COOL-LAMPS in a Dark Sky

Mike Gladders

for the **ChicagO Optically-selected Lenses – Located At the Margins of Public Surveys** collaboration

What is COOL-LAMPS?

- *A research collaboration centered in a 2-quarter research-intensive class - “The Astronomy and Astrophysics Field Course”- at the University of Chicago that serves primarily 3rd year astro majors. The class is typically taken by ~10 students each year, out of a class of typically 20-25 majors per year.*

- *Students spend the first quarter developing background knowledge, and observing and data analysis skills, then participate in multiple observing runs, and spend the second quarter analysing the resulting data and moving their results toward publication.*

Who Are We?

2020:
Katya Gozman (U Michigan)
Erza Sukay (Johns Hopkins)
Michael Martinez (UW Madison)
Jason Lin
Liz Medina
Daniel Stein
Emily Sisco (U Mass)
Finian Ashmead (Pittsburgh)
Owen Matthews-Acuña (UW Madison)
Jorge Sanchez (Arizona State)
Kaiya Merz (STScI)
Kiyan Tavangar (Columbia)

2021:
Will Cerny(Yale)
Isaac Sierra(UC Davis)
Ben Levine (Stony Brook)
Viraj Manwadkar (Stanford)
Daniel Marohnic
Yunchong Zhang (Pittsburgh)
Eric Zaborowski (Ohio State)

2022:
Nathalie Chicoine(U Pittsburgh)
Yue Pan(Princeton)
Alexandra Masegian(Columbia)
Grace Wagner(CSM)
Rowan Glusman (Amsterdam)
Aidan Cloonan(UMass Amherst)
Marcos Tamargo(U Pittsburgh)
Diego Garza (UC Santa Cruz)
Ruoyang Tu (Yale)
Gabriela Horwath
Simon Mork (Arizona State)

2023:
Marie Tagliavia (Notre Dame)
Andi Kisare (UChicago)
Isaiah Escapa
Jamar Sullivan (UChicago)
Josh Garza (Google)
Kabelo Tsiane (U Michigan)
Kunwanhui Niu
Raul Teixeira (Duke)
Riley Rosener
Megan Zhao (U Penn)
Natalie Malagon (RIT)

2024:
Sarah Grannis
Rohit Venuturupalli
Joseph Yeung
Daniel Babnigg
Camila Silva
Paxson Swierc
Emory Murff
Jason Wu

Gourav Khullar (Pittsburgh → Washington)
Håkon Dahle (Oslo)
Kate Napier (U Michigan → Rubin)
Tony Stark (SAO)
Michael Florian (Arizona)
Keren Sharon (U Michigan)
Maxwell Klein (U Michigan)

Jane Rigby (GSFC)
Guillaume Mahler (Liege)
Matt Bayliss (U Cincinatti)
Lindsey Bleem (ANL)
Kate Whitaker (UMass Amherst)
Sasha Brownsberger (Harvard)

What Have We Been Doing?

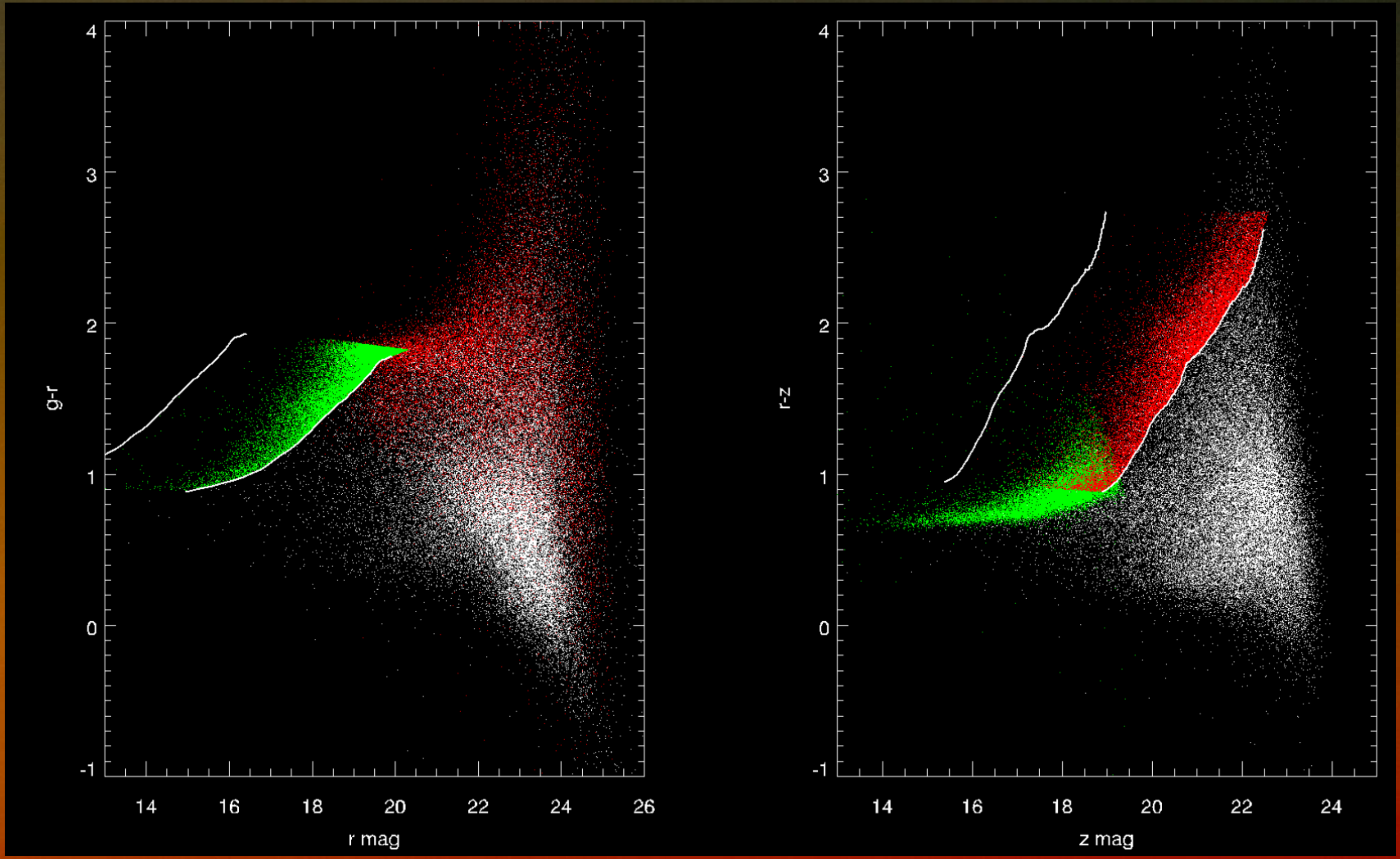
- *The framing of the class and collaboration is set by the need to engage students quickly in research work, while providing an authentic experience that generates research that is of interest to the broader community, and that is worth spending telescope time on. (For those in the know, this is based in the CURE pedagogy.)*
- *Searching for rare gems in publicly available data - in this case the `gems' are strong lenses – works well in this context.*
- *Strong lenses are (broadly speaking) morphologically distinct, and prior work (e.g. SGAS, SpaceWarps) has shown that minimal training is needed to find strong lenses by visual examination in imaging data, so that's where we started.*
- *In addition, we have an ongoing catalog-based search for wide-separation lensed quasars, motivated in part by a desire to also engage students in catalog-based research, and because they are spectacular lenses with enormous scientific potential!*
- *But what about machine learning searches…?*

What Have We Been Doing?

- *There's been an enormous amount of great recent work using machine learning to find strong lenses in imaging data and it is clear that in the long term this is where we are headed as standard practice. However, it seemed impossible to get such a search up and running with a class of undergrads in a short timescale in a way that allows them sufficient ownership and agency in the process.*
- *So we have done something easier – visual examination of lines-of-sight selected to contain luminous red galaxies (LRGs), that are possible lenses.*

- *In addition, arguably the most interesting discovery space for follow-up observations is rare lenses; the M=Margins in COOL-LAMPS alludes to this, as we have focused our effort on primarily lens systems where the lensed sources (and occasionally the foreground lenses) are at the margins of photometric distributions. These margins may be poorly explored by ML methods (that was at least true in 2020, though ML methods in the strong-lensing search space are developing quickly) and so direct visual examination remains a productive discovery approach.*

What Have We Been Doing?

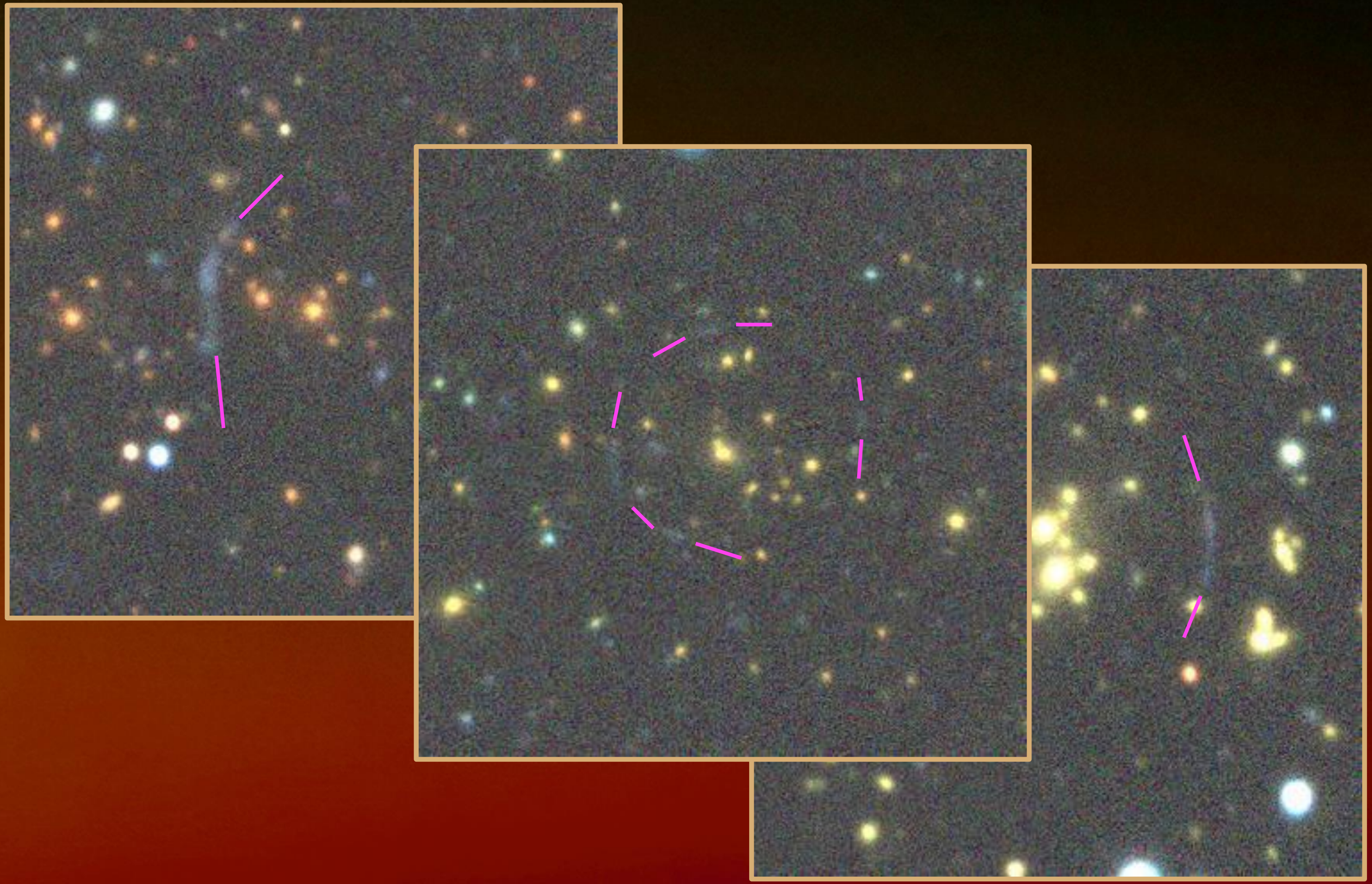


Potential lens lines-of-sight selected by simple color-magnitude cuts that track the expected photometric behaviour of a luminous red galaxy at some notional luminosity.

Depth of the cut (i.e. that notional luminosity) has ben set by available resources (in this case, people) for a given search, since a deeper cut rapidly increases # of images to score.

Galaxy richness computed at each location and cutouts are sized to match richness; adjacent objects (in position and inferred redshift) are grouped to minimize duplication.

What Have We Been Doing?



Lens searches to date have been piecemeal, due both to emergence of searchable data over the course of the program (e.g., DELVE) and nature of the available search effort preceding any given observing run from a yearly class across two academic terms each year. To provide at least some consistency, one person (me!) has scored every image considered. Images are made with custom scaling/pipeline.

The richest (→ most massive) locations at lower redshifts have been scored one at a time; the least rich in images in a grid up to fifteen at a time. A simple scoring strategy with integer score from 0 (no evidence of strong lensing) to 3 (obvious strong lens) was used in all cases.

