# Overview of the Dark Energy Spectroscopic Instrument (DESI)

*Enrique Gaztañaga*
*for the BCN-MAD DESI group (=PAUcam)*

# DESI Concept

- **MS-DESI is the Mid-Scale Dark Energy Spectroscopic Instrument**
- **DESI will be installed at the Mayall Telescope on Kitt Peak, AZ**
- **Kitt Peak is operated by NOAO for the NSF**

corrector



slide from: Michael Levi (LBNL)

# DESI Concept

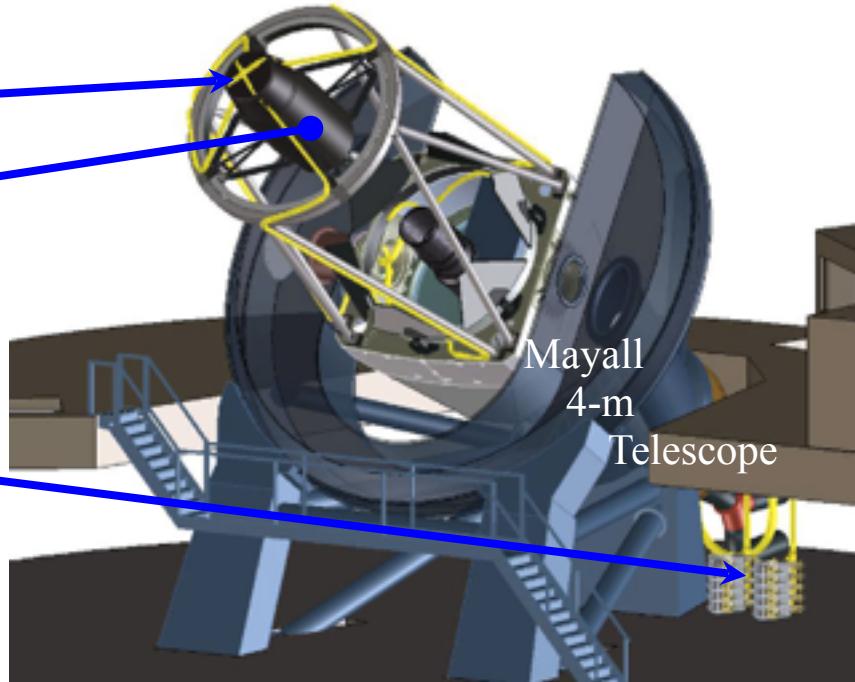
- Scale up BOSS to a massively parallel fiber-fed spectrometer with 5x more fibers, larger telescope aperture, robotic fiber positioners
- Stage-IV BAO over a broad redshift range: $0.5 < z < 1.6$, $2.2 < z < 3.5$
- Sky area: 14,000 square degrees
- Number of galaxy redshifts: 30 million
- Medium resolution spectroscopy, R ~ up to 5500

## Three main hardware components:

5000 fiber actuators

New 8 deg$^2$ field-of-view corrector
DES heritage

10 New spectrographs
BOSS heritage




slides from: Michael Levi (LBNL)

# DESI Science Requirements

- **Survey area:**
  - —**cover at least 9000 sq. degrees (threshold survey), with volume density of galaxies nP ~ 1**
  - —**baseline survey with margin: 14000 sq. degrees**
- **Measure the distance scale from BAO:**
  - — **0.28% precision from $0 < z < 1.1$**
  - — **0.39% precision from $1.1 < z < 1.9$**
- **Measure the Hubble Parameter to 1.05% at $1.9 < z < 3.7$ from BAO**
- **Galaxy survey at $z < 1.5$ should be capable of separately determining $D_A(z)$ and $H(z)$ from BAO**
  - —**systematic errors from instrument and observational effects must not exceed 0.16% for $D_A$ and 0.26% for H.**

# Additional Science Goals

- **Gravitational growth**
  - **— measure the growth factor to < 1% at 0.5 < z < 1.4 using redshift space distortions**
- **Inflation**
  - **— constrain the spectral index of primordial perturbations and its running to < 0.4%**
- **Neutrino Masses**
  - **—measure sum of neutrino masses to < 0.02 eV**
- **These goals do not drive the survey design or science requirements, but are achievable using the baseline survey**

# Science Requirements

## SCIENTIFIC OBJECTIVE: PERFORM A STAGE-IV BAO SPECTROSCOPIC SURVEY

### LEVEL 1

#### SCIENTIFIC REQUIREMENTS

- Survey area > 9000 deg$^2$ with volume density $nP \sim 1$ (galaxies)
- Measure the distance scale $R$ to < 0.28% for $0.0 < z < 1.1$ and < 0.39% for $1.1 < z < 1.9$
- Measure the Hubble parameter $H$ to < 1% for $1.9 < z < 3.7$
- Systematic error < 0.16% for $D_A$ and < 0.26% for $H$

#### ADDITIONAL SCIENTIFIC GOALS

- Constrain growth factor at few percent level up to $0.5 < z < 1.6$
- Constrain inflation spectral index and running to < 0.4%
- Measure the sum of neutrino masses to $\sigma$ < 0.017 eV

### LEVEL 2

#### DATA SET REQUIREMENTS

- Redshift range:
  - LRGs $0.4 < z < 1.0$
  - ELGs $0.6 < z < 1.6$
  - QSOs $z < 2.1$
  - Ly-α $z > 2.1$
- Successful $z$ object density/deg$^2$
  - LRGs > 300
  - ELGs > 1280
  - QSOs > 120
  - Ly-α > 50
- Number of redshifts: $\approx O(24M)$
- ELG redshift accuracy
  - $\Delta z < 0.0005\,(1+z)$ rms with < 5% catastrophic failures
- ELG completeness
  - > 90% for object fluxes > ~$8 \times 10^{-17}$ erg/s/cm$^2$

