BP4

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Annual Seminar

The era of low surface brightness galaxies

JUNAIS

Collaborators: K. Małek, H. Thuruthipilly, S. Boissier, A. Boselli, L. Ferrarese, P. Côté, S. Gwyn, J. Roediger, S. Lim, E.W. Peng, J.-C. Cuillandre, A. Longobardi, M. Fossati, G. Hensler, J. Koda, J. Bautista, M. Boquien, P. Amram, Y. Roehlly

16 December 2022

Outline

- **Introduction**
  - ➔ Importance of low surface brightness galaxies (LSBs)

- **LSB galaxies in the Virgo cluster**
  - ➔ A new sample of diffuse and ultra-diffuse galaxies in Virgo
  - ➔ Modelling the role of cluster environment in their evolution

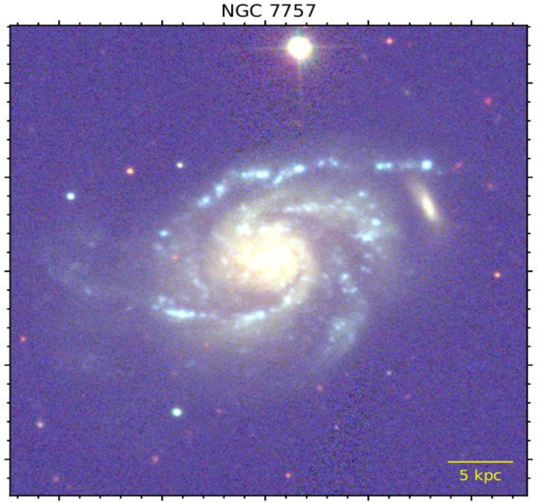
- **LSB galaxies in large sky surveys**
  - ➔ Discovery of thousands of new LSBs in the Dark energy survey

- **Conclusions**

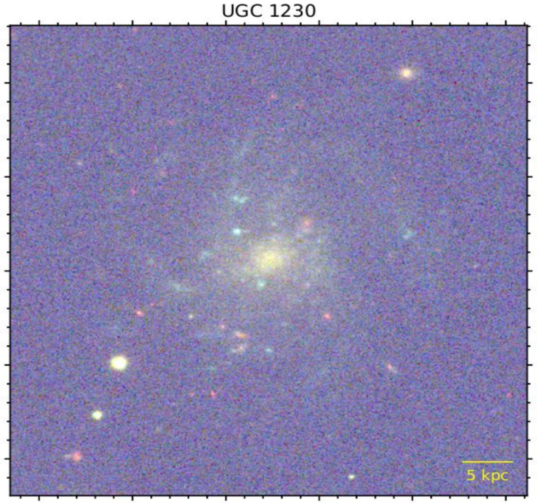
What is a Low surface brightness galaxy?

An example

Two galaxies which are about the same distance and size, but very different in their light.



High surface brightness galaxy (HSB)



Low surface brightness galaxy (LSB)

Low surface brightness galaxy

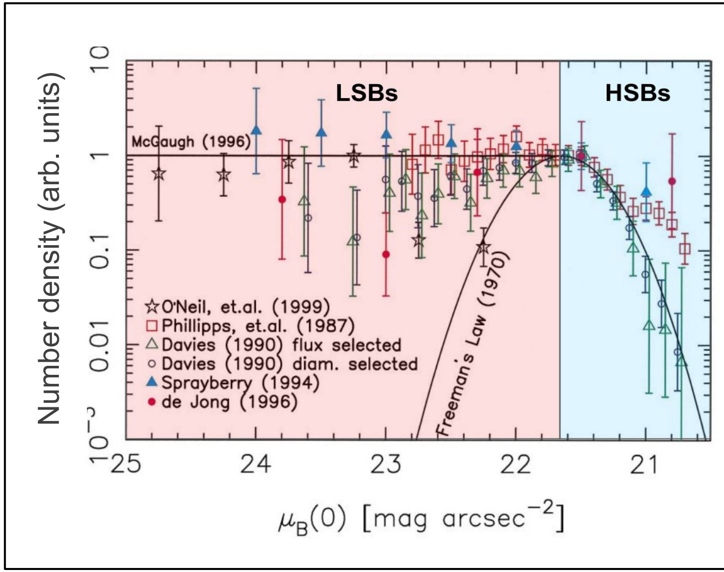
=

Galaxy that emit much less light per unit area than “normal” galaxies.

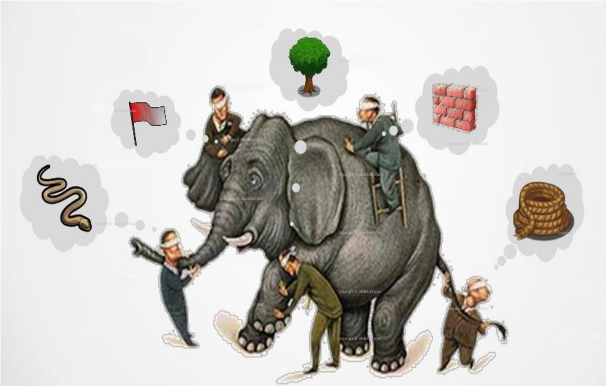
Image credit: McGaugh 2021

Why should we study LSBs?

- LSBs may account up to 50% (or more) of all the galaxies in the universe.
- They might redefine our knowledge of galaxy formation & evolution.
- Until now our limitations in technology did not allow us to observe them.
- A new interest in LSBs with recent powerful instruments (e.g. Dragonfly, Megacam, DECam)



O'Neil & Bothun (2000)

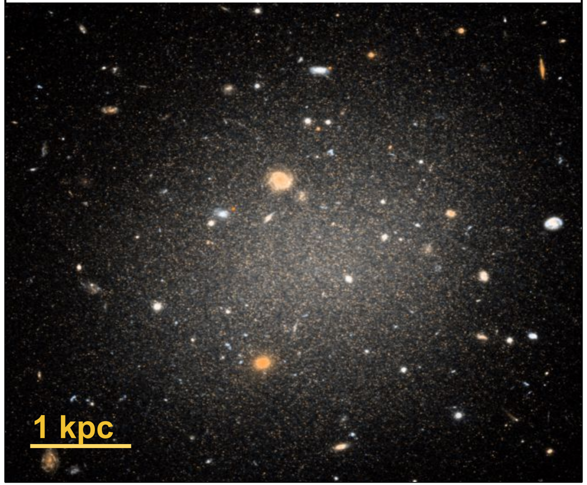


Our understanding of the universe should not be biased by HSBs

Interest for Ultra-diffuse galaxies

- UDGs are as large as Milky Way in size, but with the mass of a dwarf galaxy.
- They attracted a lot of attention in recent years (e.g., van Dokkum et al. 2015; Koda et al. 2015; Román & Trujillo 2017; Prole et al. 2019, Lim et al. 2020).
- UDGs are found in large numbers in galaxy clusters, but also in groups and field.

