Strong Lensing Surveys and Statistics

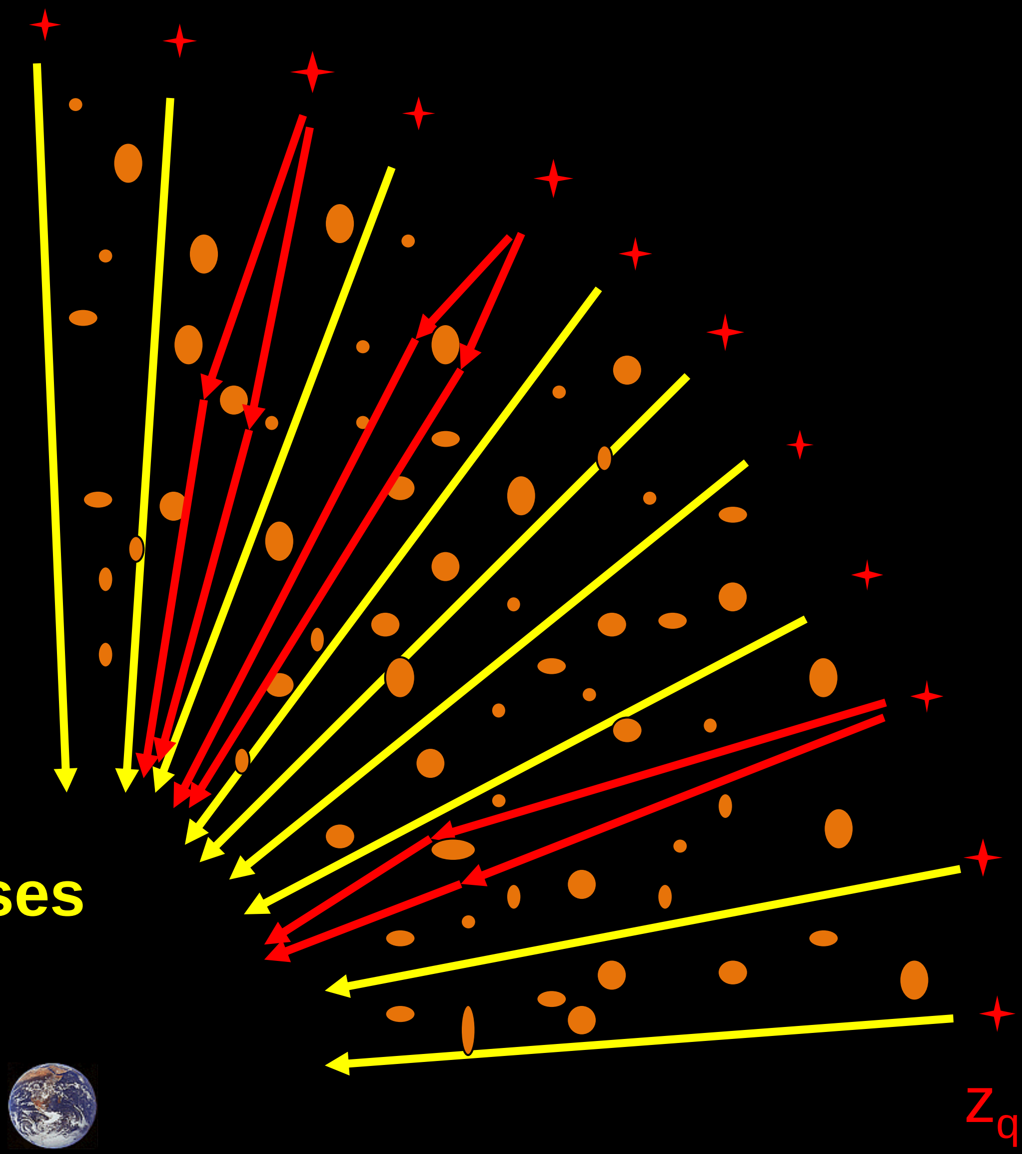
Dan Maoz

Survey strategies:

Search among **source** population for lensed cases

or

Search behind potential **lenses** for lensed sources



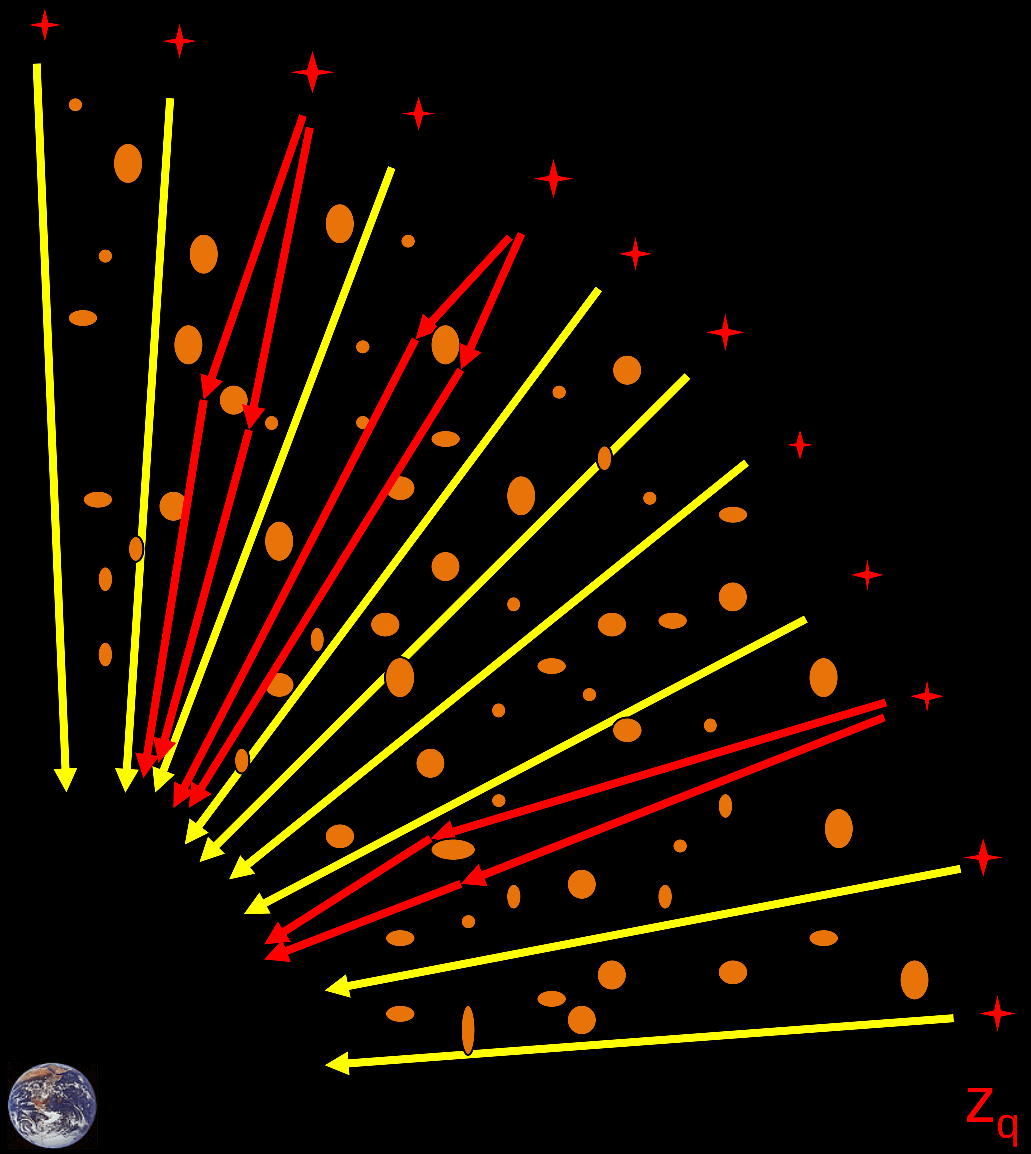
Lensing statistics:

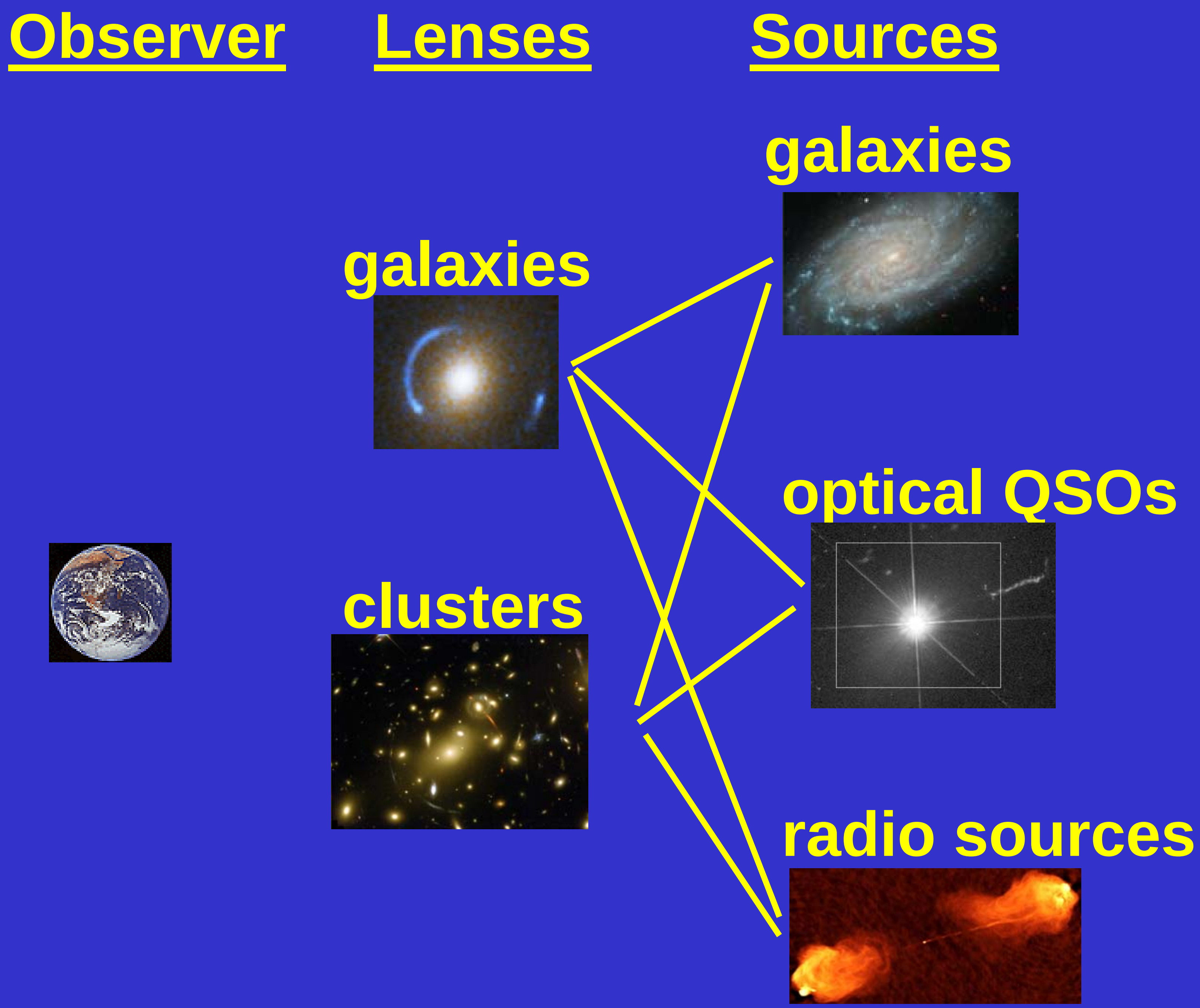
Source Image properties:

- source lensed fraction
- separation distribution
- quads/doubles
- arc length/width
- flux ratios

Lens properties:

- redshift
- mass/profile




Observer
Lenses
Sources
galaxies
galaxies
optical QSOs
clusters
radio sources

$$P \sim n\,\sigma\,D$$

lensing prob. — lens density — lensing cross section — distance to source

$\sim \pi \theta_E^2 D_{ol}^2$

Galaxies: 0.5×10^{-2} Mpc^{-3} x π (5 kpc)^2 x 2 Gpc ~ 10^{-3}

Clusters: 10^{-7} Mpc^{-3} x π (100 kpc)^2 x 2 Gpc ~ 10^{-5}

× B --- magnification bias:

~10 for bright quasar samples

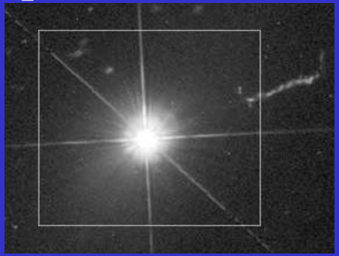
~few for radio samples

Observer **Lenses** **Sources**

galaxies

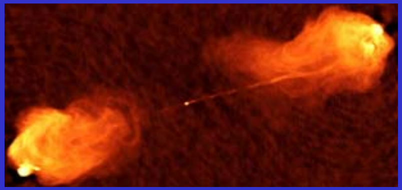
galaxies

optical QSOs



clusters

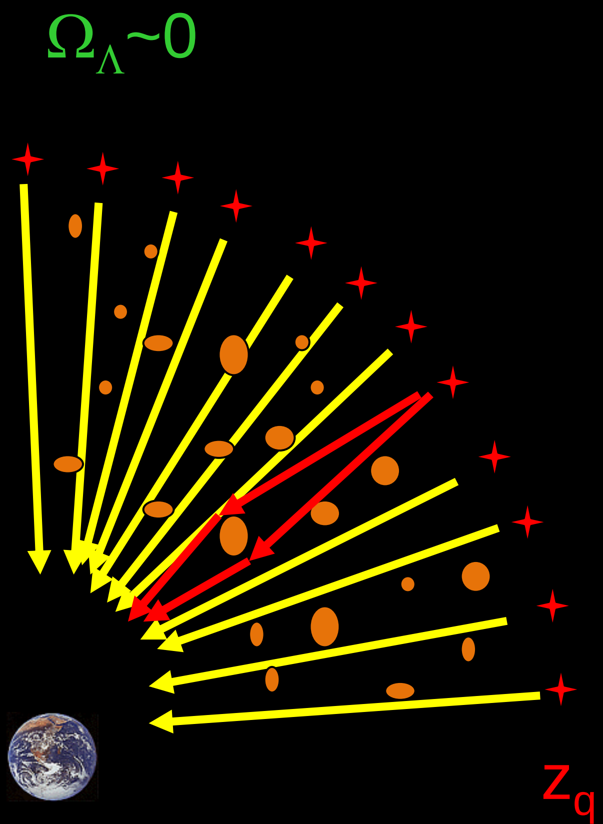
radio sources

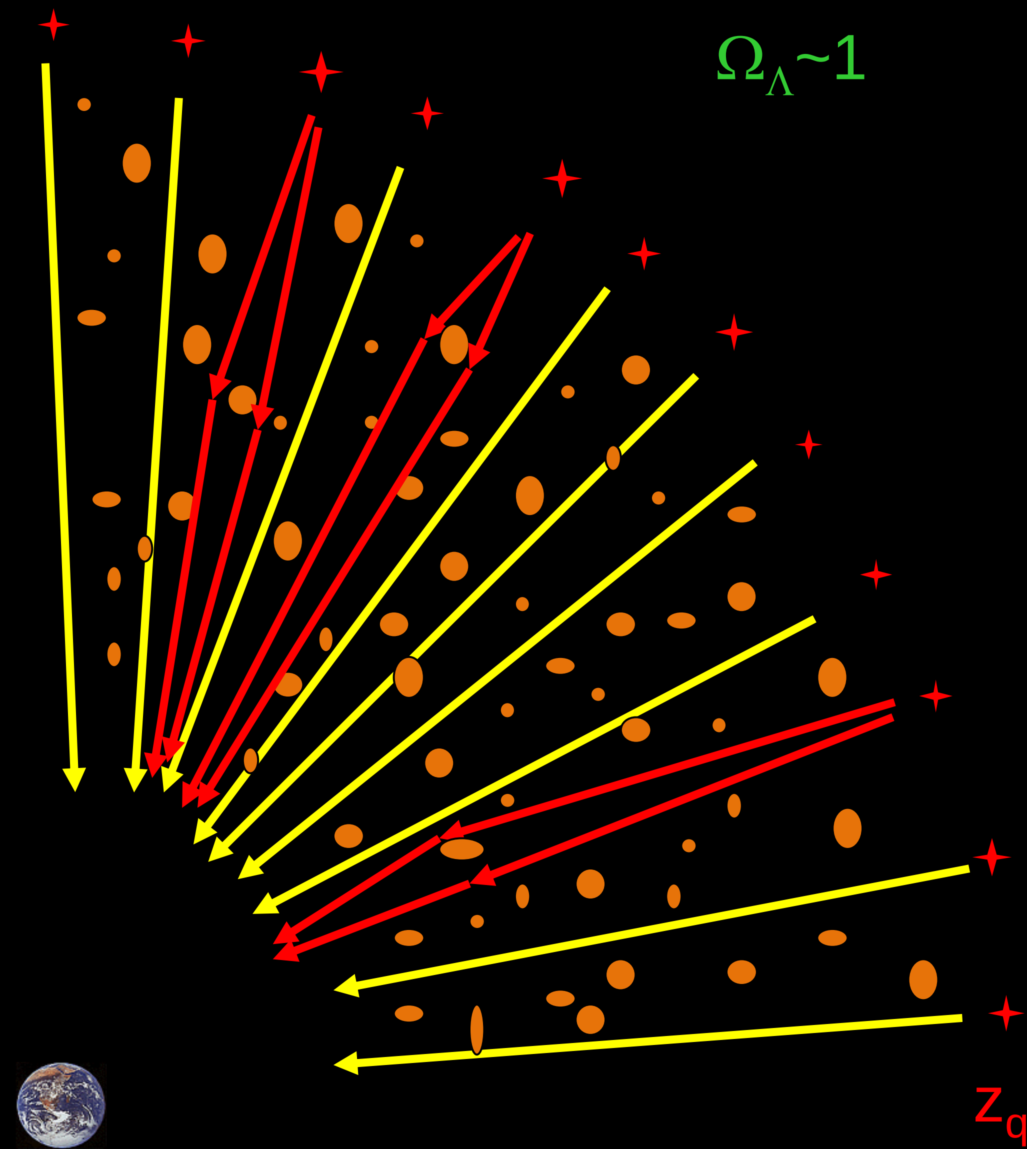


Turner Ostriker & Gott 1983,

Turner 1990 ,

Fukugita & Turner 1991

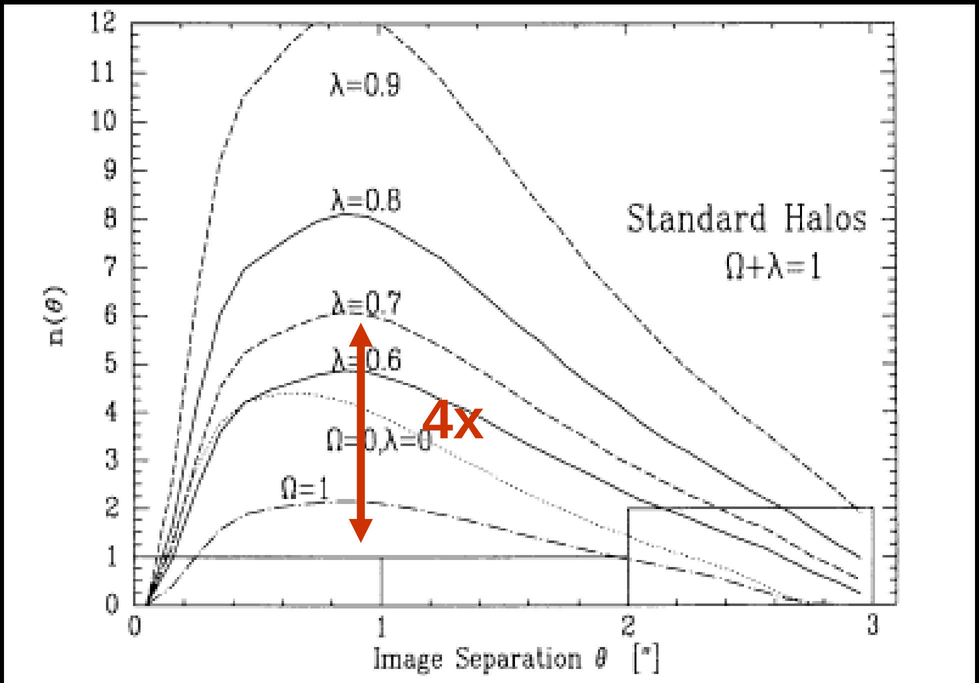




HST Snapshot Lensing Survey: (Maoz et al. 1993)

4 / 502 = 1% of luminous quasars are lensed

→ $\Omega_\Lambda < 0.7$ (95% C.L.)



"hybrid" model:

de vaucouleurs +CIS

Maoz & Rix (1993)

Kochanek (1996): SIS + 5 / 864 quasars lensed

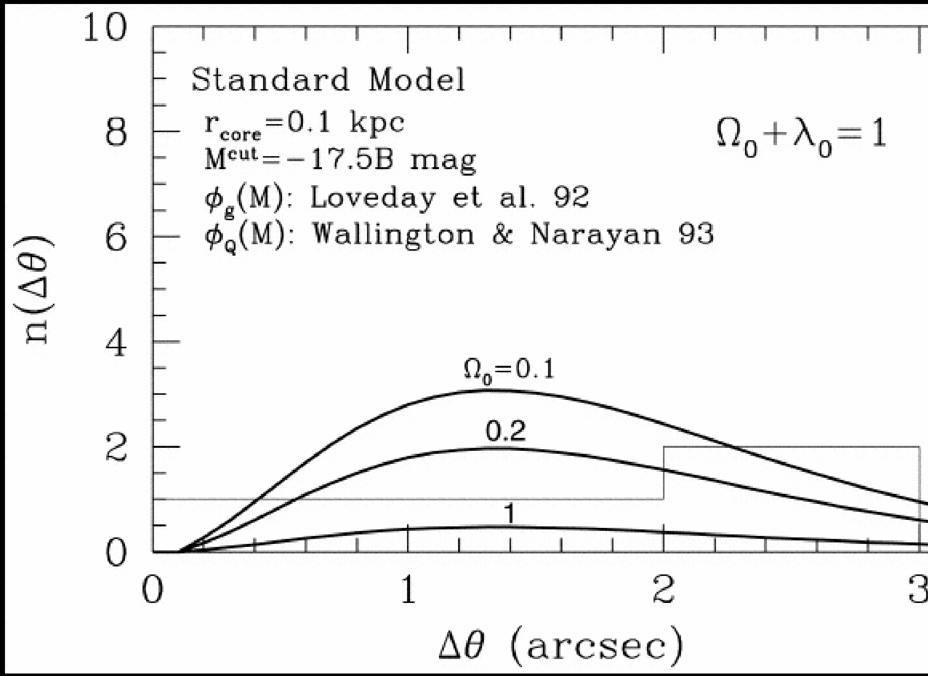
→ $\Omega_\Lambda < 0.66$ (95% C.L.)

Chiba & Yoshii (1997, 1999)

$\Omega_\Lambda \sim 0.8$, $\Omega_\Lambda = 0.7^{+0.1}_{-0.2}$

Waga & Miceli (1999)

$\Omega_\Lambda \sim 0.67$

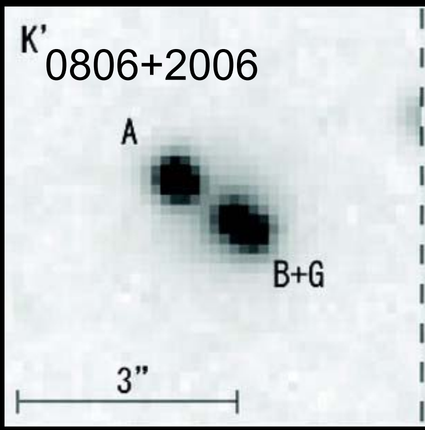


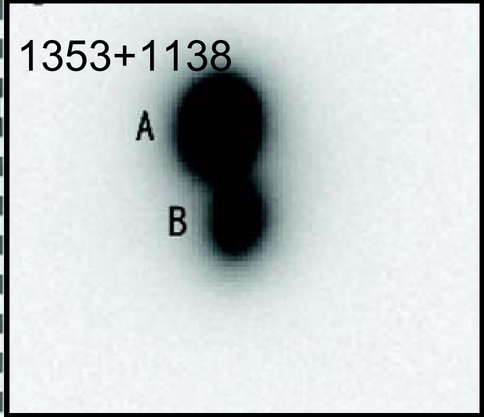
2nd HST Snapshot Survey (Morgan et al. 2003): 3/320 quasars lensed

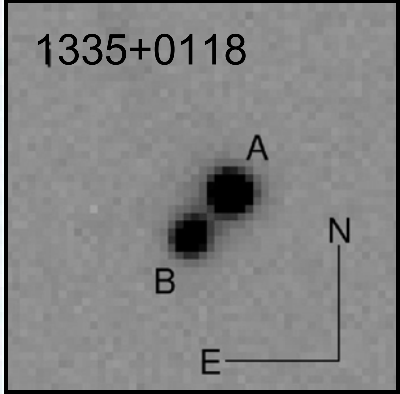
-- Still ~ 1% !

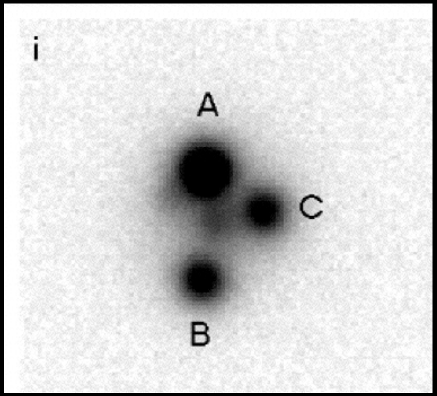
SDSS Quasar Lens Search: <u>~20 new lensed QSOs</u>

(Pindor et al. 2003; Inada et al. 2006, Oguri et al. 2006)









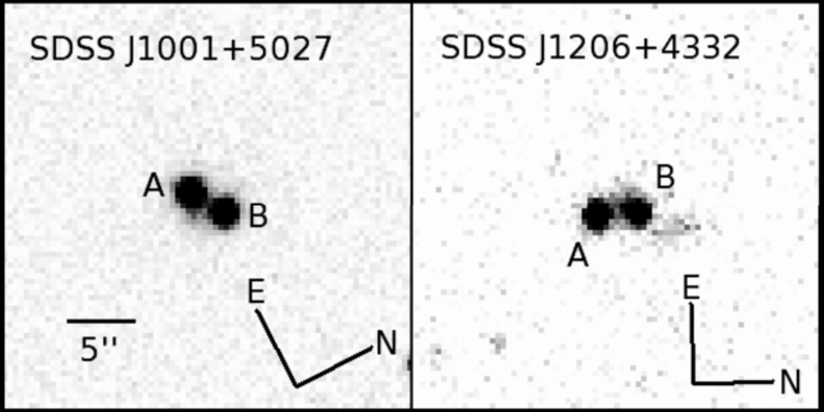
Lensed QSOs from SDSS spectroscopic (i<19 mag) QSO sample

0.6<z<2.2

"Extended" QSOs at <1.5"

Like-color companions at >1.5"

Statistical analysis: Inada et al., in prep.

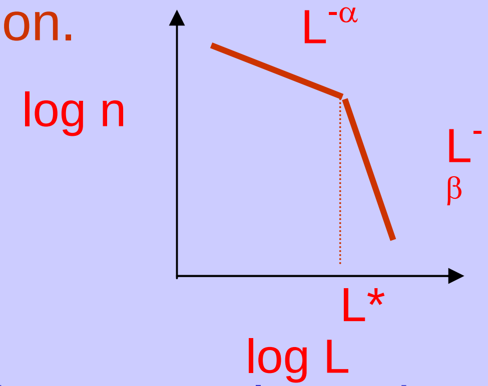


SDSS lensed QSOs at z>3:

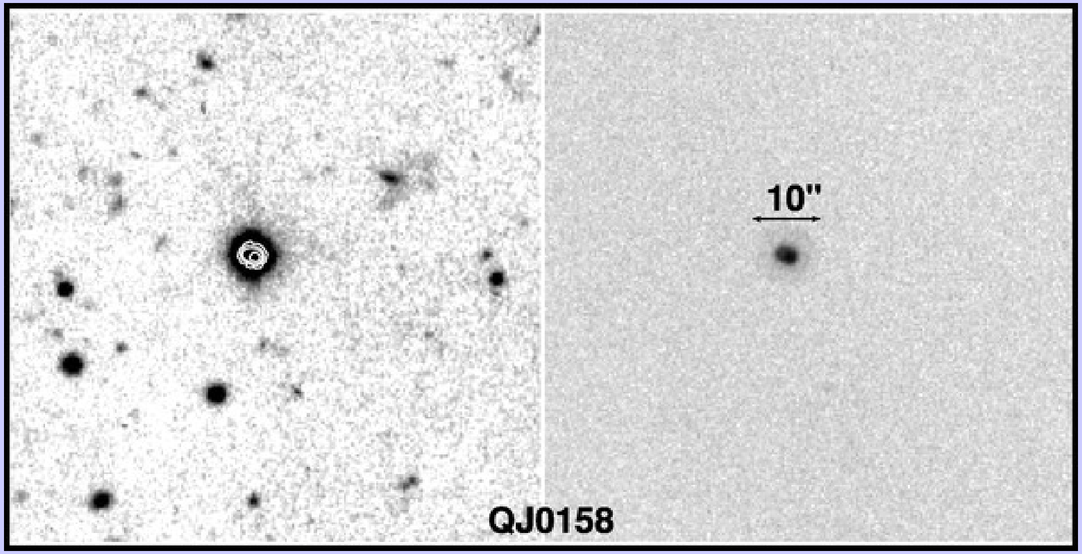
Richards et al. (2004) HST Snapshot imaging of high-z SDSS QSOs,

Lensed fraction=0/154 (sample strongly biased against lenses)

Limit on steepness of high-z QSO luminosity function.



Future: Kochanek et al. 2006 -- Variable extended sources= lensed quasars



Observer

Lenses

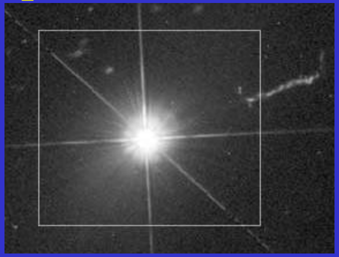
galaxies

clusters

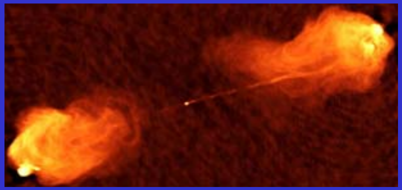
Sources

galaxies

optical QSOs



radio sources



Surveys of radio sources:

☺ no extinction/glare by lenses, large uniform samples

☹ Source population redshift and L-function poorly characterized

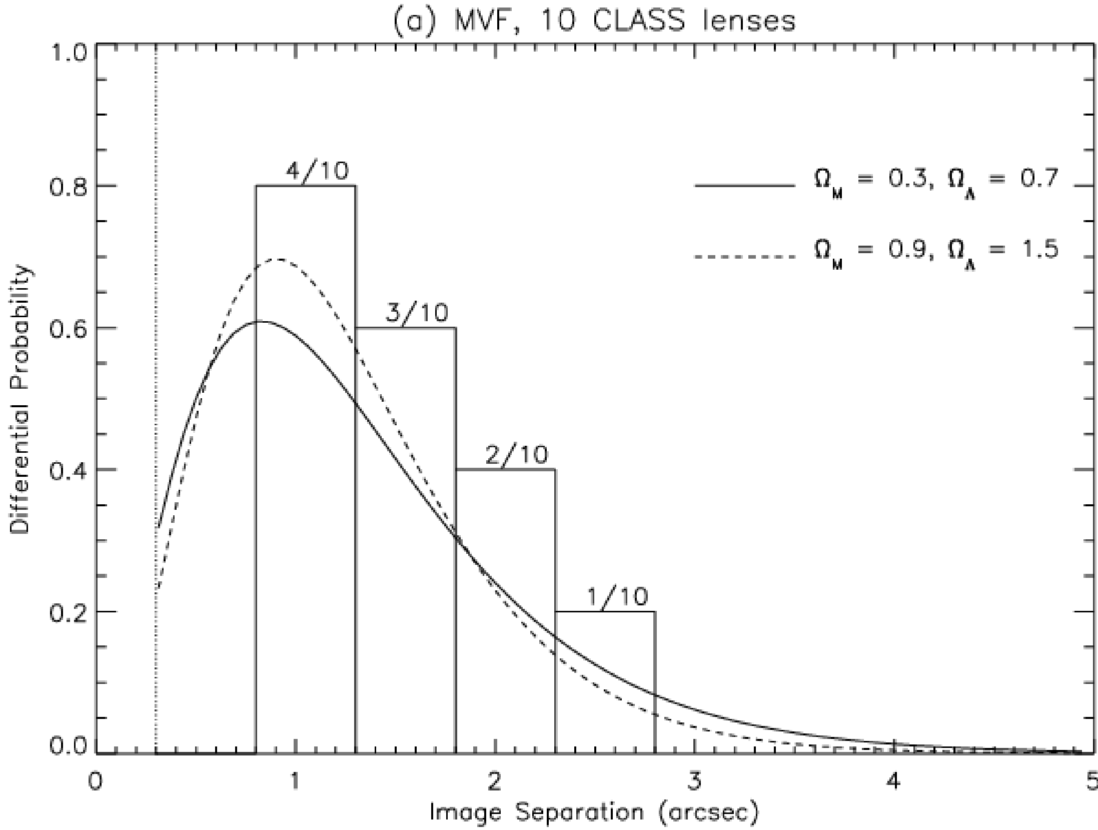
JVAS/CLASS

Browne et al. (2003)
Myers et al. (2003)

