

# DECaLS DR10: Updating the Dark Energy Camera Legacy Survey

Aaron Meisner (NSF's NOIRLab) on behalf of the DECaLS team

2022 September 13

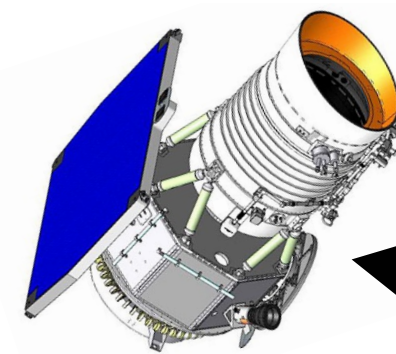
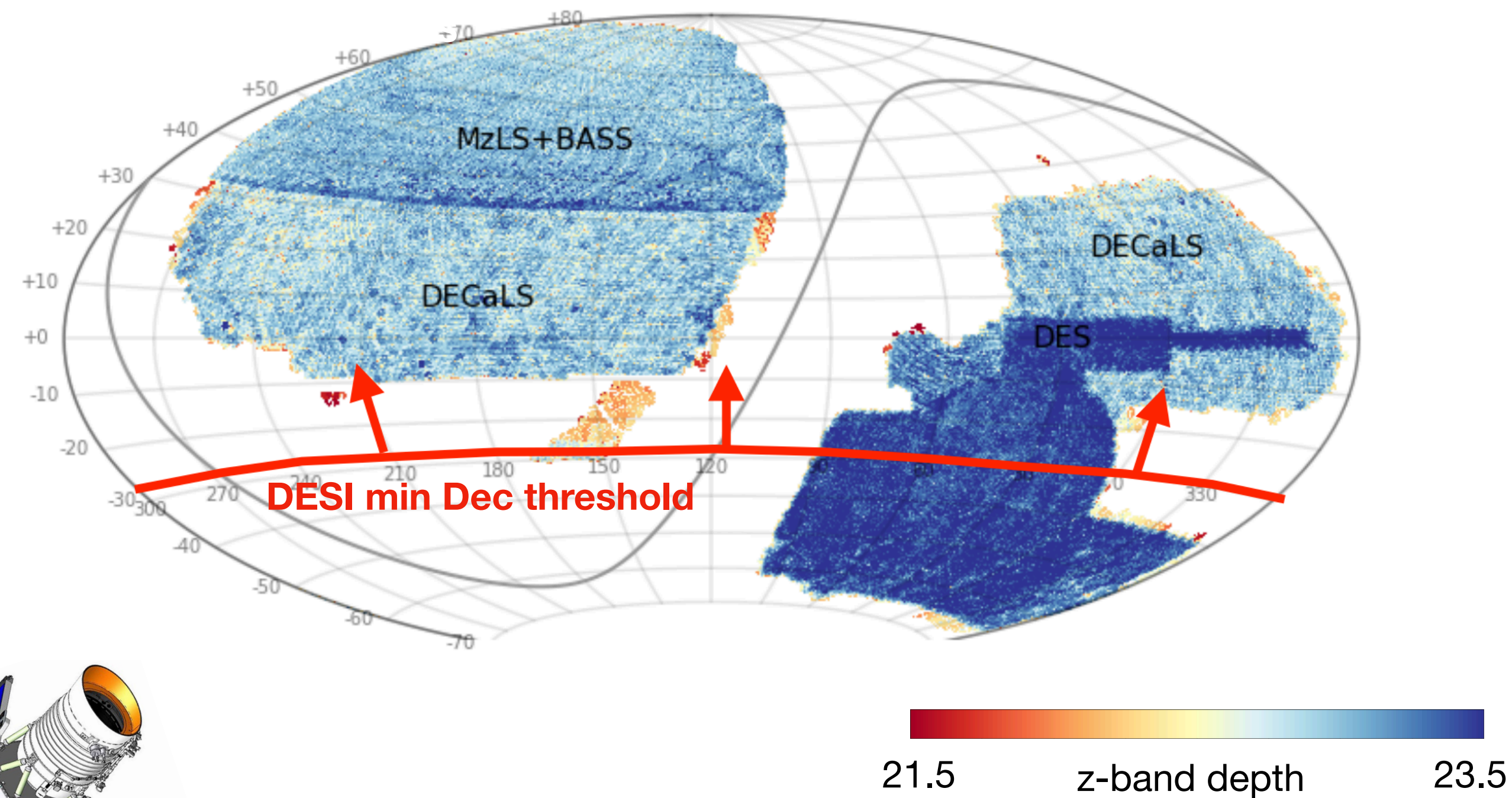
DECam grz

WISE 3-5  $\mu\text{m}$



# original DECaLS motivation — DESI targeting

DESI requires ~14,000 sq. deg. of optical imaging deeper than SDSS, PS1



WISE (entire sky)

**DECaLS** = **D**ark **E**nergy **C**amera **L**egacy **S**urvey

**DESI** = **D**ark **E**nergy **S**pectroscopic **I**nstrument



# DECam: centerpiece of DESI's pre-imaging multi-telescope, multi-year observing campaign

|                                                                                                                    |                                                                                                                      |                                                                                                                     |
|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|
|  <p>Bok 2.3m, 90prime (g+r)</p> |  <p>Blanco 4m, DECam (g+r+z)</p> |  <p>Mayall 4m, Mosaic-3 (z)</p> |
| <p><b>BASS</b></p> <p><b>B</b>eijing-<b>A</b>rizona<br/><b>S</b>ky <b>S</b>urvey</p>                               | <p><b>DECaLS</b></p> <p><b>D</b>ark <b>E</b>nergy <b>C</b>amera<br/><b>L</b>egacy <b>S</b>urvey</p>                  | <p><b>MzLS</b></p> <p><b>M</b>ayall <b>z</b>-band<br/><b>L</b>egacy <b>S</b>urvey</p>                               |

“DESI Legacy Imaging Surveys”



# what is DECaLS?

## DECaLS is a public survey...

- No proprietary period, anyone can join
- Folds in all (public) archival DECam imaging (e.g., DES, DeROSITAS, ...)
- Inference-based model of the sky (“The Tractor”, Dustin Lang)
  - Inherently multi-instrument/multi-wavelength (includes WISE, Gaia)
- Frequent world public data releases
  - 10 data releases in ~8 years since first DECaLS observations
- <https://www.legacysurvey.org/>, <https://www.legacysurvey.org/viewer>

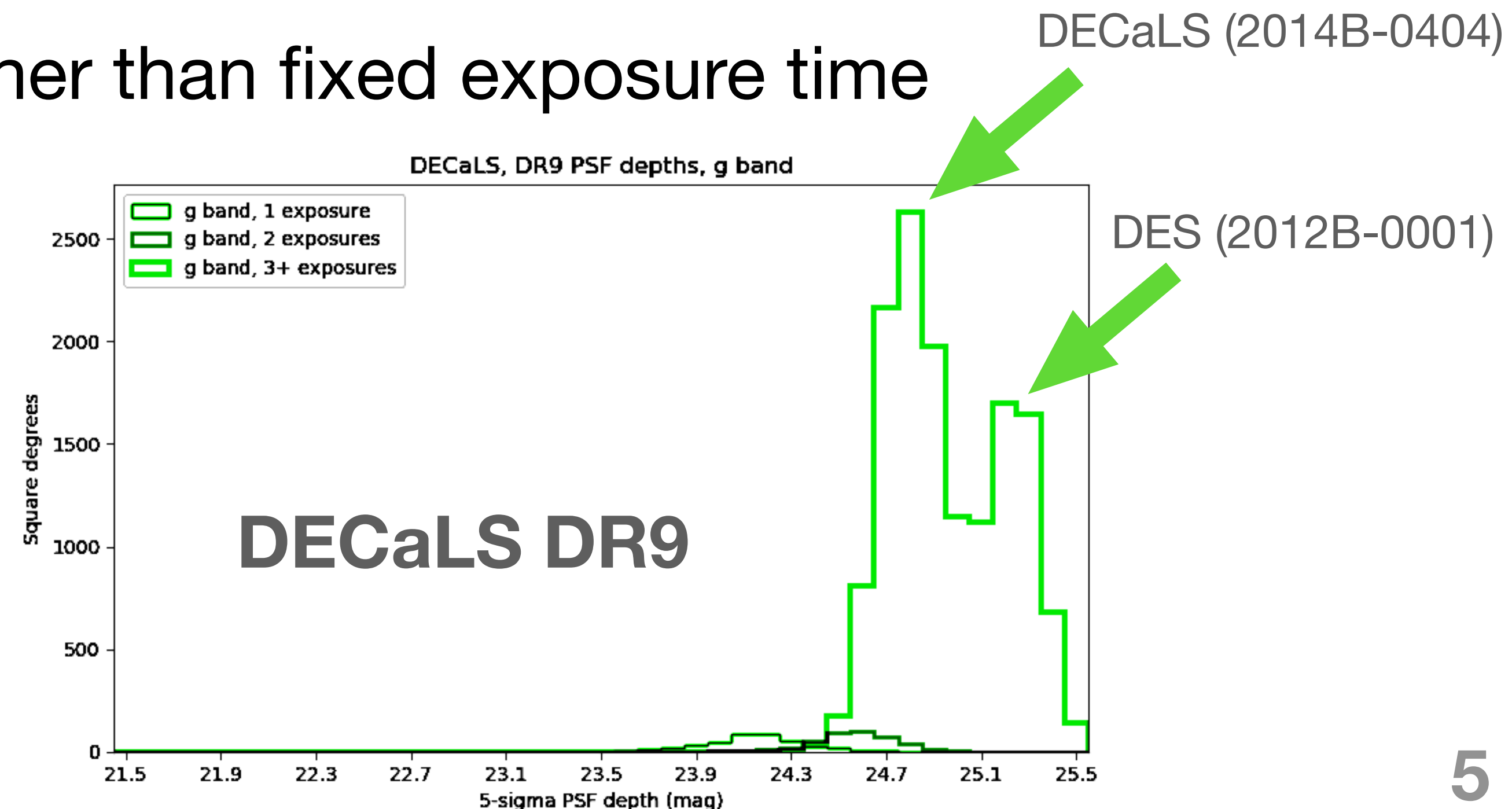
| Band/Number of Passes | ≥ 1                     | ≥ 2                     | ≥ 3                     |
|-----------------------|-------------------------|-------------------------|-------------------------|
| <i>g</i> -band        | 19,919 deg <sup>2</sup> | 19,256 deg <sup>2</sup> | 16,606 deg <sup>2</sup> |
| <i>r</i> -band        | 19,915 deg <sup>2</sup> | 19,177 deg <sup>2</sup> | 16,333 deg <sup>2</sup> |
| <i>z</i> -band        | 20,242 deg <sup>2</sup> | 19,420 deg <sup>2</sup> | 16,972 deg <sup>2</sup> |
| All bands jointly     | 19,721 deg <sup>2</sup> | 18,813 deg <sup>2</sup> | 14,756 deg <sup>2</sup> |

**DR9; including DECaLS,  
MzLS & BASS**



# six-year DECaLS observing campaign

- 203 scheduled nights between 2014 August and 2019 March
  - DECaLS observations (2014B-0404) are only in grz
  - 3 “passes” (exposures) per band per sky location
- 128 unique observers drawn from 43 institutions (DECaLS+MzLS)
- Uniform depth for each exposure rather than fixed exposure time

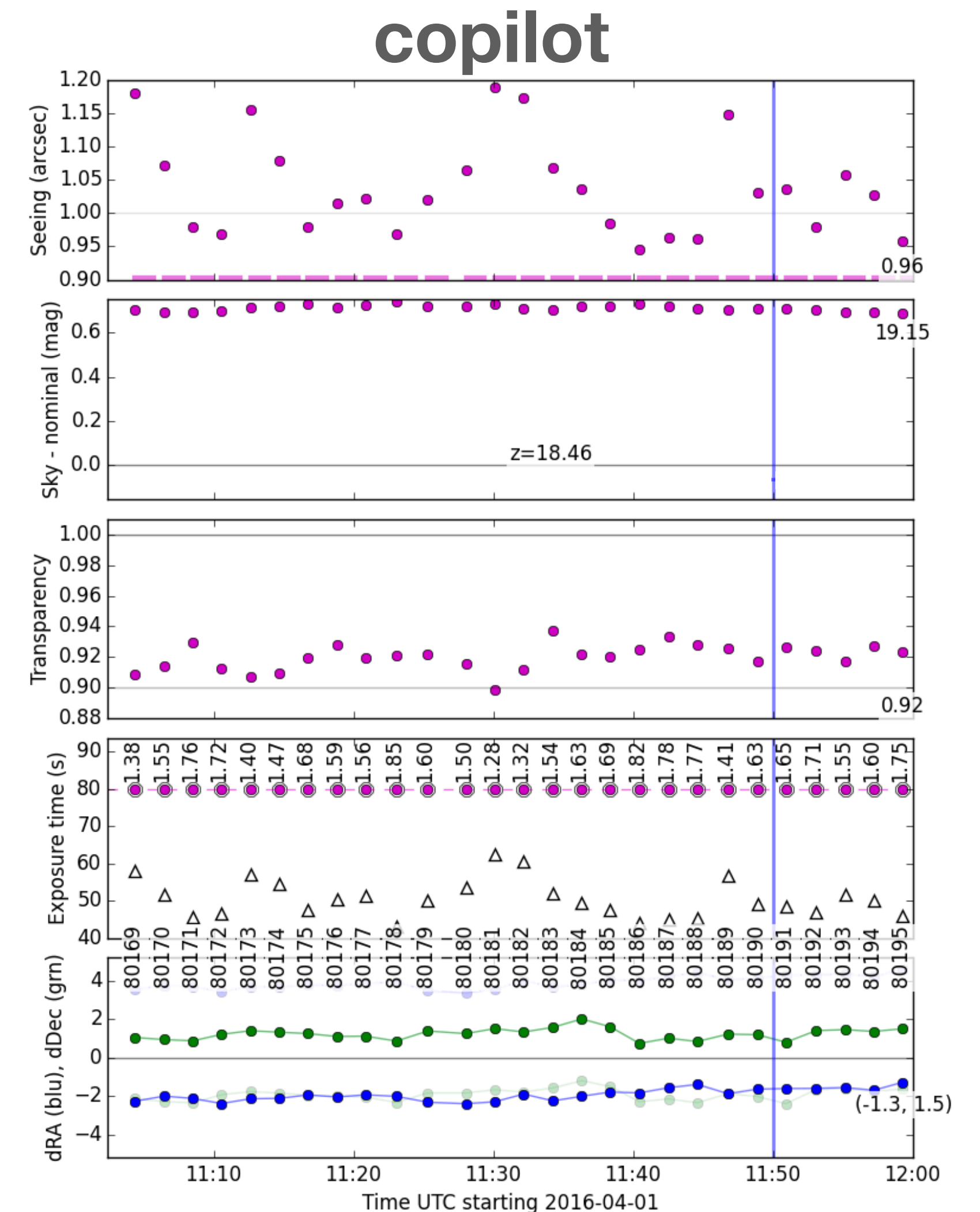




# DECaLS dynamic observing strategy

## observing on autopilot...

- “copilot” software (Dustin Lang) measures seeing, transparency, sky brightness, pointing offsets in as soon as raw DECam data read out
- Each exposure’s requested integration time is dynamically adjusted based on prior two samples
- DECam ICS API access thanks to Klaus Honscheid
- See David Schlegel’s talk later today for more details!

