The Dynamic Lives of Supermassive Black Holes in Merging Galaxies

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Ample evidence suggests that the evolution of supermassive black holes and their host galaxies is connected, but the physical processes driving this link remain unclear. The role of galaxy mergers in triggering black hole growth and in creating the empirical black hole/galaxy bulge correlations is a matter of particularly active debate. Galaxy mergers are of additional interest as the precursors of supermassive black hole binaries, which may merge and produce powerful gravitational waves. This gravitational wave emission can also eject the merged black hole from its host nucleus, leaving the galaxy without a central black hole and producing an offset ("recoiling") quasar. There has been rapid recent progress from both theory and observations in constraining the merger/AGN connection and identifying signatures of active black hole pairs. I review these findings and discuss ongoing work to address remaining open questions. I also describe the handful of candidate recoiling black holes discovered to date, as well as results from numerical models that indicate promising avenues for identifying a population of such objects in current and future wide-field surveys.

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1. Introduction and Motivation

It is now well established that supermassive black hole (SMBH) masses are correlated with properties of their host galaxies, including stellar bulge mass, luminosity, and velocity dispersion [e.g., 1, 2, 3]. This suggests a physical link between SMBH growth and galaxy evolution on scales much larger than the SMBH sphere of influence. Mergers between galaxies are often invoked as a possible mechanism for driving coordinated growth of SMBHs and their hosts. Galaxy mergers increase the size of stellar bulges through dynamical heating, and they cause gravitational instabilities that can trigger new star formation and rapid fueling of the central SMBH [e.g., 4, 5, 6]. Feedback from star formation and active galactic nuclei (AGN) can in turn influence host galaxy evolution, for example by self-regulating nuclear activity and hastening the galaxy's transition to a "red and dead" elliptical [e.g., 7, 8, 9]

Galaxy mergers also inevitably lead to the formation of SMBH *pairs*, which, if both SMBHs are actively accreting, could be detected as *dual AGN*. These systems are of particular interest, as they provide unambiguous confirmation of an ongoing late-stage galaxy merger and point to highly favorable environments for rapid SMBH accretion. In addition, the SMBHs themselves can later merge, releasing enormous amounts of energy in gravitational waves (GWs). The field of GW astronomy was recently revolutionized by the first ever direct detection of GWs from the merger of two $\sim 30\,M_\odot$ BHs with LIGO [10], opening an entirely new window for exploring the Universe in GWs and providing a spectacular confirmation of general relativity in the strong-field regime. In the coming years, GWs from SMBH binary inspiral and merger could also be detected with pulsar timing arrays (PTAs) or a space-based interferometer such as *eLISA* [e.g., 11, 12].

In a generic merging SMBH system (with unequal masses and spins), the GW emission will be asymmetric. This imparts a "recoil kick" to the merged BH, which can be large enough to eject the BH from the galaxy entirely [e.g., 13, 14]. If actively accreting, recoiling BHs could be detected as AGN that are spatially or kinematically offset from their hosts. These could provide the only evidence of SMBH mergers prior to direct GW detections.

The merger-driven paradigm is by no means a complete picture of SMBH and galaxy evolution. The importance of mergers in triggering AGN and setting the BH-bulge relations is still a matter of active debate, and attempts to quantify the connection between mergers and AGN empirically must overcome significant selection biases. Moreover, evidence for AGN pairs has been notoriously scarce even on large (kpc) scales; until recently only a few serendipitously discovered pairs were known. Much progress has been made in recent years in identifying candidate kpc-scale dual AGN, opening a new window into the merger/AGN connection. The subsequent evolution of SMBH pairs on smaller scales is still somewhat uncertain, however, and while numerous SMBH binary candidates have been identified, none have yet been confirmed. The search for *recoiling* SMBHs is just beginning. Here I review recent progress in understanding merger-driven SMBH evolution, including ongoing efforts to identify signatures of SMBH inspiral, merger and recoil.

2. When Do Mergers Matter?

Numerous studies have demonstrated that the majority of AGN hosts do *not* shows signs of ongoing or recent merger activity, indicating that secular mechanisms are more common triggers of

AGN fueling [e.g., 15, 16]. However, there is strong evidence that merger events do trigger AGN, in agreement with theoretical predictions. In samples of close galaxy pairs, the fraction that host at least one AGN increases with decreasing (projected) pair separation [17, 18, 19]. This is true for AGN selected at optical, hard X-ray, and near-IR wavelengths, and the dual AGN fraction shows an even stronger trend. These results strongly suggest a causal link between galaxy interactions and AGN fueling, where SMBHs are more likely to be active as the strength of the interaction increases.

