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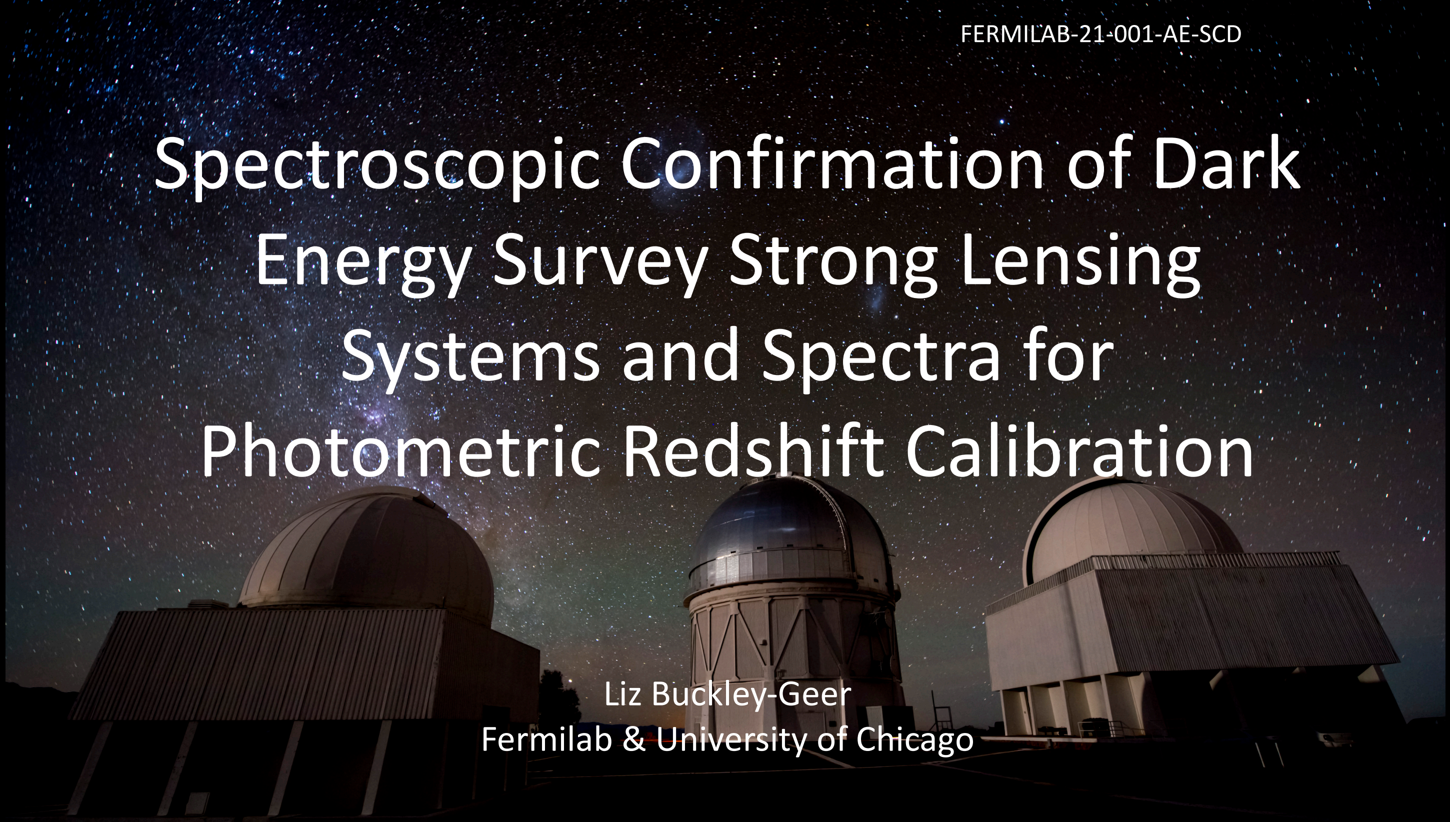

Spectroscopic Confirmation of Dark Energy Survey Strong Lensing Systems and Spectra for Photometric Redshift Calibration

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Extragalactic Astronomy with Gemini Large and Long Programs
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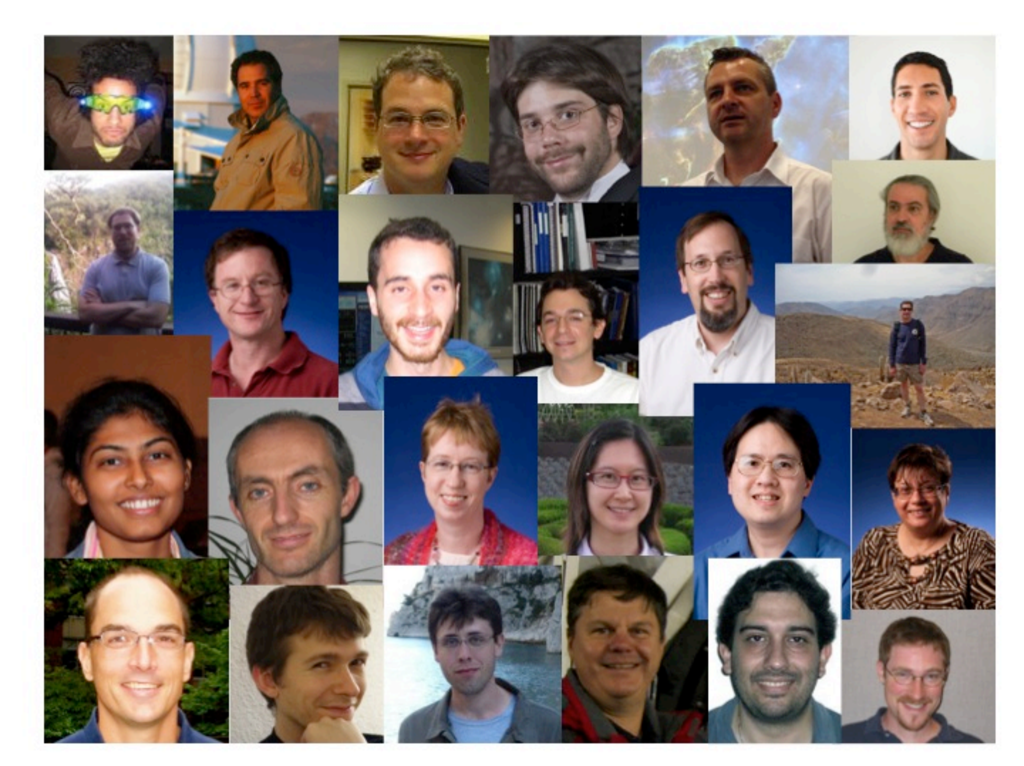
Gemini LLP Collaborators



