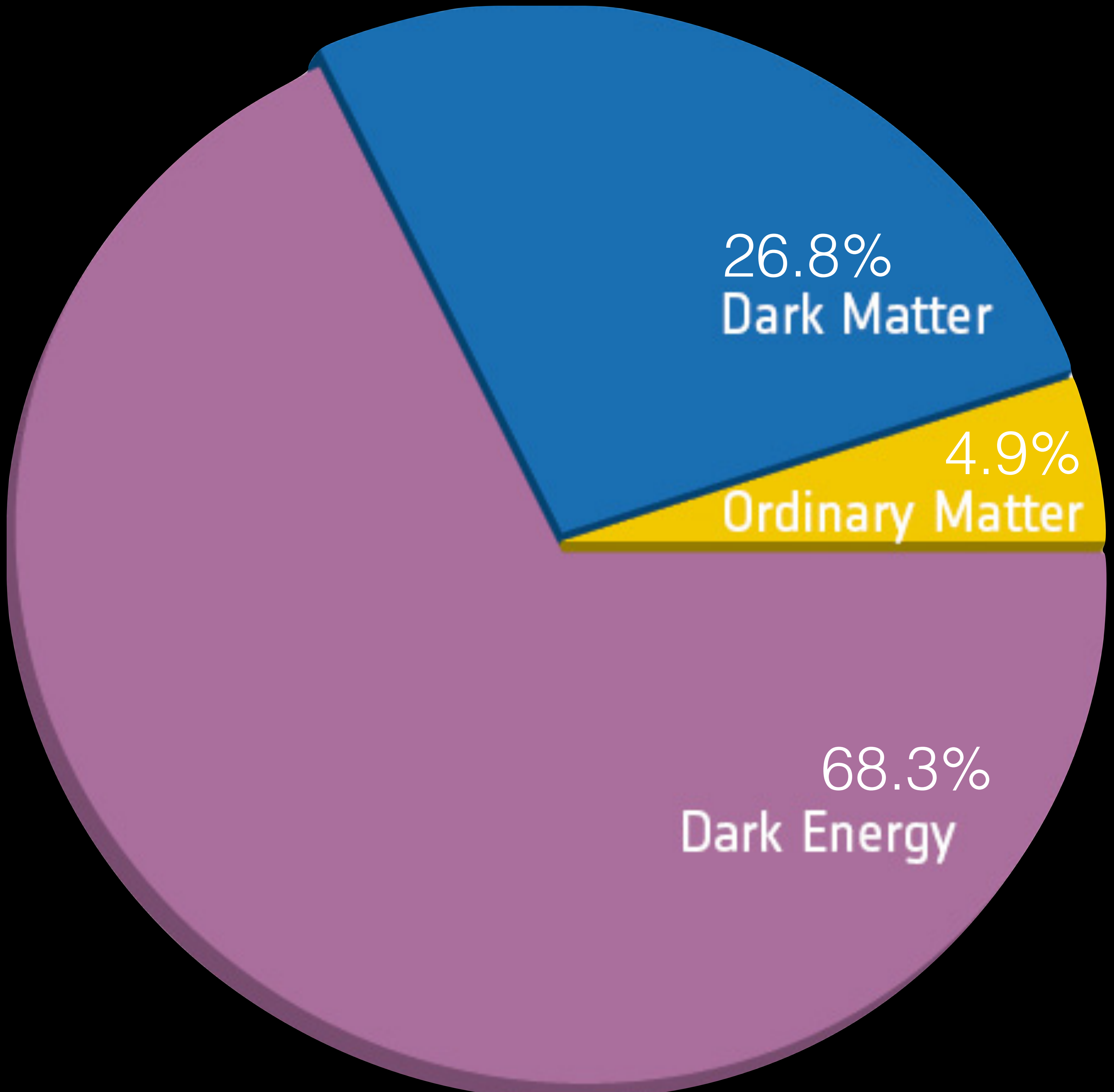
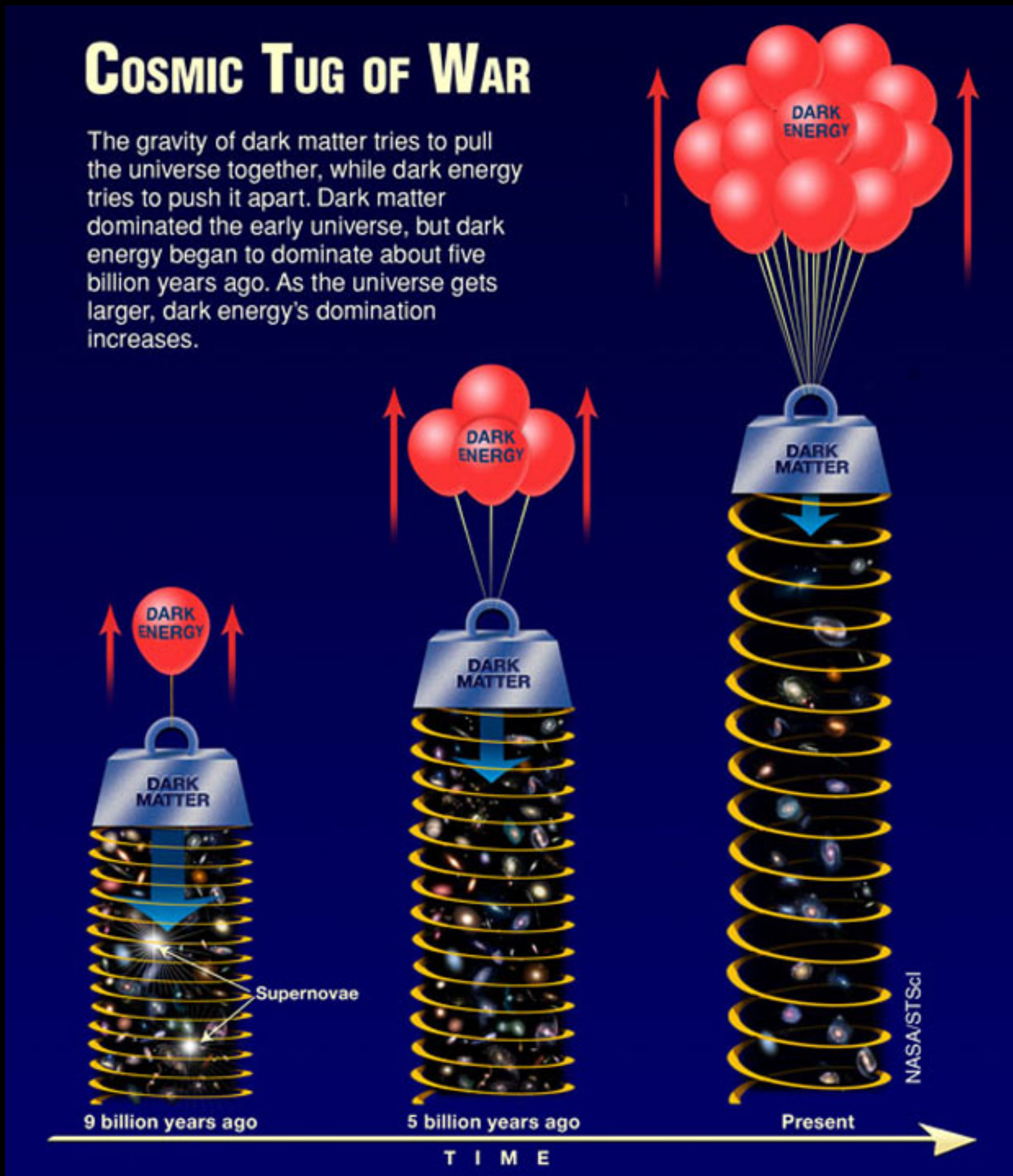
Dark Energy Surveys

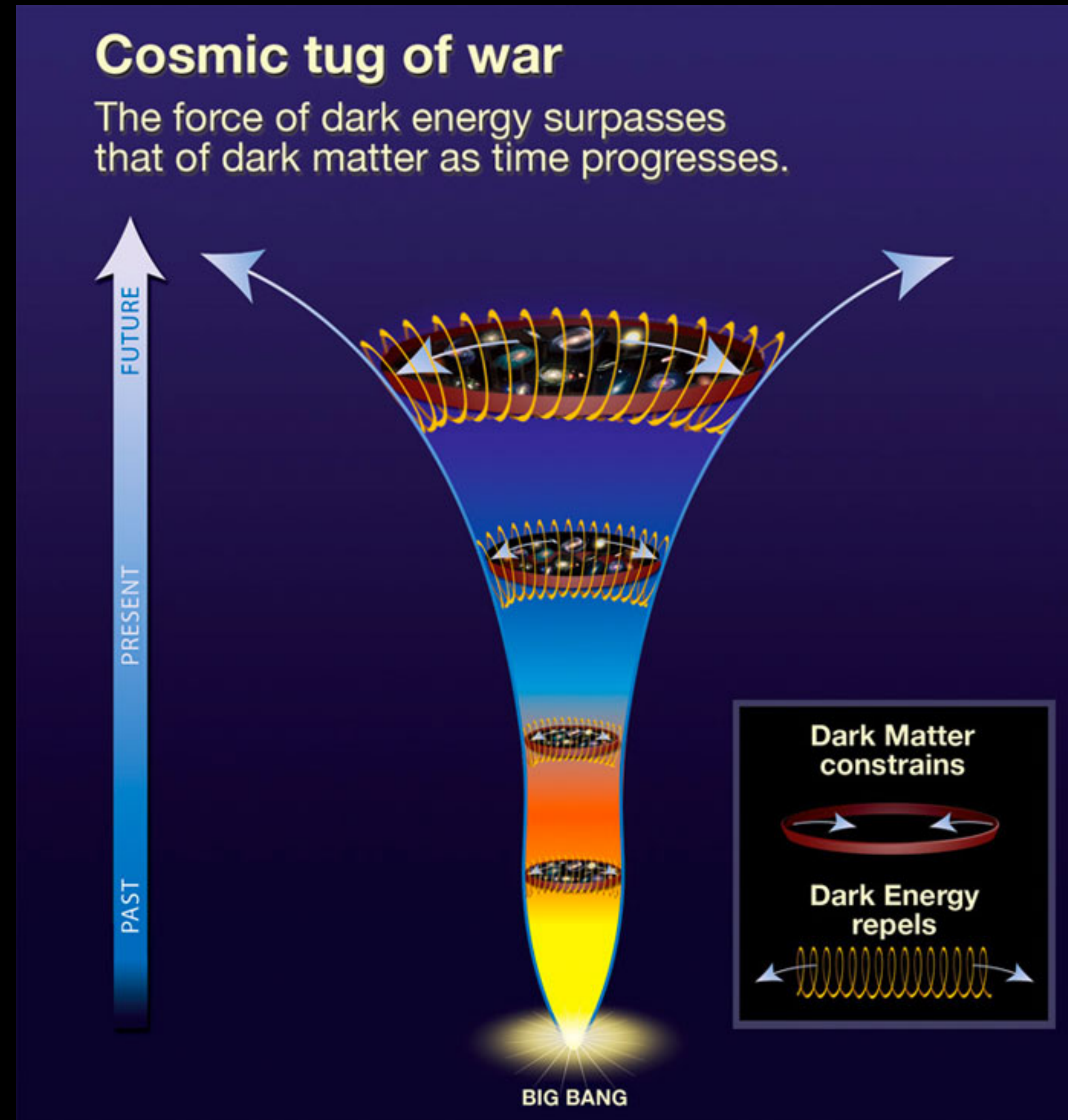
Juan Estrada

Fermilab

LEPTON PHOTON 2015

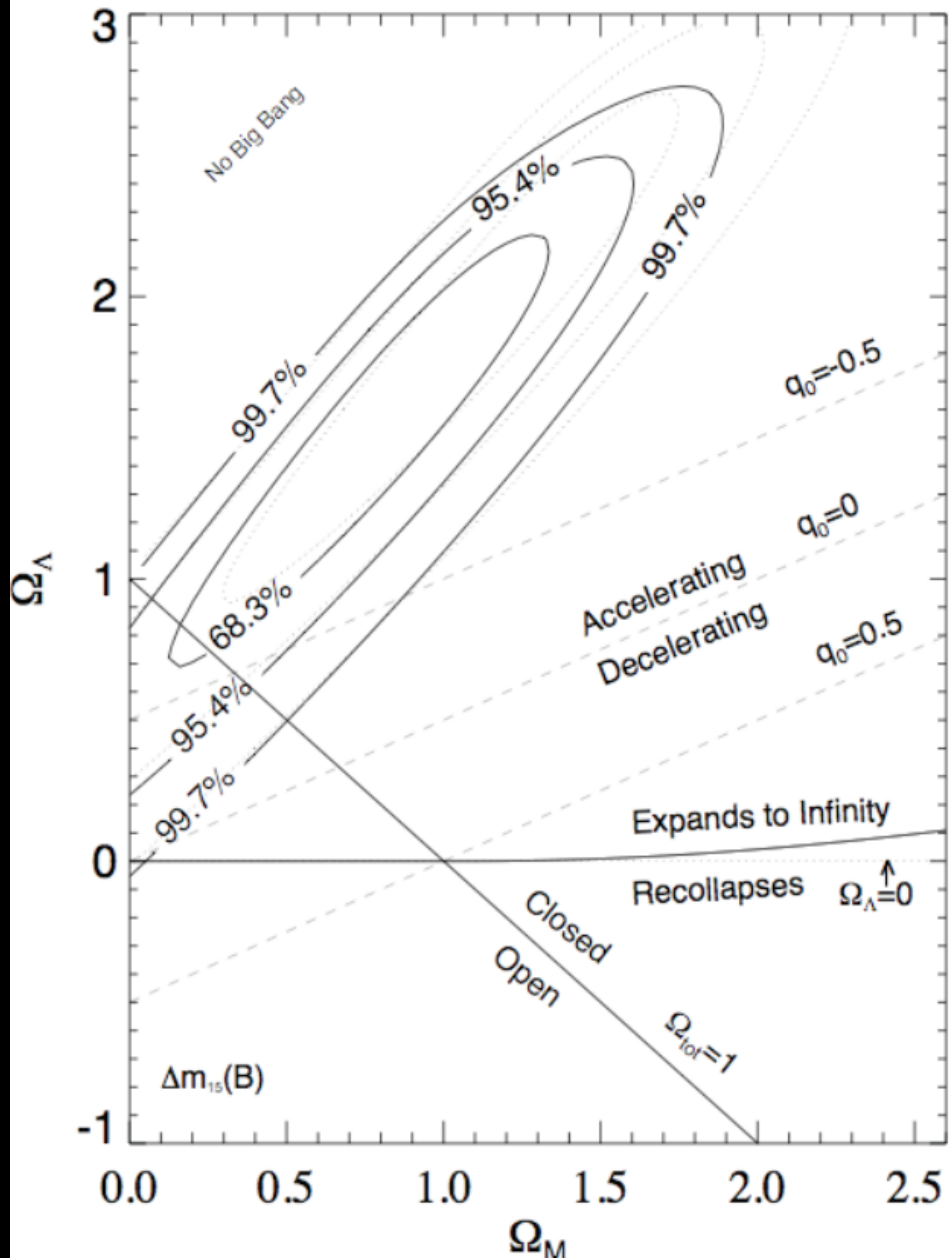

26.8%
Dark Matter
4.9%
Ordinary Matter
68.3%
Dark Energy





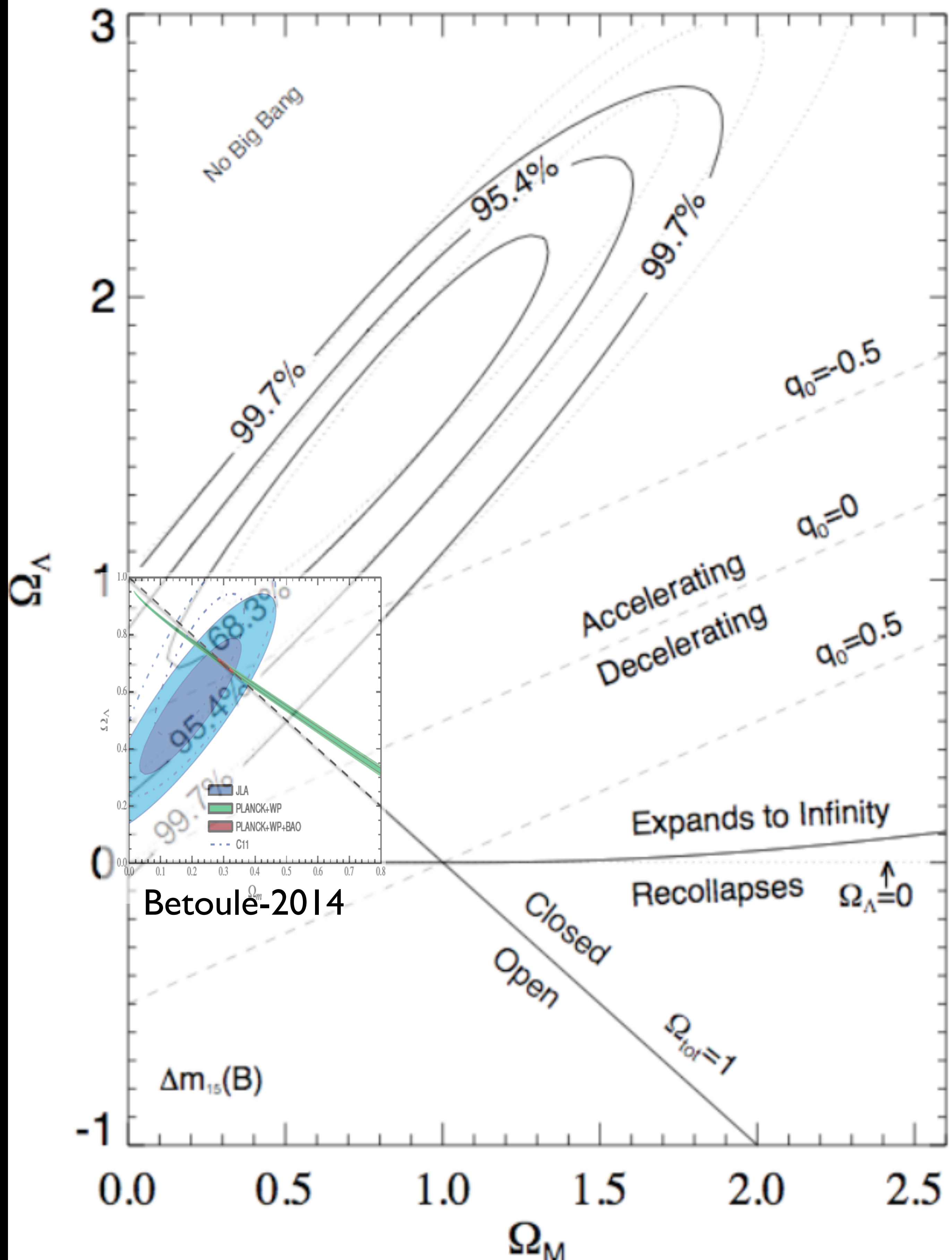
National Aeronautics and Space Administration

Riess et al. (1998, AJ)



Huge progress seen in the last 14 years.

Riess et al. (1998, AJ)



Betoule-2014

Hubble constant H determines the rate of expansion and depends on density

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3}$$

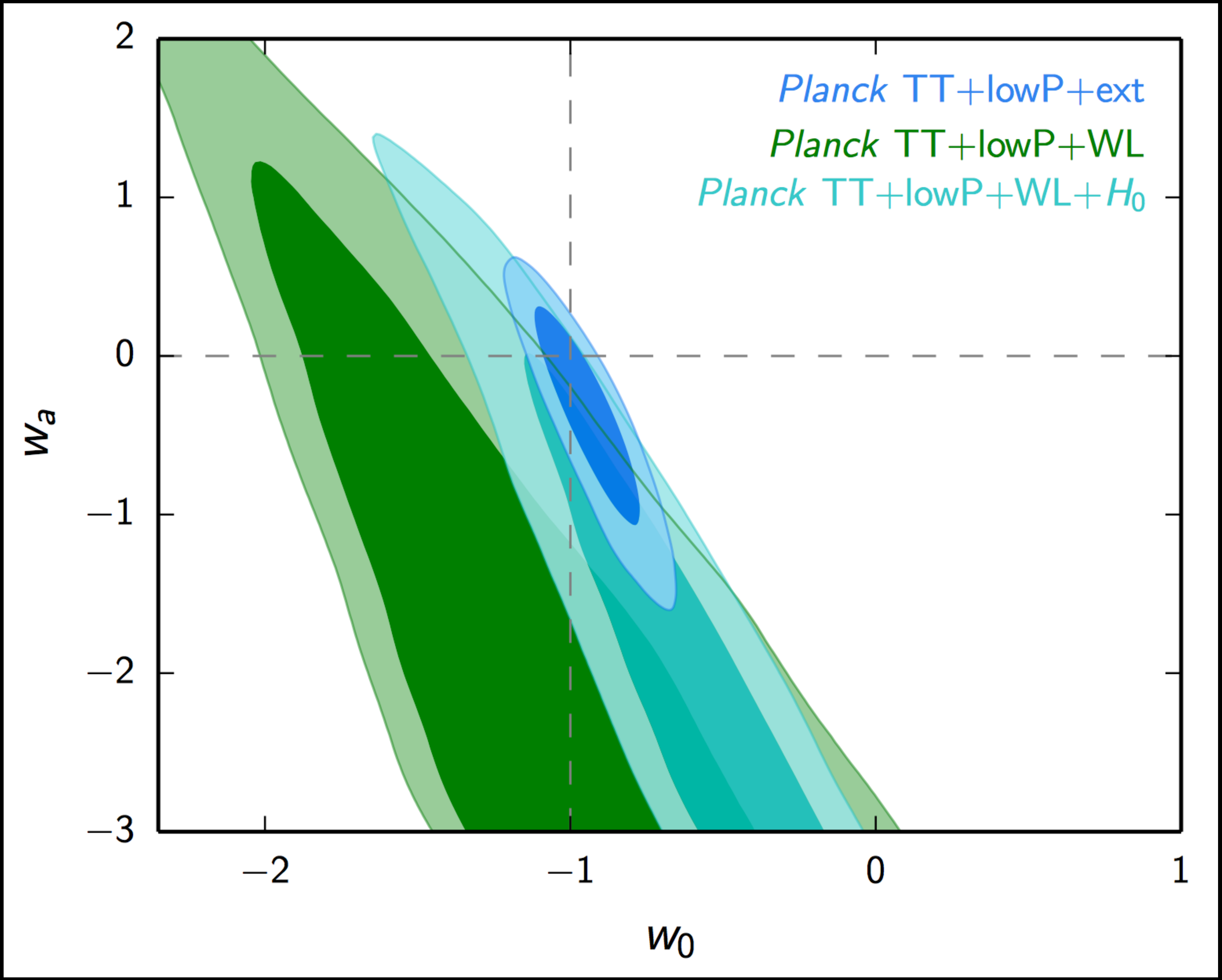
the density for mass goes down with the expansion and DE density does not if w=-1

$$\frac{R_{now}}{R_{then}} = 1 + z \qquad \text{R=a}$$

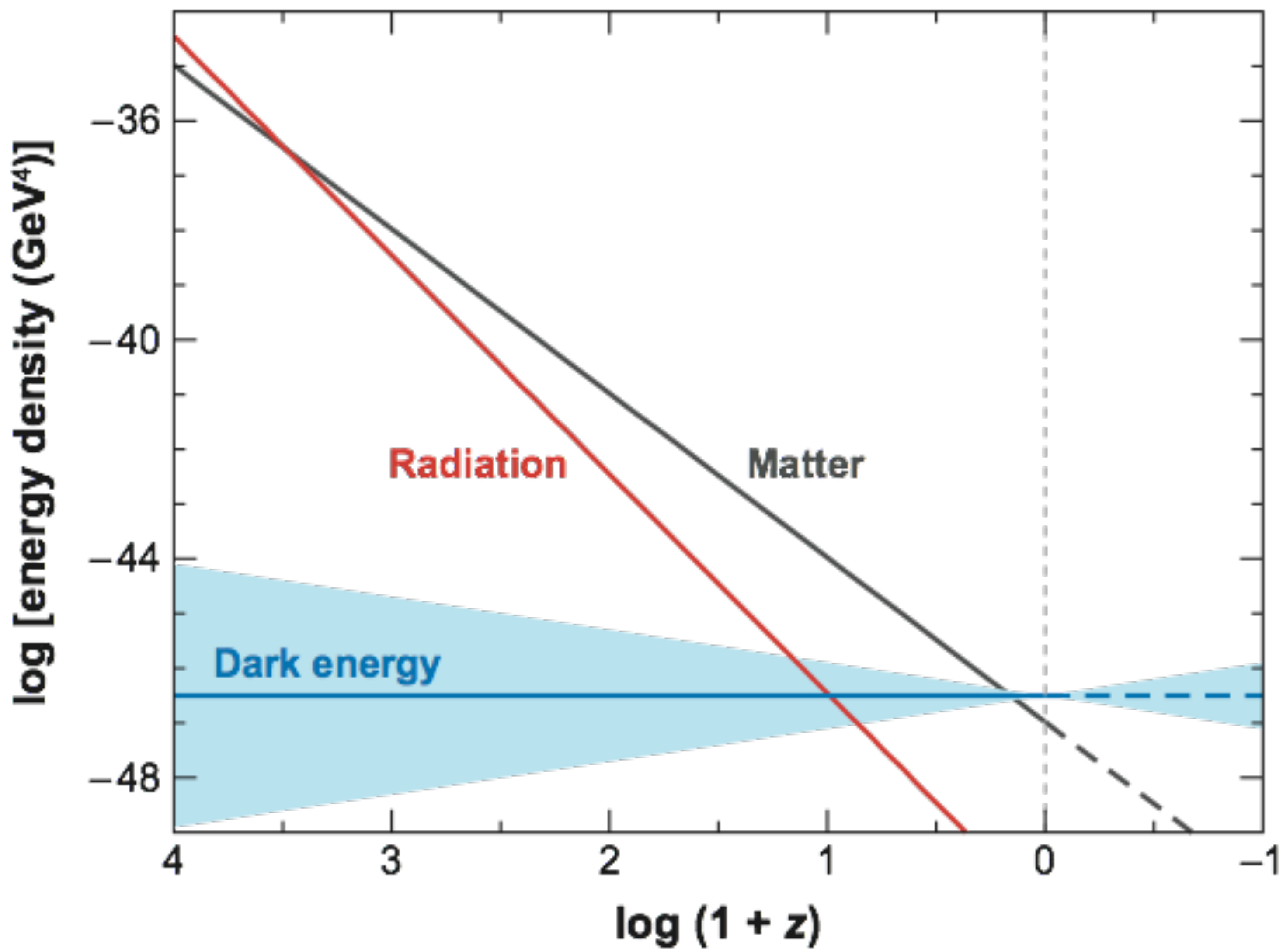
$$H^2 = H_0^2\left[\Omega_m (1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}\right]$$

<u>the goal is measure "w" and how it changes with time</u>

Planck Collaboration Cosmological Results (Ade et al 2015)



time dependence is parameters as $w(a) = w_0 + w_a(1 - a(t)/a_0)$



Evolution of radiation, matter, and dark energy densities with redshift. For dark energy, the band represents $w = -1 \pm 0.2$.

the data is converging to a very interesting situation, where we have the privilege to observe matter and dark energy in “balance”.

