GRAVITATIONAL LENSING

LENS FINDING

R. Benton Metcalf

2022-2023

LENSING CROSS SECTION

Probability of an object at redshift z_l with velocity dispersion σ *, axis ratio q and other characteristics being a lens.*

$$P(z_l, \sigma, q, ...) = \int_{z_l}^{\infty} dz_s \left[\frac{\partial D}{\partial z_s}\ \eta(z_s, F > F_{\min}\mu)\right] A_c(z_l, z_s, \sigma, q, ...)$$

$A_c(z_l, z_s, \sigma, q, ...)$ *is the area on the source plane in which a source would produce an image that would be recognised as a lens. This is the* ***cross section*** *for this lens.*

$\eta(z_s, F > F_{\min}\mu)$ *is the number density of sources with observed flux larger than the minimum observable flux.*

LENSING CROSS SECTION

Some complications :

No easy way to find the area within the tangential caustic analytically even for simple lens models.

Not all sources within the cut, or caustics would be recognised as lenses. Some would have images that are too dim.

Not all sources within the cut, or caustics would be recognised as lenses. Some would have images that are too dim.

Finite sources can be partly inside and partly outside the caustic.

In the end, the probability depends on what you recognise as a lens and thus on how you find them.

The probabilities and cross sections usually need to be calculated by simulating lenses and then applying observational cuts that sort the simulated images into observable lenses and not.


First detections where serendipitous…
Q0957+561, discovered in 1979

THE FIRST OBSERVATION

Discovery of the first galaxy-QSO lens system (1979)

0957+561 A, B: twin quasistellar objects or gravitational lens?

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0957+561 A, B are two QSOs of mag 17 with 5.7 arc s separation at redshift 1.405. Their spectra leave little doubt that they are associated. Difficulties arise in describing them as two distinct objects and the possibility that they are two images of the same object formed by a gravitational lens is discussed.

SPECTROSCOPIC observations have been in progress for several years on QSO candidates using a survey of radio sources made at 966 MHz with the MkIA telescope at Jodrell Bank. Many of the identifications have been published by Cohen *et al.*[1] with interferometric positions accurate to ~2 arc s and a further list has been prepared by Porcas *et al.*[2]. The latter list consists of sources that were either too extended or too confused for accurate interferometric positions to be measured, and these were observed with the pencil-beam of the 300 ft telescope at NRAO, Green Bank at λ 6 cm and λ 11 cm. This gave positions with typical accuracy 5–10 arc s and the identifications are estimated as ~80% reliable.

The list of Porcas *et al.* includes the source 0957+561 which has within its field a close pair of blue stellar objects, separated by ~6 arc s, which are suggested as candidate identifications. Their positions and red and blue magnitudes, m_R and m_B, estimated from the Palomar Observatory Sky Survey (POSS) are given in Table 1 and a finding chart is given in Fig. 1. Since the images on the POSS overlap, the magnitude estimates may be of lower accuracy than normal, but they are very nearly equal and object A is definitely bluer than object B. The mean position of the two objects is 17 arc s from the radio position, so the identification is necessarily tentative.

Observations

The two objects 0957+561 A, B were observed on 29 March 1979 at the 2.1 m telescope of the Kitt Peak National Observatory (KPNO) using the intensified image dissector scanner (IIDS). Sky subtraction was used with circular apertures separated by 99.4 arc s. Some observational parameters are given in Table 2. The spectral range was divided into 1,024 data bins, each bin 3.5 Å wide, and the spectral resolution was 16 Å. After 20-min integration on each object it was clear that both were QSOs with almost identical spectra and redshifts of ~1.40 on the basis of strong emission lines identified as C IV λ1549 and C III] λ1909. Further observations were made on 29 March and on subsequent nights as detailed in Table 2. By offsetting to observe empty sky a few arc seconds from one object on both 29 and 30 March it was confirmed that any contamination of the spectrum of one object by light from the other was negligible.

Table 1 Positions and magnitudes of 0957+561 A, B

Object	RA	Dec (1950.0)	M_R	M_B
0957+561A	09 57 57.3	+56 08 22.9	17.0	16.7
0957+561B	09 57 57.4	+56 08 16.9	17.0	17.0

0028–0836/79/0279—0381$01.00

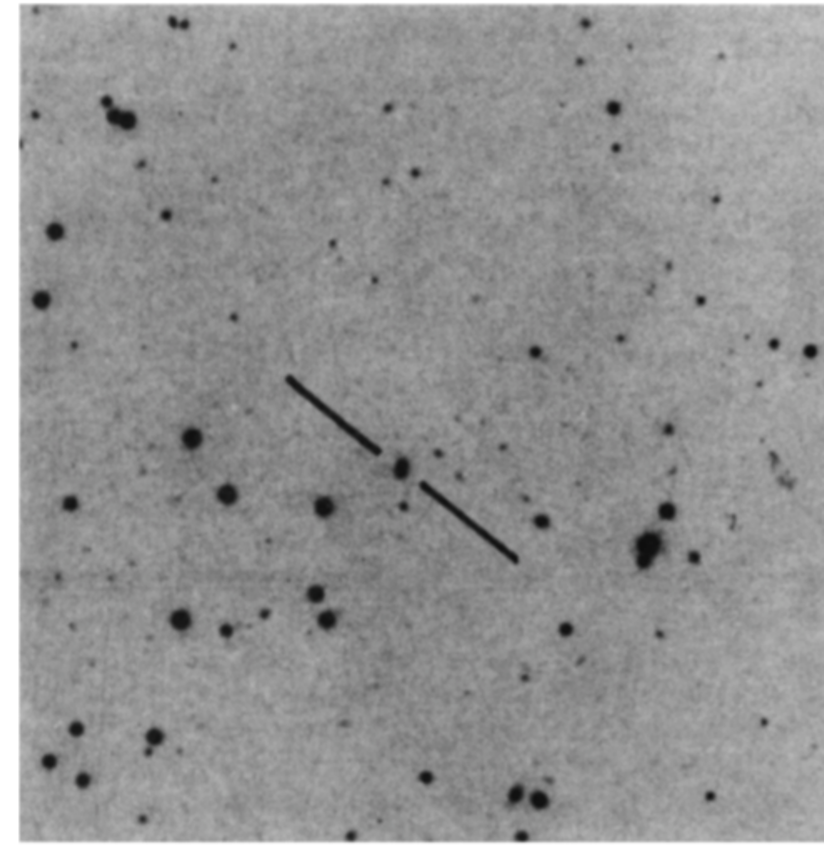


Fig. 1 Finding chart for the QSOs 0957+561 A and B. The chart is 8.5 arc min square with the top right hand corner north preceding and is from the E print of the POSS.

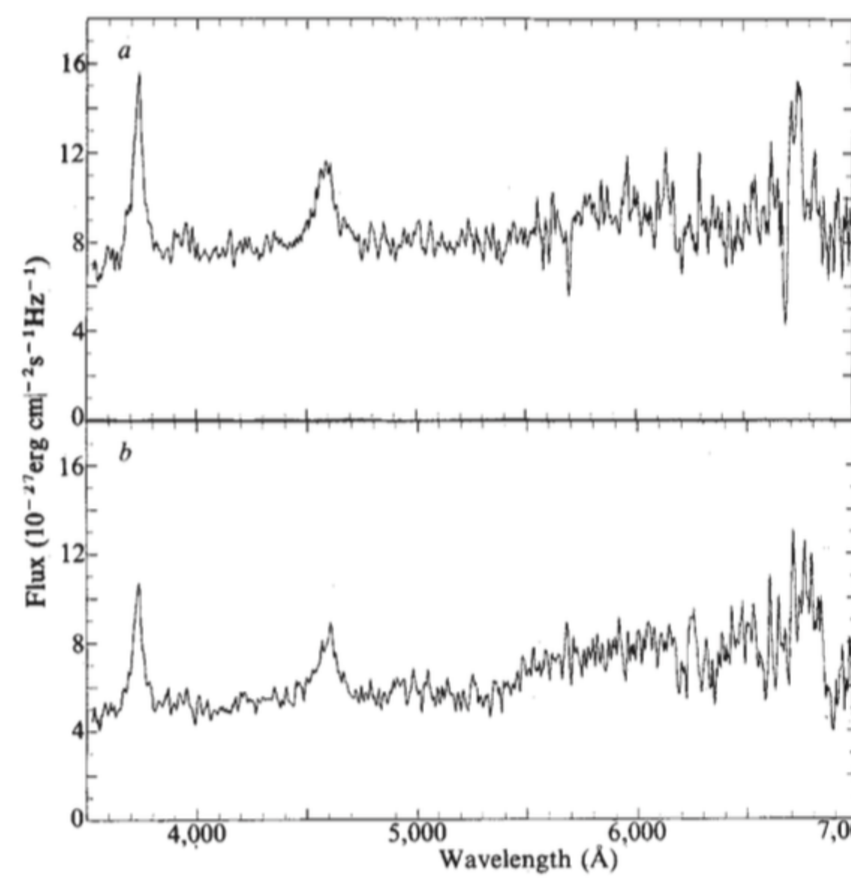
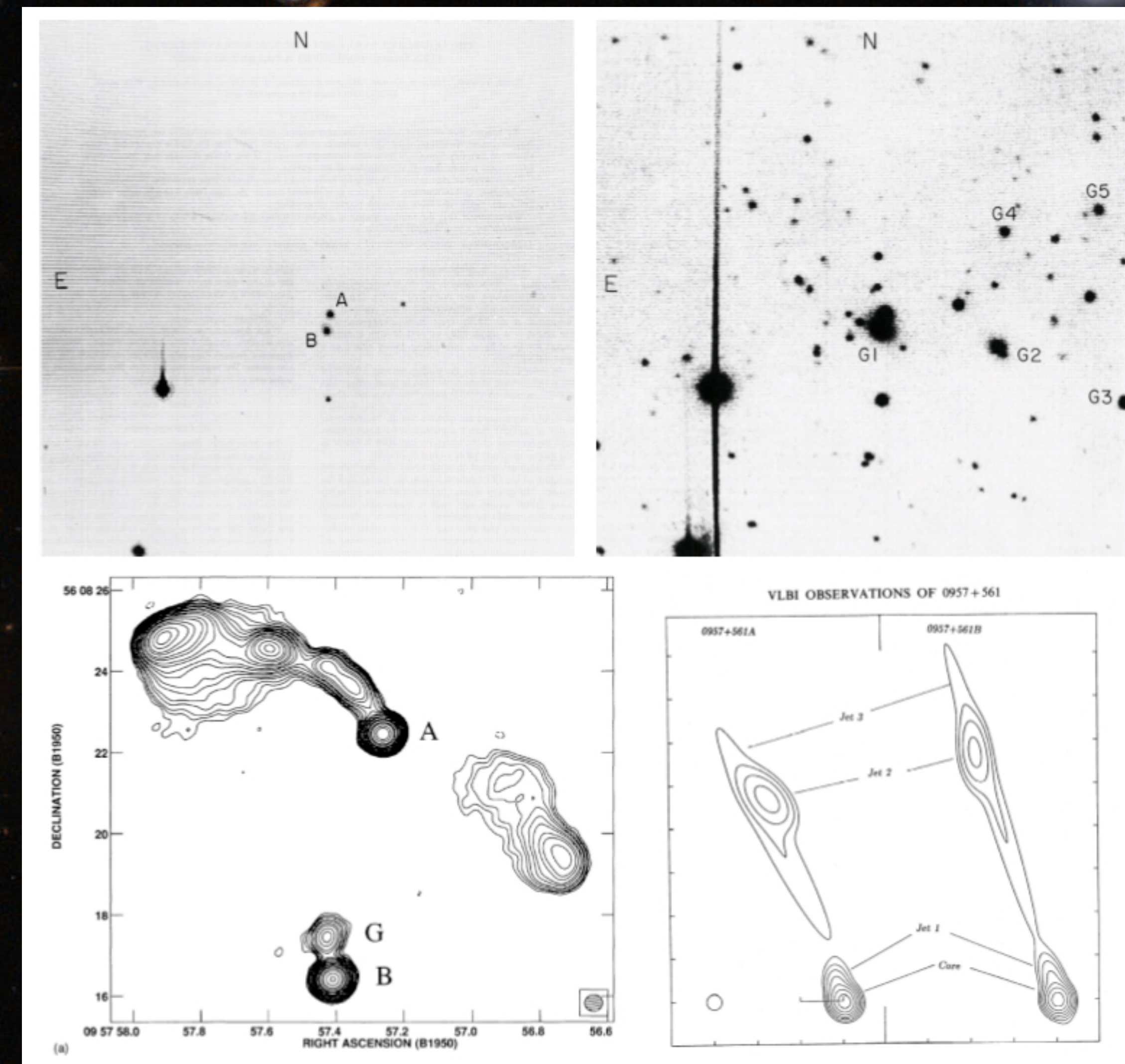
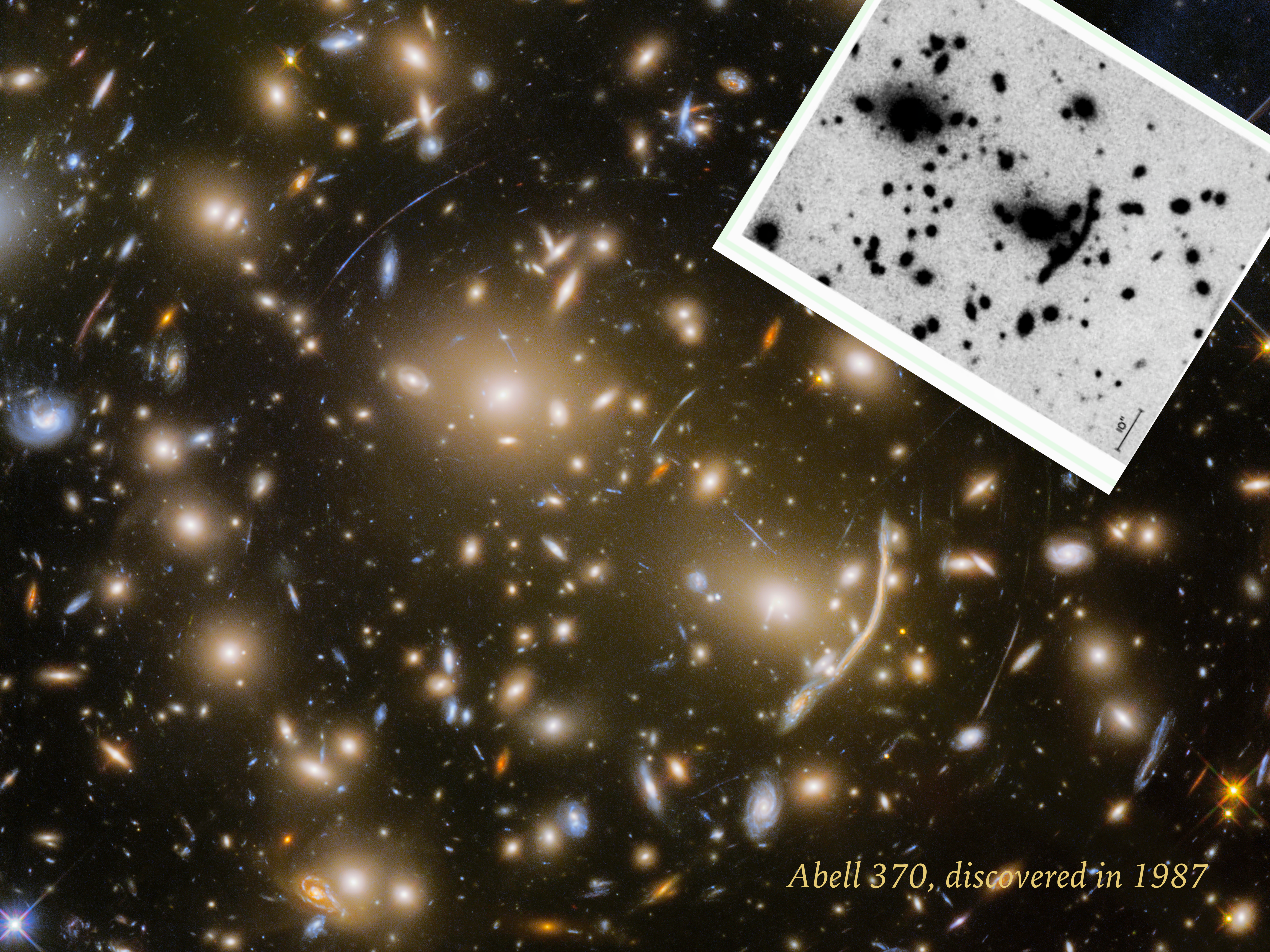


Fig. 2 IIDS scans of 0957+561 A(*a*) and B(*b*). The data are smoothed over 10 Å and the spectral resolution is 16 Å.

