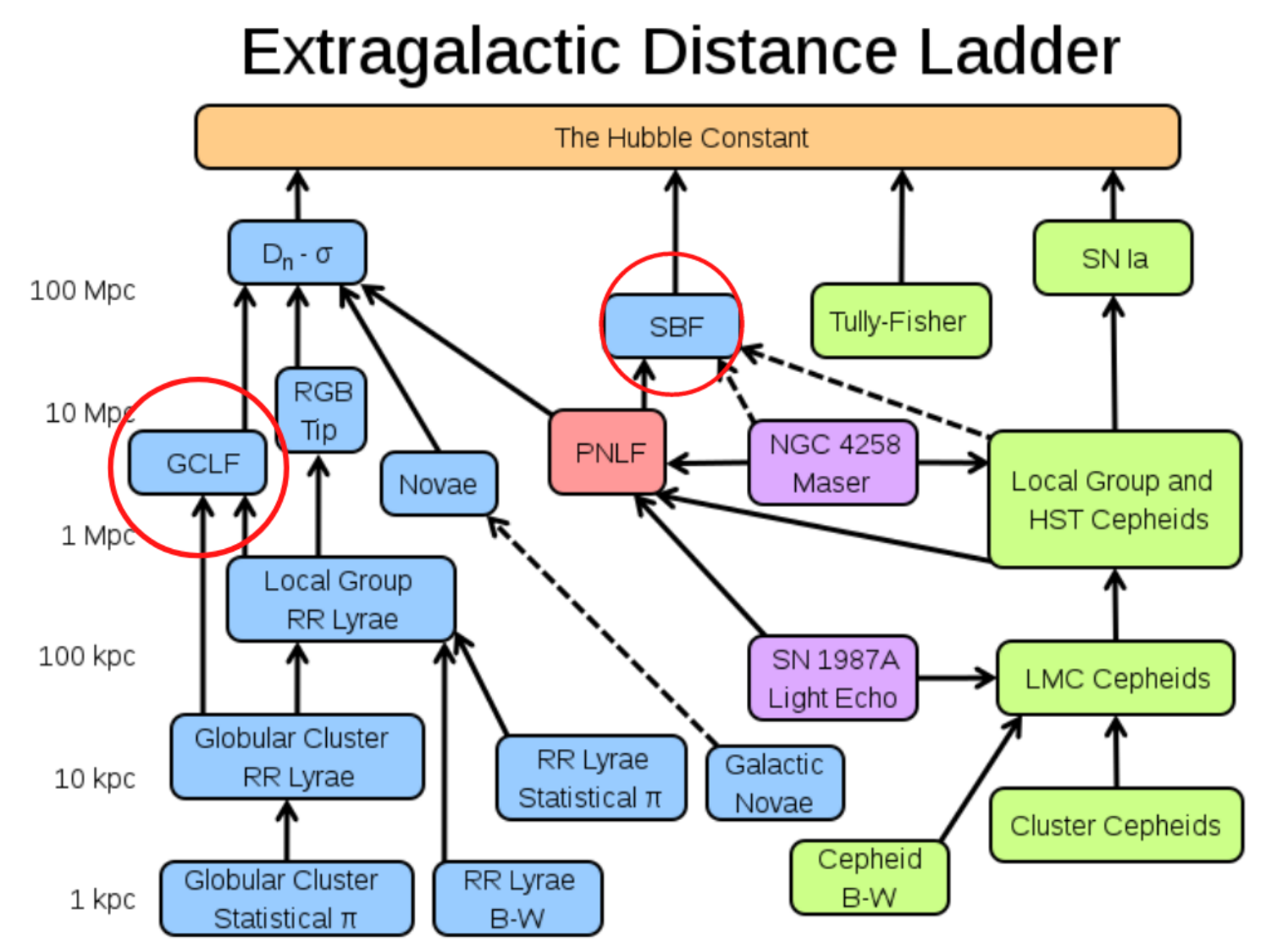
Distance Indicators for Cosmology

Nandini Hazra
GSSI L'Aquila/INAF-OAAb Teramo

Advisors
Marica Branchesi, Michele Cantiello

October 14, 2022

GRAN SASSO SCIENCE INSTITUTE


Extragalactic Distance Ladder
The Hubble Constant
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
D_n - σ
SBF
Tully-Fisher
SN Ia
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

Recap: Our objective

Subaru Telescope, Mauna Kea

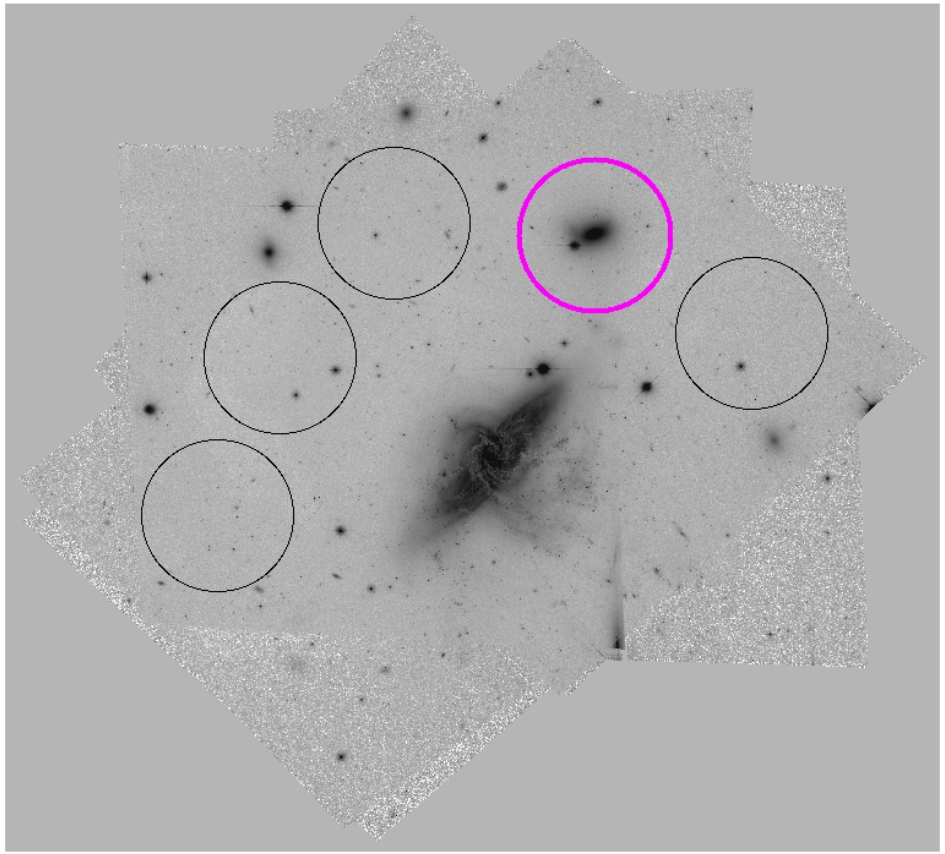
- Build a pipeline with Python for SBF distance measurements that requires minimal human intervention, to exploit all the potentialities of Vera Rubin Observatory data
- Calibrate and test the pipeline using data from Hyper Suprime Cam(HSC) of Subaru, which is a precursor survey for LSST
- Make it accessible to the scientific community
- Use the pipeline for globular cluster science

Roadmap

- Globular Cluster science with Hubble and JWST
- Surface Brightness Fluctuations update: Rubin and JWST
- Perspectives for kilonova detection with the Vera Rubin Observatory, and synergy with Einstein Telescope (ET)

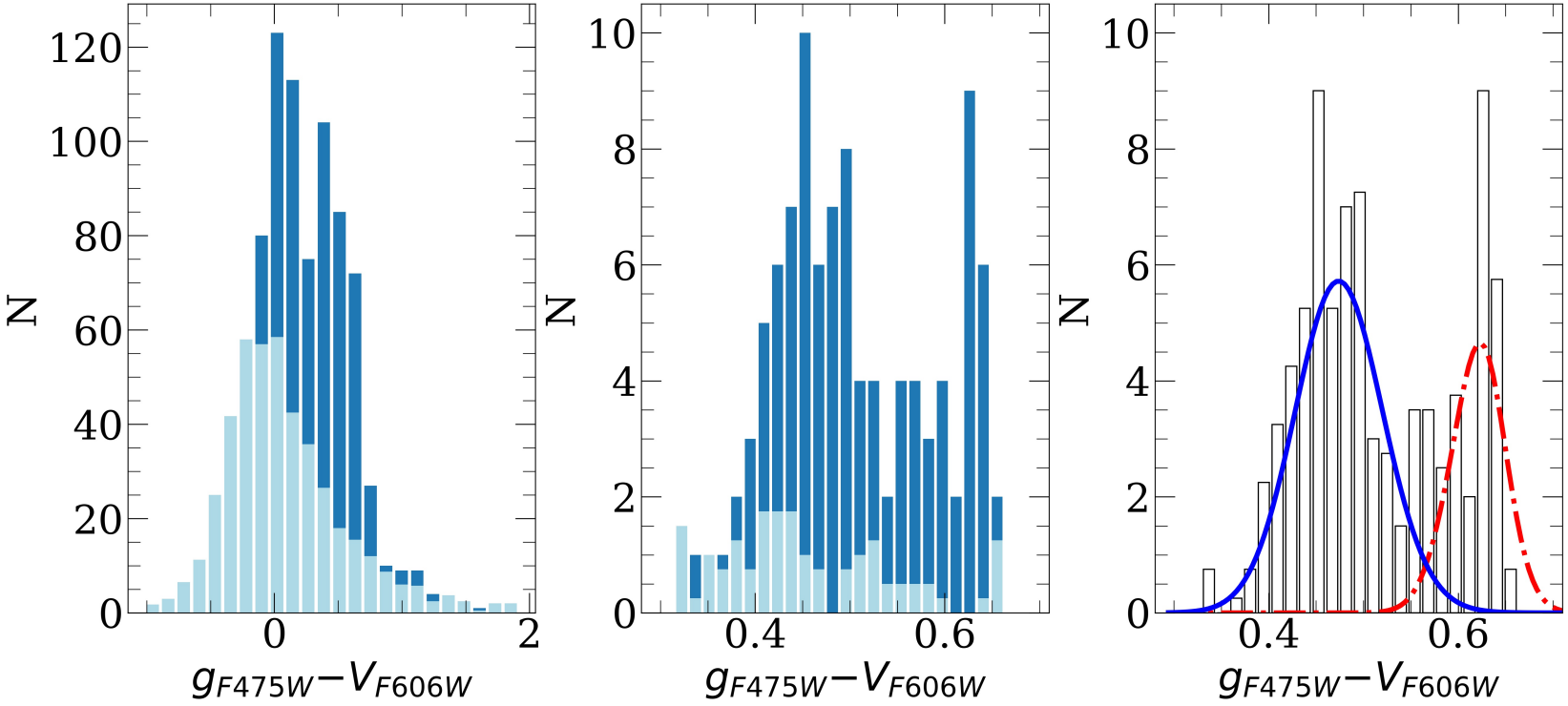
Globular clusters in Hydra I: with the Hubble Space Telescope

- PGC 087327: Lenticular Galaxy in Hydra I cluster, close to NGC 3314A/B
- Some of the deepest images observed by the Hubble Space Telescope: F606W and F475W bands of ACS/WFC