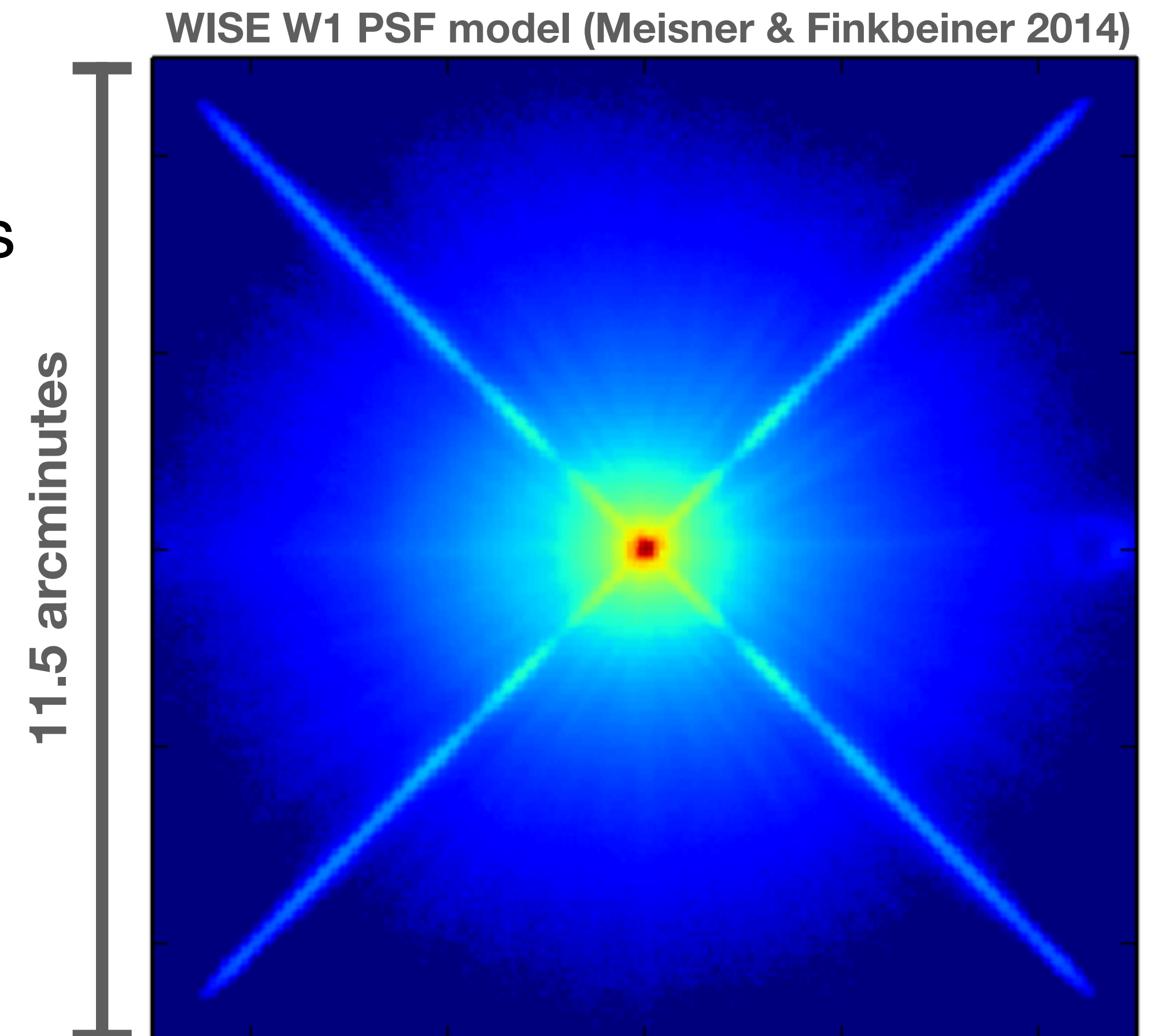


DECam copilot example screenshot (Dustin Lang)



# Tractor processing inputs

- NOIRLab Community Pipeline DECam reductions (Frank Valdes)
- WISE/unWISE — custom all-sky coadds (Aaron Meisner, Dustin Lang, Eddie Schlafly)
- Gaia — astrometry
- PS1 — where available, for photometric zeropoints
- PSF models — optical & infrared
- Custom calibration products —
  - ubercal: Eddie Schlafly
  - fringes: Rongpu Zhou





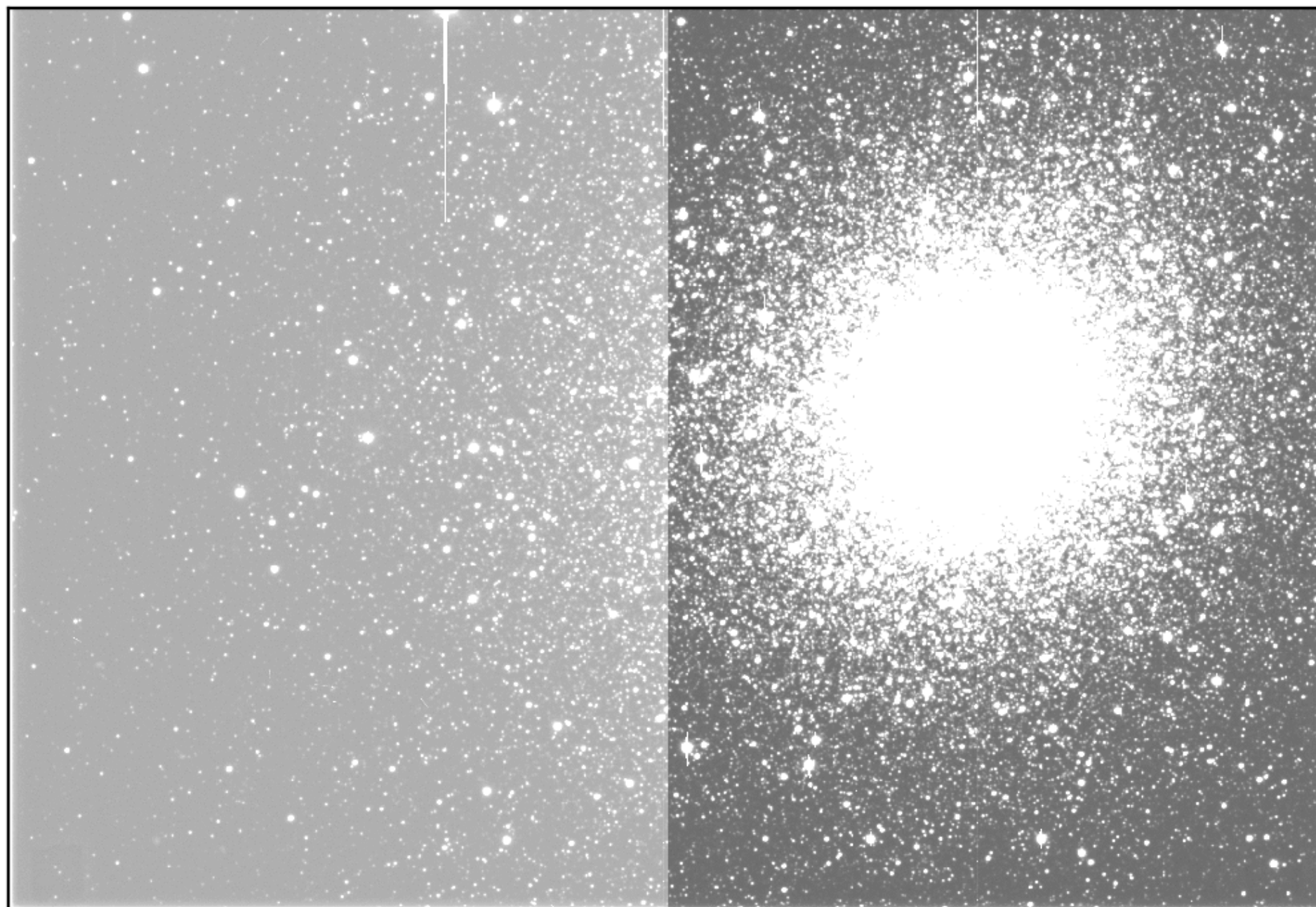
# reducing DECam data en masse with the LSST pipelines

## DECaLS is our proof-of-concept data set

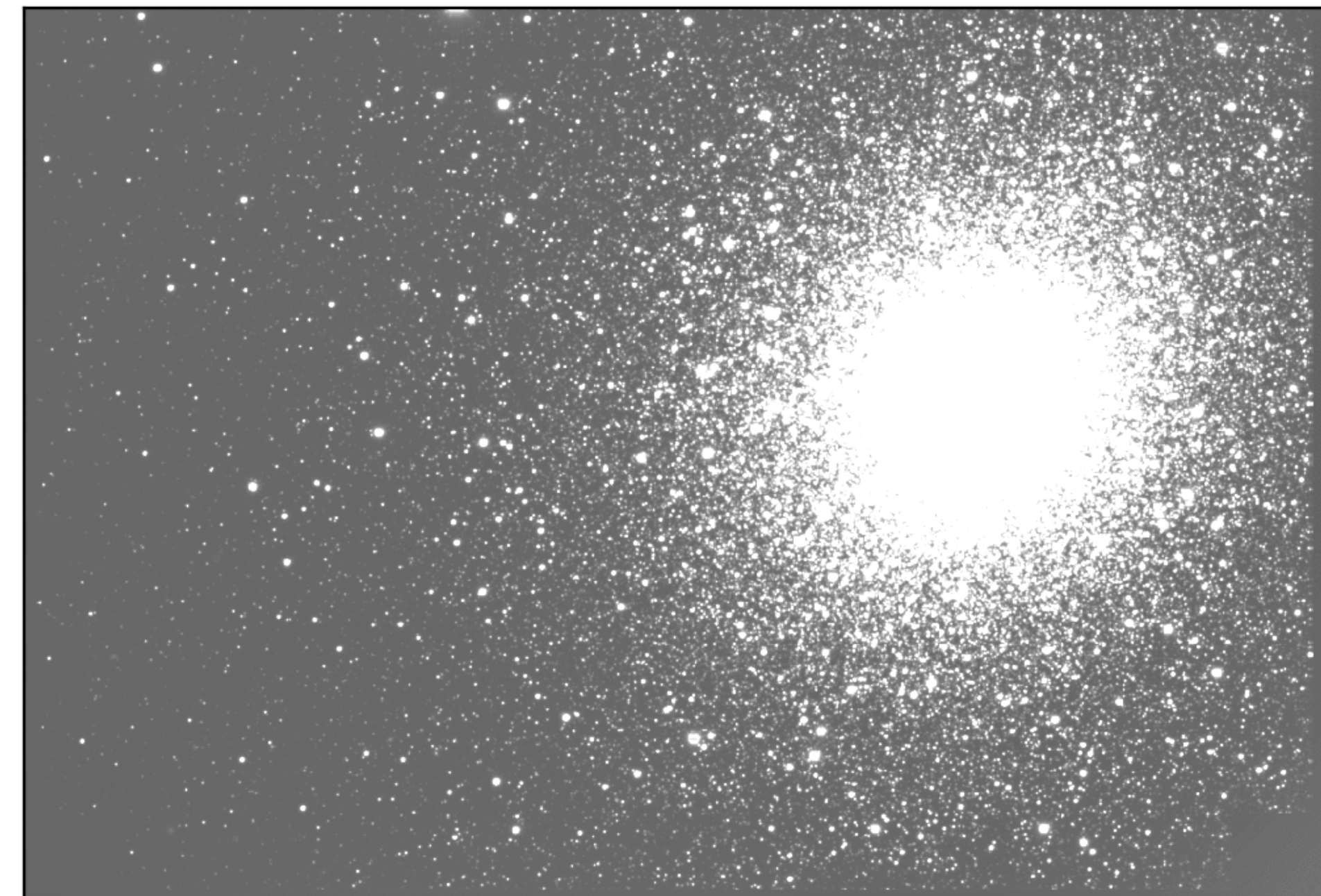
ongoing R&D work at NOIRLab/CSDC by  
Aaron Meisner, Shenming Fu and Tom Matheson



M2 ; raw



M2 ; reduced



- Example of DECam CCD-level calibration (detrending, astrometric/photometric solutions) performed with the LSST pipeline
- Exposure-level source catalogs are also written by the LSST pipeline as a byproduct of these reductions

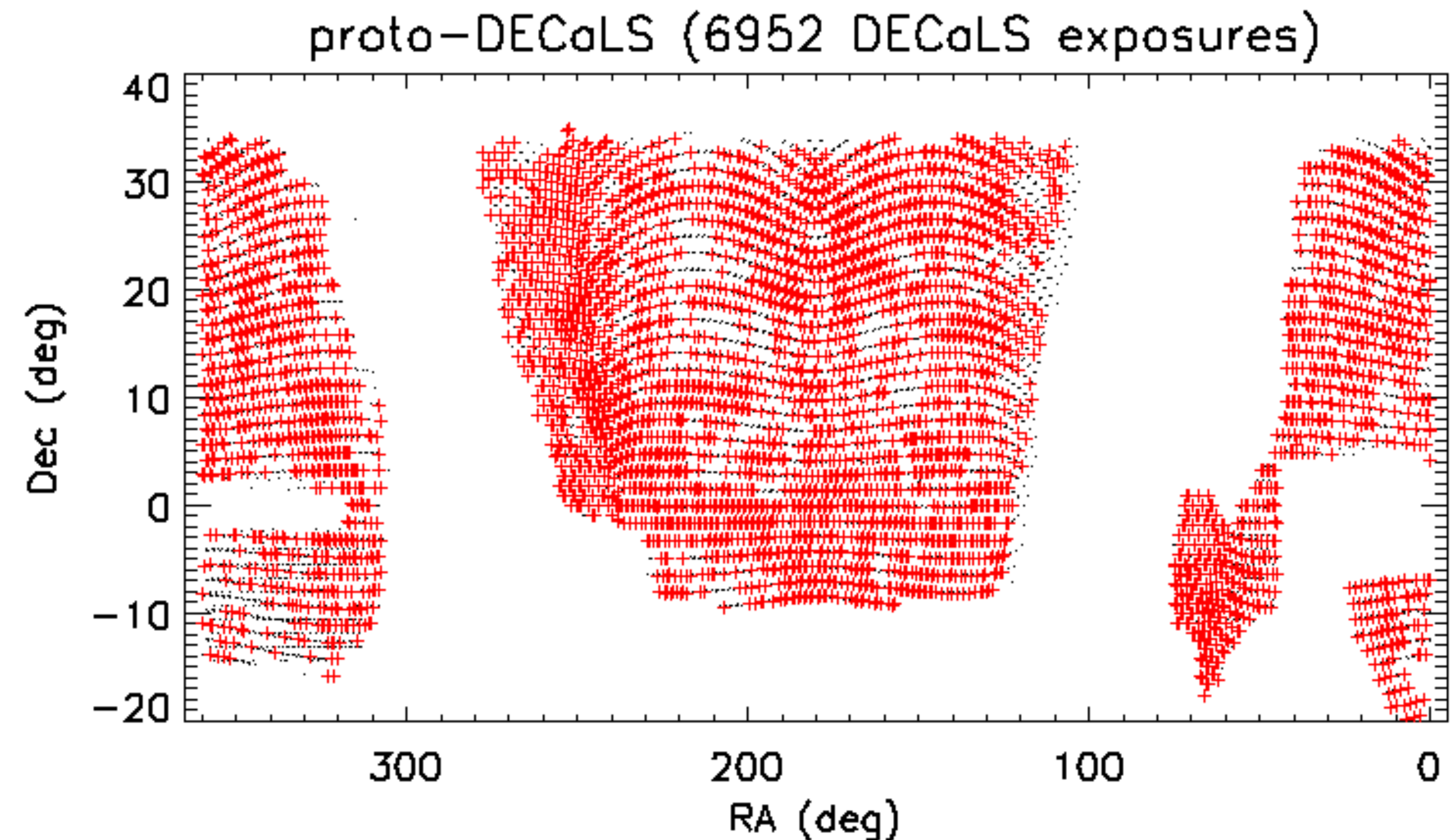


# reducing DECam data en masse with the LSST pipelines

DECaLS is our proof-of-concept data set



- Demonstrated ability to rapidly reduce ~20% of DECaLS imaging with the LSST pipeline
- > 99.7% of CCDs reduce successfully
  - The few failures are bad weather, otherwise unusable raw images
- Could reduce all DECaLS exposures using only ~500 NERSC charge hours

