Instrumentation needs in Dark Energy

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Fermilab

- Probes for dark energy
- Quick survey of the main players (DES, MS-DESI, EUCLID, LSST)
- MKIDs or my own prejudice of what to do during or after LSST

July 2012 SPIE Proceedings: "Ground-based and Airborne Instrumentation for Astronomy IV"

Probes for Dark Energy

Two kinds of probes are used to measure dark energy:

1. **Distance measurements (to track the expansion of the Universe)**

2. **Growth of cosmic structure (to answer the question: is the acceleration due to dark energy of modified gravity?)**

In linearized GR both quantities depend on the Hubble ratio:

$$H(z) = \frac{\dot{a}}{a} = H_0 \sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda}$$

With $W=p/E=W_0+W_a\,(1-a)$ we have:

$$\Omega_\Lambda = \Omega_{DE} \exp\left\{3\,(1+W_0+W_a)\ln(1+z) - W_a\, z/(1+z)\right\}$$

For a cosmological constant $W_0=-1$ and $W_a=0$

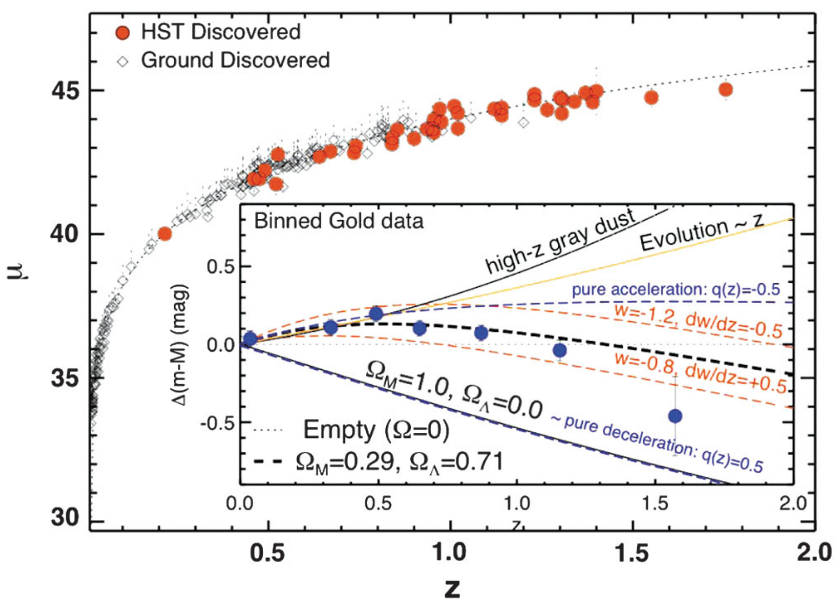
Distance measurements

Then the co-moving distance is:

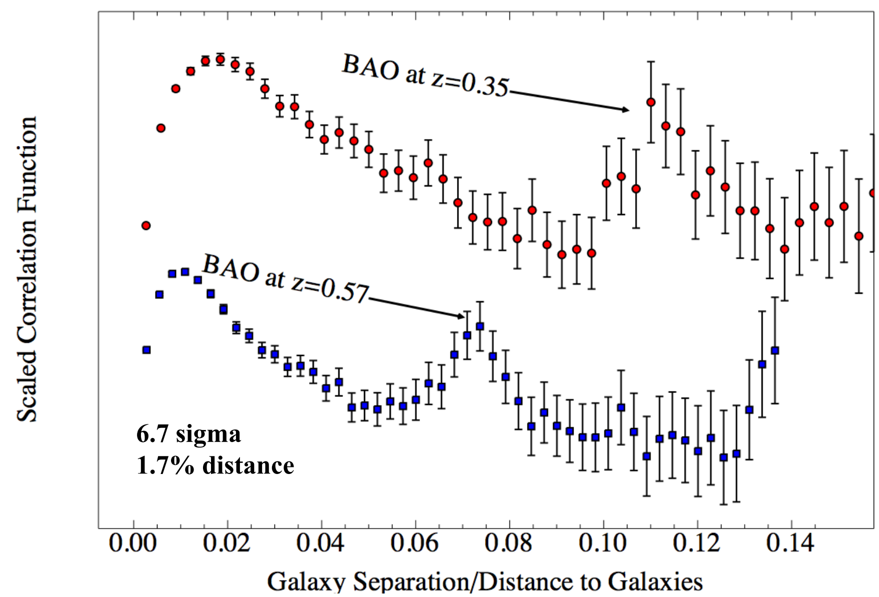
$$D_c = c\int_0^z \frac{dz'}{H(z')}$$

Two proven forms of measuring distances are:

Supernovae



Baryon Acoustic Oscillations (BAO)



(Courtesy of M. Levi)

Structure measurements

The two "common" methods are:

- **Weak Lensing (WL)**
- **Galaxy cluster counting (CC)**

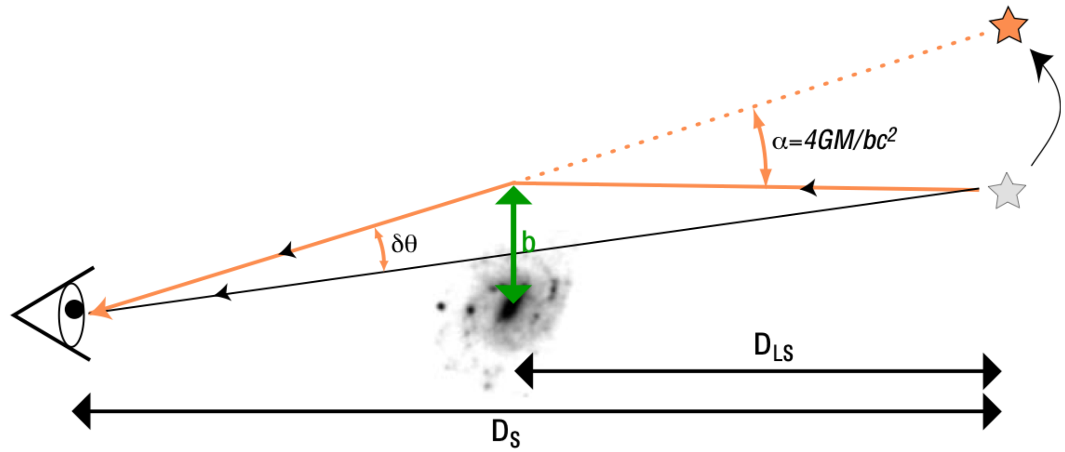
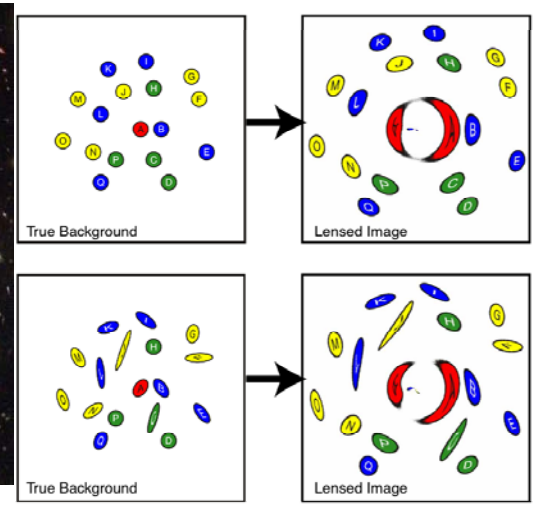


Fig. VI-6: Schematic of gravitational lensing: the deflection angle apparent to the observer at left depends both upon the mass of the deflector and on the distance ratios between source, lens, and observer.



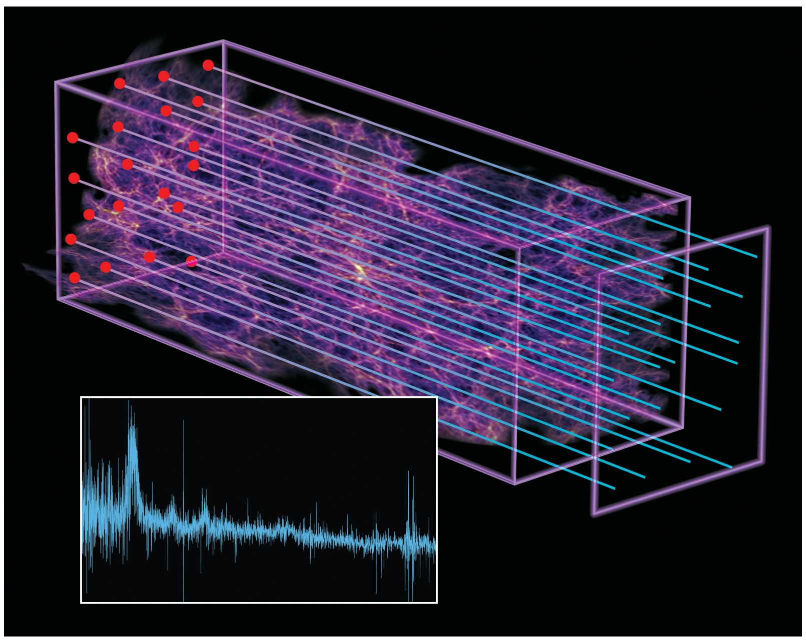
DETF, Albrecht et al.

