

UV tracing of the recent star formation activity in galaxy disks within the S⁴G sample: from strangulation to XUV emission

Formación estelar en el UV en discos de galaxias de la exploración S⁴G: estrangulamiento y emisión UV extensa

PhD dissertation presentation

Friday, June 1, 2018

by PhD candidate: Alexandre Yuichiro Kléber Bouquin

supervised by: Dr. Armando Gil de Paz Universidad Complutense de Madrid (UCM)

Departamento de Física de la Tierra y Astrofísica

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The Big Picture

Planck's Cosmic Microwave Background map at z=1089



ESA & the Planck Collaboration (2013)



HUDF 2014 HST

NASA/STScl

The Big questions: How do galaxies form and evolve?

The Big Picture



NASA/WMAP Science Team (2012)



NGC5055 (M63)





Morphological classifications and star formation



SINGS galaxies by Kennicutt et al. (2003)

tuning-fork diagram

NOTE: we use the more simplistic numerical morphological type (T) classification of RC2 (de Vaucouleurs 1991) for the rest of the work



Numerical morphological types

NOTE: we use the more simplistic numerical morphological type (T) classification of RC2 (de Vaucouleurs 1991) for the rest of the work

$$E = [-5.0; -3.5]$$

$$E-S0 = [-3.4; -2.5]$$

$$S0 = [-2.4; -1.5]$$

$$S0-a = [-1.4; 0.5]$$

$$Sa = [0.6; 2.5]$$

$$Sb = [2.6; 4.5]$$

$$Sb = [2.6; 4.5]$$

$$Sc = [4.6; 7.5]$$

$$Sd = [7.6; 8.5]$$

$$Sm = [8.6; 9.5]$$

$$Irr = [9.6; 10.0]$$

One of the goals of this thesis is to find a way to distinguish between **internal** and **environmental** effects on star formation.



Reproduction of the morphological box (Zwicky 1957) of galaxy evolution processes updated by Kormendy & Kennicutt 2004, and adapted for this presentation.



3 4.1 4.2 4.3 4.4 4.5 5 6 1 2 1. Introduction

Right: nearby galaxies in optical bands

Bottom: distribution of galaxies in optical color-color diagrams per redshift bins

The bimodal distribution of galaxies





But, caveat...:

optical bands are not able to dissociate well between SF, quiescent, and green valley galaxies.

All galaxies

3.0

2.5

2.0

1.5

1.0

9.0

9.5

10.0

"u-r colour

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 Star formation (in GMC) 1. Introduction

collapse of giant molecular cloud and birth of stars (the amount of each depends on the IMF) massive young stars emits in the UV ionizing the gas that remains and becomes an HII region

FUV+NUV; t=107 to 109 years

The remaining gas is blown off by SNe+massive stars driven winds after a few Myr



 $3.6\mu m; t > 10^9 years$

Ha; $t=10^6$ to 10^7 years

As there is no more gas, we are left with the less-massive stars.

Young and massive OB associations emit in the UV. —> GALEX FUV+NUV

Low-mass MS stars and Red Giants emit in the IR. —> Spitzer/IRAC1

Therefore, FUV, NUV and 3.6 micron are ideal to study young to old stellar populations.



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Environmental effects:

Ram pressure stripping, dry/wet, major/minor mergers (and other interactions with companions), harassment, strangulation, near-collisions (fly-bys).



Tail of ionized gas in NGC 4569. Boselli et al. (2016) The "jellyfish" galaxy ESO137-001. Credit: NASA/ESA, Ming Sun (UAH), and Serge Meunier. (2014)

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2. Sample

We use the **Spitzer Survey of Stellar Structure in Galaxies (S4G)** sample of nearby galaxies as a base (**Sheth et al. 2010**).

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The S4G is a volume-limited, size-limited, magnitude-limited sample and goes to unprecedented depth of ~26.5 mag arcsec⁻² in the IRAC1 channel



1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 2. Sample

scripts credit: **Erik Tollerud** Data: Cosmicflows-2 (**Tully et al., 2013**) S⁴G (**Sheth et al., 2010**)

150

150

-100

Tully (2013)
 S⁴G

The S⁴G sample

size N = 2352 galaxies Galactic latitude $|b| \ge 30^{\circ}$ Angular diameter D₂₅ > 1' Radial velocity vrad < 3000 km s⁻¹ (corresponds to ~40 Mpc) (obtained from HI 21cm obs.)

Photometry obtained with the Infrared Array Camera (IRAC) in channel 1 (3.6 µm) and 2 (4.5 µm) by Muñoz Mateos et al., 2015

We gather GALEX raw product tiles from GR6/7 for the S4G galaxies via the publicly available online tool GalexView: http://galex.stsci.edu/galexview/



⁵⁰VIV/Mpc⁵⁰



100

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3. Data analysis



1234.14.24.34.44.5563. Data analysis — Preparations

Sky Measurement



An elliptical ring-annulus is placed at 1.5xD25 and divided into 90 boxes.

The average is computed in each box, which is then averaged using all the boxes.

Masking



Semi-automatic masking based on (FUV - NUV) color.

Each mask is visually checked and corrected for false-detection, companions, and foreground stars.

Interpolation



The masked regions are then interpolated using the average of neighbor pixels, vertically and horizontally.

1234.14.24.34.44.5563. Data analysis — Measurements

Photometry



Photometry is performed in fixed PA and ϵ elliptical ringannuli with 6" steps. The average is computed for each ring.

For the FUV and NUV, we use the same apertures as the ones used to do the 3.6 μm photometry.

