VERA C. RUBIN
OBSERVATORY

Probing Dark Energy

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From Particles to the Universe
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The mystery of dark energy

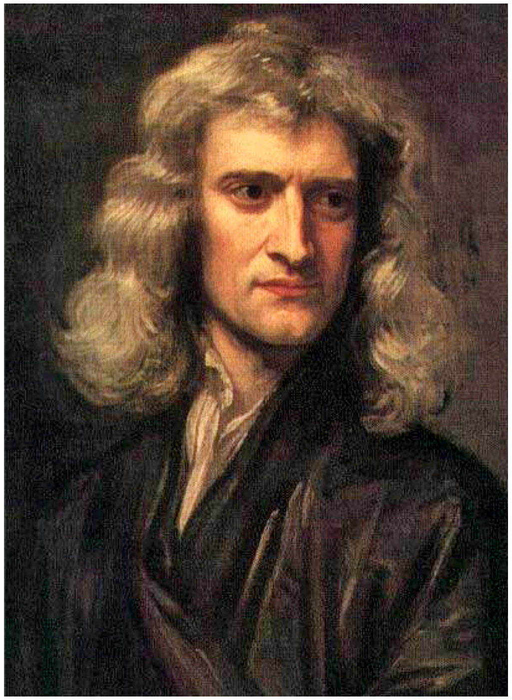
- The discovery of “dark energy” in the late 1990’s was one of the greatest events in physics in the last fifty years. It was recognized by the award of the Nobel Prize to Saul Perlmutter, Brian Schmidt, and Adam Reiss in 2011.

- In the words of the well known cosmologist, Michael Turner, “we know less than zero about dark energy”. This mystery is so profound, that it cuts to the core of our understanding of physics in general, and the nature of the universe in particular.

- In a nutshell, the term “dark energy” refers to the fact that the universe is not only expanding, its rate of expansion is increasing with time. That is quite counter-intuitive, and it appears to require the existence of some mysterious medium that permeates all of space. The medium carries energy, but does not otherwise interact with any other constituents of the universe. Hence the term “dark energy”.

Gravitational instability

- The paradox of dark energy is related to the phenomenon of gravitational instability.
- Isaac Newton was the first to realize that his own theory of gravity implied that a uniform universe would be unstable to gravitational collapse.
    - "It seems to me that if the matter of our sun and planets, and all the matter of the universe were evenly scattered throughout all the heavens and every particle had an innate gravity towards all the rest… (and) if the matter were evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses…"
- Newton was initially pleased with this result, because he thought it explained the origin of stars. However, he later realized that the stars would fall into one another.
- His stated solution to the latter problem was that it required the existence of God, to keep the universe from collapsing!



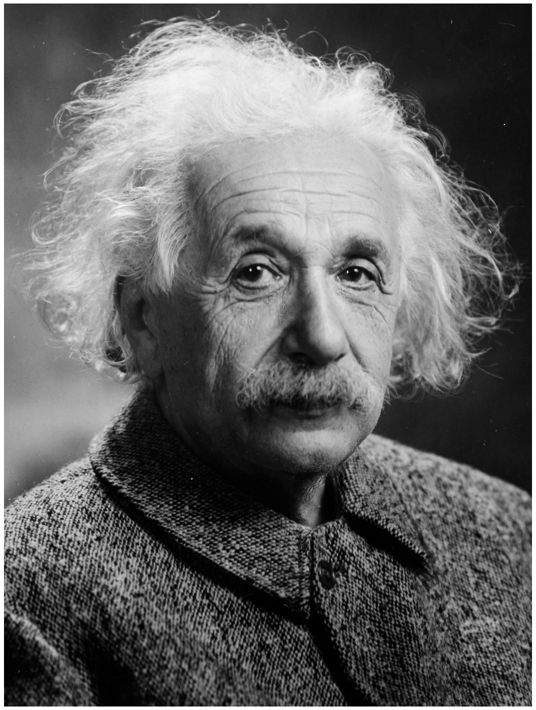
Einstein and the cosmological constant

- Albert Einstein also wrestled with this issue after he reformulated Newton’s theory of gravity into his theory of General Relativity.

- In General Relativity, the existence of mass or energy curves spacetime in its surroundings. The apparent gravitational forces on moving objects are the result of their motion through this curved spacetime.

- A uniform universe would also be gravitationally unstable in this new theory. Einstein preferred the concept of an infinite, static universe. To make his equations fit that concept, he added an “integration constant” to his equations, the so-called cosmological constant, Λ, which acted against the gravitational attraction.

- Later, Edwin Hubble discovered that the universe is not static, it is in fact expanding. Einstein then abandoned his cosmological constant, and called it his “greatest blunder”.



The cosmological constant as vacuum energy

- Actually, the concept of a cosmological constant arises naturally in quantum field theory due to the sea of virtual particles which impart energy density to the vacuum. This results in a medium that carries positive energy density, but negative pressure.

- In general relativity, not only energy density, but also pressure contributes the curvature of spacetime and acceleration:

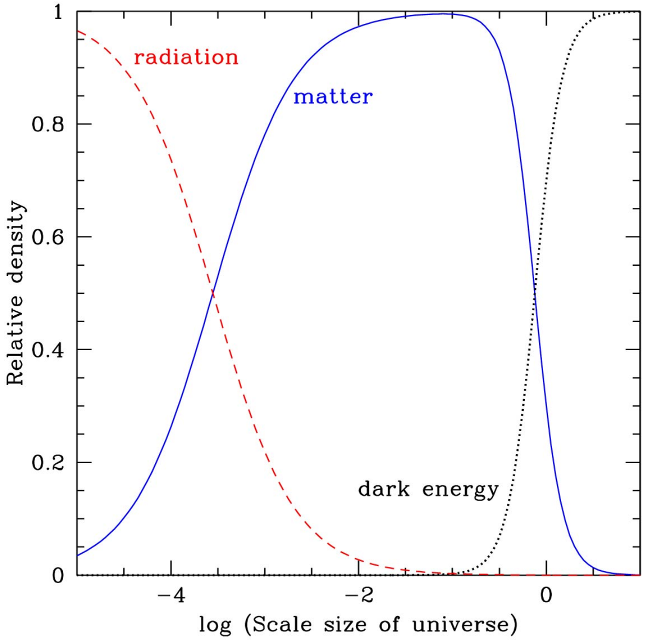
$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

- If the pressure is negative, this can lead to a universe that is accelerating in its expansion. The so-called "equation of state paramer" $w = P/\rho$ must be $< -1/3$. A pure cosmological constant is equivalent to $w = -1$.

