Ultra-diffuse galaxies in the IllustrisTNG cosmological simulation

Astronomy Department Seminar
Faculty of Mathematics
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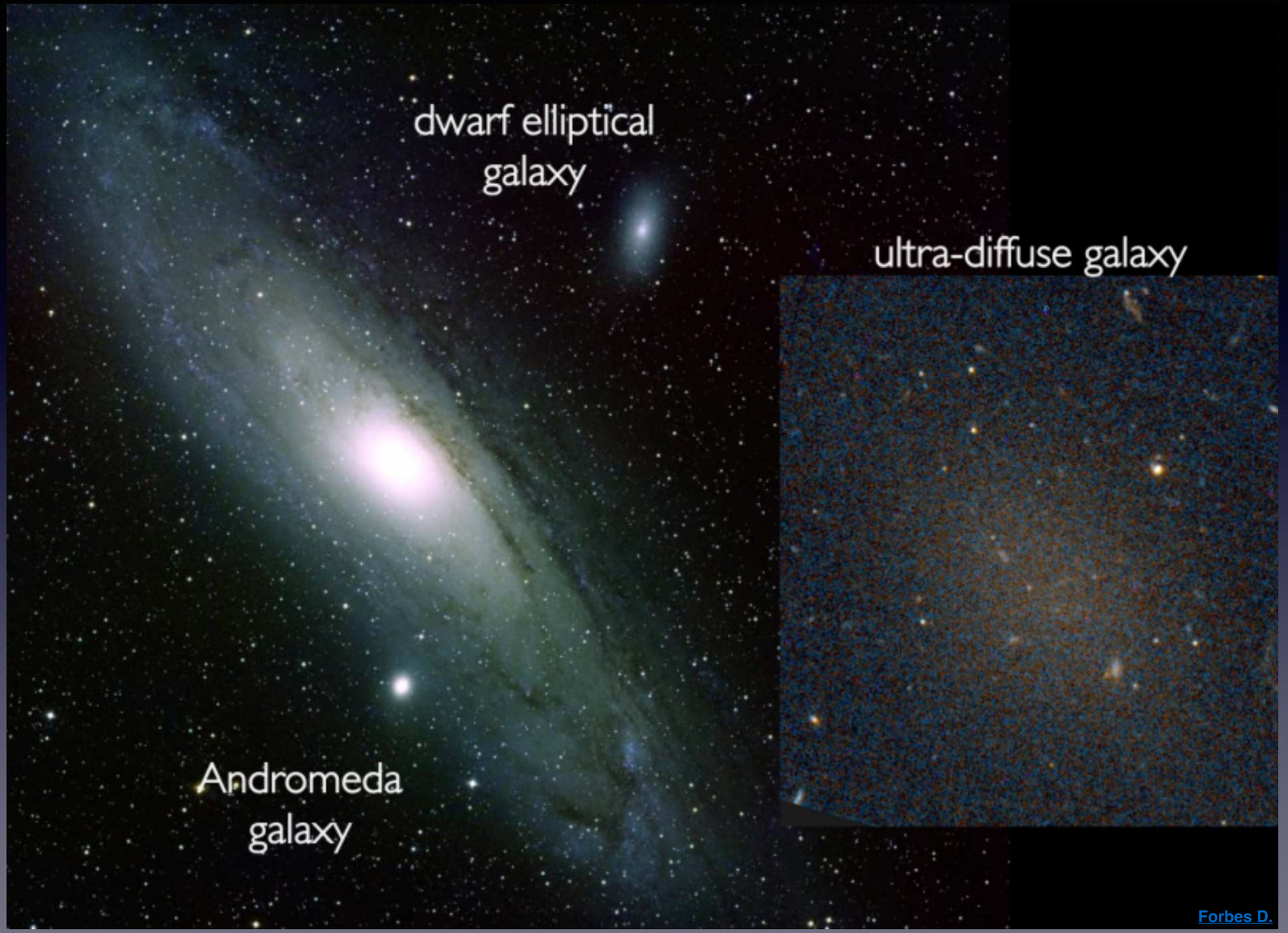
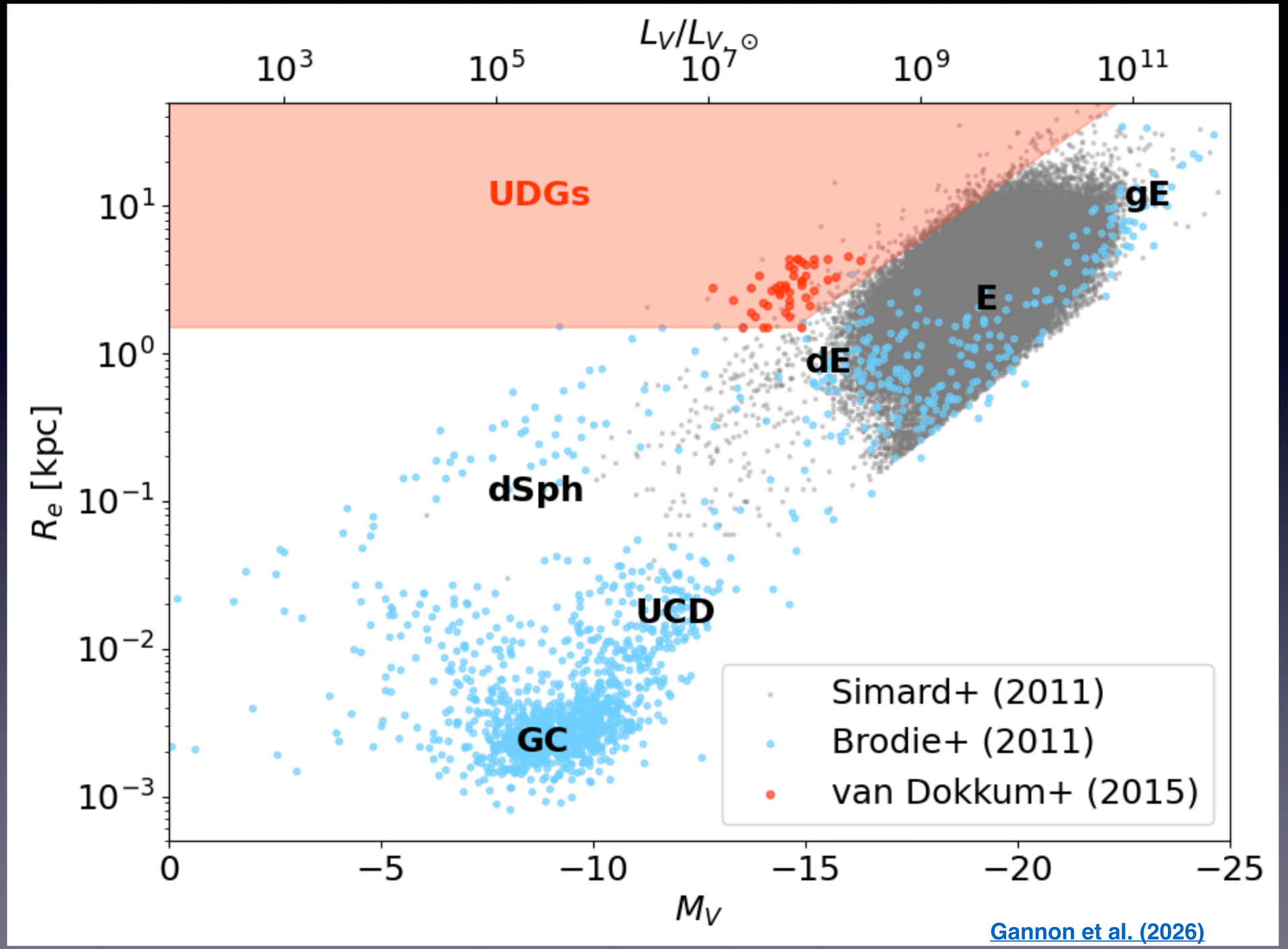
Outline

- What are UDGs and their properties
- Where can we study them (observations & simulations)
- A special outlier - Nube (observations)
- A Nube-like galaxy in simulations
- Implications and limitations
- Conclusion and future work


dwarf elliptical
galaxy
ultra-diffuse galaxy
Andromeda
galaxy

Forbes D.



