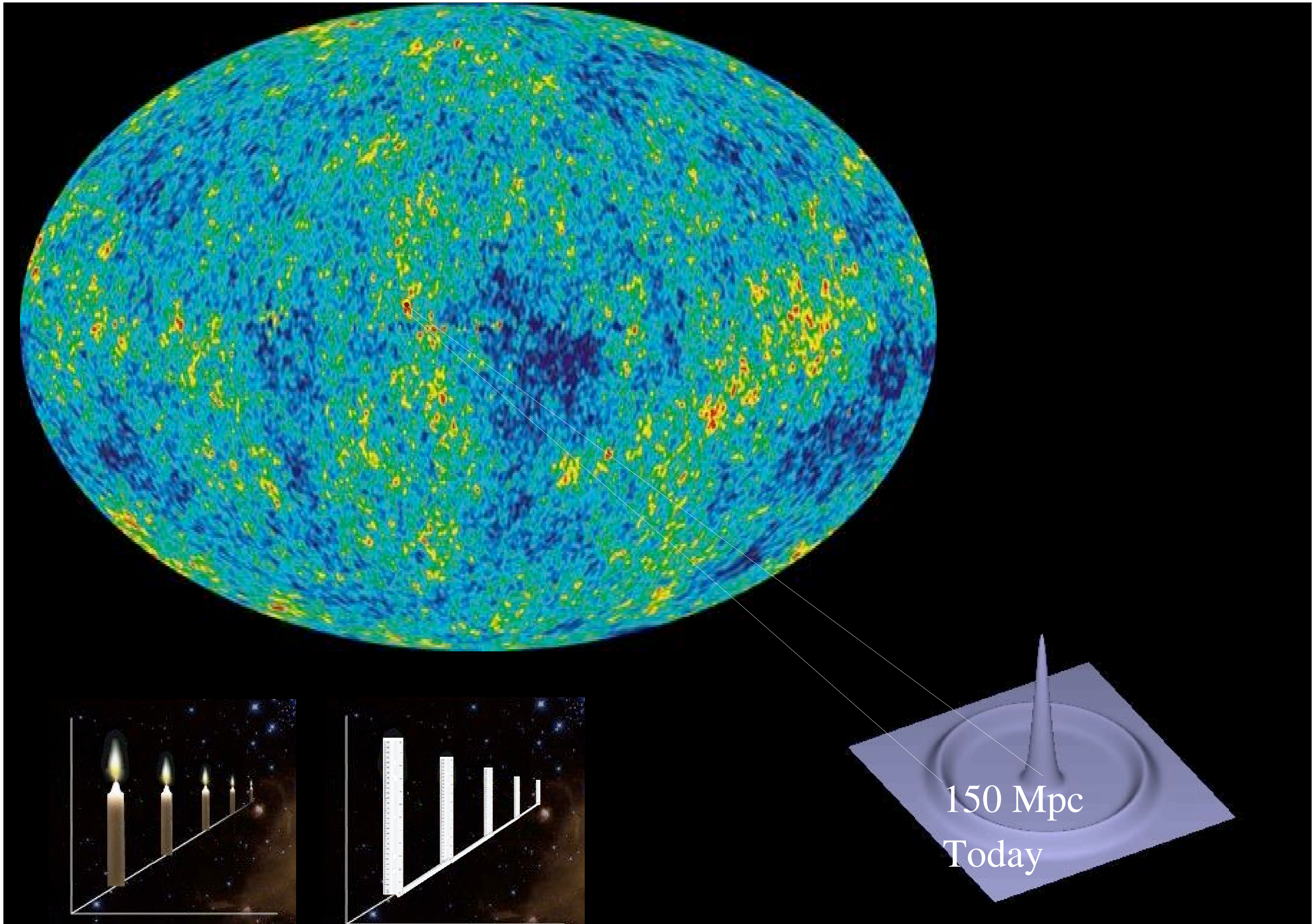
Expansion History of the Universe



Expansion History of the Universe



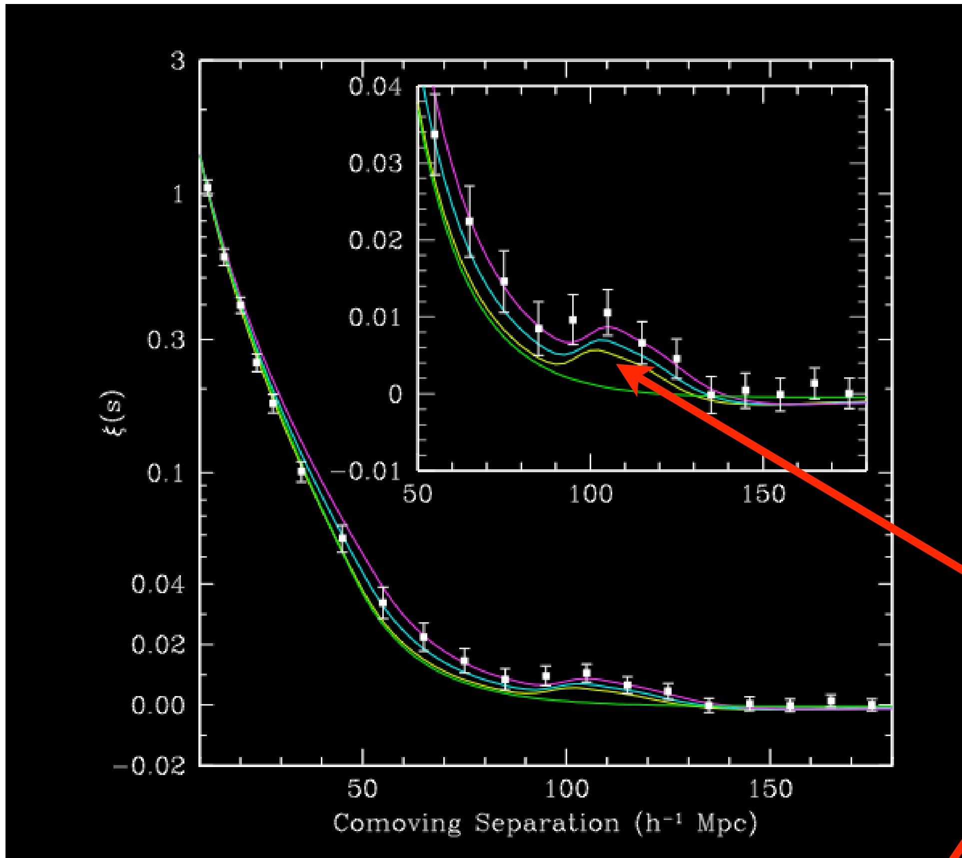
Acoustic Oscillations on the surface of last scattering (CMB) ...and today in galaxy distribution



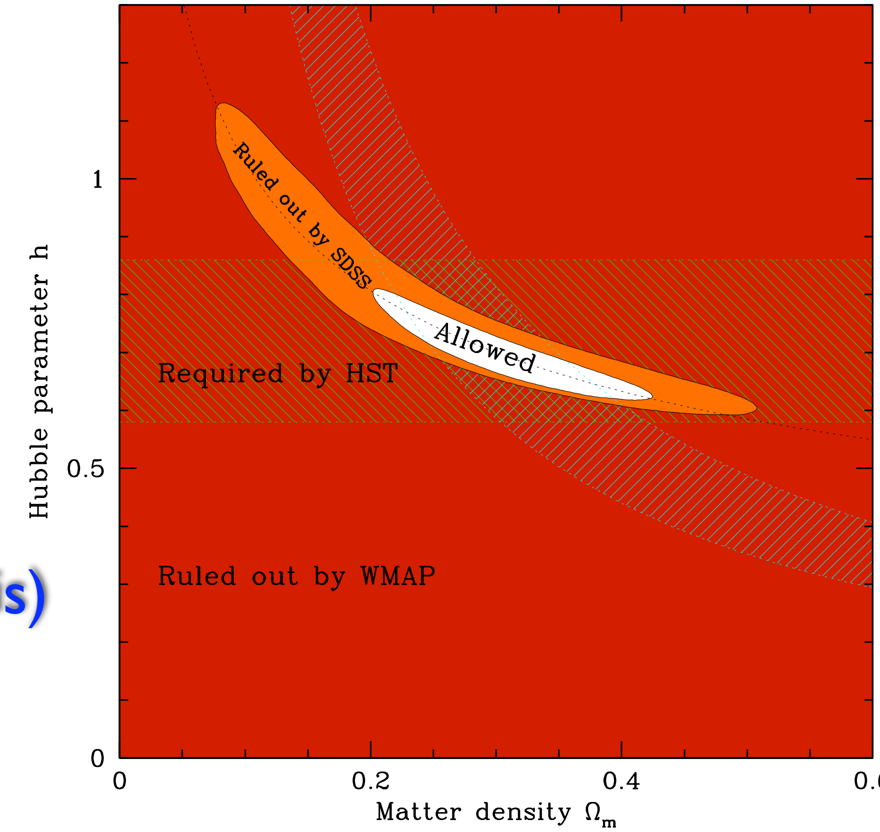
Supernovae
standard candles

Baryon oscillations
standard rulers

Baryon acoustic oscillations: First Results

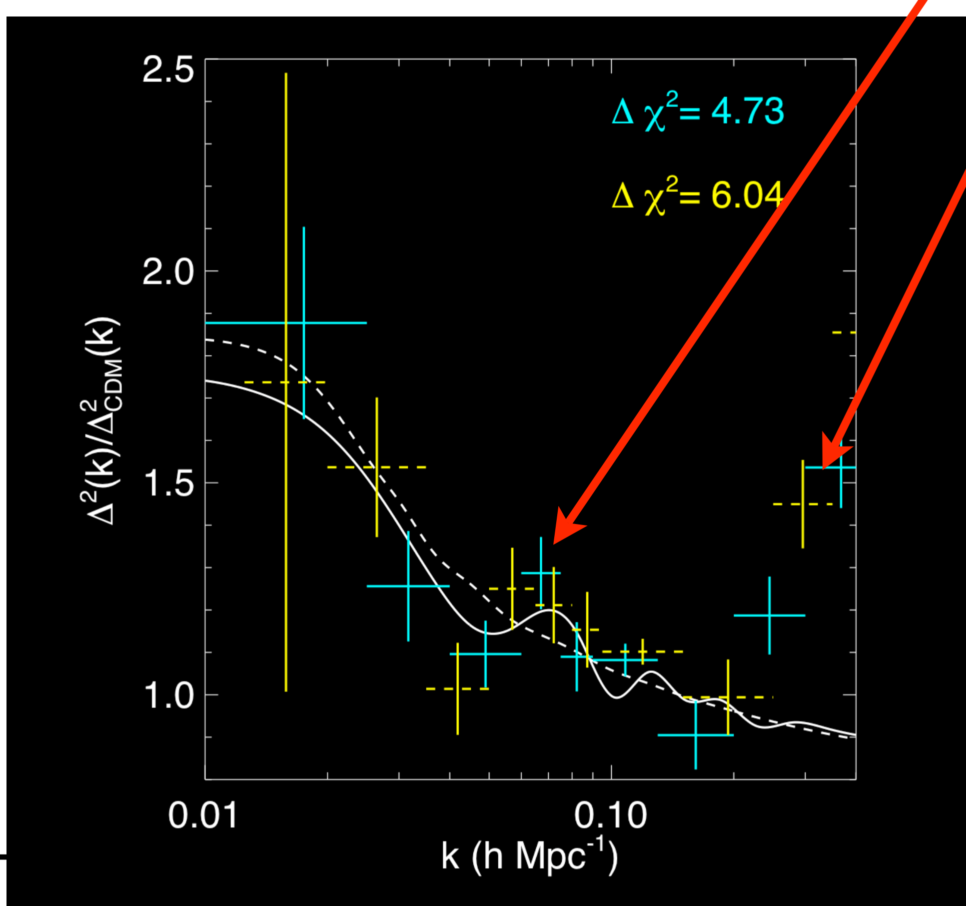


Eisenstein et al. 2005
SDSS spectro-z
40,000 red galaxies
0.15 < z < 0.40
3.5-sigma detection
(configuration-space analysis)

