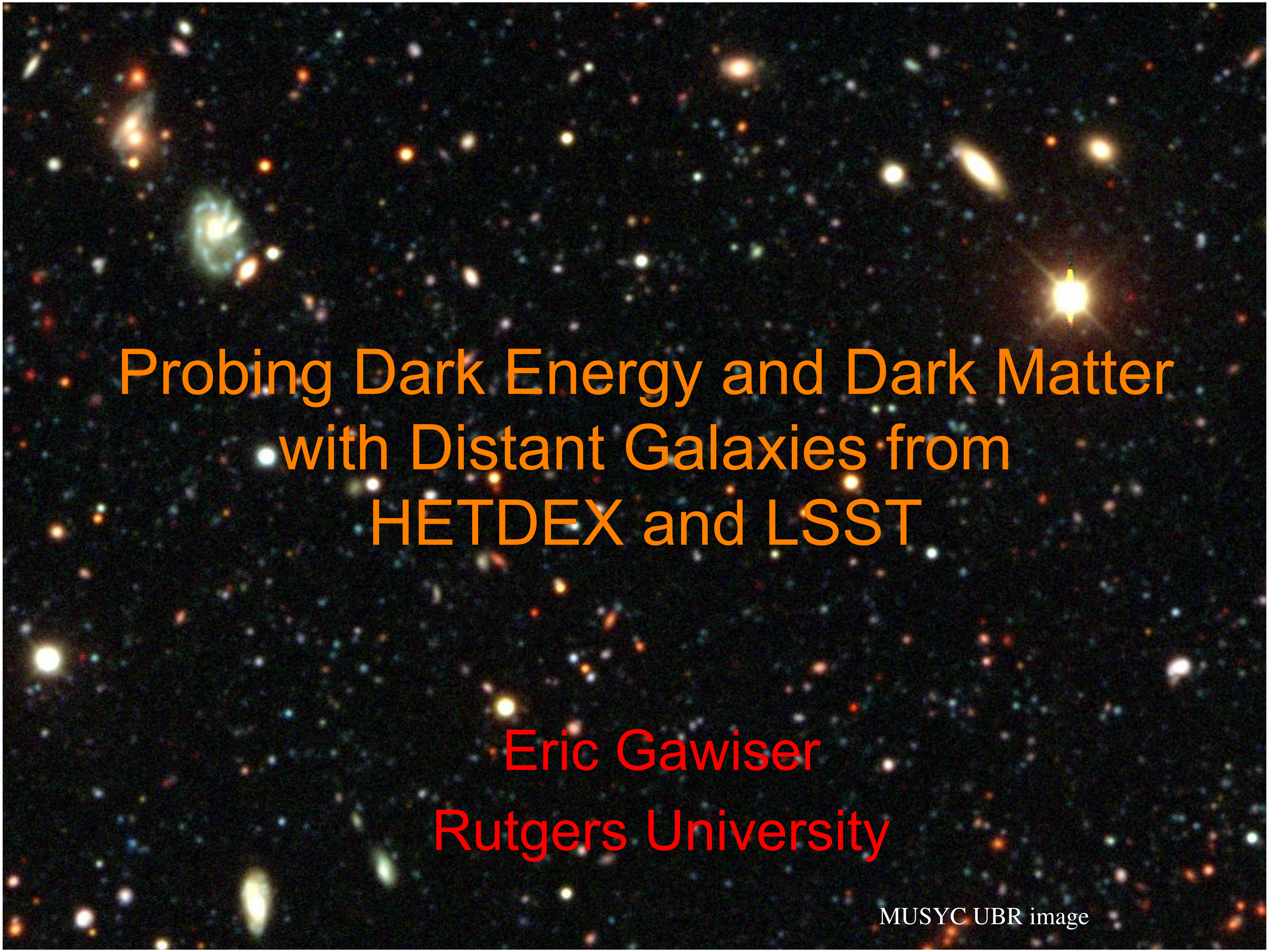
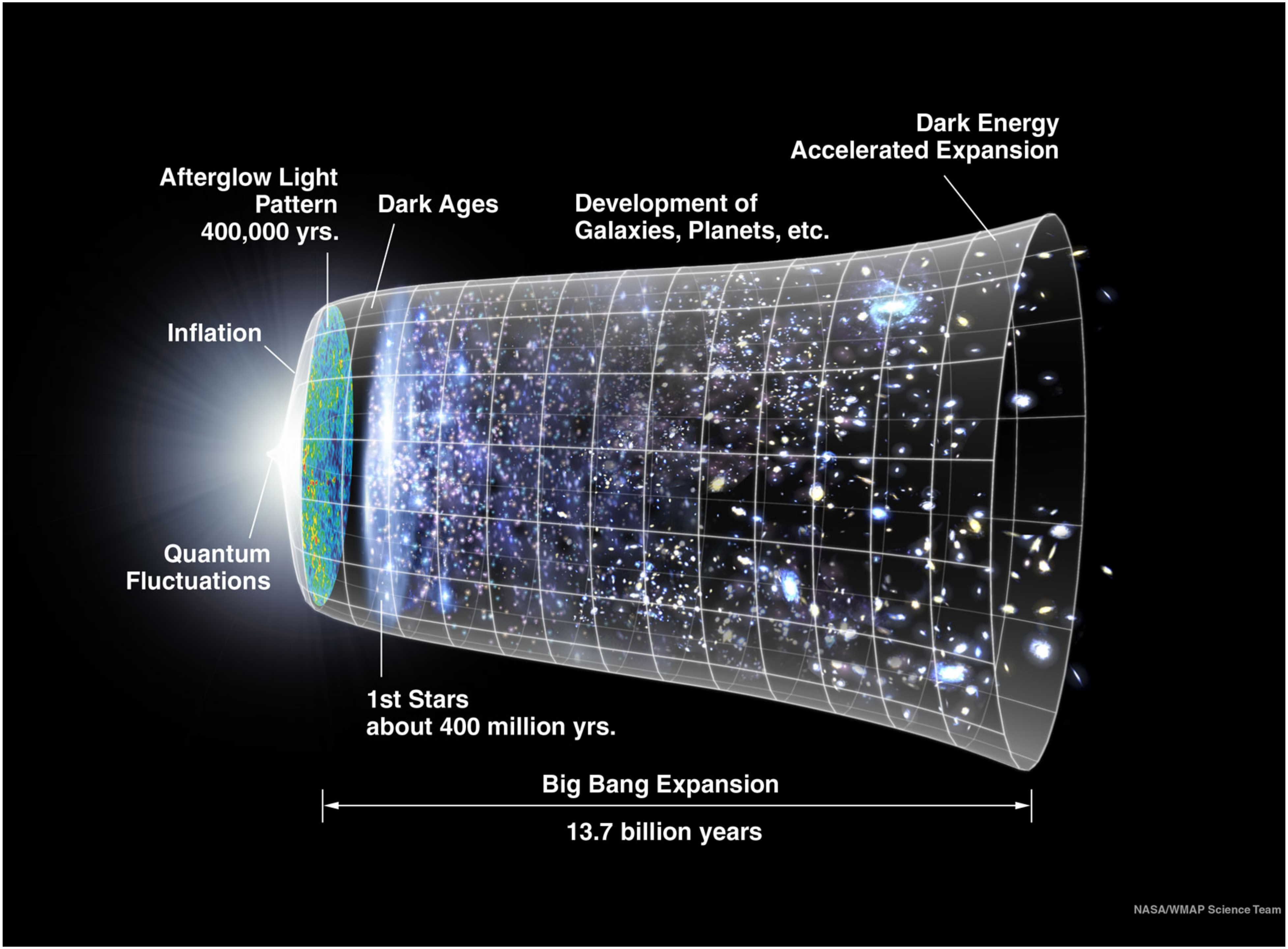


Probing Dark Energy and Dark Matter with Distant Galaxies from HETDEX and LSST

Eric Gawiser
Rutgers University

MUSYC UBR image


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

A Standard Model of Cosmology: ΛCDM

Age of universe:	13.8 Gyr
Average curvature:	flat (Ω_{total}=1.00)
Dark Energy:	74% (Ω_{DE} =0.74)
Dark Matter:	22% (Ω_{DM} =0.22)
Baryons:	4% (Ω_{B} =0.04)

Primordial power spectrum: n=0.95
(consistent with inflation)

Motivation

"A revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration."

(Dark Energy Task Force, Albrecht et al. 2006)

Coming Attractions:
A Tale of Three Collaborations

Overview of Cosmological Principle and Cosmological Structure Formation

Dark Matter "Halo" Masses of Lyman Alpha Emitting Galaxies from MUSYC
-Show that their present-day descendants are typical galaxies like the Milky Way
-Enable these galaxies to be used for future experiments

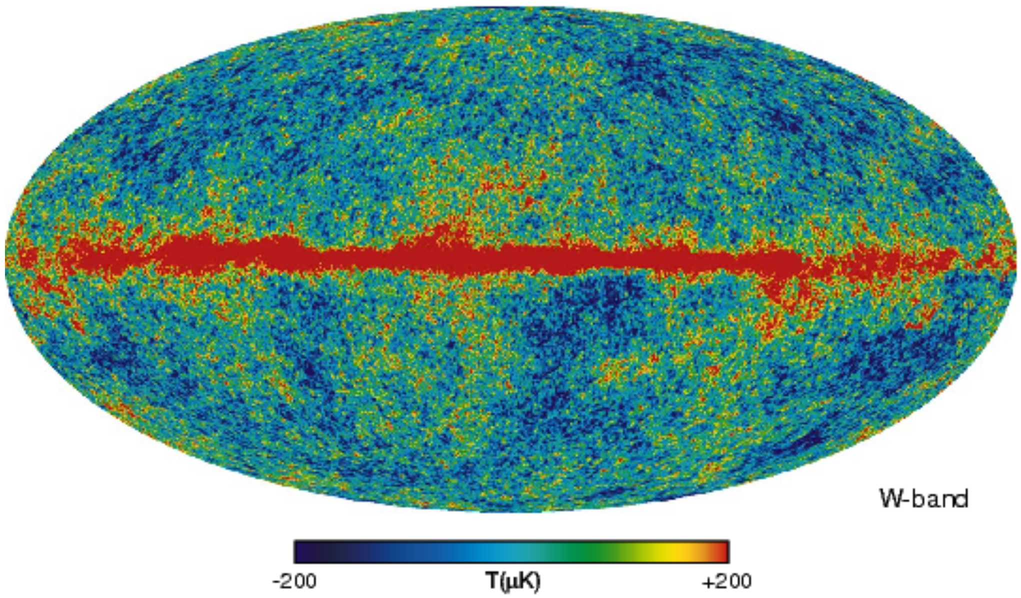
Near-future Studies Using Lyman Alpha Emitting Galaxies found by HETDEX
-Probe dark energy using Baryon Acoustic Oscillations as a "standard rod"
-Measure curvature and dark matter properties (including neutrino masses)