Geometry and structure:
Dark Energy also inhibits the growth of structure.

$$H^2 = H_0^2\left[\Omega_m(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}\right]$$

distance calculations

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

supernovae as standard candles
geometry

evolution of structure (growth)

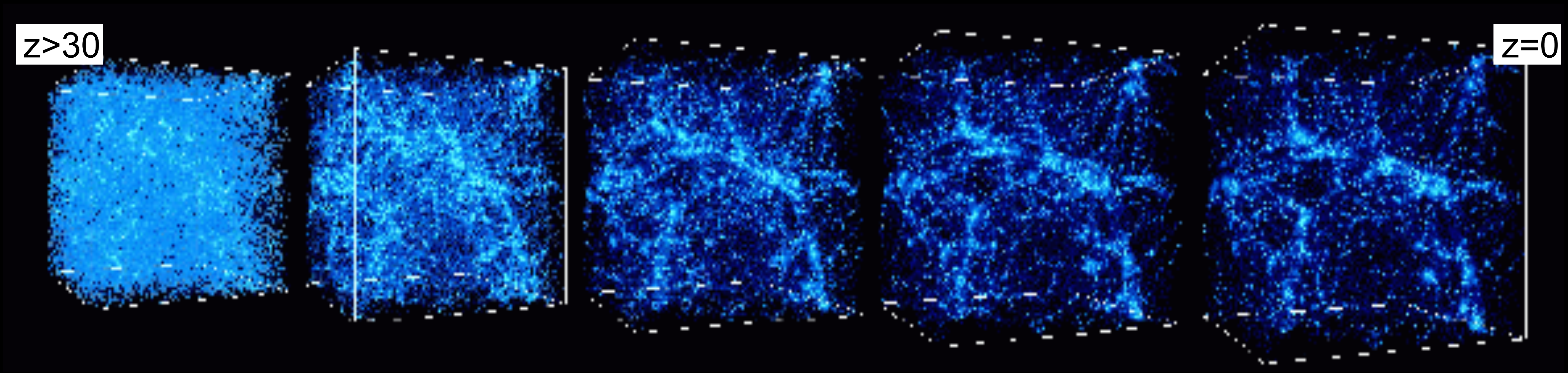
$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_m\delta = 0$$

large scale structure
structure

two measurable consequences of dark energy

Four Probes of Dark Energy:

Complementary techniques to characterize dark energy



Expansion and gravity

1.Count the Galaxy Clusters as a function of red shift and cluster mass

2.Measure the distortion in the apparent shape of galaxies due to intervening galaxy clusters and associated clumps of dark matter (Weak Lensing)

Expansion

3. Measure the spatial clustering of galaxies as a function of red shift (Baryon Acoustic Oscillations)

4. Use Supernovae as standard candles to measure the expansion rate

Two ways to determine redshift

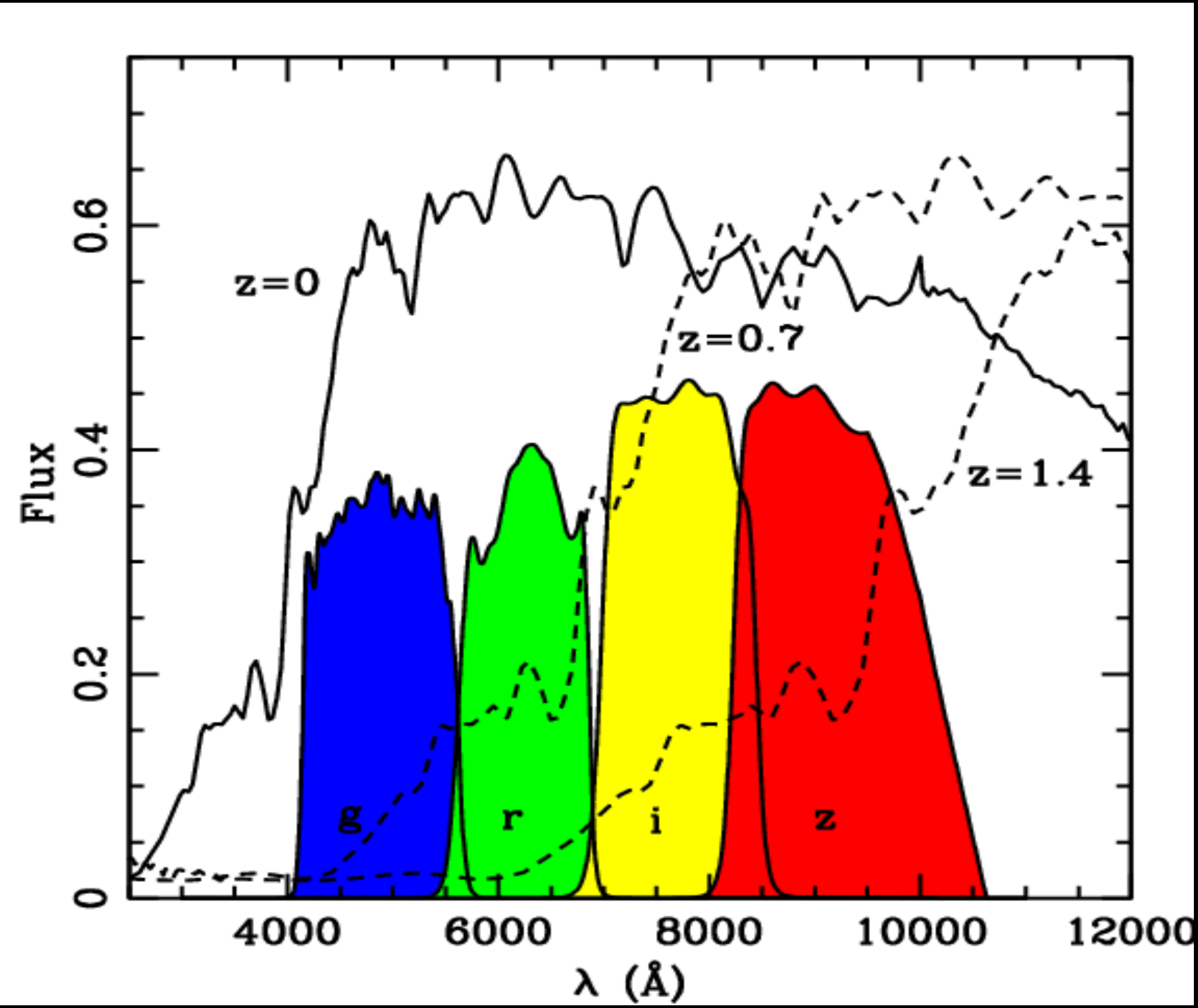
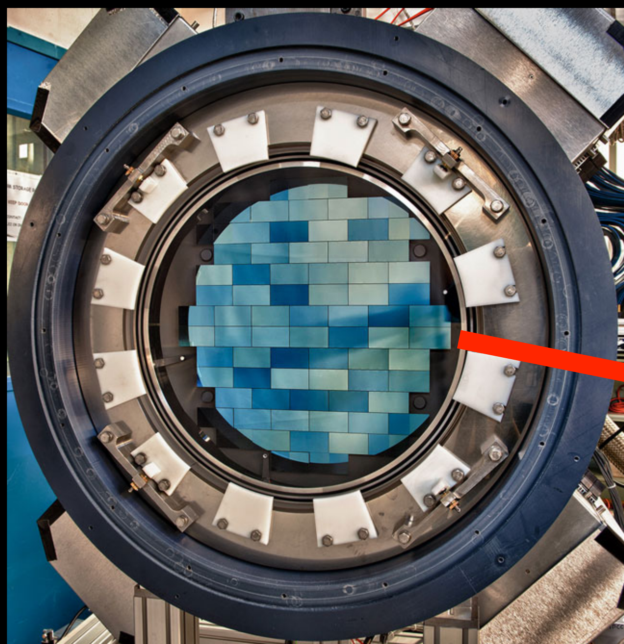


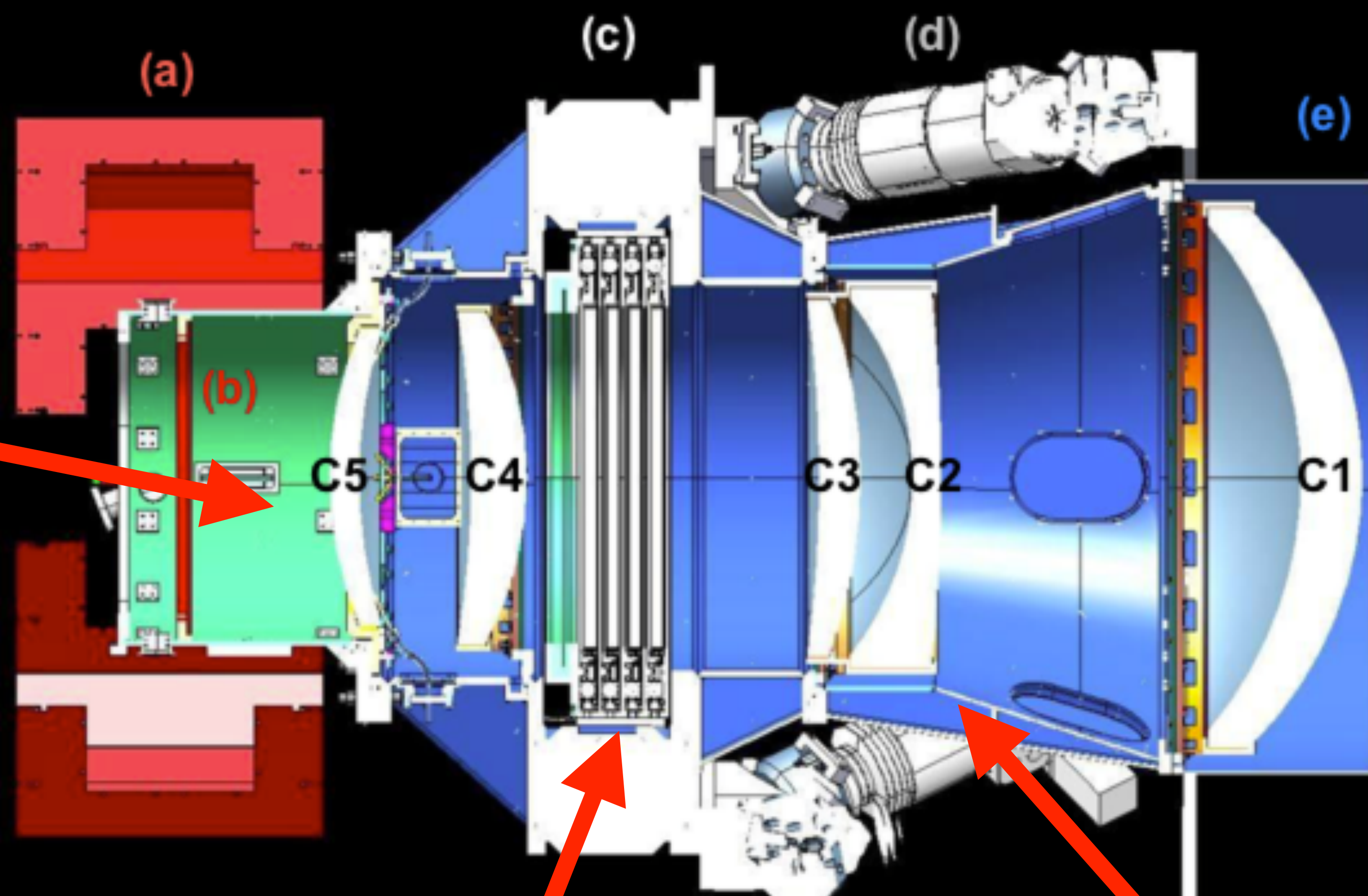
Photo-Z : imaging with few filters

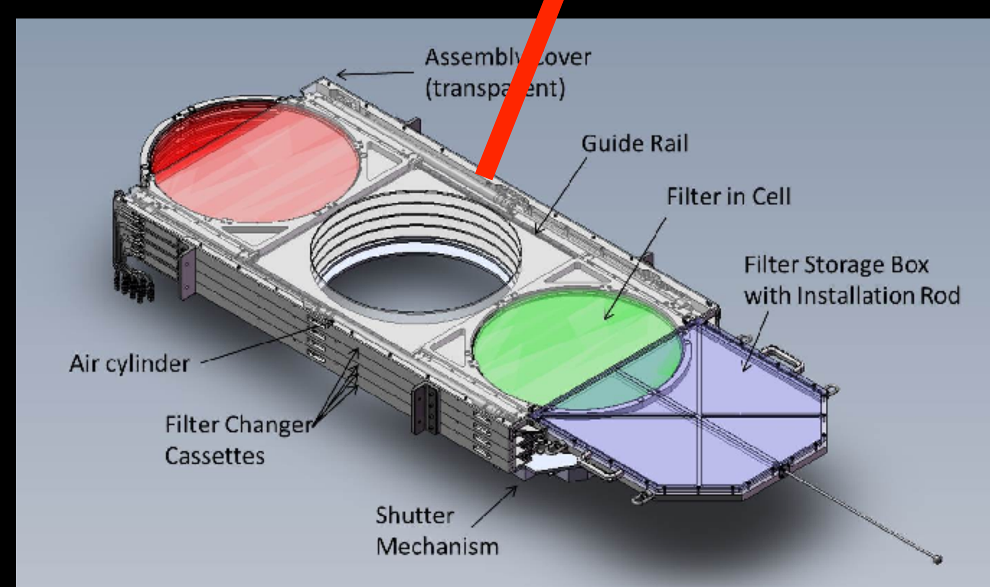
spectroscopy : spectrum of pre-selected objects

Traditional Photo-Z machine : DECam



focal plane
with many
CCD sensors
(600Mpix)

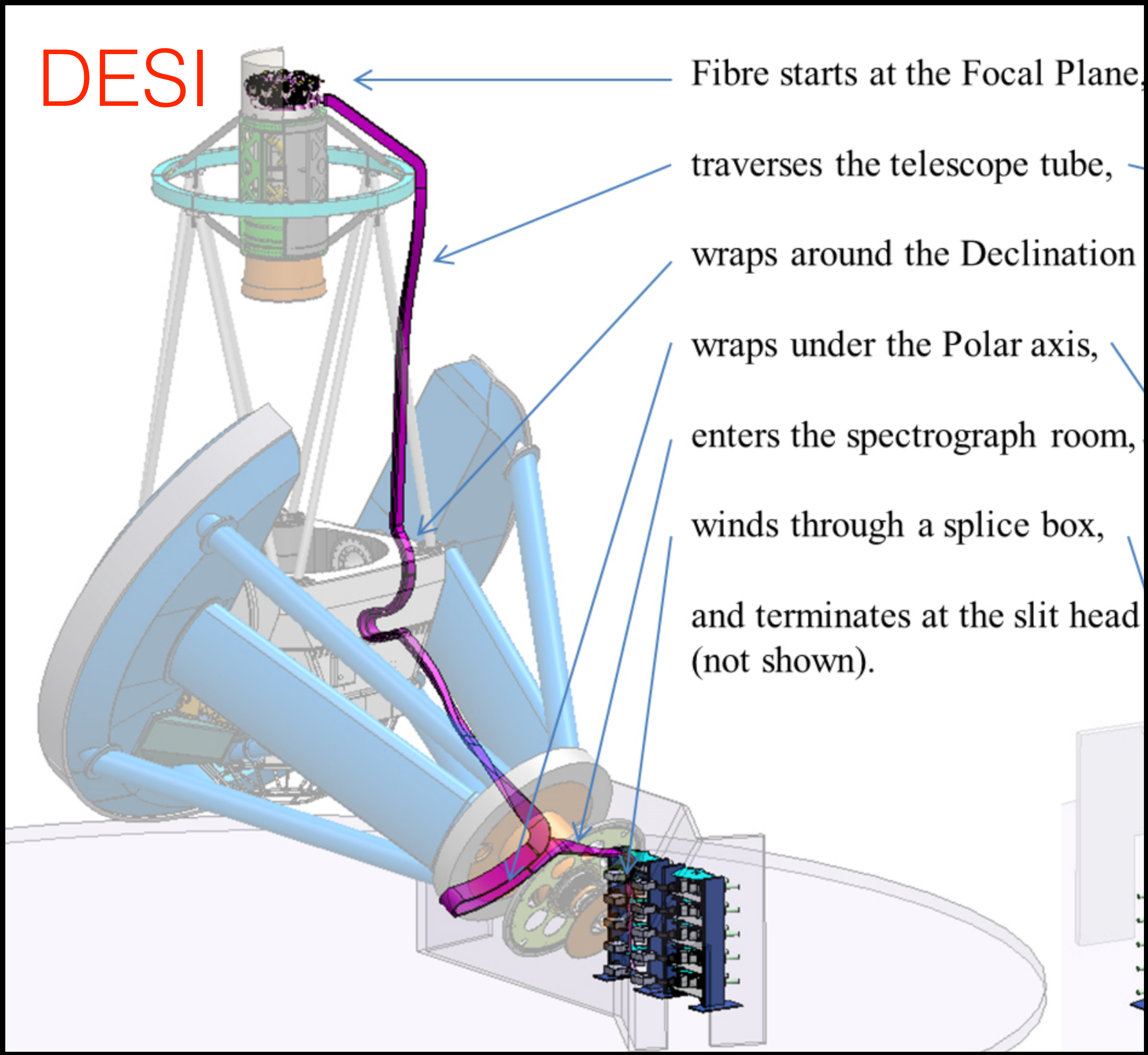




filter changer

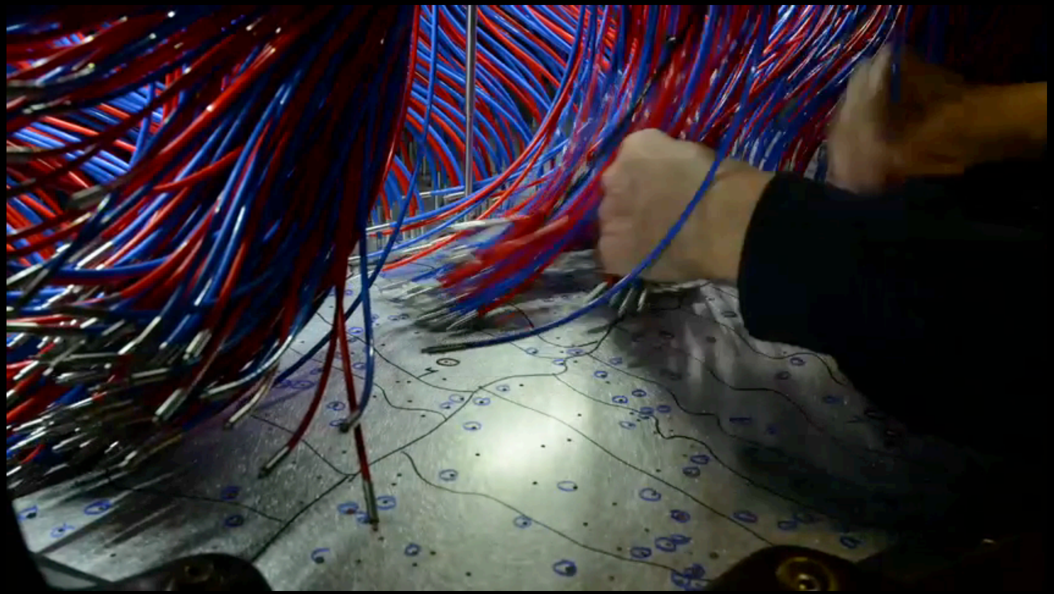
wide field
corrector

Traditional spectroscopy machine



replace the CCDs with fibers.
Take light to spectrograph.

BOSS



point the fibers to the right place by hand, or robotic.

need prior knowledge of galaxy location.

Dark Energy Surveys

- Spectroscopic:
  - BOSS/SDSS-III (2009-14):
    - SDSS 2.5m: 1.5M LRGs to z<0.7, 150,000 QSOs for Lya at z=2.5 for BAO
  - WiggleZ, 2dFGRS (completed):
    - AAO 4m
  - Future: eBOSS (SDSS-IV), HETDEX (HET), PFS (Subaru), DESI (Kitt Peak 4m), 4MOST (ESO 4m),…
- Photometric:
  - PanSTARRS (1.8m), DES (4m), HSC (8m), KIDS (2.6m)
  - Future: LSST (8.4m)
- Both:
  - Space: Euclid, WFIRST

- X-ray:
  - XMM, Chandra
  - eROSITA
- SZ:
  - ACT,SPT, Planck

took this slide from J.Frieman's LP2013 talk
will not talk about all these efforts…

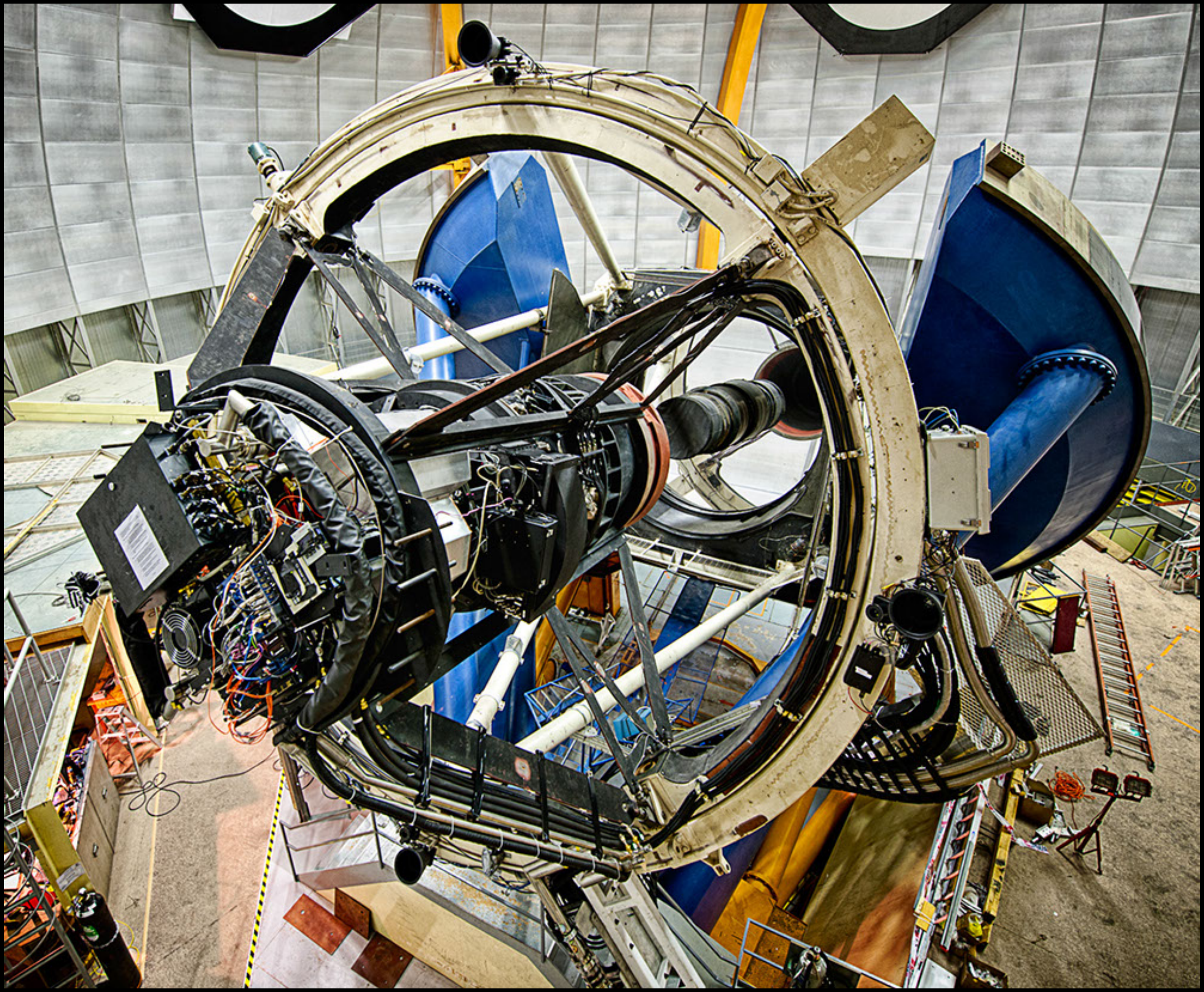
Dark Energy Surveys

- Spectroscopic:
  - BOSS/SDSS-III (2009-14):
    - SDSS 2.5m: 1.5M LRGs to z<0.7, 150,000 QSOs for Lya at z=2.5 for BAO
  - WiggleZ, 2dFGRS (completed):
    - AAO 4m
  - Future: eBOSS (SDSS-IV), HETDEX (HET), PFS (Subaru), DESI (Kitt Peak 4m), 4MOST (ESO 4m),…
- Photometric:
  - PanSTARRS (1.8m), DES (4m), HSC (8m), KIDS (2.6m)
  - Future: LSST (8.4m)
- Both:
  - Space: Euclid, WFIRST

- X-ray:
  - XMM, Chandra
  - eROSITA
- SZ:
  - ACT,SPT, Planck

selected a few… and added the low resolution spectroscopy ideas.

DES-DECam



First light on Sept-2012.

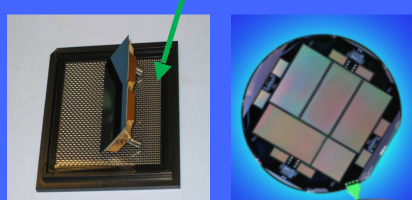
Science survey started on Sept-2013. **Results are coming out NOW.**

the key is a large focal plane....

