On the Angular Momentum History of Galactic Disks

Alvio Renzini

1 INAF - Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Accepted March 24, 2020; Received February 7, 2020, in original form

ABSTRACT

The stellar mass, size and rotational velocity of galactic disks all grow from redshift \( z \approx 2 \) to the present by amounts that are estimated from observationally derived scaling relations. The product of these three quantities, the angular momentum of stellar disks, is then estimated to grow by a remarkably large factor, between \( z \approx 20 \) and \( z \approx 50 \), whereas other evidences suggest a more moderate increase. This requires that the specific angular momentum of the accreted gas should systematically increase with time while remaining co-rotational with the disk over most of the last \( z \approx 10 \) Gyr. Thus, the baryonic gas vorticity of the circumgalactic medium appears to emerge as a major driver in galaxy evolution, and this paper is meant to attract attention on the sheer size of the angular momentum increase and on the need to explore to which extent this can be observed in nature and/or in simulations.

Key words: galaxies: evolutionn – galaxies: formation – galaxies: high redshift

1 INTRODUCTION

Most galaxies in the local Universe are rotationally supported and since they grew from small seeds to giant dimensions their stellar angular momentum (hereafter AM, or \( J_\star \)) must have grown accordingly. Yet, the AM evolution of individual galaxies remains largely unexplored. In a recent paper (Peng & Renzini 2020, hereafter PR20) we have argued that the stellar AM of galaxies that remain star-forming all the way to the present should increase by a very large factor over the last \( z \approx 5 \) Gyr. Thus, the baryonic gas vorticity of the circumgalactic medium appears to emerge as a major driver in galaxy evolution, and this paper is meant to attract attention on the sheer size of the angular momentum increase and on the need to explore to which extent this can be observed in nature and/or in simulations.

The size of the AM increase follows directly from the scaling relations for star-forming galaxies to their implied history of AM growth, to finally asking what physical conditions may have ensured such growth, including the extent to which they may have been established in relevant simulations.

The size of the AM increase follows directly from the scaling relations for galaxies that remain close to the main sequence (MS) in the course of their evolution, as the AM of a galaxy is:

\[
J_\star \propto M_\star R_h v_{\text{rot}},
\]

where the three factors represent the stellar mass, the half-mass radius and the rotational velocity, respectively.

We start by briefly recapping the PR20 estimate of the AM evolution, though with slightly different numbers. From the specific star formation rate (sSFR) of MS galaxies evolving as \( \sim (1 + z)^{1.8} \), PR20 argue that on average star-forming galaxies increase their stellar mass by a factor \( \sim 10 \) since \( z \approx 2 \) thought the size of such increase is very sensitive to the actual zero point of the MS relation (Renzini 2009). Moreover, the extent to which the MS bends at high stellar masses still differs substantially from one study to another (Popesso et al. 2019), which adds further uncertainty to the result of the MS integration. An alternative way of estimating the typical mass increase of MS galaxies rests on the consideration that the cosmic stellar mass density (in \( M_\odot\,\text{cm}^{-3} \)) increases by a factor \( \approx 4 \) since \( z \approx 2 \) (Madau & Dickinson 2014), whereas the shape of the mass function of star-forming galaxies does not change much over the corresponding time interval (e.g., Peng et al. 2013, Ilbert et al. 2013, Muzzin et al. 2013). Thus, an increase by a factor of \( \sim 4 \) represents a strict lower limit to the mass increase of individual MS galaxies. Indeed, at \( z \approx 2 \) most galaxies are still star forming near the MS whereas at \( z = 0 \) over 50 percent of stellar mass resides in quenched galaxies. Since only star-forming (MS) galaxies contribute to the increase of the cosmic stellar mass density, each of them has to increase its stellar mass by more than a factor of 4, so to compensate for those galaxies that cease to contribute as they quench. Thus, a fair estimate of the average stellar mass increase is by a factor \( \approx 8 \), or just a little less than that, with a decreasing trend for the most massive galaxies.
over, at fixed stellar mass, no sAM evolution since
$z = 2$, as fixed stellar mass, plus the
effect of the mass increase by a factor of $\sim 8$ implying
an additional increase by a factor $\sim 1.5$, making a total of
$\sim 4.5$ times for the typical size increase of individual disks.
Concerning the third factor in $J_*$, the rotational velocity $v_{rot}$
of individual MS galaxies increases by a factor $\sim 1.5$ since
$z \simeq 2$ (Simons et al. 2017), an effect that was mentioned,
but neglected, in PR20. In summary, the resulting AM in-
crease is by a factor $\sim 8 \times 4.5 \times 1.5 \simeq 50$. The dominant factor
is the mass increase, which is perhaps the less constrained
one by direct observations. If one adopts the factor of 4 as a
lower limit, then the increase in AM is still by a factor $\sim 20$.
Clearly, further refining the scaling relations for the three
quantities in Equation (1) is of great importance for a re-
duction of the uncertainty in the size of the AM evolution.
Moreover, it is worth emphasizing that not only the total
AM of disks increases with time, but so does also their spe-
cific AM (sAM), as from Equation (1) $J_*/h = J_*/M_\star \propto R_0/v_{rot}$
and this latter product increases by a factor $\sim 6$ since red-
shift $2$, if the adopted scaling is correct. This factor applies
to the sAM of the whole stellar disk, therefore implying that
the sAM of the gas being accreted (and turned into stars)
must secularly increase by an even much larger factor over
the same time interval.

