TAUP 2013 summer school

Observational Cosmology: Dark Energy Surveys

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Dark Energy Task Force:

Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation for its existence or magnitude. The acceleration of the Universe is, along with dark matter, the observed phenomenon that most directly demonstrates that our theories of fundamental particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible.

What we know and don’t know about dark energy

- SNe observations: acceleration
- appears to be uniformly distributed in space
- acts like a negative pressure
- equation of state (pressure / energy density) w~ -1
- simplest idea: cosmological constant (w=-1)
- vacuum energy? off by 10^{120}
- does it change with time?
- or is GR wrong?

VI. A Dark Energy Primer

In General Relativity (GR), the growth of the Universe is described by a scale factor $a(t)$, defined so that at the present time t_0, $a(t_0) = 1$. The time evolution of the expansion in GR obeys

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3},$$

where P and ρ are the mean pressure and density of the contents of the Universe, and Λ is the *cosmological constant* proposed and then discarded by Einstein. Remarkably, several lines of evidence (described below) confirm that at the present time, $\ddot{a} > 0$. This acceleration immediately implies that either

1. The Universe is dominated by some particle or field (*dark energy*) that has negative pressure, in particular $w = P/\rho < -1/3$; ***or***
2. There is in fact a non-zero cosmological constant; ***or***
3. The theoretical basis for this equation, GR or the standard cosmological model, is incorrect.

Any of these three explanations would require fundamental revision to the underpinning theories of physics. It is of great interest to determine which of these three explanations is correct.

Dark Energy Primer

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right],$$

The term Ω_X represents the cosmological constant if $w = -1$. Otherwise, it represents dark energy with constant w.

$$\Omega_k = -\frac{k}{H_0^2},$$

The quantity Ω_k describes the current curvature of the universe. For $\Omega_k < 0$, the Universe is closed and finite; for $\Omega_k > 0$ the Universe is open and potentially infinite; while for $\Omega_k = 0$ the geometry of the Universe is Euclidean (flat).

Dark Energy Primer

Dark energy can be detected observationally either through H(z) - expansion history of Universe - or through the growth of cosmic structure.

Quantum fluctuations in the early Universe create density perturbations. Measured in great detail as temperature fluctuations in the CMB at $z=1088$. As the Universe expands, there is a competition between the expansion and gravitational collapse. More rapid expansion - due to dark energy - retards the growth of structure.

The amplitude of matter fluctuations provides an additional observable handle on dark energy.

Dark Energy Task Force:

A properly executed dark energy program should have as its goals to

1. Determine as well as possible whether the accelerating expansion is consistent with a cosmological constant.

2. Measure as well as possible any time evolution of the dark energy.

3. Search for a possible failure of general relativity through comparison of the effect of dark energy on cosmic expansion with the effect of dark energy on the growth of cosmological structures like galaxies or galaxy clusters.

Equation of State

Since we don't know what it is, not clear how to parameterize it in terms of evolution with time.

Often written as:

$$w(a) = w_0 + (1-a)w_a$$

w_0 is value today

w_a parameterizes evolution of w(a)

a is scale factor of Universe : 1/(1+z)

dw/da = w' = -a w_a

Key measurements:

- supernovae (SNe)
- BAO (baryon acoustic oscillations)
- cluster counts
- weak lensing

- needed at multiple redshifts
- want several of these to test for consistency
- complementary constraints

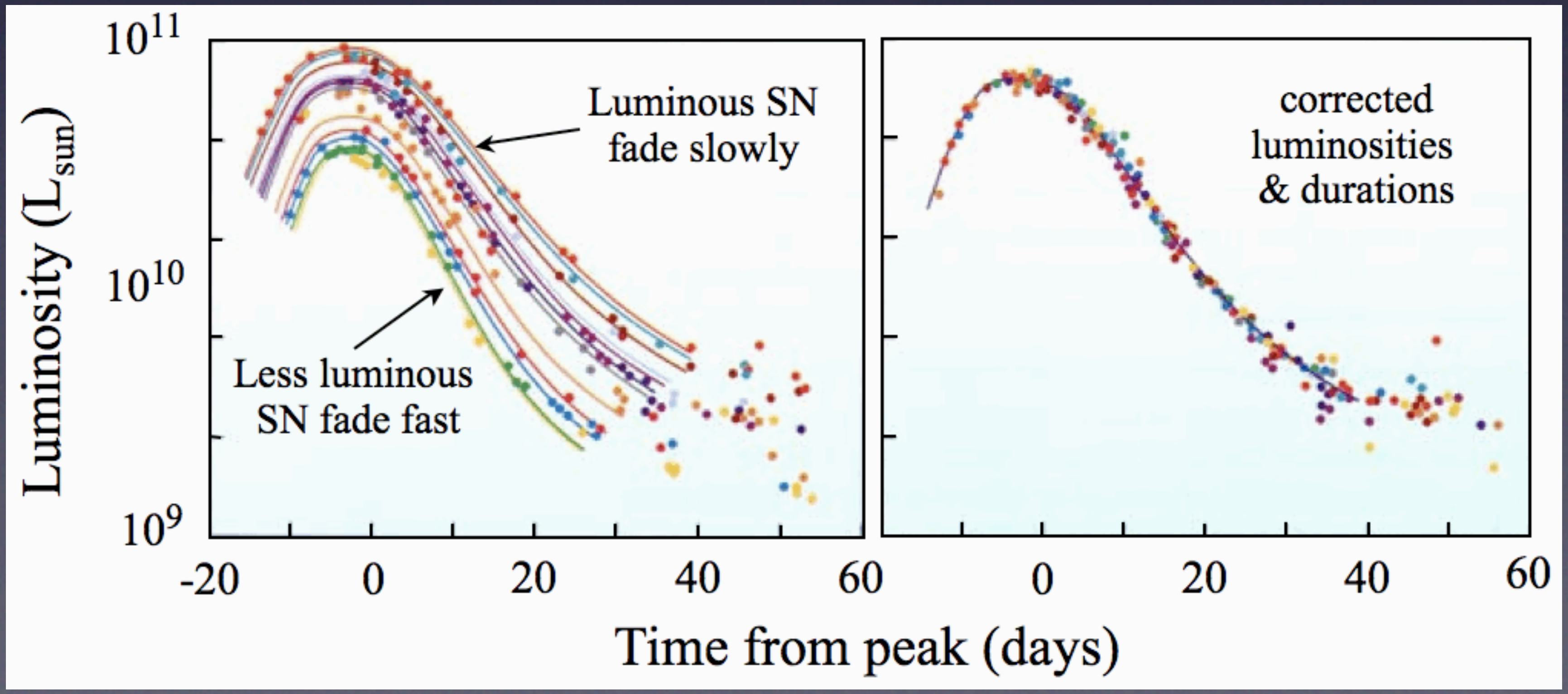
Supernovae

- use SNe 1a as 'standard candles'
- explosion of white dwarf stars as they reach 1.4 M_{Sun}
- measure luminosity distance vs redshift
- difference in apparent vs absolute magnitude depends on H_0 at low-z and q (deceleration parameter) at intermediate z: $q(t) = 1/2\ \Omega_M - \Omega_\Lambda$

