Lensed quasars in SDSS-III and Pan-STARRS

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PS1 ExGal meeting, Durham, Jan. 9th, 2013

Overview

- lensed quasars are useful tool for cosmology (through their probability distribution) and galaxy evolution (as lenses)
- but rare (< 1/1000) and confused with QSO pairs, star alignments, etc.
- It requires large scale surveys and careful detection methods
- detection methods currently based on morphology for small separation or colour, starting from QSO spectroscopic samples
- can we detect lensed quasars starting from a photometric sample?
- Idea: using weighted colour difference
- PSPS Wish-list

PS1 White paper

PS1 Key Project 10: Active Galactic Nuclei and High-redshift Quasars

K. C. Chambers & Fabian Walter

IfA, MPG

Abstract.

The focus of this key project is the study of the quasar population that will be accessible with PS1. One of the main goals of this project is the identification and in-depth study of the highest-redshift ($z \gtrsim 6$) QSOs and galaxies in the universe. The study of these systems in the first Gyr after the Big Bang is a primary science goal of many large facilities that are currently under construction (LOFAR, ALMA, JWST, and SKA) and this PS1 key project is of fundamental importance to identify these objects. Science with galaxies and quasars at $z \lesssim 6$ will rely purely on photometric redshifts for point sources, addressing the luminosity function of quasars and galaxies, their clustering properties, and a search for lensed quasars. This project also includes studies of variability selected quasars, high-redshift radio galaxies and narrow-line Seyfert 1s. PS1 data will also be used as part of KP10 to search for tidal disruption events, and, finally, to trigger observations with HESS.

3. Subproject B – Photometrically selected quasars at $z \lesssim 6$ in 3π and MDS: luminosity functions, clustering, lensing

3.1. Preliminary list of scientists

Hans-Walter Rix, Sebastian Jester, Coryn Bailer-Jones, Fabio Fontanot (all MPIA), Paul Price (IfA), Phil Hopkins (CfA); as external collaborators: Gordon Richards (Penn State), Adam Myers (UIUC)

3.3. Identifying the Multiply-imaged and Strongly Magnified QSOs in PS1

(Rix, Jester, Student N.N.)

QSOs have proved over the last years to be a productive astrophysical tool: the separation statistics is a powerful and independent tool to probe the concentration of potential wells (galaxies and groups); the relative image brightnesses may be one of the best ways to constrain dark-matter sub-halos; and the high magnifications that occur allow studies of the host galaxies at unprecedented flux sensitivity and physical resolution.

Drawing on the sample of color-identified QSOs we plan to devise a statistically well-defined sample of multiply-images QSO candidates, and to follow-up the most promising candidates. Following the experience with SDSS (14), we will employ two separate approaches, one to identify "small separation lenses" ($0\farcs4$ - $2''$); and one to search for wide-separation lenses ($> 2''$). In the first case, the underlying assumption is that IPP only detects on source, that the subsequent analysis shows that this source has QSO-like colors, but that the source shape is not consistent with the PSF; subsequent multi-band deblending exercises can help remove QSO–star projection pairs. In the second, 'wide-separation' case the approach will be to search for separate "catalog entries" or sources, that have similar, QSO-like colors and that lie within $\lesssim 20''$ of each other. We expect dozens of wide-separation candidates, and many hundreds of small separation candidates.

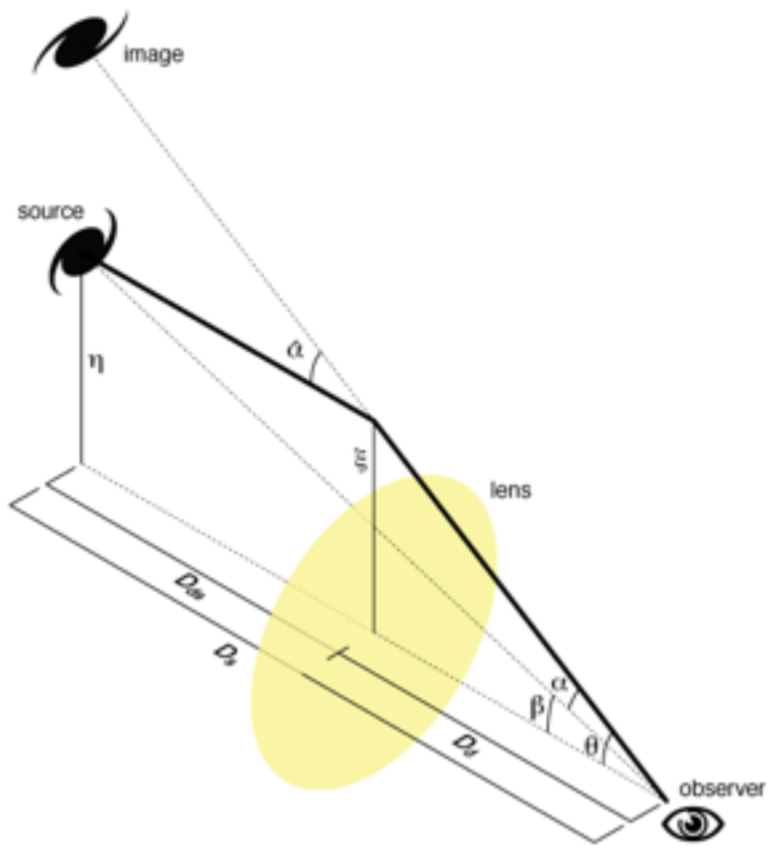
Using the PMAS IFU spectrometer at CAHA we then plan to get follow-up spectra for all wide-separation candidates, and selected small-separation candidates (e.g. very high redshift objects).

This sub-project is to be carried out in the context of a PhD thesis at MPIA.

Motivations

- Cosmology
  - Lenses depend of the volume, hence on the cosmological parameters
  - Time-delay
- QSOs evolution
  - Faint QSOs Luminosity Function
  - Close QSO pairs, small-scale clustering
- Galaxy evolution
  - Mass of lensed objects

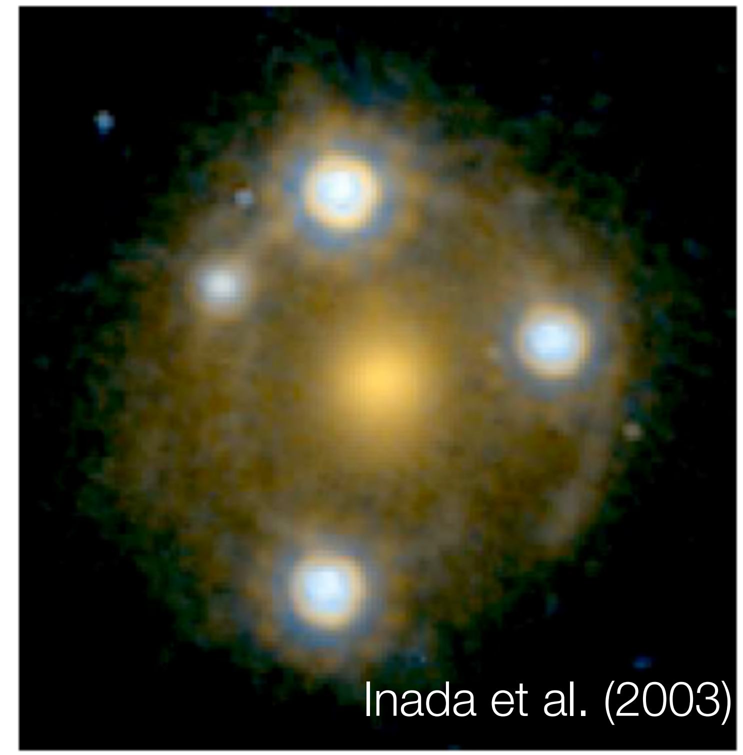
Lensed quasars

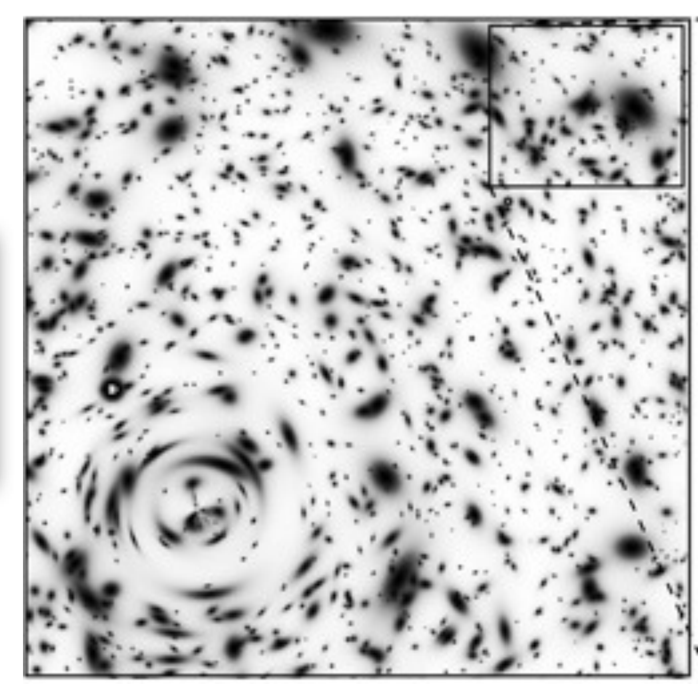


Deflection angle depends
on mass and distances

if perfectly aligned,
creates multiple images
-> strong lensing regime

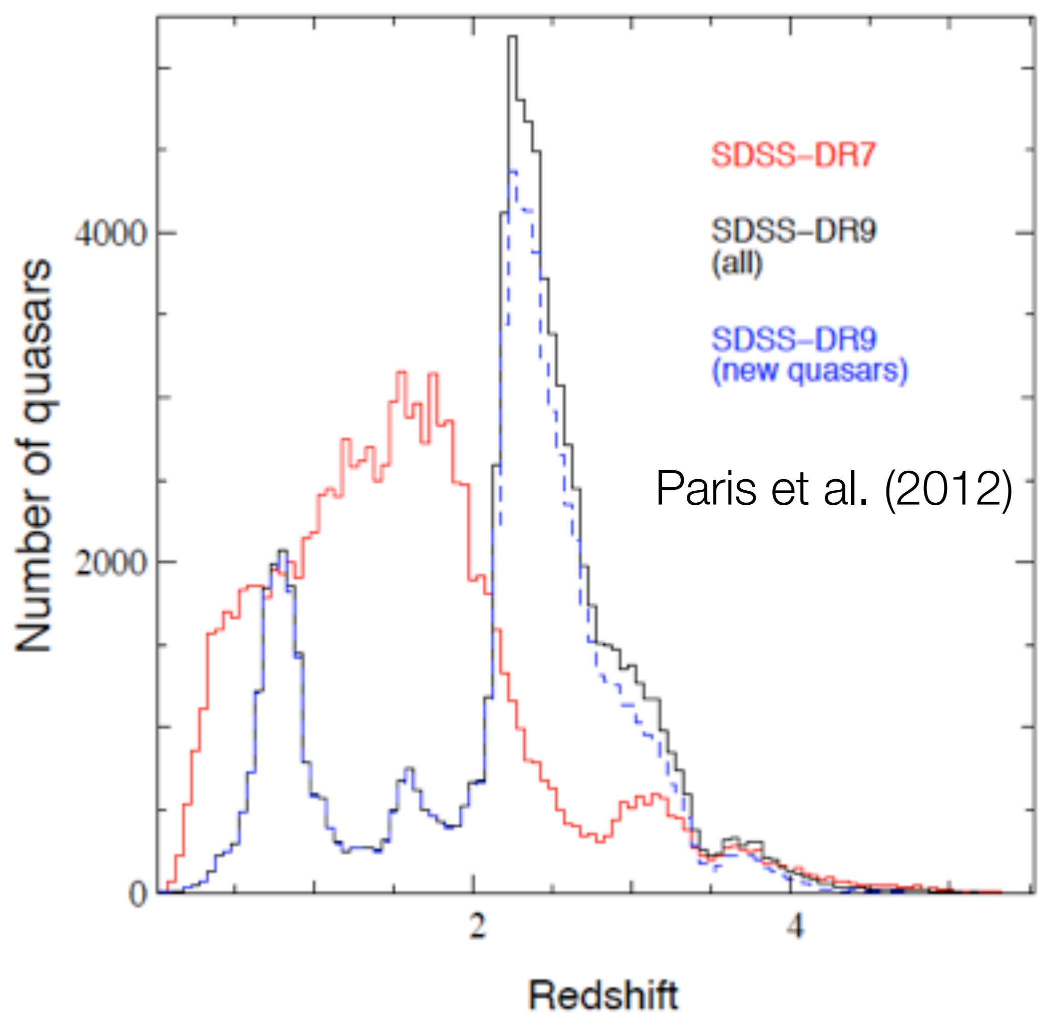
QSO are also affected by
lenses at large separation
-> weak lensing regime


Inada et al. (2003)


Y. Mellier

QSOs in SDSS

- SDSS, 8000 deg2 100,000 QSOs in 1 < z < 2
- BOSS-SDSS DR9, currently 3000 deg2, 90,000 QSOs at z > 2

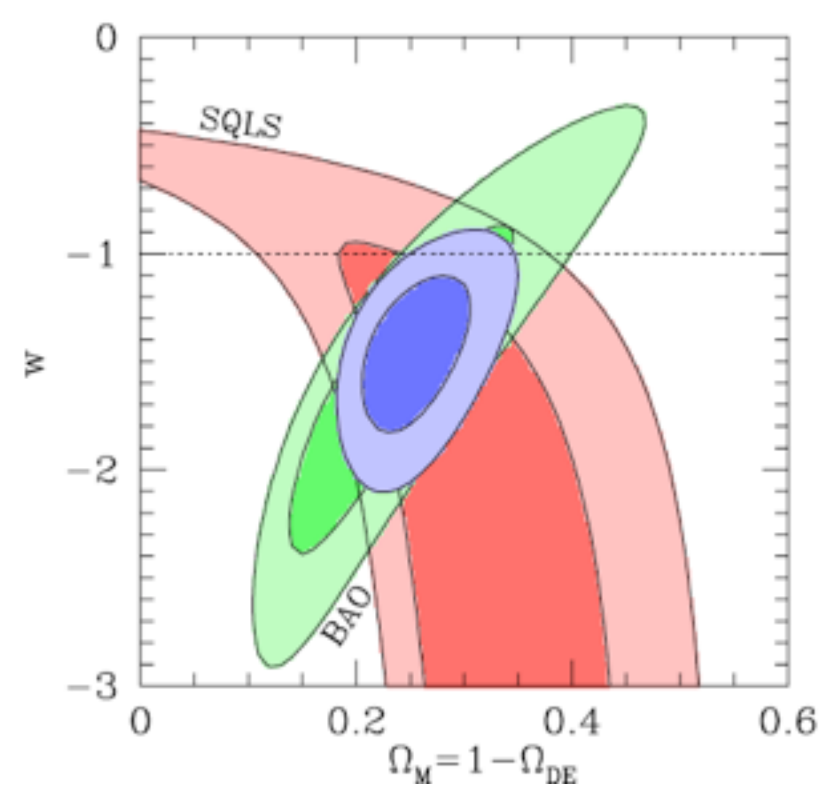


SDSS Quasar Lens Search

N	image	name	N_{im}	sep	z_s	z_l	i_{cor}	flag	references
1		SDSS J0246-0825	2	1.09	1.686	0.723	17.76	DR3stat	Inada et al. AJ 130(2005)1967
2		SDSS J0743+2457 (ULAS J0743+2457)	2	1.03	2.165	0.381	19.01	DR3	Jackson et al. MNRAS 419(2012)2014 Inada et al.
3		SDSS J0746+4403	2	1.08	1.998	0.513	18.71	DR5stat	Inada et al. AJ 133(2007)206
4		SDSS J0806+2006	2	1.49	1.538	0.573	18.89	DR5stat	Inada et al. AJ 131(2006)1934
5		SDSS J0819+5356	2	4.04	2.239	0.294	18.52	DR5	Inada et al. AJ 137(2009)4118
6		SDSS J0820+0812 (ULAS J0820+0812)	2	2.20	2.024	0.803	19.05	DR5	Jackson et al. MNRAS 398(2009)1423
7		SDSS J0832+0404	2	1.98	1.116	0.659	18.89	DR3	Oguri et al. AJ 135(2008)520
8		SDSS J0903+5028	2	2.84	3.584	0.388	19.50	DR3	Johnston et al. AJ 126(2003)2281
9		SDSS J0904+1512	2	1.13	1.826	-	17.51	DR7	Kayo et al. AJ 139(2010)1614
10		SDSS J0924+0219	4	1.81	1.523	0.394	18.12	DR3stat	Inada et al. AJ 126(2003)666

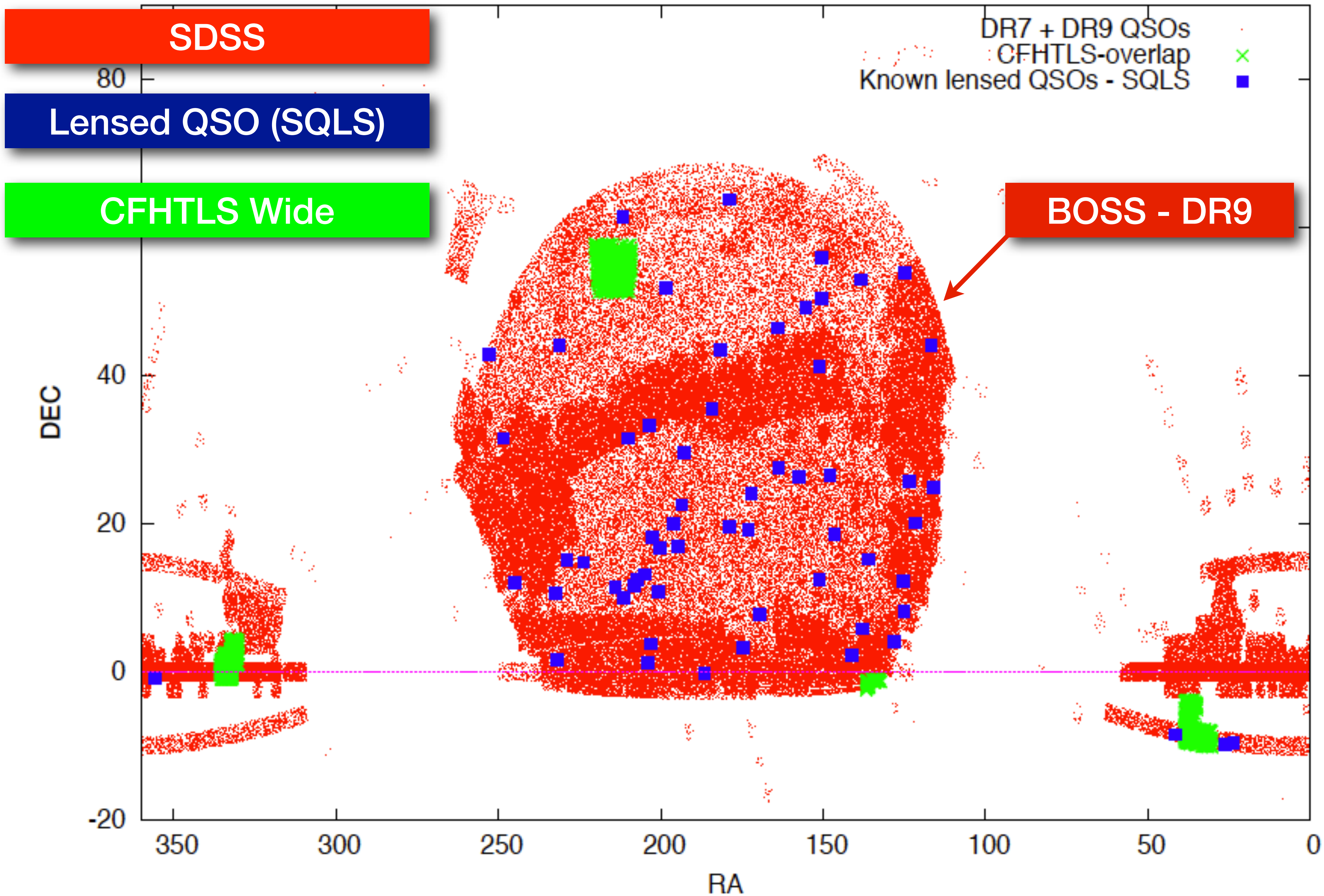
http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/lens.html

Lensed QSOs in SDSS
~ **60** confirmed systems
used to constrain cosmology



Oguri et al. (2012)

SDSS QSO distribution



How to detect strongly lensed QSO?

