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Galaxy Zoo DESI: large-scale bars as a secular mechanism for triggering AGN

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ABSTRACT

Despite the evidence that supermassive black holes (SMBHs) co-evolve with their host galaxy, and that most of the growth of these SMBHs occurs via merger-free processes, the underlying mechanisms which drive this secular co-evolution are poorly understood. We investigate the role that both strong and weak large-scale galactic bars play in mediating this relationship. Using 72,940 disc galaxies in a volume-limited sample from Galaxy Zoo DESI, we analyse the active galactic nucleus (AGN) fraction in strongly barred, weakly barred, and unbarred galaxies up to $z = 0.1$ over a range of stellar masses and colours. After controlling for stellar mass and colour, we find that the optically selected AGN fraction is $31.6 \pm 0.9$ per cent in strongly barred galaxies, $23.3 \pm 0.8$ per cent in weakly barred galaxies, and $14.2 \pm 0.6$ per cent in unbarred disc galaxies. These are highly statistically robust results, strengthening the tantalising results in earlier works. Strongly barred galaxies have a higher fraction of AGNs than weakly barred galaxies, which in turn have a higher fraction than unbarred galaxies. Thus, while bars are not required in order to grow a SMBH in a disc galaxy, large-scale galactic bars appear to facilitate AGN fuelling, and the presence of a strong bar makes a disc galaxy more than twice as likely to host an AGN than an unbarred galaxy at all galaxy stellar masses and colours.

Key words: galaxies: active – galaxies: bar – galaxies: disc – galaxies: Seyfert

1 INTRODUCTION

Supermassive black holes (SMBHs) reside in the centre of the majority of galaxies, gaining most of their mass during active phases, where the accretion systems are known as active galactic nuclei (AGNs). Yet what triggers the “switch on” of an AGN is equivocal. This question is critical to understanding the interplay between AGNs and their host galaxies, including the effectiveness of AGN feedback and SMBH-galaxy co-evolution (see e.g., Kormendy & Ho 2013; Heckman & Best 2014, for a review). Recent simulation studies have shown that the majority of SMBH growth occurs via secular (merger-free) mechanisms (Martin et al. 2018; McAlpine et al. 2020; Smethurst et al. 2023), meaning that mergers are not the primary drivers of the relationships known to exist between SMBHs and their host galaxies. Disc-dominated, bulgeless galaxies have had a history free from major mergers (1:10 mass ratio) since at least $z \approx 2$ (Martig et al. 2012), and so by exclusively looking at a population of disc-dominated, bulgeless galaxies and the kiloparsec scale structures within them (such as large-scale galactic bars), we can gain a better understanding of AGN triggering in the absence of major mergers. The bulge present in some disc-dominated galaxies could be merger-formed, but it could also be formed through a number of other mechanisms, including minor mergers, and potentially bars. By looking at a population of disc-dominated galaxies as

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a whole, we can investigate structures such as bars across the entire disc-dominated galaxy population.

Large-scale strong bars are observed at optical wavelengths in the Sloan Digital Sky Survey (SDSS; York et al. 2000) in 29.4 ± 0.5 per cent of disc galaxies at redshift 0.01 < z < 0.06 (Masters et al. 2011), and when using either a deeper optical survey or one with better seeing, such as DECaLS, this increases to around 45 per cent when combining galaxies with either weak or strong bars (Géron et al. 2021). This distinction between strong and weak bars is important, despite their being on a continuum, since work has shown that they may have different formation mechanisms (e.g., Géron et al. 2023), although separating out strong and weak bars consistently poses a challenge. In general, a bar is classified as strong if it dominates the galaxy flux, and weak as containing a smaller fraction of the total flux (Nair & Abraham 2010). These bars can cause transfers of a disc’s angular momentum, leading to gas being transported down to the central kiloparsec region (Friedli & Benz 1993; Athanassoula 2003), where it could be accreted onto a black hole. Thus, by tracing these kiloparsec-scale structures, we can gain insight into the dynamics within a galaxy that facilitate the transfer of angular momentum, and hence the fuelling which gives rise to the AGN characteristics that we observe.

Simulations have shown that it is physically possible for bars to provide the necessary inflow of gas to match the accretion rates we see in AGNs (Sakamoto 1996; Maciejewski et al. 2002; Regan & Teuben 2004; Lin et al. 2013), and this is mirrored in observational work by Smethurst et al. (2021). Several other studies have pointed to either an increase in the bar fraction of AGN hosts compared to inactive galaxies, or an increase in AGN fraction in barred galaxies compared to unbarred (Knapen et al. 2000; Laine et al. 2002; Coelho & Gadotti 2011; Oh et al. 2012; Galloway et al. 2015; Alonso et al. 2018; Silva-Lima et al. 2022; Garland et al. 2023). However, many of these previous studies have suffered from low statistical significance or sensitivity to methodology and selection effects.

