The Search for Dual Active Galactic Nuclei

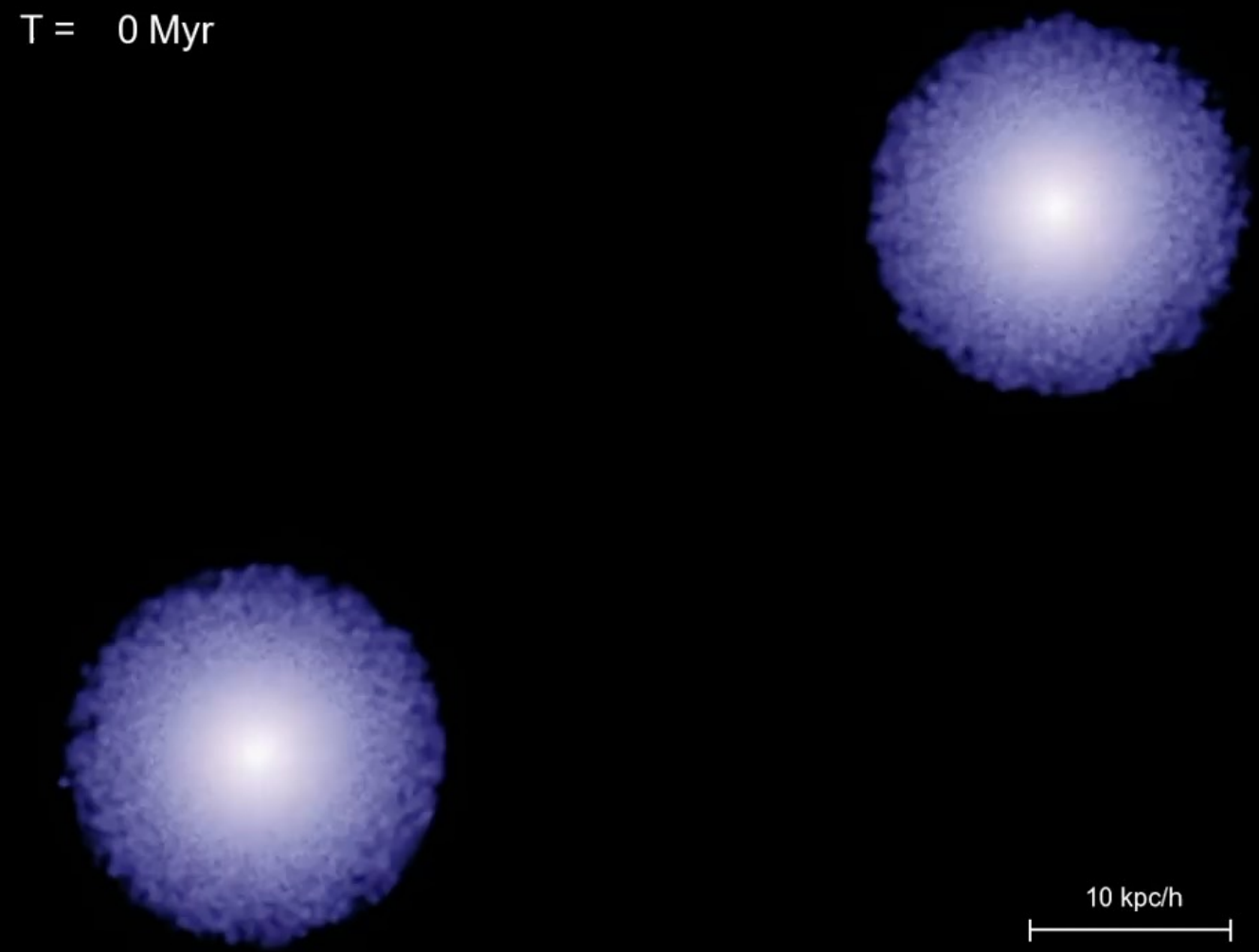
Dr. Adi Foord

Porat Postdoctoral Fellow, Stanford University

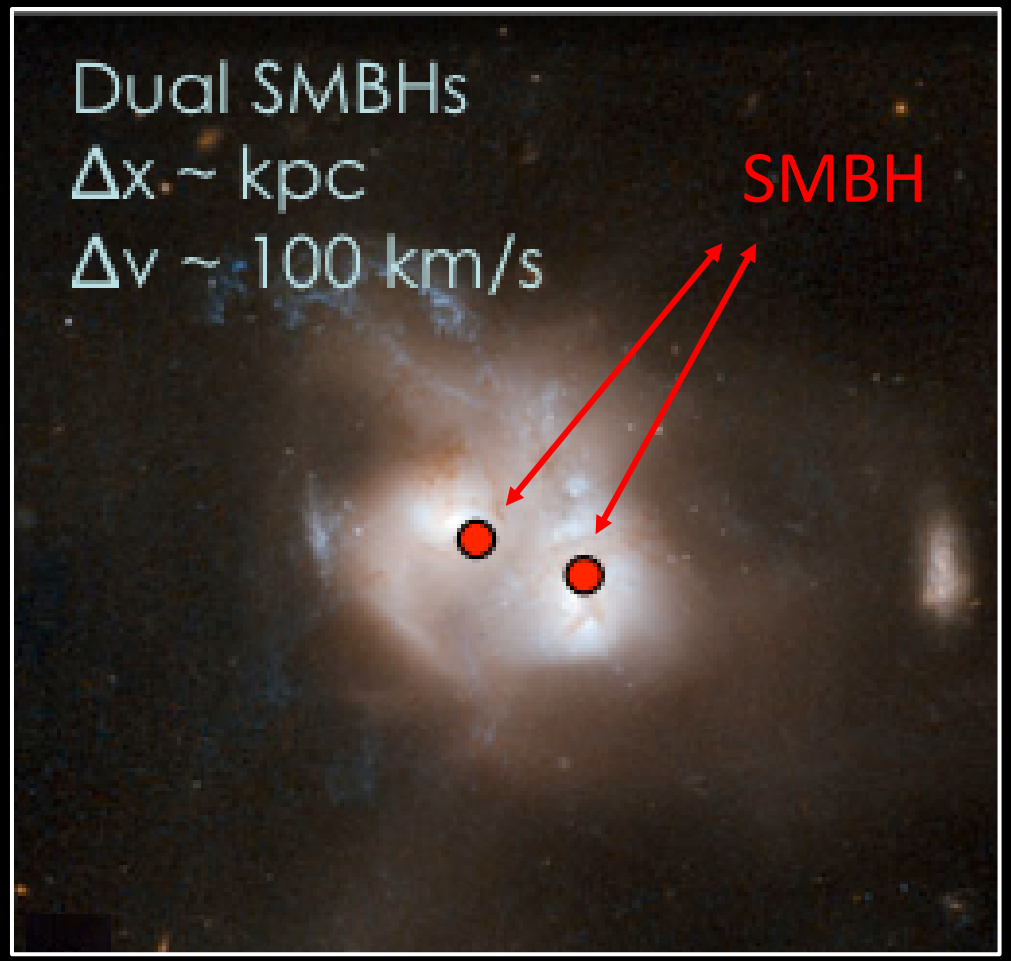
"Evidence for supermassive black hole binaries"

April 14th, 2023

Mergers are believed (*by some*) to play an important role in AGN fueling and growth



Dual AGN are *unique* observational flags of merger-driven SMBH growth



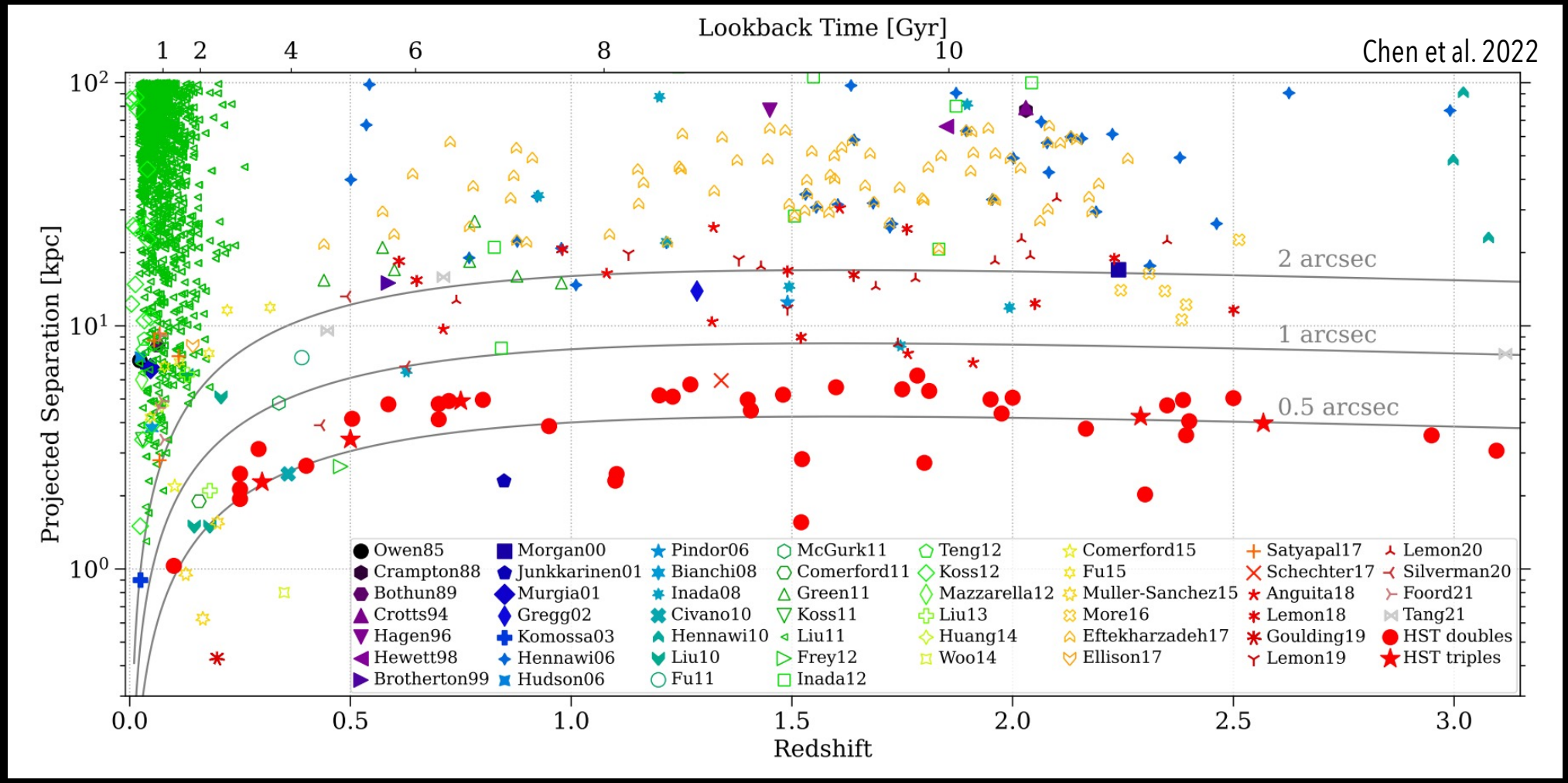
Supermassive black hole pairs are a result of galaxy mergers, where each galaxy has its own central SMBH

"Dual SMBH" =

- SMBH pair at kpc-scale separations
- **not yet** gravitationally bound
- system is losing energy and decreasing separation via dynamical friction

"Dual AGN" = actively accretion dual SMBH

We are still trying to quantify the population of dual AGN



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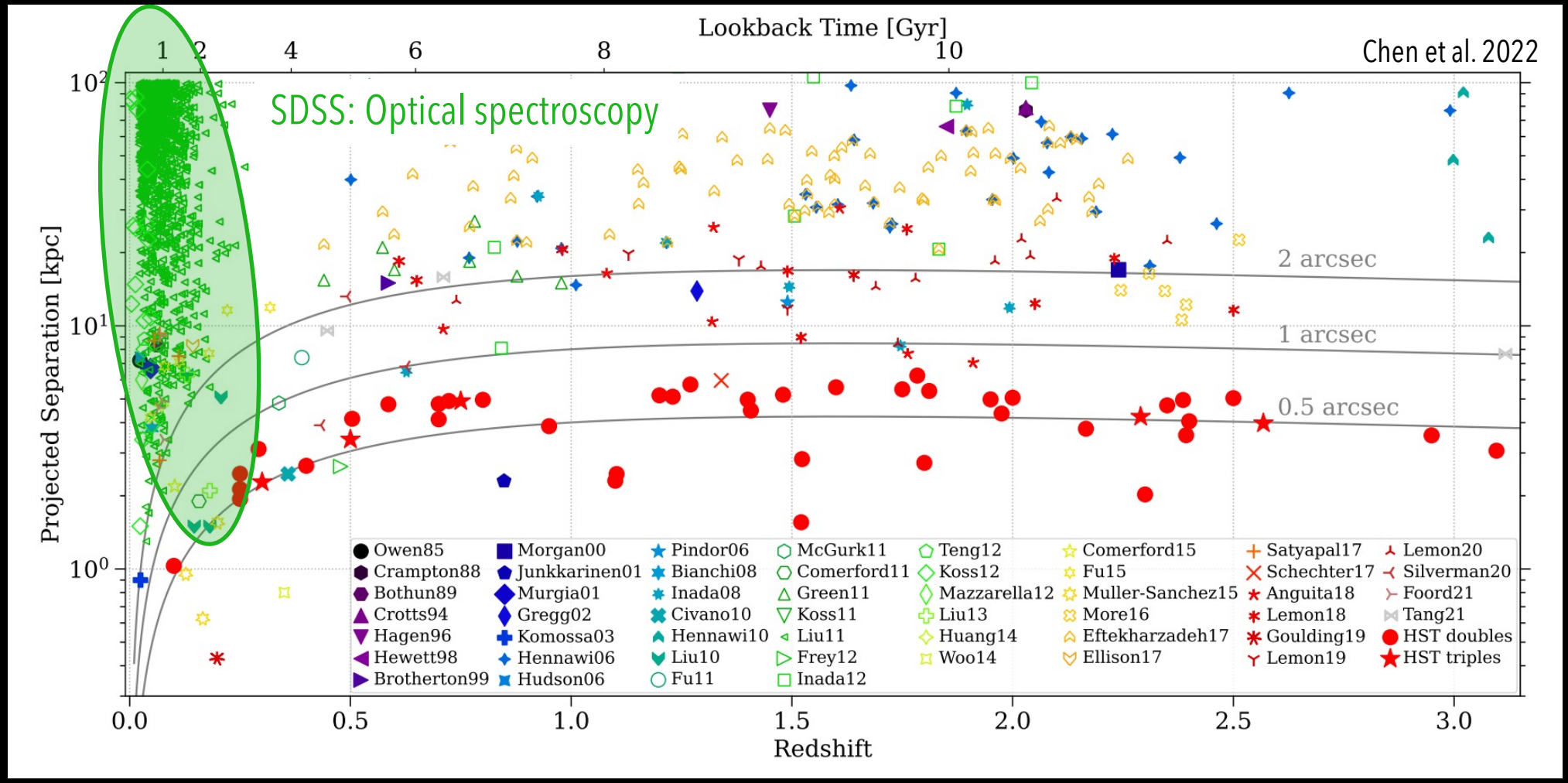

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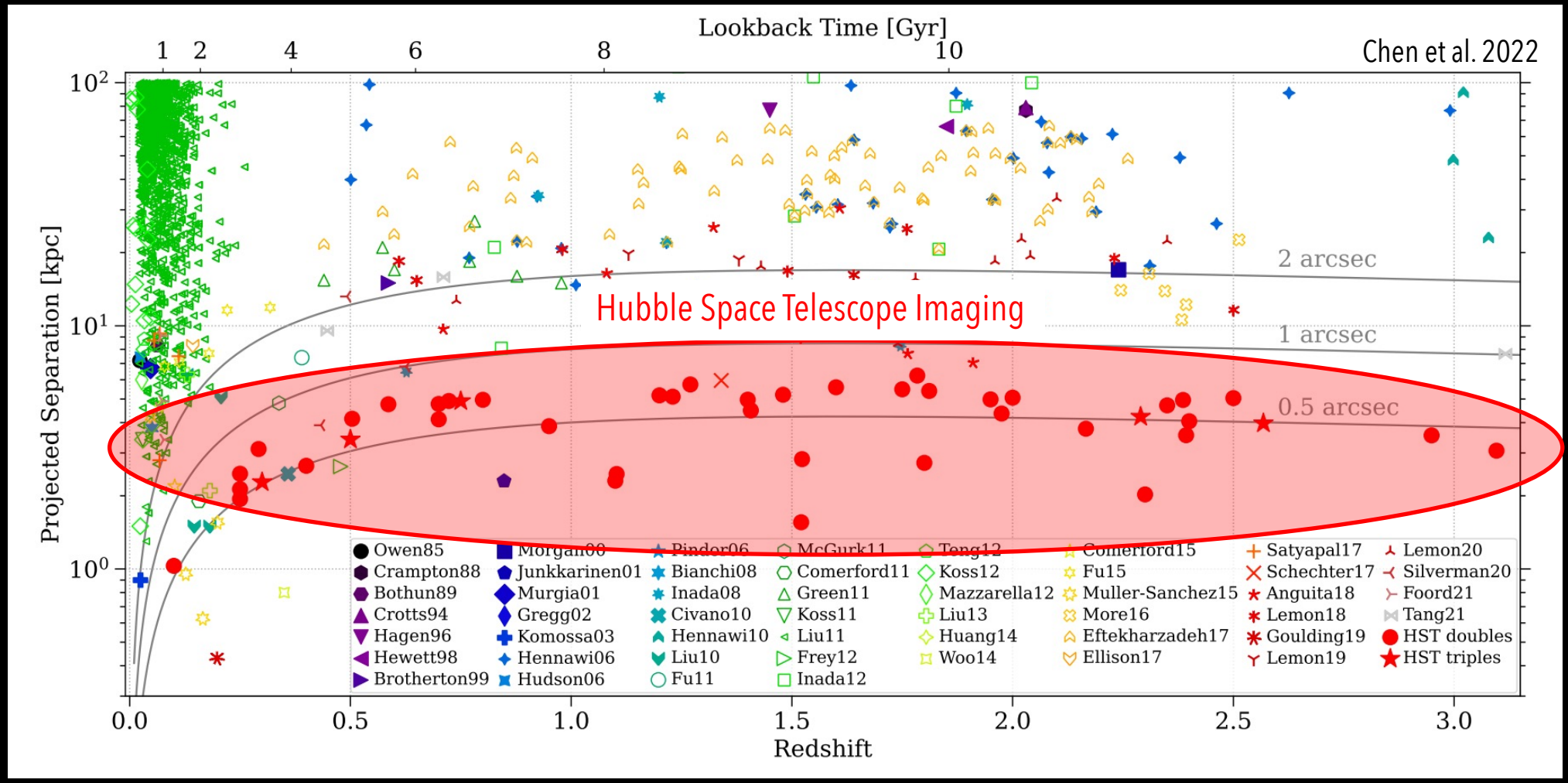
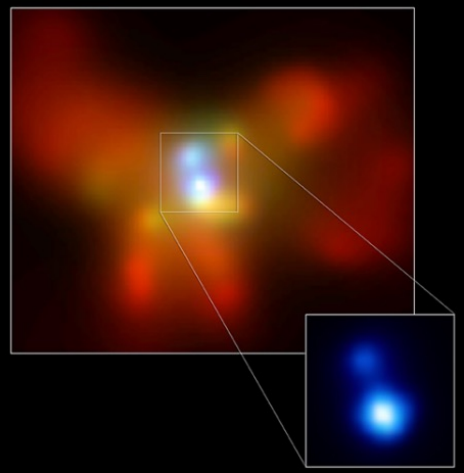
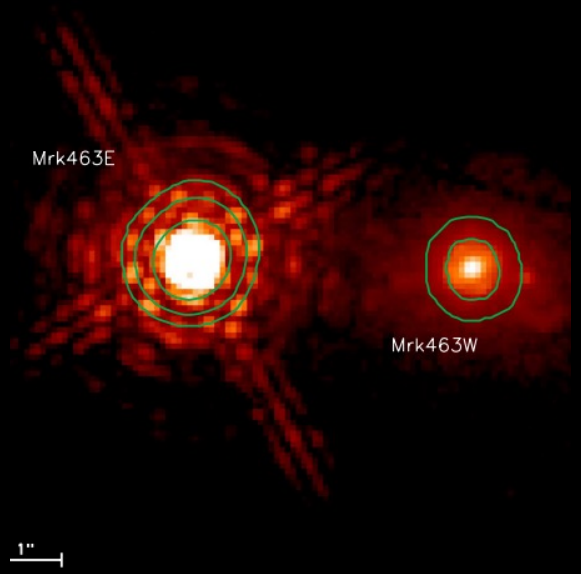


