



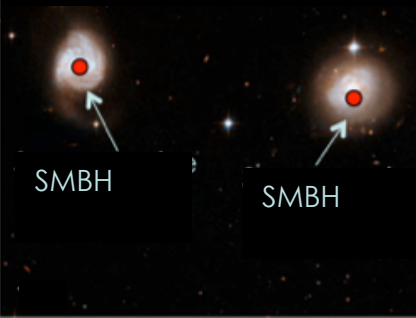



Observations of Dual Supermassive Black Holes at Kpc-scale Separations

Julie Comerford

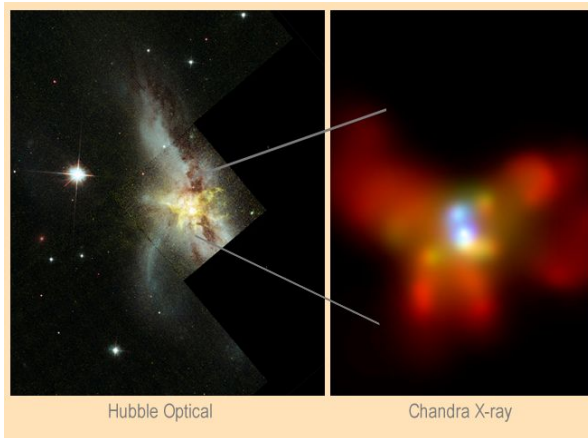
University of Colorado, Boulder

Massive Black Holes: Birth, Growth, and Impact
August 6, 2013

Supermassive Black Hole Pairs Are Direct Tracers of Galaxy Evolution

<p>SMBHs in galaxy pairs $\Delta x \sim 10 - 100 \text{ kpc}$</p> 	<p>Dual SMBHs $\Delta x \sim \text{kpc}$ $\Delta v \sim 100 \text{ km/s}$</p> 	<p>Binary SMBHs $\Delta x < \text{pc}$ $\Delta v \sim 1000 \text{ km/s}$</p> 	<p>SMBH coalescence Gravitational radiation</p> 
<p>SMBHs in galaxy pairs</p> <p>Thousands of confirmations</p> <p>e.g., Hennawi et al. 2006, 2010; Myers et al. 2008; Shen et al. 2010; Liu et al. 2011; Koss et al. 2012; Ellison et al. 2013</p>	<p>Dual SMBHs</p> <p>13 confirmations, many candidates</p> <p>e.g., Barrows+, Bianchi+, Comerford+, Fabbiano+, Fu+, Ge+, Gerke+, Greene+, Hudson+, Komossa+, Koss+, Liu+, Mazzarella+, McGurk+, Rodriguez+, Rosario+, Shen+, Shields+, Smith+, Tingay+, Wang+</p>	<p>Binary SMBHs</p> <p>No confirmations yet, many candidates</p> <p>e.g., Gaskell 1983, 1984; Valtonen et al. 2008; Bogdanovic et al. 2009; Boroson & Lauer 2009; Dotti et al. 2009; Decarli et al. 2010; Burke-Spolaor 2011; Tsalmantza et al. 2011; Eracleous et al. 2012; Ju et al. 2013; Shen et al. 2013</p>	<p>Recoiling SMBHs</p> <p>No confirmations yet, several candidates</p> <p>e.g., Komossa et al. 2008; Shields et al. 2009; Comerford et al. 2009; Civano et al. 2010, 2012</p>

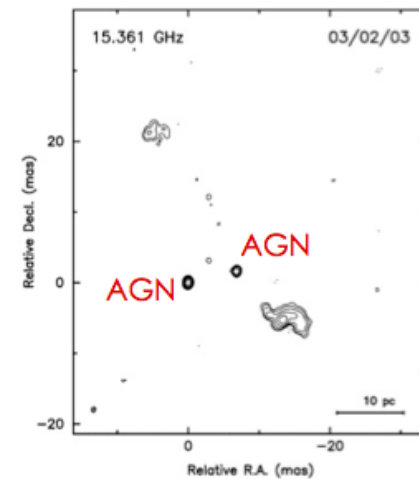
First Dual AGN Discoveries Were Serendipitous



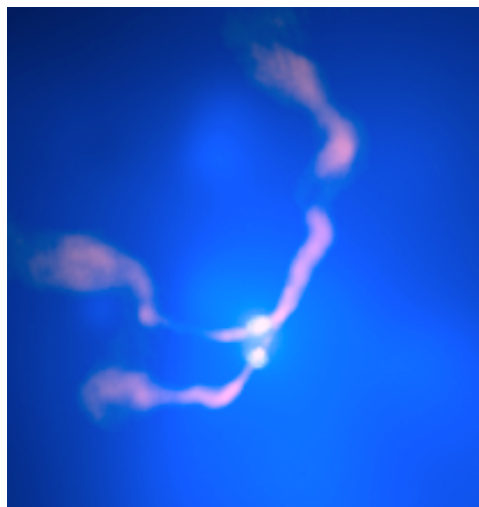
Hubble Optical

Chandra X-ray

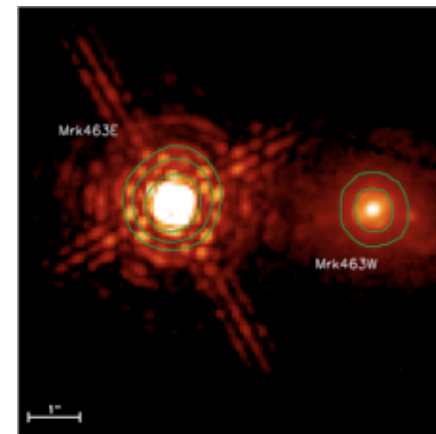
NGC 6240
 $z = 0.02$
 $\Delta x = 0.7 \text{ kpc}$
Komossa et al. 2003



0402+379
 $z = 0.06$
 $\Delta x = 7 \text{ pc}$
Rodriguez et al. 2006



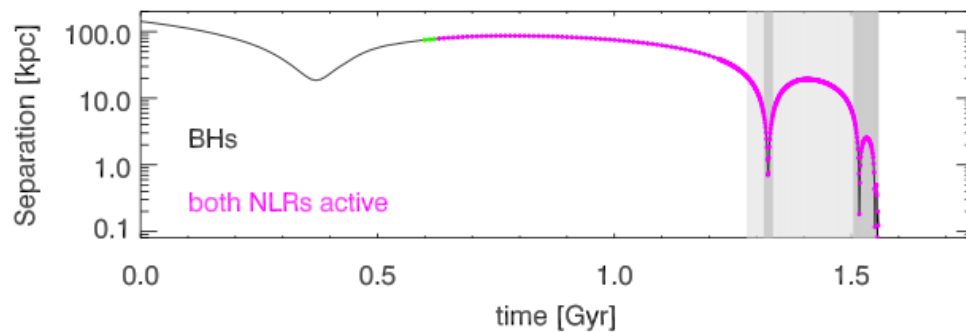
3C 75
 $z = 0.02$
 $\Delta x = 7 \text{ kpc}$
Hudson et al. 2006



