Observational Constraints on the Formation of Dark-matter Deficient Galaxies from Morphologies, Stellar Populations and Globular Clusters

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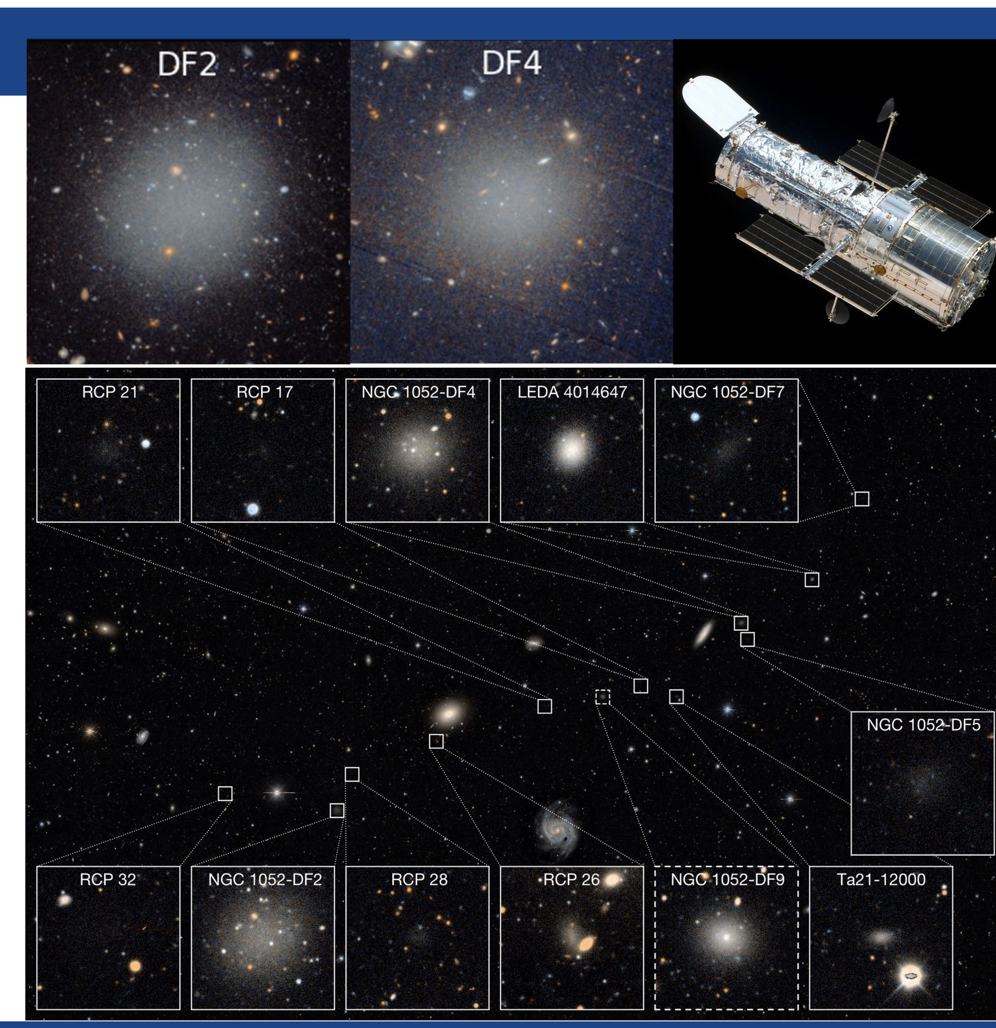
A Trail of Dwarf Galaxies

NGC 1052-DF2 and -DF4 are two ultra-diffuse galaxies (UDGs) that have been reported as deficient in dark matter and associated with the same galaxy group. Traditional models for dark matter deficient galaxies (e.g., tidal stripping and tidal dwarfs) seem unable to simultaneously explain the other unusual properties of DF2 and DF4, especially their overluminous globular clusters (GCs).

Recent findings[1] suggest that DF2 and DF4 are part of a large linear substructure of dwarf galaxies that could have been formed from a high-velocity head-on encounter of two gas-rich galaxies, known as a bullet dwarf collision[2].

