The Photometric and Astrometric Properties of DECam as Enablers of Precision Science

Douglas L. Tucker
DES Calibration Scientist

DECam Community Science Workshop 2018
Tucson, Arizona
21 May 2018

The Photometric and Astrometric Calibration of DECam using DES and BLISS as Examples

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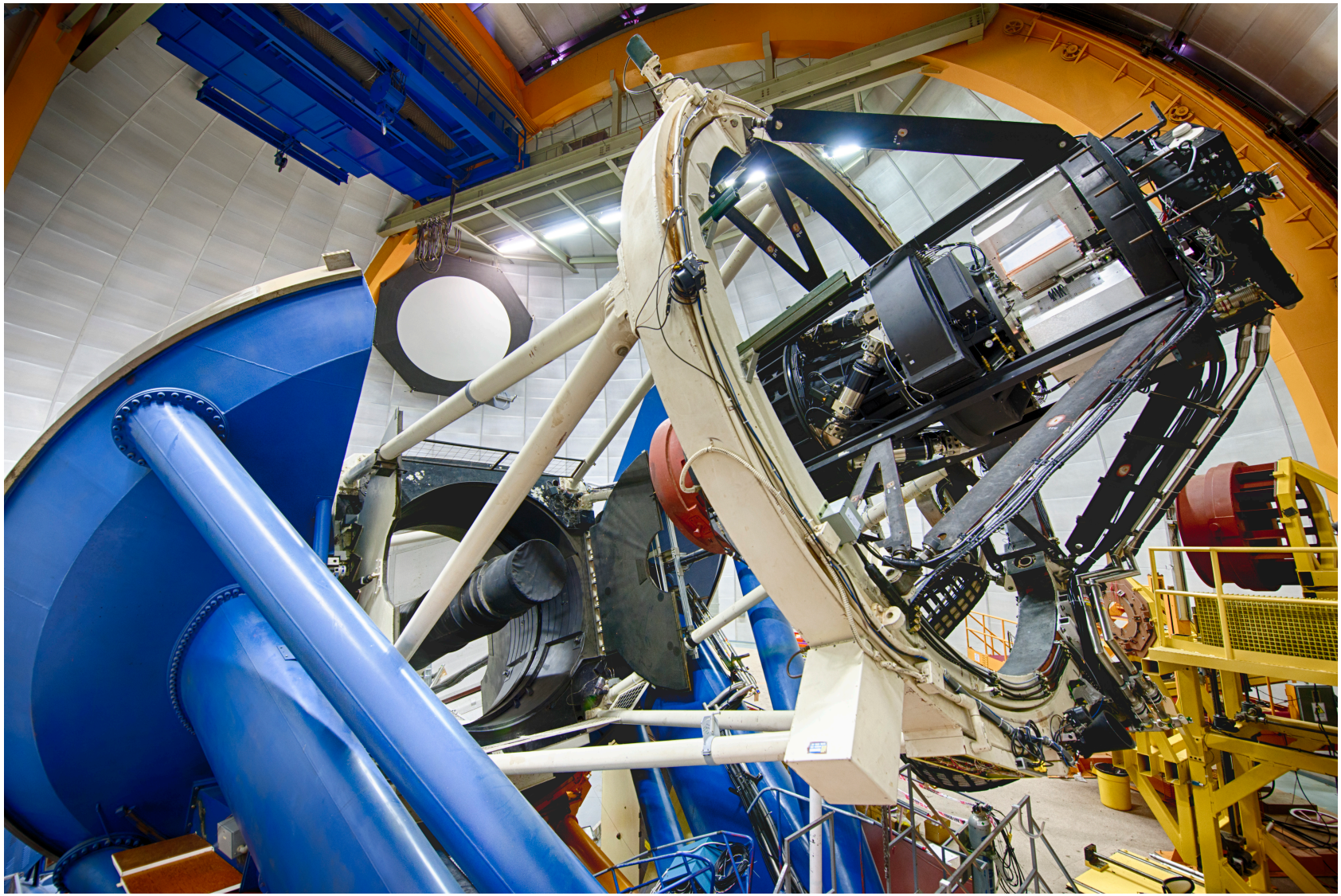
DARK ENERGY
SURVEY

Background

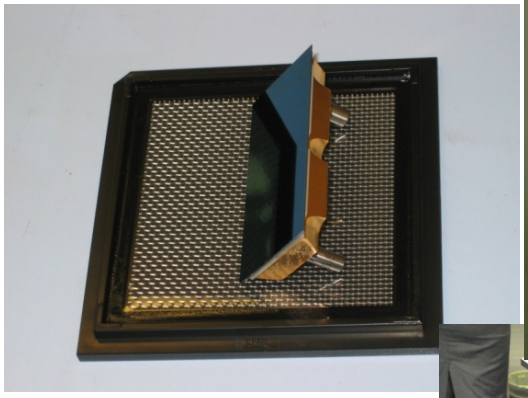
Blanco + DECam

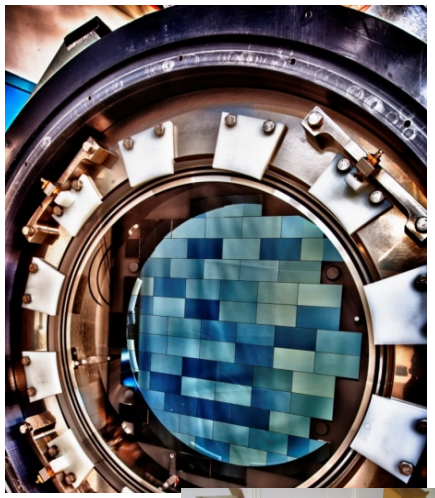
DARK ENERGY
SURVEY

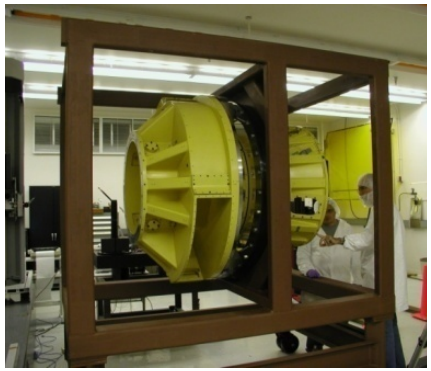


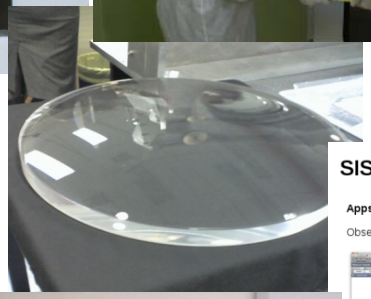
Dark Energy Camera Parts (2008-2012)

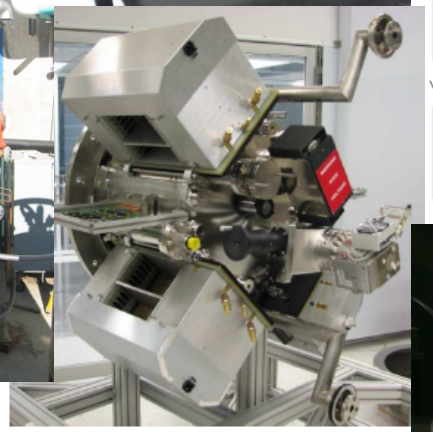
DARK ENERGY SURVEY

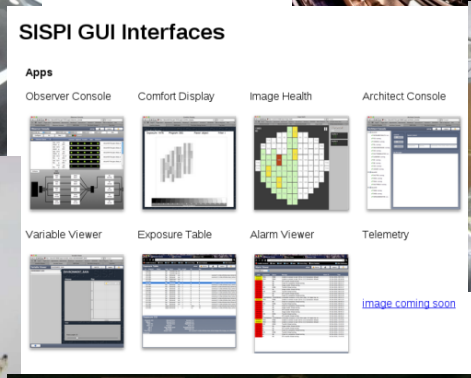


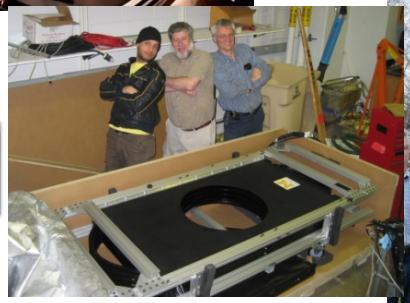










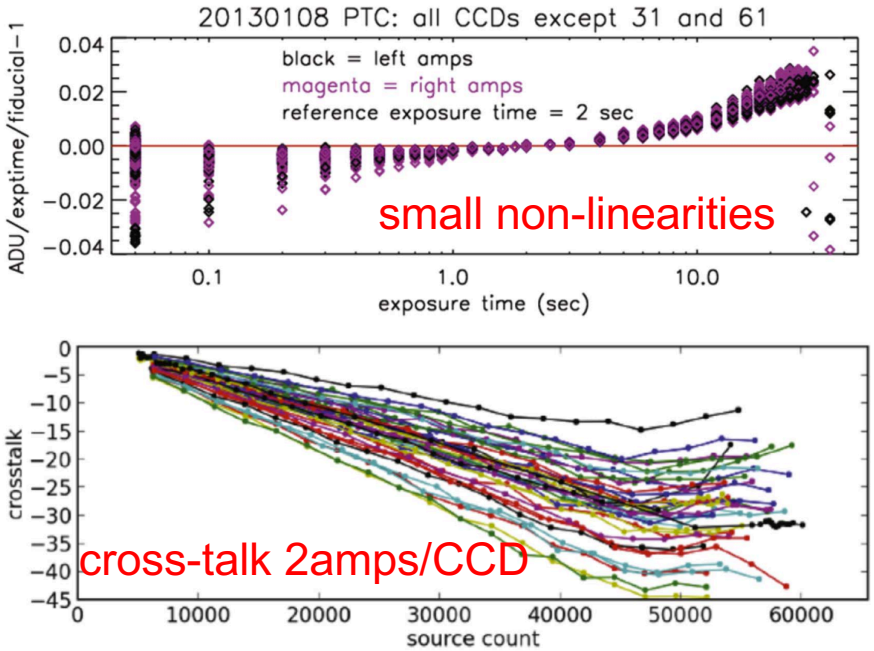


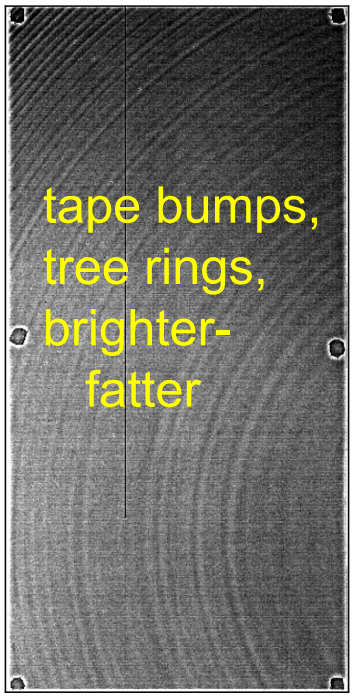
Credit: H.T. Diehl

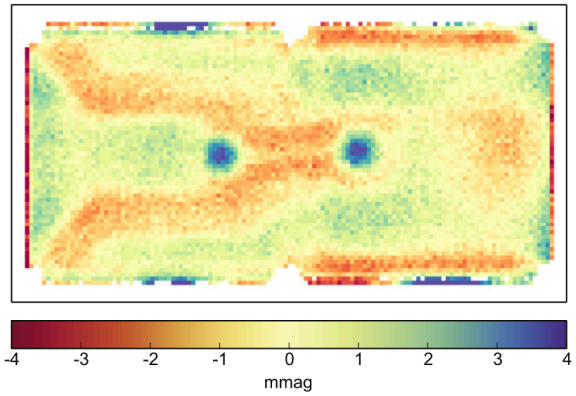
Instrumental Effects

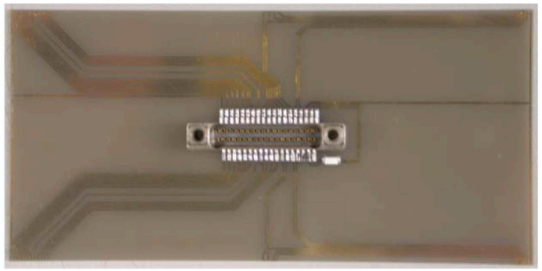
DARK ENERGY SURVEY

- CCD effects
- Amplifier effects
- Gain measurement
  - Linearities and non-linearities







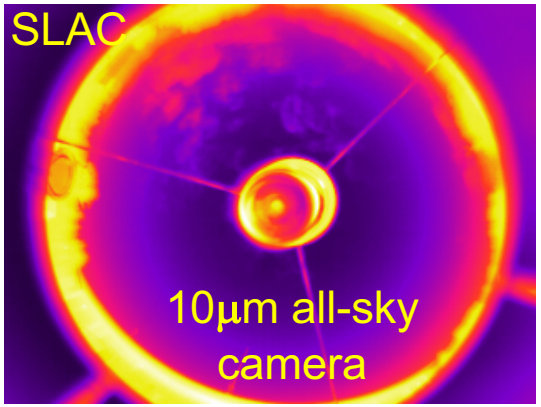


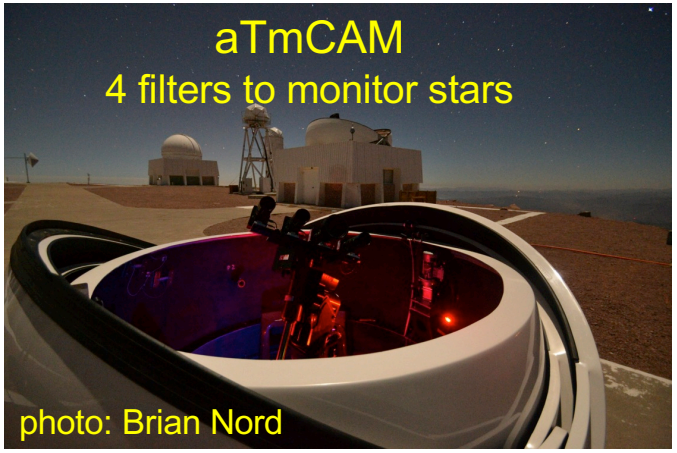
Bernstein et al. 2017, PASP 129, 074503: "Astrometric Calibration and Performance of the Dark Energy Camera"
Bernstein et al. 2017, PASP 129, 114502: "Instrumental response model and detrending for the Dark Energy Camera"
Bernstein et al. 2018, PASP 130, 054501: "Photometric Characterization of the Dark Energy Camera"

