GRAVITATIONAL LENSING

21 - STRONG LENSING SEARCHES
STRONG LENSING MODELING

Massimo Meneghetti

AA 2017-2018

LENS SURVEYS

- CFHT-LS
- Muscles
- Haggles
- Cosmos
- SWELLS
- **SLACS**
- **JVAS/CLASS**
- SLS-AEGIS
- OLS
- PANELS
- SOAR
- SGAS
- **Herschel-ATLAS**
- SDSS
- 2dF Lens Survey
- HST Snapshot Lens Survey
- FKS Lens Survey
- NOT Lens Survey
- APM Lens Survey
- MG Survey
- SARCS
- SBAS
- LoCUSS
- **CLASH**
- **Frontier Fields**

EXAMPLE 1: THE CLASS SURVEY (SOURCE ORIENTED)

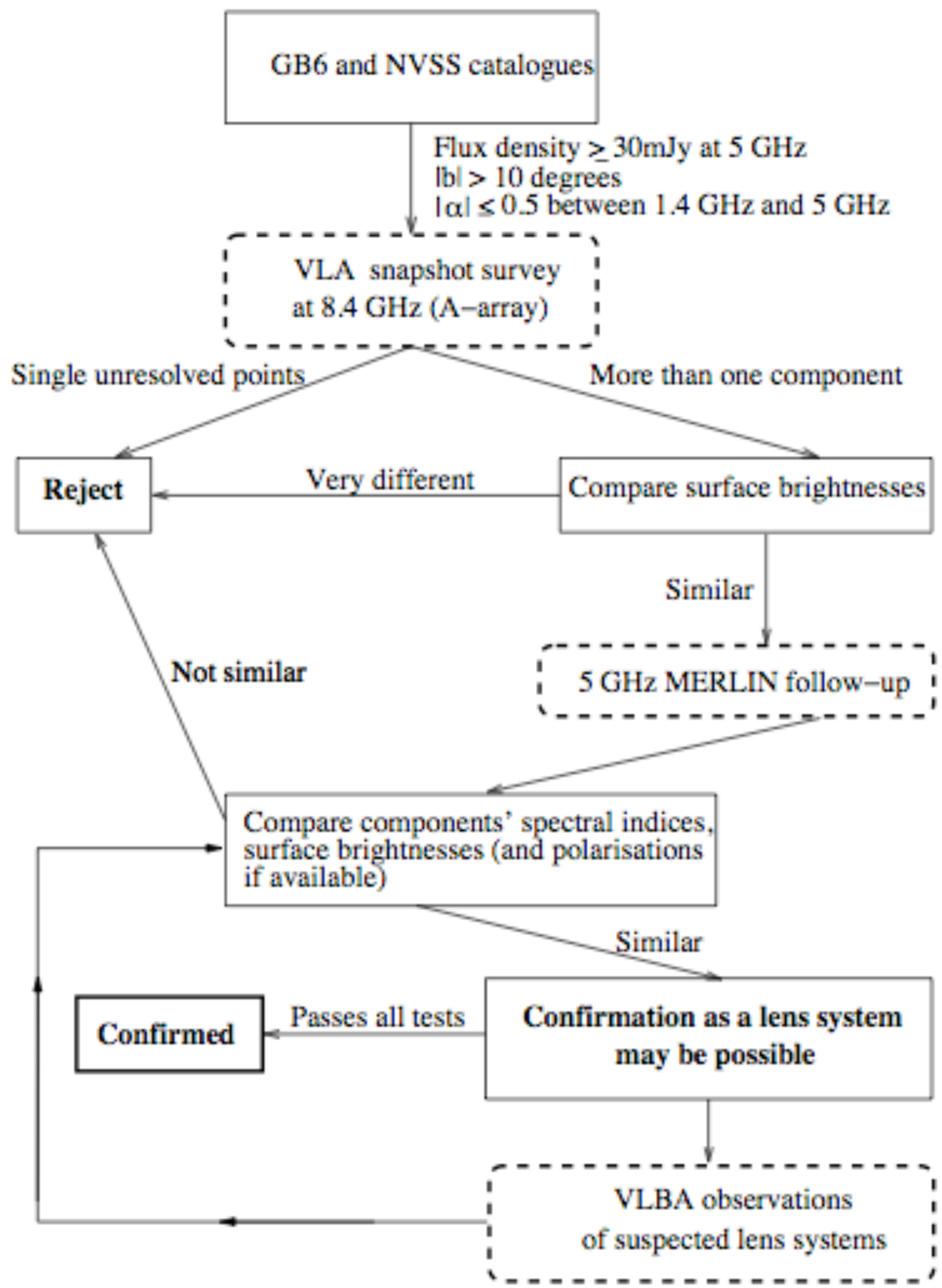
The CLASS (Cosmic Lens All-Sky Survey) was an international project (UK, USA, Netherlands) whose goal was searching for gravitational lenses in the radio domain.

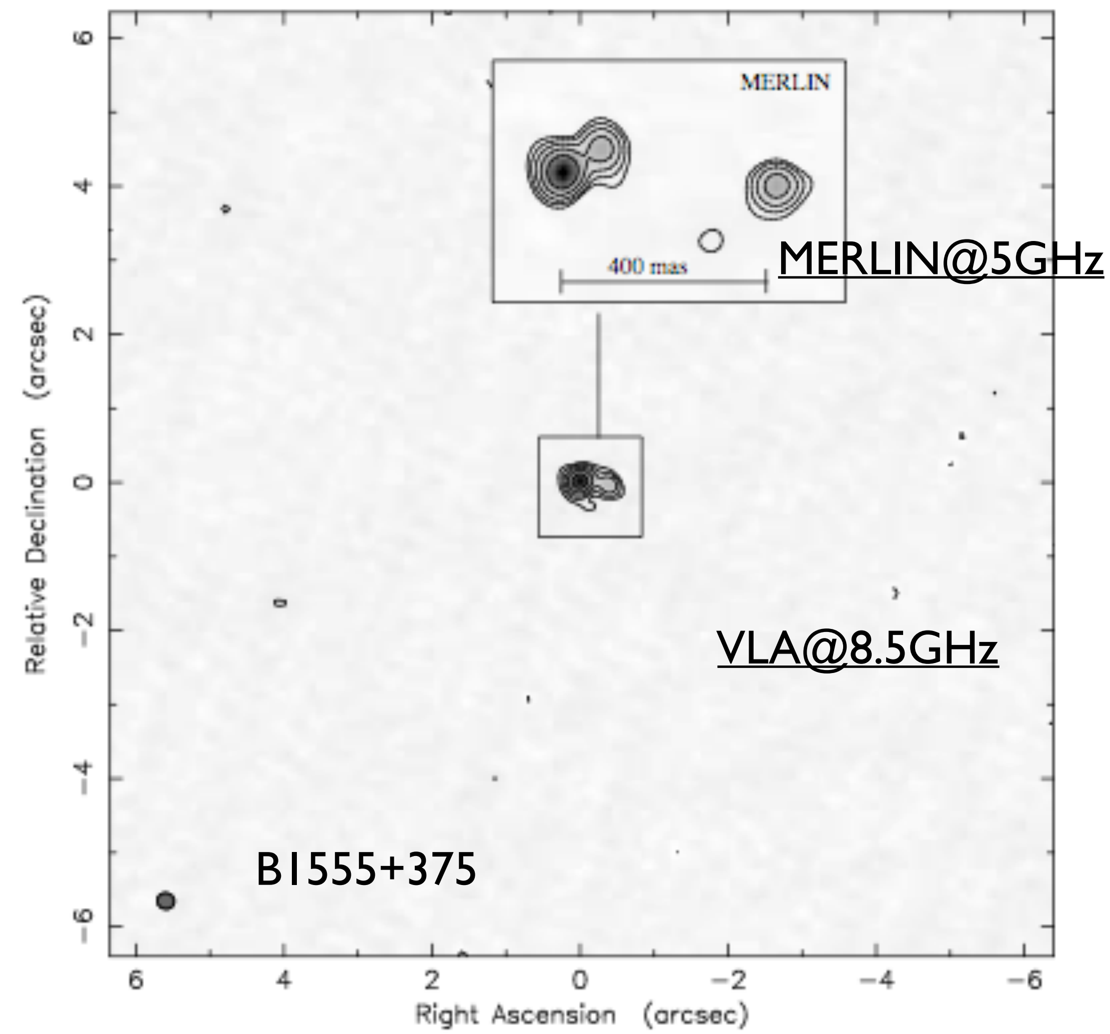
The survey was conducted between 1990 and 1999. During the survey 16503 flat-spectrum radio sources were monitored. Such objects are usually quasars and have very simple radio structures; they are typically point sources, and occasionally weak extended emission is visible. The point-like radio emission 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).

