The Dark Energy Spectrograph

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Fermilab PAC, October 16, 2012

U.S. Dark Energy Program

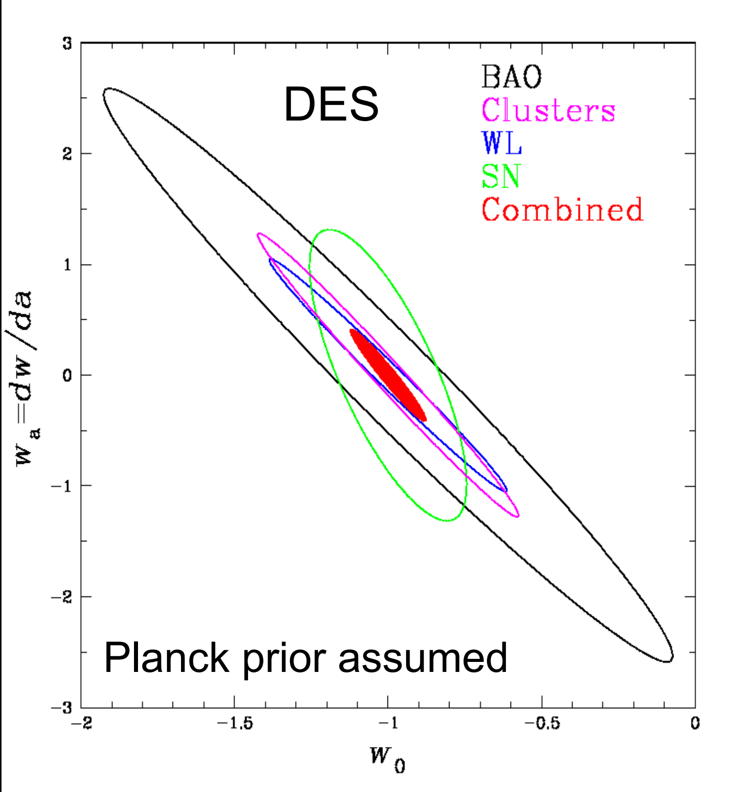
- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - What is the DE equation of state parameter w?
- BOSS, DES, and later LSST well designed to make major advances in addressing these questions.
- The DE program would be substantially enhanced in the intermediate term by a massive galaxy redshift survey that optimally synergizes (overlaps) with the DES imaging survey and in the longer term by a larger redshift survey selected from LSST.

Recent Developments

- Rocky III Report:
  - “compelling case for…wide-field spectroscopic survey”
- NSF AST Portfolio Review Report:
  - High-multiplex, optical spectroscopy on >= 4m telescopes a critical technical capability for Cosmology & Fundamental Physics; Blanco, Mayall very well-suited
- DOE approves CD-0 for mid-scale Dark Energy Spectroscopic Instrument Experiment
- DECam First Light
  - optical corrector working well
- DESpec White Paper released, workshops being held (May, Dec. 2012), R&D underway

DES Science Summary

Forecast Constraints on DE Equation of State



Factor 3-5 improvement over Stage II DETF Figure of Merit

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Massive Spectroscopy of DES and LSST Targets Enables New and Improved DE Probes

- Weak Lensing and Redshift-Space Distortions
  - Powerful test of Dark Energy vs Modified Gravity
- Galaxy Clustering
  - Radial BAO for $H(z)$ and improved $D_A(z)$
- Photometric Redshift Calibration
  - Determine DES and LSST $N(z)$ from angular correlation, improve DE constraints from all methods in the imaging surveys
- Galaxy clusters
  - Dynamical masses from velocity dispersions, improve halo mass-observable calibration, reduce the major cluster DE systematic
- Weak Lensing
  - Reduce systematics from intrinsic alignments
- Supernovae
  - Reduce systematics from host-galaxy typing

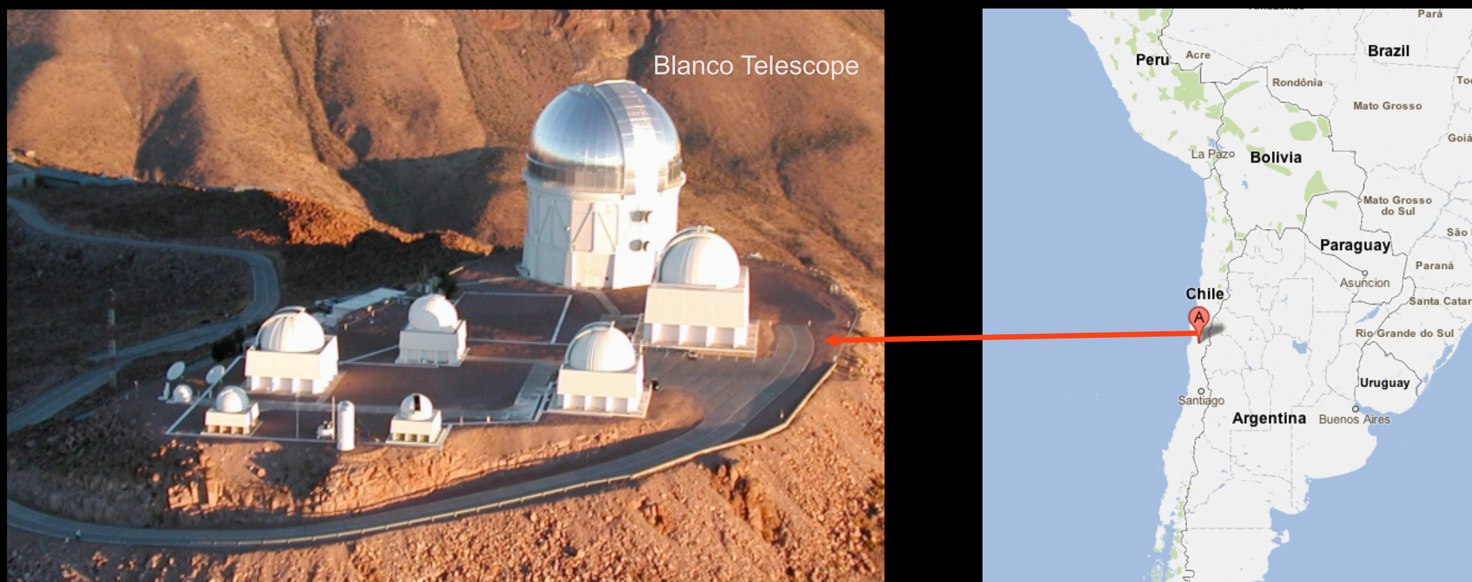
Massive Spectroscopic Surveys in the Southern Hemisphere

- 8-million Galaxy Redshift Survey in 350 nights
  - Uniformly selected from deep, homogeneous DES imaging over 5000 sq. deg. (2018+)
- 23-million Galaxy Redshift Survey in 1000 nights
  - Uniformly selected from deep, homogeneous LSST imaging over 15,000 sq. deg. (2021+)
- Deep, uniform multiband imaging from DES, LSST
  - Enable efficient, well-understood selection of spectroscopic targets
- Photometric+Spectroscopic Surveys over same Sky
  - Enable powerful new science beyond what either can provide alone

Dark Energy Spectrograph Concept

- 4000-fiber optical spectrograph system for the Blanco 4m
- Mohawk robotic fiber positioner
  - Based on Echidna system, has demonstrated requisite pitch
- Feed 10 2-arm, high-throughput spectrographs
  - 10 spare DECam CCDs (red) and 10 blue-sensitive CCDs
- Fibers tile full 3.8 deg^2 DECam Field of View
- Fiber positioner rapidly interchangeable with DECam imager
  - Maintain wide-field imaging capability for the Blanco
- Use much of the DECam infrastructure installed on Blanco
  - Prime focus cage, hexapod, 4 of the 5 optical corrector elements, shutter
- DESpec White Paper released Sept. 11
  - arXiv: 1209.2451 (Abdalla, etal)