### LEVEL 3

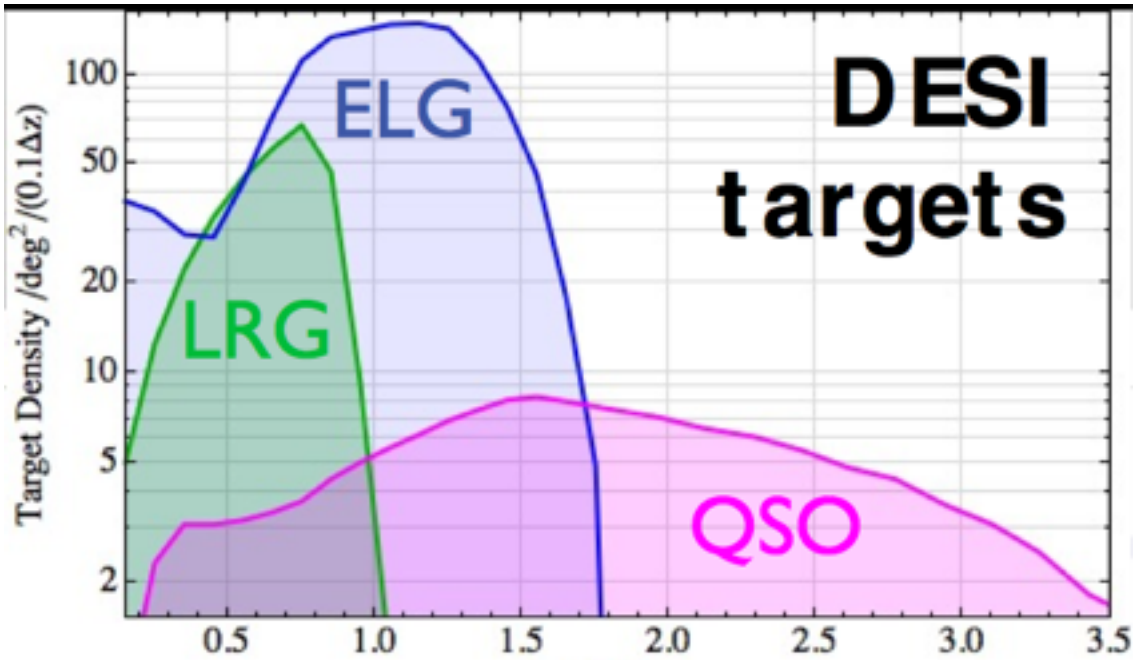
#### TECHNICAL REQUIREMENTS

- Operational constraints
  - ≤ 5 Years
  - Median seeing 1.1″ (i-band) with Moffat β = 3.5 profile
  - Astrometric error of target catalog ≤ 100 mas rms
- Field of view > 7 deg$^2$
- Fiber density < 700/deg$^2$
- Operational overheads
  - ≤ 10% deadtime
- Spectral range and resolution
  - 360 nm < λ < 555 nm: R > 1500
  - 555 nm < λ < 656 nm: R > 3000
  - 656 nm < λ < 980 nm: R > 4000

slides from: Michael Levi (LBNL)

# DESI Survey

- Will produce the best measurement of BAO by performing a spectroscopic survey over 14,000 sq. degrees out to redshifts of 3.5
- 4 million Luminous Red Galaxies (LRGs)
- 23 million Emission Line Galaxies (ELGs)
- 1.4 million quasars (QSO)
- 0.6 million quasars at z>2.2 for Lyman-alpha-forest




**slides from: Michael Levi (LBNL)**

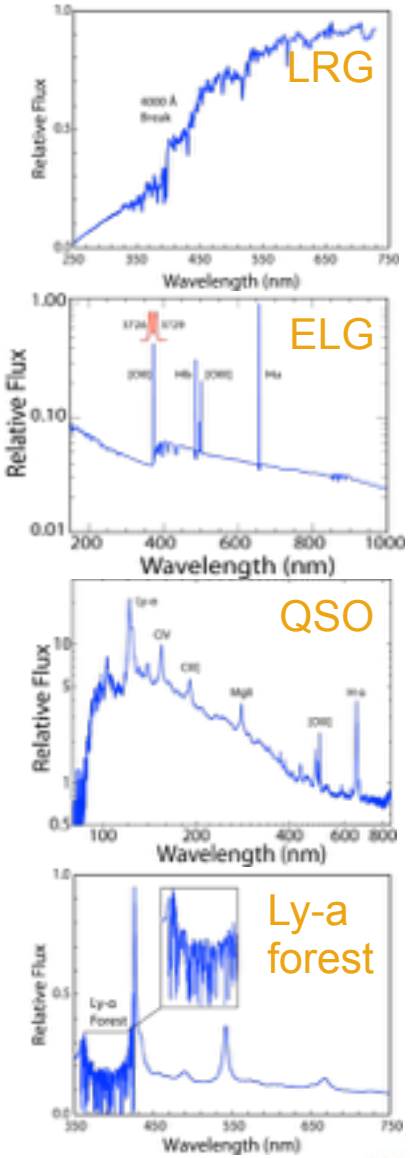
# Bright Galaxy Survey

- **DESI Key Project will use all of the dark time but cannot use full time when moon is too bright or other observing conditions too poor for Key Project**
- **A survey of 10M bright (r<19.5) galaxies over 14k square degrees will have considerable cosmological reach, complementing the Key Project in several ways:**
  - **Increases FOM by 23-36%(14-20K), improves z<0.4 BAO to better than 1%**
  - **Measures the amplitude/growth of structure at low redshift, where dark energy dominates: Multi-tracer RSD, Cluster/group counts, weak lensing cross-correlations**
  - **Significant synergies with imaging surveys (DES, LSST and others) including redshift calibration, host galaxy redshifts for SN, combined constraints**

**slides from: Michael Levi (LBNL)**

# Survey Drives the Design

- **Target spectral features in their redshift bands**
  - — ***Bandpass*** **from 360 – 980 nm**
- **Single exposure ELG measurement at S/N > 7 for 8-10 x $10^{-17}$ erg/sec/cm$^2$**
  - — **Drives *throughput***
  - — **Drives *exposure time* – posit 1000sec at zenith, no extinction**
- **Target redshift**
  - — **Precision 0.0005-0.0025• (1+z) → *spectral res.* 1500–2000**
  - — **Redshift error rate → ELG [OII] doublet resolution > 4000**
- **Survey size (14000 deg$^2$), galaxy target density (~3000/deg$^2$), exposure times, and survey duration**
  - — **Total number of exposures → ~10000**
  - — ***Number of spectra per exposure*** **→ ~5000**
  - — ***Field of view*** **→ ~8 deg$^2$**