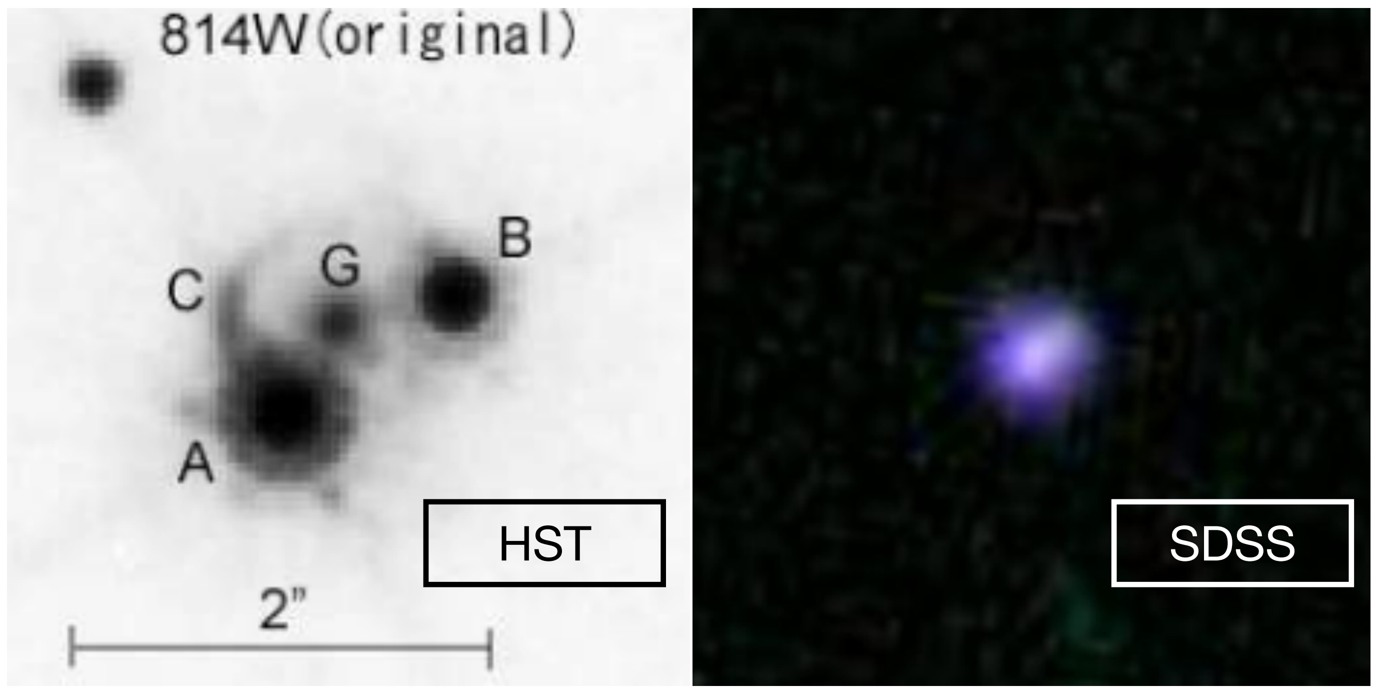
- From spectroscopic QSO sample,
- look for blended objects through morphology measurement (departure from PSF-shaped QSO)
- if not blended, look for close pairs with identical colours
- see e.g. Jackson et al. (2012), Inada et al. (2012), Oguri et al. series

QSO samples are not complete

colours suffer from magnitude errors (especially if blended)

difficult to detect systems with large separation because of higher “random” contamination

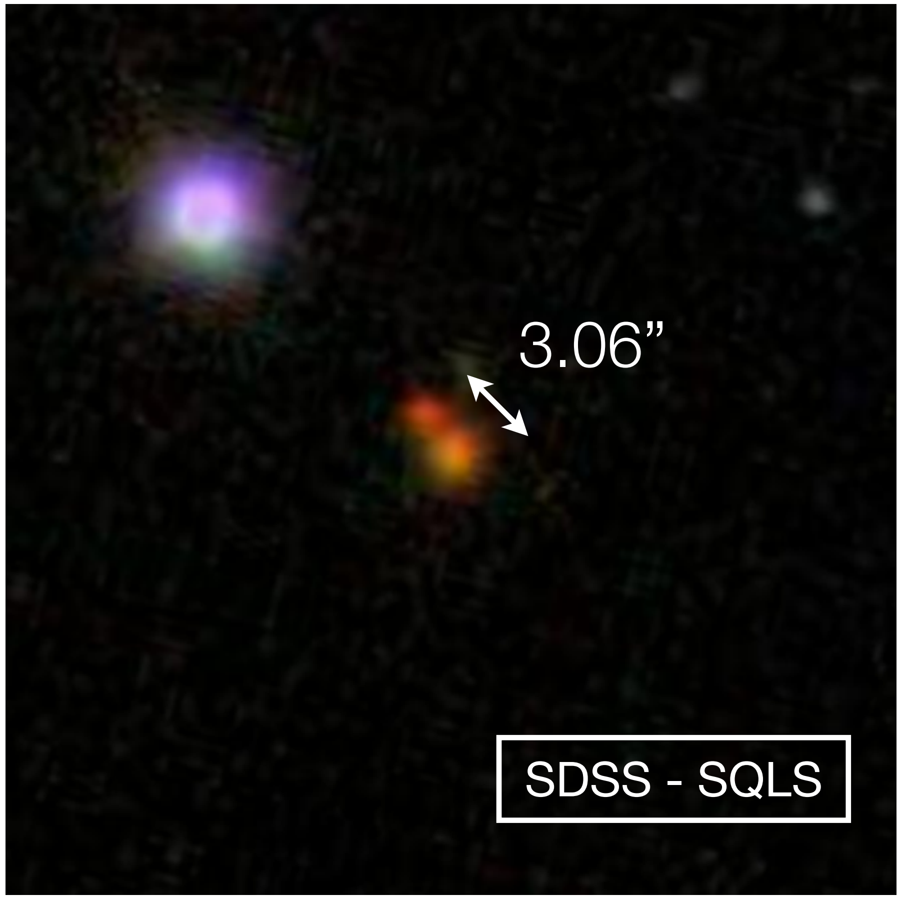
Morphology



Inada et al. (2005)

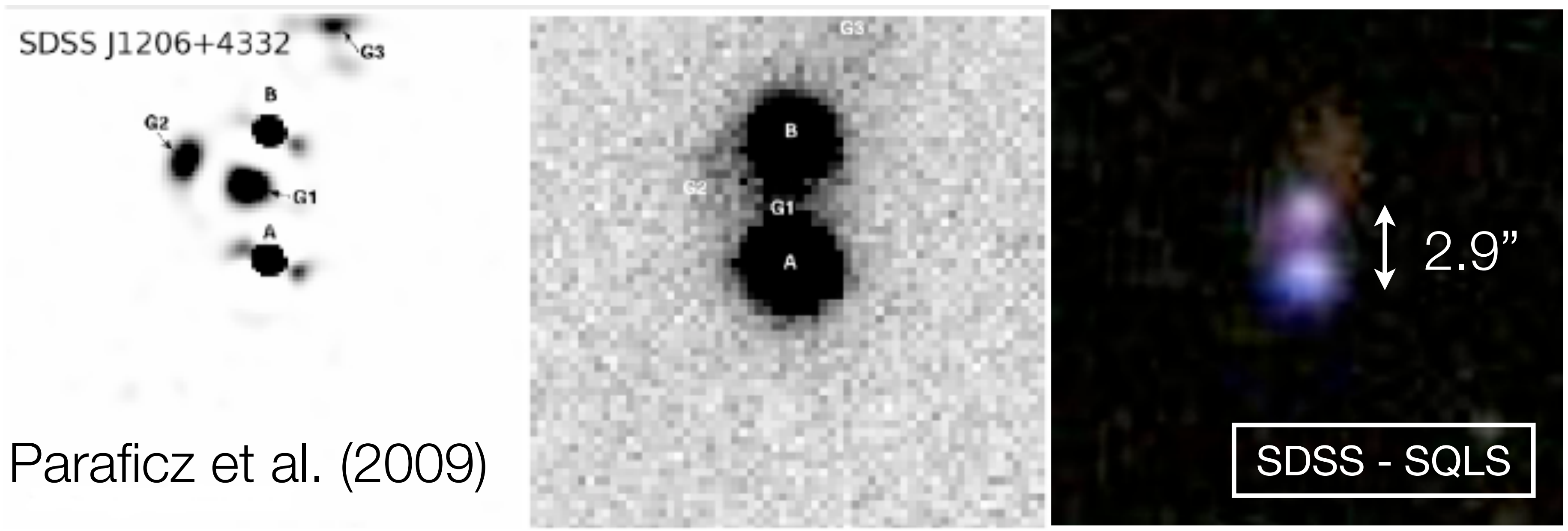
For blended pairs the detection relies on morphology
(departure from PSF)

Close pairs with identical colors



When the separation is much larger than the PSF, the detection relies on colour

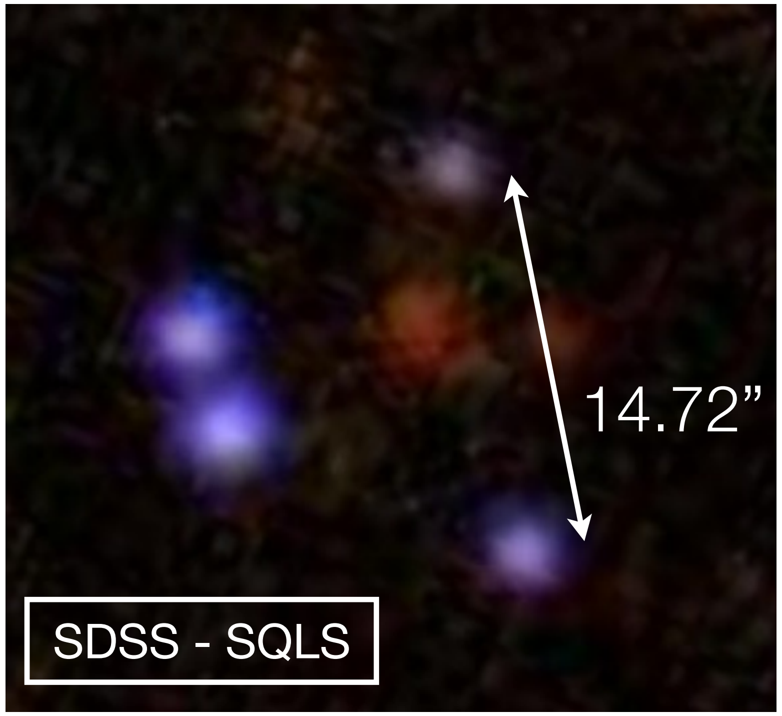
Close pairs with identical colors

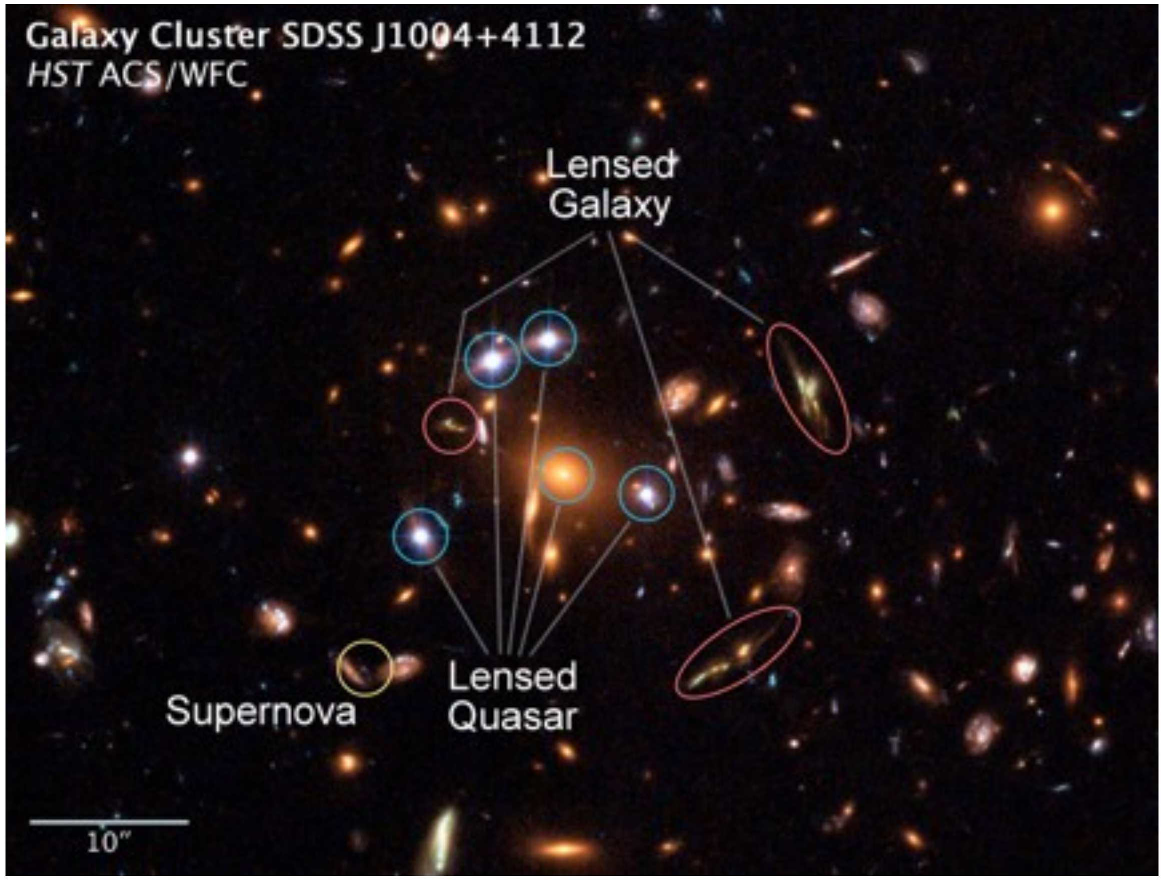


Paraficz et al. (2009)

De-convolved pair

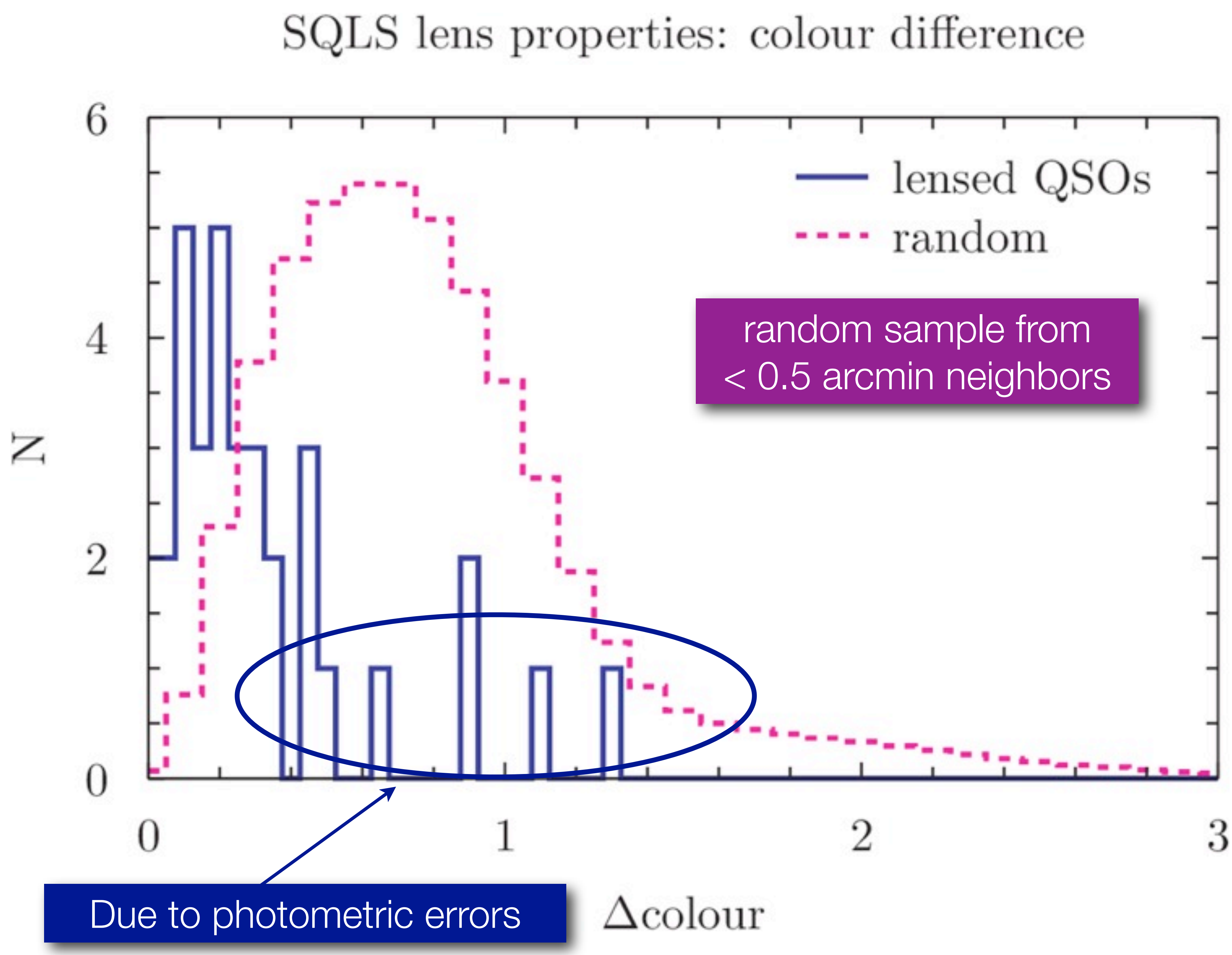
Large separation





Lensed quasars around cluster have large separation

Colour difference



Weighted colour difference

Colour difference weighted by magnitude errors

$$\Delta_c = \sqrt{\left(\frac{\sum_i w_{c_i} \Delta^2_{c_i}}{\sum_i w_{c_i}}\right)}$$

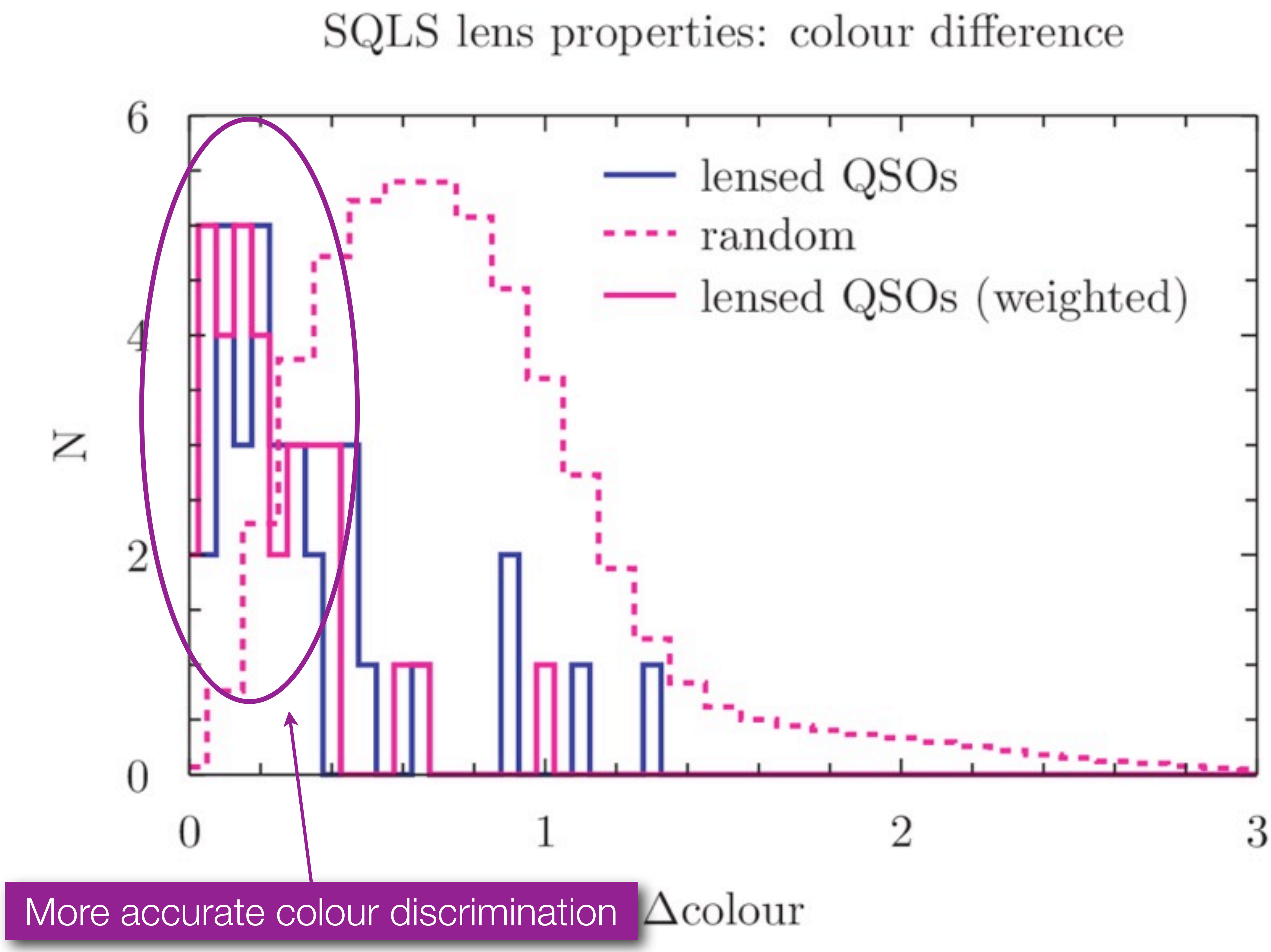
where

$c_i = (u - g) - (u - g)_{\text{neighbor}}$, etc.

