The Dark Energy Survey Strong Lensing Science program

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On Behalf of the DES Collaboration

Galaxies and Cosmology in Light of Strong Lensing
KAVLI IPMU
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Outline

- Dark Energy Survey brief overview and status
- Strong Lensing Science Goals
- Lensing Forecasts
- Search strategies
- Plans for follow-up observations
- Summary

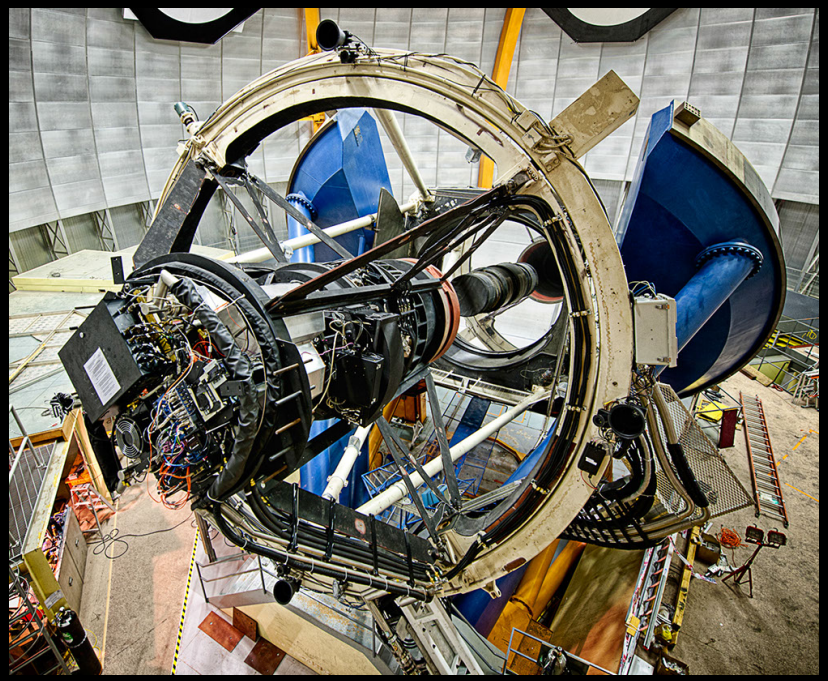
The Dark Energy Survey

- Probe Dark Energy and the origin of Cosmic Acceleration
  - Distance vs. redshift
  - Growth of Structure

- • Two surveys:
  - Wide fields - 5000 deg^2 in grizY to g=24
  - SN 1a - repeated visits over 30 deg^2

- Built new camera for CTIO Blanco telescope
  - 570 Mpixels
  - 3 deg^2 FOV
  - Facility instrument

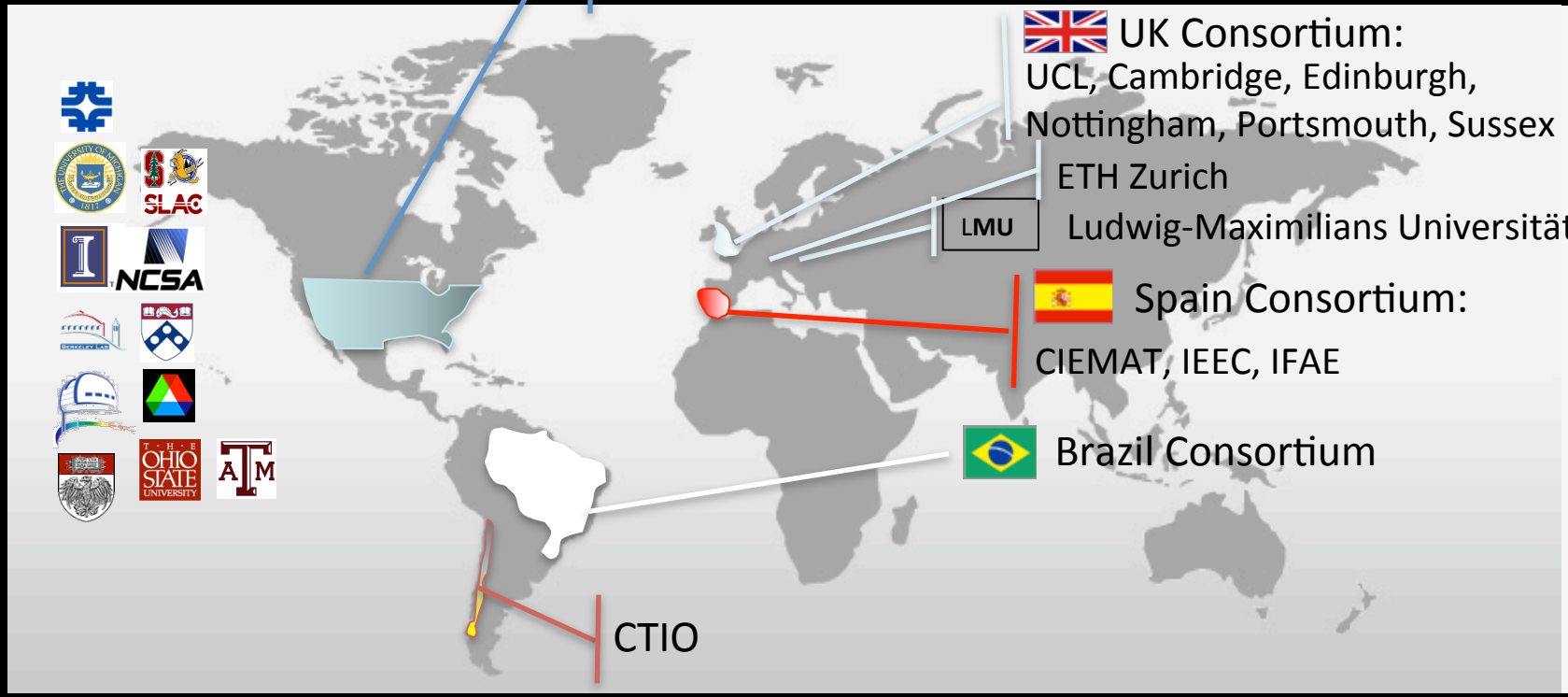
- • Five-year Survey
  - 525 nights (Aug - Feb)