Example of a UDG: NGC 1052-DF2



- Several debated formation scenarios for UDGs:
  - ➔ Failed Milky Way like galaxies (van Dokkum et al. 2015)
  - ➔ Puffed-up dwarf galaxies (Di Cintio et al. 2017)
  - ➔ High initial angular momentum spin (Amorisco & Loeb 2016)

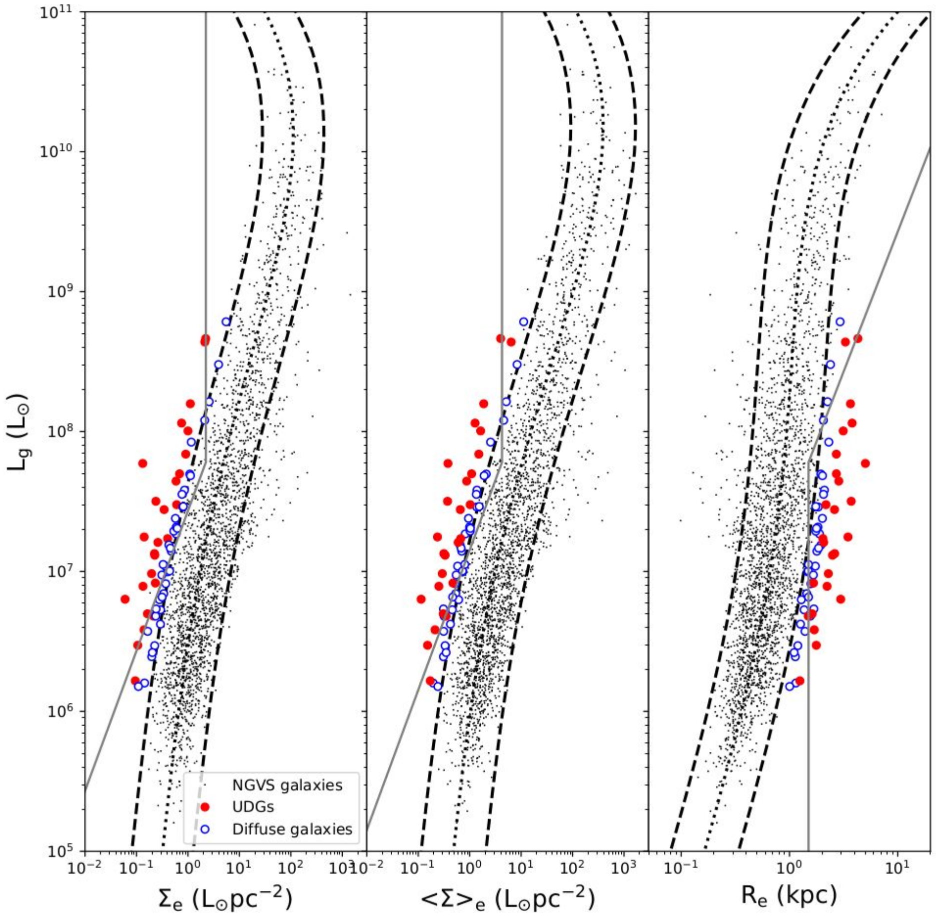
Image credit: Shen et al. 2021

A new sample of UDGs and diffuse galaxies in the Virgo cluster

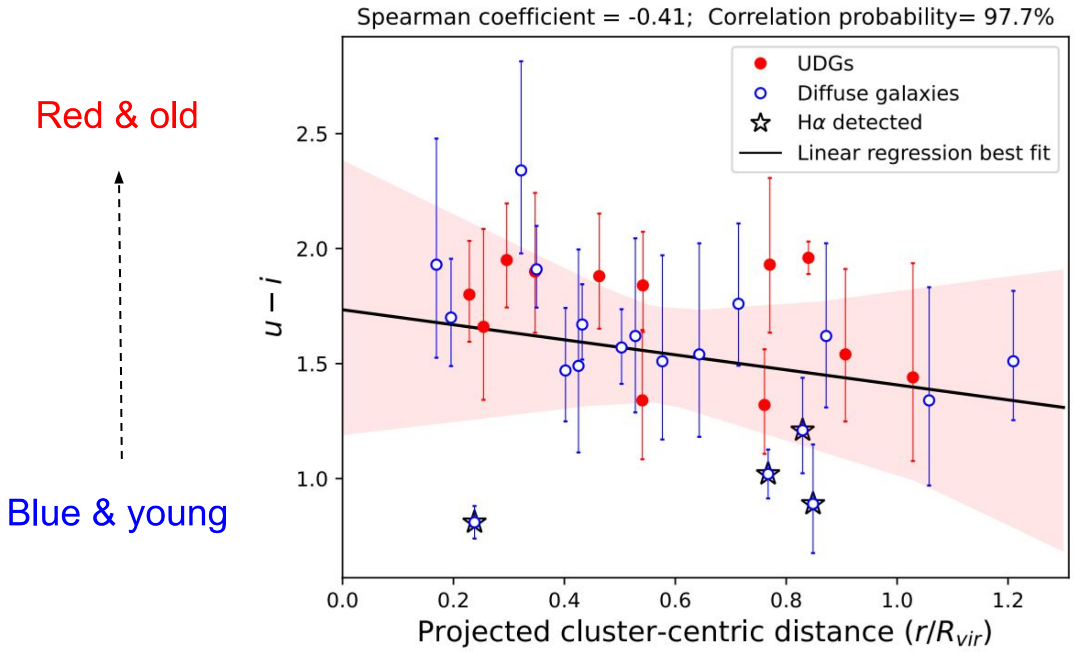
Junais et al. 2022

- Virgo cluster is an ideal location for UDG studies
- Used the NGVS catalogue with ~3700 galaxies (following Lim et al. 2020)
- 64 LSBs selected as outliers from the mean distribution
  - ➔ 26 UDGs (>2.5σ)
  - ➔ 38 Diffuse galaxies (within 2 and 2.5σ)

- Data in 8 wavelengths (FUV, NUV, u, g, r, i, z, Hα) from GUViCS, NGVS and VESTIGE
- Measured multi-wavelength surface brightness profiles and colors



Color variation with the cluster centric distance



- Galaxies at the edge of the cluster are bluer
- Few of these blue galaxies have counterparts HI and Hα
- Possible influence from the cluster environment in their evolution

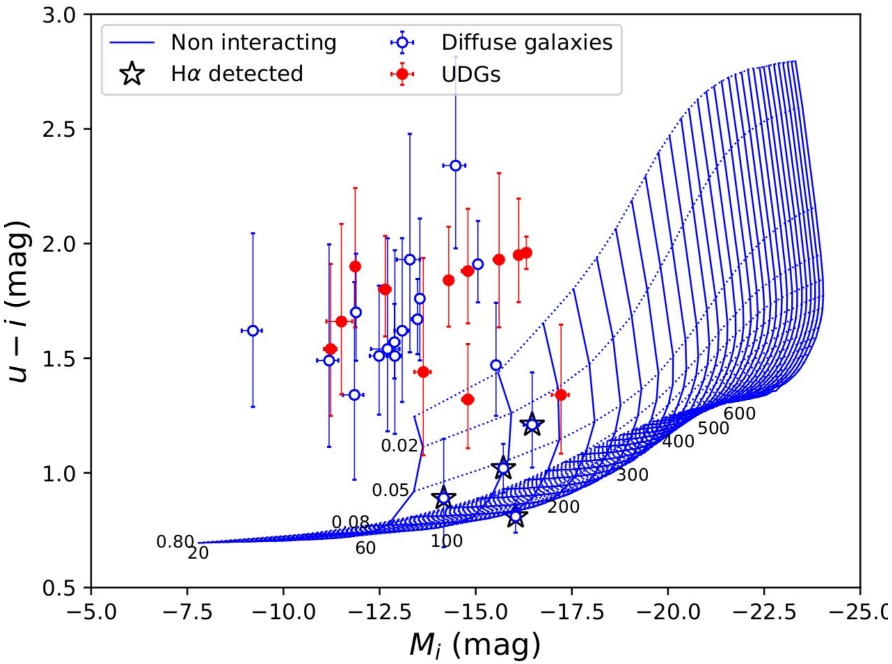
Modelling the environmental interaction

- Galaxy clusters generally have a lot of hot gas within them
- This results in the effect of ***ram pressure stripping*** (RPS)
    - A galaxy moving fast through the cluster experience a pressure which strips off its gas content
- We tested the effect of RPS in our LSB galaxies using a set of models (Boissier & Prantzos 2000)