Outline

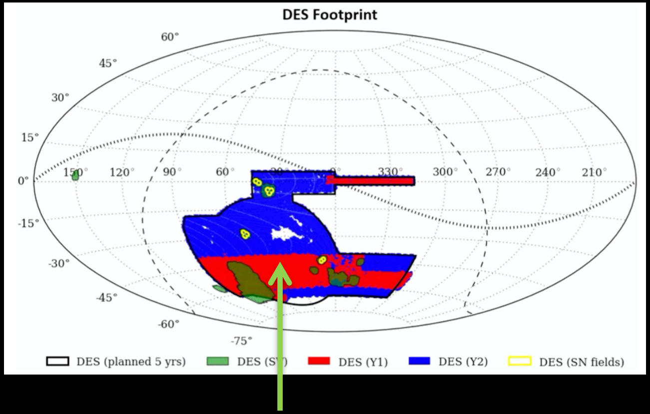
- Gemini Program
- Lens Search strategies
- Results from
  - Nord et al. ApJ 827, 51, 2016 “OBSERVATION AND CONFIRMATION OF SIX STRONG-LENSING SYSTEMS IN THE DARK ENERGY SURVEY SCIENCE VERIFICATION DATA“
  - Nord et al. MNRAS 494, 1308, 2020 “Observation and Confirmation of Nine Strong Lensing Systems in Dark Energy Survey Year 1 Data “
  - Poh et al, in preparation
  - Lin et al. ApJ 383, 15, 2017 “Discovery of the Lensed Quasar System DES J0408-5354”
  - Shajib et al. MNRAS 494, 6072, 2020 “STRIDES: a 3.9 per cent measurement of the Hubble constant from the strong lens system DES J0408−5354 “
  - Buckley-Geer et al. MNRAS 498, 3241, 2020 “STRIDES: Spectroscopic and photometric characterization of the environment and effects of mass along the line of sight to the gravitational lenses DES J0408-5354 and WGD 2038-4008"
  - Collett et al. ApJ 843, 148, 2017 “Core or Cusps: The Central Dark Matter Profile of a Strong Lensing Cluster with a Bright Central Image at Redshift 1“
- Photometric-redshift calibration
- Summary

Gemini Program

- Spectroscopic confirmation of strong lens candidates
- Spectroscopy of galaxies in the strong lensing fields for photometric redshift training
- Awarded 276 hours on Gemini South with GMOS over three years 2014-2016
- Observing for years 1&2 done in Priority Visitor mode/queue and year 3 in queue
- We observed 43 lens candidates and confirmed 17 of them as gravitational lenses (40% success rate)
- We obtained 659 redshifts from 950 galaxy targets (70% success rate)
- Year 1 - 68% completion, Year 2 - 64% completion, Year 3 - 9% completion (low completion related to bad El Nino in 2015B)

Strong lensing search strategies

- 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 galaxy clusters
  - ✦ Multiple scanners looked at each field and then the targets were rank ordered
- Y1 data
  - ✦ Examine RedMaPPer and SPT clusters (redM, SPT)
  - ✦ Catalog searches – very successful strategy in SDSS



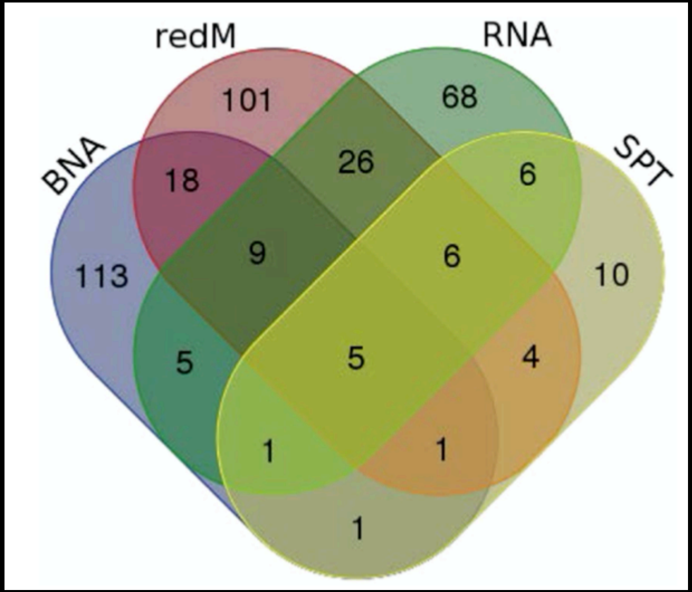
Overlap with the South Pole Telescope Survey (SPT)