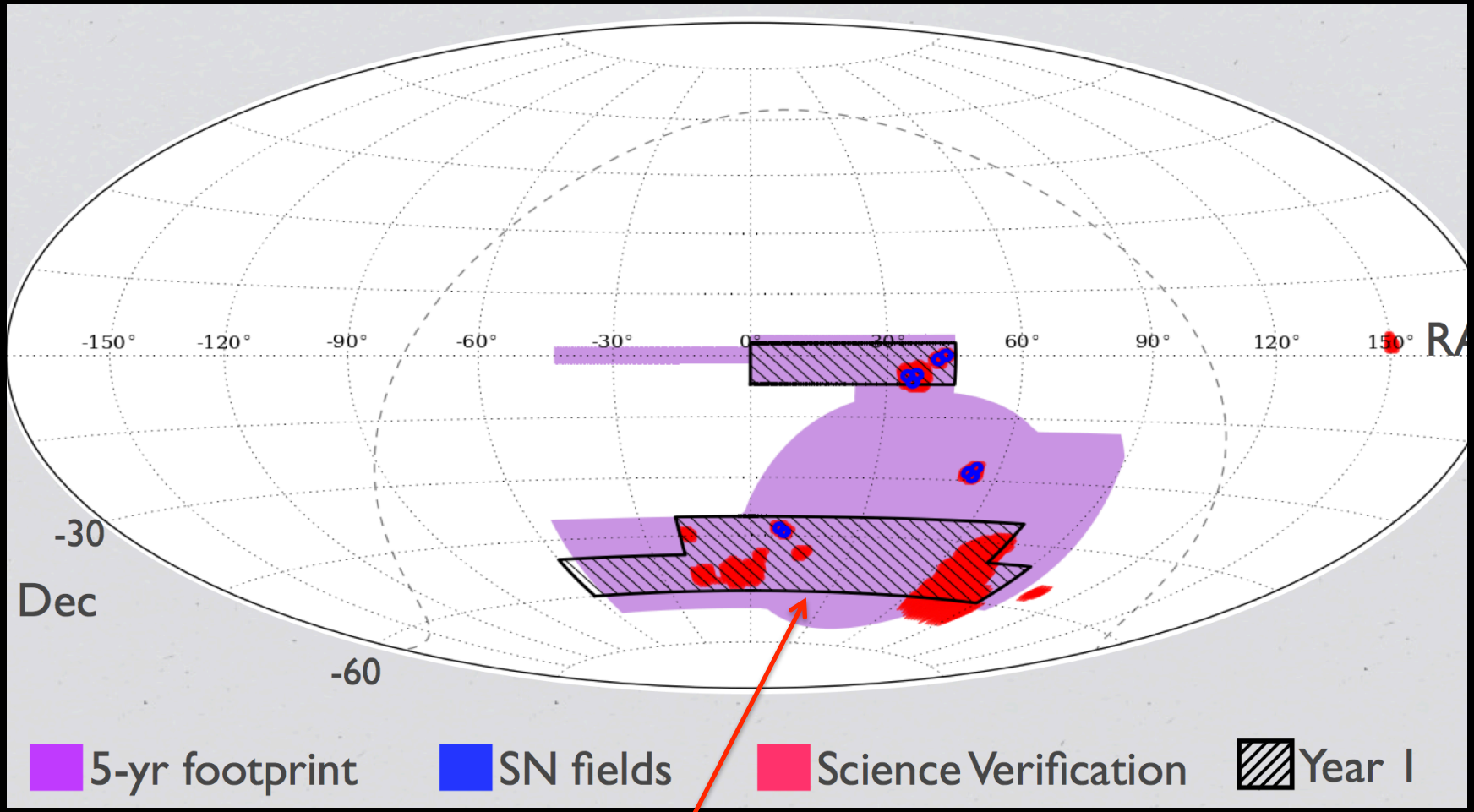
Dark Energy Survey Collaboration

~300 scientists

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M

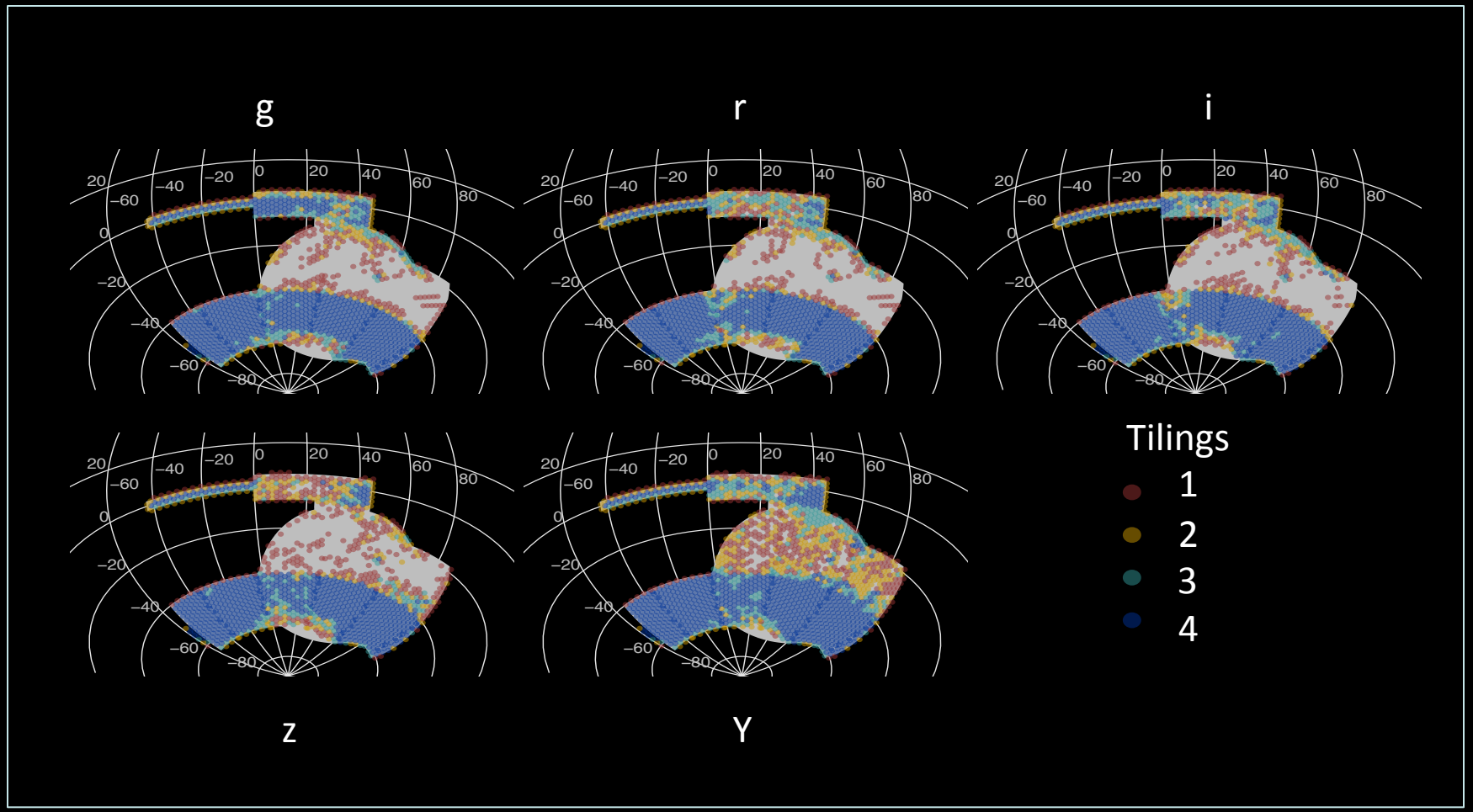


Survey Footprint



Overlap with the South Pole Telescope Survey (SPT)

Survey Progress
(Y1 + Y2 as of 11/10/2014)



DES Strong Lensing Science Goals

- One of the main objectives of the strong lensing science program in DES is to derive constraints on dark energy. The two key components of this part of the program will be exploiting
  - ✦ Lenses with background sources at multiple redshifts
  - ✦ Lensed quasars.
- In addition to cosmology we will also be able to use the sample to study dark matter mass profiles on varying scales from individual galaxies to massive clusters.
- We will also have a large sample of sources at varying redshifts which will be very valuable for studies of galaxy evolution. The excellent red-sensitivity of the DECam CCDs, along with the grizY filter set, mean that we will be sensitive to high-redshift Lyman Break Galaxies (e.g., g-band dropouts at z~ 4 or r-band dropouts at z~ 5).