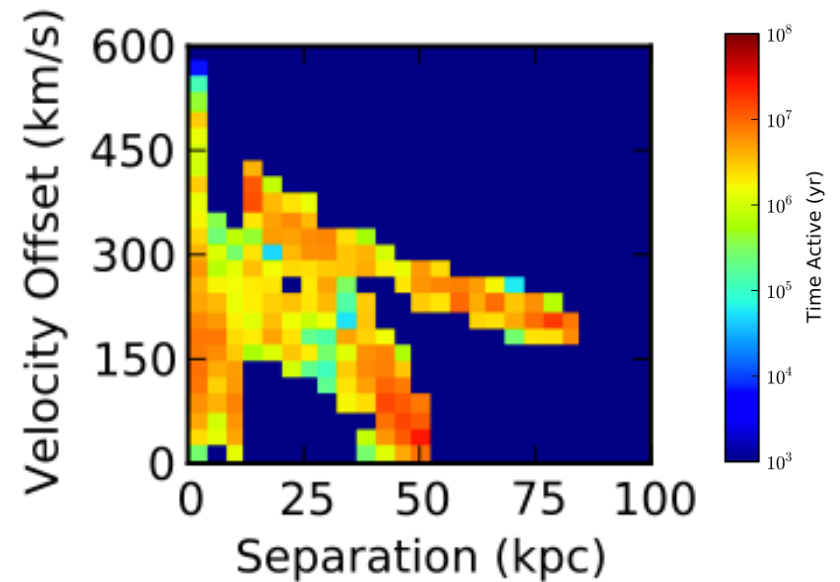
Mrk 463
 $z = 0.05$
 $\Delta x = 4 \text{ kpc}$
Bianchi et al. 2008

There Should Be Many Dual AGN at Kpc-scale Separations

Dual AGN lifetimes are ~few to ~hundreds Myr



Blecha et al. 2012

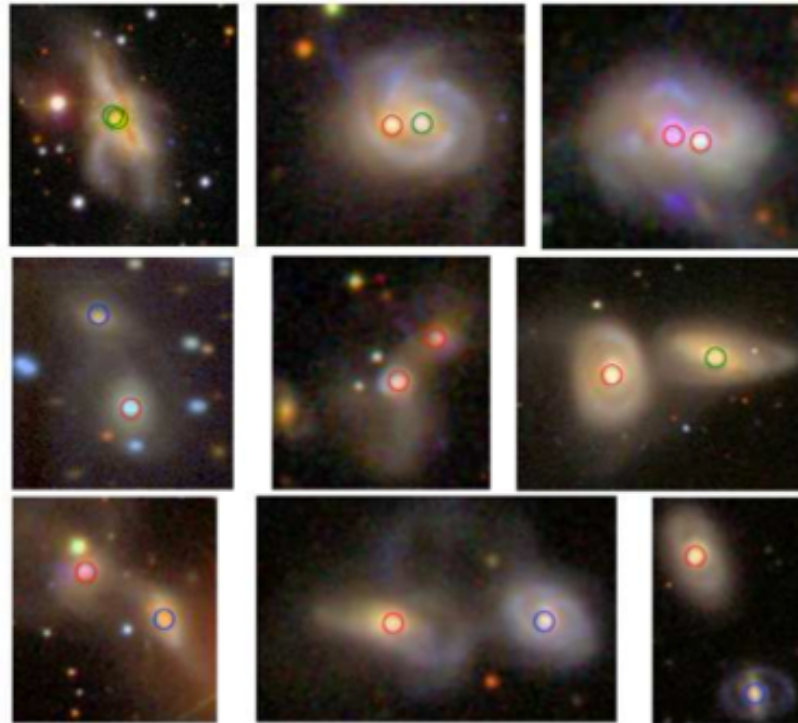


Van Wassenhove et al. 2012

Systematic Searches for Dual AGN

Swift BAT survey: 16/167 (10%) of AGN at $z < 0.05$ are in AGN pairs with separations < 100 kpc (Koss et al. 2012)

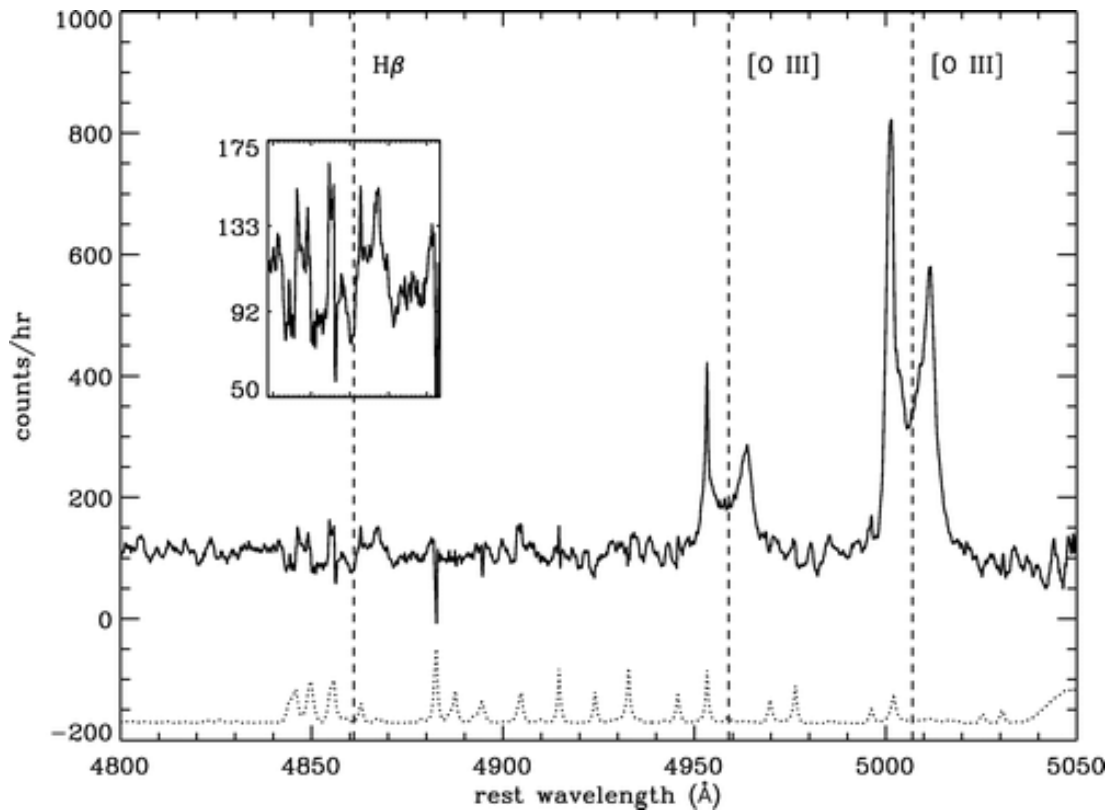
Includes 4 dual AGN with < 10 kpc separations



