

中国科学技术大学

本科毕业论文



星系的重子物质质量-尺寸关系

作者姓名:	华紫辰
学 号:	PB21020565
专 业:	天文学
导 师:	Federico Lelli 容昱 特任研究员
完成时间:	2025 年 6 月 3 日

摘 要

星系质量-尺寸关系的研究通常仅单独考虑恒星或气体成分。本文使用总重子物质质量 (M_{bar}) 和重子半质量半径 ($R_{50,\text{bar}}$), 首次系统研究星系的重子质量-尺寸关系。我们分析 SPARC 数据库中的恒星形成星系 (Sa 至 dI), 并汇编宁静星系 (E、S0、dE、dSph 及所谓 UDGs) 样本——对于后者, 重子质量-尺寸关系退化为常规的恒星质量-尺寸关系。本文主要结论如下:

- (1) 恒星形成星系在 $M_{\text{bar}} - R_{50,\text{bar}}$ 平面呈现两条清晰的序列: 高面密度 (HSD)、恒星主导的 Sa-Sc 星系序列, 与低表面密度 (LSD)、气体主导的 Sd-dI 星系序列。LSD 星系的质量-尺寸关系斜率接近 2, 表明其平均表面密度恒定; 而 HSD 星系斜率接近 1, 显示较小质量漩涡星系更为致密。
- (2) 这种二分性在重子 Tully-Fisher 关系 (M_{bar} 与平坦旋转速度 V_f 的关系) 中消失, 但在角动量关系 (M_{bar} 与 $V_f \times R_{50,\text{bar}}$ 的关系) 中部分显现, 说明该现象源于固定 M_{bar} 下 $R_{50,\text{bar}}$ 的差异。因此, 重子质量-尺寸关系是区分星系类型和研究演化的最佳经验工具。
- (3) 巨椭圆星系与 SPARC 星系以及透镜星系的核球构成独立序列, 位于恒星形成 HSD 盘序列上方, 表明漩涡星系需通过并合才能演化至该序列。与此同时, 透镜星系盘的序列与 HSD 星系盘的序列部分重合。这可能暗示着, 漩涡星系在气体耗尽后自然演化为透镜星系。
- (4) 宁静矮星系 (dE/dSph/UDG) 形成独立序列, 位于恒星形成 LSD 盘序列下方。若移除 LSD 星系的气体成分, 其恰好落在宁静矮星系序列上, 暗示气体剥离是主导演化机制。次要演化效应可能是恒星成分适度膨胀 (2-3 倍), 促成从富气体到贫气体矮星系 (包括 UDGs) 的形态转变。

关键词: 星系形成与演化, 星系结构, 星系动力学, 星系类型

ABSTRACT

The mass-size relations of galaxies are generally studied considering only stars or only gas separately. Here we study the baryonic mass-size relation of galaxies, using the total baryonic mass (M_{bar}) and the baryonic half-mass radius ($R_{50,\text{bar}}$). We consider star-forming galaxies (Sa to dI) from the SPARC database. We also build a compilation of passive galaxies (E, dE, S0, dSph, and the so-called UDGs) for which the baryonic mass-size relation reduces to the usual stellar one. Our results can be summarized as follows:

- (1) Star-forming galaxies define two distinct sequences in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane: one formed by high-surface-density (HSD), star-dominated, Sa-to-Sc galaxies, and one by low-surface-density (LSD), gas-dominated, Sd-to-dI galaxies. The $M_{\text{bar}} - R_{50,\text{bar}}$ relation of LSD galaxies has a slope close to 2, pointing to a constant average surface density, whereas that of HSD galaxies has a slope close to 1, indicating that less massive spirals are progressively more compact.
- (2) The HSD-LSD dichotomy is absent in the baryonic Tully-Fisher relation (M_{bar} versus flat circular velocity V_f) but moderately seen in the angular-momentum relation (approximately M_{bar} versus $V_f \times R_{50,\text{bar}}$), so it is driven by variations in $R_{50,\text{bar}}$ at fixed M_{bar} . Thus, the baryonic mass-size relation is the most effective empirical tool to distinguish different galaxy types and study their evolution.
- (3) Giant ellipticals, SPARC bulges and S0 bulges form a sequence that is offset from that of star-forming HSD disks to higher masses, so spirals may potentially move there only through mergers. Meanwhile, lenticular galaxies partially overlap with the HSD sequence. This suggests that spirals simply evolve into lenticulars as they run out of gas.
- (4) Passive dwarfs (dE, dSph, UDG) form a sequence that is offset from that of star-forming LSD disks to lower masses. If one removes the gas content from star-forming LSD galaxies, they end up along the sequence of passive dwarfs, suggesting that gas stripping is the dominant evolutionary effect. A secondary evolutionary effect may be a moderate expansion of the stellar component (by a factor of 2-3) for a full morphological transformation from gas-rich to gas-poor dwarfs (including UDGs).

Key Words: Galaxy formation and evolution; Galaxy structure; Galaxy dynamics;
Galaxy types

Contents

Chapter 1	Introduction	4
1.1	Galaxy formation and evolution	4
1.2	Studies on the mass-size relation	7
1.3	This study	9
Chapter 2	Star-forming galaxies	12
2.1	Data analysis	12
2.2	Results	14
2.2.1	Two sequences in the baryonic mass-size plane	14
2.2.2	Best-fit baryonic mass-size relations	16
2.2.3	The effect of stellar bulges	17
2.3	A dichotomy in star-forming galaxy disks	18
2.4	Relations with dynamical scaling laws	20
Chapter 3	Passive galaxies	23
3.1	Data analysis	23
3.1.1	Ellipticals	23
3.1.2	Lenticulars	23
3.1.3	Dwarf ellipticals and dwarf spheroidals	24
3.1.4	Ultra-diffuse galaxies in galaxy clusters	25
3.2	Results	26
3.2.1	General results of passive galaxies	27
3.2.2	High-mass galaxies	27
3.2.3	Low-mass galaxies	28
Chapter 4	Connections with MOND	30
Chapter 5	Summary and conclusion	33
	Bibliography	35
Appendix A	Tables	49

Appendix B	Error Estimation	52
Appendix C	The effect of the division point between LSDs and HSDs	53
Acknowledgements		55

Notation

M_x	The mass of x -component, x can be “bar” (baryons), “disk”, “bul” (bulges), “star” or “gas”
$R_{50,x}$	The radius inclosing 50% of the total mass of x -component
$\Sigma_{50,x}$	The average surface density of x -component within $R_{50,x}$
Υ_x^A	The mass-to light ratio of x -component in A -band. If A is not specified, it means the mass-to-light ratio in the <i>Spizter</i> $3.6\mu m$ band.
α	The best-fit slope of a relation
β	The best-fit intercept of a relation
σ_{int}	The intrinsic scatter of a relation
H_0	The Hubble constant. In this thesis, $H_0 = 73 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$.

Chapter 1 Introduction

1.1 Galaxy formation and evolution

Galaxies are self-gravitating systems that consist of stars, gas, dust, and dark matter. As the building blocks of our universe, their formation and evolution mechanisms are one of the key questions in the field of astronomy.

The first step tackling this problem is to classify galaxies. The earliest classification of galaxies was proposed by Hubble^[1], who divided them into three main morphological classes: ellipticals, spirals, and irregulars. Elliptical galaxies are spheroidal systems with smooth light profiles, while spiral galaxies have disk-like structures with spiral arms, and irregular galaxies lack a well-defined structure. Spiral galaxies with bars were later added as a fourth class parallel to the spiral galaxies^[2], and lenticulars were introduced as a transitional class between ellipticals and spirals^[3]. As shown in Fig. 1.1, this classification scheme is known as the Hubble tuning fork, which has been widely used in the astronomical community. Originally, Hubble^[1] considered that galaxies may evolve from the left-hand side of the tuning fork to the right-side, which, however, is not the case in reality.

In the second half of 20th century, after the discovery of the dark matter^[4-5], several pioneering studies (e.g., Fall et al.^[6], Fall^[7], White et al.^[8]) proposed the Cold Dark Matter (CDM) paradigm of galaxy formation and evolution. In this framework, dark matter haloes form through gravitational instability, creating gravitational wells that attract baryonic matter (gas and dust). Then, as the gas cools, it falls into the center of the haloes and start to form stars. Meanwhile, the baryons, along with the dark matter haloes, acquire angular momentum from cosmological tidal torques (e.g. Hoyle^[9], Peebles^[10], Doroshkevich^[11], White^[12]). If the angular momentum is high enough, the baryons may form a disk-like structure, which might be the origin of spiral galaxies (e.g., Mo et al.^[13]). On the contrary, if the angular momentum is too low, the baryons may collapse rapidly, forming a spheroidal structure and extensively consuming the cold gas, which might be the origin of elliptical galaxies^[14-16].

Further studies added more mechanisms to this framework. The first issue that may strongly influence the formation and evolution of galaxies is the environment. When a

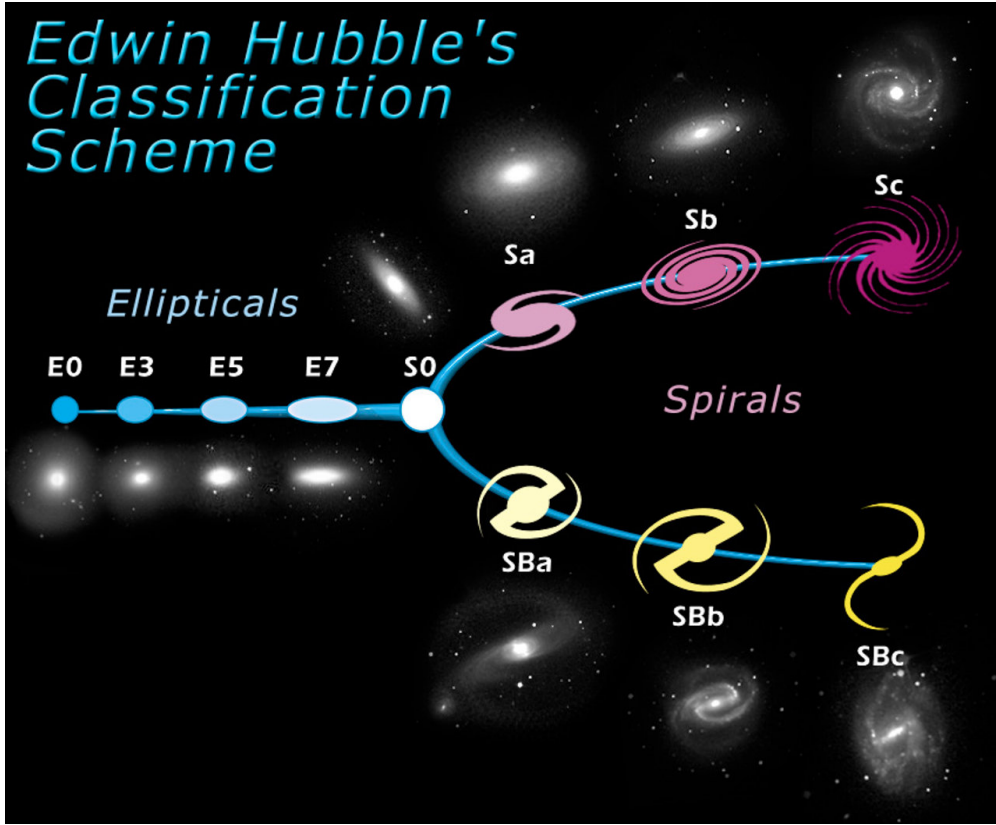


Figure 1.1 The Hubble tuning fork.

galaxy falls into a dense environment, such as a galaxy cluster, it may experience tidal interactions, harassment, and/or ram-pressure stripping. These processes can strip the gas from the galaxy, quenching its star formation and transforming it into a passive galaxy (see Boselli et al.^[17] for a review). Another important mechanism is the feedback processes. Active galactic nuclei (AGN) and supernovae (SNe) can inject energy into the interstellar medium, heating the gas and preventing it from cooling and forming stars (see Fabian^[18], Veilleux et al.^[19] for reviews). Such a process may also lead a star-forming galaxy to become a passive galaxy. These processes are more vital when considering galaxies with small masses (stellar mass $M_{\star} < 10^{9.5} M_{\odot}$), i.e., the dwarf galaxies (e.g., Dekel et al.^[20], Mac Low et al.^[21], McQuinn et al.^[22]). The potential wells of these dwarf galaxies are shallow, so it is more difficult for them to maintain their gas reservoirs when facing environmental effects or feedback processes. Finally, mergers may also play a role in galaxy evolution, as they can change the configurations of galaxies extraordinarily (see Barnes et al.^[23] for a review).

Along with the discovery of the dark energy (Λ)^[24-25], this current model of galaxy formation and evolution is known as the Λ Cold Dark Matter (Λ CDM) paradigm, as

depicted in Fig. 1.2. Although Λ CDM has successfully explained many properties of galaxies we observed and is considered as the standard model of galaxy formation and evolution (e.g. Mo et al.^[26]), it is not the end of the story. Λ CDM is also facing some challenges, such as the “missing satellite” problem (e.g., Klypin et al.^[27], Moore et al.^[28]), “cusp or core” problem (e.g., Flores et al.^[29]), and the “too big to fail” problem (e.g., Boylan-Kolchin et al.^[30], Brooks et al.^[31]). A very recent study on the clustering of dwarf galaxies^[32] also raised a severe challenge to Λ CDM, suggesting that dark matter may be self-interacting.

Other alternative theories without the need of CDM also exist. At the same time when CDM paradigm was born, Milgrom^[33] proposed an alternative theory, the Milgromian dynamics (or Modified Newtonian Dynamics, MOND), which modifies the standard laws of gravity and/or inertia rather than adding dark matter. In this paradigm, the behaviour of the gravity deviates from the Newtonian one where the acceleration a is below a critical value $a_0 \simeq 1.2 \times 10^{-10} \text{ m s}^{-2}$. By modifying the laws of gravity as,

$$a = \sqrt{a_0 a_N}, a_N \ll a_0, \quad (1.1)$$

where a_N is the Newtonian acceleration, MOND can account for dark matter as an observational effect of the modified gravity. Meanwhile, MOND can also explain many observational phenomena of galaxies naturally, e.g.,

1. The flatness of the rotation curves^[33],
2. The stability of the galactic disks^[33],
3. The slope and the tightness of the baryonic Tully-Fisher relation (BTFR, Milgrom^[33], McGaugh et al.^[34], Lelli et al.^[35,36]),
4. The radial acceleration relation (RAR, Milgrom^[33], McGaugh et al.^[37], Lelli et al.^[38]), and
5. The central-density relation (CDR, Lelli et al.^[39], Milgrom^[40]).

Especially, Λ CDM suffers from the “fine-tuning problem” (e.g., McGaugh^[41,42]) when explaining the BTFR, RAR and CDR. This makes MOND a promising alternative to the Λ CDM paradigm. However, MOND itself is facing some crucial challenges. Therefore, the nature of dark matter and gravity is still an open question in astronomy.

In conclusion, studying the formation and evolution of galaxies is a fundamental task in astronomy. Not only will it deepen our understanding of the galaxies themselves,

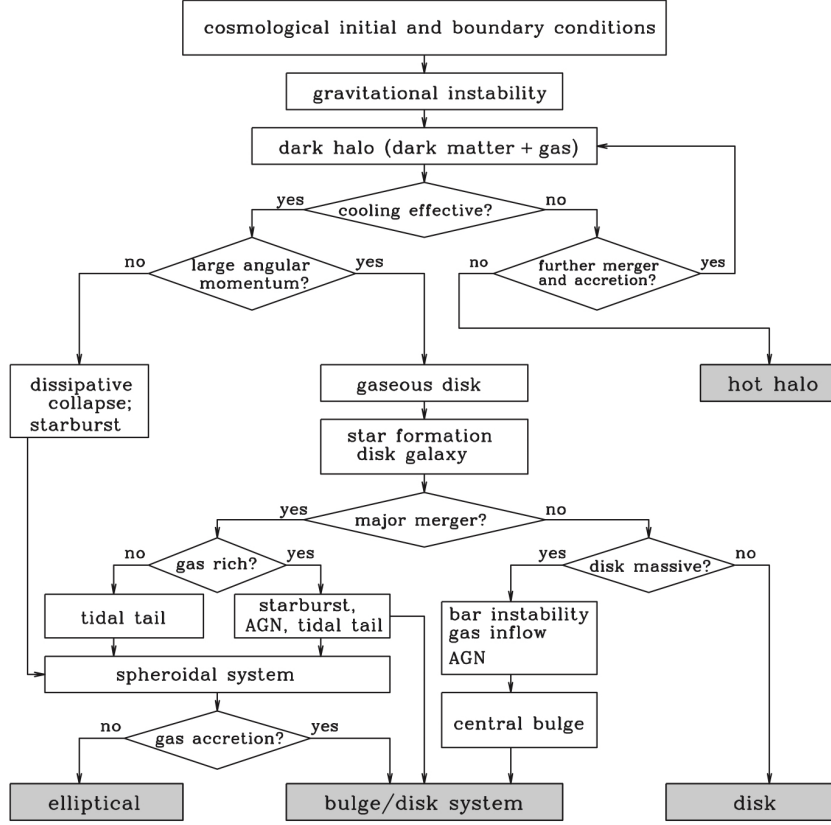


Figure 1.2 The logic flow chart of galaxy formation and evolution in the Λ CDM paradigm^[26].

it may also help us to understand the nature of gravity, one of the most fundamental and challenging tasks in modern physics. It may also contribute to our understandings of the evolution of the universe itself, which is of highest importance in both science and philosophy.