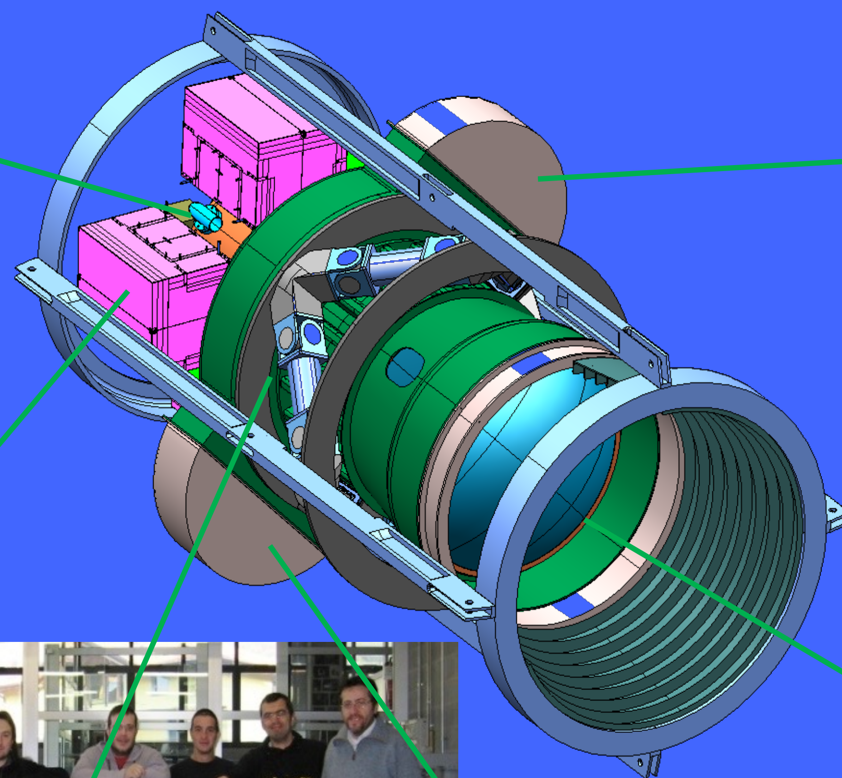
is the new prime focus camera for the Blanco 4m Telescope at CTIO

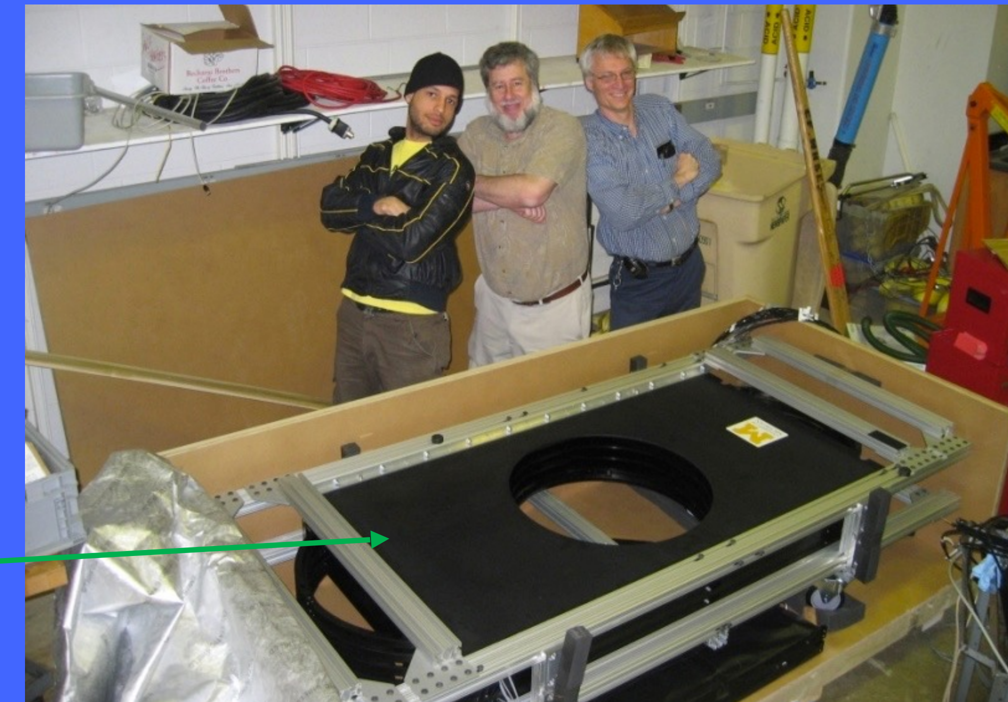
DECam Systems

Imager, FNAL

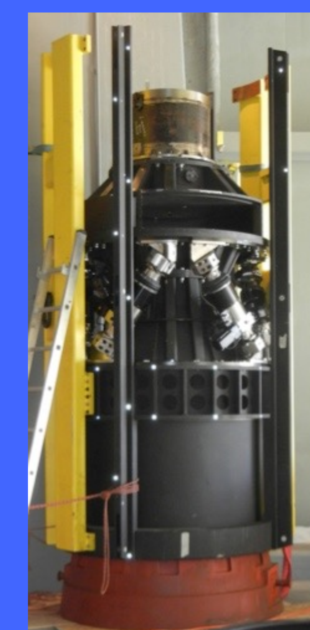


CCDs, wafer from LBNL, packaged at FNAL





Filter changer, Univ. of Michigan



Barrel and Cage (FNAL, no lenses)

Hexapod, Italy

Electronics, Spain and FNAL

Shutter, Germany

Focal Plane Detectors

Science goal for DES: z~1

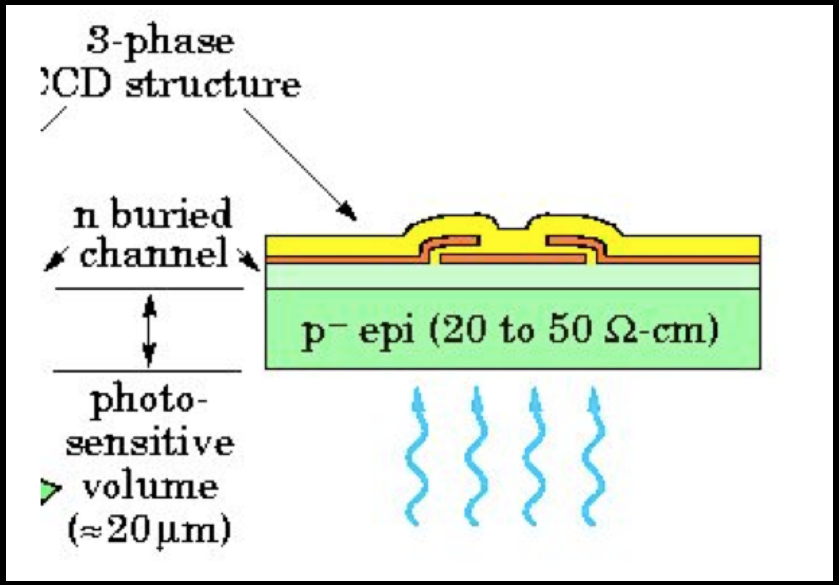
~50% of time in z-filter
825-1100nm

Astronomical CCDs are usually thinned to 30-40 microns (depletion):
Poor 900nm response

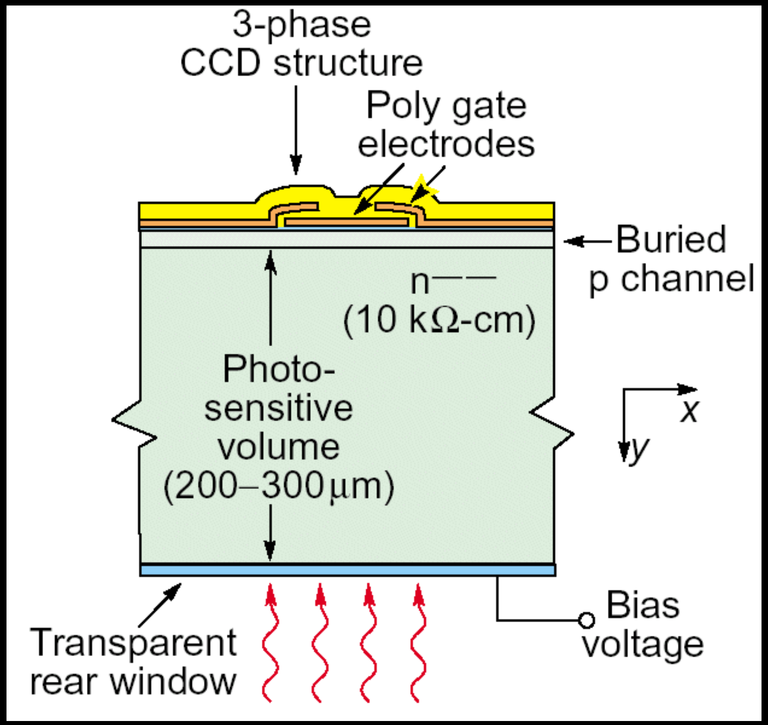
LBNL full depletion CCD

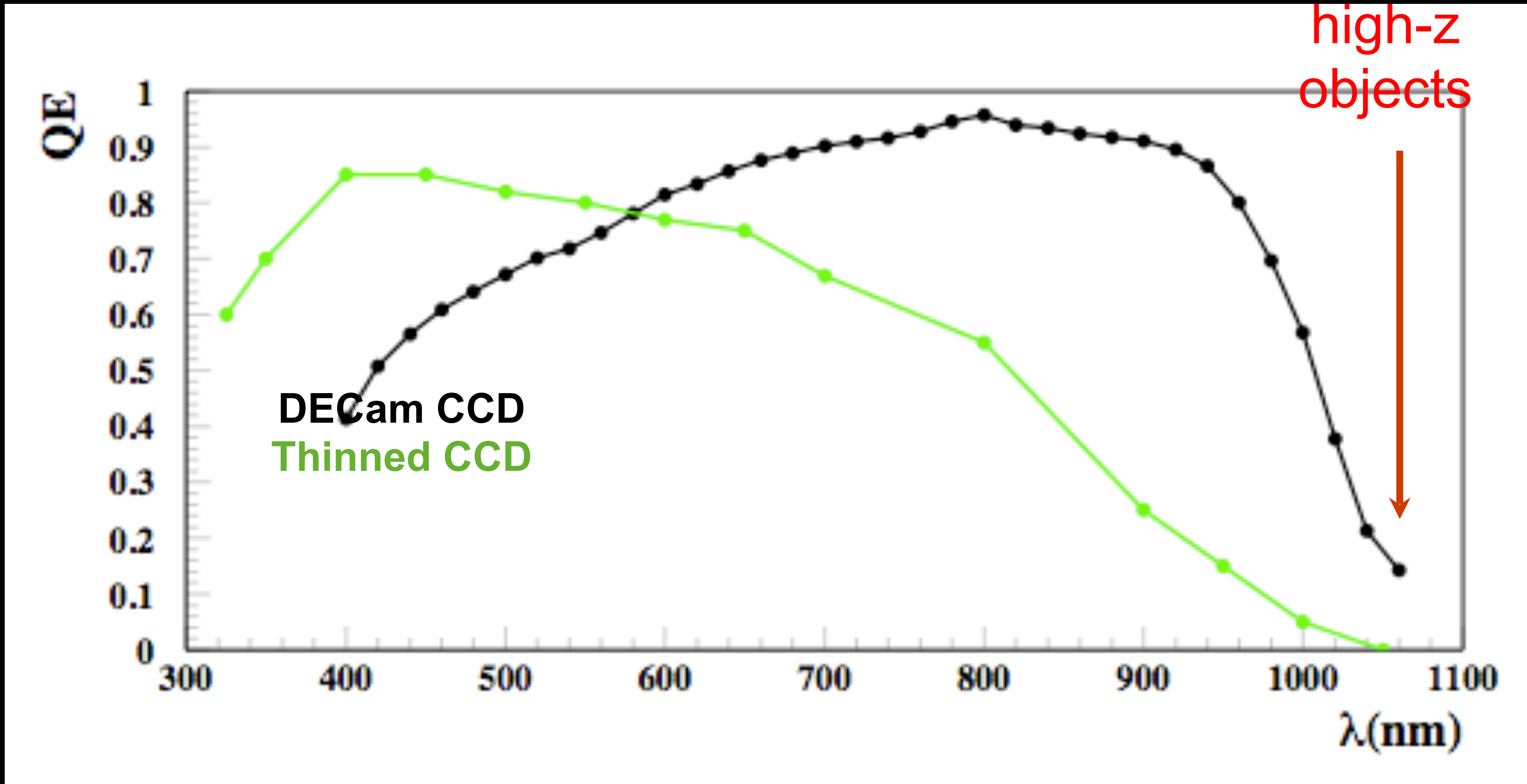
- **250 microns thick**
- **high resistivity silicon**
- **QE> 50% at 1000 nm**

thin CCD

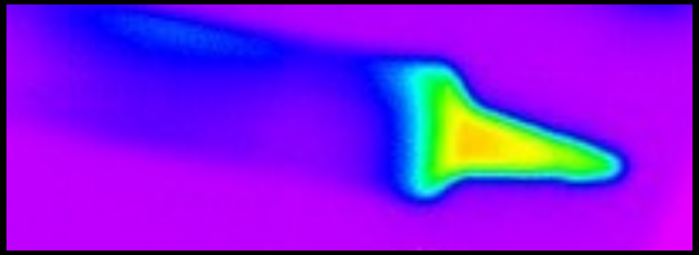


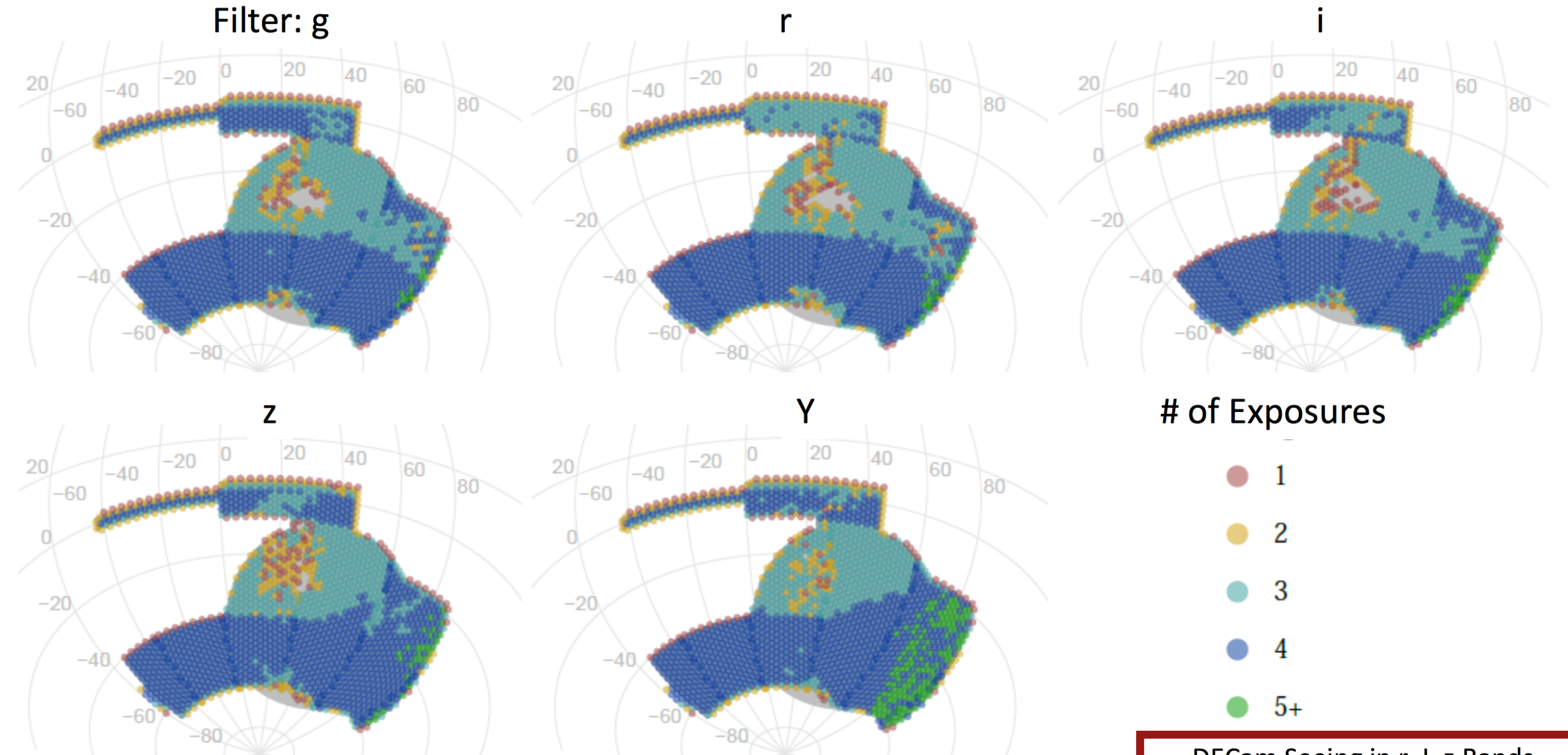
DECam CCD





IR image of soldering iron with a DECam CCD (K.Kuk)

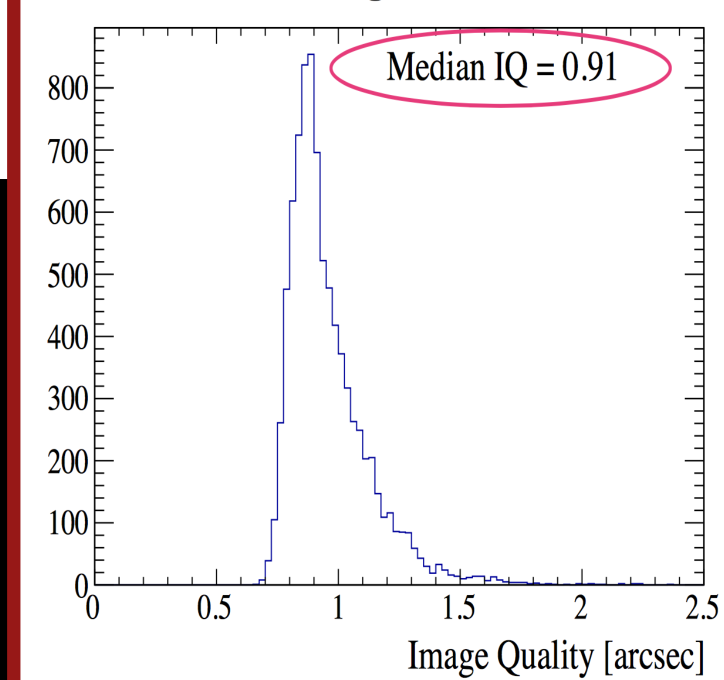




After 2 of 5 years:

Entire 5000 sq-deg footprint covered.
About 200 sq-deg at full depth.
With image quality meeting specs, and not dominated by instrument contribution.

DECam Seeing in r, I, z Bands



Galaxy Clusters

Good probe because dark energy inhibits the formation of clusters.

Science Verification has 9000+ clusters.

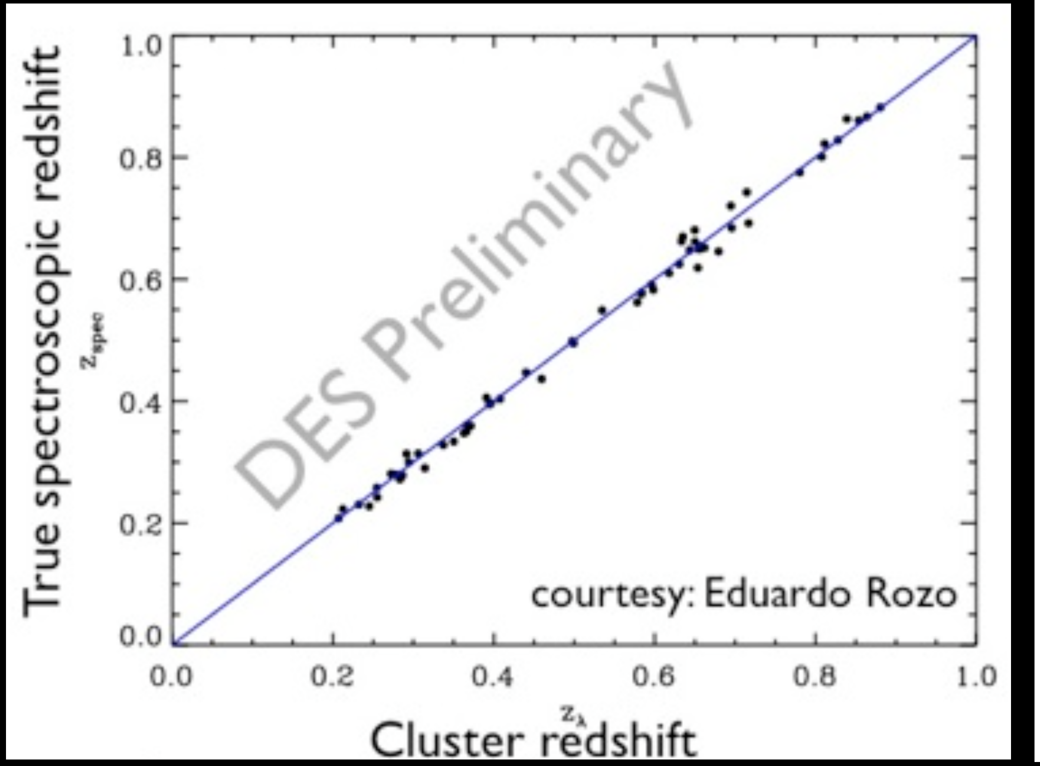
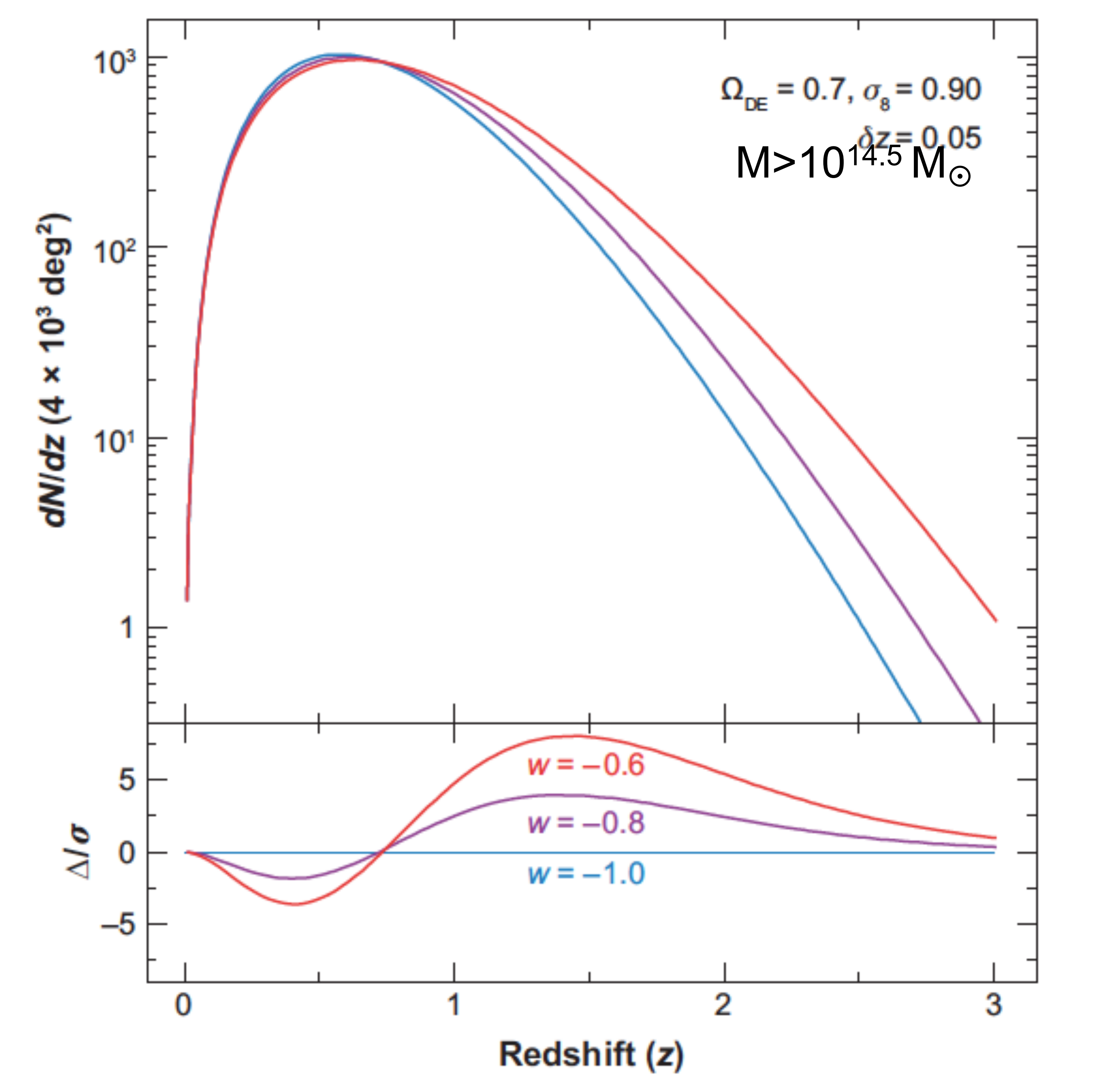


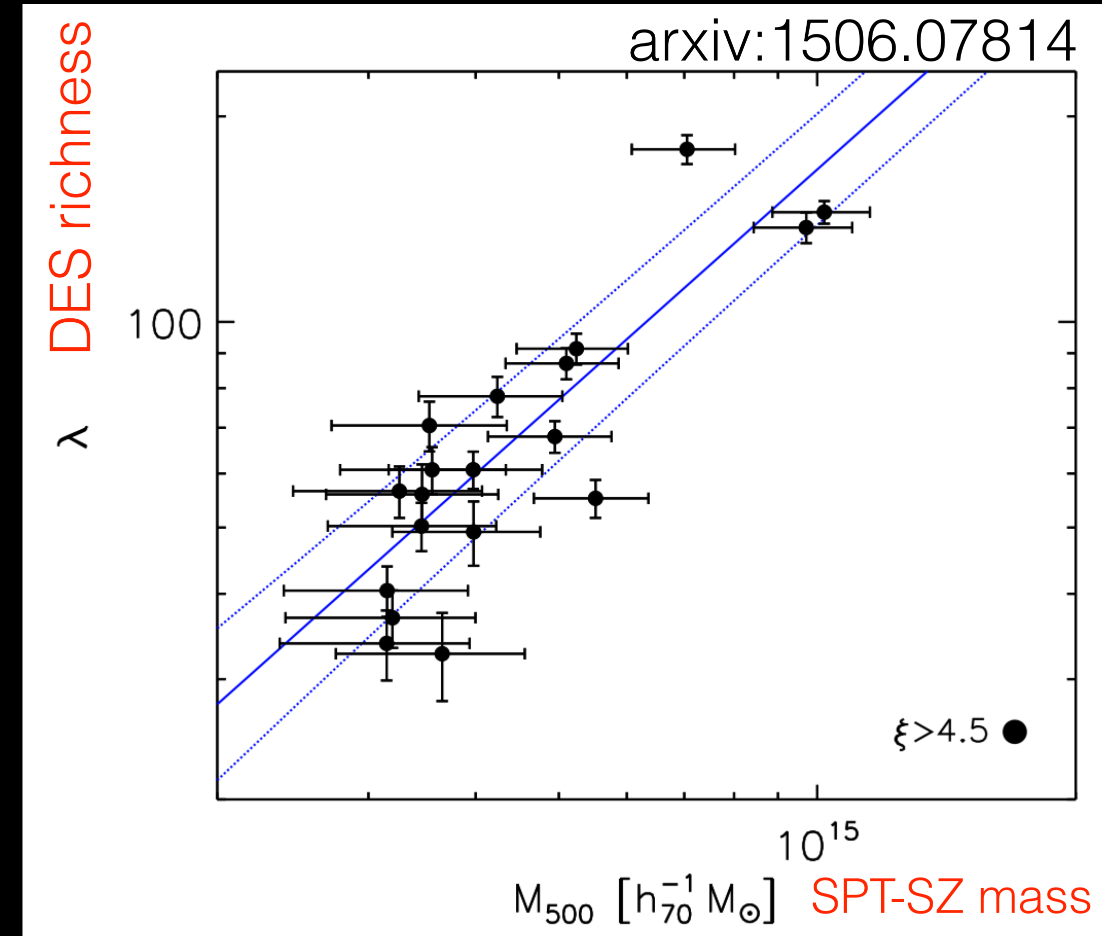
photo-z redshift works!

