XLI Meeting of Polish Astronomical Society

Exploring the dust content of low surface brightness galaxies: Implications for the LSST survey

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Outline

- **Introduction**
  - ➔ Quick overview of LSST
  - ➔ Role of dust and attenuation in galaxies
  - ➔ Low surface brightness galaxies (LSBs) and dust
- **LSB galaxies in the NEP field**
  - ➔ Multi-wavelength SED modelling
  - ➔ Stellar and dust properties as a function of surface brightness
- **Conclusions**

Legacy Survey of Space and Time (LSST)

- Upcoming Vera Rubin Observatory in Chile
- 8.4 meter diameter primary mirror
- Observes a large area of the sky (~18000 deg^2) in the optical *ugrizy* bands
- Image the full sky every 3 nights
- Deepest optical large sky survey in 10 years (5σ depth of 27.5 mag in *r*-band)

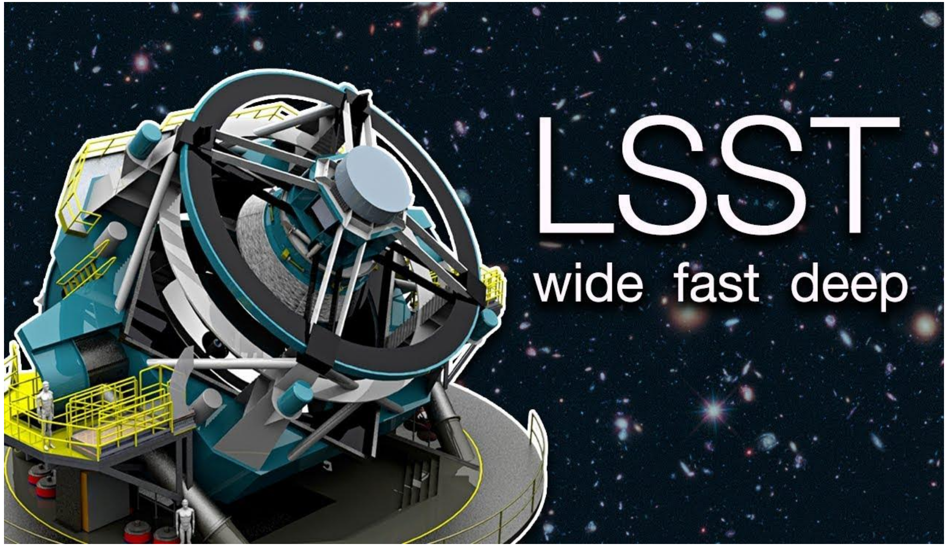
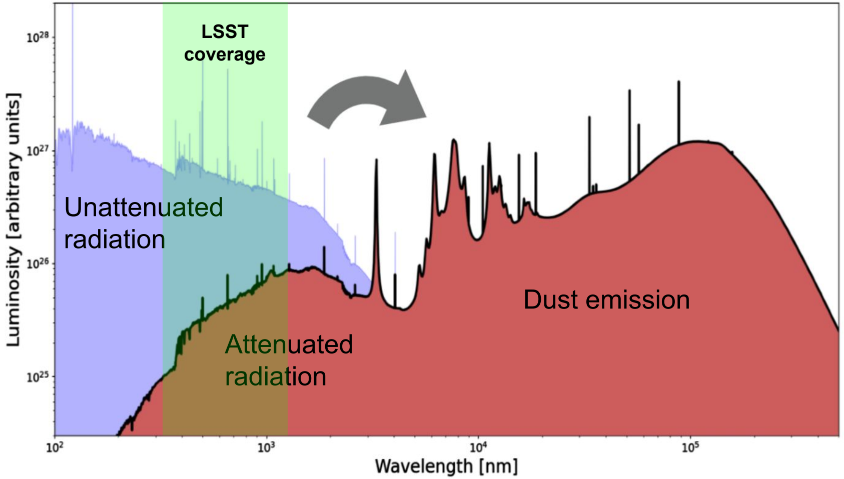


Image credit: Launch Pad Astronomy

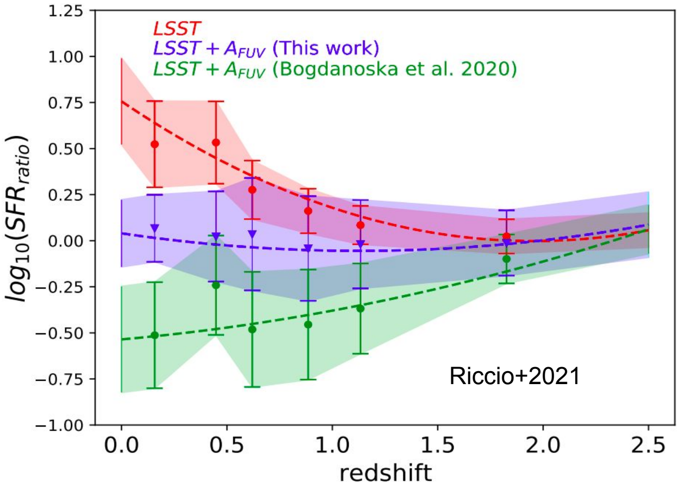
Role of dust in galaxies

- Dust is a key component in a galaxy's evolution (important in the cycle of star formation)
- Affects the observations, especially at shorter wavelengths - known as *attenuation*
- Attenuation is a crucial quantity to consider while estimating galaxy properties
- Using LSST data alone, without a prior on attenuation, overestimates the SFR by ~1 dex (Riccio+2021)

Dust attenuation of an SED



Credit: Mahmoud Hamed

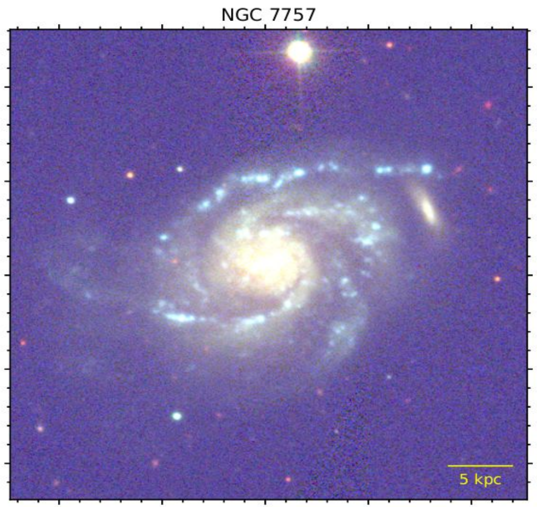


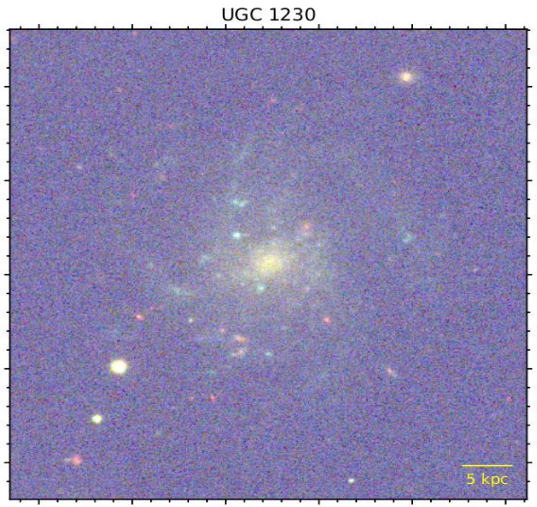
What is a Low surface brightness galaxy?

An example

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

HSB Galaxy





LSB Galaxy

Low surface brightness galaxy

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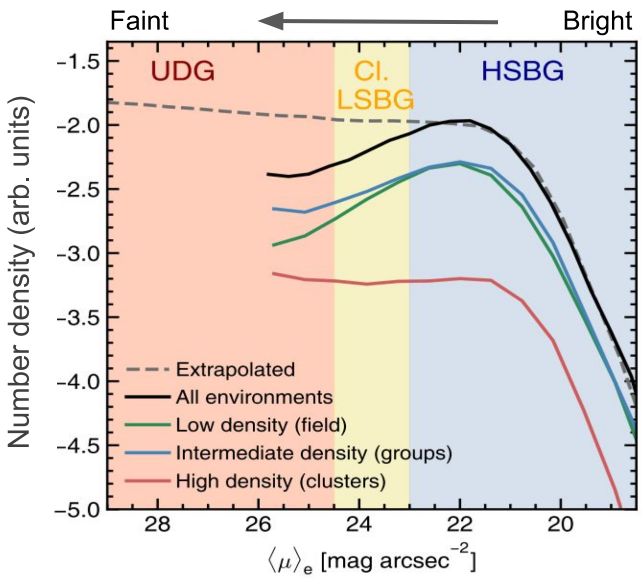
Galaxy that emit much less light per unit area than "normal" galaxies.

