The Population II Extragalactic Distance Scale: A TRGB Distance to the Fornax Cluster with JWST

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Reporter：Chenyanchi

Outlines

1. Introduction
2. Data and Data reduction
3. TRGB measurement
4. The next step: Calibration the SBF distance scale
5. Summary and future outlook

Introduction

- The local Hubble constant value measured via the distance ladder differs from the cosmic microwave background-inferred value by over 5σ. To determine if this discrepancy is due to new physics or systematic errors, it is crucial to develop high-precision distance ladders independent of traditional Cepheid and Type Ia supernovae methods, minimizing systematic uncertainties.

- For at least a half a century, the Virgo Cluster has been crucial in establishing the extragalactic distance scale. However, its depth and ongoing accretion of new members present challenges. The Fornax Cluster, though with smaller virializing region, is more compact with a depth of about ±5% of its distance and shows little evidence of recent accretion.

Introduction

◆ Fornax cluster is only slightly more distant than Virgo cluster, $\frac{d_F}{d_v} = 1.21 \pm 0.02$ (Blakeslee et al. 2009). In this paper, they present JWST observations of three early-type Fornax Cluster galaxies: NGC 1404, NGC 1380, and NGC 1399, to measure their TRGB distances and provide a first look at SBF measurements with JWST.

- **NGC 1404**: with a prior HST TRGB measurement and a host to two Type Ia supernova.
- **NGC 1380**: hosted a single Type Ia supernova
- **NGC 1399**: the central dominant galaxy in the cluster.

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Data and Data Reduction

- **Data source:** the first of 14 targets of Cycle 2 JWST program GO-3055 (Tully et al. 2023a)
- **Filter:** F090W + F150W (Short wavelength channels)
  - F090W: is optimal for TRGB and SBF because of the minimal variance of RGB magnitudes at lower metallicities. (Anand et al. 2024)
  - F150W: is also a good choice for SBF in the high metallicity domain of the galactic cores because the fluctuation signal is very bright and near its peak, making F150W SBF measurable to large distances.

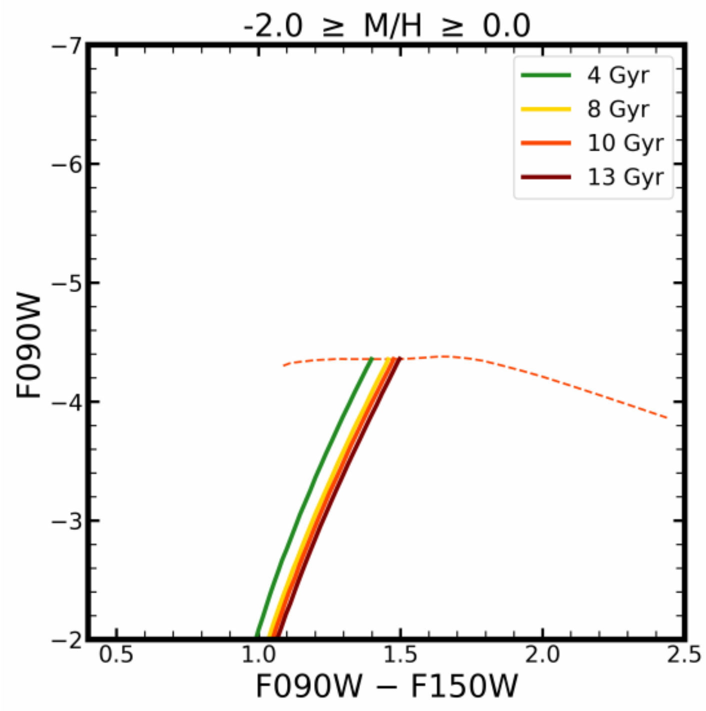
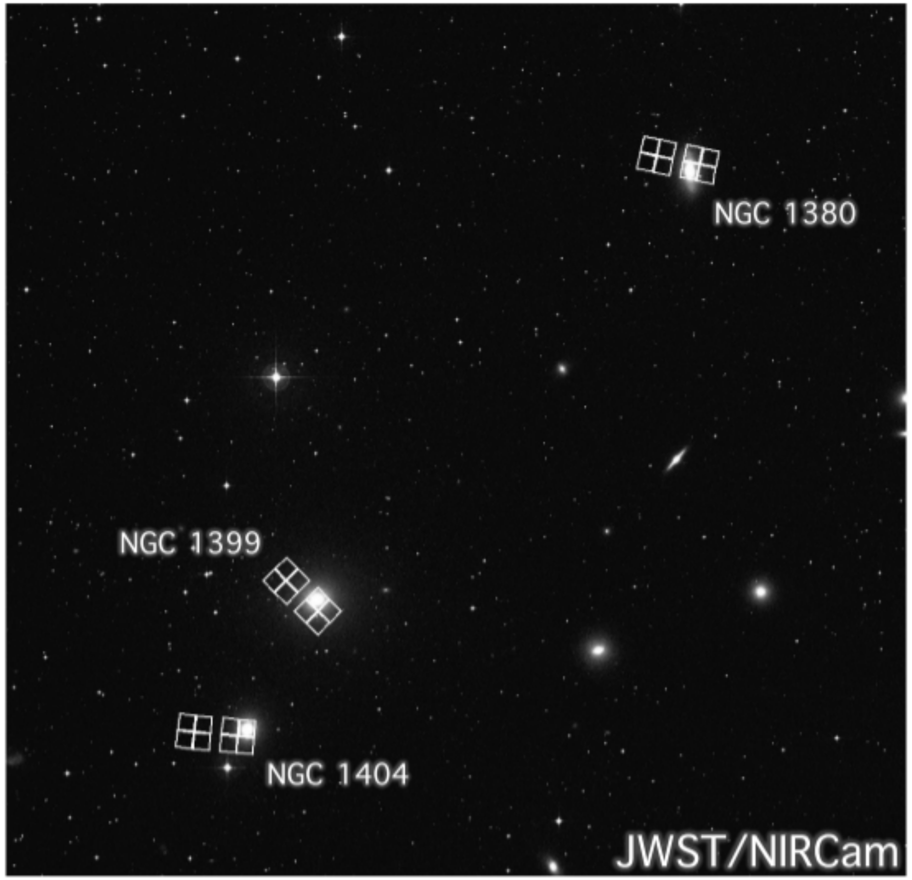