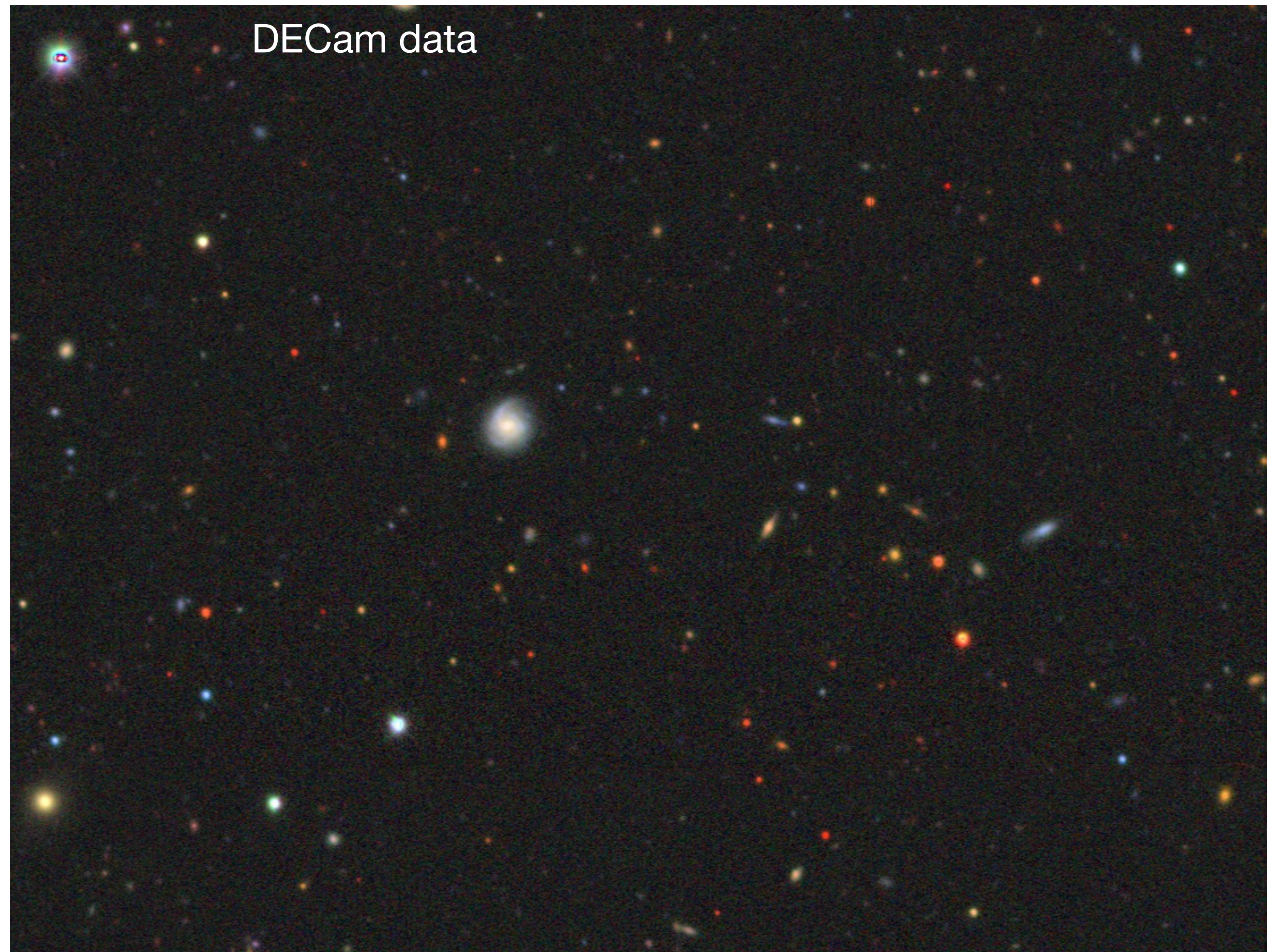


sky coverage from (partial) DECaLS re-reduction with LSST pipelines, ~7000 exposures in total



# The Tractor

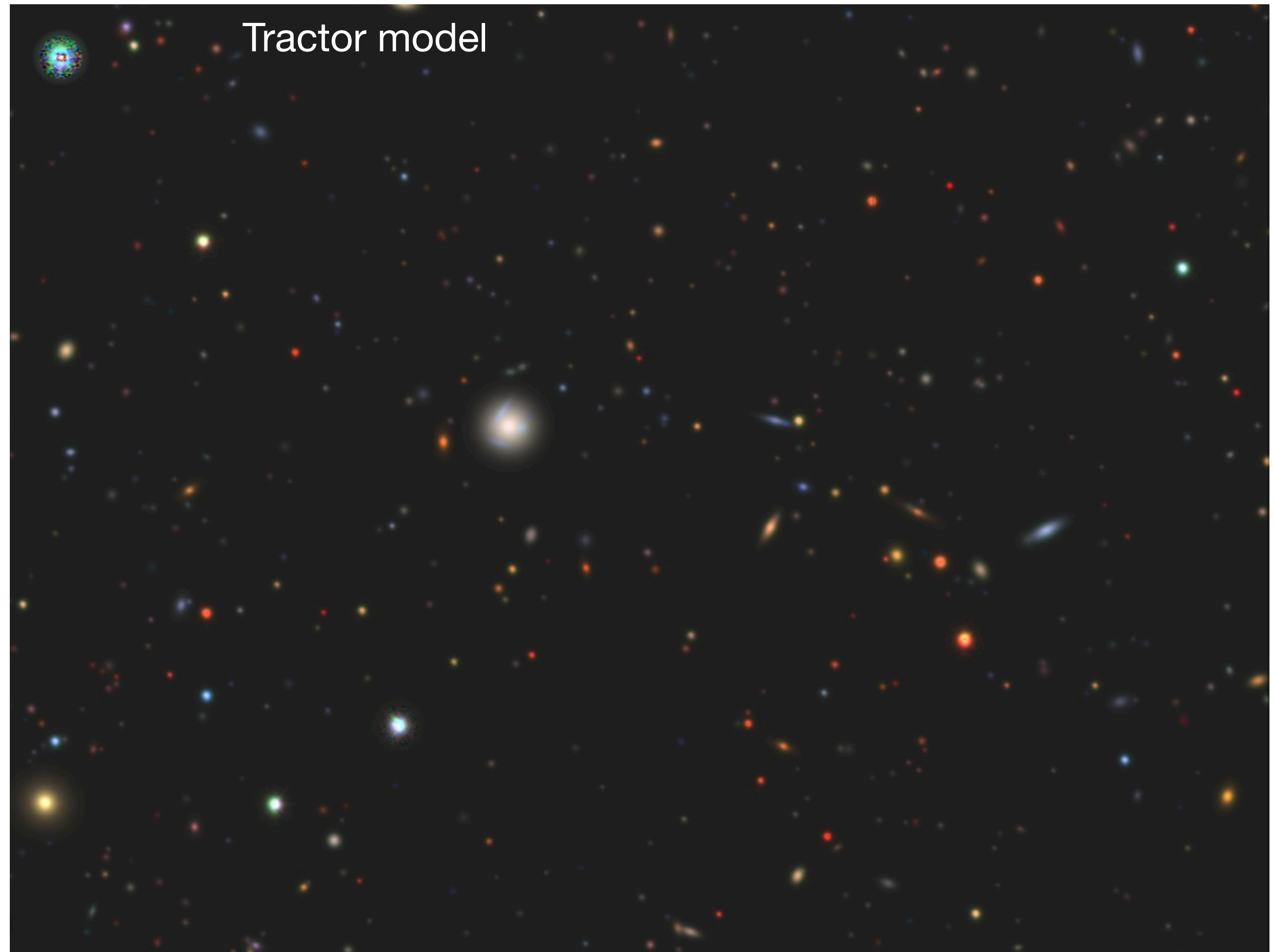
- Tractor jointly models all exposure-level pixels overlapping a given sky region
- Tractor uses a generative model including point-like and extended sources
- Coadds are only made for visualization, not for scientific measurements





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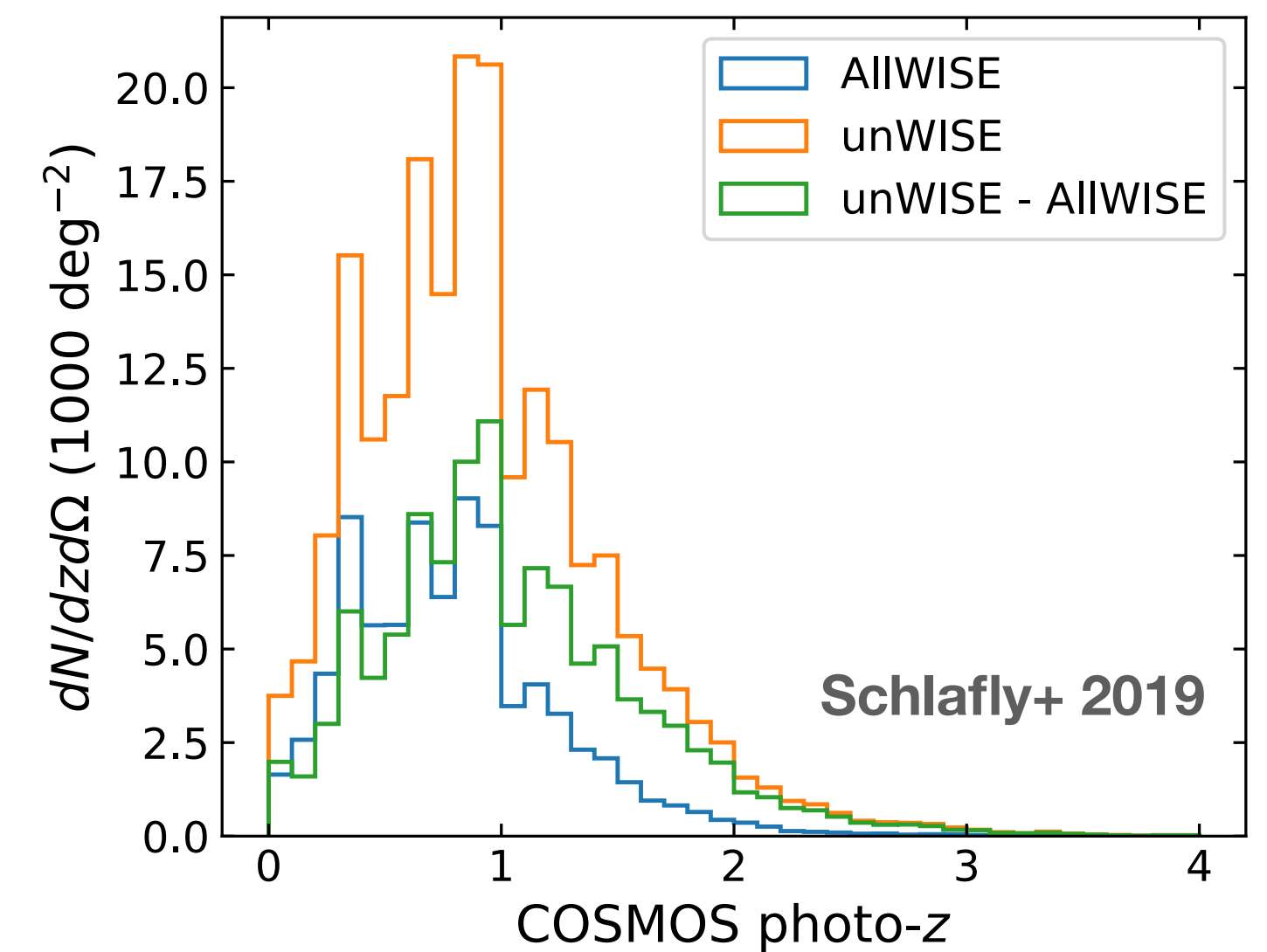
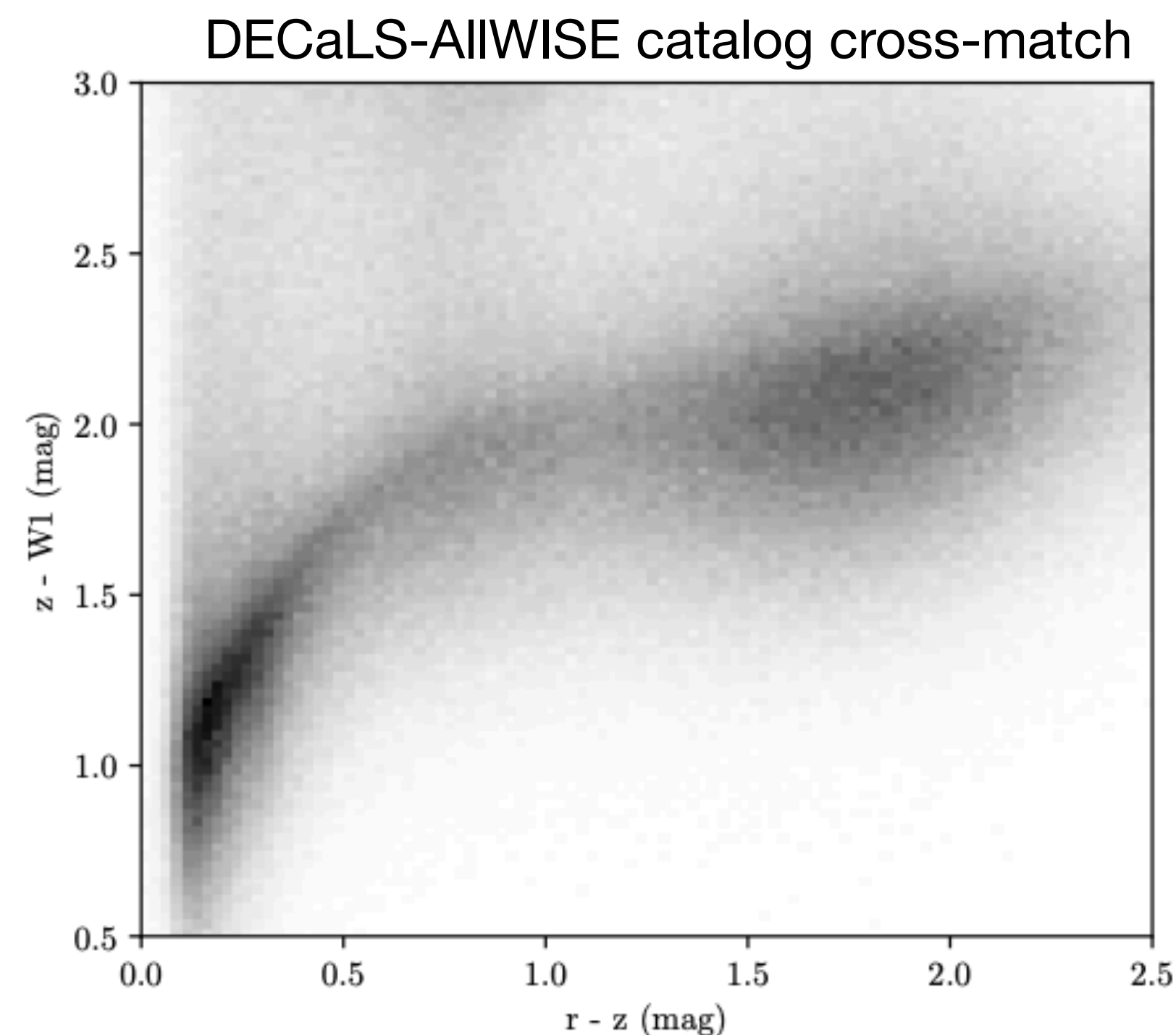
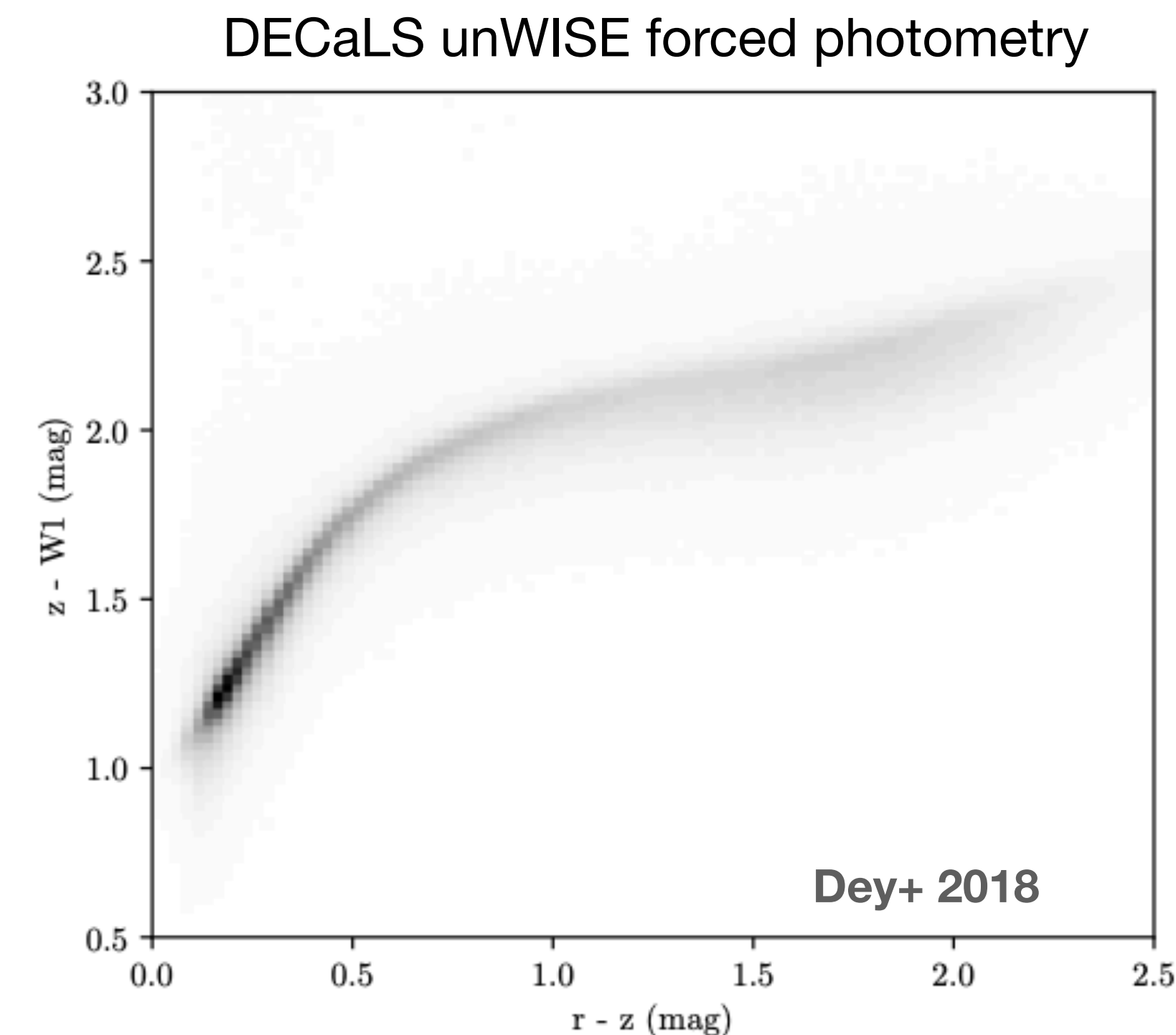
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# unWISE forced photometry for DECaLS

