Distance Indicators for Cosmology
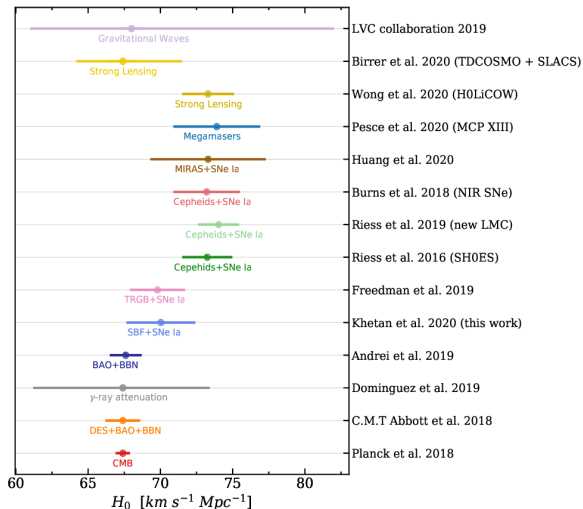
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GSSI L'Aquila/INAF-OAAb Teramo

Advisors
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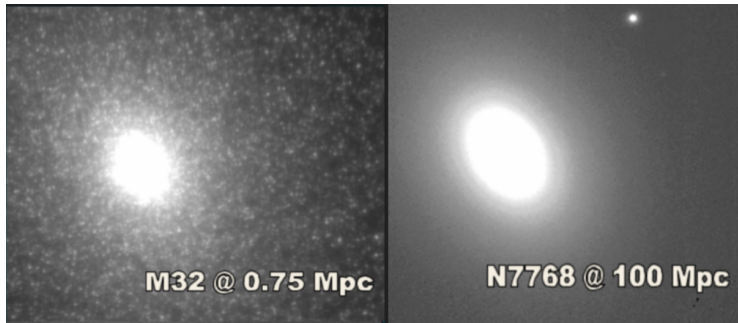# Why do we need precise distances?

- Astrophysics: precisely measure intrinsic source parameters, such as size and luminosity

- Cosmology: Hubble tension

Source: Khetan et al. 2021

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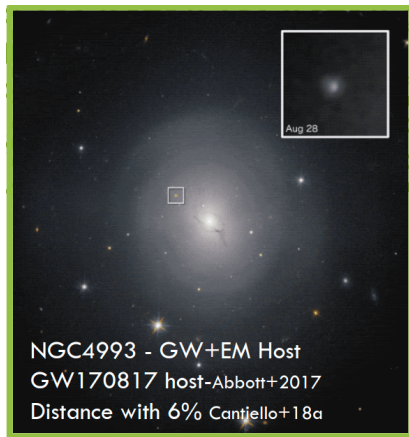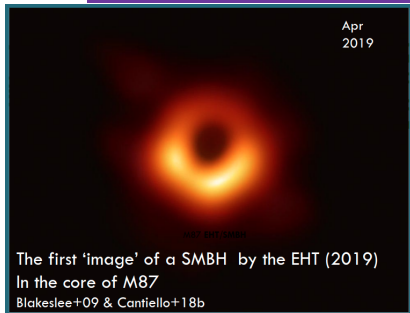# Extragalactic Distance Ladder

The idea behind the Surface Brightness Fluctuations (SBF) Method

- 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

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SBF recent results

NGC1052-DF2 'DM-free' galaxy
Van Dokkum+18 / Blakeslee & Cantiello (2018)

Apr 2019

The first 'image' of a SMBH by the EHT (2019)
In the core of M87
Blakeslee+09 & Cantiello+18b

Aug 28

NGC4993 - GW+EM Host
GW170817 host-Abbott+2017
Distance with 6% Cantiello+18a

Cosmology with SBF: The Vera Rubin Observatory

- Vera Rubin Observatory: Legacy Survey of Space and Time(LSST)
  - 8.4 m telescope, $\sim$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)