- The problem is that naïve calculations of Λ lead to values that are 120 orders of magnitude too large. The problem is not how to generate a cosmological constant, but rather how to keep it small.

The "why now" problem

- Especially puzzling is the "why now" problem. We believe the universe began in a "big bang", initially very hot, and then cooled as it expanded. So it was initially radiation dominated, then matter dominated, and now dark energy dominated.
- 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 in dark energy.
- This suggests that although a cosmological theory invoking a cosmological constant works very well, there must be some new physics lurking behind it!



How do we study dark energy?

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

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

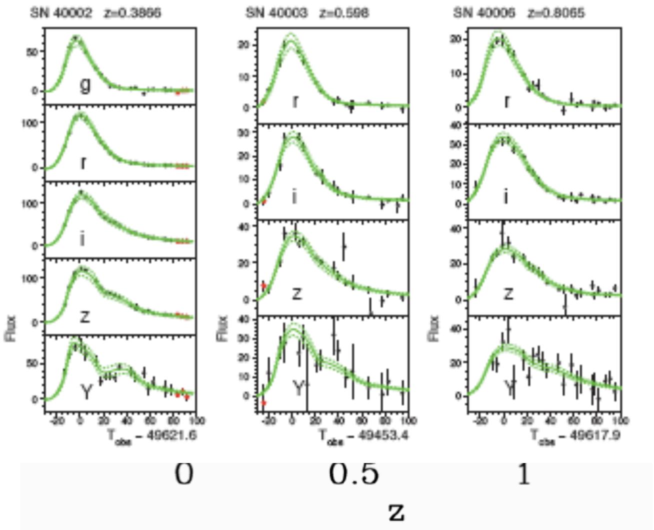
- We need to measure distances to distant galaxies, and relate them to redshift, so that we can infer *H(z).* We do that by measuring the apparent brightness of “standard candles”. We can also measure the angular size of “standard rulers”. These are both kinematic measurements.

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

- Growth of structure is a dynamic measurement. It also depends on the nature of gravity on large scales, so a comparison of these measurements to the kinematic measurements can potentially distinguish between dark energy models and modified gravity models as explanations of the cosmic acceleration. It is clearly crucial to do both.

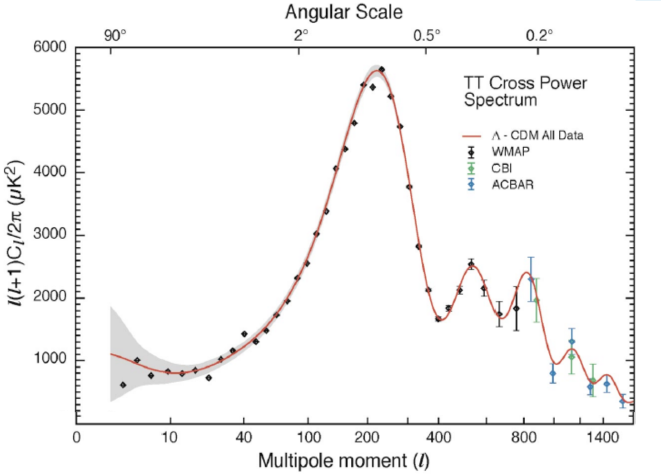
Type Ia Supernovae

- Type 1a Supernovae are a class of stellar explosions that are associated with a particular kind of degenerate star exceeding the maximum mass needed for it to remain stable against gravitational collapse.
- It is believed that the characteristic shape of the observed outburst is nearly always the same, so that we can determine the intrinsic brightness of these objects from the shapes of their lightcurves.
- Thus these form a class of “standard candles”. If we can observe large numbers of them at a range of redshifts, we can determine the cosmic expansion.
- This is the approach Perlmutter, Schmidt, and Reiss used to discover dark energy in the first place.



Baryon acoustic oscillations

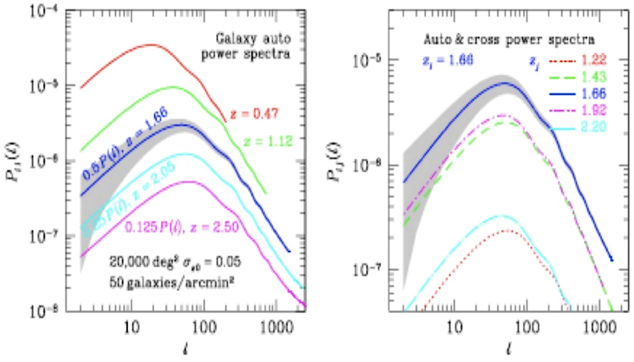
- The very early universe was very hot, so all of the atoms were fully ionized. The universe was basically a sea of protons, electrons, and photons, particles of light interacting strongly with the protons and electrons.
- In this medium, disturbances or slight overdensities give rise to sound waves which propagate outward at the sound speed, $c/\sqrt{3}$.
- However, at some point, the universe cooled sufficiently that the atoms could "recombine", becoming electrically neutral. When this occurred, the radiation "decouples", and propagates independently. The leftover radiation from that era is observable today as the Cosmic Microwave Background.
- 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 acoustic oscillations form an imprint in the galaxy distribution.
- This persists as the universe expands, although it gets weaker with time.
- The effect can be measured in the spectrum of galaxy density versus angular size.