First detections where serendipitous…



Q0957+561, discovered in 1979



Abell 370, discovered in 1987

HOW TO FIND STRONG LENSES

- Then the search became more systematic
- Strong lens searches followed two approaches so far:
  - Find sources that are likely to be lensed (source oriented)
  - Find strong lensing features around the most probable lenses (lens oriented)

EXAMPLE 1: THE CLASS SURVEY (SOURCE ORIENTED)

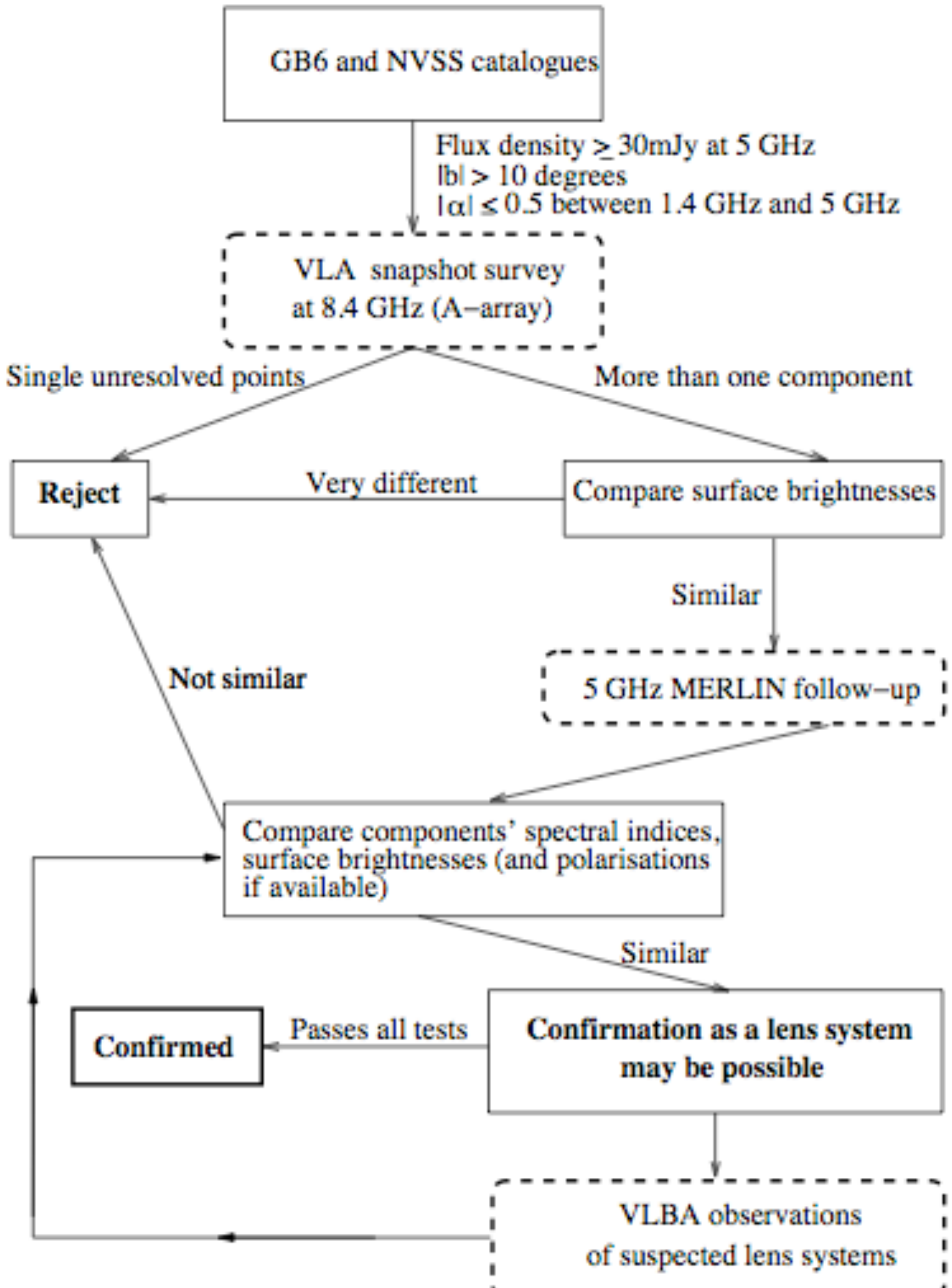
The CLASS (Cosmic Lens All-Sky Survey) was an international project (UK, USA, Netherlands) whose goal was searching for gravitational lenses in the radio domain.

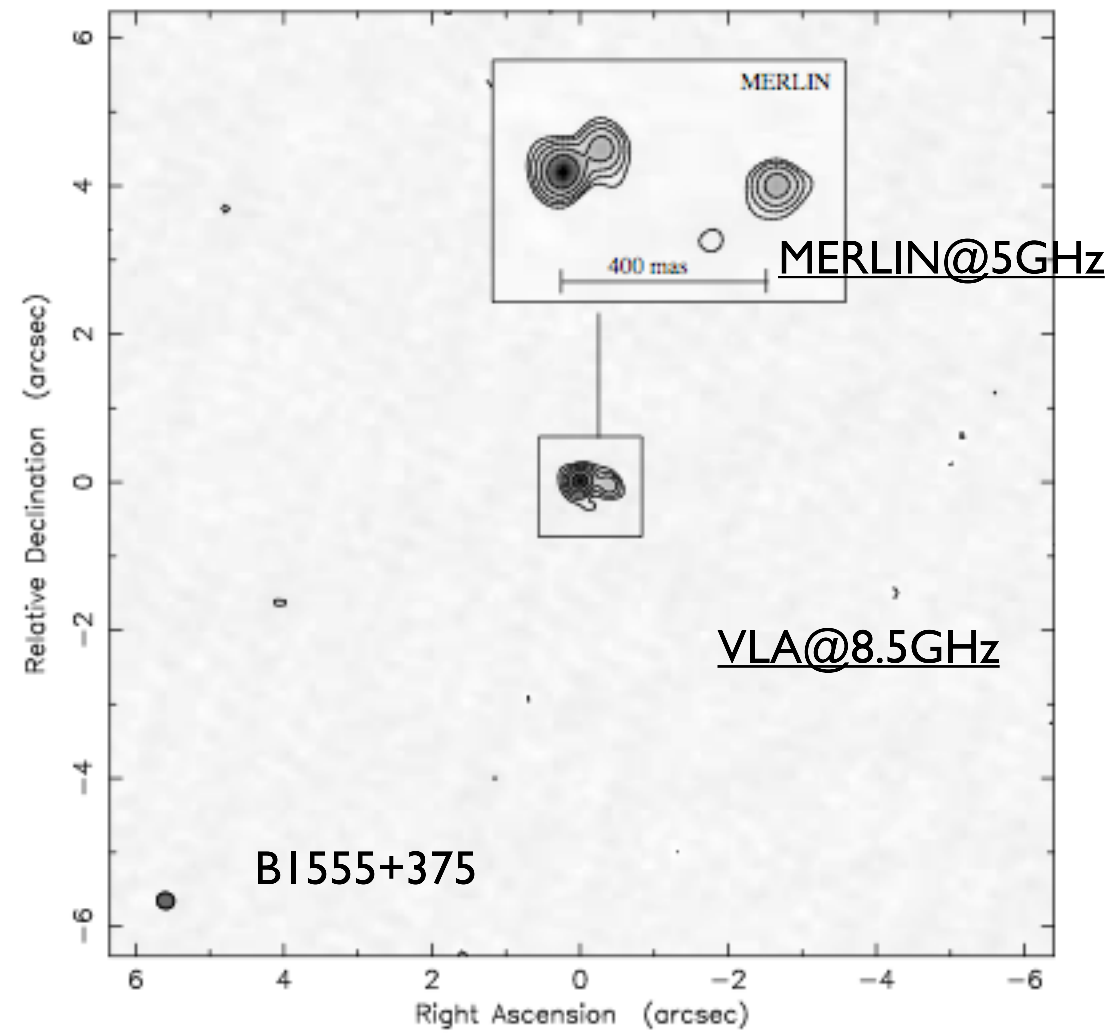
The survey was conducted between 1990 and 1999. During the survey 16503 flat-spectrum radio sources were monitored. Such objects are usually quasars and have very simple radio structures; they are typically point sources, and occasionally weak extended emission is visible. The point-like radio emission is thought to originate from the base of a relativistic radio jet in an active galaxy, which points more or less at the observer.

The simplicity of these sources is useful for gravitational lensing searches. This is because any flat-spectrum radio source which has extended structure is a possible gravitational lens, as the extended structure could represent multiple images of a point-like radio source, produced by the gravitational field of an intervening galaxy.

Instruments: VLA (radio maps at 0.2” res.) + follow-up with MERLIN (0.05” res.) and VLBA (0.003” res).