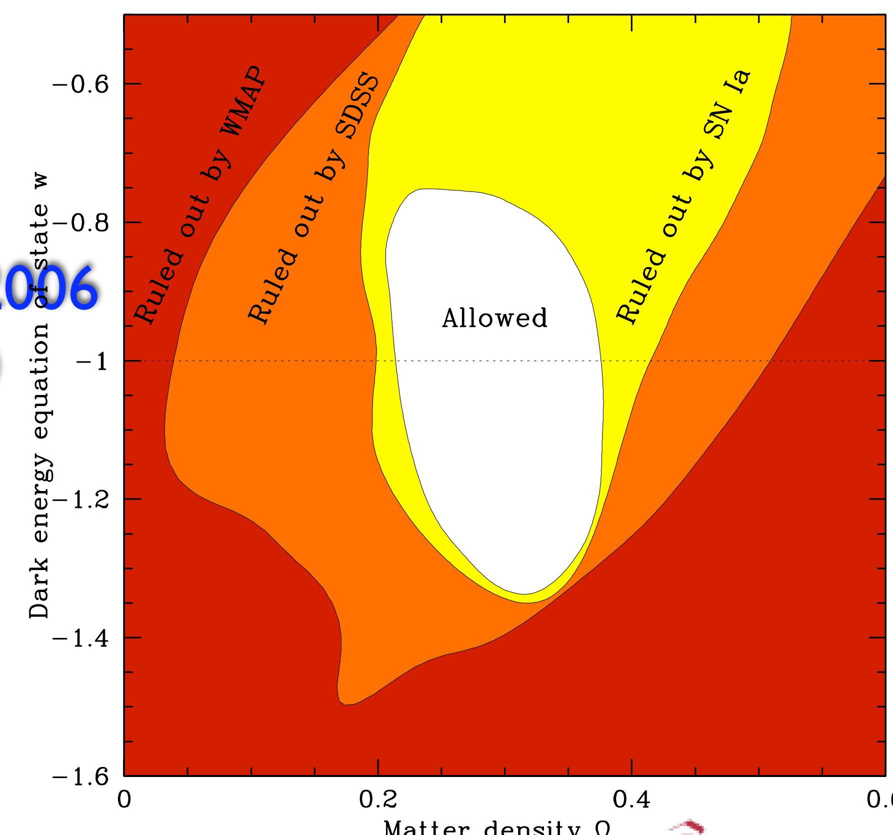


baryon acoustic peak

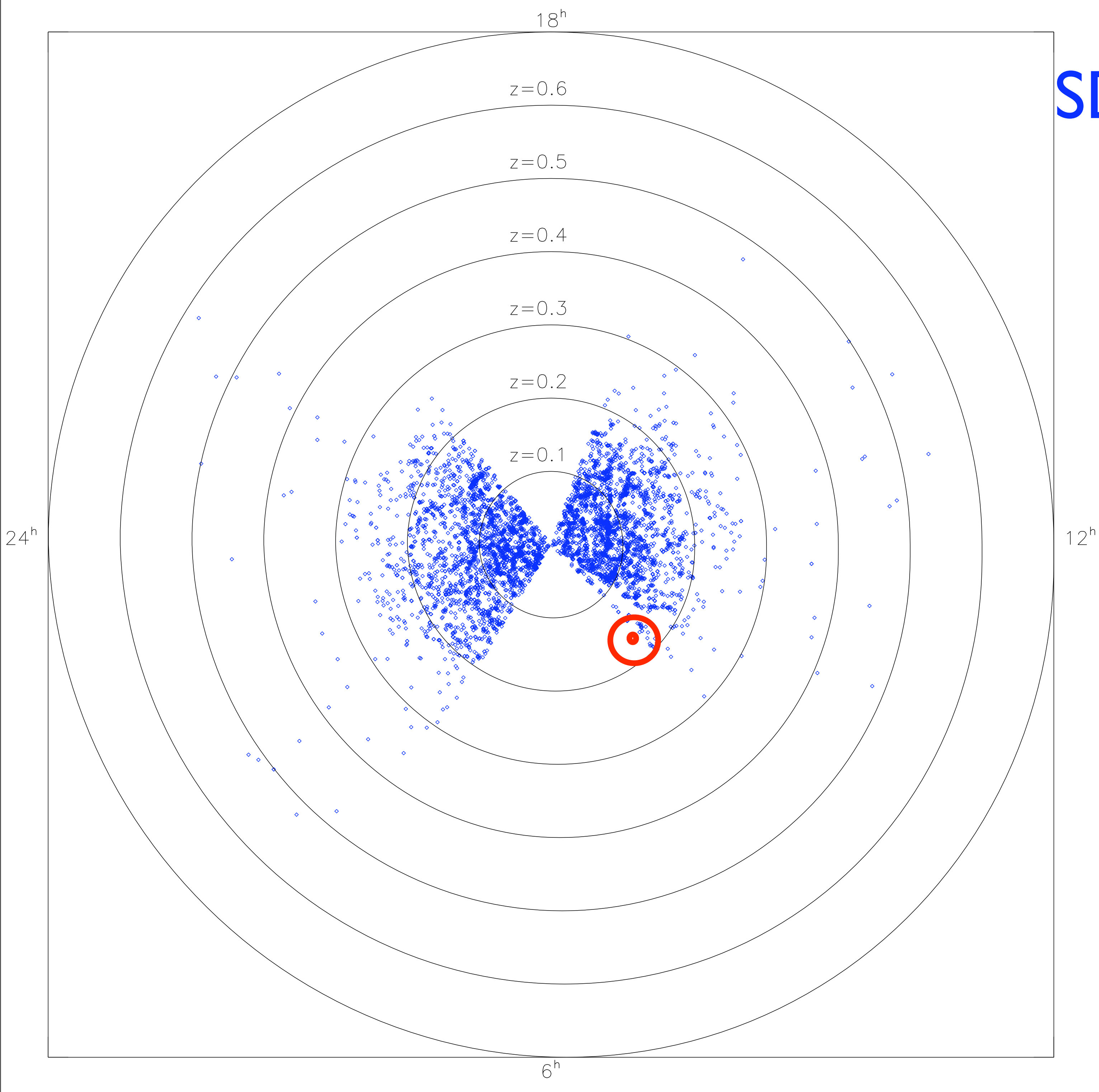
non-linear growth of structure



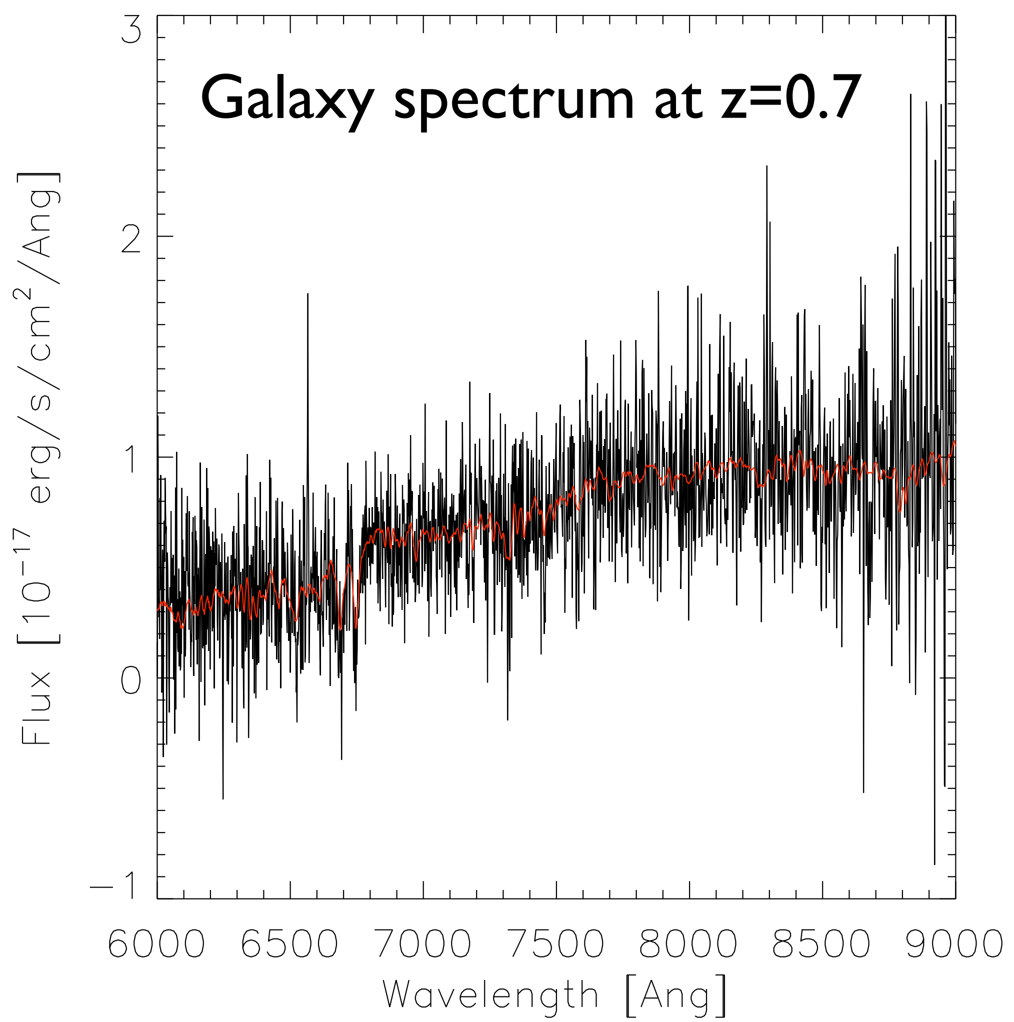
Padmanabhan,Schlegel et al 2006
SDSS photo-z (less accurate)
600,000 red galaxies
0.15 < z < 0.60
2.5-sigma detection
(power spectrum analysis)



Baryon acoustic oscillations:
The tool is large galaxy redshift surveys.

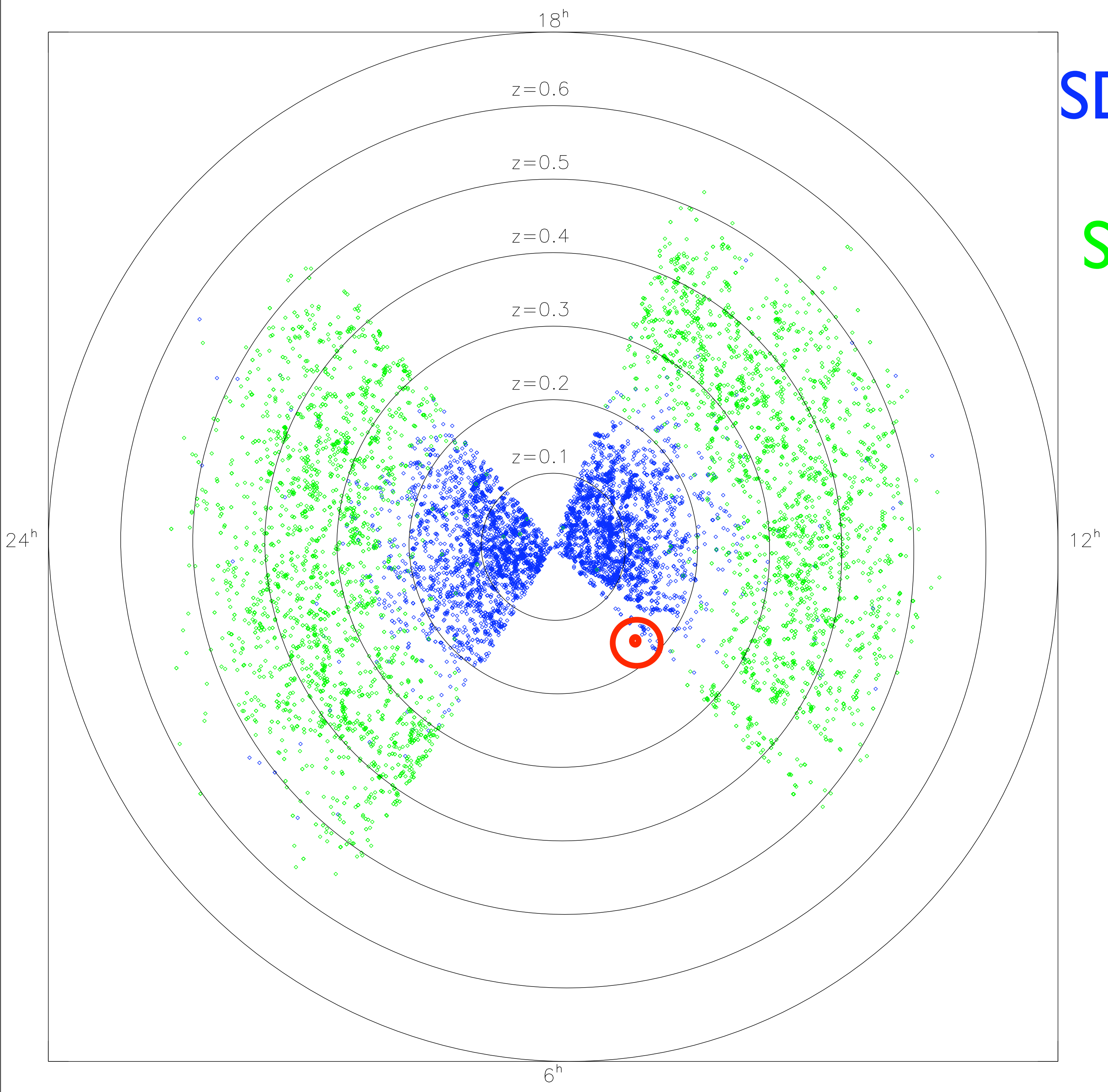


SDSS main survey (too small!)



Baryon acoustic oscillations:

The tool is large galaxy redshift surveys.

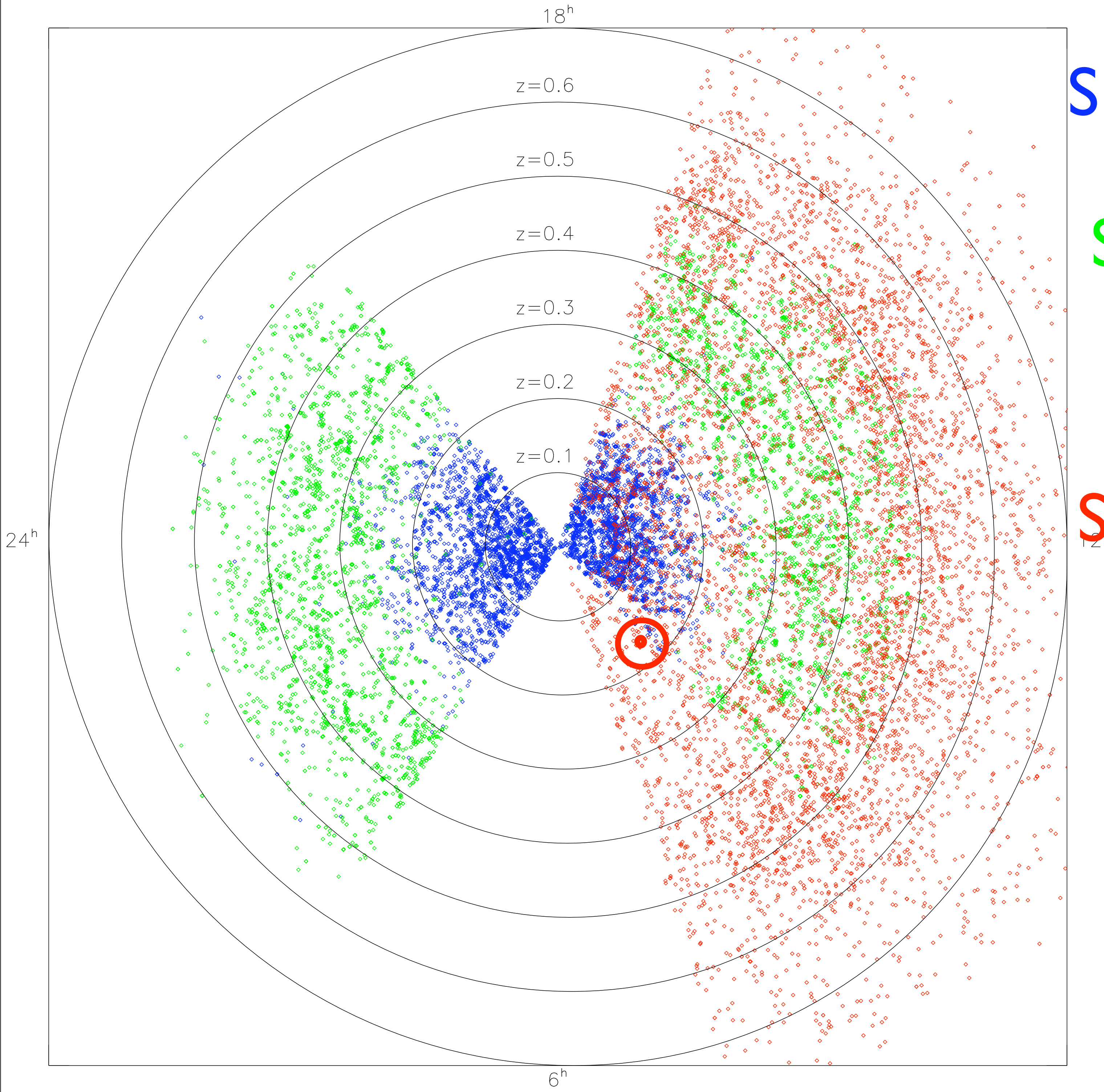


SDSS main survey (too small!)