1.2 Studies on the mass-size relation

As discussed in Section 1.1, studying the formation and evolution of galaxies is of great importance. Among the tools achieving this, a classic approach is studying the structural relationships between total luminosity (proxy for the total stellar mass, $M_{\star}$), physical size, and surface brightness. For example, passive “quenched” galaxies in galaxy clusters follow different luminosity-size-surface brightness relationships (e.g., Kormendy^[43], Binggeli et al.^[44]): one set by giant ellipticals (E) and one by dwarf ellipticals (dE). This fact indicates that dE are not a “miniature” version of giant E, despite their similar morphology and resulting historical nomenclature. Rather, dE follow the same structural relations of dimmer dwarf spheroidals (dSph) in the Local

Group and other nearby groups. This evidence has led Kormendy et al.^[45] to rename passive dwarfs (dE and dSph) as “spheroidals” in contrast to classic giant “ellipticals”. In addition, Kormendy et al.^[46] proposed a revised Hubble tuning fork (following van den Bergh^[47]), in which lenticulars (S0) and dE/dSph form a parallel sequence to the classic one of spirals (S) and dwarf irregulars (dI), as depicted in Fig. 1.3. For star-forming galaxies (S and dI), a similar separation between “dwarfs” and “giants” has been found by studying the stellar mass-size plane^[48] and the main sequence of star formation^[49].

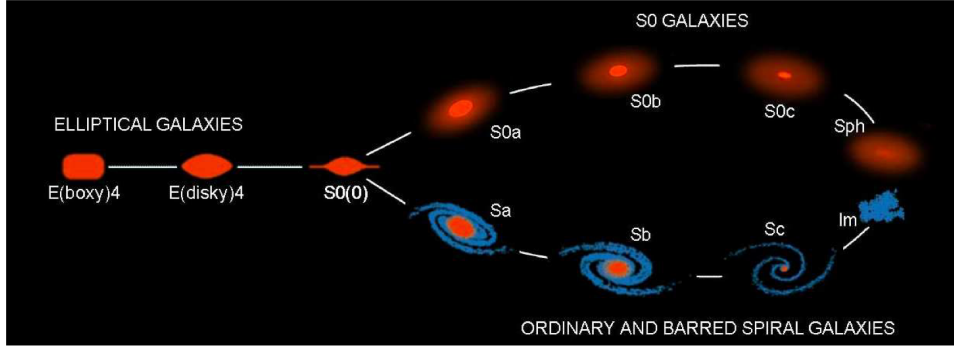


Figure 1.3 The revised Hubble tuning fork^[46].

Over the past decades, many studies focused on the stellar mass-size relation that relates $M_{\star}$ to the effective radius $R_{50,\star}$, which encompasses half of the stellar mass (the half-mass radius) or luminosity (the half-light radius). Strictly speaking, the effective radius $R_{50,\star}$ is not a measurement of “size” with the usual intuitive meaning of “maximum spatial extension” of an object because galaxies do not have a hard boundary. Rather, the effective radius is a measurement of how concentrated the stellar mass or stellar light is^[50]. Other possible definitions of “galaxy sizes” consider isophotal or isodensity radii, which are taken at some fixed surface brightness (e.g., the Holmberg radius) or surface density value (e.g., Trujillo et al.^[51]). In this paper, we will consider different types of half-mass radii and refer to them as “size” for simplicity.

The stellar mass-size relation has been studied in relation to other galaxy properties, such as morphology (e.g., Schombert^[48], Shen et al.^[52], Bernardi et al.^[53]), surface brightness (e.g., Greene et al.^[54]), specific star formation rates (e.g., Nedkova et al.^[55]), specific angular momentum (e.g., Kim et al.^[56], Rong et al.^[57]), environment (e.g., Fernández Lorenzo et al.^[58], Rodriguez et al.^[59], Afanasiev et al.^[60]), mergers and tidal interactions (e.g., Du et al.^[61], Liao et al.^[62]). In addition, one can

probe the assembly history of galaxies by observing the evolution of the stellar mass-size relation with redshifts (e.g., Nedkova et al.^[55], Afanasiev et al.^[60], van der Wel et al.^[63], Roy et al.^[64], Mowla et al.^[65], Yang et al.^[66]). One can also study the distinct mass-size relations of different stellar components in galaxies, such as bulges and disks, so trace their evolutionary paths separately (e.g., Nedkova et al.^[55]).

Another well-studied structural relation is the H I mass-size relation of late-type galaxies^[67]. Given that atomic hydrogen largely dominates the gas budget of star-forming galaxies (e.g., Cortese et al.^[68]), the H I mass-size relation is effectively the gaseous counterpart of the stellar mass-size relation. For historical reasons, the H I radius (R_{HI}) is not defined as the radius that contains 50% of the H I mass, but rather as the radius where the H I surface density equals $1 M_{\odot}/\text{pc}^2$ (after correction to face-on view), so it is effectively an isophotal radius. Interestingly, the H I mass-size relation has a slope close to 2, indicating that the average surface densities of H I disks are approximately constant^[69-75]. This phenomenon may be related to the transformation of H I into H_2 ^[76], which is a crucial step in the star-formation process.

1.3 This study

Previous studies of the mass-size relation of galaxies focused only on stars or only on gas, but galaxies consist of both mass components. In passive “quenched” galaxies (E, S0, and dE/dSph), the amount of gas is often negligible (but see Serra et al.^[77] for several counter examples), so the stellar mass-size relation is virtually equivalent to the baryonic one. The situation is very different in star-forming galaxies, especially in low-mass dwarfs where the gas mass can be much higher than the stellar mass (e.g., Lelli^[78]). Therefore, in star-forming galaxies, neither the gaseous mass-size relation nor the stellar mass-size relation can thoroughly trace the matter distribution in their disks. Therefore, it is important to study the baryonic mass-size relation of star-forming galaxies, linking the total baryonic mass ($M_{\text{bar}} = M_{\star} + M_{\text{gas}}$) with the baryonic effective radius ($R_{50,\text{bar}}$) that encloses half of M_{bar} .

Additionally, the baryonic mass-size relation can be used to study the potential formation mechanisms of passive galaxies. The basic idea is simple. If a galaxy converts its gas into stars in a close-box fashion, it will move across the stellar plane but stay

nearly at the same location of the baryonic plane (apart from minor variations in $R_{\text{bar},50}$ depending on where the star formation occurs). Instead, if a galaxy suddenly loses its gas due to external mechanisms, it will move across the baryonic mass-size plane but stay almost at the same location of the stellar mass-size plane, unless the gas loss take place together with a significant change in the stellar distribution.

Furthermore, the baryonic mass-size relation may provide a new perspective on the nature of the dark matter and the gravity. In the standard Λ CDM paradigm, galaxies reside in halos consist of dark matter, and the baryonic mass is a small fraction ($\sim 5\% - 10\%$ [13]) of the total mass. Therefore, the properties of the dark matter haloes determine the observed properties of galaxies. Current studies suggest that the most important quantity connecting the baryonic properties of galaxies and their dark matter haloes is $M_\star$ (e.g. Guo et al. [79], Behroozi et al. [80], Kravtsov [81]). Hence, the stellar mass-size relation is extensively studied in Λ CDM, in particular in relation with the halo spin [13,56-57,62,82] and/or halo virial radius [59,81,83-84]. However, in MOND the dynamics of galaxies are determined merely by the baryons. So in MOND context, the baryonic mass-size relation is expected to be a more fundamental relation than the stellar mass-size relation. As discussed in Section 1.1, there is a characteristic acceleration scale $a_0 \simeq 1.2 \times 10^{-10} \text{ m s}^{-2}$ in MOND, below which the gravitational force is modified (e.g., Lelli et al. [38], Lelli [78]), whereas no acceleration scale is predicted in the Λ CDM context. Since a_0 can be recasted as a critical surface density [85-86],

$$\Sigma_M = \frac{a_0}{2\pi G} \simeq 137 M_\odot \text{ pc}^{-2}, \quad (1.2)$$

it may lead to observable consequences in the baryonic mass-size relation that are not present in the Λ CDM paradigm. Therefore, the baryonic mass-size relation may provide a new perspective to distinguish the two paradigms and help us to better understand the nature of gravity.

In this thesis, we study the baryonic mass-size relation of galaxies. In Chapter 2, we present the data-analysis and the resulting baryonic mass-size relation of star-forming galaxies. We find that star-forming galaxies follow two sequences: high surface density (HSD) disks and low surface density (LSD) disks. We further connect this result with other scaling relations to show that the baryonic mass-size relation is a powerful tool to study galaxy formation and evolution. Next, in Chapter 3, we present the baryonic mass-

size relation of passive galaxies and discuss its potential evolutionary connection with star-forming galaxies. Then, in Chapter 4, we discuss the potential connection between the baryonic mass-size relation and MOND. Finally, in Chapter 5, we summarize the main results of this thesis and discuss the future work.

Chapter 2 Star-forming galaxies

In this chapter, we first show how we derive M_{bar} and $R_{50,\text{bar}}$ in Section 2.1. Then, in Section 2.2, we exhibit the resulting baryonic mass-size Relation, showing that there are two distinct sequences, LSDs and HSDs, on the $R_{50,\text{bar}} - M_{\text{bar}}$ plane. Next, we discuss the physical inference of the two galaxy populations in section 2.3. Finally, in Section 2.4, we show that the dichotomy observed in the baryonic mass-size plane can well explain the features in the the angular momentum relation^[7,87-88]. This indicates that the baryonic mass-size relation can serve as a powerful tool in studying galaxy formation and evolution.

2.1 Data analysis

The half-mass radius can be measured by either fitting a parametric function (such as the Sérsic⁸⁹ profile) to the matter distribution, or by constructing the so-called “curve of growth” (CoG) that gives the cumulative mass as a function of radius R . In general, the baryonic mass distribution of galaxies cannot be described by a simple parametric function, so we compute $R_{50,\text{bar}}$ by constructing the baryonic CoG (Fig. 2.1). This requires the gas and stellar surface density profiles corrected for face-on view.

The Surface Photometry and Accurate Rotation Curves (SPARC) sample is the ideal dataset for our purposes because it contains 175 disk galaxies (Sa to dI)^① with both near-infrared (NIR) images at $3.6 \mu\text{m}$ from *Spitzer*, tracing the stellar mass distribution, and interferometric H I data, tracing the gas distribution and kinematics^[72]. The first SPARC data release^[72], however, did not provide the H I surface density profiles because the gravitational contribution of the gas disk (parametrized via the expected circular velocity V_{gas}) was directly taken from previous works. Thus, we searched the literature and found H I surface density profiles for 169 galaxies out of 175 galaxies. Unfortunately, for the remaining six galaxies (D512-2, D564-8, D631-7, NGC 5907, NGC 7339, UGC 06818), the H I rotation-curve references do not provide the H I surface density profiles. The references for the H I surface density profiles are listed in

^①The SPARC database contains three S0s (NGC 4138, UGC 2487, UGC 6786) that are detected in the ultraviolet and/or in the $H\alpha$ line, suggesting recent star formation. For simplicity, in the following, we will consider them as early-type spirals (Sa-Sc).

Table A.1.

To obtain the face-on H I surface density profiles, we followed the same procedure applied by Lelli et al.^[72] to the NIR surface brightness profiles. In short, we run the task Rotmod in the Gipsy software^[90], which takes the observed surface brightness profile and total disk mass as inputs, then returns the expected circular velocity and face-on surface density (integrated along the z axis of the disk) as outputs. We use the same H I masses and distances given in Lelli et al.^[72]. In addition, we assumed an exponential vertical density profile with scale height of 100 pc, but this assumption plays virtually no role in our results.

The H I and NIR data have different spatial resolutions, so the resulting surface brightness profiles are sampled at different radii. To sum up the two components, the profiles are linearly interpolated and sampled on a common radial grid. Different choices in the interpolation play virtually no role in the final measurement of the half-mass radii. During this analysis, we also revisited some bulge-disk decompositions and outer extrapolations of the stellar profiles to ensure that the resulting CoGs are well-behaved with no unphysical jumps or discontinuities. We recall that SPARC bulge-disk decompositions are non-parametric and assign non-axisymmetric structures (bars, lenses, pseudo-bulges) to the stellar disk^[72].

The final step to build the baryonic CoG is to choose appropriate mass-to-light ratios for the stellar disk ($\Upsilon_{\star, \text{disk}}$) and the stellar bulge ($\Upsilon_{\star, \text{bul}}$), as well as the factor to correct the H I mass for the contribution of heavier elements ($M_{\text{gas}}/M_{\text{HI}}$). In analogy to previous SPARC papers, we assume $\Upsilon_{\star, \text{disk}} = 0.5$, $\Upsilon_{\star, \text{bul}} = 0.7$, and $M_{\text{gas}}/M_{\text{HI}} = 1.33$ for all galaxies. The choice of constant values provides the most empirical representation of the data because it just puts gas mass and stellar mass on a common physical scale, without any model-dependent variation from galaxy to galaxy. Of course, it is possible to choose variable mass-to-light ratios^[91-92] and gas correction factors^[93]; we may implement such improvements in future work.

Formally, our measurements of M_{bar} and $R_{50, \text{bar}}$ neglect molecular gas. In practice, however, molecular gas has a similar spatial distribution (on kpc scales) as the stellar disk, so its contribution can be implicitly included in the stellar density profile. On average, the molecular gas mass of nearby galaxies is 7% of the stellar mass^[93], so accounting for molecular gas would be equivalent to assuming $\Upsilon_{\star, \text{disk}} = 0.535$ rather than

$\Upsilon_{\star, \text{disk}} = 0.5$, which would make no difference to our results. This statistical correction is smaller than expected variations in $\Upsilon_{\star, \text{disk}}$ due to differences in the star-formation history^[94], chemical enrichment history^[91], or stellar initial mass function^[95], which are ultimately the most relevant uncertainties in the measurements of M_{bar} and $R_{50, \text{bar}}$.

Fig. 2.1 shows the baryonic CoG for three characteristic galaxies: a gas-dominated case, a star-dominated case, and an intermediate case. For the gas-dominated galaxy, the baryonic half-mass radius is nearly identical to the gaseous half-mass radius ($R_{50, \text{gas}}$). Conversely, for the star-dominated galaxy, one has $R_{50, \text{bar}} \simeq R_{50, \star}$. For the intermediate case, $R_{50, \text{bar}}$ is somewhat in between $R_{50, \text{gas}}$ and $R_{50, \star}$, highlighting the importance of considering both stars and gas when studying galaxy sizes.

2.2 Results

2.2.1 Two sequences in the baryonic mass-size plane

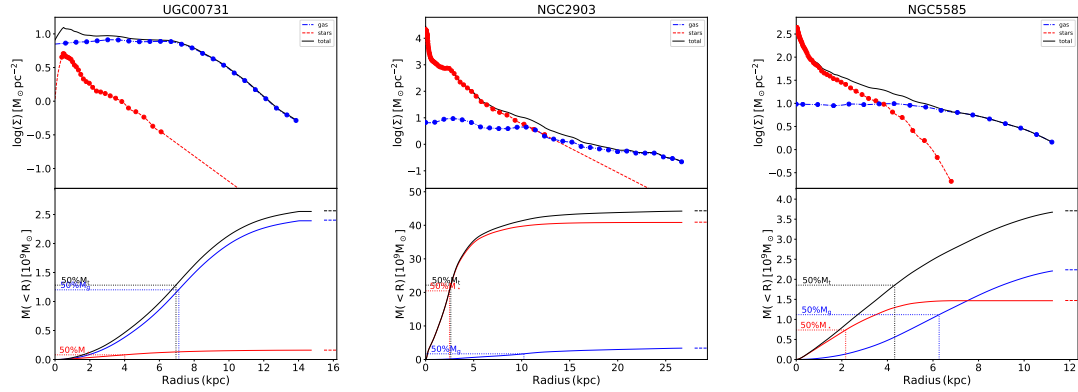


Figure 2.1 Measurements of $R_{50, \text{gas}}$, $R_{50, \star}$, and $R_{50, \text{bar}}$ for three example galaxies: a gas-dominated one (UGC 731), a star-dominated one (NGC 2903), and an intermediate case (NGC 5585). The upper panels show the surface density profiles for gas (blue points), stars (red points), and total baryons (black line); the stellar profile is extrapolated at large radii with an exponential function (red dashed line). The lower panel shows the curve of growth of gas (blue line), stars (red line) and total baryons (black line); the dashed lines show the location of the corresponding half-mass radii.

Fig. 2.2 shows the gaseous, stellar, and baryonic mass-size relations of SPARC galaxies. The gaseous mass-size relation is a tight power law (in log space), in agreement with previous studies that used the “isophotal” HI radius (e.g., Broeils et al.^[69], Verheijen et al.^[70], Swaters et al.^[71], Lelli et al.^[72], Wang et al.^[73]). The stellar mass-size relation, instead, displays two distinct sequences, which were noted by Lelli et al.^[72] in the luminosity-size plane (their Fig. 2) and are in agreement with

the seminal work of Schombert^[48]. These two sequences roughly correspond to high surface brightness (HSB), star-dominated, early-type spirals (Sa to Sc) and to low surface brightness (LSB), gas-dominated, late-type disks (Sd to dI). The baryonic mass-size relation makes the two sequences even more evident. The LSB sequence, indeed, becomes tighter because it mostly consists of gas-dominated objects, highlighting the importance of adding the gas component in the mass-size relation. In the following, we will consider baryonic surface densities rather than surface brightnesses, so we will refer to the two distinct populations as high-surface-density (HSD) and low-surface-density (LSD) galaxies.