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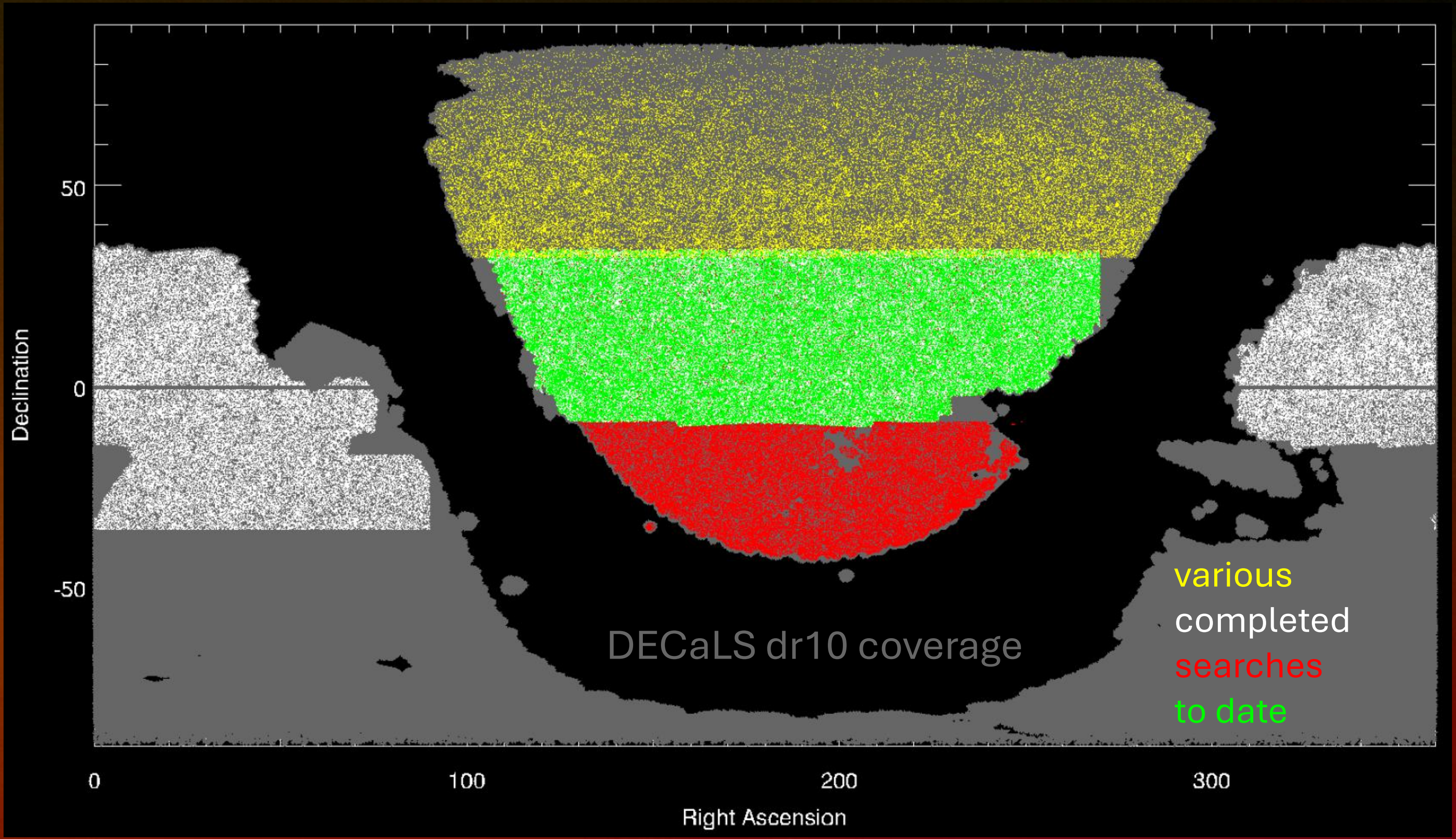

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Each search push – often prompted by an upcoming observing run – has examined ~100K images, with typically 4 "scores" per image. The total number of classified images to date is ~900K, including some smaller efforts not plotted here.

What Have We Been Doing?

Follow-up spectroscopy (and in some cases imaging) has primarily come from the Magellan 6.5m telescopes and the NOT 2.5m telescope. We have focused resources on:

- ***wide separation lensed quasars***
- ***lensed early-type galaxies***
- ***lensed high redshift galaxies***
- ***high redshift+massive lenses***

Particularly compelling discoveries have led to HST and JWST follow-up in addition to ground-based large telescope observations, as well as sub-mm and radio observations. And student-led papers:

COOL-LAMPS I. An Extraordinarily Bright Lensed Galaxy at Redshift 5.04, Khullar et al. 2021

COOL-LAMPS II. Characterizing the Size and Star Formation History of a Bright Strongly Lensed Early-Type Galaxy at Redshift 1.02, Sukay et al. 2022

COOL-LAMPS III: Discovery of a 25".9 Separation Quasar Lensed by a Merging Galaxy Cluster, Martinez et al. 2023

COOL-LAMPS IV: A Sample of Bright Strongly-Lensed Galaxies at 3<z<4, Zhang et al. 2023

COOL-LAMPS V: Discovery of COOL J0335−1927, a Gravitationally Lensed Quasar at z=3.27 with an Image Separation of 23.3", Napier et al. 2023

COOL-LAMPS VI: Lens model and New Constraints on the Properties of COOL J1241+2219…, Klein et al. 2024

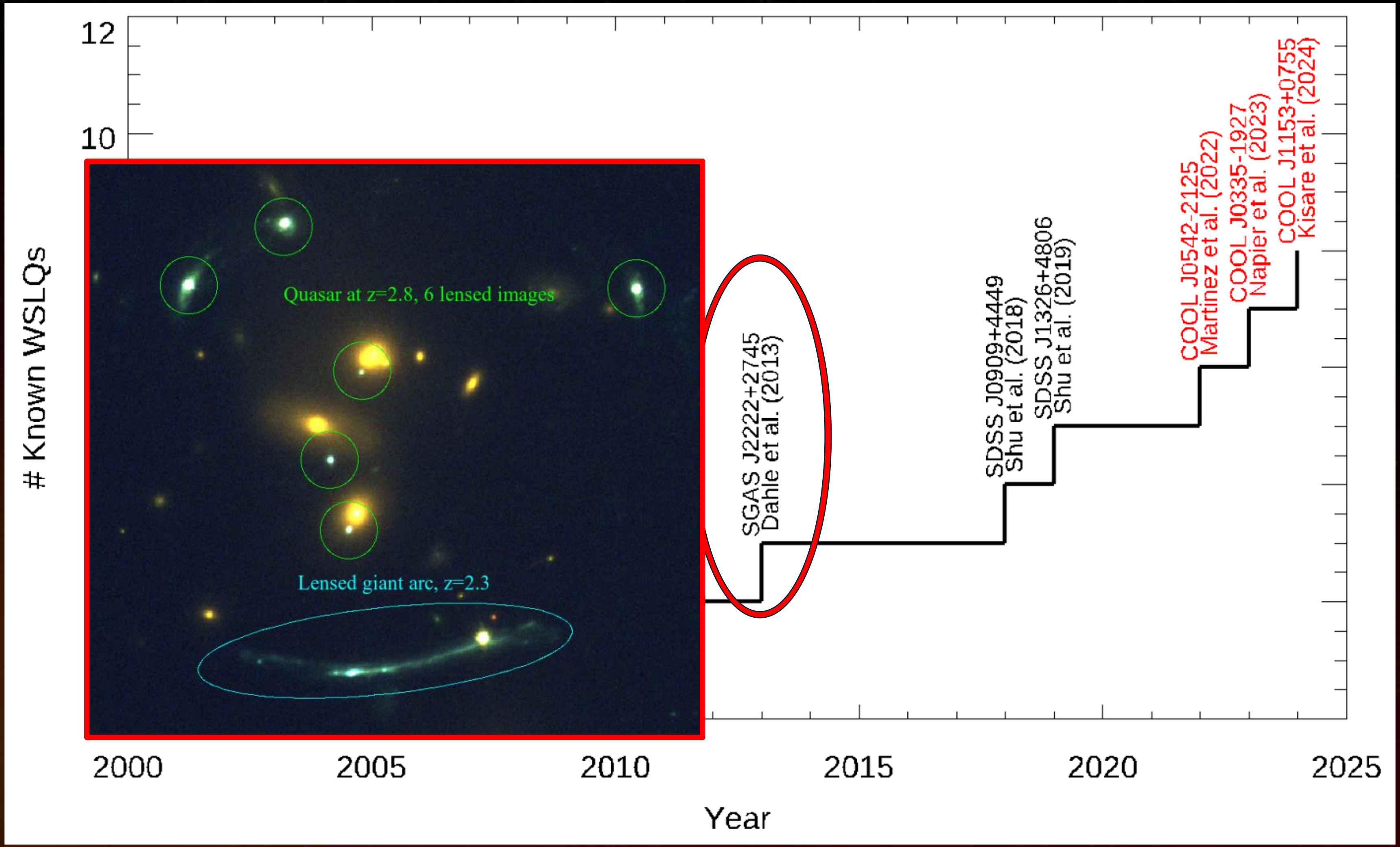
COOL-LAMPS VII: Quantifying Strong-lens Scaling Relations with 177 Cluster-scale Gravitational Lenses in DECaLS, Mork et al. 2024

COOL-LAMPS VIII: The MBH- M Relation in wide-separation lensed quasars and their host galaxies at z~2*

COOL-LAMPS IX: The Extreme Hyperbolic Umbilic Catastrophe Lens COOL J0745+0945, A Highly Magnified Dwarf Galaxy at z=3.5, Tagliavia et al. 2024

COOL-LAMPS X: COOL J1153+0755, a Multiple Wide-Separation Lensed Quasar System with Lensed Group Members, Kisare et al., 2024

Results: Wide Separation Lensed Quasars

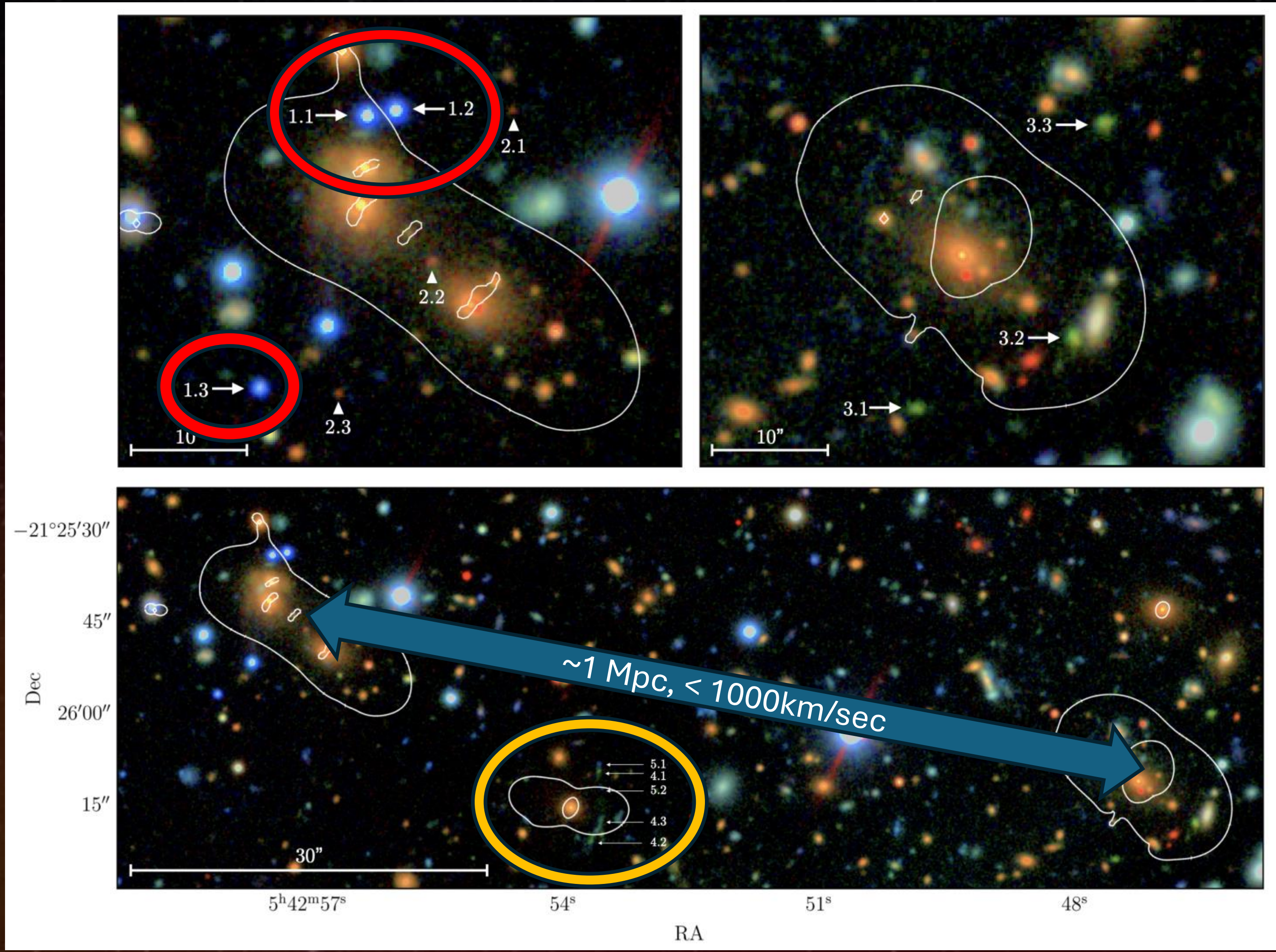


Strong lensing by clusters of galaxies is rare – though clusters have larger individual lensing cross sections, the clusters themselves are rare, so most instances of strong lensing in the cosmos are mostly by individual massive galaxies rather than clusters.

Lensed quasars are also rare by comparison to lensed galaxies, as quasars are far less common on the sky than galaxies at a given flux value.