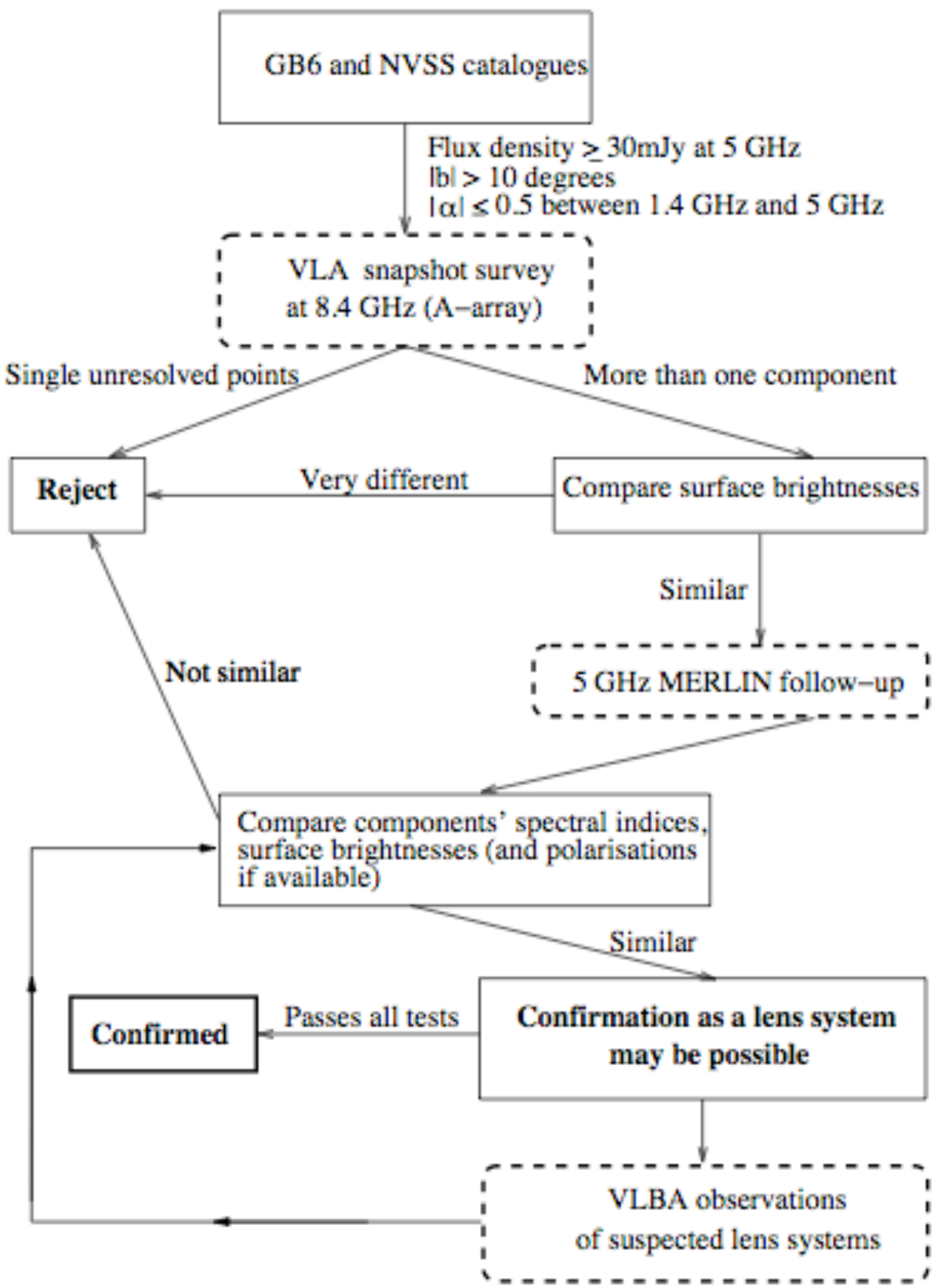
CLASS STRATEGY

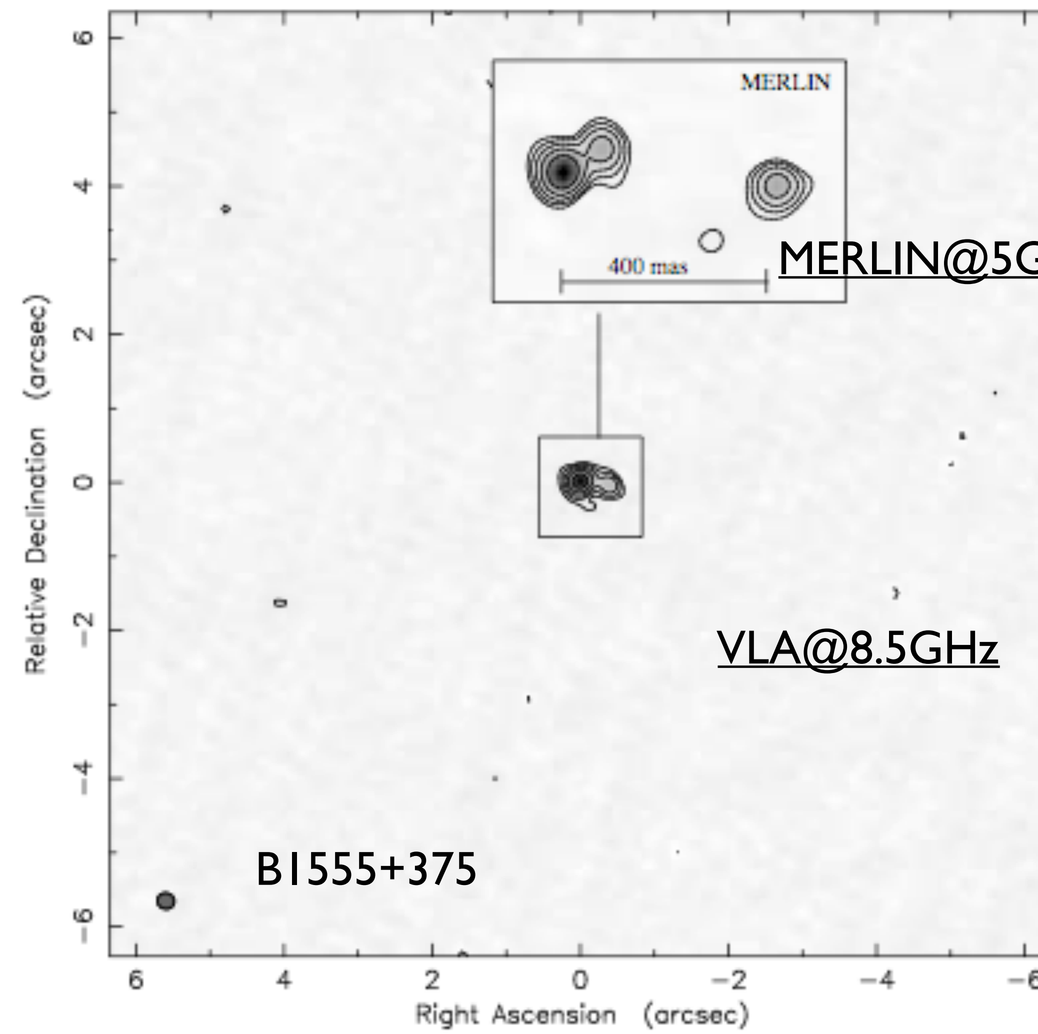




Browne et al. 2002

CLASS STRATEGY



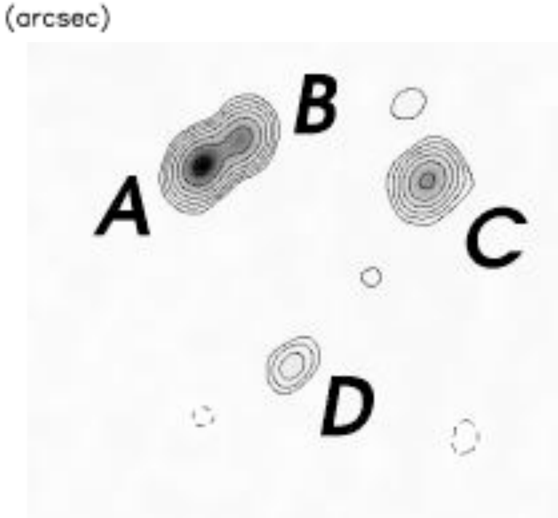


MERLIN@5GHz

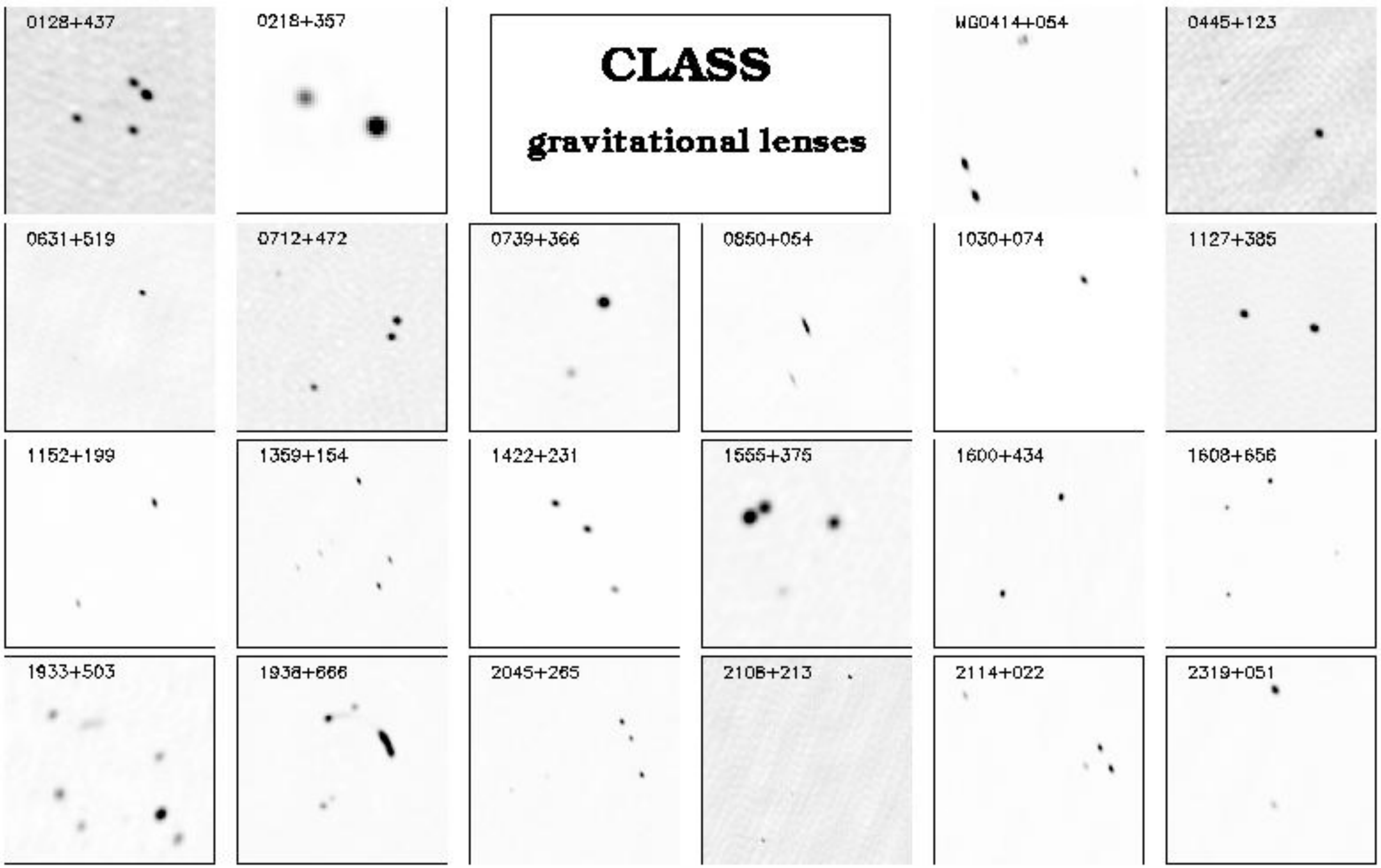
VLA@8.5GHz

B1555+375

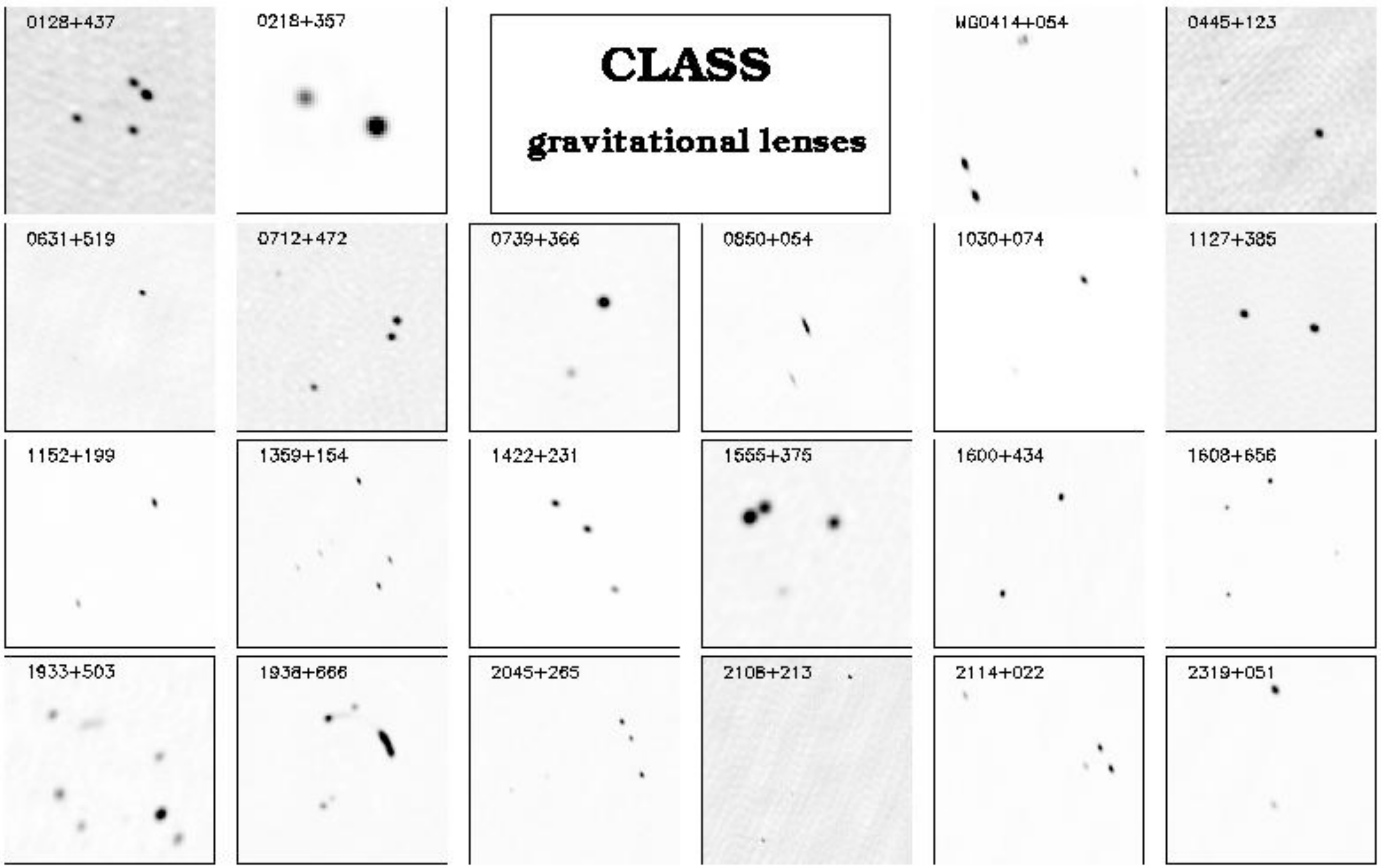
Browne et al. 2002



CLASS LENSES

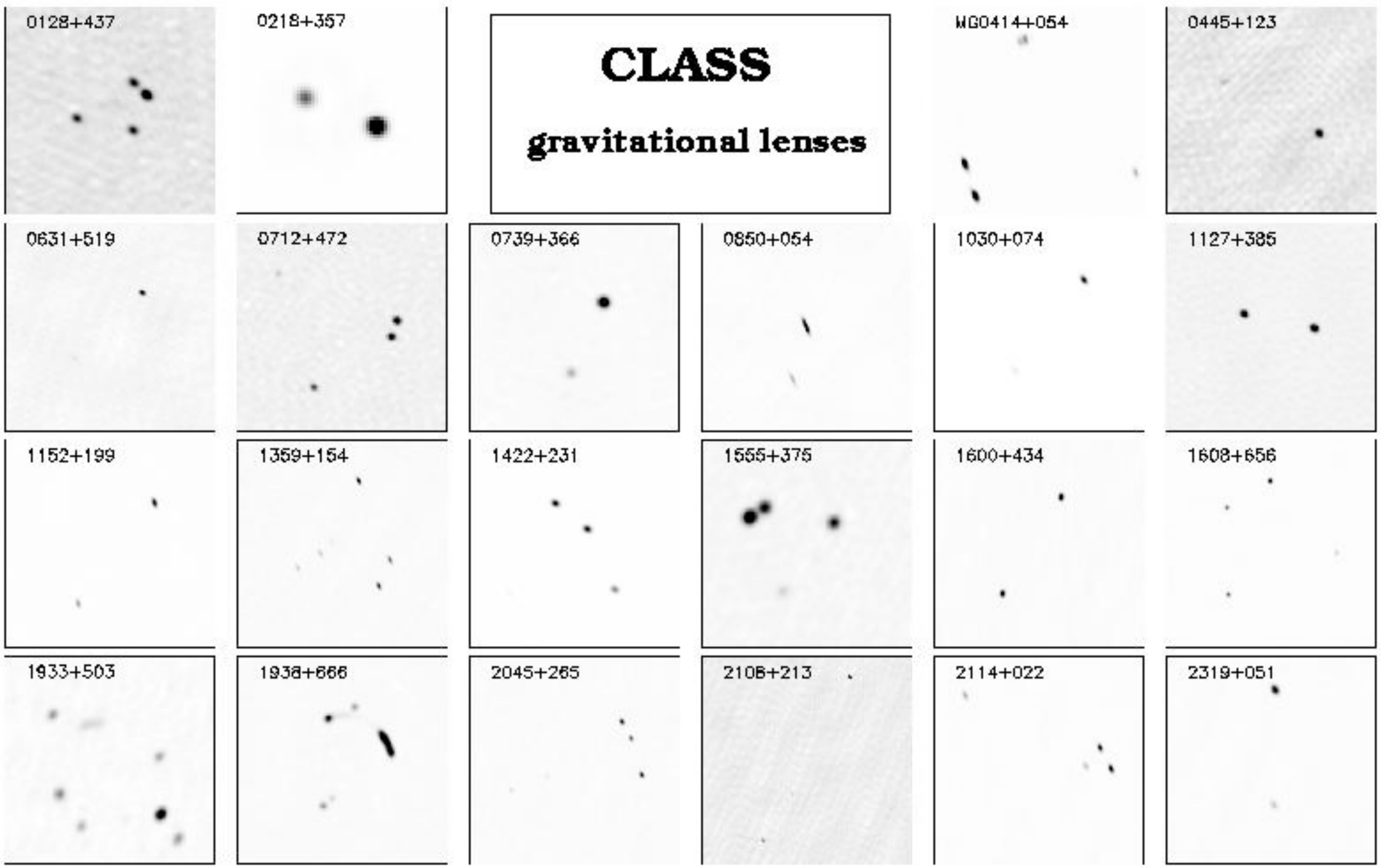


CLASS LENSES



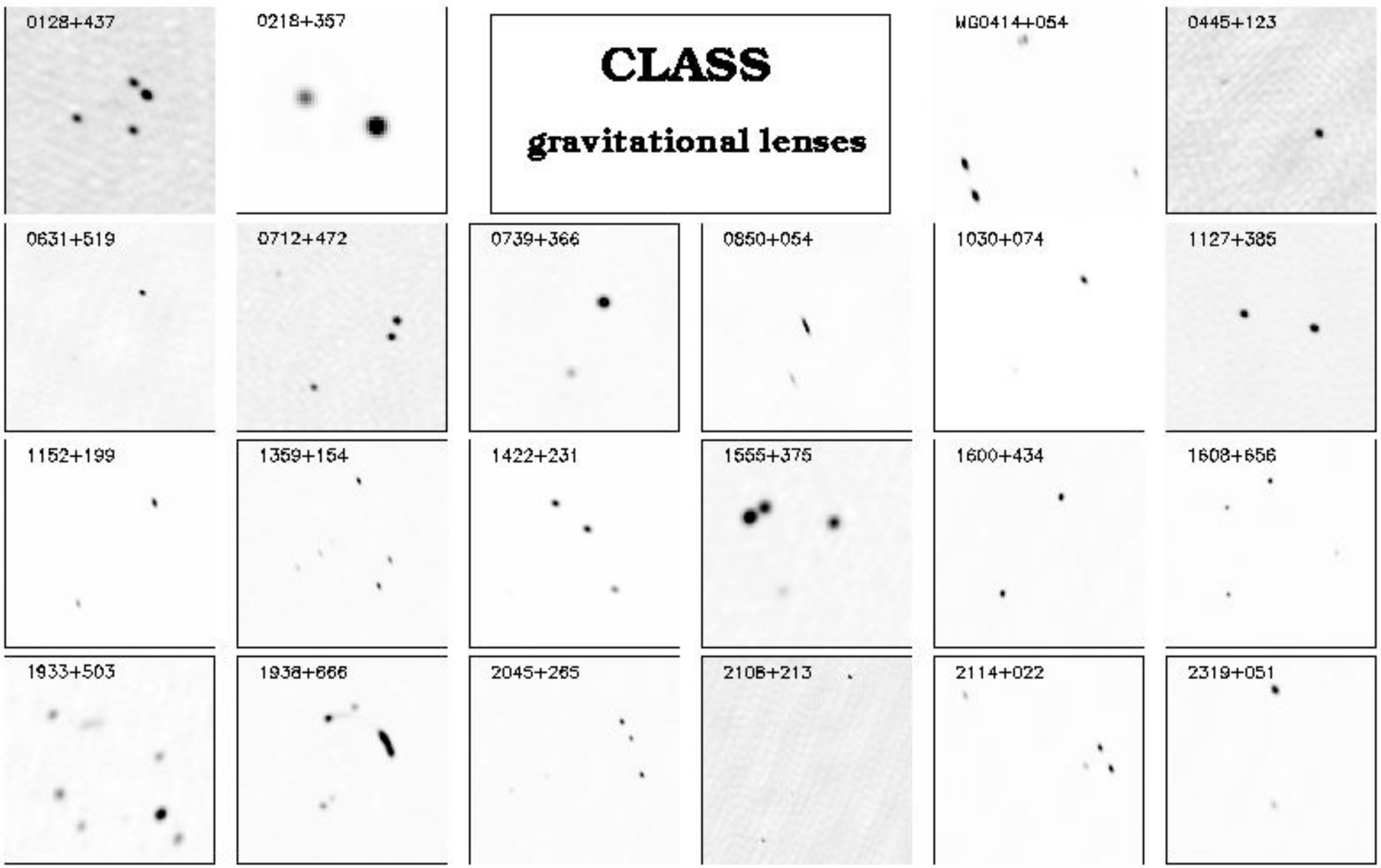
12 double

CLASS LENSES