The existence of two distinct sequences is confirmed by the DbSCAN algorithm^[96], which can rigorously identify clusters of points. This algorithm is robust against irregular boundaries and does not need a-priori information about the number of clusters. We use DbSCAN in a normalized five-dimensional space, consisting of $\log(M_{\text{bar}})$, $\log(R_{\text{bar}})$, gas fraction f_{gas} , Hubble type T , and effective surface density $\log(\Sigma_{50,\text{bar}})$. The gas fraction is defined as $f_{\text{gas}} = M_{\text{gas}}/M_{\text{bar}}$, while the baryonic effective surface density as $\Sigma_{50,\text{bar}} = M_{\text{bar}}/(2\pi R_{50,\text{bar}}^2)$. We set the input parameters of DbSCAN as $\text{Eps} = 0.239$ and $\text{Minpts} = 10$ (see Ester et al.^[96] for details). As expected, DbSCAN divides our sample of galaxies into two groups. Figure 2.3 shows that the two groups separate around $f_{\text{gas}} \simeq 0.3$, $T \simeq 5$, and $\log(\Sigma_{50,\text{bar}}/[M_{\odot} \text{ kpc}^{-2}]) \simeq 8.1$. We use the characteristic $\Sigma_c \simeq 125 M_{\odot} \text{ pc}^{-2}$ to divide our sample galaxies into LSDs ($\Sigma_{50,\text{bar}} < \Sigma_c$) and HSDs ($\Sigma_{50,\text{bar}} \geq \Sigma_c$). Using the characteristic f_{gas} or T instead of Σ_c provides similar results (see Appendix A).

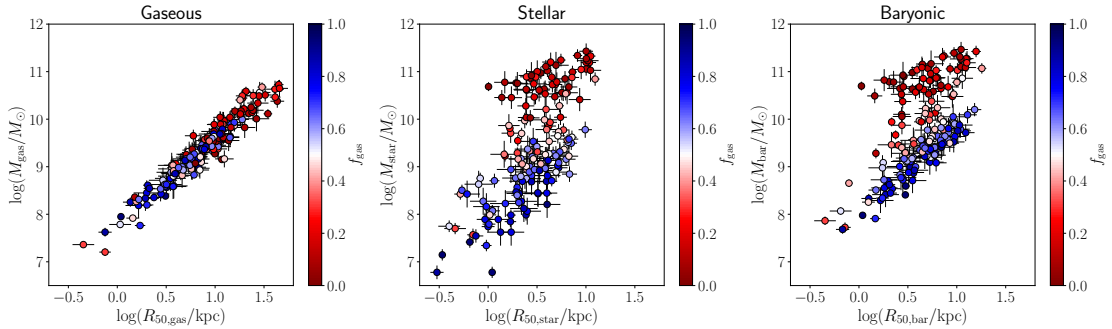


Figure 2.2 The gaseous (left panel), stellar (middle panel) and baryonic (right panel) mass-size relations of SPARC galaxies. Data points are color-coded by the gas fraction f_{gas} ; the error bars denote the 1σ errors. The three panels span the same dynamic range on both axes. Two sequences are evident in the stellar and baryonic mass-size relations.

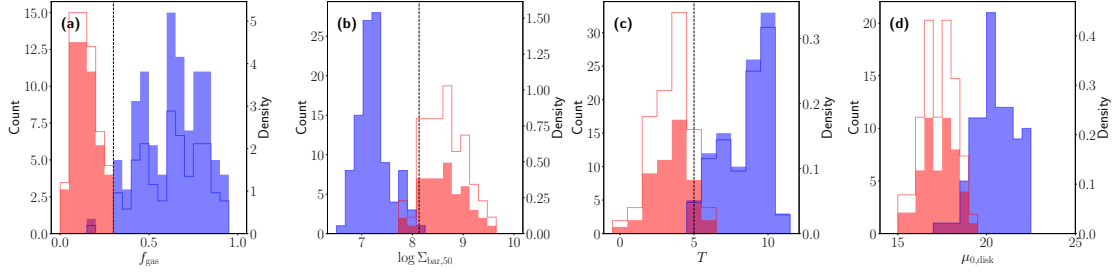


Figure 2.3 The distributions of f_{gas} , $\Sigma_{50,\text{bar}}$, and T for the two groups identified by Dbscan, which are represented by the red and blue histograms. The filled histogram shows the number counts, while the open histograms the number density of each group normalized to the total number of galaxies in each bin. The black-dashed lines show the separation values reported in Table A.2.

2.2.2 Best-fit baryonic mass-size relations

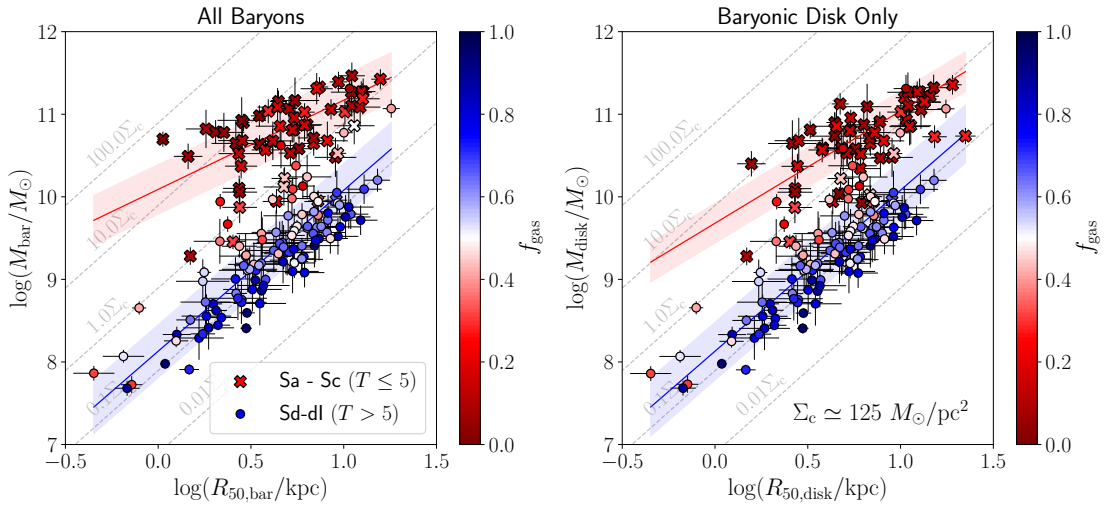


Figure 2.4 Baryonic mass-size relations considering all baryons (left panel) and the baryonic-disk only (excluding stellar bulges, right panel). Galaxies are color-coded by the gas fraction f_{gas} . Crosses represent S0-to-Sc galaxies (Hubble type $T \leq 5$), while circles represent Sd-to-dI galaxies ($T > 5$). The red and the blue solid lines show the best-fit relations to the HSD and LSD sequences, respectively; the red and blue shaded areas indicate the best-fit intrinsic scatters. Dashed lines correspond to constant surface densities for multiples of $\Sigma_c = 125 \text{ M}_{\odot} \text{ pc}^{-2}$ (see Sect. 2.2 for details).

We fit each galaxy group with a straight line:

$$\log M_{\text{bar}} = \alpha \log R_{50,\text{bar}} + \beta, \quad (2.1)$$

where α is the slope, β is the intercept. Fitting a straight line to data points with intrinsic scatter and errors on both variables is not a trivial exercise. For example, the BayesLineFit software^[36] uses a Markov-Chain Monte-Carlo approach in a Bayesian framework, assuming that the two variables are independent. In the case of the mass-size relation, however, the two variables are not independent because they both vary with galaxy distance D ($M_{\text{bar}} \propto D^2$ and $R_{50,\text{bar}} \propto D$). Thus, we use the Roxy package^[97] that can take the covariance between the variables into account. Details on the estimation of

the covariance matrix are given in Appendix B. The current implementation of Roxy, however, can fit only for the vertical intrinsic scatter, not the orthogonal intrinsic scatter perpendicular to the best-fit line. Appendix A of Lelli et al.^[36] discusses the systematic differences between the two approaches.

The best-fit relations are shown in Fig. 2.4 (left panel). The baryonic mass-size relation of LSD galaxies has $\alpha = 1.95 \pm 0.12$, while that of HSD galaxies has $\alpha = 1.08 \pm 0.18$. This indicates that LSD galaxies share a similar $\Sigma_{50,\text{bar}} \simeq 13 \text{ M}_{\odot} \text{ pc}^{-2}$, which is largely driven by the gas component. On the other hand, HSD galaxies become less dense and compact as their M_{bar} increase. Interestingly, the intrinsic scatters (σ_{int}) of the two sequences are the same within the errors. The HSD sequence shows higher observed scatter (evident by eye) because M_{bar} is dominated by the stellar mass, which has higher uncertainties than the gas mass dominating M_{bar} in the LSD sequence. Intrinsically, however, the two sequences may be similarly tight.

2.2.3 The effect of stellar bulges

One may wonder whether the HSD-LSD dichotomy is driven by the presence of stellar bulges because HSD galaxies mostly have early Hubble types (Sa-Sc), whereas LSD galaxies are virtually bulgeless (Sd-dI). Lelli et al.^[72] performed bulge-disk decompositions for 28 HSD galaxies out of 51 (mostly Sa-Sb types), whereas bulge-disk decompositions were performed for only two peculiar LSD galaxies out of 118. We use these bulge-disk decompositions to measure the baryonic CoG of the baryonic disk (stars plus gas) and its half-mass radius, $R_{50,\text{disk}}$, excluding the bulge component.

Fig. 2.4 (right panel) shows the baryonic-disk mass-size relation, excluding stellar bulges. The two HSD-LSD sequences are still evident by eye, and formally confirmed by the Dbsacan algorithm. Thus, the HSD-LSD dichotomy is not driven by the presence of bulges. Note, however, that the non-parametric bulge-disk decompositions of Lelli et al.^[72] assign stellar bars, ovals, and pseudo-bulges to the disk component. These structures are mostly present in HSD galaxies, which are clearly more prone than LSD galaxies to gravitational instabilities driven by the disk self-gravity and its secular evolution.

2.3 A dichotomy in star-forming galaxy disks

The existence of two sequences in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane suggests that there is a dichotomy in star-forming disks: galaxies tend to be either HSD or LSD, so tend to avoid intermediate surface densities around $100 \text{ M}_{\odot} \text{ pc}^{-2}$. It is then natural to ask whether the observed HSD-LSD dichotomy may be driven by potential selection effects. The SPARC sample is the result of decades of interferometric HI observations from different groups (see Lelli et al.^[72] for references), so it does not have a well-defined selection function. However, selection effects should generally bias against LSD or LSB galaxies, which are instead very well represented in SPARC. We cannot identify any sensible observational effect that would bias against intermediate surface densities. The upcoming BIG-SPARC database^[98], which will combine HI observations with NIR photometry for thousands of galaxies, will clarify the situation.

Reassuringly, the same dichotomy was found by Schombert^[48] studying the stellar mass-size plane of a different galaxy sample. In addition, a similar dichotomy was found in terms of the disk central surface brightness $\mu_{0,\text{disk}}$ in other independent studies^[99-103]. Clearly, a dichotomy in $\mu_{0,\text{disk}}$ has a similar physical meaning of a dichotomy in $\Sigma_{50,\text{bar}}$. Indeed, if we run DbSCAN replacing $\Sigma_{50,\text{bar}}$ with $\mu_{0,\text{disk}}$ (see Sect. 2.2.1), we still find two distinct groups of galaxies in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane (see Fig. 2.3, rightmost panel). The surface density of baryons (stars plus gas) is a more physical quantity than the surface brightness in some optical or NIR band. Moreover, it allows us to account for the dominant gas component in LSD galaxies, so we urge (when possible) to use $\Sigma_{50,\text{bar}}$ and the baryonic mass-size plane.

The dichotomy between HSD and LSD galaxies relates to other fundamental properties of galaxies, such as their gas fractions and gas depletion times. HSD galaxies tend to have low gas fractions ($\lesssim 30\%$ of their baryonic mass), so have been very efficient in converting gas into stars during the Hubble time. Indeed, HSD galaxies will run out of gas in a few Gyr (e.g., McGaugh et al.^[49]), unless their gas reservoir is constantly replenished to sustain the current star-formation rates (e.g., Sancisi et al.^[104], Marinacci et al.^[105]). On the other hand, LSD galaxies have high gas fractions (30–90% of their baryonic mass), so have been very inefficient in forming stars. Their gas depletion times are remarkably large; LSD galaxies could keep forming stars for another 10-100

Gyr without any need of accreting new gas (e.g., McGaugh et al.^[49], van Zee^[106]).

Another key difference between HSD and LSD galaxies regards their morphological properties, as indicated by their Hubble types. HSD galaxies (Sa-Sc) can have bulges, spiral arms, bars, and bar-driven structures (such as stellar lenses, rings, and pseudo-bulges). On the contrary, LSD galaxies usually lack these morphological features and their optical morphology is characterized by irregular and clumpy star formation. These morphological differences are likely driven by the different dynamical state of their baryonic disks. In HSD galaxies, the stellar disk is basically self-gravitating in the inner regions (near maximal, e.g., van Albada et al.^[107], Starkman et al.^[108]), so it can sustain spiral arms and form stellar bars^[109-110]. In LSD galaxies, instead, the stellar disk is not self-gravitating: the baryonic mass is dominated by the gas, while the total mass is dominated by dark matter (in the standard cosmological paradigm) down to small radii (e.g., Tully et al.^[99], de Blok et al.^[111]). Both effects make the baryonic disk relatively stable against the propagation of density waves and formation of bars. Interestingly, the gap between the two populations may suggest that the co-domination of baryons and dark matter is avoided^[99].

The LSD-HSD dichotomy suggests that the two galaxy populations form and evolve along different paths. If the initial baryonic disk is relatively heavy and dense (the HSD case), gravitational instabilities may lead to the formation of spiral arms, bars, bulges, and pseudo-bulges (e.g., Lin et al.^[109], Sellwood et al.^[110], Sellwood^[112]). These structures will then trigger gas condensations and shocks, thus efficient star formation and gas consumption (e.g., Roberts^[113], Kim et al.^[114], Yu et al.^[115]). Conversely, if the initial baryonic disk is relatively light and diffuse (the LSD case), large-scale gravitational instabilities are less effective, resulting in inefficient star formation and abundant gas content (e.g., Wyder et al.^[116]). Importantly, a LSD galaxy evolving in isolation will continue to be a LSD galaxy for at least another 10-100 Gyr. In this evolutionary scenario, the ability (or not) of sustaining density waves may be crucial because spiral arms are a very efficient mechanism to convert gas into stars. It remains unclear, however, why there should be a gap between the two populations.

The gap between HSD and LSD may potentially represent a rare and rapid transitional stage, in which galaxies transform from LSD to HSD. Given the low star formation rates and high gas depletion times of LSD galaxies (e.g., McGaugh et al.^[49]),

it will take more than a Hubble time for them to reduce their gas fractions toward those of HSD galaxies. The transformation of LSD into HSD galaxies (if any) must necessarily involve external mechanisms, such as galaxy interactions, which can trigger spiral arms, bars, and gas inflows (e.g., Ramón-Fox et al.^[117], Peschken et al.^[118]). Some studies^[99,102] found that galaxies in the transition region tend to have close neighbours, suggesting that galaxy interactions may indeed play a key role in such a transformation.

2.4 Relations with dynamical scaling laws

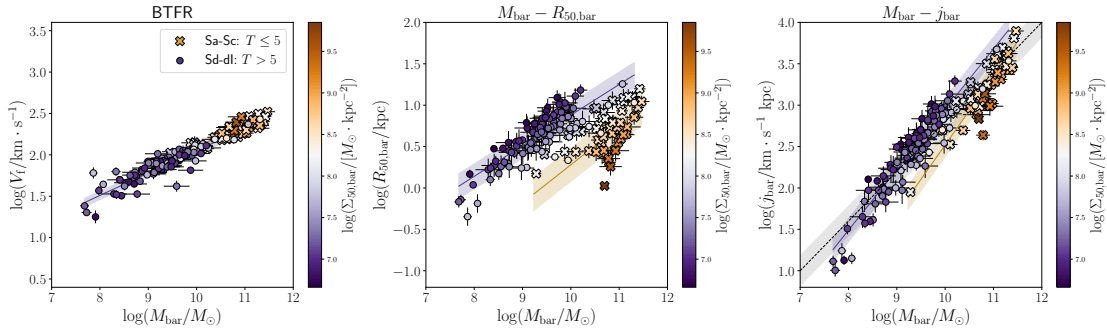


Figure 2.5 Scaling relations of galaxy disks: the baryonic Tully-Fisher relation (left panel), the baryonic mass-size relation (middle panel), and the baryonic angular-momentum relation (right panel). The three panels cover the same dynamic range on the y-axis, so one have *the same scales* on both axes. The circles and squares are the same as those in Fig. 2.4, colorcoded by the effective baryonic surface density $\Sigma_{50,\text{bar}}$. The blue and gold solid lines are the best-fit lines for LSDs and HSDs, respectively. The left panel: the BTFR. The medium panel: the $M_{\text{bar}} - R_{50,\text{bar}}$ relation. The dashed-black line in the right panel is the best-fit line for all the 157 galaxies.

