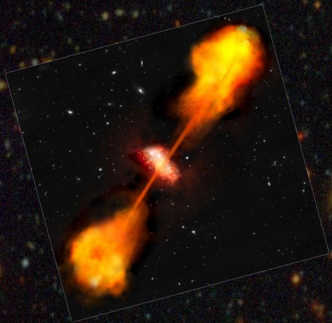
Green valley (GV) galaxies and the role of AGN in galaxy evolution



Mirjana Pović

[1] Ethiopian Space Science and Technology Institute (Ethiopia)

[2]Instituto de Astrofísica de Andalucía (Spain)

Seminar Katedre za Astronomiju, Matematicki Fakultet u Beogradu
(virtual talk)
13 of April, 2021

Background: ALHAMBRA survey. Credits: A. Molino and ALHAMBRA team

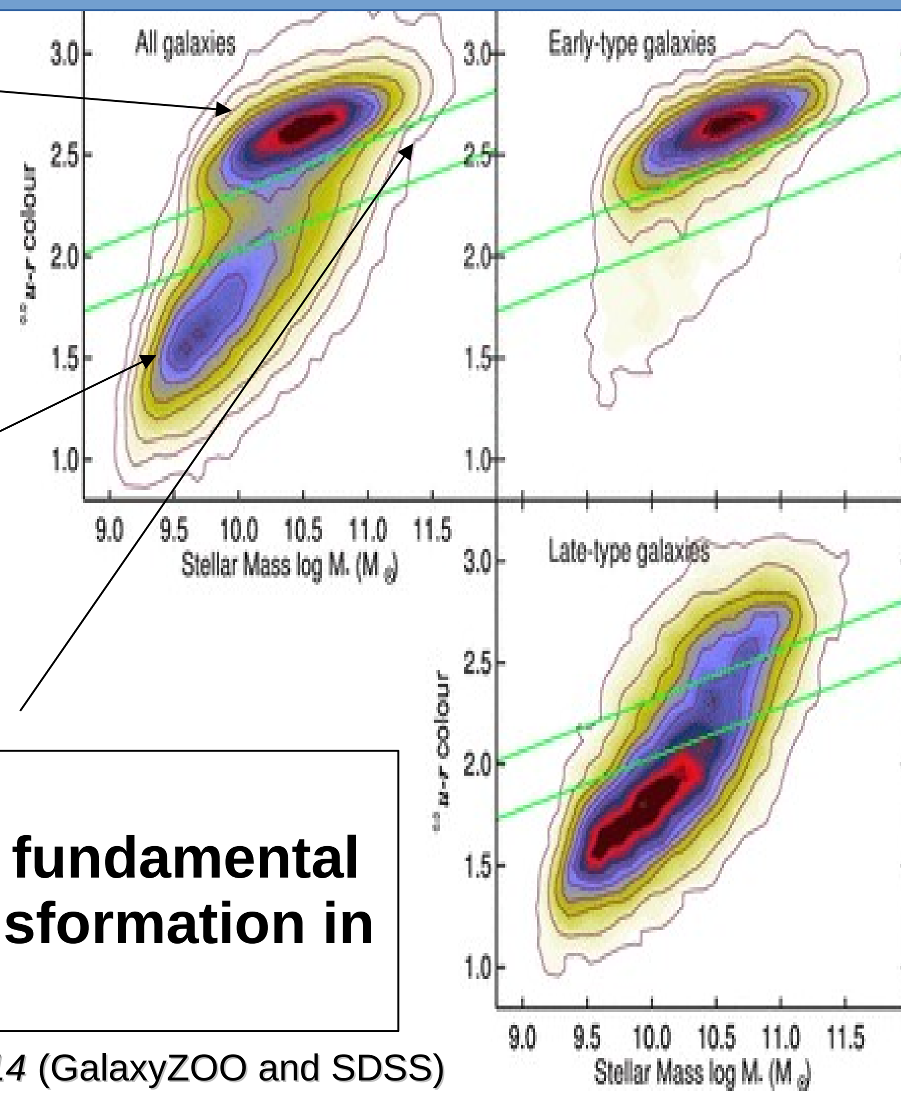
Introducing GV and bi-modal distribution of galaxies

Bi-polar (or bi-modal) distribution of galaxies has been found when comparing any of the two parameters: colours (optical, NUV), stellar mass, SFR, sSFR
(e.g., Kauffmann et al. 2003; Baldry et al. 2004; Salim et al. 2007; Brammer et al. 2009; Pović et al. 2013; Schawinski et al. 2014; Lee et al. 2015; Ge et al. 2018; Phillips et al. 2019)

Red Sequence (RS) – mainly populated by early-type galaxies (also some population of late-type galaxies (up to 30%?) with large amounts of dust, edge-on spirals, and spirals with disturbed morphologies)

Blue Cloud (BC) – mainly populated by late-type galaxies (also can contain early-type galaxies with recent SF and/or AGN)

Example at low redshift (z < 0.1)



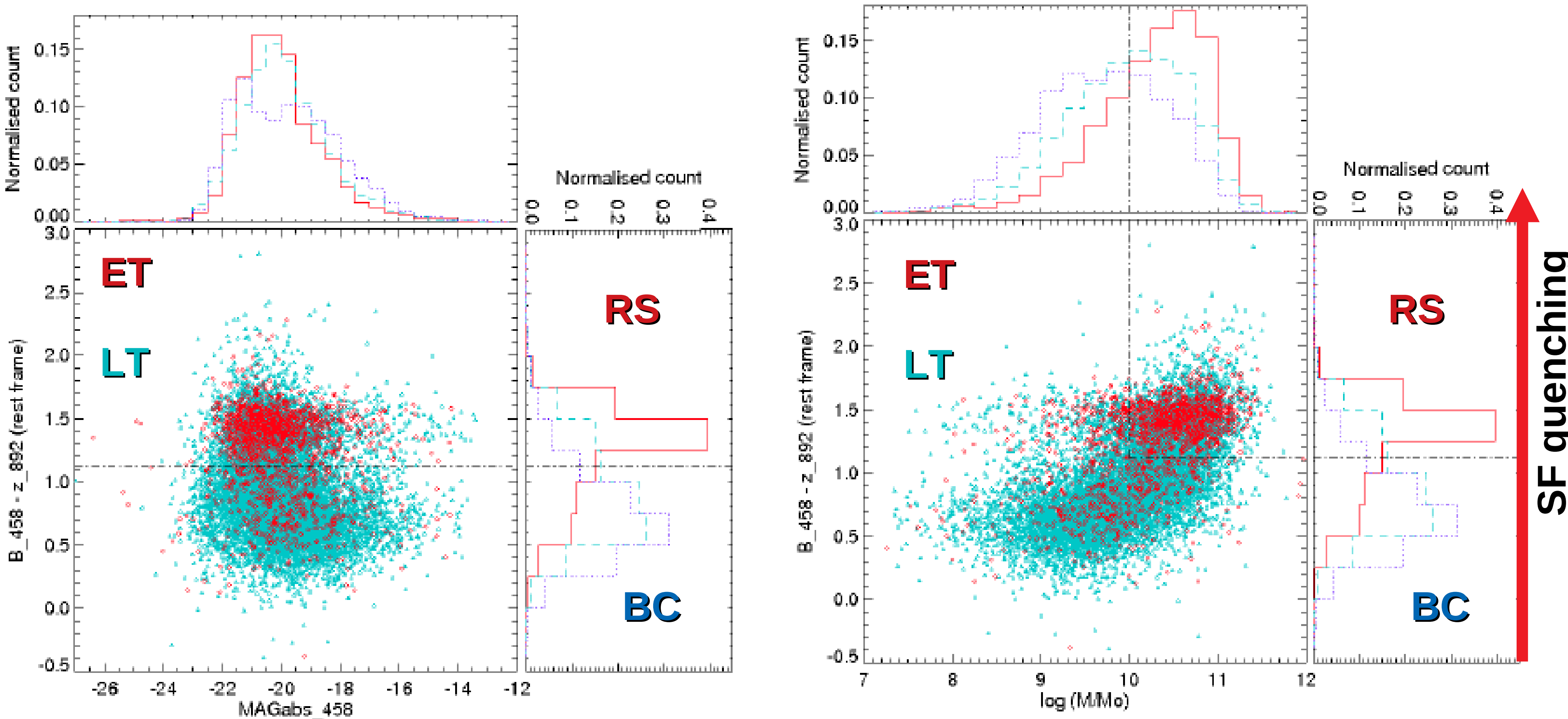
galaxy evolution?

Green Valley (GV)
- suggested to be the transition area, fundamental for understanding morphological transformation in galaxies

Schawinski et al. 2014 (GalaxyZOO and SDSS)

Introducing GV and bi-modal distribution of galaxies

Example of bi-modality at higher redshift (z ~ 1)



Pović et al. 2013, MNRAS, 435, 3444

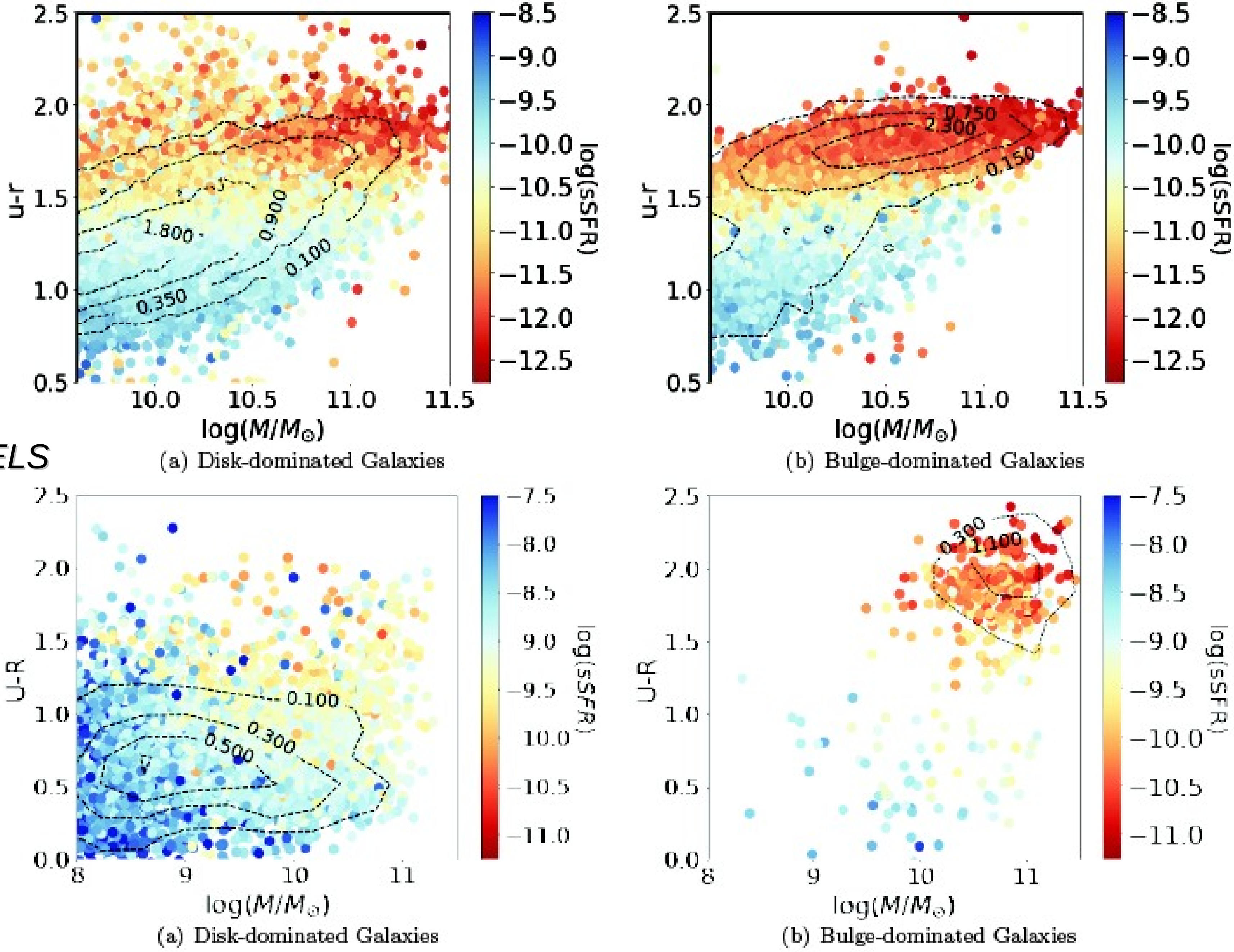
(ALHAMBRA survey, morphological classification of galaxies into early-type and late-type using galSVM code, Huertas-Company et al. 2008)

Introducing GV and bi-modal distribution of galaxies

Ghosh et al. 2020 *(CNN classification based on bulge-to-total light ratio)*

SDSS (z ~ 0)

CANDELS (z ~ 1)

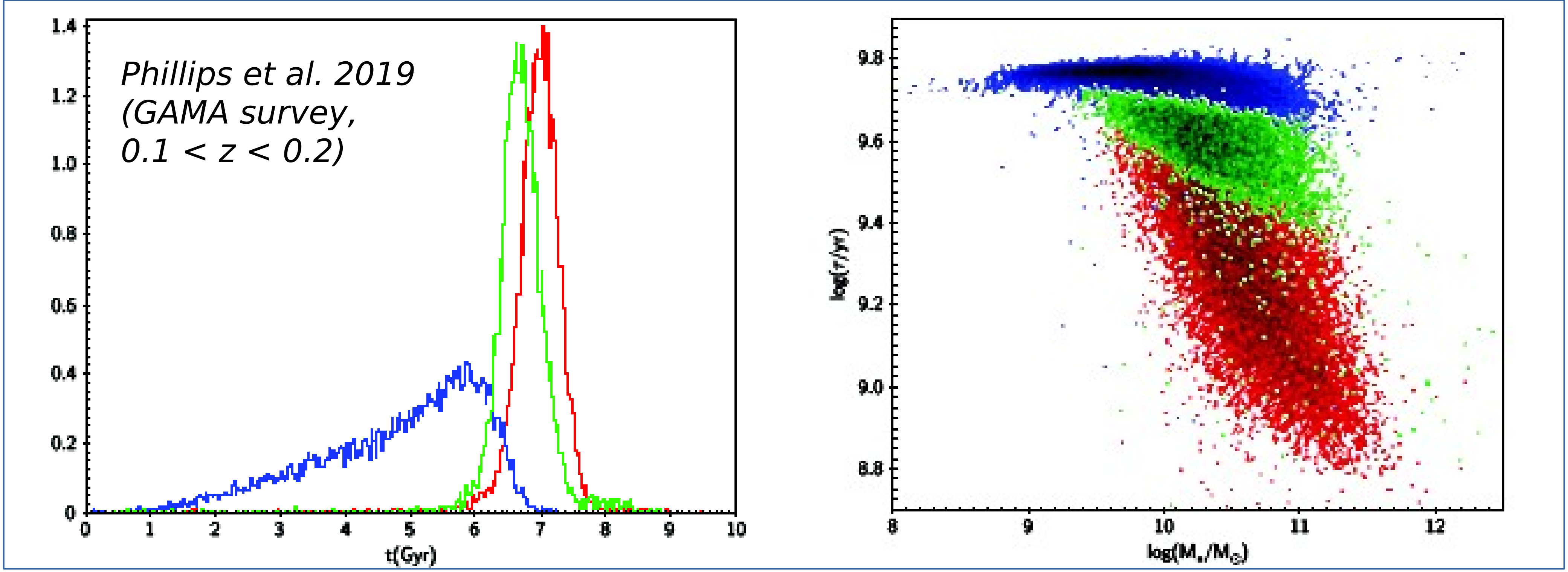


Properties of GV galaxies

GV galaxies are intermediate population, having properties between those of blue cloud and red sequence galaxies.

