Dwarf Galaxies and Small-Scale Structure
Part 1: Observed Dwarf and Satellite Galaxies

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AIP

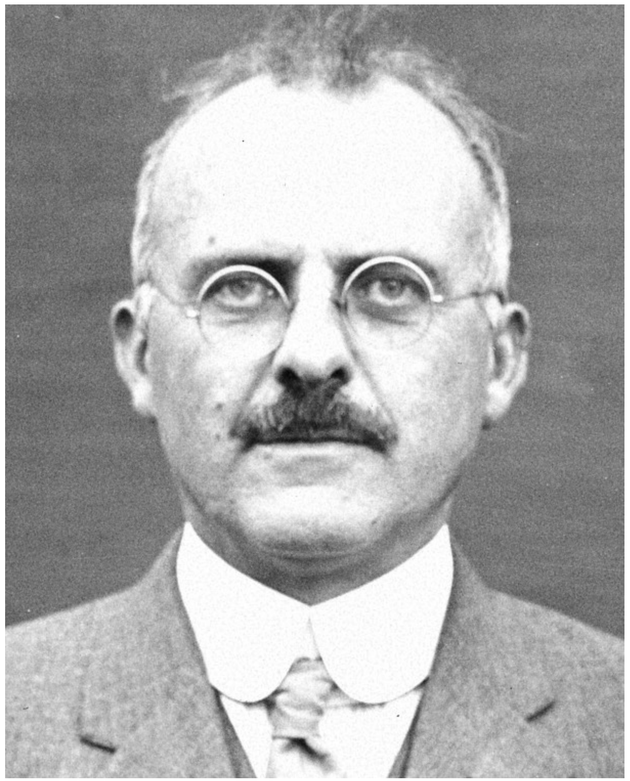
Composite by K. J. Kanehisa (Image Credits: N. Rissiger 2009 (Milky Way), R. Pendler 2002 (M31), ESO/VISTA VMC (LMC))

What is a galaxy?

Great debate in 1920:

Harlow Shapley: Milky Way is entire universe, we don't sit in its center, diameter is 3×10^5 ly.

Heber Curtis: There are other galaxies (island universes), we sit in center, diameter 3×10^4 ly.



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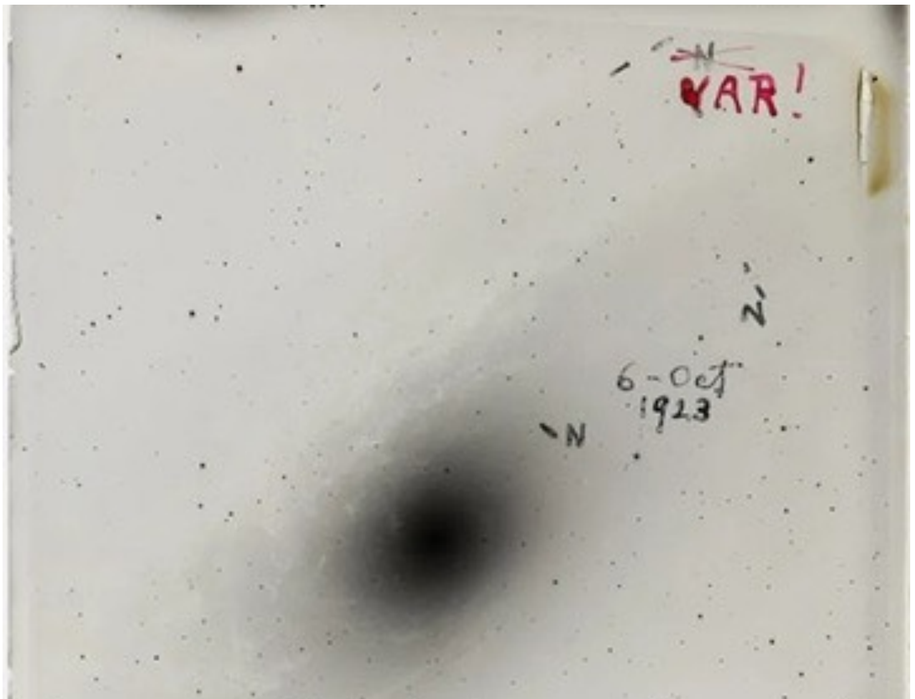

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Discriminating galaxies from star clusters becomes very difficult at the low-mass end.

What is a dwarf galaxy?

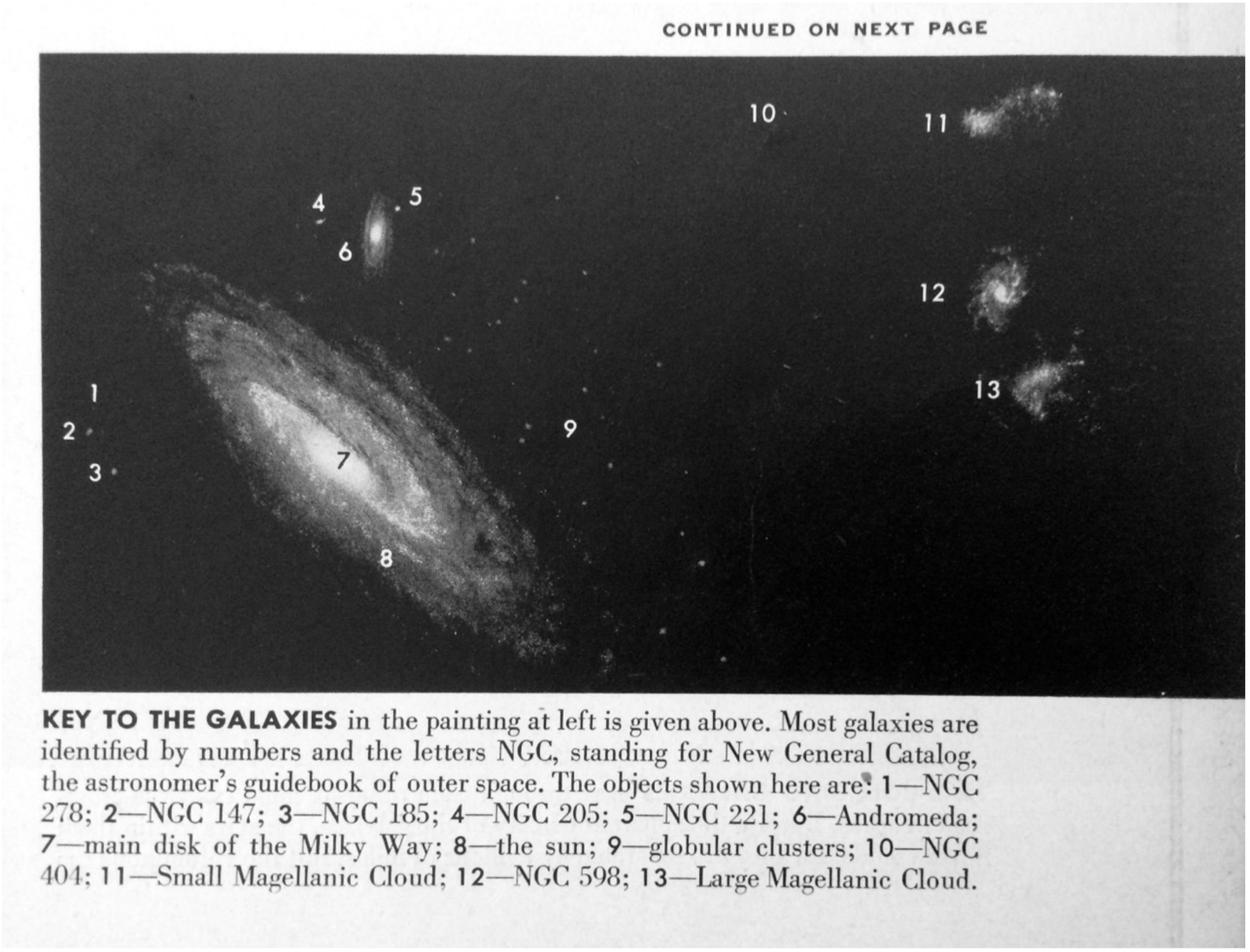
Common definition: any galaxy of Large Magellanic Cloud size/mass or smaller.

Many different types and classes of dwarfs: *dwarf Spheroidals* (dSphs), *dwarf Irregulars* (dIrrs), *ultra-faint dwarfs* (UFDs), *ultra-compact dwarfs* (UCDs), *tidal dwarf galaxies* (TDGs), *ultra-diffuse galaxies* (UDGs, are they even dwarfs?)

Bullock & Boylan-Kolchin (2017):

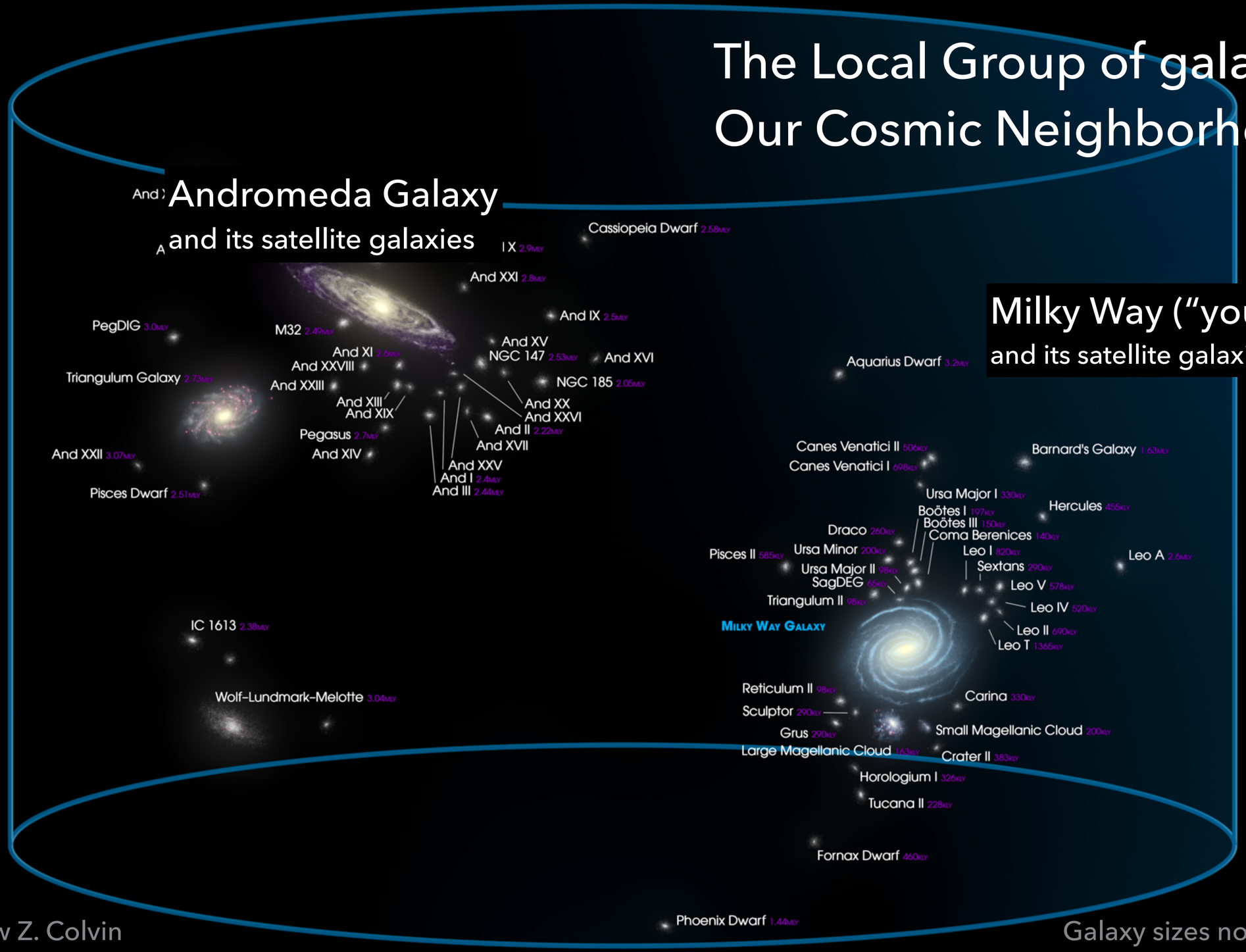
- **Bright Dwarfs:** $M_\star \approx 10^{7-9}\,M_\odot$ – the faint galaxy completeness limit for field galaxy surveys
- **Classical Dwarfs:** $M_\star \approx 10^{5-7}\,M_\odot$ – the faintest galaxies known prior to SDSS
- **Ultra-faint Dwarfs:** $M_\star \approx 10^{2-5}\,M_\odot$ – detected within limited volumes around Milky Way/M31.

The Local Group of Galaxies: Milky Way, Andromeda, and many Dwarfs



KEY TO THE GALAXIES in the painting at left is given above. Most galaxies are identified by numbers and the letters NGC, standing for New General Catalog, the astronomer's guidebook of outer space. The objects shown here are: 1—NGC 278; 2—NGC 147; 3—NGC 185; 4—NGC 205; 5—NGC 221; 6—Andromeda; 7—main disk of the Milky Way; 8—the sun; 9—globular clusters; 10—NGC 404; 11—Small Magellanic Cloud; 12—NGC 598; 13—Large Magellanic Cloud.

The Local Group of galaxies: Our Cosmic Neighborhood



by Andrew Z. Colvin

Galaxy sizes not to scale!

The Local Group of galaxies: Our Cosmic Neighborhood

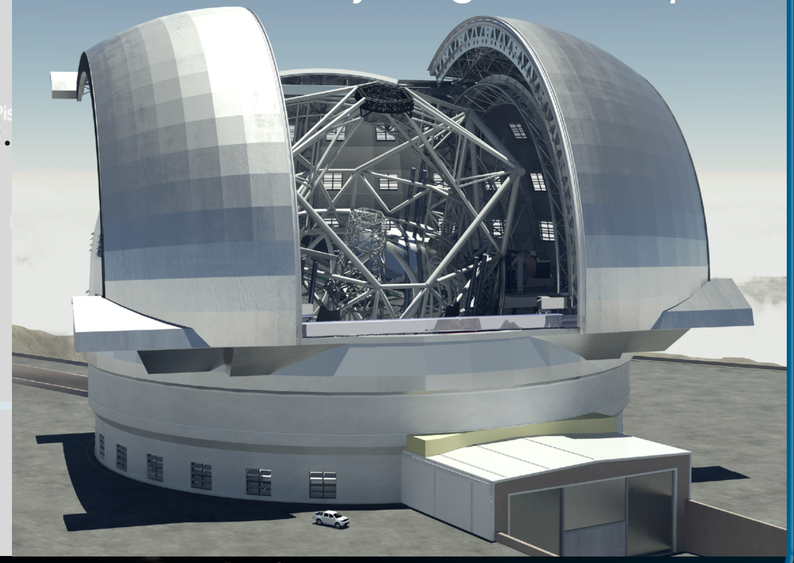
Andromeda Galaxy
and its satellite galaxies

Milky Way (“you are here”)
and its satellite galaxies

Knowledge of nearby dwarf galaxies has exploded (11 → 50 MW satellites in past 15 years).

This is ongoing. New surveys like LSST will detect many more nearby dwarfs and new facilities like the ELT will make them accessible at larger distances.

ESO’s *Extremely Large Telescope*



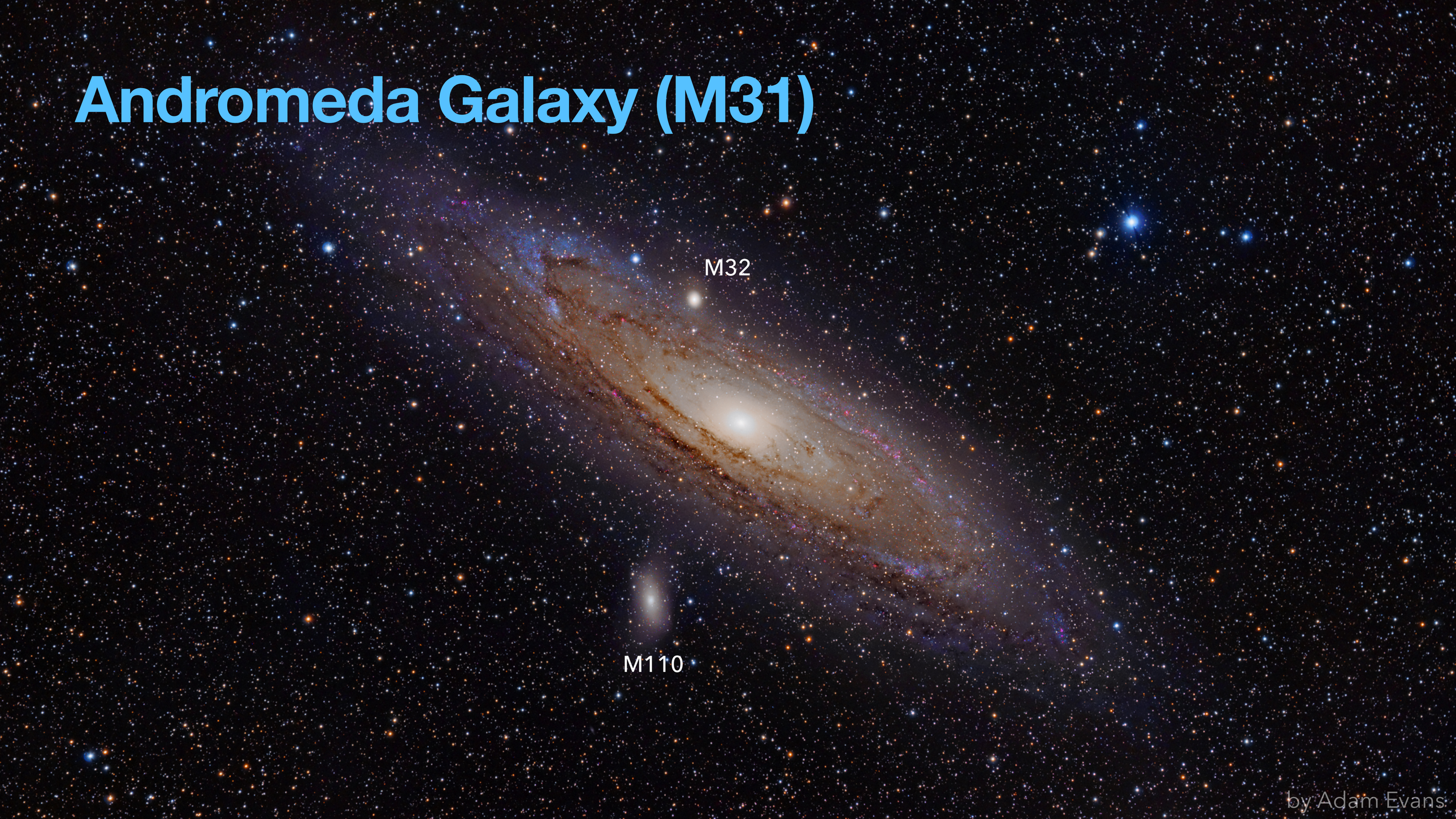
by Andrew Z. Colvin

Galaxy sizes not to scale!