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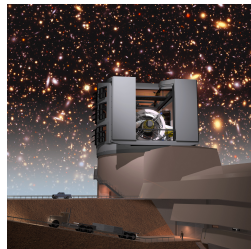
Cosmology with SBF: Euclid and JWST
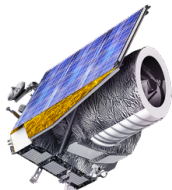
- Euclid wide survey
    - ∼15000 sq deg. field of view, H-band depth 24 mag, FWHM 0.2"
    - SBF ≤100 Mpc
- James Webb Space Telescope
    - 6.5 m aperture, 7 times collecting area of HST
    - FWHM 0.06-0.08"

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Our objective

Source: NAOJ

- Build a pipeline with Python for SBF distance measurements that requires minimal human intervention, to exploit all the potentialities of VRO 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

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
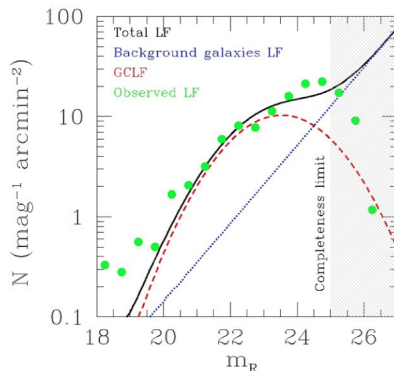   - 38 galaxies: brighter than B-band magnitude 17

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
 $I \otimes PSF \rightarrow \bar{I} \times PSF$
6.
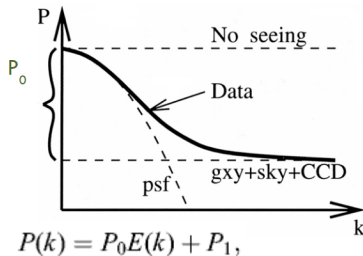
$$\overline{L} = \frac{\sum_j n_j L_j^2}{\sum_j n_j L_j},$$

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

Steps of SBF analysis: Overview

1. Model the galaxy
2. Obtain the residual frame
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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

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

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Modelling the galaxy

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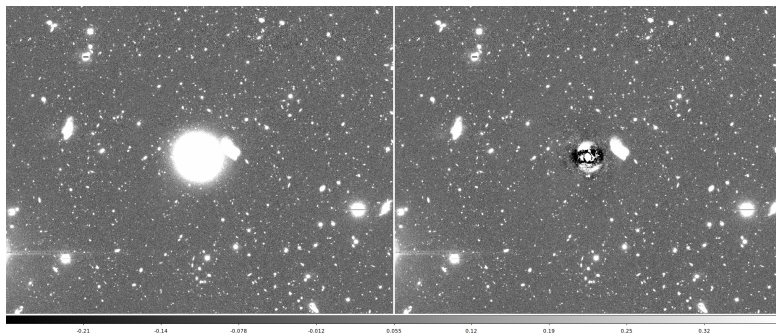
Generating a mask

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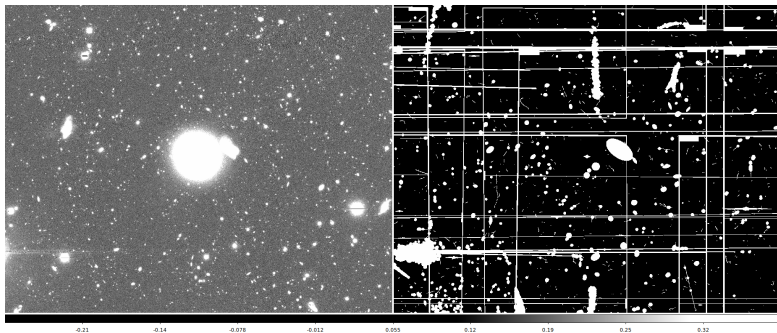
Creating a photometric catalog

- SExtractor: photometry tool
- Detects and generates list of extended and compact objects in frame
- Need to mask everything except underlying stellar population
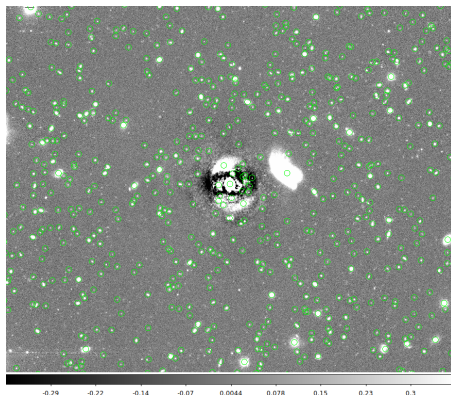
Pipeline first application and scientific results: Globular clusters