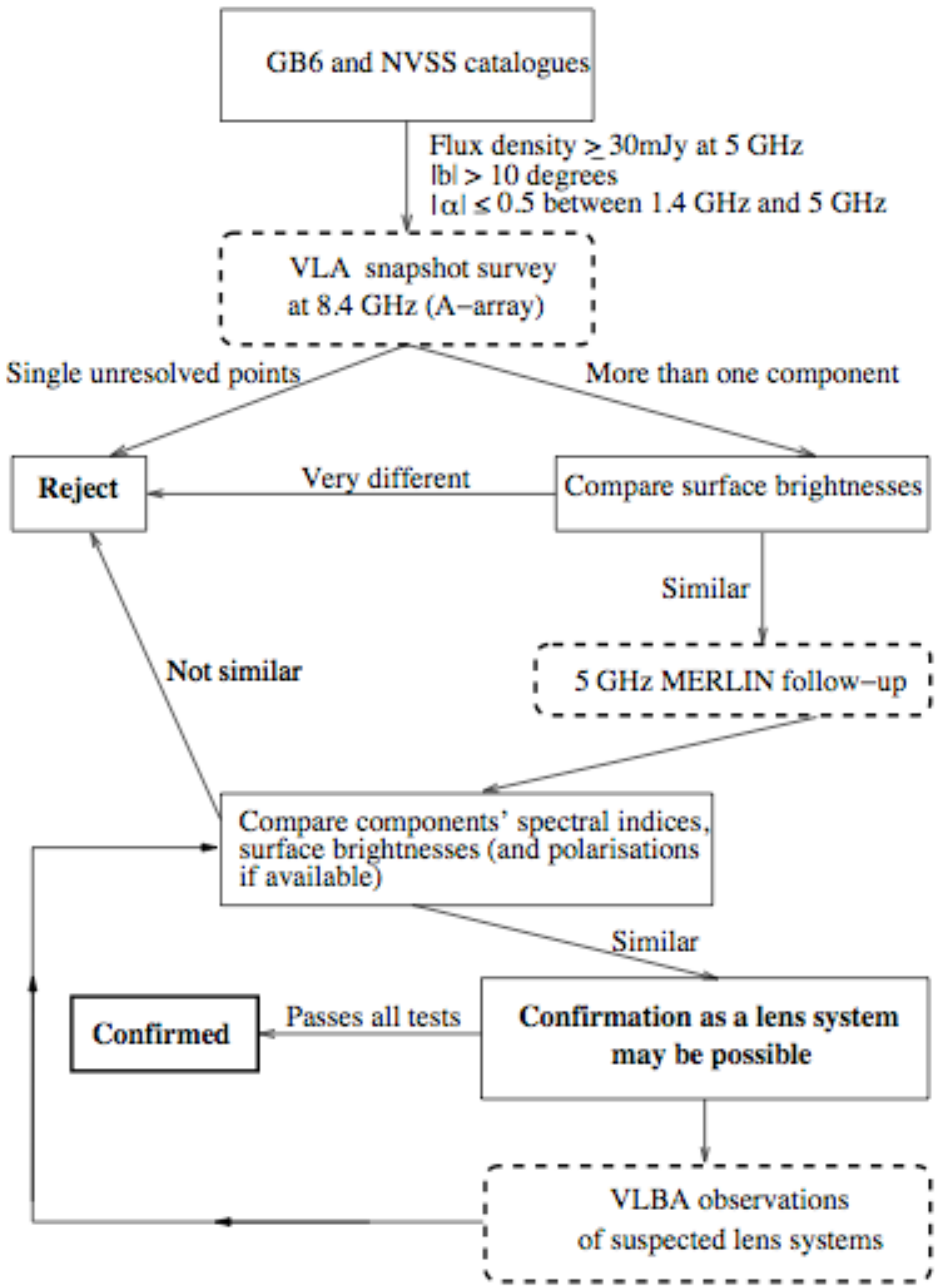
CLASS STRATEGY

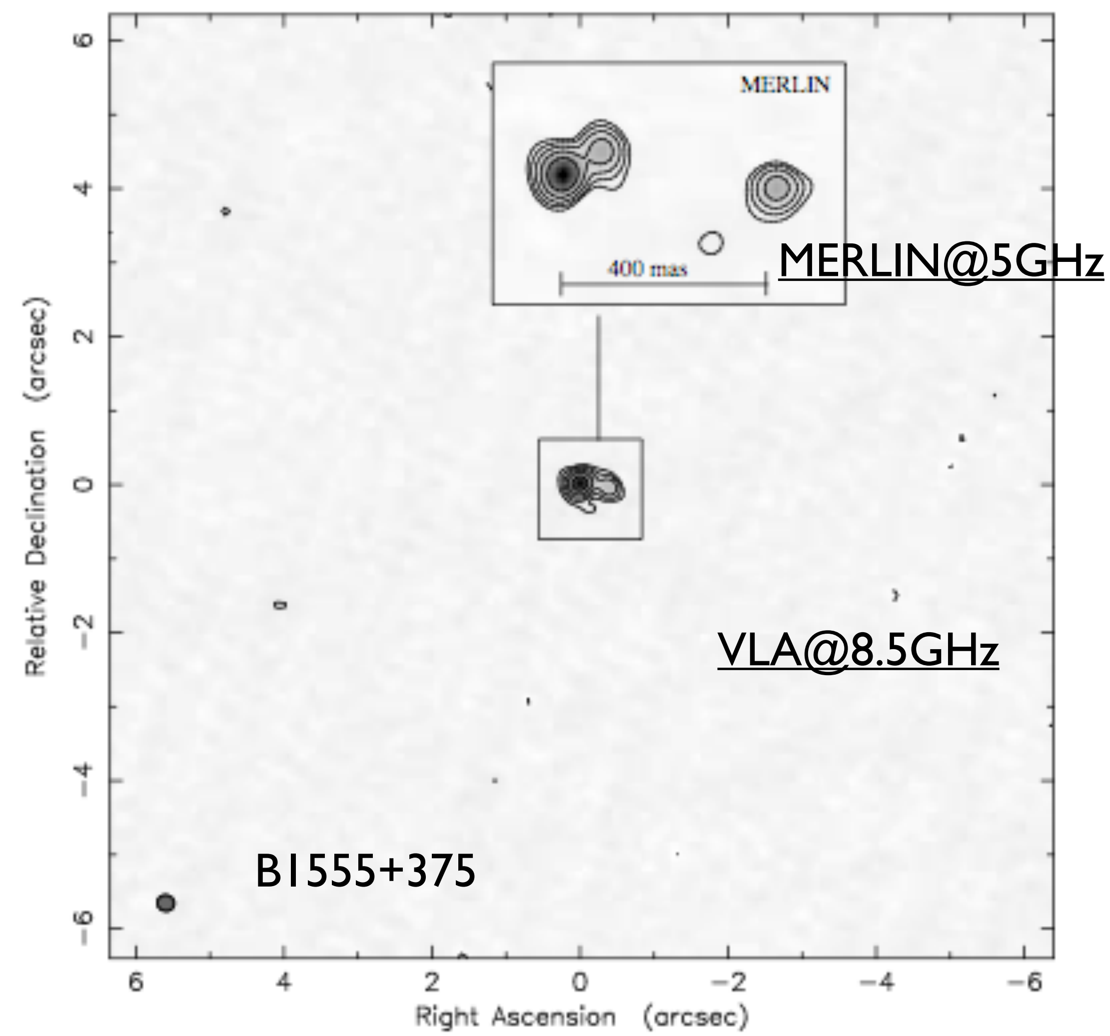




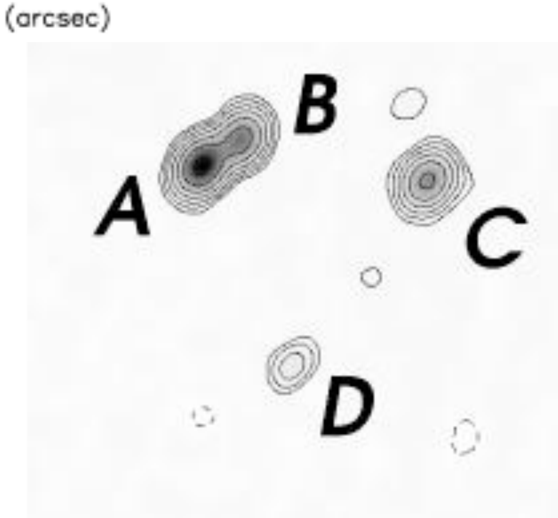
Browne et al. 2002

CLASS STRATEGY

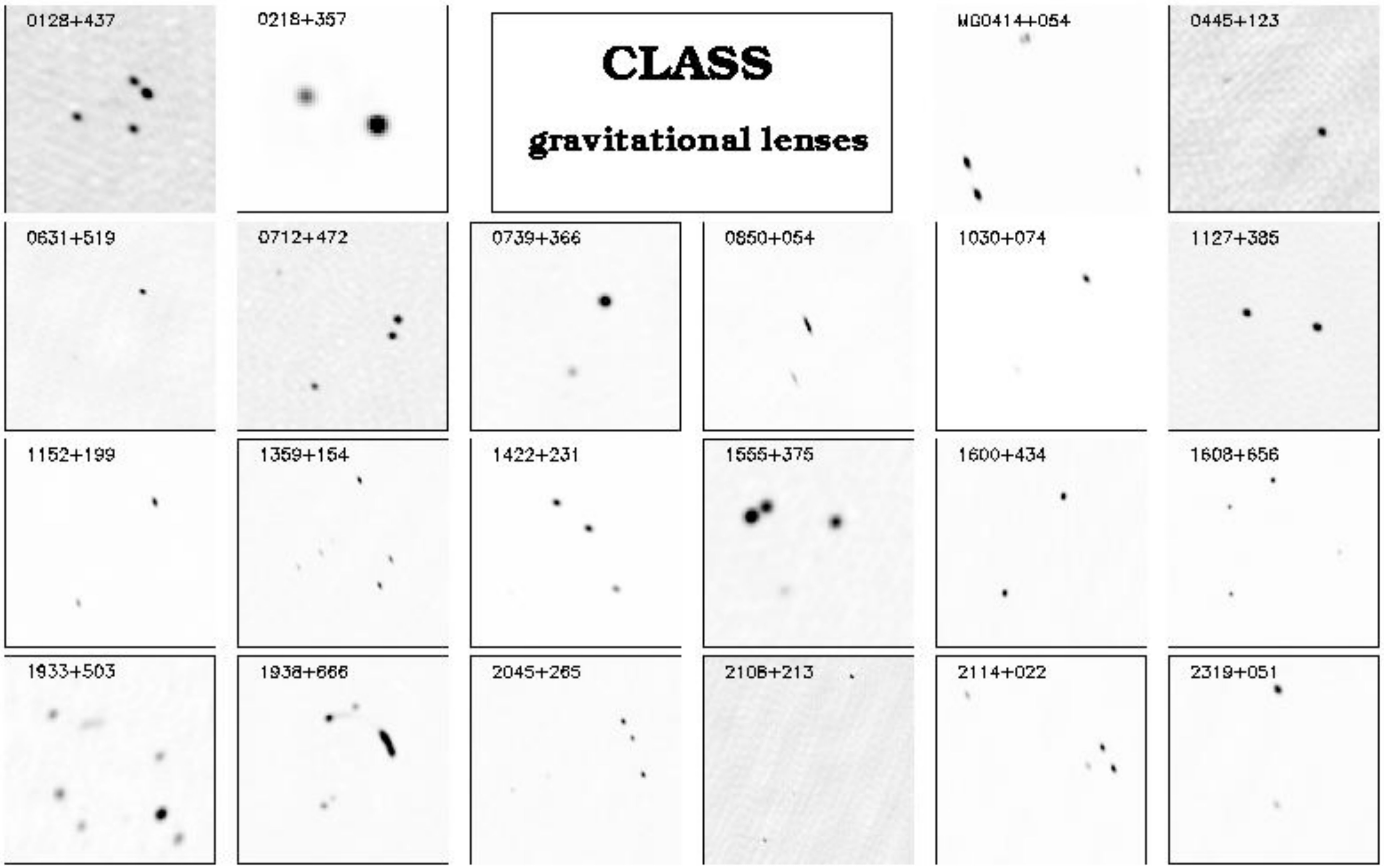




Browne et al. 2002

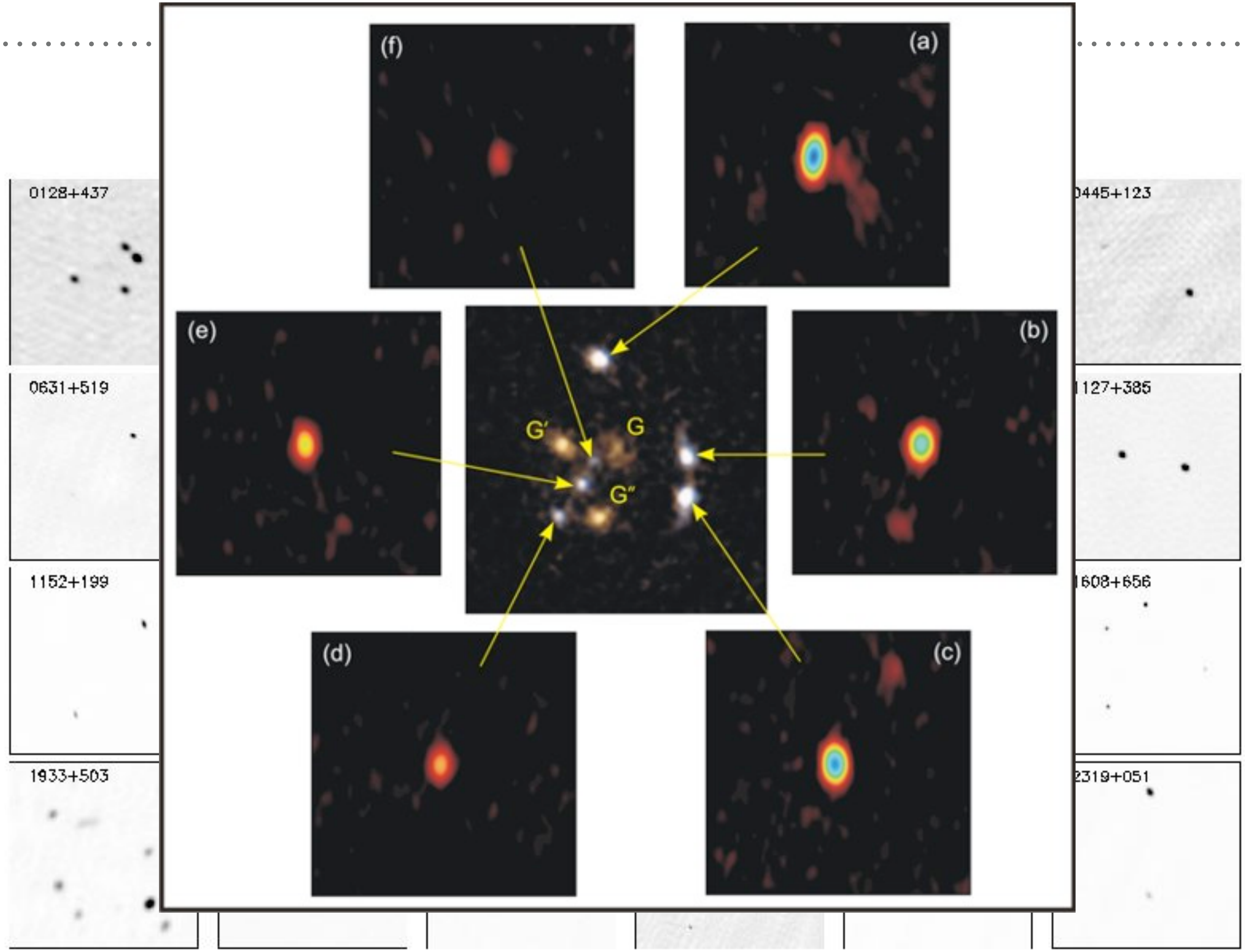


CLASS LENSES



12 double 9 quadruple 1 sextuple

CLASS LENSES

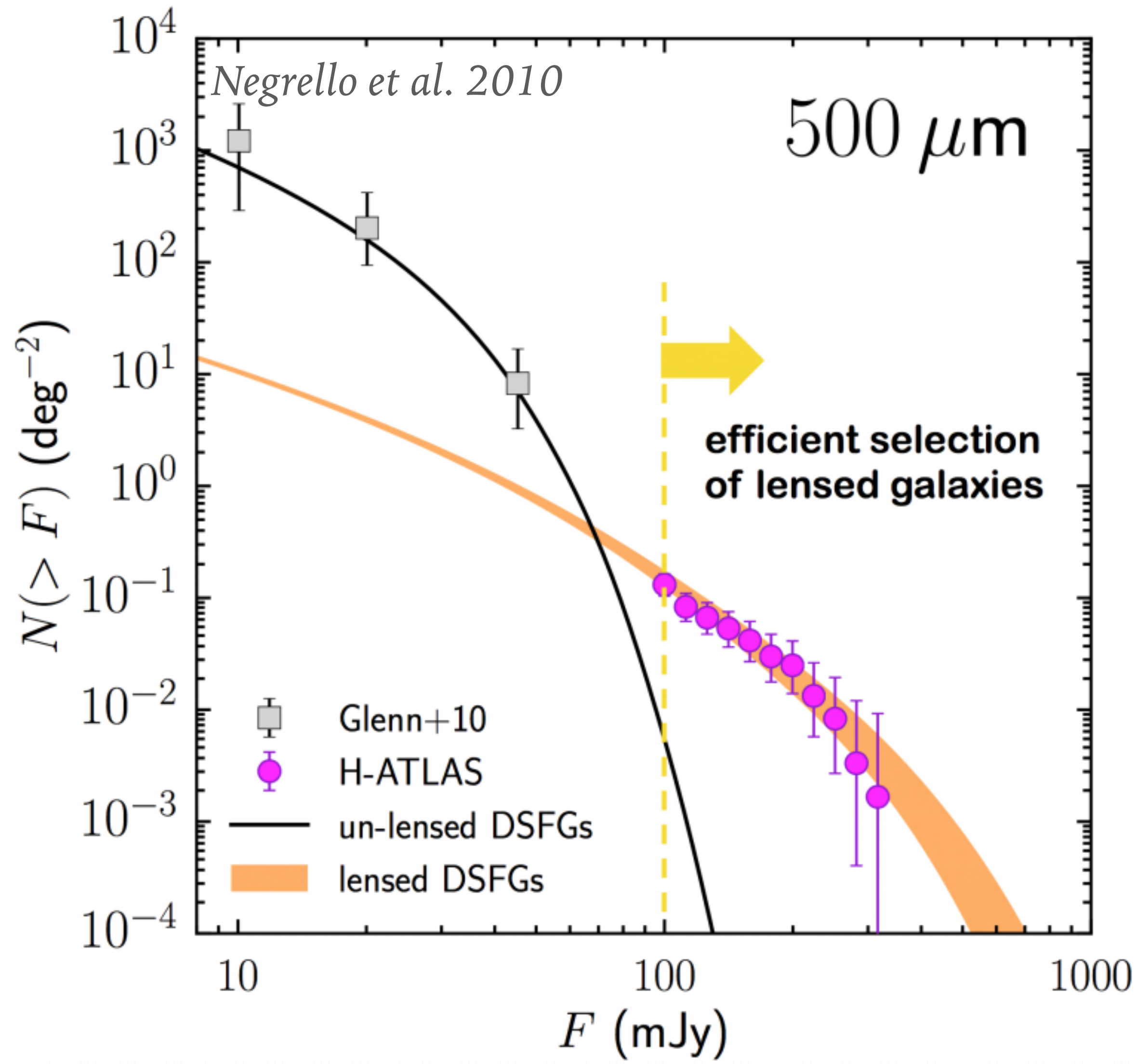


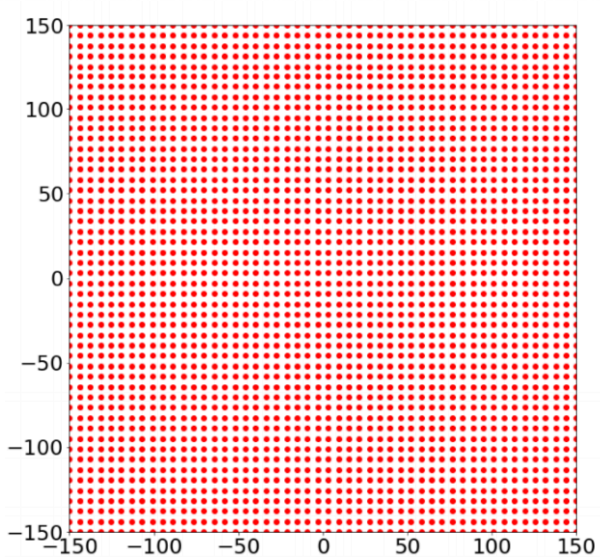
12 double

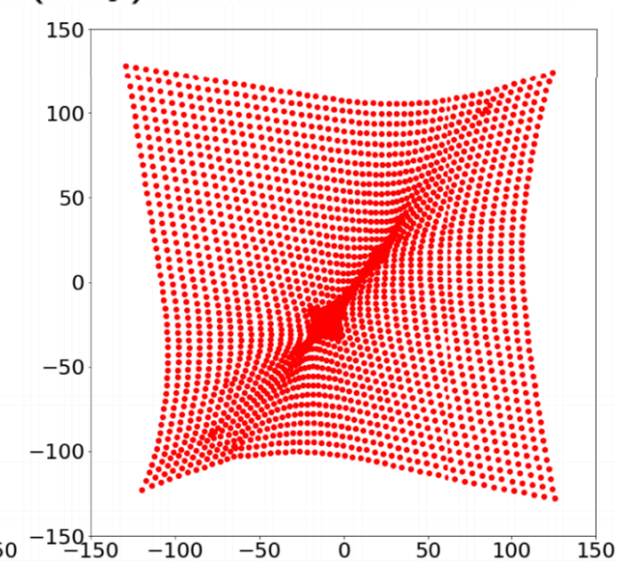
9 quadruple

1 sextuple

SEARCHES AT THE SUB-MM WAVELENGTHS: MAGNIFICATION BIAS







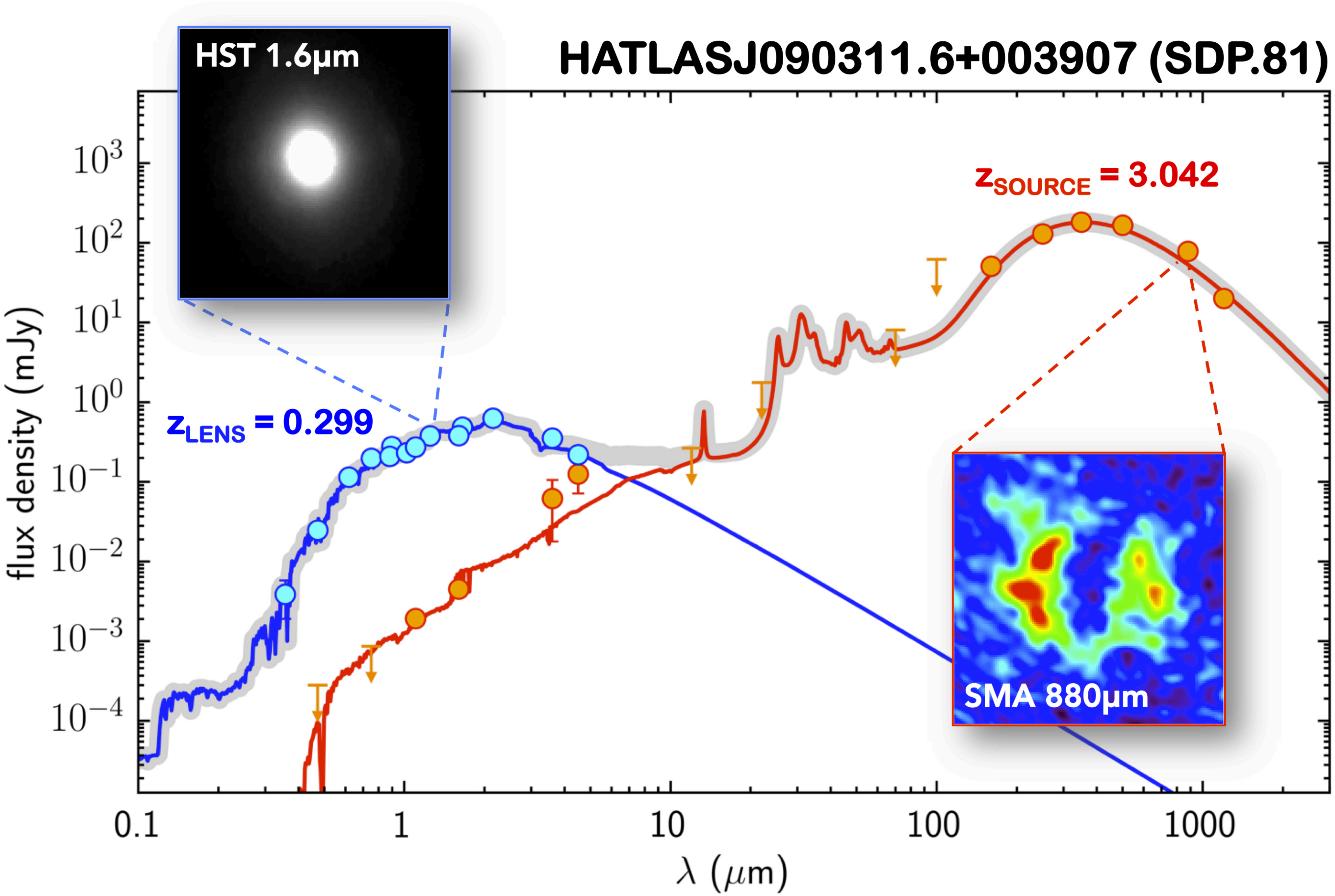
$$N_0(>F) = QF^{-\alpha}$$

$$N_{obs}(>F) = \frac{N_0(>F/\mu)}{\mu}$$

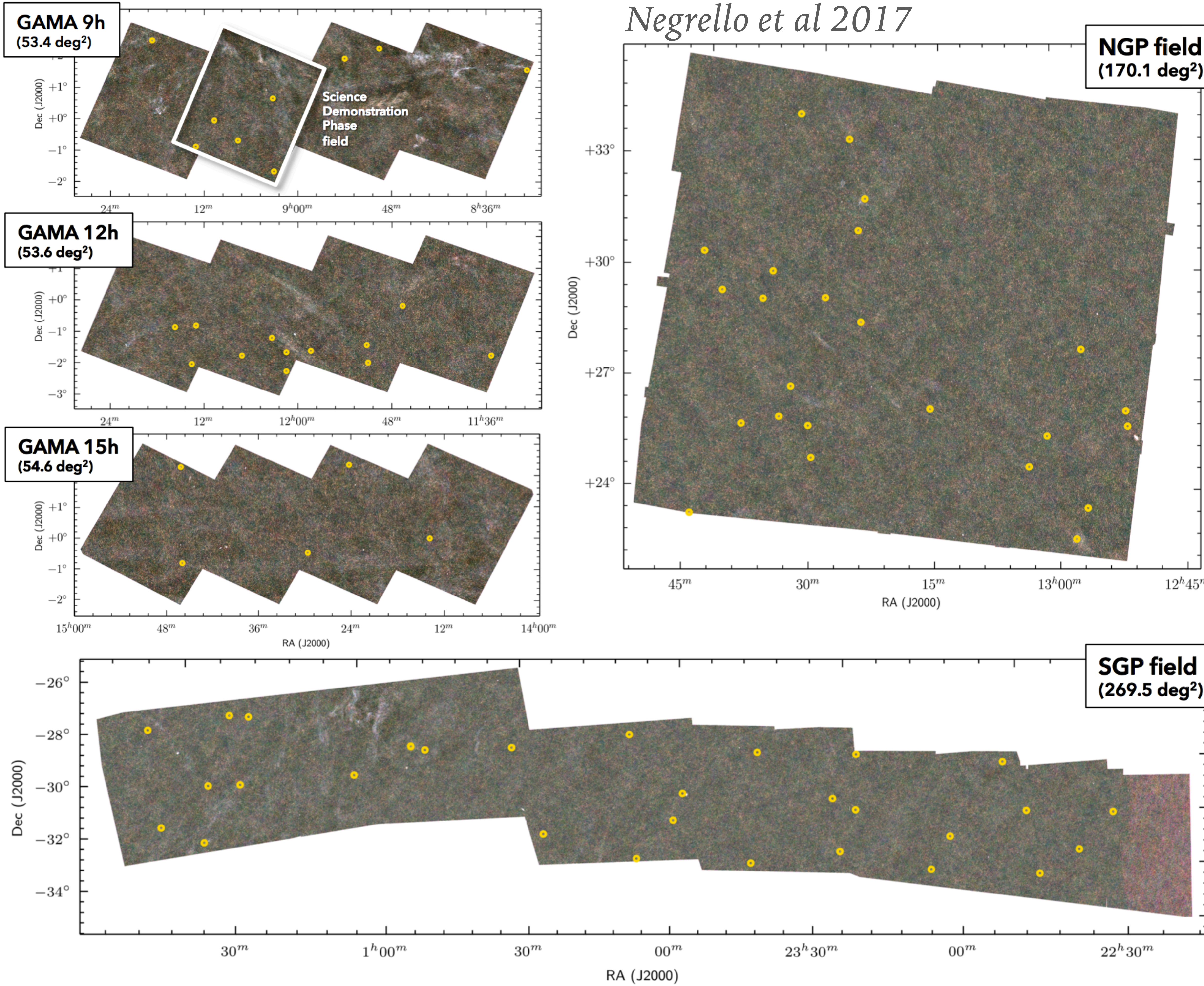
$$N_{obs}(>F) = Q\frac{(F/\mu)^{-\alpha}}{\mu}$$
$$= Q\frac{F^{-\alpha}}{\mu^{1-\alpha}}$$

$$= N_0(>F)\mu^{\alpha-1}$$

SEARCHES AT THE SUB-MM WAVELENGTHS



Negrello et al. 2010


Negrello et al 2017
GAMA 9h
(53.4 deg²)
Science Demonstration Phase field