DES Strong Lensing Forecasts

- Our current predictions are based on extrapolations from various studies in the literature. We are currently refining some of these using simulations.
  - ✦ We expect to find about 1000 lenses in DES with 18" > θ_E > 2" (where θ_E is the Einstein radius) of which about 200 would contain giant arcs (with arc length-to- width ratio > 8) based on extrapolations from the CFHTLS-Strong Lensing Legacy Survey (using the 54 systems with rank 3 and above from More et al. 2012).
  - ✦ In addition we also expect to find a sample of about 120 lensed quasars where the 2nd image has i < 21 (for a double) including 20 high information-content quads where the 3rd brightest image has i < 21 (Oguri & Marshall 2010)

Simulations of galaxy-galaxy lenses

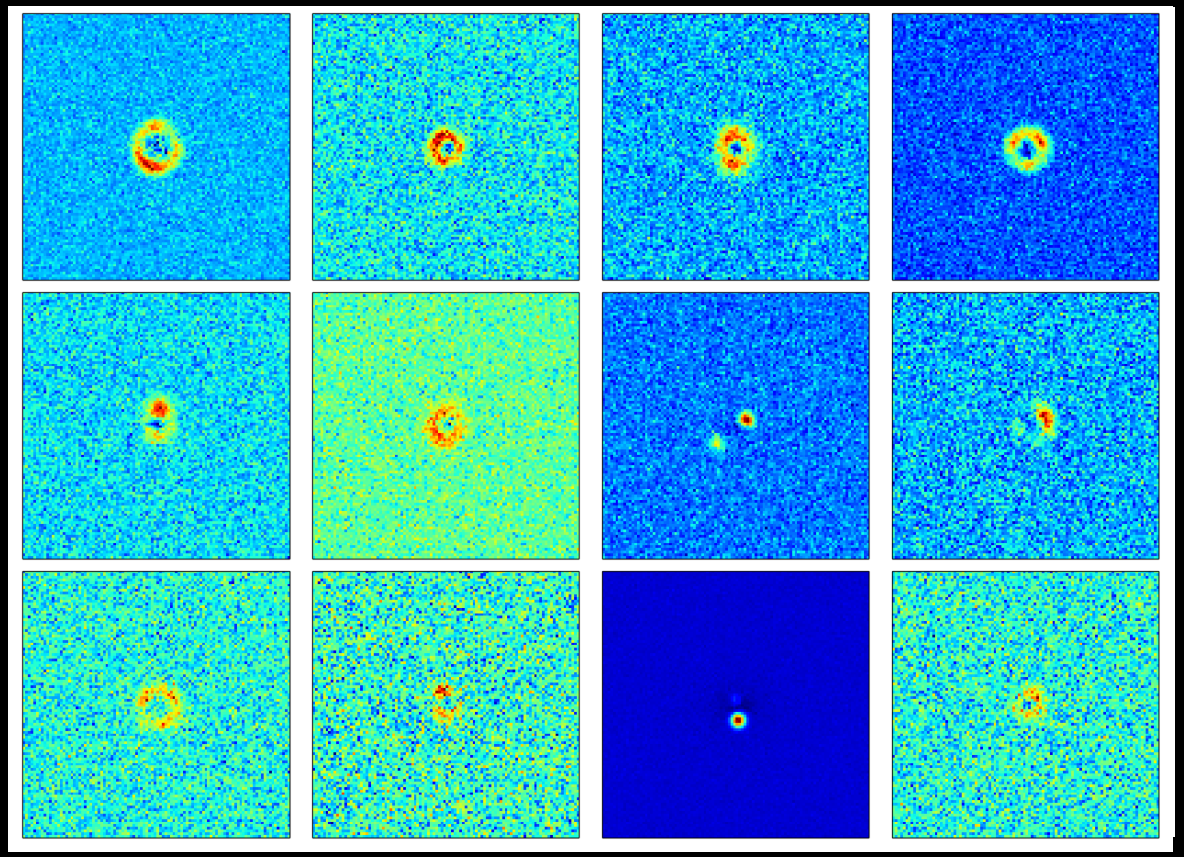
Deflectors: 4 million (σ_V>200 km/s)
Grade 1 or better: 720
Grade 2 or better: 370
Grade 3: 110

Grade 3: Almost unmissable.