Color bimodality

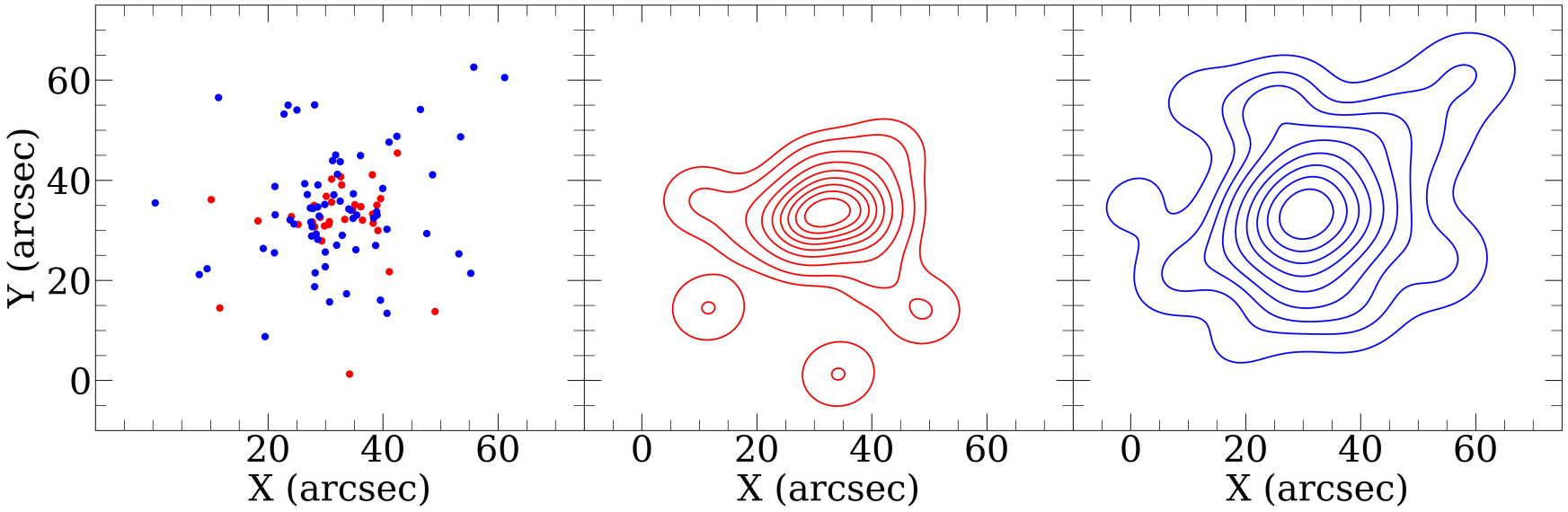
In spite of the small separation of wavelengths, and the intermediate mass of the galaxy, we see a clear separation of metal-poor and metal-rich subpopulations of GCs



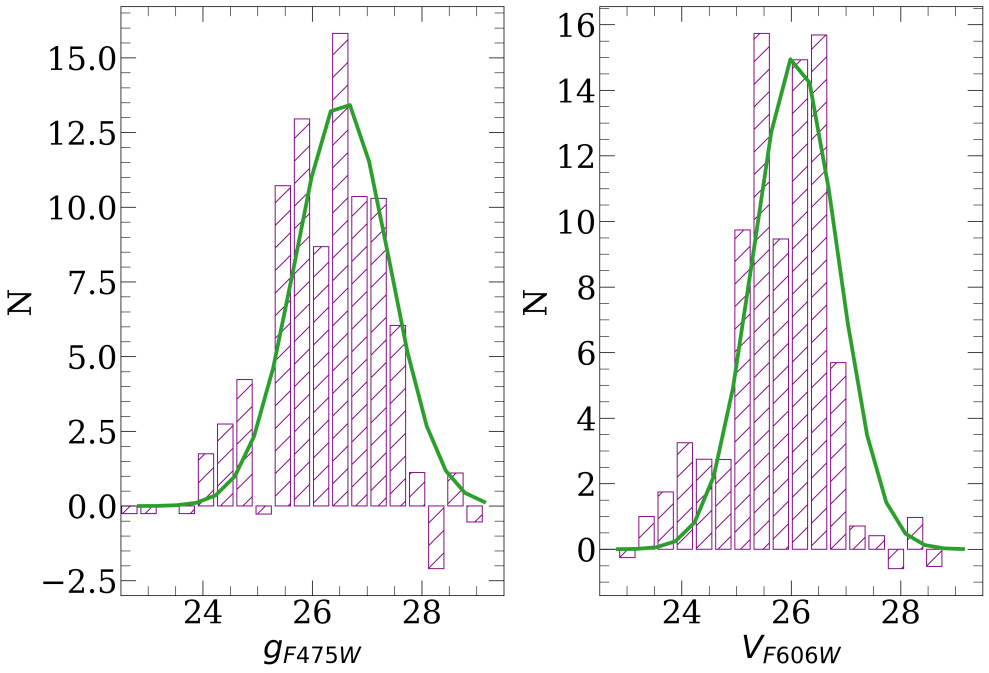
Hazra et al. 2022

Spatial distribution and colors

Spatial distribution of red and blue globular clusters in the galaxy frame



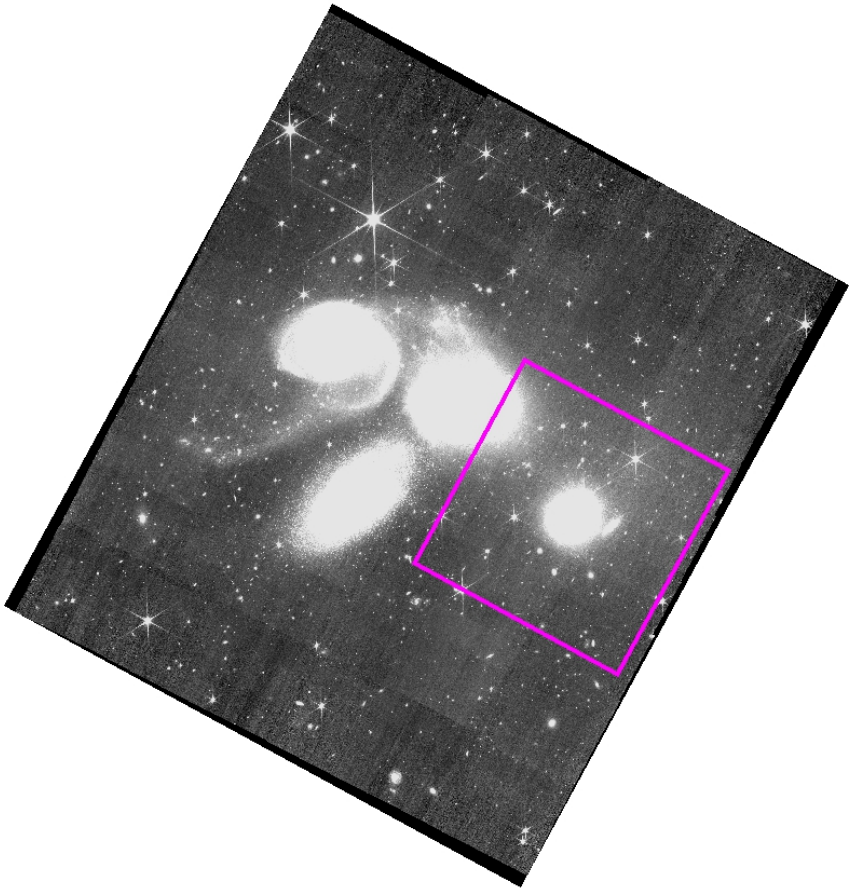
GCLF in PGC 087327



- Turnover magnitude: m^{TO}
- Calibrate: M^{TO} from literature- ACS dwarfs survey Georgiev et al. for $F606W$, ACSVCS Villegas et al. for $F475W$
- $(m - M)^{TO} = 33.77 \pm 0.17$ mag, $D = 56.7 \pm 4.3$ Mpc
- Preliminary estimate of Hubble constant $H_0 \approx 78.5 \pm 6.0(statistical) \pm 7.3(systematic)\ km\ s^{-1} Mpc^{-1}$

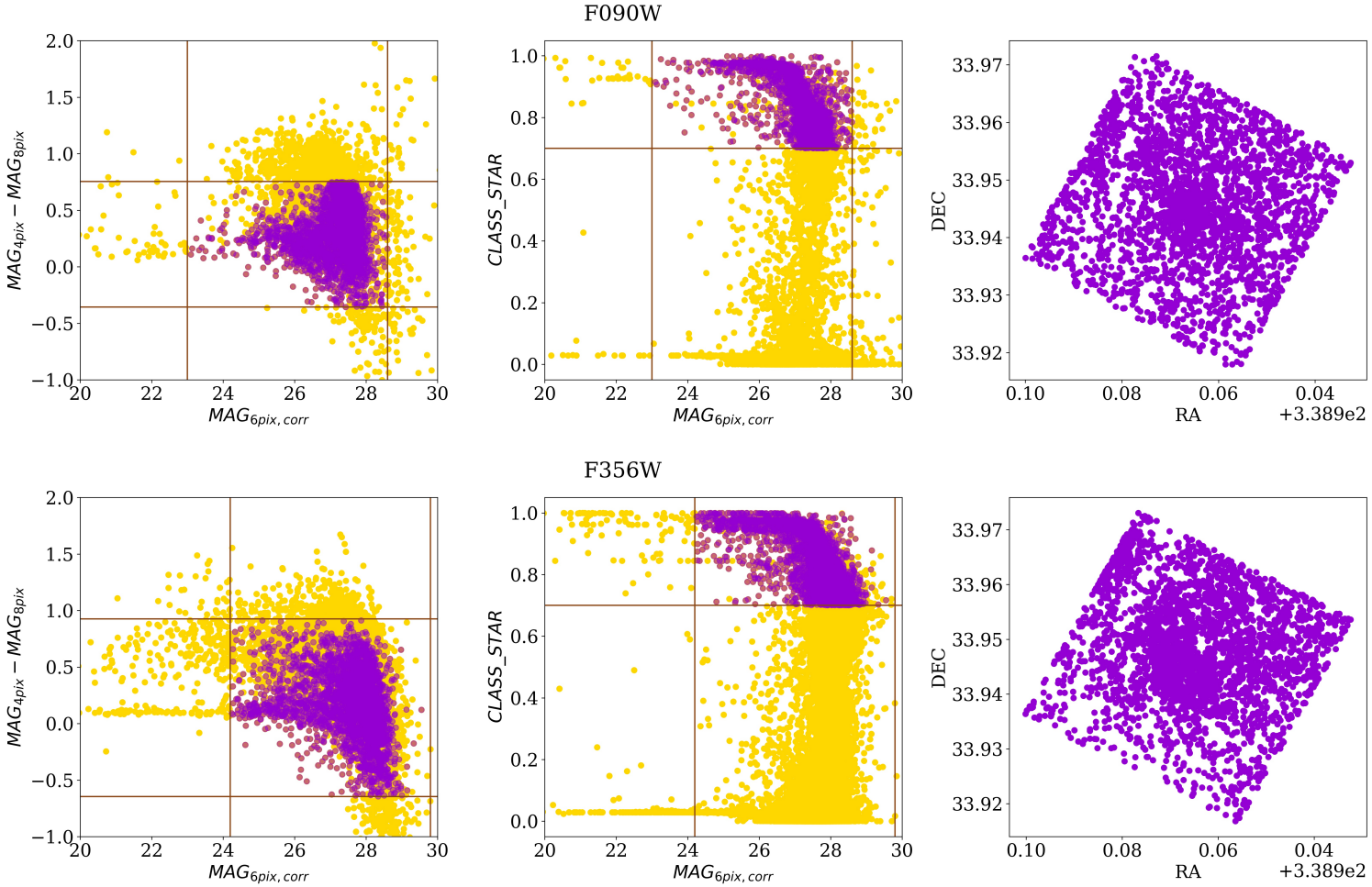
Globular clusters in NGC 7317: with JWST public data