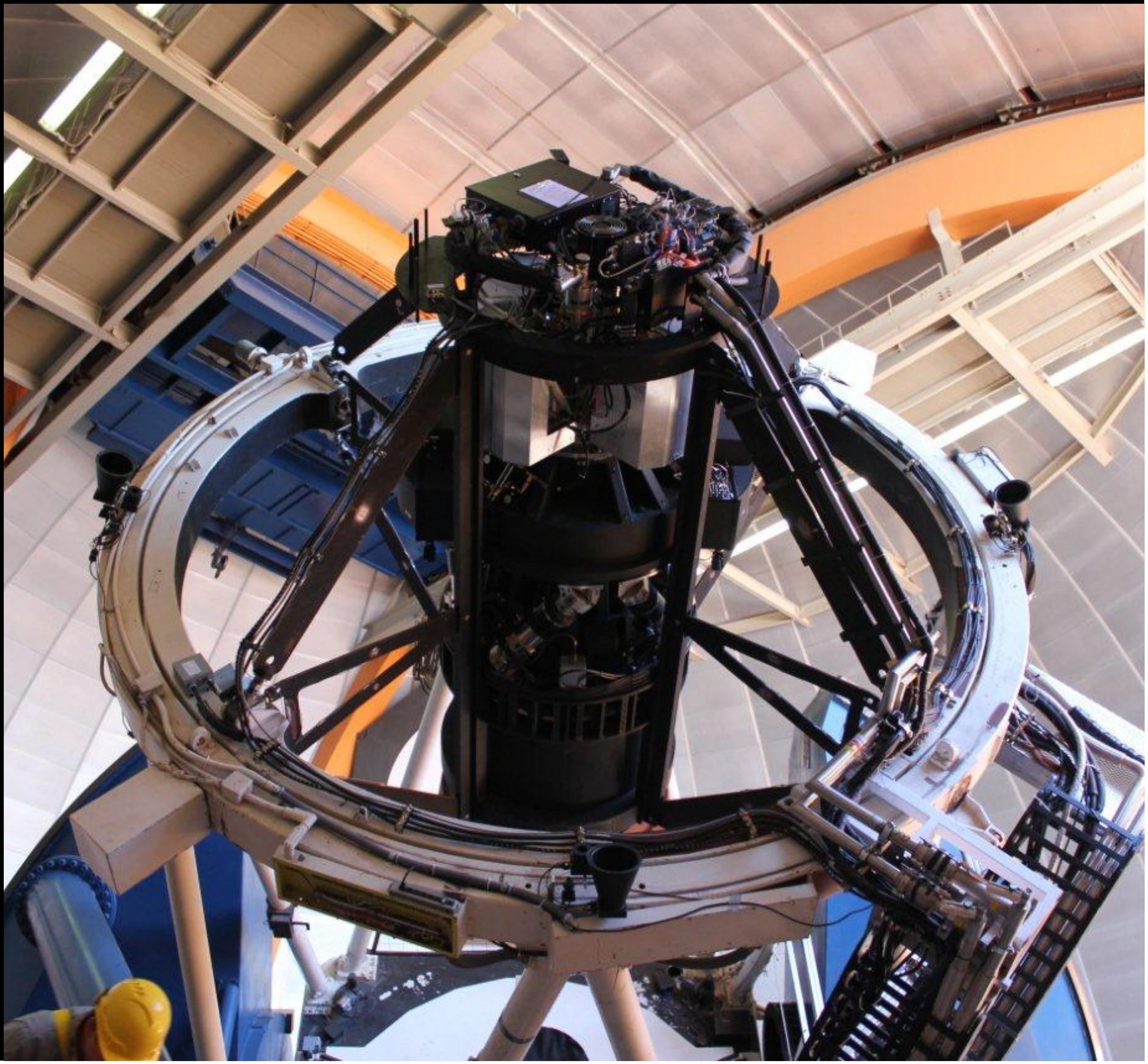
Cerro Tololo



high, dry; excellent seeing, 80% useable nights, high fraction of photometric nights. Its advantages for photometry (DES) apply to spectroscopy (DESpec) as well, yielding fast (hence relatively cheap) surveys. Next door to LSST and Gemini.

DECam

Prime Focus Cage Installed on Blanco Telescope



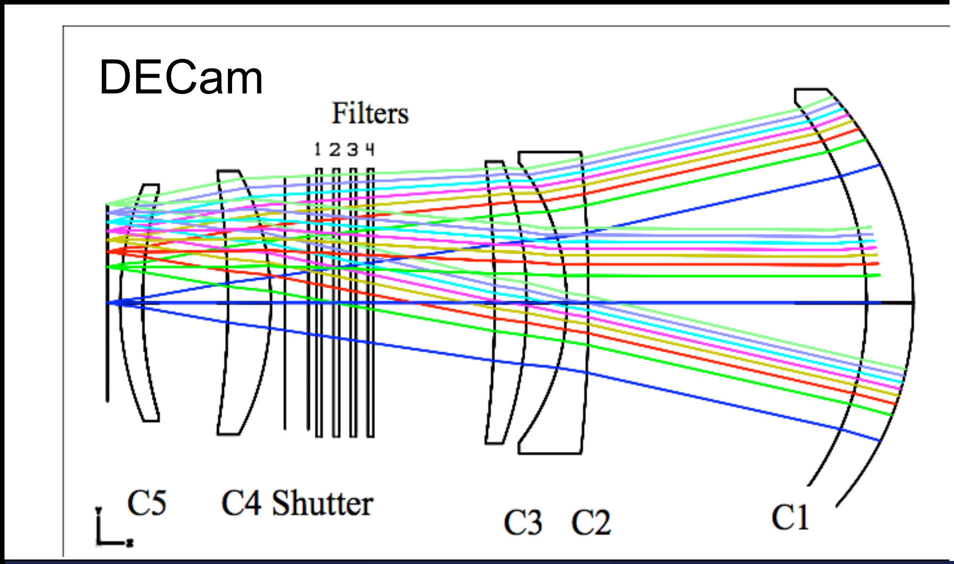
DECam
+DESpec
Prime Focus
Cage
Installed on
Blanco
Telescope