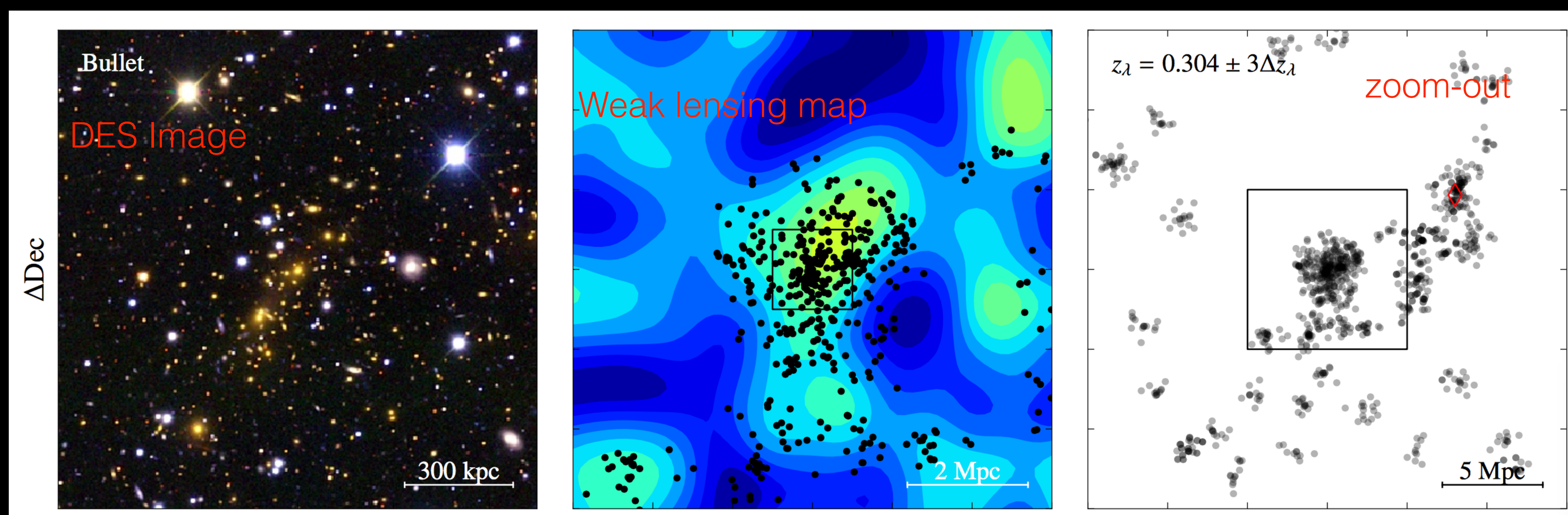


Cluster mass calibration critical for cosmology.

DES is doing cluster mass calibrations with weak lensing, and SZ signal in CMB.

Cosmology coming soon.

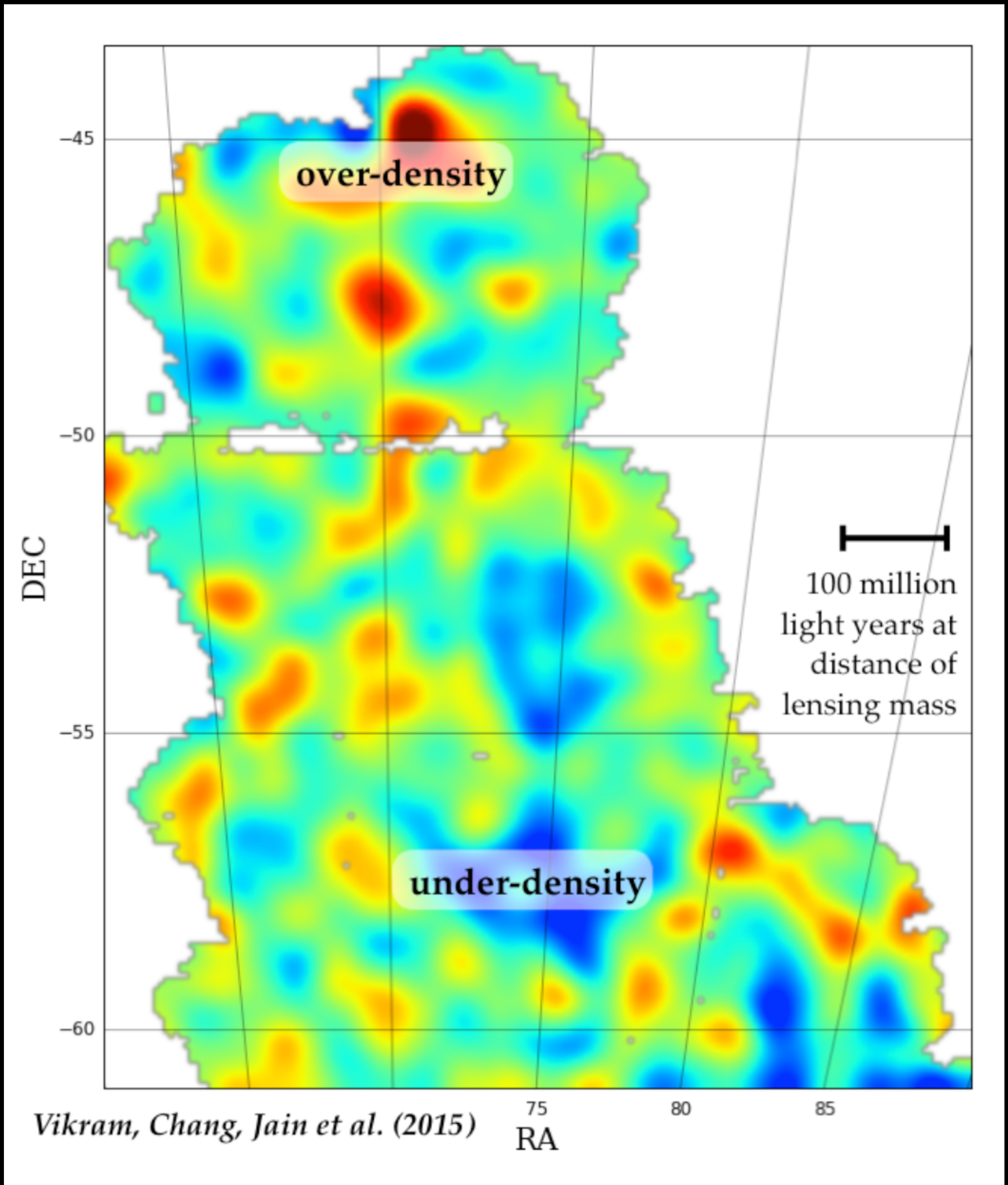


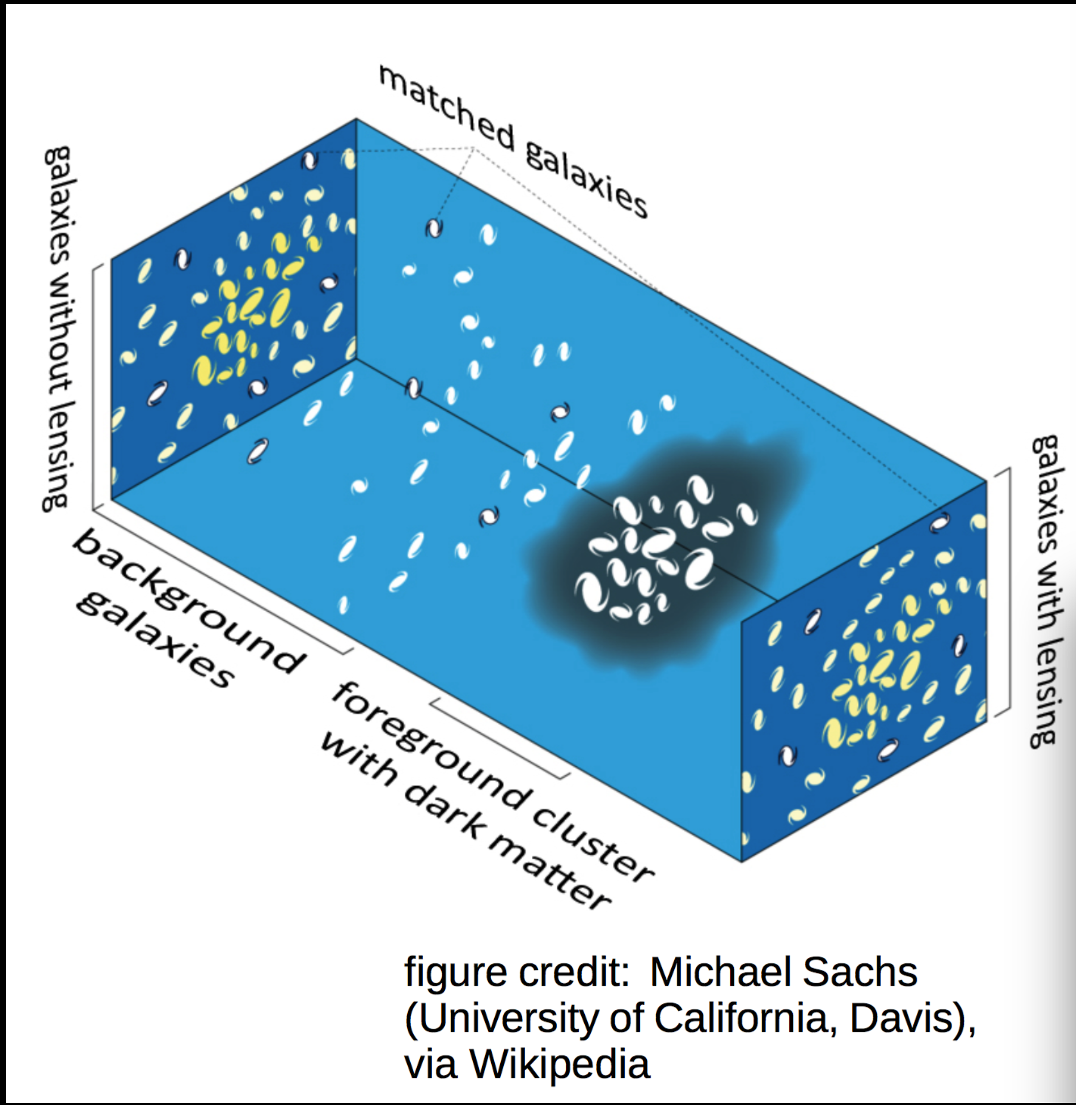


Cluster name	M_{200c} 10^{14}	λ	z_λ	Literature value M_{200c}
RXC J2248.7-4431	$17.5^{+4.3}_{-3.7}$	203 ± 5	0.346 ± 0.004	$22.8^{+6.6}_{-4.7}$ (Gruen et al. 2013), 20.3 ± 6.7 (Umetsu et al. 2014), 16.6 ± 1.7 (Merten et al. 2014)
1E 0657-56	$13.0^{+6.5}_{-5.2}$	277 ± 6	0.304 ± 0.004	17.5 (Clowe et al. 2004)[i], 12.4 (Barrena et al. 2002, D)
SCSO J233227-535827	$9.6^{+3.9}_{-3.3}$	77 ± 4	0.391 ± 0.008	$11.2^{+3.0}_{-2.7}$ (Gruen et al. 2014b), $4.9 \pm 3.3 \pm 1.4$ (High et al. 2010, R)
Abell 3261	$6.4^{+3.2}_{-2.5}$	71 ± 3	0.216 ± 0.003	—

arxiv:1405.4285

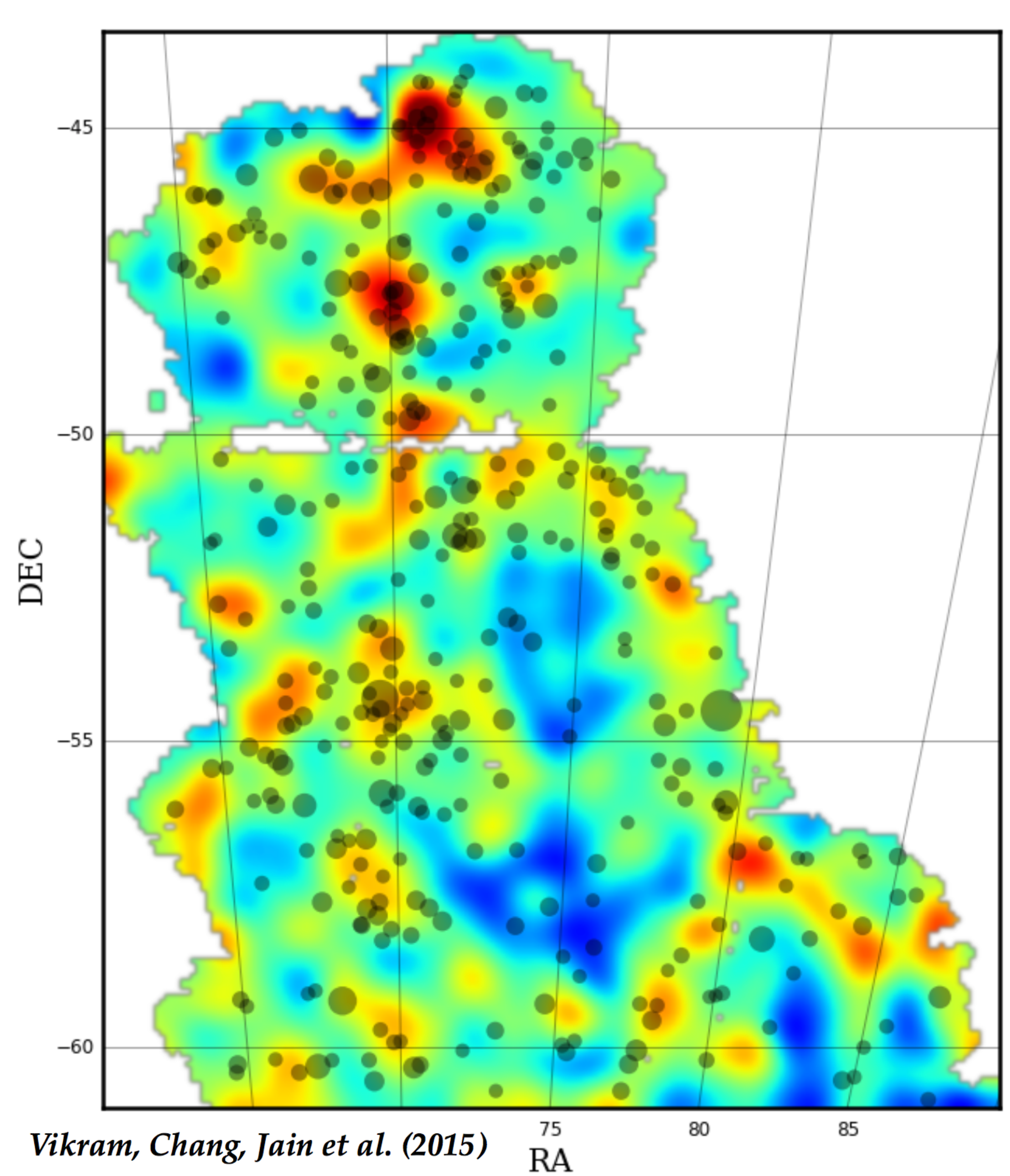
Weak lensing map



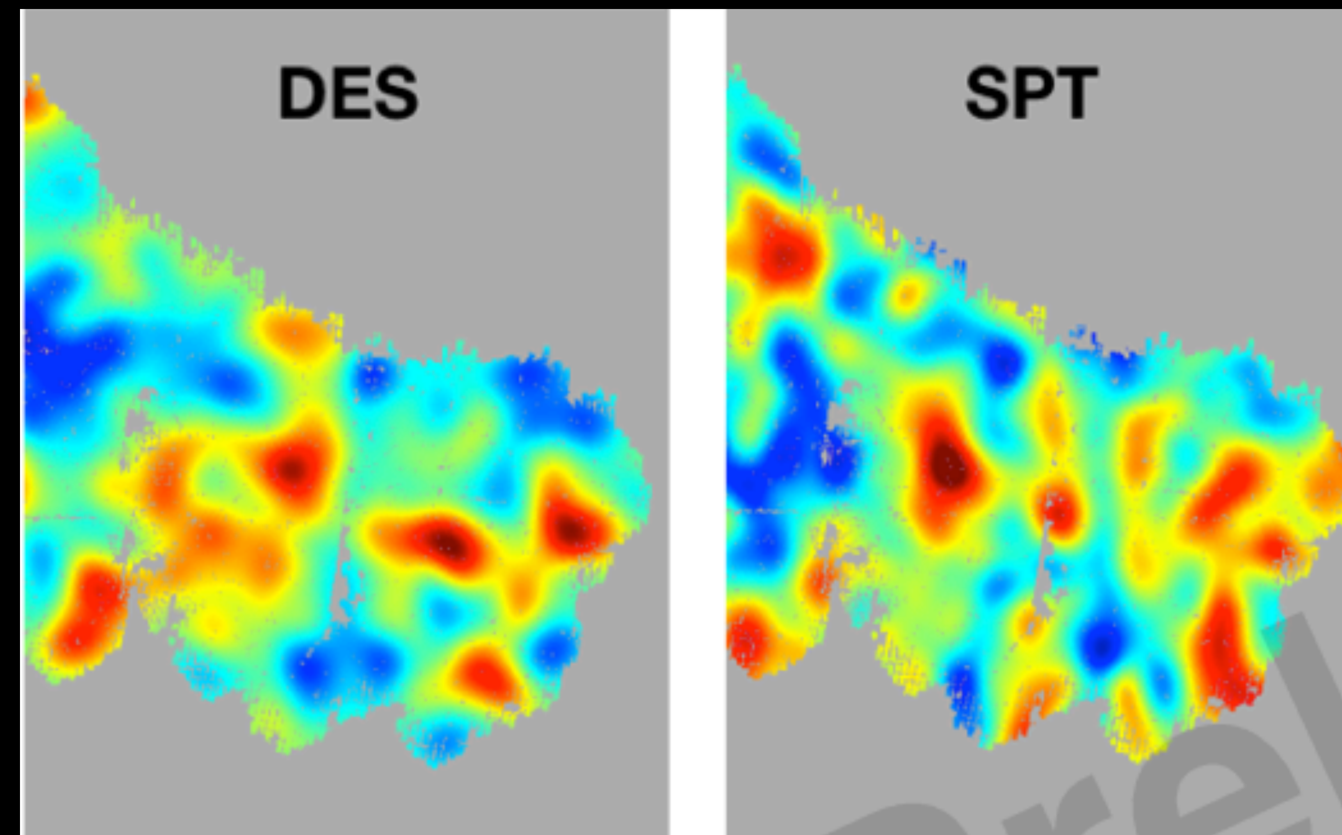


139 sq-deg (largest contiguous map with only 3% of DES coverage)

Source redshift 0.6<z<1.2
About a million galaxies
Standard ΛCDM cosmology
arxiv: 1505.01871



here comparing the WL signal
with the clusters.



Preliminary as shown in CIPANP-2015
(K.Honscheid)

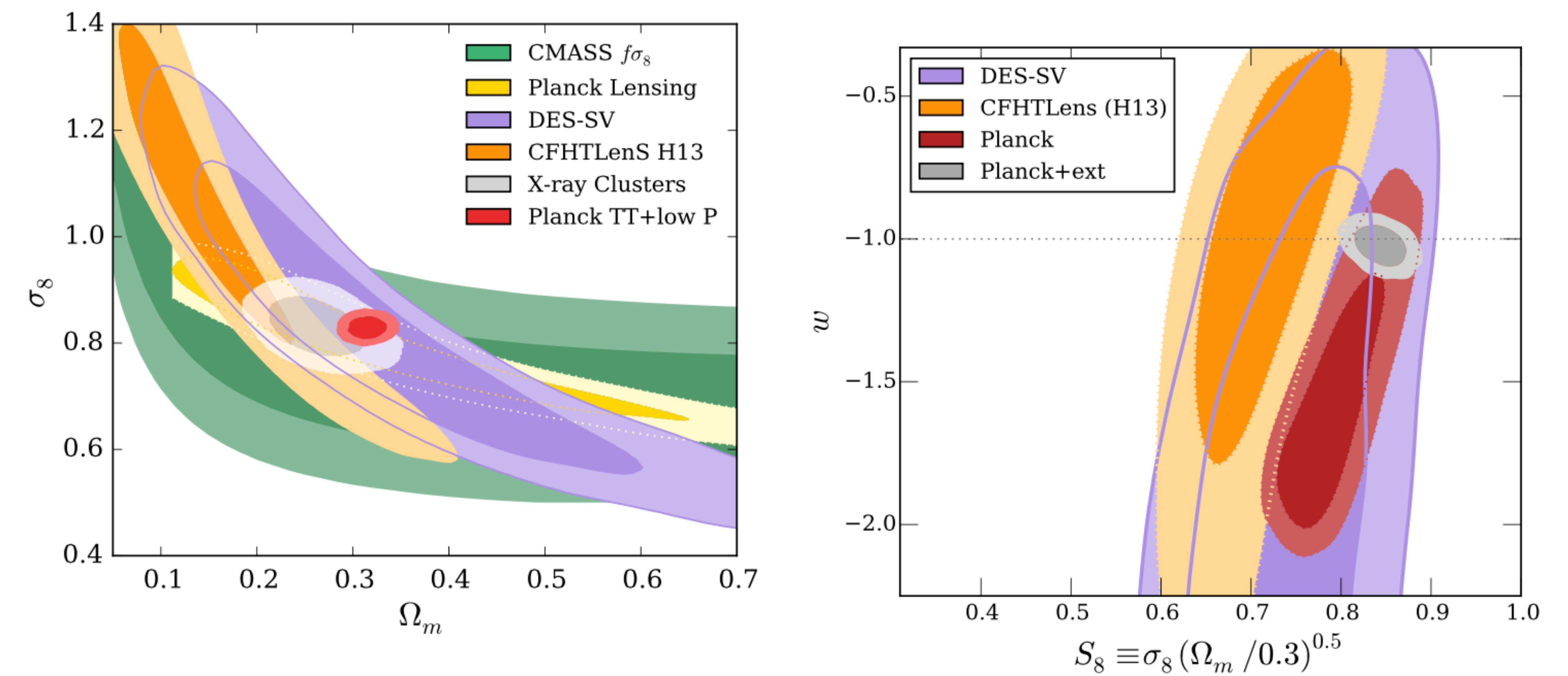
DES shares the sky with the South Pole Telescope observations of CMB. So we can compare the lensing signal from both surveys. Visible from Chile and microwaves from the South Pole. This gives us some very interesting control on systematics…

arXiv:1507.05552

Cosmology from Cosmic Shear with DES Science Verification Data

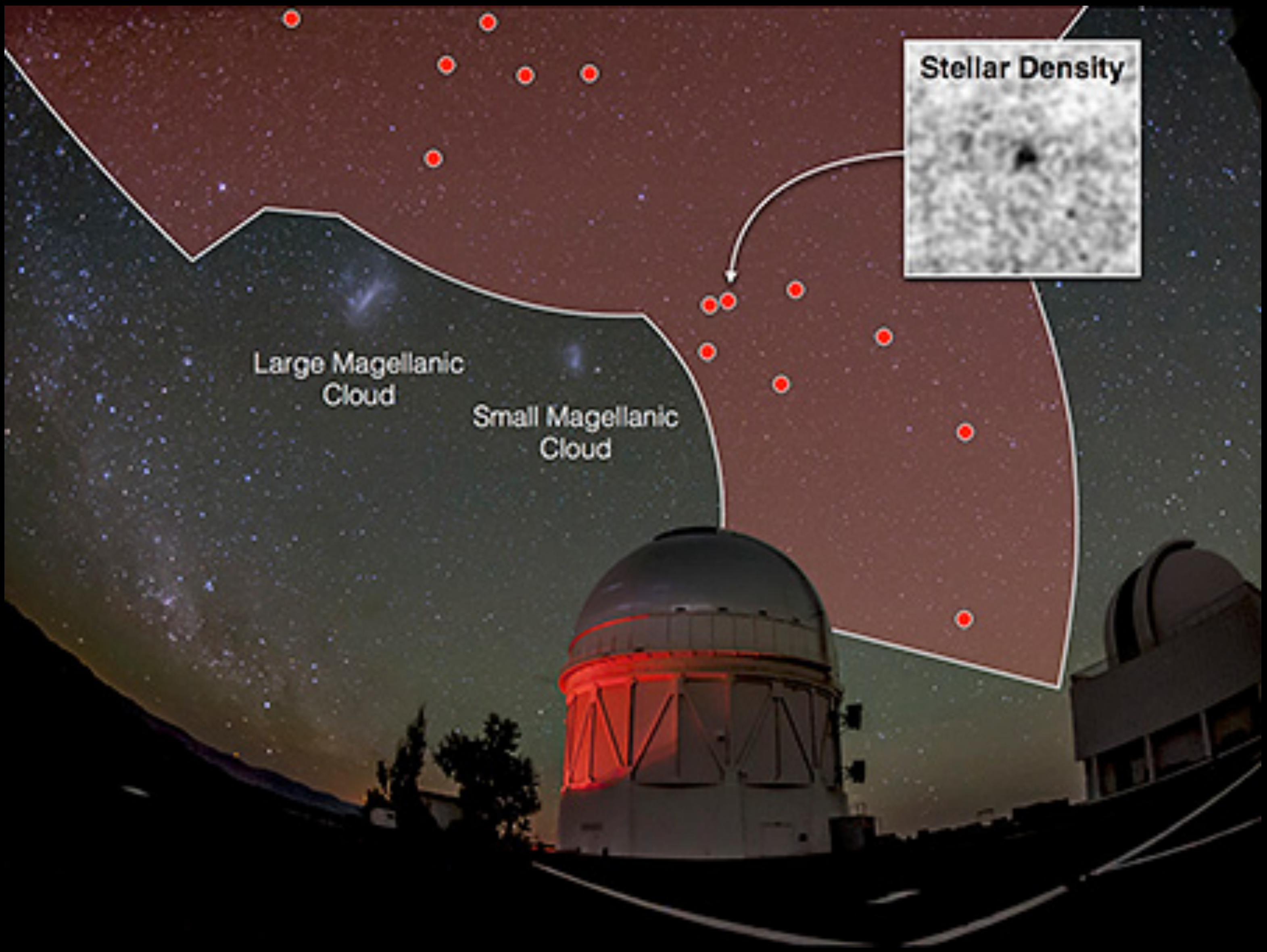
The Dark Energy Survey Collaboration: T. Abbott[1], F. B. Abdalla[2], S. Allam[3], A. Amara[4], J. Annis[3], R. Armstrong[5], D. Bacon[6], M. Banerji[7,8], A. H. Bauer[9], E. Baxter[10], M. R. Becker[11,12], A. Benoit-Lévy[2], R. A. Bernstein[13], G. M. Bernstein[10], E. Bertin[14,15], J. Blazek[16], C. Bonnett[17], S. L. Bridle[18], D. Brooks[2], C. Bruderer[4], E. Buckley-Geer[3], D. L. Burke[11,19], M. T. Busha[11,12], D. Capozzi[6], A. Carnero Rosell[20,21], M. Carrasco Kind[22,23], J. Carretero[9,17], F. J. Castander[9],

σ_8 : normalization parameter for density fluctuations



Not competitive yet, with only 3% of the coverage.
More Coming soon!

