LSST / Clusters Group

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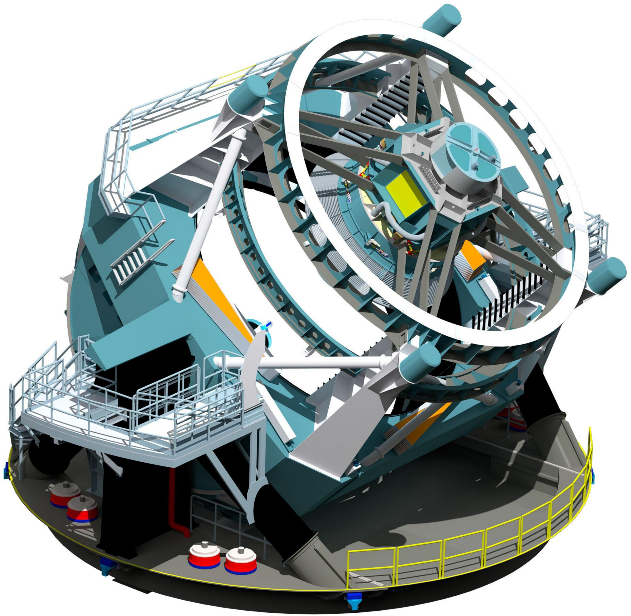
Driving Questions:

- **LSST Techniques**
  - Which **combinations of techniques** will ensure that the LSST results are as **precise and robust as possible**? What type of **external data** would be particularly beneficial to include?
- **Clusters in Multiple Bands**
  - Cluster data in ***optical***, ***X-ray***, and ***microwave***
  - What are the **strengths and weaknesses** of these three techniques? How are they **complementary**? How should we **combine** them to obtain the best dark energy constraints possible from galaxy clusters in the 2020s?
- **Post-LSST Surveys**
  - What **ground based survey project** do you propose should be carried out **after LSST**? Consider telescope size, location, observing wavelength, instrumentation and anticipated cost alongside the expected ***science payoffs***.

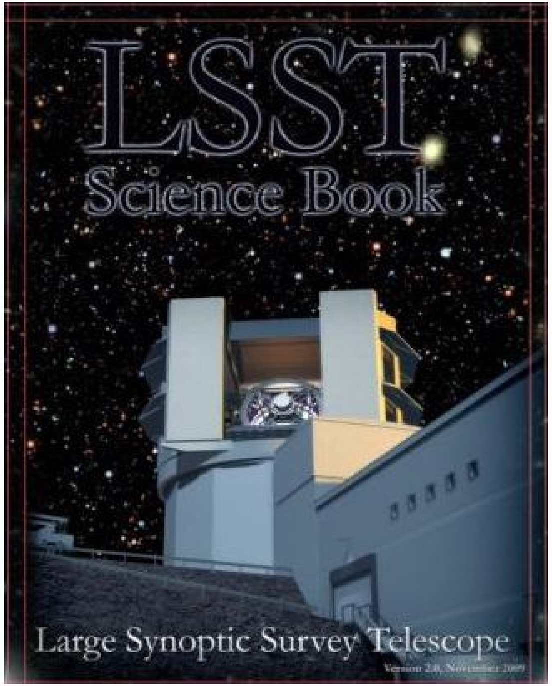
Large Synoptic Survey Telescope (LSST)

Most ambitious optical survey to date:

- 8.4 m primary mirror with a **3.5 deg** field of view
- 3.2 gigapixel camera in **6 bands** (ugrizy)
- **18,000 deg^2** coverage of southern sky
    - **Full footprint imaged every ~3 days**
- Estimated 40 billion objects (20 billion galaxies) to be imaged over 10 years
    - For the expected 800 visits, that is ***32 trillion observations*****!**



LSST Science Goals



"*Massively parallel astrophysics*"

- A Comprehensive Survey of the Solar System
- Structure and Stellar Content of the Milky Way
- The Variable Universe
- The Evolution of Galaxies
- **Cosmological Models, and the Nature of Dark Energy** and Dark Matter

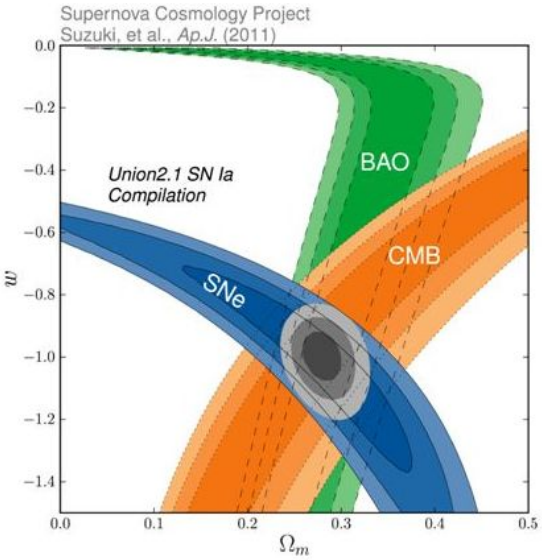
From LSST Science Book: https://arxiv.org/abs/0912.0201

LSST Dark Energy Probes

Large Synoptic Survey Telescope

LSST will be able to distinguish between different models of dark energy by using a number of cosmological probes sensitive to cosmic **growth** and **geometry**; largely independent from one another

- **Weak Gravitational Lensing: Growth; Geometry**
- **Strong Gravitational Lensing: Geometry**
- **Supernovae: Geometry**
- **Baryonic Acoustic Oscillations (BAO): Geometry**
- **Galaxy Clusters: Growth; geometry**



These different probes can also be used as *cross checks* to understand and ***calibrate systematic errors***

LSST Dark Energy Probes

Large Synoptic Survey Telescope

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- **Weak Gravitational Lensing:** ***Cluster mass calibrations***, *shear correlations, halo-mass function*
- **Strong Gravitational Lensing:** ***Time delays, 10^3-10^4 SL AGN***
- **Supernovae:** ***SN peculiar velocities, ~100 strongly lensed SN***, *color calibration*
- **Baryonic Acoustic Oscillations (BAO):** *Better statistics in angular matter power spectrum*
- **Galaxy Clusters:** *Evolution of mass function*, ***Cluster density at high z***

These different probes can also be used as *cross checks* to understand and ***calibrate systematic errors***

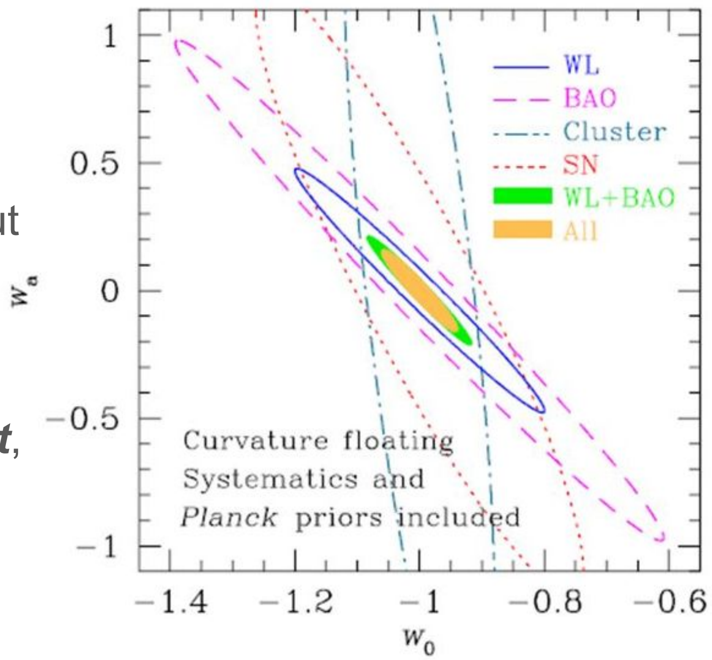
Robustness: Breaking Degeneracies and Consistency

As we only get one realization of the universe, it is important to have numerous ***cross-checks*** and ***independent measures*** of cosmological parameters.

Individual probes are only sensitive to some params, but independent probes can help ***break degeneracies*** in parameter space.

As all of these probes come from the ***same experiment***, it is easier to ***calibrate systematics*** and maximize ***consistency*** of comparison (same cosmic volume).

Further enhanced by the survey's excellent ***uniformity*** and ***completeness***.



(LSST Science Book)

Complementary Probes: BAO and Weak Lensing

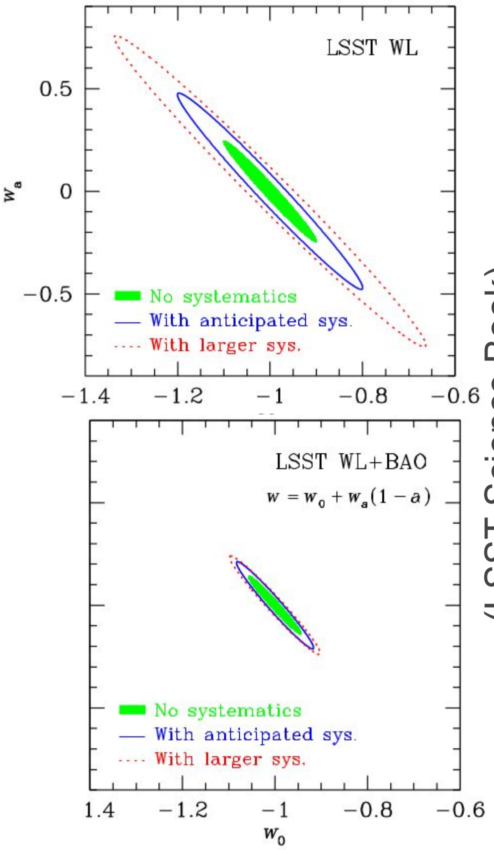
Constraints from WL are sensitive to photo-z errors, but not the shear power spectrum itself

- Galaxy # density correlation in cross-bin galaxy power spectra ***calibrates photo-z's***!

Galaxy clustering bias degenerate for angular BAO measurements

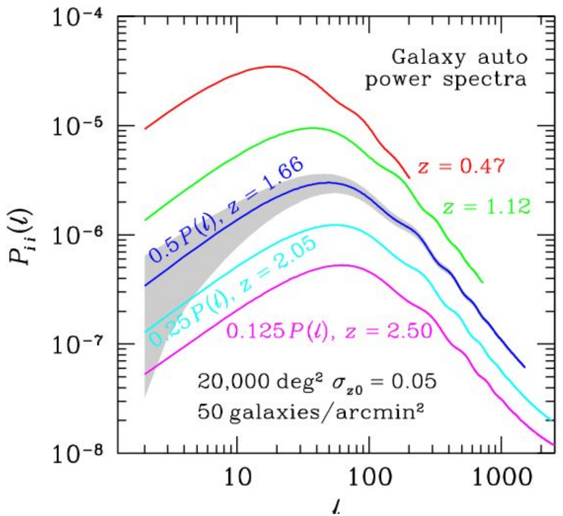
- gg, gγ, $\gamma\gamma$ power spectra sensitive to different powers of galaxy bias; ***calibrates bias*** for BAO

These probes ***mutually calibrate systematics*** and strengthen parameter constraints with information ***not captured in either technique alone***

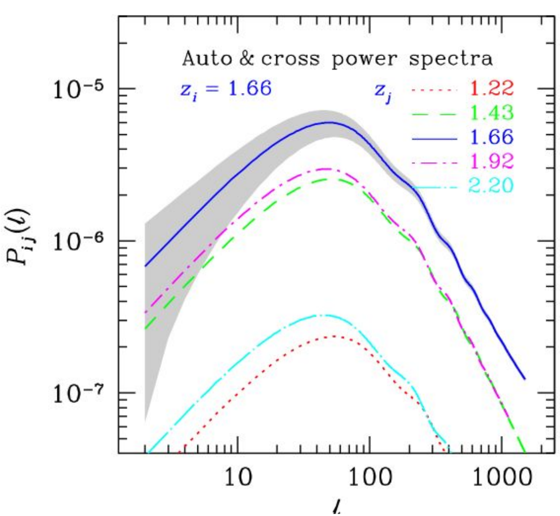


(LSST Science Book)