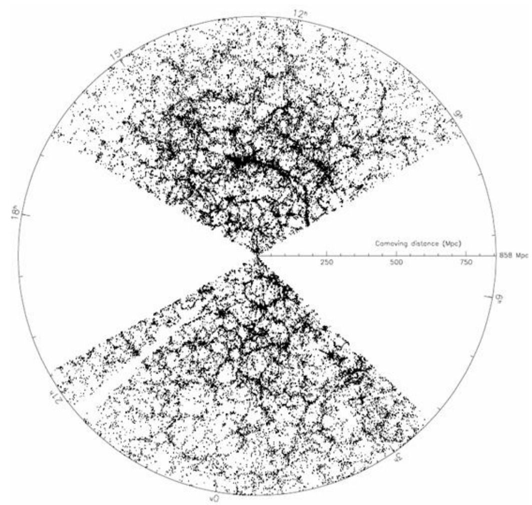
Future Studies Using High-redshift Galaxies found by LSST
-Measure dark energy properties as a function of time
-Test the Cosmological Principle

The Cosmological Principle

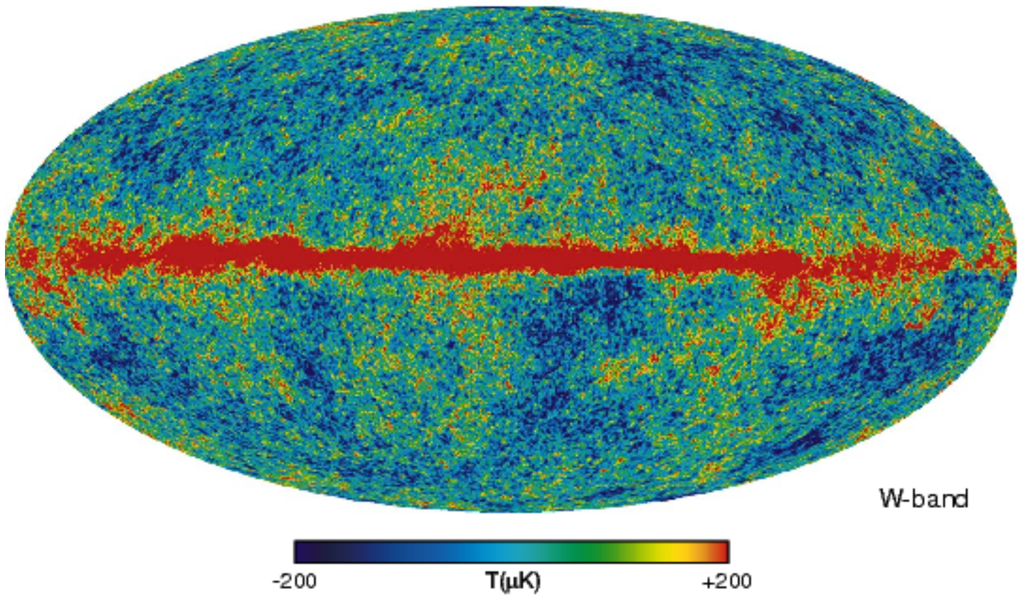
On *large scales*, the Universe looks *statistically* the same at all locations (*homogeneity*) and in all directions (*isotropy*).

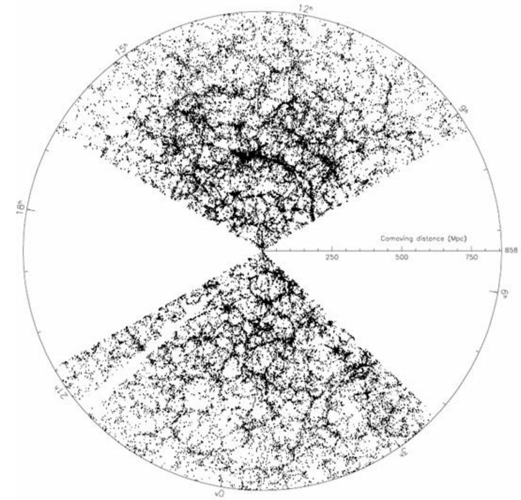
Cosmic Microwave Background anisotropy, Large-scale structure

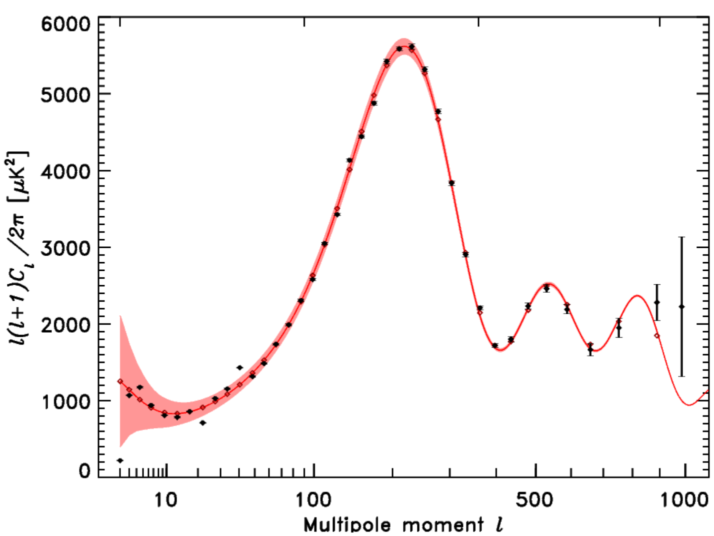




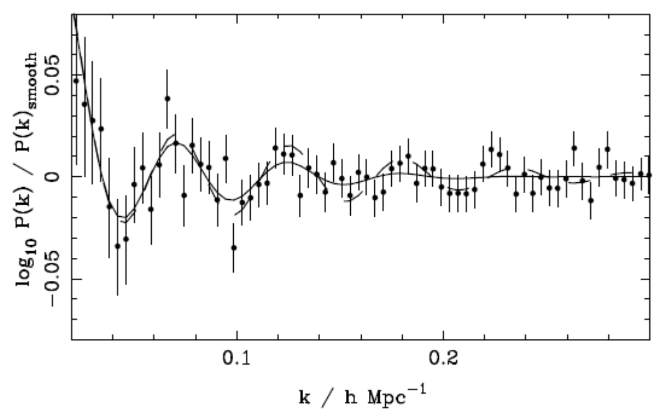
Cosmic Microwave Background anisotropy, Large-scale structure
both show baryon acoustic oscillations







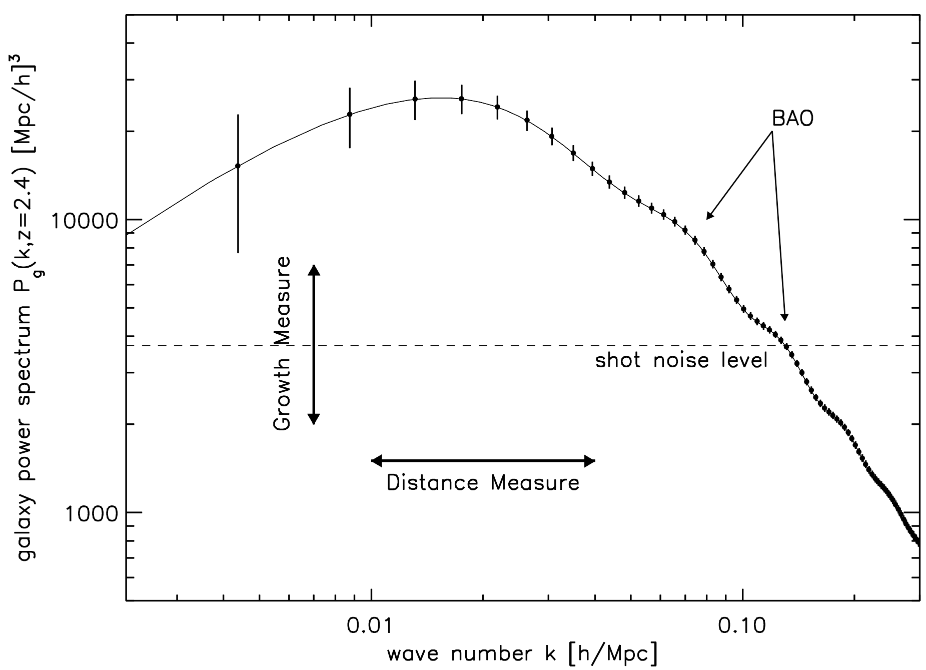
SDSS-DR5



Percival et al. 2007

Galaxy Power Spectrum P(k) offers 5 measures to exploit:

1. Baryon Acoustic Oscillation (BAO) standard rod: geometry
2. Amplitude of oscillations: structure growth
3. Amplitude of galaxy P(k): structure growth
4. Linear/non-linear transition: geometry, structure growth
5. General shape (e.g., turn-over, slope, cutoff): dark matter



The Friedmann Equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} \qquad \left(c \equiv 1, k \to 0\right)$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\rho + 3p\right) = \frac{-4\pi G\rho}{3}\left(1 + 3w_{eff}\right) \qquad \left(p \equiv w\rho\right)$$

$$p = -\frac{dE}{dV} = -\frac{d(\rho a^3)}{d(a^3)} \longrightarrow \rho \propto a^{-3(1+w)}$$

Expansion History of the Universe

$\lambda_{obs}/\lambda_{rest} = a_0/a = (1+z)$

$H^2(z)=H_0^2 \left\{\Omega_m(1+z)^3+\Omega_{DE}\exp\left(3\int(1+w(z))/(1+z)\,dz\right)\right\}$

(w is the equation-of-state of dark energy, $p = w\,\rho$)

$r(z) = c\int dz/H(z)$

Baryon acoustic oscillation fundamental mode gives scale R_s

Measured radial scale Δz probes $H(z)=c\,\Delta z\,/R_s$ and transverse angular scale $\Delta\theta$ probes $r(z)=R_s/\Delta\theta$

MUSYC

(Multiwavelength Survey by Yale-Chile)

Eric Gawiser (Rutgers, P.I.)
Pieter van Dokkum (Yale)
Paulina Lira (U. Chile)
Meg Urry (Yale)
Viviana Acquaviva (Rutgers)
Michael Berry (Rutgers)
Nicholas Bond (NASA GSFC)
Carie Cardamone (MIT)
Robin Ciardullo (Penn State)
John Feldmeier (Youngstown State)
Harold Francke (P.U. Católica)
Marijn Franx (Leiden)
Lucia Guaita (Stockholm)
Caryl Gronwall (Penn State)
Minh Huynh (Western Australia)
Leopoldo Infante (P.U. Católica)
Sheila Kannappan (UNC)
Sugata Kaviraj (Imperial College)
Mariska Kriek (Harvard-CfA)
Peter Kurczynski (Rutgers)
Danilo Marchesini (Tufts)
Ana Matkovic (Penn State)
Nelson Padilla (P.U. Católica)
Ryan Quadri (OCIW)
Kevin Schawinski (Yale)
Ezequiel Treister (Hawaii)
Carlos Vargas (Rutgers)
Jean Walker Soler (Rutgers)

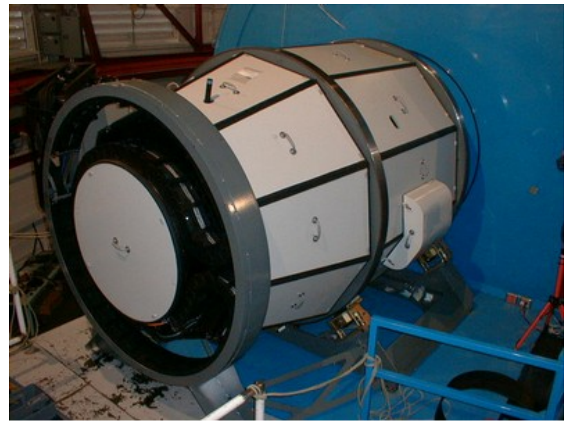
Public Data Release and 60 Refereed Publications available at:

http://physics.rutgers.edu/~gawiser/MUSYC

(see also Gawiser et al 2006a, ApJS 162, 1)

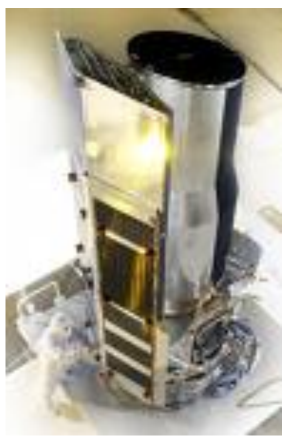
Where did we obtain the data?