Quasars lensed by massive clusters – so called wide-separation lensed quasars – are thus doubly rare (and valuable!). But we are making some progress in discovery…

Results: Wide Separation Lensed Quasars

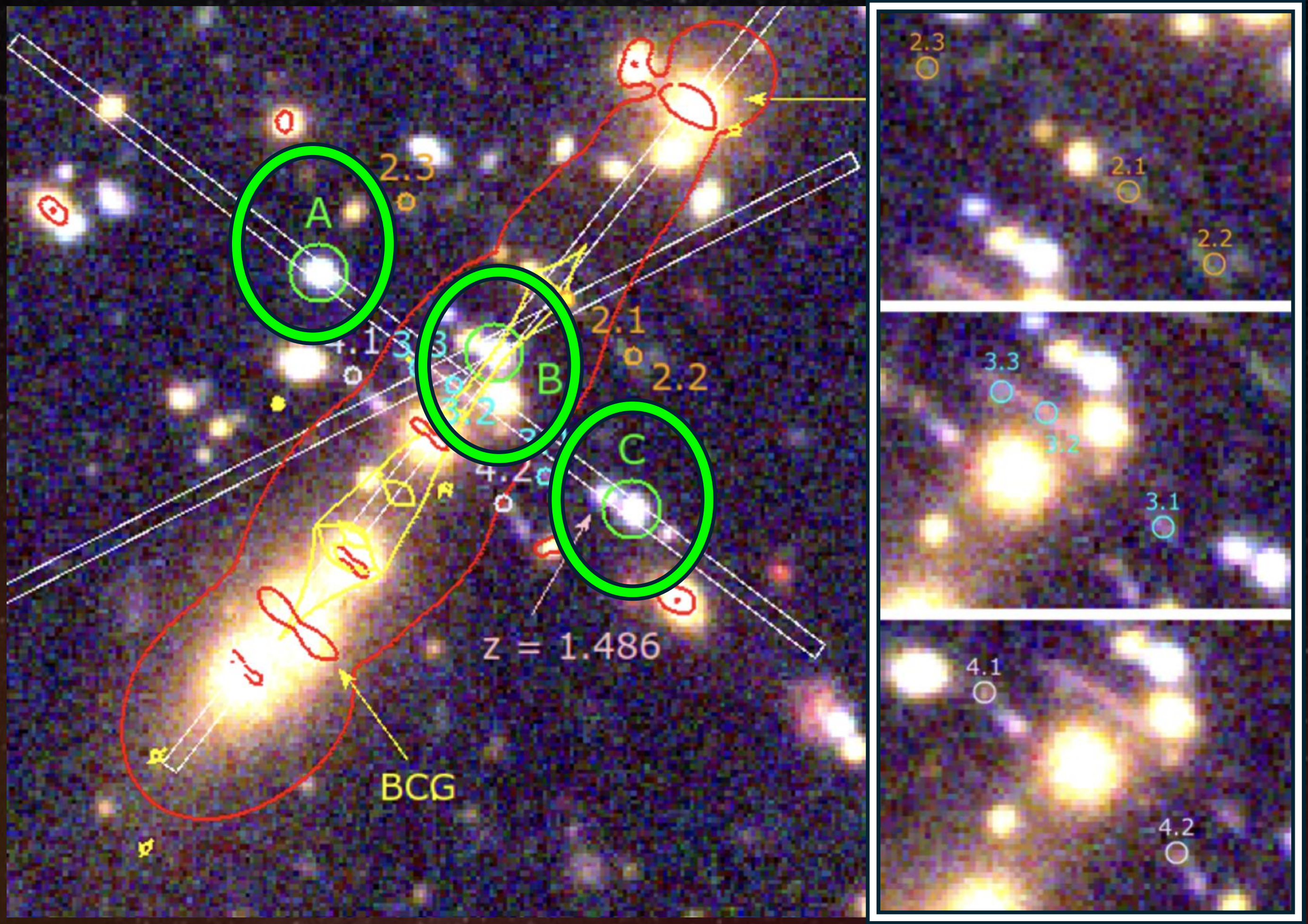


COOL-LAMPS III: Discovery of a 25".9 Separation Quasar Lensed by a Merging Galaxy Cluster, Martinez et al. 2023

Michael N. Martinez
(Field Course 2020, now Ph.D. candidate UW Madison Physics)

COOLJ0542-2145, at z=1.84, is the widest-separation known, at 25".9. It is lensed by a massive cluster at z=0.61, which is one of a pair of massive strong-lensing clusters by ~1Mpc and <1000 km/sec. The clusters are likely merging. There is evident strong le sters cores as well, much like the famous "Bullet Cluster" merging system.

Results: Wide Separation Lensed Quasars



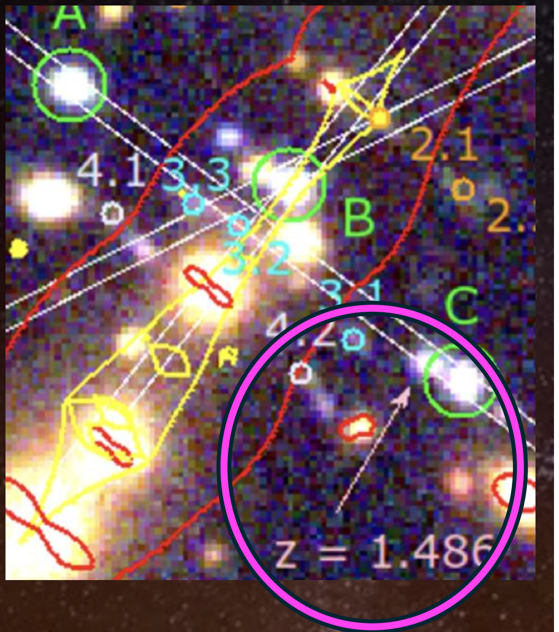
COOL-LAMPS V: Discovery of COOL J0335−1927, a Gravitationally Lensed Quasar at z=3.27 with an Image Separation of 23.3", Napier et al. 2023

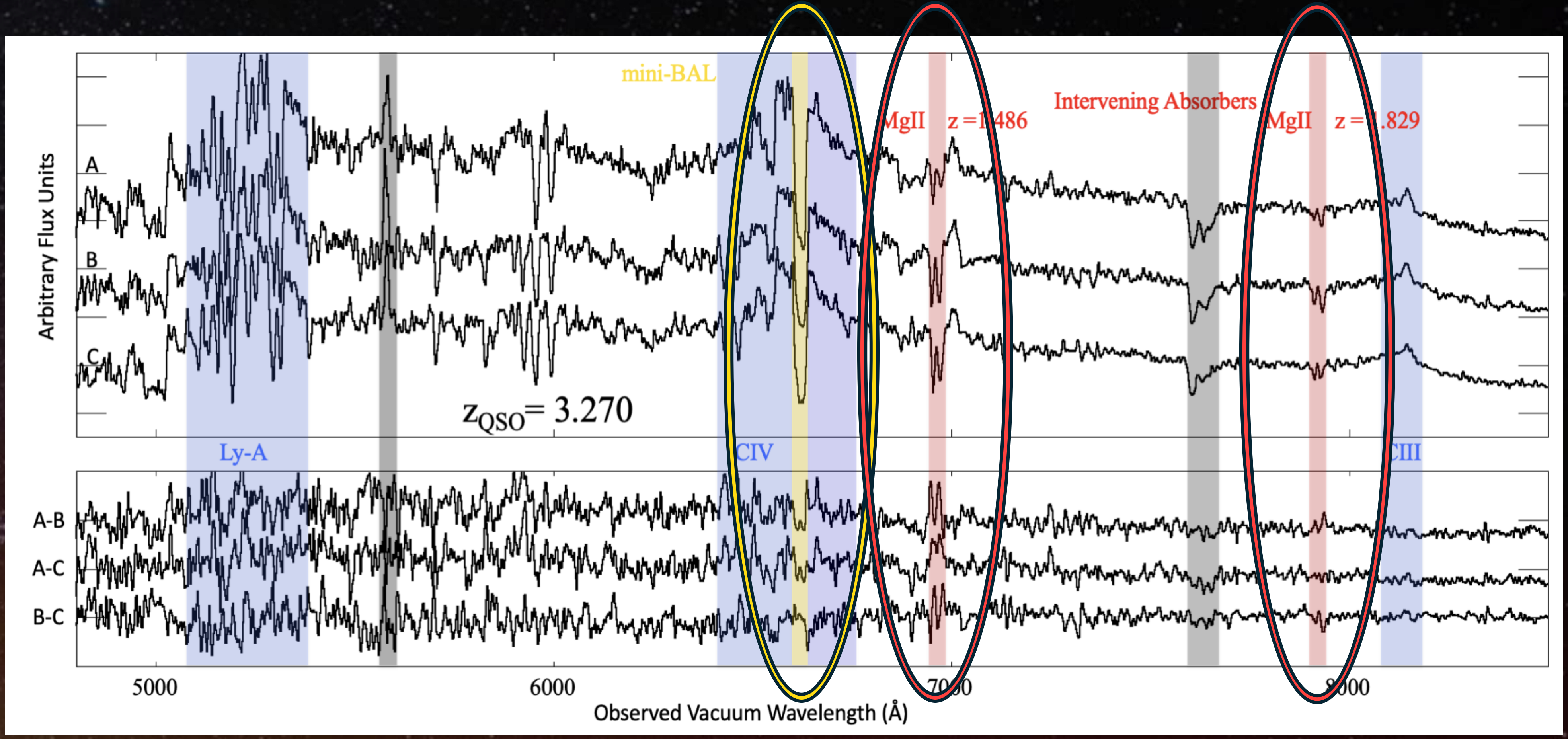
Kate Napier
(Ph.D. candidate, U Michigan)

COOLJ0335-1927, at z=3.27, is the highest redshift wide-separation [redacted] known, with a maximum image separation of 23".3. It is lensed by a massive cluster at z=0.42. It is notable in part for various absorption features visible in the quasar spectra.

It is also notable because two of the three quasar images are NOT tagged as point sources (but as Sérsic profiles, i.e. distinctly as galaxies) and was found in the COOL-LAMPS visual pipeline based on visible len[redacted] the catalog-based search.

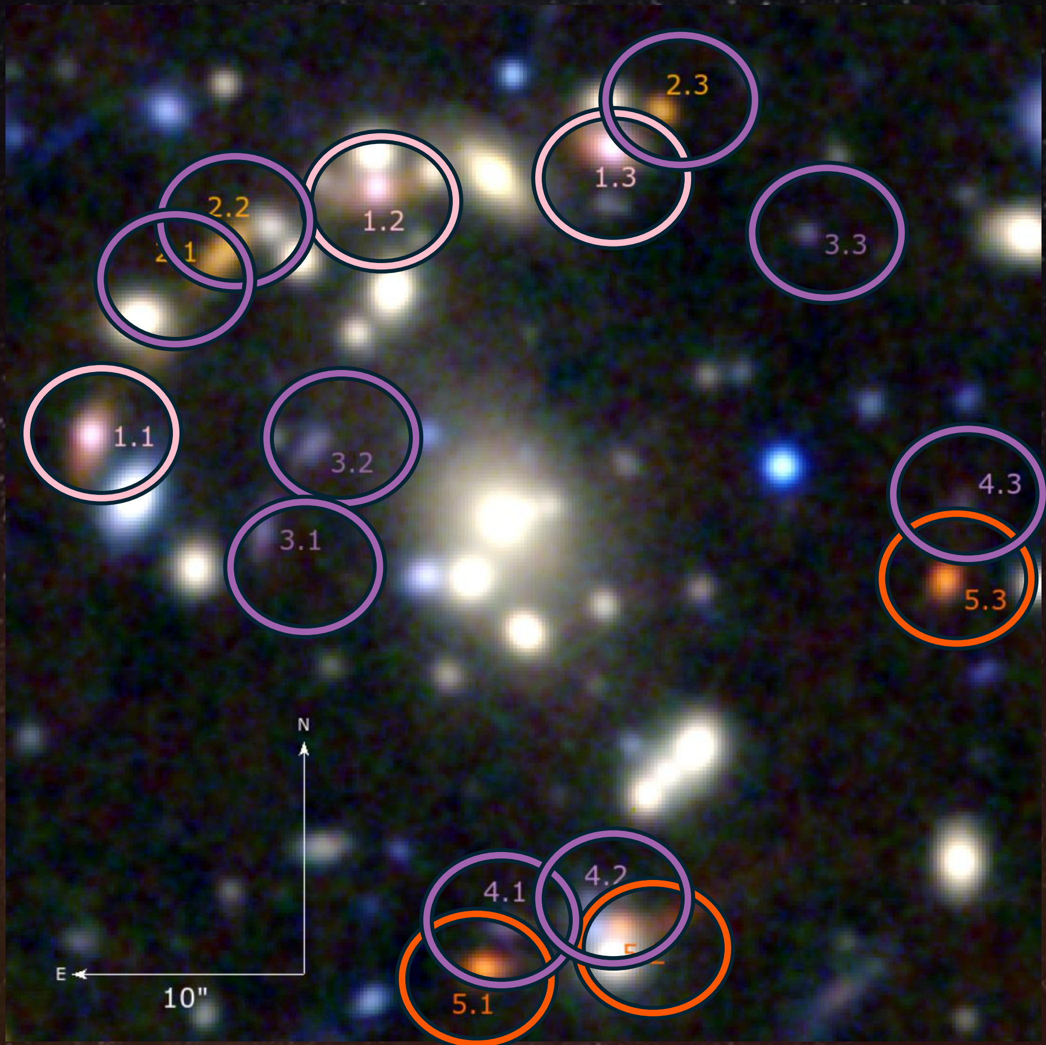
Results: Wide Separation Lensed Quasars





COOLJ0335-1927 shows a mir[redacted]IV, and several foreground Mg II [redacted]ith varying strength across the three lensed quasar images; one of the absorbing g[redacted]entified.