Angular power spectrum

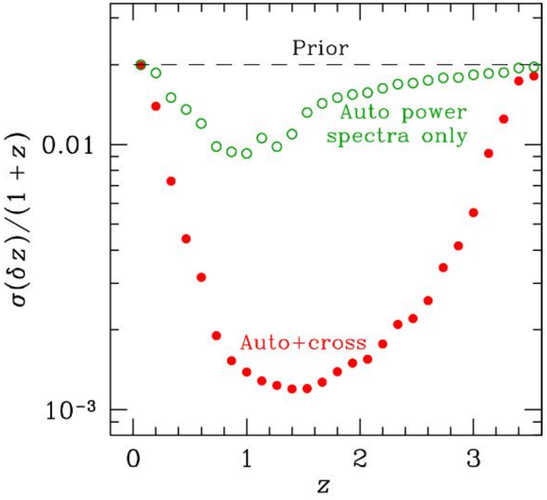


Cross-bin power spectrum

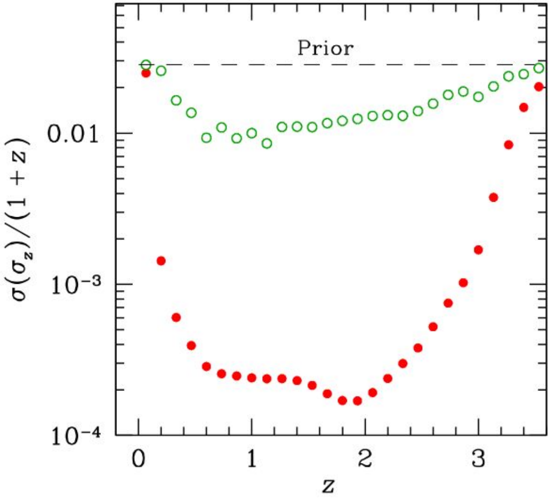


(LSST Science Book)

Priors on photo-z bias



Priors on photo-z RMS



Robustness of LSST Approach: ***“Wide, Deep, Fast”***

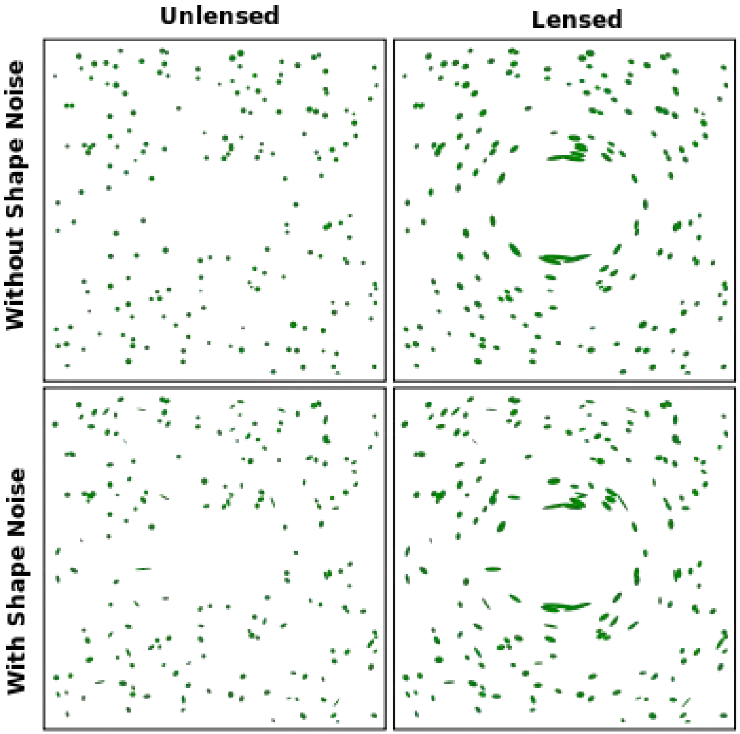
‘By **simultaneously measuring** the redshift/distance relation and the **growth of cosmic structure**, LSST data can test whether the recent acceleration is due to dark energy or modified gravity. Because of its **wide area coverage**, LSST will be uniquely capable of constraining more general models of dark energy. LSST’s **redshift coverage** will bracket the epoch at which dark energy began to dominate the cosmic expansion. Much of the power of the LSST will come from the fact that **all the different measurements will be obtained from the same basic set of observations**, using a facility that is optimized for this purpose. The wide-deep LSST survey will allow a unique probe of the isotropy and homogeneity of dark energy by mapping it over the sky, using weak lensing, supernovae and BAO, especially when normalized by Planck observations.’ - ***Science Book Introduction***

LSST Robustness: Shapes and Photo-z Calibration

Some of the worst errors in imaging surveys are photo-z estimation and galaxy shape noise

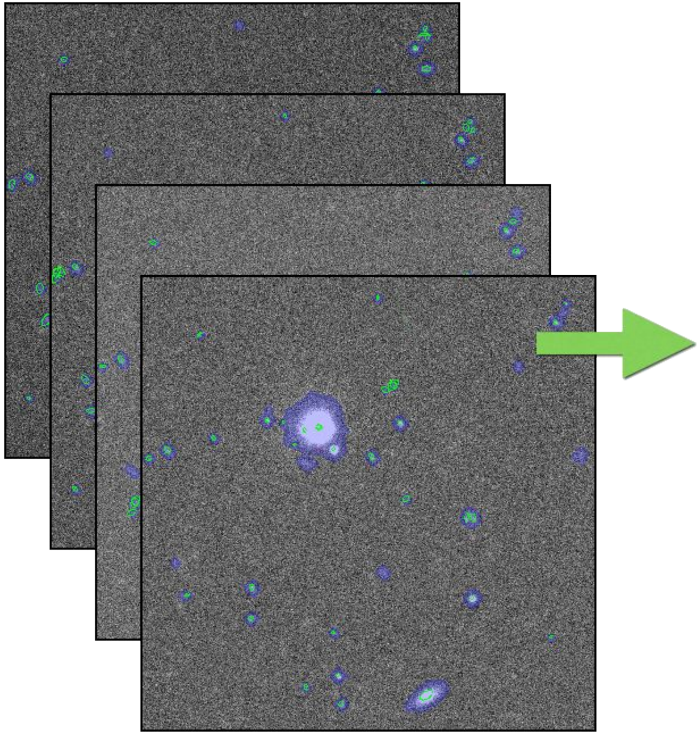
If the distribution of photo-z's to 'real' spectroscopic z's isn't ***well calibrated***, can lead to ***catastrophic*** redshift errors for many probes

Additionally, need to understand effects of ***shape distortions*** in combining galaxy images for accurate weak lensing results



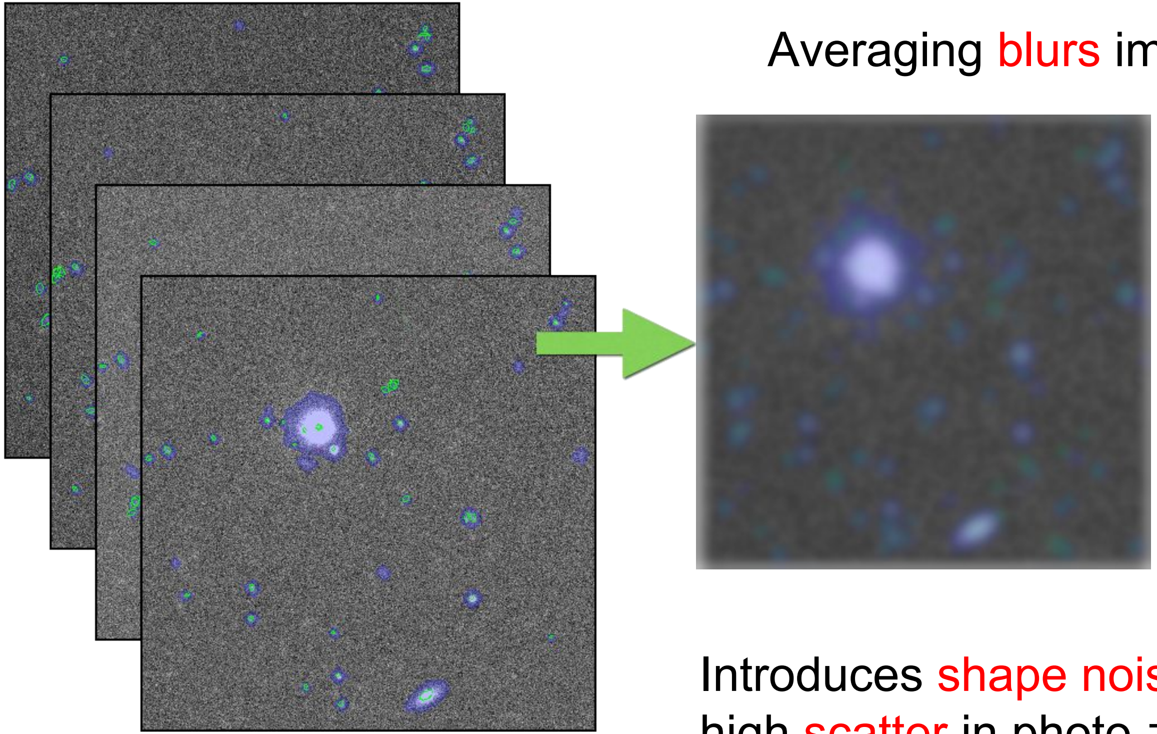
Simple Coadd

Simple Coadd



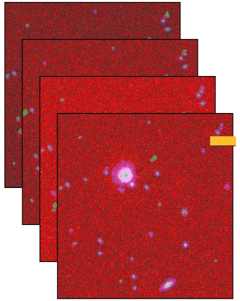
Simple Coadd

Averaging blurs image

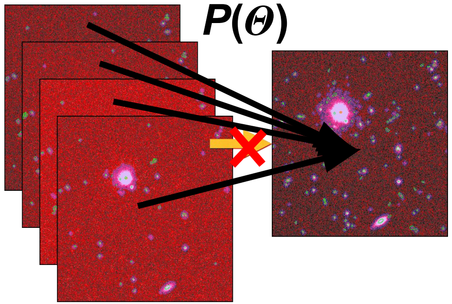


Introduces shape noise (bad for wl),
high scatter in photo-z estimate

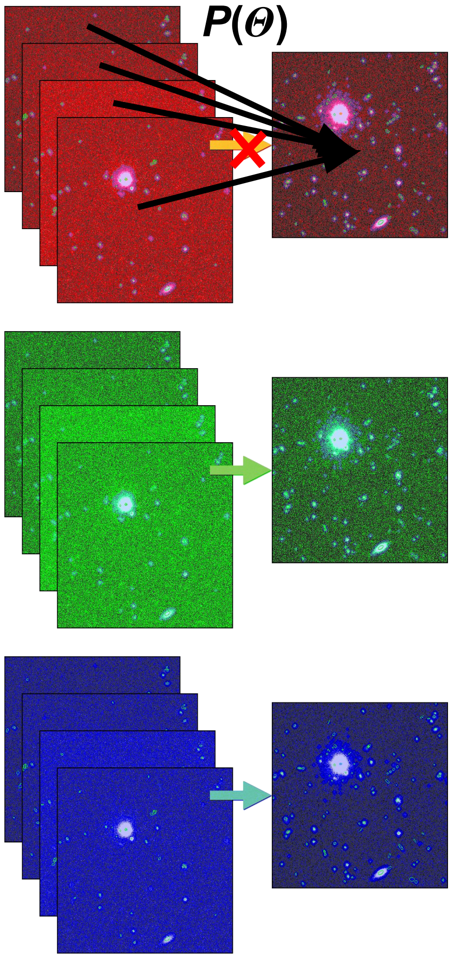
Using all data...