Data products

- False-color RGB images
- Surface brightness profiles
- Color profiles
- Growth curves
- Asymptotic magnitudes
- Spatial resolution of data: 6 arcsec
- corrected for foreground MW attenuation using A_{FUV}=7.9E(B-V) and A_{NUV}=8.0E(B-V).
- Final galaxy count: 1931 with homogenized FUV, NUV, and 3.6 µm data

We call this the **GALEX/S4G sample**







Dec (J2000)



Dec (J2000)

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 3. Data analysis — Models

Complemented by

- environmental info of Tully et al. (2013) and Laine et al. (2014)
- SSP from Bruzual & Charlot (2003) and (2007)
- Ram-pressure stripping model from Boissier (2006)
- Disk-models from Boissier & Prantzos (2000)
- Kinematic data from HyperLEDA



Below: 3.6 µm surface brightnesses of disk models from **Boissier & Prantzos (2000)**

Prantzos (2000)



red = S4G sample (**Sheth+ 2010**), white, blue = GALEX/S4G sample (**Bouquin+ 2015**) colors = Cosmicflows-2 samples (**Tully+ 2013**)

Left:

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4.1 Results: Global properties

Publication Bouquin et al. 2015, ApJL, 800, 19

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THE GALENS⁴G UV IR COLOR CODOR DIAGRAM CATCHING SPIRAL GALANIES AWAY FROM THE BLUE SEQUENCE

 ALEXANDAR Y, K. BORQUEN¹, ACCENCE EL., DE PAZ¹, STORME DERMAR¹²⁰, LAW-CALLER M. PROS-MATROR⁴, KALLER SALTA⁵, BERRER JANETROV, ALEX⁴, LEWEN, CALLER VALLE, PALENDER JANETROV, R. BERR⁴, ²⁴, ²⁵, ²⁵,

NESTRACT.

We obtained GALEXPTIV, NUV, and Solver/IRAC 5.6 pr., thetenetry for p-vantegalaxies, exclude to R 966 of the S/G variable We that a wave eight GM SZ blue requests (GRS) in the (H, V, NUV) create (MIV, 3, 6), to co-color diagram, which is populated by integalar and spice galaxies, and is non y driven by changes in the formation threesends (F) and a digeneracy between τ and does reddening. The injtimest to the GRS provides an improvement of GRS is not the GRS in the formation three formation $T_{\rm eff}(r)$ and a digeneracy between τ and does reddening. The injtimest to the GRS provides an improvement of GRS is called a spice r of the original distribution of the GRS is the SI Sa's, and matter as the original distribution of the original distribution of the GRS is the SI Sa's, and the original distribution of the GRS is the or

L INTERDUCTION

Even-magnitude and other-color diagrams are proven galaxy evolution diagnostic mode. Becaut studies rational set of Q(MdX) and SDSS does not be Wesler as (2007), have elastly shown the existence of a bimodal distribution of galaxies. In $(NUX)^2$, where is calse magnitude diagnost (TM), by where the redder and higher aspins a pope and mutity be early-type galaxies in a "red sequence," and others the block and histore part of the diagnost is populated mainly by biology subjects on the redder and T.

Isla-type galaxies in a "lithe sequence." We construct a color-magnitude and a pelor-color diagram. using for UV (HUV; effective wavelength 151.6 mm and near 10V (NUV) 226 Juni) insiges from GUUX (Martin et al. 2005) and 5.6 pm images more the images solvated by the Solow Survey of Status Smears in Chinaks (340; Stoch et al. 2010). The near IR (NIR) bundls censitive mainly to old stars and the UV bands to young case for EQs). As we show below, a combination of UV and NIR bands allows us to expanses our forming from passively marking galaxies, while the use of the two (A112) UV bands analysis this analysis when sansitive to installions, galaxies and to the marships threasede, as the FUV hard is most consider to the presence of young (UD-type) since the sample is based on the Solutor Servey of Stellar Severare in Calaxies (STI: Shellow of 2010), in this study, we getter the publicity evolution (*GMESZ* does (from time relevant GRAP) for these 57G galaxies and necessary NUV and FUV surface and asymptotic photometry for over 2000 galaxies. (~90% of the S'O galaxies). We then combine this with creatisters and asymptotic 3.5 yas photometry more

S²G. We adopt a value of $H_0 = 75\,{\rm km\,s^{-1}}$ Mpc 2 for galaxian haloing a scalabili independent distance measurement (as in Shorh or d=20,0)

2 SAMALE

The S^*G is a variance induct [2] < d0 kdpc], reagain induction [26, and 2, constrained for inclination, galactic contrasts, and X convection], and since intrastic (16% 5–17) survey avoiding the galactic equatorial plane (5–5–50) of 2352 galactics, consisting of 3.5 and (-5 µm). EAC band image: Galactic environment for inclination of the analysis of the significantly shorts galactics is one encouple of methylic order of the significant prior galactics is one encouple of methylic order of the significant prior galactics is one encouple of methylic order of the significant prior galactics of all the field of the significant prior galactics of all the field parameters methylic galactics (150^{-1}) targets of 100^{-1} . (100^{-1} methylic of 100^{-1} , 100^{-1} methylic of the starts (100^{-1} methylic of 100^{-1}). (100^{-1} methylic of 100^{-1} , 100^{-1} methylic of 10^{-1} methylic of 10^{-1}

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The (FUV - NUV) vs. (NUV - [3.6]) colorcolor diagram shows the bimodal distribution of galaxies with narrower sequences than the 'classical' (optical) one.

Important: NOT corrected for internal dust attenuation. For Av=0.5 mag, using the Calzetti (1994) attenuation law, (NUV-[3.6]) would change by -1, and (FUV-NUV) by -0.25. The correction is degenerated in the sense that it follows a similar slope than that of the Blue Sequence. ^{M[3.6]} We define the GALEX Blue Sequence (GBS), GALEX Red Sequence (GRS) and GALEX Green Valley (GGV) as follows: GBS: $0.12x + 0.16 - 2\sigma_{\text{GBS}} \le y \le 0.12x + 0.16 + 2\sigma_{\text{GBS}}$ GRS: $-0.23y + 5.63 - 1\sigma_{\text{GRS}} \le x \le -0.23y + 5.63 + 1\sigma_{\text{GRS}}$

GGV: $y > 0.12x + 0.16 + 2\sigma_{\text{GBS}}$ and $x < -0.23y + 5.63 - 1\sigma_{\text{GRS}}$

where $\sigma_{\text{GBS}} = 0.2$ x = (NUV - [3.6])and $\sigma_{\text{GRS}} = 0.45$ y = (FUV - NUV)



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These are 'classical' (optical) color-magnitude diagrams showing the 'red sequence' and 'blue cloud'.