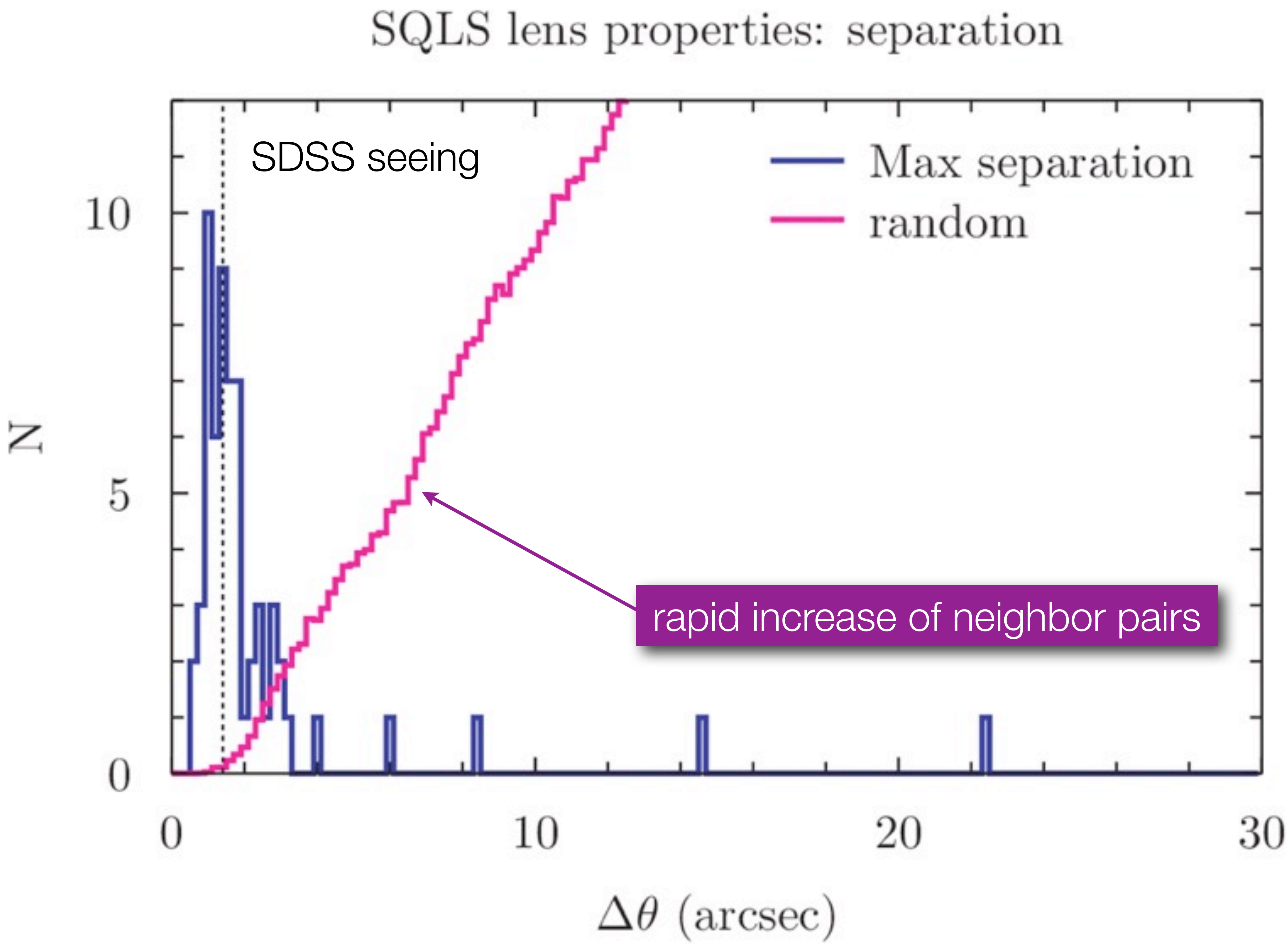
and

$w_{c_i} = 1/(\delta^2_u + \delta^2_g + \delta^2_{u,\text{neighbor}} + \delta^2_{g,\text{neighbor}})$, etc.

Weighted colour difference



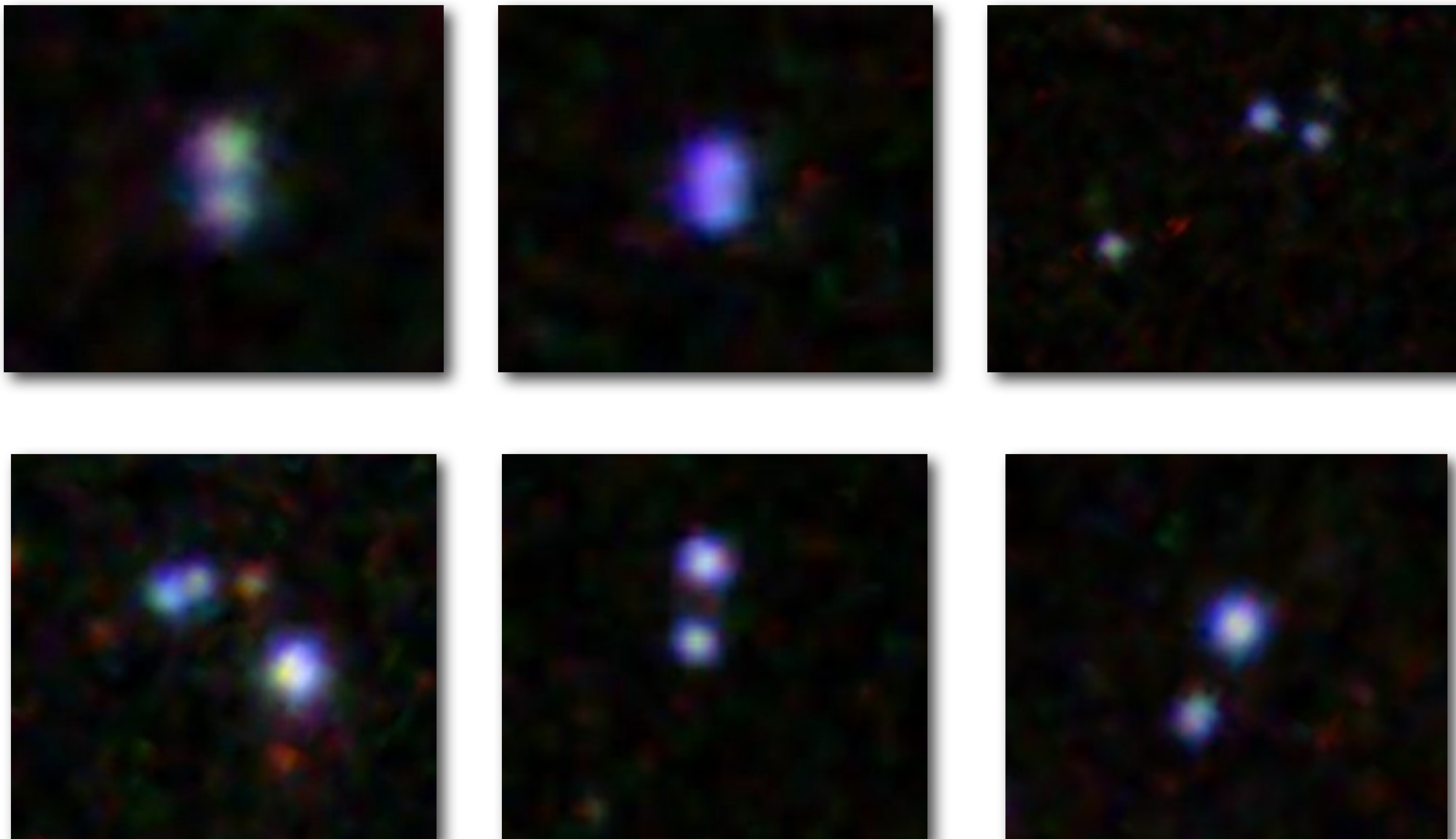
Angular separation



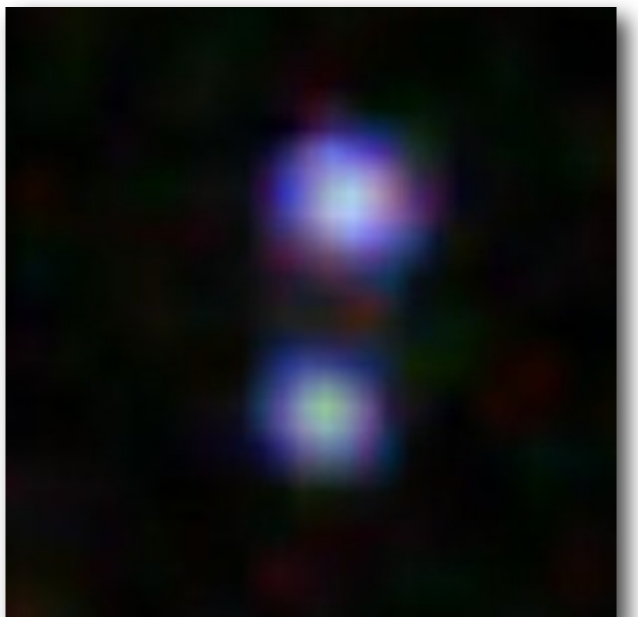
Blind selection based on colour in DR9

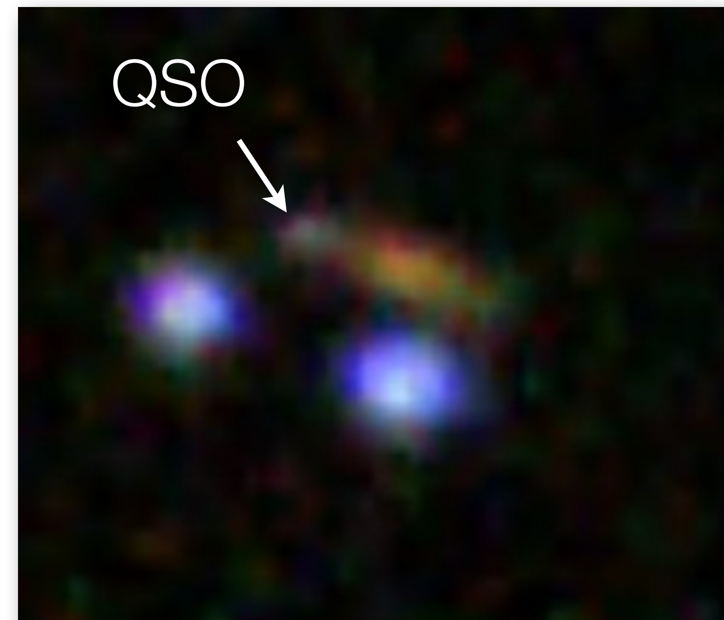
- **sep < 2.0** -> morphology selection (P_{PSF} < 0.1) and relaxed colour selection (delta colour < 1.0)
- **2.0 < sep < 5.0** colour diff < 0.2
- **sep > 3.0** colour diff < 0.2 and N > 2
- recovery rate: 22 out 28 known lenses (in neighbor’s catalogue).
- total candidates: ~500/170,000 QSOs

Close pair candidates (all new from DR9)

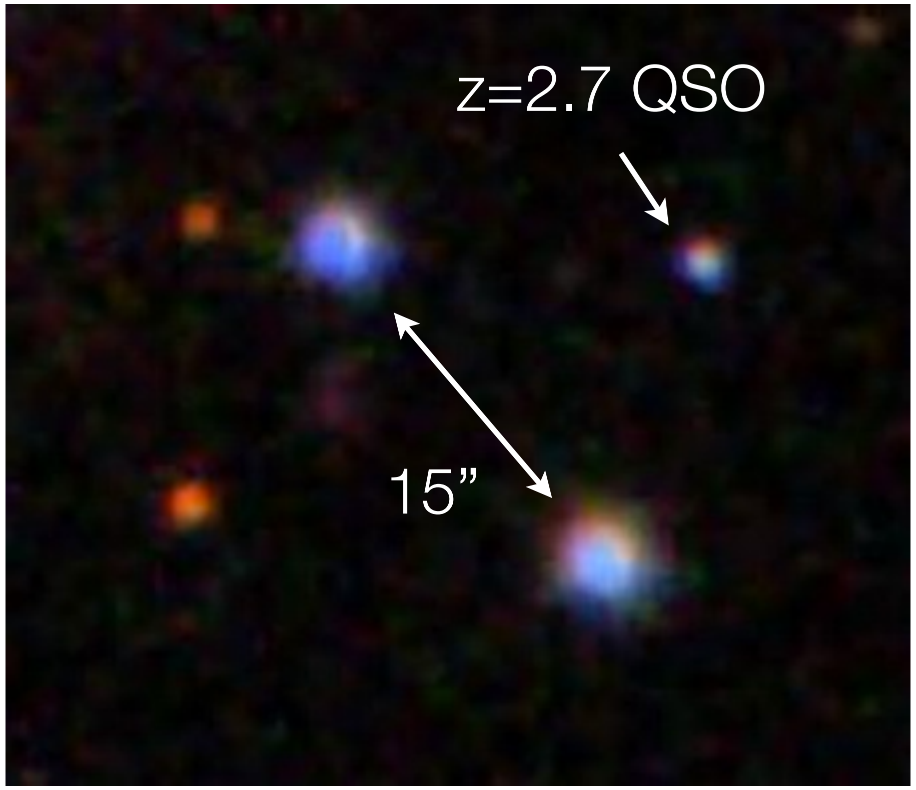


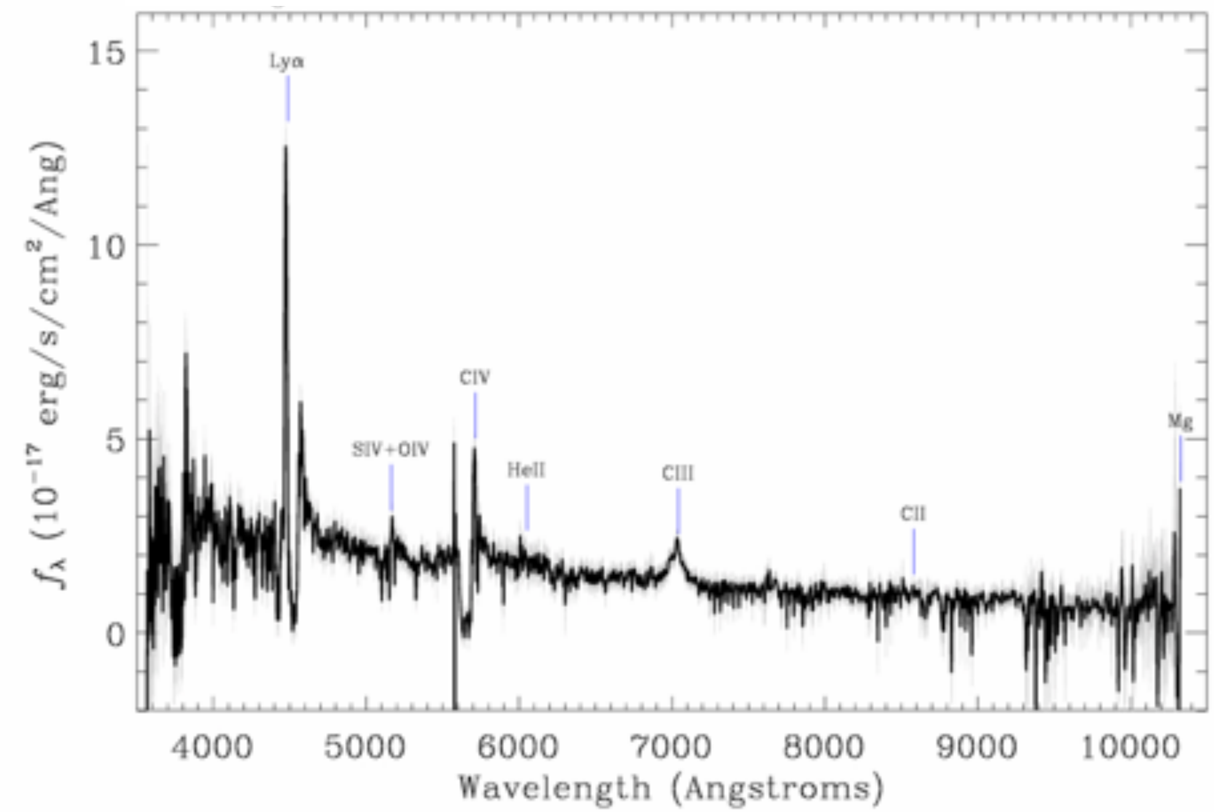
Close pair candidates (more)





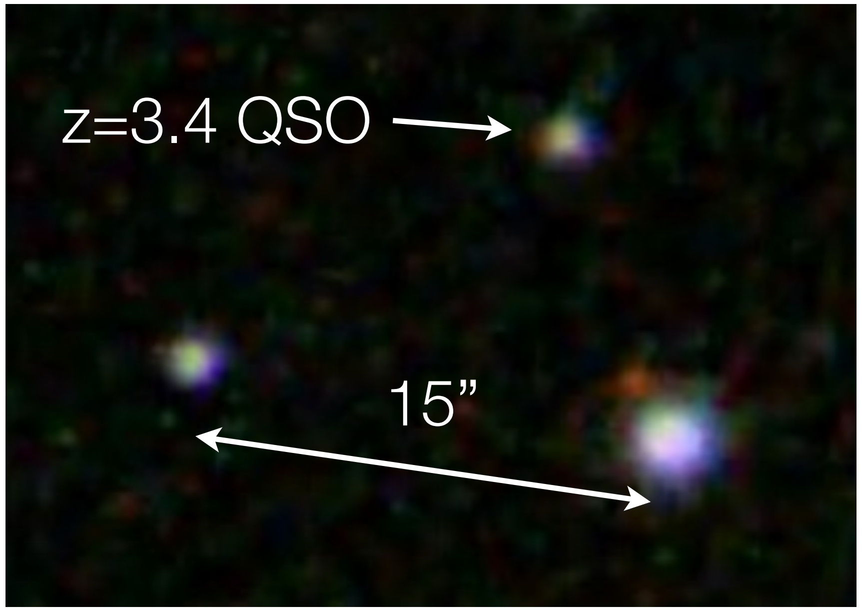
Interesting candidate close-up 1

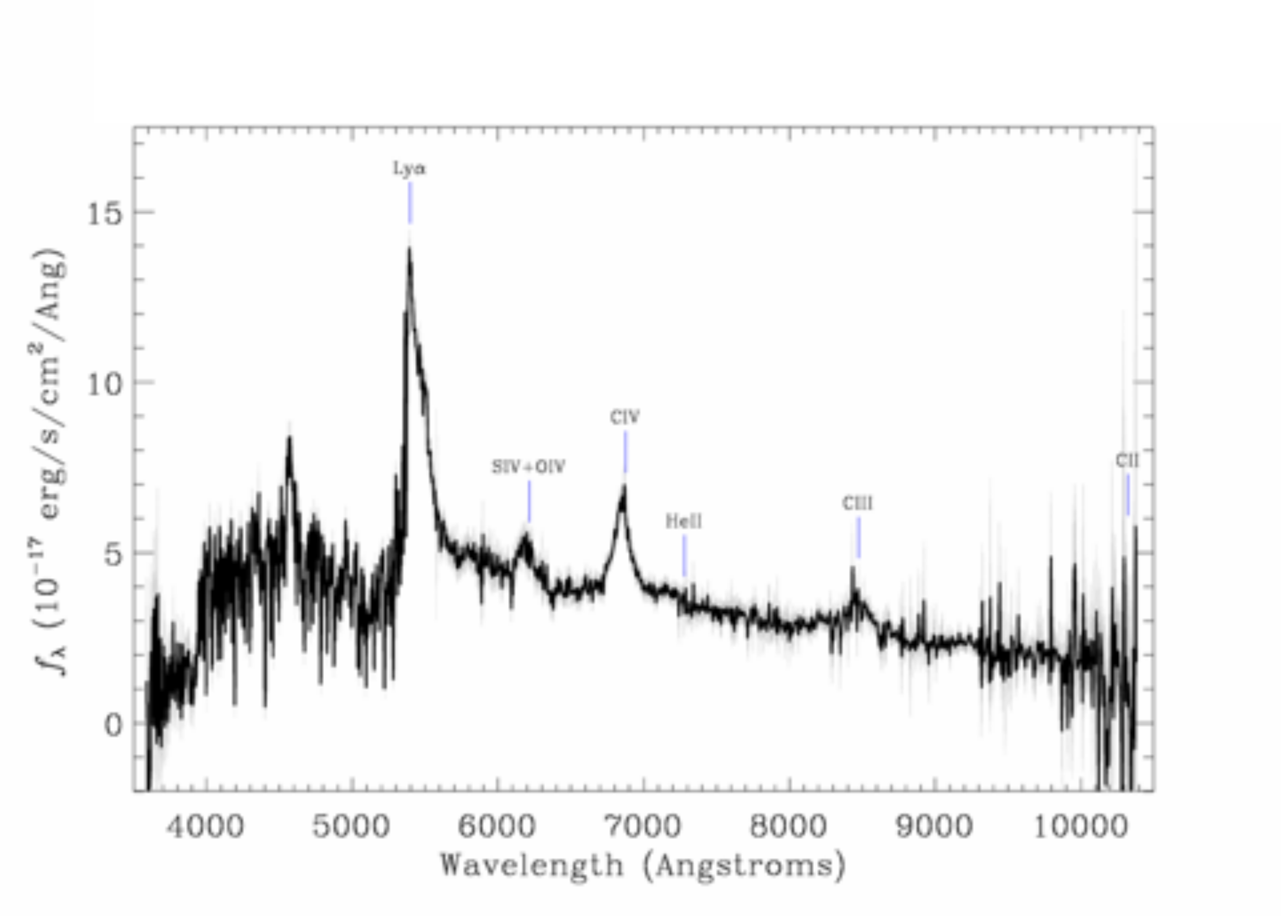




Unlikely configuration?
too large separation?