Results: Wide Separation Lensed Quasars



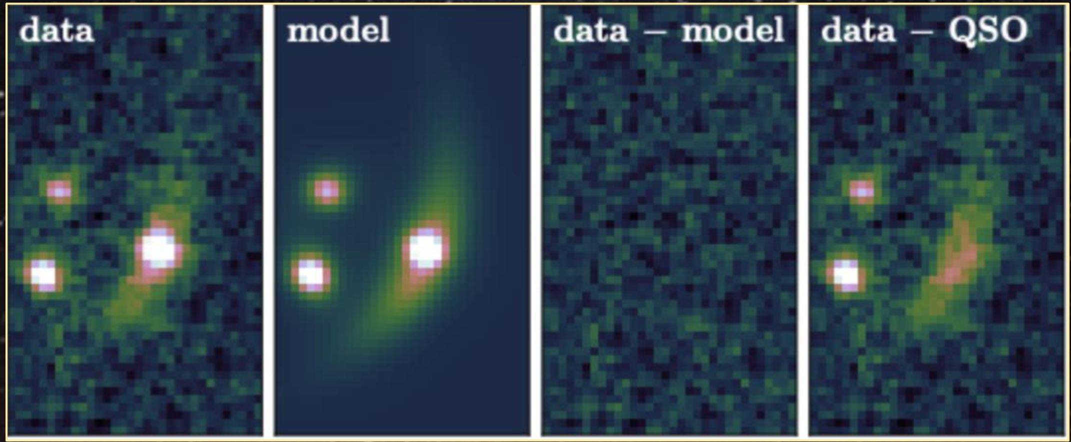
COOL-LAMPS X: COOL J1153+0755, a Multiple Wide-Separation Lensed Quasar System with Lensed Group Members, Kisare et al., 2024

***Andi Kisare** (Field Course 2023)*

*COOLJ1153+0755, is a massive cluster at z=0.42, strongly lensing two quasars, at **z=1.5**[redacted]**=1.93.** [redacted]her redshift quasar is extremely obscured, though broad Balmer emission lines are visible in NIR spectroscopy from Magellan+FIRE. It was found in a catalog search without morphological catalog filtering. All three images of the unobscured quasar are classified as extended.*

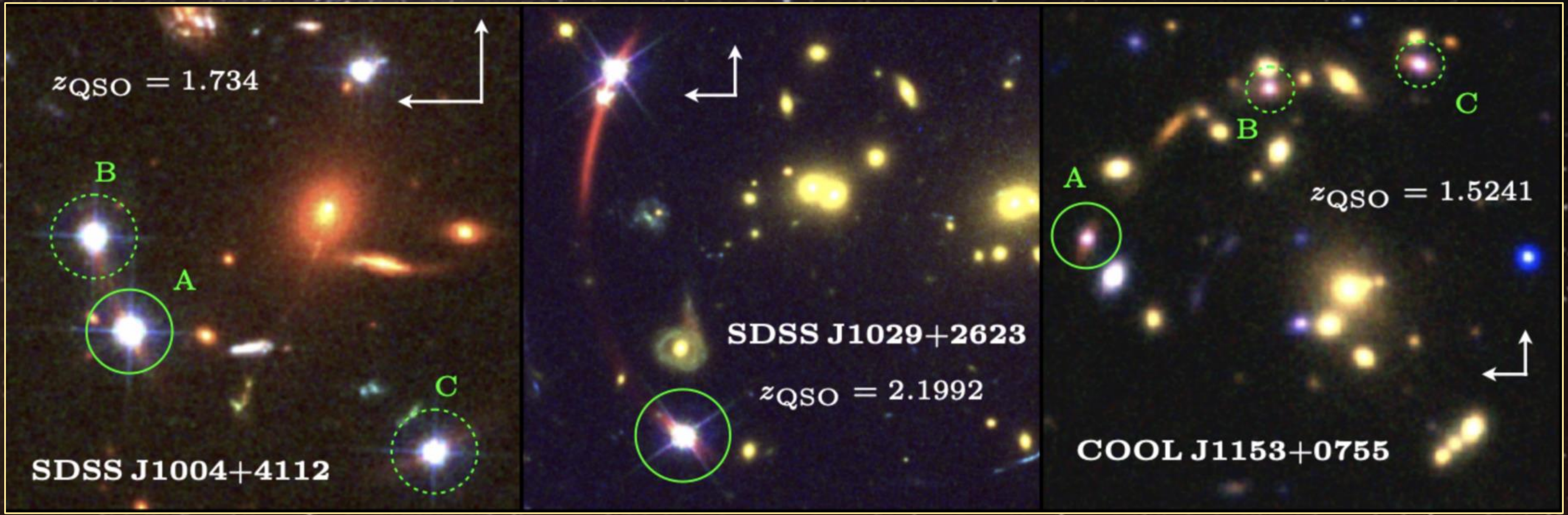
In addition, BOTH quasars are embedded in groups of galaxies detected spectroscopically, with three distinct members of those groups also [redacted] *at z=1.93) .*

Results: Wide Separation Lensed Quasars



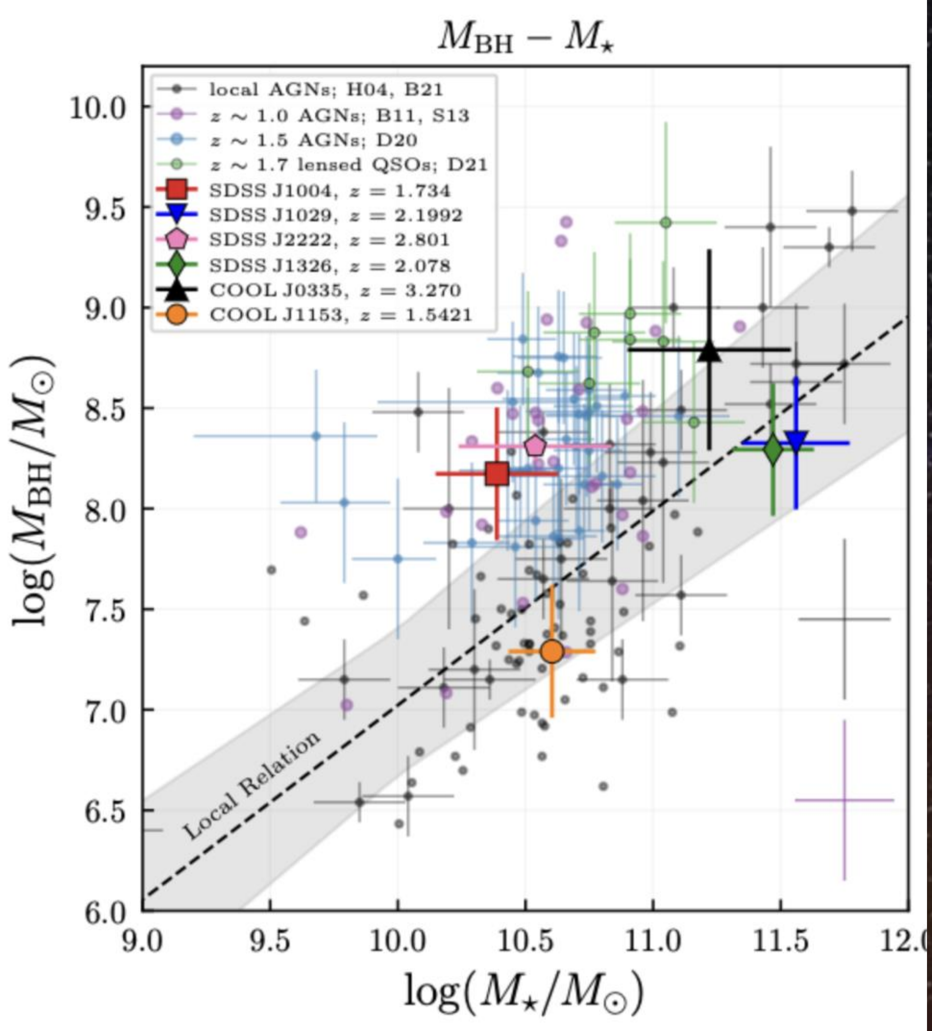
COOL-LAMPS VIII: The MBH- M Relation in wide-separation lensed quasars and their host galaxies at z~2*

***Aidan P. Cloonan** (Field Course 2022, now Ph.D. candidate UMass Amherst)*

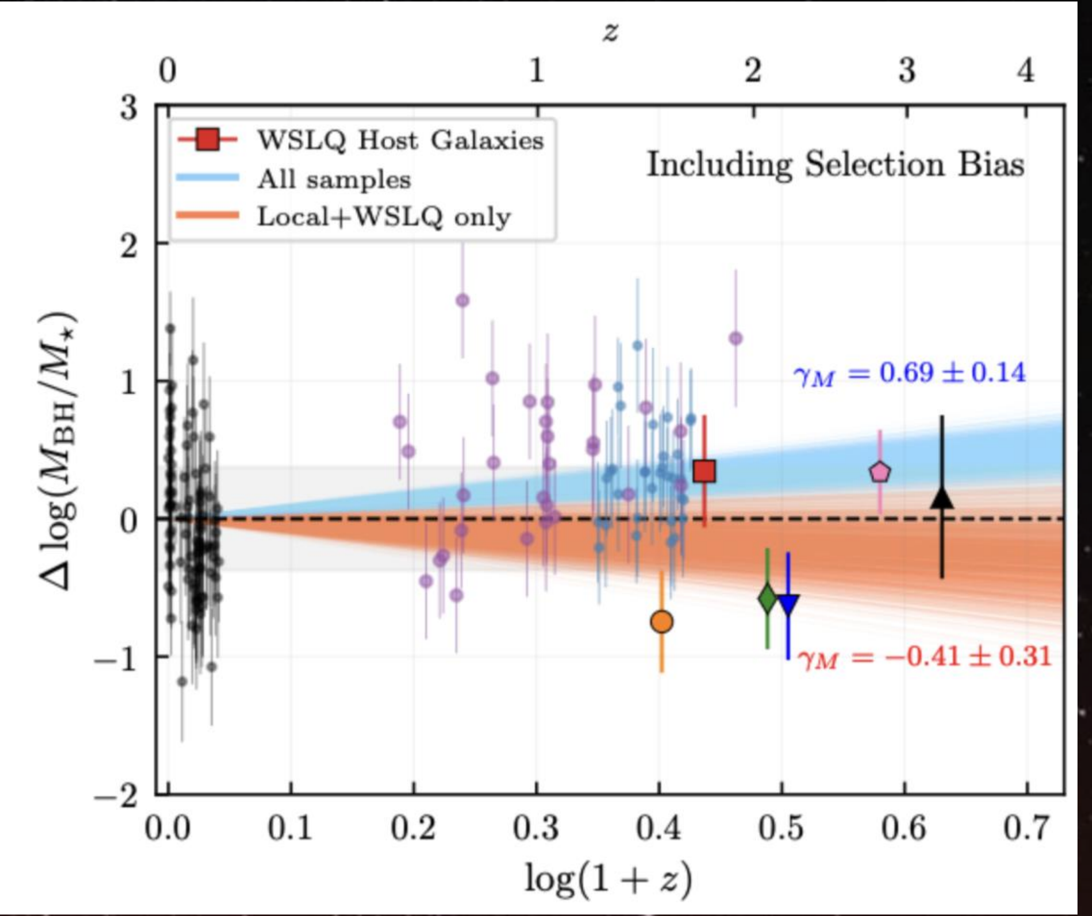


WSLQs show typically larger magnifications than quasars lensed by individual foreground galaxies, and the lensed images are typically much better isolated from foreground light as well, and hence offer a unique opportunity to measure quasar host galaxies in detail.

Results: Wide Separation Lensed Quasars

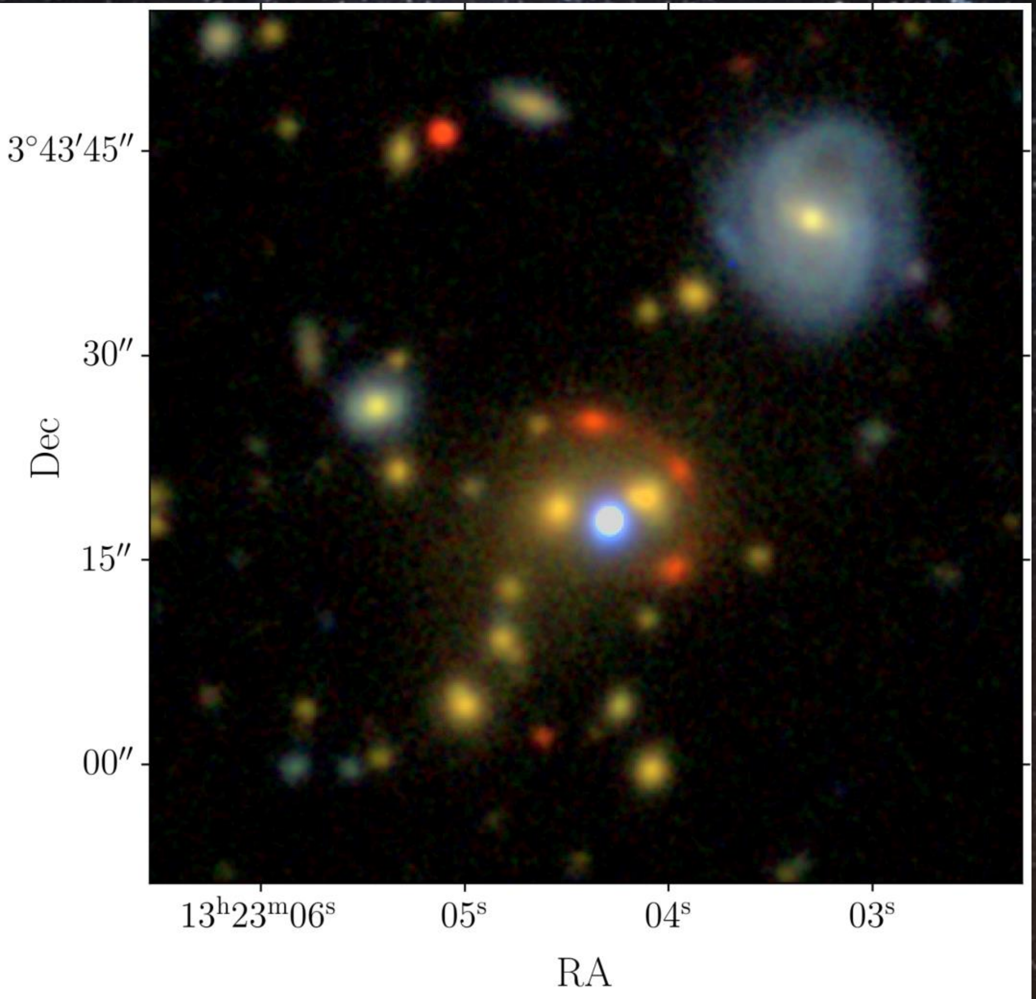


The $M_{BH} - M_{STAR}$ from the 6 WSLQs with detected host galaxies…



… shows no significant evolution from the z=0 relation, out to z~2.