- DR10 custom ‘unWISE coadds’ uniformly combine 8 years of WISE/NEOWISE imaging at 3-5 microns, allowing DECaLS to go much deeper than AllWISE
- Forced photometry of unWISE coadds performed using optical positions/morphologies
- unWISE forced photometry was critical for DESI’s luminous red galaxy & quasar targeting



**2× more galaxies at  $0 < z < 1$**   
**3× more galaxies at  $1 < z < 2$**   
**6× more galaxies at  $z > 2$**



# DECaLS data processing at NERSC

National Energy Research Scientific Computing Center



- 245,000 DECam exposures (~39,000 with DECaLS PROPID)
  - 110 TB of input raw DECam exposures
- 41 million WISE W1/W2 exposures
  - 280 TB of input WISE exposures
- Roughly 20-25 million Tractor CPU hours per data release



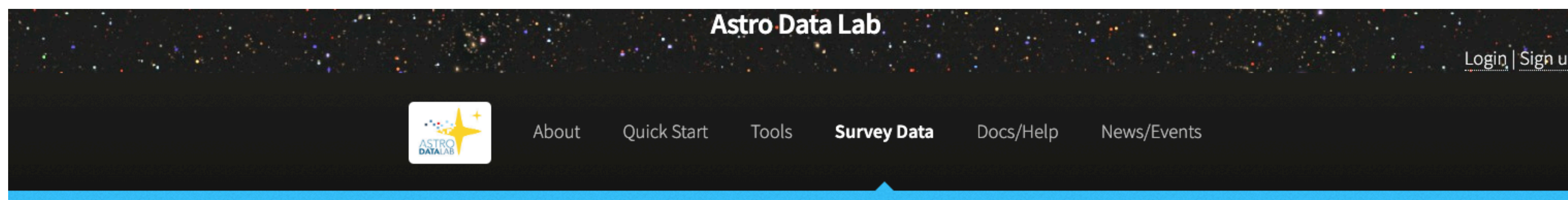


# data access

## NOIRLab Astro Data Lab & NERSC



- File-based access: NERSC, <https://www.legacysurvey.org/>
- Databases: NOIRLab Astro Data Lab, <https://datalab.noirlab.edu/ls/ls.php>
  - Astro Data Lab kindly hosts bonus DECaLS-affiliated products, including photo-z catalogs (R. Zhou) & the unWISE Catalog (E. Schlafly, A. Meisner)



### Overview

DECaLS

MzLS

BASS

### Legacy Survey - Overview

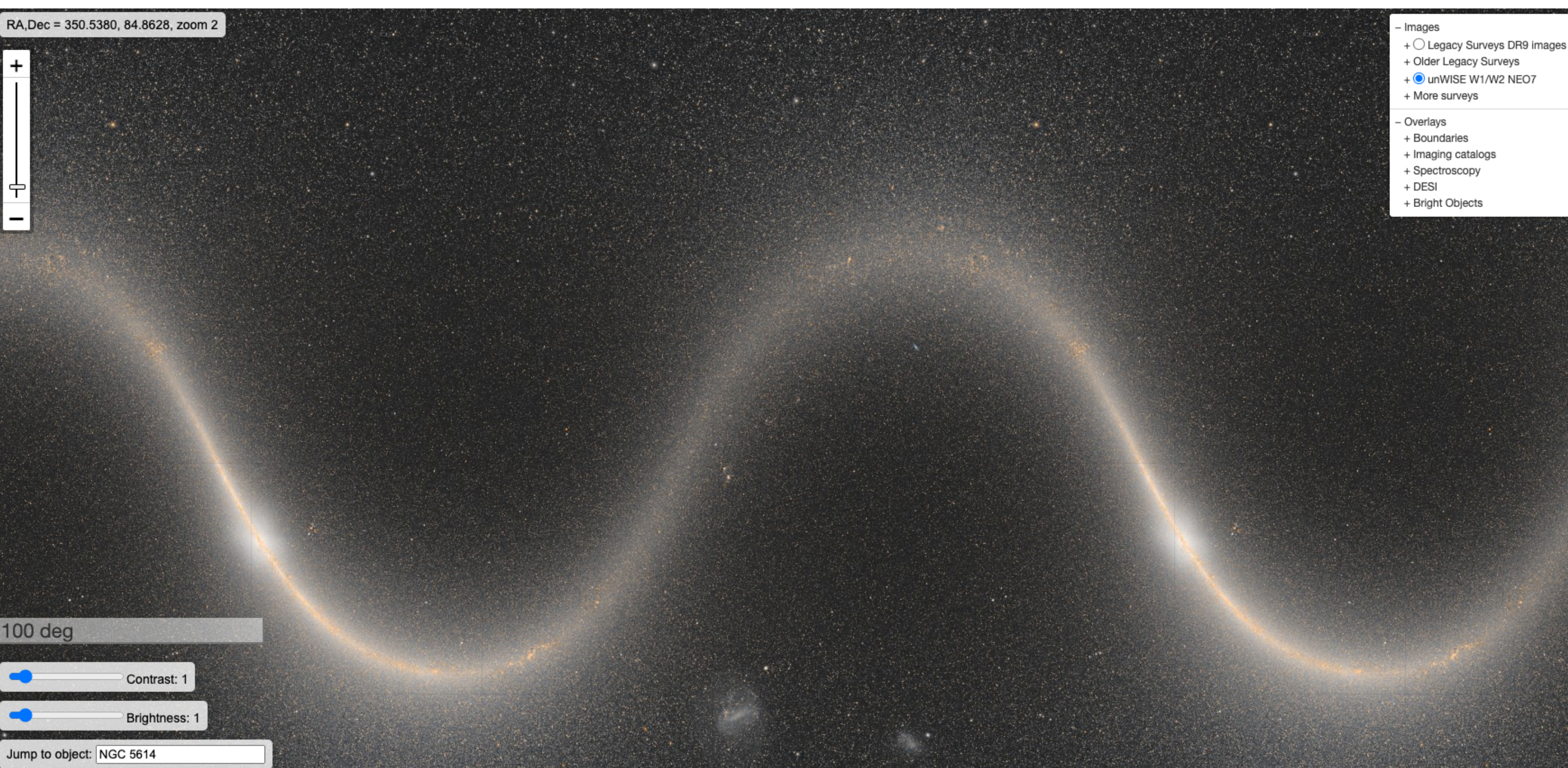
The Legacy Surveys cover 14,000 square degrees of the extragalactic sky, and yield high-quality optical and near-infrared photometric catalogs. The sky coverage is approximately bounded by  $-18^\circ < \delta < +84^\circ$  in celestial coordinates and  $|b| > 18^\circ$  in Galactic coordinates. Resulting images, models, and catalogs will enhance current and future wide area surveys such as SDSS/BOSS/eBOSS and DESI.



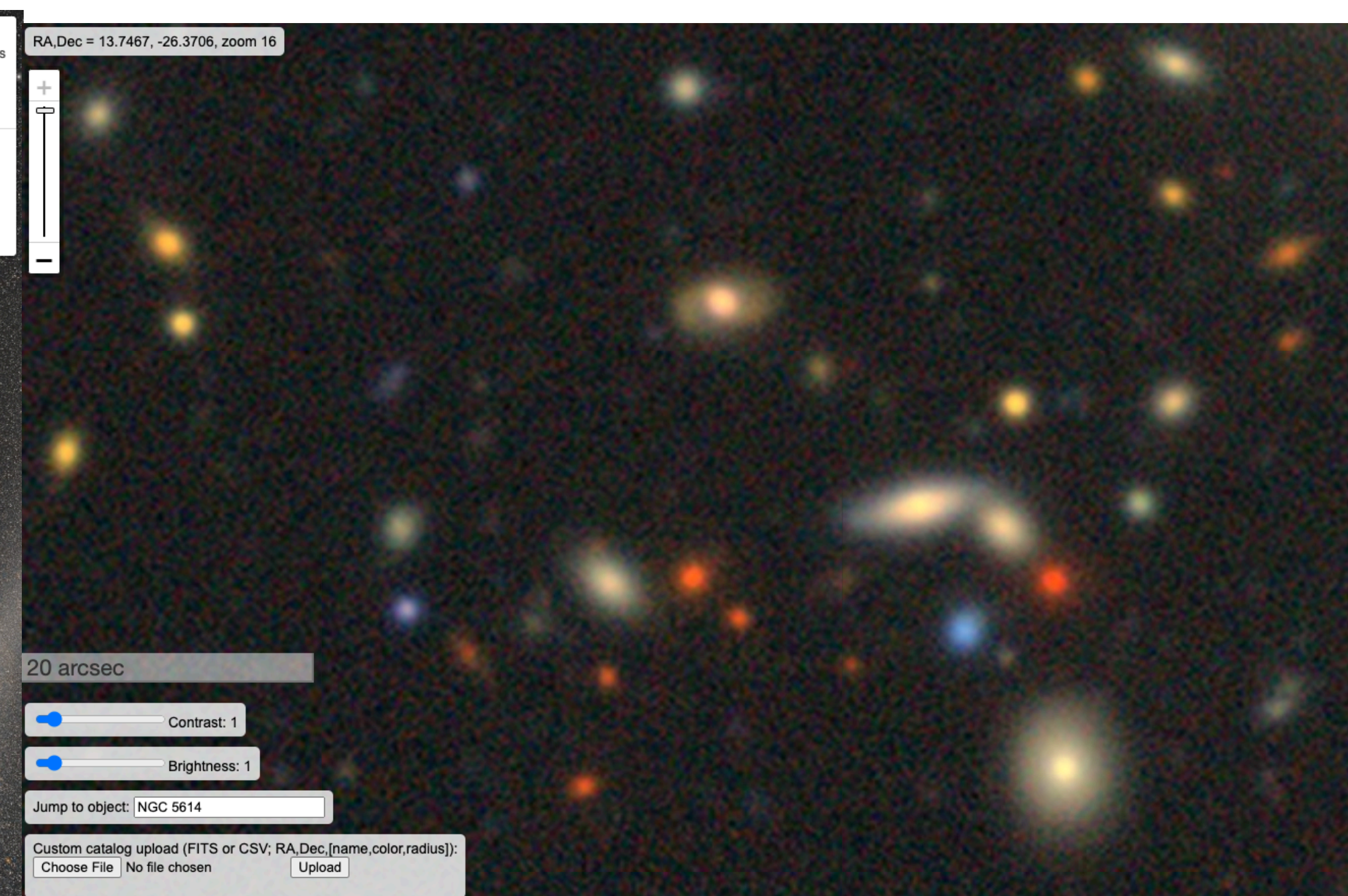
# DESI Legacy Imaging Surveys Sky Viewer

created by Dustin Lang

- interactively explores a factor of  $\sim 20,000$  in zoom!



8-year static sky unWISE coadds (entire sky rendered)

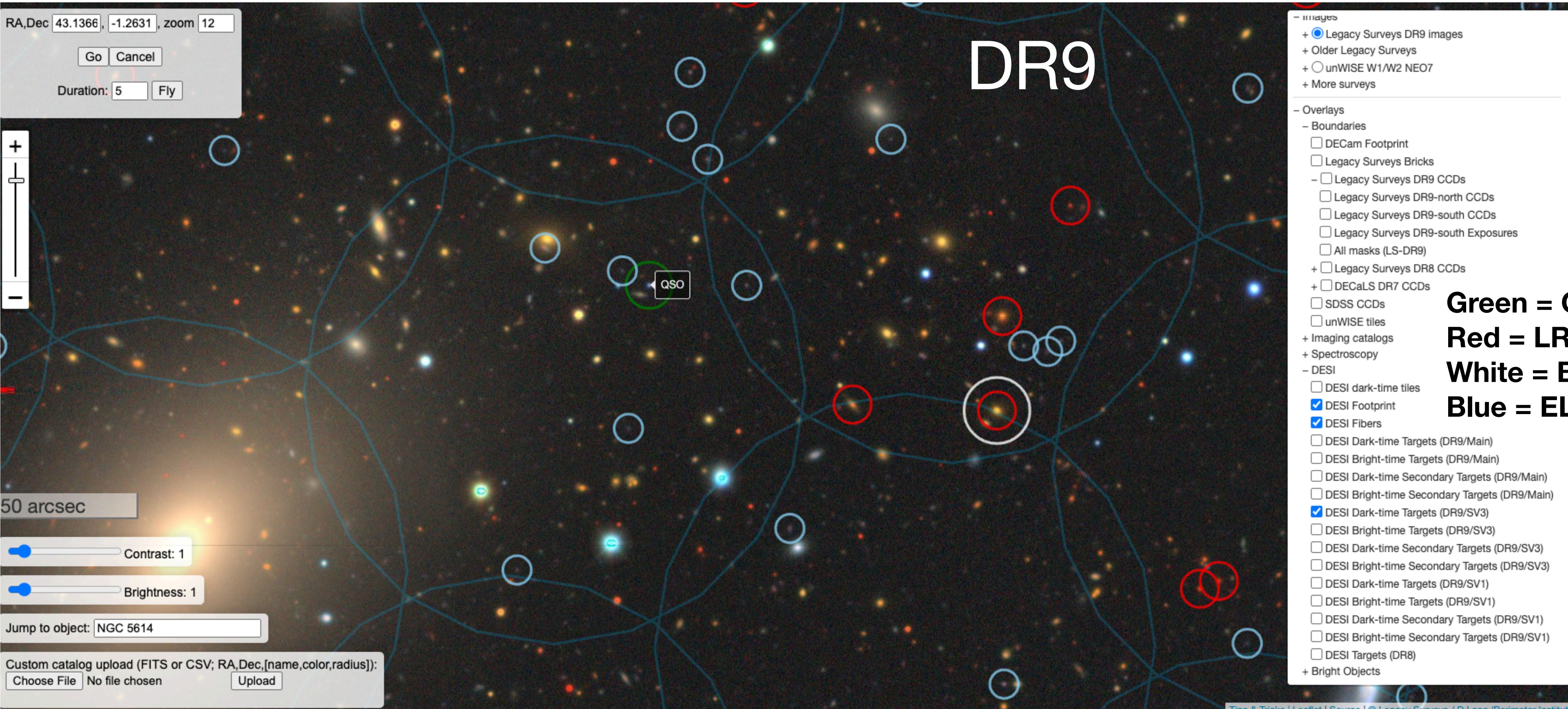


DECaLS DR9 grz (max zoom)