- LEDA087327: Lenticular Galaxy in Hydra I cluster, close to NGC3314A/B
- Very deep images from legacy archive of the Hubble Space Telescope: F606W and F475W bands of ACS/WFC

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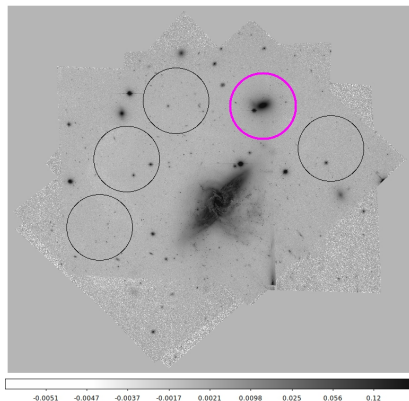
Globular Cluster Luminosity Function (GCLF)

Can be used as a distance indicator
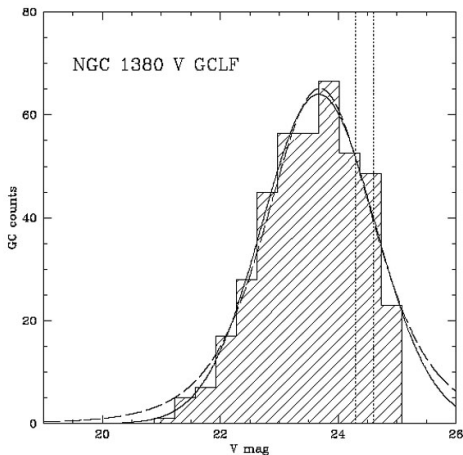
Source: Della Valle et al. 1998

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GCLF in LEDA087327

Perform modelling and photometry exactly as for SBF analysis and evaluate the residuals
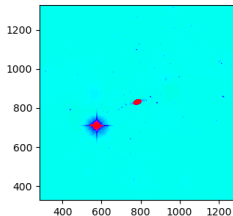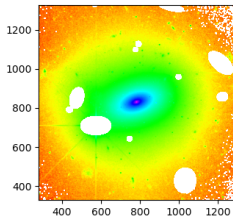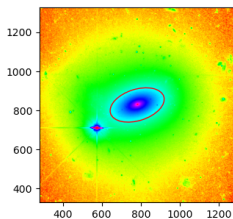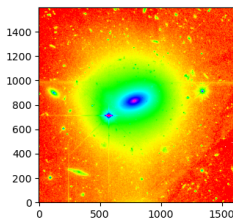
Identifying the Globular Clusters

Globular clusters are identified on the basis of different parameters:
compactness and concentration index selection

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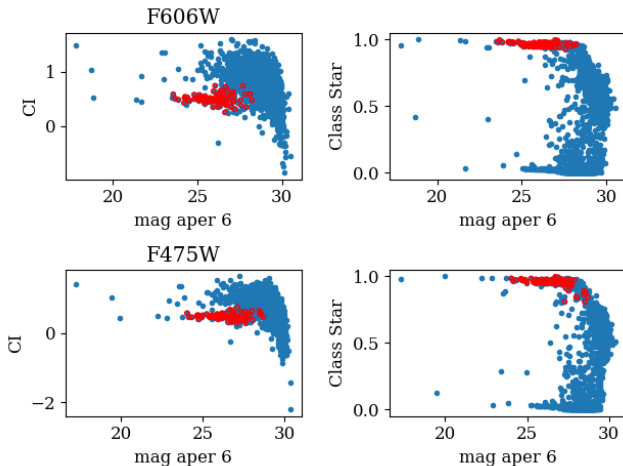
Identifying the Globular Clusters