(e.g. Salim et al. 2007; Pan et al. 2013; Schawinski et al. 2014; Salim 2014; Lee et al. 2015; Smethurst et al. 2015; Trayford et al. 2016; Coenda, Martínez & Muriel 2018; Ge et al. 2018; Phillips et al. 2019)

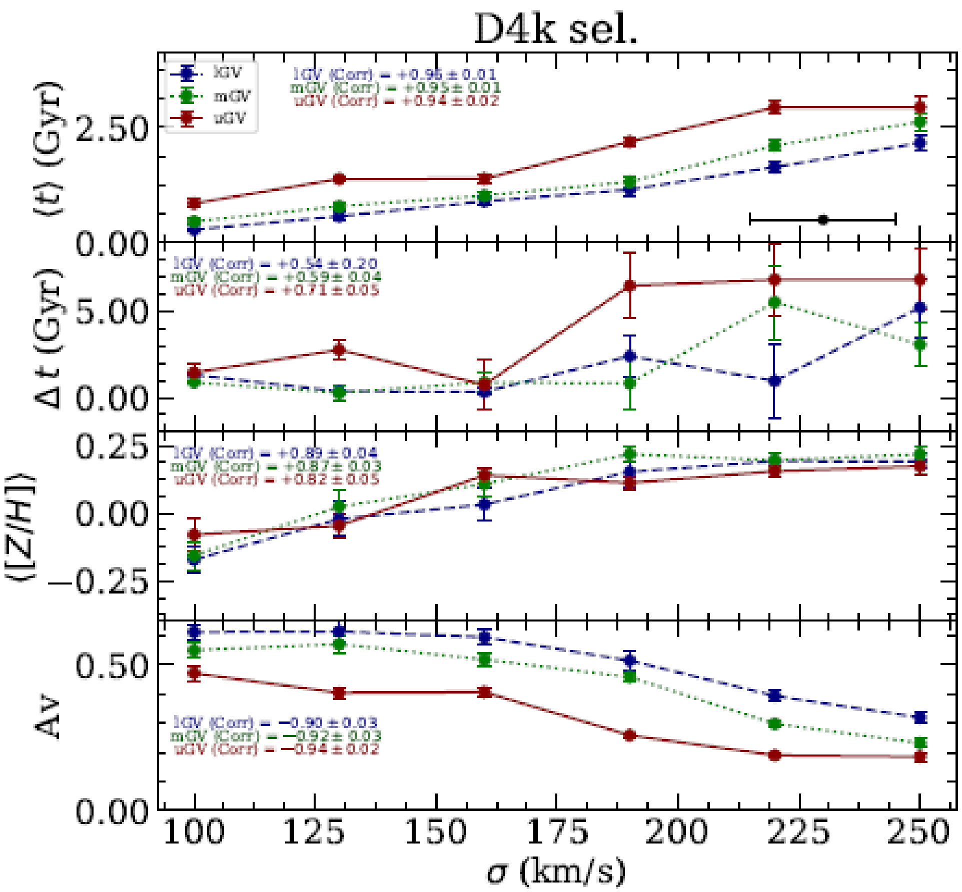
GV galaxies, stellar ages and timescales in comparison to BC and RS

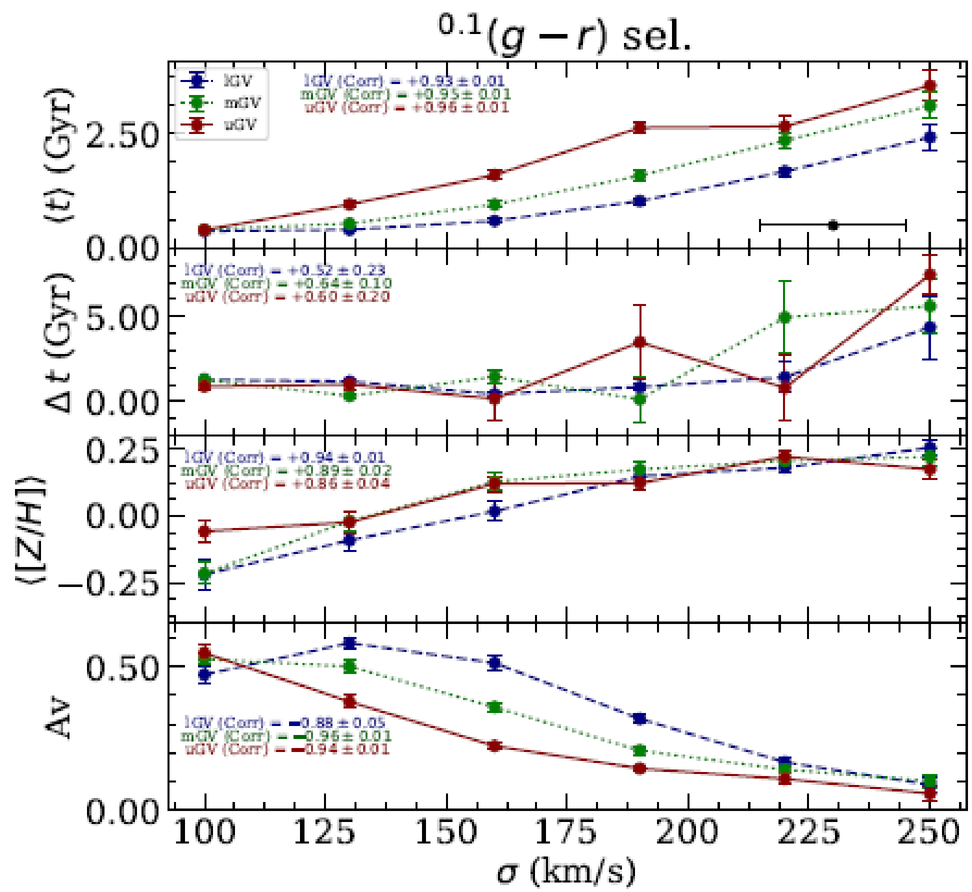


GV galaxies with intermediate ages and e-falling time. Stronger change in SFHs with stellar mass for GV and RS galaxies than for BC.

Properties of GV galaxies

GV galaxies and stellar populations, velocity dispersions, Z, and Av



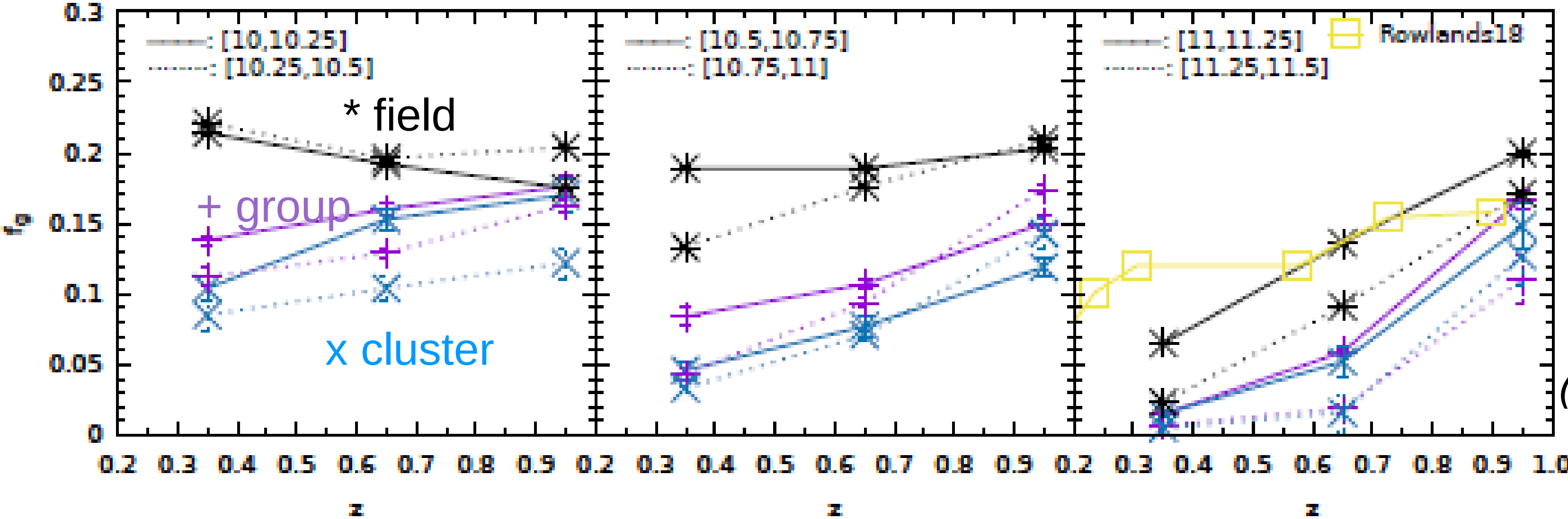


Angthopo et al. 2020

(SDSS Survey)

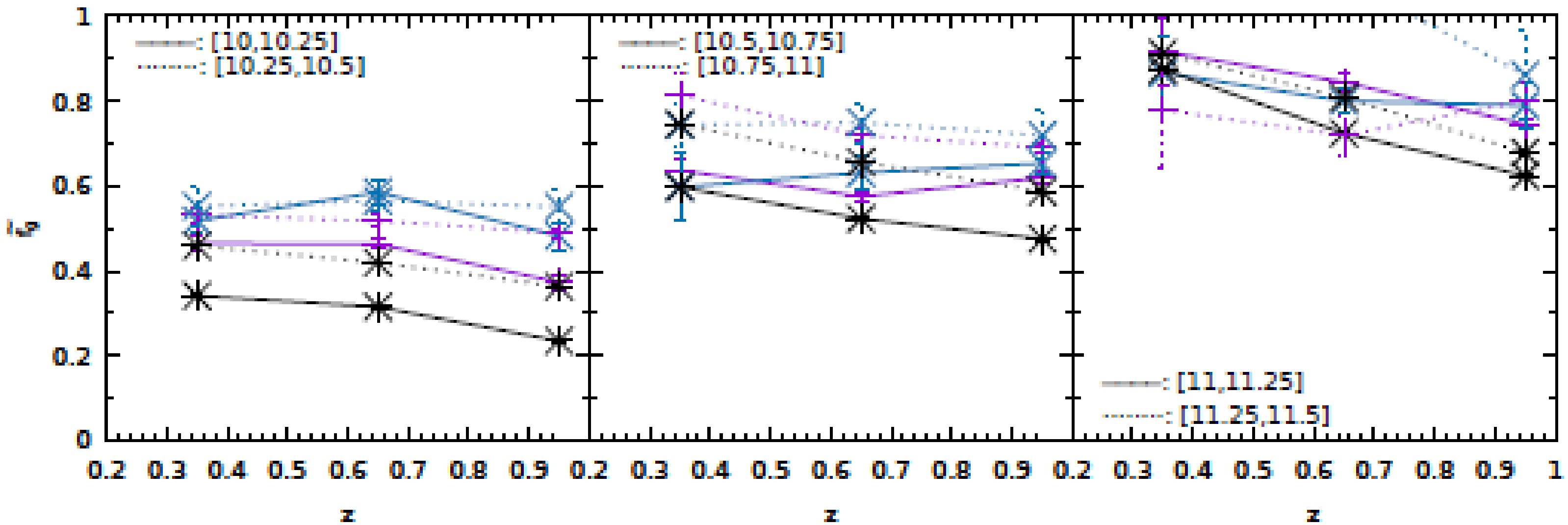
Properties of GV galaxies

<u>GV galaxies and environment</u>: **inconsistencies found from strong, through mild, and without environmental dependence,** *e.g., Coenda et al. 2018, Jian et al. 2020, Das et al. 2021***)**



Jian et al. 2020 (Hyper Suprime-Cam Survey)

Normalised the num. of GV galaxies with the num. of non-quiescent galaxies



→ **Slow quenching mechanisms are operating in denser environments**
→ **GV fraction (regarding total pop.) is higher in the field, and decreases with increasing M***
→ **Effective GV fraction is lower for field galaxies, has strong mass effect**

Properties of GV galaxies

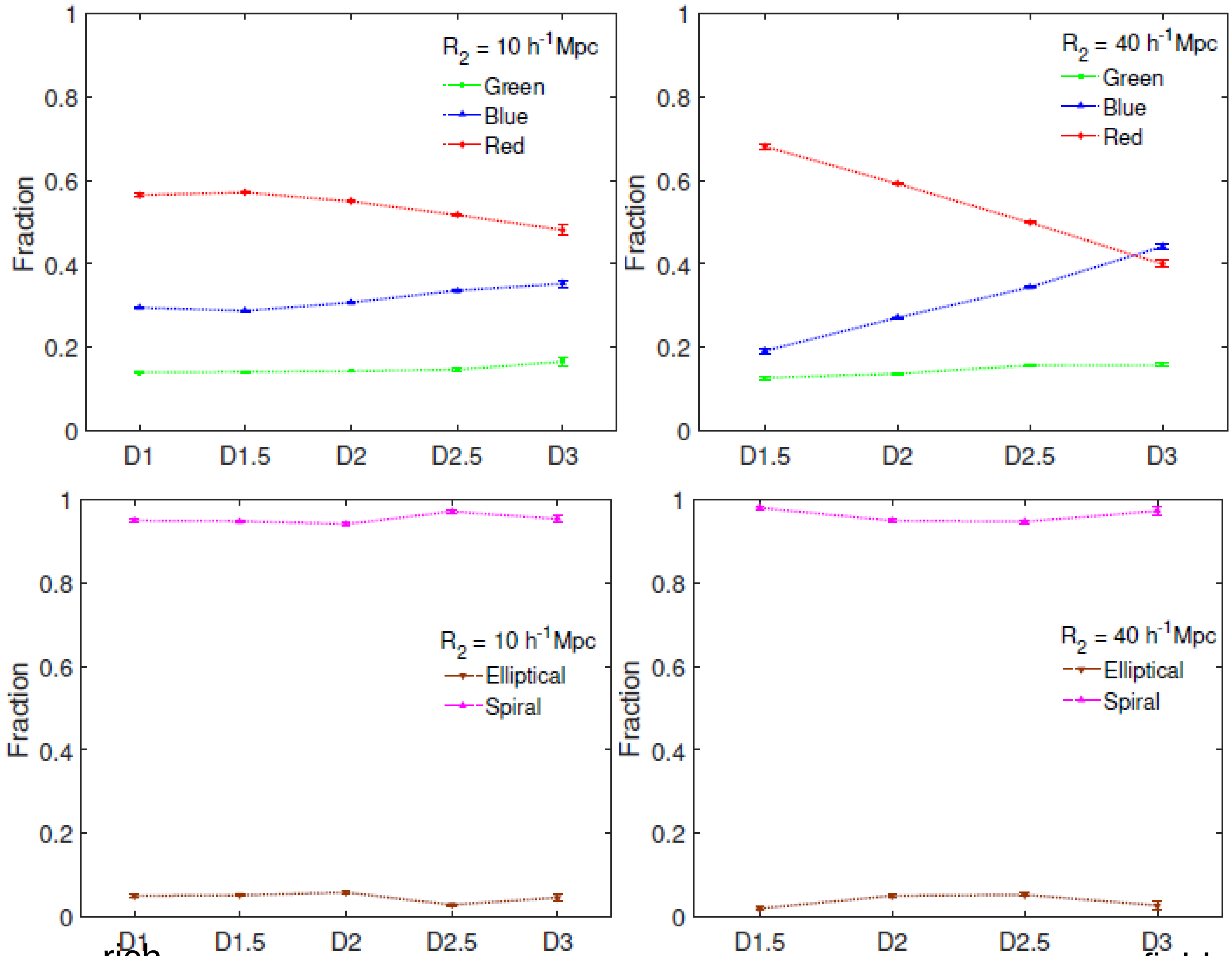
Fraction of GV galaxies and morphology

Das et al. 2021 (SDSS Survey)

→ **GV fraction < 20% in all environments**
(in line with e.g., Schawinski et al. 2014, Jian et al. 2020)

→ **Different results regarding morphologies of GV galaxies**

(from 70% - 95% being spirals, and from 5 – 30% being ellipticals,
e.g., Schawinski et al. 2014, Das et al. 2021)



rich environments

field galaxies

Selection of GV galaxies

Using:

- different colours (e.g., U – V, U – B, NUV – r, g – r, u – r) and colours vs. M* or Mabs

(e.g., Wyder et al. 2007; Salim et al. 2007; Brammer et al. 2009; Mendez et al. 2011; Walker et al. 2013; Salim 2014; Lee et al. 2015; Trayford et al. 2015, 2017; Mahoro et al. 2017; Coenda et al. 2018; Eales et al. 2018; Bremer et al. 2018; Eales et al. 2018; Kelvin et al. 2018; Ge et al. 2018; Phillipps et al. 2019; Mahoro et al. 2019)

- sSFR, sSFR vs. colour

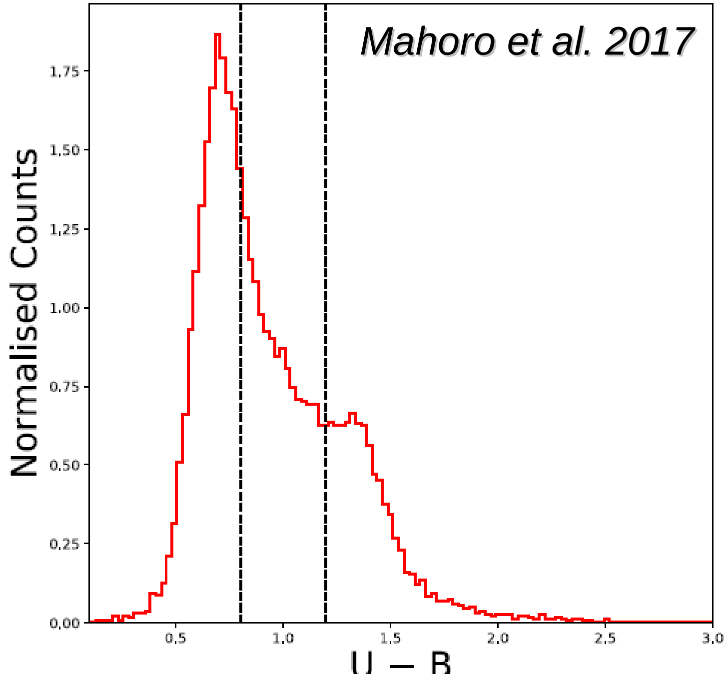
(e.g., Schiminovich et al. 2007; Salim et al. 2009; Salim 2014; Phillipps et al. 2019; Starkenburg et al. 2019, Koyama et al. 2019)