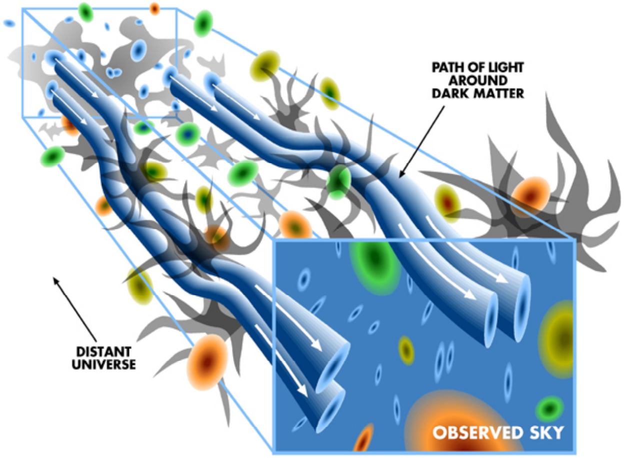


Gravitational lensing and cosmic shear

- In Einstein’s theory of General Relativity, the curvature of spacetime due to matter also deflects light rays. This gives rise to “gravitational lensing”, the deflection of light due to mass concentrations.

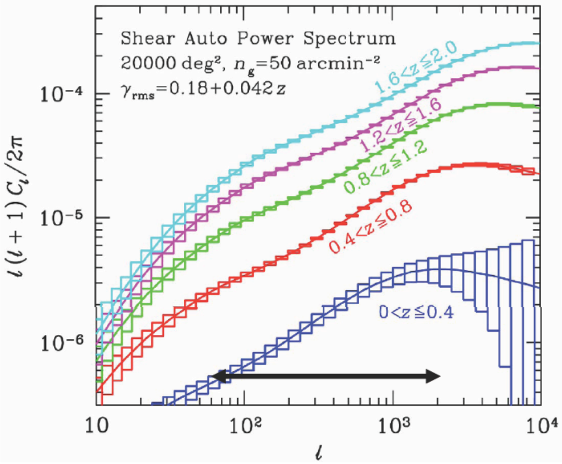
- The term “cosmic shear” refers to the systematic and correlated distortion of the appearance of background galaxies due to weak gravitational lensing by the clustering of dark matter in the intervening universe. A given galaxy image is both displaced and sheared.

- 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 power spectrum

- 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 tight constraints on dark energy.
- However, the effect is very subtle. Since galaxies have intrinsic shapes, we need to average over a huge number of galaxies (billions) to reliably measure the effect.



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 need to use for cosmic shear studies.
- Instead, we can 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.

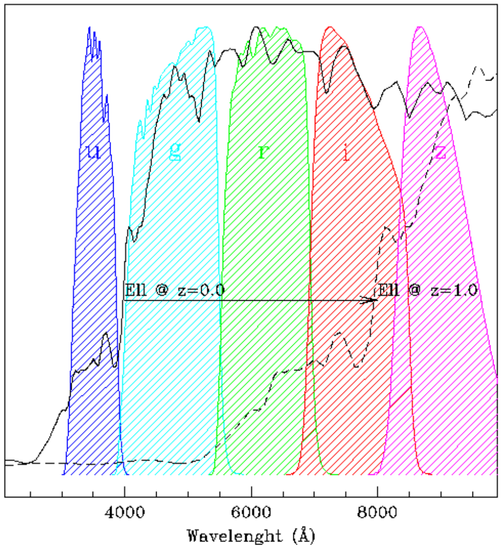
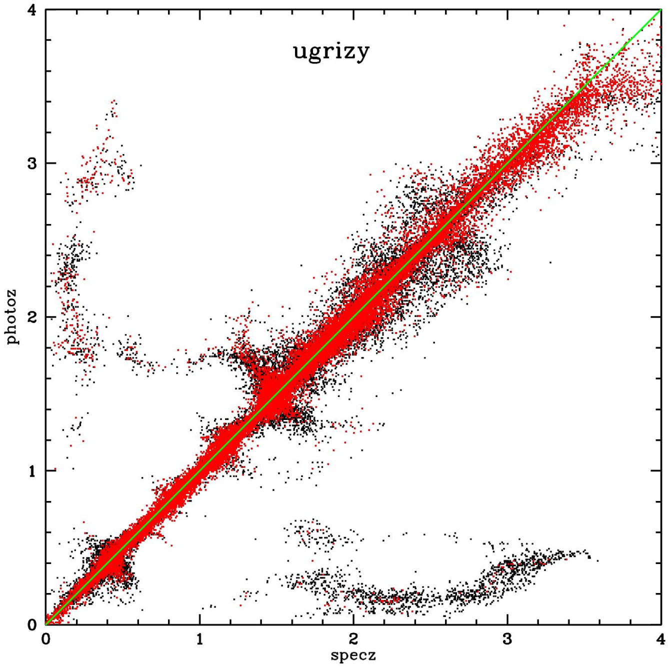


Photo-z systematics

- 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.