- I am working on the public release data from the JWST's NIRCam: F090W, F150W, F200W (SW), and F277W, F356W, F444W (LW)
- Target: NGC 7317, an elliptical galaxy in the Stephan's Quintet
- Extragalactic GCs have not been characterised in LW bands



Globular clusters in NGC 7317

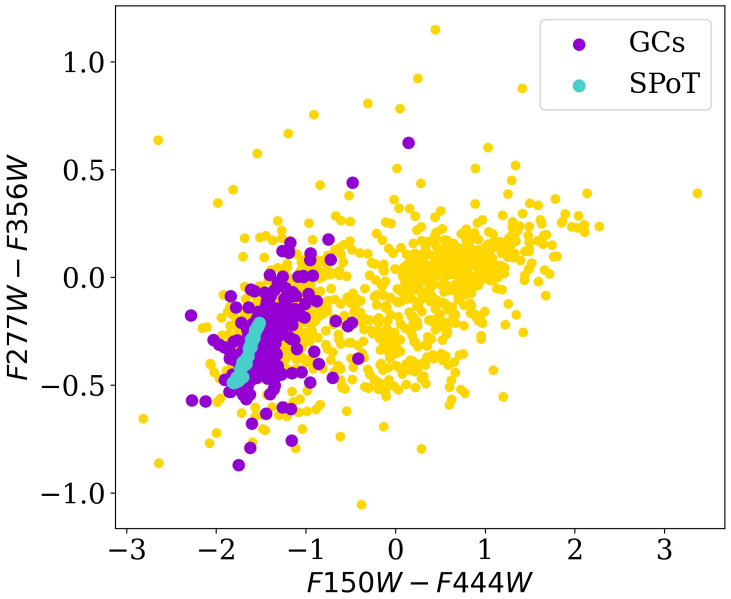
- Selection by compactness and magnitude

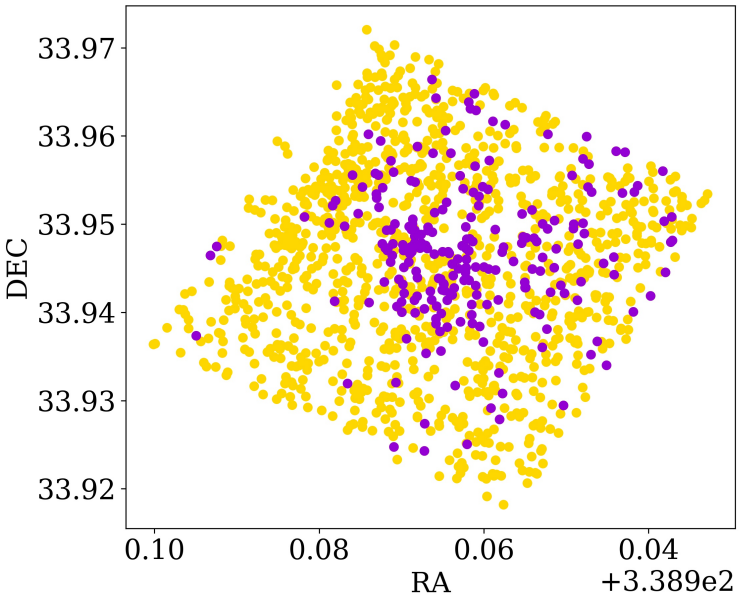


Hazra et al. (in prep)

Colors and models

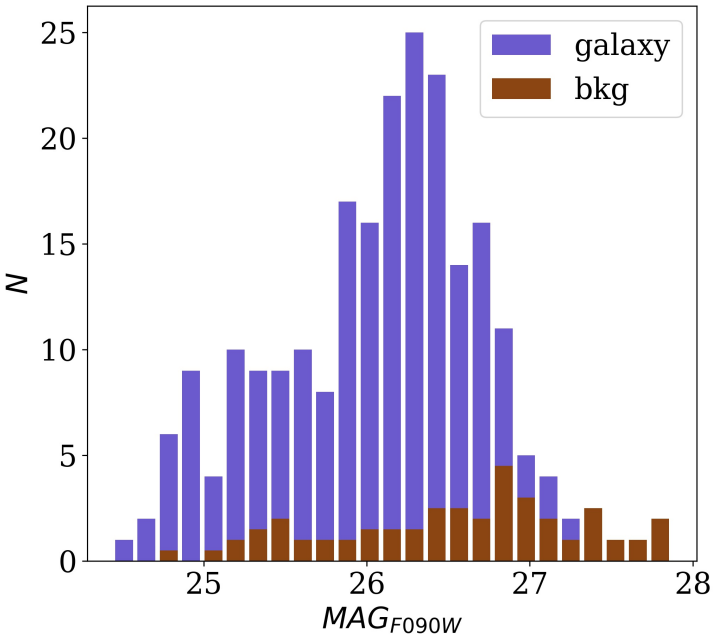
- Catalogs are matched across all passbands
- Color-color sequences separate into two clear series
- Agree well with SPoT models

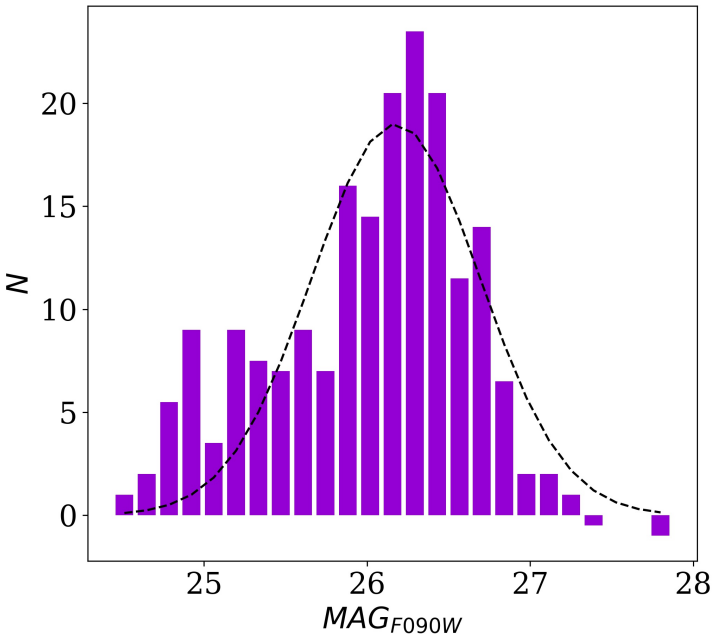




Color distribution and GCLF

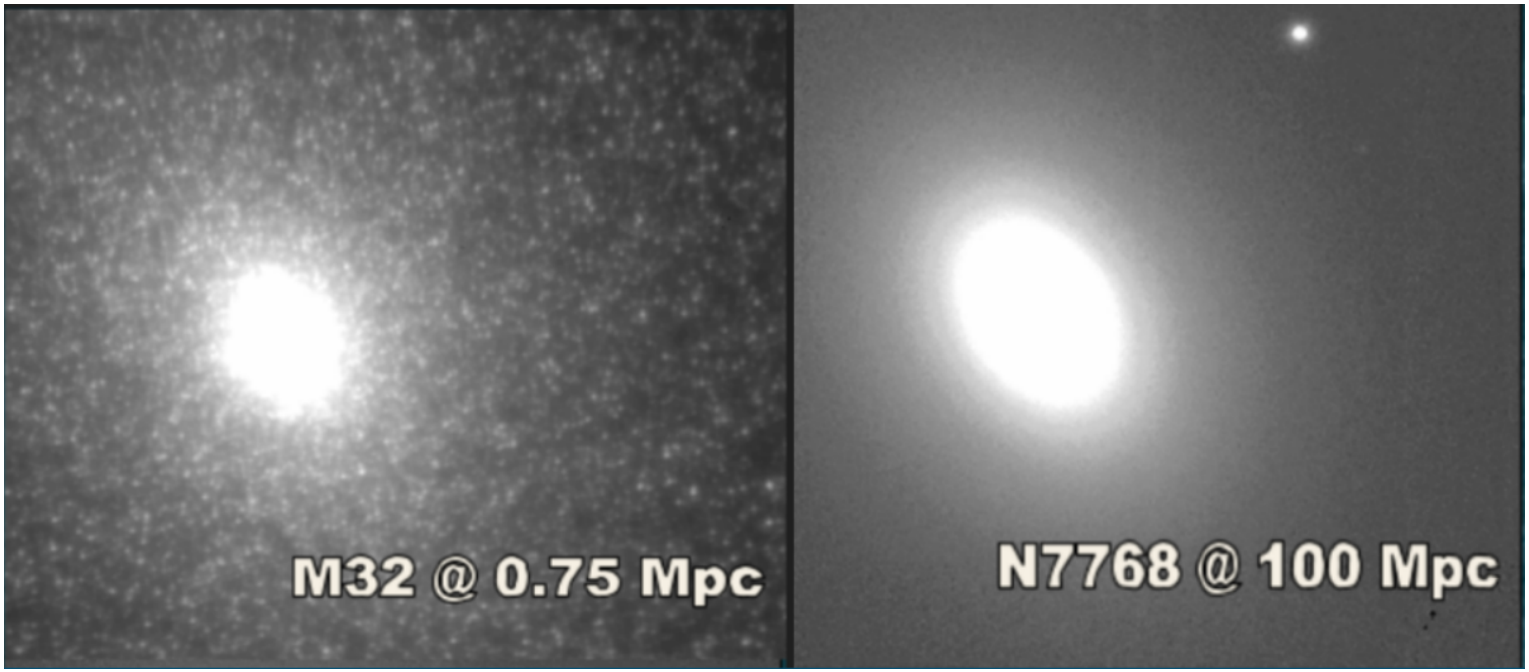
- Unclear if color distributions show bimodality: even after background-decontamination
- Working on characterising the GCLF in LW bands by using the objects near the GCLF peak in the SW bands: the farthest distance measured by GCLF
- Our work also provides valuable calibration information to the NIRCam team





The idea behind the Surface Brightness Fluctuations (SBF) Method: recap

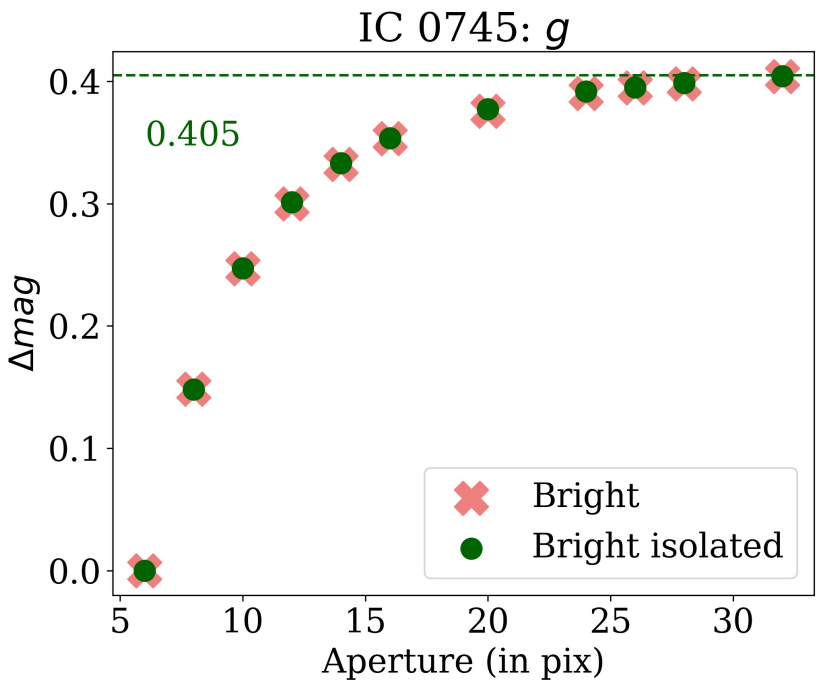
- Closer galaxies display more "mottling" than farther ones, due to unresolved stellar populations: quantified by Tonry et al. in 1988
- SBF can be used to measure precise (6% error) individual distances