As emphasized in PR20, this macroscopic increase in
the AM of galactic disks requires a systematic increase with
time of the AM of the gas being accreted from the envi-
ronment, coupled with the accretion itself being nearly co-
planar and co-rotating with the disks themselves. Thus, the
AM stored in the circumgalactic medium (CGM), actually
of the fraction of it which is actually accreted, drives the
growth of the disk. This rises a series of questions: is all
this really taking place in nature? What empirical evidence
does exist for it? What is the size and AM distribution
of the CGM domain having fed local galaxies? Do simula-
tions offer any hint in this respect? This paper does not offer
answers, it is rather meant to attract the attention on the
sheer size of the AM growth, hence on its implications for
the mechanisms that promote the growth of disks.

Yet, this large increase of the sAM is not expected in
the frame of canonical dark matter theory, that predicts the
sAM of disks to evolve as $\sim (H(z)/H_0)^{-1/3}$, corresponding
to a just $\sim 40$ per cent increase since $z = 2$, in agreement
with the results of the integral field spectroscopic survey of
$z \sim 1–3$ galaxies discussed by Burkert et al. (2010). More-
over, at fixed stellar mass, no sAM evolution since $z = 1$
is found by Maresco et al. (2019) in a subsample of galaxies
from same survey, though these galaxies may have been
originally selected for being among the most mature disks
at this redshift (N. M. Förster Schreiber, private communi-
cation). On the other hand, the radial growth rate of local
disks is estimated to be $\sim 0.35$ times that of the stellar mass
(Pezzulli et al. 2015), that if constant over time would
imply a size increase by a factor 2–3 for our estimated
mass increase since $z = 2$. Moreover, even the empirical
size scaling with redshift as from Eq. (2) may not imply
the full corresponding growth of individual galaxies, if smaller,
denser disks were more prone to quench than the bigger ones
(van Dokkum et al. 2015), hence implying an increase in the
average size of the surviving, star-forming disk. Thus, by
no means univocal evidence has yet emerged concerning the
evolution of the sAM.

2 DO GALAXY FILAMENTS DRIVE THE GROWTH OF DISKS?

This large increase of the AM of disks could not happen were
the gas accretion chaotic. It requires instead a long term co-
herence to maintain near co-planarity and co-rotation while
the AM of accreting gas has to increase with time. Thus,
what we need is a persistent structure around galaxies with
a naturally built-in organization that must be automatically
conducive to the required co-planarity and co-rotation of the
gas inflow with secularly increasing AM. Galaxy filaments
appear to be obvious candidates for making all this hap-
pening, as filaments naturally arise from the gravitational
instability of the (dark) matter distribution, hence setting
preferential directions.

However, for filaments to do the job their structure
should satisfy certain conditions that may or may not be
established in nature. Qualitatively, we may expect the bary-
onic gas to rotate around the axis of a filament, as it is
attracted by the filament gravitational pull, while roughly con-
serving the AM it may have acquired from tidal interactions
with other forming structures nearby. A gradient in specific
AM, perpendicular to the filament, will also naturally arise,
as the more distant material is expected to have experienced
stronger tidal interactions with its surroundings, though
cross section of filaments is typically of the order of a Mpc
(Tempel et al. 2014), much larger than galaxies. Such a rot-
ating baryonic cylinder would quite naturally administer
galaxies the raw material for their growth, with increas-
ing AM, hence growing disks whose rotational vector should
align with the filament. This would indeed be the predicted
signature of such a scenario, that can be subject to test in
observations and simulations.