Quantitatively, however, the empirical relationship between mergers and AGN is strongly influenced by selection effects. The above studies of AGN in galaxy pairs illustrate that the observed AGN fraction depends on merger stage and viewing angle. More importantly, the same merger-induced instabilities that trigger gas inflow to the central SMBH can also trigger bursts of star formation. The copious amounts of dust produced by these starbursts can heavily obscure the nuclear region in ongoing mergers, weakening or masking entirely the signatures of AGN at optical and soft X-ray wavelengths. It has long been known that ultra-luminous infrared galaxies (ULIRGs), in which the bulk of emission is reprocessed by dust, commonly show signs of ongoing merger activity and contain obscured quasars [Figure 1; e.g., 20, 21]. In addition, a recent study of X-ray selected AGN found a correlation between the degree of AGN obscuration (column density) and the host merger fraction [22]. The most heavily obscured (Compton-thick) AGN have column densities $N_H > 10^{24}$ cm^2 that attenuate even hard X-ray emission; studies indicate that Compton-thick AGN may comprise a significant fraction ($\sim$ 30 - 50%) of all AGN [e.g., 23, 24].

These empirical findings are well-supported by hydrodynamic simulations of galaxy mergers, which demonstrate that an obscured quasar phase should be generic to major, gas-rich mergers [e.g., 25, 26, 27]. Specifically, the peak obscuring column density and AGN luminosity should both occur during or shortly after the galaxies' final coalescence (Figure 2).

Figure 1: *Hubble Space Telescope* (*HST*) image of NGC 6240, a well-known ULIRG in the late stages of a major merger. *Chandra* observations have revealed two AGN in the nucleus that are separated by about a kpc; they are completely obscured at optical wavelengths [28]. Image credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University).

The clear implication is that the fraction of merger-triggered AGN is likely to be underestimated in many surveys, because they are preferentially obscured. Indeed, when selected via near-IR signatures of AGN-heated dust (using data from the *Wide-field Infrared Survey Explorer, WISE*), AGN are found in a substantially higher fraction of merging galaxies than when optical selection is used [19]. A similar result is obtained for ultra-hard X-ray selected AGN; [29] found that 25% of their *Swift*-BAT (14-195 keV) AGN sample are in apparent mergers, versus 4% of AGN in a comparison sample selected via optical emission line diagnostics.

The prediction that late-stage mergers often produce luminous quasars is supported by observations. Specifically, the fraction of AGN hosted in apparent mergers is a strong function of AGN luminosity. At the highest quasar luminosities (bolometric luminosity $L_{bol} \gtrsim 10^{45-46}$ erg s^{-1}), *most* AGN are hosted in major mergers [e.g., 30, 31]. Consequently, even though the majority of AGN by number are triggered by secular processes, merger-induced fueling is thought to dominate AGN population by luminosity and mass density [e.g., 32, 33, 34]. This suggests that mergers play a crucial role in setting the SMBH mass function and SMBH-bulge relations.
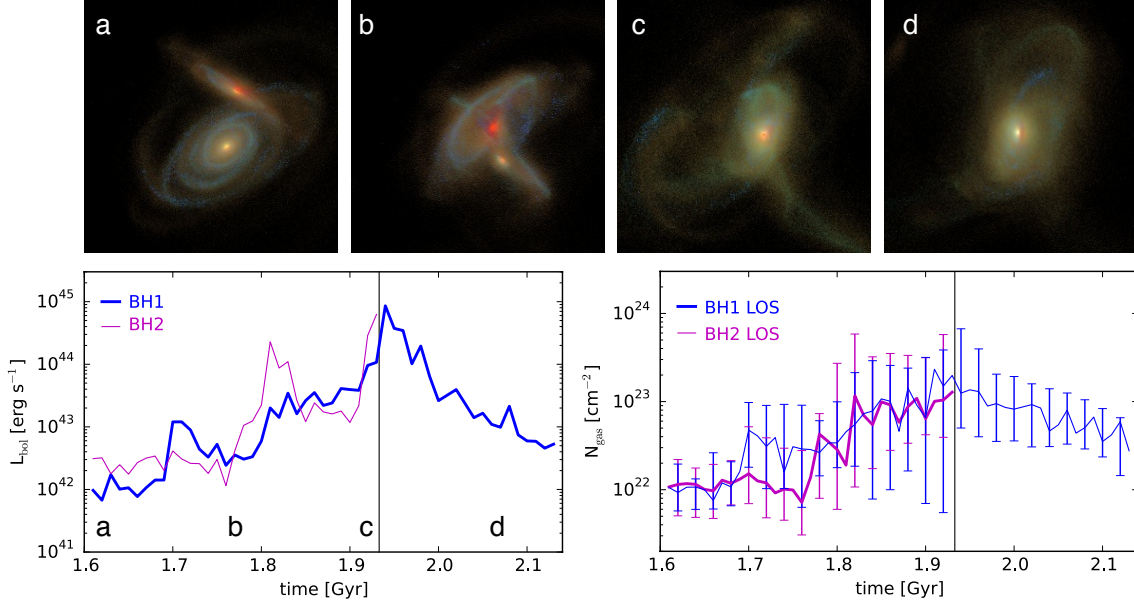