- = galaxies identified in the GALEX Red Sequence
 - = galaxies identified in the GALEX Green Valley
- = galaxies identified in the GALEX Blue Sequence

Caveats of optical colors:

(1) hard to classify Red Sequence, Green Valley, Blue Cloud galaxies(2) many GBS galaxies appear in the optical Red Sequence

1234.14.24.34.44.5564.1Results:Global properties

Bouquin et al. 2015



Left: evolution of SSP models of **Bruzual and Charlot (2003)** of various metallicities in the (FUV - NUV) and (NUV - [3.6]) colors.

Highly-evolved systems (>10¹⁰ Gyr) are shown in red.



Right: evolution of UV+IR colors for disk+bulge models and a Ram-Pressure Stripping (RPS) model. The disks are from **Boissier & Prantzos**, **2000**, and are controlled by two parameters: *circular velocity* v_c and *spin parameter* λ .

We simulate a bulge by taking a highly-evolved SSP and by varying the B/T ratio of **Laurikainen** et al., 2007.

An RPS model of **Boselli et al., 2006** is also shown (red triangles).

1234.14.24.34.44.5564.1Results:Global properties



Bouquin et al. 2015

The distribution of the GALEX/S4G galaxies in the (FUV - NUV) vs. (NUV - [3.6]) CCD per morphological type.

): galaxies in the Virgo cluster.

: galaxies in high-density regions as defined by Laine et al. (2014).

: field galaxies

We find a **higher fraction** (29%) of GGV galaxies in our sample to be in the Virgo cluster, as compared to the GBS (7%) or the GRS (14%) galaxies, and 162/1931 (8%) galaxies overall.

1234.14.24.34.44.5564.1Results:Global properties

Conclusions of 4.1:

- Galaxies are distributed into two narrow sequences in the (FUV NUV) versus (NUV [3.6]) color-color diagram: the GALEX Blue Sequence (GBS) is populated by actively star-forming late-type galaxies and the GALEX Red Sequence (GRS) is populated by quiescent early-type galaxies.
- In the region of intermediate-colors, the GALEX Green Valley (GGV), a large fraction of galaxies are early-type spirals of type Sa and S0-a.
- The GGV can be interpreted as a zone of rapid transition (≤1 Gyr) due to the quenching or damping of star formation in the disk resulting in its reddening, consistent with timescales of ram-pressure stripping in denser environment. It is worth noting, however that these results do not exclude the possibility of having rejuvenated galaxies from the GRS to fall into the GGV as well.
- We also find that a higher fraction of galaxies in the GGV (compared to the GBS or the GRS) belong to the Virgo cluster, suggesting that the environment is at play.

4.1 **4.2** 4.3 4.4

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4.5

4.2 Results: UV-color and stellar M/L ratio correlation in ETGs

Publications: Zaritsky, Gil de Paz, Bouquin 2014, ApJL, 780, 1

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"An empirical connection between ultraviolet color of early-type galaxies and the stellar initial mass function"

Zaritsky, Gil de Paz, Bouquin 2015, MNRAS, 446, 2030

"The connection between the UV colour of early type galaxies and the stellar initial mass function revisited"

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The connection between the UV colour of early-type galaxies and the stellar initial mass function resisted

Dennis Zertricky, ¹⁴ A mando Gilde Par² and Alexandra Y K. 'Armpula¹ Standard Review States and the State Complete Feet Alexandra (States), ¹⁰ Review States and States and States (States), ¹⁰ Review States and States and States (States), ¹⁰ Review States and States and States and States and States and States (States), ¹⁰ Review States and States and States and States and States and States (States), ¹⁰ Review States and States and States and States and States (States), ¹⁰ Review States and States and States and States and States and States (States), ¹⁰ Review States and States and States and States and States and States and States (States), ¹⁰ Review States and St

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protections: is instant our initial study of the concentron between the UV orders of galaxies will be is indicated within some integration for. Two and a some rise of a softward system of the first order of the some galaxies of monthly $(x_1, C_1, v_{1,1}, v_{1,2})$, and galaxies fitted within the first order of the some galaxies of monthly $(x_1, C_1, v_{1,2})$, and gauging the measurement $W_{1,2}$ is most larger sample of warry type galaxies. FFOM, with gauging the some galaxies of the source of the source

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4.2 Results: UV-color and stellar M/L ratio correlation in ETGs



mag-mag and color-mag diagrams.

- =Blue outliers
- Red outliers

N=32 galaxies

1 2 3 4.1 **4.2** 4.3 4.4 4.5 5 6

4.2 Results: UV-color and stellar M/L ratio correlation in ETGs



Correlations revisited 192 galaxies of ATLAS^{3D} q = 3 **Cappellari et al. (2013,** 2014)

Note the reversal of trend
 between
 (FUV - r) and (NUV - r)

 \bigcirc = points excluded on the basis of their (NUV - K) color ≤7.5 cut to select only reddest systems with low H₂ content.

1 2 3 4.1 **4.2** 4.3 4.4 4.5 5 6

4.2 Results: UV-color and stellar M/L ratio correlation in ETGs



Correlations revisited 192 galaxies of ATLAS^{3D} q = 3 **Cappellari et al. (2013,** 2014)

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4.2 Results: UV-color and stellar M/L ratio correlation in ETGs



1 2 3 4.1 **4.2** 4.3 4.4 4.5 5 6

4.2 Results: UV-color and stellar M/L ratio correlation in ETGs

Conclusions of 4.2:

A strong empirical correlation is found between (FUV - NUV) color and the stellar M/L in ETGs, in the sense that **a bluer color** yields **a higher stellar M/L**.

