Cosmological dark matter simulations with baryons: recent developments at the smallest, dwarf-galaxy scales

Arianna Di Cintio
ULL & IAC (Tenerife)
adicintio@iac.es

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
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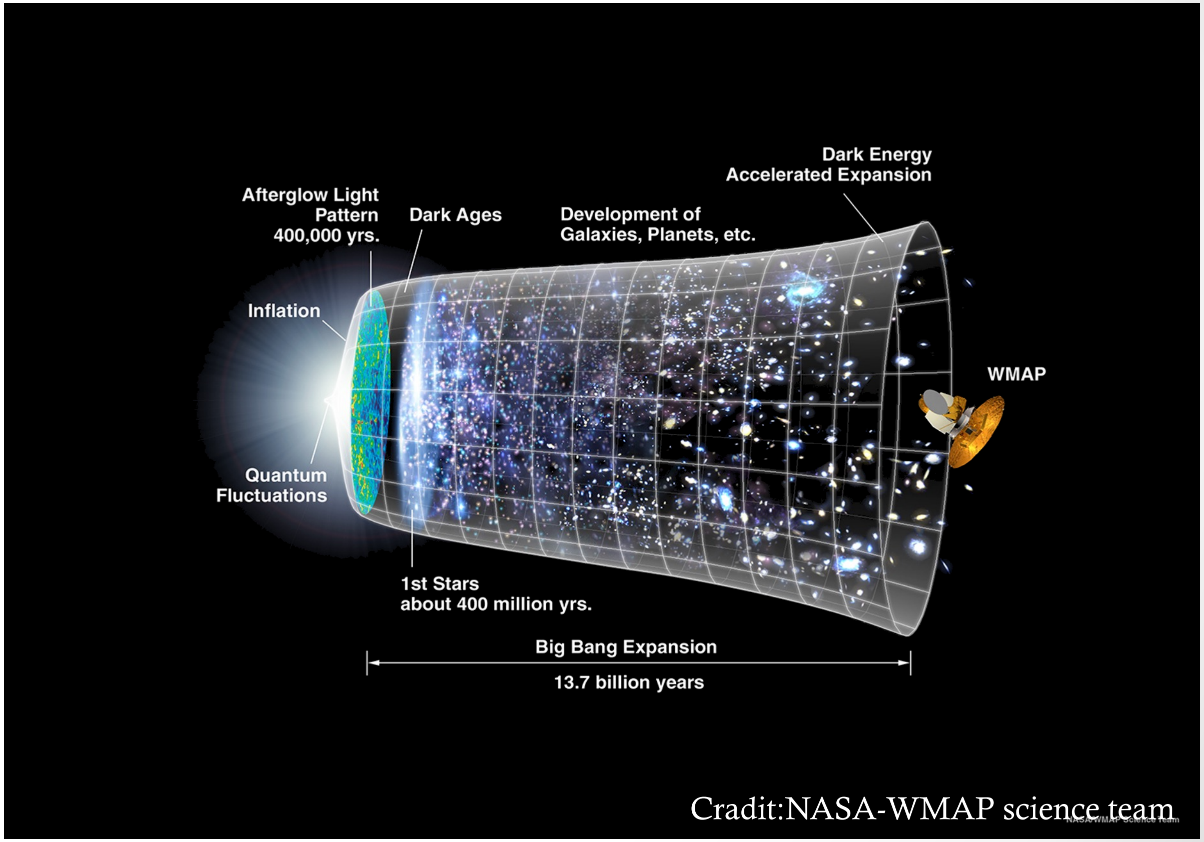
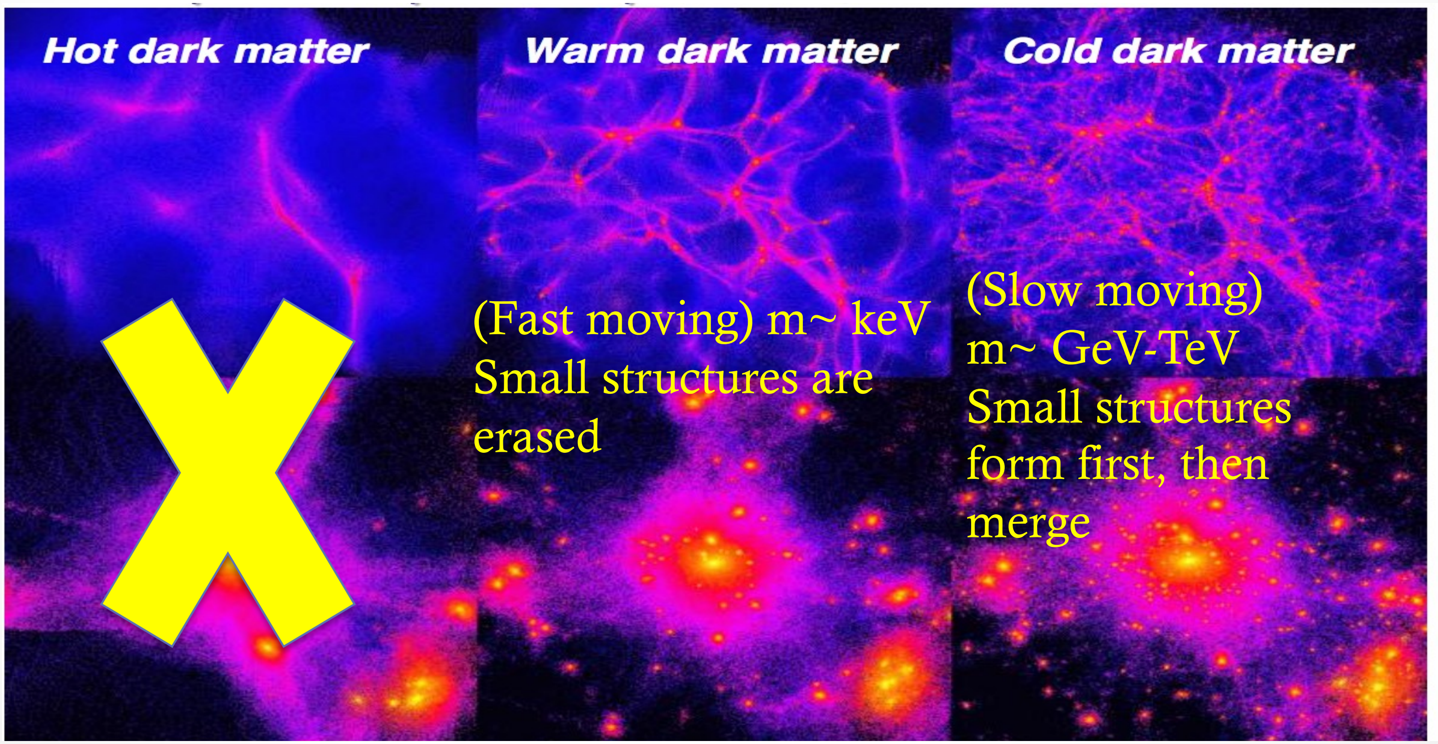
Galaxy formation across cosmic time

In a Cold-DM Universe, small perturbations in the primordial density field can grow via gravitational instabilities, and then merge with each other to create the much bigger structures, like clusters and groups of galaxies, that we observe today



Hierarchical structure formation

LCDM is the standard cosmological model of structure formation , based on Cold dark matter (CDM), particles which have 10-100 times the mass of a proton. => LCDM implies a bottom up galaxy formation



