Exploring Simple-Population and Multiple-Population Globular Clusters in the Outer Galactic Halo using the Hubble Space Telescope

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Reporter: Jiayu Qi

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Introduction

- First Population (1P): **formed** during the first star formation burst; **observed** in Galactic-halo field; old stars **rich in C, O and Mg.**
- Second Population (2P): **formed** in gas donors (1P); **rarely** detected in the field; **enriched in He, N, Na and Al.**
- **Chromosome map (ChM):** pseudo two-color diagram; disentangle 1P and 2P stars of star clusters.

$$m_{F275W} - m_{F814W} \longrightarrow \textbf{He}$$

$$C_{F275W,F343W,F438W} = (m_{F275W} - m_{F343W}) - (m_{F343W} - m_{F438W})$$

$$\downarrow$$

C、N、O

Introduction

- **Four outer-halo clusters:** Ruprecht 106, Terzan 7, Arp 2 and Terzan 8.
- Threshold value for the onset of MPs: $\sim \mathbf{1.5 \times 10^5} \boldsymbol{M_\odot}$ proposed by Milone et al. (2020).
- whether MPs are a widespread trait or whether only clusters surpassing a specific mass threshold can sustain the formation of MPs.

Table 1. Main parameters of the four globular clusters analyzed in this work: cluster ID, galactocentric distance (R_{GC}), iron content ([Fe/H]), reddening (E(B−V)), actual mass (M), initial mass (M_{in}), half-light radius (r_{hl}), escape velocity (v_{esc}), age.

Cluster	R_{GC} (kpc)	[Fe/H] (dex)	E(B−V) (mag)	M ($10^4\,M_\odot$)	M_{in} ($10^5\,M_\odot$)	r_{hl} (arcmin)	v_{esc} ($km\,s^{-1}$)	Age (Gyr)
Arp 2	21.39	-1.75	0.10	3.87	0.912	1.70	4.5	13.00
Ruprecht 106	18.04	-1.68	0.20	3.40	1.259	1.26	5.6	11.50
Terzan 7	16.85	-0.32	0.07	2.23	0.525	0.90	4.6	8.00
Terzan 8	20.43	-2.16	0.12	7.59	7.586	1.89	6.0	13.50

Data Analysis

- Images collected by HST in the bands F275W, F336W, F438W, F606W and F814W.
- Data reduction: software *IMG2XYM*.
- Select stars: q-fit provided by the software.
- Determine the cluster membership: large temporal baseline of observations and proper motions (PMs).

✓ Displacement of stars observed at different epochs with respect to the motion of reference stars.

✓ Field stars and cluster members separated by PM diagrams.

- Differential reddening doesn’t affect photometry of clusters significantly.

✓ Corrected the photometry for the effects of spatial-dependent variation of the photometric zero point.