One may wonder whether the HSD-LSD dichotomy is imprinted in other scaling relations of galaxies. In the following, we consider (1) the baryonic Tully-Fisher relation (BTFR) that links M_{bar} with the mean velocity along the flat part of the rotation curve V_f (e.g., McGaugh et al.^[34], Lelli et al.^[35,36], McGaugh^[41]); and (2) the angular momentum relation (AMR) that links M_{bar} with the specific angular momentum j_{bar} (e.g., Mancera Piña et al.^[87,88]). To this aim, we adopt a subsample of 157 galaxies with high-quality rotation curves ($Q \neq 3$, see Lelli et al.^[72]). We take V_f from Lelli et al.^[36]. For some galaxies without measured V_f (due to rising rotation curves up to the last measured point), we use the outermost velocity point as a first-order approximation, so that the same 157 galaxies appear in both dynamical scaling relations.

To a first-order approximation, j_{bar} is given by^[7,119-120]:

$$j_{\text{bar}} \simeq V_f \times R_{50,\text{bar}}. \quad (2.2)$$

In this approximation, the AMR is the mathematical convolution of the BTFR with the $M_{\text{bar}} - R_{50,\text{bar}}$ relation, so it cannot contain extra information^[36]. In the following, differently from Lelli et al.^[36], we compute j_{bar} in a more rigorous way by integrating the rotation curve and baryonic surface density profiles, following similar procedures as Posti et al.^[121] and Mancera Piña et al.^[88].

Figure 2.5 shows the three scaling relations. Importantly, the vertical axes cover the same dynamic range in V_f , $R_{\text{bar},50}$, and j_{bar} , so that the scatter around the relations and any eventual dichotomy can be visually assessed. It is evident that the tightest among the three is the BTFR, as already pointed out and quantified in Lelli et al.^[36].

The BTFR does not distinguish between LSD and HSD galaxies. Even if we fit the two galaxy populations separately, we recover the same best-fit relation within the uncertainties. This is in agreement with previous studies, which do not find additional correlations between the BTFR residuals and other galaxy properties (e.g., Lelli et al.^[35, 36], Ponomareva et al.^[122], Desmond et al.^[123], Hua et al.^[124]). The BTFR seems to have irreducible scatter; adding any additional variable to V_f at fixed M_{bar} will only degrade the original relation.

The AMR relation displays a moderate dichotomy: HSD and LSD galaxies follow different AMRs with a small offset in normalization. This offset must be driven by differences in the baryonic distribution (so in $R_{50,\text{bar}}$) at fixed M_{bar} because the $M_{\text{bar}} - V$ relations display no residual correlations for each and every radius at which V is measured^[123]. In other words, the dichotomy in $M_{\text{bar}} - j_{\text{bar}}$ plane is the same as that in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane, but appears less evident because the optimal variable ($R_{50,\text{bar}}$) is effectively multiplied by another variable (V_f) that has a near-perfect correlation with M_{bar} .

The moderate dichotomy in the AMR is in agreement with the results of Mancera Piña et al.^[87], who found that gas-rich galaxies have a larger intercept than gas-poor ones. Gas fraction is known to correlate with surface brightness or surface density (see, e.g., Fig. 2.2), so the offset found by Mancera Piña et al.^[87] is the same as the HSD-LSD dichotomy. Importantly, the $j_{\text{bar}} - M_{\text{bar}} - f_{\text{gas}}$ plane proposed by Mancera Piña et al.^[87] seems to be the result of a circular argument. Essentially, one takes an intrinsically thin relation (the BTFR) and multiply it with a radial variable (such as $R_{50,\text{bar}}$) to obtain a new relation with increased scatter (the AMR). Next, the increased scatter in the AMR

is reduced considering a fourth variable (f_{gas}) that correlate with $\Sigma_{50,\text{bar}}$ and/or $R_{50,\text{bar}}$ at fixed M_{bar} , effectively removing the extra dependency that was introduced in building the AMR in the first place.

The previous reasoning is confirmed by a simple mathematical exercise. The “effective” AMR relation is given by

$$\log(V_f \times R_{50,\text{bar}}) = S \times \log(M_{\text{bar}}) + N \quad (2.3)$$

where the slope S is the sum of the slopes of the BTFR and $M_{\text{bar}} - R_{50,\text{bar}}$ relation. By fitting LSD and HSD galaxies separately, we find that ~ 0.64 for LSDs and ~ 0.72 for HSDs. This is roughly in agreement with the best-fit slopes of the AMR relation (~ 0.73 for LSD and ~ 0.83 for HSD galaxies). Of course, the slopes are not exactly the same because j_{bar} is not calculated as $V_f \times R_{50,\text{bar}}$ but by integrating across the rotation curve and surface density profiles.

As we discussed in Section 2.3, the HSD-LSD dichotomy may indicate two distinct evolution paths of galaxies. Thus, the $M_{\text{bar}} - R_{50,\text{bar}}$ plane may be a better probe of galaxy evolution than the $M_{\text{bar}} - j_{\text{bar}}$ plane because the two galaxy populations separate the most in the former one, leaving little space for ambiguity.

Chapter 3 Passive galaxies

In this chapter, we will first introduce our sample and data analysis in Section 3.1. We will then present our results, and discuss the evolutionary links between passive galaxies and star forming galaxies in Section 3.2.

3.1 Data analysis

In Section 2.1, we do not separate galaxies by their morphology. However, as introduced in Sections 1.1 and 1.2, passive galaxies with different morphologies may evolve through distinct paths. Therefore, in this section, we will analyse E, S0, dE/dSph and UDG separately.

3.1.1 Ellipticals

We consider 140 ellipticals (Es) from Schombert^[125] that have Spitzer images at $3.6 \mu\text{m}$. This dataset is fully consistent with the SPARC dataset in terms of photometric band and photometric procedures. To derive $M_\star$, we adopt $Y_\star = 0.9 M_\odot/L_\odot$ ^[38,91]. This value comes from the same stellar population models that set $M_\star$ for SPARC galaxies, so the two datasets are on a common stellar mass scale. In the following, we will refer to this dataset as ‘‘Spitzer Es’’.

Some of these Es are in the field and contain atomic gas. However, the H I mass fraction is very small (typically $\lesssim 0.01$ ^[77]), so we can safely assume that $M_{\text{bar}} \simeq M_\star$ and $R_{50,\text{bar}} \simeq R_{50,\star}$ to a good approximation.

3.1.2 Lenticulars

We consider a sample of lenticulars (S0s) that have available bulge-disk decompositions from the literature:

- (a) twelve S0s from Lelli et al.^[38]. These galaxies have Spitzer images at $3.6 \mu\text{m}$, and the bulge-disk decompositions performed in the same way as SPARC galaxies. We estimate M_{diak} and M_{bul} using the same $Y_\star = 0.8 M_\odot/L_\odot$ following Lelli et al.^[38]. $R_{50,\text{disk}}$ and $R_{50,\text{bul}}$ are estimated following the same procedures as SPARC galaxies.

- (b) seven S0s from Kormendy et al.^[46]. Specifically, we select only S0s with “classical bulges” to be consistent with the SPARC bulge-disk decompositions, which assign “pseudo-bulges” to the disk component (see Lelli et al.^[72]). Kormendy et al.^[46] provides the V -band absolute magnitude, so we compute M_{bul} and M_{disk} assuming $\Upsilon_{\text{bul}} = \Upsilon_{\text{disk}} = 5 M_{\odot}/L_{\odot}$ in the V -band^[91]. This value comes from the same stellar population models that set $M_{\star}$ in SPARC galaxies, so the galaxies are on a common stellar mass scale, but we note that the uncertainties in $M_{\star}$ from V -band data are significantly larger than those from Spitzer data at $3.6 \mu\text{m}$.
- (c) ten S0s from Rizzo et al.^[126]. This work provides three different estimates of $M_{\star}$. For consistency with the SPARC sample, we use $M_{\star}$ from the K -band luminosity assuming $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Upsilon_{\star}^K = 1$ for both bulge and disk. This value is consistent with the SPARC stellar mass scale because $\Upsilon_{\star}^K \simeq 1.29 \Upsilon_{\star}^{[3.6]}$ with no significant color term^[127], so $\Upsilon_{\star}^{[3.6]} = 0.8$ ^[38] translates into $\Upsilon_{\star}^K \simeq 1.0$. To derive M_{bul} and M_{disk} separately, we use the r -band B/T from Rizzo et al.^[126]. $R_{50,\text{bul}}$ and $R_{50,\text{disk}}$ are estimated by a parametric decomposition in the r -band as described by Rizzo et al.^[126].

Most of these S0s are in galaxy clusters, so we can assume that they have negligible gas fractions^[77] and that $M_{\text{bar}} \simeq M_{\star}$ and $R_{50,\text{bar}} \simeq R_{50,\star}$. Lenticulars in the field environment, instead, could have significant amounts of atomic and molecular gas (e.g., Shelest et al.^[128]).

3.1.3 Dwarf ellipticals and dwarf spheroidals

We consider passive dwarfs (dEs/dSphs) in the core regions of galaxy clusters, so we can assume that they are devoid of gas and that $M_{\text{bar}} \simeq M_{\star}$ and $R_{50,\text{bar}} \simeq R_{50,\star}$. In particular, we consider galaxies with available photometry from the following surveys:

- (a) 404 galaxies from the Next Generation Virgo Cluster Survey (NGVS^[129]). $R_{50,\star}$ is given by the effective radius of a Sersic fit to the g -band surface brightness profile.
- (b) 627 galaxies from the Next Generation Fornax Cluster Survey (NGFS), specifically 243 from Eigenthaler et al.^[130] and 384 from Ordenes-Briceño et al.^[131]. $R_{50,\star}$ is estimated from i -band images.

Given the availability of i and g magnitudes, we calculate stellar masses using the relation from Taylor et al.^[132]:

$$\log \left(\frac{M_{\star}}{M_{\odot}} \right) = \log \left(\frac{L_i}{L_{\odot}} \right) + 0.68 (g - i), \quad (3.1)$$

For low-mass galaxies, this relation is virtually the same as the one from Schombert et al.^[91] see their Fig. 3, so these stellar masses are again on the same mass scale as SPARC galaxies. The catalog from Ordenes-Briceño et al.^[131] does not provide $(g - i)$ values, so we assume $(g - i) = 0.85$ that is the average value of dEs/dSphs from Eigenthaler et al.^[130].

Finally, we exclude 22 galaxies from Ferrarese et al.^[129] because they are Es/S0s rather than dEs/dSphs. In fact, they have $M_{\star} > 10^9 M_{\odot}$ using Eq. 3.1 (their stellar mass may be even higher because the stellar population models of Schombert et al.^[91] give higher $M_{\star}$ than those of Taylor et al.^[132] for red colors typical of Es/S0s). We do not consider these galaxies in our sample of S0s because they do not have available bulge-disk decompositions. Thus, we have a final sample of 1009 dEs/dSphs.

3.1.4 Ultra-diffuse galaxies in galaxy clusters

The term “ultra-diffuse galaxies” (UDGs) has been introduced by van Dokkum et al.^[133] to describe galaxies with central surface brightness lower than 24.5 mag arcsec⁻² in the g band and effective radius larger than 2.5 kpc. It is debated whether UDGs are a new type of galaxies (such as “failed $L_{\star}$ galaxies”, van Dokkum et al.^[133]), or just the extension of usual dwarf galaxies to lower surface brightnesses (e.g., Rong et al.^[57,57], Conselice^[134], Chilingarian et al.^[135], Iodice et al.^[136], Marleau et al.^[137], Rong et al.^[138], Li et al.^[139], Wright et al.^[140], Zöller et al.^[141], Lelli^[142]). In the following, we will use the term “UDGs” to simply distinguish them from the historical population of dEs/dSphs.

We consider a sample of UDGs in the Coma cluster^[133] and a sample of UDGs in other clusters compiled by Gannon et al.^[143]. Similarly to cluster dEs/dSphs, these UDGs can be assumed to be devoid of gas, so that $M_{\text{bar}} \simeq M_{\star}$ and $R_{50,\text{bar}} \simeq R_{50,\star}$. For the Coma UDGs, $R_{50,\star}$ comes from g -band images and $M_{\star}$ is derived using Eq. (3.1) with $g - i = 0.8$ ^[133]. For the UDGs from Gannon et al.^[143], both $R_{50,\star}$ and $M_{\star}$ are directly taken from their catalog. As we will show in Section 3.2, the data are

approximately on the same mass scale without any strong systematics.

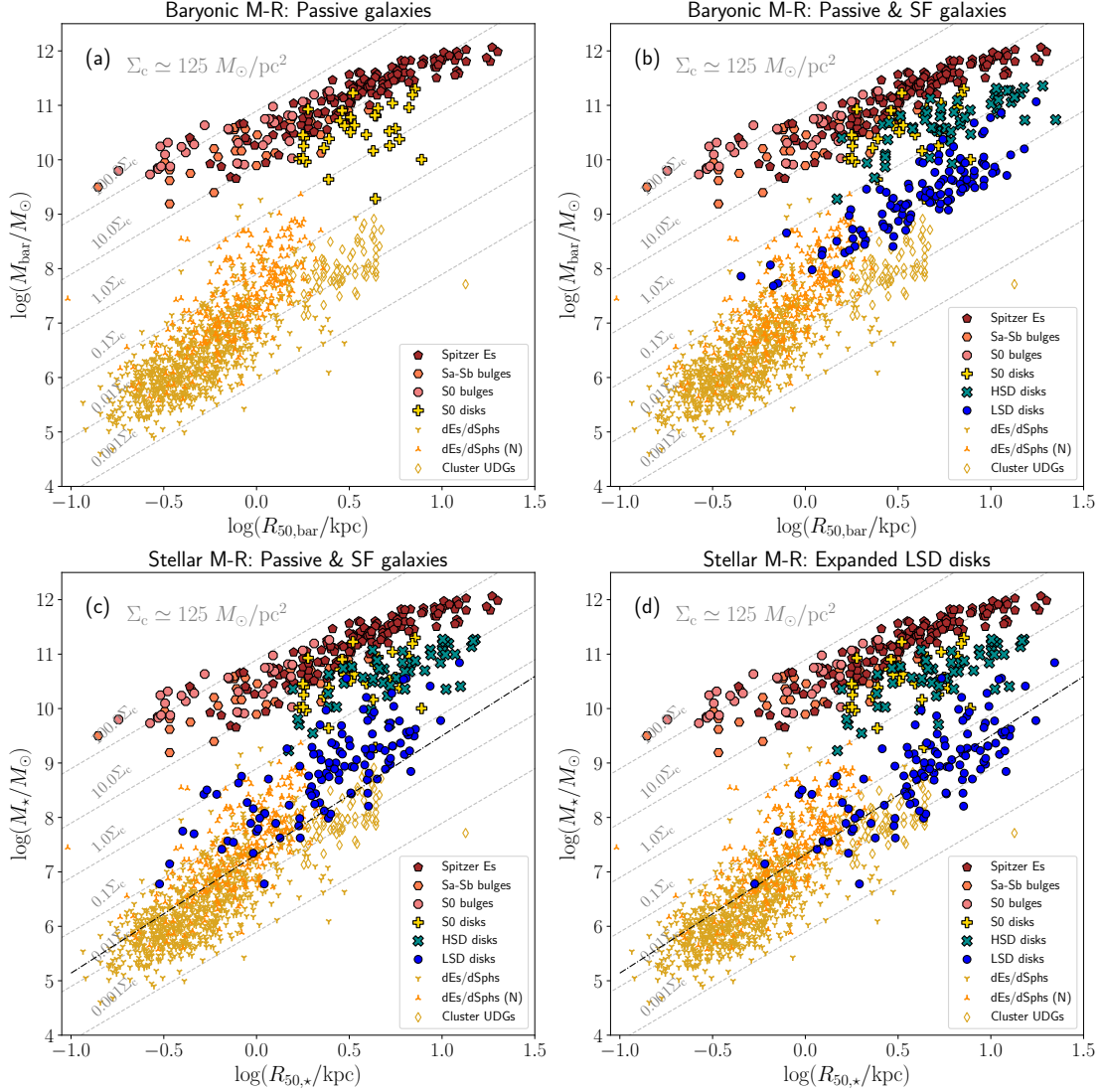


Figure 3.1 Mass-size relations of galaxies. Panel (a): The $M_{\text{bar}} - R_{50,\text{bar}}$ plane of passive galaxies and bulges of star-forming galaxies. Panel (b): Same as panel (b) but adding the disks of star-forming galaxies. Panel (c): The $M_{\star} - R_{50,\star}$ plane for our entire galaxy sample. Panel (d): Same as panel (c) but shifting the $R_{50,\star}$ of LSD disks to simulate an expansion of the stellar component, as discussed in Sect. 3.2.2. The grey-dashed lines are the same as those in Fig. 2.4. The black dot-dashed lines in panels (c) and (d) are the best-fitting lines of the passive dwarf galaxies.