RPS is similar to hair flying away during a fast bike ride

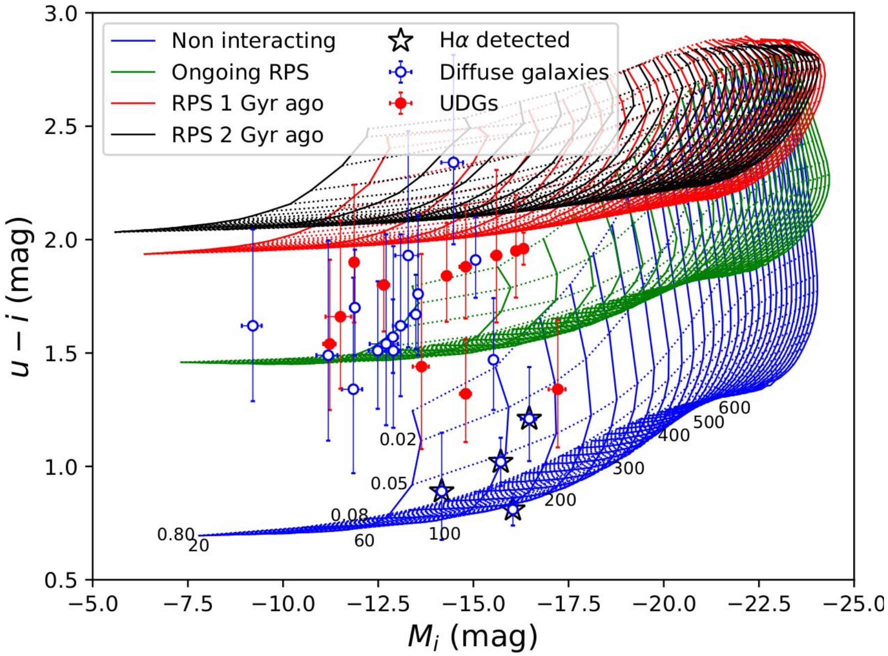
Ram pressure stripping in a Virgo cluster spiral galaxy NGC 4569 (Boselli et al. 2016)

Color-Magnitude Diagram: Observation and Models



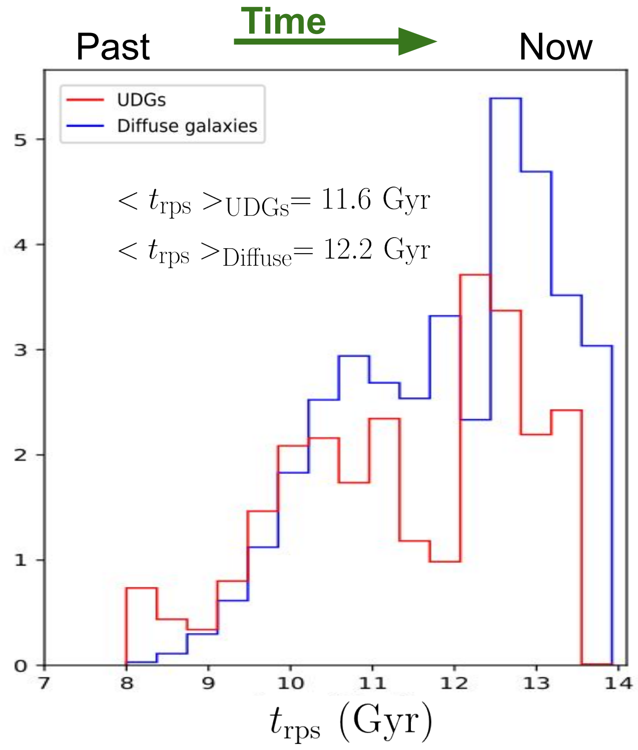
- Blue grid corresponds to model colors of non-interacting galaxies
- Observed redder colors of low mass galaxies cannot be reproduced by the non-interacting models

Color-Magnitude Diagram: Observation and Models



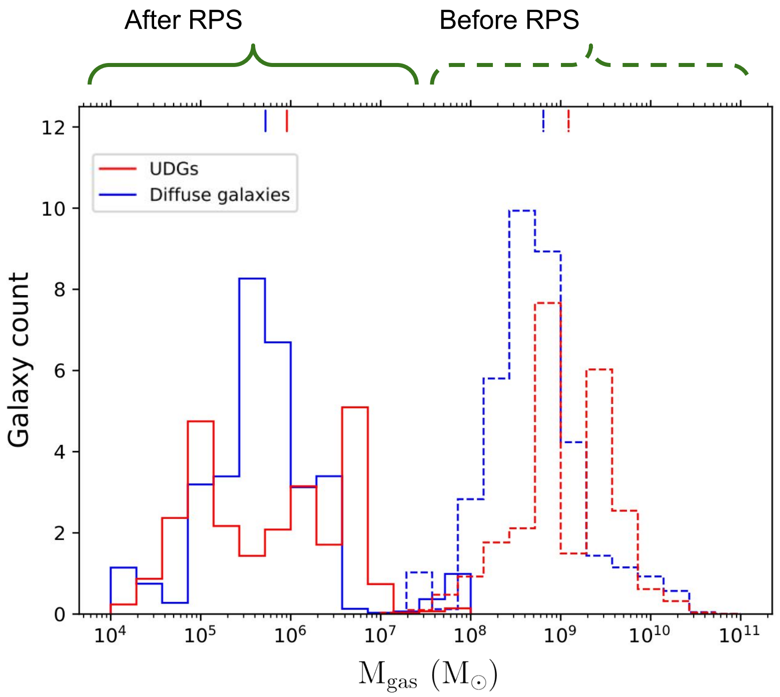
- A quenching event like ram-pressure stripping can easily reproduce the redder colors
- We fitted the observed profiles of our sample to estimate the time of the stripping

Time of experiencing ram pressure stripping



- Almost all sources experienced RPS events (average 1.6 Gyr ago and some with ongoing RPS)
- UDGs are slightly more massive, extended and experienced RPS at earlier times