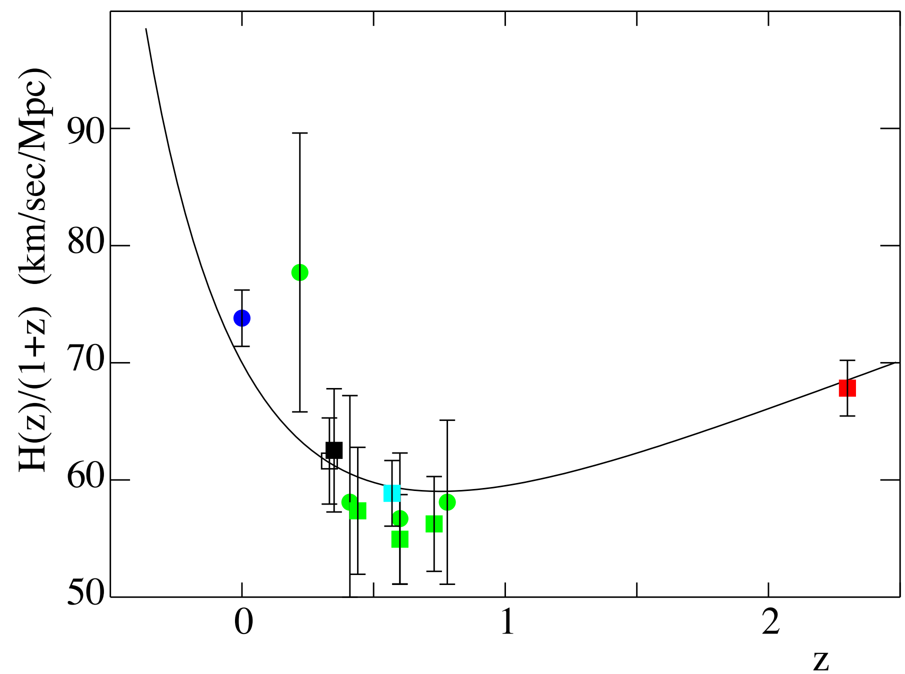
Two questions

1. **How far in redshift do we need to go?**

2. **What kind of redshift resolution do we need?**

Beautiful new result: "BAO in the Lyα forest of BOSS quasars" arXiv:1211.261v1, Nov 2012.





Growth of structure (I)

After the matter-radiation equality epoch (at z ≈ 3000) non-relativistic matter evolves pretty much following Newton's gravity. The correct treatment (GR + Boltzmann's equation) in the linear approximation give the same equations and for me at least it is easier to think in Newtonian terms. Newton's gravity is expressed in Euler's equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{V}) = 0$$

Conservation of mass

$$\frac{\partial (\rho \, \mathrm{v}_i)}{\partial t} + \nabla.(\rho \, \mathrm{v}_i \, \vec{V}) = \text{(i-axis force)/volume}$$

Newton's second law

The force has two components, one due to pressure and the other due to gravity, so one has to add Poisson's equation. Using co-moving coordinates and writing the matter density as

$$\rho = \rho_0 \, (1+\delta) = \frac{\rho_m}{a^3} \, (1+\delta), \qquad (\rho_m = \text{matter desity today})$$

One ends up with a second order differential equation for δ

Growth of structure (II)

$$\frac{d^2\delta}{dt^2} + 2H\frac{d\delta}{dt} - \frac{v_s^2}{a^2}\nabla_c^2\delta - 4\pi G\rho_0\,\delta = 0$$

We can see that if that the sound speed v_s is large the density contrast δ forms traveling waves. But after recombination (z≈1000) the speed of sound becomes zero and the waves "freeze". From there on δ just changes amplitude, the structure sits in place and just grows. If there is no dark energy and v_s=0 the solution of the above equation is just

$$\delta(x,t) = G(t)\,\delta(x), \quad \text{with} \;\; G(t) = a(t)$$

When dark energy is present the growth slows down and can be written as:

$$G(a) = (\text{constant})\,H\int_0^a \frac{da'}{(a'H)^3}$$

G is called the growth factor and (constant) is usually set such that G(a<<1)=a

The growth factor

The growth factor can also be written as:

$$G(a) = \exp\left\{-\int_a^1 \frac{da'}{a'} f(a')\right\}$$

Where the growth rate f(a) can be approximated by:

$$f = \frac{a}{G}\frac{dG}{da} \approx [\Omega_m(a')]^\gamma, \quad \text{with } \Omega_m(a) = \frac{\Omega_m}{a^3}\left(\frac{H_0}{H}\right)^2$$

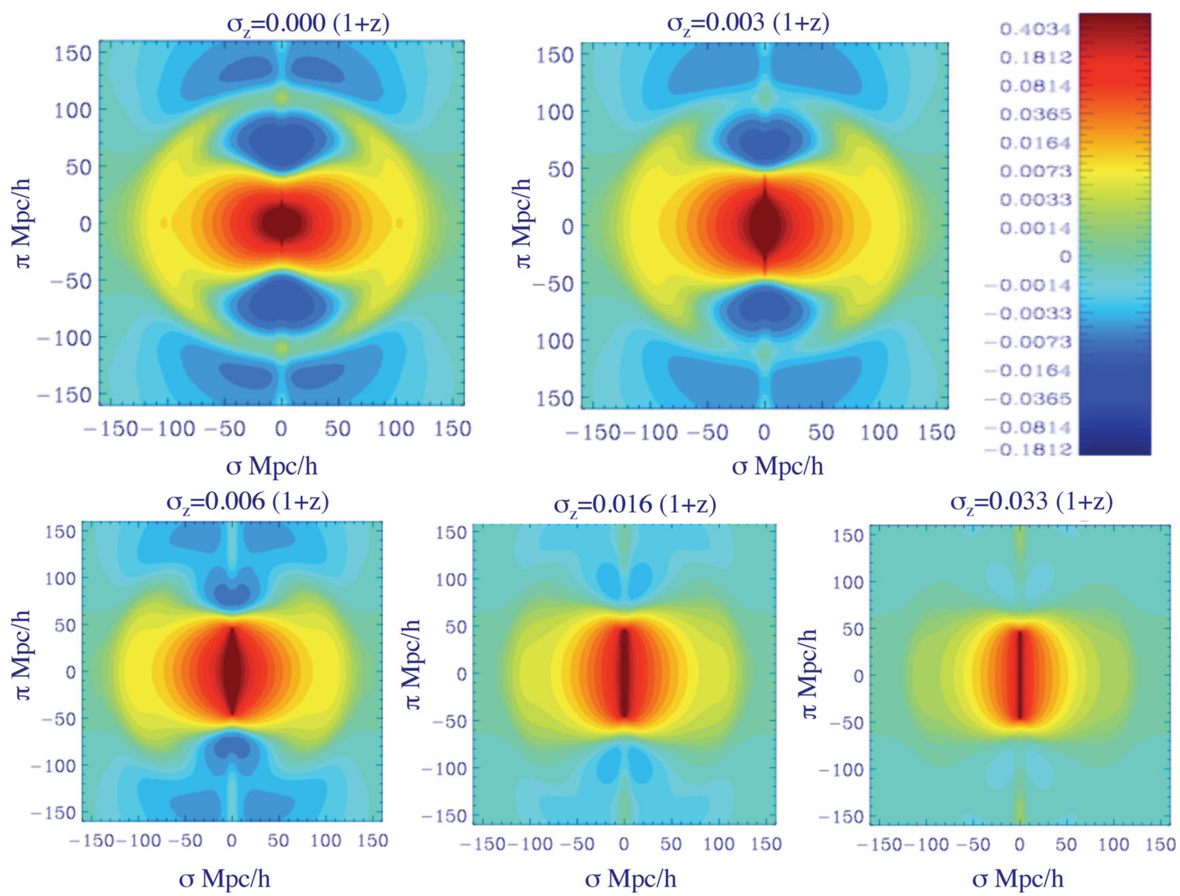
In GR γ=0.55, an any deviation from this number will indicate a modification of GR. Since measures the change in growth is not surprising that it will sensitive to matter velocities on large scales. Which brings as to Redshift Space Distortions.