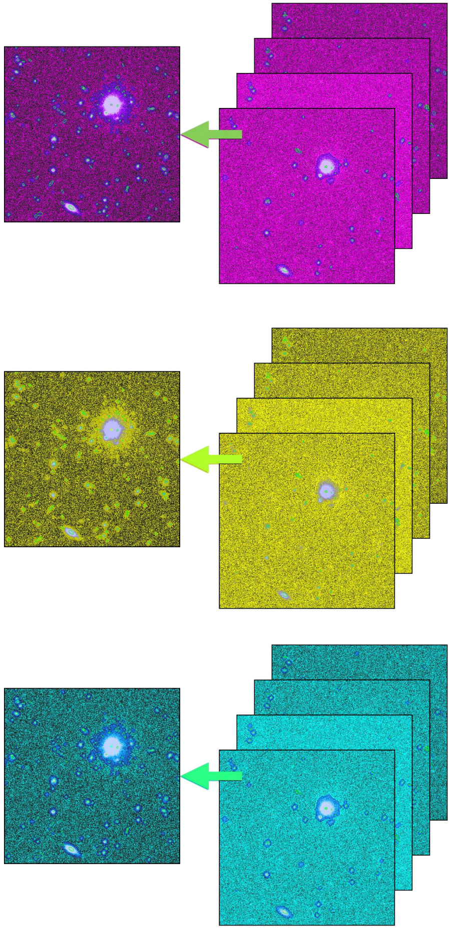
Using all data...



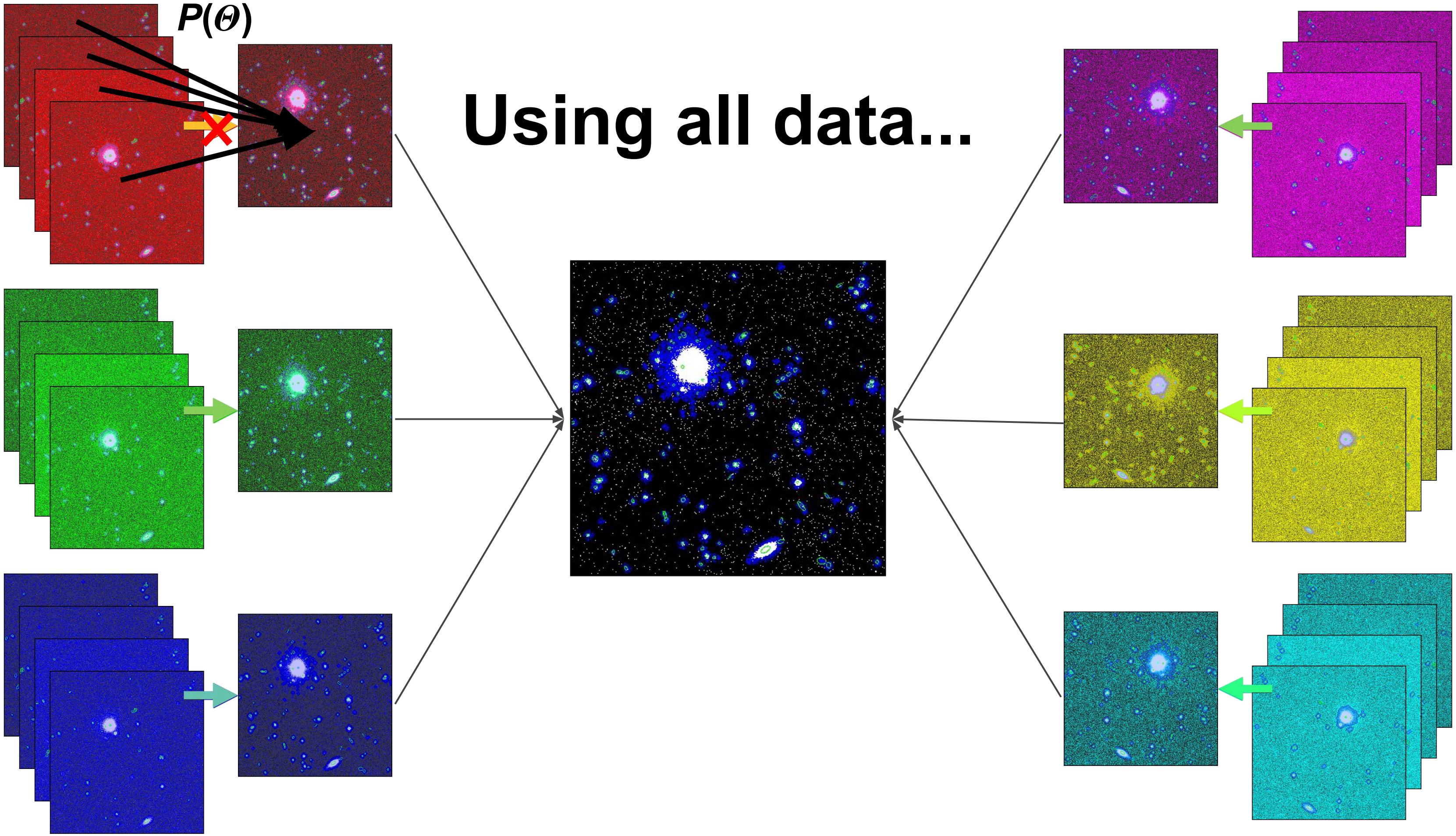
Using all data...

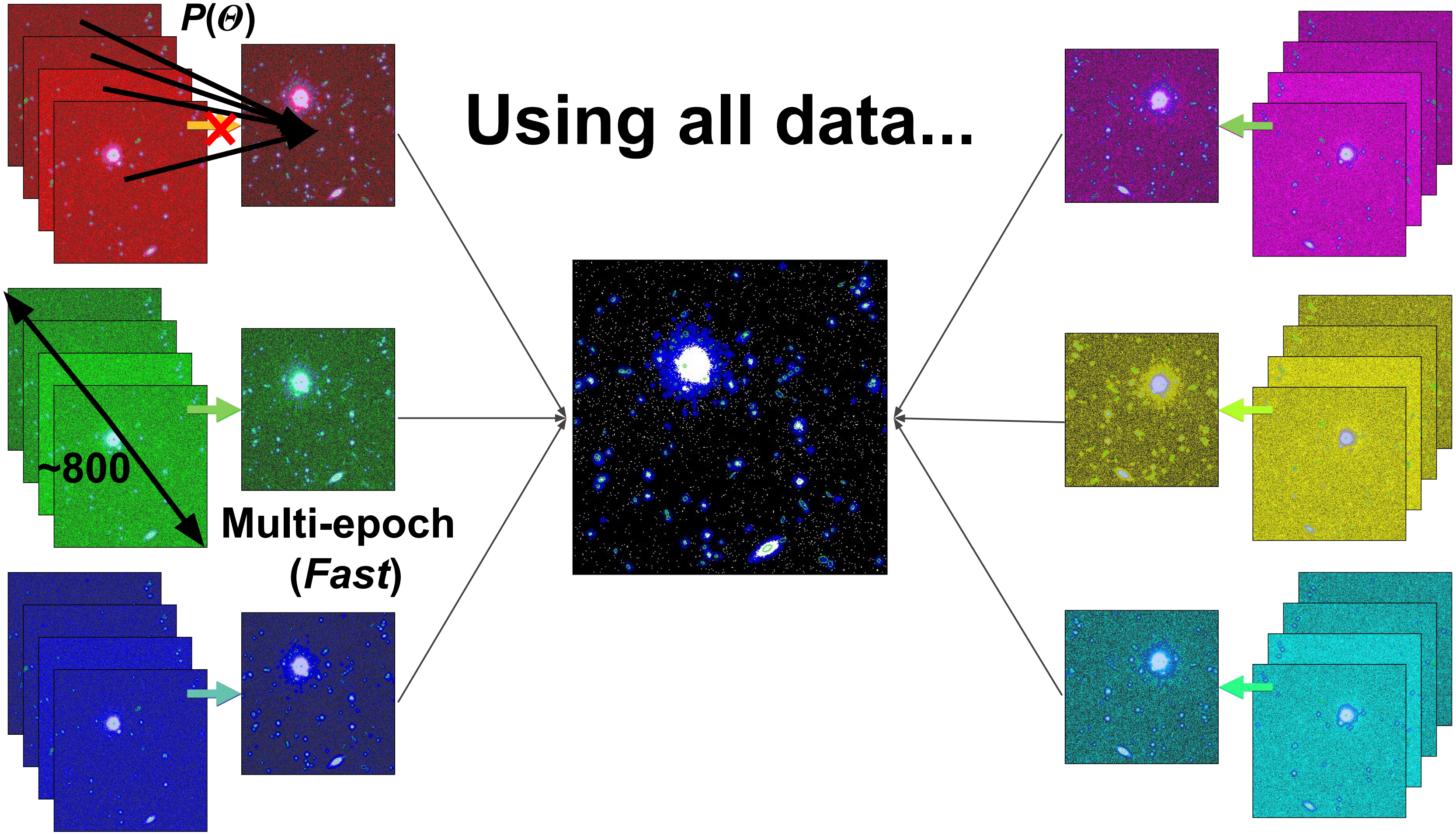


Using all data...

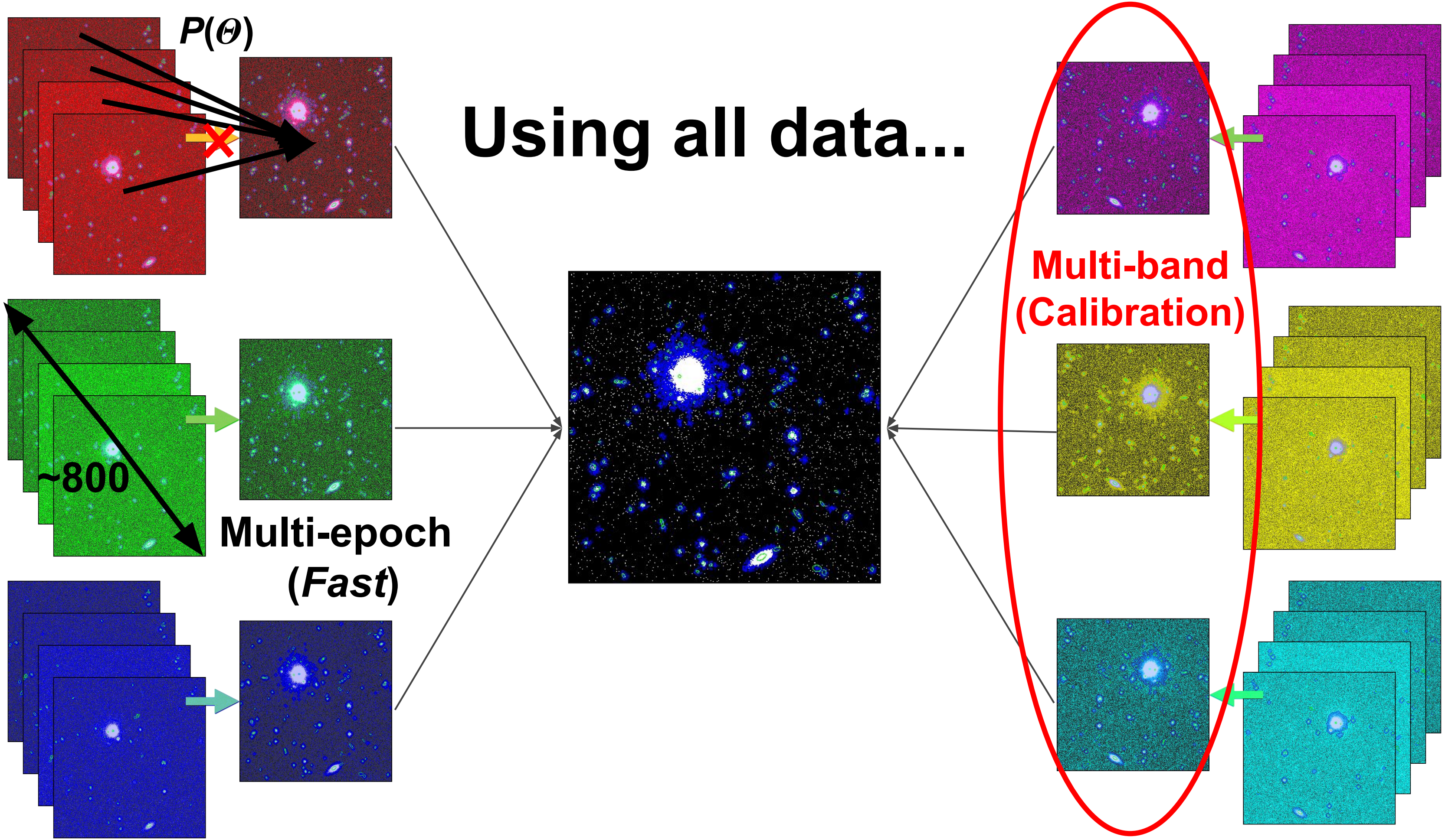


Using all data...