Fig2, Anand et al. 2024

PARSEC red giant branch isochrones

Data and Data Reduction

- Footprints of their JWST/NIRCam visits in the Fornax Cluster, overlaid on a one square degree image from the Digitized Sky Survey.

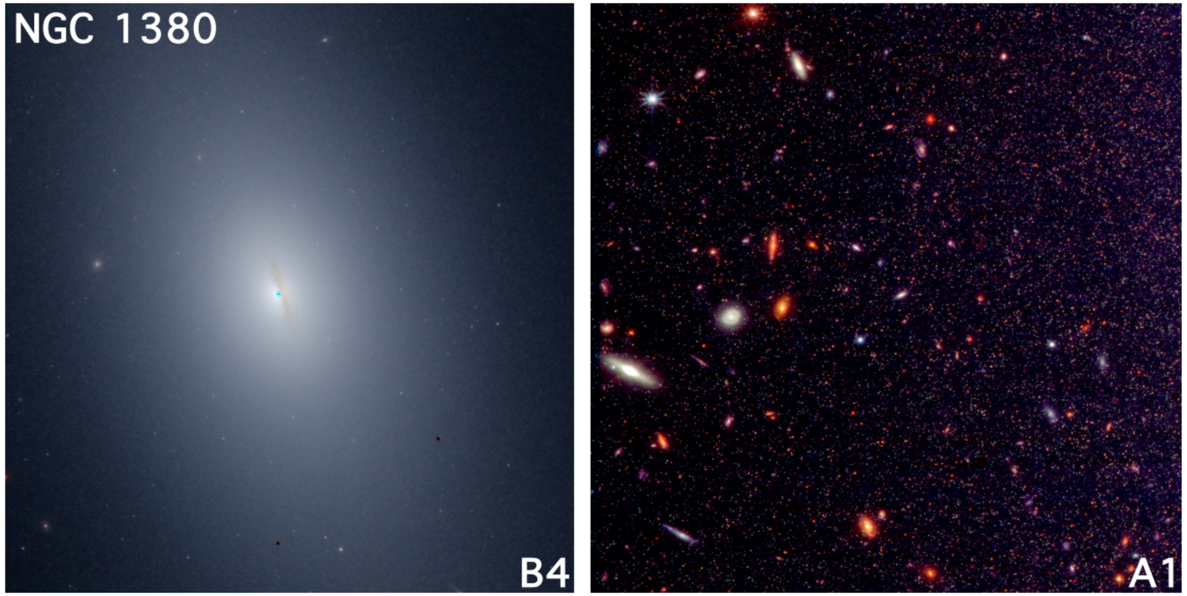


- Observation log for the data used in this paper.

Date	Target	Obs. ID	Filter	Time [s]
2023-10-12	NGC 1399	o002_t002	F090W	8761.204
2023-10-12	NGC 1399	o002_t002	F150W	2104.408
2023-11-09	NGC 1380	o001_t001	F090W	8761.204
2023-11-09	NGC 1380	o001_t001	F150W	2104.408
2023-11-14	NGC 1404	o003_t003	F090W	8761.204
2023-11-14	NGC 1404	o003_t003	F150W	2104.408

Data and Data Reduction

Simultaneous long-wavelength observations are made in both F277W and F356W, although they do not make use of these filters in this work.



Color (F090W+F150W+F356W) images of individual chips from the NGC 1380 visit

- The core of NGC1380 is centered on B4 chip.
- A small dust lane is apparent in the center. Individual stars can't be resolved due to crowding, but a few scattered globular clusters are visible. Some background galaxies can also be seen.

- A1 chip: one of the furthest chips from the core of the galaxy.
- Thousands of giant branch stars populate the region and they are easily separable due to the lower surface brightness. A variety of background galaxies are also visible.

