A BREAK IN SPIRAL GALAXY SCALING RELATIONS AT THE UPPER LIMIT OF GALAXY MASS

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ABSTRACT

Super spirals are the most massive star-forming disk galaxies in the universe (Ogle et al. 2016, 2019). We measured rotation curves for 23 massive spirals and find a wide range of fast rotation speeds (240–570 km s$^{-1}$), indicating enclosed dynamical masses of $0.6-4 \times 10^{12} M_{\odot}$. Super spirals with mass in stars $M_{\text{stars}}/M_{\odot}>11.5$ break from the baryonic Tully-Fisher relation (BTFR) established for lower mass galaxies. The BTFR power-law index breaks from 3.75 ± 0.11 to 0.25 ± 0.41 above a rotation speed of $\sim340$ km s$^{-1}$. Super spirals also have very high specific angular momenta that break from the Fall (1983) relation. These results indicate that super spirals are undermassive for their dark matter halos, limited to a mass in stars of $M_{\text{stars}}/M_{\odot}<11.8$. Most giant elliptical galaxies also obey this fundamental limit, which corresponds to a critical dark halo mass of $M_{\text{halo}}/M_{\odot} \approx 12.7$. Once a halo reaches this mass, its gas can no longer cool and collapse in a dynamical time. Super spirals survive today in halos as massive as $M_{\text{halo}}/M_{\odot} \approx 13.6$, continuing to form stars from the cold baryons they captured before their halos reached critical mass. The observed high-mass break in the BTFR is inconsistent with the Modified Newtonian Dynamics (MOND) theory (Bekenstein & Milgrom 1984).

1. INTRODUCTION

Super spiral galaxies are extreme by many measures, with r-band luminosities of $L = 8-14L^*$, stellar masses of $M_{\text{stars}} = 2-6 \times 10^{11} M_{\odot}$, and giant isophotal diameters of $D_{25} = 55-134$ kpc (Ogle et al. 2016, 2019). They represent a very rare population of massive disk galaxies in which star formation has not quenched. As such, they provide a unique opportunity to extend studies of galaxy scaling laws into an entirely new regime.

The discovery of flat, high-velocity rotation curves firmly established the presence of dark matter in galaxies (Bosma 1978, Rubin et al. 1978). Dark matter halos (White & Rees 1978, Navarro et al. 1997, Gao et al. 2008) are fundamental to galaxy formation, forming the scaffolding for gas accretion and star formation. Though the composition of dark matter remains unknown, it is a crucial component of A-Cold Dark Matter (ACDM) cosmology, describing the expansion history of the universe. The rotational angular momenta of galaxies may be imparted by torques on their primordial dark matter halos by the surrounding irregular matter distribution prior to their collapse (Fall 1979, Fall & Efstathiou 1980). When the baryons cool and collapse, they spin up, retaining most of their original angular momentum. The specific angular momentum of galaxies generally increases following the Fall (1983) relation $j_v \sim M_{\text{stars}}^{0.6}$.

The high rotation speeds of galaxies have alternatively been attributed to a breakdown in Newtonian dynamics in the regime of low gravitational acceleration (Milgrom 1983, Lelli et al. 2017). In particular, the Modified Newtonian Dynamics theory (MOND) suggests a specific form for the gravitational potential that leads to flat rotation curves and obviates the need for dark matter (Bekenstein & Milgrom 1984).

The Tully-Fisher relation (TFR, Tully & Fisher 1977) between galaxy optical (B-band) luminosity and H I line width has played an important role in galaxy evolution studies and mapping galaxy peculiar velocities in the local universe (e.g., Willick et al. 1997, Haynes et al. 1999, Freudling et al. 1999, Springob et al. 2007, Tully et al. 2010). Substituting I-band or mid-infrared (MIIR) for B-band photometry reduces the scatter in the TFR because of reduced extinction and smaller scatter in mass-to-light ratio (e.g., Giovannelli et al. 1994, Tully & Curtois 2012, Lagatutta et al. 2013, Sorce et al. 2013, Neill et al. 2014, Zaritsky et al. 2014, Lelli et al. 2016). The resultant infrared Tully-Fisher relation (ITFR) relates mass in stars $M_{\text{stars}}$ to the rotation velocity and gravitational potential of the baryonic plus dark dynamical mass within radius $r$: $M_{\text{dyn}}(r) \sim r v_r^{\text{rot}}$.