UV-upturn stars are thought to be the main contributors of the UV emission in ETGs. The amount of UV-upturn stars depends on the low-mass end of the IMF.

We conjecture that we can use the (FUV - NUV) color to differentiate between ETGs having different IMFs.

4.2 4.3 4.1 4.4

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4.5

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4.3 Results: Spatially-resolved properties

Bouquin et al. 2018, ApJS, 234, 18

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"The GALEX/S⁴G Surface Brightness and Color Profiles Catalog. I. Surface Photometry and Color Gradients of Galaxies"

Online Data available on VizieR



The GALEXOS⁴G Surface Brightness and Color Profiles Catalog. I. Surface Photometry and Color Gradients of Galaxies

Alexandre Y. K. Bouquia¹0, Arnando Gil de Par¹0, Juan Carlos Muños-Maños², Sannal Boissier³0, Karlik Shefr⁴0, Dennis Zartzky² G., Koynier F. Pelerier⁶ G., Johns H. Kauper^{7,2} G., and Jeols Gallegy¹ D. Department de Attributes y CC. de la Attribute. The world of Completenes de Madrid, B 2000 Madrid, Spain Entrypon Studien Observatory, Califa 19003. Santage 36. Cells ⁹ Ale Mendalment (New LAW, Laboratory of Watershopson de Marchit, Marchite, Prace ² SAEs Hendquares, Washington, DC 20046-0001, USs ² SMAR Hendrammer, Waldhagter, DC 2004000, USA ² Stronge Observation, Discouting of Advance, Without Charty, Annual, Daniel, A.S. RYDN, USA ² Stronger, International Institute: Product 806, 5700 AV Constitute, The Netherlands ³ Exclusive de Antonion, Waldhame, SJM, S 20200 La Lagues, Threads, Spain ⁴ Departments de Antonion, UN Edense, SJM, S 20200 La Lagues, Threads, Spain ⁴ Departments de Antonion, UN Edense, SJM, S 20200 La Lagues, Threads, Spain ⁴ Departments de Antonion, UN Edense, SJM, S 20200 La Lagues, Threads, Spain ⁴ Departments de Antonion, UN Edense A, anapted 100.7 Contern 8, pendolend 300.8 Antony 327

Abstract

We present new spatially needwed surface photometry in the far-sharviolet (FUV) and non-sharviolet (NUV) from images obtained by the Galaxy Exclusion Explorer (CALEX) and BACI (Mi ser) photometry from the Sylayer Survey of Stellar Structure in Galaxies ($S^{(1)}()$). We analyze the radial surface hightness gravitles $\mu_{\rm CAL}$ ($\mu_{\rm CAL}$) and plans as well as the radial profiles of (FUV - NUV), (NUV - [3,6]), and (FUV - [3,6]) values in 1991 nearby solvates (z < 0.01). The analysis of the 5.6 am surface brightness profiles also allows us to separate the bullet and dask components in a quasi-antomatic way and to compare their high and color distribution with these predicted by the chemo spectrophotometric models for the evolution of galaxy disks of Boissien & Frantzes. The exponential disk component is best isolated by setting an inner and all cutoff and an upper surface brightness limit in stellar mass surface density. The best-litting models to the measured scale length and central surface brightness values yield distributions of spin and circular velocity within a finite of two of draws obtained via direct biocaution measurements. We find that as a suffice brightness (sinter than $\mu_{p,eq} = 20.8$ magnetizes ⁻², to below 3 × 10⁵ M_{\odot} keys⁻² is stillar mass sufficiently, the average specific surformation care (SFR) for surfaceing and quiescan galaxies measurements interface density, the strong specific surformation care (SFR) for surfaceing and quiescan galaxies measurements interface density. show a racial decrease in SSER. This behavior suggests that an outside-in damping mechanism, possibly related to environmental effects, could be testimony of an early exclusion of galaxies from the blue sequence of sur-forming galexics toward the rad sequence of entracent galexies.

Key words, catalogs = galaxies; photometry = galaxies; star furmation = influend; galaxies = ultraviolet; galaxies Supporting sectorial: machine-readable tables

1. Introduction

Observing the ultraviolat (UV) part of the electromagnetic spectrum is a direct way to determine the current sor formation rate (SFK) in nearby galaxies. The for-altraviolet (FUV) $\lambda_{eff} = 1516 \Lambda$) band and neur-altravielet (NUN; $\lambda_{eff} =$ 2255 Å) band limitorities are tracers of the most recent star formation in galaxies, up to about 100 million yr, because they are mainly produced by short-lived O and B stars and an directly related to the current SPR of galaxies (Kenniculi 1940). Consequently, the FUV observations of nearby galaxies by the Gelasy Evolution Explorer (GALEX) space telescope (Matin at al. 2005) allow us to obtain the amount of stars formed in nearby click galaxies and dwarfs. In the last two decades, resthane UV observations have also been used to analyse the evolution of the SFR throughout the history of the universe (see the review by Madan & Diokineon 2014). However, a detailed analysis of the spatial distribution of the SFR, starting from local galaxies, is needed if we want to understand the origin and mechanisms involved in the evolution of the SFR in

general and the observed decay in the SFR since $z \sim 1$. In spite of the rather guick evolution since z = 1, many galaxies have kept forming stars until now, some of them rigonously it all galaxisemitic distances (the co-called extended UV-disk galaxies constitute a prime example in that

regenti; Gil de Pas et al. 2005, 2007; Thilker et al. 2005, 2007). However, many others (repecially mansive ones, but not coclusies(y) have hed their stat formation quarched or at least damped, in the same that their star formation substantially doctbased (and not in the sense that gas has been calcusted) at different spacts and galaciecanitic distances. Our ultimate goal is to address the study of these objects using multiwavelength surface photometry combined for an unprecedented large ample of galaxies in the local universe. The sensitivity of the UV emission to even small amounts of star formation flows as to identify objects that are going through a transition phase and to determine whether this transition occurs at all radii at the same time or in an outside in or inside-out fashion. However, in order to mine the current SFS with that having occurred in the part, the distribution of the UV emission must be compared with that of the galaxy's shellor mass all the way to the very faint outskirts of galaxies. Deep resi-frame nearinfraned imaging data are key in that regard, such as those provided by the Infrared Army Camera (IRAU) onboard the Sylper saidline in the case of nearby galaxies and seen by the James Webb Space Telescope at intermediate-te-high redshifts. These observations allow us to probe the radial variations of the SFR in relation to the stellar mass surface density. Scatially, resolved radial police profiles are a powerful diagnostic tool to