Grade 2: We should find.

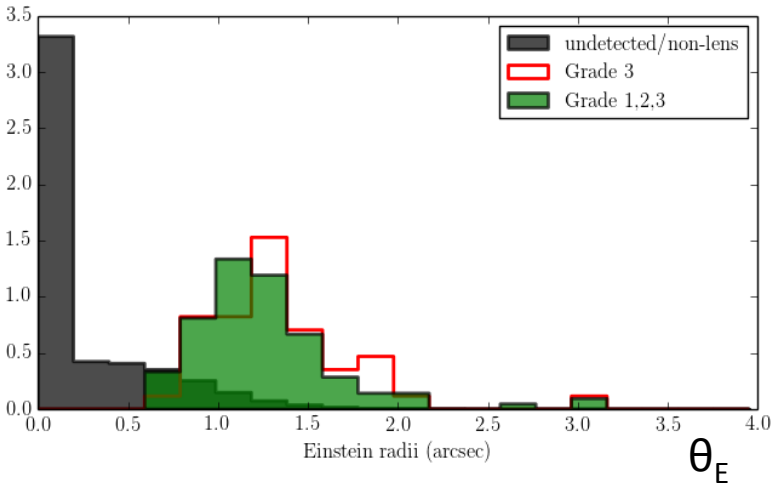
Grade 1: We could find.

Grading based on g-r residuals, not color images

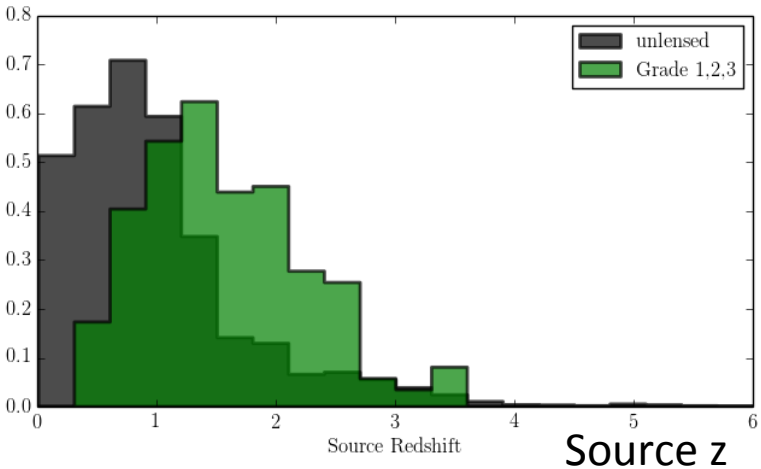


Work by Tom Collett (ICG, Portsmouth)

Simulations of galaxy-galaxy lenses

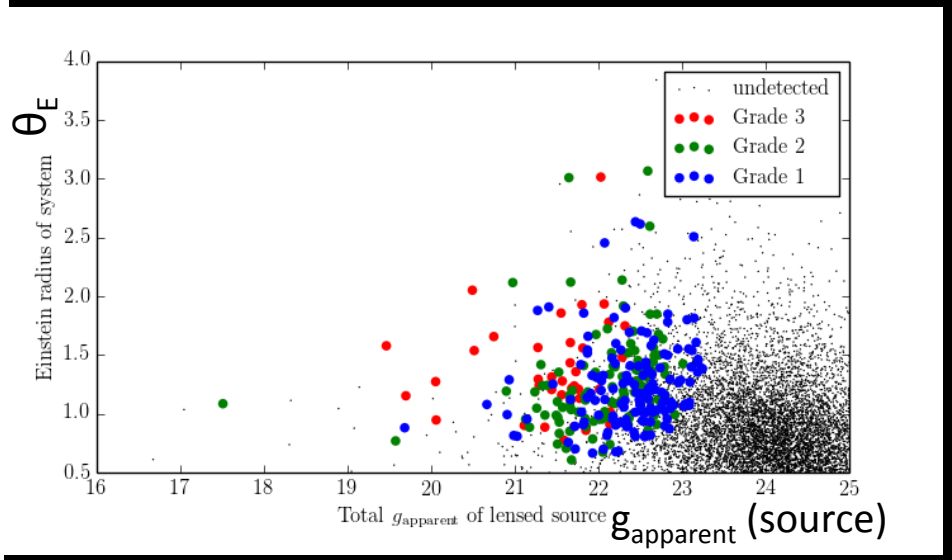


θ_E



Source z

Finding the double source plane lenses in the imaging data will be challenging given the DES resolution. Will probably need an HST Snapshot program. Would need to decide how to pre-select systems for such a program.