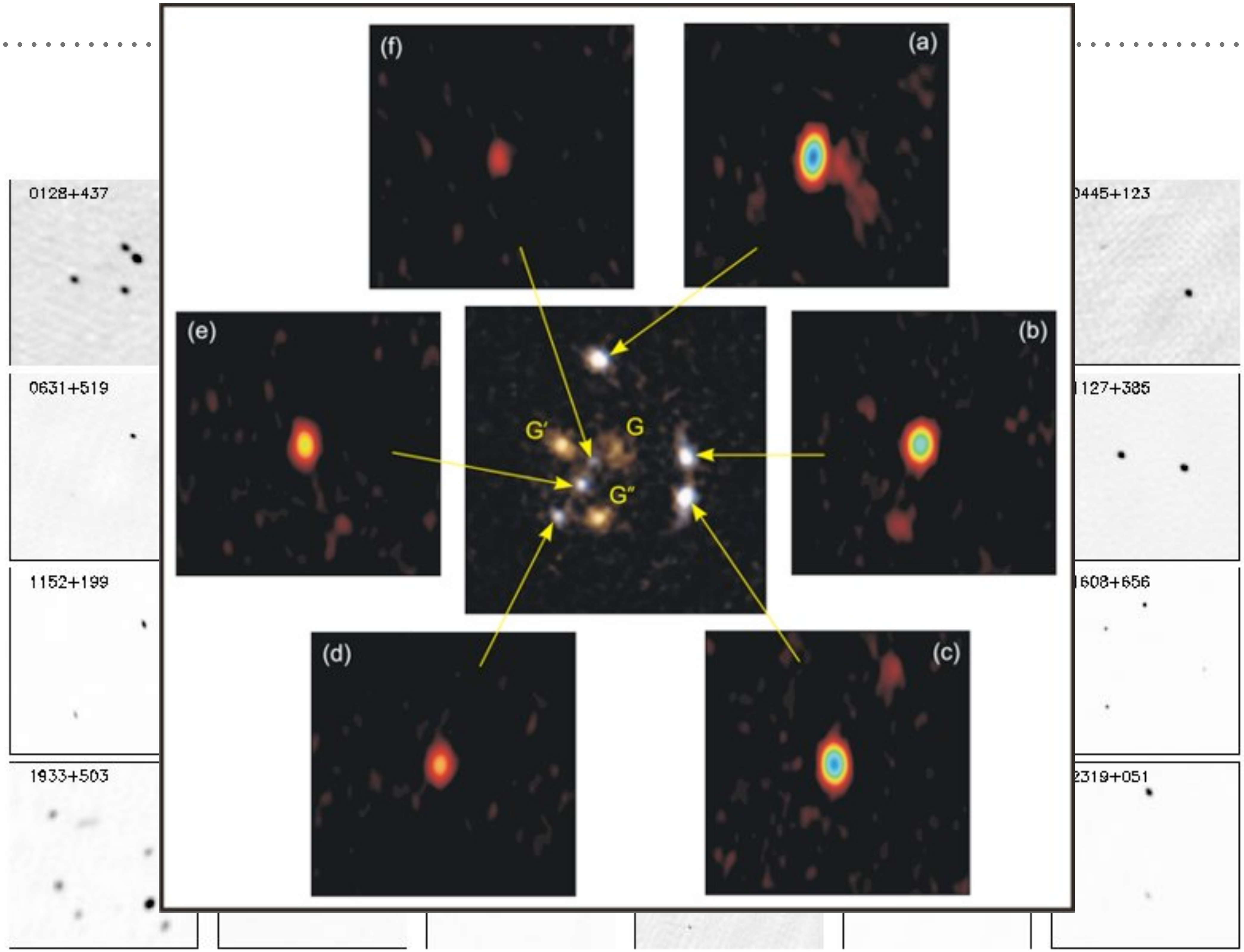
12 double 9 quadruple

CLASS LENSES



12 double 9 quadruple 1 sextuple

CLASS LENSES

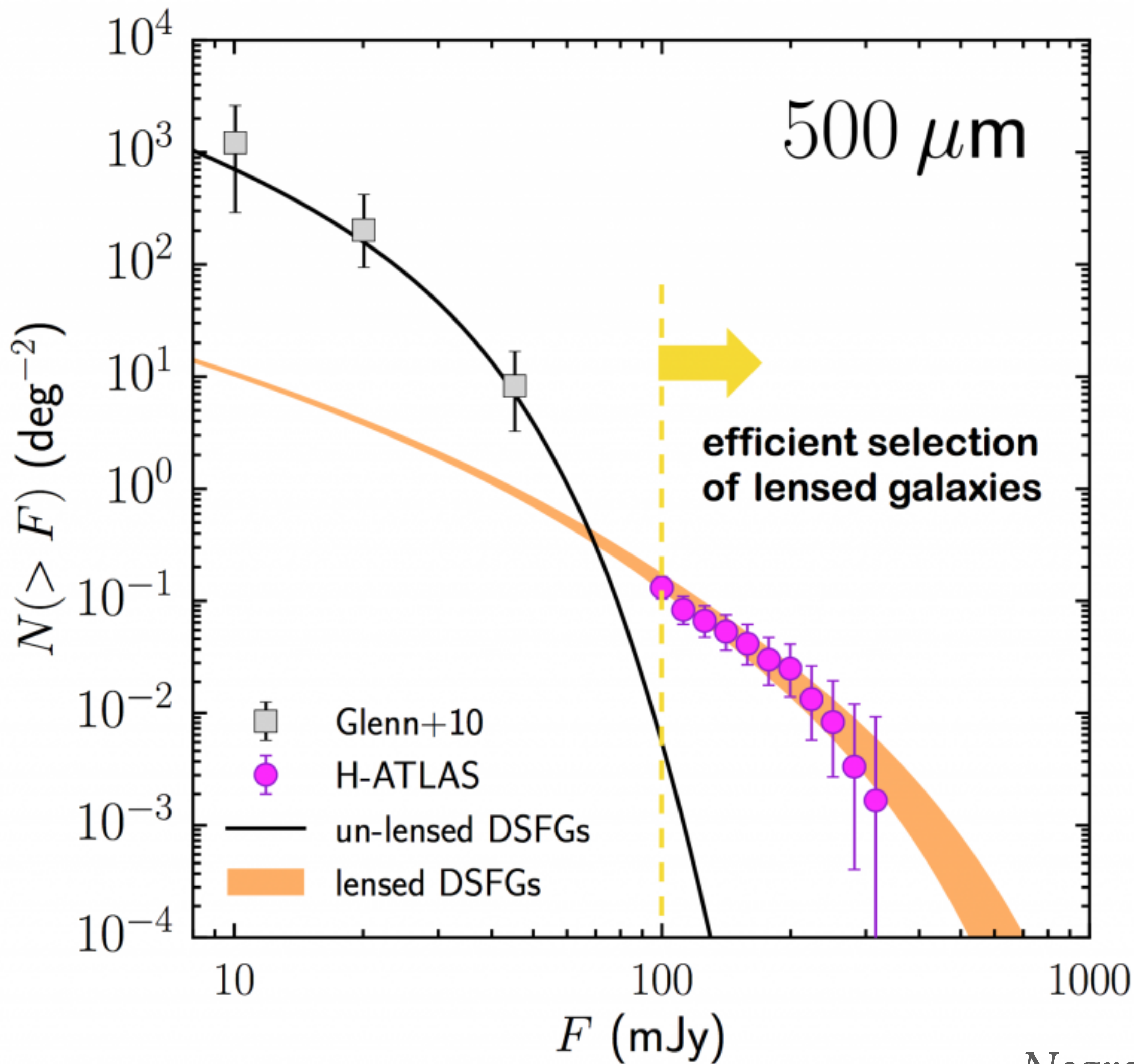


12 double

9 quadruple

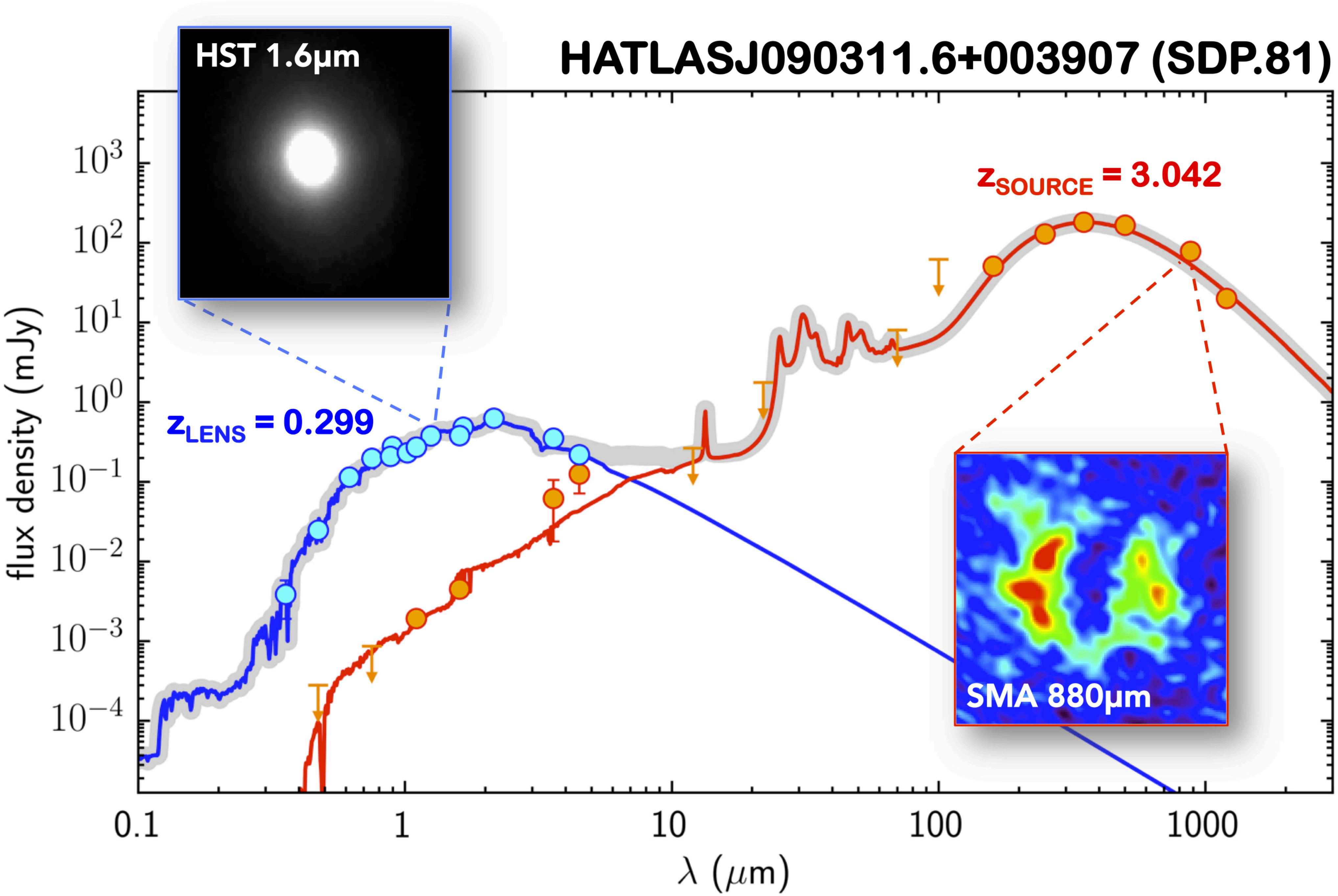
1 sextuple

SEARCHES AT THE SUB-MM WAVELENGTHS

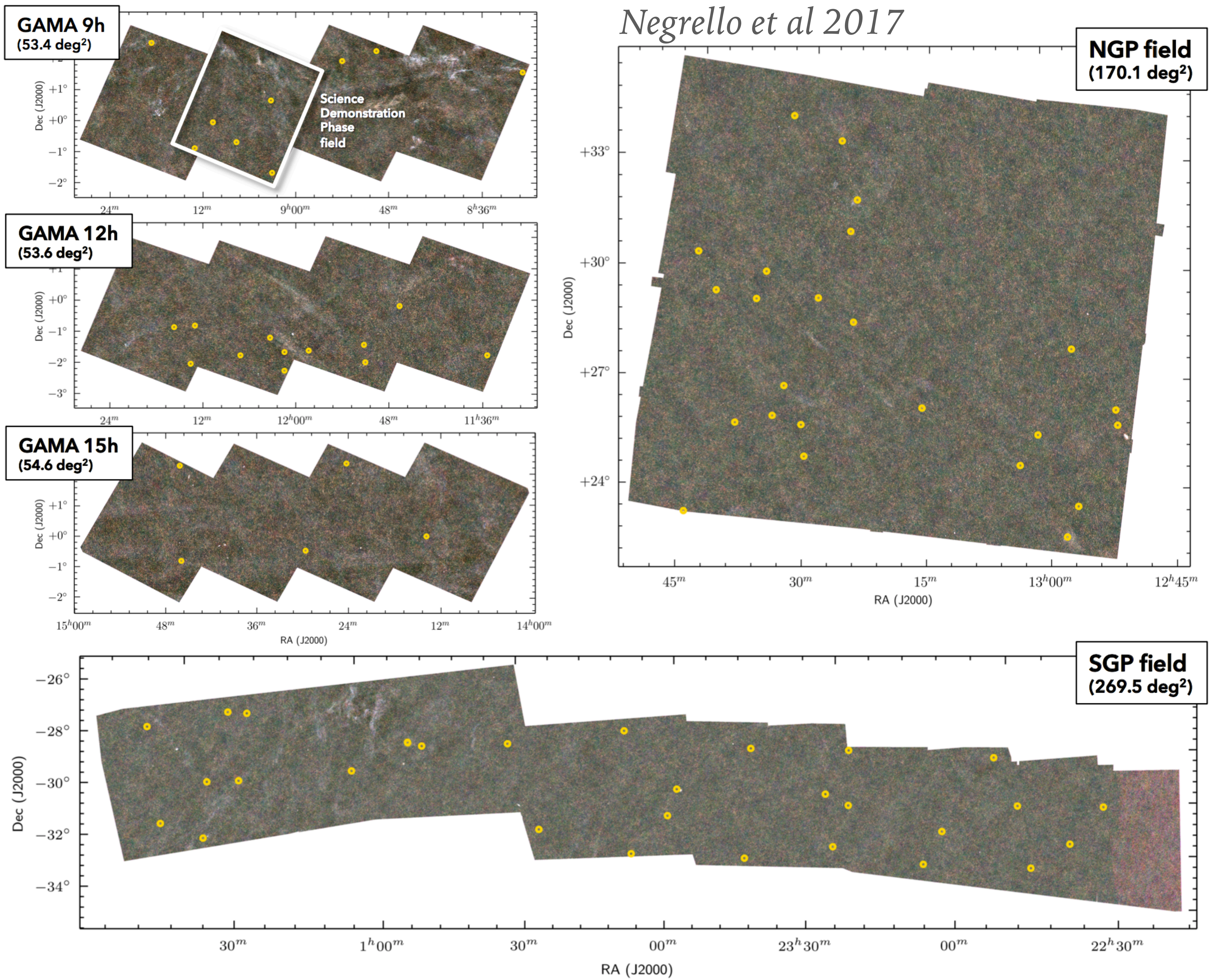


Negrello et al. 2010

SEARCHES AT THE SUB-MM WAVELENGTHS



Negrello et al. 2010



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

SLACS (OPTICAL)