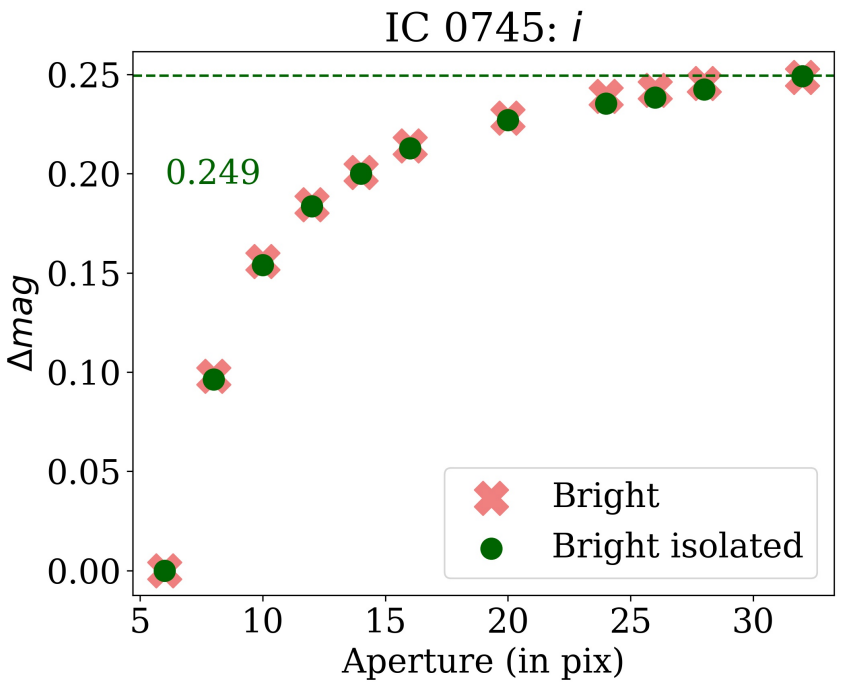


Source: M. Cantiello

Calibration: Aperture Correction

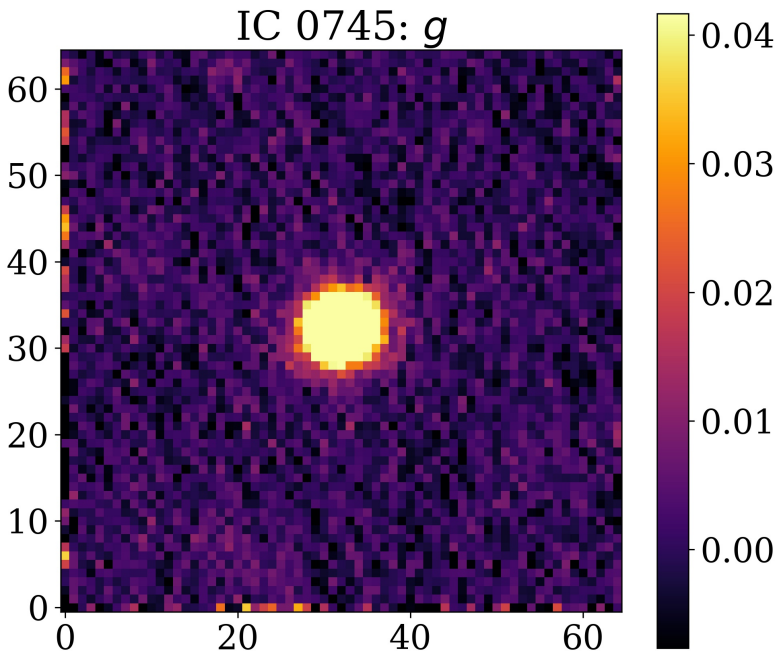
- SBF test sample: bright ellipticals in the footprint of HSC, a precursor survey of Rubin
- Photometry using the tool `SExtractor`
- Obtained from bright, compact, isolated objects

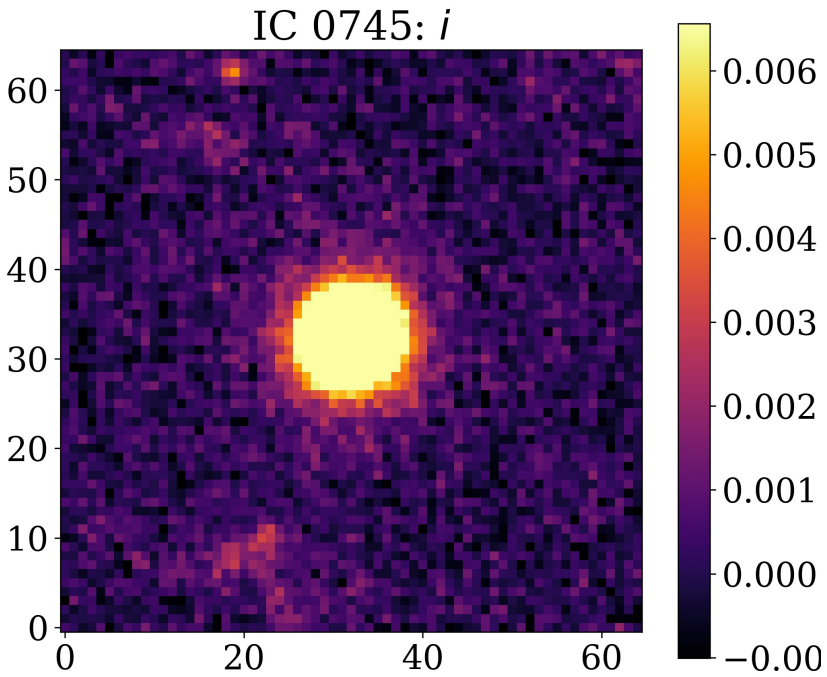




Deriving the Point Spread Function (PSF)

- Obtained by interpolating between brightest, compact, isolated objects
- Reliable PSF: essential for measuring SBF signal
- Effective PSF determined using Photutils in Astropy





Testing the PSF

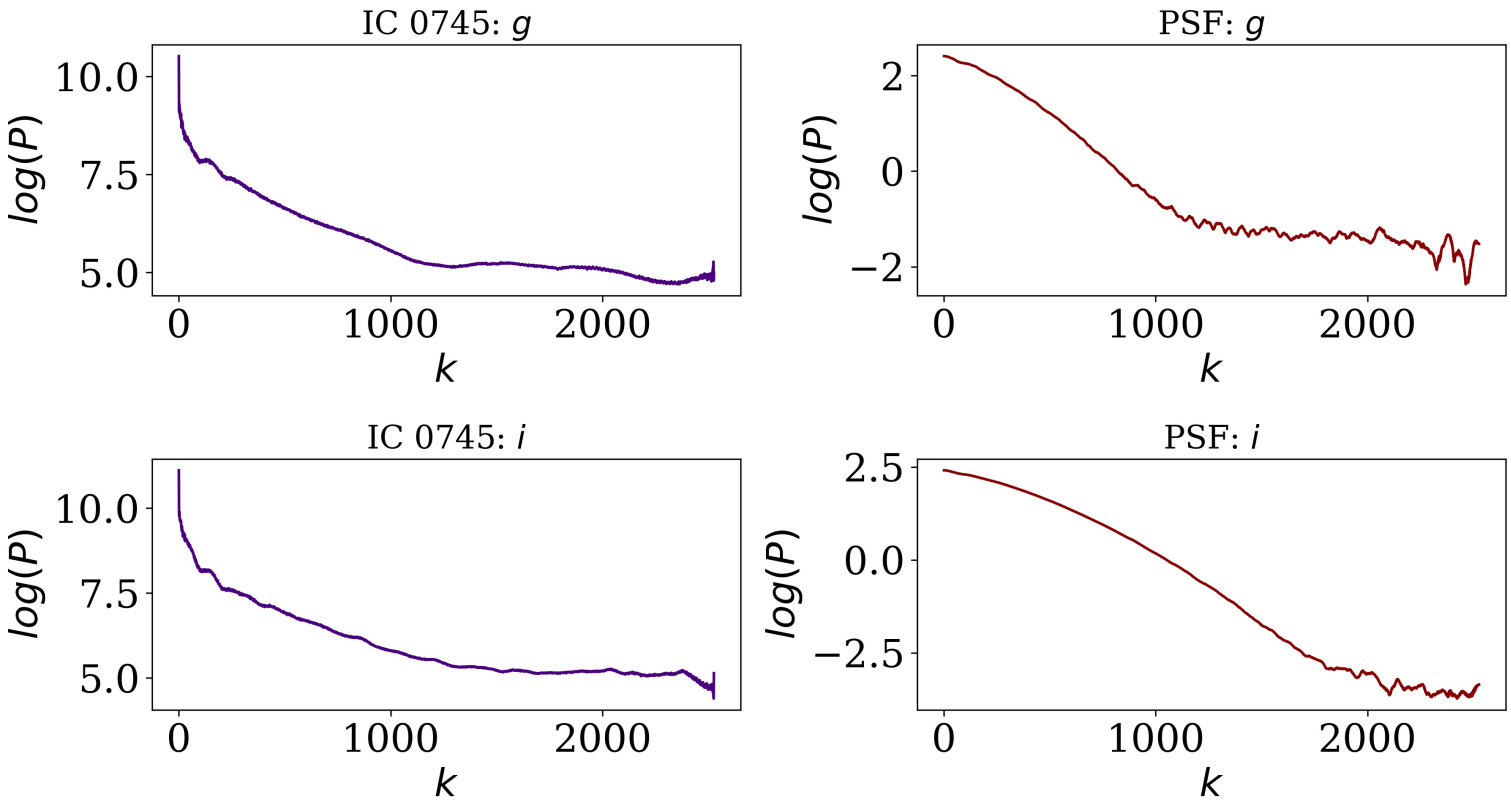
- Using DAOPhot: different photometry tool, to detect point-like sources
- Iteratively subtracting the PSF model built by us