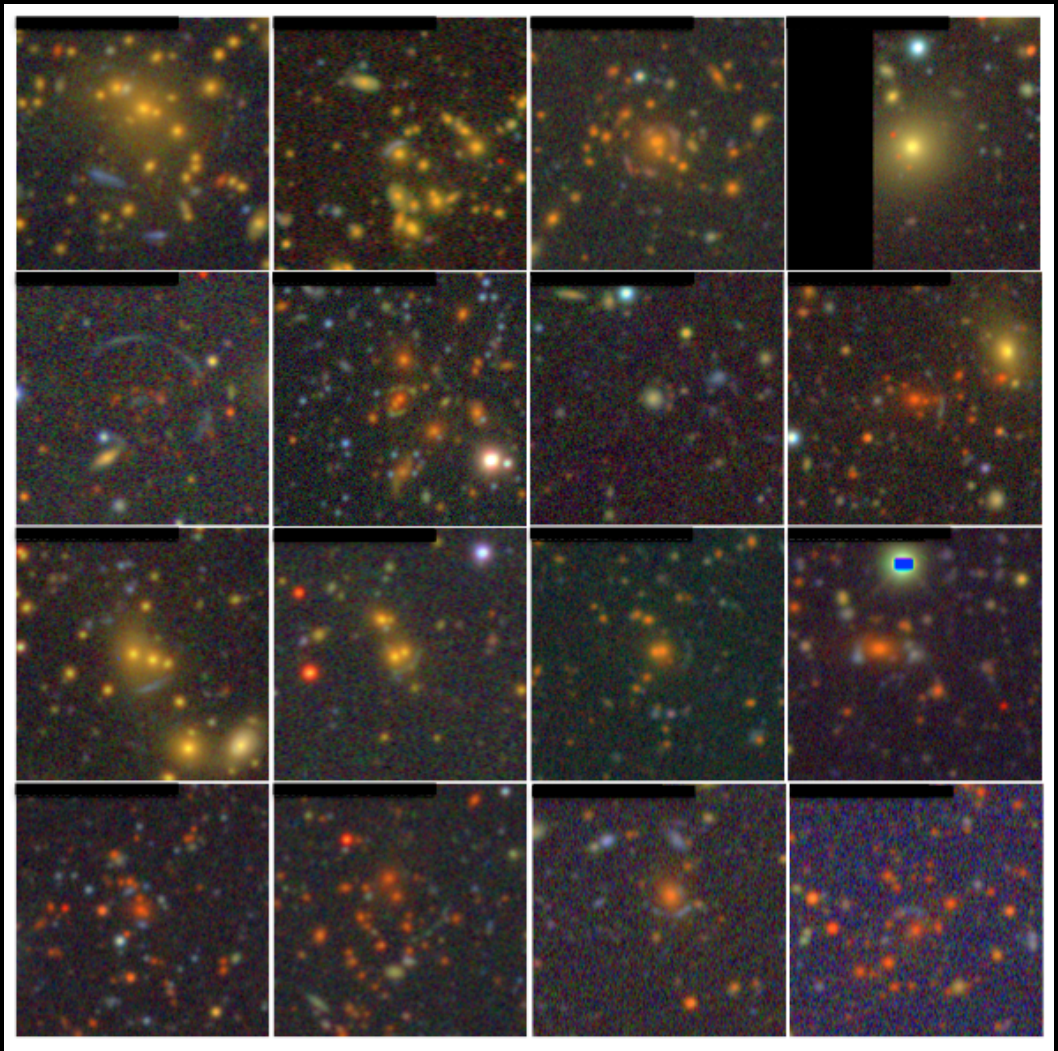
θ_E

$g_{apparent}$ (source)

Search strategies - Arcs

- Science Verification Data (SV-A1) ≈120 deg^2 to full 5 year depth in the SPT-E region of the footprint
  - ✦ Galaxy-scale and group-scale lenses selected via a visual inspection of all the wide field and SN field tiles
  - ✦ Cluster-scale lenses selected via a visual inspection of all known SPT cluster and visual inspection of RedMaPPer clusters
  - ✦ Multiple scanners looked at each field and then the targets were rank ordered
- Y1 data and beyond
  - ✦ Introduce automated arc finding, ARCFINDER code from More et al. Anupreeta is a DES External Collaborator.
  - ✦ Working with the SpaceWarps team to do a targeted search around DES LRGs using citizen scientists starting with the Y1 data release
  - ✦ Continue to examine RedMaPPer and SPT clusters
  - ✦ Implement a ring-finder ala Gavazzi – Tom Collett pursuing this.
  - ✦ Catalog searches looking for blue objects in association with LRGs – very successful strategy in SDSS but does require good de-blending in the object detection step