SDSS-I + SDSS-II red galaxies
8000 deg^2 (finish in 2008)
samples 10^{-4} galaxies/Mpc^3

Baryon acoustic oscillations:

The tool is large galaxy redshift surveys.



SDSS main survey (too small!)

SDSS-I + SDSS-II red galaxies
8000 deg^2 (finish in 2008)
samples 10^{-4} galaxies/Mpc^3

SDSS-III red galaxies
10,000 deg^2
5x sample density (shot noise)
2x volume

↑

PROPOSED
(very similar to the Padmanabhan et al photo-z sample)

Our proposal

- Image additional 2000 deg^2 in Fall by end of 2008
  - 8500 deg^2 footprint in Spring
  - 2500 deg^2 footprint in Fall

Tegmark "heresy plan" ca. 2002

- Upgrade spectrographs in summer 2008 or 2009
  - 640 3-arcsec → 1000 2-arcsec fibers
  - SITe 2048^2 24μ CCDs → Fairchild & LBNL fully-depleted 4096^2 15μ CCDs
  - Ruled gratings → VPH gratings
- (Milky Way program 2008-2009)
- Only spectroscopy from 2009-2013
  - 1.5 million LRGs $i<20$, $z<0.8$, over 10,000 deg^2 (dark+grey time)
  - 0.1 million QSOs $g<22$, $2.3<z<3$, over 5,000 deg^2 (dark time)

BAO standard ruler at $z=0.5,0.7$

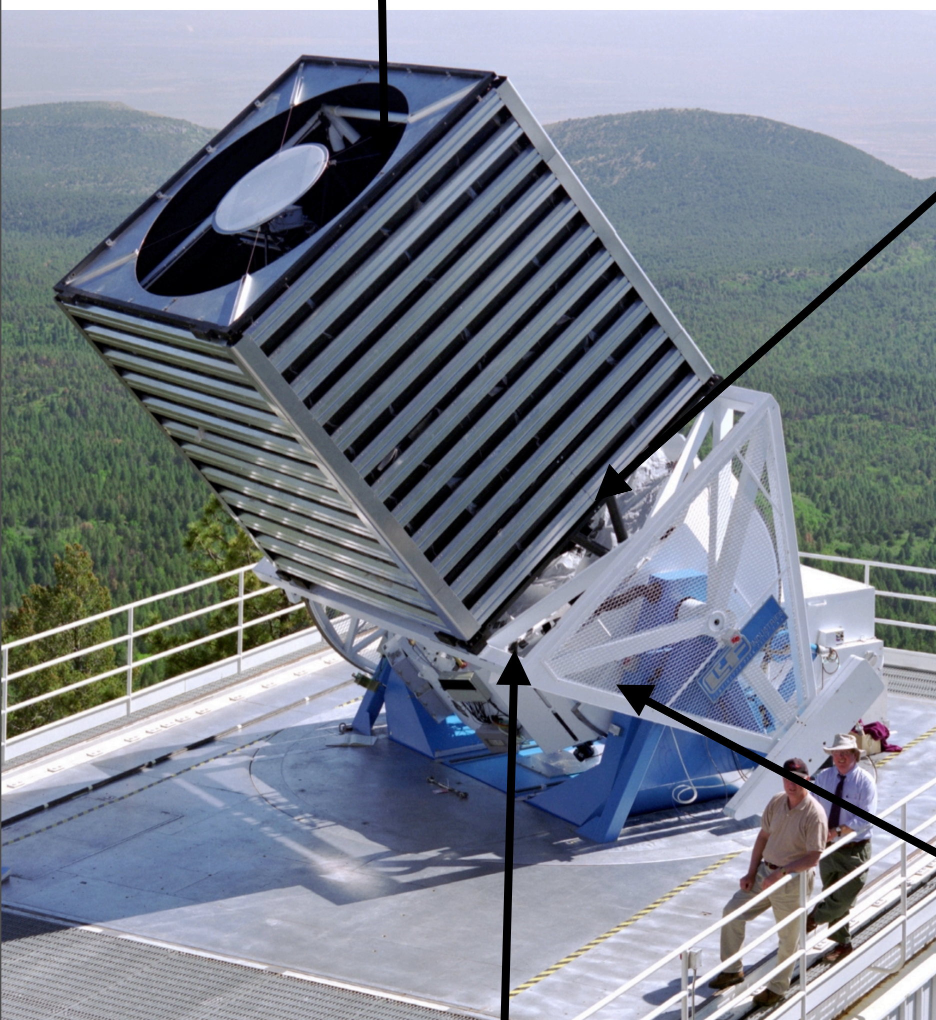
BAO from Lyα forest $z=2.5$

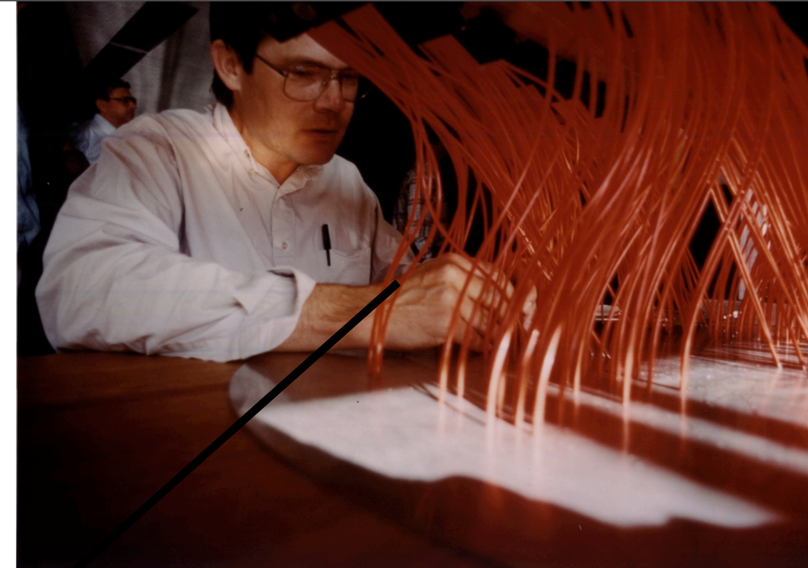
Other science

- Cosmology: parameter constraints, break bias degen.?, kinetic SZ, ISW, A.P. tests, ...
- Galaxy formation + evolution
- Piggy-back programs?
  - Luminous blue galaxies?
  - Fainter in galaxy lum. fn?
  - More stellar kinematics & metallicities?

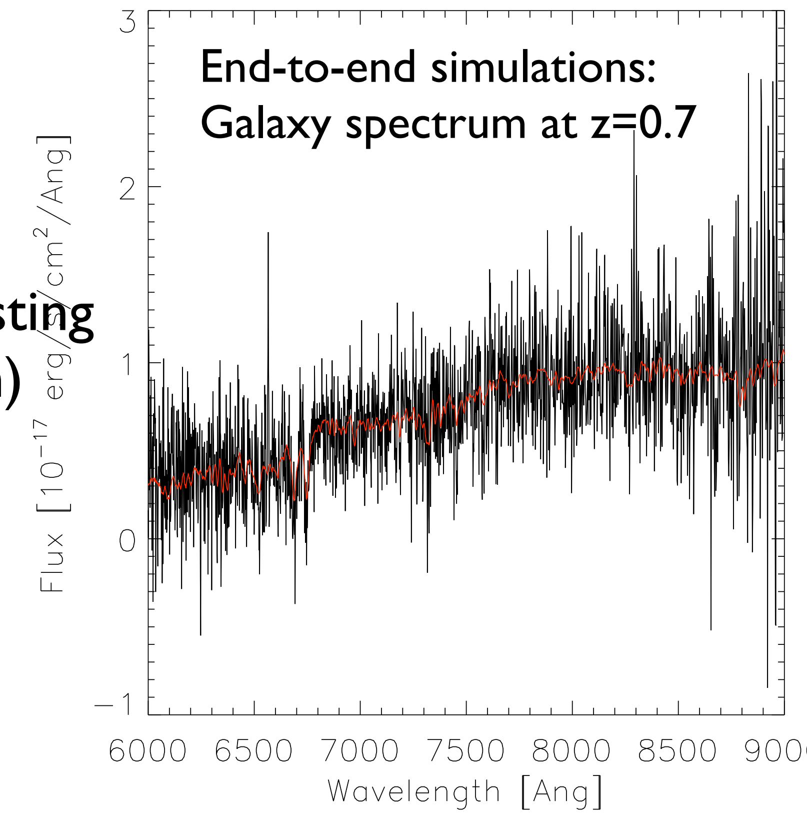
Hardware upgrades

Largest field-of-view of
any large telescope -- DONE!

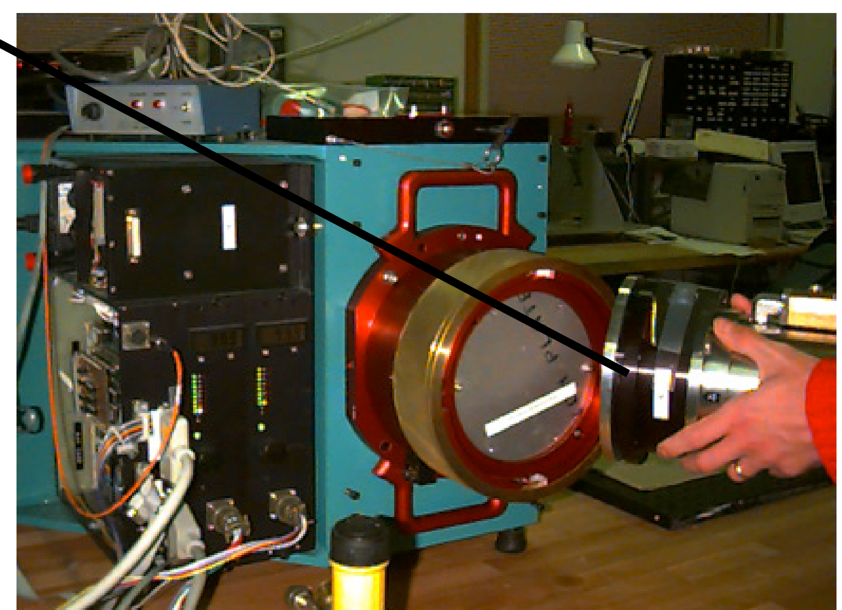




1000 small-core fibers to replace existing
(more objects, less sky contamination)



