DECaLS and DECaPS: DECam Surveys of the Northern Galactic Cap and Southern Galactic Plane

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LBL

DECam NFC 2018
June 27, 2018

The DESI Legacy Imaging Surveys

- Extragalactic sky with $\delta > -10^\circ$, 14,000 deg^2
- *grz* filters
- Three telescopes and instruments
  - Blanco 4m + DECam (*grz*, $\delta < 33^\circ$)
  - Bok 2.3m + 90Prime (*gr*, $\delta > 33^\circ$)
  - Mayall 4m + Mosaic3 (*z*, $\delta > 33^\circ$)
- WISE forced photometry
- 3 epochs per filter
- Coadded depths >24.0, 23.4, 22.5 mag *grz* for small galaxies

DESI Legacy Imaging Survey Objectives

- DESI targeting
- Gas in IGM
- Finding and characterizing galaxy clusters
- High redshift quasars
- Milky Way dwarfs & streams

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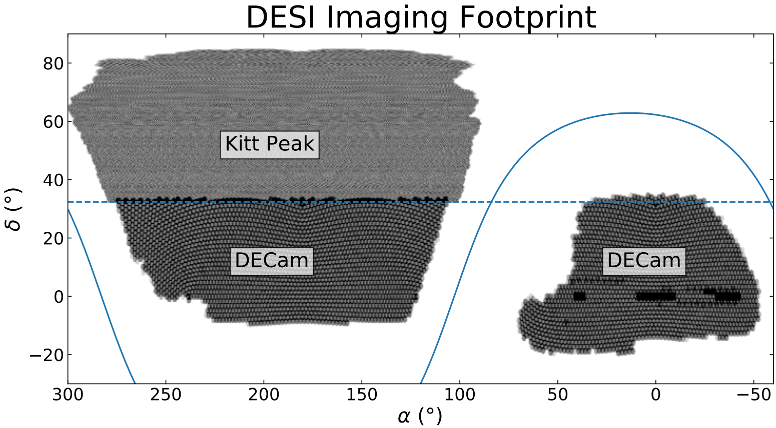
DESI Legacy Imaging Survey Coverage



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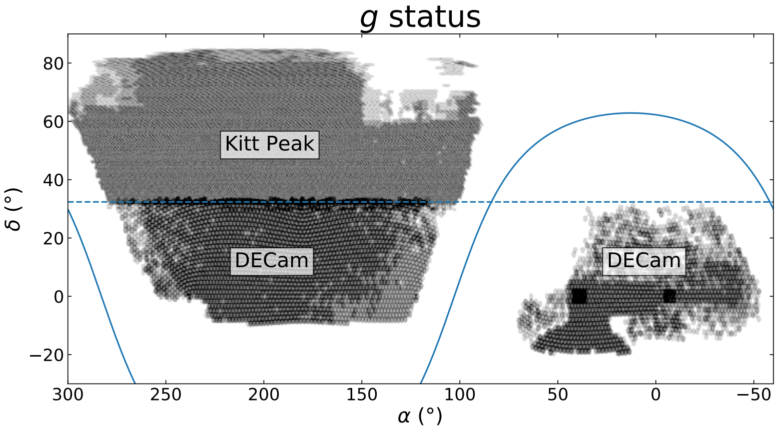

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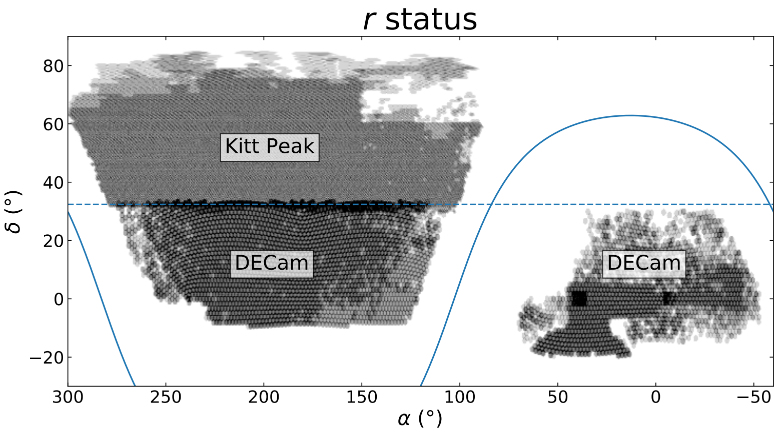

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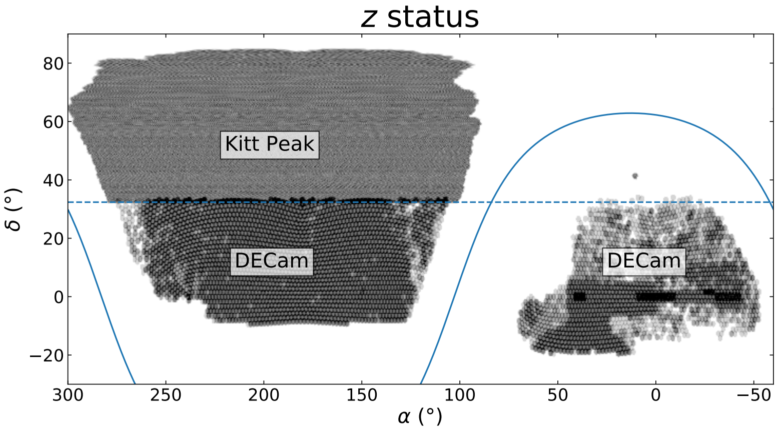
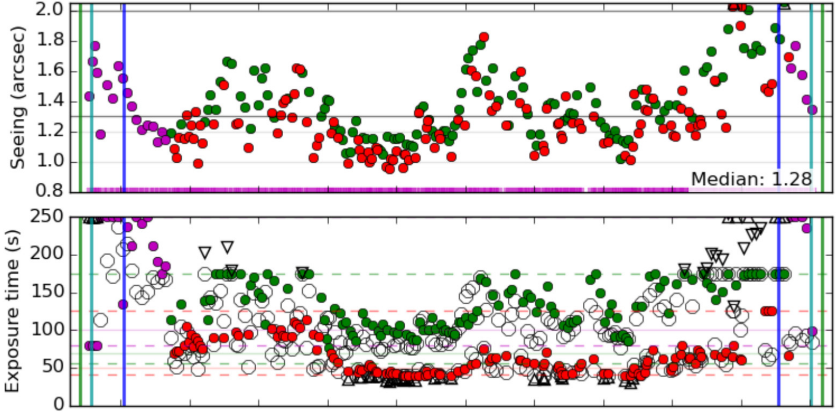


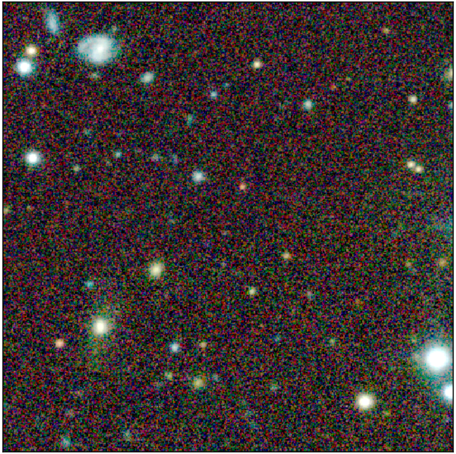
Dynamic Exposure Times

- Ideally want each exposure to robustly detect emission line galaxies of a particular mass and redshift
- Using past exposures, guess exposure time necessary to achieve this
- In DESI, plan is to do this in real time from guider PSF