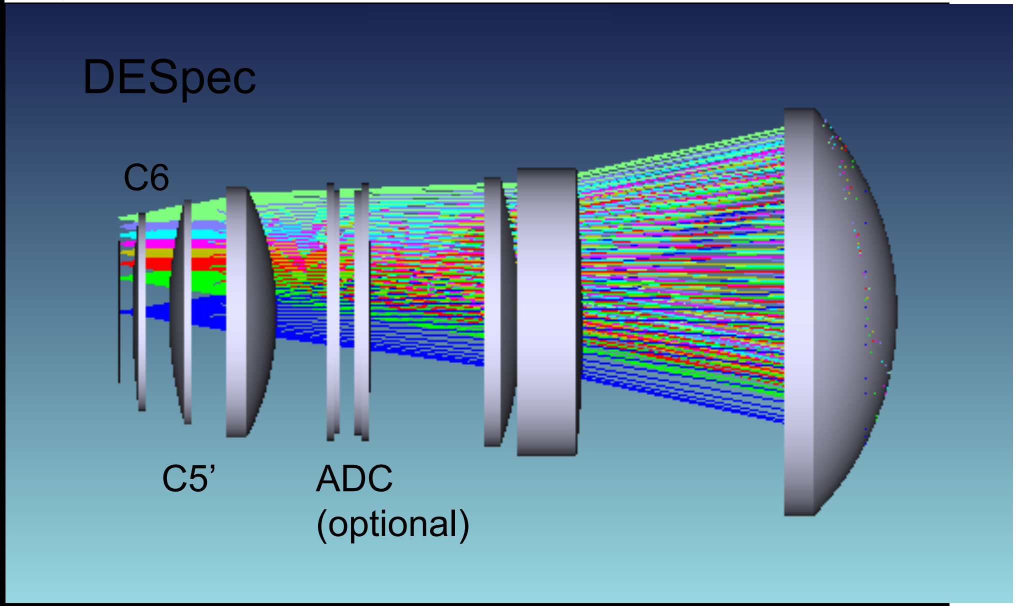
Saunders, etal

Optics

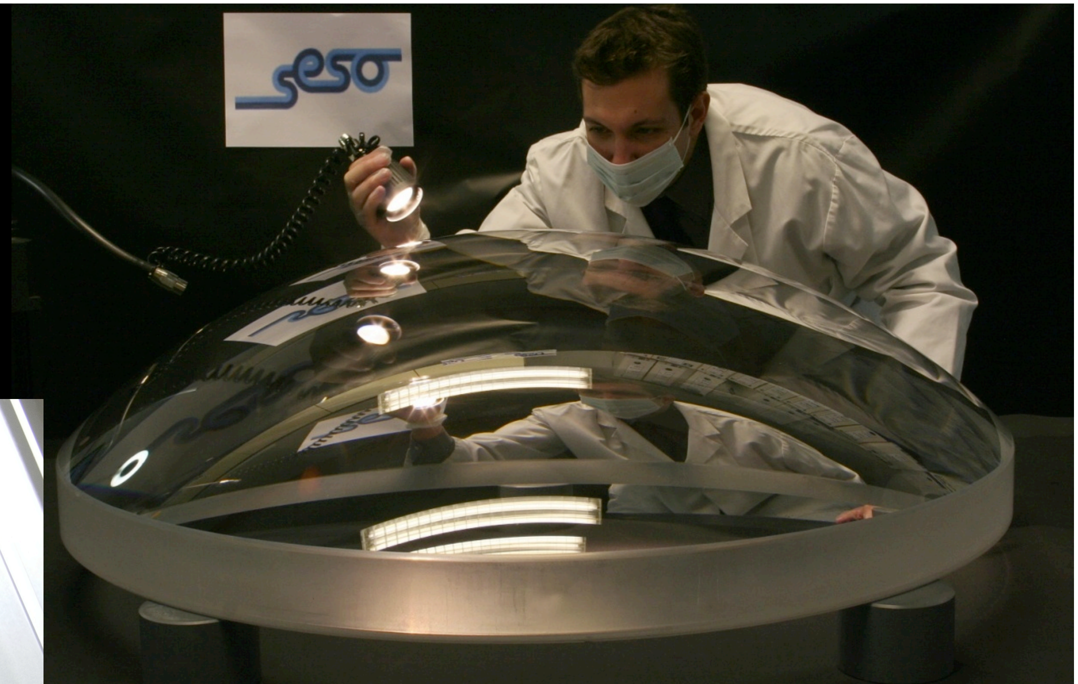
- Field of View 2.2^{o} diameter, 3.8 deg^2
- DECam corrector demonstrated on the telescope to deliver good image quality across FOV
- Corrector was longest lead-time item for DECam
- DESpec optical design still being optimized
- Optical work to be done at UCL as for DECam
- 2 new optical elements (C5', C6) rapidly interchangeable with C5 (DECam dewar window): maintain DECam imaging capability

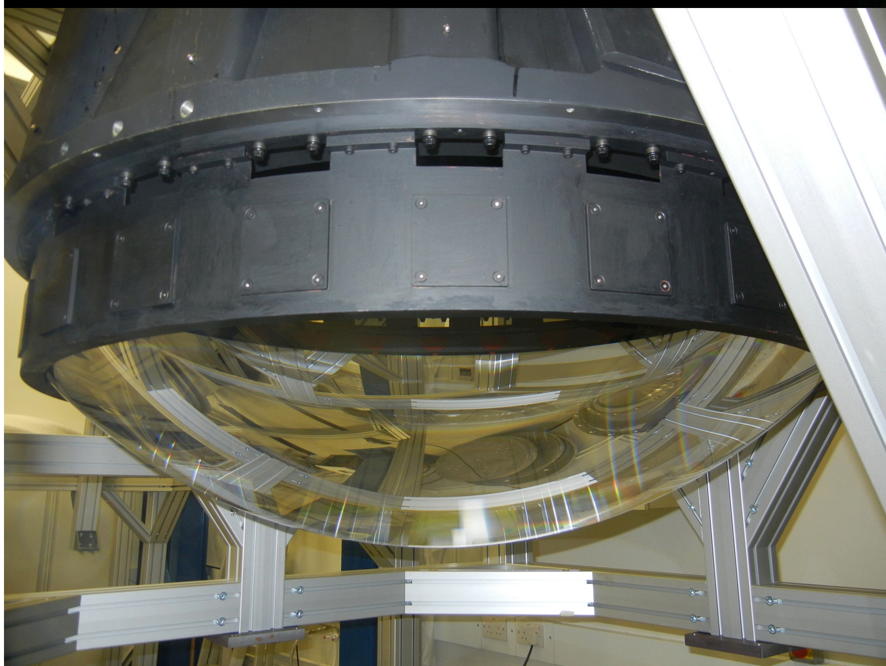
S. Kent, W. Saunders





DECam/DESpec C1 Lens



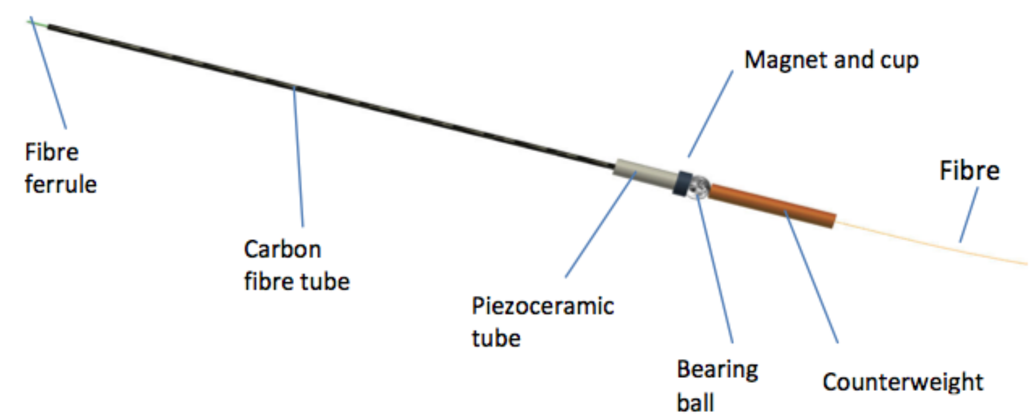


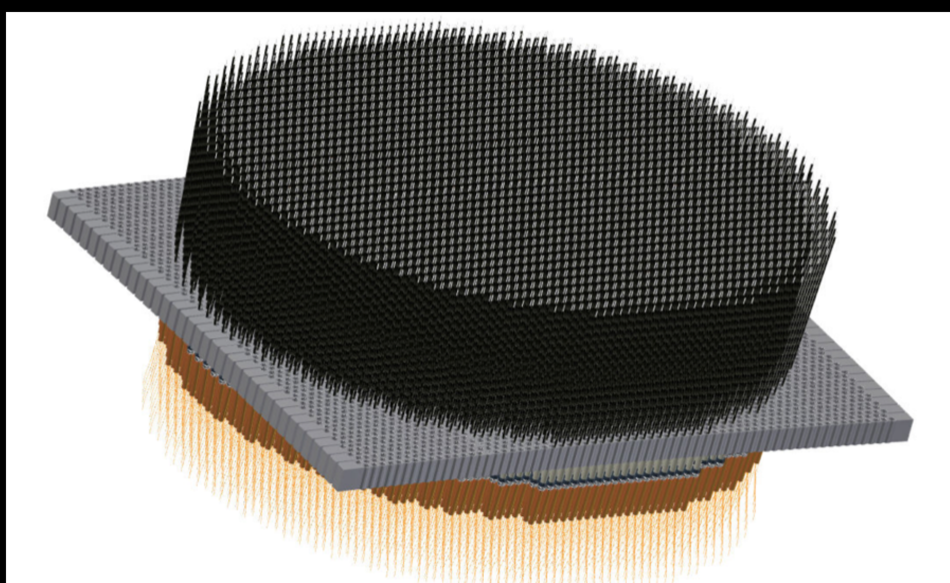
DECam optical corrector installed on Blanco in May

Mohawk Fiber Positioner System

- Proposed for DESpec by Australian Astronomical Observatory
    - R&D program described in Saunders, etal, Proc. SPIE
- Derived from existing Echidna system
    - 400-fiber system deployed on Subaru 8m telescope
- Builds on R&D done for WFMOS
- 4000 fibers in nominal design, with tilting spine technology
    - 6.75 mm pitch (interfiber separation)
- Modular design
- Actuators prototyped at AAO
    - 15 sec reconfiguration times with position errors < 7 microns

Mohawk Fiber Positioner





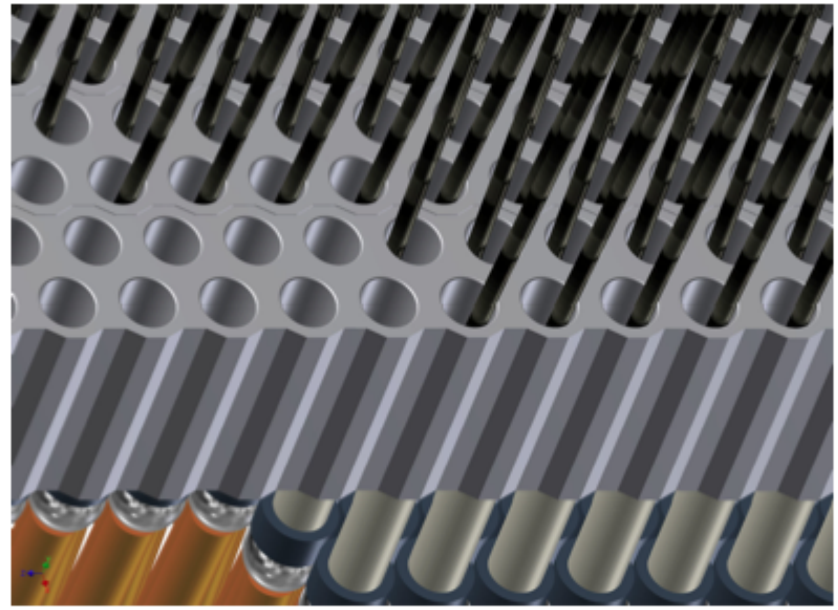


Figure 10. Close up of 3 adjacent modules.