There are also a number of studies finding no correlation (e.g., Cheung et al. 2013; Goulding et al. 2017). Thus, in this work, we aim to revisit this correlation between large-scale bars and AGNs, using Galaxy Zoo DESI (Walmsley et al. 2023a) to obtain robust morphologies from deeper imaging, and observed emission lines using Galaxy Zoo DESI (Walmsley et al. 2023a) to obtain robust AGN characteristics in Sections 4 and 5. Throughout this work, we consider AGNs and LINERs (low-ionisation nuclear emission line regions) to be two distinct categories, rather than LINERs being a subset of AGN. We use WMAP9 cosmology (Hinshaw et al. 2013), incorporated via Astropy, where we assume a flat universe, $H_0 = 69.3$ \(\text{km s}^{-1} \text{Mpc}^{-1}\) and $\Omega_m = 0.287$.

### 2 DATA COLLATION

In the subsections below, we describe the use of multiple surveys to obtain the data required for this study. We collate a sample of disc-dominated galaxies (divided into strongly barred, weakly barred and unbarred) which are either AGN hosts, star-forming, or undetermined.

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1 Available at https://www.mpa-garching.mpg.de/SDSS/DR7/
To select disc galaxies, we require that the vote fraction for “features or disc” is $f_{\text{smooth or featured, featured or disk}} \geq 0.27$.

We also require that any discs must not be edge-on so that a bar can be identified if present, since in an edge-on galaxy, the bar can be obscured. GZD categorise each featured galaxy as “edge-on” or “not edge-on”, and for our purposes, we require $f_{\text{disk edge-on no}} \geq 0.68$. Galloway et al. (2015) examine the relationship between inclination angle and observed bar fraction, and show (their Fig. 2) that the exact threshold used for “not edge-on” does not have a significant effect. These limits follow those used in Géron et al. (2021) and Walmsley et al. (2022).

To complete our sample, we require that the galaxy in the image does not appear to be merging with another galaxy. GZD classifies every image with a merger class of “merger”, “major disturbance”, “minor disturbance”, or “none”. We consider galaxies with any significant level of disturbance to be potential contaminants to a sample of discs undergoing secular evolution. Thus we create a parameter we refer to as merger prominence, $\xi_{\text{avg}}$, analogous to the bulge prominence parameter in Masters et al. (2019). We define $\xi_{\text{avg}}$ as:

$$
\xi_{\text{avg}} = 0.2 \times f_{\text{merging minor disturbance}} + 0.8 \times f_{\text{merging major disturbance}} + f_{\text{merging merger}}
$$

We require our sample to contain only galaxies which are not merging, which we identify as $\xi_{\text{avg}} \leq 0.3$. This value has been visually checked to be consistent with undisturbed galaxies, via spot checking of ~50 galaxies around the selected cut-off value.

In order to reduce selection effects, we select a volume-limited sample having $z \leq 0.10$ and and $M_r \leq -19.2$, as shown in Fig. 1. The 48,871 galaxies that form our final, complete sample (i.e., within the volume limit, disc-dominated, not edge-on, not merging) are shown in teal.

Within this volume-limited sample, we subsequently identify whether each of our galaxies has a bar, and the strength of that bar. GZD asks the models to distinguish between “strongly barred”, “weakly barred”, and “not barred”. We classify a galaxy as unbarred if $f_{\text{strong bar}} < f_{\text{weak bar}} < 0.5$. We then divide the barred galaxies into strong and weak bars in order to investigate the effect of bar strength on AGN presence. We define a barred galaxy as strongly barred if $f_{\text{strong bar}} \geq f_{\text{weak bar}}$, and weakly barred if $f_{\text{strong bar}} < f_{\text{weak bar}}$. These limits follow the criteria used successfully in Géron et al. (2021, 2023). This means that every galaxy in our volume-limited disc sample is categorised as unbarred (Ubar, 27,291 galaxies), strongly barred (Sbar, 7,069 galaxies) or weakly barred (Wbar, 14,411 galaxies).

As with any measurement, the GZD vote fractions do have errors associated with them. When the vote fractions are varied within their errors (assumed to be Gaussian) using a bootstrapping method iterated 1000 times with replacements, our results do not change.

### 2.3 Activity Classification

We use emission line ratio diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987) to classify the galaxies in our sample as either: undetermined, star-forming, composite, AGN, or LINER. We use the emission lines from MPA-JHU DR7 to place galaxies on the diagram, and we show the distribution in Fig. 2.

In order for a source to be classifiable according to this method, we require that the signal-to-noise ratio (S/N) in [OIII], Hβ, [NII] and Hα be S/N $\geq 3$, in order to ensure good quality emission lines. If a galaxy does not fulfil this first requirement, it may still be classifiable depending on where the limits lie (e.g., Brinchmann et al. 2004; Salim et al. 2007; Rosario et al. 2016), which we discuss below. If a source fulfills this requirement only in Hα it is classified as undetermined.