DES data has also discovered 17 new neighbors, likely satellite dwarf galaxies… (almost doubling the number)

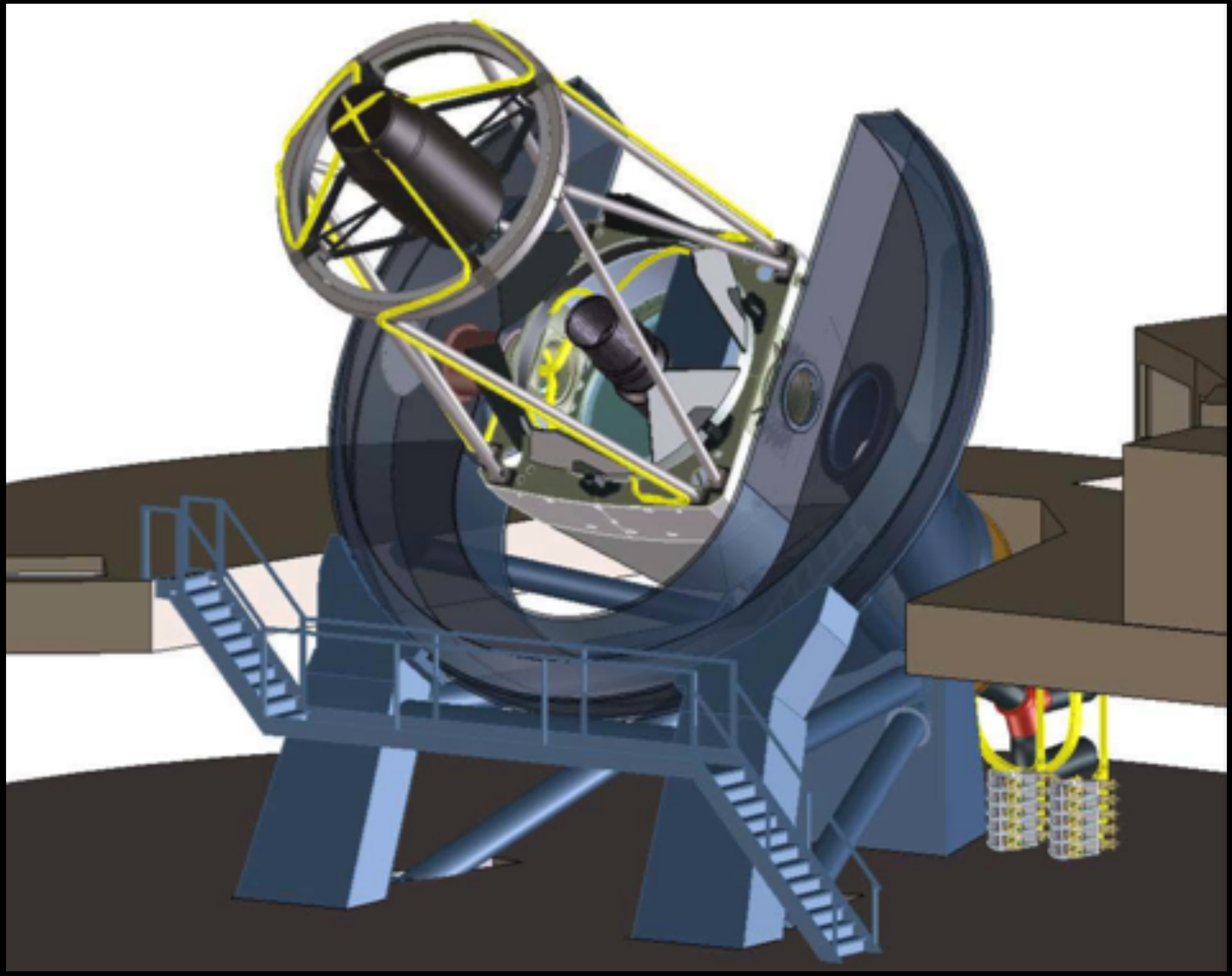


large impact for our understanding of Dark Matter. (Miguel’s talk yesterday)

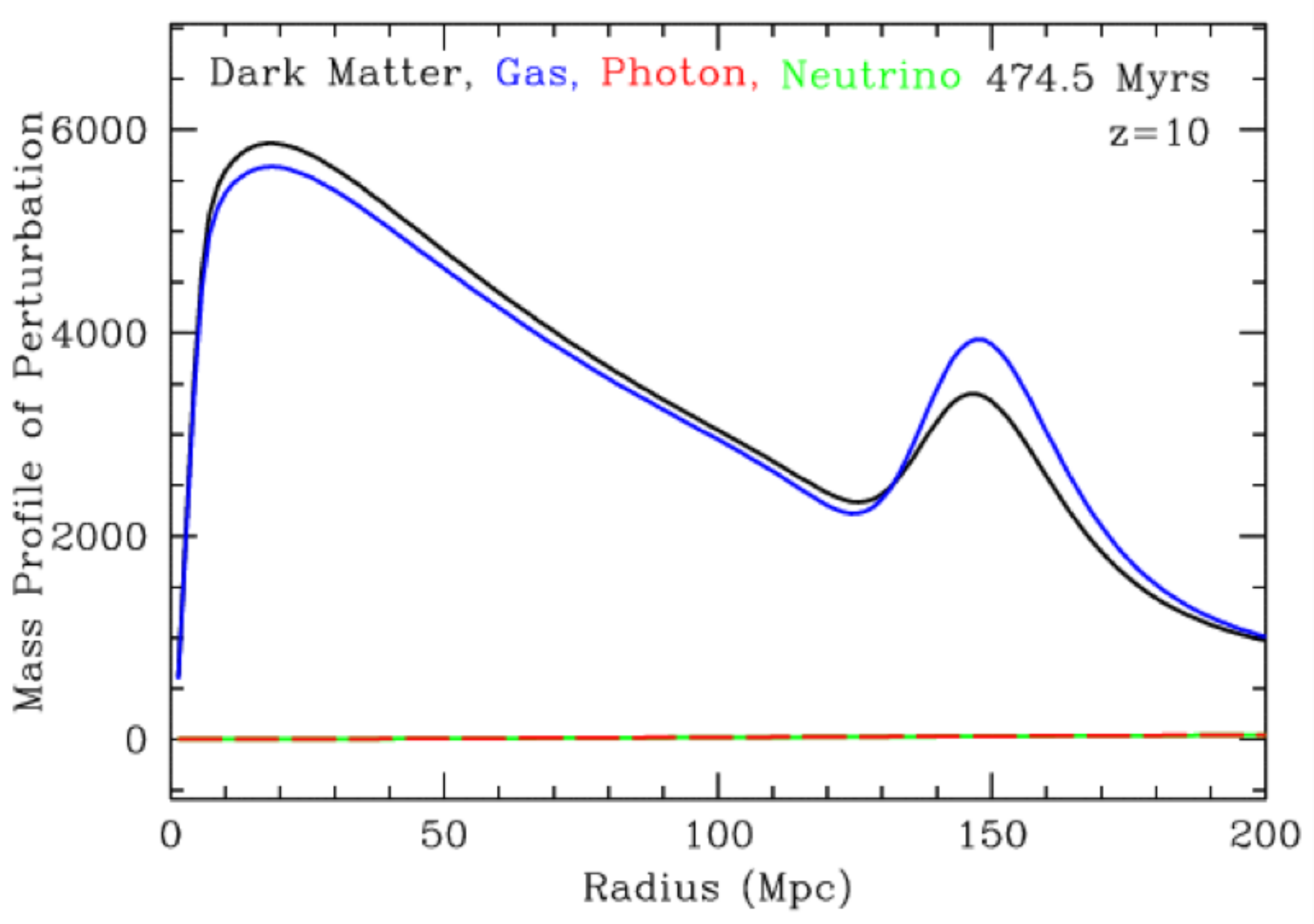
Dark Energy Spectroscopic Instrument

- 4 m telescope in Arizona (Kitt Peak)
- 5000 fiber, 3 arm spectrograph,
- R~4000
- Spectra for 1800 objects/deg² (~10% of available galaxies)
- Magnitude limit ~22.5, z~3.5
- Will cover 14,000 deg² in 3 years
- 20 M galaxies, 0.6 M QSO

Starting construction in ~2015+.



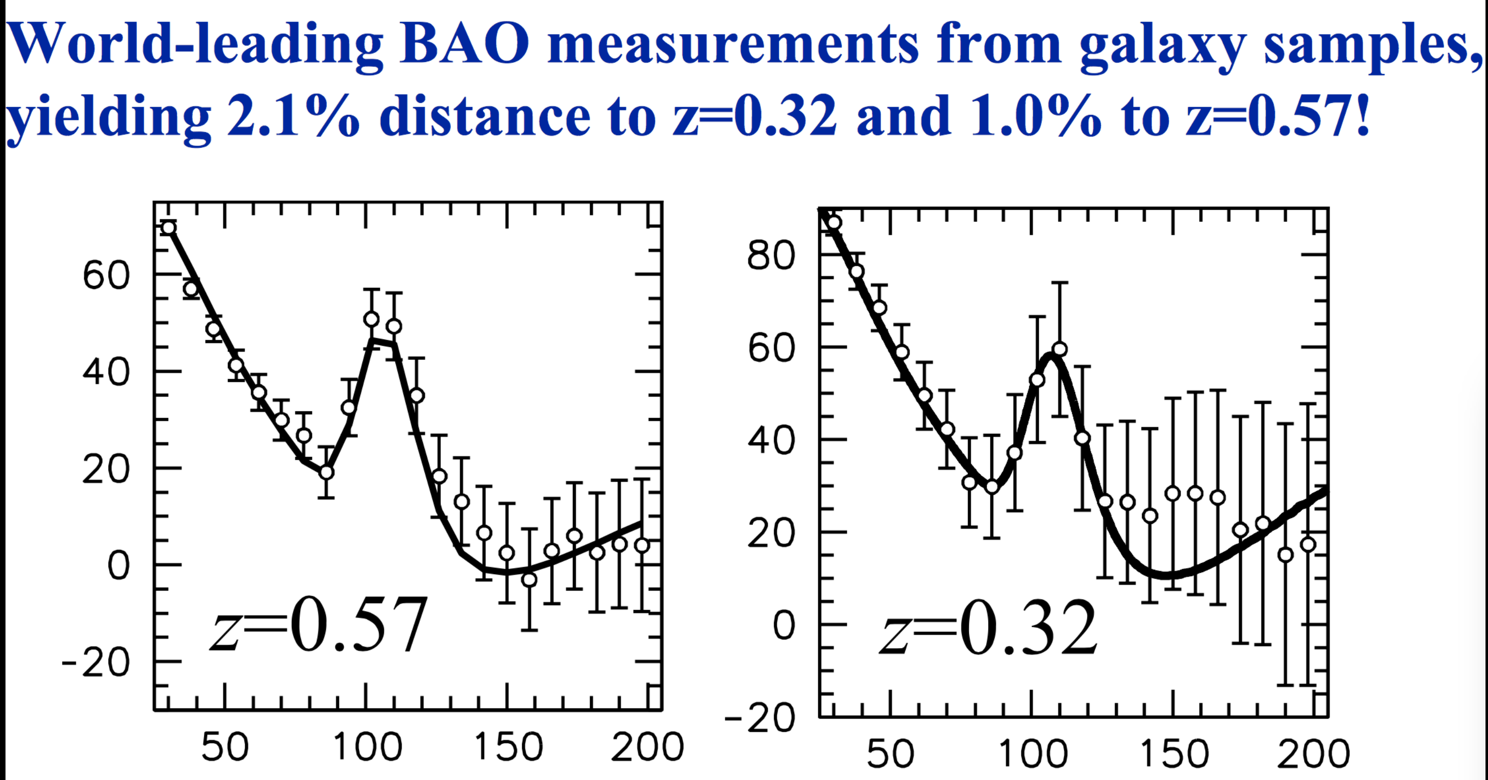
Moving along in the DoE decision process. Successful CD-2 Review in July 2015, expecting official CD-2 soon.



Baryon Acoustic Population

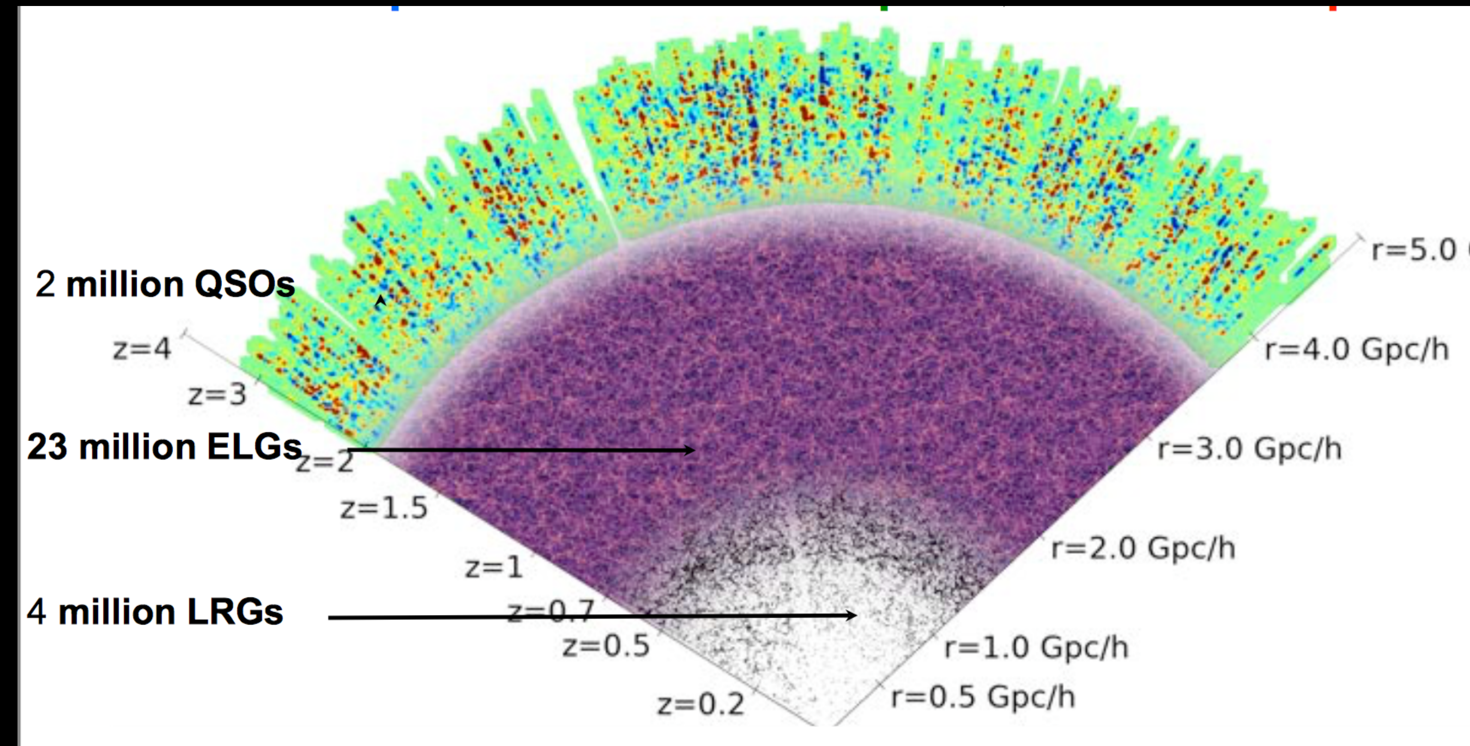
in the early universe photons and baryons form a gas with pressure. A wave expands to 149 Mpc until the photons decouple. This is now a standard ruler than can be measured as a function of z (also in CMB).

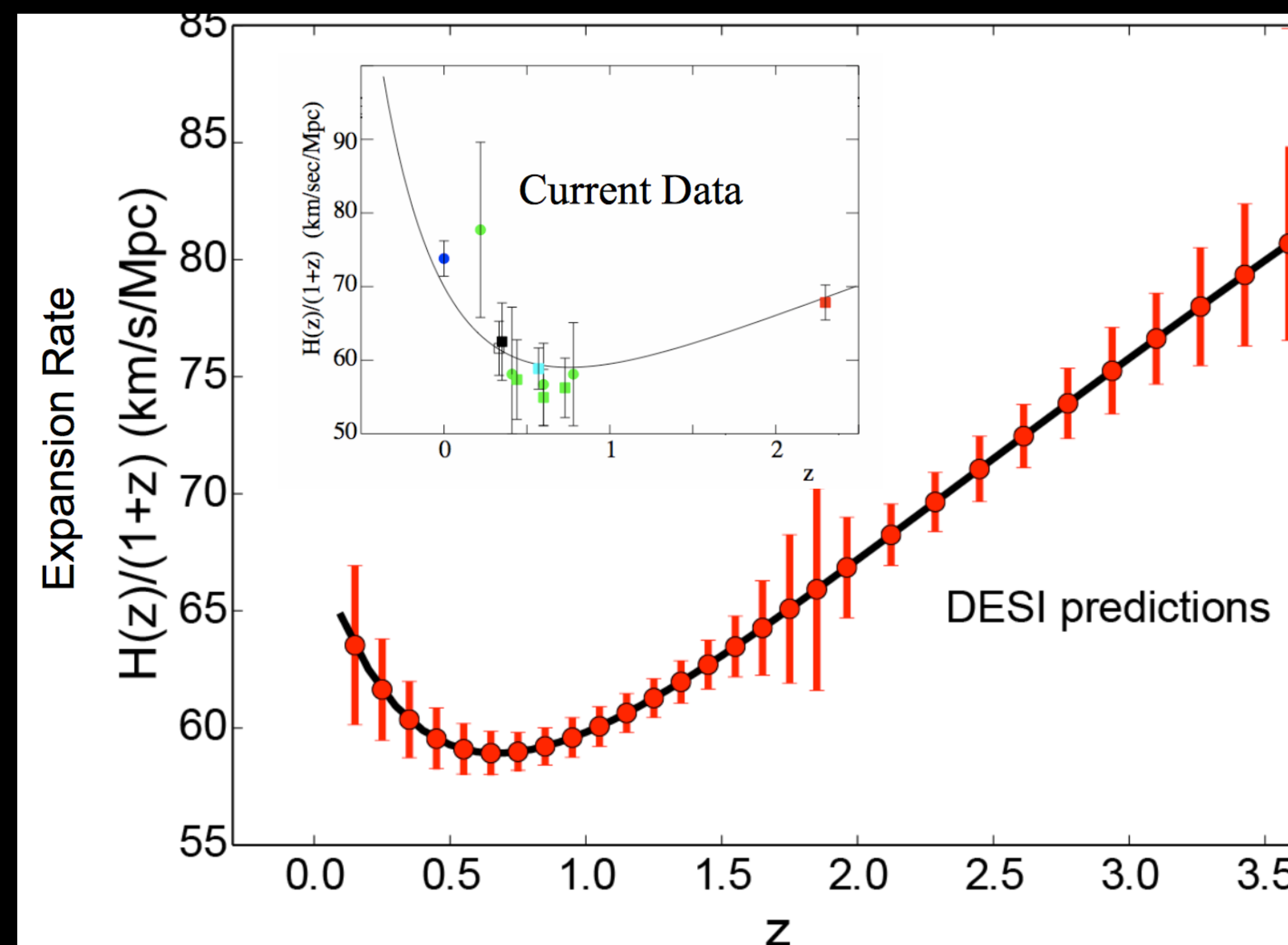
BOSS produced the current best measurements of this standard ruler. DESI will be the next huge step for this.



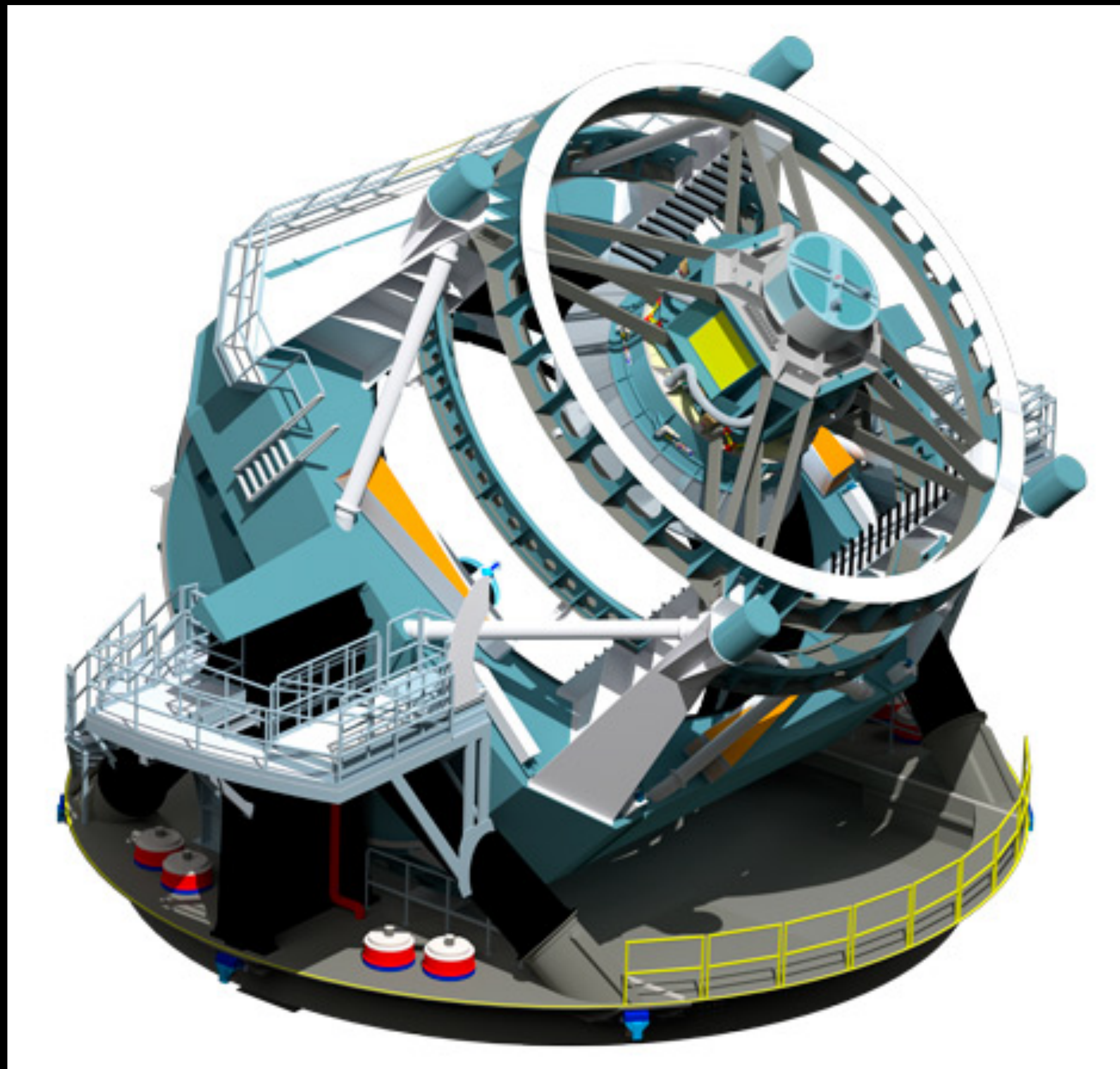
Anderson et al. (2014); Tojeiro et al. (2014)

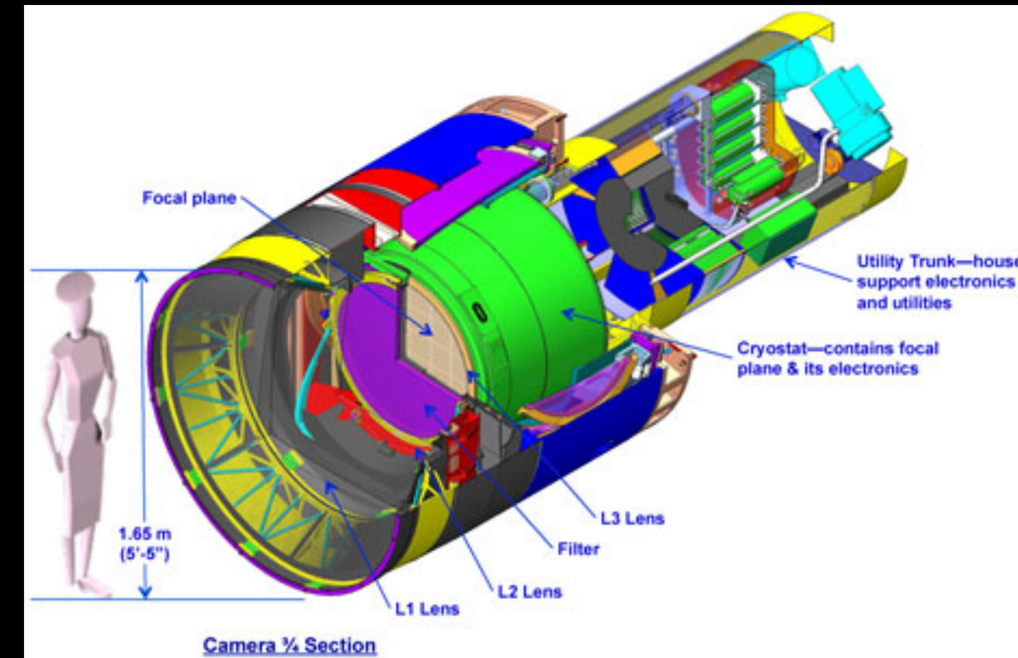
Using measurements of the BAO scale with galaxies and quasars, DESI will get unprecedented precision in the hubble diagram.



