Late Universe Cosmology: The Physics of Dark Energy

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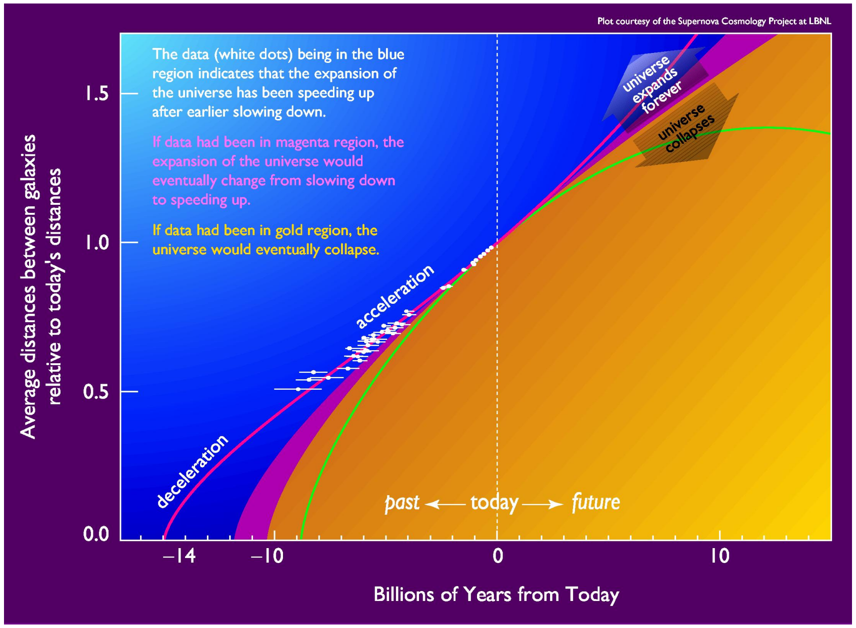
The Physics of Dark Energy

- The acceleration of the cosmic expansion for a homogeneous and isotropic universe is given by the equation:

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

- For a NR gas, P ~ 0. For radiation, P = ρ/3. In both cases, the universe should be decelerating if there is no cosmological constant.

- Positive acceleration can occur for a non-zero value of Λ, or for an energy field with negative pressure. The so-called equation of state parameter: *w* = *P/ρ,* must be < -1/3.



Plot courtesy of the Supernova Cosmology Project at LBNL

The data (white dots) being in the blue region indicates that the expansion of the universe has been speeding up after earlier slowing down.

If data had been in magenta region, the expansion of the universe would eventually change from slowing down to speeding up.

If data had been in gold region, the universe would eventually collapse.

The Physics of Dark Energy

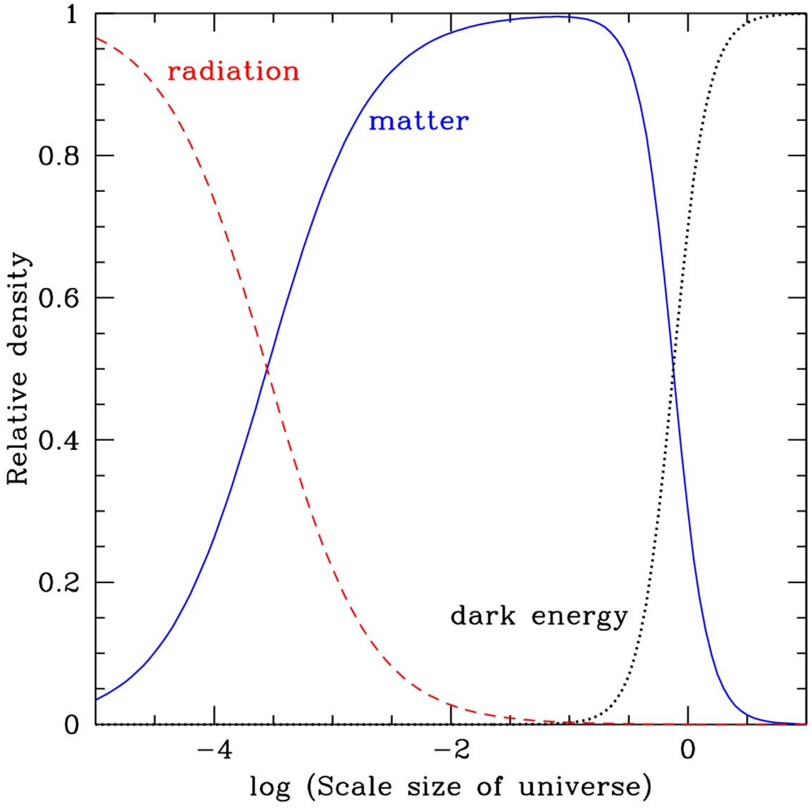
- The existence of dark energy poses a major problem for modern theoretical physics.

- Quantum field theory predicts a cosmological constant due to vacuum modes, unless the expansion is truncated at some mass scale. Truncation at the Planck scale yields a value of Λ 120 orders of magnitude larger than observed. Truncation at the TeV scale only reduces the problem by 60 orders magnitude.

- Supersymmetry can eliminate the cosmological constant, since fermion modes cancel boson modes. But it is difficult to get a small but non-zero value of Λ from such theories. The relevant mass scale for the observed value of Λ is in the meV range. We thought we understood physics in that energy range!

The Physics of Dark Energy

- Especially puzzling is the "why now" problem.
- The energy density in radiation drops like a^{-4}. The energy density in matter drops like a^{-3}. The energy density in Λ is constant.
- It is incredibly unlikely that we should be living in an era when the energy density in matter is comparable to that dark energy.
- This suggests that although the standard ΛCDM cosmological model works very well, there must be some new physics lurking behind it!



Constraining Dark Energy

- The only observational handle that we have for unambiguously understanding the properties of dark energy is the expansion history of the universe itself. This is parametrized by the Hubble parameter:

$$H(z) = \frac{\dot{a}}{a}$$

- Cosmic distances are proportional to integrals of H(z)$^{-1}$ over redshift. We can constrain H(z) by measuring luminosity distances of standard candles (Type 1a SNe), or angular diameter distances of standard rulers (baryon acoustic oscillations).