The UV-OPTICAL-NIR CMDs

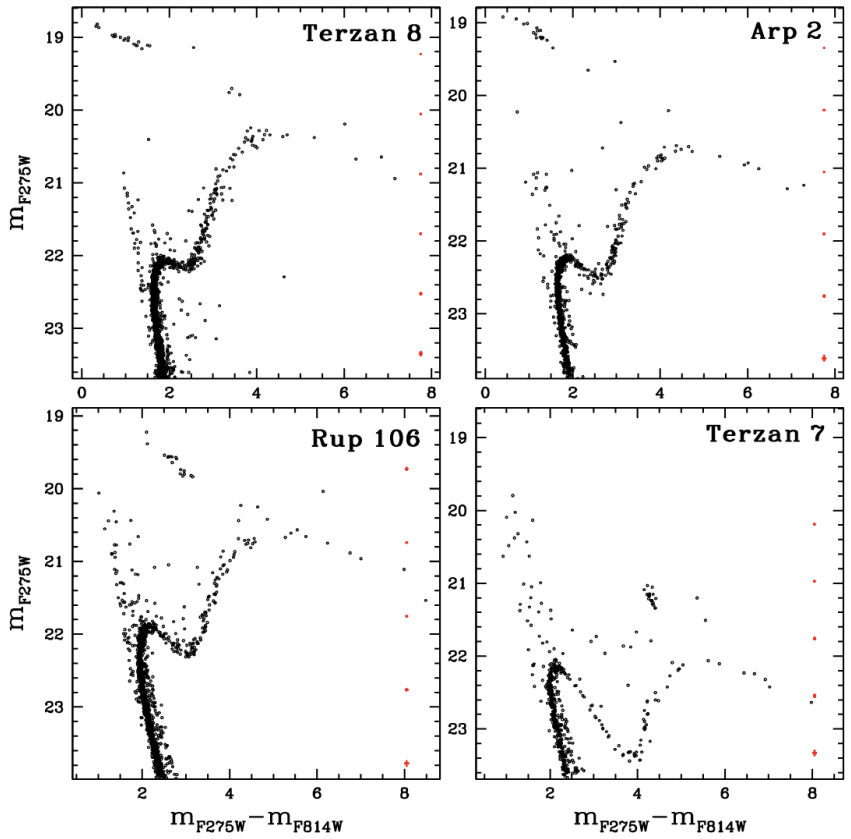

Figure 1 CMDs of the four clusters.

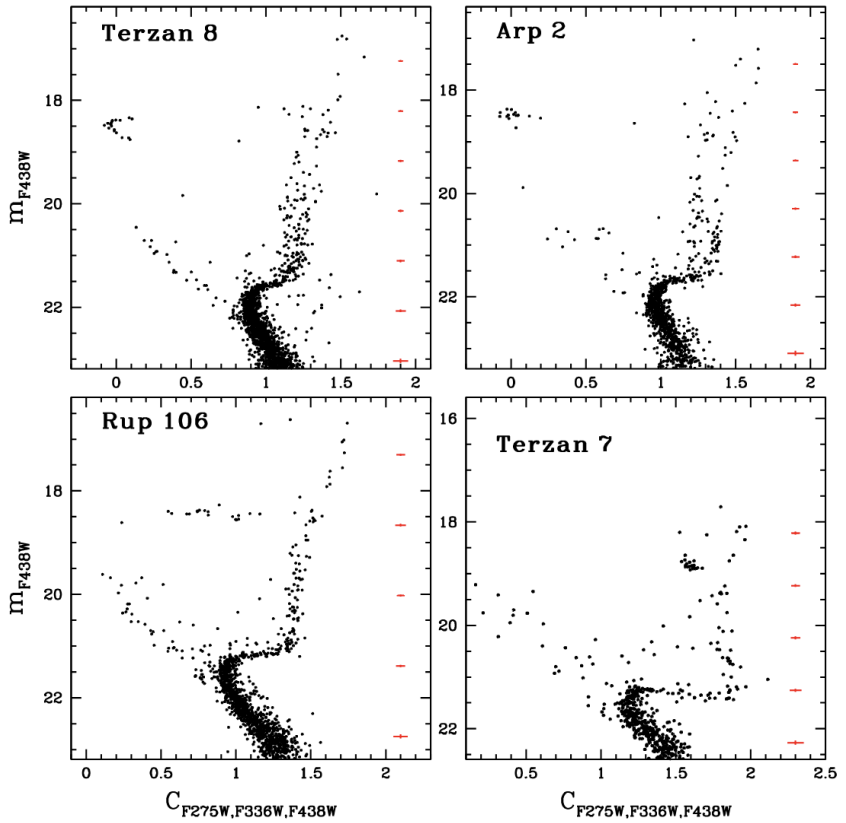

Figure 2 pseudo-CMDs of the four clusters.

- HB stars have short color distribution.
- Young and metal-rich GCs display HBs in theory, but the same phenomenon in intermediate-metallicity GCs : Ruprecht 106.
- Terzan 8 and Arp 2 display more extended HBs: ~ 1.5 mag.

- Arp 2 has a distinct split along RGB.
- Terzan 8 displays a broad color spread.