Milky Way

Quelle: ESO/S. Brunier

Andromeda Galaxy (M31)



by Adam Evans

Andromeda Galaxy (M31)

Apple's OS X Lion
Desktop Background

by Adam Evans

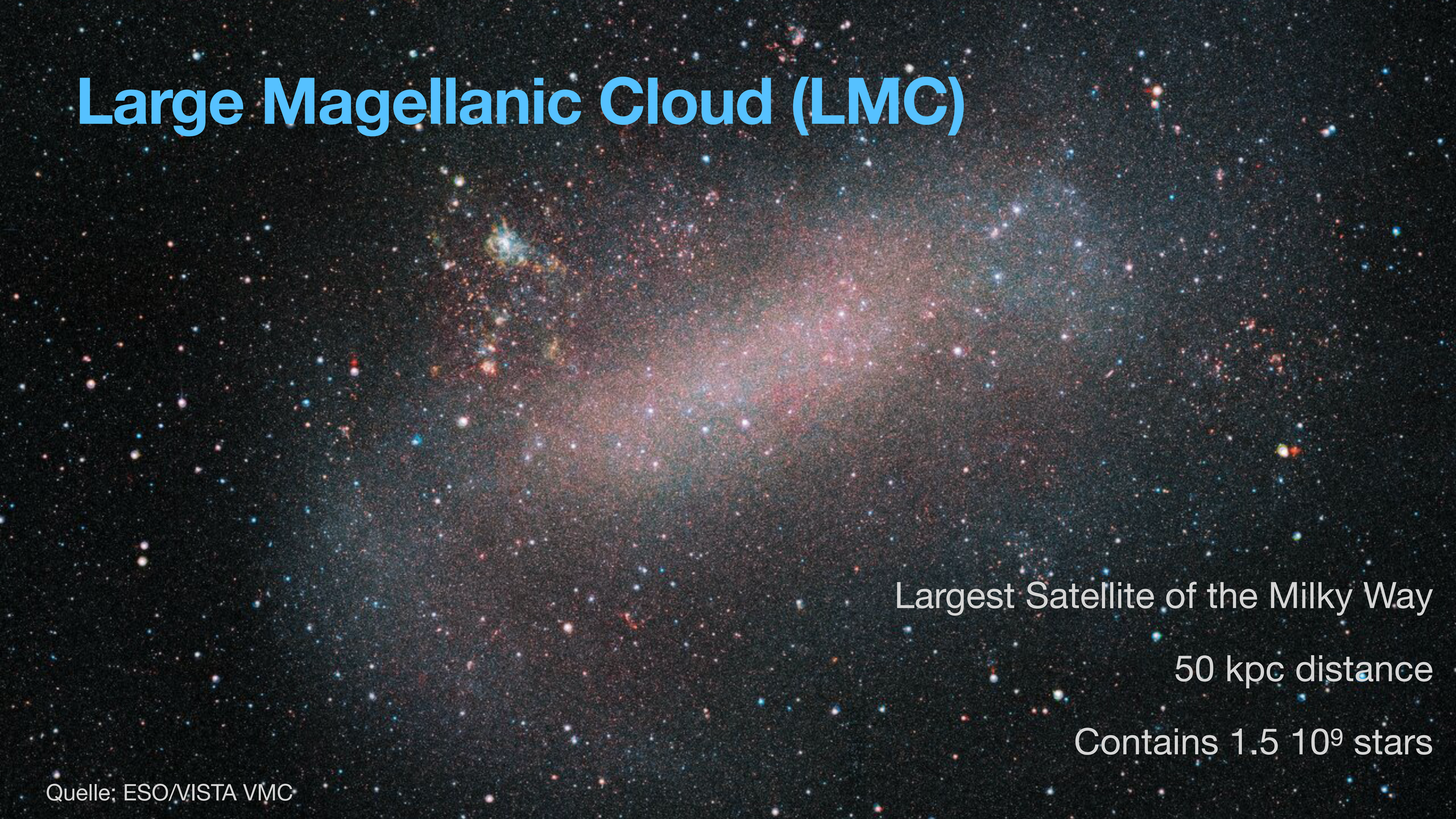
Triangulum

3rd-largest galaxy in the Local Group

Satellite of Andromeda

Quelle: ESO

Large Magellanic Cloud (LMC)



Largest Satellite of the Milky Way

50 kpc distance

Contains 1.5 10^9 stars

Quelle: ESO/VISTA VMC

Sculptor Dwarf Galaxy

Discovered 1938 by Shapley on photographic plates

First known dwarf-spheroidal (dSph) satellite galaxy

Quelle: ESO/Digitized Sky Survey 2

Sculptor Dwarf Galaxy

Discovered 1938 by Shapley on photographic plates

First known dwarf-spheroidal (dSph) satellite galaxy

Quelle: ESO/Digitized Sky Survey 2

Fornax Dwarf Galaxy

ESO/Digitized Sky Survey 2

Carina Dwarf Galaxy

ESO/G. Bono & CTIO

Discovering Dwarf Galaxies in the Local Group as Stellar Overdensities

- Example: discovery of Pegasus V from Collins et al. (2022)
- First identified as partially resolved overdensity in the DESI Legacy Imaging Survey (left) by amateur astronomer Giuseppe Donatiello.
- Follow-up photometric observations deep imaging with Gemini to resolve its stellar populations (right).

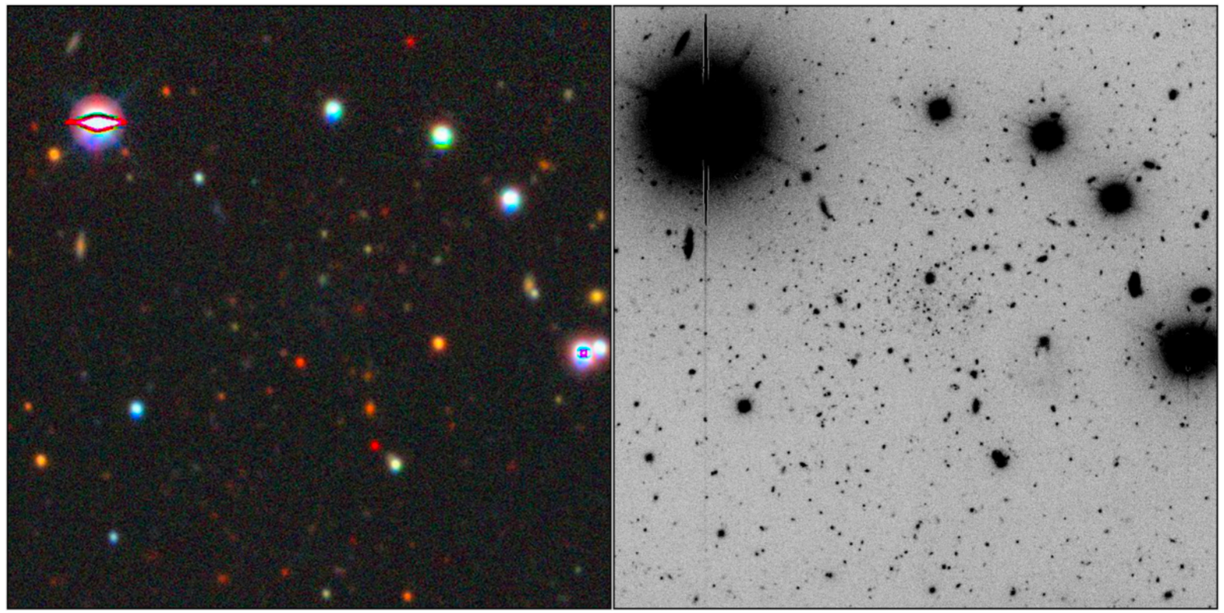


Figure 1. Left-hand panel: Image of the dwarf galaxy Peg V from the DESI Legacy Imaging Survey. Right-hand panel: *Gemini/GMOS-N* combined *g*- and *r*-band image of the galaxy obtained from *Gemini* follow-up observations (see Section 2). North is up, east is left. In both images, the field of view is 150 arcsec × 150 arcsec.

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- Filtered map of stars shows clear over density, not present for background galaxies.

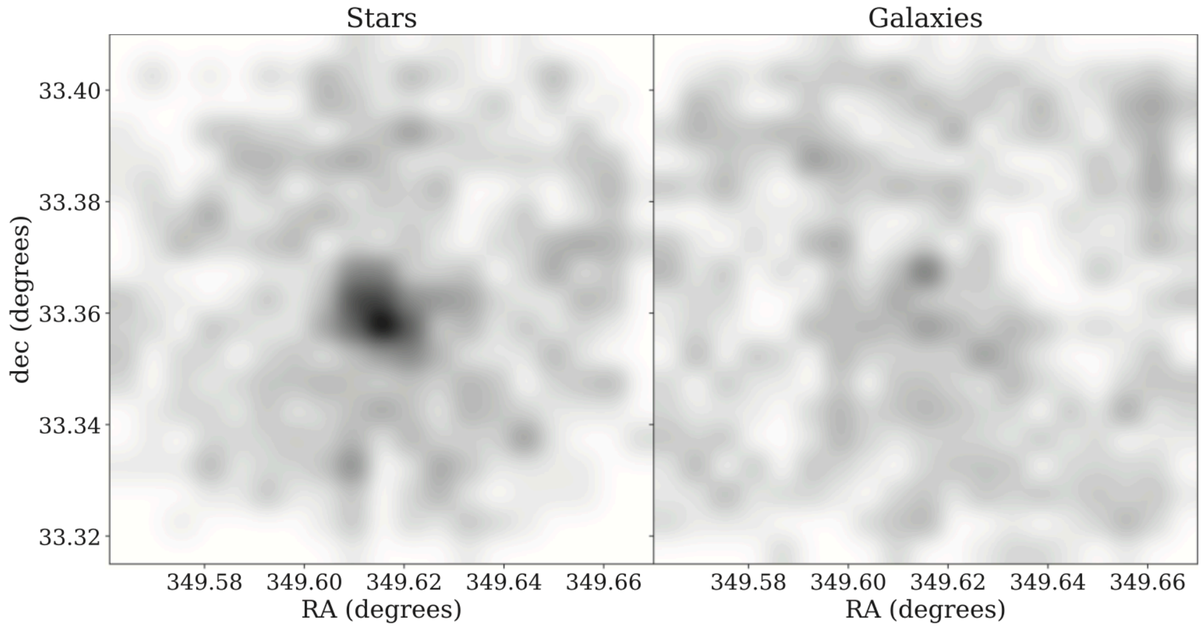

Figure 2. Filtered maps of all sources considered stars (left) versus galaxies (right) within our *GMOS-N* field of view. A clear overdensity is seen in the stellar map that is not reproduced in the galaxies panel.

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- Color-magnitude diagram of object vs. surrounding annulus,, overplotted isochrone in grey (12.5 Gyr, Fe/H = -3.2, shifted to 692 kpc distance to match horizontal branch).

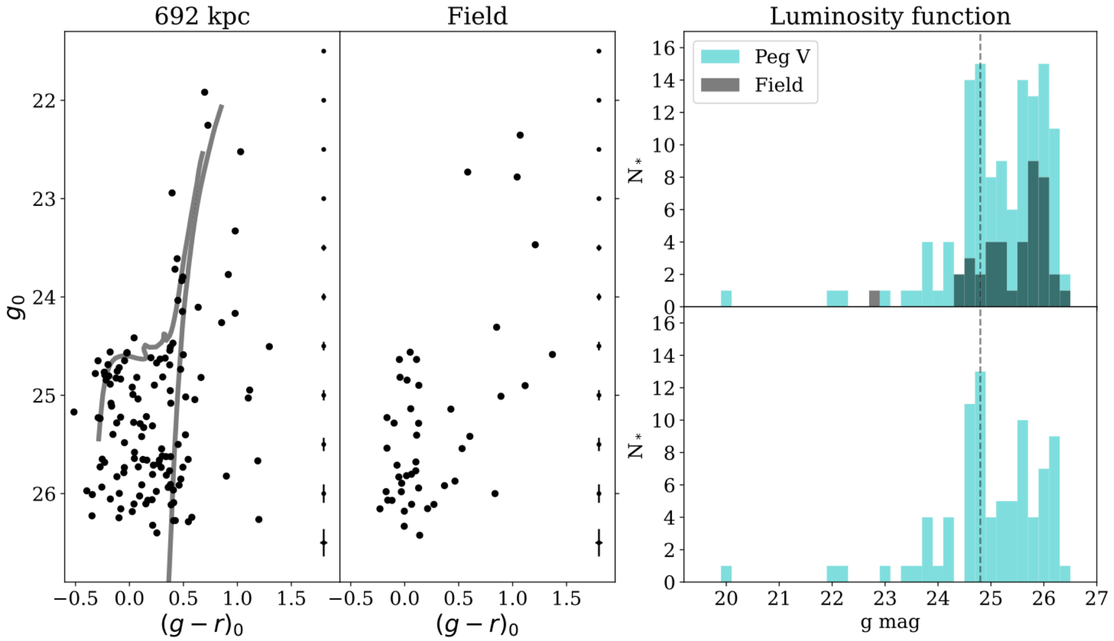
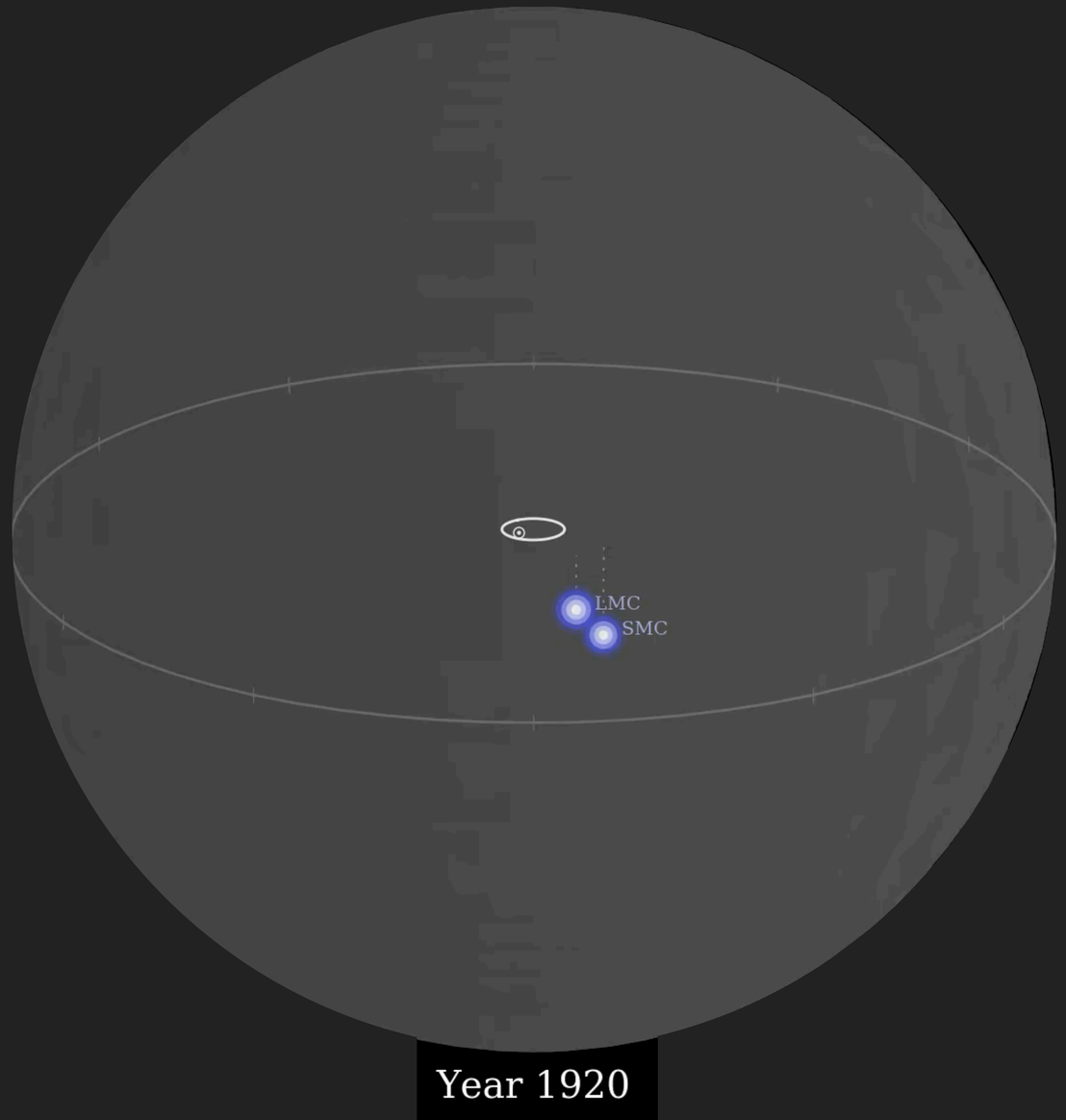
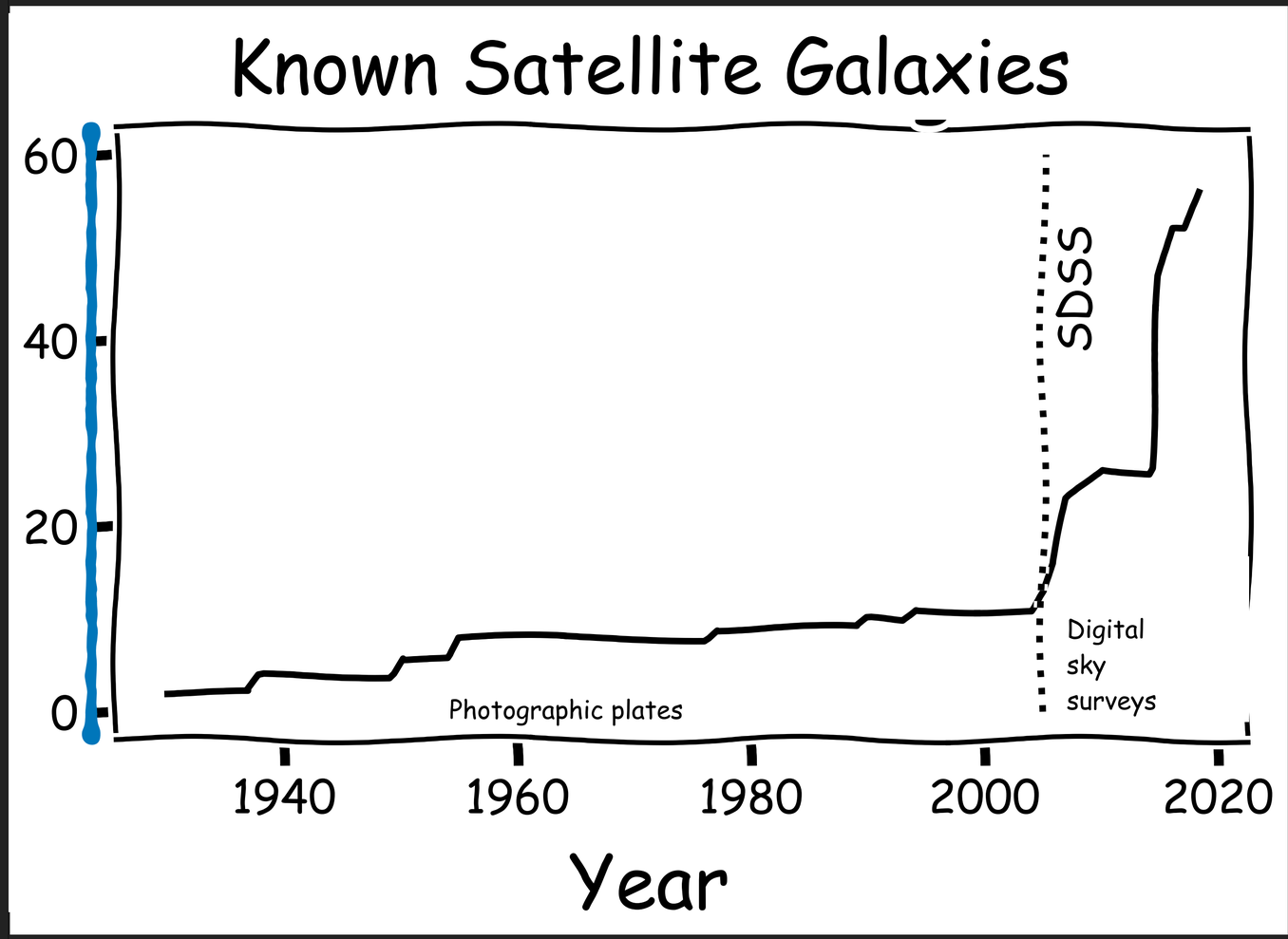