Evolution of the gas mass of the galaxies

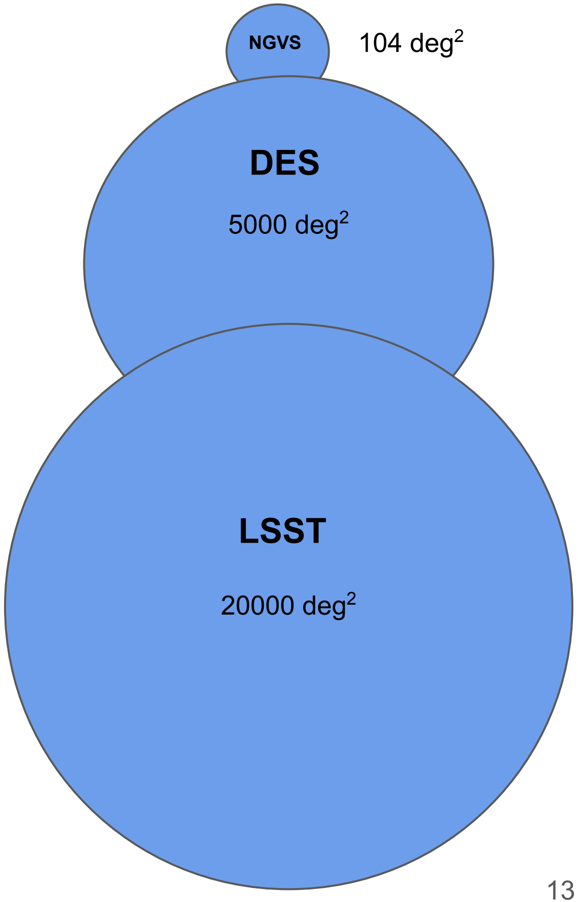


- RPS completely transformed initially gas rich (M_{HI}~$10^9 M_\odot$) LSBs to gas poor (M_{HI}~$10^6 M_\odot$) sources
- Both the UDGs and diffuse galaxies show similar trend.
- Ram-pressure stripping could be the major mechanism for quiescent UDG formation in clusters

Search for LSB galaxies in large sky surveys

- We have a lot of current and upcoming very deep surveys covering large part of the sky
  - Virgo cluster survey (NGVS) ~ 100 deg^2
  - Dark Energy Survey (DES) ~ 5000 deg^2
  - Legacy Survey of Space and Time (LSST) ~ 20000 deg^2

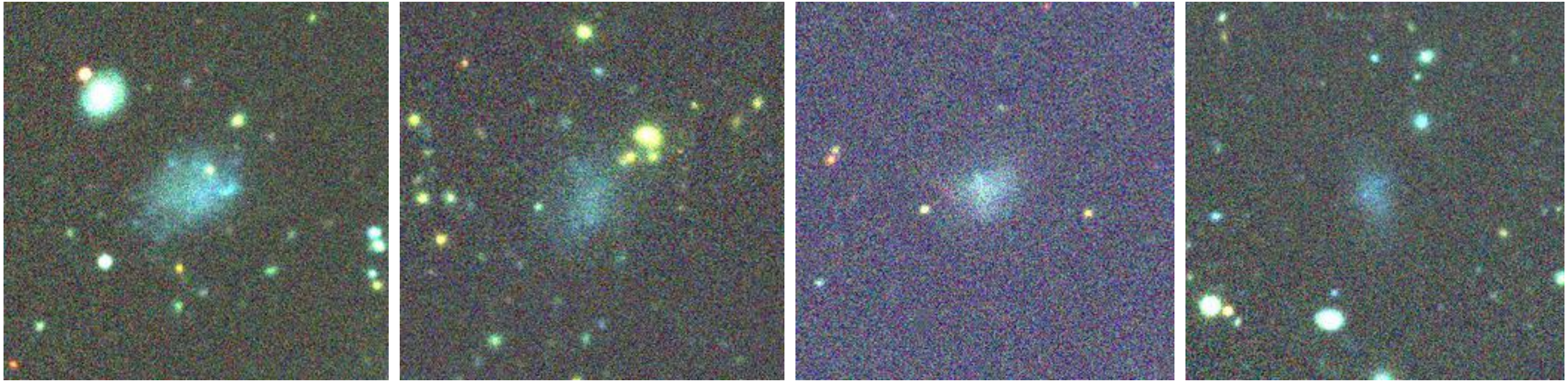
- Thousands of LSB galaxies will be detected by them
- Towards this direction, we used the DES data to search for new LSBs
- We have to use Machine learning (ML) techniques to search in such a large set of data



Discovery of thousands of new LSBs in DES

Thuruthipilly et al. in prep.

- Used a combination of CNN and Transformer based ML models
- Searched for LSB galaxies in the complete 5000 deg^2 area covered by DES
- Models have about 95% accuracy in detecting LSBs
- About **5000 new LSBs discovered**, apart from the already known ones in DES.

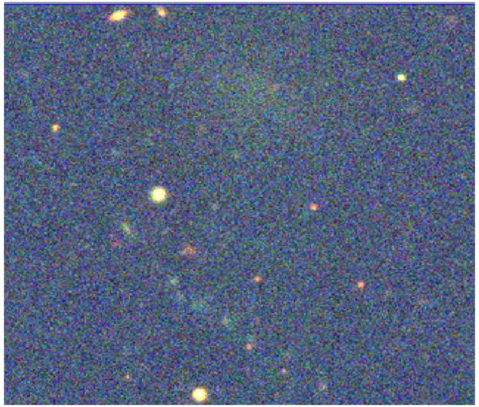


Few examples of the discovered LSBs

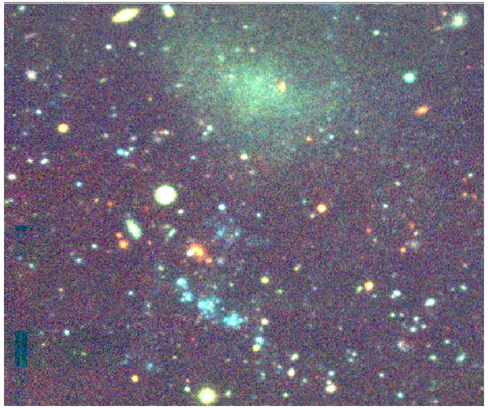
Conclusions

- Low surface brightness galaxies constitute a large fraction of all the galaxies in the universe, but their actual number and formation is still debated
- Ram-pressure stripping could be a major mechanism for quiescent LSB formation in clusters
- We observed thousands of new LSBs in DES
- Upcoming surveys like LSST will increase this number much more and shed more light on the nature of LSB galaxies.

SDSS



NGVS



LSST

?

We might be missing thousands of objects like this !!

Thank you

Extra slides

Let's look at the sky for a moment

Sky seen by the eye

Sky seen through a telescope

Image credit: Hubble Ultra Deep Field

- Previously unknown/unseen objects: revolutionized our knowledge of the universe.
- **Low surface brightness galaxies** are one among them.

Note: These images are only for illustration. They are not at the same part of the sky and scale.

