# The Origin of dark matter deficient galaxies

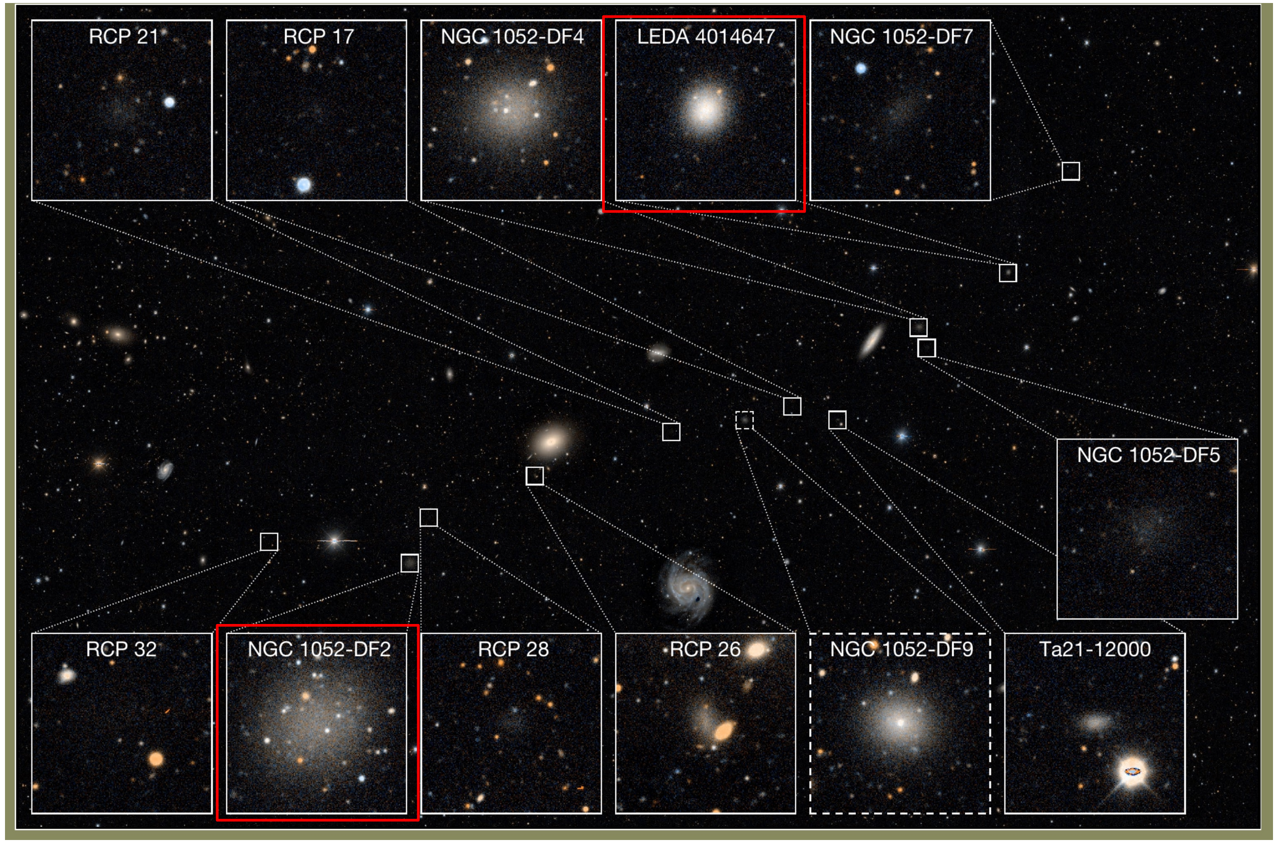
Yu Wang 王雨 2022.06.06

Galactic Physics term presentation

# Outline

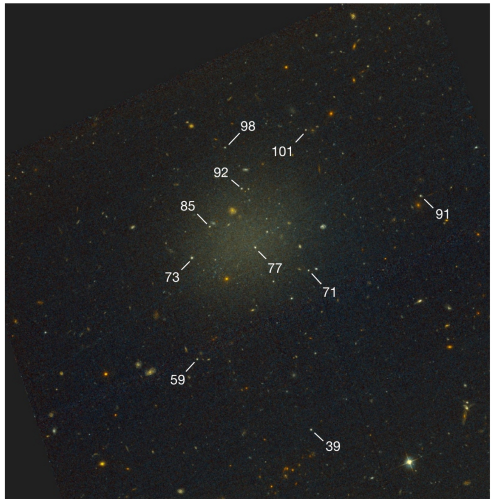
- Observation debates: dark-matter-deficient or not?
- Possible theoretical models and their implications.
- Backup slides: More details.

# First detection of a dark matter deficient galaxy




Van Dokkum et al, Nature, 2022

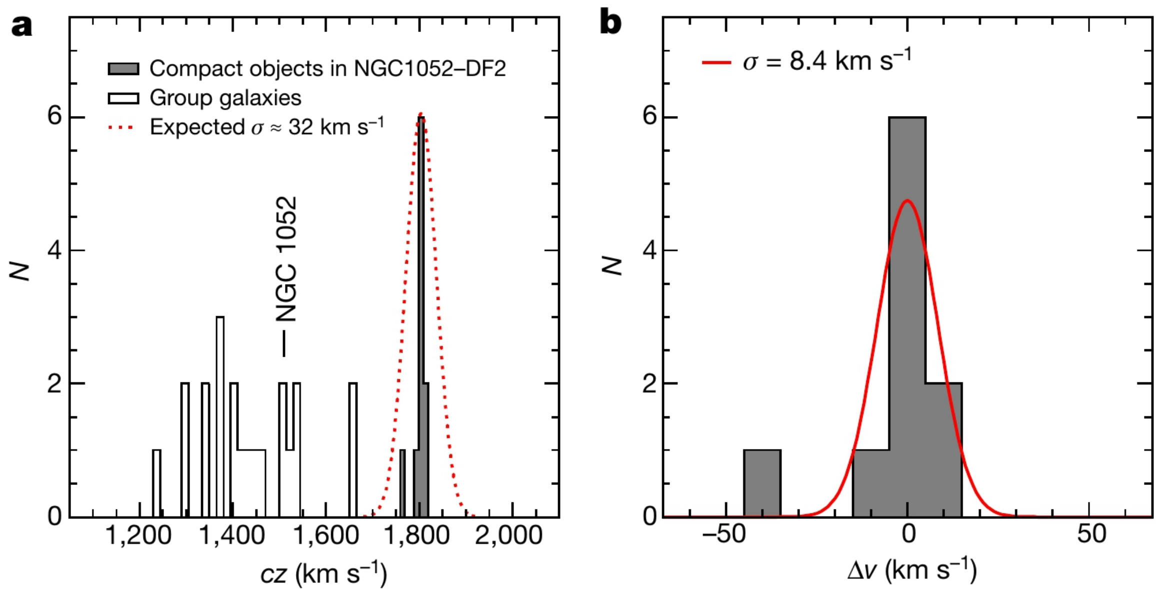
NGC 1052-DF2: An ultra diffused galaxy (UDG) with many compact globular clusters shown as bright point sources.

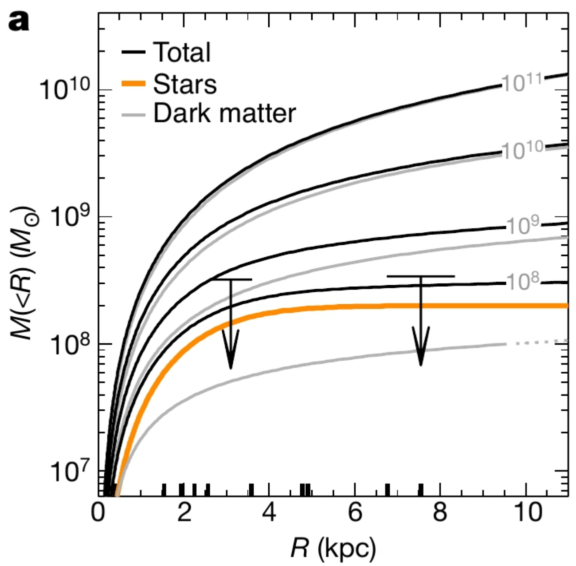



Van Dokkum et al, Nature, 2018

HST/ACS image of DF2

# First detection of a dark matter deficient galaxy



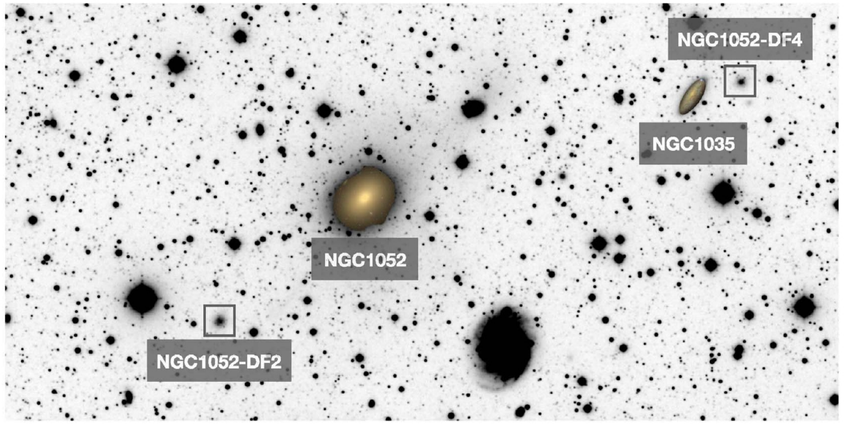

Van Dokkum et al, Nature, 2018

Measured velocity dispersion distribution of **10 Globular clusters**, corresponds to an intrinsic velocity dispersion of $\sigma_{intr} = 3.2^{+5.5}_{-3.2}\ \mathrm{km\ s^{-1}}$

**Much smaller** than typical value of 32 km/s in local clusters.

Dark matter mass derived from NFW model expectations compared with stellar mass derived from luminosity-mass conversion, assuming a distance of **~ 20 Mpc**.