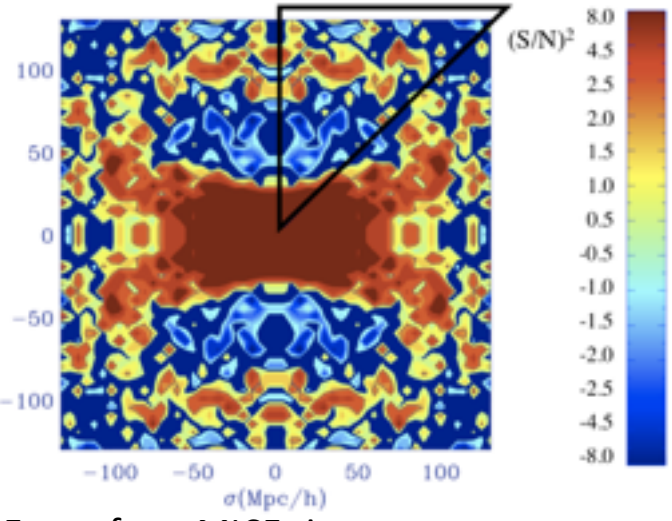



slides from: Michael Levi (LBNL)

Anna Cabré's PhD Thesis arXiv:0807.3551
Crocce etal 2011

# Redshift Space Distortions (RSD)

DR7




Errors from MICE sim

## 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

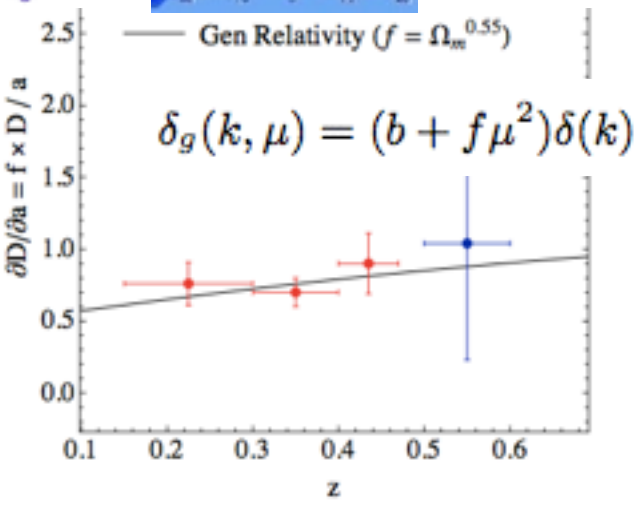
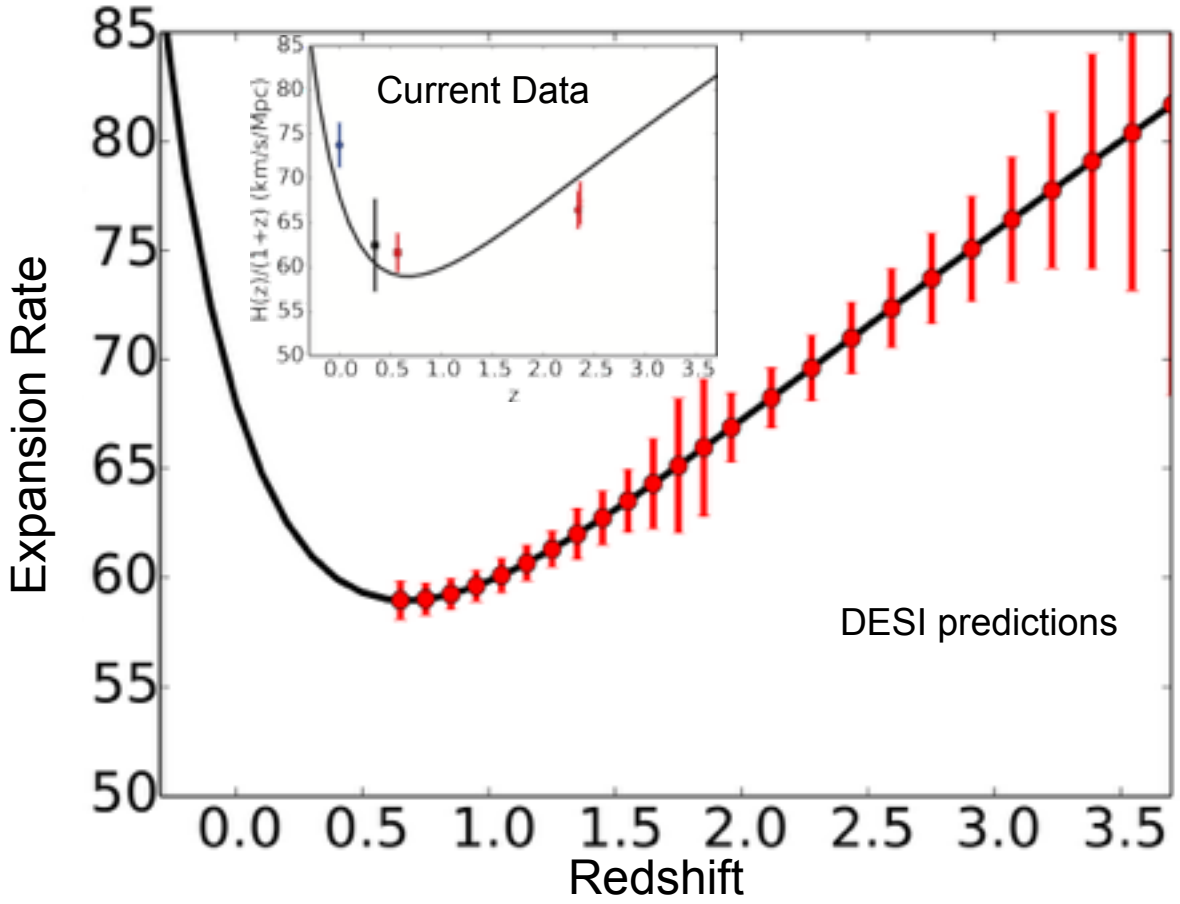



**Figure 17.** Linear growth rate of structure from LRG spectroscopic data in the range [0.15-0.47], as presented in Cabré & Gaztañaga (2009), and from our analysis of photometric data at $z = 0.55$ (assuming $\sigma_8(0) = 0.8$). These data leads to $\gamma = 0.54 \pm 0.17$ in a model where $f = \Omega_m(z)^\gamma$.