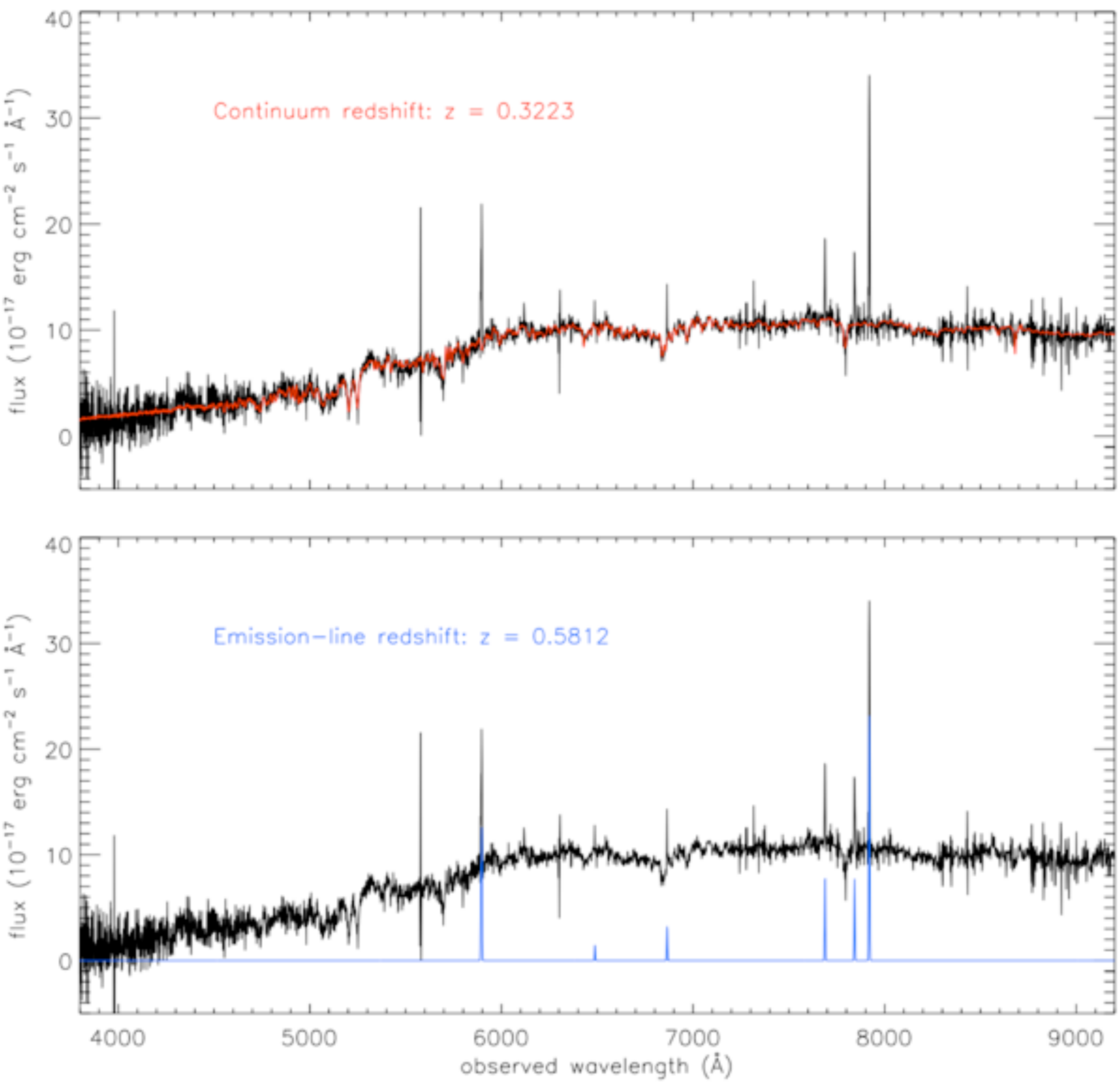
The SLACS (Sloan Lens ACS survey, Bolton et al. 2006) is a very successful project whose goal was finding strongly lensed galaxies behind SLOAN selected galaxies.

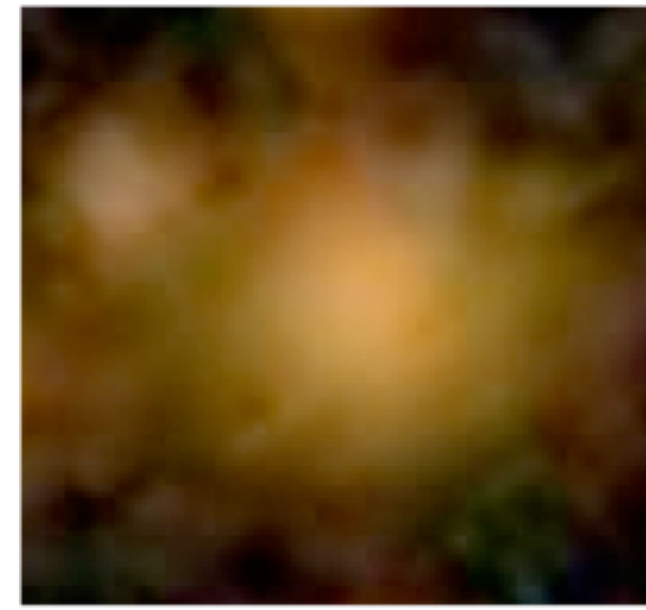
The candidate lenses are selected from the spectroscopic database of the Sloan Digital Sky Survey. This survey has produced imaging and spectra for galaxies on a huge portion of the sky (8400 sq. degree). The observations were conducted between 2000-2005 (SDSS-I) and 2005-2009 (SDSS-II) using a dedicated 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)

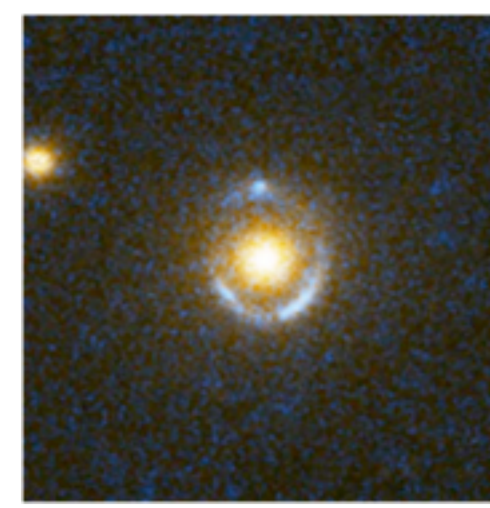
The selected candidates are observed at high-resolution with the ACS onboard HST.

SLACS STRATEGY



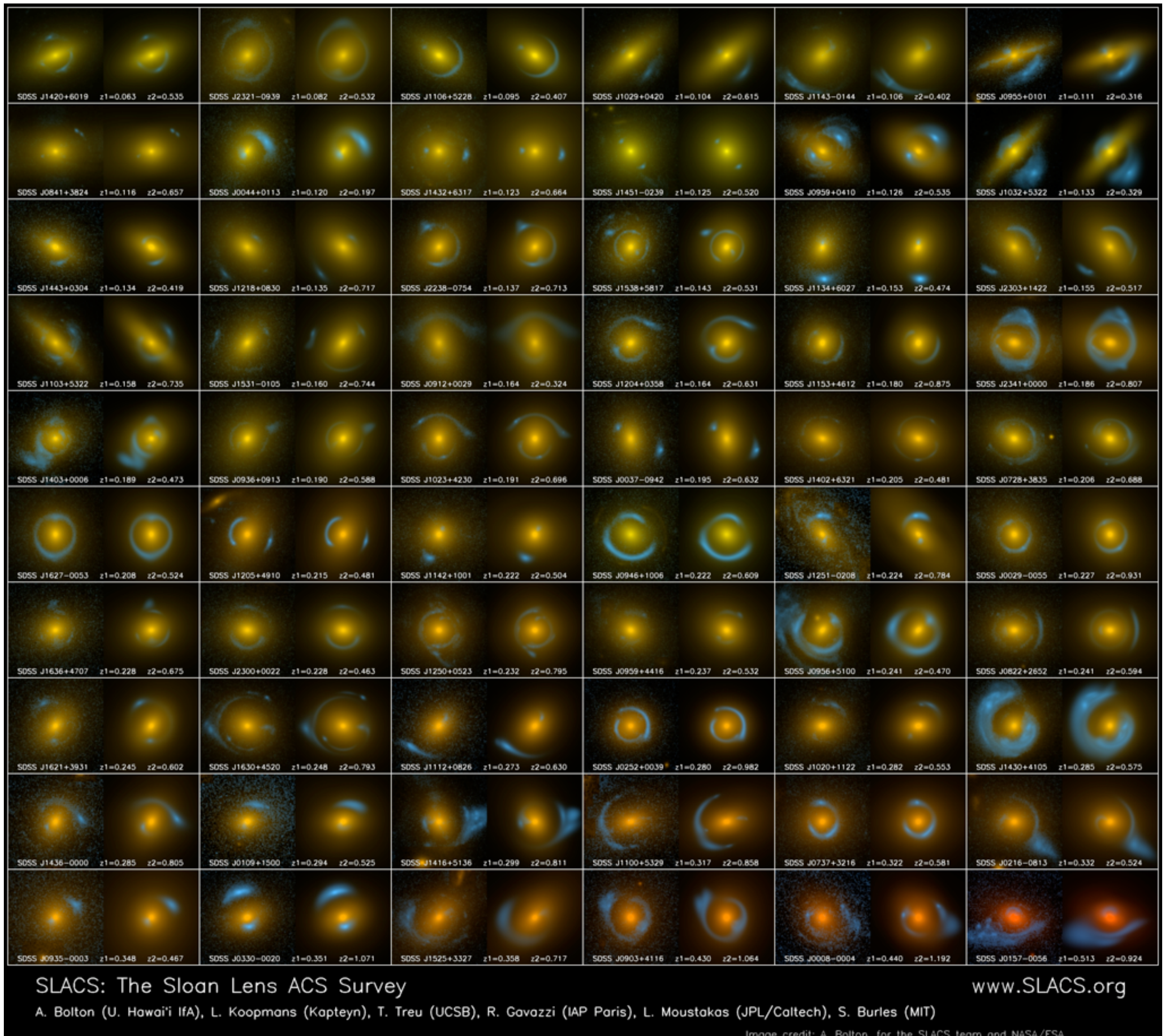


SLOAN image



HST follow-up

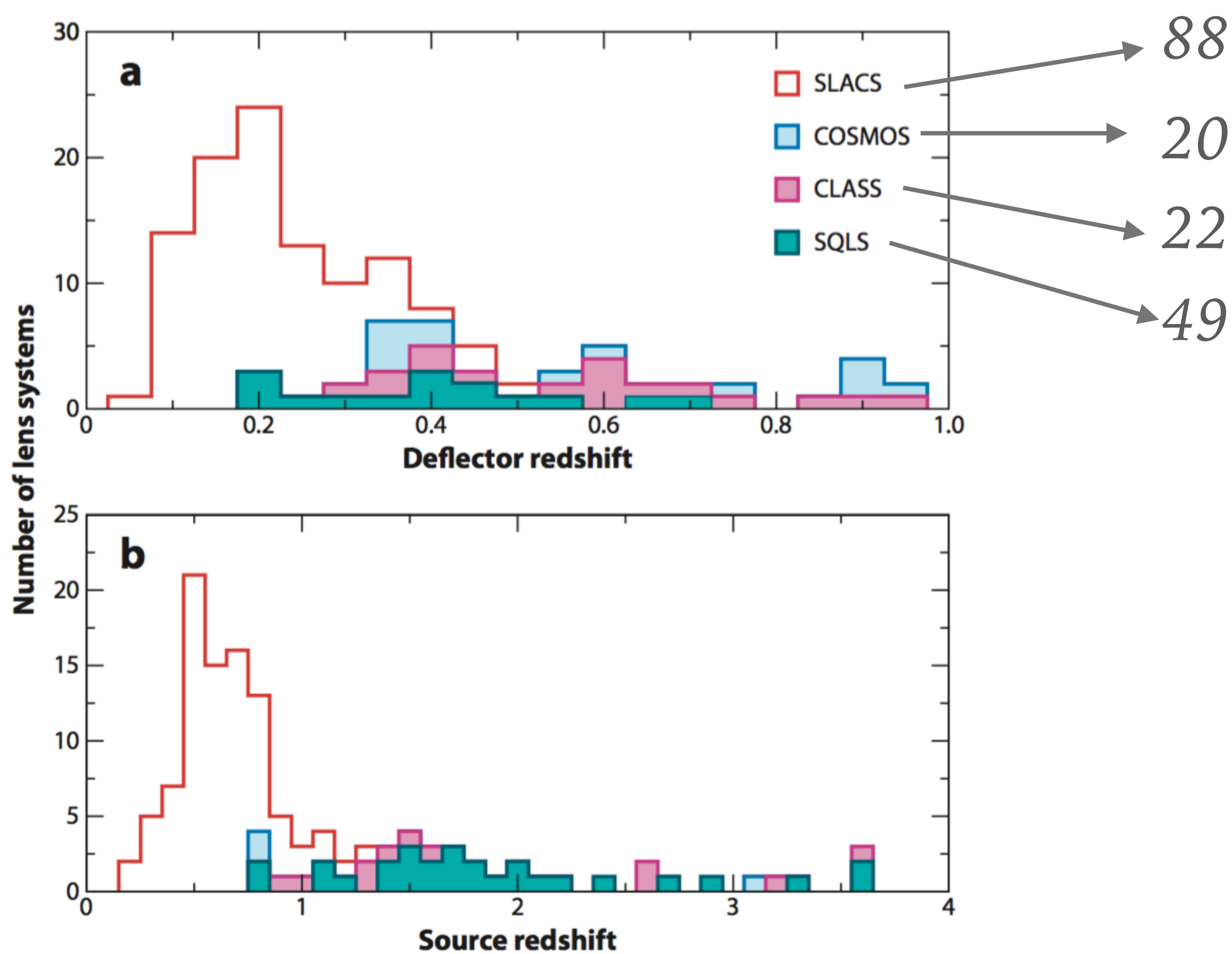
SLACS LENSES



- 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)

CURRENT STATE OF THE ART

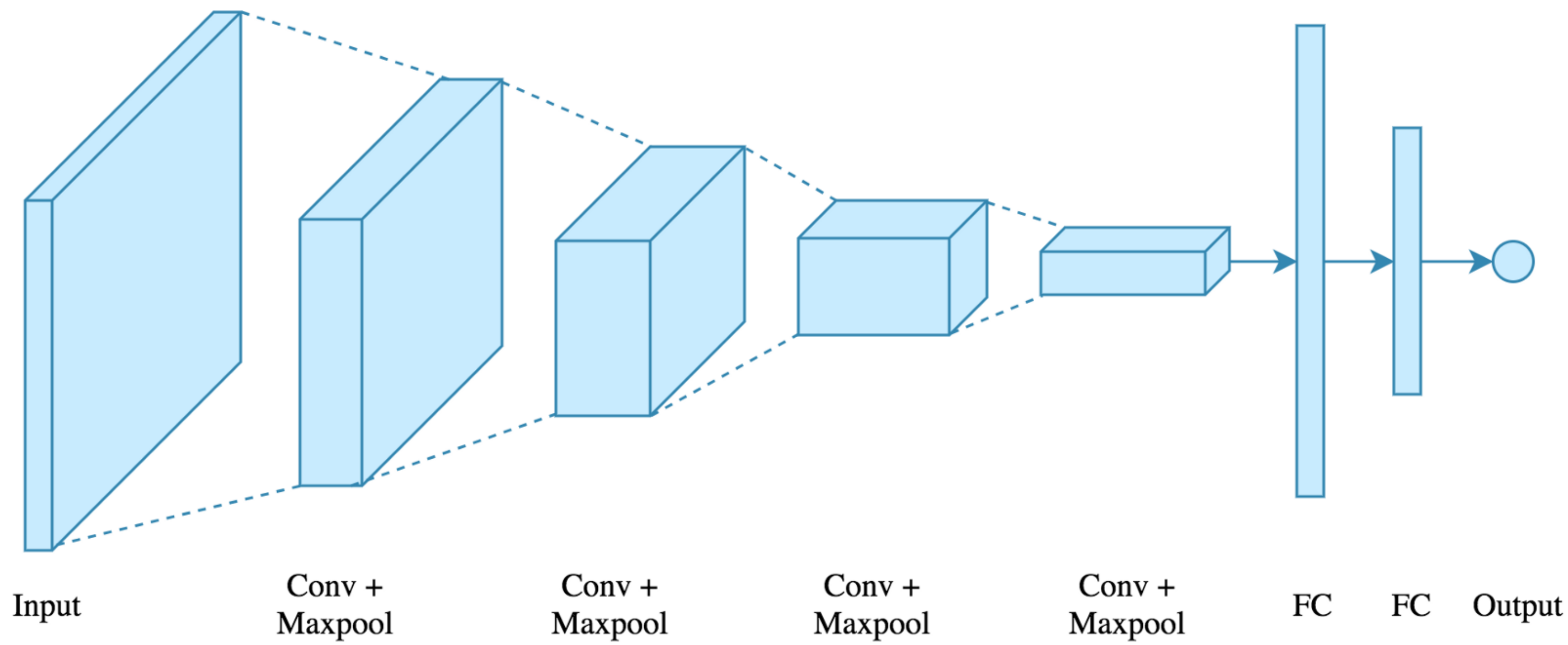
- ~300 galaxy strong lenses (secure; source www.masterlens.org)
- ~80 galaxy clusters (mainly found by visually inspecting ground based imaging data or HST WFC2/ACS/WFC3 images)



