# A SEARCH FOR BINARY BLACK HOLES IN NEARBY VELOCITY-OFFSET AGNs

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**ABSTRACT: Given our current framework of hierarchical formation, binary black holes should be common in galaxies that experienced recent mergers. However, to date, only a handful of close pairs of binary black holes have been confirmed. We search for supermassive binary black holes in nearby velocity-offset AGNs using the Gemini telescope. We present the integral field unit (IFU) and broad-band imaging data for seven offset-AGN candidates taken with the Gemini Multi Object Spectrograph (GMOS). The goal of the observations is to search for evidence of AGNs spatially offset from the nucleus, in addition to the kinematic offsets found in 1-D spectroscopy.**

**BACKGROUND:**

Many of the recent efforts in the binary black hole search had been focused on finding double AGNs. However, the two black holes do not necessarily have to be accreting at the same time. An alternative approach to finding AGN in merging galaxies is to look for single AGN that is offset from the centers of inactive (but presumably SMBH-hosting) galaxies. This offset should manifest itself as ***a velocity difference between the AGN emission lines and stellar absorption lines***. A search for offset AGN by Comerford & Greene (2014; CG14) recently turned up 351 candidates from a list of ~18000 type 2 AGN with good-quality SDSS spectra. The goal of this project is to use IFU spectroscopy to investigate the cause of this velocity offset, and to confirm the ***spatial*** offset of any genuine offset AGNs.

**OBSERVATIONS:**

We observed seven of the candidates in CG14 using the IFU on GMOS (FOV 3.5" x 5"). We selected the closest candidates (z < 0.03) because with these we can obtain the highest spatial resolution and therefore the best chance of spatially separating the stellar and emission-line peaks. Also, AGN detected at sub-kpc separations are vanishingly rare to date, and therefore of much greater interest than those at several kpc.

