# The SDSS Quasar Lens Search

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and

The SDSS Lensers

The Sloan Digital Sky Survey: from Asteroids to Cosmology
15 August 2008 @ Chicago Merchandise Mart

# Motivation-1

**Lensed Quasars** are unique tools for …..

- individual mass models K
  mass distribution & substructure of lensing galaxies.
- absorption lines in multiple QSO images K
  interstellar medium of lensing galaxies.
- microlensing K
  host galaxies & accretion disks of source QSOs.
- statistics, time delay K
  cosmology…. dark energy, Hubble constant.
- cluster scale lensed quasars K
  dark matter distributions in galaxy clusters.

# Motivation-2

~100 lensed quasars have studied with various methods and wavebands. In particular, the CLASS, the HST survey, etc. have done great works but …..

- lack of *completely* homogeneous and large statistical samples.

2. lack of "cluster-scale" lensed quasars.

To construct the largest lensed quasar catalog, we are now carrying out "**The SDSS Quasar Lens Search** (SQLS)".

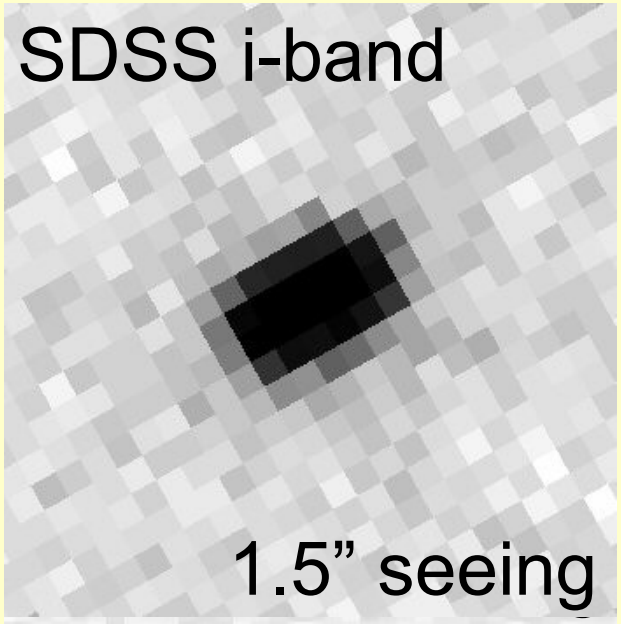
The *100,000* spectroscopically confirmed SDSS Quasars will allow us to make the largest complete statistical sample, and the first discovery of cluster scale lensed quasars.

# Problem for Searching LQs in the SDSS

A serious problem for searching lensed quasars in the SDSS data is ….

- pixel scale of images = 0.4”
- typical seeing size of ~1.3”
- spatial resolution of spectroscopy = 3.0”

typical separation of lensed quasars is K~1.0”




We developed a selection algorithm based on the nature of the first SDSS lensed quasar, J1226K0006, which has been *manually* discovered from the SDSS commissioning data.

# Flowchart of our Lens Identification

## 1. SDSS QSOs

We have surveyed 90% of the SDSS data, ~90,000 QSOs.

## 2. Selection Algorithm

We use **morphologies** for unresolved (K 2.5") objects and **colors** for deblended (K 2.5") objects.

## 3. Candidates

**~600 candidates**.
~100 objects have no follow-up obs.

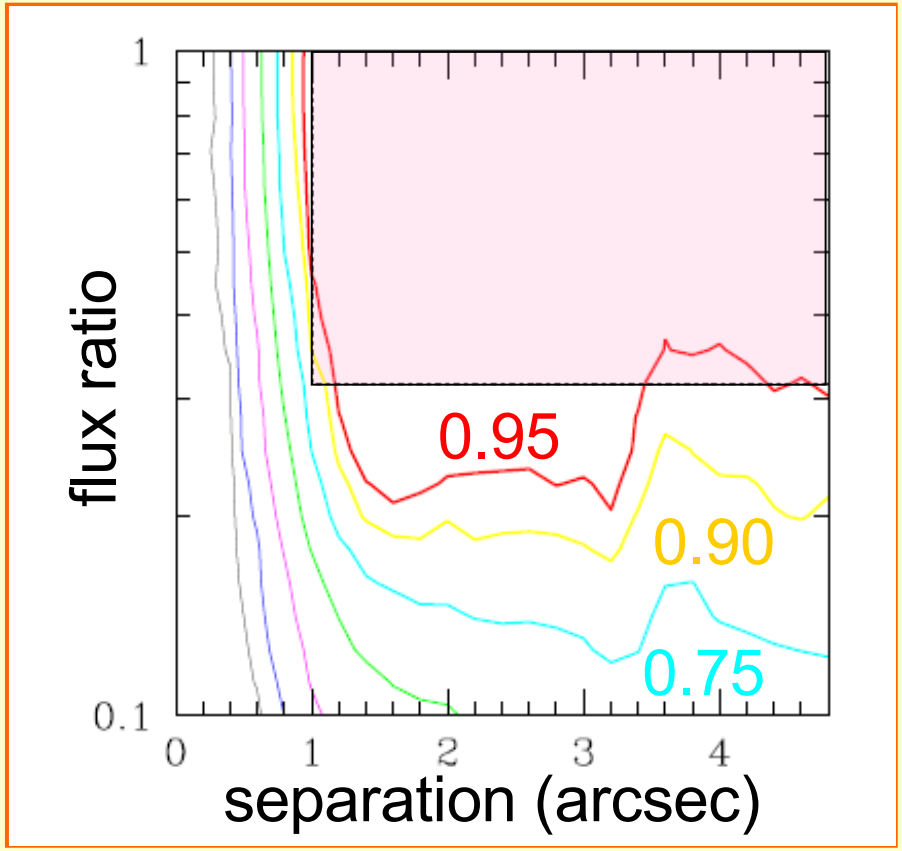
## 4. Follow-up Observations

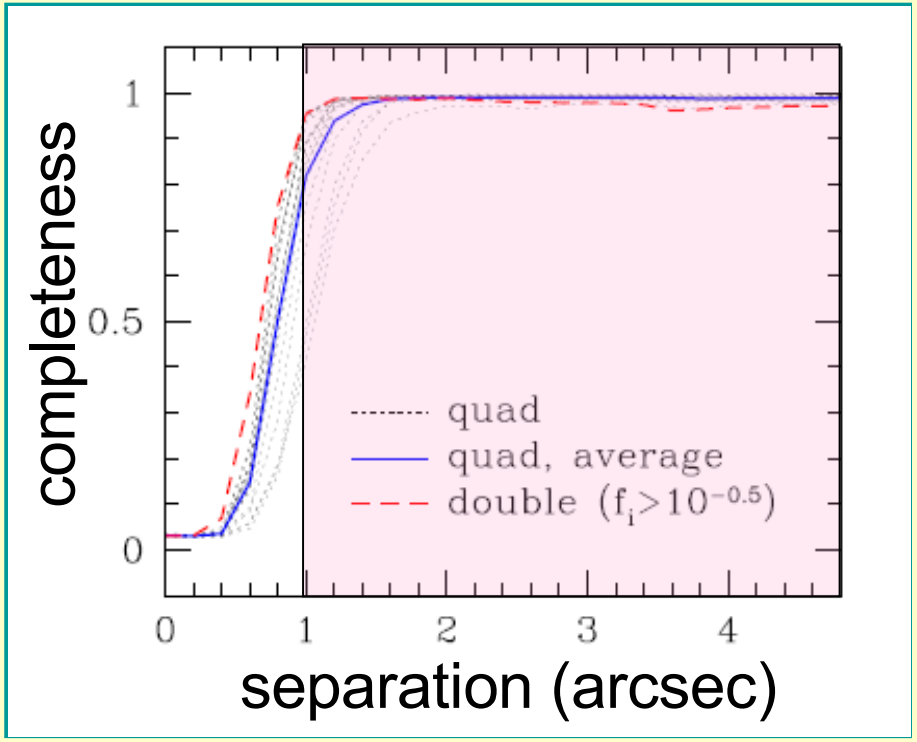
We then conduct **follow-up observations** for the candidates.

## 5. Confirmed Lensed Quasars

Confirmation is made by both existences of **lensing objects** AND **identical SEDs** of lensed images.

# Completeness of our Selection Method




<u>double lenses</u>: 95%, 90%, 75%, 50%, 25%, 10%, 5%.

*complete for f > 0.32 and m> 1.0”*

<u>quadruple lenses</u>: blue solid line. (red dotted line is completeness for doubles.)