Dec (J2000)
+1°
+0°
−1°
−2°
24^m
12^m
9^h00^m
48^m
8^h36^m
GAMA 12h
(53.6 deg²)
+0°
−1°
−2°
−3°
24^m
12^m
12^h00^m
48^m
11^h36^m
GAMA 15h
(54.6 deg²)
+1°
+0°
−1°
−2°
15^h00^m
48^m
36^m
24^m
12^m
14^h00^m
RA (J2000)
NGP field
(170.1 deg²)
+33°
+30°
+27°
+24°
45^m
30^m
15^m
13^h00^m
12^h45^m
SGP field
(269.5 deg²)
−26°
−28°
−30°
−32°
−34°
30^m
1^h00^m
30^m
00^m
23^h30^m
00^m
22^h30^m

SLACS (OPTICAL)

The SLACS (Sloan Lens ACS survey, Bolton et al. 2006) is a very successful project whose goal was finding strongly lensed sources behind probable lens galaxies selected in the Sloan Digital Sky Survey.

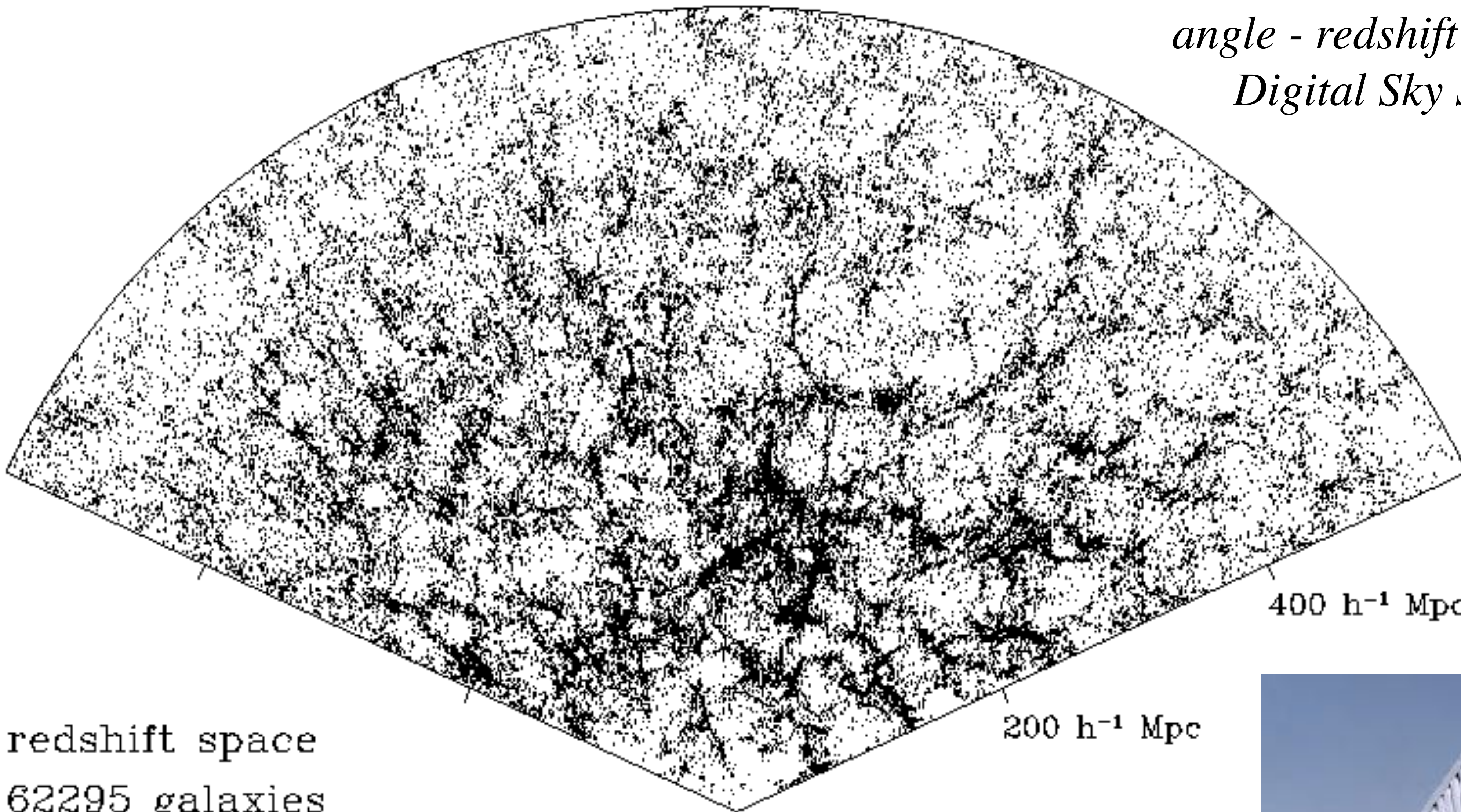
The candidate lenses are selected from the spectroscopic database. This survey has produced imaging and spectra for galaxies on a huge portion of the sky (8400 sq. degree). The observations were conducted between 2000-2005 (SDSS-I) and 2005-2009 (SDSS-II) using a dedicated 2.5m-telescope at Apache Point (New Mexico).