3.2 Results

Figure 3.1 shows the mass-size plane in terms of both the total baryonic mass (top panels) and the stellar mass (bottom panels). For clarity, we start with passive galaxies only and subsequently add star-forming galaxies to the picture. Comparing the various panels of Fig. 3.1 provides key information on the possible evolutionary links between galaxies, as we now discuss.

3.2.1 General results of passive galaxies

Panel (a) of Fig. 3.1 considers passive galaxies devoid of substantial amounts of gas, so that the stellar and baryonic mass-size planes are nearly identical. We also consider the “classical” bulges of spiral galaxies (mostly Sa-Sb) and those of S0s, which can be considered as a population of passive spheroids.

The dichotomy between Es and dEs/dSphs^[43-45] is evident. In addition, stellar bulges form a continuous sequence with Es but distinct from dEs/dSphs, in agreement with previous studies (e.g., Kormendy et al.^[45,46]).

Interestingly, nucleated and non-nucleated dEs/dSphs seem to follow two different $M_{\text{bar}} - R_{50,\text{bar}}$ relations. The non-nucleated dEs/dSphs approximately lie on a line of constant $\Sigma_{50,\text{bar}} \simeq 1 \text{ M}_{\odot} \text{ pc}^{-2}$, whereas nucleated dEs/dSphs tend to be more massive and show a steeper slope in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane. In particular, there is a rarer population of bright and compact dEs with $\log(M_{\star}/M_{\odot}) \simeq 8.5 - 9.5$. These bright dEs partially fill the gap region around $\Sigma_{50,\text{bar}} \simeq 100 \text{ M}_{\odot} \text{ pc}^{-2}$, so they have led some authors to challenge the E-dE dichotomy (e.g., Graham et al.^[144], Gavazzi et al.^[145]) and propose that passive galaxies form a continuous but non-monotonic sequence in the stellar mass-size plane^[130]. These bright dEs tend to have inner nuclei and Sersic indexes higher than 1^[44], which progressively increase with luminosity connecting with those of Es^[146]. Possibly, bright nucleated dEs may form a different “breed” than non-nucleated dEs, which are instead of the same “breed” as dSphs and UDGs (see also Jerjen et al.^[146]).

UDGs extend the sequence of non-nucleated dEs/dSphs to larger half-light radii, along the line of constant $\Sigma_{50,\text{bar}} \simeq 1 \text{ M}_{\odot} \text{ pc}^{-2}$. This suggests that UDGs do not constitute a distinct population from passive (non-nucleated) dwarfs, which has already been pointed out by several authors^[134-135,137,141]. Clearly, UDGs do not appear to be “failed Milky-Way-like galaxies”^[133] but just normal dwarf galaxies.

3.2.2 High-mass galaxies

Panel (b) of Fig. 3.1 add star-forming galaxies to the $R_{50,\text{bar}} - M_{\text{bar}}$ plane. The star-forming disks of Sa-Sc galaxies lie below the sequence of Es, in line with the obvious fact that ellipticals cannot form by merely depleting gas in spirals. Indeed, the

majority of Es probably form and quench in the early Universe ($z \simeq 10$) through very rapid processes (e.g., McGaugh et al.^[147]), differently from disk galaxies that form at a slower pace. Occasionally, however, two spiral galaxies may merge (e.g., Toomre^[148]), changing their structure from disks to spheroids (or developing a classical bulge), doubling their baryonic mass, and moving towards the elliptical sequence in the baryonic mass-size plane.

There is some overlap between the disks of S0 and those of Sa-Sc. This may indicate that star-forming HSD disks naturally evolve into S0 as they run out of gas, in agreement with previous studies^[46,126,128]. This result lends support to the classification scheme proposed by van den Bergh^[47], in which S0s and spirals form two parallel sequences.

3.2.3 Low-mass galaxies

In the baryonic mass-size plane (Panel b of Fig. 3.1), passive dwarfs (dEs/dSphs/UDGs) form a third distinct sequence, below that of star-forming dwarfs (Sd-dI). In the stellar mass-size plane (Panel c of Fig. 3.1), instead, the most massive dEs/dSphs ($M_{\star} \simeq 10^7 - 10^9$) approximately overlap with the least massive star-forming dwarfs. This confirms the well-known fact that the stellar component of star-forming dwarfs is similar to that of passive dwarfs (e.g., Ferguson et al.^[149]).

A possible interpretation is that passive dwarfs arise from star-forming dwarfs that have lost their gas component, moving down in the baryonic mass-size plane but staying almost in the same position of the stellar mass-size plane. In this context, we note that star-forming dwarfs consume their gas in a very inefficient way and have gas depletion times much longer than the Hubble time (e.g., McGaugh et al.^[49]). In addition, there is mounting evidence that stellar feedback is unable to eject substantial amounts of gas from the potential wells of dwarf galaxies (e.g., Lelli et al.^[150,151], Concas et al.^[152], Marasco et al.^[153]). Thus, star-forming dwarfs evolving in isolation will probably remain on the LSD sequence of the mass-size plane for most of their lifetime. The only way to remove the dominant gas component of star-forming dwarfs is to have some external mechanisms due to the environment. For example, there is overwhelming evidence for gas stripping in galaxy clusters due to a variety of different mechanisms, such as ram-pressure stripping, tidal stripping, and galaxy harassment

(e.g., Boselli et al.^[17]). Similar mechanisms may also be effective in galaxy groups, as suggested by the strong morphology-density relation of dwarf galaxies (e.g., Tolstoy et al.^[154]).

A long-standing issue with the proposed evolutionary scenario is that the overlap between star-forming and passive dwarfs mostly occurs in the mass range where dEs are nucleated, whereas dIs rarely show nuclei^[155-156]. One possibility is that some star-forming dwarfs experience a starburst before losing their gas and evolving into a dEs, creating a central nuclei^[151]. Another possibility is that star-forming dwarfs evolve into non-nucleated dwarfs, but this would require an overall expansion of the stellar component of dIs to have a proper overlap with non-nucleated dwarfs in the $M_\star - R_{50,\star}$ plane (see panel c of Fig. 3.1).

We evaluate the possible amount of stellar expansion in the following way. We first fit the $R_{50,\star} - M_\star$ relation of passive dwarfs using the roxy package^[97]. Then, we shift star-forming dwarfs along the x -axis using a constant factor η . We determine the optimal value of η by minimizing the residuals along the best-fit relation of passive dwarfs. The result is shown in panel (d) of Fig. 3.1). We find that $\eta \simeq 2$ when we fit the $R_{50,\star} - M_\star$ relation of all passive dwarfs (nucleated and non-nucleated), whereas $\eta \simeq 2.6$ when considering only non-nucleated dwarfs. Therefore, the average amount of stellar expansions must be a factor of $\sim 2 - 3$ to turn the population of star-forming LSD galaxies into that of passive dwarfs in galaxy clusters.

An intuitive interpretation for such expansion is that cold gas takes up a large budget in the baryons of LSDs (see Fig. 2.4). Therefore, when the gas is removed, the gravity potentials of these galaxies becomes shallower. Then, stars must occupy orbits with larger radii in order to keep the dynamical equilibrium, leading to an expansion of the stellar disks. However, it remains unclear whether the expansion due to the gas removal is sufficient to explain η we observe. Simulations of such processes are needed to clarify this issue.

Chapter 4 Connections with MOND

The previous discussion is largely independent of the current cosmological model and the nature of dark matter. Our findings, however, have a potential connection with MOND. As discussed in Chapter 1, the characteristic scale a_0 may be imprinted in the galaxy structures as the critical surface density Σ_M (equation (1.2)).

The central density relation (CDR) of galaxies is particularly relevant in this context^[39]. The CDR links the central “observed” baryonic surface density $\Sigma_{0,\text{bar}}$ with the “dynamical” surface density $\Sigma_{0,\text{dyn}}$ inferred from the inner steepness of the rotation curve. The CDR is a non-linear relation that displays a knee around Σ_M . Galaxies with $\Sigma_{0,\text{bar}} > \Sigma_M$ are along the one-to-one relation, so they are baryon-dominated in the inner parts (in the Newtonian regime in a MOND context). Galaxies with $\Sigma_{0,\text{bar}} < \Sigma_M$ systematically deviate from the one-to-one line, so they are progressively more and more DM-dominated in the inner parts (in the Milgromian regime in a MOND context).

Interestingly, the division between HSD and LSD galaxies ($\Sigma_c \simeq 125 M_\odot/\text{pc}^2$) from the baryonic mass-size plane is practically indistinguishable from the characteristic MOND surface density $\Sigma_M \simeq 137 M_\odot/\text{pc}^2$. Approximately, using the adequate mass-to-light conversions, this corresponds to the historical Freeman’s limit for the central surface brightness of galaxy disks^[157]. Similarly, as shown in Section 3.2, S0s and dEs/dSphs are also divided approximately at the same surface-density value. This fact is quite remarkable because MOND is a theory of dynamics; yet the presence of a_0 is also imprinted on the structural properties of galaxies, such as the baryonic mass-size relation and the baryonic surface density distribution, which do not involve any kinematic measurement.

In the MOND context, the HSD-LSD dichotomy may naturally arise because the theory has a characteristic surface density scale, Σ_M , which distinguishes between different physical regimes. Galaxies (or proto-galaxies) with $\Sigma_{50,\text{bar}} \gtrsim \Sigma_M$ are in the Newtonian regime in the inner regions (with no dark matter), so they are prone to bar-like instabilities^[158]. By internal disk evolution, they will increase their central surface densities until they possibly reach a near-stable configuration due to the formation of bars and pseudo-bulges^[159-160]. Thus, galaxy disks with $\Sigma_{50,\text{bar}} \simeq \Sigma_M$ would necessarily be

rare because they have evolved towards higher $\Sigma_{50,\text{bar}}$, forming the HSD sequence. On the other hand, galaxy disks with $\Sigma_{50,\text{bar}} < \Sigma_M$ are in the deep MOND regime, which increases their stability. These galaxies will form the LSD sequence and remain there for most of their lifetime, consuming gas in a slow, inefficient fashion (unless some external mechanism alters their internal stability). Thus, LSD galaxies are expected to have low SFRs and low metallicities, as observed (e.g. Bothun et al.^[161]). For LSD galaxies, the mean value of $\Sigma_{50,\text{bar}} \simeq 10 - 15 M_\odot \text{pc}^{-2}$ must then be set by the hydrodynamical properties of atomic gas, rather than by stellar dynamics. After the separation between LSDs and HSDs, they further evolve in dEs/dSphs/UDGs and S0s by losing their gas, respectively. The gap in surface density between LSDs and HSDs remains, so that only few passive galaxies fulfill the region where $\Sigma_{50,\text{bar}} \simeq \Sigma_M$. As for ellipticals, they may form rapidly as dense objects in the early time, or they may be the result of the merger of two or more galaxies. In both cases, they are expected to have high surface densities, so they do not affect the presence of the gap. Large sets of hydrodynamical simulations of galaxy formation in MOND (e.g., Combes^[159], Nagesh et al.^[160], Wittenburg et al.^[162]) are necessary to further test these ideas.

This evolutionary scenario may be closely related to the initial baryonic angular momentum in MOND. As pointed out by Milgrom^[85], MOND defines a fiducial specific angular momentum that depends on the baryonic mass of the galaxy:

$$j_M(M_{\text{bar}}) = \left(\frac{G^3 M_{\text{bar}}^3}{a_0} \right)^{1/4} \simeq 382 \left(\frac{M_{\text{bar}}}{10^{10} M_\odot} \right)^{3/4} \text{ km s}^{-1} \text{ kpc}, \quad (4.1)$$

A proto-galaxy with mass M_{bar} and $j_{\text{bar}} \gg j_M$ will settle into a LSD disk. Instead, a proto-galaxy with mass M_{bar} but $j_{\text{bar}} \lesssim j_M$ will settle into a HSD disk with $M_{\text{disk}} = (j_{\text{bar}}/j_M)M_{\text{bar}}$ and develop a low- j component (such as a pseudo-bulge) that takes up the rest of the mass. In addition, Milgrom^[85] shows that

$$j_{\text{bar}} \simeq \sqrt{\frac{\Sigma_{\text{disk}}}{\Sigma_M}} j_M \simeq 382 \left(\frac{\Sigma_{\text{disk}}}{\Sigma_M} \right)^{1/2} \left(\frac{M_{\text{bar}}}{10^{10} M_\odot} \right)^{3/4} \text{ km s}^{-1} \text{ kpc}, \quad (4.2)$$

where Σ_{disk} is the mean surface density of the baryonic disks, which can be approximated by $\Sigma_{50,\text{disk}}$ within a factor of $O(1)$.

Gas-dominated LSD disks in the SPARC sample have $\Sigma_{50,\text{bar}} \simeq 0.1 \Sigma_M$ (Fig. 2.4), so MOND predicts that their $M_{\text{bar}} - j_{\text{bar}}$ relation should have a slope of $3/4 = 0.75$, which is entirely consistent with the best-fitting slope of 0.73 ± 0.02 (see Table A.4).

The situation in star-dominated HSD disks is more difficult to quantitatively assess for two main reasons: (1) these disks are mostly made of stars, so the computation of j_{bar} is a very rough approximation because we do not have access to the actual stellar kinematics (through spectroscopic observations), but we use H I rotation curves to infer the stellar rotation and stellar angular momentum assuming an average pressure term in the Jeans equations (similar to Posti et al.^[121]); (2) these disks must undergo a redistribution of their angular momentum through secular evolution due to the formation of bars and pseudo-bulges, so the modeling of these components in the computation of j_{bar} and $\Sigma_{50,\text{disk}}$ becomes critical; for example, our bulge-disk decompositions assign bars and pseudo-bulges to the disk (because they are expected to have a similar $\Upsilon_{\star}$) so they are included in j_{bar} and $\Sigma_{50,\text{disk}}$, which is different from the definitions given by Milgrom^[85]. From a qualitative perspective, however, HSD disks are in broad agreement with the MOND prediction, being systematically below the AMR relation defined by LSD disks.

Chapter 5 Summary and conclusion

We introduced the baryonic mass-size relation of SPARC galaxies, which links the total baryonic mass (stars plus gas) with the baryonic half-mass radius. We found the following results:

1. SPARC galaxies follow two distinct sequences in the $M_{\text{bar}} - R_{50,\text{bar}}$ plane: one defined by HSD, star-dominated, Sa-Sc galaxies and one defined by LSD, gas-dominated, Sd-dI galaxies. The two sequences, which are evident by eye, are confirmed by the clustering algorithm DBSCAN.
2. The baryonic mass-size relation of LSD galaxies has a slope close to 2, pointing to a constant average baryonic surface density of the order of $10\text{-}15 M_{\odot} \text{ pc}^{-2}$. The baryonic mass-size relation of HSD galaxies has a slope close to 1, indicating that less massive spirals are progressively more compact. The same results hold if we consider baryonic disk-only relations, excluding stellar bulges from the computation.
3. The HSD-LSD dichotomy is totally absent in the baryonic Tully-Fisher relation (M_{bar} versus V_{flat}) but moderately seen in the angular-momentum relation (M_{bar} versus $V_{\text{flat}} \times R_{50,\text{bar}}$), so it is driven by variations in the baryonic distribution ($R_{50,\text{bar}}$) at fixed baryonic mass. This fact indicate that the baryonic mass-size relation is the most effective empirical tool to distinguish between different galaxy types and may serve as a better probe for galaxy evolution.

Our results confirm the early findings of Schombert^[48] for a different galaxy sample. In addition, the HSD-LSD dichotomy is in line with previous studies that found a dichotomy in terms of the disk central surface brightness^[99,102-103]. To put these results on firmer grounds, we are currently building a much larger sample of galaxies with both spatially resolved H I data and NIR photometry (BIG-SPARC^[98]).

Furthermore, we observe some evidence suggesting that HSDs and LSDs become S0s and passive dwarfs (dE/dSph/UDGs), respectively, when they run out their gas. Especially, passive dwarfs may have lost their gas due to the environmental effects of rich clusters. This result strongly supports the new classification method proposed by van den Bergh^[47] and Kormendy^[163]. However, we notice that an expansion may

be necessary to explain the observed sizes of passive dwarfs. The mechanism, and the amplitude of this expansion is still unclear, and simulations are needed to further investigate this issue.

Finally, our results may potentially support the MOND theory, indicating that we may need to further investigate this scaling relation from a dynamical perspective. Especially, large simulations are vital to tell if the same dichotomy in the baryonic mass-size relation can be reproduced in the standard Λ CDM paradigm. This may help us to better distinguish between the two theoretical frames and result in a better understanding of gravity, which may lead us to a better understanding of galaxy formation and evolution.