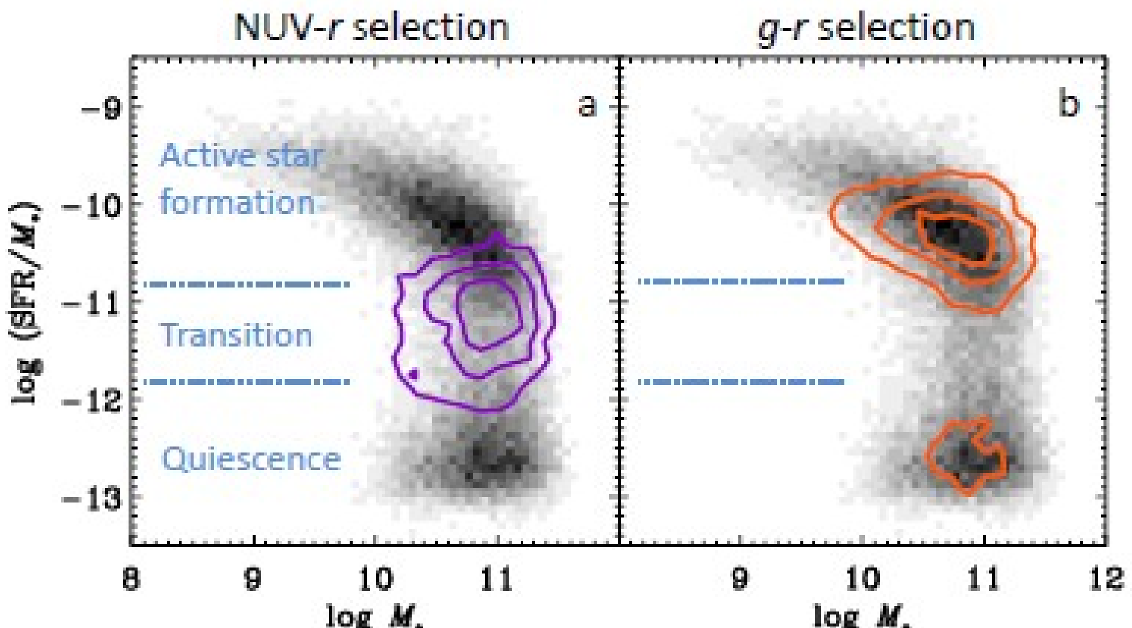
- SFR vs. M*

(e.g., Noeske et al. 2007; Chang et al. 2015; Pandya et al. 2017; Jian et al. 2020)

- recently proposed Dn4000 index (e.g., Angthopo et al. 2019)

- fittings and combination of previous + use of different samples (e.g., optical and NUV)





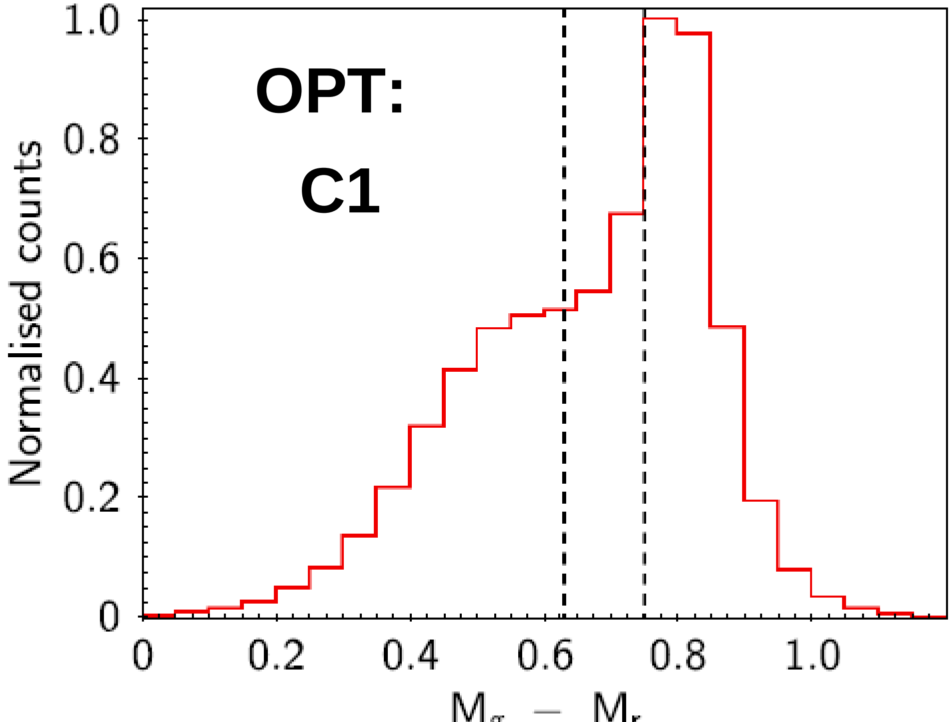
Salim et al. 2014

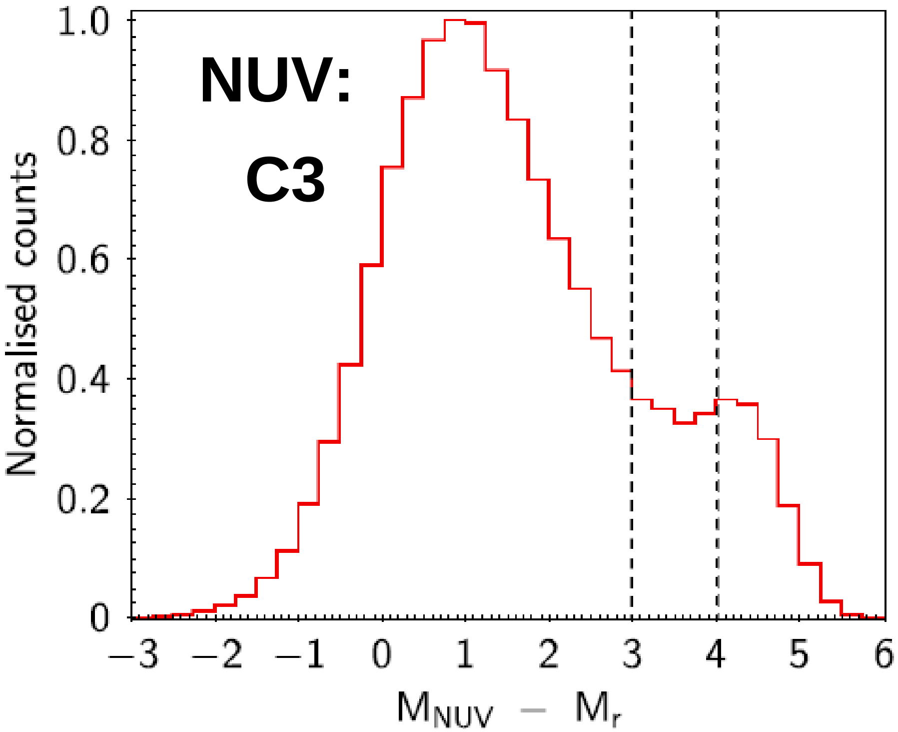
Study of the GV selection criteria

Beatrice Nyiransengiyumva
(now PhD student at MUST, Uganda, supported by the ISP)

Rwanda, Ethiopia, Uganda, South Africa, and Spain

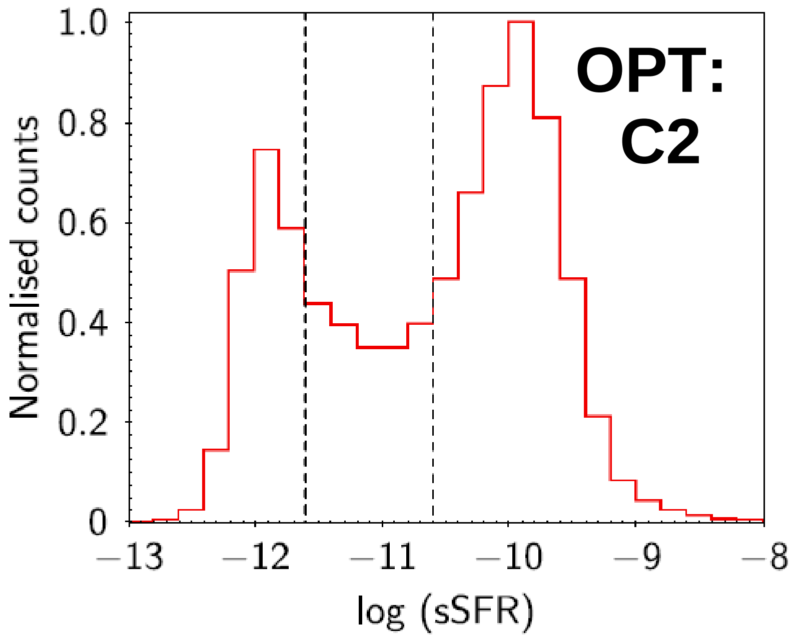
Using the SDSS optical and UV data (z < 0.1), we are testing for the first time 6 of the most used GV selection criteria and how they may affect results reported in previous studies.

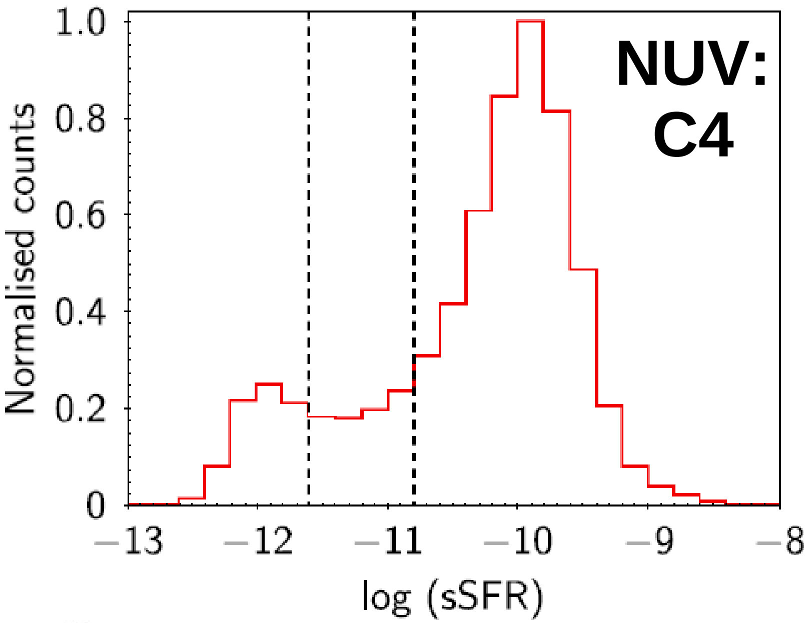


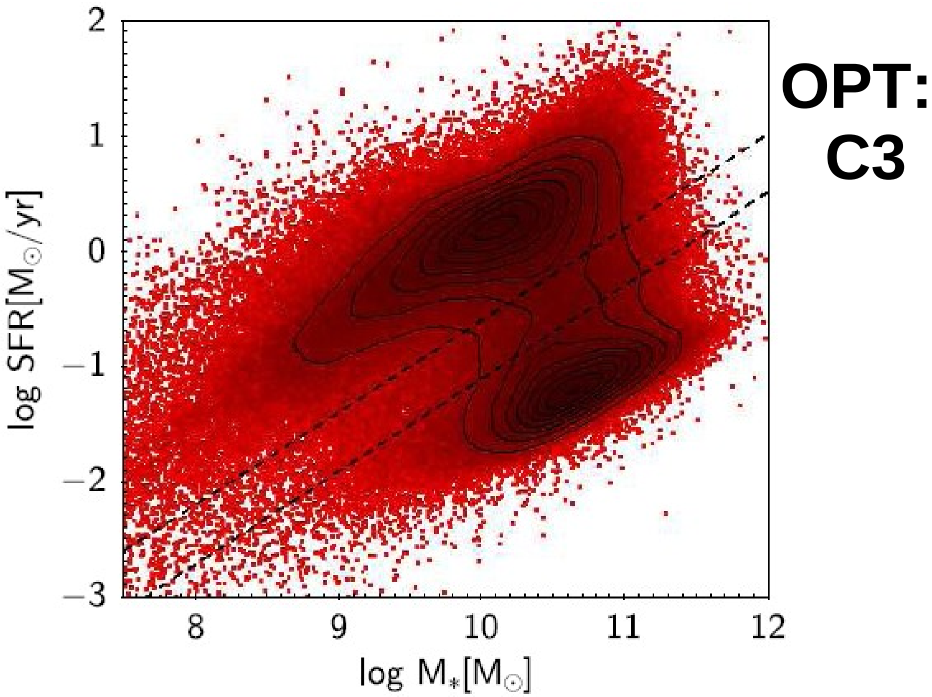


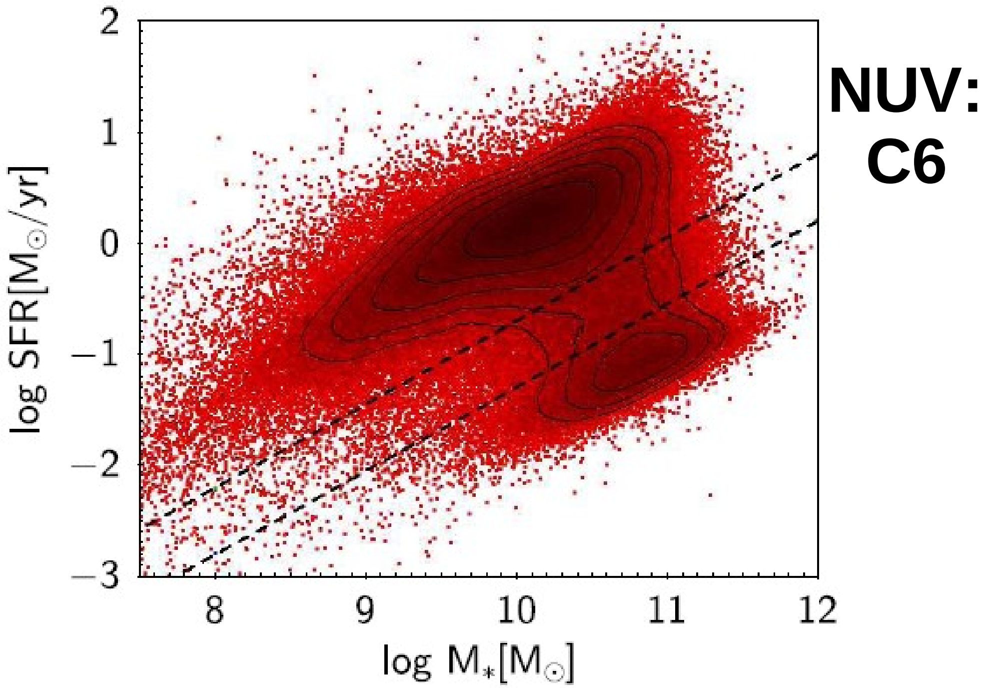
(e.g., Wyder et al. 2007; Salim et al. 2007; Walker et al. 2013; Salim et al. 2014; Lee et la. 2015; Trayford et al. 2015, 2017; Belfiore et al. 2017; Eales et al. 2018)