The Chromosome Maps

$$a)\ \Delta_{F275W,F814W} =$$

$$W_{F275W,F814W}\ \frac{X - X_{fiducialR}}{X_{fiducialR} - X_{fiducialB}}$$

$$b)\ \Delta_{C\ F275W,F343W,F438W} =$$

$$\boldsymbol{W_{C\ F275W,F343W,F438W}}\ \frac{Y_{fiducialR} - Y}{Y_{fiducialR} - Y_{fiducialB}}$$

$$X = m_{F275W} - m_{F814W}$$

$$Y = C_{F275W,F336W,F438W}$$

$W_{F275W,F814W}$ and $W_{F275W,F343W,F438W}$: the RGB widths

fiducialR and fiducialB : red and the blue RGB boundaries.

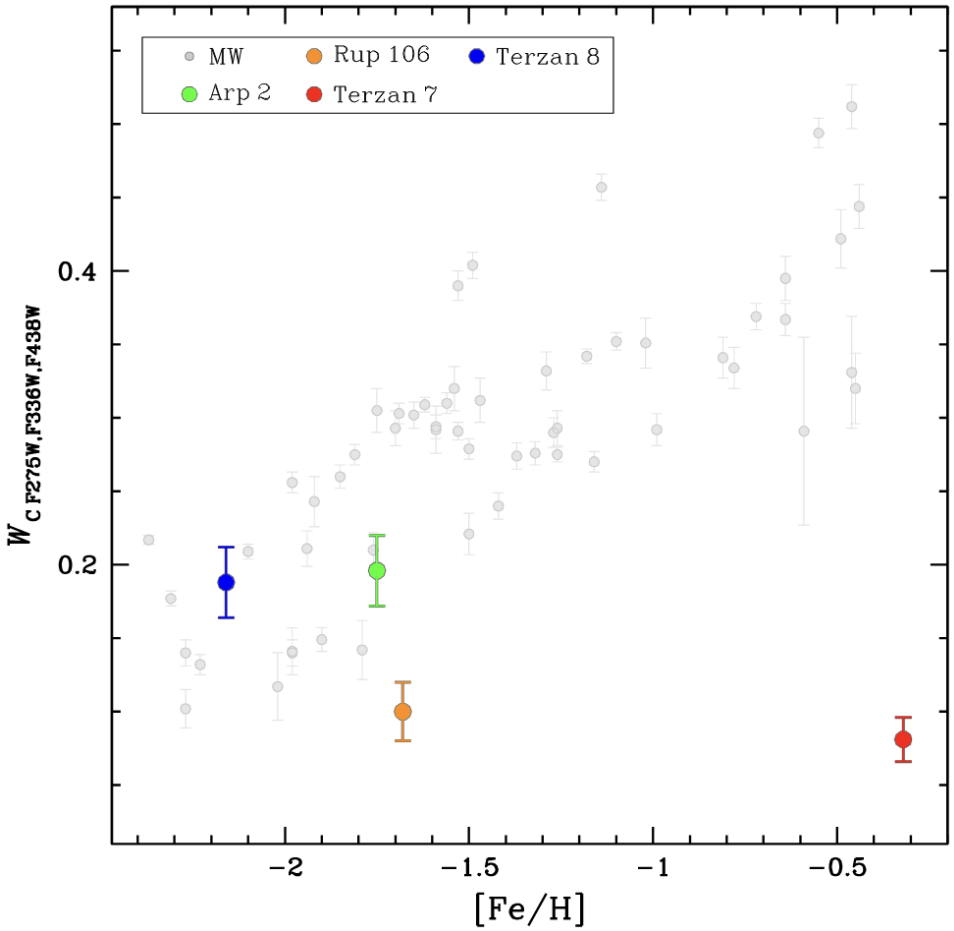

Figure 3 Intrinsic RGB width in the pseudo-color $C_{F275W,F336W,F438W}$ as function of iron abundance.