Systematic Searches for Dual AGN: Double-Peaked Narrow AGN Emission Lines



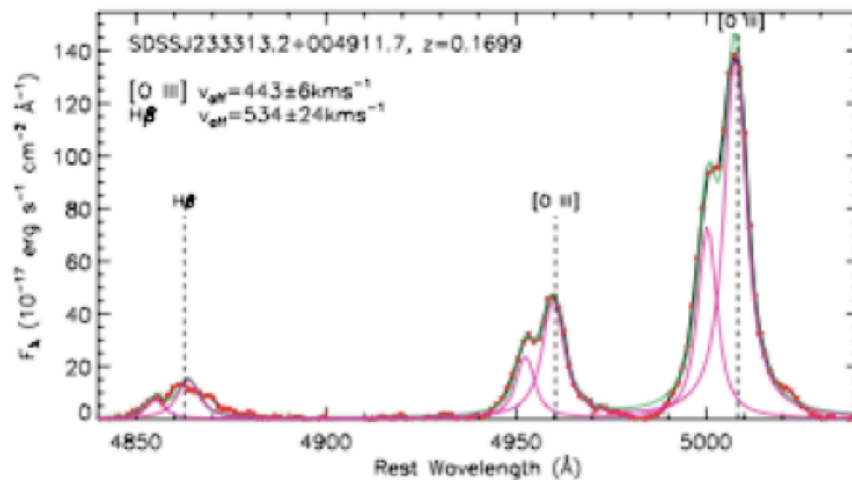
- Double peaks
can be
produced by:
- Outflows
 - Rotating disks
 - Dual AGN



Gerke et al. 2007

~1% of AGN Are Double-peaked

Survey	Redshift	% of AGN with double peaks	Reference
SDSS	$0.8 < z < 1.6$	0.3 %	Barrows et al. 2013
DEEP2	$0.34 < z < 0.82$	$2.2^{+2.8}_{-0.7}$ %	Comerford et al. 2009
AGES	$z < 0.37$	$1.1^{+1.4}_{-0.4}$ %	Comerford et al. 2013
SDSS	$z < 0.15$	$1.3^{+0.1}_{-0.1}$ %	Wang et al. 2009 Xu & Komossa 2009 Liu et al. 2010 Smith et al. 2010 Ge et al. 2012



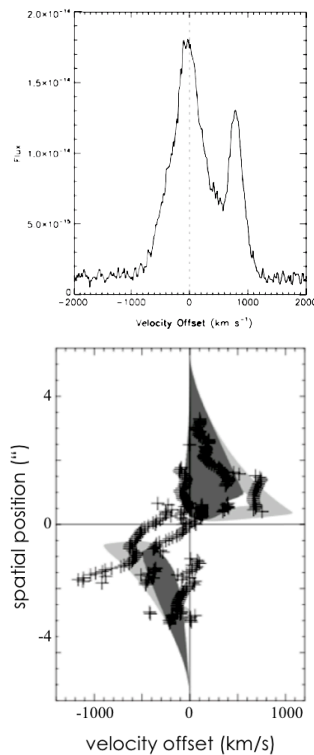
Liu et al. 2010

Follow-up Observations of Double-peaked AGN Needed to Confirm Dual AGN

1. Optical/NIR longslit or integral field spectroscopy

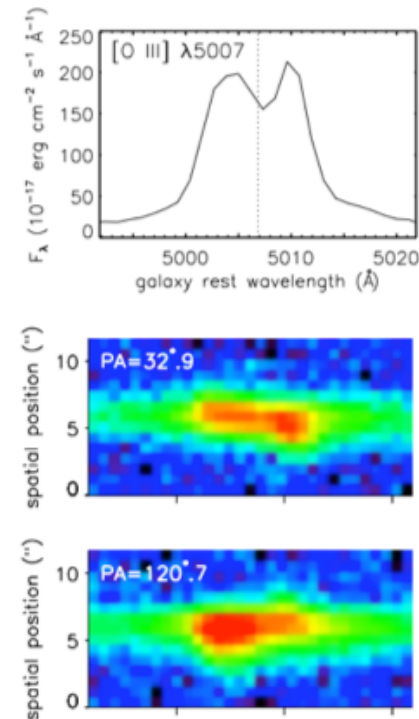
Purpose: Map spatial extent of AGN emission to help identify dual AGN

[O III] in AGN outflow:



Fischer et al. 2011

[O III] in dual AGN:



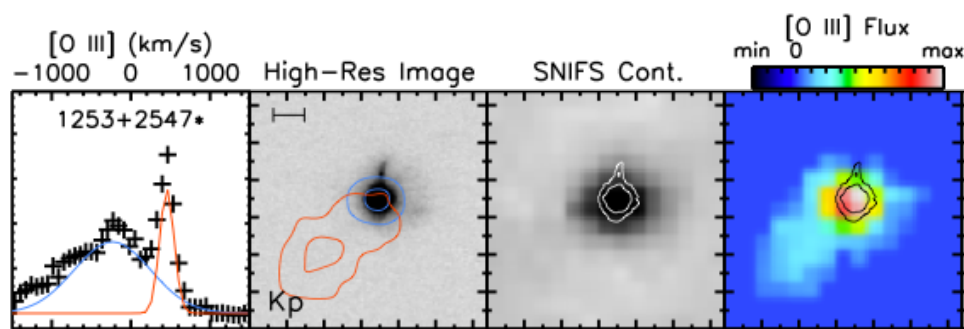
Comerford et al. 2012

Longslit/IFU Follow-up Observations

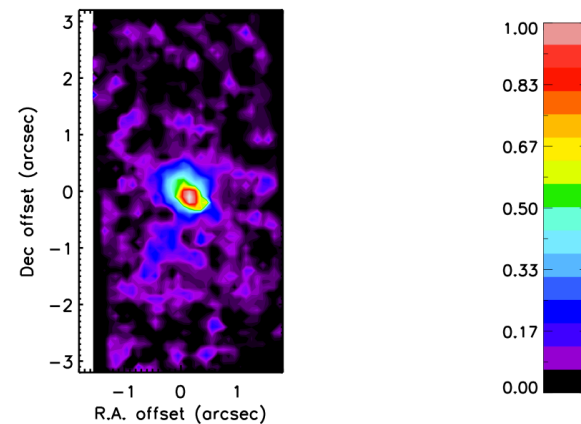
Longslit: 113 observations of double-peaked AGN in SDSS (Liu et al. 2010; Shen et al. 2011; Comerford et al. 2012; Greene et al. 2012)