Software development underway
at LBL, Princeton, NYU



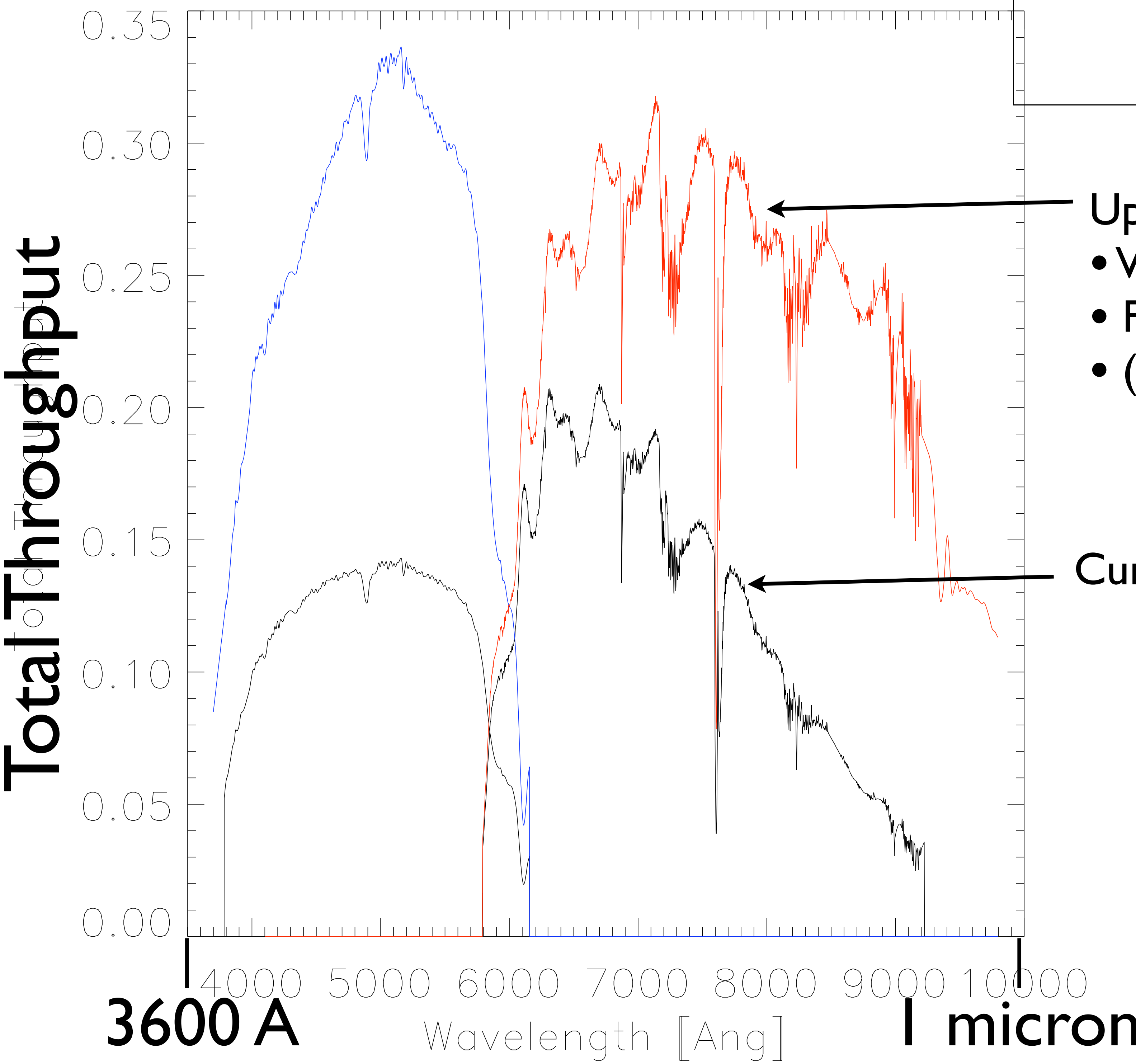
Replace red CCDs w/red-sensitive
LBL/SNAP CCDs, making it
possible to go to higher-z

Replace blue CCDs w/UV-sensitive
Fairchild CCDs, making it possible
for Lyα at z=2.3→3

Swap gratings for VPH

Hardware upgrades

		Current (SDSS-I)	Modified (APO-LSS)
	Number of fibers	640	1000
	Fiber diameter	$180\mu m$ = 3 arcsec	$120\mu m$ = 2 arcsec
Blue side	CCDs	SITe 2K x 2K $24\mu m$	Fairchild 4K x 4K $15\mu m$
	Grating	640 l/mm grism	VPH
	λ coverage	3850 – 6000 Å	3700 – 6000 Å
	Resolution	1800	2000
Red side	CCDs	SITe 2K x 2K $24\mu m$	LBNL 4K x 4K $15\mu m$
	Grating	440 l/mm grism	VPH
	λ coverage	5800 – 9200 Å	5800 – 9800 Å
	Resolution	1800	2400



Updated throughput

- VPH gratings
- Fairchild + LBNL CCDs
- (However, more fiber losses not included)

Current throughput

Current + proposed BAO experiments

SDSS & SDSS-II	ARC 2.5-m, 3° FOV	640 fibers	2000-2008	8000 deg^2	<z>=0.35
AGES (Eisenstein)	MMT 6.5-m, 1° FOV	300 fibers	2005-...	(small)	
SDSS-III LRGs **2.3**	ARC 2.5-m, 3° FOV	1000 fibers	2009-2013	10,000 deg^2	<z>=0.7
SDSS-III QSOs	ARC 2.5-m, 3° FOV	1000 fibers	2009-2013	5,000 deg^2	<z>=2.5
LAMOST	Chinese 6-m, 2° FOV	4000 fibers	???	???	<z>=0.7
AAOmega LRG	AAT 4-m, 2° FOV	400 fibers	Rejected		
AAOmega WiggleZ **0.7**	AAT 4-m, 2° FOV	400 fibers	2006-... (200 nights)	1,000 deg^2	<z>=0.8
HETDEX	Hobby Eberly 11-m	200 IFUs	???	200 deg^2	z=1.8→3.8???
FMOS	Subaru 8.4-m, 0.5° FOV	200 fibers	2007-... (200 nights)	200 deg^2	<z>=1.4
WFMOS (previously KAOS) **3.4**	Subaru 8.4-m, 1° FOV	~3000 fibers	2014? (120 nights)	1000 deg^2	<z>=1
WFMOS (previously KAOS)	Subaru 8.4-m, 1° FOV	~3000 fibers	2014? (60 nights)	150 deg^2	<z>=3
ADEPT (JDEM proposal) **6.0**	Earth orbit 1.3-m	Grism 1→2μm	2014?	30,000 deg^2	z=1→2
Cosmic Inflation Probe	L2 orbit 1.8-m, 0.3° FOV	Grism 2.5→5μm	???	140 deg^2	z=3→6.5

Figure of merit from Dark Energy Task Force

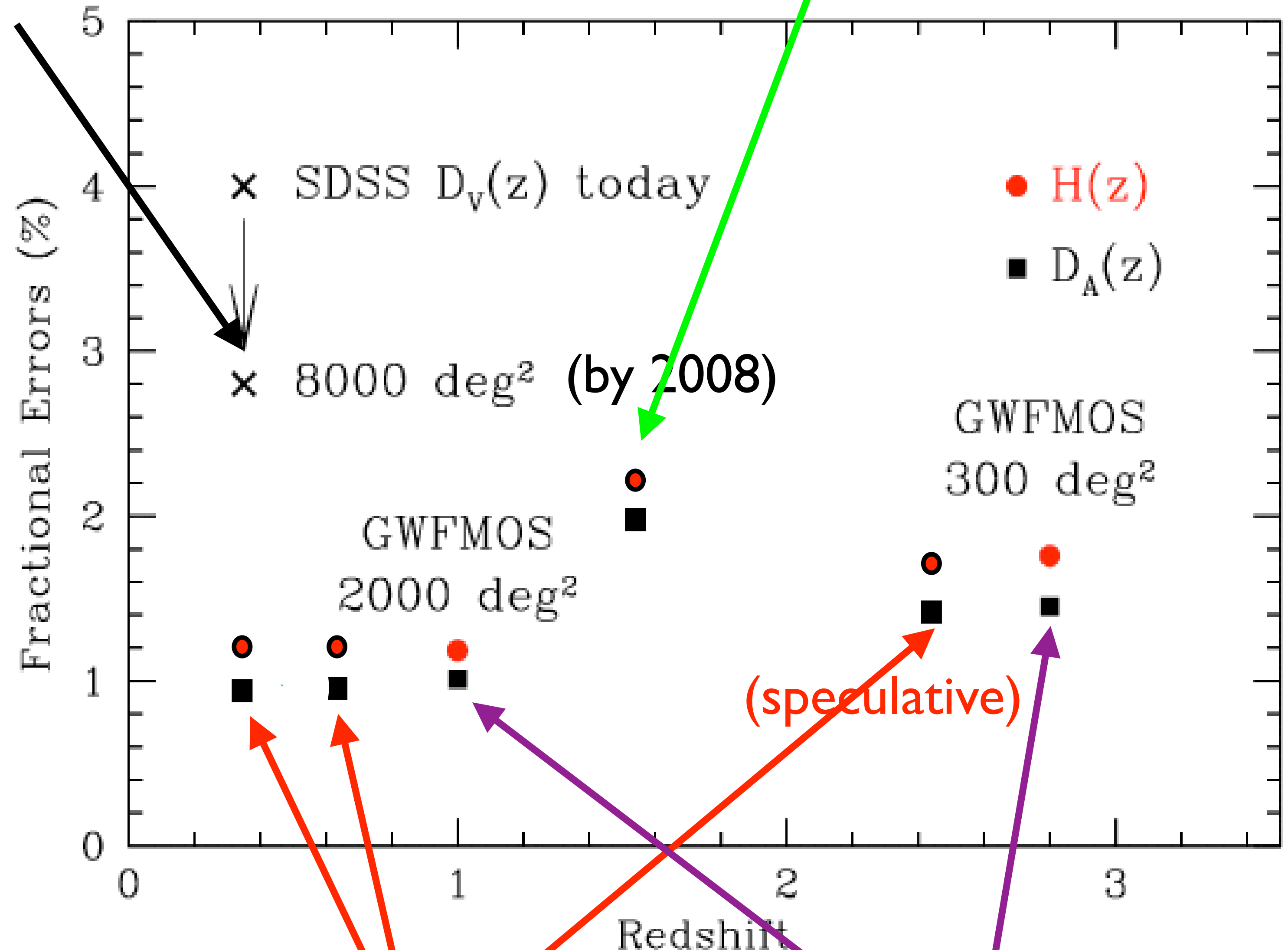
(White & Padmanabhan, priv com)

Chasing the acoustic peak: SDSS-III

- Proposed ground-based surveys will measure the position of the acoustic peak to high precision.
- Measure distance versus redshift via a robust geometric test.
- SDSS-III will improve the measurement at z<0.8, where the dark energy is most dominant.
- SDSS-III may extend to z=2.4 using quasar absorption lines (speculative)

SDSS-II (underway)

Subaru FMOS proposal
200 deg^2 1.3<z< 1.7



SDSS-III proposal
to begin in 2008
10,000 deg^2 z=0.4,0.6
5,000 deg^2 z=2.4

Subaru+NOAO concept,
possibly starting 2013

Target selection: LRGs

Reasonably well-established from existing data from AGES (MMT) and 2SLAQ (AAT)