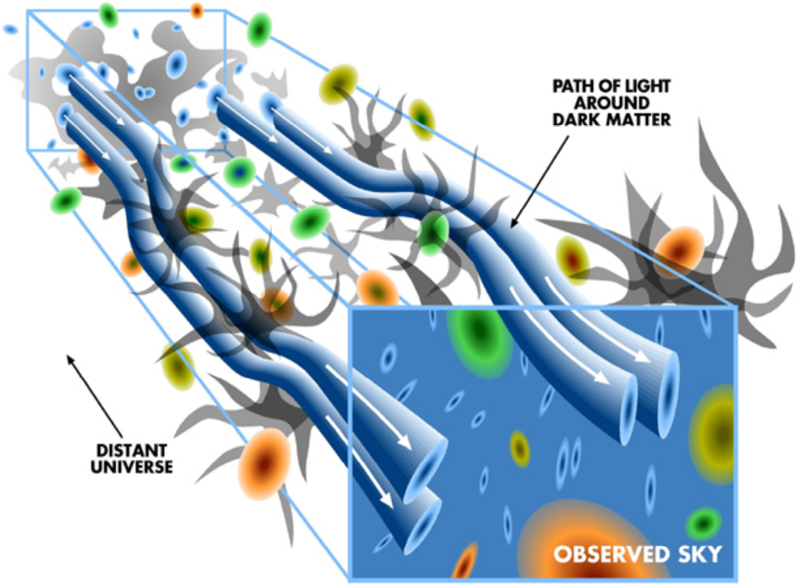
- Another powerful approach involves measuring the growth of structure as a function of redshift. Stars, galaxies, clusters of galaxies grow by gravitational instability as the universe cools. This provides a kind of cosmic "clock" - the redshift at which structures of a given mass start to form is very sensitive to the expansion history.

Cosmic Shear

- The term "cosmic shear" refers to the systematic and correlated distortion of the appearance of background galaxies due to weak gravitational lensing by the clustering of dark matter in the intervening universe.

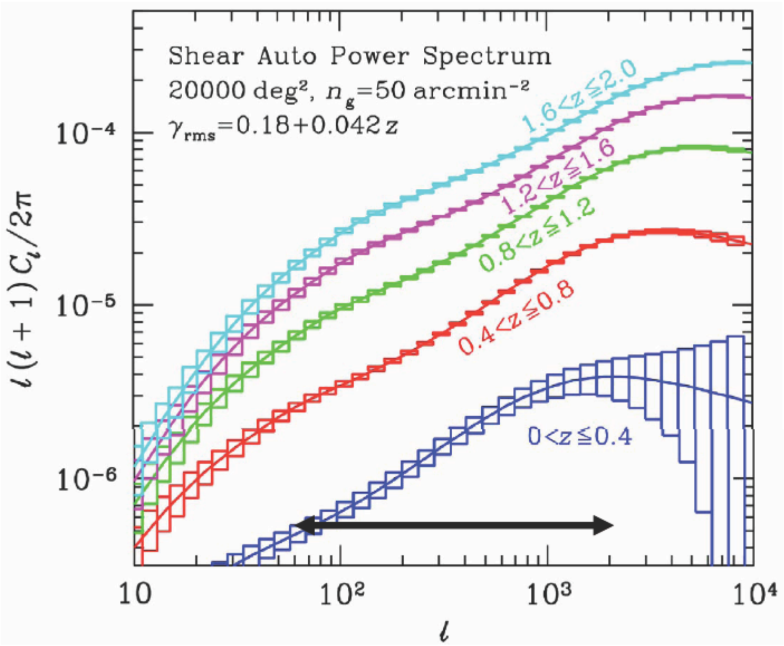
- As light from background galaxies passes through the intergalactic medium, it gets deflected by gravitational potentials associated with intervening structures. A given galaxy image is both displaced and sheared.

- The effect is detectable only statistically. The shearing of neighboring galaxies is correlated, because their light follows similar paths on the way to earth.



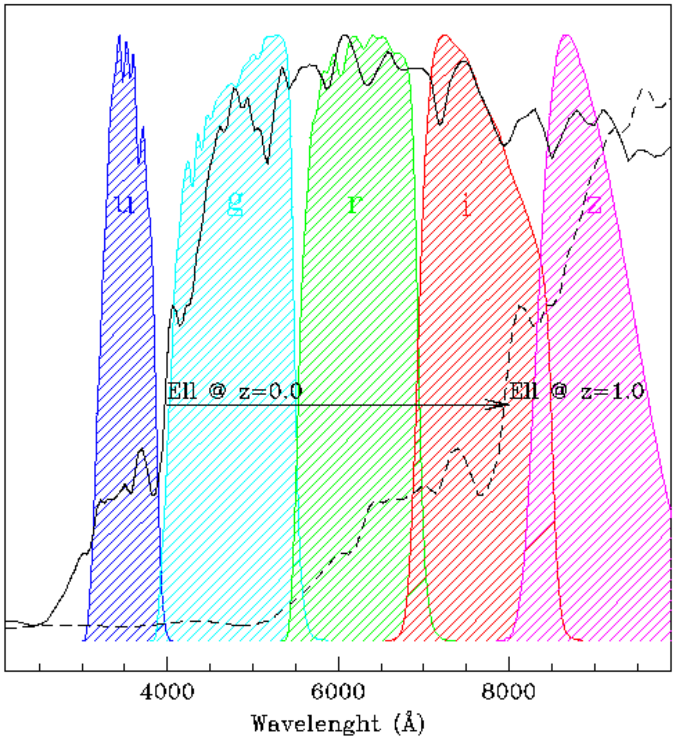
Cosmic Shear

- The simplest measure of cosmic shear is the 2-pt correlation function measured with respect to angular scale.
- This is usually plotted as a power spectrum as a function of multipole moment (similar to the CMB temperature maps).
- Note the points of inflection in these curves. This is a transition from the linear to the non-linear regime.
- The growth in the shear power spectrum with the redshift of the background galaxies is very sensitive to H(z). This provides the constraints on dark energy.



Photometric Redshifts

- Galaxies have distinct spectra, with characteristic features at known rest wavelengths.
- Accurate redshifts can be obtained by taking spectra of each galaxy. But this is impractical for the billions of galaxies we will use for the next generation of cosmic shear studies.
- Instead, we use the colors of the galaxies obtained from the images themselves. This requires accurate calibration of both the photometry and of the intrinsic galaxy spectra as a function of redshift.



Cosmic Shear - Dealing with Systematics

- The cosmic shear signal on larger angular scales is at a very low level.

- To make this measurement, we must be confident that we understand and can remove spurious sources of shear. These can arise in the atmosphere or in the optics of the telescope and camera.