Power Spectral Analysis

- Power spectrum of masked residuals
- Matched to PSF power spectrum

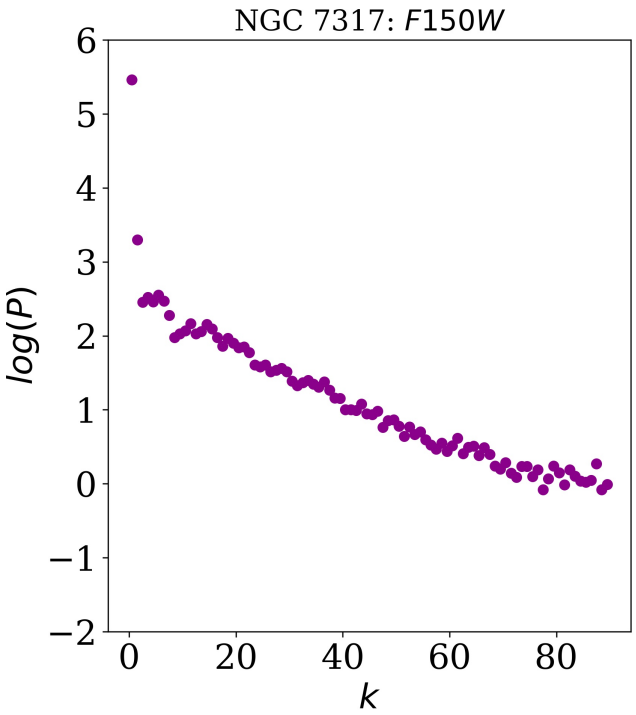
$$P(k) = P_0 E(k) + P_1$$

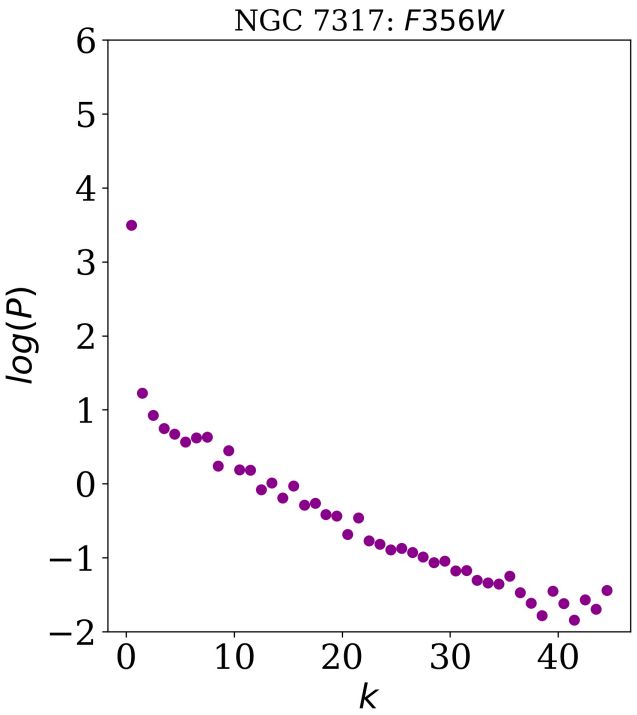
$$m_X = -2.5 log(P_0 - P_r) + m^X_{z.p.}$$



Future steps

- Measuring the SBF amplitude
- Calibration with existing literature
- Extending SBF analysis to JWST: no existing body of work on LW , or in any infra-red wavelengths to date





Introduction

- 3rd generation gravitational wave(GW) observatories like the Einstein Telescope (ET) will detect $\sim 10^5$ binary neutron star (BNS) mergers each year, a fraction of which are expected to have detectable EM counterparts
- We are developing observational strategies to follow-up BNS mergers and detect optical signals from kilonova transients using the Vera Rubin Observatory (photo: Rubin/NSF/Aura)

BNS mergers in the era of ET

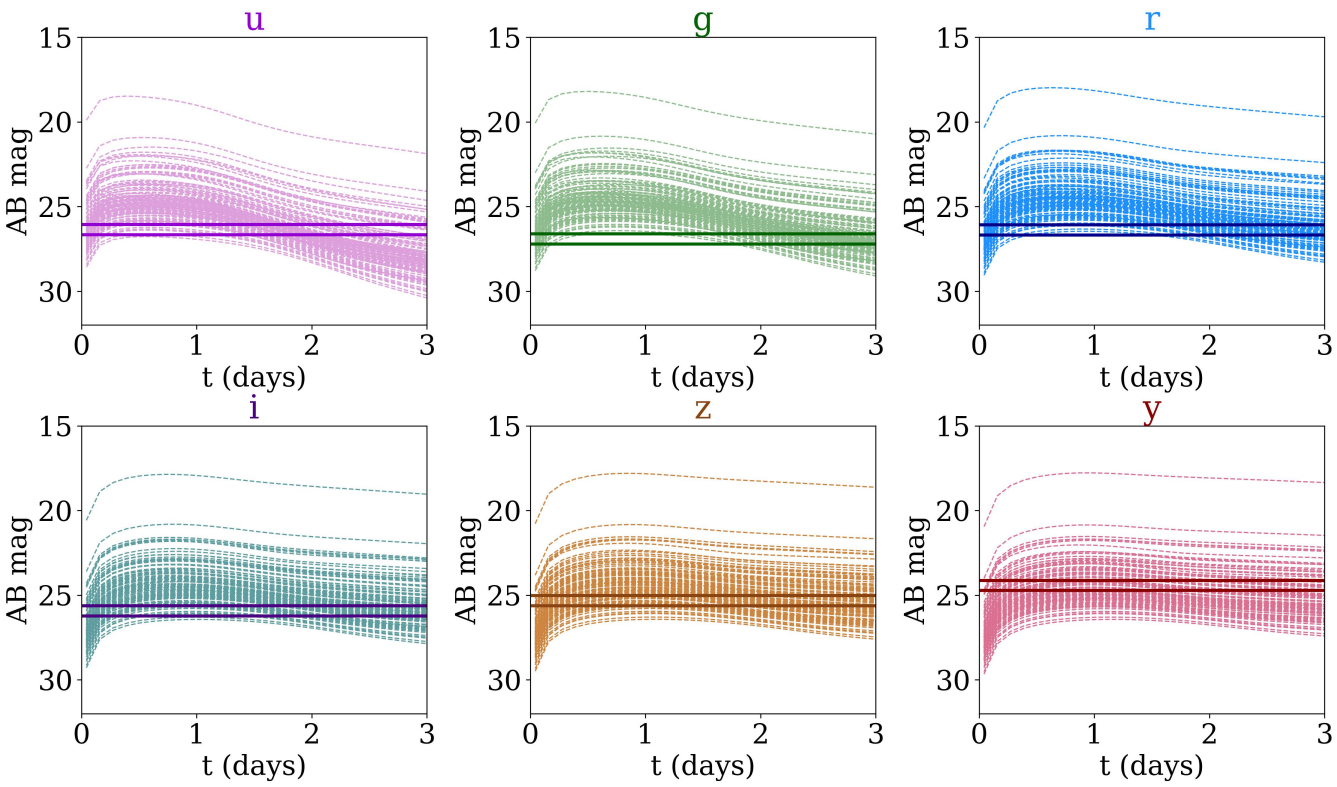
- Using an astrophysically motivated population of BNS mergers we estimate the detection efficiency and parameter estimation of ET by using a Fisher matrix code (`GWFish`) developed at GSSI (Harms et al. 2022)
- We model a KN reproducing the one associated with *GW*170817 (*see Eleonora's presentation*) and we associated to each BNS merger of the population a kilonova emission
- We built light curves in the *ugrizy* filters of Rubin for each BNS merger

Detection in Rubin

- We are using the *rubin_sim* repository, which simulates the baseline parameters of the decadal survey to be carried out by Rubin: *LSST*. We used it to explore the capabilities of Rubin for Target-of-Opportunity (ToO) observations
- We chose two filters: g and i to sample the spectral properties of the kilonova and still be sensitive enough to detect them up to larger distances
- We evaluated the joint detections for different configurations of ET (triangle vs 2L) operating in synergy with Rubin (this work is under embargo within the ET Observational Science Board)

KNe with Rubin

Evaluating the expected detections of kilonovae associated with BNS mergers localized by ET within 20, 40, and 100 sq. deg.



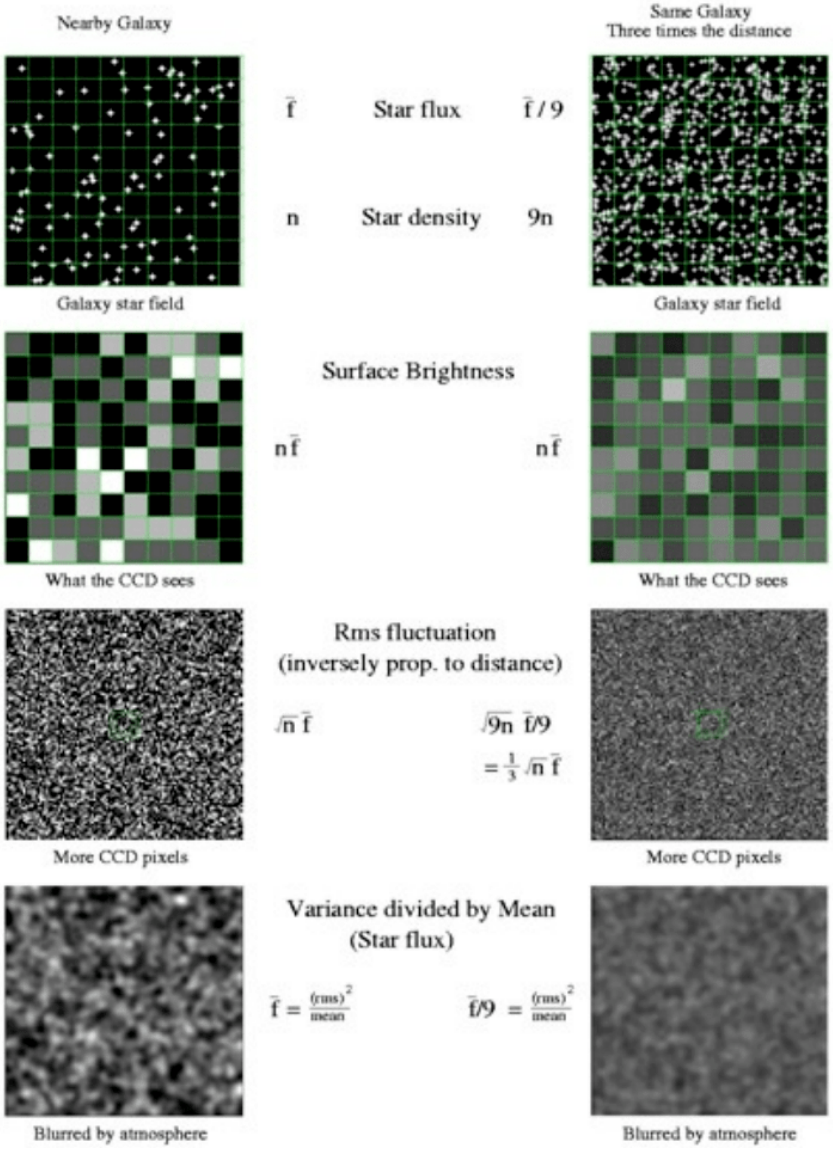
Observational strategy: mosaic of each sky-localization region, in 2 filters, for 2 nights post-merger. 2 scenarios: $t_{exp} = 600$s and 1800s

Future steps

- We will extend this work to a sample of 10 years of observations
- Using KN modelling that relies on on realistic progenitor parameters (*see Eleonora's talk*)
- We plan to develop a more refined and realistic ToO observational strategy