Image credit: McGaugh 2021

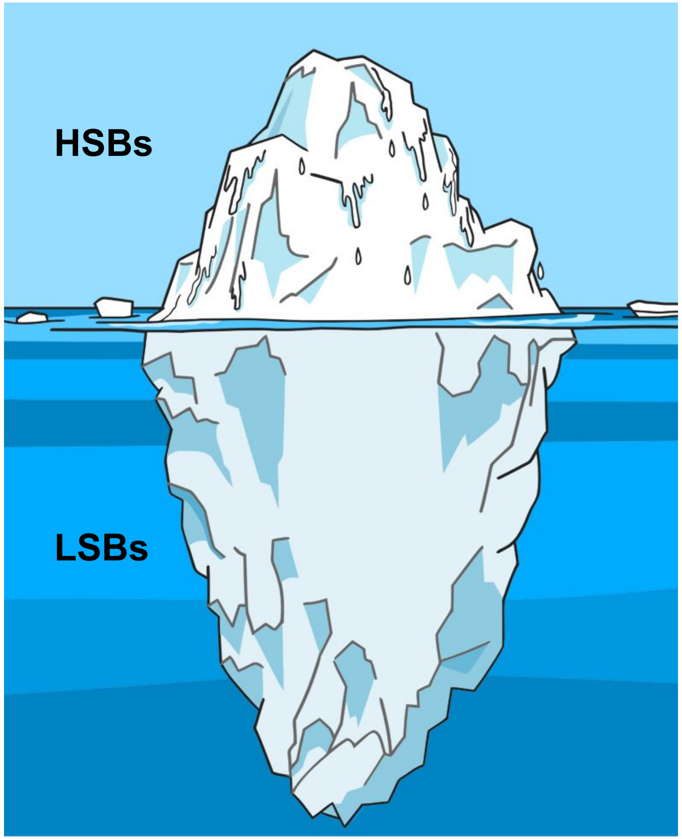
Importance of LSB galaxies

- LSBs generally defined as galaxies with average surface brightness $\mu_{e,r} > 23$ mag arcsec^{-2}
- LSBs may account up to 50% (or more) of the galaxy population (Martin+2019).
- Only limited studies on LSBs due to their faintness
- Vast discovery space for LSBs with LSST



Martin+2019

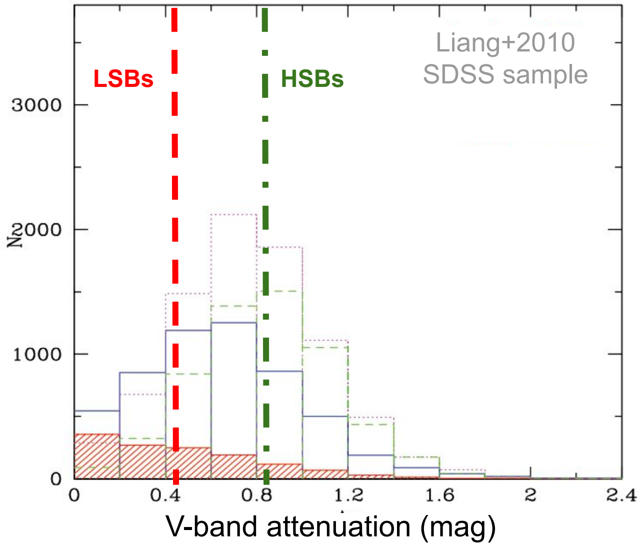
Galaxy population

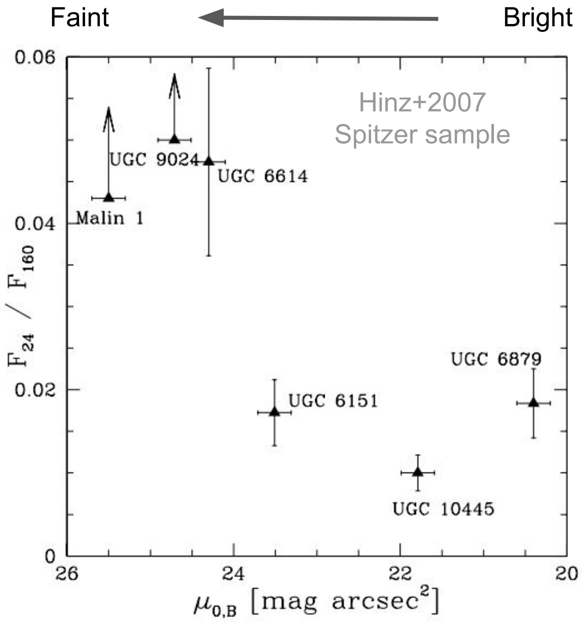


openclipart.org

Dust content of LSBs

- LSBs are generally considered to be "dust poor" (Liang+16; Hinz+07; Rahman+07)
- Mostly undetected in IR wavelengths
- Studies only based on either small samples or shallow data
- Need to study attenuation as a function of surface brightness





A large sample of LSBs and HSBs with deep data: NEP field

Junais et al., A&A, 676, A41 (2023)

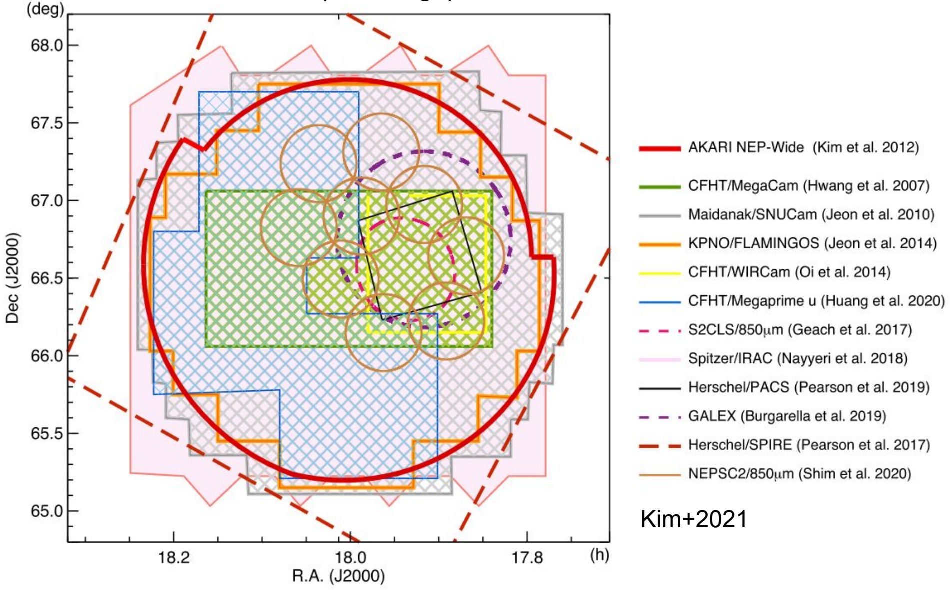
- The North Ecliptic Pole (NEP) wide field contains a large set of deep multi-wavelength data
- NEP optical bands (*ugrizy*) are close to the 10 year LSST depth

  ugrizy (5σ)*:* 25.4, 28.6, 27.3, 26.7, 26.0, 25.6 mag

- Sample selection:
  - HSC+Megacam ***ugrizy* detected** sources
  - ***z* < 0.1** (photo-z from Huang+2020)
  - **1631** galaxies (1003 LSBs, 628 HSBs)