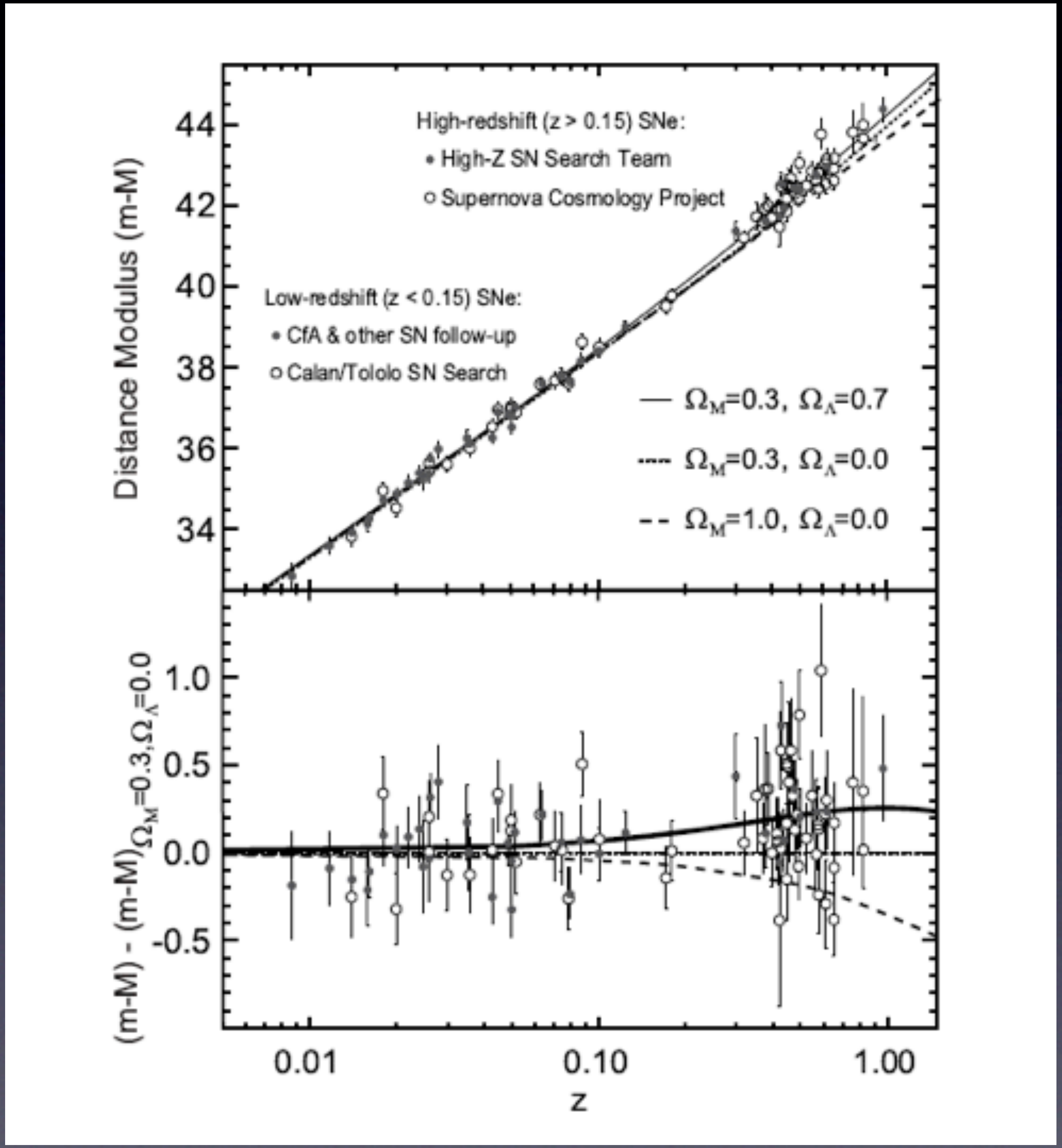
$$M = m - 5(\log_{10} D_L - 1)$$

$$D_L = 10^{\frac{(m-M)}{5}+1}$$

$$F = \frac{L}{4\pi D_L^2}$$

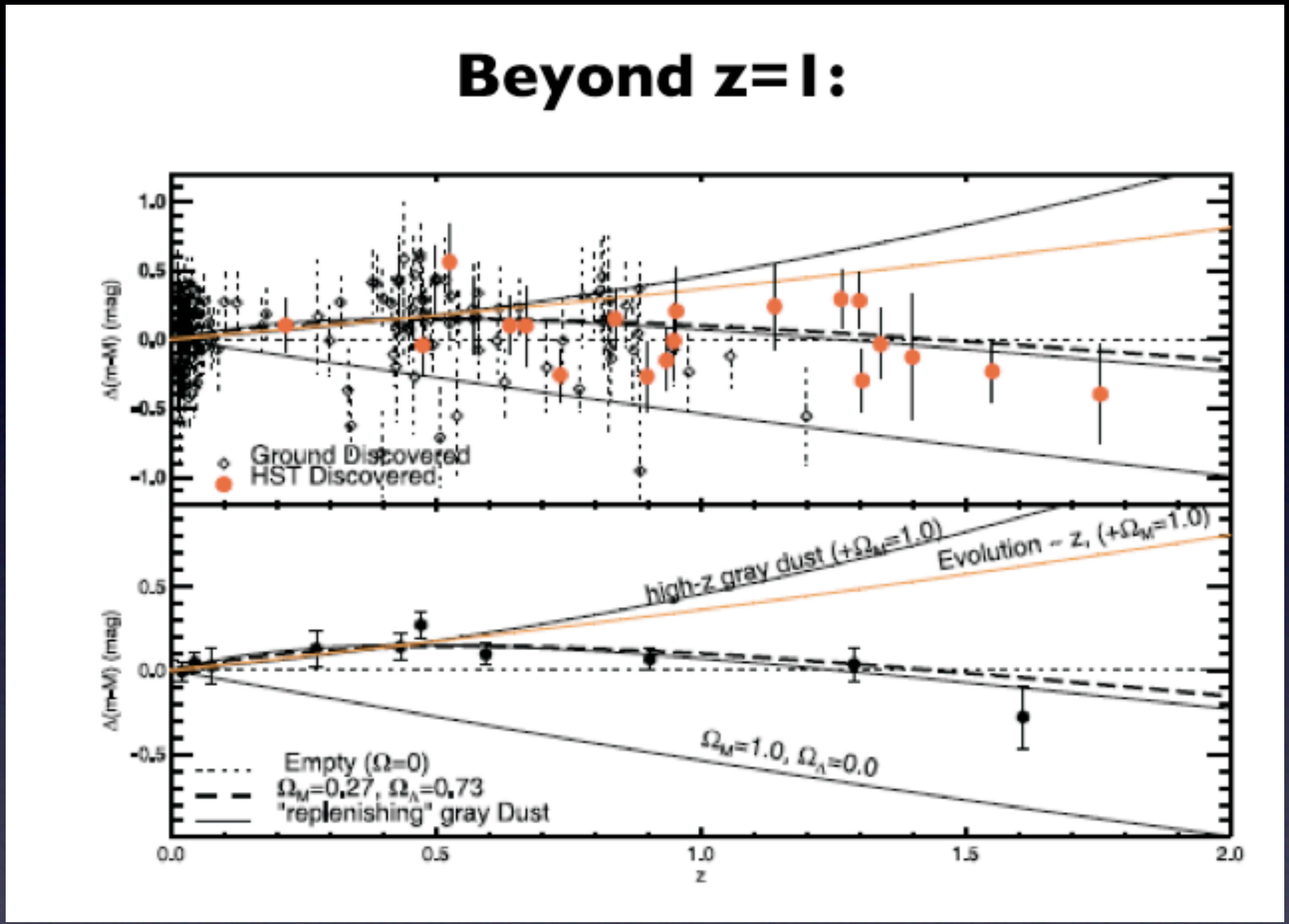


Supernovae

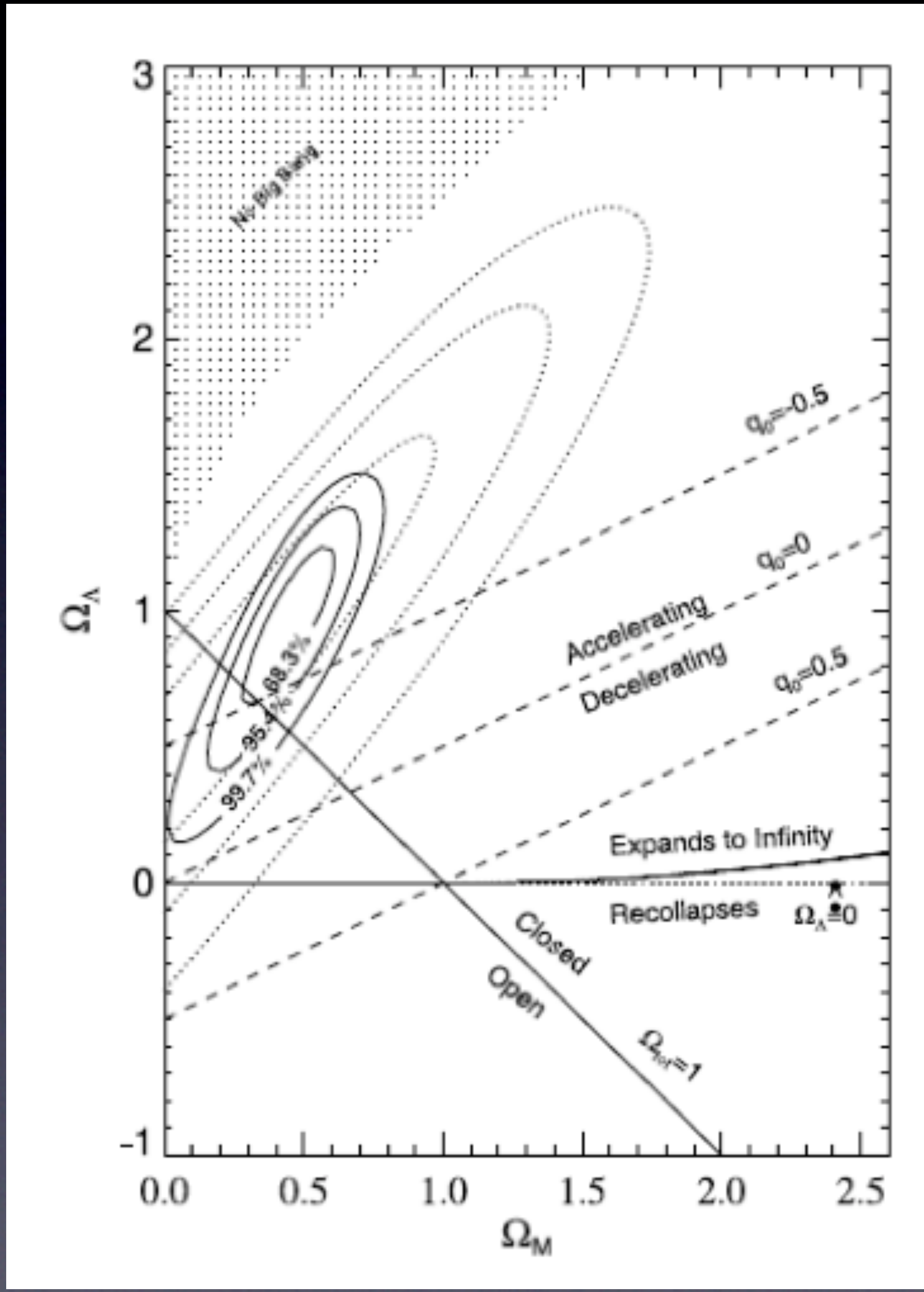


High-redshift (z > 0.15) SNe:
High-Z SN Search Team
Supernova Cosmology Project
Low-redshift (z < 0.15) SNe:
CfA & other SN follow-up
Calan/Tololo SN Search
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Distance Modulus (m-M)
44
42
40
38
36
34
(m-M) - (m-M)$_{\Omega_M=0.3,\Omega_\Lambda=0.0}$
1.0
0.5
0.0
-0.5
0.01
0.10
1.00
z

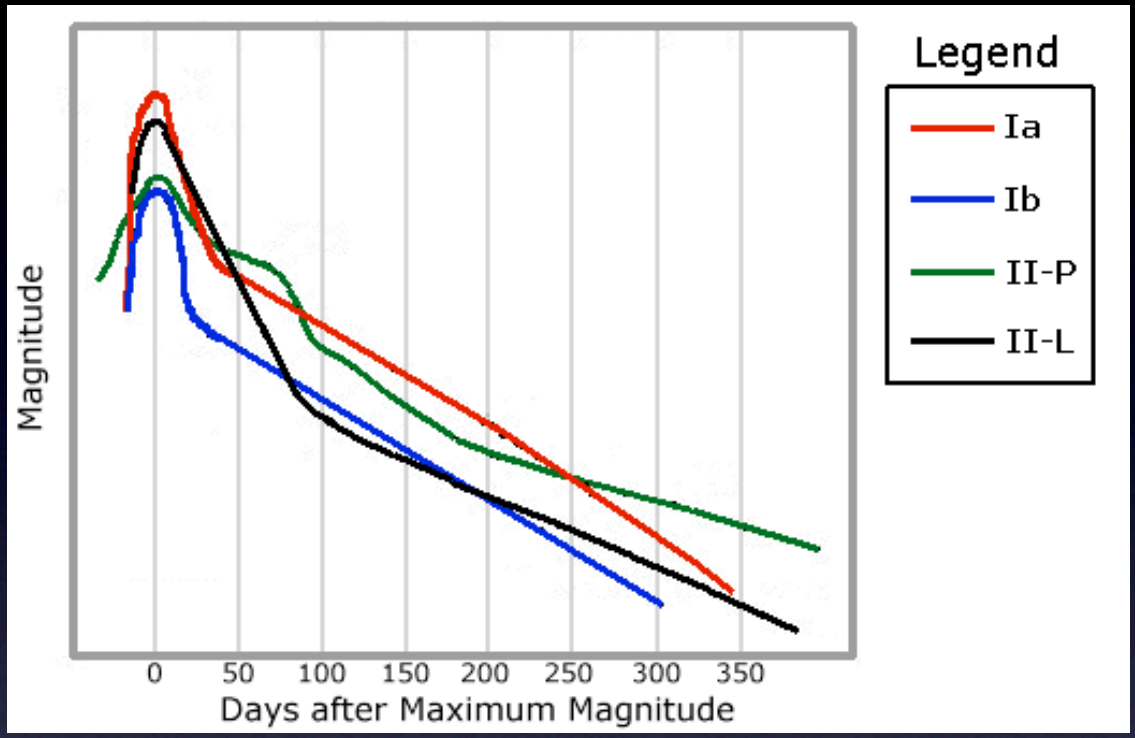
Supernovae

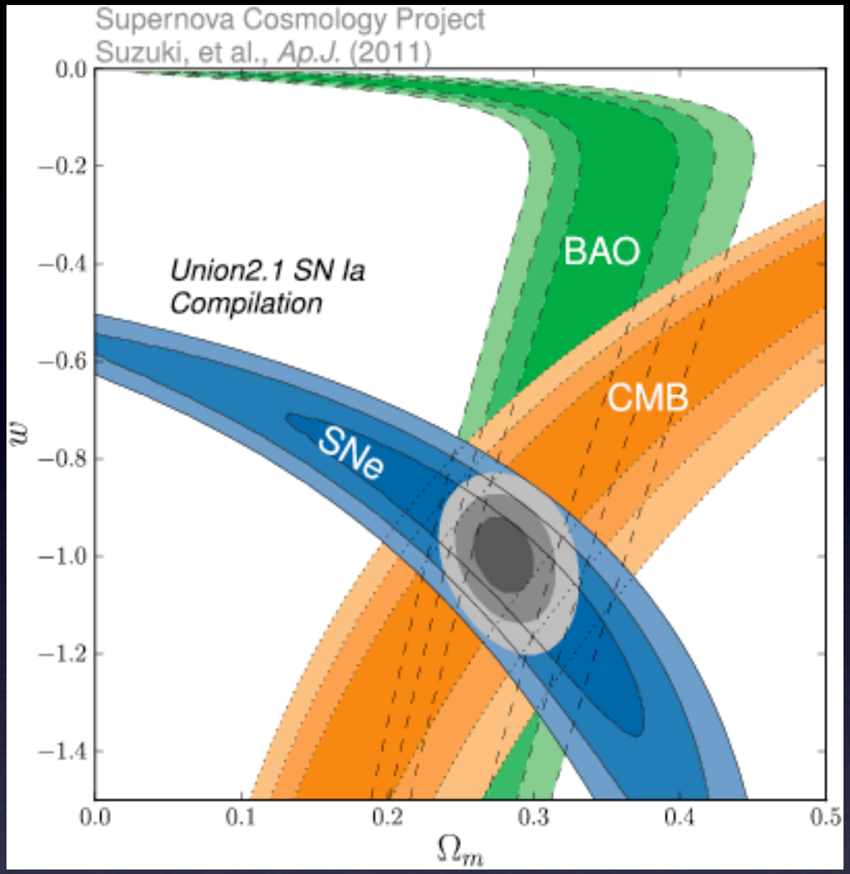


Reiss et al.



Supernovae





- need precise multi-band photometry
- catch ‘on the rise’ - frequent time monitoring
- survey wide areas (~1 SNe per galaxy per 100 yrs)
- ideally have spectroscopic follow-up soon after max. (use type Ia only, need redshift) - lowers systematics significantly
- systematic errors are *roughly* few % (dominant error is photometric calibration)

Baryon Acoustic Oscillations (BAO):

- hot, dense plasma in very early Universe
- tight coupling b/w baryons and photons