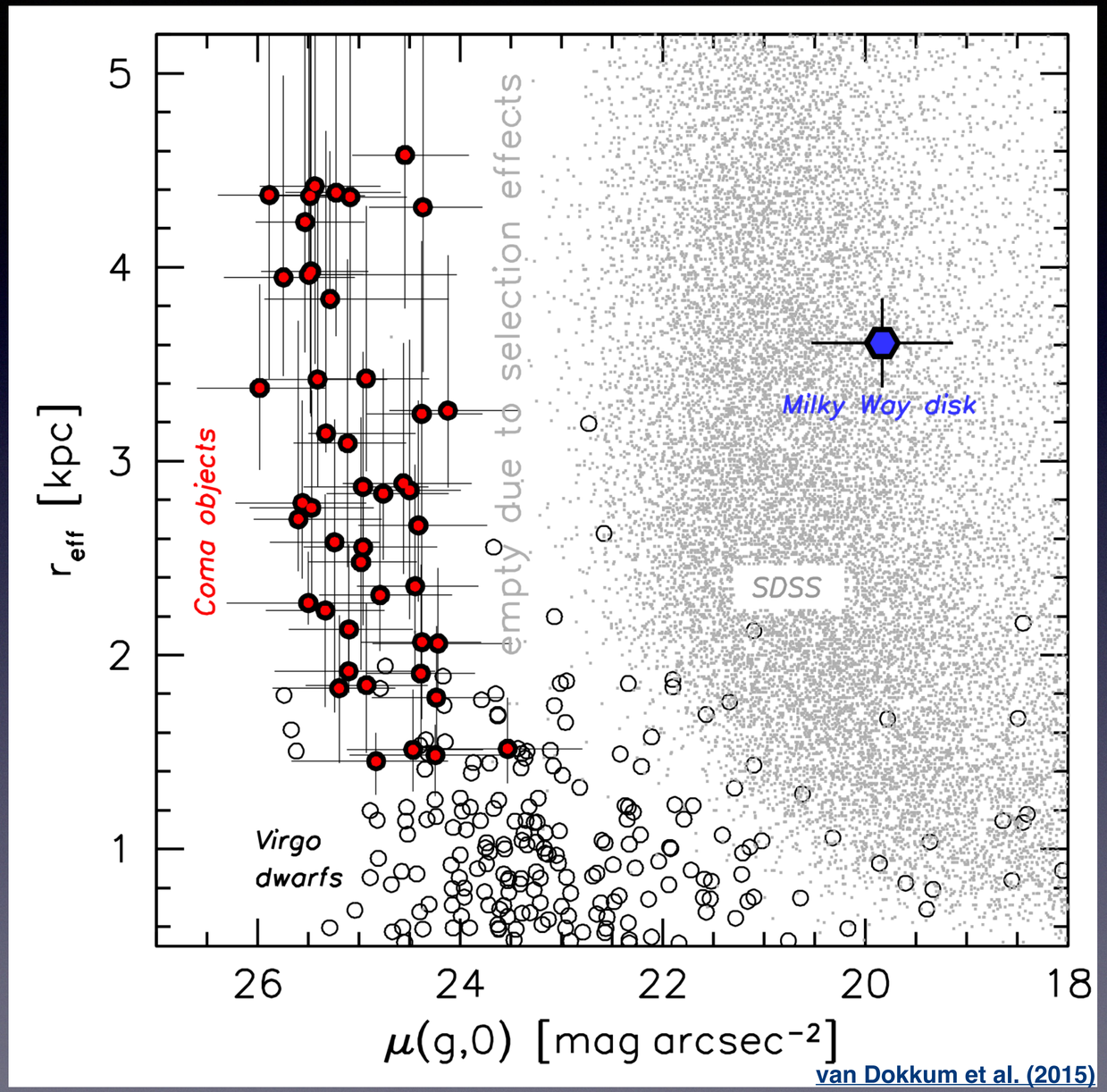
Gannon et al. (2026)

Discovery of UDGs (or rather defining)

Just some LSB galaxies (Sandage et al. (1984))

Until UDGs were detected in large numbers in the Coma cluster (van Dokkum et al. (2015))

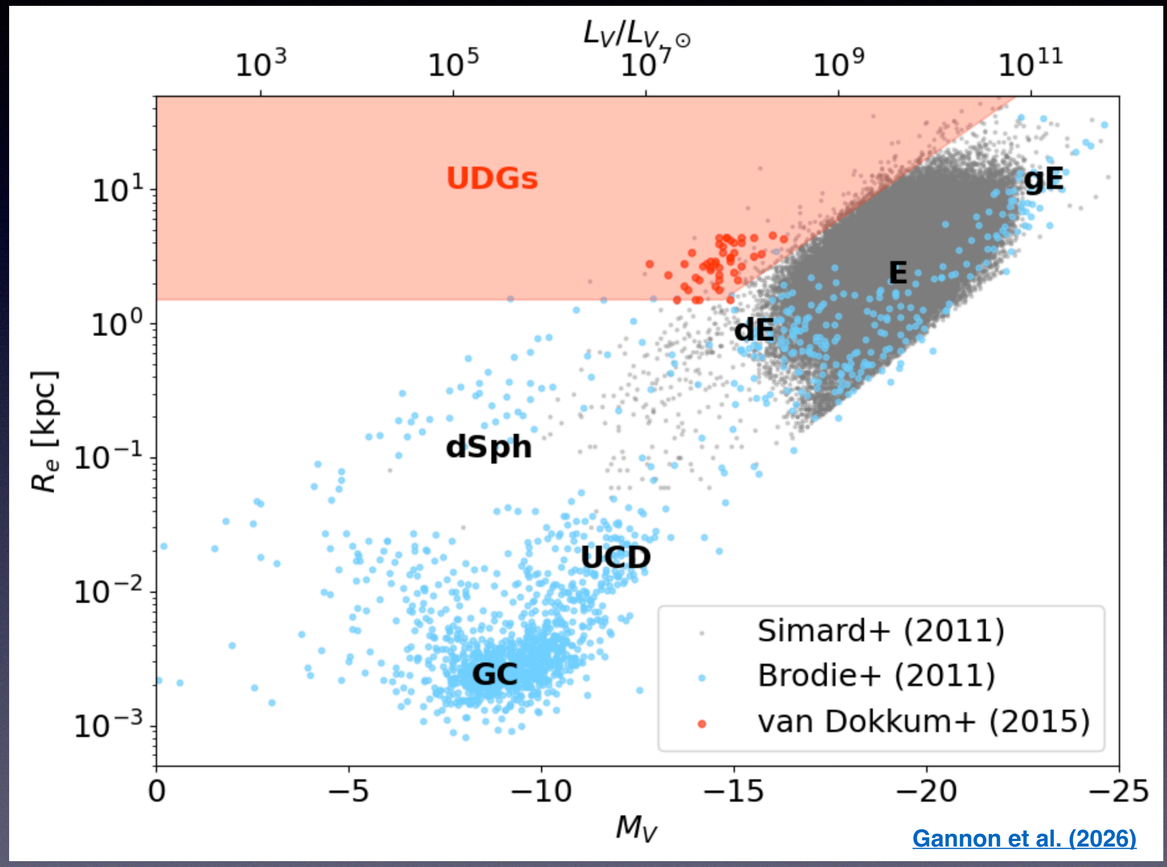
Interesting "new objects" because of their size (comparable to the MW) in large numbers!



van Dokkum et al. (2015)

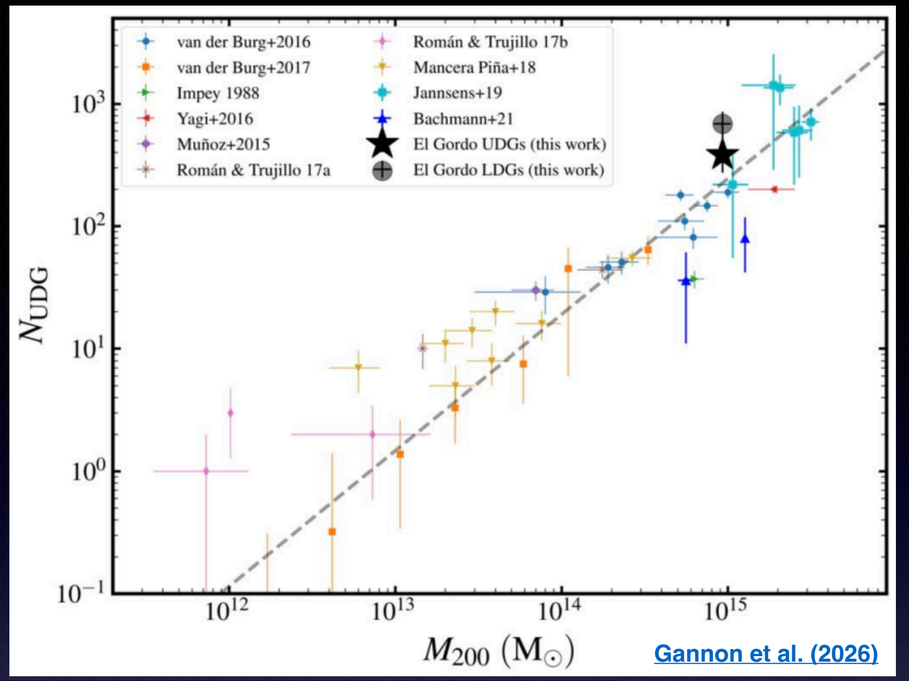
Properties of UDGs

stellar mass: $(10^7<)\ M_*<10^9\ M_\odot$
halo mass: $10^{10}< M_{halo}<10^{12}\ M_\odot$
surface brightness: $\mu_{V,eff} > 25$ mag arcsec^{-2}
effective radius: $R_e > 1.5$ kpc



Properties of UDGs

- diffuse and hard to study, but not rare, ~5% of all galaxies (Jones et al. (2018), Li et al. (2023), Weaver et al. (2024))
- abundance scales with host halo mass (Lee et al. (2020))



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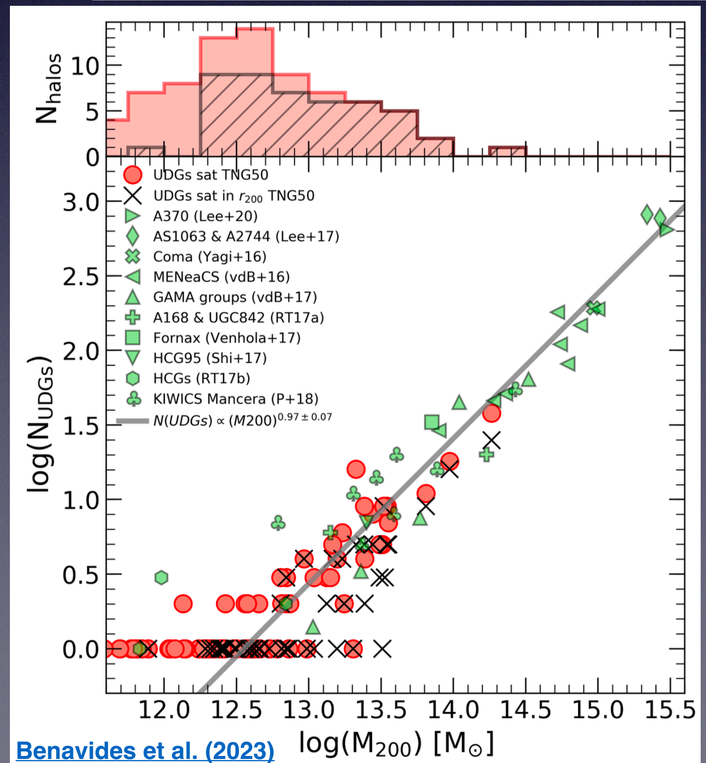