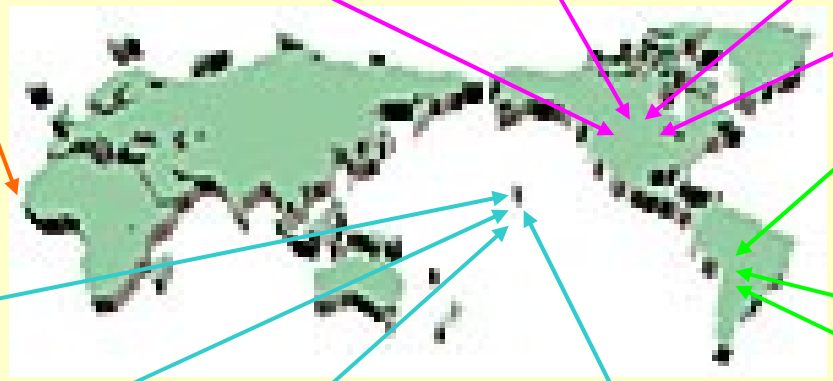
*complete for m> 1.0”*

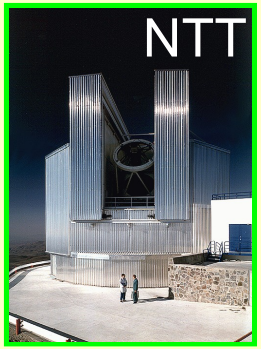
# Telescopes for follow-up

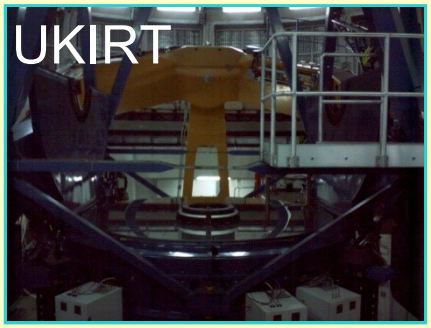

chandra




WIYN

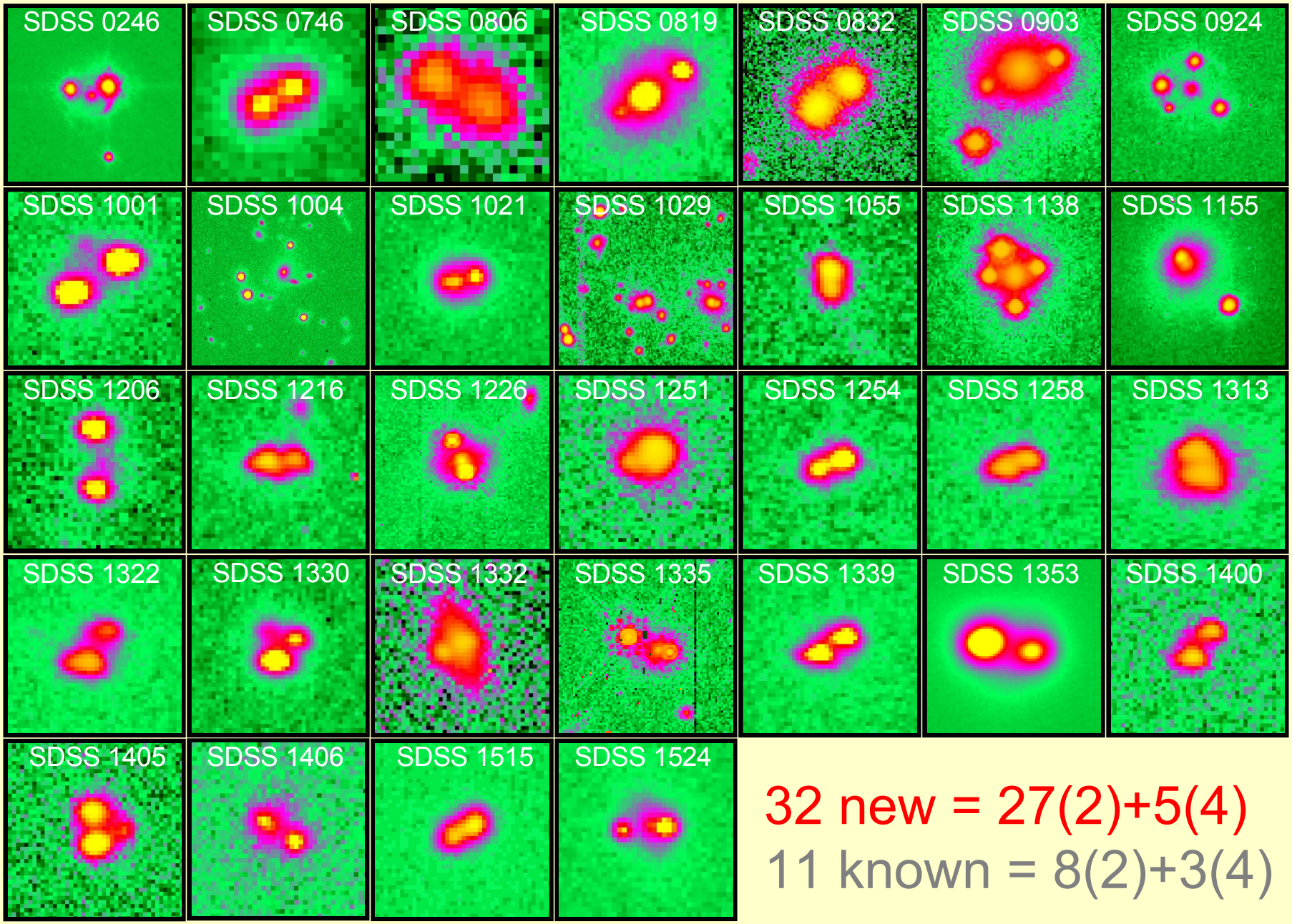







# Results!




32 new = 27(2)+5(4)

11 known = 8(2)+3(4)

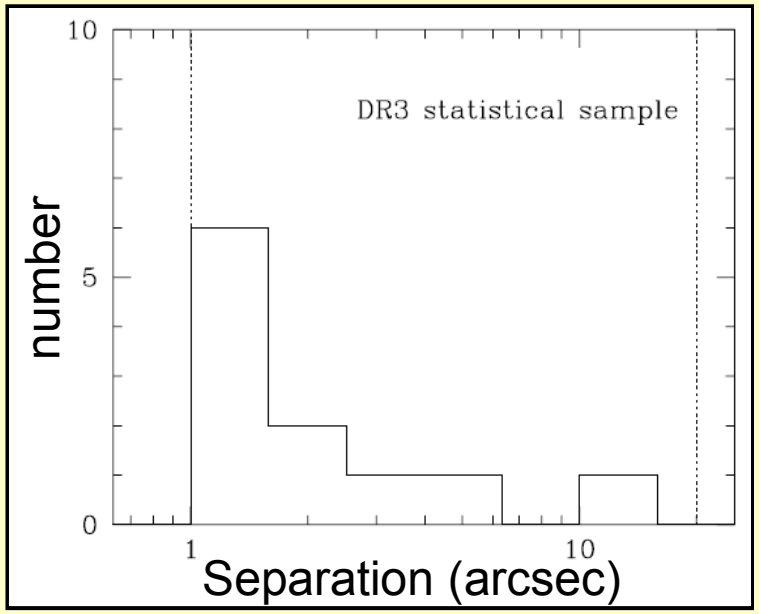
# SDSS DR3 Statistical Sample

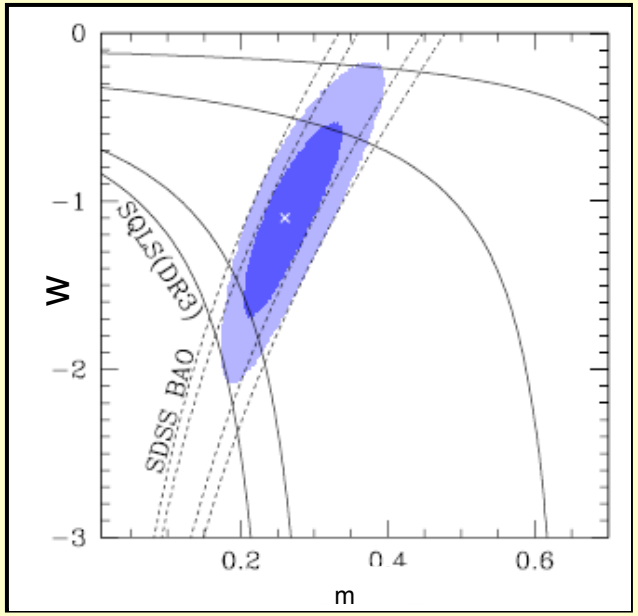
From the discoveries, we constructed our first statistical sample for quasars of the SDSS Data Release 3.

Source: 22,683 QSOs from the SDSS DR3 (with 0.6 < z < 2.2, i < 19.1, and seeing < 1.8")

Candidate: total 220 candidates (90 by morphology, 132 by color, 2 duplicates)

Lenses: 22 lensed quasars. 11 lenses are in our "complete" survey region, 1.0" < K < 20.0" and f > 0.32.




for w = K1 :

$K_K$ = 0.74

for w K K1 :