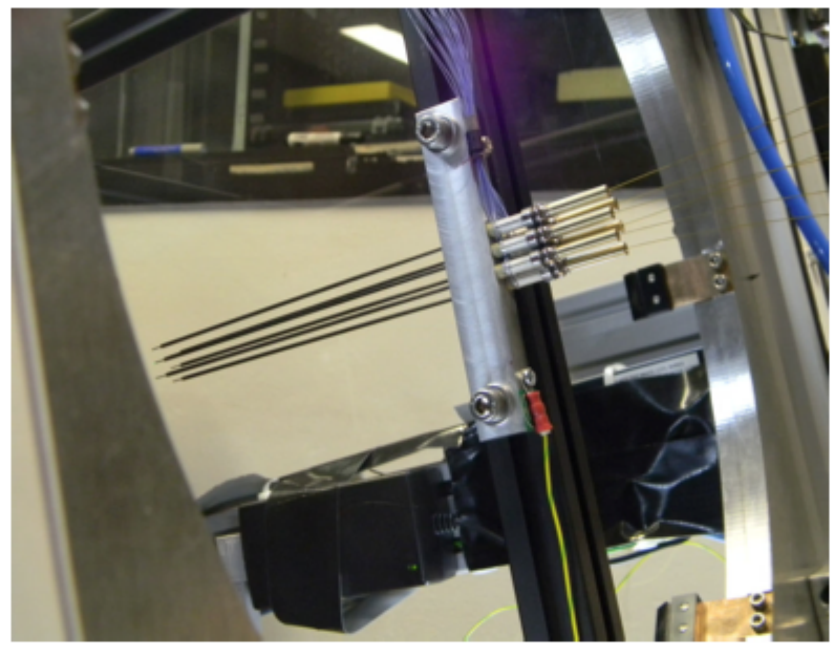


Figure 11. 6-actuator 'Minihawk' Prototype, mounted in the AAO rotatable testing rig.

Tilting Spines

- Estimated 15% throughput loss (non-telecentricity, focal ratio degradation)
- 84% of potential targets observed per pointing
- DESpec survey plans 2 pointings per field to achieve high completeness and target density

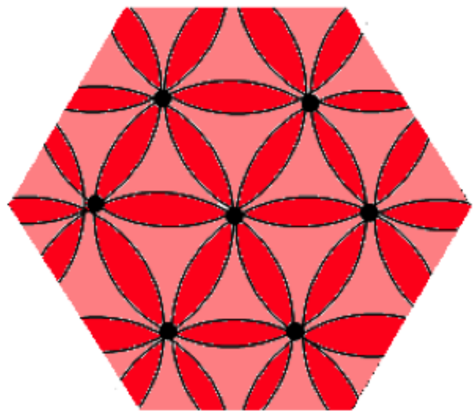


Figure 3. Schematic view of the patrol areas of adjacent actuators, when the patrol radius is equal to the pitch. The pink areas can be reached by 3 different actuators, while the red areas can be reached by 4 (and the black home positions by 7).

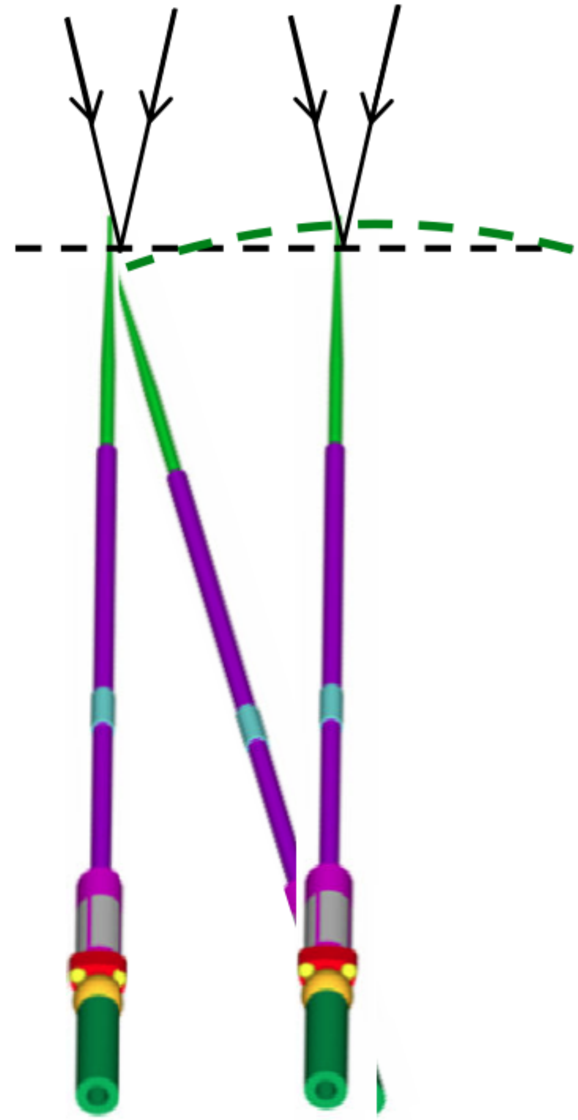


Figure 4. Schematic drawing of adjacent Echidna spines, showing the focus change with tilt and the telecentricity error at large tilt angle. Black line is focal plane, green line is locus of spine tip.

Spectrographs

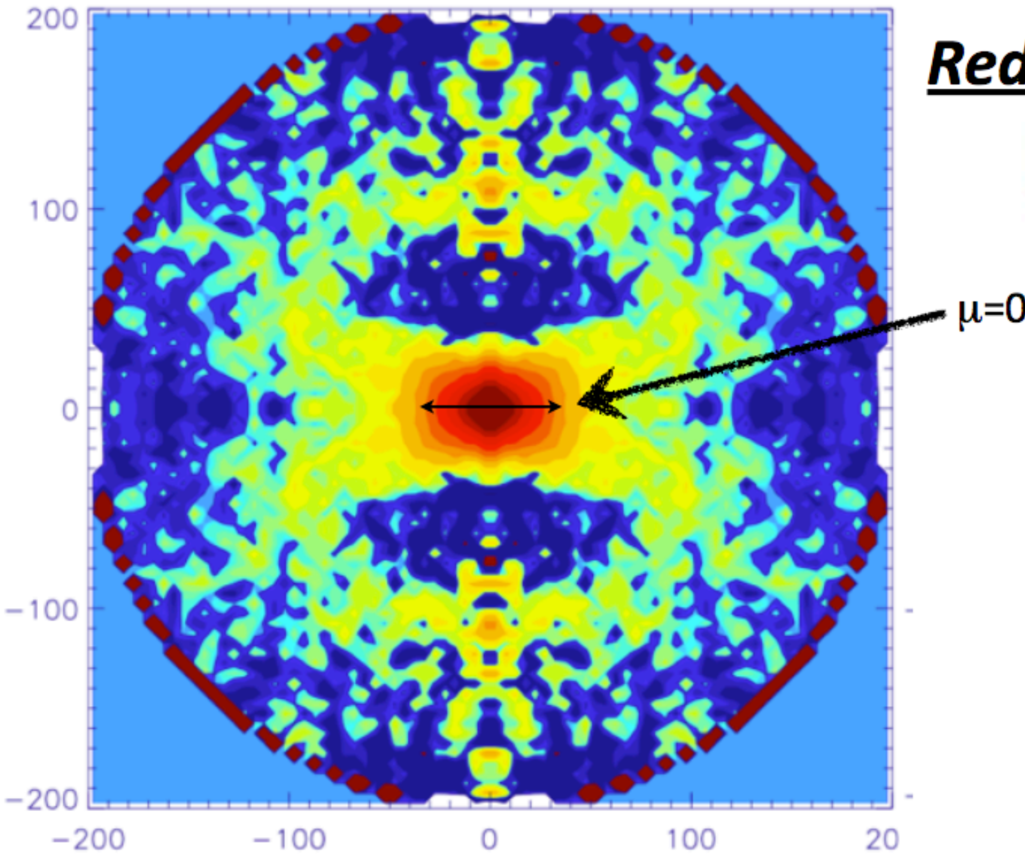
- Two-arm design with dichroic
  - 400 fibers per spectrograph, 10 spectrographs, 20 CCDs
- Wavelength range 480-1050 nm
  - cover spectral lines over redshift range of interest
- Resolution 0.228 nm
  - detect/resolve galaxy lines and reduce sky contamination
- Extension to UV (for Lyman-alpha BAO) under study
  - preliminary optical design reaches 350 nm with good spot size, could require 3-arm spectrographs for res.