Data and Data Reduction

Quality cut

- **Software for PSF photometry**: DOLPHOT along with its NIRCam module

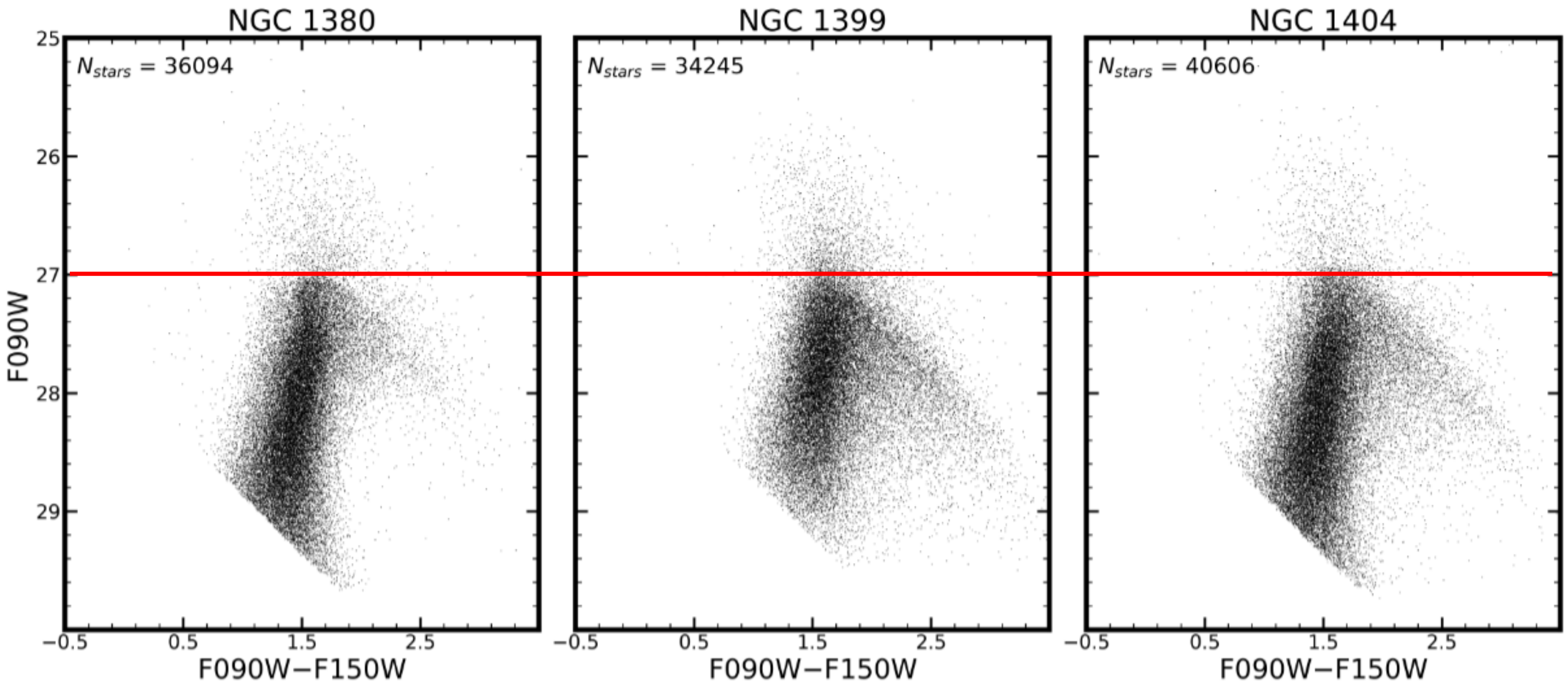
- They only include sources which meet the following DOLPHOT criteria in both filters in their final object list (except for type, which is not a filter specific output)
  (Warfield et al. (2023)Weisz et al. (2023))
  (1) Crowding <0.5
  (2) Sharpness2 ≤ 0.01
  (3) Object Type ≤ 2
  (4) S/N≥ 5
  (5) Error Flag ≤ 2

- All of their PSF photometry is transformed to the Vega system (and not the Sirius–Vega variant).

They conducted artificial star experiments with DOLPHOT, inserting and recovering 100,000 artificial stars per chip. These stars matched the spatial distribution of real stars, and the same quality filtering was applied. In order to quantify photometric bias and incompleteness.

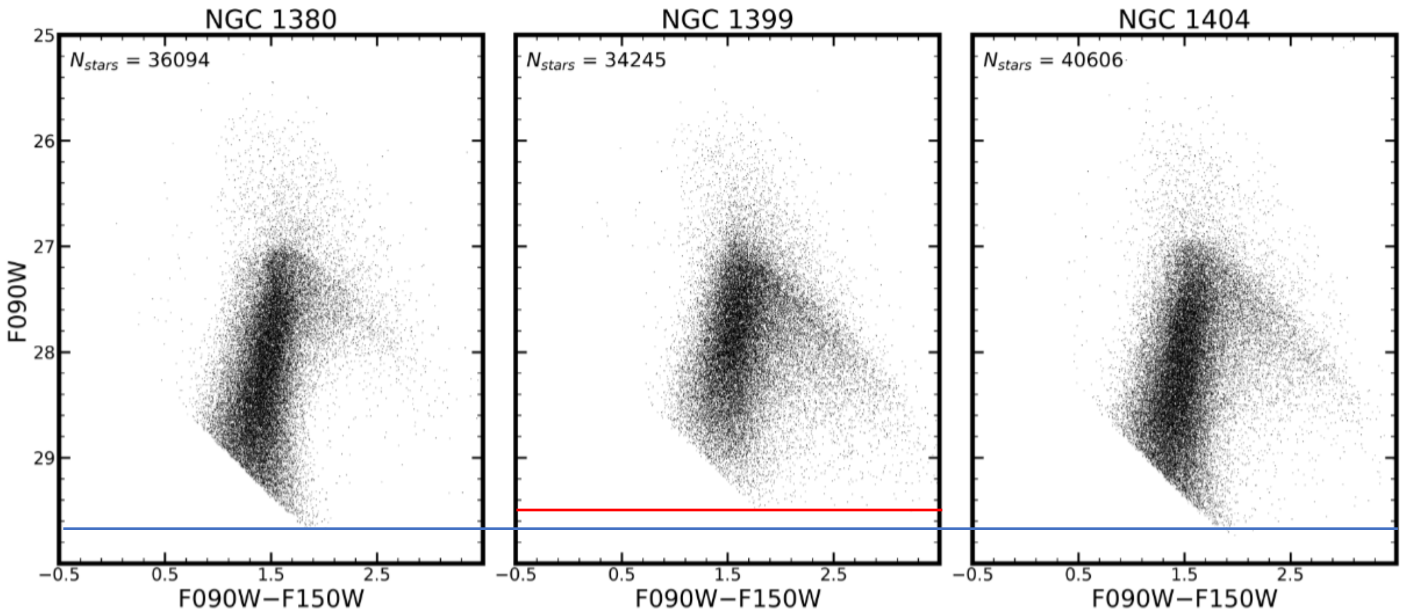
Data and Data Reduction

CMDs are limited to the two SW NIRCam chips that are furthest from the galaxy's core (A1+A2).