WE ENTERED A NEW ERA: AUTOMATED SEARCHES FOR LENSES

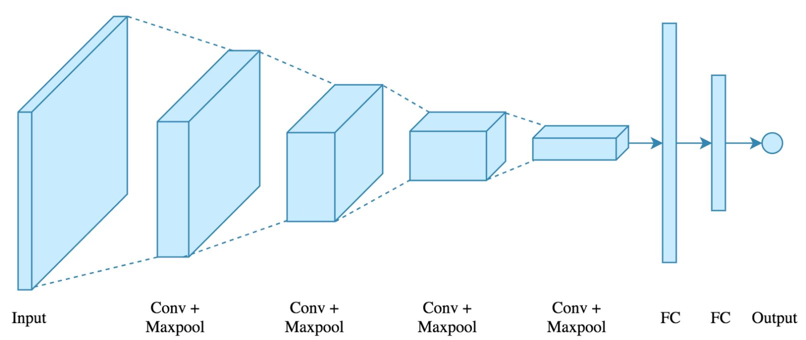
- Recently, some imaging surveys begun covering large areas of the sky with good depth and good spatial resolution
- These surveys were proposed manly as cosmological experiments employing weak lensing
- However, the data are of good quality also to exploit strong lensing
- The strategy had to be changed: large areas, big depth, large number of potential lenses, making difficult the lens identification in the usual way
- The idea of “automated detection” took place

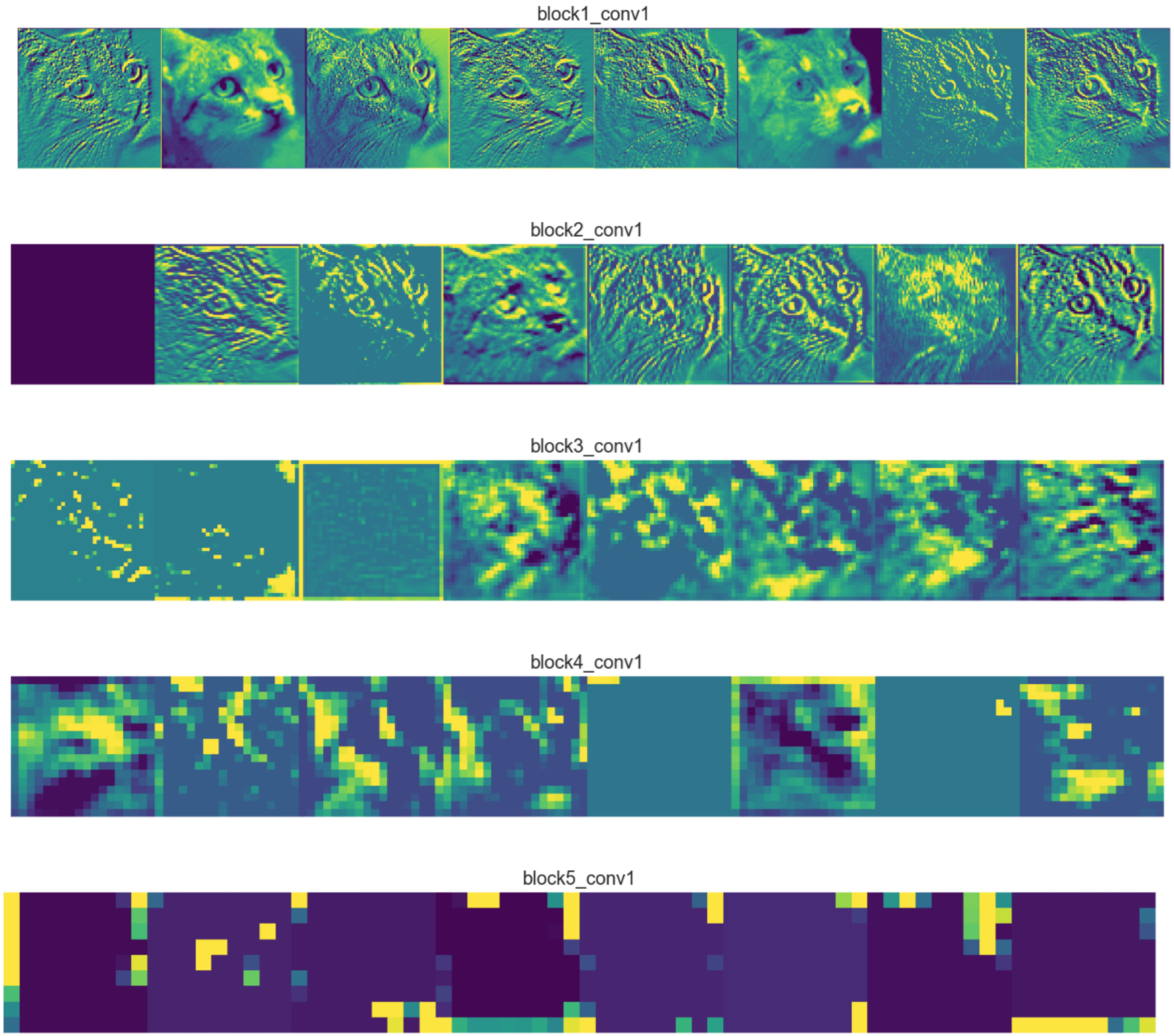
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)



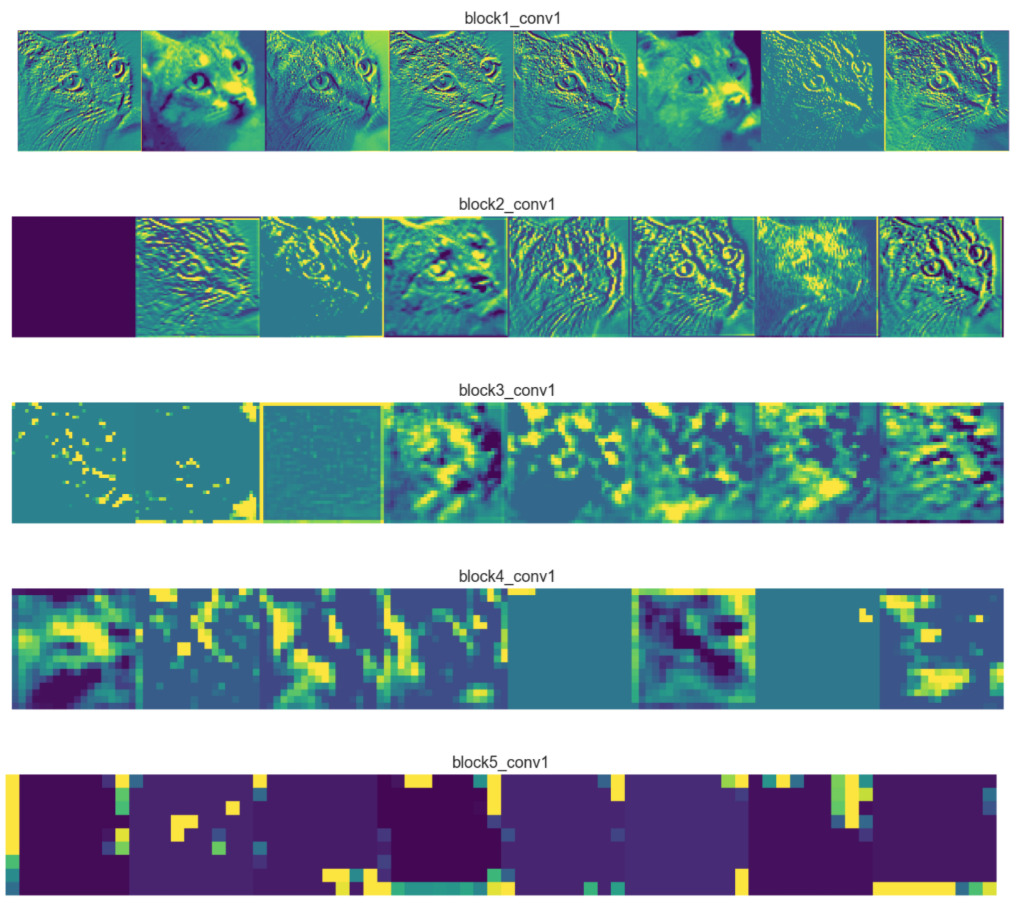
https://towardsdatascience.com/applied-deep-learning-part-4-convolutional-neural-networks-584bc134c1e2

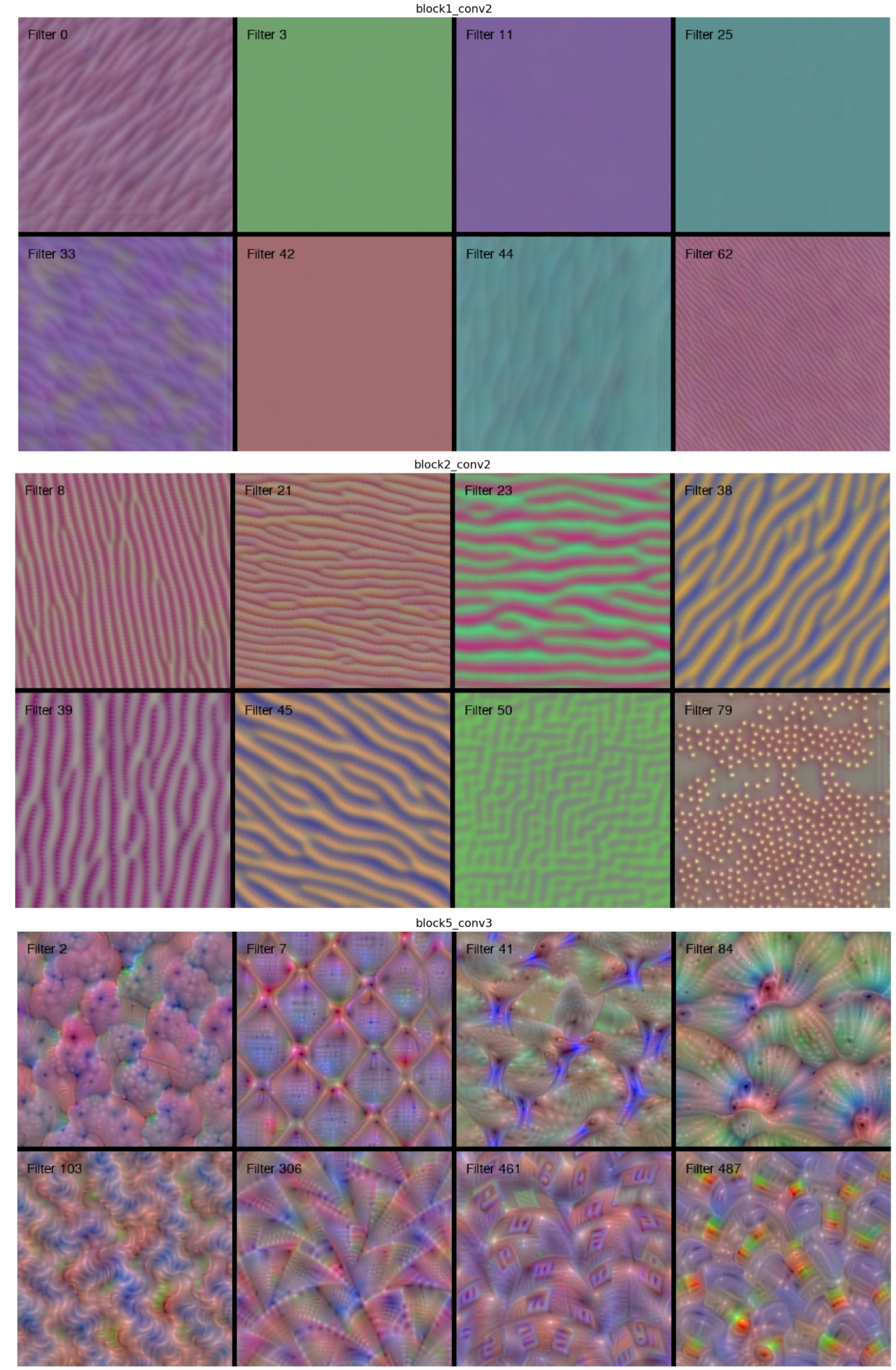
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)





CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)