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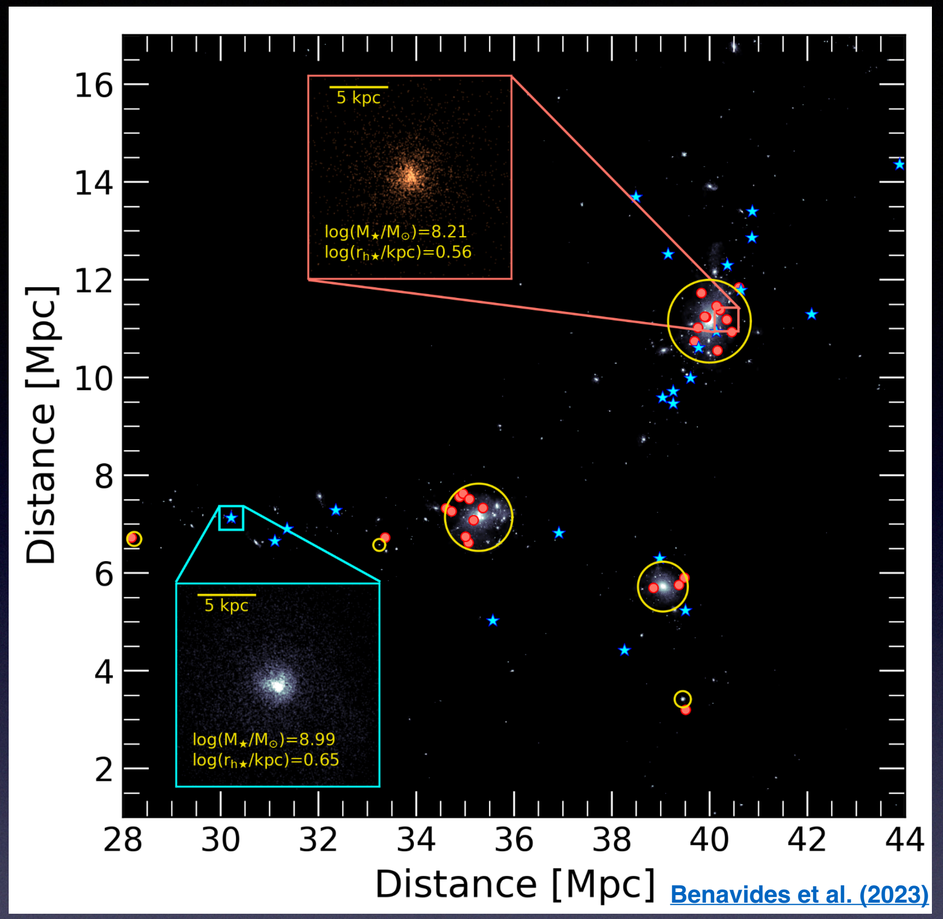
- mostly featureless (no bulge, no disk, no bar)
- sometimes some features: GC/UCD (central nucleus)
- well fitted by Sersic profile n~1
- types: cluster/satellites (red, no gas) OR field (blue, some gas)
- tidal disruption signs are rare



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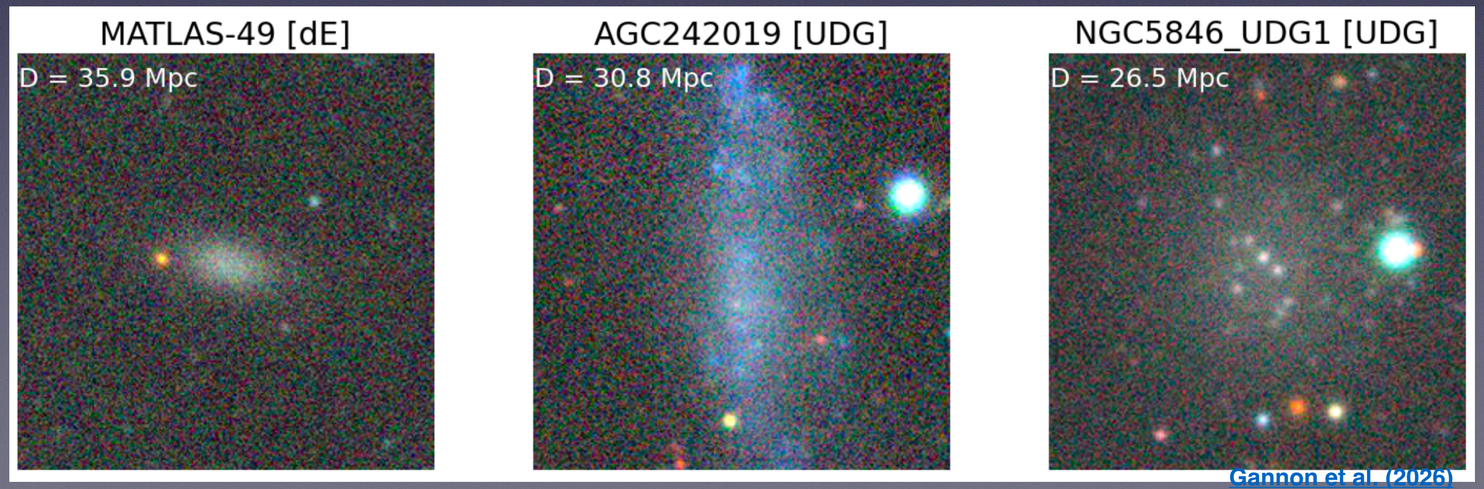


Gannon et al. (2026)

Pathways of formation

Basic:
1. dwarfs that puffed-up
2. failed (large DM halos)

Advanced (review: Gannon et al. (2026)):
- internal (high halo spin, SN feedback, high gas spin)
- external (tidal heating/puffing, tidally stripped galaxes, mergers, ram pressure stripping
- born as UDGs (tidally stripped stars, tidally stripped gas, bullet dwarf, failed galaxies)

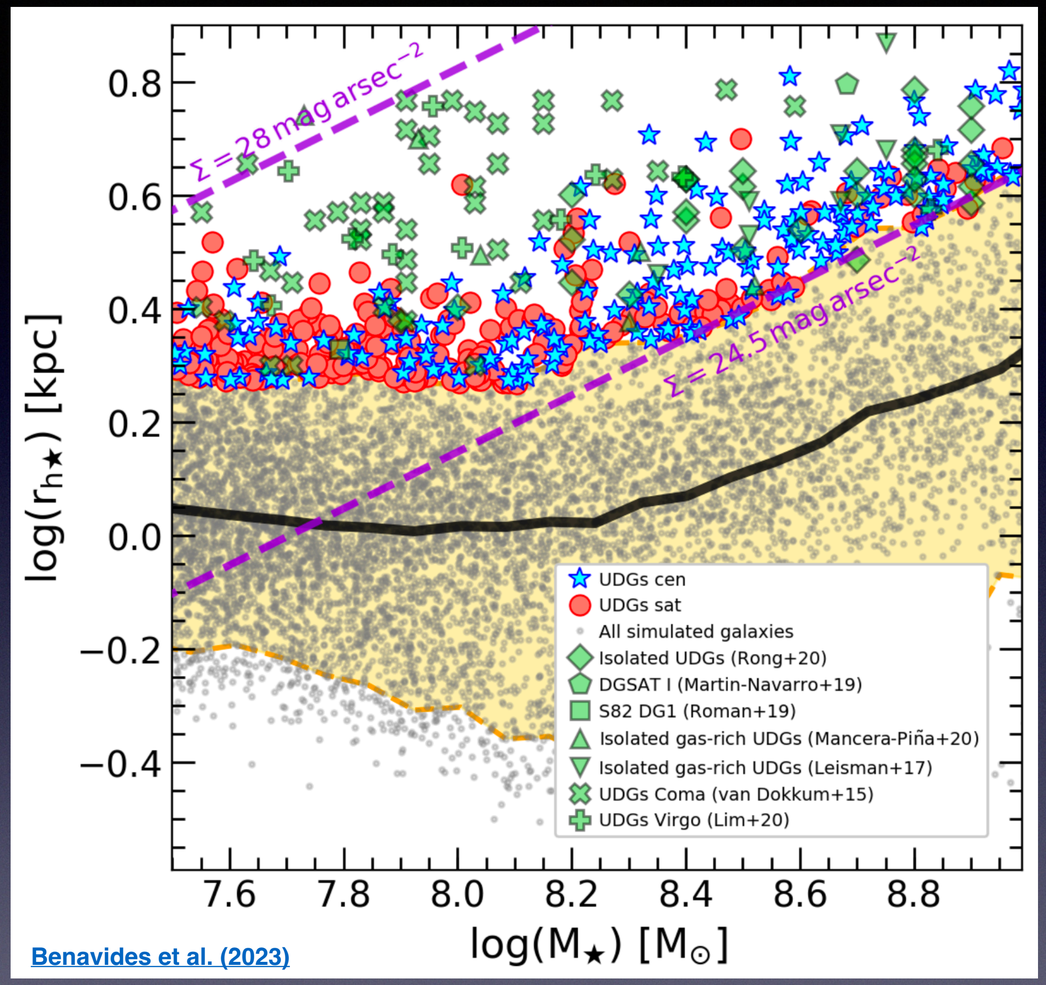
????????