CTIO4m
+MOSAIC
Found LAE galaxies in narrow-band images



Magellan
+IMACS
Confirmed LAE redshifts, purity of sample

Spitzer
+IRAC
Measured stellar mass (number of stars) in LAE galaxies

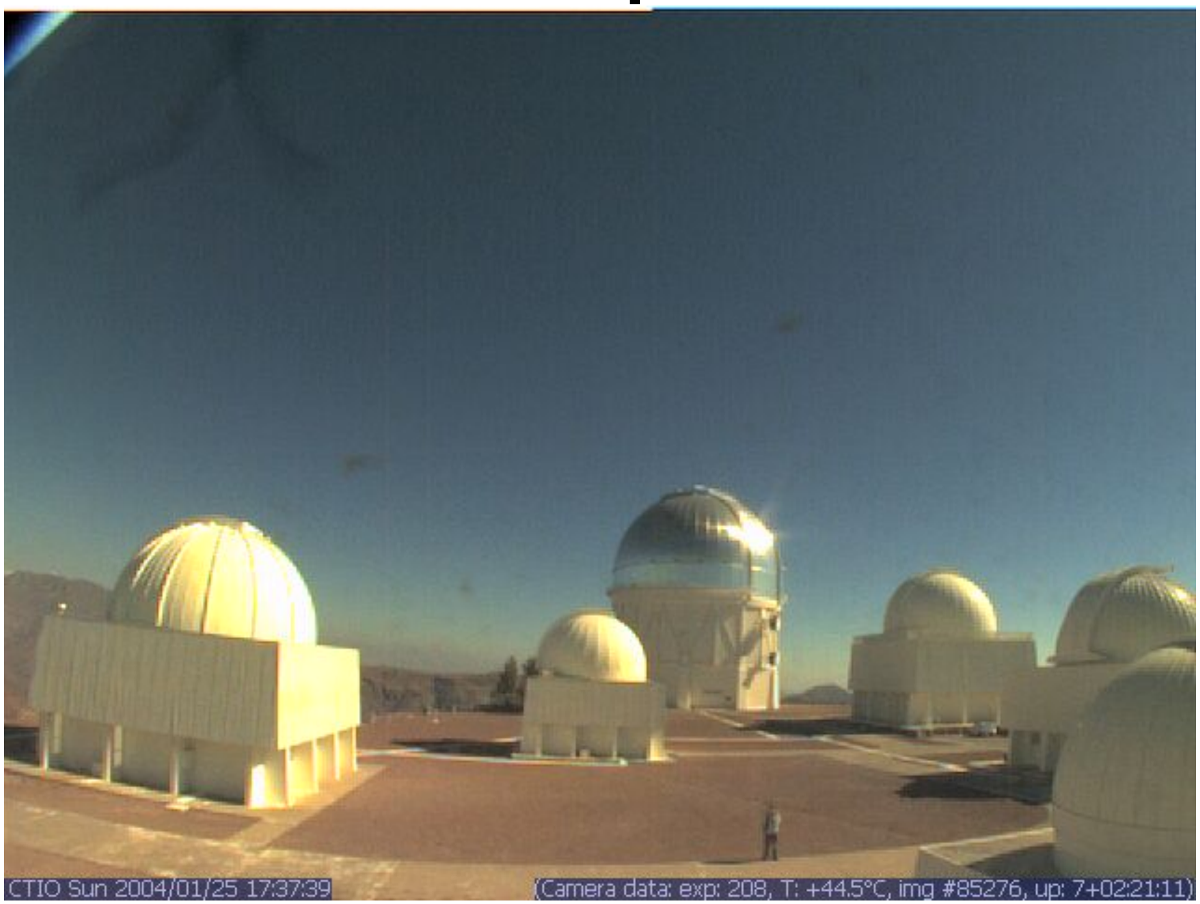


HST
+ACS
Determined sizes of LAE galaxies from archival images

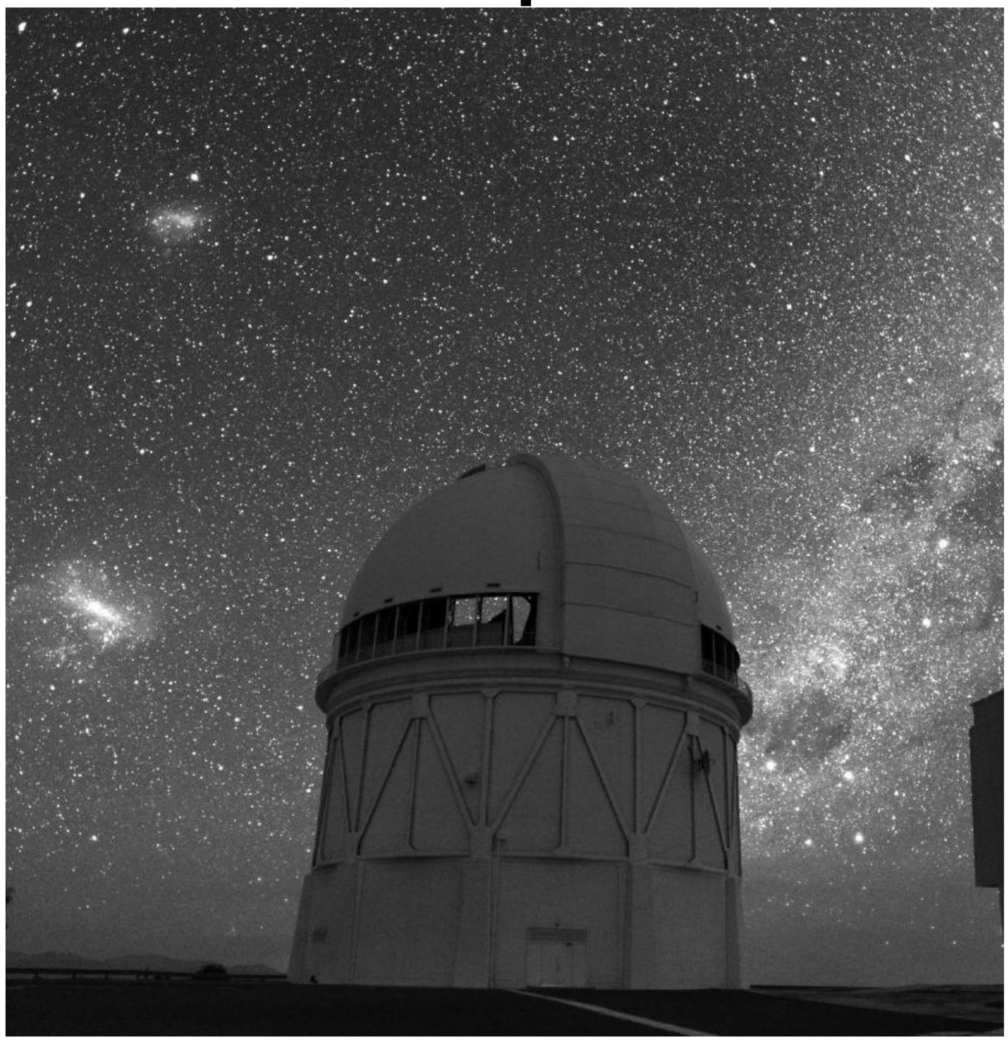
LAE = Lyman Alpha Emitting

4m Telescope at CTIO

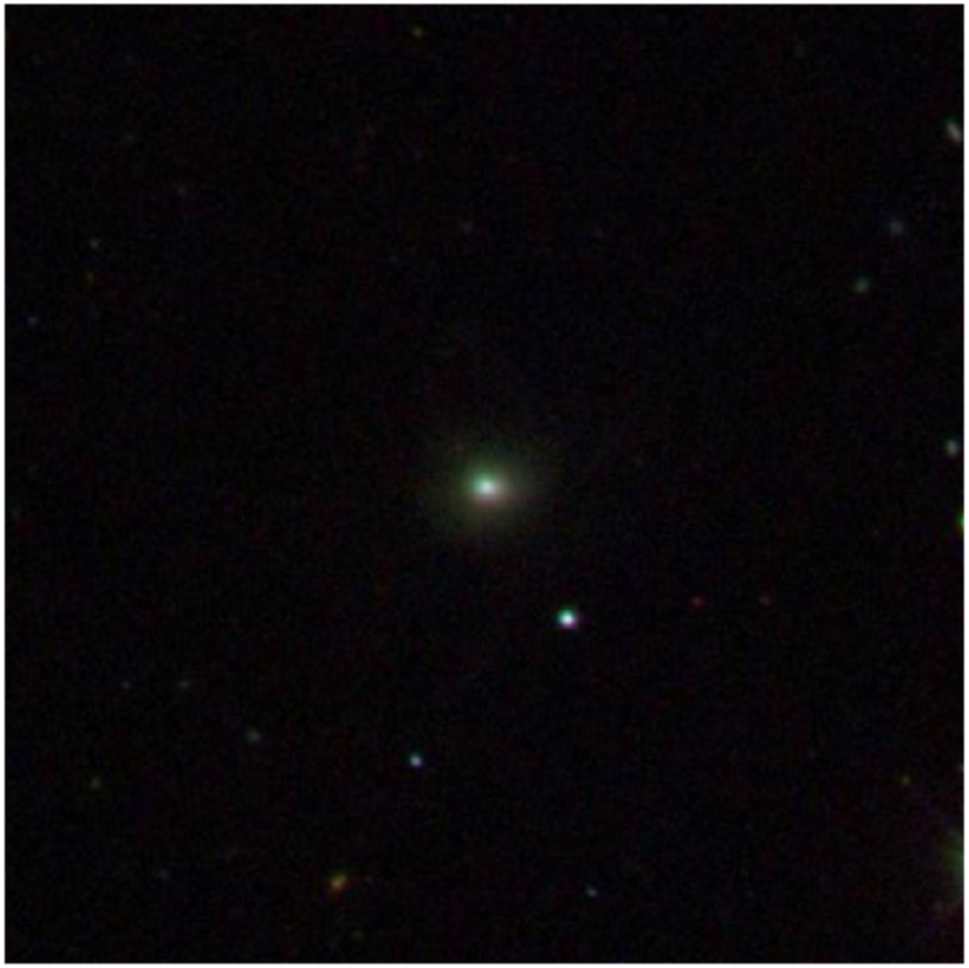
4m Telescope at CTIO



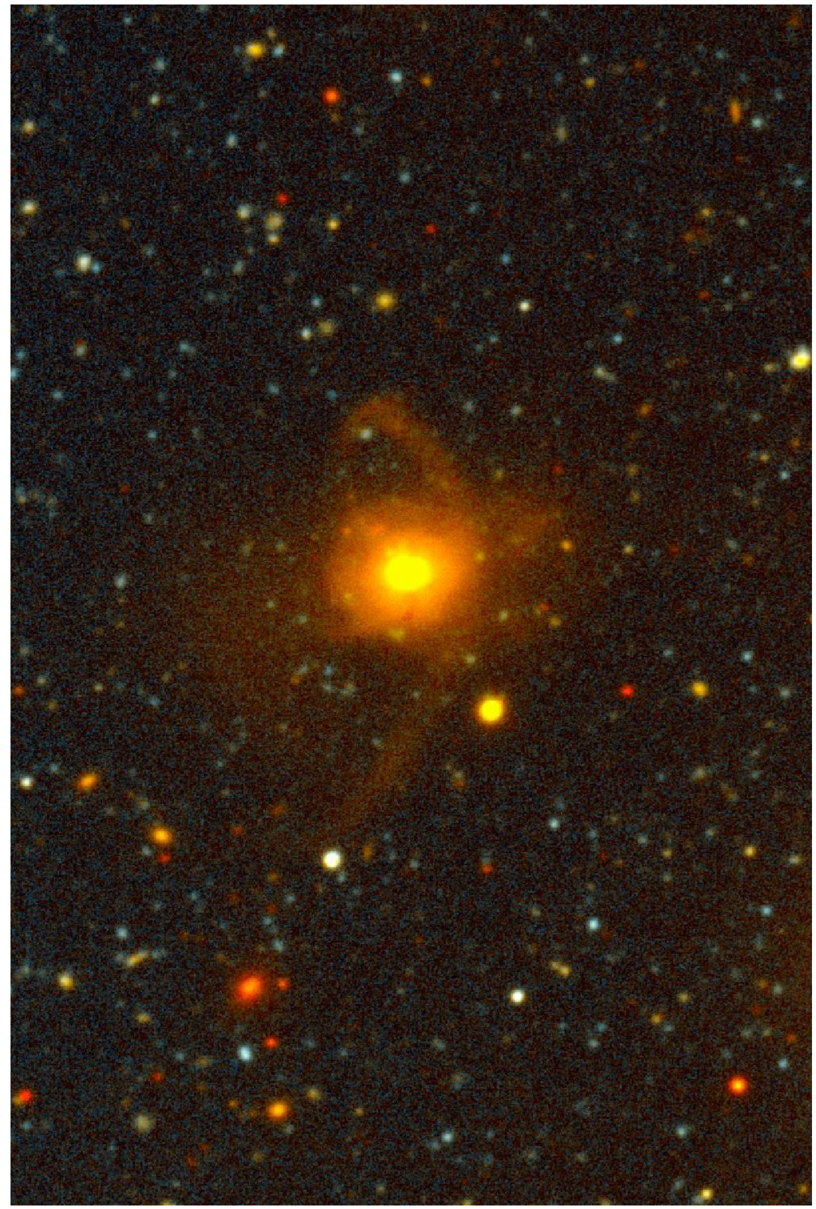
4m Telescope at CTIO



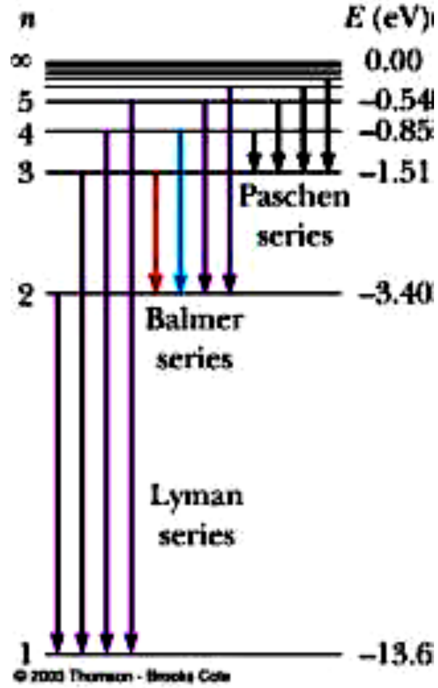
Sloan Digital Sky Survey



MUSYC (100X better sensitivity)

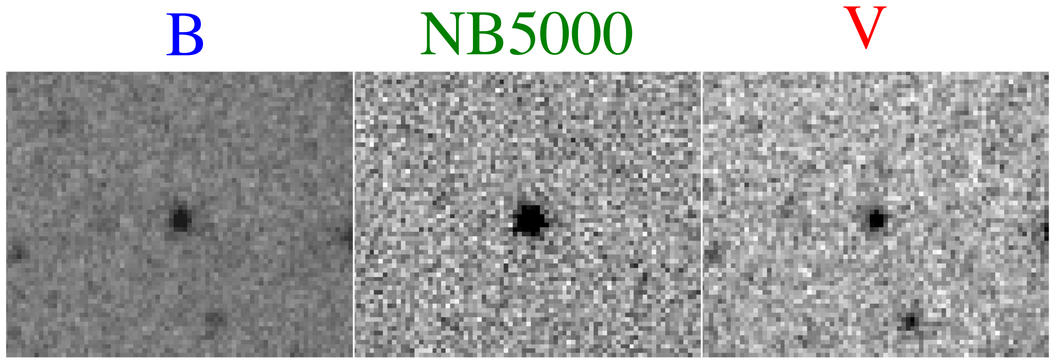


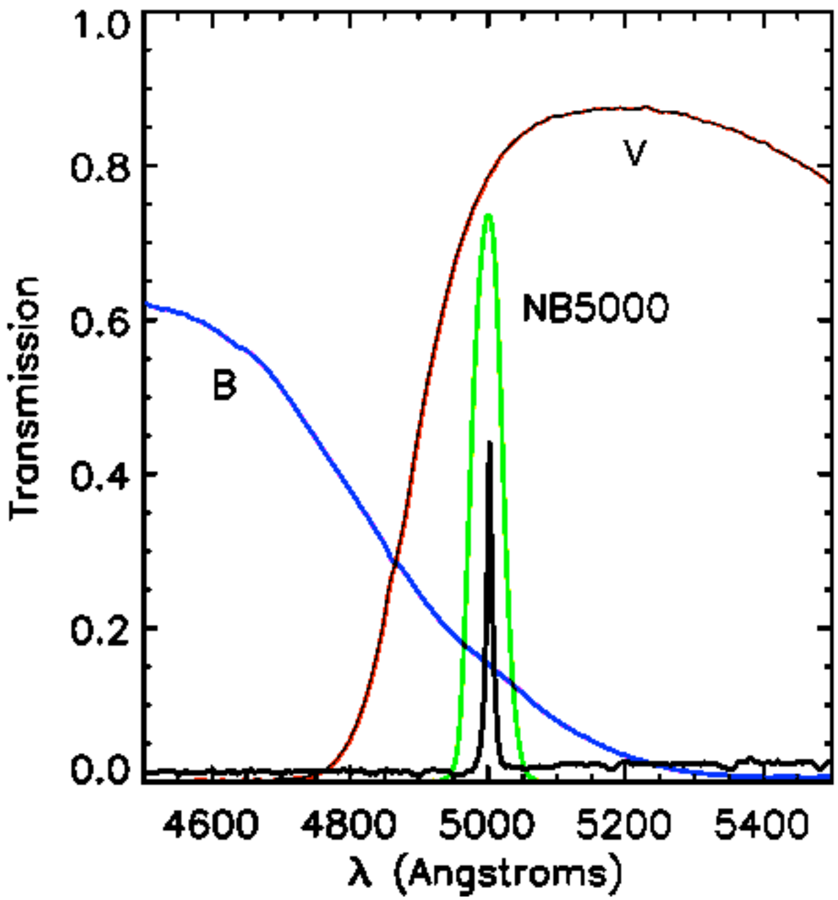
75% of the baryons are hydrogen