- Selection based on color
- Simple Stellar Population models: *COSM²IC* Group at Yonsei University
- Using Ks band magnitude from 2MASS, mass of this galaxy $\sim 10^{10.15} M_\odot$
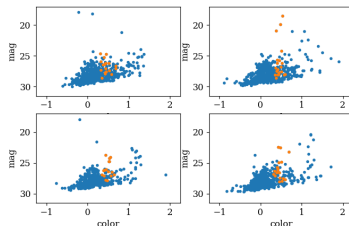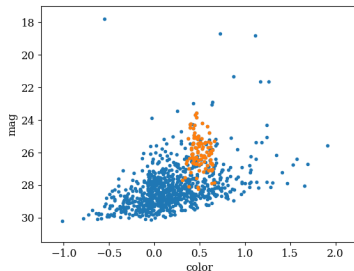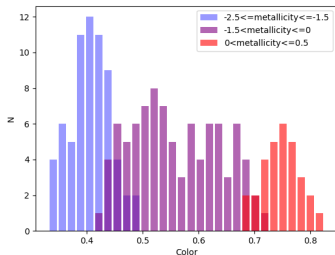
Radial profile and colors

Spatial distribution of red and blue globular clusters in the frame

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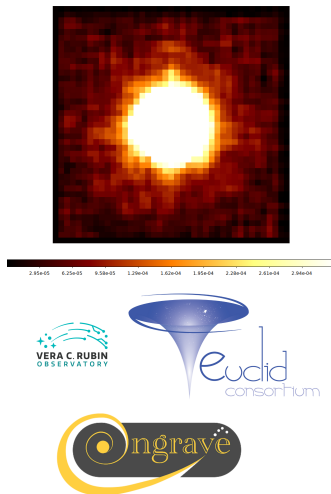
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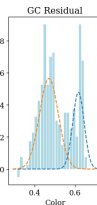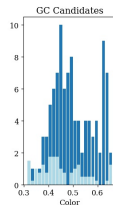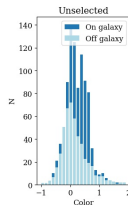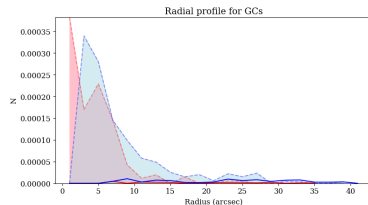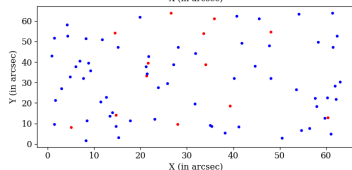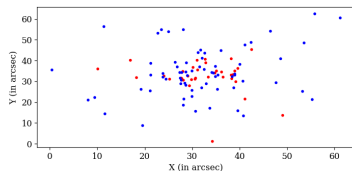
GCLF in LEDA087327

- Turnover magnitude: m
- Calibrate: M from literature
- $D = m - M \approx 33.9 \pm 0.2$
- Preliminary estimate of Hubble constant
  $H_0 = 72.4 \pm 7.8$ $km\ s^{-1} Mpc^{-1}$
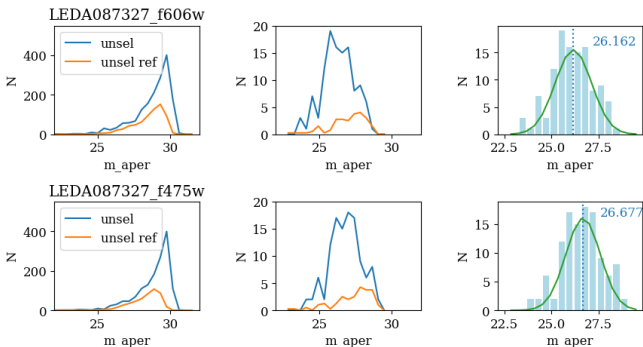
Future steps

- More than half-way through pipeline, laid the groundwork for the final steps
- Optimize the pipeline to VRO and Euclid data
- Finalize the paper on GCLF distance to LEDA087327
- Work on the 0th Data Preview of Rubin
- Optimize observational strategy for joint detections of VRO and GW detectors for cosmology

Summary

- SBF method can give us fast, accurate distances up to 100 Mpc
- We are developing an automated SBF pipeline on the precursor survey data of the Vera Rubin Observatory
- With minor modifications, adaptable to other instruments (Euclid)
- At its current status, the pipeline can already give us interesting science results with globular clusters