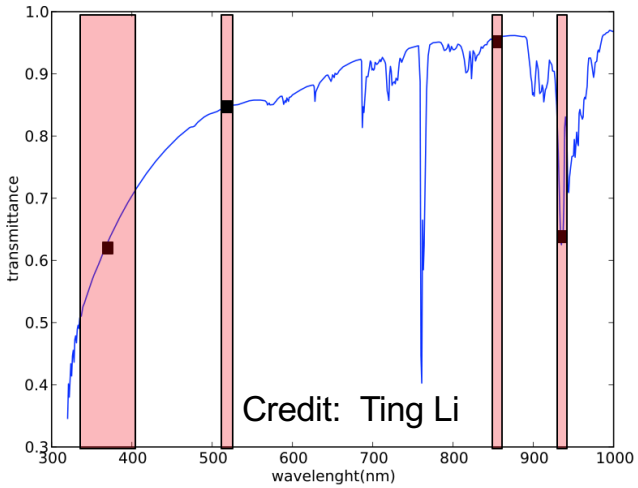
Slide credit: William Wester

Ancillary Hardware

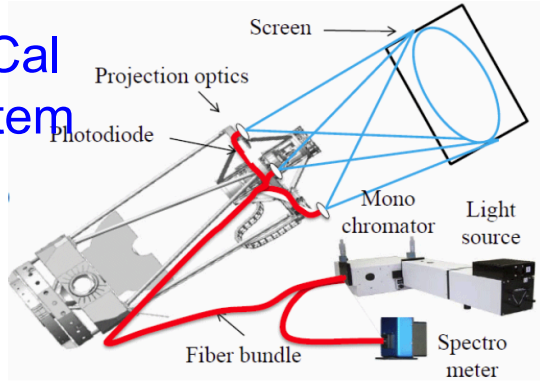
DARK ENERGY SURVEY



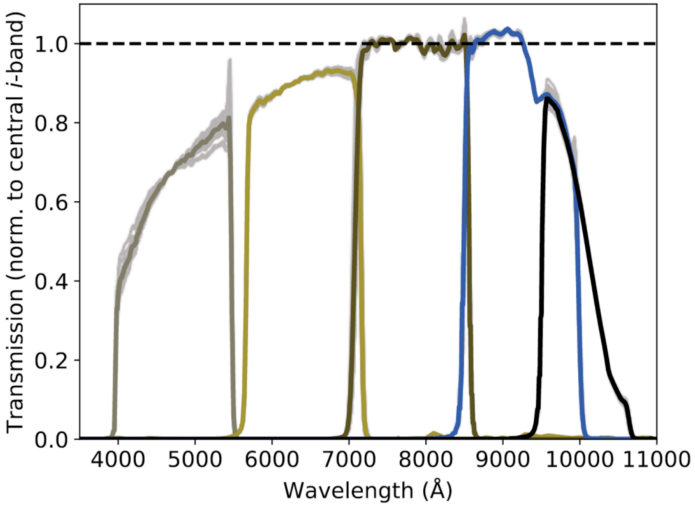


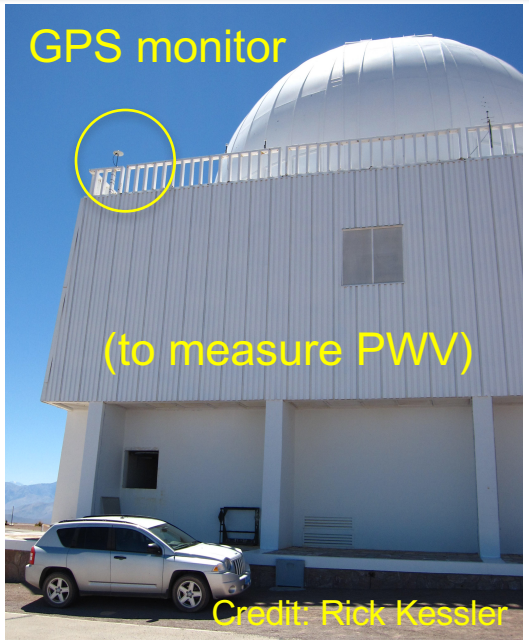


DECal system



Marshall et al. 2013





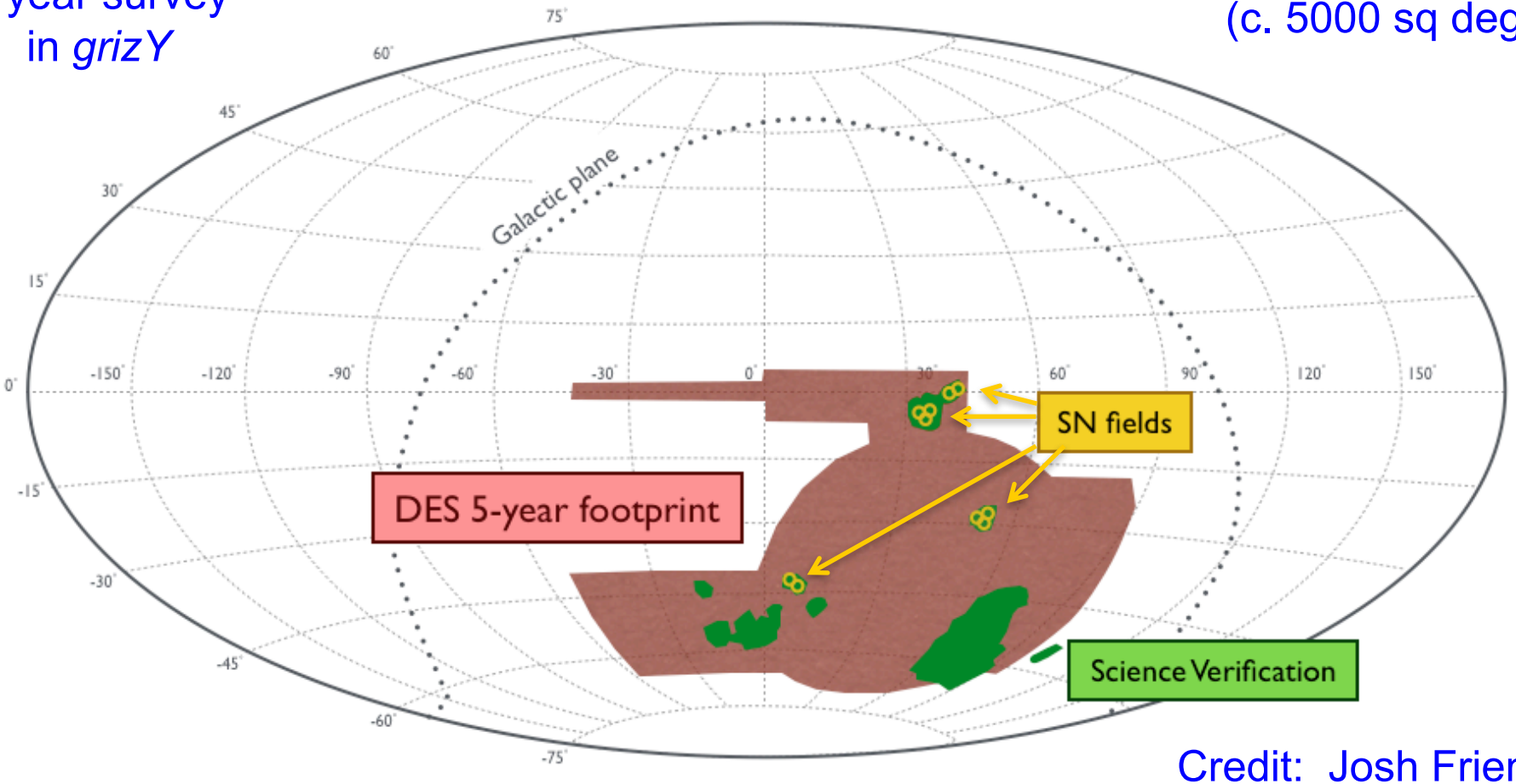
Slide Credit: William Wester

The Dark Energy Survey (DES)

DARK ENERGY SURVEY

5-year survey in *grizY*

¼ of southern sky (c. 5000 sq deg)



Credit: Josh Frieman

DARK ENERGY
SURVEY

Astrometry

DES Astrometry
SCAMP

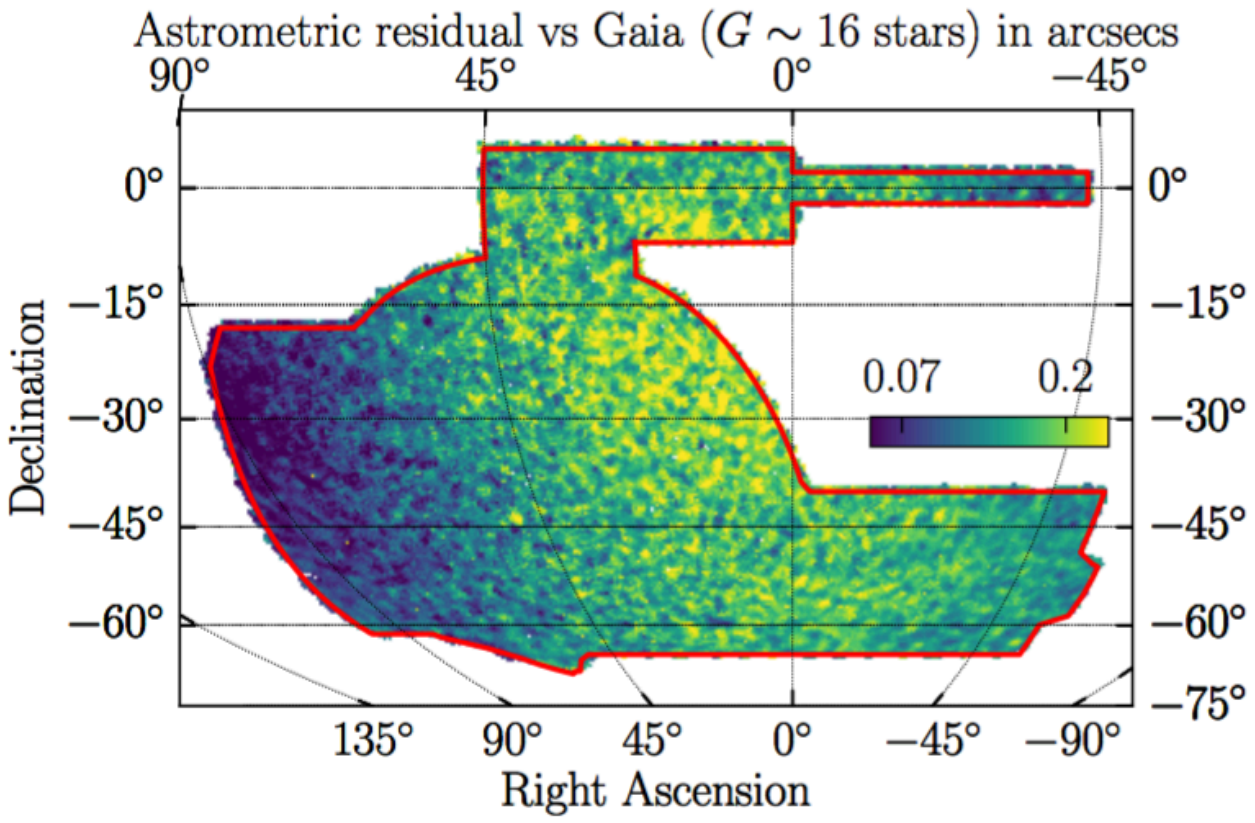
- **SCAMP astrometric software (E. Bertin)**
  - Current DES Data Management/Community Pipeline
  - UCAC4: Science Verification through Year 3 processing; DES DR1
  - 2MASS: Year 4 processing & Year 5 processing(?)
  - Gaia DR2: Year 5 processing(?) and beyond

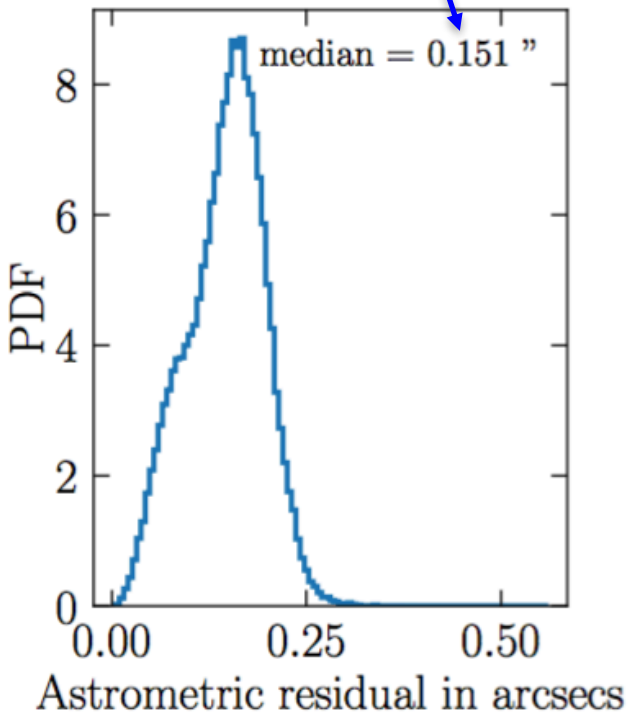
DES DR1 Astrometry

SCAMP

DARK ENERGY SURVEY

	g	r	i	z	Y
Single-epoch Astrometric Repeatability (total distance, mas)	42	36	37	39	56
Coadd Astrometric Precision (total distance, mas)	30 (internal); 151(vs. Gaia)				





DES DR1 vs. Gaia DR1

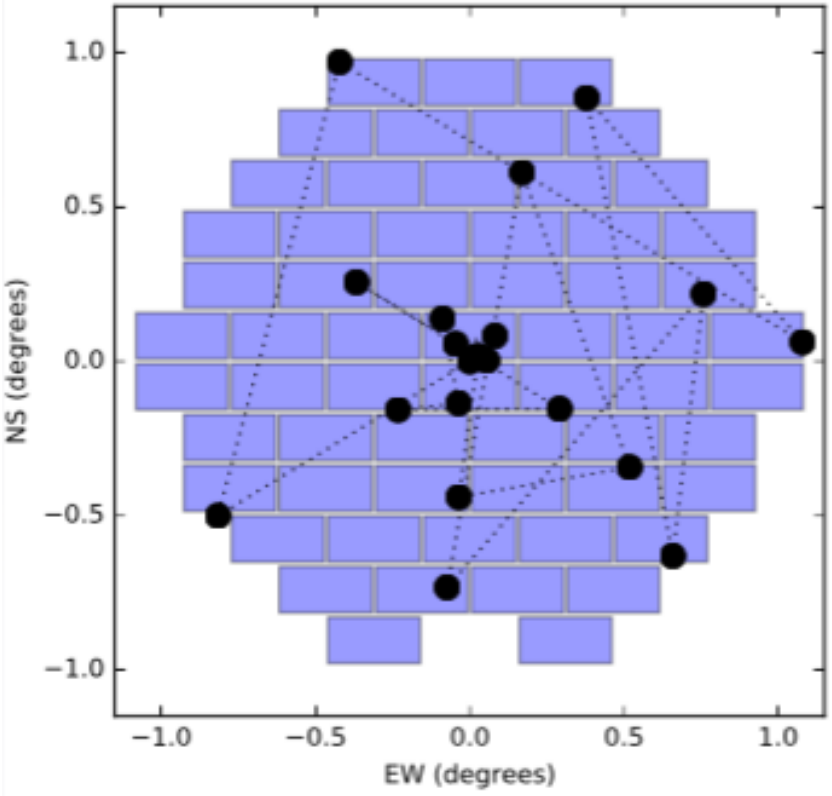
Abbott et al. 2018, arXiv:1801:03177 (DES DR1 paper)

DES Astrometry
wcsFIT

DARK ENERGY SURVEY

- **wcsFIT (G. Bernstein et al 2017)**
  - DECam starflats (taken ~ 4x per year)
  - Gaia DR1 used to stabilize low-order behavior of solutions (soon: DR2)

DECam Star Flat Dither Pattern



Astrometric model includes:

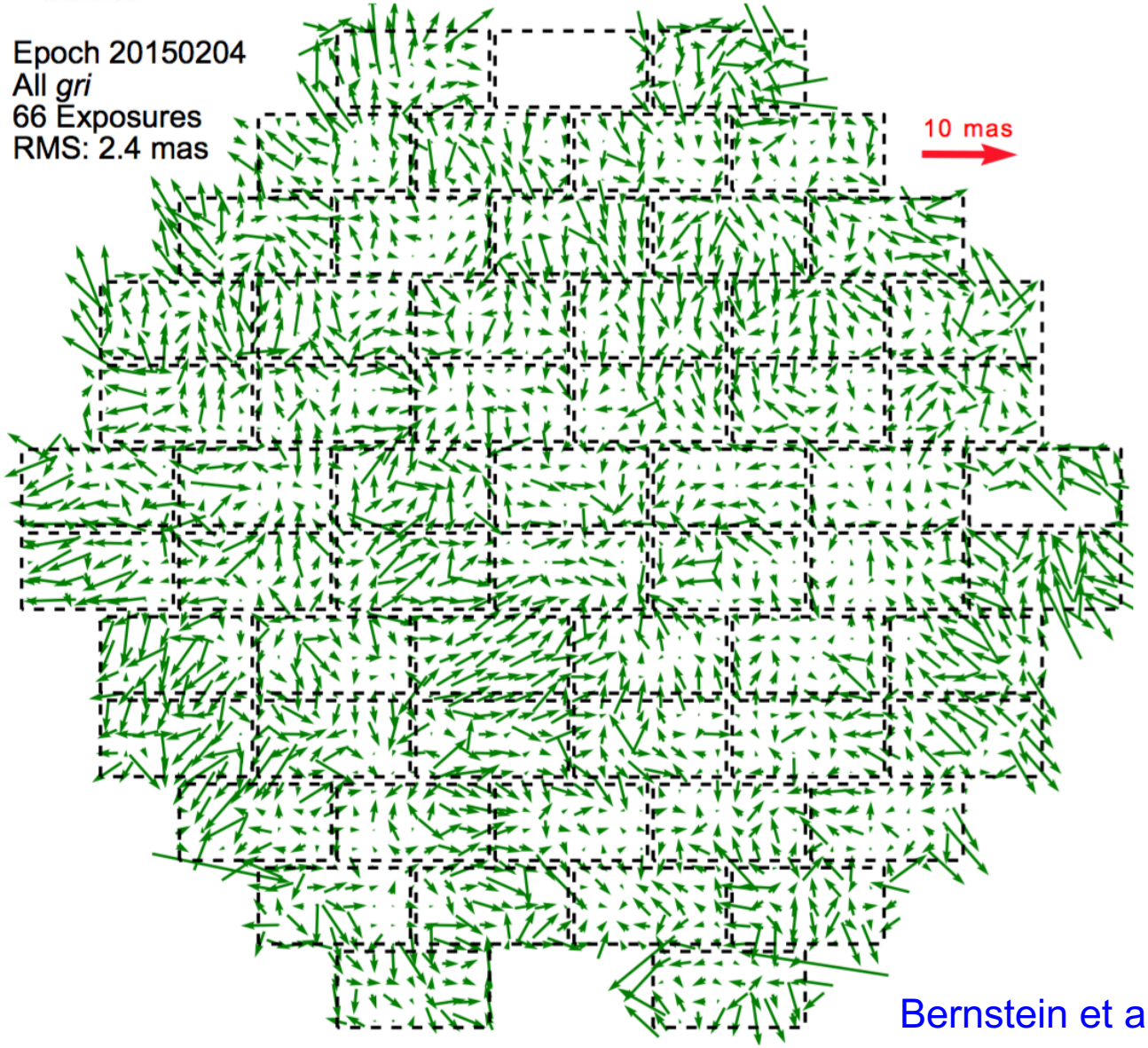
- Tree ring distortions (template)
- Serial register edge distortions (template)
- Optics (polynomial)
- Lateral color
- CCD linear shifts
- Exposure linear shifts
- Differential chromatic refraction

wcsFit refinements to DES Year 4 and beyond…

DES Astrometry

wcsFIT

DARK ENERGY SURVEY



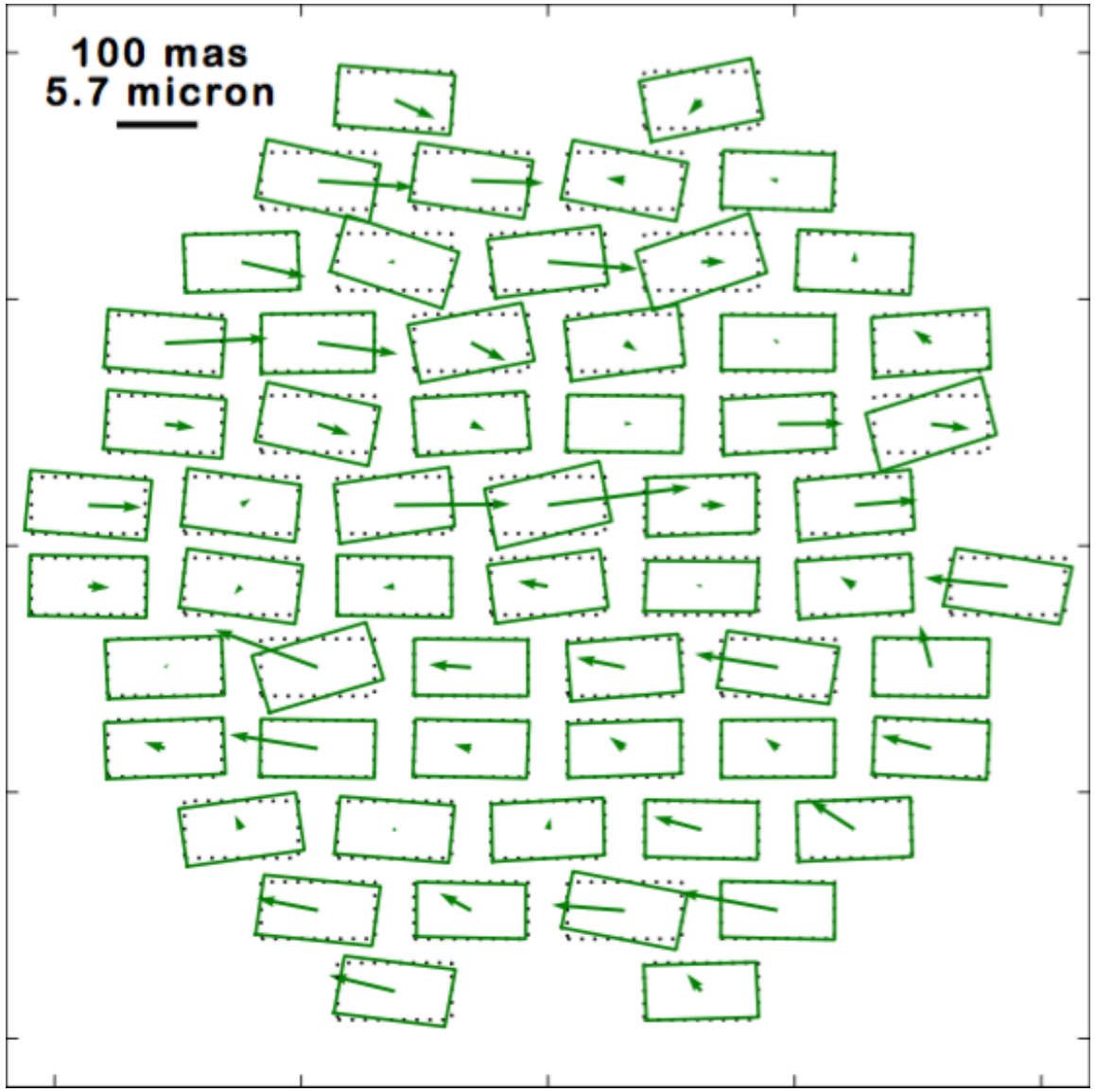
- Mean astrometric error of all detections in g,r,i for starflat epoch 20150204 vs. position on focal plane.
- Distortion field is multiplied by 50,000 to match red scale bar.
- **RMS: 2.4 milli-arcsec!**