IFU: 43 observations of double-peaked AGN in SDSS (Fu et al. 2011, 2012; McGurk et al. 2011)

~50-60% of double-peaked AGN have spatially extended narrow line emission



Fu et al. 2012

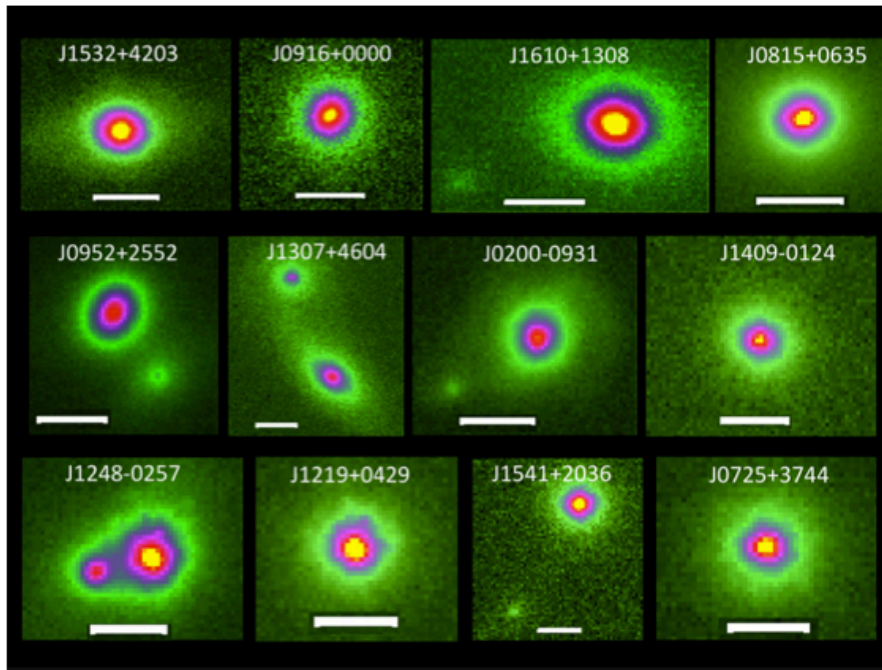


Mueller-Sanchez

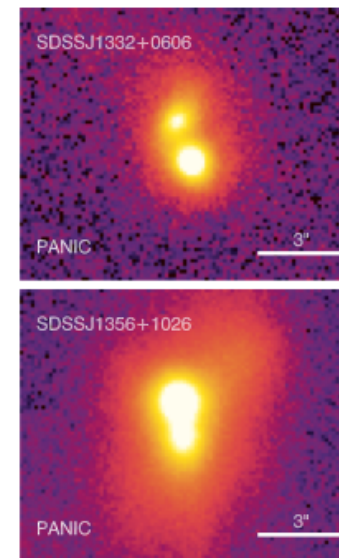
2. NIR Imaging Follow-up Observations

149 observations of double-peaked AGN in SDSS (Liu et al. 2010; Fu et al. 2011, 2012; McGurk et al. 2011; Rosario et al. 2011; Shen et al. 2011)

~30% of double-peaked AGN have companions within 3''



