Dual AGN as Tracers of Galaxy Evolution

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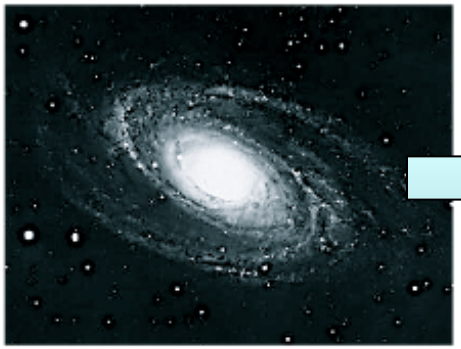
Binary Black Holes & Dual AGN workshop
November 30, 2012

Merger-driven Galaxy Evolution

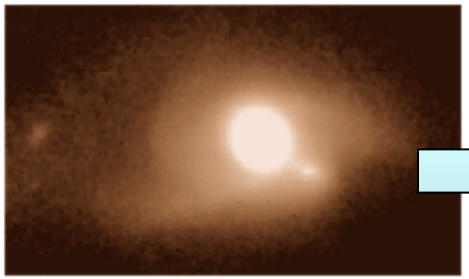
Spiral galaxy



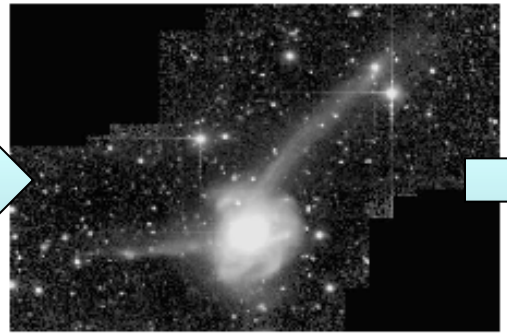
Galaxy merger

Coalescence

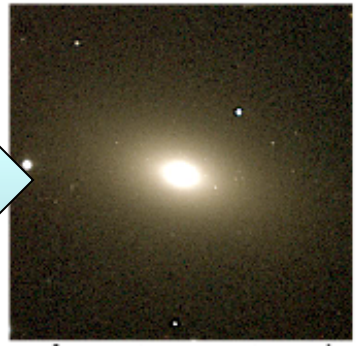
Remaining gas/dust expelled



Galaxy fades and reddens



Elliptical galaxy



Adapted from Hopkins et al./NOAO/AURA/NSF

Open Questions in Galaxy Evolution

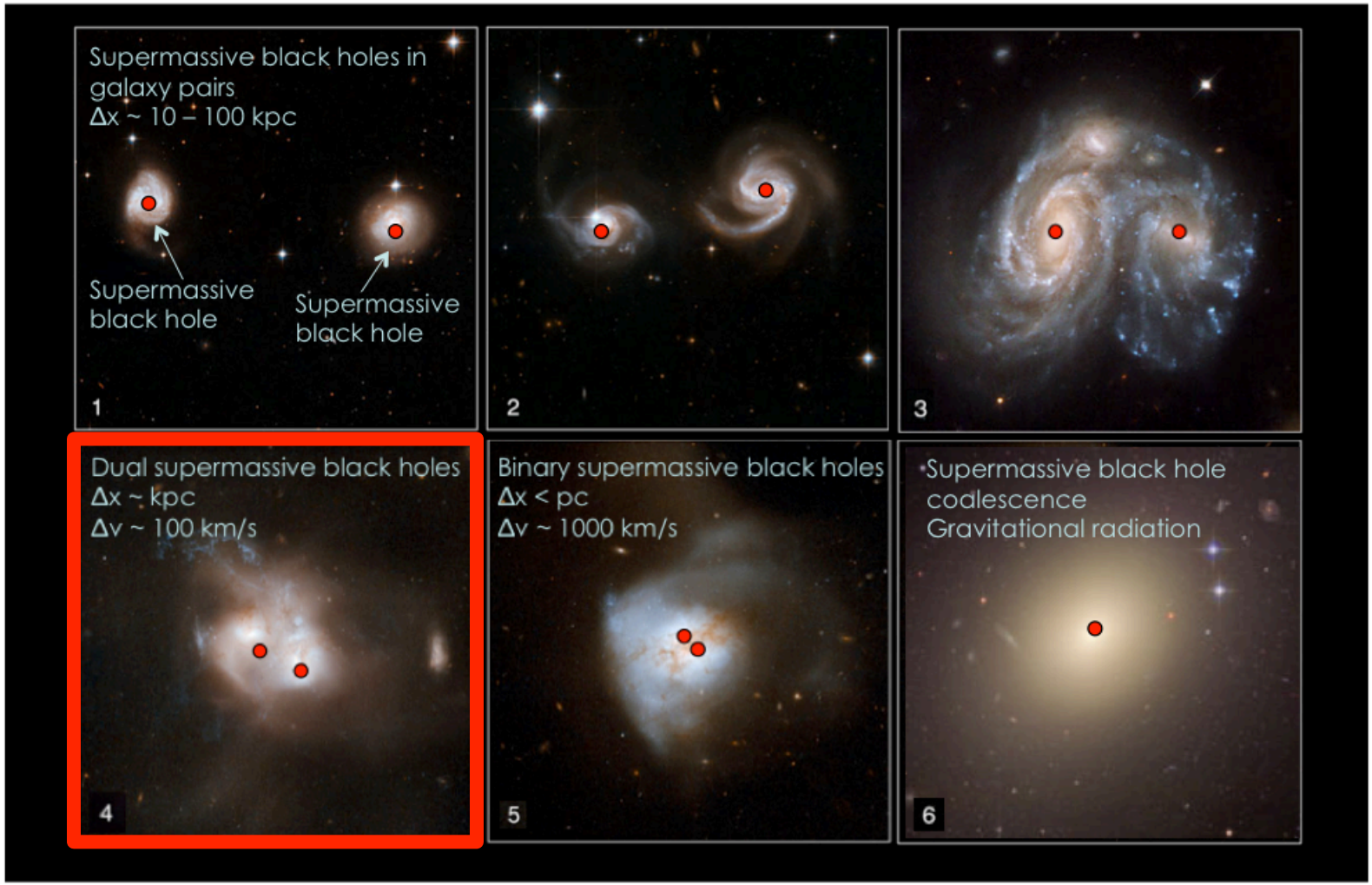
What is the nature of the link between galaxy mergers and AGN?

How much do supermassive black holes grow in mass through gas accretion during galaxy mergers?

What is the supermassive black hole merger rate?

Dual AGN are well-suited to addressing these questions

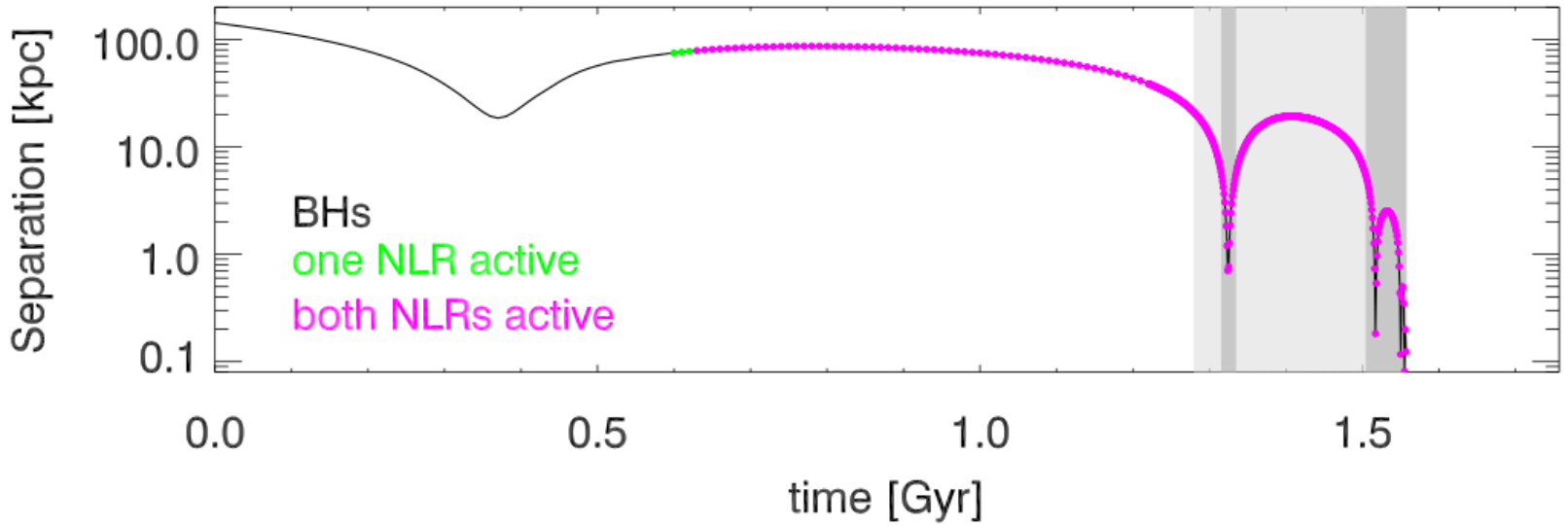
Supermassive Black Hole Pairs Are Direct Tracers of Galaxy Evolution



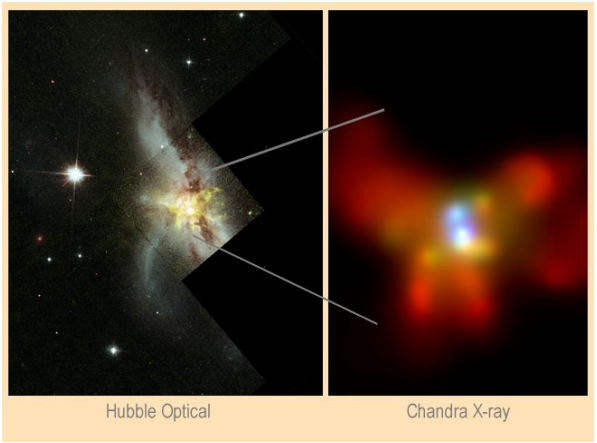
HST/NASA/STScI/ESA

There Should Be Many Dual AGN at Kpc-scale Separations

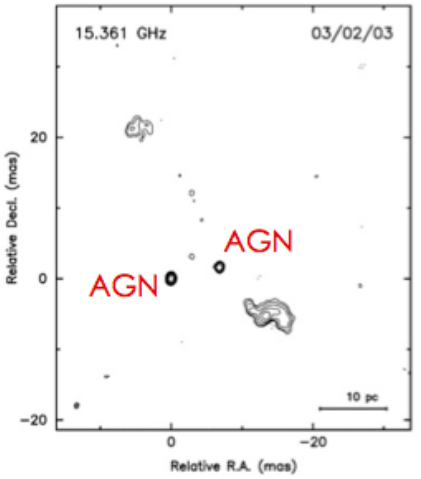
Simulations of galaxy mergers show dual AGN lifetimes are typically 3 - 6 Myr (Blecha, Loeb, & Narayan 2012)



