Searching for Low-Surface-Brightness Galaxies
with the Hyper Suprime-Cam Survey

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Pre 1923: The **Realm of the Nebulae**
80 years later...
Low-surface-brightness galaxies (LSBGs)

- Surface brightness **fainter than night sky**
- Span **all galaxy types** and environments
- Underrepresented in previous optical surveys
The **Hidden** Galaxy Population

LSBGs as a testing ground for LCDM...

How do dwarf galaxies occupy dark matter halos?

Weinberg et al. 2014
The Latest Craze: Ultra-Diffuse Galaxies (UDGs)

Ultra-diffuse galaxy in Coma (van Dokkum et al 2014)

Image credit: Pieter van Dokkum
Ultra-Diffuse Galaxies (UDGs)

- UDGs have $M_{\text{stellar}} \sim 10^7 M_\odot$ spread over $r_{\text{eff}} \sim 1.5-5$ kpc
- UDG-like objects known to exist for decades (e.g., Sandage & Bingelli 1984; Dalcanton et al. 1997)
~1000 UDG candidates in Coma!

Dragonfly 44

Coma Cluster

van Dokkum et al. 2015, 2016; Koda et al. 2015
UDGs common in rich clusters

New UDGs also found in Virgo (Mihos et al. 2015)

Fornax (Munoz et al. 2015)

... and 8 low-z clusters: (van der Burg et al. 2016)
UDGs in groups and the field

New UDGs also found in….

Small groups
(Merritt et al. 2016)

The field
(Leisman et al. 2017)
Need deep + wide blind search
Need **deep** + **wide** blind search

Ultra-LSB sources in SDSS
Need **deep** + **wide** blind search

A *new view* with the **Hyper Suprime-Cam (HSC)**

Ultra-LSB sources in SDSS
The Hyper Suprime-Cam Subaru Strategic Program
Hyper Suprime-Cam

Typical Apparent Diameter of the Moon (0.5 degrees)

Suprime-Cam
First Light Release
January 1999

Suprime-Cam
Image Release
September 2001

Hyper Suprime-Cam
Image Release
July 2013

Image credit: NAOJ
Hyper Suprime-Cam Survey

5 years, 300 Nights

<table>
<thead>
<tr>
<th></th>
<th>Wide</th>
<th>Deep</th>
<th>Ultra-Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>1400 deg$^2$</td>
<td>27 deg$^2$</td>
<td>3.5 deg$^2$</td>
</tr>
<tr>
<td>Filters</td>
<td>grizy</td>
<td>grizy+2NBs</td>
<td>grizy+2NBs</td>
</tr>
<tr>
<td>Depth ($i$-band)</td>
<td>25.9</td>
<td>26.8</td>
<td>27.4</td>
</tr>
</tbody>
</table>

Figure credit: A. Nishizawa
1.5 Our data, our collaboration

Figure 1.2: The limiting magnitudes (in \( r \)) and solid angles of the HSC-Wide, Deep, and Ultradeep (UD) layers, compared with other existing, on-going, and planned surveys. The three layers are complementary to each other, and each of the three layers covers a significantly wider area than do other on-going surveys of comparable depth.

The design of the HSC Survey with its three-layer design, and choice of survey fields, are described in Chapter 3. The survey strategy, which is designed for highly accurate photometric calibration, is detailed in Chapter 4. We describe the software pipelines that will analyze the survey data in Chapter 5. Studies of both galaxies and cosmology requires determining galaxy redshifts, which we do from their broad-band colors, as discussed in Chapter 6.

