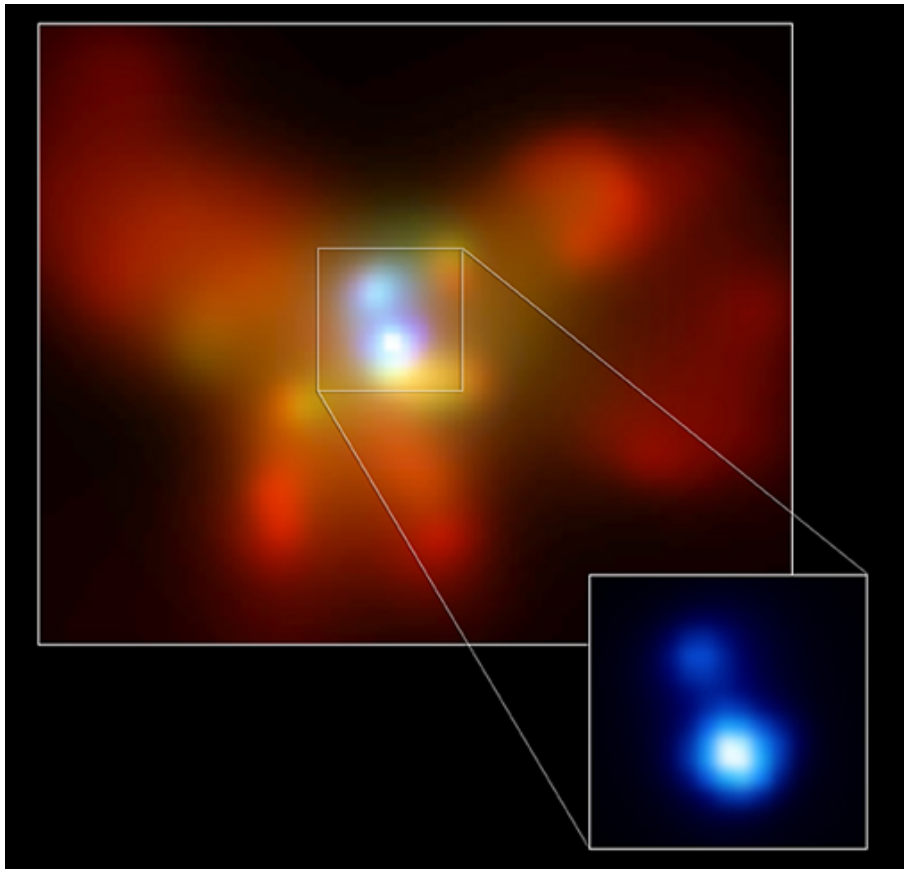
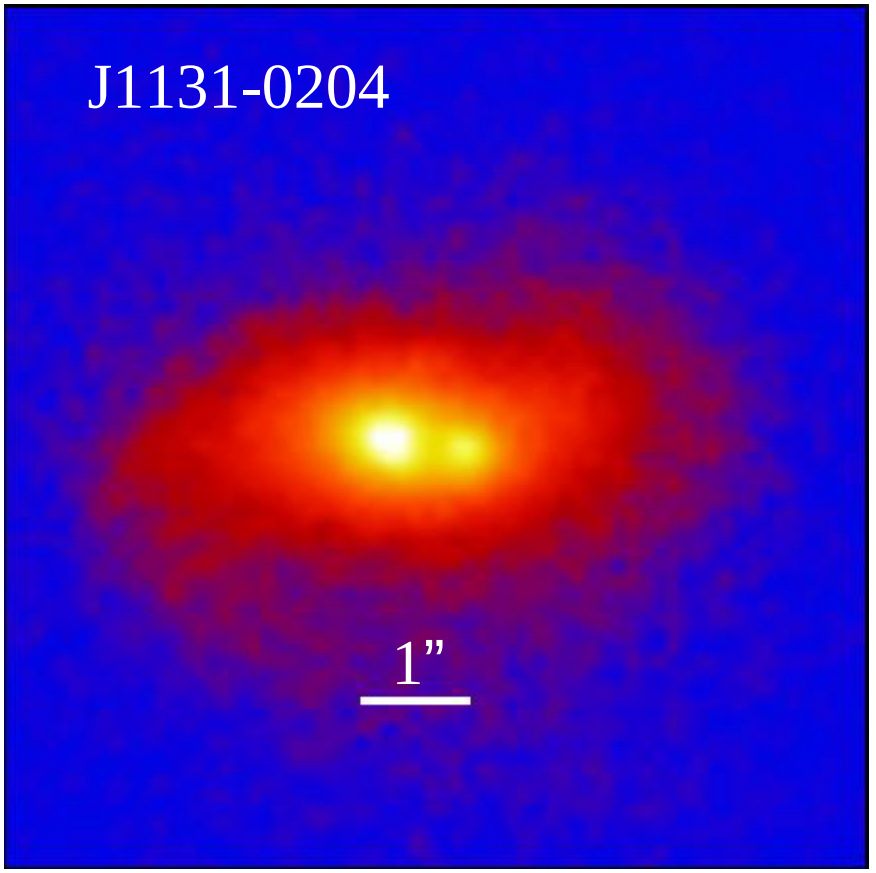




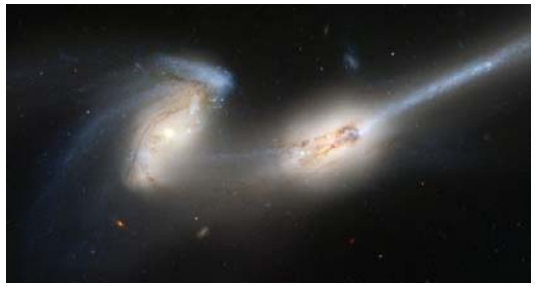
Searching for binary SMBHs: from hundreds of kpc to sub-pc scales

Yue Shen

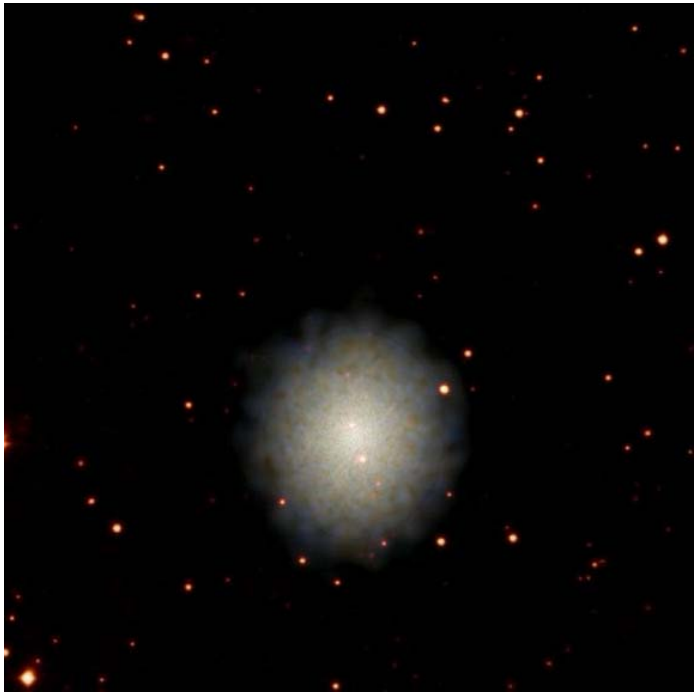
Harvard-Smithsonian Center for Astrophysics

Why binary SMBHs?

- Expected from hierarchical mergers
- Direct evidence (resolved binaries) and empirical evidence (“core” ellipticals; X-shaped radio jets, etc).
- Constraints for gravitational wave detections and galaxy formation models



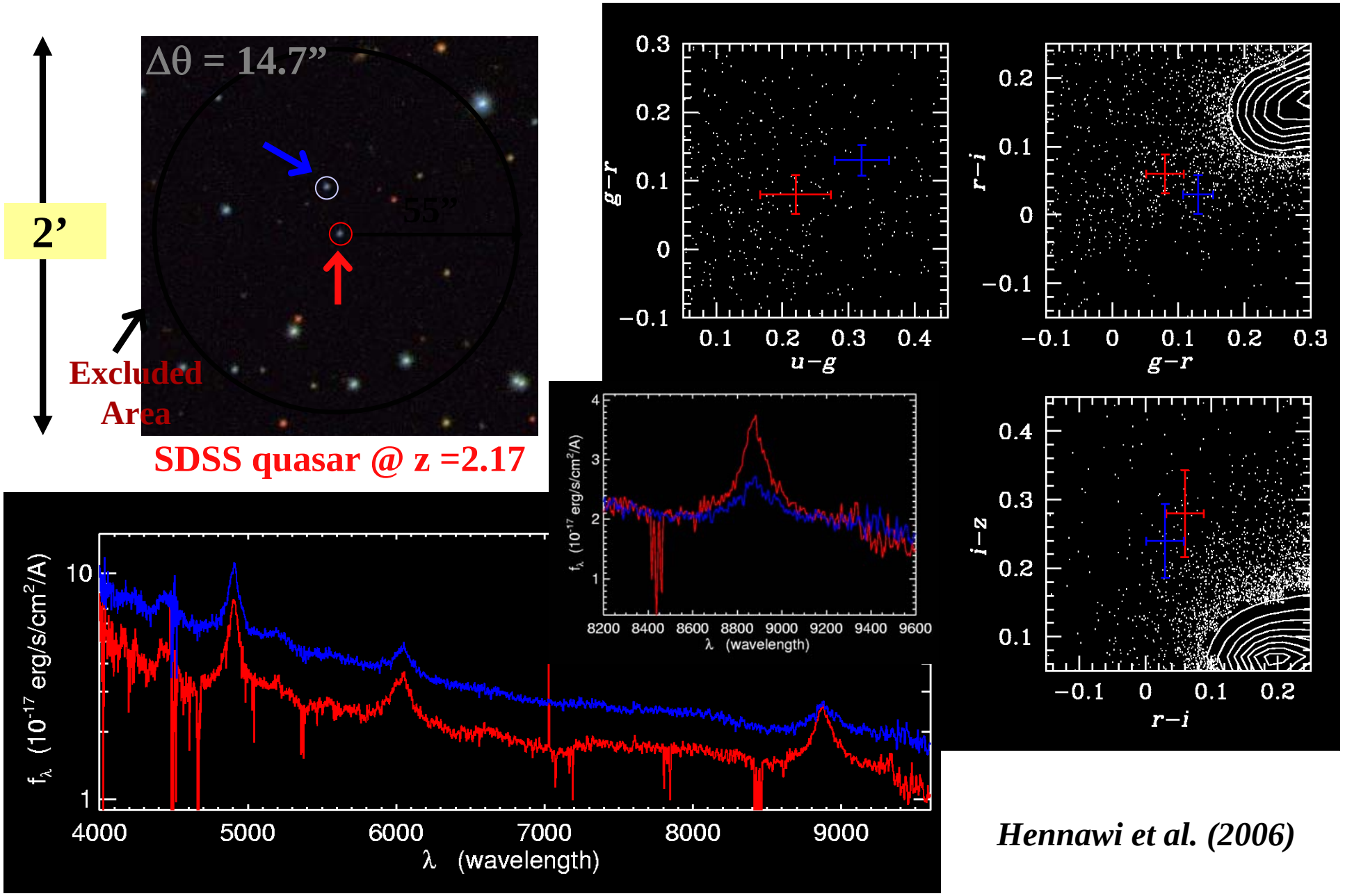
Time sequence of a galaxy merger



Volker Springel

Binaries on halo scales (hundreds – tens of kpc)	**Binaries on galactic scales (several kpc)**	**Binaries on sub-galactic scales (pc – sub-pc)**
Known: hundreds quasar pairs at z>~1 Frequency: ~0.1%	Known: <5 at z<~1 Frequency: ?	Known: 0? Frequency: ???