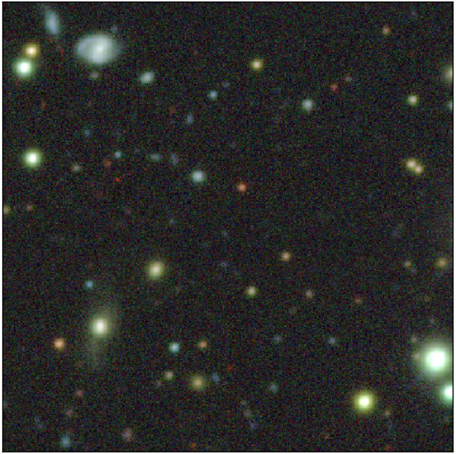


The Tractor

SDSS



DECam Coadd



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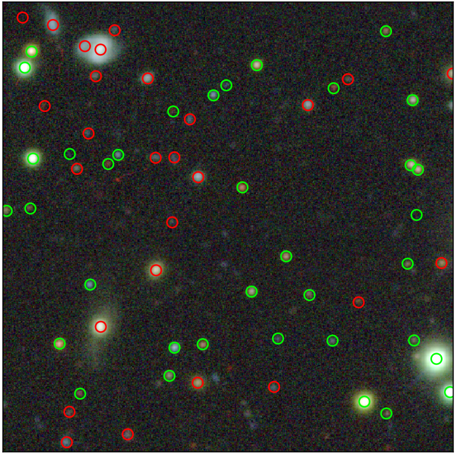
SDSS sources



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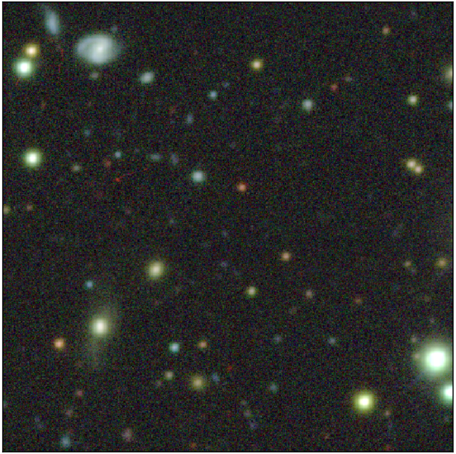

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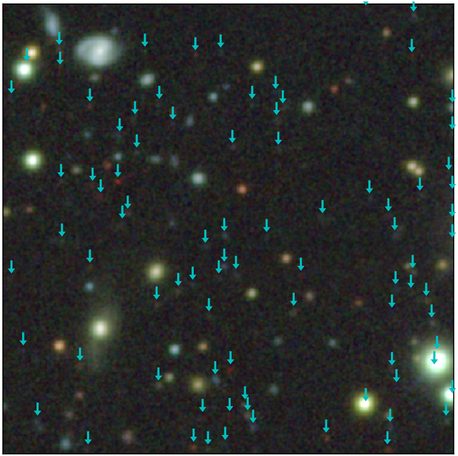
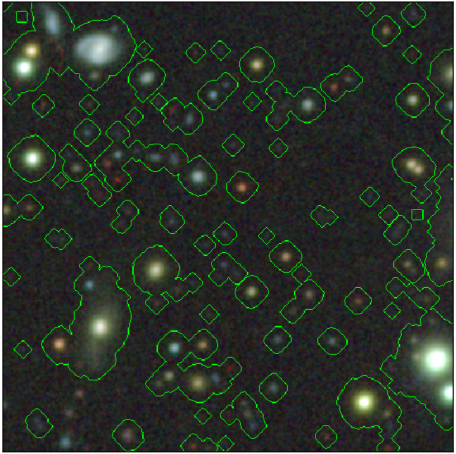
New sources



DECam Coadd

The Tractor

Blobs



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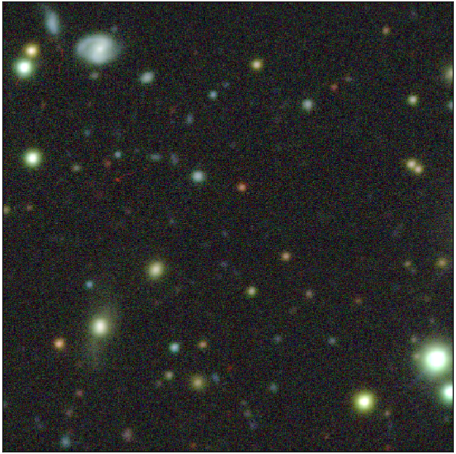

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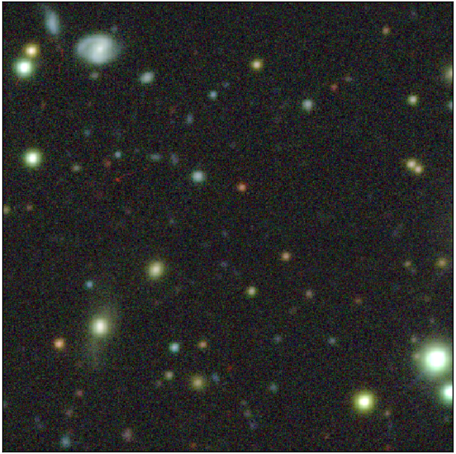
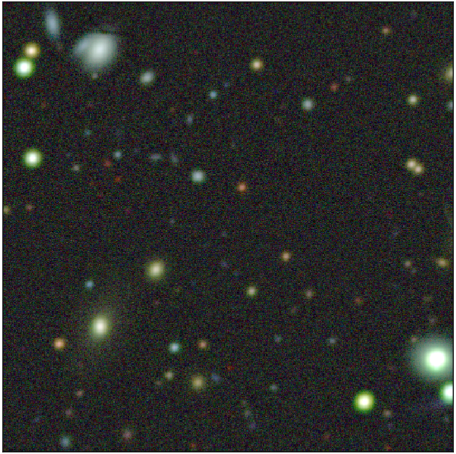


The Tractor

Model + Noise



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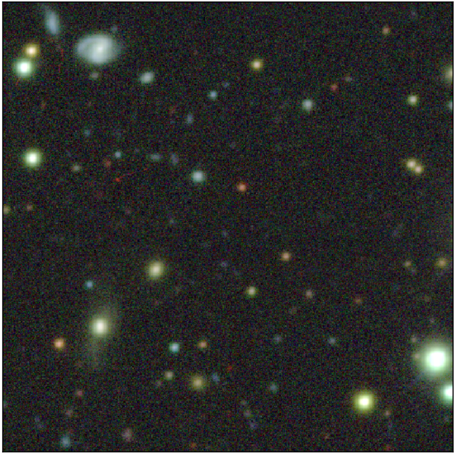

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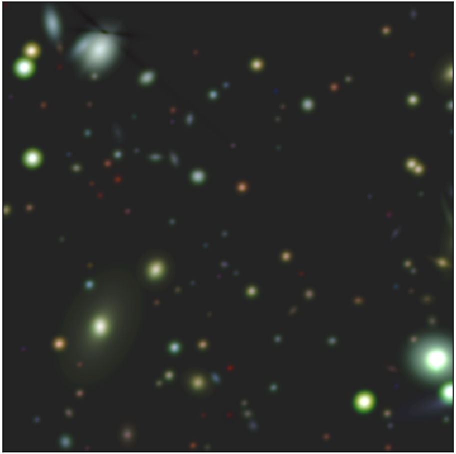
Model