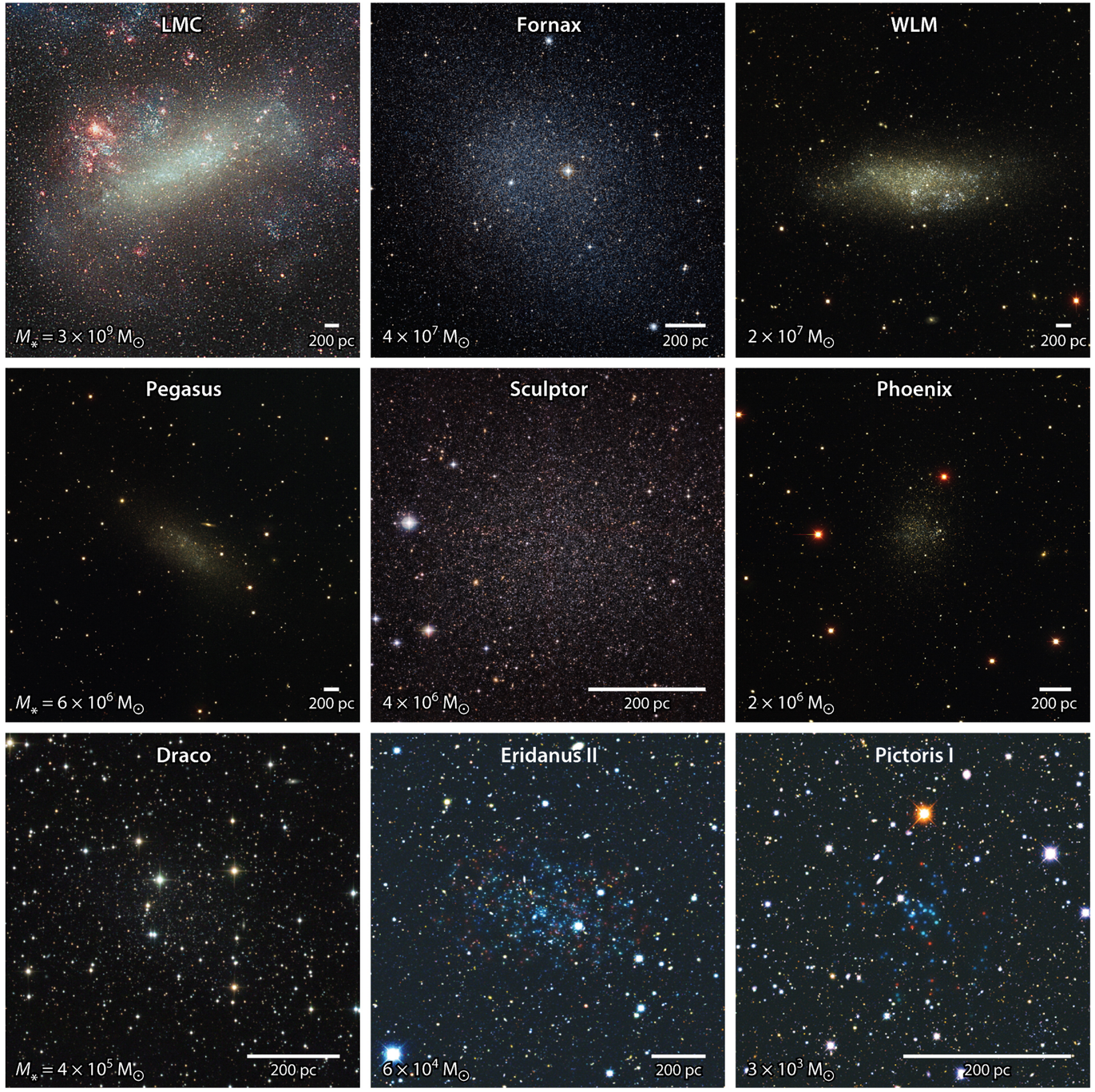
Figure 3. In the first two panels, we show the CMD for all stars within $2r_{\rm half}$ of Peg V (left) compared with the stellar populations in an equal area annulus beyond the dwarf to demonstrate the field contamination (right). We overlay a metal-poor ([Fe/H] $= -3.2$) isochrone with age 12.5 Gyr shifted to 692 kpc (centre), representing the distance measured from the HB. Finally, we show the luminosity function in the rightmost panels. The top shows all stars within $2r_{\rm half}$ (cyan) and the field population (grey), and the lower panel shows the background-corrected case. The dashed grey line shows the position of the blue HB feature.

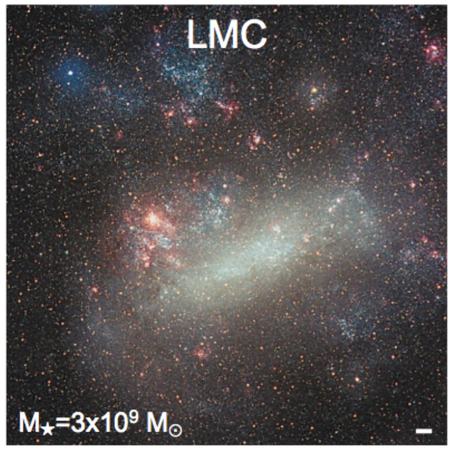
Discovery History of Milky Way Satellite Galaxies

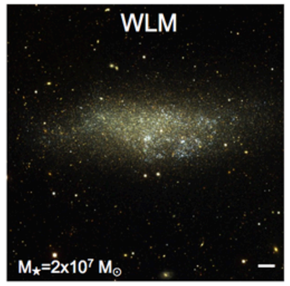


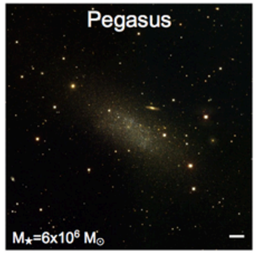


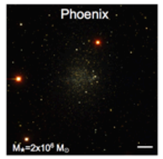
Quelle Video: http://marcelpawlowski.com/research/movies-astronomy/

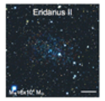

LMC
$M_* = 3 \times 10^9\ M_\odot$
200 pc
Fornax
$4 \times 10^7\ M_\odot$
200 pc
WLM
$2 \times 10^7\ M_\odot$
200 pc
Pegasus
$M_* = 6 \times 10^6\ M_\odot$
200 pc
Sculptor
$4 \times 10^6\ M_\odot$
200 pc
Phoenix
$2 \times 10^6\ M_\odot$
200 pc
Draco
$M_* = 4 \times 10^5\ M_\odot$
200 pc
Eridanus II
$6 \times 10^4\ M_\odot$
200 pc
Pictoris I
$3 \times 10^3\ M_\odot$
200 pc











On same scale!

Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

Dwarf Galaxies: Properties and Observations

- Most abundant type of galaxies, but difficult to detect.
- Lowest-luminosity/smallest systems approach globular cluster properties.
- Main difference: GCs are free of dark matter.

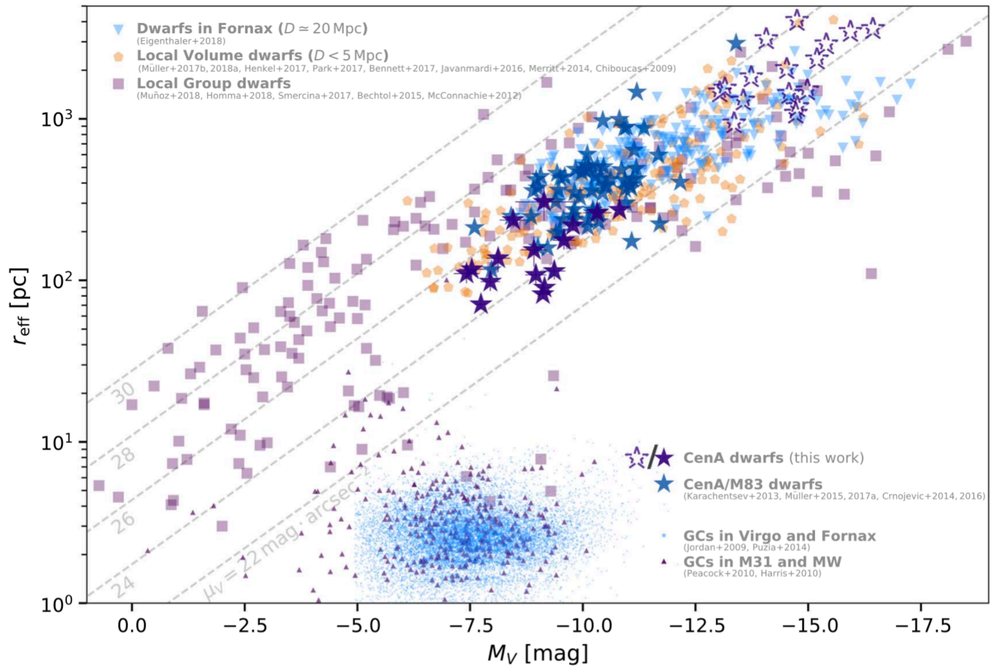
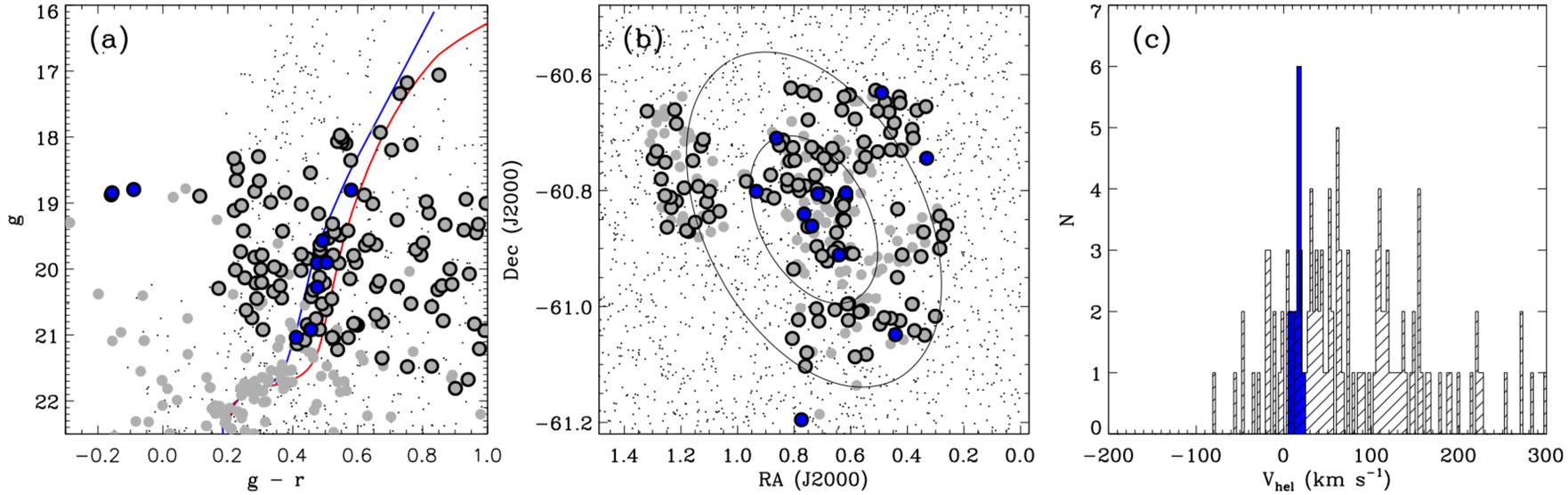


Figure 3. Size–luminosity diagram including the present dwarf candidates, LG ultra-faint dwarfs and dSphs, and other dwarf galaxies within the LV and nearby universe, including Fornax cluster dwarfs, and dwarf galaxies associated with more isolated nearby ($\lesssim$50 Mpc; see Section 3.3) giant galaxies. We differentiate those already known in the Centaurus A/M83 complex for easier comparison to the candidates presented in this Letter (purple vs. blue stars). Where available, we plot V-band luminosities and convert g' and r' magnitudes to V using the relation of Jester et al. (2005); if this is not possible, we plot g' or r'-band photometry as available from the literature. Empty dashed stars show the sample from this Letter shifted to the distance of a background group at a distance of 50 Mpc (see Section 4).

Follow-Up Spectroscopy (Example: Grus II)

- Do the stars belong to a coherent structure?
- What velocity does the object have?
- Is the object dark matter dominated?

The Astrophysical Journal, 892:137 (16pp), 2020 April 1



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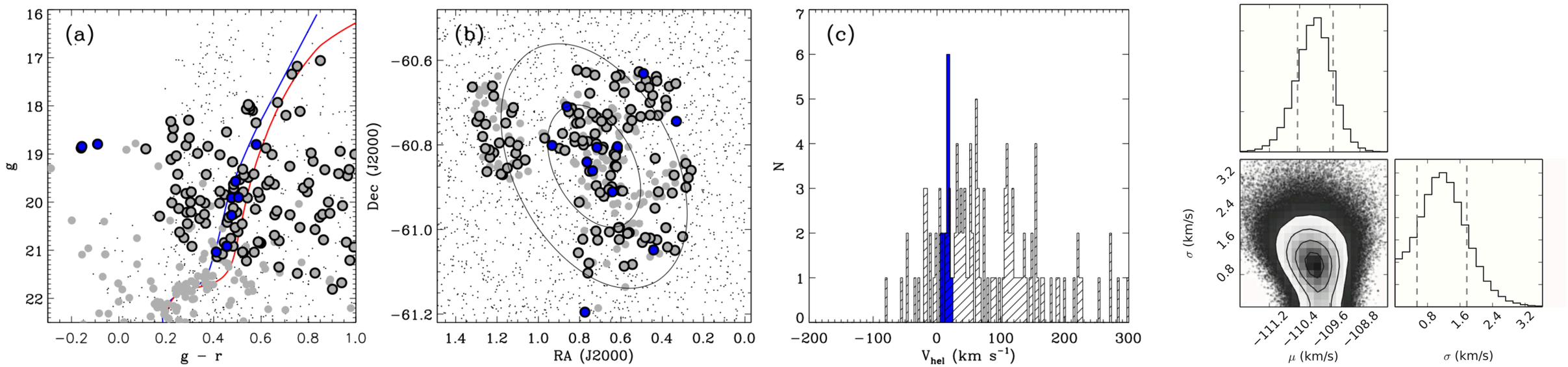


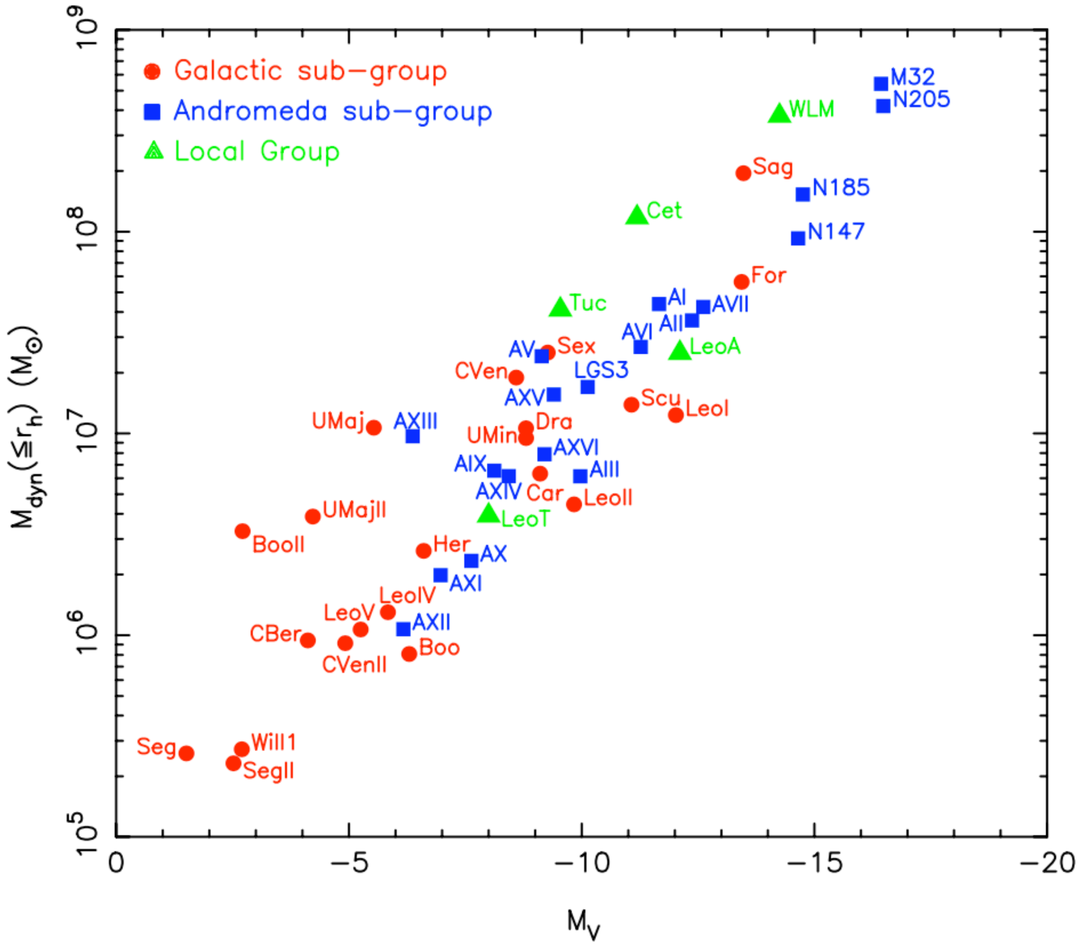
Dwarf Galaxies: Mass Estimates

- Via velocity dispersion, using viral theorem
- Best-constrained mass when velocity anisotropy is unknown is dynamical mass within half-light radius (Wolf et al. 2010):

$$M_{1/2} = 930 \left(\frac{\sigma}{\mathrm{km\ s^{-1}}} \right)^2 \left(\frac{R_{1/2}}{\mathrm{pc}} \right) \mathrm{M}_\odot$$