- perturbations (overdensities) can't grow
- instead, they oscillate as sound waves
- at recombination (z~1088) baryons and photons decouple, and perturbations grow
- sound waves are frozen into plasma at decoupling
- scale is the sound horizon at last scattering
- scale grows as Universe expands
- detected as enhancement in clustering on scales ~100 Mpc/h at z=0 (or series of wiggles in power spectrum)
- acoustic length scale is precisely measured by CMB (at just one z)
- use low-z galaxy measurements as 'standard ruler'

Baryon Acoustic Oscillations (BAO):

- low systematic uncertainties!
- simple, linear physics
- small non-linear effects (<0.5%) - calibrated well
- measuring the angle subtended by this scale determines a distance to that redshift (angular diameter distance)
- doesn't tell you about growth rate of structure

$$d_A = \frac{x}{\theta}$$

$$d_A = \frac{r(\chi)}{1+z}$$

$$r(\chi) = \begin{cases} \sin\left(\sqrt{-\Omega_k} H_0 \chi\right) / \left(H_0 \sqrt{|\Omega_k|}\right) & \Omega_k < 0 \\ \chi & \Omega_k = 0 \\ \sinh\left(\sqrt{\Omega_k} H_0 \chi\right) / \left(H_0 \sqrt{|\Omega_k|}\right) & \Omega_k > 0 \end{cases}$$