Before 2010, only a handful of dual AGN were known …

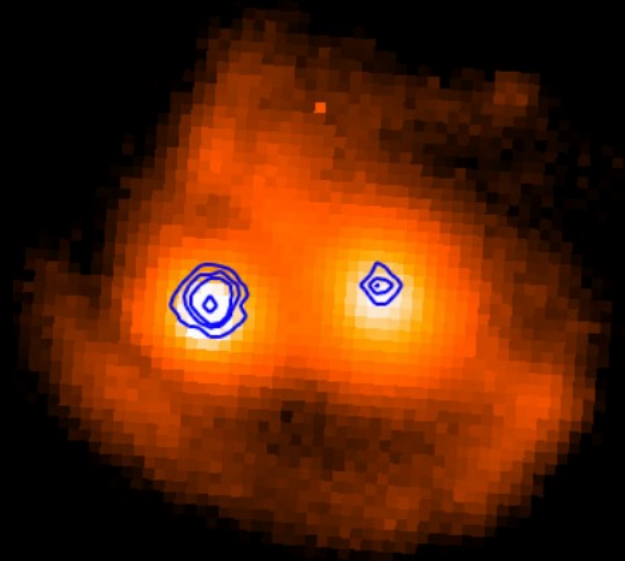
Most dual AGN were serendipitous discoveries, or follow-up X-ray/Radio observations of known galaxy mergers



NGC 6240 (Komossa+2003)
X-ray confirmation



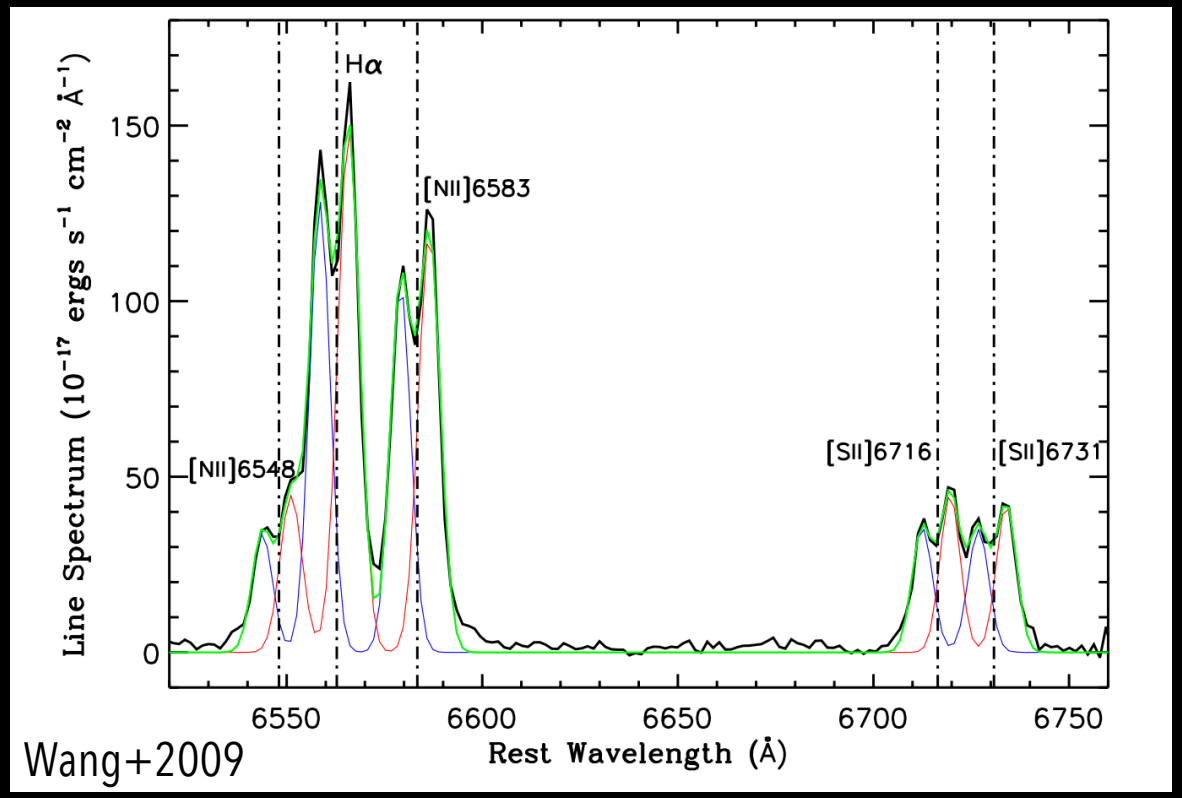
MRK 463 (Bianchi+2008)
X-ray confirmation



MRK 739 (Koss+2011)
X-ray confirmation

SDSS: Large spectroscopic searches change the field

With the advent of large spectroscopic surveys of galaxies, like SDSS, the number of dual AGN candidates exponentially increased

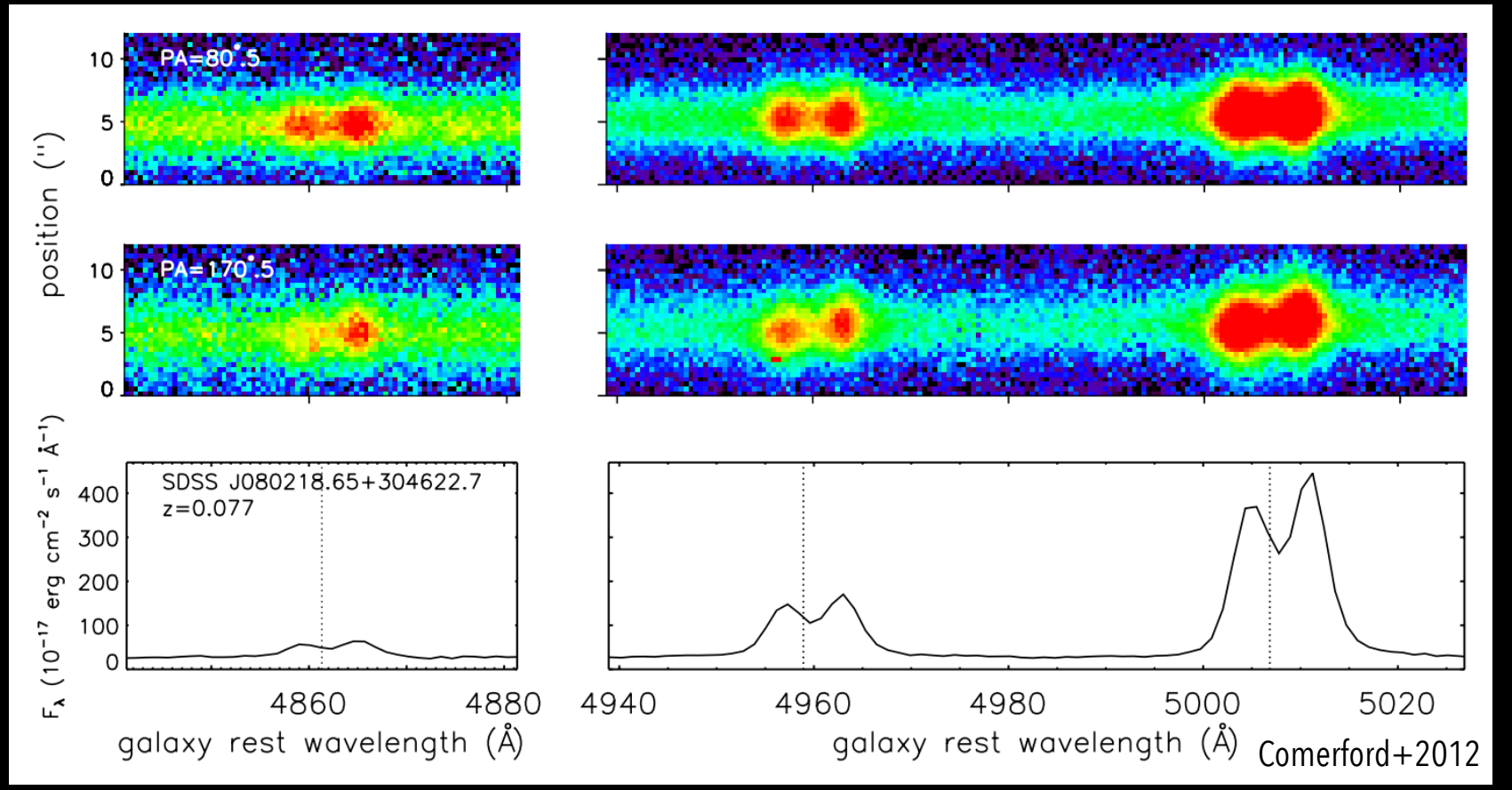


Wang+2009

Sifting through available SDSS spectra ,100s of double peaked found in SDSS spectral archives

Check out:
Wang+2009, Comerford+2009, Smith+2010, Liu+2010

SDSS: Large spectroscopic searches change the field

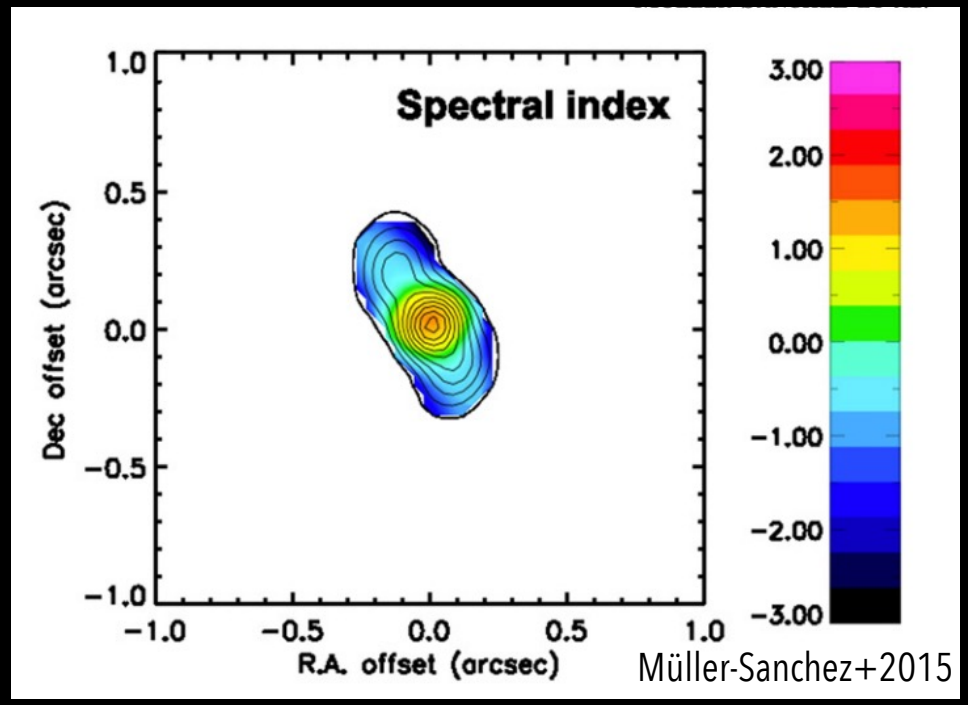


Spatially resolved spectroscopy shows locations are coincident with galactic nuclei

(Check out: Gerke+2007, Comerford+2009, Comerford+2012)

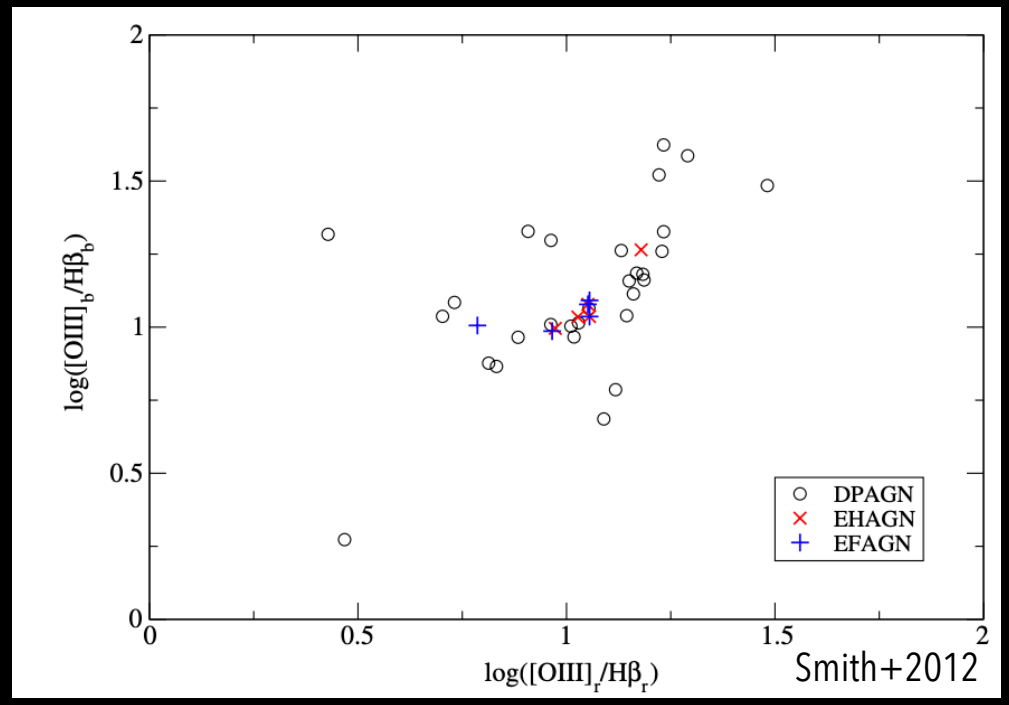
Double peaked emitters: dual AGN or outflows?

Even for spatially resolved double peaked sources, follow-up observations showed that the majority were likely single AGN …



Müller-Sanchez+2015

Follow-up with VLA on 18 dual AGN candidates show that 5 are dual AGN (7 are AGN wind-driven outflows, 5 are radio-jet driven outflows, and 1 is rotating narrow-line region)

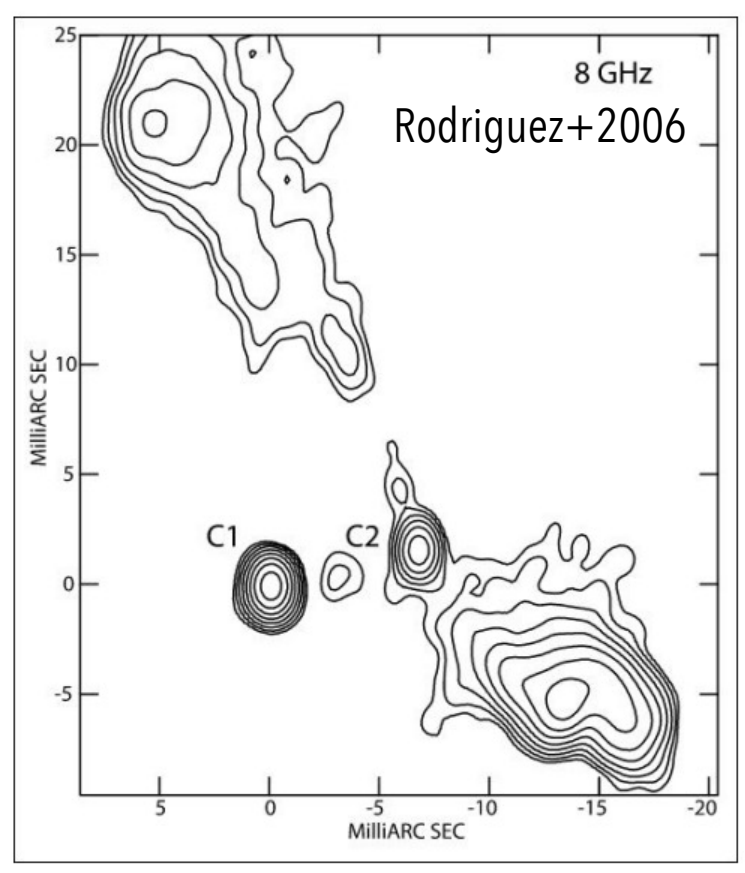


Smith+2012

Many sources have [O III] lines have nearly equal intensities, and line ratios are more similar to each other, suggesting a single ionizing source (and are inconsistent with a binary scenario)

Candidates to direct detection: follow-up is necessary

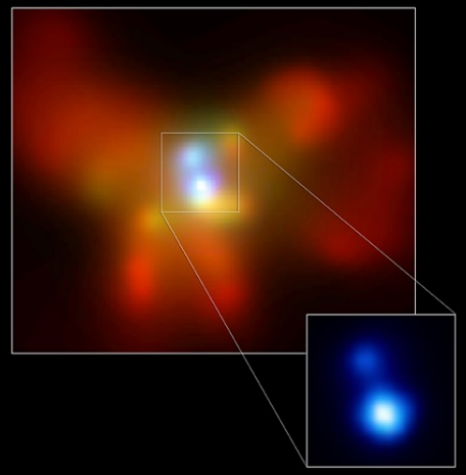
Directly detecting radio emission from each SMBH is one the best ways to confirm closely separated dual AGN



The typical mas-scale angular resolution achievable with VLBI networks allows directly resolve as small as ~1 pc in the local Universe and ~ 10 pc at any redshift.