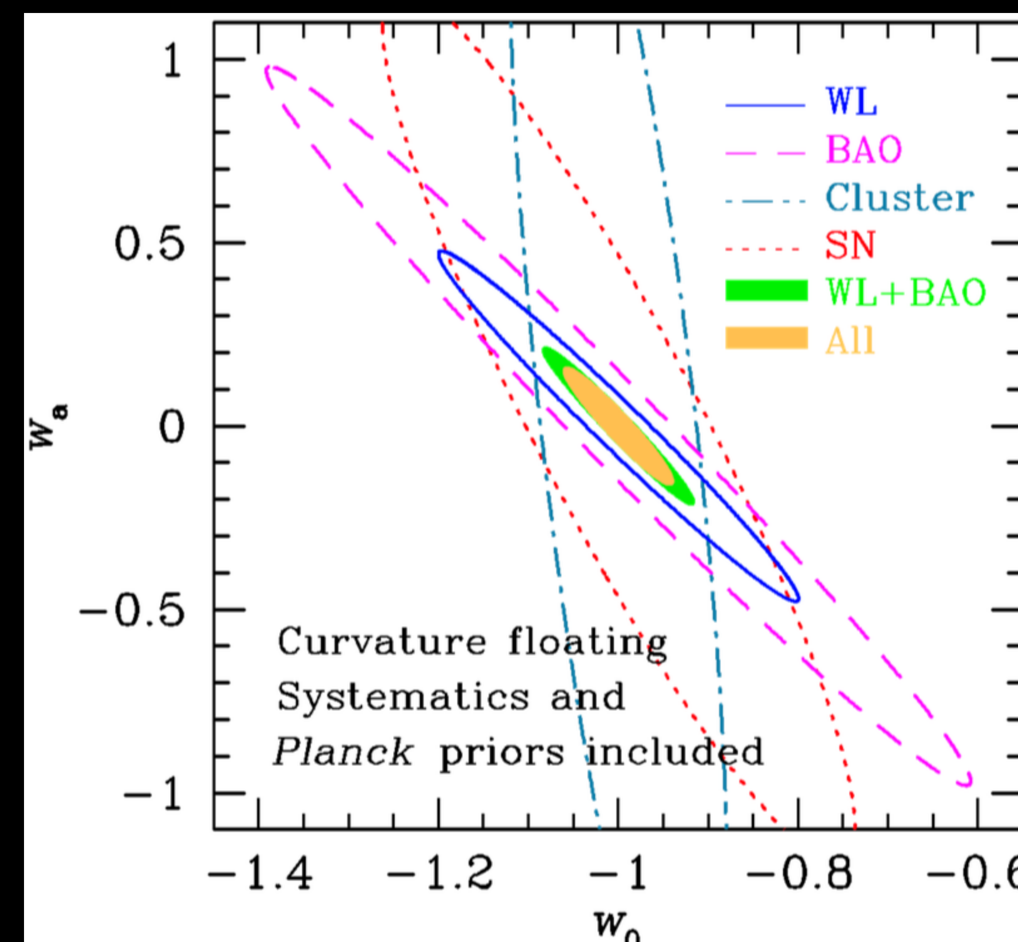


LSST





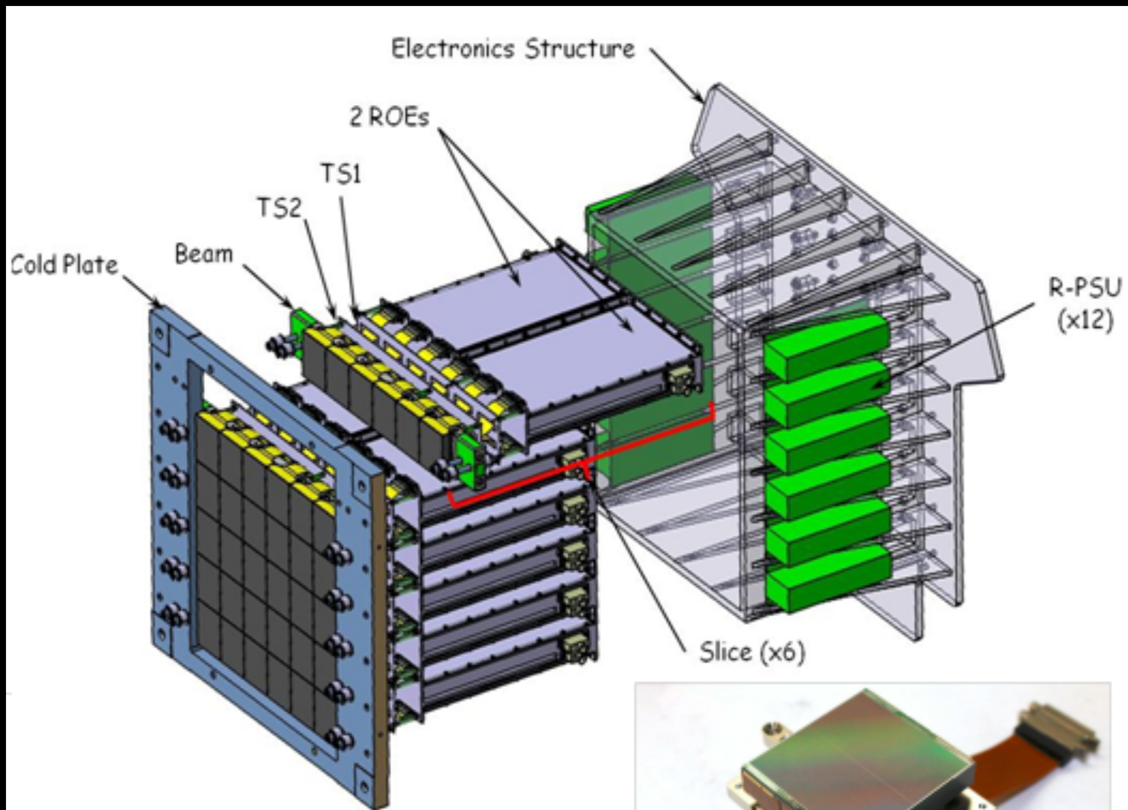
Faster and larger photometric survey. Operations to start in 2021. 8.2m dedicated telescope, 3.2 Gpix camera, 3.5 deg field of view.

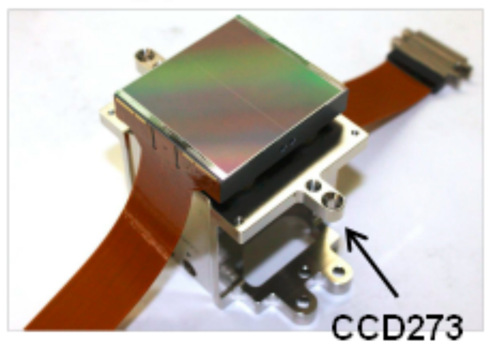


LSST Camera Passes DOE Critical Decision (CD)-3 Review 8/2015

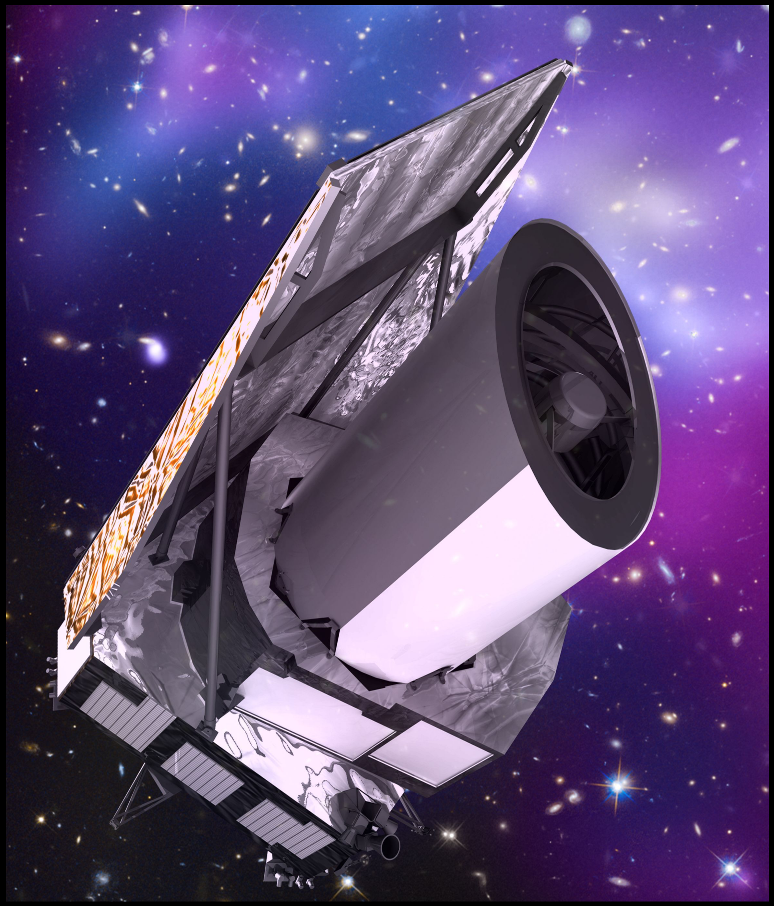
From space: EUCLID

http://www.euclid-ec.org





CCD imager
0.57 sq-deg
one filter 550-990 nm



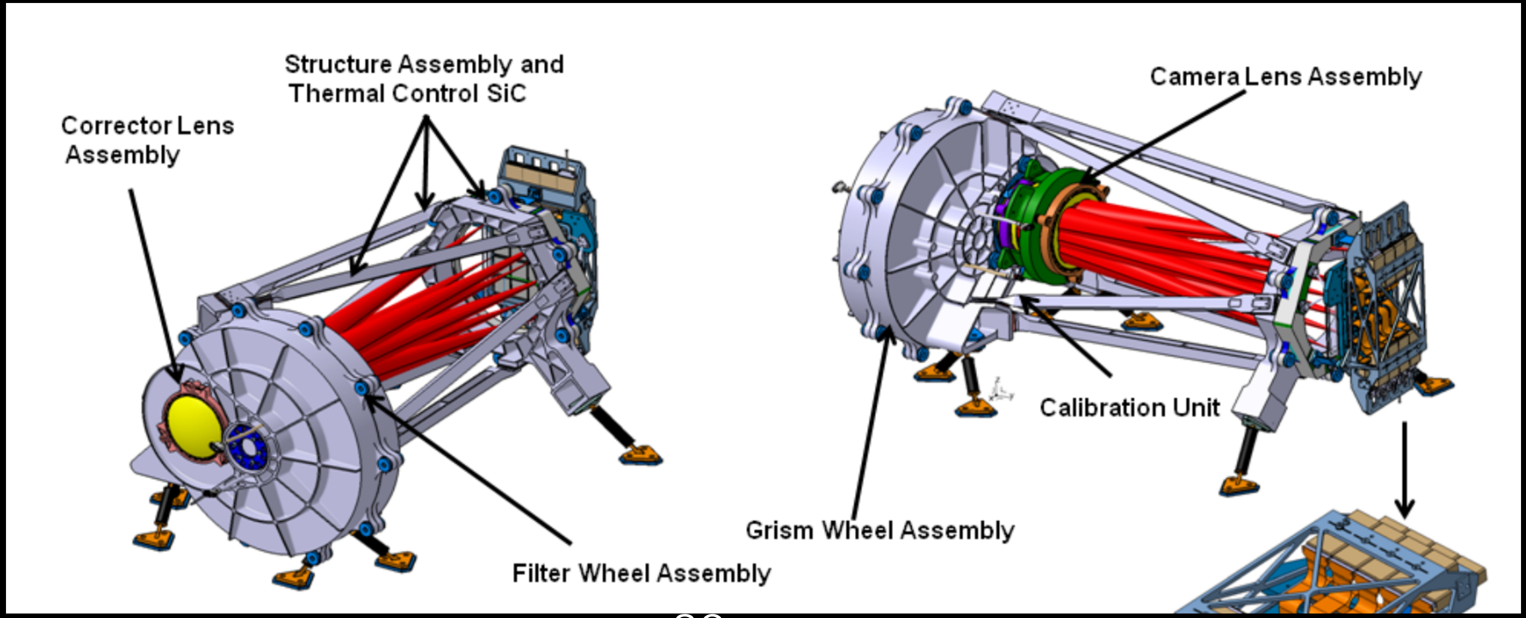
1.2 m telescope in space.

50M redshifts
1.0B weak lensing galaxies.

Launch 2020

(a bit earlier than WFIRST)

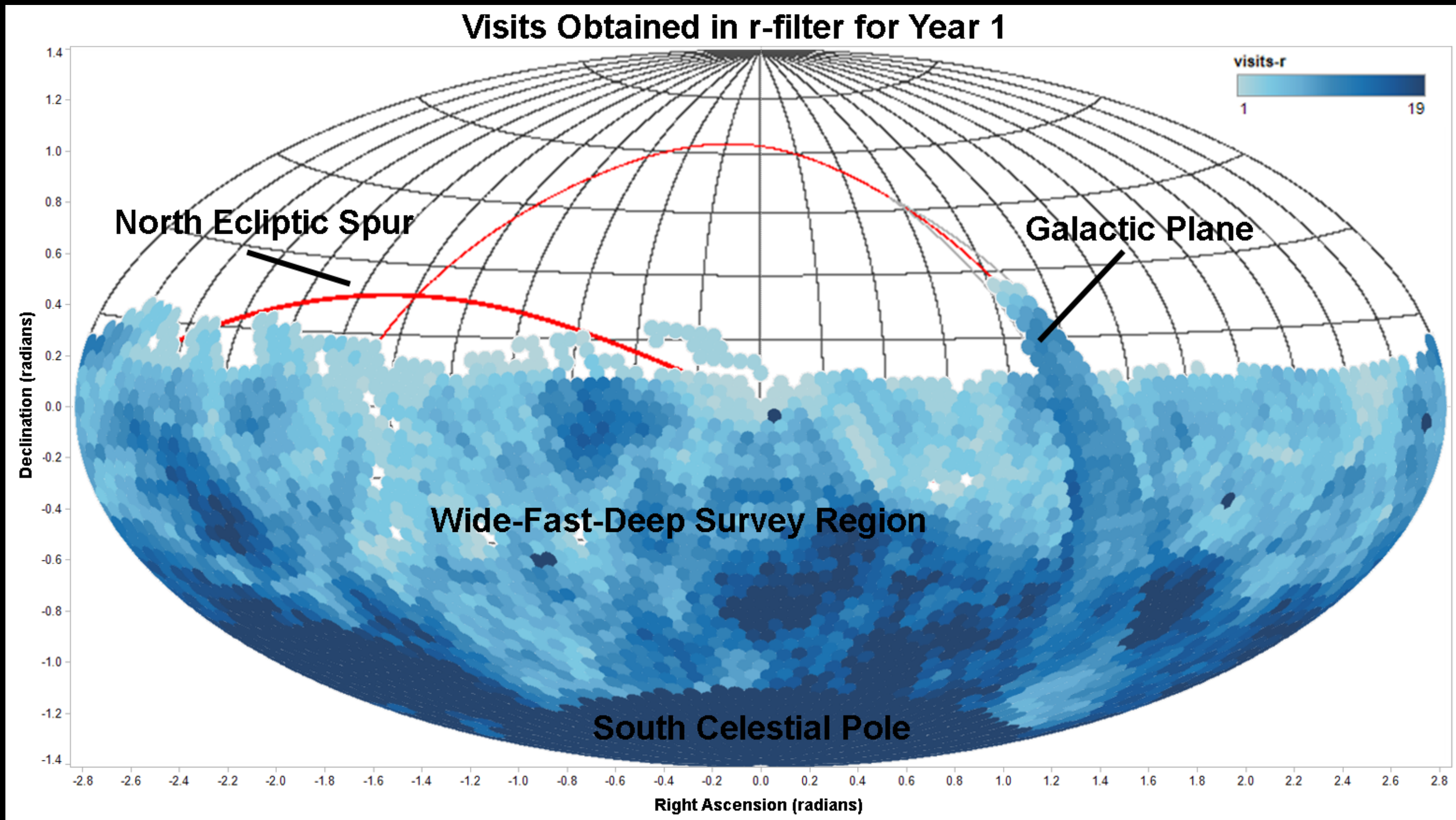
NIR imager
0.53 sq-deg
3 filters

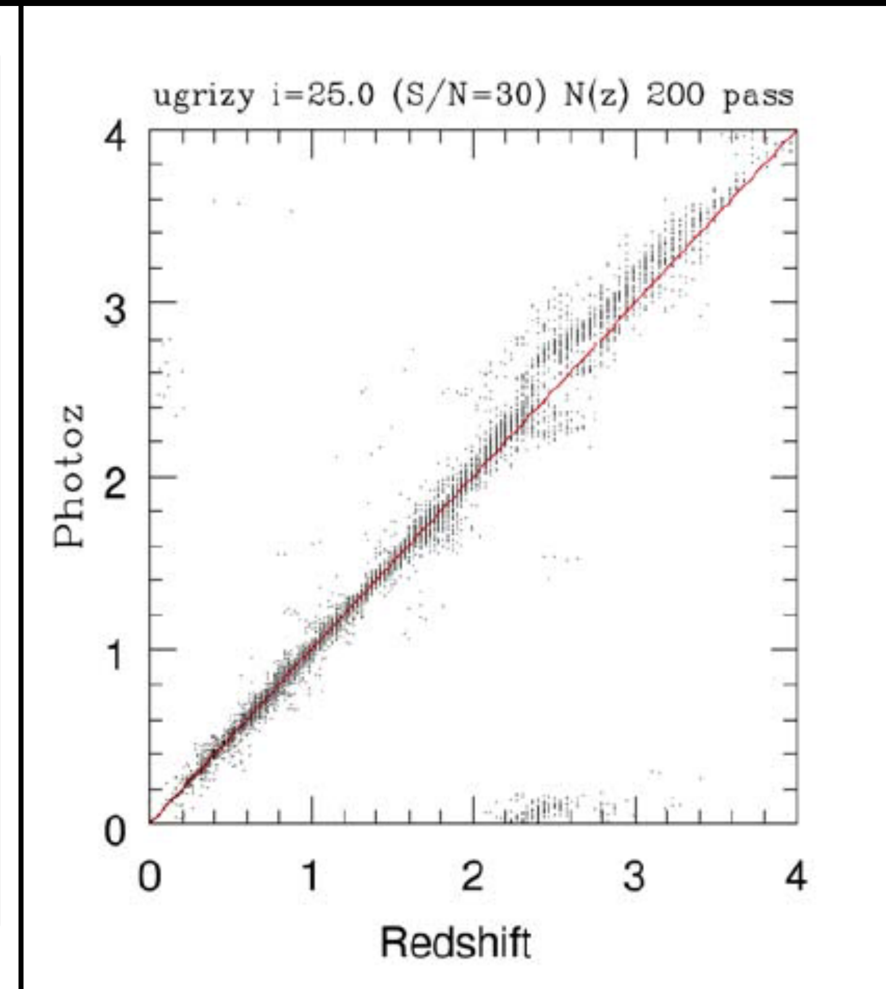


NIR imager
slit-less
spectrometer

Grism wheel
IR detectors HW
900nm-2um

Were are we going to be after LSST?

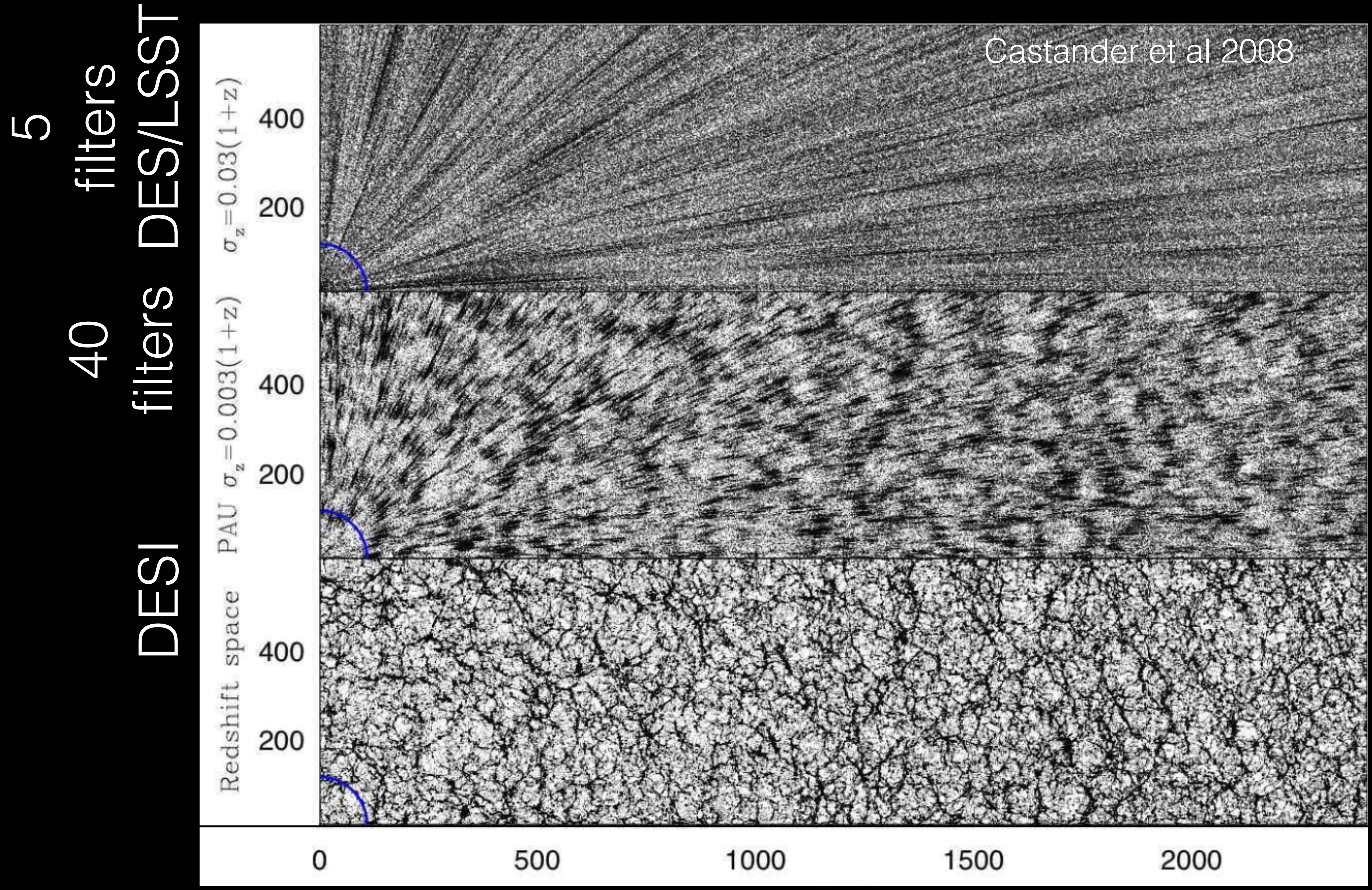




LSST will produce photometric data for 20,000 sq-deg to magnitude 27. Redshift will be estimated from the colors of the objects.

We will never have enough spectroscopic instruments to follow up all these observations using current technology.

Low Resolution Spectroscopy



Low resolution could get us a lot of information

Low Resolution Spectroscopy

Gastanaga et al 2011

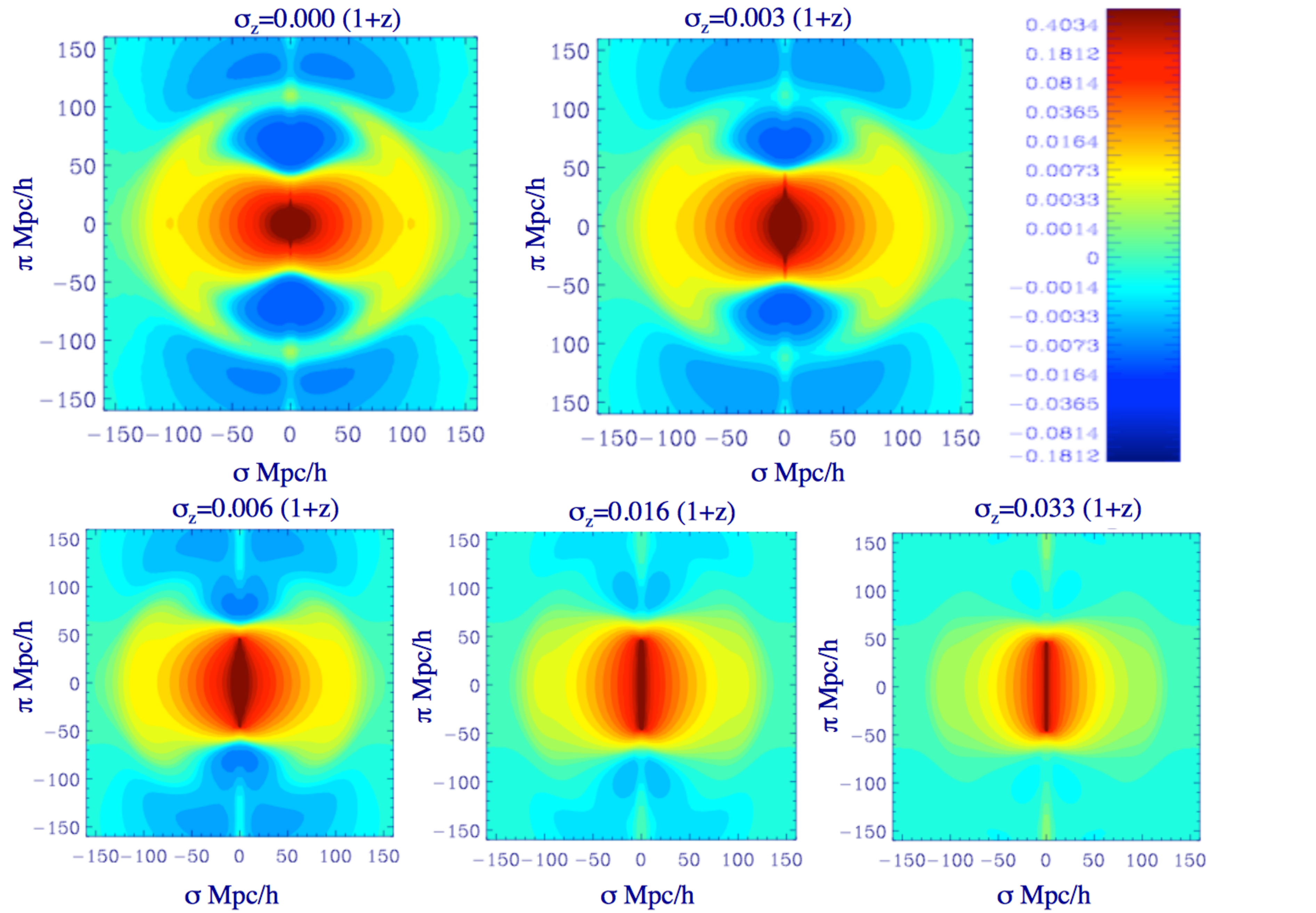


Figure 2. Top left panel shows the $\xi(\pi,\sigma)$ correlation in the Kaiser model with no photo-z error, i.e. $\sigma_z = 0$ (from Gaztañaga, Cabré & Hui 2009). The correlation is clearly squashed in the radial direction with a region of negative correlation (in blue) between $\pi = 50-100$ Mpc/h. Top right panel shows the same model but with a photo-z degradation of $\sigma_z = 0.003(1+z)$, corresponding to the PAU Survey. The difference is small and is mostly confined to small radial scales. Bottom panels show how the results are degraded as we increase σ_z to 0.006 (left), 0.016 (center) and 0.033 (right panel). As the photo-z increases the radial squashing disappears, turning instead into a radial elongation. Note also how the region of negative correlation vanishes as we increase the photo-z error.