Binary SMBHs on halo scales:
hundreds of kpc ~ tens of kpc

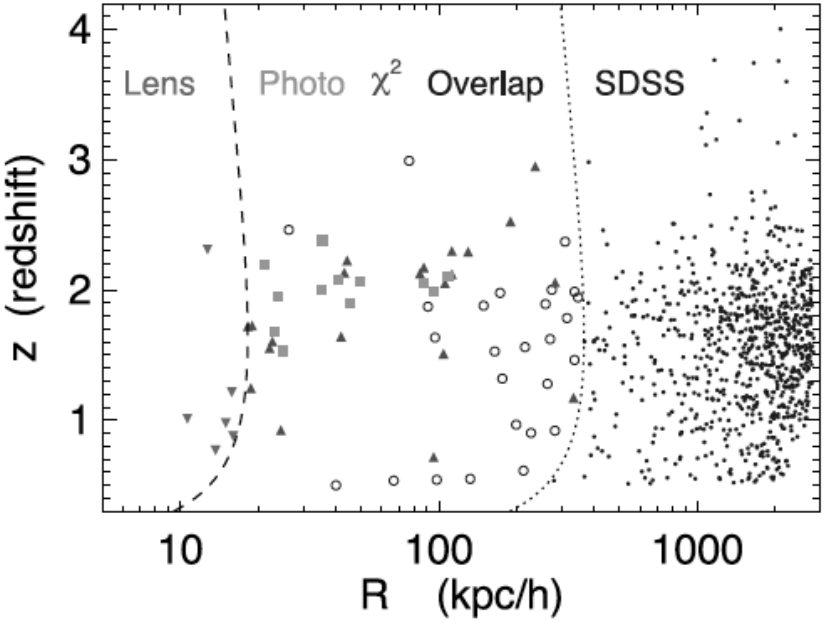


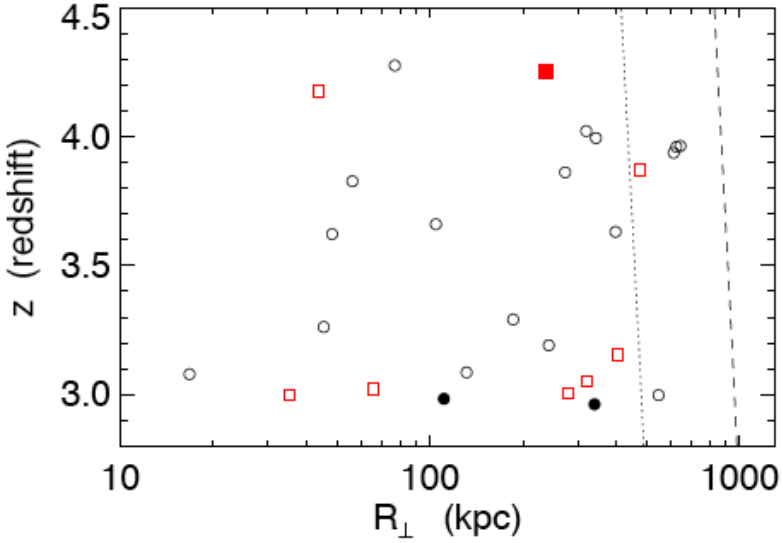
Hennawi et al. (2006)

Keck Spectrum taken by Bob Becker & Michael Gregg

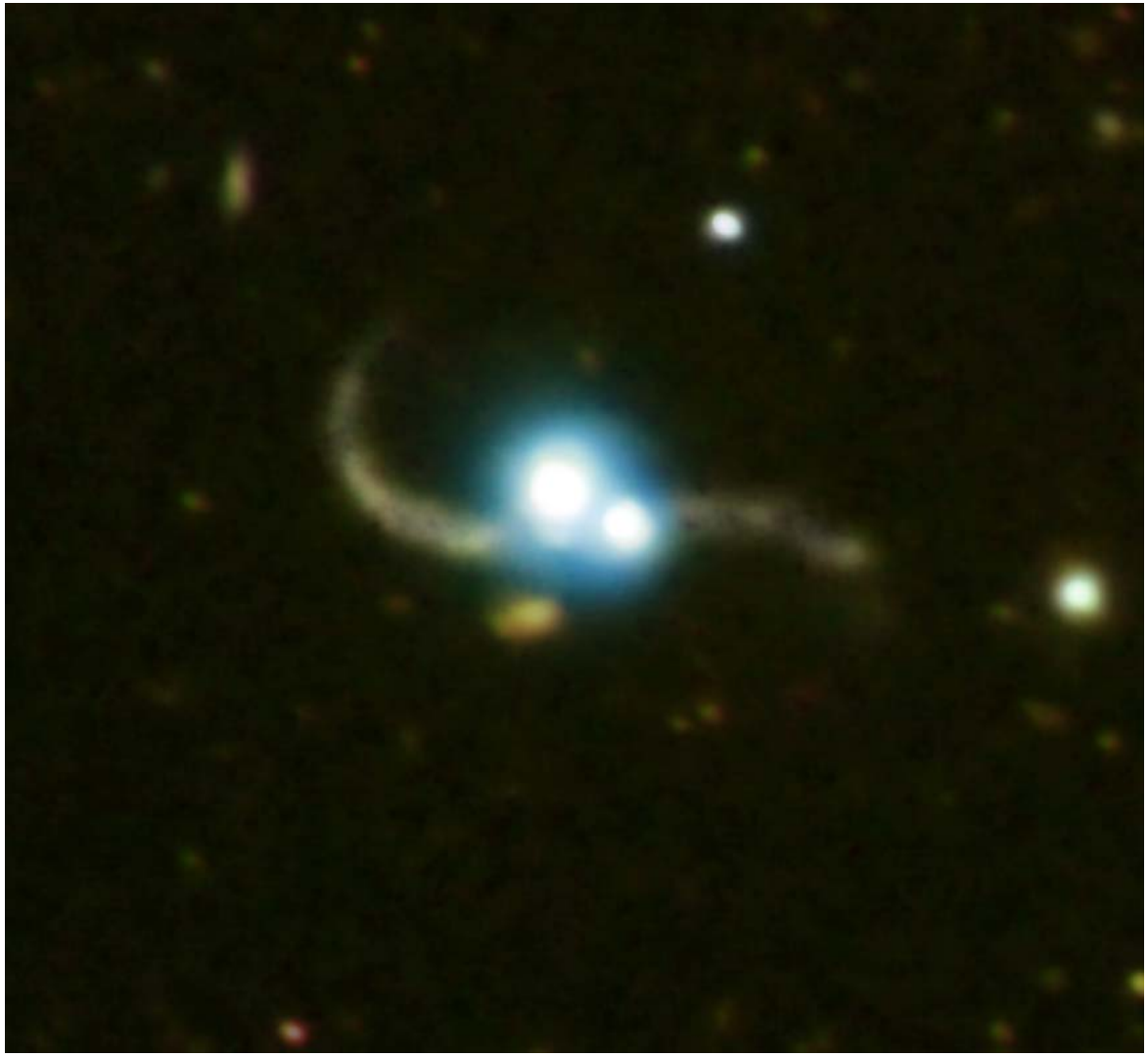
Binary quasars at z>~1

- ~ 220 quasar binaries (Rprop<1 Mpc/h) at z<3 (Hennawi et al. 2006, Myers et al. 2008)
- 24 new binaries at z>3 with physical separations 10~650 kpc (Hennawi et al. 2010; Shen et al. 2010a).





An example of binary quasars



SDSS 1254+0846
(z=0.44)

Green et al. (2010)

~20 kpc (projected)

Binary SMBHs on galactic scales:
~ a few kpc

Kpc-scale binary AGNs

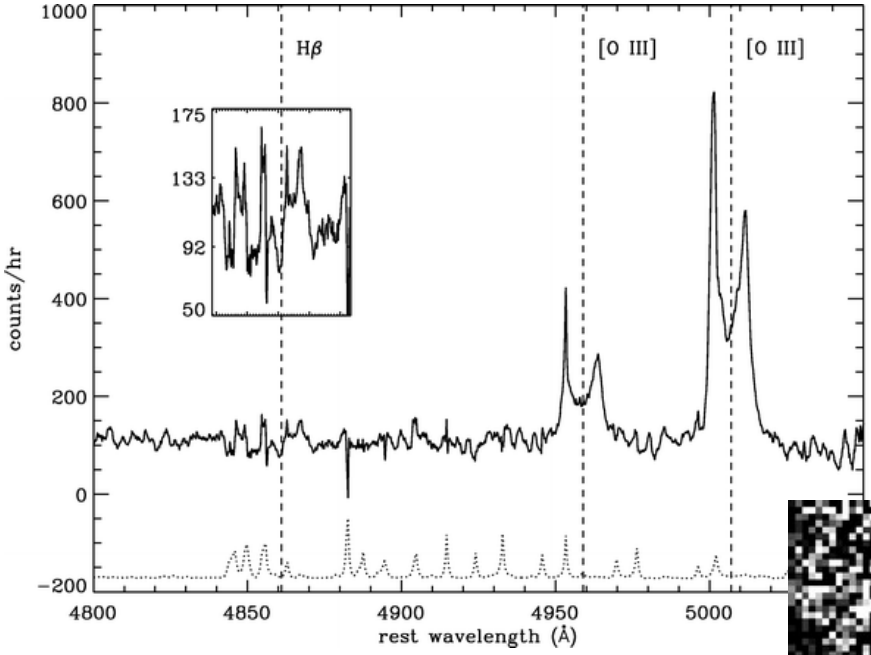
- confirmed kpc-scale binary SMBHs are rare
  - Only a handful of cases known (<~5)
  - Require good spatial resolution
  - Both BHs must be active

Kiloparsec scale SMBH binaries

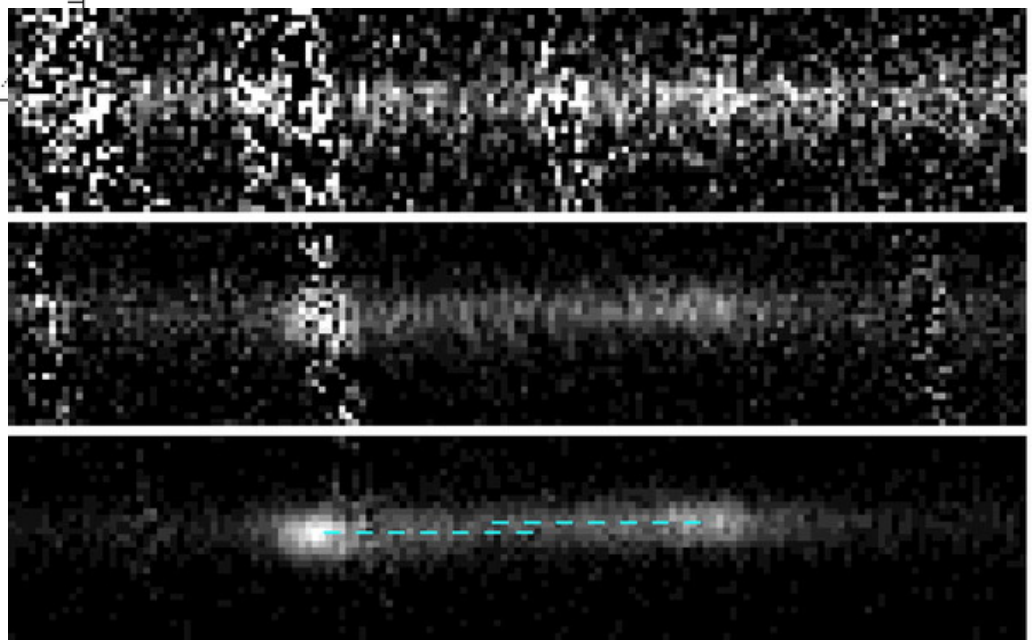
NGC 6240 Komossa et al. (2003)

The best case known so far; a ~ kpc separation, X-ray AGN pair; also see Mrk 463, Arp 299.