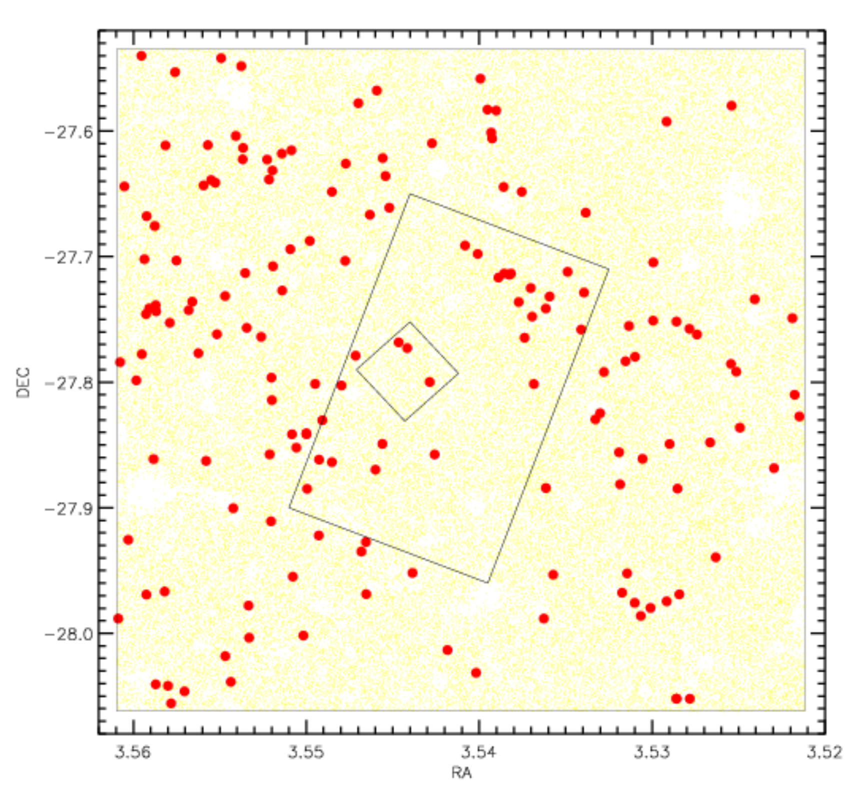
- At z=3, Lyman series falls in observed-frame optical
- Ly α photons (10.2eV=1216Å) from recombination are visible
- Ionizing photons (>13.6eV=912Å) are absorbed → "Lyman break"

Lyman α Emitting (LAE) Galaxy





LAE clustering at z=3 in MUSYC-ECDFS



162 LAEs

Gawiser et al 2007, Astrophysical Journal 671, 278

Spatial and angular auto-correlation functions:

$$dP(r) = \rho_g{}^2[1 + \xi_{gg}(r)]\ dV^2$$
$$dP(\theta) = \eta_g{}^2[1 + w_{gg}(\theta)]\ d\Omega^2$$

$w_{gg}(\theta)$ is a projection of $\xi_{gg}(r)$ via

$$w_{gg}(\theta) = \int dz_1 \int dz_2\ p(z_1)p(z_2)\ \xi_{gg}(r(z_1,z_2,\theta))$$

We invert this projection to turn observed $w_{gg}(\theta)$ into inferred $\xi_{gg}(r)$