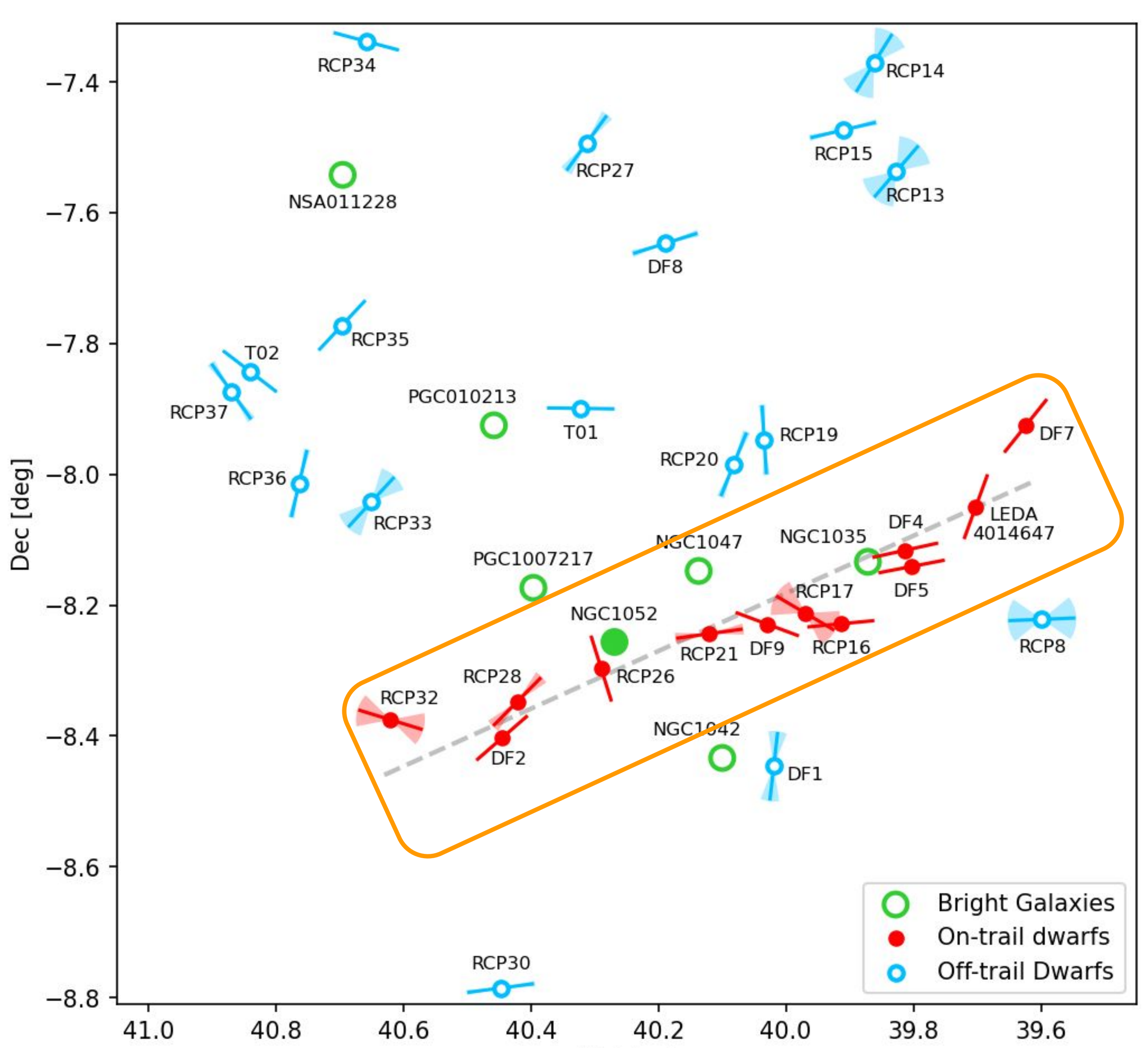
Based on new observations from the *Hubble Space Telescope* (*HST*), combined with existing imaging from the *u* band to mid-infrared, we test the bullet dwarf scenario by studying the morphologies and stellar populations of the trail dwarfs.



Position Angle Alignment

The position angles of on-trail dwarfs show striking alignment to the trail itself, not likely a random result.