# DECaLS for DESI targeting

DESI meets all of its targeting requirements, thanks in large part to DECaLS

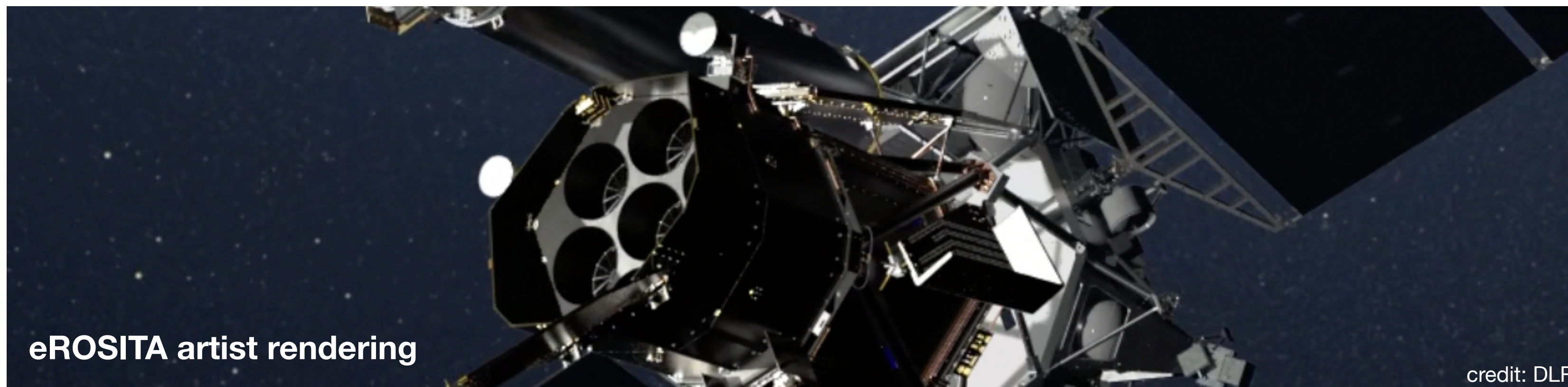


blue lines = DESI fiber patrol regions



# What's new for DECaLS DR10?

- DECam i-band included for the first time
- 1 more year of NEOWISE infrared data relative to DECaLS DR9 (7 yrs -> 8 yrs)
- Large-scale incorporation of publicly available DeROSITAS and DELVE imaging
- DR10/DeROSITAS will be used by the eROSITA team for galaxy cluster science
- DR10 expected to be used for SDSS V targeting
- DR10 expected to also be used for 4MOST targeting
  - 4MOST Chilean AGN/Galaxy Evolution Survey (ChANGES)



eROSITA artist rendering

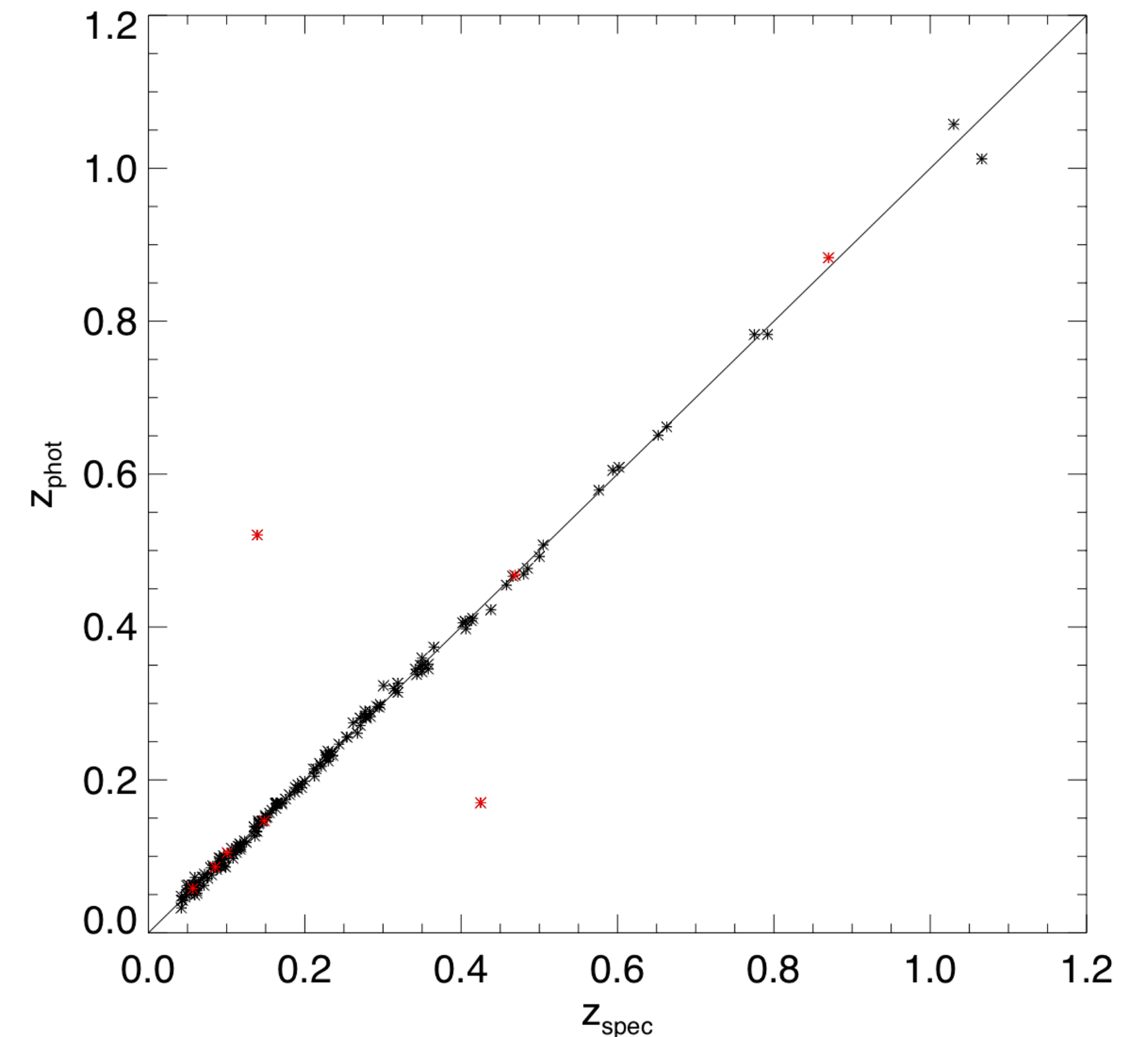
credit: DLR



# DeROSITAS

## The DECam eROSITA Survey (PI: Alfredo Zenteno)

- 100+ observing nights; griz bands; major contribution to DECaLS DR10 i-band coverage
  - iz depths similar to those of DES Y3 data set
- Optimized for accurate galaxy cluster photometric redshifts ( $z = 0-1$ )
- Close coordination of observations with DELVE e.g., same sky tiling strategy

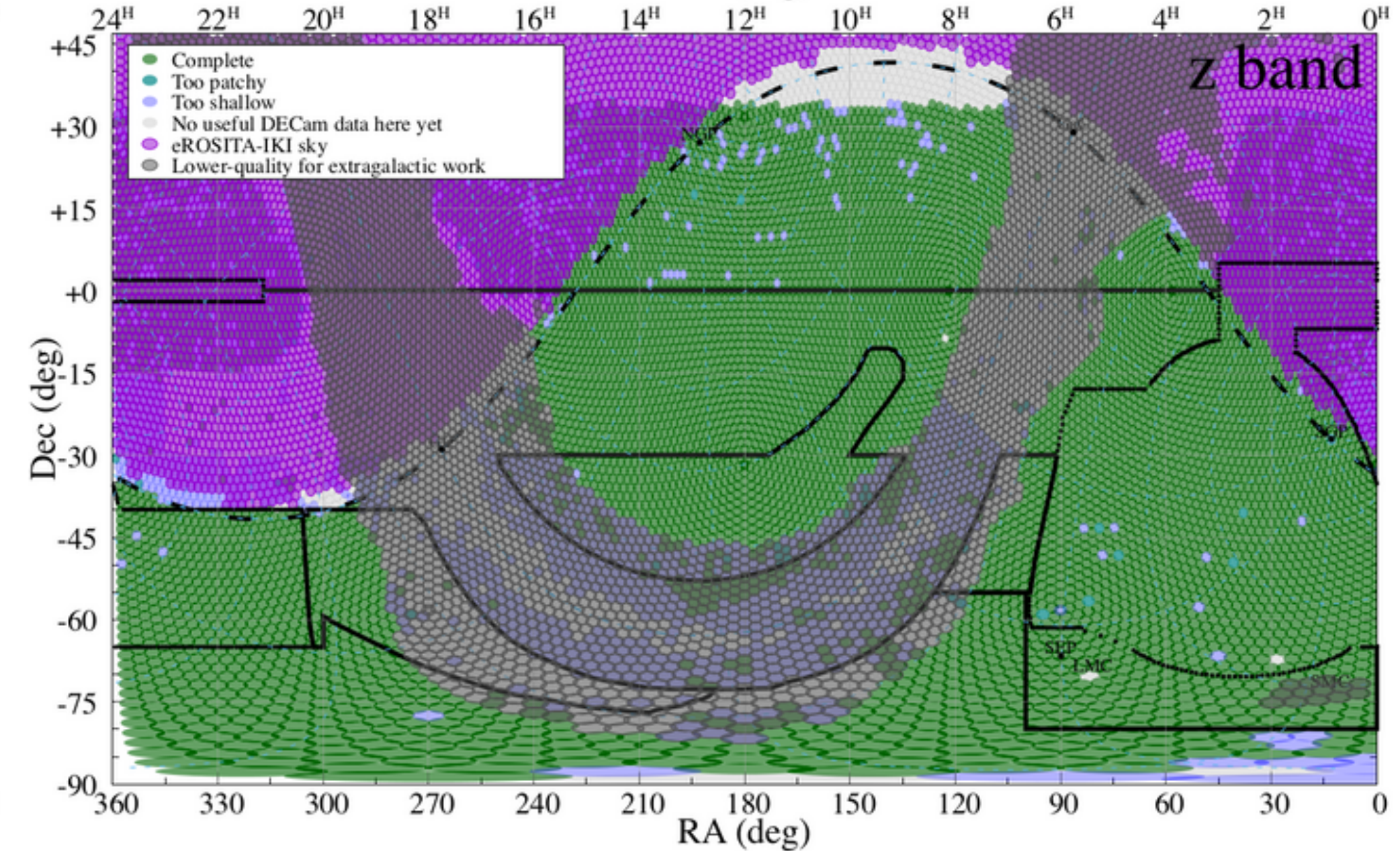
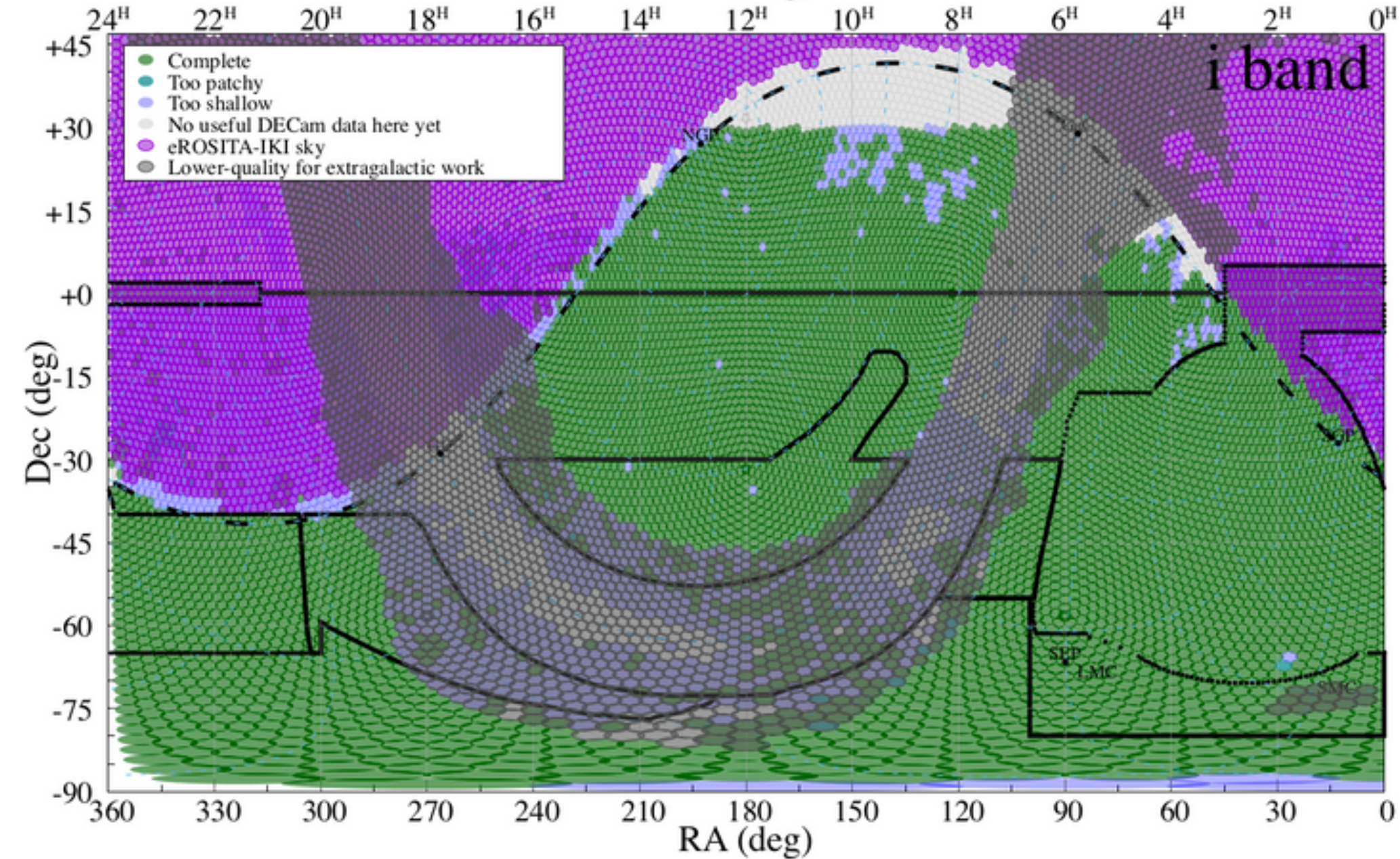
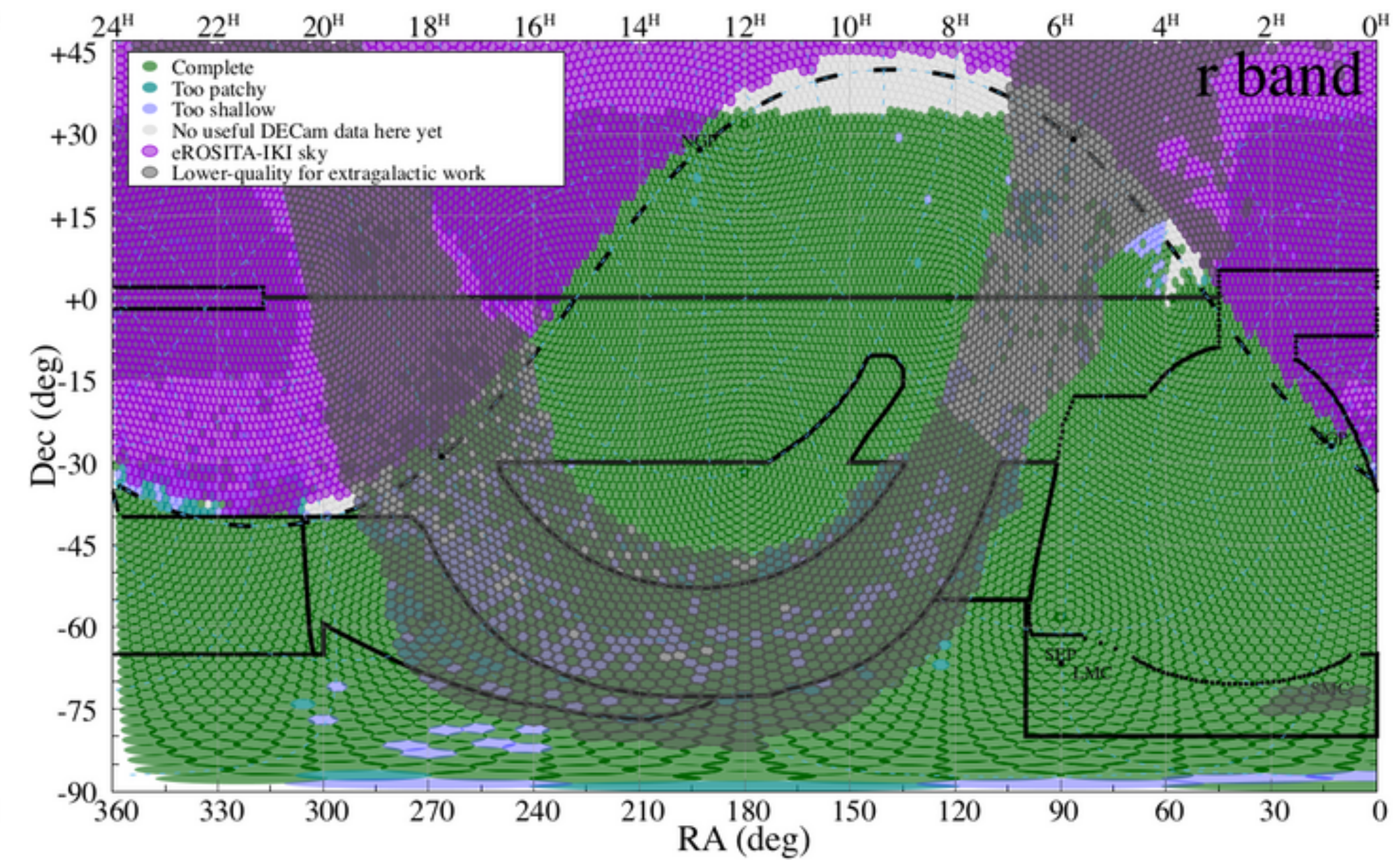
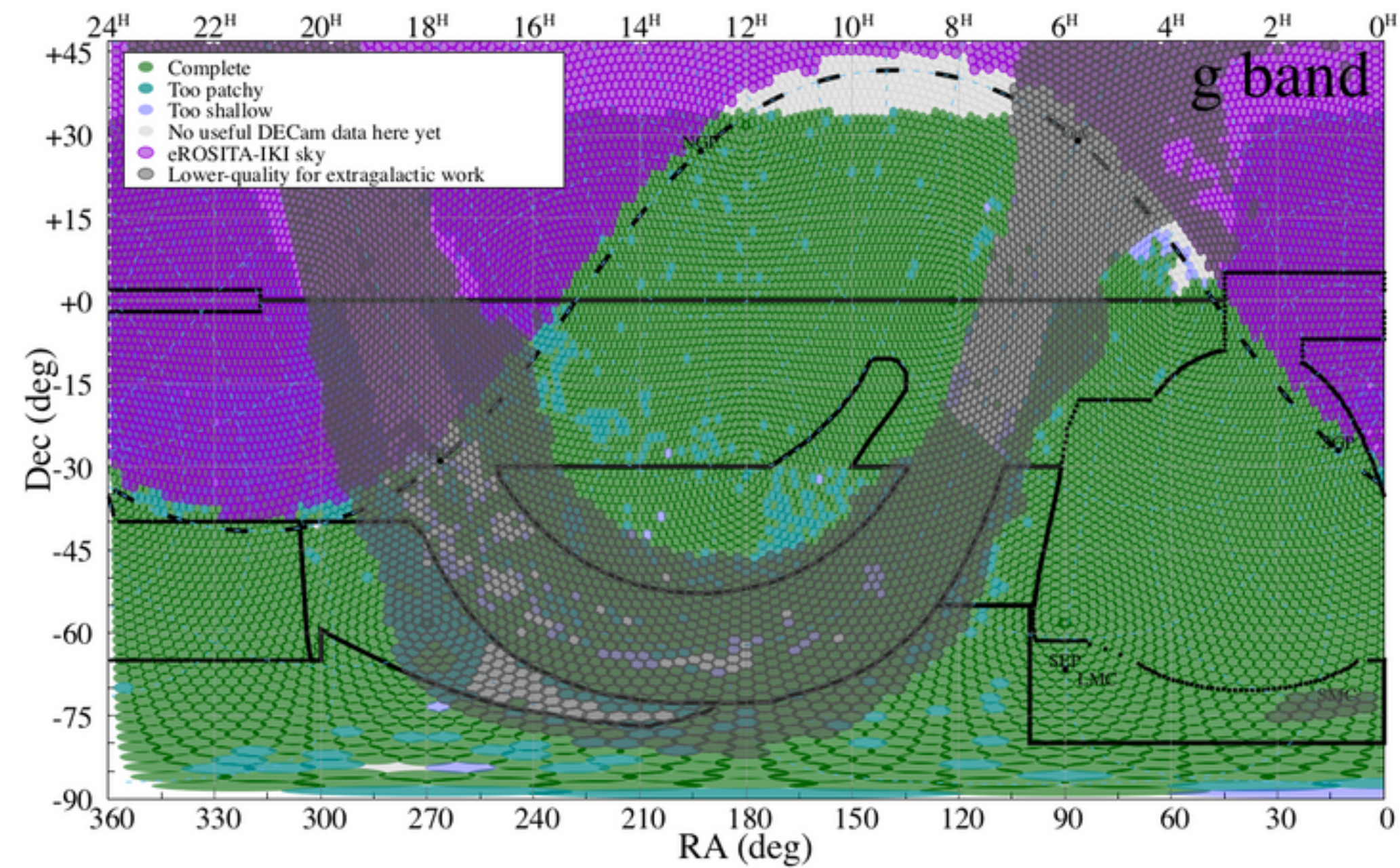