Bernstein et al 2017

DES Astrometry

wcsFIT

DARK ENERGY SURVEY



DECam CCDs move a few microns on thermal cycling…

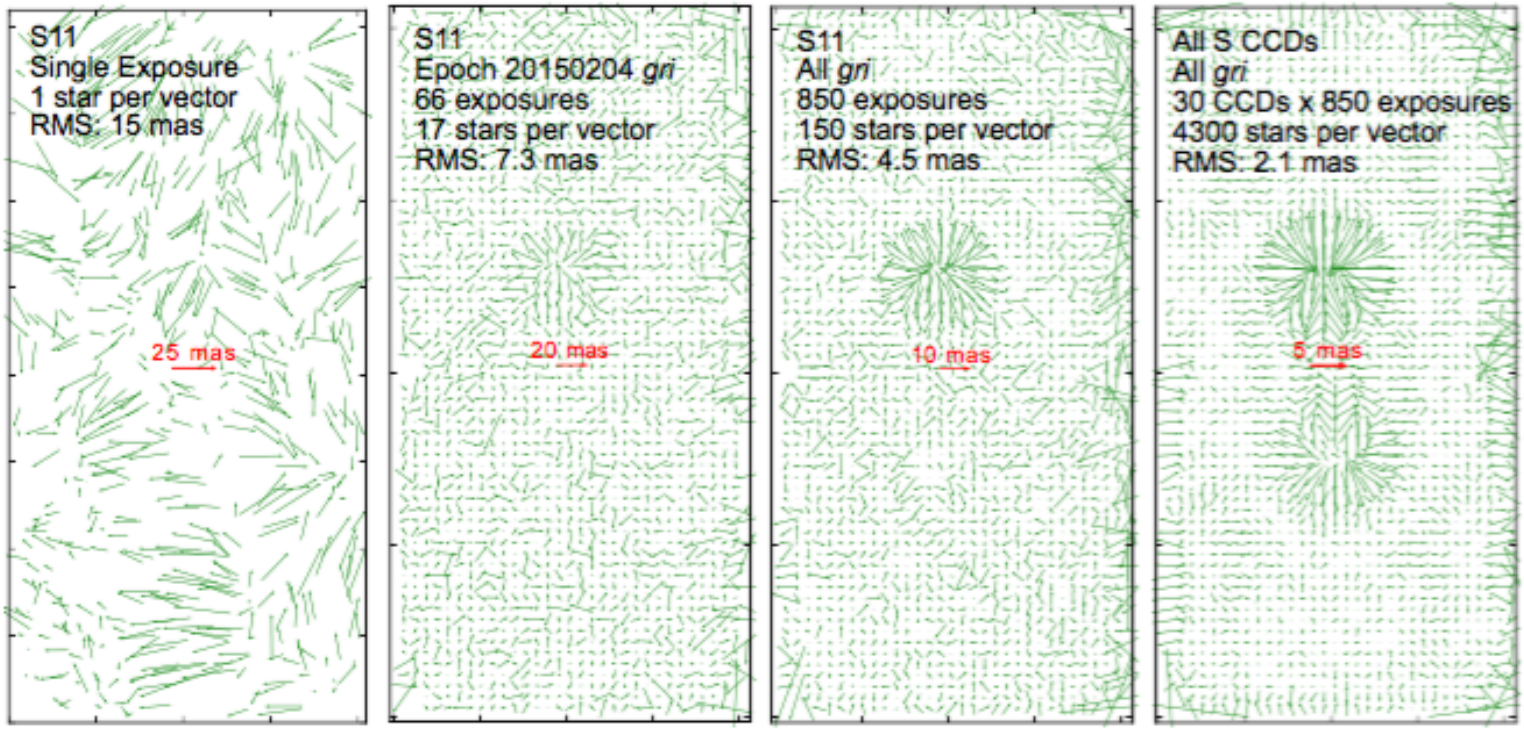
Change in CCD orientations after focal plane cooling event.

Credit: Gary Bernstein

DES Astrometry
wcsFIT

DARK ENERGY SURVEY

- Some un-modelled distortions…



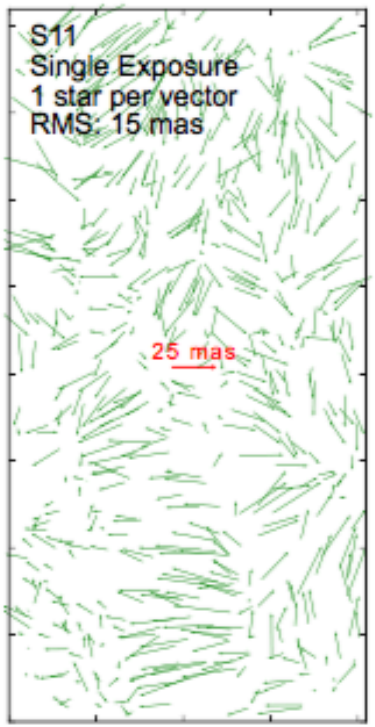
Credit: Gary Bernstein

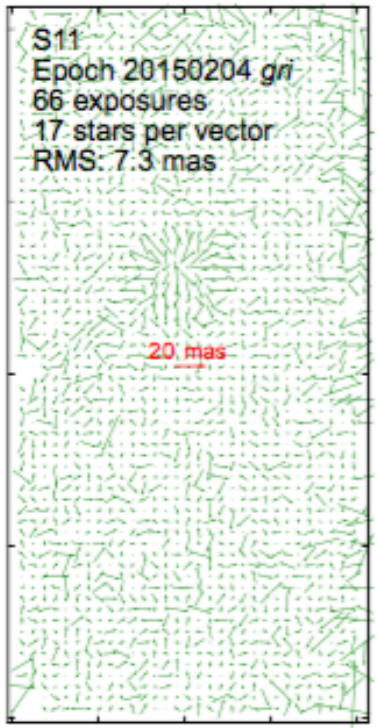
DES Astrometry

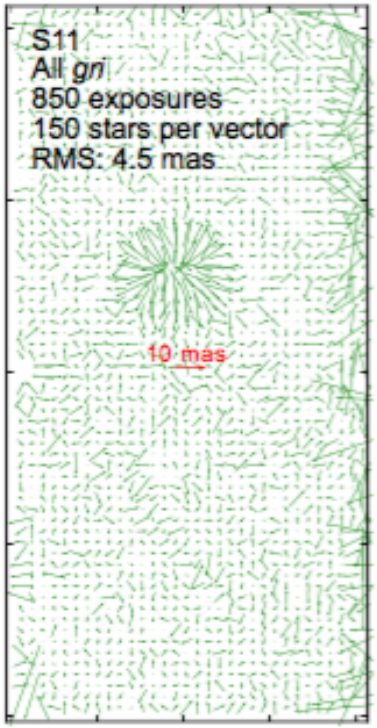
wcsFIT

DARK ENERGY SURVEY

- Some un-modelled static distortions?…







Credit: Gary Bernstein

DARK ENERGY
SURVEY

Photometry

DES Photometric Calibration Requirements* (5-year, coadded)

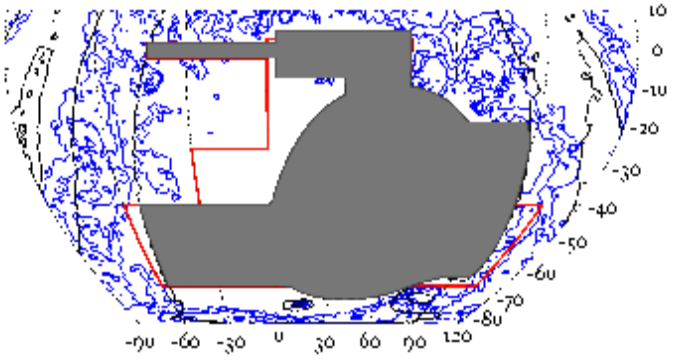
*From DES Scientific Requirements Document

DARK ENERGY SURVEY

1. **Internal:** 2% rms on scales of 0.05º- 4º.

   Goals: 1% rms and/or over 160º in RA, 30º in DEC.

   → angular galaxy clustering

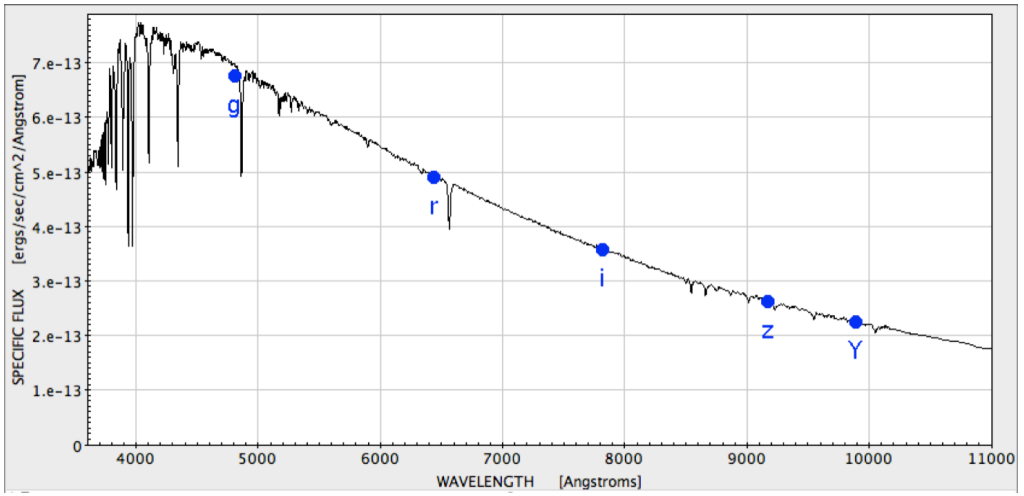


2. **Absolute Color:** 0.5% (*g-r, r-i, i-z*); 1% (*z-Y*).

   "Between-filters" calibration.

   Photometry as a "low-res. spectrum"

   → photo-z's, SNe k-corrections



3. **Absolute Flux:** 0.5% in *i*-band.

   Relative to standard star ~~BD+17 4708~~ C26202.

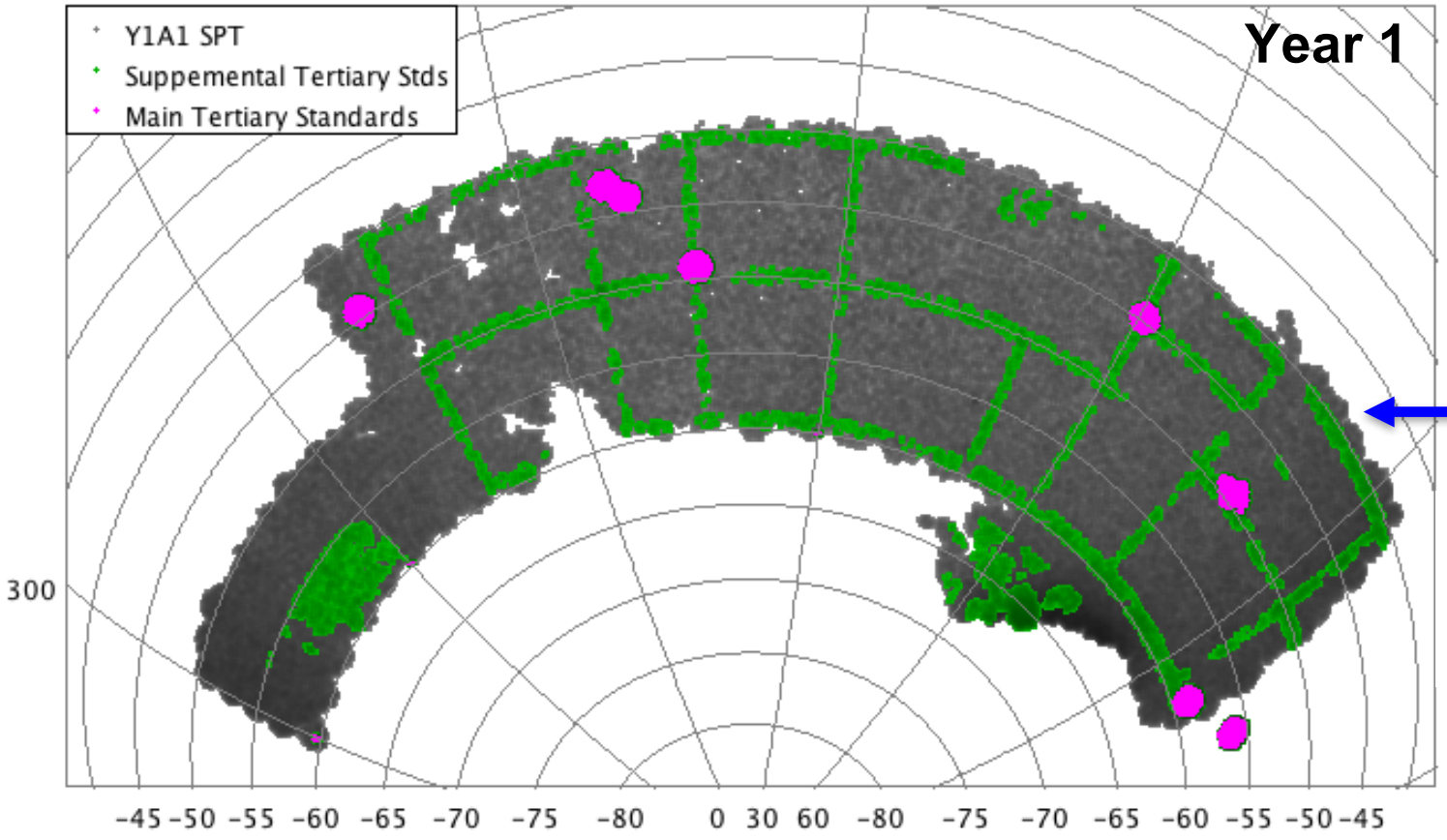
   Zeropointing the overall filter system.

   → comparison with other surveys (esp. for SNe)

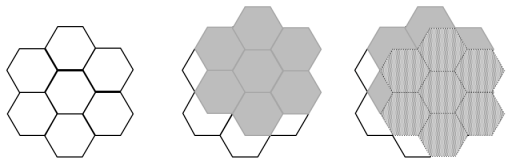
DES Photometry: SV, Y1, (Y3)
PGCM

DARK ENERGY SURVEY

- **Photometric Global Calibration Module (PGCM)**
  - Observe nightly standards to create a sparse gridwork of tertiary standards.
  - Use overlapping exposures to tie DES photometry to tertiary network.



For DES Year 1, each part of the covered footprint had 3-4 overlapping exposures in each band.