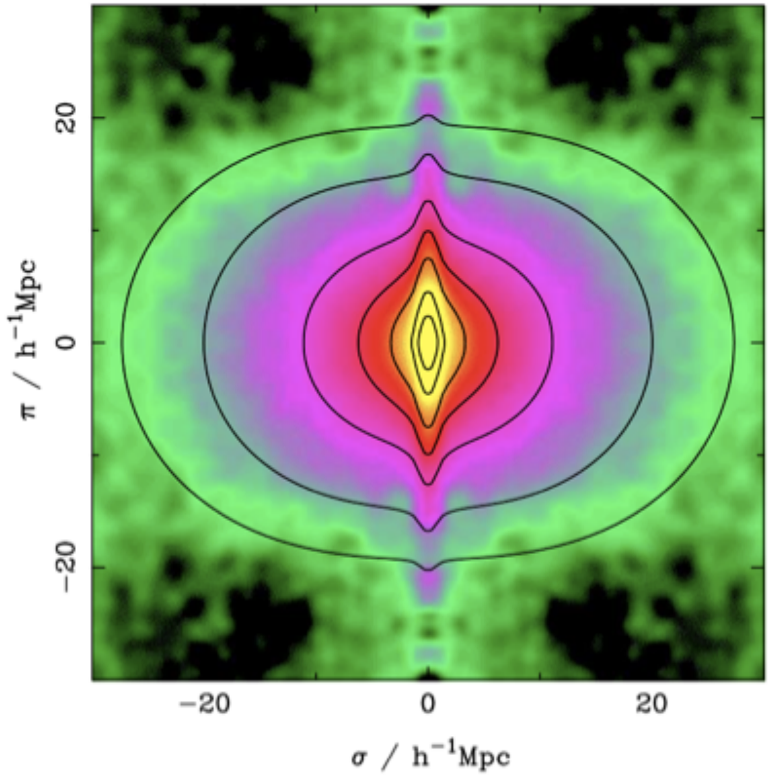
- There can also be catastrophic failures due to multiple minima associated with confusion between these two features.



Redshift space distortions

- Another probe of the growth of structure is through redshift space distortions. This involves an observed flattening (or elongation) of the distribution of galaxies when plotted versus redshift.

- It arises due to coherent doppler shifts of galaxies around mass concentrations due to their peculiar velocities. The magnitude of the effect therefore provides information on the extent of the mass fluctuations



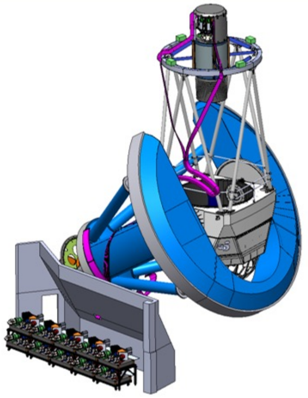
Two major new Stage IV facilities (both with in2p3!)

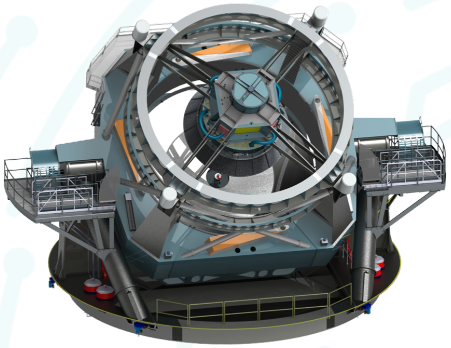
Dark Energy Spectroscopic Instrument:

- A multi-object spectrometer that will obtain spectra of tens of millions of galaxies and quasars, yielding precision measurements of BAO and RSD.
- Fielded on the Mayall 4m telescope at Kitt Peak, DESI has recently completed construction and begun operations.

Vera C. Rubin Observatory:

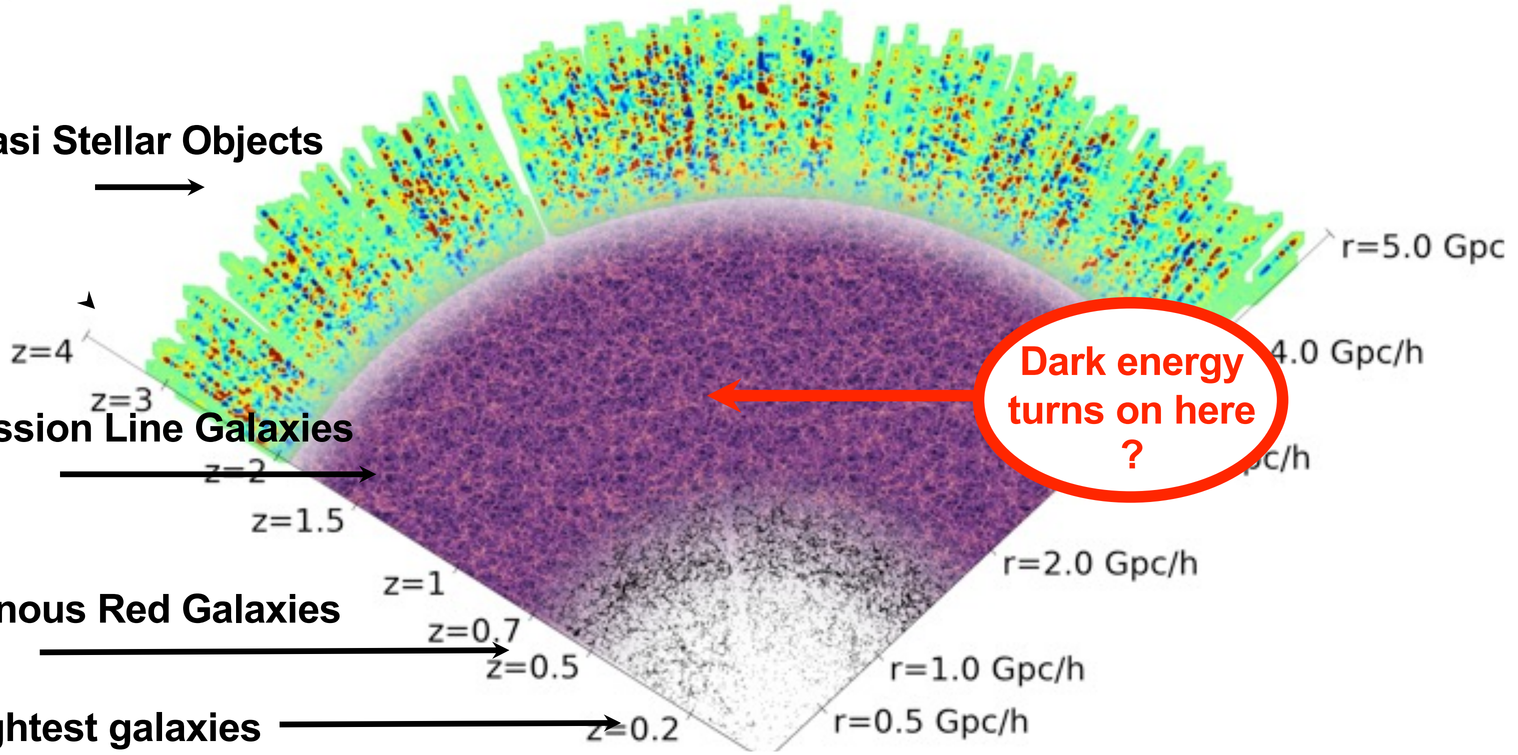
- An integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground-based telescope with a 3.2 Gpix camera.
- Rubin will acquire, process, and make available a collection of over 5 million images and catalogs with more than 20 billion galaxies.
- The ten-year Rubin Legacy Survey of Space and Time will yield high precision measurements of Type Ia supernova and cosmic shear, as well as angular measurements of BAO.
- Rubin is under construction on Cerro Pachon in Chile, and it will begin operations in ~ two years.