# Debate on mass and distance measurement




Shen et al, ApJL, 2021

Another DMDG DF4 is detected at 2019 in the same cluster, which shares very similar properties to DF2.

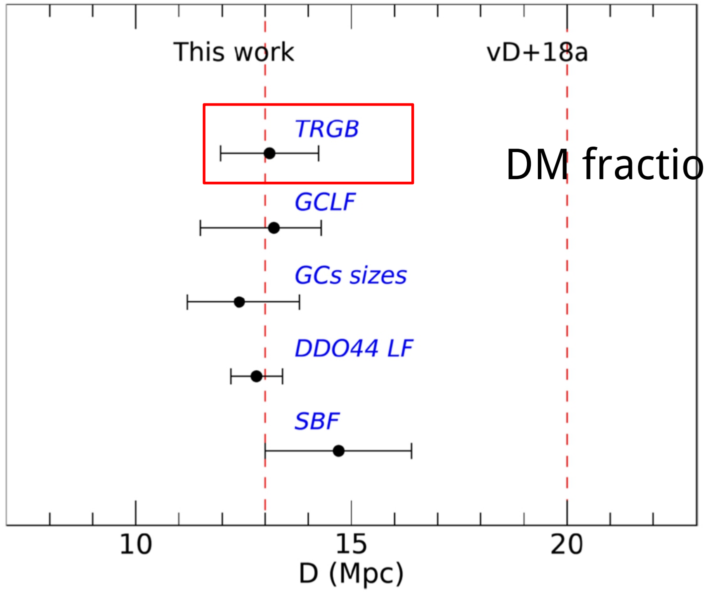
Model dependent, Empirical relation from normal galaxies, detection sensitivity. etc.

Stellar mass: FLUX $\xrightarrow{\textbf{distance}}$ Luminosity $\xrightarrow{M/L}$ M

Total mass: **velocity dispersion** as the observational given a two component (DM + stars) kinematic model.

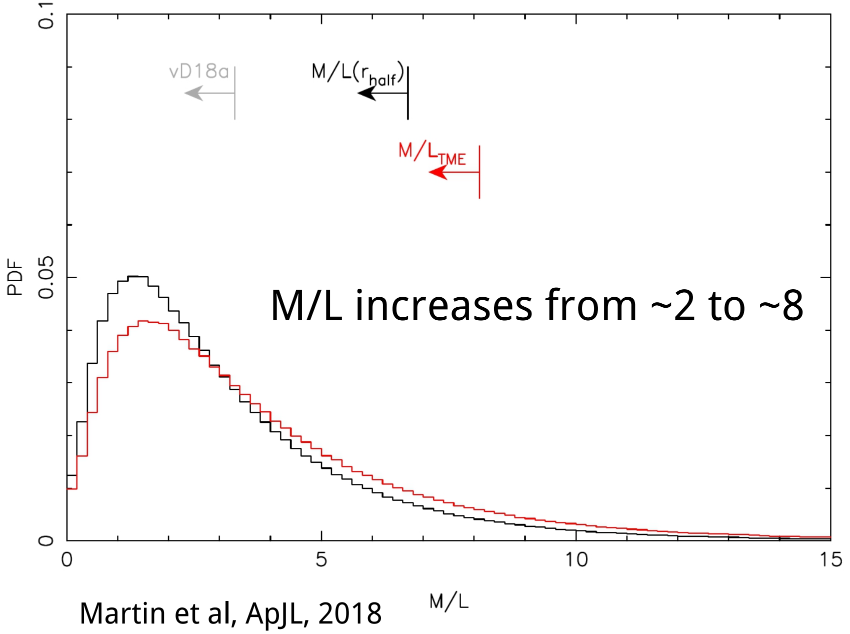
Low brightness, few dynamic proxies, large uncertainty, Statistical model robustness. etc.

# Debate on mass and distance measurement




Trujillo et al, MNRAS,2019

DM fraction increase to ~75%




Martin et al, ApJL, 2018

Tip of the Red Giant Branch at HR diagram as the standard candle.

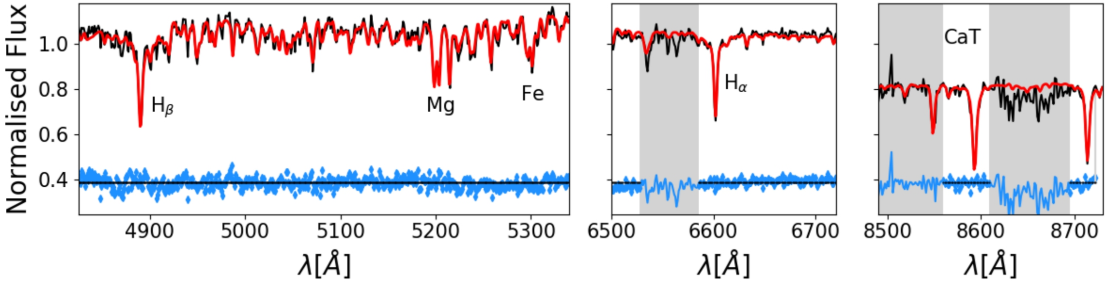
It sensitively depends on how **deep** the image reaches since stars will looks fainter when the distance is larger.

Trujillo et al 2019 only use HST **1+1** orbit data in filter F814W & F606W, which is **only able to reach D ~ 14 Mpc** claimed in Shen+ 2021.

A single outlier (GC98) give significantly different result for a small sample, which tends out to be an observational error.

# Debate on dynamical mass estimation

Final solution: MUSE integral field spectrum



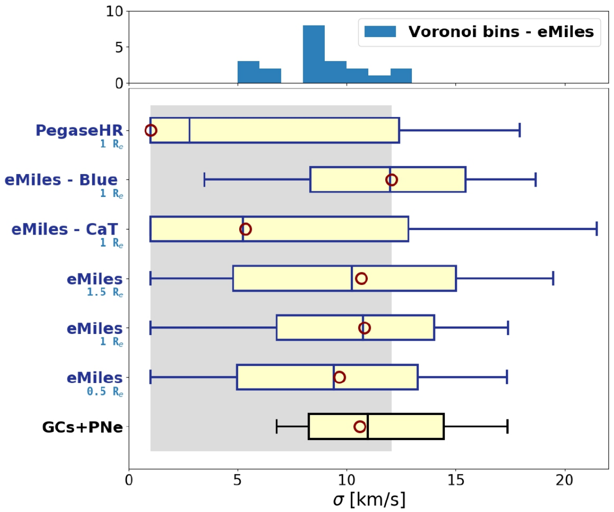

Spectrum of DF2 integrated over an aperture of 1 Re

$$\sigma_*(R_e) = 10.8^{+3.2}_{-4.0} kms^{-1}$$

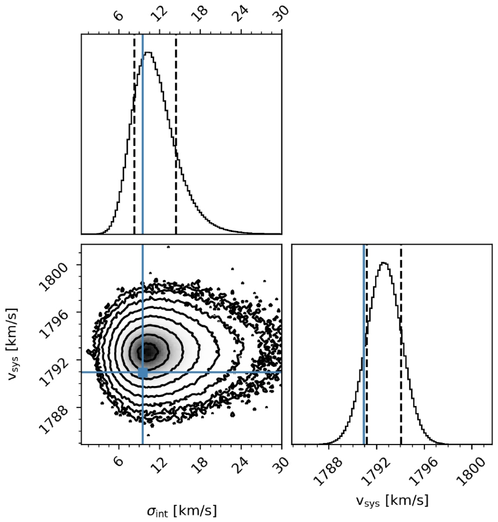
$$\sigma_{int} = 10.6^{+3.9}_{-2.3} kms^{-1}$$