Figure 2: An illustrative simulated example of an obscured, luminous AGN pair triggered by a major merger. *Top panels:* Mock SDSS *ugz* snapshots of a gas-rich major galaxy merger (from SUNRISE radiative transfer applied to GADGET hydrodynamic simulation data). *Bottom panels:* For the same simulation, the evolution of AGN L_{bol} and total gas column density (N_{gas}) along selected sight lines to each BH. The error bars show the spread in N_{gas} over 7 viewing angles. The solid vertical line corresponds to the time of SMBH merger. The time of peak column density and peak AGN activity are clearly correlated, supporting the notion that obscured, luminous AGN are a natural occurrence in late-stage mergers.

3. Dynamics and Observable Signatures of SMBH Pairs

3.1 Kiloparsec-scale Dual AGN

Pairs of AGN can provide unique insight into merger-triggered fueling. As mentioned above, the fraction of galaxy pairs in which *both* galaxies host an AGN is a strong function of their physical separation, more so than for single AGN. These close AGN pairs are unambiguous tracers of late-stage galaxy mergers, and the fact that both SMBHs are simultaneously active suggests that the nuclear environment in the merging system contains near-ideal conditions for rapid SMBH fueling.

The AGN pair in NGC 6240 [Figure 1; 28] was among the first to be identified on scales of $\lesssim 10$ kpc, but further detections of close, spatially-resolved AGN pairs have been scarce [e.g., 35, 36]. As an alternate approach, several studies have focused on AGN with double-peaked narrow

[OIII] emission line profiles [37, 38, 39]. This signature can be produced by the orbital motion of a kpc-scale SMBH pair, each with its own narrow line (NL) region. With these double-peaked NL AGN samples, the number of candidate dual AGN increased from a handful to several hundred.

However, double-peaked NL profiles can often be produced in single AGN systems, if for example the gas kinematics is dominated by outflowing winds or orbital motion in a clumpy or partially-obscured disk. Detailed follow-up is therefore required to confirm the presence of an AGN pair. In particular, systems in which two nuclei can be identified in both high-resolution imaging and resolved spectroscopy are strong dual AGN candidates (Figure 3). Follow-up studies indicate that at least 10 - 20% of double-peaked NL AGN are likely to be duals [e.g., 40, 41, 42]. In some cases, the dual AGN nature of these candidates has been confirmed by the detection of dual X-ray or flat-spectrum radio sources [e.g., 43, 44, 45].
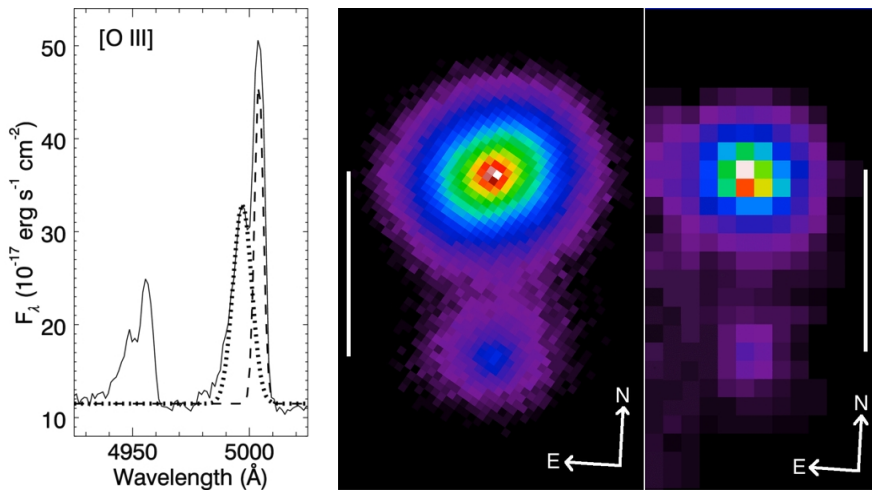