If a galaxy does fulfil all the S/N requirements, we use Panel (a) in Fig. 2, to classify a galaxy as star-forming if it falls below the Ka03 line (Kauffmann et al. 2003). If a galaxy falls between the Ka03

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**Figure 2.** Classification of disc-dominated sources on a trio of emission line ratio diagrams (Baldwin et al. 1981; Veilleux & Osterbrock 1987). The grey histogram represents anything classed ‘star-forming’, ‘LINER’ or ‘composite’, the teal points represent optically classified AGN and the red triangles represent WISE-classified AGN. From panel (a), we assume that any source falling below the Ka03 line (Kauffmann et al. 2003) is purely star-forming. Anything above the Ke01 line (Kewley et al. 2001) is either an AGN or a LINER, and thus any source lying between those two lines is classed as composite. To distinguish between AGNs and LINERs, we use Panels (c), then (b), then (a) in that order. This is where a source has S/N > 3 in Ke01 line (Kewley et al. 2001), then Panel (c) is the most reliable, and we consider any source lying above the Ke06 (Kewley et al. 2006) line to be an AGN, whereas a source below is a LINER. Where a source has S/N < 3 in [OIII], but S/N > 3 in [SII], we use Panel (b). Again, a source lying above the Ke06 line is classified as an AGN and below is a LINER. Where both [SII] and [OIII] in a source have S/N < 3, we use [NII]. Any source lying above the S07 line (Schawinski et al. 2007) is classified an AGN, and below is a LINER.
line and the Ke01 line (Kewley et al. 2001), then it is classified as composite, and the emission is likely due to a combination of star formation and AGN/LINER activity. If a galaxy falls above the Ke01 line, we classify it as either an AGN or a LINER (Low-Ionisation Nuclear Emission-line Region). We explain how these two objects are differentiated below.

If a source only fulfils the S/N criteria in Hα, [Oii] and Hβ, this provides an upper limit on the Hα/[Nii] ratio. Thus if this source falls below the Ka03 line, it is still classifiable as star-forming. Else, it is classified as uncertain. If a source only fulfils the S/N criteria in Hα, [Nii] and Hβ, this provides an upper limit on the [Oii]/Hβ ratio. Thus if this source falls below the Ka03 line, it is still classifiable as star-forming. Else, it is classified as uncertain. If a source only fulfils the S/N criteria in Hα and Hβ, this provides a lower limit on the [Oii]/Hβ ratio. Thus if this source falls above the Ke01 line, it is still classifiable as either an AGN or a LINER. Else, it is classified as uncertain. If a source only fulfils the S/N criteria in Hα and Hβ, this provides a lower limit on the [Nii]/Hα ratio, and an upper limit on the [Oii]/Hβ ratio. Thus if this source falls above the Ke01 line, it is still classifiable as star-forming. Else, it is classified as uncertain.

There are three different emission lines we can use to distinguish AGNs from LINERs – [Sii], [Oii] and [Nii]. The most reliable line is [Oii] (Kewley et al. 2006) and this should be used where possible, so if S/N[Oii] ≥ 3, we can use Panel (c), and classify any source falling below the Ke06 line as an AGN. This results in the hard cut-off line we see in Panel (c) that is not present in (a) or (b) for distinguishing between AGNs and LINERs. Where S/N[Oii] is too low, [Sii] is the next best emission line, and so if S/N[Sii] ≥ 3 we can use Panel (b), and classify any source falling below the Ke06 line as a LINER. Where both S/N[Sii] and S/N[Oii] are too low, we can resort to Panel (a), and use the S07 line (Schawinski et al. 2007), since a source must have S/N[Nii] ≥ 3 in order to be classified as either an AGN or a LINER at all. Anything both below this line and above the Ke01 line can be classified as an LINER.

This leaves our volume-limited disc sample with: 712 undetermined galaxies, 2,518 uncertain galaxies, 28,807 starforming galaxies, 8,669 composite galaxies, 4,843 LINERs and 3,160 optically classified AGNs. When the fluxes are varied within their errors (assumed to be Gaussian) using a bootstrapping method iterated 1000 times with replacements, our results do not change.

Some AGNs are not optically classifiable, and are instead observable primarily in the infrared regime. We match our catalogue to the Wide-Field Infrared Survey Explorer (WISE) AGN catalogue (Assef et al. 2018), and any AGNs which are present in this catalogue, but not classified as AGNs according to the method described above, we add to our sample. There are 5 WISE AGNs which appear in our volume-limited galaxy sample, 1 of which is classified as an AGN using emission line ratio diagrams, so we can reclassify an additional 4 galaxies as AGN, to give us a total of 3,164 AGNs.