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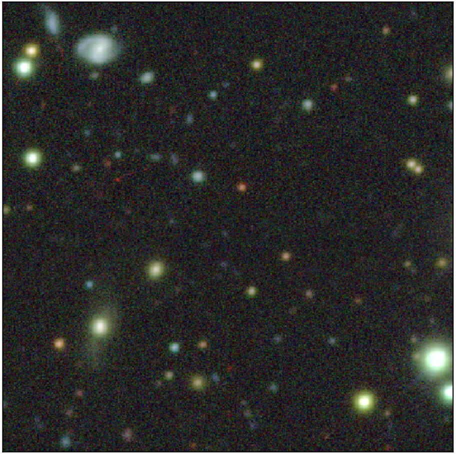

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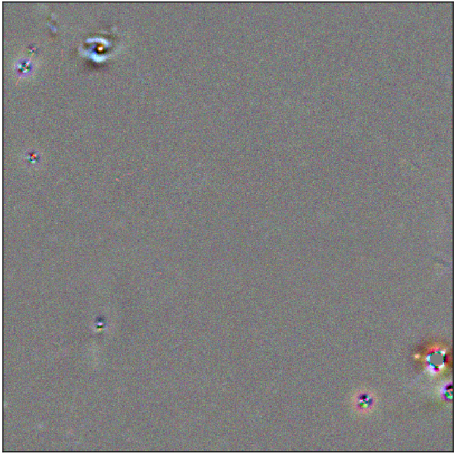
Residuals



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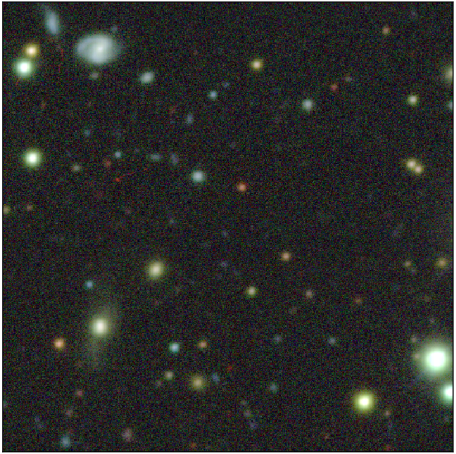

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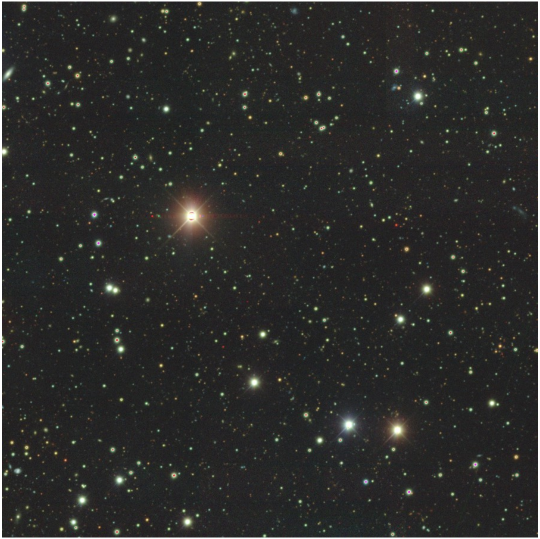

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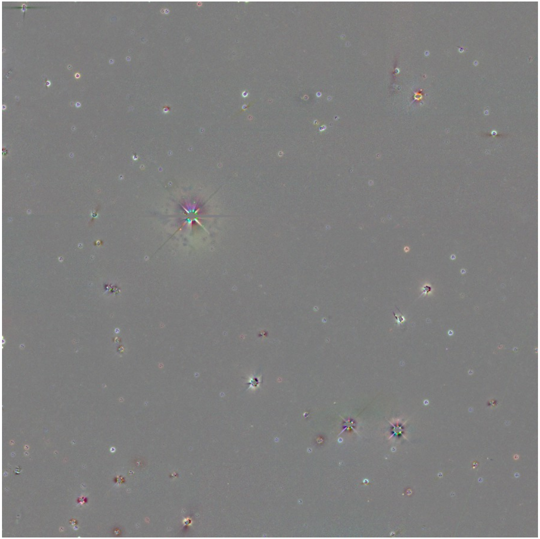
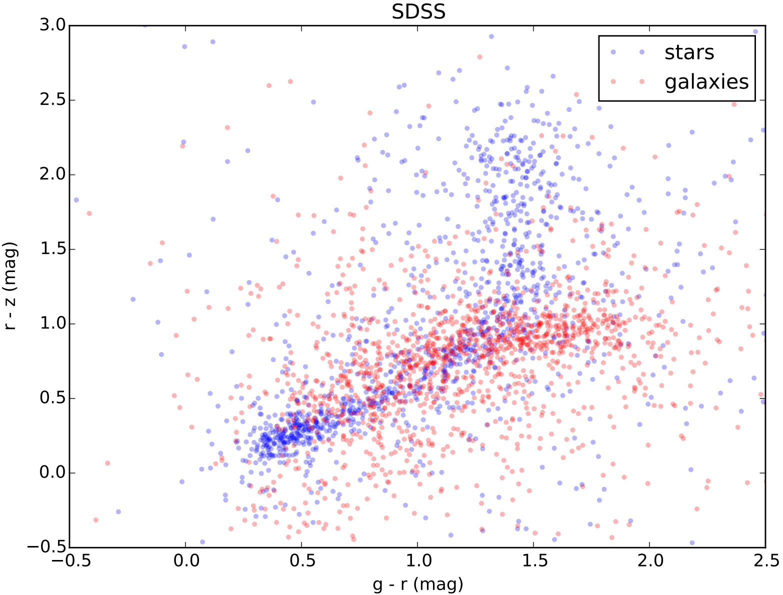