Data and Data Reduction

- In each CMD, the vast majority of resolved stars are those on the red-giant branch, with the TRGB visible at mF090W ≃ 27 mag (D = 19 Mpc) for each target.



- The magnitude limit of the CMD for NGC1399 is ~ 0.3 mag brighter than for the other two targets, likely due to crowding effects at the faint end. ((NGC1399 is the cD galaxy)

- For this TRGB work, they will only use the lower metallicity stars, which have little-to-no variation in their magnitude when observed in F090W.

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TRGB measurement

Two main techniques for measuring TRGB :

- **An edge-detection algorithm** (Lee et al. 1993; Beaton et al. 2019)
- **Fitting a model luminosity function to the observed data** (M´endez et al. 2002)

- For each target, they perform measurements on each of the two chips that are furthest from the galaxy's core: **A1** and **A2** chips.
- With both of their chosen measurement techniques, they also restrict their analysis to the color range of $0.5 \leq \mathrm{F090W}-\mathrm{F150W} \leq 1.75$ mag.

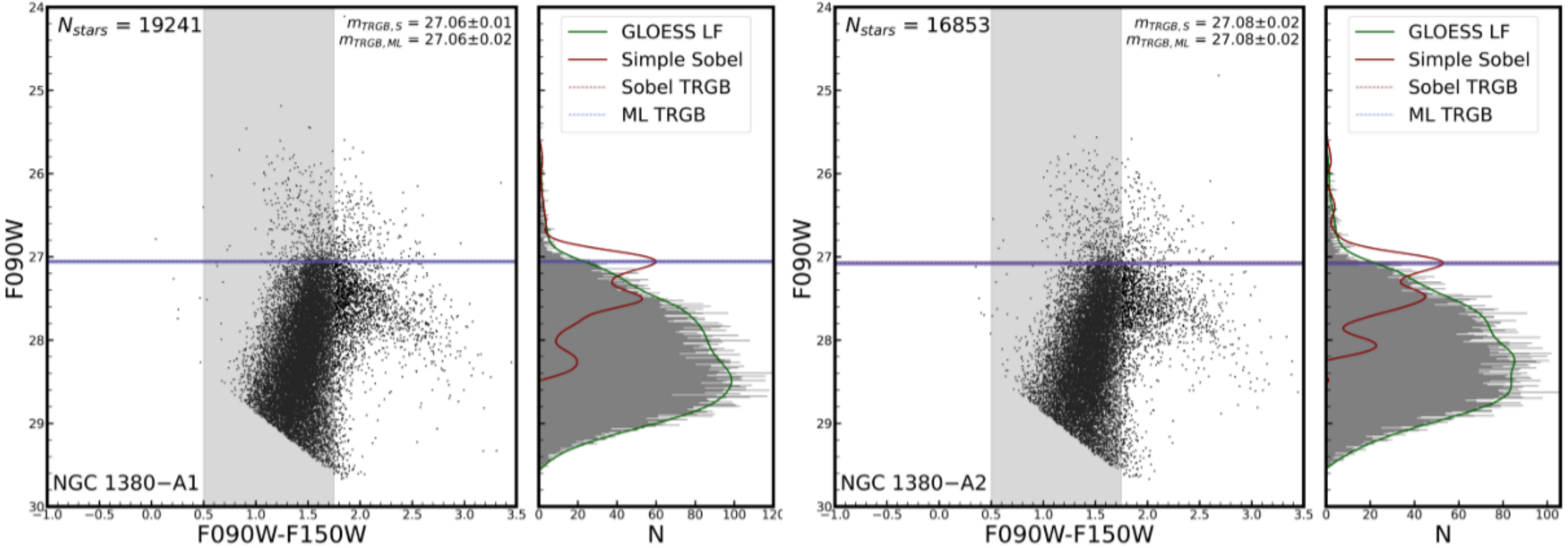
Sobel edge-detection

- **Restrict color range**: 0.5mag<F090w-F150w<1.75mag
- **Marginalize over color axis**: Generate a binned luminosity function with a bin-width of 0.01 mag.
- **Apply GLOESS smoothing**: Use a GLOESS smoothing kernel with a smoothing scale of σs = 0.10 mag.
- **Apply Sobel edge detection** : Use a Sobel edge detection algorithm with a kernel of [−1, 0, 1], similar to a first derivative.
- **Determine TRGB brightness**: Assign the first prominent response as the brightness of the TRGB.

The uncertainties are obtained via 1000 bootstrap resampling with replacement trials.