Figure 3: [From 46, Figs. 1 & 3]. Example of an AGN pair (4.8 kpc separation) in SDSS J0952+2552, which was initially selected as a double-peaked NL AGN. *Left:* the [OIII] $\lambda 4959$ and [OIII] $\lambda 5008$ profiles, exhibiting clear double peaks. *Middle & right:* Keck AO *H*-band imaging of the system with NIRC2 and OSIRIS, respectively (the OSIRIS image show the integrated flux in each spatial pixel). Both images reveal two spatially well-resolved components, corresponding to the dual AGN host galaxies.

The nature of many double-peaked NL AGN is still ambiguous, however. In order to better understand connection between double-peaked NL AGN and dual SMBHs, [47] developed a prescription for tracing NL gas kinematics in high-resolution hydrodynamic simulations of galaxy mergers. They find that double-peaked NL AGN are a generic but short-lived feature of gas-rich major mergers (Figure 4). Even within the kpc-scale phase of SMBH pair evolution, only a minority of double-peaked NL profiles are found to directly result from relative motion of the SMBHs. Most double-peaked NLs arise from gas kinematics in the dynamic merger environment. However, in many such cases the dual SMBH motion still influences NL profile. In [47] we identify some additional signatures, including large velocity separation or overall velocity shifts, that may point to the presence of an SMBH pair.

Biconical outflows are another important mechanism for producing double-peaked NL profiles around single AGN in isolated galaxies. Indeed, resolved spectroscopy of many double-peaked NL AGN reveals spatially extended emission, which likely signals the presence of outflowing winds
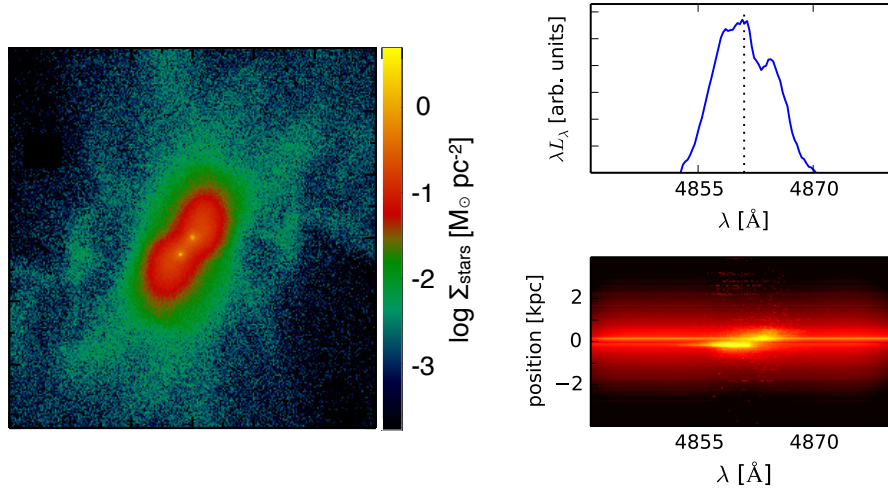
Figure 4: *Left:* From [47]. Example of a simulated AGN pair (2.3 kpc separation) in which orbital SMBH motion produces double-peaked NLs. The stellar density of the host galaxies is shown 20 Myr prior to the SMBH merger, in a hydrodynamic galaxy merger simulation with the GADGET-3 code [48, 49]. *Top right:* double-peaked narrow Hβ profile produced by a kpc-scale AGN pair, generated with the SUNRISE dust radiative transfer code [50, 51] from the simulations of [47]. The dotted line indicates the rest frame. *Bottom right:* same, but for a resolved "slit" spectrum. Two emission components well-separated in velocity and physical space are apparent, indicating that the double-peaked profile is produced by the dual SMBH.

[42, 52]. Roughly a third of these appear to be associated with kpc-scale radio jets [45]. These systems are interesting in their own right, as they present an opportunity to study the detailed kinematics and energetics of AGN feedback on sub-galactic scales. Moreover, although dual SMBHs account for only a minority of double-peaked NL AGN, these spectroscopically-selected samples have nonetheless greatly increased the number of known dual AGN.