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Color radial profiles

data points are taken at steps of 6 arcsec

we normalize the galactocentric distance to R80 unit (radius at which 80% of the IR-light is enclosed)





Average SB and color radial profiles normalized (to R80)



Average SB and color radial profiles normalized (to R80)





FUV - NUV VS. FUV - [3.6]

We readily see the radial color distributions of all our galaxies.

ETGs are clearly populating the 'red-red' corner but still having some bluer component.

Low-mass late-type are only found in the 'blue-blue' corner but some are found with reddened outer disks.

1234.14.24.34.44.5564.3Results:Spatially-resolved properties



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 μ_{FUV} VS. $\mu_{[3.6]}$ per zone



3 4.1 4.2 **4.3** 4.4 4.5 5 2 4.3 Results: Spatially-resolved properties

 μ_{FUV} VS. $\mu_{[3.6]}$ per zone



 μ_{FUV} VS. $\mu_{[3.6]}$ per zone



4.3 Results: Spatially-resolved properties Distribution of outer disk sSFR per zone



1234.14.24.34.44.5564.3Results: Spatially-resolved properties



(FUV - [3.6])
 colors
 VS.
 μ[3.6]

locus of R80 (yellow star) well separated for GBS, GGV and GRS galaxies

1234.14.24.34.44.5564.3Results: Spatially-resolved properties



 (FUV - [3.6]) colors VS.
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1234.14.24.34.44.5564.3Results: Spatially-resolved properties



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(FUV - NUV)
(NUV - [3.6])
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colors
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(FUV - NUV)
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µ[3.6]



Median color profiles of GBS, GGV, GRS galaxies.

Both GGV and GRS galaxies have reddening disks, followed by a flattening of sSFR @>20.89 mag/arcsec⁻²





Median color profiles of GBS, GGV, GRS galaxies.

Both GGV and GRS galaxies have reddening disks, followed by a flattening of sSFR @>20.89 mag/arcsec⁻²





1234.14.24.34.44.5564.3Results:Spatially-resolved properties



						ŀ	R/R80 Cuto	ffs						
			0.00		0.25		0.50		0.75		1.00		1.25	
		-	$\langle \chi^2 \rangle$	Nª	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N
$\mu_{[3.6]}$ cutoffs	21.5	1	26.20	(1577)	20.84	(1554)	15.72	(1451)	9.68	(1240)	4.04	(794)	2.87	(535)
	22	1	10.64	(1489)	8.63	(1474)	6.97	(1387)	5.85	(1191)	3.26	(781)	2.48	(530)
	22.5		4.89	(1384)	4.28	(1375)	3.54	(1298)	3.11	(1126)	2.02	(756)	1.62	(518)
	23		2.34	(1232)	2.17	(1228)	1.81	(1165)	1.63	(1014)	1.14	(693)	0.98	(482)
	23.5		1.37	(1034)	1.28	(1033)	1.12	(987)	0.96	(863)	0.68	(591)	0.56	(419)
	24		0.78	(755)	0.77	(754)	0.73	(723)	0.67	(630)	0.40	(426)	0.35	(296)
			Av	erage Redu	iced χ^2 of the	he Linear F	it in the $\mu_{[3]}$.6] vs. R/R	80 Plane wi	ith Oblique	Cuts			
						S	lope (a) Cu	toff						
		-6		-5		-4		-3		$^{-2}$		-1		
			$\langle \chi^2 \rangle$	N	$\langle \chi^2 angle$	N	$\langle \chi^2 angle$	N	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N	$\langle \chi^2 \rangle$	N
y intercept (b)	cutoff	20	777.55	(1717)	649.14	(1716)	569.63	(1713)	469.68	(1712)	393.01	(1707)	304.54	(1699)
		22	205.61	(1697)	158.46	(1691)	129.09	(1684)	88.95	(1668)	52.78	(1644)	27.10	(1592)
		24	61.96	(1633)	44.50	(1607)	28.48	(1563)	13.20	(1528)	5.58	(1412)	2.07	(1233)
		25	33.19	(1578)	23.64	(1540)	11.19	(1482)	6.19	(1375)	2.21	(1202)	0.78	(831)
		26	20.87	(1516)	10.53	(1445)	6.24	(1339)	2.50	(1166)	0.96	(845)	0.44	(219)
		28	6.20	(1260)	3.12	(1090)	1.74	(838)	0.89	(471)	0.79	(127)	0.72	(5)
		30	2.46	(858)	1.56	(596)	0.87	(322)	1.27	(103)	1.04	(8)		(0)
									0		Best cutoff@		D ad arcsoc-2	
28		0.5	1.0		$\frac{1.5}{R/1}$	2.0 R-00	.0 2.5		3.0	3.5	³ .5 and			
					K / 1	~80					R/R80	0 = 0.5		

Average Reduced χ^2 of the Linear Fit with $\mu_{[3.6]}$ and R/R80 Cuts



Boissier & Prantzos (2000) disk models.

The SB profiles are generated by varying the circular velocity and spin parameter.