We Expect Dual AGN in Merger-remnant Galaxies, Yet Very Few Have Been Found

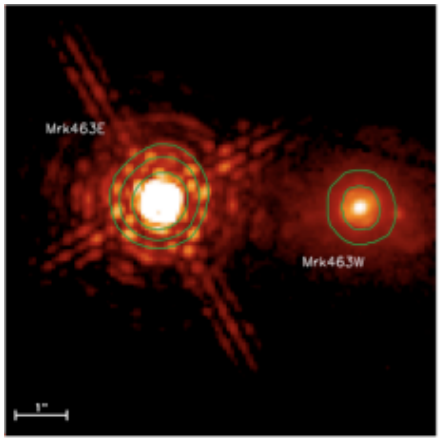


NGC 6240
z = 0.02
Δx = 0.7 kpc
Komossa et al. 2003



0402+379
z = 0.06
Δx = 7 pc
Rodriguez et al. 2006

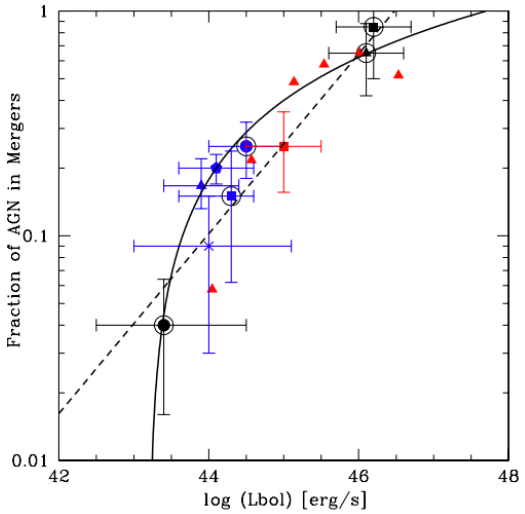
3C 75
z = 0.02
Δx = 7 kpc
Hudson et al. 2006



Mrk 463
z = 0.05
Δx = 4 kpc
Bianchi et al. 2008

A Large Observational Sample of Dual AGN Would Measure:

What is the nature of the link between galaxy mergers and AGN?



Treister et al. 2012

How much do supermassive black holes grow in mass through gas accretion during galaxy mergers?

What is the supermassive black hole merger rate?

ACS/NASA

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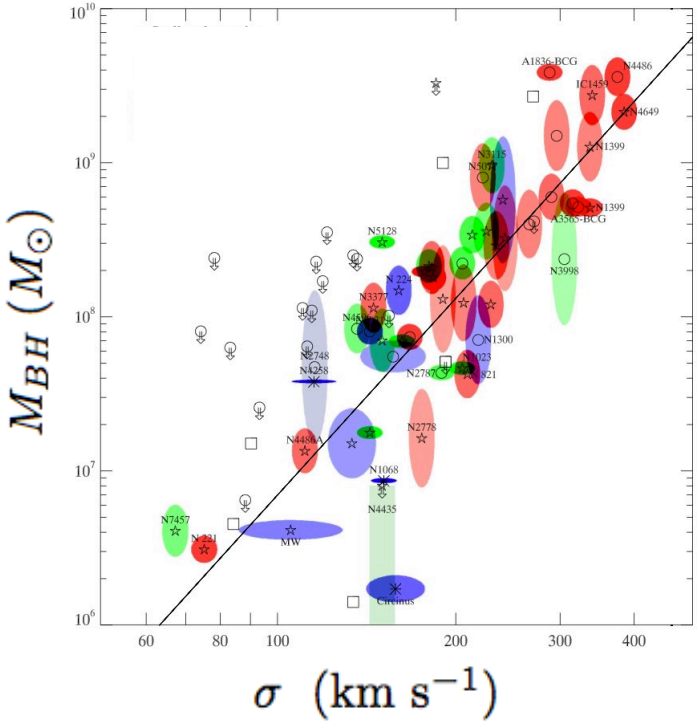

Gültekin et al. 2009

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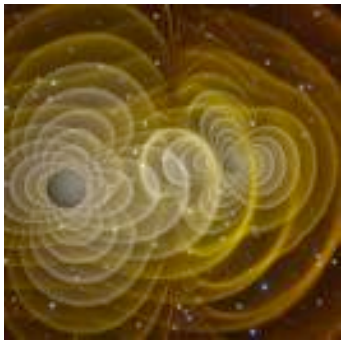
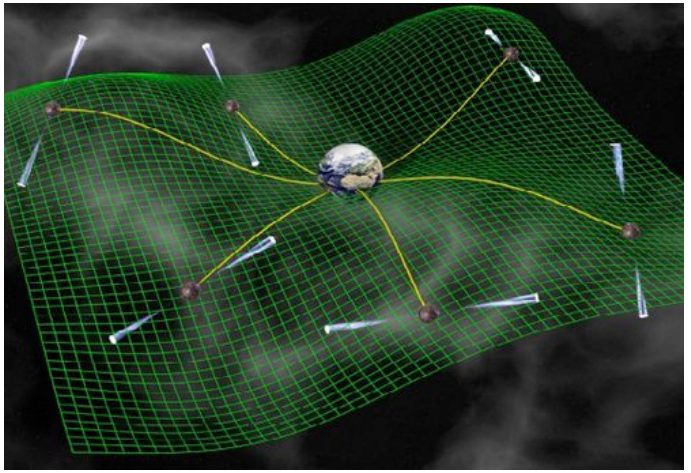


C. Henze/NASA

How much do supermassive black holes grow in mass through gas accretion during galaxy mergers?

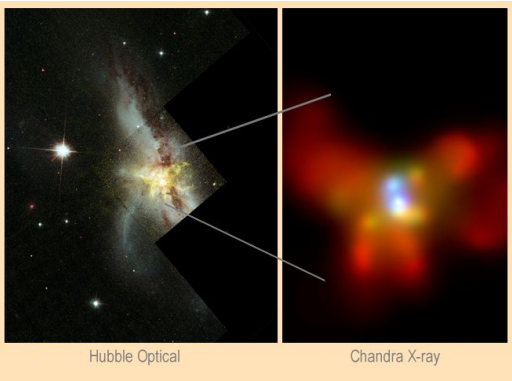
What is the supermassive black hole merger rate?

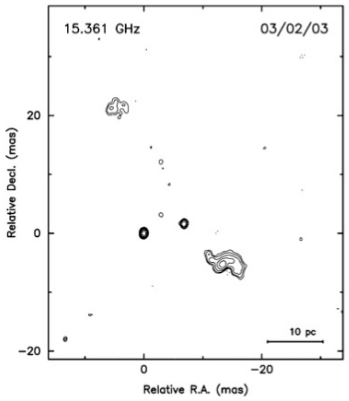


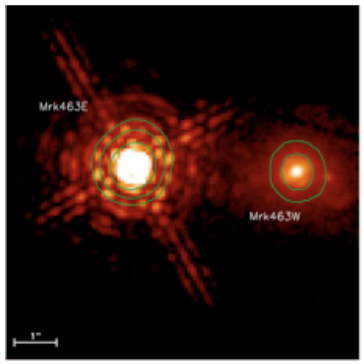
NRAO

Goal: Build a Large Catalog of Dual AGN to Use as Tracers of Galaxy Mergers, Black Hole Growth, and Black Hole Mergers

Need systematic approach to advance from individual systems to assembling a large catalog of dual AGN





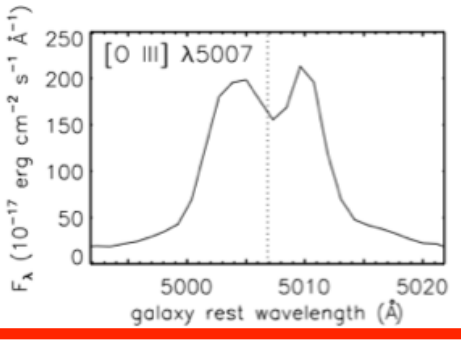


$0.02 < z < 0.06$

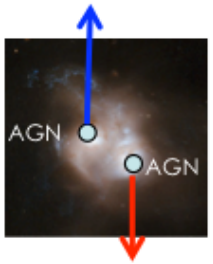
A Systematic Search for Dual AGN in Three Steps