$K_m$ = 0.26

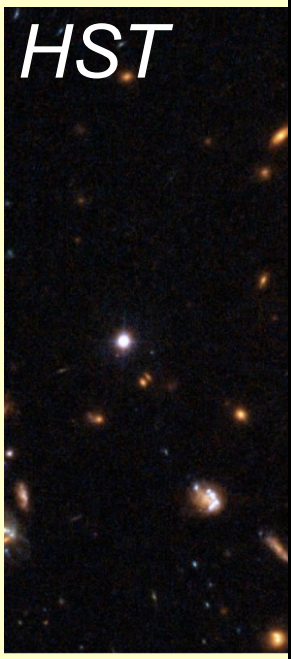
w = K1.1

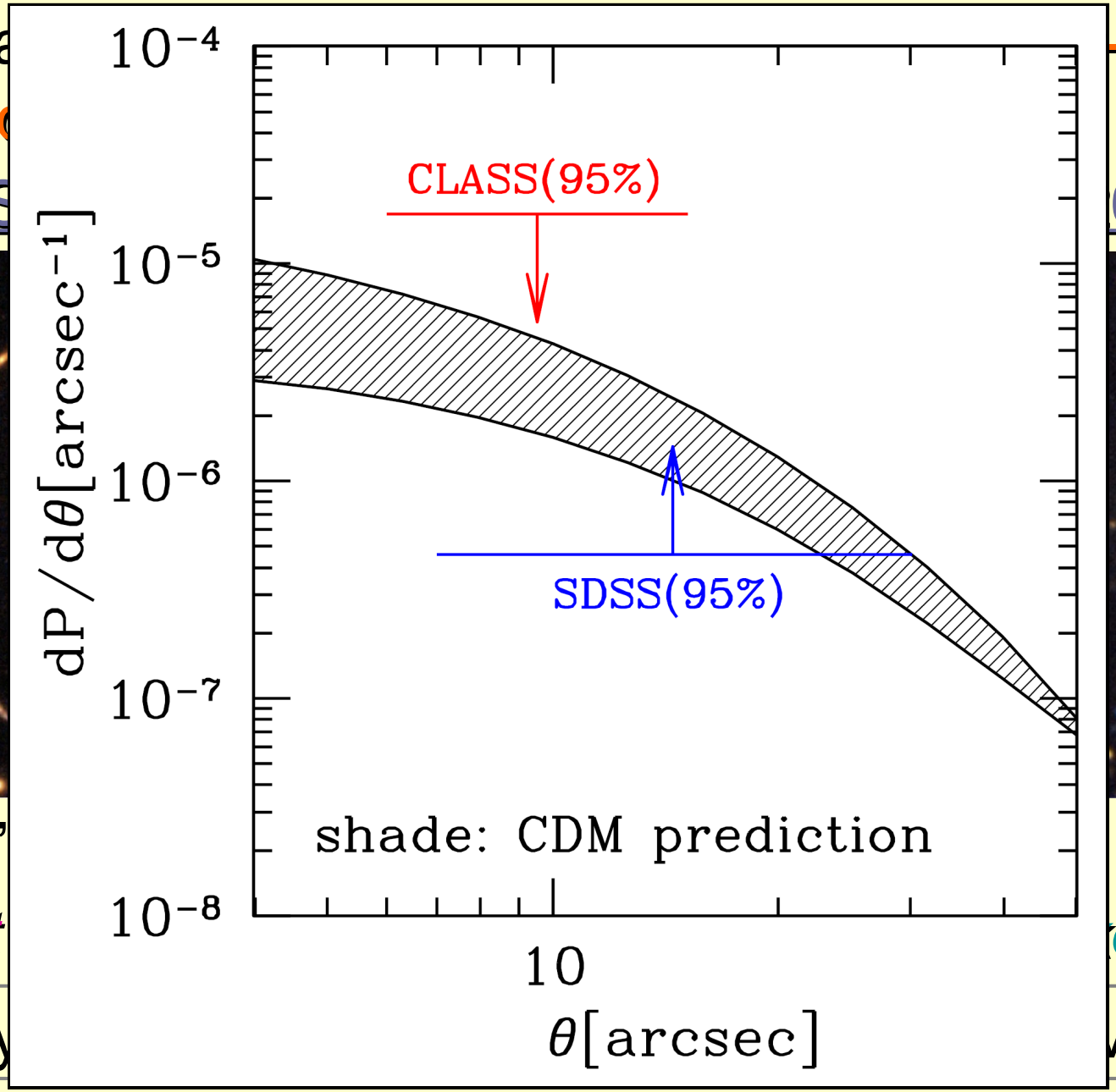
# Discovery of 2 Cluster Scale Lenses

We ha -scale

lense

SDS 623





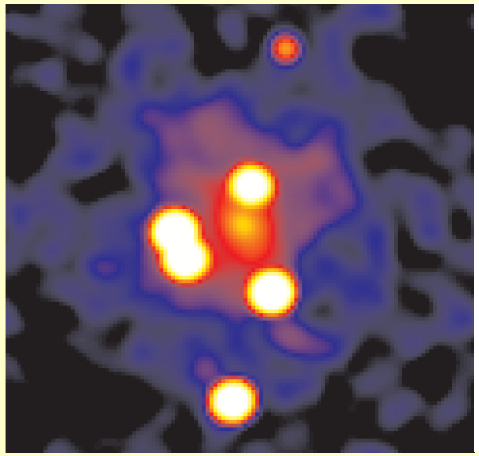
´ = 14.6" $z_L$=0.60

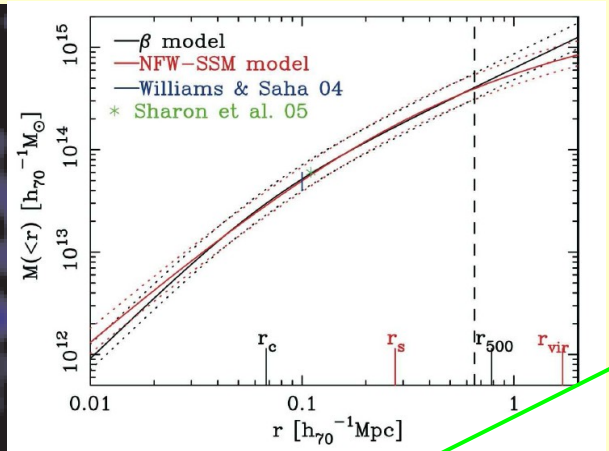
The *first* *ed cusp*

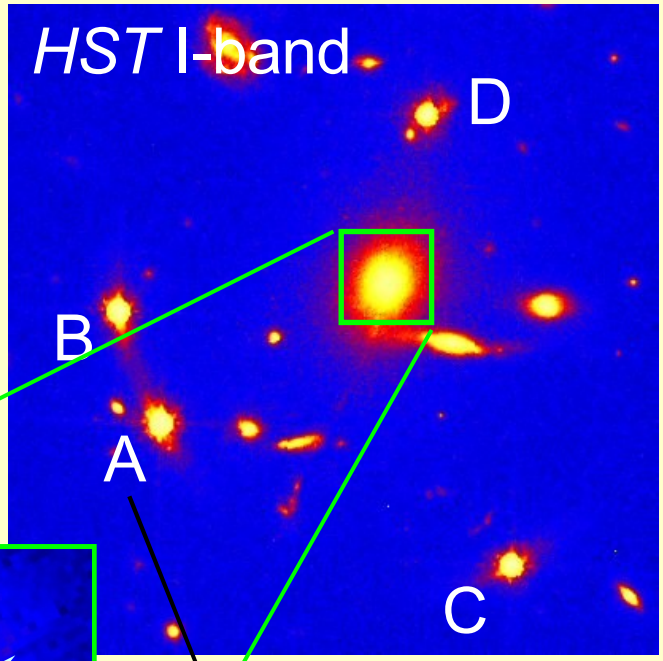
They vidually.

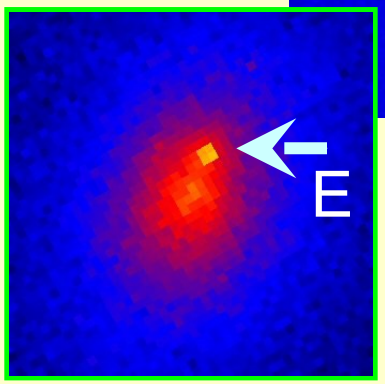
# Discoveries from SDSSJ1004+4112

## Chandra image K

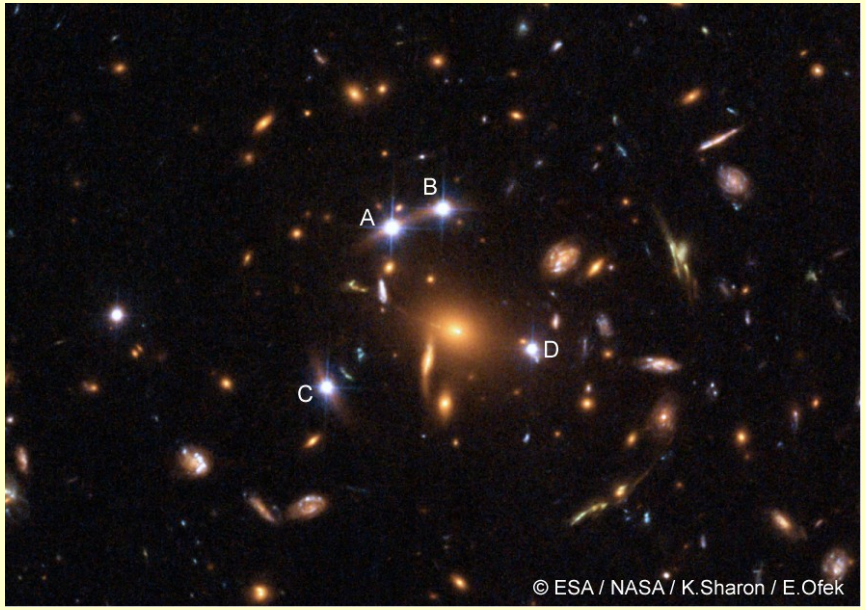




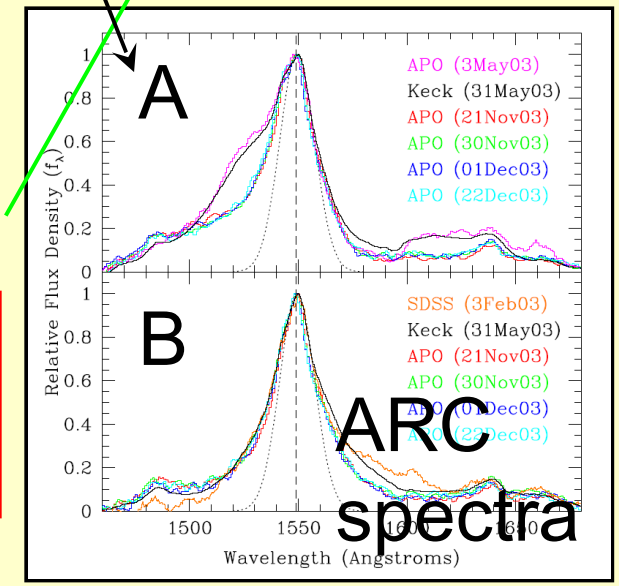

## HST image K




$Kt_{AB}$=40.6

$Kt_{AC}$=821.6

Fohlmeister et al.