Examples of different bar strengths in star-forming, AGN-host, and undetermined galaxies are shown in Fig. 3. For a complete breakdown of how many galaxies are in each morphology category, see Table A1 in Appendix A. Note that whilst the classification of LINERs, uncertain sources and composite galaxies is important, it is simply so they can be confidently removed from our sample for analysis. We do not explicitly make use of these galaxies, as they are possible contaminants in our otherwise pure sample of Seyferts.

Figure 3. Examples of each morphology and activity classification. The left-hand column shows unbarred galaxies, the middle shows weakly barred, and the right-hand shows strongly barred galaxies. The top row shows AGN-host galaxies, the middle row shows star-forming galaxies, and the bottom row shows undetermined galaxies according to classification using emission line ratio diagrams. The undetermined galaxies are predominantly red spirals.

Figure 4. The distributions in M∗ and (g − r)0 colour for a variety of subsamples, with strongly barred galaxies in solid lines, unbarred in dashed lines, AGNs in red, star-forming in teal, composite in orange and undetermined in navy blue. Weakly barred galaxies are not shown for simplification, but lie between the strongly barred and unbarred samples.
Table 1. The percentage of each activity category within each bar classification, as shown in Fig. 5. AGN presence in strongly barred galaxies is around twice as prolific as in weakly barred or unbarred galaxies.

<table>
<thead>
<tr>
<th>Bar Category</th>
<th>Strongly Barred</th>
<th>Weakly Barred</th>
<th>Unbarred</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN</td>
<td>31.6 ± 0.9</td>
<td>23.3 ± 0.8</td>
<td>14.2 ± 0.6</td>
</tr>
<tr>
<td>Star-forming</td>
<td>63.6 ± 0.9</td>
<td>73.6 ± 0.8</td>
<td>83.9 ± 0.6</td>
</tr>
<tr>
<td>Undetermined</td>
<td>4.7 ± 0.4</td>
<td>3.1 ± 0.3</td>
<td>1.9 ± 0.2</td>
</tr>
</tbody>
</table>

3 RESULTS

We look at the variation in stellar mass ($M_*$) and ($g-r)_0$ colour, where the 0 indicates we have corrected the ($g-r$) colour for galactic absorption, between strongly barred (Sbar), weakly barred (Wbar) and unbarred galaxies (Ubar), and the results are shown in Fig. 4. For visualisation purposes, we omit the results for Wbar since they lie between the two other samples (however this inclusive plot is shown in Fig. B1 in Appendix B). As expected, the star-forming galaxies are less massive and slightly bluer than the AGN hosts. The composite galaxies have overlap with both star-forming and AGN hosts, which confirms that their activity is due to a mixture of star formation and AGN. This is very similar to the undetermined galaxies, whose signal to noise is too low to classify their activity. The undetermined galaxies are predominantly a mix of quenching and fully quenched disc galaxies. There are also some small differences between the barred and unbarred samples, with bars tending to reside in more massive, redder discs, particularly in both the star-forming samples and the undetermined samples, in agreement with previous studies (e.g., Masters et al. 2011).

For further analysis, we limit our sample to only star-forming, undetermined and AGN host galaxies to avoid any ambiguity from the LINER and composite samples.

We divide our sample of star-forming, undetermined and AGN host galaxies into our Sbar, Wbar and Ubar samples. Within these three samples, we divide the $M_*$ and colour each into 15 bins of equal width (over 7.0 ≤ log($M_*/M_\odot$) ≤ 12.0 and 0.4 ≤ ($g-r)_0$ ≤ 2.0), and assign weights to each galaxy such that the weighted distributions of $M_*$ and colour are matched between the Sbar, Wbar and Ubar subsamples. This is because AGN presence is known to correlate with $M_*$ and colour, and we want to reduce selection effects, and ensuring that the distributions are the same will aid this. We can then determine the fraction in each bar category of AGN, star-forming and undetermined galaxies. However, when determining the activity fractions, we introduced a more conservative mass cut of 10.0 ≤ log($M_*/M_\odot$) ≤ 12.0 before weighting the distributions. This is because AGN are more easily observable in higher mass galaxies (Aird et al. 2012), and this conservative mass cut reduces this selection bias. Changing this lower mass limit between 10^{9-10}M_\odot and 10^{10.0}M_\odot does not change our results. The weighted results are shown in Fig. 5, and Table 1. Errors arise from the binomial distribution (Cameron 2014).

Given the small errors on each of these fractions within each bar category, it is highly unlikely that any of these subsamples are drawn from the same parent distribution. These initial results indicate that AGNs are more likely to reside in strongly barred galaxies than in weakly barred, and even less likely to reside in unbarred. However, given the ranges of $M_*$ and colour, we endeavour to examine these fractions as a function of both, whilst simultaneously examining how the AGN fractions may vary across $M_*$-colour space. Given that we cannot classify the star-formation rate of the AGN hosts, we do not consider SFR as a parameter, and thus we combine star-forming galaxies and undetermined galaxies into one category, which we refer to as ‘inactive’ galaxies.