Parameter	Blue Side	Red Side
Fiber Diameter	100 μm (1.75”)	
Wavelength Range (nm)	$480<\lambda<780$	$750<\lambda<1050$
CCD	E2V	DECam 2kx4k
Resolution ($\Delta\lambda$ nm/res. el.)	0.228 nm	0.228 nm
# pixels/fiber	3	3
Camera f/#	f/1.5	f/1.5
Camera Type	refractive	

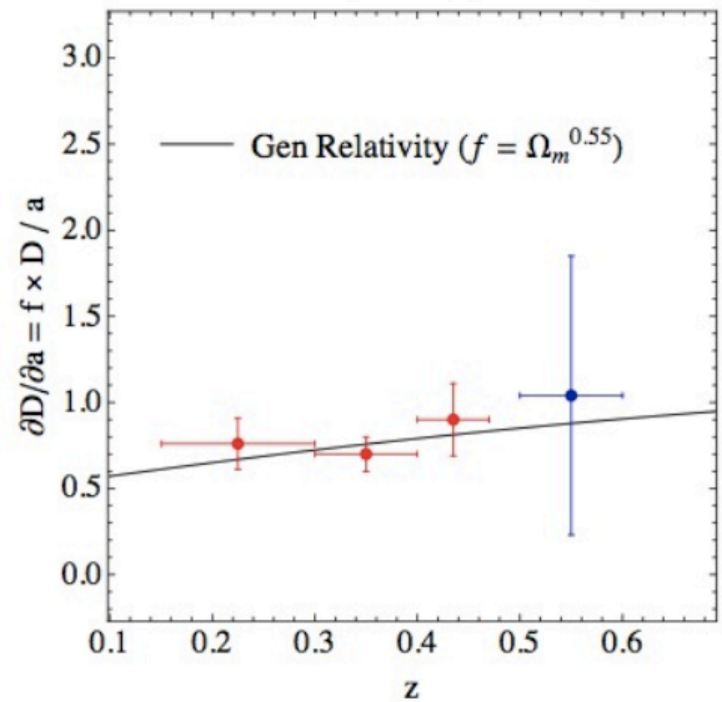
Redshift Space Distortions (RSD)

$$\delta_g(k,\mu) = (b + f\mu^2)\delta(k)$$

$f \equiv d\ln\delta / d\ln a = \Omega_m^\gamma$ growth rate

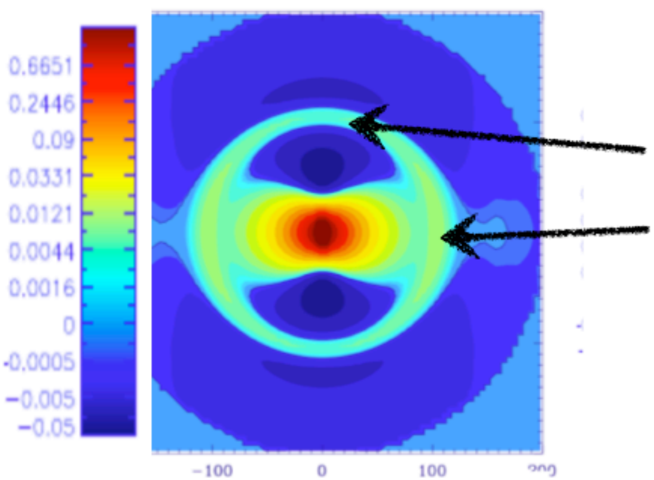


Anna Cabré's PhD Thesis arXiv:0807.3551



$$\gamma = 0.54 \pm 0.17.$$

FoMγ= 6 Crocce etal 2011
(Forecast for DES: Ross etal 2011)



BAO:

radial H(z)

H(z=0.34) = 83.8 ±3.0± 1.6

EG, Cabre & Hui (2009)

Transverse $\int$ cdz/H(z)

θ(z=0.34) = 3.90 ± 0.38

Carnero etal 2011

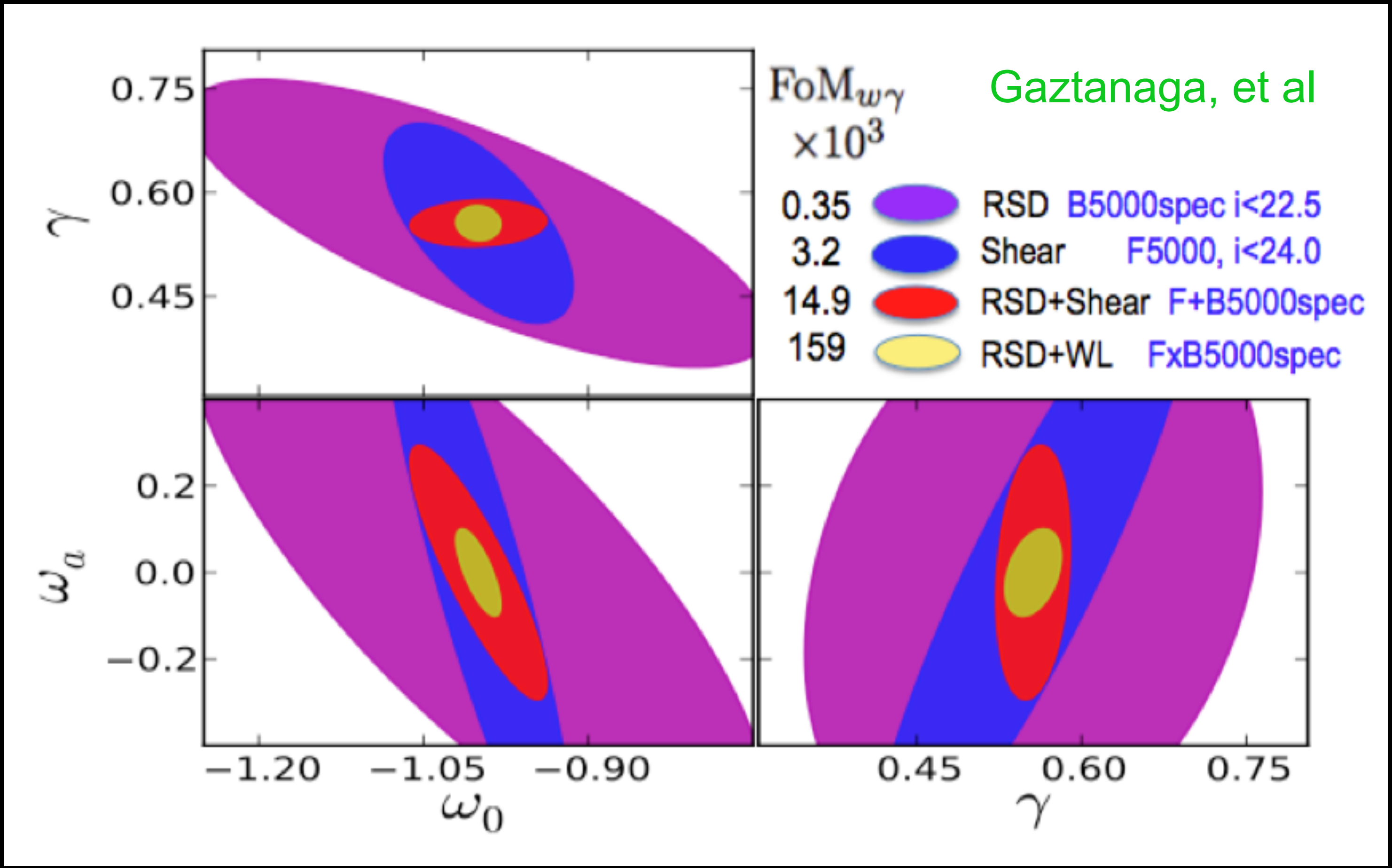
Slide from Enrique Gaztanaga

Weak Lensing and Redshift Space Distortions

- Powerful test of Dark Energy vs. Modified Gravity
- RSD from DESpec
  - Measures degenerate combination of growth *f* and bias *b*
- Weak Lensing from DES
  - constrains bias, breaks degeneracy
- RSD and WL over *same sky*
  - RSD, shear-shear, galaxy-shear correlations in redshift bins → RSD in multiple bias bins to reduce cosmic variance