- First time to perform a large statistical study of dust in LSBs

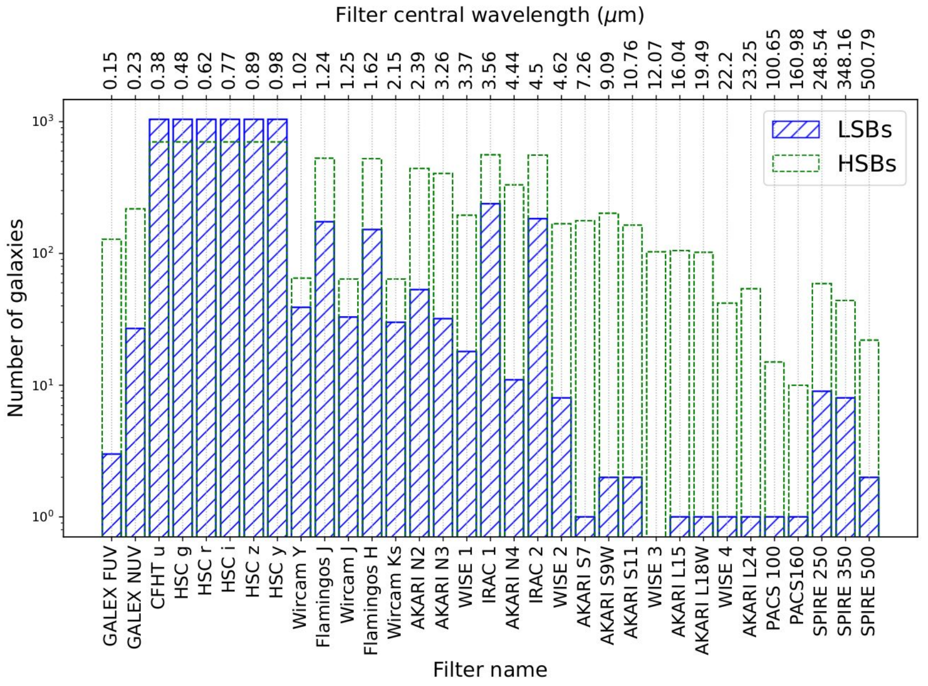
NEP Wide (5.4 deg^2)



Kim+2021

Crossmatch with multi-wavelength data

- Compiled multi-wavelength counterparts for the sample (33 filters):
    - GALEX (FUV, NUV)
    - CFHT (*u, Y, J*)
    - HSC (*grizy*)
    - KPNO/FLAMINGOS (*J, H*)
    - AKARI (2-24 μm)
    - *Spitzer*/IRAC (3.5, 4.5 μm)
    - WISE (3-22 μm)
    - *Herschel/*PACS (100, 160 μm)
    - *Herschel/*SPIRE (250, 350, 500 μm)

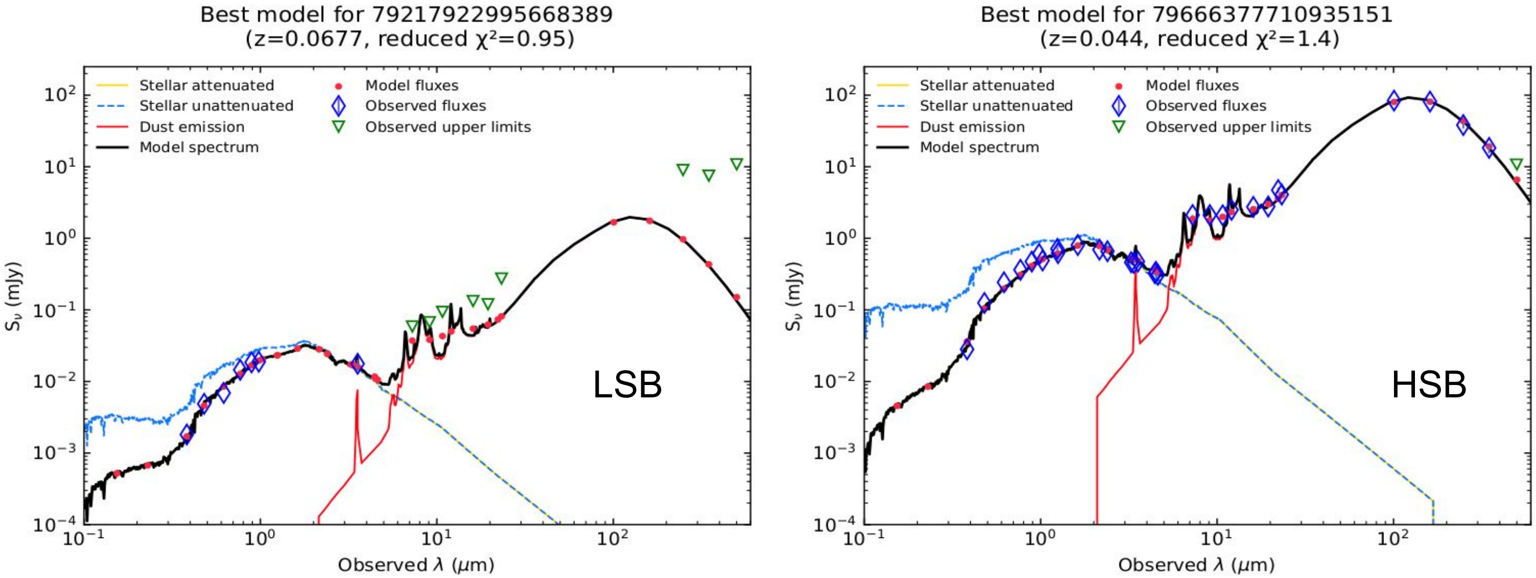


Junais+2023

- A large fraction of LSBs do not have MIR/FIR detections -> we use upper limits to constrain range

Spectral energy distribution fitting

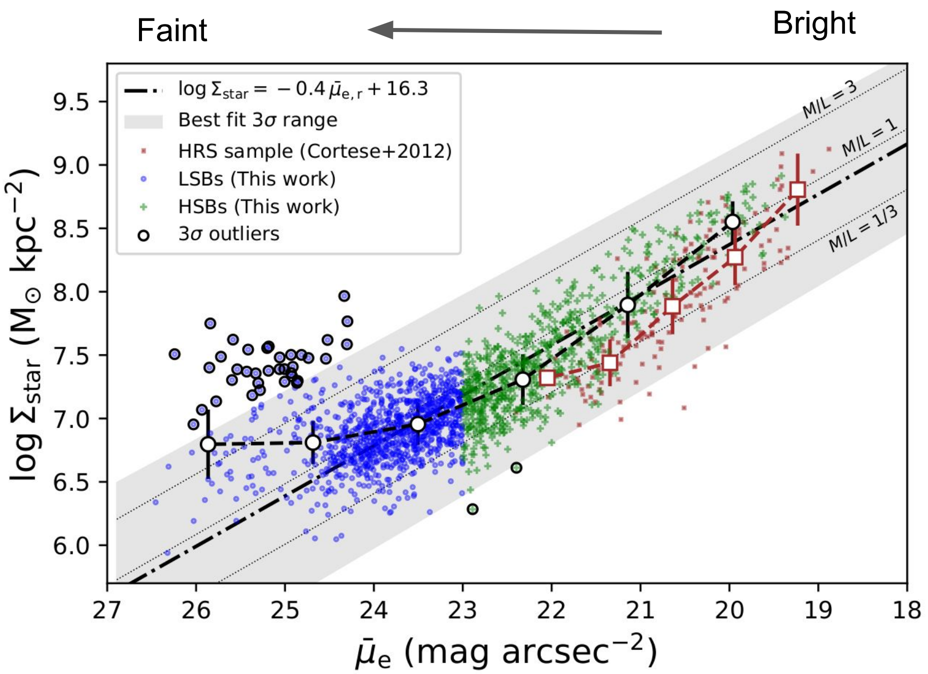
- Used the CIGALE SED fitting tool (Boquien+2019)
- Works with energy balance: UV radiation absorbed by dust is re-emitted in IR
- Used 5σ upper limits for non-detection in IR -> crucial for LSBs
- Assumed BC03 SSP, delayed star formation, Dale+2014 dust emission models
- Obtained M_{star} and A_V



Junais+2023

Surface brightness vs stellar mass surface density

- Surface brightness and stellar mass surface density (Σ_{star}) are related by mass-to-light ratio (M/L)
- We explored this relation for our sample.
- Mostly follow a linear trend, except at faintest end with a flattening in Σ_{star}
- About 40 galaxies are 3σ outliers ($M/L_r > 3$)
- Compared with HSBs from Herschel Reference Survey (HRS; Boselli+2010)