3.1 AGN-bar correlation with stellar mass and colour

We divide our sample of AGN hosts and inactive galaxies into nine bins in $M_*$ and nine bins in ($g-r)_0$ colour. Within each bin, we calculate the AGN fraction in strongly barred galaxies, $f_{AGN,Sbar}$, and the AGN fraction in unbarred galaxies, $f_{AGN,Ubar}$. We then find the difference in these two fractions, and this is shown in Fig. 6a. It can be assumed that there is one, real, intrinsic value for this difference, but when we sample it, we get some scatter. Thus, by sampling it multiple times by varying the binning, we should get an approximately Normal distribution that centres around the true value. The difference between the two fractions is shown as a colour bar, where green indicates that the fraction of strongly barred galaxies which host AGNs is greater than the fraction of unbarred galaxies which host AGNs. In order to reduce noise, we only show bins where there are at least 17 AGNs in a bin. Varying the minimum AGN count per bin within reasonable values does not change our qualitative result. Every bin is green, with approximately $f_{AGN,Sbar} - f_{AGN,Ubar} = 0.18$. This is a small but significant increase in the number of AGNs in strongly barred galaxies.

When we repeat this analysis for Wbar and Ubar our result is qualitatively similar, in that weakly barred galaxies appear more likely to host an AGN. But the signal is much less strong, indicating that any effect that weak bars have on AGN presence is less pronounced than for strong bars, which is also reflected in the lower fractions over the full $M_*$-colour-matched sample. This is plotted in...
Figure 6. The difference between the AGN fraction in two bar categories for every combination of Sbar, Wbar and Ubar with M\textsubscript{r} on the x-axis and (g − r)\textsubscript{0} colour on the y-axis. In each case, the label along the top is written as ‘Category 1 v. Category 2’. The black contours indicate the population of disc galaxies (AGN-host and inactive) within the volume limit. The 2D histogram indicates the distribution of AGN-host disc galaxies, where there are a minimum of 17 AGN in a bin. Where the bin is more green, this indicates that the fraction of Category 1 galaxies hosting AGNs is greater than the fraction of Category 2 galaxies hosting AGNs. Where the bin is more purple, the reverse is true.

Fig. 6b. Overall the AGN fraction is still higher in weakly barred galaxies than in disc galaxies without bars.

We can directly compare Sbar and Wbar across the M\textsubscript{r}-colour diagram as well (Fig. 6c), and we find that the fraction of strongly barred galaxies hosting AGNs is significantly greater than the fraction of weakly barred galaxies hosting AGNs although again this is less pronounced than in Fig. 6a.

Given that any increase in AGN fraction is small, we check that this value is not overly dependent on binning, and we repeat these calculations for every M\textsubscript{r} and colour bin combination from 5 bins to 17 bins, for a total of 169 bin combinations. For each binning combination, we calculate the median difference in AGN fraction (e.g., \(\Delta f_{\text{AGN, Sbar}} = f_{\text{AGN, Sbar}} - f_{\text{AGN, Ubar}}\)), and we plot these medians in Fig. 7a.

We assume that the different binning choices each sample the true value of the difference in AGN fraction between subsamples, such that the distribution of values recovered from all binning choices represents the measured value and its uncertainty. This means that the histogram for each comparison does not consist of independent measurements, but rather is expected to peak around the true value of the difference in the AGN fraction.

If there was no difference in the likelihood of hosting an AGN between these three subsamples, we would expect the histograms to centre around 0 (e.g., \(f_{\text{AGN, Sbar}} = f_{\text{AGN, Ubar}}\)). We always take the weaker bar category from the stronger bar category, so if the centre of the histograms is greater than 0, the stronger bar category is more likely to host an AGN than the weaker, and vice versa if the centre of the histogram is less than 0.

Fig. 7a shows that the stronger bar category is more likely to host an AGN than the weaker bar category in every case: strongly barred galaxies are more likely to host an AGN than weakly barred galaxies, which are in turn more likely to host an AGN than unbarred galaxies. Yet this excess of AGNs we see is very small. The difference in AGN fraction between strongly barred and unbarred galaxies is 0.17±0.01, between strongly barred and weakly barred is 0.07±0.01, and between weakly barred and unbarred is 0.09±0.01.

A Shapiro-Wilk test (Shapiro & Wilk 1965) shows that we cannot reject Normality for any of the distribution of the medians, with p-values in each case greater than \(p_{SW} > 0.21\) (< 1.3\(\sigma\)). Given these distributions are consistent with the Normal distribution, we can perform a simple T-test (Student 1908) to quantify the significance of this excess of AGN. In each of these cases, the p-value resulting from a T-test is \(p_T < 1 \times 10^{-6}\) (\(> 5\sigma\)), and thus we reject the hypothesis that the likelihood of each of these bar categories hosting an AGN are identical to each other. Furthermore, we can say that the galaxies in Ubar are less likely to host an AGN than the galaxies in Sbar or Wbar category to a 5\(\sigma\) confidence.