A larger circular velocity translates to a fixed central surface brightness and an increase in the scale length.

$$\frac{v_c}{220} = \left(\frac{M}{M_{\rm MW}}\right)^{1/3}$$

A larger spin parameter translates to a decrease in central surface brightness and an increase in the scale length.

The dimensionless spin parameter $\boldsymbol{\lambda}$ is defined as:

$$\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$$

where J is the angular momentum, E is the energy of the halo, G is the gravitational constant M is the total baryonic mass



We also fit these disk models and obtain a single pair (slope, y-intercept) for each of them

1234.14.24.34.44.5564.3Results:Spatially-resolved properties



slope vs. y-intercept per morphological type

grid = **Boissier & Prantzos (2000)** disk models 6258 models created specifically for this project.

value ranges: $20 \le v_{circ} \le 430 \text{ km s}^{-1}$ (10 km s⁻¹ steps) $0.002 \le \lambda \le 0.15$ (0.001 steps)

MC sampling of 1000 particles (with elliptical 2D Gaussian distribution) and matching with closest disk model's circular velocity and spin parameter.

We then measure the mean (red), median (blue) and mode (purple) of these distributions.



MC sampling of 1000 particles (with elliptical 2D Gaussian distribution) and matching with closest disk model's circular velocity and spin parameter.

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MC sampling of 1000 particles (with elliptical 2D Gaussian distribution) and matching with closest disk model's circular velocity and spin parameter.

We then measure the mean (red), median (blue) and mode (purple) of these distributions.





circular velocity v_c vs. spin parameter λ per morphological type

= mode values.

 \bigcirc = extreme values in either v_c or λ ; using central values instead.

low-mass galaxies clearly have low circular velocities

1234.14.24.34.44.5564.3Results:Spatially-resolved properties

Comparisons with observations: the median yields larger scatter than when using the mode due to the skewness of the circular velocity distribution. The mode however yields a good estimate (within factor of 2) of the circular velocity.

From the simple linear fitting of the 3.6 µm SB profile of a galaxy, we are able to obtain its circular velocity.



3 4.1 4.2 **4.3** 4.4 4.5 5 2 4.3 Results: Spatially-resolved properties



- redder gradient Color gradients (slopes) vs.
 - circular velocity

 - v_c (mode)
 - spin λ (mode)
 - stellar mass (log)

we see that most lowmass galaxies and a nonnegligible fraction of massive galaxies show positive gradients.

Conclusions:

- We see disk-reddening occurring in both GRS and GGV galaxies, with GGV galaxies slightly bluer than the GRS, but definitively redder than GBS.
- Galaxies are well-separated in the μ_{FUV} vs. $\mu_{[3.6]}$ (spatially-resolved "star-forming main sequence")
- Galaxies are well-separated in the spatially-resolved (FUV [3.6]) vs. μ_[3.6]. This diagram seems to indicate **a clear cut at 10⁻¹² yr⁻¹ in sSFR**. Moreover, GGV and GRS galaxies remain with a constant radial values sSFR below 10⁻¹², beyond μ_[3.6]=20.89 mag arcsec⁻².
- From the slopes and y-intercepts of the outerdisk linear fits and comparing them to the disk models of Boissier & Prantzos (2000) we are able to obtain circular velocity and spin parameters within a factor of 2 to the truly-measured ones. This could be a powerful technique for much larger surveys.

2 3 4.1 4.2 4.3 **4.4** 4.5 5

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4.4 Results: XUV-disk galaxies classification

Discovery: Gil de Paz et al. 2005, Thilker et al. 2005

Classification: Thilker et al. 2007





Declination







1 2 3 4.1 4.2 4.3 **4.4** 4.5 5 6

4.4 Results: XUV-disk galaxies classification

Visual classification of Type 1 (Outer-Structure) XUVs

Comparison between μ_{FUV} =27.25 AB mag arcsec⁻² and optical DSS-R band.

Type1 XUV Criteria:

- 1) structures are seen beyond the μ_{FUV} contour
- 2) structures are also beyond the D25 ellipse,
- 3) structures are invisible in the DSS-R image





Examples of Type 1 XUV-disk galaxies

TOTAL in the GALEX/S4G sample: 217/1931 (11%)

3 4.1 4.2 4.3 **4.4** 4.5 5 6 2 4.4 Results: XUV-disk galaxies classification Type 2 (Blue Disk) XUVs matching with 17 "classical" Type 2 e.g.: NGC 2541 2MASS (J, H, K) Spitzer IRAC1 3.6 μ m 49°09' 06' Declination 03' 00' 48°57

Right Ascension

40'

35

30'

45'

123°50'

3 4.1 4.2 4.3 **4.4** 4.5 5 6 2 4.4 Results: XUV-disk galaxies classification Type 2 (Blue Disk) XUVs matching with 17 "classical" Type 2 e.g.: NGC 2541 2MASS (J, H, K) Spitzer IRAC1 3.6 µm 49°09' µ_{FUV}=27.25 AB 06' Declination 03' 00' 48°57 40' 45' 35 123°50' 30' **Right Ascension**











1 2 3 4.1 4.2 4.3 **4.4** 4.5 5 6

4.4 Results: XUV-disk galaxies classification

We try to match our Type 2 criteria to be used with our 3.6 μ m images to be able to closely reproduce the selection of the "classical" Type 2 of **Thilker+,2007**, which were defined from 2MASS K_s images.