Since Peebles (1969), tidal interactions are seen as the
origin of the AM of galaxies. This tidal-torque theory has
been widely explored (including its limitations) in partic-
ular with N-body simulations, to infer the spin (AM) of
dark matter halos (e.g., Porciani, Dekel & Hoffman 2002;
Hahn et al. 2007) and their tendency to form bigger and
bigger spheroidal halos. Encouragingly, Laigle et al. (2013)
and Codis, Pichon & Pogosyan (2013) find that the result-
ing vorticity of the dark matter tends to align with the fil-
aments. Yet, what matters here is the vorticity and AM of
the baryons and their tendency to dissipate and form (thin)
disks.

However, the observation of the dynamical configura-
tion of the gas in filaments is largely beyond our current
capabilities. Yet, in principle this is thoroughly observable
in simulations. The baryon inventory in cosmic knots, fila-
ments, sheets and voids in one such simulation has been re-
cently illustrated by Martizzi et al. (2019). They provide the

---

1 But see Lilly & Carollo (2016) for a different interpretation of
the apparent correlation between quenching and galaxy density

© 2002 RAS, MNRAS 000 [1]
distribution of the various gas phases among the mentioned structures also at different redshifts, but do not extract from the simulation how the gas moves within the filaments. This may come in a later paper by the same team.

Galaxy alignment (or lack of) with respect to filaments has been instead quite widely explored, both from direct observations and in simulations. In simulations, Dubois et al. (2014) find indeed that at $z = 1.8$ the spin vector of galaxies tend to align with filaments, and even more with the vorticity vector of the baryonic gas, as expected in this picture. But the signal is very weak, with only a $\sim 10\%$ per cent excess of alignments with respect to random, with the signal decreasing with cosmic time down to $z \sim 1.2$ and vanishing altogether by $z = 0$ in the same simulation (Codis et al. 2015). Moreover, the spin tends to orient orthogonal to the filaments above a critical mass ($\sim 3 \times 10^{10} M_{\odot}$), as a result of merging. In another simulation (Ganeshaiah Veena et al. 2019) preference for perpendicular alignment at all masses is found, though the simulated cosmic volume is considered insufficient. In essence, it appears that simulations produce some galaxy spin-filament alignment, but too weak to claim support for our ansatz of gas filament global vorticity being the prime driver for the growth of galactic disks.

On the observational side, on SDSS, hence $z \sim 0$ data, Tempel, Stoica & Saat (2013) and Tempel & Lesekind (2013) find the spin vector of spirals to be preferentially parallel to filaments whereas that of ellipticals is preferentially parallel to filaments, which implies a spin vector perpendicular to them, apparently at variance with the Tempel et al. findings (Krolewski et al. 2013) who find no clear alignment signal with the galaxy spin being derived from MaNGA integral field spectroscopy, whereas Blue Bird et al. (2020) find a prevalence of spin-filament alignments in a sample of ten late type galaxies whose spin direction is derived both for the stellar and the gas kinematics. These trends, modest spin-filament alignment for spiral/low mass galaxies and modest orthogonal alignment for elliptical/high mass galaxies is also found in the SAMI galaxy survey (Welker et al. 2020), basically in agreement with (most) previous studies over real data and simulations.