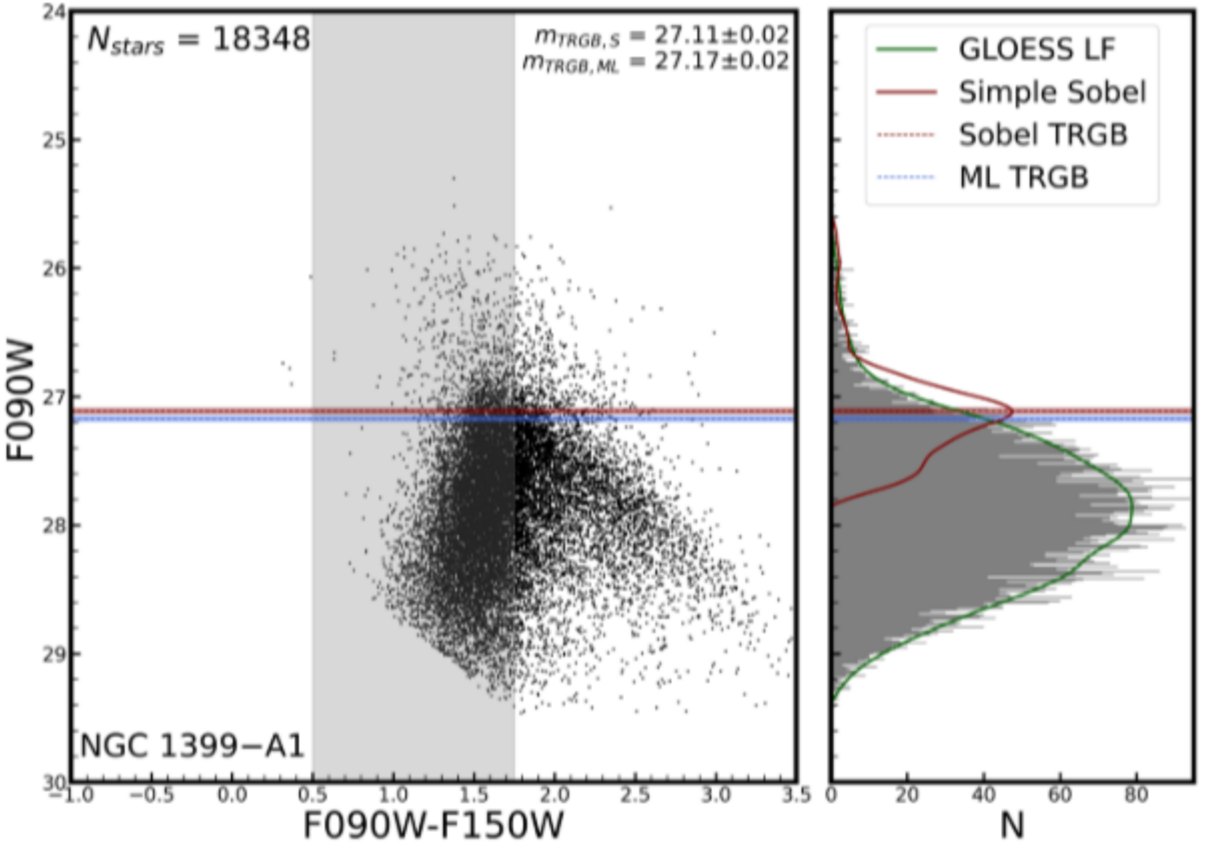
Sobel edge-detection

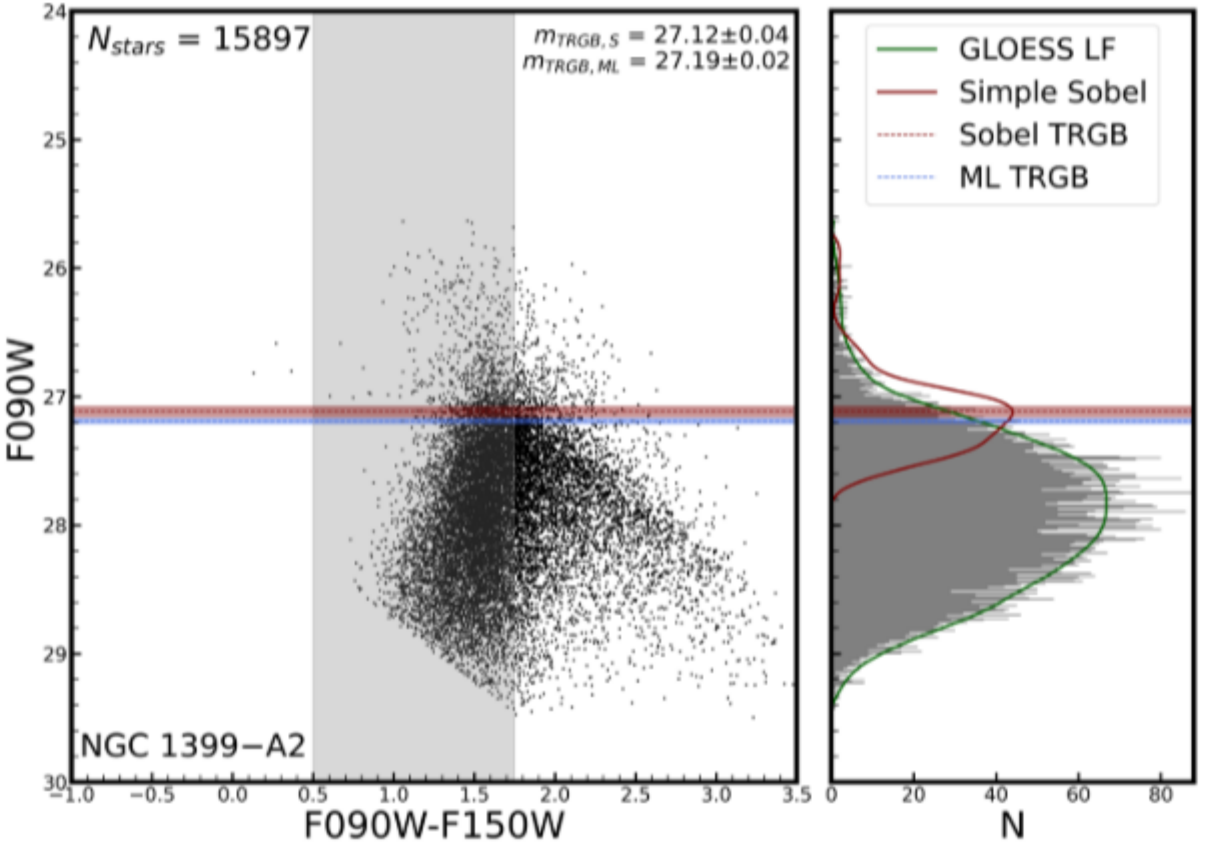
NGC1380



Sobel edge-detection

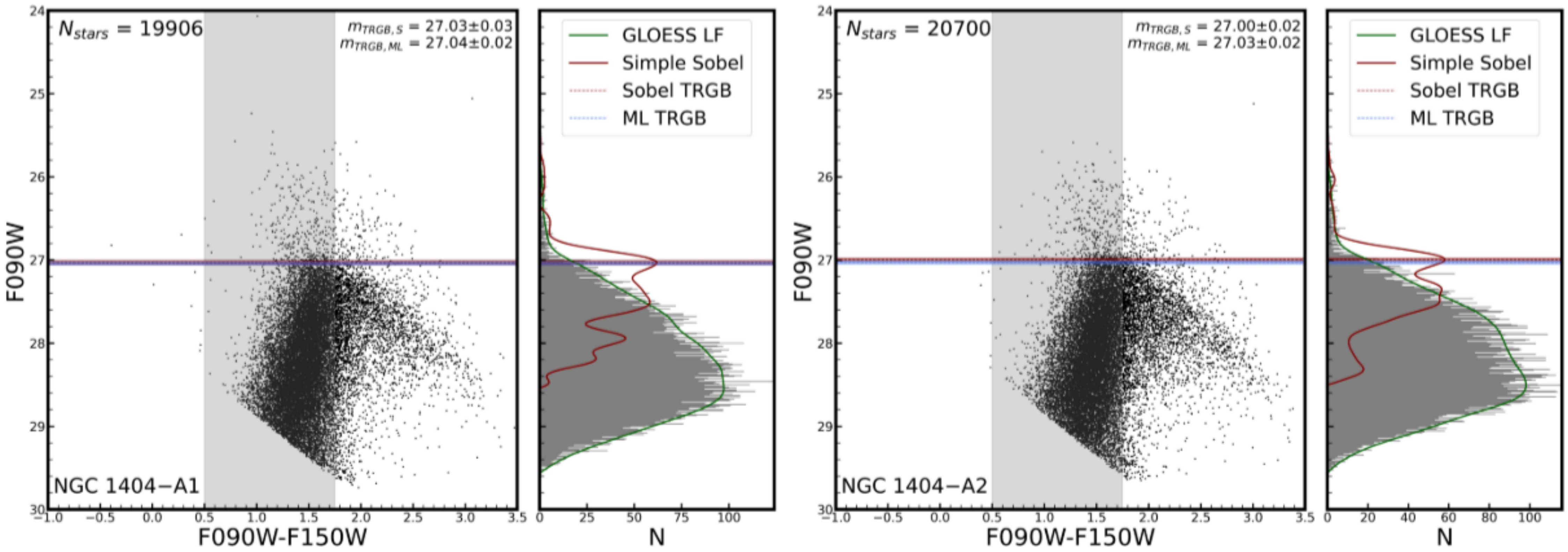
NGC1399





Sobel edge-detection

NGC1404



They find good agreement between measurements from the two distinct chips for each galaxy, with the differences ranging from 0.01 mag (NGC1399) to 0.03 mag (NGC 1404).

Model LF Fitting

They use the maximum likelihood TRGBTOOL(Makarov et al. (2006)) and adopt a theoretical luminosity function (LF) of the form:

$$\psi = \begin{cases} 10^{\,a(m-m_{\rm TRGB})+b}, & \text{if } m \geq m_{\rm TRGB} \\ 10^{\,c(m-m_{\rm TRGB})}, & \text{if } m < m_{\rm TRGB}, \end{cases}$$

This theoretical LF is used to fit the observed data, while taking into account the photometric bias, completeness, and errors derived from their artificial star experiments.

Field	m_{TRGB}	A_{F090W}	μ
NGC 1380−A1	27.061 ± 0.017	0.021	31.387 ± 0.066
NGC 1380−A2	27.081 ± 0.018	0.021	31.407 ± 0.066
NGC 1399−A1	27.169 ± 0.023	0.016	31.500 ± 0.068
NGC 1399−A2	27.190 ± 0.023	0.016	31.521 ± 0.068
NGC 1404−A1	27.035 ± 0.020	0.014	31.368 ± 0.067
NGC 1404−A2	27.026 ± 0.019	0.014	31.359 ± 0.067

Model LF Fitting

- The TRGB measurements for NGC 1380 and NGC 1404 show excellent agreement between the Sobel and maximum-likelihood techniques, with differences of 0.00 and 0.02 mag, respectively.
- However, NGC 1399 has a larger difference of 0.07 mag due to moderate crowding and photometric bias. The edge-detection results for NGC 1399 are likely biased brighter by blended RGB stars, while the maximum-likelihood method accounts for this bias.
- Given this, they use the maximum-likelihood results for final distances and recommend others check for photometric bias when performing TRGB measurements. And the final distance modulus for each galaxy is the average value from two chips.