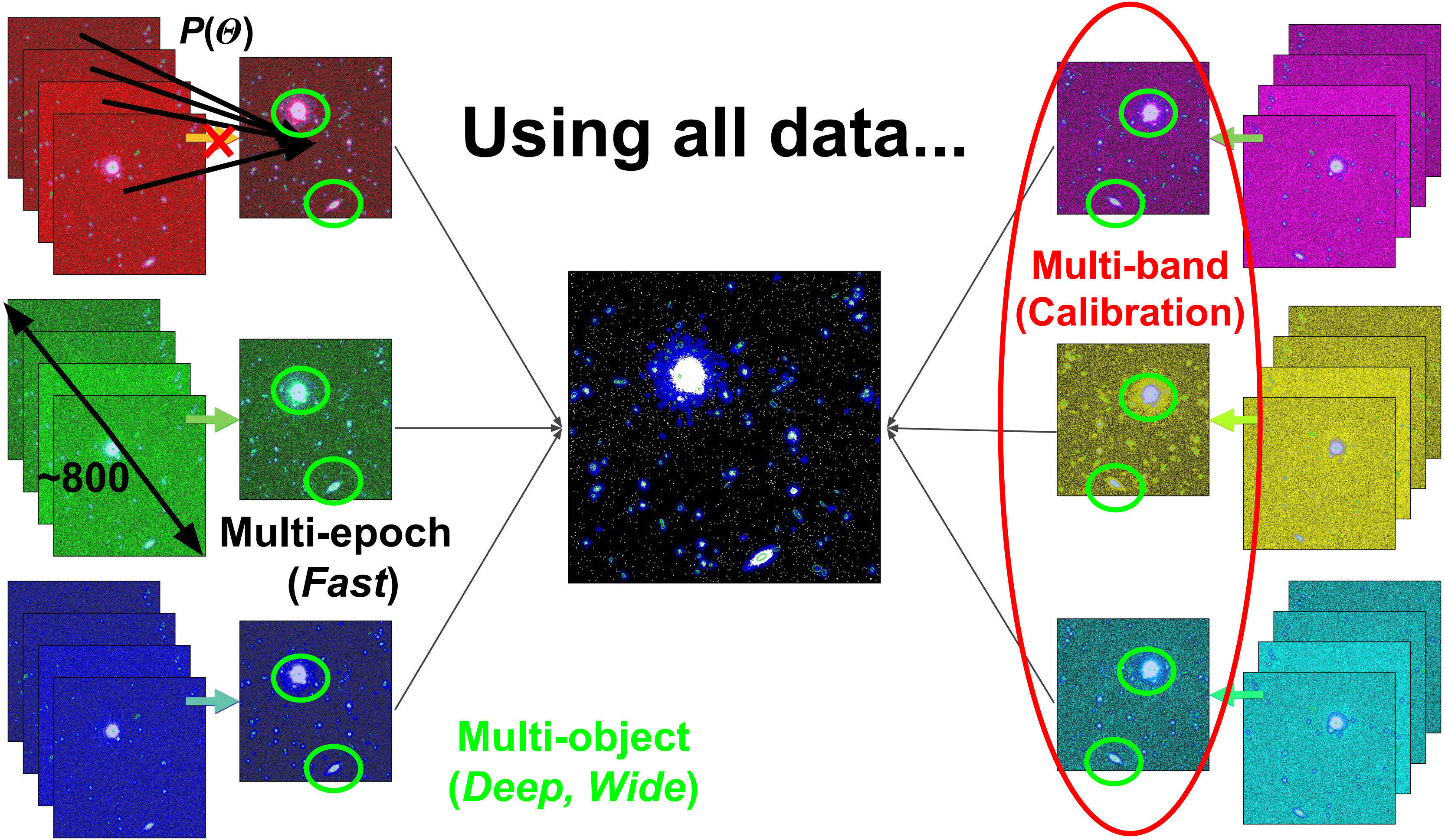




P(Θ)
Using all data...
~800
Multi-epoch
(Fast)



P(Θ)
Using all data...
~800
Multi-epoch
(Fast)
Multi-band
(Calibration)

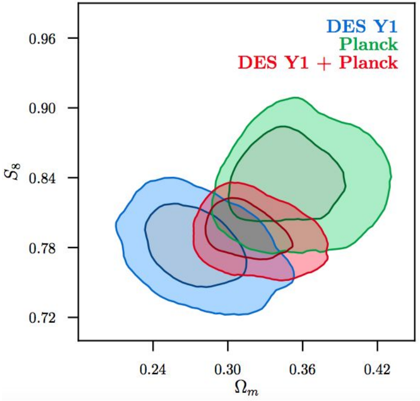


P(Θ)
Using all data...
~800
Multi-epoch
(Fast)
Multi-object
(Deep, Wide)
Multi-band
(Calibration)

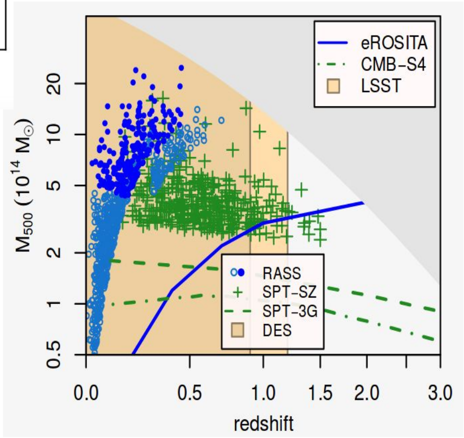
Complementary Surveys

While LSST will be revolutionary for optical astronomy and precision cosmology, there are many complementary surveys in a variety of bands that help further break degeneracies, calibrate systematics, and allow ***cross-correlation studies***:

- **Radio:** FAST
  - 21 cm HI, **Integrated Sachs-Wolfe**
- **Microwave:** Planck, SPT
  - CMB priors, **cluster CMB lensing**, **SZ effect**
- **Optical (Photometric):** SDSS, DES
  - Combined catalogs, cross-correlations
- **Optical (Spectroscopic)**: DESI, BOSS
  - Spectroscopic z measurements, Ly-α forest, BAO, RSD
- **X-Ray**: eROSITA, ATHENA
  - **Cluster ICM, Cluster Mis-centering**



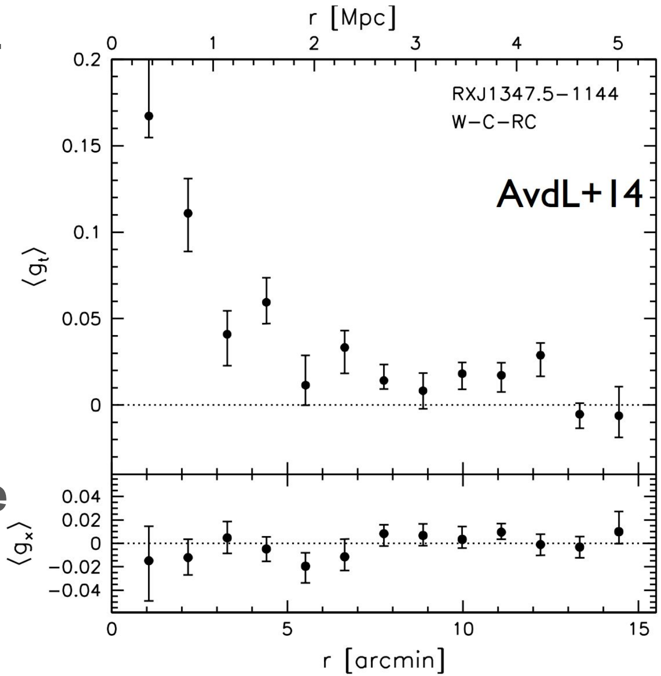
(DES Y1 Abbott et al. 2017)



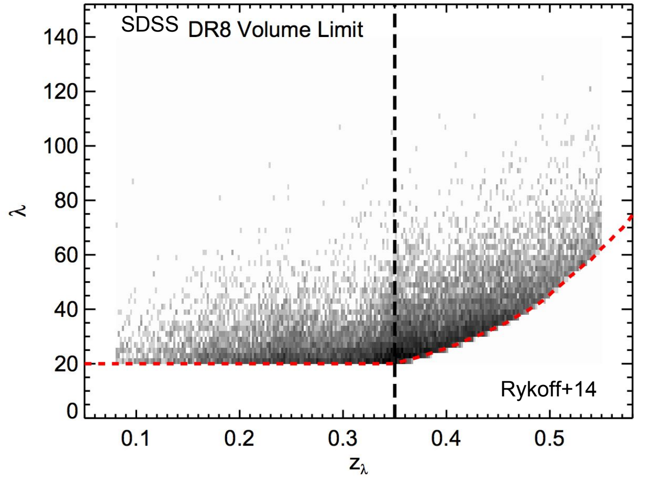
(Adam Mant'z talk)

Clusters in Optical: Weak Lensing

- Can provide the best estimates for cluster masses.
- Requires **shear** measurements and knowledge of the **galaxy redshift distribution**.
- This gives the 2D surface mass distribution.
- Additional assumptions required about **halo shape** to convert to the 3D distribution.
- Typically used to calibrate other observable-mass relations.



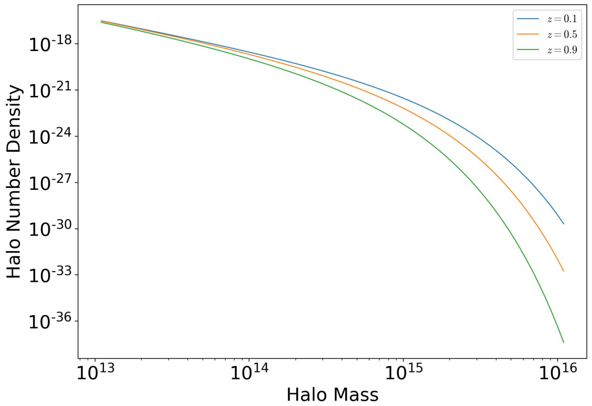
Clusters in Optical: Number Density



- We can measure a simple tracer of cluster mass, the richness, or the number of galaxies in the cluster.

- Using a **low-scatter proxy**, like weak lensing mass, we can convert richness to an estimate on mass.

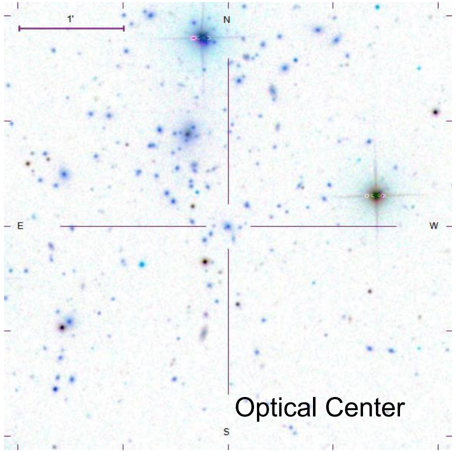
- Finally, we can arrive at cosmology by fitting the halo mass function.

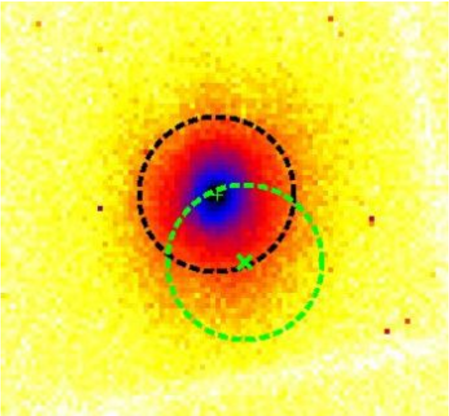


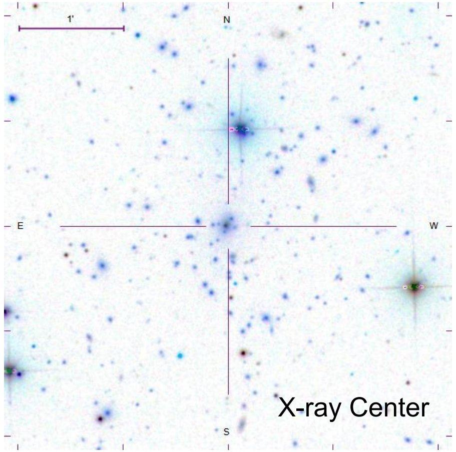
Clusters in X-ray: Miscentering

- We need to know where the centers of the clusters are to measure their 3D mass distribution.