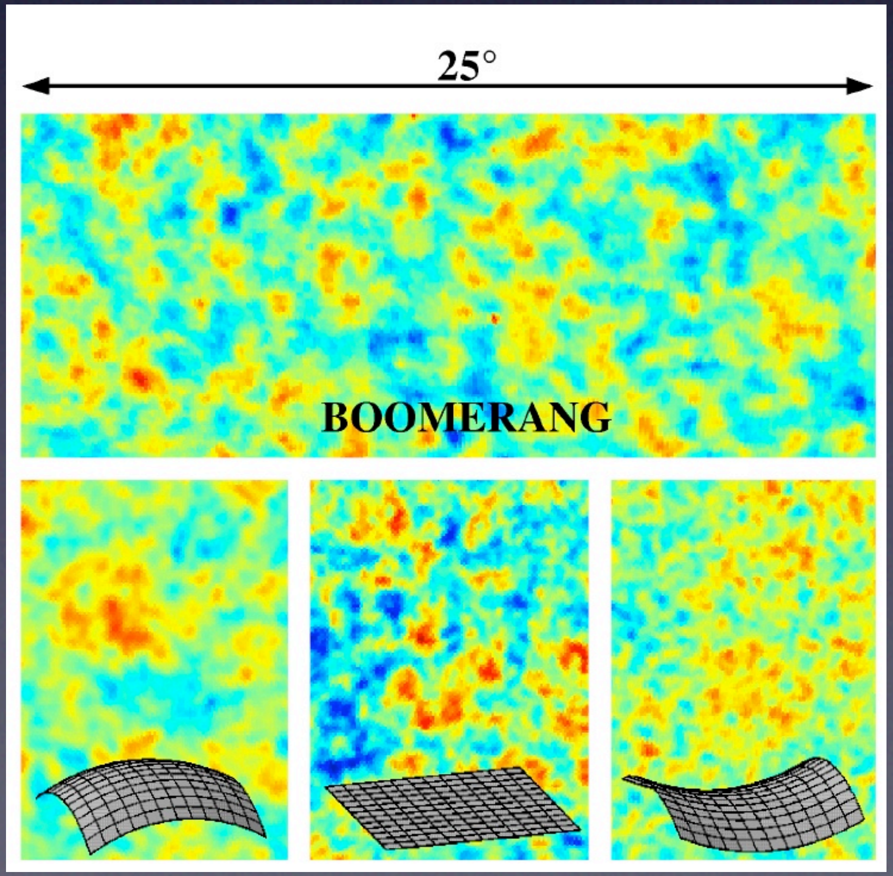
Baryon Acoustic Oscillations (BAO):

- can use any ‘tracers’ of large-scale structure
- want to probe large volumes, can use fairly low density tracers
- can use bright, rare sources - are also strongly clustered
- challenge is to do very large surveys to get high statistical precision
- in principle can be done w/ photo-z’s, but better not to

Sensitive to curvature or

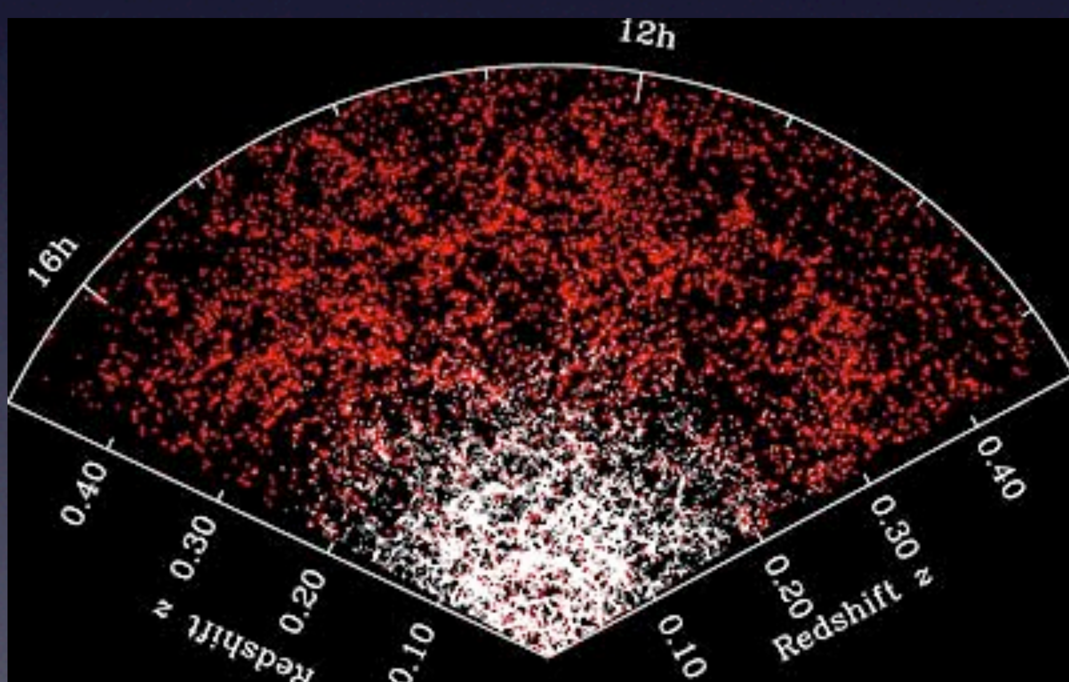
Ω_{total}

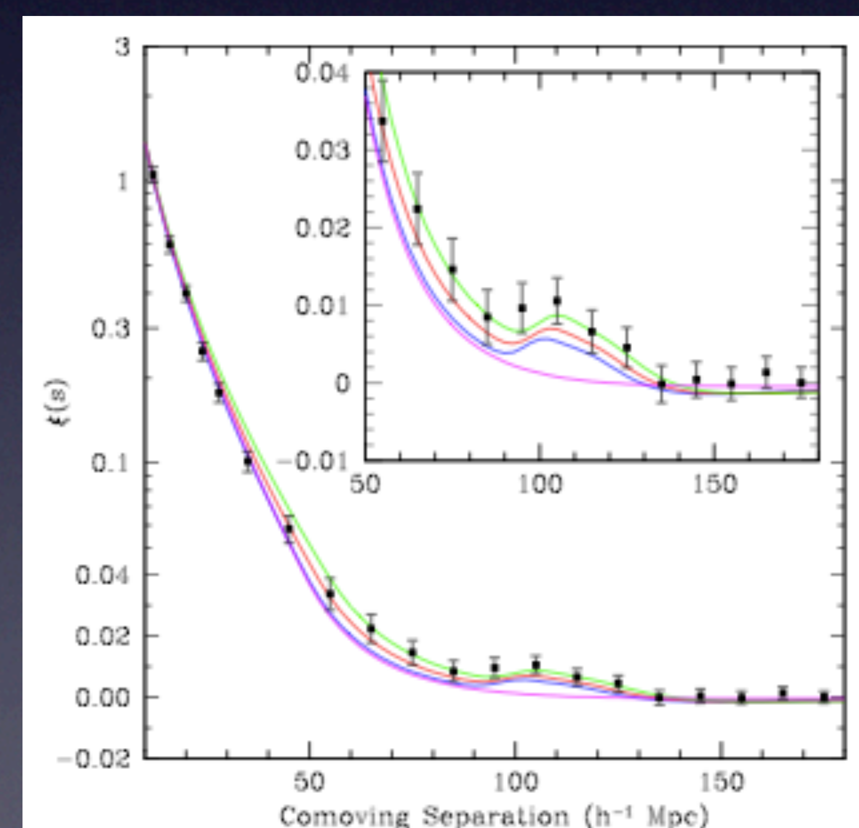
- complementary to SNe



Baryon Acoustic Oscillations (BAO):

- first measured well in SDSS w/ 45k luminous red galaxies (LRGs) at z=0.35
- 4% distance measure relative to CMB
- 5% absolute distance measure
- should be able to measure to 1% or less