Results: Lensed Early-Type/Quiescent Galaxies

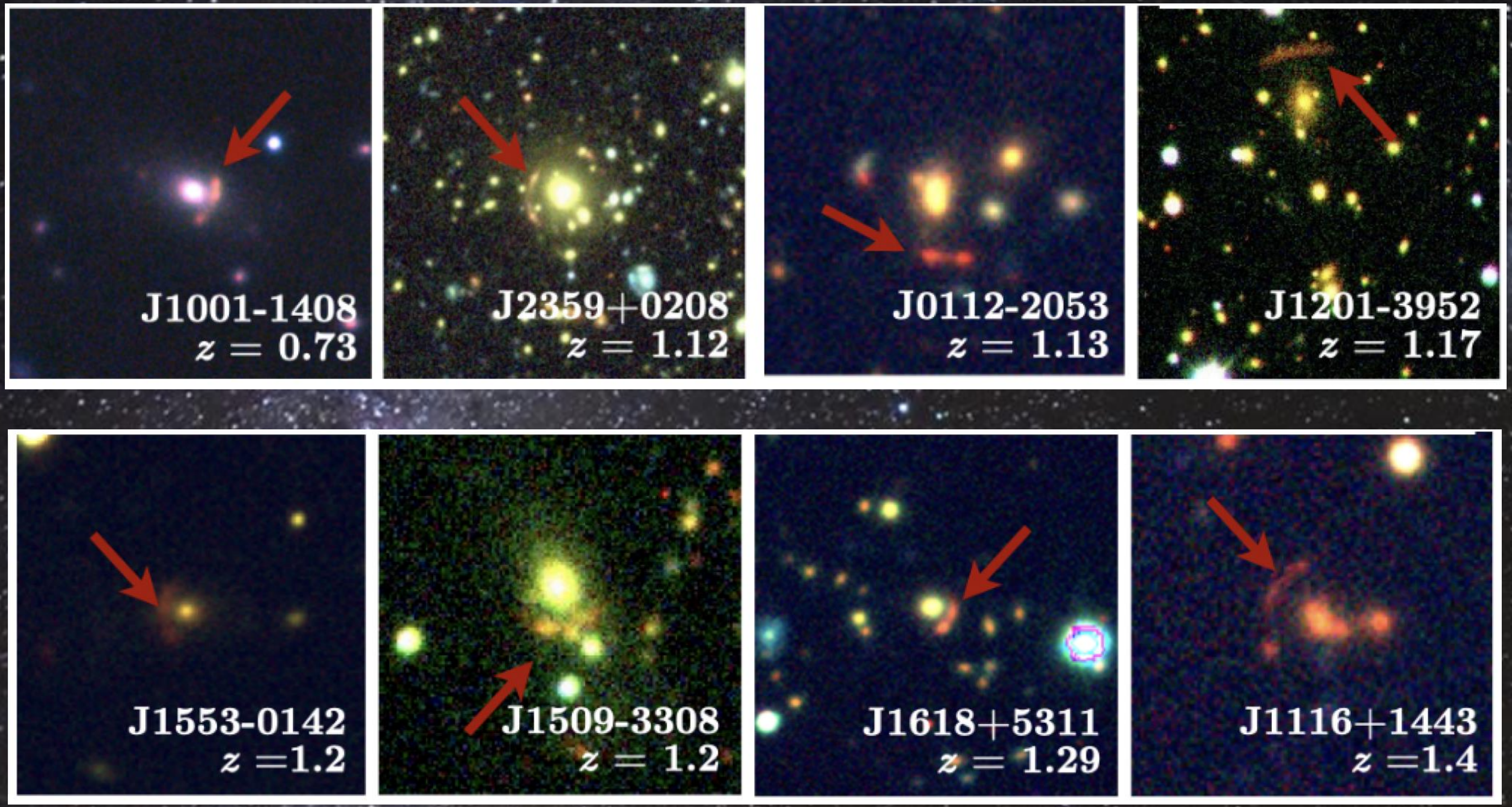


COOL-LAMPS II. Characterizing the Size and Star Formation History of a Bright Strongly Lensed Early-Type Galaxy at Redshift 1.02, Sukay et al. 2022

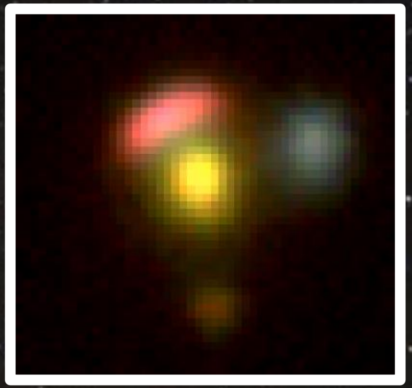
Ezra Sukay*(Field Course 2020, now Ph.D. candidate Johns Hopkins)*

COOLJ1326+0343, at z=1.02, is strongly-lensed early-type/quiescent galaxy that at H_{AB}=18 is one of the brightest such galaxies known at higher redshifts. Intrinsically it is a moderate stellar mass (4.3×10^{10}, revised to 1.3×10^{11} *in Zhuang et al. 2023 primarily from a changed best-fit magnification from an HST-based lens model) quiescent galaxy (stellar age at z=1.02 is 5.6 Gyr from Zhuang et al.) with an intermediate morphology (Sérsic index=2.2).*

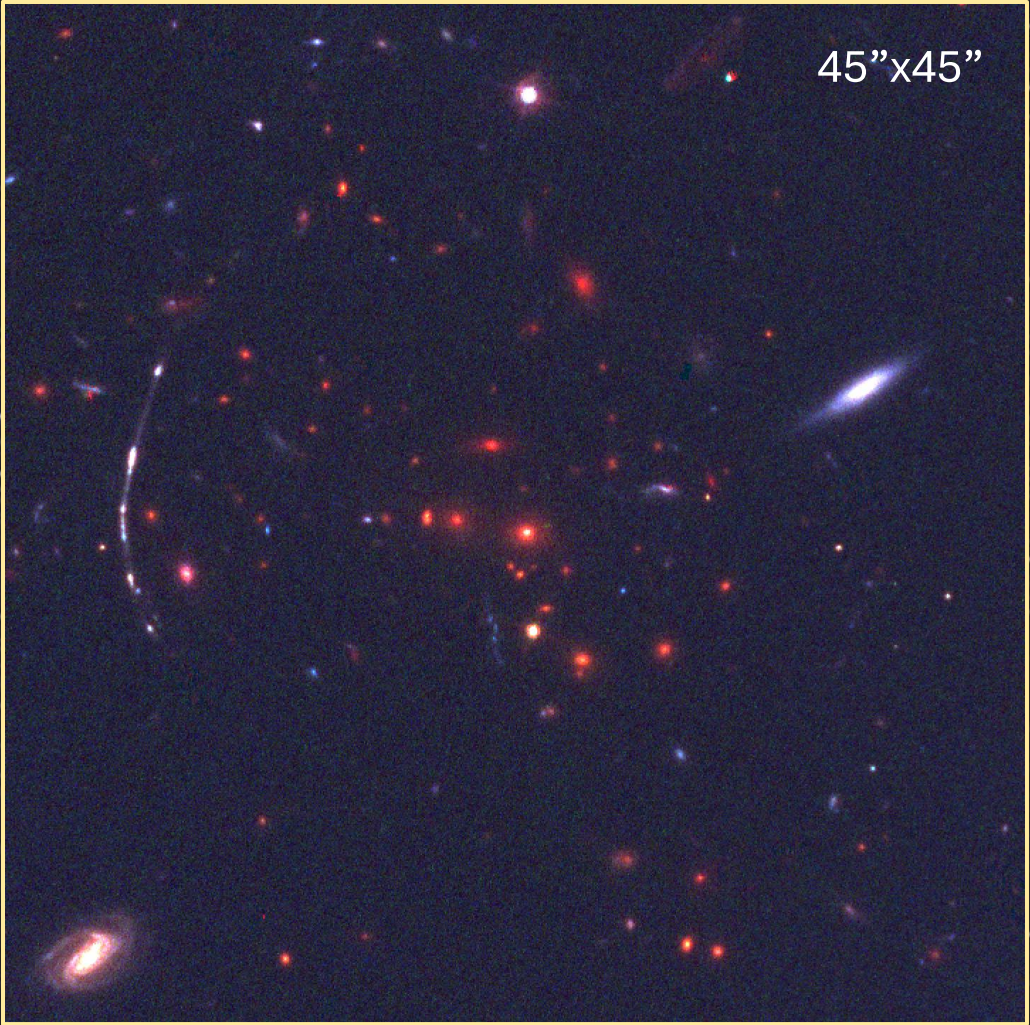
Results: Lensed Early-Type/Quiescent Galaxies



We have continued to accrue a sample of lensed ETGs with confirming spectroscopy, as an ongoing process. Most are around redshift z~1, as we might expect from a sample of red lensed arcs in grz imaging data. Also interesting, and perhaps not surprising given this redshift, some of these systems have post-starburst spectra suggestive of galaxies actively quenching.



Results: z >1 Cluster Strong Lenses



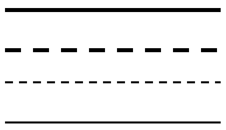
COOL J2129-0126 is the highest redshift spectroscopically confirmed strong-lensing galaxy cluster known, with a bright lensed arc from a z=3.29 galaxy, and a foreground massive cluster at z=1.33, and an Einstein radius θ_{RAD} = 18”

The cluster is not well-detected at the catalog level, but is apparent in the DECaLS imaging data to visual inspection. The brightest few central galaxies do pass our luminous red galaxy filter, and the lensed arc is obvious in the DECaLS imaging.

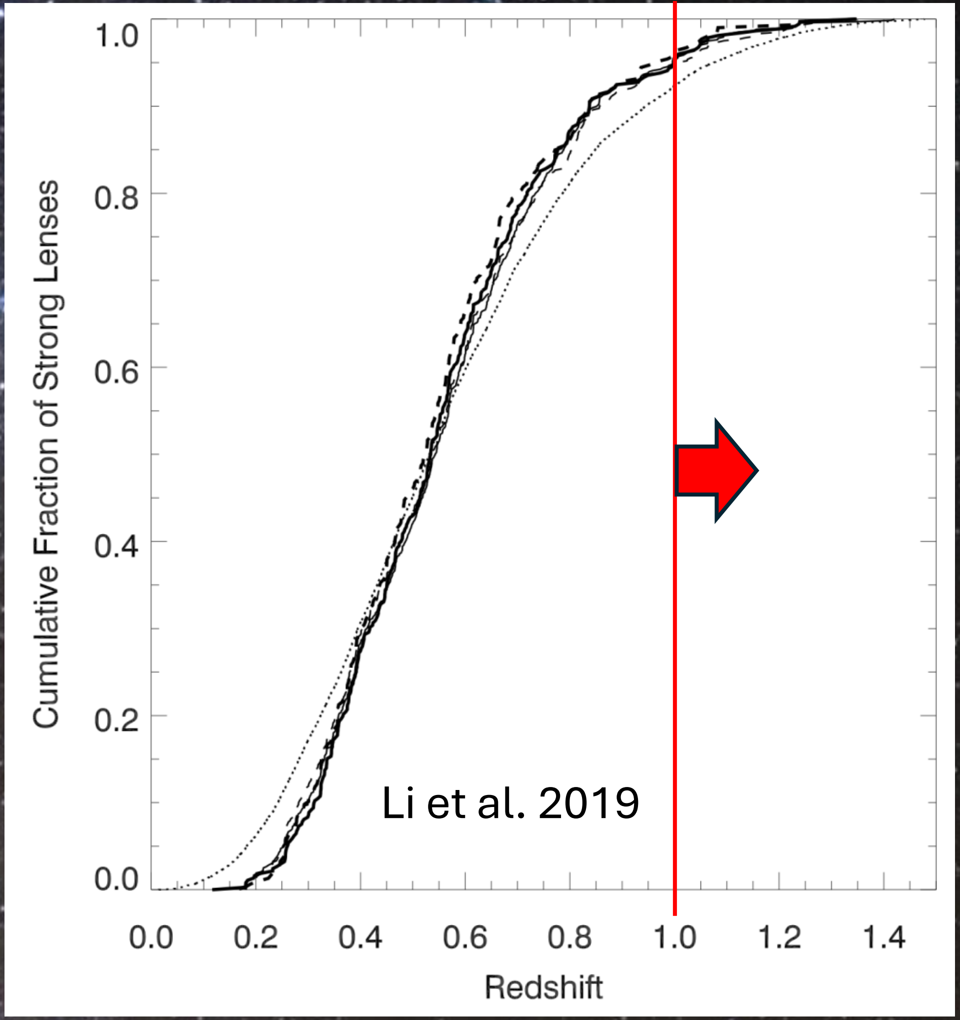
The cluster is obvious with appropriately deeper and redder imaging (in this case HST F160W).

Results: z >1 Cluster Strong Lenses

Simulations of strong lensing samples for SPT-like massive clusters using a variety of selection strategies



from the overall massive cluster population

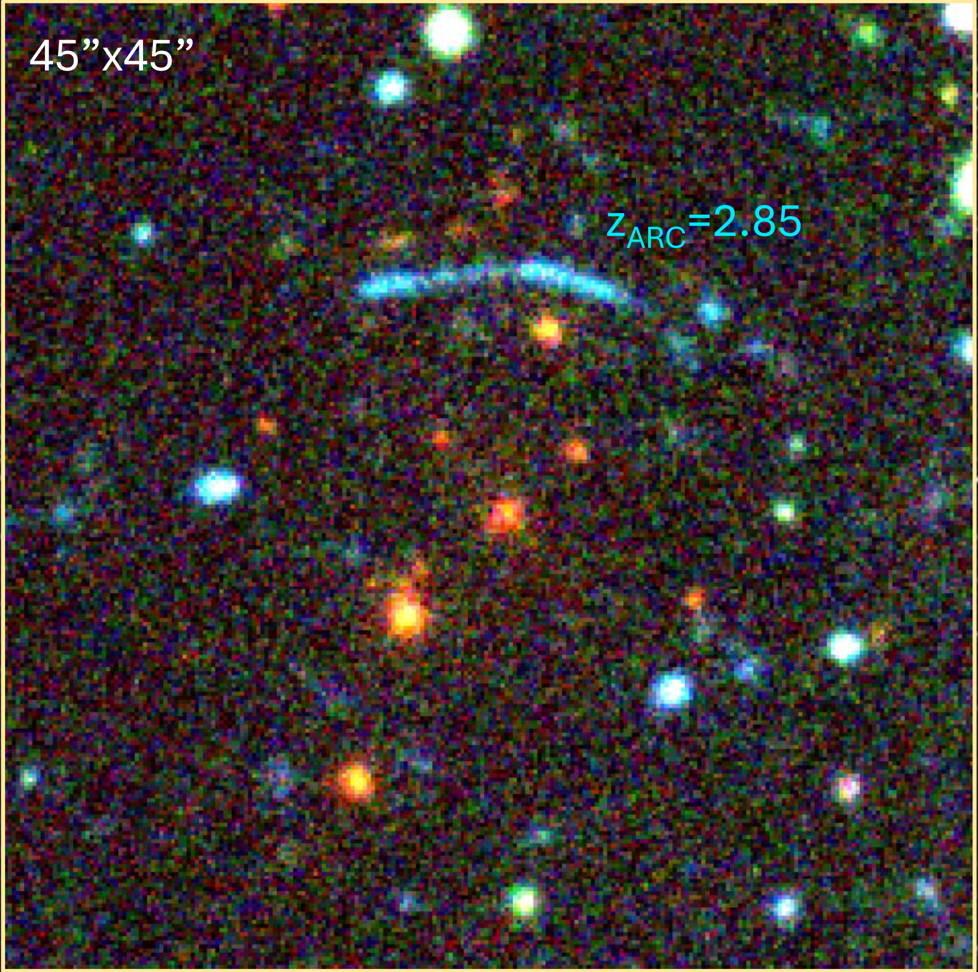


Why do we care?