A Systematic Search for Dual AGN in Three Steps

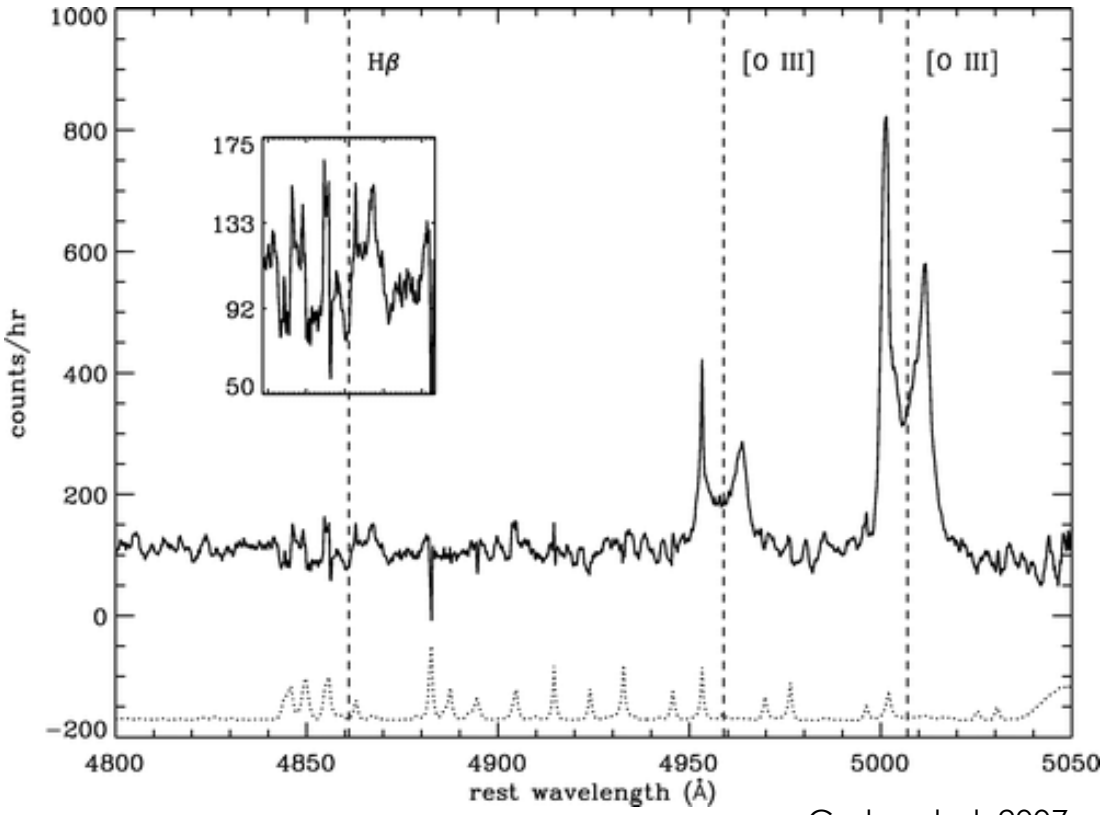
1. Select dual AGN candidates as galaxies with double-peaked AGN emission lines



Spectroscopic Signature of Dual AGN: Double-Peaked Narrow AGN Emission Lines



In this example, double-peaked [O III] emission lines separated by 630 km/s



Gerke et al. 2007

Two Double-peaked AGN in the DEEP2 Galaxy Redshift Survey

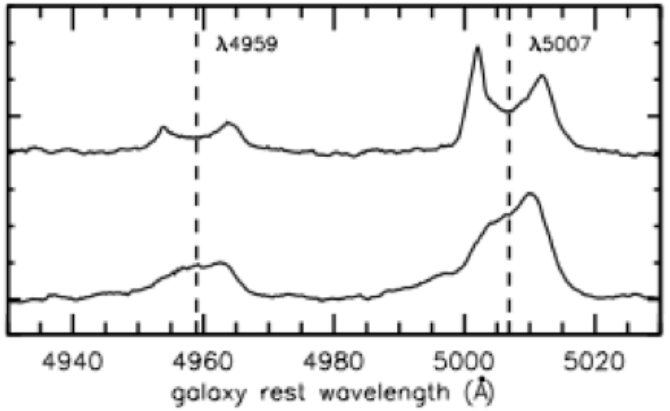
DEEP2 Galaxy Redshift Survey (Davis et al. 2007, Newman et al. 2012), uses the DEIMOS spectrograph on Keck

The two double-peaked AGN have:

$z = 0.71$, $\Delta v = 630$ km/s

$z = 0.62$, $\Delta v = 440$ km/s

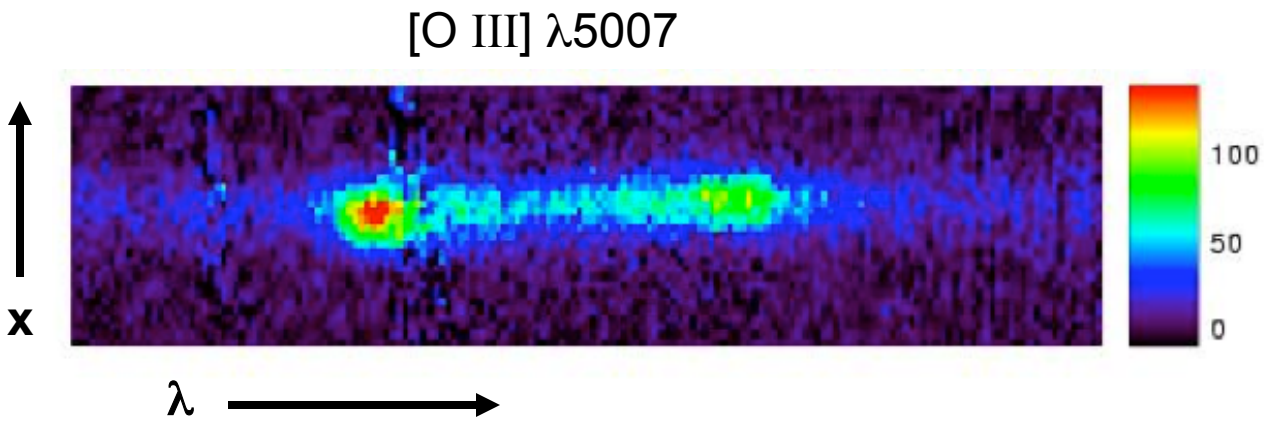
$2.2^{+2.8}_{-0.7}$ % (2/91) of Type 2 AGN at $0.34 < z < 0.82$ are double-peaked AGN



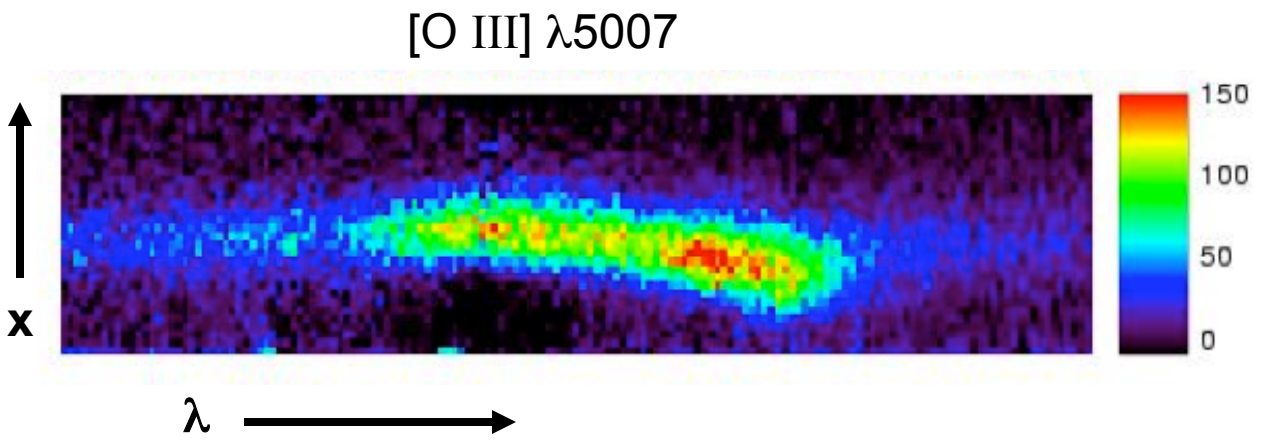
Comerford et al. 2009

Two Double-peaked AGN in DEEP2

z = 0.71
Δv = 630 km/s
Δx = 1.2 kpc



z = 0.62
Δv = 440 km/s
Δx = 2.3 kpc



Comerford et al. 2009

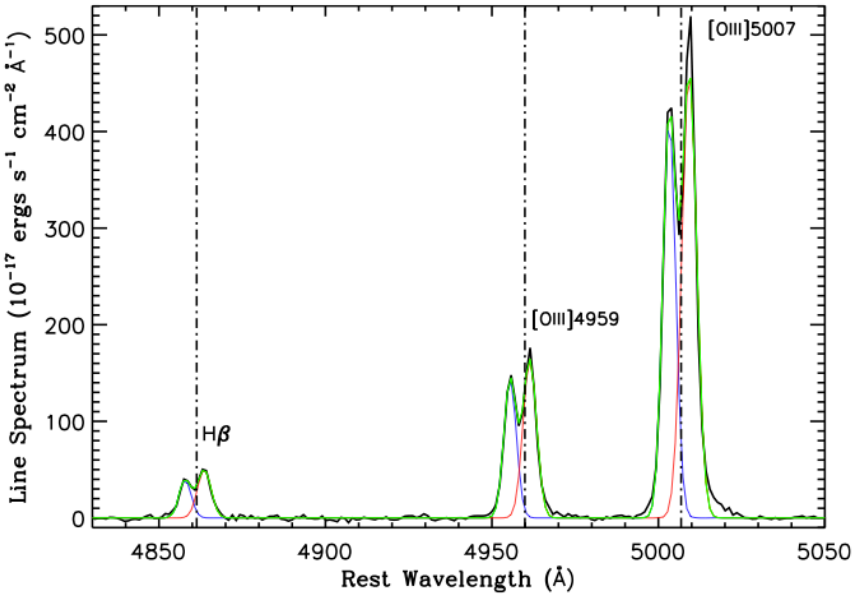
Hundreds of Double-peaked AGN in SDSS

$0.01 < z < 0.64, \quad 160 \text{ km/s} < \Delta v < 740 \text{ km/s}$

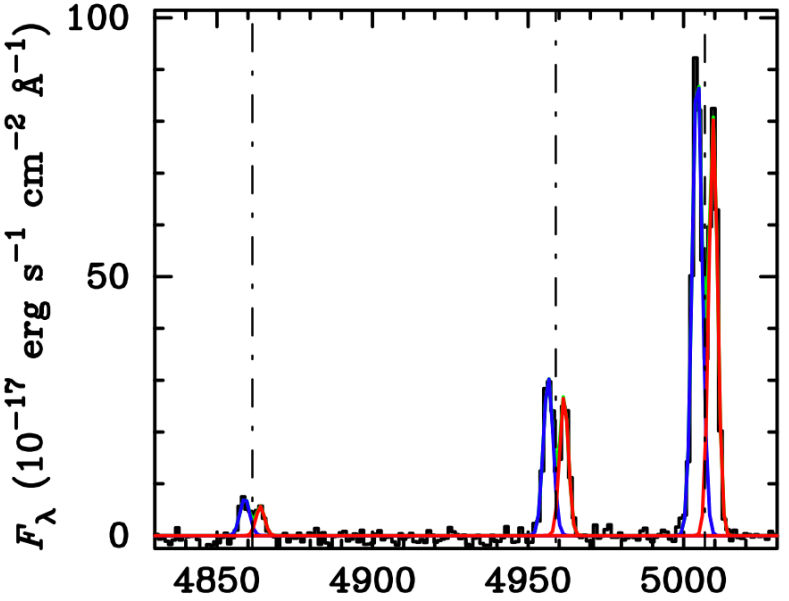
$1.3^{+0.1}_{-0.1}$ % of Type 2 AGN at $z < 0.15$ are double-peaked AGN