Study of the GV selection criteria





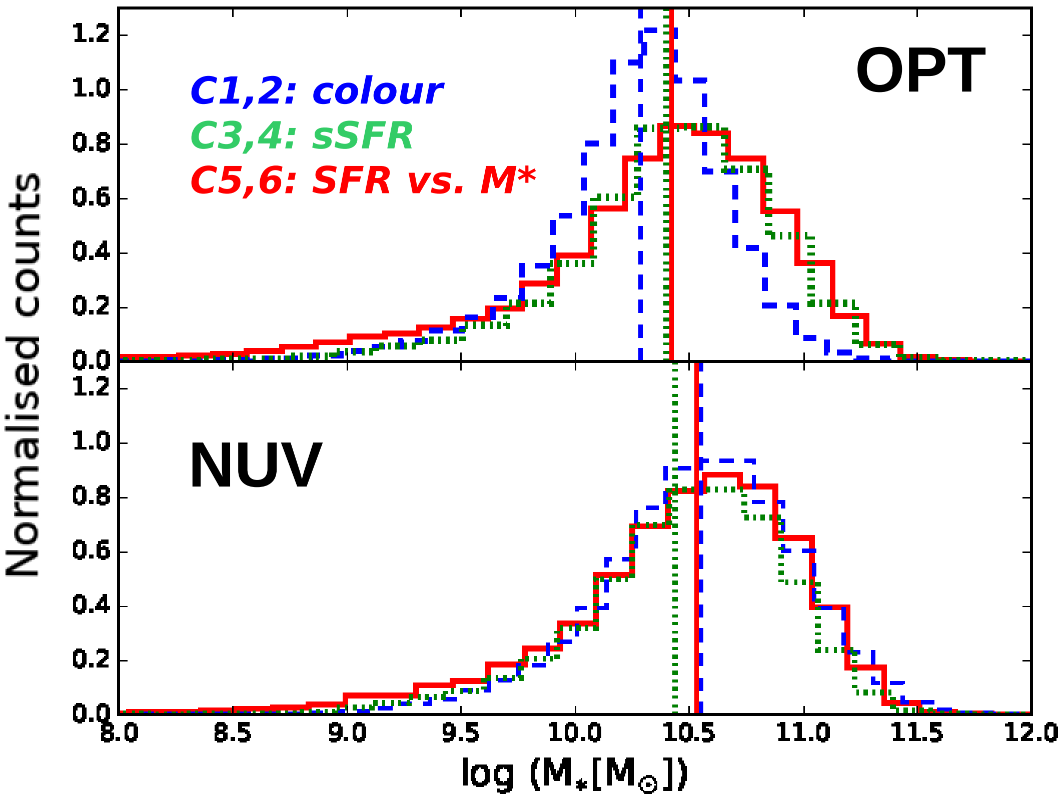


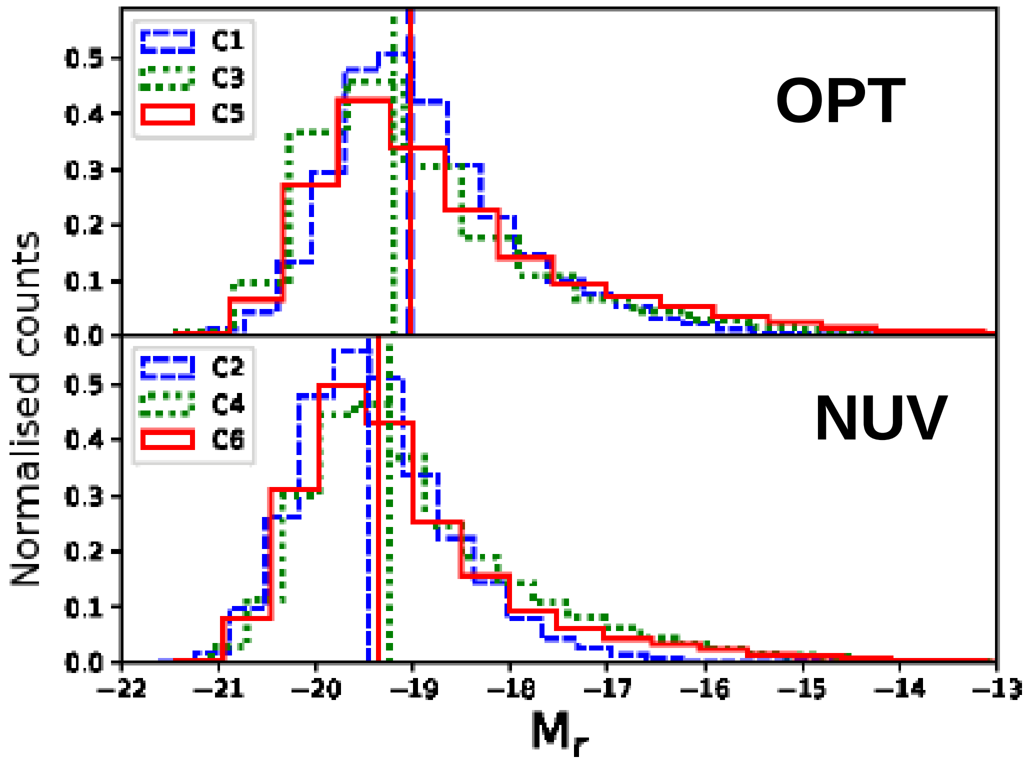


(e.g., Schiminovich et al. 2007; Noeske et al. 2007; Salim et al. 2009, 2014; Chang et al. 2015; Phillipps et al. 2019; Starkenburg et al. 2019; Koyama et al. 2019; Jian et al. 2020)

Study of the GV selection criteria

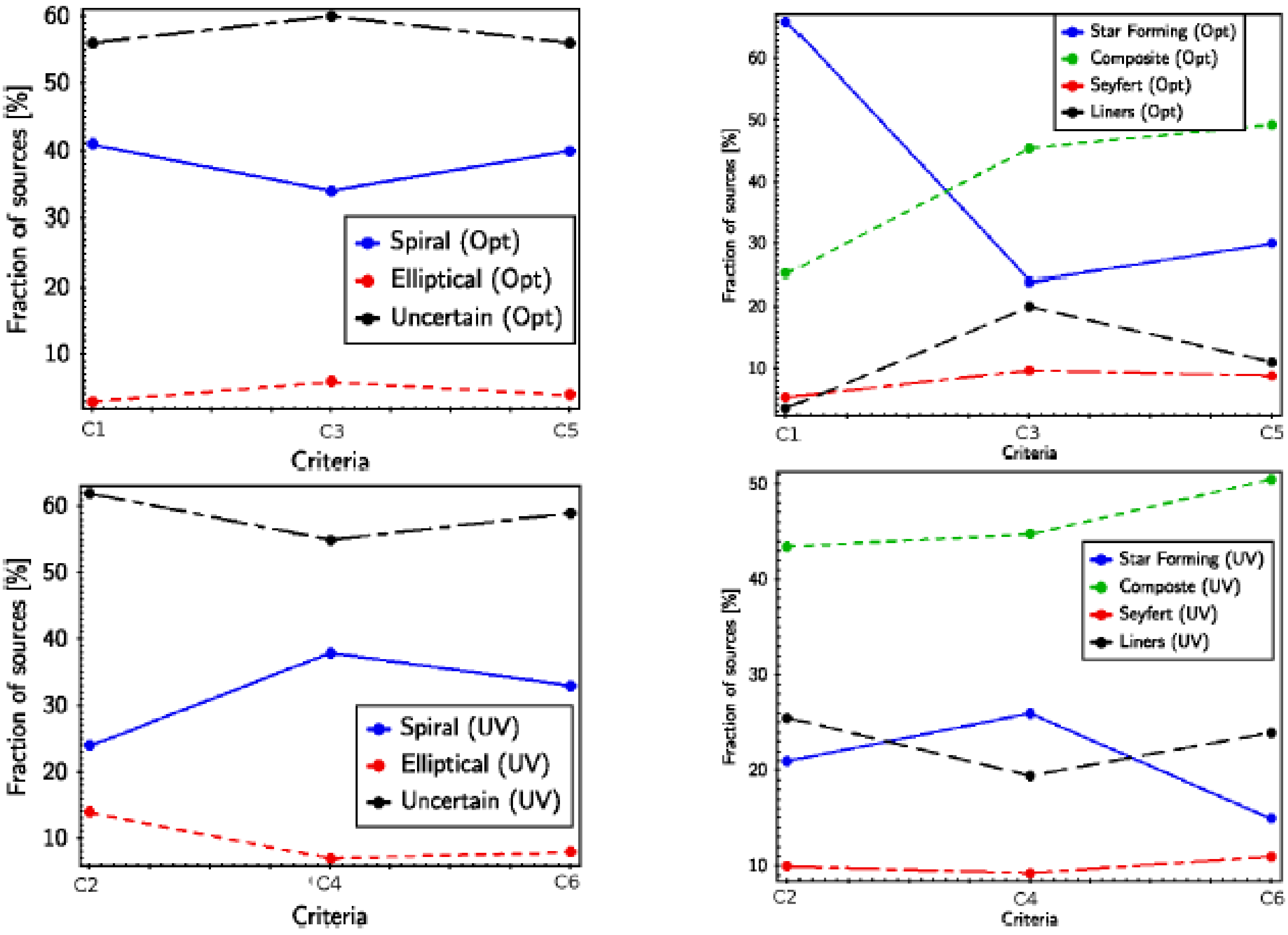
We studied different properties of GV galaxies selected in all C1-C6 criteria: stellar masses, absolute magnitudes, SFRs, morphologies, spectroscopic types





Nyiransengiyumva et al. 2021, in close submission

Study of the GV selection criteria



Nyiransengiyumva et al. 2021, in close submission

Study of the GV selection criteria

Main findings:

→ **GV galaxies selected using different criteria in optical and NUV may present different types of galaxies in terms of their M*, luminosity, SFR, spectroscopic type, and morphology,**

→ **largest difference has been observed for colour criteria,**

→ **SFR vs. M* and sSFR criteria are more recommendable to be used in GV selection.**

Importance of GV galaxies and transition timescales

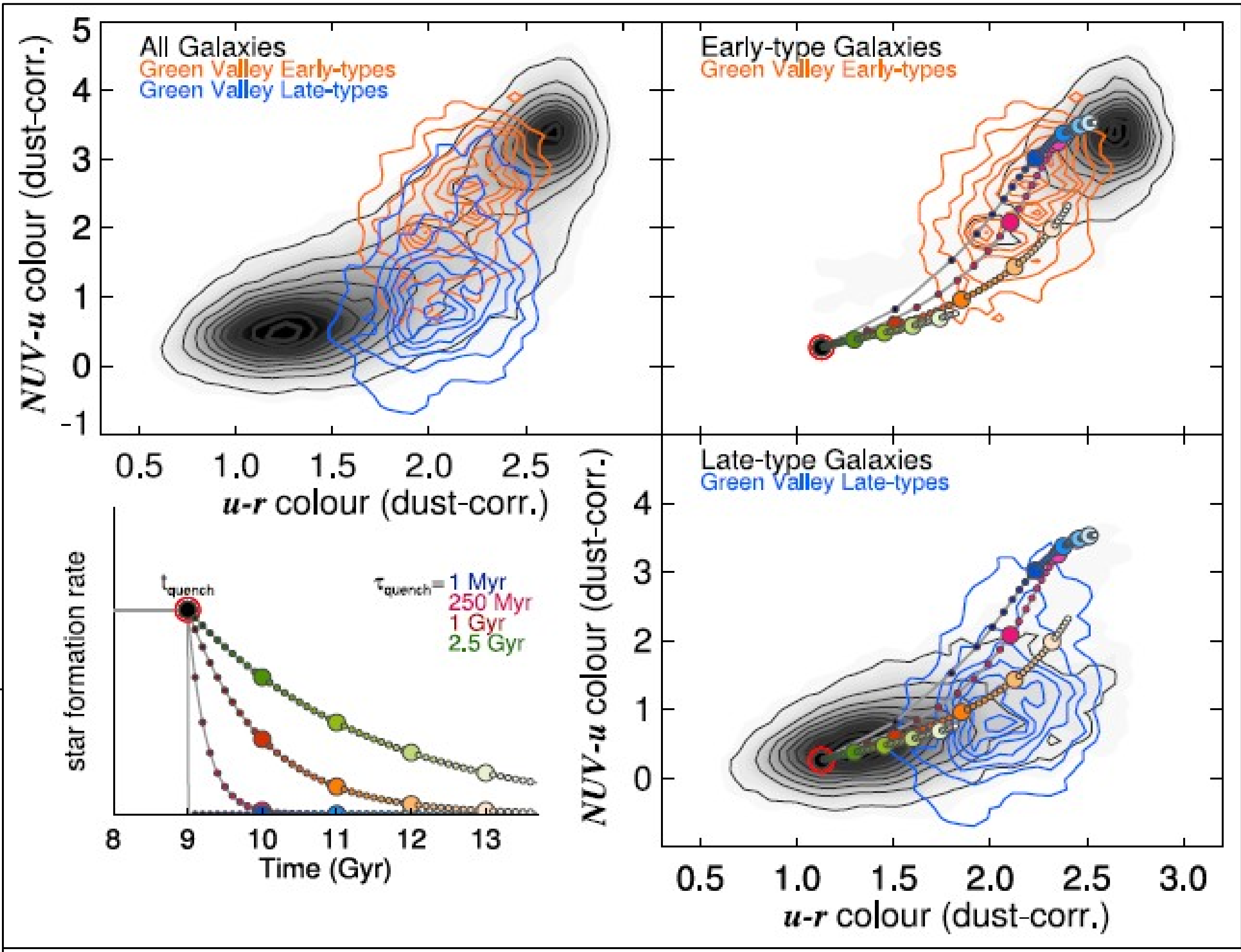
GV galaxies are crucial for understanding the process of SF quenching and how galaxies transform from late- to early-types.

Lower density of sources (in optical!) than in BC and RS
→ transition on more rapid time-scales

Different time-scales have been reported: from short ones < 1 Gyr to non-single transitions of intermediate (1-2 Gyr) time-scales or slow quenching (> 2 Gyr).

(e.g, Faber et al. 2007; Pan, Kong & Fan 2013; Schawinski et al. 2014; Smethurst et al. 2015; Trayford et al. 2016; Bremer et al. 2018; Belfiore et al. 2018; Phillips et al. 2019; Angthopo et al. 2019)

Quenching time-scales of early-type galaxies are rapid (< 250 Myr), while late-type galaxies are quenching much slower (> 1 Gyr)



Schawinski et al. 2014 (GalaxyZOO and SDSS)

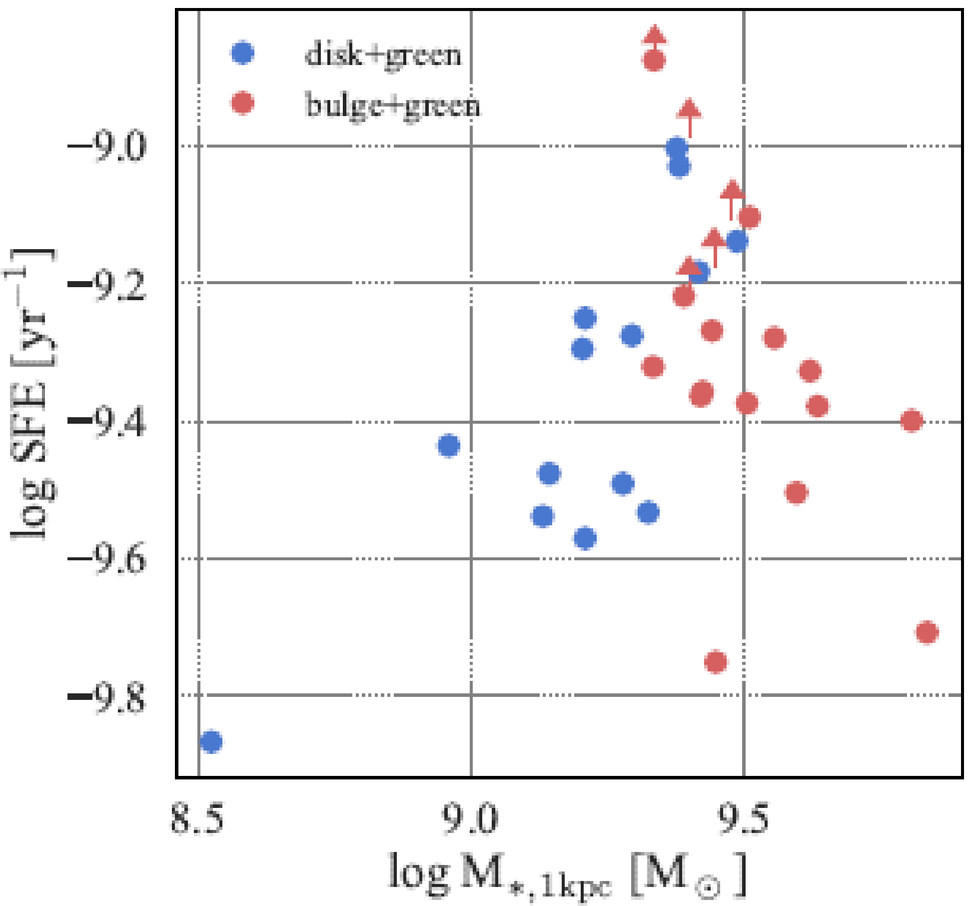
Importance of GV galaxies and transition timescales

→ Suggested that the presence of stellar bulge may suppress the efficiency of star formation in early-type galaxies

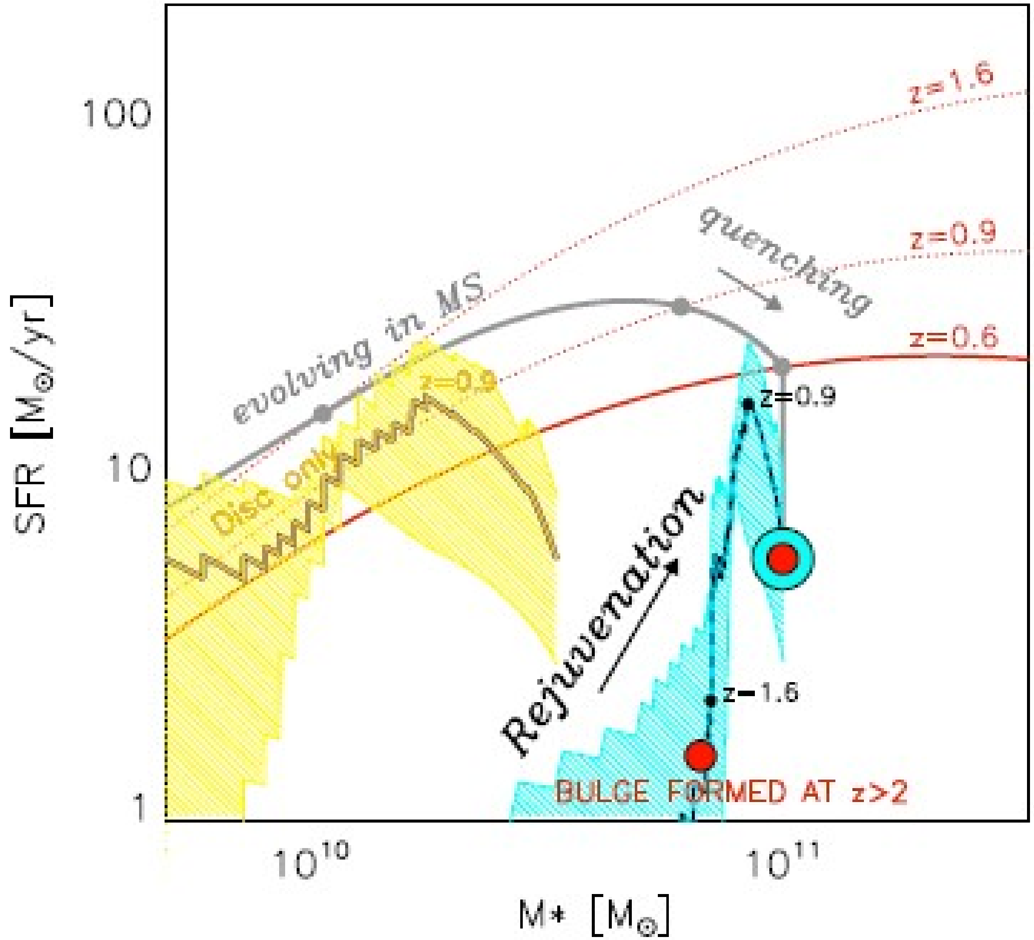
(e.g., Martig et al. 2009; Saintonge et al. 2011; Davis 2014; Schawinski et al. 2014; Colombo et al. 2018)

→ In contradiction with some of the recent results

(e.g., Koyama et al. 2019; Mancini et al. 2019)



Koyama et al. 2019
(13 disc- and 15 bulge-dominated galaxies)



Mancini et al. 2019
(10 galaxies at 0.45 < z < 1)

GV and IOAG candidates

Using the CALIFA data it was suggested that the **highest growth rate in galaxies** corresponds to certain range of stellar mass of **approx. logM* = 10.73 – 11.03**
→ Shorter assembly times within inner regions (< 0.5 Reff)
(Pérez et al. 2013)

AGN and Star-Formation Properties of Inside-out Assembled Galaxy (IOAG) Candidates at z < 0.