Double-peaked [OIII]4959,5007 narrow line AGNs



Spectroscopic features of kpc binary AGNs

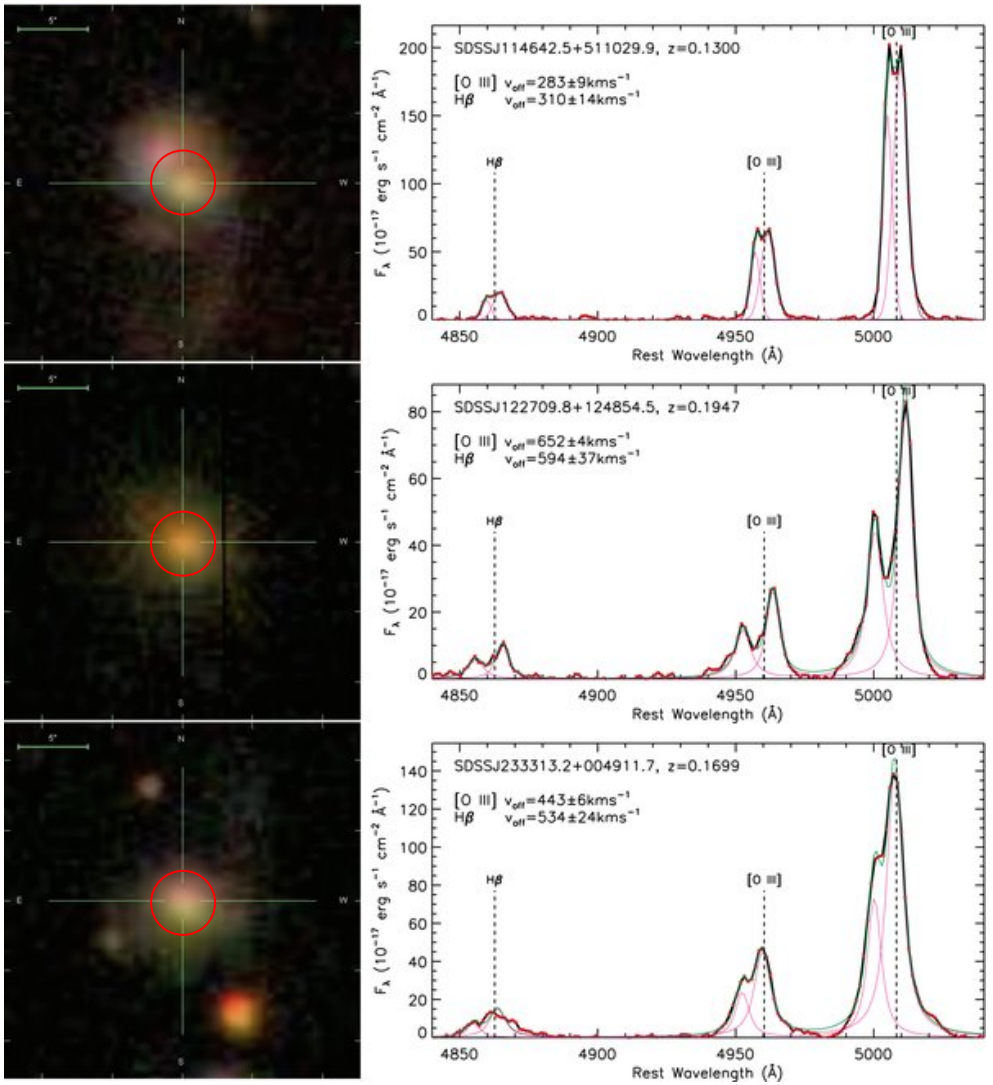


Gerke et al. (2007); Comerford et al. (2009a,b)
2 objects found in DEEP2, and one found in COSMOS (but see Civano et al. for an alternative interoperation)

Narrow-line AGNs with double-peaked [OIII] from SDSS spectroscopic data

- 167 narrow-line AGNs with double-peaked [OIII] in SDSS (Liu et al. 2010a; also see Smith et al. 2010, Wang et al. 2009)

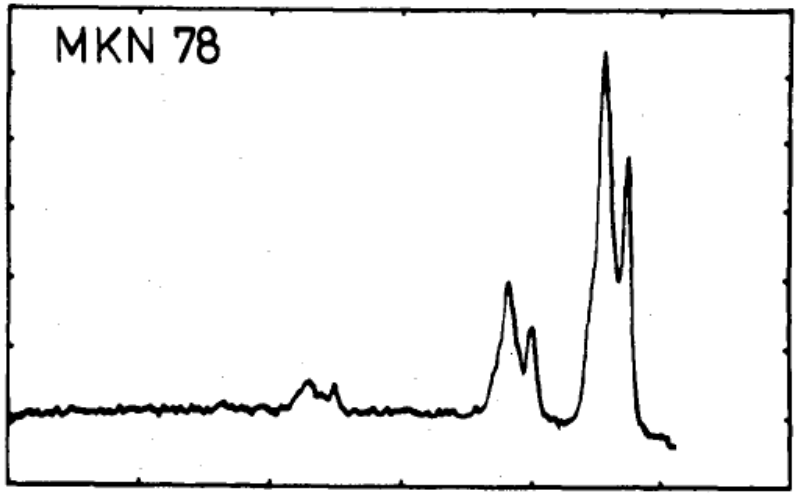
Liu, Shen, Strauss, & Greene (2010)



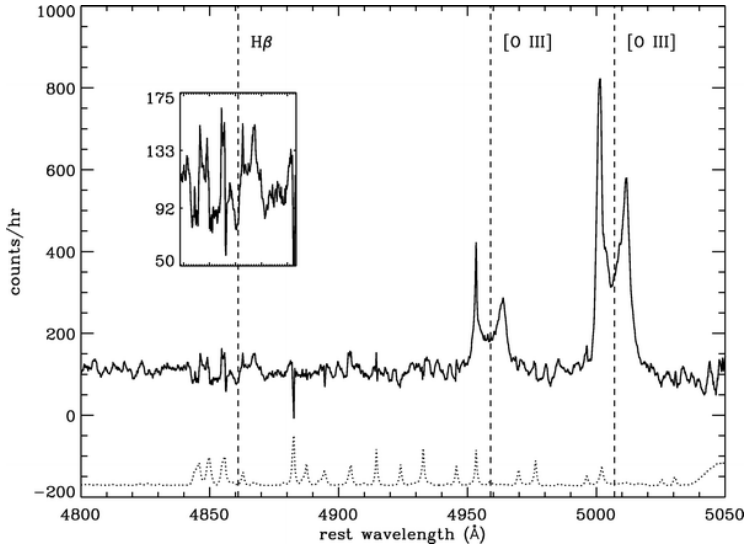
Double-peaked [OIII] AGNs

- Binary AGNs?
- Kinematics of the narrow line region around single AGNs? There are known local examples!

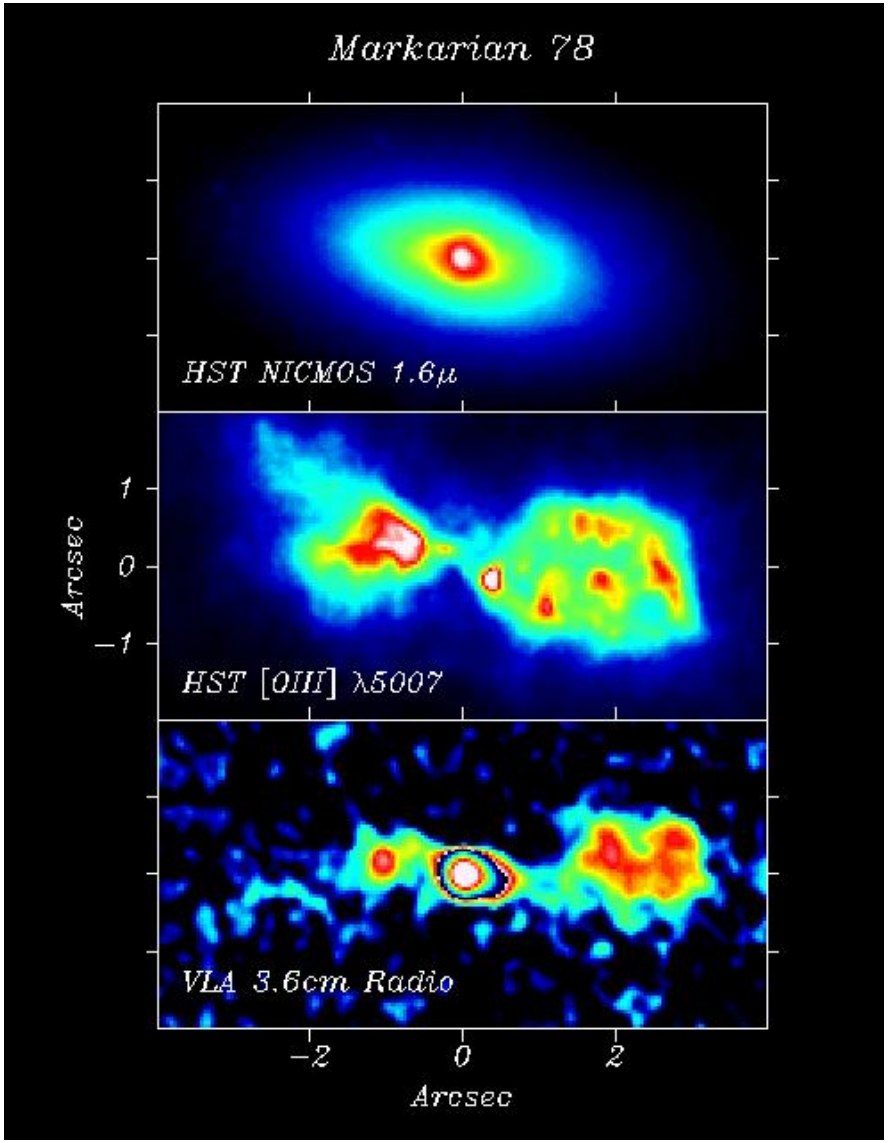
Mrk 78



Heckman et al. (1981)



The DEEP2 object from Gerke et al.



M. Whittle

- Not all double-peaked narrow line AGNs are kpc binaries
- SDSS is not good enough because: 1) spectra have no spatial information; 2) imaging has poor resolution
- Need spatially resolved imaging and spectroscopy