Strong-lensing massive clusters at z>1 are expected to be extremely rare objects, both because of the rarity of sufficiently massive clusters at these early times, and because lensing becomes geometrically less favorable for lenses at high redshift compared to an otherwise identical lens at lower redshifts.

Hence opportunities to use strong lensing to study the cores of such clusters are at present almost totally lacking, and discovery of more examples are desired.

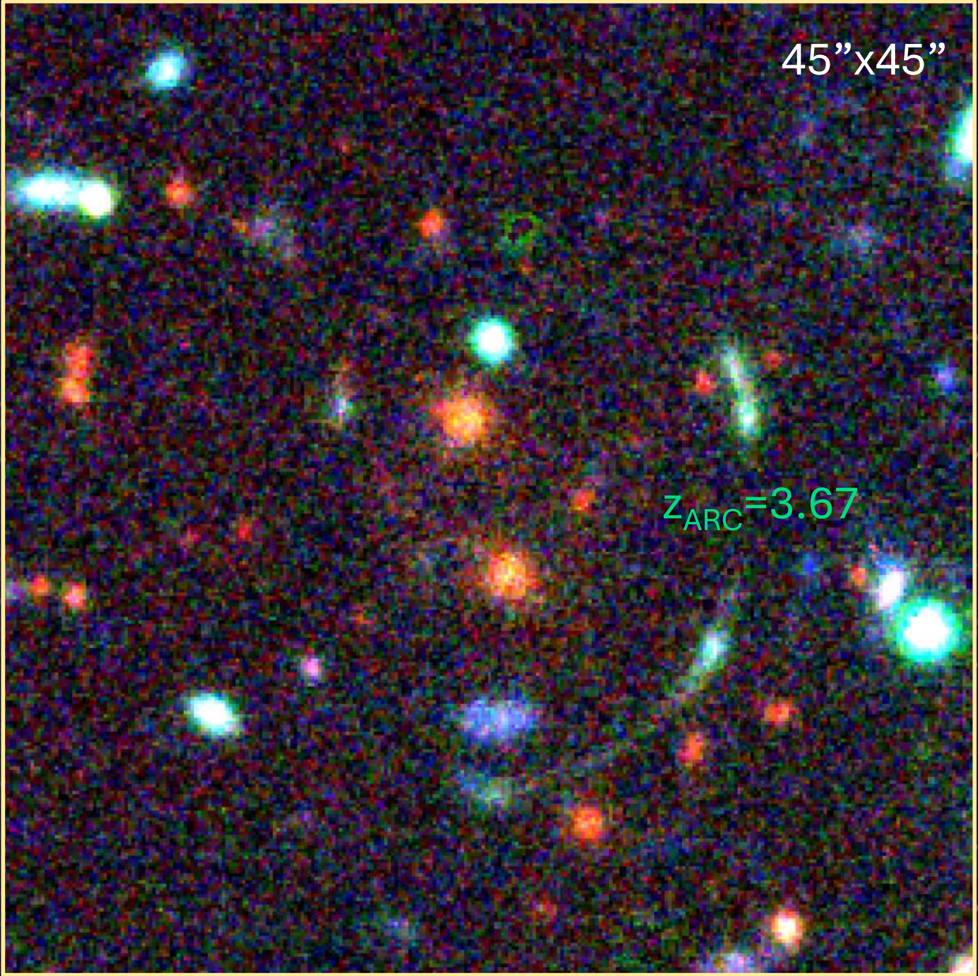
Results: z >1 Cluster Strong Lenses



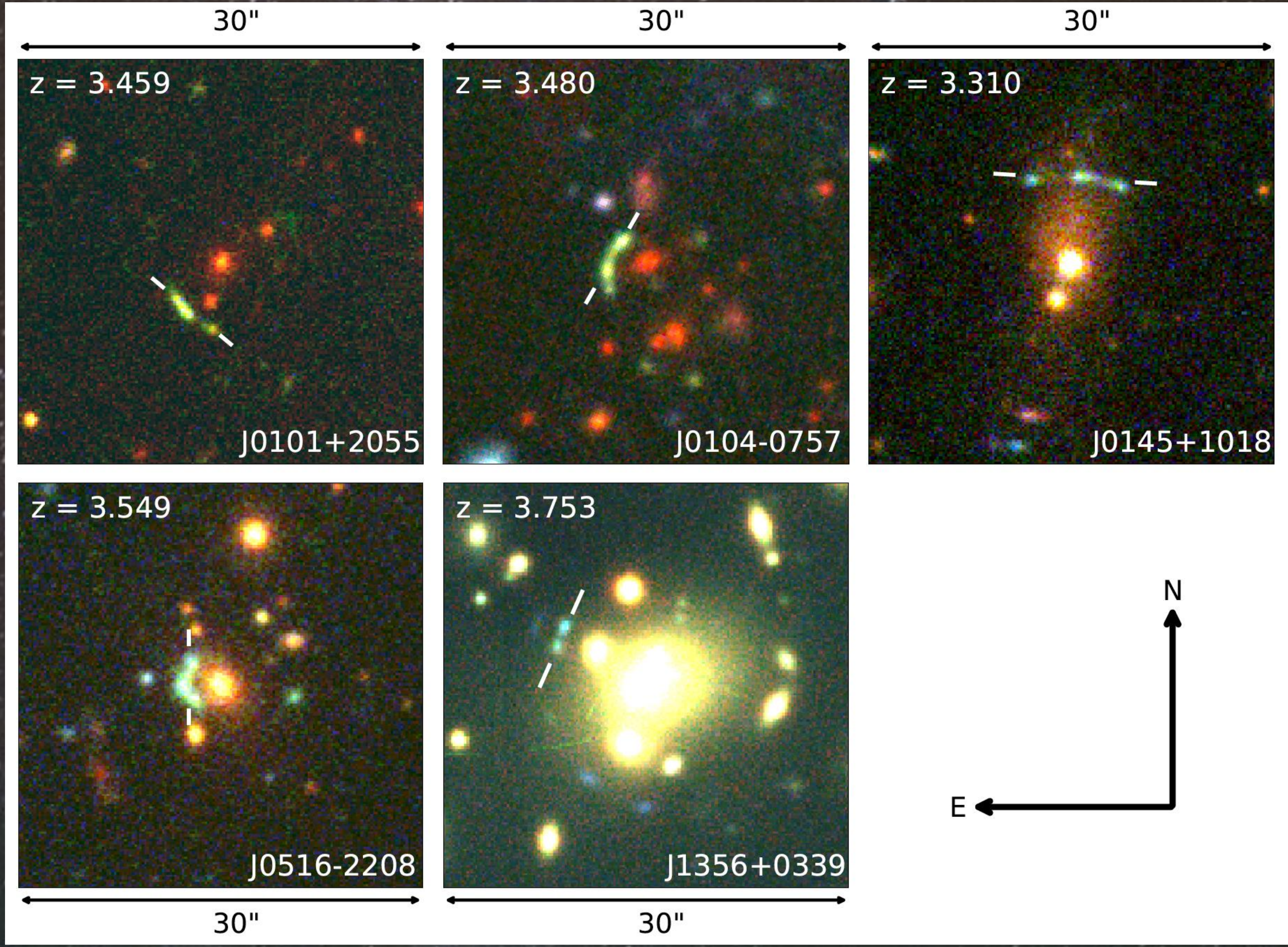
Here are two more examples, from the latest lens searches and observing by field course students…

z_{LENS}=1.08
θ_{RAD} = 16”

z_{LENS}=1.02
θ_{RAD} = 17”



Results: Lensed High Redshift Galaxies



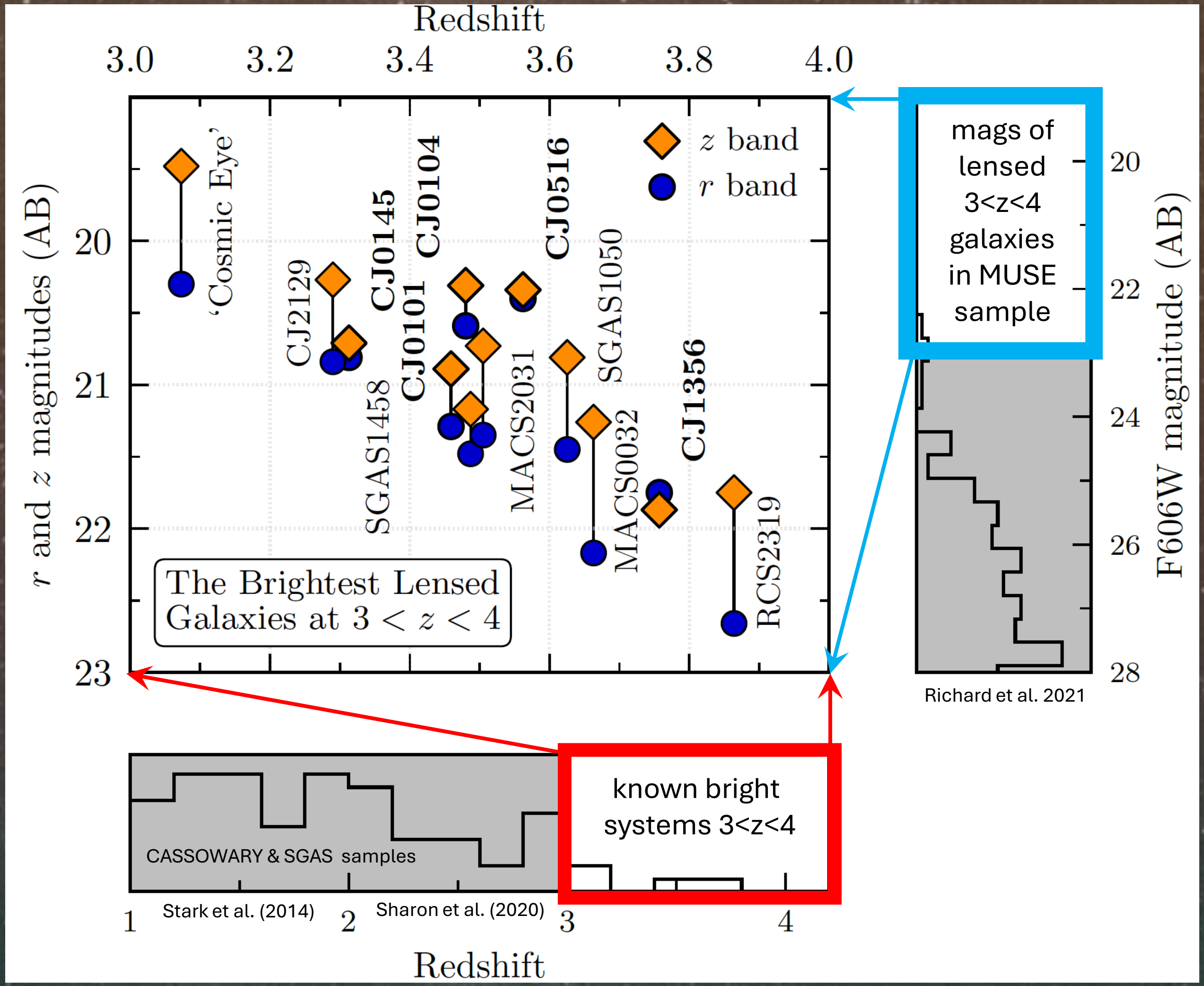
COOL-LAMPS IV: A Sample of Bright Strongly-Lensed Galaxies at 3<z<4, Zhang et al. 2023

Yunchong Zhang *(Field Course 2021, now Ph.D. candidate UPittsburgh)*

In previous generation public imaging surveys (i.e., the SDSS, BigData1.0) bright strongly-lensed galaxies at z>3 are mostly lacking. This is primarily a consequence of depth, and for the highest redshifts in particular a lack of depth in the reddest bands.

Current big imaging data, i.e. DECaLS, BigData2.0, is much better for finding such systems, with huge sample gains at 3<z<4, and extreme systems visible to z~6. So, we have focused some effort on these!