M. Klein (2020, 2021)  $\sigma \sim 0.01 \times (1+z)$

DeROSITAS team: Alfredo Zenteno, Daniel Hernandez-Lang,  
Jose Luis Nilo-Castellon, Mara Salvato, Patricia Arevalos, Héctor Cuevas, Rodrigo Carrasco,  
Valeria Mesa, Amelia Ramirez++



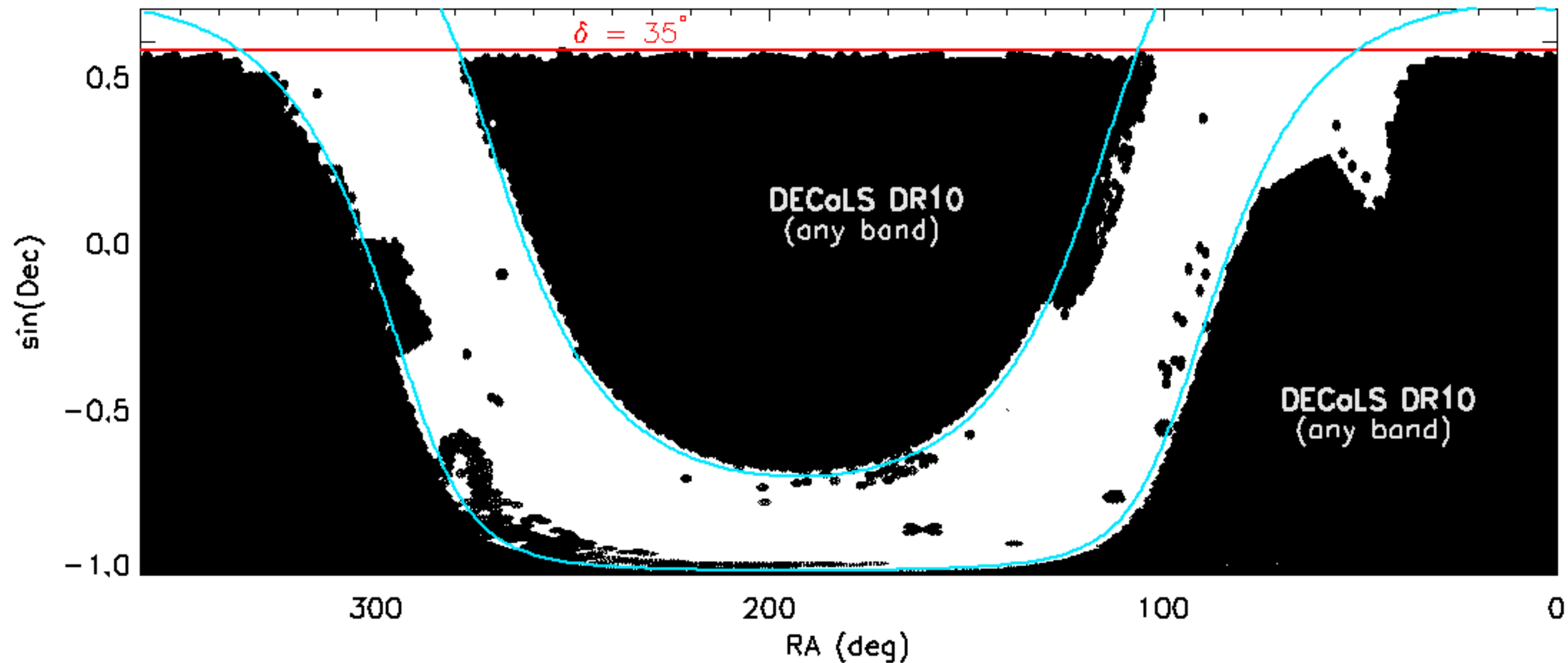
# DeROSITAS: helping DECam fill in the southern sky





# DECaLS DR10 sky coverage

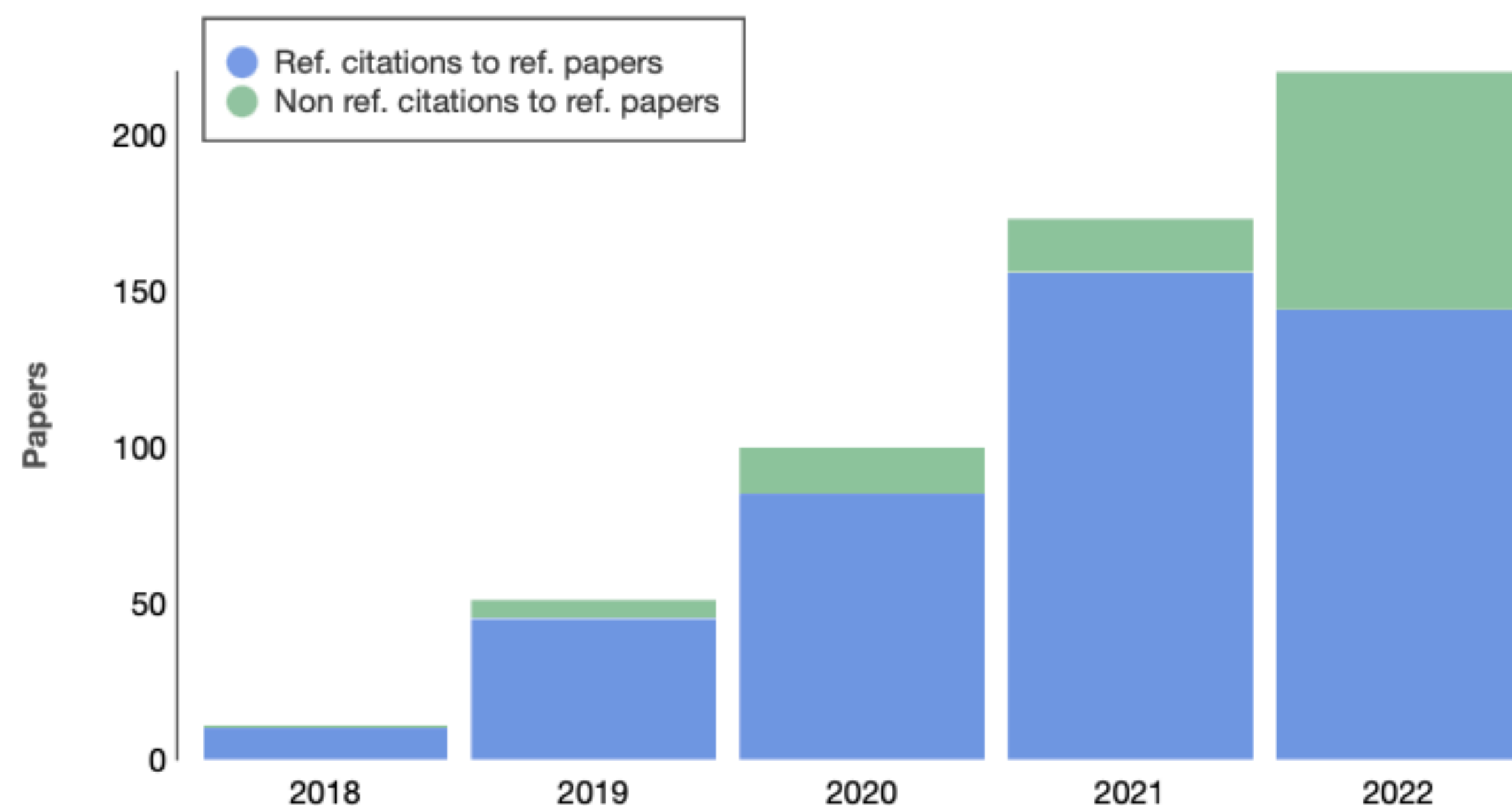
DECaLS DR10 DECam CCDs



- 2.8 billion unique objects!
- Approximately 22,850 square degrees — more than half the sky.



# DECaLS scientific impact



THE ASTRONOMICAL JOURNAL, 157:168 (29pp), 2019 May  
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<https://doi.org/10.3847/1538-3881/ab089d>



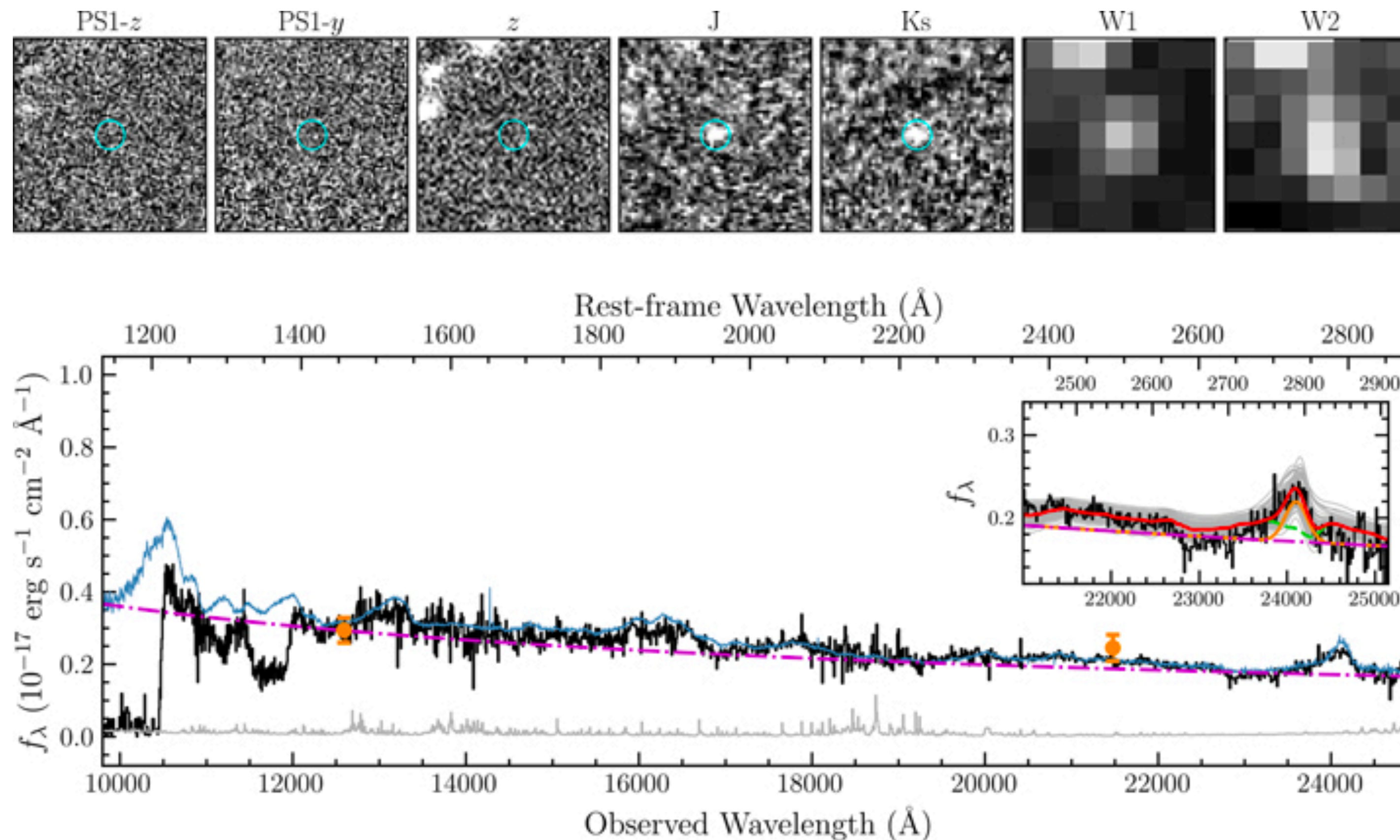
## Overview of the DESI Legacy Imaging Surveys