# DESI Hubble Diagram

| Target type | z range | Target density deg$^{-2}$ | Good z density deg$^{-2}$ | Δz/(1+z) precision | Δz/(1+z) systematic | Bad z assignment | Complete -ness |
|---|---|---|---|---|---|---|---|
| LRG | 0.4–1.0 | 350 | 300 | 0.0005 | 0.0002 | < 5% | > 95% |
| ELG | 0.6–1.6 | 2400 | 1280 | 0.0005 | 0.0002 | < 5% | > 90% |
| QSO | < 2.1 | 170 | 120 | 0.0025 | 0.0004 | < 5% | > 90% |
| Ly-α | > 2.1 | 90 | 50 | 0.0025 | - | < 2% | > 72% |

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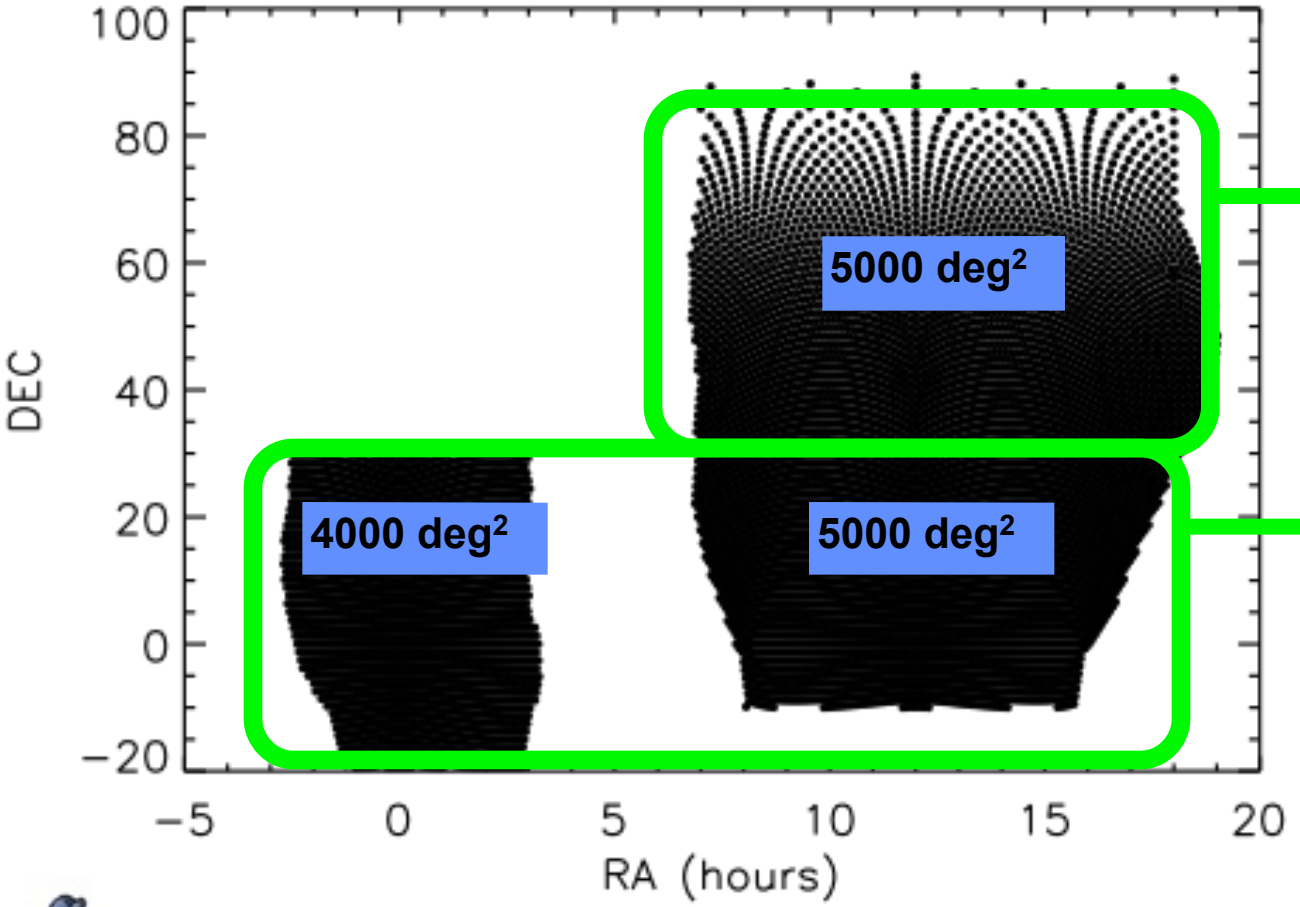
# DESI Survey Area & Imaging

- 14,000 sq. degree footprint defined by low Galactic and atmospheric extinction
- DESI targeting requires new imaging over this area




**"North cap":**

**Accessible from Northern telescopes only**

Observing gr bands with Bok
Plan to observe z with upgraded z band on Mayall.

**"Equatorial":**

**Accessible from Northern or Southern telescopes**

Observing grz with DECam.
Approved project for 6700 sq. degrees.

slides from: Michael Levi (LBNL)