Credit: Ben Moore

Why do we need simulations? GALAXY FORMATION IS NON-LINEAR

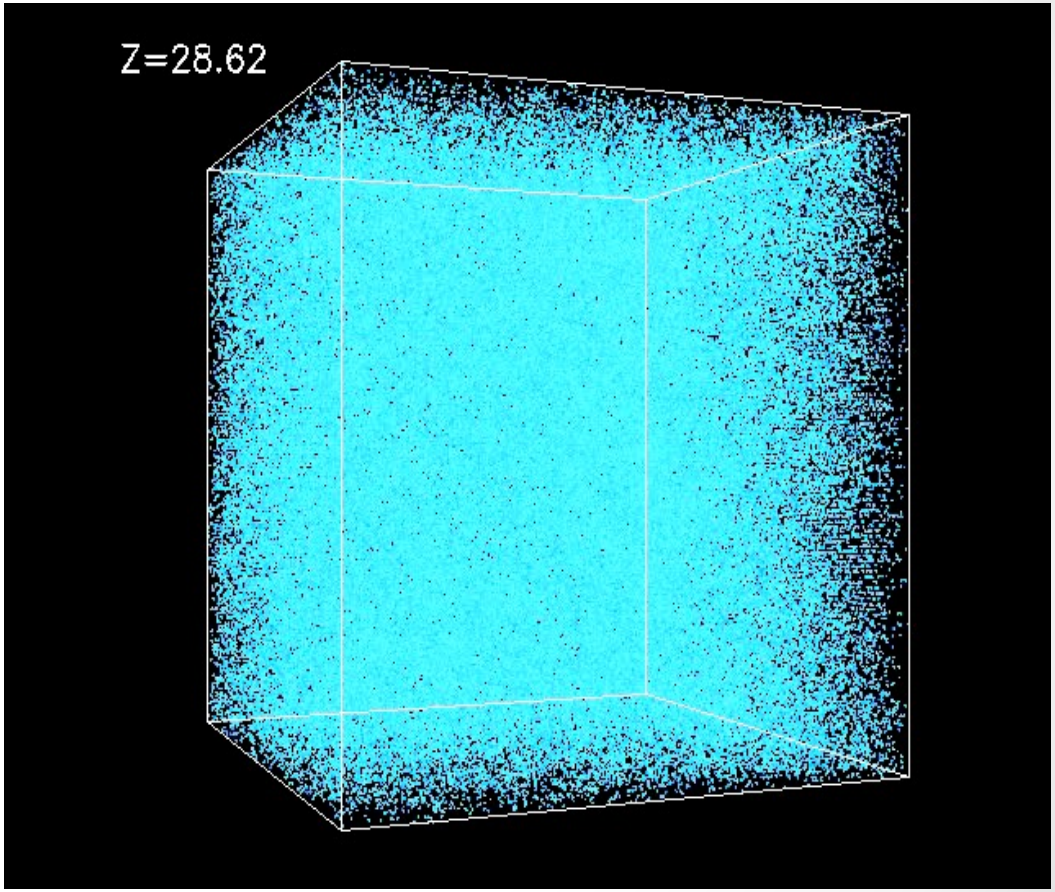
We must rely on sophisticated simulations to study the formation and evolution of galaxies. Initial overdensities grow quickly into the non-linear regime.

The simplest simulation include a system of DM particles only, that interact only through gravity. It's called a N-body problem, therefore **N-body or DM only simulations**

N-BODY simulations

Numerical simulations follow the growth & collapse of structures by solving the equations of motion for dark matter particles.
Impose initial conditions from cosmology

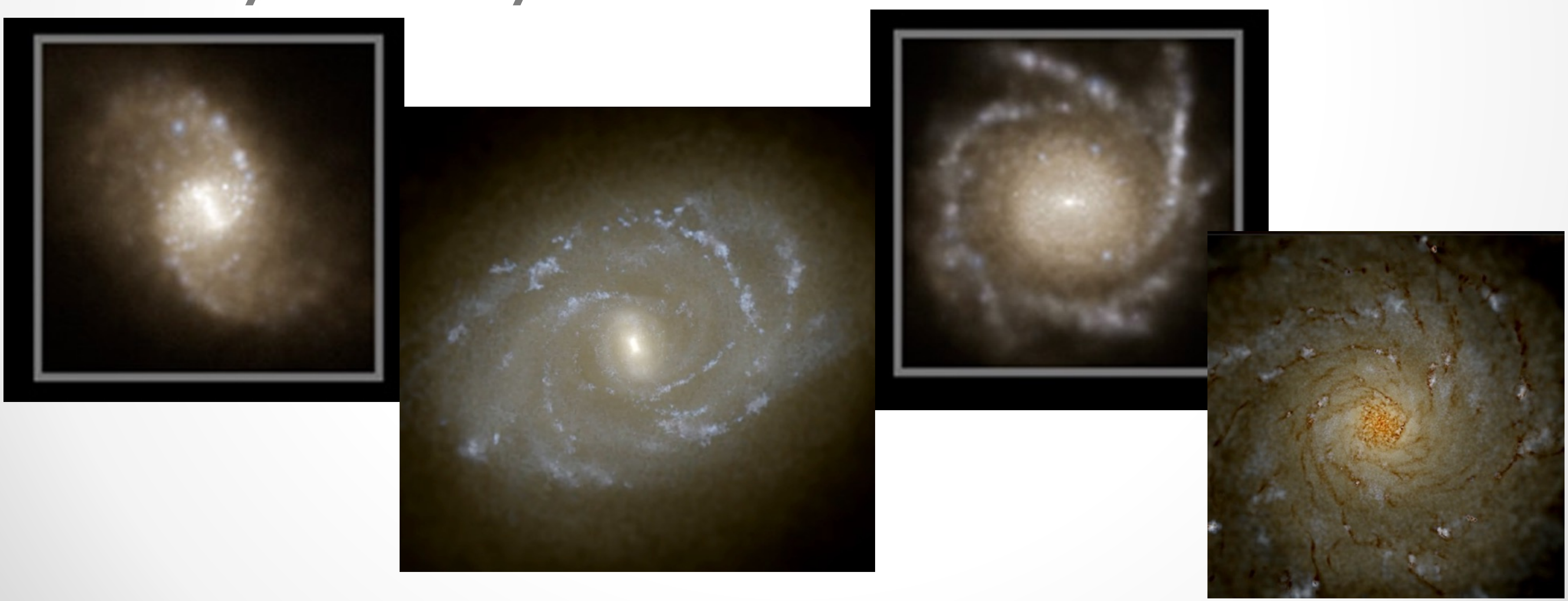
DM particles in sims represent a PHASE SPACE of DM, mass much bigger than real DM particle



Credit: A.Kravtsov, A. Klypin

Hydro simuations

- At small, galactic scales, more sophisticated simulations shall be used, including gas, stars, and their relative feedback mechanisms. Called **baryonic or hydro simulations.**



Illustris sims, NIHAO UHD

Why dwarf galaxies

Dwarf galaxies are the most numerous and dark matter-dominated galaxies in the Universe, making them essential to understand galaxy evolution and the nature of DM itself

NIHAO sims

Numerical Investigation (of) Hundred Astrophysical Objects

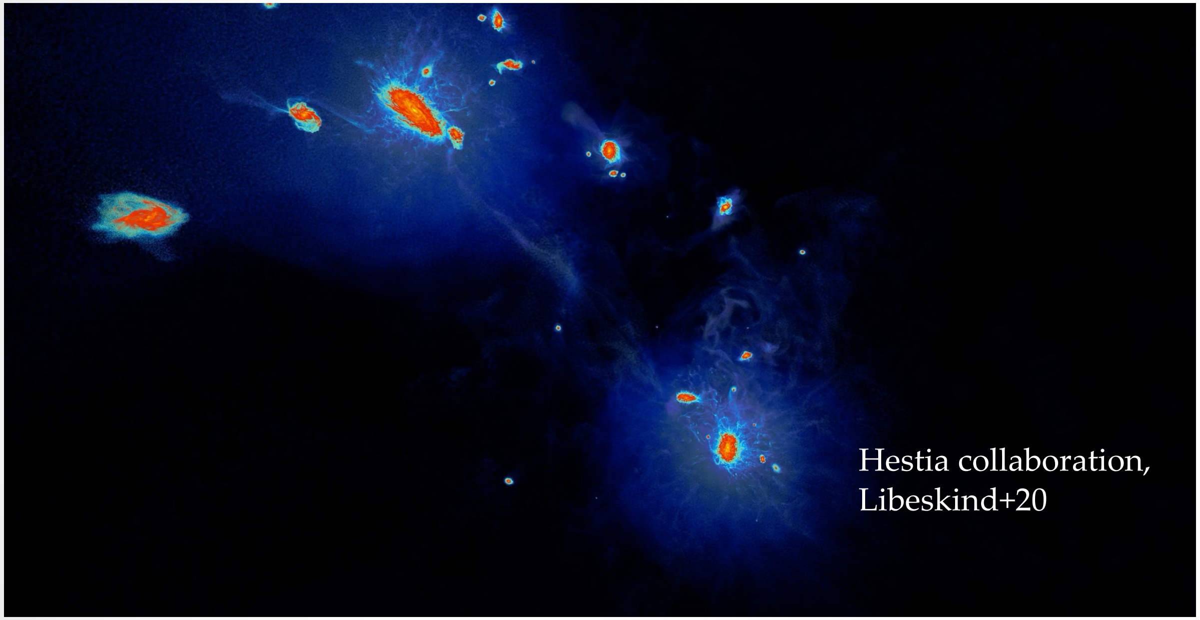
NIHAO (Gasoline2)