- Optical cluster finding algorithms choose a center statistically using the **Brightest Cluster Galaxy,** but this is not always correct.

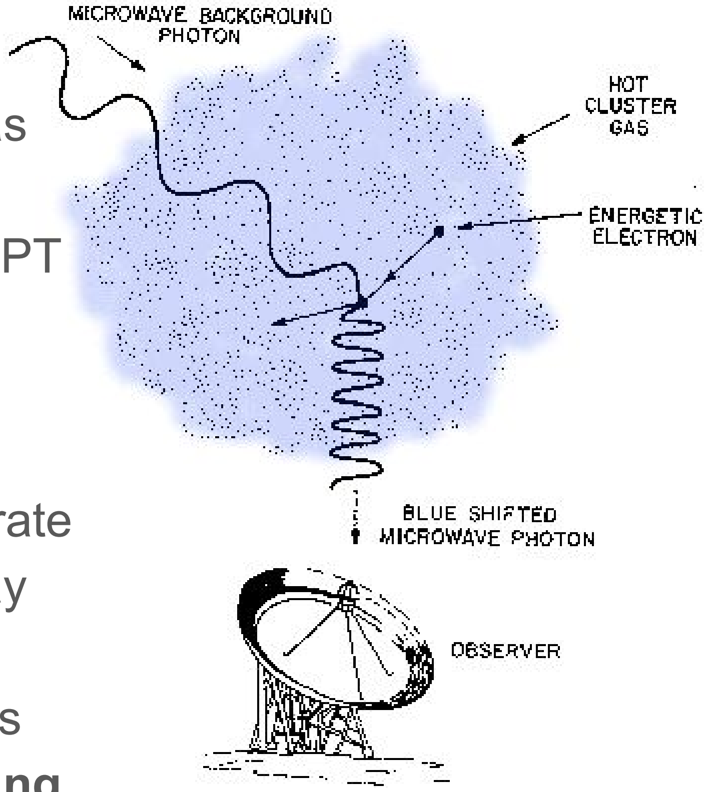






Clusters in Microwave: SZ Effect

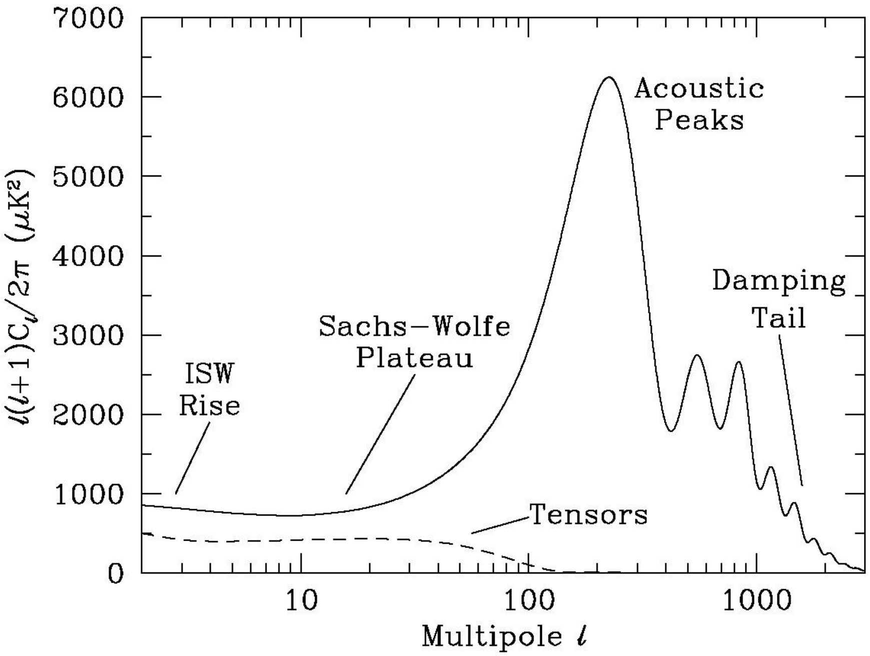
- The **SZ effect** describes how CMB photons get *up-scattered* when passing through energetic gas clouds in clusters.
- LSST will provide **optical counterparts** to the SPT SZ survey and the Planck SZ survey.
- The deep imaging offered by LSST will allow for **calibration of the mass distribution function** through gravitational lensing. This will help calibrate observable mass relations in mm-wave and X-ray maps.
- Comparison with catalogs at different wavebands will also help **improve systematics and modeling** related to cluster detection.



Cross-correlation with CMB maps

The **Integrated Sachs-Wolfe (ISW)** effect describes the process in which CMB photons are gravitationally red-(or blue-) shifted upon entering a gravitational potential, and retain some of the momentum difference upon exiting the potential well due to the change in the slope of the potential caused by the expanding universe.

This effect is the primary cause of temperature fluctuations in the CMB at low multipoles.



Cross-correlation with CMB maps

- Using **stacked galaxy samples** from LSST, cross-correlation of superclusters and voids with maps of the CMB will provide greater insight into the ISW effect.
- LSST will be able to measure ISW to **7σ precision**, greater than current efforts at 4σ correlating SDSS with Planck and WMAP.
- The ISW will be able to be measured up to z=2, enabling us to track the **evolution of the effect over cosmic time**.
- LSST will be able to place constraints on the smoothness of the dark energy potential at the 3-5% level on scales of ~1 Gpc.

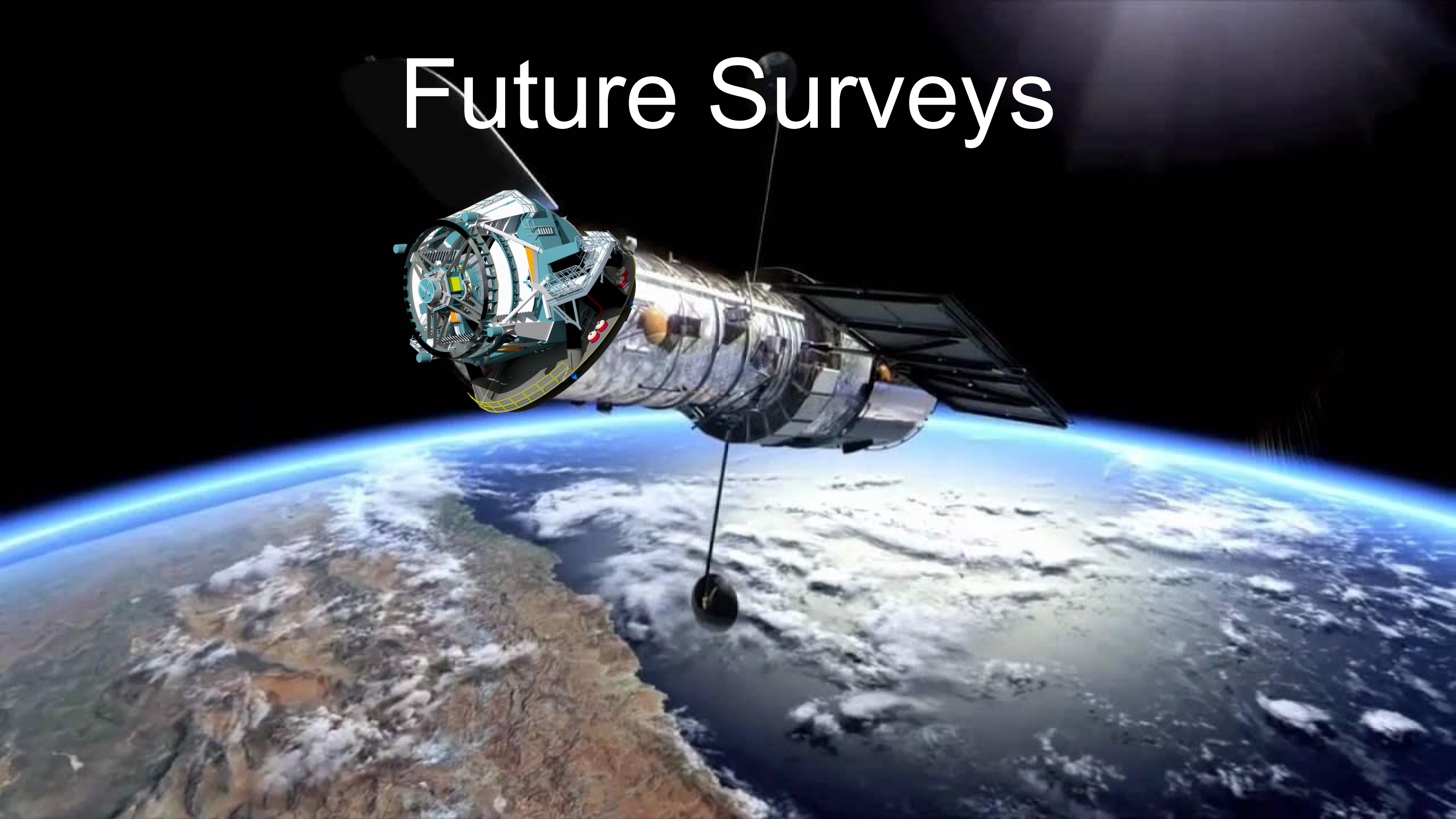
LSST / Clusters Summary

LSST cosmology constraints will be ***robust*** due to ***wide***, ***deep***, ***fast***:

- Survey data will be largely ***uniform*** and ***complete****;*
- Survey strategy will allow better techniques/calibrations (e.g. photo-z's);
- Multiple and independent cosmological probes ***break degeneracies*** in parameter space;
- LSST will be **complemented** by a variety of other surveys in many bands
  - FAST, SPT, DES, DESI, eROSITA, and many, many more…

Galaxy clusters are a nice case study of these advantages

Future Surveys



Obvious ones...

- LSST in the North

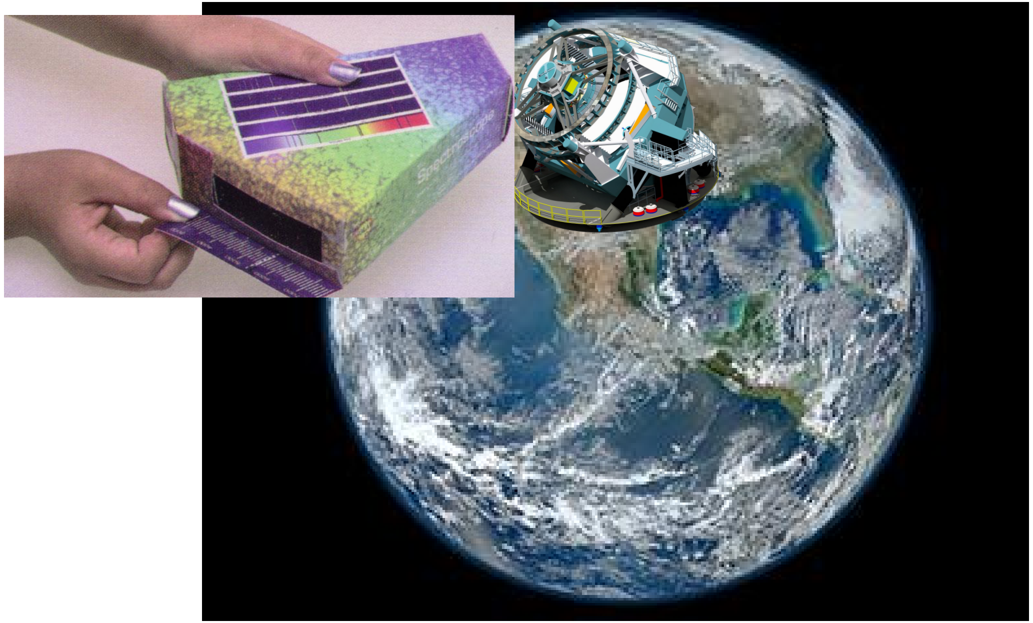
Obvious ones...

