Dynamical black-hole mass measurements with molecular gas: NGC0524

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1 Scientific Justification

1.1 Scientific rationale:

Understanding galaxy formation is central to contemporary astrophysics, but the myriad of processes involved make this a formidable challenge. A key result of the 1990s was the realisation that supermassive black holes (SMBHs) are ubiquitous, one lurking at the centre of every giant galaxy. More importantly, the growing number of measured SMBH masses has led to the discovery that SMBH mass (M_{BH}) correlates with a multitude of global galaxy (or more specifically spheroid) properties (total luminosity, Sersíc index n, dark halo circular velocity, etc; e.g. Magorrian et al. 1998; Graham et al. 2001), and most tightely with the central stellar velocity dispersion (σ_V), a measure of the depth of the potential well. The exact form of the relation is debated (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Gultekin et al. 2009), but the intrinsic scatter is very small (if any) and the implication is clear: galaxies and BHs grow hand-in-hand, and their co-evolution likely involves self-regulation mechanisms (e.g. feedback).

The number of theoretical papers attempting to explain the M_{BH}-σ_V correlation ($M_{BH} \propto \sigma^{4?5}$) or exploiting it to derive further correlations, is impressive (e.g. Silk & Rees 1998). However, one must realise that the M_{BH}-σ_V correlation relies both on i) an uncomfortably small number of reliably determined SMBH masses, and ii) a limited number of observational techniques, each with its own set of limitations and biases (e.g. Ferrarese & Ford 2005). In particular, most SMBH masses in the massive early-type galaxies (ETGs, lenticulars and ellipticals) are measured from challenging absorption line stellar kinematics via complex numerical modeling (Schwarzschild method) with contentious issues (number of orbits necessary, true number of degrees of freedom, treatment of chaotic orbits, etc; e.g. Cretton & Emsellem 2004; Valluri et al. 2004). Increasing the number of SMBH masses available and expanding the tool box used to measure them is thus of great importance to an increasingly large body of current work in galaxy formation. We aim to do both in the project proposed here.

Through the SAURON and ATLAS^{3D} projects (de Zeeuw et al. 2002; Cappellari et al. 2011), we have now convincingly shown that a large number of ETGs harbour a substantial amount of cold molecular gas as traced by CO (Combes et al. 2007; Young et al. 2011), largely unbiased with respect to most global galaxy properties (luminosity, ellipticity, environment, etc). Crucially, the gas in most galaxies shows very regular, rotationally-dominated kinematics (Alatalo et al., 2012). In fact, we showed in Young et al. (2008) and Davis et al. 2012, CO is superior to stellar and ionised gas kinematics and is the best (nearly perfect) available tracer of the circular velocity curve (directly related to the gravitational potential and thus the total mass, including any BH). Our work thus opens the exciting possibility of relatively easily measuring the SMBH mass in a large number of galaxies of all types, as long as molecular gas is present and regular at the small spatial scales required for the measurement.

Our team recently published the first ever dynamical measurement of a SMBH mass with molecular gas, in the fast-rotating ETG NGC$\tilde{4}$526 **(REF)**. We showed with high resolution CARMA observations that it is possible to resolve relaxed molecular gas in the inner 20 pc of an ETG, and clearly