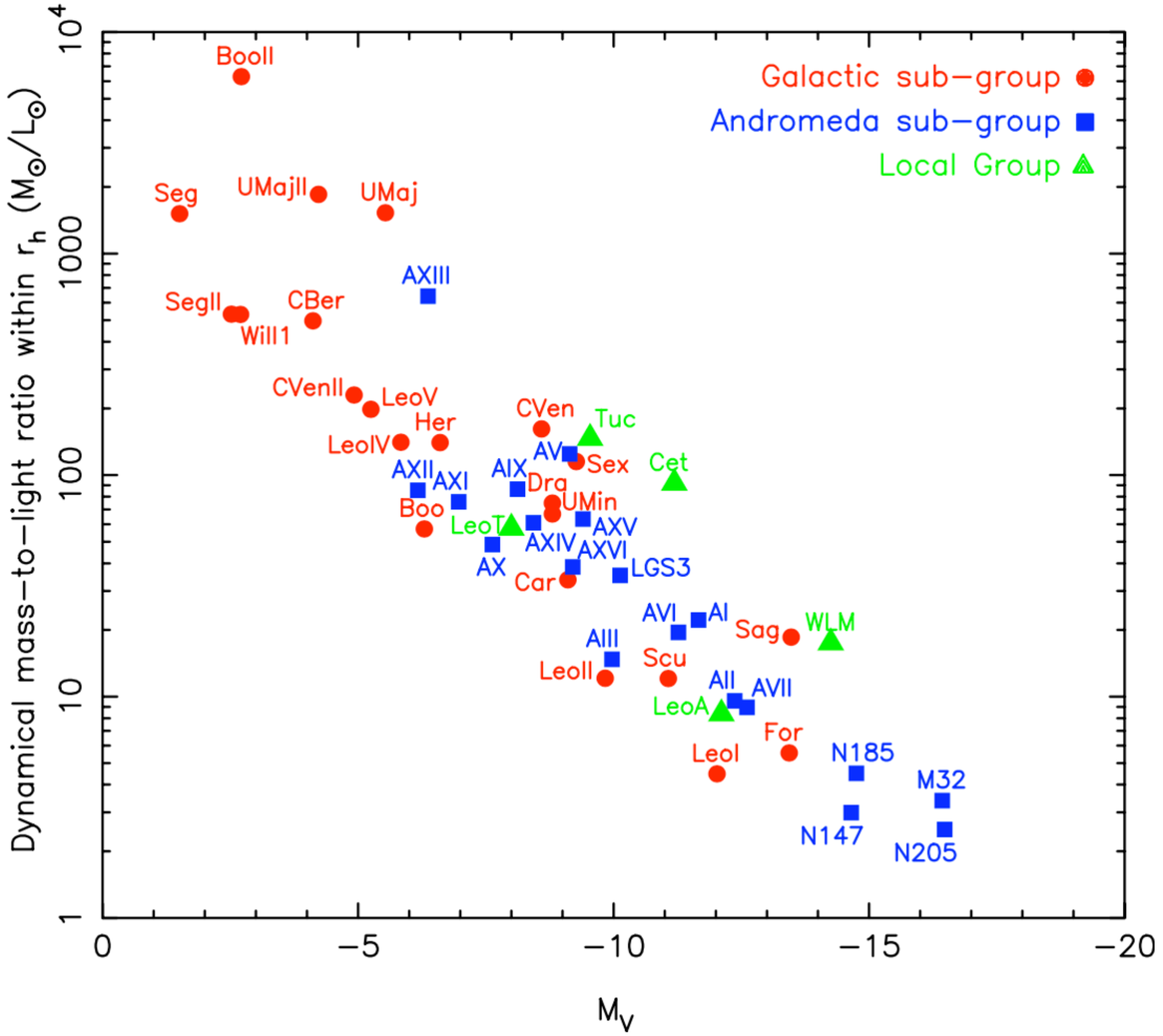
- Need to know stellar velocity dispersion σ and a half-light radius $R_{1/2}$.
- While limited, such a dynamical mass estimate is at least relatively homogeneous and hence comparable.

The Astronomical Journal, 144:4 (36pp), 2012 July



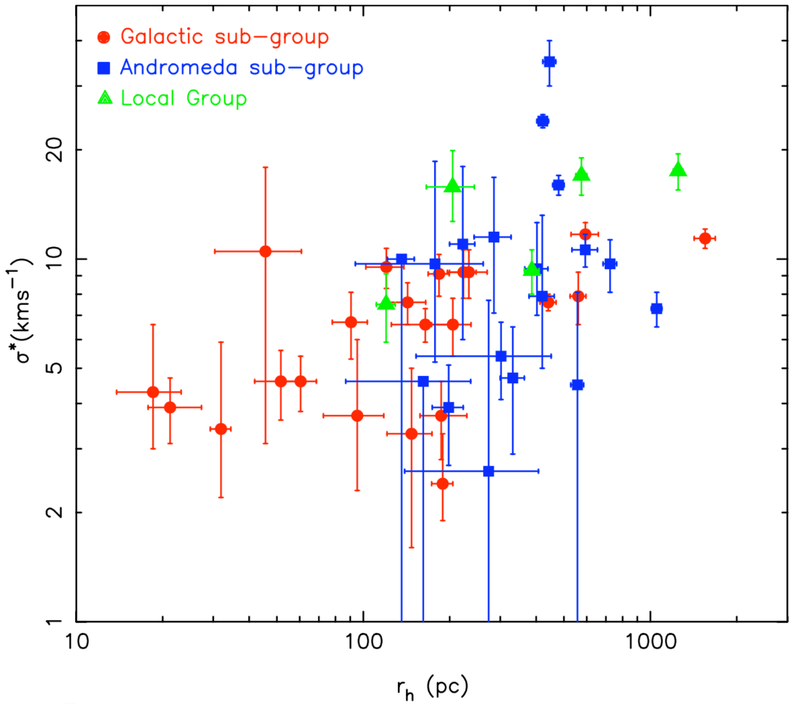
Dwarf Galaxies: Results for Missing Mass

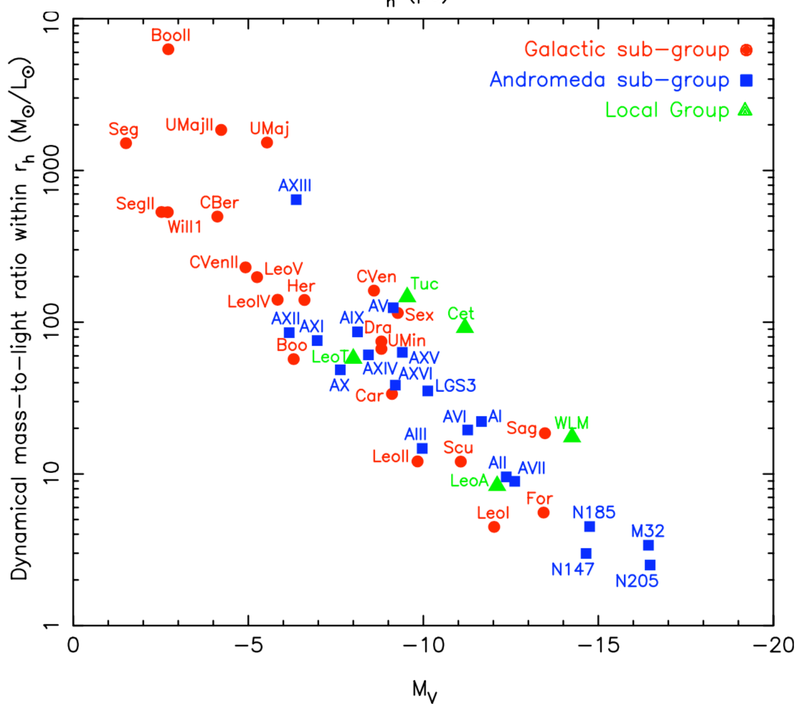
- Mass-to-light (*M/L)* ratios increase to fainter systems.
- Dwarf galaxies are the most dark matter dominated galaxies!
- Possibly useful when trying to study dark matter properties.



Dwarf Galaxies: Observational Caveats

- Faintest dwarfs have very low velocity dispersions of a few km/s. Comparable to spectroscopic measurement uncertainty.
- In addition, for faintest dwarfs with ~100 stars you run out of dynamical tracers → statistical uncertainties due to low numbers.
- Binary stars can further inflate the measured velocity dispersion → use multi-epoch data to identify and remove them.





Metallicities / Chemistry

- More massive galaxies have higher metallicity.
- Scatter increases to the faint end and observed ultra-faints seem to show a plateau (possible metallicity floor?).
- Less massive galaxies more easily lose their gas, thus self-enrich less efficiently.

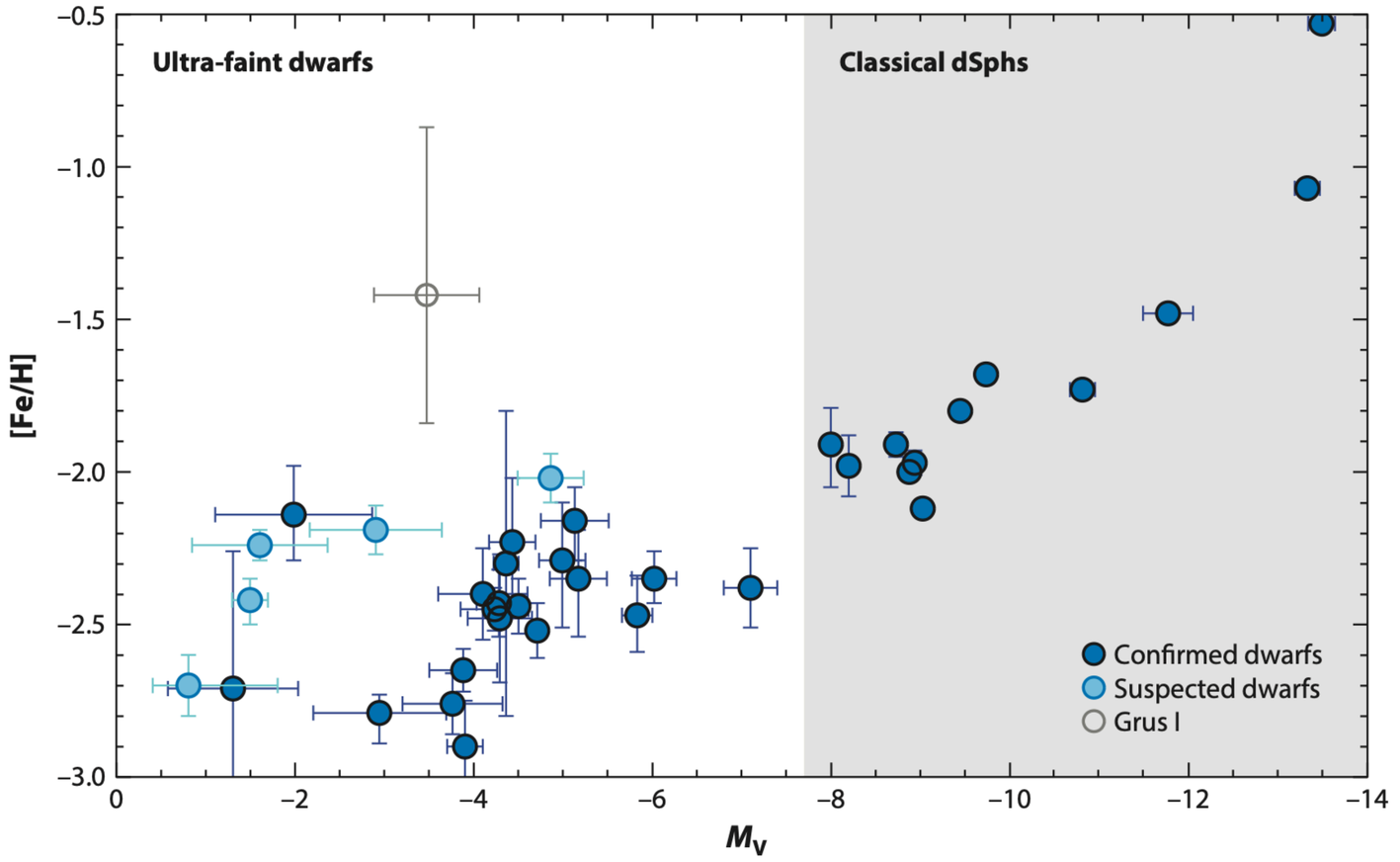


Figure 5

Mean stellar metallicities of Milky Way satellites as a function of absolute magnitude. Confirmed dwarf galaxies are displayed as dark blue filled circles, and objects suspected to be dwarf galaxies but for which the available data are not conclusive are shown as cyan filled circles. Grus I, for which there is no published classification, is shown as an open gray circle. The error bars in the vertical direction indicate the uncertainty on the mean metallicity of each object. The dwarf galaxy/candidate data included in this plot are listed in **Supplemental Table 1**. The overall relationship between metallicity and luminosity is clear, although the scatter is large at the faint end. Abbreviation: dSphs, dwarf spheroidal galaxies.

Star-Formation Histories

The Astrophysical Journal, 789:147 (23pp), 2014 July 10

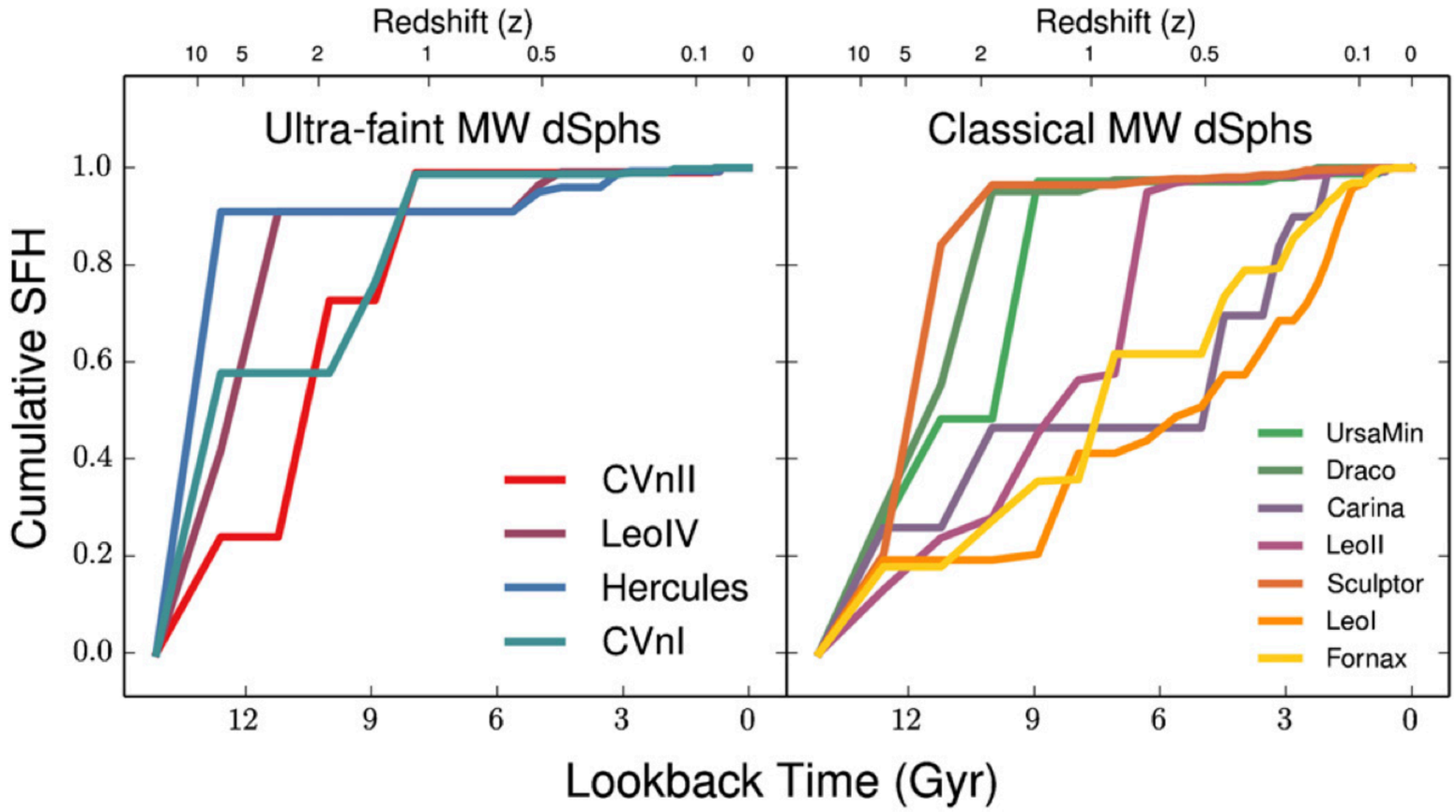


Figure 12. Cumulative SFHs of the MW ultra-faint and classical dSphs. The classical dwarfs show a diversity in SFHs: Hercules and Leo IV are purely old, while CVn I and CVn II have extended SFHs. The classical dwarfs also have both predominantly old galaxies (e.g., Sculptor, Draco) and those with extended SFHs (e.g., Carina, Fornax). There are no apparent systematic differences between the SFHs of the ultra-faint and classical dwarfs in our sample.