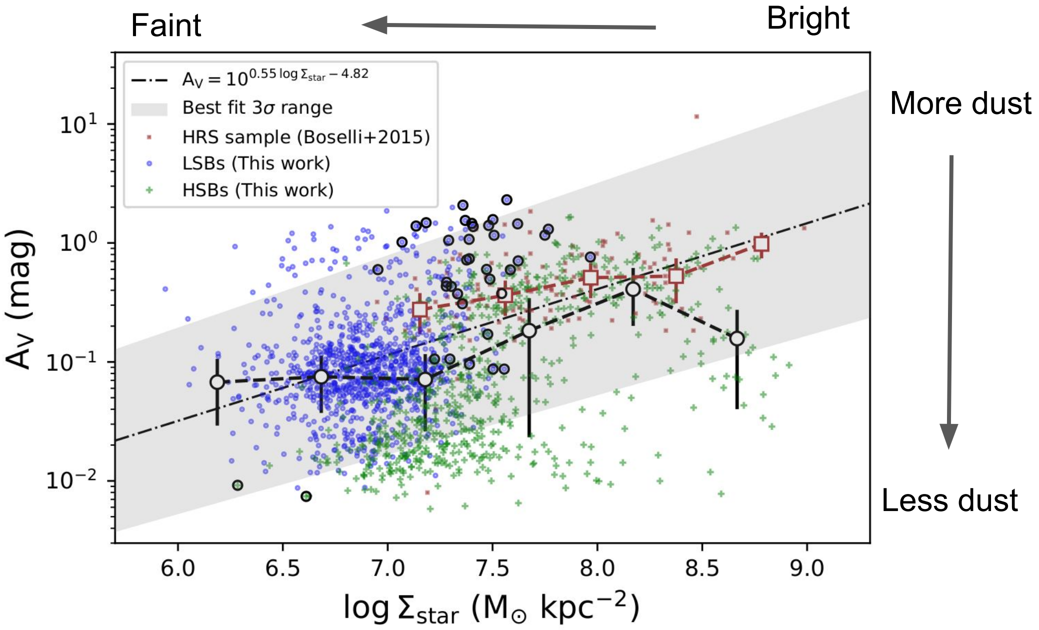


$$\Sigma_{star} = \frac{M_{star}}{2\pi R_e^2}$$

Junais et al. 2023

Attenuation vs surface brightness

- Attenuation steeply declines with stellar mass surface density, but with a large scatter
- Majority of the LSBs have a low attenuation ($A_V < 0.1$ mag)
- About 4% of them have significant attenuation (mean $A_V \sim 0.8$ mag)
- They are the 3σ outliers of $\mu_{e,r}$ - Σ_{star} relation
- Could be used as a method to identify dust-rich LSBs.



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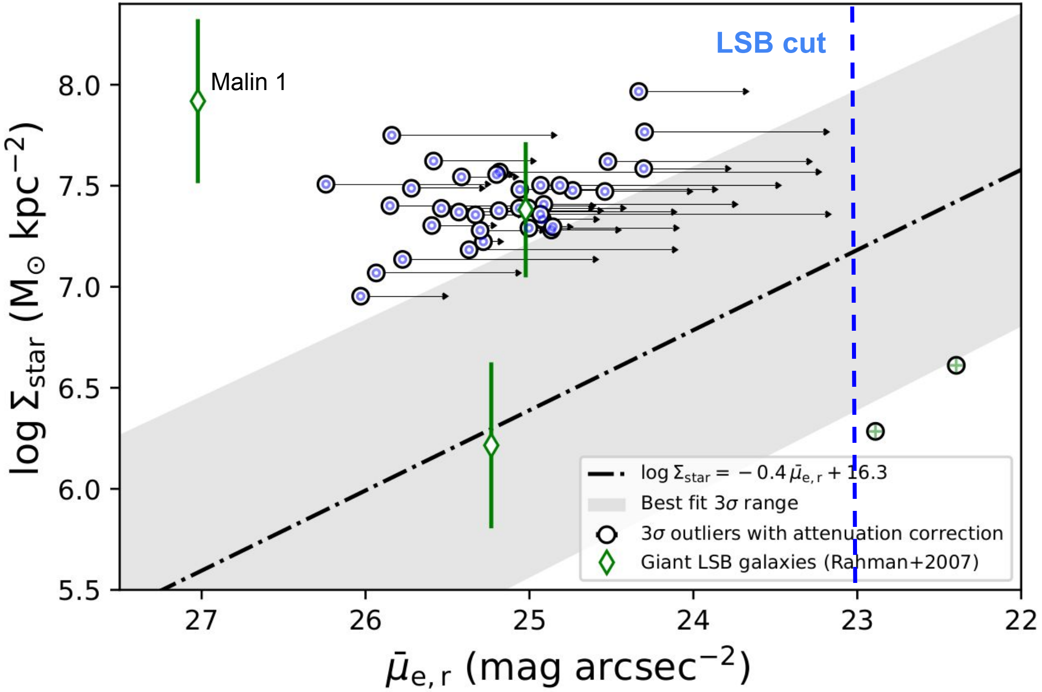
Outliers after correcting for attenuation

- All of them remain LSBs even after correcting the surface brightness for attenuation
- About 50% falls within the 3σ range after the correction
- Outliers have similarity with giant LSBs (e.g., Malin 1, UGC 6614)



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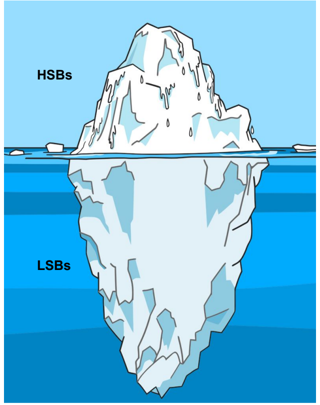
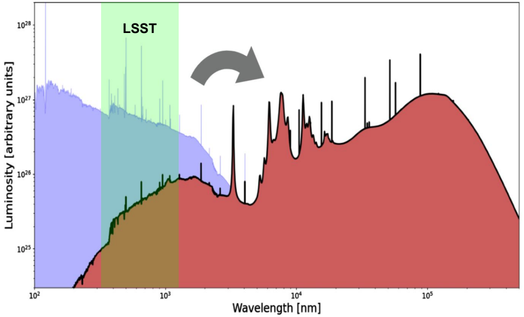
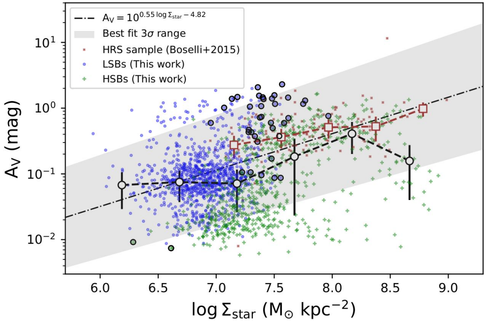
Conclusions

- Dust attenuation plays an important role in the observation of galaxies
- Low surface brightness galaxies have more varied dust content than previously thought
- About 4% of LSBs are dust-rich, making them fainter than their intrinsic value
- Upcoming LSST will observe thousands of LSBs - require proper estimation of attenuation
- Use the knowledge on LSBs from this work to analyse future observations