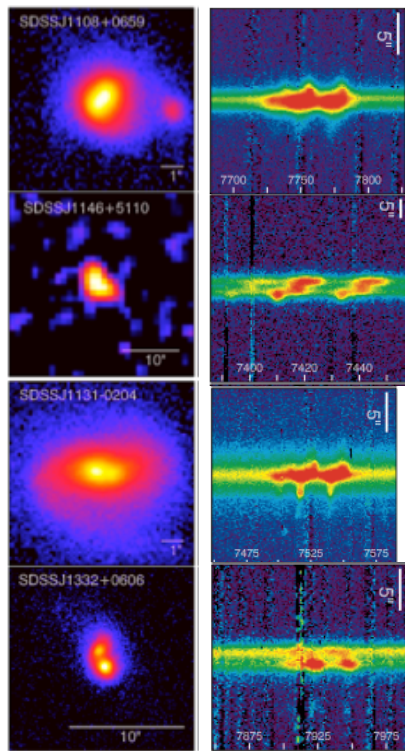
Rosario et al. 2011



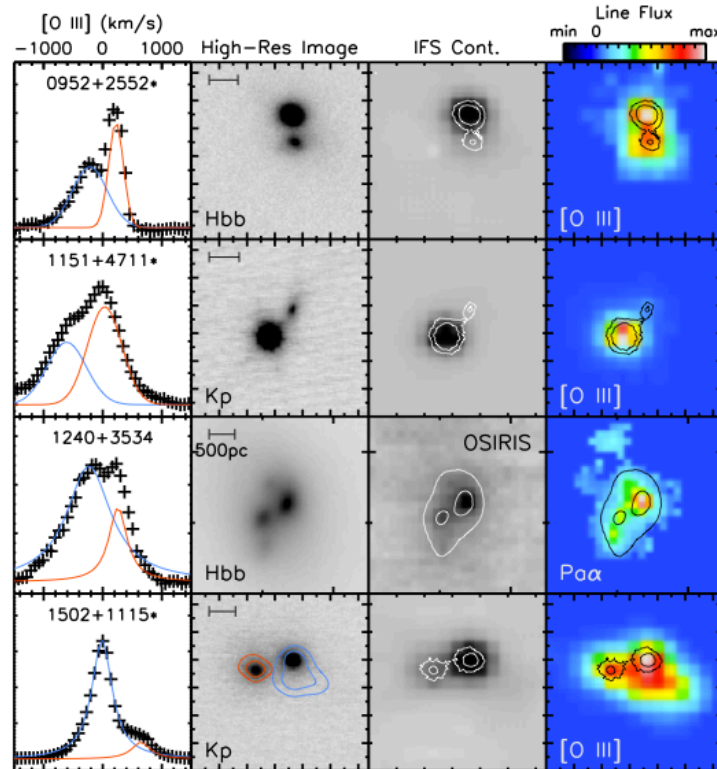
Shen et al. 2011

Dual AGN Candidates from Longslit/IFU and NIR Imaging

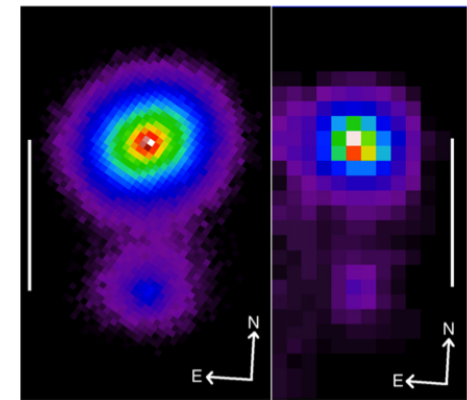
~10% of double-peaked AGN in SDSS have double narrow emission components spatially coincident with double stellar components



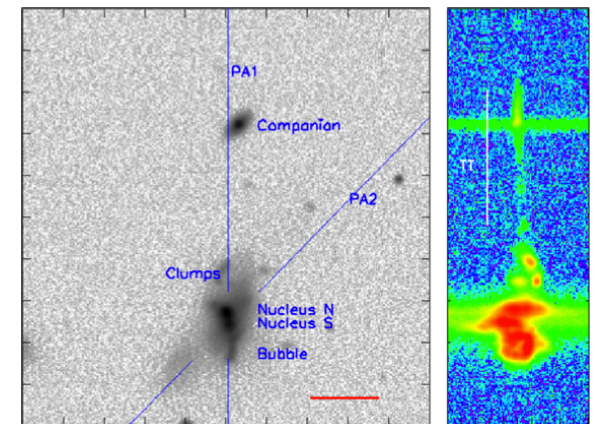
Liu et al. 2010



Fu et al. 2012

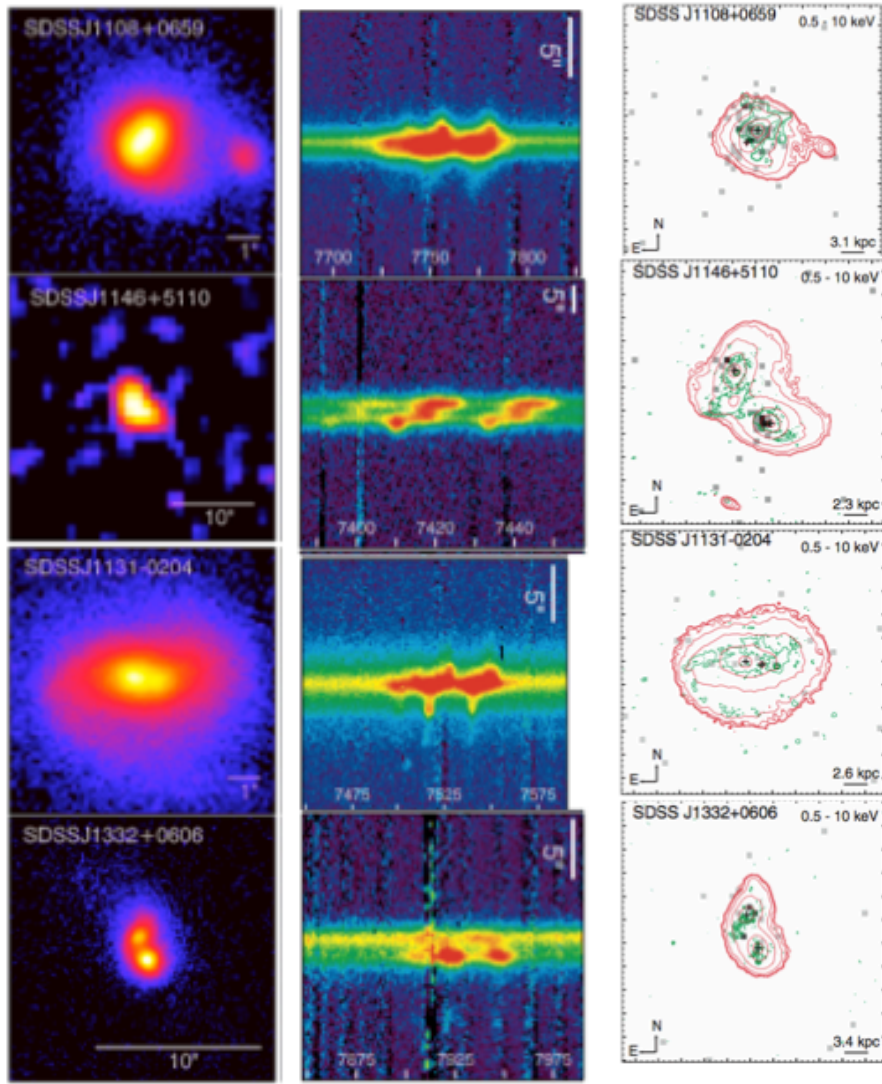


McGurk et al. 2011

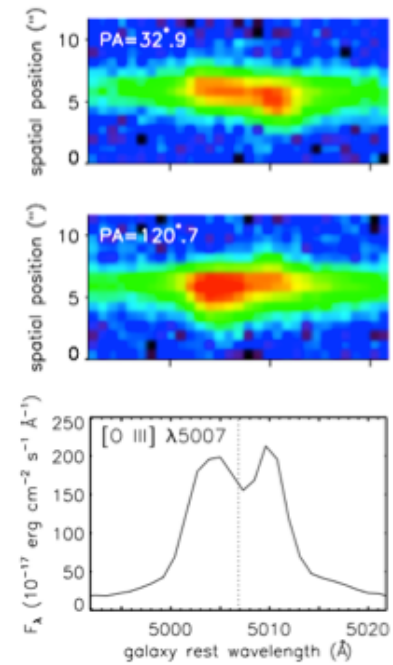
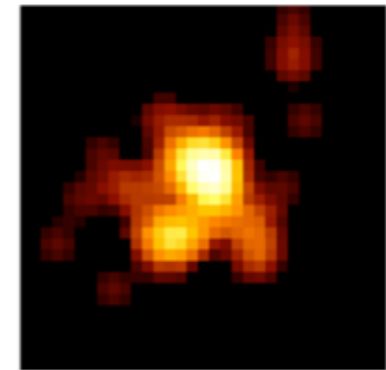