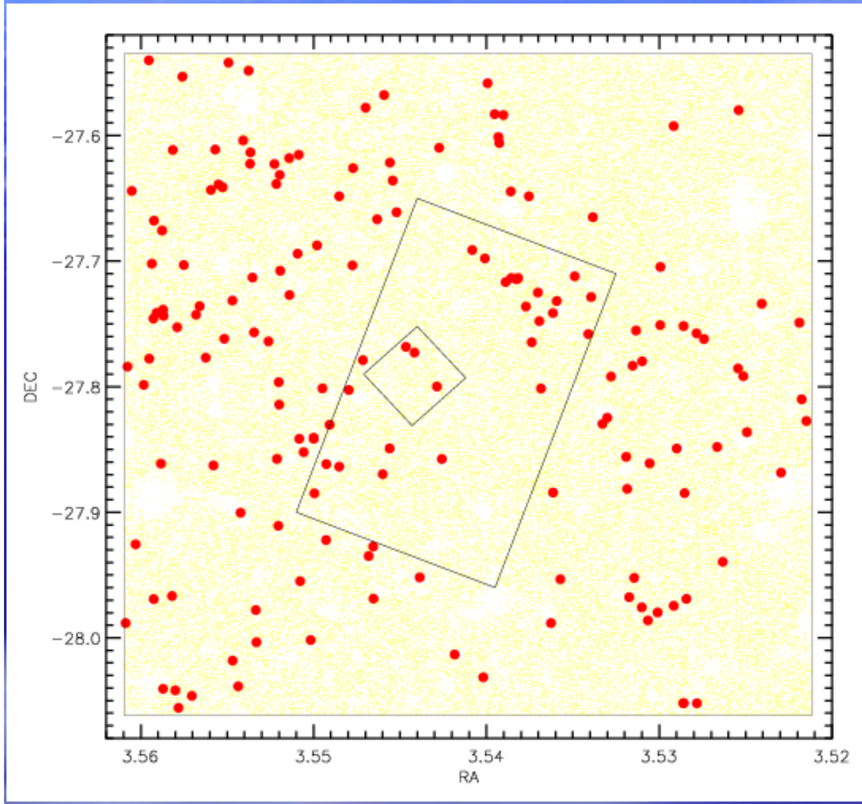
$$\xi_{gg}(r) = b_g^2 \, \xi_{DM}(r)$$

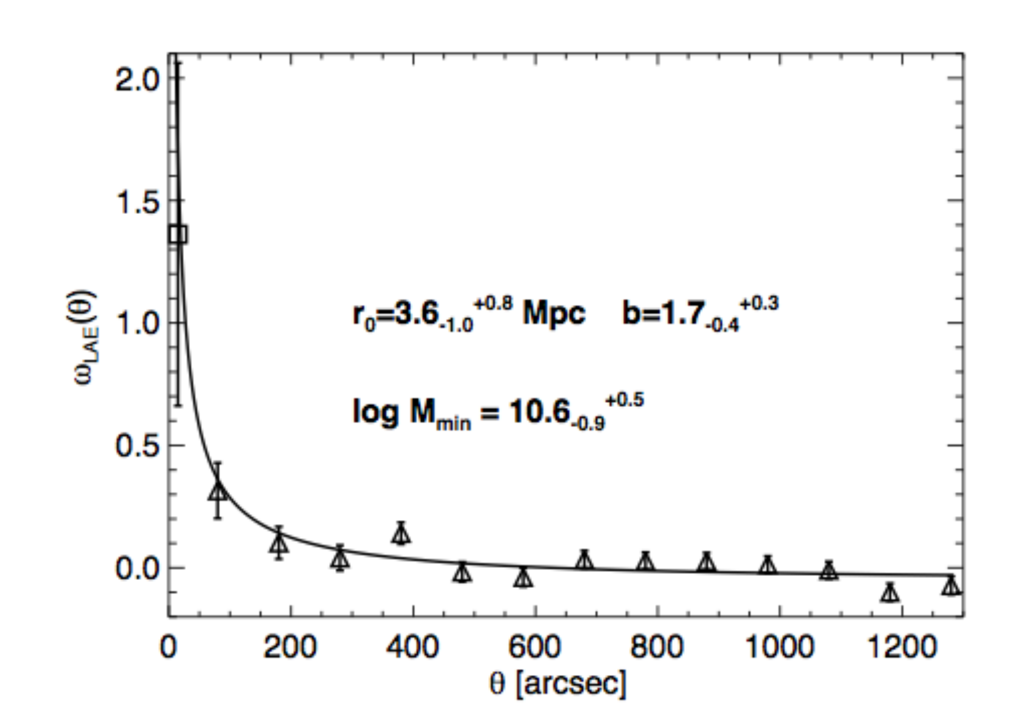
Since $\xi_{DM}(r)$ is well predicted by our standard model of cosmology, we can now solve for b_g, the "bias" factor that determines typical dark matter halo masses of these galaxies

Method for auto-correlation from Mo & White (1996, MNRAS 282, 347)

First applied to cross-correlation by Gawiser et al (2001, ApJ 562, 628)