ARC spectra

# Summary

- We are now carrying out "The SDSS Quasar Lens Search, which discovered 32 lensed quasars, including 2 cluster-scale lensed quasars with large separations. The SQLS is the current largest lensed quasar survey!
- From these discoveries, we have completed our first statistical sample from the SDSS DR3. The constraint for dark energy is consistent with the results from SN survey and WMAP.
- At the end of the SDSS (I &II), we are completing our lensed quasar survey. The statistical sample from DR5 is coming soon, and the final statistical sample from DR7 is expected to be constructed within a few years.

# References


slide-2:
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Fukugita et al. 1990, MNRAS, 264, 24
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Mao & Schneider 1998, MNRAS, 295, 587
Narayan & White, 1988, MNRAS, 231, 97
Refsdal 1964, MNRAS 128, 307
Turner 1990, ApJ, 365, L43
and MANY

slide-3:

Browne, et al. 2003, MNRAS, 341, 13
Maoz et al. 1993, ApJ, 409, 28
Munoz et al. 2003, Apj, 605, 614
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Schneider et al. 2007, AJ, 134, 102

slide-4:
None

slide-5:
Inada et al. 2008, AJ, 135, 496

slide-6:
Oguri et al. 2006, AJ, 132, 999

slide-7
none

slide-8:
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Richards et al. 2004, ApJ, 610, 679
Sharon et al. 2005, 629, L73
Fohlmeister et al. 2008, ApJ, 676, 761

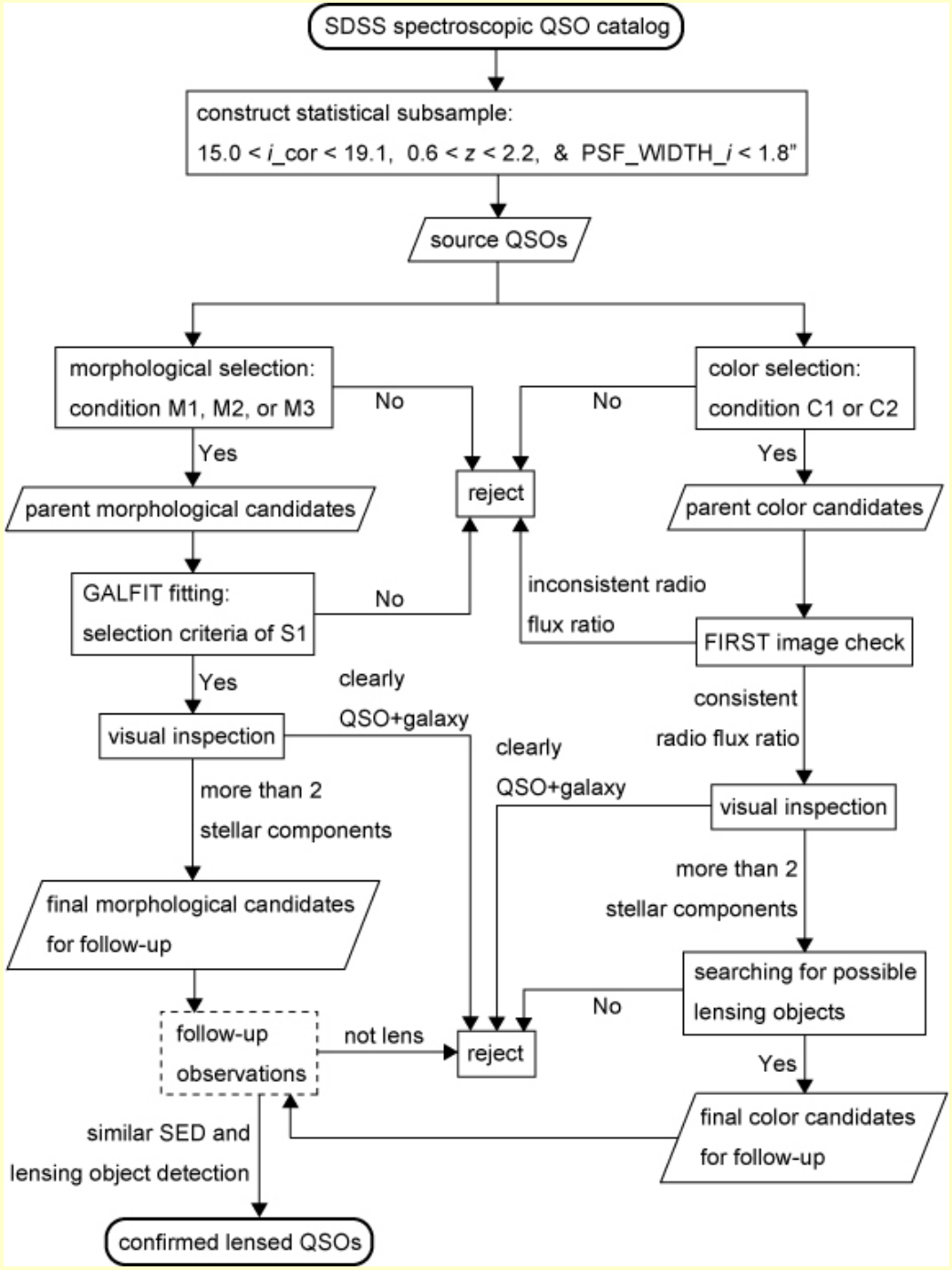
CLASS:

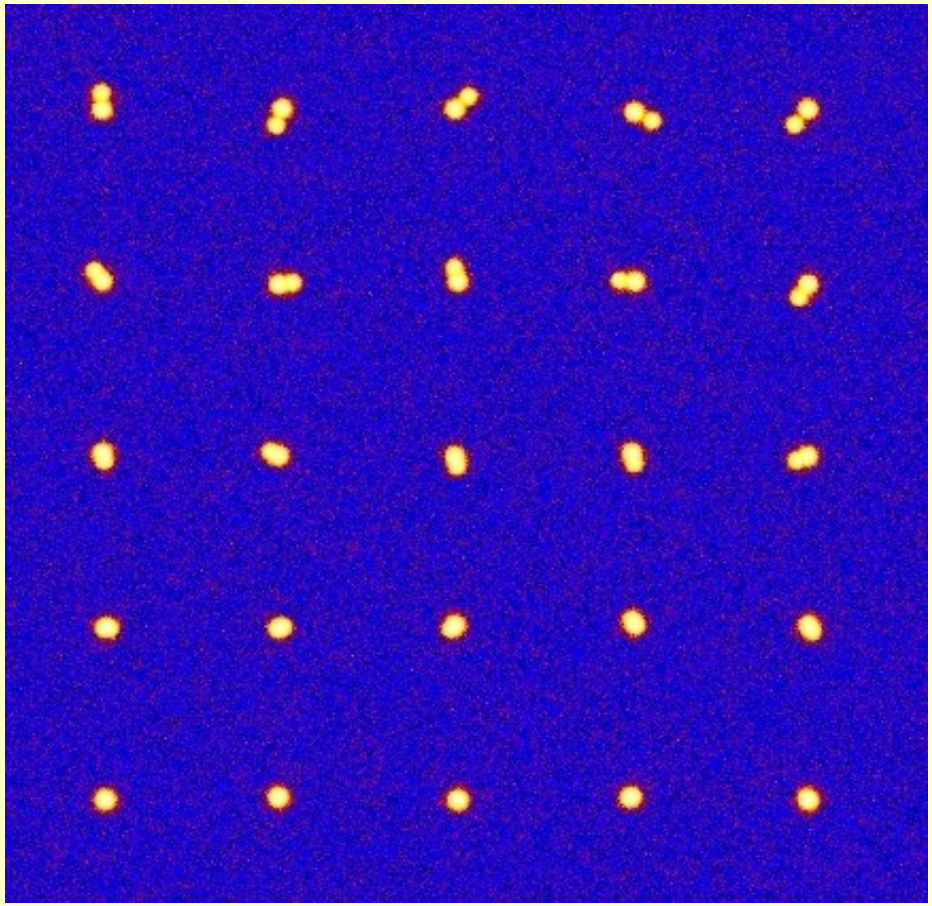
22 lenses from 16,000 radio sources.