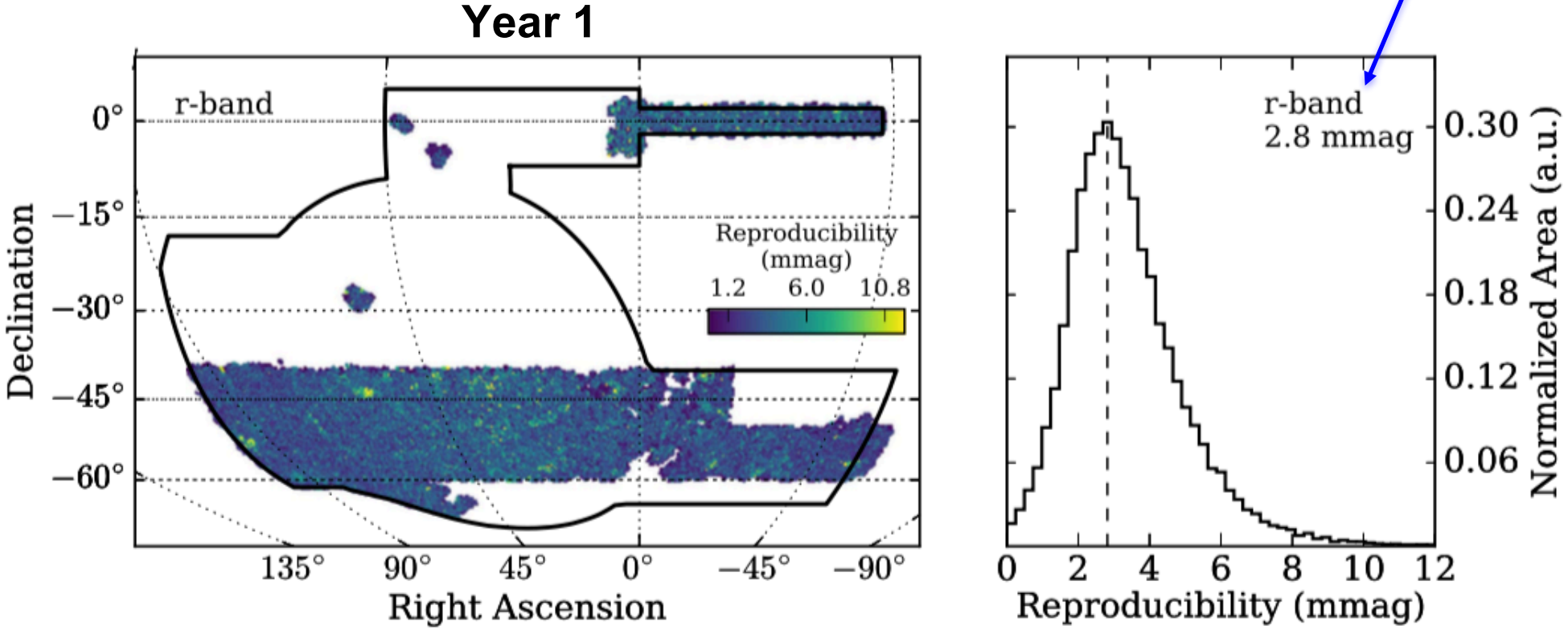
DES Photometry: SV, Y1, (Y3)

PGCM

DARK ENERGY SURVEY

Internal Photometric Reproducibility (overlapping CCDs): c. 3 mmag

Year 1



Drlica-Wagner et al. 2018, ApJS, 235, 33 (Y1A1-Gold paper)

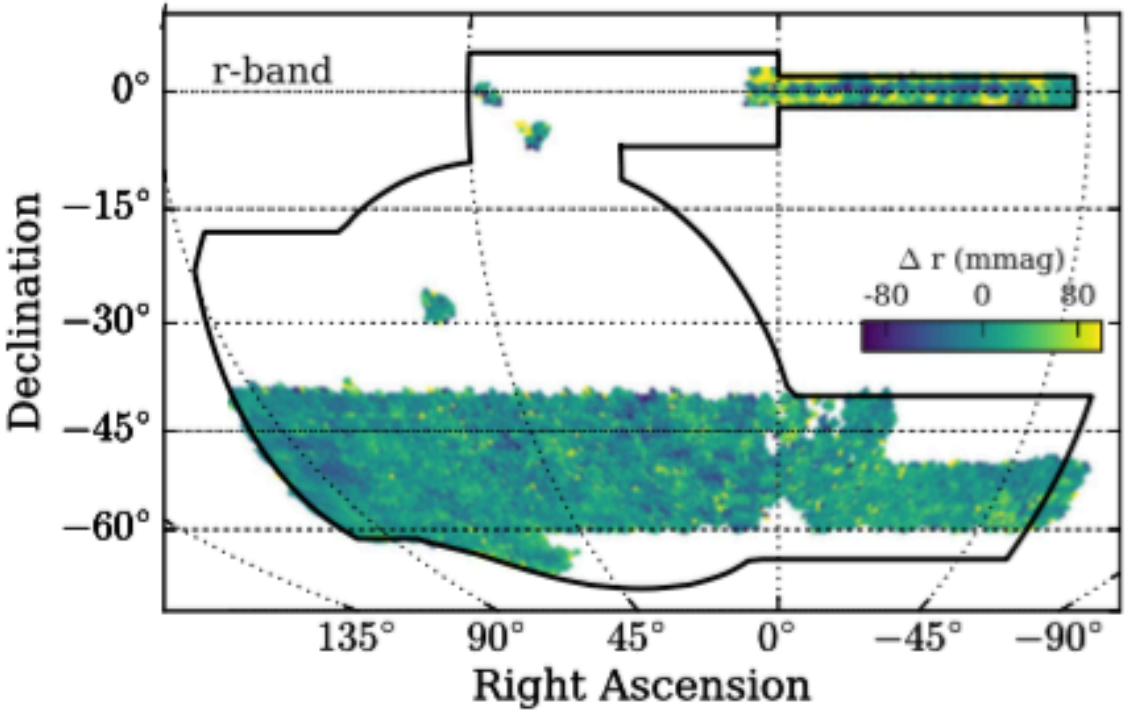
DES Photometry: SV, Y1, (Y3)

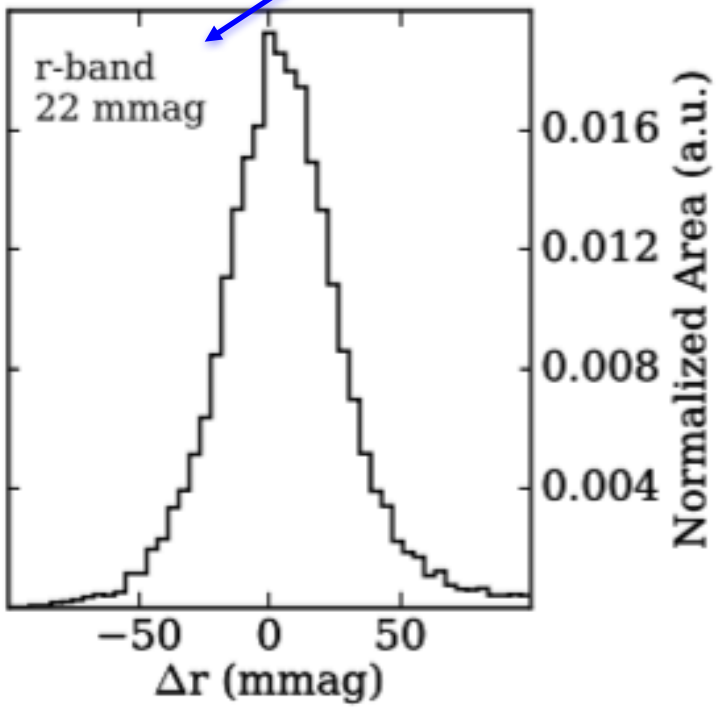
PGCM

DARK ENERGY SURVEY

Photometric Uniformity (APASS/2MASS comparison): ~20 mmag (~2%)

Year 1



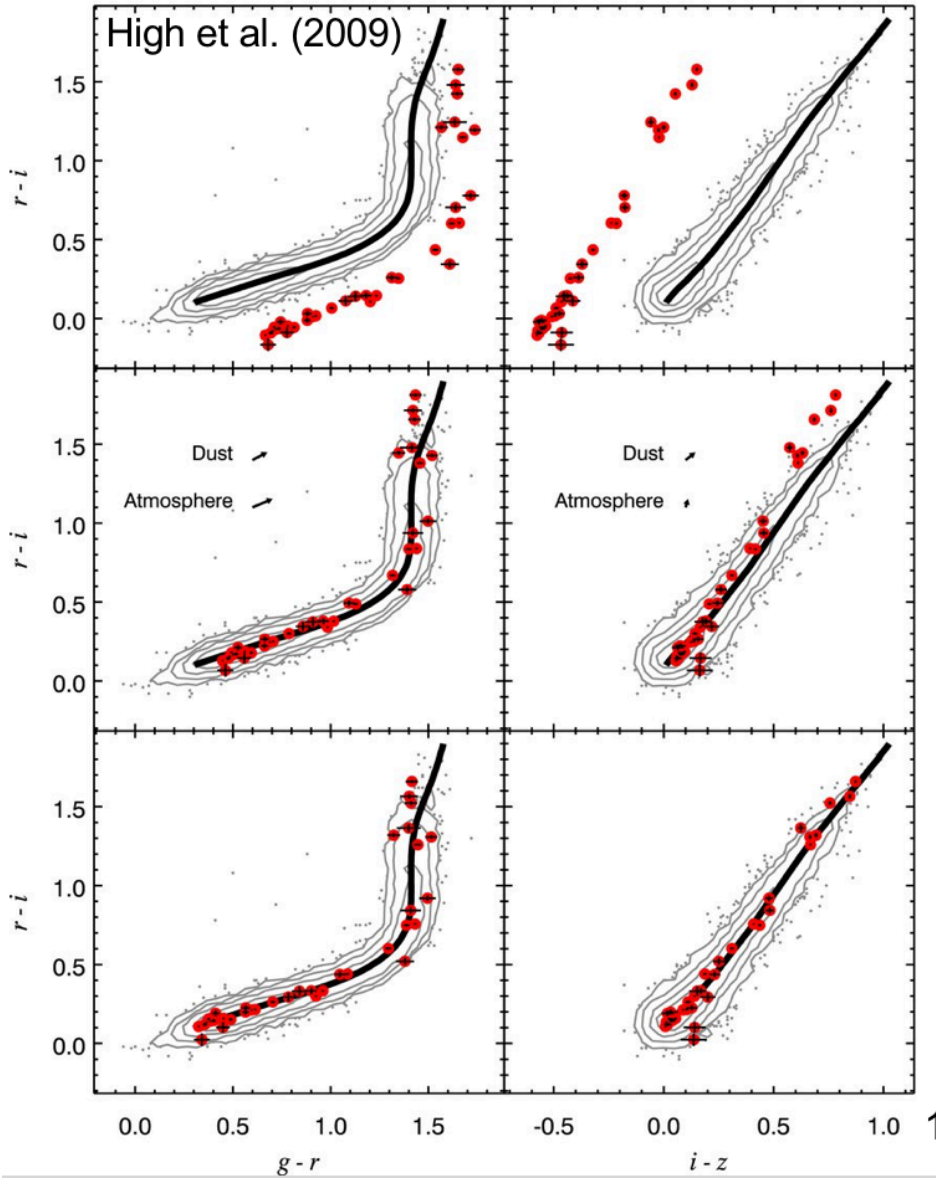


Drlica-Wagner et al. 2018, ApJS, 235, 33 (Y1A1-Gold paper)

DES Photometry: SV, Y1, Y2
SLR

DARK ENERGY SURVEY

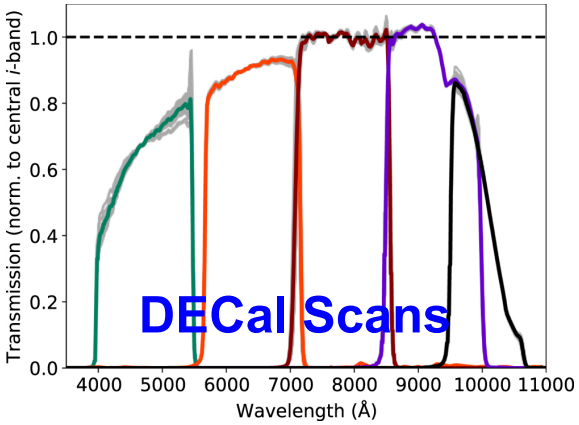
- **Stellar Locus Regression (SLR)**
  - Match the observations against the stellar locus.
  - ”Top of the Milky Way” as opposed to “Top of the Atmosphere”
  - Colors good to ~1%.
  - Could be affected by variations in stellar populations.



DES Photometry: DR1 (& Y3, Y4, Y5)
FGCM

DARK ENERGY SURVEY

- **Forward Global Calibration Method (FGCM)**
  - Burke et al. 2018, AJ, 155, 41
  - Take all the inputs and build and exposure-by-exposure model of the camera response + atmosphere prior to iterative fits of stars.



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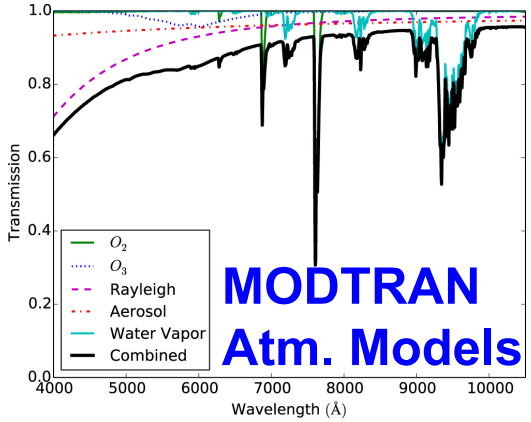
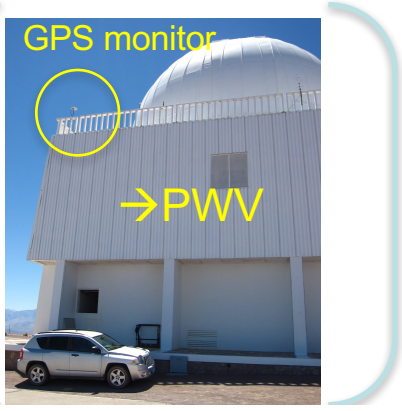
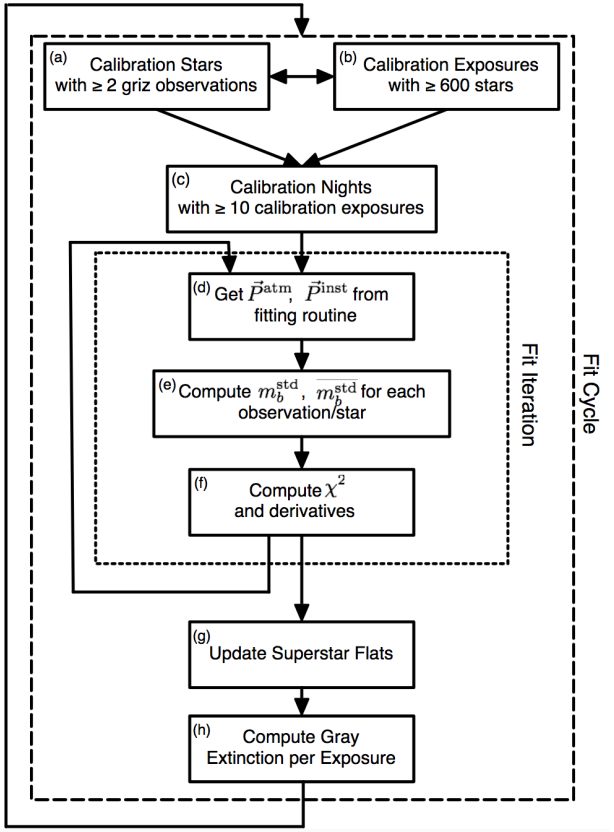




+ **Barometric Pressure Measurements**

+

Millions of stars observed 2+ times in griz under photometric conditions



DES Photometry: DR1 (& Y3, Y4, Y5)
FGCM

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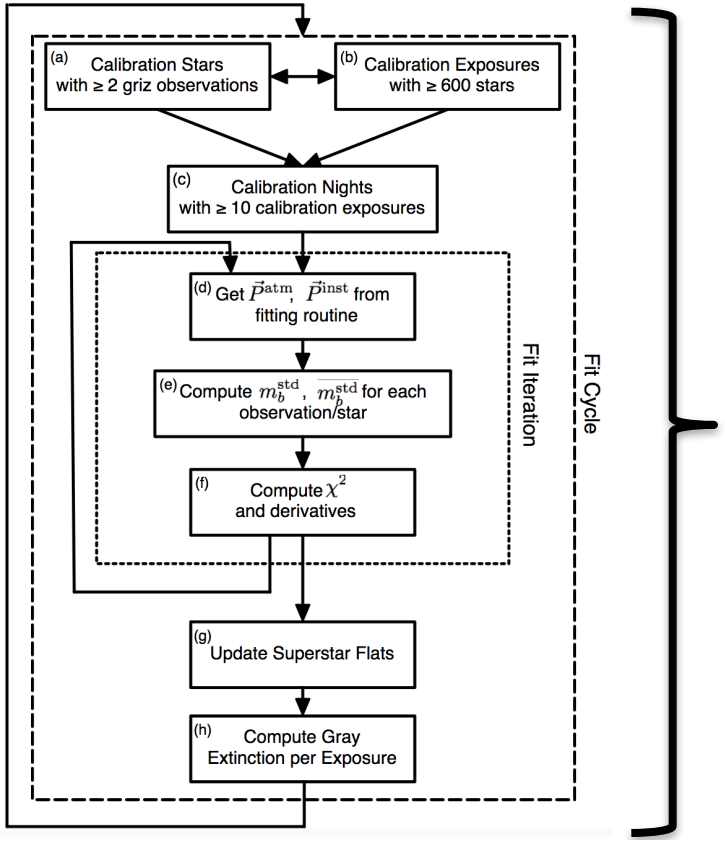


Y3 Annual Processing Results

- 8.7 million *griz* cal stars
- 6.2 million Y cal stars
- 3.2 million CCD image ZPs
- Fit residuals: 6-7 mmag rms
- Estimated uniformity over the DES footprint of <7mmag rms (compared to Gaia DR1) (even better for Y4 annual processing -- see next slides)

DES Photometry: DR1 (& Y3, Y4, Y5)