- 58 Galactic GCs studied by Milone et al. (2018a, gray dots)

The Chromosome Maps

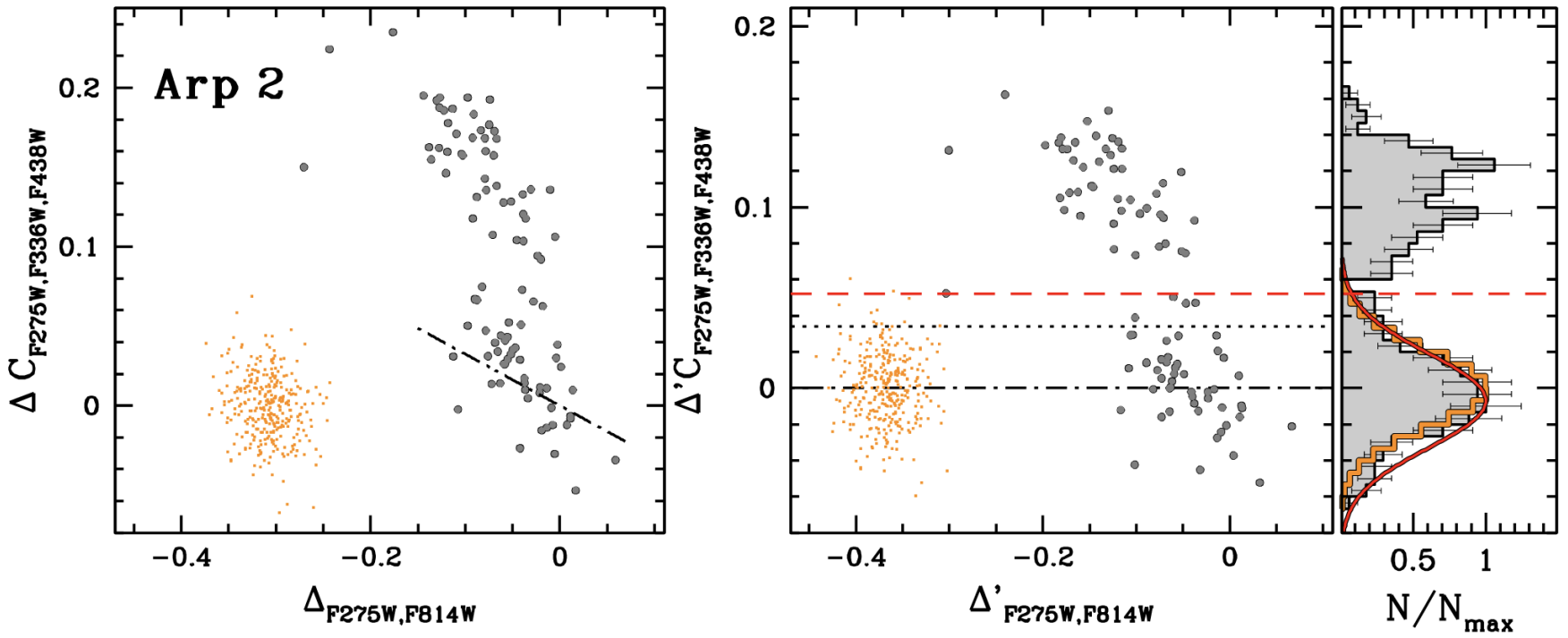

Figure 4 Tag the different stellar populations in Arp 2.

- Orange dots: photometric error distribution.
- Dot-dash line: inclination of 1P stars and has an inclination of 18°.
- Dotted line: 95^{th} percentile of photometric error distribution.
- Red curve: best-fit Gaussian to the region of the histogram.
- Red dashed line: corresponding to twice the dispersion of the best-fit Gaussian above its peak.