Wang et al. 2009, Liu et al. 2010, Smith et al. 2010, Ge et al. 2012

See Barrows et al. for double-peaked AGN in SDSS at $z > 0.8$



Wang et al. 2009



Ge et al. 2012

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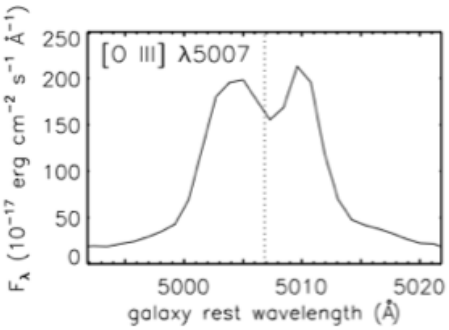
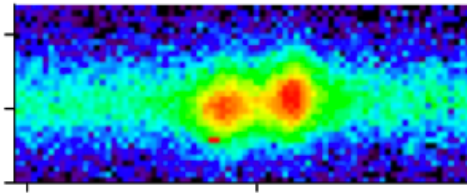
1. Select dual AGN candidates as galaxies with double-peaked AGN emission lines

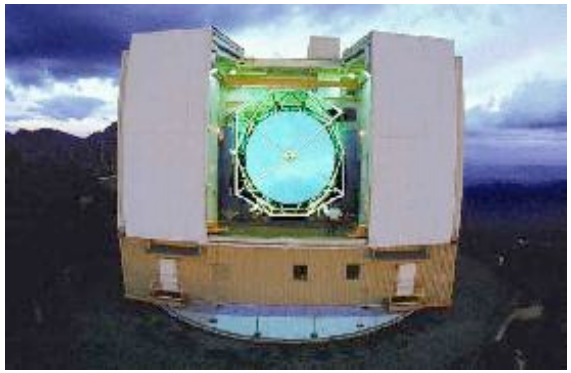


2. Use follow-up observations to identify best dual AGN candidates



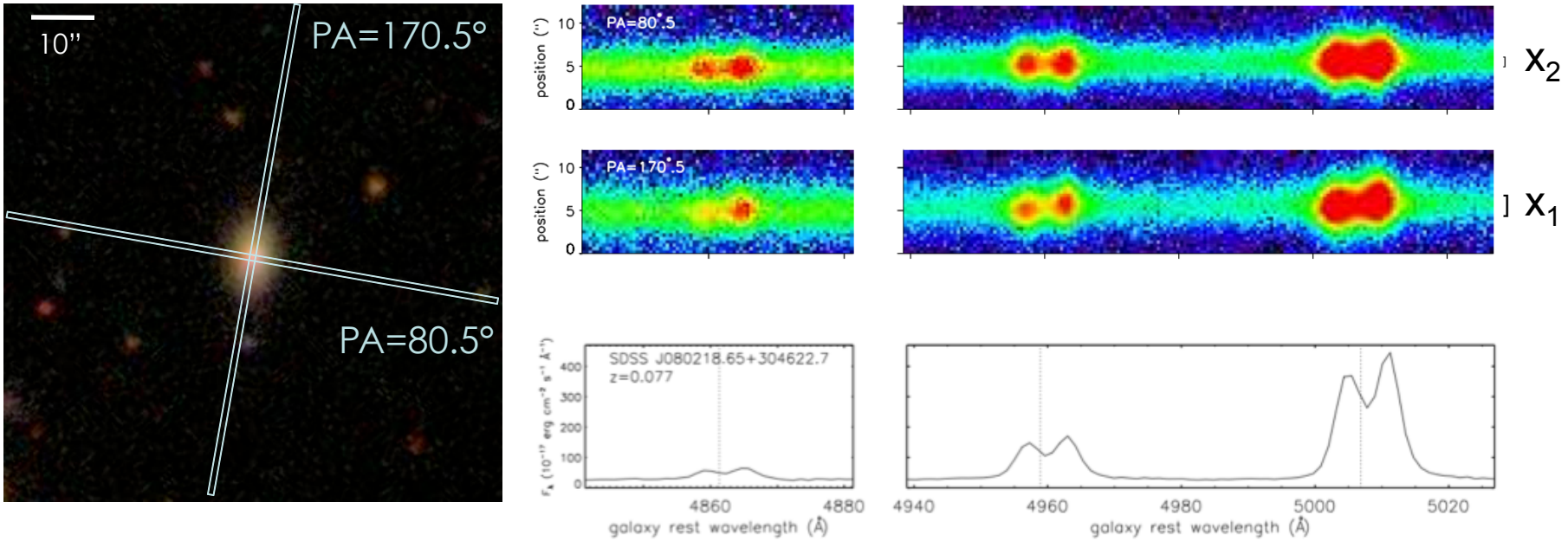
Use Longslit Spectroscopy to Identify the Most Promising Dual AGN Candidates

Obtained Lick, Palomar, MMT, Keck, and Gemini longslit spectroscopy for 132 of the double-peaked AGN in SDSS ($0.03 < z < 0.64$)



Measure Physical Separation and Orientation of the Two Emission Components on the Sky

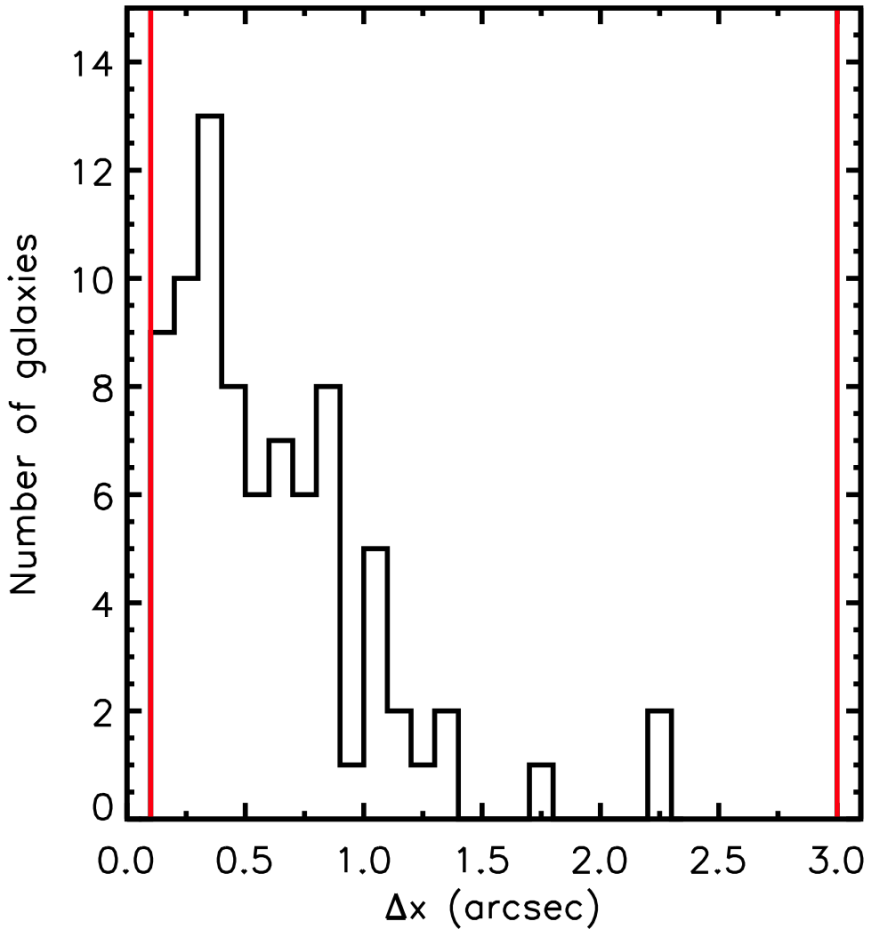


separation x_1 at position angle θ_1
separation x_2 at position angle θ_2

→ full separation on the sky Δx
position angle on the sky θ_{sky}

$$x_1 \cos\left(\theta_{sky} - \theta_2\right) = x_2 \cos\left(\theta_{sky} - \theta_1\right) \qquad \Delta x = x_1 / \cos\left(\theta_{sky} - \theta_1\right)$$

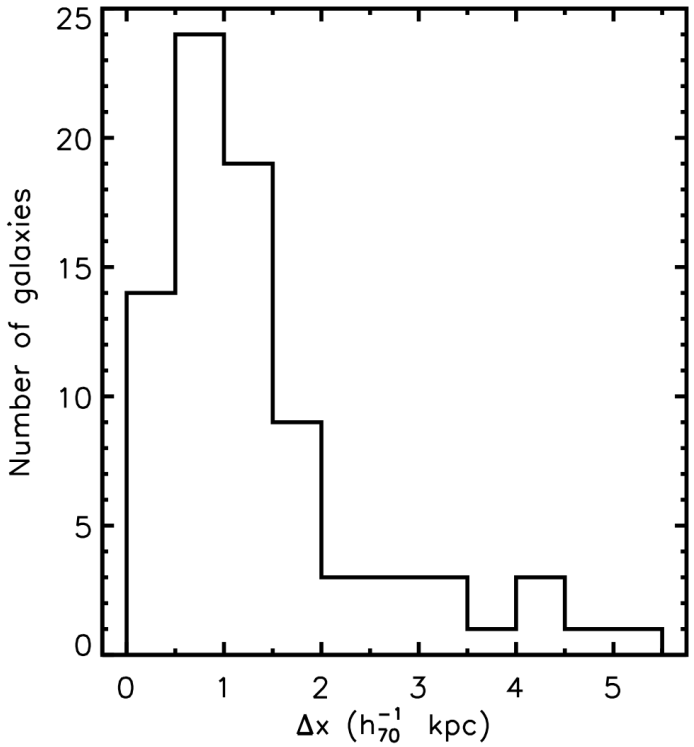
Angular Separations between Double Emission Components