Redshift Space Distortions (RSD)

The two point correlation function ξ looks like:

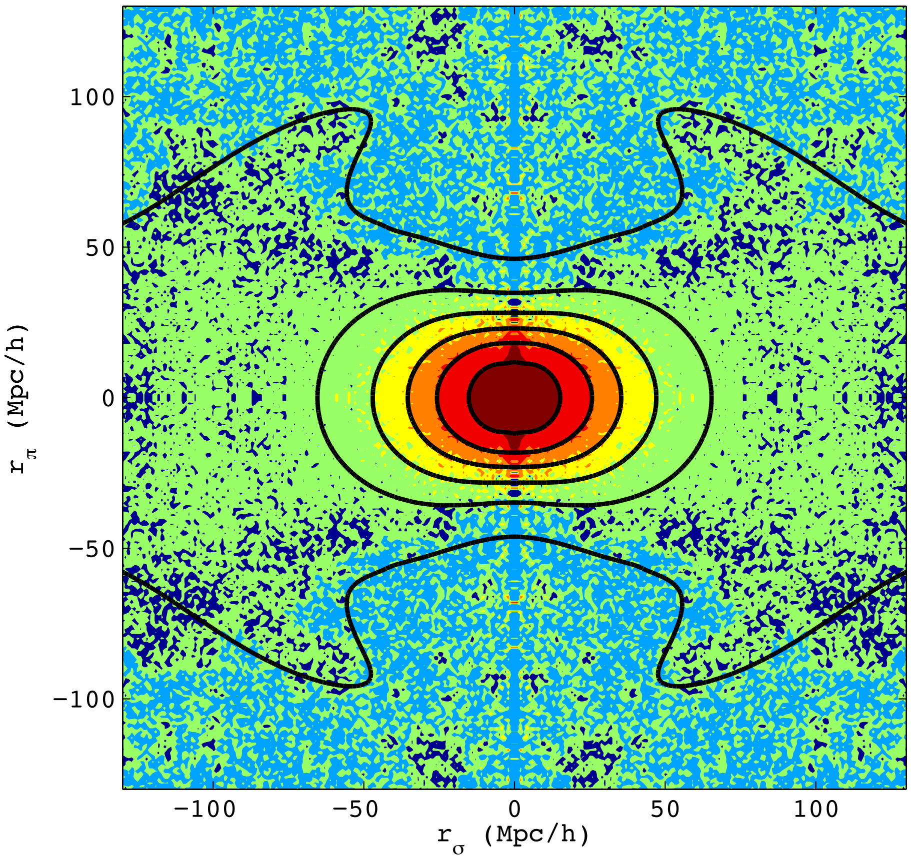
$$\xi(r,\cos\theta,f) = \xi_0(r,f)P_0(\cos\theta) + \xi_2(r,f)P_2(\cos\theta) + \xi_4(r,f)P_4(\cos\theta)$$

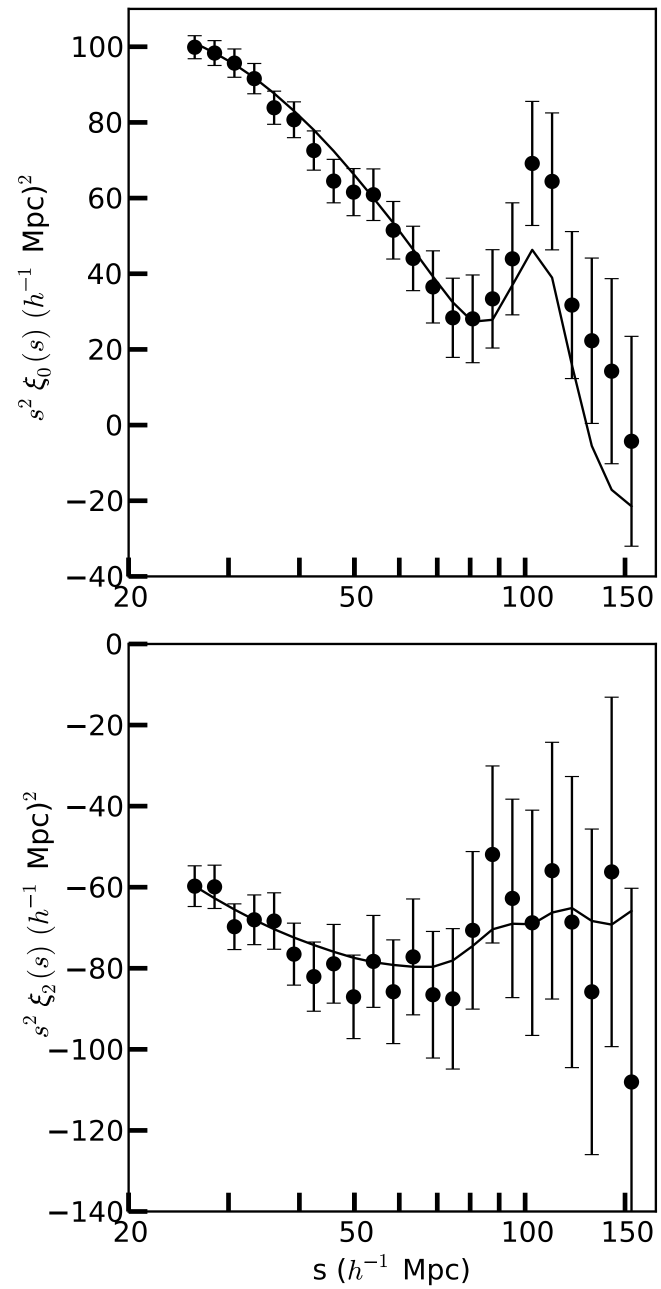
Simulations from:
Enrique Gaztañaga et al,
MNRAS 422, 2904 (2012)



RSD with BOSS

Reid et al, arXiv:1203.6641v1, Mar 2012





So, what needs to be measured to study DE?

Then for Dark Energy studies we want to measure the following objects over as large a volume as possible (many Gpc^3):

1. **Galaxy shapes, types, angular position and redshifts.**

2. **Supernovae (SNe Ia).**

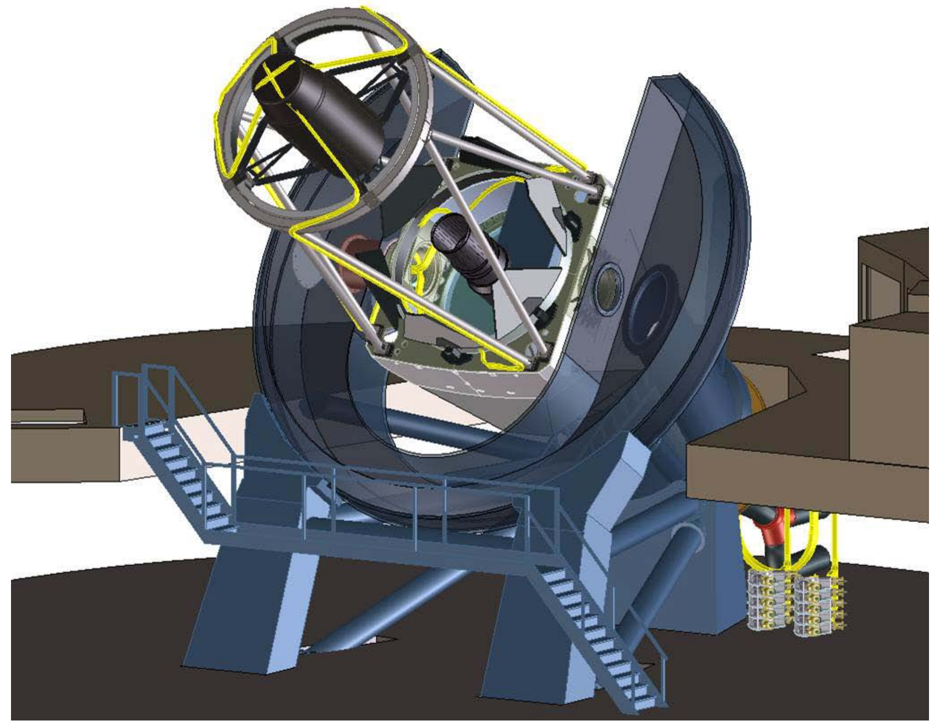
3. **Angular position and spectrum of quasars. Mapping of hydrogen clouds.**