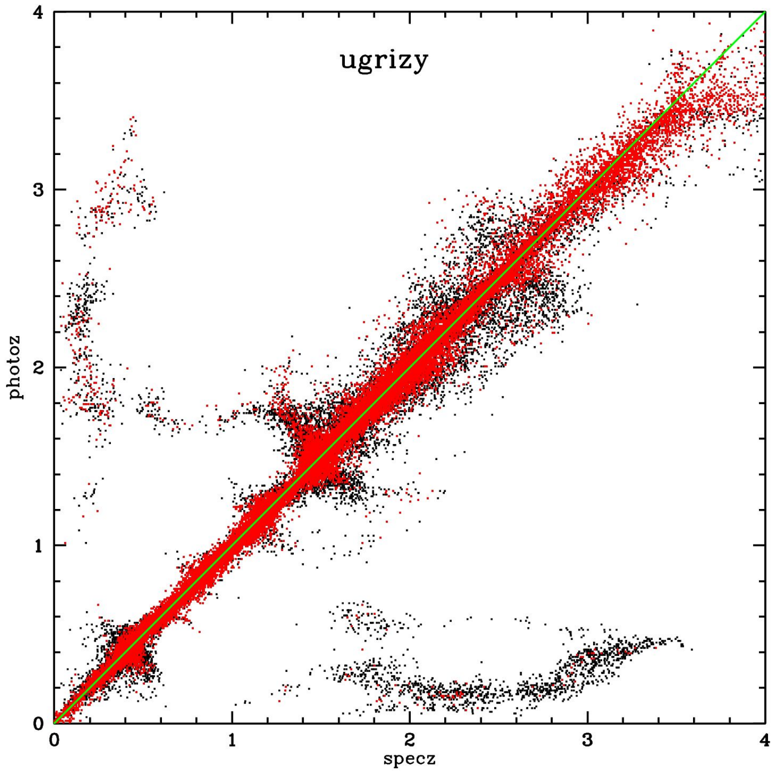
- Fortunately, the sky has given us some natural calibrators to control for PSF systematics: There is one star per square arcmin bright enough to measure the PSF in the image itself. Light from the stars passes through the same atmosphere and instrumentation, but is not subject to weak lensing distortions from the intergalactic medium. By interpolating the PSF' s, we can deconvolve spurious shear from the true cosmic shear signal we are trying to measure. The key issue is how reliable is this deconvolution at very low shear levels.

Systematics in Photo-z's

- Photometric redshift accuracy is limited by the statistical quality of the data and by the location of the key spectral features with respect to the passbands which are used.

- The dominant features are the Balmer and Lyman breaks at 400 nm and 91 nm, respectively. As these move through the bands, the noise in the photo-z inversion rises and falls.

- There can also be catastrophic failures due to multiple minima associated with confusion between these two features.

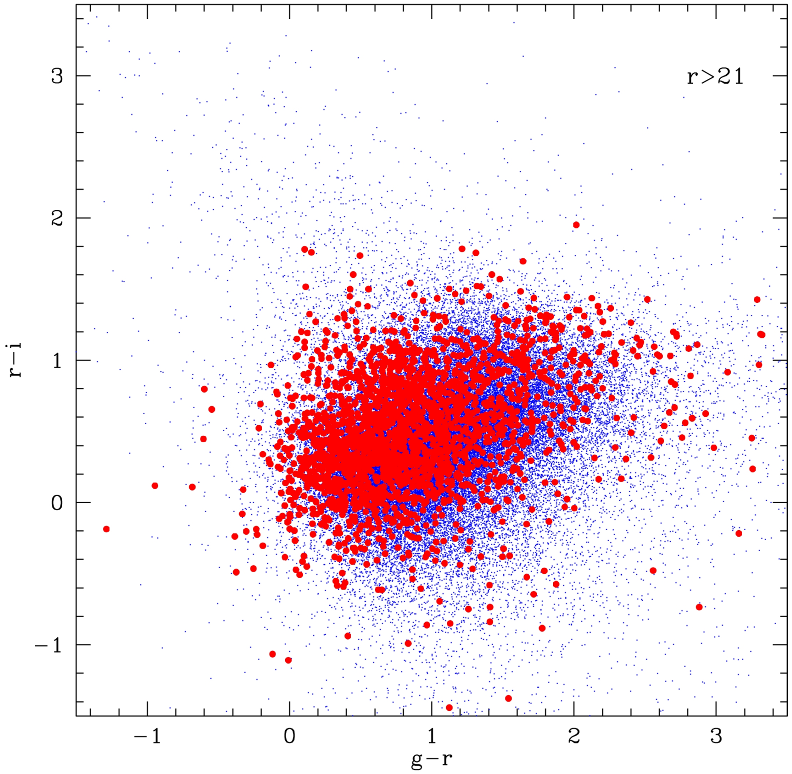


Systematics in Photo-z’s

- There are various statistical issues that can be investigated using Monte Carlo techniques to quantify the impact of photo-z errors on dark energy parameter estimations. Priors on size and mag can help to reduce the catastrophic failutres.

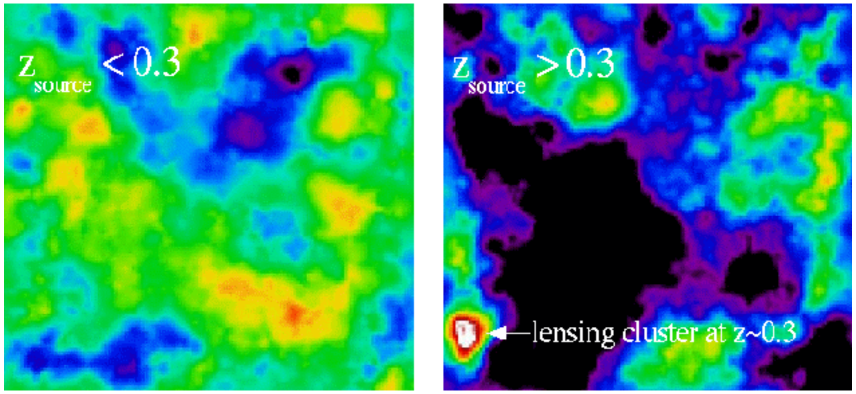
- But we are still left with the fundamental issue of calibration, since we don’t know the distribution of intrinsic galaxy spectra at higher redshifts.

- Brute force calibration would require an enormous number of spectroscopic measurements. Fortunately, it appears that making use of the intrinsic clustering properties of galaxies can reduce this number to a manageable level.