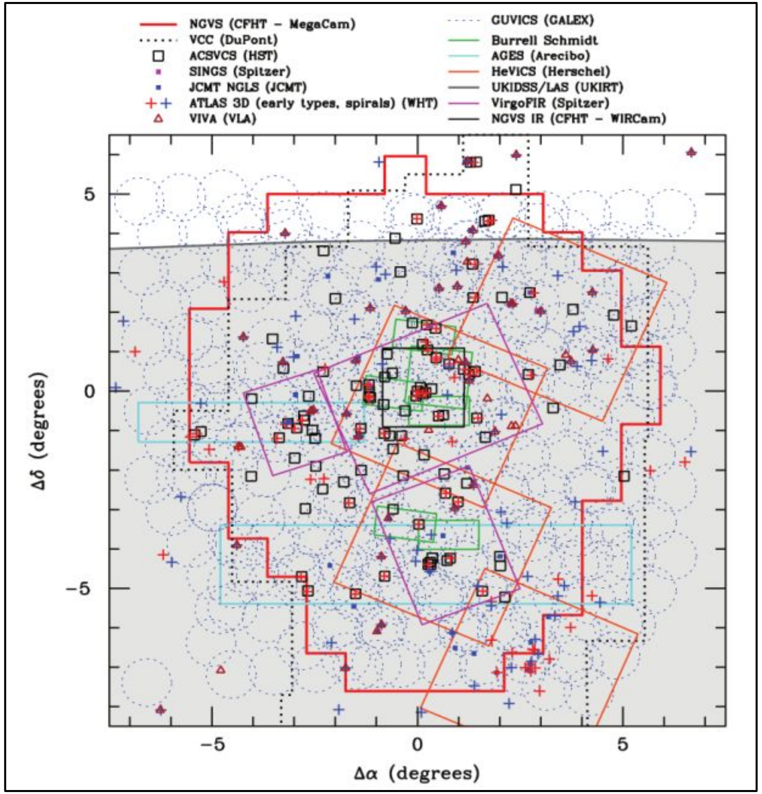
An ideal location for UDG studies: Virgo galaxy cluster

- Virgo is the most close-by (16.5 Mpc) and rich cluster of galaxies.

- A prime candidate for deep and blind surveys

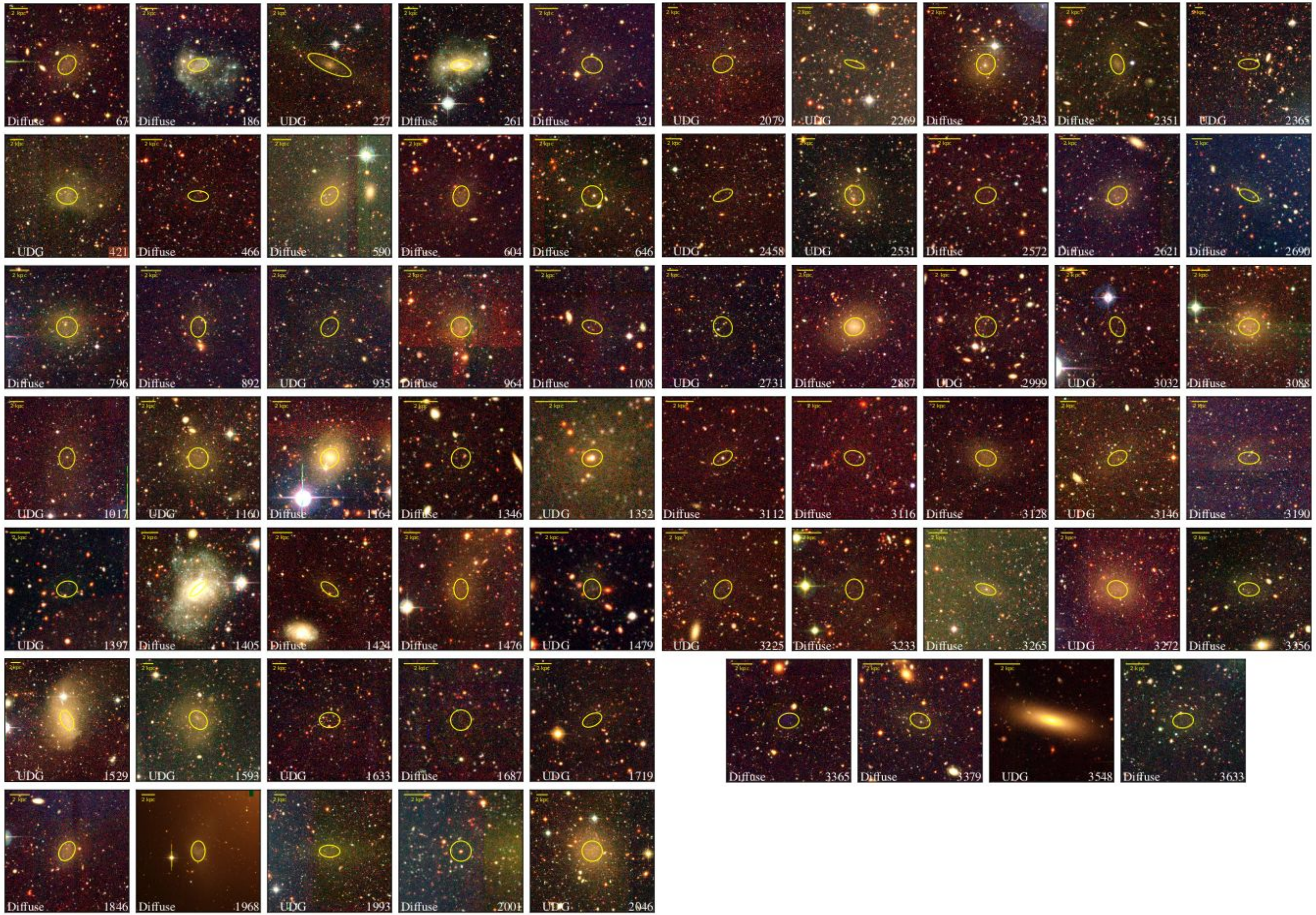
- Large amount of multi-wavelength data available:
  GUViCS (Boselli et al. 2011) → UV
  NGVS (Ferrarese et al. 2012) → Optical
  VESTIGE (Boselli et al. 2018) → Hα narrow-band
  ALFALFA (Haynes et al. 2018) → HI

- With all this data we can study UDGs in great detail.