For spiral galaxies with $M_{\text{stars}} = 10^{10} - 10^{11} M_{\odot}$, the ITFR has a power-law index of $3.75 \pm 0.11$ (Lelli et al. 2016). This is greater than the index of 3.0 that would be predicted under the assumption of constant stellar mass fraction (McGaugh et al. 2012), indicating that star-formation efficiency increases with $M_{\text{dyn}}$ for galaxies in this mass range. Massive spiral galaxies with $M_{\text{stars}} \sim 10^{11} M_{\odot}$ may be the most efficient at converting gas into stars, with low gas fractions and high stellar mass fractions that approach the cosmic baryon fraction of 0.167 (Posti et al. 2019a, b, Komatsu et al. 2009). Adding in the neutral gas masses of spirals gives a tighter
relation that removes the low-mass break in the TFR for
dwarf galaxies (McGaugh et al. 2000, 2012; Lelli et
al. 2016). This baryonic Tully-Fisher relation (BTFR)
demonstrates a strong connection between the cold bary-
onic (stars + cold atomic and molecular gas) and dark
matter content of spiral galaxies. The slope and scatter
of the BTFR depend in detail on the prescription used
to estimate the mass-to-light ratio of stars and which
galaxy samples are selected (McGaugh & Schombert
2015; Sorce & Guo 2016; Ponomareva et al. 2018). Evidence
for a flatter TFR slope is found for high-redshift
galaxies (Christensen & Hjorth 2017). However, MOND
predicts a BTFR slope of exactly 4.0, and any deviation
from this is at odds with that theory.

The shape of the TFR should reflect that of the
stellar-mass/halo-mass (SMHM) relation, constructed by
matching galaxies drawn from the observed luminosity
function to simulated dark halos and subhalos (Kravtsov
et al. 2004; Hopkins et al. 2010; Moster et al. 2013;
Behroozi et al. 2013). The SMHM relation has a char-
acteristic break at log \( \frac{M_{\text{stellar}}}{M_\odot} \approx 10.5 \), corresponding
to the observed break in the Schechter (1976) luminosity
function at \( L^\star \). Since the dark matter halo mass function
is scale-invariant, this break in star formation efficiency
must reflect the baryonic physics of galaxy formation and
evolution. It is commonly attributed to a transition from
stellar feedback to AGN feedback dominance (e.g., Dekel
& Birnboim 2006; Croton et al. 2006; Schaye et al.
2015; Su et al. 2019). However, the BTFR does not
show a break at the same scale (Trujillo-Gomez et al.
2011; Desmond 2012), pointing to a different SMHM
relation for spirals and ellipticals (Posti et al. 2019b).

Previous studies of the BTFR have been limited to
galaxies with stellar masses \(< 2 \times 10^{11} \, M_\odot\), because galax-
ies with higher masses are quite rare and because it is
difficult to detect H I at \( z > 0.1 \). The extreme stellar
masses and sizes of super spirals allow us to probe spiral
disk dynamics and massive galaxy dark matter halos at
radii of up to \( \sim 50 \, \text{kpc} \). We use optical long-slit spec-
troscopy of the H\alpha line to measure the rotation curves
of 23 massive spirals and place them on the BTFR.

We assume a LCDM cosmology with \( H_0 = 70 \, \text{km s}^{-1}
\text{Mpc}^{-1} \), \( \Lambda = 0.7 \) and \( \Omega = 0.3 \) to derive all distances,
linear sizes, and luminosities.

2. SAMPLE AND OBSERVATIONS

We selected our rotation curve sample (Table 1) from
color-selected samples selected by \( r \)-band or \( K_s \)-band luminos-
ity. First, we selected galaxies with inclination \( i > 39^\circ \)
from the OGC sample of super spirals with \( z < 0.3 \) and Sloan Digital Sky Survey (SDSS) \( r \)-band luminosity
\( > 8L^\star \) (Ogle et al. 2019). Next, because extinction
in the disk limits the number of high-inclination galaxies
in the OGC, we created a new sample of IR-selected
massive spirals drawn from the set of 2 Micron All-Sky
Survey Extended Source Catalog (2MASX) galaxies with
SDSS-measured redshifts, \( i > 39^\circ \), \( K_s \)-band luminosity
\( L(K_s) > 2 \times 10^{11} L_\odot(K_s) \), and \( r \)-band isophotal diameter
\( D_{25} > 50 \, \text{kpc} \). The \( K_s \)-band luminosity and \( D_{25} \) criteria
were designed to yield a sample that overlaps Ogle et al.
(2019) super spirals, which have \( M_{\text{stars}} > 2 \times 10^{11} M_\odot \)
and \( D_{25} > 55 \, \text{kpc} \).