Bibliography

- [1] Hubble E P. Extragalactic nebulae.[J]. *ApJ*, 1926, 64: 321-369.
- [2] Hubble E P. Realm of the Nebulae[M]. 1936.
- [3] Sandage A. The Hubble Atlas of Galaxies[M]. 1961.
- [4] Rubin V C, Ford W K, Jr., Thonnard N. Extended rotation curves of high-luminosity spiral galaxies. IV. Systematic dynamical properties, Sa $\rightarrow$ Sc.[J]. *ApJL*, 1978, 225: L107-L111.
- [5] Rubin V C, Ford W K, Jr., Thonnard N. Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc).[J]. *ApJ*, 1980, 238: 471-487.
- [6] Fall S M, Efstathiou G. Formation and rotation of disc galaxies with haloes.[J]. *MNRAS*, 1980, 193: 189-206.
- [7] Fall S M. Galaxy formation - Some comparisons between theory and observation[C]//Athanasoula E. IAU Symposium: Vol. 100 Internal Kinematics and Dynamics of Galaxies. 1983: 391-398.
- [8] White S D M, Rees M J. Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering.[J]. *MNRAS*, 1978, 183: 341-358.
- [9] Hoyle F. The Origin of the Rotations of the Galaxies[C]//Problems of Cosmical Aerodynamics. 1951: 195.
- [10] Peebles P J E. Origin of the Angular Momentum of Galaxies[J]. *ApJ*, 1969, 155: 393.
- [11] Doroshkevich A G. The space structure of perturbations and the origin of rotation of galaxies in the theory of fluctuation.[J]. *Astrofizika*, 1970, 6: 581-600.
- [12] White S D M. Angular momentum growth in protogalaxies[J]. *ApJ*, 1984, 286: 38-41.
- [13] Mo H J, Mao S, White S D M. The formation of galactic discs[J]. *MNRAS*, 1998, 295(2): 319-336.
- [14] Eggen O J, Lynden-Bell D, Sandage A R. Evidence from the motions of old stars that the Galaxy collapsed.[J]. *ApJ*, 1962, 136: 748.
- [15] Larson R B. Models for the formation of elliptical galaxies.[J]. *MNRAS*, 1975,

- 173: 671-699.
- [16] Arimoto N, Yoshii Y. Chemical and photometric properties of a galactic wind model for elliptical galaxies.[J]. *A&A*, 1987, 173: 23-38.
 - [17] Boselli A, Gavazzi G. On the origin of the faint-end of the red sequence in high-density environments[J]. *A&ARv*, 2014, 22: 74.
 - [18] Fabian A C. Observational Evidence of Active Galactic Nuclei Feedback[J]. *ARA&A*, 2012, 50: 455-489.
 - [19] Veilleux S, Cecil G, Bland-Hawthorn J. Galactic Winds[J]. *ARA&A*, 2005, 43 (1): 769-826.
 - [20] Dekel A, Silk J. The Origin of Dwarf Galaxies, Cold Dark Matter, and Biased Galaxy Formation[J]. *ApJ*, 1986, 303: 39.
 - [21] Mac Low M M, Ferrara A. Starburst-driven Mass Loss from Dwarf Galaxies: Efficiency and Metal Ejection[J]. *ApJ*, 1999, 513(1): 142-155.
 - [22] McQuinn K B W, van Zee L, Skillman E D. Galactic Winds in Low-mass Galaxies[J]. *ApJ*, 2019, 886(1): 74.
 - [23] Barnes J E, Hernquist L. Dynamics of interacting galaxies.[J]. *ARA&A*, 1992, 30: 705-742.
 - [24] Schmidt B P, Suntzeff N B, Phillips M M, et al. The High-Z Supernova Search: Measuring Cosmic Deceleration and Global Curvature of the Universe Using Type IA Supernovae[J]. *ApJ*, 1998, 507(1): 46-63.
 - [25] Perlmutter S, Aldering G, Goldhaber G, et al. Measurements of Ω and Λ from 42 High-Redshift Supernovae[J]. *ApJ*, 1999, 517(2): 565-586.
 - [26] Mo H, van den Bosch F C, White S. Galaxy Formation and Evolution[M]. 2010.
 - [27] Klypin A, Kravtsov A V, Valenzuela O, et al. Where Are the Missing Galactic Satellites?[J]. *ApJ*, 1999, 522(1): 82-92.
 - [28] Moore B, Ghigna S, Governato F, et al. Dark Matter Substructure within Galactic Halos[J]. *ApJL*, 1999, 524(1): L19-L22.
 - [29] Flores R A, Primack J R. Observational and Theoretical Constraints on Singular Dark Matter Halos[J]. *ApJL*, 1994, 427: L1.
 - [30] Boylan-Kolchin M, Bullock J S, Kaplinghat M. Too big to fail? The puzzling darkness of massive Milky Way subhaloes[J]. *MNRAS*, 2011, 415(1): L40-L44.
 - [31] Brooks A M, Zolotov A. Why Baryons Matter: The Kinematics of Dwarf

- Spheroidal Satellites[J]. *ApJ*, 2014, 786(2): 87.
- [32] Zhang Z, Chen Y, Rong Y, et al. Unexpected clustering pattern in dwarf galaxies challenges formation models[A]. 2025: arXiv:2504.03305. arXiv: [2504.03305](https://arxiv.org/abs/2504.03305).
- [33] Milgrom M. A modification of the Newtonian dynamics - Implications for galaxies.[J]. *ApJ*, 1983, 270: 371-383.
- [34] McGaugh S S, Schombert J M, Bothun G D, et al. The Baryonic Tully-Fisher Relation[J]. *ApJL*, 2000, 533(2): L99-L102.
- [35] Lelli F, McGaugh S S, Schombert J M. The Small Scatter of the Baryonic Tully-Fisher Relation[J]. *ApJL*, 2016, 816(1): L14.
- [36] Lelli F, McGaugh S S, Schombert J M, et al. The baryonic Tully-Fisher relation for different velocity definitions and implications for galaxy angular momentum [J]. *MNRAS*, 2019, 484(3): 3267-3278.
- [37] McGaugh S S, Lelli F, Schombert J M. Radial Acceleration Relation in Rotationally Supported Galaxies[J]. *Phys. Rev. Lett.*, 2016, 117(20): 201101.
- [38] Lelli F, McGaugh S S, Schombert J M, et al. One Law to Rule Them All: The Radial Acceleration Relation of Galaxies[J]. *ApJ*, 2017, 836(2): 152.
- [39] Lelli F, McGaugh S S, Schombert J M, et al. The Relation between Stellar and Dynamical Surface Densities in the Central Regions of Disk Galaxies[J]. *ApJL*, 2016, 827(1): L19.
- [40] Milgrom M. Central-surface-densities correlation in general MOND theories[J]. *Phys. Rev. D*, 2024, 109(12): 124016.
- [41] McGaugh S S. Balance of Dark and Luminous Mass in Rotating Galaxies[J]. *Phys. Rev. Lett.*, 2005, 95(17): 171302.
- [42] McGaugh S S. The Baryonic Tully-Fisher Relation of Gas-rich Galaxies as a Test of Λ CDM and MOND[J]. *AJ*, 2012, 143(2): 40.
- [43] Kormendy J. Families of ellipsoidal stellar systems and the formation of dwarf elliptical galaxies.[J]. *ApJ*, 1985, 295: 73-79.
- [44] Binggeli B, Cameron L M. Dwarf galaxies in the Virgo cluster. I. The systematic photometric properties of early-type dwarfs.[J]. *A&A*, 1991, 252: 27.
- [45] Kormendy J, Fisher D B, Cornell M E, et al. Structure and Formation of Elliptical and Spheroidal Galaxies[J]. *ApJS*, 2009, 182(1): 216-309.
- [46] Kormendy J, Bender R. A Revised Parallel-sequence Morphological Classifi-

- cation of Galaxies: Structure and Formation of S0 and Spheroidal Galaxies[J]. *ApJS*, 2012, 198(1): 2.
- [47] van den Bergh S. A new classification system for galaxies.[J]. *ApJ*, 1976, 206: 883-887.
- [48] Schombert J M. On the Structural Differences between Disk and Dwarf Galaxies [J]. *AJ*, 2006, 131(1): 296-303.
- [49] McGaugh S S, Schombert J M, Lelli F. The Star-forming Main Sequence of Dwarf Low Surface Brightness Galaxies[J]. *ApJ*, 2017, 851(1): 22.
- [50] de Vaucouleurs G. Recherches sur les Nebuleuses Extragalactiques[J]. *Annales d'Astrophysique*, 1948, 11: 247.
- [51] Trujillo I, Chamba N, Knapen J H. A physically motivated definition for the size of galaxies in an era of ultradeep imaging[J]. *MNRAS*, 2020, 493(1): 87-105.
- [52] Shen S, Mo H J, White S D M, et al. The size distribution of galaxies in the Sloan Digital Sky Survey[J]. *MNRAS*, 2003, 343(3): 978-994.
- [53] Bernardi M, Meert A, Vikram V, et al. Systematic effects on the size-luminosity relations of early- and late-type galaxies: dependence on model fitting and morphology[J]. *MNRAS*, 2014, 443(1): 874-897.
- [54] Greene J E, Greco J P, Goulding A D, et al. The Nature of Low-surface-brightness Galaxies in the Hyper Suprime-Cam Survey[J]. *ApJ*, 2022, 933(2): 150.
- [55] Nedkova K V, Häußler B, Marchesini D, et al. Bulge+disc decomposition of HFF and CANDELS galaxies: UVJ diagrams and stellar mass-size relations of galaxy components at $0.2 \leq z \leq 1.5$ [J]. *MNRAS*, 2024, 532(4): 3747-3777.
- [56] Kim J H, Lee J. How does the surface density and size of disc galaxies measured in hydrodynamic simulations correlate with the halo spin parameter?[J]. *MNRAS*, 2013, 432(2): 1701-1708.
- [57] Rong Y, Guo Q, Gao L, et al. A Universe of ultradiffuse galaxies: theoretical predictions from Λ CDM simulations[J]. *MNRAS*, 2017, 470(4): 4231-4240.
- [58] Fernández Lorenzo M, Sulentic J, Verdes-Montenegro L, et al. The stellar mass-size relation for the most isolated galaxies in the local Universe[J]. *MNRAS*, 2013, 434(1): 325-335.
- [59] Rodriguez F, Montero-Dorta A D, Angulo R E, et al. The galaxy size-halo mass scaling relations and clustering properties of central and satellite galaxies

- [J]. *MNRAS*, 2021, 505(3): 3192-3205.
- [60] Afanasiev A V, Mei S, Fu H, et al. The galaxy mass-size relation in CARLA clusters and proto-clusters at $1.4 < z < 2.8$: Larger cluster galaxy sizes[J]. *A&A*, 2023, 670: A95.
- [61] Du M, Ma H C, Zhong W Y, et al. The physical origin of the mass-size relation and its scatter for disk galaxies[J]. *A&A*, 2024, 686: A168.
- [62] Liao S, Gao L, Frenk C S, et al. Ultra-diffuse galaxies in the Auriga simulations [J]. *MNRAS*, 2019, 490(4): 5182-5195.
- [63] van der Wel A, Franx M, van Dokkum P G, et al. 3D-HST+CANDELS: The Evolution of the Galaxy Size-Mass Distribution since $z = 3$ [J]. *ApJ*, 2014, 788 (1): 28.
- [64] Roy N, Napolitano N R, La Barbera F, et al. Evolution of galaxy size-stellar mass relation from the Kilo-Degree Survey[J]. *MNRAS*, 2018, 480(1): 1057-1080.
- [65] Mowla L A, van Dokkum P, Brammer G B, et al. COSMOS-DASH: The Evolution of the Galaxy Size-Mass Relation since $z \sim 3$ from New Wide-field WFC3 Imaging Combined with CANDELS/3D-HST[J]. *ApJ*, 2019, 880(1): 57.
- [66] Yang L, Roberts-Borsani G, Treu T, et al. The evolution of the size-mass relation at $z = 1-3$ derived from the complete Hubble Frontier Fields data set[J]. *MNRAS*, 2021, 501(1): 1028-1037.
- [67] Broeils A H, Rhee M H. Short 21-cm WSRT observations of spiral and irregular galaxies. HI properties.[J]. *A&A*, 1997, 324: 877-887.
- [68] Cortese L, Catinella B, Janowiecki S. ALMA Shows that Gas Reservoirs of Star-forming Disks over the Past 3 Billion Years Are Not Predominantly Molecular [J]. *ApJL*, 2017, 848(1): L7.
- [69] Broeils A H, Rhee M H. Short 21-cm WSRT observations of spiral and irregular galaxies. HI properties.[J]. *A&A*, 1997, 324: 877-887.
- [70] Verheijen M A W, Sancisi R. The Ursa Major cluster of galaxies. IV. HI synthesis observations[J]. *A&A*, 2001, 370: 765-867.
- [71] Swaters R A, van Albada T S, van der Hulst J M, et al. The Westerbork HI survey of spiral and irregular galaxies. I. HI imaging of late-type dwarf galaxies [J]. *A&A*, 2002, 390: 829-861.
- [72] Lelli F, McGaugh S S, Schombert J M. SPARC: Mass Models for 175 Disk

- Galaxies with Spitzer Photometry and Accurate Rotation Curves[J]. *AJ*, 2016, 152(6): 157.
- [73] Wang J, Koribalski B S, Serra P, et al. New lessons from the H I size-mass relation of galaxies[J]. *MNRAS*, 2016, 460(2): 2143-2151.
- [74] Lutz K A, Kilborn V A, Koribalski B S, et al. The H IX galaxy survey - II. H I kinematics of H I eXtreme galaxies[J]. *MNRAS*, 2018, 476(3): 3744-3780.
- [75] Gault L, Leisman L, Adams E A K, et al. VLA Imaging of H I-bearing Ultra-diffuse Galaxies from the ALFALFA Survey[J]. *ApJ*, 2021, 909(1): 19.
- [76] Stevens A R H, Diemer B, Lagos C D P, et al. Origin of the galaxy H I size-mass relation[J]. *MNRAS*, 2019, 490(1): 96-113.
- [77] Serra P, Oosterloo T, Morganti R, et al. The ATLAS^{3D} project - XIII. Mass and morphology of H I in early-type galaxies as a function of environment[J]. *MNRAS*, 2012, 422(3): 1835-1862.
- [78] Lelli F. Gas dynamics in dwarf galaxies as testbeds for dark matter and galaxy evolution[J]. *Nature Astronomy*, 2022, 6: 35-47.
- [79] Guo Q, White S, Li C, et al. How do galaxies populate dark matter haloes?[J]. *MNRAS*, 2010, 404(3): 1111-1120.
- [80] Behroozi P S, Wechsler R H, Conroy C. The Average Star Formation Histories of Galaxies in Dark Matter Halos from $z = 0-8$ [J]. *ApJ*, 2013, 770(1): 57.
- [81] Kravtsov A V. The Size-Virial Radius Relation of Galaxies[J]. *ApJL*, 2013, 764(2): L31.
- [82] Dutton A A, van den Bosch F C, Dekel A, et al. A Revised Model for the Formation of Disk Galaxies: Low Spin and Dark Halo Expansion[J]. *ApJ*, 2007, 654(1): 27-52.
- [83] Huang K H, Fall S M, Ferguson H C, et al. Relations between the Sizes of Galaxies and Their Dark Matter Halos at Redshifts $0 < z < 3$ [J]. *ApJ*, 2017, 838(1): 6.
- [84] Somerville R S, Behroozi P, Pandya V, et al. The relationship between galaxy and dark matter halo size from $z \sim 3$ to the present[J]. *MNRAS*, 2018, 473(2): 2714-2736.
- [85] Milgrom M. MOND fiducial specific angular momentum of disc galaxies[J]. *Phys. Rev. D*, 2021, 104(6): 064030.

- [86] Milgrom M. Central-surface-densities correlation in general MOND theories[J]. *Phys. Rev. D*, 2024, 109(12): 124016.
- [87] Mancera Piña P E, Posti L, Pezzulli G, et al. A tight angular-momentum plane for disc galaxies[J]. *A&A*, 2021, 651: L15.
- [88] Mancera Piña P E, Posti L, Fraternali F, et al. The baryonic specific angular momentum of disc galaxies[J]. *A&A*, 2021, 647: A76.
- [89] Sérsic J L. Influence of the atmospheric and instrumental dispersion on the brightness distribution in a galaxy[J]. *Boletín de la Asociación Argentina de Astronomía La Plata Argentina*, 1963, 6: 41-43.
- [90] Vogelaar M G R, Terlouw J P. The Evolution of GIPSY—or the Survival of an Image Processing System[C]//Harnden F R, Jr., Primi F A, Payne H E. *Astronomical Society of the Pacific Conference Series: Vol. 238 Astronomical Data Analysis Software and Systems X*. 2001: 358.
- [91] Schombert J, McGaugh S, Lelli F. Stellar Mass-to-light Ratios: Composite Bulge+Disk Models and the Baryonic Tully-Fisher Relation[J]. *AJ*, 2022, 163(4): 154.
- [92] Desmond H. The underlying radial acceleration relation[J]. *MNRAS*, 2023, 526(3): 3342-3351.
- [93] McGaugh S S, Lelli F, Schombert J M. Scaling Relations for Molecular Gas and Metallicity: Impact on the Baryonic Tully-Fisher Relation[J]. *Research Notes of the American Astronomical Society*, 2020, 4(4): 45.
- [94] Schombert J, McGaugh S, Lelli F. The mass-to-light ratios and the star formation histories of disc galaxies[J]. *MNRAS*, 2019, 483(2): 1496-1512.
- [95] Kroupa P, Weidner C. Galactic-Field Initial Mass Functions of Massive Stars[J]. *ApJ*, 2003, 598(2): 1076-1078.
- [96] ESTER M, KRIEGEL H P, SANDER J, et al. A density-based algorithm for discovering clusters in large spatial databases with noise[C]//kdd: Vol. 96. 1996: 226-231.
- [97] Bartlett D J, Desmond H. Marginalised Normal Regression: unbiased curve fitting in the presence of x-errors[A]. 2023: arXiv:2309.00948. arXiv: [2309.00948](https://arxiv.org/abs/2309.00948).
- [98] Haubner K, Lelli F, Di Teodoro E, et al. BIG-SPARC: The new SPARC database [A]. 2024: arXiv:2411.13329. arXiv: [2411.13329](https://arxiv.org/abs/2411.13329).