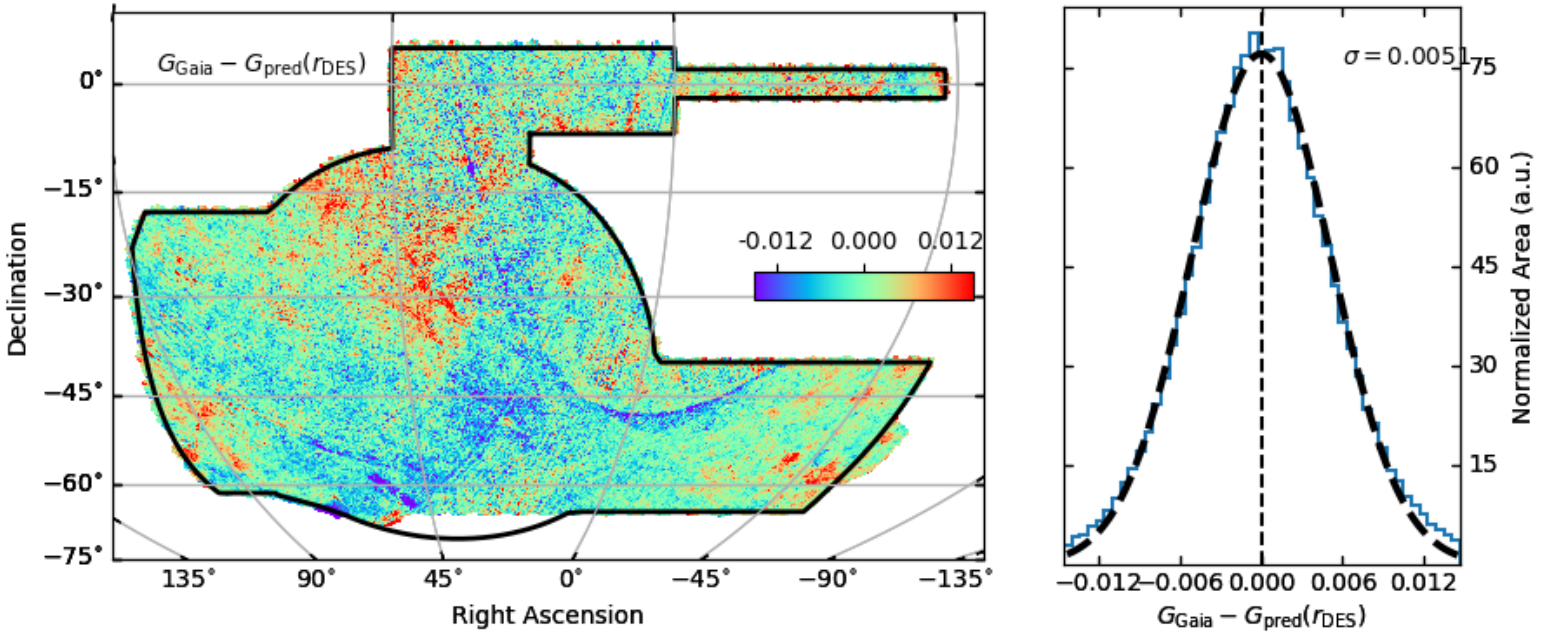
FGCM

DARK ENERGY SURVEY

(Y4 processing)

DES r-band and Gaia DR1

- Offset map (G - r) for Gaia DR1
- Uniform with RMS of 5.1 mmag



Credit: Eli Rykoff

DES Photometry: DR1 (& Y3, Y4, Y5)

FGCM

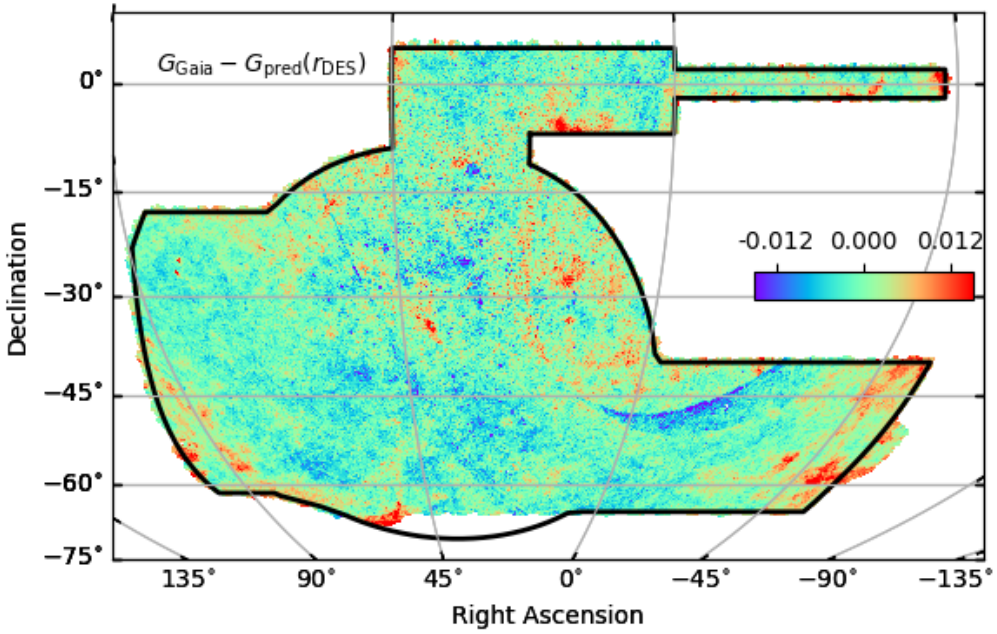
DARK ENERGY SURVEY

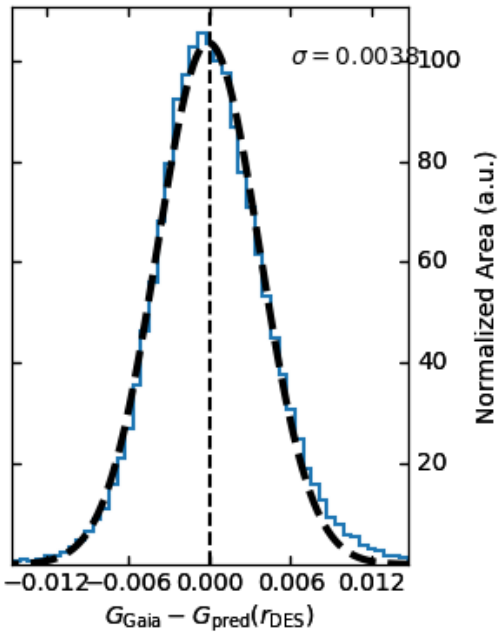
(Y4 processing)

DES r-band and Gaia DR2

- Offset map (G - r) for Gaia DR2
- Uniform with RMS of 3.8 mmag

Preliminary





Credit: Eli Rykoff

DES Photometry: DR1 (& Y3, Y4, Y5)

FGCM

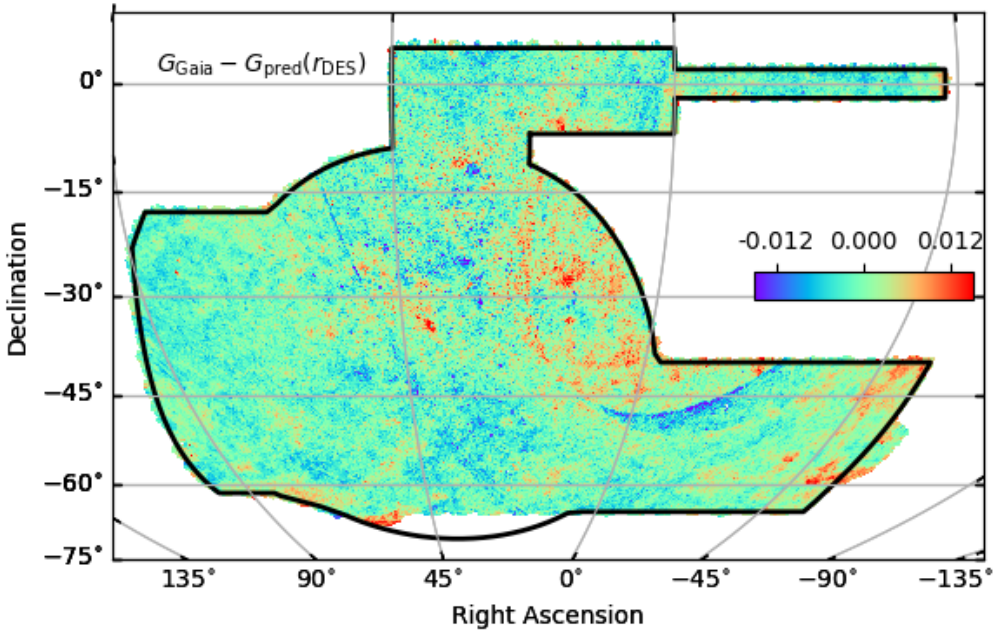
DARK ENERGY SURVEY

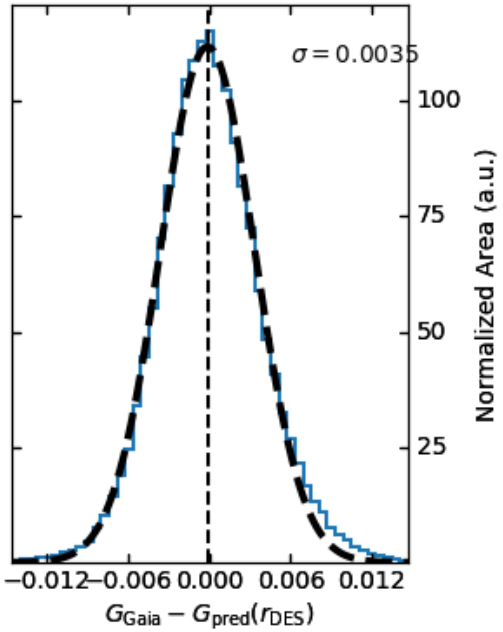
(Y4 processing)

DES r-band and Gaia DR2

- Now with a simple reddening correction
- RMS is 3.5 mmag

Preliminary





Credit: Eli Rykoff

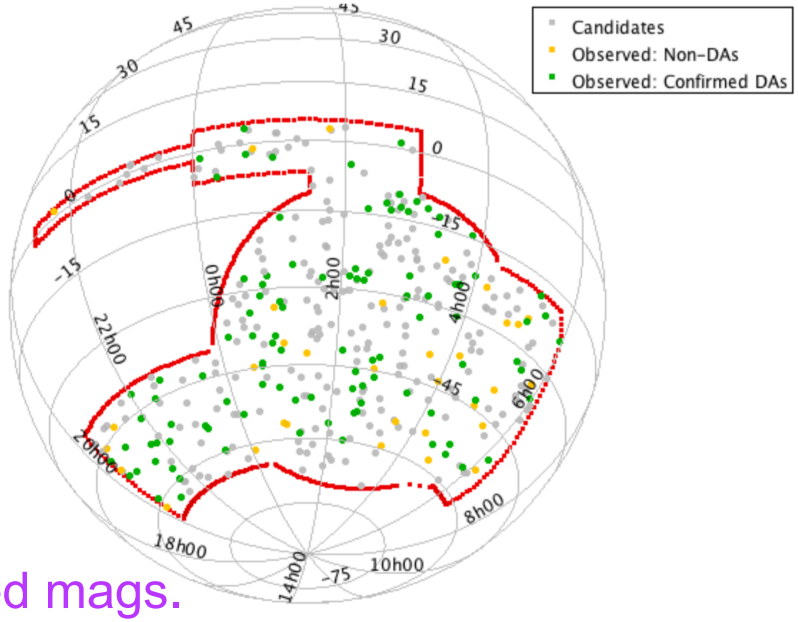
FGCM Absolute Calibration

(also relevant to other calibration methods)

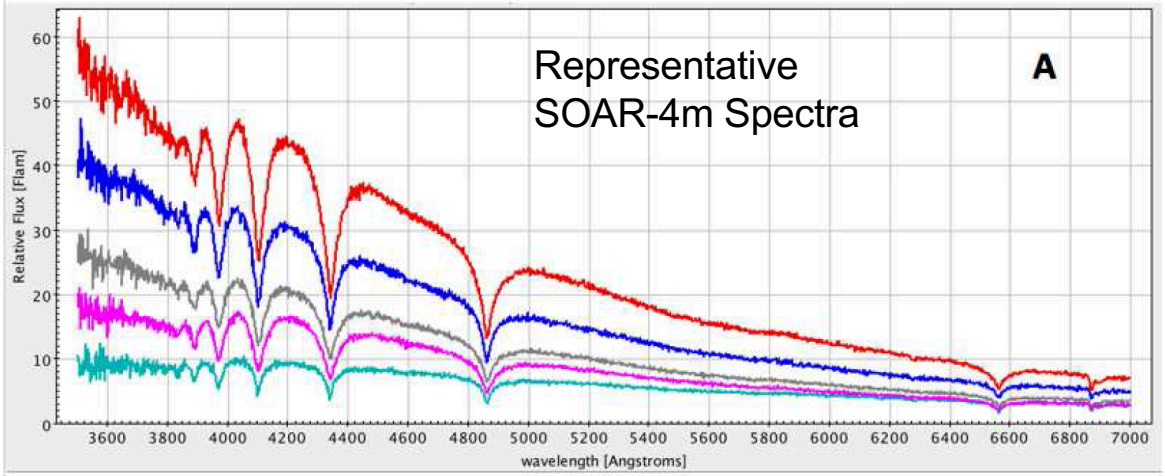
DARK ENERGY SURVEY

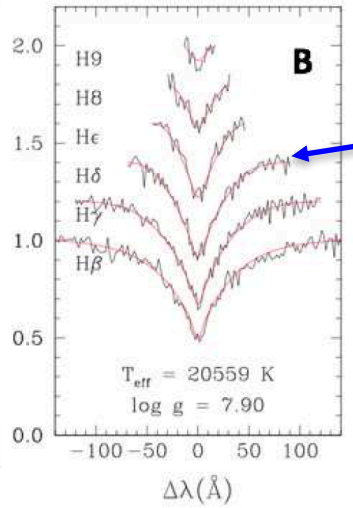
- Three CALSPEC standards in DES footprint. Only one is a faint standard. FGCM has absolute scale set to C26202.
- DES DR1: 3-5 mmag uncertainty, relative to C26202.
- Multi-year program of identifying white dwarf candidates (~100), obtaining spectra, and performing model fits giving synthetic spectra.

SOAR-4m Spectra of Candidate DA WDs



Synthetic photometry can be compared with observed mags.





DA WD atm. model fits (P.-E. Tremblay) (Also using G. Narayan's WDmodel)

Slide credit: William Wester

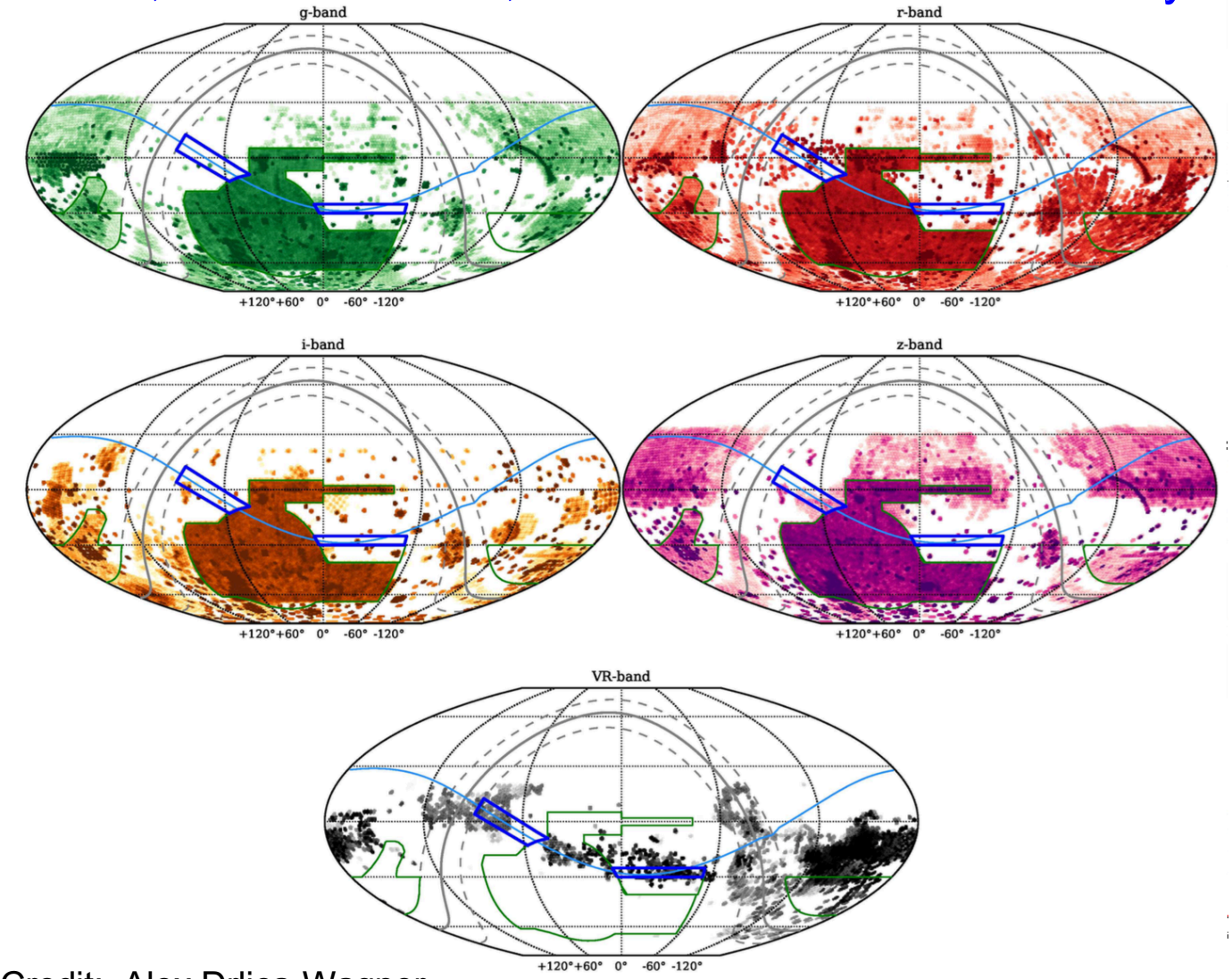
DARK ENERGY
SURVEY

BLISS

Blanco Imaging of the Southern Sky (BLISS; PI: Marcelle Soares-Santos)