Falco, Kochanek & Munoz (1998):

6 / 2500 of JVAS sources lensed

Cooray (1999):



Chae (2003):

13 / 9000 of CLASS sou

lensed → Ω_Λ=0.8+/-(

Mitchell et al. (2005):

10 or 12 / 9000 of CLASS sources lensed

→ Ω_Λ=0.75+/-0.05

What's the problem? DEGENERACY (see Maoz 2005)

$$P \sim n\, \sigma\, D\;\; B$$

magnification bias:

lensing prob. galaxy density lensing cross section distance to source

Future: Haarsma et al. 2005: New search for lensed radio lobe sources

SKA (Koopmans et al. 2004)

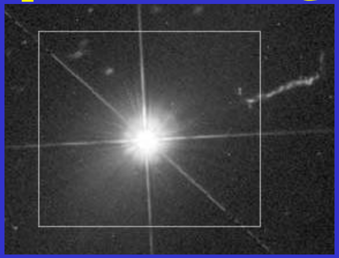
Observer | **Lenses** | **Sources**

galaxies

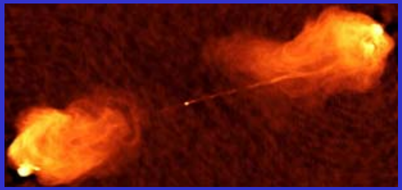
clusters

galaxies

optical QSOs

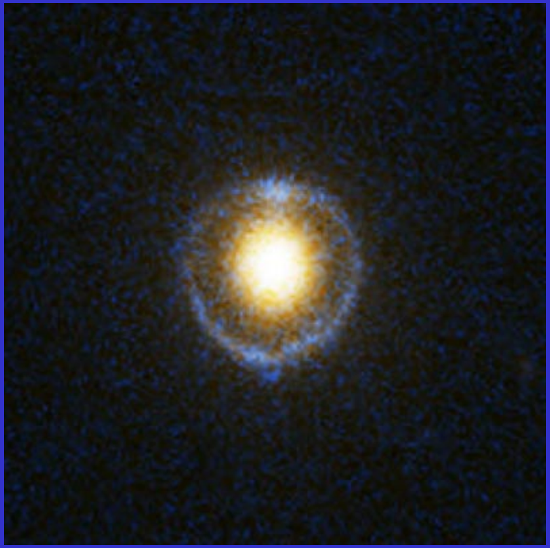


radio sources



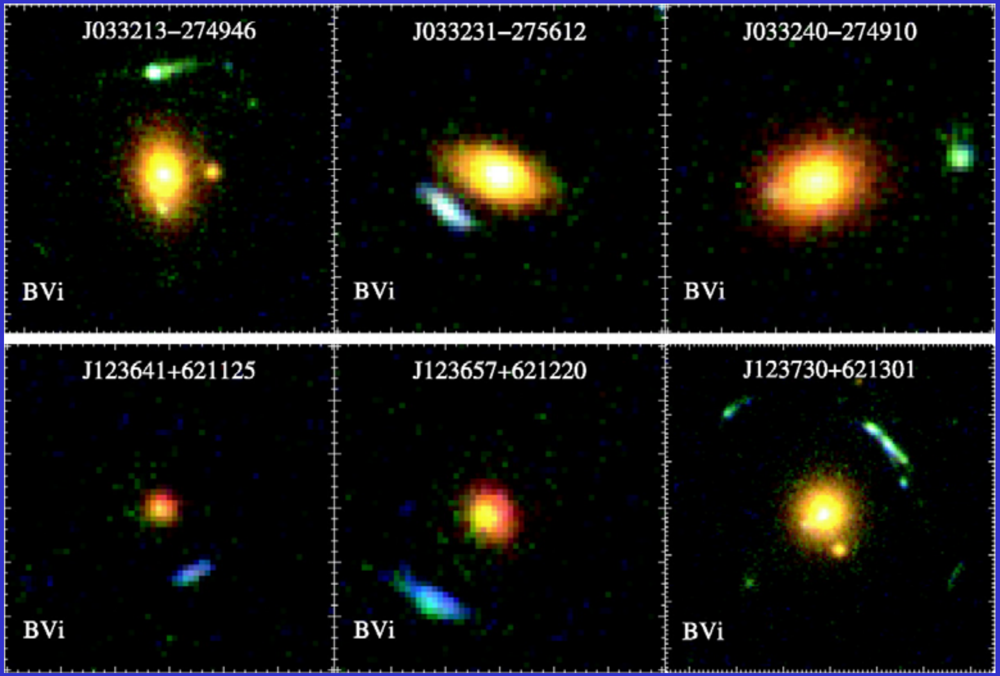
SDSS: HST-SLACS Bolton, Treu, Koopmans et al. 2006

Willis et al. 2005, 2006



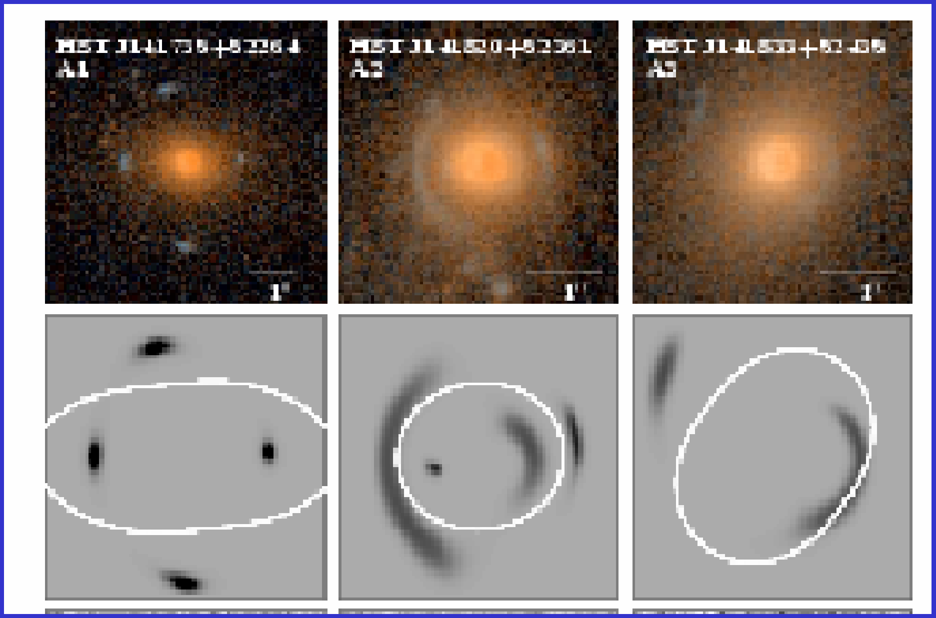
HST-GOODS:

Fassnacht et al. (2004)

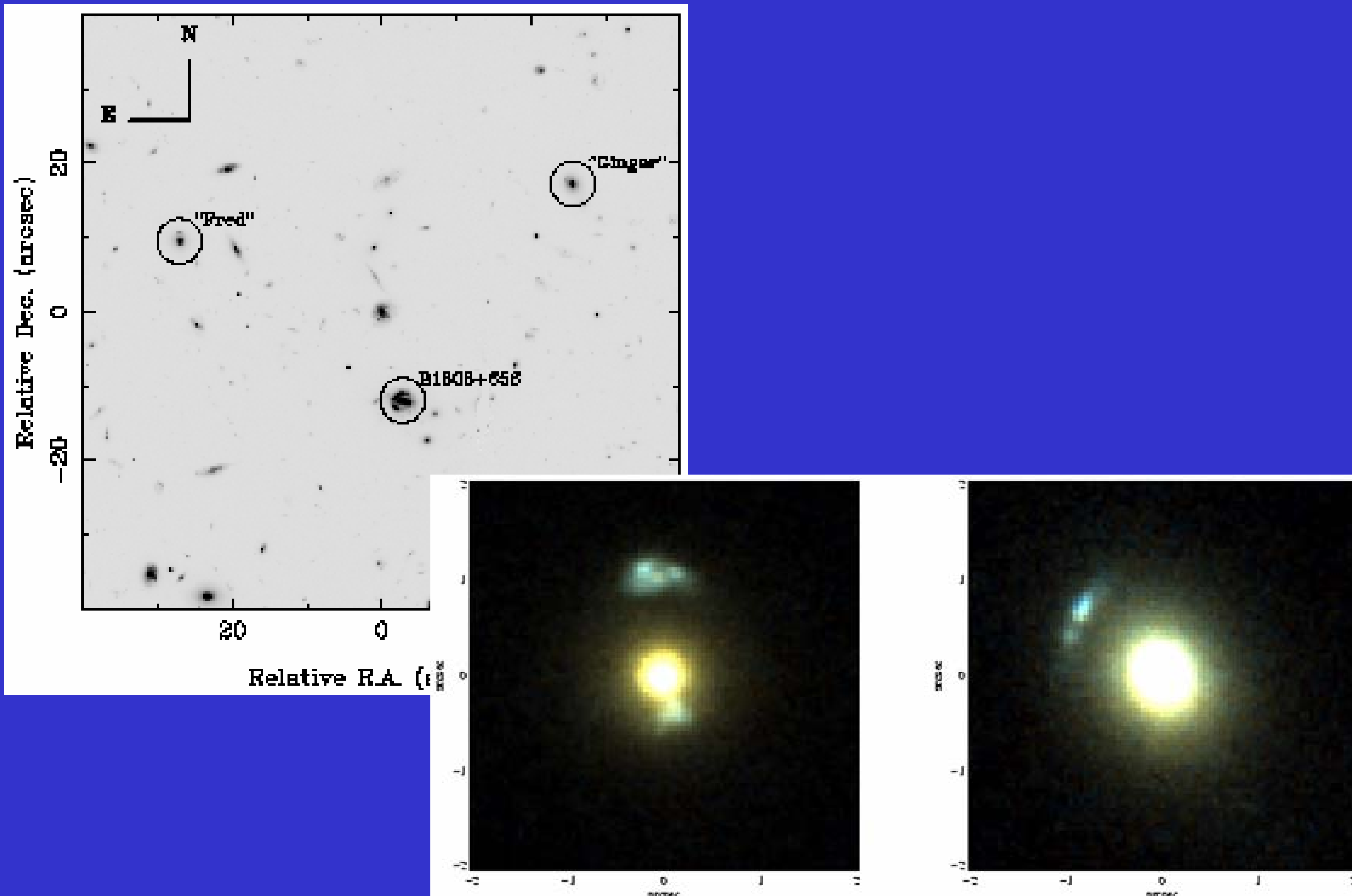


HST-AEGIS:

Moustakas et al. (2006)



Fassnacht et al. (2006): B1608+656



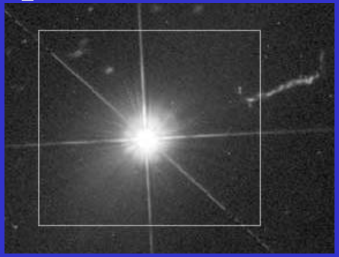
Observer | Lenses | Sources

galaxies

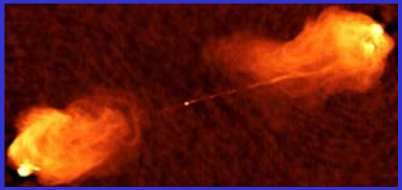
galaxies

clusters

optical QSOs



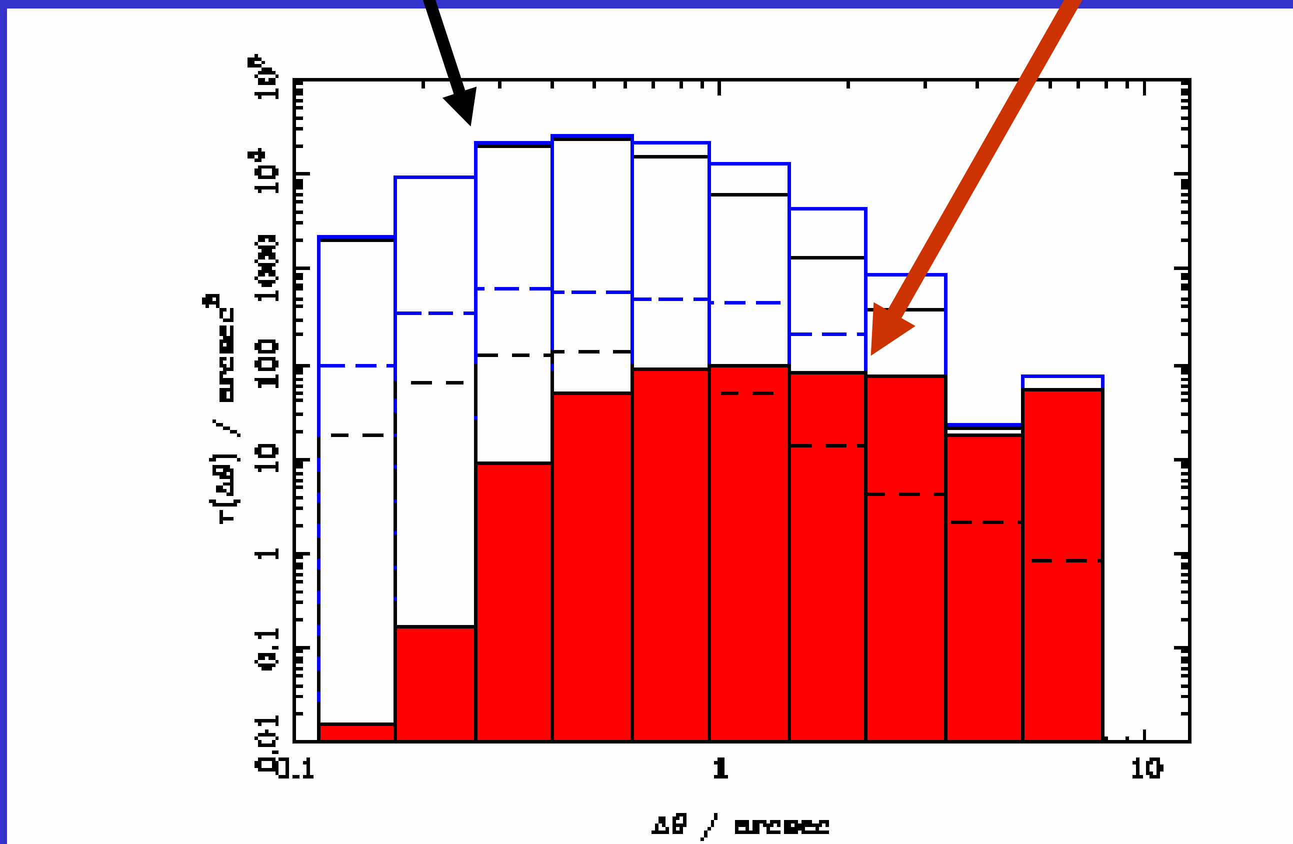
radio sources



Moeller et al. (2006): Predicted image separation distribution

DM+bulge+ disk

DM only



Strong lensing dominated by DM, not baryons

Null results:

Maoz et al. (1997)

Phillips et al. (2001)