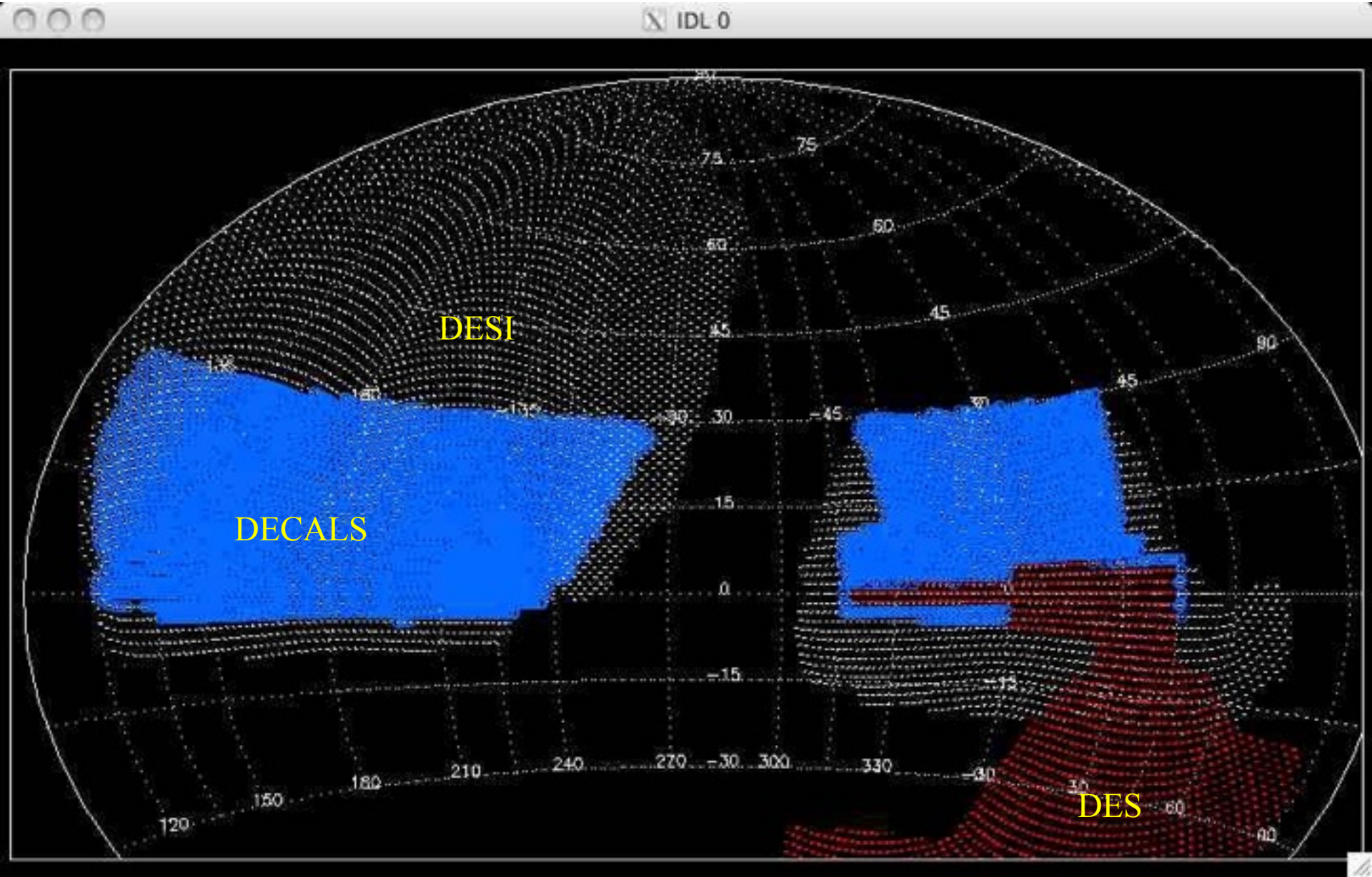
# Survey Sources

- **South:**
  - **6200 sq. deg. of SDSS footprint south of dec=+30 and excluding areas covered by DES, plus 500 sq. deg. from DES**
  - **Allocated 65 nights with Blanco/DECam in 2014B-2017A**
  - **g, r, z-bands**
  - **First public data release DR1 on March 18, 2015**
- **North:**
  - **Bok Telescope using 90Prime instrument**
    - **5500 sq. deg.**
    - **Survey started**
    - **g, r-bands**
  - **Mayall 4m using Mosaic 3 instrument**
    - **Focal plane upgrade to Mosaic 1.1 instrument (from CTIO)**
    - **5500 sq. deg. to start in 2016**
    - **z-band**
- **Combined imaging: g=24.0, r=23.6, z=23.0**

  **(compare to SDSS g=22.2, r=22.2, z=20.5)**

**slides from: Michael Levi (LBNL)**

# DECaLS vs DESI vs DES footprint



# DES Image Validation

logged in as gaztanaga | Logout | Preferences

Wiki | Timeline | Roadmap | Browse Source | View Tickets | New Ticket | Sear

wiki: ImagingWG / ImageValidation  Up | Star

## Image Validation Task Force

### Charge

The Imaging Validation Working Group will conduct the task of validating that the imaging being collected and reduced by the DESI Project, Collaboration, and its affiliates will satisfy the science requirements of the DESI Collaboration, particularly that of spectroscopic target selection.

Image Valid
Charge
Current P
Imaging R
Spring 20
Image Val
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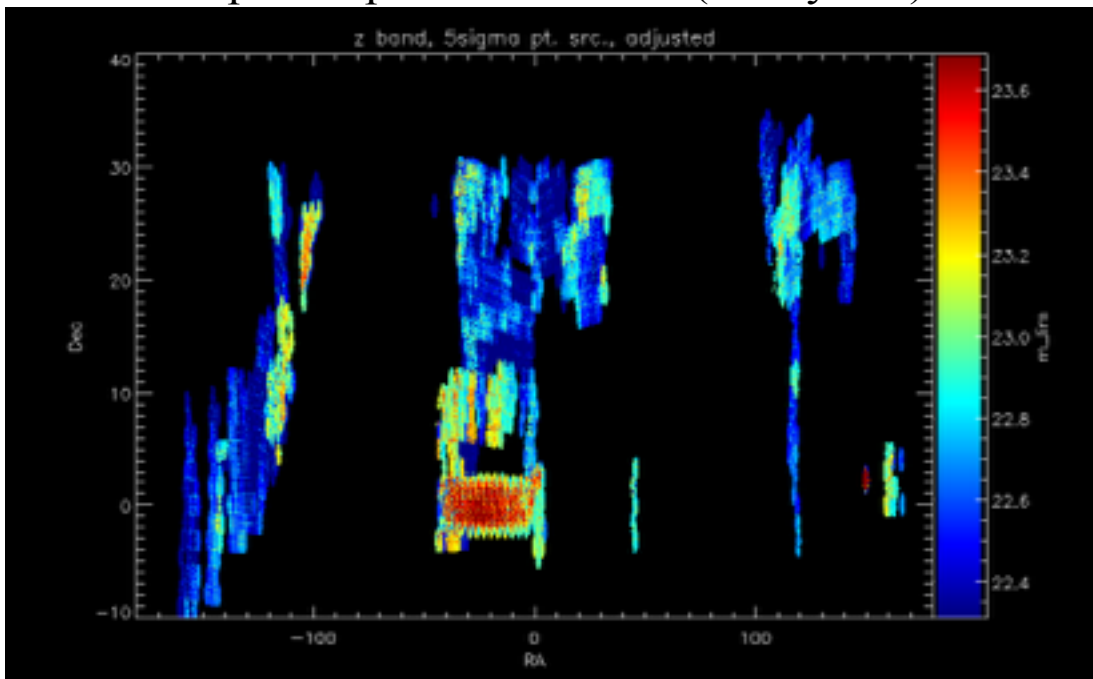
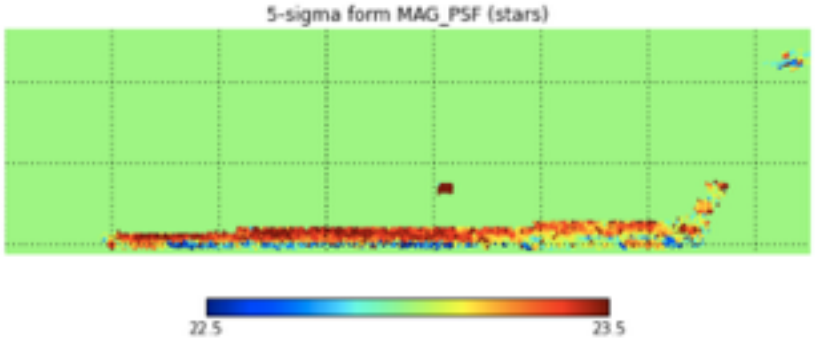
### People