Catalog Comparison



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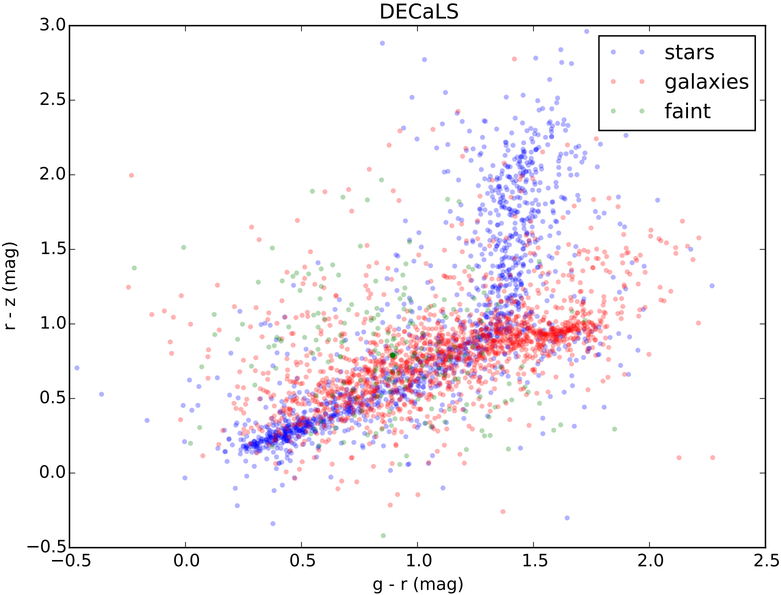
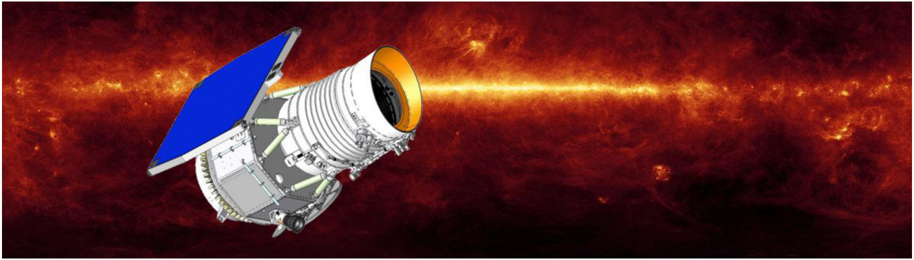
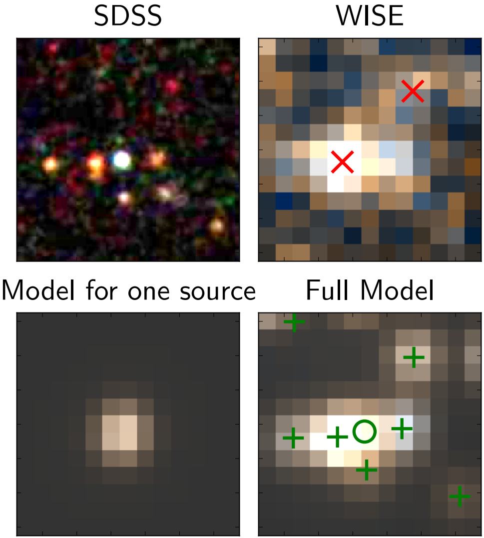


WISE Satellite

- Wide-field Infrared Survey Explorer
- Mid-infrared: W1 (3.4μ), W2 (4.6μ), W3 (12μ), W4 (22μ)
- Primary survey: 2010-2011; reactivated in 2014–present
- W1 & W2: $\sim$ 100 exposures of each part of the sky
- 6–7 arcsec FWHM



WISE photometry

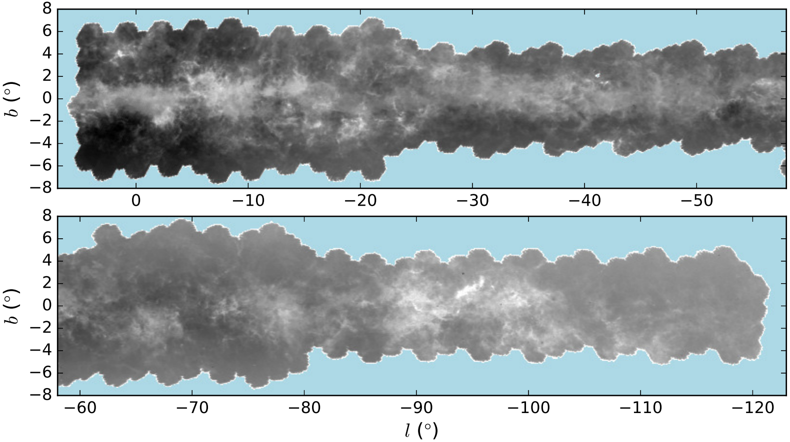


(Targeted in BOSS W3 ancillary; quasar at $z = 2.71$)

The DECam Plane Survey

- DECam survey of southern Galactic plane
- *grizY* filters
- $\delta < -30^\circ$, $|b| < 4^\circ$ ($5^\circ > l > -120^\circ$)
- roughly main-sequence turn-off at 8.5 kpc through $E(B-V) = 1.5$
- 23.7, 22.8, 22.3, 21.9, 21.0 mag in *grizY* in single exposures
- 3 epochs per filter, observed on adjacent nights
- 3D structure of the Milky Way's stars, gas, and dust

Source Density



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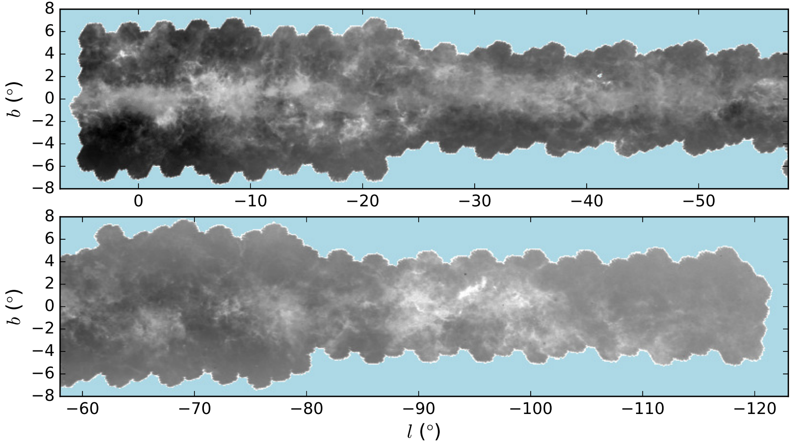
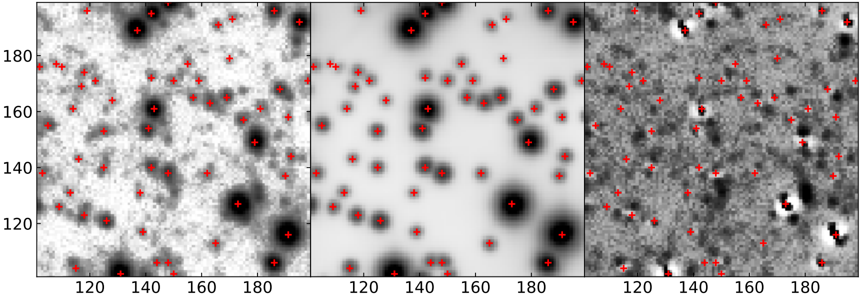


- 20 billion detections of 2 billion objects
- Extending to $|b| < 10^\circ$ now!

Pipeline

- Concept: find and fit sources to steadily improve model of image
  - repeat source finding on residual images to find fainter, blended sources
  - Same idea as DAOPHOT, DOPHOT, DOLPHOT.
- Steps:
  1. Sky subtraction
  2. Source detection
  3. Position, flux, and sky determination
  4. PSF determination
  5. Repeat



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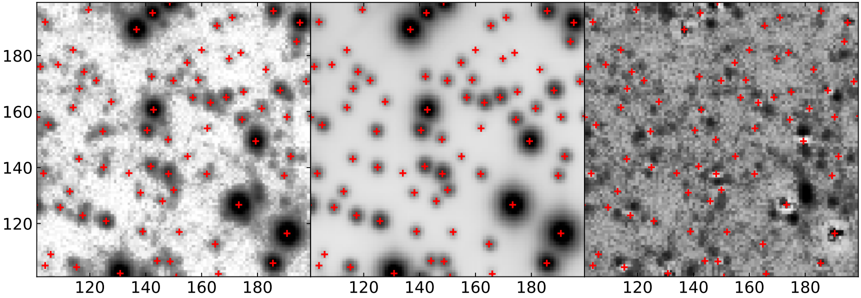