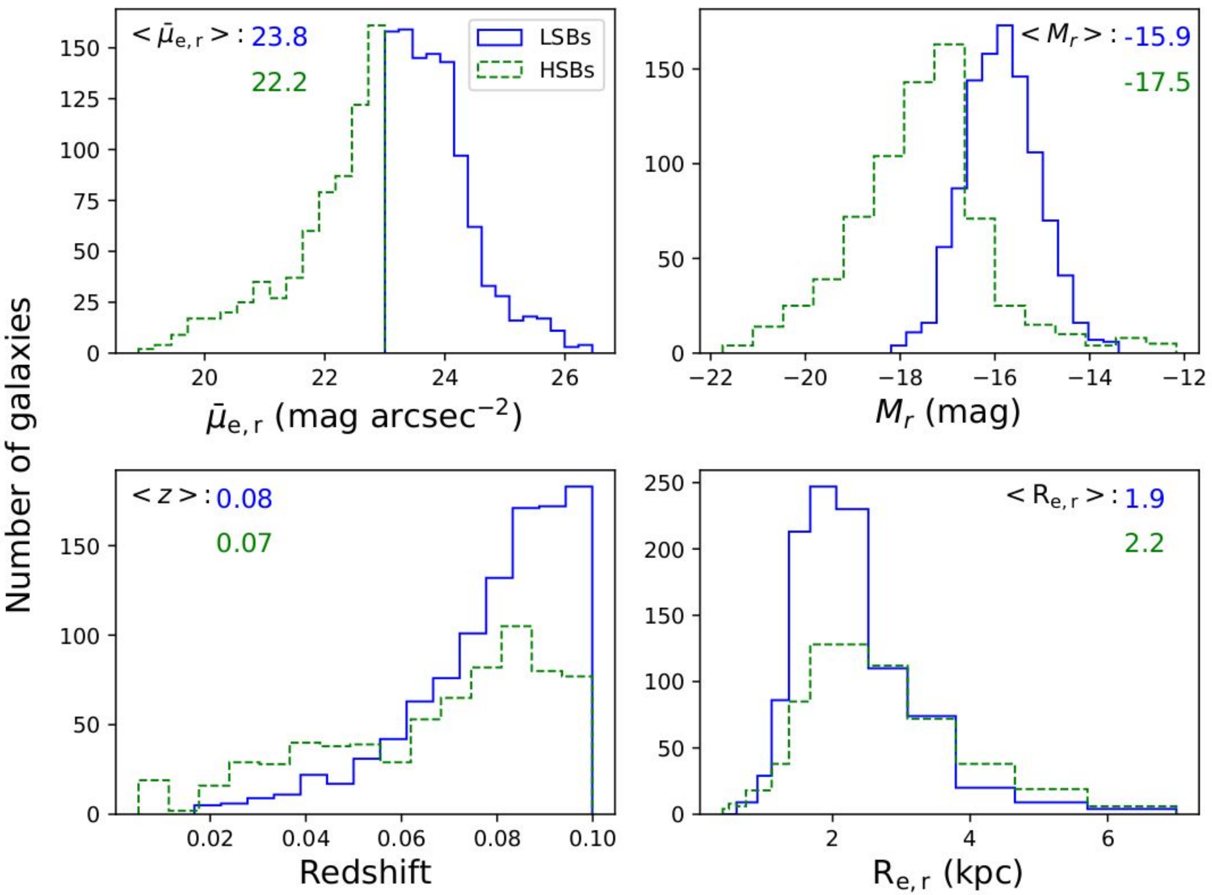




Thank you

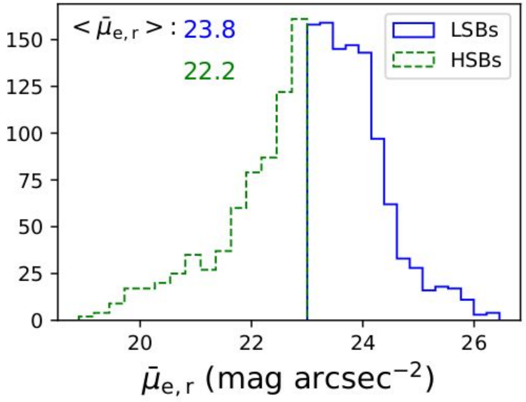
Extra slides

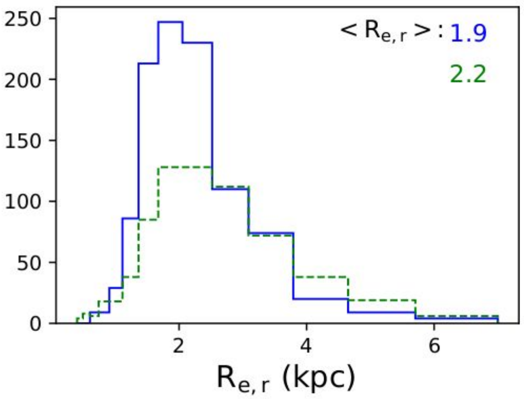
Basic parameters

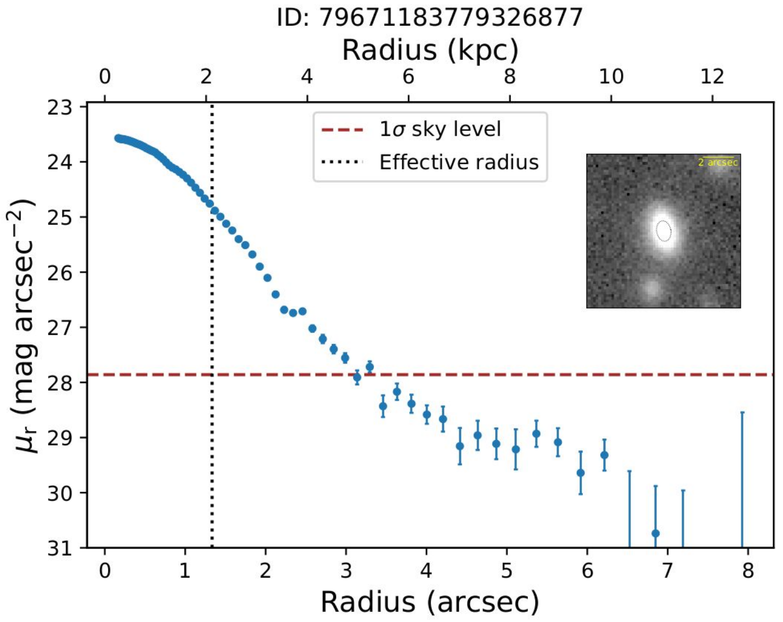


Radial profiles and surface brightness

- Extracted non-parametric *r*-band radial profiles using the AutoProf tool (Stone+2021)
- Obtained effective radii and average surface brightness ($\mu_{e,r}$)
- With a $\mu_{e,r}$ cut of 23 mag arcsec^{-2}
  - LSBs: 1003
  - HSBs: 628







Junais+2023

SED fit inputs

Table 1: Input parameters for CIGALE SED fitting

Model and Input parameters	Values
Star-formation history: `sfhdelayedbq` (Ciesla et al. 2017)	
e-folding time of the main stellar population model (Myr)	500, [1000,10000] with a spacing of 1000
Age of the main stellar population in the galaxy (Myr)	[10000,13000] with a spacing of 500
Age of the burst/quench episode (Myr)	100, 200, 400, 600, 800, 1000
Ratio of the SFR after and before the burst/quench (Myr)	0,0.2,0.4,0.6,0.8,1,1.2,1.4,1.6,1.8,2
Stellar population: `bc03` (Bruzual & Charlot 2003)	
Initial mass function	Chabrier (2003)
Metallicity	0.008
Dust attenuation: `dustatt_modified_starburst` (Calzetti et al. 2000; Leitherer et al. 2002)	
$E(B-V)_{\rm lines}$, the color excess of the nebular lines (mag)	0, [0.001,2] log sampled with 40 values
Reduction factor to compute $E(B-V)_{\rm continuum}$	0.44
Amplitude of the UV bump	0.0
Slope delta of the power law modifying the attenuation curve	0.0
Extinction law for attenuating emission lines flux	Milky Way (Cardelli et al. 1989)
R_V	3.1
Dust emission: `dale2014` (Dale et al. 2014)	
AGN fraction	0.0
Slope of the interstellar radiation field (α)	2.0