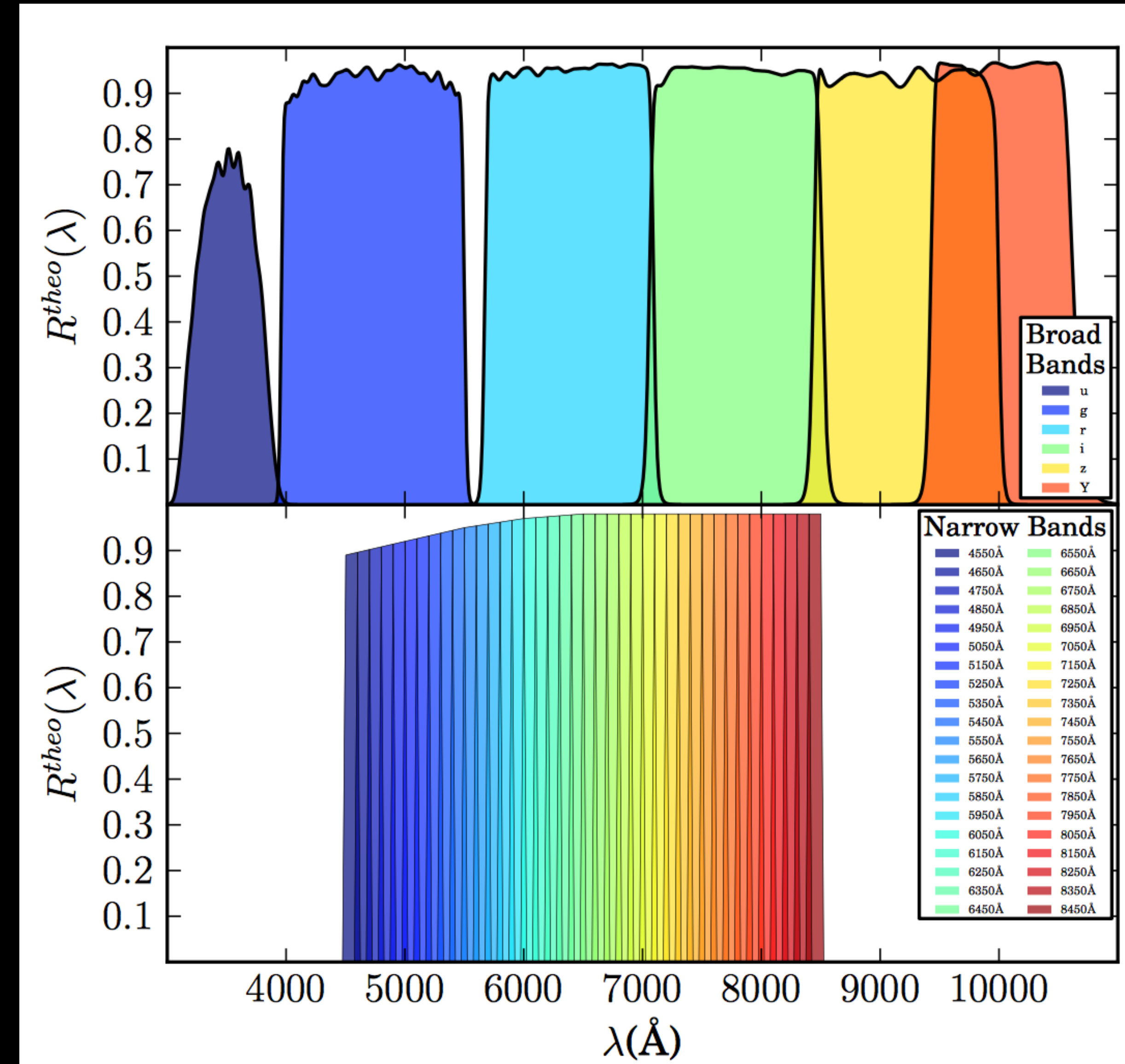
Low resolution could get us a lot of information

PAU http://www.pausurvey.org/

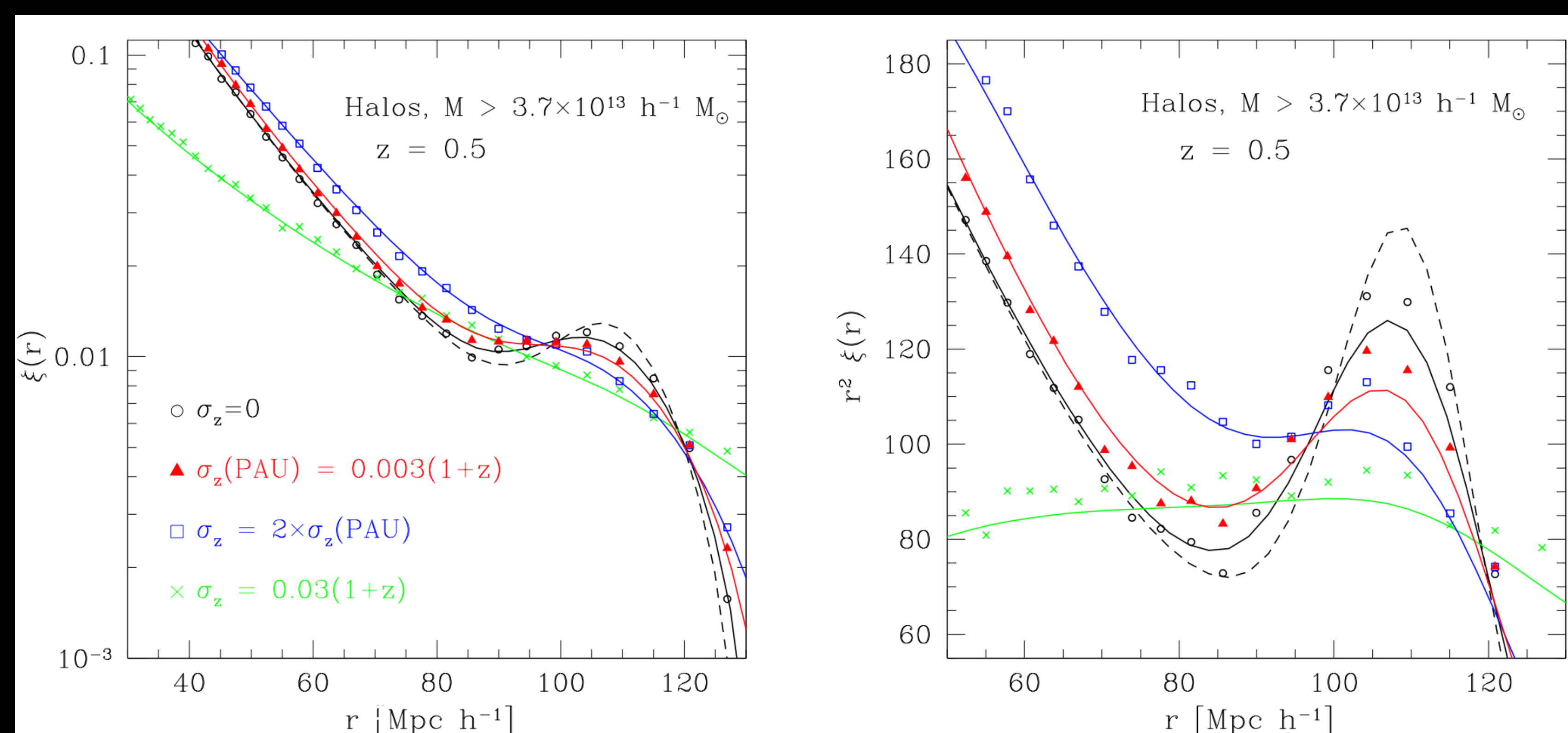
Physics of the Accelerating Universe

This project takes does photometry in 40 filter. It is starting to operate now. The point is **a lot of cosmology could be done with low resolution spectroscopy**

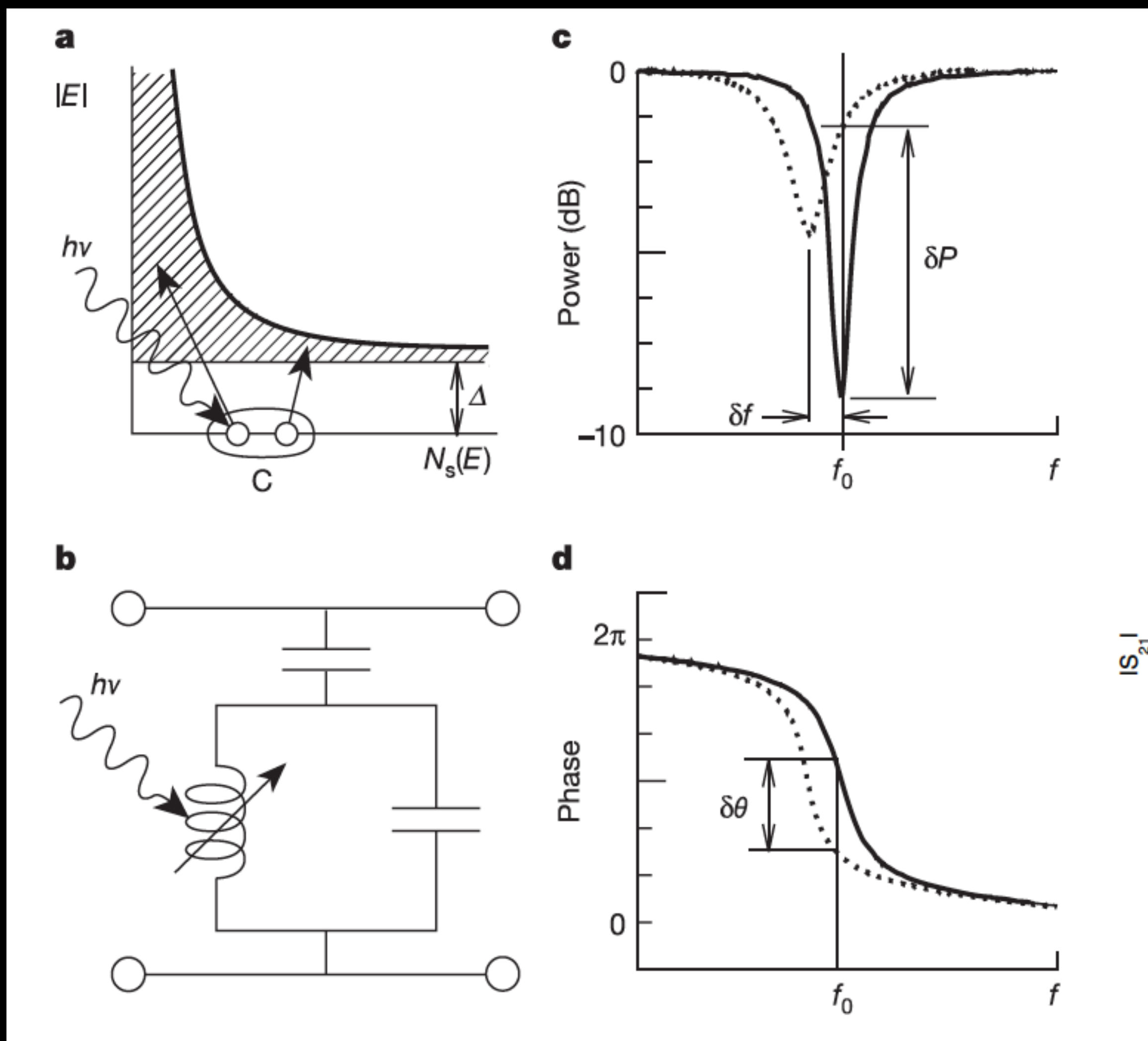
The issue is that if you use 40 filters, you are discarding 39/40 of the photons on each observation. A DES like survey would take 40 years instead of 5.



Example of potential of BAO measurement with 10 times better photo-z. Castander et al 2008.



MKIDs



Superconductor detectors. Each pixel is a resonator with frequency changing when it sees a photon.

The change in frequency is proportional to the photon energy. (gap 1meV)

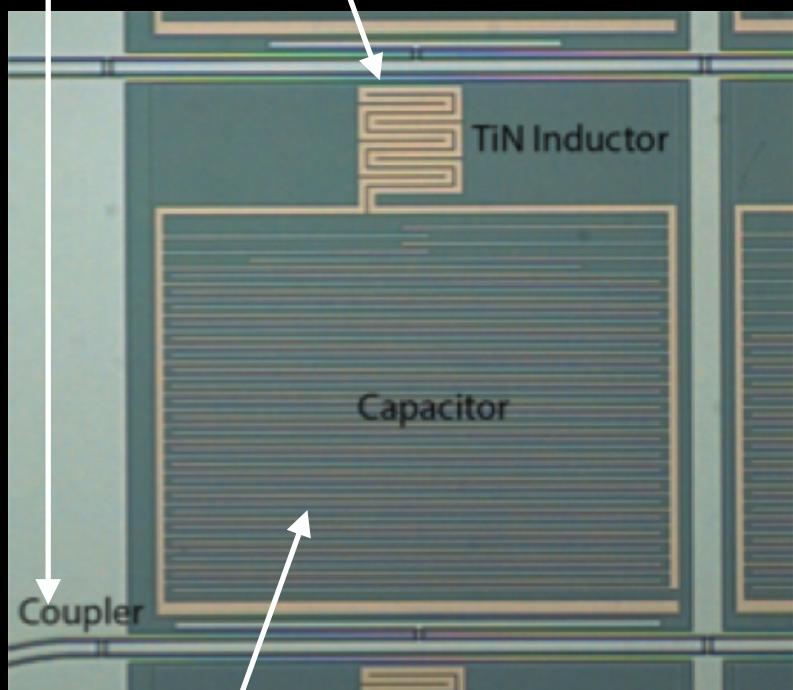
This enables the possibility of large arrays of superconductor detectors for visible and near-IR astronomical instruments.

On-sensor Spectroscopy.

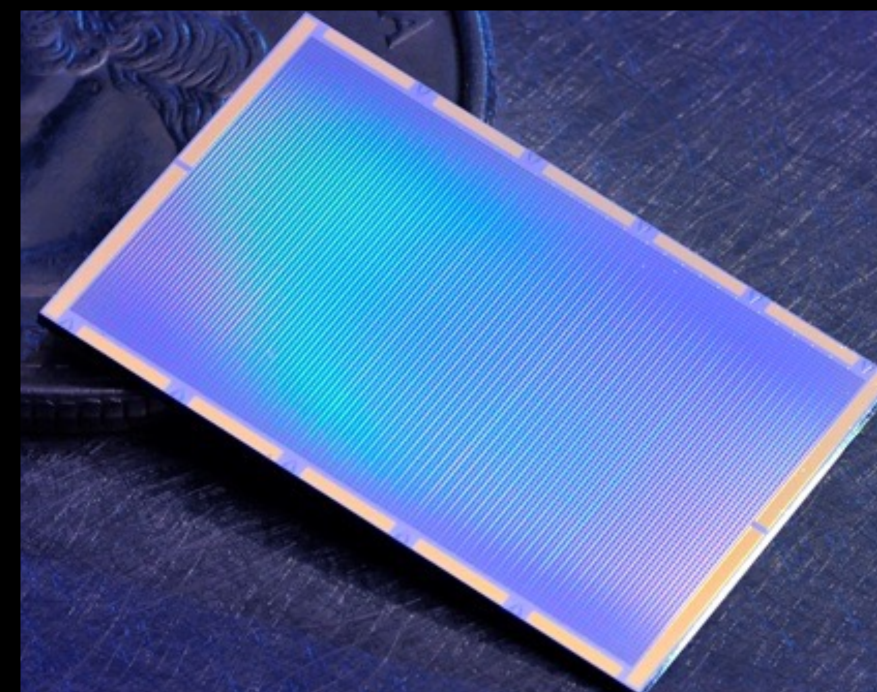
MKID pixel- designed by B.Mazin (UCSB)

RF feedline

capacitor



capacitor

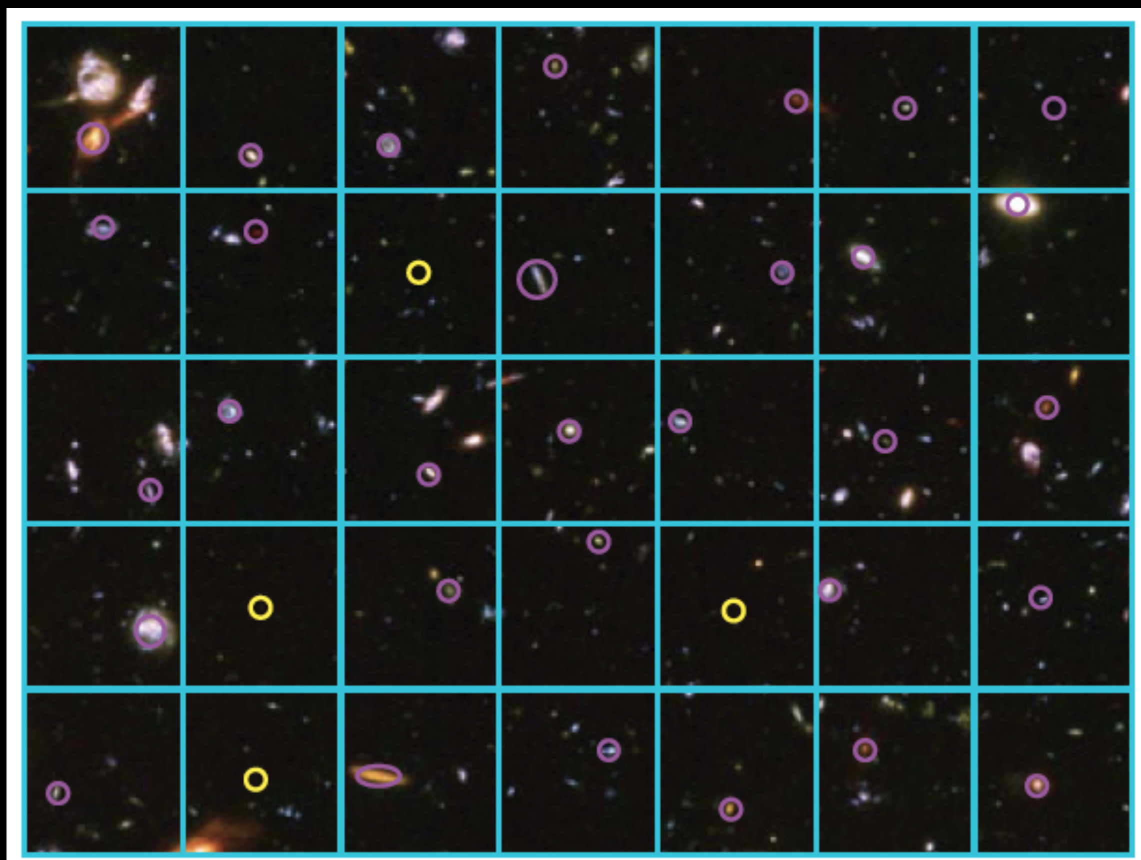


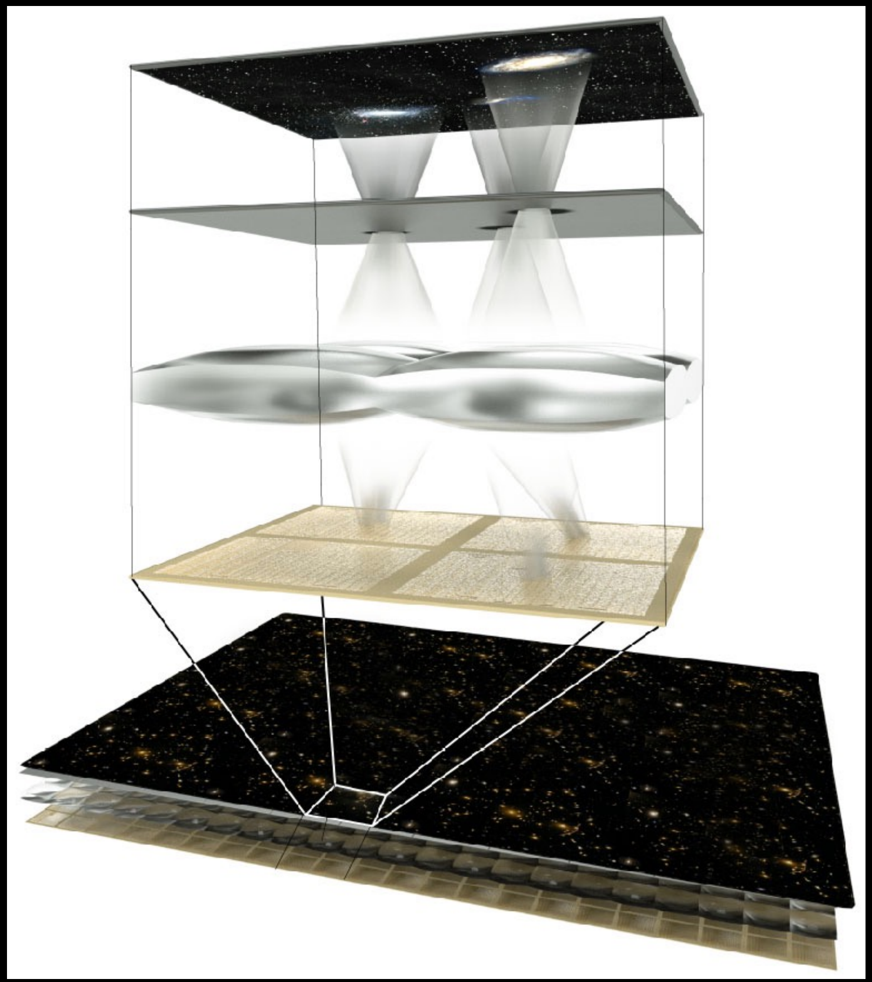
10k pixels in a sensor
4-8 GHz

Current performance R=E/ΔE~10, the sensors should be able to achieve R~100. Lot's of R&D still needed. DAQ is a big challenge.

GigaZ/MegaZ : Photo-z machine

- Marsden et al 2013
- LOI ESO 2014 (Oxford,Fermilab,UCSB)





Make large pixels, and use mask to select a galaxy for each pixel. **<u>100,000 spectroscopic channels in 1 square deg. is possible (20x DESI). Resolution R~100.</u>** White paper to Snowmass 2013. Large project after LSST. (See comment from P5)

Conclusion - Outlook

- Since LP2013 big news: DES start producing results, LSST and DESI making progress in the review process and start construction.

- LP2017 will see lots of interesting cosmology results from DES. DESI and LSST will be also at full construction. Maybe one DE talk will not be enough…

- Start thinking about low-resolution spectroscopy as a next step in Dark Energy surveys. Maybe even with superconducting detectors (MKIDs)

Marsden et al 2013.

This paper discusses what is possible with an MKID base survey. Some aspects of the science with MKIDs after LSST are presented.

There is still a lot of work to do in this area.