  MacDonald & Seljak, Bernstein & Cai, Cai & Bernstein, Gaztanaga, etal, Kirk, et al (in prep)

Weak Lensing and Redshift Space Distortions



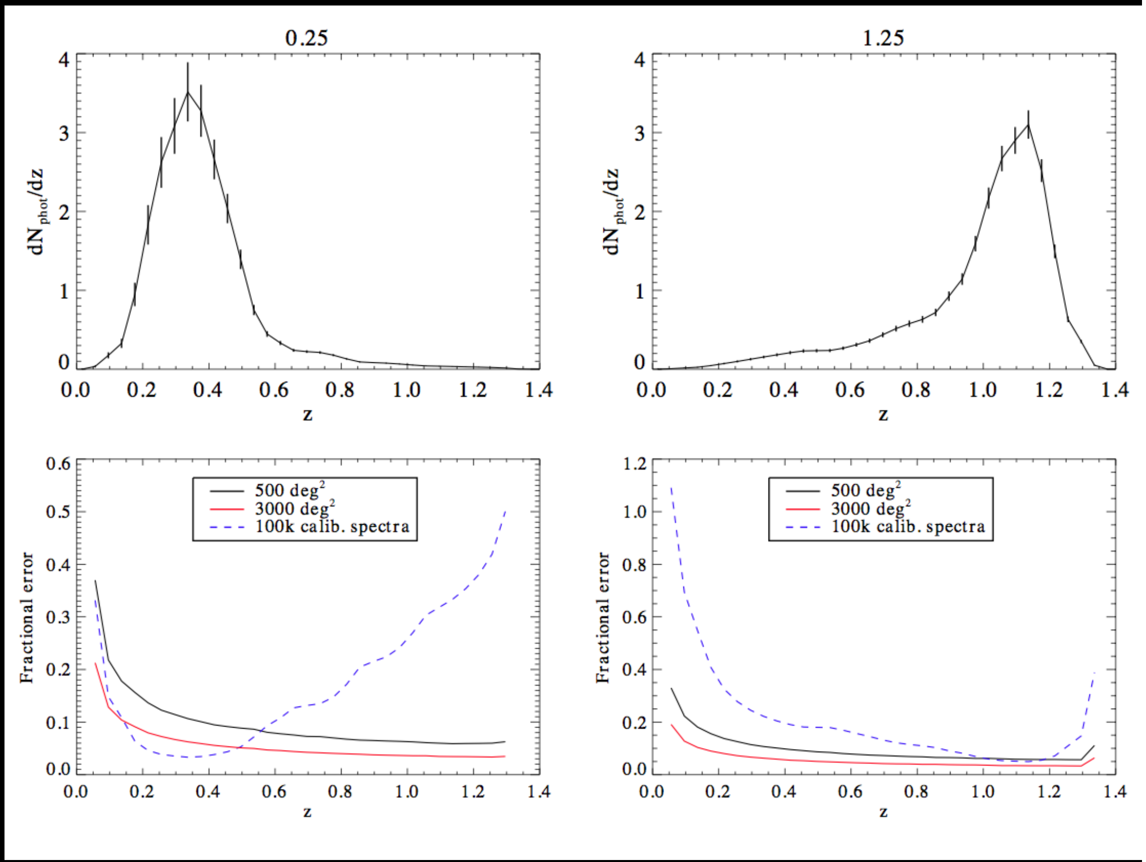
- Constraints strongest if imaging and spectroscopy cover ***same sky***: galaxy-shear cross-correlations constrain bias

DES and LSST Photo-z Calibration

Angular Cross-Correlation of Photometric Survey with shallower Spectroscopic Survey

Requires *same sky* coverage of imaging and spectroscopy

Photo-z systematics could otherwise limit DES, LSST Dark Energy reach



DES-BigBOSS Joint Working Group Report

Clusters

- Spectroscopy of DES Clusters
  improve *z* precision, reduce outliers
- Precise estimates of cluster membership & richness
  optimize richness estimates
- Cluster velocity dispersion (dynamical mass)
  calibrate mass-richness relation: complement WL, SZ, and X-ray estimates

Number of clusters above mass threshold

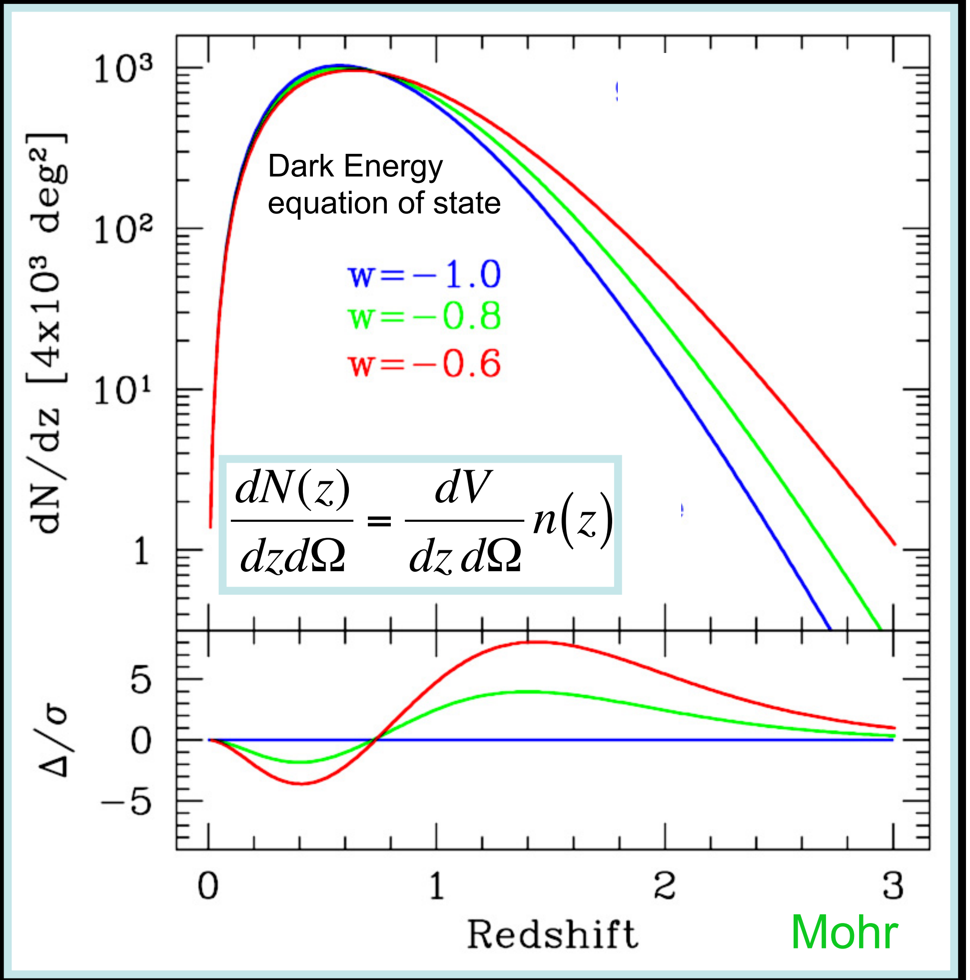
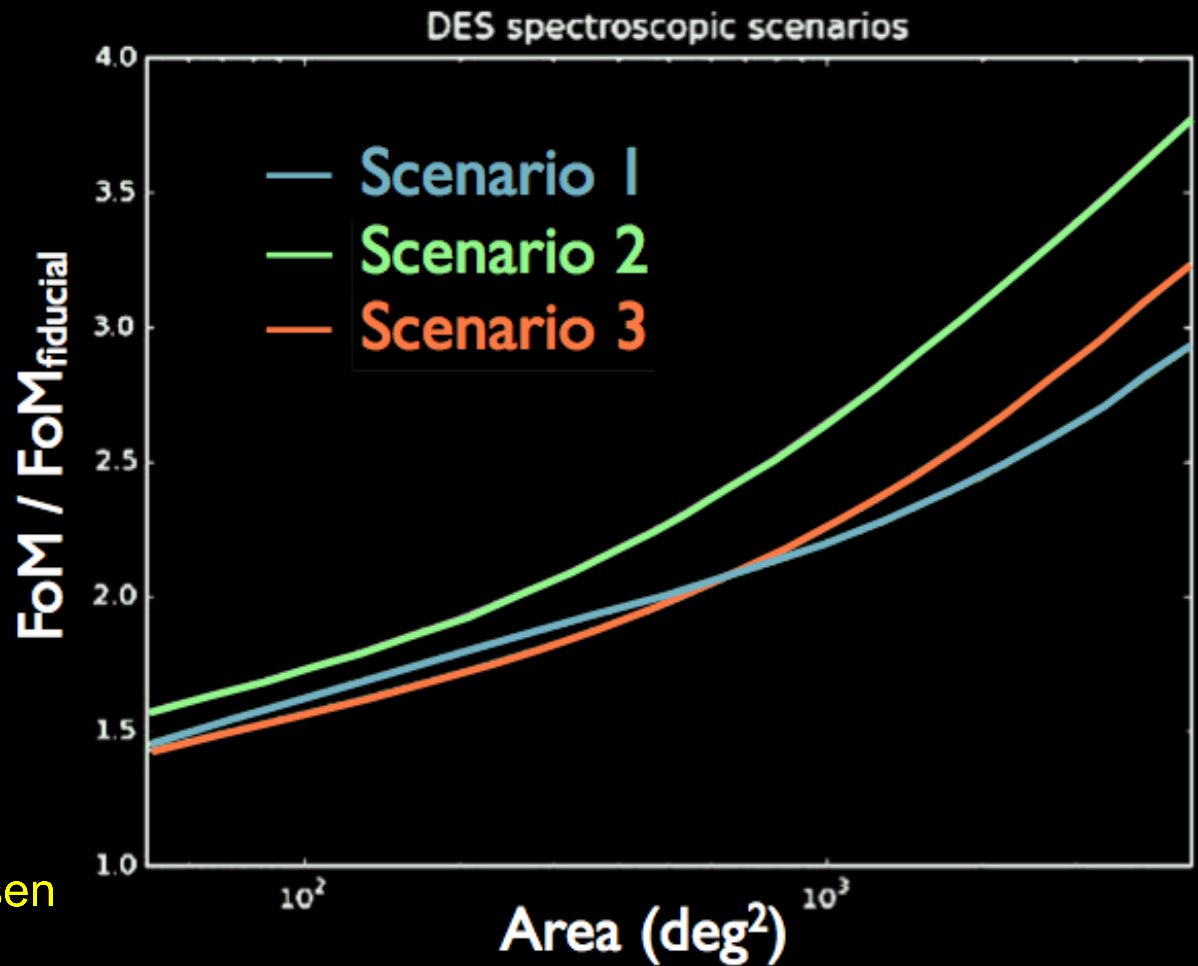