Arjun Dey<sup>1</sup> , David J. Schlegel<sup>2</sup> , Dustin Lang<sup>3,5,4</sup> , Robert Blum<sup>1,6</sup> , Kaylan Burleigh<sup>2</sup>, Xiaohui Fan<sup>7</sup> , Joseph R. Findlay<sup>8</sup>,  
Doug Finkbeiner<sup>9</sup> , David Herrera<sup>1</sup> , Stéphanie Juneau<sup>1</sup> , Martin Landriau<sup>2</sup> , Michael Levi<sup>2</sup> , Ian McGreer<sup>7</sup> ,  
Aaron Meisner<sup>2</sup> , Adam D. Myers<sup>8</sup>, John Moustakas<sup>10</sup> , Peter Nugent<sup>2</sup> , Anna Patej<sup>7</sup>, Edward F. Schlafly<sup>2</sup> ,  
Alistair R. Walker<sup>11</sup> , Francisco Valdes<sup>1</sup> , Benjamin A. Weaver<sup>1</sup>, Christophe Yèche<sup>12</sup>, Hu Zou<sup>13</sup> , Xu Zhou<sup>13</sup>,  
Behzad Abareshi<sup>1</sup>, T. M. C. Abbott<sup>11</sup> , Bela Abolfathi<sup>14</sup> , C. Aguilera<sup>11</sup>, Shadab Alam<sup>15</sup>, Lori Allen<sup>1</sup> , A. Alvarez<sup>11</sup>,  
16, 17, 18, 19, 20, 21



# $z = 7.64$ quasar redshift record

supermassive black holes, reionization, early Universe



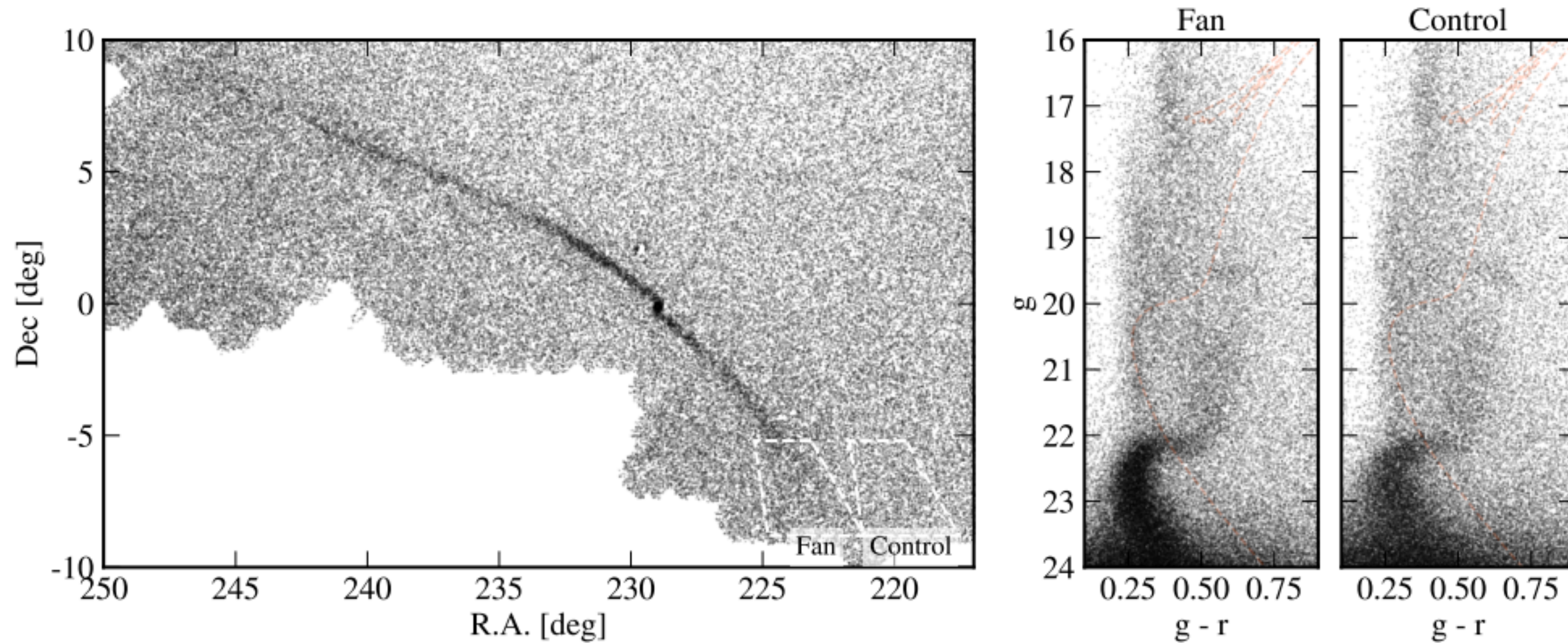
## A Luminous Quasar at Redshift 7.642

Wang et al. 2021



# exquisitely detailed portrait of the Pal 5 stream

Milky Way, stellar streams, dark matter



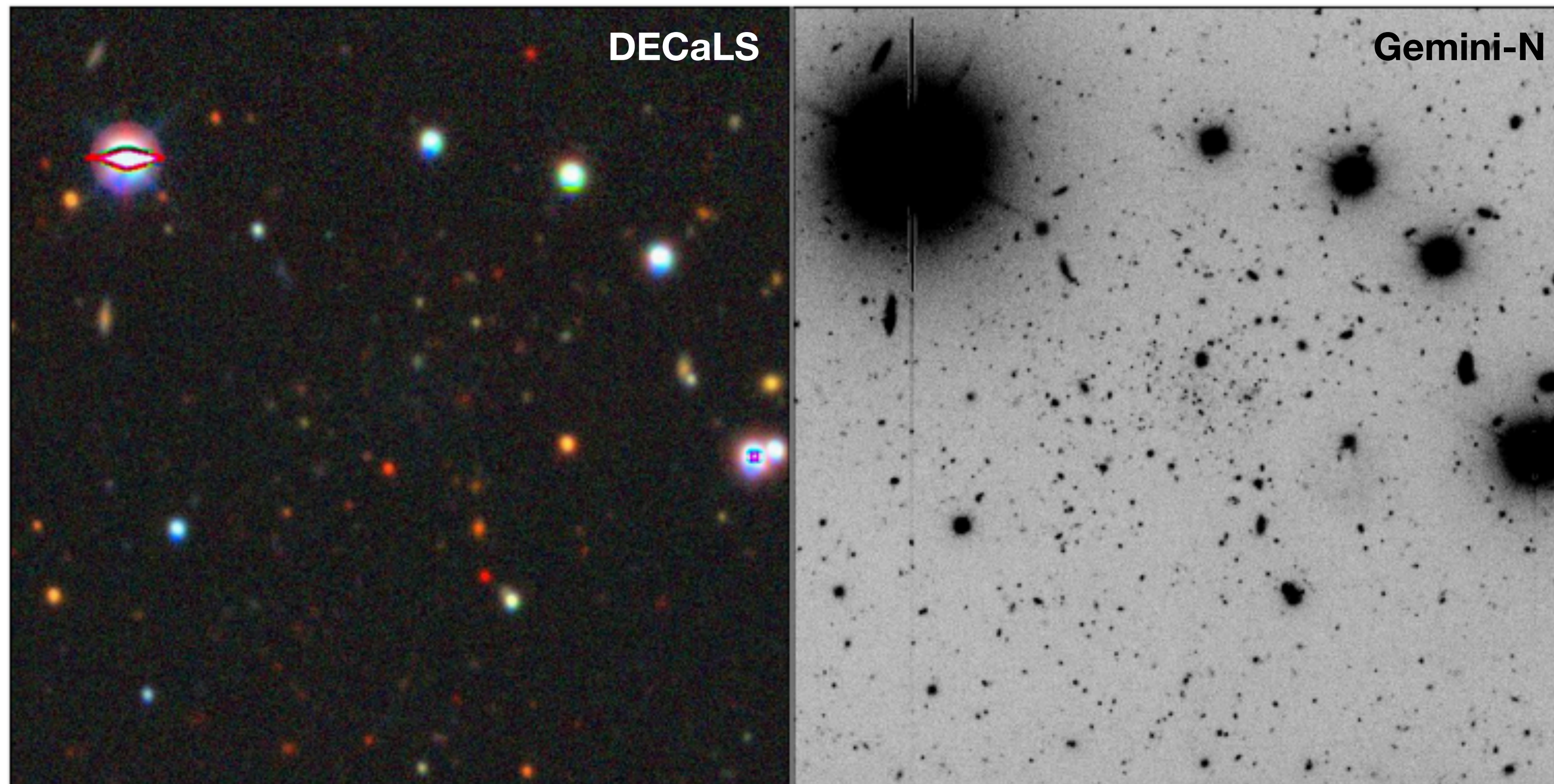
**Variations in the Width, Density, and Direction of the Palomar 5 Tidal Tails**

Bonaca et al. 2020



# Pegasus V dwarf — at Dec = 33.5° !

local group, dwarf galaxies, galaxy formation



**Figure 1.** *Left panel:* Image of the dwarf galaxy Peg V from the DESI Legacy Imaging Survey. *Right panel:* Gemini/GMOS-N combined *g*- and *r*-band image of the galaxy obtained from Gemini follow-up observations (see Sec. 2). North is up, East is left. In both images, the field of view is 150'' × 150''.

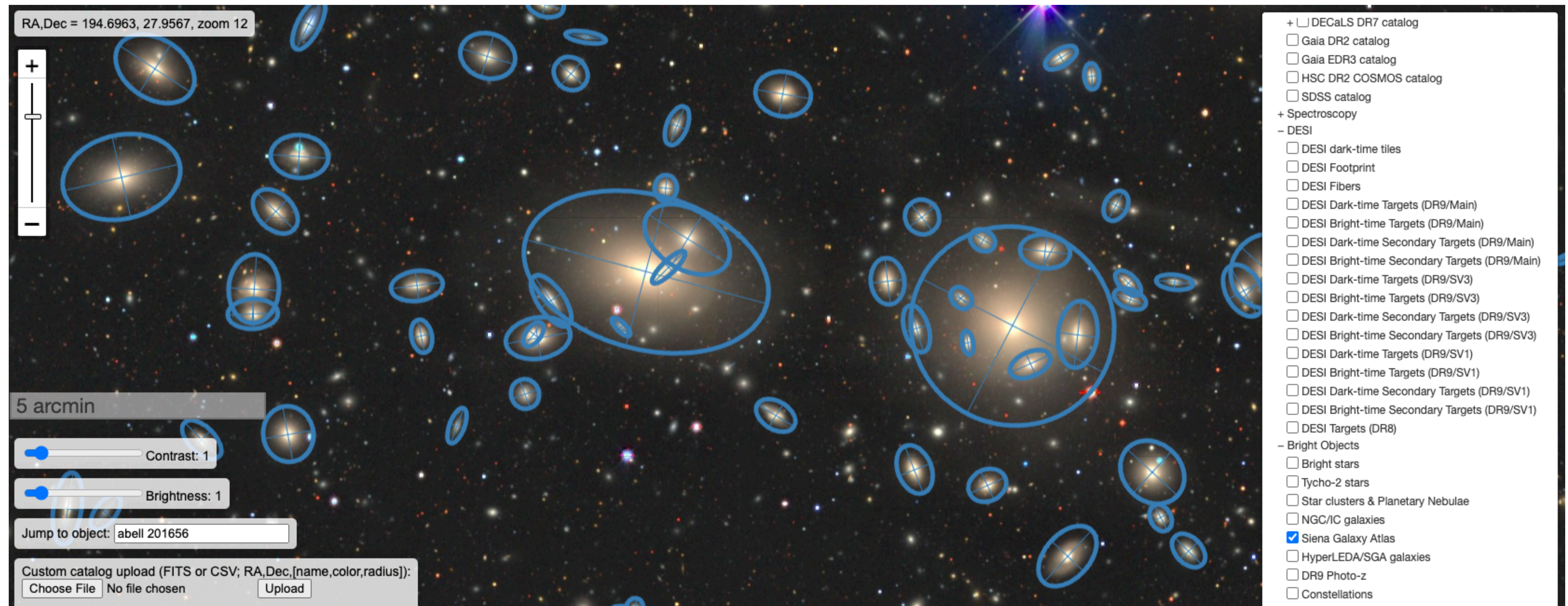
**Pegasus V - a newly discovered ultra-faint dwarf galaxy on the outskirts of Andromeda**

Collins et al. 2022



# Siena Galaxy Atlas (SGA)

John Moustakas, Dustin Lang et al.

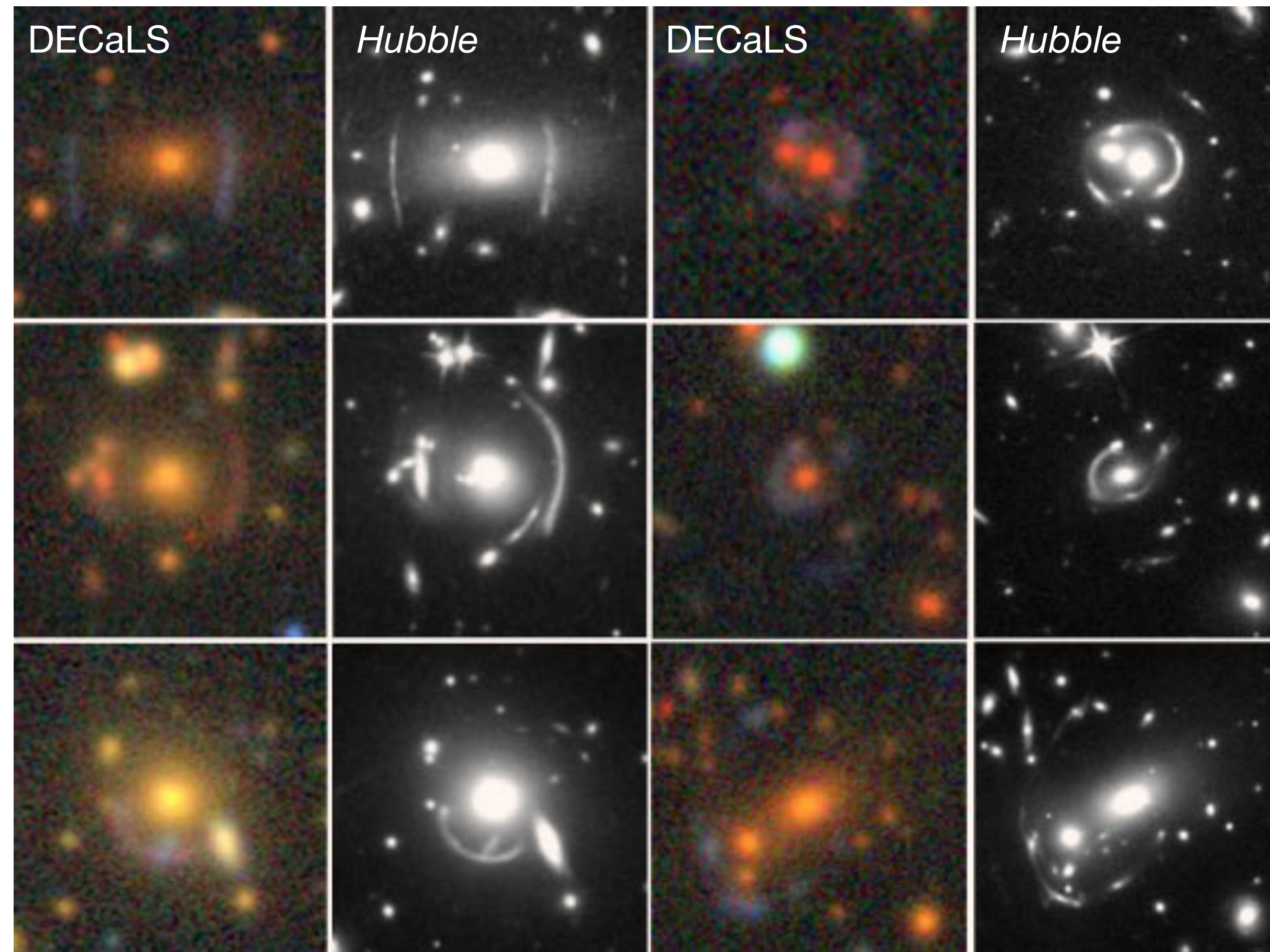


- 383,620 nearby galaxies, based in large part on DECaLS data products
- More details in the following talk by Stephanie Juneau!