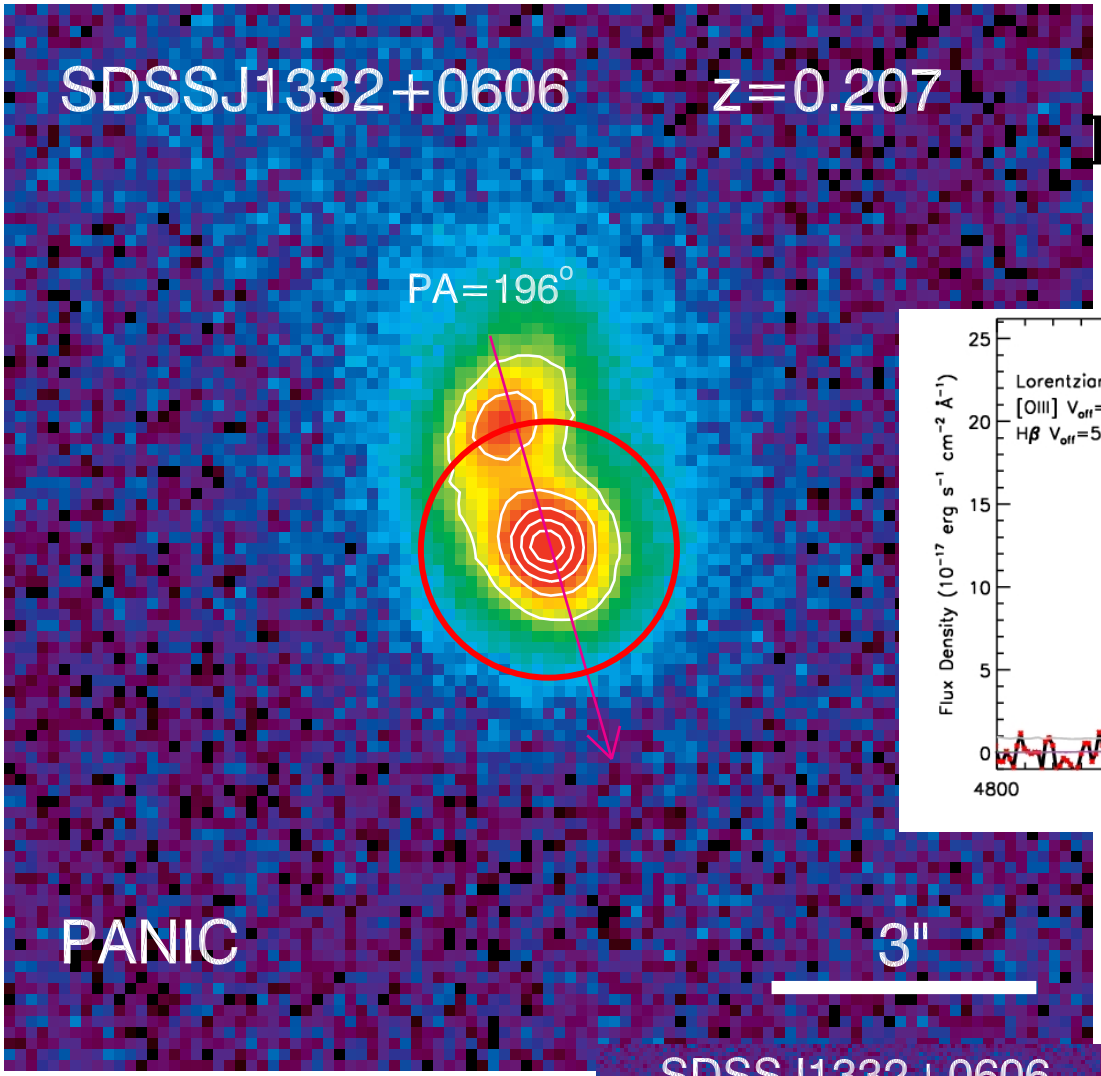
NIR imaging and long-slit spectroscopy

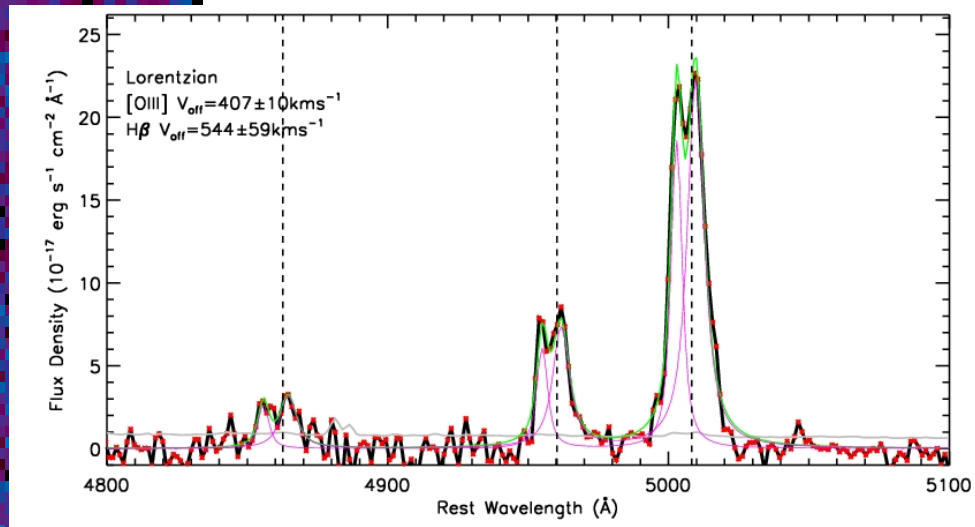
- NIR imaging with PANIC on Magellan; ~0.4” seeing in K: several spatially resolved double stellar nuclei
- Optical slit-spectroscopy with LDSS3 on Magellan and DIS on ARC 3.5m: most have spatially resolved [OIII] emission (~ kpc)
- ~ 60 targets observed with NIR imaging, half of which had slit spectroscopy

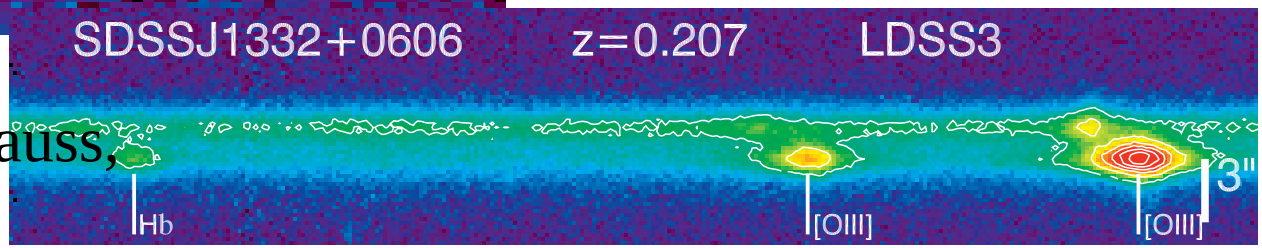
Kpc binary AGNs from SDSS

- 6 out of ~60 objects show spatially resolved double nuclei in NIR and corresponding NLR emission – best cases for kpc binary AGNs in the double-peaked narrow line AGN sample.

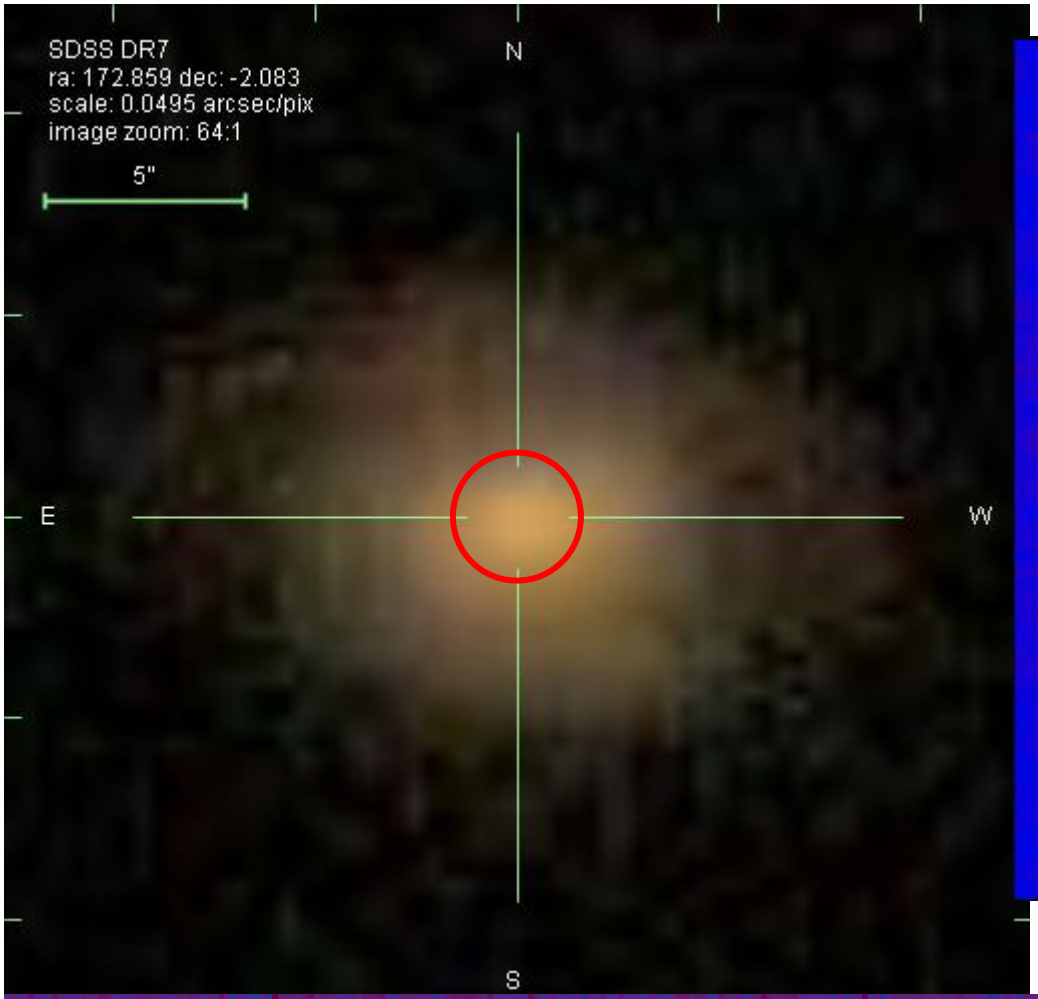
nary AGNs

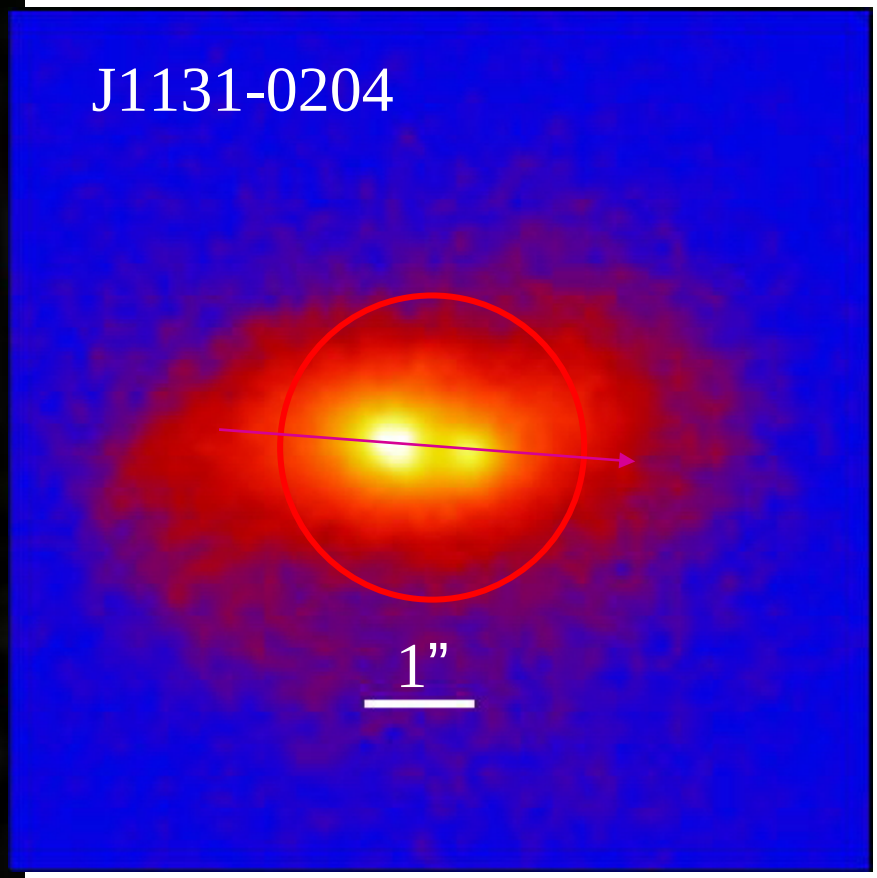


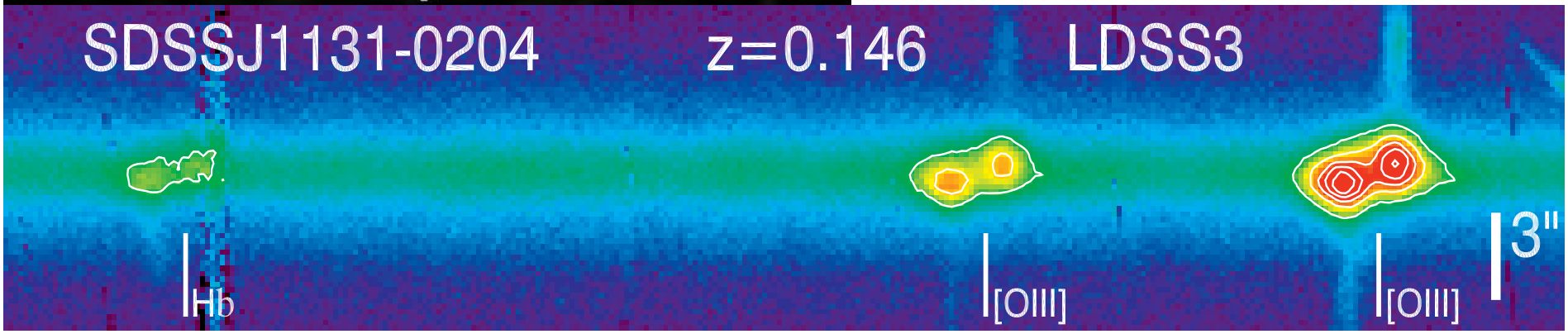




Liu, Greene, Shen, Strauss, 2010, ApJL


SDSS DR7
ra: 172.859 dec: -2.083
scale: 0.0495 arcsec/pix
image zoom: 64:1
5"
N
E
W
S