Such an alignment seems expected from the bullet dwarf collision scenario. After the collision, the gas clumps may be stretched along the collision direction, and the newly formed dwarfs may show the same "stretching" (position angle) along the trail.

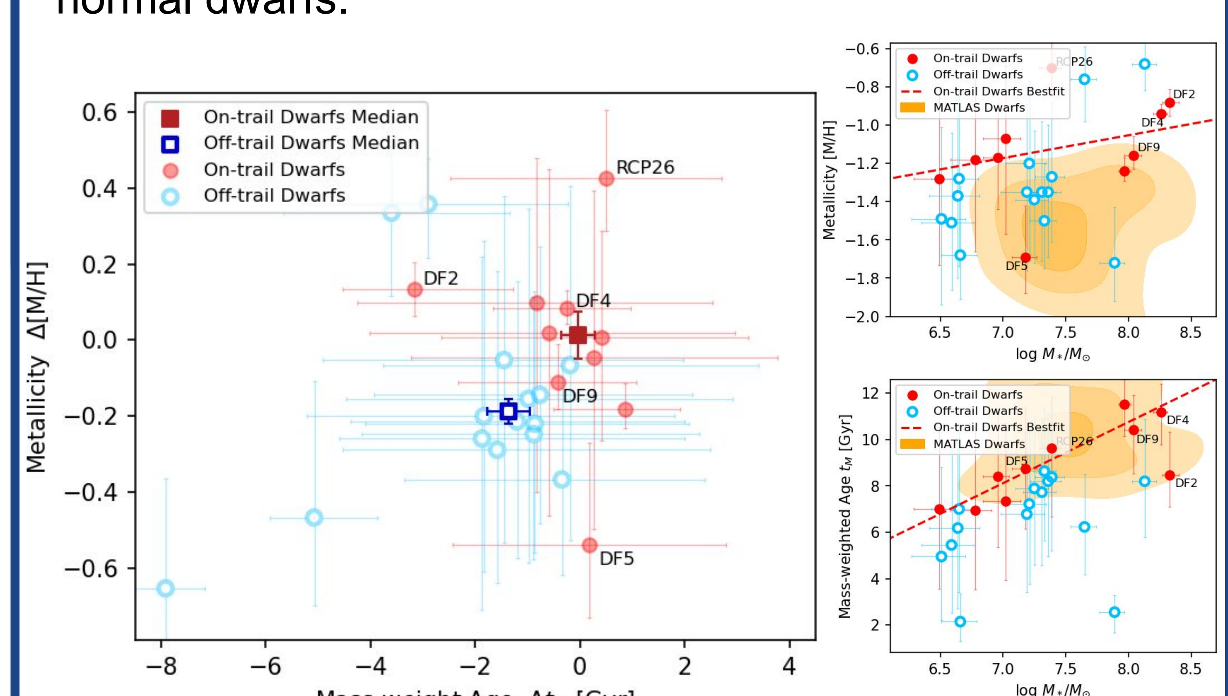


Sky positions of on-trail dwarfs and off-trail dwarfs, with isophote position angles represented by the direction of the line segment through each galaxy. The shading around the line segments represents the uncertainty. Most of the trail dwarfs align parallel to the trail itself (gray dashed line). The non-trail dwarfs are also preferentially aligned in the same direction, although with a lower significance.

Stellar Population

On-trail dwarfs are significantly older and metal-rich in their stellar populations compared to off-trail dwarfs. On-trail dwarfs have similar ages of ~ 8 Gyr within uncertainties, roughly consistent with the backward extrapolation time of DF2 and DF4's orbits (~ 6 Gyr).

These stellar population results are also expected in the bullet dwarf collision theory. The newly formed dwarfs may get quenched rapidly due to strong feedback, while normal dwarfs in the group would have extended star formation (thus younger). The progenitor galaxies of the collision may already be enriched in metallicity, so the newly formed dwarfs have higher metallicity than the normal dwarfs.



Right panels: The distribution of mass-weighted age t_M and metallicity [M/H] of on-trail dwarfs, off-trail dwarfs and MATLAS dwarfs[3]. The red dashed line is the best-fit linear relation for trail dwarfs.