Distance

They adopted an absolute calibration of TRGB from their recent work (Anand et al. 2024)

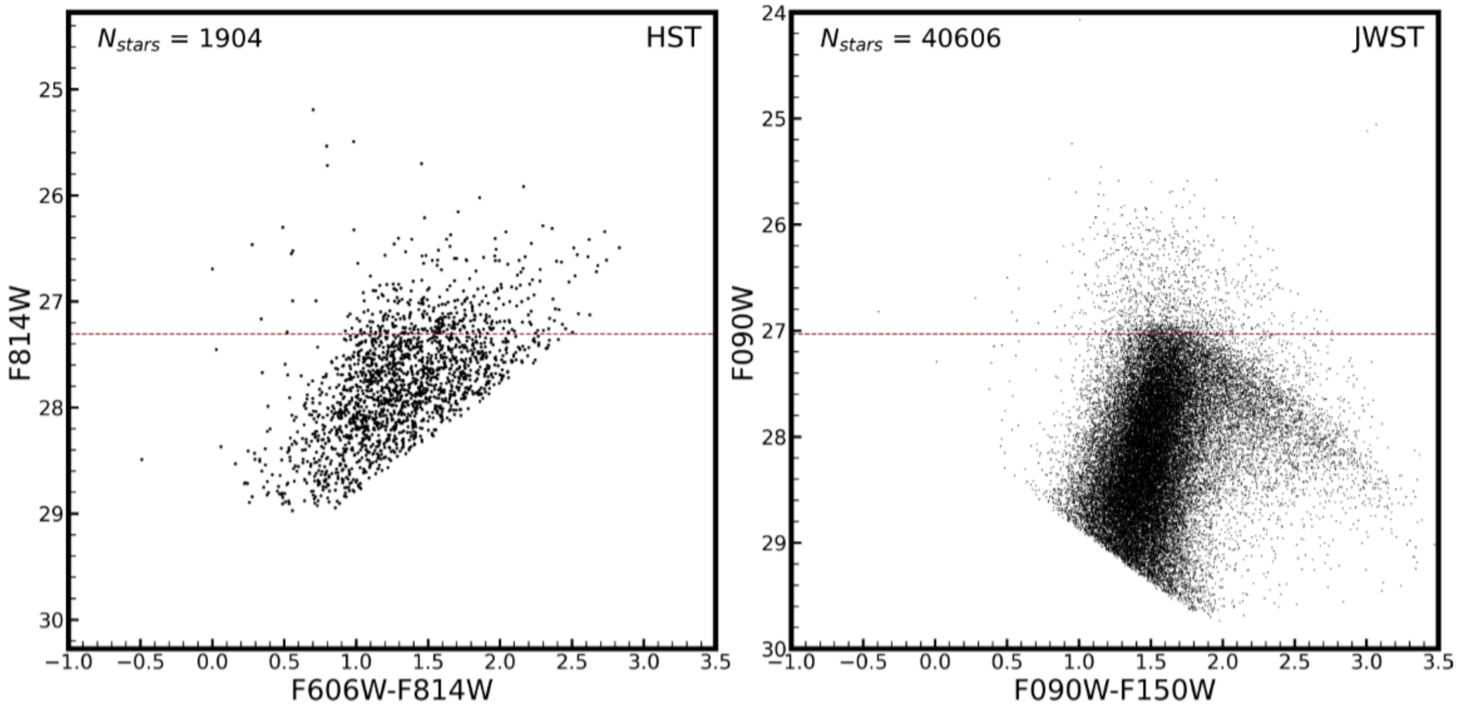
$$M_{TRGB}^{F090W} = -4.362 \pm 0.033\,(stat) \pm 0.045\,(sys)\ mag$$

Extinction：**NGC 1380**: A_{F090W}=0.021mag; **NGC 1399**: A_{F090W}=0.016mag; **NGC 1404**：A_{F090W}=0.014mag

Galaxy	JWST TRGB	HST TRGB	HST Cepheid
NGC 1316		$31.35 \pm .10$	
NGC 1326A			$31.009 \pm .100$
NGC 1365		$31.40 \pm .09$	$31.378 \pm .056$
NGC 1380	$31.397 \pm .066$		
NGC 1399	$31.511 \pm .068$		
NGC 1404	$31.364 \pm .067$	$31.27 \pm .10$	
Average	$31.424 \pm .077$	$31.34 \pm .07$	$31.194 \pm .260$