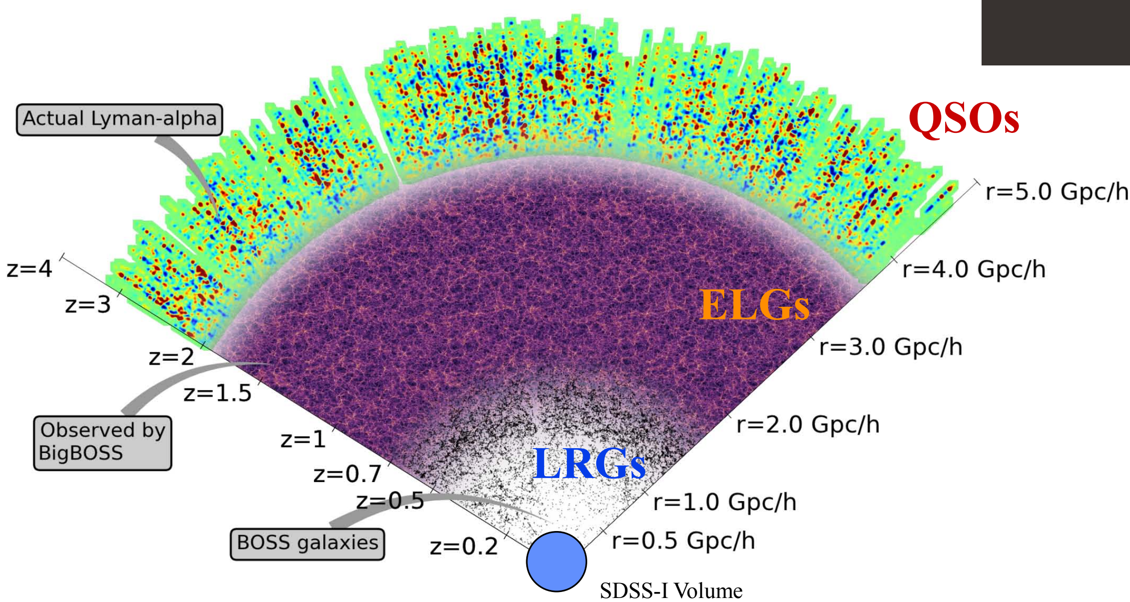
Future projects that will do that on a large scale are:

- DES: imager with 5 filters. In 5 years will cover 5000 square degrees to magnitude 24 and z up to ~1.5. Status: running.
- MS-DESI (BigBOSS/DESpec): Spectrograph. Status: start in 2017?
- EUCLID: Space imager and spectrograph. Status: launch date ~2019.
- LSST: imager with 6 filters. Status: scheduled to start in 2021.

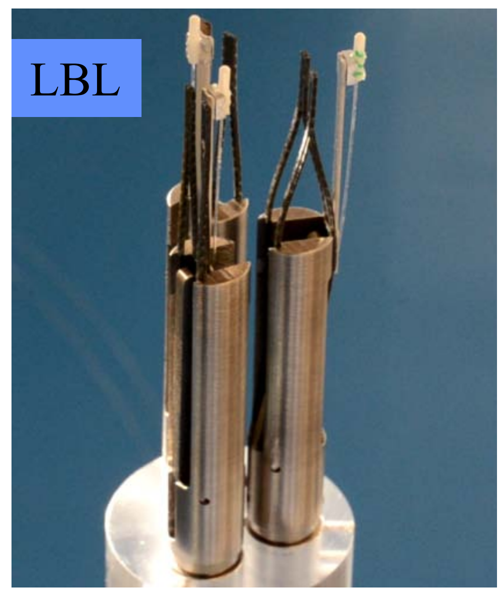
BigBOSS

1. 4 m telescope
2. 5000 fiber, 3 arm spectrograph, R~4000
3. Spectra for 1800 objects/deg^2 (~10% of available galaxies)
4. Magnitude limit ~22.5, z~3.5
5. Will cover 14,000 deg^2 in 3 years
6. 20 M galaxies, 0.6 M QSO