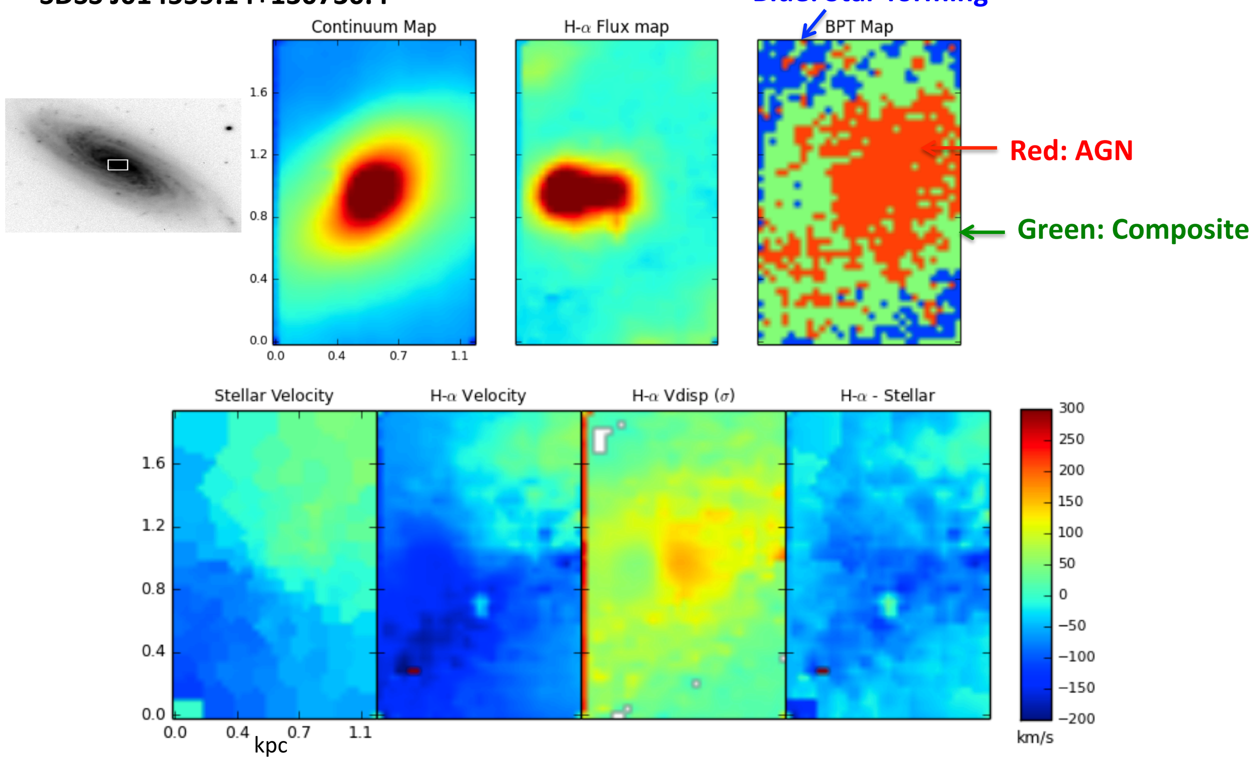
TABLE 1
GALAXY PROPERTIES

| SDSS Nomenclature (1) | other names (2) | redshift (3) | distance Mpc (4) | scale kpc/″ (5) | $\Delta\nu$ km s$^{-1}$ (6) | Morphology (7) | Radio Luminosity Watts Hz$^{-1}$ (8) |
|---|---|---|---|---|---|---|---|
| SDSS J014659.14+130730.4 | NGC 671 | 0.018 | 79.8 | 0.286 | -52.6 $\pm$10.2 | Spiral | – |
| SDSS J134640.79+522836.5 | SBS 1344+527 | 0.029 | 127.8 | 0.585 | -51.5 $\pm$10.3 | Elliptical | $2.4 \times 10^{21}$ |
| SDSS J143642.64+395636.9 | CGCG 220-034 | 0.020 | 87.1 | 0.406 | -51.6 $\pm$ 11.0 | Elliptical | $1.7 \times 10^{21}$ |
| SDSS J144412.18+075658.7 | UGC0949 | 0.028 | 121.1 | 0.556 | -66.7 $\pm$ 11.2 | Spiral | – |
| SDSS J151505.55+430902.0 | CGCG 221-045 | 0.018 | 77.7 | 0.363 | 99.1 $\pm$ 10.5 | Uncertain | $4.5 \times 10^{21}$ |
| SDSS J171522.99+572440.2 | NGC6338 | 0.027 | 119.4 | 0.548 | -73.7 $\pm$ 11.3 | Uncertain | $8.4 \times 10^{22}$ |
| SDSS J204719.06+001914.8 | NGC6962 | 0.014 | 60.7 | 0.286 | -59.3 $\pm$ 10.6 | Spiral | – |

NOTE. — Column (1) Name on the SDSS nomenclature; column (2) other common names; column (3) SDSS redshift; column (4) luminosity distance in Mpc derived with Wright's (2006) cosmology calculator; column (5) physical scale in kpc/″; column (6) weighted velocity offsets measured by CG14; column (7) Galaxy Zoo morphological type ; column (8) Radio luminosity at 1.4 GHz calculated from the FIRST radio survey catalog.