Thank You

The idea behind the SBF Method



Source: John Tonry

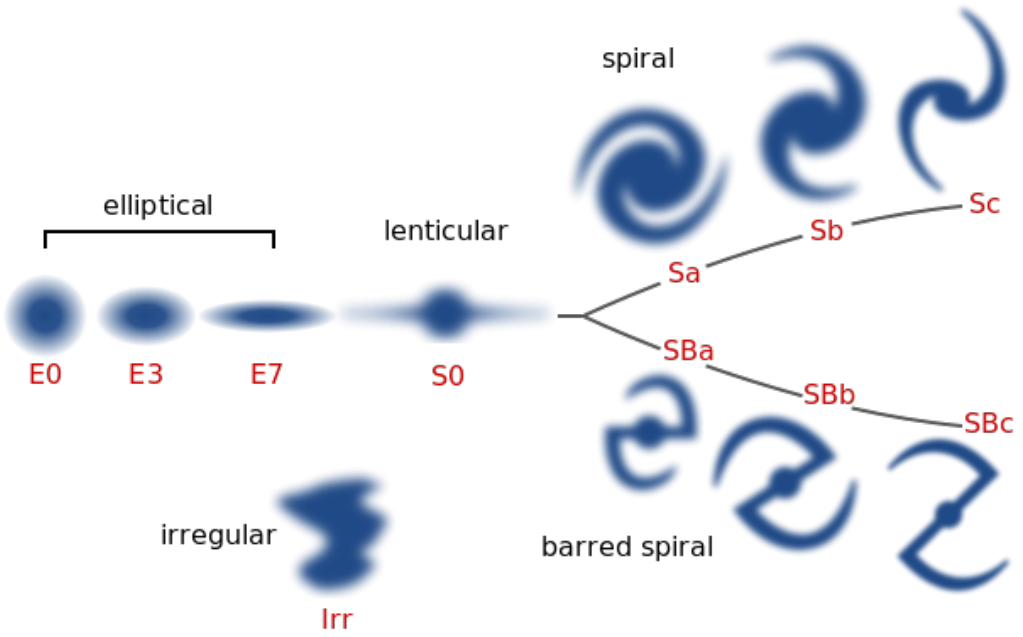
Quantify the pixel-to-pixel variation of surface brightness

$$\overline{\mathrm{L}} = \frac{\sum_j n_j L_j^2}{\sum_j n_j L_j},$$

Calibration sample

Galaxy	RA	Dec	B Mag	t type	Dist (Mpc)
I0745	178.551	0.136	14.04	-2.2±1	22.23
N4753	193.095	-1.199	10.57	-1.3±1.1	22.08
N5813	225.297	1.702	11.52	-4.9±0.4	31.77
N5831	226.03	1.221	12.43	-4.8±0.5	27.29
N5839	226.367	1.635	13.69	-2±0.5	20.82

Galaxies suitable for SBF analysis



- Spiral galaxies: dust, active star forming regions
- Ellipticals: ideal
- Low surface brightness (LSB), dwarf galaxies
- Distance < 100 Mpc

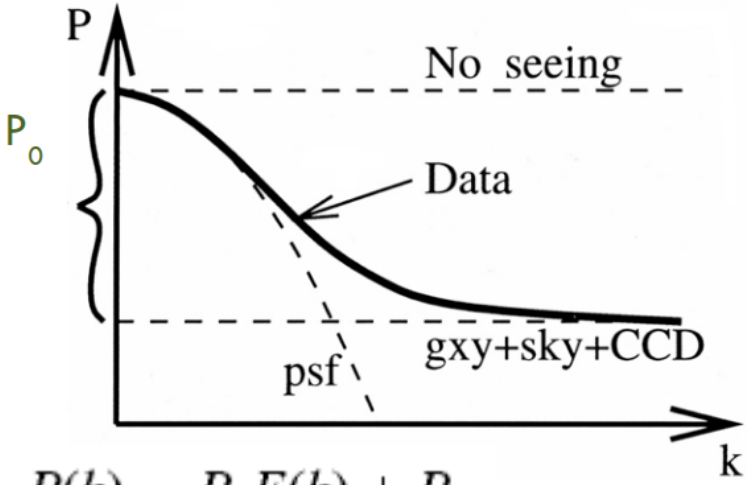
Galaxy sample selection

- Calibrating the pipeline on an existing sample from literature
  - 383 galaxies with measured SBF were taken from the major publications in 2001-2007
  - 16 galaxies were found within the observation footprint of HSC
  - 5 had coverage in g and i bands: these were chosen as calibration sample
- Building a new sample for further measurements
  - Bright, elliptical galaxies in HSC footprint
  - Distance smaller than 50 Mpc
  - Multi-band coverage: g and i bands
  - 38 galaxies: brighter than B-band magnitude 17

Steps of SBF analysis: Overview

1. Model the galaxy
2. Obtain the residual frame
3. Normalize the residual frame to the sqrt of the model
4. Mask all sources of non stellar fluctuations
5. Estimate the amplitude of the SBF in the Fourier domain
   $I \otimes PSF \rightarrow \bar{I} x PSF$
6.

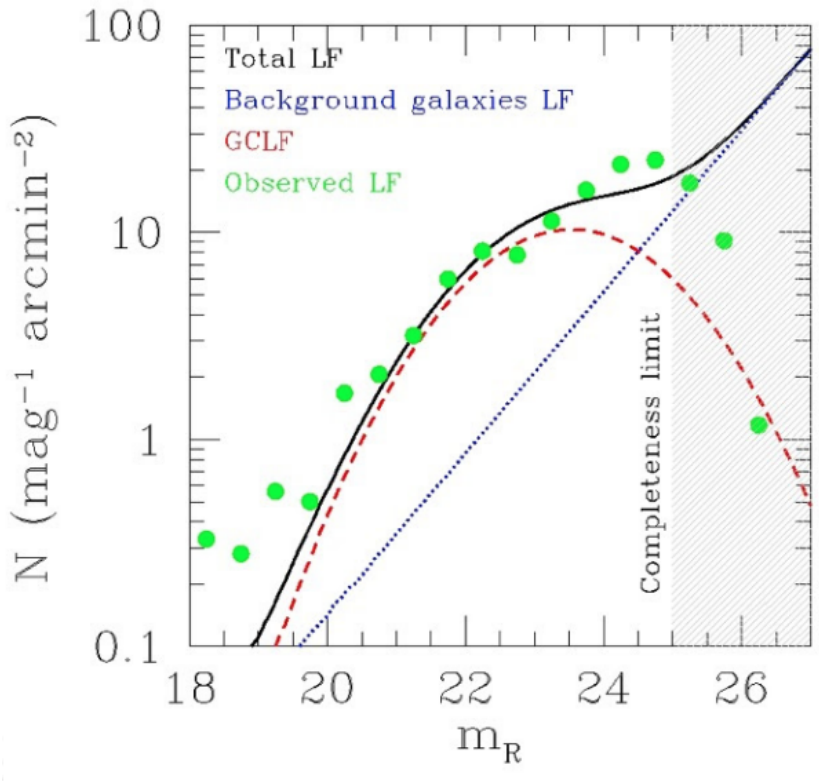
$$\overline{\mathrm{L}} = \frac{\sum_j n_j L_j^2}{\sum_j n_j L_j},$$



$$P(k) = P_0 E(k) + P_1,$$

Steps of SBF analysis: Overview

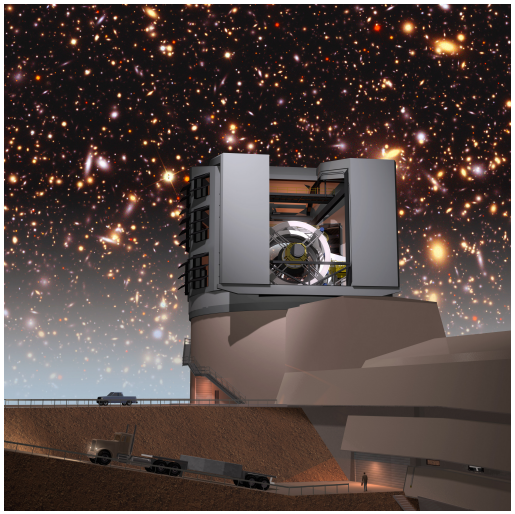
1. Model the galaxy
2. Obtain the residual frame
3. Normalize the residual frame to the sqrt of the model
4. Mask all sources of non stellar fluctuations
5. Estimate the amplitude of the SBF in the Fourier domain $I \otimes PSF \rightarrow \tilde{I} x \widetilde{PSF}$
6. Estimate and subtract the flux contribution of un-excised sources: P_r



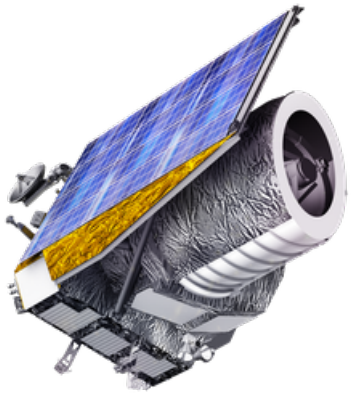
$$m_X = -2.5 log(P_0 - P_r) + m^X_{z.p.}$$

Cosmology with SBF: The Vera Rubin Observatory

- Vera Rubin Observatory: Legacy Survey of Space and Time(LSST)
  - 8.4 m telescope, ∼18000 sq deg. survey area, in SDSS ugrizy filters
  - i-band 5σ depth at 10 years 26.8 mag, FWHM 0.7"
- VRO will enormously increase the data of galaxies suitable to measure SBF distances up to 100 Mpc
- Extremely promising to measure the Hubble constant using SBF stand-alone or to calibrate SN type Ia (as shown in Khetan et al. 2021)



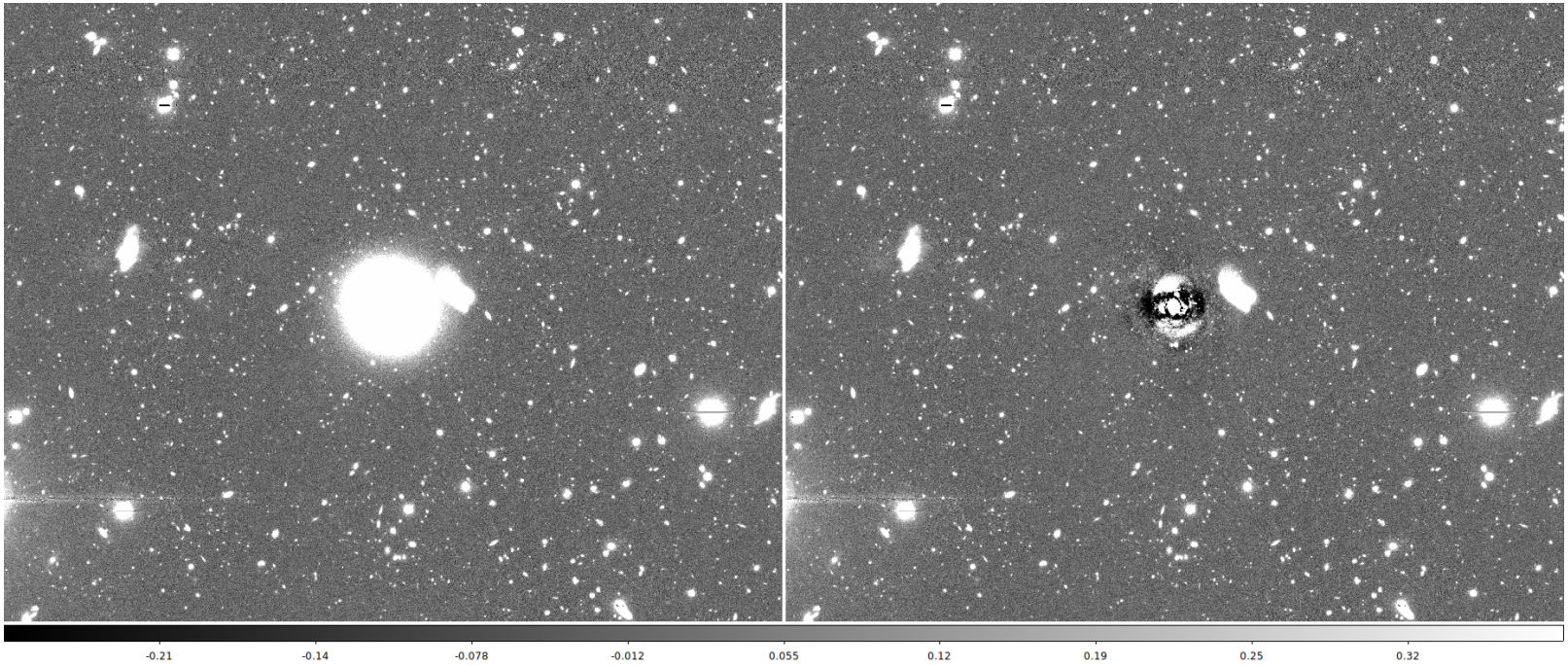
Cosmology with SBF: Euclid and JWST



- Euclid wide survey
  - $\sim$15000 sq deg. field of view, H-band depth 24 mag, FWHM 0.2"
  - SBF $\leq$100 Mpc
- James Webb Space Telescope
  - 6.5 m aperture, 7 times collecting area of HST
  - FWHM 0.06-0.08"