Star-Formation Histories

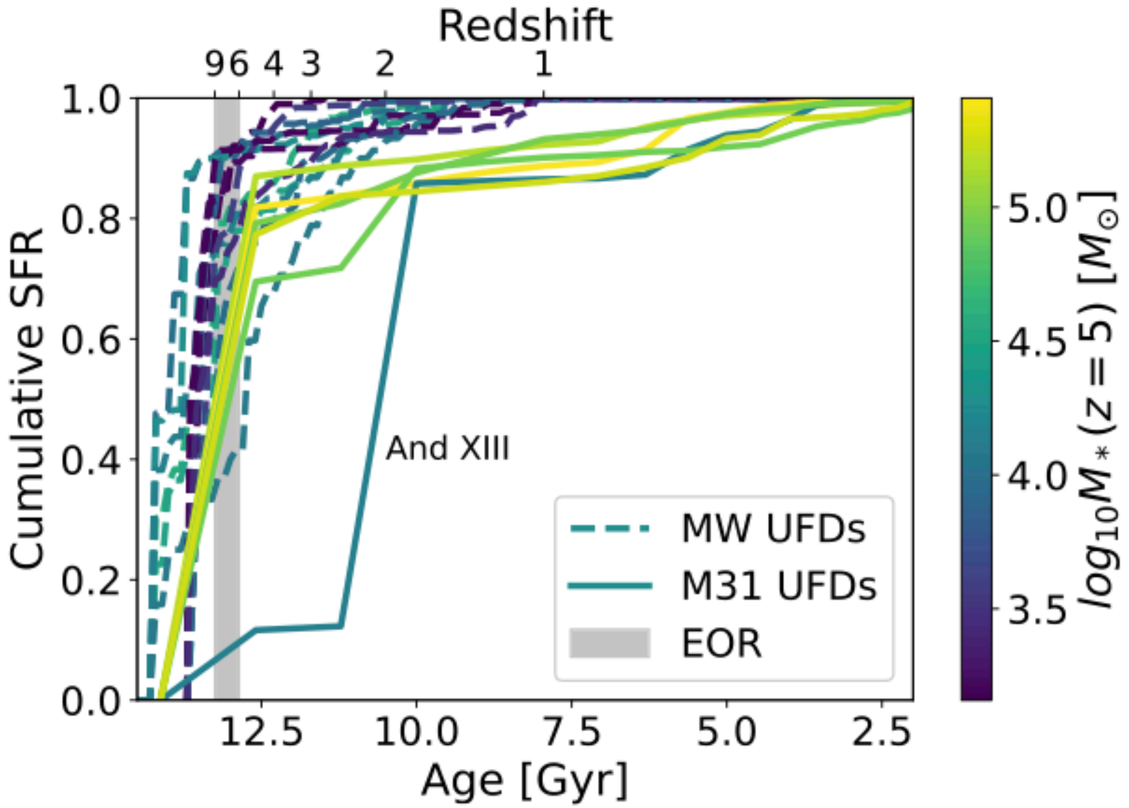
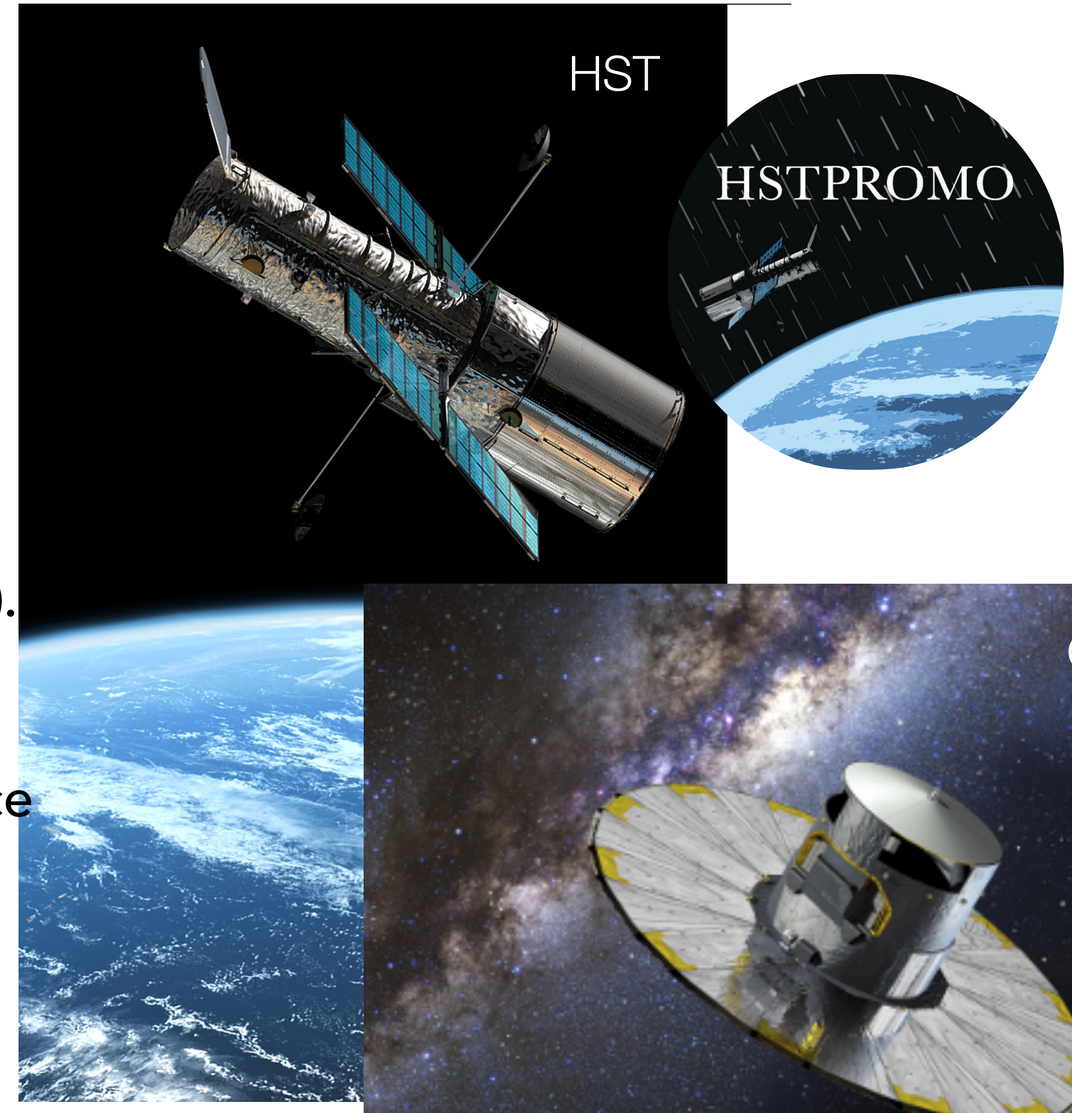
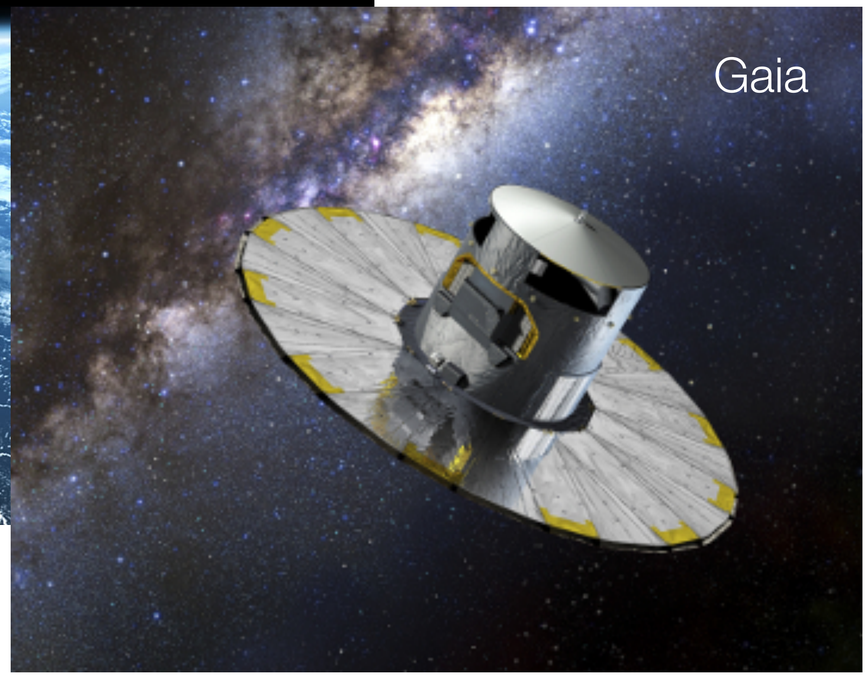


Figure 6. Lifetime cumulative SFHs for our six M31 UFDs (solid lines), compared to those of MW UFD satellites (dashed lines), color-coded by total stellar mass at $z = 5$. The shaded gray region delineates the epoch of reionization. The SFH of And XIII is highlighted in the figure.

Proper Motions

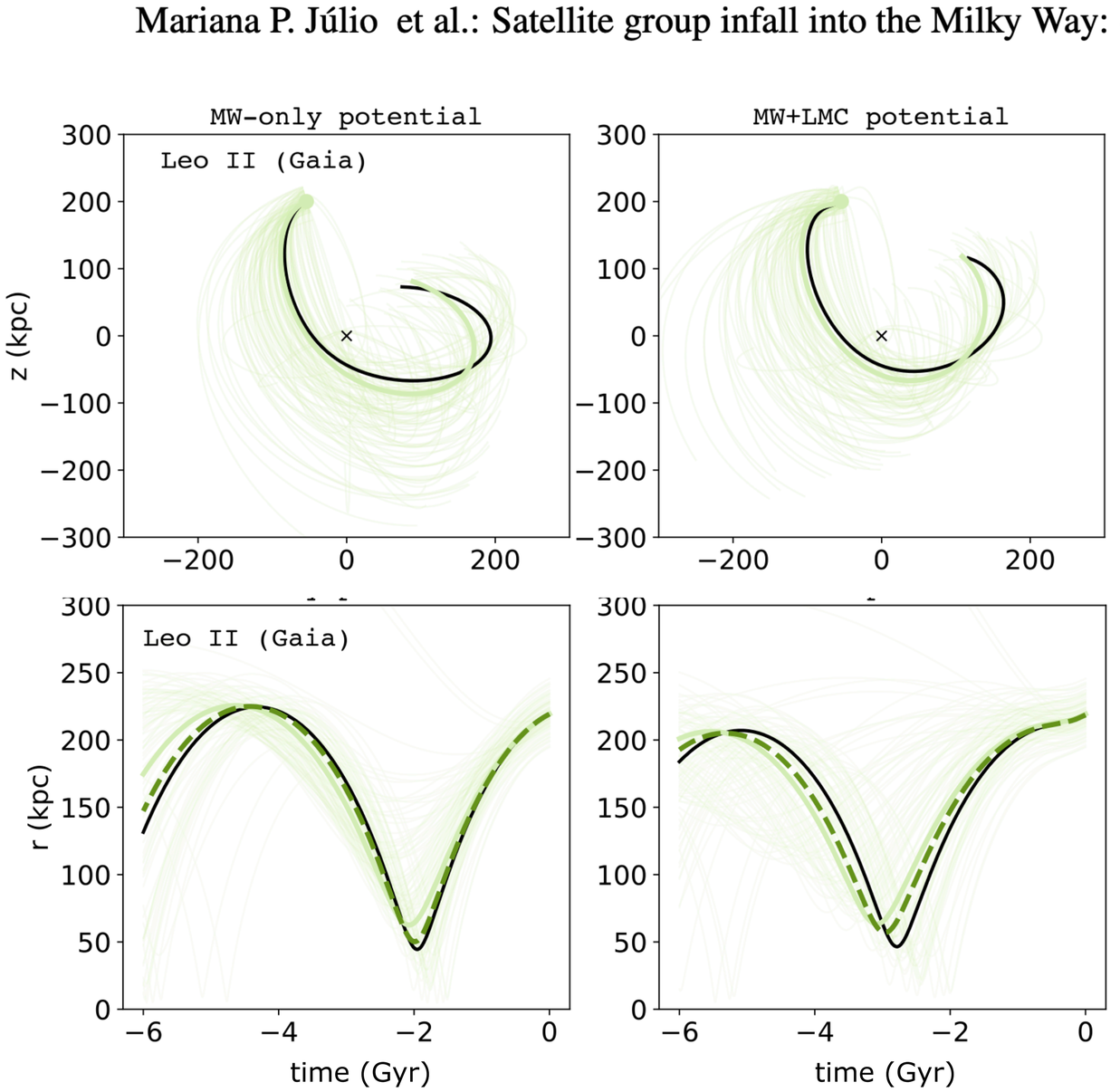
- Measure how dwarf galaxies move on the sky (tangential velocity):
  - Typical velocities >100 km/s.
  - But distances of many 10 to 100 kpc (10^{18} km).
  - Angular velocities < 1 mas / year
    ~ growth of human hair seen from the distance of the moon.

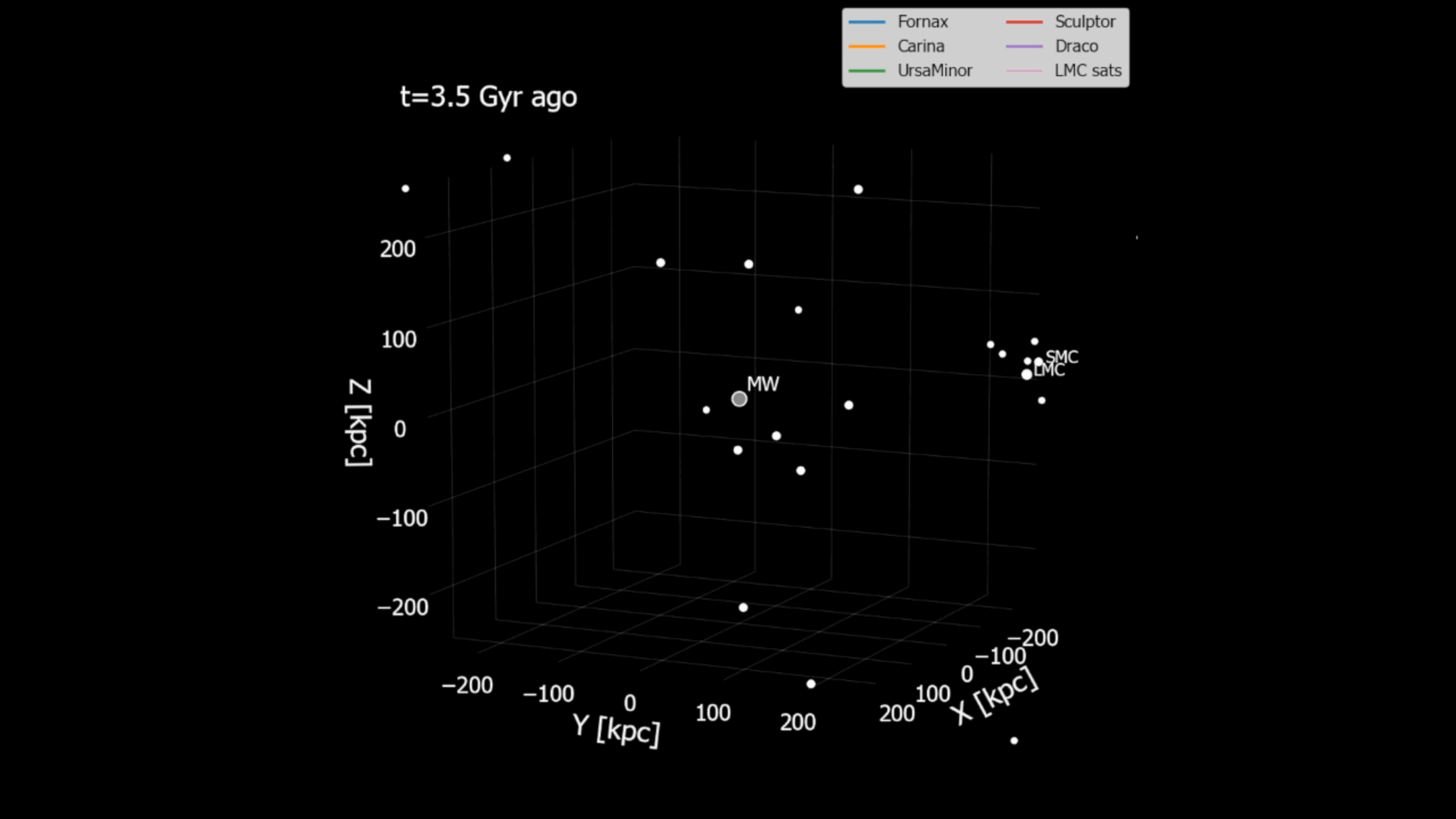




Orbits

- Orbit integration in fixed potential (better: time-evolving, e.g. due to massive LMC).
- Easy to use python tools available:
  - GalPy: https://docs.galpy.org/
  - Gala: https://gala.adrian.pw/
- Obtain orbital parameters (apo- and pericenter, orbital period, energy, angular momentum, orbital phase, …)
- Infer how susceptible to tidal disruption, or whether associated with more massive galaxy like the LMC,




Fornax
Carina
UrsaMinor
Sculptor
Draco
LMC sats
t=3.5 Gyr ago
MW
SMC
LMC
200
100
0
−100
−200
Z [kpc]
−200
−100
0
100
200
Y [kpc]
200
100
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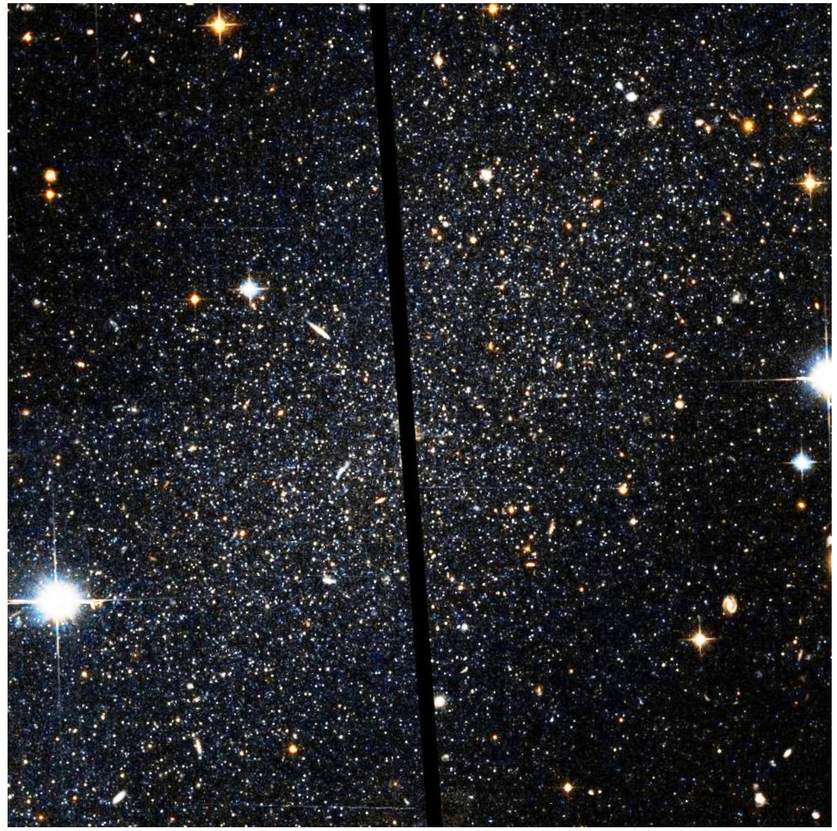
−100
−200
X [kpc]