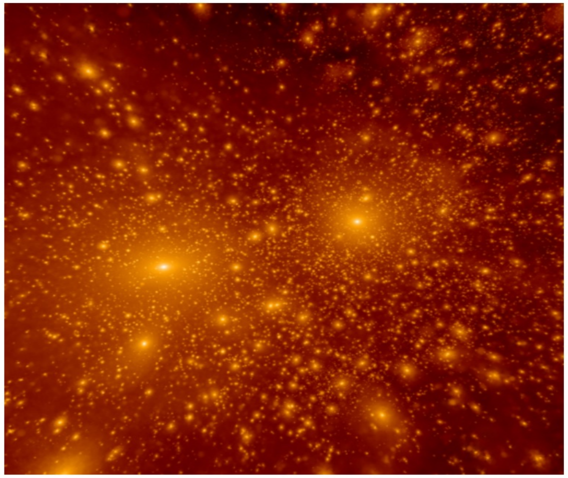
- **Gas particle mass:** ~$10^{3\text{-}4}$ M$\odot$
- **DM particle mass:** ~10^5 M$\odot$
- **Softening length:** ~70–400 pc (from dwarfs to MW)
- **Feedback ingredients:** Early stellar feedbac kfrom massive stars before they explode as Snae, stellar winds, supernova energy injection, metal-line cooling, UV background.

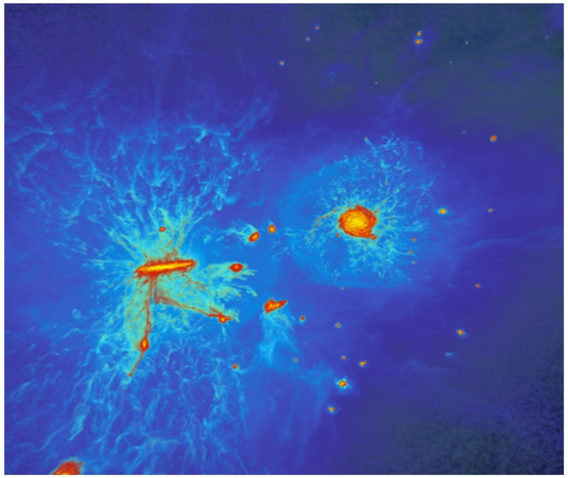
PI: A.Maccio´(NYUAD)

Local Group sims: HESTIA project

Constrained initial conditions of the large scale structure of the Universe.
Local Group reproduced in great detail within correct environment.





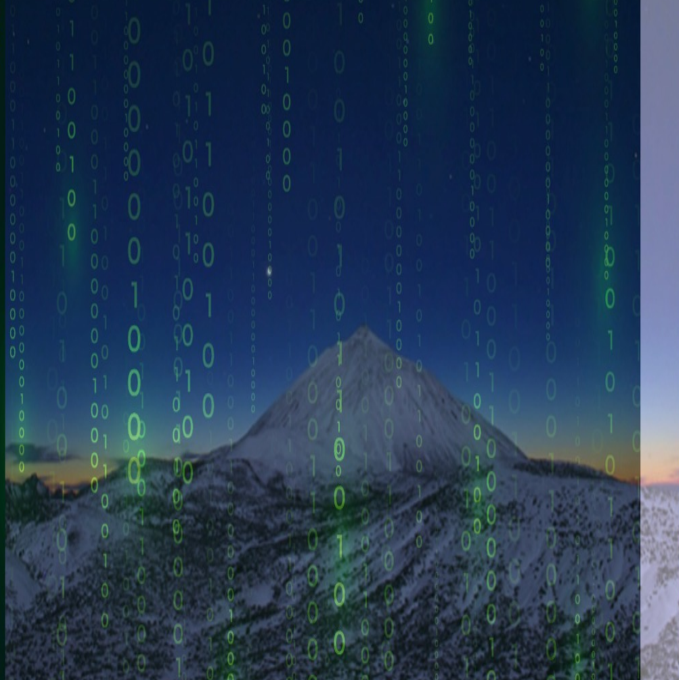


HESTIA simulations :
AREPO, Feedback from SNae and AGNs, UV background and gas metal cooling, resolution m_dm =1.5×10^{5}Msun, m_gas=2.2×10^{4}M, e= 220 pc. Star formation density threshold n_{th}=0.1 cm $^{-3}$

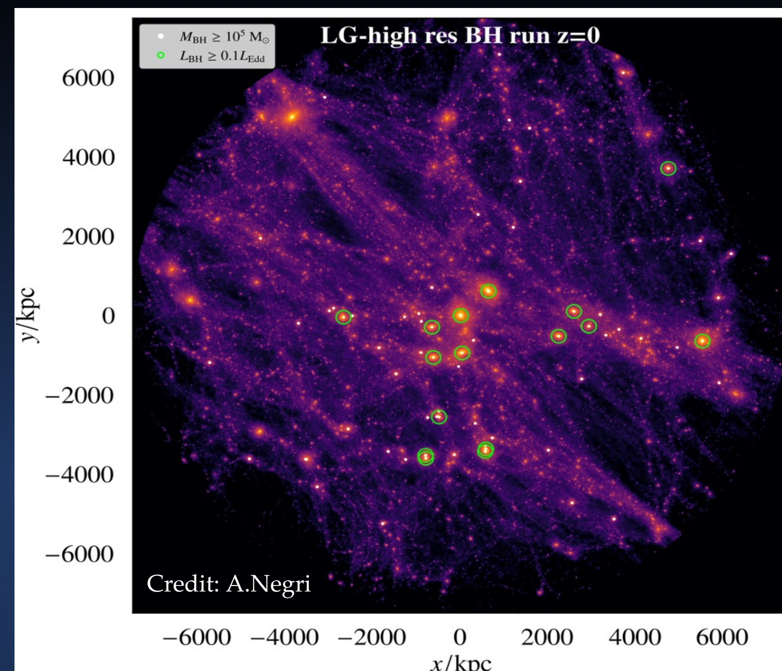
NIVARIA

NUMERICAL INVESTIGATION OF DWARF GALAXIES INCLUDING AGN FEEDBACK

Constrained Local Groups ICs + NIHAO feedback (Gasoline) + AGNs/noAGNs + Nth =100 cm-3



Contreras-Santos, ADC, Negri + in prep
PI Di Cintio

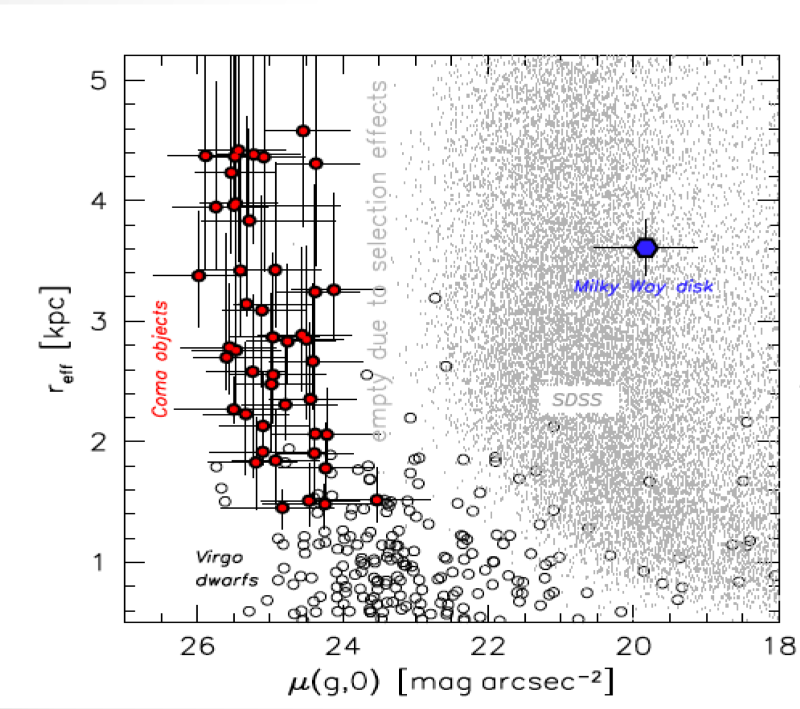


NIVARIA, 'snow's island', is the ancient Roman name given to Tenerife island, from Latin 'nivis'