DARK ENERGY SURVEY

DES, Public DECam, and BLISS data as of c. Early 2017



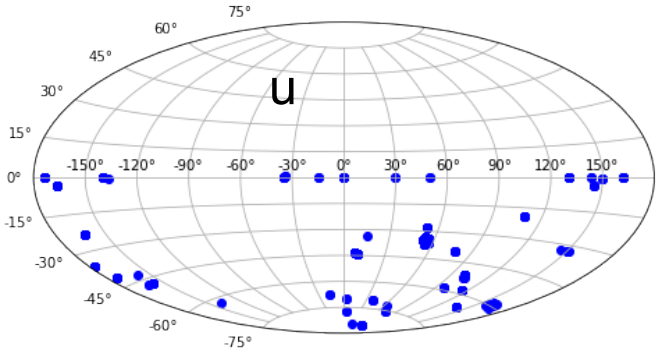
- Public DECam data supplemented with new observations to cover Southern sky to |b| = 10º in griz.
- Processed with DES pipeline at Fermilab.
- Science:
  - Templates for Optical Counterparts to LIGO/Virgo events
  - Dwarf Galaxy searches
  - Planet 9 searches

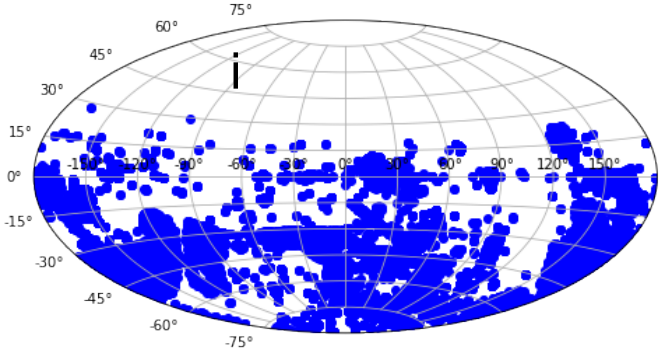
Credit: Alex Drlica-Wagner

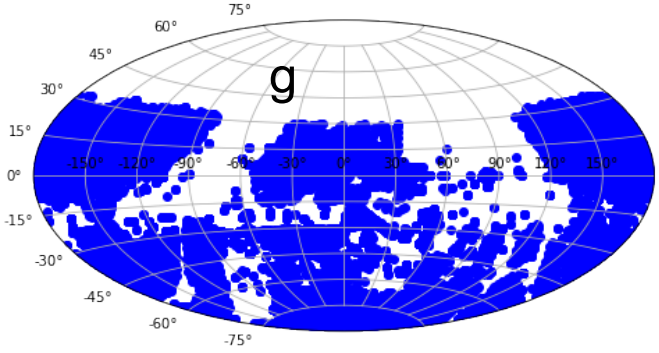
Blanco Imaging of the Southern Sky (BLISS; PI: Marcelle Soares-Santos)

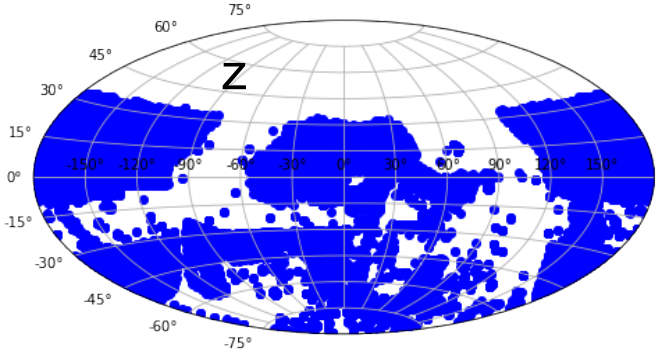
DARK ENERGY SURVEY

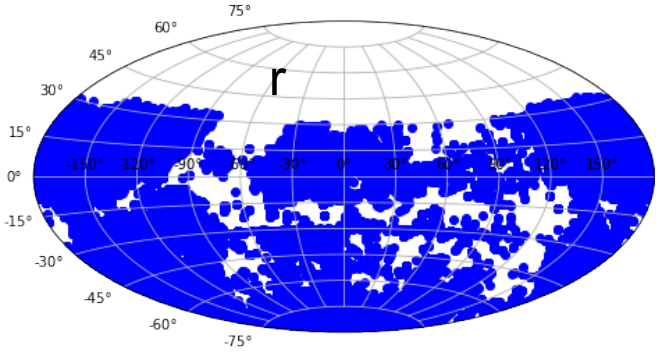
Public, non-DES exposures processed (current status)

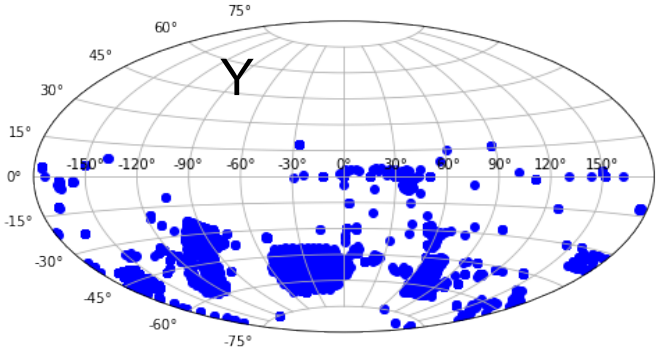













```
bandList = ['u','g','r','i','z','Y']
```

```
for band in bandList:
    print band,
    mask = (processed_bliss_exp_df.band == band)
    ntot = processed_bliss_exp_df[mask].radeg.size
    print ntot
print
```

```
u 337
g 28480
r 31962
i 18426
z 25195
Y 4316
```

Photometric calibration via "expCalib"

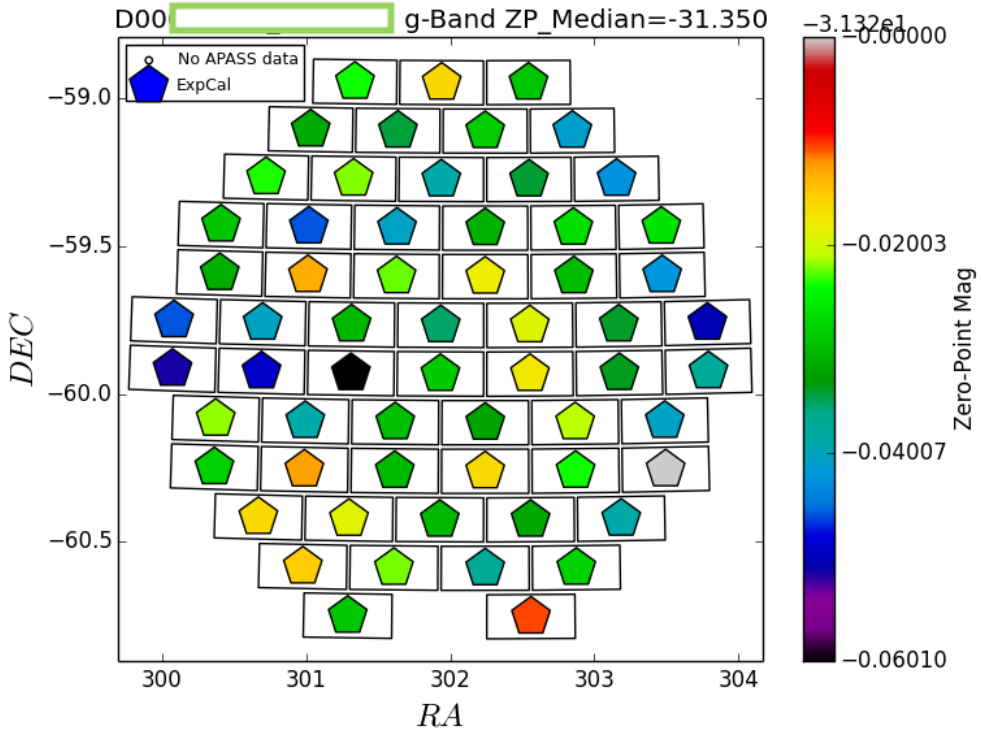
expCalib: On-the-fly nightly calibration and zeropoint estimation

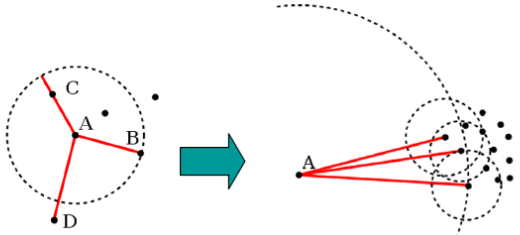
Sahar Allam (Fermilab)

DARK ENERGY SURVEY

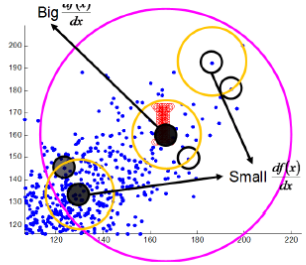
What is expCalib?

- Quick zero point estimate for single epoch exposures.
- Useful for on-the-fly calibration.
- Can easily identify ZP gradient over an exposure.
- Currently uses APASS/2MASS transformed to DES {u,g,r,i,z,Y}
- Future: use Gaia DR2 or Gaia + APASS/2MASS/Galex hybrid for transformed DECam u,g,VR,r,i,z?
- ZP outlier rejection for each exposure via scikilearn Local Outlier Factor (LOF**)
- Estimated ZPs for the following programs:- DES, DES-SNe, DES-CalSpec, DES-TMO, DECam Engineering, DES-GW, IceCube, BLISS, MagLiteS, BLINK, and others.





Local-density in Multi-dimensional Feature Space



Comparing with Self or others: change of local-density

**http://www.dbs.ifi.lmu.de/Publikationen/Papers/LOF.pdf

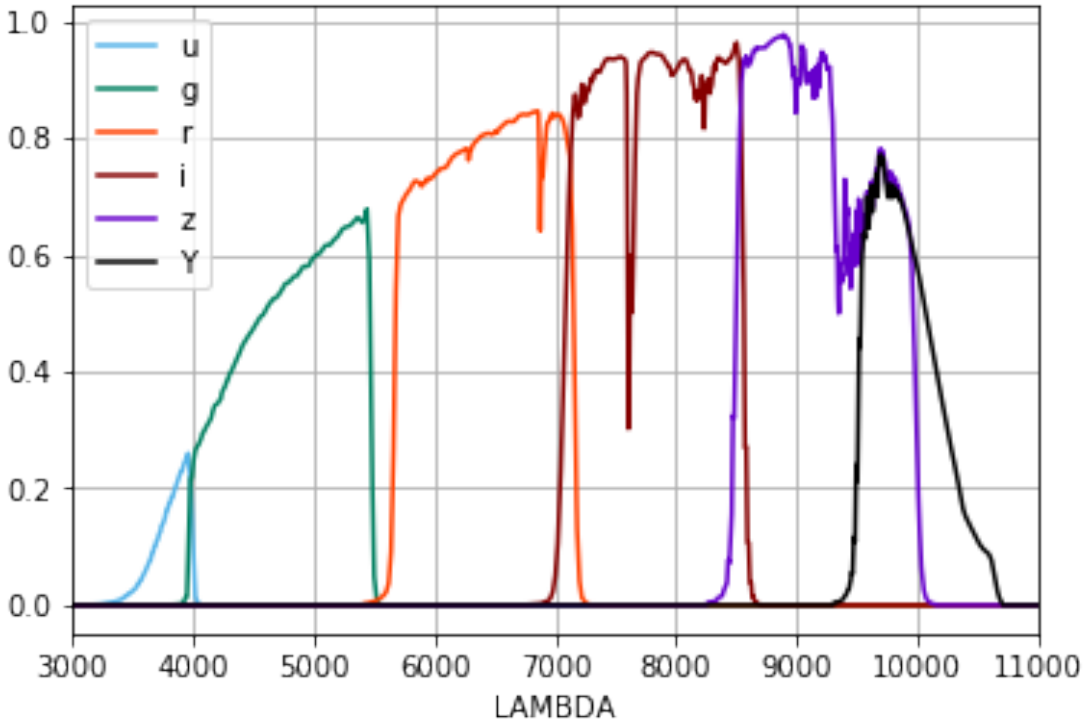
DARK ENERGY
SURVEY

Miscellanea

DECam Filters: Normalization Factors

DARK ENERGY SURVEY

DES DR1 Standard Passbands



Synthetic photometry:

$$m = -2.5 \log \frac{\int d(\log \nu) f_\nu S_\nu}{\int d(\log \nu) S_\nu} - 48.60,$$

Exposure Time Calculations:

$$N_* = A\, t \int \frac{\lambda}{hc}\, f_\lambda\, S_\lambda\, d\lambda$$

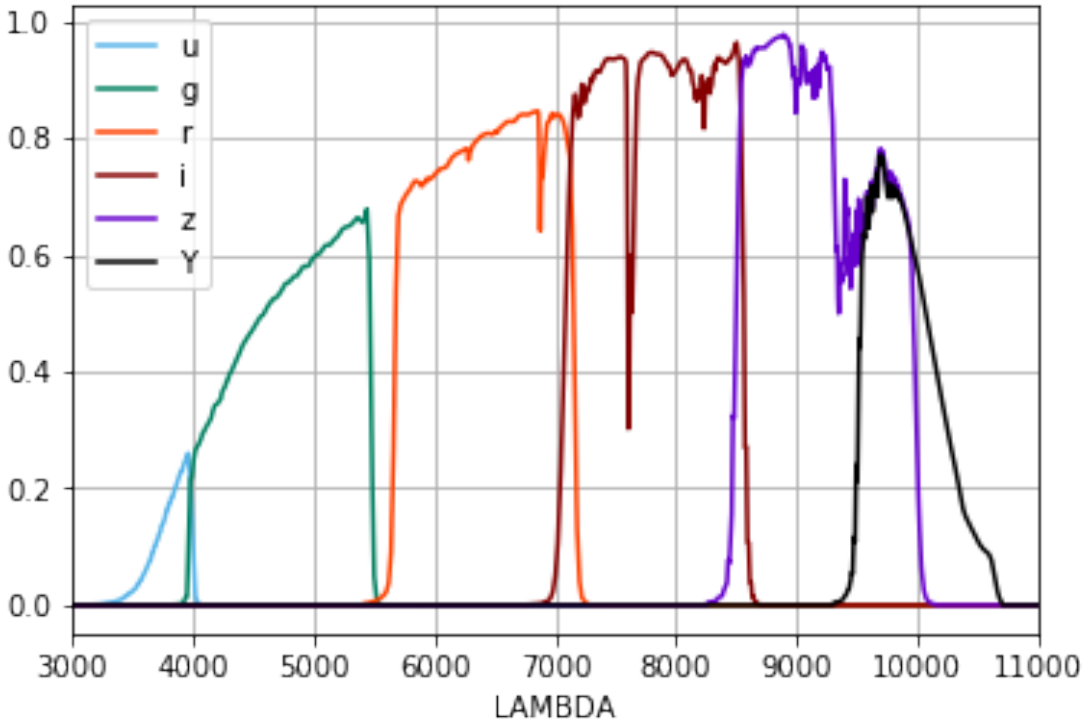
filter	synthetic count rate [e-/sec]	observed count rate [e-/sec]	Scaling Factor (= obs./synthetic) [dimensionless]
g	931.41	519	0.557
r	1064.7	623	0.585
i	999	589	0.590
z	778.56	457	0.587
Y	299.87	187	0.624

Multiply by these scaling factors **(Preliminary!)**

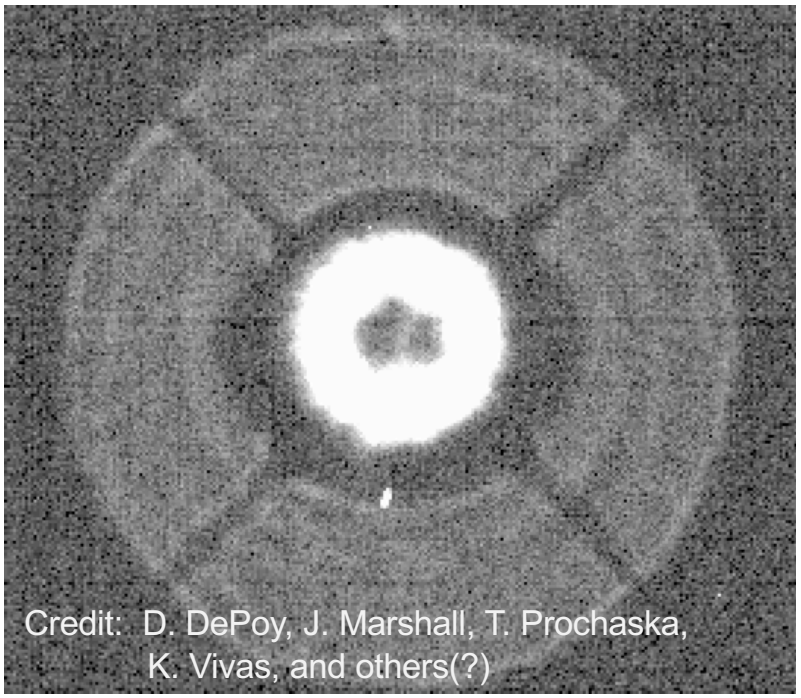
DECam Filters: Out-of-Band Leaks

DARK ENERGY SURVEY

DES DR1 Standard Passbands



Out-of-focus "g+i" image of ɣ Crucis

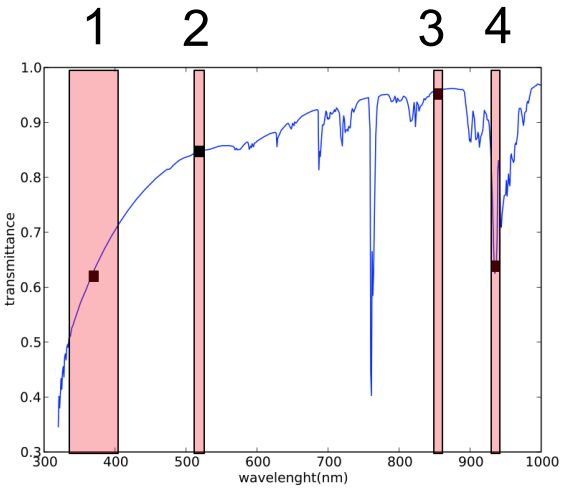


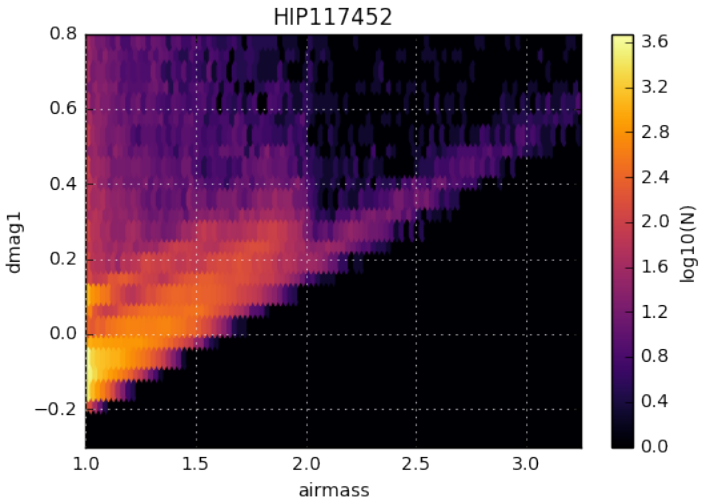
- DECal is not precise enough to measure out-of-band leaks below the ~10^{-4} level.
- During the January and March 2018 DECam engineering runs, the Texas A&M team observed bright stars through double filters, trying all possible combinations.
- Evidence for out-of-band leakage in u-band and either g- or i-band.
- Detailed analysis is still in progress.