Simulations

FIRE-2 simulation - UDGs match observed properties
NIHAO simulations - UDGs naturally occur in isolated dwarf-sized halos
UDG cluster subpopulation in the **RomulusC zoom-in** simulation (Tremmel et al. 2019)

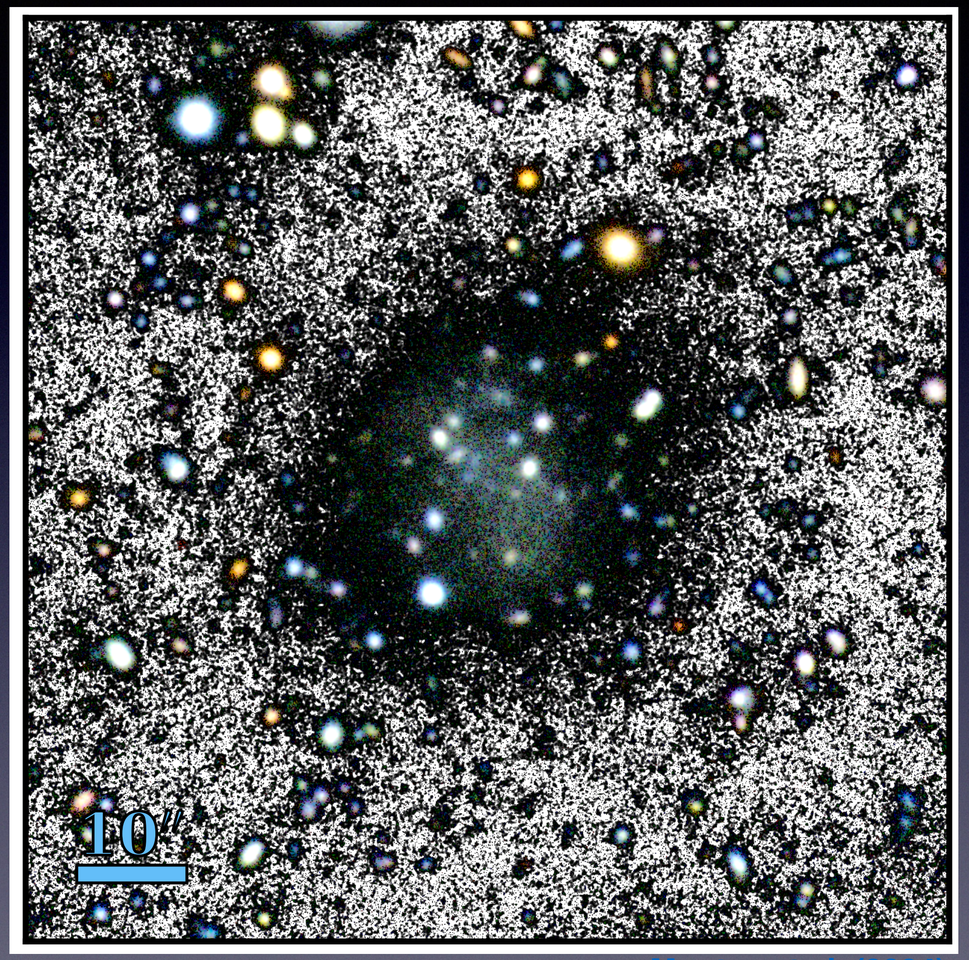
UDGs form through multiple intrinsic/extrinsic mechanisms in different environments in the **TNG50 simulation** (Benavides et al. (2023))

UDGs in galaxy clusters in the **TNG100 simulation** also confirmed (Sales et al. (2020))



Benavides et al. (2023)

An outlier - Nube



Montes et al. (2024)

An outlier - Nube

An example of a "too extended" UDG (R_e ~ 7 kpc)

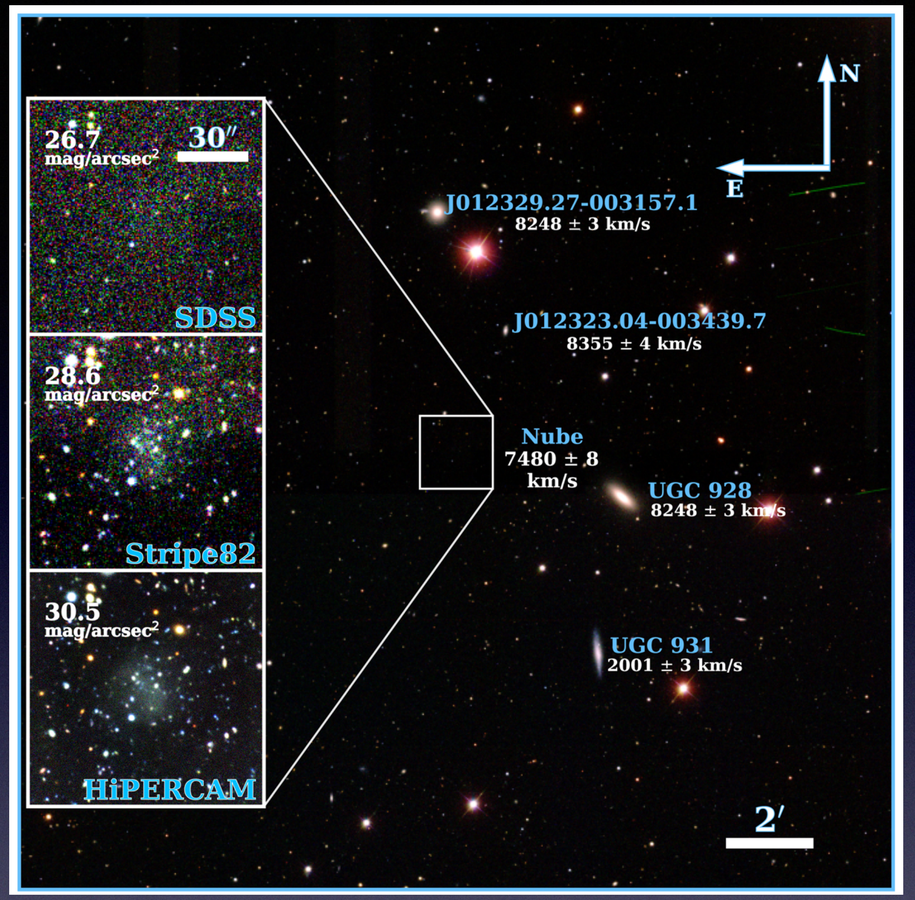
current simulations do not reproduce Nube

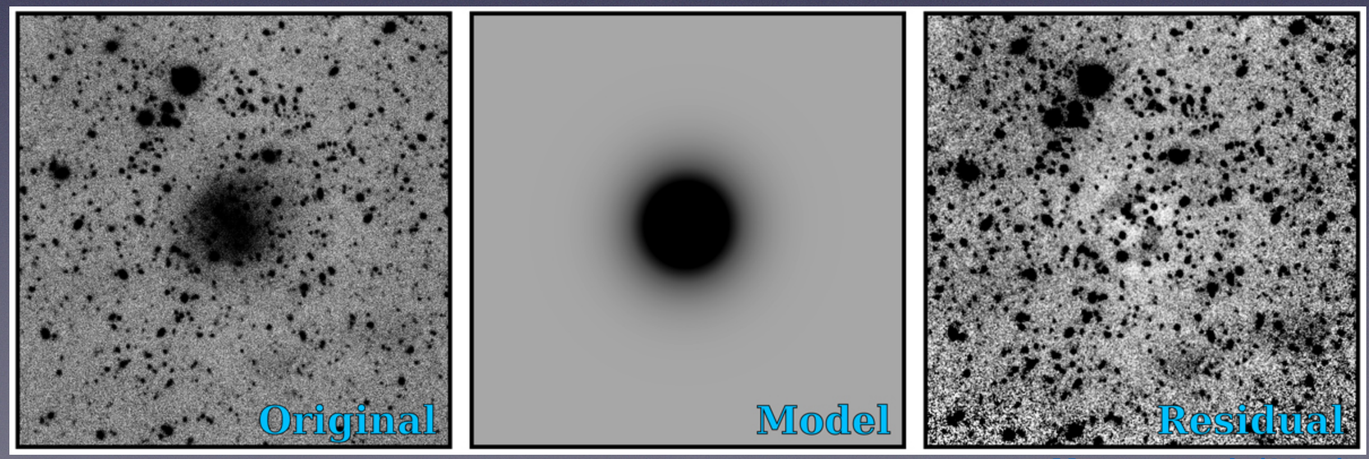
seemingly in tension with the CDM model; consistent with the fuzzy dark matter model

speculated formation mechanisms: TDG and puffing-up

none of which was conclusive

(Montes et al. 2024)