0402+379 at 8 GHz. Components C1 and C2 correspond to the two radio nuclei at projected separation of 7.3 pc

X-rays are great rays to find dual AGN (& high-resolution is the best!)



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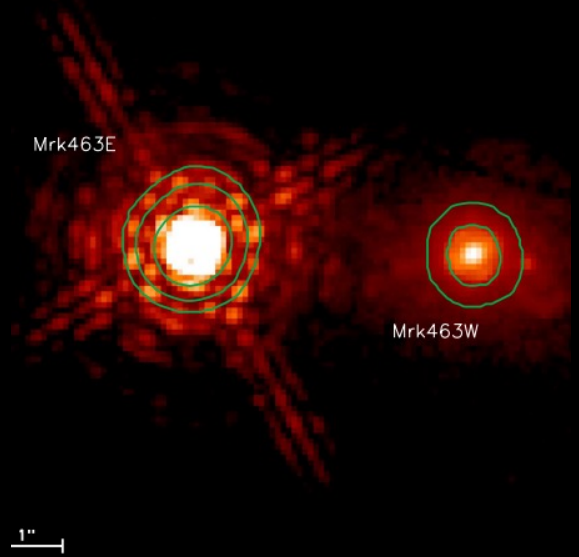

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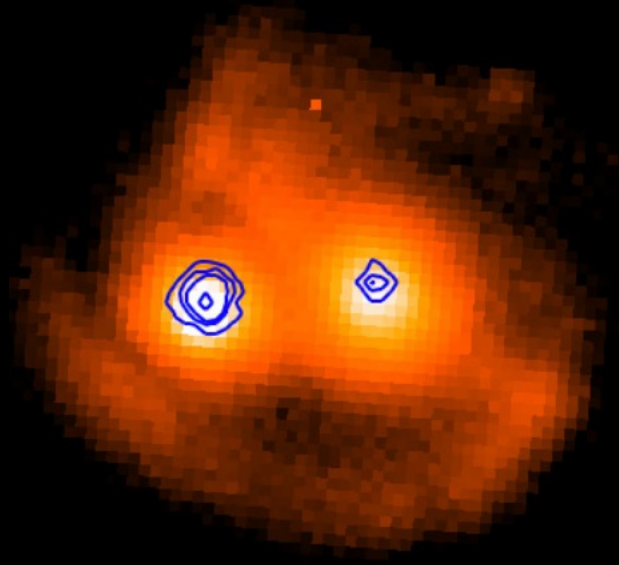
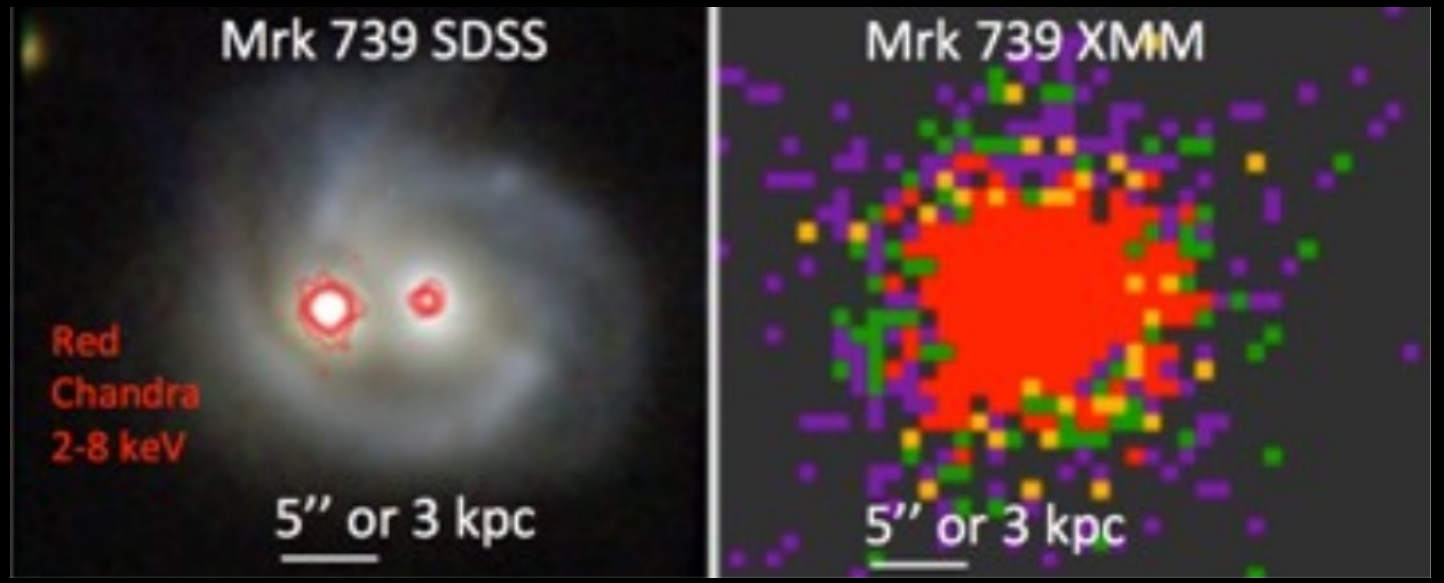


MRK 739 (Koss+2011)
X-ray confirmation

Resolving 2 X-ray point sources with X-ray luminosities $>10^{41}$ erg s^{-1} can confirm any dual AGN candidates

X-rays are great rays to find dual AGN (& high-resolution is the best!)



With Chandra we can find the most closely separated systems

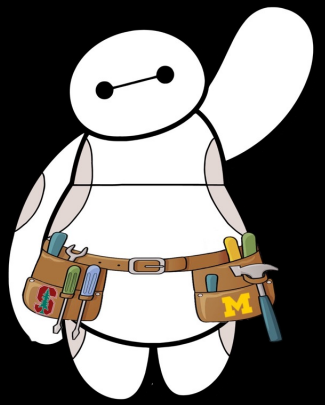
BAYMAX (Bayesian AnalYsis of Multiple AGN in X-rays) allows for statistical analyses on *Chandra* observations

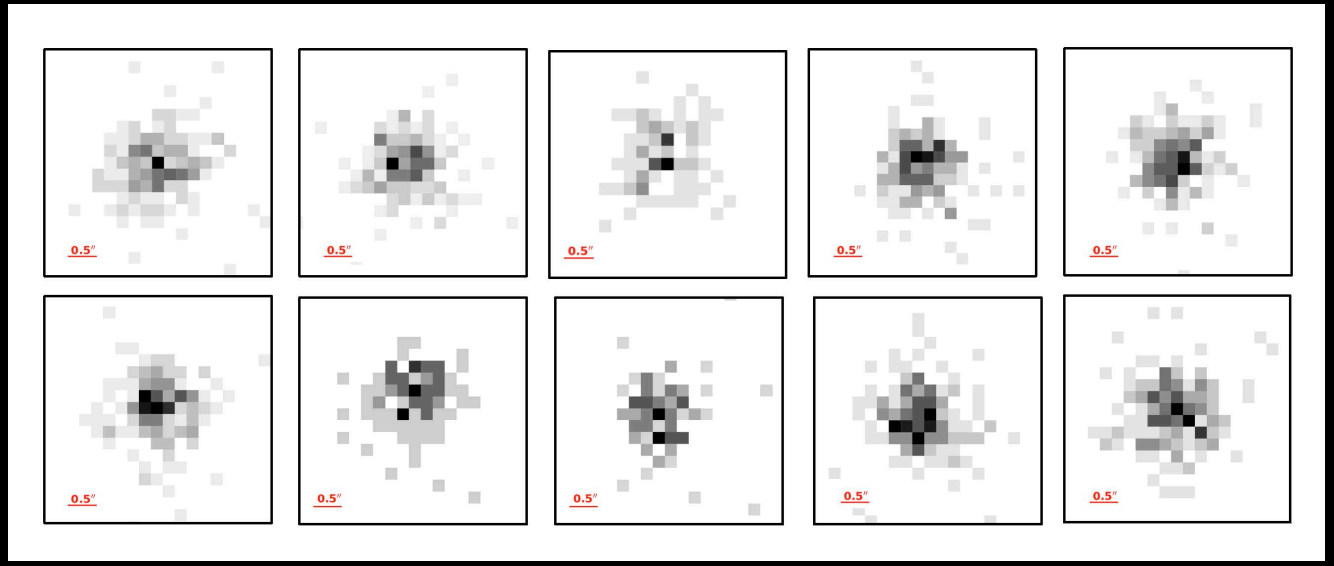
BAYMAX calculates the Bayes factor:

$$P(M|D) = \frac{\int P(D|\theta_1, M_1) P(\theta_1|M_1) d\theta_1}{\int P(D|\theta_2, M_2) P(\theta_2|M_2) d\theta_2} ,$$

which represents the posterior odds or the

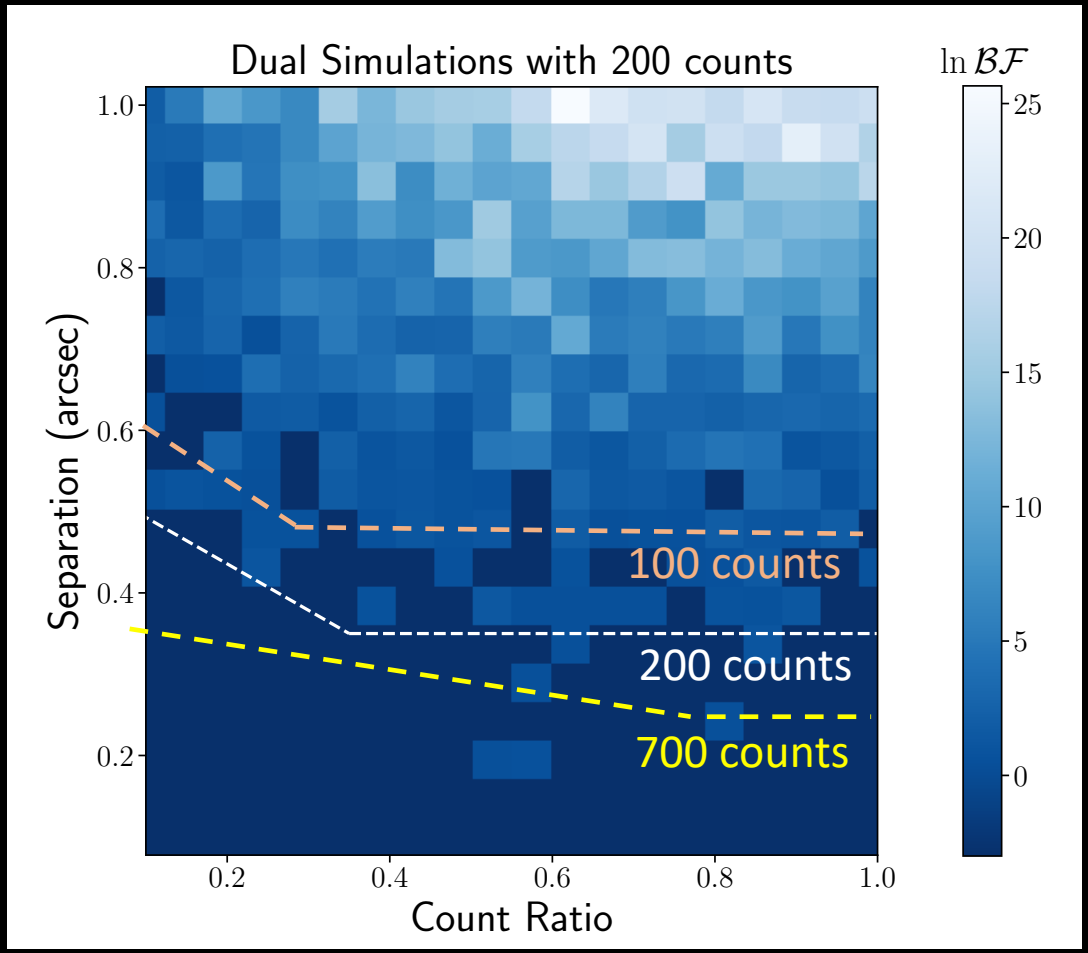
degree to which we favor one hypothesis over the other





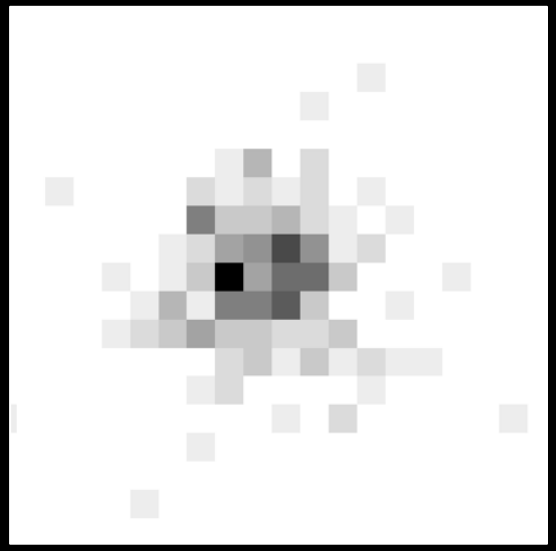
Bolded simulations are the dual AGN

BAYMAX (Bayesian AnalYsis of Multiple AGN in X-rays) allows for statistical analyses on *Chandra* observations

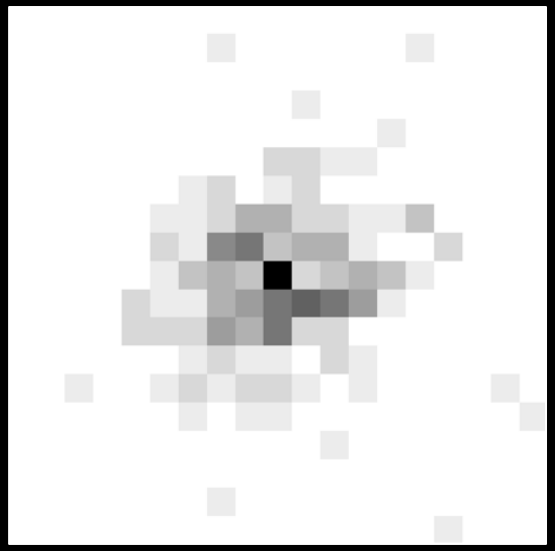


Denotes the count fraction between the secondary and the primary

Single AGN,
N_c = 200



r = 0.43”, f=0.62,
N_c = 200



At z=1, 0.43” = 3.5 kpc

Analyzing AGN activity in nearby triple galaxy mergers

Foord et al. 2021a

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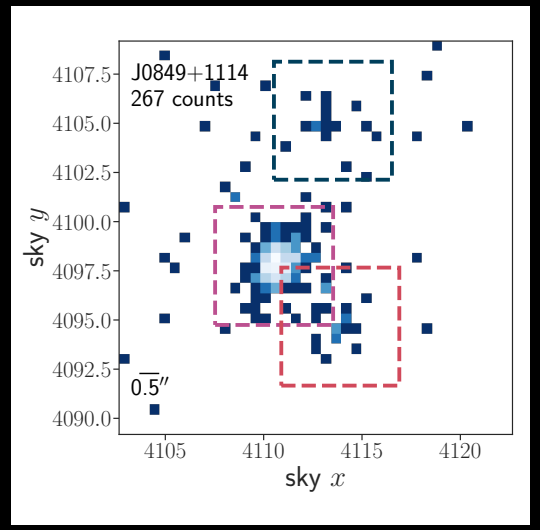