Impact on mass to light ratio

$$M_{dyn}/L_V = 3.7^{+3.3}_{-1.5}, 3.9^{+2.3}_{-2.6}$$



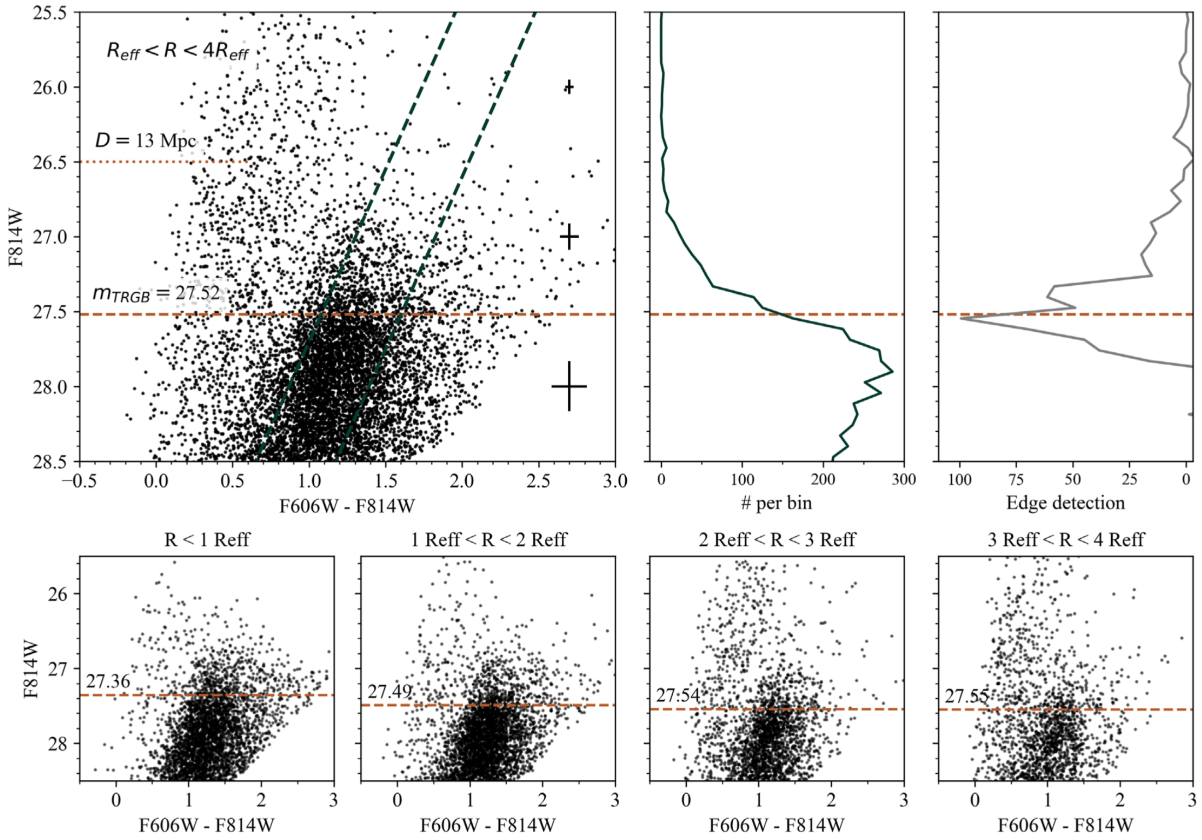

Stellar light




Point sources

Emsellem et al, A&A, 2019

# Debate on distance measurement

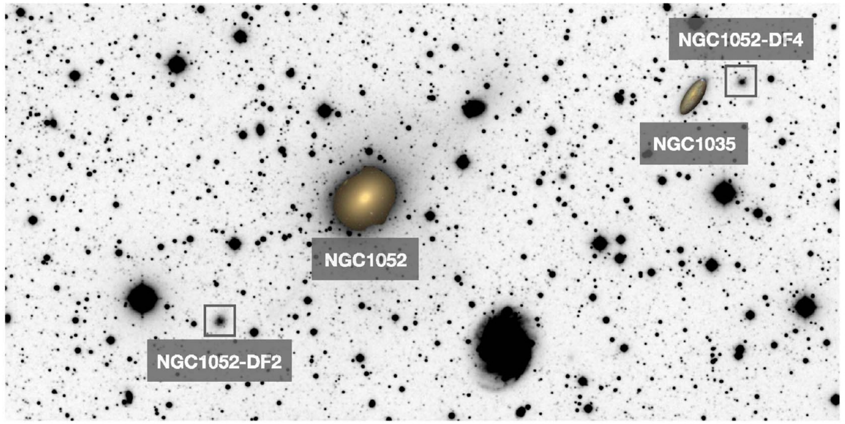



Shen et al, ApJL, 2021

Danieli et al, ApJL, 2020

HST 20+20 orbits data

HST 8+4 orbits data




D_DF2 = 22.1 ± 1.2 Mpc

D_DF4 = 20.0 ± 1.6 Mpc

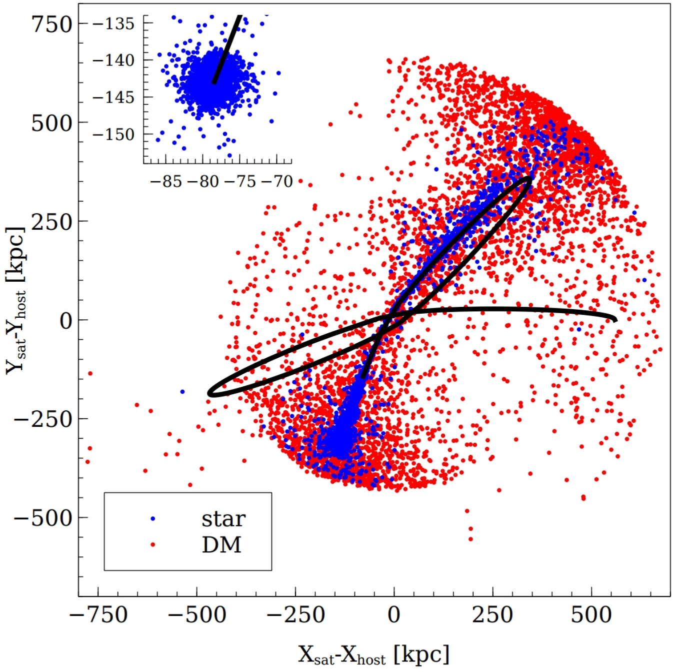
**δD= 2.1 ± 0.5 Mpc**

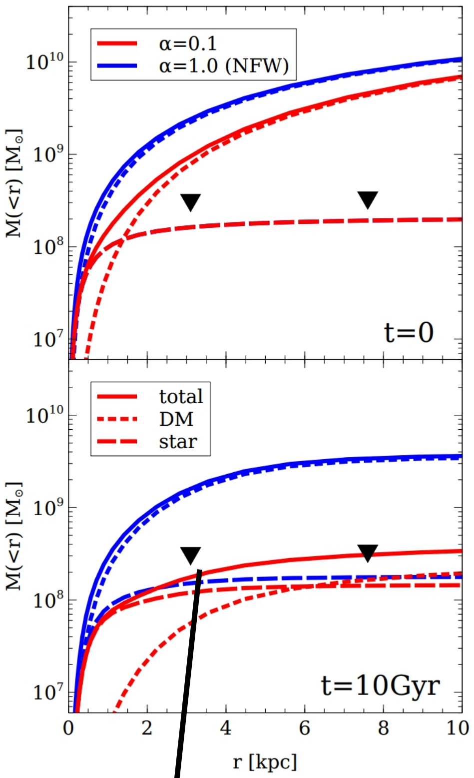
DF2, DF4 have similar size, color, morphology, luminosity, population of GCs and extremely low velocity dispersion.

# Possible theoretical explanations

1. Tidal dwarf galaxy
2. extreme tidal stripping (by NGC 1052, NGC 1035)
3. intrinsic offset to mean SMHM function
4. bullet-galaxy like collision
5. MOND

# Tidal stripping by host galaxy

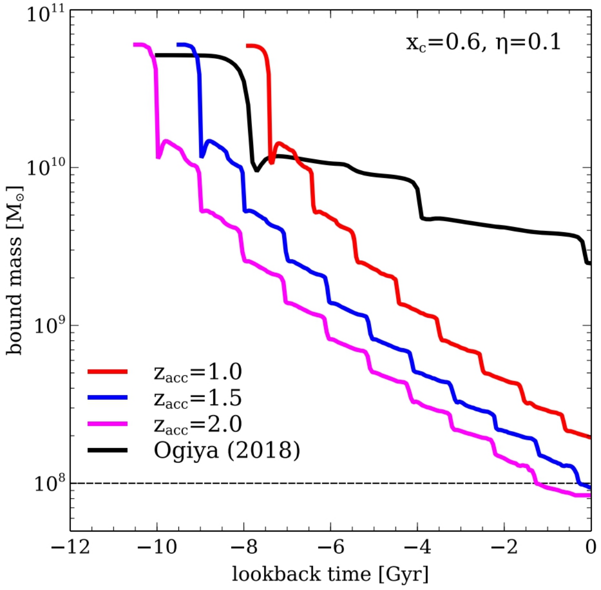



Ogiya, MNRAS, 2018

The satellite needs to have a cored dark matter profile. It should be tightly bounded to host galaxy and has a very radial orbit, which is very **rare** in cosmological simulations.

Upper limit of the mass of DF2 from the obs.