Greene et al. 2012

3. X-ray Follow-up Observations



Liu et al. 2013

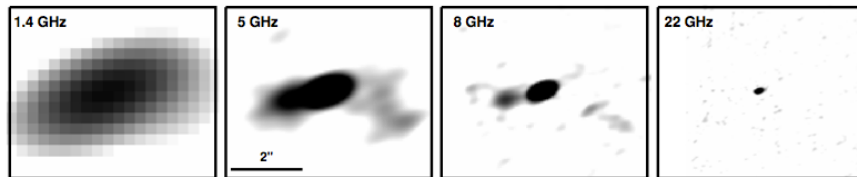
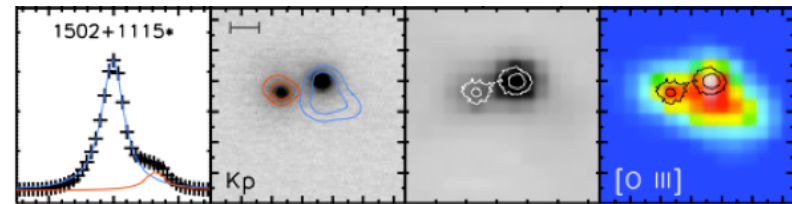
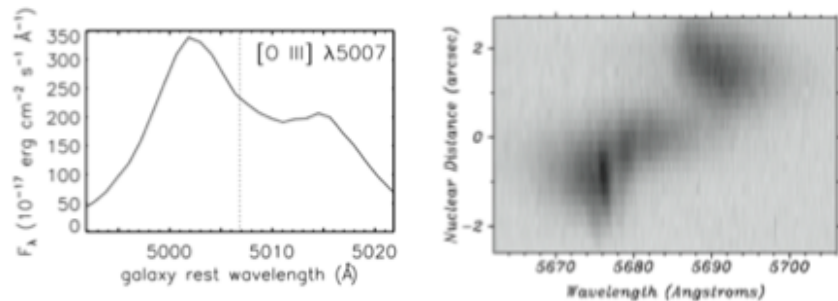


Comerford et al. 2011

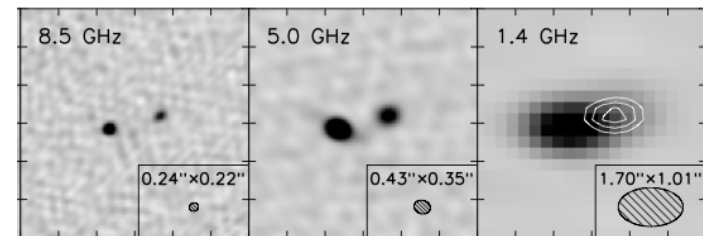
4. Radio Follow-up Observations

VLBA: Observations of 11 double-peaked AGN in SDSS, revealed no double radio cores (Tingay & Wayth 2011)

Jankys VLA: Observations of 2 double-peaked AGN in SDSS revealed one jet-driven outflow (Rosario et al. 2010) and one dual AGN (Fu et al. 2011)