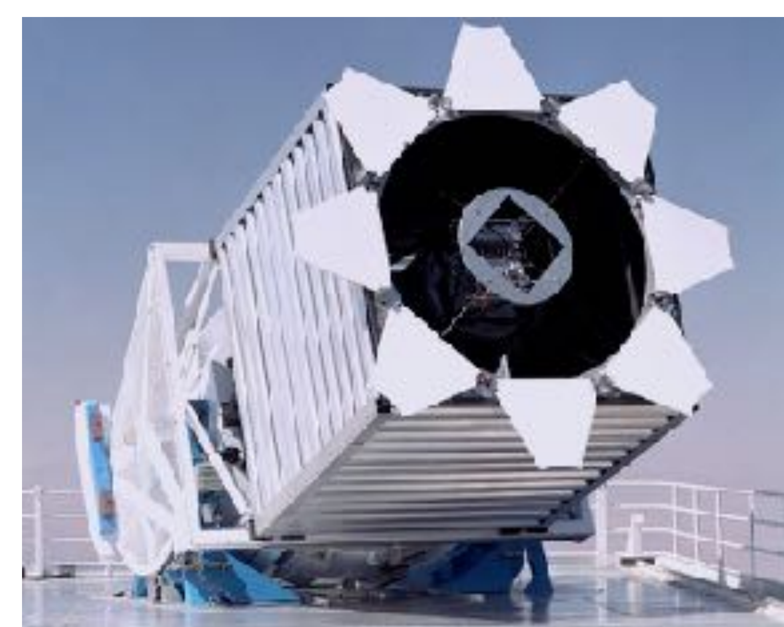
The candidate lenses are galaxies whose spectra can hardly be fitted with a single spectrum. This is an indication of superposition of two different galaxies along the line of sight. This technique follows the discovery of a lens system by Warren et al. (1996)

The selected candidates are observed at high-resolution with the ACS onboard HST.

SLACS (OPTICAL)

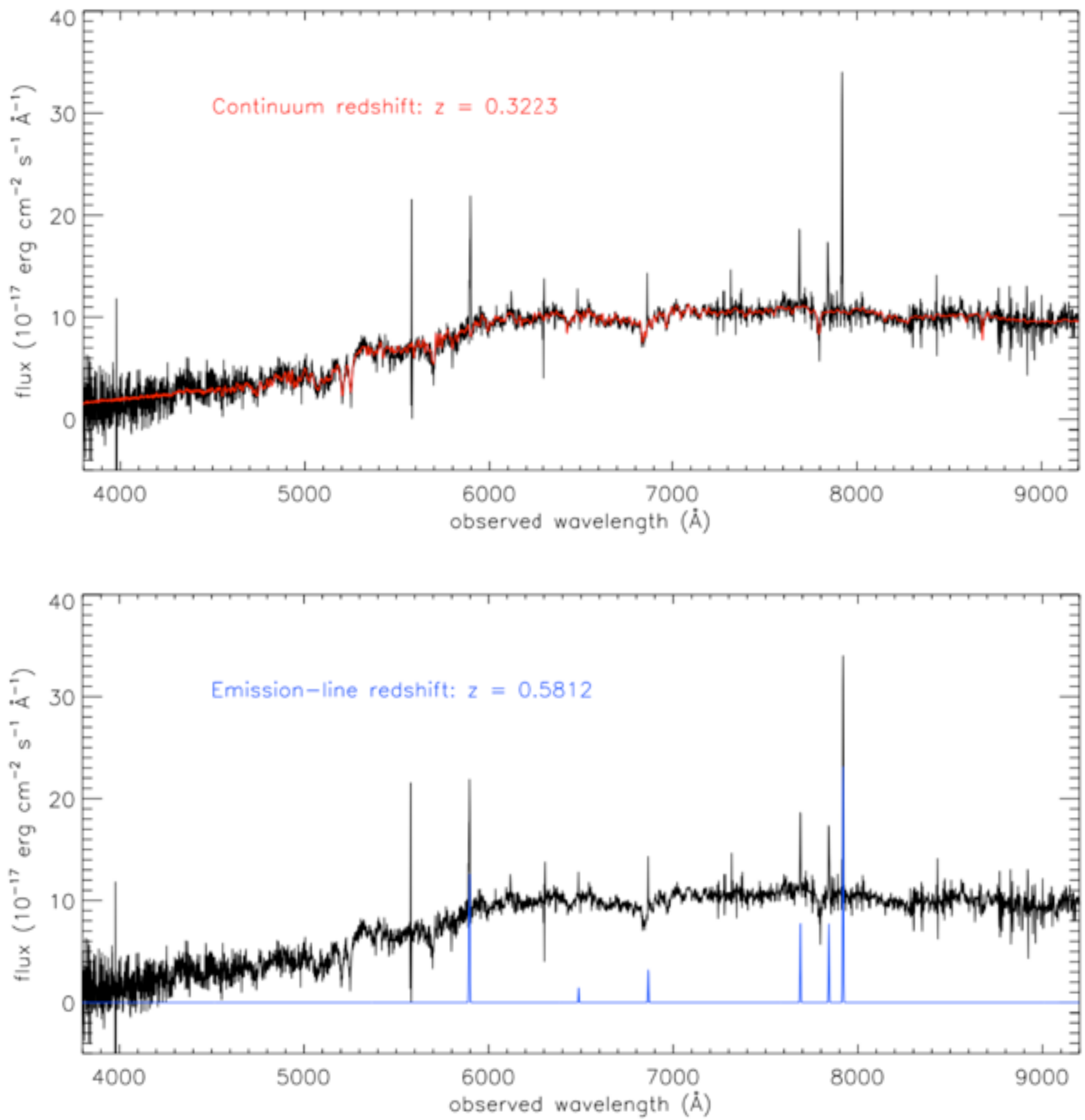
angle - redshift slice of the Sloan Digital Sky Survey (SDSS)



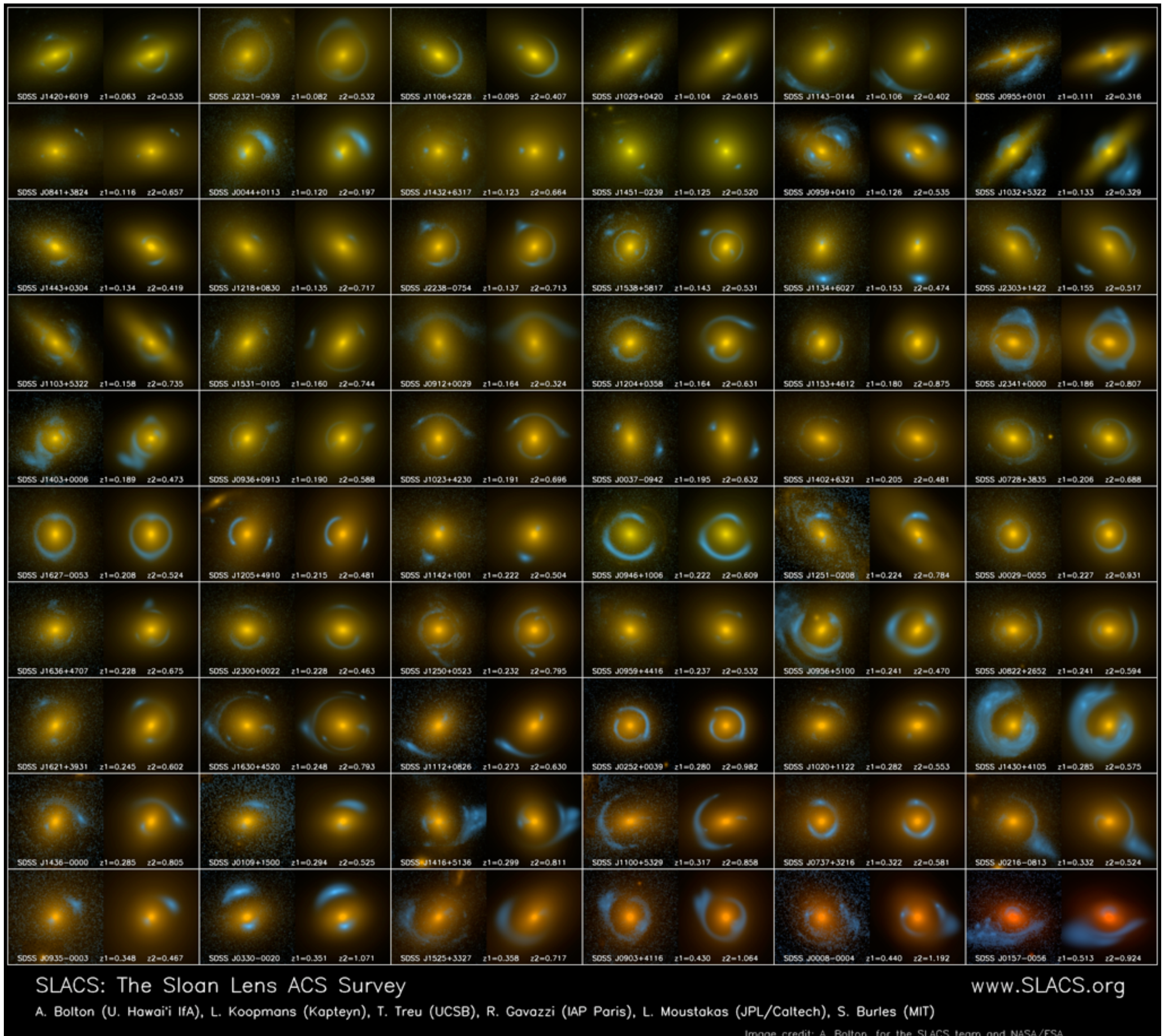


SLACS (OPTICAL)

The SLACS survey looked for unusual spectra that are the combination of galaxies at different redshifts - source and lens.



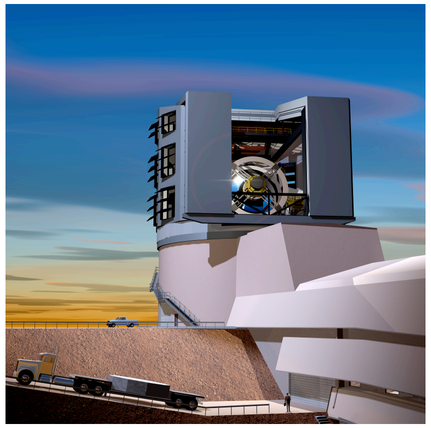
SLACS LENSES



- 85 galaxy lenses
- 13 probable lenses
- redshifts for all systems
- 80% ellipticals
- 10% lenticular
- 10% spirals (mostly bulge dominated)
- big galaxies with v. disp. ~200-300 km/s (average: 248 km/s)

THE NEXT GENERATION OF LENSING SURVEYS

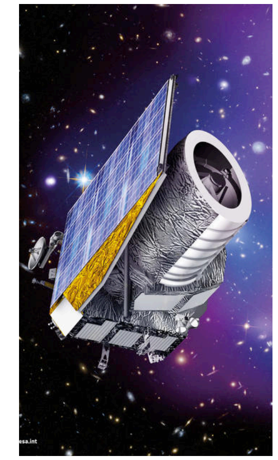
- Some ongoing surveys (KiDS, DES, Pan-STARRS, HSC) are producing large amounts of imaging data (thousands of sq. degrees)
- Between 2022-2025, some other telescopes will become operative and start imaging nearly the whole sky at large depths and with good spatial resolution.
- These surveys were proposed manly as cosmological experiments employing weak lensing
- However, the data will be of good quality also to exploit strong lensing
- Large-Synoptic-Survey-Telescope (LSST), Vera Rubin Observatory
- **Euclid**
- WFIRST



LSST
Legacy Survey of Space and Time

Vera C. Rubin
Observatory

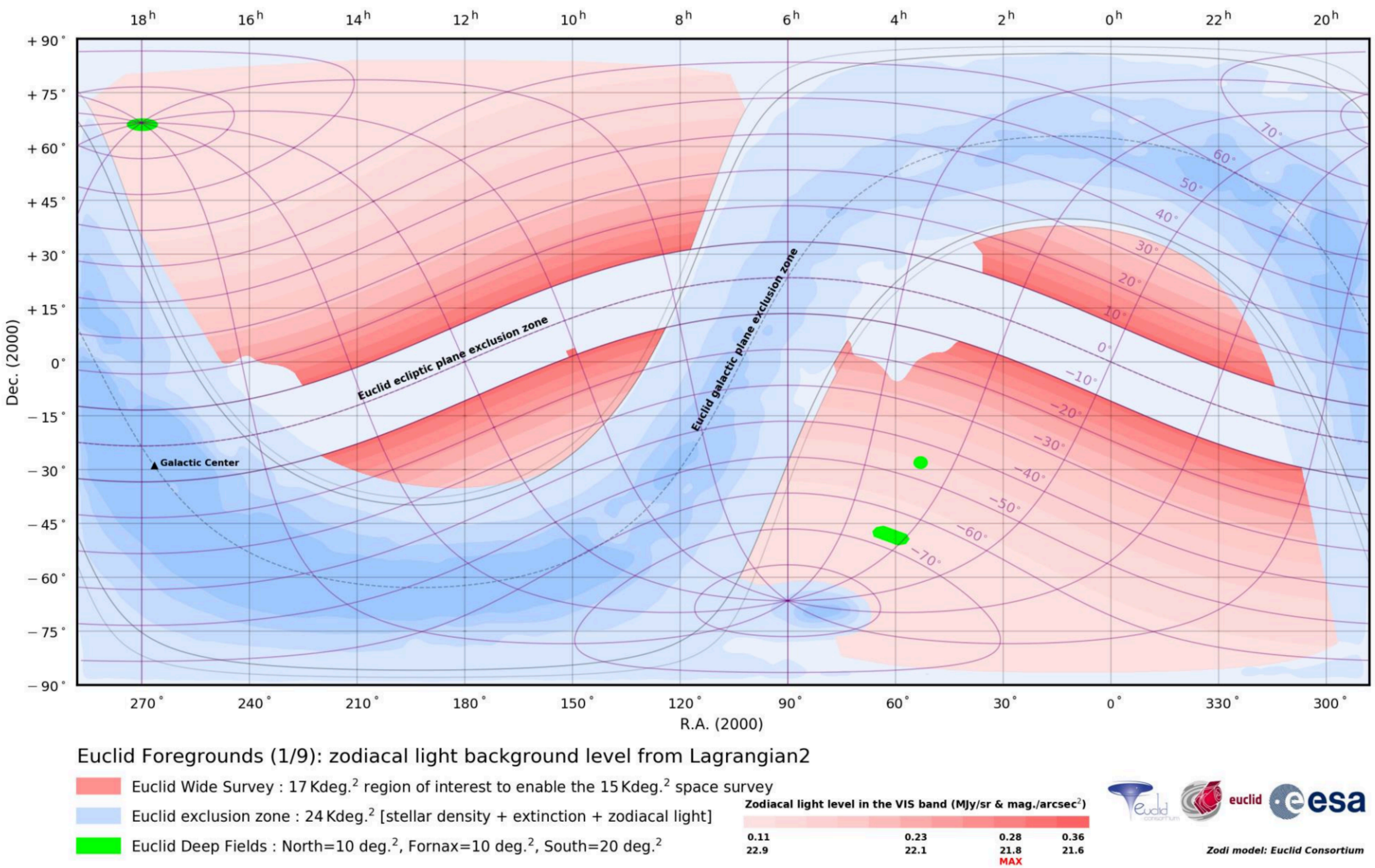
Euclid



Wide-Field Infrared Survey Telescope
WFIRST
Astrophysics • Dark Energy • Exoplanets