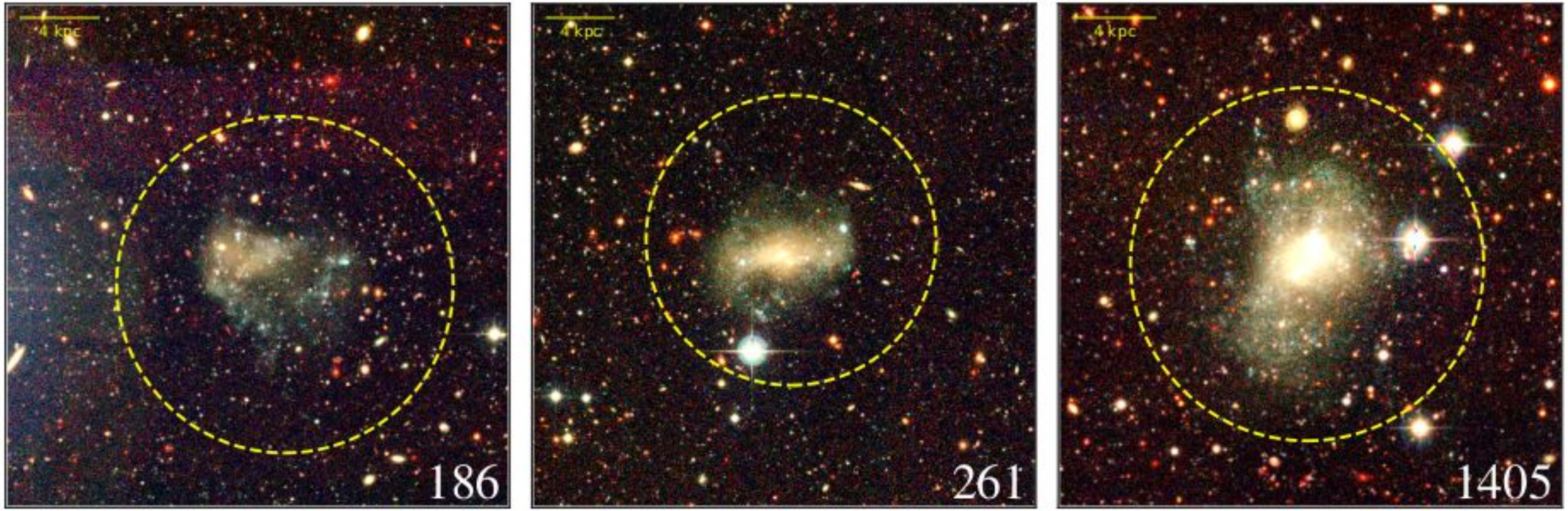


Ferrarese et al. 2012

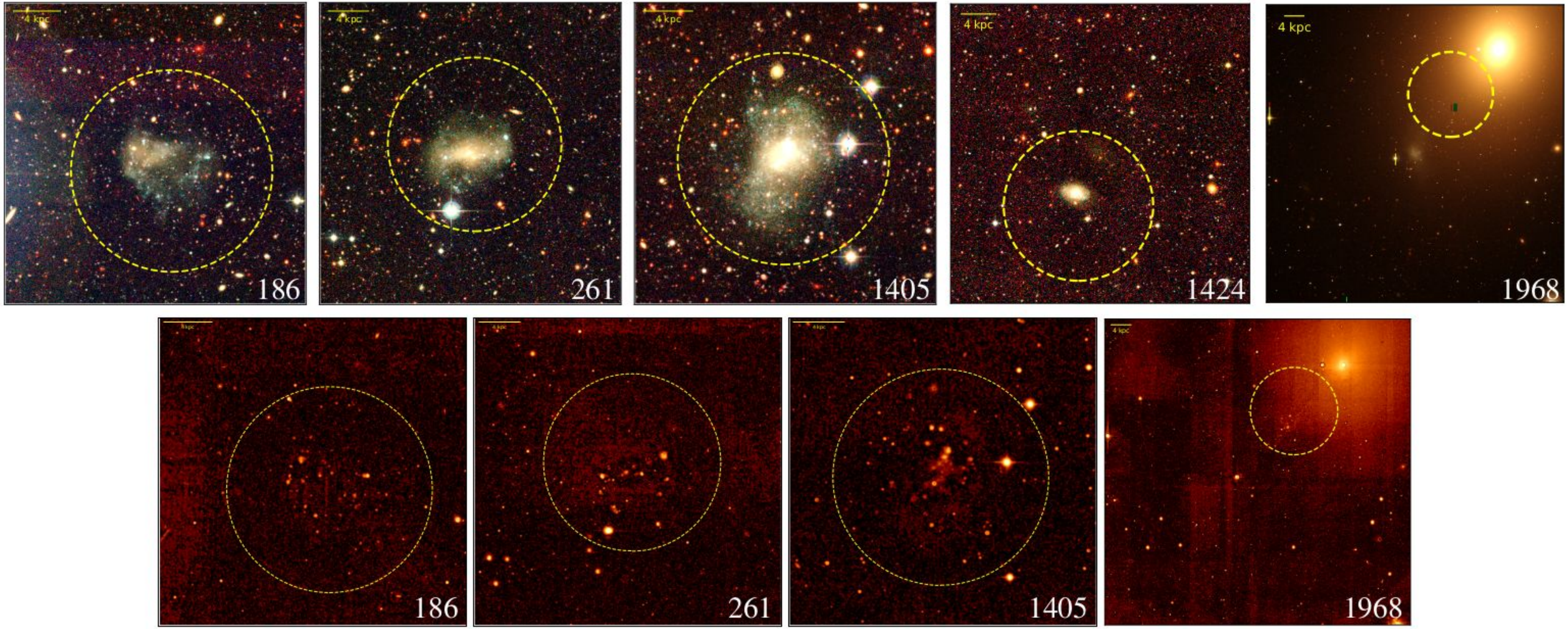
Optical cutouts of the sample



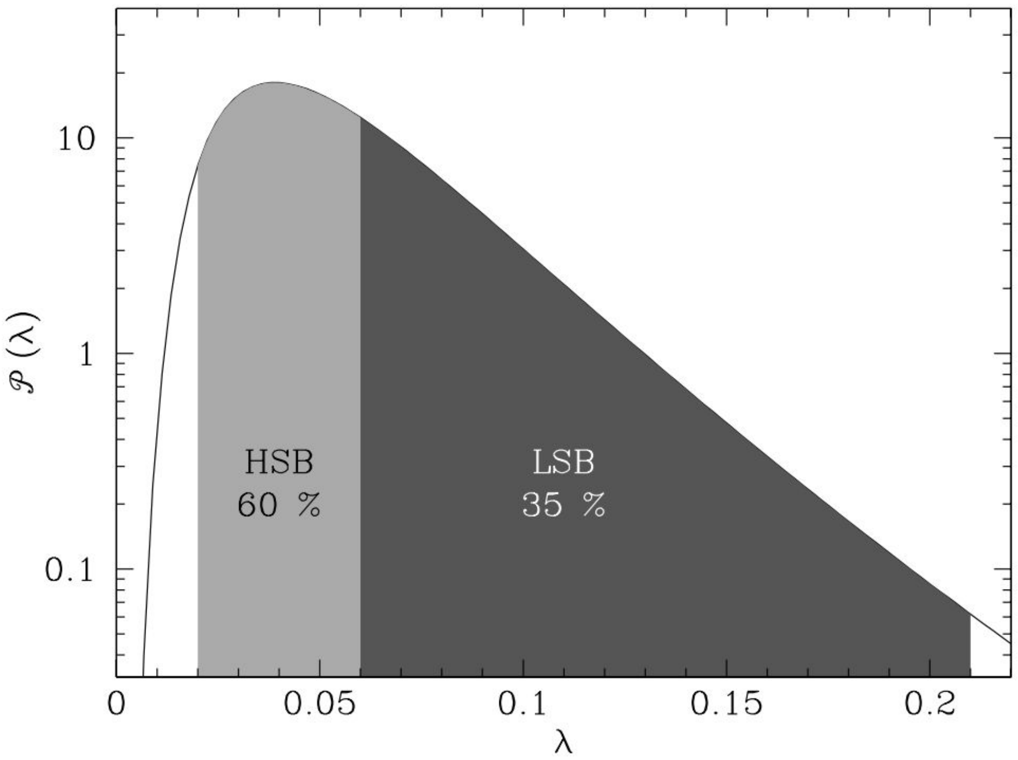
Hα detected galaxies



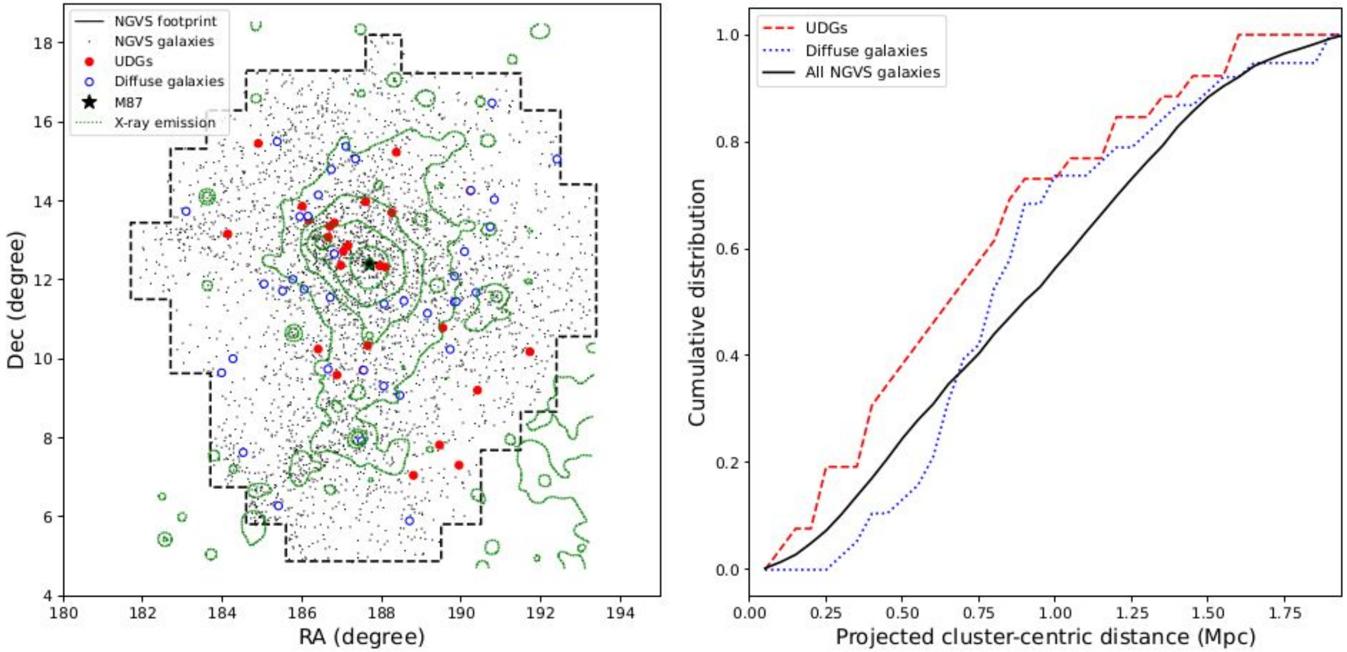
HI and Halpha detected sub-sample



Spin Distribution
(Boissier et al. 2003)

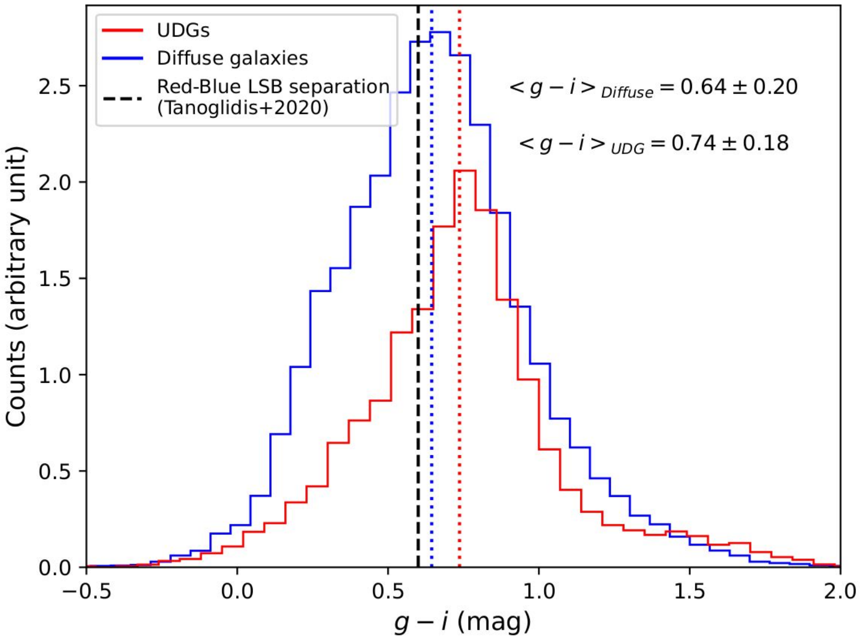


Spatial distribution within the cluster