- [99] Tully R B, Verheijen M A W. The Ursa Major Cluster of Galaxies. II. Bimodality of the Distribution of Central Surface Brightnesses[J]. *ApJ*, 1997, 484(1): 145-162.
- [100] McDonald M, Courteau S, Tully R B. Bulge-disc decompositions and structural bimodality of Ursa Major cluster spiral galaxies[J]. *MNRAS*, 2009, 393(2): 628-640.
- [101] McDonald M, Courteau S, Tully R B. The near-IR luminosity function and bimodal surface brightness distributions of Virgo cluster galaxies[J]. *MNRAS*, 2009, 394(4): 2022-2042.
- [102] Sorce J G, Courtois H M, Sheth K, et al. Bimodality of galaxy disc central surface brightness distribution in the Spitzer 3.6 μm band[J]. *MNRAS*, 2013, 433(1): 751-758.
- [103] Sorce J G, Creasey P, Libeskind N I. Properties of galaxies in the disc central surface brightness gap[J]. *MNRAS*, 2016, 455(3): 2644-2655.
- [104] Sancisi R, Fraternali F, Oosterloo T, et al. Cold gas accretion in galaxies[J]. *A&ARv*, 2008, 15(3): 189-223.
- [105] Marinacci F, Binney J, Fraternali F, et al. The mode of gas accretion on to star-forming galaxies[J]. *MNRAS*, 2010, 404(3): 1464-1474.
- [106] van Zee L. The Evolutionary Status of Isolated Dwarf Irregular Galaxies. II. Star Formation Histories and Gas Depletion[J]. *AJ*, 2001, 121(4): 2003-2019.
- [107] van Albada T S, Sancisi R. Dark Matter in Spiral Galaxies[J]. *Philosophical Transactions of the Royal Society of London Series A*, 1986, 320(1556): 447-464.
- [108] Starkman N, Lelli F, McGaugh S, et al. A new algorithm to quantify maximum discs in galaxies[J]. *MNRAS*, 2018, 480(2): 2292-2301.
- [109] Lin C C, Shu F H. On the Spiral Structure of Disk Galaxies[J]. *ApJ*, 1964, 140: 646.
- [110] Sellwood J A, Masters K L. Spirals in Galaxies[J]. *ARA&A*, 2022, 60.
- [111] de Blok W J G, McGaugh S S. The dark and visible matter content of low surface brightness disc galaxies[J]. *MNRAS*, 1997, 290(3): 533-552.
- [112] Sellwood J A. Secular evolution in disk galaxies[J]. *Reviews of Modern Physics*, 2014, 86(1): 1-46.

- [113] Roberts W W. Large-Scale Shock Formation in Spiral Galaxies and its Implications on Star Formation[J]. *ApJ*, 1969, 158: 123.
- [114] Kim Y, Kim W T. Gaseous spiral structure and mass drift in spiral galaxies[J]. *MNRAS*, 2014, 440(1): 208-224.
- [115] Yu S Y, Ho L C, Wang J. Spiral Structure Boosts Star Formation in Disk Galaxies [J]. *ApJ*, 2021, 917(2): 88.
- [116] Wyder T K, Martin D C, Barlow T A, et al. The Star Formation Law at Low Surface Density[J]. *ApJ*, 2009, 696(2): 1834-1853.
- [117] Ramón-Fox F G, Aceves H. Accretion of small satellites and gas inflows in a disc galaxy[J]. *MNRAS*, 2020, 491(3): 3908-3922.
- [118] Peschken N, Łokas E L. Tidally induced bars in Illustris galaxies[J]. *MNRAS*, 2019, 483(2): 2721-2735.
- [119] Romanowsky A J, Fall S M. Angular Momentum and Galaxy Formation Revisited[J]. *ApJS*, 2012, 203(2): 17.
- [120] Fall S M, Romanowsky A J. Angular Momentum and Galaxy Formation Revisited: Scaling Relations for Disks and Bulges[J]. *ApJ*, 2018, 868(2): 133.
- [121] Posti L, Fraternali F, Di Teodoro E M, et al. The angular momentum-mass relation: a fundamental law from dwarf irregulars to massive spirals[J]. *A&A*, 2018, 612: L6.
- [122] Ponomareva A A, Verheijen M A W, Papastergis E, et al. From light to baryonic mass: the effect of the stellar mass-to-light ratio on the Baryonic Tully-Fisher relation[J]. *MNRAS*, 2018, 474(4): 4366-4384.
- [123] Desmond H, Katz H, Lelli F, et al. Uncorrelated velocity and size residuals across galaxy rotation curves[J]. *MNRAS*, 2019, 484(1): 239-244.
- [124] Hua Z, Rong Y, Hu H. The baryonic Tully-Fisher relation of H I-bearing low-surface brightness galaxies implies their formation mechanism[J]. *MNRAS*, 2025, 538(2): 775-781.
- [125] Schombert J M. Colors of Ellipticals from GALEX to Spitzer[J]. *AJ*, 2016, 152 (6): 214.
- [126] Rizzo F, Fraternali F, Iorio G. S0 galaxies are faded spirals: clues from their angular momentum content[J]. *MNRAS*, 2018, 476(2): 2137-2167.
- [127] McGaugh S S, Schombert J M. Color-Mass-to-light-ratio Relations for Disk

- Galaxies[J]. *AJ*, 2014, 148(5): 77.
- [128] Shelest A, Lelli F. From spirals to lenticulars: Evidence from the rotation curves and mass models of three early-type galaxies[J]. *A&A*, 2020, 641: A31.
- [129] Ferrarese L, Côté P, MacArthur L A, et al. The Next Generation Virgo Cluster Survey (NGVS). XIV. The Discovery of Low-mass Galaxies and a New Galaxy Catalog in the Core of the Virgo Cluster[J]. *ApJ*, 2020, 890(2): 128.
- [130] Eigenthaler P, Puzia T H, Taylor M A, et al. The Next Generation Fornax Survey (NGFS). II. The Central Dwarf Galaxy Population[J]. *ApJ*, 2018, 855(2): 142.
- [131] Ordenes-Briceño Y, Eigenthaler P, Taylor M A, et al. The Next Generation Fornax Survey (NGFS). III. Revealing the Spatial Substructure of the Dwarf Galaxy Population Inside Half of Fornax's Virial Radius[J]. *ApJ*, 2018, 859(1): 52.
- [132] Taylor E N, Hopkins A M, Baldry I K, et al. Galaxy And Mass Assembly (GAMA): stellar mass estimates[J]. *MNRAS*, 2011, 418(3): 1587-1620.
- [133] van Dokkum P G, Abraham R, Merritt A, et al. Forty-seven Milky Way-sized, Extremely Diffuse Galaxies in the Coma Cluster[J]. *ApJL*, 2015, 798(2): L45.
- [134] Conselice C J. Ultra-diffuse Galaxies Are a Subset of Cluster Dwarf Elliptical/Spheroidal Galaxies[J]. *Research Notes of the American Astronomical Society*, 2018, 2(1): 43.
- [135] Chilingarian I V, Afanasiev A V, Grishin K A, et al. Internal Dynamics and Stellar Content of Nine Ultra-diffuse Galaxies in the Coma Cluster Prove Their Evolutionary Link with Dwarf Early-type Galaxies[J]. *ApJ*, 2019, 884(1): 79.
- [136] Iodice E, Cantiello M, Hilker M, et al. The first detection of ultra-diffuse galaxies in the Hydra I cluster from the VEGAS survey[J]. *A&A*, 2020, 642: A48.
- [137] Marleau F R, Habas R, Poulain M, et al. Ultra diffuse galaxies in the MATLAS low-to-moderate density fields[J]. *A&A*, 2021, 654: A105.
- [138] Rong Y, Hu H, He M, et al. Gas-rich Ultra-diffuse Galaxies Are Originated from High Specific Angular Momentum[A]. 2024: arXiv:2404.00555. arXiv: [2404.00555](https://arxiv.org/abs/2404.00555).
- [139] Li J, Greene J E, Greco J P, et al. Beyond Ultra-diffuse Galaxies. I. Mass-Size Outliers among the Satellites of Milky Way Analogs[J]. *ApJ*, 2023, 955(1): 1.
- [140] Wright A C, Tremmel M, Brooks A M, et al. The formation of isolated ultradiffuse galaxies in ROMULUS25[J]. *MNRAS*, 2021, 502(4): 5370-5389.

- [141] Zöller R, Kluge M, Staiger B, et al. Ultradi diffuse Galaxies—A Distinct Population? Dwarf Galaxies in the Coma Cluster and A262 from Deep $u'-g'-r'$ Wendelstein Imaging Data[J]. *ApJS*, 2024, 271(2): 52.
- [142] Lelli F. Gas-rich “ultra-diffuse” galaxies are consistent with the baryonic Tully–Fisher relation and with Milgromian dynamics[J]. *A&A*, 2024, 689: L3.
- [143] Gannon J S, Ferré-Mateu A, Forbes D A, et al. A Catalogue and analysis of ultra-diffuse galaxy spectroscopic properties[J]. *MNRAS*, 2024, 531(1): 1856-1869.
- [144] Graham A W, Guzmán R. HST Photometry of Dwarf Elliptical Galaxies in Coma, and an Explanation for the Alleged Structural Dichotomy between Dwarf and Bright Elliptical Galaxies[J]. *AJ*, 2003, 125(6): 2936-2950.
- [145] Gavazzi G, Donati A, Cucciati O, et al. The structure of elliptical galaxies in the Virgo cluster. Results from the INT Wide Field Survey[J]. *A&A*, 2005, 430: 411-419.
- [146] Jerjen H, Binggeli B. Are “Dwarf” Ellipticals Genuine Ellipticals?[C]//Arnaboldi M, Da Costa G S, Saha P. Astronomical Society of the Pacific Conference Series: Vol. 116 The Nature of Elliptical Galaxies; 2nd Stromlo Symposium. 1997: 239.
- [147] McGaugh S S, Schombert J M, Lelli F, et al. Accelerated Structure Formation: The Early Emergence of Massive Galaxies and Clusters of Galaxies[J]. *ApJ*, 2024, 976(1): 13.
- [148] Toomre A. Mergers and Some Consequences[C]//Tinsley B M, Larson R B G, D. Campbell. Evolution of Galaxies and Stellar Populations. 1977: 401.
- [149] Ferguson H C, Binggeli B. Dwarf elliptical galaxies[J]. *A&ARv*, 1994, 6(1-2): 67-122.
- [150] Lelli F, Verheijen M, Fraternali F. Dynamics of starbursting dwarf galaxies. III. A H I study of 18 nearby objects[J]. *A&A*, 2014, 566: A71.
- [151] Lelli F, Fraternali F, Verheijen M. Evolution of dwarf galaxies: a dynamical perspective[J]. *A&A*, 2014, 563: A27.
- [152] Concas A, Maiolino R, Curti M, et al. Being KLEVER at cosmic noon: Ionized gas outflows are inconspicuous in low-mass star-forming galaxies but prominent in massive AGN hosts[J]. *MNRAS*, 2022, 513(2): 2535-2562.
- [153] Marasco A, Belfiore F, Cresci G, et al. Shaken, but not expelled: Gentle baryonic

- feedback from nearby starburst dwarf galaxies[J]. *A&A*, 2023, 670: A92.
- [154] Tolstoy E, Hill V, Tosi M. Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group[J]. *ARA&A*, 2009, 47(1): 371-425.
- [155] Côté P, Piatek S, Ferrarese L, et al. The ACS Virgo Cluster Survey. VIII. The Nuclei of Early-Type Galaxies[J]. *ApJS*, 2006, 165(1): 57-94.
- [156] Lisker T, Grebel E K, Binggeli B, et al. Virgo Cluster Early-Type Dwarf Galaxies with the Sloan Digital Sky Survey. III. Subpopulations: Distributions, Shapes, Origins[J]. *ApJ*, 2007, 660(2): 1186-1197.
- [157] Freeman K C. On the Disks of Spiral and S0 Galaxies[J]. *ApJ*, 1970, 160: 811.
- [158] Ostriker J P, Peebles P J E. A Numerical Study of the Stability of Flattened Galaxies: or, can Cold Galaxies Survive?[J]. *ApJ*, 1973, 186: 467-480.
- [159] Combes F. Bulge formation in disk galaxies with MOND[J]. *A&A*, 2014, 571: A82.
- [160] Nagesh S T, Kroupa P, Banik I, et al. Simulations of star-forming main-sequence galaxies in Milgromian gravity[J]. *MNRAS*, 2023, 519(4): 5128-5148.
- [161] Bothun G, Impey C, McGaugh S. Low-Surface-Brightness Galaxies: Hidden Galaxies Revealed[J]. *PASP*, 1997, 109: 745-758.
- [162] Wittenburg N, Kroupa P, Famaey B. The Formation of Exponential Disk Galaxies in MOND[J]. *ApJ*, 2020, 890(2): 173.
- [163] Kormendy J. Brightness distributions in compact and normal galaxies. II. Structure parameters of the spheroidal component.[J]. *ApJ*, 1977, 218: 333-346.
- [164] de Blok W J G, McGaugh S S, van der Hulst J M. HI observations of low surface brightness galaxies: probing low-density galaxies[J]. *MNRAS*, 1996, 283(1): 18-54.
- [165] Noordermeer E, van der Hulst J M, Sancisi R, et al. The Westerbork HI survey of spiral and irregular galaxies. III. HI observations of early-type disk galaxies [J]. *A&A*, 2005, 442(1): 137-157.
- [166] Richards E E, van Zee L, Barnes K L, et al. Baryonic distributions in the dark matter halo of NGC 5005[J]. *MNRAS*, 2015, 449(4): 3981-3996.
- [167] Richards E E, van Zee L, Barnes K L, et al. Baryonic distributions in galaxy dark matter haloes - I. New observations of neutral and ionized gas kinematics [J]. *MNRAS*, 2016, 460(1): 689-728.

- [168] Broeils A H. Dark and visible matter in spiral galaxies[D]. University of Groningen, Netherlands, 1992.
- [169] Begeman K G. HI rotation curves of spiral galaxies[D]. University of Groningen, Kapteyn Astronomical Institute, 1987.
- [170] van der Hulst J M, Skillman E D, Smith T R, et al. Star Formation Thresholds in Low Surface Brightness Galaxies[J]. *AJ*, 1993, 106: 548.
- [171] van Zee L, Haynes M P, Salzer J J, et al. A Comparative Study of Star Formation Thresholds in Gas-Rich Low Surface Brightness Dwarf Galaxies[J]. *AJ*, 1997, 113: 1618-1637.
- [172] Spekkens K, Giovanelli R. The Structure of Rapidly Rotating Late-Type Spiral Galaxies. I. Photometry, H I, and Optical Kinematics[J]. *AJ*, 2006, 132(4): 1426-1444.
- [173] Gentile G, Salucci P, Klein U, et al. The cored distribution of dark matter in spiral galaxies[J]. *MNRAS*, 2004, 351(3): 903-922.
- [174] Côté S, Carignan C, Freeman K C. The Various Kinematics of Dwarf Irregular Galaxies in Nearby Groups and Their Dark Matter Distributions[J]. *AJ*, 2000, 120(6): 3027-3059.
- [175] Begum A, Chengalur J N, Hopp U. The little galaxy that could: kinematics of [10.1016/S1384-1076\(02\)00238-5](https://arxiv.org/abs/10.1016/S1384-1076(02)00238-5) & Camelopardalis B [J]. *New A*, 2003, 8(4): 267-280.
- [176] Begum A, Chengalur J N, Karachentsev I D. A dwarf galaxy with a giant HI disk [J]. *A&A*, 2005, 433(1): L1-L4.
- [177] Fraternali F, Sancisi R, Kamphuis P. A tale of two galaxies: light and mass in NGC 891 and NGC 7814[J]. *A&A*, 2011, 531: A64.
- [178] Hallenbeck G, Huang S, Spekkens K, et al. HIghMass—High H I Mass, H I-rich Galaxies at $z \sim 0$ High-resolution VLA Imaging of UGC 9037 and UGC 12506 [J]. *AJ*, 2014, 148(4): 69.
- [179] Carignan C, Puche D. H I Studies of the Sculptor Group Galaxies. II. NGC 7793 [J]. *AJ*, 1990, 100: 394.
- [180] Carignan C, Puche D. H I Studies of the Sculptor Group Galaxies. IV. NGC 247 [J]. *AJ*, 1990, 100: 641.
- [181] Begum A, Chengalur J N. Kinematics of two dwarf galaxies in the NGC 6946

- p group[J].
- A&A*
- , 2004, 424: 509-517.
- [182] Barbieri C V, Fraternali F, Oosterloo T, et al. Extra-planar gas in the spiral galaxy NGC 4559[J]. *A&A*, 2005, 439(3): 947-956.
- [183] Boomsma R, Oosterloo T A, Fraternali F, et al. HI holes and high-velocity clouds in the spiral galaxy NGC 6946[J]. *A&A*, 2008, 490(2): 555-570.
- [184] Carignan C, Sancisi R, van Albada T S. H I and Mass Distribution in the Dwarf “Regular” Galaxy UGC 2259[J]. *AJ*, 1988, 95: 37.
- [185] Carignan C, Beaulieu S. Optical and H i Studies of the “Gas-rich” Dwarf Irregular Galaxy DDO 154[J]. *ApJ*, 1989, 347: 760.
- [186] Chemin L, Carignan C, Drouin N, et al. H I Studies of the Sculptor Group Galaxies. VIII. The Background Galaxies: NGC 24 and NGC 45[J]. *AJ*, 2006, 132(6): 2527-2538.
- [187] Cote S, Carignan C, Sancisi R. A Dark-Halo-Dominated Galaxy: NGC 5585[J]. *AJ*, 1991, 102: 904.
- [188] Jobin M, Carignan C. The Dark Side of NGC 3109[J]. *AJ*, 1990, 100: 648.
- [189] Kepley A A, Wilcots E M, Hunter D A, et al. A High-Resolution Study of the H I Content of Local Group Dwarf Irregular Galaxy WLM[J]. *AJ*, 2007, 133(5): 2242-2257.
- [190] Lake G, Schommer R A, van Gorkom J H. The Distribution of Dark Matter in the Dwarf Galaxy DDO 170[J]. *AJ*, 1990, 99: 547.
- [191] Puche D, Carignan C, Wainscoat R J. H I Studies of the Sculptor Group Galaxies. III. NGC 55[J]. *AJ*, 1991, 101: 447.
- [192] Rhee M H, van Albada T S. Short WSRT HI observations of spiral galaxies.[J]. *A&AS*, 1996, 115: 407-437.
- [193] Roelfsema P R, Allen R J. Radio observations of HI in UGC 2885, the largest identified SC galaxy.[J]. *A&A*, 1985, 146: 213-222.
- [194] Verdes-Montenegro L, Bosma A, Athanassoula E. The ringed, warped and isolated galaxy NGC 6015.[J]. *A&A*, 1997, 321: 754-764.
- [195] Walsh W, Staveley-Smith L, Oosterloo T. The Giant, Gas-Rich, Low-Surface-Brightness Galaxy NGC 289[J]. *AJ*, 1997, 113: 1591-1606.