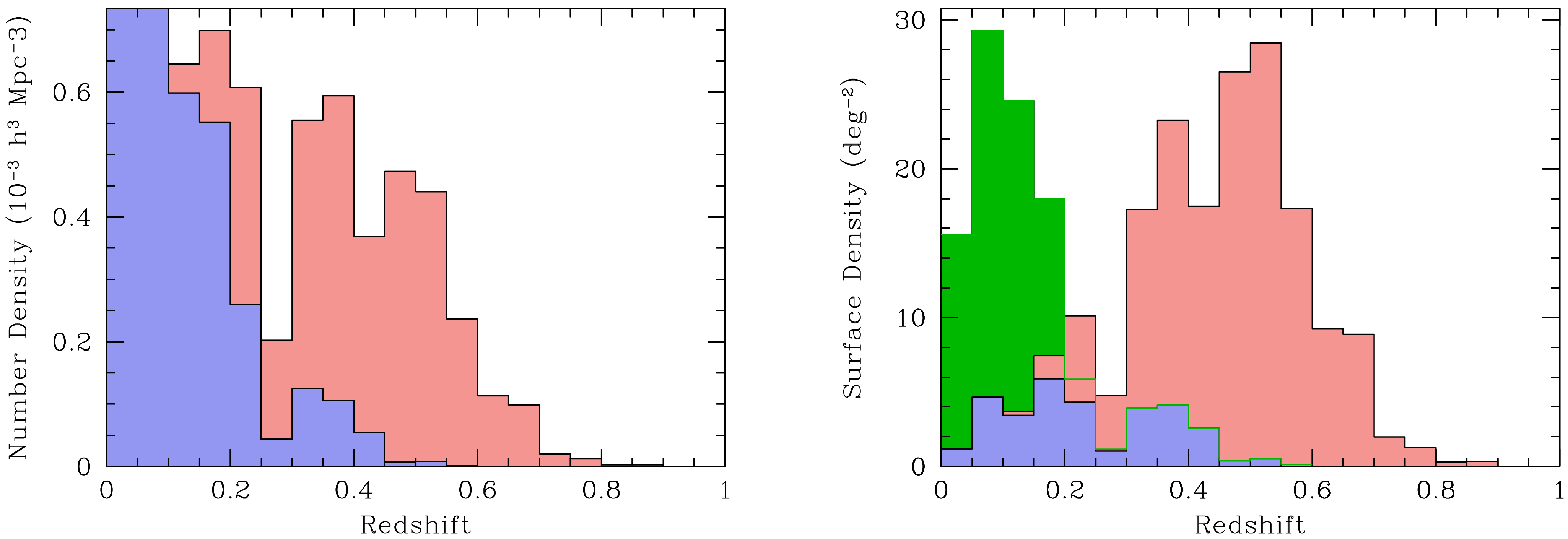


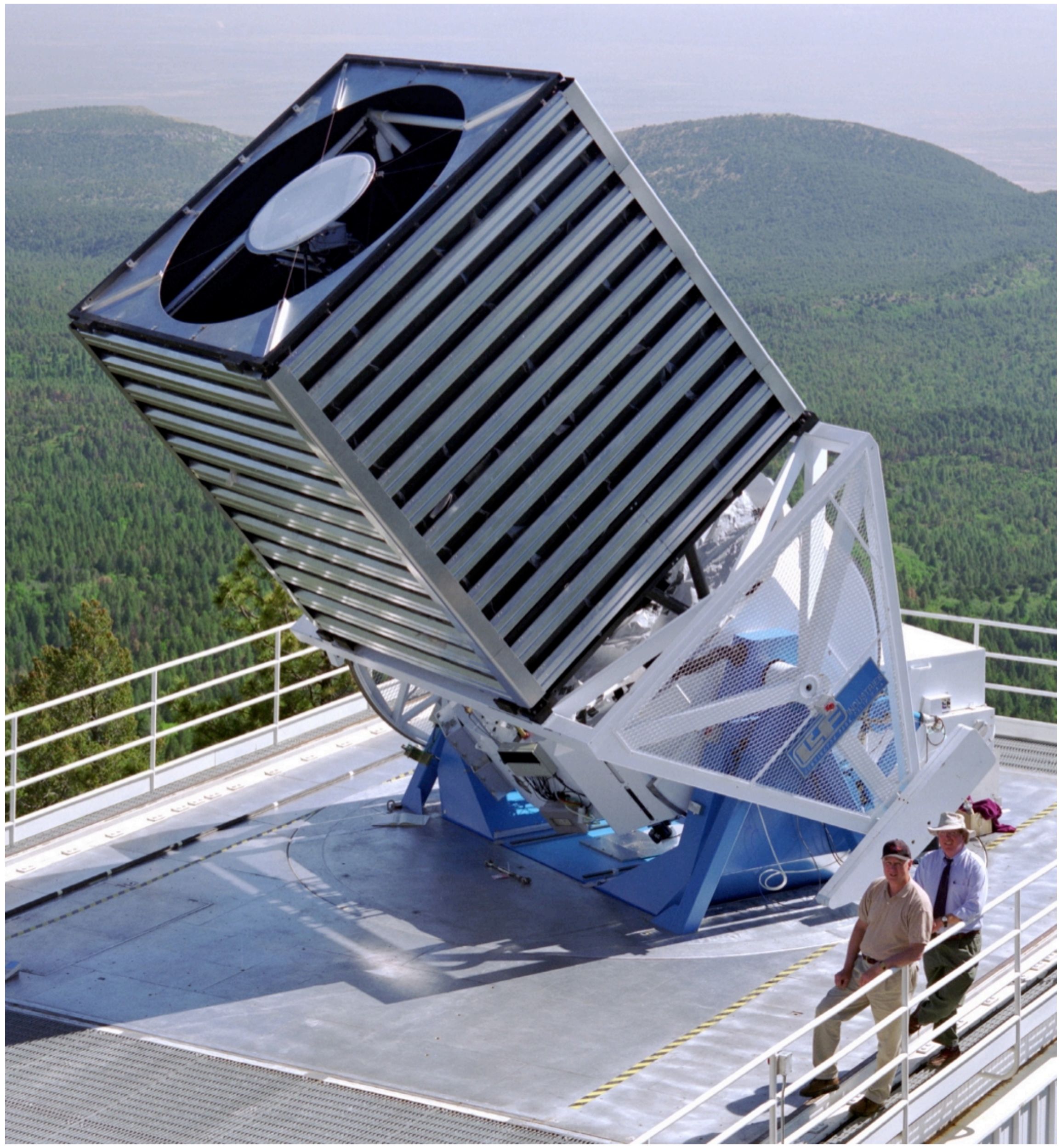
Fig. 2.— The redshift distribution of the APO-LSS LRG survey for our baseline target selection. These targets are selected from SDSS imaging over 7.6 square degrees, with spectroscopic redshifts from the AGES survey (Kochanek et al. 2006). (*Left*) The comoving number density versus redshift. The red histogram is the total APO-LSS selection; the blue histogram are those targets that already have redshifts from SDSS-I. (*Right*) The areal density versus redshift. The red histogram is the total APO-LSS selection; the blue histogram are those targets that already have redshifts from SDSS-I. The green histogram is the total sample from SDSS-I. Because the data is drawn from only 7.6 square degrees, one can see the large-scale structure in both redshift histograms; nevertheless, the figure demonstrates that high quality samples with tailored number densities can be extracted from SDSS imaging to the required depth of $i = 20$.

Target selection: QSOs

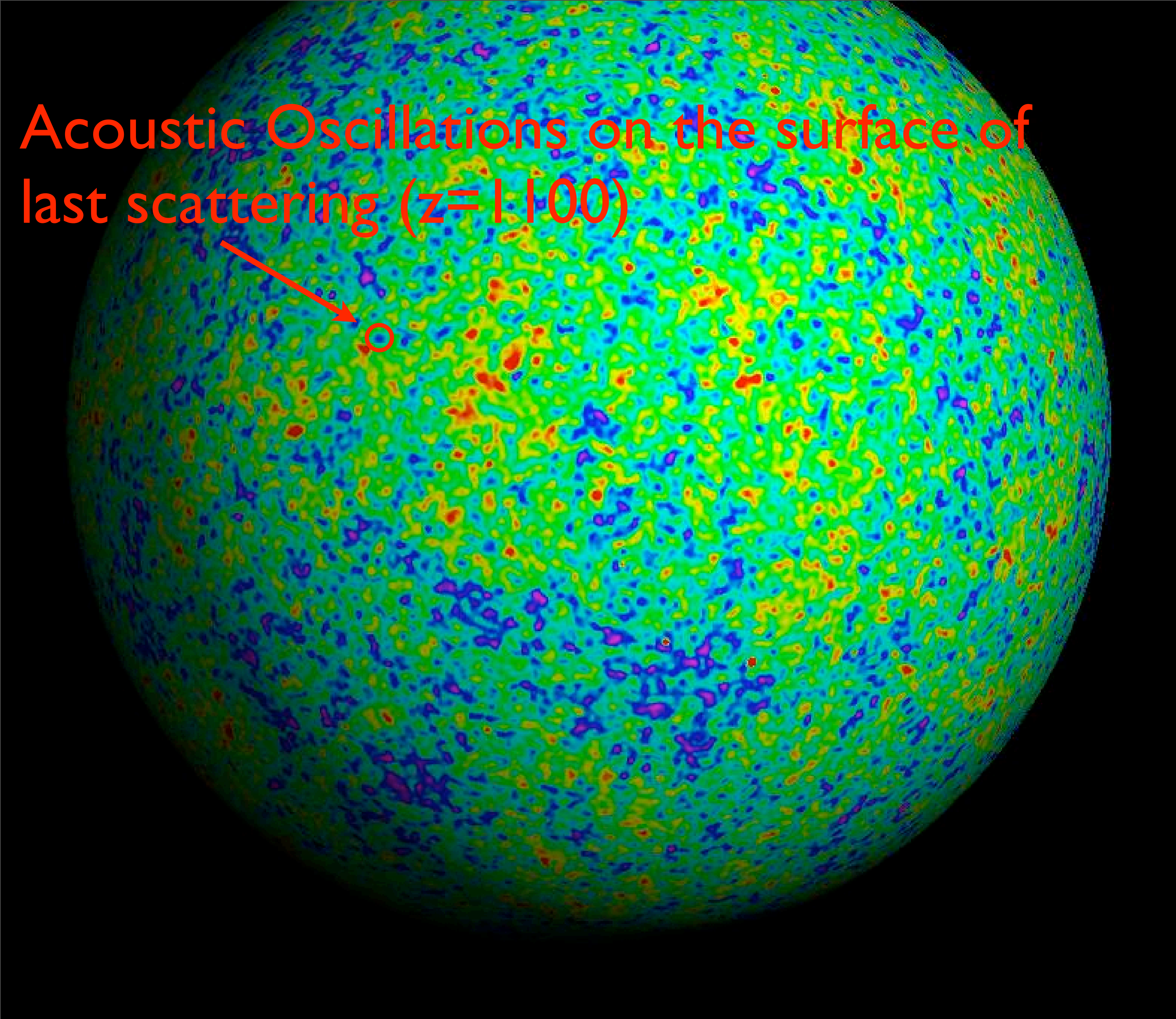
Work in progress...

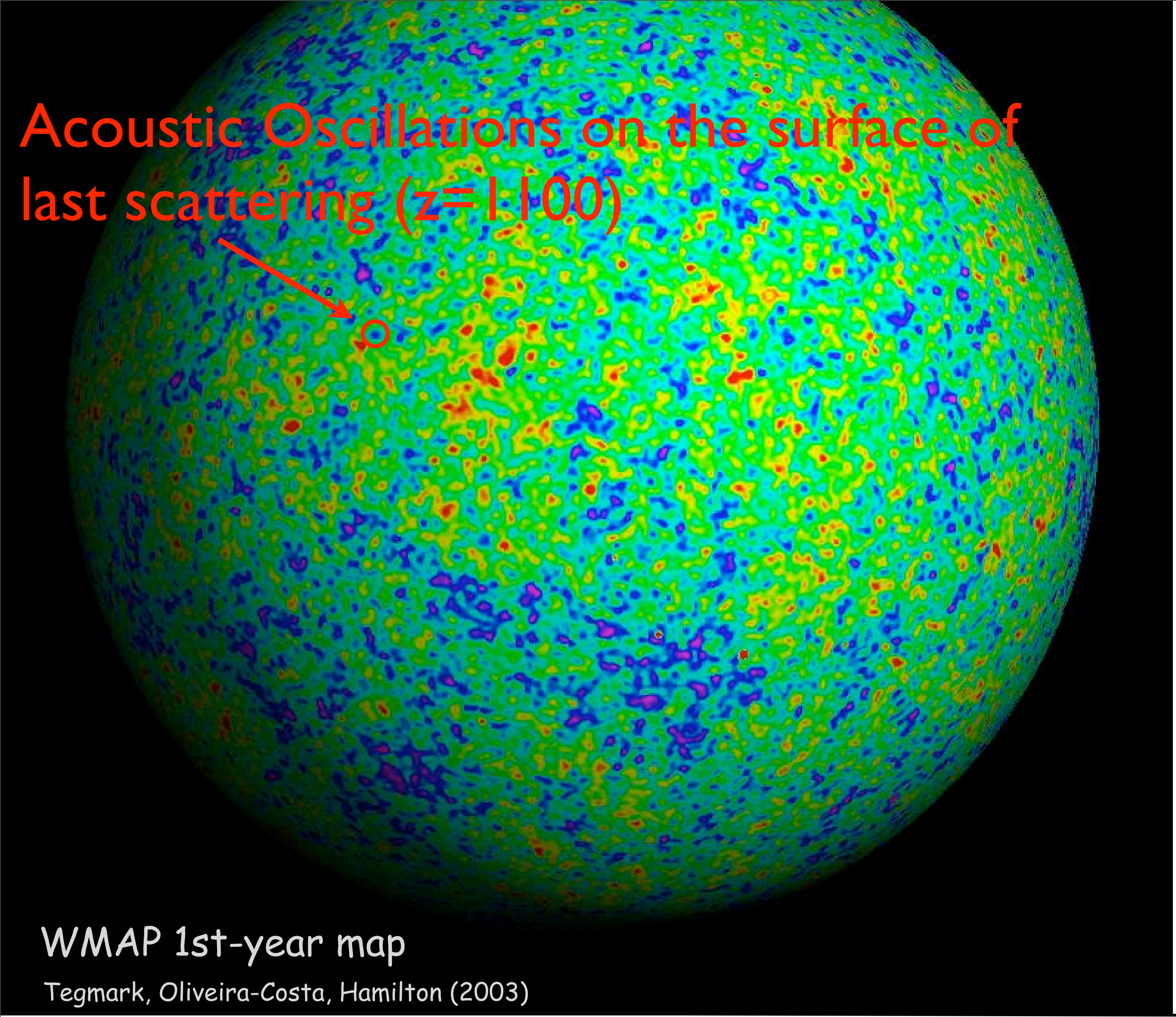
SDSS-III status

- Current collaborators include LBNL, Princeton, NYU, Arizona, UC Santa Cruz, JHU, U. Washington, U. Chicago, Case Western, Drexel, U. Michigan, MIT, Ohio State
- Design work on new dewars, Princeton
- Design work on new gratings, JHU
- Design work on new optical fibers, U. Washington
- New red CCDs in fabrication, LBNL + Dalsa
- Software development begun at LBNL + NYU (target selection, plate design, data reduction, analysis, databasing), building upon current operations + expertise
- Visit by LBNL to Apache Point Observatory in July to review both hardware + review operating costs
- Plate design code rewrite; ***test data being taken now (Dec/Jan 2007)***
- Proposal to ARC submitted July 31; ***awarded 5 full years of telescope time*** on Nov 13
- Collaboration workshop in NYU/Princeton 17/18 Nov. 2006
- ***Oh yeah, we have to pay for this…***



Extra Slides


Acoustic Oscillations on the surface of
last scattering (z=1100)

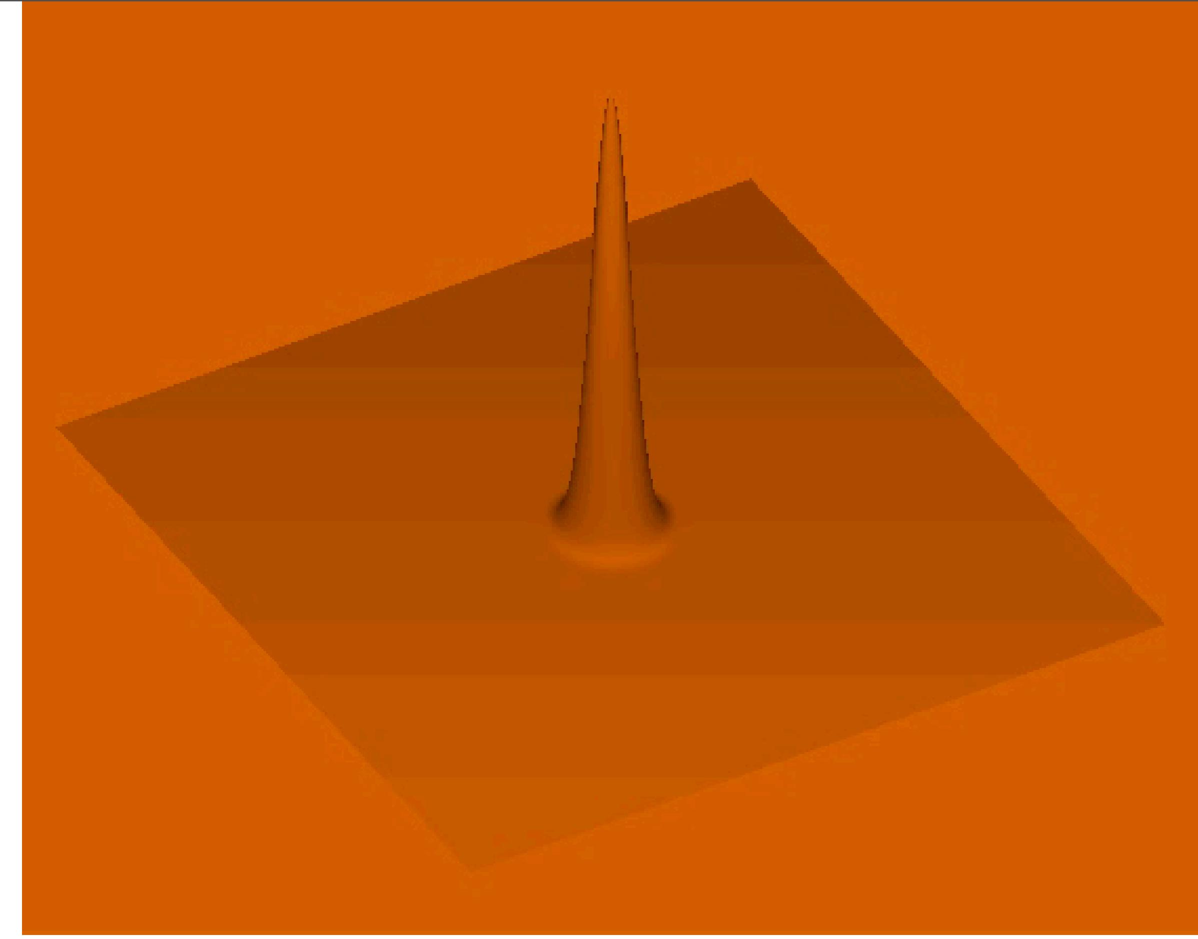

Acoustic Oscillations on the surface of
last scattering (z=1100)
WMAP 1st-year map
Tegmark, Oliveira-Costa, Hamilton (2003)