Left panel: The distribution of Δ[M/H] and Δt_M (metallicity and mass-weighted age relative to the mass trend we fit) for on-trail dwarfs and off-trail dwarfs. The dark red solid square and blue open square represent the medians.

Theory vs. Observation

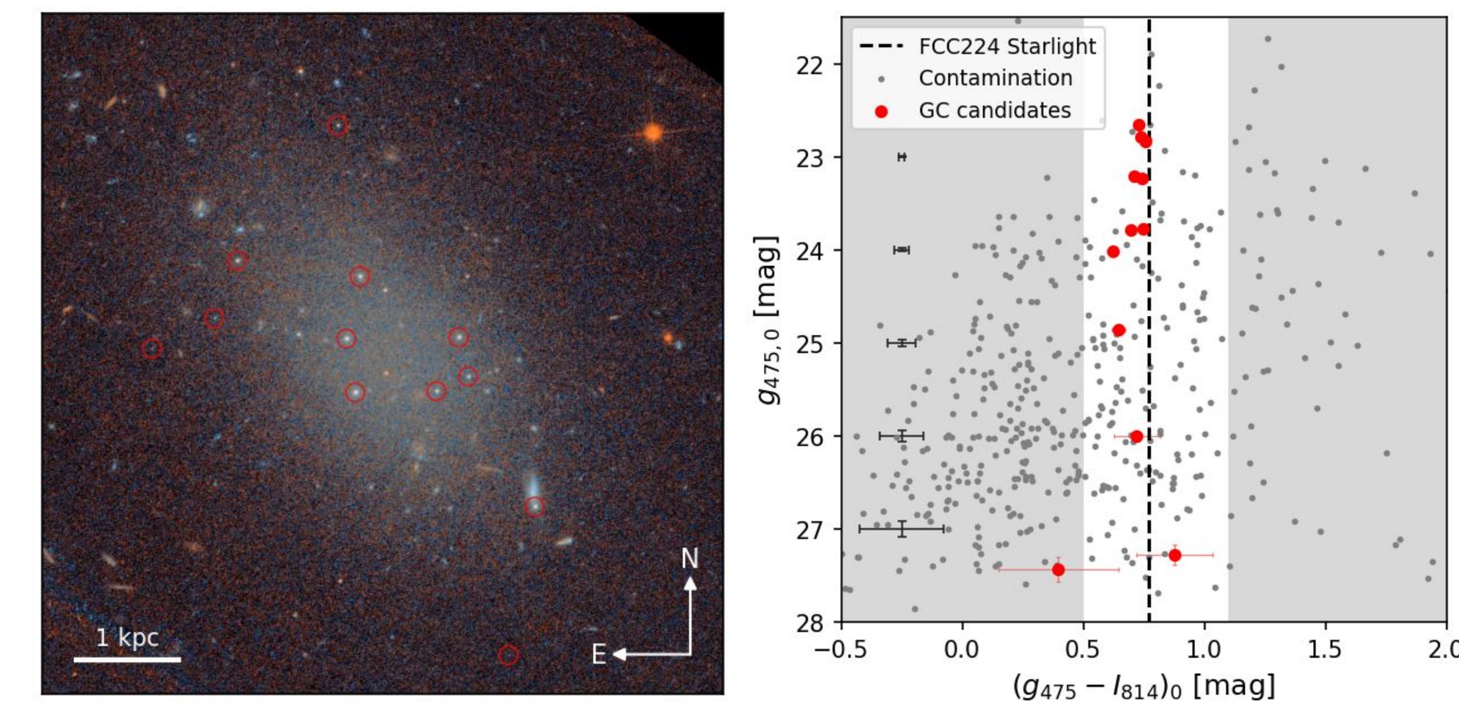
	Bullet dwarf	Tidal stripping	Extreme feedback	...
Position angles	similar along the trail ✓	no correlation ✗	no correlation ✗	
Stellar population	similar age along the trail ✓	a range of ages ?	a range of ages ?	...

The bullet dwarf collision is currently the most promising model, but more observations (especially on dark matter, distance and velocity) and theoretical work are needed!