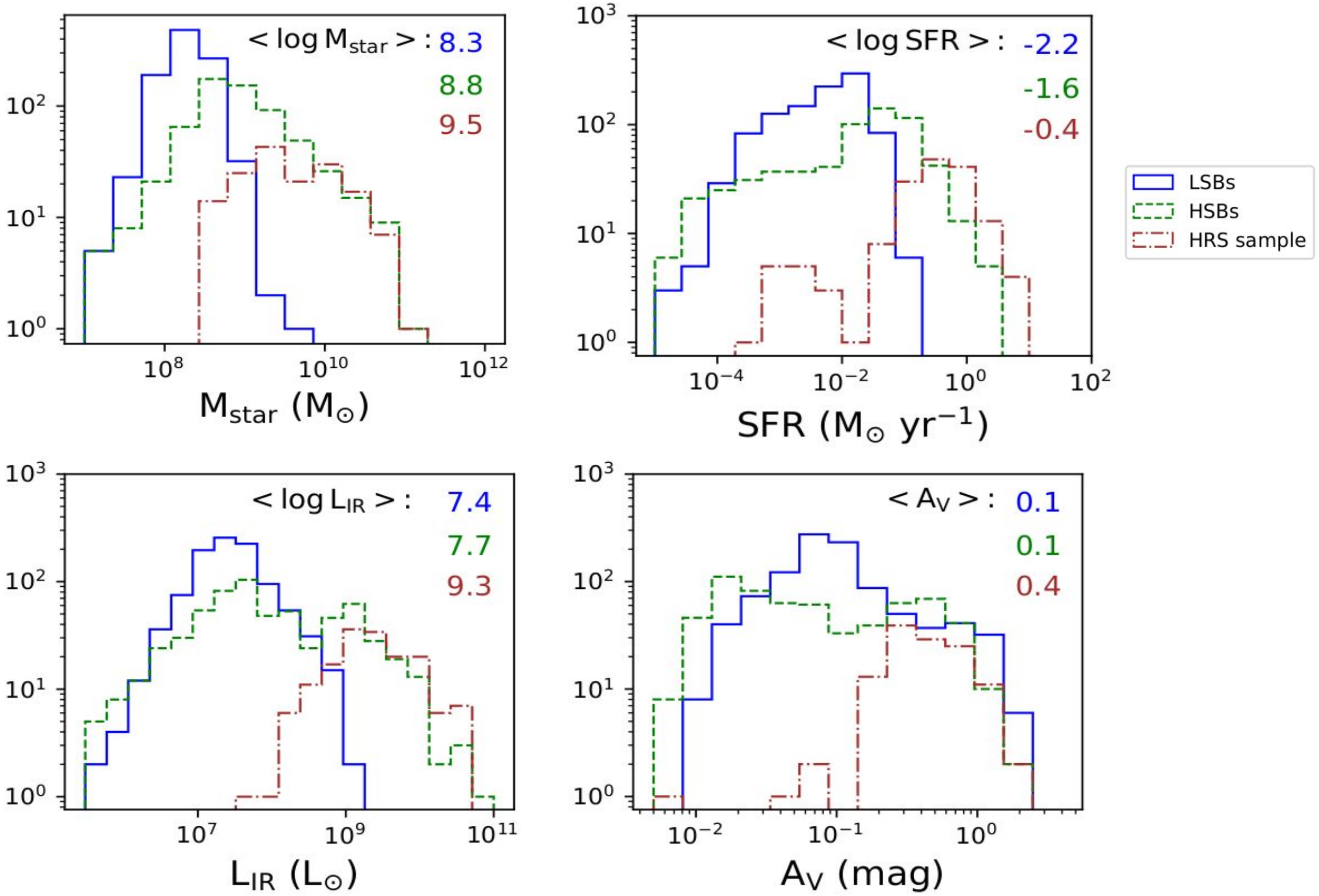
Data and upper limits

Table 1. Summary of the multiwavelength data sets: the detection limits.

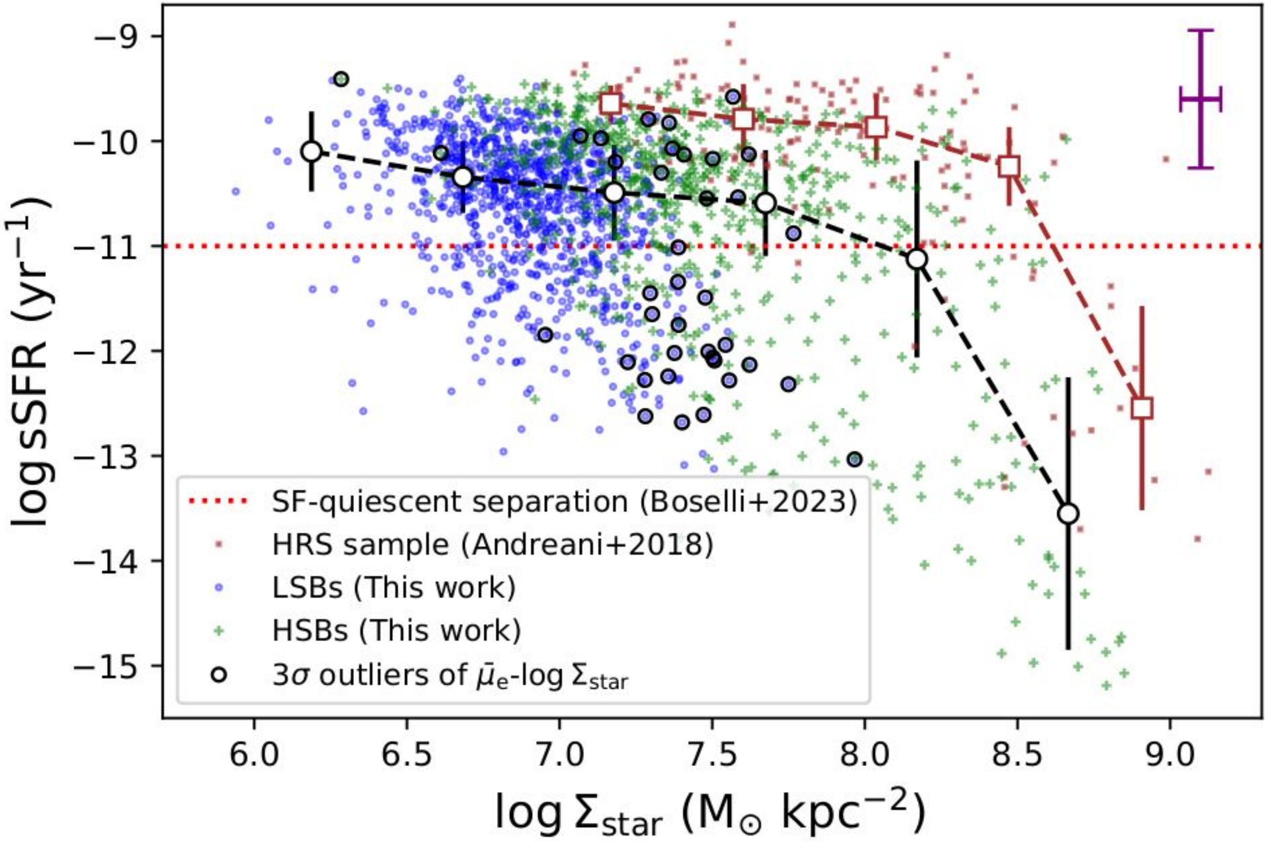
Data	Band	Effective wavelength (μm)	(5σ) detection limit AB/μJy
AKARI/IRC NEP-Wide survey 5.4 deg^2 (Kim et al. 2012)	N2	2.3	20.9/15.4
	N3	3.2	21.1/13.3
	N4	4.1	21.1/13.6
	S7	7	19.5/58.6
	S9W	9	19.3/67.3
	S11	11	19.0/93.8
	L15	15	18.6/133
	L18W	18	18.7/120
	L24	24	17.8/274
Subaru/HSC 5.4 deg^2 (Oi et al. 2020)	*g*	0.47	28.6/0.01
	r	0.61	27.3/0.04
	i	0.76	26.7/0.08
	z	0.89	26.0/0.14
	y	0.99	25.6/0.21
CFHT/MegaPrime 3.6 deg^2 (Huang et al. 2020)	*u*	0.36	25.4/0.25
CFHT/MegaCam[a] 2 deg^2 (Hwang et al. 2007) 0.7 deg^2 (Oi et al. 2014)	u^*	0.39	26.0/0.16
	g	0.48	26.1/0.13
	r	0.62	25.6/0.21
	i	0.75	24.8/0.39
	z	0.88	24.0/0.91
Maidanak/SNUCam 4 deg^2 (Jeon et al. 2010)	*B*	0.44	23.4/1.58
	R	0.61	23.1/2.09
	I	0.85	22.3/4.36

Data	Band	Effective wavelength (μm)	(5σ) detection limit AB/μJy
KPNO/FLAMINGOS 5.1 deg^2 (Jeon et al. 2014)	*J*	1.2	21.6/8.32
	H	1.6	21.3/10.96
CFHT/WIRCam 0.7 deg^2 (Oi et al. 2014)	*Y*	1.02	23.4/1.58
	J	1.25	23.0/2.29
	K_s	2.14	22.7/3.02
Spitzer/IRAC 7 deg^2 (Nayyeri et al. 2018) 0.4 deg^2 (Jarrett et al. 2011)	IRAC1	3.6	21.8/6.45
	IRAC2	4.5	22.4/3.95
	IRAC3	5.8	20.3/27.0
	IRAC4	8	19.8/45.0
WISE (Jarrett et al. 2011)	W1	3.4	18.1/18
	W2	4.6	17.2/23
	W3	12	18.4/139
	W4	22	16.1/800
Herschel/PACS[b] 0.44 deg^2 (Pearson et al. 2019)	Green	100	14.7/4.6 mJy
	Red	160	14.1/8.7 mJy
Herschel/SPIRE[c] 9 deg^2 (Pearson et al. 2017)	PSW	250	14/9.0 mJy
	PMW	350	14.2/7.5 mJy
	PLW	500	13.8/10.8 mJy
SCUBA-2/NEPSC2[d] 2 deg^2 (Shim et al. 2020)	850	850	1.0–2.3 mJy