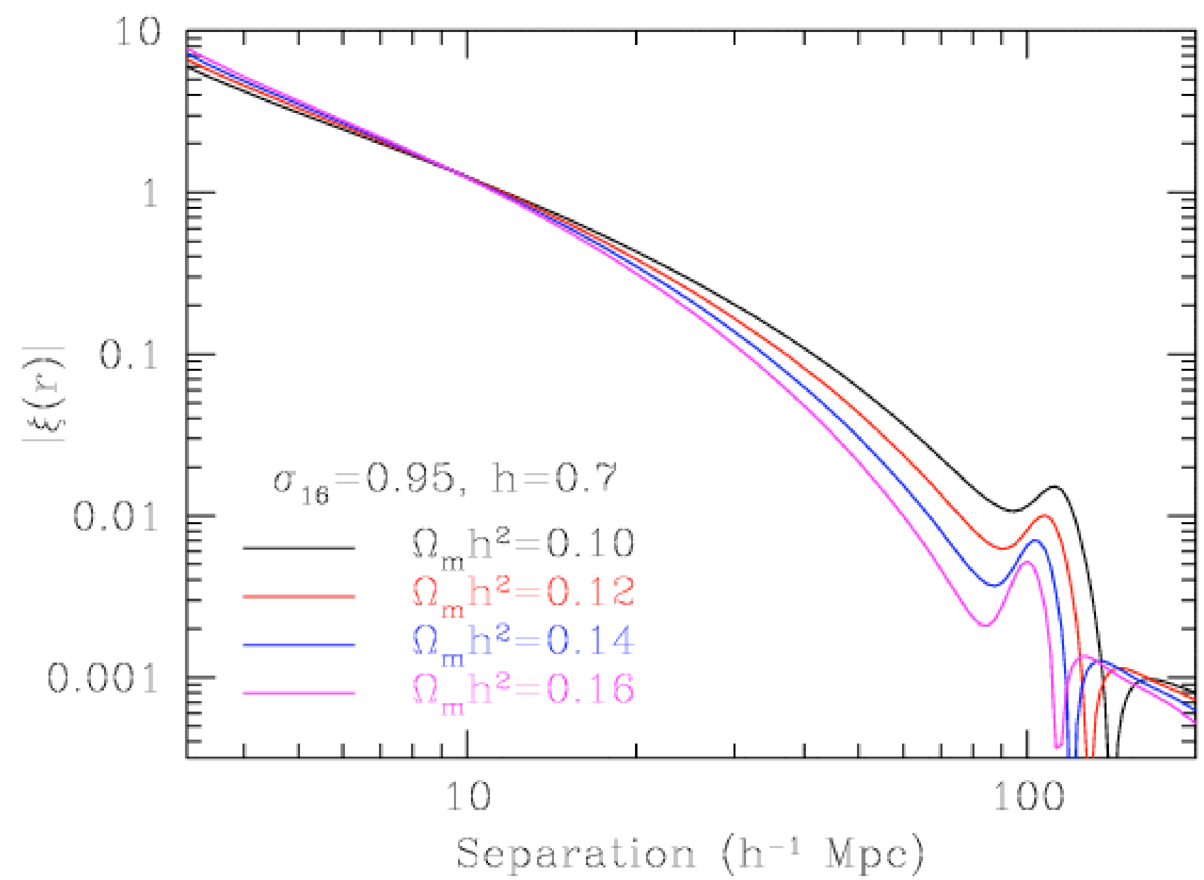
Acoustic Oscillations

...our newest tool

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

standard ruler!



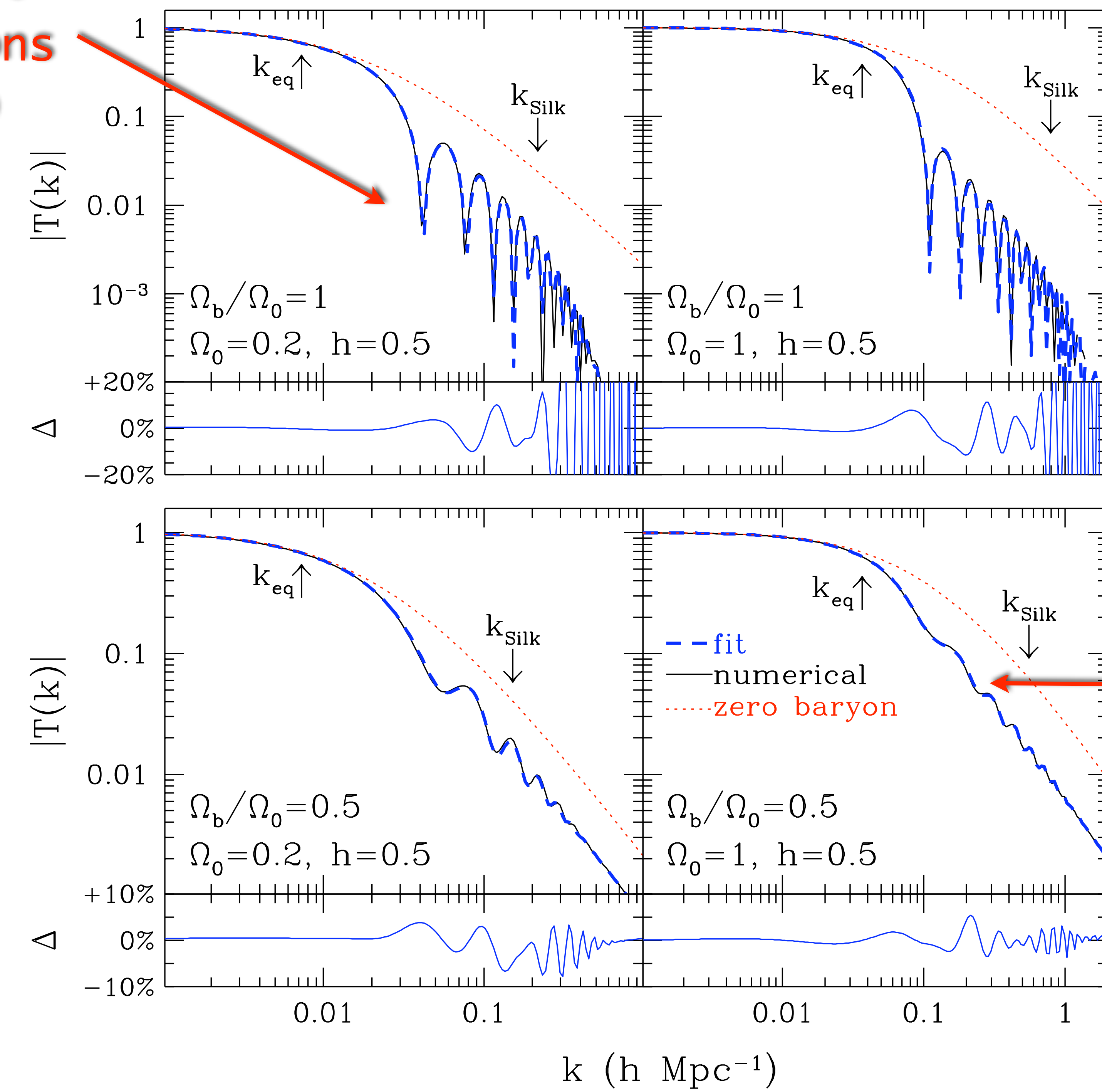


- “This is the method least affected by systematic uncertainties, and for which we have the most reliable forecasts of resources required to accomplish a survey of chosen accuracy. This method uses a standard ruler understood from first principles and calibrated with CMB observations.” --- DETF

- “An advantage of BAO is that it does not require precision measurements of galaxy magnitudes, though if photo-z’s are used then precision in galaxy colors is important. In contrast to weak lensing, BAO does not require that galaxy images be resolved; only their three-dimensional positions need be determined.”

Power spectra from galaxy surveys

If the Universe were all baryons (huge wiggles)



Closer to what we expect to see

Fig. 3.— Four examples of the fit compared to numerical results. The larger plots show the numerical result (solid) and the fit (dashed). The smaller subplots show the residuals, defined as the difference between the two divided by a non-oscillatory envelope. Note that in the fully baryonic models, the oscillations have alternating sign in the transfer function. Also shown is the zero baryon case (dotted); note the strong suppression on scales below the sound horizon due to the baryons.

From Eisenstein & Hu '97

Baryon acoustic oscillations: Future Constraints SDSS-III

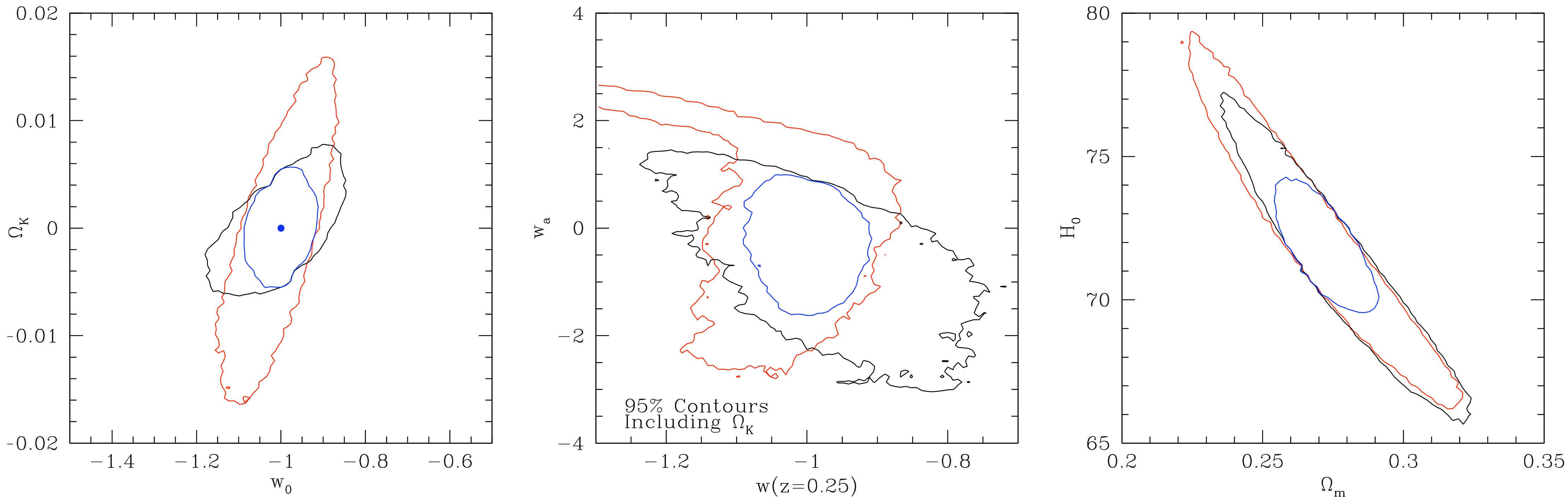


Fig. 4.— (*Left*) The 95% confidence region for constraints on a constant equation of state w and spatial curvature. The red line is the current SDSS BAO measurement plus an aggressive forecast for Type Ia SNe. The black line is from APO-LSS alone. The blue line is APO-LSS plus the SNe. (*Middle*) The 95% confidence region for constraints on the equation of state w at $z = 0.25$ and the time derivative w_a, marginalizing over spatial curvature. The area of these curves is the figure of merit put forward by the Dark Energy Task Force. The lines are the same. The redshift $z = 0.25$ is chosen because it is near the redshift for which the errors on w are minimized. (*Right*) The 95% confidence region for Ω_m and the Hubble constant, marginalizing over spatial curvature and the $w(z) = w_0 + (1 - a)w_a$ parameter space. APO-LSS plus supernovae at $z = 0.5$ and $z = 0$ would measure the Hubble parameter to ± 1 km/s/Mpc and Ω_m to ± 0.007. The lines are the same.

Dark Energy Task Force findings: (13 Feb 2006)

All are geometric measures of dark energy

1. Four observational techniques dominate White Papers:

a. Baryon Acoustic Oscillations (BAO) large-scale surveys measure features in distribution of galaxies. BAO: $d_A(z)$ and $H(z)$.