- Enrique Gaztanaga (coordinator)
- Daniel Eisenstein, Risa Wechsler
- Eric Bell, David Schlegel
- Ray Carlberg, Nacho Sevilla
- Francisco Castander
- Arjun Dey, Yu Feng
- Doug Finkbeiner
- Josh Frieman Martin White
- Shirley Ho, Dustin Lang
- Ian McGreer Nigel Metcalfe
- Jeff Newman Ashley Ross
- Eli Rykoff Amelie Saintonge

Depth Map from DECaLS (Eli Rykoff)

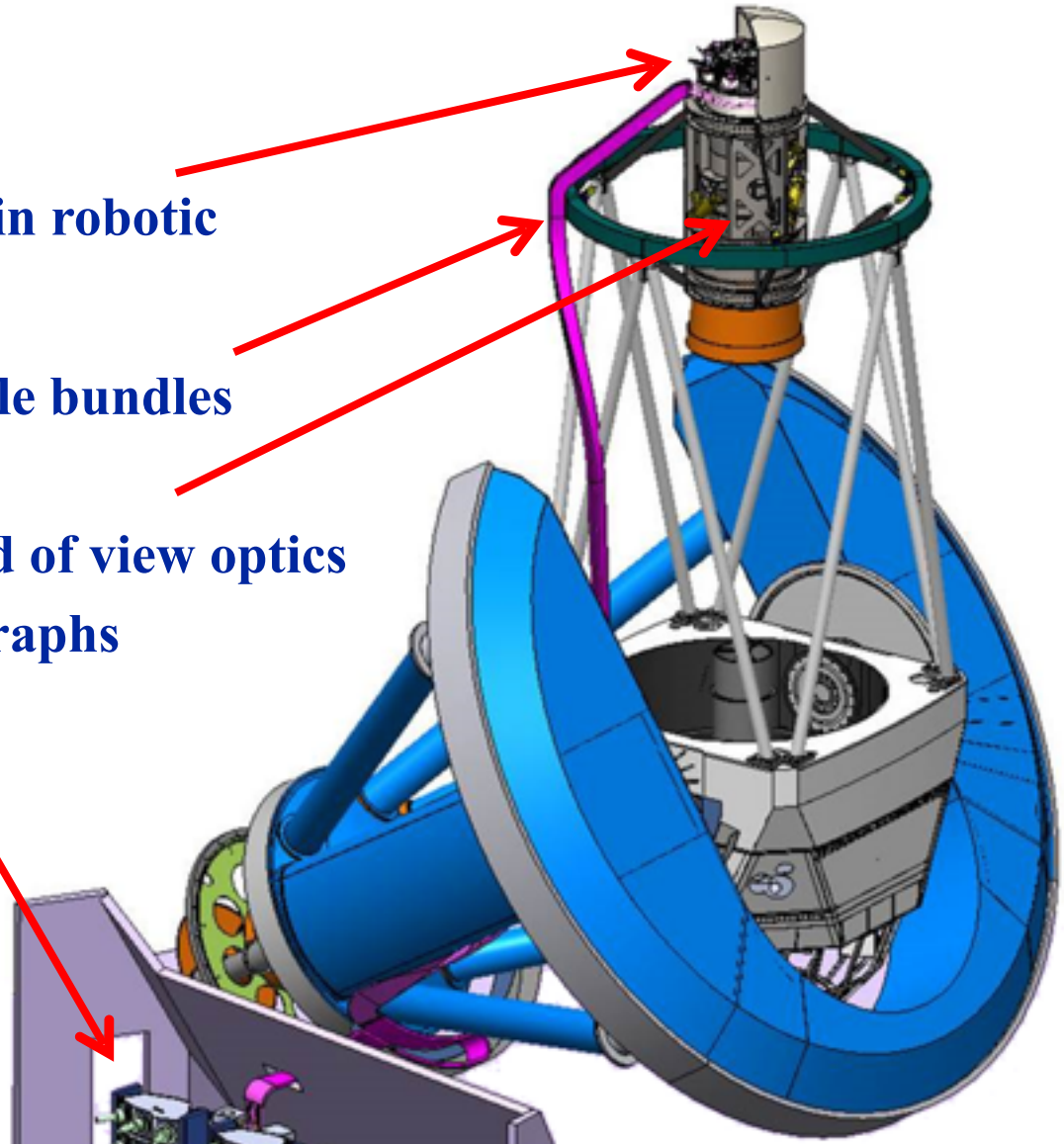



Depth Map from BASS (Nacho Sevilla)



# DESI

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



Mayall 4m Telescope
Kitt Peak
Tucson, AZ

Readout & Control

slides from: Michael Levi (LBNL)

# DESI Expert Collaboration

## Partners are experienced

**BCN-MAD:** Guiders (GFA)
*DECam PAUcam*

**Fermilab (U.S.):** Telescope top-end + lens cell
**w/ UCL (U.K.):** Telescope optics
*Dark Energy Survey top-end + optics*