DES Year 1 Catalog searches

- Diehl et al., ApJS 232, 15, 2017
- Lens candidates are selected as galaxies with at least one of g,r,i < 21.5
- Blue objects near any galaxy (BNA)
  - Source object has at least one of g,r,i < 21.5
  - $g - r < 1.0 \;\; r - i < 1.0$
  - Select objects within 8” of lens. Multiple objects associated to the same lens need to have similar colors $|\Delta(g-r)|, |\Delta(r-i)| < 0.25$
- Red objects near any galaxy (RNA)
  - Source object has at least one of g,r,i < 21.5
  - $g, r, i \; < \; 21.5, g > 23, g - r > 0 \;\; r - i > 0$ OR $g, r, i \; < \; 21.5, g > 23, r > 23, r - i > 0 \;\; i - z > 0$
  - Select objects within 8” of lens. Multiple objects associated to the same lens need to have similar colors $|\Delta(r-i)|, |\Delta(i-z)| < 0.25$

Catalog search results

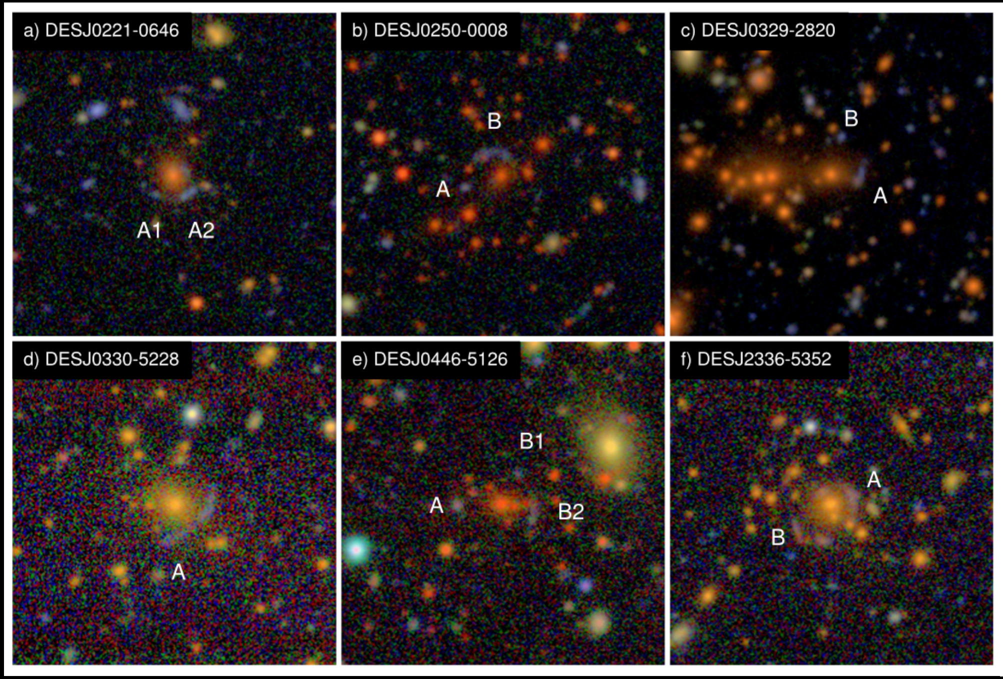
- redMaGiC galaxies (Rozo et al. 2016)
  - ✦ 3 million galaxies
  - ✦ Look for 3 or more blue objects within 10” of the galaxy, $-1 < g - r < 1, -1 < r - i < 1, r < 22$
- All systems were scanned by 5 people who assigned a score 0 = non a lens, 1 = possible lens, 2 = most likely to be a lens
- Scores were summed and those with rank > 3 were taken as the final list of 374 (348 are new systems)