Figure of Merit Improvement

DETF
FOM
gain for
clusters



FOM$_{fiducial}$
from
DES clusters
with
self-calibration

Slide from
Sarah Hansen

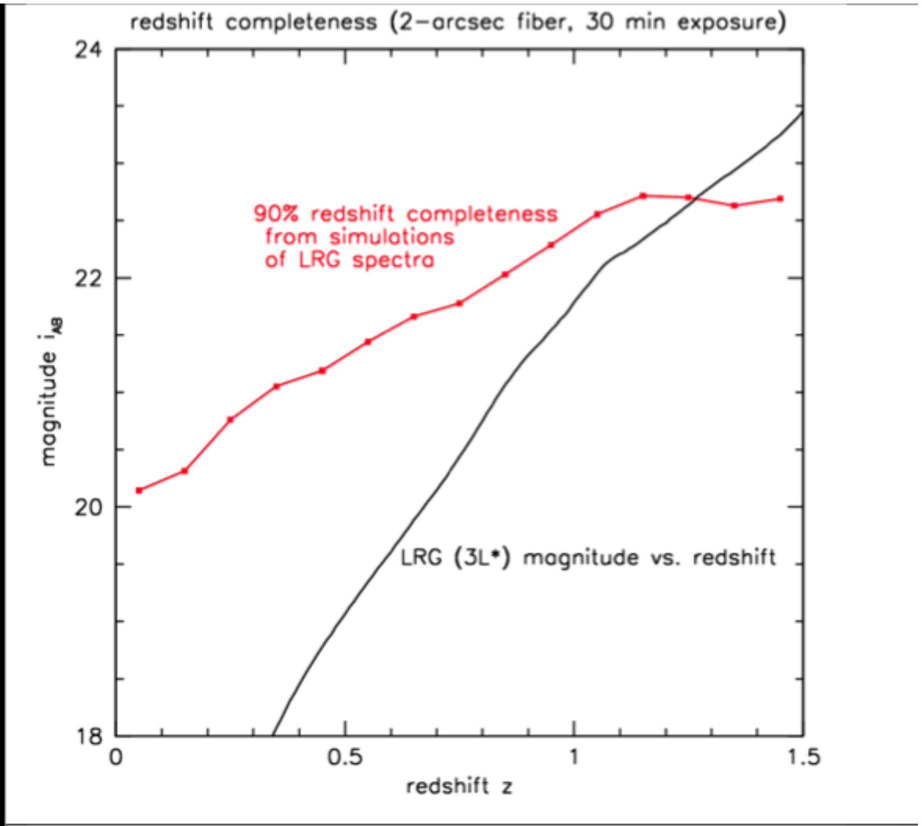
- Scenario 1: 100% completeness to r=21 with 80 km/s redshift accuracy
- Scenario 2: 100% completeness to r=21 + 50% completeness to r=22.5 with 80 km/s redshift accuracy
- Scenario 3: 100% completeness to r=22 with 300 km/s redshift accuracy

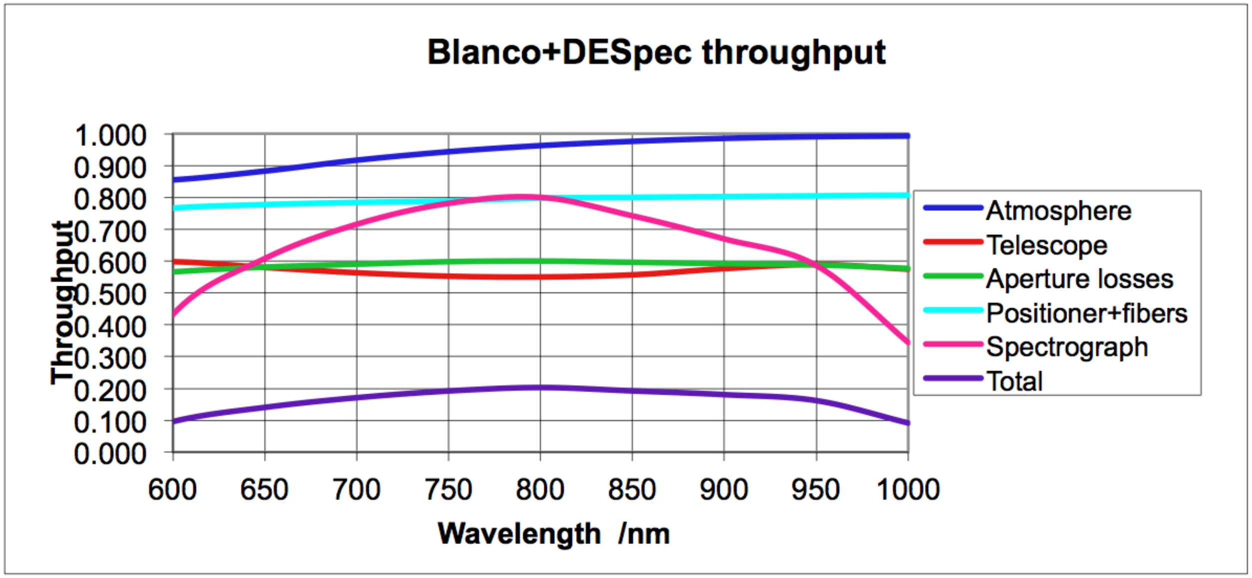
The Dark Energy Spectroscopic Survey

- Dark Energy Redshift Survey optimized for
  - Baryon Acoustic Oscillations
  - Redshift Space Distortions
- Target DES+VHS Galaxies (from grizYJHK colors, fluxes)
  - 6.4 million Emission Line Galaxies (to z~1.5, BAO)
  - 1.2 million Luminous Red Galaxies (to z~1.3, RSD)
- Survey Design
  - 2 exposures each field to reach target density and high completeness (1500 successful redshifts per sq. deg.)
  - 30-min exposures to reach requisite depth
  - 350 survey nights with DESpec on the Blanco 4m (overheads, weather)