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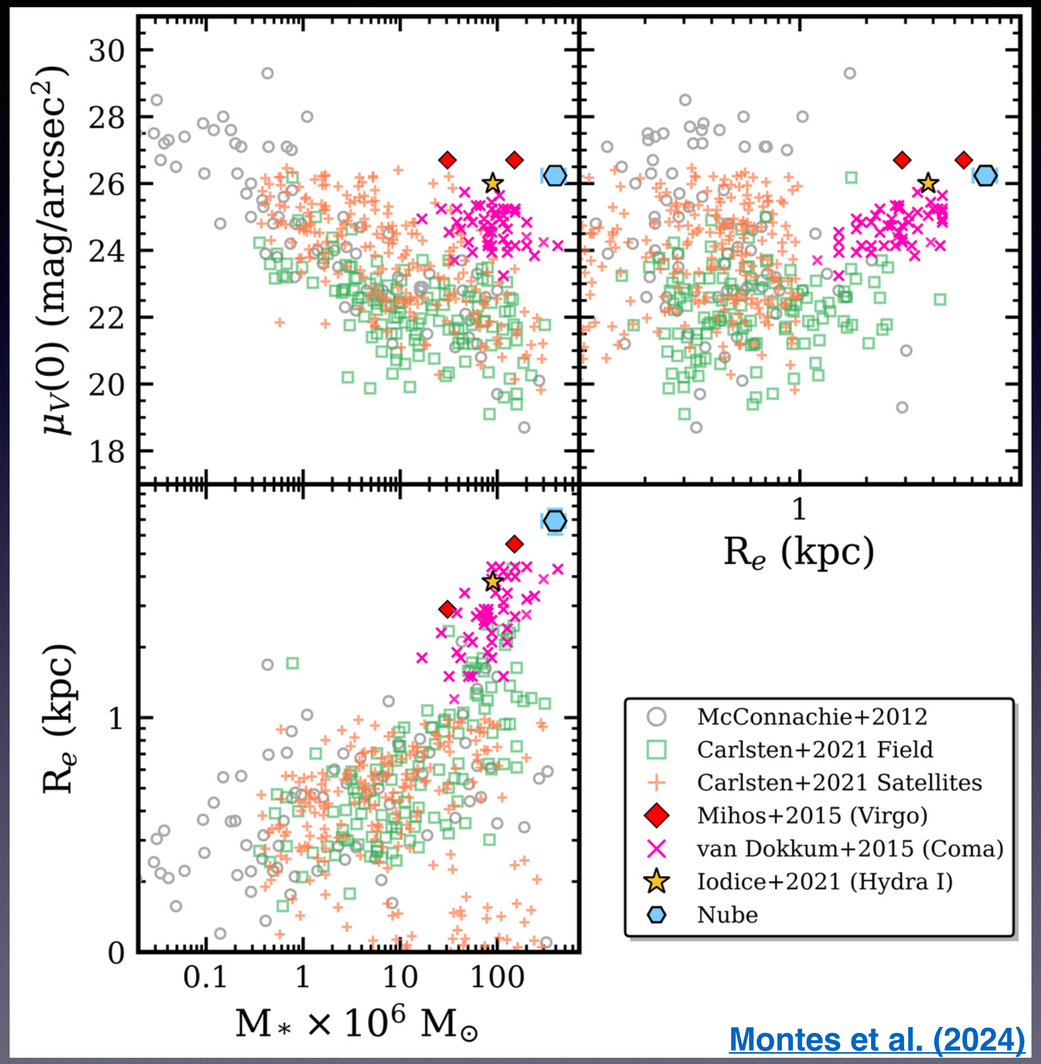


Montes et al. (2024)

Motivation

previous studies **failed to replicate rare galaxies such as Nube** using cosmological and zoom-in simulations (limited range of environmental effects, examined population of UDGs may be narrow)

seemingly in tension with the cold dark matter (CDM) model; consistent with the fuzzy dark matter model (Montes et al. 2024)

galaxy formation mechanisms and evolutionary paths, probe the nature of dark matter, and test different cosmological models

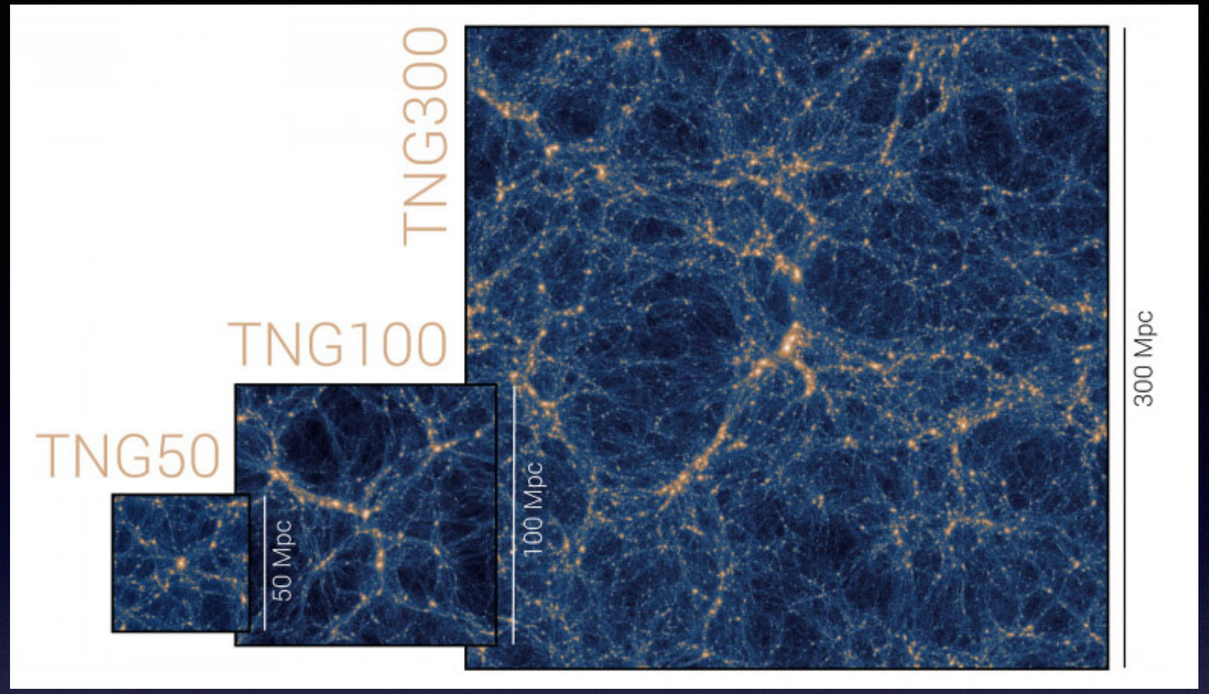
fundamental component of our understanding of dwarf galaxy formation, as some of their observed properties, such as size, globular cluster (GC) content or inferred dynamical mass, **remain difficult to reconcile with theoretical models** (Sales et al. 2022)

The IllustrisTNG Project

TNG100 - balances volume and resolution

Nube-like galaxy would have about 250 particles

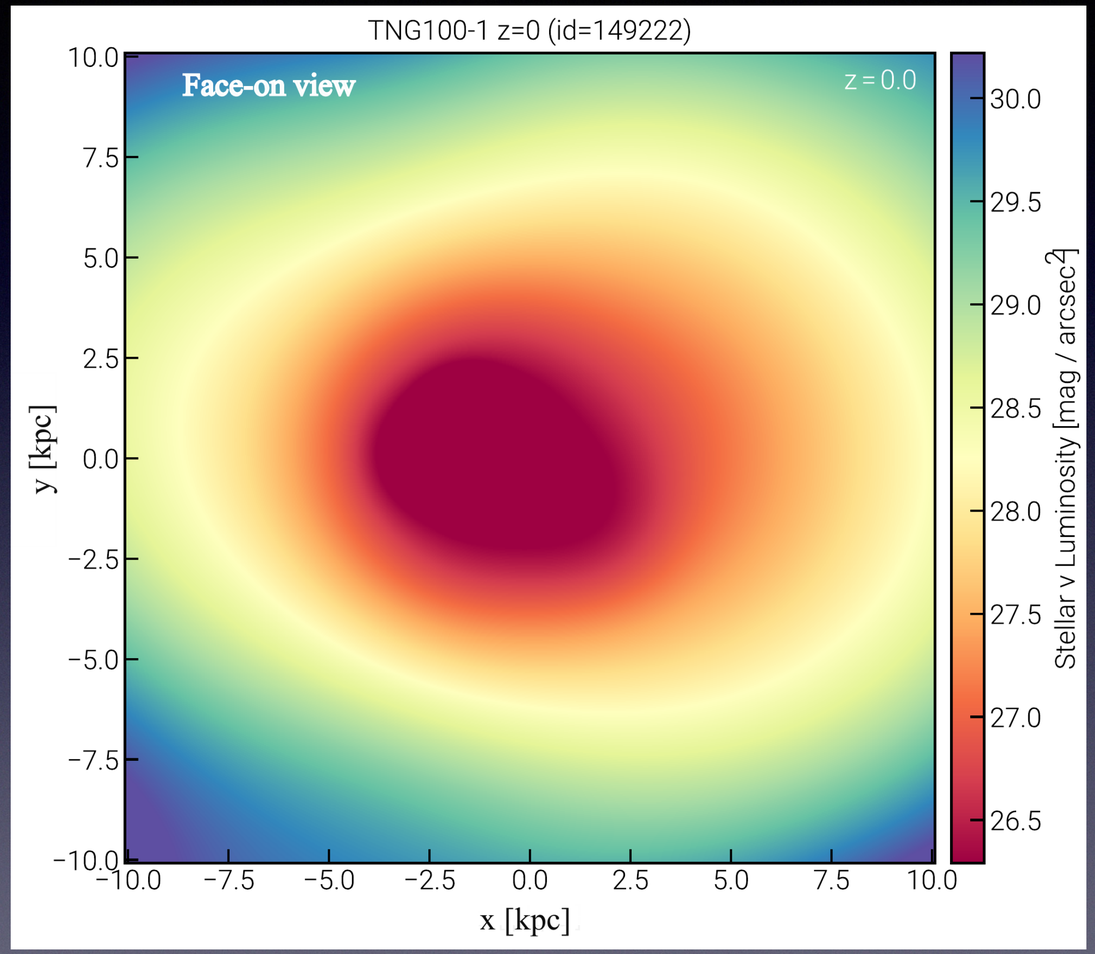
a galaxy of stellar mass similar to Nube can have its **global** (stellar) fundamental properties recovered reliably (Onions et al. 2012)