The Chromosome Maps

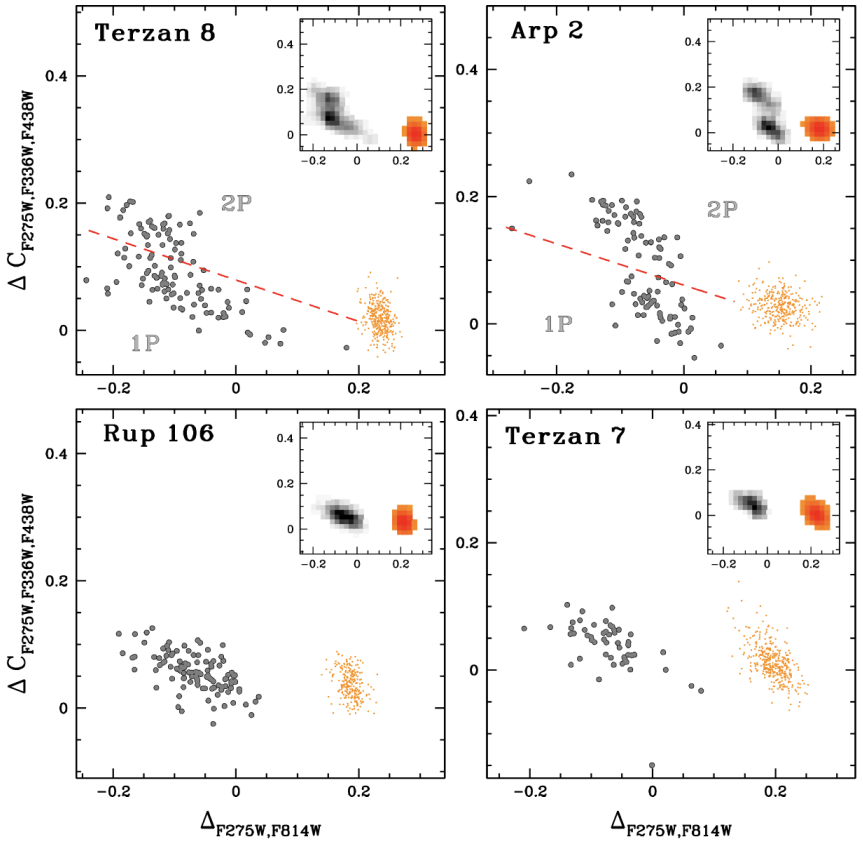

Figure 5 Chromosome maps of the RGB stars in the four target clusters.

- Inset: density diagram of the ChM and error distribution.
- dashed line: delimit the region of the ChM where 1P and 2P candidate stars lie.

Table 3. Values of the RGB widths, fraction of 1P candidate stars, total number of stars analyzed in the chromosome map, and maximum radial distance from the cluster center (r_{max}) as a fraction of the cluster half-light radius (r_{hl}).

Cluster	$W_{F275W,F814W}$ (mag)	$W_{C_{F275W,F336W,F438W}}$ (mag)	N_{1P}/N_{TOT}	N_{TOT}	r_{max}/r_{hl}
Arp 2	0.111 ± 0.096	0.196 ± 0.024	0.533 ± 0.052	96	0.98
Ruprecht 106	0.125 ± 0.006	0.100 ± 0.020	1.000 ± 0.010	109	1.25
Terzan 7	0.152 ± 0.051	0.081 ± 0.015	1.000 ± 0.020	53	1.66
Terzan 8	0.203 ± 0.021	0.188 ± 0.024	0.705 ± 0.044	114	0.84