We then turn to the principal science drivers. We describe gravitational lensing techniques, with emphasis on understanding systematics, in Chapter 7. Chapter 8 presents studies of the lensing signal around galaxies allows one to understand galaxies in their dark matter context. Cosmological applications of gravitational lensing are discussed in Chapter 9. Clusters of galaxies are also important, both as a key part of the galaxy evolution puzzle, and for their cosmological implications, as described in Chapter 10. We then go on to describe the work we can do in galaxy evolution studies, up to \( z = 5 \) (Chapter 11) and up to \( z = 7 \) (Chapter 12). Quasars and Active Galactic Nuclei (AGN) are a crucial part of this story, as described in Chapter 13. We then discuss various transient phenomena, including Type Ia supernovae that is an additional key cosmological probe, in Chapter 14. Two scientific areas that are further from our core science goals, but which will have a wealth of data from our survey, are studies of the main belt and Kuiper belt of asteroids in our Solar System (Chapter 15) and of the halo of the Milky Way (Chapter 16).
1. Our data, our collaboration

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Special issue of PASJ with \(~40\) HSC papers
Public DR1 now available \((100\;\text{deg}^2)\)!
Our search for LSBGs

- Carry out search in HSC Wide layer
- ~200 deg$^2$ with full Wider layer depth in gri
Search using **HSC catalog?**
Source extraction in two steps:

- Initial image processing with LSST codebase: http://dm.lsst.org
- Final source detection with SExtractor
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**LSBG Detection Pipeline: Source Extraction**

Source extraction in two steps:

- Initial image processing with LSST codebase: [http://dm.lsst.org](http://dm.lsst.org)
- Final source detection with *SExtractor*
Our LSBG definition:
\[ \mu_{\text{eff}}(g) > 24.3 \text{ mag arcsec}^{-2} \]
\[ r_{\text{eff}} > 2.5'' \]

- Model LSBG candidates as single-component Sersic functions
- Make selection on best-fit parameters
- Visually inspect remaining candidates
- Final sample size: 781 LSBGs
LSB False Positives: **Tidal Debris?**

LSB False Positives: Tidal Debris?

\[ \sim 50 \text{ kpc at } z = 0.043 \]

1'
**LSBG Sample: Parameter Distributions**

**Graphs:**
1. **Ellipticity Distribution:**
   - Ellipticity values are plotted against normalized counts for Spirals, Blue LSBGs, Red LSBGs, and Coma UDGs. 
2. **Normalized Count Distribution:**
   - Normalized count values are shown for $\mu_{eff}(g)$ in mag arcsec$^{-2}$ for Spirals, Blue LSBGs, Red LSBGs, and Coma UDGs. 

**Equation:**
- $g - i = 7 \log_{10}(\text{age/yr})$
LSBG Sample: Spatial Distribution

[Graphs showing spatial distribution of LSBG samples with coordinates α [deg] and δ [deg].]
LSBG Sample: Spatial Distribution

Cluster-\(z\) Signal

\[
\frac{dN}{dz} \text{ (Normalized)}
\]
LSBG Sample: Catalog Crossmatching
Size-Luminosity Relation

- Early-type galaxies (Brodie+11)
- UDGs (van Dokkum+15)
- Giant LSB spirals (Strayberry+95)
- HSC-SSP LSBGs (Greco+17)
- Our GMOS+Gemini pilot LSBGs
- Our HST ultra-LSB targets

Plot with logarithmic scale for $r_{\text{eff}}$ and $M_V$. Classes of galaxies include dSphs, dEs, cEs, UDGs, and gEs.
What’s Next?
What’s Next?

UDGs & rich globular cluster systems

Data from Harris et al. 2013

Peng et al. 2016

Beasley et al. 2016
What’s Next?

Counting **globular clusters** with HST

**Group B** ($M_{\text{halo}} \sim 10^{13.9} \, M_\odot$)

**Group A** ($M_{\text{halo}} \sim 10^{12.5} \, M_\odot$)
What’s Next?

Redshifts with GMOS on Gemini

HSC-SPP gri

Galex NUV+FUV
Redshifts with GMOS on Gemini

Observed Wavelength (Å)

$z = 0.00747$

Greco et al. 2017, in prep.
Summary

Low-surface-brightness galaxies (LSBGs) are a significant yet poorly understood component of the galaxy population

Exquisite imaging afforded by HSC promises to provide an unprecedented view of LSBGs over 1400 deg²

We have a diverse sample of ~800 LSBGs, which we are actively following up from the ground and space

Special thanks to my collaborators!

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