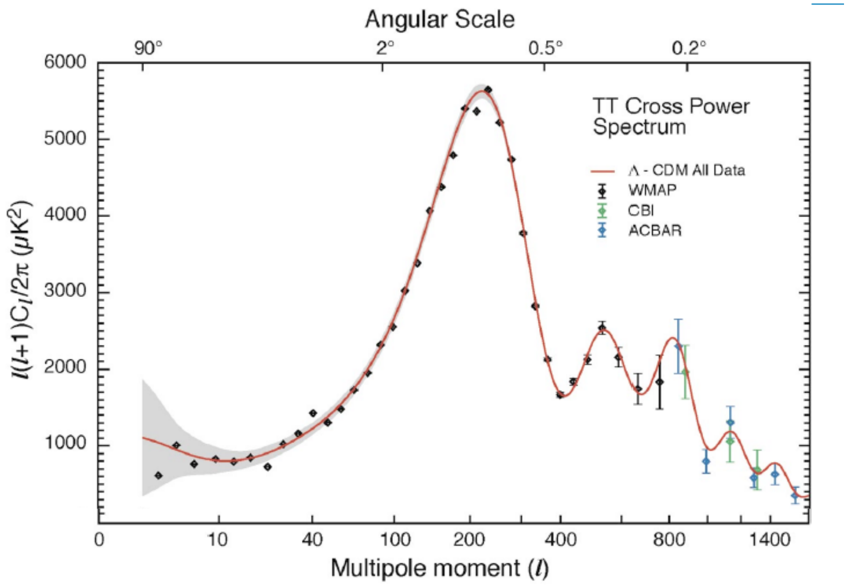
Clusters of Galaxies

- Clusters of galaxies are the most massive bound structures in the Universe, and both their number density and spatial power spectrum are sensitive to the growth of structure.
- Clusters can be detected via galaxy counts, the X-ray emission produced by hot gas trapped in the cluster potential well, or inverse Compton scattering of CMB photons due to the hot gas (the Sunyaev Zeldovich effect).
- They can also be detected directly via the weak and strong lensing signals. However, all of these techniques have systematics associated with them, and must be accurately calibrated.



Baryon Acoustic Oscillations

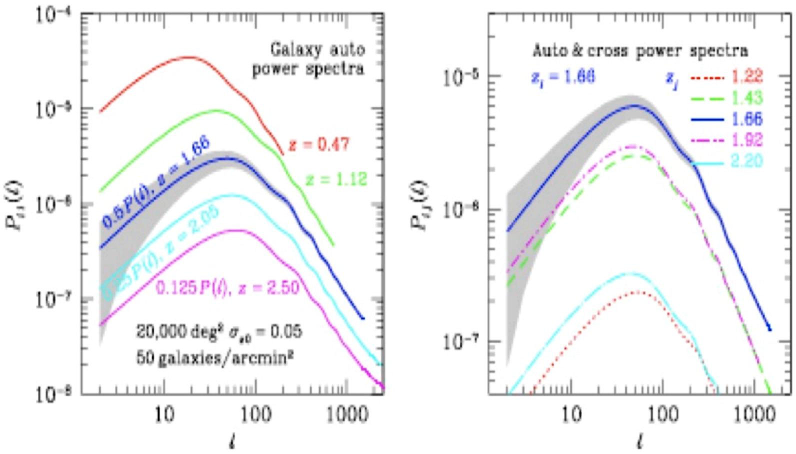
- Prior to recombination, the baryons are tightly coupled to the radiation in the universe.
- An overdensity perturbation gives rise to an acoustic wave in this tightly coupled fluid, which propagates outward at the sound speed, $c/\sqrt{3}$.
- After recombination, the matter and radiation decouple. The sound speed drops to zero, and the propagating acoustic wave stops.
- This gives rise to a characteristic scale in the universe: 150 Mpc, the distance the sound waves have traveled at the time of recombination.



These acoustic waves are visible as the peaks in the CMB power spectrum.

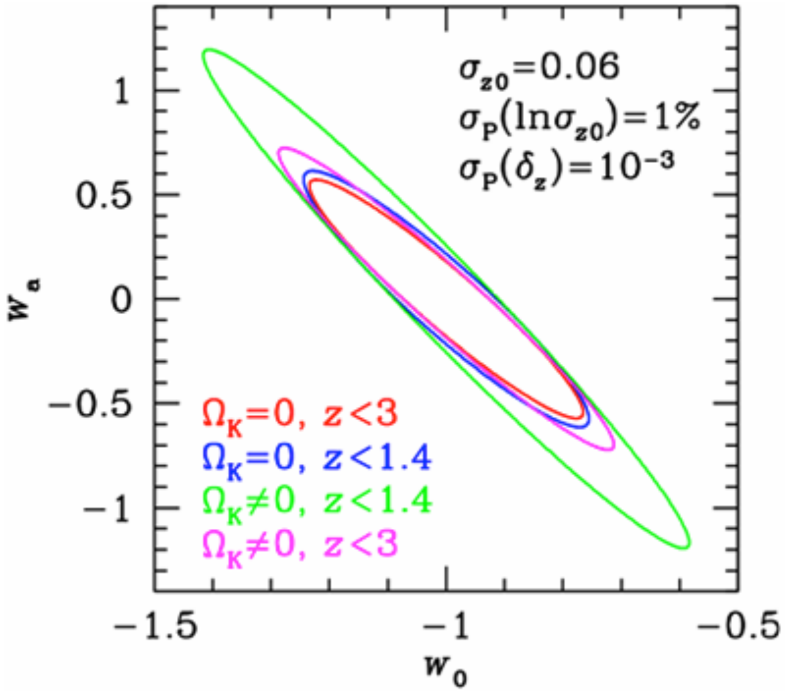
Baryon Acoustic Oscillations

- Following recombination, gravitational instability causes the birth of stars and galaxies.
- The gravitational coupling between the dark matter and the baryons creates an imprint of these acoustic oscillations in the galaxy distribution.
- This persists as the universe expands, although it gets weaker with time.
- The effect can be measured in the power spectrum of the galaxy distribution.



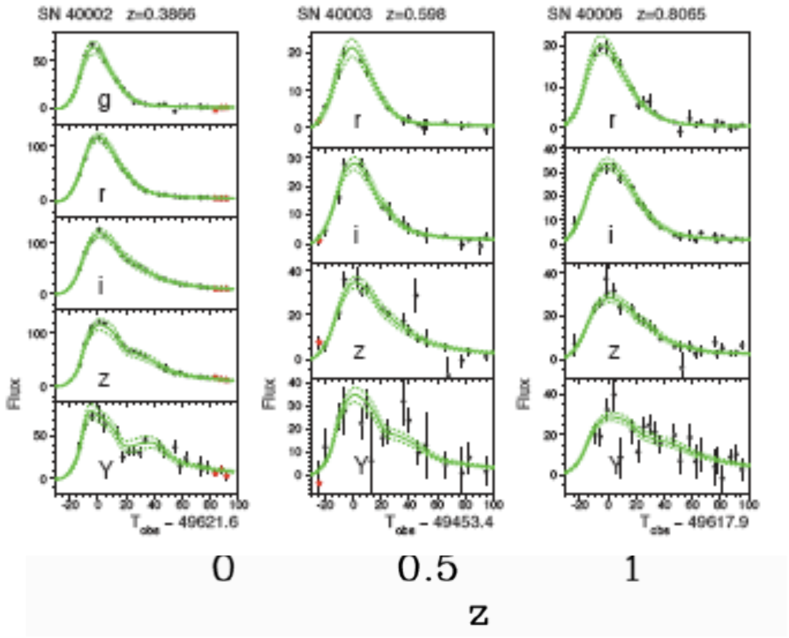
Baryon Acoustic Oscillations

- Since the physical scale is known precisely, the angular scale of the measured peaks provides an angular diameter redshift relation.
- The "new" feature introduced by measurement of the BAO's is the ability to constrain the expansion history at higher redshift, before DE became dominant.
- This is important for breaking the degeneracy between non-zero curvature and alternate forms of dark energy. Allowing Ω_K to depart from zero, weakens constraints on w and w_a.