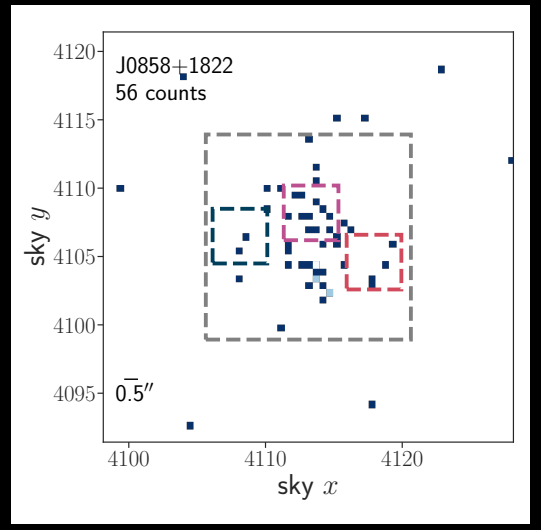

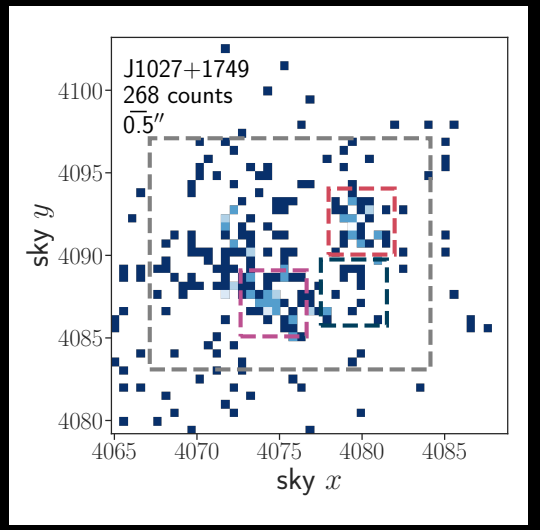

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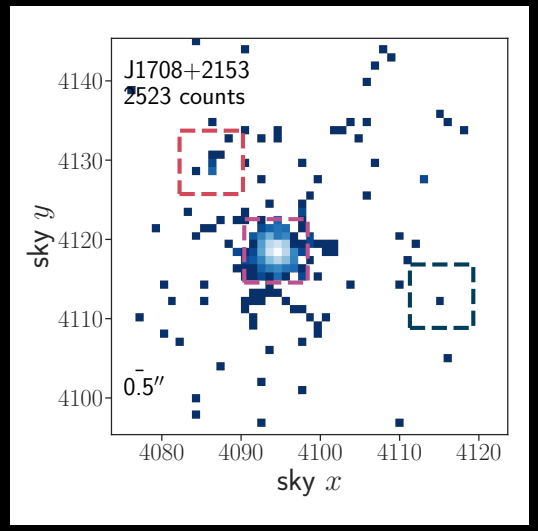
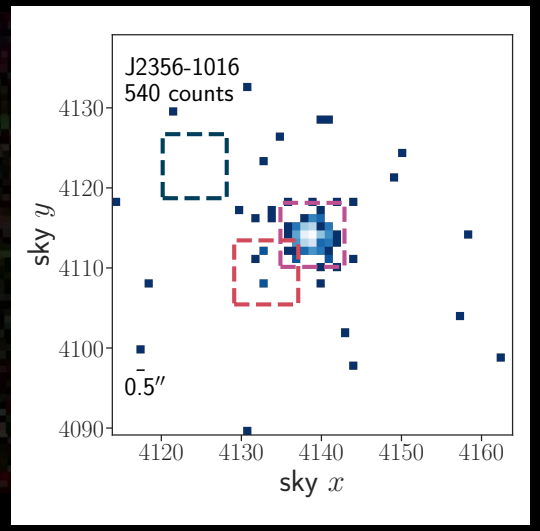
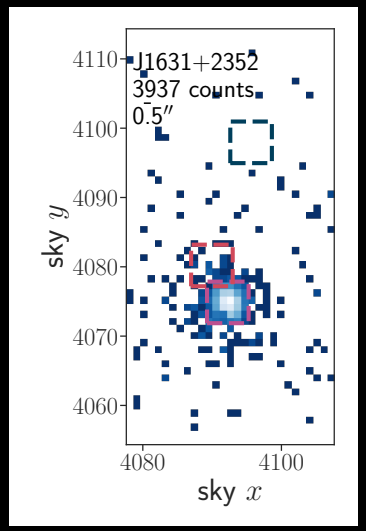
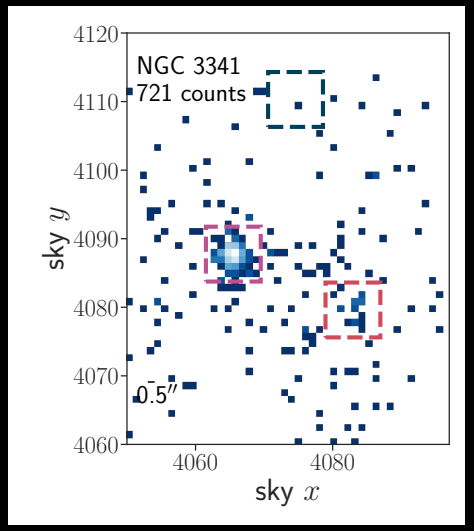
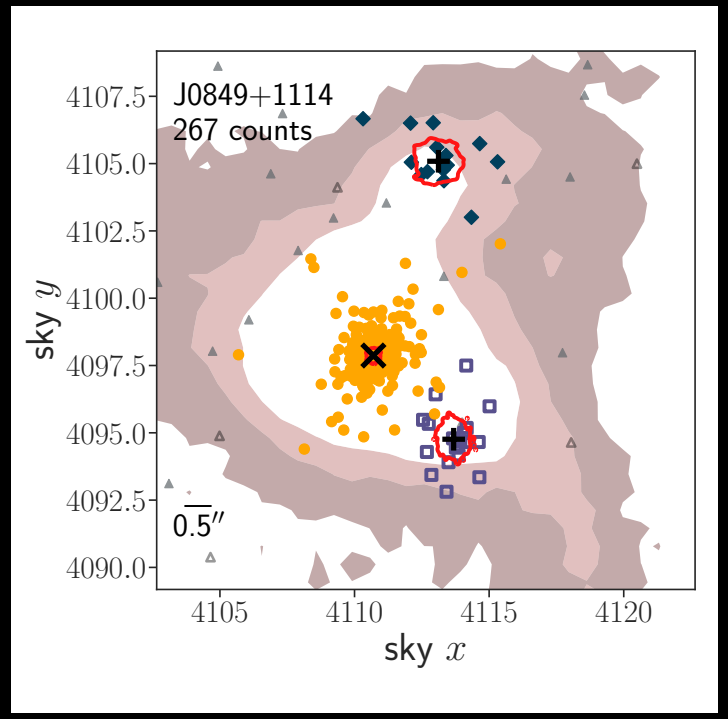


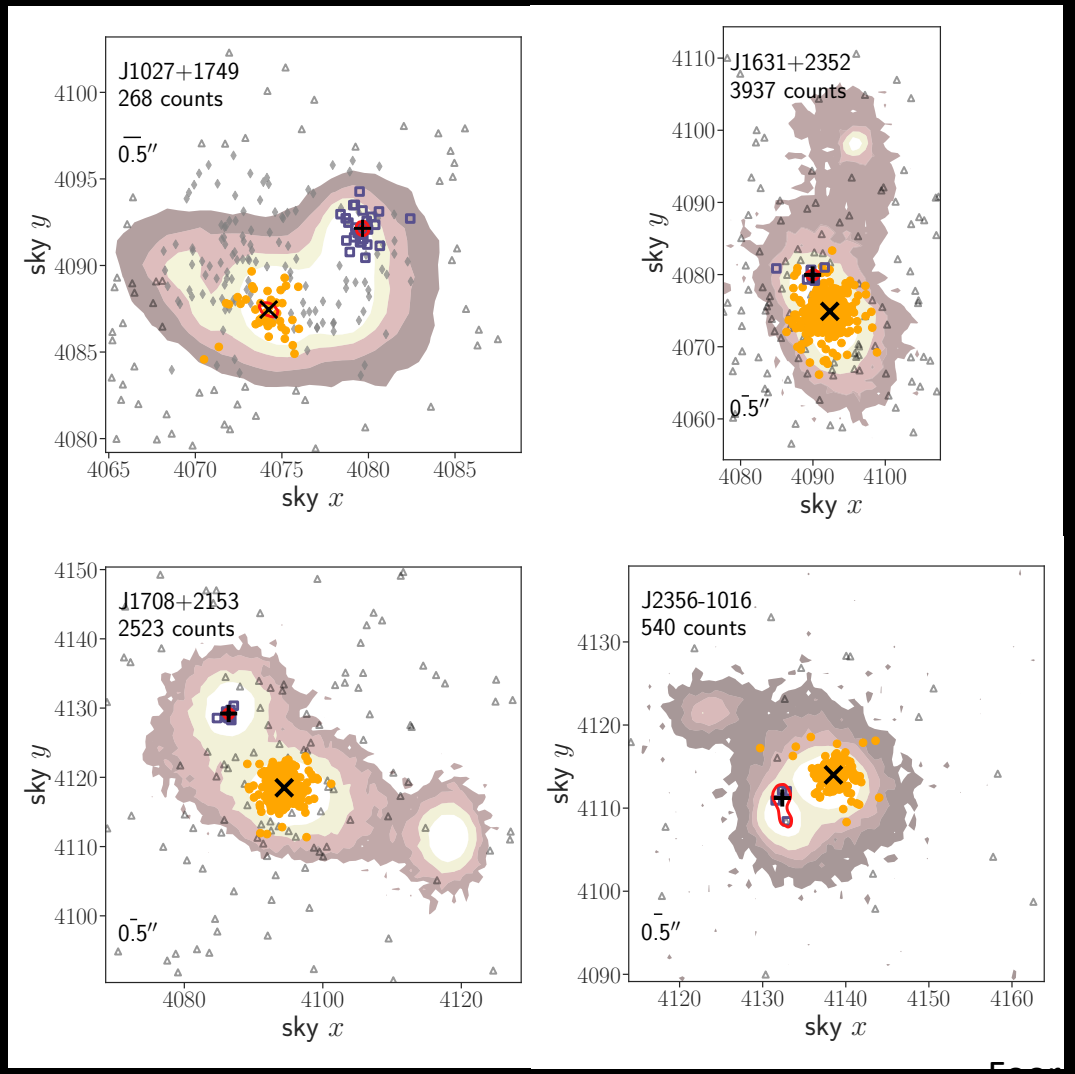






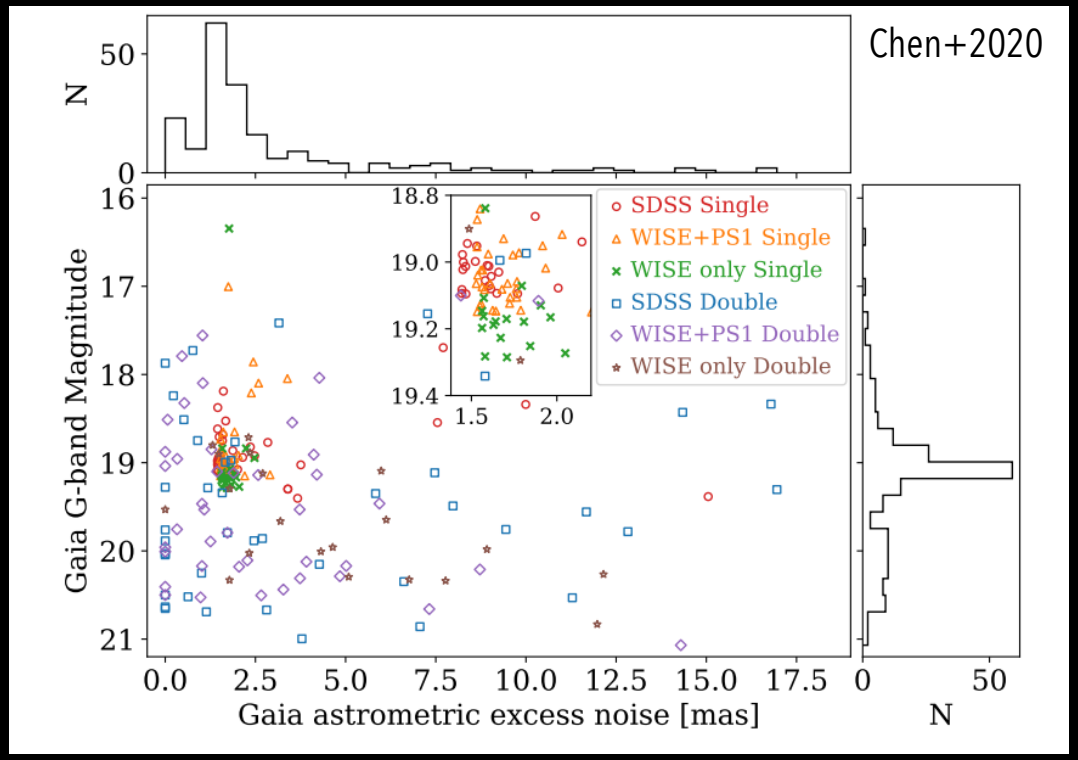
Analyzing AGN activity in nearby triple galaxy mergers





Gaia is making a mark in the dual AGN community

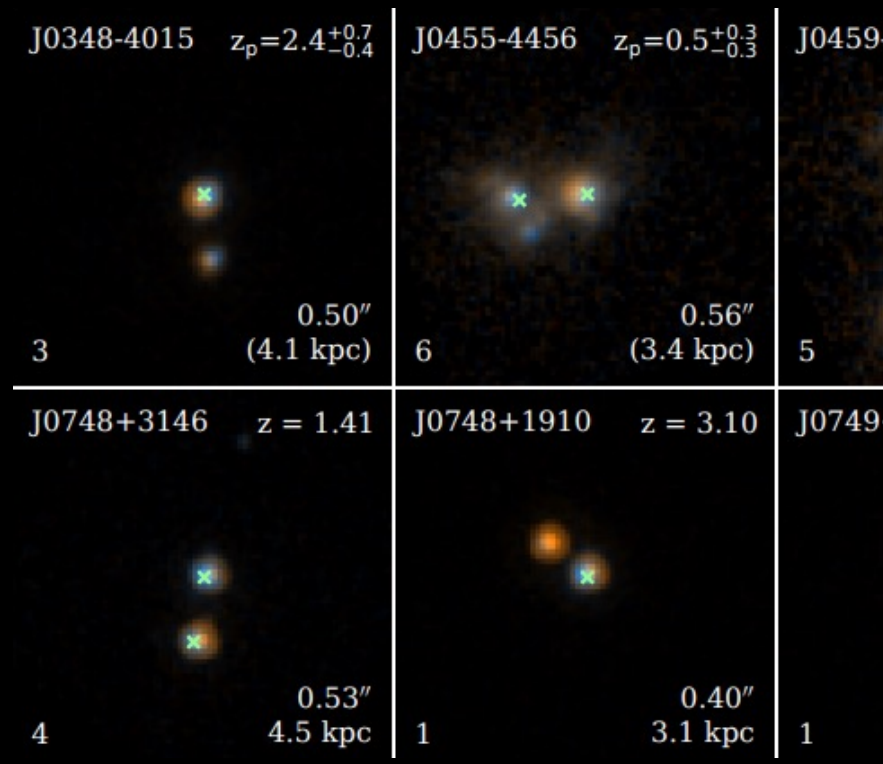
'Varstrometry' – where variability-induced astrometric jitter, i.e., temporal displacements of photocenter in unresolved sources, can be used to search for dual AGN.



Gaia is making a mark in the dual AGN community

'Varstrometry' – follow up Hubble Space Telescope images shows multiple sources at most locations! Many are lenses, but some a likely dual AGN.

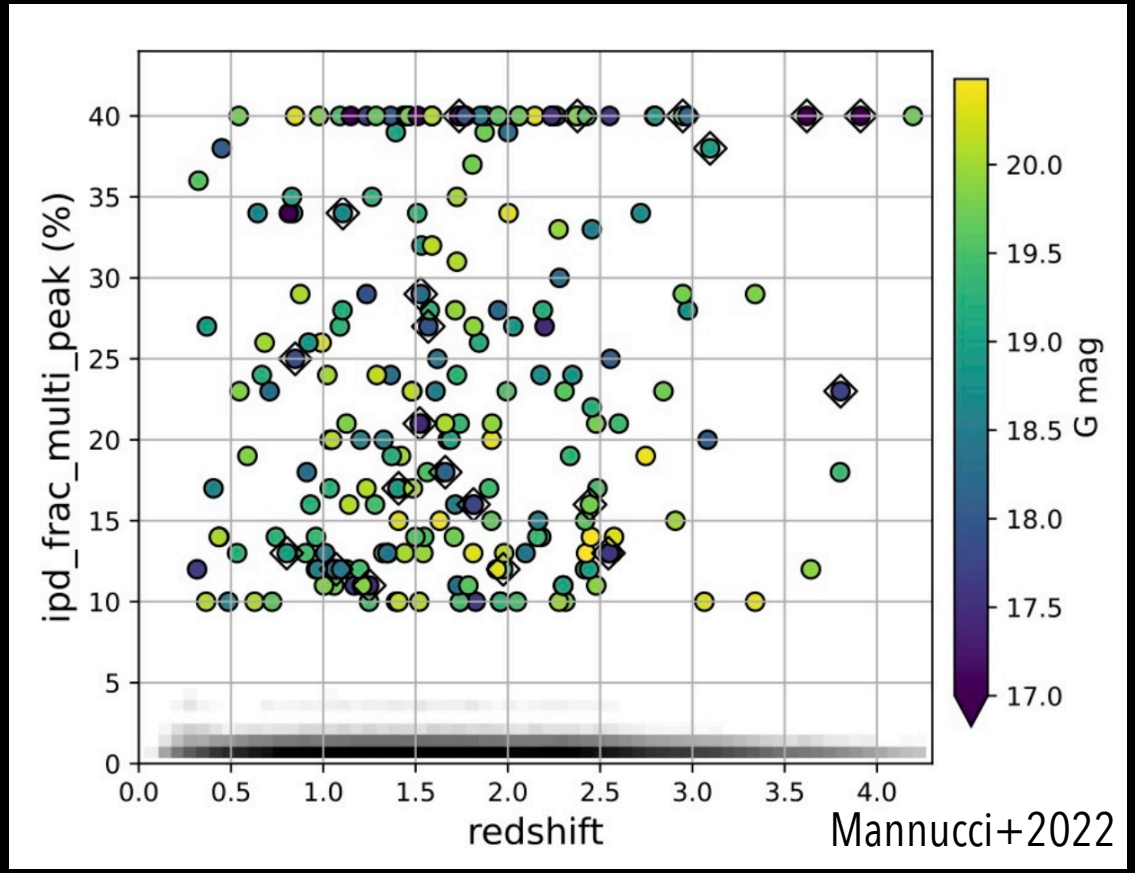
Chen+2020



Gaia is making a mark in the dual AGN community

'Gaia Multipeak (GMP) method' – searching for the presence of multiple peaks in the observed 1D light profiles

"ipd_frac_multi_peak" is Gaia catalogue parameter that gives the fraction of Gaia transits in which the object appears to have multiple peaks inside the photometric aperture