3.2 SMBH Binaries

Below kpc scales, a SMBH pair inspirals via dynamical friction until it forms a gravitationally-bound binary at separations of a few parsec. Spatially resolving such binaries in the nearby Universe is possible with very long baseline interferometry (VLBI). However, only one such system is known: the galaxy 0402+379 has two compact radio cores separated by 7pc [53]. A subsequent search of > 3000 objects with archival VLBI data yielded no further candidates, suggesting that binary radio-loud AGN are rare [54].

It is unclear whether the lack of observed binaries is primarily due to the difficulty in resolving them, or whether it indicates that they are short lived. The predicted timescales for SMBH binary inspiral depend strongly on environment. These range from a few Myr if the inspiral is driven by a cold, massive circumnuclear disk [e.g., 55, 56] to more than a Hubble time in gas-poor stellar cores, where the supply of gas and stars capable of driving inspiral may be depleted [the "final parsec problem"; e.g., 57, 58]. A cold gas reservoir is not required to evolve SMBH binaries beyond the parsec scale, however. If the stellar distribution is even slightly triaxial, low angular momentum stars will be continuously supplied to the galactic nucleus, where they can interact with the SMBH binary. And while simulating binary inspiral down to the GW-driven regime ($\sim$ milliparsec scales)

is still quite computationally challenging, recent work indicates that in most galactic nuclei, stellar dynamical processes should be capable of evolving SMBH binaries well past the "final parsec" in much less than a Hubble time [e.g., 59, 60, 61].

Spatially resolving sub-parsec binaries is essentially impossible with current instruments, but at ∼ milliparsec separations, periodic signatures in the light curve or SED that arise from the binary orbit could be observed on human timescales. No such binaries have yet been robustly confirmed, but a number of intriguing candidates have been identified [e.g., 62, 63, 64, 65, 66, 67]. Continued monitoring is needed to reveal which, if any, of these are binary SMBHs.

4. Gravitational-Wave Recoil

4.1 Physical Mechanism and Predicted Signatures

SMBH binary inspiral and merger events are extremely powerful GW sources. Pulsar timing arrays (PTAs) could detect GWs from individual massive ($> 10^9$ M$_\odot$) SMBH binaries at low redshift ($z \lesssim 1$), and in the coming years they may detect the stochastic background of GWs from SMBH binaries [e.g., 68]. Current constraints on the GW background from PTAs are already beginning to place interesting limits on theoretical models of SMBH inspiral [e.g., 69]. In the future, a space-based interferometer such as eLISA could detect GWs from lower-mass SMBH merger events ($\sim 10^5$ - 10^6 M$_\odot$) at redshifts as large as ~ 20 [e.g., 12].

Because merging SMBHs will generally have unequal masses and spins, the GWs are radiated asymmetrically. The resulting net linear momentum flux from the system imparts a "recoil kick" to the merged SMBH at the moment of merger [70, 71]. Numerical relativity simulations indicate that these kicks may be up to ~ 5000 km s^{-1} in some cases, far greater than galactic escape speeds [14, 72]. While such extreme kicks should be exceedingly rare, even much smaller kicks would be astrophysically interesting. If the BHs are rapidly spinning ($a = 0.9$) and their spins are randomly oriented, $\sim 1/3$ of kicks will be > 500 km s^{-1}. However, the kick velocity depends strongly on the SMBH spins just before merger, which are unknown. Theoretical work suggests that if the SMBHs are embedded in a circumnuclear gas disk, torques from the disk can align their spins with each other and with the disk angular momentum [73, 74, 75]. If the spins are perfectly aligned, the maximum recoil kick is < 200 km s^{-1}. The efficiency of this process in real systems is not known; near-alignment of SMBH spins may be difficult to avoid if the binary inspiral is gas-driven, but little to no alignment may occur in cases where the inspiral is driven by stellar dynamics.

Gas dynamics can also have a large effect on the recoiling SMBH trajectory. In gas-rich galaxy mergers, cold gas inflow creates a steep potential well in the galactic nucleus during coalescence. This can efficiently prevent recoiling SMBHs from leaving the nuclear region, and gas dynamical friction further damps their orbital motion [76, 77, 78]. The outcome of a given recoil event therefore depends sensitively on the rapidly-varying galactic merger environment, in addition to the SMBH masses and spins.