SDSS ~ 2h^{-3}Gpc^3 ⟹ BOSS ~ 6h^{-3}Gpc^3 ⟹ BigBOSS ~50h^{-3}Gpc^3

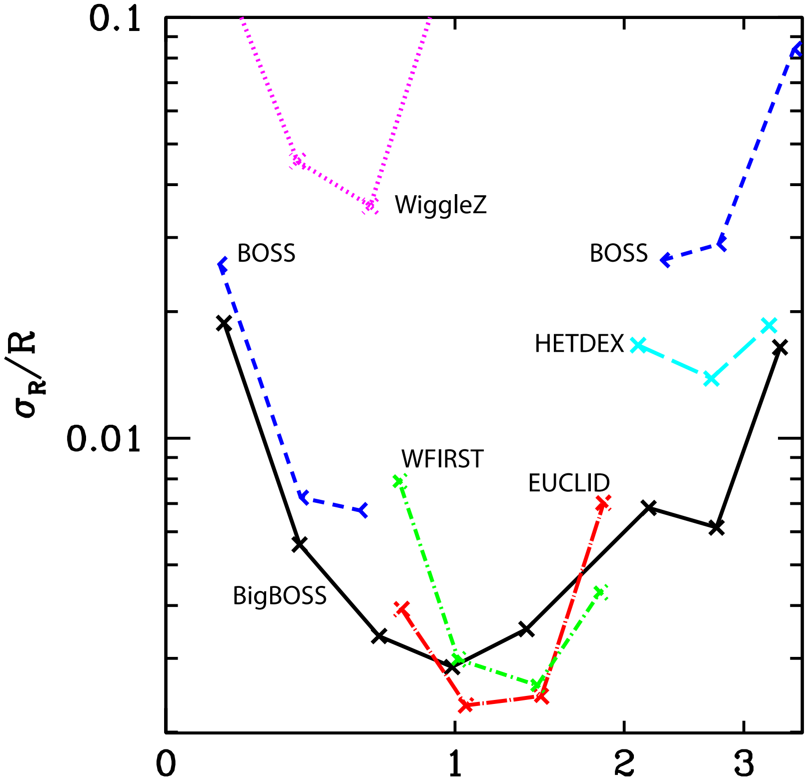


~5 µm resolution

~12 mm actuator pitch

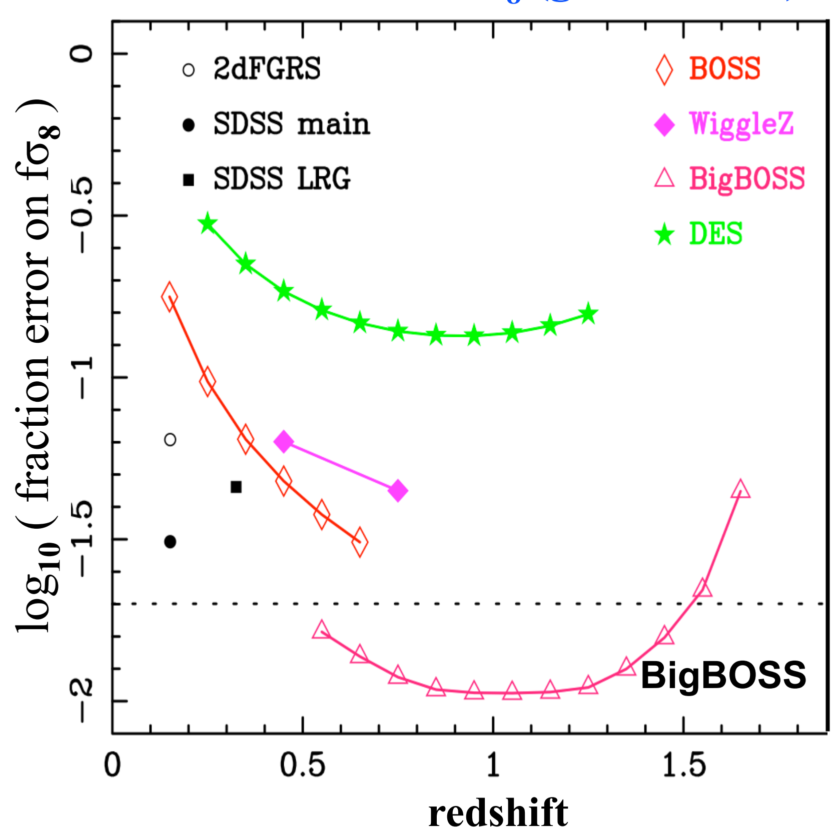
BigBOSS

Sub-1% distance error



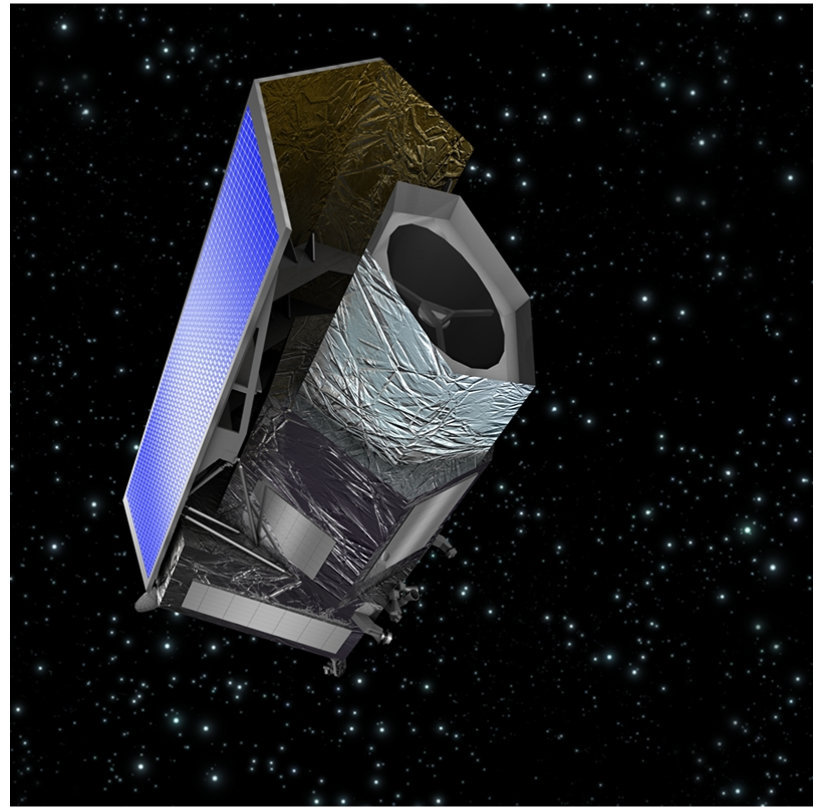
NASA WFIRST Science Definition Team

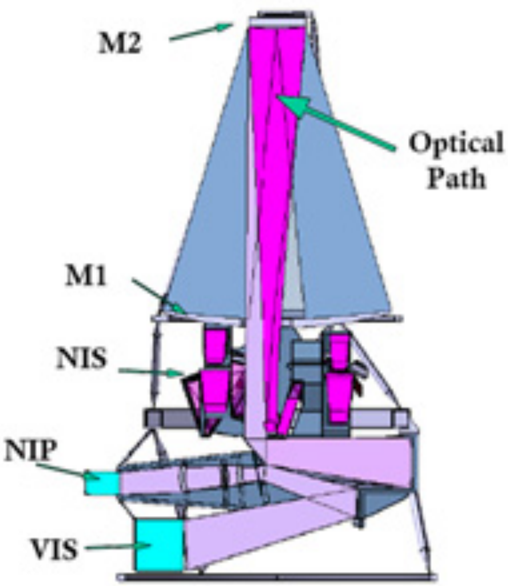
~1% error on $f\sigma_8$ (growth rate)



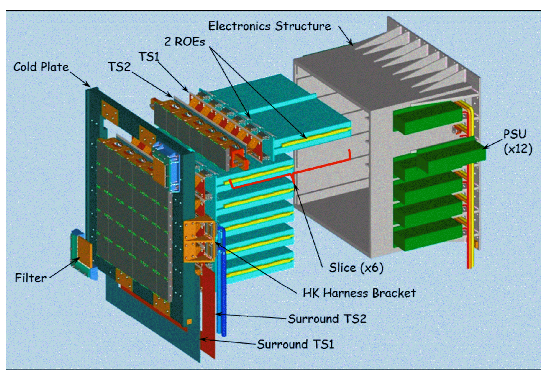
EUCLID

1. 1.2 m telescope
2. Visible imager (VIS), NIR photometry, low resolution NIR spectroscopy R~250 to 0.7<z<2.1
3. Visible m~24.5, NIR m~24
4. Shapes for ~1.5 B galaxies
5. Low resolution spectra for ~50 M galaxies to 0.7<z<2.1
6. Will cover 15,000 deg^2 in 6 years