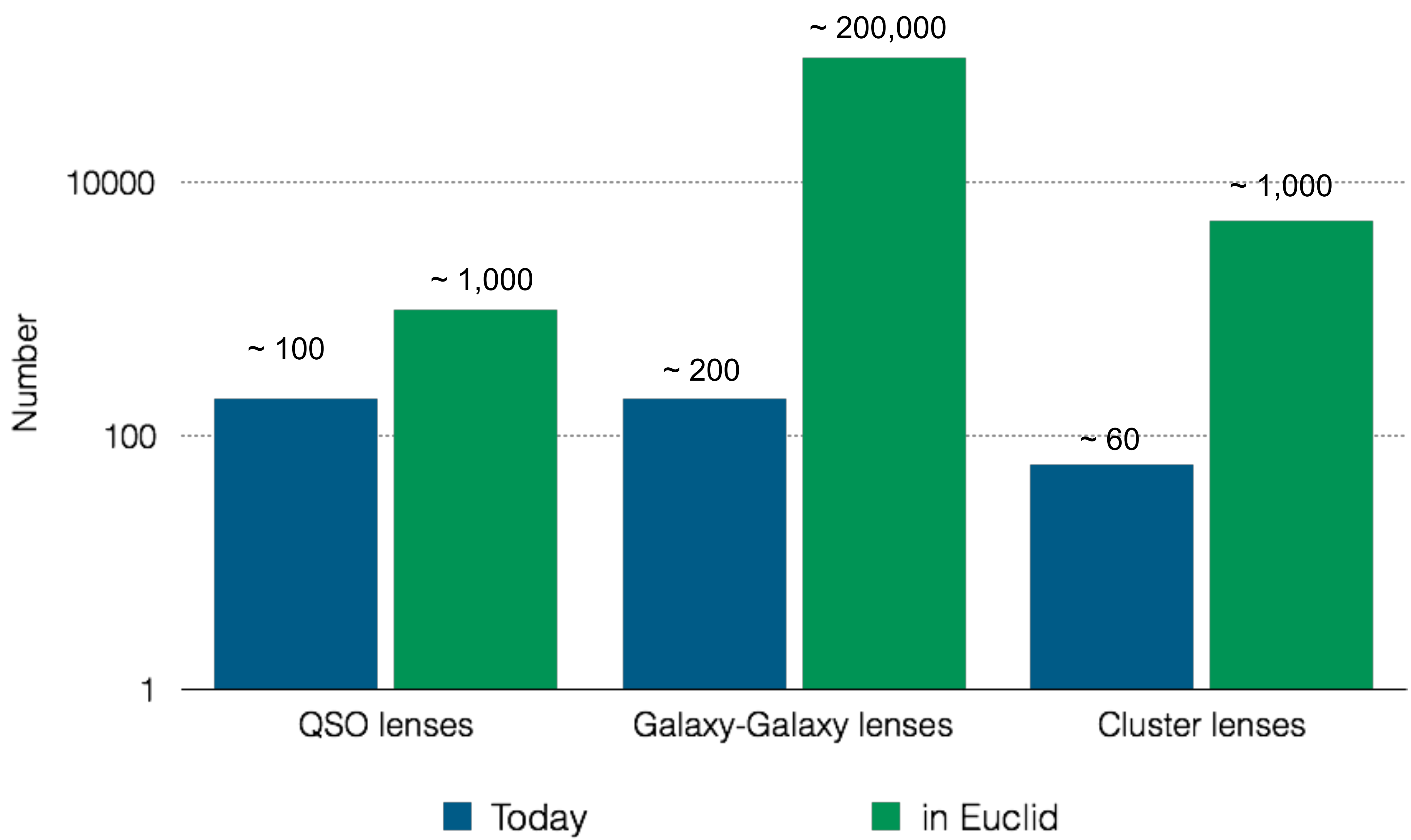


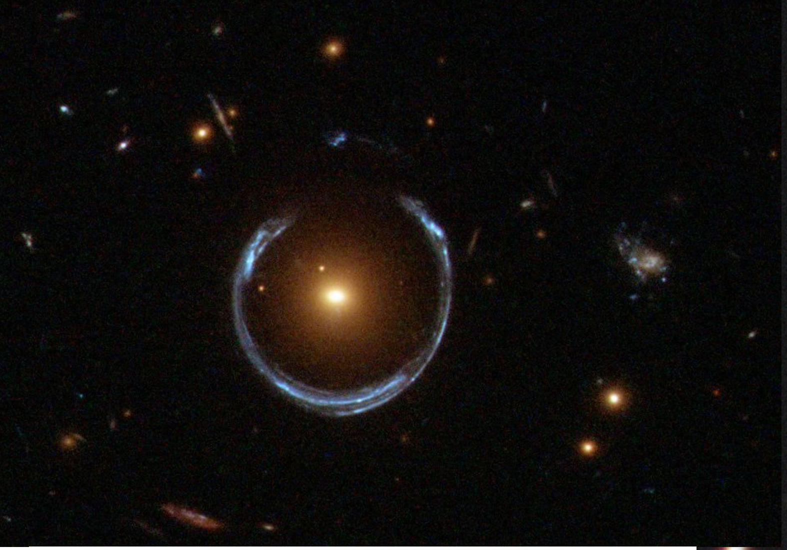


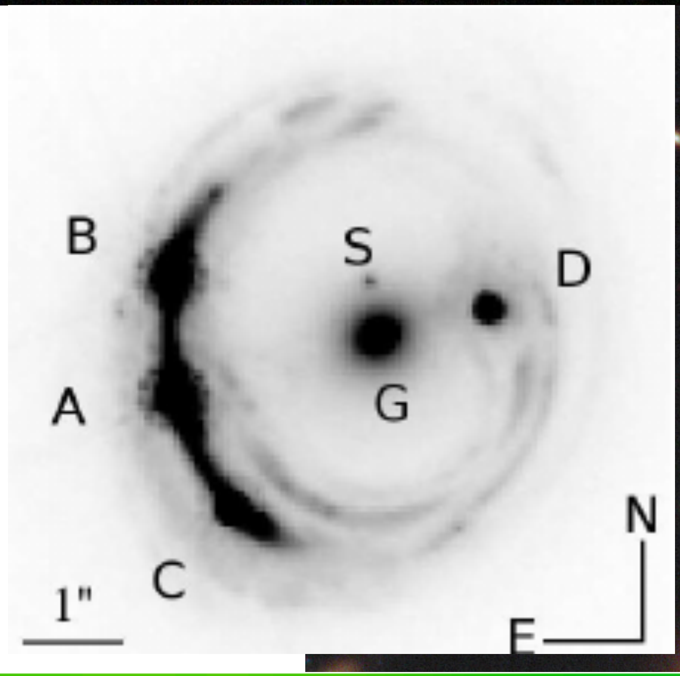
CONVOLUTIONAL NEURAL NETWORKS (AND THEIR VARIANTS)

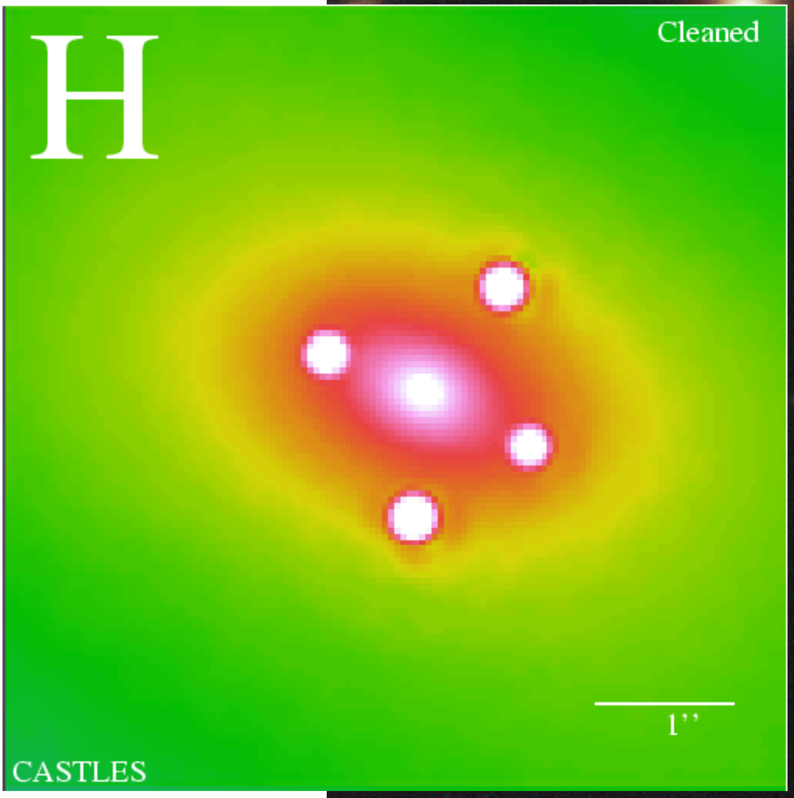
- Filters and weights are “learned” by the networks, using a process called “supervised learning”
- The network is initialized with random numbers and fed with examples (images with known classification)
- During the training phase, the weights and the filters adjust their value/shapes to obtain the correct classification of the given examples
- In a subsequent phase, one has to verify that the method works on a test sample
- Finally, the method can be applied to any image with unknown classification

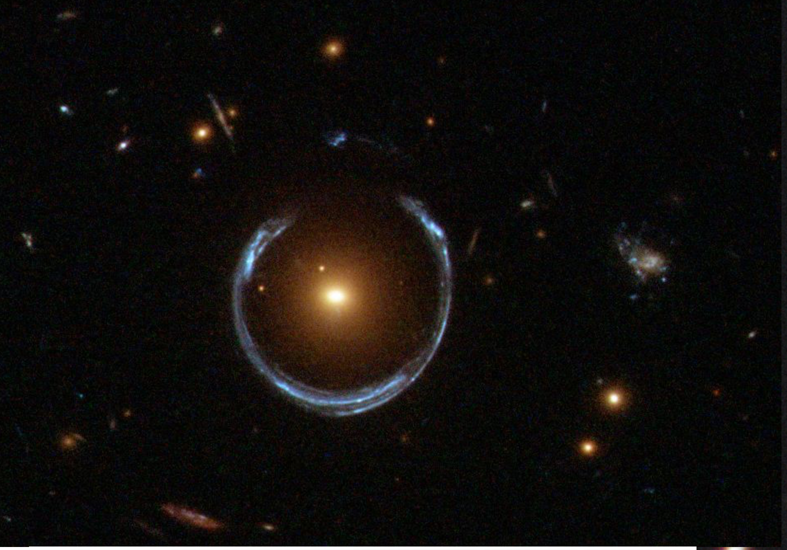
THE FUTURE OF GRAVITATIONAL LENSING: LSST AND EUCLID

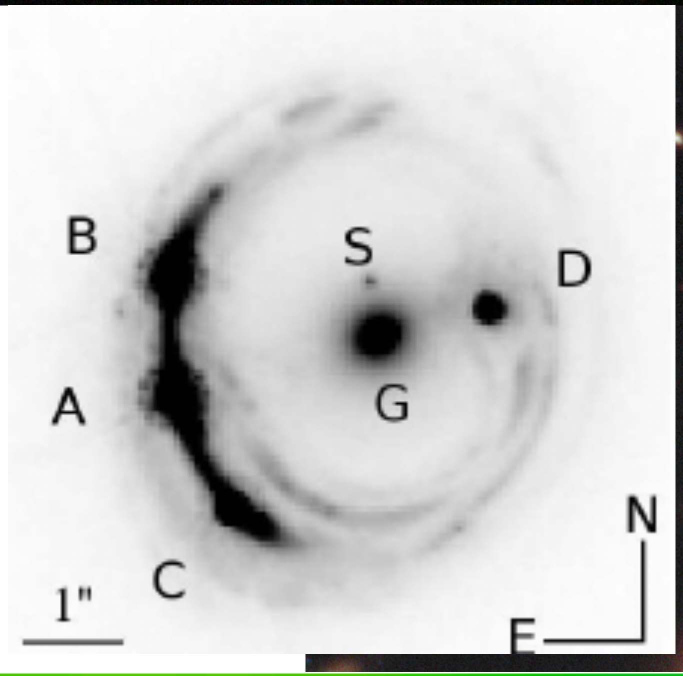


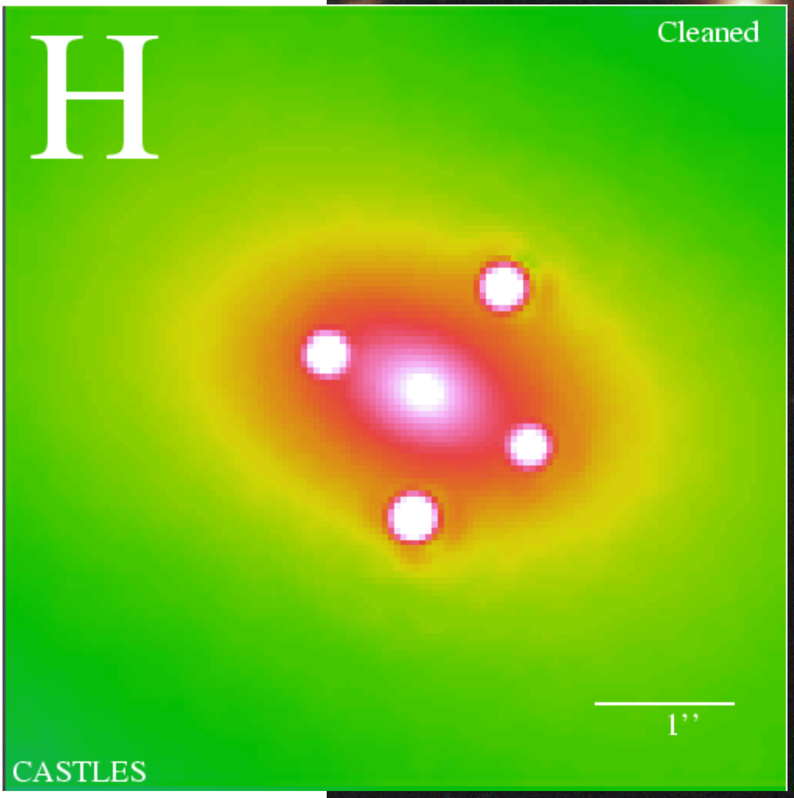


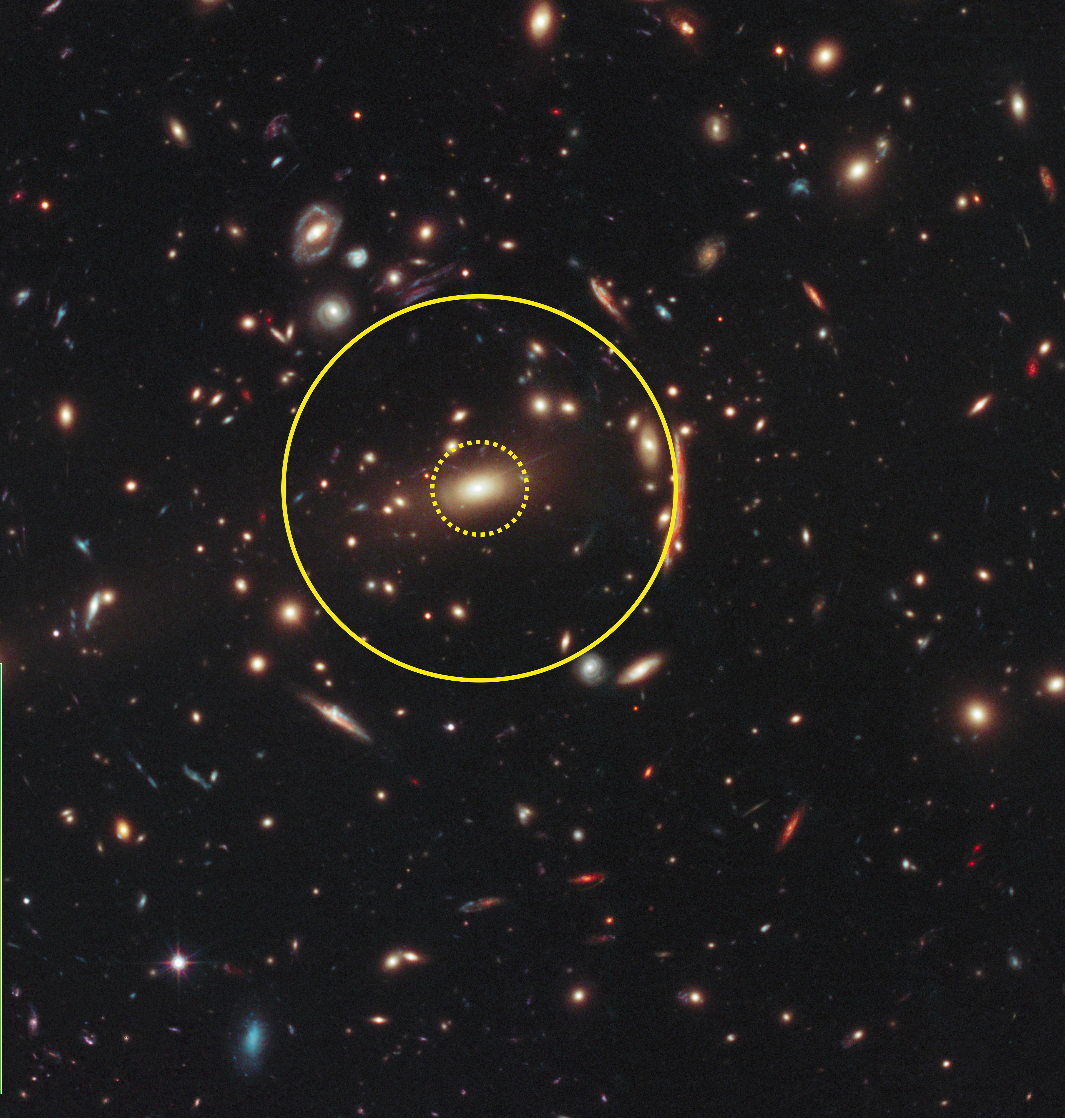

B
S
D
A
G
C
N
E
1"