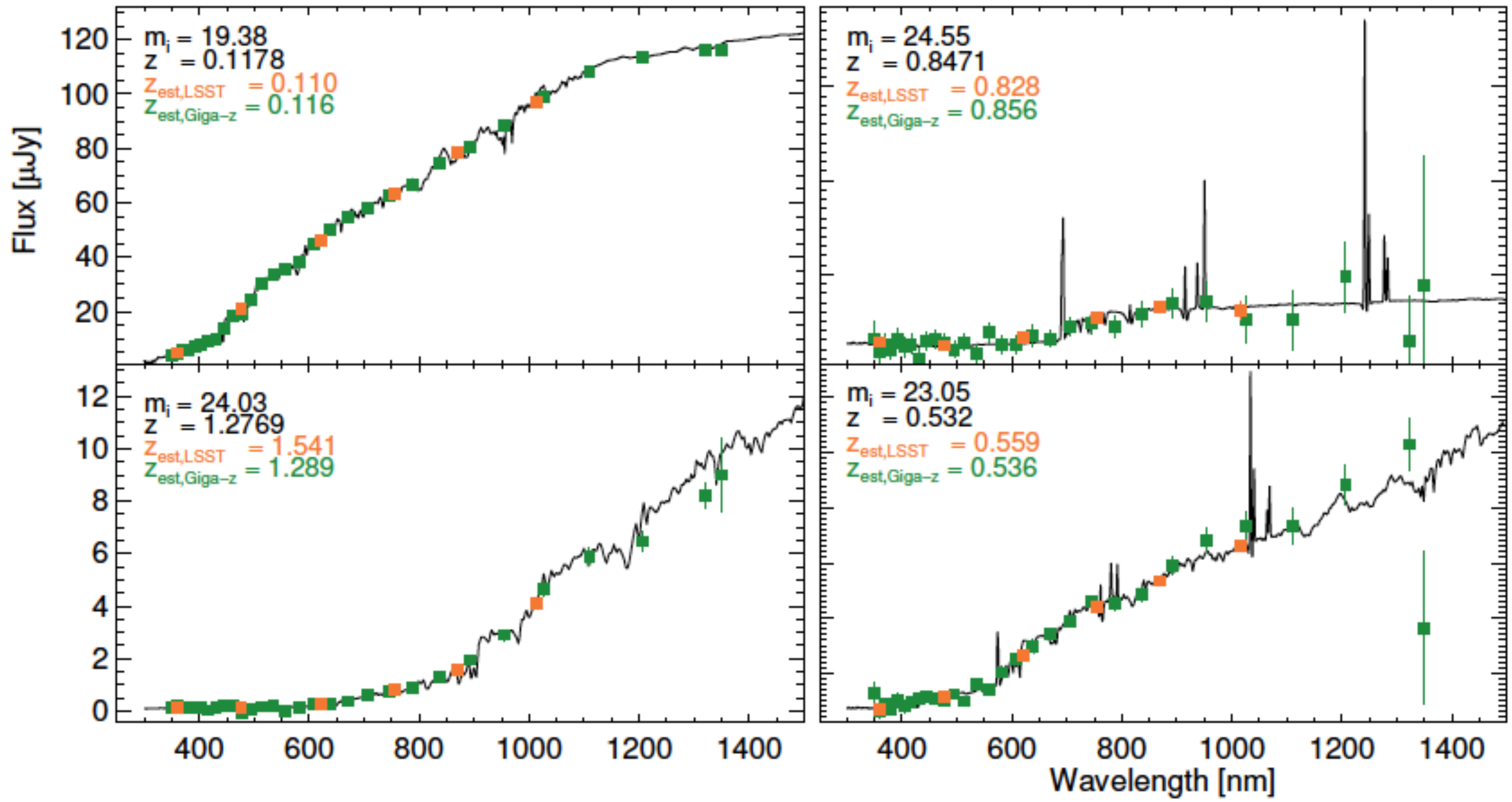
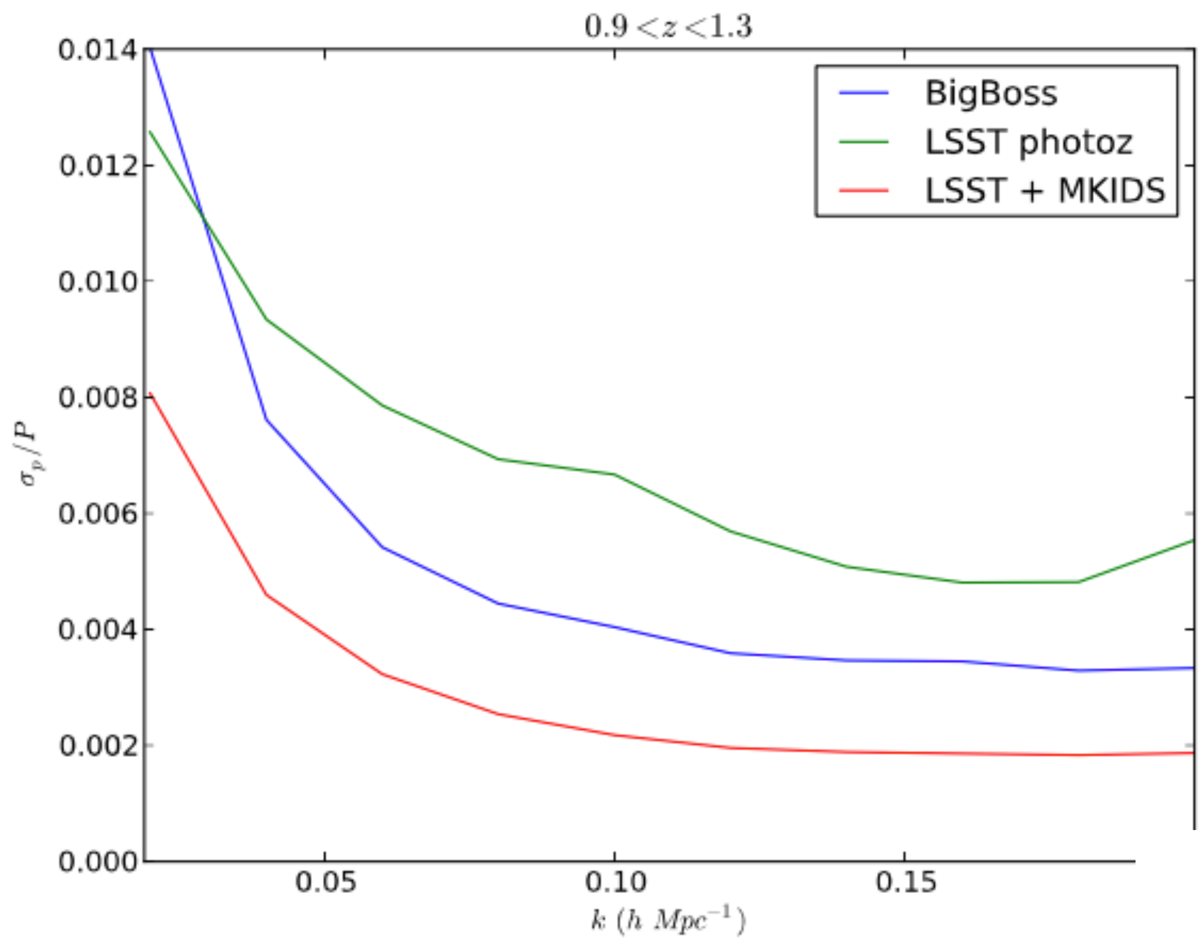


TABLE 4

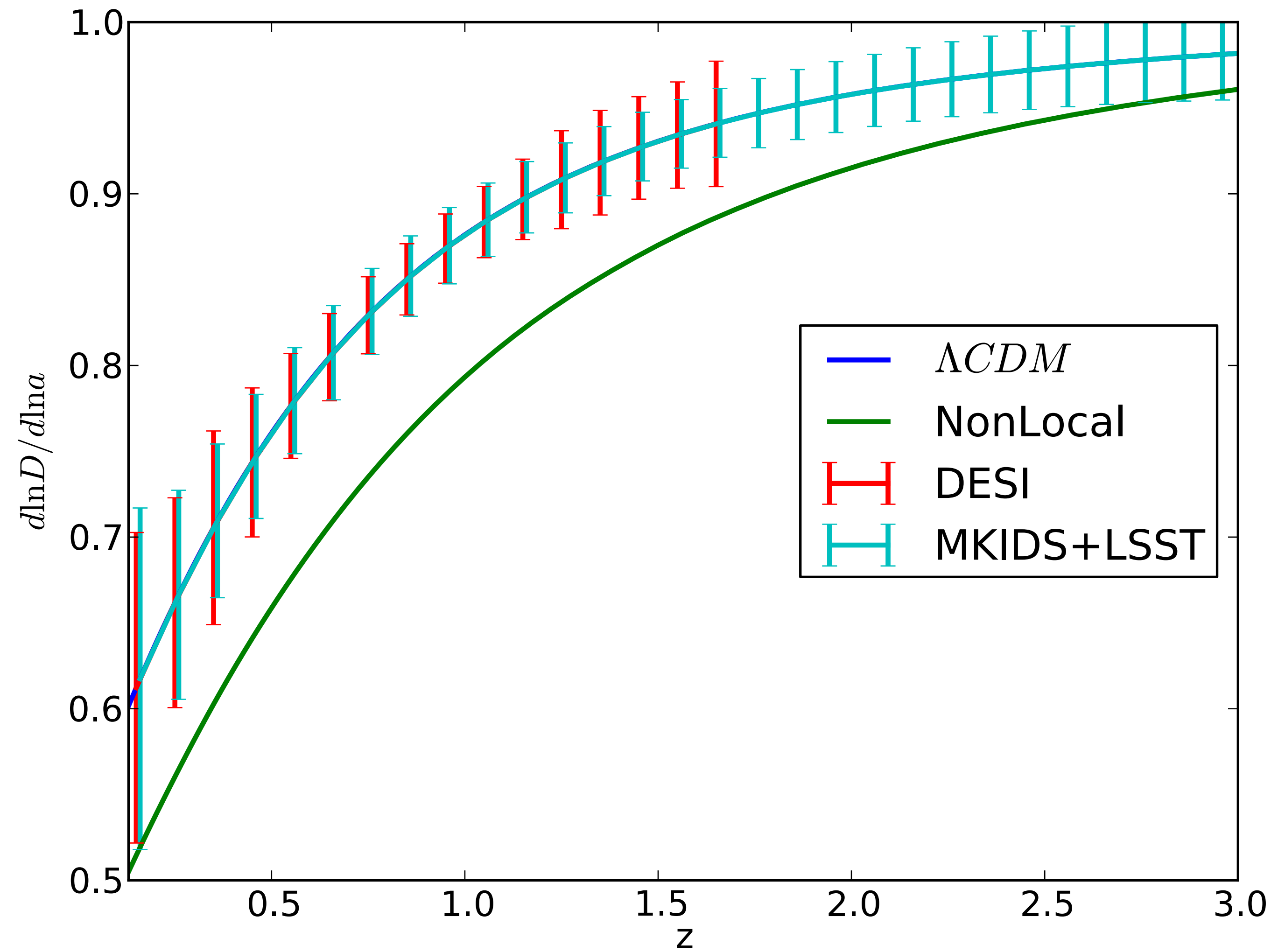
A comparison of redshift recovery statistics between multi-band photometry or multi-object spectroscopy experiments, both past and planned.

Experiment	N_{gals}	Area [deg^2]	Magnitude Limit	N_{filts}/Resolution	Scatter	Cat. Failure Rate
COMBO 17 [a]	∼10,000	∼0.25	$R < 24$	17	0.06	$\lesssim 5\%$
COSMOS [b]	∼100,000	2	$i^+_{AB} \sim 24$	30	0.06	∼20%
	∼30,000	2	$i^+ < 22.5$	30	0.007	< 1%
CFHTLS - Deep [c]	244,701	4	$i'_{AB} < 24$	5	0.028	3.5%
CFHTLS - Wide [c]	592,891	35	$i'_{AB} < 22.5$	5	0.036	2.8%
PRIMUS [d]	120,000	9.1	$i_{AB} \sim 23.5$	$R_{423} \sim 90$	∼ 0.005	∼2%
WiggleZ [e]	238,000	1,000	$20 < r < 22.5$	$R_{423} = 845$	$\lesssim 0.001$	$\lesssim 30\%$
Alhambra [f]	500,000	4	$I \leq 25$	23	0.03	…
BOSS [g]	1,500,000	10,000	$i_{AB} \leq 19.9$	$R_{423} \sim 1600$	$\lesssim 0.005$	∼2%
DES [h]	300,000,000	5,000	$r_{AB} \lesssim 24$	5	0.1	…
EUCLID [i]	2,000,000,000	15,000	Y,J,K $\lesssim 24$	3+	$\lesssim 0.05$	$\lesssim 10\%$
	50,000,000	15,000	$H_\alpha \geq$ 3e-16 erg/s/cm^2	$R_{1\mu m} \sim 250$	$\lesssim 0.001$	< 20%
LSST [j]	3,000,000,000	20,000	$i_{AB} \lesssim 26.5$	6	$\lesssim 0.05$	$\lesssim 10\%$
Giga-z	2,000,000,000	20,000	$i_{AB} \lesssim 25.0$	$R_{423} = 30$	0.03	∼ 19%
	224,000,000	20,000	$i_{AB} \lesssim 22.5$	$R_{423} = 30$	0.01	0.3%

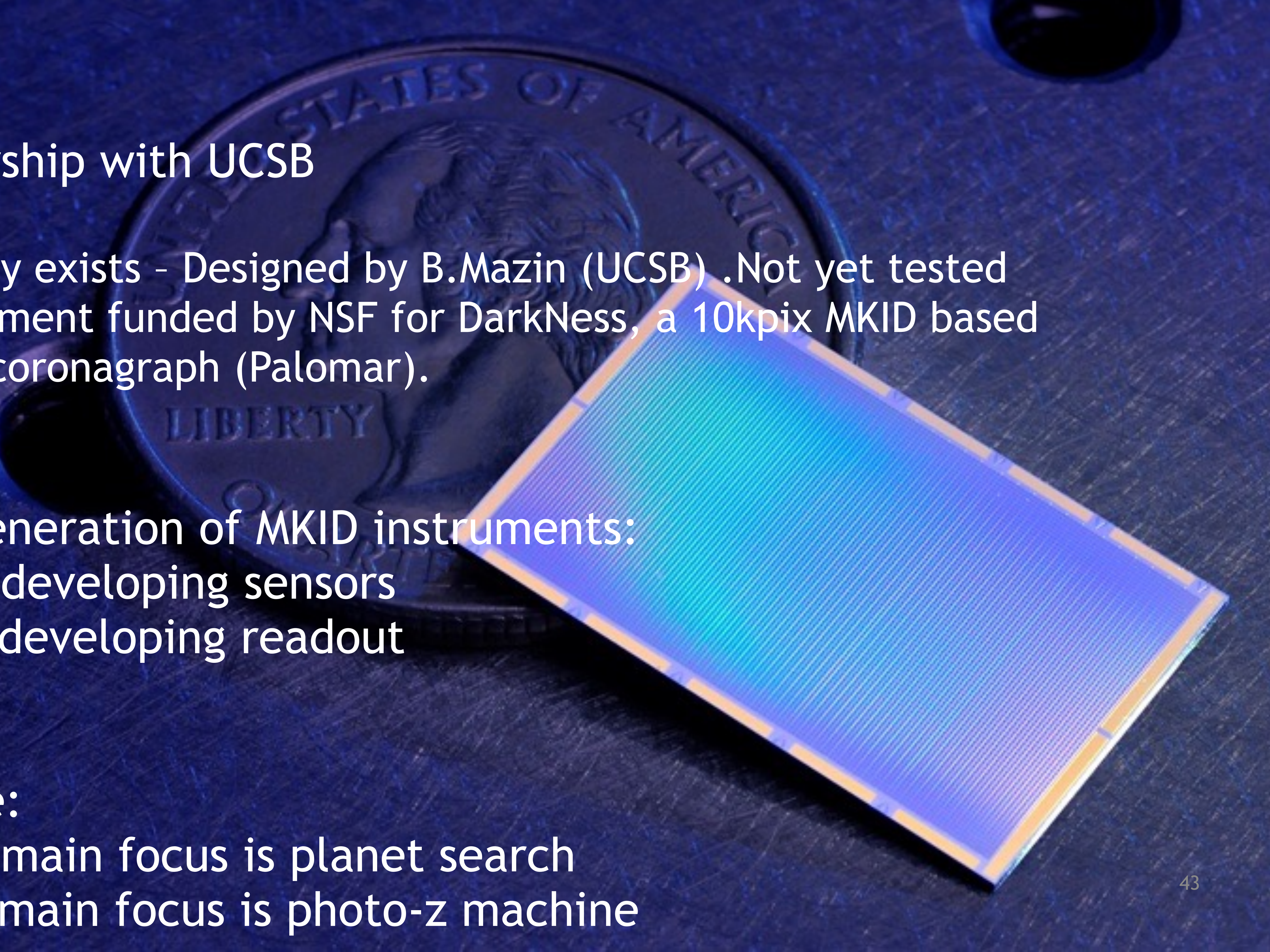
from Scott Dodelson



How well could we measure the power spectrum if we reduce the redshift error in LSST from 0.1 to 0.01. From R~5 (5 filters) to R~50 (MKIDs)?



GR versus non-local gravity. The logarithmic derivative of the growth function as a function of redshift; this is directly measured in spectroscopic surveys capable of probing redshift space distortions. (arXiv:1310.4329)



rship with UCSB

y exists – Designed by B.Mazin (UCSB) .Not yet tested
ment funded by NSF for DarkNess, a 10kpix MKID based
coronagraph (Palomar).

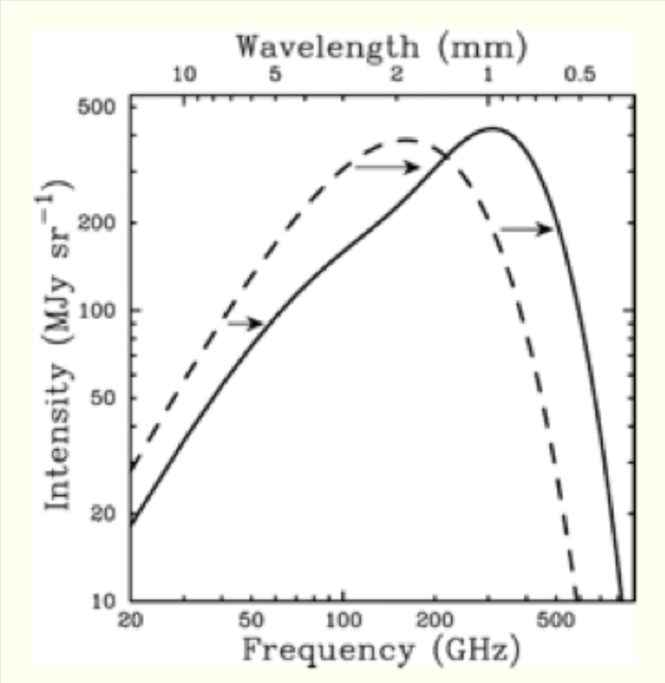
eneration of MKID instruments:
developing sensors
developing readout

e:
main focus is planet search
main focus is photo-z machine

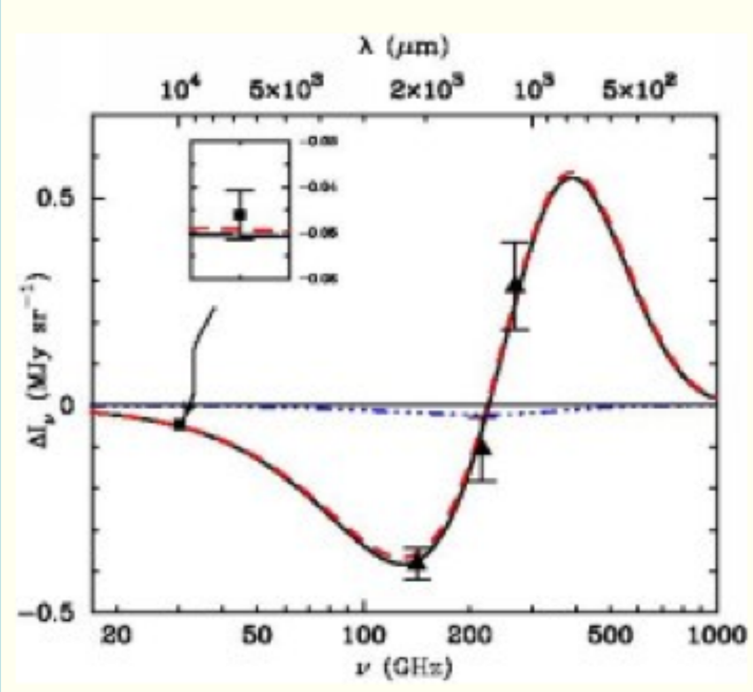
South Pole Telescope (SPT)

4000 deg^2 are shared with SPT. Started operations in 2007.

Cluster mass measurements and detections with SPT combined with photo-z from DES produce a powerful sample for cosmology.



Abel 2163



http://astro.uchicago.edu/sza/primer.html

CMB photons are blue-shifted by scattering with the hot gas in the cluster.

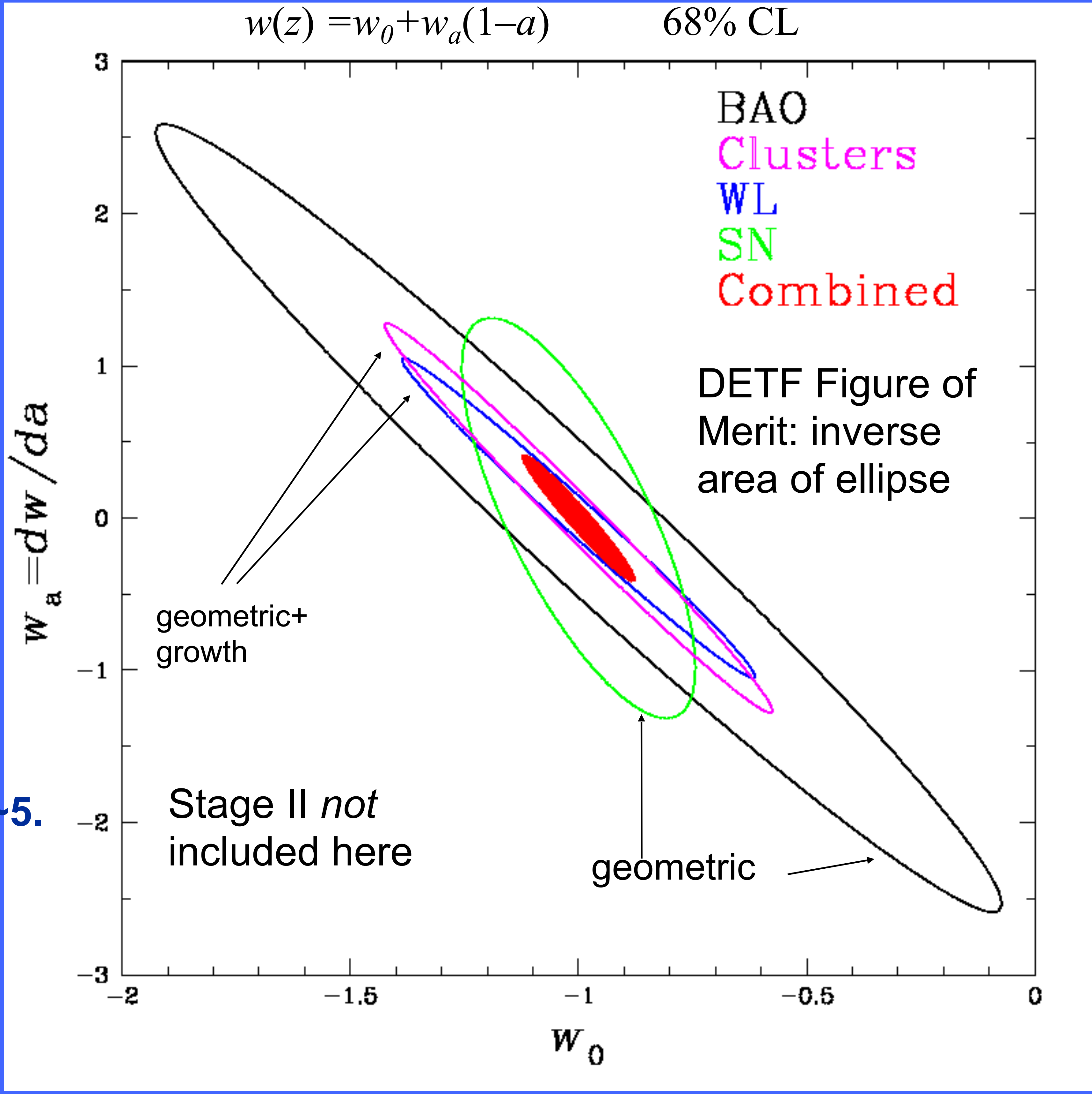
Does not depend much on distance to cluster...

Forecast when considering the 4 techniques

Assumptions:
Clusters:
σ_8=0.75, z_{max}=1.5,
WL mass calibration
BAO: l_{max}=300
WL: l_{max}=1000
(no bispectrum)
Statistical+photo-z
systematic errors only

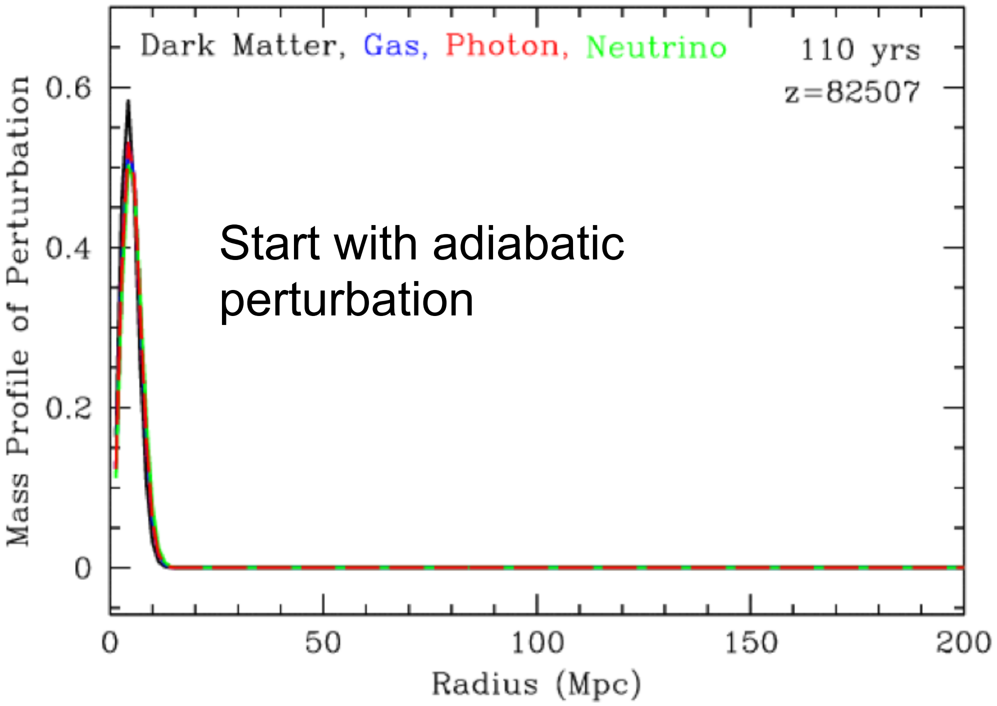
Spatial curvature, galaxy bias marginalized, Planck CMB prior
In terms of the DETF:
Factor 4.6 improvement over Stage II

Smaller is better, and we have 4 independent methods. DES will reduced this area by a factor of ~5.

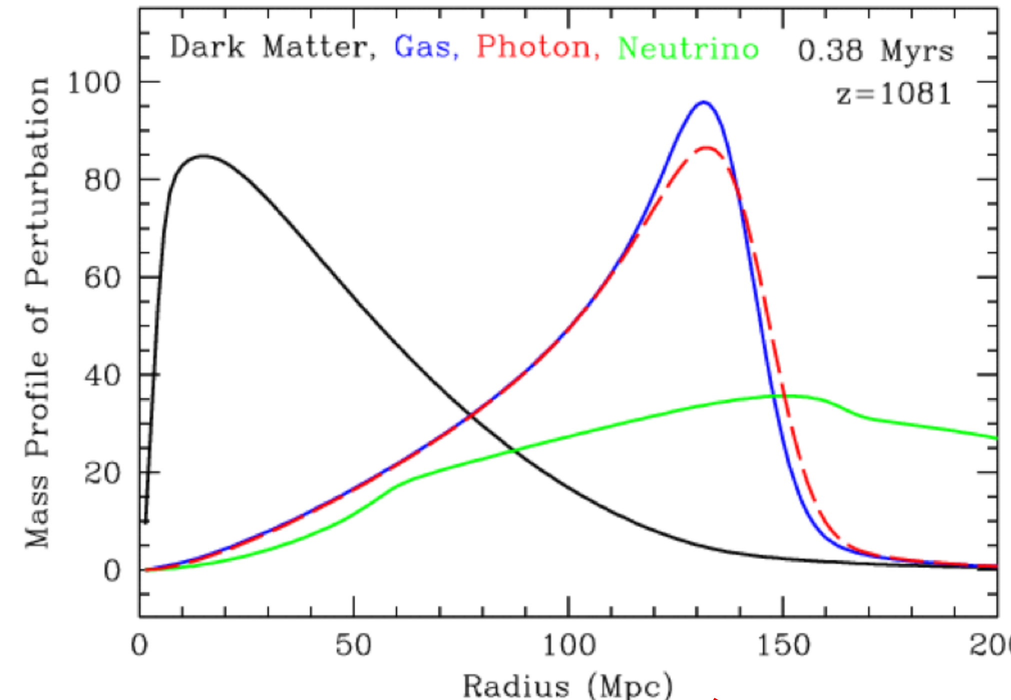


BAO (goal #2)

DARK ENERGY SURVEY



Pressure in photons produces a sound wave, gas follows.



Baryon Acoustic Oscillations imprint the sound horizon scale into the DM distribution. Standard rod.