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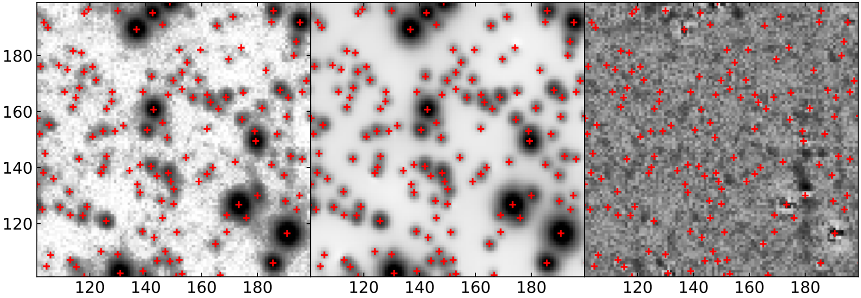

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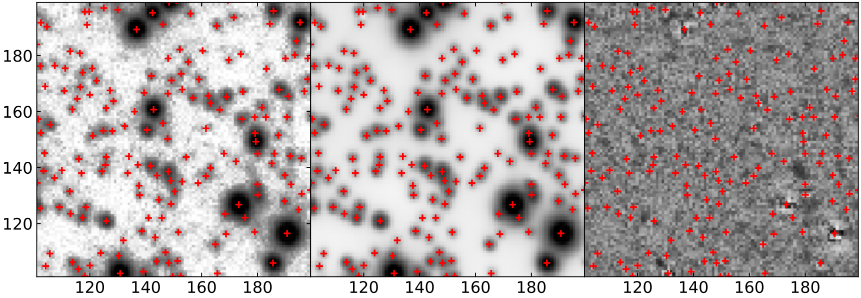

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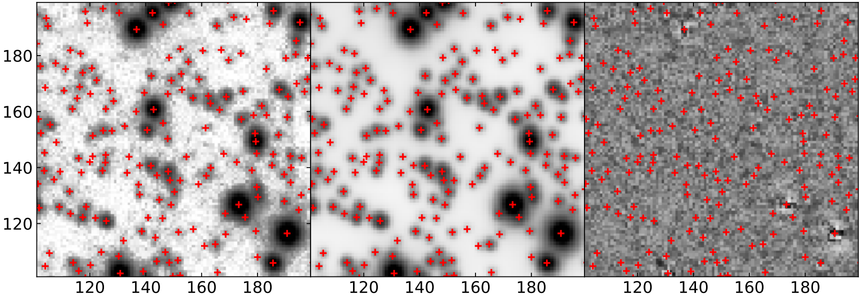

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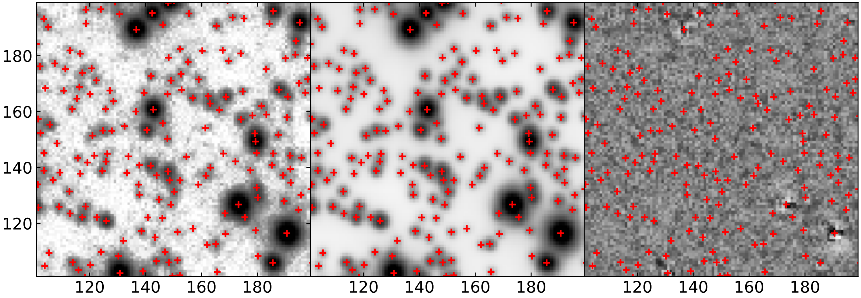
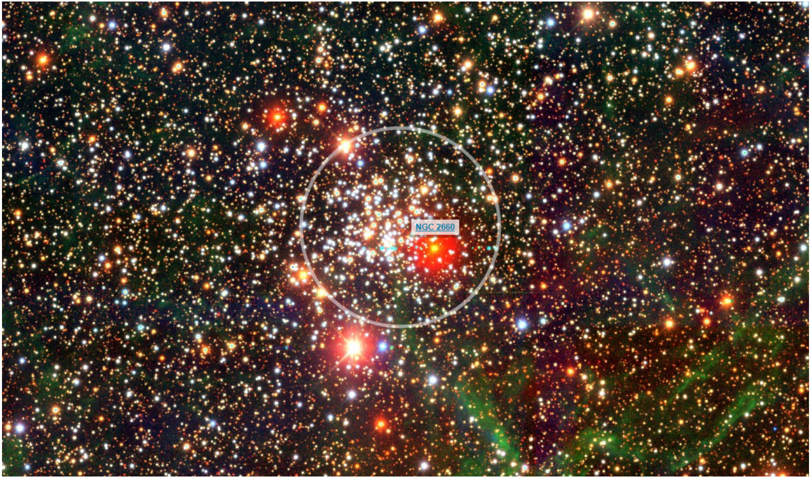


Open Cluster NGC 2660



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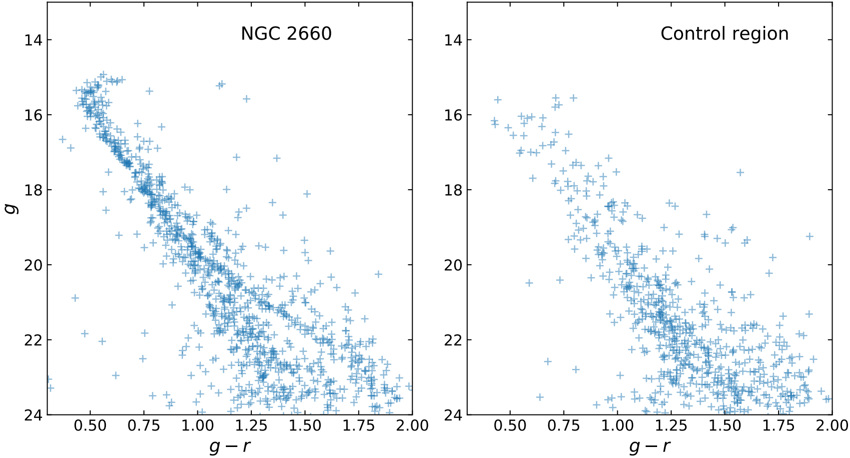
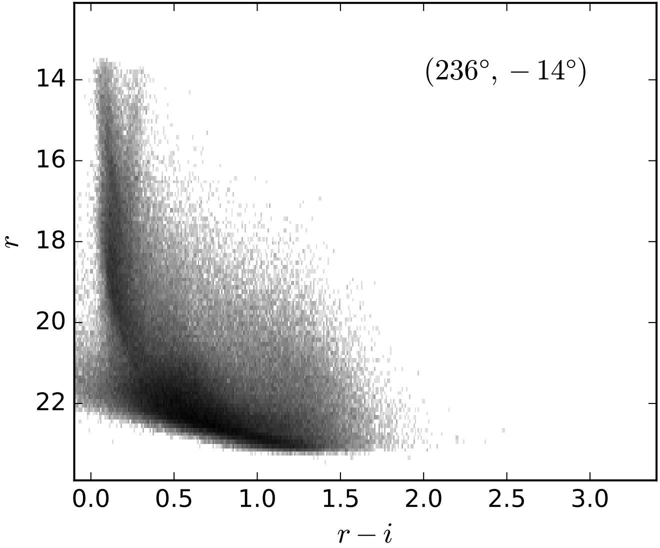


Very narrow sequence! Secondary binary sequence visible?