For each binning combination, we also calculate the fraction of bins where the stronger bar category hosts a greater AGN fraction than the weaker bar category (e.g., \(f_{\text{AGN, Sbar}} > f_{\text{AGN, Ubar}}\)), and we plot these values in Fig. 7b.
For example, if we have 5x5 bins, and 20 bins have \( f_{\text{AGN,Sbar}} > f_{\text{AGN,Ubar}} \), we would report a value of 0.8 for this bin combination. If there was no difference in the likelihood of hosting an AGN between our three subsamples, we would expect the distributions to centre around 0.5 – half of the bins would show a greater fraction of AGNs in one bar category than the other. This point is signified by a dashed line.

Comparing Sbar and Ubar, the fraction of bins where Sbar has a greater AGN fraction is 0.95 ± 0.03. For Sbar and Wbar this is 0.78 ± 0.06, and for Wbar versus Ubar, the fraction of bins where Wbar has a greater AGN fraction is 0.90 ± 0.04, where errors arise from the standard deviation.

Again, we perform a Shapiro-Wilk test for Normality. For the combination Wbar vs. Ubar, we obtain a p-value of \( p_{SW} = 0.10 (1.6\sigma) \), and thus for this comparison, we can use a T-test to quantify the significance of the excess of bins containing a higher AGN fraction in the weakly barred category. The p-value resulting from this T-test is \( p_T < 1 \times 10^{-6} (\gg 5\sigma) \).

Since we can reject Normality for Sbar vs. Ubar, and Sbar vs. Wbar, \( (p_{SW} < 0.03) \), we must use the more conservative method of calculating the number of standard deviations between the mean and the null result of 0.5. For Sbar v. Ubar, with a mean value of 0.95, and a standard deviation, \( \sigma_{SD} \), of 0.03, we can say that the mean is 15\( \sigma_{SD} \) away from 0.5, and therefore is not in agreement. For Sbar v. Wbar, with a mean value of 0.78, and a standard deviation, \( \sigma_{SD} \), of 0.06, we can say that the mean is 13\( \sigma_{SD} \) away from 0.5, and therefore is not in agreement. Thus, in each case, the stronger bar category has an AGN fraction that is greater than the weaker bar category. This occurs across the \( M_\ast \)-colour regime, meaning that there is not one specific combination of \( M_\ast \) and colour driving this relationship, further justifying that our results are not sensitive to the choice of binning.

The trends between bar strength and AGN activity are likely a mix of relatively straightforward and more complex results. We discuss these further below.

4 DISCUSSION

Our overall result, with AGN activity in both unbarred and barred disc galaxies, confirms that a large-scale bar is not \textit{required} to feed an AGN in the secular-evolution regime. There are multiple secular channels by which matter from the kiloparsec-scale disc can flow into the SMBH sphere of influence, according to both simulations (e.g., Ciotti et al. 1991; Friedli & Benz 1993; Sakamoto 1996; Maciejewski et al. 2002; Regan & Teuben 2004; Hopkins & Hernquist 2006; Ciotti & Ostriker 2012; Lin et al. 2013; Slater et al. 2019) and observations (e.g., Davies et al. 2007; Smethurst et al. 2021). However, our primary result also shows clear evidence for an increase in AGN activity in both strongly and weakly barred systems, and we focus on discussing this result below.

As described in Section 3, we find that strong bars are clearly linked to a higher incidence of AGN activity, and that weak bars show a more subtle, but still positive, correlation. These results clarify the debate over the last few years regarding whether (and how much) bars are associated with AGN activity. They also highlight an emerging consensus regarding the link between bars and AGN. For example, our results agree with Silva-Lima et al. (2022), who counter for selection effects and find that barred galaxies have a higher accretion parameter than unbarred, and that AGNs are found more commonly in galaxies with a bar. Since we are looking at incidence rather than luminosity or accretion, this study is particularly complementary.

Given that recent studies have shown that strong and weak bars must be considered separately (Géron et al. 2023), this could also be responsible for some of the discrepancies seen in contradicting previous studies (e.g., Cheung et al. 2013; Goulding et al. 2017; Zee et al. 2023), who find no correlation between bars and AGNs.

It is natural at this point to consider inverting the question we have been considering throughout this work, and instead examine the fraction of AGN that have bars. Within our sample and the defined mass limits, 40 ± 1.0 per cent of AGN have strong bars, 34.7 ± 1.0 per cent have weak bars, and the remaining 25.3 ± 1.0 per cent are unbarred. 24.5 ± 0.5 per cent of inactive galaxies have strong bars, 43.2 ± 0.6 per cent have weak bars, and the remaining 32.3 ± 0.5 per cent are unbarred. This agrees qualitatively with multiple previous studies, such as Oh et al. (2012) and Garland et al. (2023), although the exact numbers can vary with the study because of the sample selection and bar sensitivities of each individual study. This is the largest study so far to examine the disc galaxy population for evidence of correlation between bars and AGN and there is clearly a positive correlation in both directions. AGN are most likely to host strong bars, and strongly barred galaxies are most likely to host AGN, within the disc galaxy population.