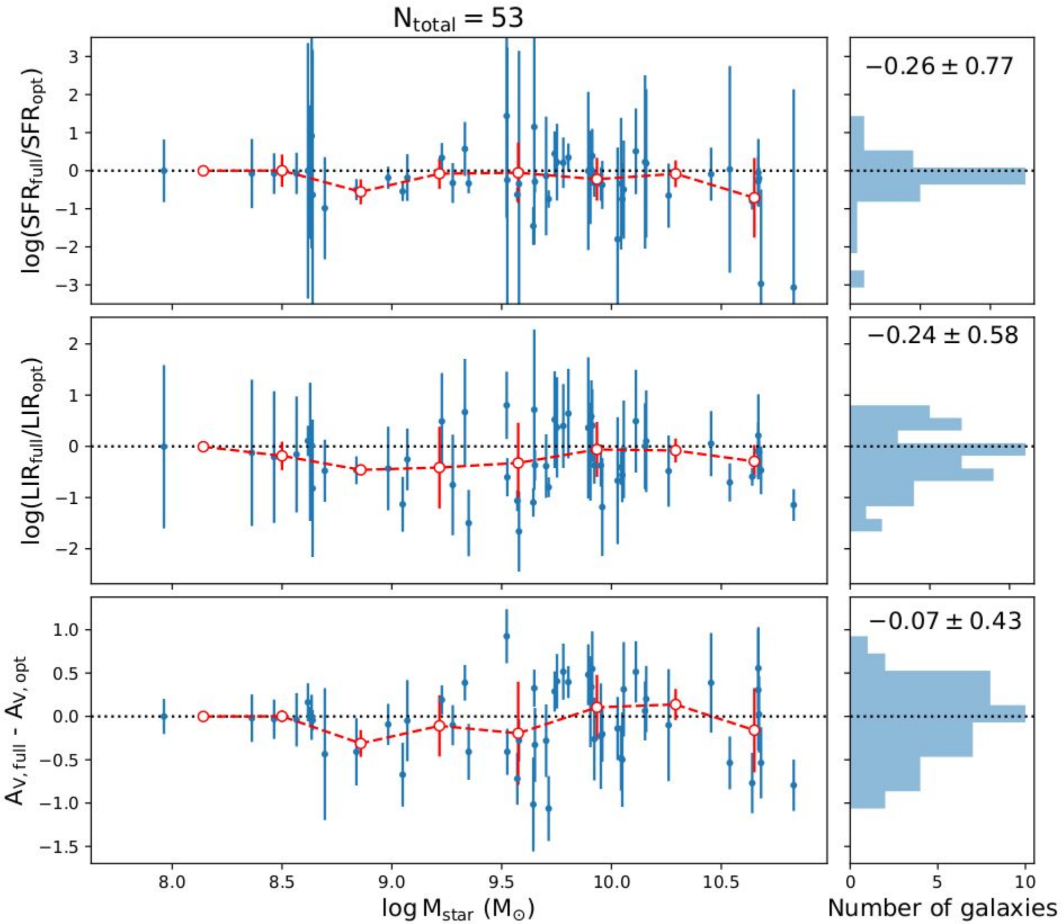
SED fit results



sSFR vs sigmastar

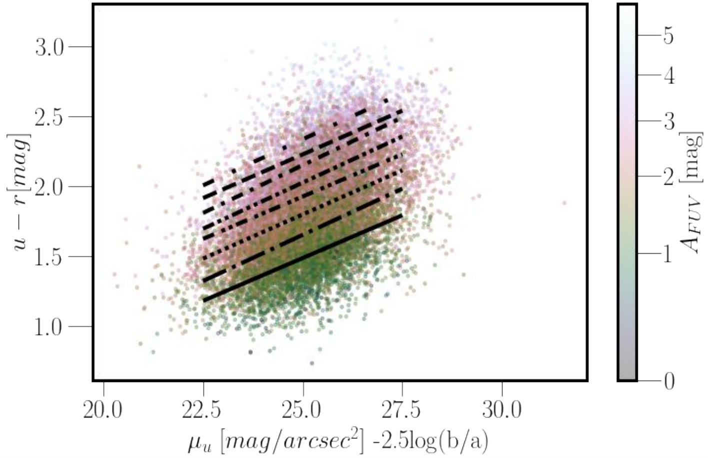


Optical vs FIR fit



Related works of our team

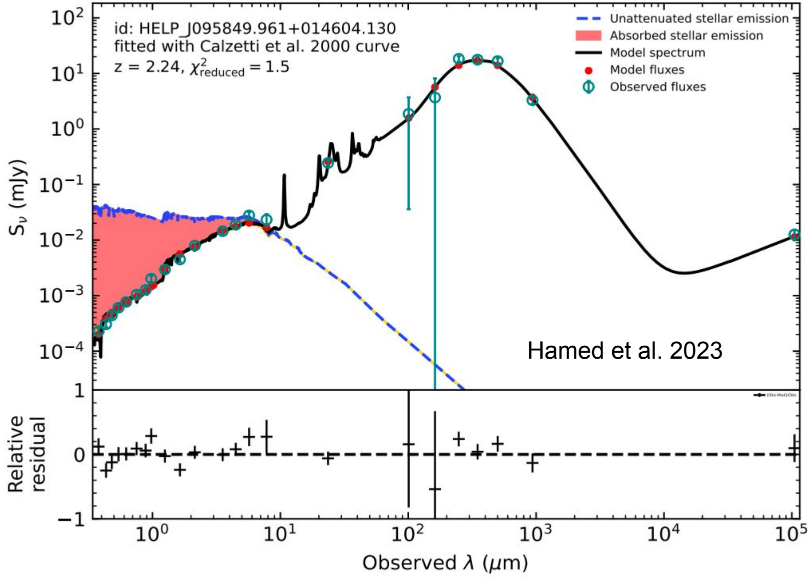
Małek et al. in prep.



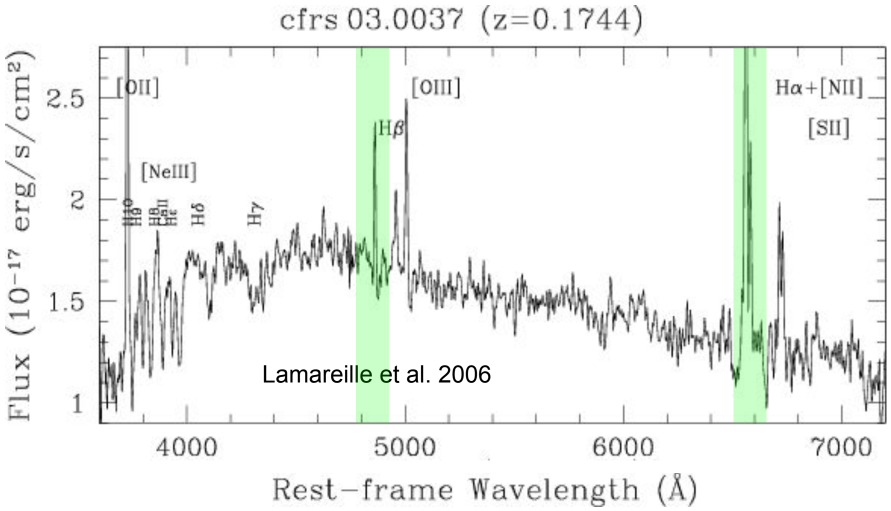
- A combination of *u-r* color and surface brightness to estimate attenuation
- Calibrated using the GALEX-SDSS-WISE data (Salim+2016)
- Ideal for LSST sources without multiwavelength counterparts

Estimation of dust attenuation

- Two commonly used methods:
  - SED modelling: UV + optical + IR (photometry)
  - Balmer decrement: Hα/Hβ ratio (spectroscopy)
- We don't always have access to such high quality data



Hamed et al. 2023



Lamareille et al. 2006

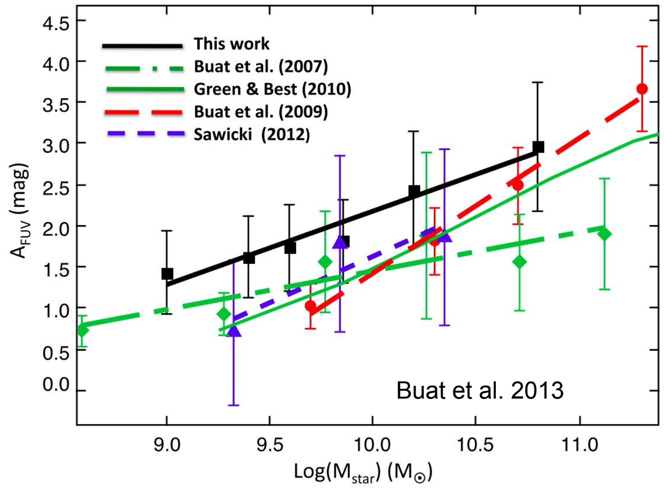
$$A(\mathrm{H}\alpha) = 6.55 \log \left[\frac{(\mathrm{H}\alpha/\mathrm{H}\beta)_{\mathrm{obs}}}{2.86} \right]$$