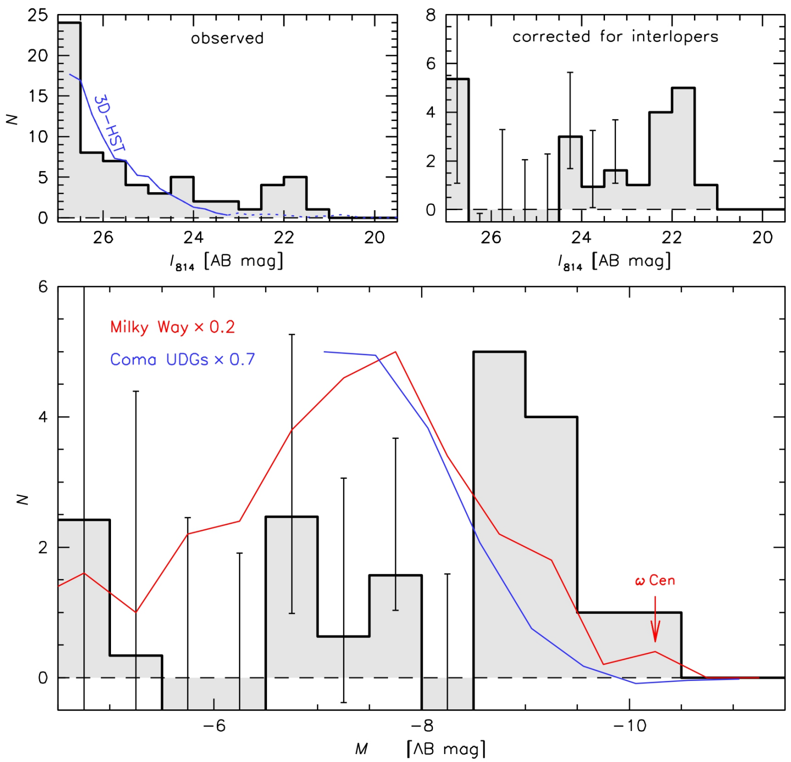

NFW profile used here

Ogiya et al, MNRAS, 2021

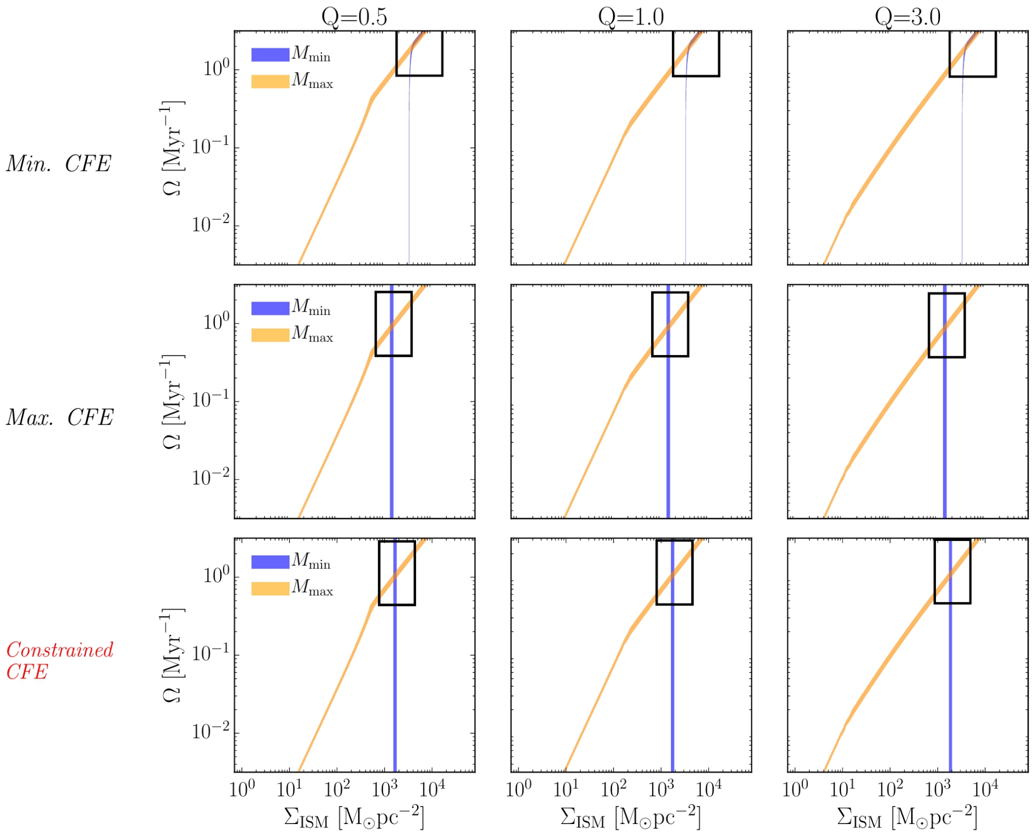
Or the satellite is gradually stripped by a smoothly growing host halo for a long enough time.

# Unusual GC luminosity of DF2

$$\Omega \geq 0.7 Myr^{-1}$$
$$\Sigma_{ISM} \geq 10^3 M_{\odot} pc^{-2}$$




Van Dokkum et al, MNRAS, 2018b




Trujillo-Gomez et al, MNRAS, 2020

An obvious offset of GC luminosity function found in nearby clusters, implying very dense formation environment.

Birth galactic environmental conditions required by the observed GCMF.

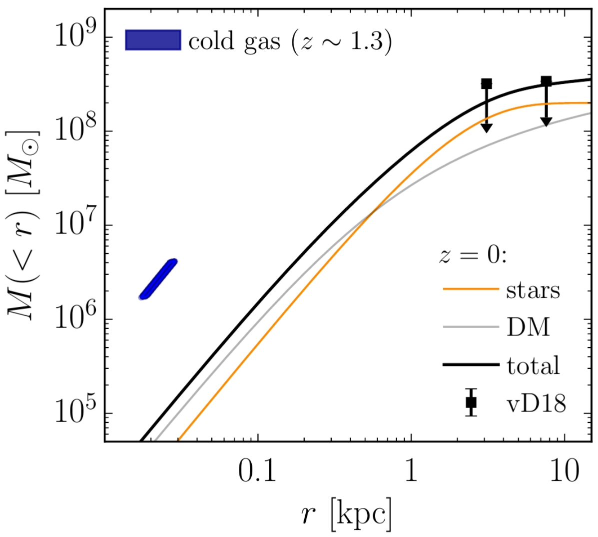
# Major merger or nuclear-starburst history

Typical value found in galaxies in local universe:

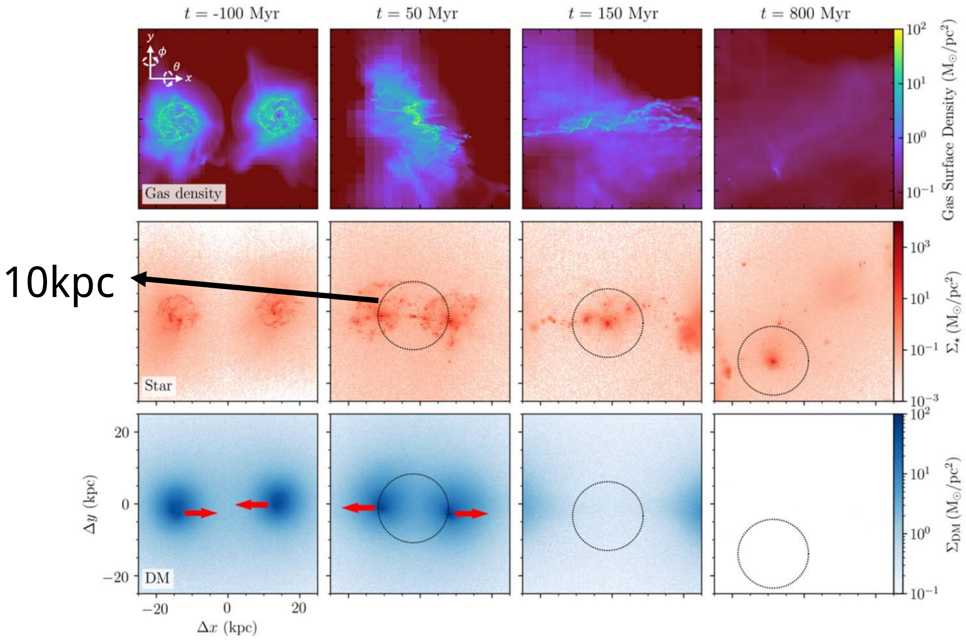
$$\sum_{ISM} < 50 M_{\odot} pc^{-2}$$
$$\Omega < 0.05 Myr^{-1}$$

Implying severe formation environment:

1. dense circumnuclear starbursts
2. mergers




Trujillo-Gomez et al, MNRAS, 2020



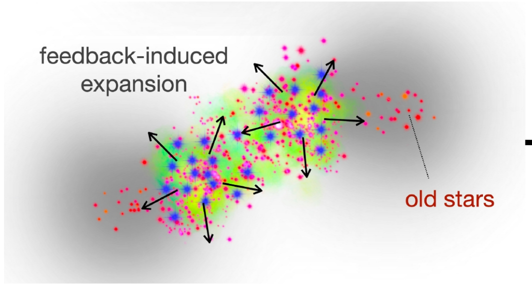

Lee et al, ApJL, 2021

**Well, then how a initially extremely dense GC population/Galaxy become Ultra-Deficient?**

nuclear starburst scenario requires very small formation region, easily leading to nuclear star cluster, which is not seen in DF2. Fine tuning needed.

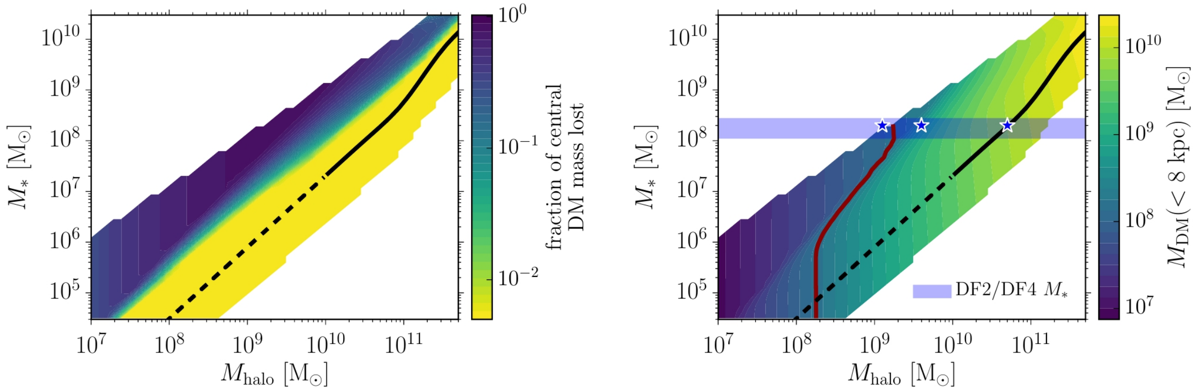
A major merger might explain why GCs have lower metallicity since they may mainly form during the merger by incoming low-metallicity gas of low mass satellite.