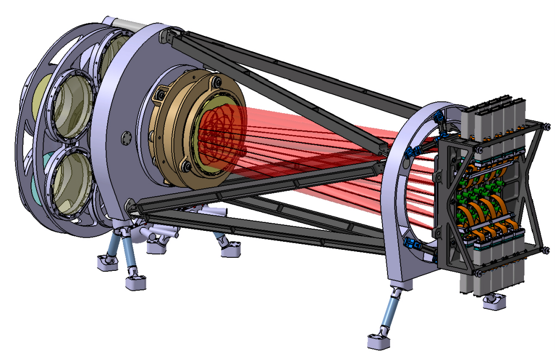




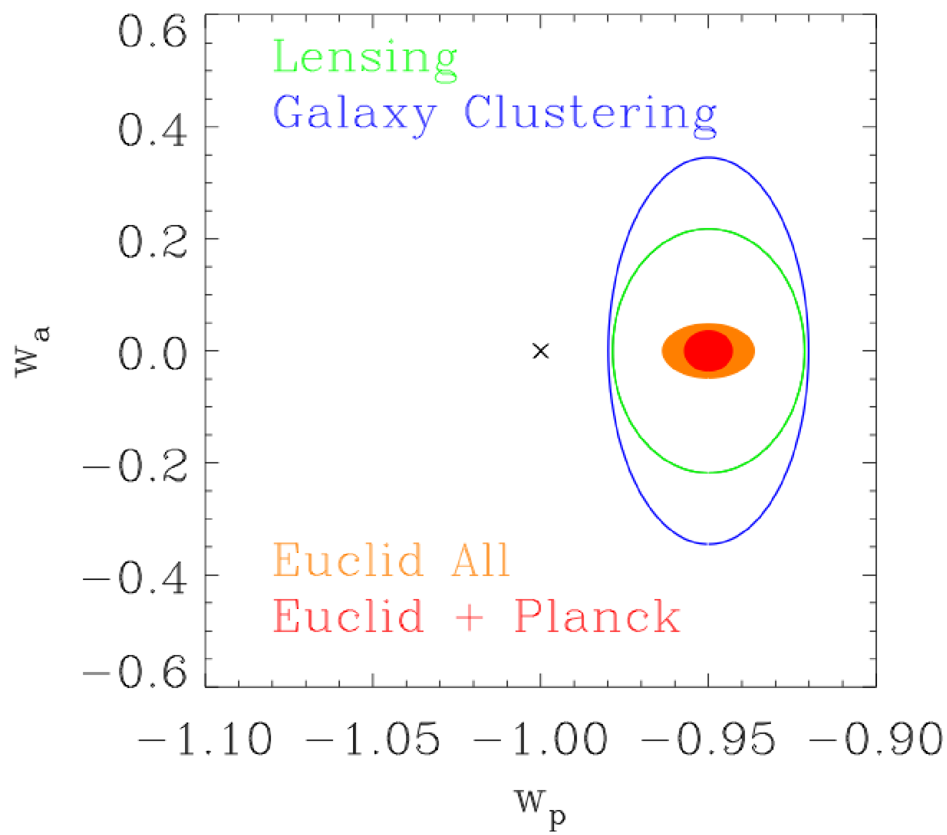
VIS



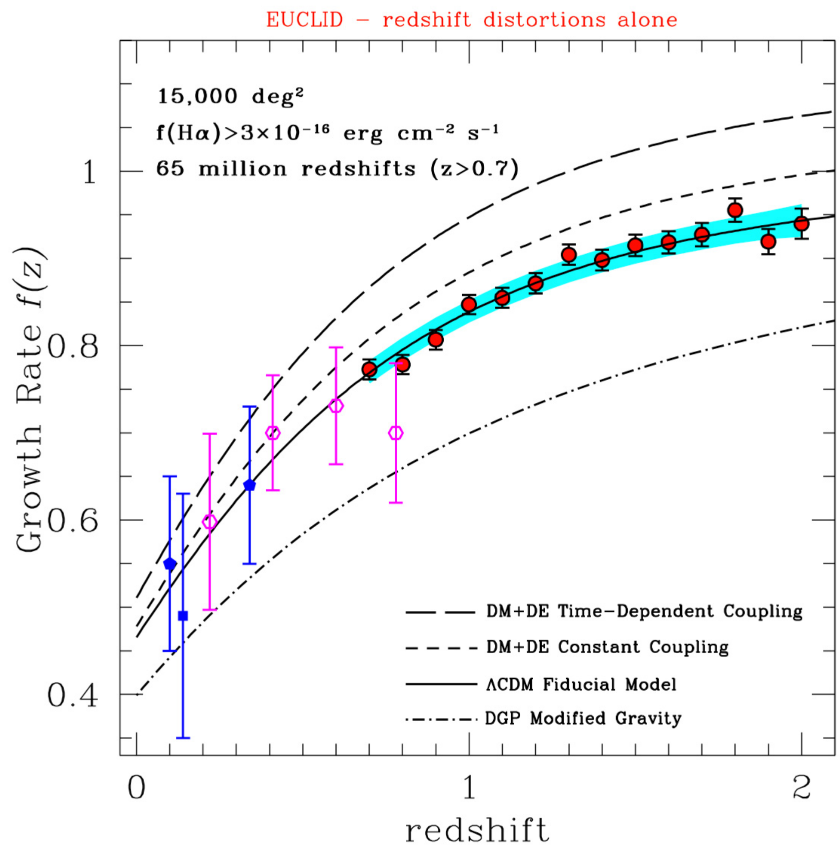
NISP



EUCLID



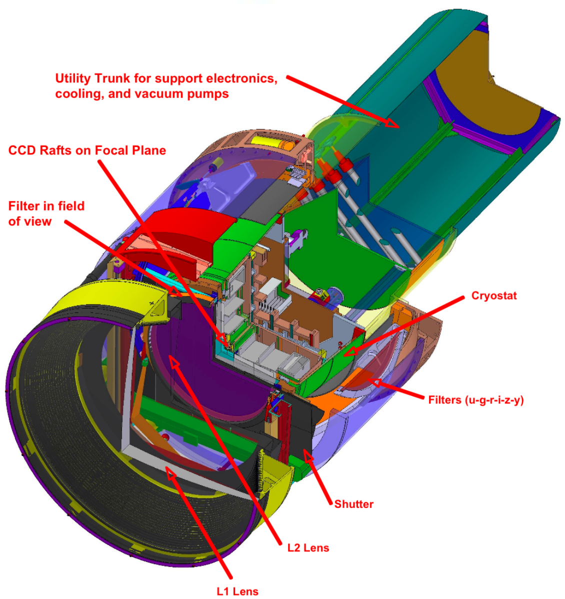
Lensing
Galaxy Clustering
Euclid All
Euclid + Planck
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−1.10 −1.05 −1.00 −0.95 −0.90
w_a
w_p

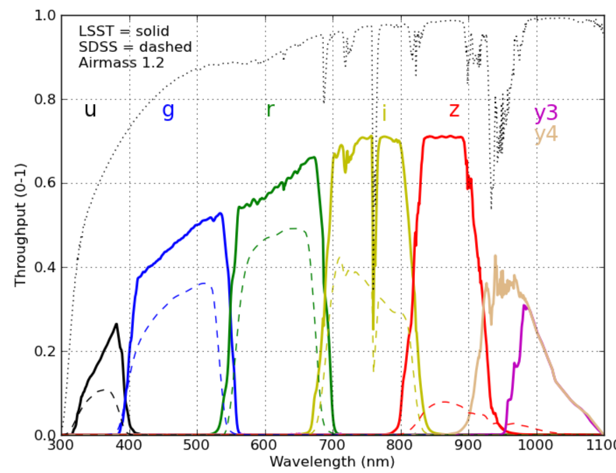


EUCLID − redshift distortions alone
15,000 deg²
f(Hα)>3×10⁻¹⁶ erg cm⁻² s⁻¹
65 million redshifts (z>0.7)
Growth Rate f(z)
redshift
1
0.8
0.6
0.4
0
1
2
DM+DE Time−Dependent Coupling
DM+DE Constant Coupling
ΛCDM Fiducial Model
DGP Modified Gravity

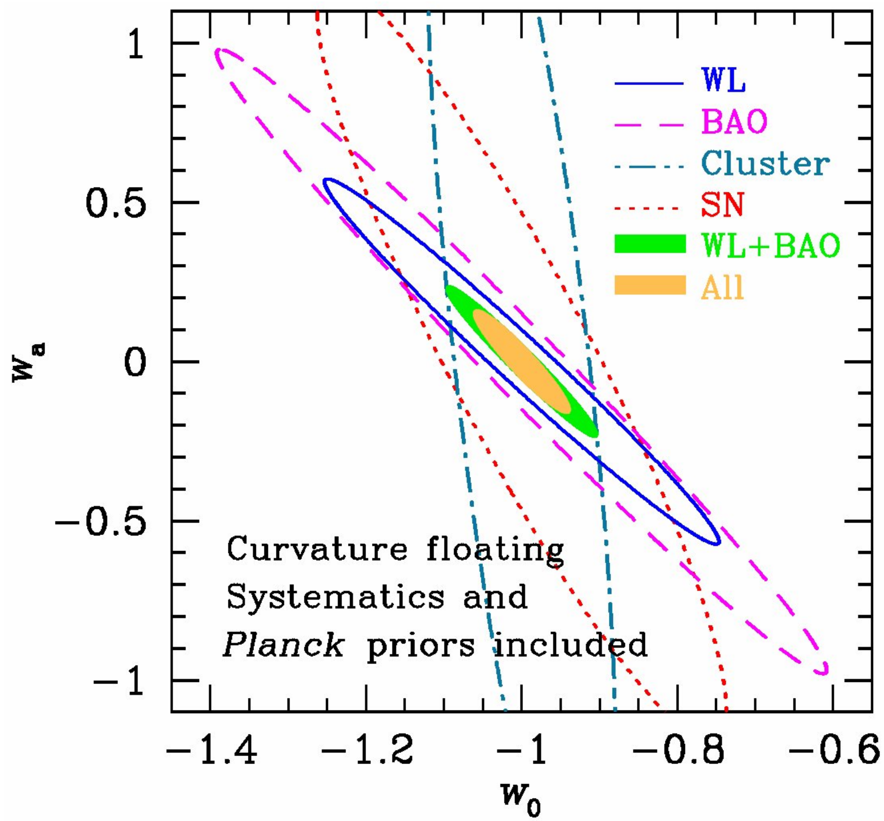
LSST

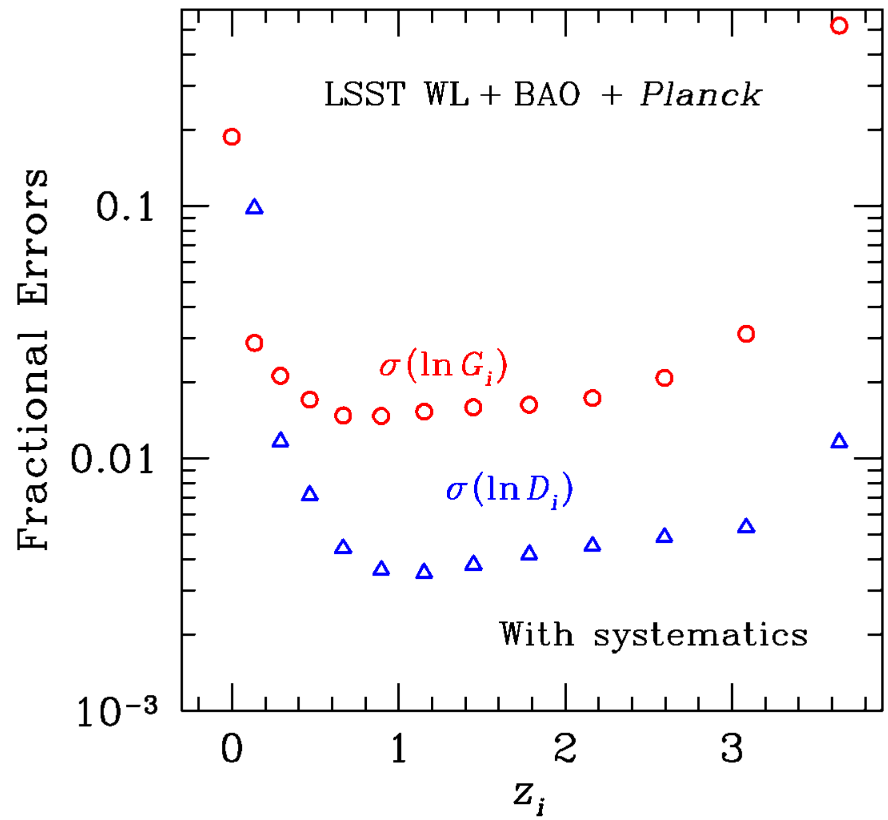
1. ~8 m telescope
2. 6 filter for visible photometry
3. Reach up to magnitude ~27.5
4. Will cover 20,000 deg^2 in 10 years.
5. Will measure ~20 B galaxies