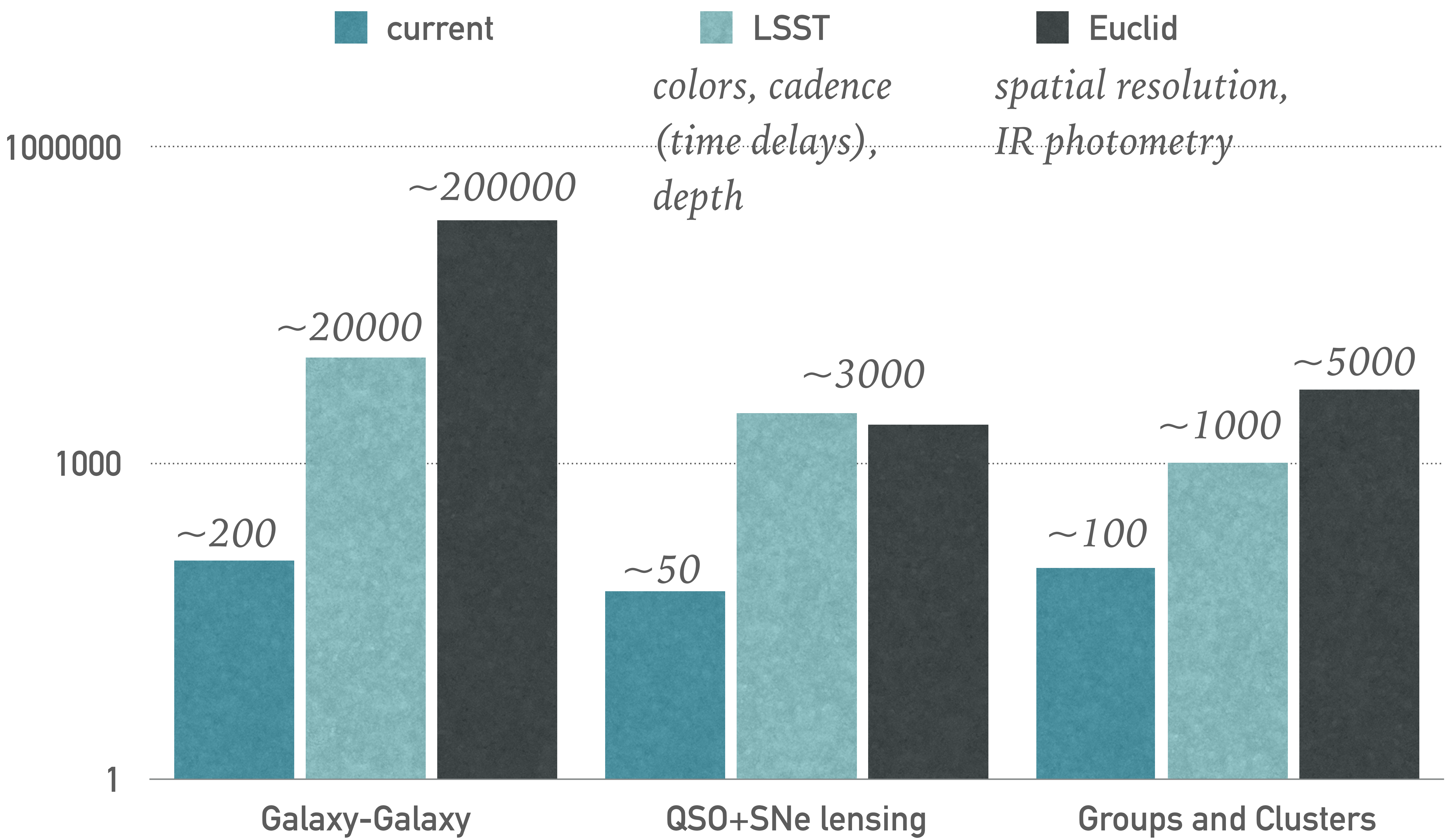
Proposed lifetime	2022 - 2032	2022 - 2029	2025 - 2031
Mirror size (m)	6.5 (effective diameter)	1.2	2.4
Survey size (sq deg)	~20,000	15,000	2,227
Median z (WL)	0.9	0.9	1.2
Depth (AB mag)	~27.5	~24.5	~27
FoV (sq deg)	9.6	0.5 (Vis) 0.5 (NIR)	0.28
Filters	u-g-r-i-z-y	Y-J-H-Vis	Y-J-H-F184
PSF Size	~0.7”	~0.2” (optical)	~0.2” (NIR)
Mode	Photometry	Photometry/Grism	Photometry/Grism

Euclid Survey



ECSURV (plots by J.C. Cuillandre)

STRONG LENSING IN THE ERA OF EUCLID AND LSST



Source: LSST science book; Euclid SL white paper (in progress)

WE ENTERED A NEW ERA: AUTOMATED SEARCHES FOR LENSES

- The strategy had to be changed: large areas, big depth, large number of potential lenses, making difficult the lens identification in the usual way
- The idea of “automated detection” has taken place
- Machine learning! Deep learning with CNNs…

WE ENTERED A NEW ERA: AUTOMATED SEARCHES FOR LENSES

The strategy needs to be changed : large area, large depth, large number of potential lenses and no spectra make it difficult to identify lenses in the traditional ways.

Human inspection

Tens of billions of galaxies will need to be inspected, at least at the first stage, which will be difficult even for crowd sourcing.

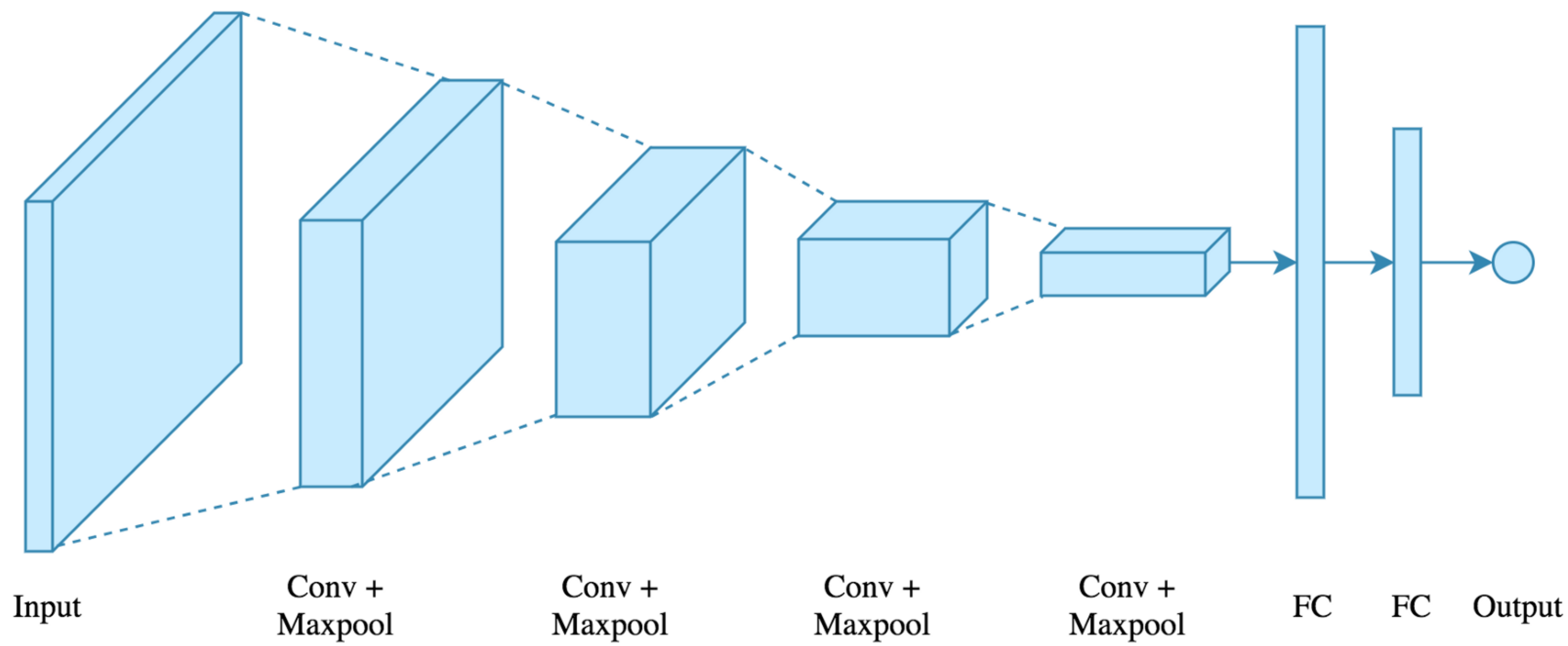
Objectivity and consistency is difficult to assess.

automated "arc finders"

This may be useful for giant arcs in clusters.
Does not seem to be competitive for galaxy-galaxy lenses

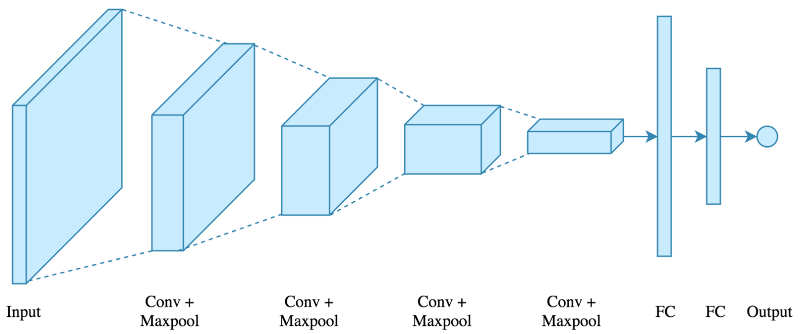
machine learning / deep learning with Convolutional Neural Networks (CNNs)

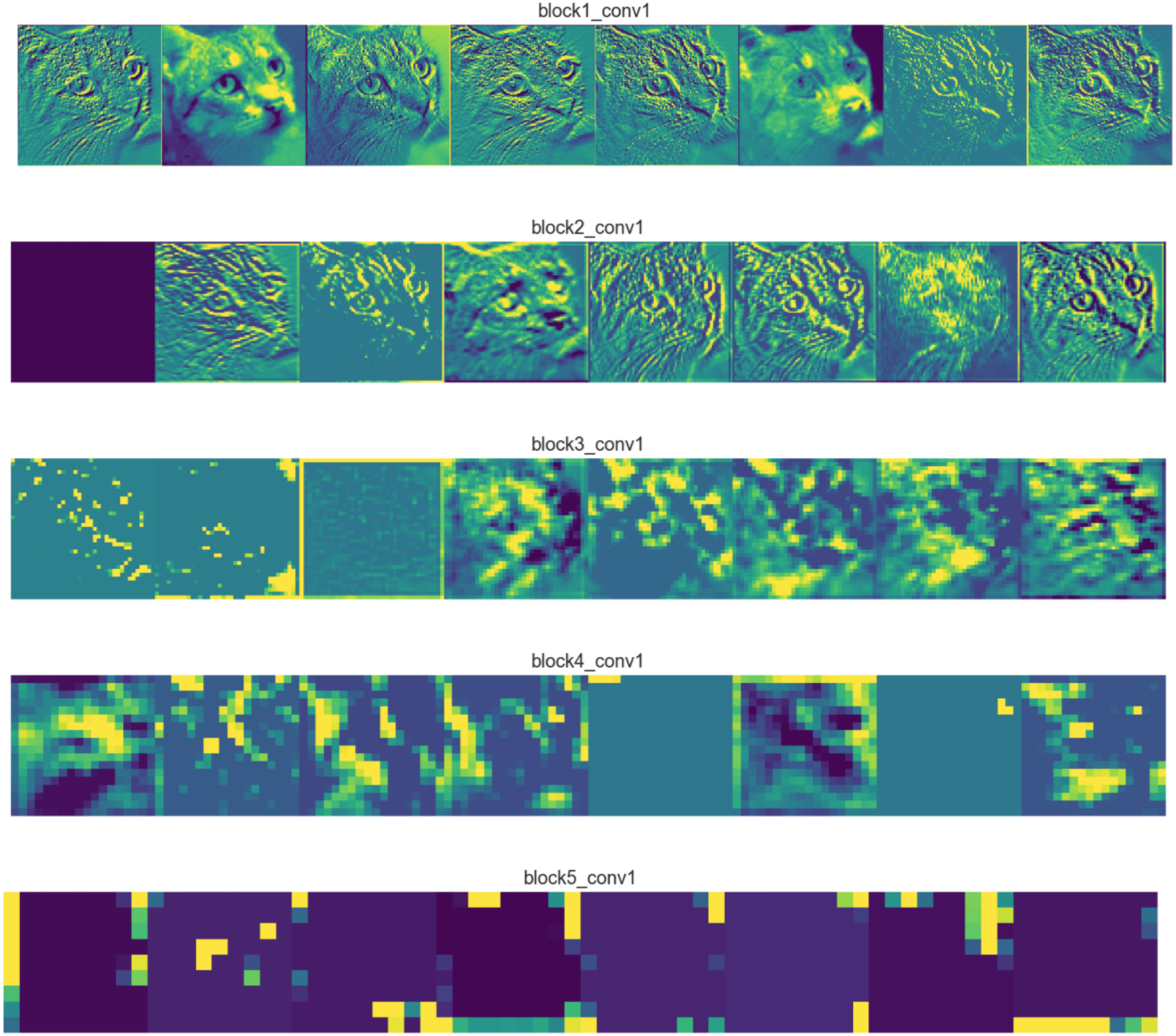
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)