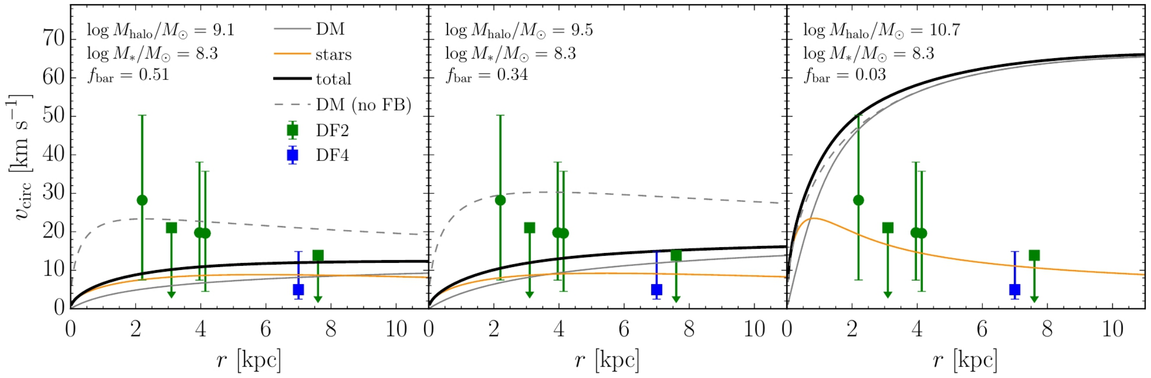
# Stellar feedback driven expansion to diffuse the galaxy




UDGs

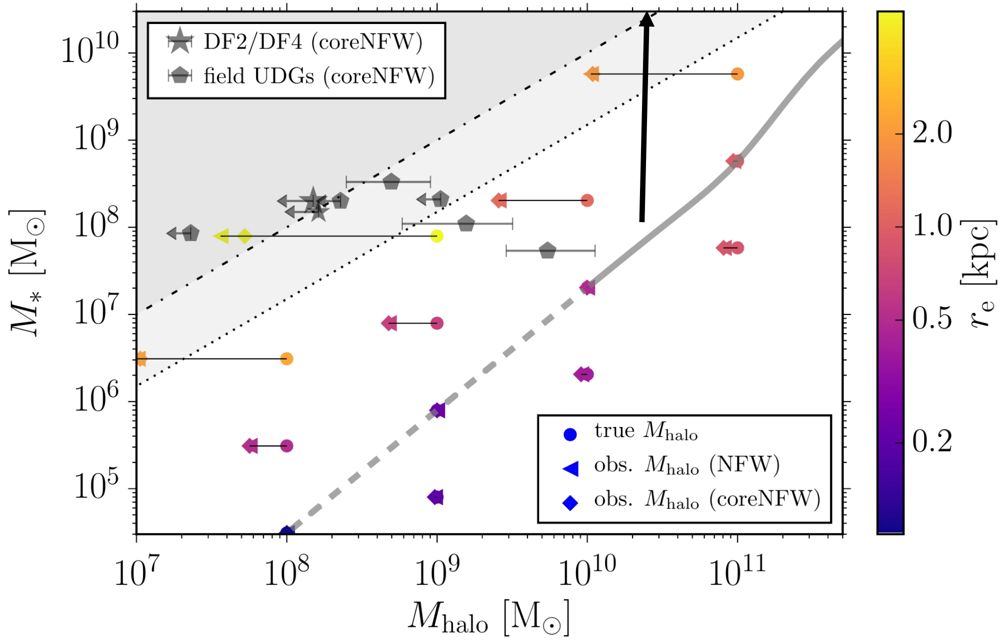
Van Dokkum et al, Nature, 2022





Trujillo-Gomez et al, MNRAS, 2021

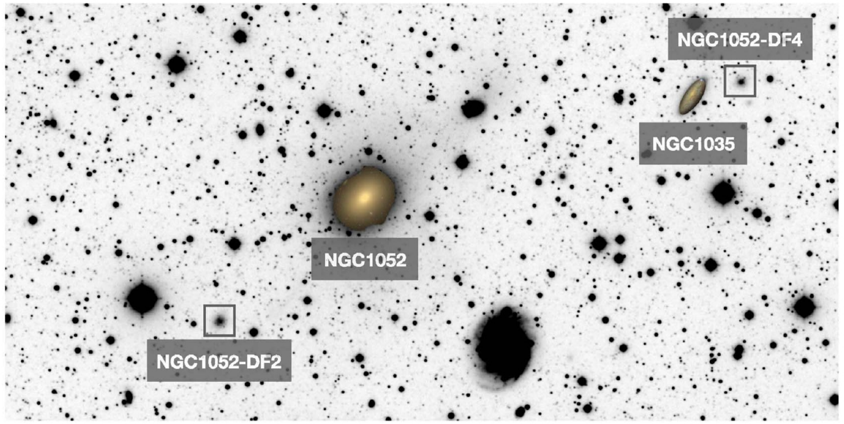
mean SMHM function obtained from $\Lambda CDM$



Trujillo-Gomez et al, MNRAS, 2021

**An intrinsic upward scatter** to mean SMHM give rise to enhanced SN feedback, driving expansion to a cored DM profile with r_e > 10kpc and significantly reduce DM fraction as well.

# New evidence on collision scenario




Shen et al, ApJL, 2021

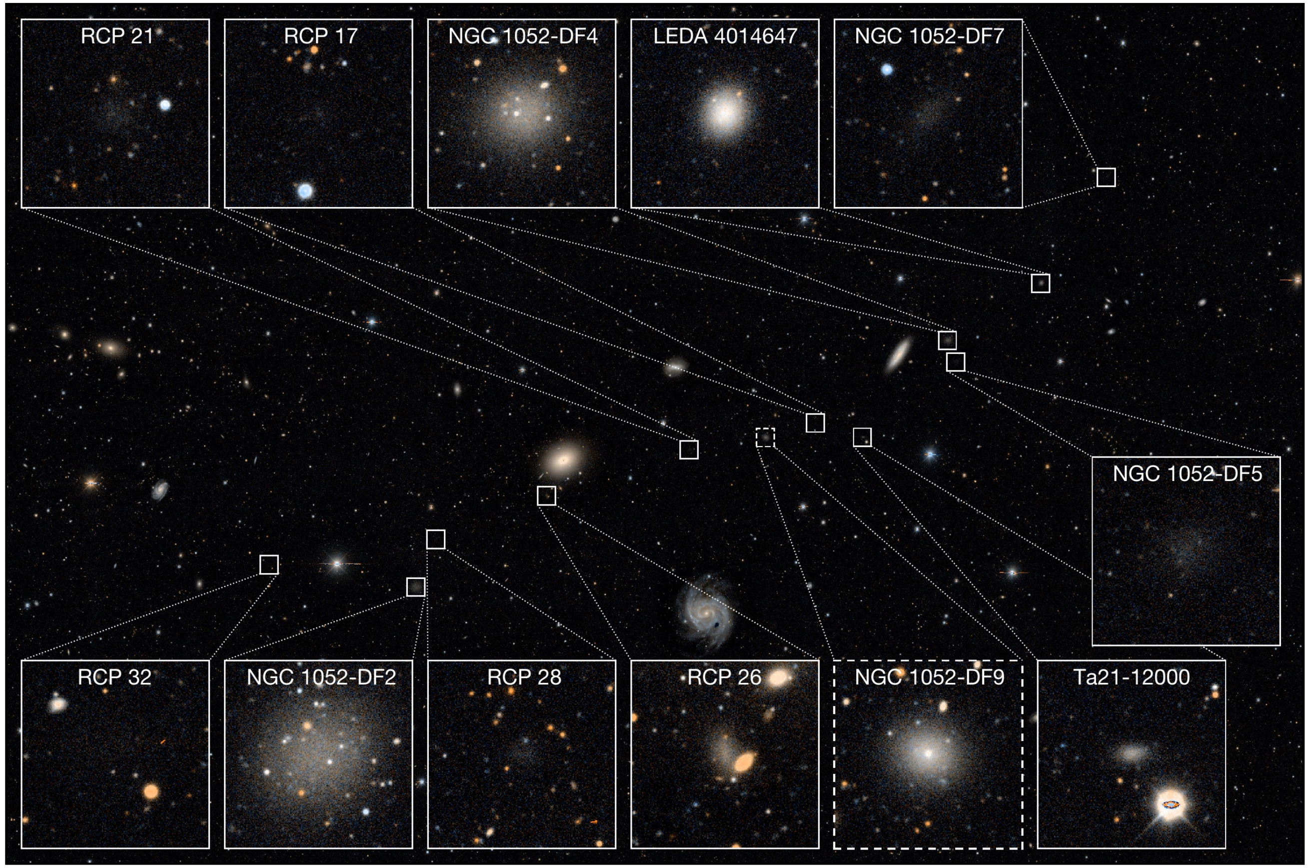
**δD= 2.1 ± 0.5 Mpc**

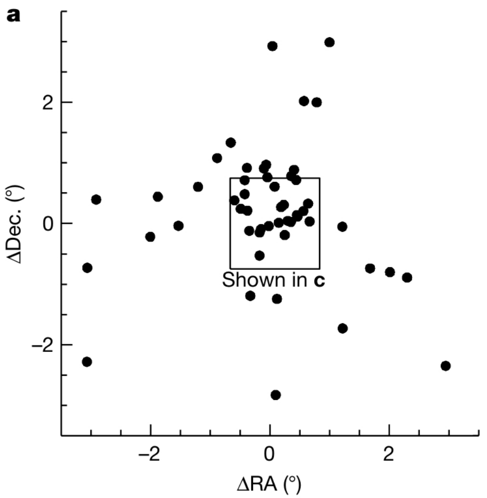
Large distance of DF2 & DF4 indicates as least one of them in **not bounded** in NGC 1052. It implies different mechanisms work for them if consider they form independently.