Clustering of 162 LAEs at z=3 in MUSYC-ECDFS

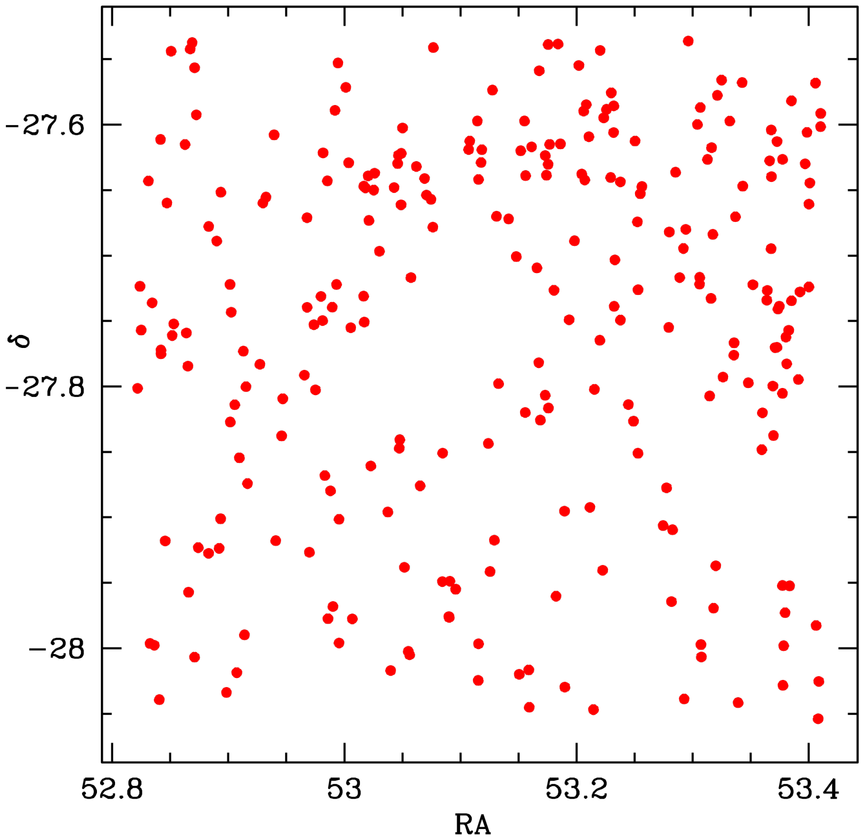


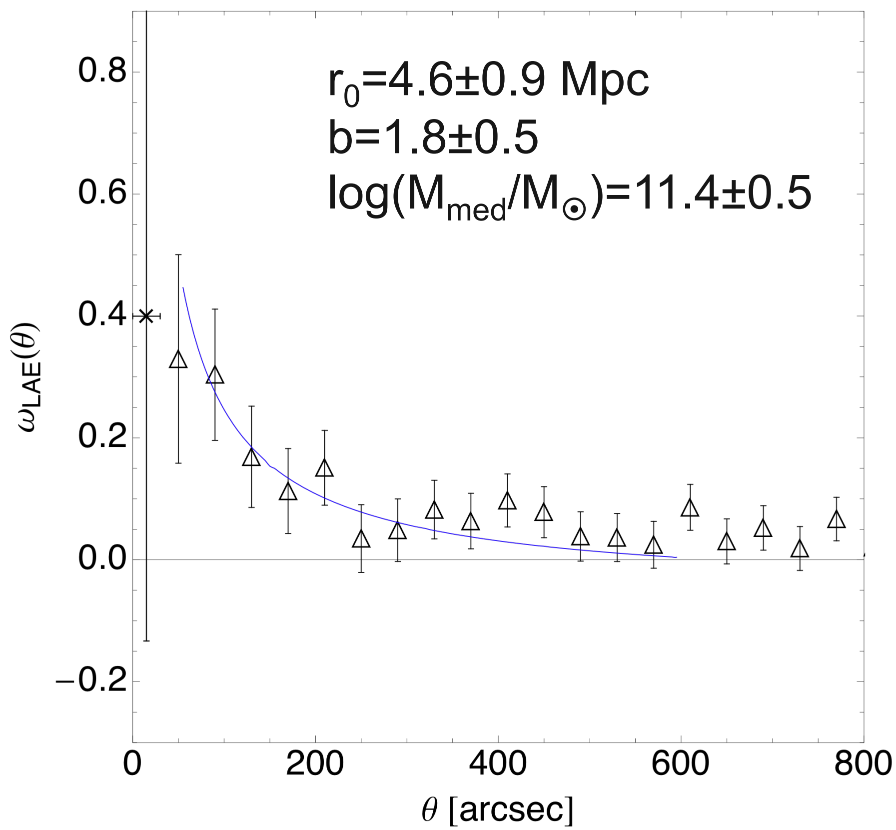


Clustering analysis by Harold Francke

Gawiser et al 2007, Astrophysical Journal 671, 278

Clustering of 250 LAEs at z=2 in MUSYC-ECDFS

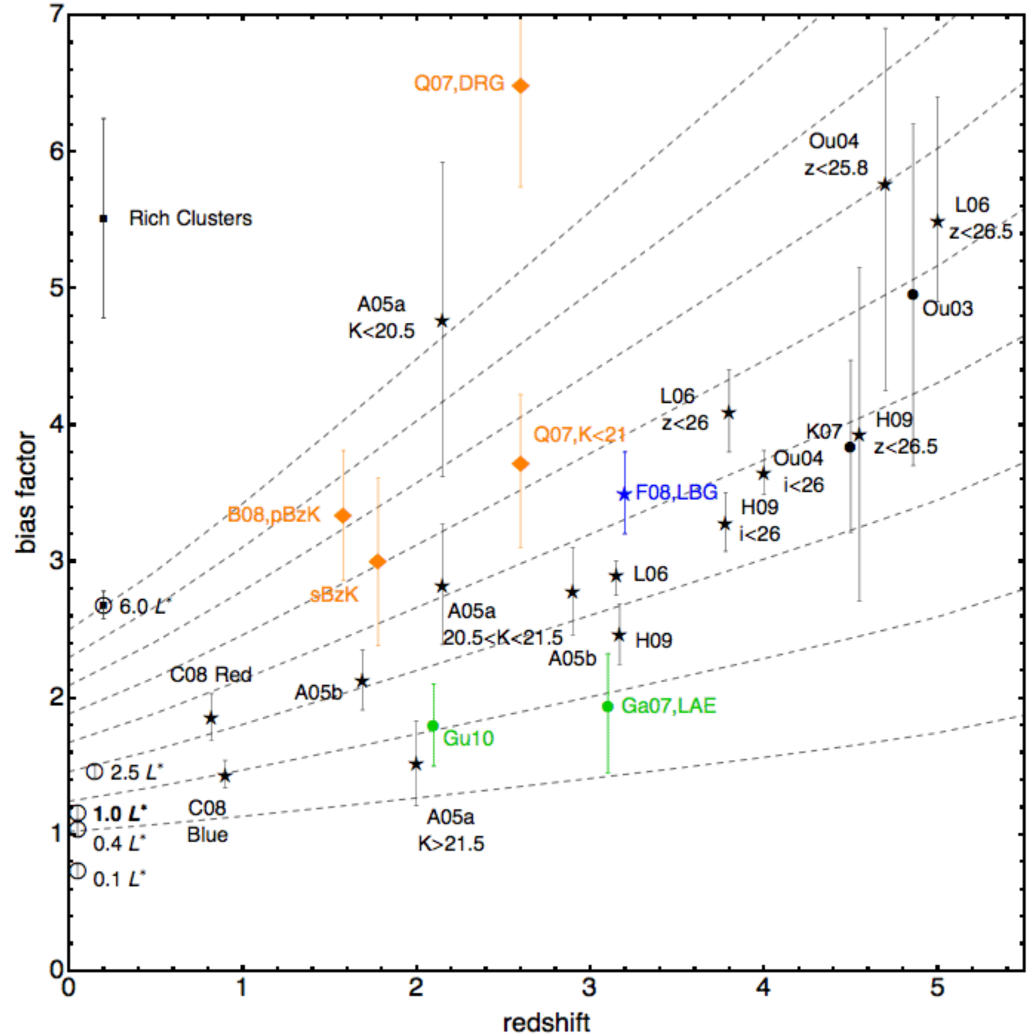




Guaita et al 2010, Astrophysical Journal 714, 255

LAEs at 2<z<3 evolve into ~L* galaxies at *z*=0

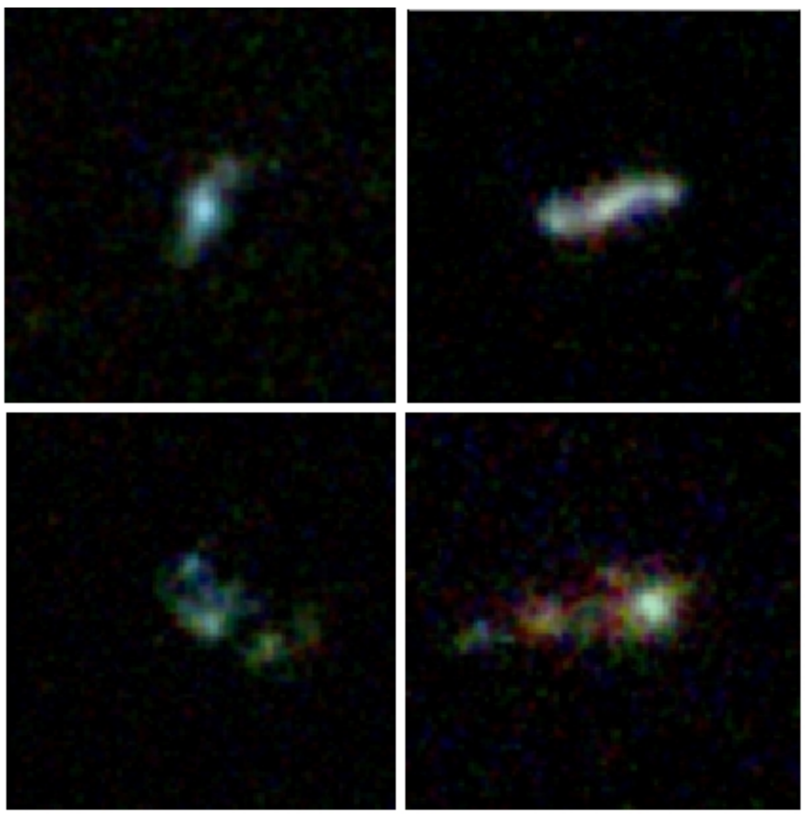
(Guaita et al. 2010, ApJ 714, 255, Gawiser et al. 2007, ApJ 671, 278)



Evolution of clustering bias (versus dark matter, dashed tracks are median of conditional mass function)

Lyman Alpha Emitting galaxies are the smallest distant galaxies yet studied (half-light radii of 0.5-2 kpc)

(Bond et al 2009 ApJ 705, 639)



2"x2" HST-ACS (GOODS-S)

Name that spiral…

MUSYC Results on Lyman Alpha Emitting Galaxies

- LAE stellar masses are small, $<\sim 10^9 M_\odot$, 1/40 the stellar mass of the Milky Way.
- The dark matter halo masses of LAEs are $\sim 10^{11} M_\odot$, 1/20 the dark matter mass of the Milky Way.
- LAEs evolve into typical present-day galaxies like the Milky Way.
- The clustering properties of LAE dark matter halos are consistent with predictions of the cold dark matter model.
- The near future will bring **much** larger samples of LAEs (10^6 from HETDEX) and of distant star-forming galaxies with similar luminosity (10^9 from LSST).

HETDEX

University of Texas:

Josh Adams
Guillermo Blanc
Mark Cornell
Taylor Chonis
Karl Gebhardt (PS)
Lei Hao
Gary Hill (PI)
Donghui Joeng
Eiichiro Komatsu
Hanshin Lee
Phillip MacQueen
Jeremy Murphy
Marc Rafal (PM)
Masatoshi Shoji

MPE/USM:

Ralf Bender
Niv Drory
Ulrich Hopp
Ralf Koehler
Helena Relke
Jochen Weller

Penn State University:

Robin Ciardullo
Caryl Gronwall
Larry Ramsey
Don Schneider

AIP:

Andreas Kelz
Volker Mueller
Martin Roth
Mathias Steinmetz
Lutz Wisotzki

Texas A&M:

Darren DePoy
Steven Finkelstein
Jennifer Marshall
Nicolas Suntzeff

Rutgers:

Eric Gawiser
Viviana Acquaviva

LCO:

Povilas Palunas

The Hobby Eberly Telescope Dark Energy Experiment (HETDEX) is:

→ blind spectroscopic survey on 9.2m Hobby-Eberly Telescope

→ 420 square degrees in 140 nights over 3 years

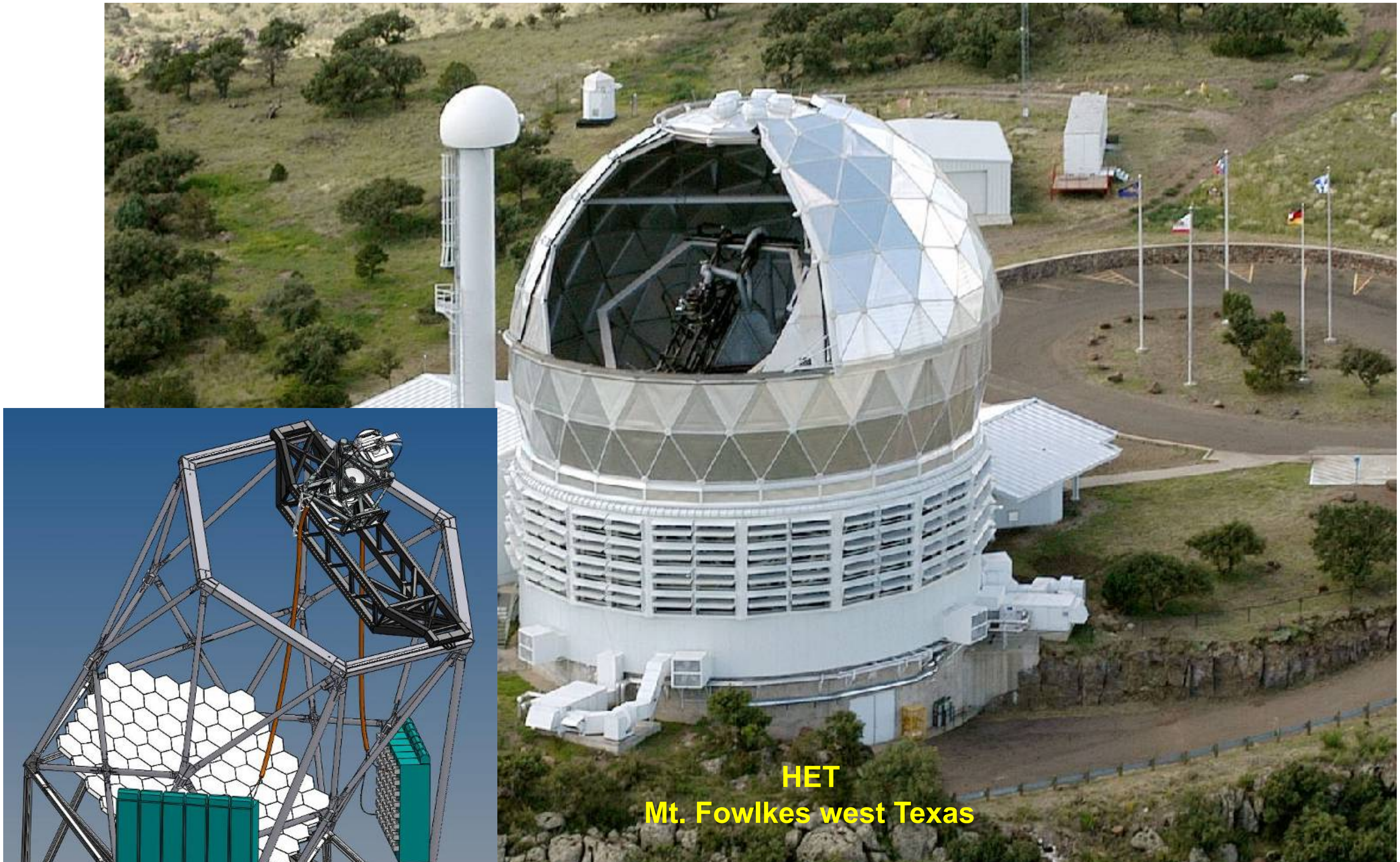
→ 800,000 redshifts from $1.9<z<3.5$ (Ly-alpha emitters)

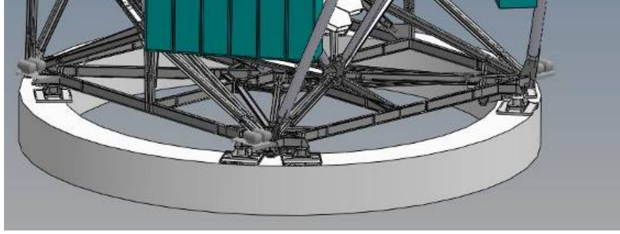
→ upgraded telescope with new top-end, including 22’ field of view

→ new instrument, VIRUS, with 150 "integral field" spectrographs
($\lambda / \Delta \lambda = 800$ from 350 – 580nm)