Examples of systems from SV-A1

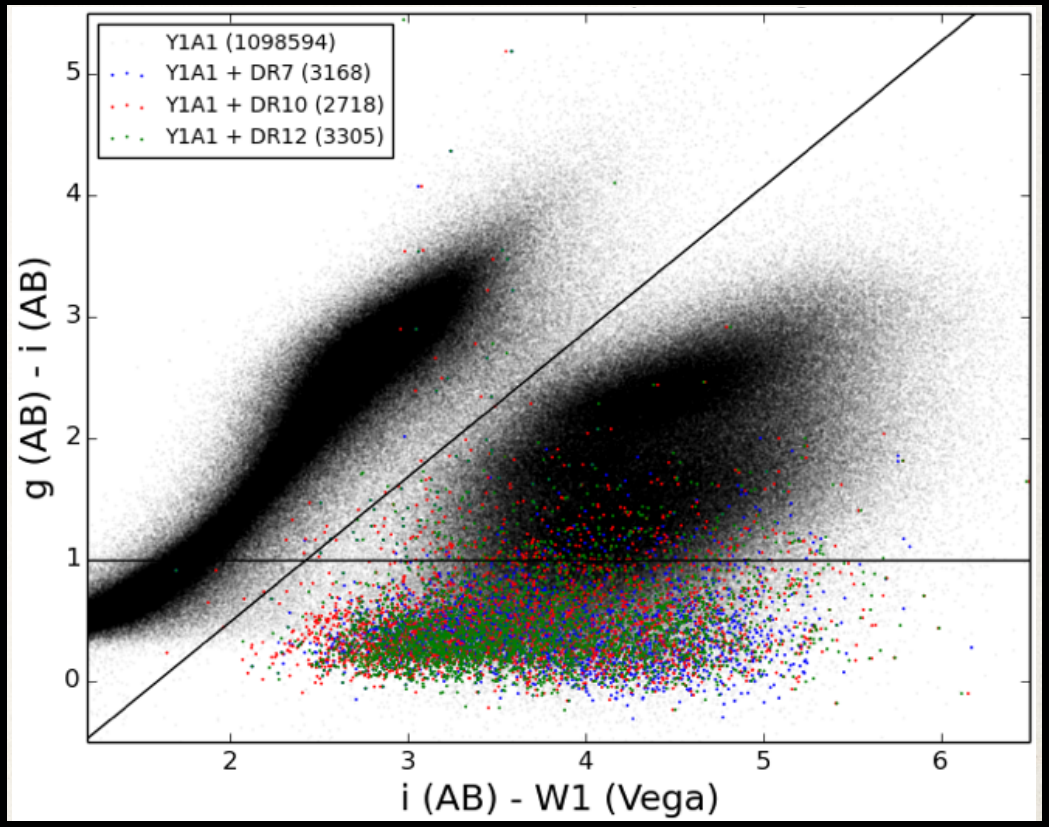


Search strategies – Lensed QSOs

- We have a DES External Collaboration called STRIDES (STRong lensing Insights into Dark Energy Survey) – PI - Tommaso Treu, Co-PIs - Matthew Auger, Liz Buckley-Geer, Frederic Courbin , Chris Fassnacht, Josh Frieman , Phi Marshall, Richard McMahon, Georges Meylan, Sherry Suyu
- Use a combination of color selection, morphology and variability
  - ✦ Wide separation lenses using a color selection – Fernanda Ostrovski and Richard McMahon (Cambridge)
  - ✦ Color selection + morphology plus machine learning – Adriano Agnello (UCLA)
  - ✦ Variability selection – Liz Buckley-Geer (Fermilab)

Search for wide separation lensed QSOs

- Require:
  - $i < 21.0$
  - $(g-i) < 1.0$
  - $(g-i) < 1.2(i-W1) - 2.8$
  - Looks like a point source
  - $N_{neighbors} < 20$ (within 15”)
- From Y1-A1 Stripe 82
  - Quasar candidates: 14199
  - Pair candidates with separation < 5”: 58



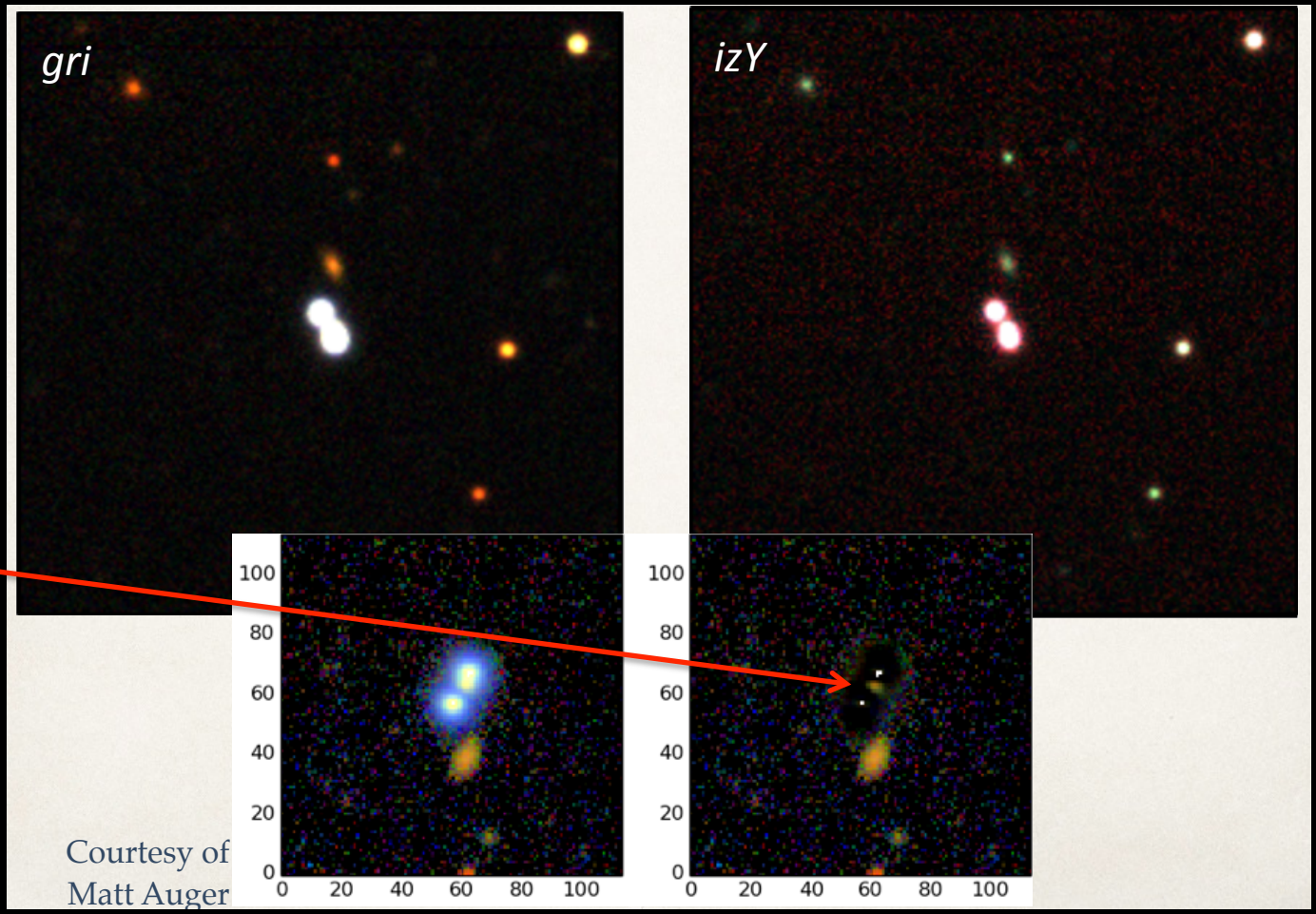
Y1-A1 Stripe 82 QSOs matched to SDSS QSO catalog

Example object from Y1-A1

Separation = 2.53”
Δ_{color} = 0.013

Do a fit to two point sources and see if there is any evidence for the lensing galaxy. Hint of a orange residual in the subtracted image.

Unfortunately this object is a pair of stars.