## Are They Binary SMBHs? What Are They?

### SDSS J014559.14+130730.4



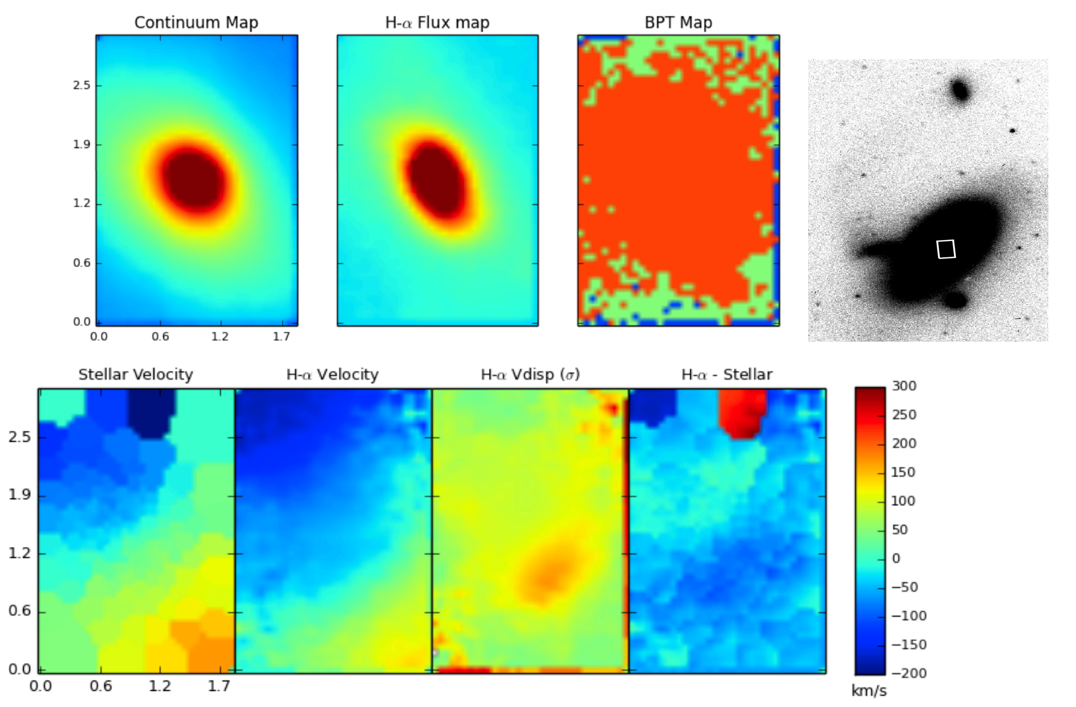

**Host Galaxy Morphology**: Spiral galaxy in a low density environment with no evident sign of past interactions or mergers. Star-forming clumps along its spiral arms.

**Emission-Line Flux Distribution vs. Continuum Map**: Elongated Hα emission with an off-center "blob" ~ 1.3 kpc from the nucleus. The emission line ratio of this off-center blob is consistent with the composite region in the BPT diagram. This is visible on the BPT map as a green area. The origin of this blob is likely to be a star forming region also ionized by the AGN due to its proximity to the nucleus of the galaxy.

**Ionized Gas vs. Stellar Velocity Structure**: The stellar velocity map shows a rotation characteristic of a spiral galaxy. The Hα emission line is blueshifted compared to the stellar continuum by about ~50 to 100 km/s.

***Reason for Velocity offset:*** *The extended patch of blueshifted Hα emission likely represent outflowing gas, possibly driven by the star-forming blob offset from the nucleus.*