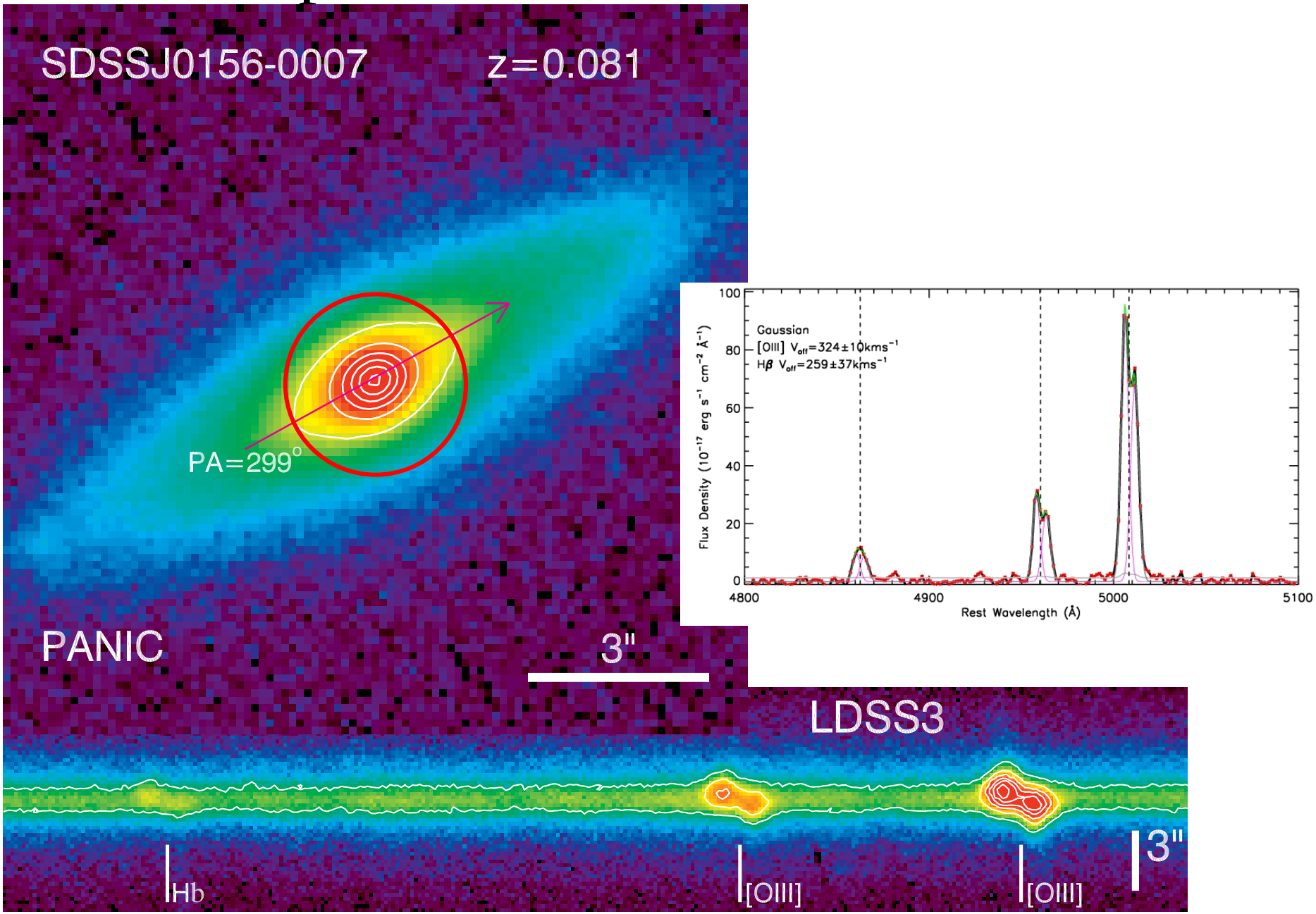

J1131-0204
1”

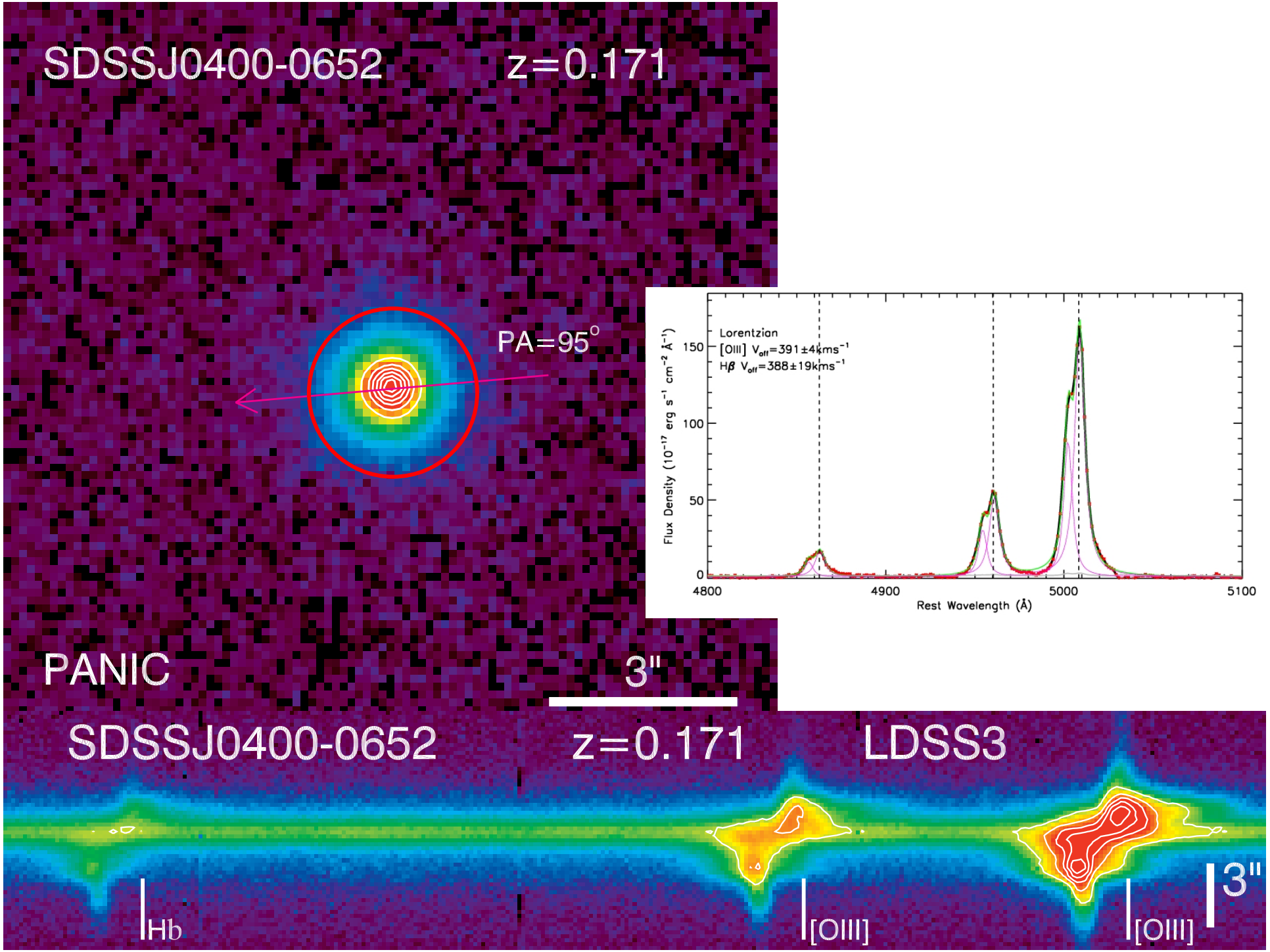

SDSSJ1131-0204
z=0.146
LDSS3
Hb
[OIII]
[OIII]
3"

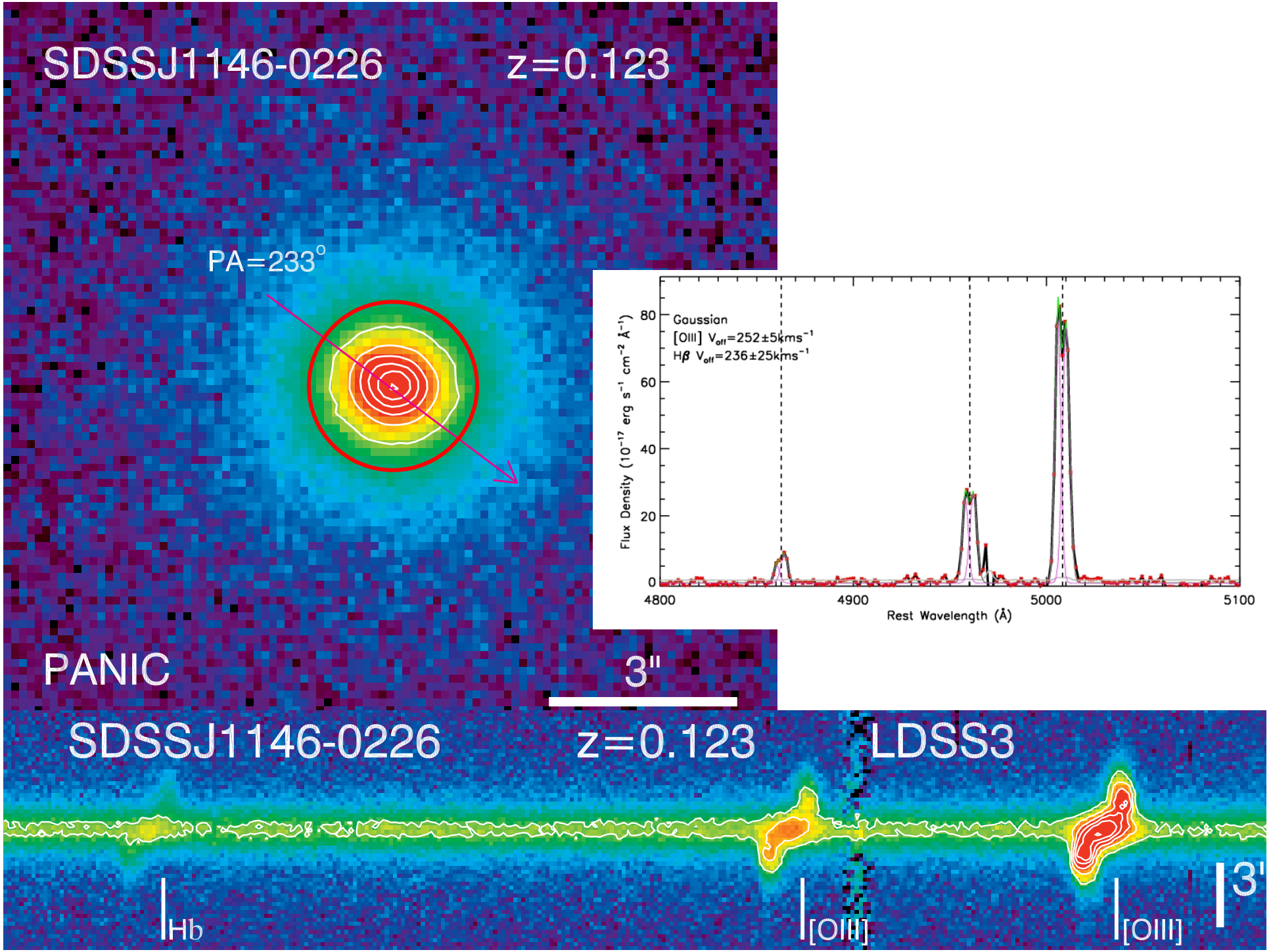
NLR kinematics around single AGNs

- Many double-peaked [OIII] objects seem to be of a kinematics origin: smooth stellar distribution, but two spatially offset [OIII] components.