Andromeda III Proper Motion and implied Orbits

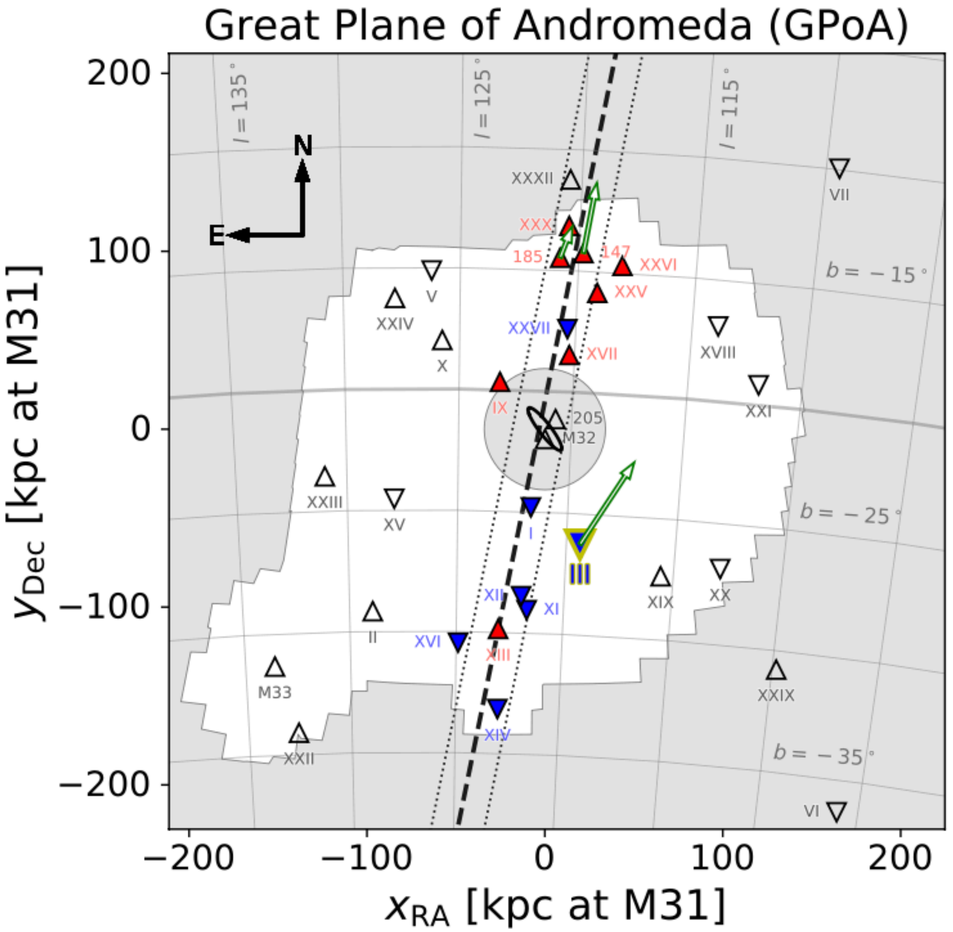
- HST observations (ACS/WFC and WFPC2) spanning 22-year time baseline!



Casetti-Dinescu, Pawlowski et al. (2024)

Andromeda III Proper Motion and implied Orbits

- HST observations (ACS/WFC and WFPC2) spanning 22-year time baseline!
- Only third M31 satellite with measured PM. All are part of the satellite plane.
  → **consistent with co-orbiting along sat. plane!**

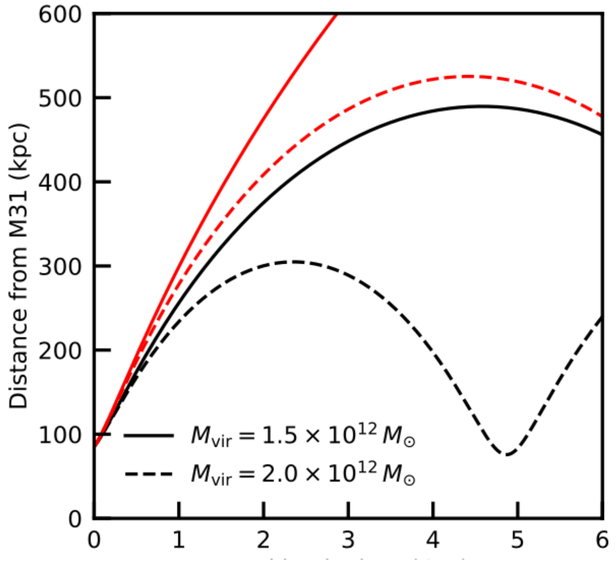


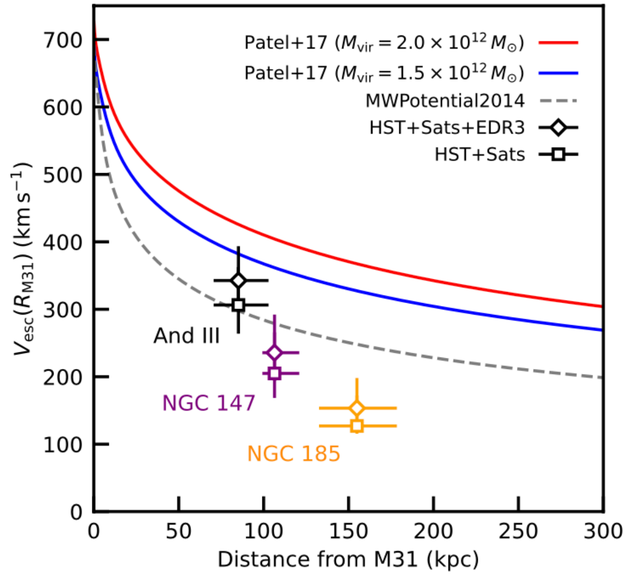
Casetti-Dinescu, Pawlowski et al. (2024)

Andromeda III Proper Motion and implied Orbits

- HST observations (ACS/WFC and WFPC2) spanning 22-year time baseline!
- Only third M31 satellite with measured PM. All are part of the satellite plane.
  → **consistent with co-orbiting along sat. plane!**
- Relatively high implied velocity.
  → **constrains M31 to higher mass, unless And III is on first infall.**

- HSTPROMO has more M31 satellite PMs coming up
- Plus PMs for And V & VI (Casetti-Dinescu, Pawlowski et al. 2025)





Casetti-Dinescu, Pawlowski et al. (2024)

Candidate Dwarf Galaxies Beyond the Local Group

- Example from our recent Taibi et al. (2025)

Taibi, S., et al.: A&A, 699, A285 (2025)

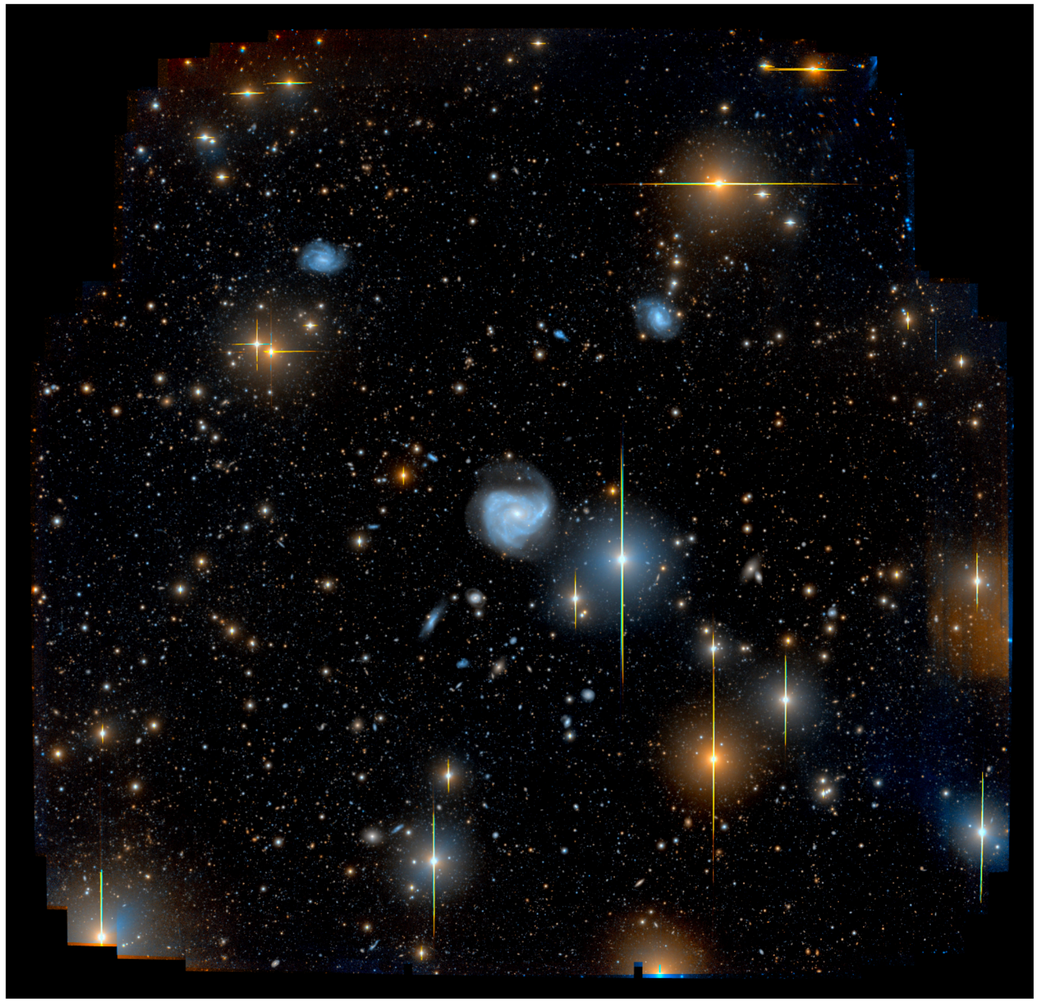


Fig. 1. Colour composition of the surveyed area around NGC 2750 obtained by combining the final co-added images in the g- and r-bands with an average $(g + r)/2$ image. The image FoV is approximately $35' \times 30'$. North is up and east to the left.

Candidate Dwarf Galaxies Beyond the Local Group

- Example from our recent Taibi et al. (2025)
- No more resolved into stars → look for fuzzy low-surface-brightness (LSB) objects.

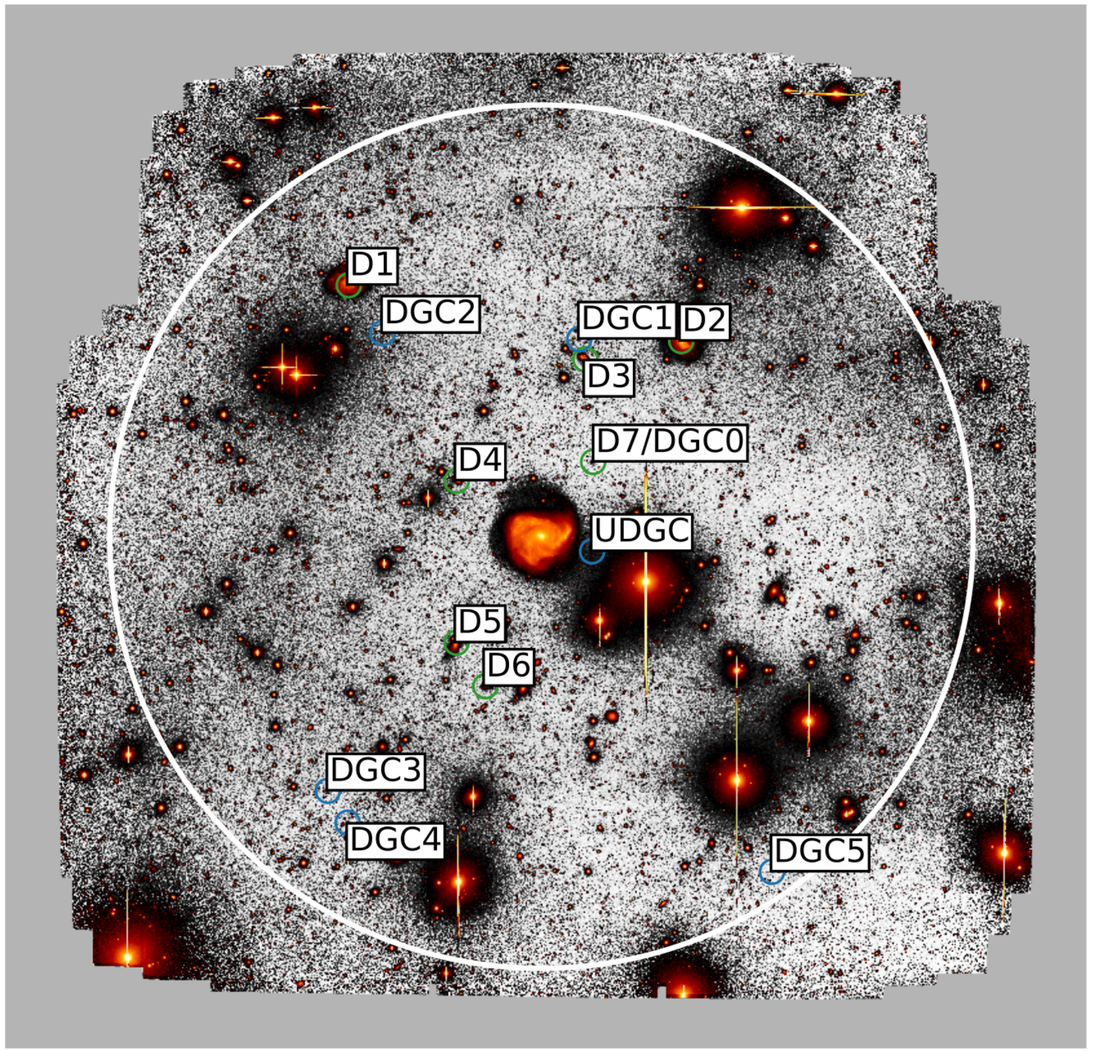


Fig. A.1. Co-added $(g + r)/2$ image of the surveyed area around NGC 2750. The position of the known and candidate galaxies is marked with

Candidate Dwarf Galaxies Beyond the Local Group

- Example from our recent Taibi et al. (2025)
- No more resolved into stars → look for fuzzy low-surface-brightness (LSB) objects.
- So far, visual inspection remains superior to automatic procedures or ML.

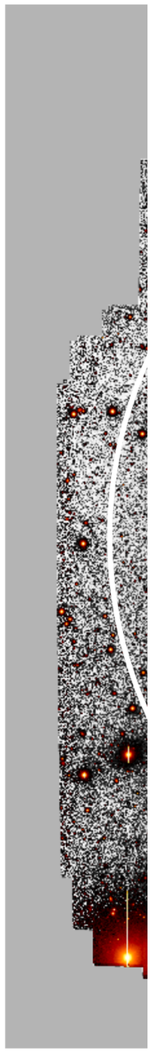


Fig. A.1. Co-added (

Taibi, S., et al.: A&A, 699, A285 (2025)

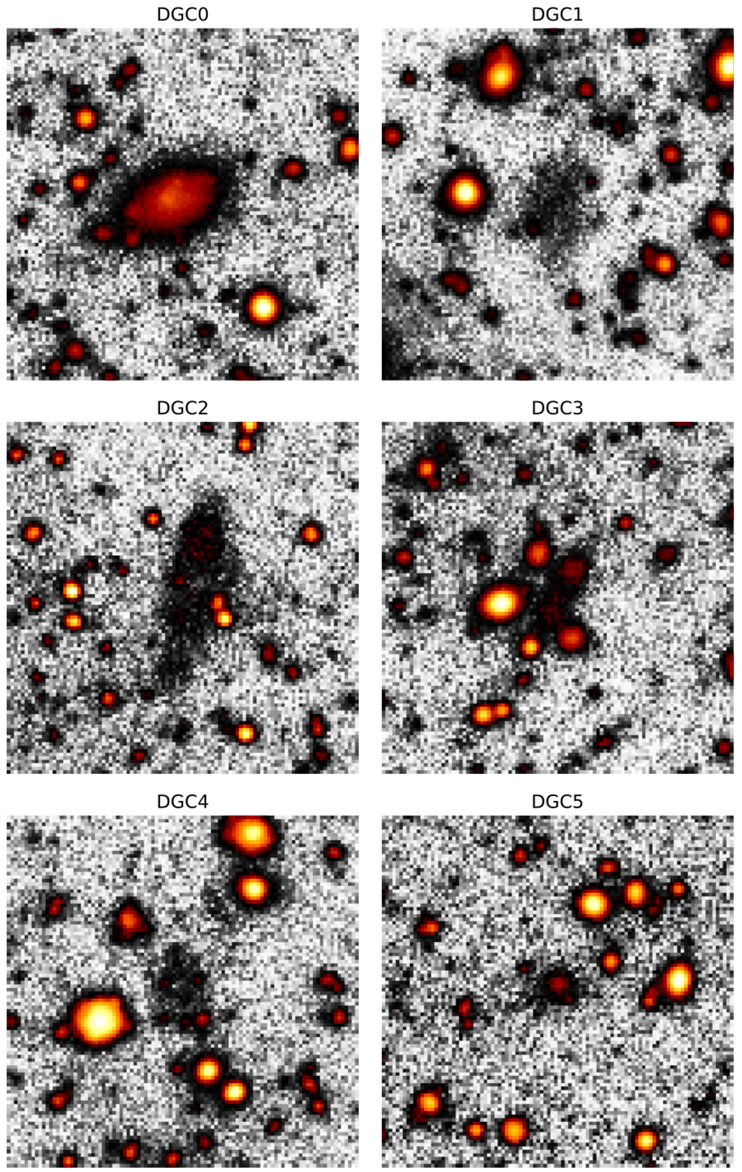


Fig. A.4. Cutouts of the co-added $(g + r)/2$ image around the candidate dwarf galaxies reported in this paper. Each image has a binning of 2×2 and a size of $45'' \times 45''$. North is up and east to the left.