$0.1'' < \Delta x < 2.3''$

Median $\Delta x = 0.5''$

The Double Peaks Are Produced by Kpc-scale Dual AGN or Outflows



Comerford et al. 2012

0.2 kpc < Δx < 5.5 kpc

Median Δx = 1.1 kpc

This means that the mechanism(s) producing double-peaked AGN are neither very small-scale nor very large-scale effects

✖ Rotation of gas in disks <100 pc, small-scale AGN outflows

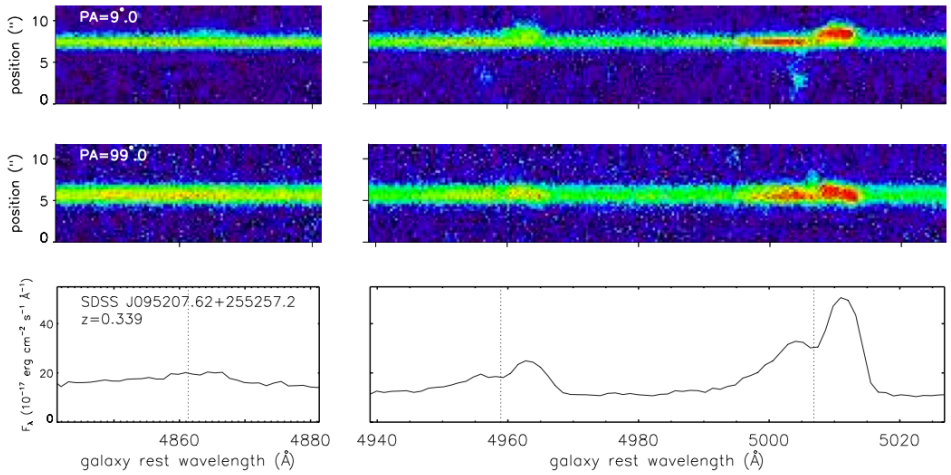
✔ kpc-scale dual AGN or kpc-scale AGN outflows

✖ AGN pairs or AGN outflows on scales ~10 kpc

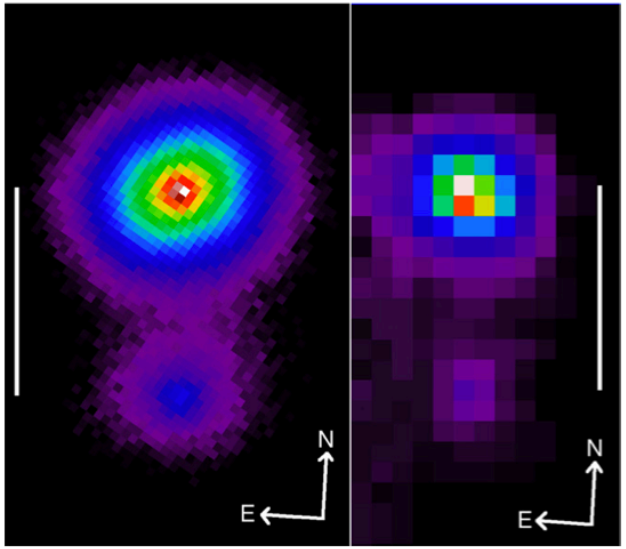
The Most Promising Candidates for Dual AGN

Good candidates for dual AGN:

The objects with double AGN emission components with the same spatial separation and orientation on the sky as the double stellar nuclei seen in adaptive optics image
(McGurk et al. 2011; Rosario et al. 2011)



Comerford et al. 2012



McGurk et al. 2011

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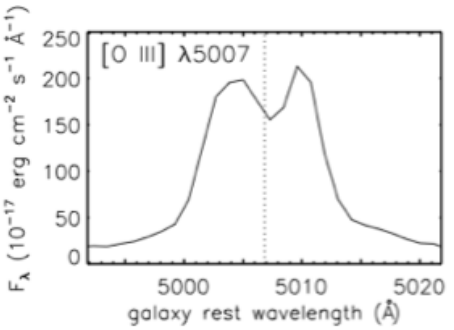

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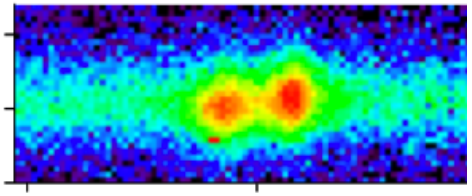
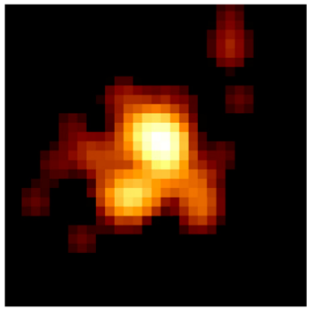


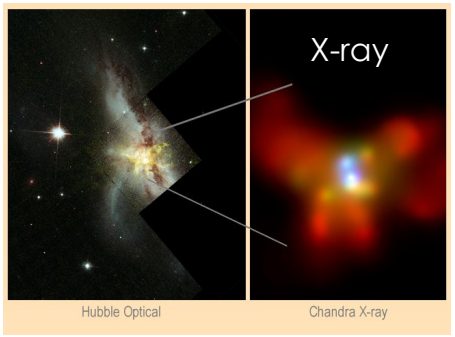
3. Confirm dual AGN with X-ray or radio observations



For Definitive Proof of Dual AGN, Need X-ray or Radio Detections

X-ray

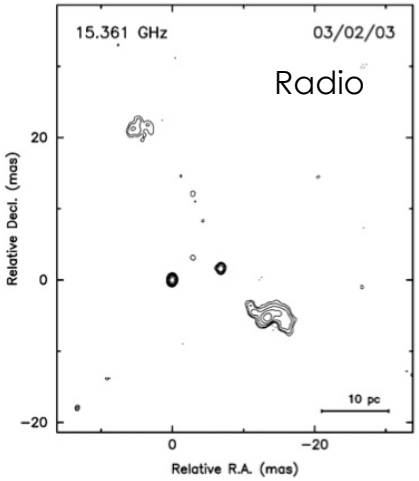
Ongoing Chandra observations for 13 dual AGN candidates



Komossa et al. 2003

Hubble Space Telescope

Ongoing HST observations for 10 of the Chandra targets; will reveal multiple stellar nuclei, tidal features, stellar populations



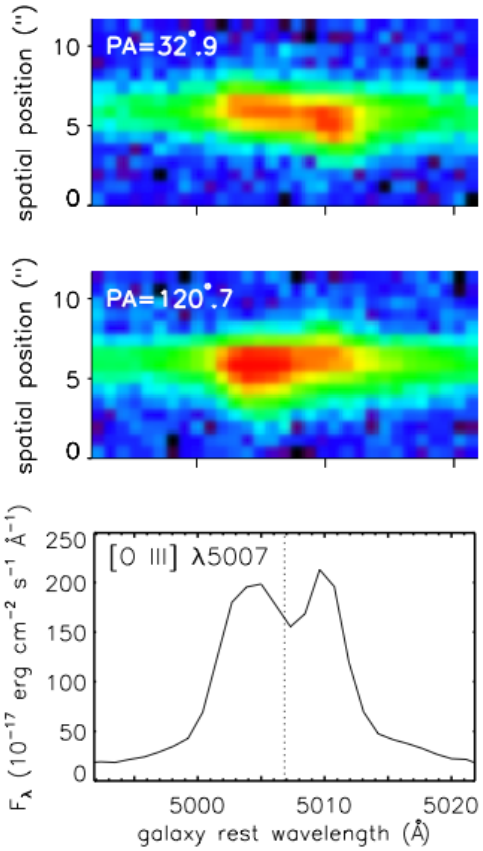
Rodriguez et al. 2006

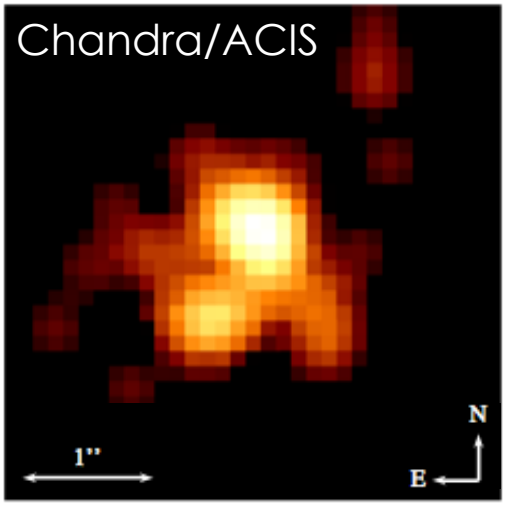
Proof of Concept: X-ray Confirmation of Dual AGN

SDSS J171544+600835 z=0.16

Δv=350 km/s, Δx=1.9 kpc (0.68"), PA=147° E of N

Double emission components in longslit observations coincide with double X-ray sources in Chandra observations