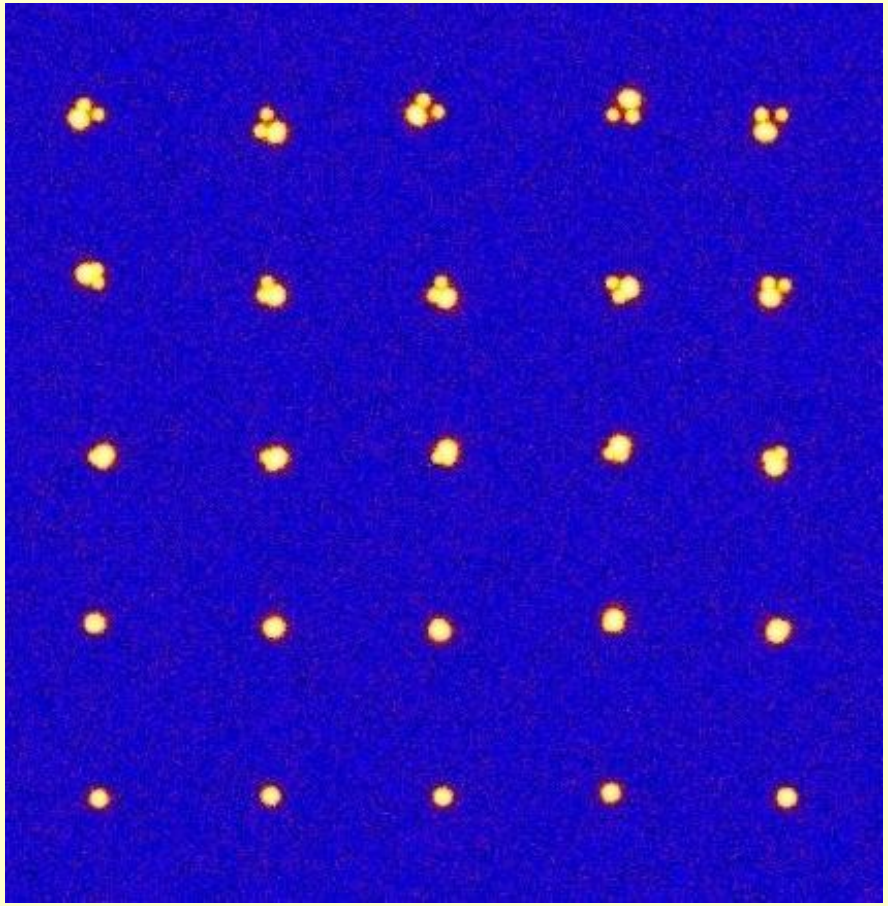
(13 statistical sample from 8,958 radio source)

HST Snap Shot Survey:

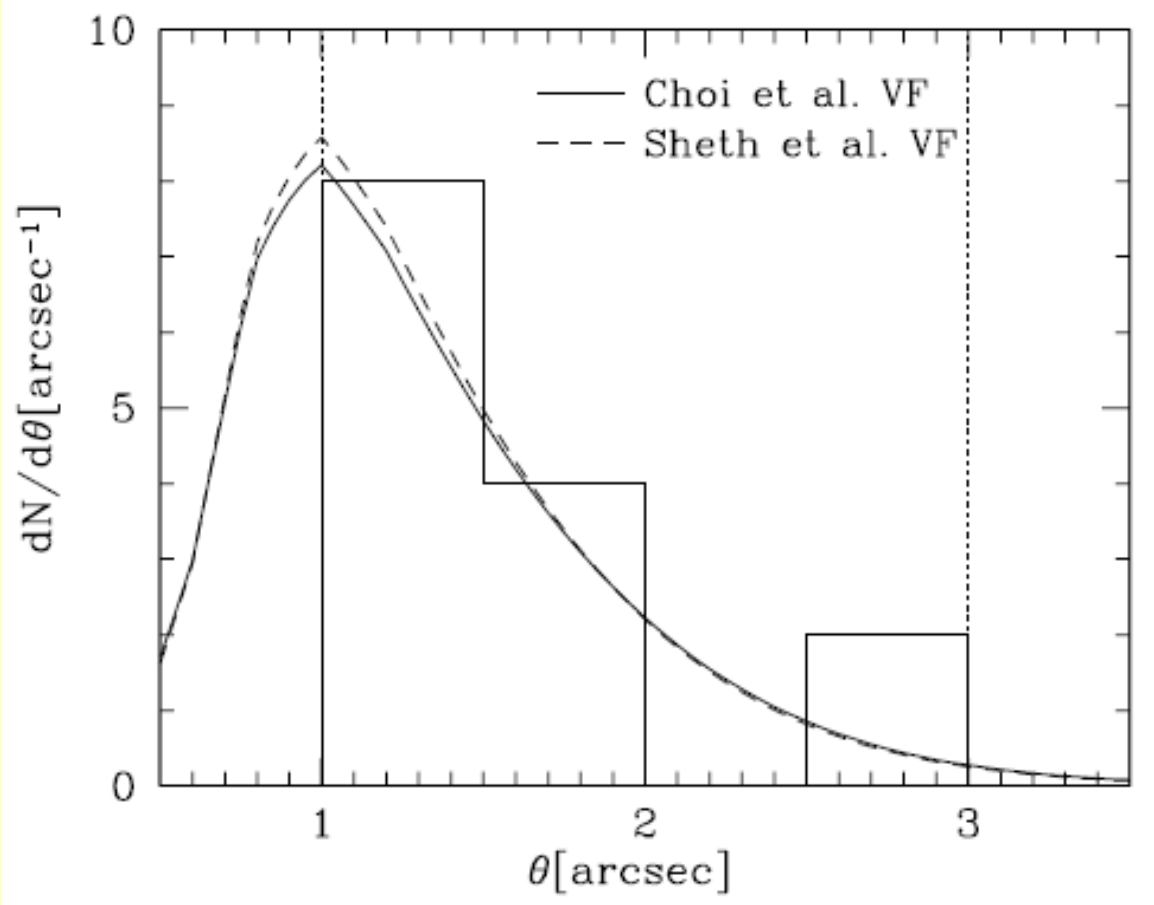
3~6 lenses from 500 quasars.


SDSS spectroscopic QSO catalog
construct statistical subsample:
15.0 < i_cor < 19.1, 0.6 < z < 2.2, & PSF_WIDTH_i < 1.8"
source QSOs
morphological selection:
condition M1, M2, or M3
No
Yes
color selection:
condition C1 or C2
No
Yes
reject
parent morphological candidates
parent color candidates
GALFIT fitting:
selection criteria of S1
No
inconsistent radio
flux ratio
FIRST image check
Yes
clearly
QSO+galaxy
consistent
radio flux ratio
visual inspection
clearly
QSO+galaxy
visual inspection
more than 2
stellar components
more than 2
stellar components
final morphological candidates
for follow-up
searching for possible
lensing objects
No
follow-up
observations
not lens
reject
Yes
final color candidates
for follow-up
similar SED and
lensing object detection
confirmed lensed QSOs