### SDSS J134640.79+522836.5



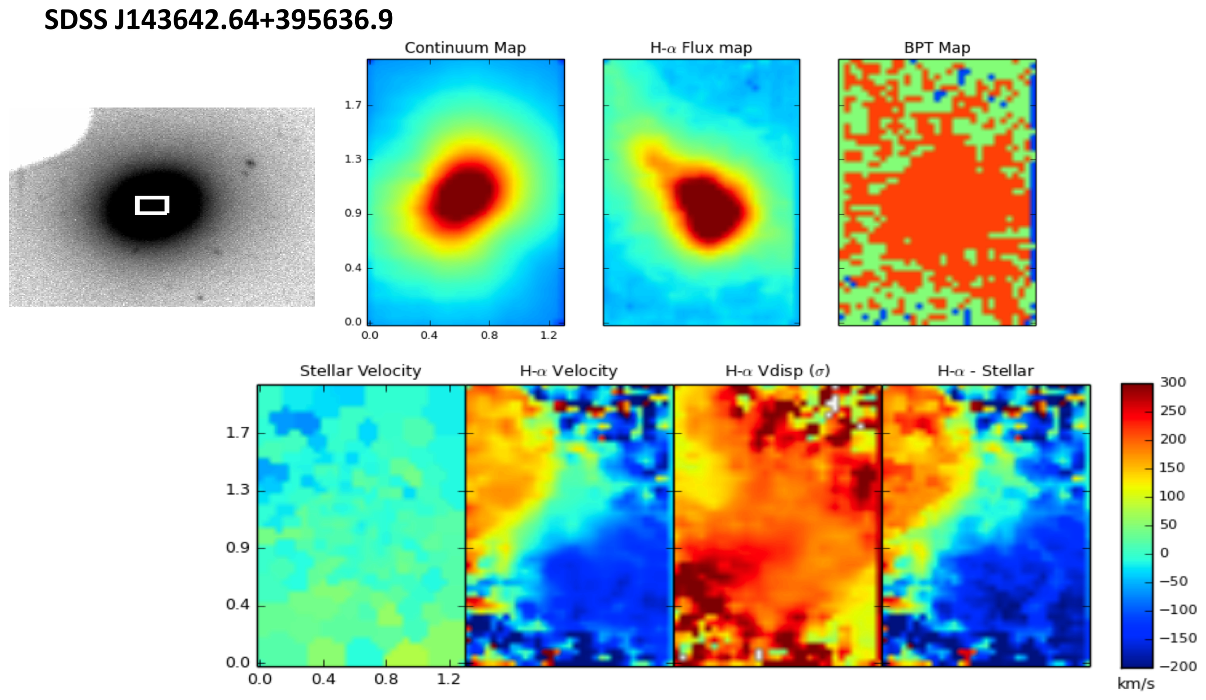

**Host Galaxy Morphology**: Interacting system of three galaxies, the main galaxy SBS 1344+527 has a smaller companion ~ 16" to the east and a second interacting galaxy ~ 45" to the north. There is a low surface brightness tidal tail between these three galaxies.

**Emission-Line Flux Distribution vs. Continuum Map**: The continuum map shows a round and symmetric geometry while the Hα map is slightly more elongated along a different position angle of ~ 15 to 20 degrees offset relative to the continuum.

**Ionized Gas vs. Stellar Velocity Structure**: The overall Hα velocity is blueshifted with respect to the continuum. There is a region of strong blueshift southwest of the nucleus which also corresponds to a region of higher Hα velocity dispersion.

***Reason for Velocity offset:*** *Given the host galaxies' recent merger, the velocity offset is likely due to disturbed gas kinematics resulting from the merger.*