Examples of Type 2 XUV-disk galaxies

TOTAL in the GALEX/S4G sample: 110/1931 (<6%)

NGC2841 is a Type 1+2

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 4.4 Results: XUV-disk galaxies classification



1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 4.4 Results: XUV-disk galaxies classification



All Type 1 are in the **GBS** \Box = Type 1 (outer-structure) O = Type 2 (blue-disk) \Box = Type 1+2 (both)

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 4.4 Results: XUV-disk galaxies classification



All Type 1 are in the **GBS** = Type 1 (outer-structure) = Type 2 (blue-disk) = Type 1+2 (both)

Most Type 2 are also in the **GBS**, but a few are found in the **GRS**
1 2 3 4.1 4.2 4.3 **4.4** 4.5 5 6

4.4 Results: XUV-disk galaxies classification

Conclusions:

- We obtain 217 Type 1 (outer-structure) XUVs (10x previous sample)
- We obtain 110 Type 2 (blue-disk) XUVs (6x previous sample)
- 21 galaxies are Type 1+2 (both)
- All Type 1 and most type 2 are found in the GBS (9 type 2 in the GRS)
- 9% are in Virgo (slightly larger fraction to overall GBS galaxies ~7%)
- 40% of XUVs are of type Sc

1234.14.24.34.44.5564.5GTC observations of
XUV-disk galaxies

The Extended Region Project (TERP)

Telescope: GTC Instrument: OSIRIS Mode: MOS Target: NGC3274 Exposure time: 1 hour

> Multi-Object Spectroscopy mask created with OSIRIS Mask Designer v3.25





We obtained spectra for 5 regions inside μ FUV=27.25 mag arcsec⁻² (yellow contour and green solid line) and 4 regions outside of the low-mass (M*~10⁹ M_{Sun}) XUV-disk galaxy **NGC 3274 @ z=0.02**



1 2 3 4.1 4.2 4.3 4.4 **4.5** 5 6

4.5 GTC observations of XUV-disk galaxies







Putting the emission-line ratios of our spectra to the test: the Baldwin-Phillips-Terlevich (BPT) diagrams (**Baldwin et al. 1981**) tell us that the observed spectra are from genuine HII regions



 $0 \le z \le 0.01$ are shown in grey

We use two calibrators (N2 and O3N2) and two calibration methods (**Pettini & Pagel, 2004**, and **Marino et al., 2013**) to get the oxygen abundance.

Oxygen abundances are lower than solar (<8.69) for the inner regions, but inconclusive for the outskirts with these data.

However, this method proved to be feasible and we were awarded 19 hours more telescope time





2 3 4.1 4.2 4.3 4.4 4.5 **5**

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5. Future work Using MEGARA@GTC to observe XUVs



1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 5. Future work

Can be prepared with the ETC!

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MEGARA Online Exposure Time Calculator (v1.0.1)

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Target Inpu	It Flux Distribution		Ir	nstrument Setup		
Source Type	Point O Extended		Observing mode	LCB IFU	¢	
Input Size	⊙ Area ◯ Radius		VPH setup	LR-B	•	
Area (arosec ²)	1.0		Atmo	spheric Conditions		
Radius (arcsec)	1.0		Sky condition	Photometric	¢	
Input flux	Continuum O Line + Continuum	m	Moon phase	Dark	\$	
Resolved line?	🔿 No 🗿 Yes		Airmass	1.0		
Input spectrum		1	Seeing (arcsec)	0.6	¢	0
	SC Ŧ		Ob	servational Setup		
Continuum band	B \$		Calculation mode	ExpTime to SNR SI	NR to Ex	pTime
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Continuum mag	25]	Exptime per frame (s)	3600	_	
Continuum flux	5e-19		Number of Sky Fibers	58	=	
Line flux (cgs units)	1e-18]	Number of Target Fibers	567	_	0
Line wavelength (Angstrom)	4363		Line aperture	1.0		
Line FWHM (Angstrom)	1]	Continuum aperture	3		
Batch process? ON O Yes				Output Setup		
	empty		Graphic output?	🔿 Na 😗 Yes		

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3 4.1 4.2 4.3 4.4 4.5 **5** 6 2 1 5. Future work

Can be prepared with the ETC!

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Calculation Mode: Exposure time to SNR Observing Mode: LCB, VPH: LR-B, Source Type: Point

Computation time: 7.1 seconds;

OUTPUT CONTINUUM SNR

 $(at lambda_c(VPH) = 4800.0 AA)$

	* Continuum SNR reached for input exptime (3600.0 seconds per frame, with 5 frames, and Total exptime of 18000.0						
	seconds) per spaxel zones due to PSF (LCB mode): fiber diameter=0.62 arcsec: Seeing FWHM=0.6 arcsec						
	** per fr	ame		** all frames			
٠	• C (45.8%) 1 fiber	C+R1 (98.20%) 7 fibers	C+R1+R2 (100.00%)	• C (45.8%) 1 fiber	C+R1 (98.20%) 7 fibers	C+R1+R2 (100.00%)	percentage of enclosed total flux
	1.02	0.85	0.53	2.28	1.89	1.18	per voxel
1Å	1.14	0.95	0.59	2.55	2.11	1.32	per AA
\bigcirc	26.38	21.71	13.49	58.99	48.54	30.16	integrated spectrum

Input source spectrum

Sky spectrum



OUTPUT LINE SNR: L

É

(at lam	bda_line = 4	363.0 AA)	
	per frame	all frames	Ī

	permanne	jaii frames	
	0.79	1.77	per fiber per detector pixel
	3.16	7.07	per fiber per voxel
(Å	3.45	7.73	per fiber in aperture per AA
6	3.45	7.73	per fiber in aperture
۲	3.05	6.82	total in aperture

INPUT PARAMETERS:	
Calculation mode:	Exposure time to SNR
Source type:	Point
Area:	0.28 arcsec ²
Observing mode:	LCB
VPH:	LR-B
Input flux type:	Line+Continuum
Source spectrum:	Sc smooth
Input continuum:	B = 25.00mag
Input flux:	6.403e-19 erg/s/cm²/Å
Continuum flux per arcsec^2 within the seeing disk (@ λ_C (VPH)):	1.862e-18 erg/s/cm ² /Å/arcsec ²
Resolved line?:	Y
Line wavelength:	4363.0 AA
Line flux (integrated):	1e-18 erg/s/cm ²
Line FWHM:	1.0 AA
*Sky Condition:	Photometric
Moon:	Dark
Airmass: X=	1.0
Seeing(@X=1):	0.6 arcsec
Sky-flux(R,@X):	8.432e-18 erg/s/cm ² /Å/arcsec ²
Seeing(@X):	0.6 arcsec

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 5. Future work

Can be prepared with the ETC!