Comerford et al. 2011

Progress towards Building a Large Catalog of Dual AGN

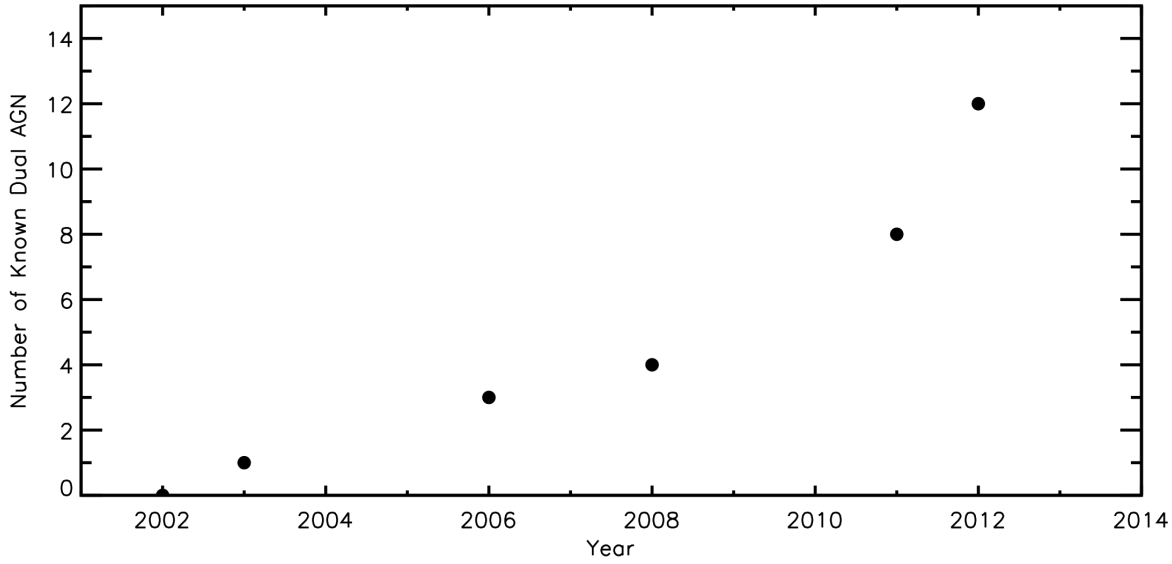
2008: 4 published dual AGN, all serendipitous discoveries

Komossa et al. 2003; Hudson et al. 2006; Rodriguez et al. 2006; Bianchi et al. 2008

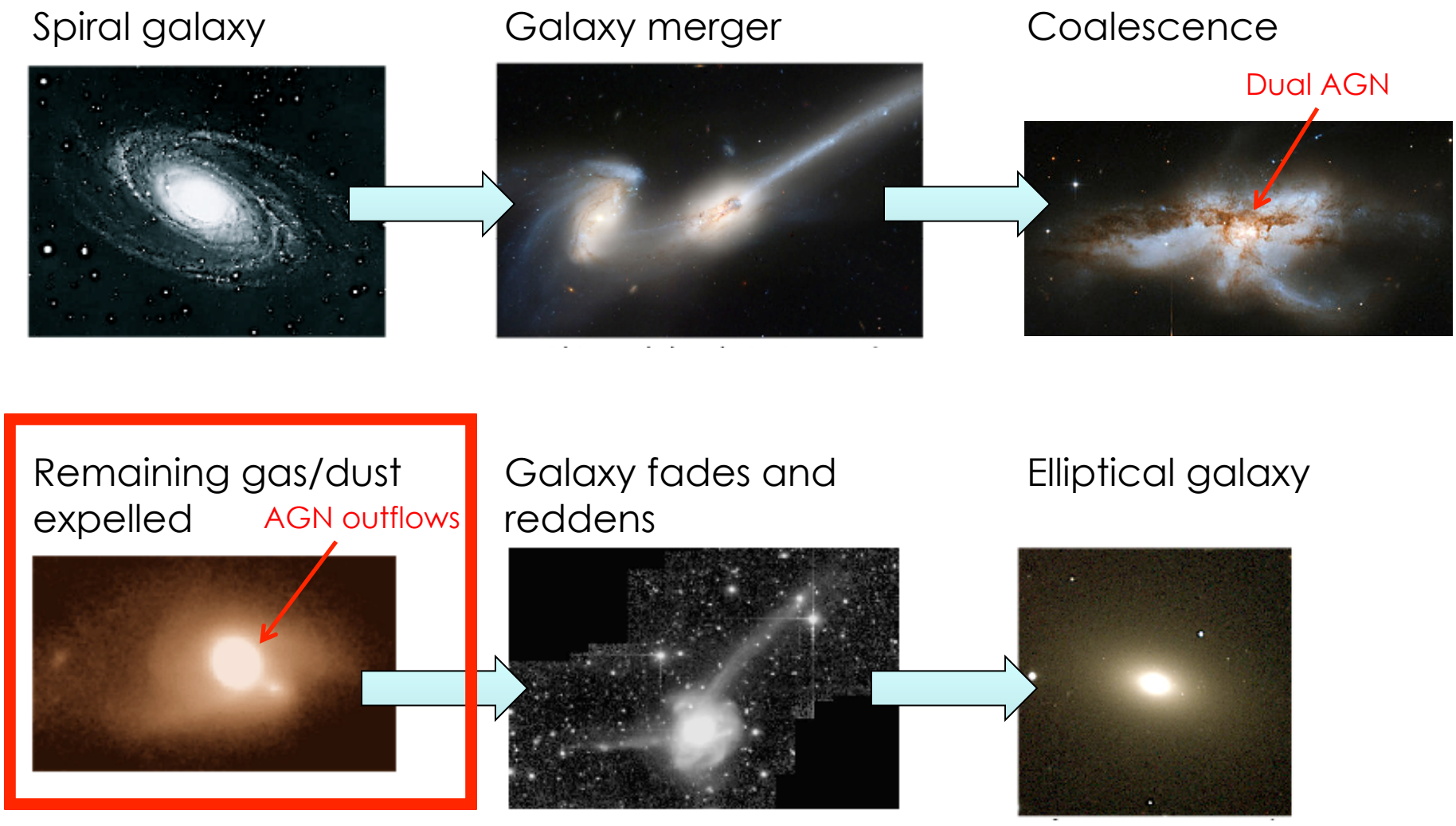
2012: 12 published dual AGN (<10 kpc)

Komossa et al. 2003; Hudson et al. 2006; Rodriguez et al. 2006; Bianchi et al. 2008; Comerford et al. 2011; Fabbiano et al. 2011; Fu et al. 2011; Koss et al. 2011, 2012; Liu et al. 2012; Mazzarella et al. 2012

2013: dozens more strong candidates awaiting confirmation of dual AGN



Merger-driven Galaxy Evolution

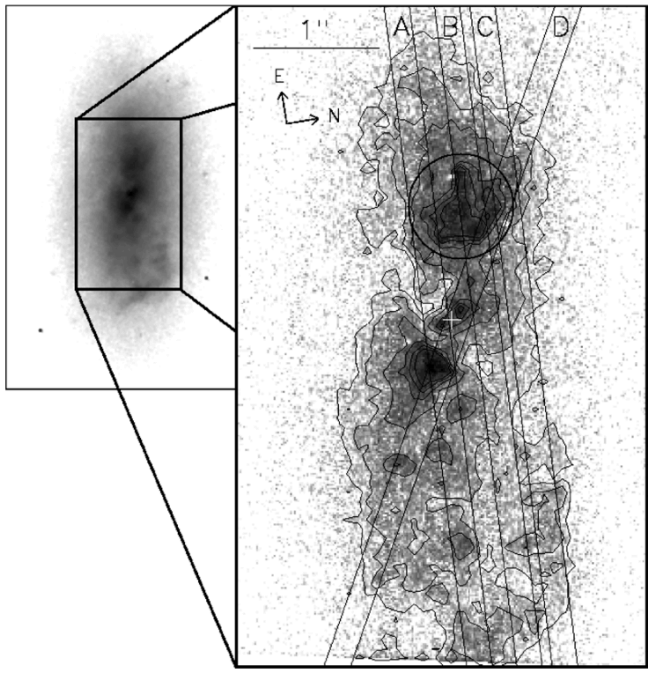


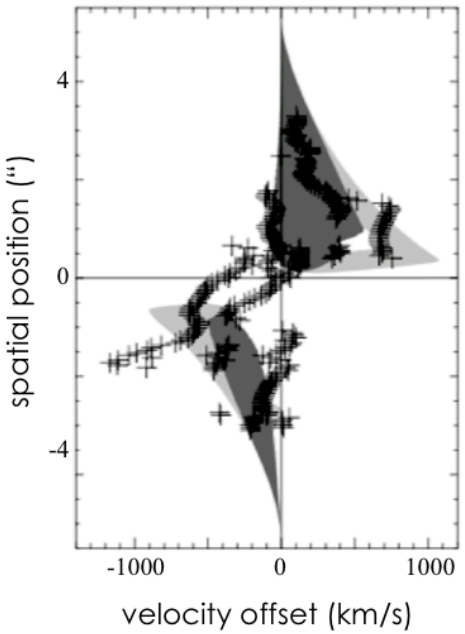
Adapted from Hopkins et al./NOAO/AURA/NSF

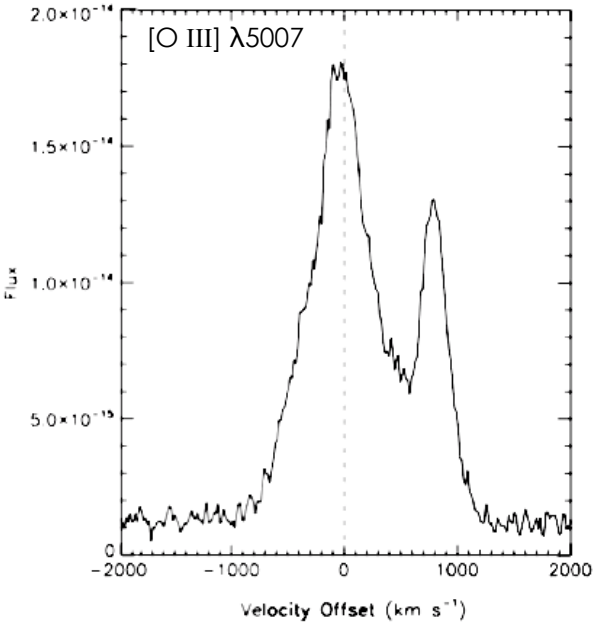
Double-peaked AGN Emission Lines Are Useful for Finding AGN Outflows

Many studies of AGN outflows that have double-peaked emission lines and/or extended emission (e.g., Richstone & Oke 1977; Heckman et al. 1981; Boroson & Oke 1984; Crenshaw et al. 2000; Veilleux et al. 2001; Whittle & Wilson 2004)

Mrk 78, z=0.04 (Fischer et al. 2011)