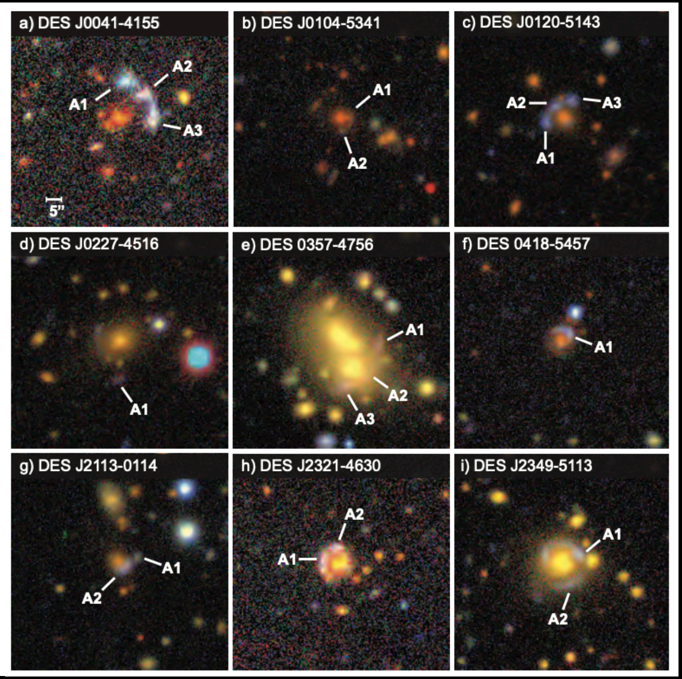
Diehl et al. 2017

Confirmed systems

SV – Nord et al. 2016

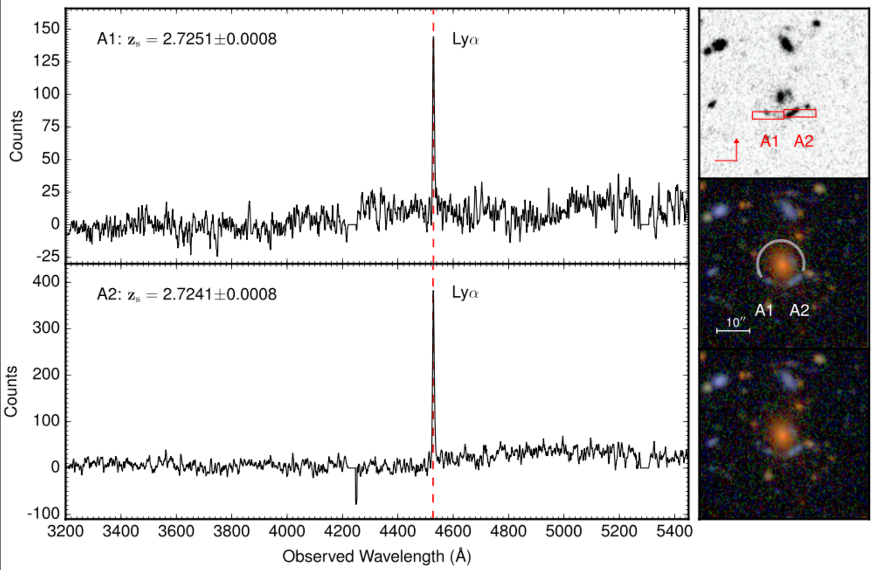


Y1- Nord et al 2020

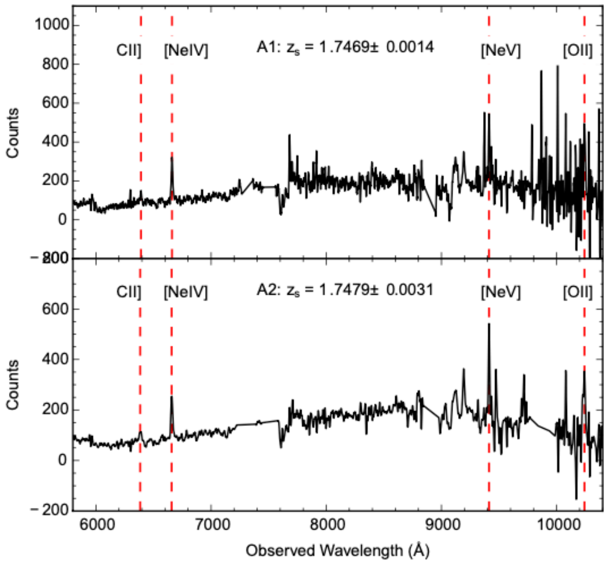


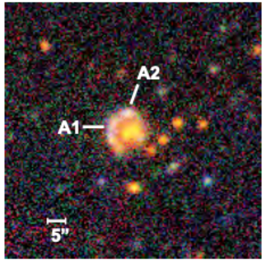
Example spectra

SV - DES J0221-0646 (Nord et al. 2016)



Y1 - DES J2321-4630 (Nord et al 2020)