Thus, the bottom line is that, at all redshifts below $z \sim 2$, $\sim 90\%$ per cent of disk galaxies are randomly oriented with respect to their closest filament. It follows that the global vorticity on the scale of filaments does not seems to play a major role on the ordered growth of disks and their AM. So, if not the filaments, what else? Well, before abandoning the idea, a closer look to some of the above studies is in order. For example, Dubois et al. (2014) postulate that filaments have no polarity and do not distinguish between spin vector orientations in one or an opposite quadrant with respect to filament. In other words, the measured angle $\theta$ between the galaxy spin and the filaments is let to vary only between 0 and $\pi/2$, not between 0 and $\pi$, and $\cos \theta$ between 0 and 1, rather than between $-1$ and 1. So, in principle all the simulated galaxies could spin with their vectors pointing in the same half space with an average $\theta$ just a little smaller than $45^\circ$, which would correspond to a much stronger co-alignment. Indeed, the same authors relax the no-polarity assumption, allow $\theta$ to vary between 0 and $\pi$, and find a stronger co-alignment between the galaxy spin and the vorticity of the gas, with parallel spins being $\sim 50\%$ more frequent than antiparallel ones. This figure refers to the simulation at $z = 1.8$, that observationally corresponds to still an incipient phase in the establishment of orderly, rotationally-supported disks. Thus, it would be interesting to explore in the simulation to which extent the degree of this co-alignment increases towards lower redshifts, because observationally it is at lower redshifts that orderly-rotating disks become the dominant MS population and evidence exists for co-rotation of the CGM (Ho & Martin 2020; Martin et al. 2019; Zabl et al. 2019). Thus, a direct role of filaments in organizing baryon vorticity cannot be excluded at this stage, but the suspicion is that intra-filament galaxy-galaxy tidal effects may mess up the picture.

3 DISCUSSION

It is widely recognized that AM and its accretion must play an important role in galaxy evolution (e.g., Danovich et al. 2014; Stewart 2017), but the sheer size of the AM increase, possibly as large as a factor of $\sim 20–50$ since $z \sim 2$, may have not been fully appreciated. The accretion of gas into galaxies is generally seen as indispensable to sustain their star formation, given the short gas depletion times (e.g., Tacconi et al. 2013 and references therein) and from the early days of theoretical galaxy formation attention has more often focused on the thermodynamical aspect of accretion, i.e., on the required cooling of the CGM (e.g., Dekel et al. 2009). On the other hand, simulations paying special attention to the role of AM may have covered only a relatively narrow interval of cosmic time, hence recovering only a fraction of the total AM growth (e.g., Danovich et al. 2015).

In the simulation discussed by Pillepich et al. (2018) disk radii grow by a large factor since $z \sim 2$, especially for $M_* > 10^{10} M_{\odot}$, (see their Figure B1), that, coupled with the large expected increase in stellar mass, implies indeed a large increase of the AM of the stellar disks. Again, this means that, to some extent, the simulation does produce a CGM with sufficient vorticity to drive the disk growth together with its AM, in a roughly consistent fashion with what indicated by the scaling relations, as quantified in Section 1. However, these authors lament that “no quantitative analysis of the spatially averaged or map-based internal kinematics of star-forming galaxies within large uniform-volume simulations exists”. Not to mention the same kind of analysis for the CGM over a volume at least as large as that from which all the baryons having fed a galaxy came from i.e., a fraction of the virial radius of the host halo, given that at most $\sim 1/3$ of the baryons in a halo are converted into stars (Behroozi, Conroy & Wechsler 2010). The simulated data exist, but they have not been observed yet. Still, this simulation produces rotational velocities that decrease with time, admittedly at tension with the observational result.

Note that Lague et al. (2013) find that segments of the (dark matter) filaments do exhibit polarity.
in which they appear to increase with time (Simons et al. 2013).

More recently, the simulations of disk galaxy evolution by Buck et al. (2020) quite effectively illustrate the appearance of a spontaneous symmetry breaking between co-rotating and counter-rotating stellar orbits starting to take place at \( z \approx 2 \) (their Figure 10). From redshift \( z \approx 4 \) down to \( z \approx 2 \) stellar orbits are characterized by high velocity dispersion and strong vertical motions, with nearly as many stars rotating in one direction as in the opposite direction, which may correspond to the formation of a bulge. At lower redshifts, especially at \( z \approx 1 \), the disk then grows very rapidly along with its AM, without further appearance of counter-rotating stars. Thus, persistent co-rotation of the accreted gas must be realised in this simulation and it would be interesting to extract from it the corresponding history of the AM stratification of the involved circumgalactic gas and of the stellar disk. In other words, the initial chaotic assembly is then superseded by smooth accretion of co-rotating gas, with this beginning at \( z \approx 2 \) being in nice agreement with the observed emergence of rotationally supported disks around this epoch (e.g., Simons et al. 2017; Förster Schreiber et al. 2018; Ubler et al. 2019).