### SDSS J143642.64+395636.9



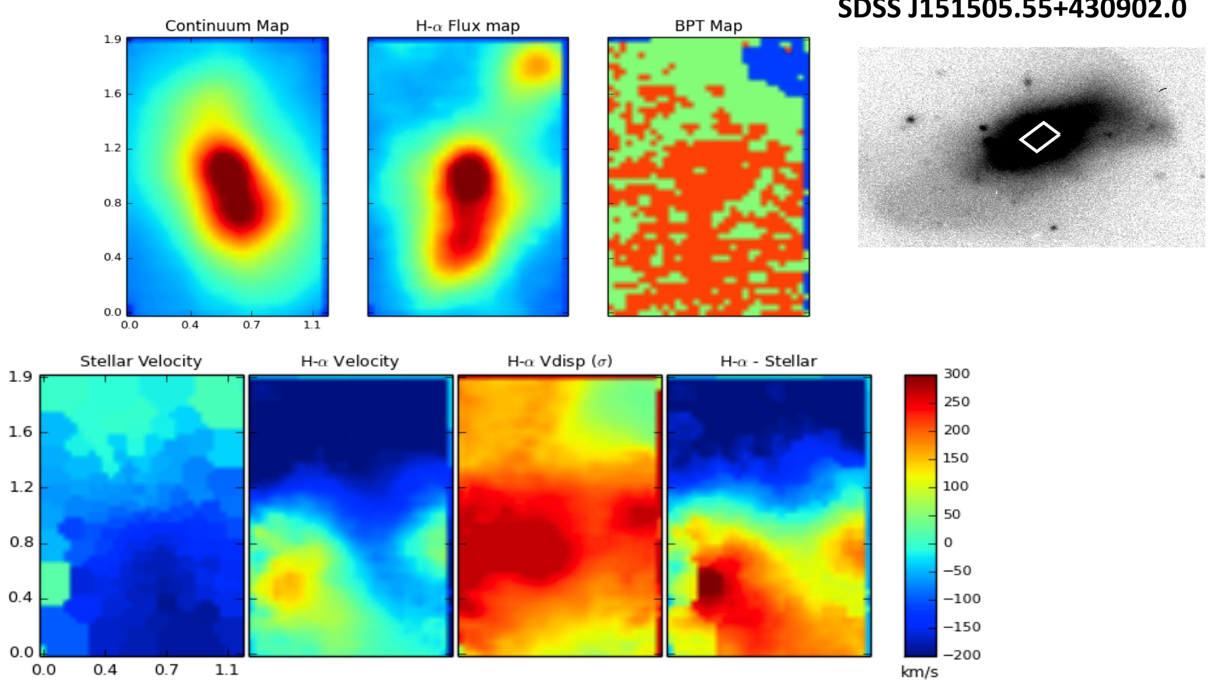

**Host Galaxy Morphology**: Elliptical galaxy with a dust lane visible across its core going on a north-east to south-west diameter. The isophotes of this galaxy are regular and well adjusted by a double Sersic profile within the inner 50".

**Emission-Line Flux Distribution vs. Continuum Map**: The dust lane attenuates the signal along a band that crosses the center of the galaxy, resulting in a "peanut' shape in the continuum map. The Hα map is elongated along the position angle of the dust lane.

**Ionized Gas vs. Stellar Velocity Structure**: The stellar velocity map show slow rotation consistent with a large elliptical galaxy. The gas kinematics show, however, a strong velocity gradient, roughly aligned with the dust lane, and very high velocity dispersion (~ 200 to 250 km/s).

***Reason for Velocity offset:*** *The disparity between stellar and gas kinematics coupled with the presence of a dust lane suggest a recent gas accretion event by an old elliptical galaxy.*