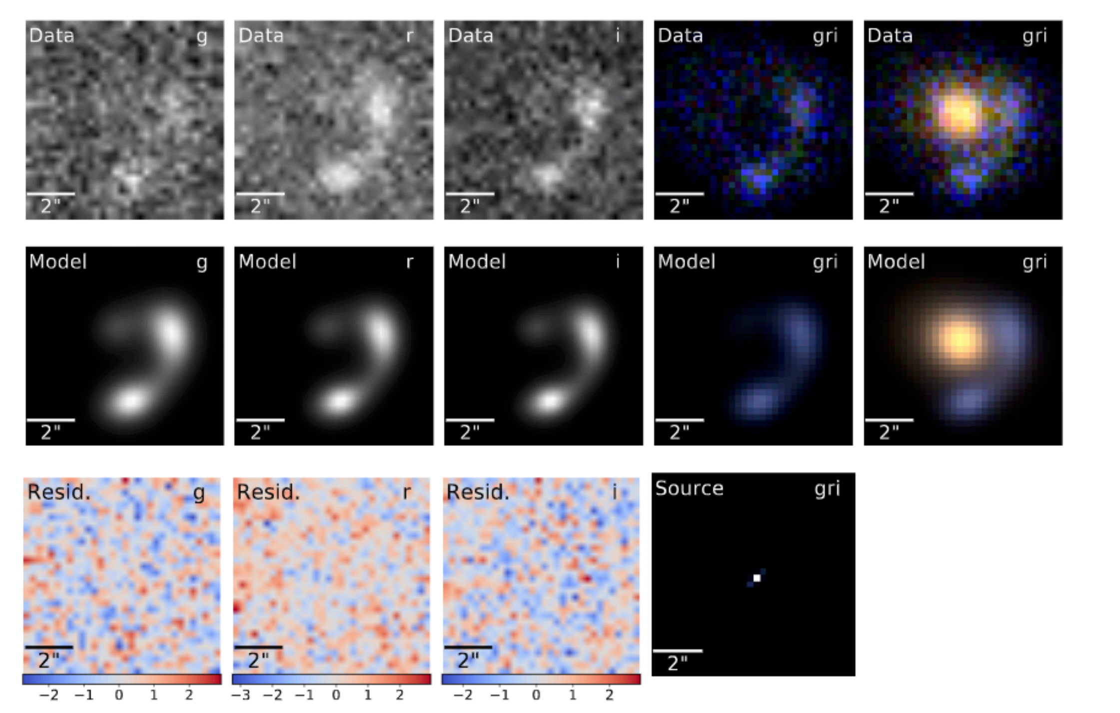


Ne emission lines in combination with OII line suggests the possibility that the source is a radio galaxy.
Humphrey et al. 2007

Lens Modeling for the Y1 lenses

- Pilot effort towards statistical study of properties of early-type galaxy lenses found in DES data.
  - In the vein of previous work done by the Sloan Lens ACS Survey (SLACS) and the Strong Lensing Legacy Survey (SL2S).
- We model the simpler 1-2 lens galaxies configurations, infer their best-fit mass model parameters, estimate their enclosed masses, mass-to-light ratios and dark matter mass fraction, and compare it with existing studies (e.g. Cardone et al, 2009).

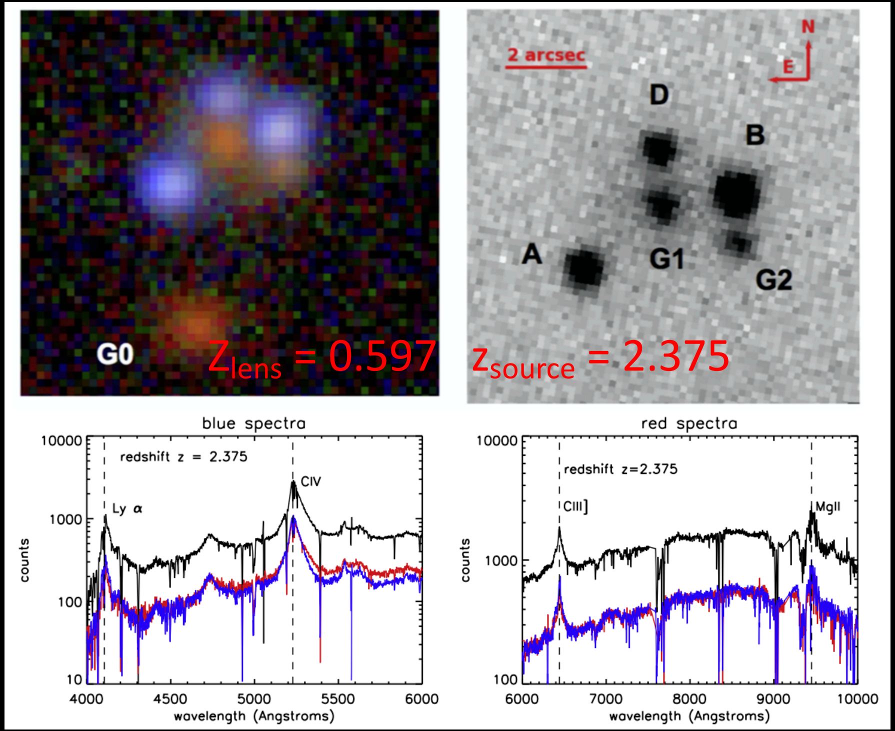
DESJ0104-5341



Poh et al., in preparation

Discovery of a lensed quad quasar – DES J0408-4354

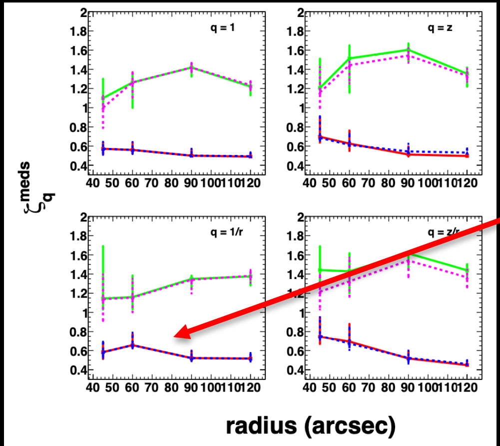
- This system showed up in the redMaGiC galaxies search. The blue objects of the lensed quasar just happened to be close enough to the galaxy G0 to get selected.
- It was confirmed in our 2015 observing- Lin et al. 2017
- First quad discovered in DES
- We took additional spectra of the lensing galaxy G1 and some of the additional lensing features using different masks
- We also had a dedicated program to get more spectra (PI: H. Lin; GS-2018B-Q-220)