Type 1a Supernovae

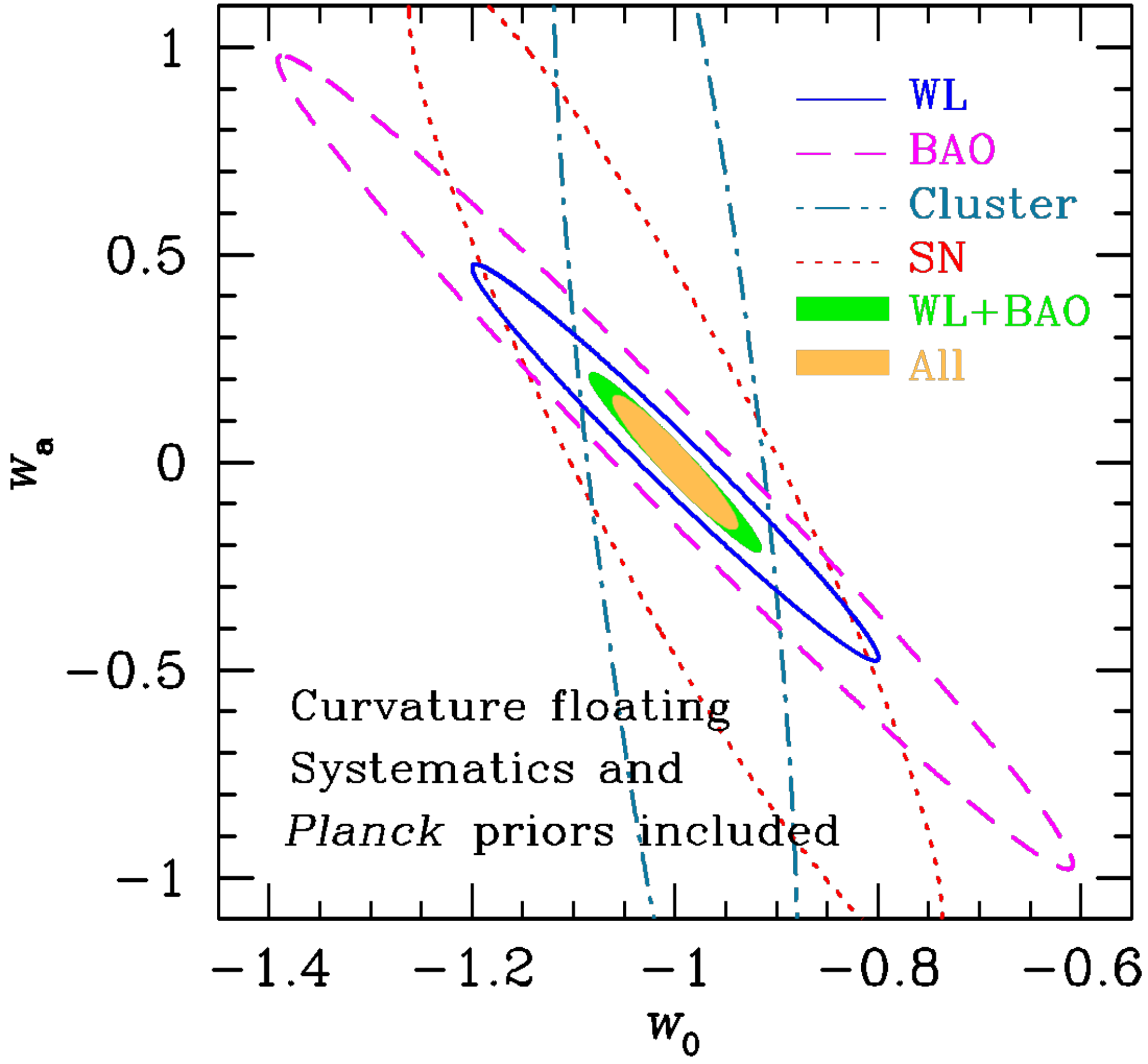
- Type 1a SNe are believed to be calibratable standard candles
- Follow-up spectroscopy, or accurate measurement of their light curves in multiple color bands can lead to a determination of their redshifts.
- The absolute magnitude/redshift relation then provides a constraint on dark energy.
- This technique led to the discovery of DE in the late 90's. Current SN cosmology, however, is limited by systematic effects associated with absolute calibration, and possible astrophysical selection effects that might couple to cosmic distances.



The Large Synoptic Survey Telescope

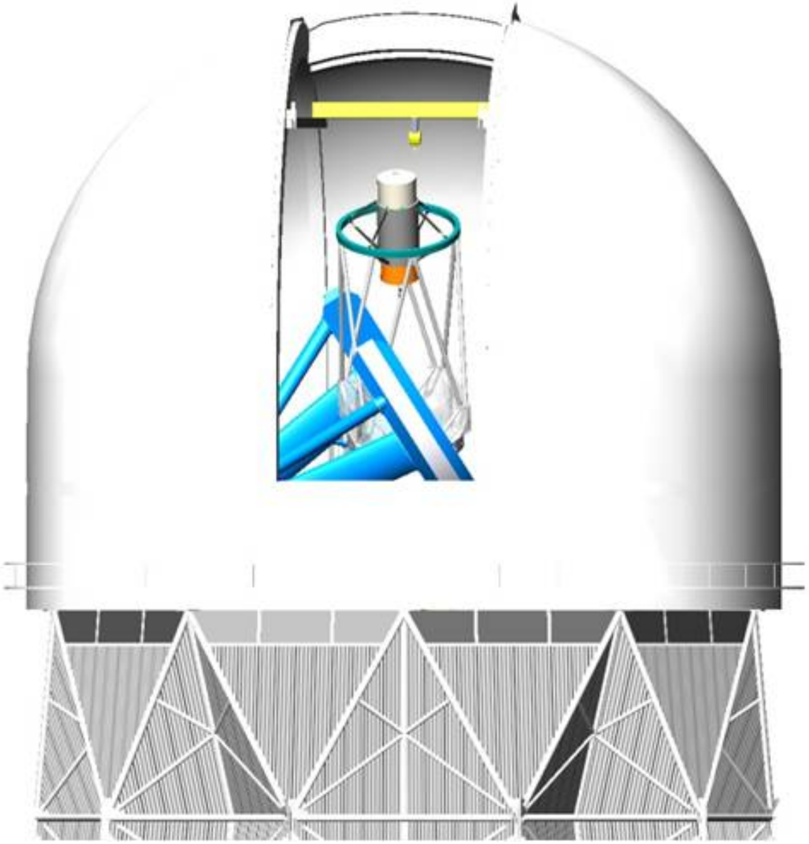
- LSST is a large-aperture, wide-field, ground-based telescope that will survey the entire southern hemisphere in six color bands.
- Over ten years of operation, LSST will measure the shapes, colors, and magnitudes of over 4 billion galaxies, and detect several million Type 1a SNe. It will enable tight constraints on dark energy to be derived using all of the probes discussed above.
- LSST is currently under construction with funding from both NSF and DOE. The ten-year survey is scheduled to begin in October, 2022.