Our findings are consistent with recent evidence that strong and weak bars have different formation mechanisms (e.g., Géron et al. 2023): strong bars are triggered by global disc instabilities, whereas weak bars are formed through tidal interactions. These formation mechanisms could both be responsible for triggering an AGN. Thus, the AGN’s presence may not be directly due to the bar, but rather to the same mechanisms that caused the bar to form. If the physical mechanisms are different for strong and weak bars, this leads to a different co-incidence between AGN and the two different bar strengths. Tidal interactions may be more efficient at depleting gas in the centre of the galaxy than secular processes that do not lead to the development of a bar, such that by the time the disc galaxy has evolved to a higher stellar mass, the AGN has been deprived of fuel and shut down, although the weak bar still remains in place.

The gas content is significantly higher in starforming discs than red spirals (Masters et al. 2012). We postulate that were a strong bar present in a galaxy, this bar is efficient at fuelling this additional gas down to the central kilo-parsec, where it can be accreted onto an AGN. If weak bars are less efficient at driving gas to the centre of the galaxy, this would explain why we see a much weaker correlation between weakly barred galaxies and AGNs than strongly barred galaxies and AGN.

There is recent evidence from IllustrisTNG that an AGN could drive changes in the bars (Lokas 2022). This is due to the AGN switching to kinetic-mode feedback, causing depletion of gas in the inner regions, leading to quenching and bar-formation. However, given the physical scales that we are looking at, this seems unlikely to be occurring on a large-scale in our sample, due to the differences in AGN and bar lifetimes.

It is important to assess the potential contribution to this result of any selection biases. As described in Section 2, we take various steps to minimise these biases, such as controlling for \( M_\ast \) and \( g - r \) colour, and using a volume limit to ensure completeness. We also consider the effects of the changing physical resolution across the sample. At higher redshifts, the minimum size of bar we can detect increases: we lose smaller bars at higher redshift. Weak bars tend to be shorter than strong bars proportional to the size of the galaxy. This means we preferentially lose weaker bars as we increase in redshift, especially in lower mass galaxies. In a low mass galaxy, a weak bar may be missed, and that galaxy classified as unbarred.

We do not have individual bar lengths and widths for all the galax-
ies in this sample, and thus we cannot fully compensate for this potential source of selection bias at an individual galaxy level. However, one way to examine how strong this effect is likely to be in our sample is to remove the high redshift sources, because this will significantly reduce the overall difference between minimum resolved bar size between the lowest and highest redshifts of the subsample.

We have thus examined the subset of our volume-limited sample with \( z < 0.05 \) (12,251 disc galaxies), and the overall trends seen in Fig. 6 still persist.

Further work could be done to investigate the inflow rates that each of these bar types could sustain, and combining this with the gas availability could show why weak bars do not correlate with AGN presence as much as strong bars, as if they cannot provide as high an inflow rate as strong bars, they require more gas to trigger an AGN.

High-resolution IFU data will allow us to measure star-formation rates of the AGN-host galaxies, and thus draw comparisons between AGN and non-AGN hosts, both in starforming and quiescent galaxies. X-ray data will allow investigation of black hole accretion rates, and spectroscopy along the axes of the bar will allow bar inflow rates to be obtained.

This phenomenon will also be investigated at more distant redshifts (Margalef-Bentabol 2023, Margalef-Bentabol et al., in prep.), along with how these AGNs are fuelled as the bar fraction decreases out to higher redshifts. Facilities such as Euclid will provide us with greater sky coverage at better resolution than currently available, and so with an increase in data, we should be able to reduce noise in our samples.

5 CONCLUSIONS

We have investigated the influence of large-scale bars on the likelihood of AGN signals in a volume-limited sample of 48,871 disc galaxies by analysing data from the DESI catalogue, Galaxy Zoo DESI morphologies, and SDSS emission line strengths. We have taken care to control for differences in stellar mass and galaxy colour distributions between subsamples of strongly barred, weakly barred, and unbarred galaxies.

99.9 per cent of our 3164 AGN in disc galaxies are identified via optical emission line diagnostics, with a mere 4 AGN only detectable via WISE infrared colours within our volume limit. We divide galaxies without clear AGN activity into multiple categories based on the detection of emission lines in SDSS spectra, and focus our comparison with the AGN host galaxies on two inactive categories: 28,807 star forming galaxies with detected nebular emission lines below the “composite” limit on an emission line ratio diagram, and 712 “undetermined” galaxies where nebular emission lines are not robustly detected in the central fibre spectra. These latter galaxies are, on visual inspection, predominantly red spirals, with a smaller fraction being discs that have red/quenched inner regions and bluer outer regions.