→ prototype unit spectrograph has been in use for over 2 years

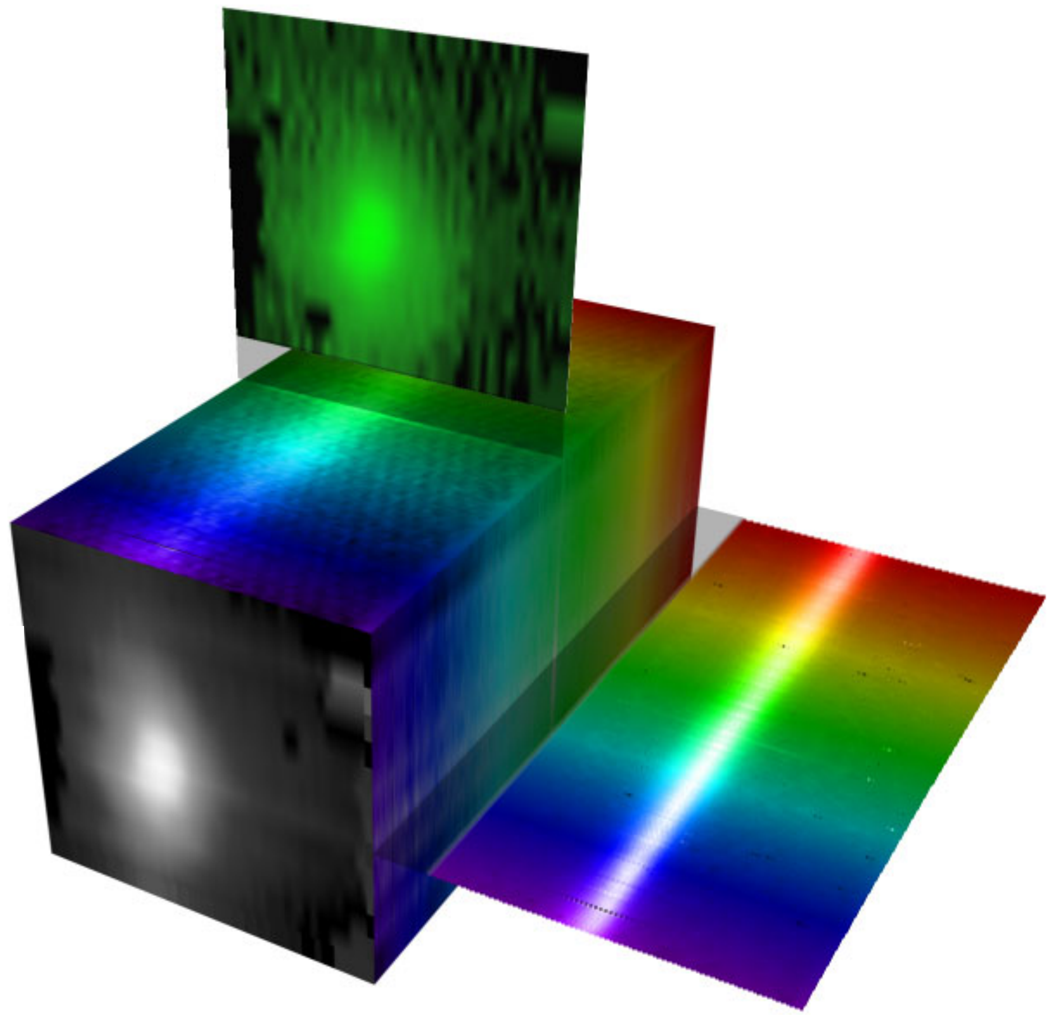
TIMELINE: 2012-2014 **PRICETAG:$35M**





HET is the world's fourth largest telescope. It will be upgraded with a powerful new instrument consisting of 150 units, VIRUS (Visible Integral-field Replicable Unit Spectrograph)

INTEGRAL FIELD SPECTROSCOPY



The active galaxy NGC1068, imaged using an Integral Field Unit

Image: Stephen Todd, ROE and Douglas Pierce-Price, JAC.

HETDEX will provide:

→ curvature measure to about 0.1% (>10x better than present)

→ H(z=2.5) to 1%

→ D(z=2.5) to 1%

→ modest improvement on dark energy today (w_0)

→ significant improvement on dark energy evolution (w_a)

→ amplitude of power spectrum to 1.5% (structure growth)

→ sum of neutrino masses to 0.05eV precision - detection expected!

Viviana Acquaviva & E.G. 2010, PRD 082001

In the concordance GR+ ΛCDM model:

- Rates of expansion of the universe and cosmological structure growth are exactly predicted from one another

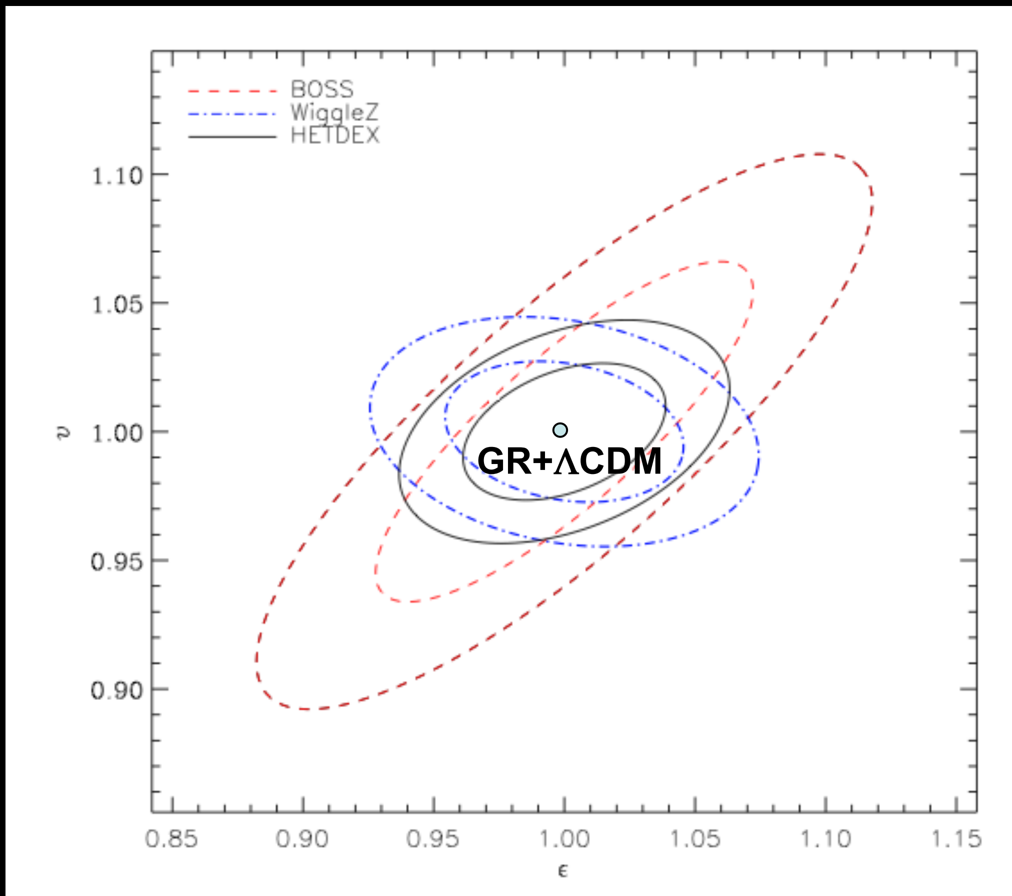
- Structure growth is independent of scale

- Neither statement is true for general dark energy or modified gravity models, and we lack a fundamental theory for those extensions

- So we should falsify GR+ ΛCDM before exploring ill-constrained parameter spaces for dark energy & modified gravity

Acquaviva & Gawiser 2010, PRD 082001

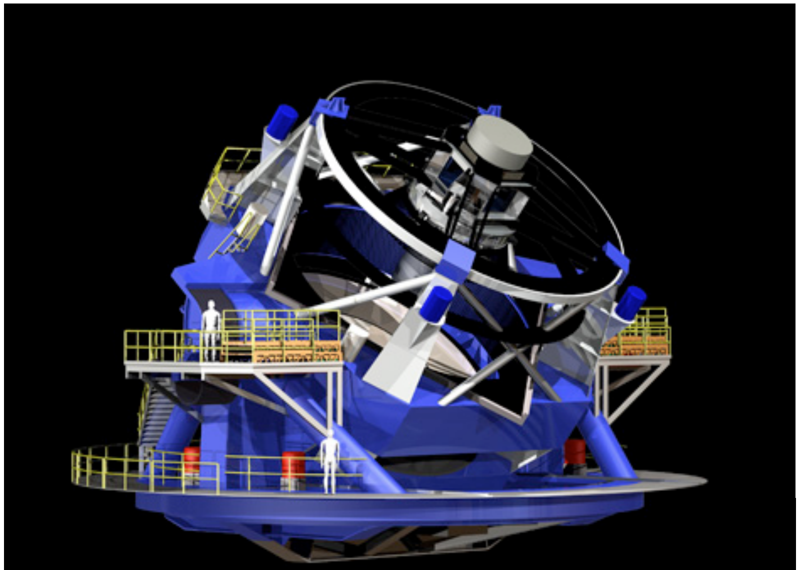
scale dependence of structure growth

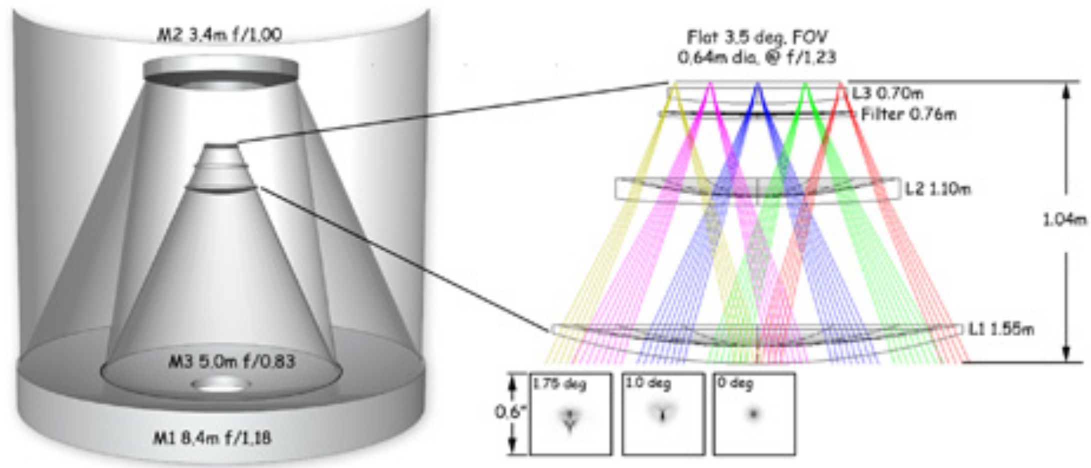


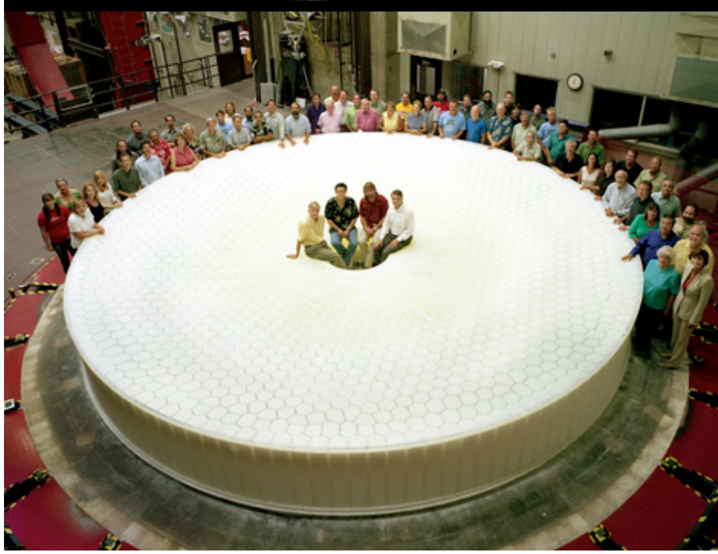
ratio between expansion rate of universe and structure growth