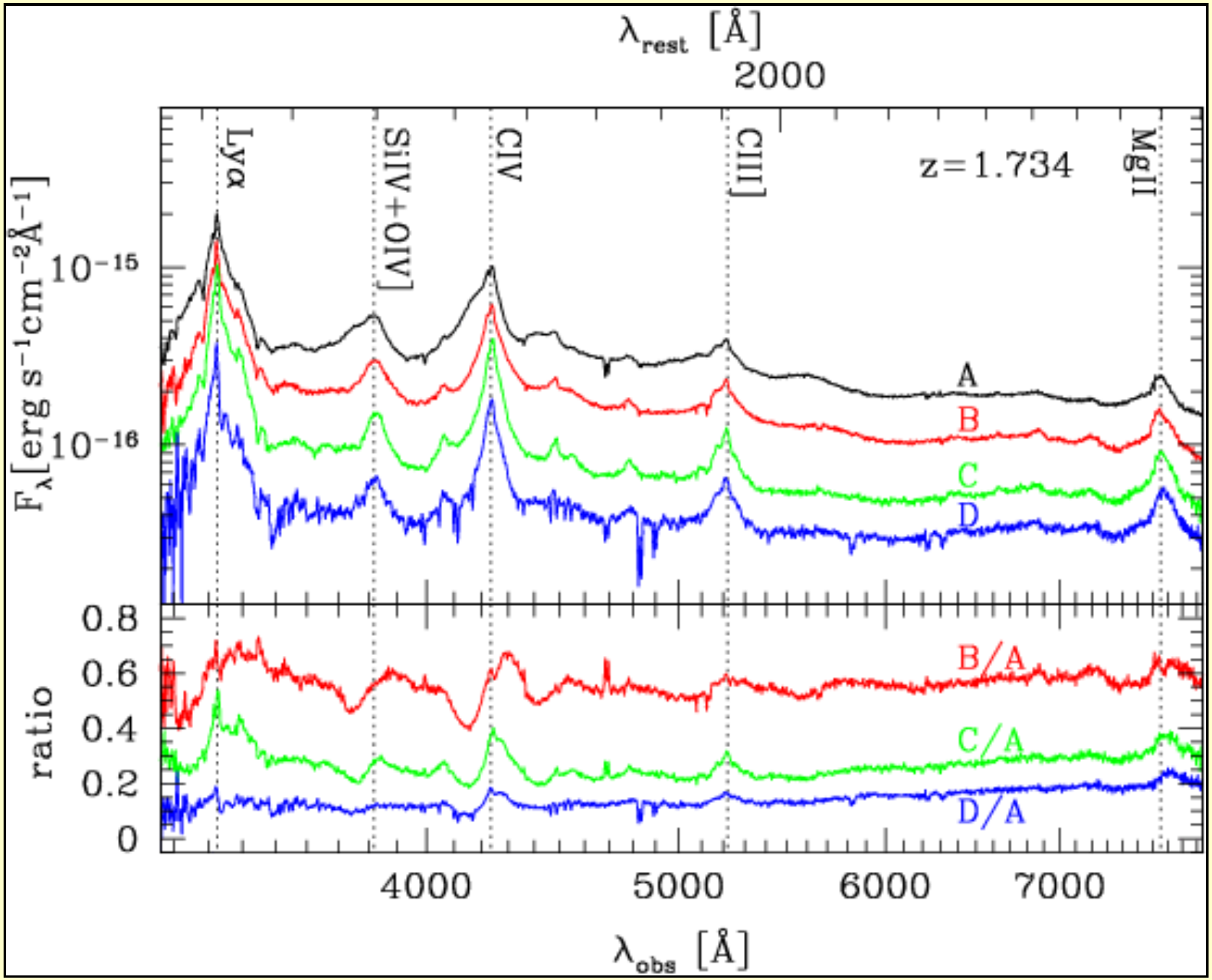
more than 1000 simulations

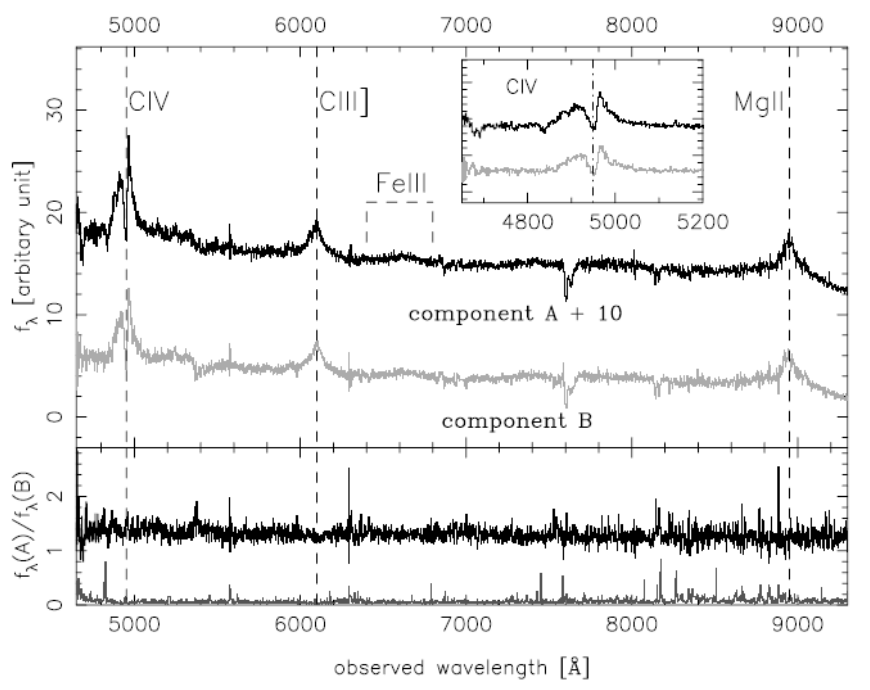


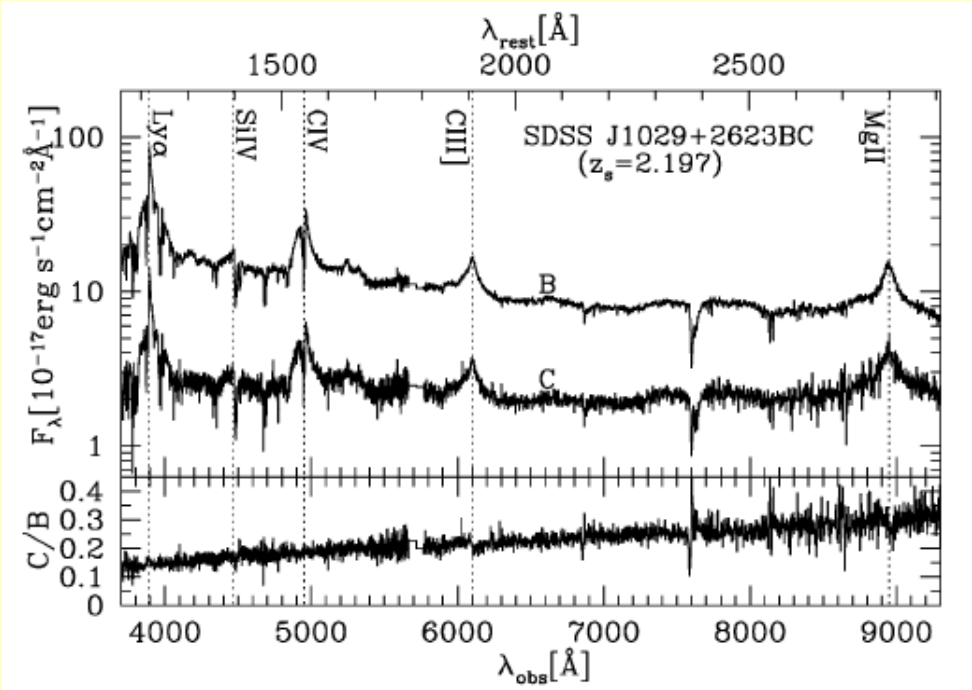

<u>for w = K1 :</u> $K_K = 0.74\ ^{+0.11}_{K0.15}\,(\text{stat})\ ^{+0.13}_{K0.06}\,(\text{syst})$

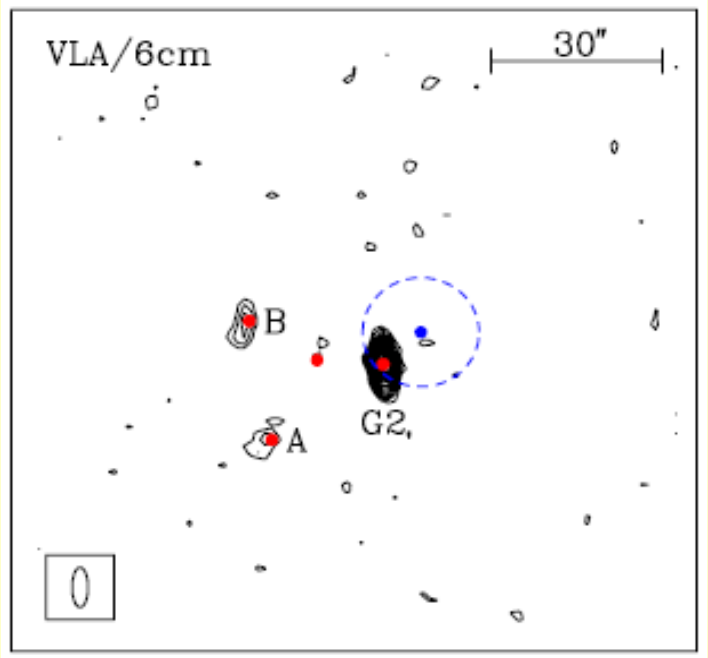
<u>for DE :</u> $w = K1.1\ ^{+0.6}_{K0.6}\,(\text{stat})\ ^{+0.3}_{K0.5}\,(\text{syst})$

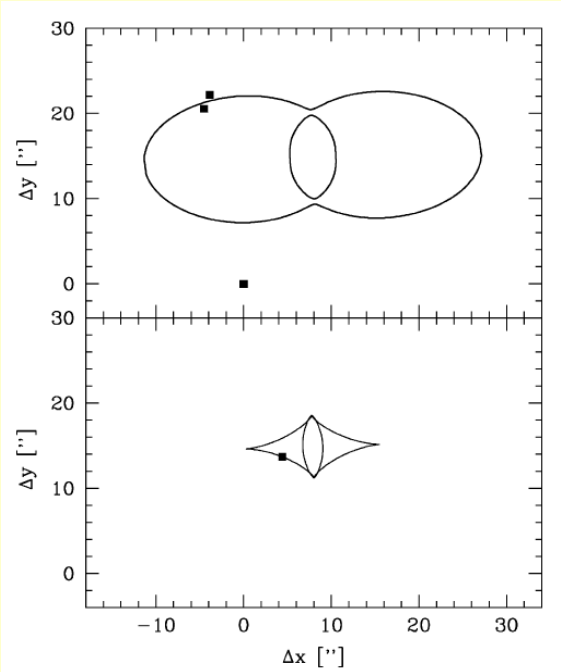
$K_M = 0.26\ ^{+0.07}_{K0.06}\,(\text{stat})\ ^{+0.03}_{K0.05}\,(\text{syst})$