Our key findings can be summarised as follows:

- Strongly barred galaxies are more likely to host an AGN than weakly barred galaxies, which in turn are more likely to host an AGN than unbarred galaxies.
- This effect is very slight, with the fraction of AGN in each bar category being, \( f_{\text{AGN,SBAR}} = 31.6 \pm 0.9 \), \( f_{\text{AGN,WBAR}} = 23.3 \pm 0.0 \) and \( f_{\text{AGN,UBAR}} = 14.2 \pm 0.6 \).

The high levels of statistical significance achieved here even after controlling for the confounding effects of colour, stellar mass, and flux limits, have been facilitated by the advent of large sample sizes from the latest generation of extragalactic surveys and the highly accurate and detailed morphological identifications of strongly barred, weakly barred, and unbarred disc galaxies. In the near future we expect to use data from surveys such as Euclid and LSST to extend these analyses to higher redshift and further refine our understanding of the interplay between various types of disc instabilities and growing supermassive black holes.

DATA AVAILABILITY

The data from GZD is available in Walmsley et al. (2023a)

Other catalogues used are publicly available from the following locations:

- MPA-JHU: https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/
- NYU-VAGC: http://sdss.physics.nyu.edu/vagc/
- DESI Legacy Surveys: https://www.legacysurvey.org/dr10/description/

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Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation...
The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; Proposal ID #2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Prop. ID #2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall z-band Legacy Survey (MzLS; Prop. ID #2016A-0453; PI: Arjun Dey). DECaLS, BASS and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, NSF’s NOIRLab; the Bok telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NOIRLab. Pipeline processing and analyses of the data were supported by NOIRLab and the Lawrence Berkeley National Laboratory (LBNL). The Legacy Surveys project is honored to be permitted to conduct astronomical research on iolkam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

NOIRLab is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. LBNL is managed by the Regents of the University of California under contract to the U.S. Department of Energy.

This project used data obtained with the Dark Energy Camera (DECam), which was constructed by the Dark Energy Survey (DES) collaboration. Funding for the DES Projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundacao Carlos Chagas Filho de Amparo, Financiadora de Estudos e Projetos, Fundacao Carlos Chagas Filho de Amparo a Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovações, the Deutsche Forschungsgemeinschaft and the Collaborating Institutions in the Dark Energy Survey. The Collaborating Institutions are Argonne National Laboratory, the University of Chicago, University of Notre Dame, University of Pennsylvania, University of Pittsburgh, University of California at Santa Cruz, the University of Washington, Brookhaven National Laboratory, the University of Pennsylvania, the University of Toronto, Lawrence Berkeley National Laboratory, the University of Illinois at Urbana-Champaign, the Lawrence Livermore National Laboratory, the University of Arizona, the University of Washington, the University of Heidelberg, the Max-Planck-Institute for Astronomy, the Max-Planck-Institute for Astrophysics, the University of Melbourne, the Leibniz-Institut für Astrophysik Potsdam, the Institut de Fisica d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig Maximilians Universität München and the Max-Planck-Institut für Extraterrestrische Physik, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zurich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l’Espai (IEEC/CSIC), the Institut de Física d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig Maximilians Universität München and the associated Excellence Cluster Universe, the University of Michigan, NSF’s NOIRLab, the University of Nottingham, the Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

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Software

This research has made use of TOPCAT (Taylor 2005), an interactive graphical tool for analysis and manipulation of tabular data.

This research has made extensive use of the following Python packages:

- **Matplotlib**, a 2D graphics package for Python (Hunter 2007).
- **NumPy** (Harris et al. 2020), a package for scientific computing.
- **Scipy** (Virtanen et al. 2020), a package for fundamental algorithms in scientific computing.

REFERENCES

Astropy Collaboration et al., 2018, AJ, 156, 123
APPENDIX A: SUBSAMPLE COUNTS

Table A1 presents the full set of number counts of all subsamples in this work. While our analysis is confined to the volume-limited sample, we also present numbers for the full set of GZD classified galaxies which also have ancillary data presented in the MPA-JHU and NYU-VAGC catalogues.

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Tab. A1 presents the full set of number counts of all subsamples in this work. While our analysis is confined to the volume-limited sample, we also present numbers for the full set of GZD classified galaxies which also have ancillary data presented in the MPA-JHU and NYU-VAGC catalogues.
Figure B1. The distributions in stellar mass and $g - r$ colour for a variety of subsamples, with strongly barred galaxies in solid lines, unbarred in dotted lines and weakly barred in dashed lines. AGNs are in teal, star-forming in red, composite in orange and undetermined in navy blue.

APPENDIX B: FULL STELLAR MASS AND COLOUR DISTRIBUTIONS

Fig. B1 shows an identical plot to that in Fig. 4, with the addition of the distributions in mass and colour for weakly barred galaxies for completeness.