Dark Energy Spectroscopic Instrument

DESI will explore a x30 larger map over a x10 larger volume than SDSS



2.4 million Quasi Stellar Objects (QSO) →

17 million Emission Line Galaxies (ELG) →

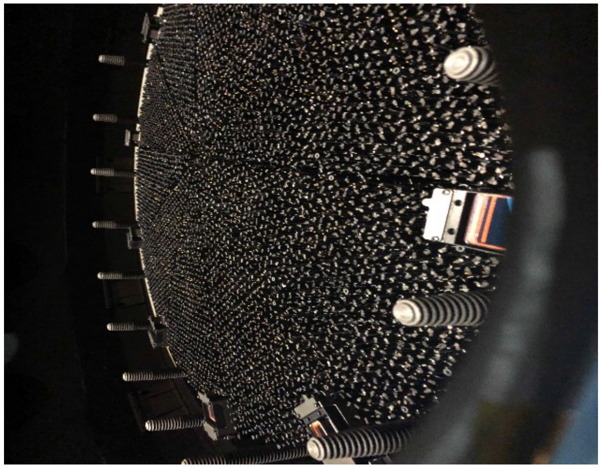
6 million Luminous Red Galaxies (LRG) →

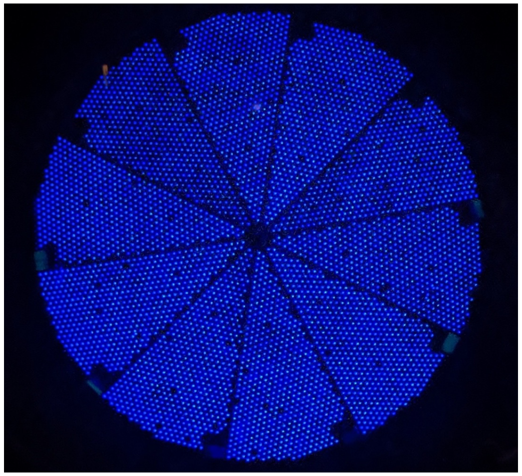
10 million brightest galaxies →

Dark energy turns on here ?

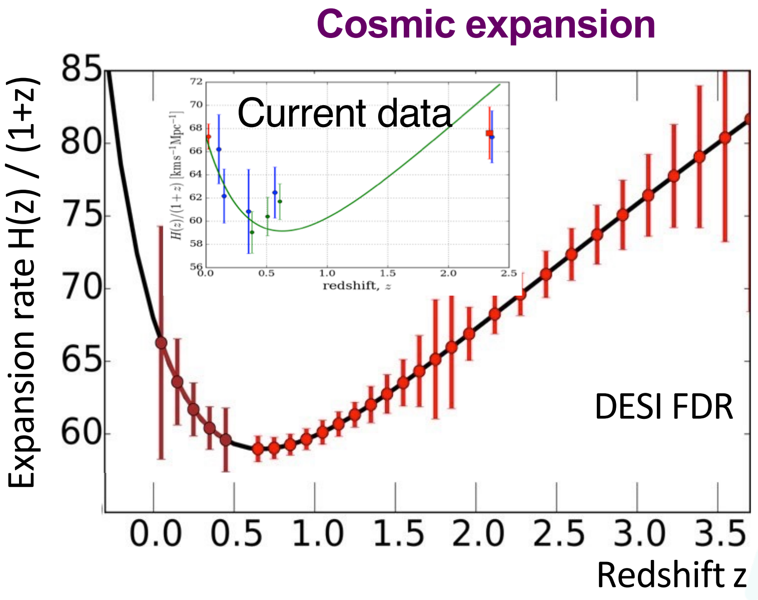
Dark Energy Spectroscopic Instrument

Installation of the focal plane instrument was completed in August of 2019. The picture shows the fiber ends of the 5,000 robotic positioners on the focal plane, back-illuminated