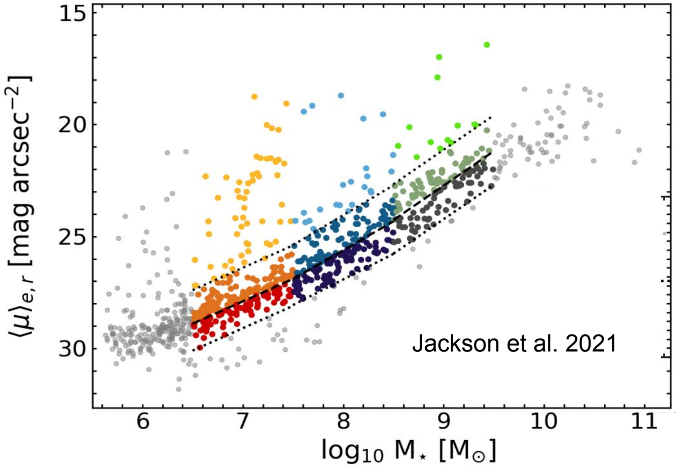
Factors influencing attenuation

- Stellar mass - attenuation relation
  - Generally low mass galaxies tend to have low attenuation (large scatter)
- Dust-to-star geometry, galaxy morphology (Buat+2019; Hamed+2023)
  - Possible dependance on surface brightness

- For a fixed stellar mass there is a large scatter (~3 dex) in surface brightness (Jackson+21)

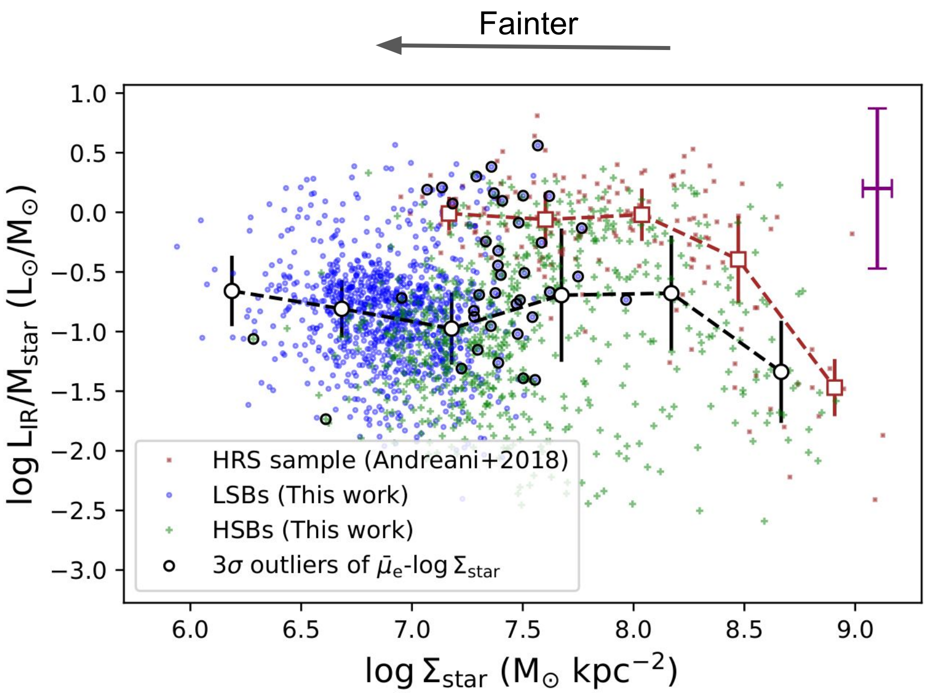
<u>Our Focus</u>
Attenuation - surface brightness relation
Low mass, low surface brightness galaxies

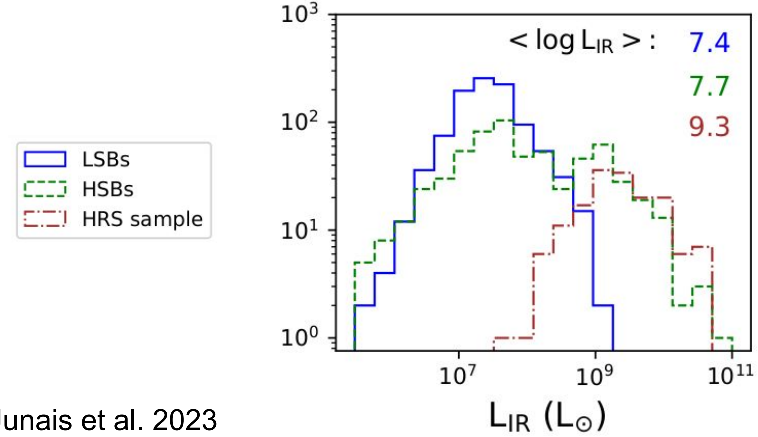




Infrared luminosity

- LSBs have lower L_{IR} than HSBs
- The specific IR luminosity (L_{IR} per stellar mass) is mostly flat for both LSBs and HSBs
- Implies LSBs and HSBs at a fixed stellar mass do have comparable L_{IR}
- Many of 3σ outliers have high specific L_{IR}





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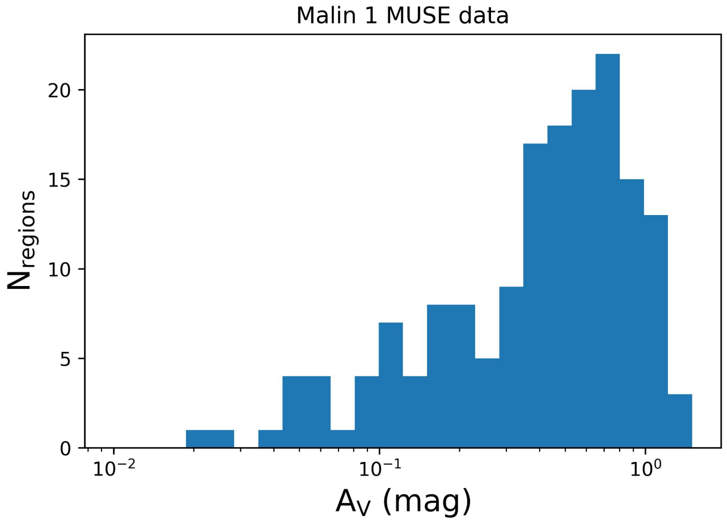
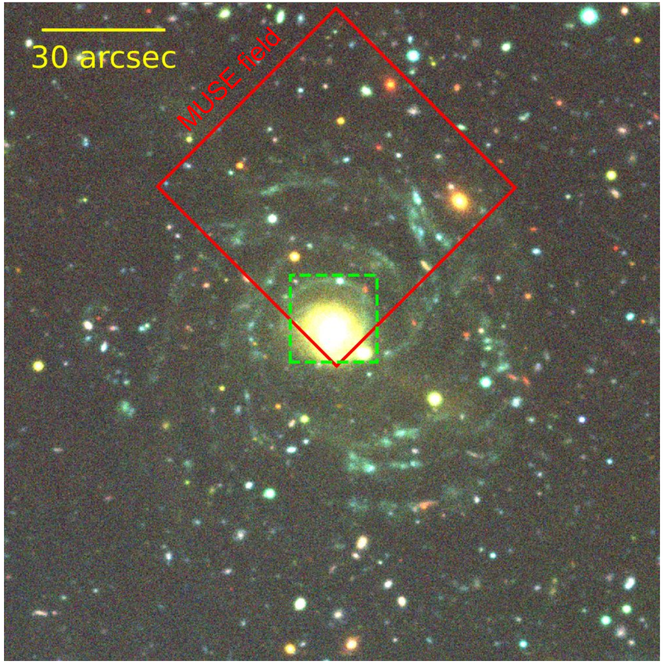
MUSE observation of the giant LSB Malin 1

Junais et al. (submitted)

- VLT/MUSE spectroscopic data recently obtained (PI: Gaspar Galaz)
- Measured attenuation using Balmer decrement
- A_V up to 1 mag (mean A_V ~ 0.4 mag)
- Hundreds of Malin 1-like giants will be observed with LSST





CFHT *u,g,i* image