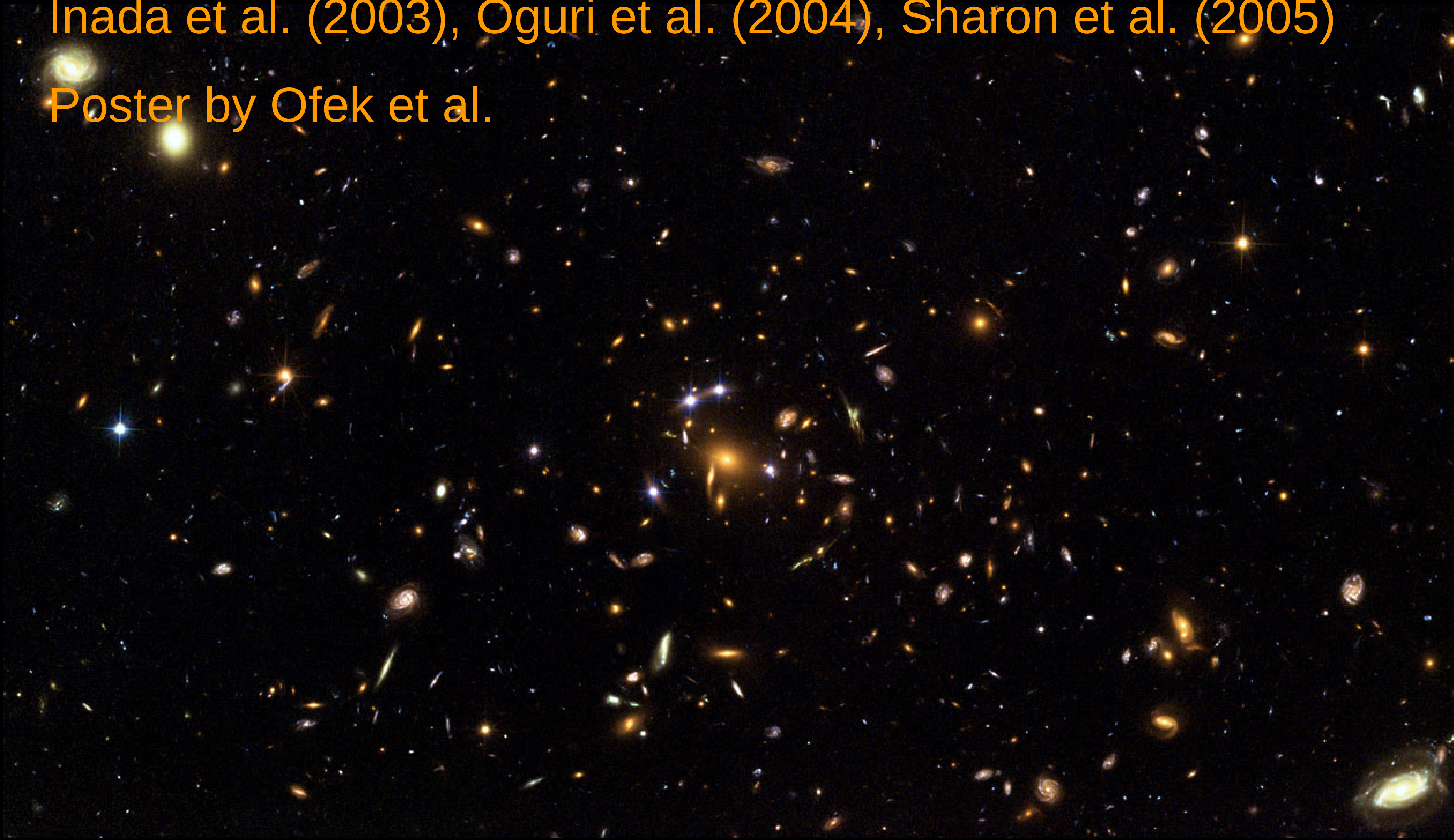
Ofek et al. (2001, 2002)

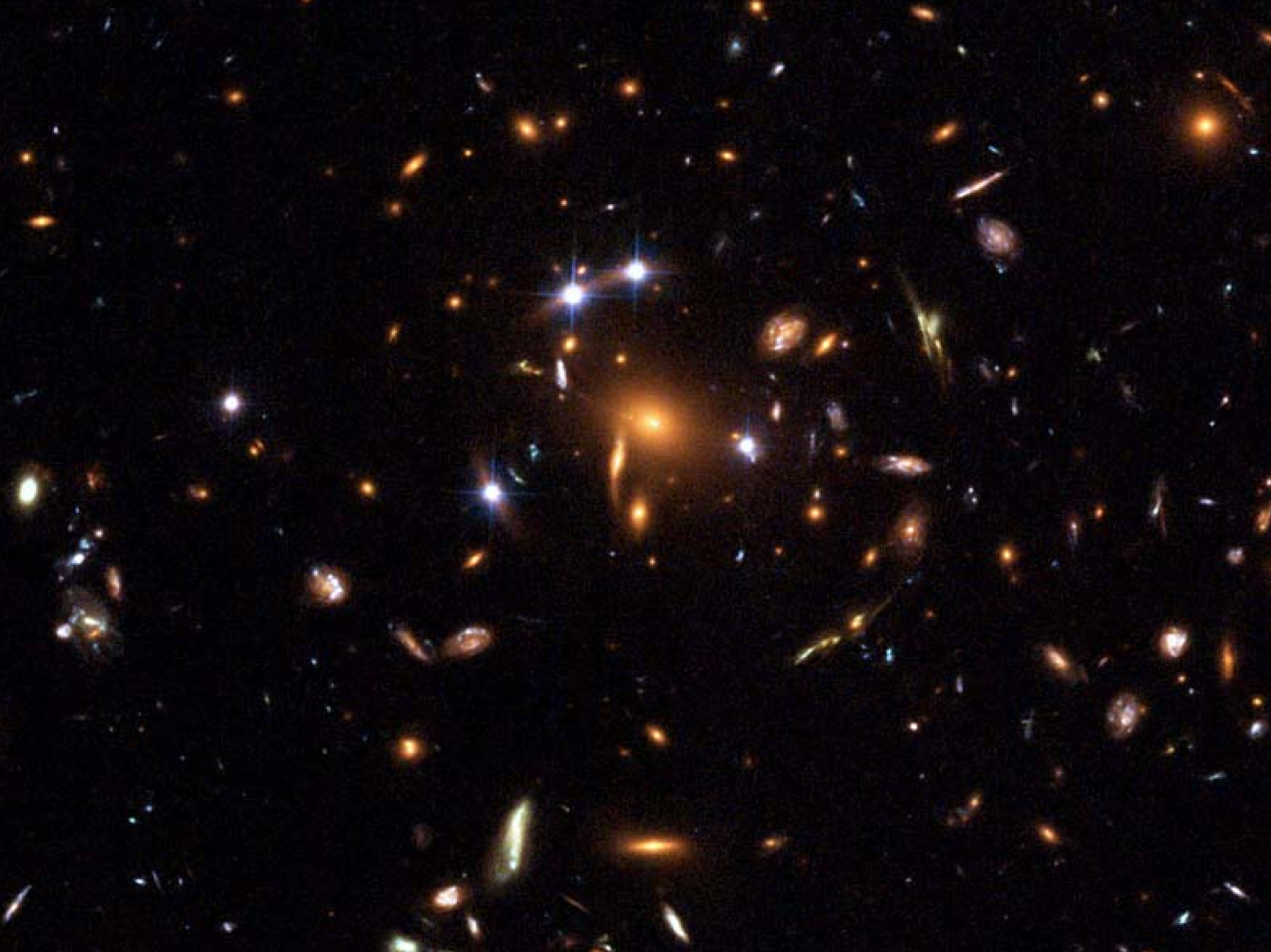
Miller et al. (2004)

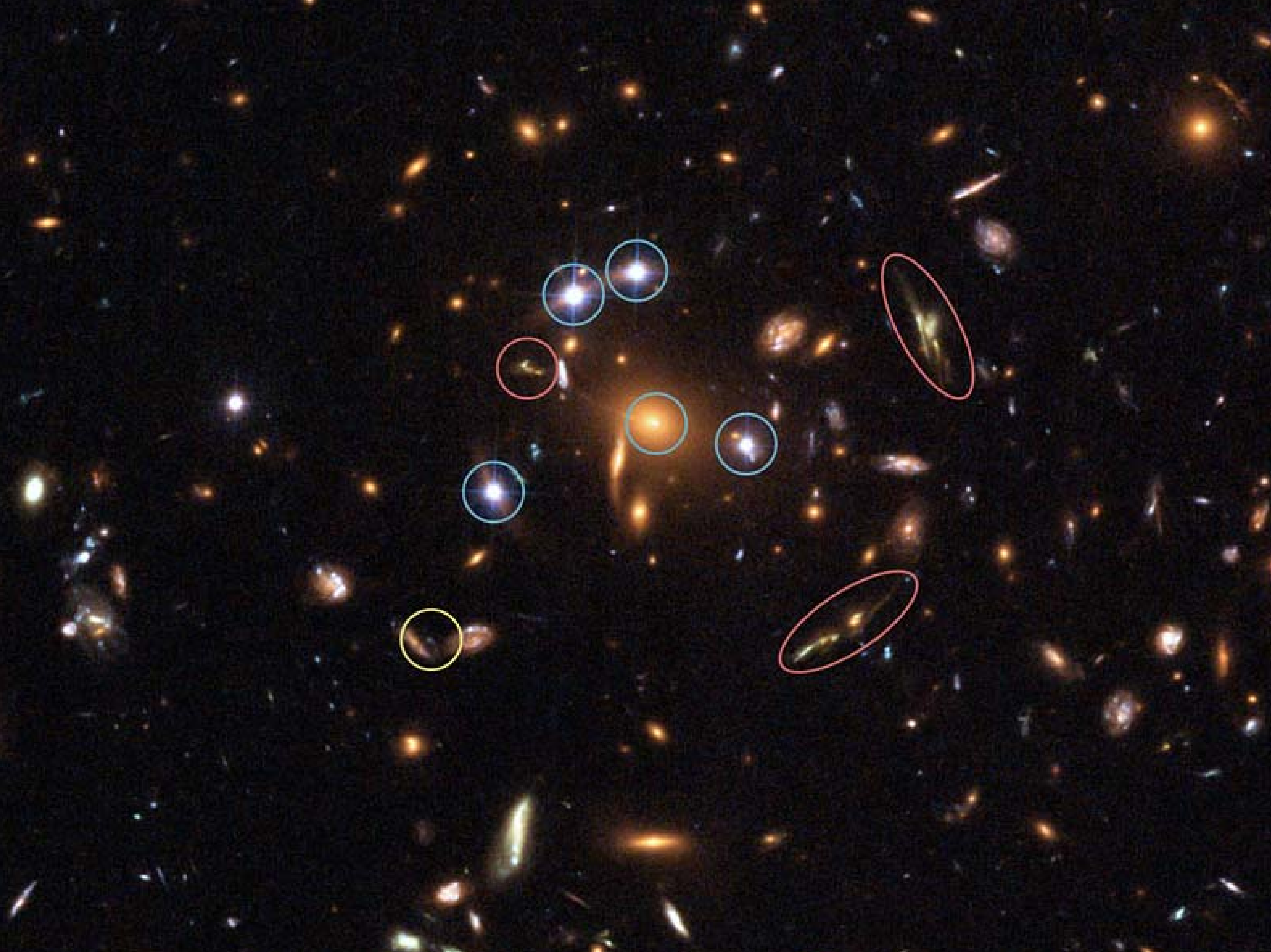
SDSS 1004+4112 Z=0.68

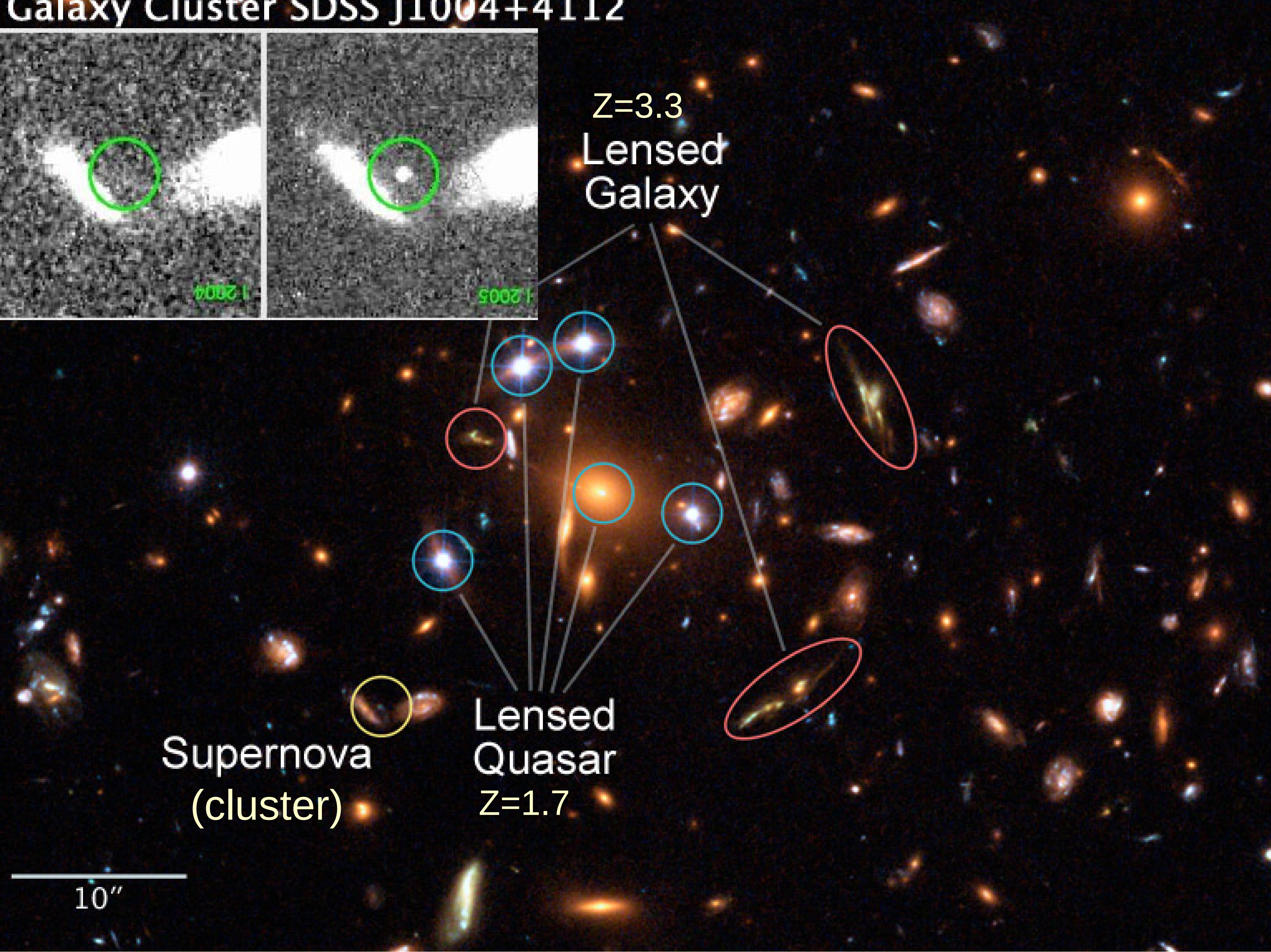
Inada et al. (2003), Oguri et al. (2004), Sharon et al. (2005)

Poster by Ofek et al.