		TNG50	TNG100	TNG300
Volume	$[\mathrm{Mpc}^3]$	51.7^3	110.7^3	302.6^3
L_{box}	$[\mathrm{Mpc}/h]$	35	75	205
N_{GAS}	-	2160^3	1820^3	2500^3
N_{DM}	-	2160^3	1820^3	2500^3
N_{TR}	-	2160^3	2×1820^3	2500^3
m_{baryon}	$[\mathrm{M}_\odot]$	8.5×10^4	1.4×10^6	1.1×10^7
m_{DM}	$[\mathrm{M}_\odot]$	4.5×10^5	7.5×10^6	5.9×10^7
$\epsilon_{\mathrm{gas,min}}$	[pc]	74	185	370
$\epsilon_{\mathrm{DM},\star}$	[pc]	288	740	1480

https://www.tng-project.org/

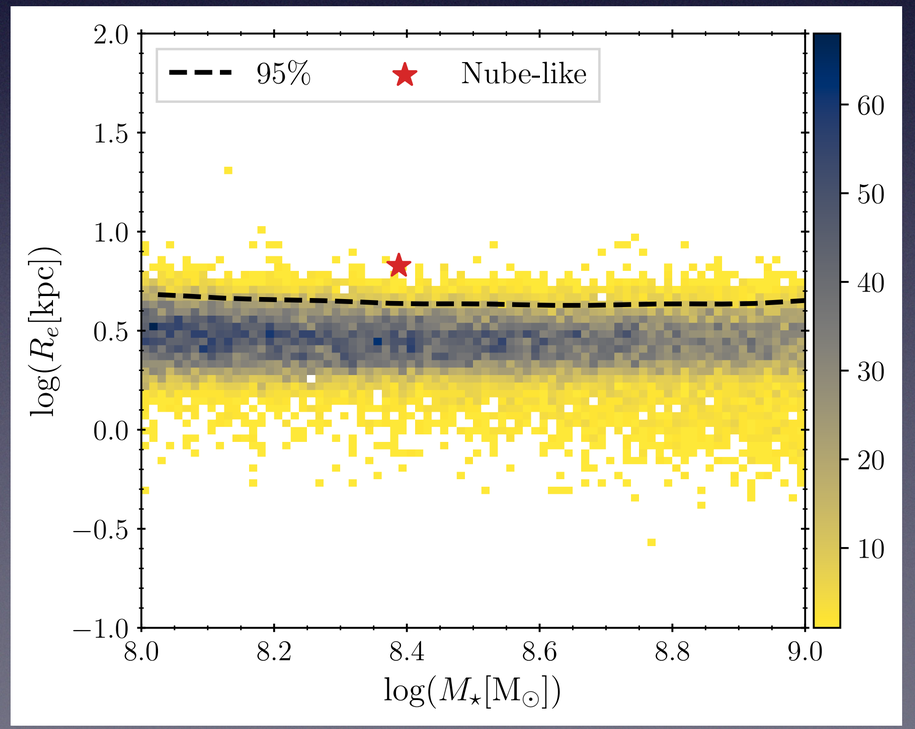
Nube-like galaxy

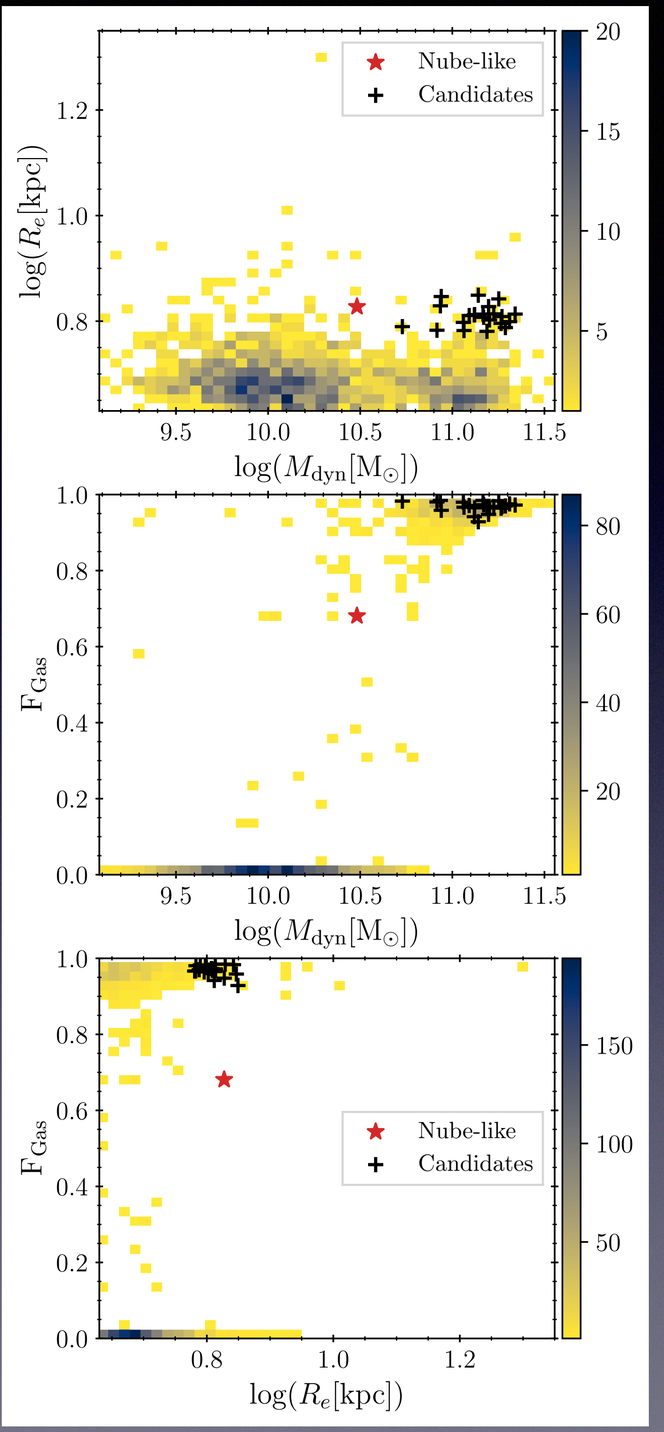


Sample selection

z = 0
8 < log $M_\star$ [$M_\odot$] < 9
6 < R_e [kpc] < 8
log M_{gas} [$M_\odot$] > 8
log M_{dyn} [$M_\odot$] >10

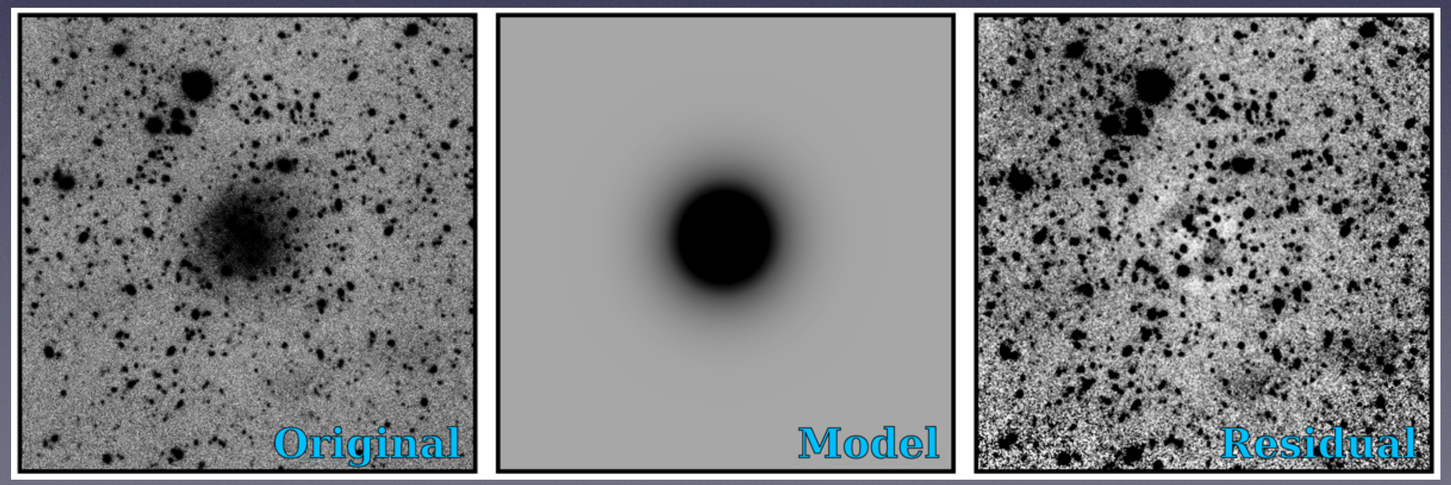
upper 5% part of the mass-size relation
(i.e., the most extended ones)
(Benavides et al. (2023))