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Sky spectrum



proper new cype.	Enorgenangen
Source spectrum:	Sc smooth
Input continuum:	B = 25.00mag
Input flux:	6.403e-19 erg/s/cm ² /Å
Continuum flux per arcsec ² within the seeing disk ($@\lambda_C$ (VPH)):	1.862e-18 erg/s/cm ² /Å/arcsec ²
Resolved line?:	Y
Line wavelength:	4363.0 AA
Line flux (integrated):	1e-18 erg/s/cm ²
Line FWHM:	1.0 AA
*Sky Condition:	Photometric
Moon:	Dark
Airmass: X=	1.0
Seeing(@X=1):	0.6 arcsec
Sky-flux(R,@X):	8.432e-18 erg/s/cm ² /Å/arcsec ²
Seeing(@X):	0.6 arcsec
*Observation:	
Number of frames:	5
Exptime per frame:	3600.0 s
Total exptime:	18000.0 s
NP_Dark:	65500.0
Sky-fibers:	56

☆ :

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 5. Future work



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1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 5. Future work



2 3 4.1 4.2 4.3 4.4 4.5 5

6

6. Conclusions (1/4)

- We start off from the **S4G sample of 2352 galaxies as our base-sample** for which we gathered GALEX FUV and NUV data.
- Sky subtraction, masking, interpolation, and photometry were performed using the same aperture for both FUV and NUV as for the 3.6 µm IRAC1 images.
- Data products are the surface brightnesses and color radial profiles μ_{FUV} , μ_{NUV} , and (FUV NUV), the asymptotic magnitudes FUV and NUV, false-color RGB images, all complemented by the [3.6] (asymptotic) and μ 3.6 data.
- The final sample comprises 1931 galaxies of all morphological types with homogenized photometry. We call this catalog of nearby galaxies the GALEX/ S4G sample. It is one of the best-to-date, in terms of (1) size, (2) multi-wavelength coverage (UV to IR), (3) homogenized data with good spatial-resolution (6 arcsec).

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 6. Conclusions (2/4) About the global properties (Bouquin et al. 2015)

- Galaxies are distributed into two extremely narrow sequences that we call the GALEX Blue Sequence (GBS) and GALEX Red Sequence (GRS). The GBS has a scatter around the mean of roughly ~1 mag (at ±2σ rms) in (FUV - NUV) color.
- The region with redder (FUV NUV) than the GBS but bluer in (NUV [3.6]) than the GRS is the GALEX Green Valley. We find a higher fraction of S0-a and Sa galaxies than any other regions of this diagram. We also find a higher fraction of GGV galaxies belonging to the Virgo cluster —> nearby galaxies evolution not only driven by mass but also by environment.
- In Zaritsky, Gil de Paz, Bouquin, 2014 and 2015, we found a correlation between the (FUV - NUV) color and the stellar mass-to-light ratio Y_{*}. The correlation is: the bluer the (FUV - NUV) the larger the Y_{*}. Adding more ETGs from other catalogs still yielded the same correlation. The UV emission from ETGs is most likely UVupturn stars of the EHB. If so, the more UV-upturn stars, the more the UV emission. Since UV-upturn stars are low-mass stars, we conjectured that the (FUV - NUV) color may be used to probe the low-mass end of the IMF.

• Future work: color-color diagram with redshift.

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 6. Conclusions (3/4)

About the spatially-resolved data (**Bouquin et al. 2018**)

- We see disk-reddening occurring in both GRS and GGV galaxies, with GGV galaxies slightly bluer than the GRS, but definitively redder than GBS. Average disk-reddening seems to flatten beyond μ_[3.6]=20.89 mag arcsec⁻².
- Galaxies are well-separated in the μ_{FUV} vs. $\mu_{[3.6]}$ and in the spatially-resolved (FUV [3.6]) vs. $\mu_{[3.6]}$. They indicate **a clear cut at 10⁻¹² yr⁻¹ in sSFR**.
- Moreover, GGV and GRS galaxies remain with a constant radial values in sSFR below 10⁻¹² yr⁻¹, in regions fainter than μ_[3.6]=20.89 mag arcsec⁻² or Σ_{*}<3x10⁸ M_o kpc⁻². Results are found to be consistent with Kauffmann et al. 2006.
- From the slopes and y-intercepts of the outer disk linear fits and comparing them to the disk models of Boissier & Prantzos (2000) we are able to obtain circular velocity and spin parameters within a factor of 2 to the truly measured ones (HyperLEDA). This could be a powerful technique for much larger surveys.

1 2 3 4.1 4.2 4.3 4.4 4.5 5 6 6. Conclusions (4/4)

About the XUV classification:

- We found **217 Type 1**, **110 Type 2**, and 21 Type 1+2. This is an **increase by tenfold for T1**, and **six-fold for T2** from previously available samples.
- We have obtained both global and spatially-resolved properties of these galaxies.
- All Type 1 XUVs and most Type 2 XUVs **are GBS galaxies** globally and/or their outskirts is in the GBS when looking at their spatially-resolved data.
- only 9% of XUVs are Virgo galaxies, hinting to XUVs preferring less-dense environments, and are excellent test-cases for secular evolution.
- We took spectra of HII regions in XUV-disk galaxy NGC 3274 (M*~10⁹M_{Sun}) and measured the most prominent emission lines. We infer the oxygen abundance 8.0
 < 12 + log(O/H) < 8.5, with a negative gradient in the inner regions (up to 5 kpc) but large uncertainties make the shape of the gradient inconclusive in the outskirts.
- Future work: analysis of spectra of HII regions of NGC6946

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