(Zewdie et al. 2020, MNRAS, 498, 4345)

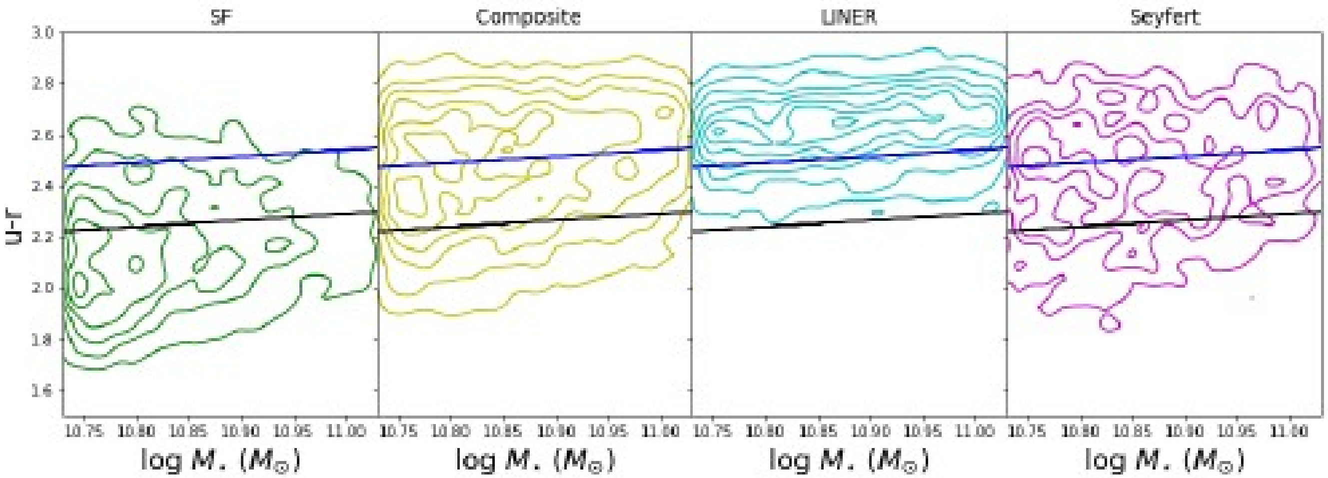
Ethiopia, Chile, Spain

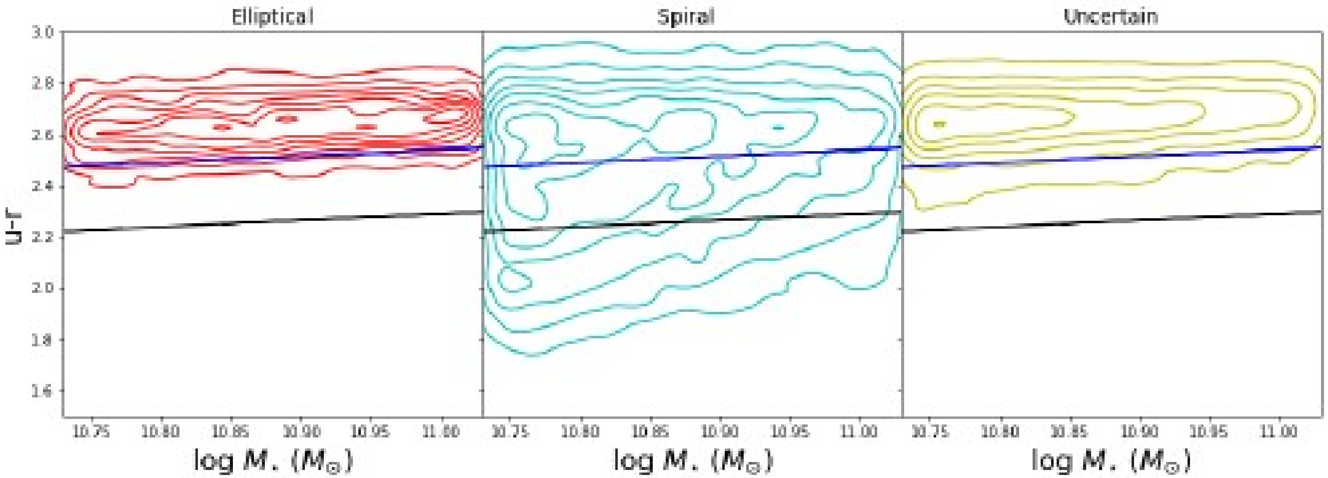
Dejene Zewdie
(MSc student at the ESSTI, Ethiopia,currenly PhD student in Chile)

Using the SDSS DR8 data (**> 48000 galaxies at z < 0.1**) for the first time we are trying to understand better the properties of these galaxies in terms of their **spectroscopic and morphological types, SFRs, location on the SF-M* and colour-M* diagrams, and IR properties.**

GV and IOAG candidates

→ Majority classified as composite (40%) or AGN (40%) with spiral morphologies
→ Majority of IOAG candidates (~ 80%) are located below the MS of SF
→ Majority of IOAG candidates are located within the GV (~30%) or red sequence (50%)





Zewdie et al. 2020

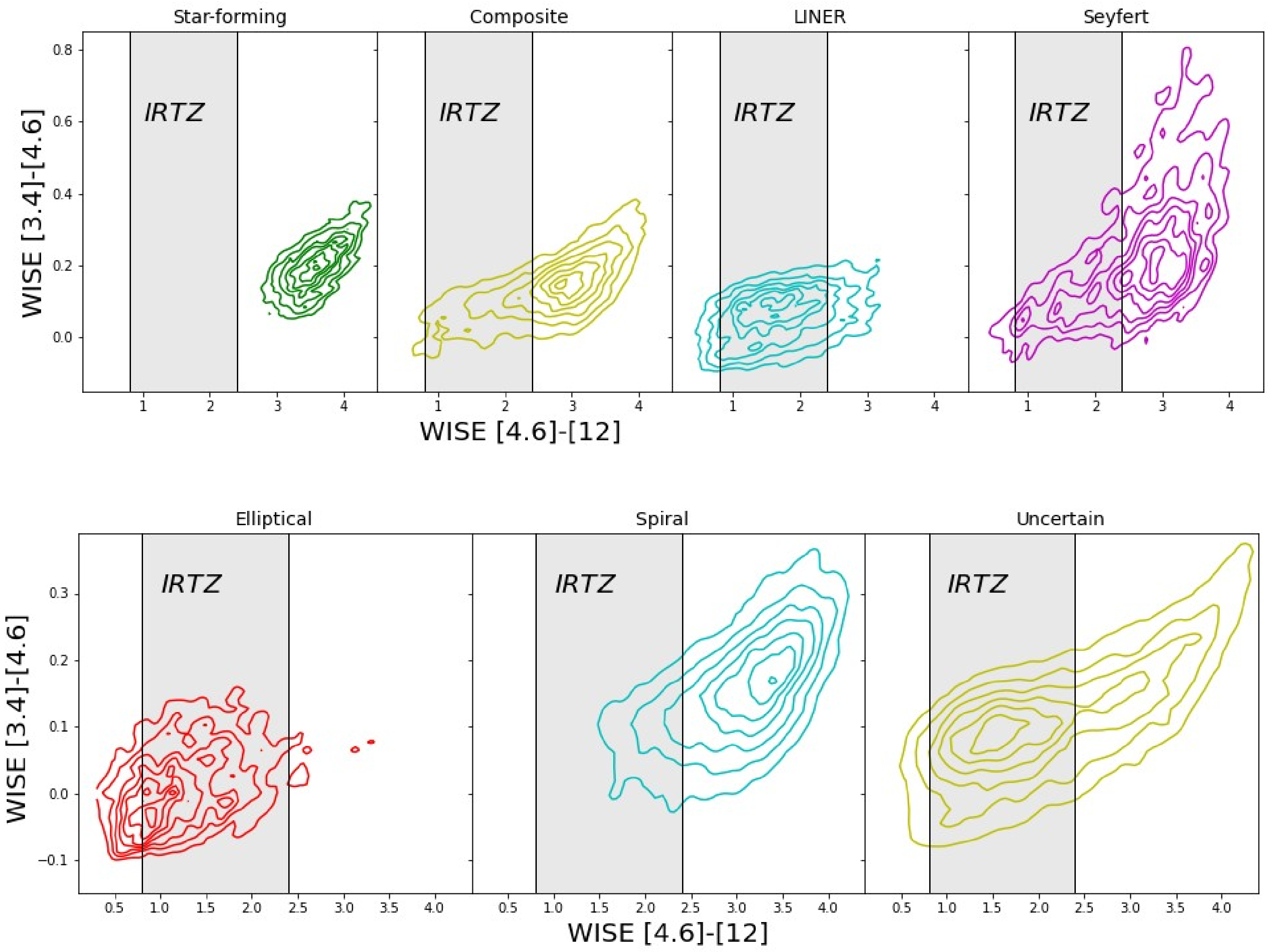
GV and IOAG candidates

Main findings:

→ High fraction of IOAG candidates may be in the process of quenching

→ Those classified as AGN have lower SFRs → signs of AGN being involved in SF quenching?

→ Spiral morphology remains in place (even in LINERs)!!
→ central SF suppressed before morphological transformation occurs



Zewdie et al. 2020, MNRAS, 498, 4345

AGN negative feedback
(e.g., Di Matteo, Springel & Hernquist 2005; Nandra et al. 2007; Pović et al. 2012; Shimizu et al. 2015; Leslie et al. 2016; Lin et al. 2019)

Secular evolution
(e.g., Mendez et al. 2011; Smethurst et al. 2015; Phillips et al. 2019)

Minor and major mergers
(e.g., Barro et al. 2013; Smethurst et al. 2015; Bryukhareva et al. 2019)

Suggested mechanisms responsible for SF quenching

Environmental effects (e.g., pressure striping, thermal evaporation, starvation, strangulation, etc.) and cluster interactions
(e.g., Gunn & Gott 1972; Cowie & Songaila 1977; Larson, Tinsley & Caldwell 1980; Bekki, Couch & Shioya 2002; Fang et al. 2013; Jian et al. 2020)

Supernovae winds
(e.g., Marasco, Fraternali & Binney 2012, and references therein)

Galaxy structure as an indication of quenching: barred GV galaxies with longer quenching timescales
(Nogueira-Cavalcante et al. 2019)

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(e.g., Di Matteo, Springel & Hernquist 2005; Nandra et al. 2007; Pović et al. 2012; Shimizu et al. 2015; Leslie et al. 2016; Lin et al. 2019)

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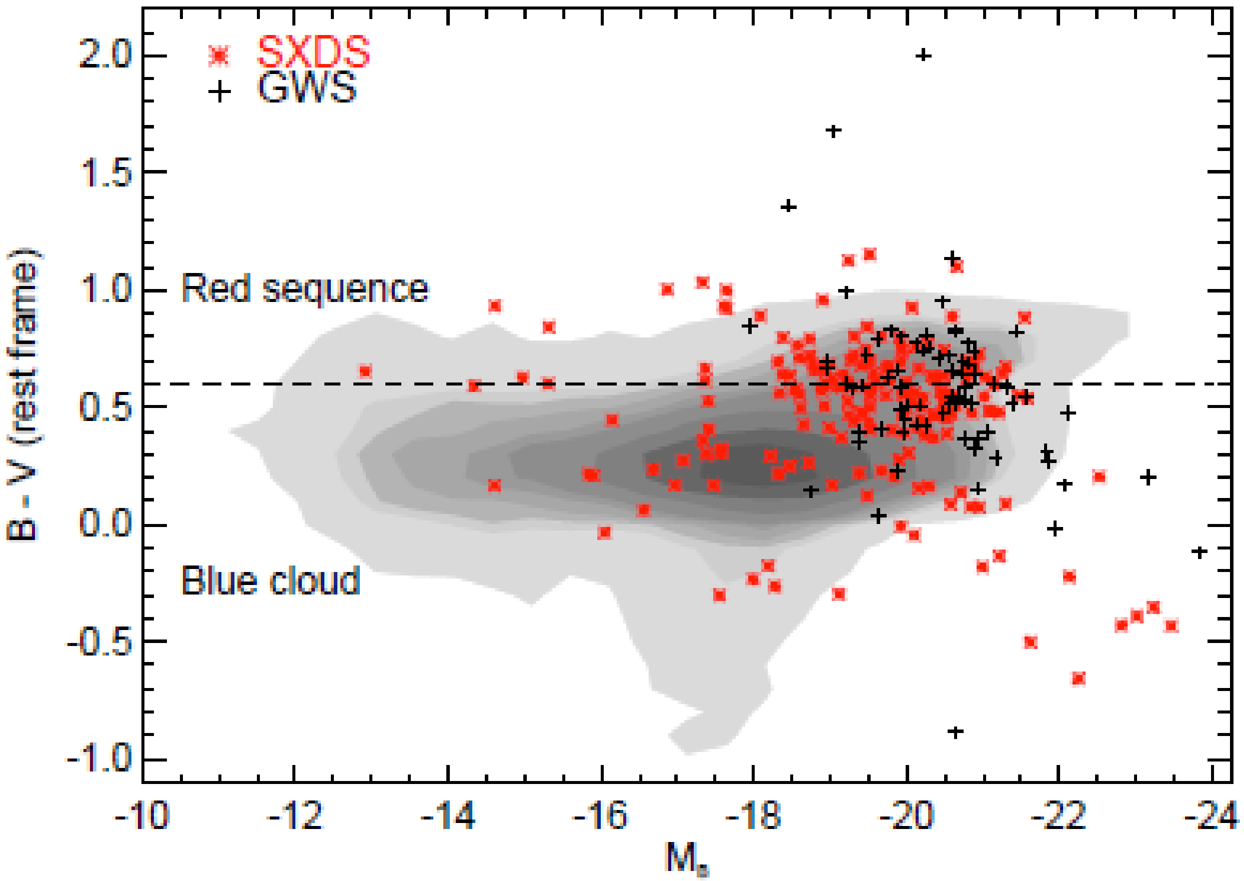
Role of AGN in SF quenching

X-ray detected AGN

Most of X-ray detected AGN are located in GV (both type-1 and type-2), between the BC and RS. They can be hosted by both early- and late-type galaxies.