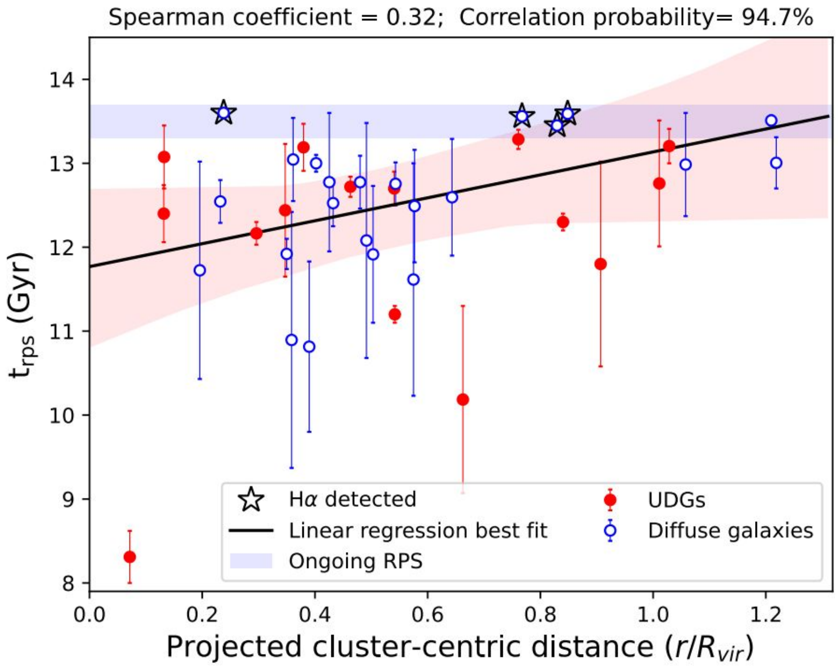
- Both UDGs and diffuse galaxies are found at all cluster-centric distances.
- Cumulative distribution shows UDGs are more centrally located, whereas diffuse galaxies favour cluster outskirts

Optical color distribution



- Predominantly a red LSB population (mean g-i > 0.6 mag), consistent with what found in clusters
- Diffuse galaxies are slightly bluer than the UDGs