If the SMBH has an accretion disk at the time of the kick, recoiling SMBHs could be detected as "AGN" that are spatially or kinematically offset from the actual galactic nucleus. These "offset AGN" may have substantial lifetimes, up to ~ 100 Myr, for a wide range in kick speeds [79, 76]. Velocity offsets could be detected as shifted broad emission lines (BLs) in the AGN SED; the BL

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region will remain bound to the recoiling SMBH, while gas at larger radii (including the NL region) will be left behind. A confirmed detection of a recoiling AGN would provide evidence of a recent SMBH merger, the only such evidence that will be available without direct detection of GWs.

4.2 Recoiling AGN Candidates

Several candidate recoiling AGN have been identified in the last few years, though none have yet been confirmed [e.g., 80, 81, 82, 83, 84]. One of the most promising candidates, CID-42, is in a morphologically disturbed galaxy containing two optical nuclei separated by 2.5 kpc. These nuclei were initially proposed to be an inspiraling AGN pair [85]. However, a spectrum later revealed a 1300 km s^{-1} offset between the broad and narrow Hβ lines, suggesting that one of the nuclei instead corresponds to an recoiling AGN with a kinematic *and* spatial offset [83]. In this scenario, the other optical nucleus is simply the "empty" stellar cusp left behind. X-ray and radio data confirms that only one of these optical nuclei is producing AGN signatures [86, 87]. Theoretical modeling of this system also supports the recoil scenario, though it is difficult to rule out the presence of a quiescent SMBH in the secondary nucleus [88].

Another recoil candidate, SDSS 1133, is a bright point source offset by 800 pc from a nearby dwarf galaxy. The object is detected over a 65-year baseline and has an AGN-like spectrum with broad and narrow emission lines [84]. It is not yet possible to exclude an alternate scenario in which a long duration ($\sim$ 50-year) luminous blue variable outburst was followed by an extremely long-lived Type IIn supernova, but in either case it is clear that SDSS 1133 is a highly unusual object without precedent. Further monitoring of this source should be able to distinguish between these scenarios in the near future.

4.3 Toward Systematic Searches for Recoiling SMBHs

The discoveries of recoiling AGN candidates to date have been mostly serendipitous; systematic searches have been hampered by large uncertainties. A few searches for velocity-offset quasars in SDSS spectra have been carried out, however [89, 63, 64]. [89] searched the DR5 quasar catalog for velocity shifts in multiple BLs and found a null result for $\Delta v > 800$ km s^{-1}. [63] and [64] searched for offset broad Hβ lines in DR7 using slightly different selection criteria and found 32 and 88 velocity-offset quasars, respectively. Most of these are likely to be double-peaked emitters, high-velocity outflows, or a subparsec *binary* SMBH in which only one SMBH is active. Thus, it is clear that recoiling AGN with large velocity offsets are rare among SDSS quasars.

Spatially-offset AGN are largely unexplored thus far. Very small offsets (< 10 pc) have been found between the AGN and the host centroid in 6 of 14 core ellipticals, including M87 [82, 90]. However, the presence of a radio jet aligned with the displacement axis in four of these objects argues against GW recoil as an explanation. No searches have yet been carried out for recoiling AGN with larger spatial offsets.