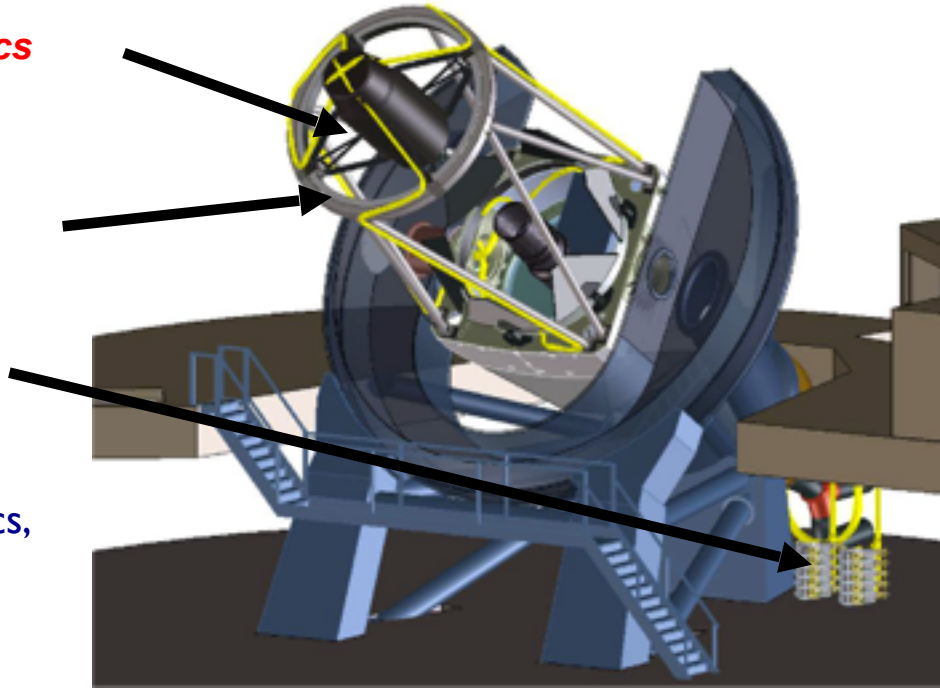
**Durham:** Fibers + testing
*FMOS + Fibers for physics exp'ts*

**LAM + CPPM (France):** Spectrographs
*VIMOS spectrographs*

**CEA (France):** Cryo systems
*Megacam cryo*

**Berkeley Lab (U.S.):** CCDs + electronics, optical design, project management
*WFIRST/JDEM optical design*
*DES, BOSS, JDEM detectors*

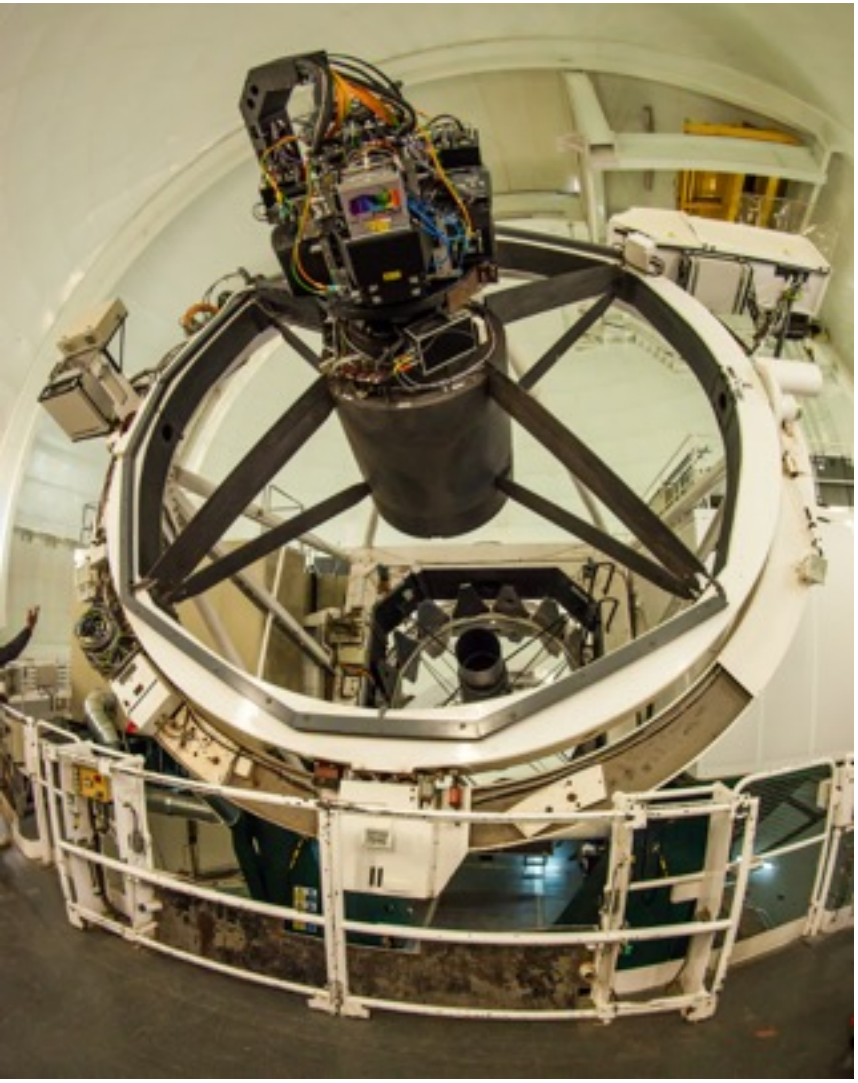
**Yale:** fiber view camera */QUEST*
**U Michigan**: positioners */DES*
**SLAC, Ohio State:** data acquisition + guiding
*BOSS, DES, LSST*
**NOAO:** telescope interface, operations *DECam*

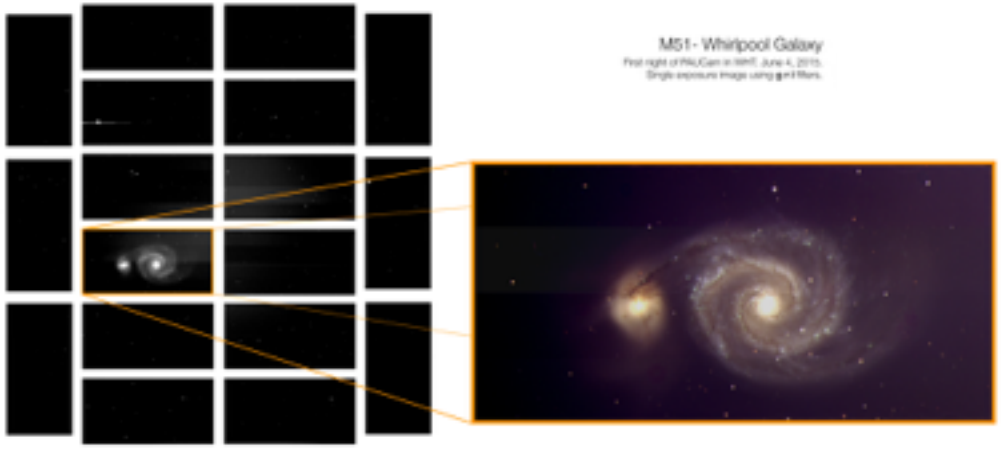


slides from: Michael Levi (LBNL)