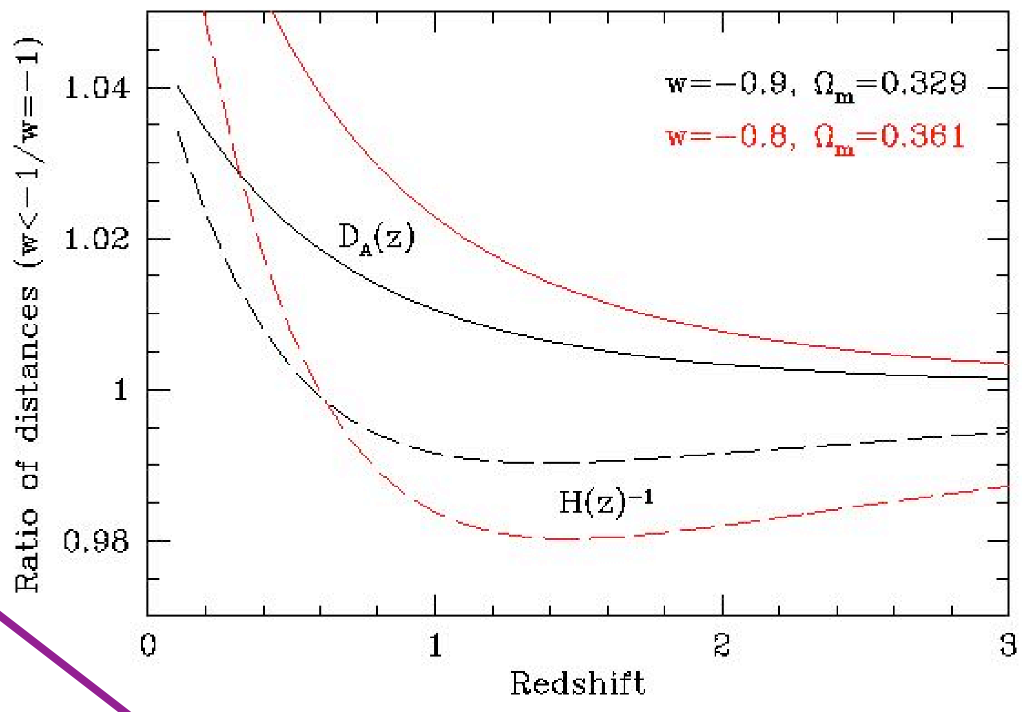
b. Cluster (CL) surveys measure spatial distribution of galaxy clusters. CL: $d_A(z)$, $H(z)$, growth of structure.

c. Supernovae (SN) surveys measure flux and redshift of Type Ia SNe. SN: $d_L(z)$.

d. Weak Lensing (WL) surveys measure distortion of background images due to garavitational lensing. WL: $d_A(z)$, growth of structure.

2. Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmo. parameters.

3. Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques. Not all missions necessarily cover all techniques; in principle different combinations of projects can accomplish the same overall goals.

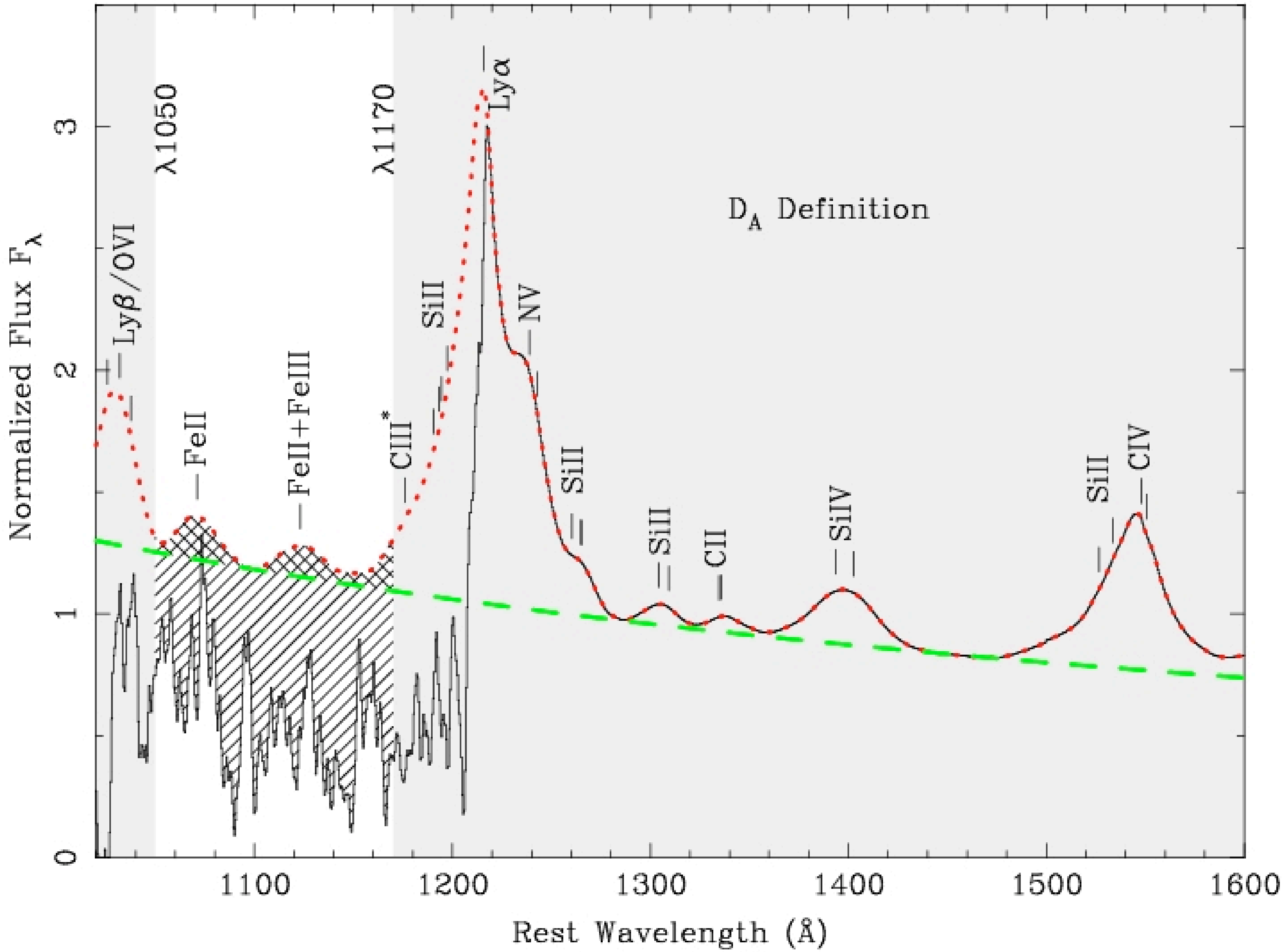


These two methods not yet proven, and complicated by astrophysics (details + evolution of structure formation)

QSO BAO: Will it work?

Only if we understand the underlying spectra...

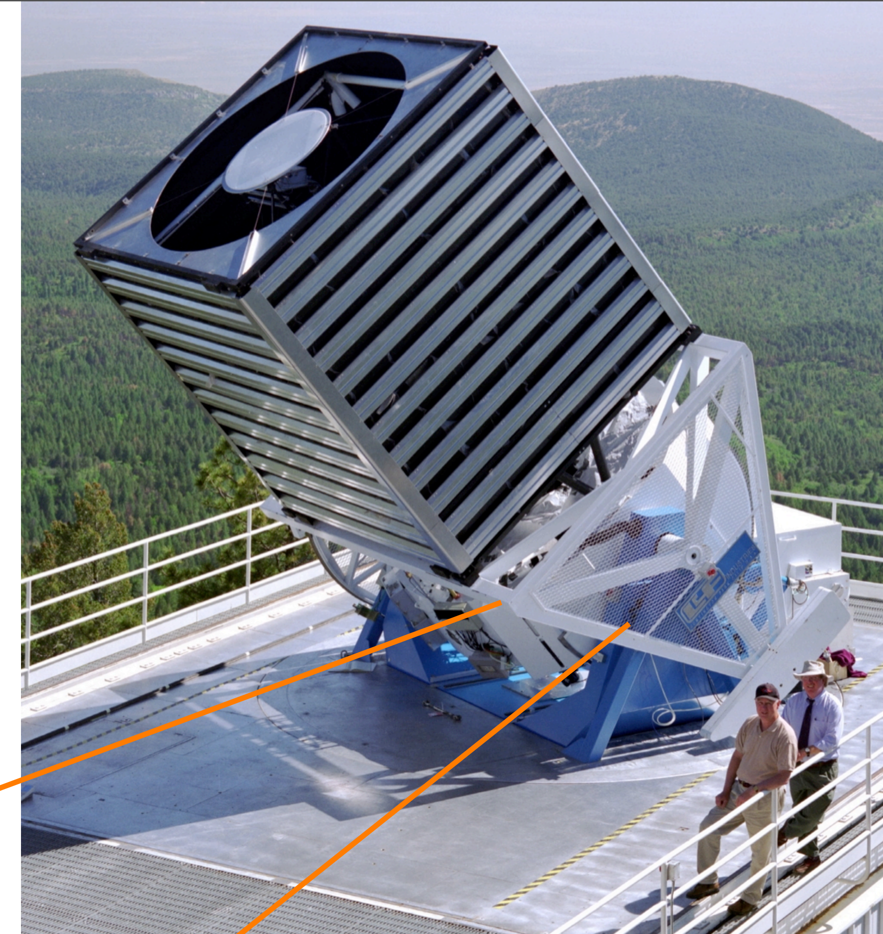
Fitting Continuum to the Ly alpha Forest



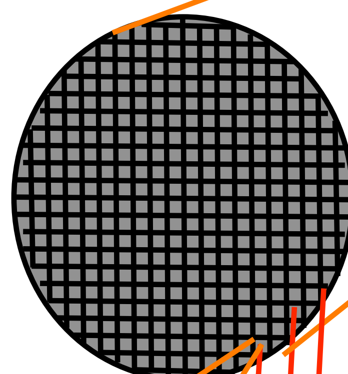
Courtesy of Nao Suzuki

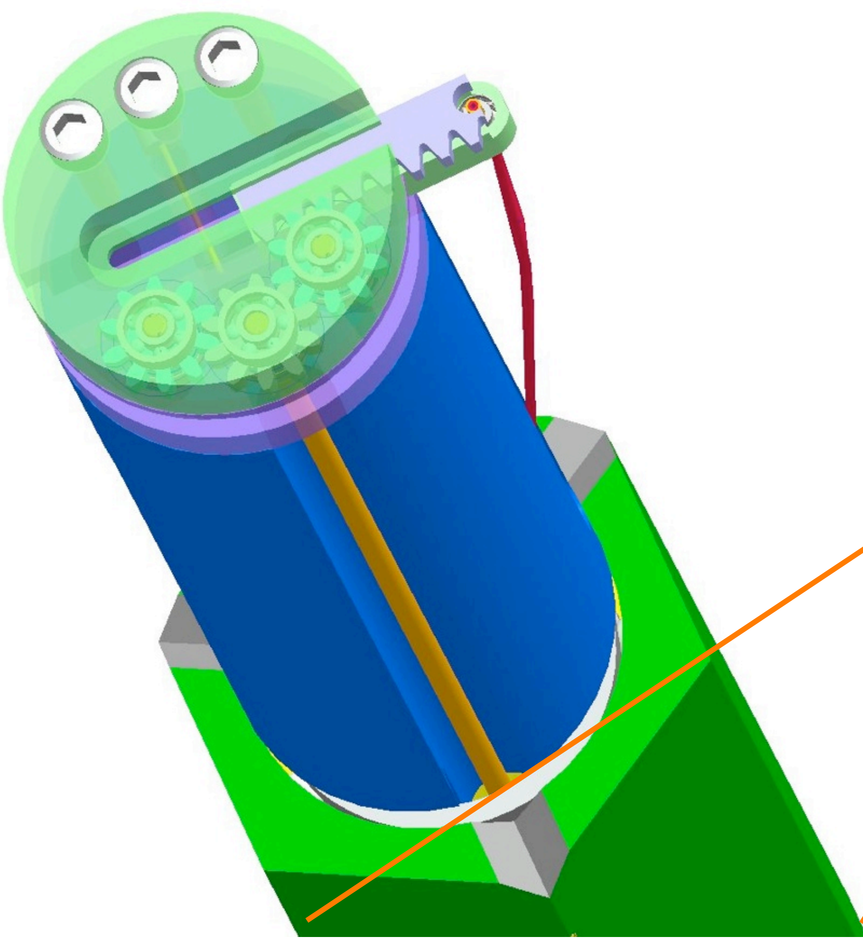
Future fiber-positioning

- Supported by Jim Siegrist in 2005/2006, on LDRD starting Oct 2006
- Optimize BAO experiment design, merging Schlegel et al. and Eisenstein & Spergel ideas
- Design + prototype fiber actuators
- Build survey apparatus (*where are the fibers?*)