Eisenstein et al. 2005

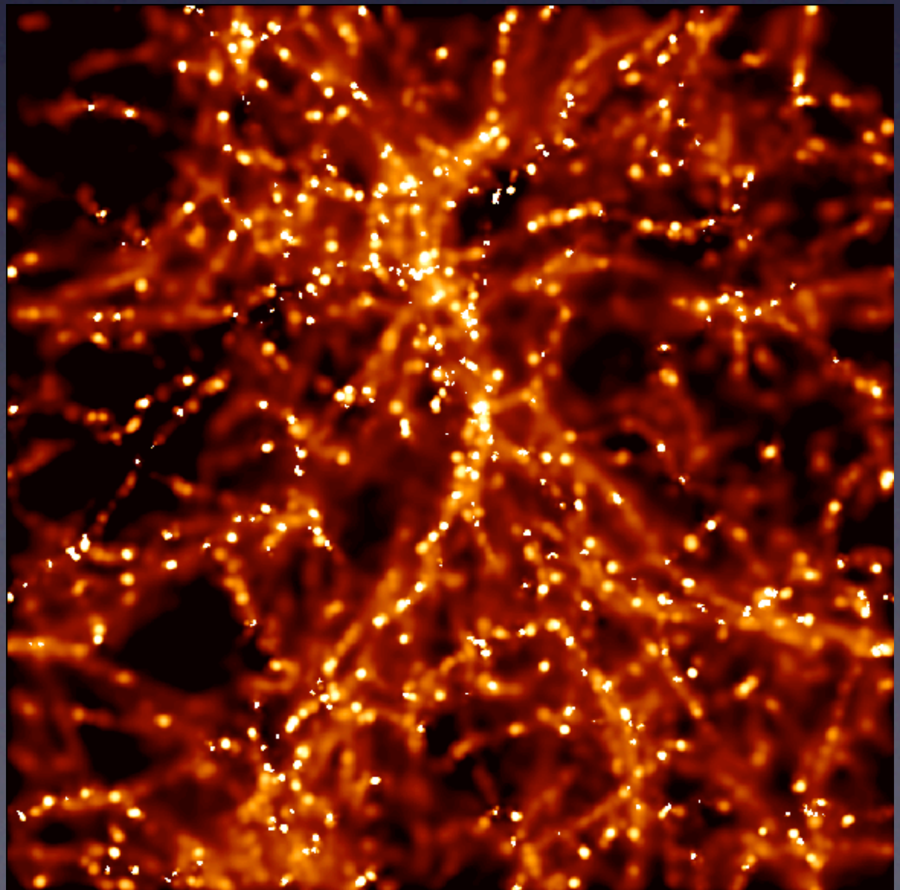
BOSS: Baryon Oscillation Spectroscopic Survey

BOSS at a glance
Dark time observations
Fall 2009 - Spring 2014
1,000-fiber spectrograph, resolution R~2000
Wavelength: 360-1000 nm
10,000 square degrees
Redshifts of 1.5 million luminous galaxies to z = 0.7
Lyman-α forest spectra of 160,000 quasars at redshifts 2.2 < z < 3

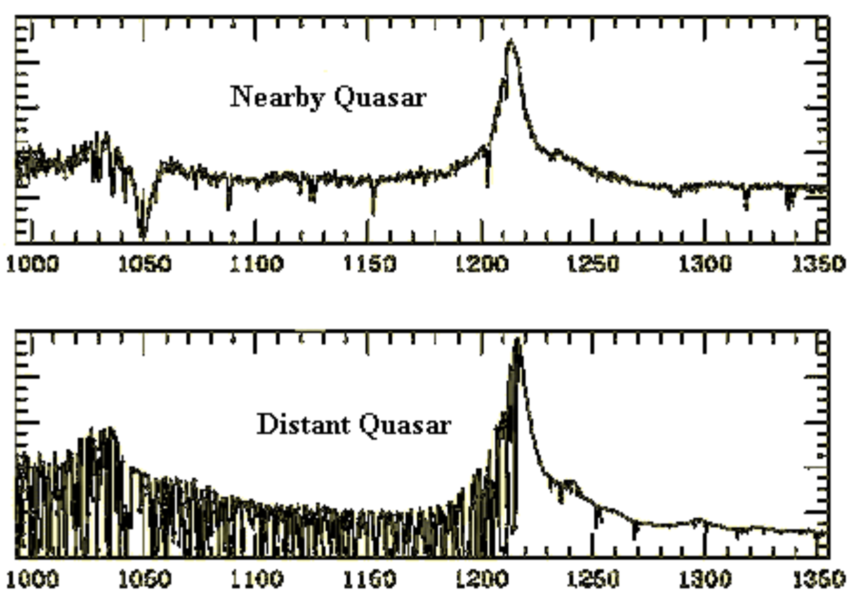
- part of SDSS-III
- spectroscopic survey!
- BAO is main science driver - goal is BAO to 1%
- probing 2 epochs: z~0.7 with LRGs, z~2-3 with QSOs
- do usual 2-pt. correlation function with LRGs
- use Lyman-alpha absorption to QSOs - many small sightlines

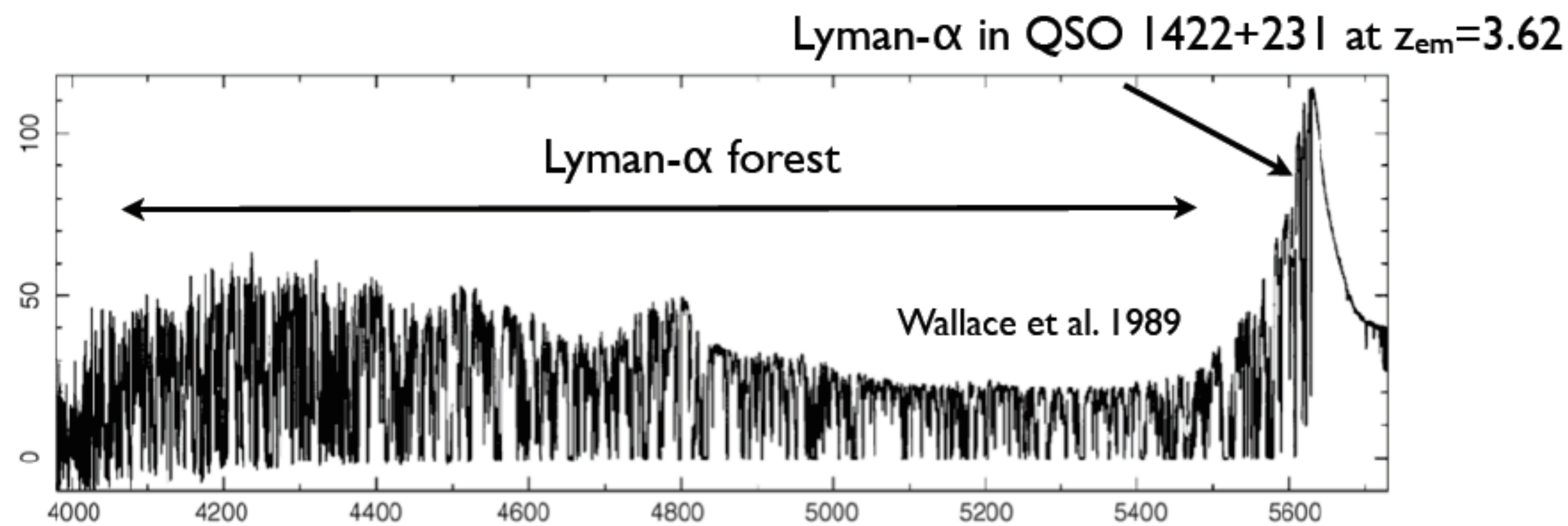
BOSS: Baryon Acoustic Spectroscopic Survey

- uses strongly clustered tracers - enhances signal
- goal: measure the absolute cosmic distance scale to 1% at z=0.35, 1.1% at z=0.6, and 1.5% at z=2.5
- tight constraints on equation of state parameter
- unlike SNe, where we need to push to higher redshift, for BAO it's most useful to have low-z measurements to compare against the CMB at very high-z
- the QSO measurements are a novel method (and could be extended to higher-z in future)