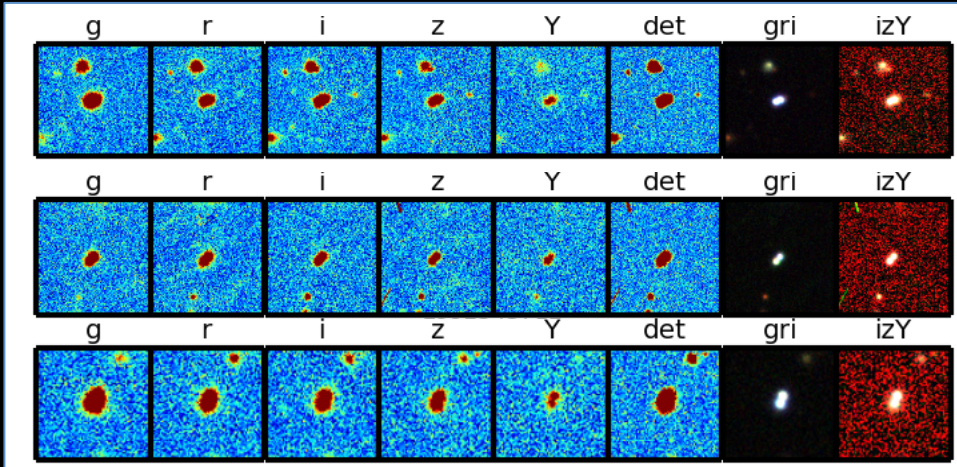


Machine learning selection

- Work done by Adriano Agnello (UCLA)
- Based on the SQLS search strategy
- Unblended objects: Look for QSO-like objects with close companions
- Blended: Look for QSO-like objects that are wider than the PSF
- Differences with SQLS
  - ✦ They had spectroscopy, DES only has *grizY*
  - ✦ We have no u band so need to use infrared, e.g. WISE
  - ✦ Lots of false positive in SQLS (QSO pairs, unlensed QSO + early type galaxies, blue galaxies)

Status of the machine learning selection

- Start with a catalog query using simple color cuts, also match to other surveys, e,g. WISE
  - $16 < i < 20$, $g - r < 0.6$, $r - i < 0.45$, $i - z < 0.4$
  - $2.5 < i - W1 < 5$, $0.5 < W1 - W2 < 1.5$
  - $g - i < 1.2(i - W1) - 2.8$
- Add other catalog variables such as photometry and second moments
- Apply pixel-by-pixel techniques to rank candidates
- Ready to apply the technique to Y1 data



Some examples of selected objects from SV-A1 with $19 < i < 20$

Variability selection

- "Selecting Quasars by their Intrinsic Variability" Schmidt et al. 2010 ApJ 714 1194
- Idea was to identify a sample of quasars using their intrinsic variability rather than their UV-excess. Motivated by surveys like Pan-STARRS 1 which, like DES, has no u-band
- Define the Variability Structure Function

$$V_{i,j}\left(\Delta t_{i,j}\right) = \Delta m_{i,j} - \sqrt{\sigma_i^2 + \sigma_j^2}$$

- $\Delta m_{i,j}$ is the measured magnitude difference between observations *i* and *j*. σ_i and σ_j are the photometric errors on the measurements and $\Delta t_{i,j}$ is the time difference between the two observations
- Based on Richards et al (2006) assume a power law increase in variability as a function of the time lag $\Delta t_{i,j}$ and fit an un-binned maximum likelihood to a set of data ($\Delta m_{i,j}$, $\Delta t_{i,j}$) ($V_{eff,I,j}$ is the observed variability)

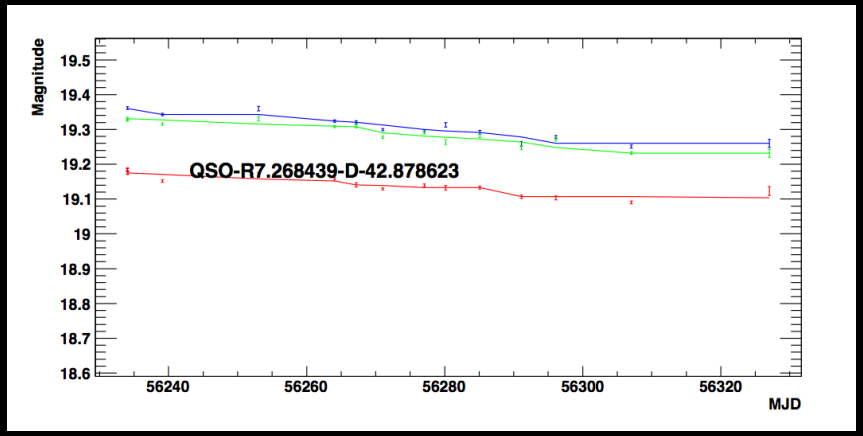
$$V_{\mathrm{mod}}\left(\Delta t_{i,j} \mid A,\gamma\right) = A\left(\frac{\Delta t_{i,j}}{1yr}\right)^{\gamma}$$

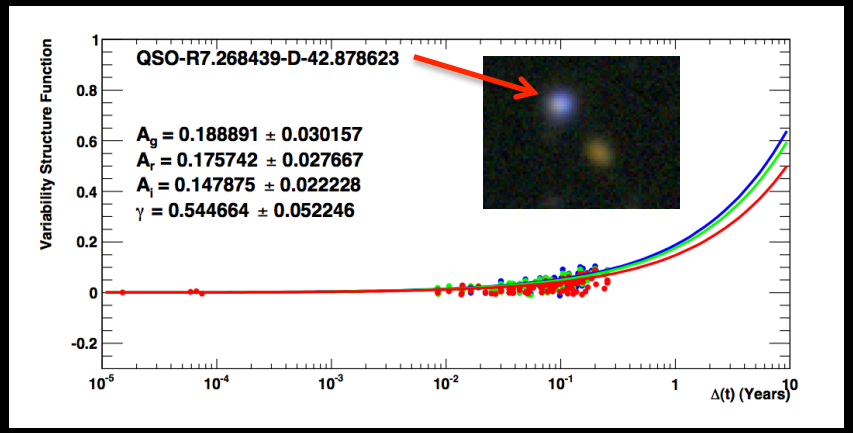
$$L_{i,j} = \frac{1}{\sqrt{2\pi V_{eff,i,j}^2}} \exp\left(\frac{\Delta m_{i,j}^2}{2V_{eff,i,j}^2}\right)$$

$$V_{eff,i,j}^2 = V_{\mathrm{mod}}\left(\Delta t_{i,j} \mid A,\gamma\right)^2 + \left(\sigma_i^2 + \sigma_j^2\right)$$