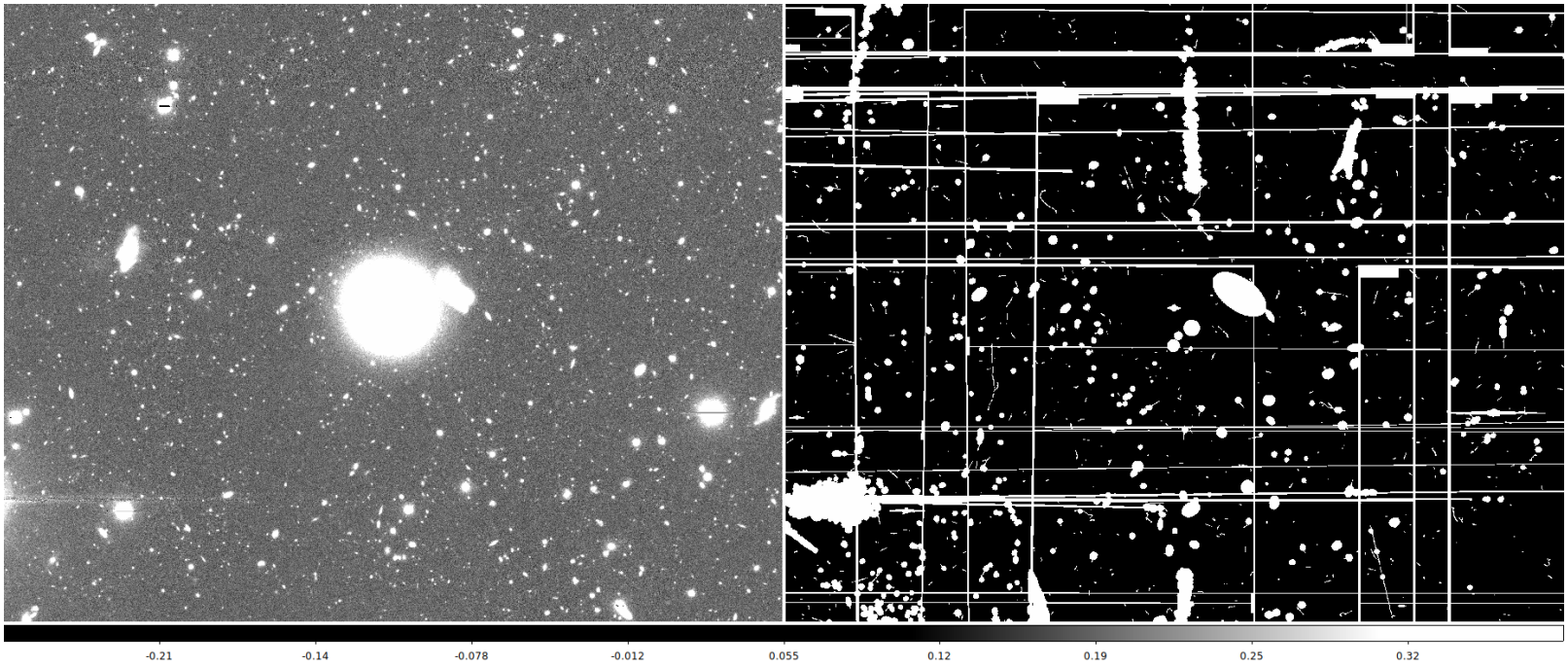
Modelling the galaxy

- Modelling with elliptical isophotes
- Subtract the profile of the galaxy from the image: IC0745



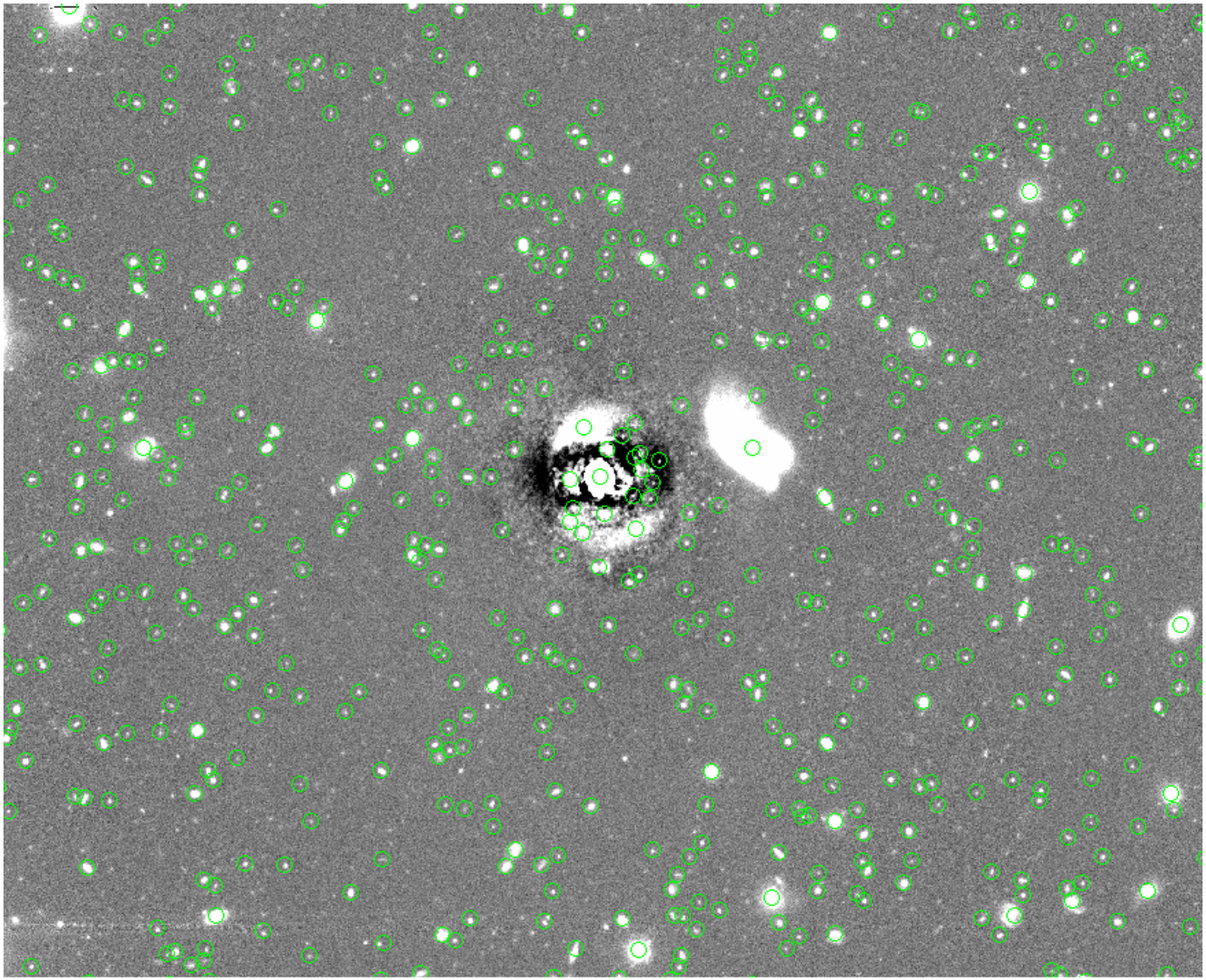
Generating a mask

- Mask dead pixels, contamination, cosmic ray hits: instrument team
- Mask bright objects
- Modelling and masking done iteratively



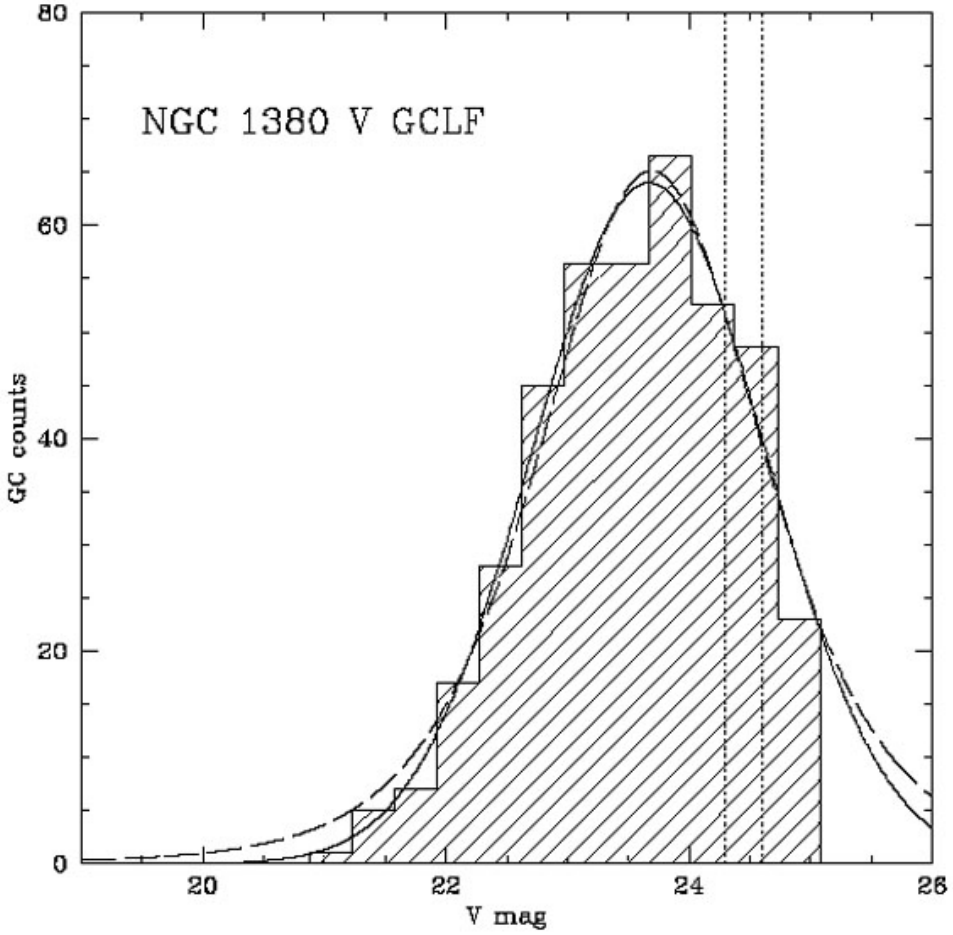
Creating a photometric catalog

- Generate list of extended and compact objects in frame
- Need to mask everything except underlying stellar population