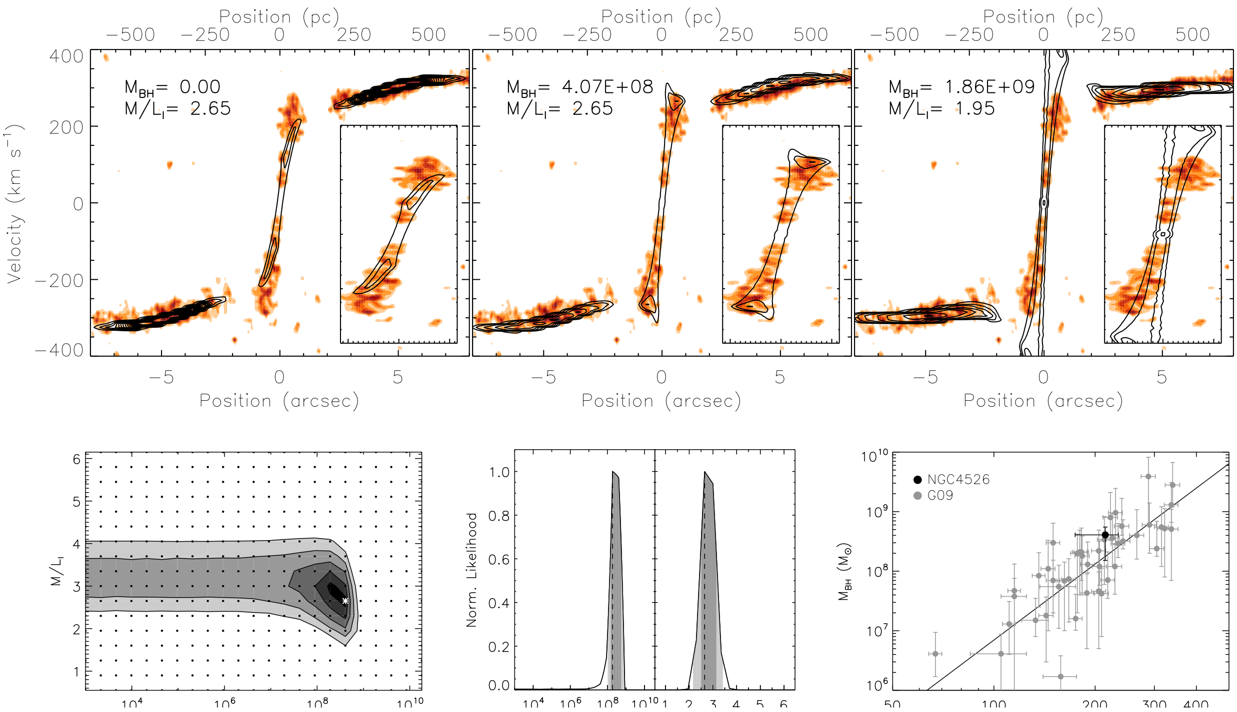

Figure 1: **Top:** Kinematic models of NGC 4526. Model position velocity diagrams (PVDs; black contours), overlaid on the observed CO(2-1) PVD extracted along the kinematic major axis. From left-to-right, the best model with no SMBH, the overall best-fit model, and a model with an overweight SMBH. The model $M_{\rm BH}$ and M/L_I are indicated in the top-left corner of each panel, and an inset of the central $\pm1\farcs15$ is shown in the bottom-right corner. **Bottom Left:** $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm minimum}$ contours (black lines and greyscale) of our fits to the CO(2-1) PVD. The contours are at the 1-5σ levels, with good models in the darkest areas. **Bottom Middle:** Likelihood functions for $M_{\rm BH}$ and M/L_I, marginalised over the other parameter. The 68% and 95% confidence levels are shaded in dark and light grey, respectively. The best fit value is shown with a dashed line. **Bottom Right:** Best-fit SMBH mass (black point), overlaid on the $M_{\rm BH}$-$\sigma_{\rm e}$ data (grey points) and relation (solid line) of Gultekin et al., 2009

detect the kinematic signature of a gravitating massive central object (Figure 1). The uncertainties on our measurement of the SMBH mass are similar to those reported by other authors, clearly demonstrating that our method is competitive to other established methods of estimating SMBH masses. We estimate that old instruments (e.g. CARMA, SMA) can allow us to measure SMBH masses in ≈10 objects, however with full ALMA many thousands of galaxies will be within our reach **(REF)**. In ALMA early-science cycle one the resolution and sensitivity available have become sufficient to begin using our technique to measure SMBH masses. In this proposal we aim to apply this pioneering method to measuring the SMBH mass in NGC0524, a galaxy that has previously had its SMBH mass estimated from stellar kinematics (Krajnovíc et al., 2009). This allows us to cross check our method, and benchmark it directly against other more established techniques.

1.2 Immediate Goals

Our goals in this project are to establish the state (both physical and kinematic) of the molecular gas within the sphere of influence of the SMBH in a carefully chosen ETG (NGC0524; $R_{SOI} \approx GM_{BH}/\sigma_V^2 = 0\farcs6$; Krajnovic et al., 2009), and to use this gas to measure the SMBH mass. As shown in Figure 2, NGC0524 is bright in CO(1-0, 2-1), is relatively nearby, has a well-defined nearly face-on inclination (i=20°), has regular rotationally-supported CO kinematics at the angular resolutions currently probed by our previous observations (3″; Fig 2), and has regular spiral dust lanes at Hubble Space Telescopes (HST) resolution ($0\farcs1$; Fig 2), suggesting regular CO kinematics all the way to the SMBH sphere of influence (a necessary condition; see Ho et al. 2002).