The Chromosome Maps

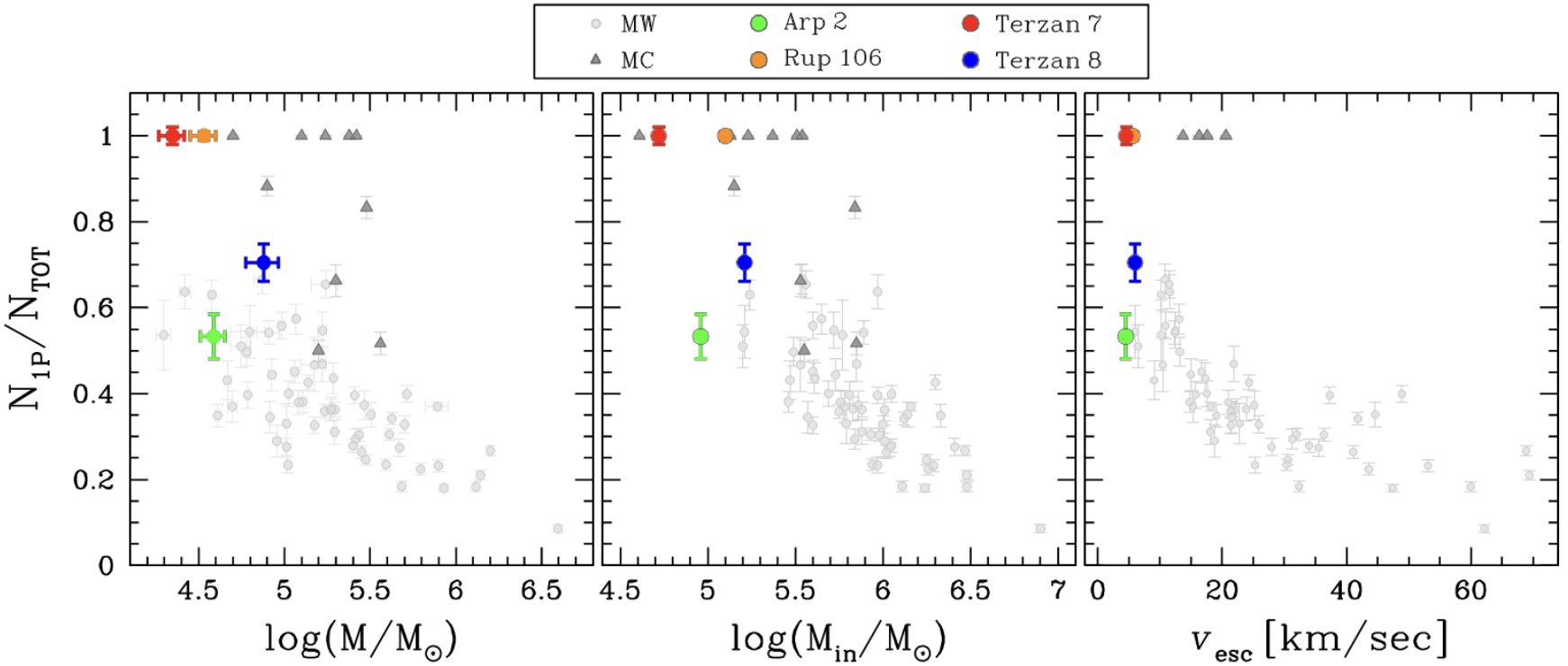

Figure 6 Fraction of 1P stars as a function of the logarithm of the GC present-day mass, initial mass, and escape velocity.

- Anti-correlation between the fraction of 1P stars cluster and both cluster mass and escape velocity.
- Arp 2 has $M_{in} \lesssim 10^5 M_\odot$, lower than the empirical mass threshold of $\sim 1.5 \times 10^5 M_\odot$ suggested by Milone et al. (2020) as the limit for the occurrence of MPs.
- First photometric evidence of the existence of SP clusters, namely Ruprecht 106 and Terzan 7, and MPs are present in the GCs Terzan 8 and Arp 2.