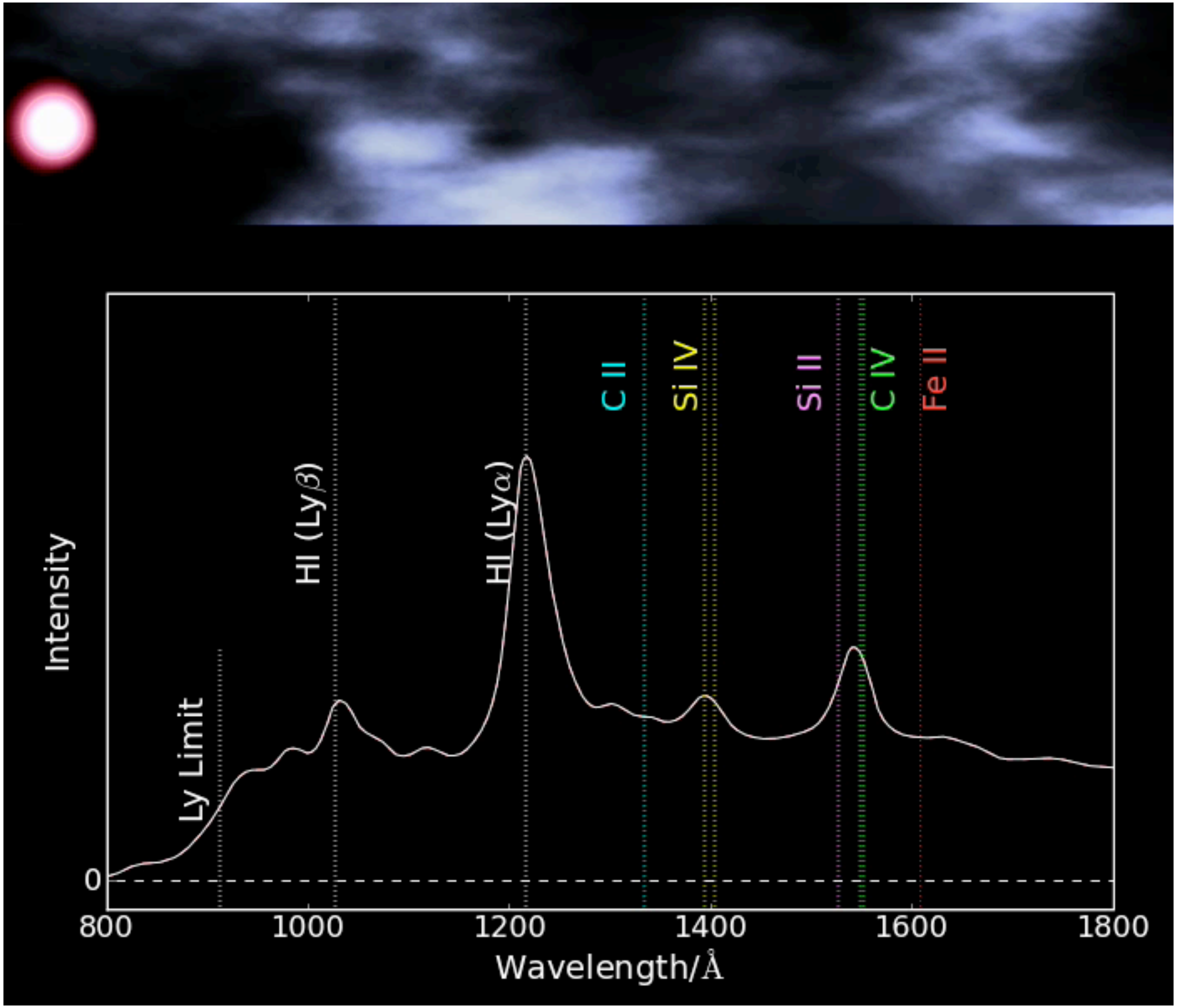
Lyman-alpha Forest





Absorption of light blueward of Lyman-alpha (n=2-1 line in hydrogen) caused by neutral hydrogen gas along the line of sight in the IGM - intergalactic medium. Light from the quasar gets absorbed by gas at different locations along the line of sight - each gas cloud 'sees' the quasar at a different redshift, and so absorbs light at different wavelengths. Each gas cloud leaves a distinct fingerprint as an absorption line at a different position in the spectrum as seen from Earth.

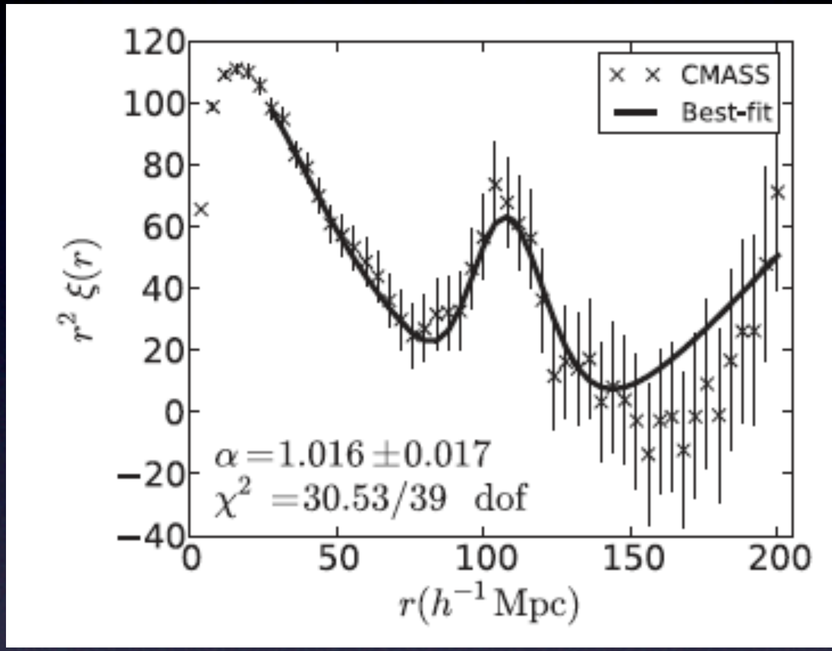
Quasar spectrum produced as the light passes through gas clouds along the line of sight

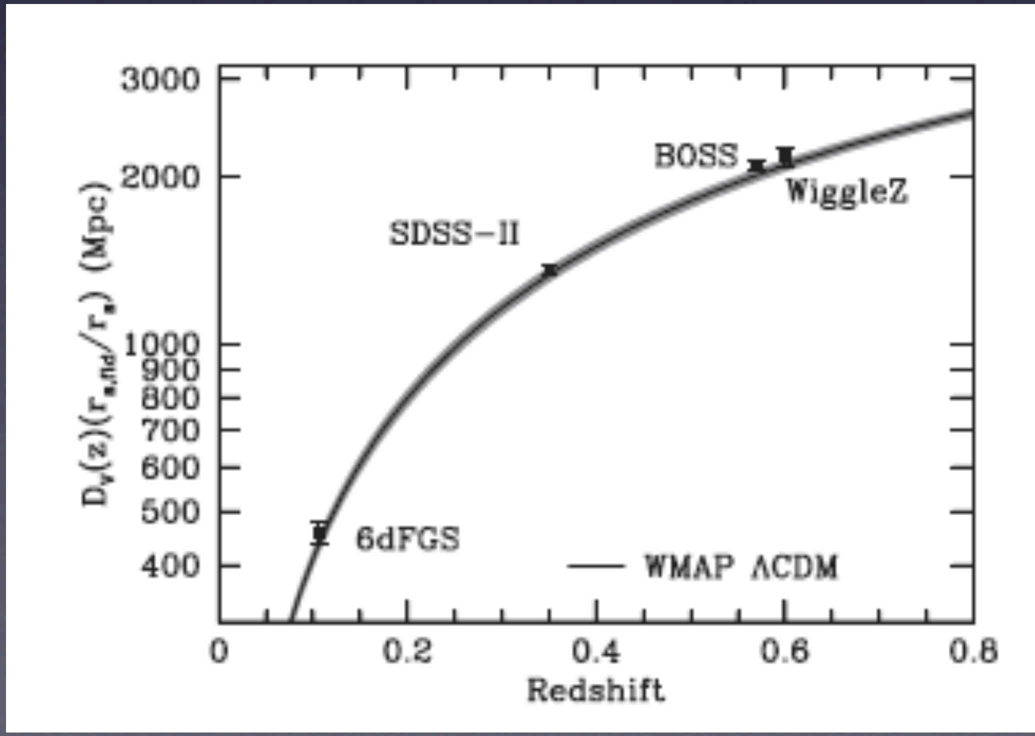


BOSS Results

- have detected BAO signal in LRGs at z=0.57 using >250k galaxies in >3k sq. deg. at the 5 sigma level to 1.7% precision

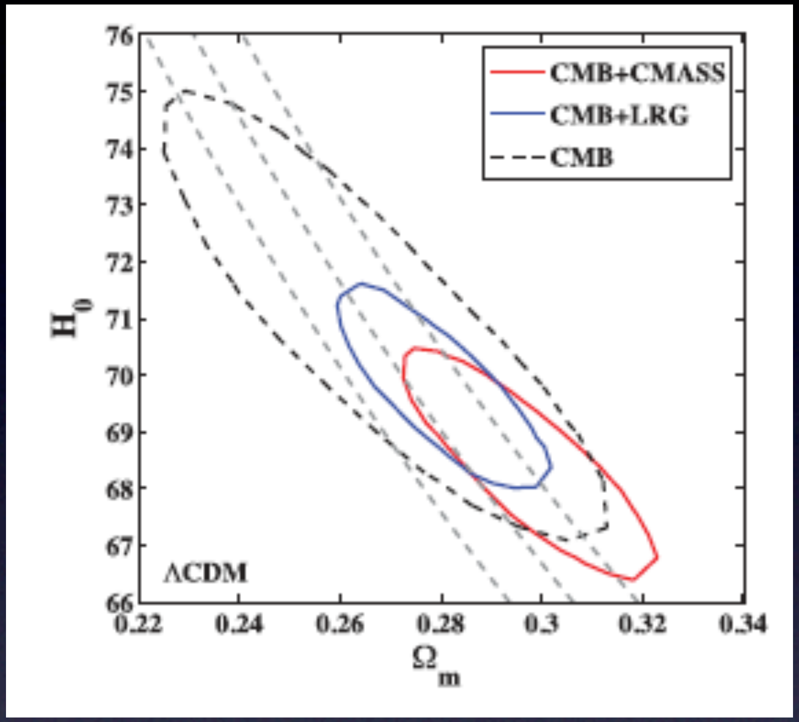
- have detected BAO signal in the QSO data at z=2.4 at the 3-5 sigma level