Results: Lensed High Redshift Galaxies

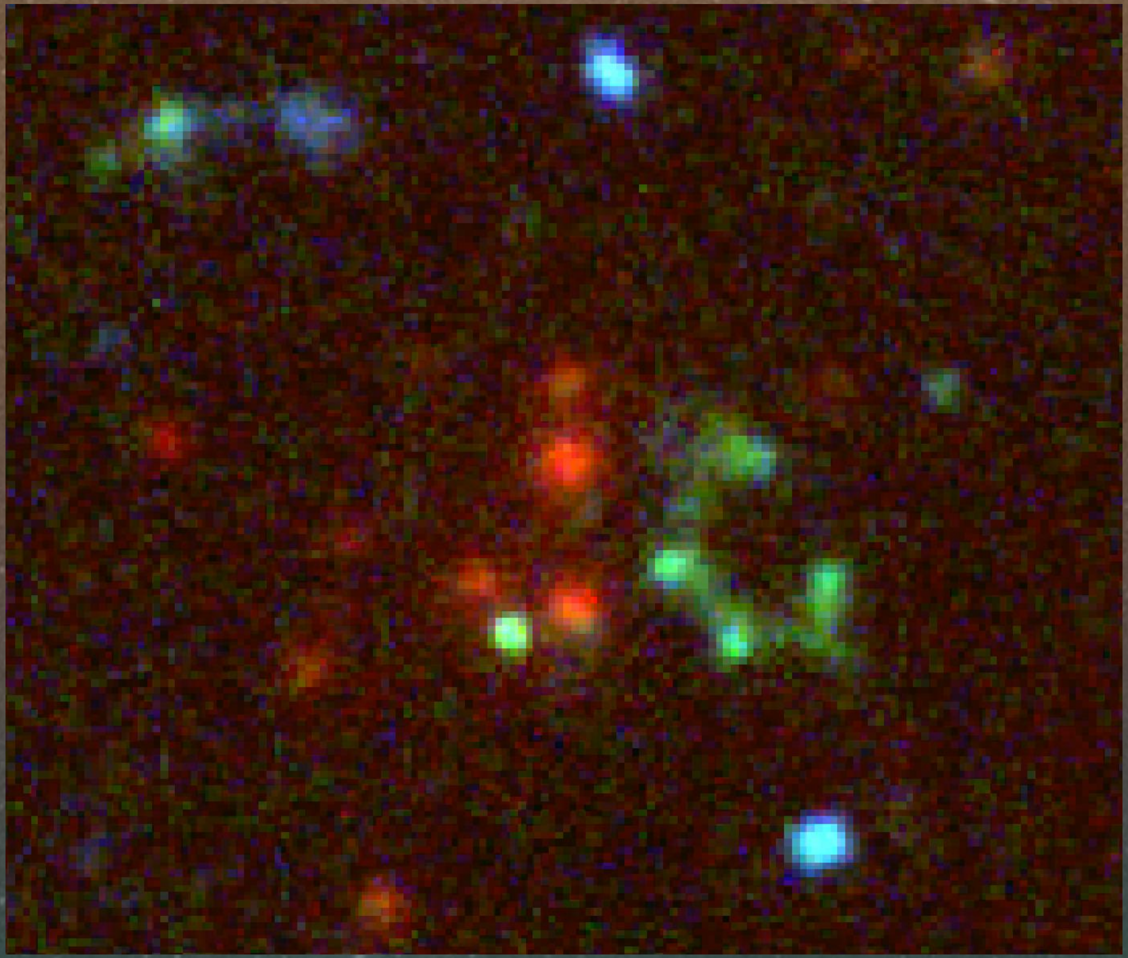


This new sample of 5 ~doubles the [redacted] *rom the SDSS and RCS surveys, and a few discoveries from pointed observation of large lensing cross-section MACS clusters (horizontal histogram).*

[redacted] *(e.g. the Hubble Frontier Fields) doesn't generally change this; though it produces many more known lensed z>3 galaxies, they are almost all as faint or fainter than the brightest unlensed galaxies at these redshift seen in deep fields (r_{AB}~23).*

To find more bright examples of such galaxies, we need to look at many lines of sight with survey imaging data sensitive to such objects, with a follow-up focus targeting high priority candidates (i.e., COOL-LAMPS!). Following Zhang et al. the students in this year's class are pushing forward an analysis on a further 47 systems - an order-of-magnitude increase over our initial result!

Results: Lensed High Redshift Galaxies



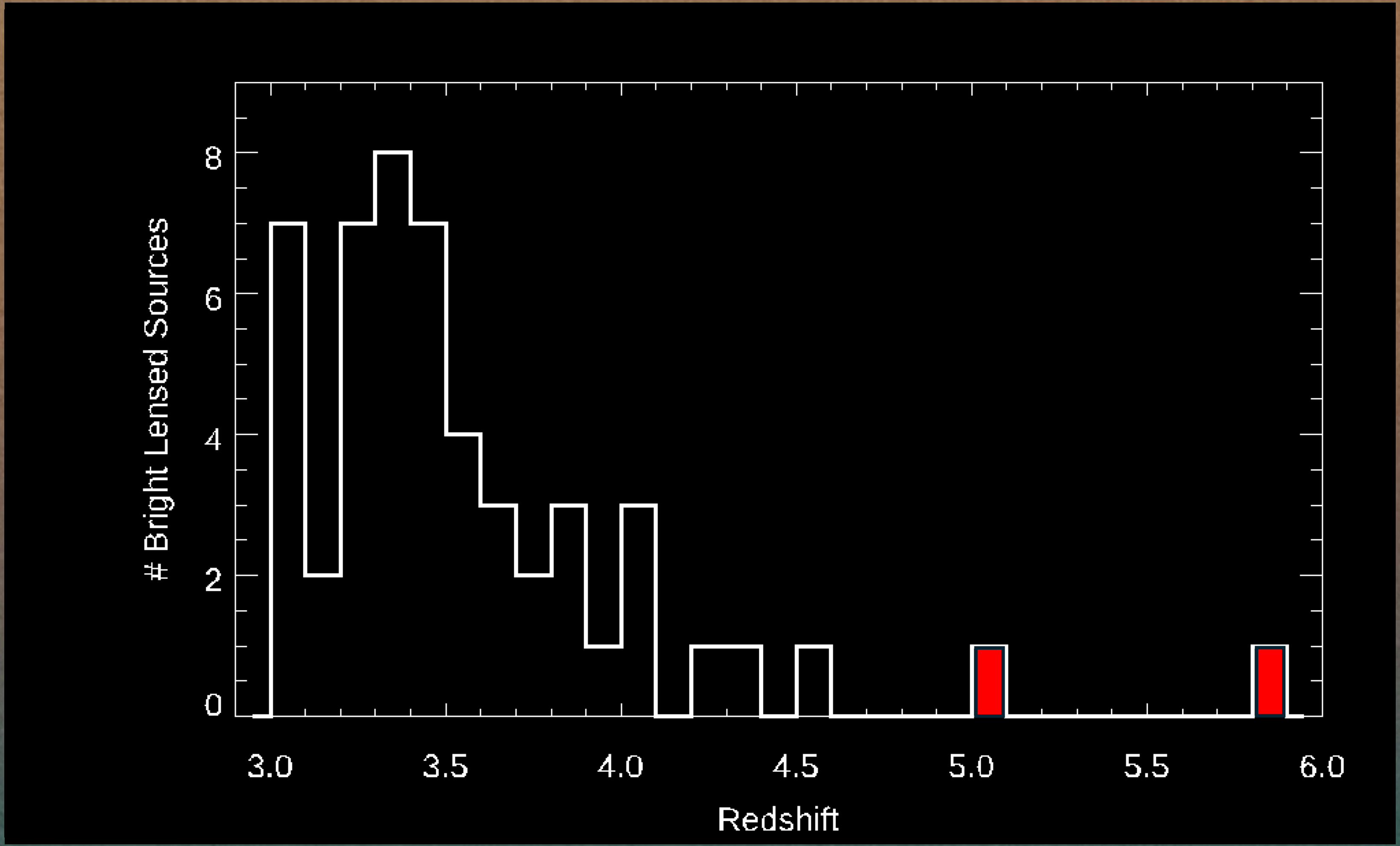
COOL-LAMPS IX: The Extreme Hyperbolic Umbilic Catastrophe Lens COOL J0745+0945, A Highly Magnified Dwarf Galaxy at z=3.5

Marie Tagliavia*(Field Course 2023, heading to Notre Dame)*

With now more than 50 bright lensed galaxies discovered at z>3, we might expect to find rare/weird/extreme objects within that sample. And we do! This is an example: an extremely rare lensing configuration (a hyperbolic umbilic catastrophe) that produces a magnification ~1000 quad ring image of a typical star-forming galaxy at z=3.55.

The extreme magnification yields an observed magnitude of r_{AB}=20.9 – unlensed this galaxy would be r_{AB}~28.5 and its star formation rate (2 M_{SUN}/yr) and stellar mass (10^8 M_{SUN}) place it firmly in dwarf galaxy territory, and on the so-called star-forming main sequence.

Results: Lensed High Redshift Galaxies



Given this redshift distribution, its reasonable to ask:

"To how high a redshift can we go with the DECaLS data?"

The answer appears to be:

"About z~6!"

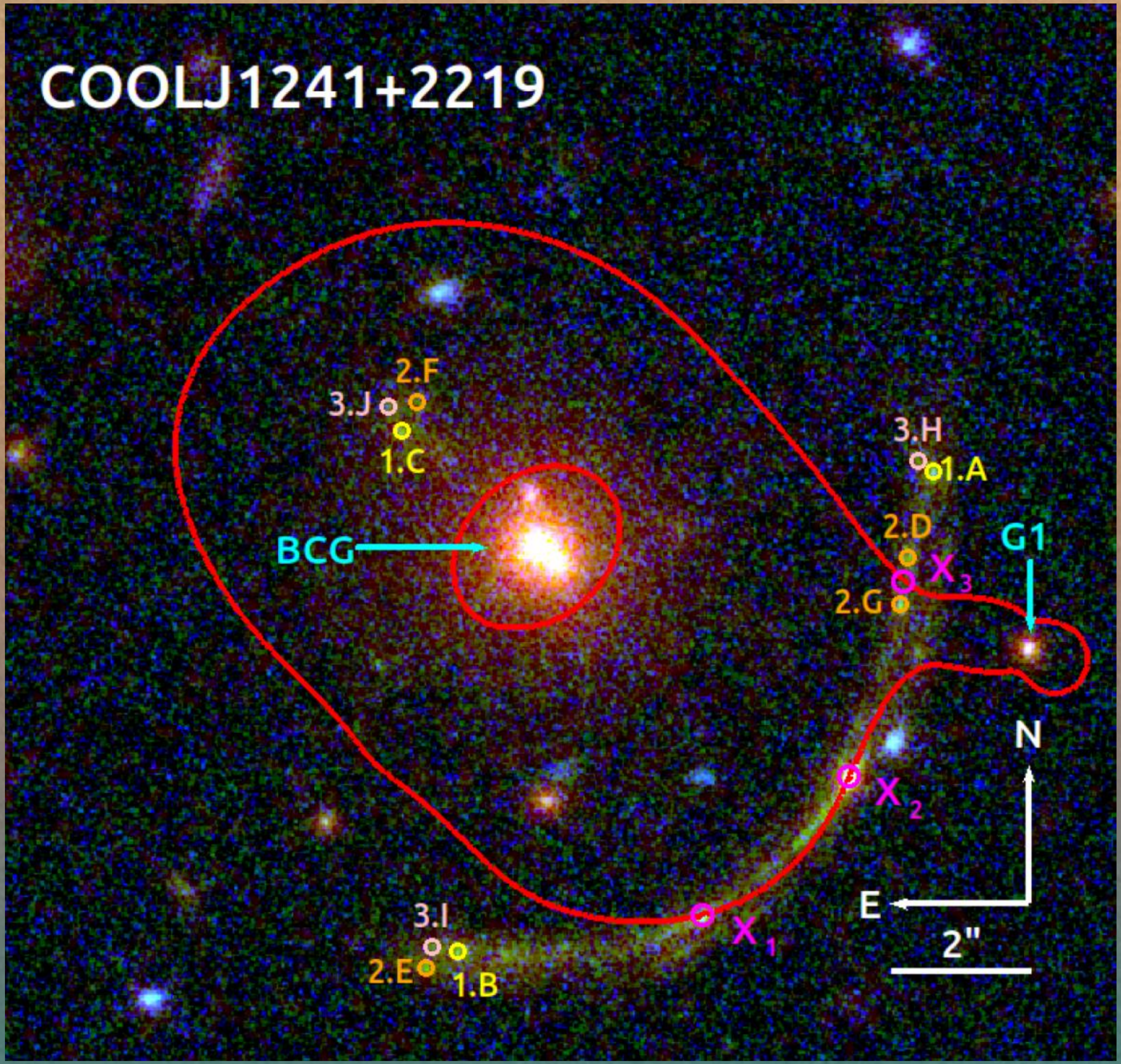
Results: Lensed High Redshift Galaxies

COOL-LAMPS I. An Extraordinarily Bright Lensed Galaxy at Redshift 5.04, Khullar et al. 2021

Gourav Khullar *(Field Course TA 2020-2021, Langley Fellow @ U Pittsburgh)*

At z_{AB}=20.5, COOL J1241+2219 is the brightest galaxy known at its redshift or higher, and 5x brighter than the next brightest object (RCS0224-C, z=4.87, Gladders et al. 2002). It is lensed by a massive group of galaxies at z=1.0. This rare gem offers a near unique opportunity to study, in great detail, a galaxy just after the epoch of reionization.