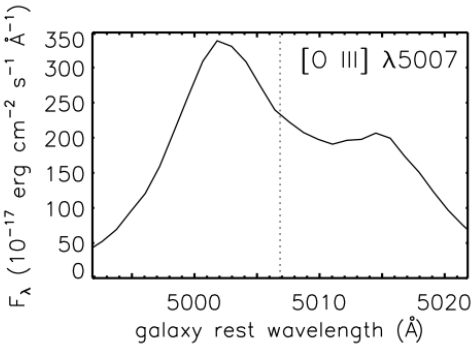


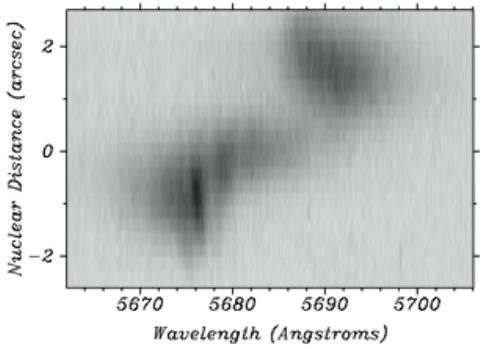


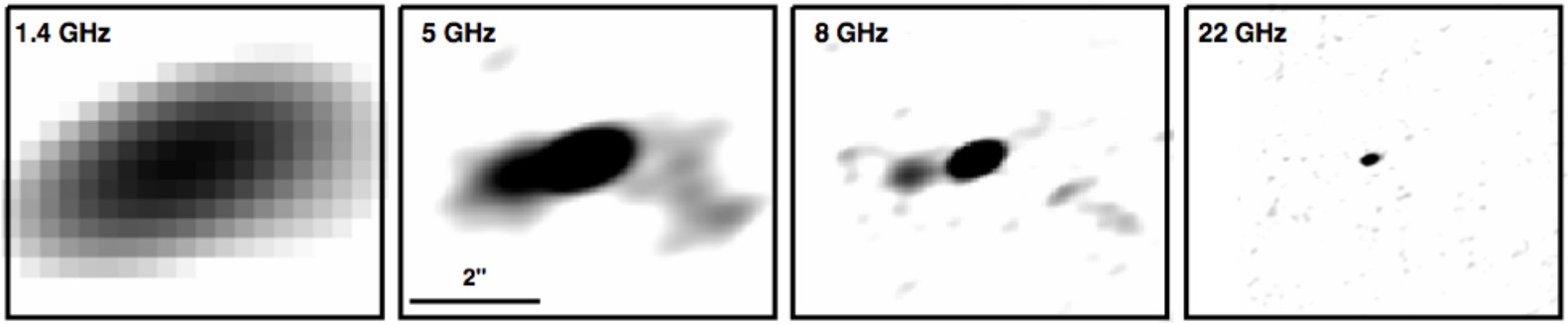


SDSS Double-peaked AGN Yield AGN Outflow Detections

SDSS J1517+3353, z=0.14
Jet spans ~12 kpc



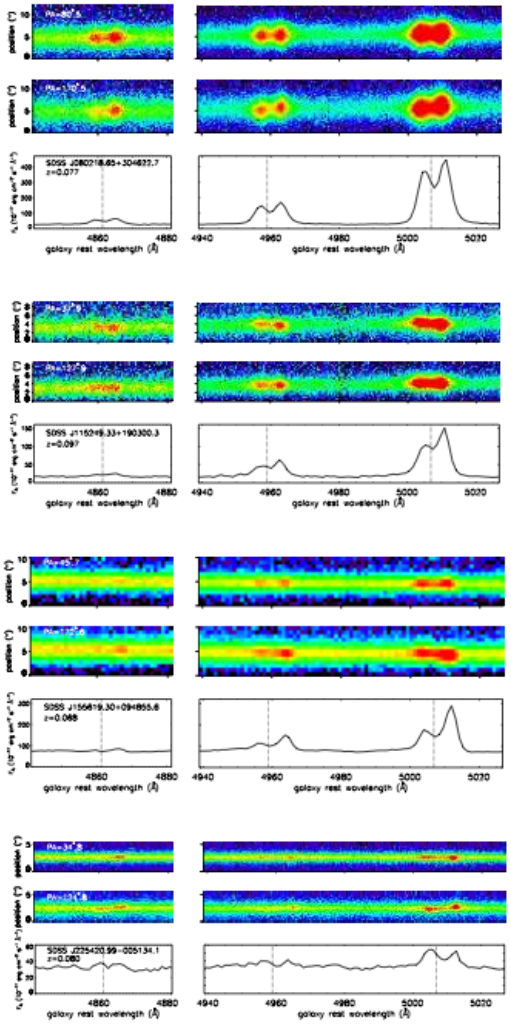




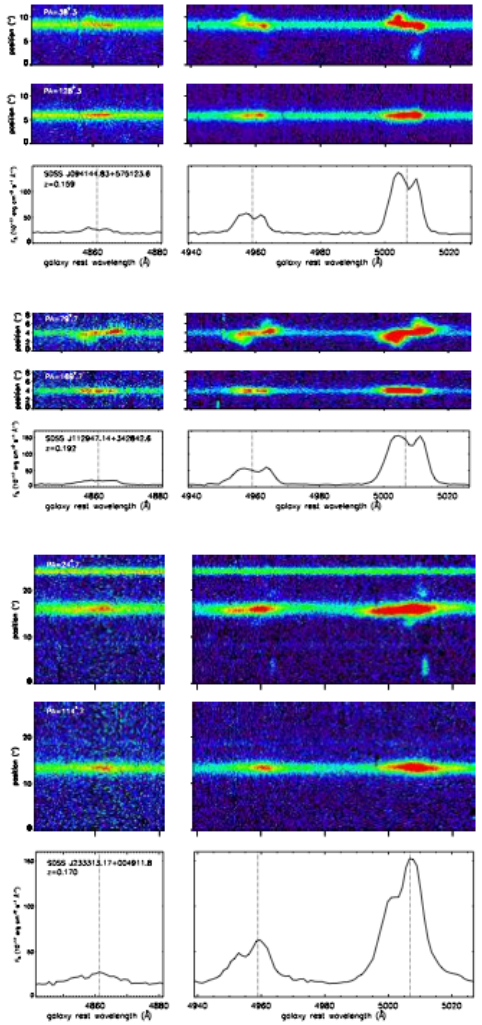
Rosario et al. 2010

Spatial Extent of Emission in SDSS Double-peaked AGN

58% exhibit **spatially compact** emission components

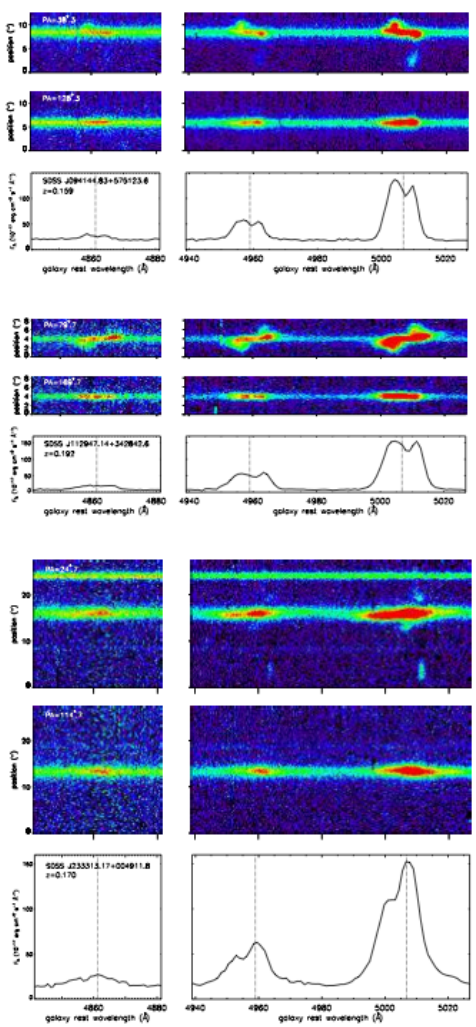


42% exhibit **spatially extended** emission components

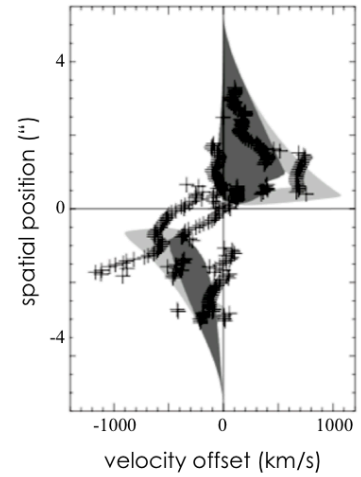


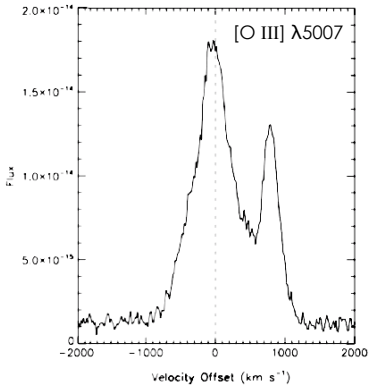
Comerford et al. 2012

Spatially Extended AGN Emission Could Be Sign of AGN Outflows



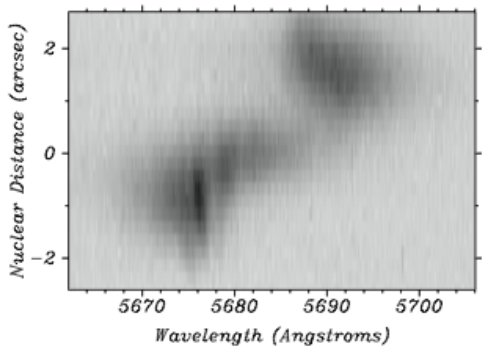
AGN outflow in Mrk 78:

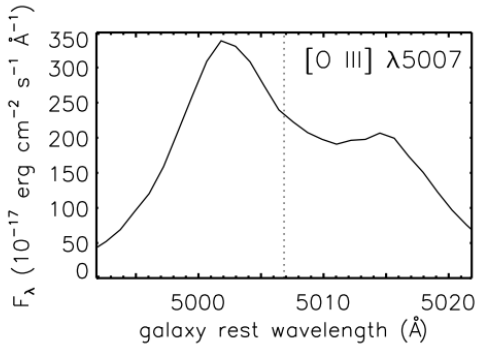




Fischer et al. 2011

AGN outflow in SDSS J1517+3353:

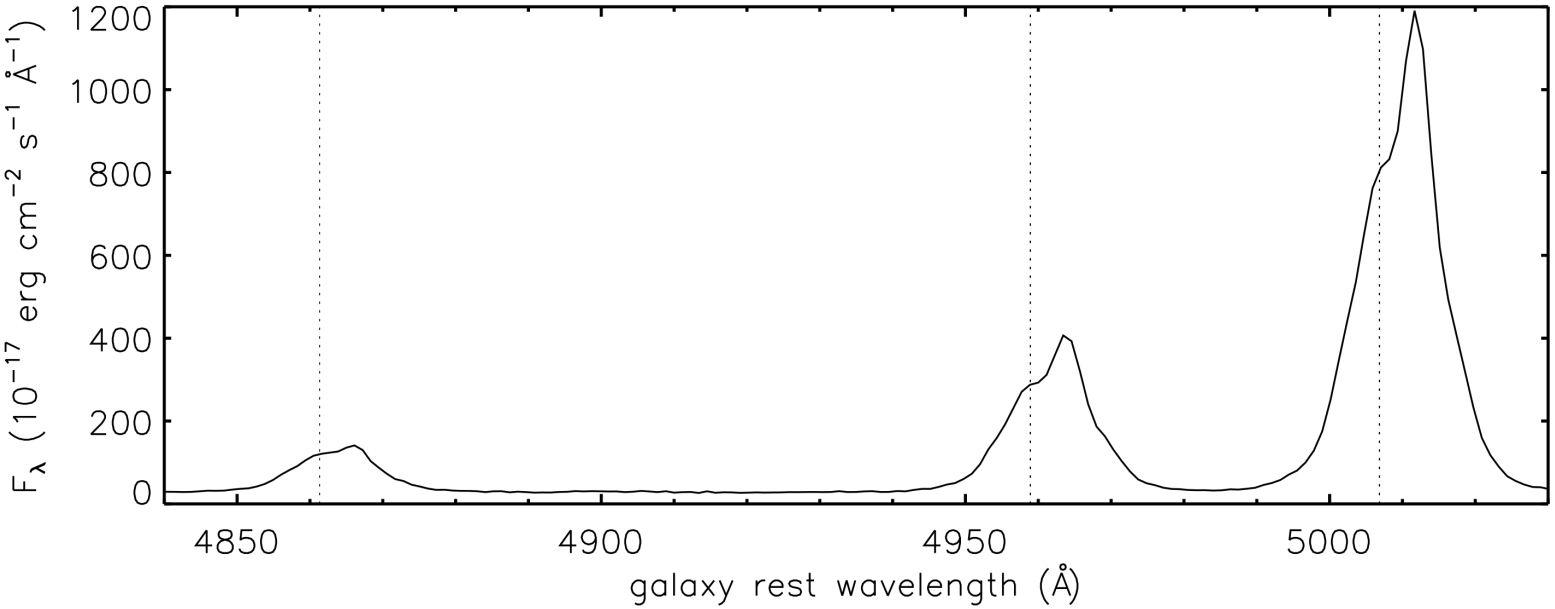




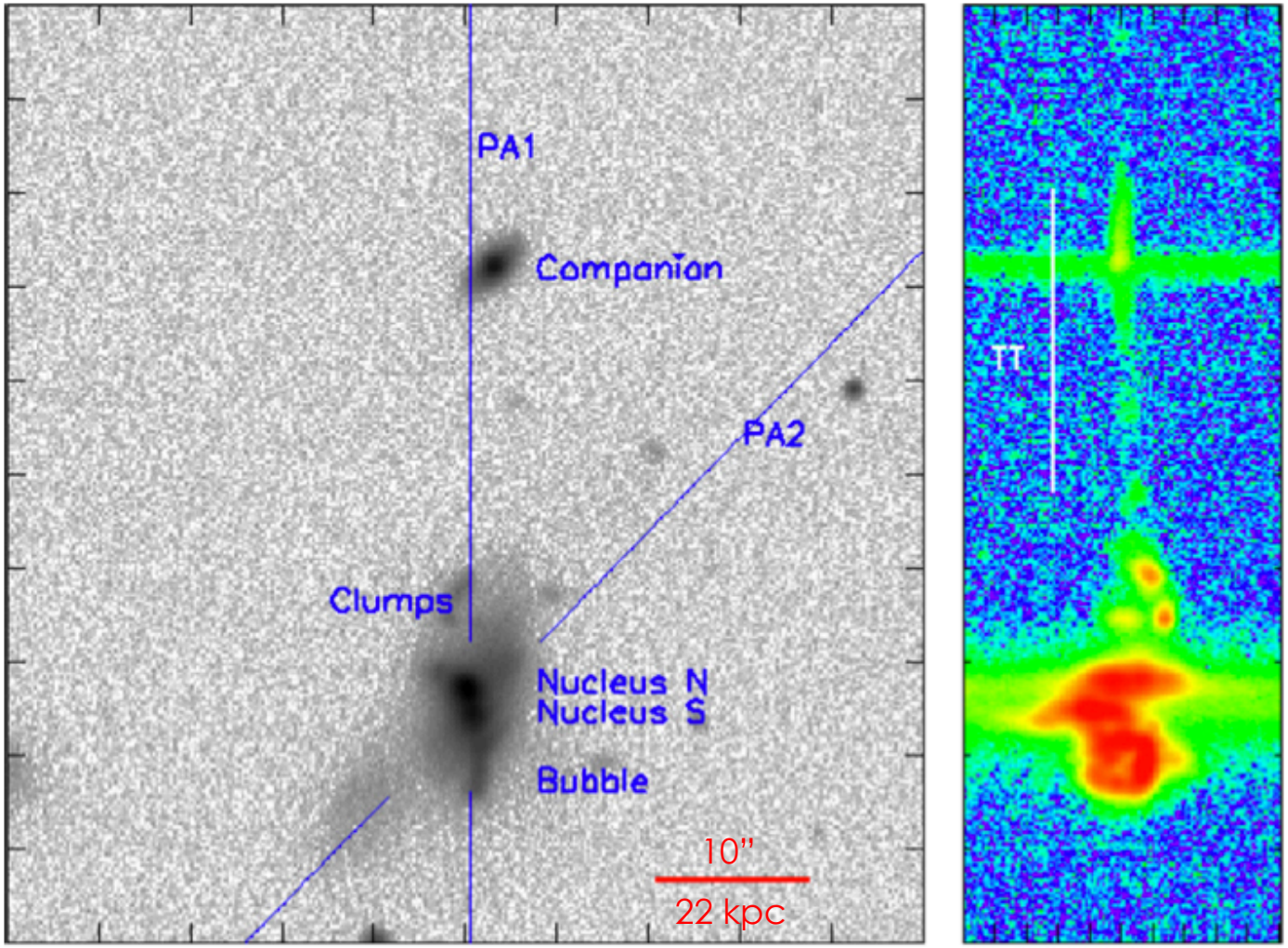
Rosario et al. 2010

SDSS J1356+1026

Double-peaked AGN at z=0.12



Extended (>50 kpc) Ionized Line Emission



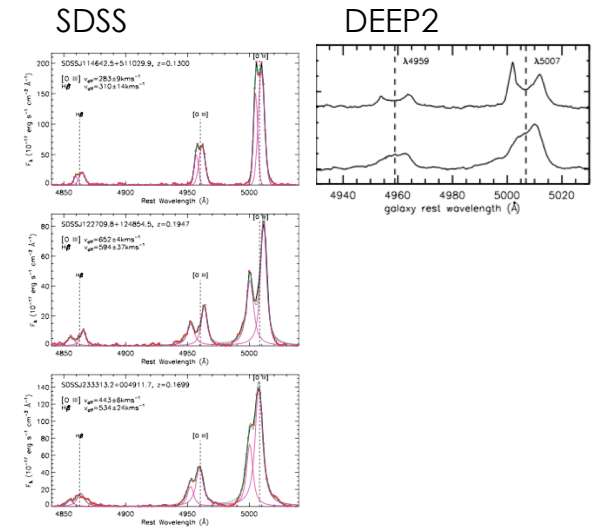
Greene et al. 2011, 2012

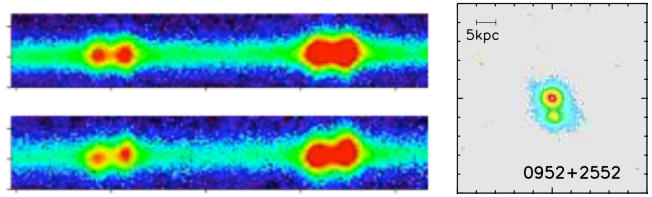
A Systematic Search for Dual AGN

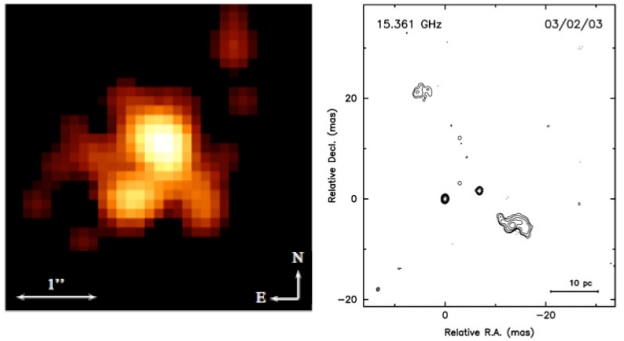
1. Identify dual AGN candidates as double-peaked AGN in spectroscopic surveys (e.g., DEEP2, SDSS)

2. Obtain follow-up observations (e.g., longslit spectroscopy) to identify most promising dual AGN candidates

3. Obtain follow-up X-ray/radio observations to confirm or refute dual AGN nature







Use large catalog of dual AGN to probe:

> galaxy mergers and AGN fueling
> supermassive black hole growth
> supermassive black hole merger rate

SDSS Double-peaked AGN as a Source of AGN Outflows

Feedback from AGN can regulate supermassive black hole mass growth and star formation