LSST Precision on Dark Energy Parameters

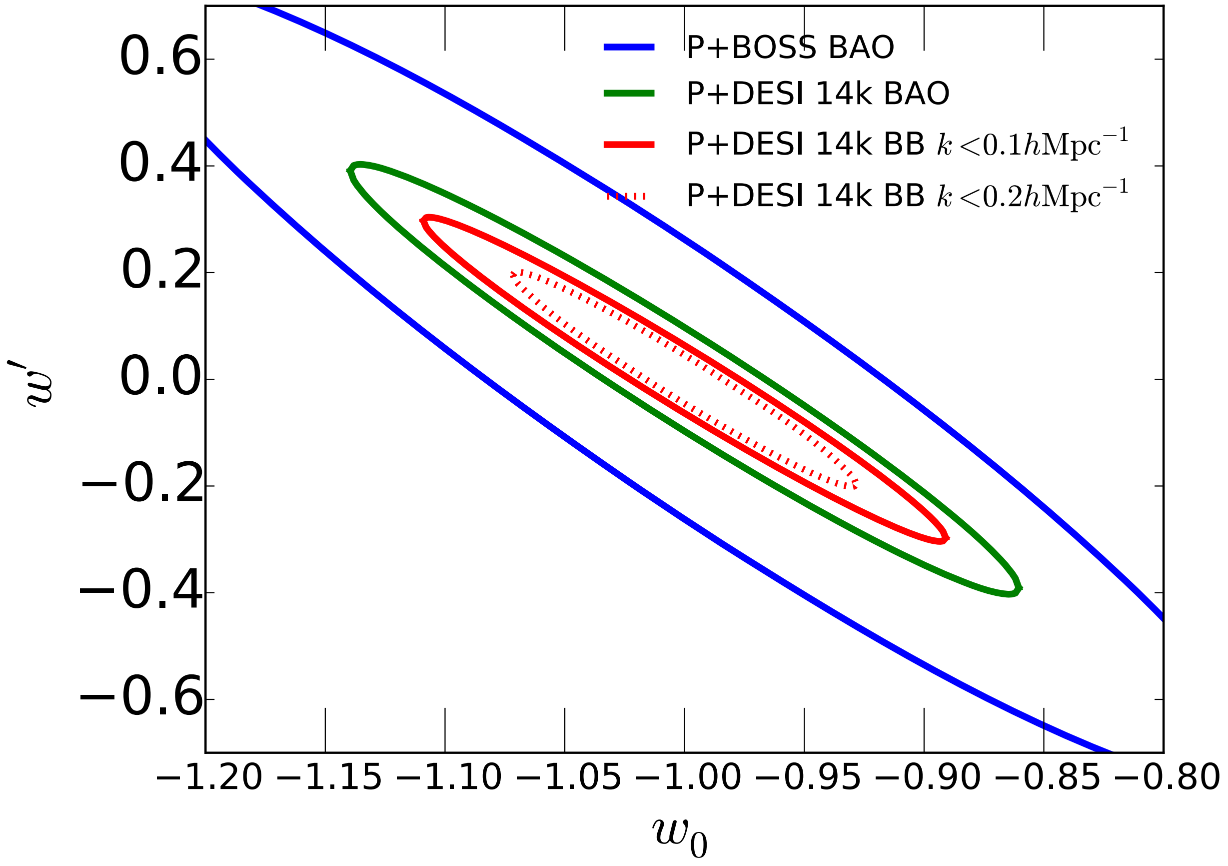


The Dark Energy Spectroscopic Instrument

- DESI is a large multi-object spectrograph that will be implemented on the Mayall 4-m telescope at Kitt Peak National Observatory.
- It will obtain tens of millions of spectra of galaxies and quasars, yielding a 3D map of the universe out to 10 billion lt-yrs.
- DESI will constrain the properties of DE from a direct measure of baryon acoustic oscillations, and from redshift space distortions.



DESI Precision on Dark Energy Parameters



Future Instrumental Directions: Energy Resolving Imaging Detectors

- Current imaging surveys utilize optical filters to define the color bands. A given part of the field is only observed in a single color at any given time.

- The overall survey efficiency of the system is limited by lack of multiplexing. If color sensitivity can be built into the imaging sensor itself, then the system efficiency can be improved accordingly.

- One such approach utilizes a multi-layer CCD, where a polychromatic image sensor is fabricated on semiconductor-on-insulator substrates with multiple device layers, and separate sense nodes for each layer.