A biased selection of hot-topics related to dwarf galaxies

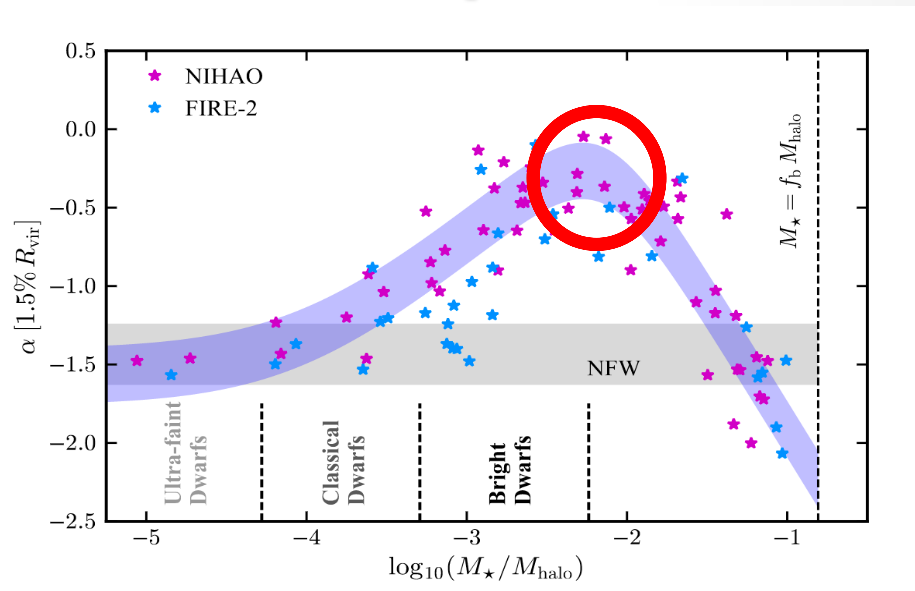
- Extremely large Ultra-diffuse galaxies
- Emergence of Dark galaxies

ΛCDM-based simulations predict Ultra Diffuse Galaxies



Discovery of UDGs in Coma
Van Dokkum+15
Koda+15

UDGs naturally emerge as result of core formation, which is mass dependent

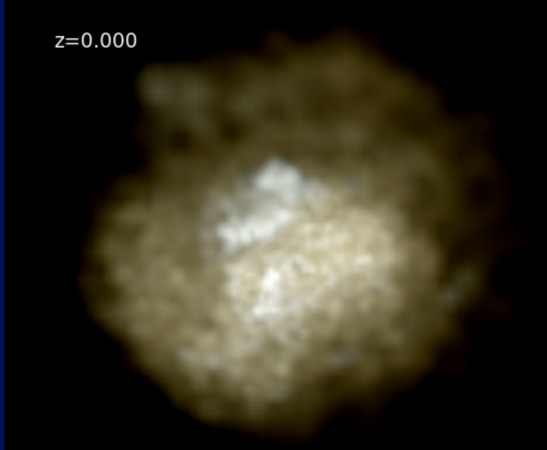


Di Cintio +14a,b
See Bullock & BK 2017 review

0.00 Gyr

SNae Feedback-driven expansion of DM and stellar component produce UDGs

Di Cintio+17 using NIHAO sims



ADC+17 using NIHAO sims

NIHAO project - NYUAD / MPIA

Are there UDGs in the Local Group?

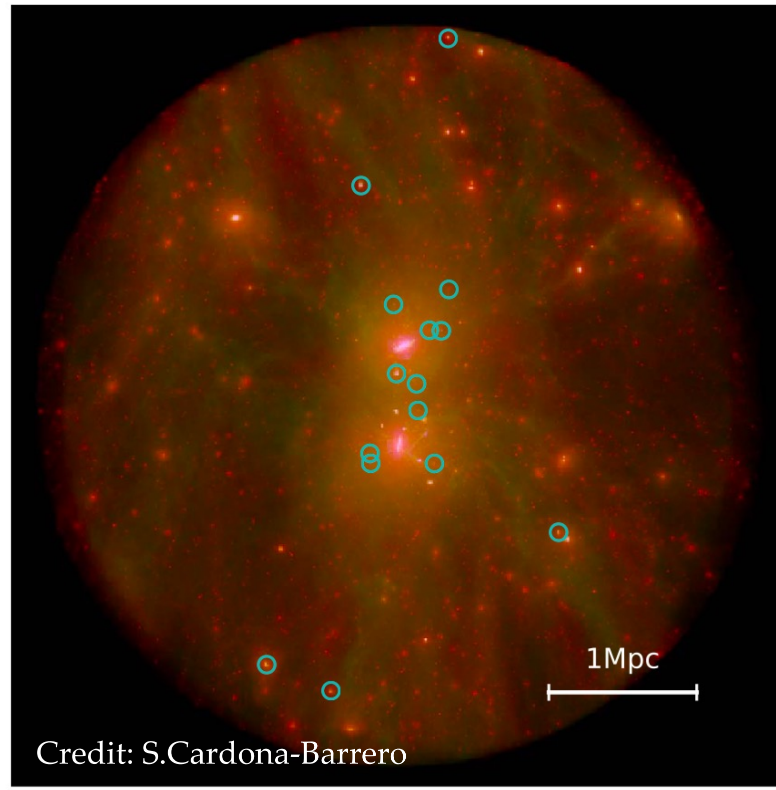
The Astrophysical Journal Letters, 946:L37 (8pp), 2023 April 1 https://doi.org/10.3847/2041-8213/acc2bb

The Undiscovered Ultradiffuse Galaxies of the Local Group

Oliver Newton[1,2], Arianna Di Cintio[3,4], Salvador Cardona–Barrero[3,4], Noam I. Libeskind[5,2], Yehuda Hoffman[6], Alexander Knebe[7,8,9], Jenny G. Sorce[5,10,11], Matthias Steinmetz[5], and Elmo Tempel[12,13]

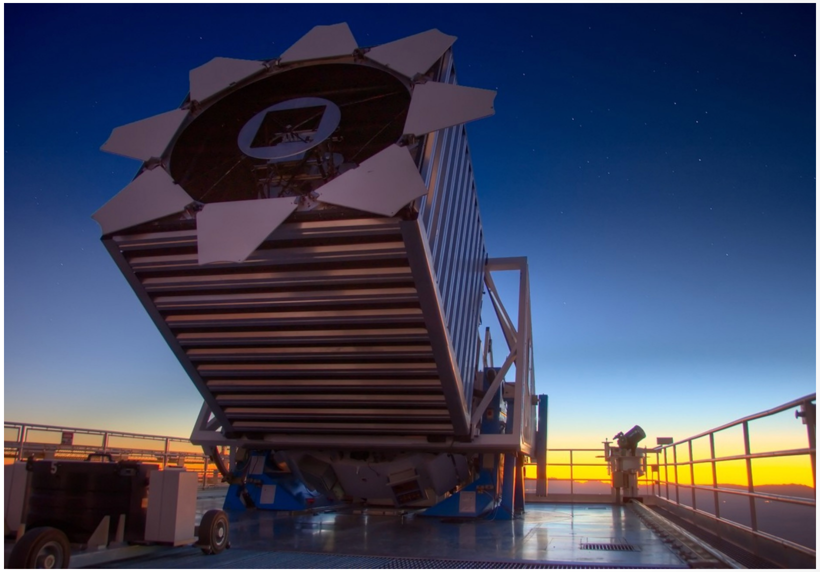
For LG mass $8*10^{12}$Msun (<2.5 Mpc) we expect 12 ± 3 UDGs in the LG field, of which 2(+2-1) detectable in SDSS footprint