A Newly Discovered Analog of DF2 & DF4

Based on archival imaging from DECaLS[4], FCC 224 in the Fornax Cluster has been identified as an interesting UDG and shows a top-heavy GC luminosity function similar to DF2 and DF4. We use newly obtained *HST* observations of FCC 224 to study its GC system and diffuse light.

The 12 GCs identified exhibit highly homogeneous F475X–F814W colors, merely 0.04 mag bluer than the diffuse starlight. Similar results found in DF2 and DF4[5]. This suggests FCC 224 has a single-burst star formation history, also confirmed with our stellar population inference using Prospector[6] by combining broad-band imaging and Keck/KCWI spectroscopy. FCC 224 has a mass-weighted age of 10 Gyr and metallicity [M/H] of −1.25 dex.



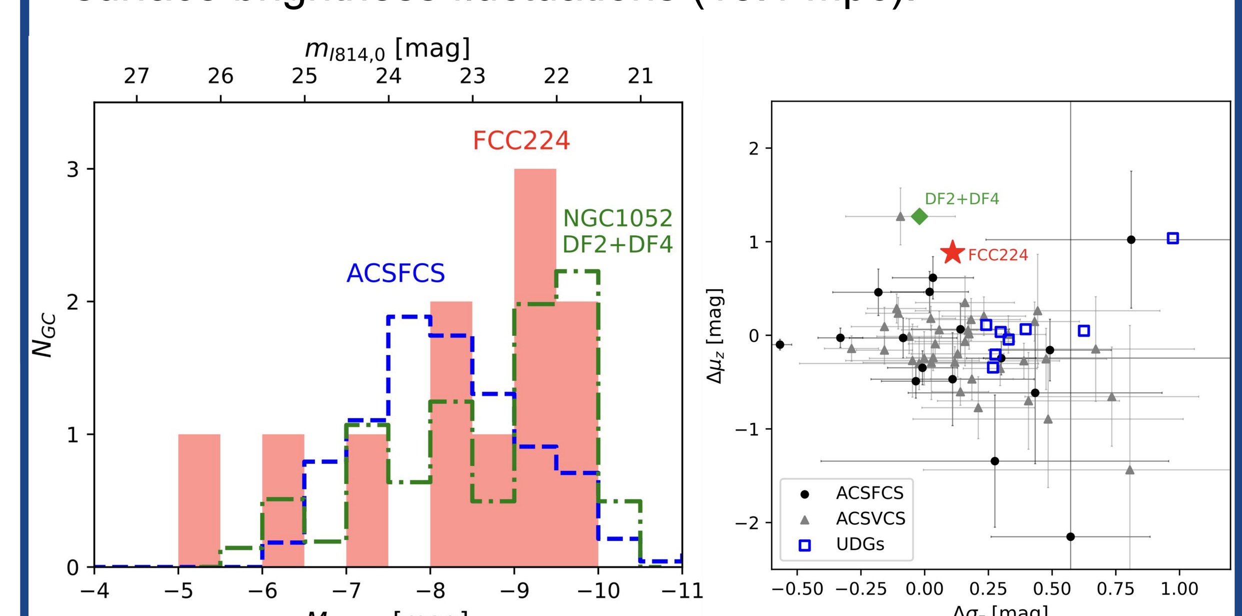
Left: HST pseudo-color image of FCC 224, with the identified GCs circled. The four outermost GCs are also the faintest in the sample – an indicator of mass segregation.

Right: Color–magnitude diagram of objects detected with SExtractor[7], with highlighting GC candidates within 2 effective radii. The vertical dashed line represents the F475X–F814W color of the galaxy's diffuse starlight, which is only slightly 0.04 redder than the 7 brightest GCs. The GC color spread is also only 0.02 mag, suggesting a single-burst formation scenario.

Globular Cluster Luminosity Function

Similar to DF2 & DF4, FCC 224 also has a top-heavy GC luminosity function, with very few faint GCs. The turnover magnitude is ~1 mag brighter than expected as a Fornax cluster galaxy, and ~0.2 mag fainter compared to DF2 & DF4.

If the turnover magnitude were normal, FCC 224 would have to be at a much closer distance of 12.5 Mpc, clearly differing from our distance estimate based on surface brightness fluctuations (18.1 Mpc).