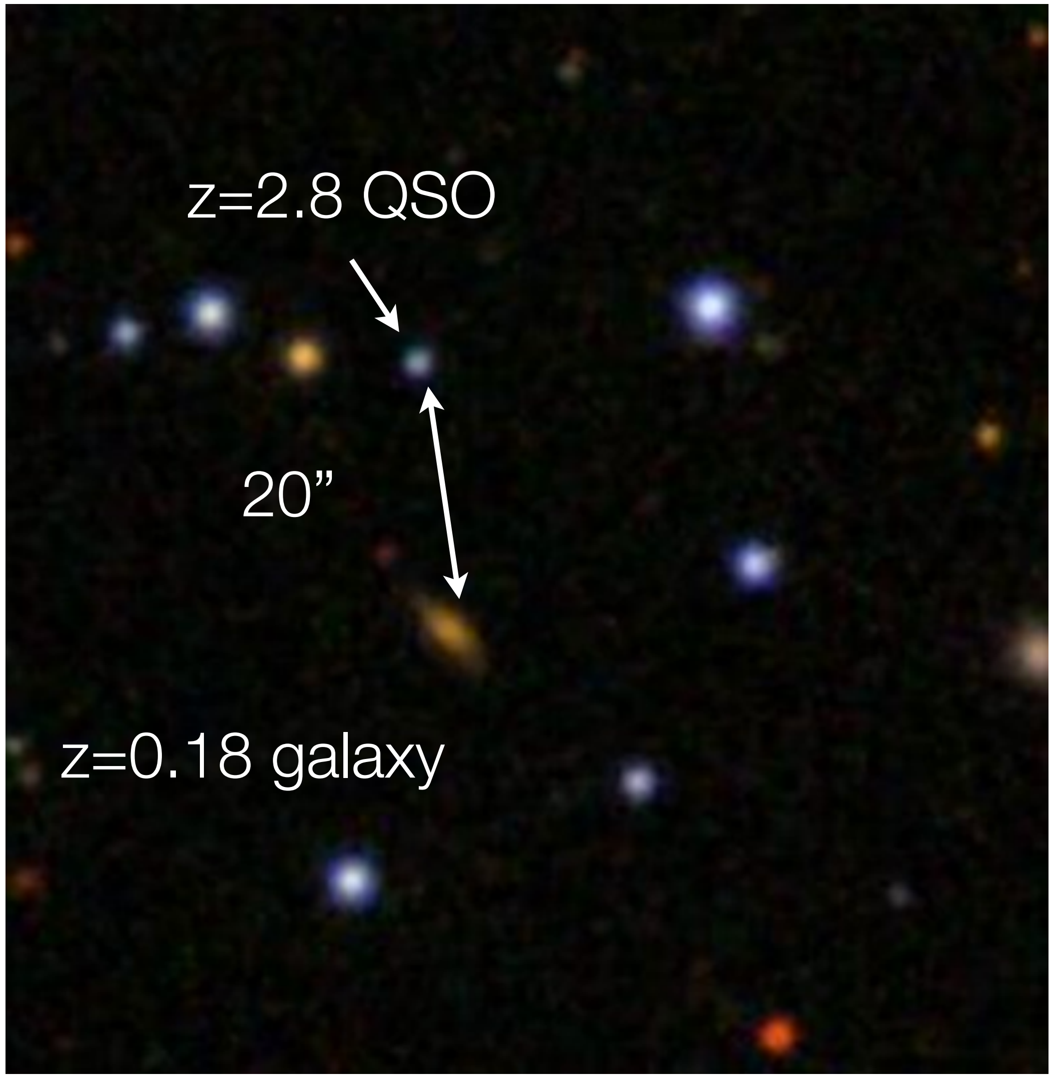
Interesting candidate close-up 2

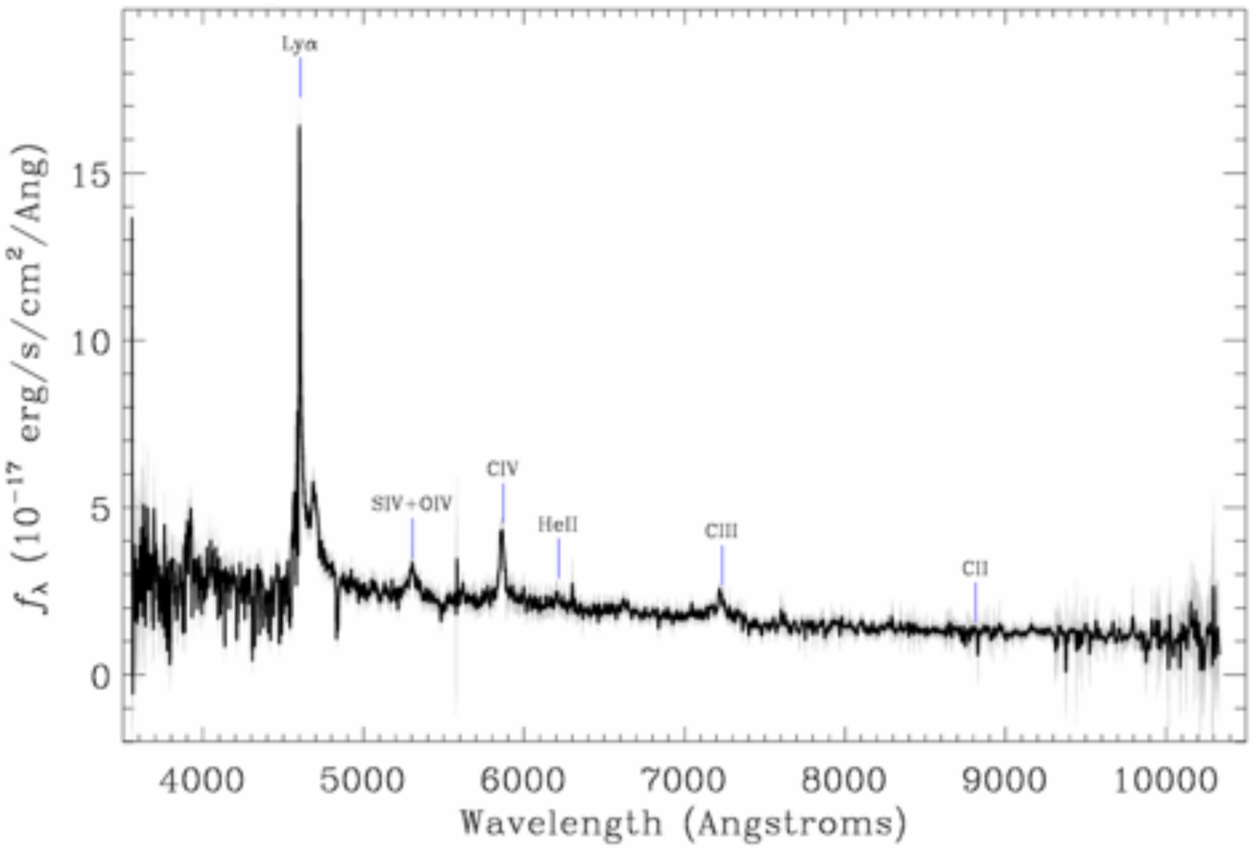




too large separation?

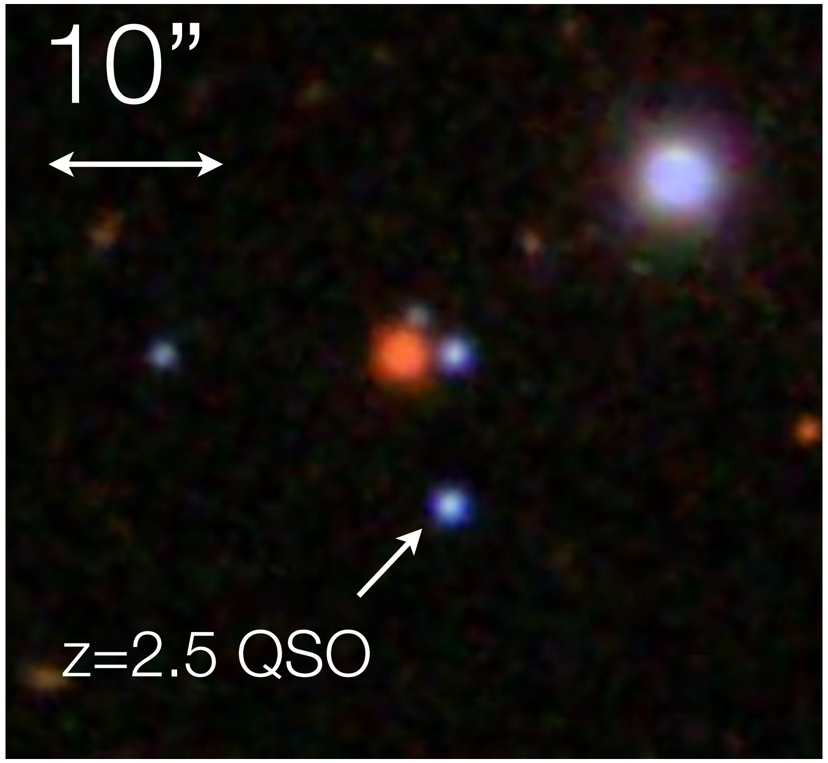
Interesting candidate close-up 3

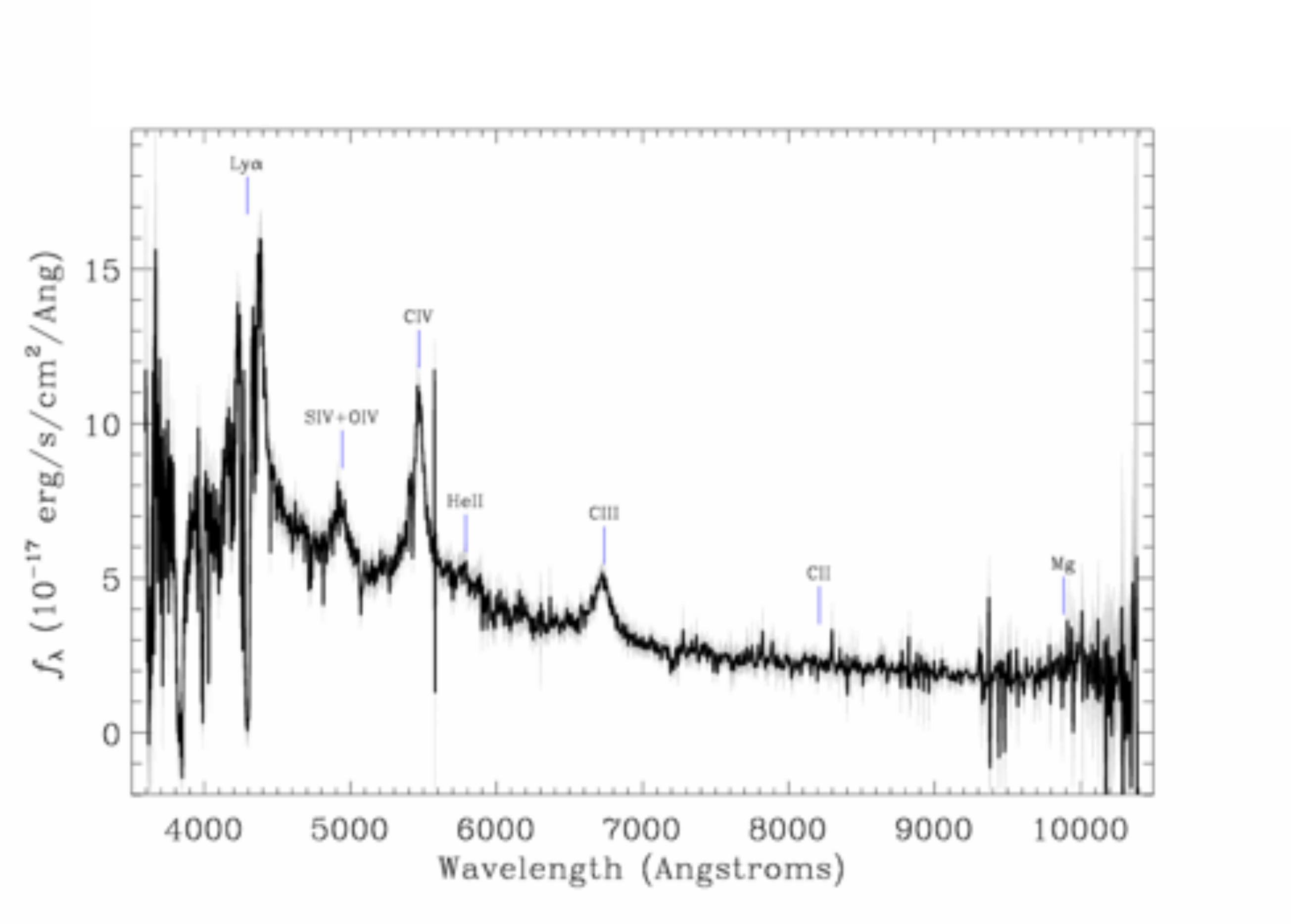




too large separation?