In order to design targeted searches for offset AGN, better theoretical constraints on their observability are needed. [92] used semi-analytic merger tree models to predict the number of spatially-offset AGN that could be detected in surveys with *HST*, *Chandra*, and the *James Webb Space Telescope* (*JWST*). They predicted up to tens of offset AGN per square degree in the most optimistic case. However, as discussed above, gas dynamical effects can be very important in determining the outcome of recoil events.
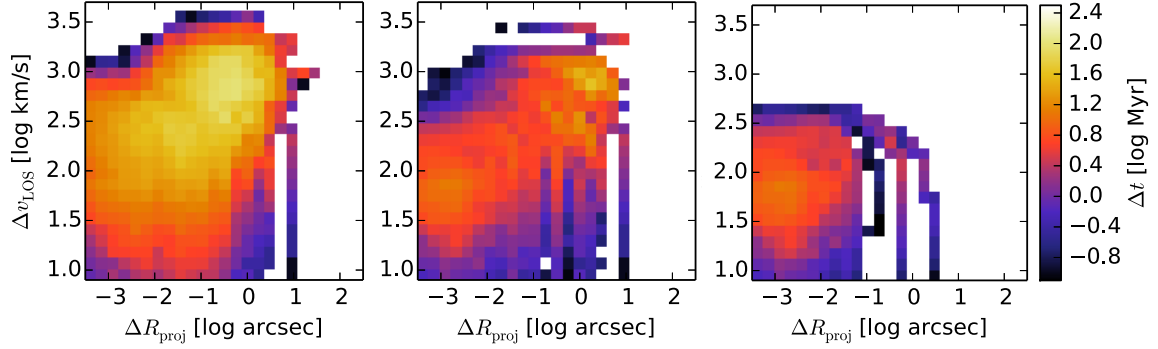
Figure 5: Time-weighted distributions of projected spatial offsets versus line-of-sight velocity offsets for recoiling AGN. The color scale indicates the amount of time a BH spends at a given (ΔR_{proj}, Δv_{LOS}) while actively fueled and offset from the host nucleus, integrated over all merger events, *regardless* of whether the event produces a resolvable offset. The sensitivity of *HST*-COSMOS is assumed. The *left panel* corresponds to a randomly-oriented spin model, the *right panel* assumes nearly-aligned spins, and the *middle panel* shows a hybrid model in which spin alignment occurs only in gas-rich mergers. Larger offsets are *favored* in the random and hybrid spin models but do not occur at all if BH spins are nearly aligned. From [91].

To this end, [91] have recently conducted a study of recoiling AGN that accounts for the effects of gas, using data from the Illustris cosmological hydrodynamic simulation [e.g., 93, 94, 95, 96]; this large-volume, high-resolution simulation was carried out with the moving-mesh hydrodynamics code AREPO [97]. After extracting SMBH merger events and host galaxy properties from the simulation, a model for recoiling AGN was implemented in post-processing, including BH spin alignment and recoil dynamics based on the gas-richness of host galaxies.

Figure 5 shows the time-weighted distributions of spatial and velocity offsets for recoiling AGN over cosmic time, based on the models of [91]. If SMBH spins are *always* aligned to within a few degrees, recoils are unlikely to be detected. In less extreme models of spin alignment, the distribution is dominated by large offsets, in part because kick velocities near the host escape speed yield the longest observable offset lifetimes. Crucially, this means that even seeing-limited observations could resolve spatially-offset AGN, making them promising targets for large-area surveys. In the most optimistic models, where spins are always randomly oriented, nearly a thousand velocity-offset AGN are predicted within the SDSS footprint. While this cannot be compared at face value with the rarity of large BL offsets observed among SDSS quasars, owing to selection effects, it provides the first tentative evidence that spin alignment plays a role in suppressing recoils.

Nonetheless, in the most physically-motivated models where spin alignment is efficient only in gas-rich mergers, hundreds of offset AGN are predicted to be observable in surveys with the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), the Large Synoptic Survey Telescope (LSST), *Euclid*, and the *Wide-Field Infrared Survey Telescope (WFIRST)* (Figure 6). These findings strongly motivate a dedicated search for offset AGN.

5. Summary and Future Outlook

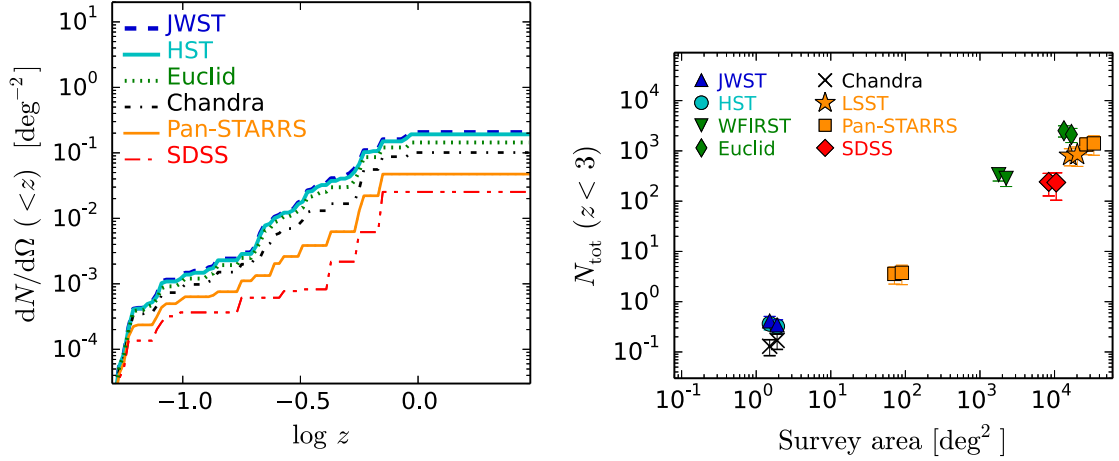Disparate results from studies of the merger/AGN connection have generated a great deal of