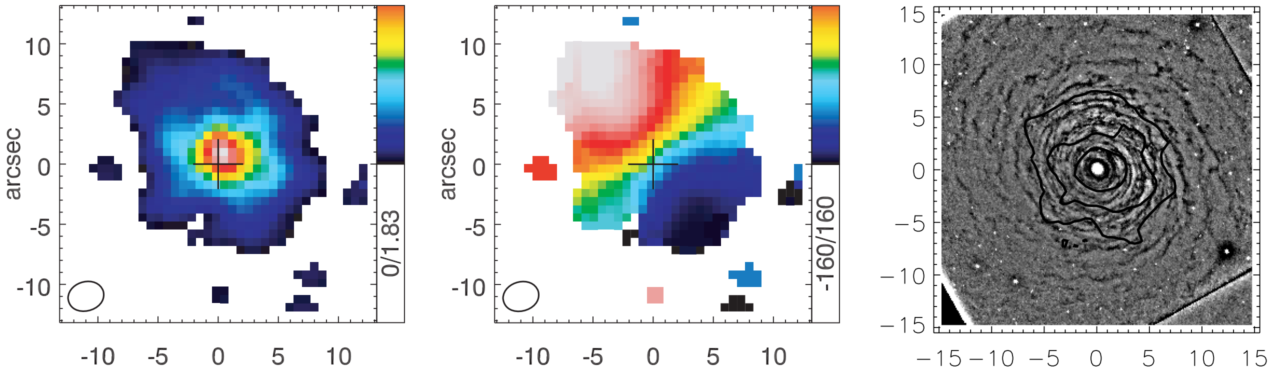

Figure 2: Low-resolution total CO(1-0) integrated intensity map (left) and moment one map (middle) of NGC4526 Centre: CO(1-0) integrated intensity contours overlaid on an unsharp-masked HST image, revealing regular dust lanes all the way to the centre. All from Crocker et al. (2011).

We already have CO(1-0) and (2-1) observations that have established the appropriateness of the molecular gas for mass modelling on intermediate spatial scales (3″; Young et al. 2008; Crocker et al. 2011; Fig 2). These can also anchor the dynamical models on those scales. We thus aim here to directly probe the small spatial scales with ALMA, within the SOI of the BH, which will increase the accuracy of our SMBH mass measurement (see Figs. 3 and 4).

Our expectation is that we will resolve the Keplerian turnover of the circular velocity curve at the smallest spatial scales (Figs. 3-4). If this is indeed the case, as in NGC4526 **(REF)** the SMBH mass measurement will be relatively easy (Keplerian disk in rotation). Our team have developed the tools to model the position velocity diagram, properly taking into account observational effects such as beam smearing, and thus to find the best fit SMBH mass (see Fig. 1). If the molecular gas kinematics prove more complex at small radii, however, we also have the numerical tools to model disks with substantial non-circular motions, from our work on ionised gas disks with HST (Sarzi et al. 2001; Beifiori et al. 2009; Dalla Bonta et al. 2009). Although the SOI of the SMBH in this

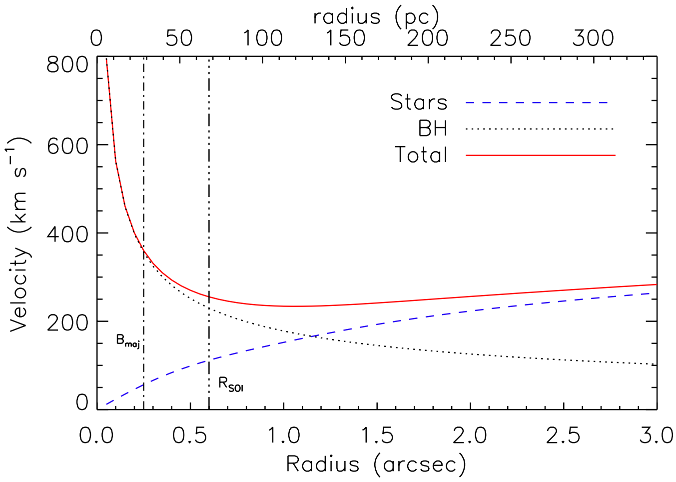

Figure 3: Circular velocity curves of NGC4526 within the inner 3″: background mass distribution without a SMBH (dashed line; Cappellari et al. 2006), predicted SMBH only (dotted line), and sum of the two (solid line). The nominal radius of the sphere of influence ($R_{\rm SOI} = 0\farcs6$) of the SMBH is indicated by a vertical line, as is the synthesized beam achieved at CO(2-1) (band 6) in the C32-6 ALMA configuration (B_{maj}= $0\farcs25$). The signature of the central SMBH (the difference between the blue dashed and red solid lines) is clearly detectable.