CMDs



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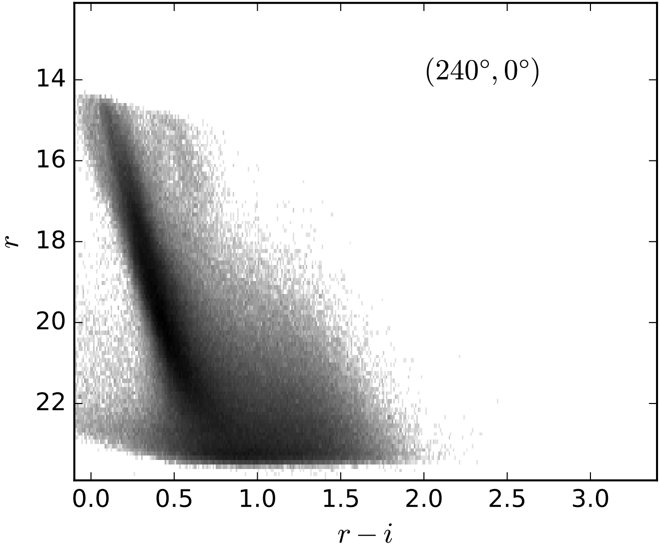

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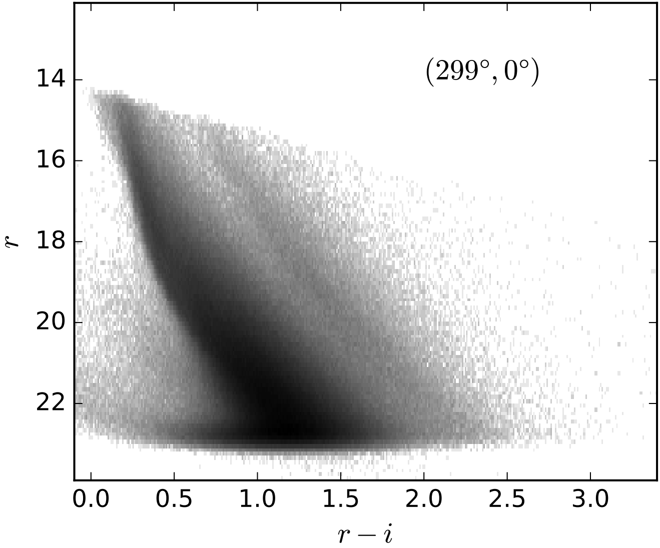

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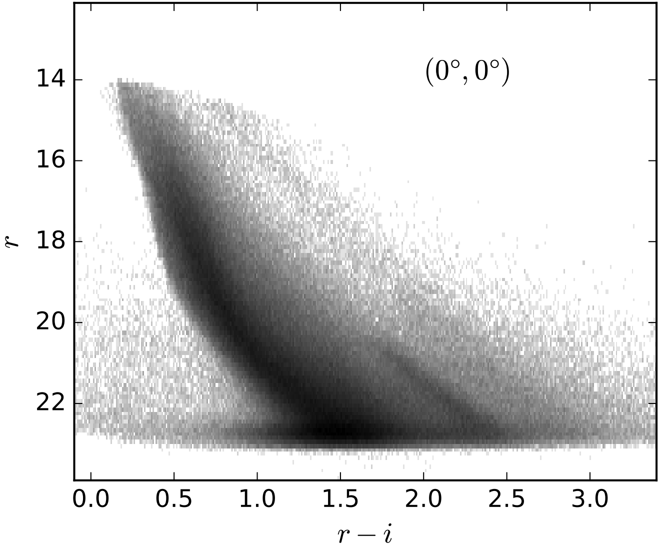
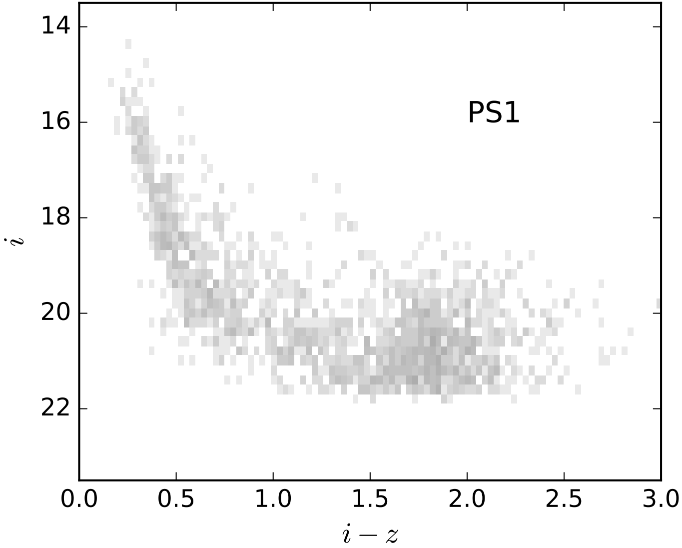


PS1 Comparison



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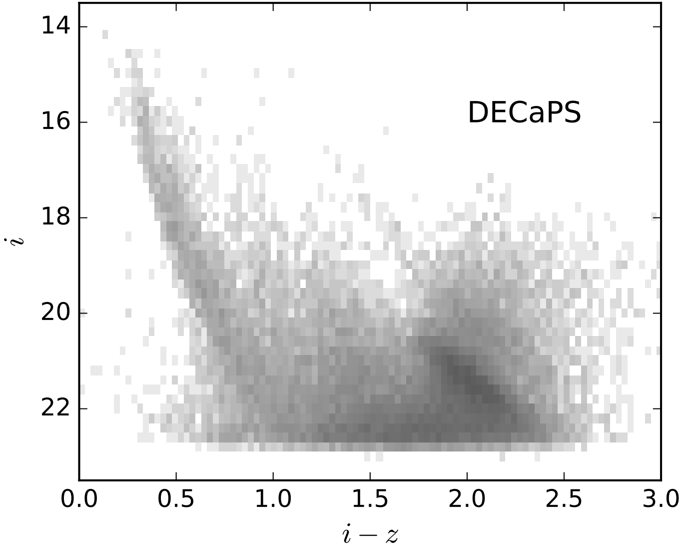

The Legacy Survey Viewer

Browse the sky plane in Dustin Lang's viewer

Things to do:

- Kitt Peak DESI footprint
- DECam DESI Footprint
- WISE
- Dust and protostars
- White dwarfs
- Clusters
- Nebulosity
- Crowding

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http://legacysurvey.org/viewer

Conclusions

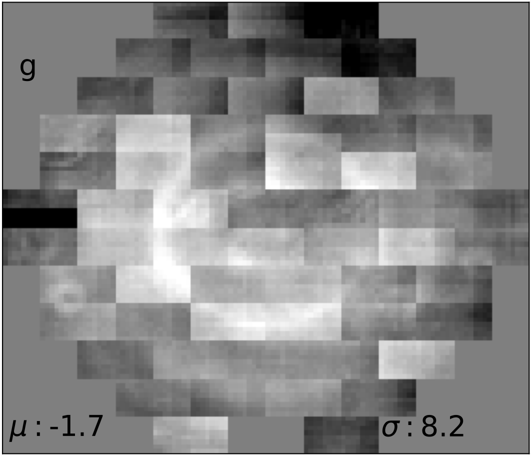
- DESI Imaging Surveys wrapping this year and early next year
- DECam Plane Survey complete in $|b| < 4^\circ$, ongoing extension to $|b| < 10^\circ$
- Large surveys largely untapped for near-field cosmology work
- Data publicly available at:
  `http://legacysurvey.org`
  `http://decaps.skymaps.info`
  - images
  - catalogs
  - viewer
  - SQL database via the NOAO Data Lab