Lin et al. 2017

H_0 measurement for DES J0408-4354

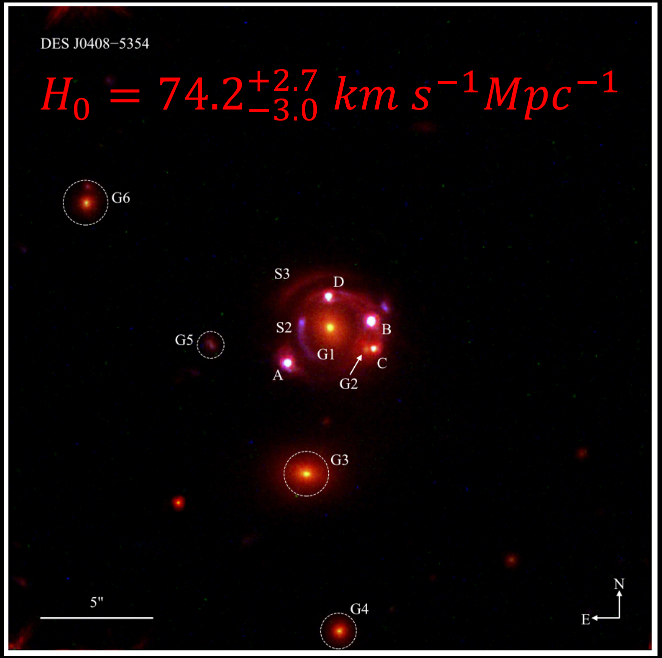
- The Gemini data were used as part of the measurement for the line-of-sight contribution (Buckley-Geer et al. 2020) to the measurement of H0 from this system in Shajib et al. 2020



Buckley-Geer et al. 2020

DES J0408 is in a significantly under-dense field compared to the random fields

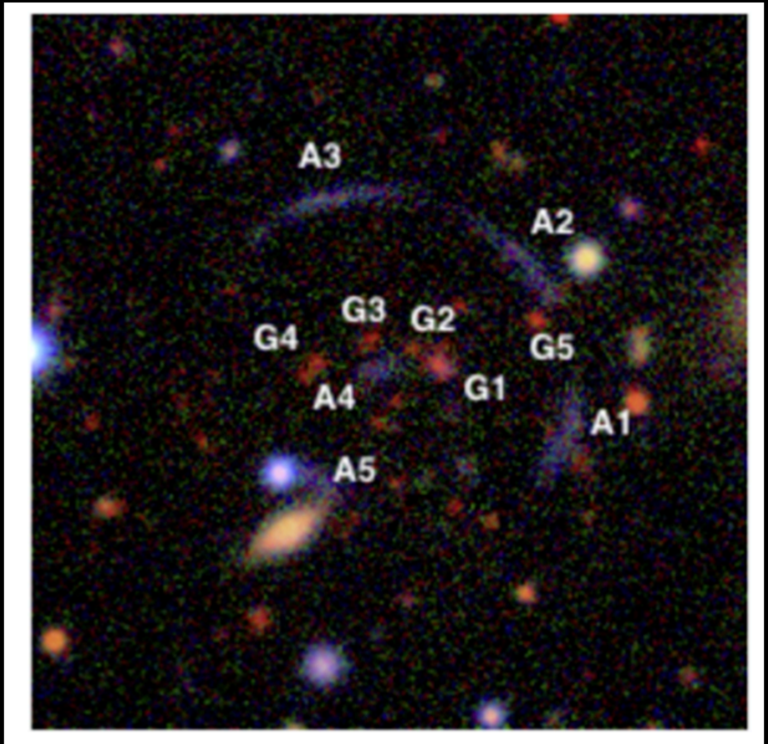
Shajib et al. 2020



HST RGB Image (F160W+F814W+F475X)

SPT-CLJ2011-5228

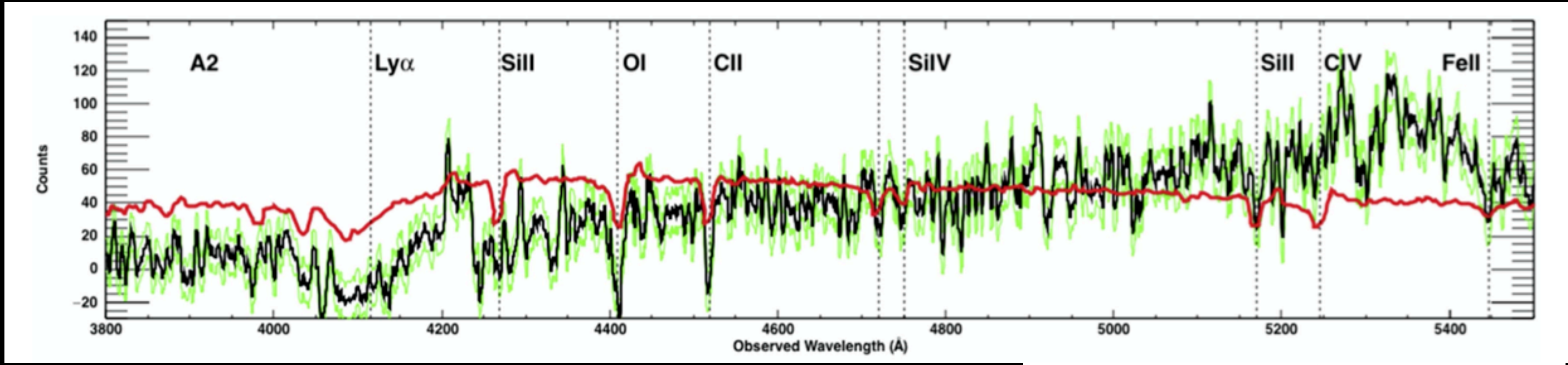
- This system was one of the 224 galaxy clusters detected in the first 720 deg^2 of the South Pole Telescope-SZ survey (Bleem et al. 2015)
- It was in the part of the DES footprint observed in Year 1 and found via the search of all known SPT clusters
- It is interesting because one can see the central image (A4) that is usually obscured by the lensing galaxy. We can use this to try and constrain the central dark matter profile of the cluster
- We took spectra of A2, A3 and A4 on one mask and G1-G5 on another mask.