LSST





D_i = co-moving distance
G_i = growth rate

What do we do in the decade 2020-2030?

Situation after DES, MS-DESI (BigBOSS), EUCLID, Panstars … :

- About 15,000 deg^2 of the sky will have been imaged to magnitude of 24-24.5. This will give about 1.5 billion galaxies.
- High resolution spectroscopy will exists for about 25 million galaxies and about 0.5-1. M QSO. Low resolution NIR spectroscopy will exists for about 50 M galaxies.

Situation during/after LSST:

- Imaging will improve by an order of magnitude. About 20,000 deg^2 of the sky will be imaged to magnitude of about 27.5. This will give about 10 billion galaxies.
- But no big improvement in spectroscopy that I know off.

So we may ask the question: can we get high or low spectroscopy for most of the LSST galaxies up to magnitude ~24.5 ?

Can we scale spectrographs like BigBOSS/DESpec?

1. Scaling from magnitude 22.5 to 24.5 requires an increase in the number of photons by a factor of 40. This can not be done by increasing the exposure time. Going to an 8 m telescope will still leaves us short of a factor of 10. Reducing R may help but not by much, so this looks difficult.

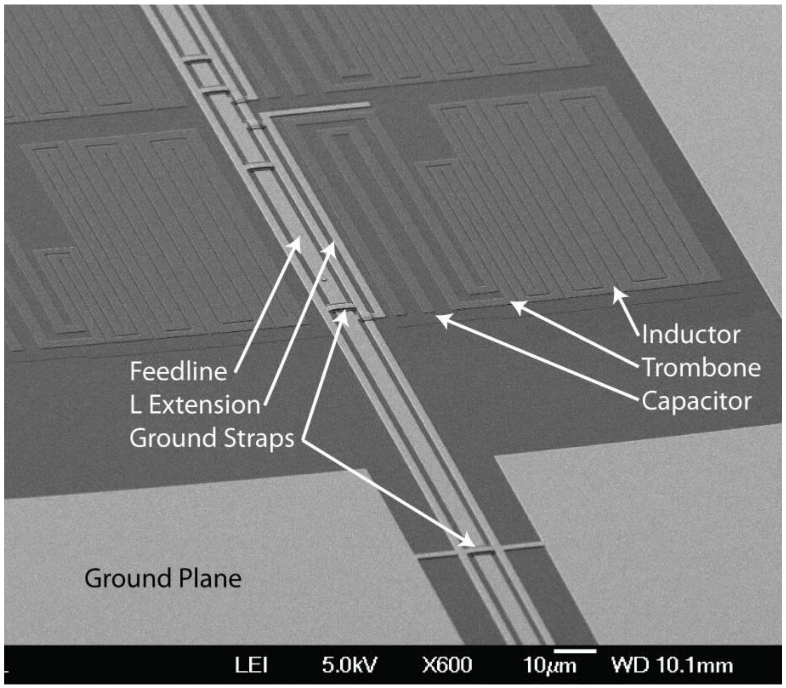
2. Right now with 4000-5000 fibers DESpec/BigBOSS measure 1500-1800 objects per deg^2 out of the 10,000 available.

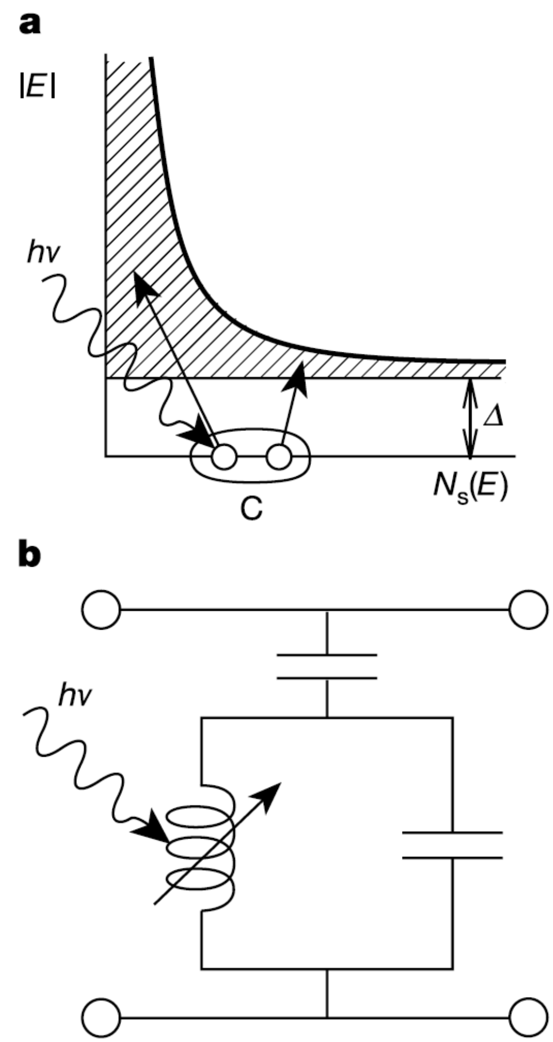
3. At magnitude 24.5 one has about 100,000 galaxies/deg^2, doing spectroscopy on half of them will require 30 times the number of fibers and 2 mm pitch between fibers. To me that kind of scaling doesn't look doable with current technology.

Can MKIDs provide a way out of this problem?

What are MKIDs ?

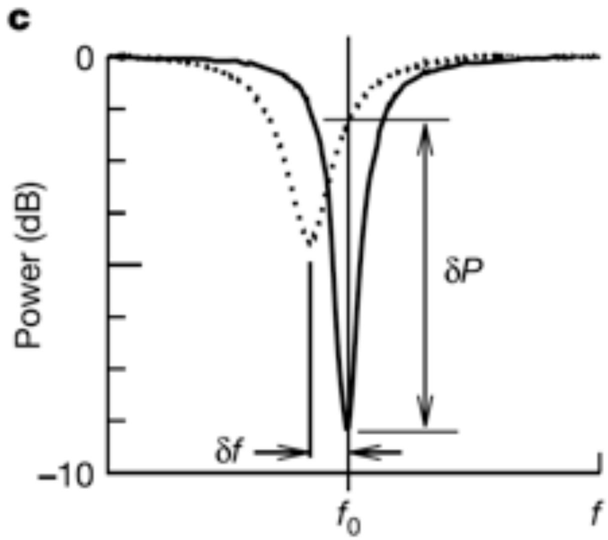
MKIDs = Microwave Kinetic inductance Detector (or a superconducting resonator)