According to an early postulate, baryons would share the same sAM of their host dark matter halo. This is not what found in several independent hydrodynamical ΛCDM simulations analyzed by Stewart et al. (2017) for the redshift range \( 1 < z < 3 \), where the sAM of the cold, effectively accreting CGM is found to systematically exceed by 4–5 times that of the host halo. Moreover, the simulations show that the cold accreting gas is typically co-planar and co-rotating with the central galaxy and slowly inspiraling towards it, i.e., exhibiting all the features that are required for the secular increase of the AM of galactic disks that is demanded by the galaxy scaling relations. Still, it remains to be established whether this remarkable, but still qualitative agreement with the expectations from the scaling relations will turn quantitative and extended to \( z = 0 \).

Thus, we still don’t know what is the AM growing factor of the simulated galaxies and how it compares to that predicted from the scaling relations (the \( \sim 20 - 50 \) factor). Indeed, at stake is a better understanding of the intimate workings of galaxy evolution, with AM—and the history of its acquisition—being a prime mover for the growth and evolution of galaxies. The mere existence of the main sequence of star forming galaxies represented a change of paradigm, with emphasis shifting from merging to quasi stationary gas inflow as the main driver. In this frame, the gas-regulator model offers a simple mechanism to smooth fluctuations in sSFR driven by fluctuations in the gas accretion rate, thus offering an explanation for the existence of the main sequence (e.g., Lilly et al. 2013). However, this gas does not carry just fuel to sustain star formation: it carries also AM. If it were to carry too much AM, then a galaxy may even starve and quench, as suggested in PR20. If it does not carry enough AM (or it comes with the wrong sign), what can be produced is perhaps something like a blue nugget (Dekel & Burkert 2014), that may soon quench as well. Possibly, only if the acquired AM keeps within certain limits then a successful disk will be produced, with baryonic gas vorticity on a circumgalactic scale acting as a natural selection process. Still, the conditions leading to success must be relatively widespread in nature, given that most galaxies spend a major fraction, if not all their lifetime, close to the main sequence and following the corresponding scaling relations. Given the enduring difficulty to fully probe empirically the CGM and its kinematical history, some light on this problem may be shed by observing it in the existing simulations, checking to what extent baryon vorticity is what determines the growth or the starvation of galaxies. Since quite many years the star formation history (SFH) of galaxies has been at the focus of both observation and theory. What needs to come on focus now is their angular momentum history (AMH), perhaps the next challenge for galaxy evolution studies.

ACKNOWLEDGMENTS

I wish to thank Emanuele Daddi, Natascha Förster Schreiber, Mauro Giavalisco, Simon Lilly, Yingjie Peng, Gabriele Pezzulli, and Giulia Rodighiero for useful conversations on these matters and acknowledge support from the INAF/PRIN-SKA 2017 ”ESKAPE-HI” grant.