Metallicity Variation among 1P stars

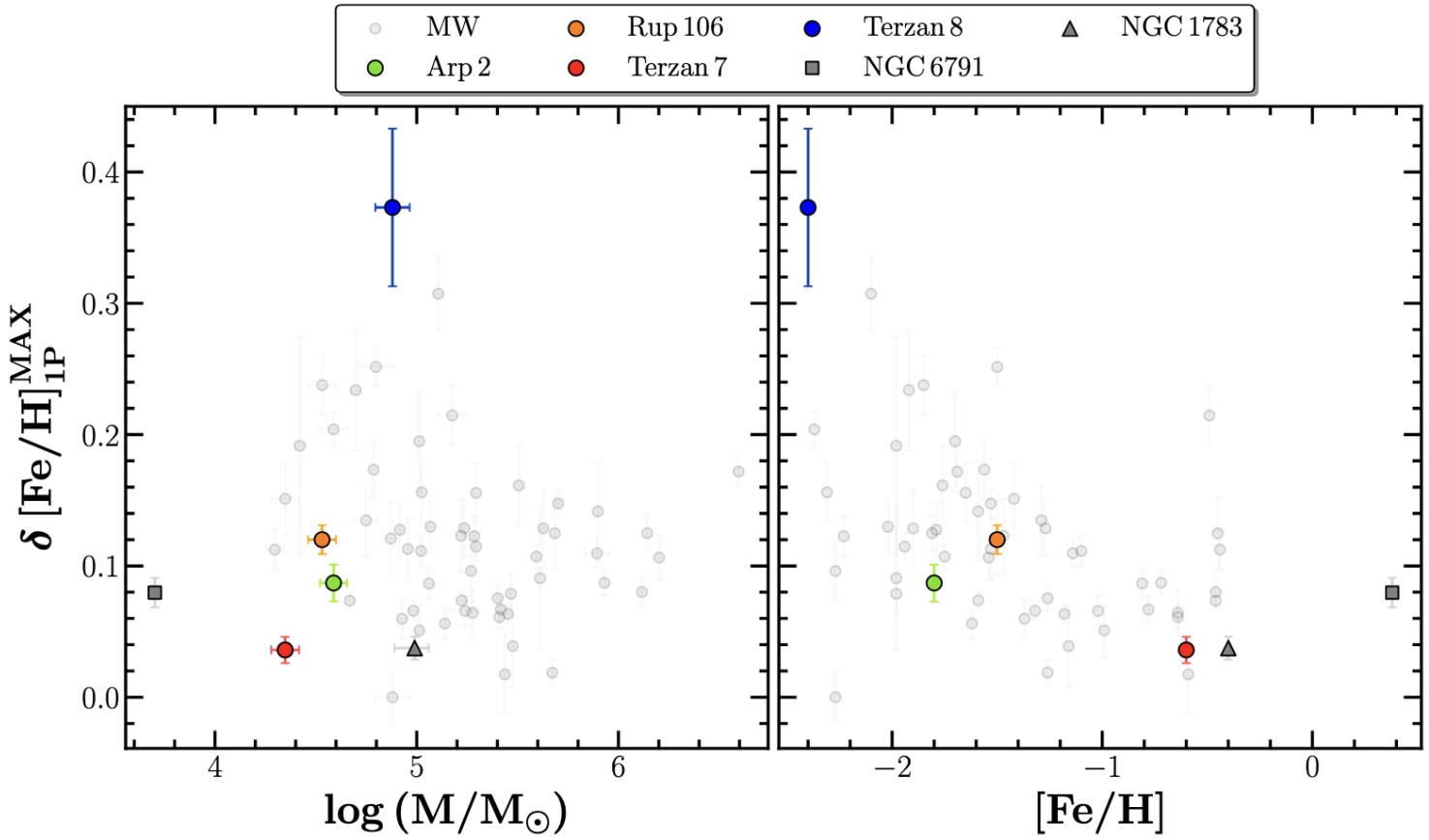

Figure 7 Maximum iron-abundance variation among 1P stars as a function of the logarithm of present-day GC mass and iron abundance.

- A mild correlation between $\delta[Fe/H]_{1P}^{MAX}$ and the metallicity, and between $\delta[Fe/H]_{1P}^{MAX}$ and mass.
- 1P stars in **Terzan 8** exhibit higher metallicity variations.
- **Metallicity variations are not peculiar to GCs with MPs but also characterize SP clusters.**

Conclusions

- First detailed study of the stellar composition of four GCs in the outer halo of the Milky Way: Arp 2, Ruprecht 106, Terzan 7, and Terzan 8.
- Ruprecht 106 and Terzan 7 are composed solely of a single stellar population, whereas Arp 2 and Terzan 8 host both first- and second-population stars.
- This paper suggests that the threshold in the initial GC mass, if present, should be smaller than approximately $10^5 M_{\odot}$.
- Star-to-star metallicity variations are a common feature of star clusters, regardless of the presence of MPs.

Thank you!