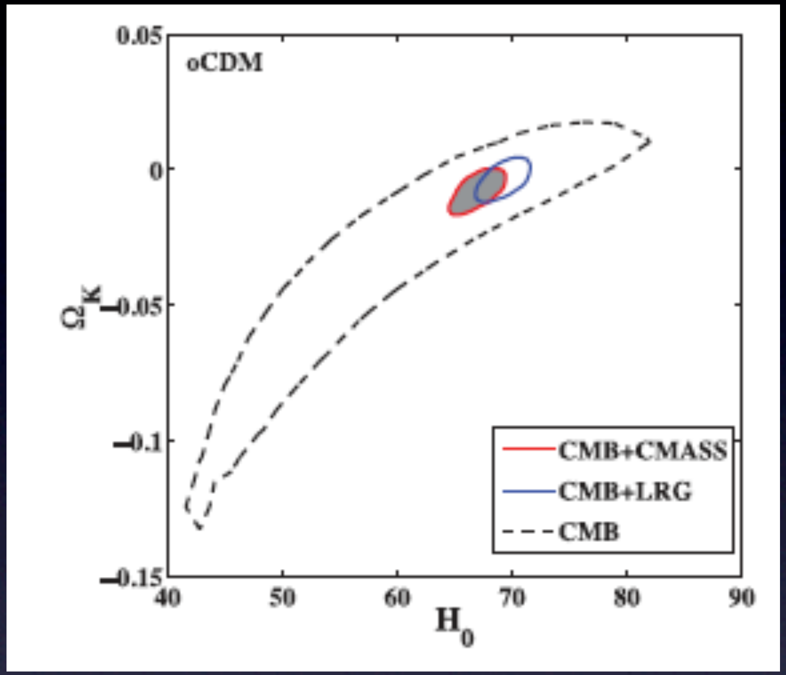


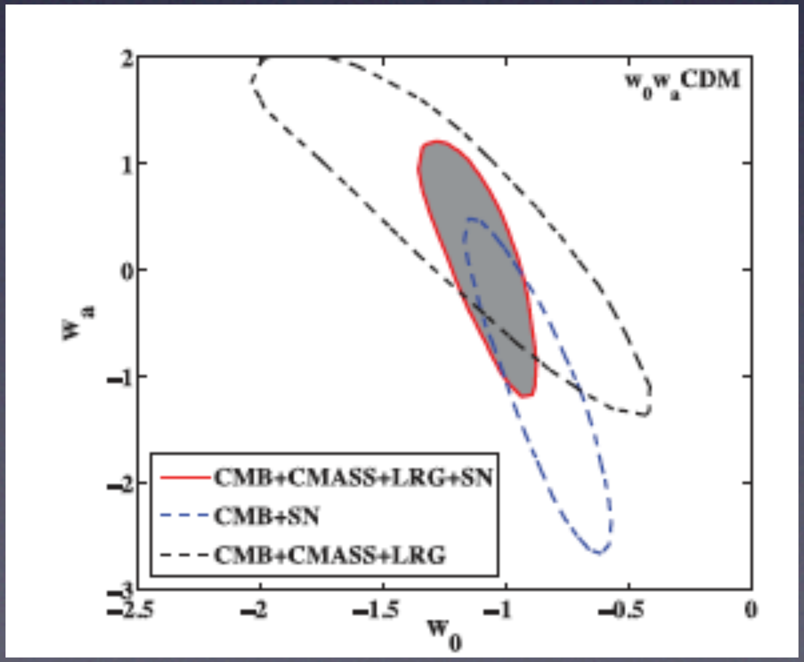


Anderson et al. 2012

BOSS Results







Anderson et al. 2012

Spectroscopic vs Photometric Surveys

Spectroscopic:

- need spectrograph ($$)
- harder to do observationally (time, $)
- higher precision
- few catastrophic z errors
- better constraints

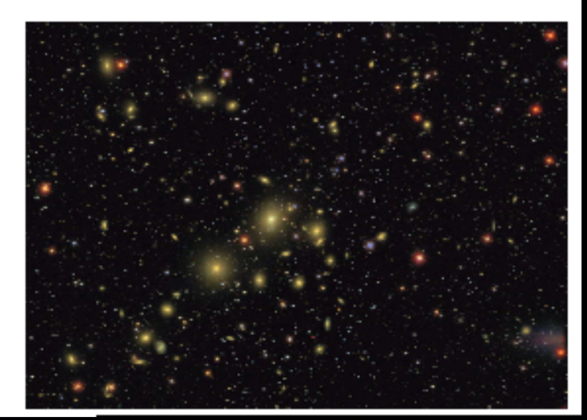
Photometric:

- easier to cover large areas of sky
- can tag on to other surveys 'for free'
- more susceptible to systematic errors in photo-z
- can't do line-of-sight correlations

Other BAO surveys

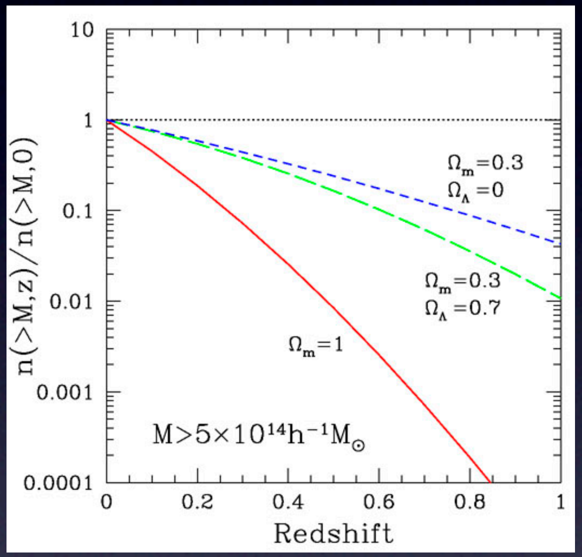
Spectroscopic:
WiggleZ (z=0.4-1.0, 1000 sq deg.)
HETDEX (z=2-4, 350 sq deg.)
WFMOS (z=0.5-1.3, 2000 sq deg. +
z=2.3-3.3, 300 sq deg.)

Photometric:
Pan-STARRS (z=0-1, 20k sq deg.)
DES (z=0-1.4, 4k sq deg.)
LSST (z=0-1.4, 20k sq deg.)
PAU (z=0-1, 10k sq deg.)

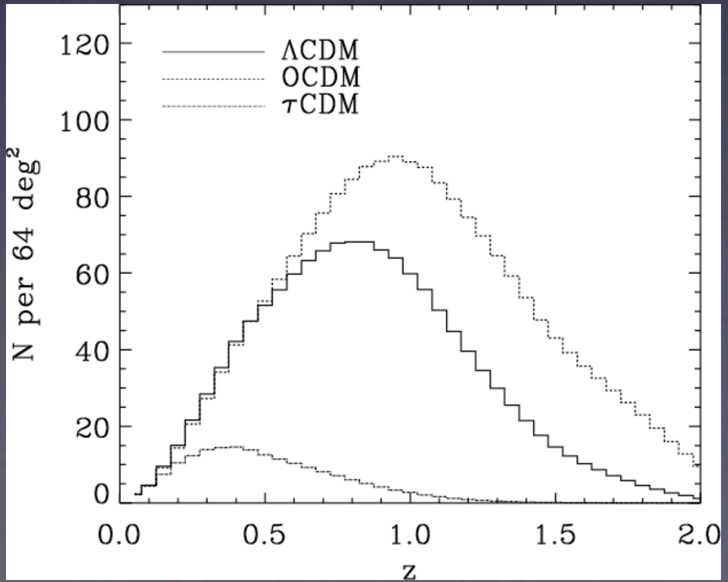


Galaxy Cluster Counts

- N-body simulations predict the cluster mass function: dN/(dM dV)
- volume element depends on expansion history
- mass function is sensitive to amplitude of density fluctutations
- measures growth rate of structure