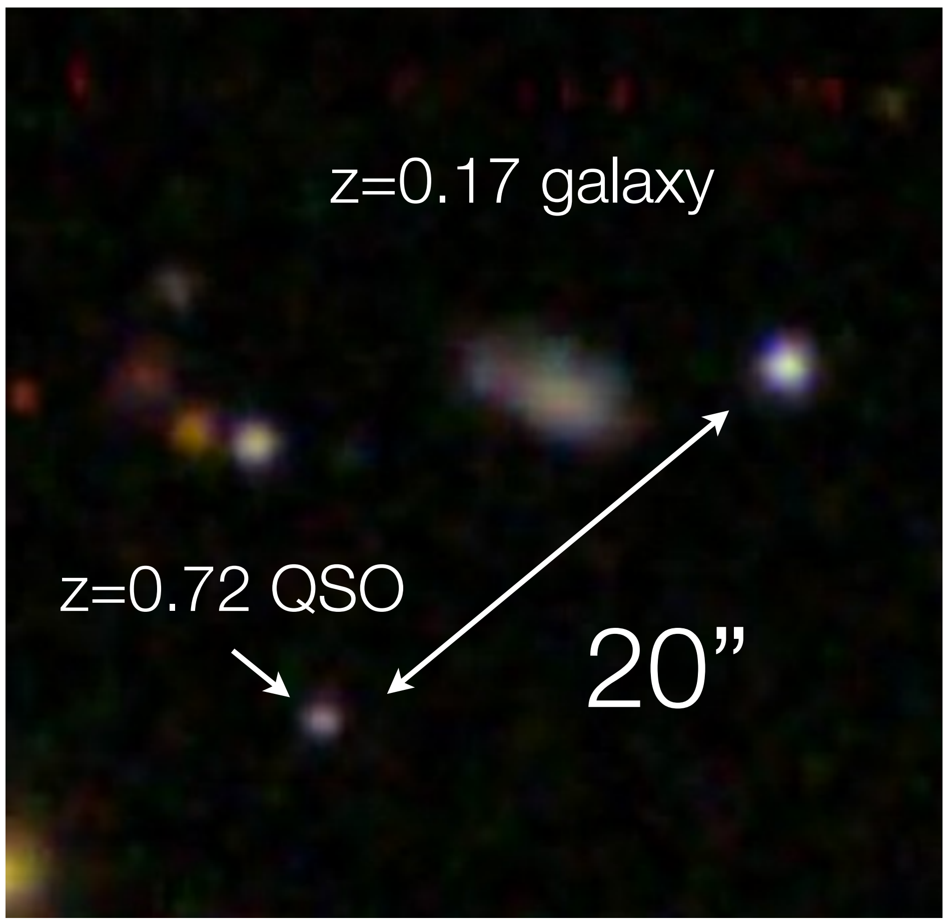
Interesting candidate close-up 4

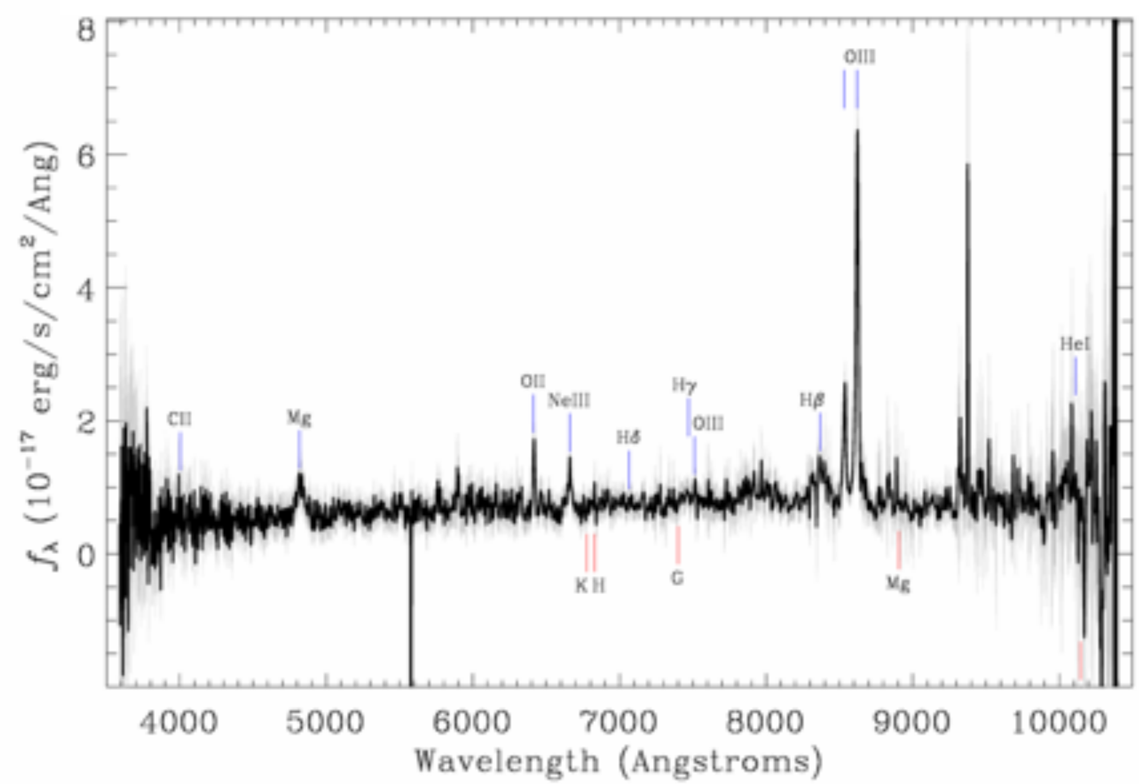




Central red object is a star

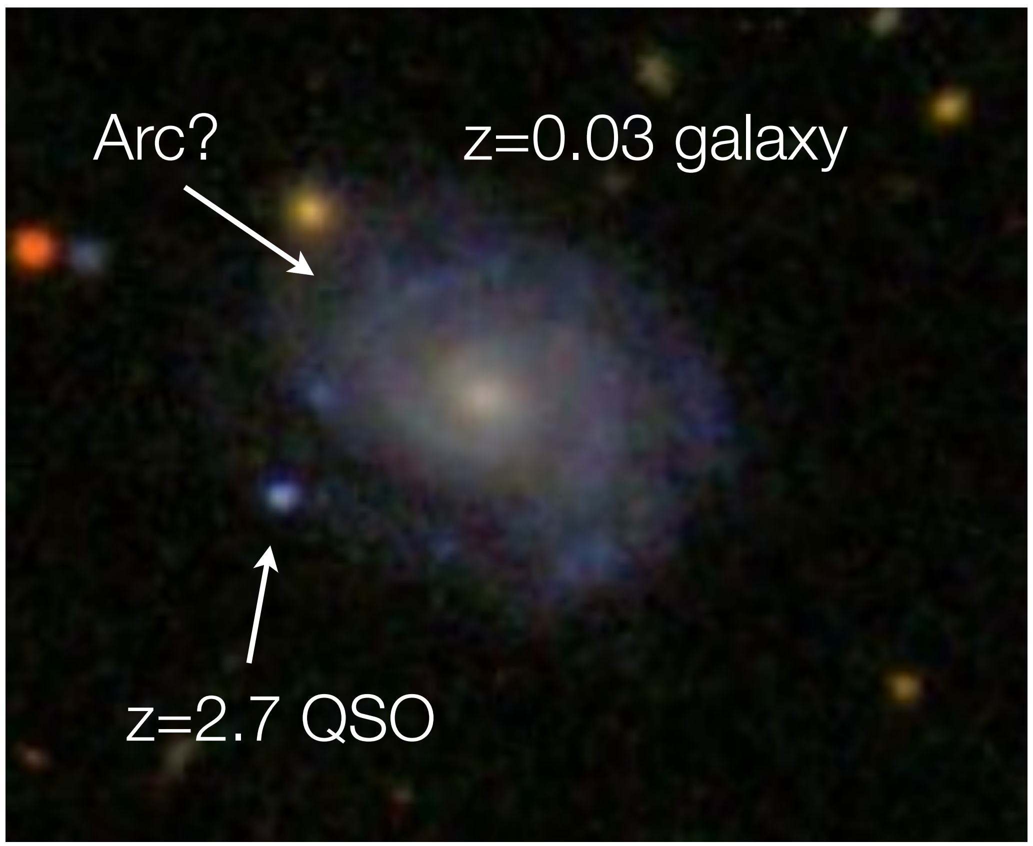
Interesting candidate close-up 5

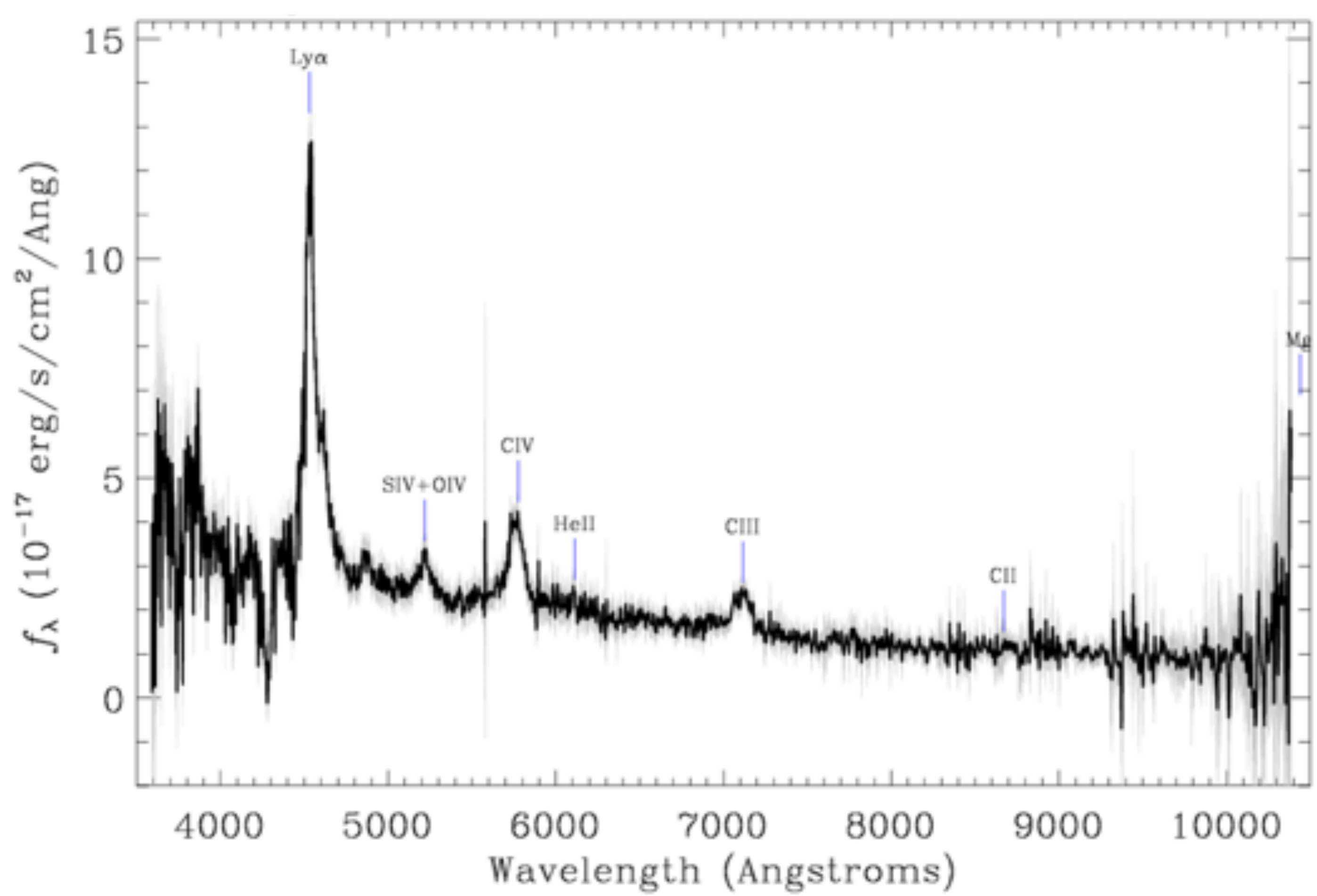




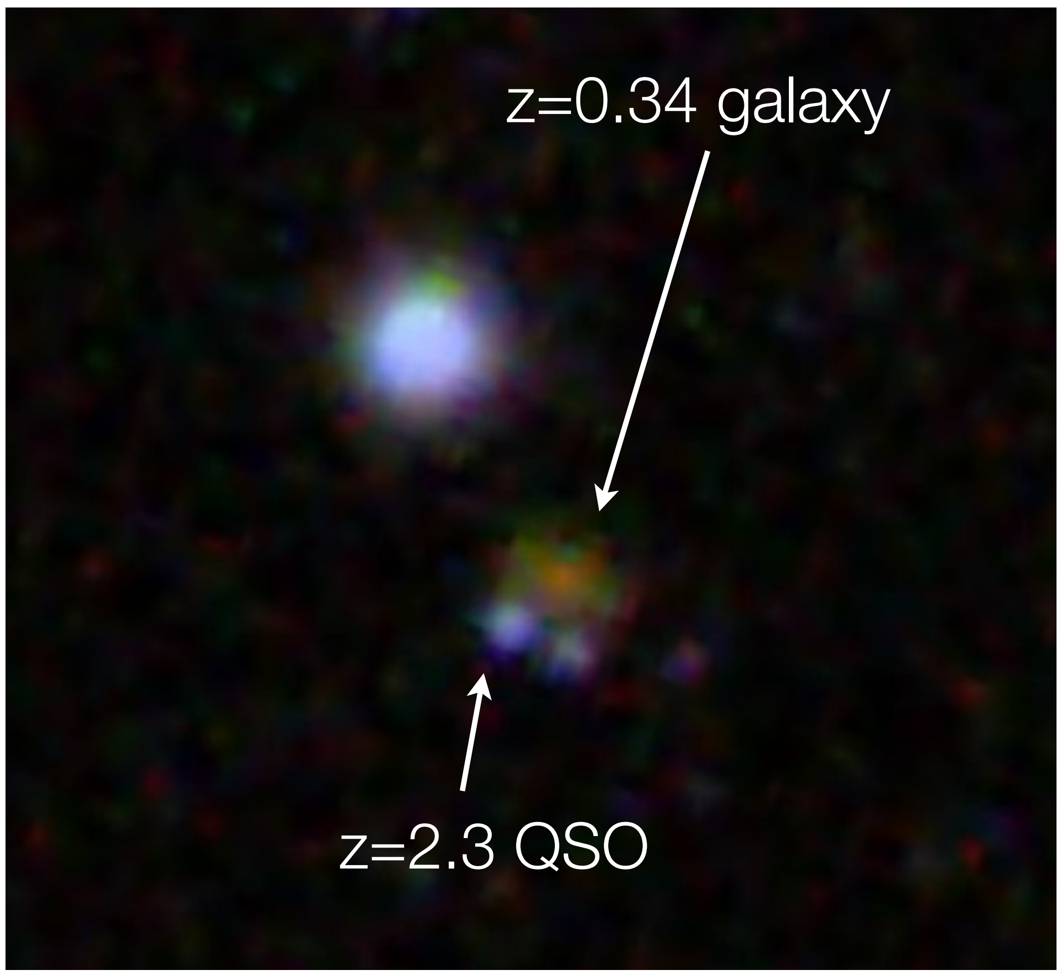
Large separation

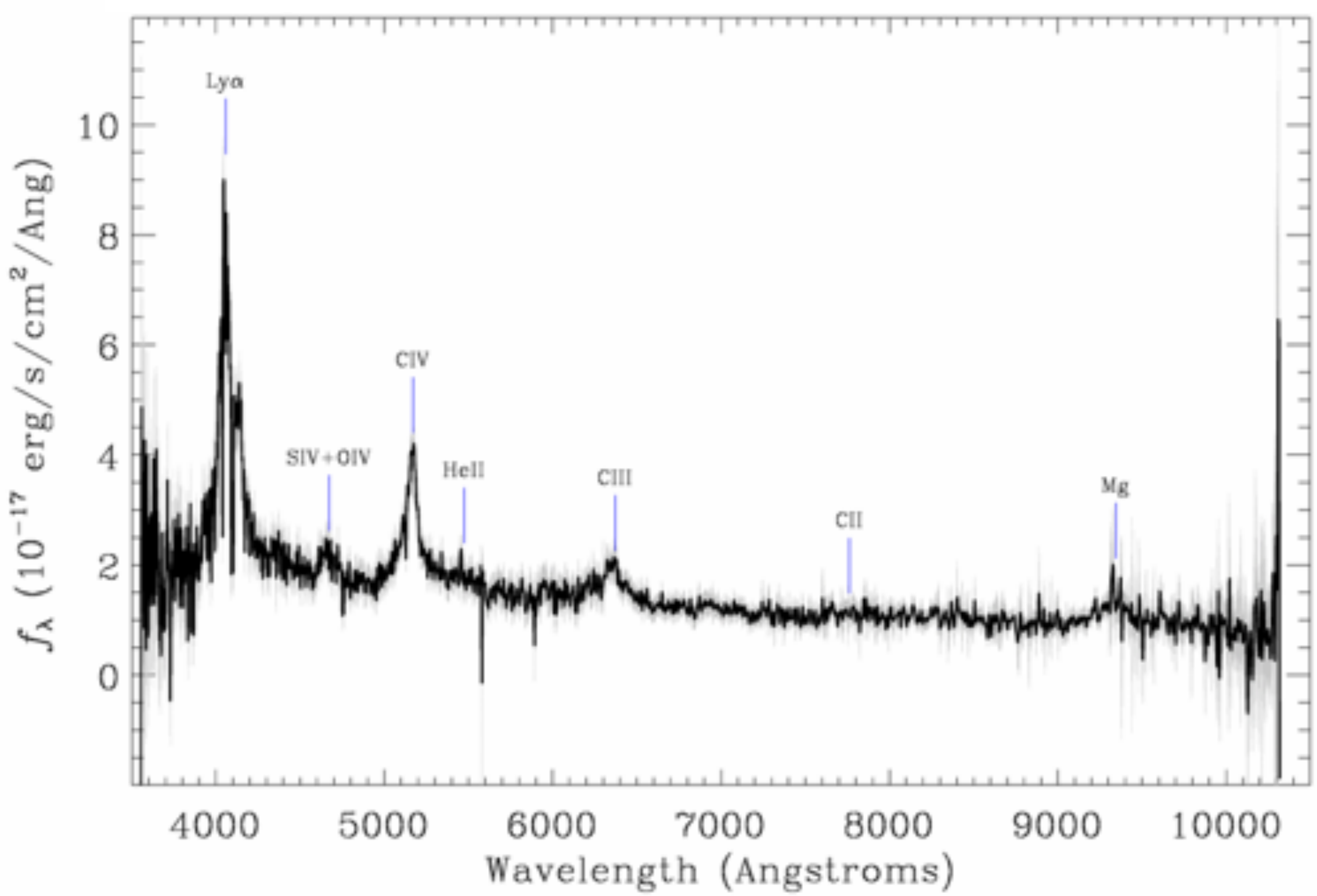
Interesting candidate close-up 6





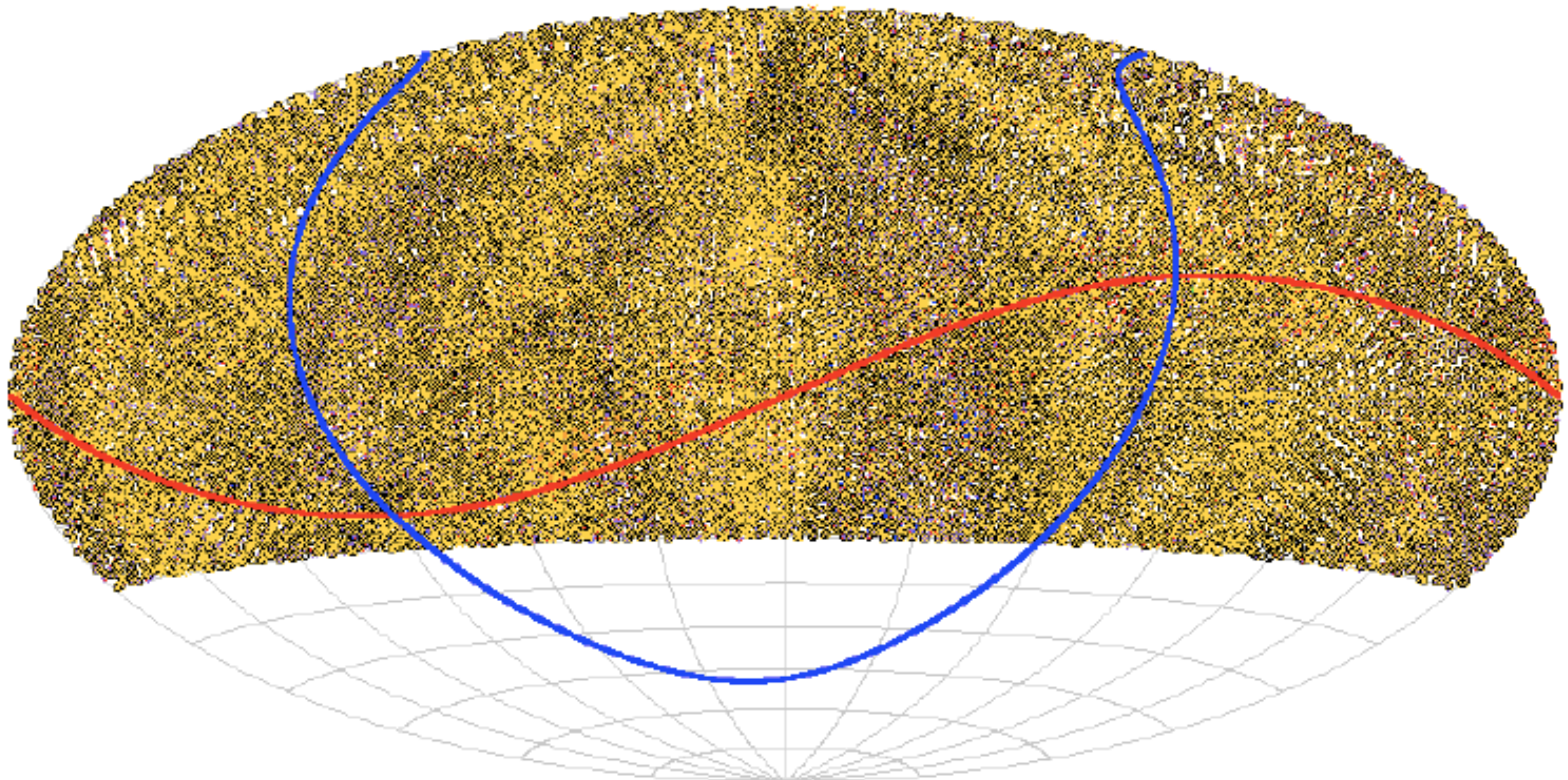
Interesting candidate close-up 5





II. lensed QSOs in Pan-STARRS (3π & MDS)

QSOs in PS1 (3π & MDS)



- SAS2: g_{AB}=23.9, r_{AB}=23.8, i_{AB}=23.7, z_{AB}=23.0 ; seeing~1.1”
- MDS: g_{AB}=25.0, r_{AB}=24.9, i_{AB}=24.7, z_{AB}=24.2, y_{AB}=22.8, (u_{AB}=25.5) ; seeing~1.0”
- Multi-Epoch: variability!

Lensed QSOs in PS1

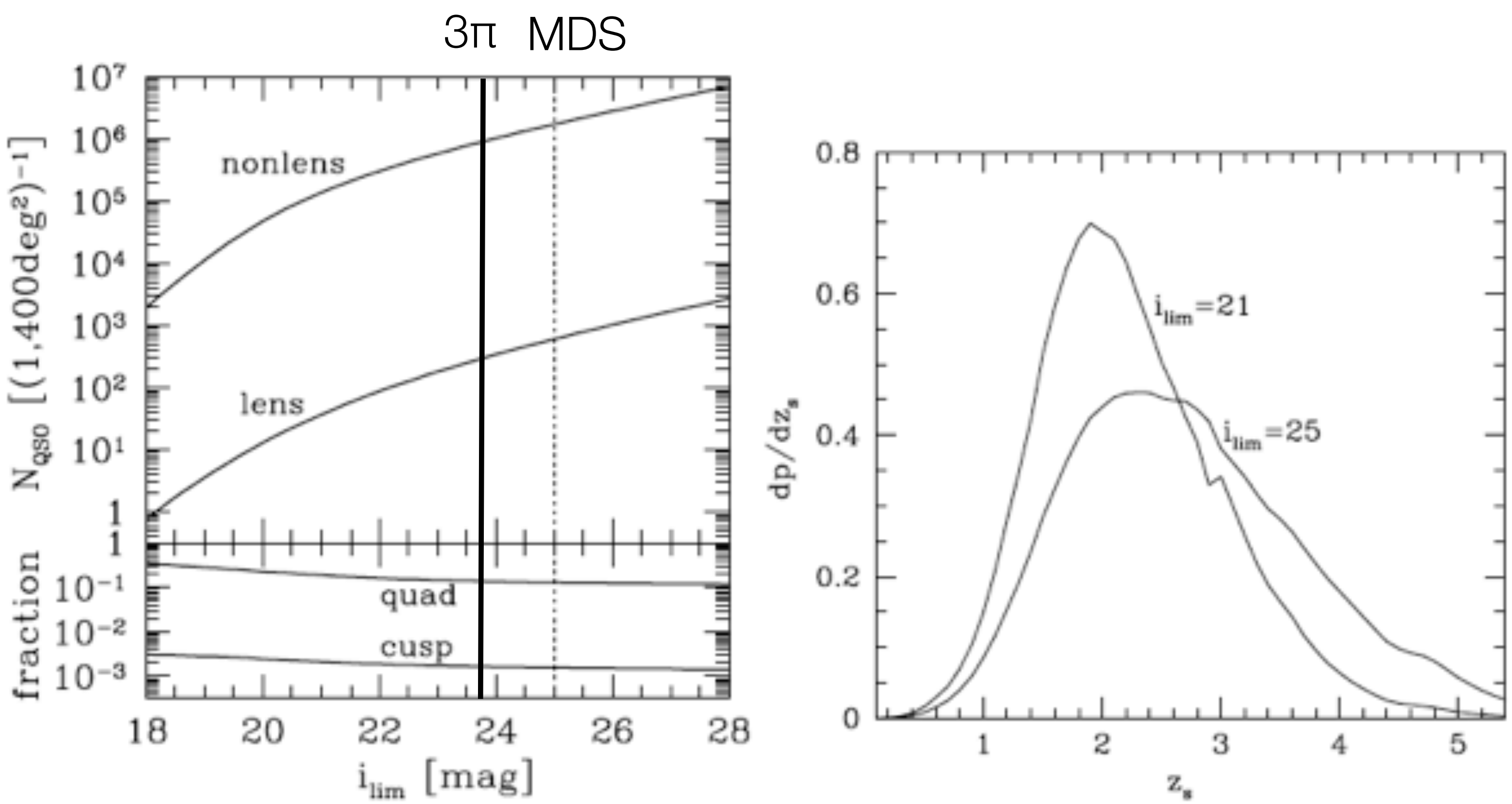


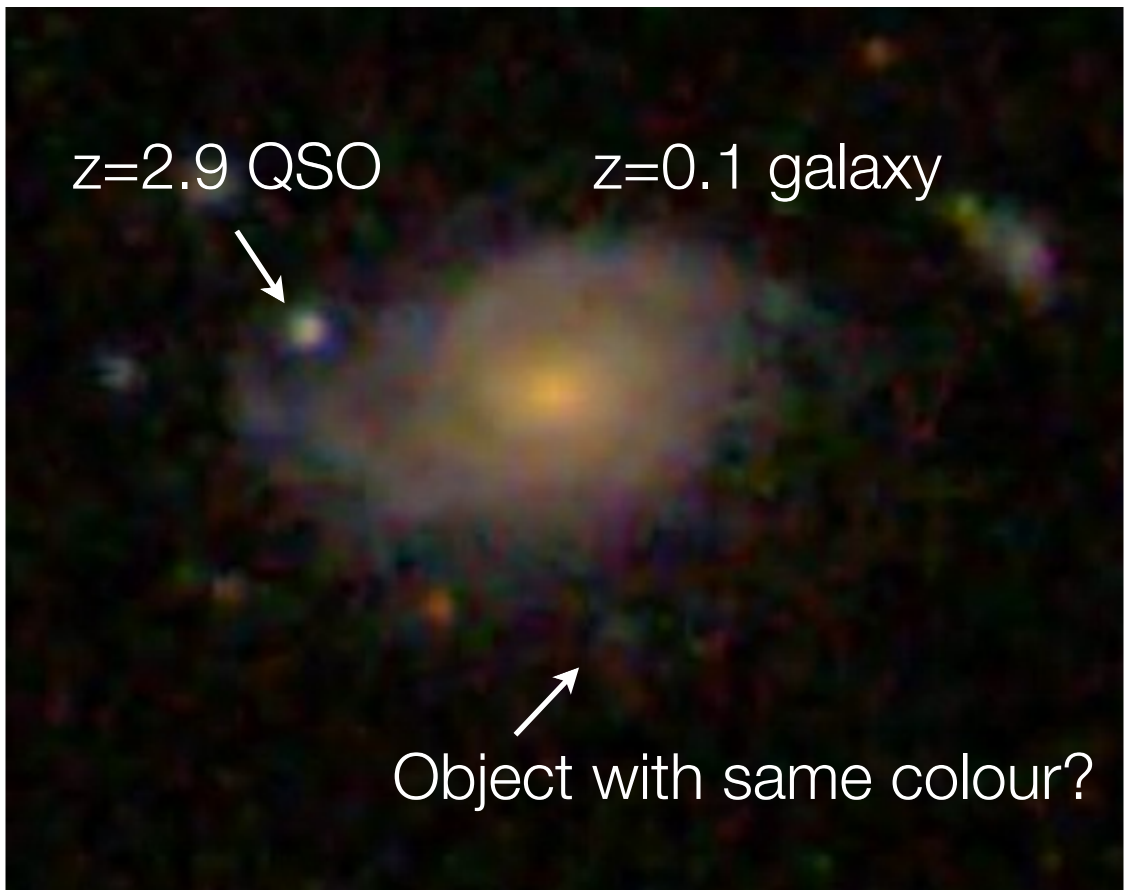
Figure 13.13.: *Left:* The expected number of quasars and lensed quasars as a function of the i-band limiting magnitude $i_{\rm lim}$ (see Oguri & Marshall 2010, for more details). A survey area of $1,400\ \deg^2$ is assumed. The lower panel shows the fraction of four-image lenses quad) and three-image lenses (cusp), as a function of $i_{\rm lim}$. The vertical dashed line indicates $i_{\rm lim}\sim 25.0$, corresponding to 10σ magnitude limit for the HSC-Wide layer. *Right:* Redshift distributions of strongly lensed quasars for the limiting magnitudes of $i_{\rm lim} = 21$ and 25.