Figure 6: From [91]. *Left:* cumulative number of spatially-offset AGN observable per deg^2 as a function of redshift. The model shown assumes that spins are nearly aligned in gas-rich mergers and randomly oriented in gas-poor mergers. Each curve assumes the sensitivity and resolution of a given instrument/survey as indicated on the plot legends. In each case, the minimum detectable offset ΔR_{proj} is assumed to be twice the resolution limit. *Right:* The total predicted number of observable spatially offset AGN at $z < 3$ is shown for various surveys, as indicated in the plot legend. Survey sensitivity and resolution is the same as assumed in the left panel, though here we also show results for the *WFIRST* high-latitude survey and the LSST Main Survey. Large populations of recoiling AGN could be detected in all-sky surveys.

controversy about the role of galaxy mergers in BH and galaxy evolution. However, much of this uncertainty can be attributed to selection biases and sample incompleteness in AGN surveys. The tendencies for merger-triggered AGN to be preferentially obscured and highly luminous are particularly important, but other effects also play a role. These include surface brightness dimming of stellar tidal features, projection effects, stochasticity of AGN fueling, redshift evolution, and delays between galaxy interactions and accretion onto the SMBH.

With this in mind, a self-consistent picture has emerged in which SMBH *growth* is dominated by efficient, merger-induced quasar phases, while the large majority of AGN *by number* are low- to moderate-luminosity events triggered by secular processes. The quantitative details of this scenario are still uncertain, however. In particular, multiwavelength studies of AGN in galaxy pairs and mergers will be crucial for constraining the effects of obscuration. Larger statistical samples of single and dual AGN in mergers are also needed to account for other observational biases. Ň

Numerous other open questions regarding SMBH/galaxy co-evolution remain. For one, the primary fueling modes of isolated AGN are not well understood. Minor mergers or close satellite encounters, gas infall onto host galaxies, or secular processes such as bar instabilities are all possible contributors, and the dominant mode likely varies with galaxy mass, redshift, and environment. Establishing a causal link to AGN fueling is nontrivial, however. For example, little to no correlation has been found between stellar bars and AGN [e.g., 98, 99]. Regardless of what triggers the initial gas inflow, a series of instabilities at different radii may ultimately be responsible for transporting gas to the smallest scales [e.g., 100, 101].

One of the greatest current challenges in understanding the SMBH-bulge relations is the difficulty in obtaining reliable BH masses. Dynamical mass measurements are the most robust but

require resolving the SMBH sphere of influence. Reverberation mapping can provide mass measurements for active SMBHs and has the advantage that it can be used at $z > 0$. Most SMBH mass estimates are obtained through more indirect means, however, and galaxy bulge properties are also increasingly difficult to measure at high z. Nonetheless, increasing evidence suggests that the SMBH-bulge relations evolve with redshift, with SMBH masses lying above the relation at high z [e.g., 102, 103]. This is expected if indeed the bulk of SMBH mass is accreted in merger-triggered quasar phases, because merging and quasar activity peaks at $z \sim 2$ - 3. In the coming years, large reverberation mapping campaigns could greatly increase the number of SMBH mass measurements. Looking further ahead, thirty-meter-class telescopes would revolutionize our ability to obtain dynamical SMBH masses.

The role of galaxy mergers in producing GW sources – namely, SMBH binary mergers – is also of great current interest. Following the recent direct detection of GWs by LIGO, the future of GW astronomy appears extremely bright. In the SMBH regime, PTAs may make a detection of the stochastic GW background within the decade, and the LISA Pathfinder mission is currently paving the way for a space-based interferometer that could directly detect GWs from SMBH mergers. Moreover, the upcoming era of time-domain astronomy will greatly aid the search for close SMBH binaries, which would constrain GW event rates and the nature of the accretion flow prior to SMBH merger. This is also an ideal time to undertake dedicated searches for recoiling AGN, as large surveys could reveal a substantial population of such objects. Even a single confirmed recoiling SMBH would provide evidence of a recent SMBH merger and would constitute an independent test of strong-field gravity.

Acknowledgements

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