- LSST in the North

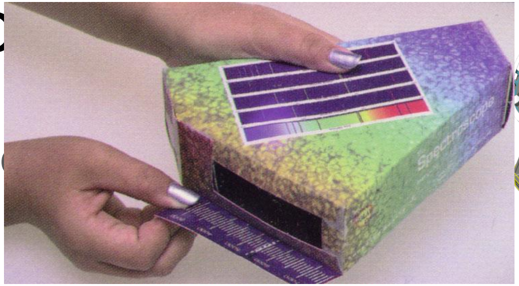
- LSST in space

Obvious ones...

- LSST in the North
- LSST in space
- LSST with spectra



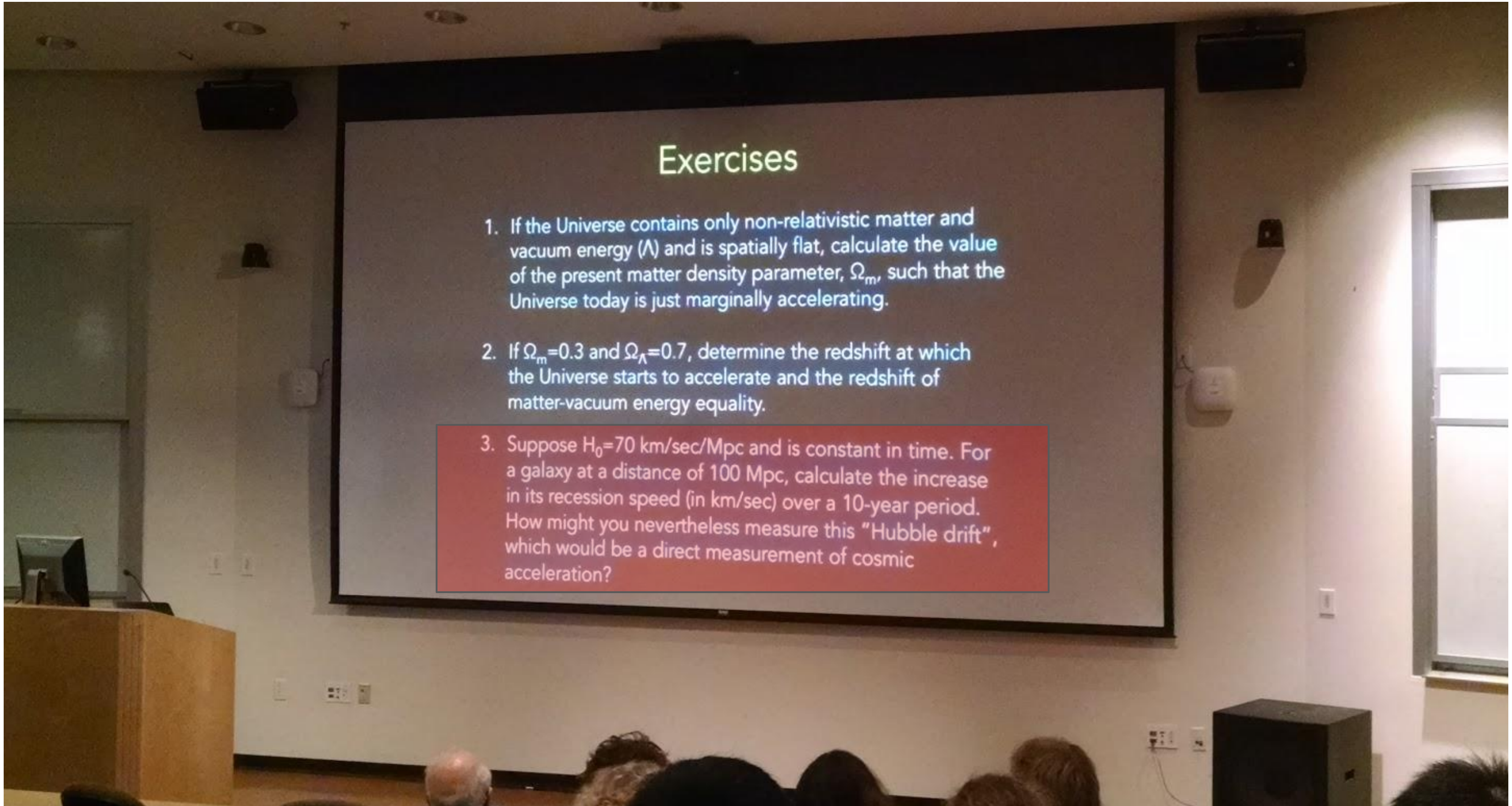
Obvious c



- LSST in th
- LSST in space
- LSST with spectra
- LSST in space with spectra

Redshift-drift

⇒ Independent cosmological probe!
Measures *dynamics*.



Redshift-drift is a 1 part in a billion effect

The redshift $z(t_o)$ is related to the scale factor $a(t)$ by

$$1 + z(t_o) = \frac{a(t_o)}{a(t_e)} \quad (1)$$

where t_o is the time of observation, and t_e the time of emission.

The derivative w.r.t. t_o is

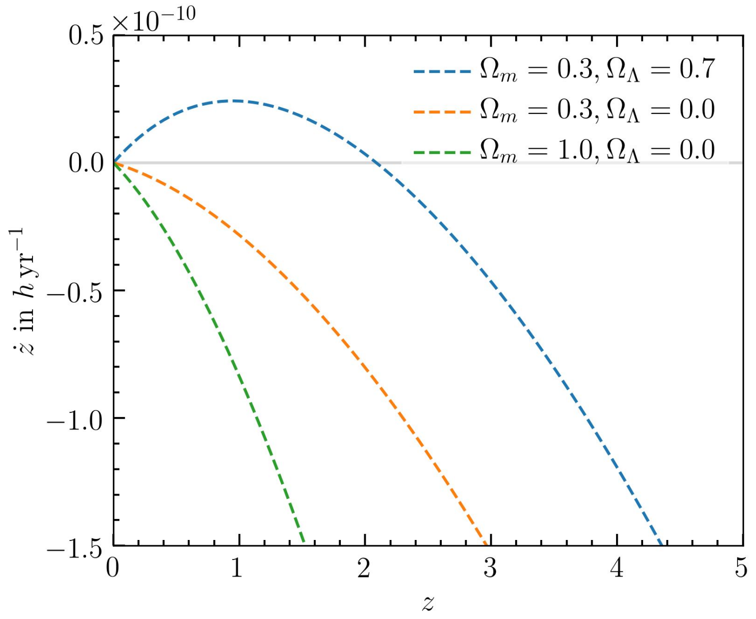
$$\dot{z}(t_o) = \frac{\dot{a}(t_o)}{a(t_o)}\frac{a(t_o)}{a(t_e)} - \frac{a(t_o)}{a^2(t_e)}\frac{da(t_e)}{dt_e}\frac{dt_e}{dt_o} \quad (2)$$

Since $H = \dot{a}/a$ and $dt_e/dt_o = 1 + z$, we get

$$\boxed{\dot{z}(t_o) = (1+z)\,H_0 - H(z)} \quad (3)$$

The Hubble parameter is

$$H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}} = 10^{-10}\,h\,\mathrm{yr^{-1}} \quad (4)$$



10 years ⇒ ~1 part in a billion

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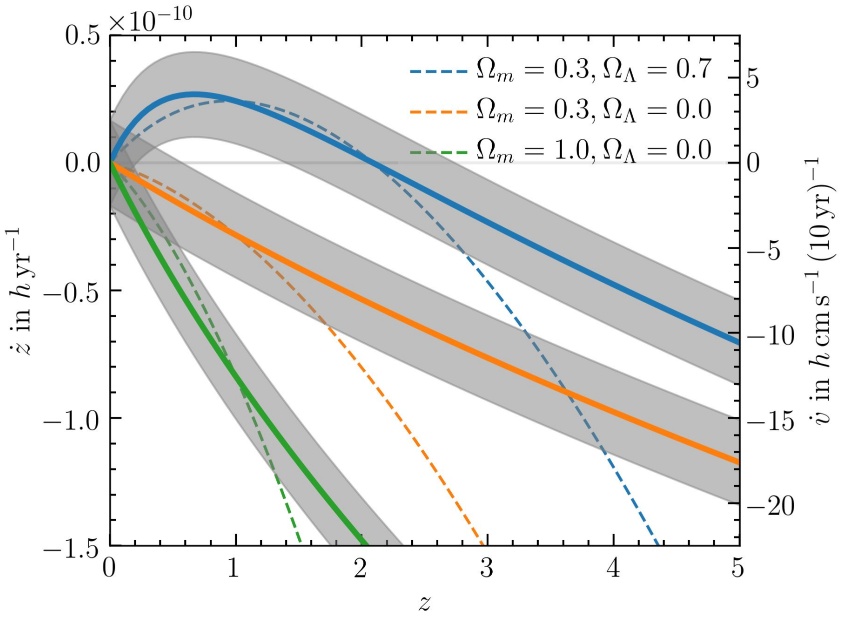
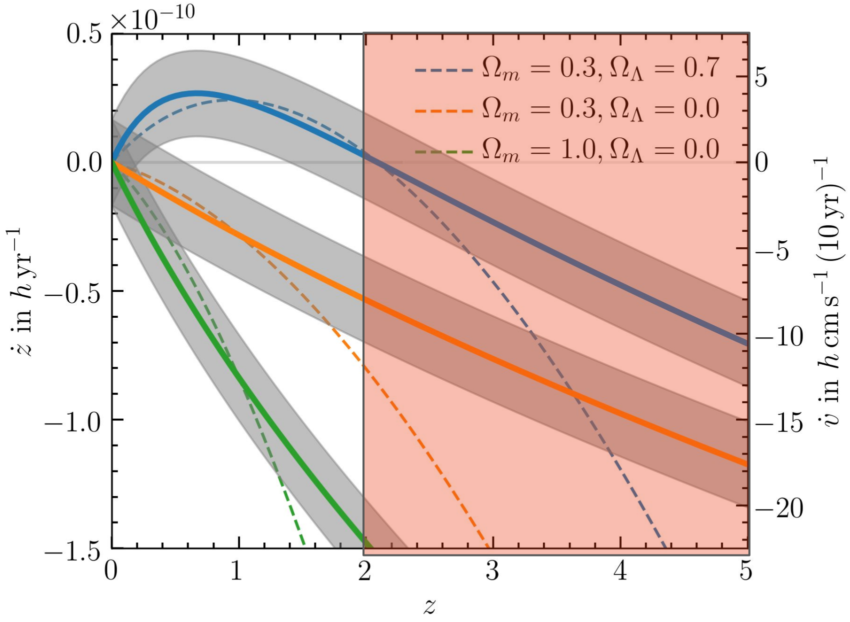


10 years ⇒ ~1 part in a billion

Is it feasible?