Up to 80% within 1.5 Mpc of the LG's center



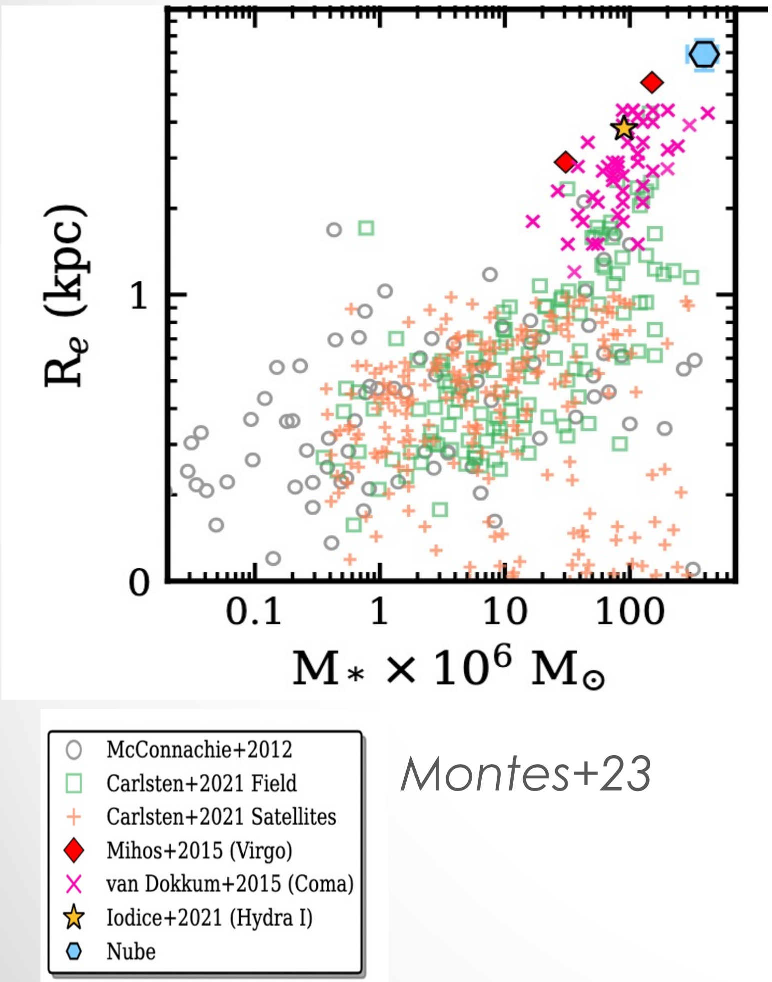
How to find these "missing" UDGs

Some field UDGs could be detectable in existing SDSS data sets and are awaiting discovery by dedicated follow-up searches of archival data



UDGs with HI gas could be detected by FAST, HIPASS and DES, providing targets for dedicated follow-up studies

Nube galaxy: the largest observed UDG



Montes+23

Reff very large for its stellar mass

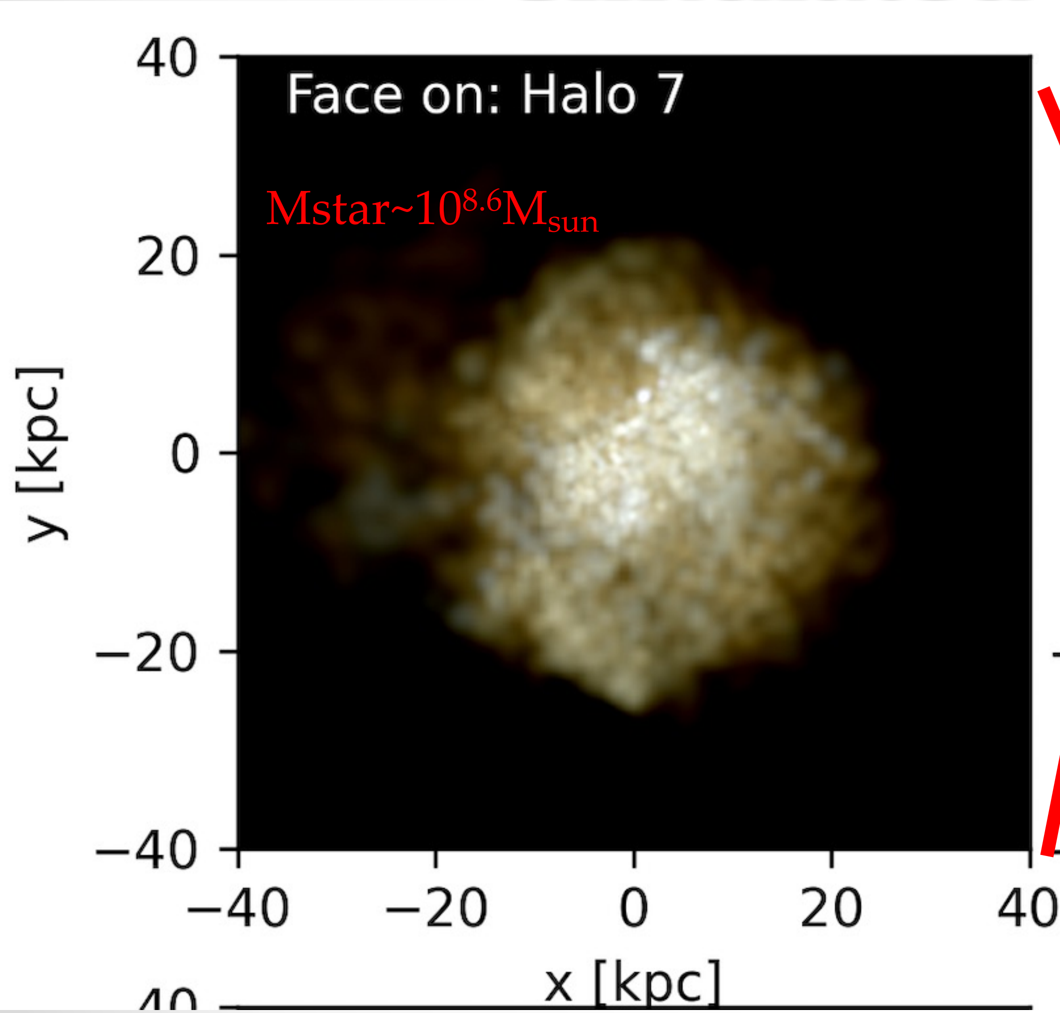
Does it invalidate LCDM?

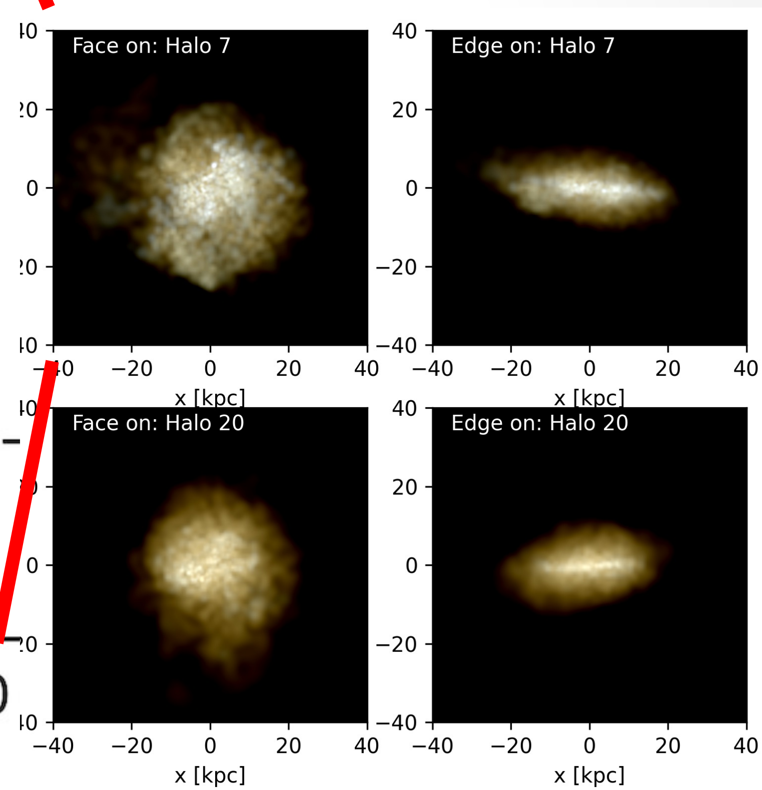
NubeSim: the largest ever simulated UDGs