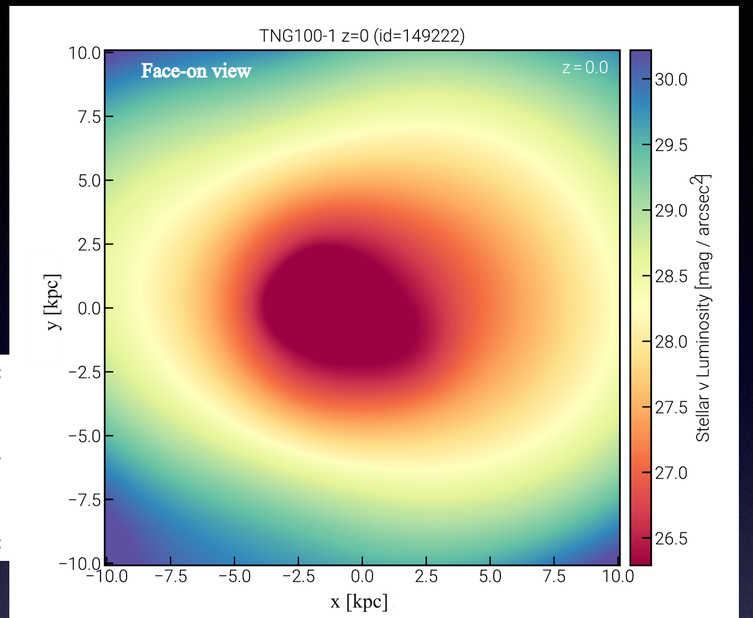


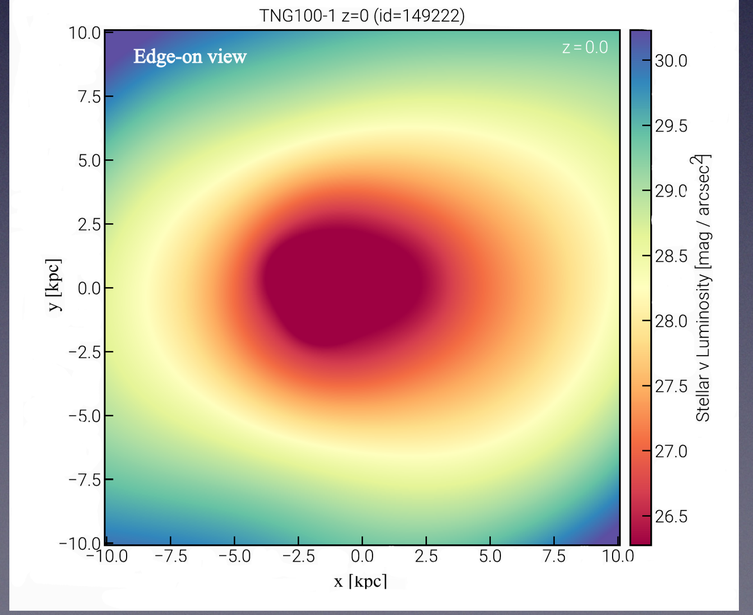


Nube-like galaxy

Galaxy	$\log M_{\rm dyn}$ ($\log M_\odot$)	$\log M_\star$ ($\log M_\odot$)	$\log M_{\rm HI}$ ($\log M_\odot$)	R_e (kpc)	Σ_e ($M_\odot\ pc^{-2}$)	$\mu_V(0)$ (mag $arcsec^{-2}$)	Age (Gyr)	b/a
Nube	10.42 ± 0.23	8.6 ± 0.1	8.35 ± 0.12	6.9 ± 0.8	0.9 ± 0.1	26.23 ± 0.07	$10.2\ ^{+2.0}_{-2.5}$	0.97 ± 0.01
ID149222	(10.12, 10.48)	8.39	8.17	6.72	(0.86, 1.53)	~ 26.3	7.479	~ 0.758







Nube-like

ultra-diffuse most likely from its formation

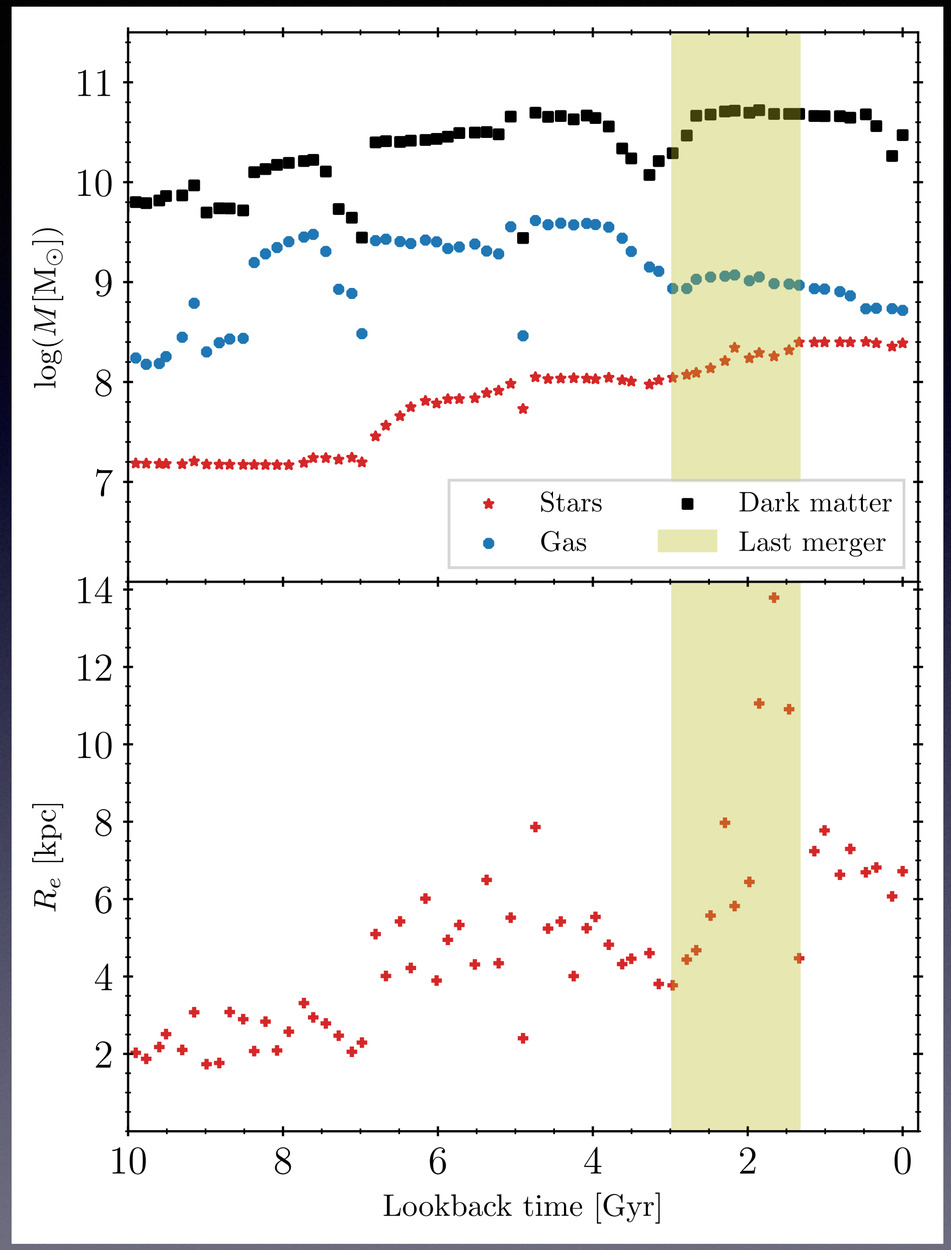
mainly evolved quietly in isolated regions

interaction (7 Gyr ago) triggered star formation built up the stellar component

last (major) merger (3 Gyr ago) - absorbed almost the entirety of the stellar content of the secondary galaxy (only 6% of stellar mass formed after merger), enormous gas content of the galaxy did not efficiently turn into stars (outer layers being blown away in this violent process)

R_e increase: stellar particles from the secondary galaxy being absorbed, not the stellar content of the host being puffed up initially (stellar particles slowly settle)

does not exhibit any distinctive tidal features or distortions

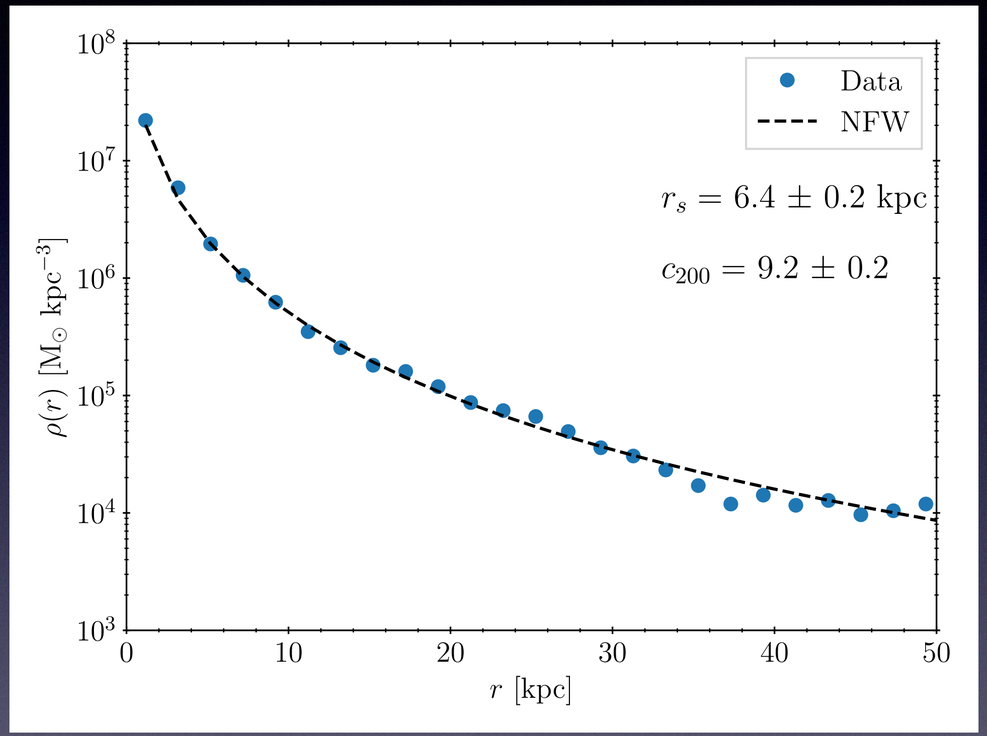


Nube-like

DM halo: log(M_{DM} [M⊙])= 10.47
NFW profile fits the dark matter profile well, with the r_s = 6.4 ±0.2, c_{200} = 9.2 ±0.2 (c_{200} low, but still within the expected scatter)

R_{vir} ≃ 58.88 kpc (expected R_{vir} ≃ 65.46 kpc --> dark matter halo not in virial equilibrium, recent merger)

formation pathway: higher-spin dark matter halos? spin parameter (Bullock et al. (2001)) - typical value



Limitations:

Particle mass resolution --> no resolved internal structure (stellar distribution, velocity fields, or stellar orbits) or faint low-mass tidal features

Even detection of tidal features challenging (intrinsically faint luminosities and low surface brightness)

more massive galaxies are located at distances of 210.67 kpc, 724.25 kpc (closest massive neighbour to Nube, the galaxy UGC 929, is found to be at a distance of 435 kpc (Montes et al. 2024).)