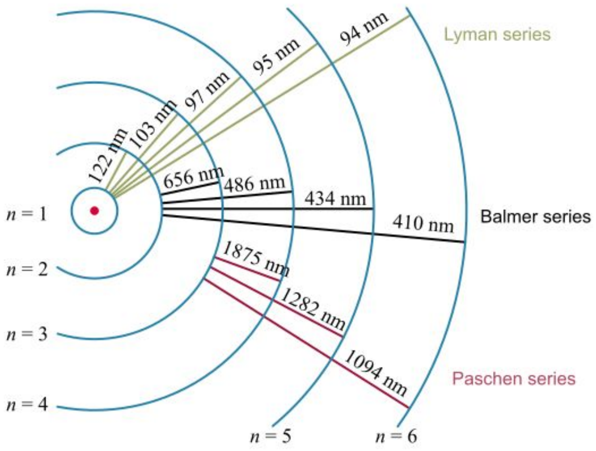
- Exoplanet spectrographs: ~ 30 cm/s   (maybe 2.5 cm/s?)
- Object of choice needs to satisfy criteria (Liske etal 2008):
  - Trace Hubble flow
  - Sharp spectral features (~30-35 km/s)
  - Large number of spectral features
  - Bright
  - Exist over a large redshift range

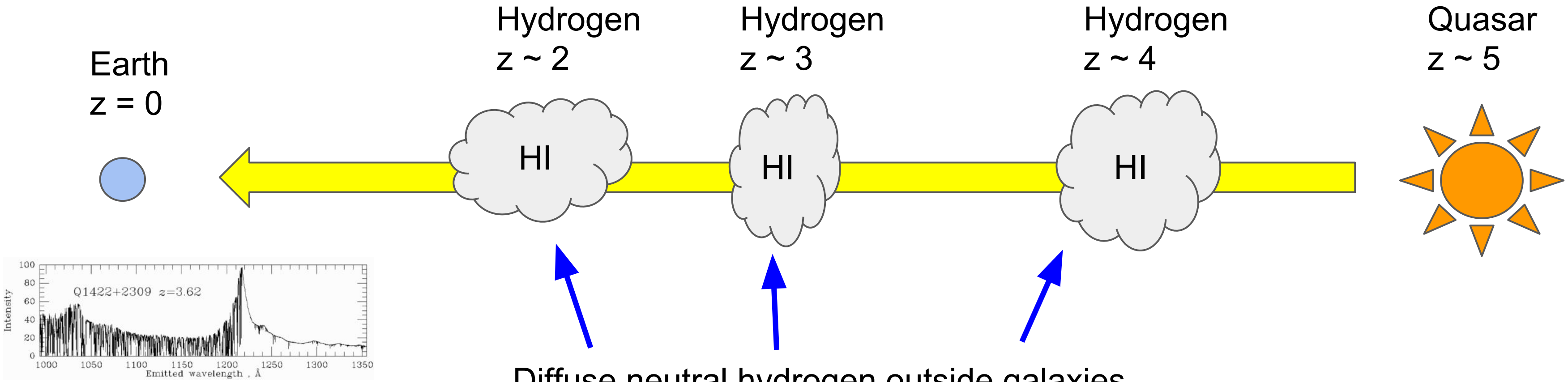


Use Lyman-α forest!

Lyman-α forest

1216 Å = 121.6 nm

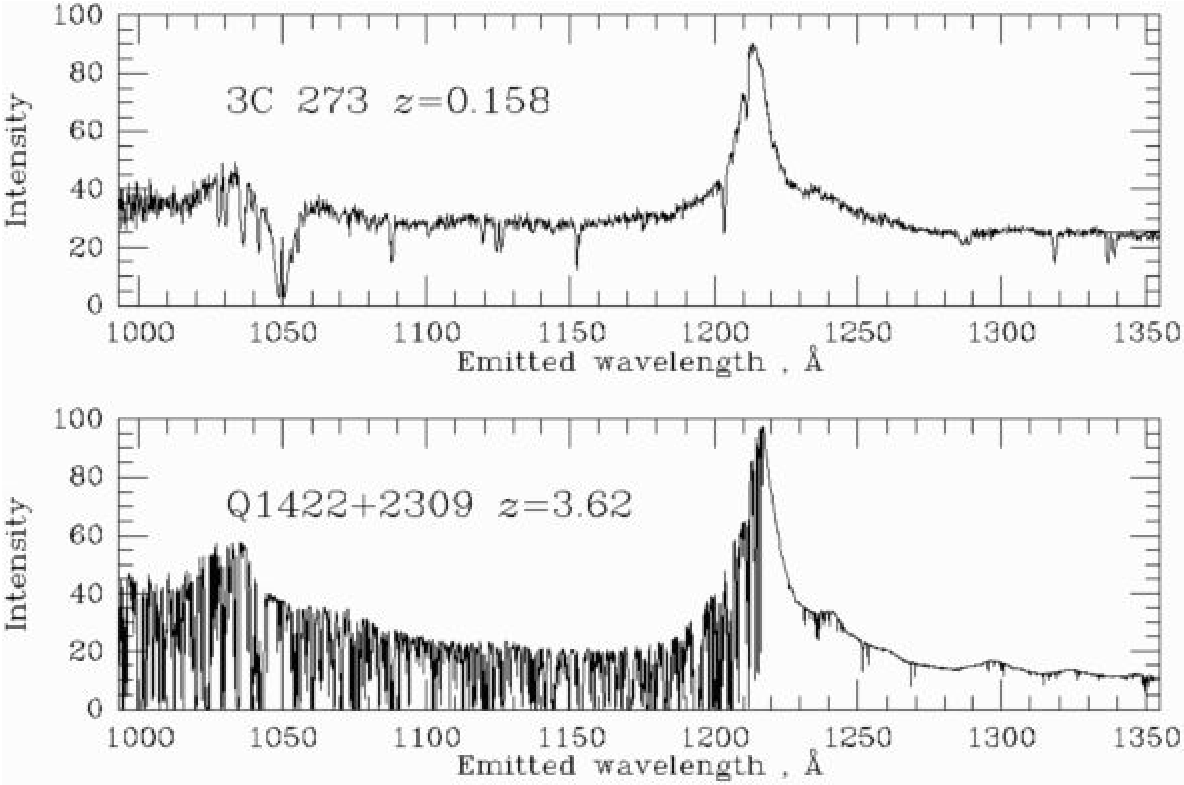




Diffuse neutral hydrogen outside galaxies absorbs Lyman-α.

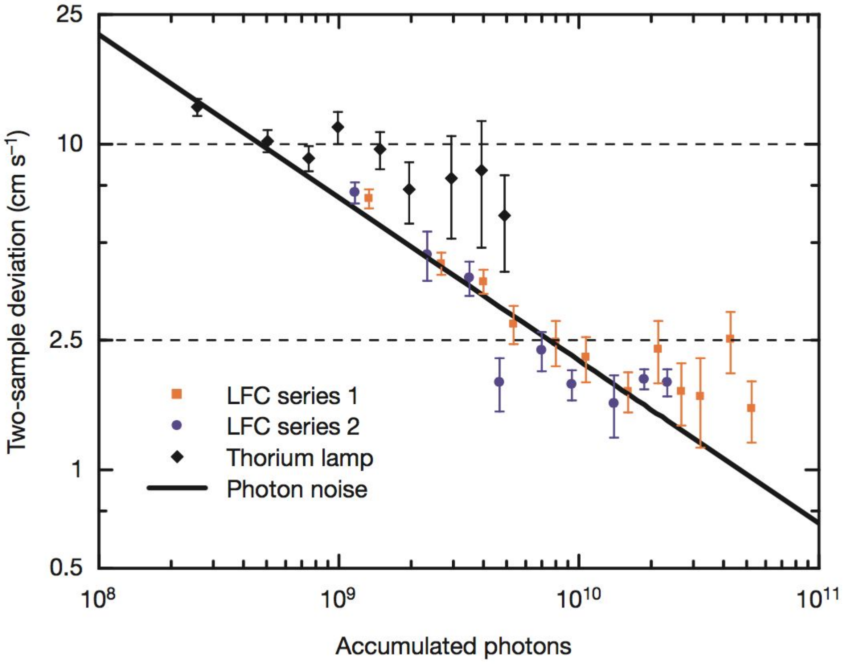
Lyman-α forest

~100-500 absorption lines per QSO

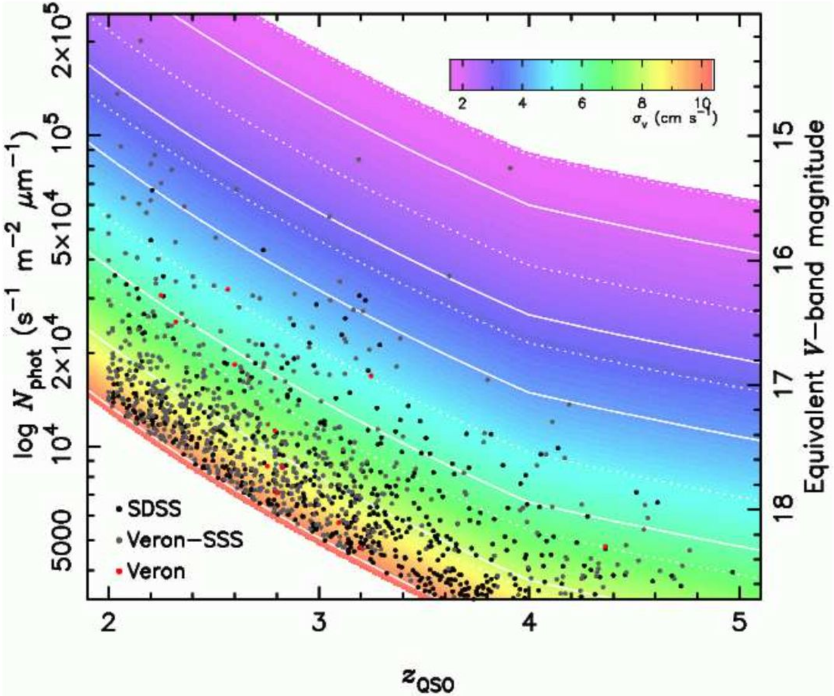


Telescope Design

Laser Frequency Comb



See Wilken et al, doi:10.1038/nature11092



Telescope Design

Number of photons from a QSO detected by a telescope:

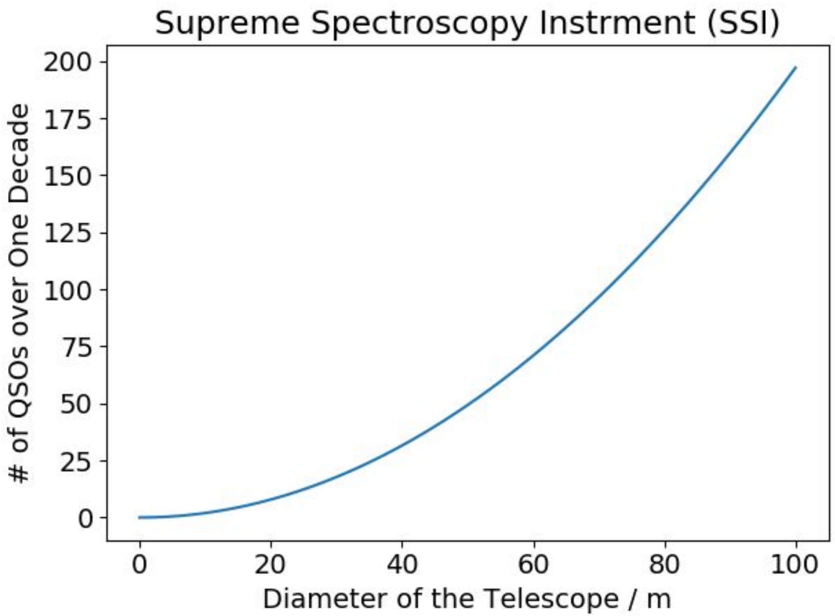
$$N_{photon} = \epsilon * N_{QSO\_flux} * A * \Delta\lambda * t$$

Assuming photon-noise limited, the exposure time to achieve 2.5 cm s^{-1} sensitivity for single absorption line:

$$t = \frac{N_{photon}}{\epsilon * N_{QSO} * A * \Delta\lambda} = \frac{10^{10}}{0.25 * 5000\, s^{-1} m^{-2} um^{-1} * \pi * \left(\frac{D}{2}\right)^2 * 0.25nm} \approx 4 * \frac{10^{10}}{D^2} s\, m^2$$

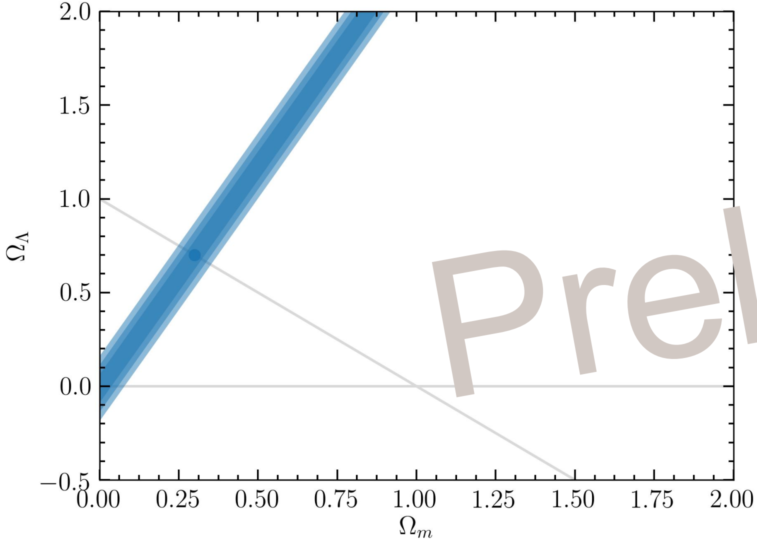
E.g. **D = 40 m**, t ~ 7000 h; assuming ~10^2 lines, **t ~ 700 h** (~ 1 month).