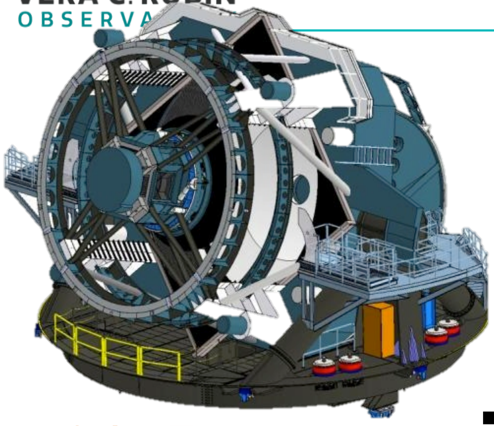




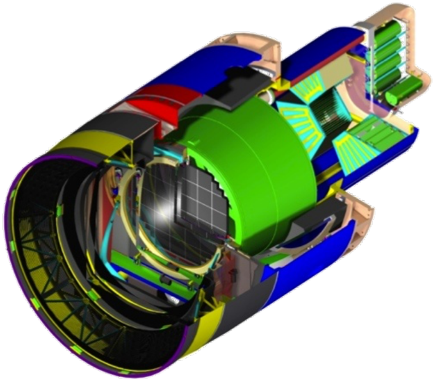
DESI constraints on cosmology



Rubin is an Integrated System

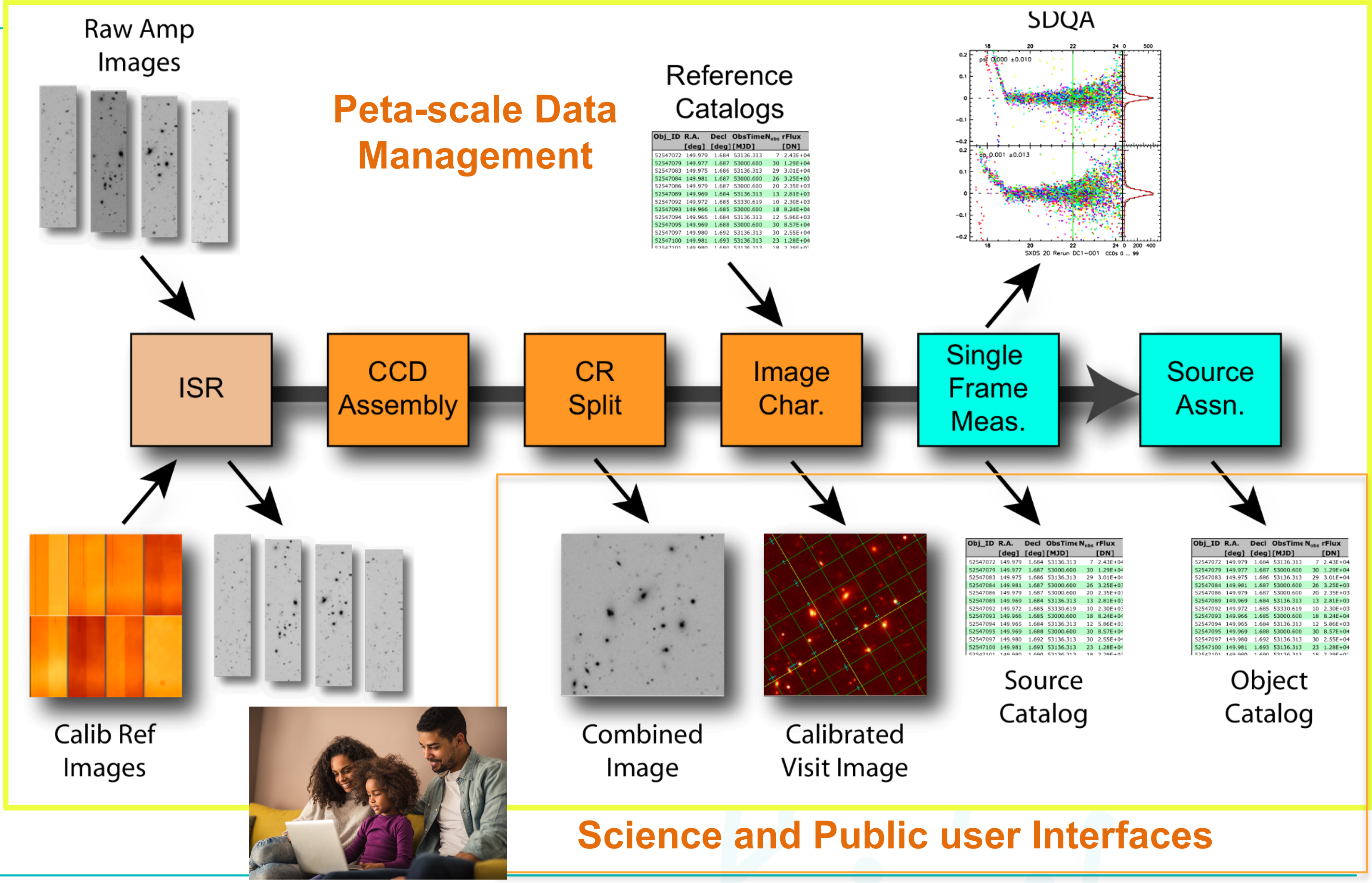


8.4m Telescope



3.2Gpix Camera

+



Raw Amp Images

Peta-scale Data Management

Reference Catalogs

SDQA

ISR

CCD Assembly

CR Split

Image Char.

Single Frame Meas.

Source Assn.