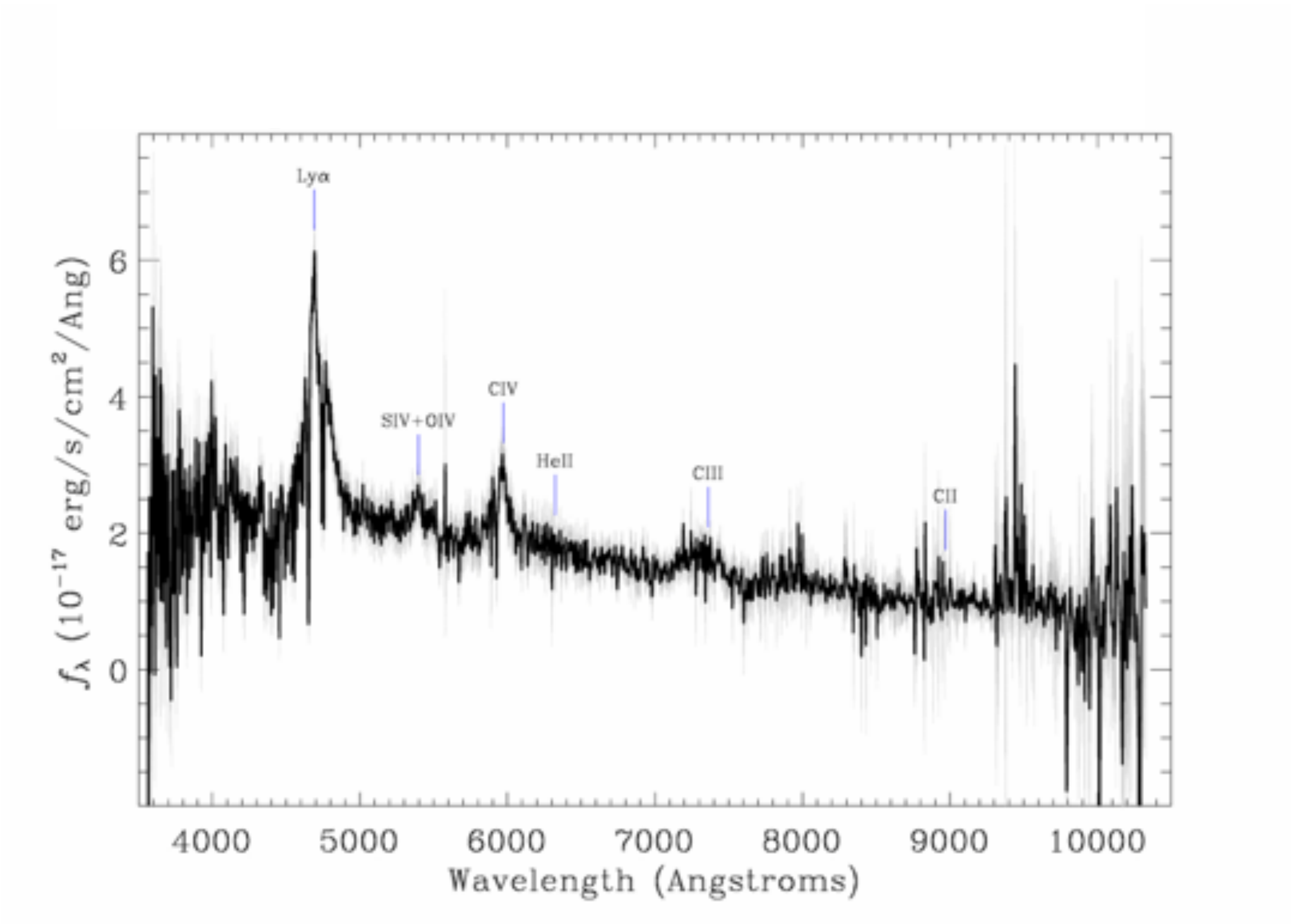
Larger area than SDSS and deeper and with better resolution

⇒ PS1-3π: expected QSO ~20 millions and lensed quasars ~6000!

⇒ PS1-MDS: expected QSO ~80,000 and lensed quasars ~30!

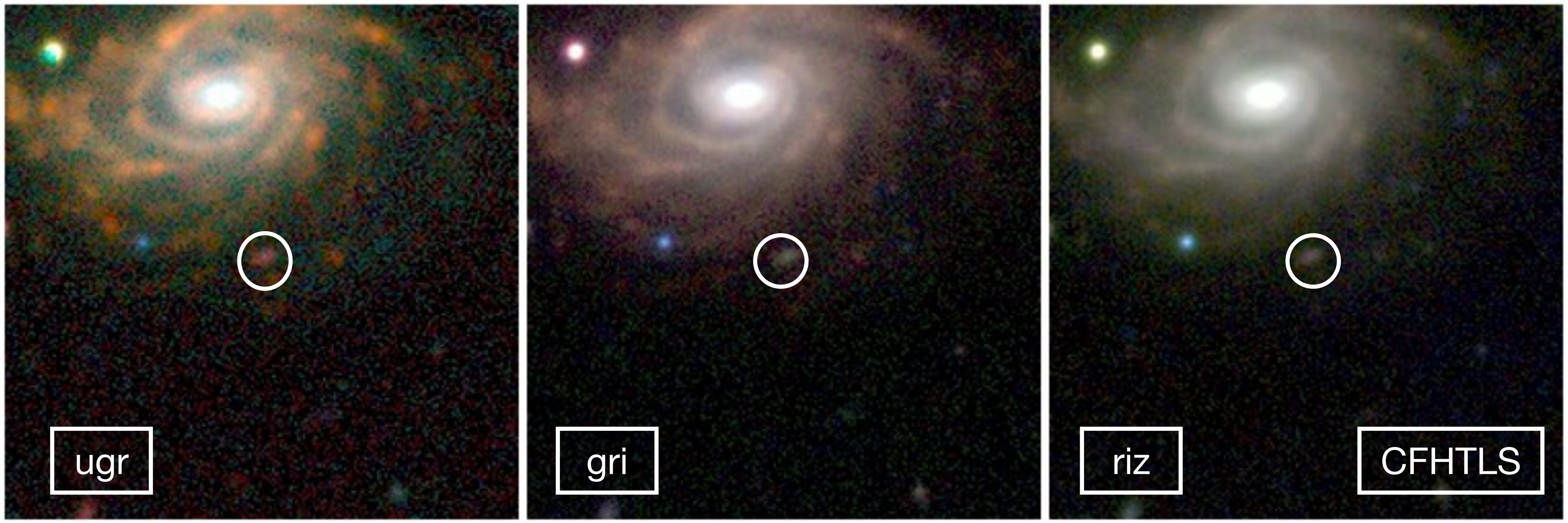
Gain from deeper photometry



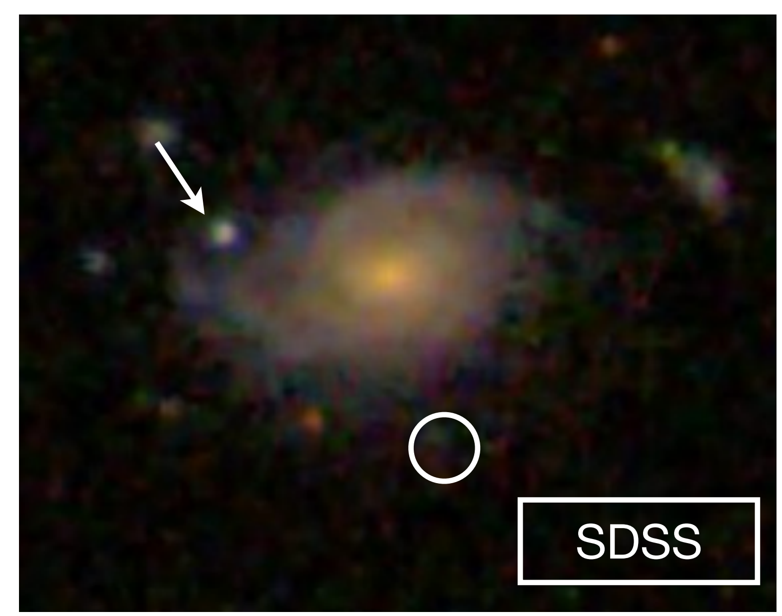


Candidate in SDSS

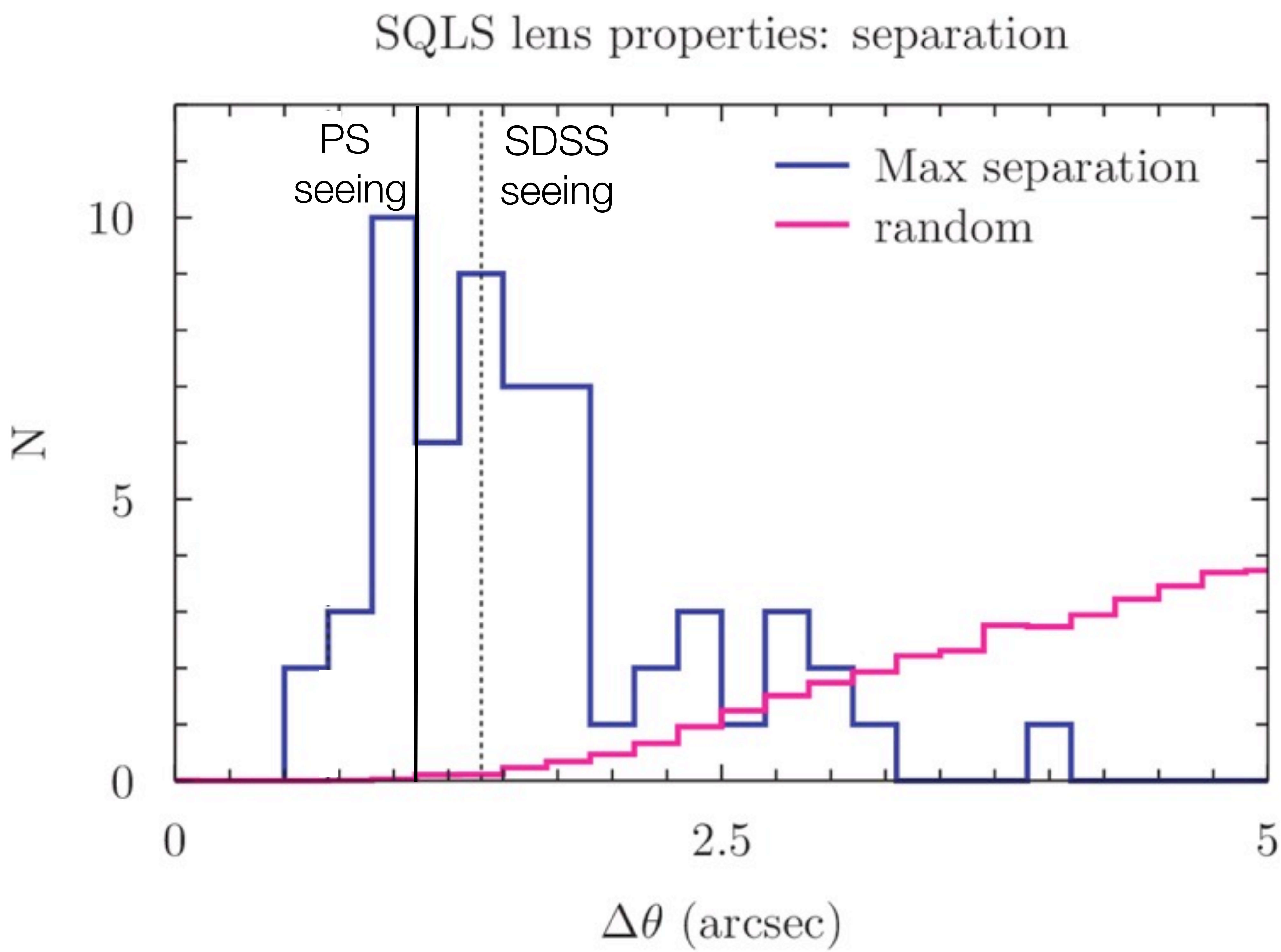
Gain from deeper photometry



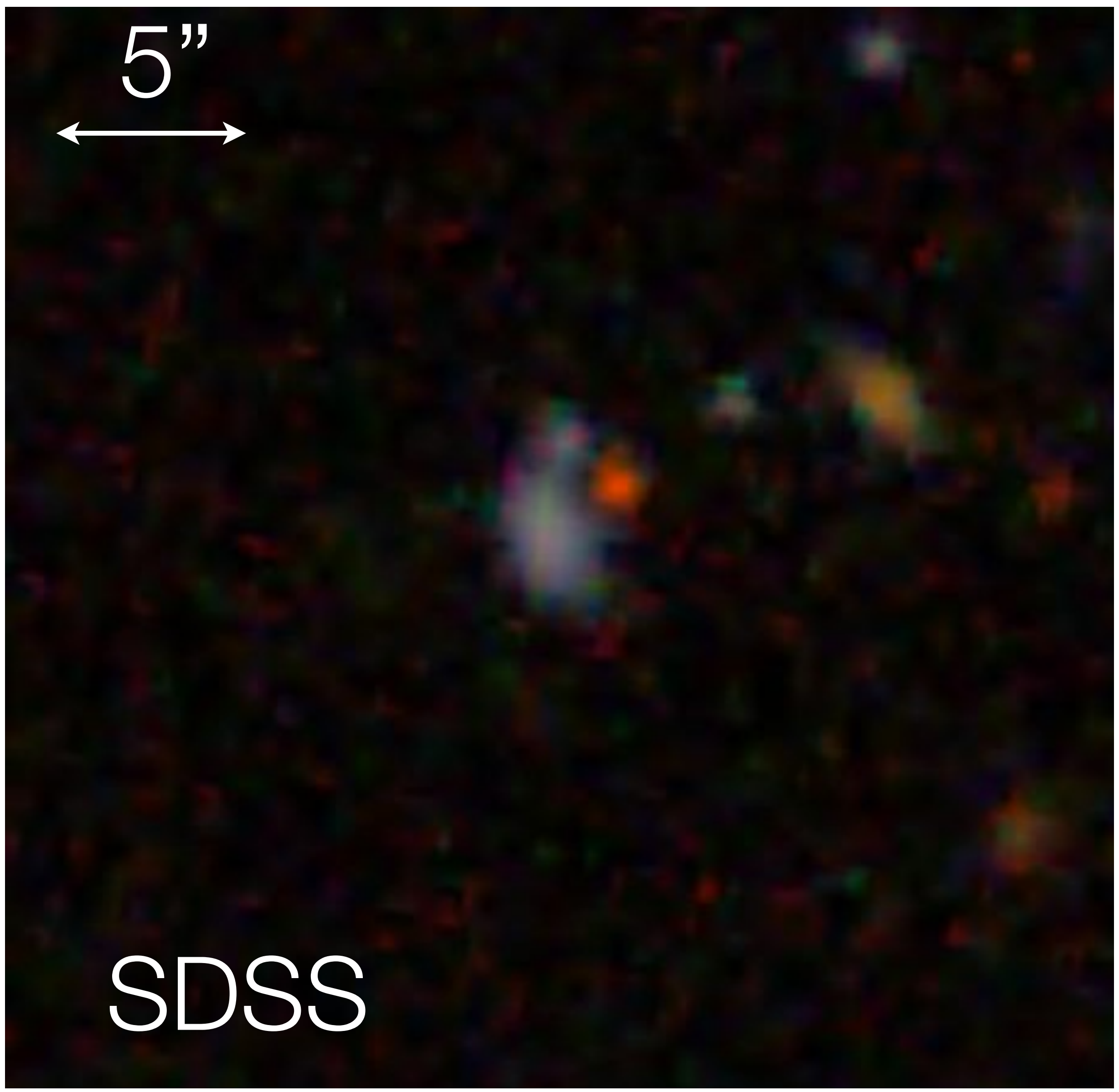
Deeper u band reveals foreground galaxy structure