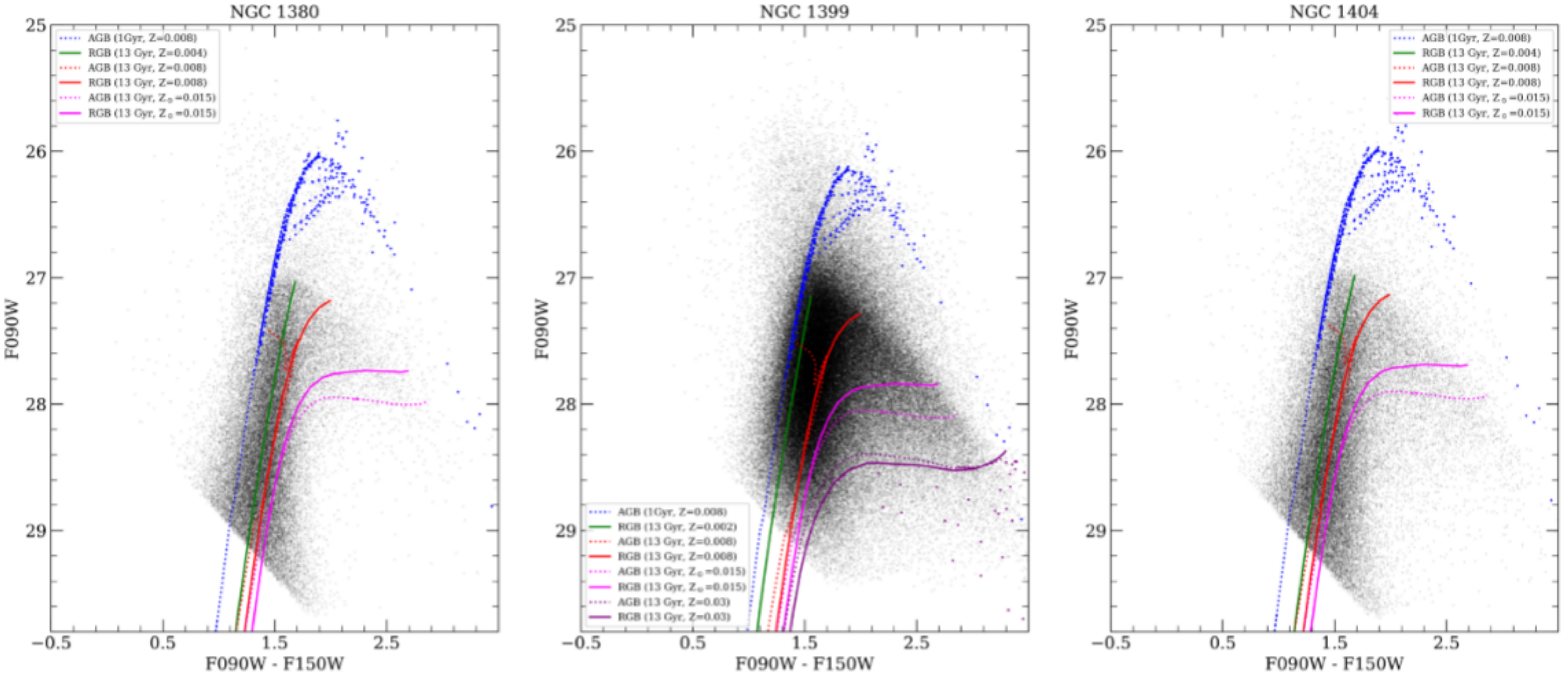
Distance

Comparison of two CMDs (down to S/N = 5) for **NGC1404** used to measure the TRGB distance to this galaxy with different telescopes.



- Dashed red lines: TRGB
- The HST data was taken over 34 orbits (51 hours) as part of the Carnegie-Chicago Hubble Program(CCHP).
- It is from the Extragalactic Distance Database.
- The JWST data was taken from the A1 and A2 chips, with only 4.74 hours of total charged time.
- <u>The efficiency of the JWST observations is remarkable!</u>

Stellar Population



Stellar Population

- **NGC 1380** (Lenticular galaxy):
  - Primarily composed of old RGB and AGB stars, but in smaller numbers.
  - Metallicity slightly below solar, but the high metallicity “tail” is smaller.
  - Outer regions contain fewer young stars.

- **NGC 1399** (Giant elliptical galaxy):
  - Dominated by old red giant branch (RGB) and asymptotic giant branch (AGB) stars, with ages around 13.7 Gyr.
  - Outer regions contain a small amount of young stars, with ages around 1-2 Gyr.
  - Metallicity slightly below solar ($Z \approx 0.008$).

- **NGC 1404** (Elliptical galaxy):
  - Stellar population composition is intermediate between NGC 1380 and NGC 1399.

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SBF: Surface Brightness Fluctuations

- The SBF technique (Tonry & Schneider 1988) is a statistical measurement of the brightness of the luminosity-weighted mean luminosity of a population of stars, which is dominated by RGB stars. Unlike the TRGB, SBF measurements do not require resolution of individual RGB stars.

- The TRGB distances presented here, based on a geometric calibration of NGC 4258, provide the basis for a new SBF zero point calibration using old, Population II stars.

- The spatial variations in surface brightness in a galaxy arise from the Poisson statistics of the discrete stars in the stellar population.

- The typical internal SBF distance errors (not including systematic uncertainty) with HST are less than 5% per galaxy, putting SBF on the same statistical level as type Ia supernovae, and capable of reaching well into the Hubble flow.

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Summary and future outlook

- High-precision measurements of the Tip of the Red Giant Branch (TRGB) in the galaxy halos of three early-type Fornax Cluster galaxies were conducted using JWST observations.
- Accurate relative distances to these targets were derived, with the need for a final adjustment of the absolute zero-point.
- Surface brightness fluctuations (SBF) measurements were also made in the cores of these galaxies with extremely high precision.
- Future observations will include 11 more early-type galaxies, aiming to establish a direct linkage between the TRGB and SBF distance scales with better than 2% accuracy.
- Building a new Population II distance ladder will involve SBF observations of approximately 40 elliptical galaxies in the Coma Cluster during JWST Cycle 3, providing a robust calibration for application at distances beyond 300 Mpc.
- This new TRGB dataset will enhance the accuracy of cosmological distance measurements and reduce reliance on indirect calibrations from different stellar populations or galaxy types.

Thank you!