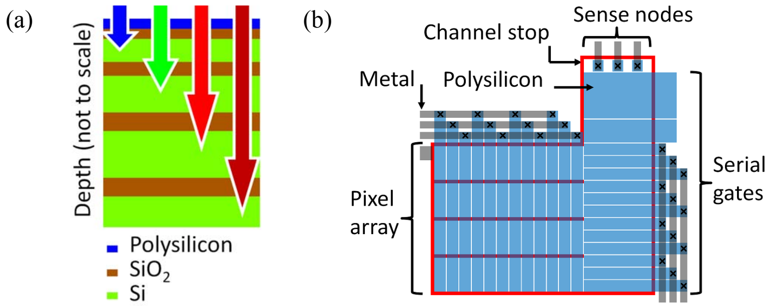


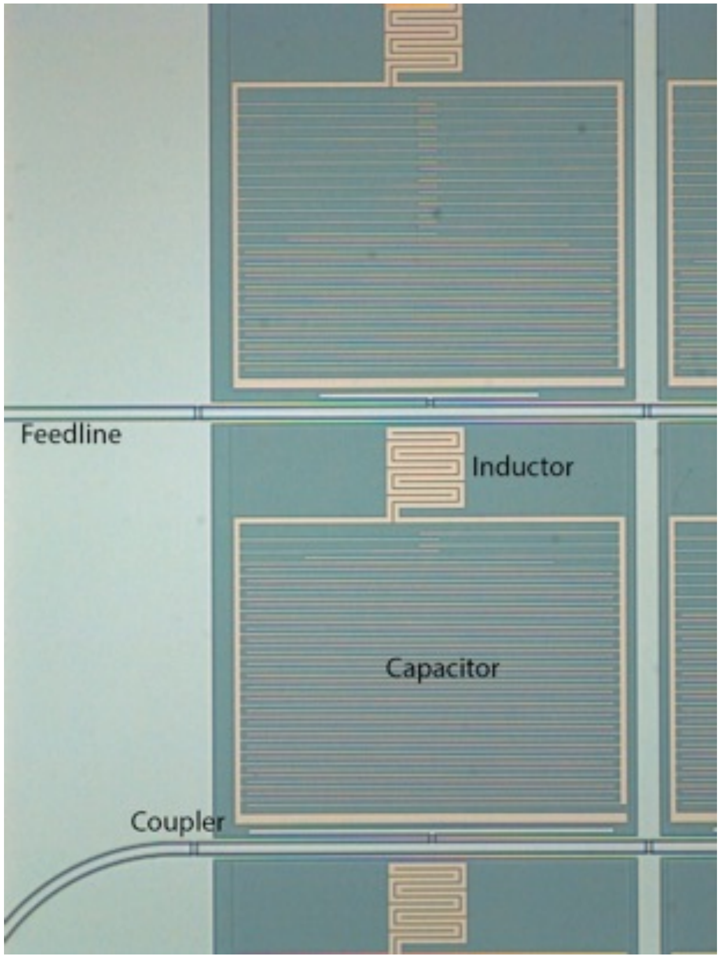
Fig. 1. SOI multiband CCD concept. (a) Each device layer in the SOI substrate interacts differently with different optical bands. (b) The layout is similar to that of conventional CCDs, except that a separate sense node is required to exclusively extract charge from each layer to avoid crosstalk. Charge collection and transfer for all layers are handled by the same set of gates that are on either the front or the back side.

From Chang et al. in press.

Future Instrumental Directions: Cryogenic Imaging Arrays

- Still higher intrinsic energy resolution can be achieved with cryogenic imaging arrays.
- These are single photon-counting devices operated at very low temperatures (< 100 mK). When a photon is absorbed, the deposited energy is detected as a heat pulse in an absorber or via quasiparticle excitations in a superconductor.
- There are several different approaches available: Transition Edge Sensors, Microwave Kinetic Inductance Detectors, or Superconducting Tunnel Junction devices. All have shown the capability for R ~ 10 or so in the optical band.
- At present, the primary limitation is on the size of the arrays that have been fabricated. Various multiplexing schemes are available, but current arrays are still ~ 10,000 times smaller than single CCDs or CMOS imagers.

From Mazin Lab webpage, UCSB



Future Instrumental Directions: 21-cm Cosmology

- The 21-cm line is the hyperfine transition in neutral hydrogen.

- Since hydrogen is by far the most abundant element in the universe, all natural transitions for hydrogen are very important for astronomy. The 21-cm line is especially important for two reasons:
  - Since it is a spin-flip transition, it has extremely low oscillator strength, which means that the line is not optically thick for typical column densities of hydrogen found in galaxies.
  - Since it is a very low energy line, its intensity is easily calculated statistically. Thus 21-cm measurements can be directly turned into measurements of hydrogen gas content.

- The line is at 1420 MHz, in the microwave regime, a relatively clean part of the spectrum in which to conduct radio observations.

- At zero redshift, 21-cm measurements have been crucial for mapping the spiral structure of the Milky Way (through both position and velocity), the hydrogen content of external galaxies, and for establishing rotation curves of external galaxies.

Future Instrumental Directions: 21-cm Cosmology

- 21-cm measurements at higher redshifts are tremendously interesting for cosmology:

- First, since this is a combined spectral and imaging measurement, 21-cm surveys provide true 3-dimensional maps of the universe. Galaxy redshifts are determined directly with the galaxy detections.

- 21-cm measurements can probe the so-called "dark ages", from the time of recombination until the so-called "epoch of reionization", when UV-light from the first stars and galaxies photoionized the gas and made the universe transparent. We know very little about the dark ages and EOR, so this is a prominent frontier for observational cosmology.

- For fundamental cosmology, 21-cm mapping can provide precision measurements of the matter power spectrum, and 21-cm imaging of high redshift galaxies can be used for weak lensing studies to provide strong constraints on dark energy at high redshift.

Future Instrumental Directions: 21-cm Cosmology

- At higher redshift, the line is extremely faint, which implies that very large collecting area is required to make the desired maps.

- Since the wavelength gets very long at the redshifts of interest, the diffraction limit prohibits achieving appropriate angular resolution, unless one goes to very large arrays, with the appropriate baselines. Of necessity, this means that these will be fairly big projects.

- At cosmological distances, the line shifts down into the range 9 – 200 MHz, where the signal detection is severely plagued by interference from man-made radio transmission (television, cell phones) and from the ionosphere. The sites for such facilities must be extremely remote to reduce such effects, and extreme attention must be paid to mitigating such interference.

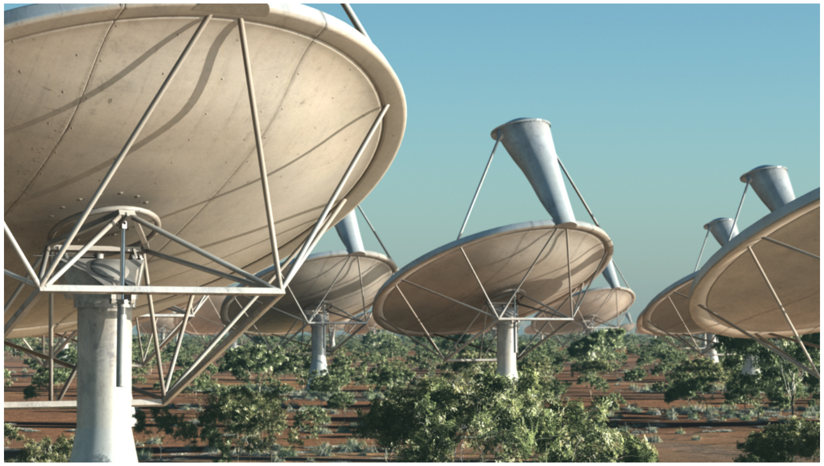
- Mapping suitable areas of sky is largely a computational problem. The data rate is enormous, and electronic solutions for fast autocorrelation to reduce the raw signals at the site are essential.