Photometric Calibration

- We wish to place all of the DECam observations onto a common magnitude scale, removing the effect of sensitivity variations between
  - the system throughput from night to night
  - the opacity of the atmosphere (from night to night)
  - different regions of the DECam focal plane
- We achieve this by adopting a simple model for the system throughput over the course of the survey
- We constrain the model using repeat observations of the same stars

Photometric Calibration Flat Field

- Flat fields show ~ 5 mmag corrections
- True effect is presumably largely chromatic
- Pupil ghost
- Tree rings
- PSF-fitting-related artifacts
- Unstable S7 amplifier
- mounting board in Y



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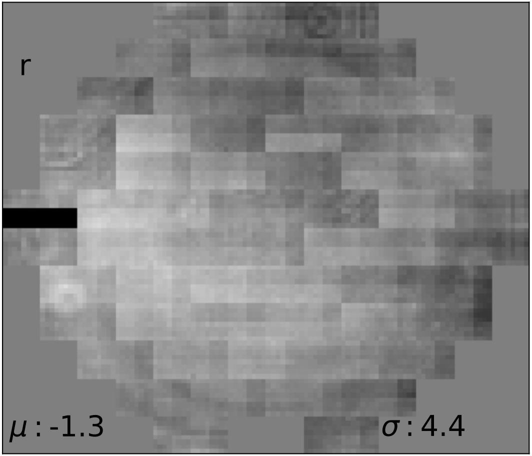

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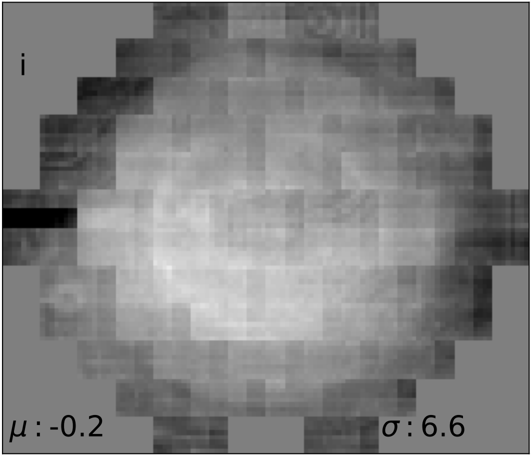

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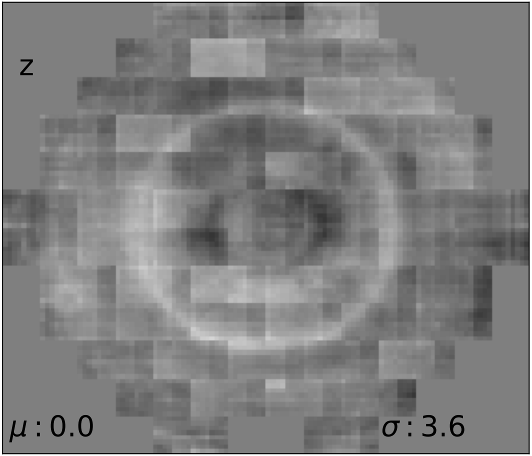

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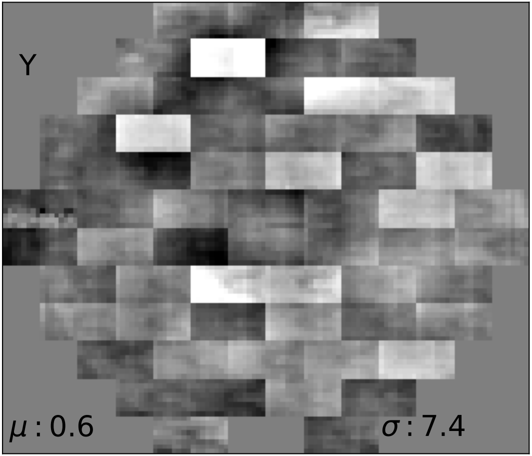
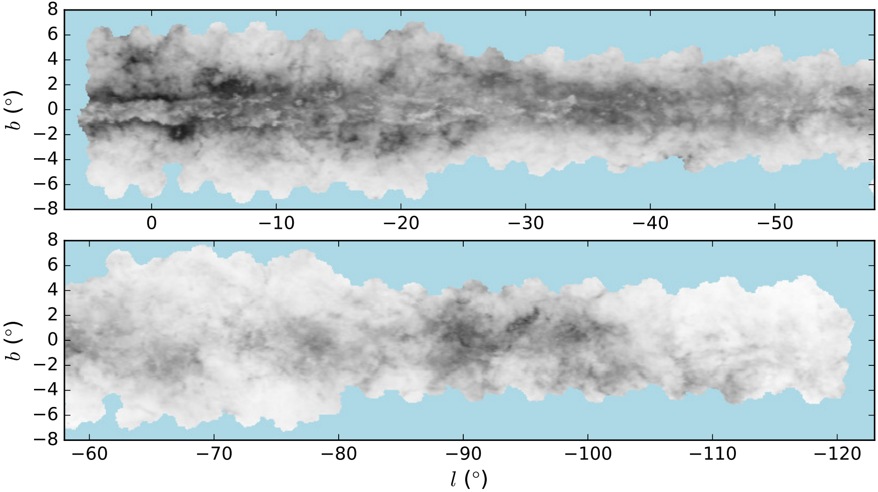


Median colors of stars



Sky Subtraction

- Improve sky relative to best model so far
- Sky determination should give zero if the model is perfect
- Needs to be fast
- We just take the median in 20×20 pixel regions
- This should change depending on seeing!

Source Detection

- Convolve image with PSF
- $> 5\sigma$ peaks are candidate sources
- Candidate sources passing blending criteria added to source list

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- Candidate sources passing blending criteria added to source list
- $S_I/S_M > 2B$ or $(S_I/S_M > B)\,\&\,(I/M > B)$

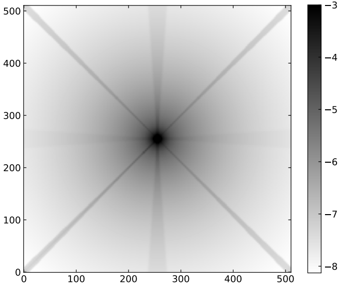
I	residual image
M	model image
S_I	signal-to-noise of residual image
S_M	signal-to-noise of model
B	blending threshhold

Position, flux, and sky determination

- Everything is a point source—life is easy!
- Sky and fluxes are completely linear
- Positions can be linearized via first derivative
- Plug into large sparse linear algebra code
- `LSQR`, conjugate-gradient type solver, Stanford Systems Optimization Laboratory
- We fit up to 30k stars per 1024×1024 pixel region, for ~ 100k simultaneous parameters

PSF determination

- Start with best model so far
- Get model for image from linear least squares fit
- Subtract neighbors around each star from model
- Use newly isolated stars to model PSF
- (though we probably should be thinking about an EM solution...)