system is large, the surface brightness required to map the molecular gas at high resolution (0.77K; see technical justification) means this measurement would take a large amount of time at any other instrument (e.g. ≈110 hours with CARMA). The necessary expertise in terms of mm interferometric observations (Davis, Bureau, Blitz) and gas dynamical modeling (Davis, Sarzi, Cappellari, Bureau) is fully present within our team. The data we request for the purposes of measuring the SMBH mass can also be used to study resolved star-formation, sources of turbulence in the ISM, and the properties of resolved giant molecular clouds (GMCs) in ETGs, ensuring we will extract the maximum from these early-science observations.

2 Technical Justification

Imaging requirements: NGC0524 has a SMBH mass of $\approx 8\times10^8$ $M_\odot$, and a velocity dispersion of ≈235km s^{-1}(Krajnovic et al., 2009). Thus the SOI of this SMBH is 0.″6. As shown in Figure 2, well resolving the SOI will increase the accuracy of our SMBH measurement. We propose to map the galaxy in CO(2-1), as its flux in this transition is known (see below). Observations at 230 GHz using the longest array configuration (C32-6) will allow us to have ≈3 independent beams inside the SOI of the BH, enough to directly observe a keplarian increase in the circular velocity if present (Fig 3). The largest angular scale visible in this array configureation is 3.″9, smaller than the total extent of the molecular disk (5″ in radius). We do not expect to resolve out flux however, as experience shows that flocculant molecular disks like the one in NGC 524 are composed of individual GMCs, which have typical sizes of 15-90 pc (Bolatto et al., 2008), or 0.″13-0.″8 at the assumed distance of NGC0524 (Cappellari et al., 2011). In order to show that the requested configuration will be able to fulfil our science goals we created a mock observation (using the simulation tools described in Davis et al., 2012a, 2012b) of the molecular gas in NGC 524, using the circular velocity curves shown in Figure 3, and a surface-brightness profile derived from our lower resolution CO observations. This was then input to the CASA ALMA simulator, and the results are shown in Figure 4. We do not resolve out the source, and the kinematic signature of the SMBH is clearly detected, showing that our proposed observations and method are sound.

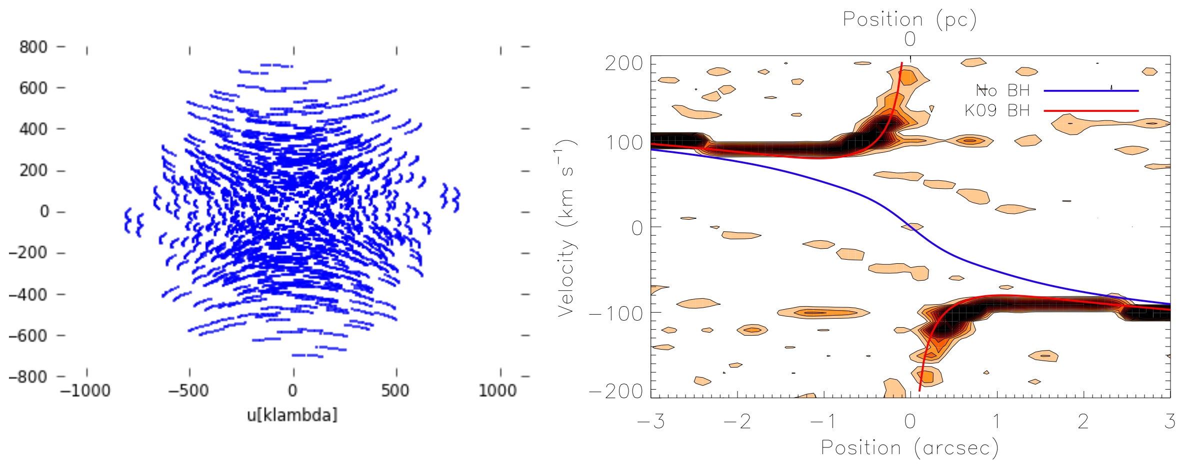

Figure 4: ALMA simulation results within the central 3″ produced (sim_observe/analyze task) in CASA. distribution. Left: uv coverage. Right: major-axis position-velocity diagram. The simulation assumes the dynamics as in Figure 3, and instrumental parameters as in the technical justification, with a scaled CO(2-1) surface brightness profile based on our CO(1-0) observations (Figure 2). The kinematic signature of the central black hole is clearly detected in the position-velocity diagram, and we do not resolve out significant flux, even though our model is likely smoother than the real gas distribution.