Examples of NLR kinematics cases




SDSSJ0400-0652
z=0.171
PA=95°
Lorentzian
[OIII] V_off=391±4kms^-1
Hβ V_off=388±19kms^-1
Flux Density (10^-17 erg s^-1 cm^-2 Å^-1)
150
100
50
0
4800
4900
5000
5100
Rest Wavelength (Å)
PANIC
3"
SDSSJ0400-0652
z=0.171
LDSS3
Hb
[OIII]
[OIII]
3"

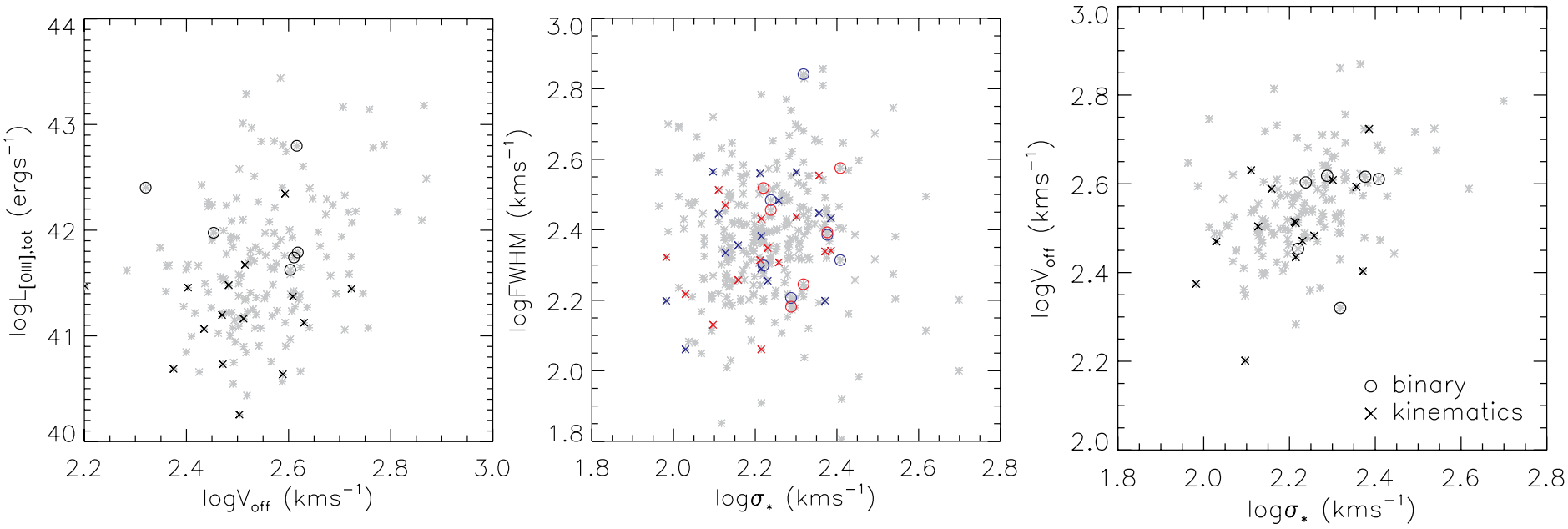

SDSSJ1146-0226
z=0.123
PA=233°
Gaussian
[OIII] V_off=252±5kms^-1
Hβ V_off=236±25kms^-1
Flux Density (10^-17 erg s^-1 cm^-2 Å^-1)
Rest Wavelength (Å)
PANIC
3"
SDSSJ1146-0226
z=0.123
LDSS3
Hb
[OIII]
[OIII]
3'

A mixed bag of objects in the double-peaked sample

- Kpc-scale binary AGNs: ~10%
- NLR kinematics in single AGNs: ~50%
- Ambiguous cases: ~40%; either NLR kinematics, or binary AGNs at smaller separations (~ sub-kpc)

More narrow line region kinematics than merging SMBH pairs (Shen, Liu, Greene, Strauss 2010, in prep.)

Statistical properties of kpc binary AGNs



Small number statistics!

Shen, Liu, Greene, Strauss (2010), in prep.

Observations VS simulations

- Observed binary AGN fraction: ~0.1-1% among all lowz (z<0.3) type 2 AGNs. (10-50% x 1-2%)
- Need a large merger simulation set to probe the parameter space.
- Factors that affect the frequency of binary AGNs: merger fraction, gas fraction, mass ratio of the merger, dust, AGN duty cycle, etc.
- Binary fraction as functions of redshift and separation.

Searches for kpc-scale binary AGNs

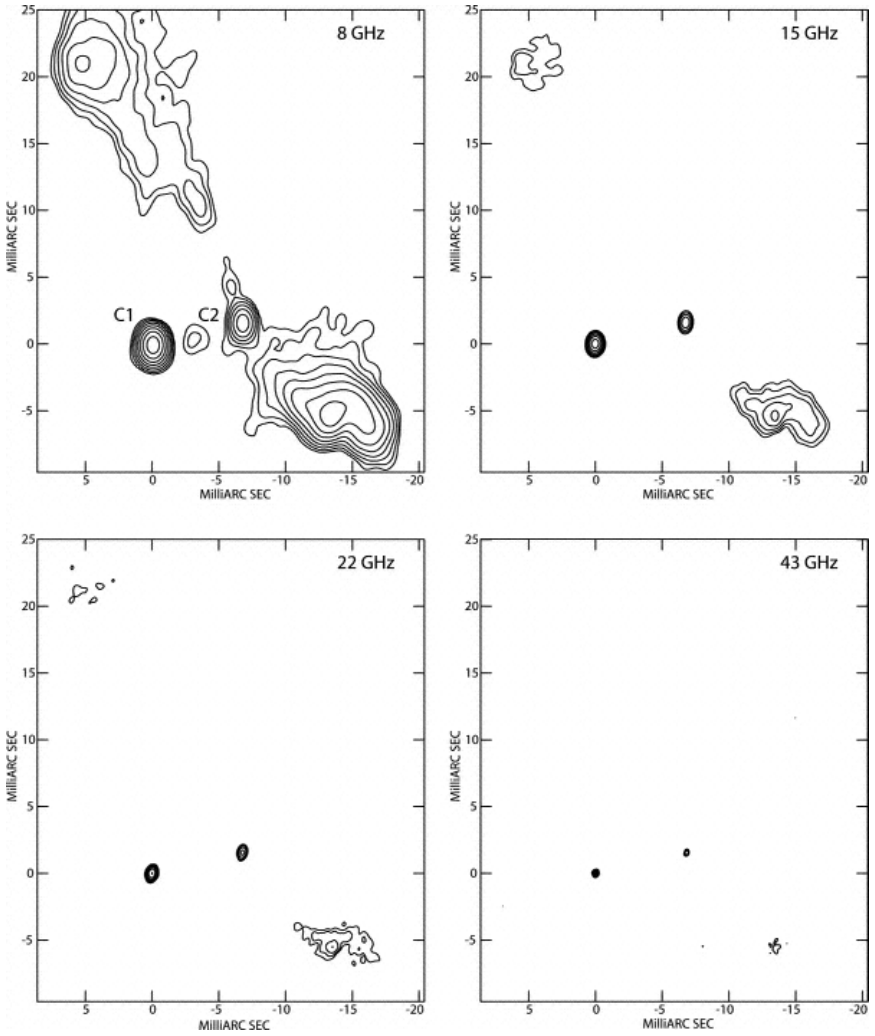
- ~10% success rate of finding kpc binary AGNs from the double-peaked narrow line sample.
- So far we have followed up a small fraction of our sample (~1/3 imaging, ~1/6 spectroscopy), and we found 6 promising binaries. Will increase the sample of confirmed kpc binary AGNs by an order of magnitude by the end of our follow-up.
- Additional follow-ups: AO, Chandra/HST, IFU, radio, etc

Binary SMBHs on sub-galactic scales: ~ sub-pc – pc

Sub-pc to pc-scale binaries

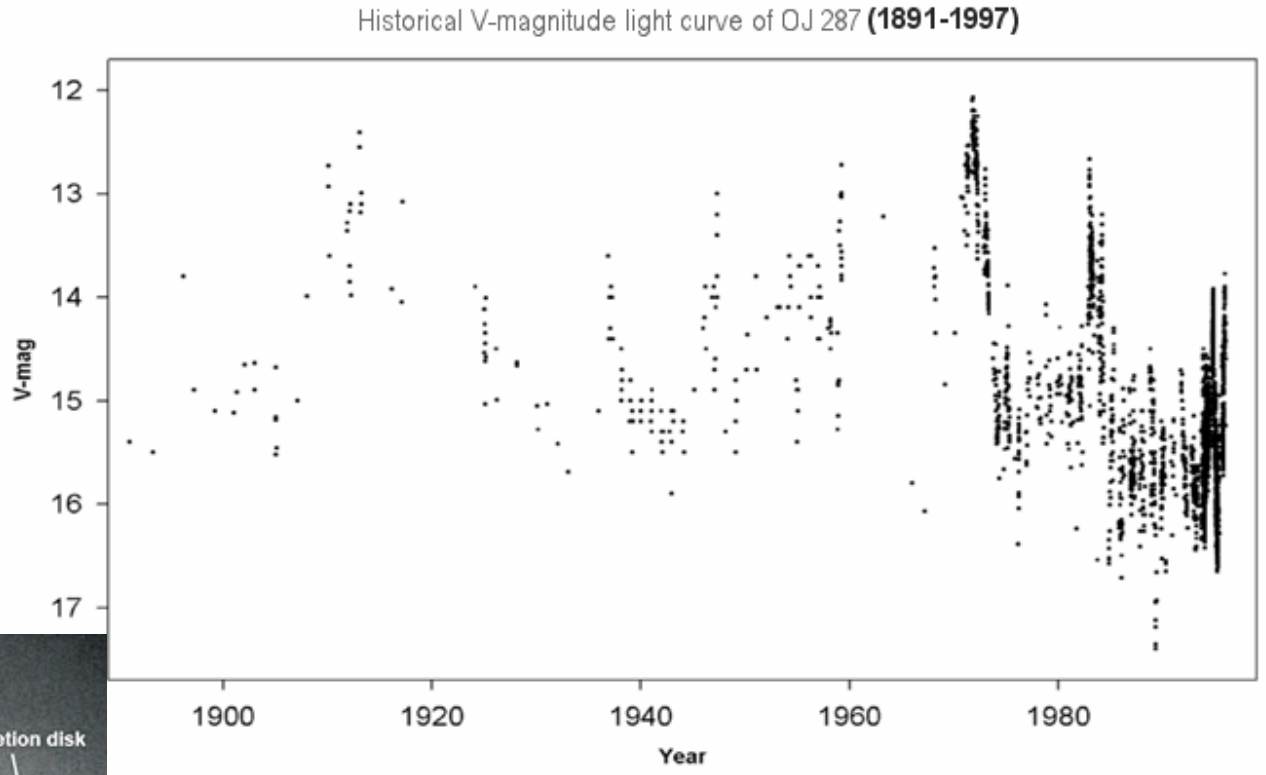
- More difficult to spatially resolve; observational signature not unique to binaries
- ~3 candidates! (0402+379, Rodriguez et al. 2006; OJ287, Valtonen et al; SDSS J1536+0441, Boroson & Lauer 2009); based on different methods

0402+379 (Rodriguez et al. 2006)

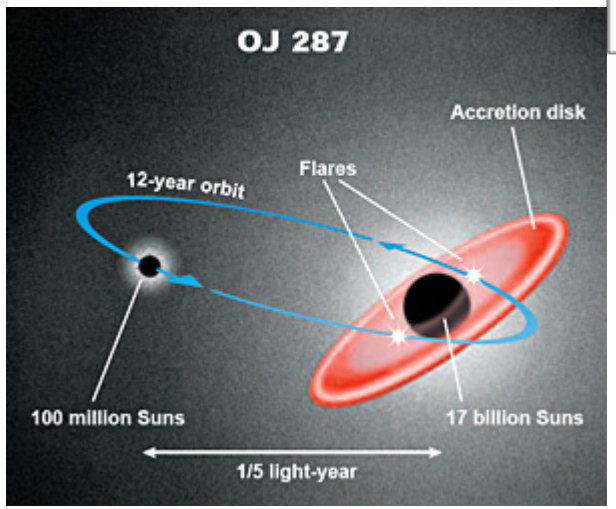


VLBA observation. 2 compact, variable flat-spectrum radio AGN in the elliptical host, separated by ~7 pc