We observed 3 massive spirals with the Double Spectro-
tograph (DBSP) on the Hale Telescope and 20 with the
Robert Stobie Spectrograph (RSS; Burgh et al. 2003;
Kobulnicky et al. 2003) on the Southern African Large
Telescope (SALT; Buckley et al. 2006). We placed a 1\"
wide, long slit along the \( r \)-band major axis of each
galaxy. We used the DBSP red 1200 line mm\(^{-1}\) grating,
yielding a dispersion of 0.300 \( \text{A} \) pixel\(^{-1}\) and a resolv-
ing power of 6000. The spectral resolution is 50 \( \text{km s}^{-1} \)
at H\alpha and the plate scale is 0\'\'293 pixel\(^{-1}\). At SALT, we
used the RSS p1800 line mm\(^{-1}\) holographic grating to-
gether with the pc04600 order blocking filter. With 2x2
pixel on-camera binning, this grating gives a resolv-
ing power of 4200 -- 5300. The spectral resolution is 71 - 57
\( \text{km s}^{-1} \) at H\alpha and the plate scale is 0\'\'254 pixel\(^{-1}\).

Exposures were median-combined to remove cosmic
ray tracks, yielding exposure times of 30-70 minutes.
Spectra were rectified and wavelength-calibrated using
image-sky lines. We subtracted sky foreground emission
using regions above and below the spectra. Galaxy
continuum profiles were measured from adjacent spectral
continuum regions, scaled and subtracted. The resulting
2D spectra were median-filtered with a 3x3 pixel kernel
to improve S/N. We measured the rotation curve (Fig.
1) from the weighted centroid wavelength of the H\alpha emis-
sion line, up-weighting high-surface brightness regions to
mitigate the effect of dilution from regions at lower pro-
jected velocity inside the slit. This diluting emission can
be seen as fainter emission at lower velocity (Fig. 1b).
The zero point of the rotation curve was set to minimize the
asymmetry between the approaching and receding
sides. The rotation curve was then sampled at int-
ervals of 1\"0 -- 1\"5, to match the seeing conditions and the maximum rotation speed \( v_{\text{max}} \) measured from the sampled rotation curve. The standard deviation of the
difference between the rotation curve and its spline
interpolation gives the uncertainty in the rotation speed
at the sampled points. The smaller linear size of the H\alpha
disks compared to the H I disks of spiral galaxies does
not produce any significant difference between their optical and H I velocity widths (Kannappan et al. 2002),
allowing a direct comparison.

3. ROTATION SPEED AND DARK MATTER CONTENT

We find de-projected super spiral maximum rotation
speeds of \( v_{\text{max}} = 243-568 \, \text{km s}^{-1} \) at radii of \( r = 14 - 54 \, \text{kpc} \) (Table 1). The rotation curves of most super
spirals follow the typical pattern of rising from the galaxy
center, then flattening at large radii. In two cases (OGC
1304 and OGC 0586), deviations from regular rotation
are seen, indicating that the disks may be warped at their
outer edges. We conservatively discard these edge points
before measuring \( v_{\text{max}} \). The rotation curves of the two
largest, most massive galaxies (OGC 0139 and 2MFGC
12344) continue to rise at the outer edge. This may lead
to an underestimate of the maximum circular velocity.
The galaxy OGC 0139 also has a high uncertainty of 90
\( \text{km s}^{-1} \) in \( v_{\text{max}} \) because of the large velocity dispersion
in two blobs at either edge of its rotation curve.