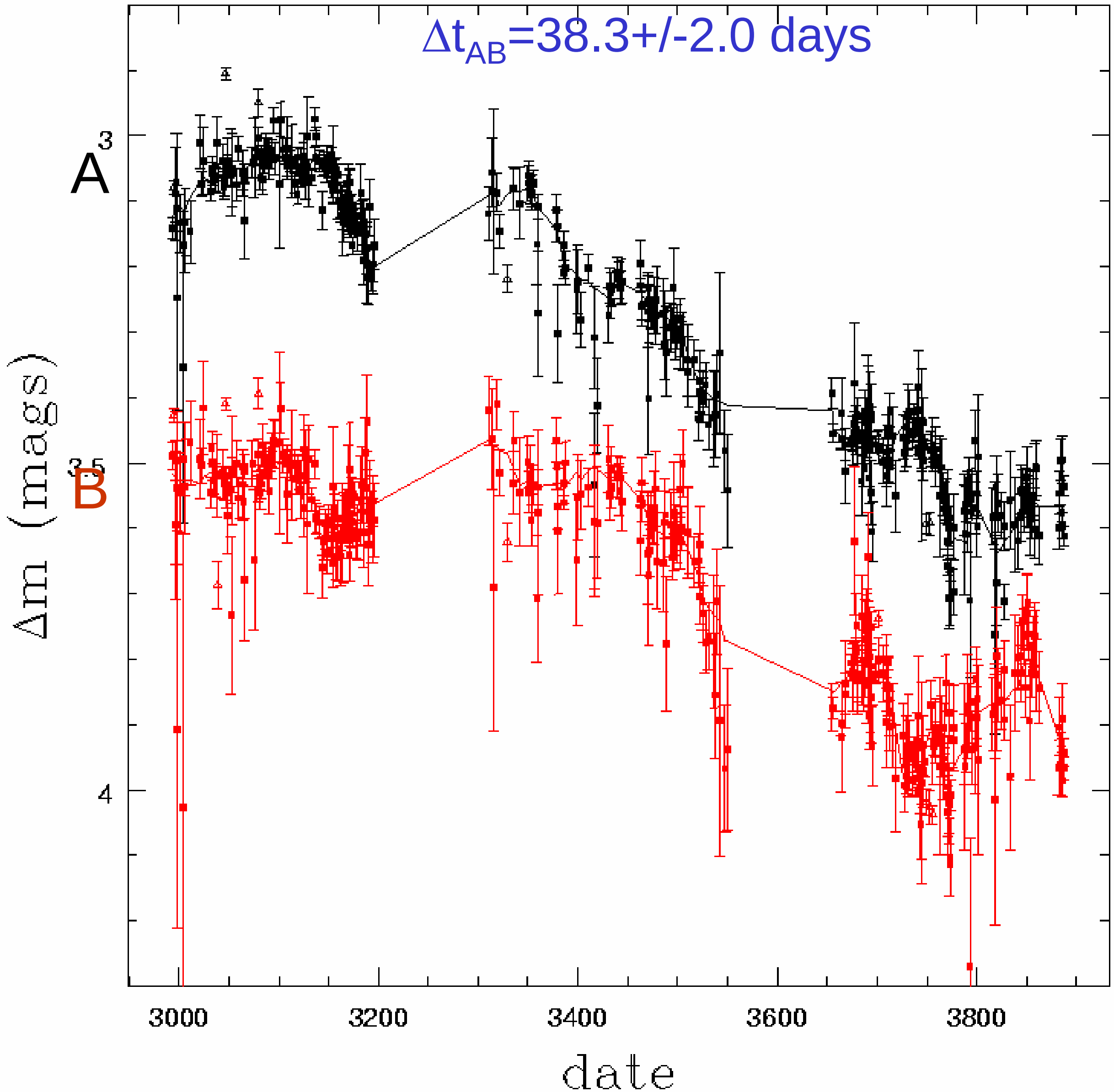






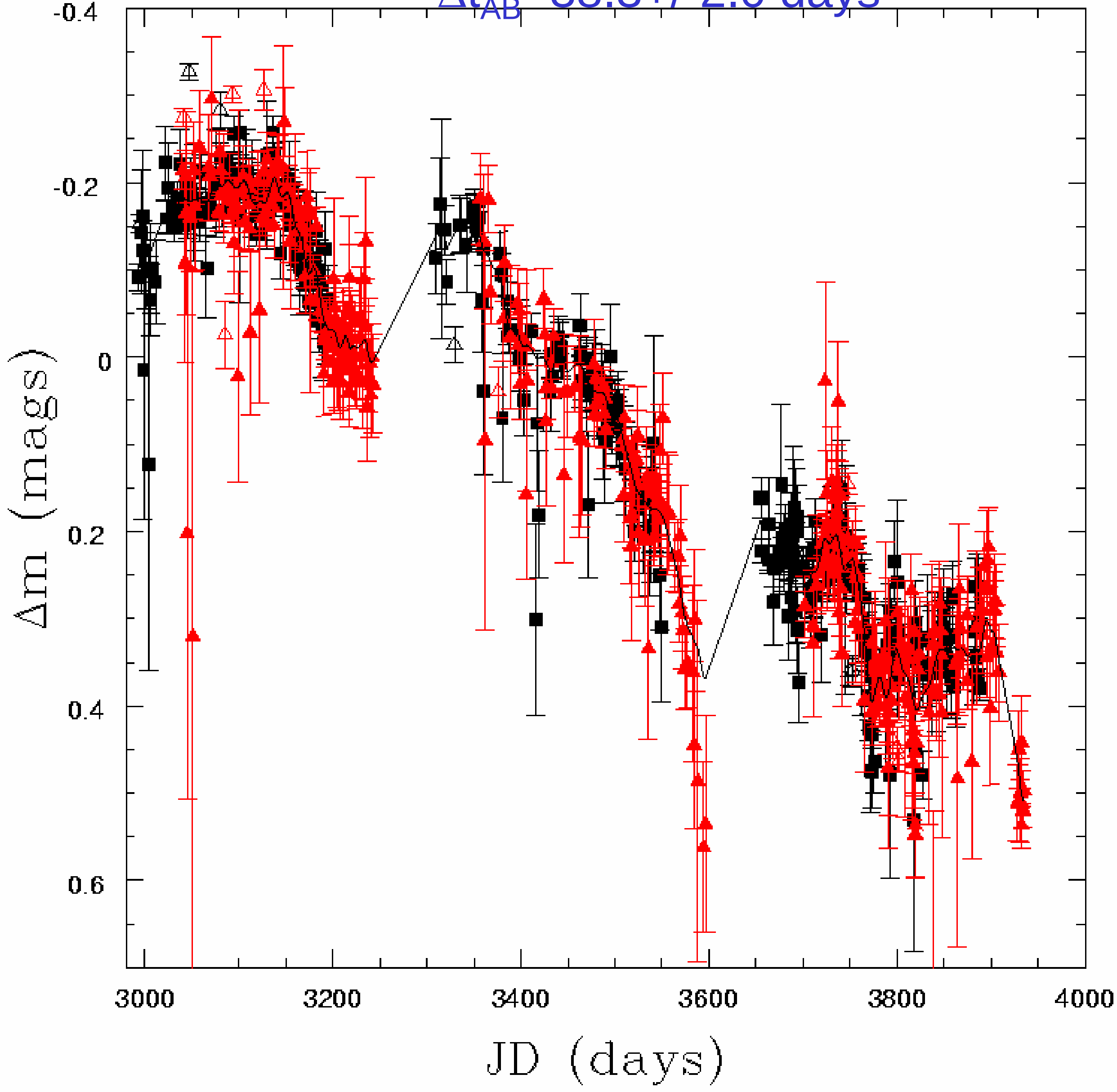

Galaxy Cluster SDSS J1004+4112
Z=3.3
Lensed
Galaxy
Lensed
Quasar
Z=1.7
Supernova
(cluster)
10″

Fohlmeister et al. 2006



Fohlmeister et al. 2006

Δt_{AB}=38.3+/-2.0 days



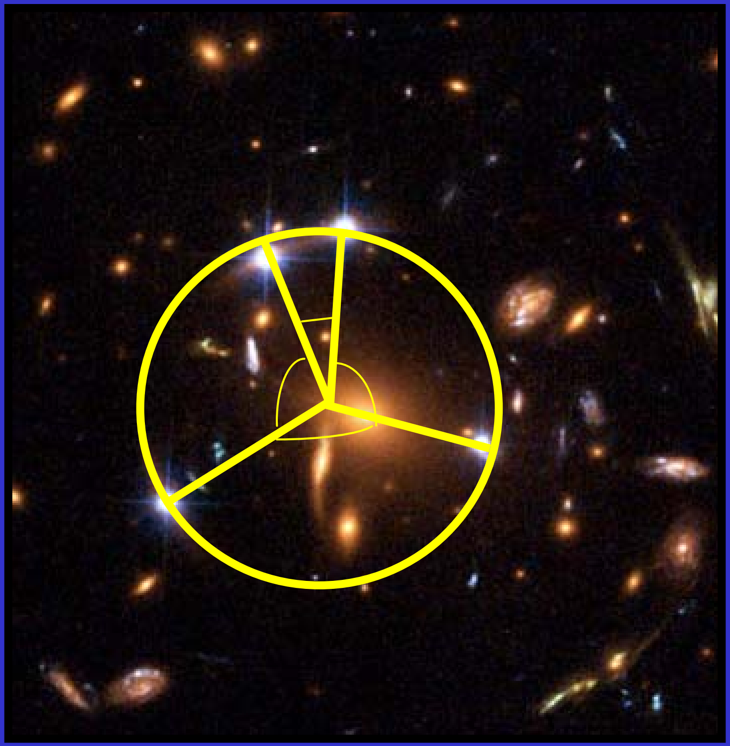
MORE?

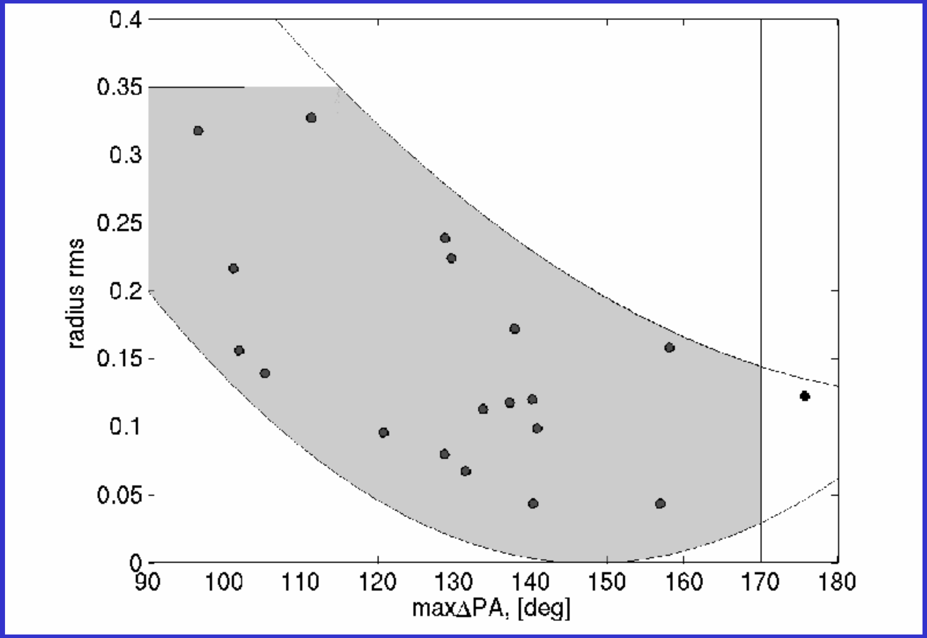
Hennawi et al. (2005):
Should be 12 cluster-QSO lenses over sky.

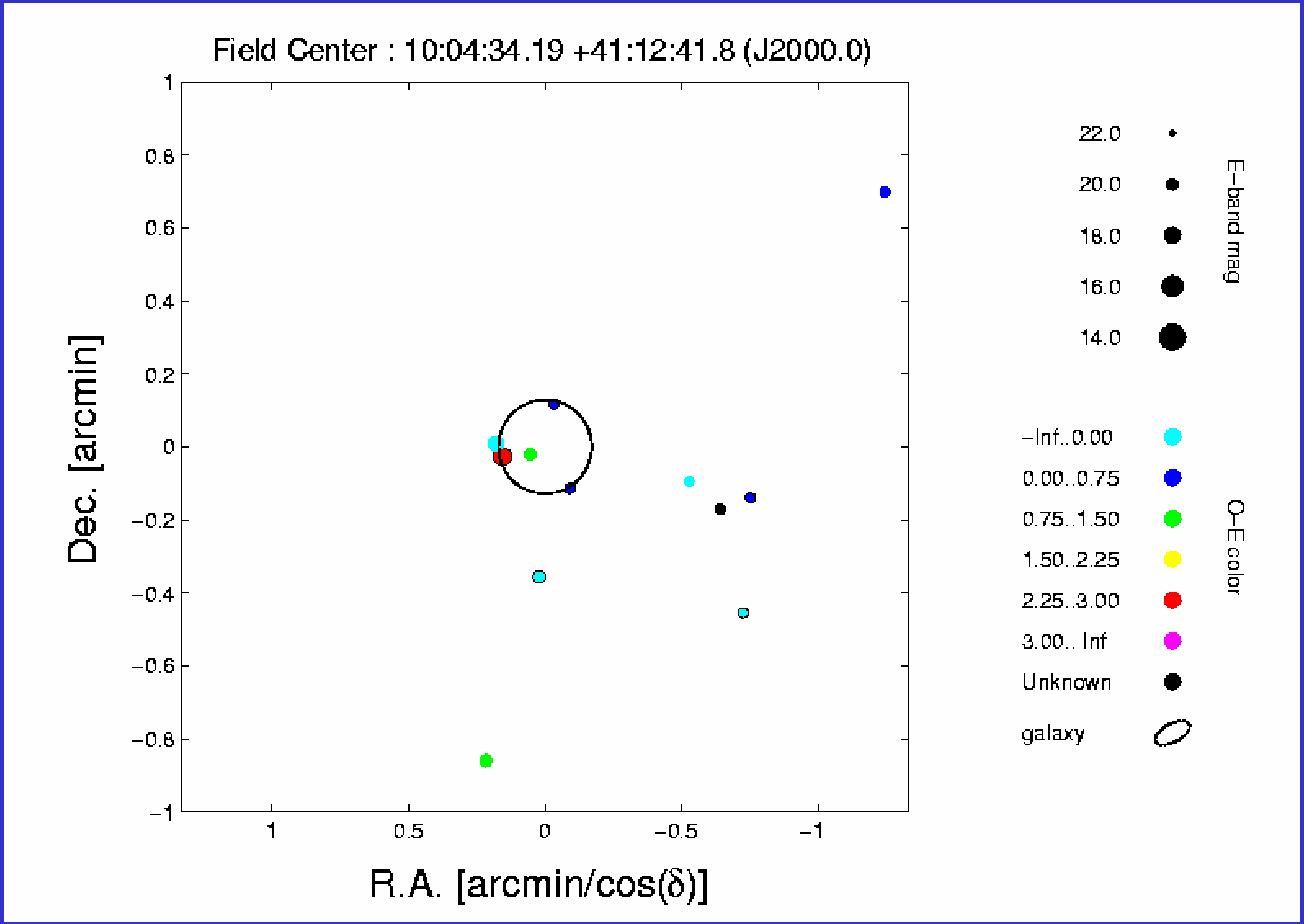
Brand new one from SDSS:
22” separation! (see Oguri’s poster)

Ofek et al. (2006): A search for wide quads in USNO-B:

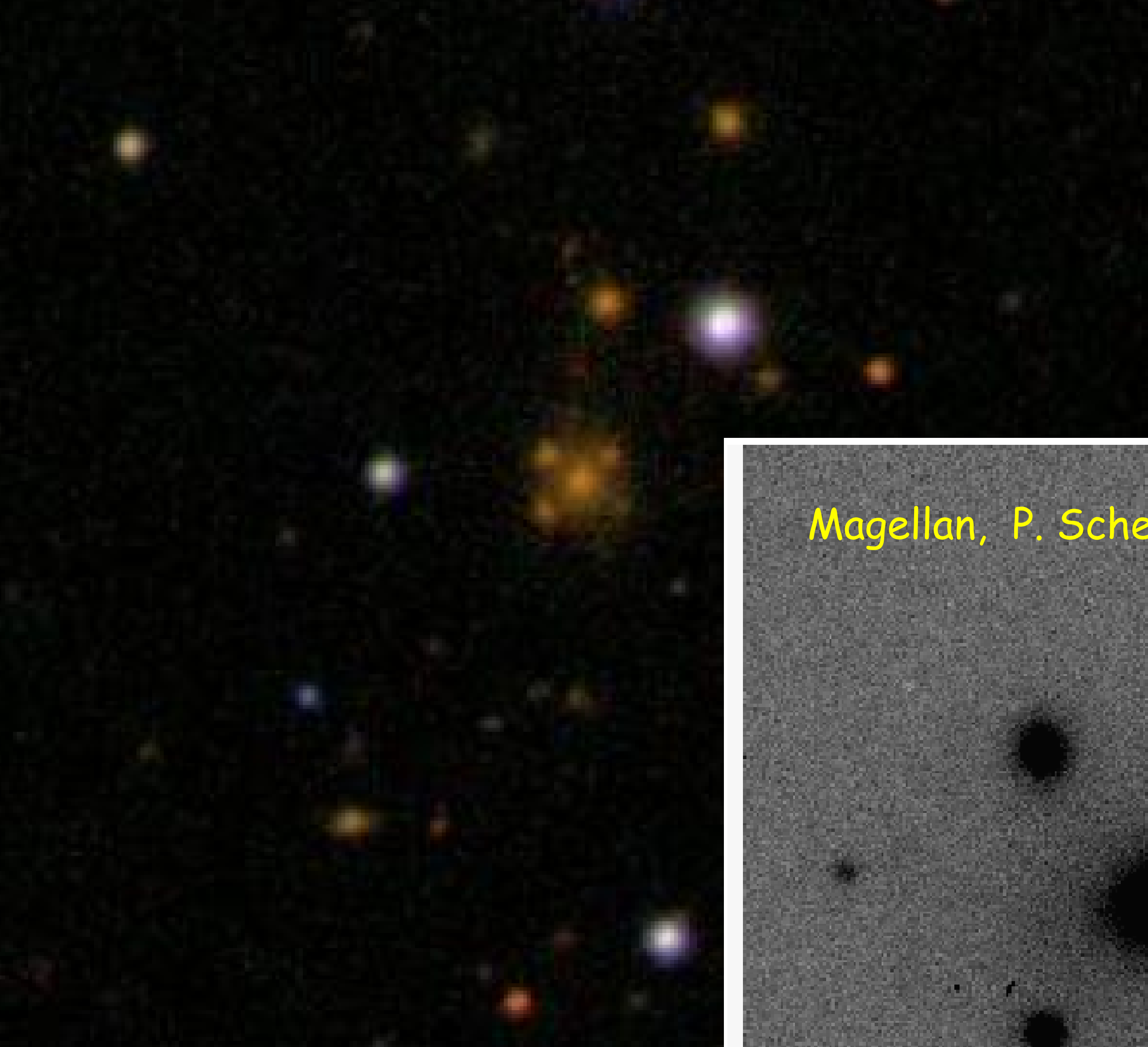
Ofek et al. (2006): A search for wide quads in USNO-B:

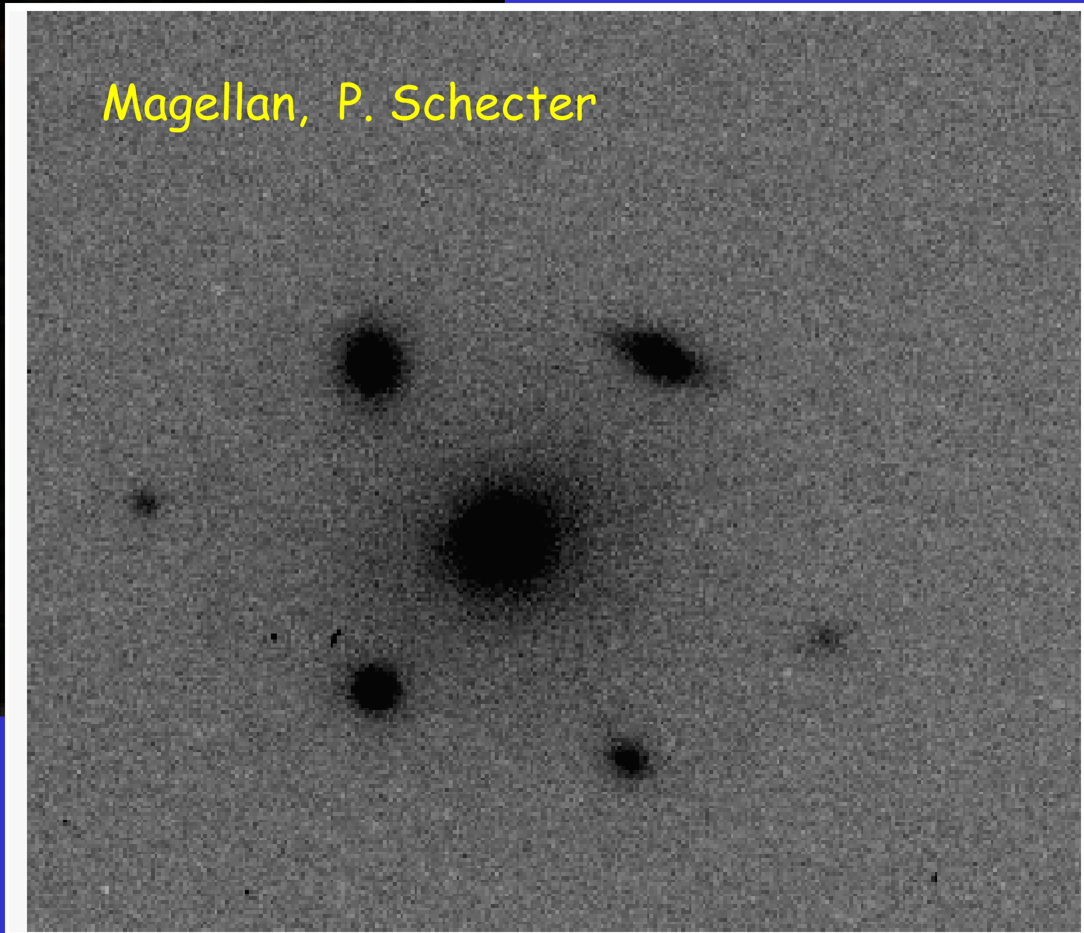






Field Center : 10:04:34.19 +41:12:41.8 (J2000.0)
Dec. [arcmin]
R.A. [arcmin/cos(δ)]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
1
0.5
0
−0.5
−1
22.0
20.0
18.0
16.0
14.0
E−band mag
−Inf..0.00
0.00..0.75
0.75..1.50
1.50..2.25
2.25..3.00
3.00.. Inf
Unknown
galaxy
O−E color




Magellan, P. Schecter

Observer

Lenses

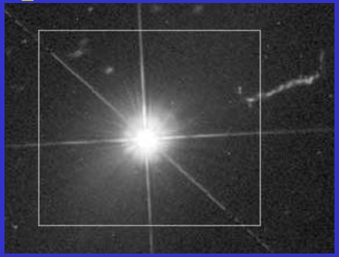
galaxies

clusters

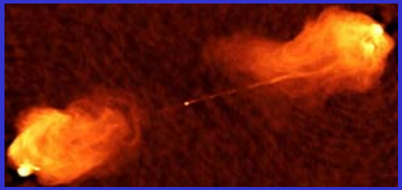
Sources

galaxies

optical QSOs



radio sources



Bartelmann et al. (1998) :

"Arc statistics":

Simulated ΛCDM clusters: $7 \times 10^{-3}\ \mathrm{deg}^{-2}$

Observed: $3.7 - 5.6 \times 10^{-2}\ \mathrm{deg}^{-2}$

- Observational studies:
- Zaritsky & Gonzalez (2003), Gladders et al. (2003)
- Recent: Sand et al. (2006)

- Theoretical studies:
- Meneghetti et al. (2000, 2003, 2005), Oguri et al. (2003), Wambsganss et al. (2004, 2005), Dalal et al. (2004), Tori et al. (2005), Puchwein et al. (2005).
- Recent: Hennawi et al. (2005), Ho & White (2005), Li et al. (2005, 2006), Fedeli et al. (2006), Rozo et al. (2006)

Horesh et al. 2005

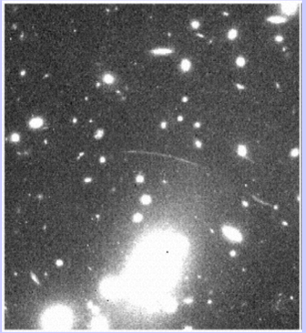
Observed sample: (Smith et al. 2004)

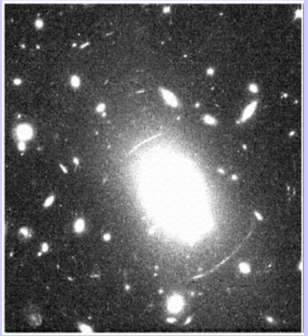
- Ten of the most X-ray luminous clusters with
  $L_x \geq 4.1 \times 10^{44}\ h_{70}^{-2} ergs\ s^{-1}$

- $0.17 \leq z \leq 0.25$

- HST → depth, resolution
  → include also faint arcs

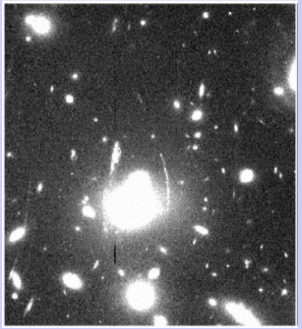
Abell 2219



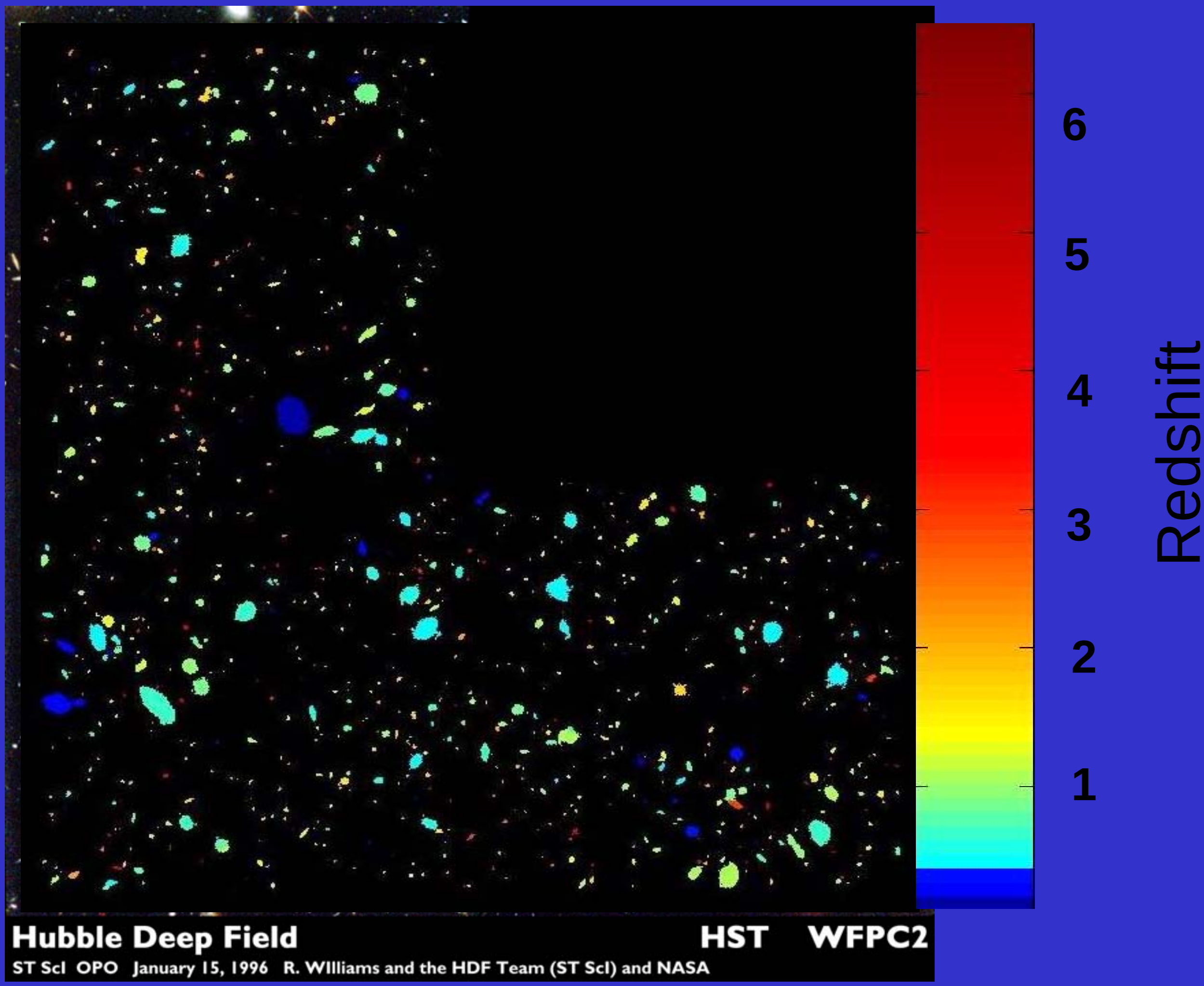


Abell 963

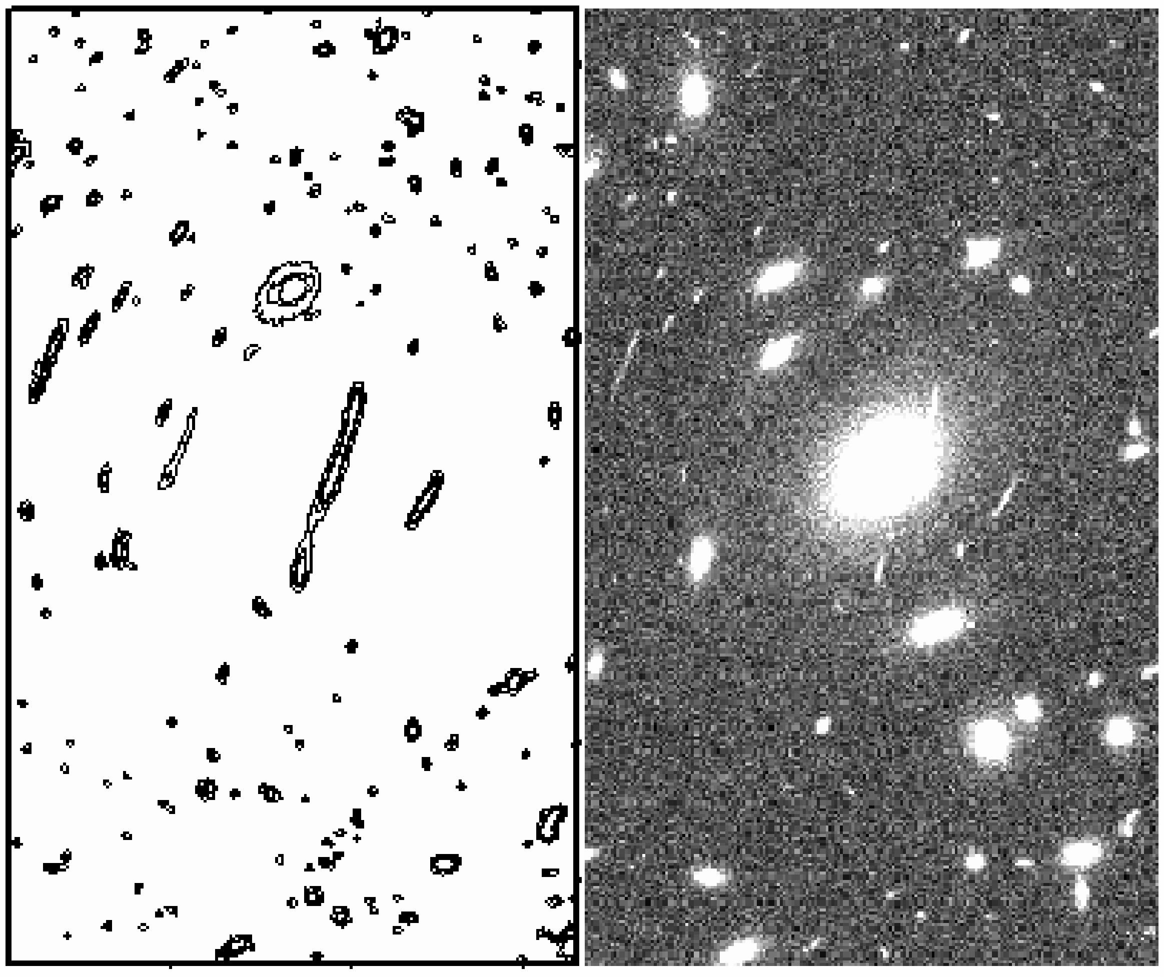
Abell 2218



Simulations:
Realistic source image



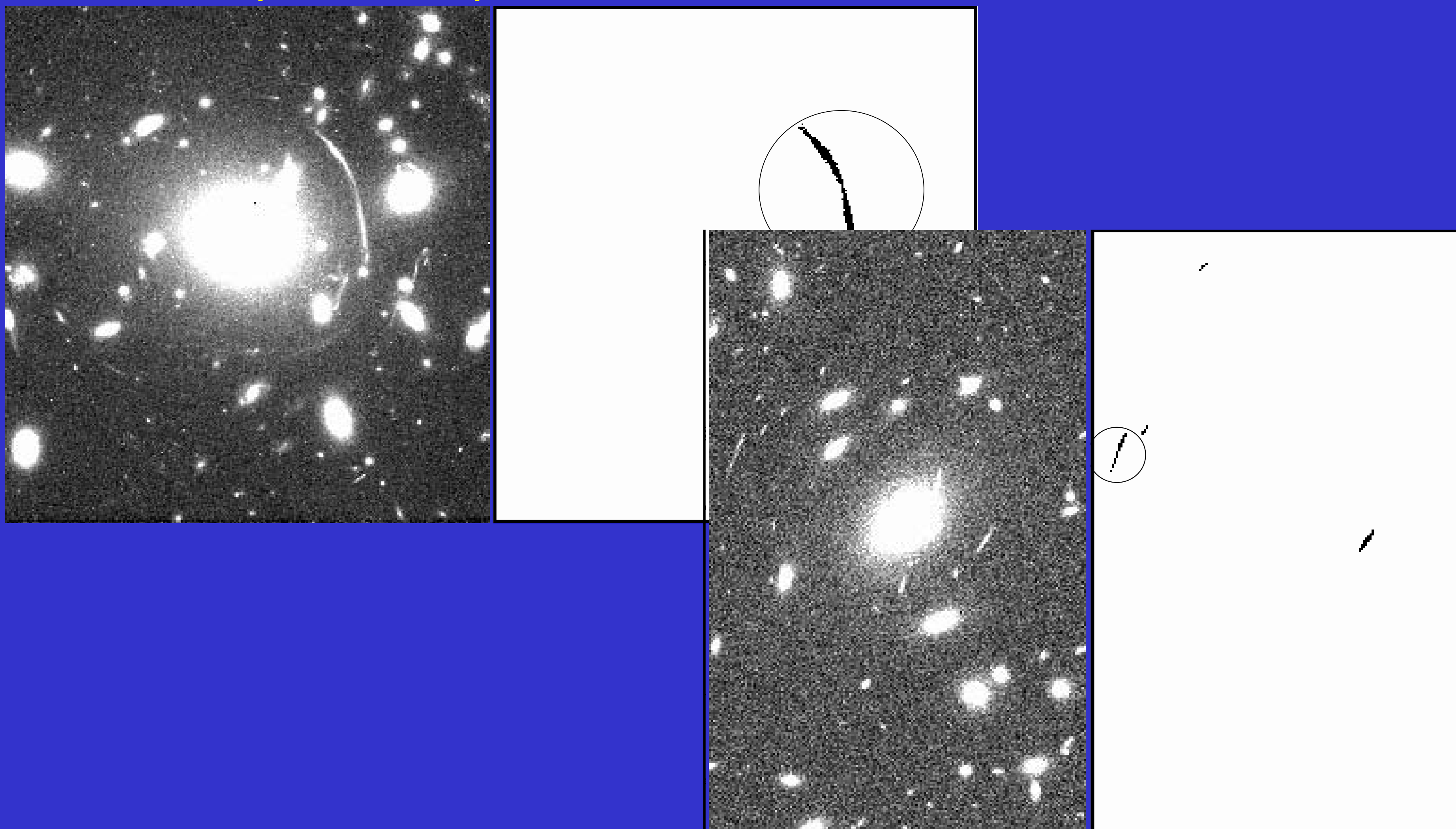
Lens HDF through N-body clusters, match all observational effects of real sample:



Automatic arc detection on real and simulated data:

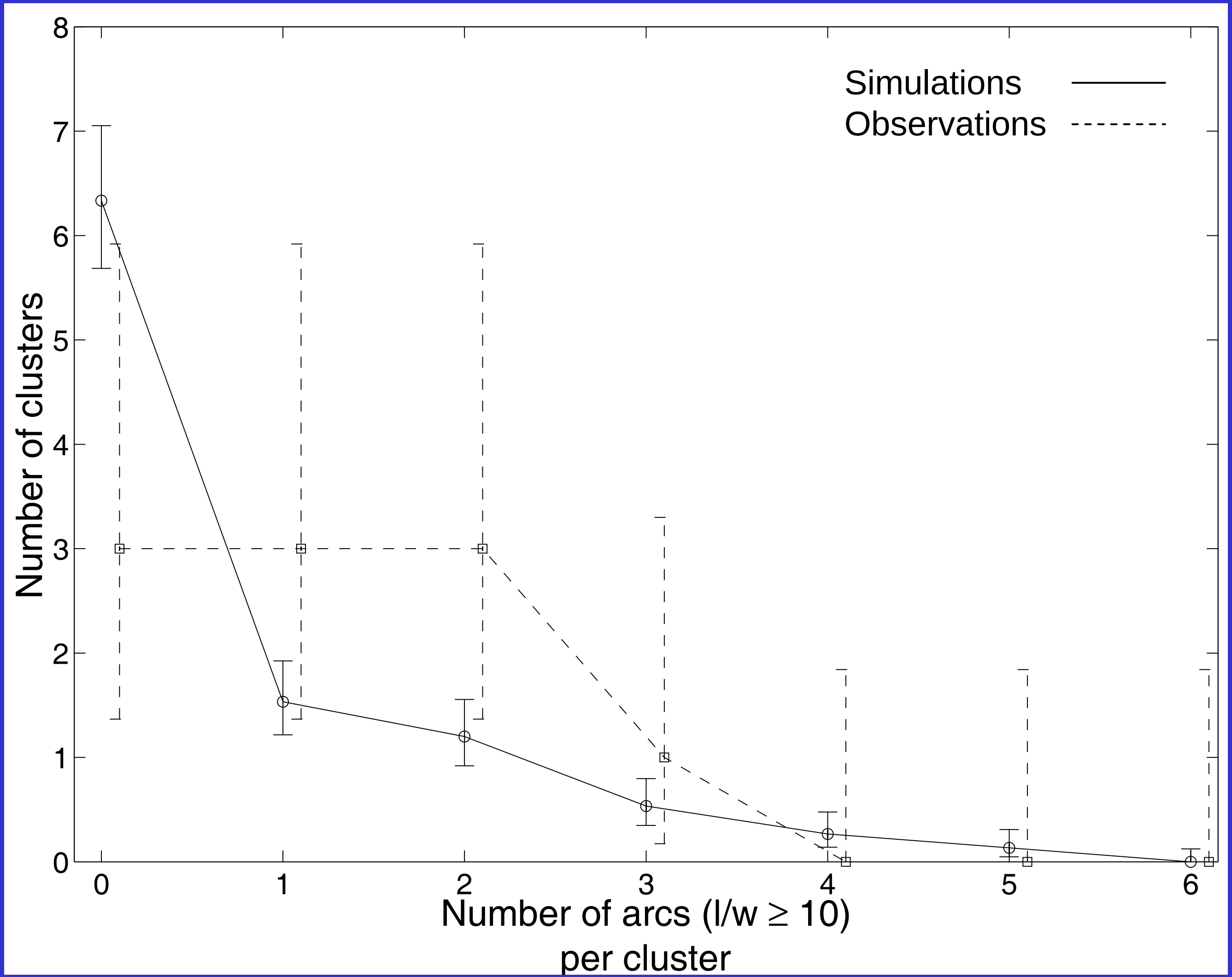
(also Lenzen at el. 2005, Alard 2006, Seidel & Bartelmann 2006)

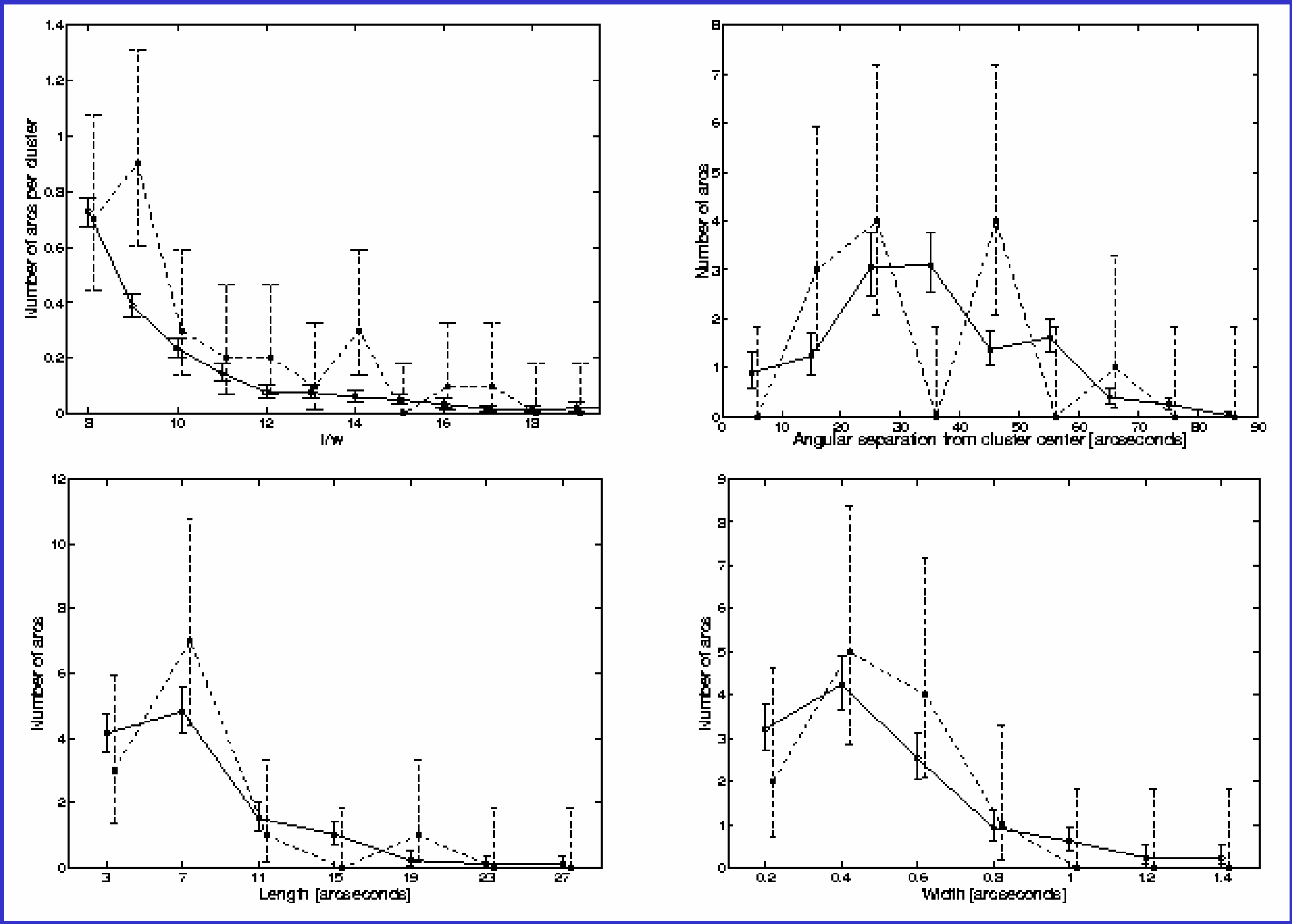
(Abell 383)



Results: No conflict in expected vs. observed arc abundance

Main problem in previous work: source flux distribution



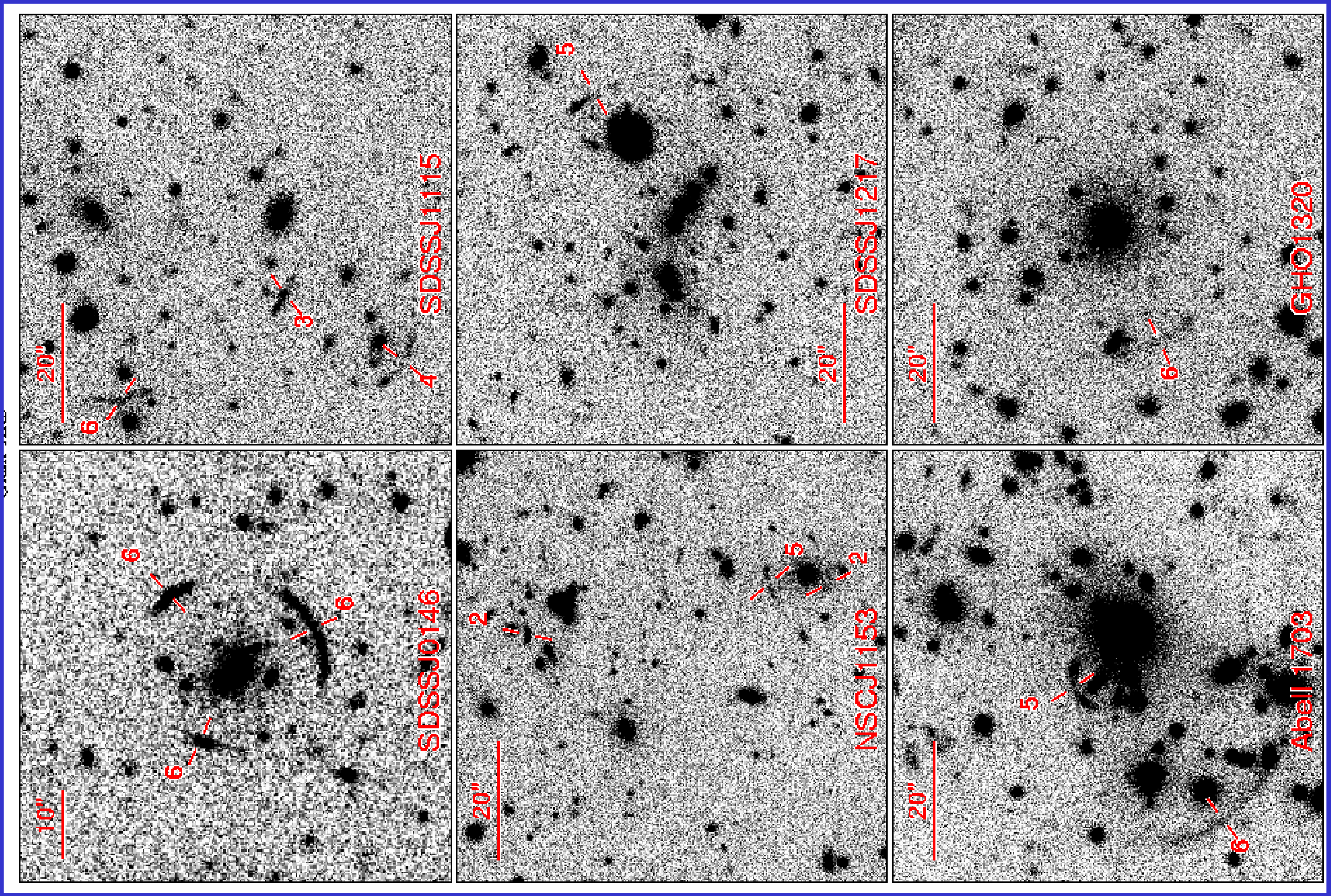


Number of arcs per cluster
l/w
Number of arcs
Angular separation from cluster center [arcseconds]
Number of arcs
Length [arcseconds]
Number of arcs
Width [arcseconds]

New arc surveys:

Hennawi et al. 2006: SDSS clusters + WIYN3.5m/UH2.2m

240 clusters, ~30 new cluster lenses.



(Near) future: "blind" arc surveys in wide and deep imaging surveys, e.g. CFHLS

0.5 degree (Subaru SuprimeCam)

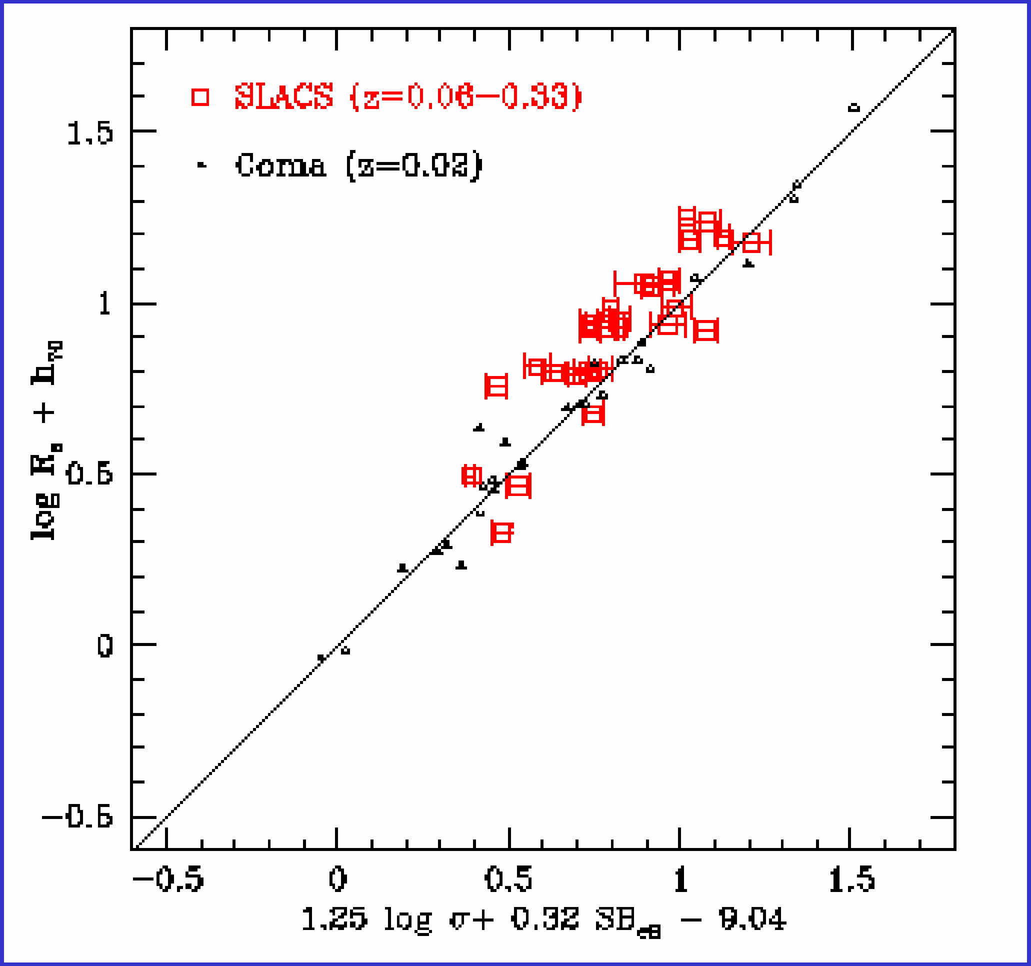
What have we learned?