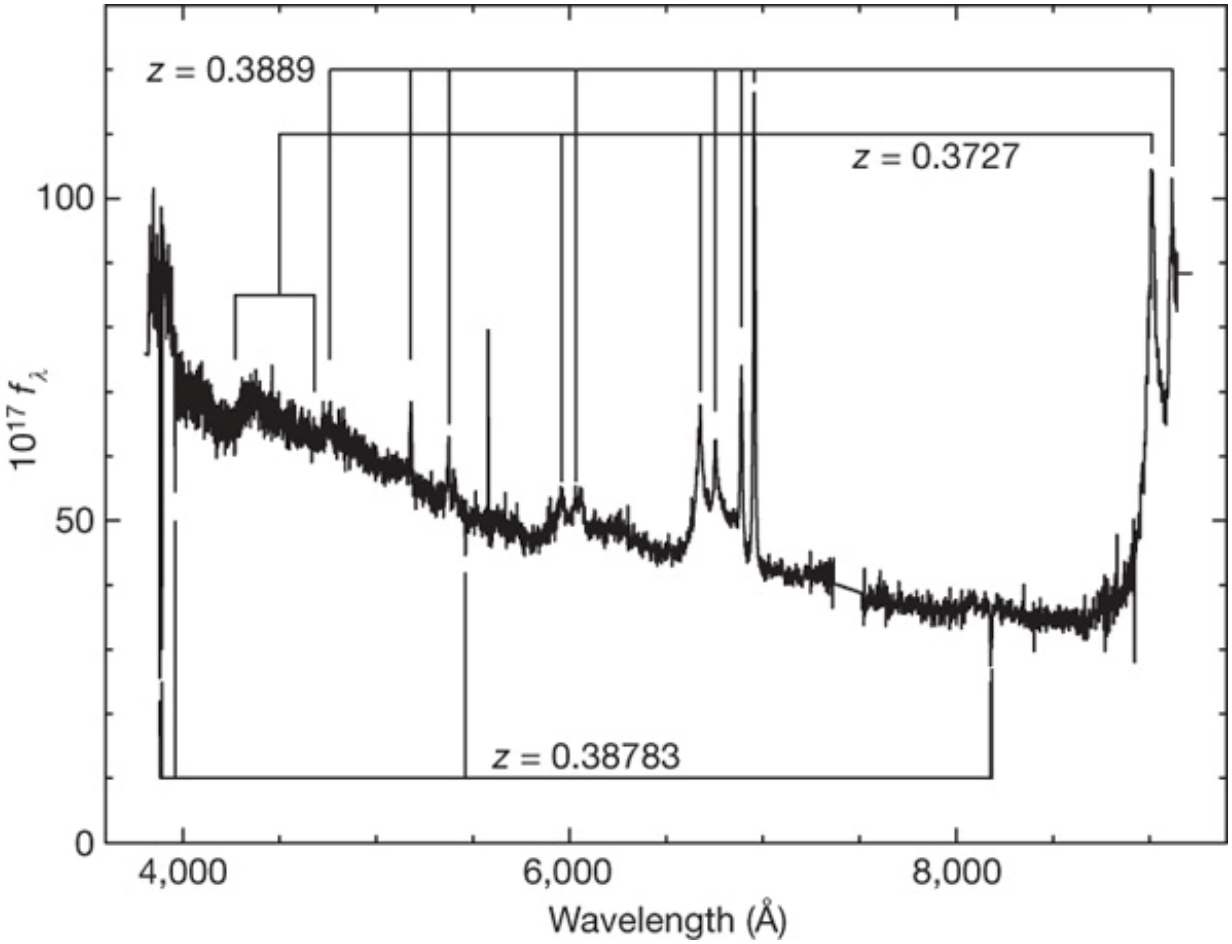
OJ 287 (Valtonen et al.)



Courtesy of A. Sillanpää



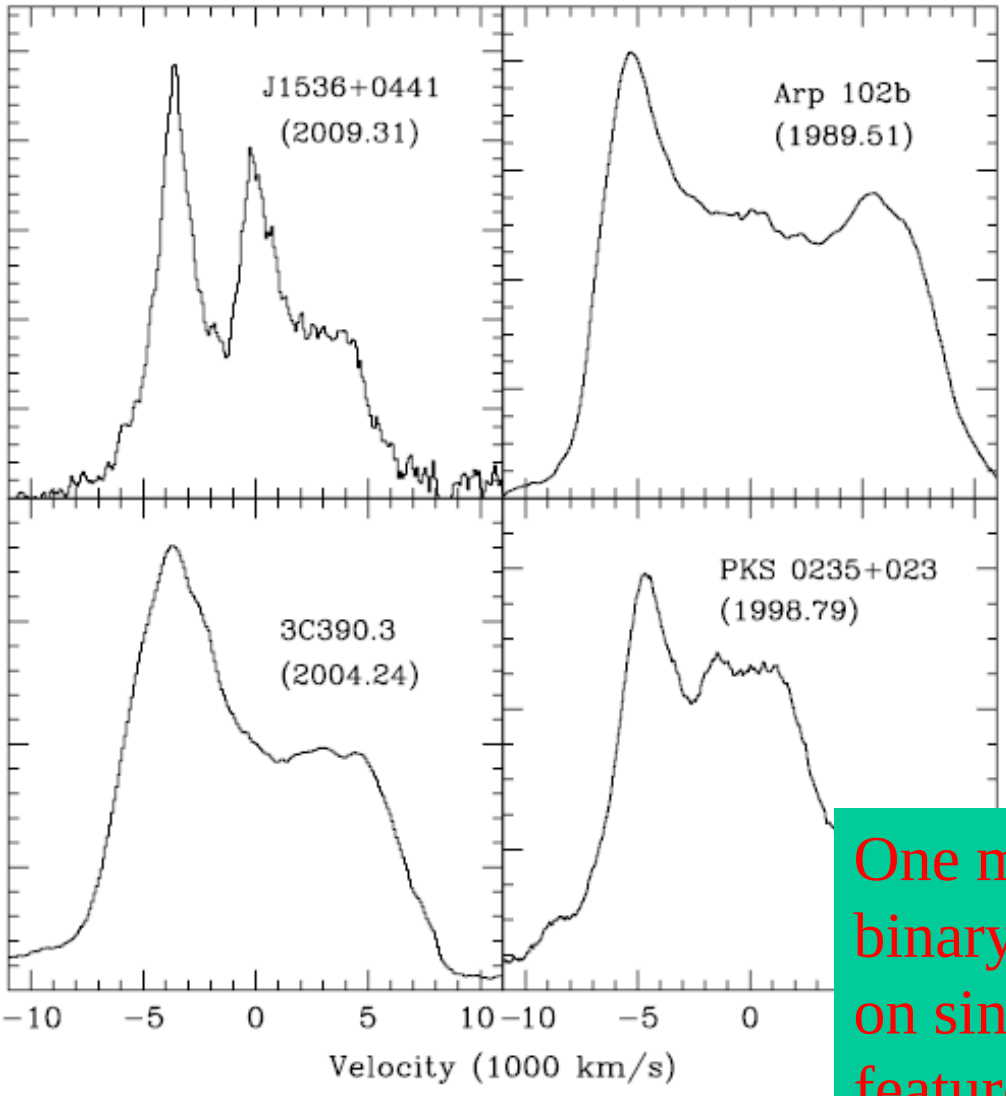
SDSS J1536+0441 (Boroson & Lauer 2009)



Double-peaked or offset broad emission lines: close binary or peculiar emission line properties?

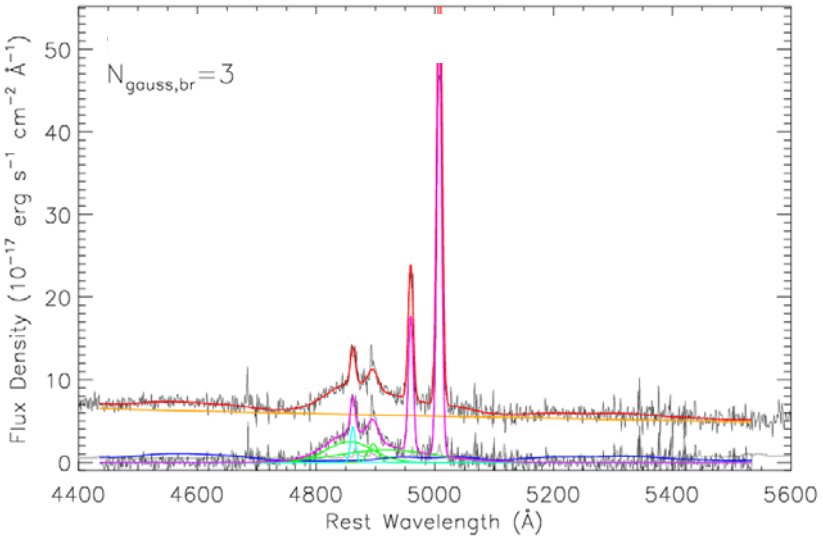
Disk emitters

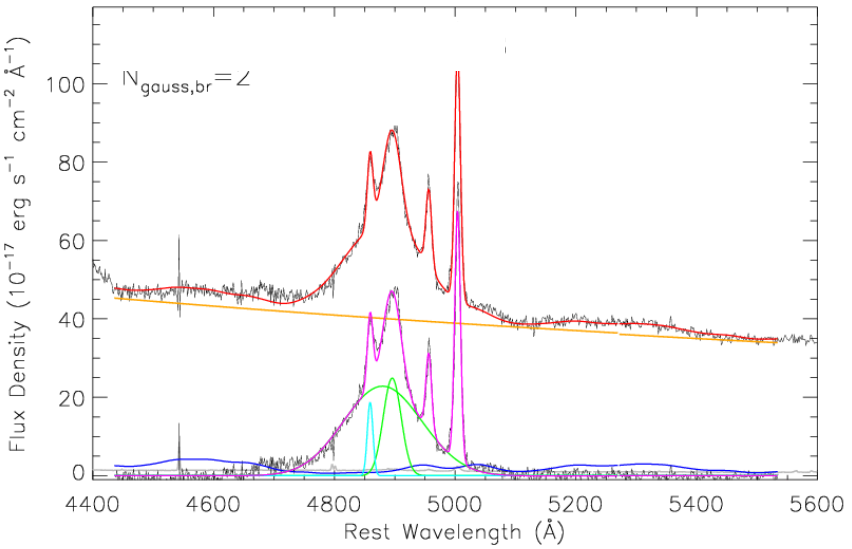
(Chen, Halpern, Eracleous et al.)

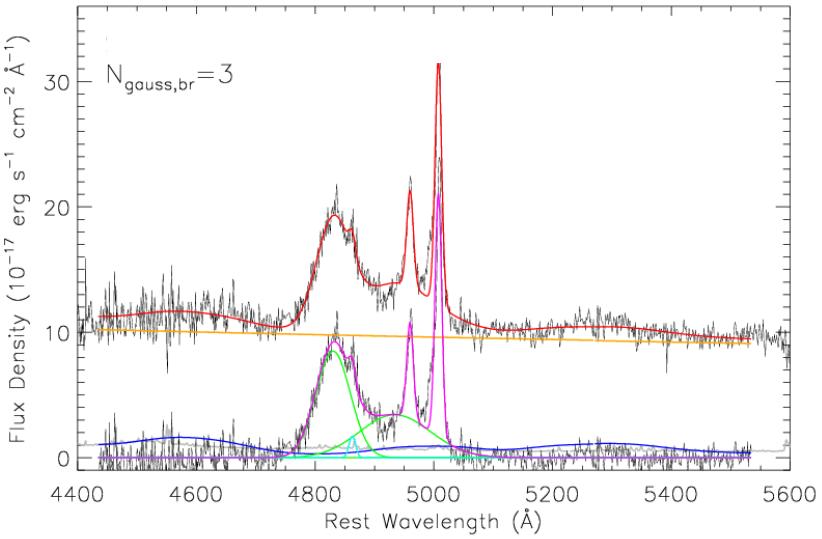


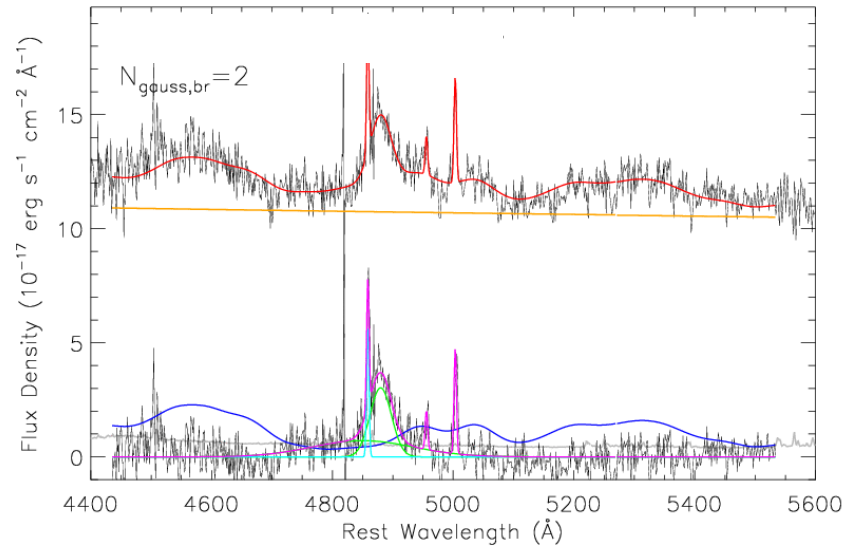
Lauer & Boroson (2009); Chornock et al. (2009)

One must be careful with the binary interpretation based on single-epoch spectral features!