# PAUCam First light

http://paucam.pic.es



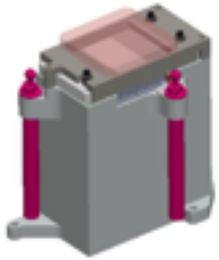



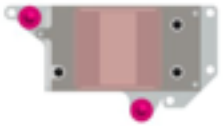

**The PAUcam team has also contribute to build DES, DESI and Euclid and will make a galaxy survey with PAUCam to enable the Dark Energy Science:**

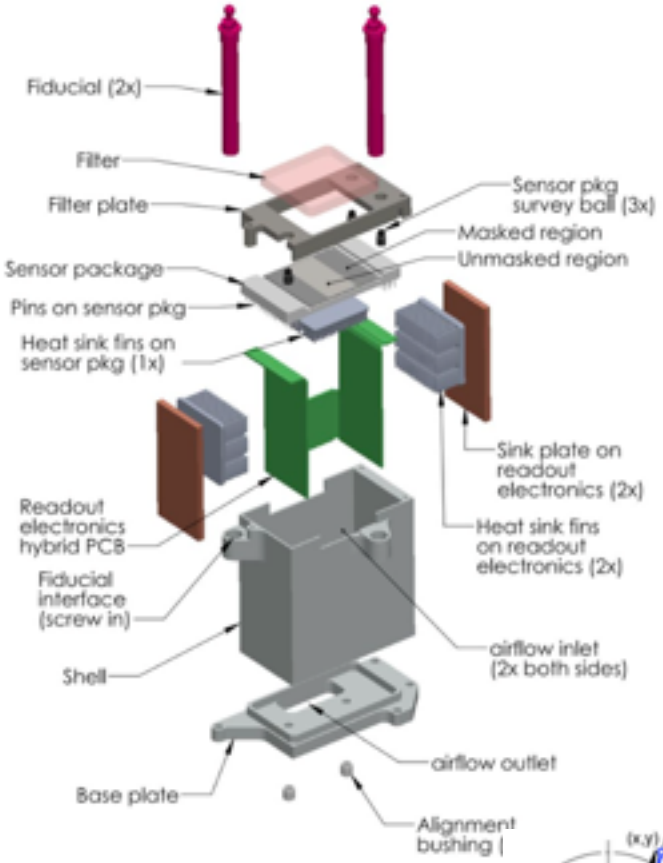
**Photo-z calibration in DES**
**Intrinsic galaxy alignments in EUCLID**
**Target selection optimization for DES**
**Novel cross-correlation techniques**

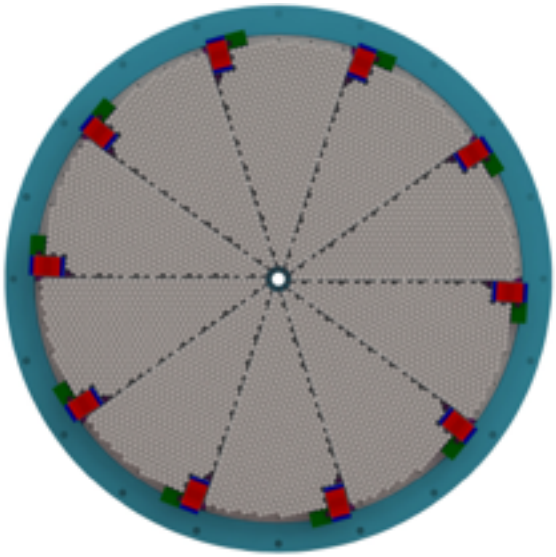
# 10xGFA Cameras
## to be build by PAUcam Team

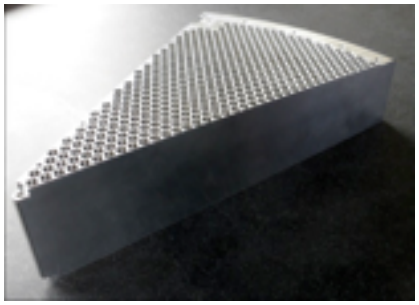
GFA= Guider, Focus & Alingment

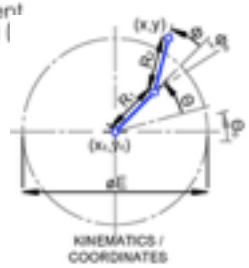


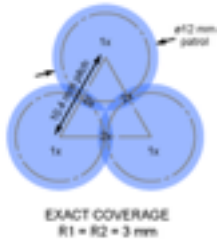









- Position a fiber tip on a galaxy
  - 5 μm RMS positioning accuracy

# Project Status

- The project is making great progress. Main focus – keep the optics off the critical path with foundation grants (non-DOE funding)
- Procurement of C1-C4 blanks is complete. Grinding and polishing is in progress (AOS and L3-Brashear).
- Procurement of ADC blanks is in progress (Schott and Ohara) Polishing contract is being placed.
- Expect all lenses to be complete by end of 2016.

| Element | Diameter (mm) | Mass (kg) | Material | Aspheric surfaces |
|---|---|---|---|---|
| C1 | 1140 | 201 | Silica | 0 |
| C2 | 850 | 151 | Silica | 1 |
| ADC1 | 800 | 102 | N-BK7 | 0 |
| ADC2 | 804 | 89 | N-BK7 | 0 |
| C3 | 834 | 84 | Silica | 1 |
| C4 | 1034 | 237 | Silica | 0 |



slides from: Michael Levi (LBNL)

# Project Status

- Sept. 2014: Successful CD-1 review. DOE Funding profile negotiations nearly settled. Expect “advanced procurement authority” in Mid March 2015.
- DOE CD-2/3a review scheduled for July 28-30, 2015 – this is the big one - nails down the design, cost and schedule.
- Spectrographs are the critical path (funding limited). Fabrication of a prototype is in progress.
- DESI installation begins Jan. 2018. Start moving the telescope with DESI installed in Oct. 2018
- On-sky commissioning will start in Jan. 2019 with 6 spectrographs, the rest arriving by July. DESI is the only instrument on the telescope
- 5 year DESI survey will start in Jan. 2020 (after a 6m science verification period)

# Conclusion

- DESI builds on the long and successful experience of multiple collaborations in defining, building and executing wide area surveys to study the mystery of Dark Energy
  - SDSS, BOSS, DES, PAucam
- DESI will essentially complete BAO measurements in the northern sky out to redshift of 1.5.
- Technical design of DESI is very mature, Private/non-DOE funding being used for lenses and prototype spectrograph
- Barcelona-Madrid DESI group will build 10xGFA cameras
- DESI prototype with GFA on sky:1 year! Commission Jan 2018!
- On track for on-sky commissioning <4 years from now in 2019!