PRELIMINARY

y, μ_e~ 26-27mag/arcsec2, $M^*\sim 10^{8.6} M_{sun}$

natching all properties of *Nube*



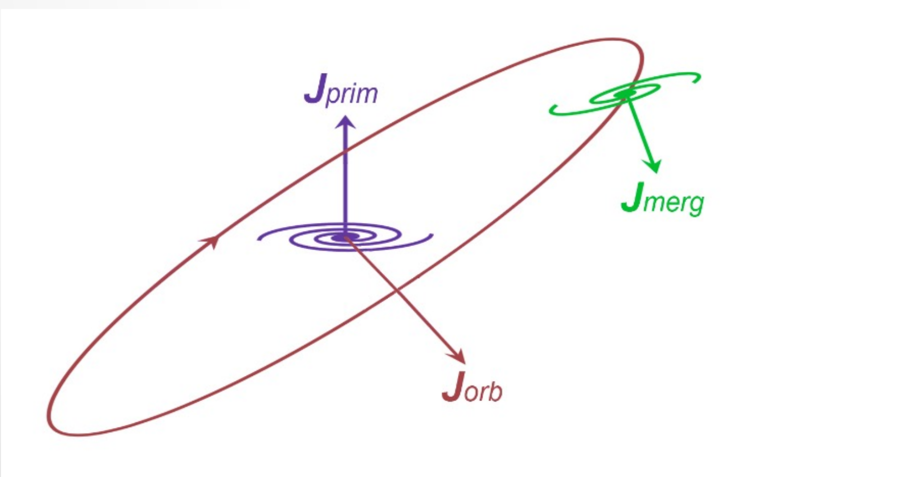


ADC, Contreras-Santos + in prep

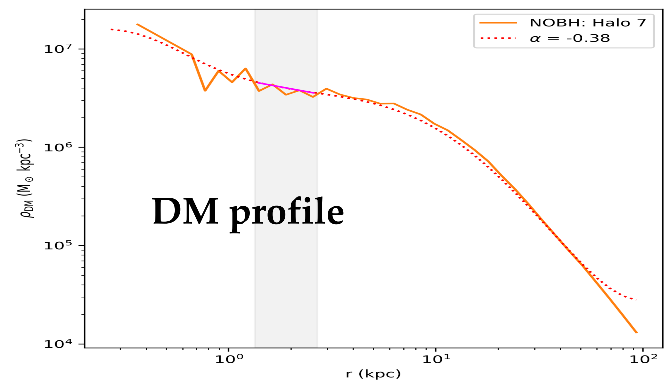
PRELIMINARY

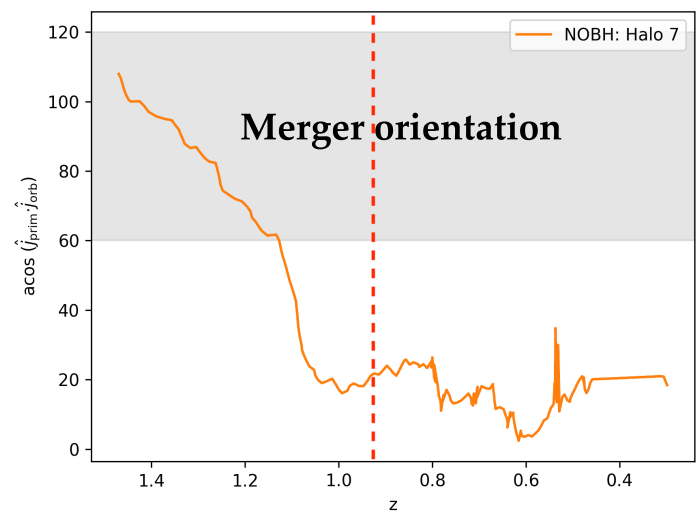
NubeSim as combination of internal + environmental processes

=>DM and stellar distributions flattened by SNae feedback
=> coplanar mergers that add angular momentum to the outskirts



(see Di Cintio+19 for larger LSBs)

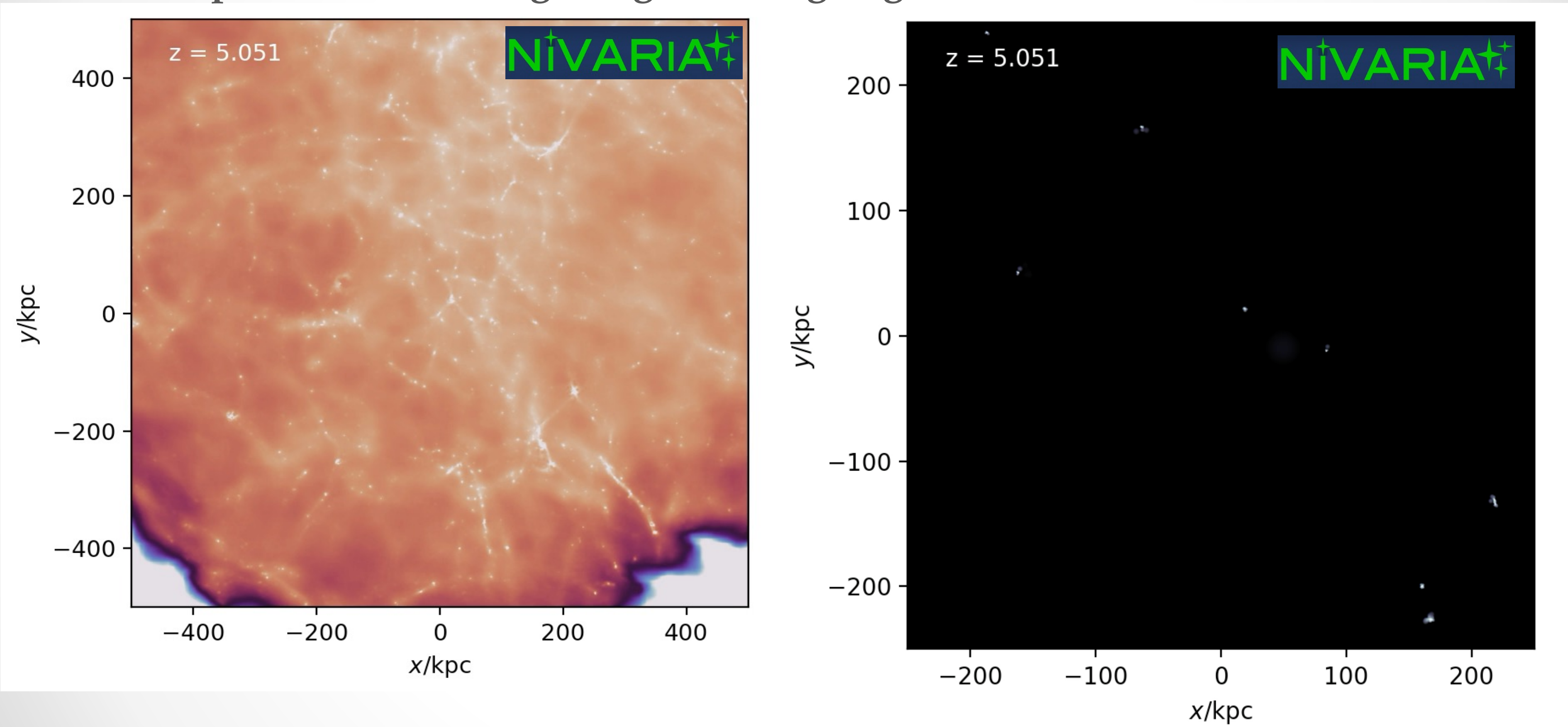




ADC, Contreras-Santos + in prep

NubeSim formation

Coplanar – corotating merger adding angular momentum to the outskirts



Less extended counterpart: no mergers or perpendicular ones

ADC, Contreras-Santos + in prep

Take home #1

- **Ultra diffuse galaxies reproduced in LCDM** simulations, within isolated environments, groups and clusters, via different formation channels