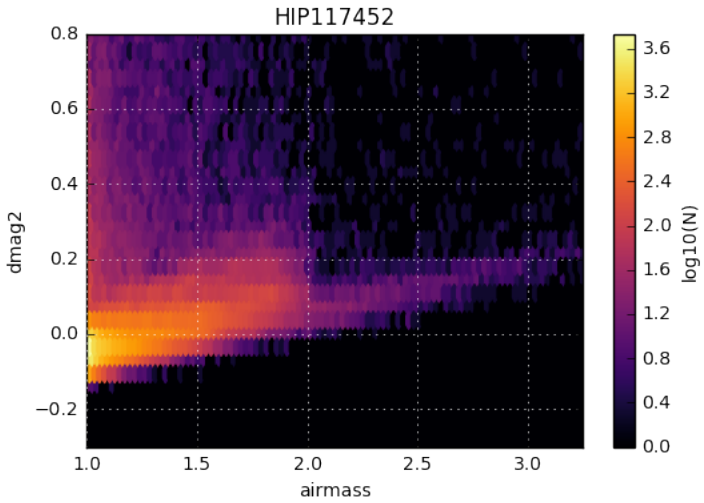
There's a lot more that can be done with aTmCam!

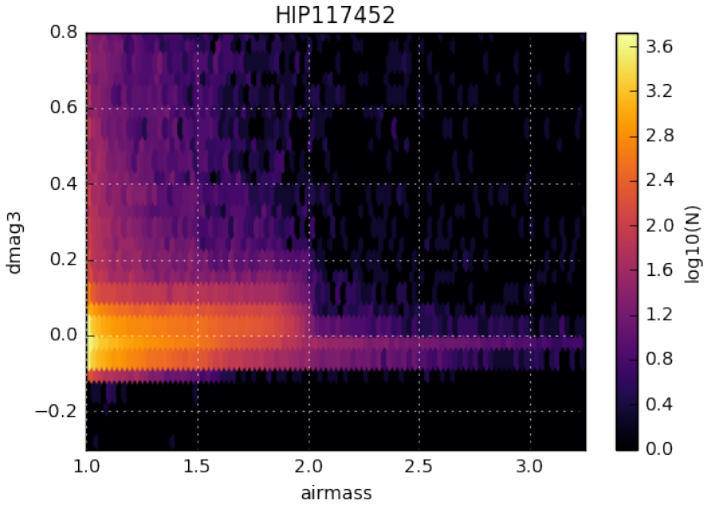
(e.g., perhaps estimating
hourly DECam ugriz extinction coefficients from aTmCam mags?)

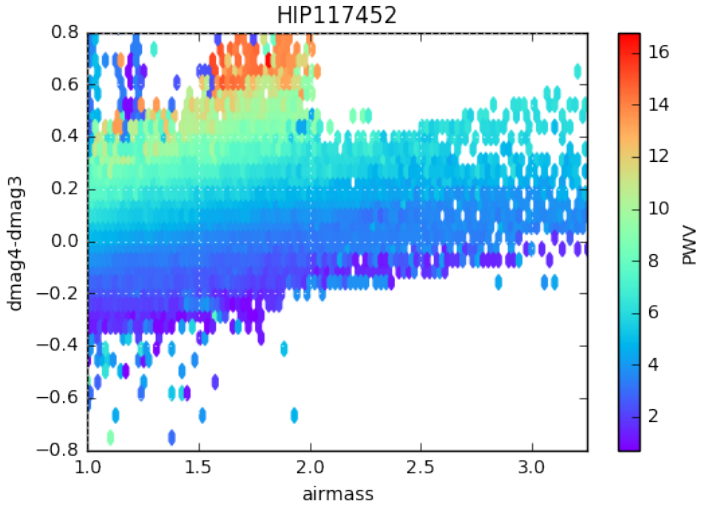
DARK ENERGY
SURVEY









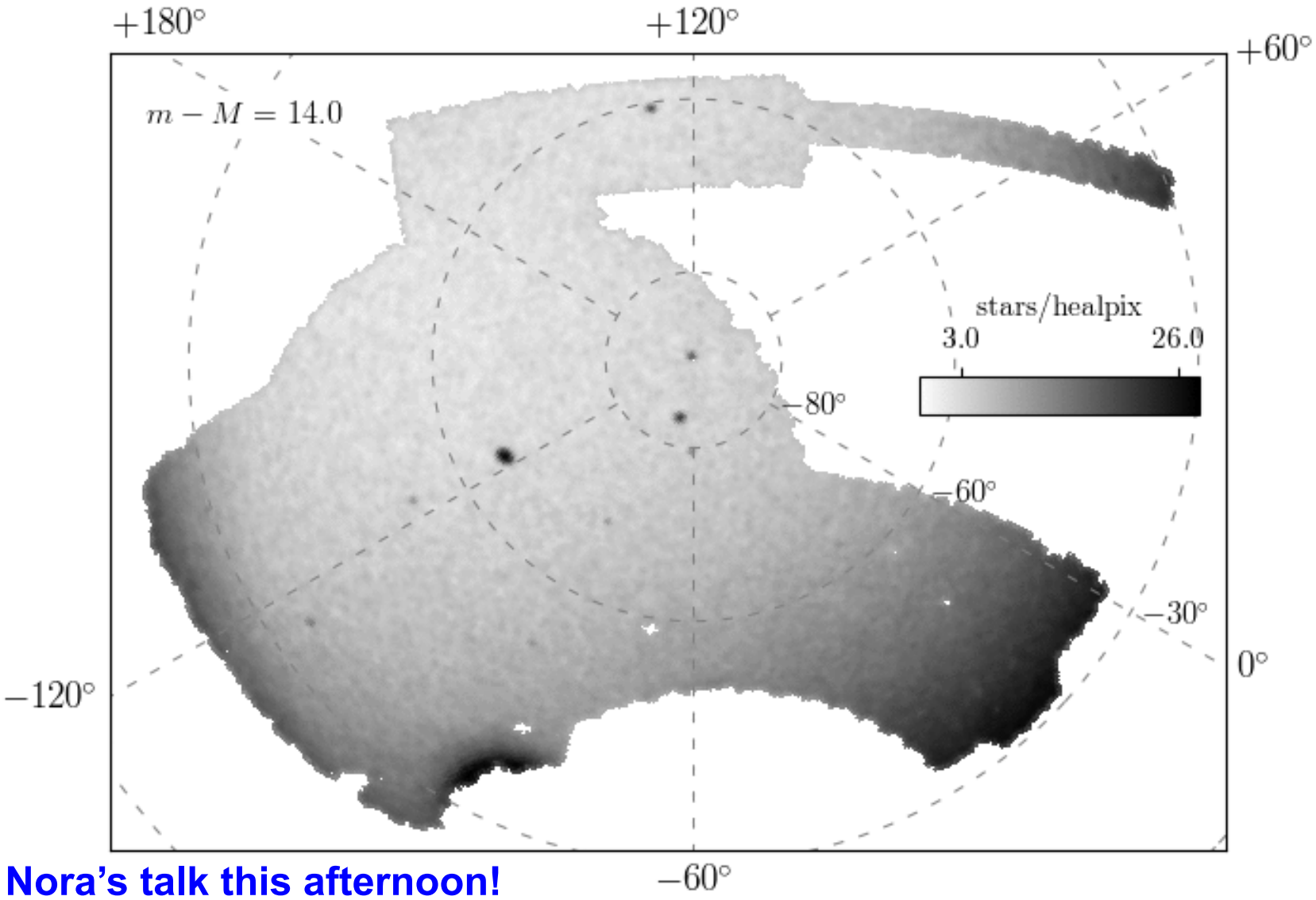


DARK ENERGY
SURVEY

DECam Calibrations Enabling Science

Stellar Streams in Milky Way Halo

(Nora Shipp et al. 2018, arXiv:1801.03097)



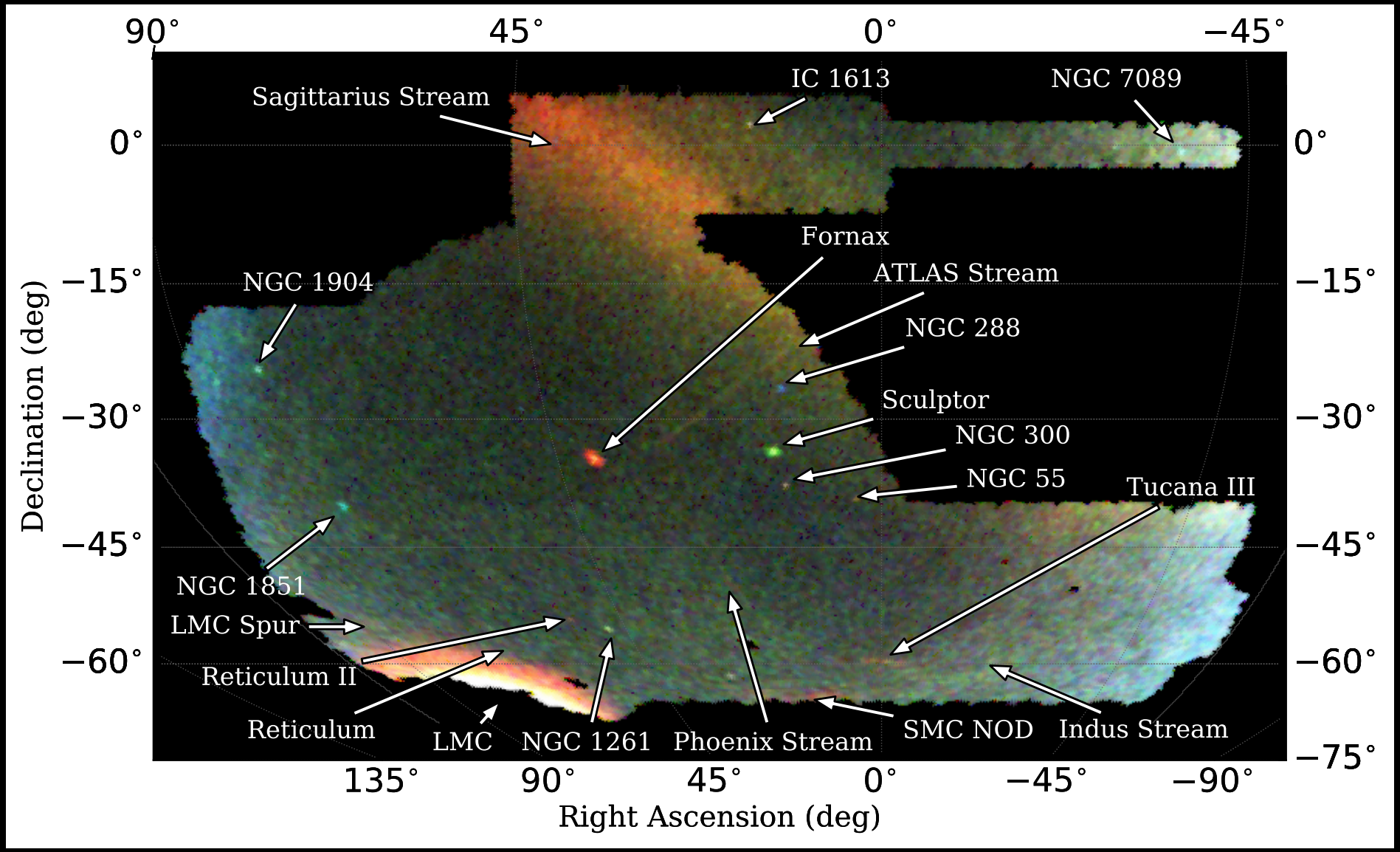
See Nora's talk this afternoon!

DARK ENERGY
SURVEY

Extra Slides

Milky Way Structure

(regions of high star density)



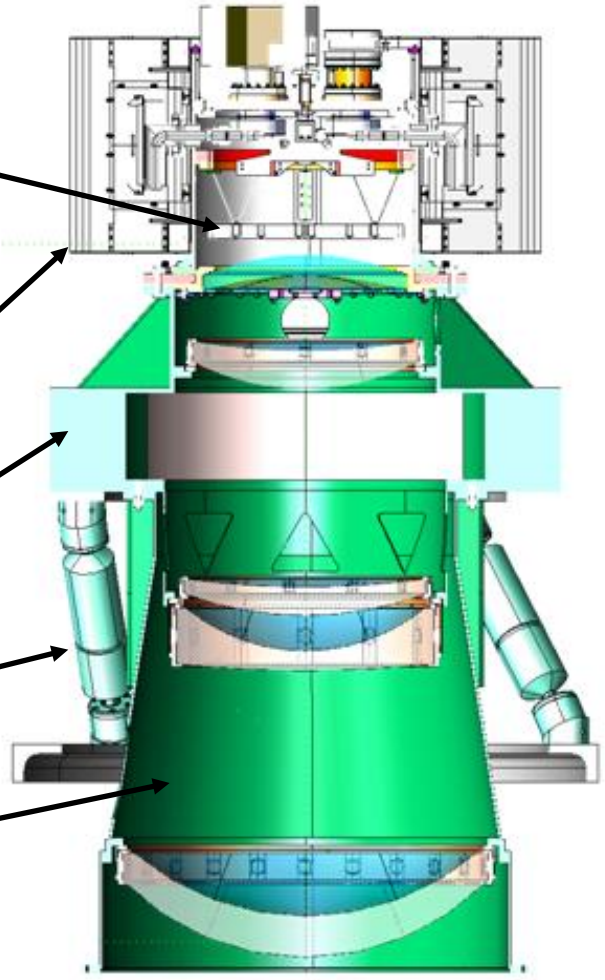
Nora Shipp

DECam overview

(Slide Credit: Brenna Flaugher)

DARK ENERGY SURVEY

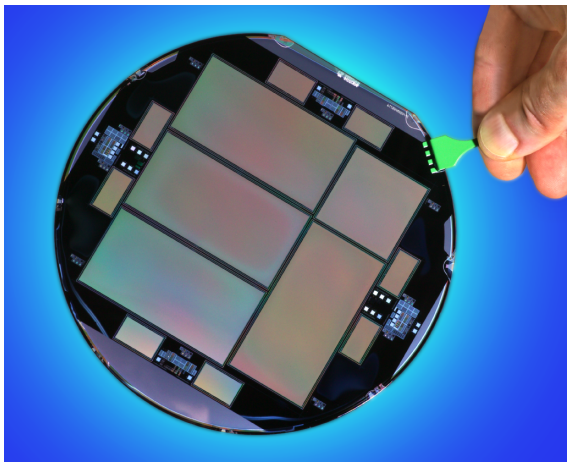
- CCD focal plane is housed in a vacuum vessel (the imager) which is supported by the barrel
- LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C
- CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled.
- Filter changer (8 filter capacity) and shutter form one mechanical unit.
- Hexapod provides focus and lateral alignment capability for the corrector-imager system
- Barrel supports the lenses and imager
- DECam weighs about 4 tons (load limit is ~ 6 tons)

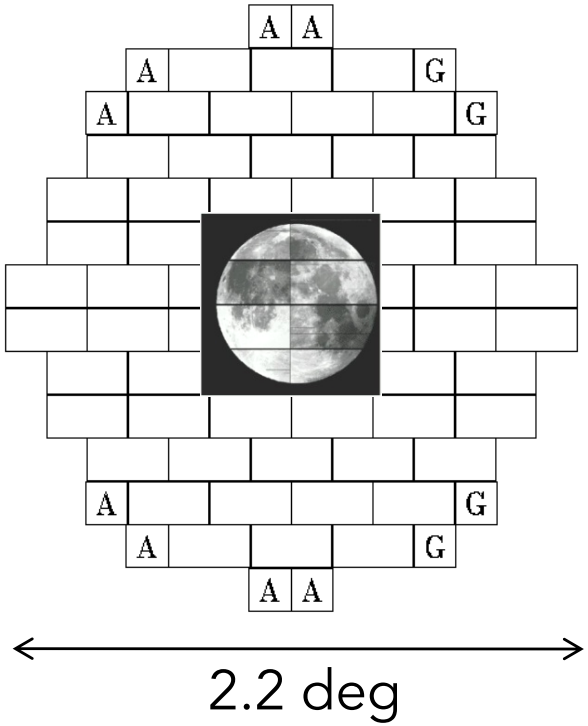


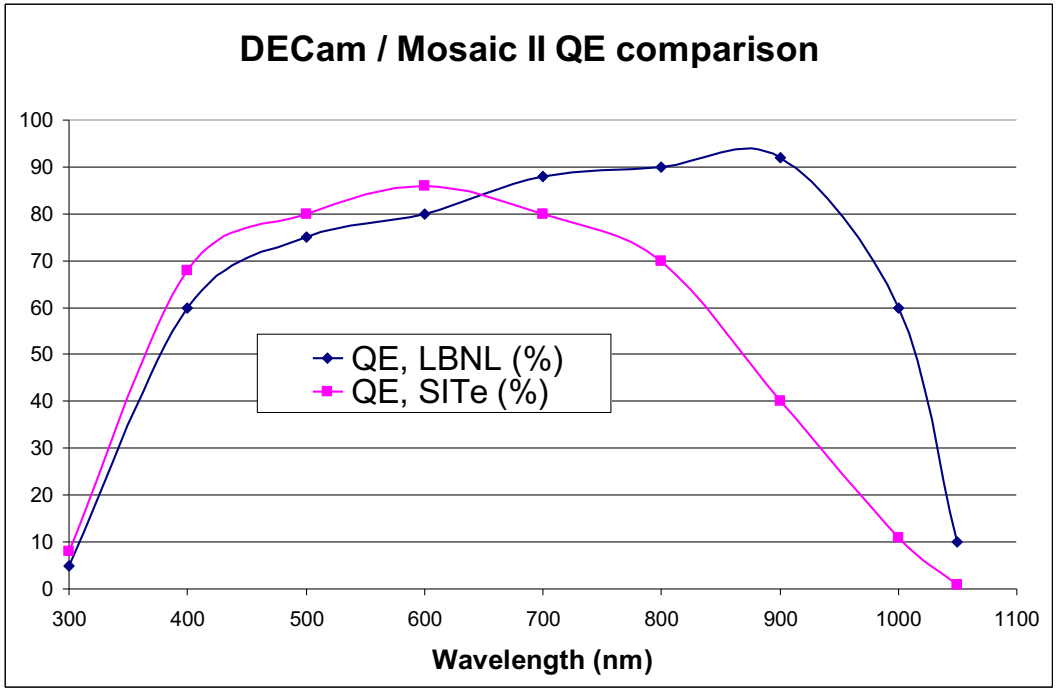
DECam CCDs

DARK ENERGY SURVEY

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips (hexapod)
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels







DES Astrometric Calibration Requirements* (single-epoch & coadded)

*From DES Scientific Requirements Document

DARK ENERGY SURVEY

1. **Internal (local):** 15 mas rms

   Mapping of centroids of bright stars between a (deeper) coadd and its overlapping single-epoch (SE) images.