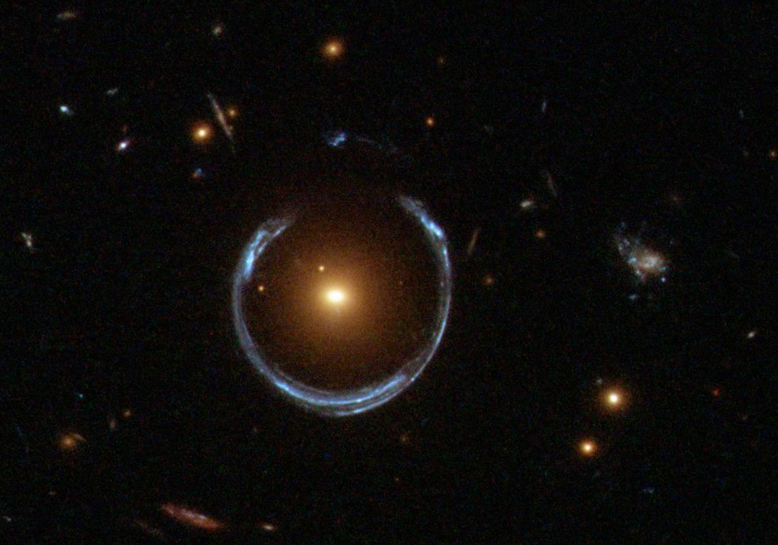

H
Cleaned
1''
CASTLES

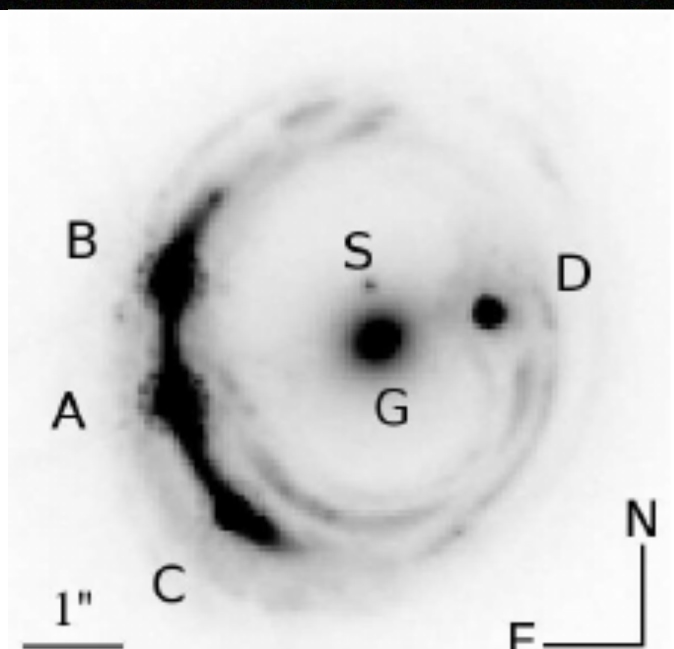


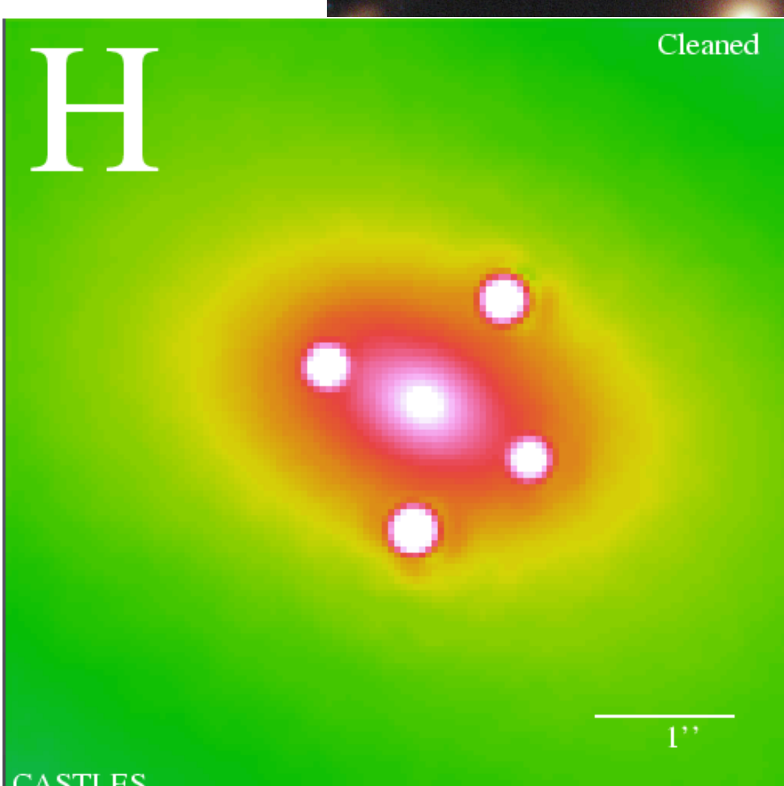

B
S
D
A
G
C
N
E
1"

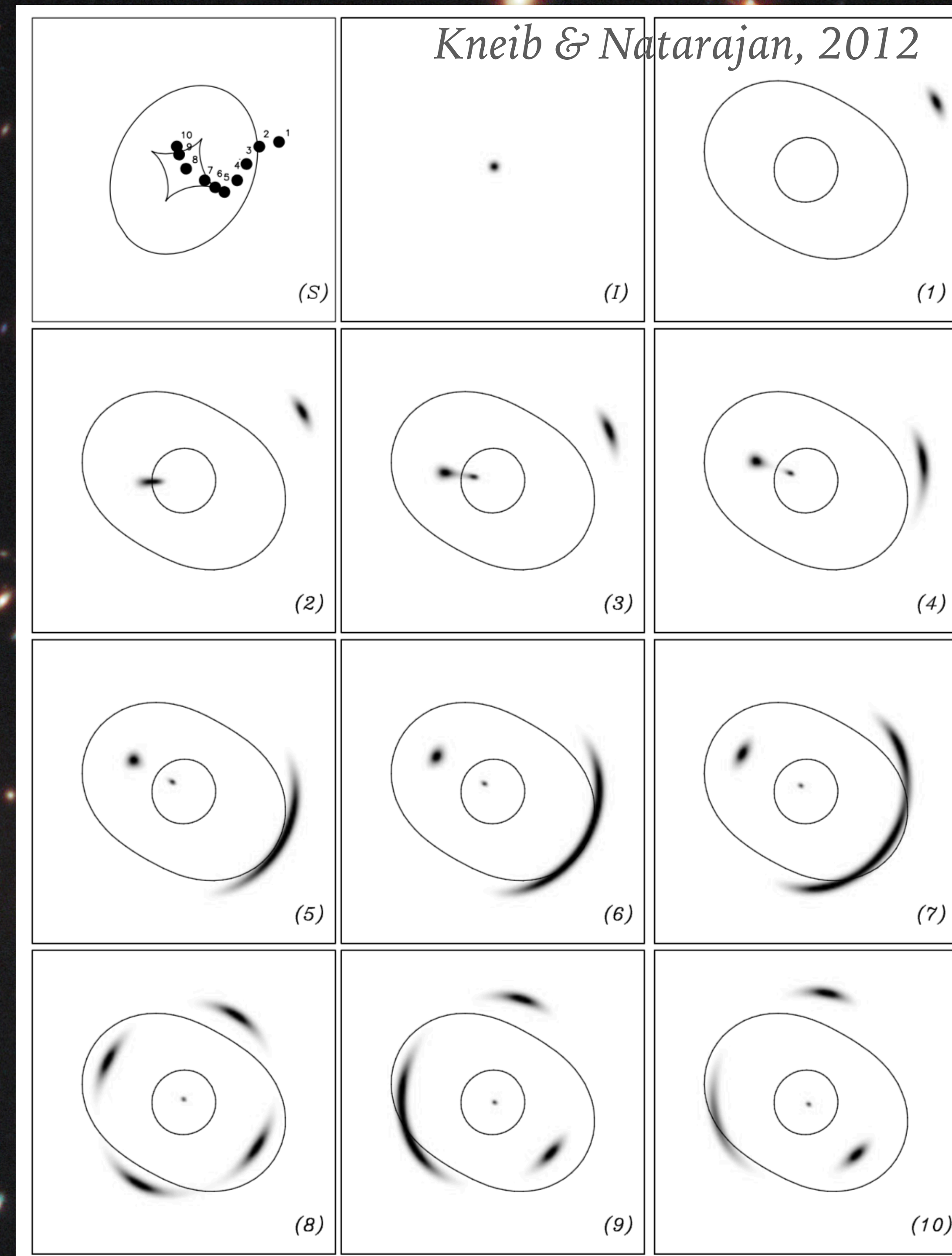

H
Cleaned
1''
CASTLES





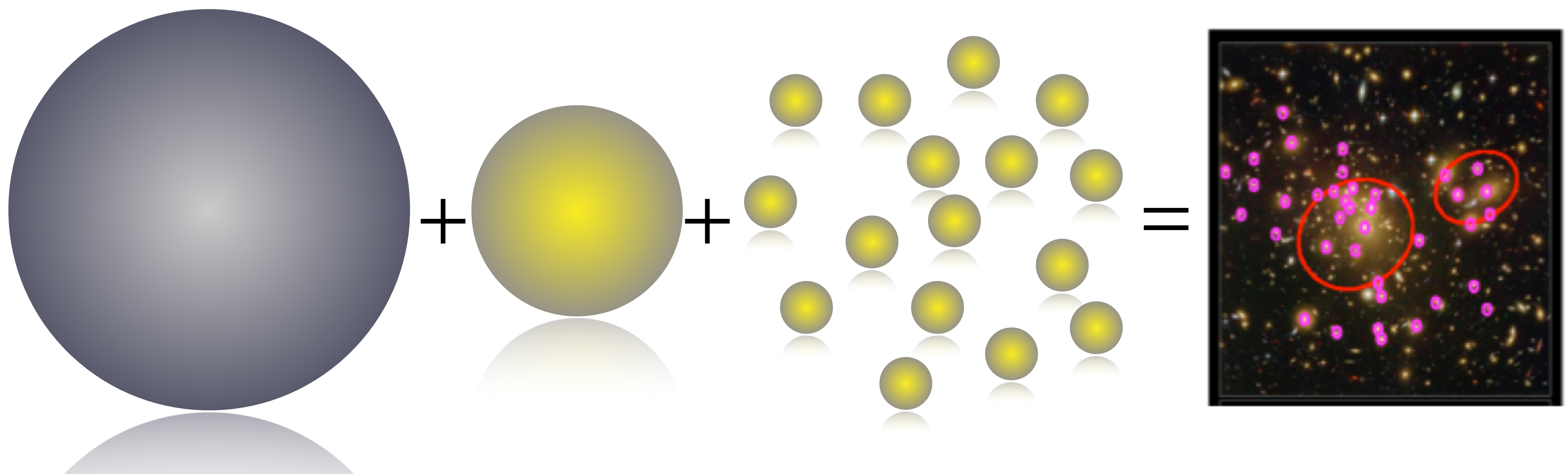






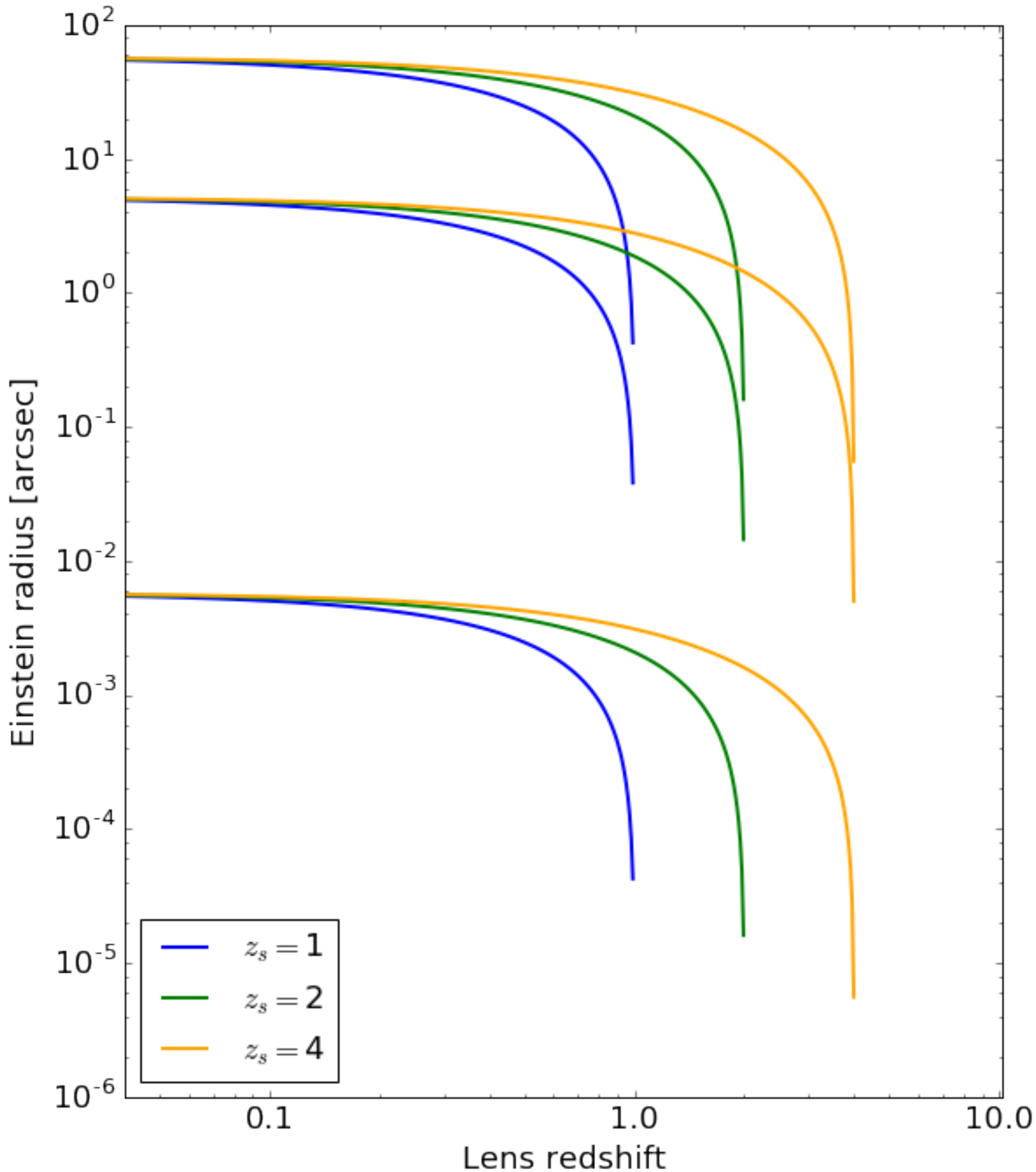
The image configurations immediately tell us that we cannot describe galaxies and galaxy clusters as circular (axially symmetric) lenses

LENS MODELING: THE PARAMETRIC APPROACH



- extended lenses as complex mass distributions (DM+baryons)
- smooth halo + clumpy structure
- choose model profile
- choose a strategy for distributing masses

SIZES OF THE EINSTEIN RADII



Galaxy cluster (1000 km/s)

Massive elliptical (300 km/s)

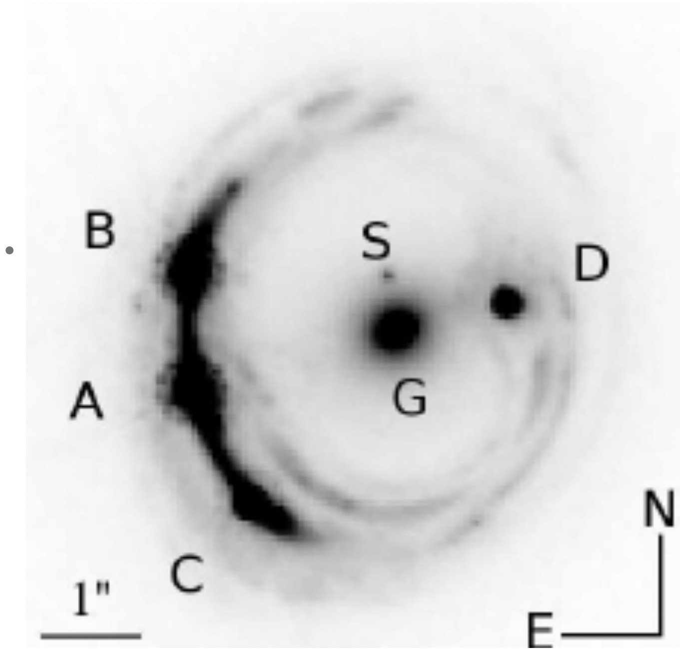
Dwarf satellite (10 km/s)

Stars

TYPICAL CONSTRAINTS

positional constraints (multiple images): probe the first derivative of the lensing potential.