0. **Not** cosmological parameters

1. Important to understand source populations, selection effects!

2. The dominant lenses are normal massive ellipticals …

Treu et al. 2006



What have we learned?

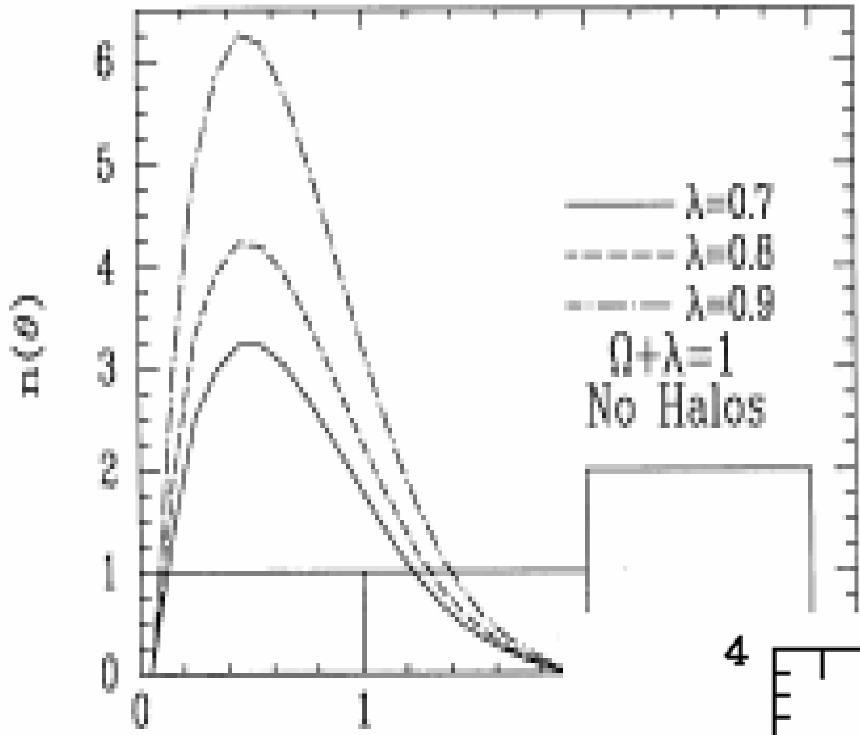
0. **Not** cosmological parameters

1. Important to understand source populations, selection effects!

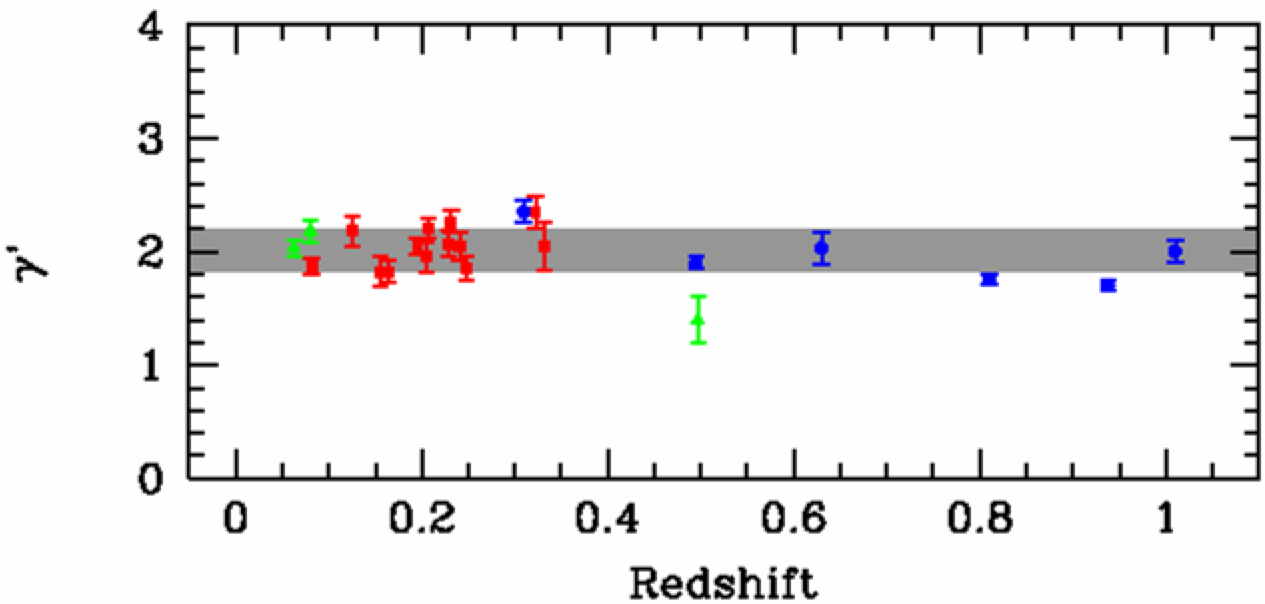
2. The dominant lenses are normal massive ellipticals …

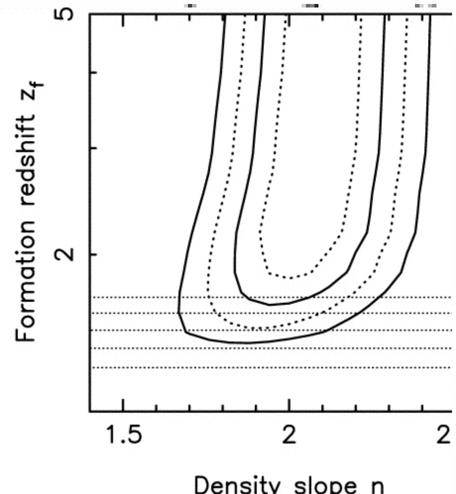
…with flat rotation curves …

Maoz & Rix 1993



Koopmans et al. 2006





Rusin & Kochanek 2005

What have we learned?

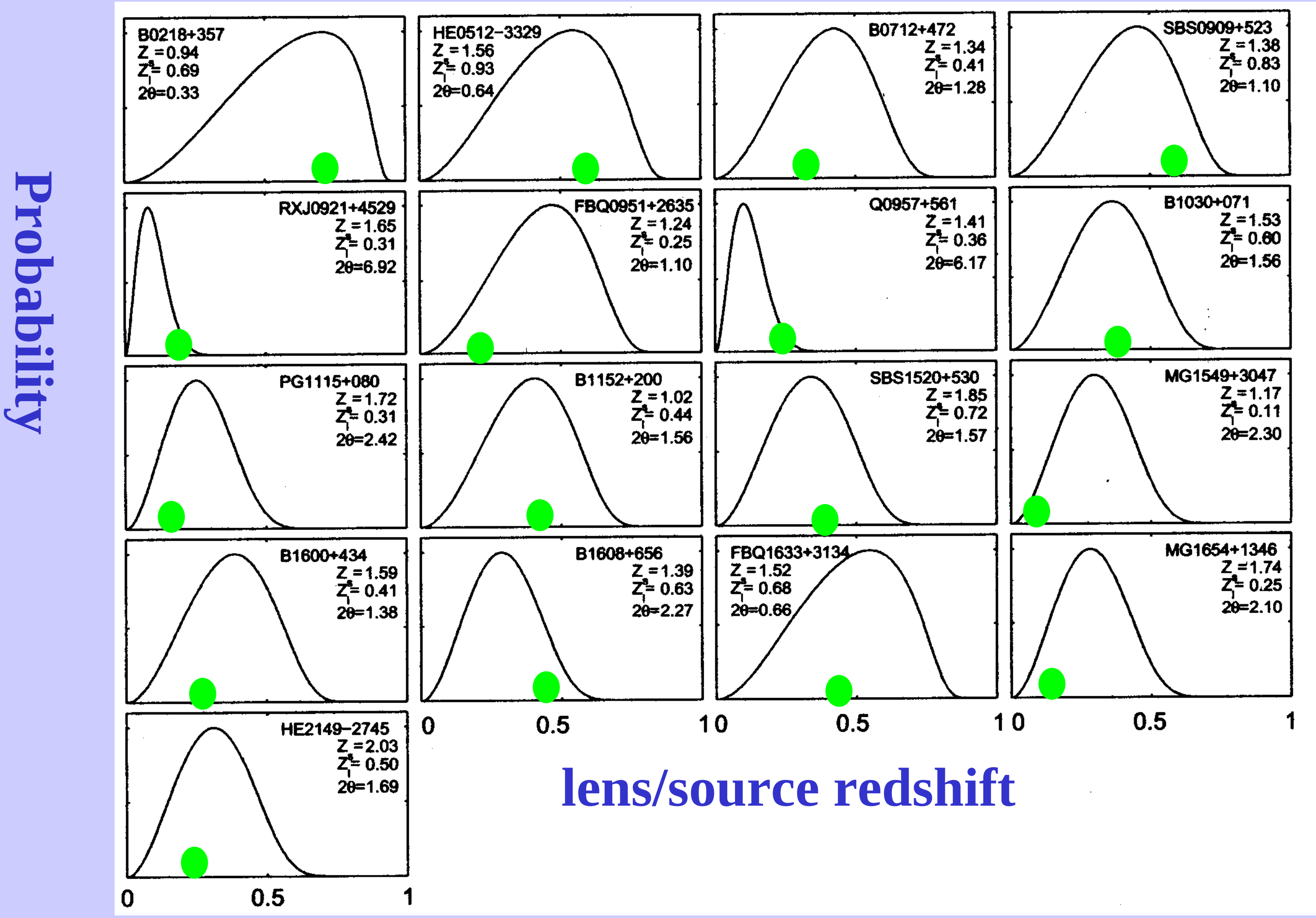
0. **Not** cosmological parameters

1. Important to understand source populations, selection effects!

2. The dominant lenses are normal massive ellipticals …with flat rotation curves …

…and little evolution out to z~1.

Ofek Rix & Maoz (2003)



→ $\sigma^*(z=1) > 0.63\ \sigma^*(0)$ (95% confidence);

most E galaxy mass was already in place by z~1

What have we learned?

0. **Not** cosmological parameters

1. Important to understand source populations, selection effects!

2. The dominant lenses are normal massive ellipticals …with flat rotation curves … and little evolution out to z~1.

3. New systems for study, both as individuals and as complete samples.

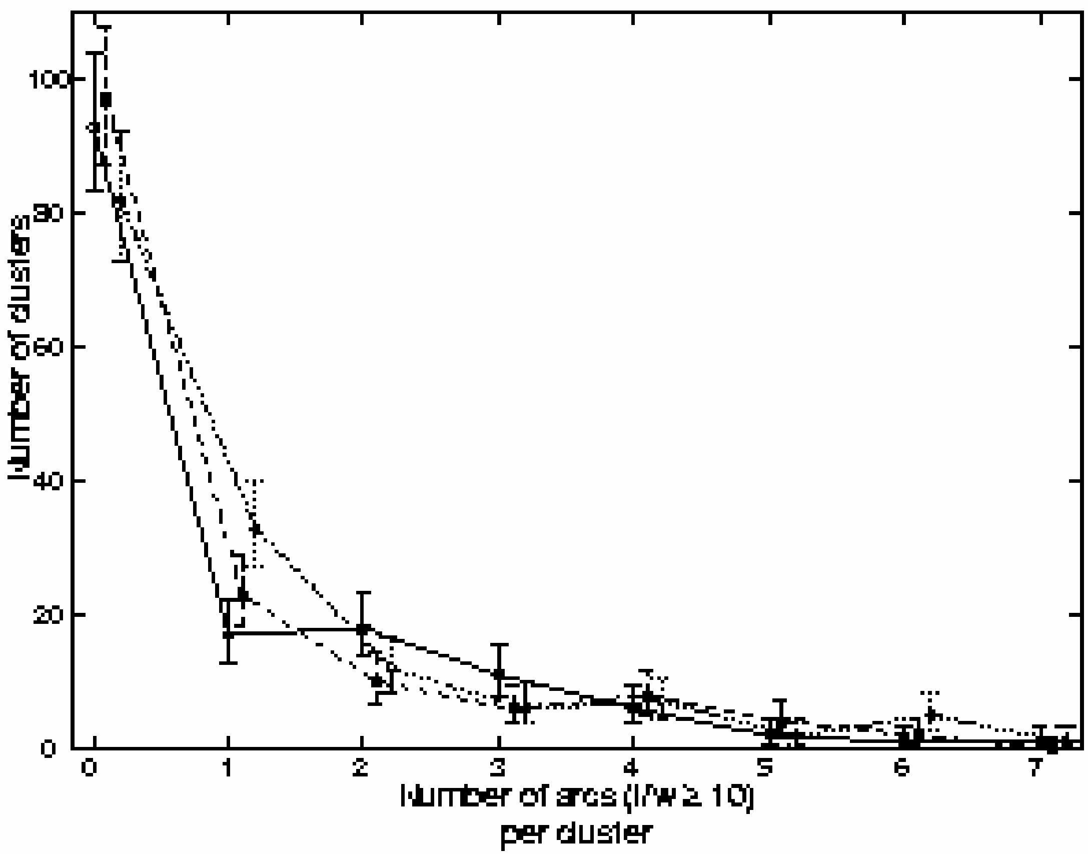


FIG. 3.— Distribution of detected arcs per cluster with $l/w \geq 10$ in the simulations, for different assumed source redshifts. Circles and solid lines represent the simulations in which sources with real photometric redshifts were lensed. Squares and dashed lines result when all sources are assigned a redshift $z_s = 1$. Diamonds and dotted lines are for all sources at $z_s = 1.5$. Poisson error bars are shown. Here and in subsequent figures, a slight offset in the horizontal direction has been induced between the curves, for the sake of clarity

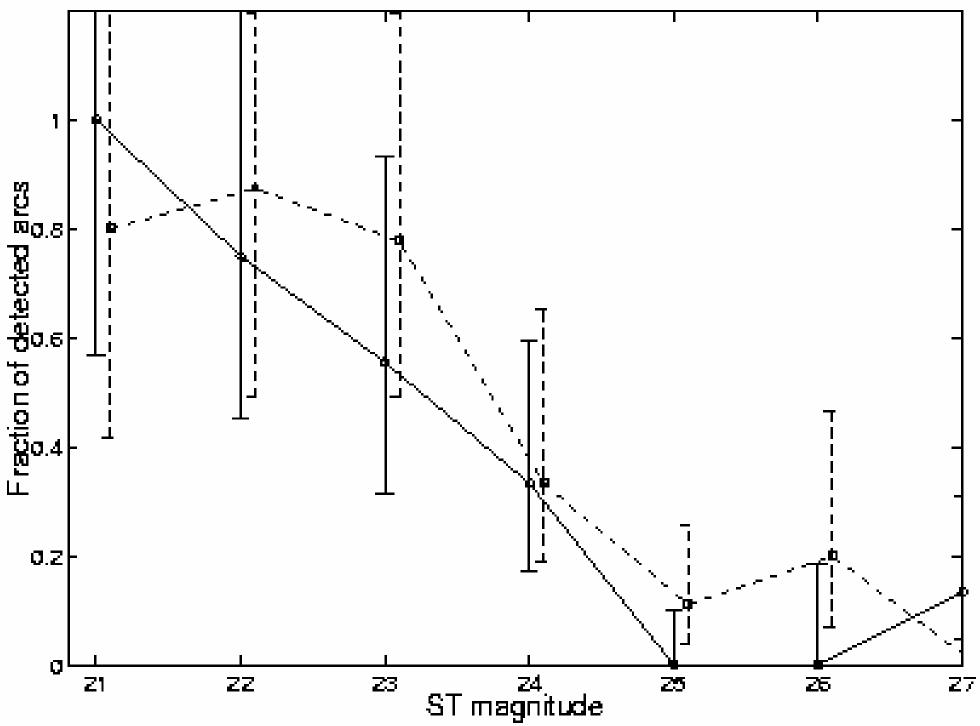


FIG. A2.— Giant arcs ($l/w \geq 10$) detected in 10 simulated lensed images with observational effects as a fraction of the arcs found in the same images without observational effects, for our arc-finding algorithm (solid line), and the Lenzen et al. (2004) algorithm (dashed line). Poisson errors are indicated.

Galaxy evolution?