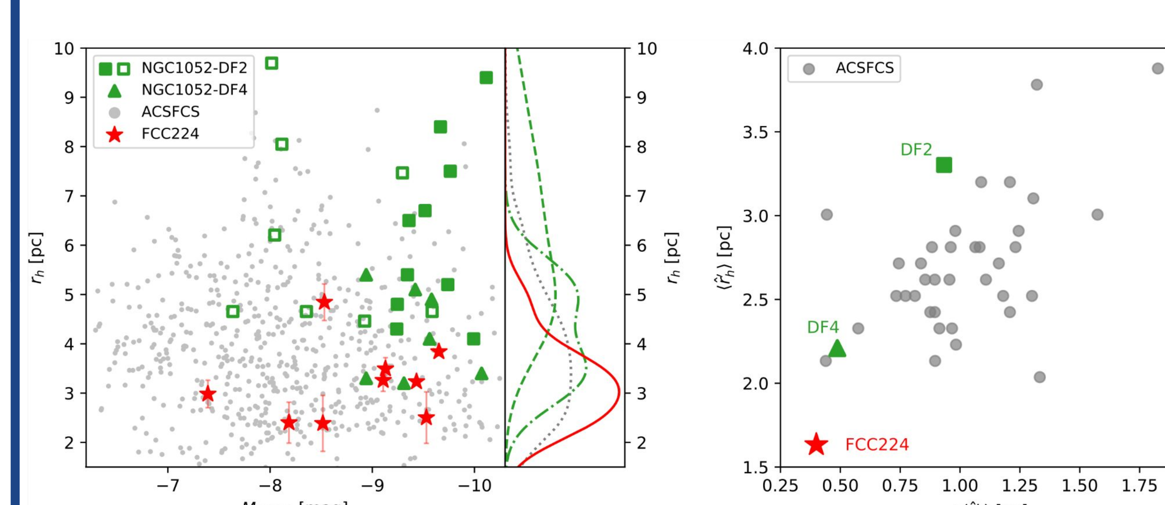
Left: The FCC 224 GCLF. The GCLFs of ACSFCS low-mass galaxies[9] ($M_z > -19$) and DF2 & DF4[10] are overplotted, and they are normalized to have the same total GC number as FCC 224.

Right: The distribution of the GCLF turnover magnitude μ and width σ in z_{850} band (ACS F850LP) filter for FCC 224, DF2 & DF4[9], other UDGs in the literature[11,12,13], low-mass ACSFCS and ACSVCS galaxies[8]. The $\Delta\mu$ and $\Delta\sigma$ mean the values after removing the dependence on the host galaxy luminosity[8].

Globular Cluster Size

Differently from the big GC sizes of DF2 & DF4, FCC 224 GCs are systematically smaller (mean size 3.2 pc) than the expected sizes (by 35%) given its low mass and low surface brightness[14]. Considering these GCs are also overluminous, they are unusually compact.

FCC 224 exhibits both similarities and differences with DF2 & DF4. It is not clear if the theoretical models for DF2 in the literature explaining the top-heavy GC luminosity function can fit the overcompact GCs found in FCC 224. More theory work is needed on this topic.



Left: The distribution of GC size and F814W absolute magnitude of FCC 224, DF2[15,16], DF4[17], and low-mass ($M_z > -19$) ACSFCS galaxies[9]. The size distributions of each group of GCs are shown on the right side (red solid line for FCC 224, green dashed line for DF2, green dotted-dash line for DF4, and gray dotted line for ACSFCS galaxies).

Right: Mean GC sizes and size scatters of FCC 224, DF2, DF4, and each ACSFCS galaxy, corrected for the GC size dependence on the host galaxy properties[13].

Potential Breakthrough with Rubin/LSST?

With the unprecedentedly deep and wide-field imaging of Rubin/LSST, we expect to discover a large number of galaxies similar to DF2, DF4, and FCC 224. This will allow us to have a large sample for systematically studying the potential connections between UDGs, unusual GCs, and dark matter halos.

If any physical connections are revealed, a large number of galaxies with unusual dark matter halos will be much easier to identify.

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