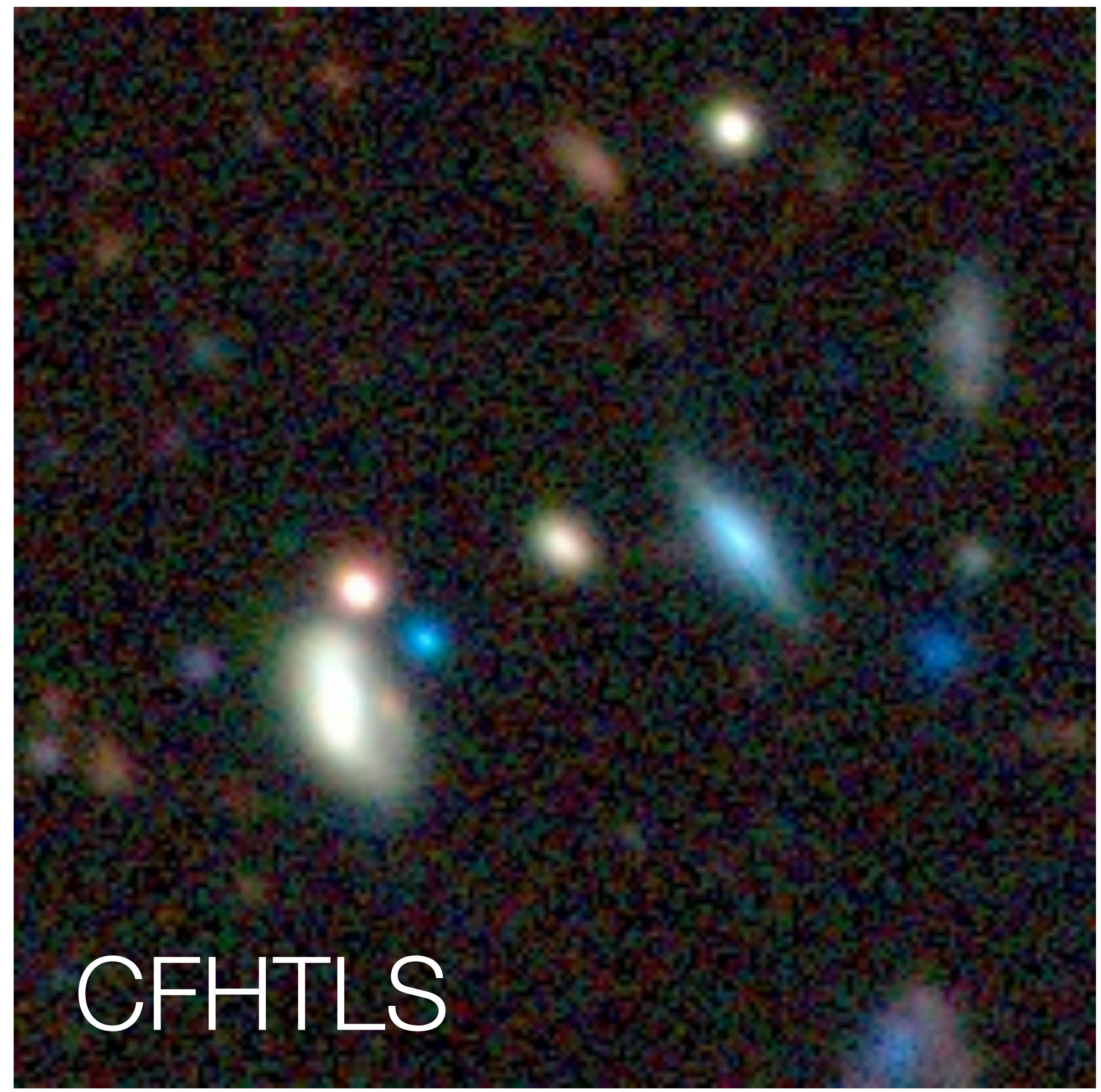


Gain from resolution

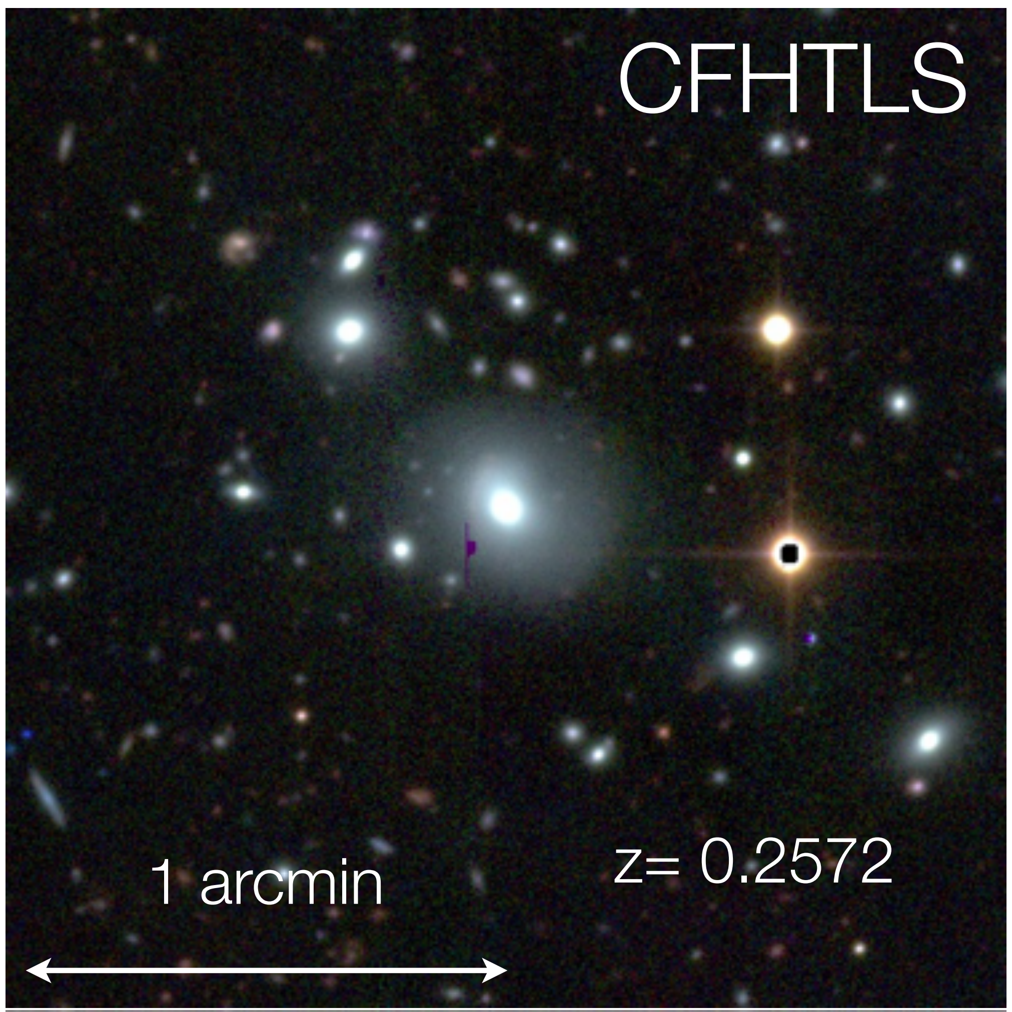


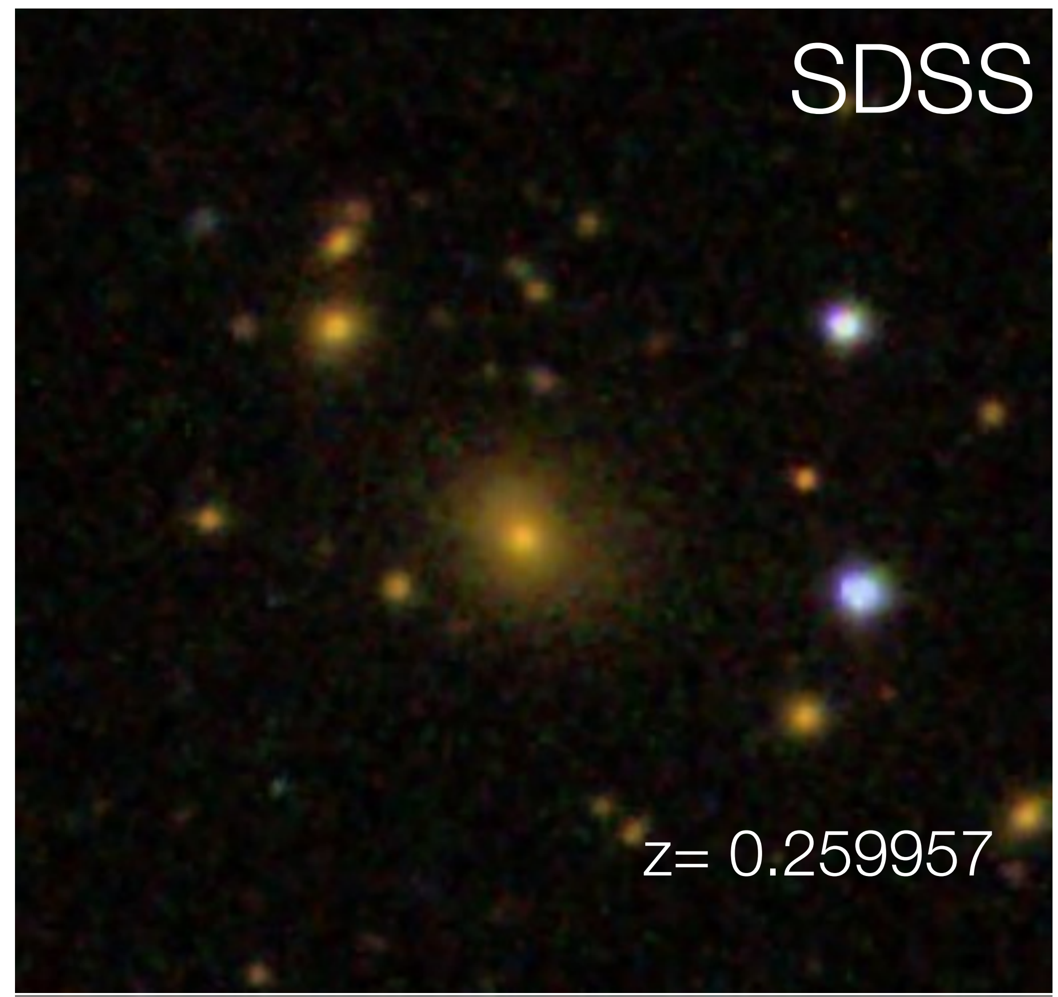
Gain from resolution



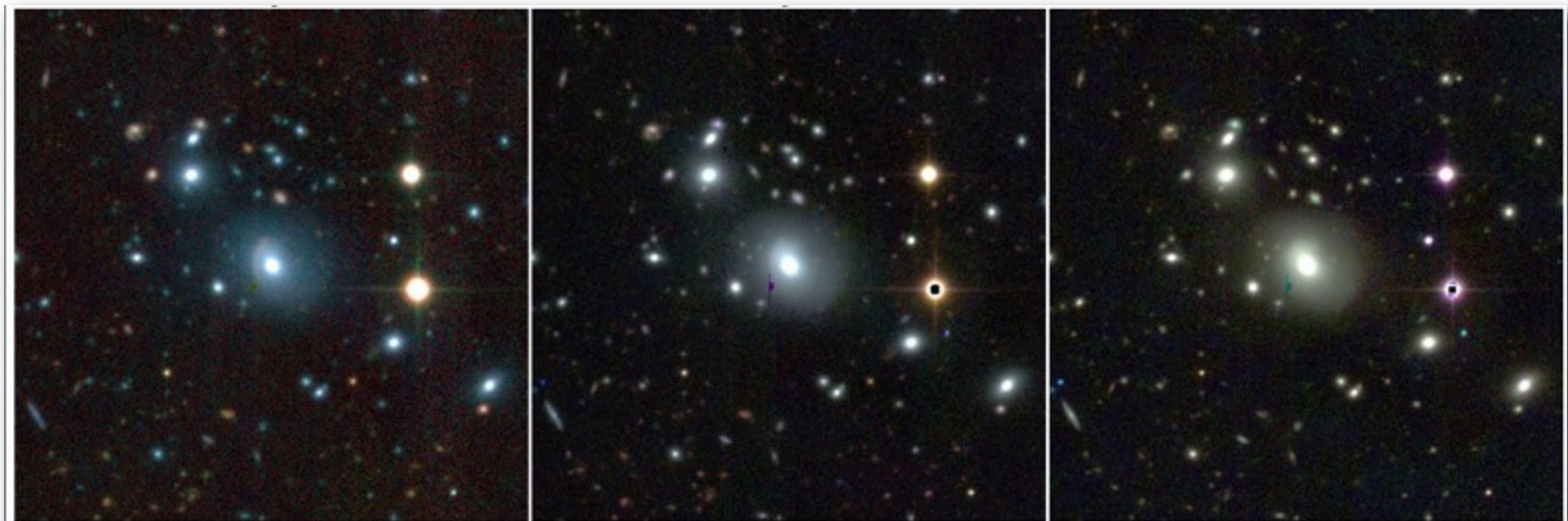


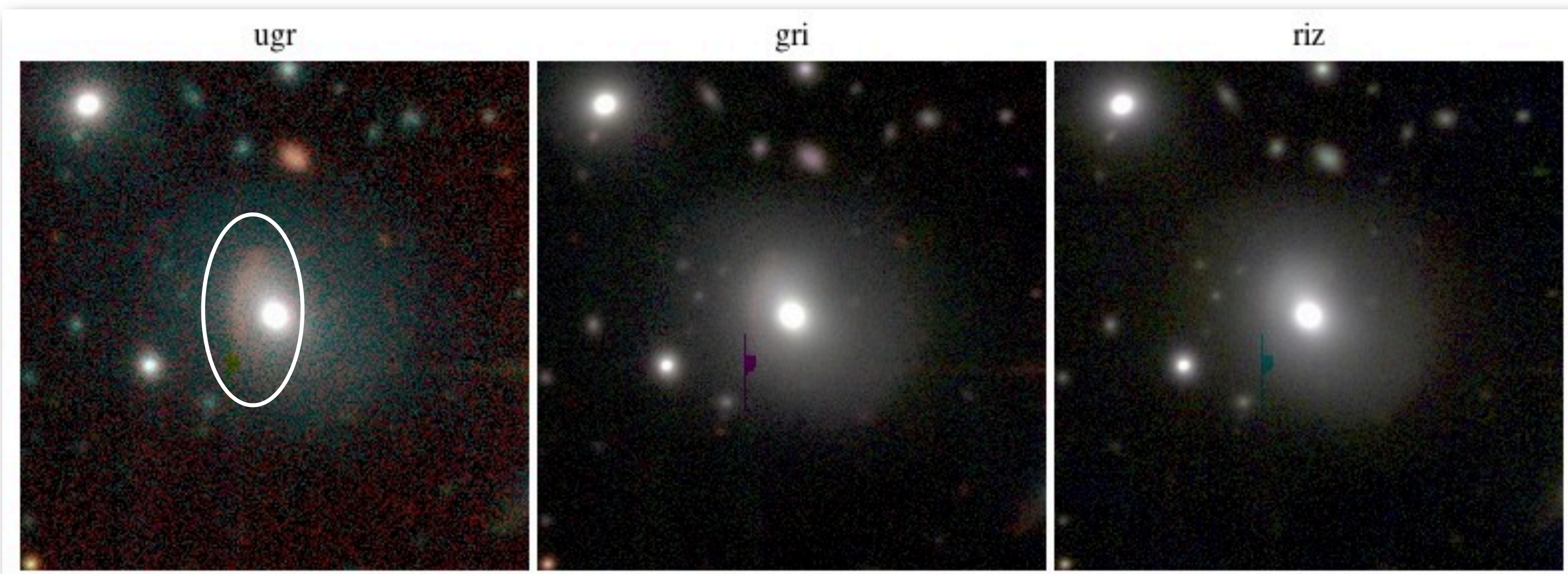
CFHTLS/SDSS





CFHTLS/SDSS





PSPS wish-list

- PSF-magnitude
- PSF-like probability (SDSS `lnLStar_ugriz`)
- Blended object flag
- Variability flag
- Local seeing information
- Neighbor table (0.5')

Conclusions and perspectives

- lensed QSOs are very powerful tools for cosmology and galaxy studies
- weighted colour detection can recover most know lenses with few candidates
- 3π expects ~6000 lensed quasars (~30 in MDS)
- represents many candidates to examine but the gain in depth and resolution from SDSS will allow a more efficient selection
- Variability should help to refine the search for QSOs

Thanks!

More information

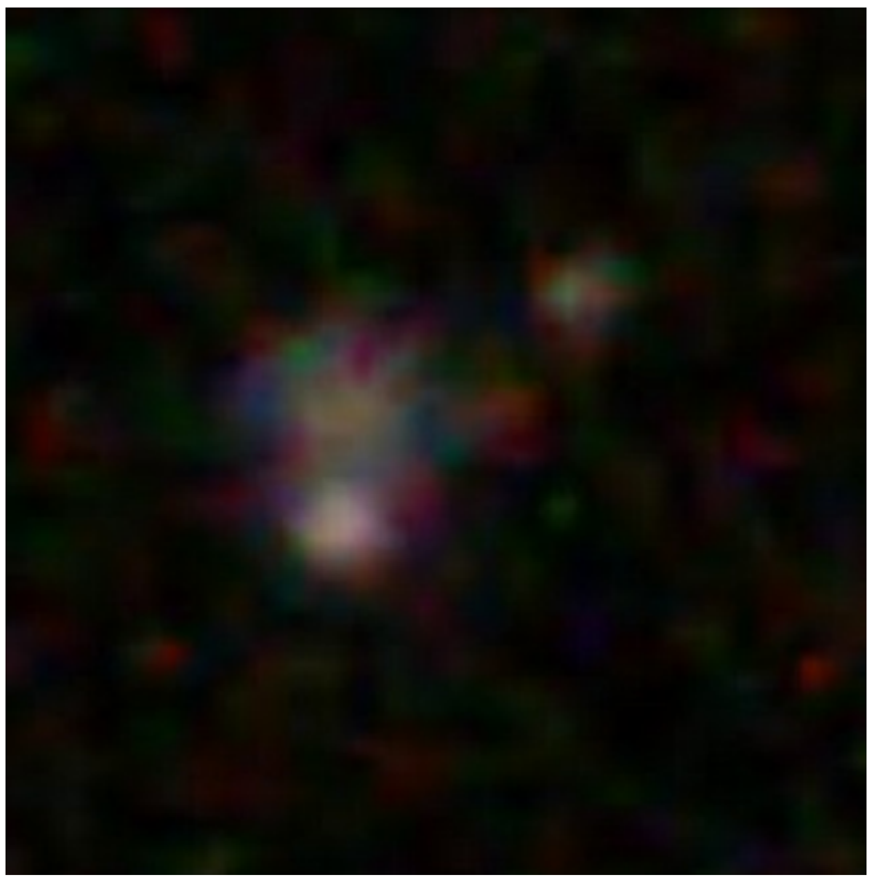
Morphology information

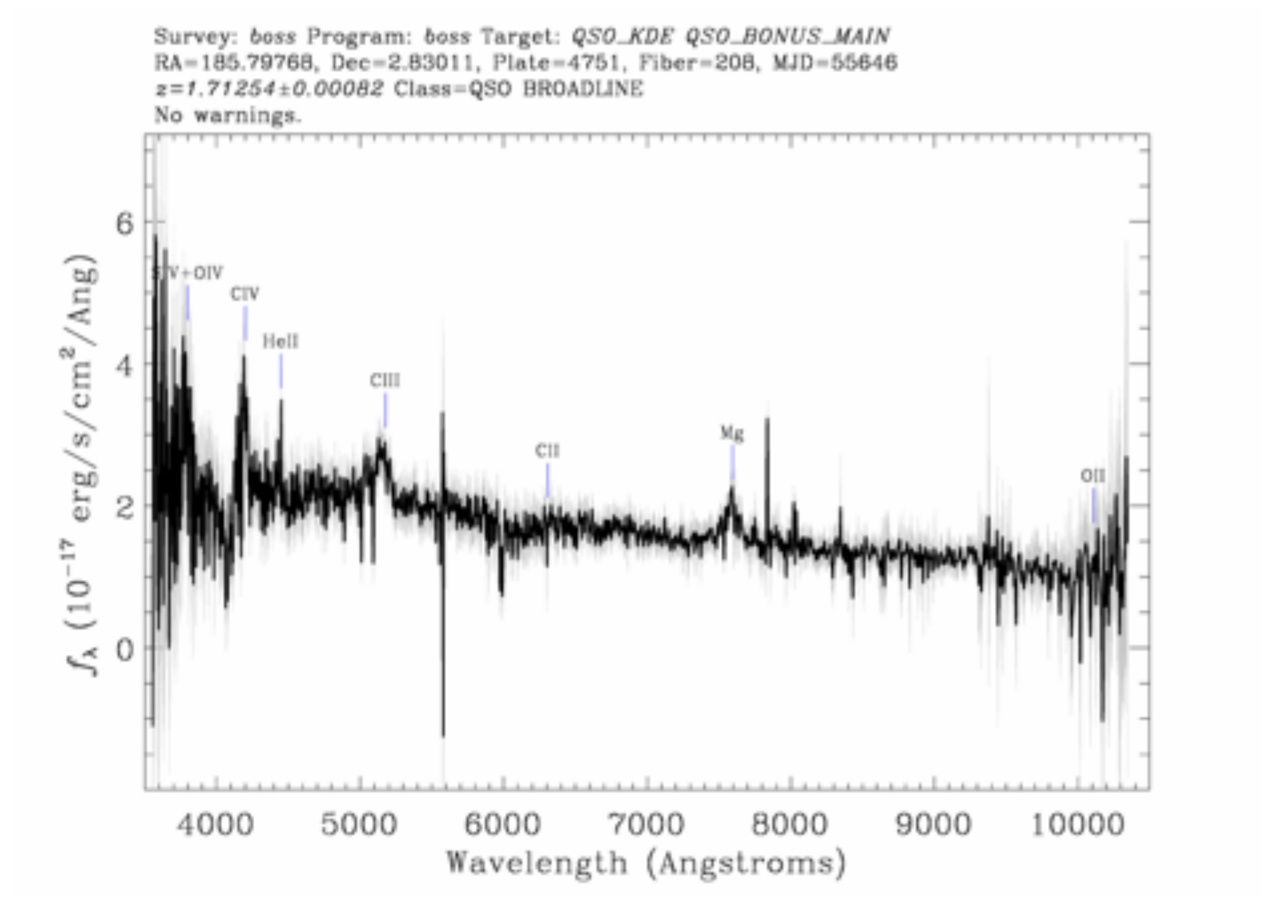
- only for de-blended objects

- Joint probability that g,r and i fit the PSF

$$P_{\mathrm{PSF}} = \exp\left(-\sum \chi^2_{i,\mathrm{PSF}}\right)$$
$$\text{where}$$
$$i = g, r, i$$