### SDSS J151505.55+430902.0



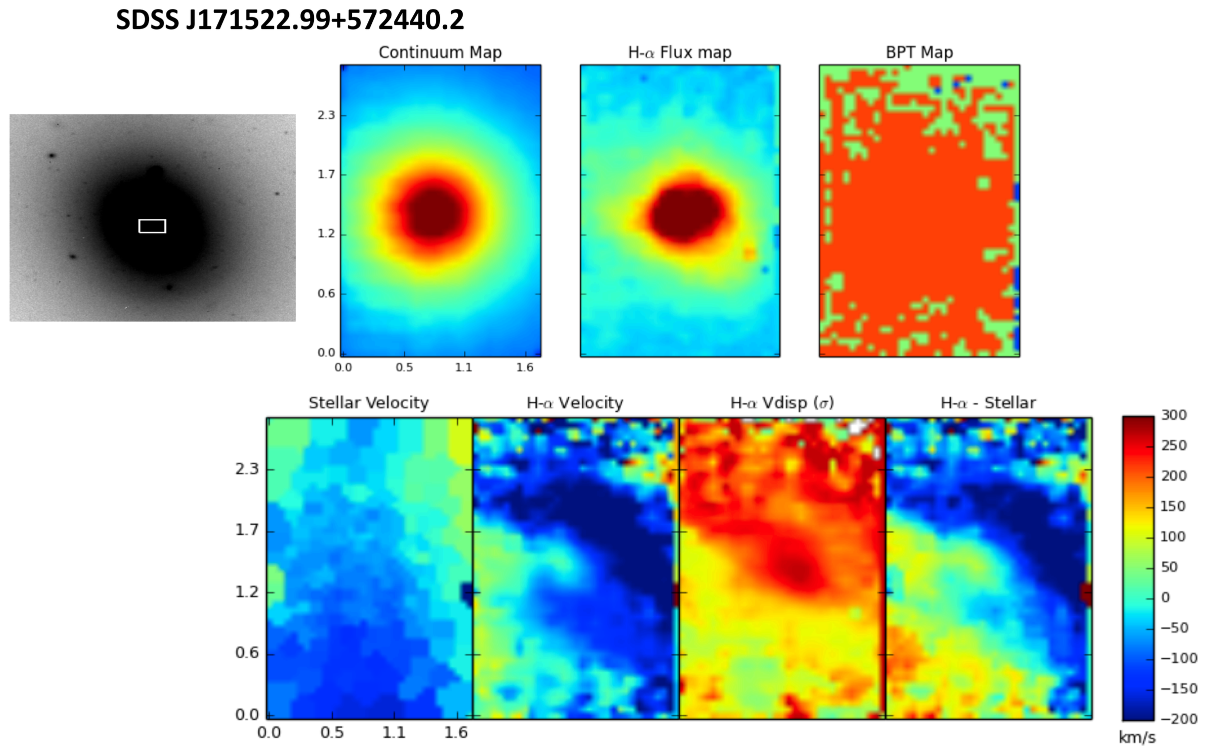

**Host Galaxy Morphology**: The most striking feature of the GMOS image is the clear presence of shells. The overall morphology of this galaxy is irregular and disturbed, the main body of the galaxy is elongated along a major axis running south-east to north-west. A clearly visible shell has circular edges and a radius of ~ 23". A second, fainter outer shell is also present and has a radius of ~ 38".

**Emission-Line Flux Distribution vs. Continuum Map**: The Hα flux distribution is quite different from the continuum morphology, with an isolated Hα blob north-west of the nucleus. The emission-line ratio of this isolated region is consistent with a star-forming region.

**Ionized Gas vs. Stellar Velocity Structure**: The stellar velocity map shows an organized rotating pattern, while the Hα velocity map reveals the chaotic motions of the ionized gas.

***Reason for Velocity offset:*** *The IFU maps are consistent with the dynamical signatures of a recent merger event, which can cause highly disturbed gas motions that deviate from the stellar kinematics.*