Results: Lensed High Redshift Galaxies



COOL-LAMPS VI: Lens model and New Constraints on the Properties of COOL J1241+2219..., Klein et al. 2024

Maxwell Klein(University of Michigan; undergraduate working Keren Sharon's group)

HST data allows for a refined lens model, yielding a robustly measured magnification of

$$< \mu_{arc} > = 76^{+40}_{-20}$$

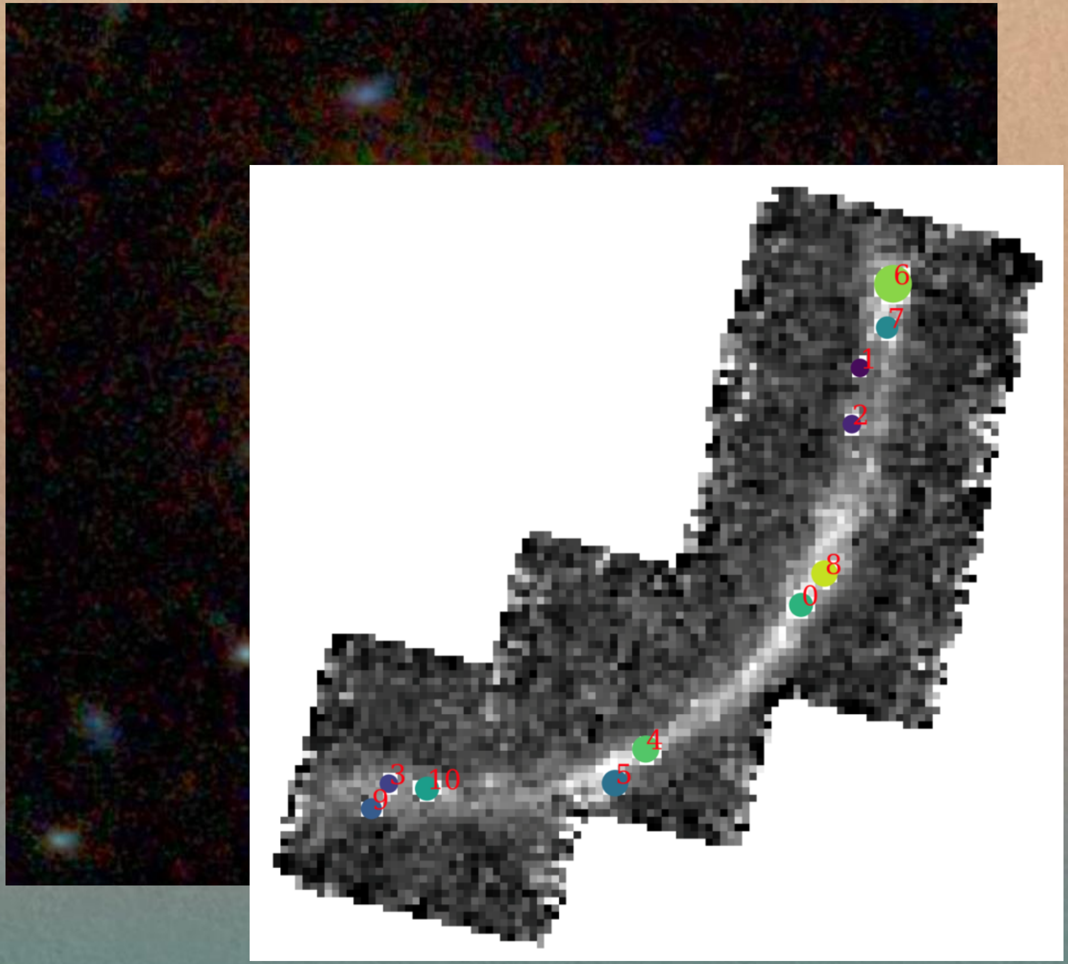
a total stellar mass of

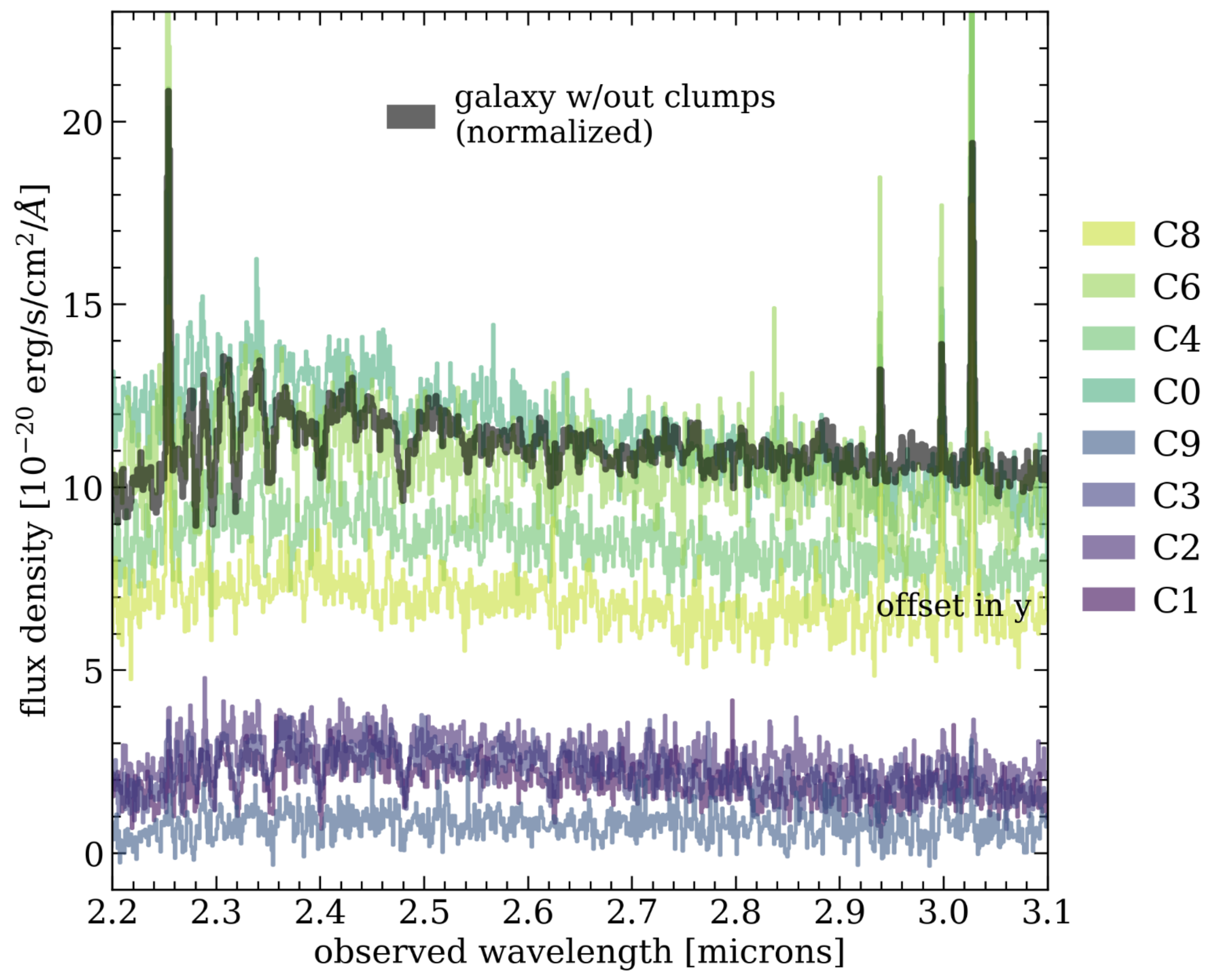
$$\log(M_\star/M_\odot) = 9.7 \pm 0.3$$

and a star formation rate of

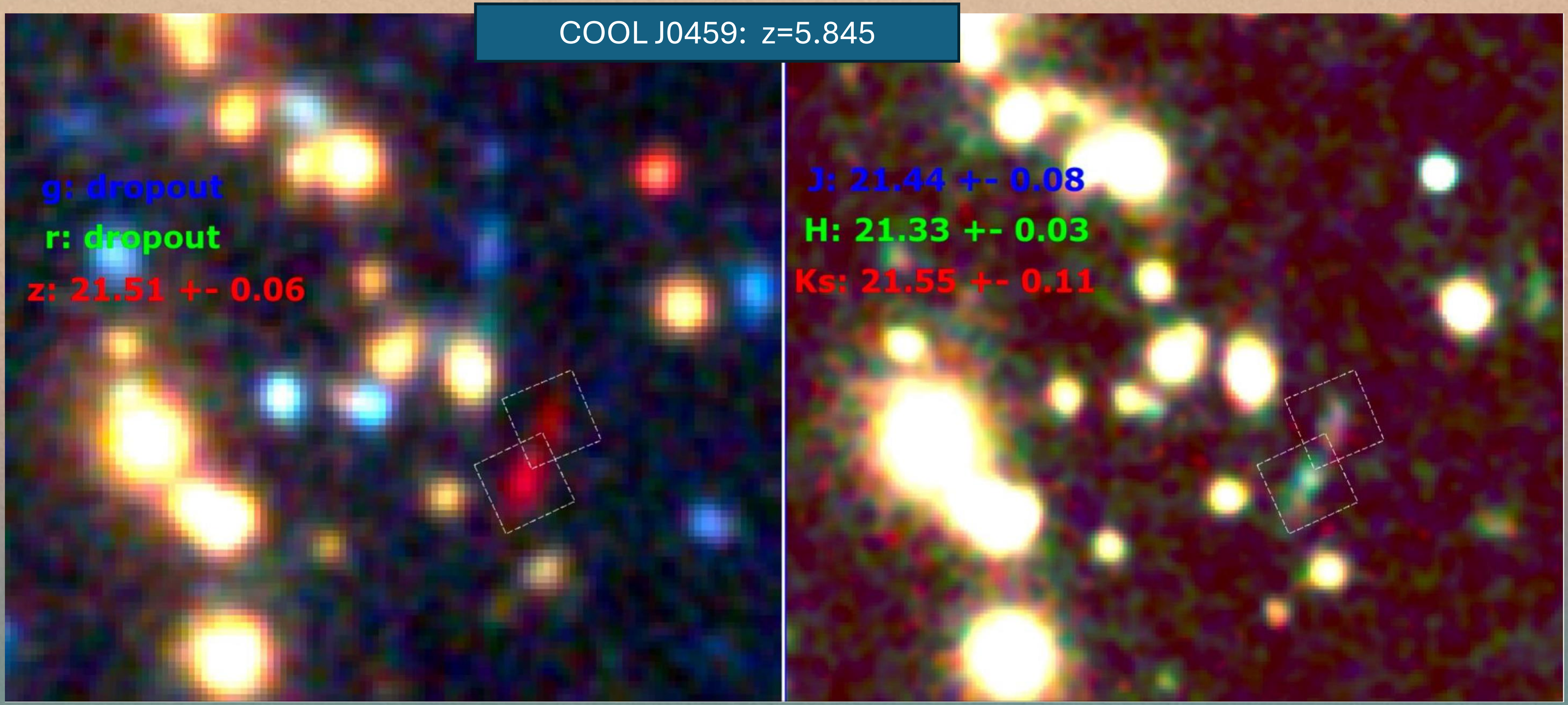
$$\mathrm{SFR} = 10.3^{+7.0}_{-4.4} M_\odot \mathrm{yr}^{-1}$$

Results: Lensed High Redshift Galaxies

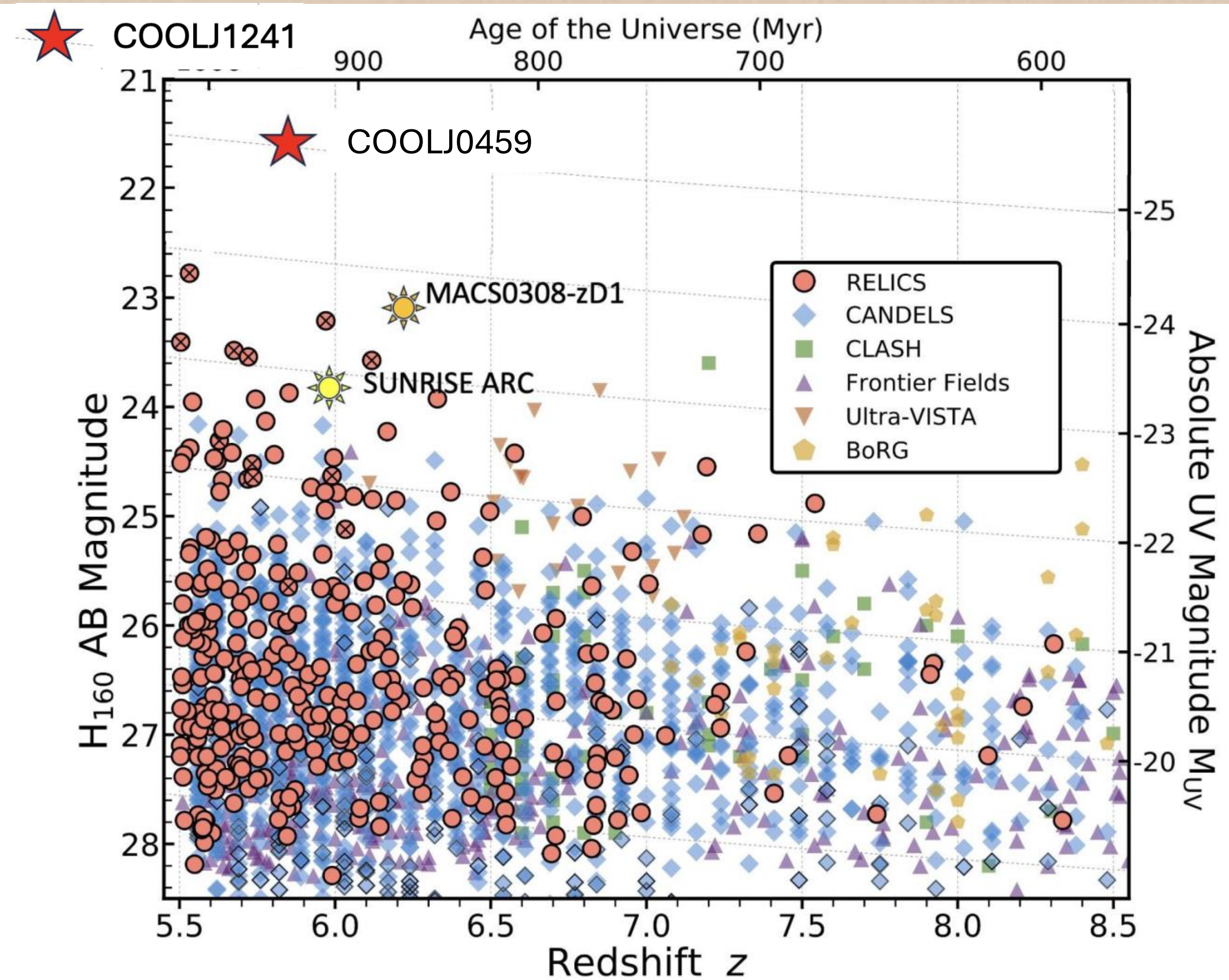




Results: Lensed High Redshift Galaxies



Results: Lensed High Redshift Galaxies



Though a magnitude fainter than COOL J1241+2219 this new rare gem is much brighter than anything else known at z~6 or higher, lensed or unlensed.

Finding the yet higher redshift analogs of these brightest galaxies will require sufficiently deeper imaging survey data over large areas of sky in the NIR – i.e., we await Euclid and Roman!

Compilation from
Salmon et al. 2020

Thank you! Questions?