# thousands of newly discovered strong lenses

## cosmology, dark matter, machine learning



“NeuraLens”  
deep learning discovery engine  
<https://sites.google.com/usfca.edu/neuralens>

**Finding Strong Gravitational Lenses in the DESI DECam Legacy Survey**

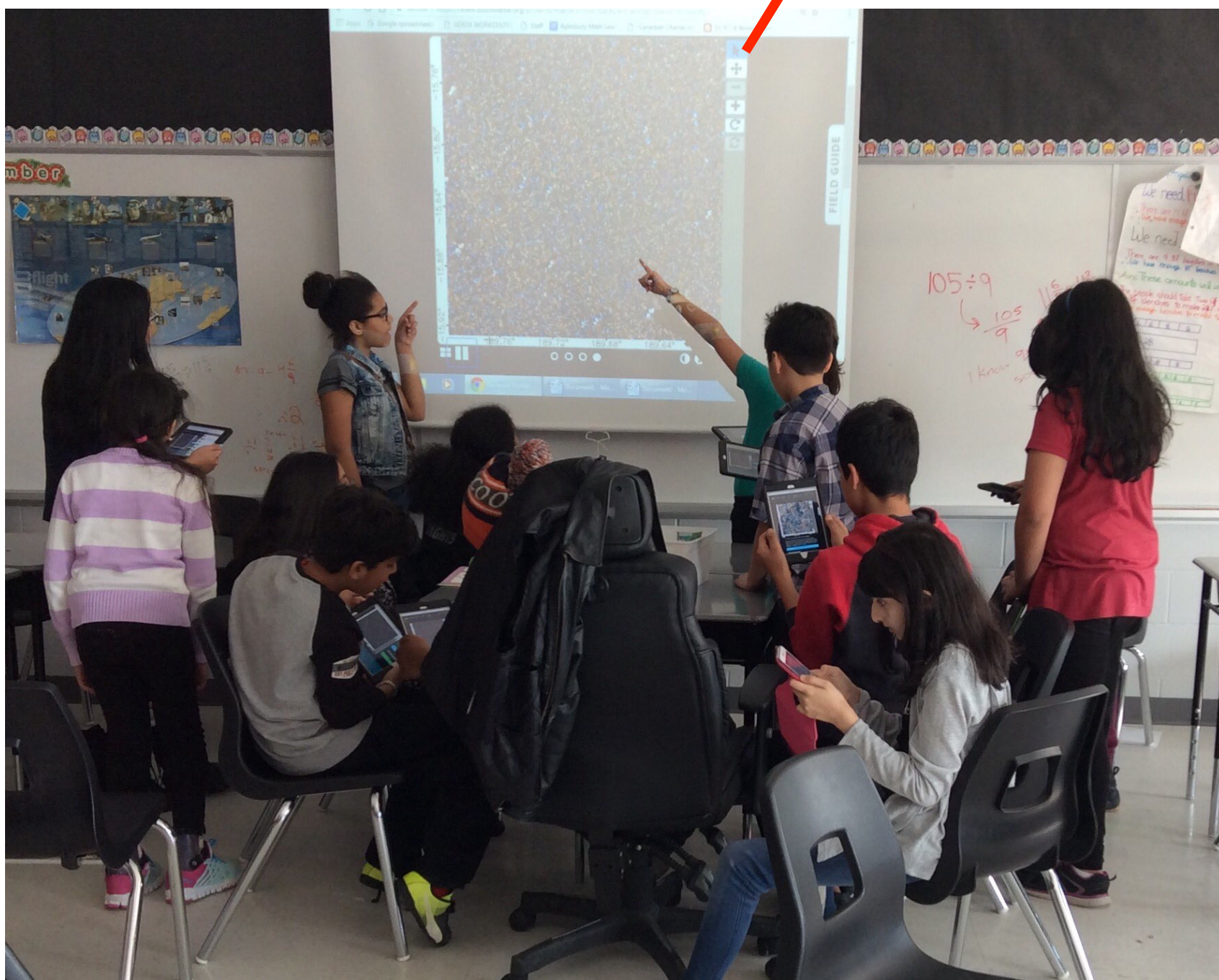
Huang et al. 2020, 2021, 2022



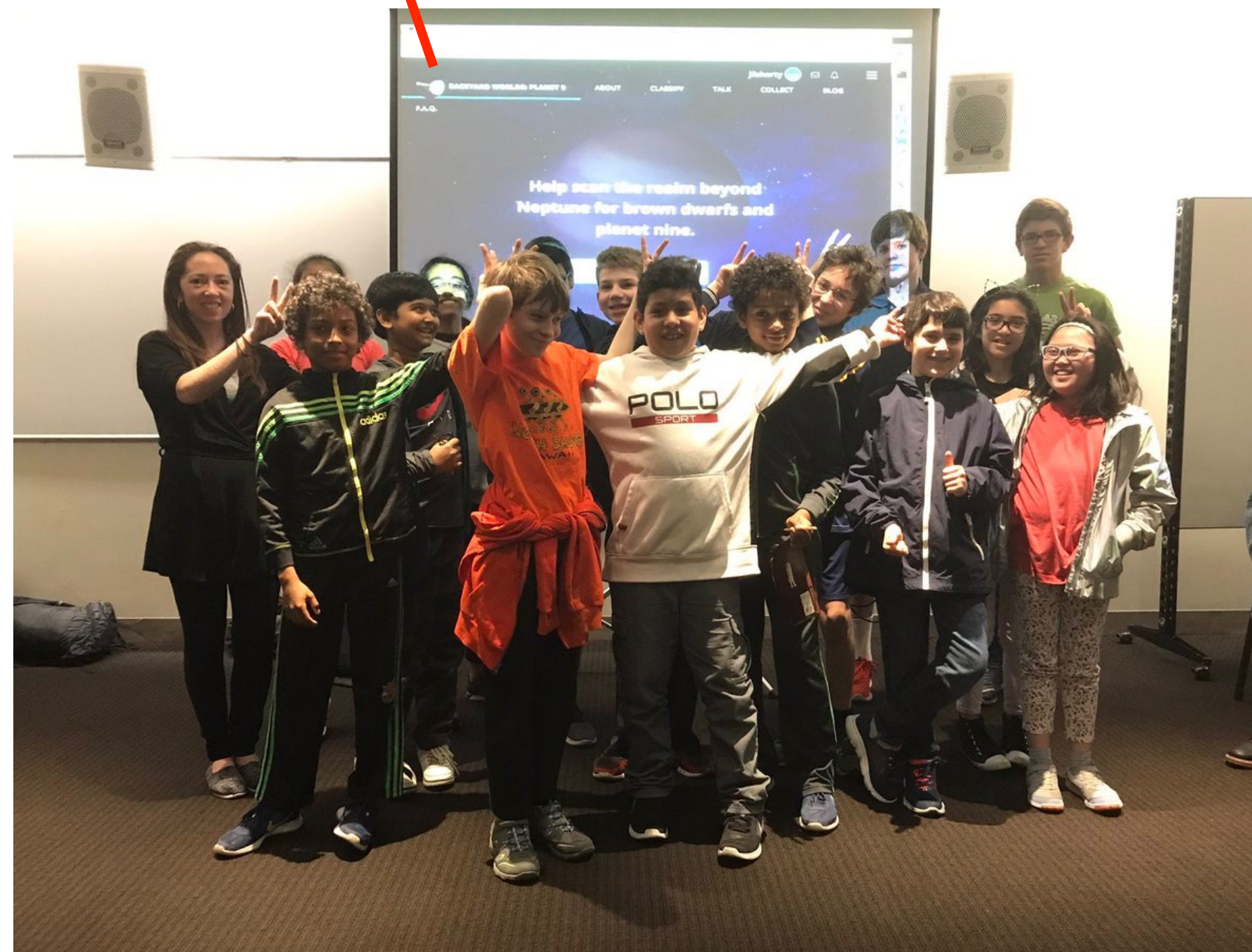
# DESI Legacy Imaging Surveys broader impacts

DESI imaging unWISE coadd

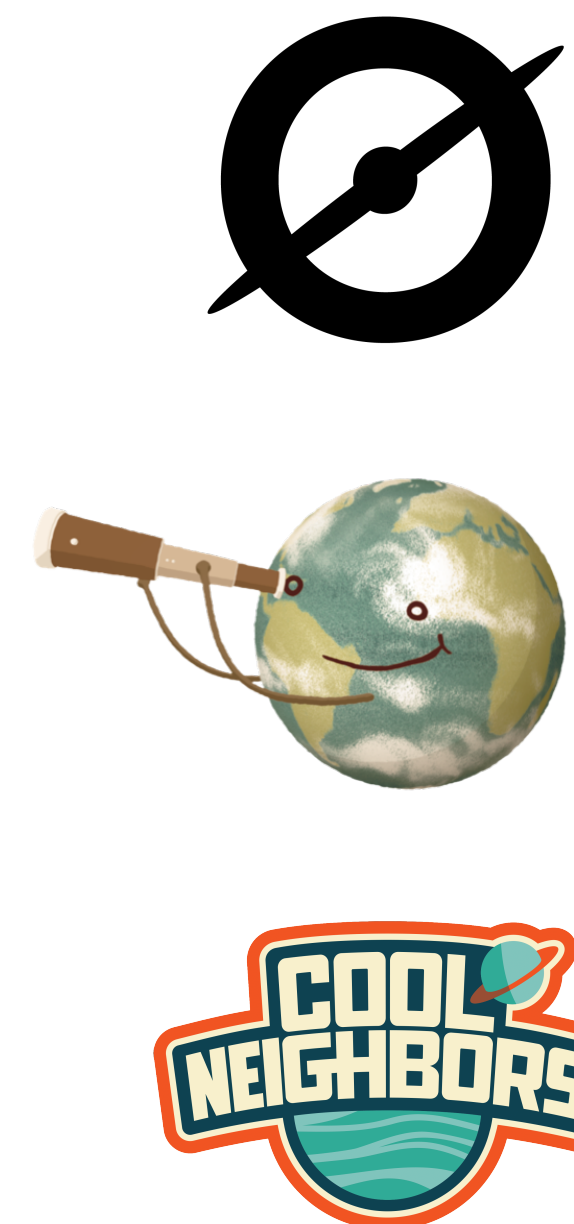
Backyard Worlds citizen science project web interface



Mr. Blake's 6th grade class  
Brampton, Ontario



World Science Fest  
New York, New York

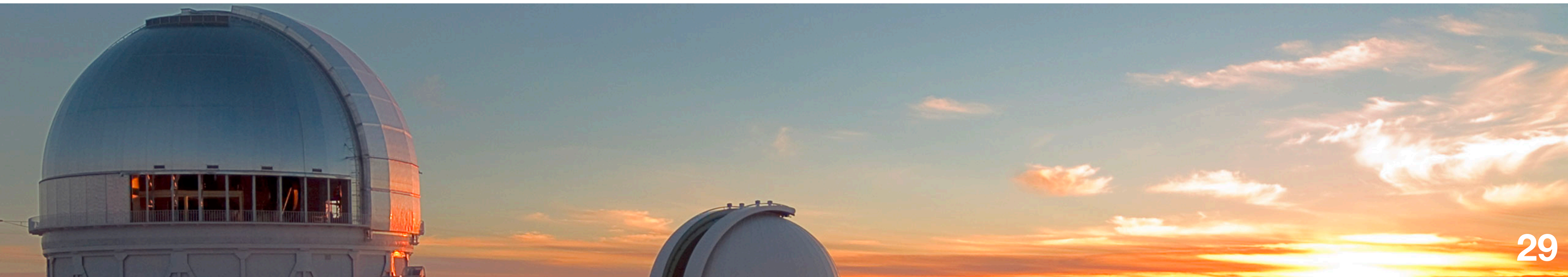


**DESI imaging 'open data' practices have allowed us to reach a broad audience, including hundreds of thousands of members of the general public.**

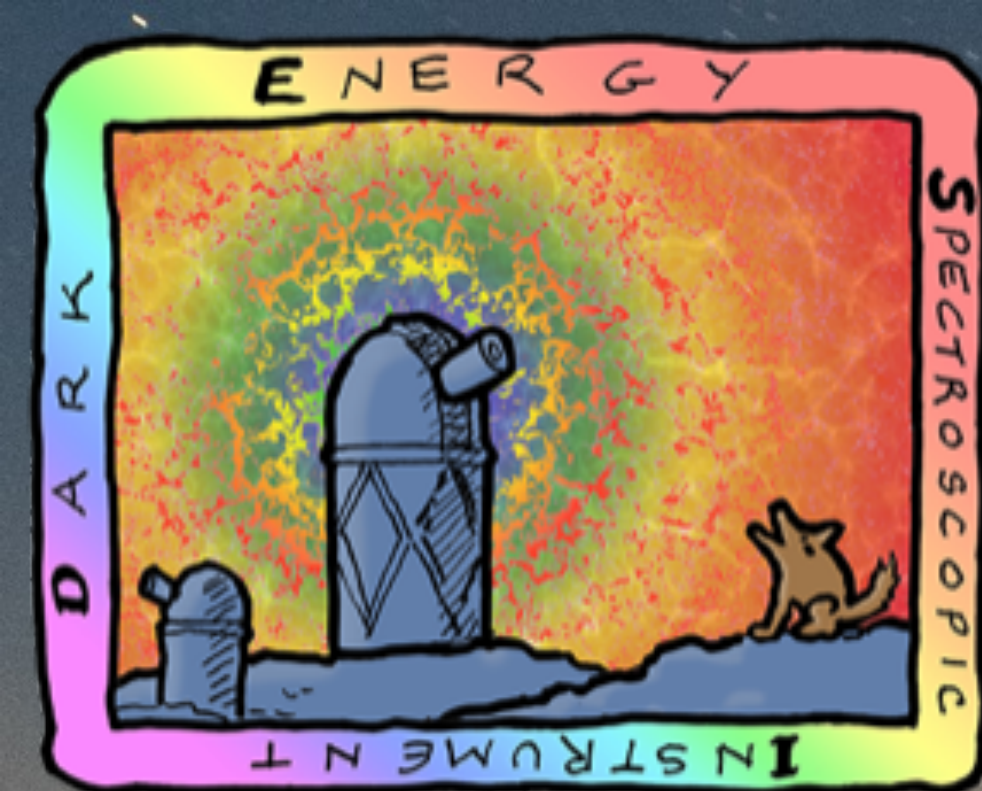


# DECaLS: future outlook

- Potential upgrades for future (post-DR10) DECaLS data releases
  - Include more recent DECam observations (2021 September onward)
  - Even more NEOWISE sky passes
    - 2021 onward, at least 2.5 more years compared to DR10
  - Include DECam Y band and DECam u band?
  - Narrow-band DECam filters?
  - Measure proper motions during Tractor processing
  - Pad out DR9/DESI footprint to allow increased DESI spectroscopic sky coverage?







# DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



Thanks to our sponsors and  
69 Participating Institutions!