### SDSS J171522.99+572440.2



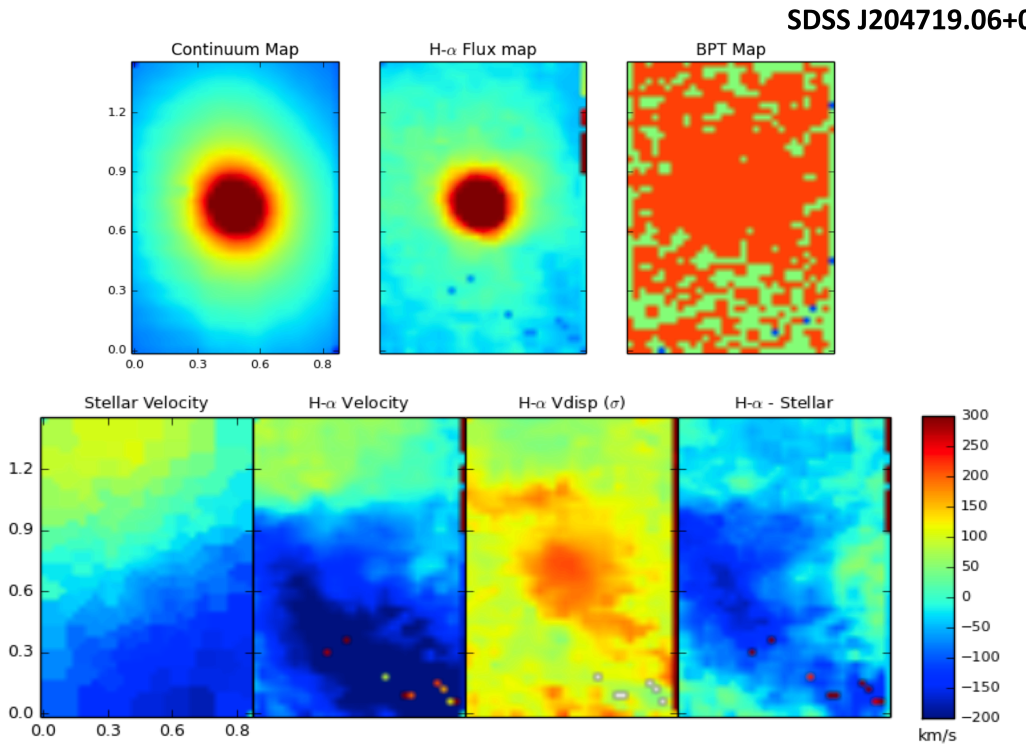

**Host Galaxy Morphology**: Slightly elongated elliptical galaxy. This galaxy is the largest one in a rich field.

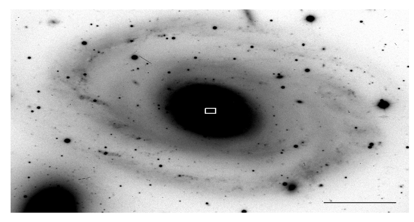
**Emission-Line Flux Distribution vs. Continuum Map**: The continuum map shows a round and symmetric geometry. The Hα map is also centrally concentrated, but slightly elongated in the north-south direction.

**Ionized Gas vs. Stellar Velocity Structure:** The stellar velocity is consistent with the slow rotation shown by elliptical galaxies. The ionized gas velocity maps shows a strongly blueshifted component in the upper right region with high velocity dispersion that indicate turbulent motions, and a redshifted region in the lower left region.

***Reason for Velocity offset:*** *Given the relatively undisturbed morphologies of both the continuum map and the Hα emission. The reason for such dramatic velocity offset is more difficult to pinpoint. It is possible that a close pair of binary SMBHs are responsible for disturbing the gas kinematics close to the nucleus. However, we cannot rule out the other possibilities, such as AGN driven outflows.*

### SDSS J204719.06+001914.8



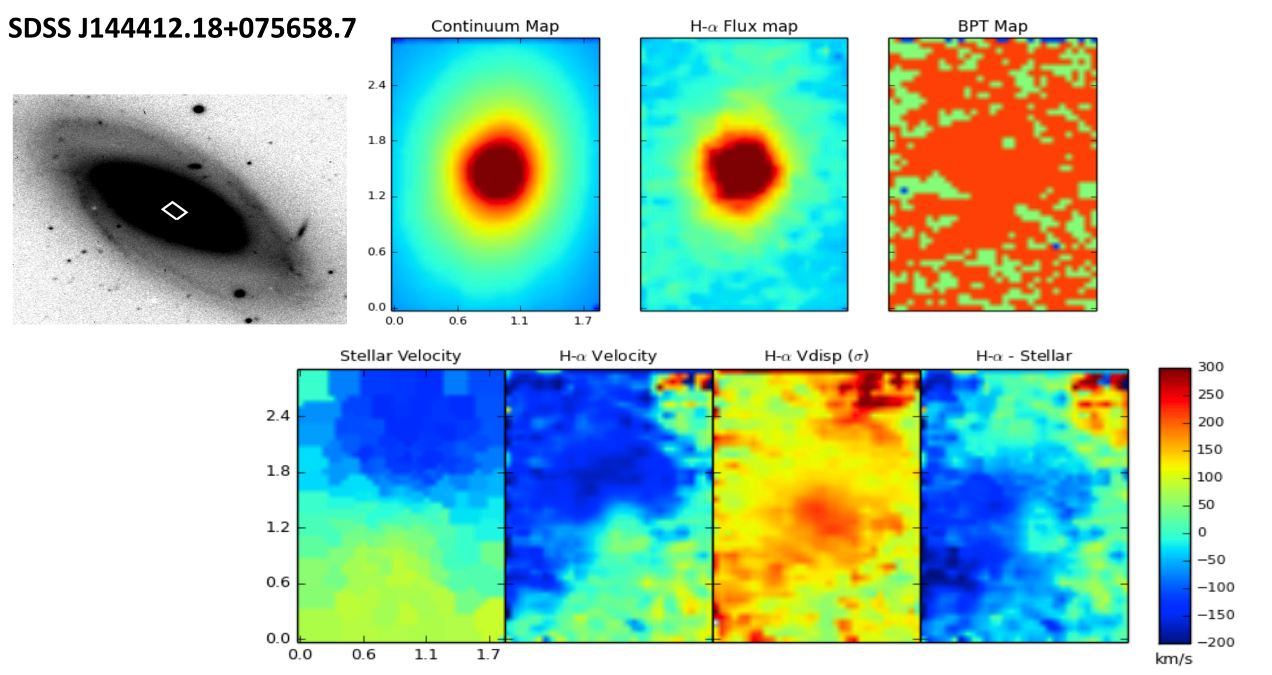
**Host Galaxy Morphology**: Spiral with clear star forming regions along its spiral arms, and a large companion to the south- east. No clear signs of interaction with the companion.