$N_{gauss,br}=3$
Flux Density (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)
0
10
20
30
40
50
4400
4600
4800
5000
5200
5400
5600


$N_{gauss,br}=4$
Flux Density (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)
0
20
40
60
80
100
4400
4600
4800
5000
5200
5400
5600

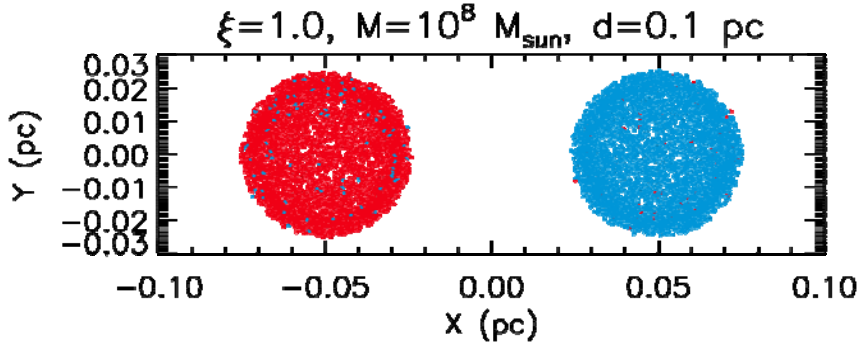

$N_{gauss,br}=3$
Flux Density (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)
0
10
20
30
4400
4600
4800
5000
5200
5400
5600

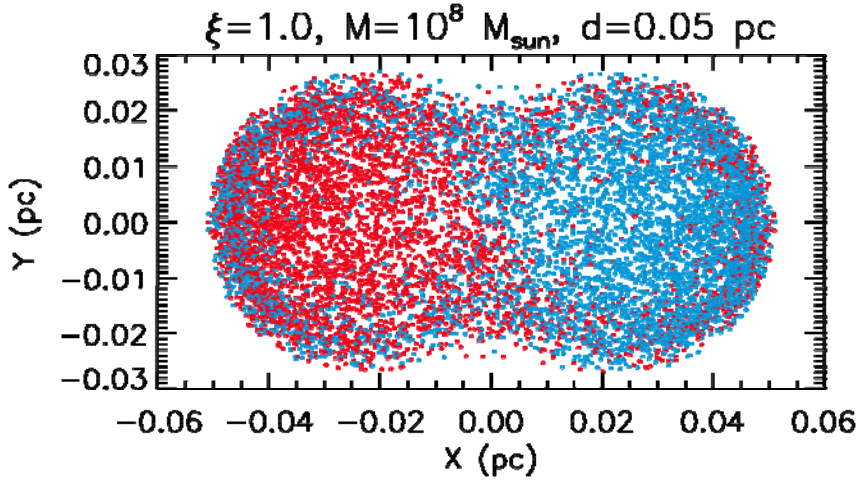

$N_{gauss,br}=2$
Flux Density (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Rest Wavelength (Å)
0
5
10
15
4400
4600
4800
5000
5200
5400
5600

How to distinguish sub-pc binary and disk emitters?

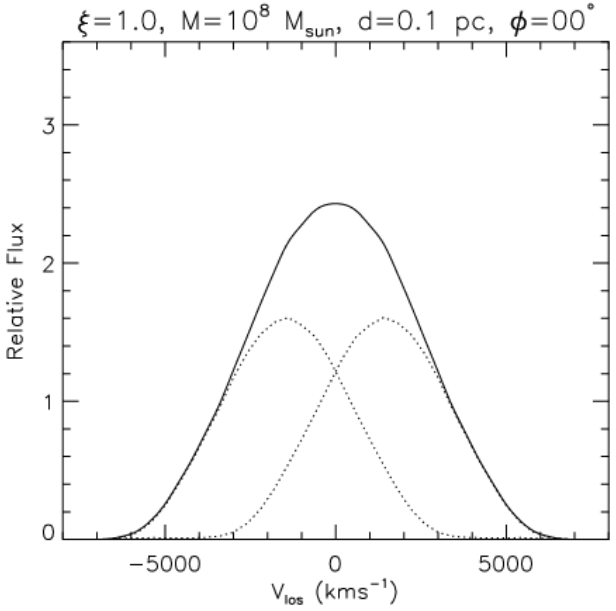
- A long history of debate (Gaskell, Peterson, Eracleous, and many more); some double-peaked emitters ruled out as binaries with distinct BLRs (e.g., Eracleous & Halpern), but circumbinary BLRs were not ruled out
- Periodic radial velocity drifts in the double-peaks – binary orbital motion
- Uncorrelated variability of the double peaks

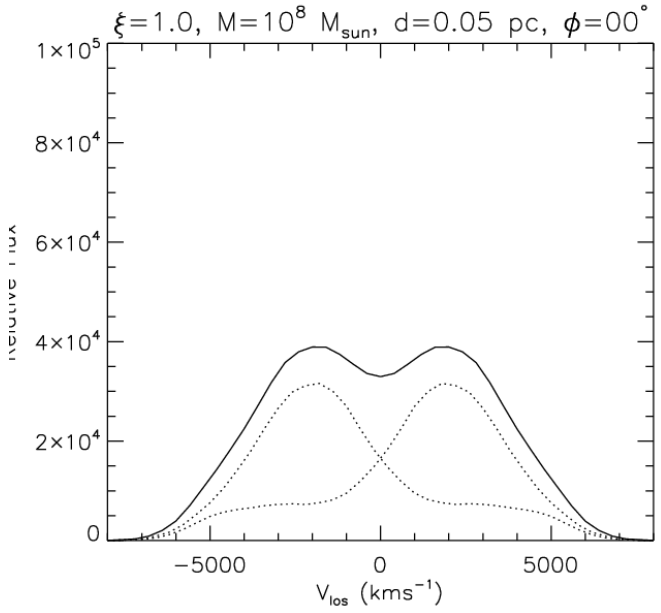
Spectroscopic sub-pc binaries based on broad line diagnosis



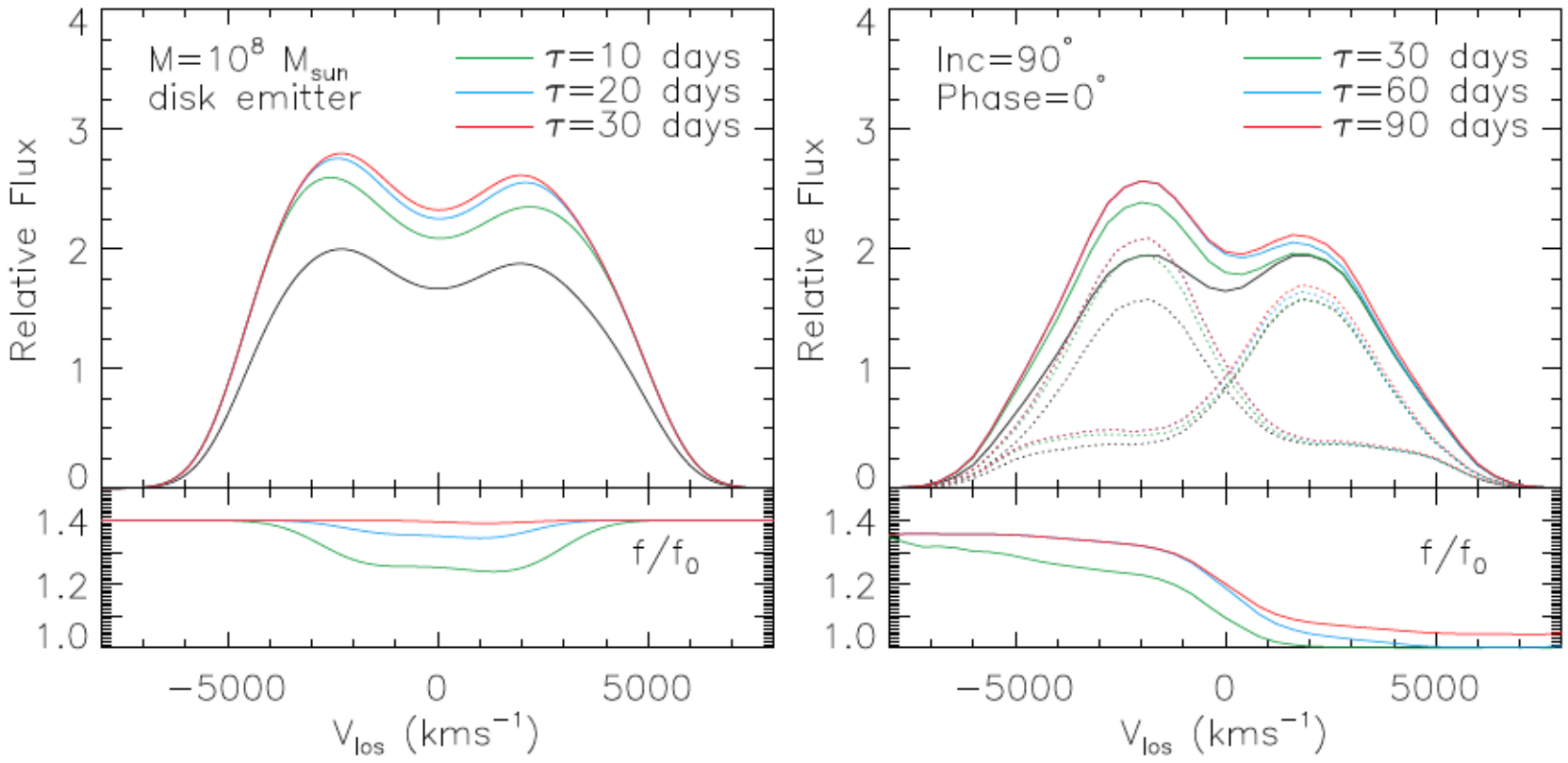


$$P \equiv 2\pi d^{3/2}(GM_{\rm tot})^{-1/2}$$
$$= 9.5 \times 10^3 \left(\frac{d}{1\ {\rm pc}}\right)^{3/2} \left(\frac{M_{\rm tot}}{10^8\ M_\odot}\right)^{-1/2}\ {\rm yr}$$





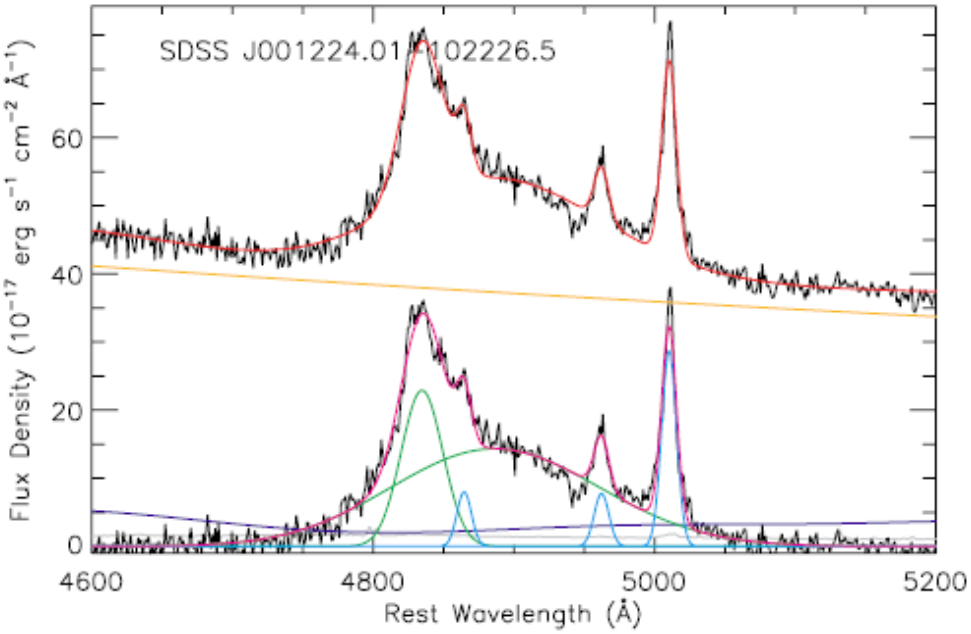
Velocity resolved reverberation mapping



Shen & Loeb (2010)

Double-peaked broad line AGNs in SDSS

- ~1000 “disk emitters” from the SDSS DR7 quasar catalog (Shen et al. 2010b).
- Some of them might be sub-pc binaries.



An example of disk emitters from SDSS