Collett et al. 2017

- The source is a Lyman Break galaxy at z_{source}=2.388 with Lyα absorption rather than emission

Collett et al. 2017



- The average redshift of G1-G5 is z=1.0644
- The mass within the Einstein radius is

$$log_{10}\left(\frac{M}{M_{\odot}}\right) = 14.170 \pm 0.004$$

Table 2
Redshifts for A2–A4

Object	R.A.	Decl.	Redshift	*R*-value
A2	302.777796	−52.468769	2.3875 ± 0.0002	4.62
A3	302.785149	−52.467079	2.3889 ± 0.0002	5.34
A4	302.783661	−52.471130	2.3875 ± 0.0004	2.26

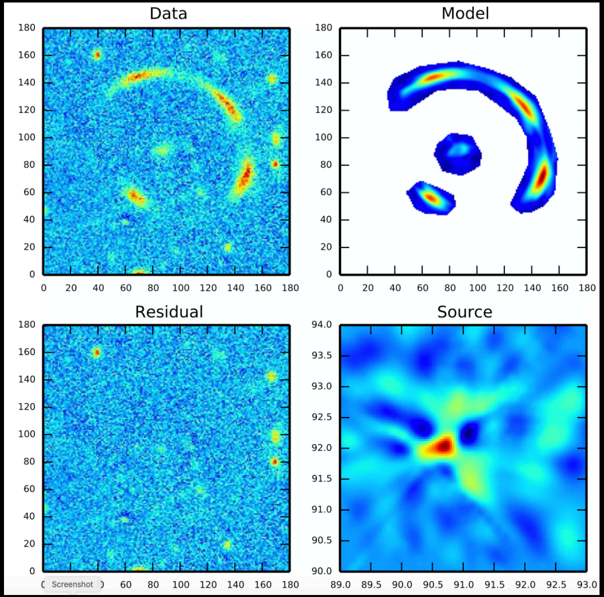
Table 3
Redshifts for G1–G5

Object	R.A.	Decl.	Redshift
G1	302.78122	−52.47105	1.0645 ± 0.0002
G2	302.78244	−52.47035	1.0737 ± 0.0002
G3	302.78418	−52.47032	1.0642 ± 0.0002
G4	302.78605	−52.47087	1.0514 ± 0.0002
G5	302.77766	−52.46994	1.0684 ± 0.0002

Mass Profile Fitting

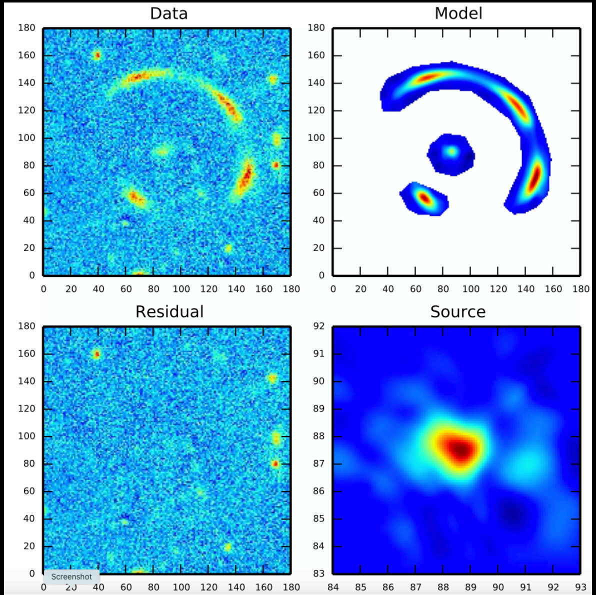
One-halo NFW profile
Inner slope $\alpha = 0.38 \pm 0.04$
Strongly excluded by CDM models

Two-halo NFW profile
Inner slope $\alpha_1 = 0.98 \pm 0.08$
$\alpha_2 = 0.79 \pm 0.08$



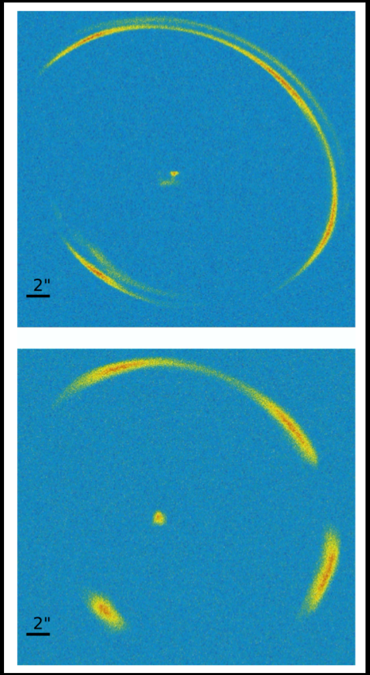
Both profiles are a good fit to the data

The ground-based images are not high-enough resolution to distinguish between the two models so we applied for HST observations