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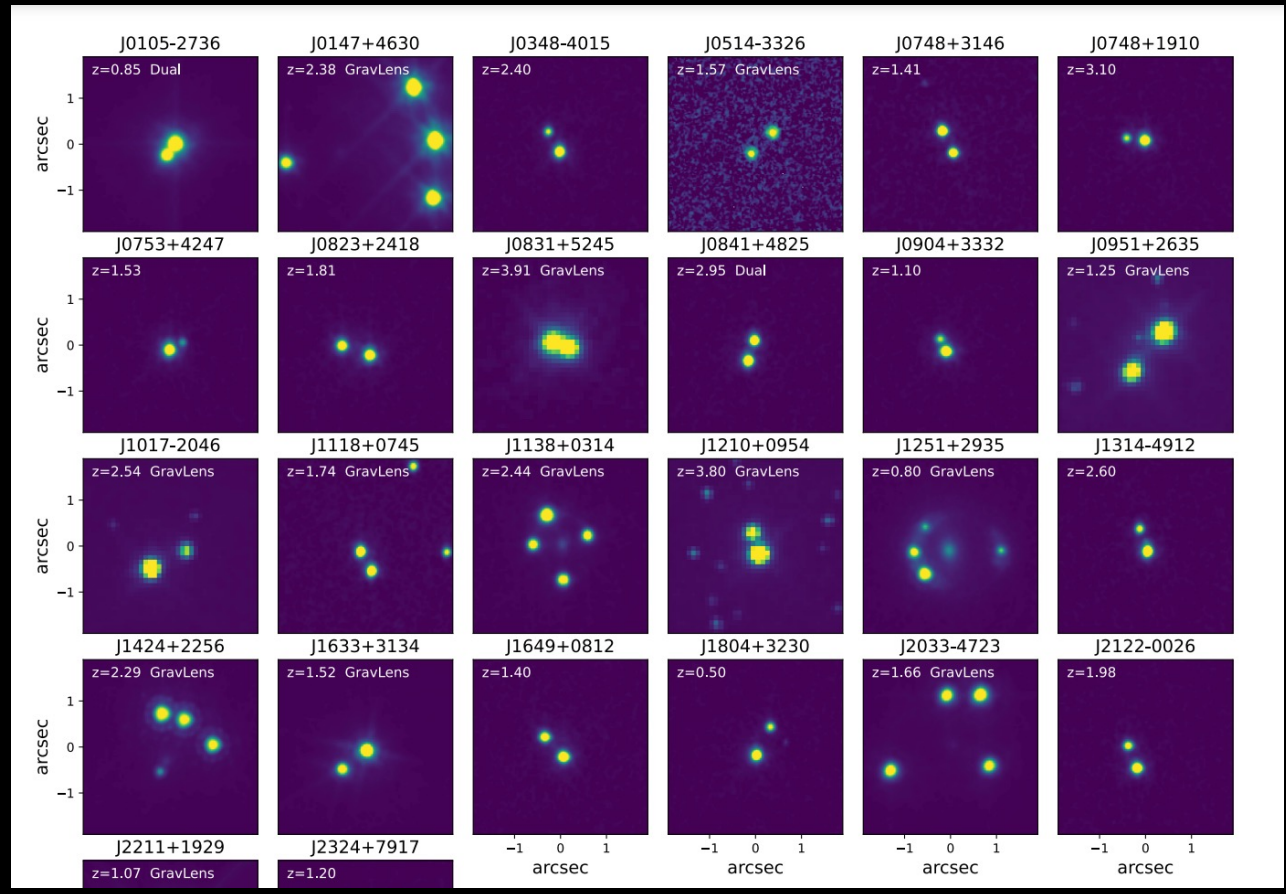
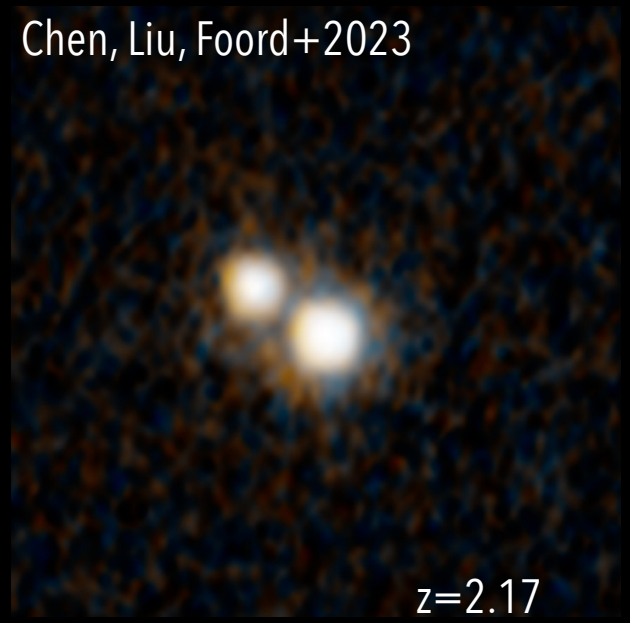
'Gaia Multipeak (GMP) method' – searching for the presence of multiple peaks in the observed 1D light profiles

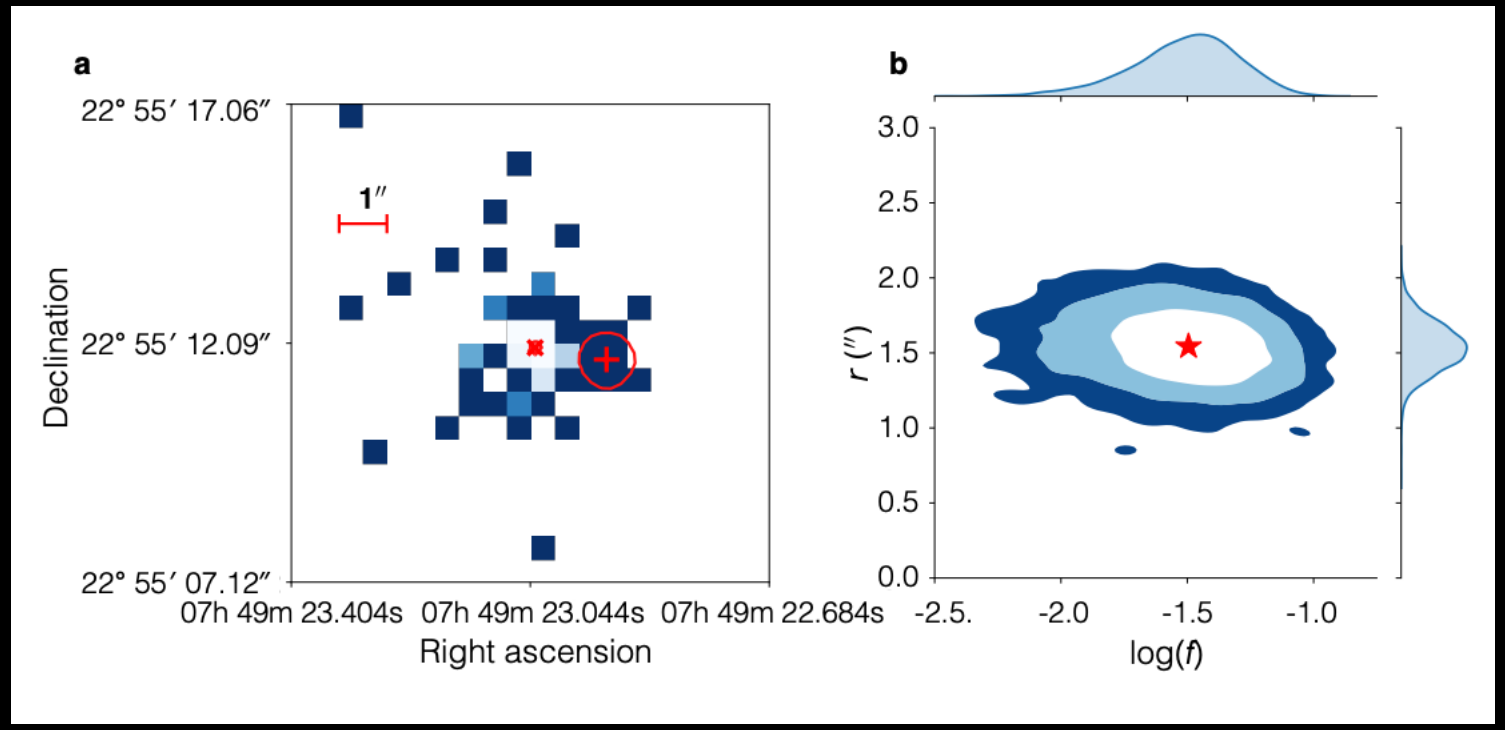
Follow-up HST once again shows many pairs of sources at each location!

Confirmation requires a multi-wavelength analysis.



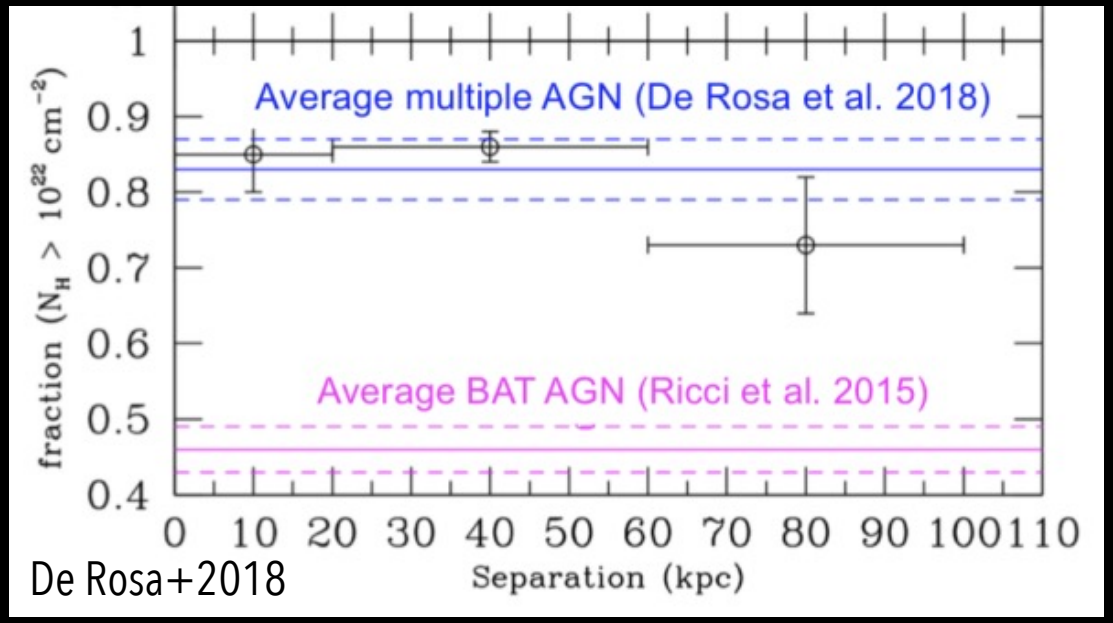
BAYMAX has recently been used in a study on a varstrometry-identified dual AGN candidate



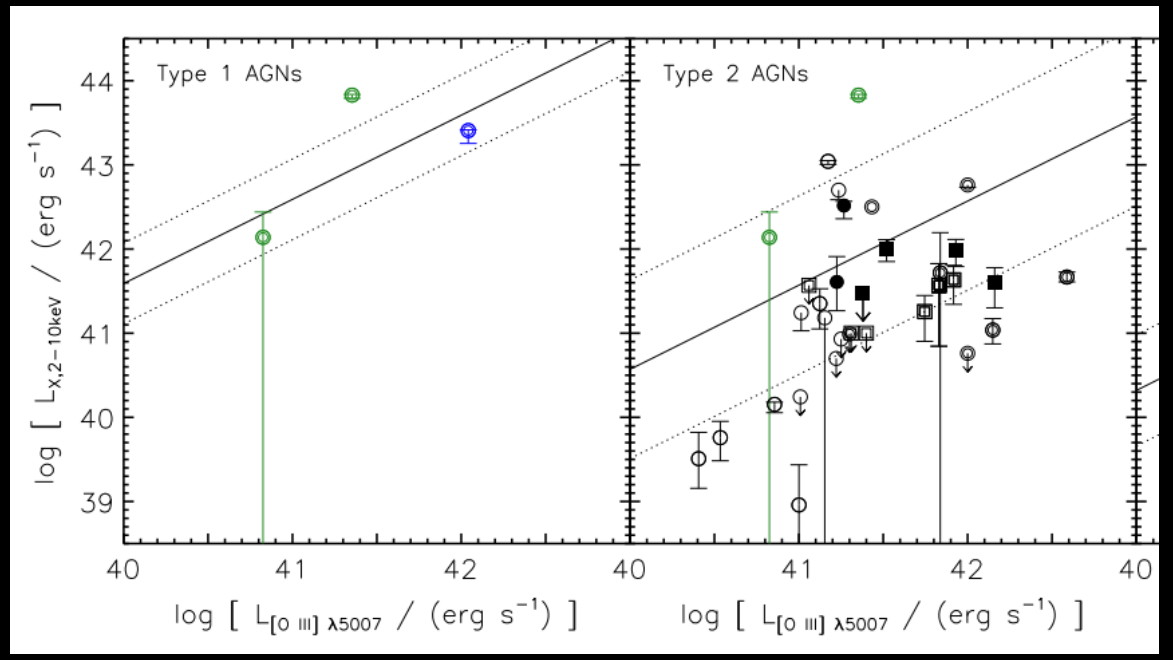


Discovered via "varstrometry" and confirmed via a multi-wavelength analysis (optical photometry and spectroscopy, radio imaging, IR imaging)

Dual AGN are usually heavily obscured …

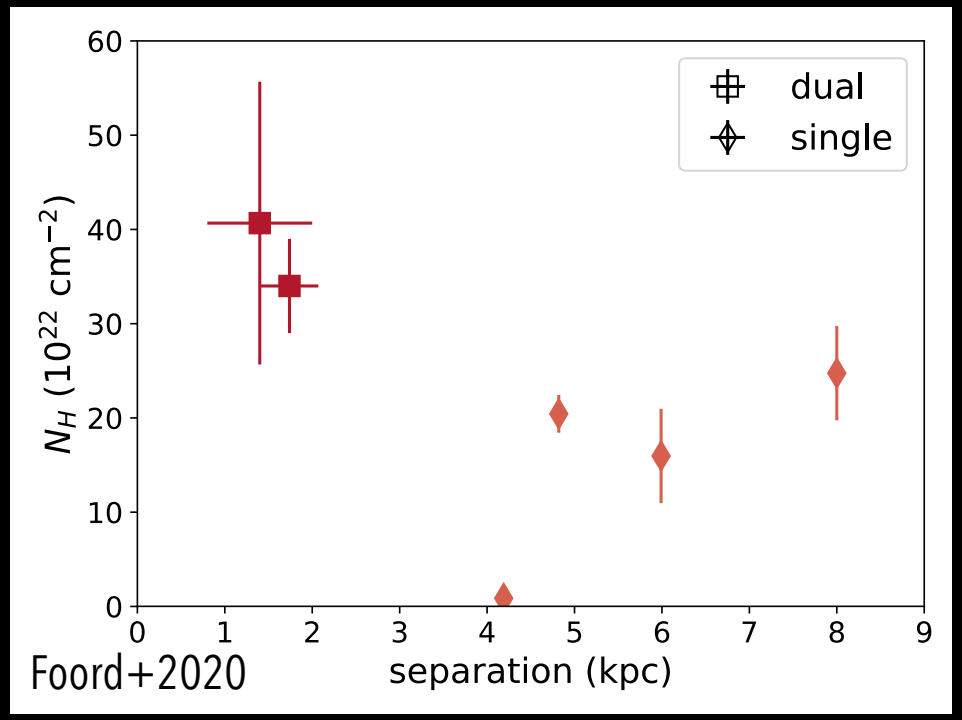


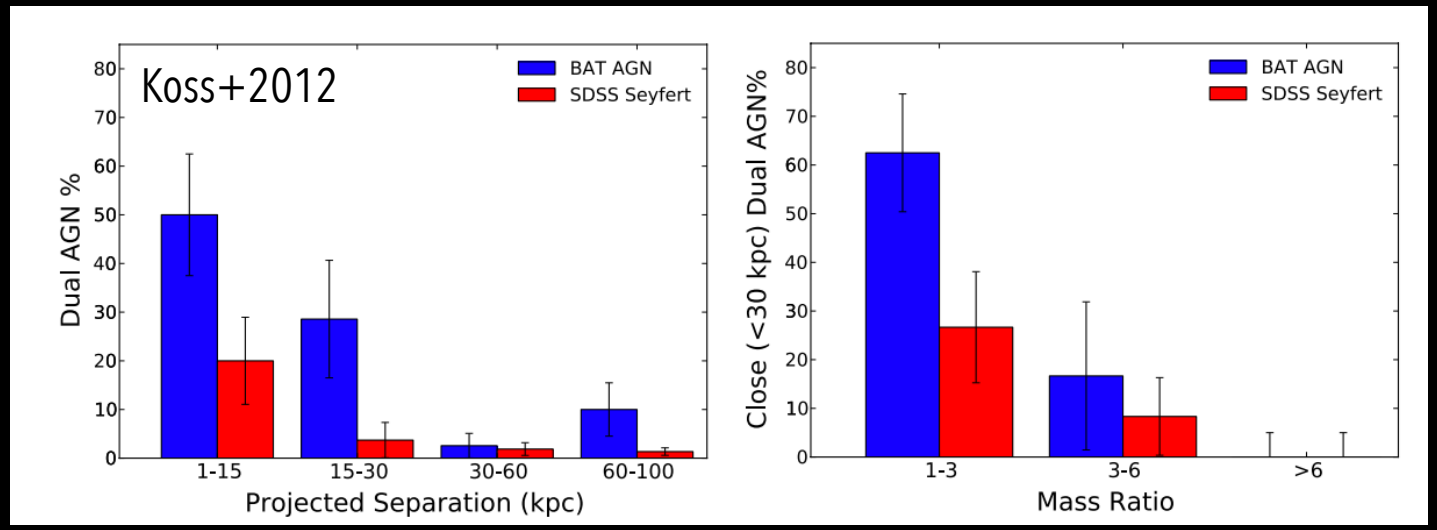
The fraction of Compton thick AGN hosted in late-merger galaxies is higher than in local hard X-ray selected AGN



Dual AGN have systematically lower hard X-Ray luminosities, at fixed [OIII] λ5007 luminosity, than single AGN

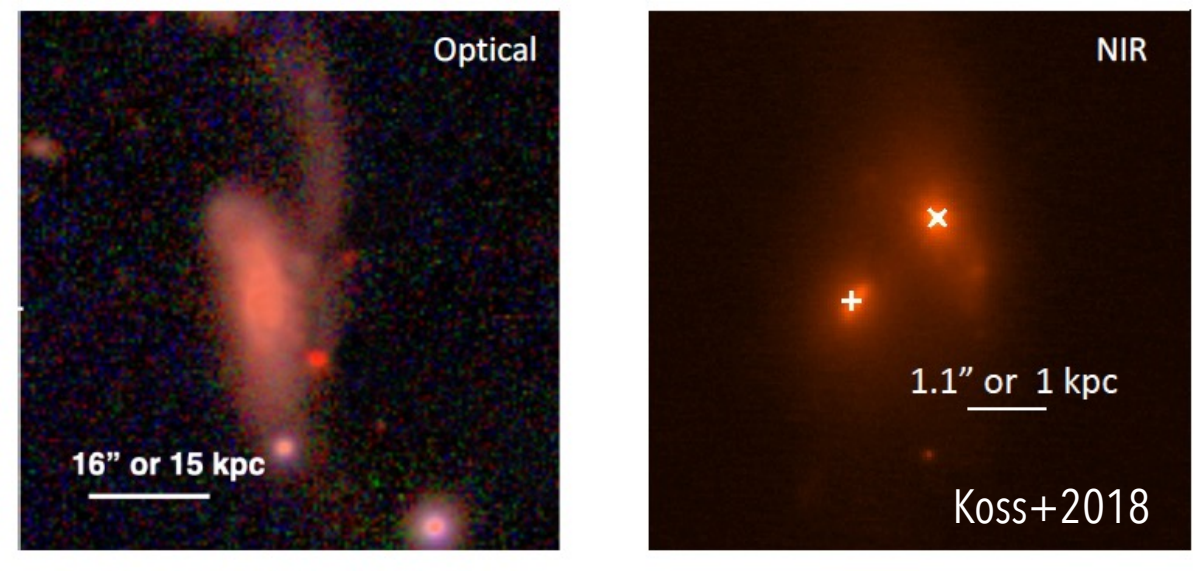
. . . and prefer later-stage galaxy mergers



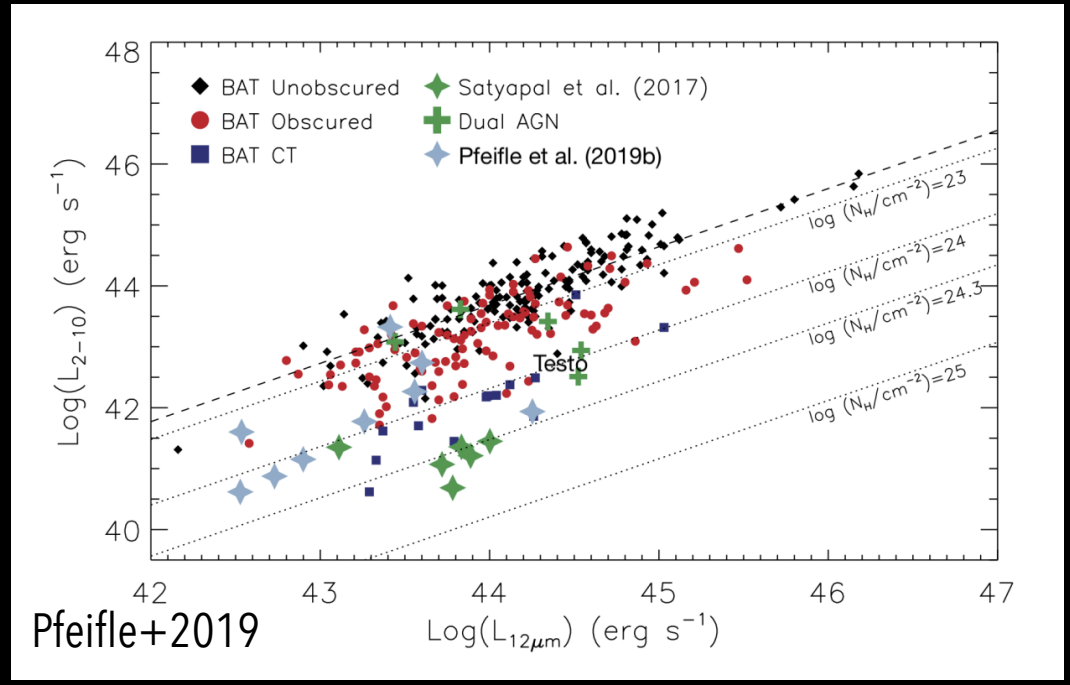


Dual AGN prefer closely separated, gas-rich environments. Late-stage major mergers are more likely to have dual AGN.