Candidate Dwarf Galaxies Beyond the Local Group

- Example from our recent Taibi et al. (2025)
- No more resolved into stars → look for fuzzy low-surface-brightness (LSB) objects.
- So far, visual inspection remains superior to automatic procedures or ML.
- Measure properties of identified candidates
  magnitude M_V, surface brightness μ_V,
  effective radius R_e, color $(g\text{-}r)_0$

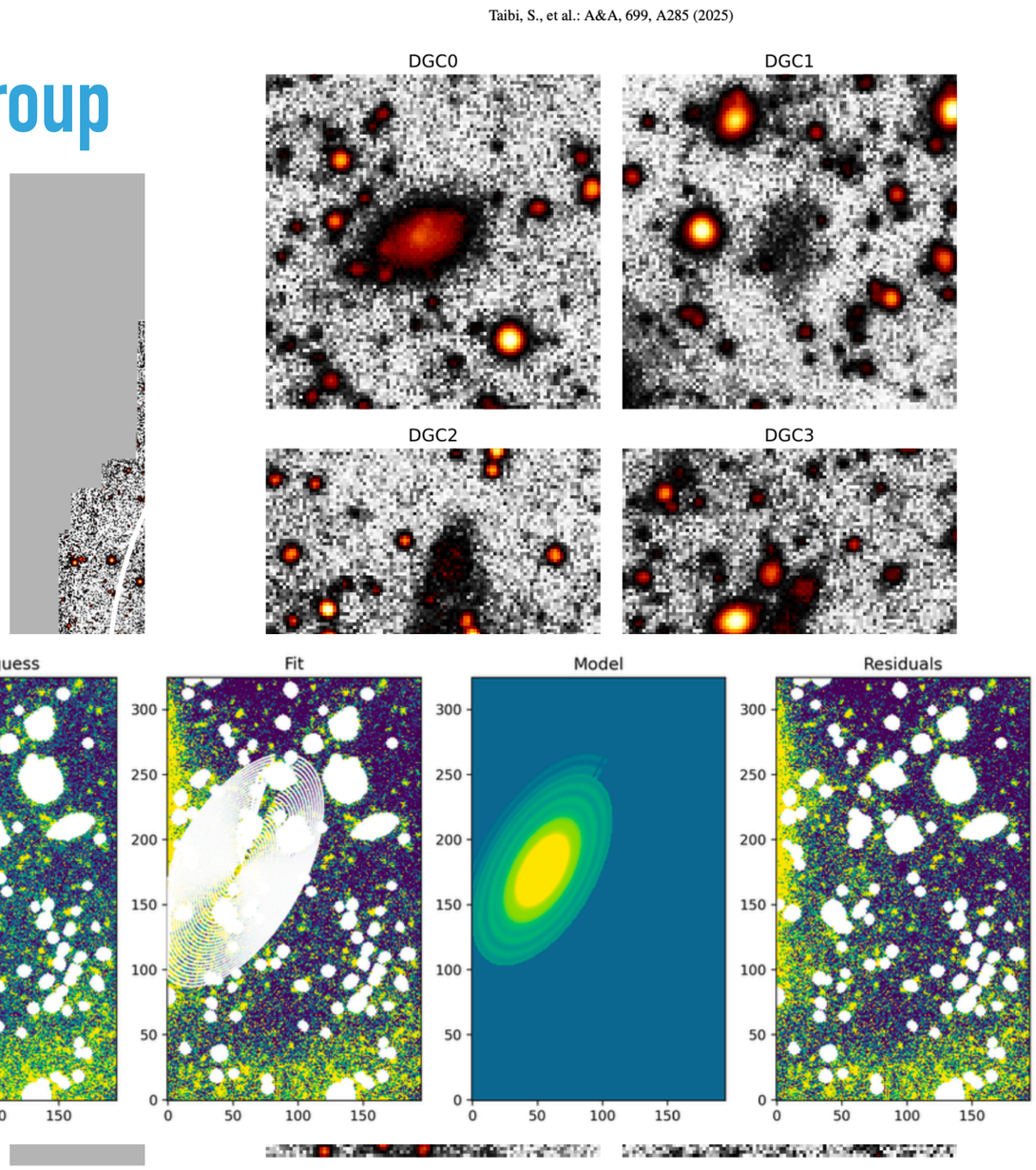


Fig. A.1. Co-added (

Fig. A.4. Cutouts of the co-added $(g + r)/2$ image around the candidate dwarf galaxies reported in this paper. Each image has a binning of 2×2 and a size of $45'' \times 45''$. North is up and east to the left.

Candidate Dwarf Galaxies Beyond the Local Group

- Example from our recent Taibi et al. (2025)
- No more resolved into stars → look for fuzzy low-surface-brightness (LSB) objects.
- So far, visual inspection remains superior to automatic procedures or ML.
- Measure properties of identified candidates magnitude M_V, surface brightness μ_V, effective radius R_e, color $(g\text{-}r)_0$
- Compare to known scaling relations to see if realistic candidates.

Taibi, S., et al.: A&A, 699, A285 (2025)

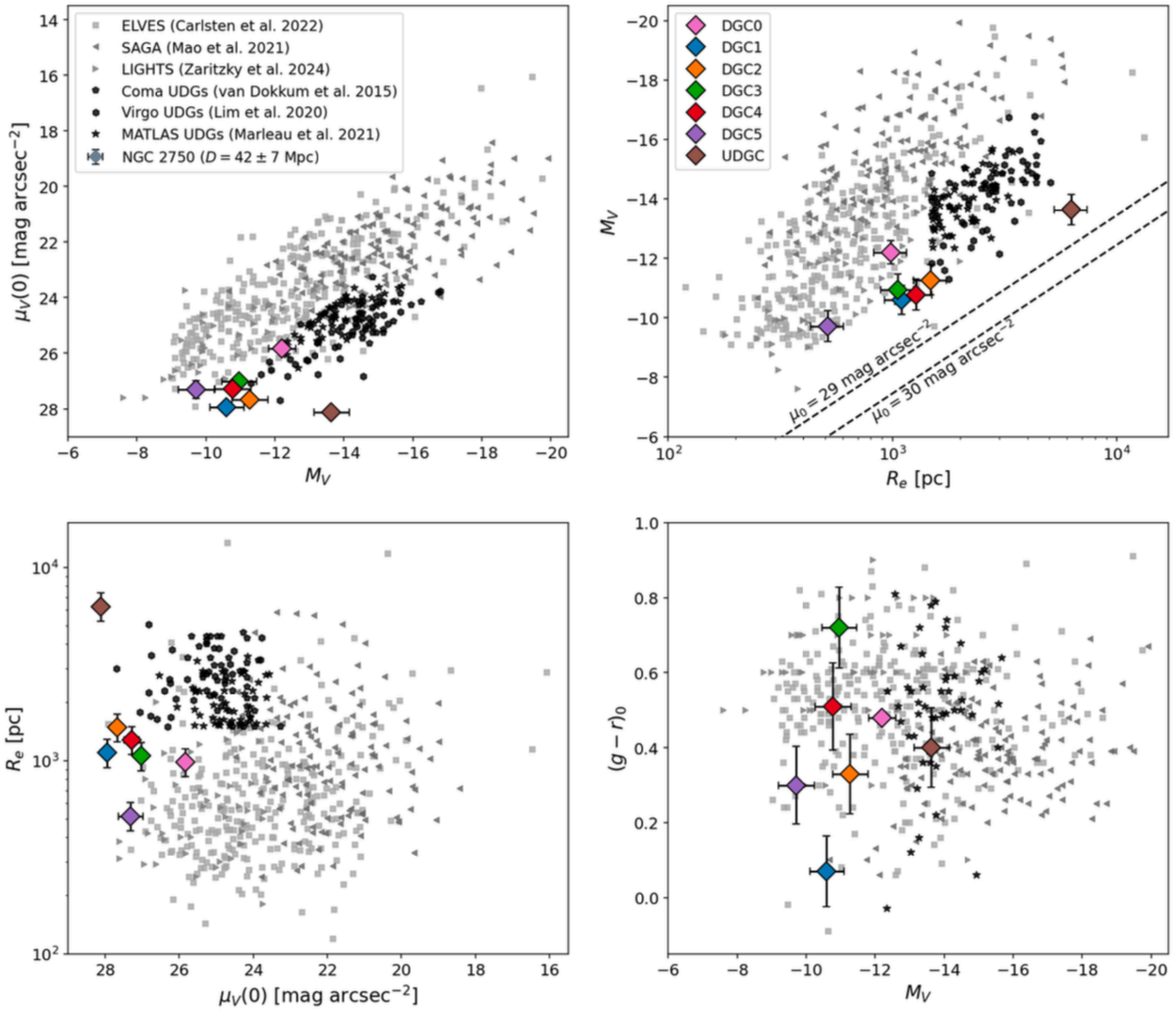


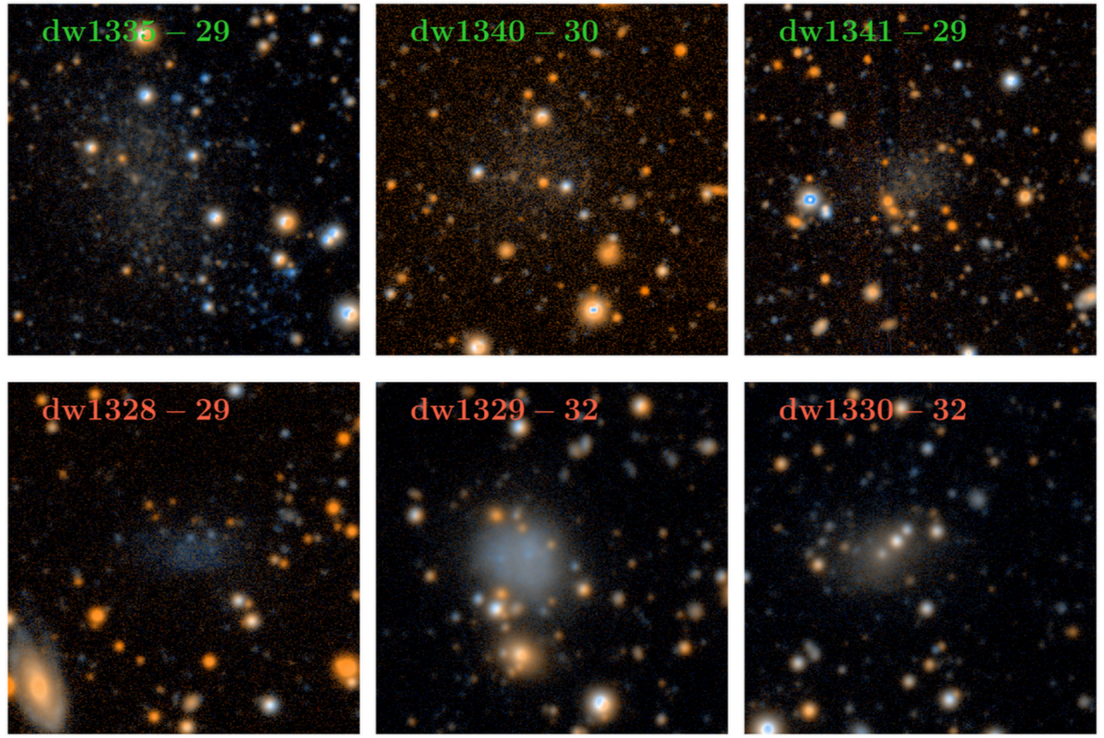
Fig. A.1. Co-added (

Fig. A.4. Cutouts of the co-added $(g + r)/2$ image around the candidate dwarf galaxies reported in this paper. Each image has a binning of 2×2 and a size of $45'' \times 45''$. North is up and east to the left.

Confirming Dwarf Galaxies Beyond the Local Group

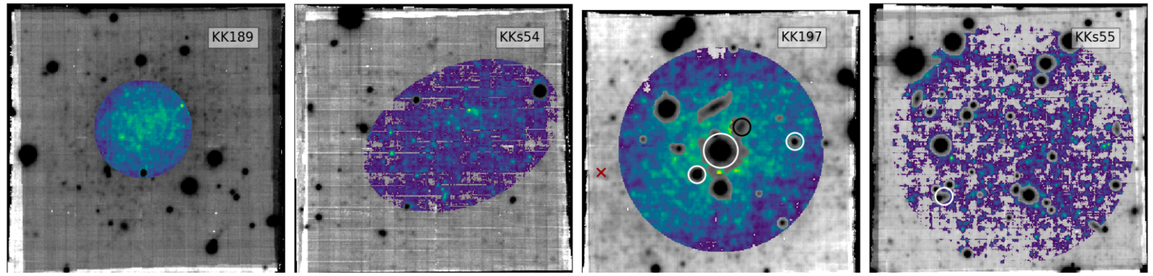
- Need to make sure candidates are indeed associated with their host, and not unassociated background objects (or e.g. galactic cirrus).
  How could we do that?
  - Does the distance match?
    (e.g. tip-of-red-giant-branch distance, or surface-brightness-fluctuation method).

Müller, O., et al.: A&A, 684, L6 (2024)



Confirming Dwarf Galaxies Beyond the Local Group

- Need to make sure candidates are indeed associated with their host, and not unassociated background objects (or e.g. galactic cirrus).
  How could we do that?
  - Does the distance match?
    (e.g. tip-of-red-giant-branch distance, or surface-brightness-fluctuation method).
  - Is velocity/redshift consistent with that of the host?
    (Spectroscopic velocity measurement … can be hard for LSB objects, but an IFU like MUSE helps).



O. Müller et al.: The properties of dwarf spheroidal galaxies in Cen A galaxy group

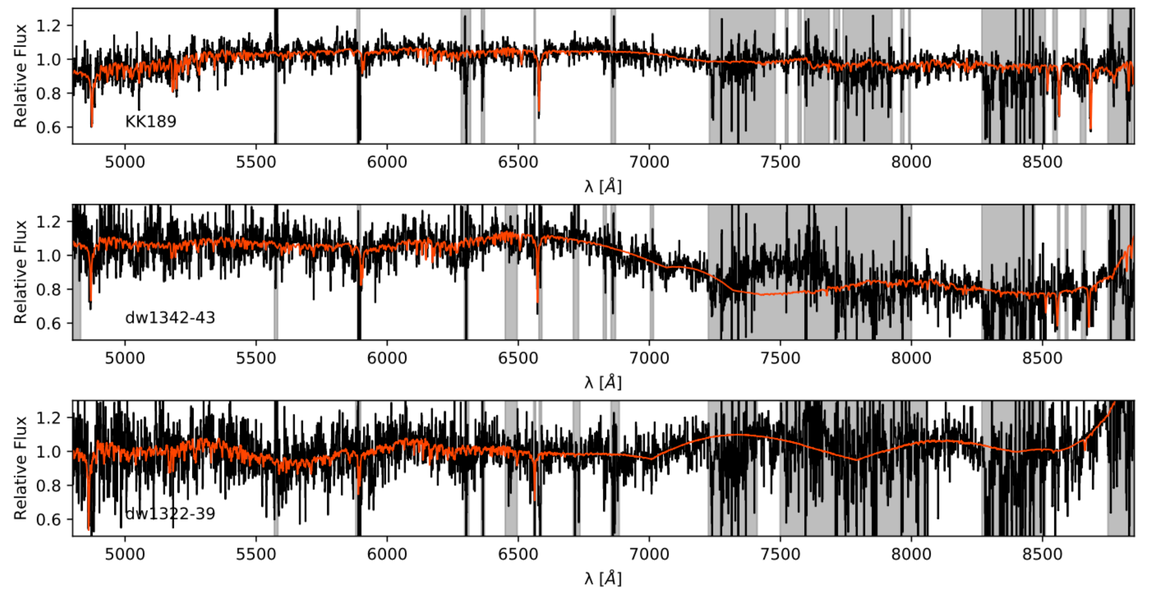
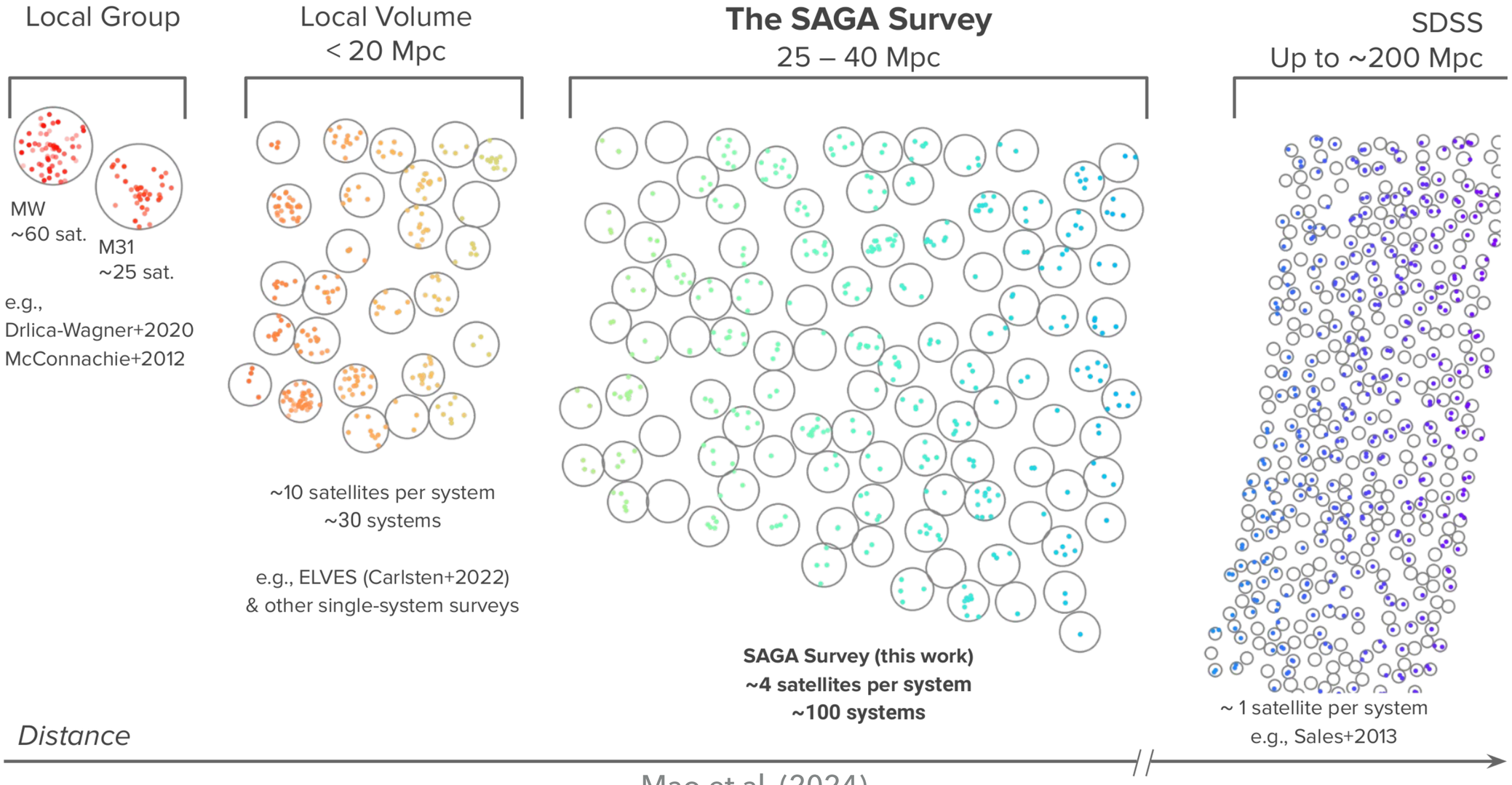


Fig. 2. Integrated MUSE spectra (black) of three example dwarf galaxies from our sample. The S/N decreases from top (S/N = 28.5) to bottom (S/N = 11.9) (see Table 1). The gray area are masked regions, the red lines correspond to the best-fit from pPXF. The spectra of the remaining galaxies are shown in Fig. C.1.