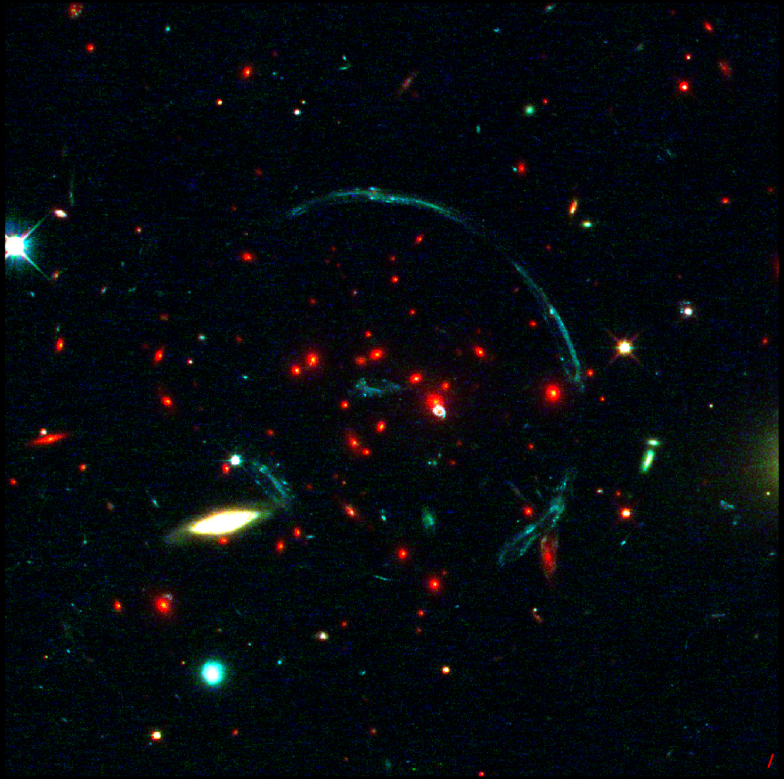
HST Image

One-halo simulation



Two-halo simulation

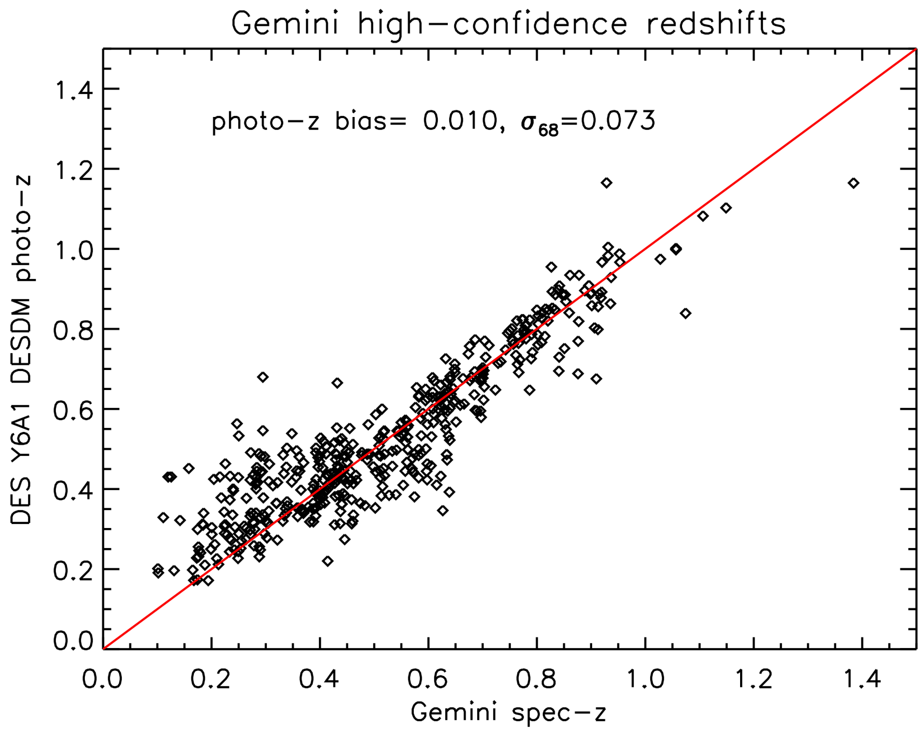
HST image clearly consistent with the two-halo simulation



Photometric redshift calibration

- Photometric redshift calibration requires spectroscopic redshifts spread over many different fields in order to reduce the biases caused by sample variance on the dark energy parameter *w* extracted from DES cosmic shear measurements (Cunha et al. 2012)
- Current spectroscopic samples are concentrated in a limited number of fields
- The lensing targets are randomly distributed across the DES footprint so we simultaneously observed about 30 additional galaxy targets in the GMOS mask of each strong lensing target.
- The galaxies were selected from DES with $i < 22.5$
- We currently have 950 spectra (the R150 spectra from Year 1 proved tricky to reduce and the ~360 photo-z targets have not yet been reduced) which yields 659 good redshifts (70% success rate)

Comparison with DES Year 6 Photo-z



- The sample has been used for photo-z testing of DES Y3 and Y6 galaxies

DARK ENERGY SURVEY

DARK ENERGY SURVEY

Summary

- Our Gemini LLP was a success.
- We confirmed 17 new strong lenses
- Published
  - ✦ 3 papers directly on the lensing confirmations
  - ✦ 1 paper on dark matter modeling
  - ✦ 2 papers using the spectra for lens modeling for the lensed quasar DES J0408
- In preparation
  - ✦ Lens modeling of some of the Y1 systems
- The galaxy spectra have been used for DES Y3 and Y6 photo-z testing