Correlator setup: We request a single frequency setups, allowing us to cover CO(2-1) with a 1875 MHz baseband and a raw resolution of $\approx$1 km s^{-1}. This will allow us to cover the entire velocity width of the expected line, including any high velocity gas detected around the BH. From Figures 2-3 it is clear that the higher the spectral resolution of your observations the better the SMBH mass determination. We aim to have $\approx$10 km s^{-1}channels here, binning the raw channels in post processing. Of course if the source is less bright than expected we can increase the binning while still detecting the SMBH (a velocity difference between the case of no SMBH and the expect SMBH mass is $\approx$300km s^{-1}at $0\farcs25$; Figure 3), and if the source is bright we can relax the binning somewhat to get tighter constraints on the SMBH mass.

Requested sensitivity: NGC 0524 has an integrated flux of 22.8 Jy km s^{-1}(Young et al., 2011), and a velocity line width of 426 km s^{-1}. The spectrum is boxcar like, with an average flux per channel of 52 mJy. Experience shows that the emission is normally only spatially resolved in one direction (tracing the spider diagram) in individual velocity channels. We thus assume that the number of synthesised beams across the source in each channel is equal to the ratio of the minor-axis length ($\approx$5) from the HST unsharp-masked dust image shown in Fig. 1) to the synthesised beam size ($0\farcs25$ in the C32-6 array). We thus expect to have $\approx$24 beams per channel across the source, yielding a predicted flux of $\approx$2mJy/beam, or 0.77 K. We request here to reach an RMS flux of 0.43 mJy, yielding a signal-to-noise ratio of 5 per synthesized beam in each channel. The ALMA OT suggests reaching such a flux limit at 230 GHz with 1.26mm PWV, 32 antennas in the C32-6 array configuration and a velocity channel width of 10 km s^{-1} will require only $\approx$2.7 hours.

3 Potential for Publicity

As BHs are perennial favourites with the public and the media, there is little doubt that a successful SMBH mass measurement with this new technique will capture their attention, and highlight the power of ALMA.

4 References

Beifiori A., et al., 2009, ApJ, 692, 856; Cappellari M., et al., 2006, MNRAS, 366, 1126; Cappellari M., et al., 2011, MNRAS, 413, 813; Combes F., Young L.M., Bureau, M., 2007, MNRAS, 377, 1795; Cretton N., Emsellem E., 2004, MNRAS, 347, L31; Crocker A.F., Bureau M., Young L.M., Combes F., 2011, MNRAS, 410, 1197; Dalla Bonta E., et al., 2009, ApJ, 690, 537; Davis T.A., et al., 2011, MNRAS, 414, 968; de Zeeuw P.T., et al., 2002, MNRAS, 329, 513; Emsellem E., et al., 2004, MNRAS 352, 721; Ferrarese L., Ford H., 2005, Space Science Reviews, 116, 523; Ferrarese F., Merritt D., 2000, ApJ, 539, L9; Gebhardt K., et al., 2000, ApJ, 539, L13; Graham A.W., Erwin P., Caon N., Trujillo I., 2001, ApJ, 563, L11; Gultekin K., et al., 2009, ApJ, 698, 198; Ho L.C., Sarzi M., Rix H.-W., Shields J.C., Rudnick G., Filippenko A.V., Barth A.J., 2002, PASP, 114, 137; Krips M., Crocker A.F., Bureau M., Combes F., Young L.M., 2010, MNRAS, 407, 2261; Kuntschner H, et al., 2010, MNRAS, 408, 97; Krips M., Crocker A.F., Bureau M., Combes F., Young L.M., 2010, MNRAS, 407, 2261; Magorrian J., et al., 1998, AJ, 115, 2285; Sarzi M., Rix H.-W., Shields J.C., Rudnick G., Ho L.C., McIntosh D.H., Filippenko A.V., Sargent W.L.W., 2001, ApJ, 550, 65; Silk J., Rees M., 1998, A&A, 331, L1; Valluri M., Merritt D., Emsellem E., 2004, ApJ, 602, 66; Young L.M., Bureau M., Cappellari M., 2008, ApJ, 676, 317; Young L.M., et al., 2011, MNRAS, 414, 940;