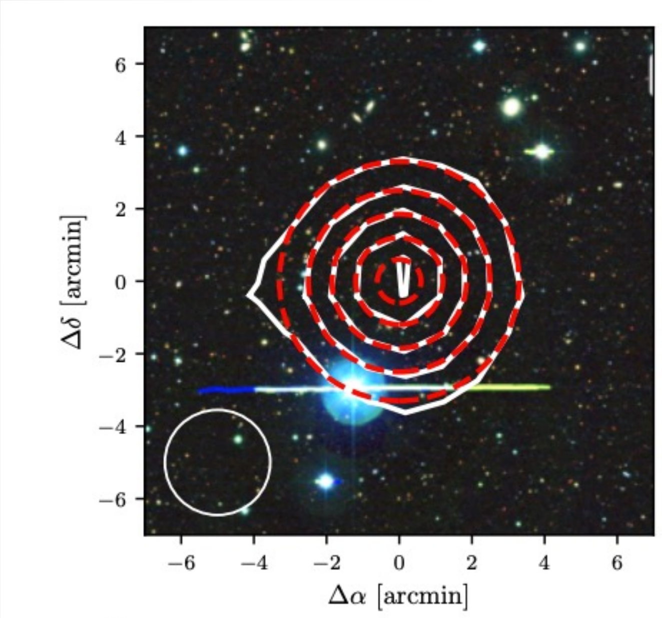
- We expect **12 ± 3 UDGs in the LG field,** yet-to-be-detected, in the vicinity of MW and M31 => if **HI rich**, detectable with **radio telescopes**

- Up to 80% are **within 1.5 Mpc of the LG's center**

- **DM and stellar core** formation + specific **merger orientation** (coplanar, co-rotating) are the key to create extreme UDGs such as ***Nube****,* with **Reff~8-11 Kpc** at a **Mstar~$10^{8.6}$ Msun**

No need for alternative DM models

A bona-fide dark galaxy candidate



Benítez-Llambay & Navarro 23

What are **dark galaxies**?

- DM Halos with gas in **thermal equilibrium** with the ultraviolet background radiation and in **hydrostatic equilibrium** in the gravitational potential of the halo (Benitez-Llambay&Frenk2020)
- **Strong prediction of LCDM**

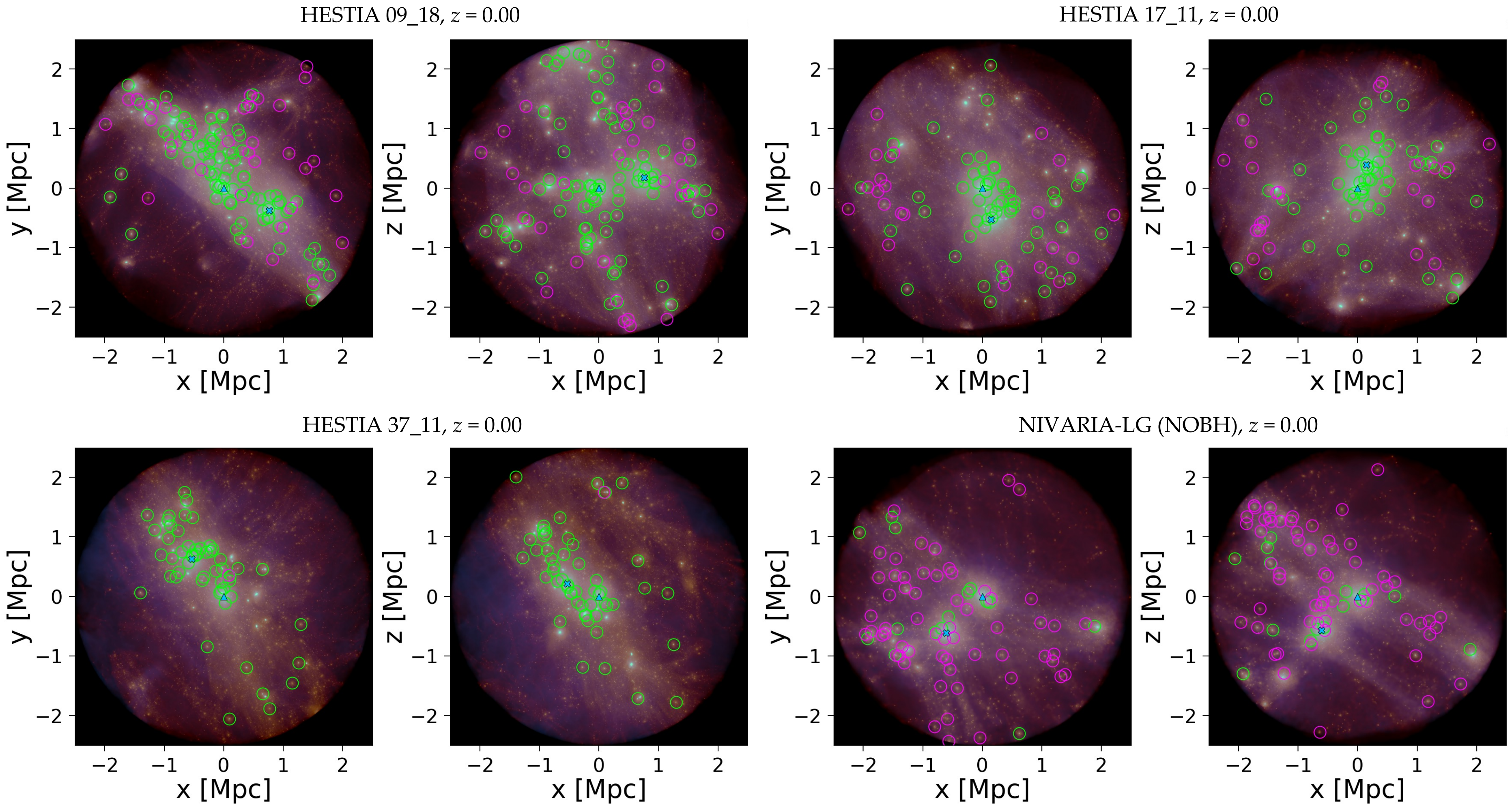
Observationally **CLOUD-9**

- **HI sources** with **no luminous** counterpart
- **Candidates** RELHIC (*REionization-Limited H I Cloud)*

Cosmological simulations to make predictions

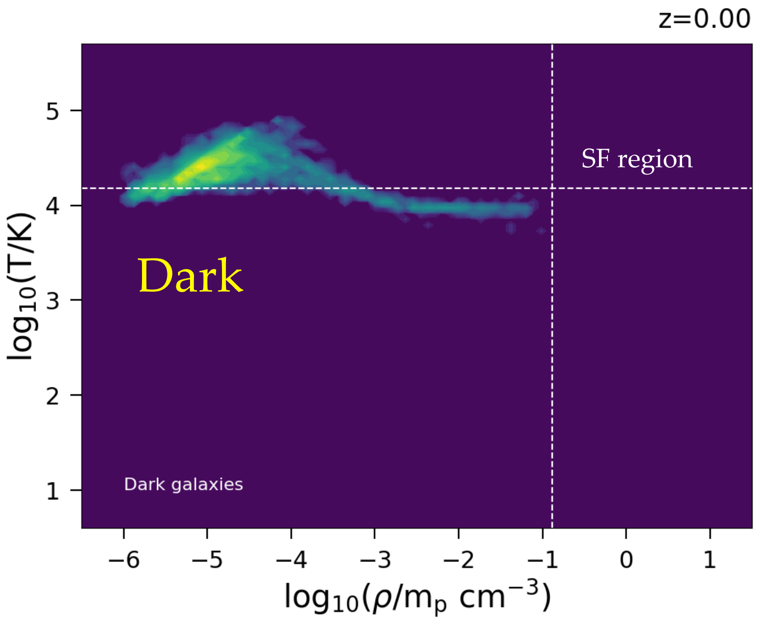
Distribution of dark and bright galaxies

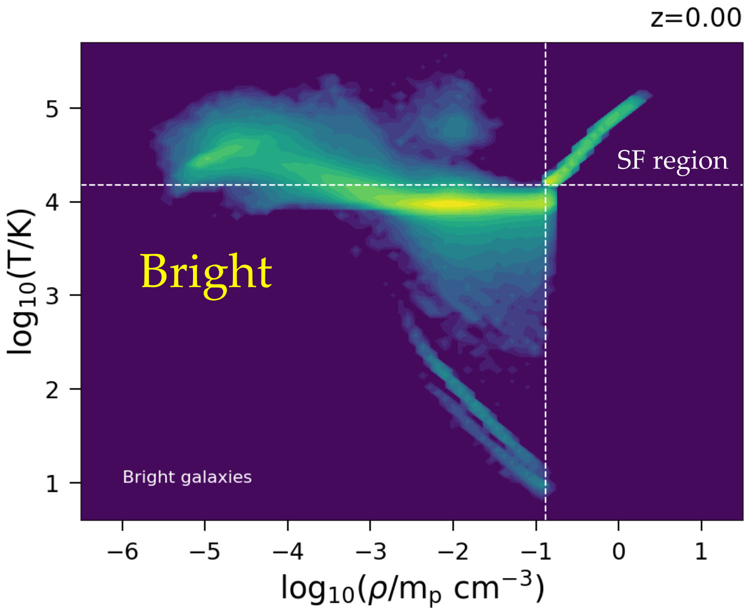
Dark galaxies are found in the outskirts of the Local Volume



Bethencourt,ADC+25, in prep

Why don't they form stars if they have gas?