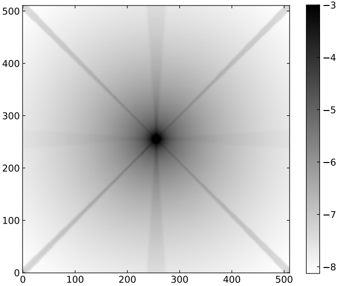


DECaPS PSF model

- start with “ideal-seeing” PSF models
- find parameters of spatially-varying Moffat that convolve with ideal-seeing PSF to match neighbor-subtracted PSFs
- pixel-by-pixel spatially varying model of PSF core (9×9 pixel)
- Need to do better!
  - “analytic” model tends to be dominated by core and fail in the wings ($\sim 2''$ from center)
  - “aperture correction” is the dominant source of photometric calibration error
  - diffraction spikes don’t quite match
  - lots of structure in PSF wings!
  - variations in PSF with color and brightness

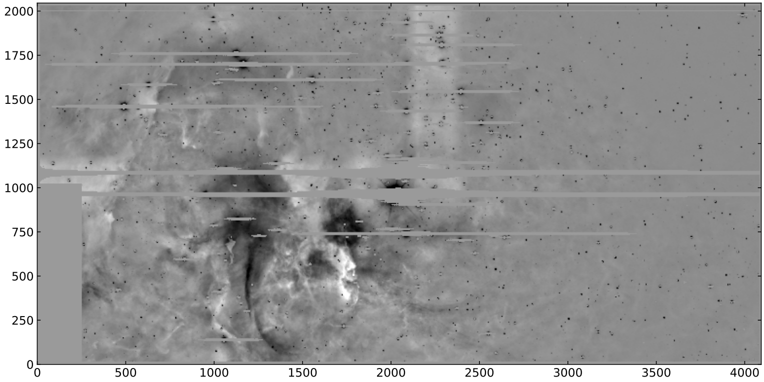
Ideal-seeing PSFs

- average PSFs over large numbers of bright stars on very good seeing nights
- Extend 255 pixels from PSF center
- Deconvolved with good-seeing Moffat
- Modeled as sum of Moffats and diffraction spikes
- $\rightarrow$ noise-free, ideal-seeing PSF
- needs improvement? ideal-seeing PSFs often dominate in the wings



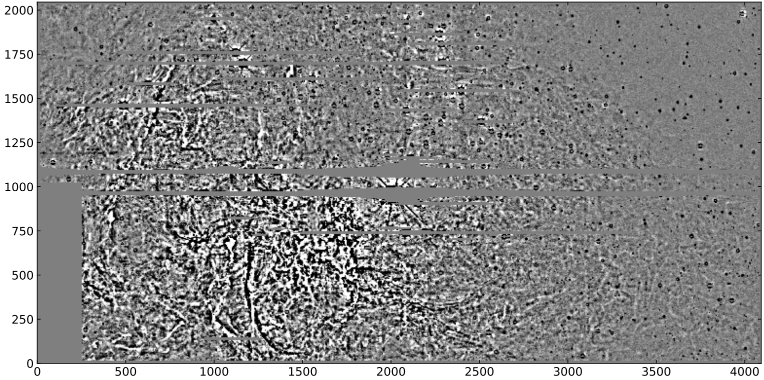
Nebulosity

- How should one deal with . . .



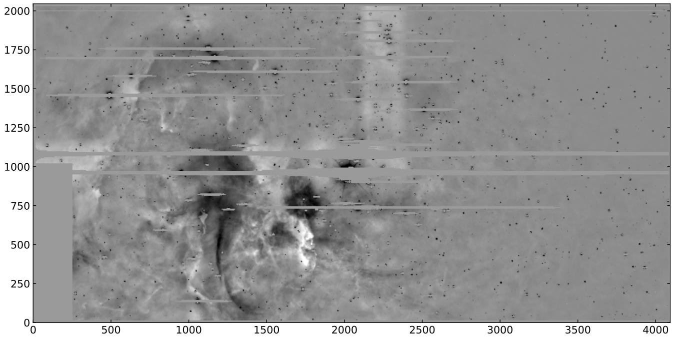
Nebulosity

- How should one deal with . . .



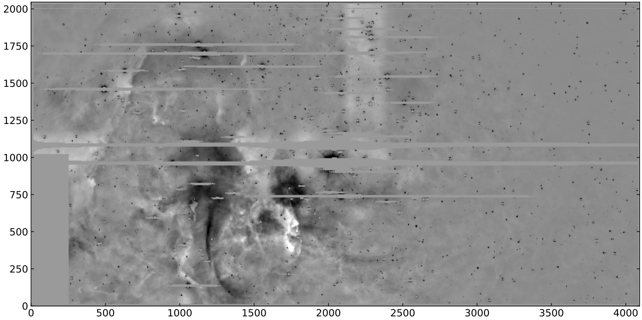
Nebulosity

- How should one deal with nebulosity?
- No good techniques I know of!
- Only 0.1% of footprint affected
- mask and apply stronger blending & sharpness cuts in these regions



Nebulosity

- How should one mask nebulosity?
- Simple approaches (variance in sky estimates on different scales) break down around bright stars and in crowded regions
- Neural network trained on $\sim$5,000 hand-classified 512×512 pixel images
- Ultimately did an excellent job flagging nebulous regions
- This image: 100% nebulous ✓



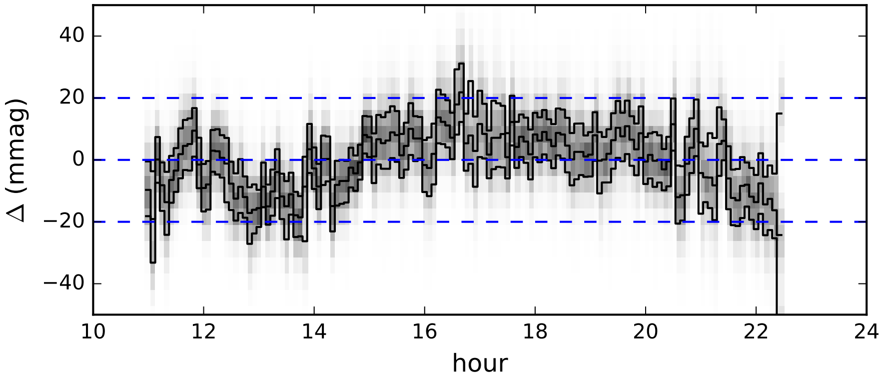
Photometric Calibration

- We calibrate each detection with a zero point Z so that $m = m_{\mathrm{inst}} + Z$
- We take $Z = a - kx + f$, with
  - a: system zeropoint (one parameter per night)
  - k: atmospheric opacity (one parameter [whole survey!])
  - x: airmass of observation
  - f: flat field (10,000 parameters)
- We then solve for the parameters of this model for Z, to minimize

$$\chi^2 = \sum_o \sum_i \frac{(m_{o,i} - \overline{m_o})^2}{\sigma_{o,i}^2}$$

- Note: 10,000 parameters, constrained using hundreds of millions of observations
- Same technique as Padmanabhan et al. (2008) for the SDSS

Photometric Calibration Nightly QA



- 5 mmag precision in any given exposure
- 1% rms residuals, correlated with wings of PSF
- poor "aperture correction"; c.f. ~ 3 mmag in PS1
- we should have enough information to get this right!

Mosaicing scheme

- Don't want to fit 4096×2048 pixel images simultaneously
- Cut into 1024×1024 pixel blocks (primary plus 50 pix overlap)
- Add stars from primary regions of other blocks to model for this block, fixing their fluxes.
- Really should have done sky subtraction, source detection, and PSF fitting steps on full image, and just introduced a mosaicing scheme for the least-squares fit.