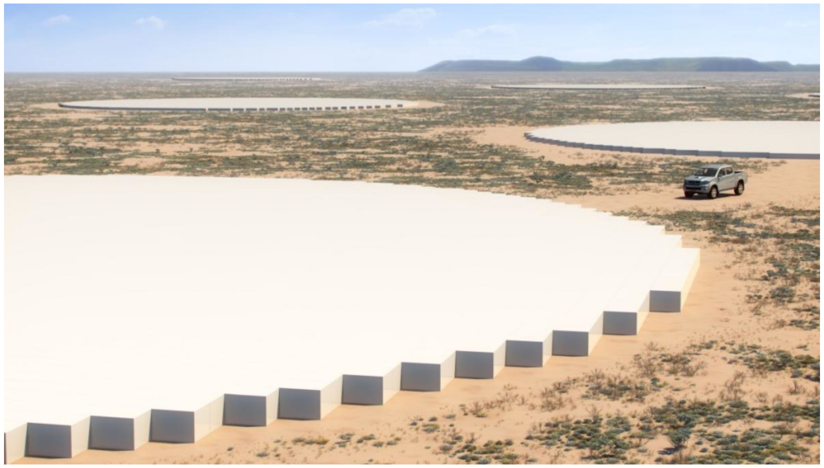
Square Kilometre Array

- This is the “mega-project” in the field. It consists of very large arrays in Australia and South Africa.
- The total cost estimate is 650 Meuro for the initial phase, although many believe this is optimistic.
- The current partners are Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, The Netherlands, United Kingdom. The US is NOT involved.
- The design effort started in earnest in 2013. They are looking for formal construction approval in 2016, with “first science” in 2020+.

Square Kilometre Array

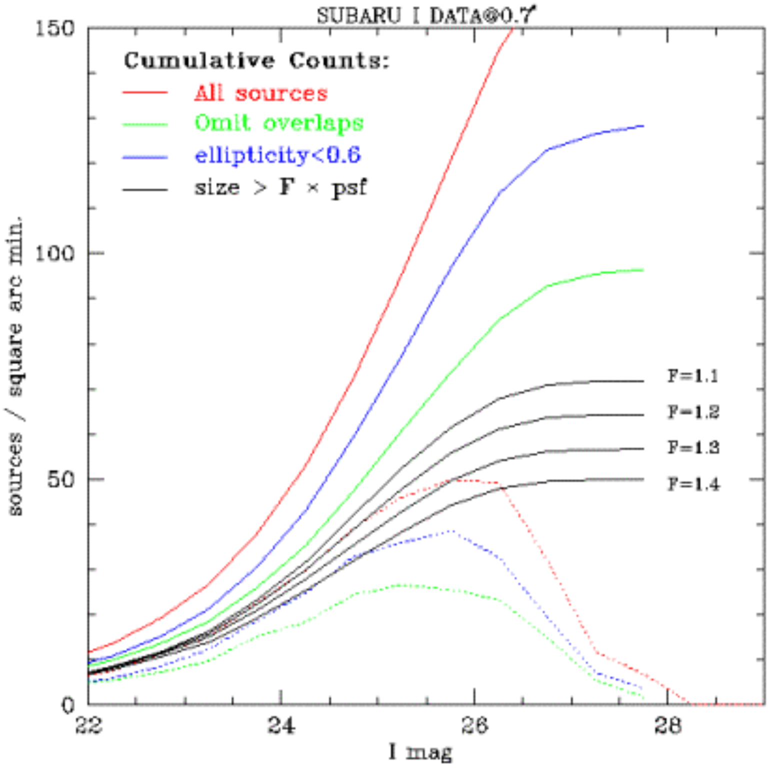
The design combines traditional arrays of dishes with aperture arrays, large numbers of small, fixed antenna elements coupled to receiver systems. For the latter, imaging is achieved through Fourier transforming the phase delays among the antennas.





However, even with improved efficiency, there is not a lot of scientific reach beyond LSST

- From the ground, the number of galaxies per squ. arcmin levels off at mag 26.5.
- With the LSST etendue, this depth can be achieved over the entire visible sky.
- A future ground-based survey is not likely to detect more galaxies.
- SKA will detect a similar number of galaxies to LSST, albeit at higher redshift.



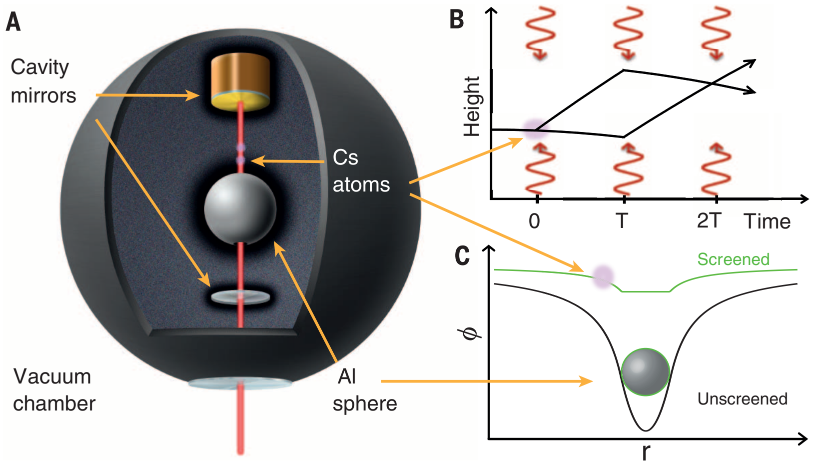
Future Instrumental Directions: Atom Interferometry

- Many theories of dark energy invoke scalar fields, which typically couple directly to matter, yielding "fifth force" type interactions.

- To avoid conflicts with precision tests of GR in the solar system, such theories must invoke screening mechanisms, called "chameleon fields" that suppress these interactions in regions of high density.

- Precision atom interferometry experiments, performed in spherical cavities, can simulate the low density regime, thereby directly testing such theoretical predictions. These experiments measure the gravitational interactions on and between individual atoms.

From Hamilton et al. 2015.



Summary

- Constraining the nature of dark energy requires precision measurements of the expansion history of the universe.

- This can be accomplished by a number of distinct probes, which invoke standard candles, standard rulers, or the growth of structure with cosmic time.

- The next major dark energy imaging experiment, LSST, and spectroscopic experiment, DESI, will make major advances using all of these techniques.

- Going further could benefit from improved efficiency through the use of energy resolving detectors, cryogenic imaging arrays, or through redshifted 21-cm emission. However, the scientific reach beyond LSST and DESI is limited.

- Particular classes of theories can be tested through precision metrology, especially using atom interferometric techniques.