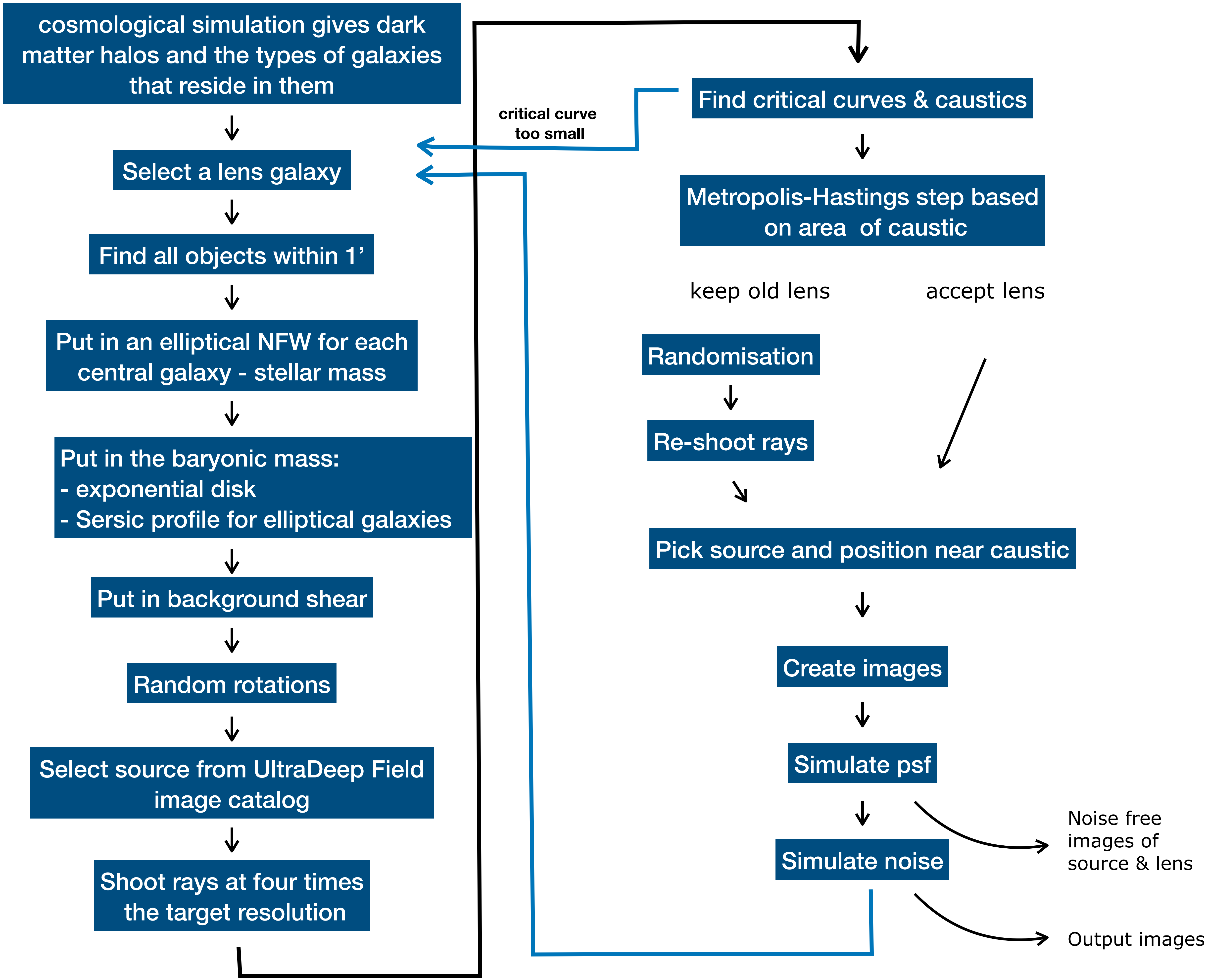


https://towardsdatascience.com/applied-deep-learning-part-4-convolutional-neural-networks-584bc134c1e2

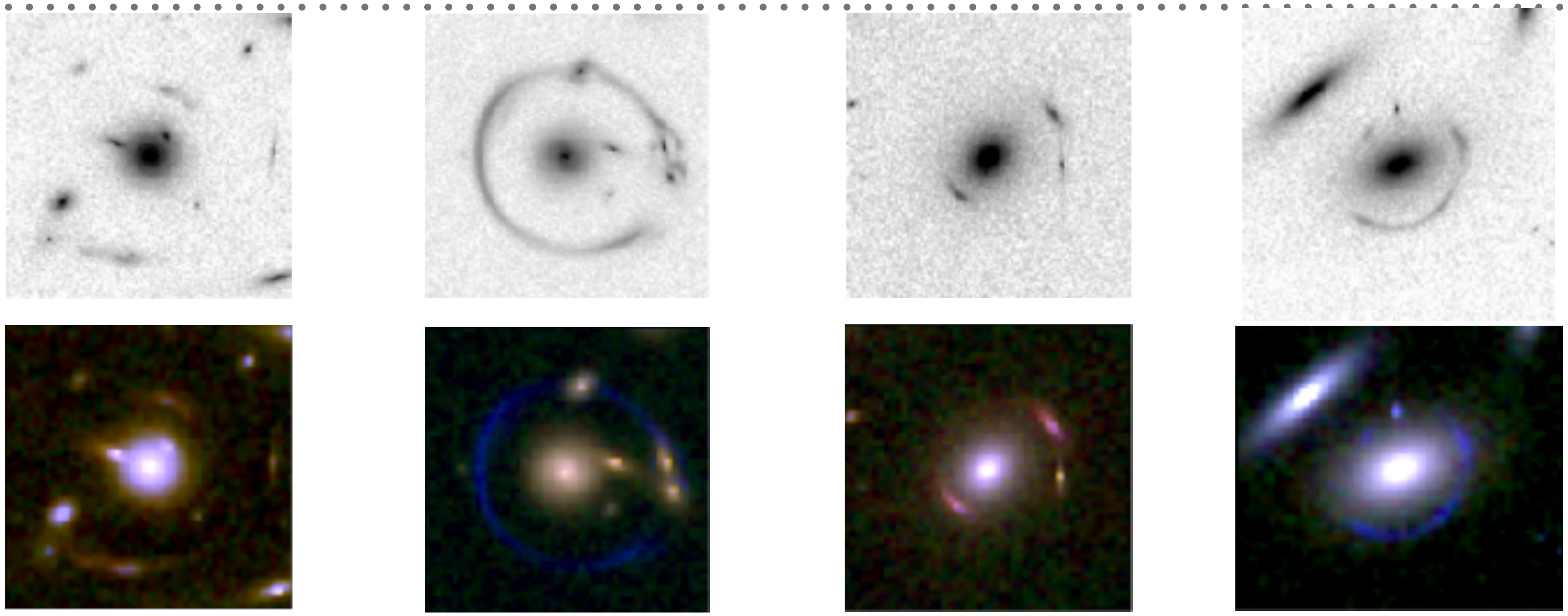
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)



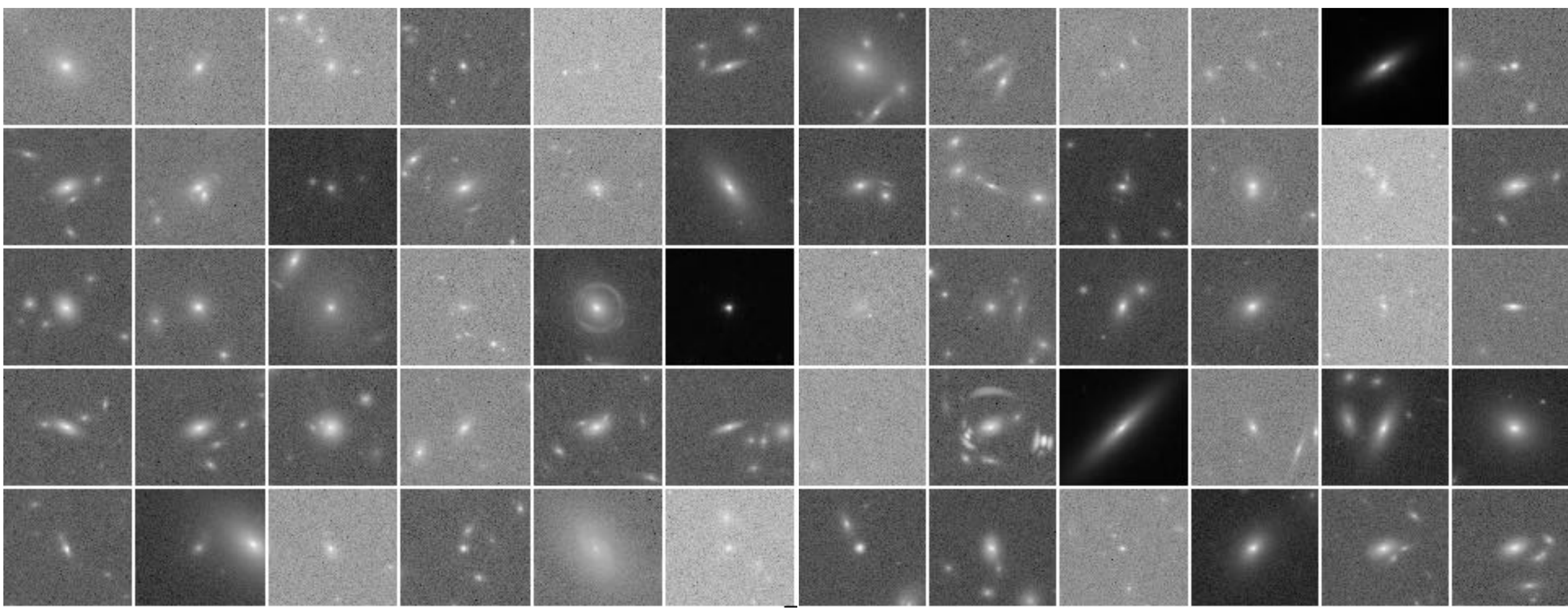



cosmological simulation gives dark matter halos and the types of galaxies that reside in them
Select a lens galaxy
Find all objects within 1’
Put in an elliptical NFW for each central galaxy - stellar mass
Put in the baryonic mass:
- exponential disk
- Sersic profile for elliptical galaxies
Put in background shear
Random rotations
Select source from UltraDeep Field image catalog
Shoot rays at four times the target resolution
critical curve too small
Find critical curves & caustics
Metropolis-Hastings step based on area of caustic
keep old lens
accept lens
Randomisation
Re-shoot rays
Pick source and position near caustic
Create images
Simulate psf
Simulate noise
Noise free images of source & lens
Output images

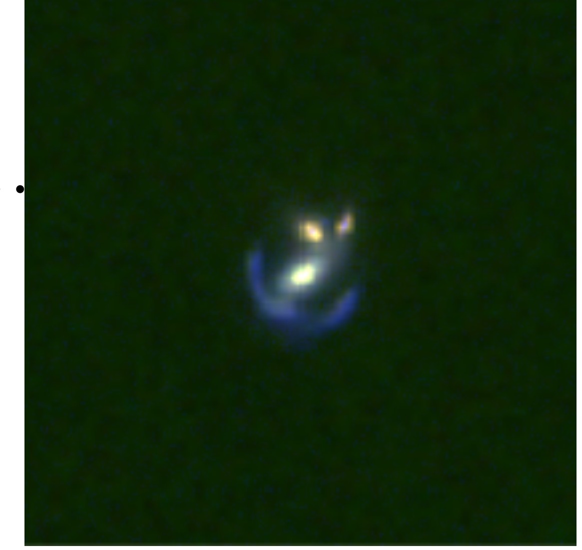
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)



Simulated gradational lenses used as a training set for the CNNs.



LENSING FINDING : EVALUATION OF ML LENS FINDERS



false positive rate

$$f_{\text{lens}} \gg FPR = \frac{FP^*}{N^*}$$

true fraction of lenses

precision in simulation

true positives simulation

$$\left(\frac{1 - Pre^*}{Pre^*}\right) \frac{TP^*}{N^*} \ll f_{\text{lens}}$$

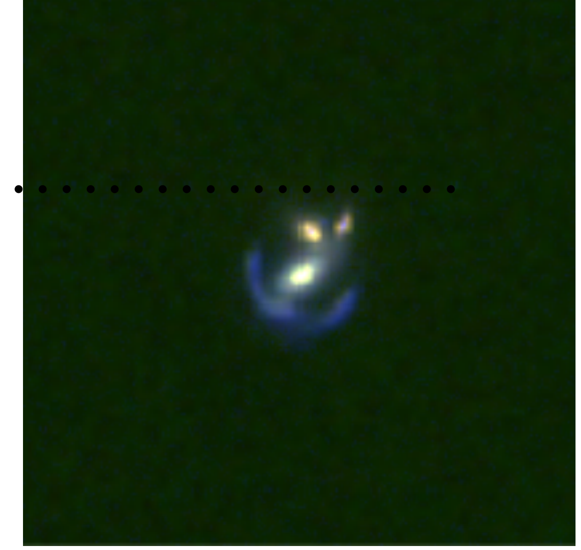
number of targets in simulation

	Is really a lens	Is not really a lens
Evaluated As lens	TP	FP
Evaluated As not lens	FN	TN

$$\text{precision} = \frac{TP}{TP + FP}$$

$$\text{recall} = \frac{TP}{TP + FN} \qquad \text{fp rate} = \frac{FP}{FP + TN} \qquad \text{accuracy} = \frac{TP + TN}{N}$$

LENSING FINDING : EVALUATION OF ML LENS FINDERS



F1 score

$$F_\beta = (1+\beta^2)\frac{\text{precision} \times \text{recall}}{\beta^2 \text{precision} + \text{recall}} \qquad F_\beta = \frac{(1+\beta^2)TP}{(1+\beta^2)TP + \beta^2 FN + FP}$$

$$0 < F_\beta < 1$$

β can be used to adjusted the importance of recall relative to precision.