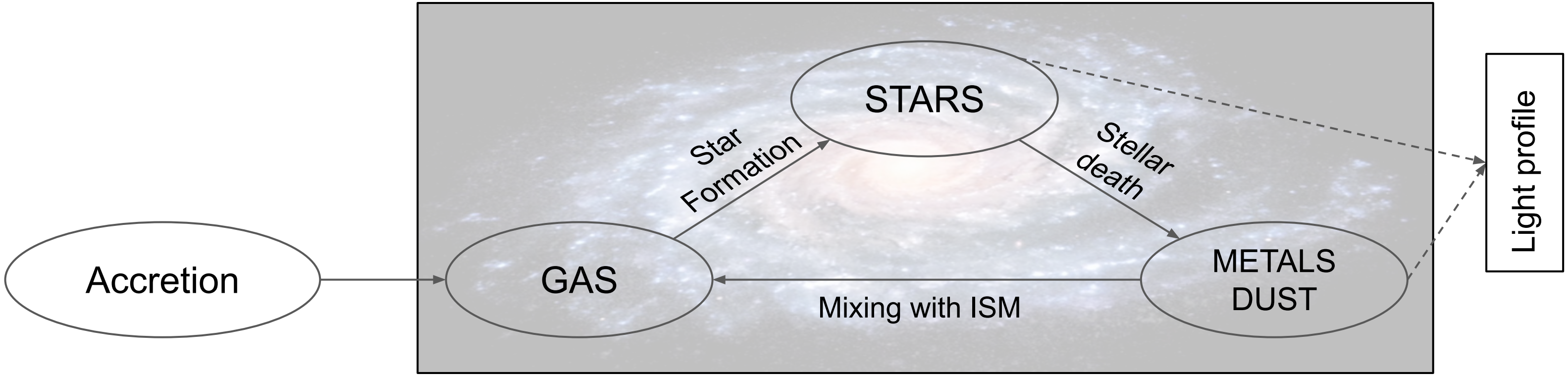
Variation of ram-pressure with cluster-centric distance



- An indication of gradient in ram-pressure stripping time with the distance from cluster center
- Galaxies towards the edge of the cluster (> 1 Mpc) have recent RPS events.
- Similar to the color gradient observed with distance.

Chemo-spectrophotometric galaxy evolution model

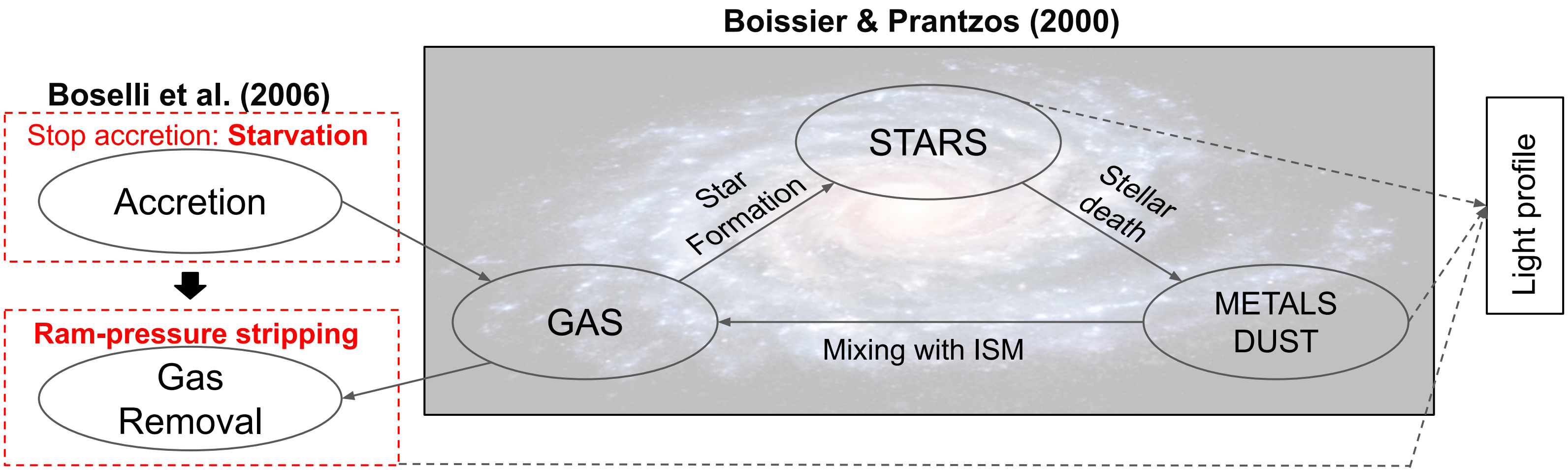
Boissier & Prantzos (2000)



- Models a disc galaxy formed from a halo of mass given by the CDM models of Mo et al (1998).
- To form a galaxy, gas is accreted at a rate exponentially varying with time.
- SFR - Rotation modulated Schmidt law (Boissier et al. 2003) $\rightarrow SFR \propto \Sigma_{\rm gas}^{1.5} V_{\rm C}$
- Calibrated on Milky Way: 2 free parameters $\mathbf{V_C}$ (circular velocity) and **λ** (spin parameter)

$\mathbf{V_C}$	$\rightarrow$	Gives the mass of the galaxy
λ	$\rightarrow$	Gives the mass distribution of the galaxy

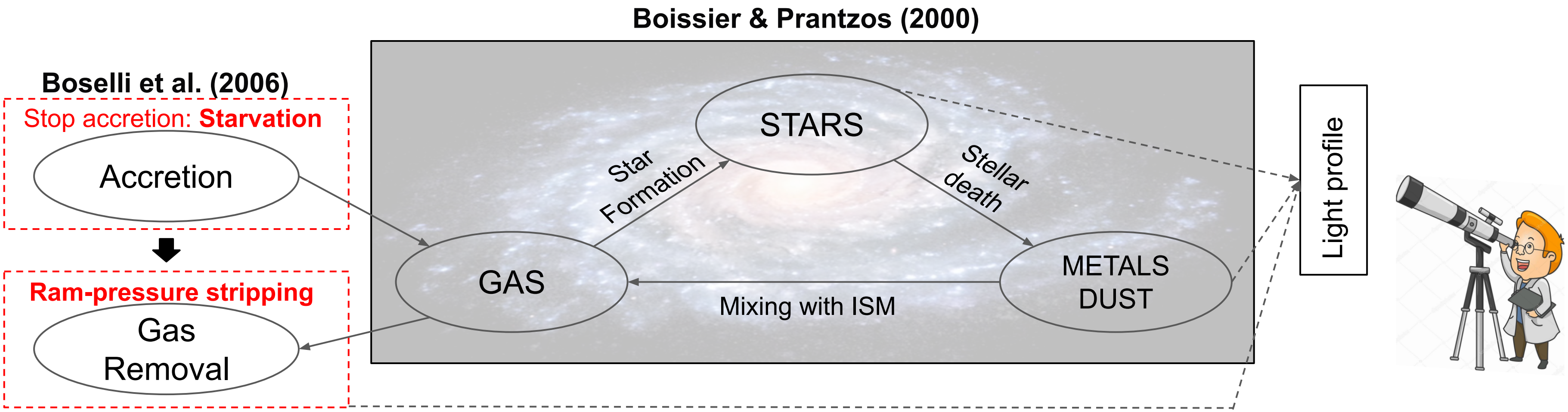
Modelling the environmental interaction



Hair flying away during a fast bike ride

Ram pressure stripping in a Virgo cluster spiral galaxy NGC 4569 (Boselli et al. 2016)

Modelling the environmental interaction



- Ram-pressure stripping (RPS) is modelled with a Gaussian peaking at time t_{rps} (Vollmer et al. 2001)

Total 3 free parameters now in the model: V_C, λ, t_{rps}

- Made a large grid of models → Obtained light profiles, colors other model predictions