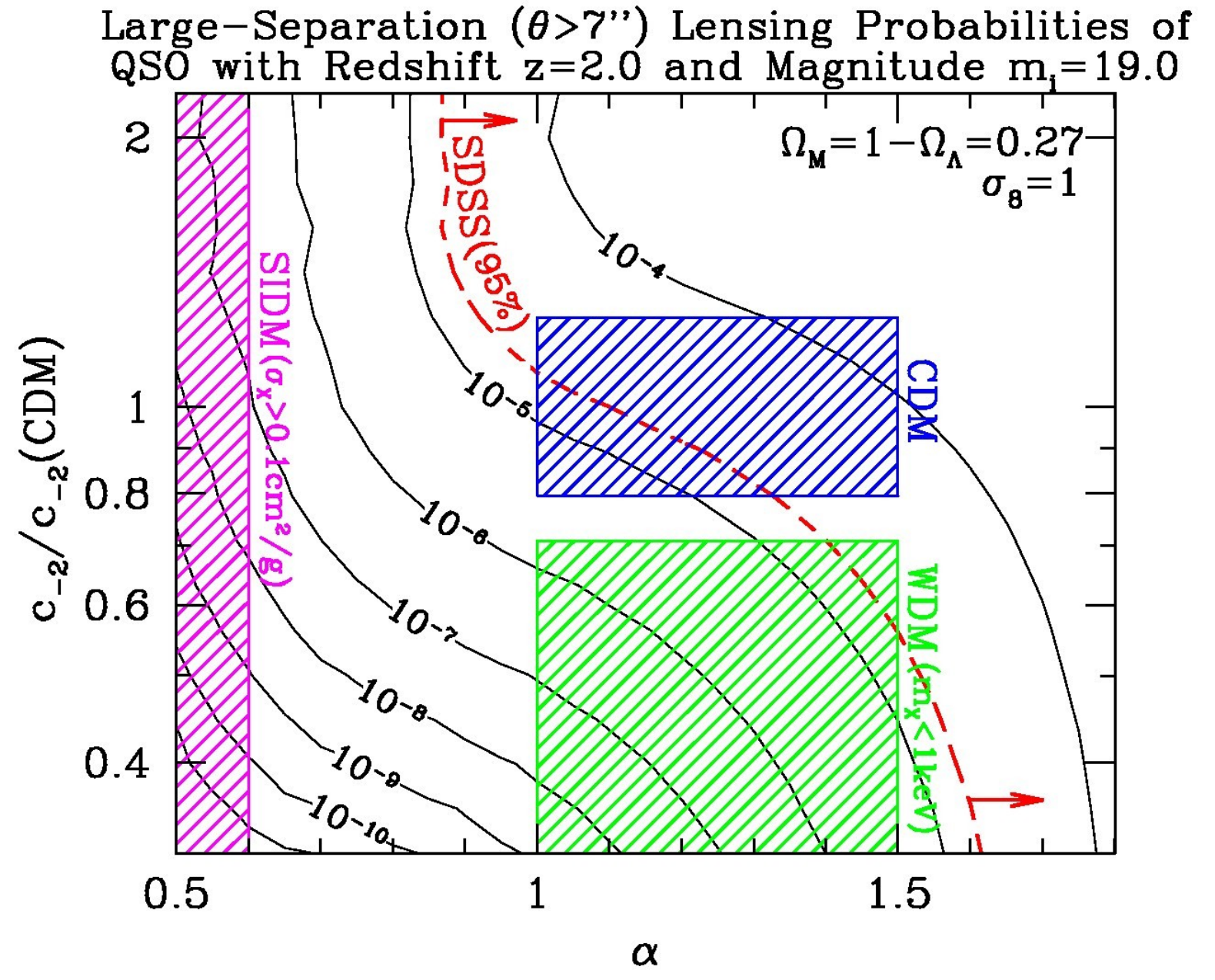

λrest [Å]
2000
Lyα
SiIV+OIV]
CIV
CIII]
MgII
z=1.734
A
B
C
D
Fλ[erg s⁻¹cm⁻²Å⁻¹]
10⁻¹⁵
10⁻¹⁶
ratio
0.8
0.6
0.4
0.2
0
B/A
C/A
D/A
4000
5000
6000
7000
λobs [Å]

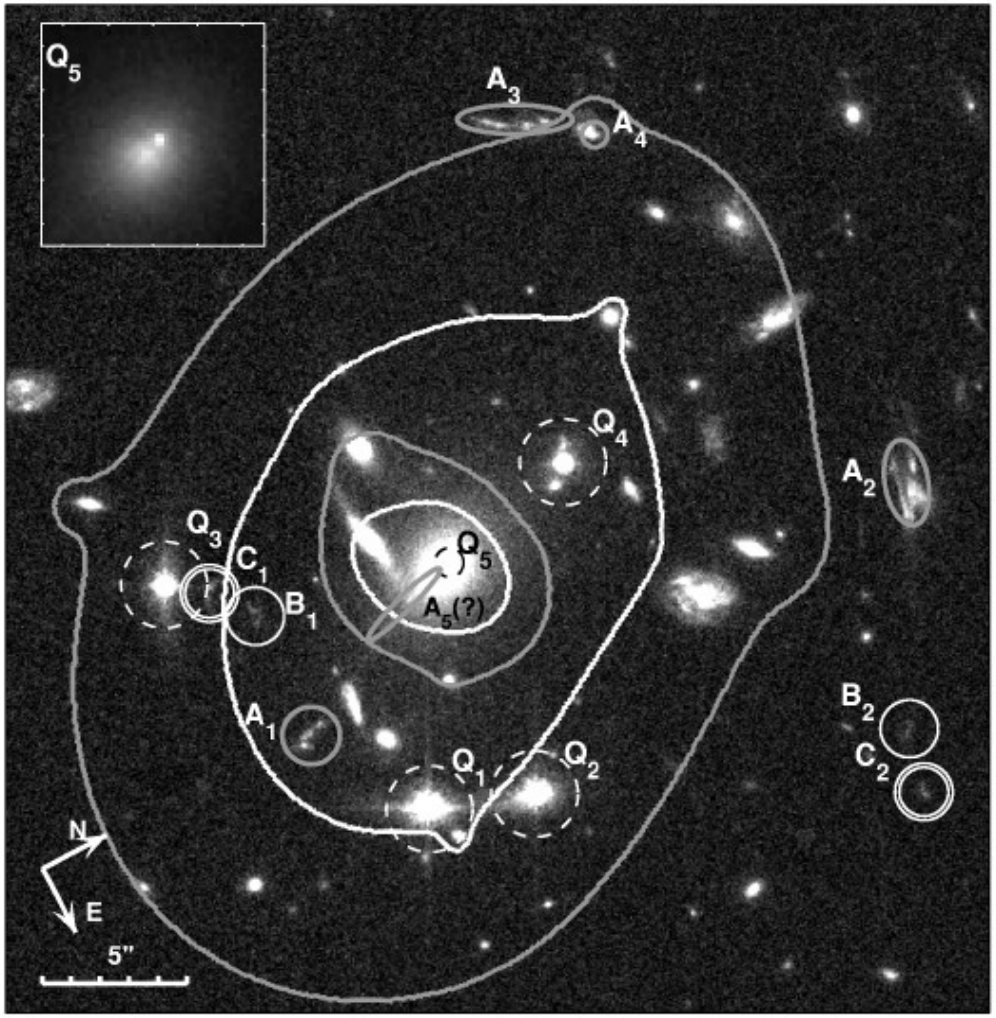

CIV
CIII]
MgII
FeIII
component A + 10
component B
observed wavelength [Å]


SDSS J1029+2623BC
(z_s=2.197)
Lyα
SiIV
CIV
CIII]
MgII
B
C
C/B
λ_obs[Å]

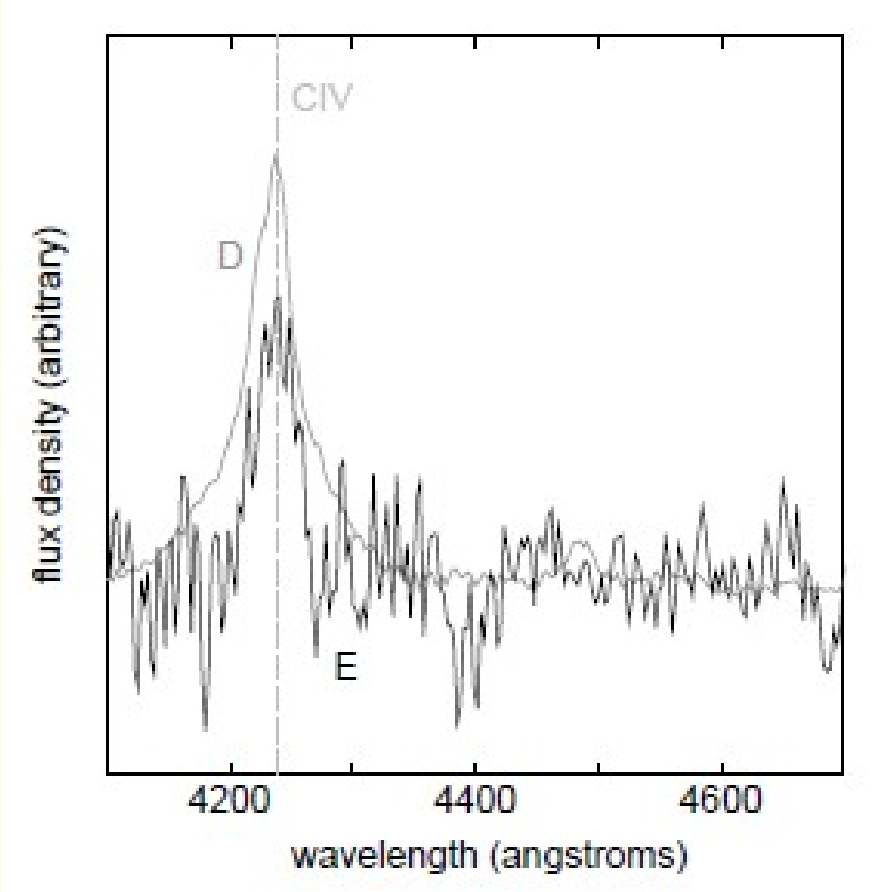

VLA/6cm
30"
B
A
G2

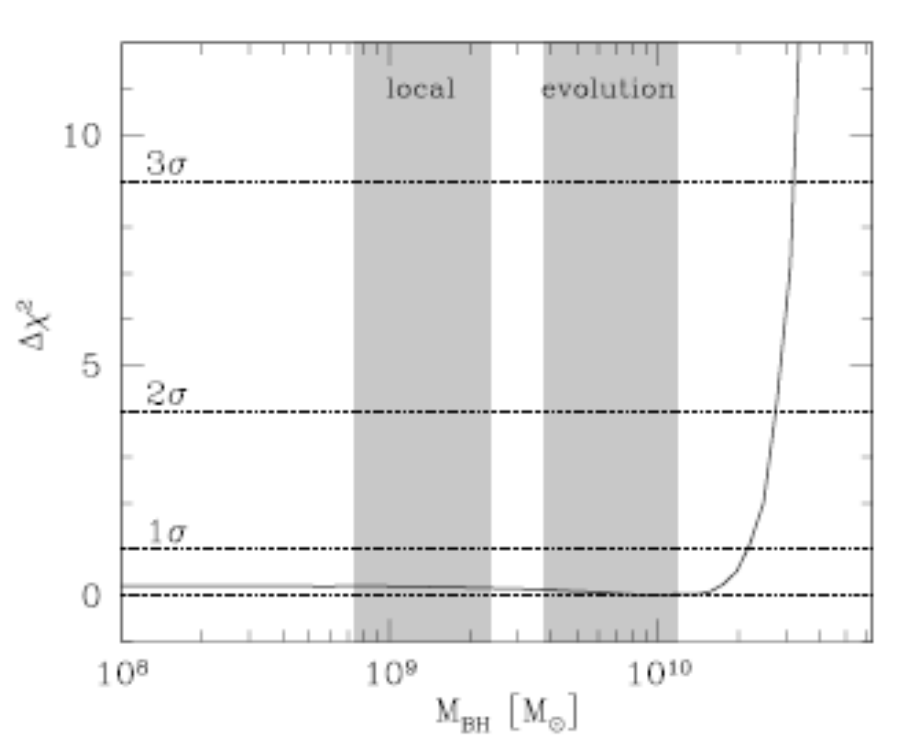

Δy ['']
Δx ['']