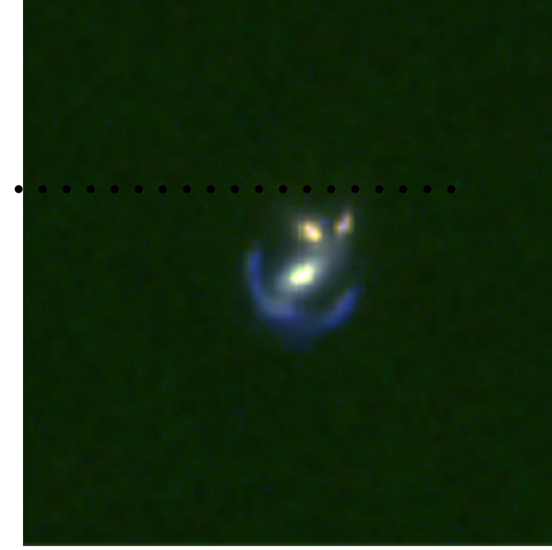
$$F_{\beta=0} = \text{precision} \qquad F_{\beta=\infty} = \text{recall}$$

	Is really a lens	Is not really a lens
Evaluated As lens	TP	FP
Evaluated As not lens	FN	TN

$$\text{precision} = \frac{TP}{TP+FP}$$

$$\text{recall} = \frac{TP}{TP+FN} \qquad \text{fp rate} = \frac{FP}{FP+TN} \qquad \text{accuracy} = \frac{TP+TN}{N}$$

LENSING FINDING : EVALUATION OF ML LENS FINDERS



The F1 score is a function of many parameters.

$$F_\beta(p, R_{Einstein}, \text{fluxes}, etc\ldots)$$

threshold of classifier

Score can be the maximum of F_β for $\beta = 0.1$ or $\beta = 0.01$

$$F_\beta(R_{Einstein}, \text{fluxes}, etc\ldots) = \max_p \left[F_\beta(p, R_{Einstein}, \text{fluxes}, etc\ldots)\right]$$

	Is really a lens	Is not really a lens
Evaluated As lens	TP	FP
Evaluated As not lens	FN	TN

$$\text{precision} = \frac{TP}{TP+FP}$$

$$\text{recall} = \frac{TP}{TP+FN} \qquad \text{fp rate} = \frac{FP}{FP+TN} \qquad \text{accuracy} = \frac{TP+TN}{N}$$

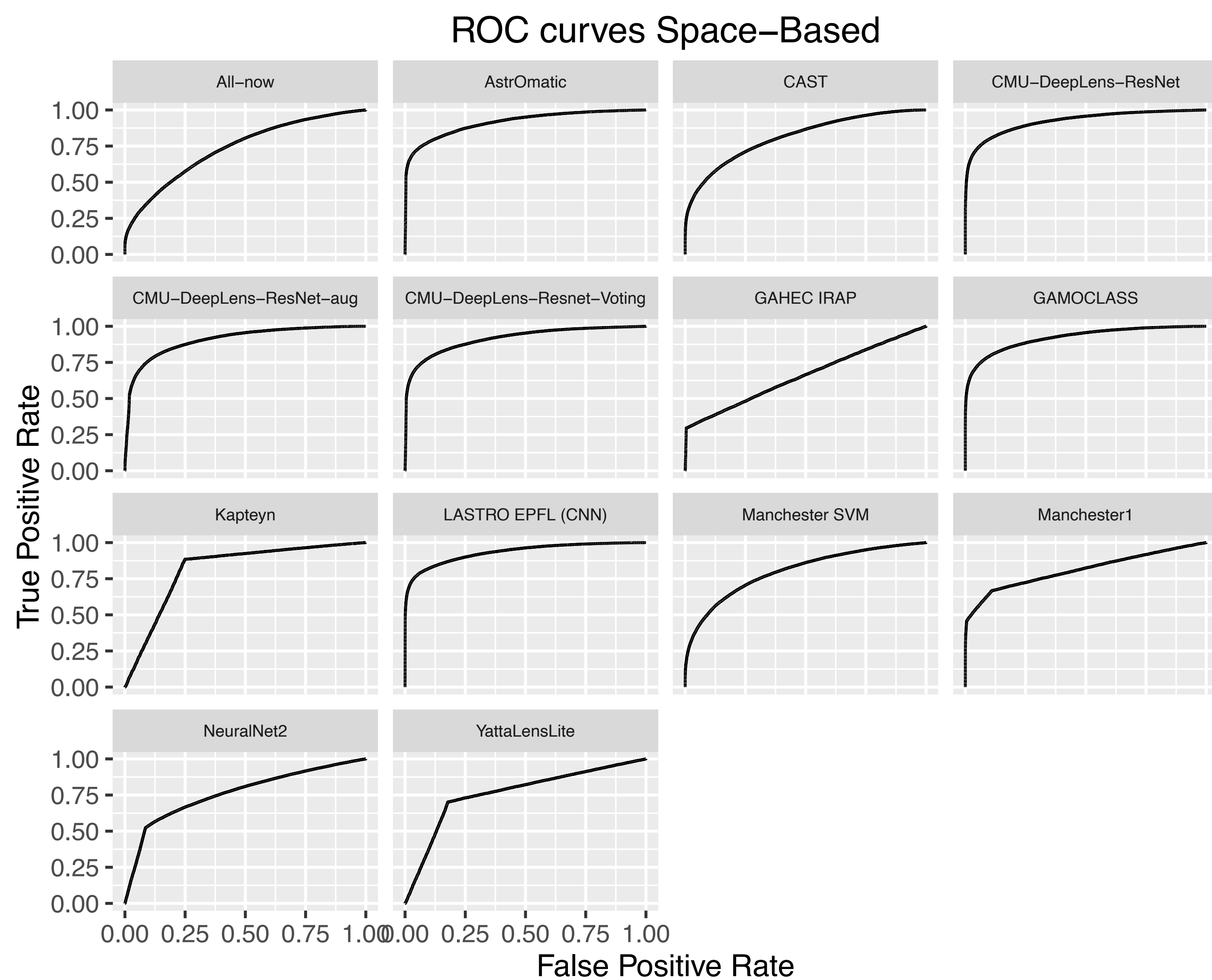
LENSING FINDING : EVALUATION OF ML LENS FINDERS

*The traditional way to evaluate classifiers is with the **ROC curve**.*

*The ROC curve is a plot of the **true positive rate vs the false positive rate.***

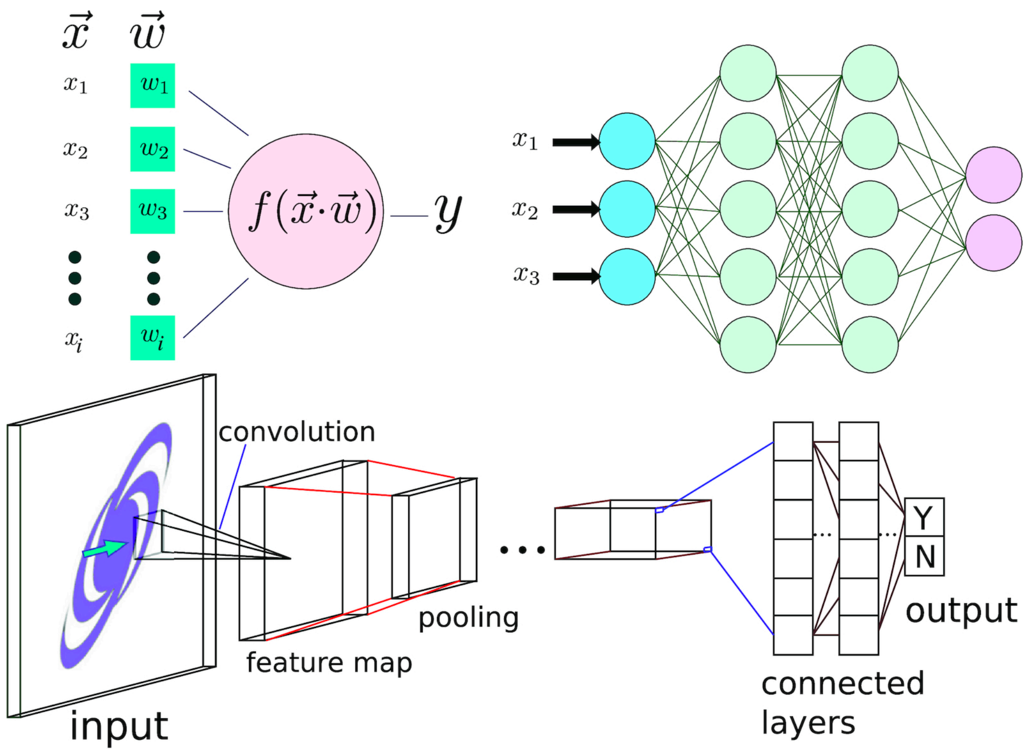
A classifier usually has a threshold parameter that when varied traces out a curve in this space.

The more area under the curve the better. The maximum is one since neither of these rates can be more than one.

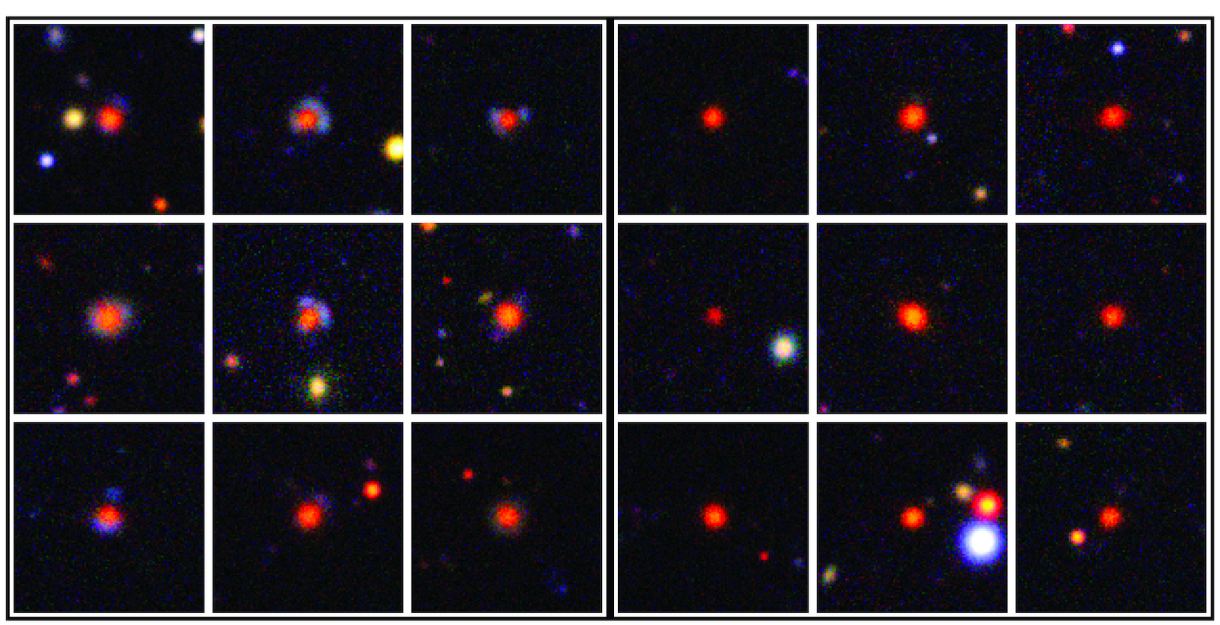


CONVOLUTIONAL NEURAL NETWORKS TO FIND STRONG LENSES

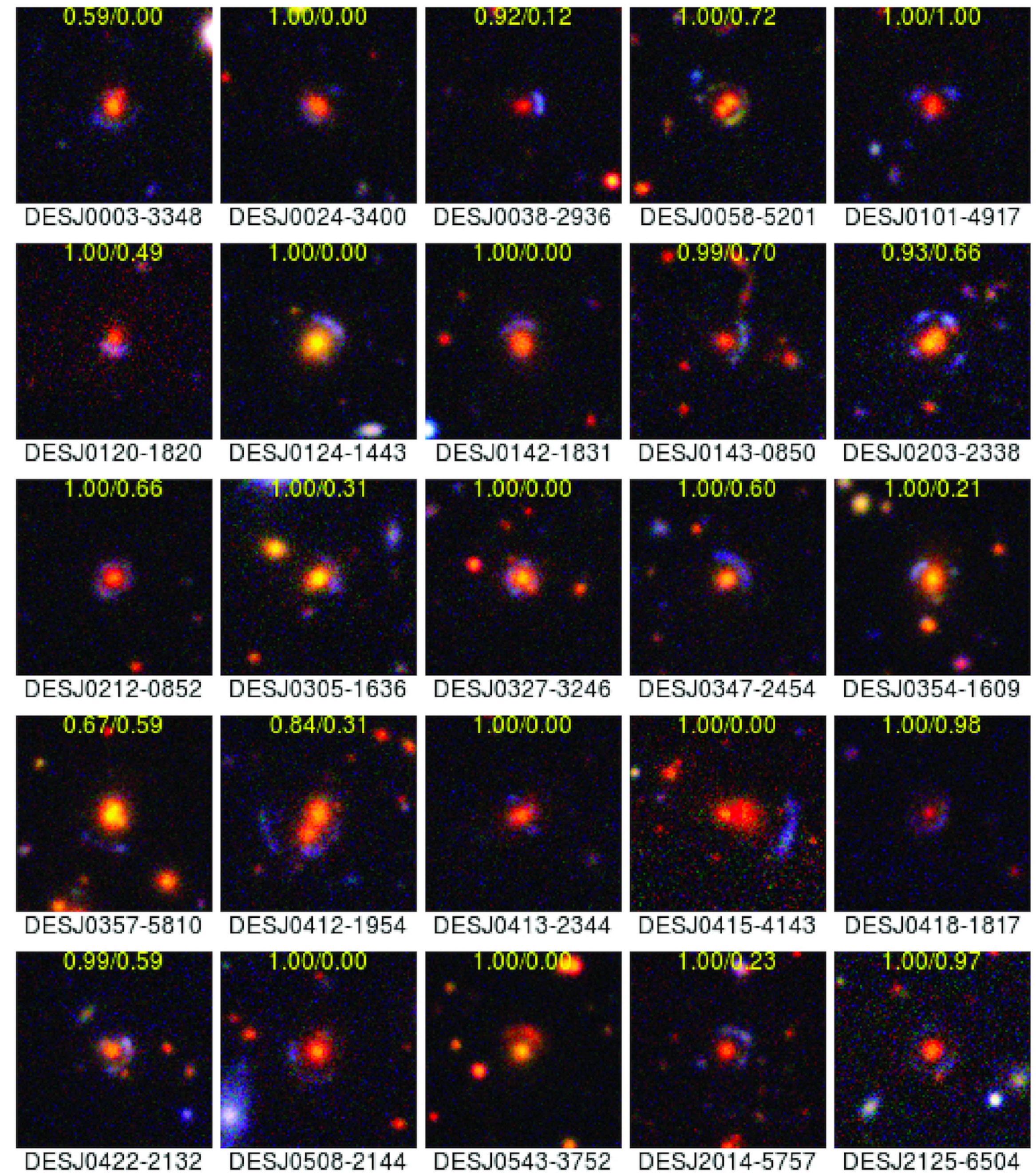
1) Choose a network architecture

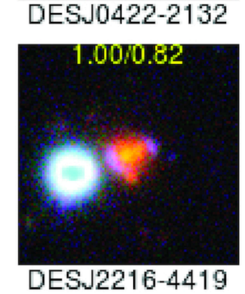


2) Training and validation with simulated lenses



3) Find the lenses:





Some DES lens candidates, Jacobs et al. 2019