We separately integrate the gravitational potential
from stars and gas (both assumed to lie in a thin disk)
and a spherical dark matter halo following a Navarro,
Frenk, & White (NFW) density profile (Navarro et al.
18) SALT programs 2018-2-SCI-027, 2019-1-SCI-028, PI: T. Jar-
rett
We use two methods to estimate $M_{\text{stars}}$ and compare their scatter relative to one another and the resulting scatter in the TFR. First, we estimate $M_{\text{stars}}$ from our custom WISE $W_1$-band (3.4 μm) photometry, assuming $M_{\text{stars}}/L_{W_1} = 0.6$. Our measurements are in good agreement with $M_{\text{stars}}$ estimated by Lelli et al. (2016) for their sample from Spitzer IRAC [3.6]-band luminosity and $M_{\text{stars}}/L_{3.6} = 0.5$, with scatter driven by photometric uncertainties of 2–5%. Next, we estimate $M_{\text{stars}}$ from WISE $W_1$-band luminosity and $M_{\text{stars}}/L_{W_1}$ estimated from $W_1 - W_2$ color, using the prescription of Cluver et al. (2014). This empirical relation was derived by comparing $W_1$-band luminosity to stellar mass estimated via stellar-population synthesis models (Lay- lor et al. 2011). This estimate is systematically offset from the constant $M/L$ estimate, yielding lower $M_{\text{stars}}$ values and a significant difference in slope for the TFR.

In summary, we find indications of baryon depletion in massive spiral galaxies, providing a potential explanation for the observed failures of cosmological mass estimates. The expected baryonic mass limit for these galaxies is lower than the observational limits, challenging the standard cosmological picture. Our results suggest that future observational campaigns should focus on understanding the processes that lead to baryon depletion in these systems.
most efficient, converting up to 70% of that into stars.

We find that super spirals with $v_{\text{rot}} > 340$ km s$^{-1}$ deviate from the established BTFR, with relatively low $M_0$ for their high rotation velocities (Fig. 2(a)). Including these galaxies, the BTFR breaks at a characteristic mass scale of $\log M_0/M_\odot \approx 11.5$. Fitting the BTFR for the 10 fastest rotating super spirals gives a power-law slope of 0.25 ± 0.41 that is much flatter than the low-mass BTFR of 3.75 ± 0.11 found by Lelli et al. (2016). Fitting all 23 massive spirals gives a power-law slope of 1.64 ± 0.30. The slopes for these two fits differ by 8σ and 7σ, respectively, from the low-mass BTFR slope. We emphasize that this high-mass break in the BTFR was not readily apparent before the discovery of extremely massive, fast-spinning super spirals, which are extremely rare (Ogle et al. 2016, 2019).

The large departure of super spirals from a power-law BTFR with slope 4.0 is inconsistent with MOND. The only way to reconcile our observations with MOND is a break in both relations is found at a critical stellar mass of $\log M_{\text{stars}}/M_\odot = 11.5$ (dashed lines). This is a factor of 10 greater than the characteristic mass of $\log M_{\text{stars}}/M_\odot = 10.5$ at the break in the galaxy SMHM relation. a) BTFR. Masses in stars for the super spiral and comparison samples are estimated using custom WISE W1-band photometry, assuming $M/L = 0.6$. The photometric uncertainty is smaller than the size of the plot symbols (0.01-0.02 dex). Gas masses for the comparison samples are estimated as $M_{\text{gas}} = 1.33 \times M_\text{HI}$ (Lelli et al. 2016) Catinella & Cortese 2015, while gas masses for our sample are estimated using the Kennicutt (1998) Schmidt law, with uncertainties < 0.05 dex (see main text). The observed BTFR (data points) is compared to the Lelli et al. (2016) power-law fit (solid line) and the $v_\text{rot}^3$ power-law for baryon fraction equal to the cosmic mean value (dotted line). b) Fall (1983) relation between galaxy specific angular momentum and mass in stars. The specific angular momenta of our sample galaxies are estimated by: $j_* = 2R_d v_{\text{rot}}$. We compare to disk-dominant spirals with bulge-to-disk mass ratios $b_t < 0.15$ and bulge-dominant ($b_t > 0.70$) ellipticals from Fall & Romanowsky (2013, 2018) and spirals and dwarf irregulars from Posti et al. (2018). Super spirals have exceedingly high specific angular momenta compared to lower mass spirals and deviate from the Fall relation (purple dotted line; Fall & Romanowsky 2018). The relation for elliptical galaxies is steeper and offset to lower $j_*$. Hence, super spirals are probing a regime where MOND would apply if it were correct. However, the radial accelerations observed in super spiral disks are greater than the MOND prediction, reflecting their high rotation speeds and deviation to the right of the MOND-predicted BTFR.