→ suggested that AGN feedback may be responsible for quenching SF in galaxies

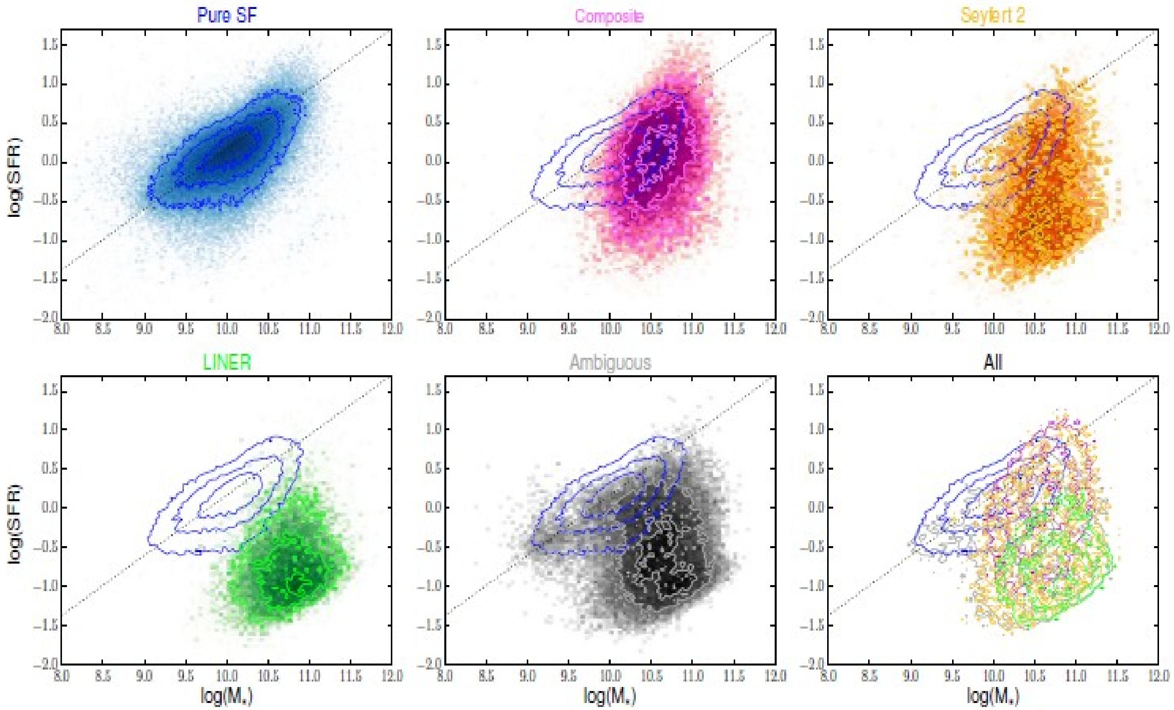


Pović et al. 2012, A&A, 541, 118

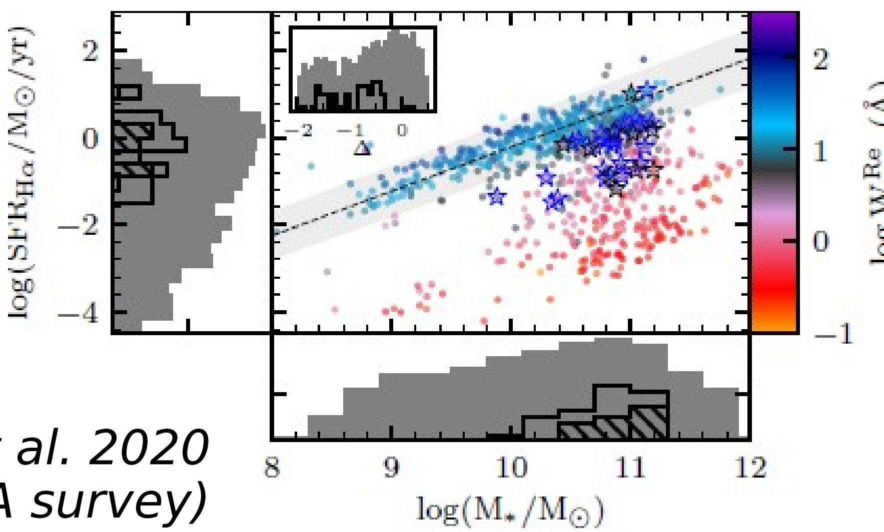
(Also e.g., Sanchez et al. 2004; Nandra et al. 2007; Georgakakis et al. 2008; Silverman et al. 2008; Treister et al. 2009; Hickox et al. 2009; Cardamone et al. 2010)

Role of AGN in SF quenching

Most of <u>optically detected AGN</u>, using emission lines, are located below the main-sequence of SF.



Leslie et al. 2016 (SDSS survey)



Lacerda et al. 2020 (CALIFA survey)

AGN negative feedback suggested to be responsible for quenching the SF in galaxies moving them from late-types to early-types (or from the blue cloud to the red sequence).

Properties of AGN and non-AGN in the GV

South Africa, Ethiopia, Rwanda, and Spain

Antoine Mahoro,
(PhD student at SAAO, South Africa)

Sample: X-ray detected AGN (317 sources, 21.5%) and non-AGN (2985 sources, 6%) GV galaxies ($0.8 \leq U - B \leq 1.2$; Willmer et al. 2006; Nandra et al. 2007) with FIR emission in the COSMOS field. $\sim$ 90% of our sources have $0.2 \leq z \leq 1.2$.

Main aim: To understand better the properties of GV galaxies and the role of AGN in galaxy morphological transition from late- to early-types through optical (using public + our SALT data) and FIR (using Herschel and Spitzer) studies.

Main studies:

- SFRs (Mahoro et al. 2017, MNRAS, 471, 3226)
- morphology (Mahoro et al. 2019, MNRAS, 485, 452)
- stellar populations (Mahoro et al. 2021, in close subm.)
- [OIII]5007 emission line (Mahoro et al. 2021, in prep.)

Properties of AGN and non-AGN in the GV: SFRs

- SFRs measured using IR luminosity (integrated over 8 – 1000μm)

$$\frac{\mathrm{SFR}}{\mathrm{M_\odot yr^{-1}}} = 1.7 \times 10^{-10} \left(\frac{\mathrm{L_{IR}}}{\mathrm{L_\odot}}\right)$$

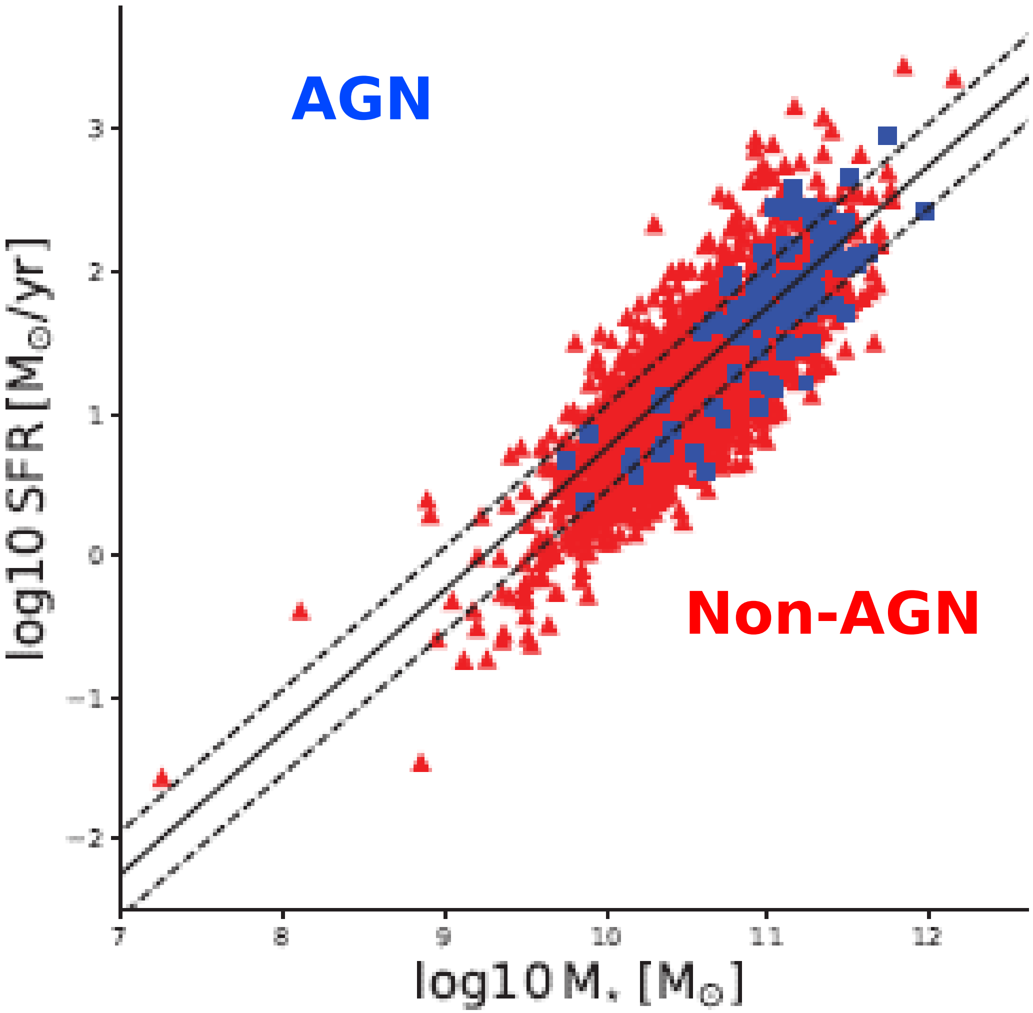
Kennicutt, 1998

- SED fittings using LePhare code *(Ilbert et al. 2006)*

- non-AGN fitted using Chary & Elbaz (2001) templates

- AGN fitted with 11 templates of Kirkpatrick et al. (2015) with a known AGN contribution (0 – 57%)

Obtained results are not in line with findings in optical: X-ray detected AGN with FIR emission not below the MS of SF

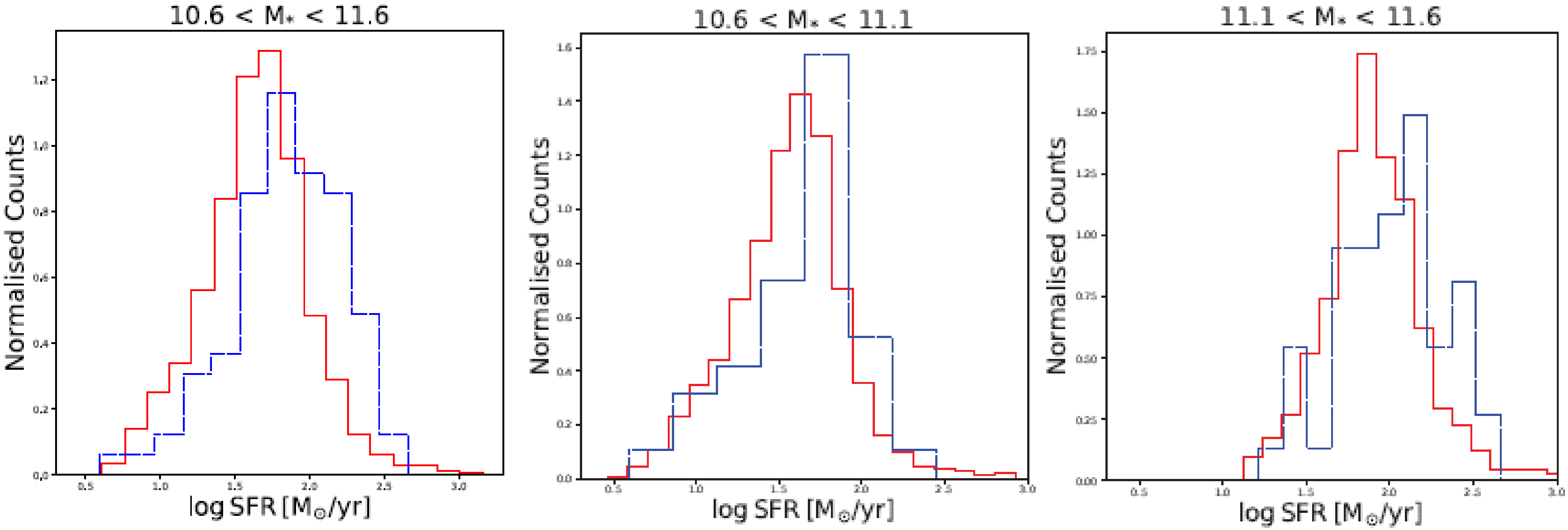


Mahoro et al. 2017, MNRAS, 471, 3226

Properties of AGN and non-AGN in the GV: SFRs

Comparison of SFRs using the same stellar mass range

AGN
Non-AGN

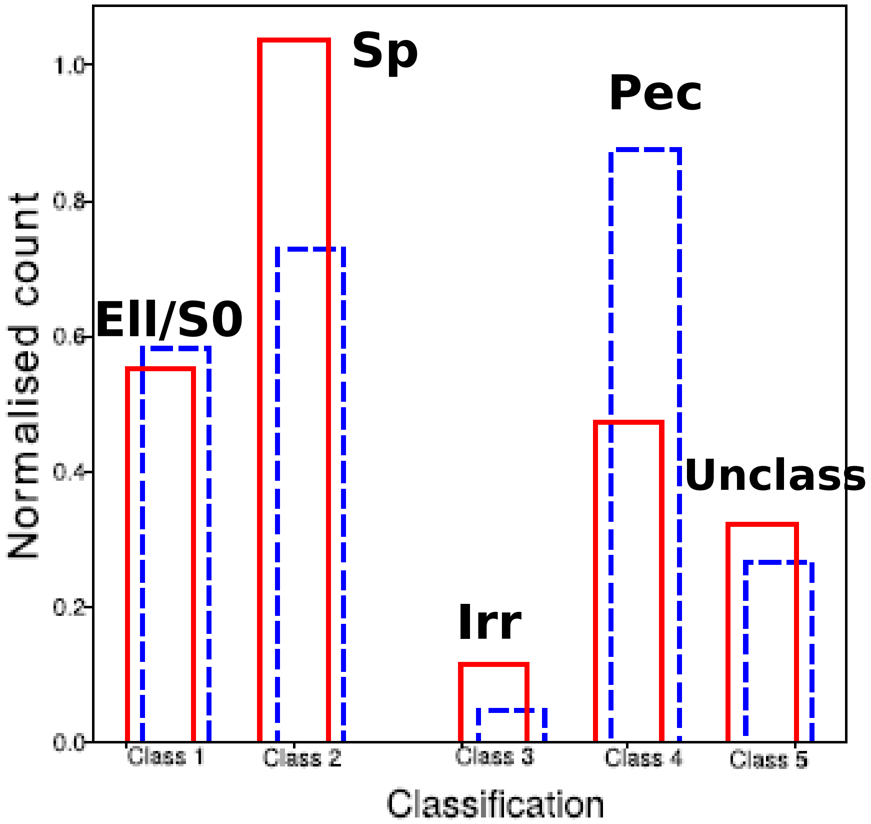


No signs of FIR AGN quenching the SF, but having enhanced SFRs → ¿possible signs of positive AGN feedback?