Status of variability search

- Verified the method on SDSS Stripe 82
- Looked at known QSOs in DES SV-A1 data
- Technique looks promising once we have a larger lever arm in Δt
- Could be used in conjunction with the machine learning or the color selection as an additional filter





Plans for follow-up observations

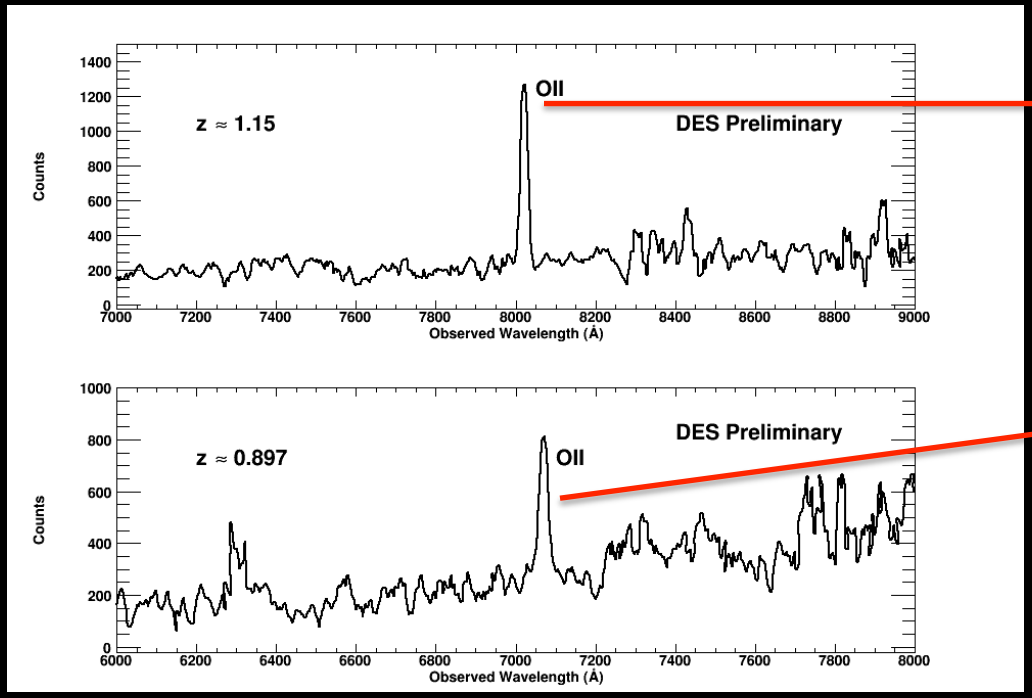
- Currently focusing on spectroscopic confirmation
  - The OzDES program in the SN fields using AAT/AAOmega – suitable for bright targets r ≤ 22.5 (5 fibers per pointing for lensing targets)
  - Magellan – currently 1-2 nights per semester through the University of Chicago using IMACS
  - Gemini South Large and Long program
    - Target the lensing features and also additional galaxies in the field for photo-z calibration to reduce biases on *w* caused by sample variance
    - Awarded 276 hours over three years
    - Initially 80 hours in 2014B and 12 hours in 2015A
    - Submitted a total of 24 targets for 2014B.
    - Spent 6 nights at the telescope in October as a Priority Visitor – you get to pick the good nights and they do the queue on the bad nights
    - We observed 12 of the 24 systems. At least 5 have obvious emission lines

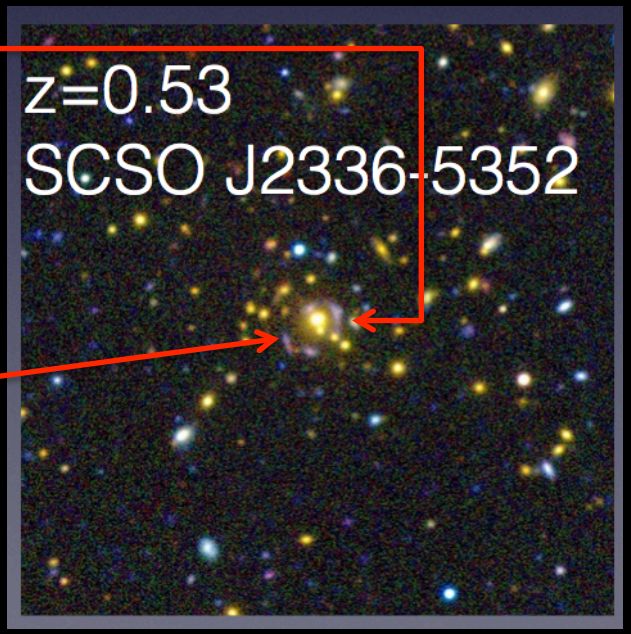
Gemini LLP Collaborators

Observing at Gemini

Example of one of the Gemini targets

- Known cluster from the Southern Cosmology Survey using the MOSAIC imager on the BLANCO (Menanteau 2010)
- Very preliminary reductions. Prominent emission line in both features at different redshifts. If we assume OII then we get z ≈ 0.897 and z ≈ 1.15





DES Image

Summary

- The Dark Energy Survey is well under way.
- We already have a number of interesting lensing candidates from the Science Verification data
  - ✦ Spectroscopic follow-up with our Gemini South LLP, AAT and Magellan
  - ✦ Starting to do some modeling using the DES images
- The Y1 data release should yield:
  - ✦ Lots more arc candidates
  - ✦ First lensed QSO candidates
- Looking forward to doing great science.