Contours assume GR+ΛCDM turns out to be best-fit model and show precision with which experiments can measure ε, υ

The Large Synoptic Survey Telescope (LSST)







TIMELINE: 2018-2028

Director: Tony Tyson

PRICETAG:$460M

The LSST Large-Scale Structure Science Collaboration

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Viviana Acquaviva (Rutgers)
Steve Allen (Stanford)
Mark Allen (Stanford)
Reza Ansari (LAL, Orsay)
Eric Aubourg (Laboratoire APC)
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Aurelien Barrau (LPSC Grenoble)
James Bartlett (U. Paris, APC)
Andreas Berlind (Vanderbilt)
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Laurent Derome (LPSC)
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Jeffrey Newman (Pittsburgh)
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Ryan Scranton (Google)
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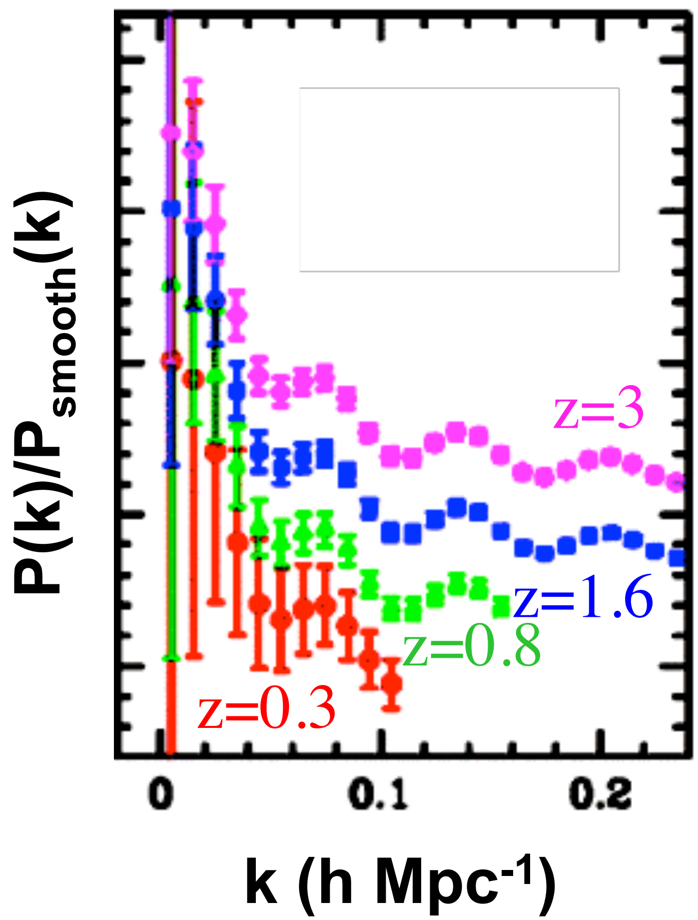
Alex Szalay (JHU)
Jon Thaler (Illinois)
Tony Tyson (UC Davis)
Licia Verde (Barcelona)
Ben Wandelt (Illinois)
Risa Wechsler (Stanford)
David Wittman(UC Davis)
Idit Zehavi (Case Western)
Hu Zhan (NAO CAS, Co-Chair)
Zheng Zheng (Yale)

LSST will study Dark Energy with 1 billion distant galaxies

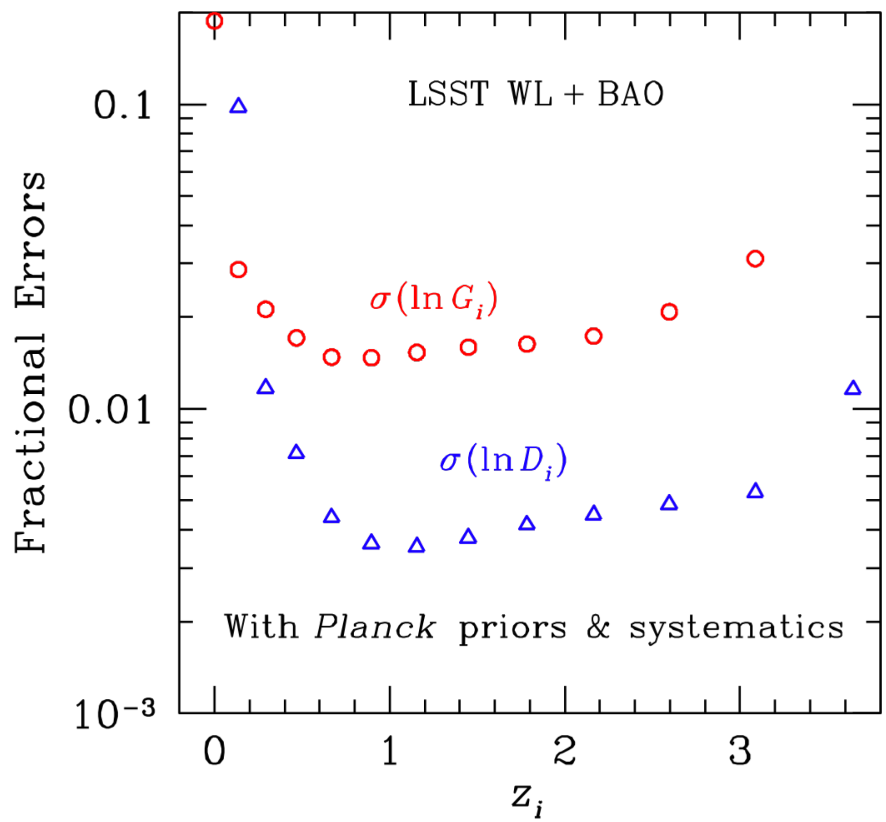
Survey covers 20,000 square degrees (half the sky)

Baryon Acoustic Oscillations via angular clustering will determine distances to 1%, which measures dark energy equation-of-state to 5% ($\delta w = 0.05$)
Blake & Bridle 2005, Seo & Eisenstein 2003

Compare with other techniques (weak lensing, Type Ia supernovae from LSST) to see evolution in w (a.k.a. w_a)

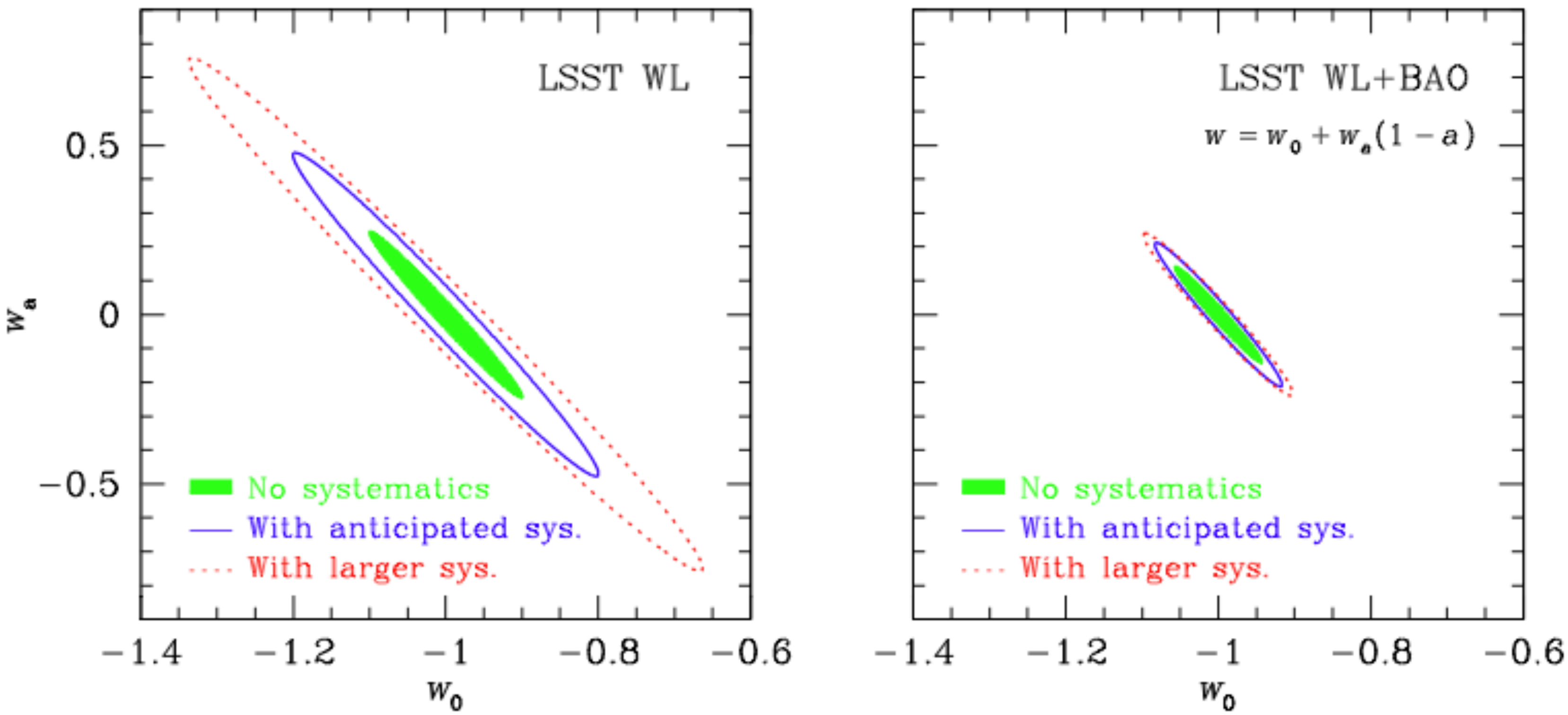


LSST Baryon Acoustic Oscillations (BAO) will measure distances to <1%, combined with weak gravitational lensing (WL) will measure growth to <2%



From Zhan et al.(2009), LSST Science Book Fig. 15.2

Dark Energy constraints from Weak Lensing + Baryon Acoustic Oscillations



LSST Science Book Fig.15.1

Testing the Cosmological Principle:

Check for inhomogeneities in behavior of dark energy/modified gravity by comparing expansion rate and structure growth along multiple lines of sight

(See LSST Science Book Fig.15.12)

Large-scale structure constraints on cosmological neutrinos

- Relativistic neutrinos suppress density fluctuations up to free-streaming length of 1.2 Gpc*(eV/m_ν)
- P(k) constrains sum of neutrino masses M_ν via $\Omega_\nu = M_\nu/(94\text{ eV } h^2)$, assuming no sterile neutrinos, no neutrino degeneracy, thermal energy spectra
- LSST will measure sum of neutrino masses to 0.02 eV precision – detection (nearly) guaranteed!

(Song & Knox 2003)

Conclusions

- Observations of distant galaxies offer constraints on dark matter properties and the dark energy equation-of-state (*w*)
-
- Control of systematics is critical; MUSYC results show that we can select pure samples of these galaxies and use them to measure large-scale structure
- Future constraints from HETDEX and LSST using high-redshift galaxies, weak gravitational lensing and Type Ia supernovae will distinguish between dark energy and modified gravity, constrain *w* to 5%, and measure the sum of neutrino masses to a precision of 0.02eV