A specific example? Broader picture needed!

no complete consensus on the dominant formation mechanism, due to the diversity of the UDG properties and their environments

Conclusions for Nube

multiple formation pathways can operate simultaneously: an already ultra-diffuse galaxy can expand its size even further under favourable conditions

UDGs may not the end product of a given galaxy evolution

extreme outliers of the mass-size relation can certainly be found in cosmological simulations

not justified to reject CDM cosmological model, but this nether confirms it (Nube & Nube-like treated as a rare example)

understanding of the ecosystem of cosmological simulations

Future work

Observations...

Our contribution: exploring UDGs evolution in simulations

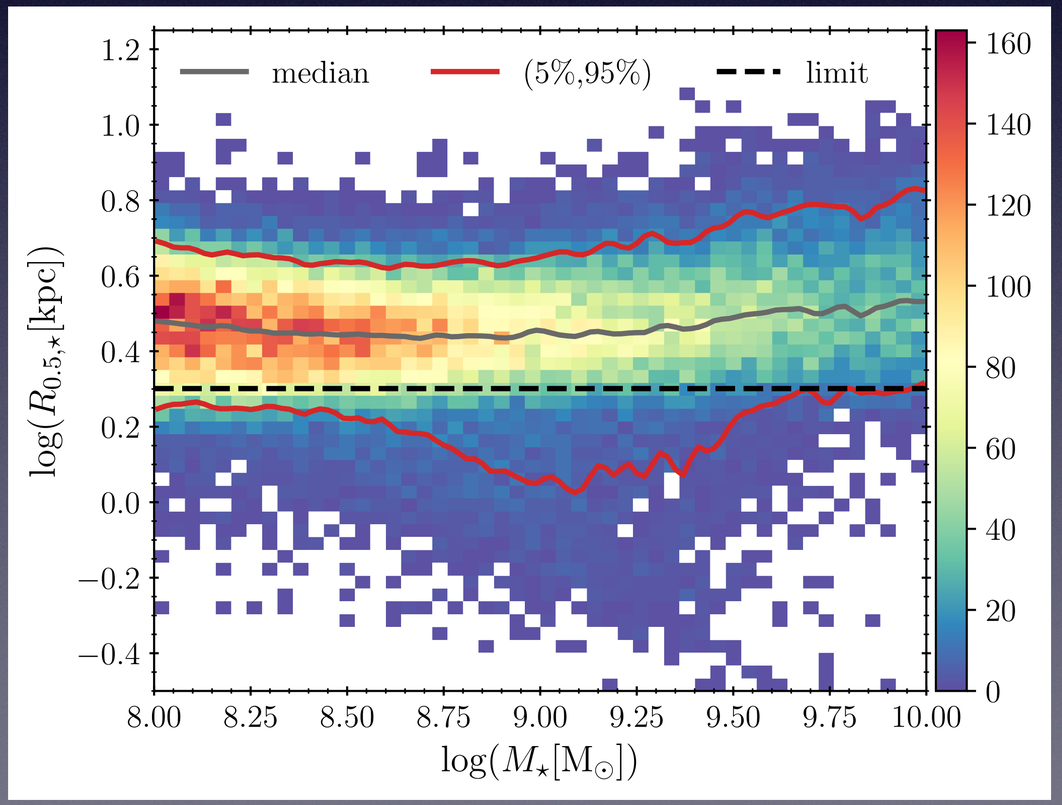
- the creation and destruction (+timescales)
- evolution pathways
- about the globular clusters...
- dark matter implications?

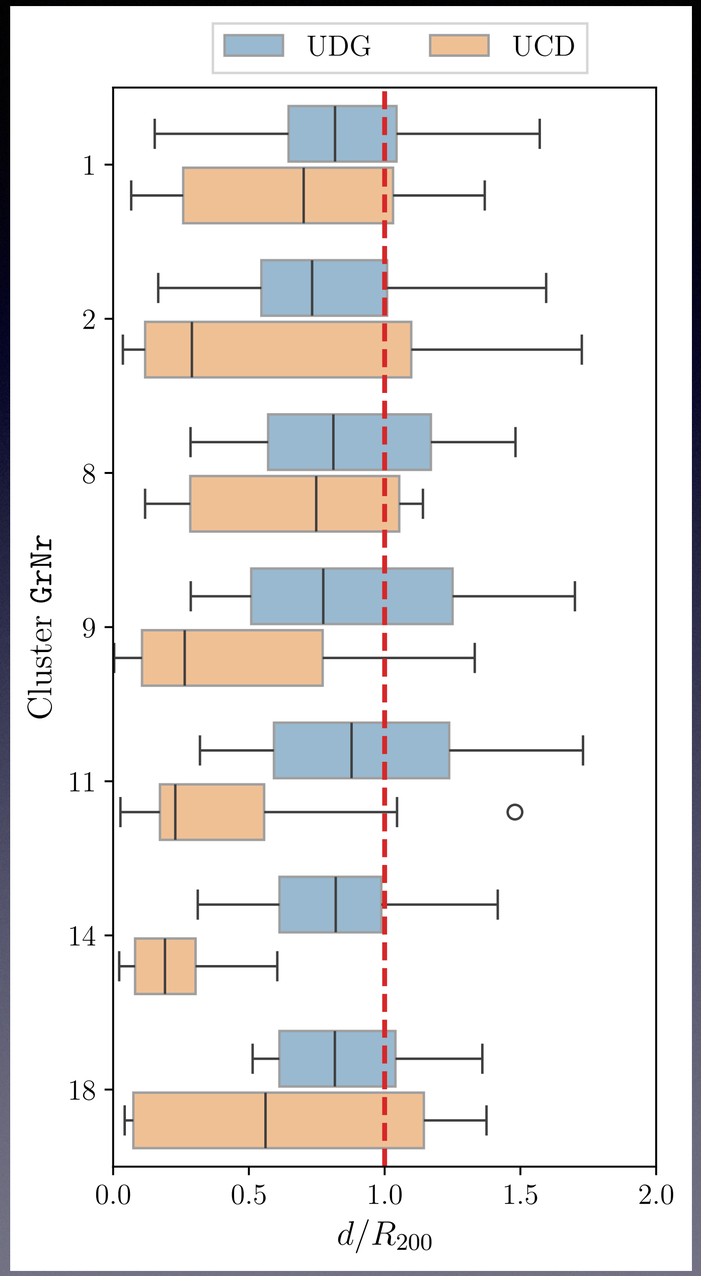
To be continued...

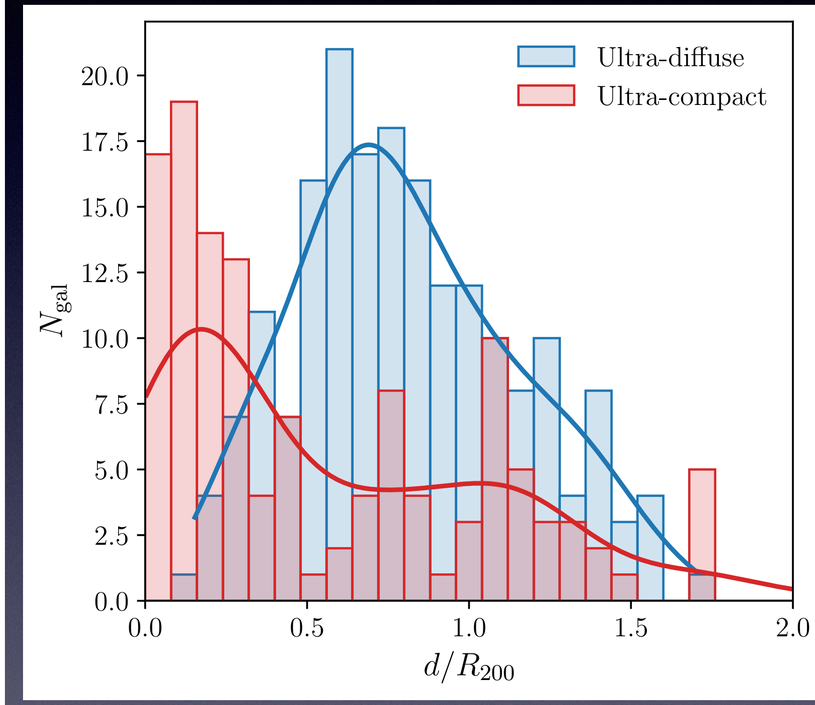
Work in preparation:

relation between UDGs and UCDs (possible evolution path?)

UDG vs UCD spacial distribution







Pavlov & Mitrašinović in prep.

Thank you for
your attention!