**Emission-Line Flux Distribution vs. Continuum Map**: Both continuum and Hα flux maps are spherically symmetric and centrally concentrated. Even if this galaxy is has many star-forming regions, the gas in the nuclear region is clearly ionized by the AGN according to the BPT map.

**Ionized Gas vs. Stellar Velocity Structure**: The stellar velocity shows standard rotation for an spiral galaxy. The Hα velocity map shows an extended region that is blueshifted compared to the stellar velocity.

***Reason for Velocity offset:*** *The extended velocity offset likely represent outflowing gas. If the star-forming region(s) or the AGN is driving roughly spherically symmetric outflows, then we would expect to see the gas closer to us to appear blueshifted.*

### SDSS J144412.18+075658.7




**Host Galaxy Morphology**: Barred spiral galaxy two prominent outer spiral arms, one to the north-west and the second one to the south-east. While this galaxy has several close companions on the field, there is no sign of recent interactions.

**Emission-Line Flux Distribution vs. Continuum Map**: The distribution of stars and ionized gas are both centrally concentrated with symmetric structures.

**Ionized Gas vs. Stellar Velocity Structure**: The stellar velocity map shows a standard rotation pattern. However, the velocity distributions of stars and gas are not entirely analogous. Overall, a larger component of the gas is blueshifted when compared to the stars.

***Reason for Velocity offset:*** *Once again, the extended region with velocity offsets likely indicate ionized gas outflow.*

**CONCLUSION**

- The IFU data show that a wide range of kinematics can occur within the 3" diameter of the SDSS fiber. In many of our objects, the ionized gas show disturbed velocity fields that are quite different from the stellar kinematics. However, we did not find any unambiguous evidence for offset AGNs in the targets we observed.
- A few of our targets show clear signs of recent merger/gas accretion, which is most likely the main cause for the disturbed gas kinematics in these systems. (SDSS J134640.79+522836.5, SDSS J143642.64+395636.9, SDSS J151505.55+430902.0)
- For the relatively undisturbed elliptical, SDSS J171522.99+572440.2, it is possible that the velocity offset is caused by an unresolved pair of SMBHs. However, without a spatially resolved offset AGN, our data cannot confirm the presence of double SMBHs. AGN driven outflows may also cause the observed velocity offsets.
- In spiral galaxies that are unlikely to have experienced recent merging events, the ionized gas are likely part of an outflow. In these systems, the ionized gas tend to be blueshifted relative to the stars, which is what we expect to see in the case of roughly spherically symmetric outflows. (SDSS J1014559.14+1307030.4, SDSS J144412.18+075658.7, SDSS J204719.06+001914.8)