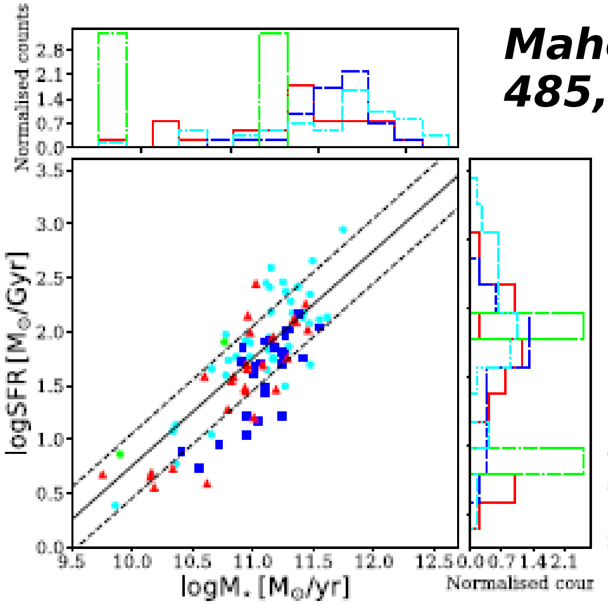
Mahoro et al. 2017, MNRAS, 471, 3226

Properties of AGN and non-AGN in the GV: morphology

- Visual morphological classification (HST/ACS images), and inspection of different morphological parameters (C, A, Gini, M20) and diagrams



Mahoro et al. 2019, MNRAS, 485, 452



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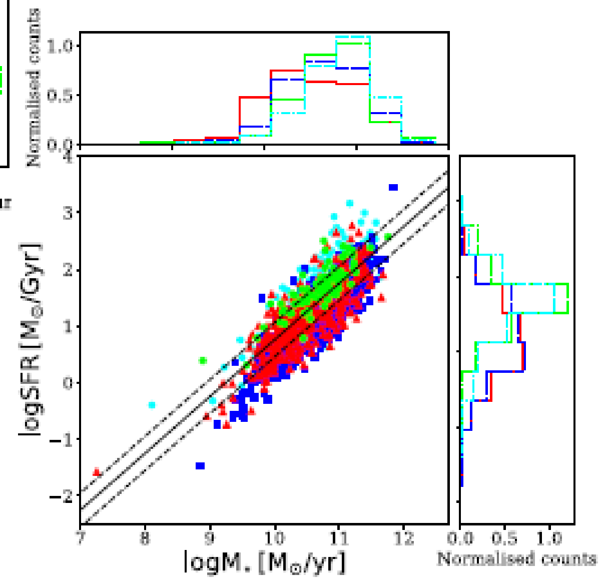
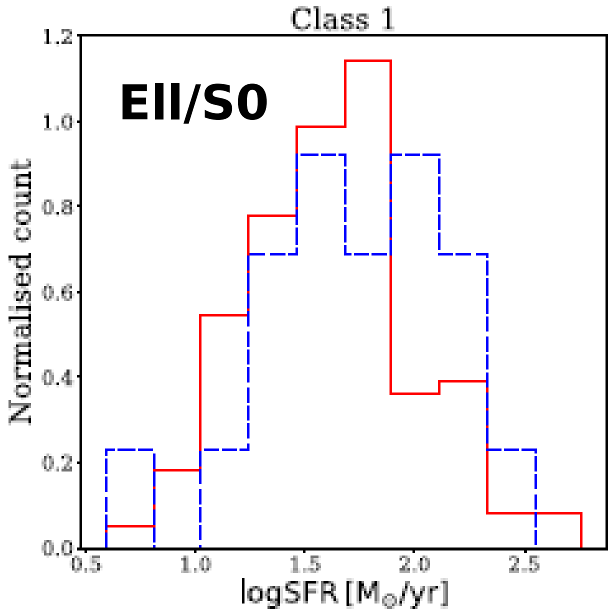
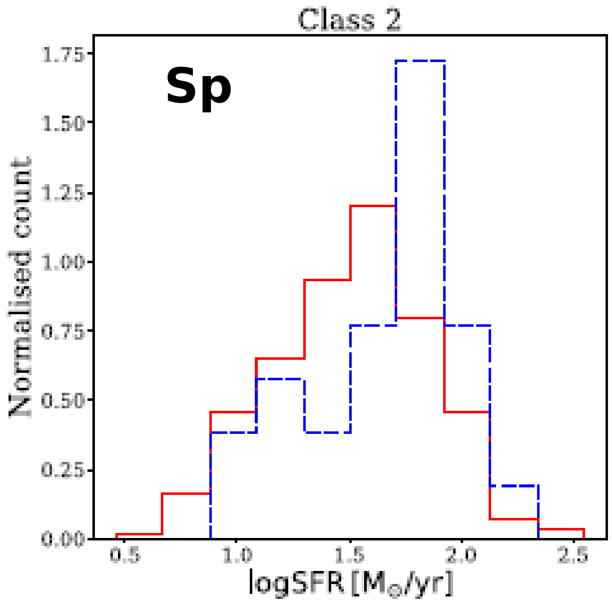


AGN
Non-AGN

- Higher fraction of peculiar AGN (38%) than non-AGN (19%)
- Lower fraction of spiral AGN (26%) than non-AGN (46%)
- AGN with different morphology on the MS of SF

Properties of AGN and non-AGN in the GV: morphology

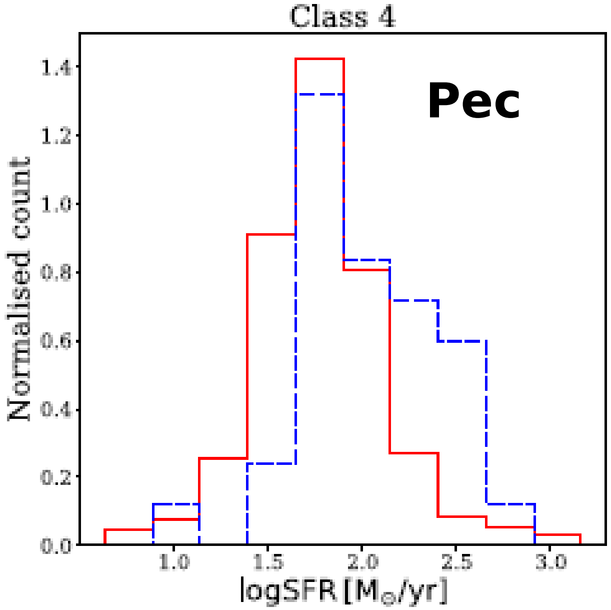




Higher SFRs in AGN independently on morphology

Per same mass range:

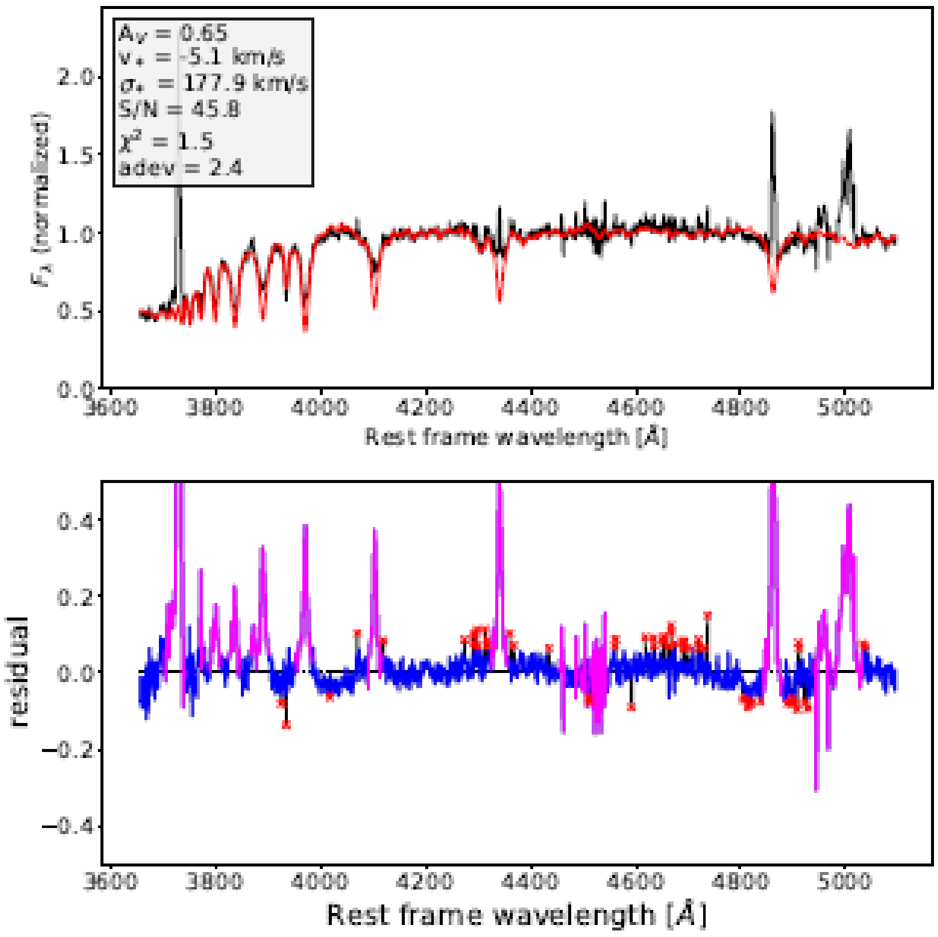
10.6 < logM* < 11.6



Mergers and interactions can not alone explain observed higher SFRs in AGN → ¿possible signs of positive AGN feedback?

Mahoro et al. 2019, MNRAS, 485, 452

Properties of AGN and non-AGN in the GV: stellar populations and ages



- **LEGA-C spectra (z = 0.6 – 1)**

- **spectral fittings using STARLIGHT code** *(Cid Fernandes et al. 2005)*

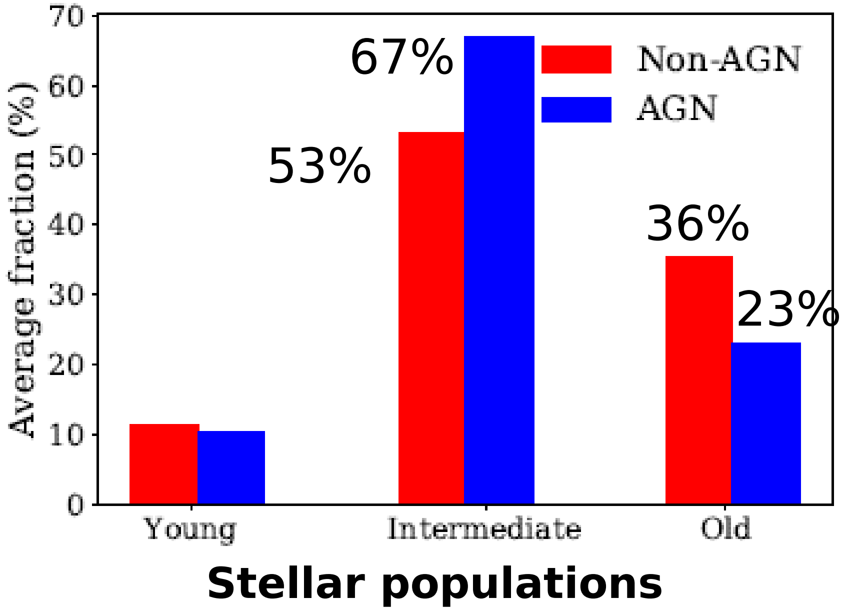
- **Bruzual and Charlot 2003 population synthesis models**

- **25 stellar ages (0.0001 - 18 x 10^9 yrs), solar Z, Salpeter IMF, Cardelli et al. 1989 extinction law**

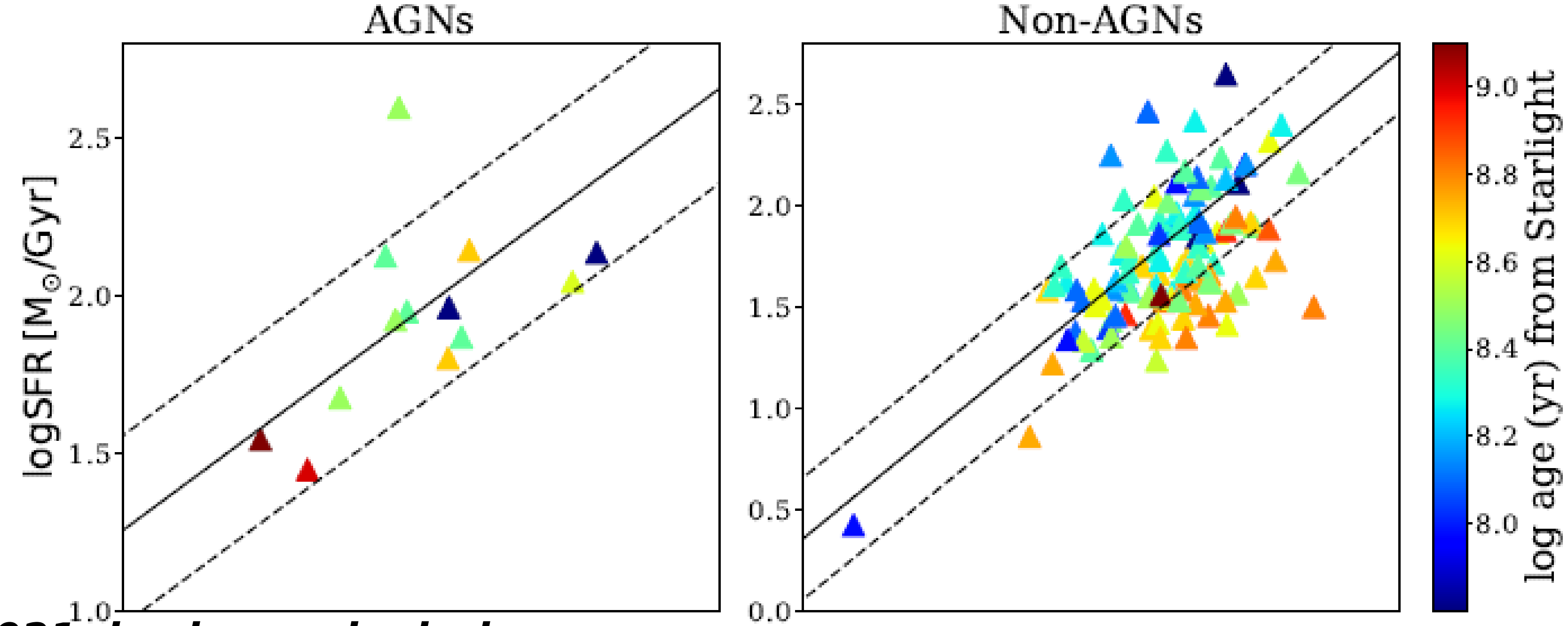
→ stellar populations, stellar ages

Mahoro et al. 2021, in close submission

Properties of AGN and non-AGN in the GV: stellar populations and ages



→ in line with previous results, in general we do not obtain older stellar populations of AGN, in contrast of what has been suggested in optical studies.

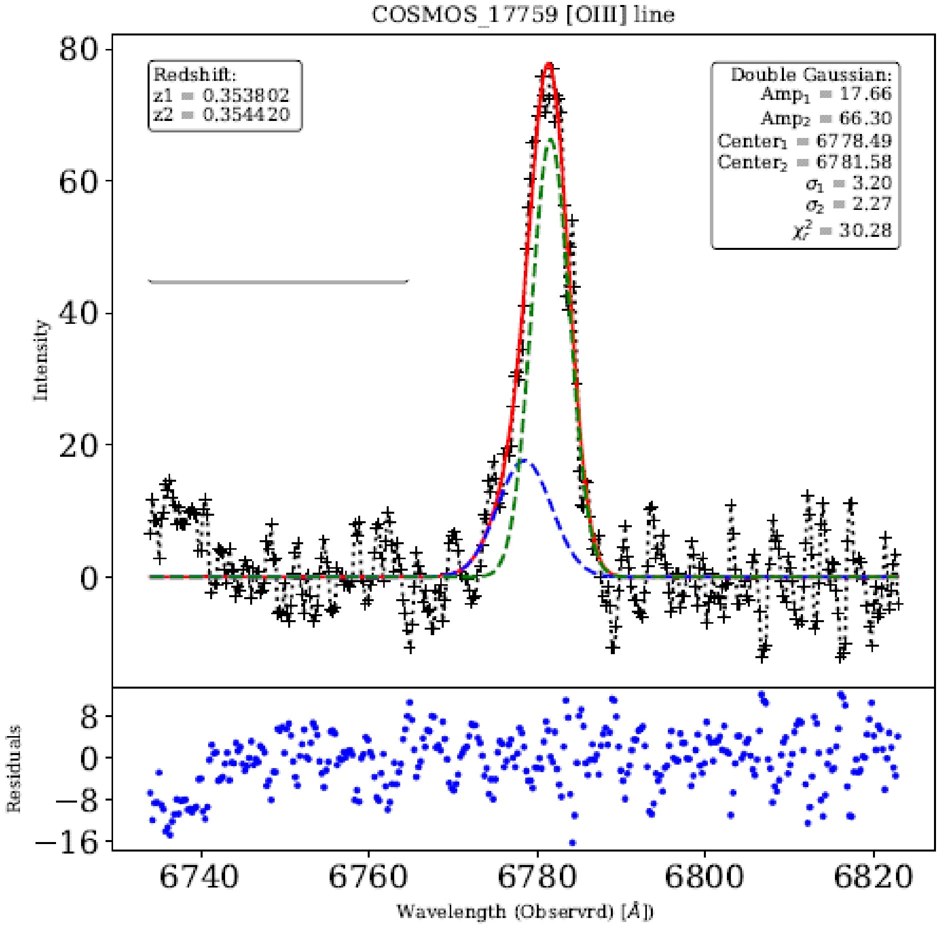


Mahoro et al. 2021, in close submission

Properties of AGN and non-AGN in the GV: [OIII]5007 profiles

- Data reduction and analysis of **11m SALT RSS [OIII] data** (observational time awarded for 4 + 20 sources)
- Comparison sample of AGN and non-AGN with the same stellar mass and located in the same part of the SFR-M* diagram