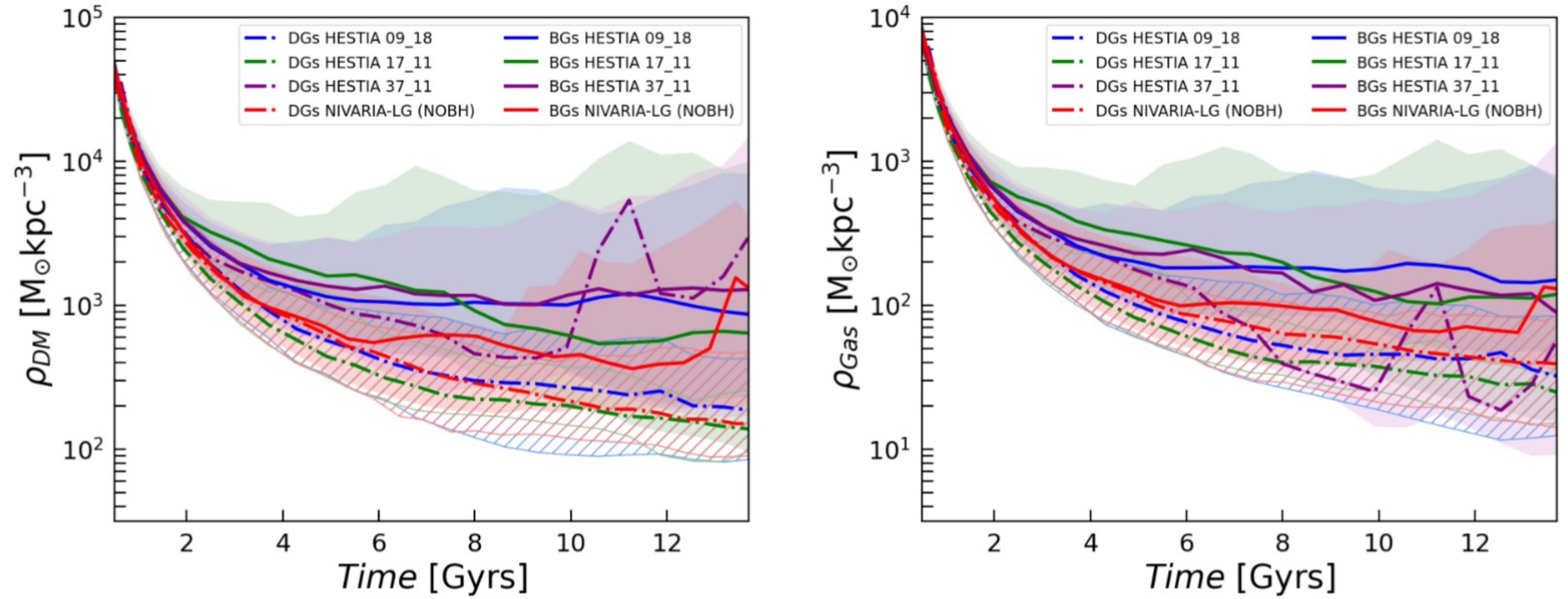


Gas less dense and hotter in dark galaxies

Bethencourt,ADC+25, in prep

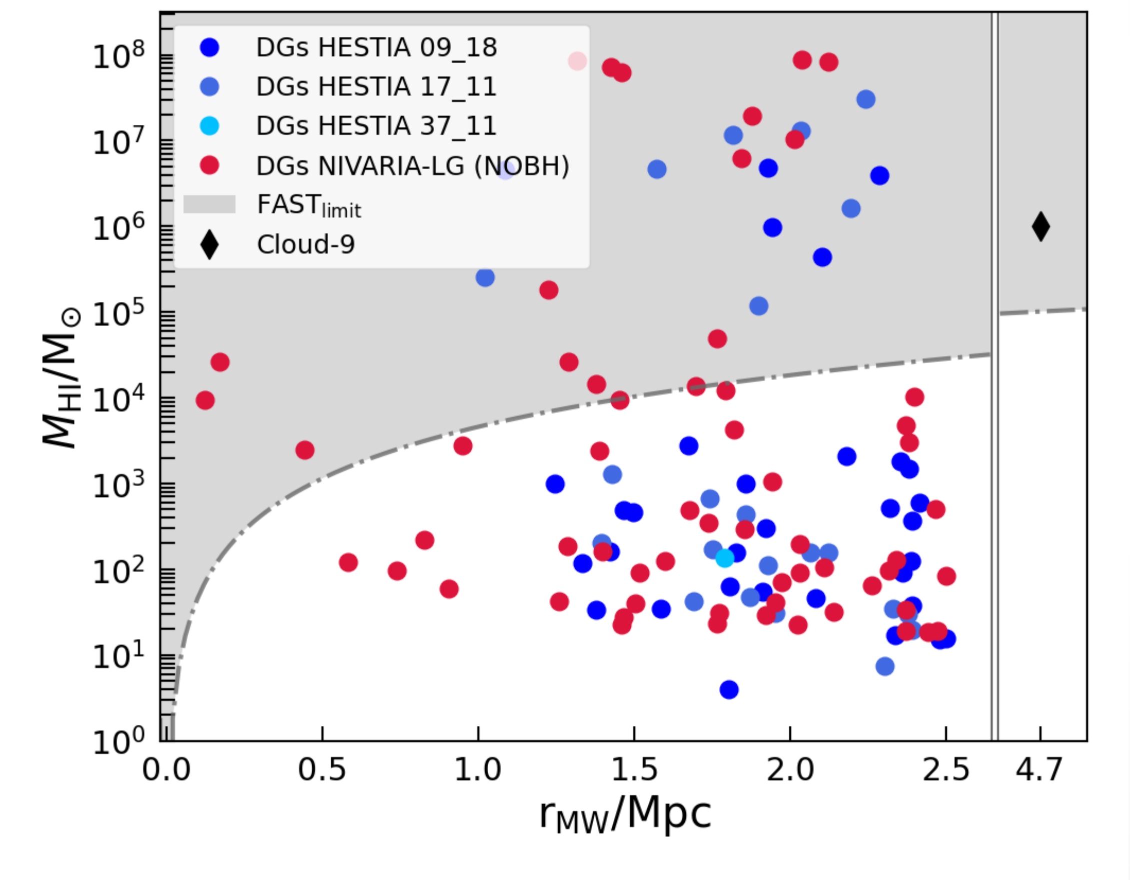
Dark Galaxies form in the outskirts of the Local Group

Dark galaxies reside in lower density regions compared to bright galaxies



Bethencourt,ADC+25, in prep

FAST to discover Dark Galaxies



Bethencourt,ADC+25, in prep

Take home point #2

- Dark galaxies exist in simulations with different codes and conditions
- We expect **dozens of dark galaxies** within 2.5 Mpc from the MW
- Dark galaxies do not form stars because **their gas is underdense**
- They are **further away** than normal galaxies, in **lower density regions**
- **FAST** radio telescope will help detecting **HI sources without a stellar component**

- Between **2 and 9 dark galaxies expected** to be detectable with FAST **within 2.5 Mpc from us**, most of which further away than 1 Mpc

Conclusions

- Existing hydrodynamical cosmological simulations of dwarf galaxies allow to explore galaxy formation at the extremes, offering concrete predictions for ΛCDM

Large UDGs

Dark Galaxies

AGNs in dwarfs