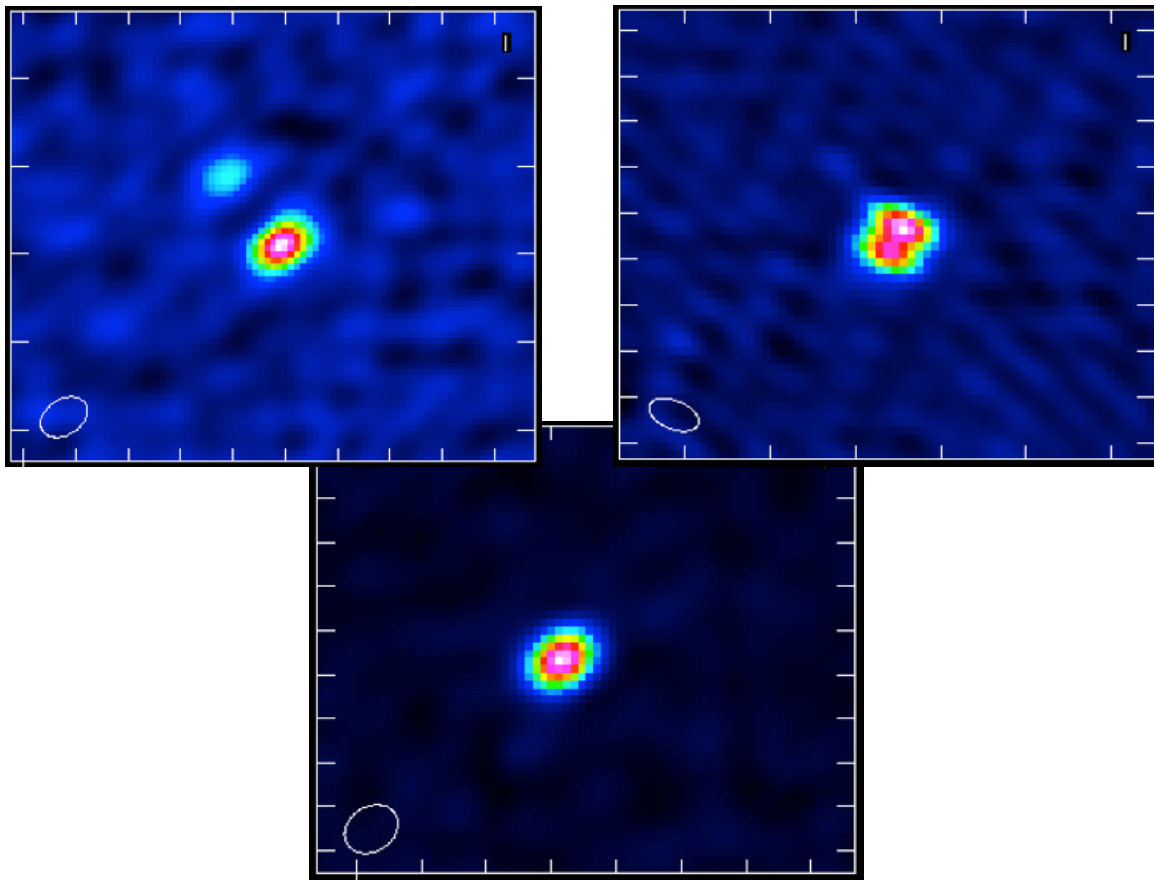
Rosario et al. 2010



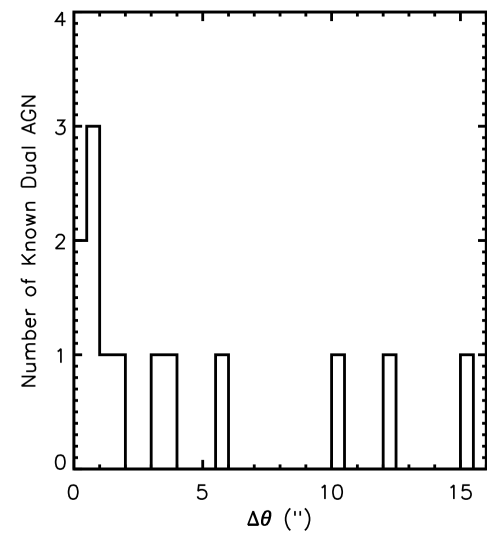
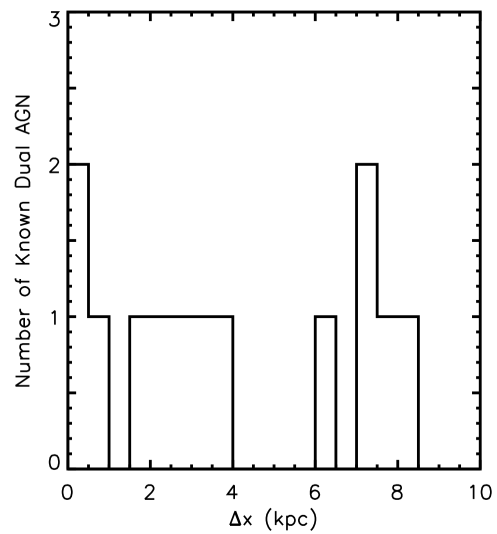
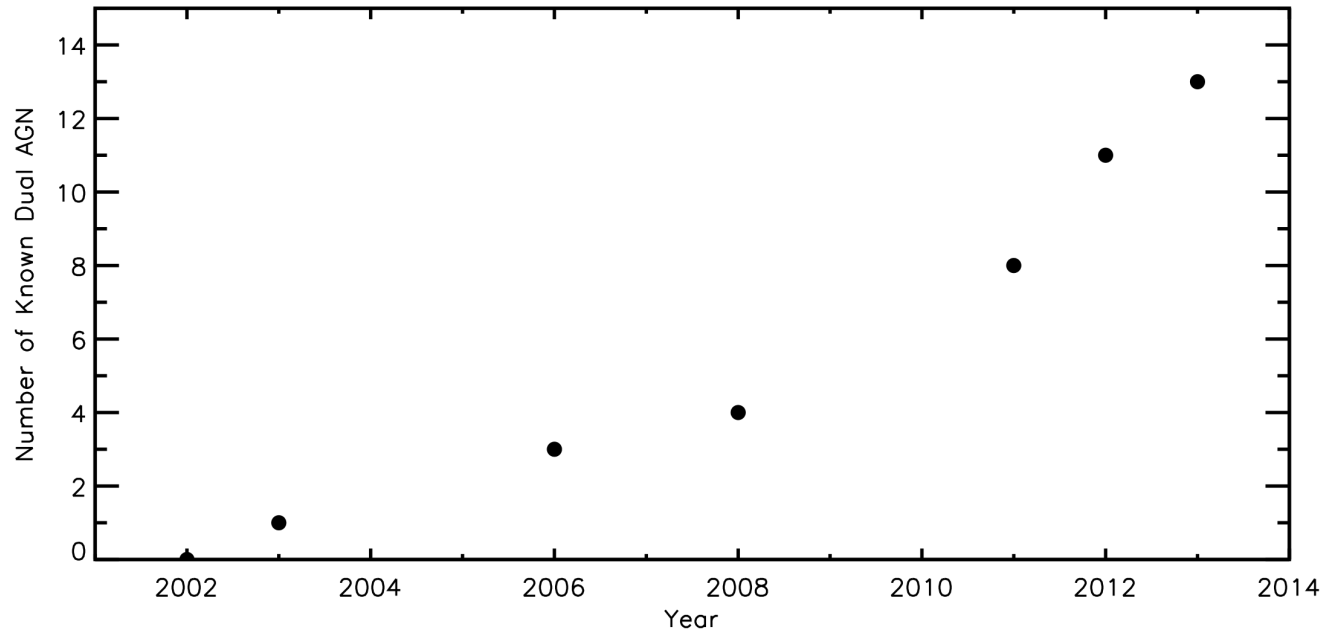
Fu et al. 2011

Jansky VLA Observations of 86 Double-peaked AGN in SDSS

With Francisco Mueller-Sanchez, Joan Wrobel,
Jenny Greene, and Mike Eracleous



Status of the Search for Dual AGN

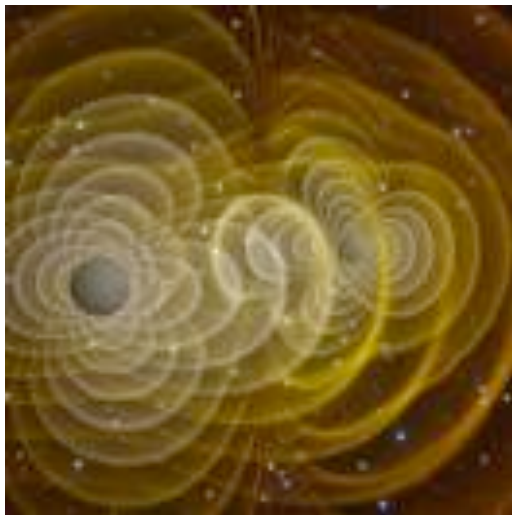


Goal: Build a Large Catalog of Dual AGN for Studies of Galaxy Evolution

What is the supermassive black hole merger rate?