Calib Ref Images

Combined Image

Calibrated Visit Image

Source Catalog

Object Catalog

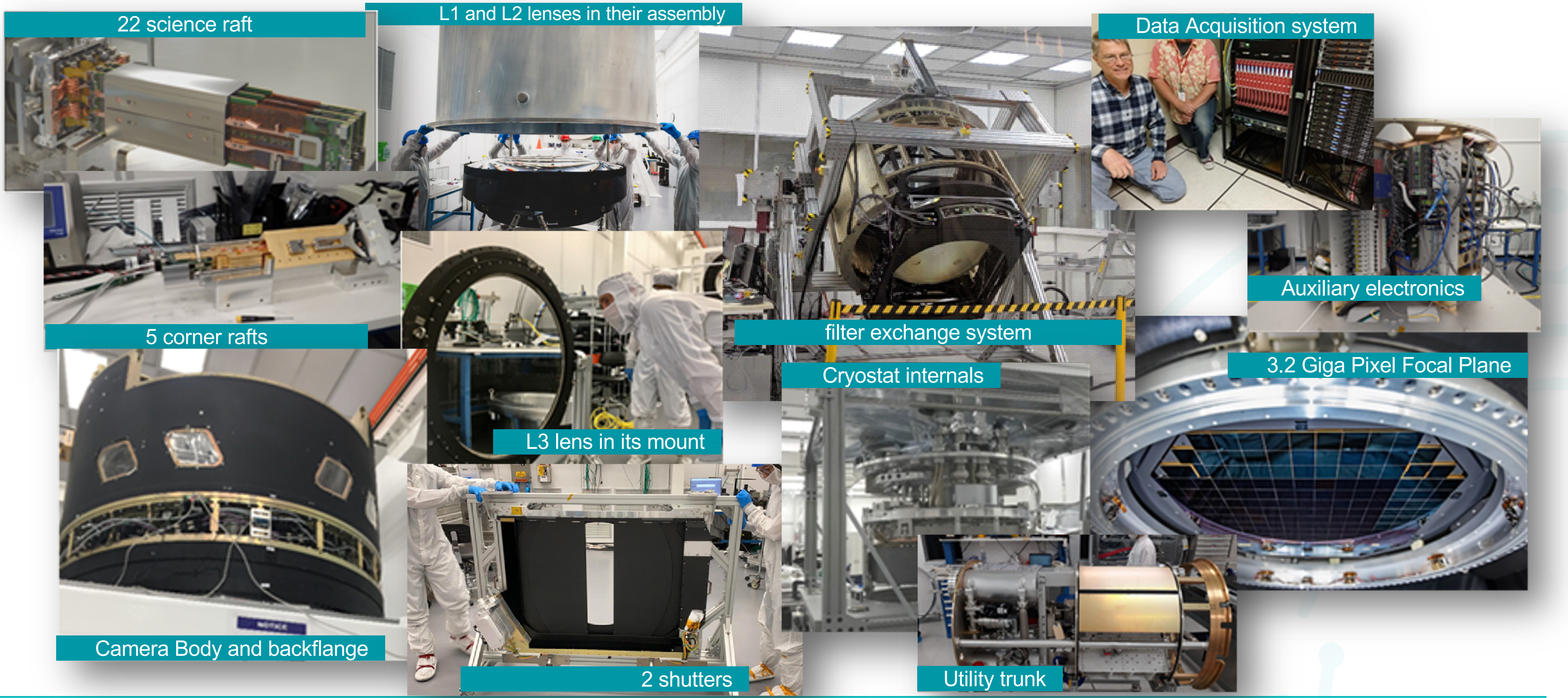
Science and Public user Interfaces

High Level Requirements Summary

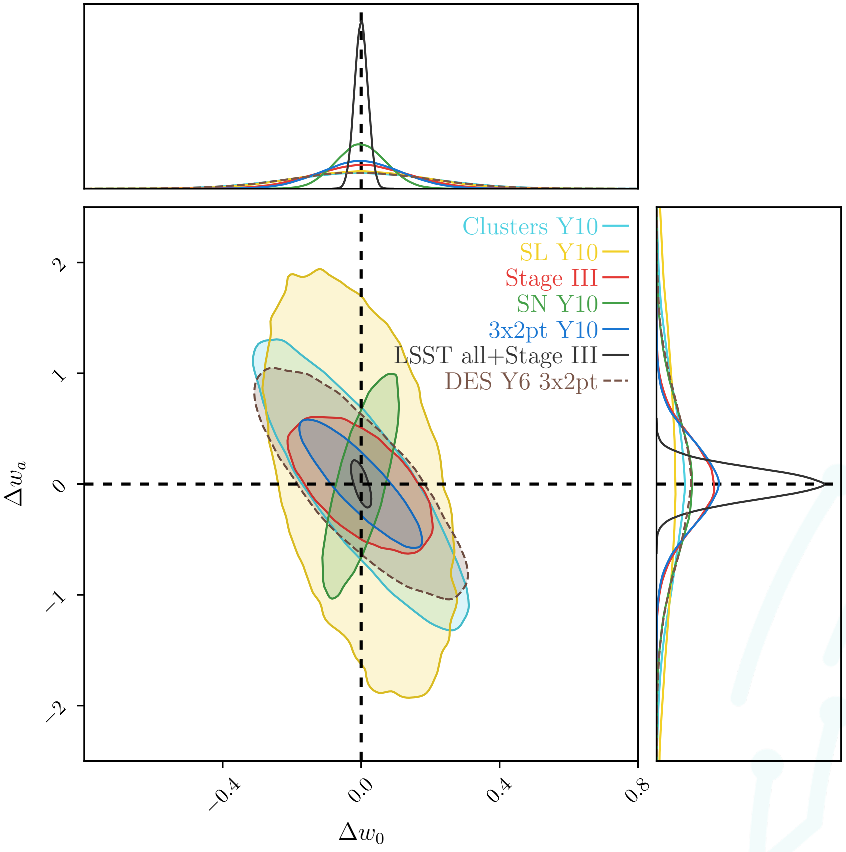
Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

Construction is at an advanced stage.

All camera individual components have been fabricated.