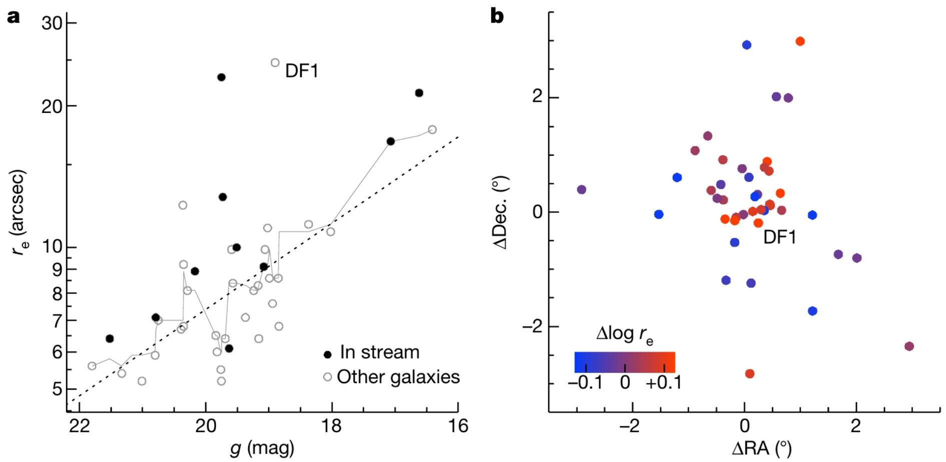
Then how about the **coincidence** the only 2 DMDGs discovered by now locates so close to each other in projection plane (0.24Mpc) and share very similar properties.

Collision probability lower or all the coincidences are more impossible?

# New evidence on collision scenario



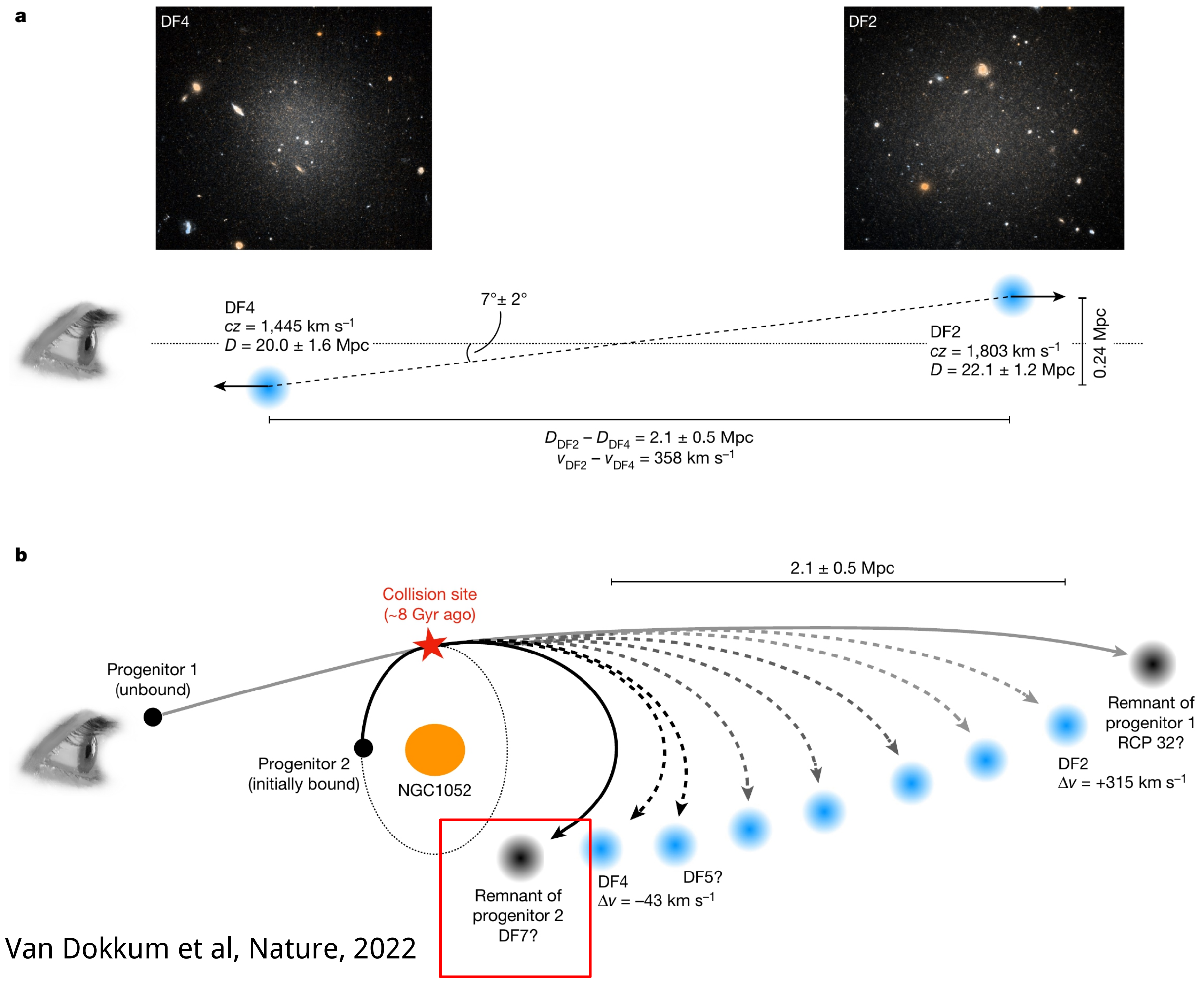




Van Dokkum et al, Nature, 2022

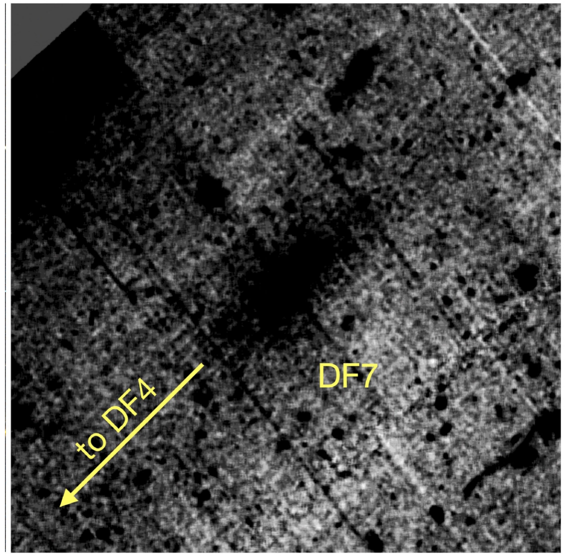
A line structure of possible collisional aftermaths.

# New evidence on collision scenario




Van Dokkum et al, Nature, 2022

Given their relative velocity and distance, it matches well with the scenario that collision happened **~8Gyrs** ago, which is in excellent agreement with the **ages** of the GCs **(9 ± 2 Gyrs).**




elongated to DF4 direction

# Summary

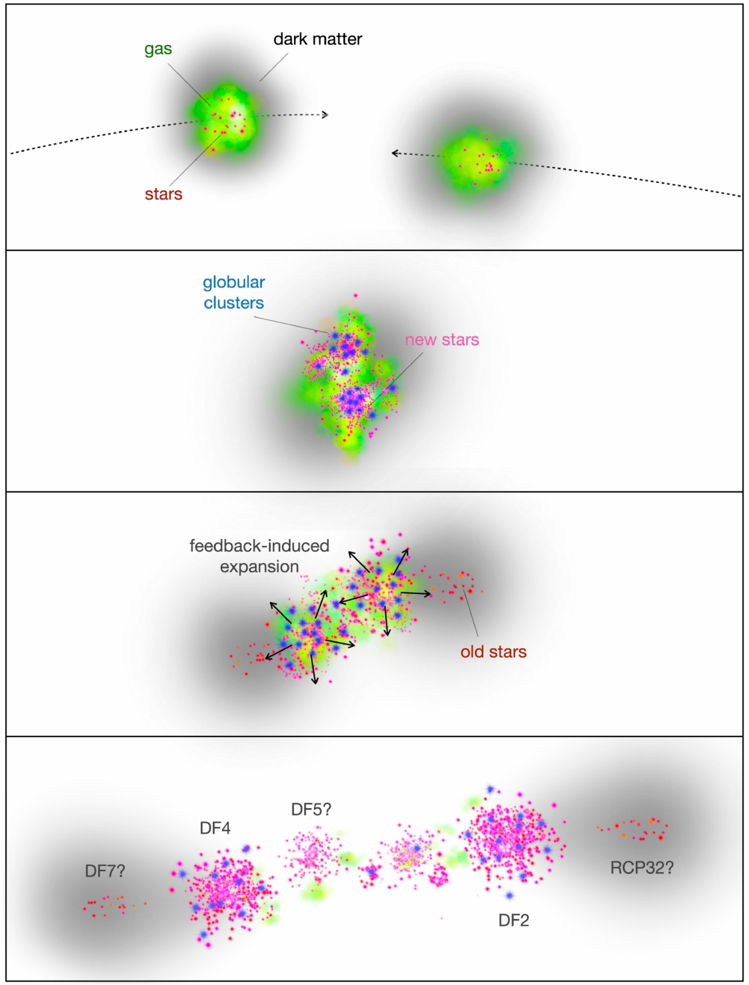
1. NGC 1052-DF2, DF4 are two galaxies confirmed to be dark matter deficient galaxies with consensus now, whose velocity dispersions are too small to account for large DM components.

2. Unusually luminous GC population suggests initially dense formation environments for DMDGs (Caused by merger etc.).

2. Model considering environmental effect like tidal stripping or the DMDGs are born to be tidal dwarf galaxies need extreme initial or evolutional conditions. It cannot be the exclusive mechanism since some UDGs are in field environments.