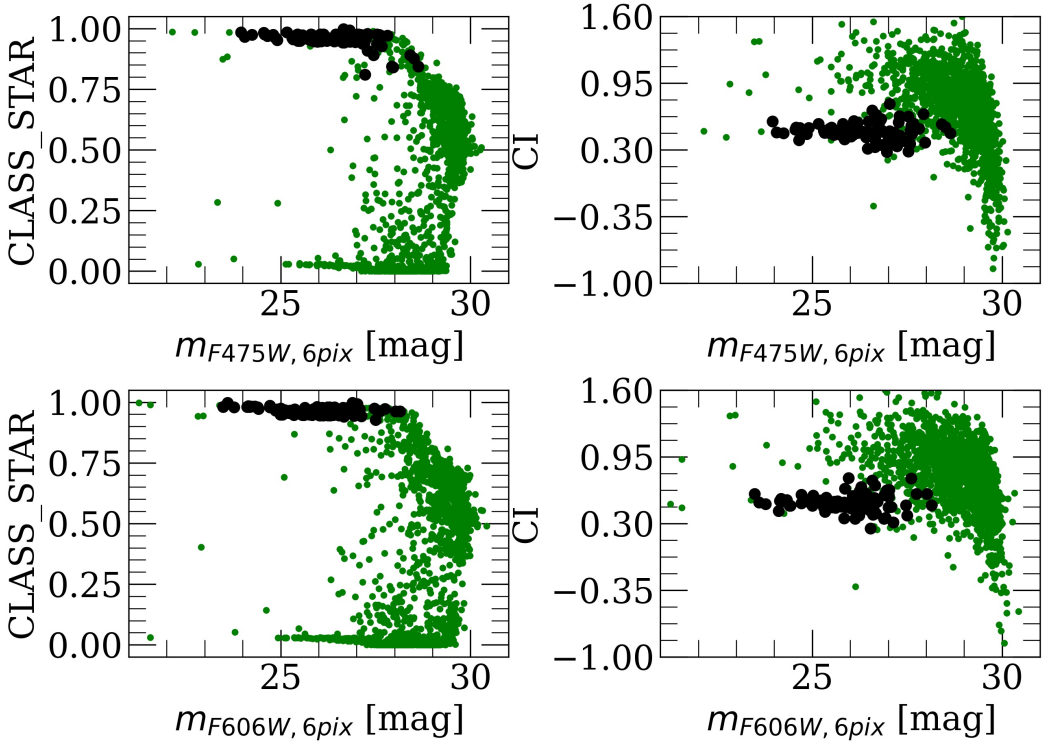
Globular Cluster Luminosity Function (GCLF)

Globular clusters are dense systems of old stars found almost ubiquitously in all galaxies: peak of luminosity function can be a distance indicator



Identifying the Globular Clusters : Part I

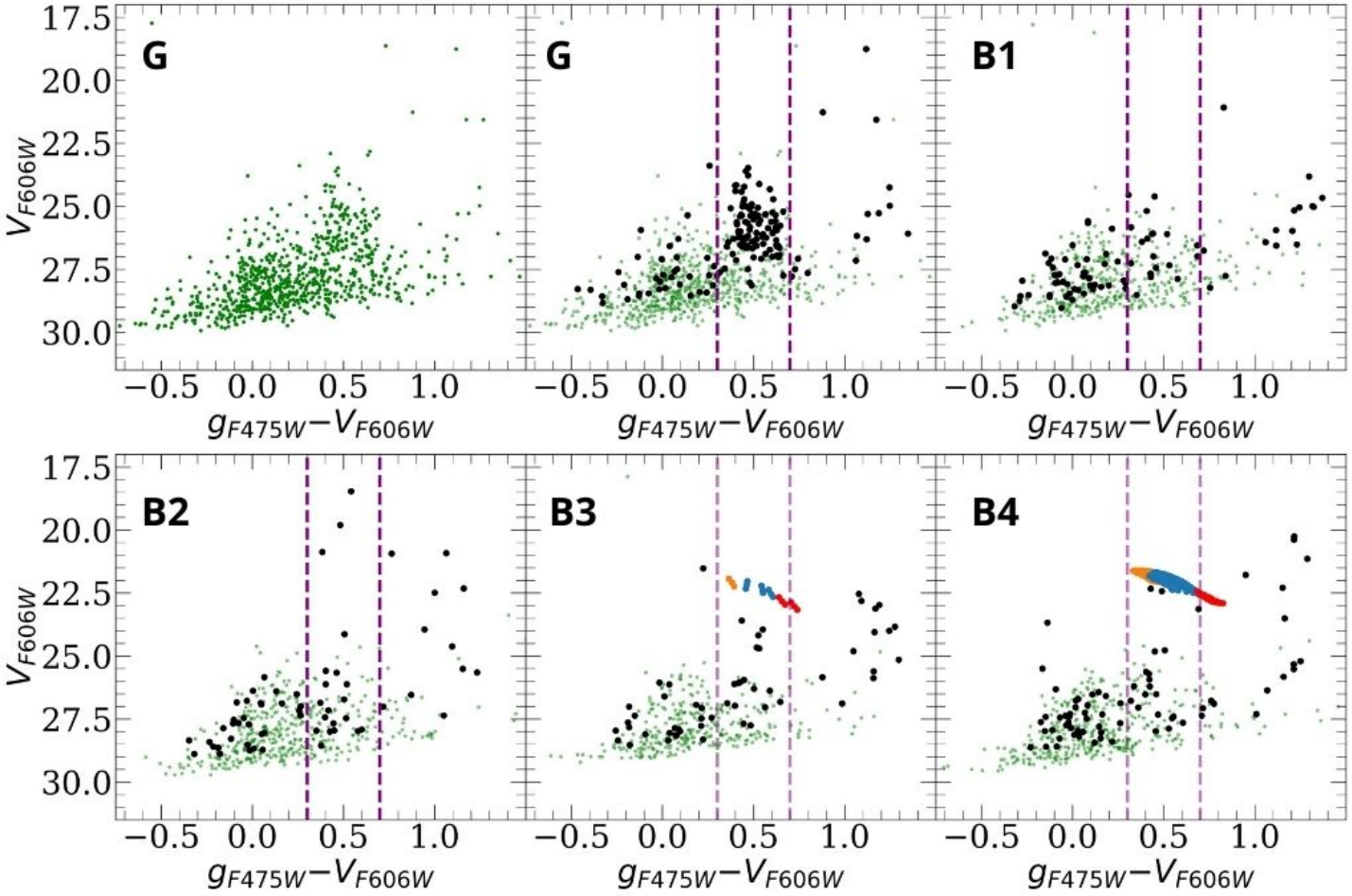
- Globular clusters are identified on the basis of different parameters: compactness
- SExtractor parameter: CLASS_STAR
- Concentration index: difference of magnitudes at two different apertures



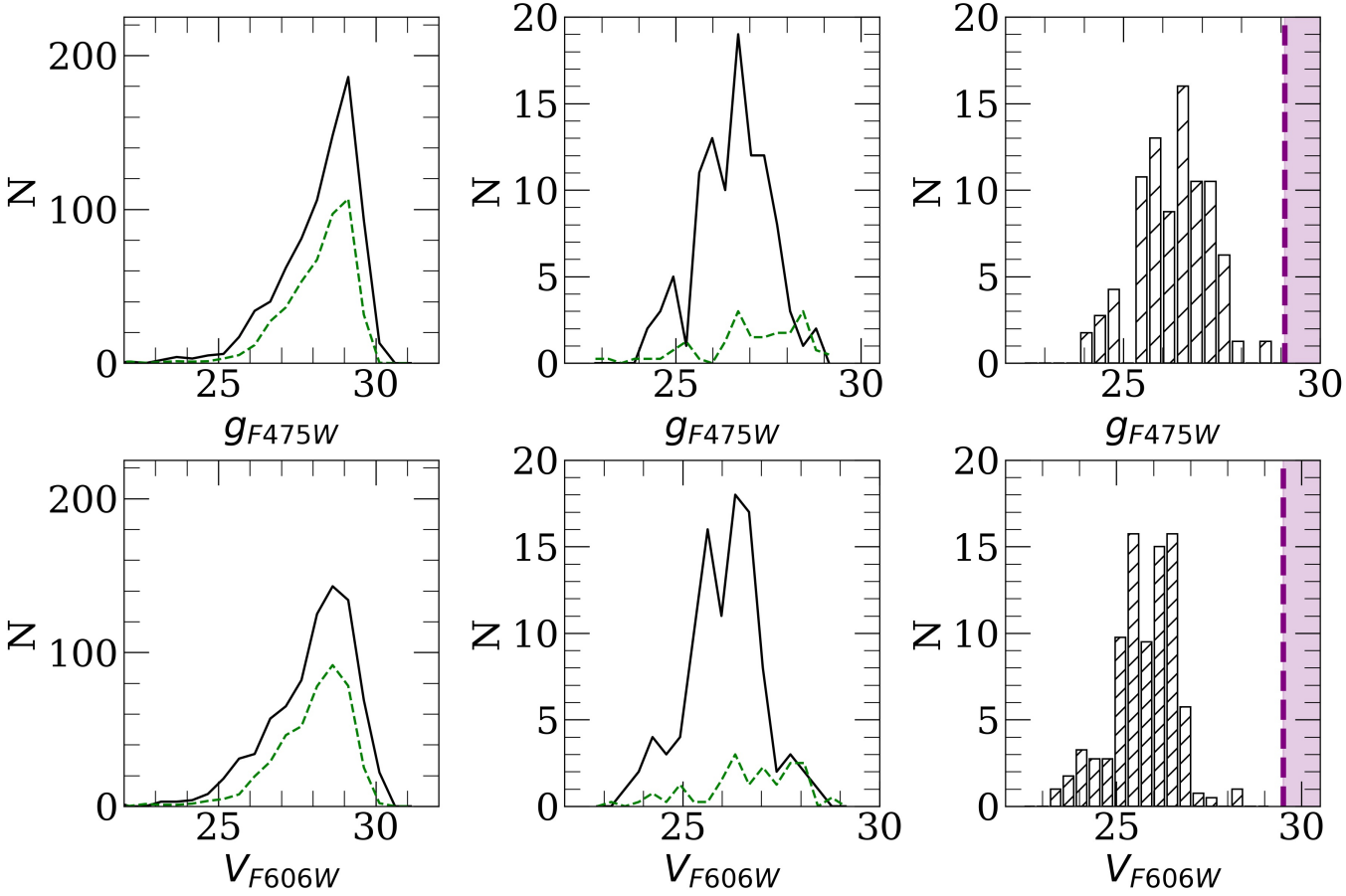
(NH, Cantiello et al. 2022)

Identifying the Globular Clusters : Part II

- Selection based on color
- Simple Stellar Population models: SPoT models from Raimondo et al., *COSM*^{2}*IC* Group at Yonsei University



GCLF in PGC 087327



- Completeness correction estimated: 90% complete at ~ 29.5