$$\alpha = \psi'$$



shape or flux constraints (magnification): probe the second derivative of the lensing potential.

$$\gamma_1(\theta) = \frac{\cos 2\phi}{2}\left(\frac{\alpha(\theta)}{\theta} - \psi''\right)$$

$$\gamma_2(\theta) = \frac{\sin 2\phi}{2}\left(\frac{\alpha(\theta)}{\theta} - \psi''\right)$$

$$\kappa(\theta) = \frac{1}{2}\left(\frac{\alpha(\theta)}{\theta} + \psi''\right)$$

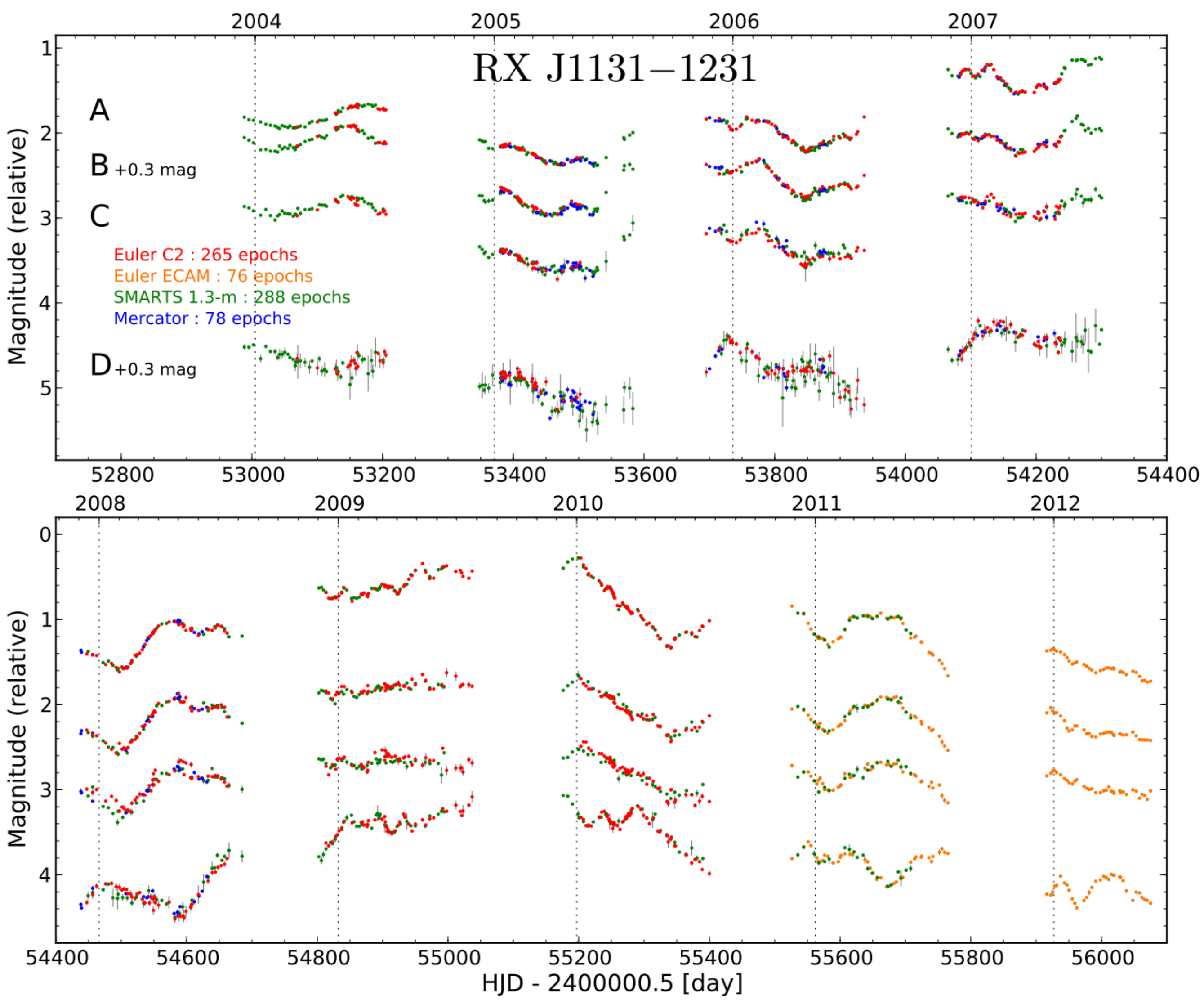
$$\mu(\theta) = [(1-\kappa)^2 - \gamma^2]^{-1}$$

LESS TYPICAL CONSTRAINTS

time delay constraints (for sources that are intrinsically variable): probe the lensing potential

$$\tau(\boldsymbol{\theta}) = \frac{D_{\Delta t}}{c} \cdot \Phi(\boldsymbol{\theta}, \boldsymbol{\beta}),$$

$$\text{where} \quad \Phi(\boldsymbol{\theta}) = \frac{1}{2}(\boldsymbol{\theta} - \boldsymbol{\beta})^2 - \psi(\boldsymbol{\theta}).$$



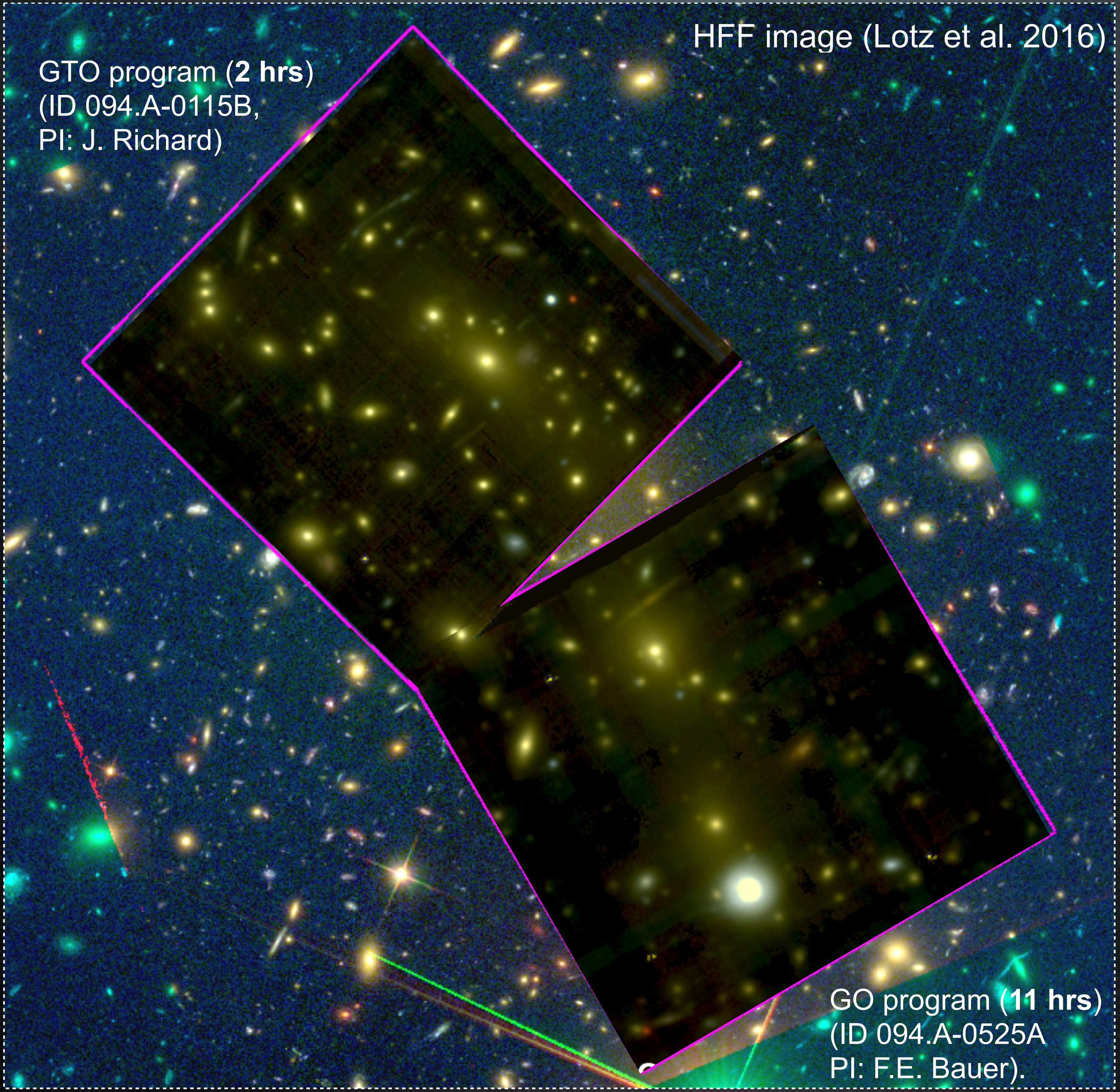
Requirements: deep, high resolution imaging (HST), time monitoring, <u>redshifts for the lenses and for the sources</u>

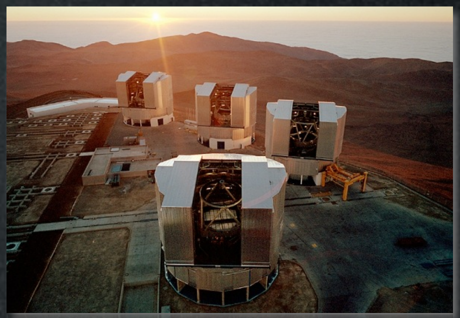
A FUNDAMENTAL INGREDIENT: REDSHIFTS

- To convert the lensing observables into physical quantities, we need redshifts
- In addition, a robust model can only be built if redshifts of the sources are known
- For this reason spectroscopic follow-up is absolutely necessary
- Spectroscopy also allows to 1) confirm lensed systems 2) identify structures along the line of sight 3) identify cluster galaxies
- e.g. CLASH-VLT (Rosati); GLASS (Treu)

Another leap forward with VLT/MUSE spectroscopy combined with deeper Frontier Field data

(Caminha et al. 2017, AA)

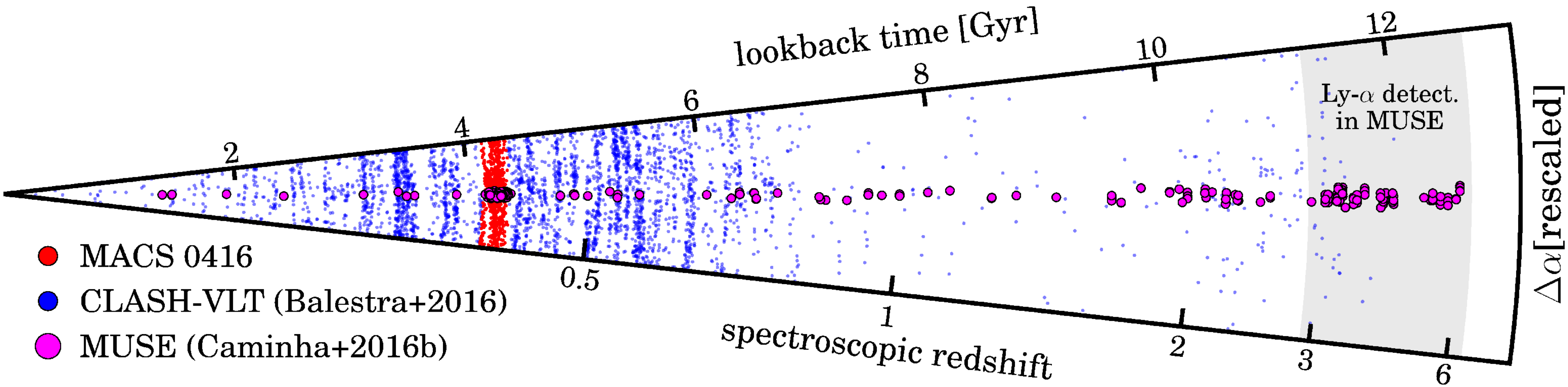




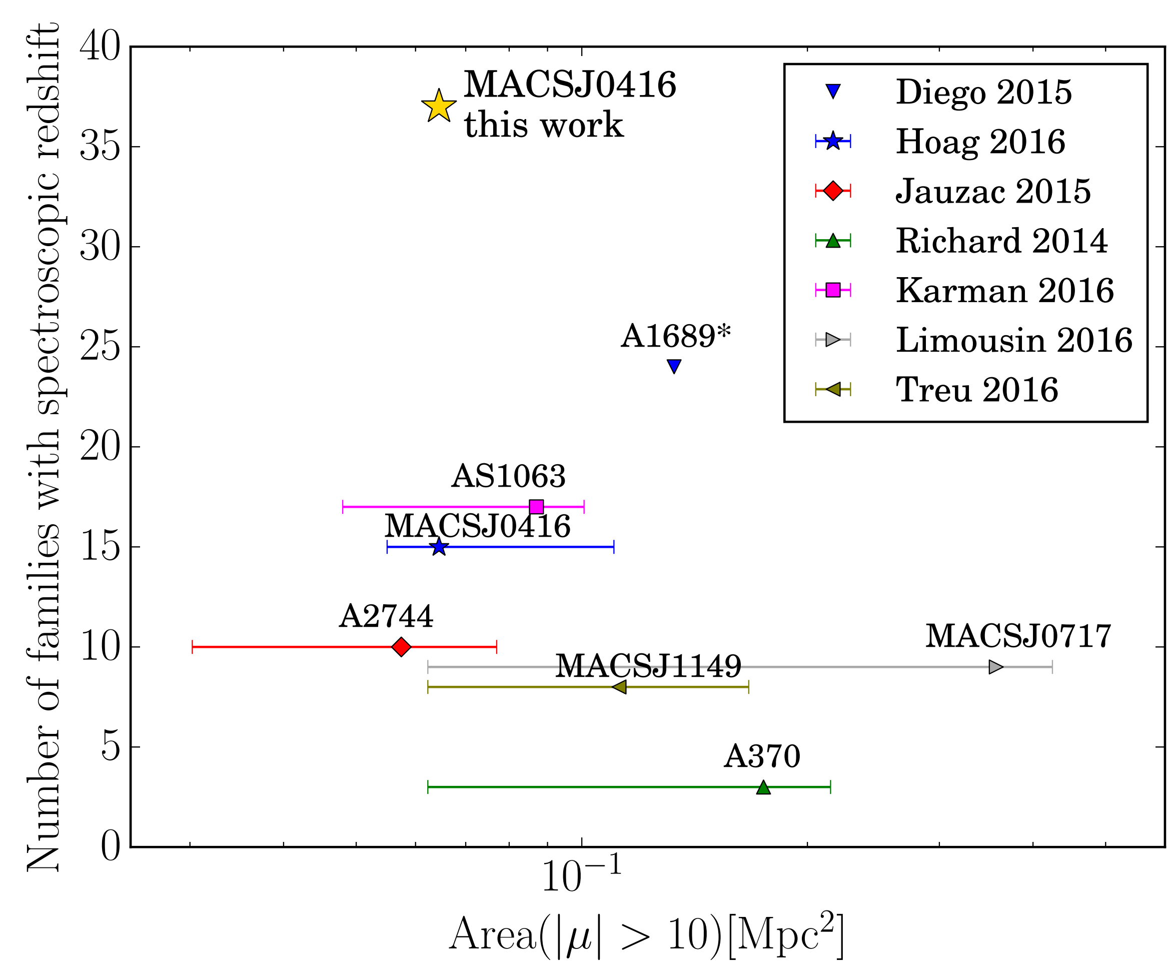
CLASH-VLT
+
MUSE campaign

1 arcmin² FoV
2.6 Å resolution
4750-9350 Å
0.2 arcsec/pxl
Exp. = 2-11 hrs

MUSE: A FANTASTIC INSTRUMENT FOR CLUSTER LENSING



- ➤ High efficiency to detect faint line emitters
- ➤ high spectral resolution to identify lines (e.g. Ly-a)
- ➤ makes it easy to associate multiple images
- ➤ improved determination of cluster membership
- ➤ **Example: Caminha et al. 2017 found 22 new families of multiple image systems in MACS0416, compared to CLASH-VLT+GLASS**



EXAMPLE: MUSE