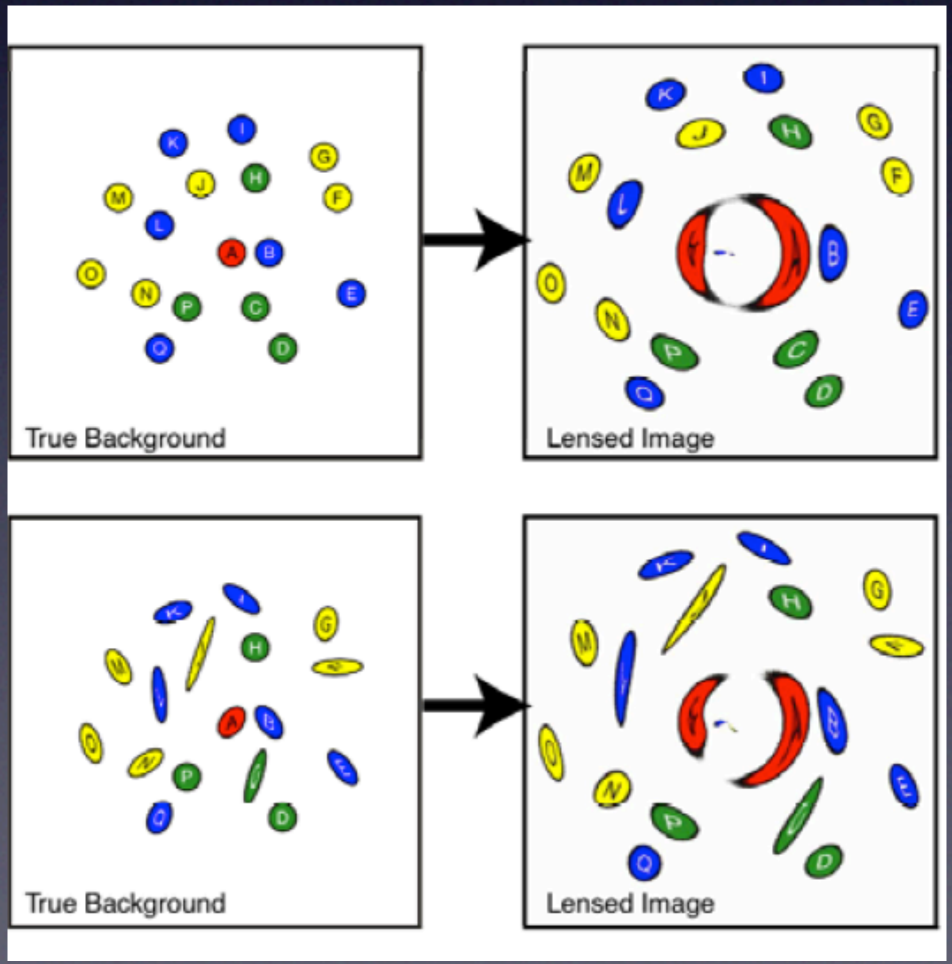
- detect clusters in optical, X-ray, SZ effect, weak lensing
- has largest systematic errors (only lensing measures mass directly)
- is exponentially sensitive to errors in calibration of mass
- lots of non-linear physics (hydrodynamics, galaxy formation)



Weak Lensing

- distortion of background galaxies due to bending of light as it passes foreground mass (galaxies, clusters)
- measure angular diameter distance vs. redshift - expansion history
- measures growth rate of structure

- has non-negligible systematic errors
- shear / deflection of light is only ~2%
- observe very large samples, find slight tendency for nearby galaxies to have aligned shapes
- need ~a billion galaxy images
- potentially very powerful, not yet as accurate as is needed



Strengths and Weaknesses

SNe:

- most established method
- if perfect standard(izable) candles, then limited only by flux calibration
- but dust or changes in Ia events w/ time could mean that they are not standard
- not sensitive to growth of structure

Strengths and Weaknesses

BAO:

- least affected by systematics
- uses a standard ruler well understood from first principles and calibrated by CMB
- but most precise measurements will be at $z>1$, where dark energy is not that important if cosmological constant
- not sensitive to growth of structure

Strengths and Weaknesses

Galaxy Cluster Counts:

- sensitive to both expansion history and growth history of Universe
- extremely sensitive to growth factor
- substantial uncertanties due to baryonic physics
- errors in “mass-observable” relations dominate

Strengths and Weaknesses

Weak Lensing:

- greatest potential for constraining dark energy
- lots of statistics that allow for internal tests and correction of potential systematic errors
- determines both expansion history and growth history
- weak lensing surveys give you shear-selected cluster counts and photo-z BAO data ‘for free’
- systematic errors due to incomplete knowledge of the photo-z distribution
- methodology is still progressing and is not yet mature
- unclear if you can measure galaxy shapes to statistical limits from the ground (have to go to space)

Ground-based Experiment

- motivated by weak lensing (potentially most powerful)
- measure galaxies to high-z over ~1/2 of sky
- design to reduce and control systematics
- need large collecting area and large field of view
- could also get BAO w/ photo-z's
- could maybe also get SNe and cluster counts
- measure expansion and growth histories separately
- lots of data for non-dark energy studies
- will depend on controlling systematic errors on shape measurements and photometry

-> DES / LSST

Space-based Experiment

- single mission could do at least SNe + WL
- by going to space reduce systematics in all methods except BAO
- less risk than ground-based - better measurements
- going to near IR could find SNe to higher-z than from ground
- also push WL to higher-z than from ground
- need optical + IR, imaging + spectroscopy (ideally)
- learn about more than just dark energy

-> JDEM - EUCLID / WFIRST

Dark Energy Survey (DES)

Led by US, also incl. Spain, UK, Brazil, Germany
Built a 570 Megapixel camera for the Blanco 4m at CTIO in Chile (run by NOAO)
Started in fall 2012, will run for 5 years
Image large area of southern sky, 300 million galaxies
Cover 5k sq. deg. in 5 optical filters
Observe some areas every few days (for SNe)
Will do SNe, BAO, clusters, and WL

Dark Energy Survey (DES)

wide-area survey: 5000 sq. deg., 24th mag, grizY imaging
- get photo-z's and galaxy shapes to z~1.3

narrow time-domain survey: 30 sq. deg., griz imaging
- 5 visits per month in 8 fields
- light curves for ~4000 type Ia SNe to z~1

- collaborating w/ other telescopes to get SZ for some clusters and JHK imaging for photo-z's

HETDEX

Hobby-Eberly Telescope Dark Energy Experiment
- at McDonald Observatory (UT-Austin)
- measure BAO over 60 sq. deg. (spread over 420 sq. deg.)
- 800k Lyman-a emitting galaxies at 1.8 < z < 3.7
- 1 million low-z galaxies with OII emission (z~0.3)
- will use 150 integral field unit (IFU) spectrographs

- a small pilot survey is underway now
- larger survey to begin in a year or so

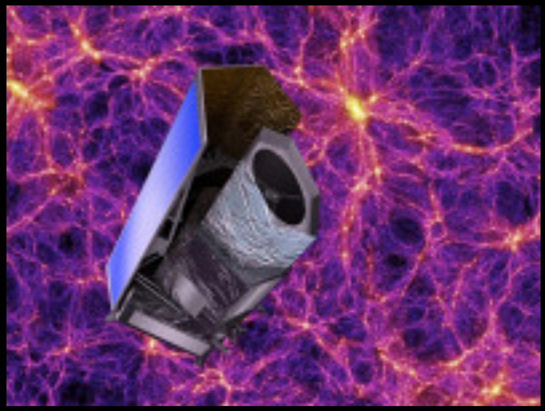
WFMOS

Wide Field Multi Object Spectrograph
- at Subaru Observatory (Mauna Kea)
Partnership w/ Gemini
BAO main driver
Wide field of view (>1 sq. deg.)
1600 fibers - optical spectroscopy

LSST

Large Synoptic Survey Telescope
- being built in Chile, Cerro Pachon
- begin ~2020
- 8m mirror + largest CCD camera (3200 Megapixels)
- 10 sq. deg. FOV (40x moon)
- take brief snapshots of wide areas of sky
- cover 20k sq. deg., each patch observed ~10k times!
- 6 bands (optical, to 1.1 micron) to depth ~27.5
- 30 terabytes of data each night
- weak lensing main driver, also do SNe + BAO
- lots of other science
- no spectroscopy
- very large collaboration

EUCLID



Led by Europe (ESA), NASA is partner
Launch 2020+, 6 yr mission
Drivers are WL + BAO
1.2 m mirror + optical imaging and NIR imaging + spectroscopy (slitless)
wide survey: 15k sq. deg. to mag~24.5
deep survey: 40 sq. deg. to mag~26.5 (focus on high-z galaxies, QSOs)

WFIRST

Wide Field Infrared Survey Telescope
- NASA, wide-field imaging + slitless spectroscopy
- use existing 2.4m mirror (from HST)
- wide range of science, incl. exoplanets + galaxy evolution
- BAO (H-alpha emission in NIR to z~2) + SNe + WL

(will also use redshift space distortions in clustering to measure growth rate)
- likely after EUCLID?