The specific angular momentum of galaxies increases with $M_{\text{stars}}$, following the Fall (1983) relation $j_* \sim M_{\text{stars}}^{0.5}$ (Fig. 2b), which is related to the BTFR via the $M_{\text{stars}}$-radius relation. The power-law index of this scaling relation for spirals ($\alpha = 0.58 \pm 0.10$) and for ellipticals ($\alpha = 0.83 \pm 0.16$) differ from the theoretical index for dark matter halos ($\alpha = 2/3$), reflecting differences in angular momentum retention for the two types of galaxy (Fall & Romanowsky 2013, 2018 and Posti et al., 2018). We estimate the specific angular momentum for our sample of super spirals as $j_* = 2v_{\text{rot}} R_d$, which holds true for pure exponential disks with characteristic radius $R_d$. We take $R_d$ from Simard et al. (2011), who fit the SDSS images with DeVaucouleurs bulges plus exponential disks. We compare our sample to the spiral and elliptical samples of Fall & Romanowsky (2013, 2018) and the spiral and dwarf sample of Posti et al. (2018), the latter drawn from the Lelli et al. (2016) BTFR sample. We find very high specific angular momenta which break from the Fall relation at $\log M_{\text{stars}}/M_\odot = 11.5$, similar to the break we find in the Tully-Fisher relation. The Fall relation connects galaxy spin to halo spin, allowing us to estimate the dark halo mass of super spirals. The halo masses that
Table 1

| Name | Alt. Name | z | D25 | R_c | log M_{dark} | log M_{stars} | log M_{gas} | log SFR | v_max | r (kpc) |
|------|----------|---|-----|-----|-------------|--------------|-------------|---------|-------|--------|
| 2MASX J09394584+0845033 | ... | 0.13674 | 76 | 11.1 | 62 | 11.9 | 11.45 | 10.7 | 1.44 | 322 (9) |
| SDSS J095727.02+083501.7 | OGC 0441 | 0.25652 | 88 | 17.0 | 39 | 12.1 | 11.60 | 10.4 | 1.03 | 444 (15) |
| 2MASX J10222648+0911396 | ... | 0.09130 | 92 | 14.5 | 76 | 11.8 | 11.42 | 10.5 | 1.22 | 311 (12) |
| 2MASX J10304263+0418219 | OGC 0926 | 0.16092 | 70 | 8.7 | 48 | 11.7 | 11.66 | 10.7 | 1.53 | 342 (12) |
| 2MASX J11052843+0736413 | 2MFGC 08638 | 0.15229 | 144 | 47.0 | 85 | 12.5 | 11.59 | 10.8 | 1.38 | 465 (13) |
| 2MASX J11232039+0100029 | ... | 0.14454 | 104 | 18.9 | 79 | 12.1 | 11.43 | 10.6 | 1.25 | 436 (11) |
| 2MASX J11483552+0325268 | ... | 0.11984 | 88 | 17.3 | 80 | 11.9 | 11.42 | 10.5 | 1.13 | 324 (12) |
| 2MASX J11535621+4923562 | OGC 0586 | 0.16673 | 90 | 15.7 | 63 | 11.5 | 11.64 | 10.8 | 1.58 | 305 (11) |
| 2MASX J12242564+0056492 | ... | 0.07936 | 52 | 6.8 | 54 | 11.4 | 11.24 | 10.2 | 1.01 | 279 (10) |
| 2MASX J12592630-0146580 | ... | 0.08311 | 67 | 10.4 | 61 | 11.8 | 11.23 | 10.2 | 0.91 | 318 (10) |
| 2MASX J13003075-0214004 | 2MFGC 10372 | 0.08425 | 71 | 8.3 | 82 | 11.8 | 11.60 | 10.7 | 1.55 | 344 (6) |
| SDSS J144917.12+003028.6 | OGC 1312 | 0.27991 | 75 | 11.6 | 63 | 11.9 | 11.60 | 10.7 | 1.55 | 344 (6) |
| 2MASX J15154614+0214004 | 2MFGC 10372 | 0.08425 | 71 | 8.3 | 82 | 11.8 | 11.60 | 10.7 | 1.55 | 344 (6) |
| 2MASX J15204057-0009331 | ... | 0.07830 | 71 | 12.2 | 67 | 11.8 | 11.39 | 10.4 | 1.10 | 304 (8) |
| 2MASX J16014061+2718161 | OGC 1304 | 0.16440 | 82 | 11.4 | 59 | 12.1 | 11.74 | 10.7 | 1.35 | 568 (16) |
| 2MASX J16184003+0034367 | ... | 0.16731 | 95 | 24.6 | 77 | 12.0 | 11.67 | 10.6 | 1.28 | 384 (16) |
| 2MASX J16394598+4609058 | OGC 0139 | 0.24713 | 134 | 33.0 | 76 | 12.2 | 11.74 | 10.9 | 1.65 | 483 (90) |
| 2MASX J20541957 | ... | 0.16731 | 95 | 24.6 | 77 | 12.0 | 11.67 | 10.6 | 1.28 | 384 (16) |
| 2MASX J21431882-0055204 | OGC 0139 | 0.08291 | 60 | 8.5 | 58 | 11.8 | 11.20 | 9.9 | 0.50 | 299 (12) |
| 2MASX J22073122-0729223 | ... | 0.06331 | 60 | 8.6 | 73 | 11.6 | 11.20 | 10.3 | 1.00 | 243 (13) |
| 2MASX J22130513-0033477 | ... | 0.11107 | 53 | 8.2 | 53 | 11.6 | 11.20 | 10.3 | 1.03 | 292 (8) |