Dual AGN are the smallest separation SMBH pairs that have been confirmed to date

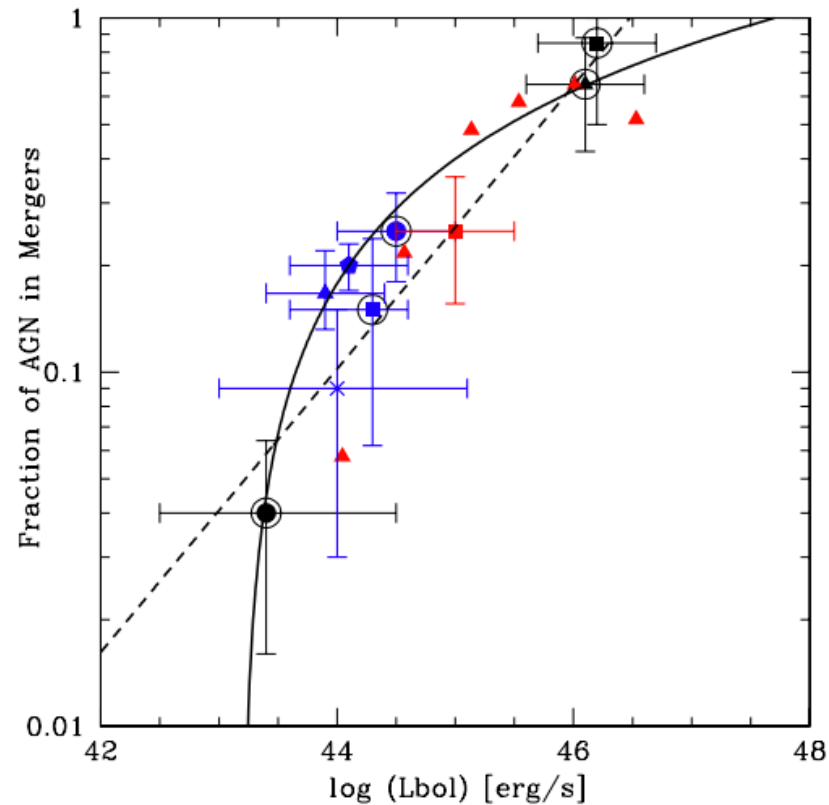
A large catalog of dual AGN will constrain the supermassive black hole merger rate



C. Henze/NASA

What Is the Nature of the Link between Galaxy Mergers and AGN?

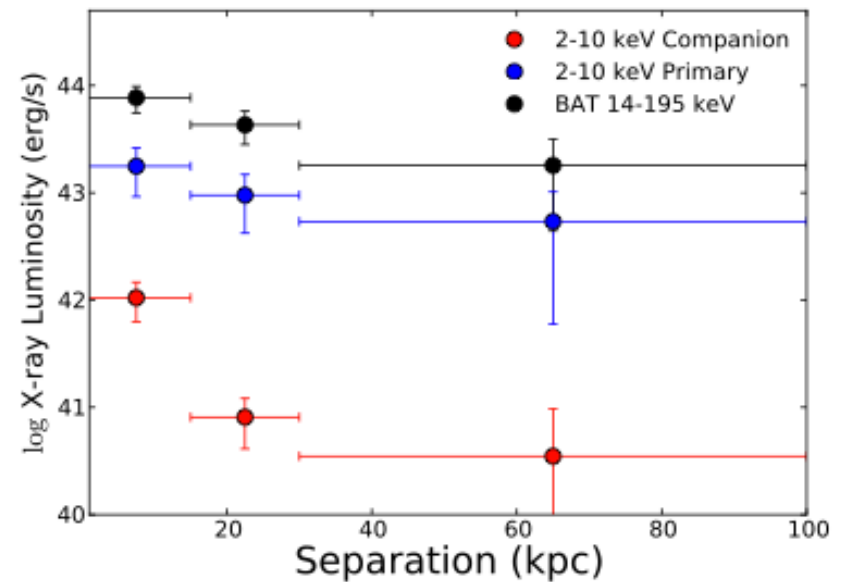
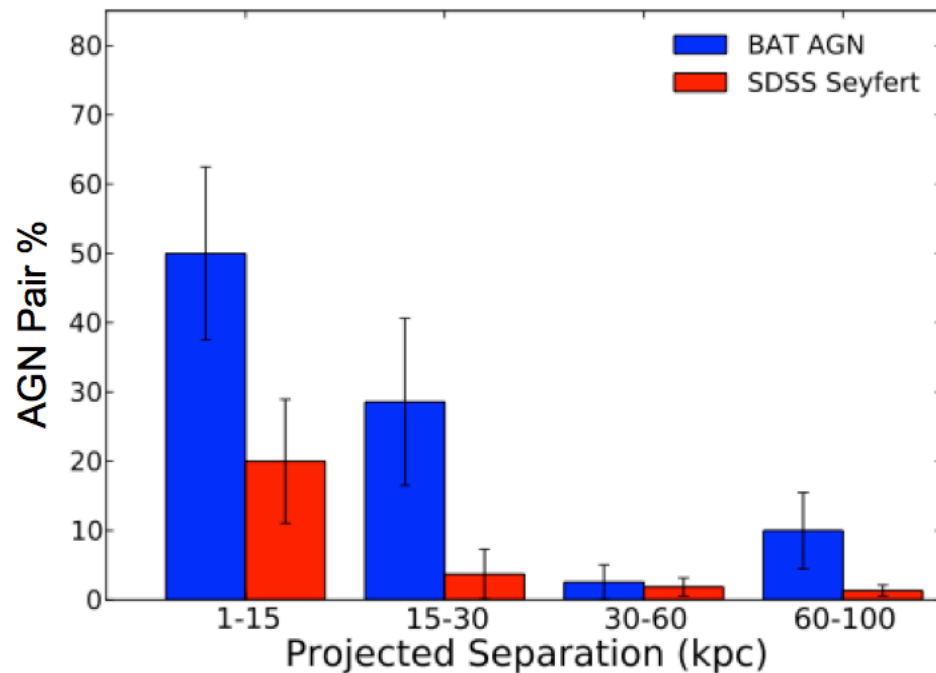
Dual AGN are direct tracers of AGN activity in mergers



Treister et al. 2012

Connection between Galaxy Mergers and Dual AGN

AGN activity preferentially triggered in smaller separation dual AGN (Koss et al. 2012)



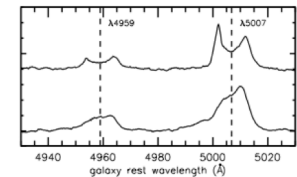
Koss et al. 2012

A Systematic Search for Dual AGN for Studies of Galaxy Evolution

Systematic searches for dual AGN

Swift/BAT AGN

Double-peaked AGN (DEEP2, AGES, SDSS)



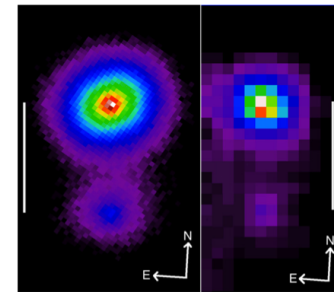
Follow-up observations of dual AGN candidates

Optical/NIR longslit and IFU

NIR imaging

X-ray

Radio



→ 13 confirmed dual AGN to date

Use large catalog of dual AGN to study

Supermassive black hole merger rate

AGN-merger connection

Dual AGN are more common than and have higher luminosities than larger-separation AGN pairs