New candidates

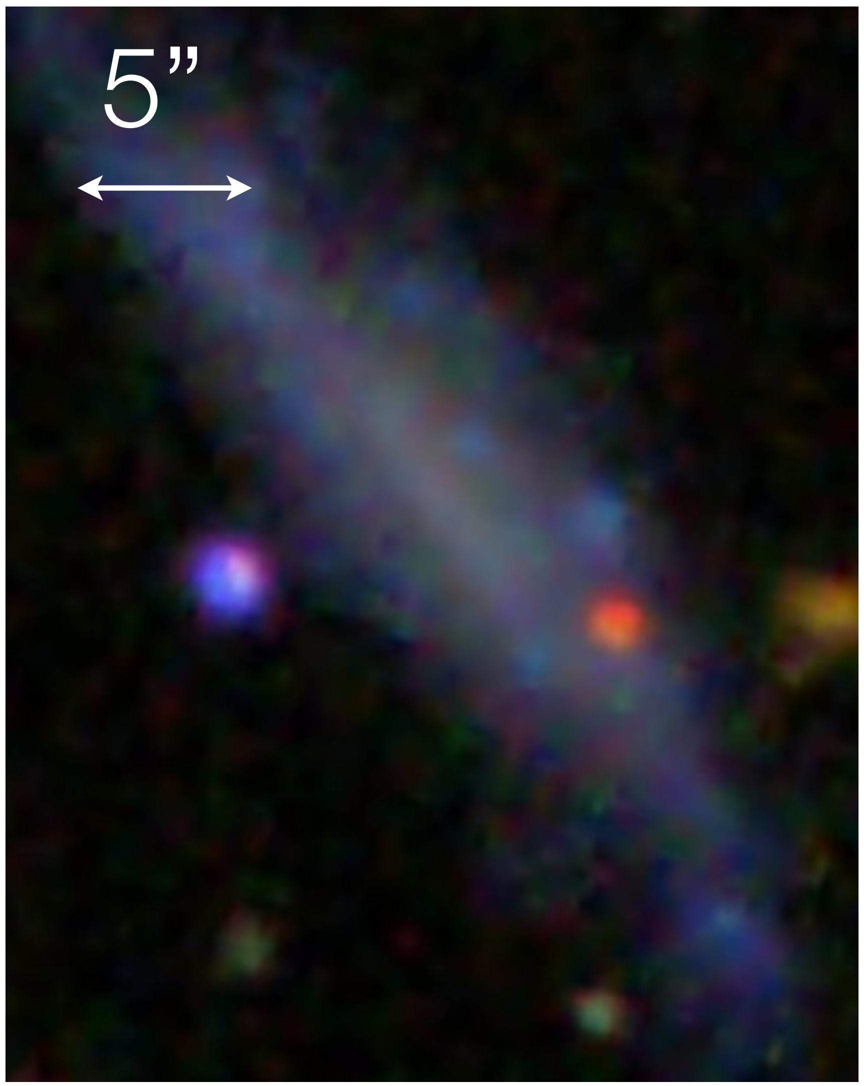


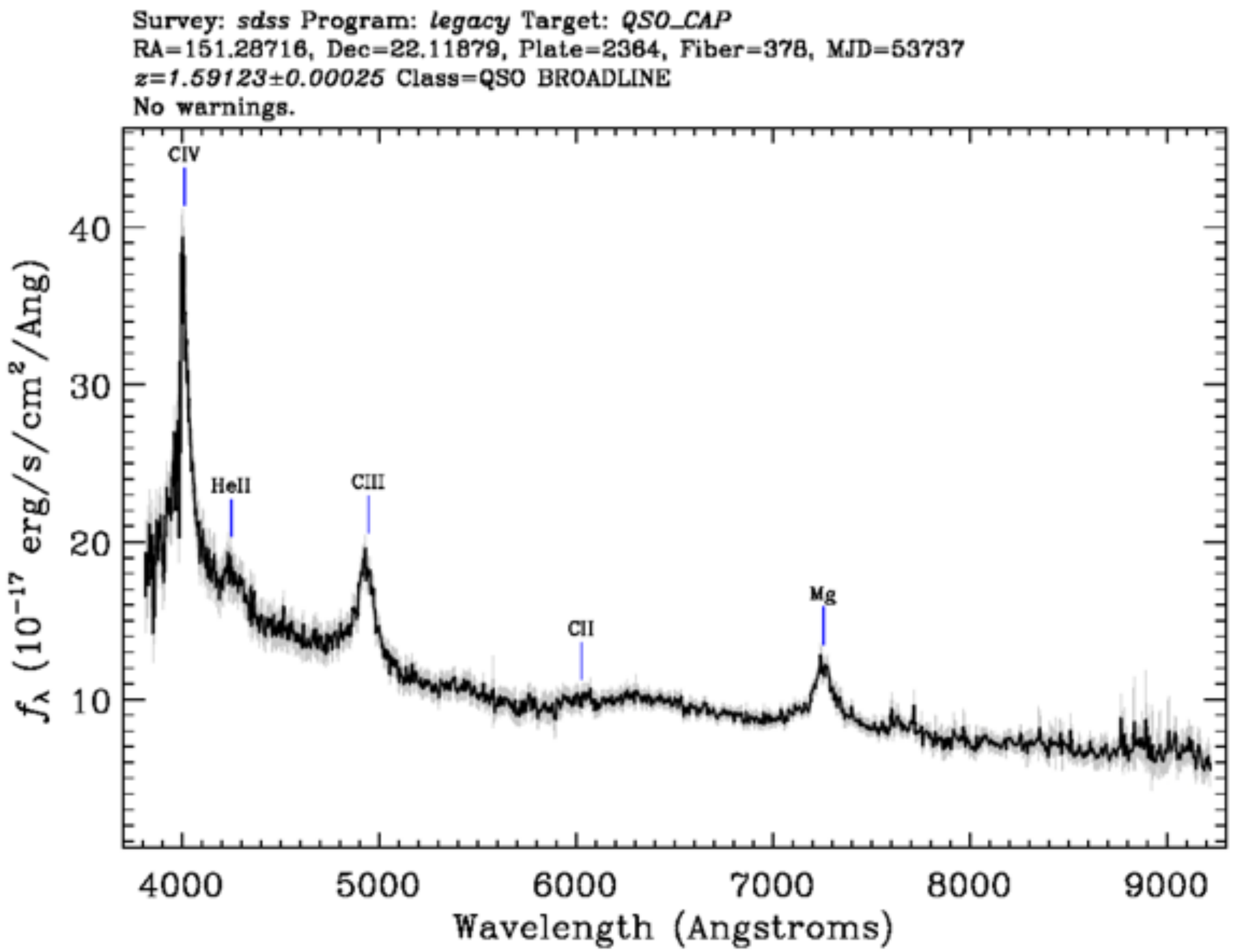


$z = 1.7$

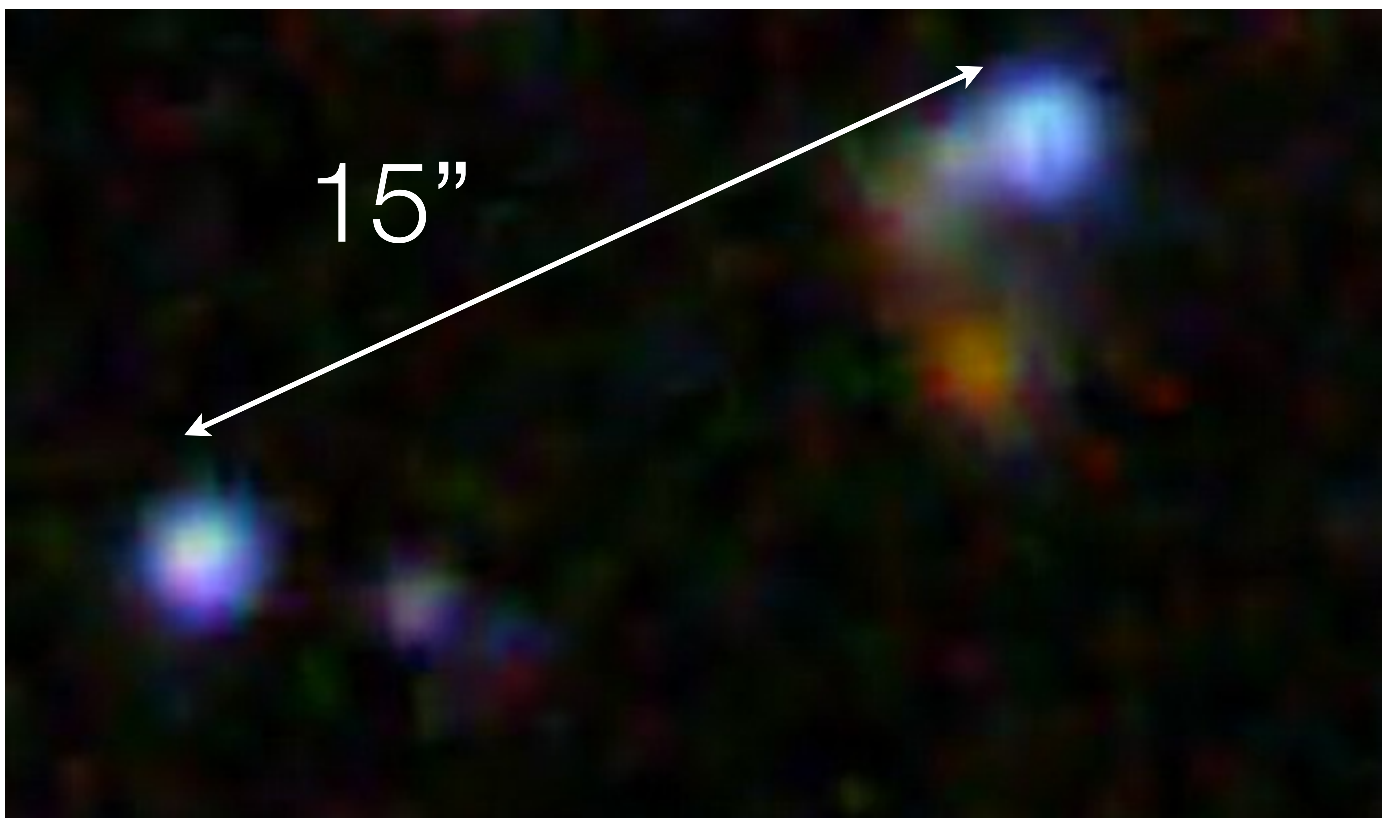
$z = 0.16$

New candidates



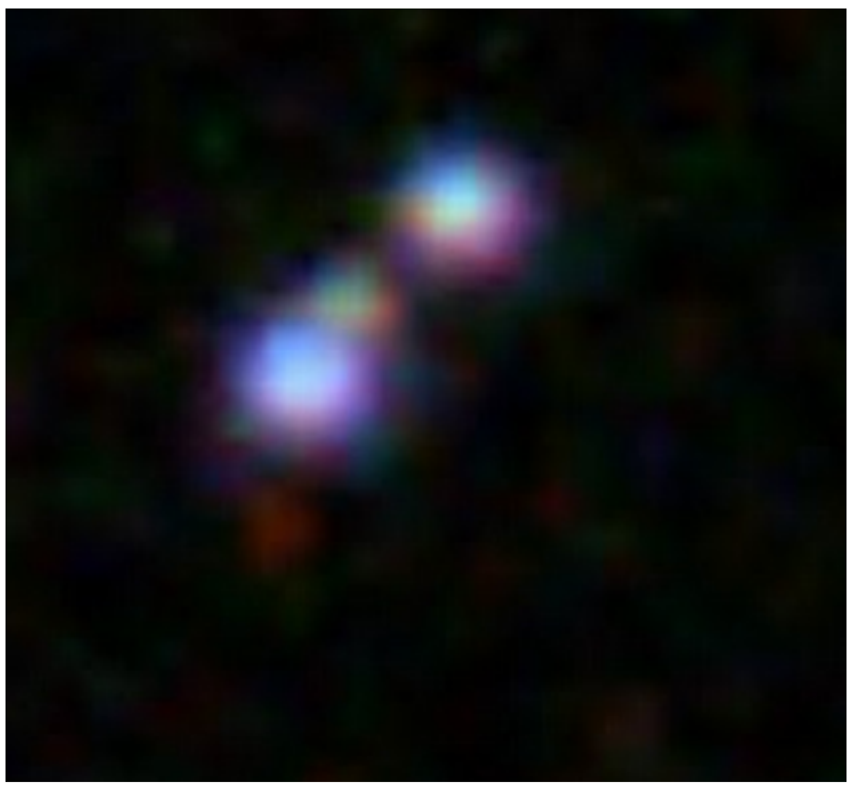


Older releases

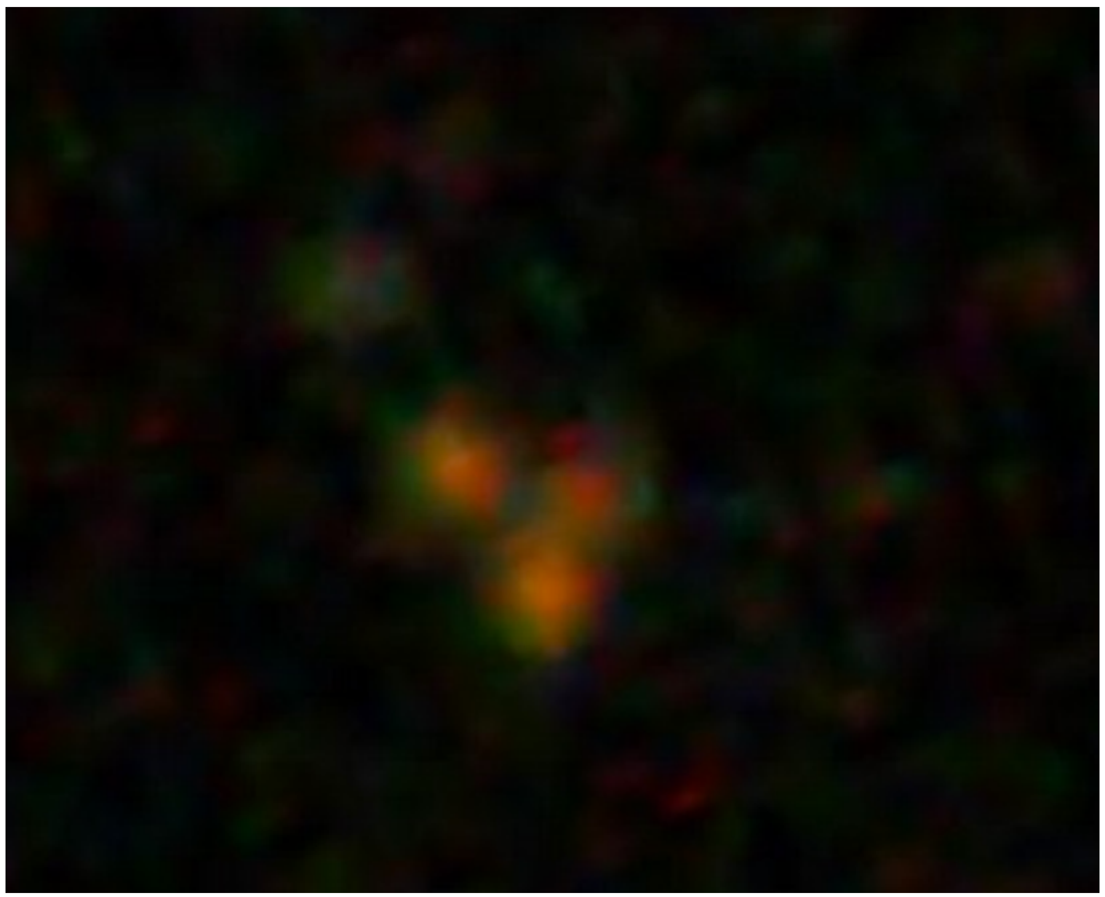


$z = 1.21$

$z = 0.3$



QSO z = 0.75
galaxy z = 0.17



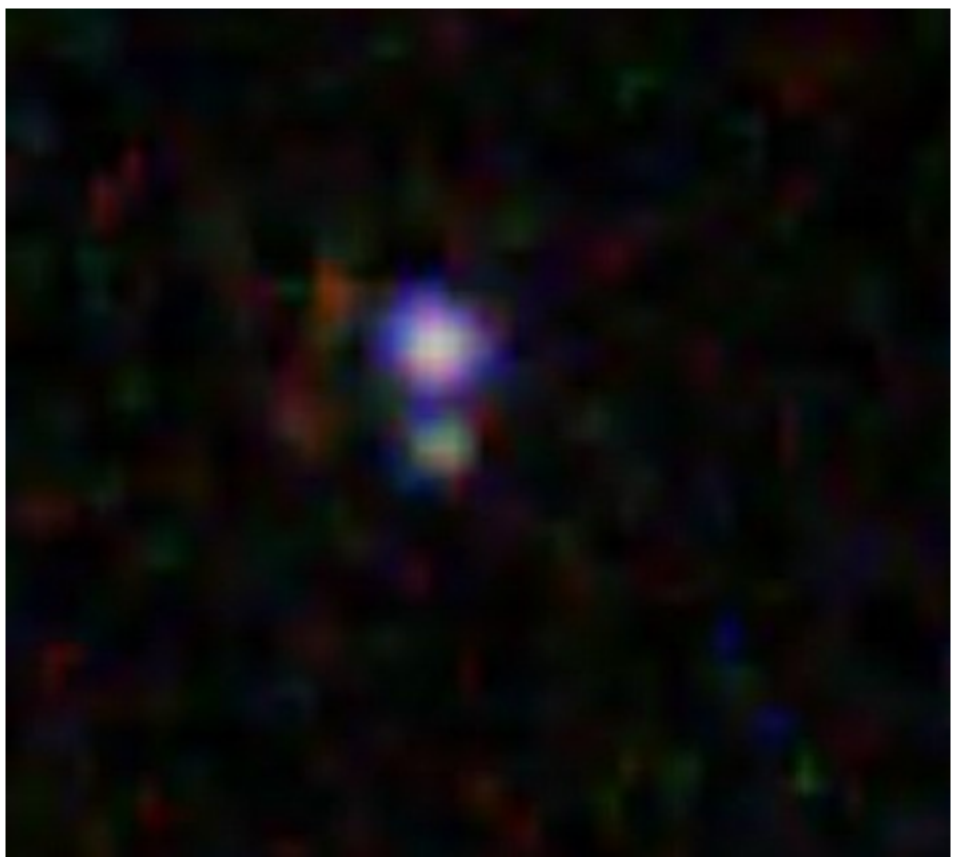
$z = 5.8$ QSO

z = 1.41

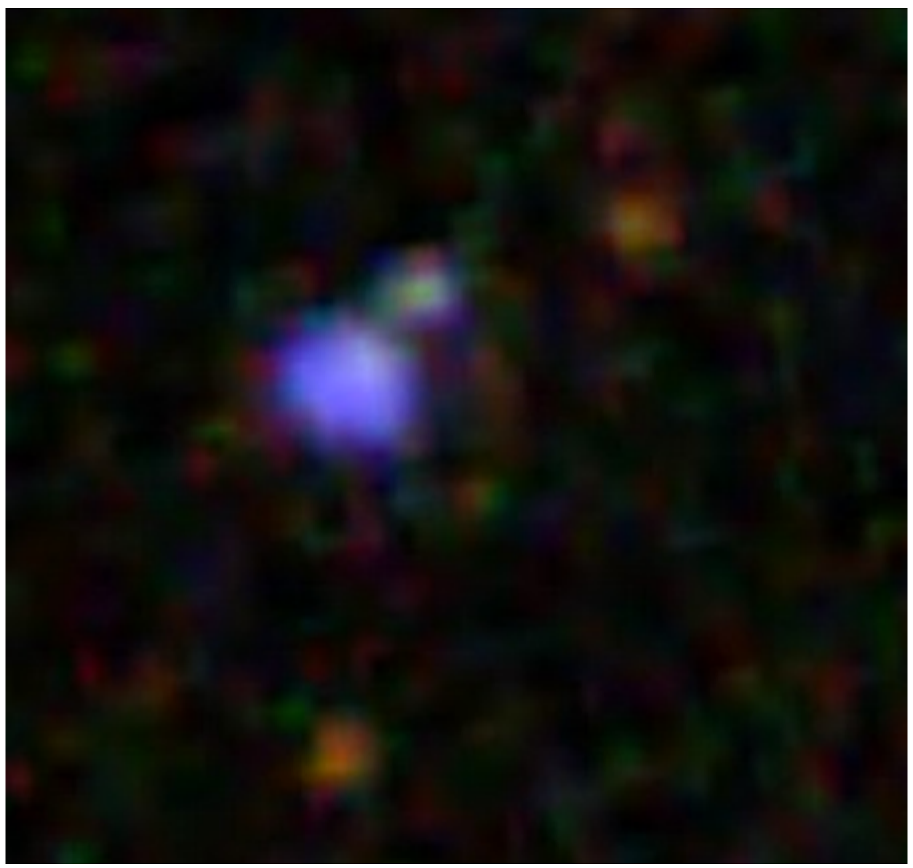
z = 0.1

deblended at edge

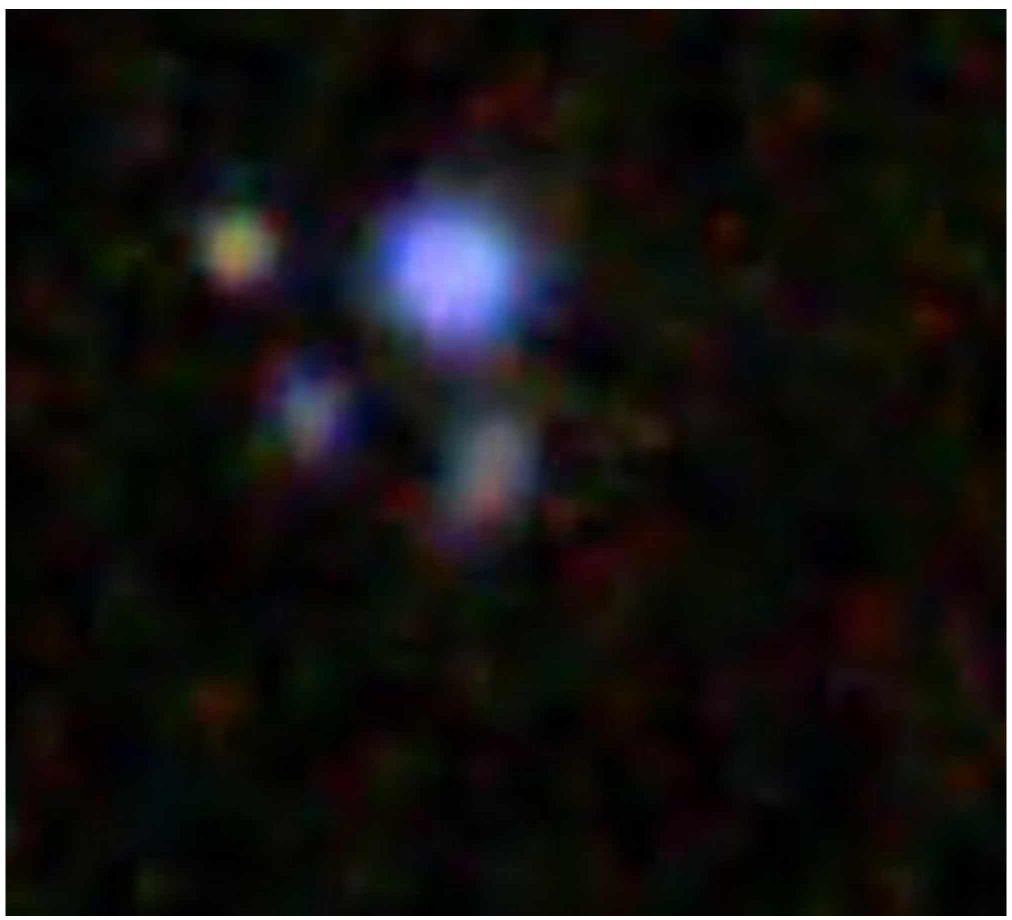
faint galaxy



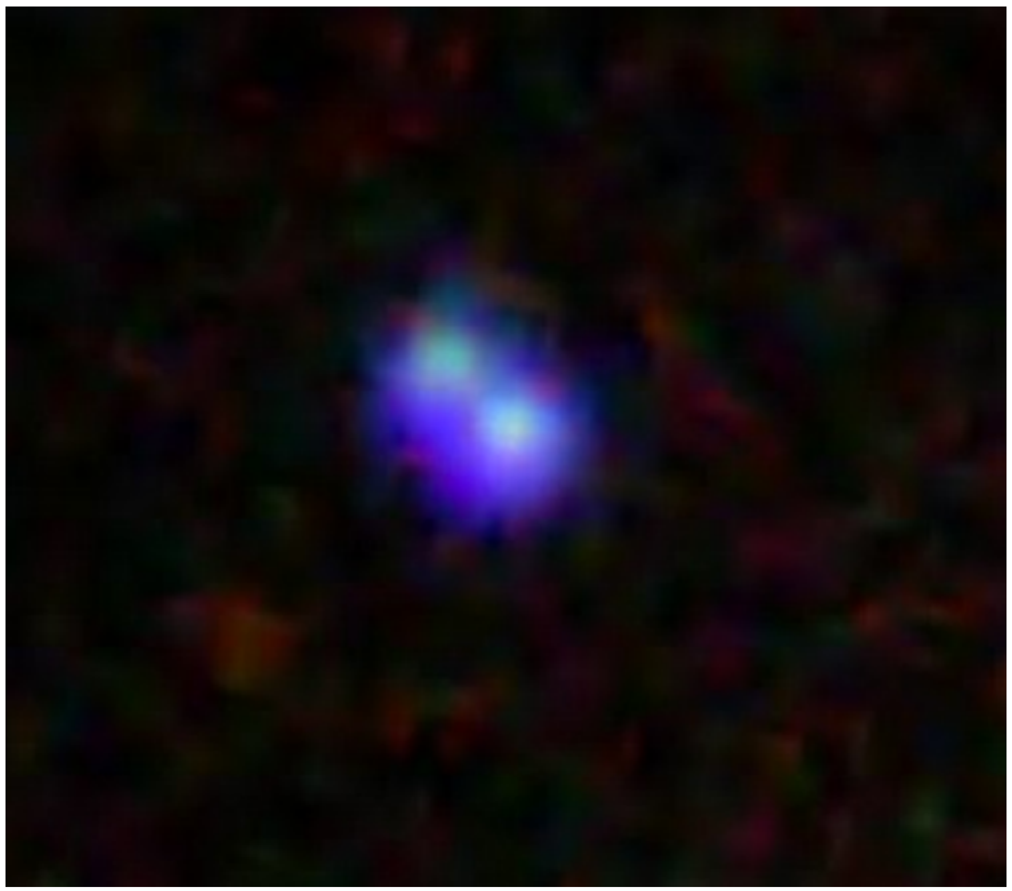
z = 1.53
“star”



$z = 2.27$
no lens



z = 1.41
z = 0.16
Delta mag = 3



z = 2.31
no lens?
QSO pair?
correct deblending ?