REFERENCES

Behroozi, P. S., Conroy, C., & Wechsler, R. H. 2010, ApJ, 717, 379
Blue Bird, J., Davis, J., Luber, N., van Gorkum, J.H., Wilcots, E. et al. 2020, MNRAS, 492, 153
Buck, T., Obreja, A., Macci, A.V., Minchev, I., Dutton, A.A. & Ostriker, J.P. 2020, MNRAS, 491, 3461
Burkert, A., Förster Schreiber, N. M., Genzel, R., Lang, P., Tacconi, L.J. et al. 2016, ApJ, 826, 214
Chen, Y., Ho, S., Blazek, J., He, S., Mandelbaum, R. et al. 2019, MNRAS, 485, 2492
Codis, S., Pichon, C. & Pogosyan, D. 2015, MNRAS, 452, 3369
Codis, S., Jindal, A., Chisari, N.E., Vibert, D., Dubois, Y. et al. 2018, MNRAS, 481, 4763
Danovich, M., Dekel, A., Hahn, O., Ceverino, D. & Primack, J. 2015, MNRAS, 449, 2087
Dekel, A. & Burkert, A. 2014, MNRAS, 438, 1870
Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T. et al. 2009, Nature, 457, 451
Dubois, Y., Pichon, C., Welker, C., Le Borgne, D., Devriendt, J. et al. 2014, MNRAS, 444, 1453
Förster Schreiber, N. M., Renzini, A., Mancini, C., Genzel, R. Bouché, N. et al. 2018, ApJS, 238, 21
Ganeshaiah Veena, P., Caitun, M., Tempel, E., van de Weeghaert, R. & Frenk, C.S. 2019, MNRAS, 487, 1607
Hahn, O., Porciani, C., Carollo, C.M. & Dekel, A. 2007, MNRAS, 375, 489
Ho, S.H. & Martin, C.L. 2020, ApJ, 888, 14
Ilbert, O., Le Fèvre, O., Aussel, H., Capak, Dunlop, J. et al. 2013, A&A, 556, A55
Krolewski, A., Ho, S., Chen, Y., Chan, P.F., Tenneti, A. et al. 2019, ApJ, 876, 52
Laigle, C., Pichon, C., Codis, S., Dubois, Y., Le Borgne, D. et al. 2015, MNRAS, 446, 2744
Lilly, S.J., Carollo, C.M., Pipino, A., Renzini, A. & Peng, Y. 2013, ApJ, 772, 119
Lilly, S.J. & Carollo, C.M. 2016, ApJ, 833, 1
Madau, P. & Dickinson, M. 2014, ARA&A, 52, 415
Maresco, A., Fraternali, F., Posti, L., Ijtsima, M. et al. 2019, A&A, 621, L6
Martin, C.L., Ho, S.H., Kacprzak, G.G. & Churchill, C.W. 2019, ApJ, 878, 84
Martizzi, D., Vogelsberger, M., Artale, M.C., Haider, M., Torrey, P. et al. 2019, MNRAS, 486, 3766
Mosleh, M., Tacchella, S., Renzini, A., Carollo, C.M. et al. 2017, ApJ, 837, 2
Muzzin, A., Marchesini, D., Stefanon, M., Franx, M., McCracken, H.J. et al. 2013, ApJ,
Newman, A. B., Ellis, R. S., Bundy, K., & Treu, T. 2012, ApJ, 746, 16
Peebles, P.J.E. 1969, ApJ, 155, 393
Peng, Y., Lilly, S.J., Kovač, K., Bolzonella, M., Pozzetti, L., Renzini, A. et al. 2010, ApJ, 721, 193
Peng, Y. & Renzini, A. 2020, MNRAS, 491, L51 (PR20)
Pezzulli, G., Fraternali, F., Boissier, S. & Muños-Mateos, J.C. 2015, MNRAS, 451, 2324
Pillepich, A., Nelson, D., Springel, V. et al. 2019, MNRAS, 490, 3196
Popesso, P., Morselli, L., Concas, A., Schreiber, C., Rodighiero, G. et al. 2019, MNRAS, 490, 5285
Porciani, C., Dekel, A. & Hoffman, Y. 2002, MNRAS, 332, 325
Renzini, A. 2009, MNRAS, 398, 58
Simons, R.C., Kassin, S.A., Weiner, B.J., Faber, S.M., Trump, J.R. et al. 2017, ApJ, 843, 46
Stewart, K.R. 2017, in Gas Accretion onto Galaxies, ed. A. Fox & R. Davé (Springer: Cham), p. 249
Stewart, K.R., Maller, A.H., Oñorbe, J., Bullock, J.S., Joung, M.R. et al. 2017, ApJ, 843, 47
Tacconi, L. J., Genzel, R., Saintonge, A., Combes, F. et al. 2018, ApJ, 853, 179
Tempel, E. & Lebeschkin, N.I. 2013, ApJ, 775, L42
Tempel, E., Steica, R.S. & Saar, E. 2013, MNRAS, 428, 1827
Tempel, E., Kipper, R., Saar, E., Bussov, M. et al. 2014, A&A, 572, A8
Übler, H., Genzel, R., Wisnioski, E., Förster Schreiber, N. M., Shimizu, T. T. et al. 2019, ApJ, 880, 48
van der Wel, A., Franx, M., van Dokkum, P.G., Skelton, R.E., Momcheva, I. G. et al. 2014, ApJ, 788, 28
van Dokkum, P.G., Nelson, E.J., Franx, M., Oesch, P., Momcheva, I. et al. 2015, ApJ, 813, 23
Welker, C., Bland-Hawthorn, J., Van de Sande, J., Lagos, C., Elahi, P. et al. 2010, MNRAS, 491, 2864
Zabl, J., Bouché, N.F., Scroetter, H., Wendl, M., Finley, H. et al. 2019, MNRAS, 485, 1961