   → shape measurements on SE images; template image subtraction

2. **Relative Between-Band :** 100 mas

   A limit on the effects of differential chromatic refraction within each passband.

   → deblending between bands; aperture photometry colors

3. **Absolute:** 100 mas rms

   How well the DES astrometric system is tied to an external reference frame.

   → co-addition without degrading image quality

   → cross-ids with other catalogs

   → spectroscopic follow-up (particularly for SNe)

From the Scientific Requirements Document
(sciReq-9.86, 10 June 2010)

DARK ENERGY SURVEY

R-10 For each of the *grizY* bandpasses of the wide-area survey, the fluctuations in the spatially varying systematic component of the magnitude error in the final co-added catalog must be smaller than 2% rms over scales from 0.05 to 4 degrees.

Internal (Relative) Calibration

$m_i = -2.5\log(f_{i1}/f_{i2}) + C$

R-11 The color zeropoints between the survey fiducial bandpasses (*g-r, r-i, i-z*) must be known to 0.5% rms. The *z-Y* color zeropoint shall be known to 1% rms.

Absolute Color Calibration

$m_i - m_z = -2.5\log(f_i/f_z) + zp_{iz}$

R-12 The i-band magnitude zeropoint relative to BD+17, and therefore the AB system, must be known to 0.5% rms.

Absolute Flux Calibration

$m_i = -2.5\log(f_i) + zp_i$

R-13 The system response curves (CCD + filter + lenses + mirror + atmosphere at 1.2 airmasses) must be known with sufficient precision that the synthesized *grizY* magnitudes of any astronomical object with a calibrated spectrum agree with the measured magnitudes to within 2%. When averaged over 100 calibrating objects randomly distributed over the focal plane, the residuals in magnitudes due to uncertain system response curves should be < 0.5% rms.

System Response

G-4 A goal of the survey is to achieve **R-10** at the enhanced level of 1% for the final co-added catalog.

G-5 A goal of the survey is to achieve **R-10** over 160 degrees of Right Ascension and 30 degrees of Declination.

From the Scientific Requirements Document
(sciReq-9.86, 10 June 2010)

DARK ENERGY SURVEY

R-14 The absolute sky position of bright stars in both the individual images and the coadded image should be measured to an rms of ≤100 mas on all scales. Absolute positions will be reported in the J2000 system.

In order to reject cosmic rays and achieve efficient photometric calibration, the survey must average together (coadd) a number of images to reach the necessary depths for the dark energy science objectives. In order for this averaging process to not degrade the PSF for photometric purposes, the images of the objects must be aligned to better than a third of a pixel, 0.1", which is **R-14**'s requirement of 100 mas. Spectroscopic followup of the Supernova survey also requires positions accurate to 0.1". **R-14** is thus a global astrometry requirement to be verified using published astrometric catalogs.

R-15 The centroid of the images of the same star in adjacent passbands of the coadd should agree to within 100 mas, over the range of airmasses allowed by the survey.

The rationale for **R-15** is that relative astrometry of 100 mas is needed for deblending and that it also minimizes systematic errors in aperture photometry colors. The issue here

R-16 The rms of the centroids of each bright star in a set of all overlapping exposures that contain it should be no larger than 15 mas. The position measured in a coadd image must be mapped to the corresponding position in the overlapping input images with an accuracy of 15 mas or better. This requirement is for each bandpass individually.

Requirement **R-16** derives from the use of the co-add images to determine the centroids of stellar and galaxy intensity distributions, which are then used for shape measurements on single exposures. It is inherently a very local requirement. This Note that this is a requirement on systematic error and not on centroid accuracy. **R-16** is the astrometric requirement most relevant to the SN survey. This also an internal

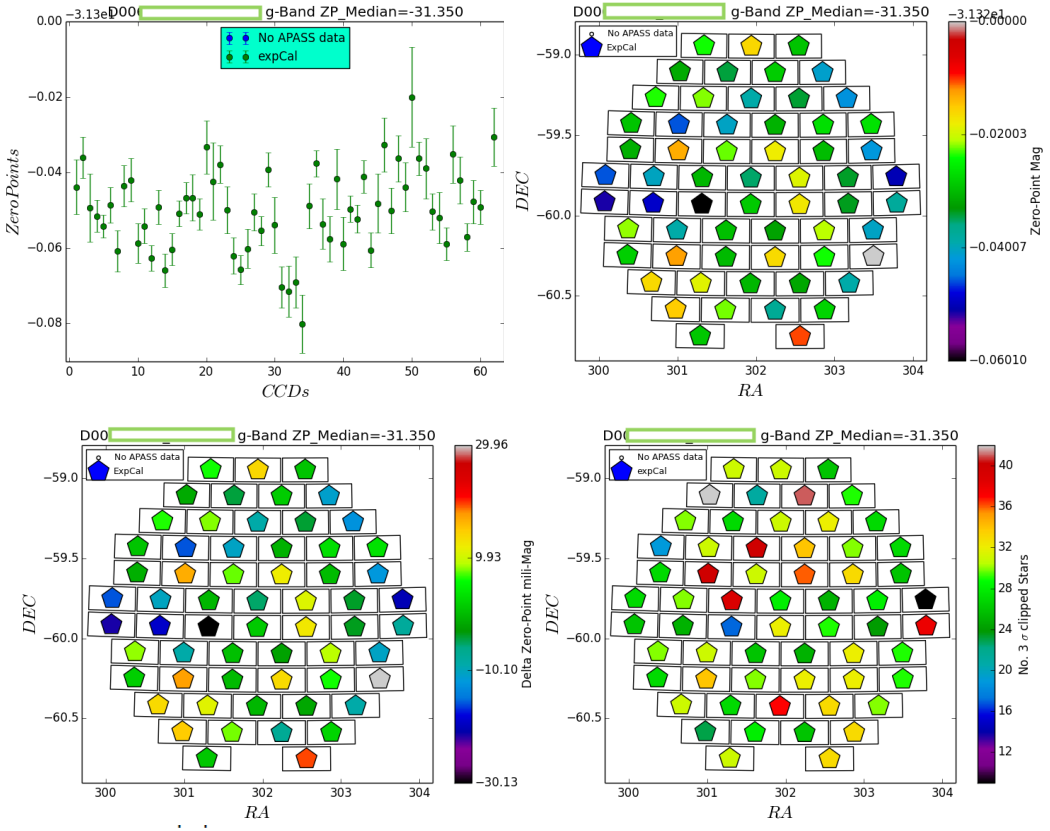
expCalib: On-the-fly nightly calibration and zeropoint estimation

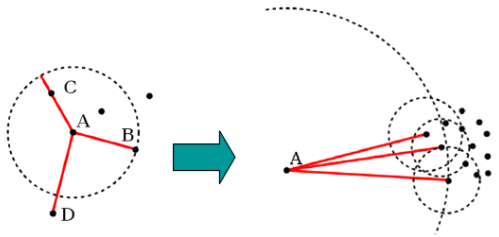
Sahar Allam (Fermilab)

DARK ENERGY SURVEY

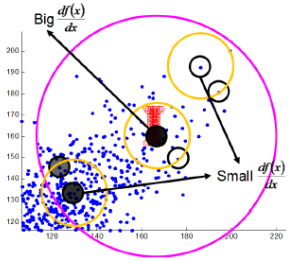
What is expCalib?

- Quick zero point estimate for single epoch exposures.
- Useful for on-the-fly calibration.
- Can easily identify ZP gradient over an exposure.
- Currently use APASS/2MASS transformed to DES {u,g,r,i,z,Y}
- ZP outlier rejection for each exposure via scikilearn Local Outlier Factor (LOF**)
- Estimated ZP for the following programs:- DES, DES-SNe, CalSpec, DECam Engineering, DES-GW, IceCube, BLISS, MagLiteS, BLINK, and others





Local-density in Multi-dimensional Feature Space



Comparing with Self or others: change of local-density

**http://www.dbs.ifi.lmu.de/Publikationen/Papers/LOF.pdf

DARK ENERGY
SURVEY

Y4A1_FINALCUT vs. APASS/2MASS

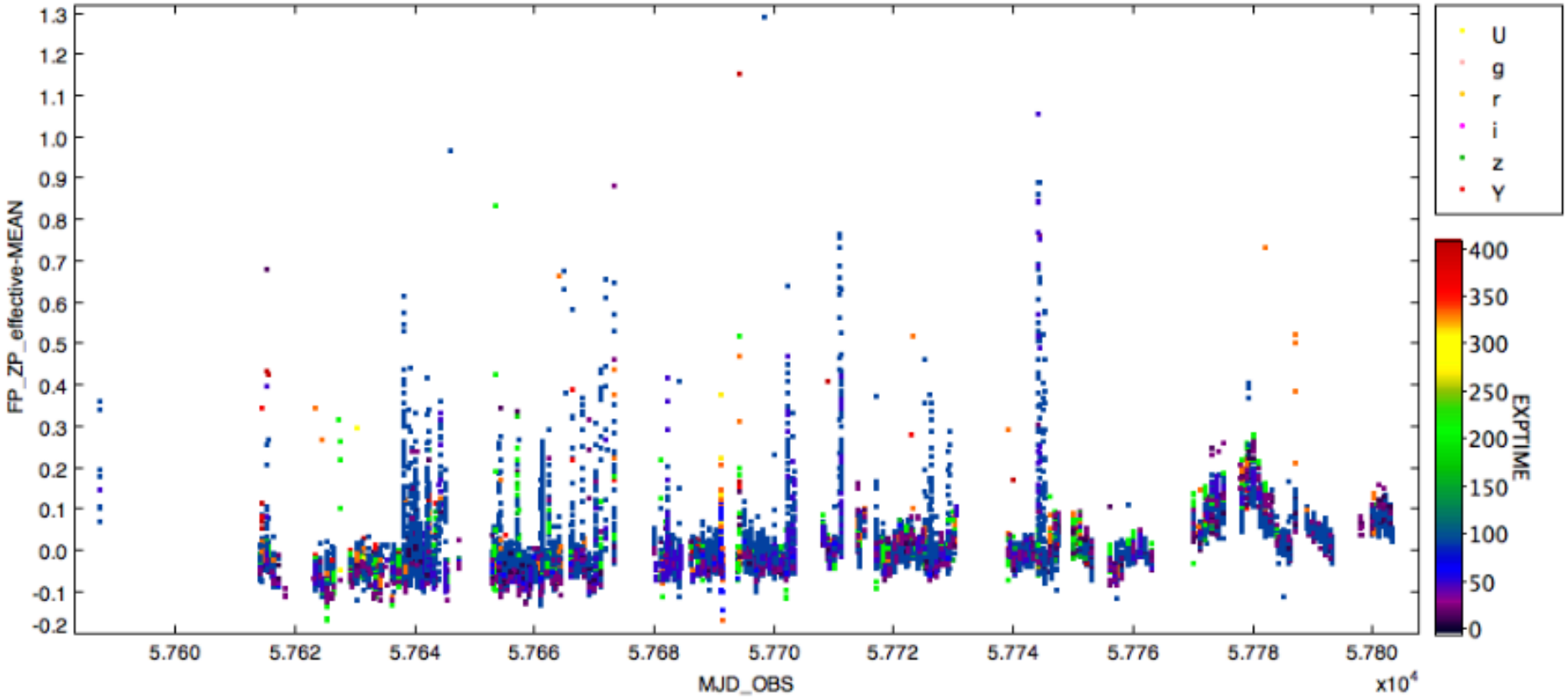
g	0.022	0.022	0.023
r	0.005	0.005	0.010
i	-0.001	-0.001	0.002
z	0.015	0.015	0.019
Y	0.053	0.053	0.054

47

expCalib

DARK ENERGY SURVEY

Y4N1 (Aug 2016-Feb 2017): Effective $ZP_{\_exp}$ vs. time

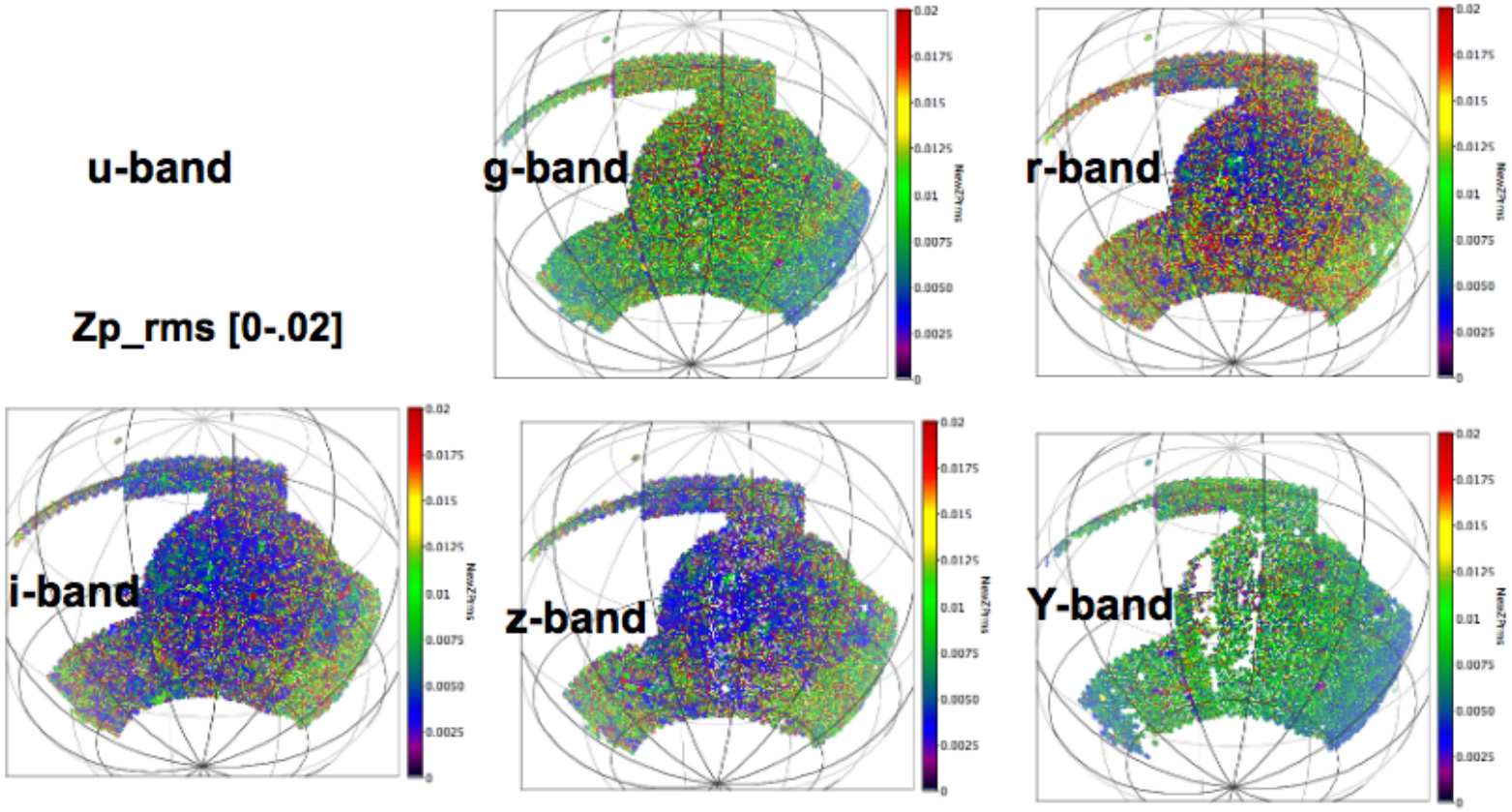


Credit: Sahar Allam

expCalib

DARK ENERGY SURVEY

Y4N1 (Aug 2016-Feb 2017):
internal error in CCD zeropoints using APASS/2MASS



Credit: Sahar Allam