Figure 3. Star-forming main sequence (SFMS) (adapted from Ogle et al. [2019], with our rotation curve sample, BTFR comparison samples, and Galaxy Zoo (GZ) early type and late type galaxies over-plotted. The observed cosmic mass limit for spiral galaxies at log M_{stars} = 11.8 is indicated by the vertical dotted line. Super spirals fall along an extrapolation of the Ogle et al. [2007] relation. Most giant ellipticals and lenticulars in the Ogle et al. [2019] sample respect the cosmic mass limit for spiral galaxies. The ones that do not may be the product of major mergers.

5.2. Galaxy Mass Limit

We suggest that the high-mass breaks in the BTFR and the Fall relation at log M_{stars}/M_{⊙} ≈ 11.5 are imposed by an upper limit to the cold baryonic mass in galaxies. Including our sample and the super spiral sample of Ogle et al. [2019], we find a maximum baryonic mass of M_{b,max} = 6.3 \times 10^{11} M_{⊙} (log M_{b,max}/M_{⊙} = 11.8) for super spiral OGC 0139, which is slightly more massive than the previous record-holder, ISOHDFS:[RFA2002] S27 (Rigopolou et al. 2002). The same mass upper limit may apply to elliptical and lenticular as well as spiral galaxies. The majority of OGC giant ellipticals and super lenticulars (Ogle et al. 2019) do have M_{stars} lower than the most massive super spiral (Fig. 3). We suggest that the giant ellipticals and super lenticulars that exceed the limit (by up to a factor of 2) may be the product of major mergers.

The observed upper limit to galaxy mass in stars agrees with the theoretical prediction of the maximum halo mass where gas can cool and collapse within a dynamical time (White & Rees 1978), but only if we assume that nearly all of the baryons in super spiral and giant elliptical subhalos have been incorporated into stars at the current epoch. For an initial power-law density perturbation spectrum with amplitude \propto M^{-1/3} and no metal enrichment, White & Rees (1978) predict a maximum
galaxy halo mass of $\log M_{\text{max}}/M_\odot \approx 12.7$, which is close to the maximum enclosed dark mass in our super spiral sample ($\log M_{\text{d,max}}/M_\odot = 12.5$). For a stellar mass fraction equal to $\sim 70\%$ of cosmic baryon fraction, this corresponds to the observed maximum mass in stars of $\log M_{\text{stars,max}}/M_\odot = 11.7$.

The excess specific angular momentum in super spirals can be explained if it is inherited from host halos that are up to 10 times more massive than $M_{\text{max}}$. In general, sub-halos will have lower $j_*$ values than their host halos, following the Fall relation, and when they merge they will create even lower $j_*$ elliptical galaxies. However, a dominant central galaxy may share the specific angular momentum of its host halo if it is formed at the halo center and subsequently cools and collapses to form a high-$j_*$ super spiral.

The continuing star formation in massive spirals appears to buck the trend of star-formation quenching in galaxies with $L > L^*$. This so-called "failed feedback" problem [Posti et al. (2019b)] may be resolved if these massive spiral galaxies are immune to quenching. The super spirals that have survived must be robust against the various proposed quenching agents, including mergers, AGN feedback, virial shocks, and ram-pressure stripping. If super spirals formed in dominant subhalos located at the centers of group-mass halos, they must not have suffered major mergers after the bulk of their stars were formed, and are not subject to ram-pressure stripping. The giant gas disks of super spirals must also be immune to disruption by AGN feedback from the supermassive black holes in their relatively small bulges.

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