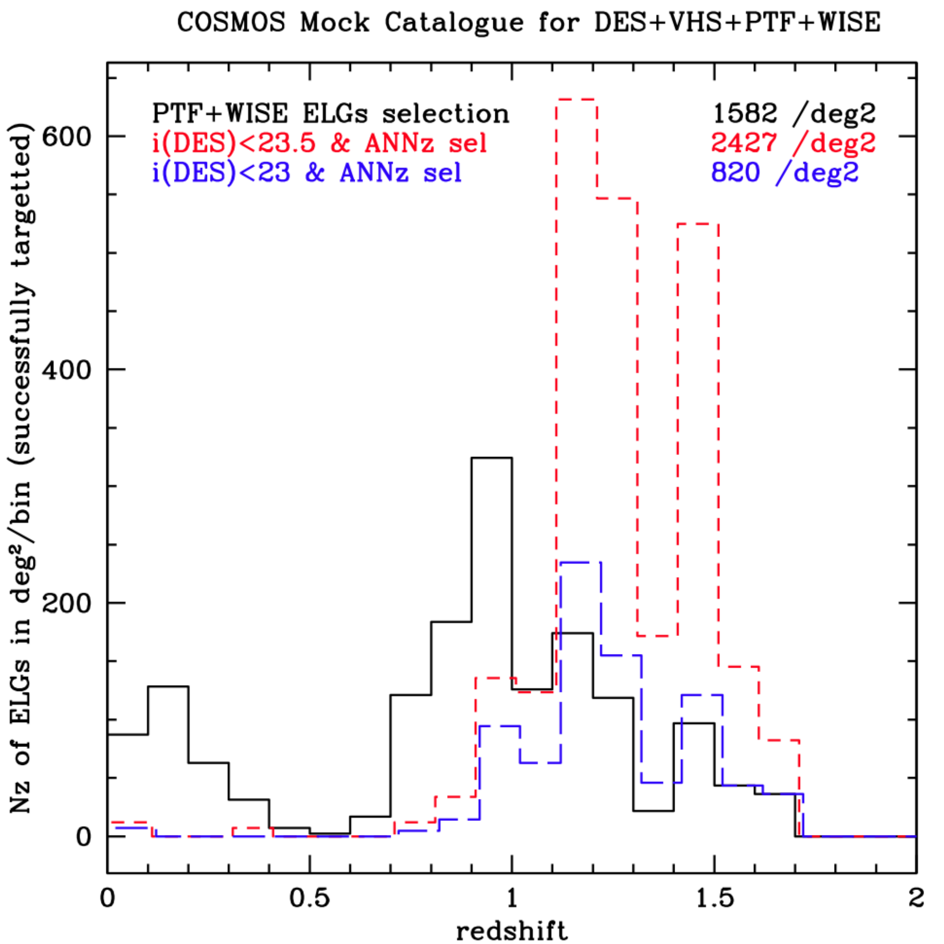
LRG Target Selection

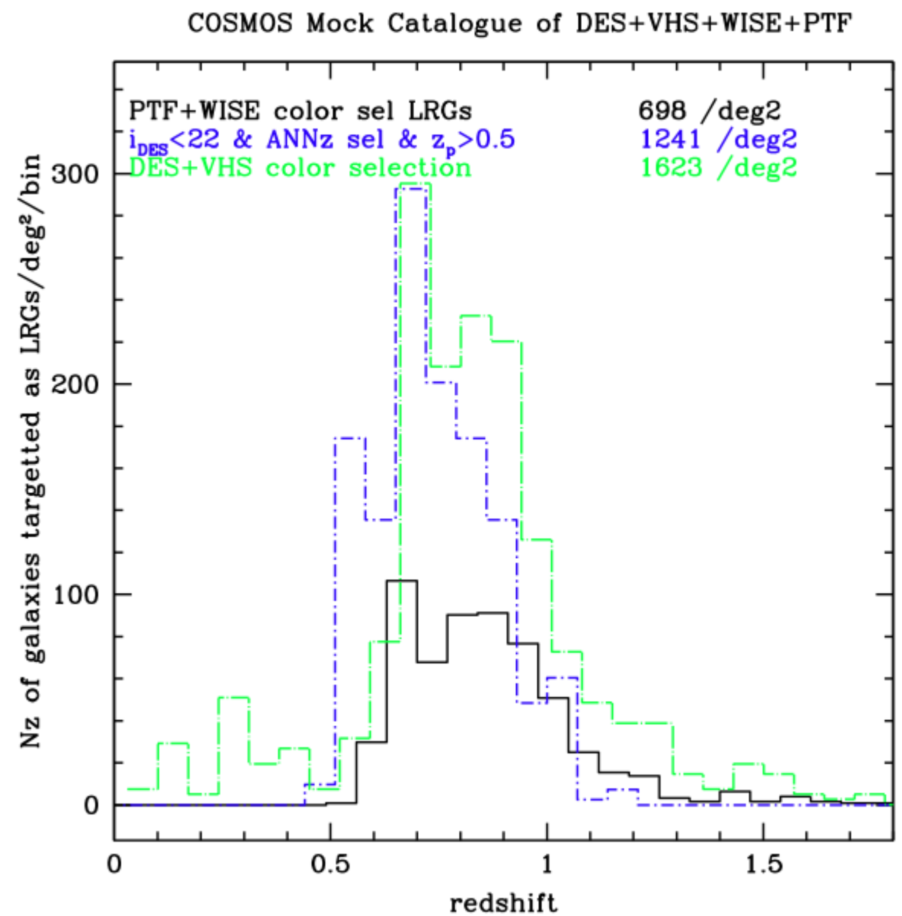
Estimate 90% redshift success for color-selected LRG targets to redshift z=1.3





Target Selection Simulations





Deep, homogeneous parent catalogs from DES, VHS, LSST enable efficient selection and sculpting of redshift distributions

DESpec R&D Program

- Seed funding from STFC (UK), KICP, Texas A&M, AAO, DOE (generic detector R&D at FNAL)
- Fiber positioner design
  - Refinement & prototyping
- Spectrograph/fiber run placement
  - Engineering studies
- Optimize spectrograph design
  - Construct prototype
- Optical design & trade studies
  - ADC/no ADC, UV reach, coverage vs. resolution
- CCD readout electronics & mechanical design
- Survey strategy simulation and optimization
  - Target selection, tiling, trade studies for Dark Energy and Modified Gravity constraints. Building end to end simulation pipeline.

DESpec and BigBOSS

- 4000-5000-fiber spectrographs on identical 4m telescopes
  - Different hemispheres, related science goals
- Dark Energy reach increases with survey area
  - Ideally survey both North and South
- Similar survey power (area/depth per unit time)
  - BigBOSS larger FOV, DESpec higher fiber density
- DESpec uniquely covers entire survey areas of DES and LSST
  - Maximize synergistic science (WL+RSD) and uniform selection
- DESpec reuses much of the DECam infrastructure
  - Cost savings and lower technical and schedule risk.
- BigBOSS has wider spectral coverage than nominal DESpec
  - UV coverage for Lyman-alpha forest BAO
  - Extended UV coverage under study for DESpec: design choice
- DESpec design enables continued use of DECam imager

Conclusions

- DESpec and BigBOSS have comparable survey power
- Two hemispheres better than one
  - By 40% for BAO
- Southern hemisphere has critical advantages:
  - DES and LSST photometric surveys for DE synergy (WL+RSD, clusters, photo-z cal) and deep, uniform target selection (Cf. SDSS)
  - Synergy with other southern facilities as well (SPT, SKA, …)
  - If we can only do 1 hemisphere, it should be the South
- DESpec capitalizes on & makes optimal use of existing, installed, tested DECam infrastructure
  - Reduces cost and technical and schedule risks
  - Fiber system interchangeable with DECam maintains Blanco imaging capability into the LSST era and provides world-class imaging plus spectroscopy facility for the astronomy community

Extra Slides

Extension to UV

- Enable Lyman-alpha BAO measurements using spectra of z>2 QSOs
- BOSS appears to have good Lya BAO measurements
  - Added value for Dark Energy constraints needs to be assessed
- Preliminary optical design without ADC delivers ~25 μm spot size at 350-450 nm
  - satisfactory for 100 μm fibers
- Differential refraction in the blue becomes a limitation for observing at zenith distances ZD > 40 deg
  - SDSS carried out 87% of its spectroscopy at ZD< 40 deg.
- Three-arm spectrographs may be necessary to maintain desired spectral resolution over full range 350-1000 nm
- Fiber losses more severe in the blue
  - Explore spectrograph location near the telescope