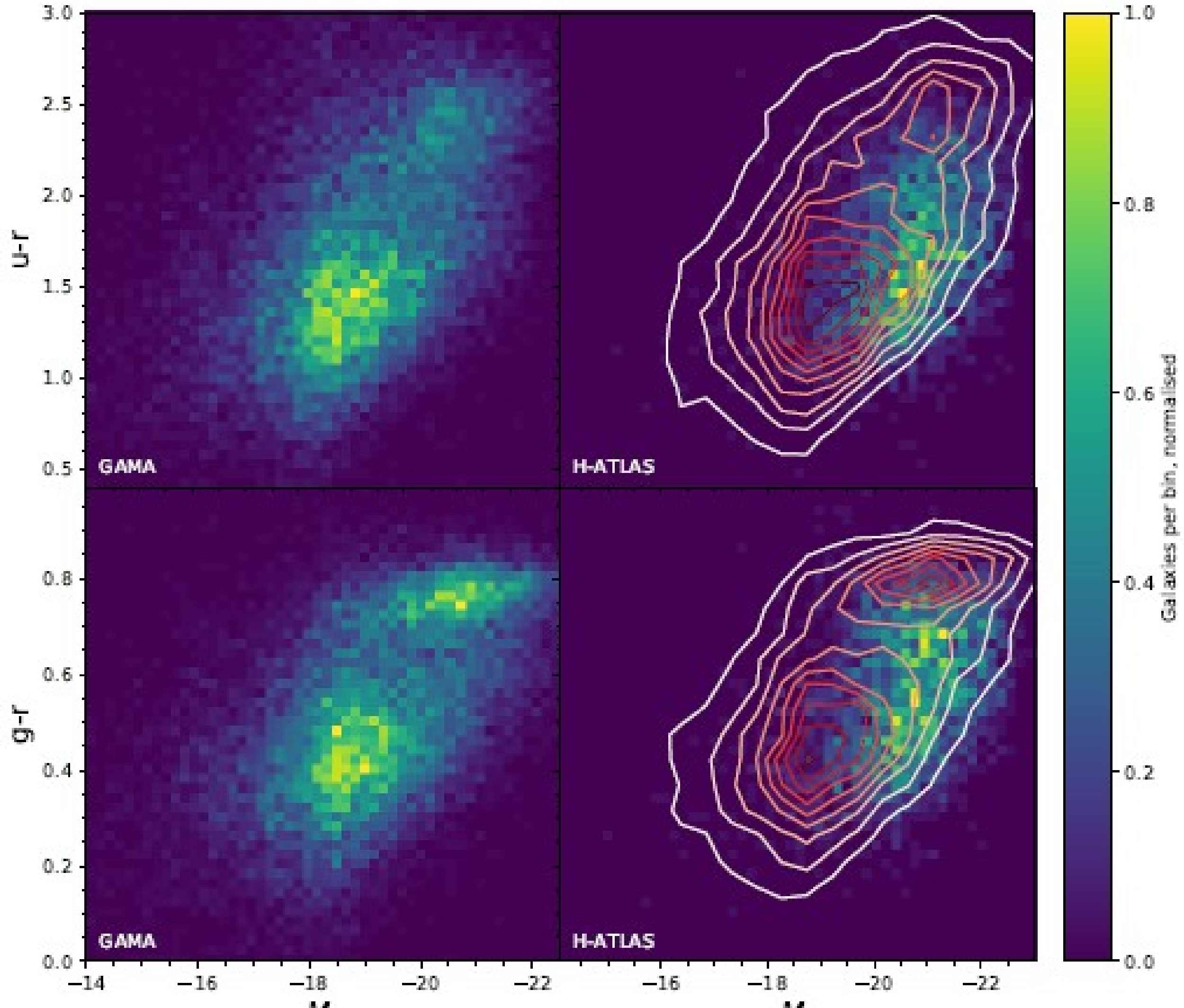
Preliminary fittings



Mahoro et al. 2021, in prep.

We are still lacking the full understanding of GV galaxies and galaxy transition when including multi-wavelength studies

Another example: green mountain in sub-mm



Stephen et al. 2018
(GAMA Survey)

Some of the take home messages

→ GV galaxies important for understanding the full picture of morphological transformation and galaxy evolution.

→ Sample selection of GV galaxies still a challenge, SFR vs. M* (or M, L) and/or sSFR criteria preferable to be used in comparison to colour.

→ Lot of progress has been done over the past years regarding the properties of GV galaxies and SF quenching mechanisms.

→ Important fraction of GV galaxies may be IOAG candidates, where AGN may contribute to SF quenching and where it seems that central SF is quenched before the morphological transformation takes place.

→ Explaining the role of AGN in SF quenching becomes more complex when using multi-wavelength studies (in optically selected AGN negative feedback suggested, while signs of positive feedback may exist in FIR AGN emitters)

→ Multi-wavelength studies are crucial to be carried out in future for understanding the full picture of galaxy evolution.

J-PAS: study of AGN and non-AGN in GV

Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS)

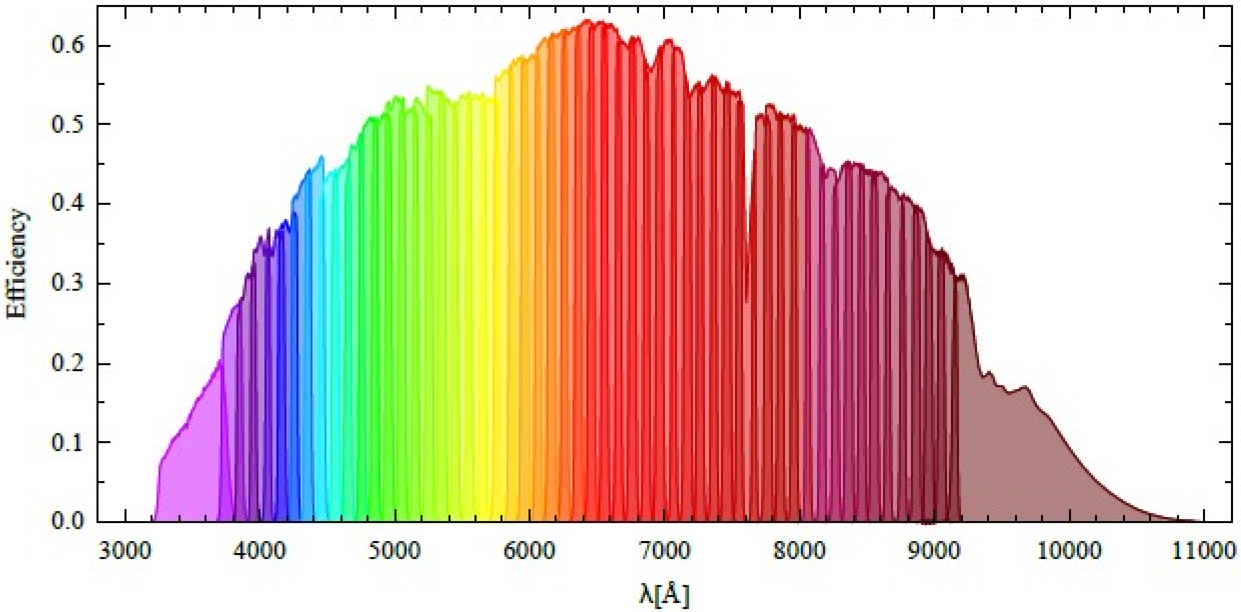
(Benítez et al. 2009, 2014; Bonoli et al. 2021)

- to map thousands of deg² with a dedicated 2.55m JST telescope
- set of 56 filters (FWHM ~ 145 Å)
- *JPCam*, 4.2 deg² FoV, 0.23 arcsec/pix pixel size

- for now MiniJPAS with *JPAS-Pathfinder* camera, ~ 1 deg² of the AEGIS field
- 54 NB filters + 2 BB in UV and NIR, + *u, g, r, i* SDSS filters
- > 64000 sources in r band, with completeness up to r (AB) = 23.6 and 22.7 for compact and extended sources, respectively.

Main aims:

- LSS
- BAOs
- Galaxy formation and evolution



Credits: Bonoli et al. 2021

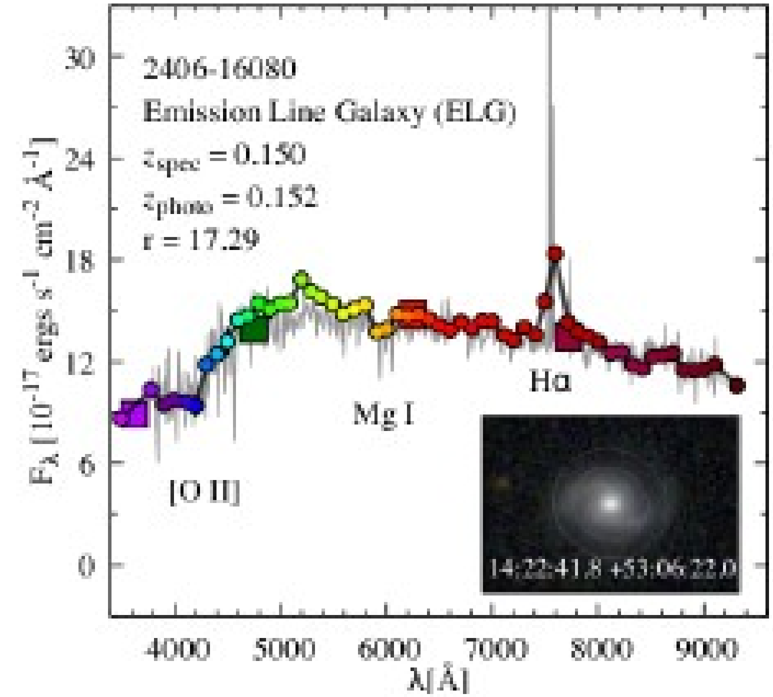
J-PAS: study of AGN and non-AGN in GV

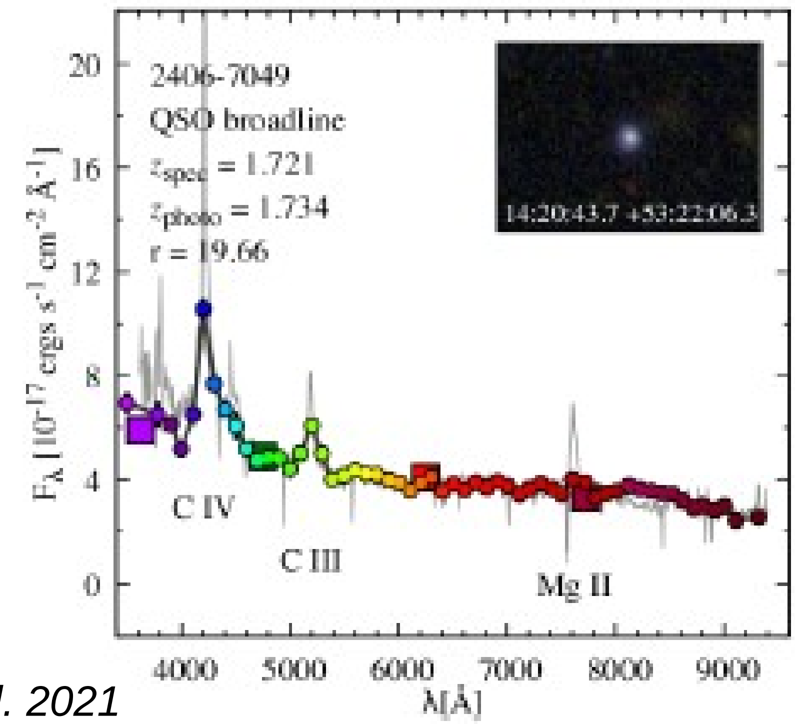
Our aim:

- to use the advantage of J-PAS filters for selecting more complete sample of GV galaxies

- to use the advantage of spectro-photometric JPAS information for separating between AGN and non-AGN

- to study the properties of AGN and non-AGN in GV in terms of their morphologies, stellar populations and metallicities





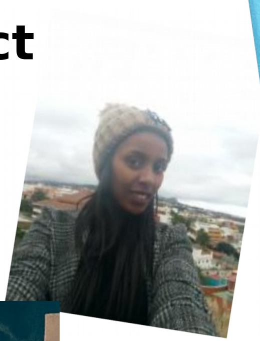
Credits: Bonoli et al. 2021

Other projects under the extragalactic group in Ethiopia

- Properties of galaxies in clusters up to z ~ 1.0
(Beyoro-Amado et al. 2019, MNRAS, 485, 1528;
Beyoro-Amado et al. 2021, MNRAS, 501, 2430)

- Morphological properties of active galaxies
(Getachew et al. 2021, in close submission; Getachew et al. 2021, in prep.)

- Dichotomy of radio-loud/radio-quiet quasars and the effect of radio jets on the gas (Terefe et al. 2021, in prep)



- Multiwavelength morphological study of ultra-hard X-ray AGN (Bilata et al. 2021, in close submission)

- Variability and SF properties of nearby quasars

- Testing the alternative method to measure the accretion rate in galaxies
(Guelle et al. 2020; Guelle et al. 2021, in prep.)

- Characterisation of LINERs and retired galaxies at z < 0.1
(Mazengo et al. 2020)

- Stellar populations of ultra-hard X-ray AGN
(Pović et al. 2020, in prep.)

Human capacity building over the past years:

→ development from scratch of extragalactic astronomy in Ethiopia, Rwanda, Uganda, and Tanzania

→ 8 MSc holders, all of them attached to some of public universities and/or research centers

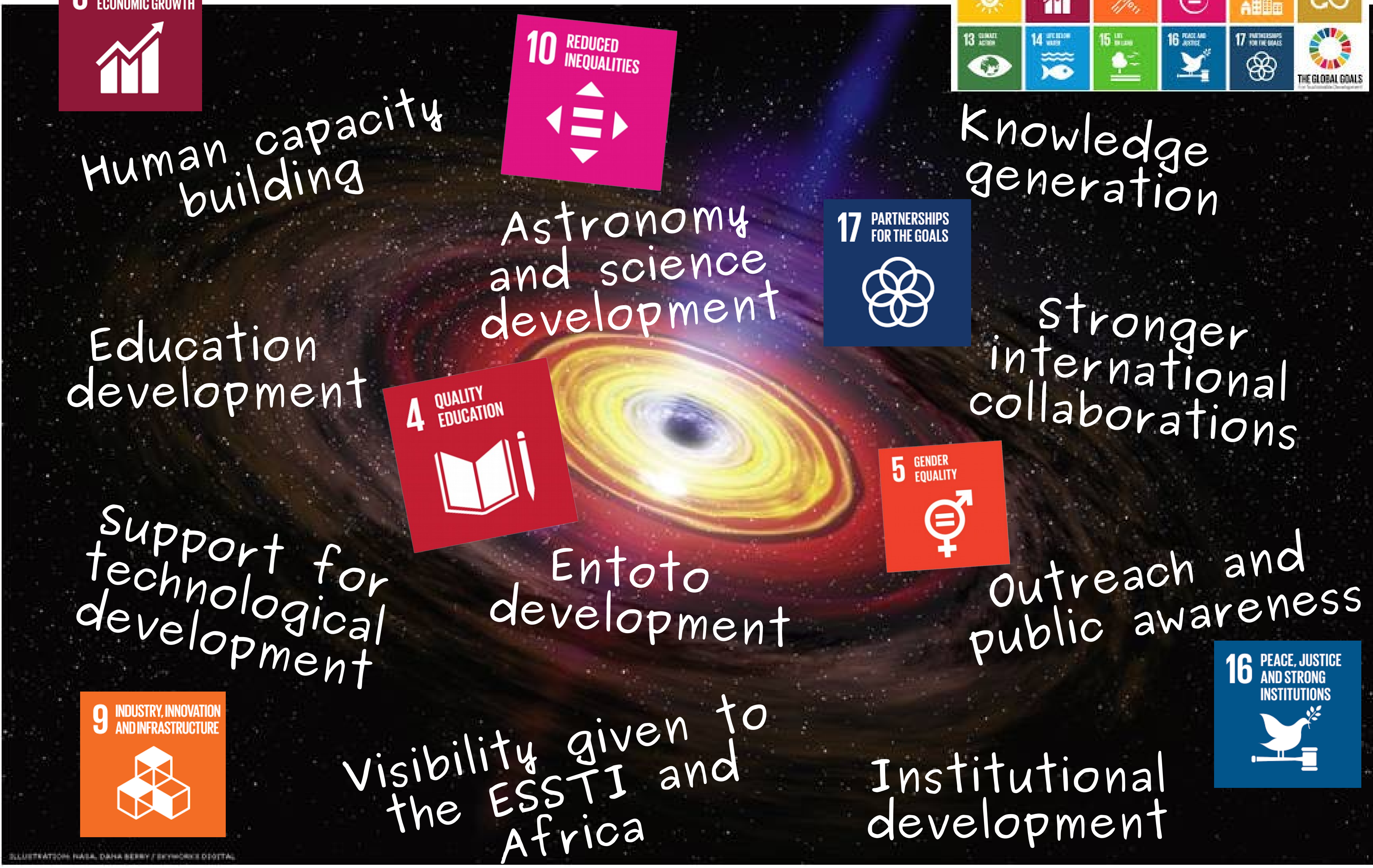
→ 5 MSc holders are currently doing their PhD in Chile, South Africa, Uganda, Tanzania, and Spain, 3 are working in Ethiopia (2 of them will posibly start soon their PhD)

→ 1 PhD holder, now working at the KMU in Ethiopia

→ 2 more PhD holders to come in 2021 and another 2 in 2022/23

→ direct contribution to science and high education development in Ethiopia and East-Africa

How AGN research can contribute to development?



Great example of impact – IAUS 356
'Nuclear Activity in Galaxies Across Cosmic Time', Ethiopia, Oct 2019

- 3rd IAU symposium in Africa and I in East Africa over the past 100 years
- > 160 participants from > 30 countries
- Students and teachers trainings
- Astronomy in Africa lunch session
- NOAO data lab training, seminars
- Outreach activities with ~ 800 children and students
- 1st book of proceedings for Ethiopia

Credits pictures: A. Solomon, V. Oknyansky, C. Harrison, M. Pović

Thank you very much for your attention!

Background photo: Tanzania, Watoto Wa Africa children center, 2007. Credits: A. Marsal