Infrared observations can find the most heavily obscured mergers



High-resolution IR observations resolve two stellar cores in nearby galaxy mergers



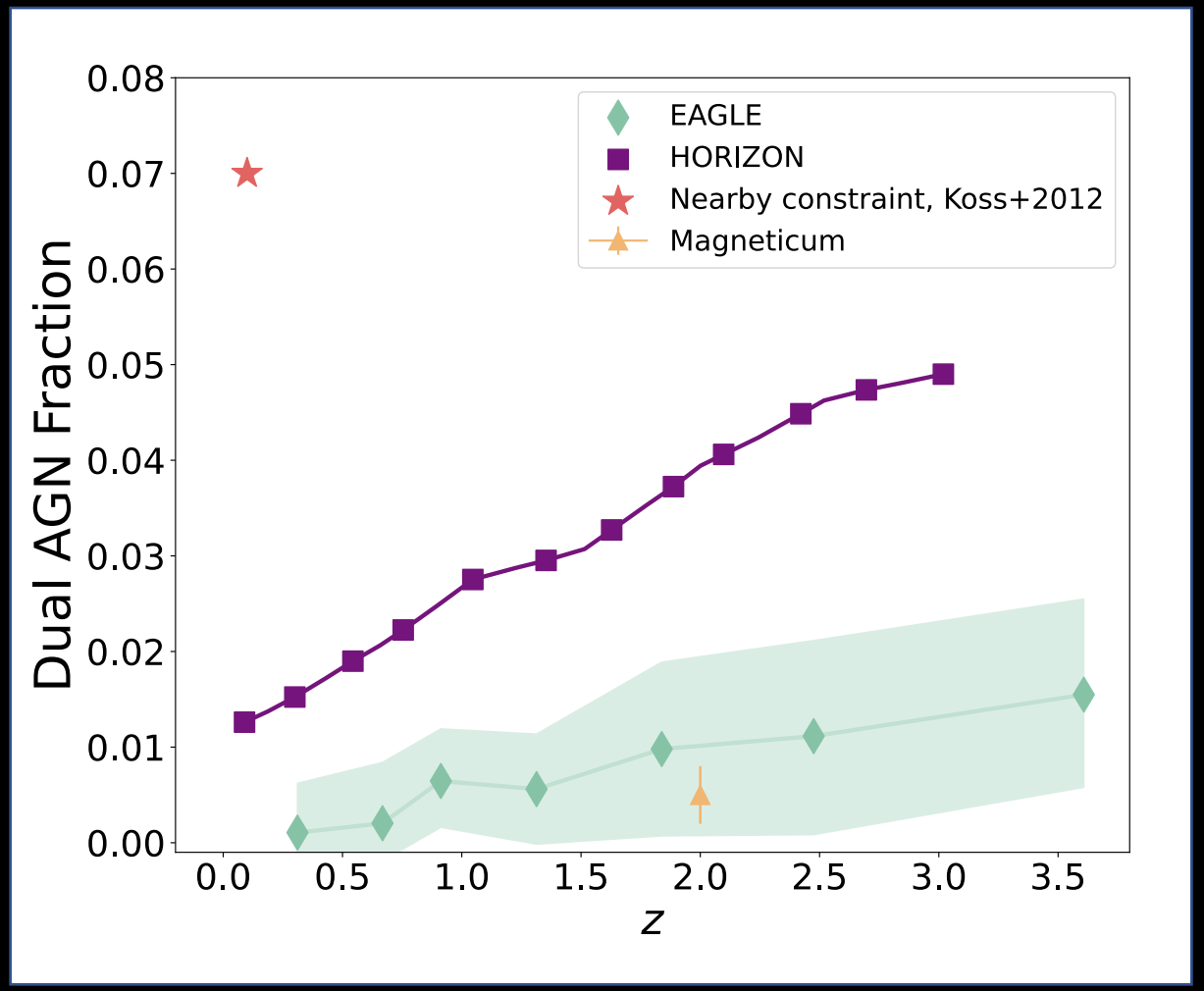
Pre-selection in the mid-IR provides an efficient way to detect dual AGN in late-mergers

Large, systematic, X-ray based surveys are a **necessary** next step to understand how SMBHs grow & evolve

Cosmological simulations predict that the fraction of dual AGN increases with redshift

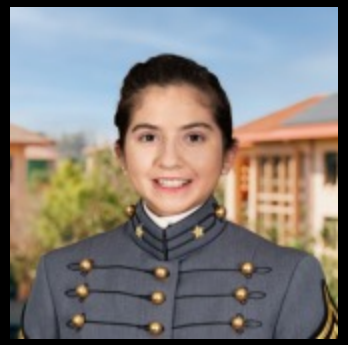
But, there is a mismatch between observations and simulations

There has yet to be a systematic, and observational, analysis of dual AGN:
1) at high-redshift and
2) as a function of redshift

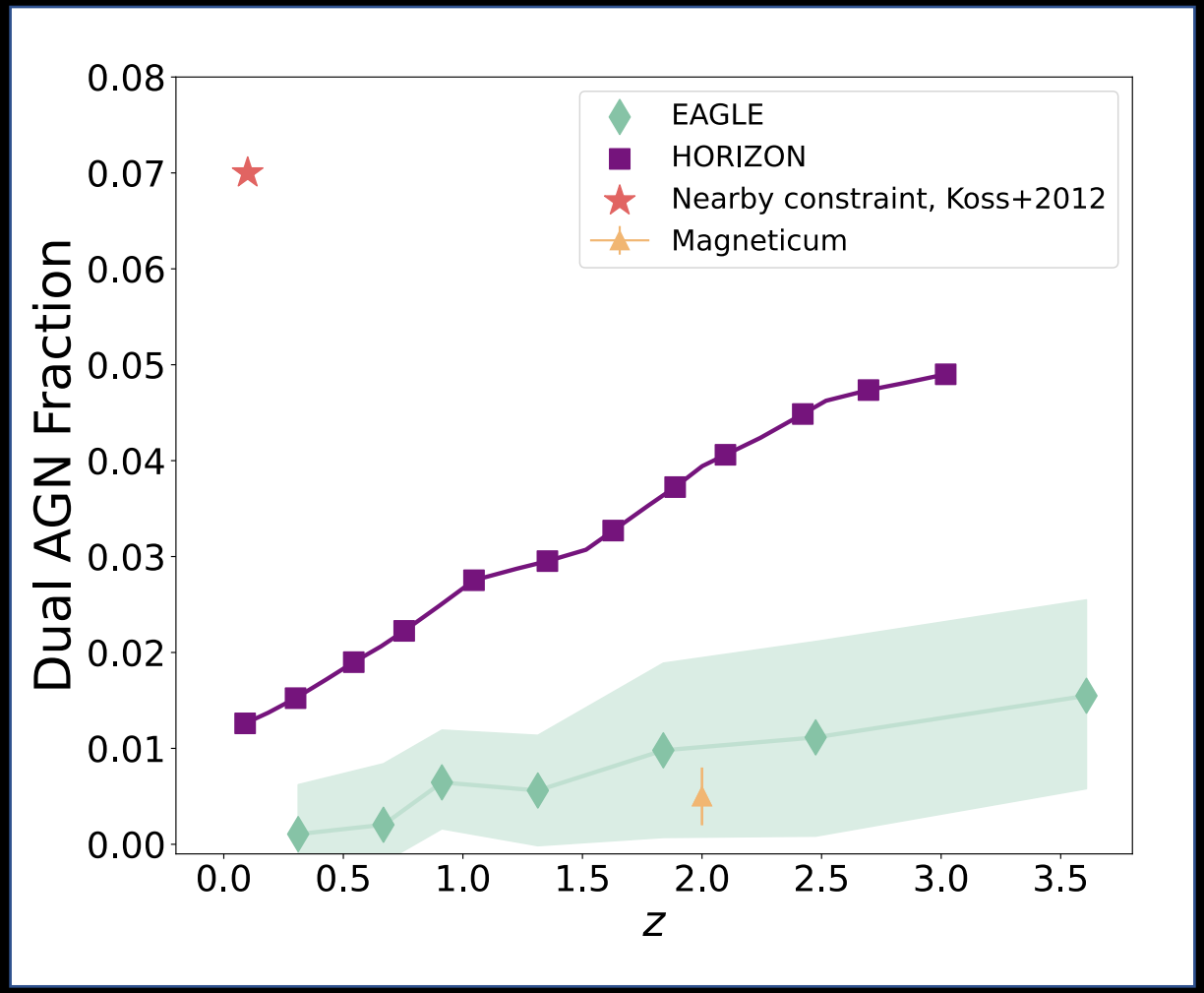


Large, systematic, X-ray based surveys are a **necessary** next step to understand how SMBHs grow & evolve

Brandon Sandoval
Graduate student @ Caltech
$2.5 < z < 3.5$



Kalista Schauer
Master's student @ Stanford
$0.5 < z < 1.0$



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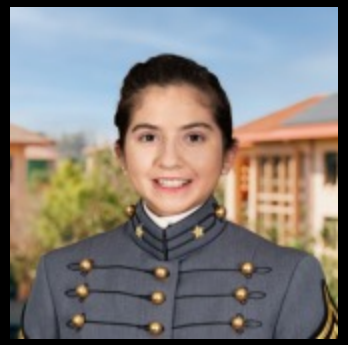

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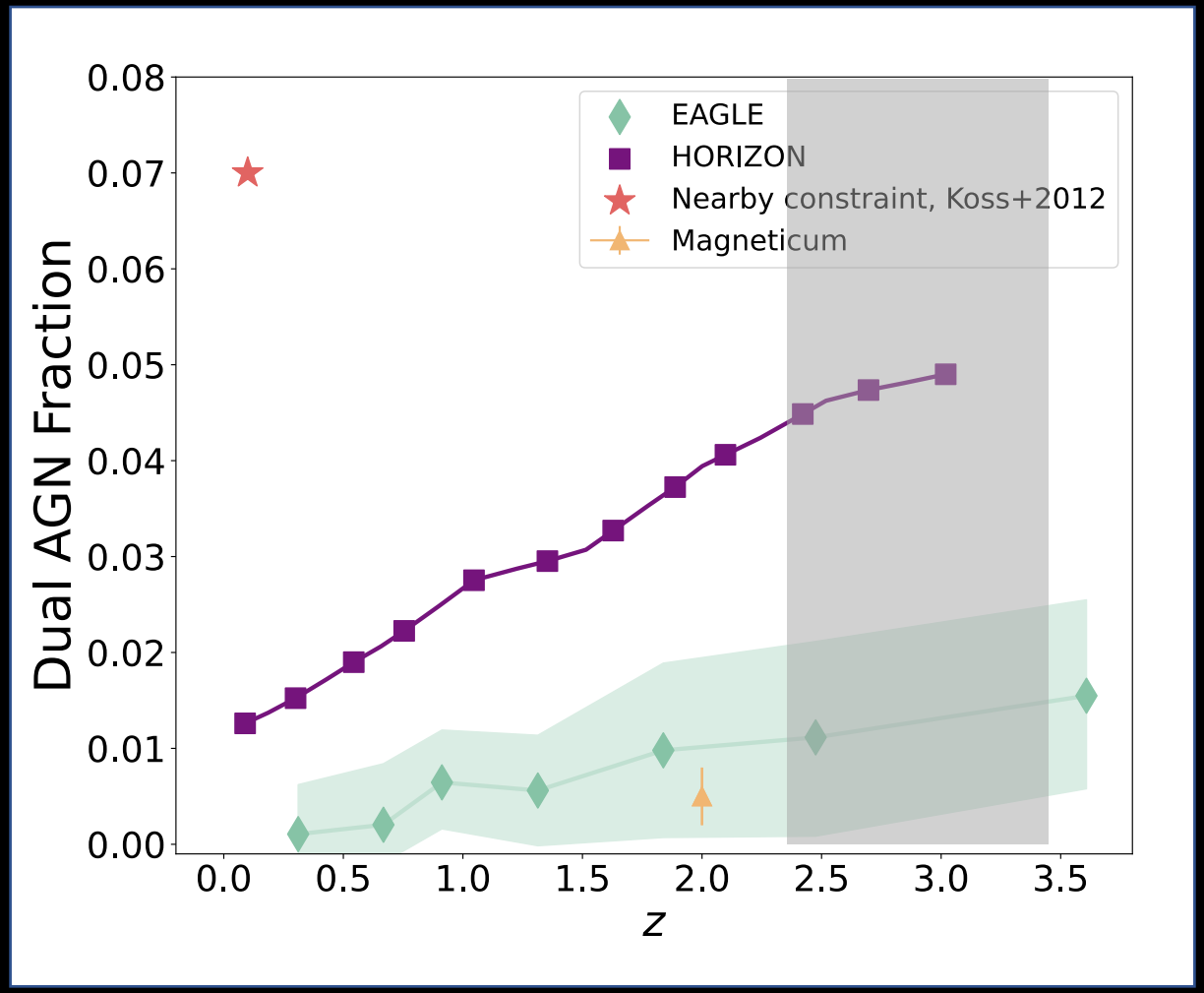


Quantifying the Rate of high-redshift Dual AGN

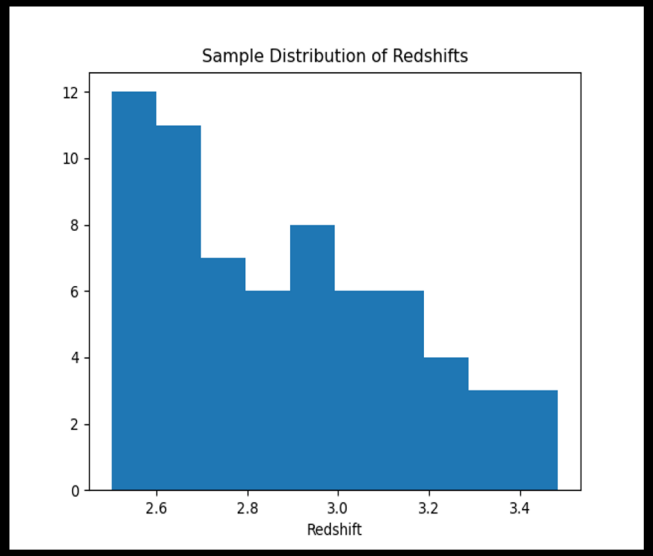
Brandon Sandoval

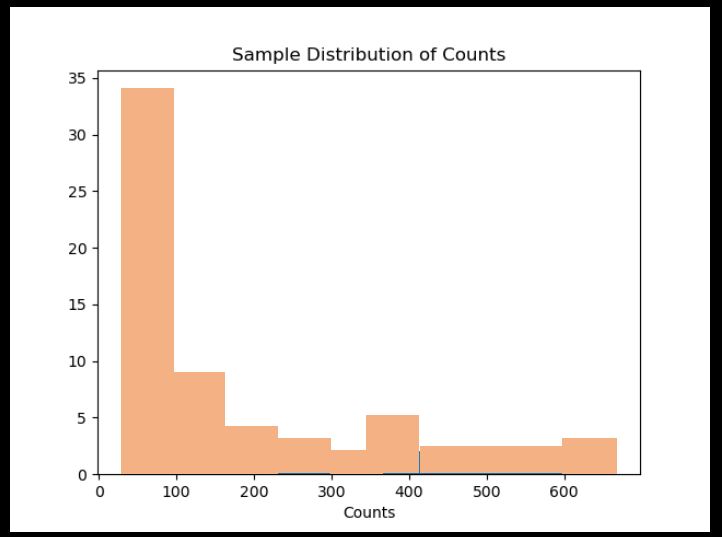
Analyzing AGN from **COSMOS**, **X-UDS**, **AEGIS-XD**, & **CDFS**, we only include observations with:

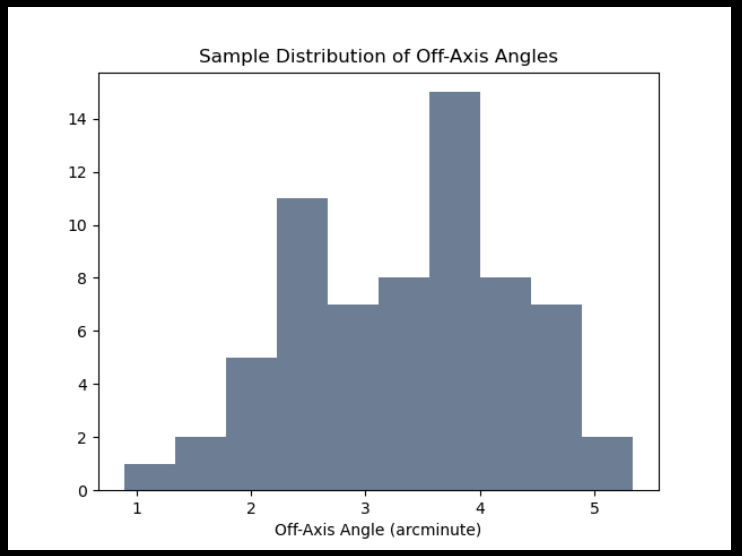
- >50 counts (0.5 – 8 keV, 10^{43} erg/sec for a source at z = 3.5)
- Off axis-angle < 5′,
- 2.5 < z < 3.5

This results in a sample size of **66 sources**

Sandoval, Foord, Allen+2023





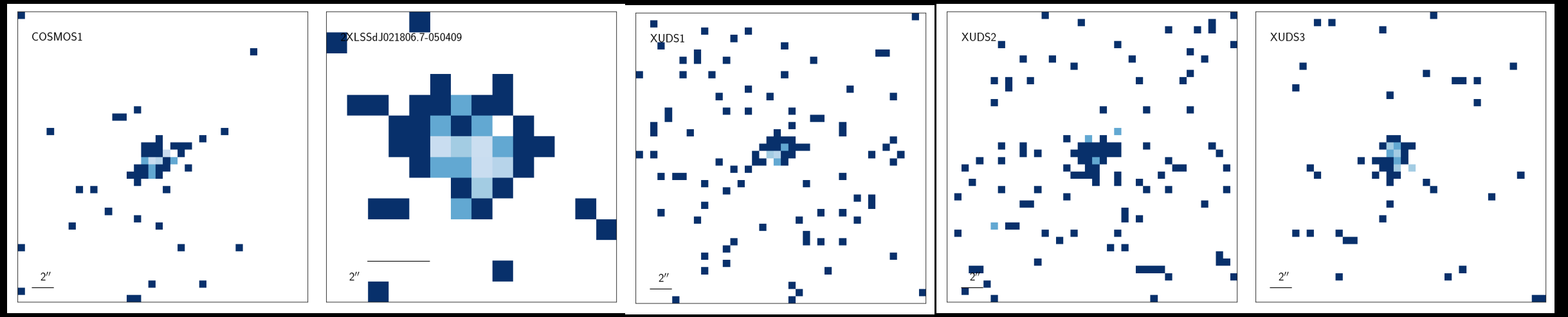


Quantifying the Rate of high-redshift Dual AGN

We find 0/66 sources with significant Bayes factors in favor of the dual point source model!

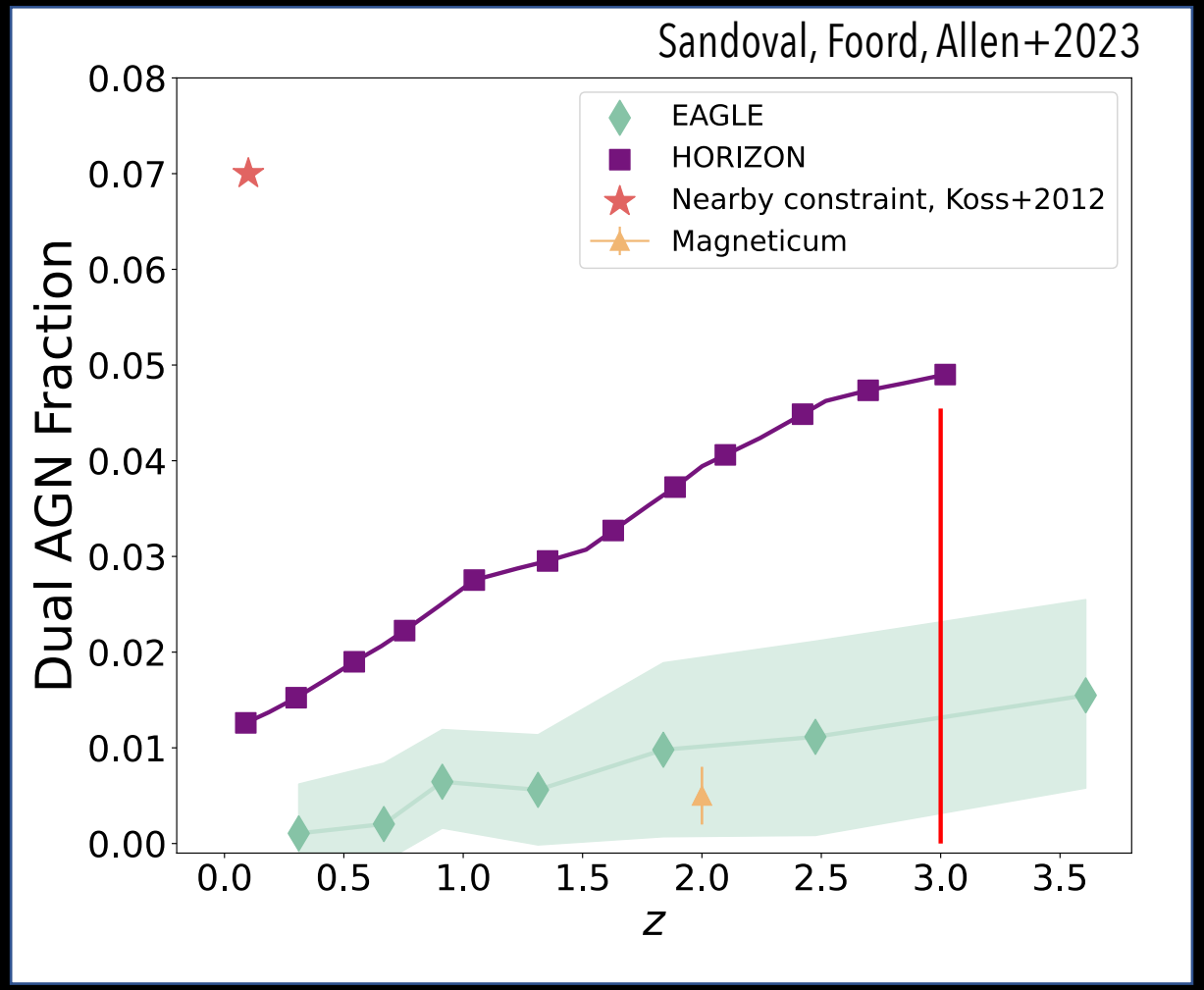
Brandon Sandoval

Sandoval, Foord, Allen+2023



This is likely due to 1) **small sample size**, 2) **low number of counts per source**, 3) **difficulty detecting duals at high OAA**

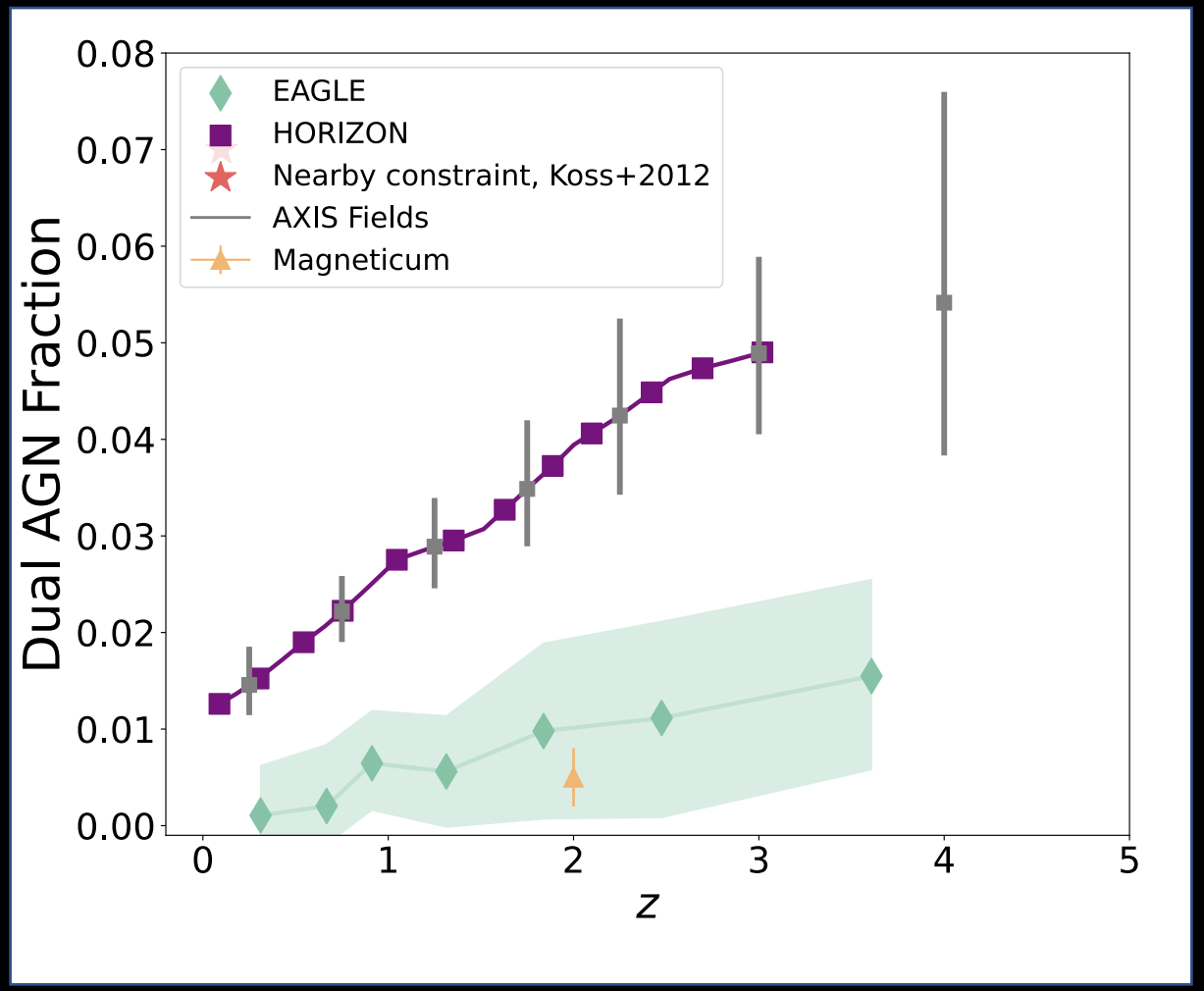
Large, systematic, X-ray based surveys are a **necessary** next step to understand how SMBHs grow & evolve



Future high-resolution, large FOV, X-ray telescopes will find over an order of magnitude more AGN pairs than currently known

AXIS will discover **> an order of magnitude** more AGN pairs than currently capable with Chandra.

With AXIS, we expect to find hundreds to thousands of new dual AGN, allowing for population studies & modeling of dynamical friction merging stage

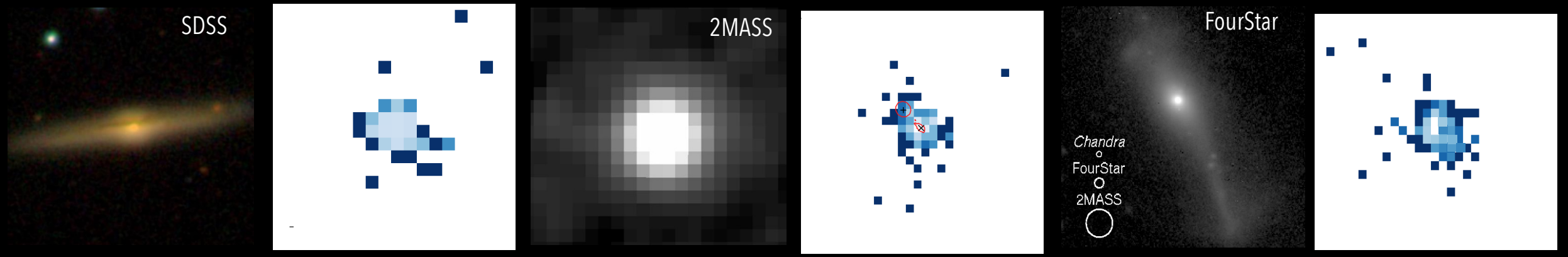


Backup

Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

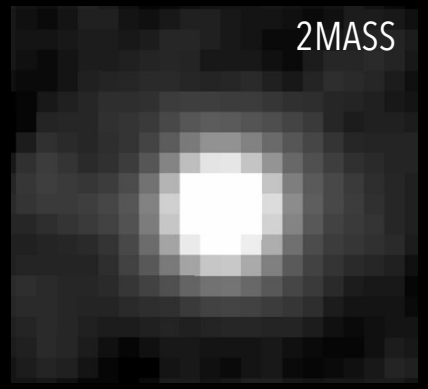
70 nearby ($z<0.037$) AGN to analyze with BAYMAX

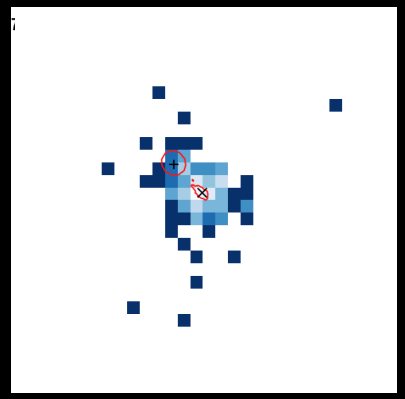
- 20/70 have archival *Chandra* observations
- 50/70 have received new *Chandra* observations



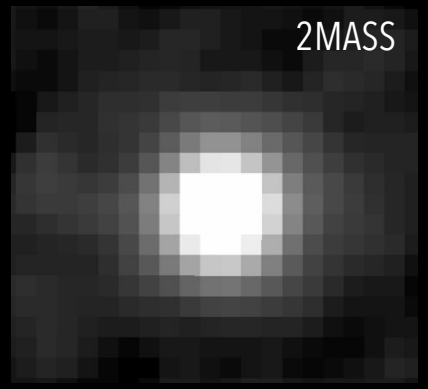
Analyzing this sample with BAYMAX, we are sensitive to dual AGN with physical separations **as small as 14 pc and complete to separations larger than 250 pc**

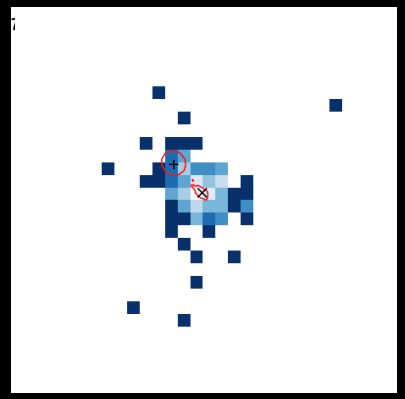
Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

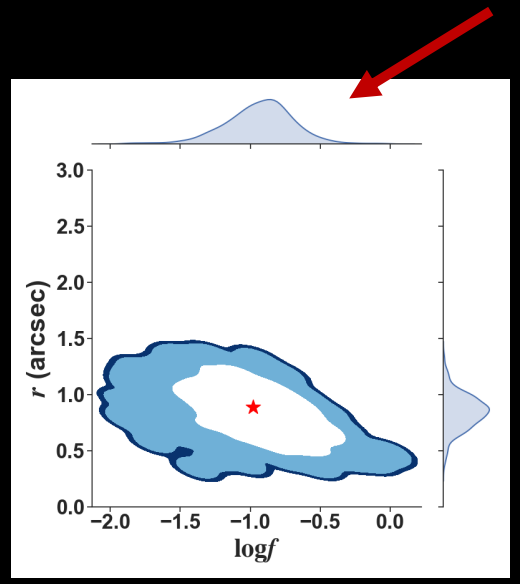




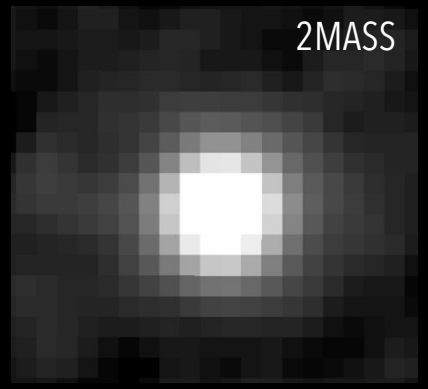
Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