3. Models proposing the intrinsic upward scatter to mean SMDM function explain how enhanced SN feedback drive a cored DM profile and dark matter loss, in which DMDGs could be produced.

4. New observation evidence show possible aftermaths of bullet galaxy like collision, which supports the joint formation of DF2 & DF4 by collision.




Van Dokkum et al, Nature, 2022

# Back-up slides

# Debate on dynamical mass estimation

1. large scatter in velocity dispersion measurement

$$\sigma_{intr} = 3.2^{+5.5}_{-3.2}\ \mathrm{km\ s^{-1}} \longrightarrow \sigma_{intr} < 10.5\ \mathrm{km\ s^{-1}}$$

Van Dokkum et al, Nature, 2018

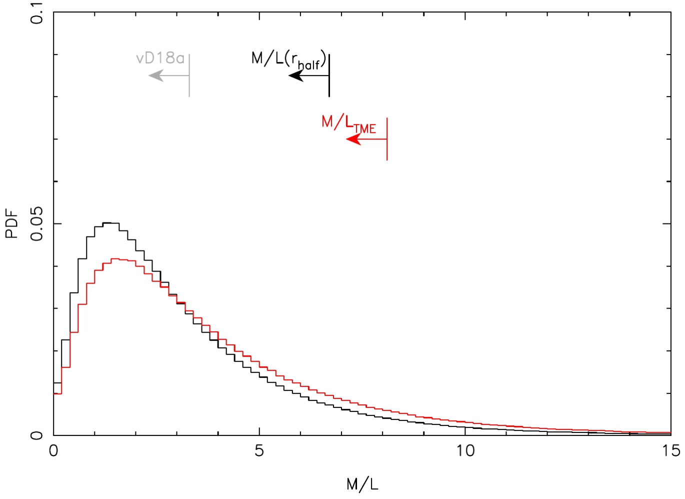
90% confidence upper limit

Small dataset with large uncertainties should be handled with simple models (multi-Gaussian).

Martin et al, ApJL, 2018

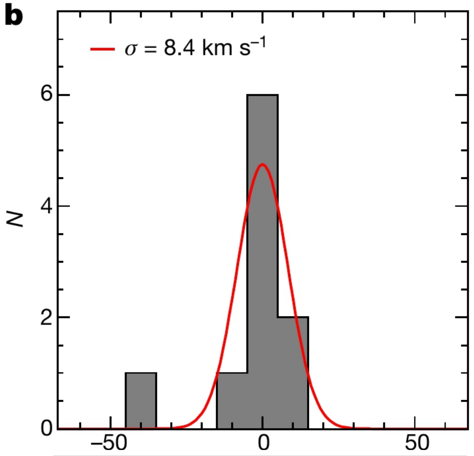
$$\sigma_{intr} < 17.3\ \mathrm{km\ s^{-1}}$$

M/L ~2 for pure stellar components



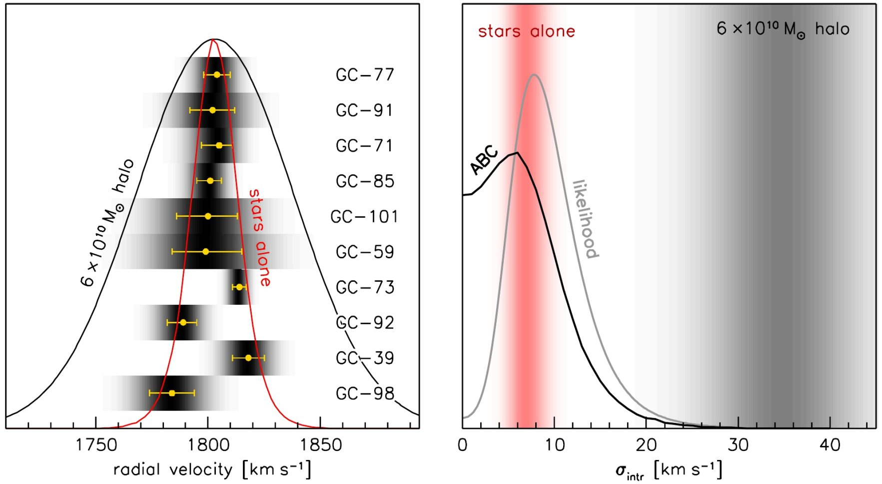

2. An outlier: GC 98

Van Dokkum et al, Nature, 2018



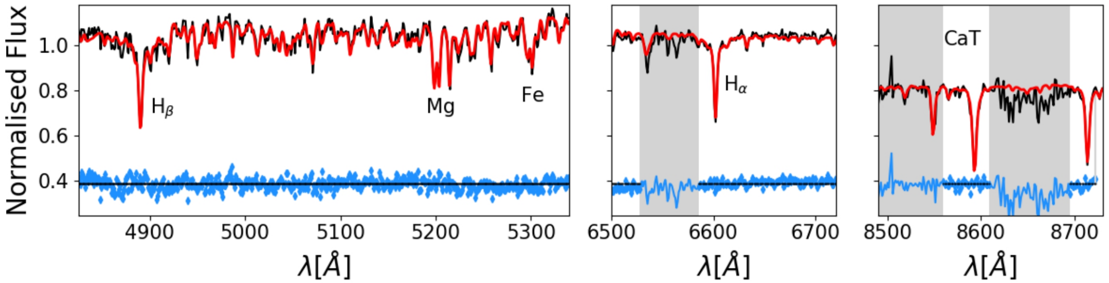

Revised velocity dispersion of GC 98 by LRIS data:
-39 km/s -> -19 km/s

Van Dokkum et al, arXiv note, 2018

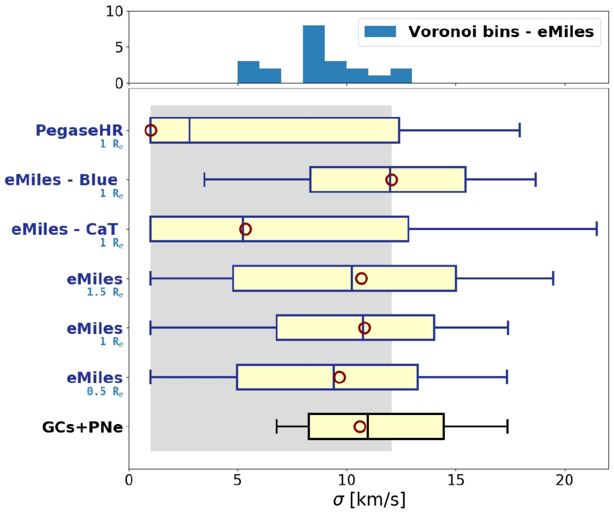


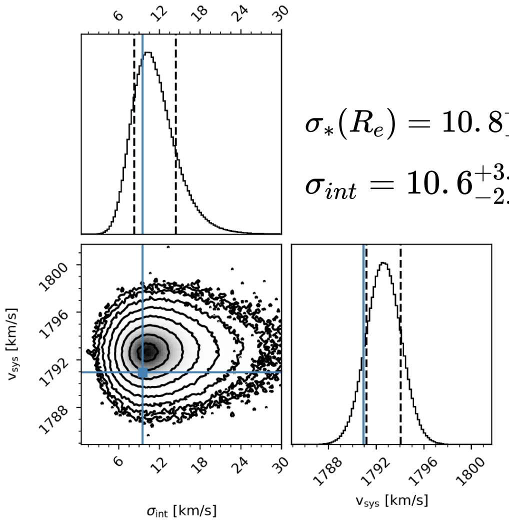
# Debate on dynamical mass estimation

3. Final solution: MUSE integral field spectrum




Spectrum of DF2 integrated over an aperture of 1 Re

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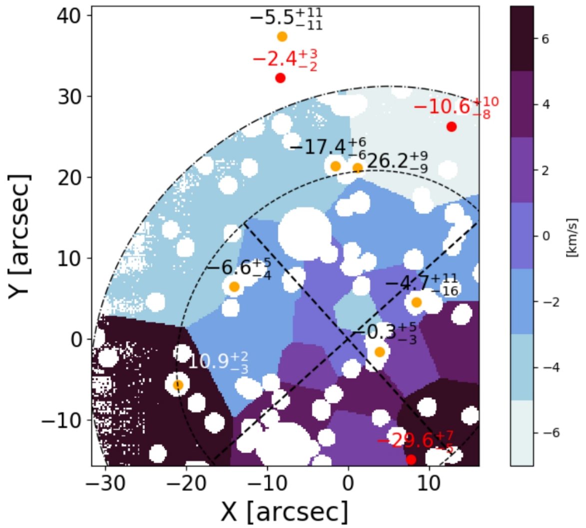
$$\sigma_{int} = 10.6^{+3.9}_{-2.3} kms^{-1}$$

Emsellem et al, A&A, 2019 Stellar light Point sources

Impact on mass to light ratio

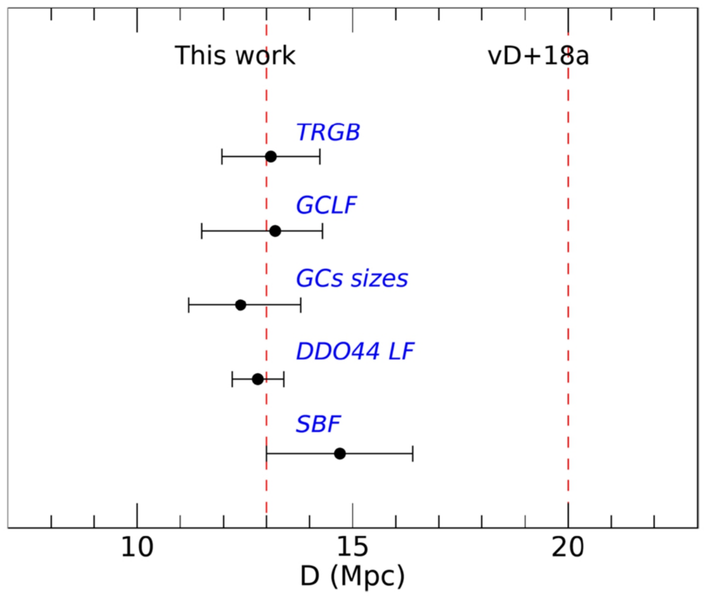
$$M_{dyn}/L_V = 3.7^{+3.3}_{-1.5}, 3.9^{+2.3}_{-2.6}$$




Emsellem et al, A&A, 2019

A concern: rotating galaxy?