Appendix A Tables

In section 2.1, we described the compilation of H I surface density profiles for 169 galaxies. References for the H I data and the corresponding number of galaxies are listed in Table A.1.

In section 2.2, we used the roxy software to fit the baryonic mass-size relations of HSD and LSD galaxies separately. Table A.2 provides the best-fit parameters of the $M_{\text{bar}} - R_{50,\text{bar}}$ relation, considering different physical properties to divide the two groups of galaxies. Table A.3 provides the same information for the $M_{\text{disk}} - R_{50,\text{disk}}$ relation, in which stellar bulges are excluded.

In Section 2.4, we used the roxy software to fit the baryonic Tully-Fisher relation, the baryonic mass-size relation (switching the axes with respect to Sect. 2.2), and the baryonic angular momentum relation for HSD and LSD galaxies separately. Table A.4 provide the best-fit parameters.

Table A.1 References for the HI surface density profiles

Source	Number of galaxies
Swaters et al. ^[71]	37
Verheijen et al. ^[70]	27
de Blok et al. ^[164]	16
Noordermeer et al. ^[165]	12
Richards et al. ^[166,167]	9
Lelli et al. ^[150]	8
Broeils ^[168]	7
Begeman ^[169]	6
van der Hulst et al. ^[170]	6
van Zee et al. ^[171]	6
Spekkens et al. ^[172]	5
Gentile et al. ^[173]	4
Côté et al. ^[174]	3
Begum et al. ^[175,176]	2
Fraternali et al. ^[177]	2
Hallenbeck et al. ^[178]	2
Carignan et al. ^[179,180]	2
Begum et al. ^[181]	1
Barbieri et al. ^[182]	1
Boomsma et al. ^[183]	1
Carignan et al. ^[184]	1
Carignan et al. ^[185]	1
Chemin et al. ^[186]	1
Cote et al. ^[187]	1
Jobin et al. ^[188]	1
Kepley et al. ^[189]	1
Lake et al. ^[190]	1
Puche et al. ^[191]	1
Rhee et al. ^[192]	1
Roelfsema et al. ^[193]	1
Verdes-Montenegro et al. ^[194]	1
Walsh et al. ^[195]	1

Table A.2 Best-fit parameters of the $M_{\text{bar}} - R_{50,\text{bar}}$ relations, dividing SPARC galaxies in two groups based on f_{gas} , $\Sigma_{50,\text{bar}}$ and T .

	$f_{\text{gas}} \leq 0.3$	$f_{\text{gas}} > 0.3$	$\Sigma_{50,\text{bar}} \geq \Sigma_{\text{M}}$	$\Sigma_{50,\text{bar}} < \Sigma_{\text{M}}$	$T \leq 5$	$T > 5$
α	1.03 ± 0.14	1.92 ± 0.10	1.08 ± 0.18	1.95 ± 0.12	0.85 ± 0.23	1.83 ± 0.13
β	10.07 ± 0.13	8.12 ± 0.08	10.09 ± 0.13	8.13 ± 0.08	10.11 ± 0.07	8.19 ± 0.08
σ_{int}	0.35 ± 0.05	0.35 ± 0.02	0.30 ± 0.03	0.32 ± 0.02	0.45 ± 0.03	0.27 ± 0.02

Table A.3 Best-fit parameters of the $M_{\text{disk}} - R_{50,\text{disk}}$ relations, dividing SPARC galaxies in two groups based on f_{gas} , $\Sigma_{50,\text{bar}}$ and T .

	$f_{\text{gas}} \leq 0.3$	$f_{\text{gas}} > 0.3$	$\Sigma_{50,\text{bar}} \geq \Sigma_{\text{M}}$	$\Sigma_{50,\text{bar}} < \Sigma_{\text{M}}$	$T \leq 5$	$T > 5$
α	1.33 ± 0.17	1.87 ± 0.12	1.36 ± 0.16	1.95 ± 0.12	1.27 ± 0.23	1.85 ± 0.12
β	9.66 ± 0.13	8.16 ± 0.08	9.68 ± 0.13	8.13 ± 0.08	9.70 ± 0.19	8.18 ± 0.08
σ_{int}	0.28 ± 0.03	0.33 ± 0.02	0.24 ± 0.04	0.35 ± 0.02	0.39 ± 0.04	0.31 ± 0.02

Table A.4 Best-fit parameters of the baryonic Tully-Fisher relation, baryonic mass-size relation, and baryonic angular-momentum relation fitting LSD galaxies (left columns) and HSD galaxies (right columns) separately.

	BTFR: M_{bar} vs V_{f}		Mass-size: M_{bar} vs $R_{50,\text{bar}}$		AMR: M_{bar} vs j_{bar}	
	LSD	HSD	LSD	HSD	LSD	HSD
α	0.26 ± 0.02	0.27 ± 0.01	0.46 ± 0.08	0.37 ± 0.02	0.83 ± 0.06	0.73 ± 0.02
β	-0.50 ± 0.12	-0.65 ± 0.10	-4.32 ± 0.85	-2.82 ± 0.02	-5.78 ± 0.64	-4.35 ± 0.23
σ_{int}	0.04 ± 0.01	0.05 ± 0.01	0.20 ± 0.02	0.15 ± 0.01	0.14 ± 0.02	0.14 ± 0.01

Appendix B Error Estimation

Following Lelli et al. ^[35], we estimate the error on M_{bar} as

$$\delta M_{\text{bar}} = \sqrt{\left(\frac{\delta F_{\text{HI}}}{F_{\text{HI}}} M_{\text{gas}}\right)^2 + \left(\frac{\delta L}{L} M_{\star}\right)^2 + \left(\frac{\delta Y_{\star}}{Y_{\star}} M_{\star}\right)^2 + \left(2 \frac{\delta D}{D} M_{\text{bar}}\right)^2}, \quad (\text{B.1})$$

where δF_{HI} is the uncertainty on the HI flux (about 10%), δL is the uncertainty on the 3.6 μm luminosity (a few %), $\delta Y_{\star}$ is the uncertainty on the stellar mass-to-light ratio (dominated by galaxy-to-galaxy variations that are assumed to be of $\sim 25\%$), and δD is the uncertainty on the galaxy distance (varying from 5% to 30% depending on the galaxy, see Lelli et al. ^[72]). The error on the disk mass (excluding the bulge) is given by the same equation by replacing $M_{\star}$ with the mass of the stellar disk and M_{bar} with the mass of the baryonic disk.

The errors on $R_{50,\text{bar}}$ are estimated as

$$\delta R_{50,\text{bar}} = \sqrt{\left(\frac{\delta \theta_{50}}{\theta_{50}} R_{50,\text{bar}}\right)^2 + \left(\frac{\delta D}{D} R_{50,\text{bar}}\right)^2}, \quad (\text{B.2})$$

where θ_{50} is half-mass radius in arcsec. We assume that $\delta \theta_{50}/\theta_{50} = 1/n$, where n is the number of HI spatially resolved elements along the disk semi-major axis (approximately the number of points along the SPARC rotation curve).

In logarithmic space, the covariance between δM_{bar} and $\delta R_{50,\text{bar}}$ is given by

$$\sigma_{M_{\text{bar}} R_{50,\text{bar}}} = 2 \left(\frac{\delta D}{D \ln 10} \right)^2. \quad (\text{B.3})$$

The values of V_f and the corresponding errors are taken directly from Lelli et al. ^[36]. For galaxies without a measured V_f , we consider the last point of the rotation curve and the corresponding error (accounting for uncertainties on inclination too). V_f does not depend on D , so there is no need to consider the covariance matrix between M_{bar} and V_f .

The error on j_{bar} is estimated following Mancera Piña et al. ^[87]. The covariance between M_{bar} and j_{bar} (in logarithmic space) can be roughly estimated as,

$$\sigma_{M_{\text{bar}} j_{\text{bar}}} = \sigma_{M_{\text{bar}} R_{50,\text{bar}}}, \quad (\text{B.4})$$

according to equation (2.2). Nevertheless, we find that even if we do not include the covariant term $\sigma_{M_{\text{bar}} j_{\text{bar}}}$, the best-fitting results do not change significantly.

Appendix C The effect of the division point between LSDs and HSDs

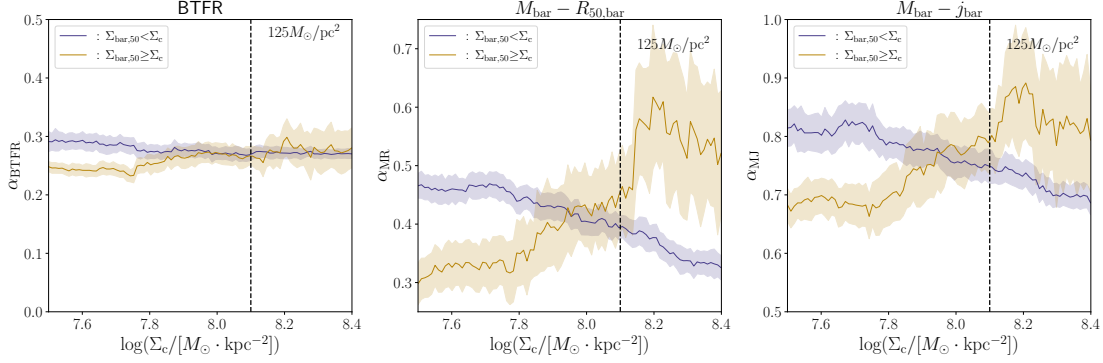


Figure C.1 The slopes (α_{BTFR} , α_{MR} and α_{MJ}) of each population as the functions of the division threshold (Σ_c). All the axes are *of the same scales*. The blue line is the group with $\Sigma_{50,\text{bar}} < \Sigma_c$ and the golden line is with $\Sigma_{50,\text{bar}} \geq \Sigma_c$. The shaded areas denoted 1σ errors. The left panel: the BTFR. The middle panel: the $M_{\text{bar}} - R_{50,\text{bar}}$ relation. The right panel: the the $M_{\text{bar}} - j_{\text{bar}}$ relation.

Different division points between LSDs and HSDs (i.e., the values of Σ_c) may affect the results in Chapter 2. Therefore, we investigate such a potential effect by varying the value of $\log \Sigma_c$ from 7.5 to 8.4, and use the same methods to fit the BTFR, the mass-size relation and the angular momentum relation. We use the variations of the slopes to quantify the effect of the division point.

Fig. C.1 shows the slopes of the BTFR, the baryonic mass-size relation and the AMR of the two galaxy populations as functions of Σ_c . From the right panel, we can see that the slopes of the BTFR only vary moderately, indicating that Σ_c has nearly zero effect on the BTFR of galaxies. This result further validates that the BTFR is a universal relation and is independent of other properties of galaxies^[35,124].

On the other hand, the slopes of the baryonic mass-size relation (the middle panel) and the AMR (the right panel) of both populations show clear trends relating to Σ_c . Especially, we see that for galaxies having $\Sigma_{50,\text{bar}} > \Sigma_c$, their slopes of both relations show a clear gap at where $\log \Sigma_c \simeq 8.1$. This clearly indicates that there are two galaxy populations in our sample. Looking at Fig. 2.5, one could see that the number of “real HSD” sequence is smaller than that of “real LSD”s. Then, imagining that we gradually decrease Σ_c . At first, the galaxy included in the HSD catalogue will be inside the “real HSD” sequence evident by eyes. Thus, the fitting algorithm will give a slope of the “real HSD” sequence. But as we decrease Σ_c to some crutial point, many “real LSD”s

will continue the samples input to the algorithm, and as there are so many “real LSD”s, the algorithm will be strongly interrupted. Therefore it will produce a slope that is much closer to the “real LSD” sequence.

Having this in mind, the gaps at the same Σ_c value further indicates that the two populations on the $M_{\text{bar}} - R_{50,\text{bar}}$ plane and those on the AMR plane are the same two populations. They clearly have similar physical origins. This further supports our original division of LSDs and HSDs in Chapter 2, and lead us to believe that $\Sigma_c \simeq 125 M_{\odot}/\text{pc}^2$ has special physical meanings.

Acknowledgements

时光荏苒，在科大的四年即将画上句号。很难说我对科大本身有着什么样独特的情感，但我对这四年来我在科大遇到的老师、同学和朋友们，确实有着不少想说的话。

首先，我要感谢在这四年遇到的各位老师。我要感谢带领我走进天文科研的容昱老师。在科研的起步阶段中，从最基本的物理图像，到数据处理，再到最后的文章撰写，我遇到了很多问题，也犯下了不少低级错误。是容老师耐心的指导带领我一步步走过这些过程，让我最终能够完成这个项目。在此期间我收获到的知识和经验，可以说是我科研的“第一桶金”，它们让我有信心和勇气去继续科研道路。同时，我也要感谢我的暑研兼本科设计导师 **Federico Lelli**。在意大利的五个月期间，不论是在科研上还是日常生活中，他都提供了很多无私的帮助。在这段经历里，与他的很多探讨让我深受启发。尤其是他对标准 **ΛCDM** 模型外其他理论的探讨，让我看到了研究星系的性质在发掘它们演化路径之外的，对我们了解自然界最基本的引力相互作用的潜力。我还要感谢 **Konstantin Haubner**, **Enrico di Teodoro**, **Stacy McGaugh** 以及 **James Schombert**。没有你们的建议和帮助，这个科研项目不可能完成。最后，我还想感谢袁业飞老师。没有他在理论力学课上各种精妙绝伦的天体物理例子，我可能也不会迈入天文学的大门。

我还要感谢在科大遇到的各位同学和朋友们。首先就是曾经和我一起试着搞讨论班的曹家赫、柯恩齐、吴铭鑫、袁悦同学。虽然讨论班无疾而终，但是你们为我打开了看待世界的全新角度，和你们的友谊也会是我一生的财富。我还要感谢天文系的姜皓辰、杨景硕和陈世江同学，和你们探讨天文问题予以了我很多启发，也鞭策着我继续努力。最后，感谢我在物理学院学生会、云南老乡会等各个地方遇到的同学和朋友们。原谅我没有将你们的名字一一打出，但没有你们的欢笑，我在科大的生活定会灰暗不少；没有你们的支持和鼓励，我前行的路上也会有更多的曲折。

最后，感谢我的父母一直以来予以我的无声的支持。上了大学以后，我才终于认识到承担责任的辛苦与不易。

“宇宙很大，生活更大，我们会再相遇的。”——对一位天文系的学生来说，这句话包含着一种不可思议的浪漫，毕竟宇宙的尺度大得难以直观想象。我知道，哪怕是在地球上，“我们会再相遇的”都只能算作一句美好的愿望。但重要的

也许不是能否再次相遇，而是生活中的每一次相遇都激起了新的热情，打开了新的视角，创造了新的故事，而这些相遇荡漾起的涟漪会在未来触发我们不曾想象的际遇。广袤的宇宙固然充满了惊喜，但生活可以比只能被动观测的宇宙更加精彩。宇宙很大，生活更大——在科大和你们每一个人相遇，才是更加浪漫的事。

2025 年 6 月