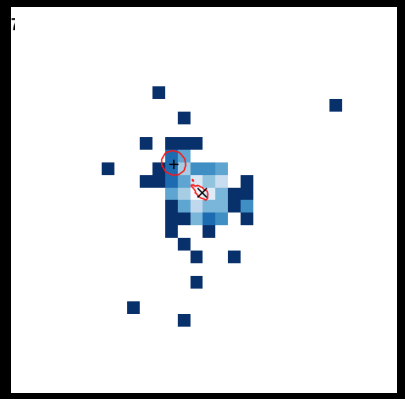


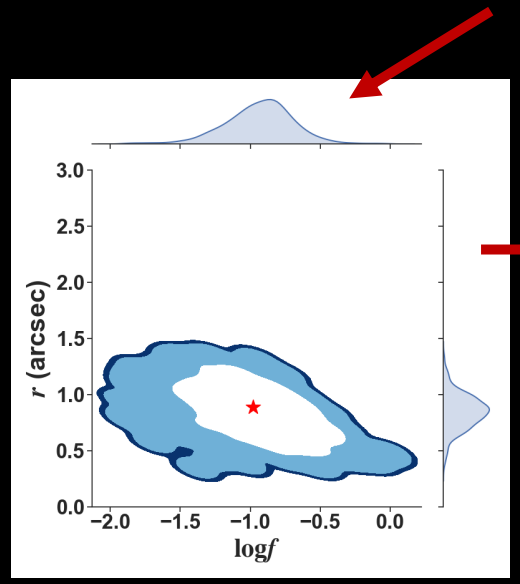


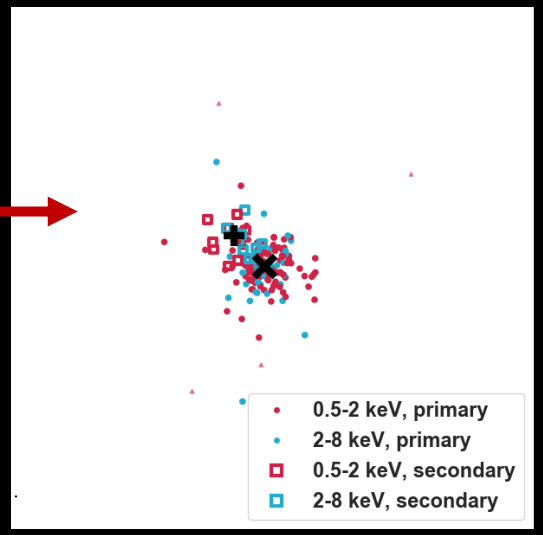


Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

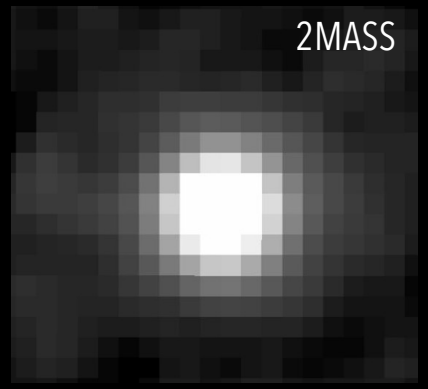


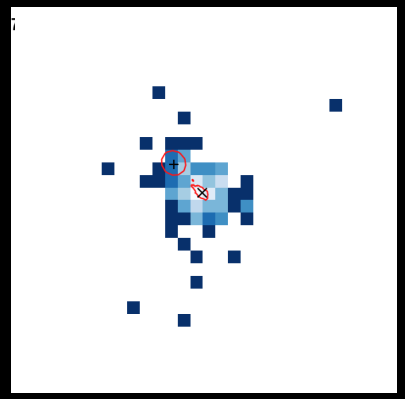


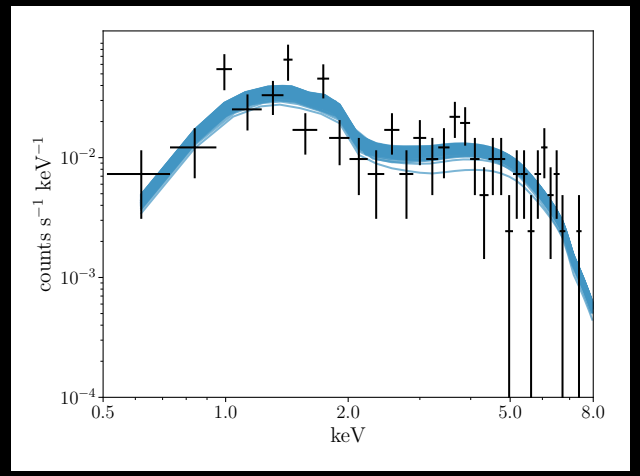




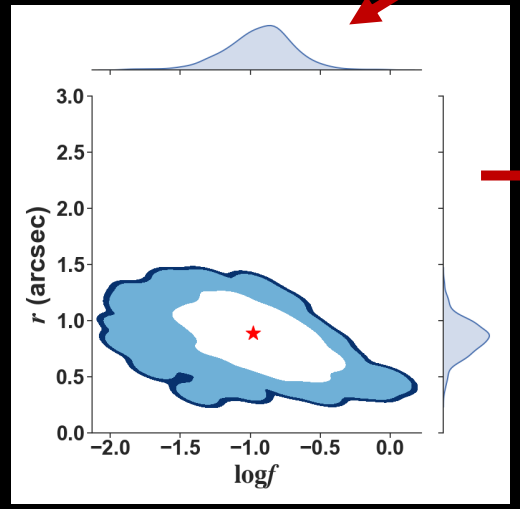
Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

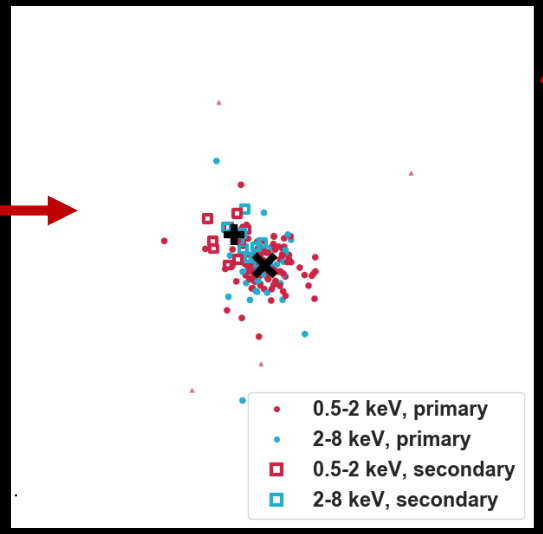


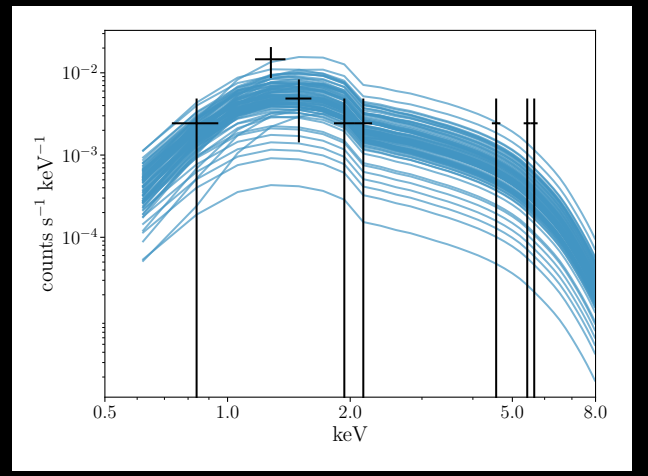




Primary point source
100 spectral realizations

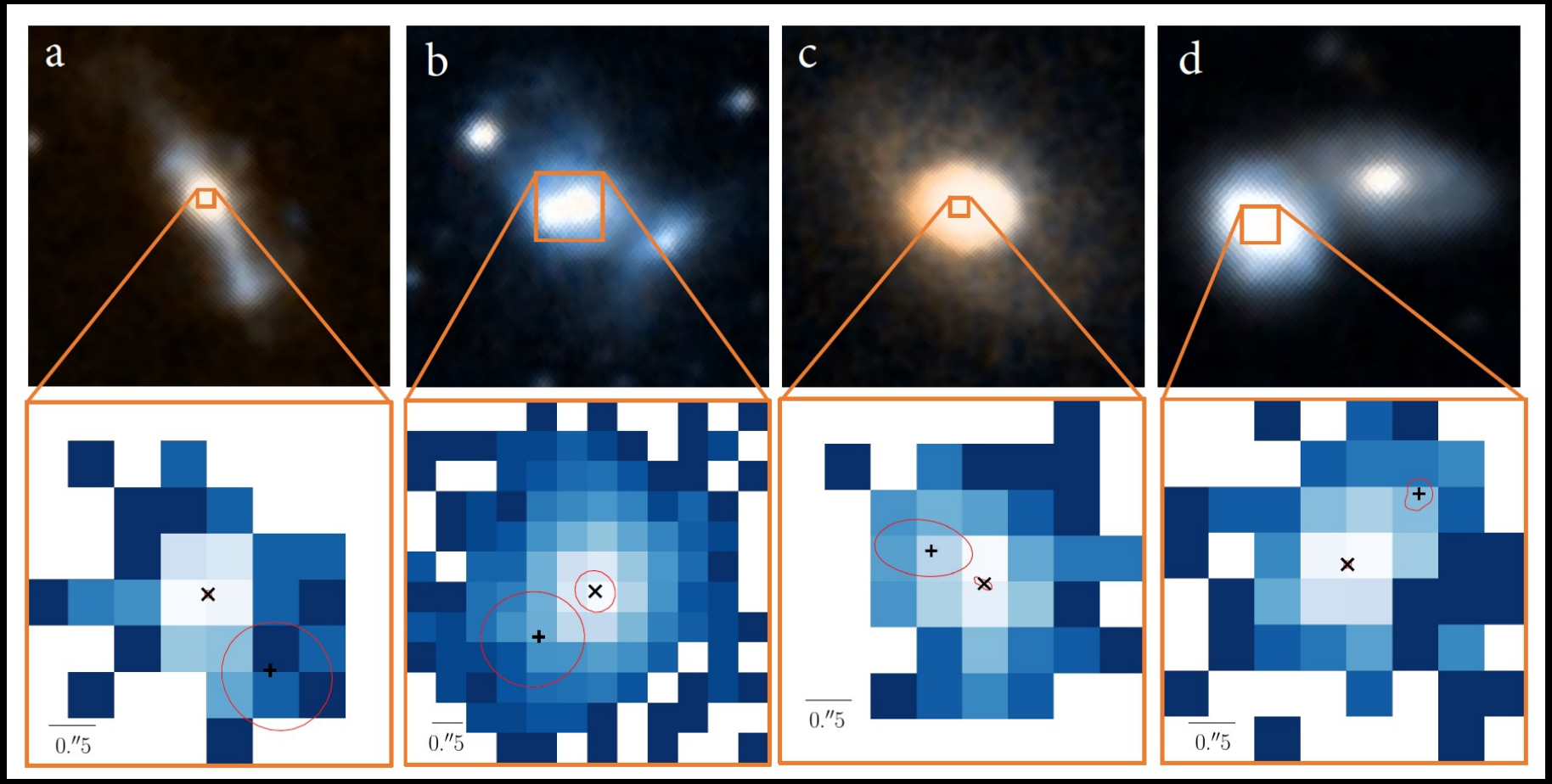






Secondary point source
100 spectral realizations

Quantifying the Rate of Nearby ($z<0.037$) Dual AGN

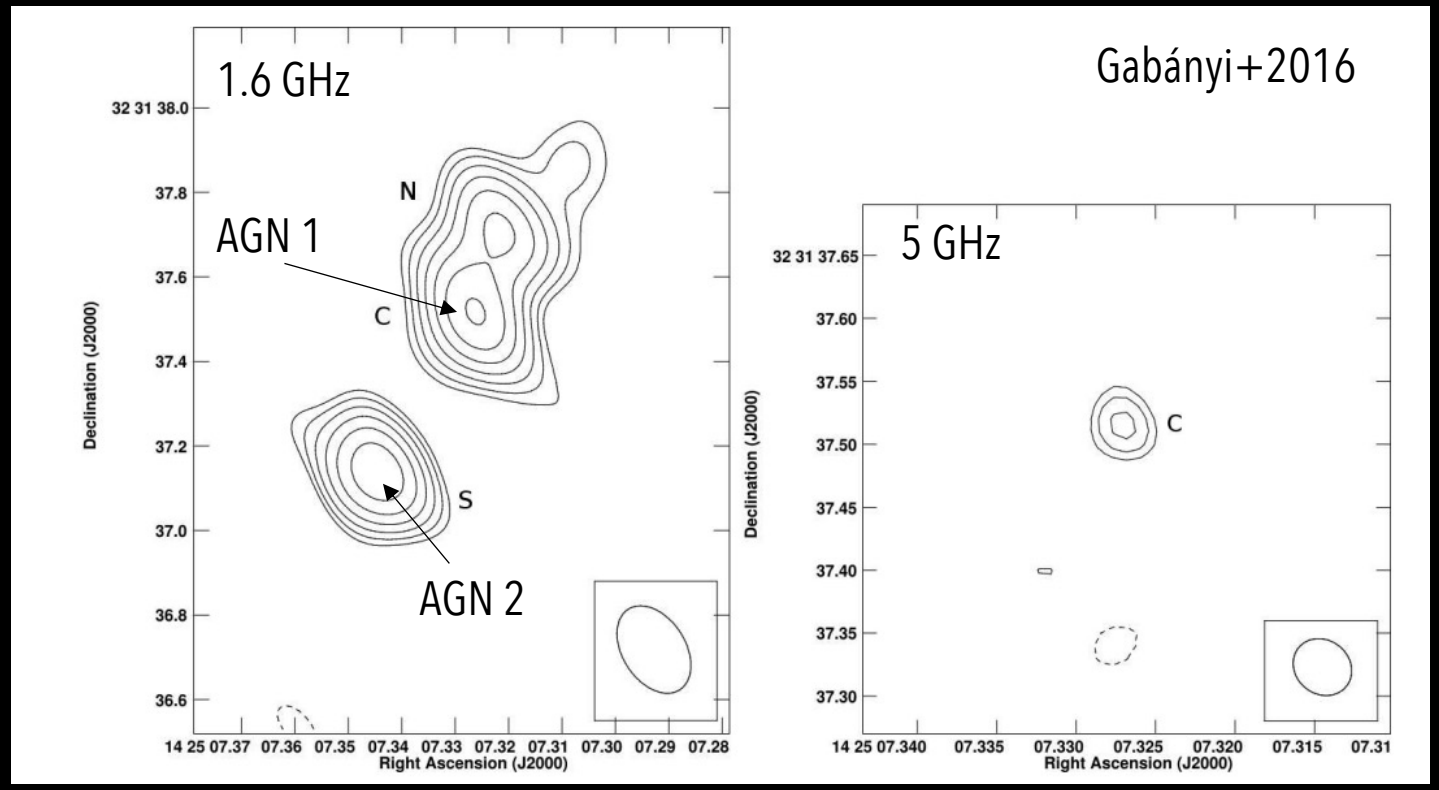


The physical separations between each dual AGN candidate span between 260 - 660 pc, and if confirmed will be some of the most closely separated dual AGN detected to date.

Foord et al. 2023, *in prep*

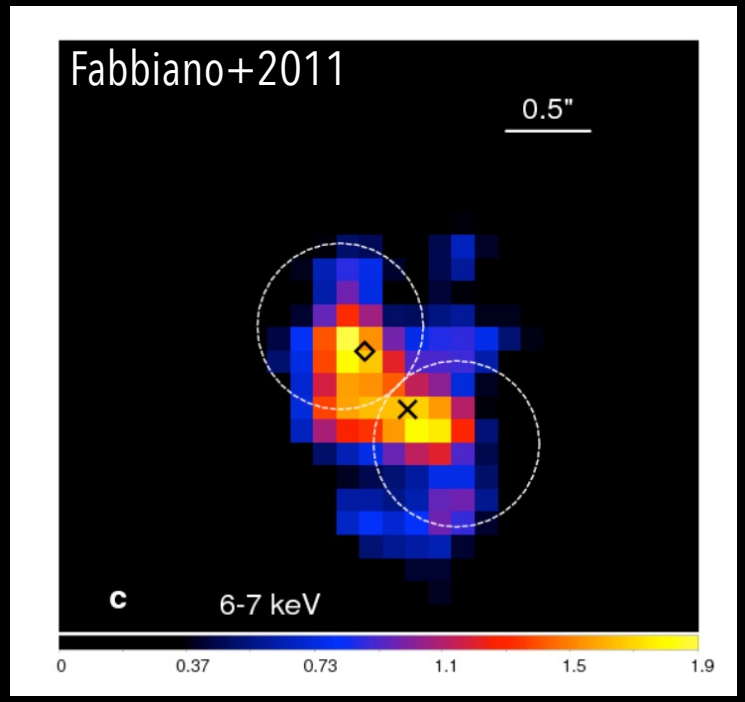
Candidates to direct detection: follow-up is necessary

Directly detecting radio emission from each SMBH is one the best ways to confirm closely separated dual AGN

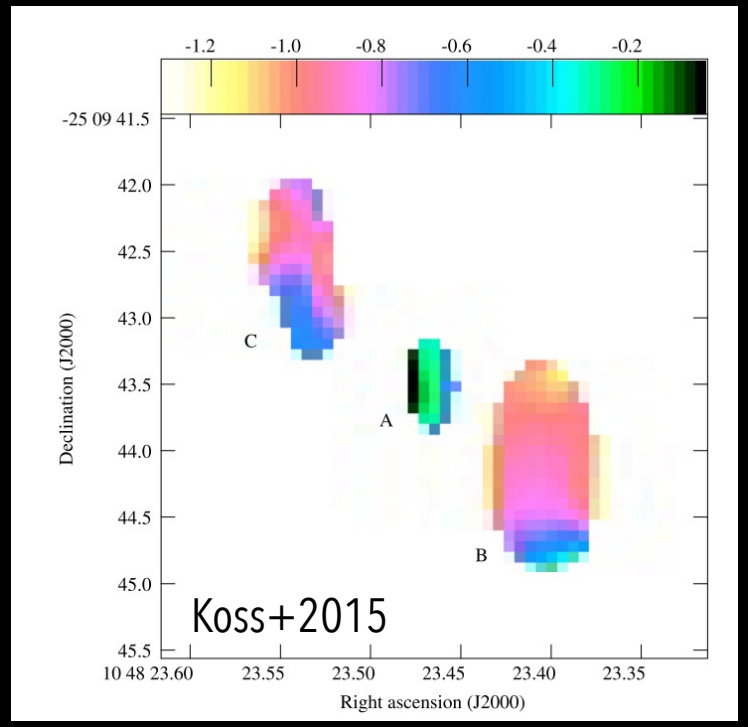


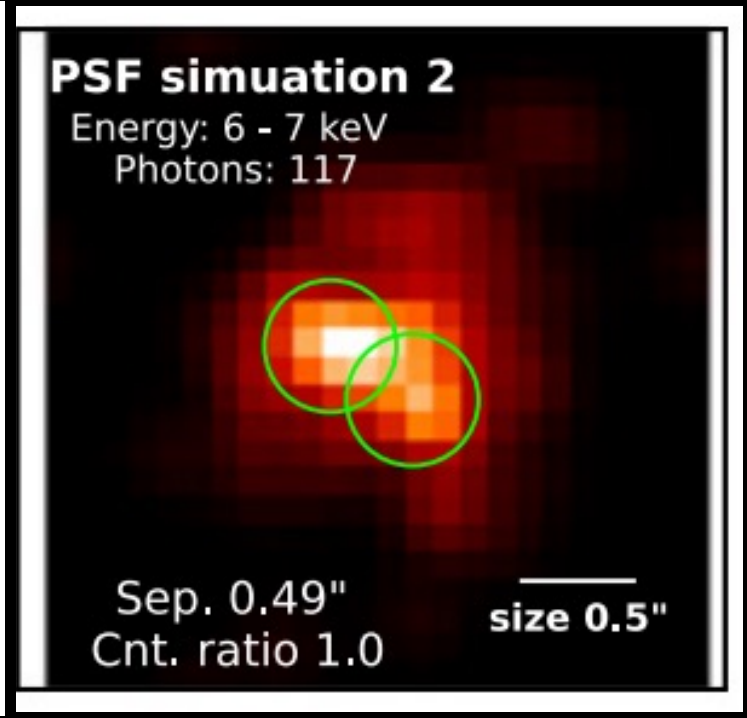
Care must also be taken when conducting only low-resolution or single-frequency measurements, **as AGN are expected to be compact & flat radio sources**

X-rays are great rays to find dual AGN (& high-resolution is the best!)



NGC 3393 (binned and smoothed Chandra data)





Follow-up shows that NGC 3393 has extended radio emission and that binning and smoothing the Chandra PSF can result in a false positive!