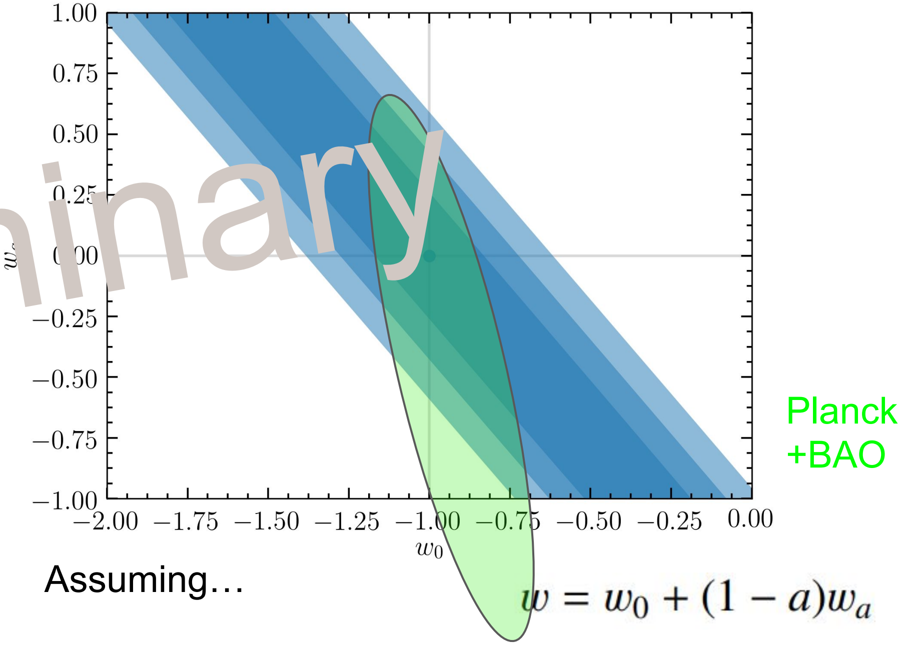
Telescope Design



Over one decade, having a D~50m telescope that operates ¼ of the time, we will be able to have high resolution spectroscopy for ~50 QSOs.

Cosmological constraints from redshift-drift





Assuming…

… 2.5 cm/s per line

… 100 lines 2 < z < 5

… over 10 years

… 3 parameters: Ω_m, Ω_Λ, H_0

Assuming…

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

… 1000 lines 2 < z < 5

… 3 parameters: Ω_m, w_0, w_a, Ω_k=0

Conclusion

Redshift-drift is an independent *dynamical* probe of cosmology.

Redshift-drift is hard, but possible to detect!

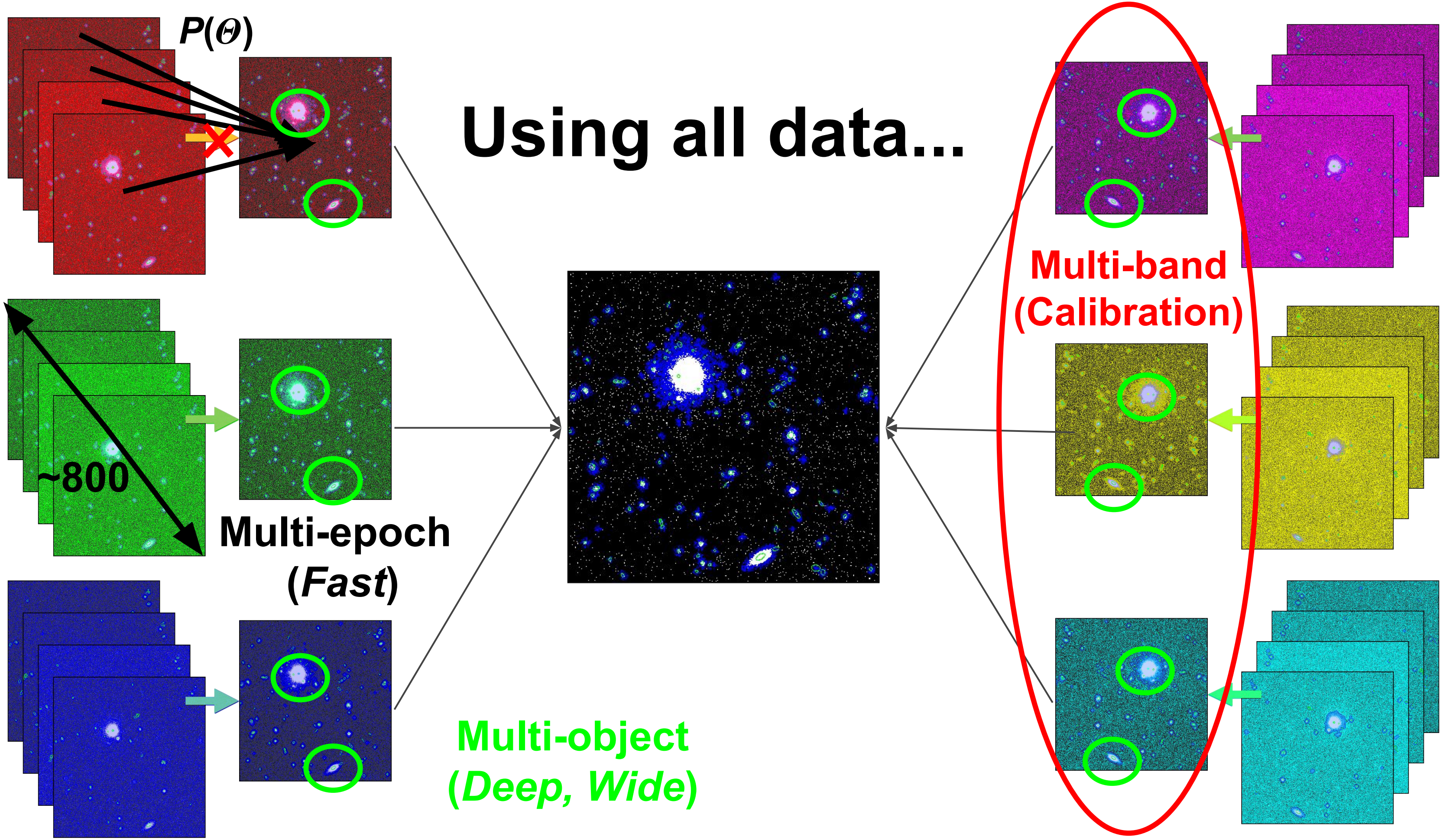
Redshift-drift can give competitive constraints with a single dedicated 50m telescope observing for two decades.

Useful papers

Sandage, A., 1962, ApJ, vol. 136, p.319

J. Liske et al, Cosmic dynamics in the era of Extremely Large Telescopes

2014, JJ Geng: Parameter estimation with Sandage-Loeb test https://arxiv.org/pdf/1407.7123.pdf



Using all data...
P(Θ)
~800
Multi-epoch
(Fast)
Multi-object
(Deep, Wide)
Multi-band
(Calibration)

Error estimate

Photon noise limited

$$\sigma_v = 2\left(\frac{S/N}{2370}\right)^{-1}\left(\frac{N_{QSO}}{30}\right)^{-1/2}\left(\frac{1+z_{QSO}}{5}\right)^{-1.7}\ \mathrm{cm\,s^{-1}}$$

R >= 30000

Z_X: zero-point in X-band

$$\frac{S}{N} = 700\left[\frac{Z_X}{Z_r}\ 10^{0.4(16-m_X)}\left(\frac{D}{42\,\mathrm{m}}\right)^2\frac{t_{int}}{10\,\mathrm{h}}\ \frac{\epsilon}{0.25}\right]^{1/2}$$

Z_r: 8.88×10^{-10} s^{-1} m^{-2} μm^{-1}

m_X: apparent magnitude

D, t_{int}, ε: telescope diameter, integration time, efficiency

(Eqs(15) and (26) in Liske et al)

Exercise Q3

August 18, 2017

Suppose H0=70 km/sec/Mpc and is constant in time. For a galaxy at a distance of 100 Mpc, calculate the increase in its recession speed (in km/sec) over a 10-year period. How might you nevertheless measure this ?Hubble drift?, which would be a direct measurement of cosmic acceleration?

$$H = \frac{\dot{a}}{a} \tag{1}$$

$$d = ax \tag{2}$$

where d is the distance between galaxies and x is the comoving distance, i.e. $\dot{x} = 0$. Therefore,

$$\dot{d} = \dot{a}x = Hd \tag{3}$$

The change in recession speed is

$$\ddot{d} = H\dot{d} = H^2 d \tag{4}$$

as H is constant in time.

Plug in $d = 100\text{Mpc}$ and $H = 70\text{km/sec/Mpc}$.

$$\begin{aligned} \ddot{d} &= 490,000 \frac{\text{km}^2}{\text{sec}^2\text{Mpc}} \\ &= \frac{(4.9E5)(3.24078E-20)}{3.17098E-8} \frac{\text{km}}{\text{sec yr}} \\ &= 5.0078 \times 10^{-7}\text{km/sec/yr} \end{aligned} \tag{5}$$

So over 10 years, the recession speed increases by 5.0078×10^{-6}km/sec, or 5mm/sec.

Redshift-drift: Sandage-Loeb test

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THE CHANGE OF REDSHIFT AND APPARENT LUMINOSITY OF GALAXIES DUE TO THE DECELERATION OF SELECTED EXPANDING UNIVERSES

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(With an Appendix by G. C. McVITTIE, University of Illinois Observatory, Urbana)

Received February 2, 1962; revised April 13, 1962

ABSTRACT

The redshift and apparent luminosity of any given galaxy are not constant with time for most models of the expanding universe. Redshifts decrease with time because of the braking action of the gravitational field in all exploding models, except for the one where the matter density is zero. Apparent luminosities decrease with time, except for the oscillating model in the contracting phase and for galaxies with very large $\Delta\lambda/\lambda_0$ values, because the distances between galaxies are increasing Redshifts increase with time for every galaxy in the steady-state model.

The theory and numerical results of the deceleration are presented for four selected world models. For a galaxy with redshift $z = \Delta\lambda/\lambda_0 = 0.4$ at the present epoch, the change of redshift with time is found

"Impossible with current technology"

Redshift-drift: Sandage-Loeb test

DIRECT MEASUREMENT OF COSMOLOGICAL PARAMETERS FROM THE COSMIC DECELERATION OF EXTRAGALACTIC OBJECTS

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ABSTRACT

The redshift of all cosmological sources drifts by a systematic velocity of order a few meters per second over a century as a result of the deceleration of the universe. The specific functional dependence of the predicted velocity shift on the source redshift can be used to verify its cosmic origin and to measure directly the values of cosmological parameters, such as the density parameters of matter and vacuum, Ω_M and Ω_Λ, and the Hubble constant H_0. For example, an existing spectroscopic technique, which was recently employed in planet searches, is capable of uncovering velocity shifts of this magnitude. The cosmic deceleration signal might be marginally detectable through two observations of $\sim 10^2$ quasars set a decade apart, with the HIRES instrument on the Keck 10 m telescope. The signal would appear as a global redshift change in the Lyα forest templates imprinted on the quasar spectra by the intergalactic medium. The deceleration amplitude should be isotropic across the sky. Contamination of the cosmic signal by peculiar accelerations or local effects is likely to be negligible.

Subject heading: cosmology: theory

Measure for 100 years!