# Debate on distance measurement

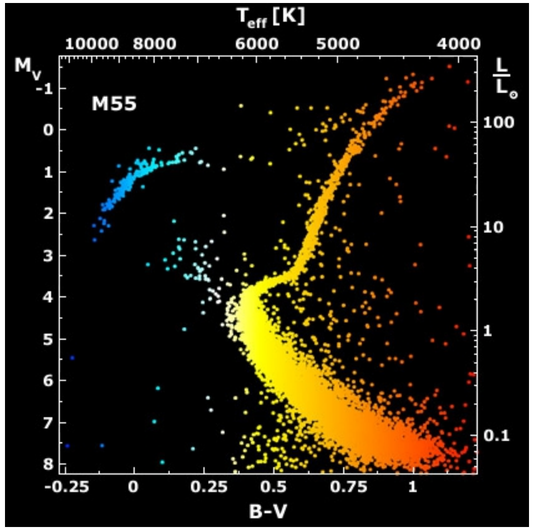



Trujillo et al, MNRAS,2019

1. Radial velocity (Hubble flow)
2. Proximity to NGC 1052 (elliptical galaxy)
3. Surface brightness fluctuation (smoother for further galaxies)
4. Tip of the Red Giant Branch as the standard candle.
5. Empirical relation from Globular clusters (peak luminosity)

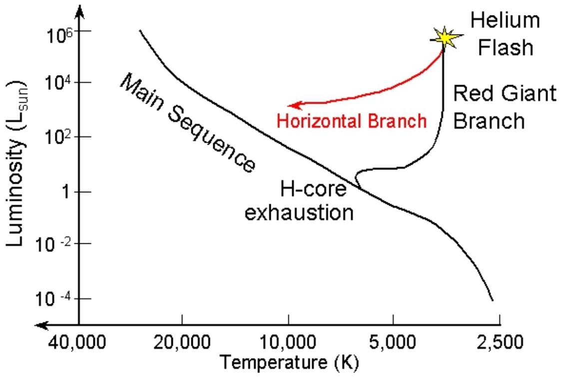
If the distance is decreased from ~20 Mpc to ~13 Mpc, the resulting DM fraction will increase to ~ 75%.

# Debate on distance measurement




M55 HR diagram [B.J. Mochejska, J. Kaluzny (CAMK), 1m Swope Telescope]

1e8 K

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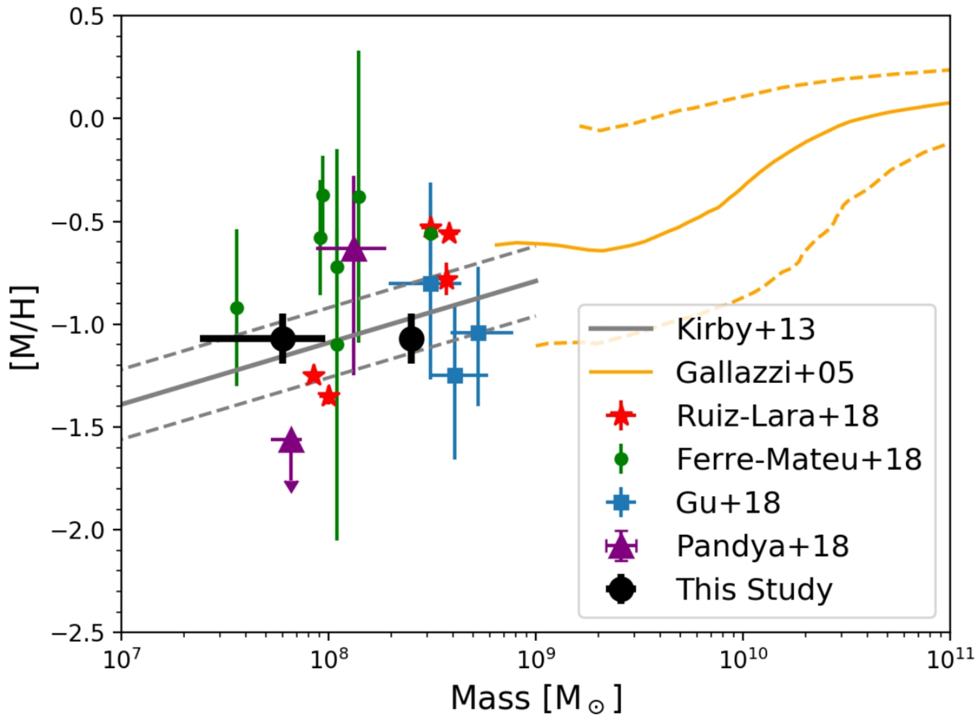
Tip of the Red Giant Branch as the standard candle.
It sensitively depends on how deep the image reaches since stars will looks fainter when the distance is larger.

Trujillo et al 2019 only use HST **1+1** orbit data in filter F814W & F606W, which is only able to reach D ~ 14 Mpc claimed in Shen+ 2021.

# Metallicity, star population

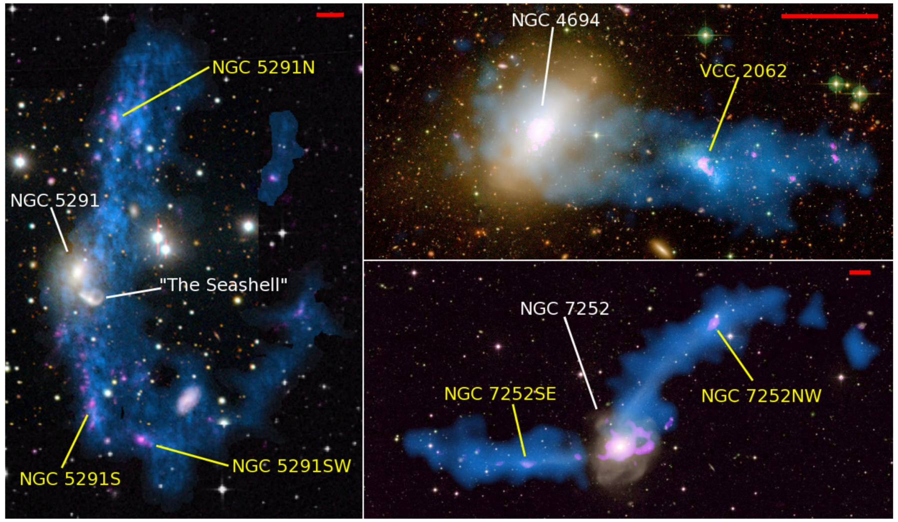



Fensch et al, A&A, 2019

DF2's stellar and GC components have similar age ~ 8.9Gyr. They are both metal poor but GC metallicity is 0.5 dex lower.

The metallicity and age of the population is consistent with other dwarf galaxies.

# Tidal dwarf galaxy




Lelli et al, A&A, 2015

HI emission of tidal dwarf galaxies.

*Fensch+ 2019* also shows the stellar population is **homogeneous** spatially, which means there should be process like merger or tidal interaction to mix it at early stage.

This process is easy to disrupt a galaxy without dark matter.

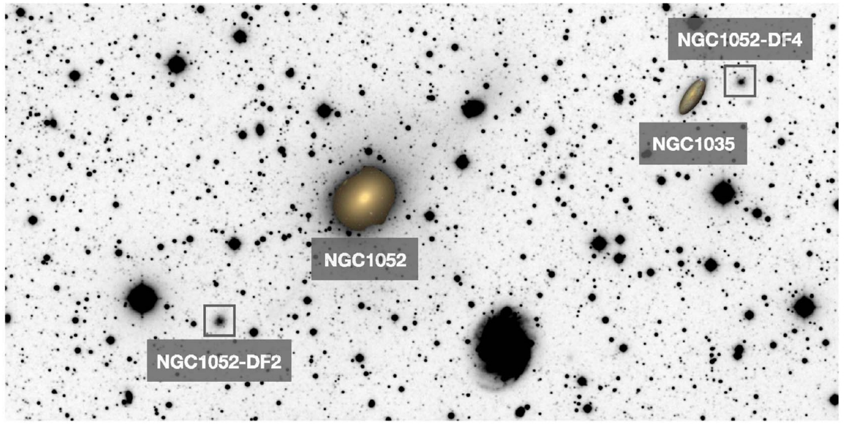
Moreover, *Muller O +2019* doesn't see any evidence of **tidal debris** around DF2.

# A few words on MOND

Van Dokkum+ 2018 comments that the discovery of DMDGs could falsify MOND since all galaxy should have similar modification.

However, Kroupa+ 2018, Haghi+. (2019), and Müller+. (2019a) found the observed velocity dispersions of both NGC 1052–DF2 and NGC 1052–DF4 are consistent with MOND in velocity dispersions if both galaxies are close to a massive galaxy ( **External Field Effect** ).

DF2 seems to be close to NGC 1052, while DF4 could possibly be close to NGC 1035. However, HST deep field image doesn't show any evidence that they could be closely related.




Shen et al, ApJL, 2021