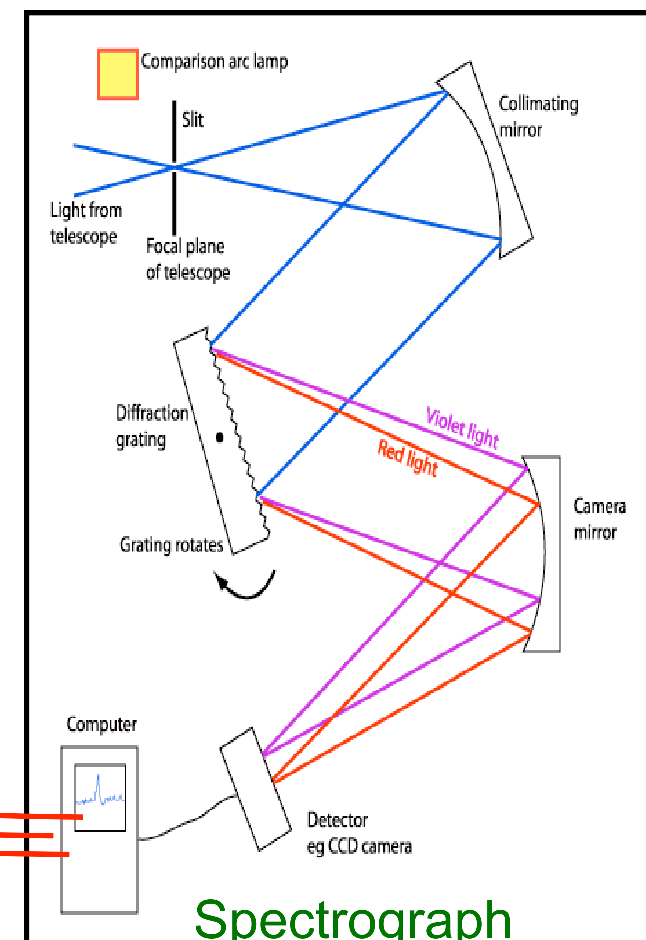
Focal plane





LBNL Fiber Actuator

Optical Fibers

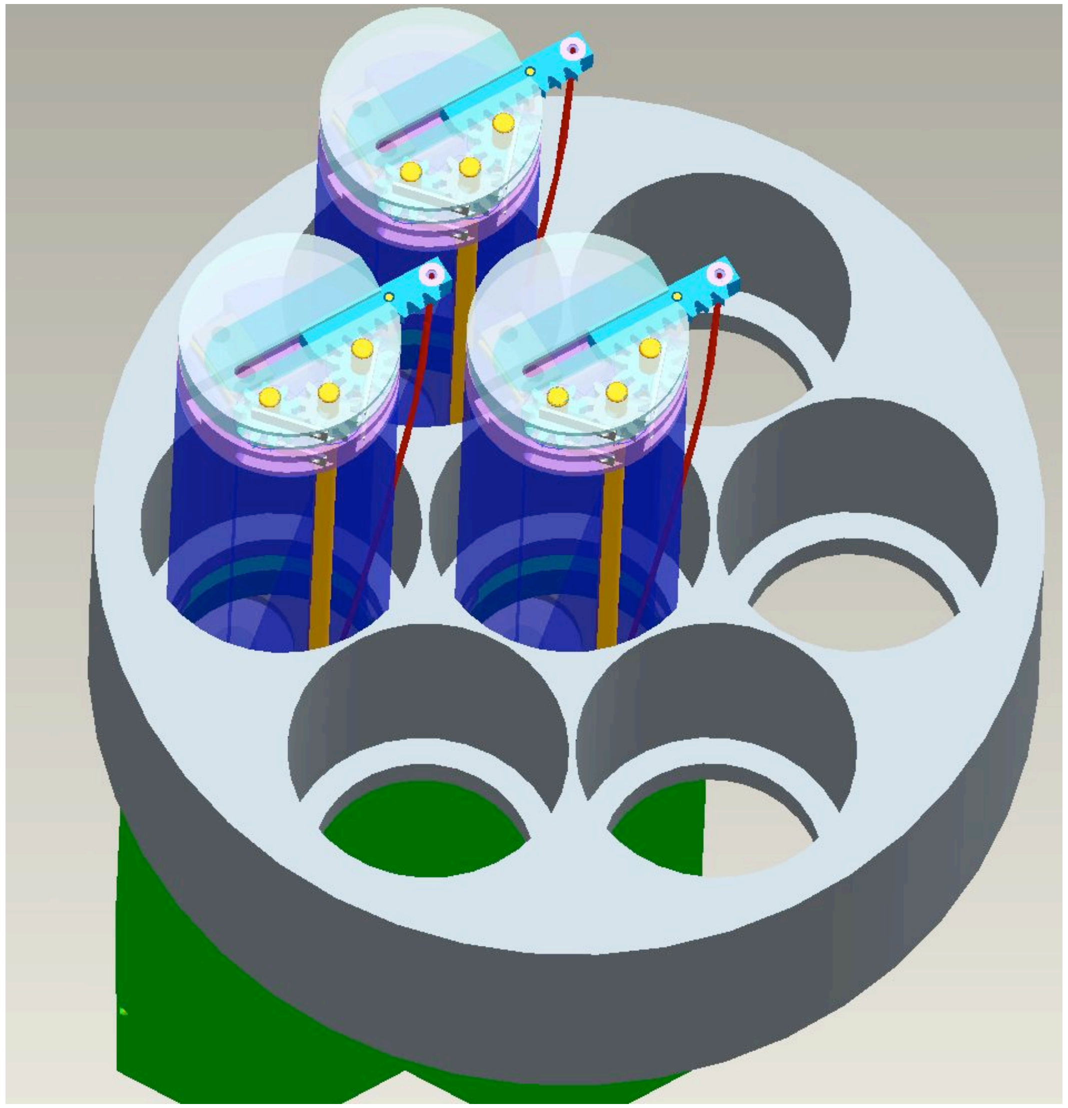


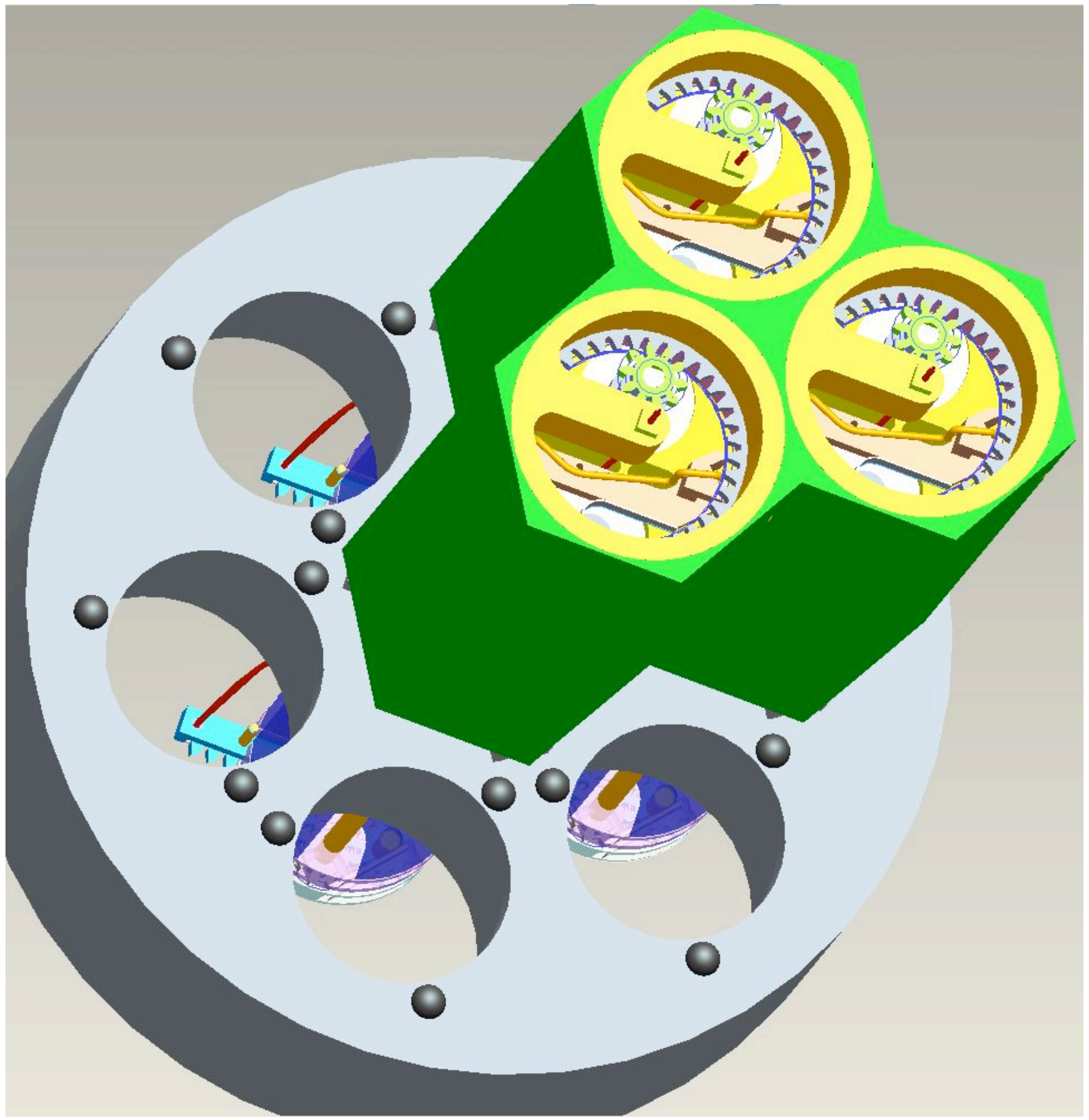
Spectrograph

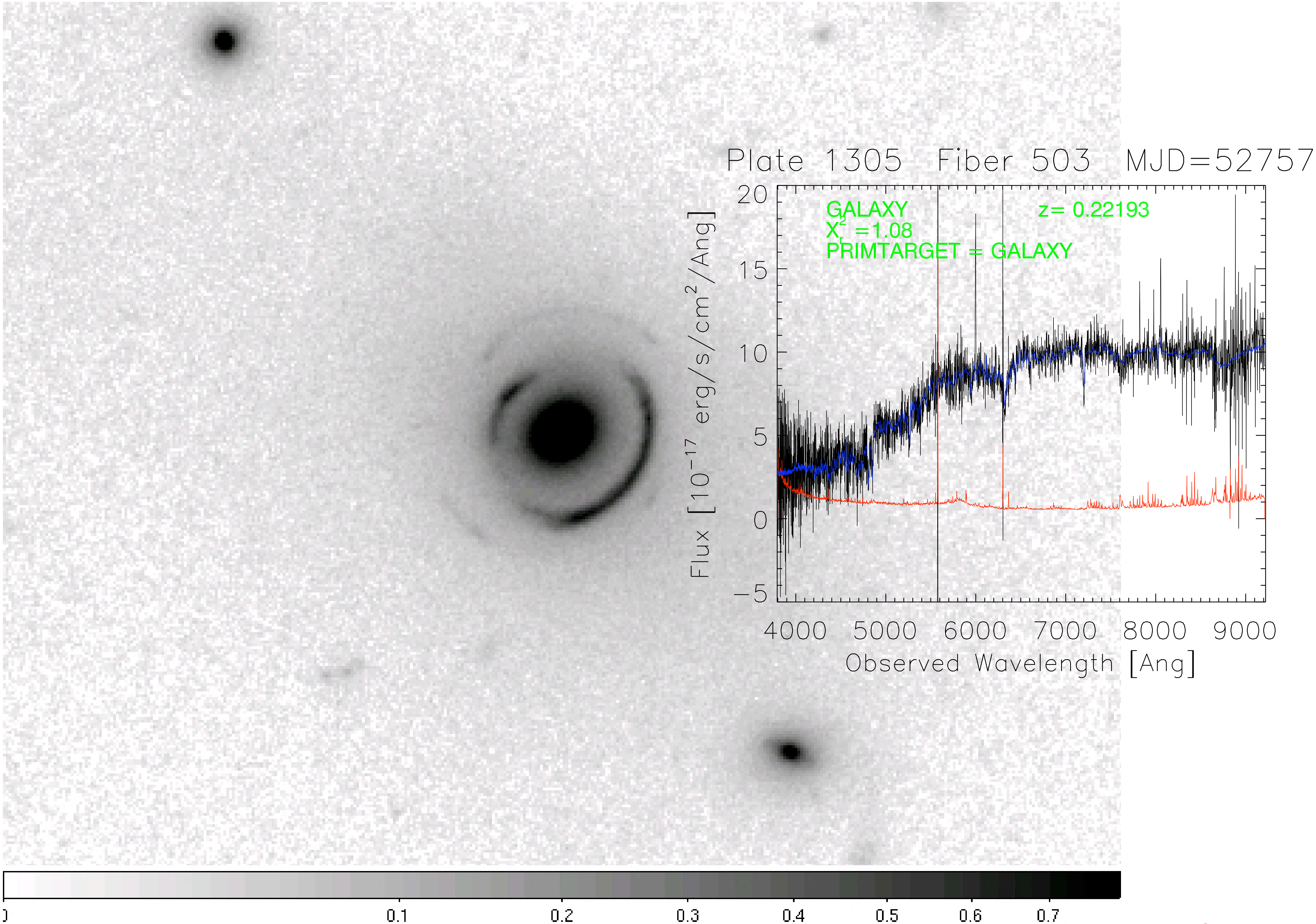
A Schematic Diagram of a Slit Spectrograph

Future Directions?

SDSS-III hits limit of 2.5-m telescope
  + old plug-plates "technology"
Future systems will require larger telescopes (Keck 10-m, Subaru 8-m, Spanish 10-m?)
  + automated fiber positioning with >1000 fibers
Huge demand for such technology for ground-based dark energy experiments:
  baryon acoustic oscillations, redshifts for weak lensing, kinetic S-Z, ...
Difficult to fund such R&D at Universities. ***Thank you LBNL!***
If we don't do this, these future experiments will have to be in space (**==*crazy!***)







Adam Bolton, Harvard, HST image from 5 Nov 2006

Conclusions

- Baryon acoustic oscillations are a rapidly maturing method for measuring the cosmological distance scale and dark energy.
  - Highly robust. Trigonometric method. Errors dominated by sample variance.
  - Complementary to supernova cosmology
- SDSS-3 will be the definitive low-redshift data point, reaching near the cosmic variance limit.
  - Data would also be the best available for large-scale structure, e.g. P(k).
  - Possible measurement at z=2.5 from QSOs (speculative)
- Study topics:
  - Observational strategy and instrument flow-down.
  - Parameter estimation in light of reconstruction.
  - How do these distance bounds compete on w(z)?
- The future?
  - R&D on fiber-positioning technology for big telescopes; push to higher redshifts z>0.7
  - What is the systematics floor on d_A? 1% ? 0.1% ?
  - Study ground-based vs. space-based experiments?