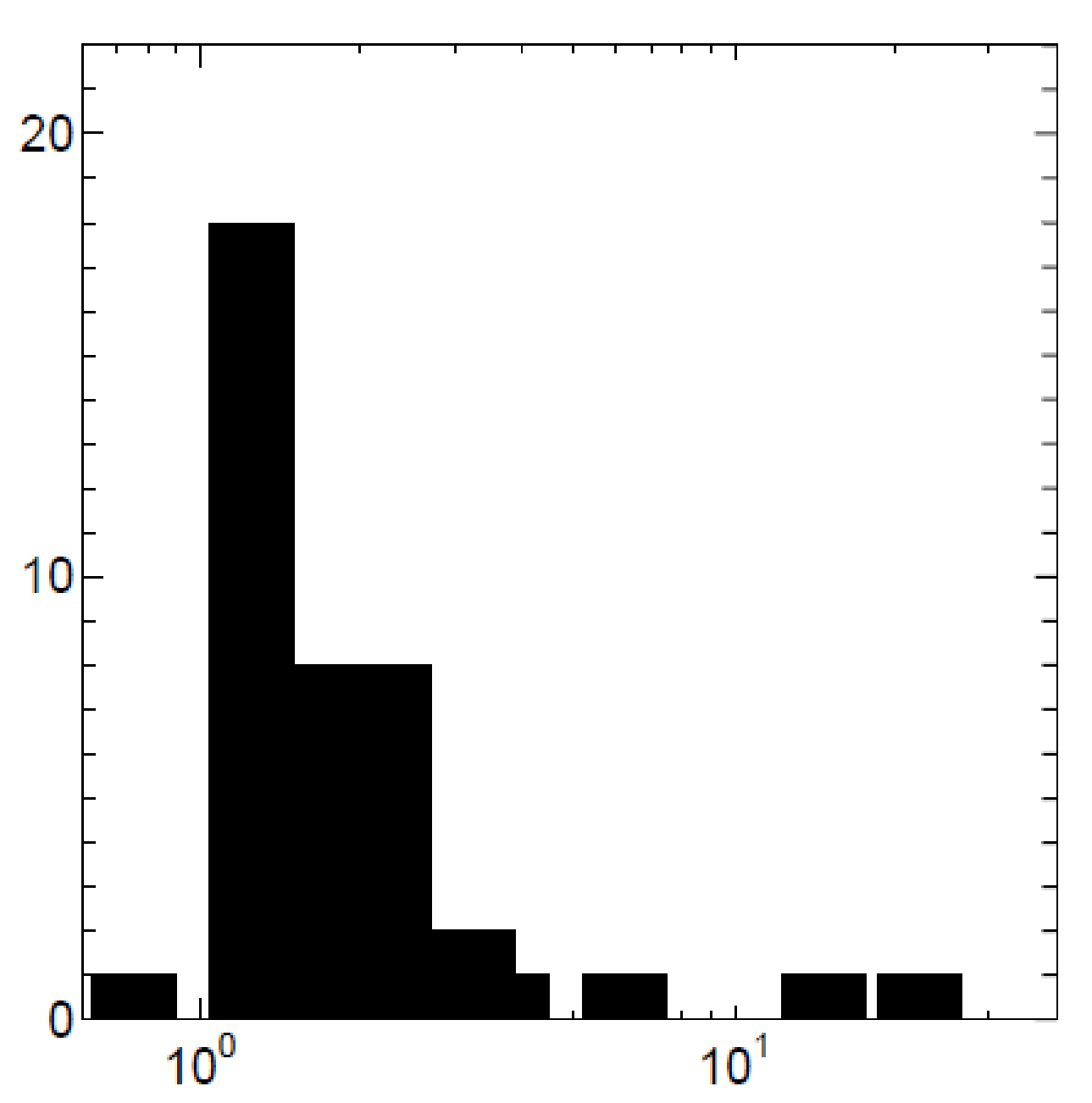

Large−Separation (θ>7'') Lensing Probabilities of
QSO with Redshift z=2.0 and Magnitude m_i=19.0
Ω_M=1−Ω_Λ=0.27
σ_8=1
SDSS(95%)
SIDM(σ_x<0.1cm²/g)
CDM
WDM (m_x<1keV)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
c_-2/c_-2(CDM)
2
1
0.8
0.6
0.4
0.5
1
1.5
α

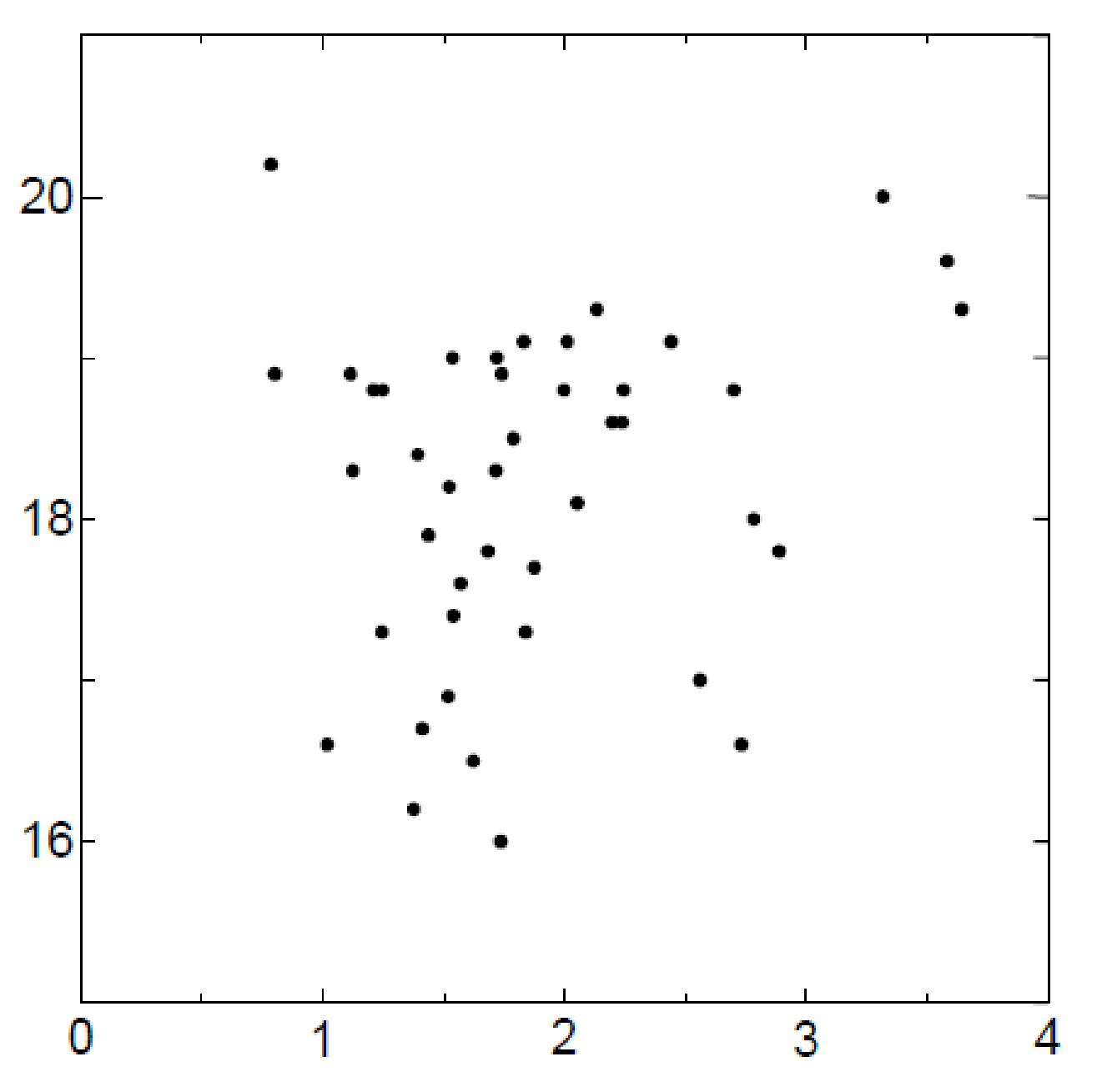



¤ K K^K£ : K K 0.5 < 1.0 (SIS)


CIV
D
E
flux density (arbitrary)
4200
4400
4600
wavelength (angstroms)


local
evolution
10
5
0
3σ
2σ
1σ
Δχ²
10⁸
10⁹
10¹⁰
M_BH [M_⊙]


20
10
0
$10^0$
$10^1$


20
18
16
0
1
2
3
4