Rubin LSST dark energy constraints



Current state of the field

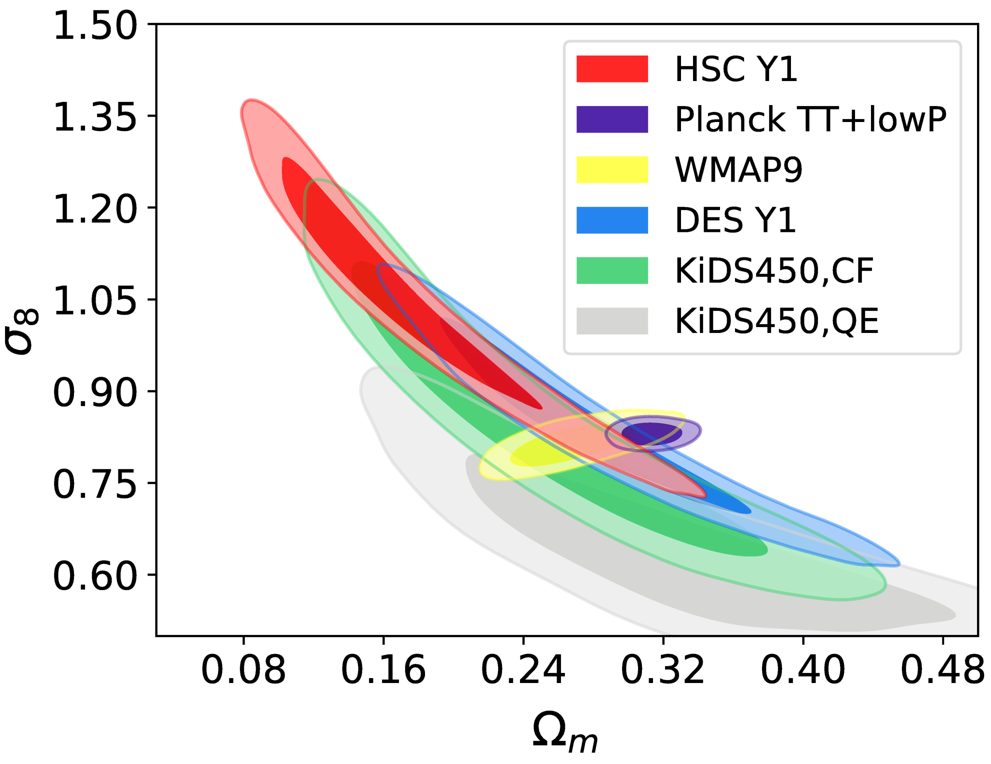
- ΛCDM – the standard cosmological paradigm, which includes a cosmological constant (w = -1) and only non-relativistic dark matter, has proven remarkably successful at explaining a wide variety of observations, with increasing precision.

- However, there has been some “tension”, specifically quantitative disagreement between measurements of certain cosmological parameters from late universe optical surveys, and their counterparts measured from the cosmic microwave background at z ~ 1000.

- The two which have received the most attention are σ_8, which is a measure of the amplitude of fluctuations, and H_0, the Hubble parameter at $z = 0$. Both are ~ few sigma discrepancies, and some different methods have yielded inconsistent results.

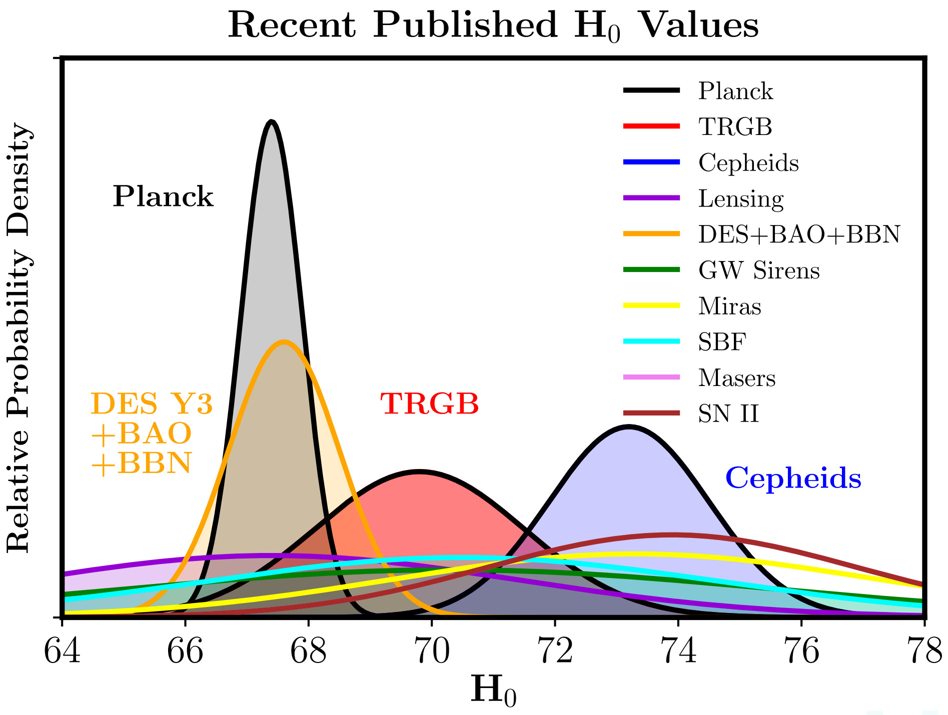
- So, this remains an open question, but it is tantalizing.

Sigma-8 discrepancy



From Hikage et al. (2018)

Hubble constant discrepancy



From Freedman (2021)

Looking beyond DESI and Rubin

- What does the future hold for dark energy research? Well, of course, it will depend on what we measure. DESI and Rubin will dramatically improve our constraints on parameters. If the current tensions are indicative of real effects, we will measure them at many sigma. The CMB constraints will also improve significantly with future facilities. If there are other departures from ΛCDM, they will also provide new clues to the origin of the cosmic acceleration. There are many ideas out there – this field will remain data driven for quite a while.

- Systematic uncertainties are likely to continue to provide the ultimate limitation. Photo-z systematics are especially important. At the faint magnitudes probed by Rubin, we simply do not know the intrinsic spectra of galaxies, and they are difficult to measure, even with the world's largest facilities. Additional spectroscopic information will certainly be required.

- Finally, complementary measurements, such as 21-cm surveys will also be invaluable. There are several projects in development to provide such data. The complementarity of the various probes is especially important.