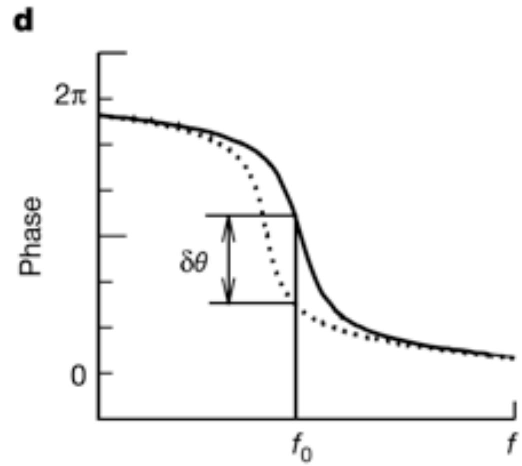




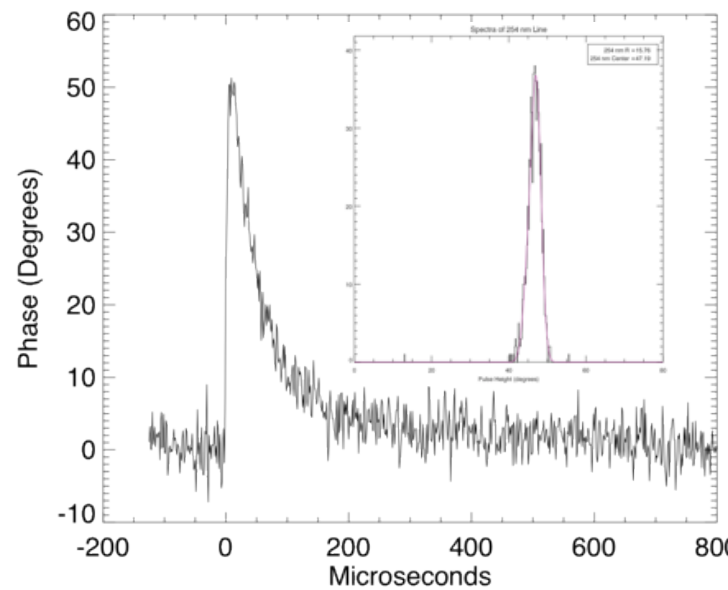
1. A photon strikes the superconductor breaking a few thousand Cooper pairs.
2. The broken Cooper pairs change the inductance of the resonator.

MKIDs (superconducting resonators)



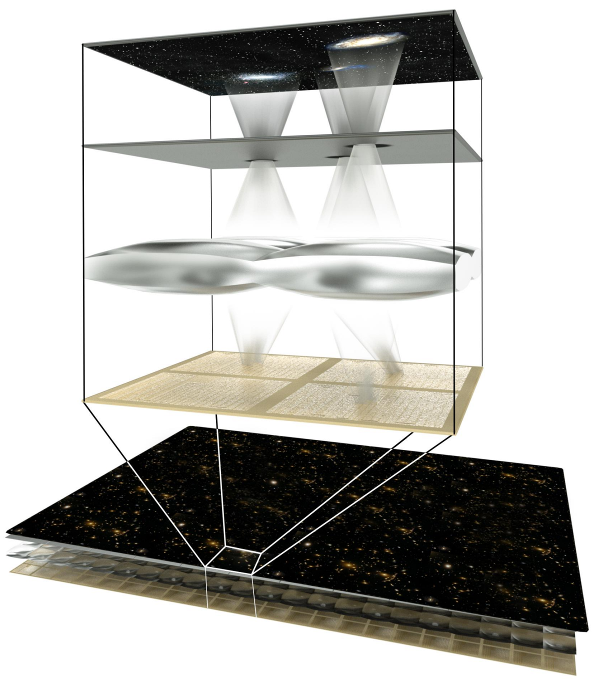


3. The resonance frequency and phase change due to the change in inductance.
4. The phase change is measured providing a time and energy measurement for each photon.
5. The theoretical energy resolution is about R=λ/Δλ≈100
6. Up to about 2000 resonators could be coupled to the same feed line.

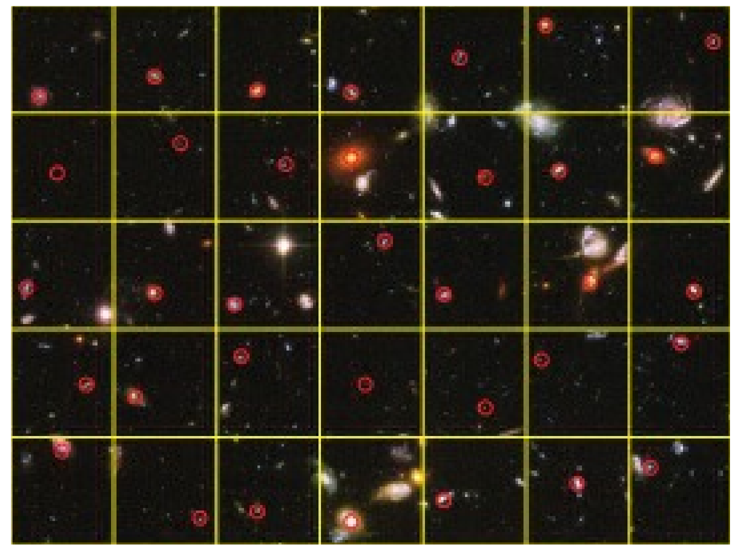


Giga-Z, a low resolution multi-object spectrograph

(See B. Mazin et al. in the SPIE Proceedings, July 2012)



Galaxies are projected on an array of 100,000 MKIDs+microlense array (~0.7 deg^2). A mask selects a galaxy in each pixel. The readout consists of about 100 feed-lines.



A 1” mask (red circles) in each of the 10” pixels is superimposed over a Hubble UDF image.

What can Giga-Z do if it works as expected?

1. In a 4 (8) m telescope it could go up to magnitude 24.5 (25.7), covering 20,000 square degrees in 3 years (7 year run).
2. It could provide a redshift resolution equivalent to a distance resolution of ≈15 Mpc, good enough to be into the non-linear regime of GR.
3. It will cover most of the available galaxies/deg^2 up to magnitude 24.5. That is about 100,000 galaxies per square degree for a total of about 2 (4) billion galaxies.

What are the problems that need to be solved?

The list is daunting but we believe doable:

1. R has to get closer to the theoretical limit.
2. The packaging need to be greatly improved.
3. The RF electronics needs improvement.
4. A flat RF cable suitable to work at 100 mK needs to be developed.
5. It will help to improve the QE.

The End

Galaxy numbers as a function of magnitude

DES goes to magnitude 24, BigBOSS/DESpec to 22.5, EUCLID to magnitude 24 and LSST to magnitude 27.

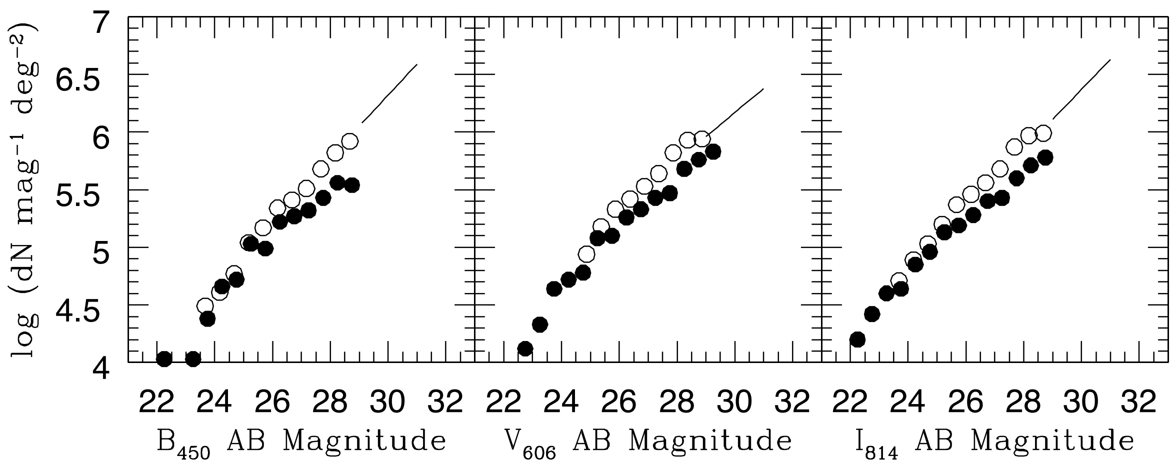


FIG. 7.—Plot of $n(m)$ final results in the F450W, F606W, and F814W filters. Filled circles represent Williams et al. (1996) differential number counts, and open circles show the results from Metcalfe et al. (2001). The solid line represents the obtained faint end (fainter than magnitude 28.8) of $n(m)$. The obtained $n(m)$ function is valid down to a magnitude of 31 at least.

A. Marín-Franch and A. Aparicio, ApJ 594, 63, 2003.

Astro, RSD

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 5058–5067
doi:10.1098/rsta.2011.0370

Review

Redshift-space distortions

By Will J. Percival*, Lado Samushia, Ashley J. Ross, Charles Shapiro and Alvise Raccanelli

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Review. Redshift-space distortions