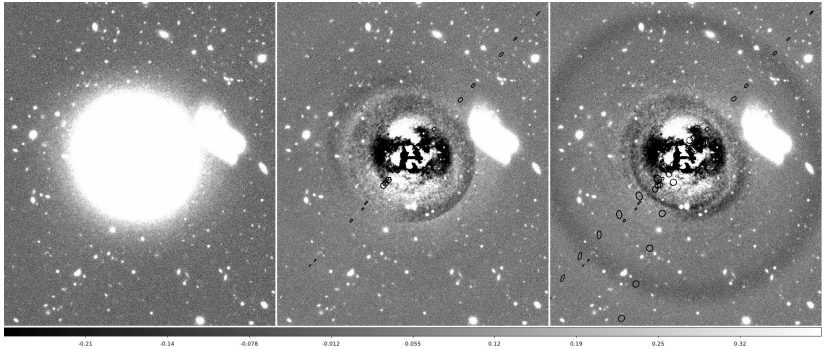# Thank You

The idea behind the SBF Method
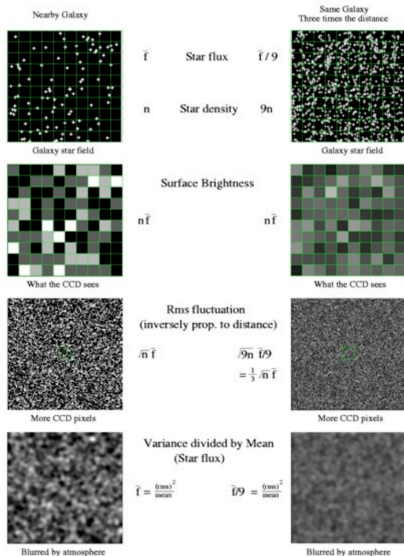
Quantify the pixel-to-pixel variation of surface brightness

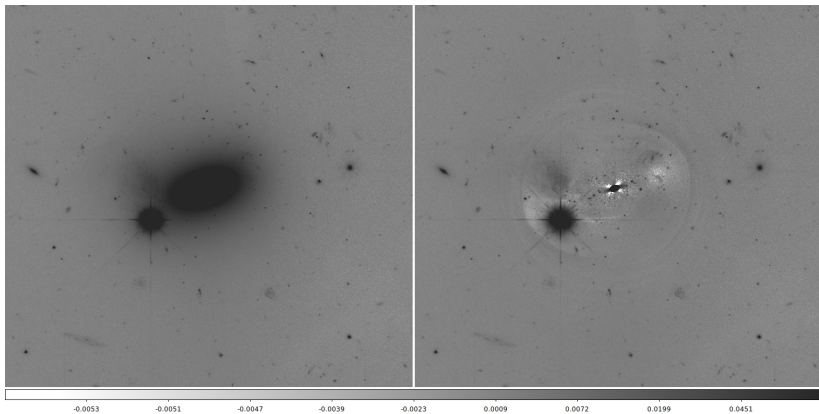$$\overline{L} = \frac{\sum_j n_j L_j^2}{\sum_j n_j L_j},$$

Source: John Tonry

Calibration sample

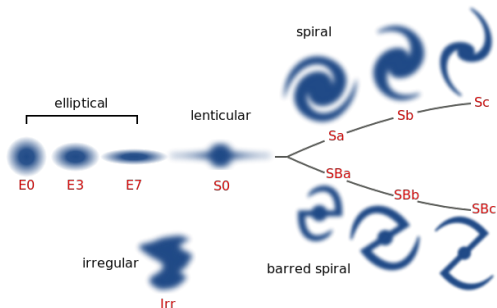| Galaxy	RA	Dec	B Mag	t type	Dist (Mpc)
I0745	178.551	0.136	14.04	-2.2±1	22.23
N4753	193.095	-1.199	10.57	-1.3±1.1	22.08
N5813	225.297	1.702	11.52	-4.9±0.4	31.77
N5831	226.03	1.221	12.43	-4.8±0.5	27.29
N5839	226.367	1.635	13.69	-2±0.5	20.82

Models : wrong

LEDA087327

Galaxies suitable for SBF analysis

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

Perspectives with SBF

- Individual distance measurements accurate up to $\sim 6 - 8\%$
- No need for targeted observation campaign
- Need for streamlined pipelines to handle large surveys data (like Vera Rubin Observatory's LSST)