Surveys for Satellite Galaxy Systems (with Spectroscopic Velocities)



Mao et al. (2024)

Summary

Dwarf galaxies have stellar masses of $\approx 10^{7-9}\,M_\odot$ or smaller.

Discovered as stellar over densities around MW and M31, ore “fuzzy blobs" around more distant hosts.

Fainter dwarfs have lower metallicity, velocity dispersion, baryonic and total mass.

The faintest dwarfs are the most dark matter dominated systems (M/L up to 1000).

For nearby dwarfs we can study 3D distribution and 3D motion → infer e.g. orbits around Milky Way.

Literature

Reviews:

- McConnachie (2012): “The Observed Properties of Dwarf Galaxies in and around the Local Group”, AJ, 144, 4.
- Simon (2019): “The Faintest Dwarf Galaxies”, ARA&A, 57, 375.

Dwarf Galaxies and Small-Scale Structure
Part 2: ΛCDM Expectations vs. Observed Systems

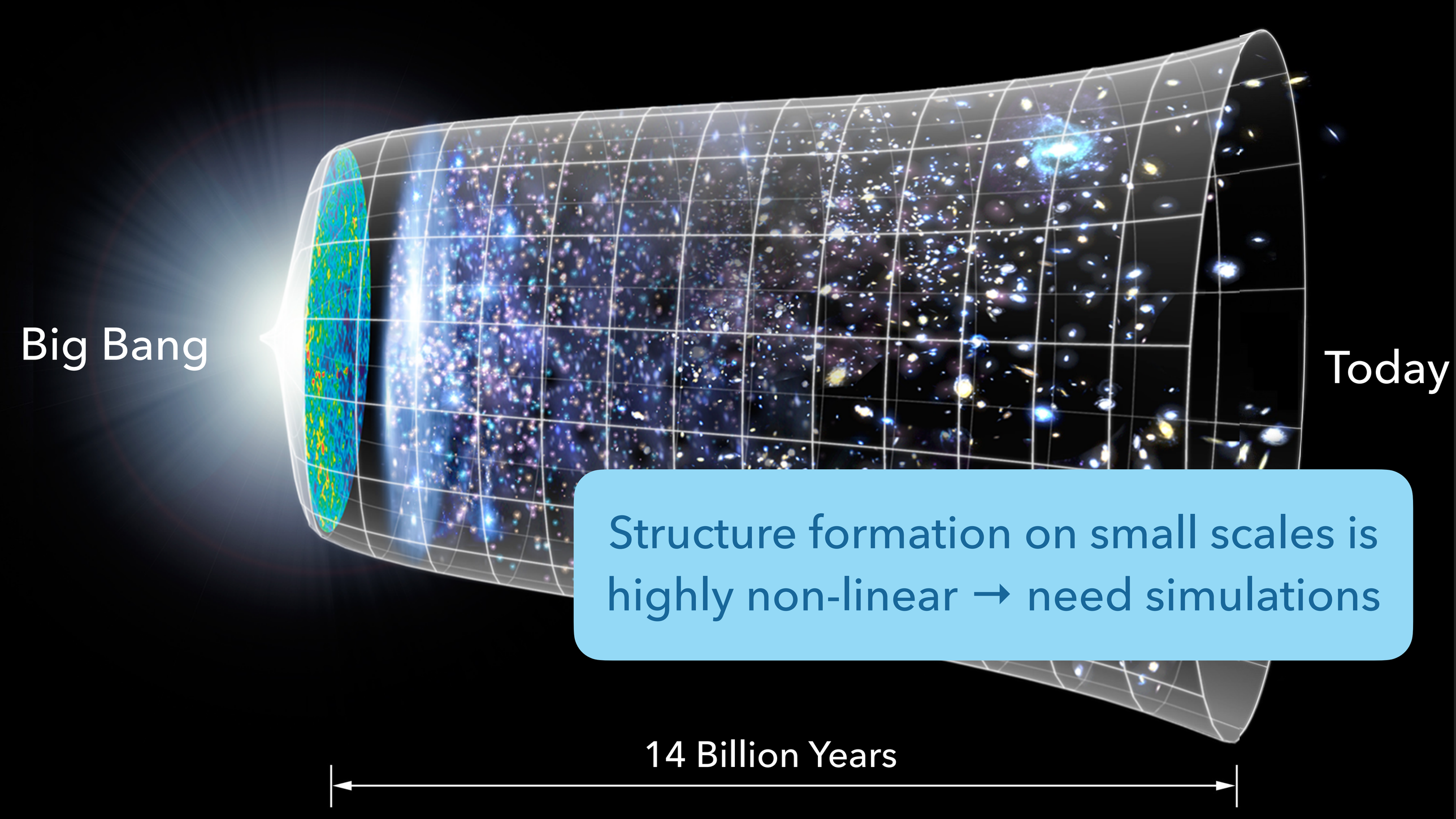
DR. MARCEL S. PAWLOWSKI

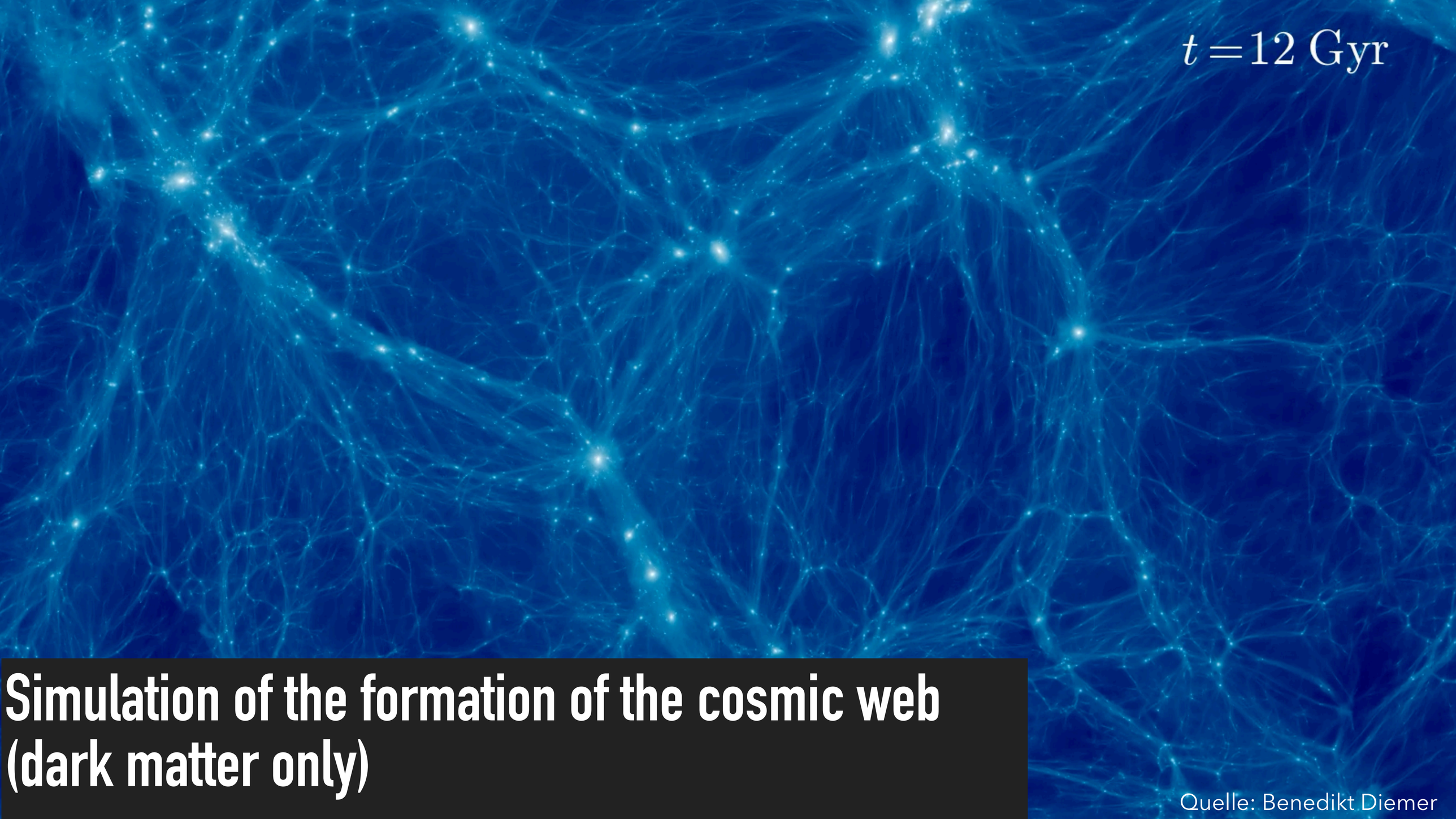
RESEARCH GROUP LEADER

LEIBNIZ-INSTITUT FÜR ASTROPHYSIK, POTSDAM

AIP

Composite by K. J. Kanehisa (Image Credits: N. Rissiger 2009 (Milky Way), R. Pendler 2002 (M31), ESO/VISTA VMC (LMC)).


Big Bang
Today
Structure formation on small scales is highly non-linear → need simulations
14 Billion Years



Simulation of the formation of the cosmic web (dark matter only)

Quelle: Benedikt Diemer

Simulation of the formation of a Milky-Way-like galaxy(dark matter only)

Quelle: https://www.caterpillarproject.org/

Millennium-II: Density Distribution

- DM density in simulation shows strong concentrations, interlinked by large filaments. ‘Cosmic Web’.
- Mass is assembled in sheets; where two sheets intersect, filaments form, and at the intersection of filaments are the more massive dark matter halos.
- Halos themselves are not smooth, but contain a rich substructure (see smaller-scale zooms).

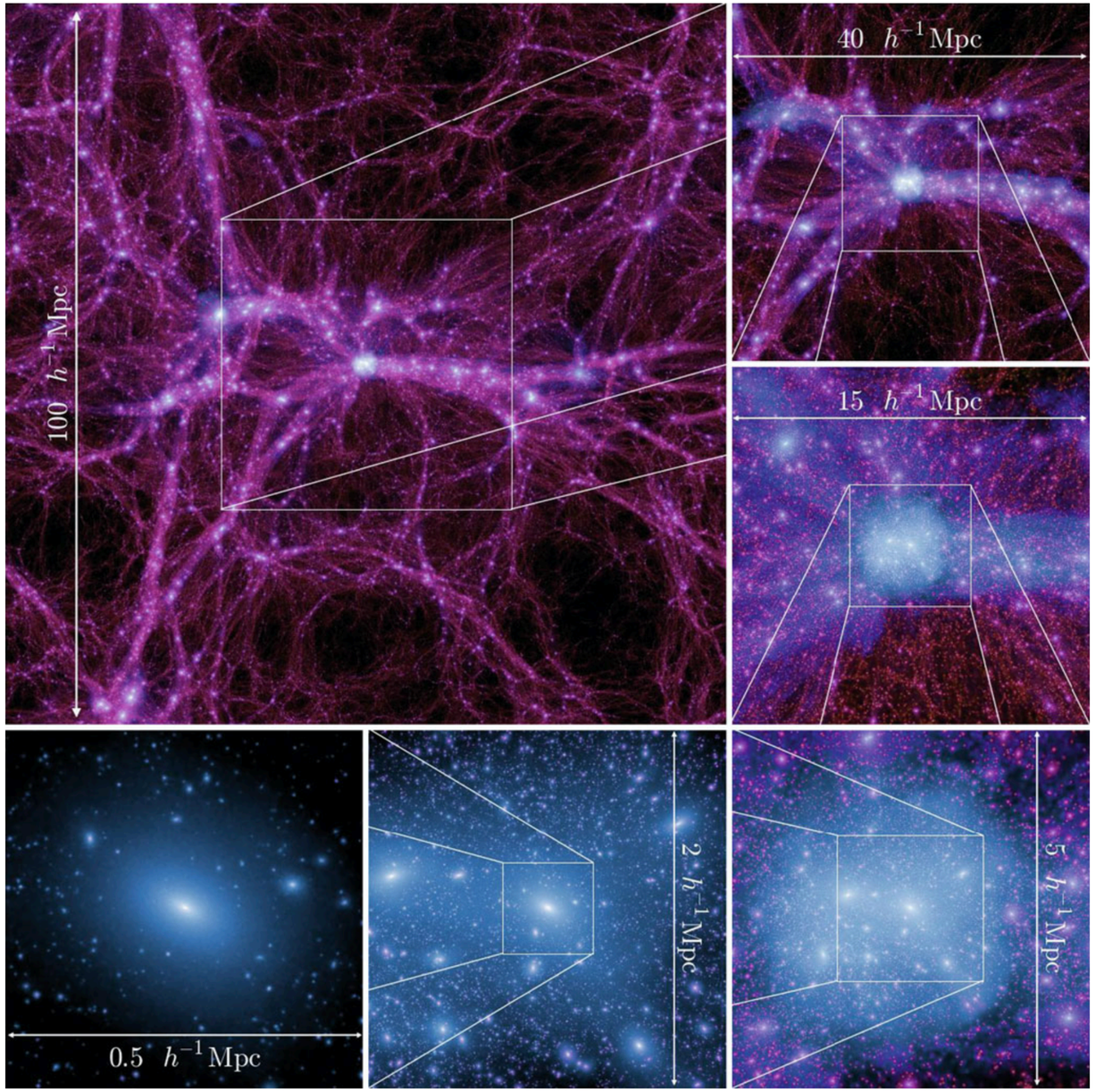


Fig. 7.15 The Millennium-II simulation. The *large upper-left panel* shows a $15h^{-1}$ Mpc slice through the full simulation, while the other *panels* display subsequent zooms of the central region, where the most massive halo in the simulation is located, with decreasing thickness of the slices. Source: M. Boylan-Kolchin et al. 2009, *Resolving cosmic structure formation with the Millennium-II Simulation*, MNRAS 398, 1150, p. 1153, Fig. 1. Reproduced by permission of Oxford University Press on behalf of the Royal Astronomical Society

Millennium-II: Evolution of Density Field

- Density contrast increases with time, as expected from gravitational instability. At high *z*, only small mass concentrations have formed; more massive ones show up only at smaller *z*.
- Low-mass halos form first, massive ones only later. This is the hierarchical built-up of structure in a CDM universe.
- Halos grow due to two processes:
  1. merging with other halos: leads to substructure (subhalos) of halos, which are the relics of earlier mergers.
  2. accretion of matter: is due to the gravitational pull of the mass concentrations on the surrounding matter. Accretion happens predominantly through filaments, thus not spherically symmetric.

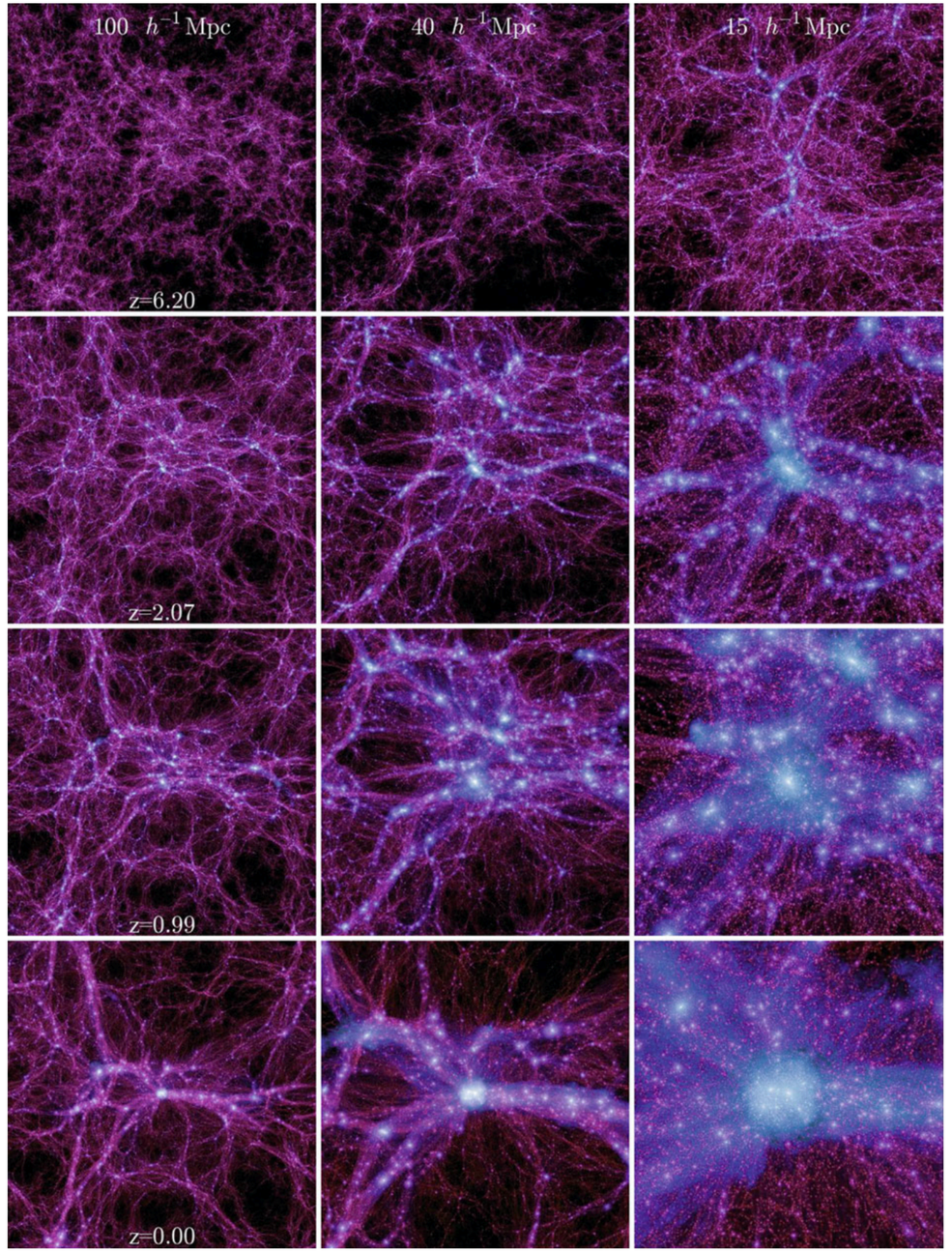
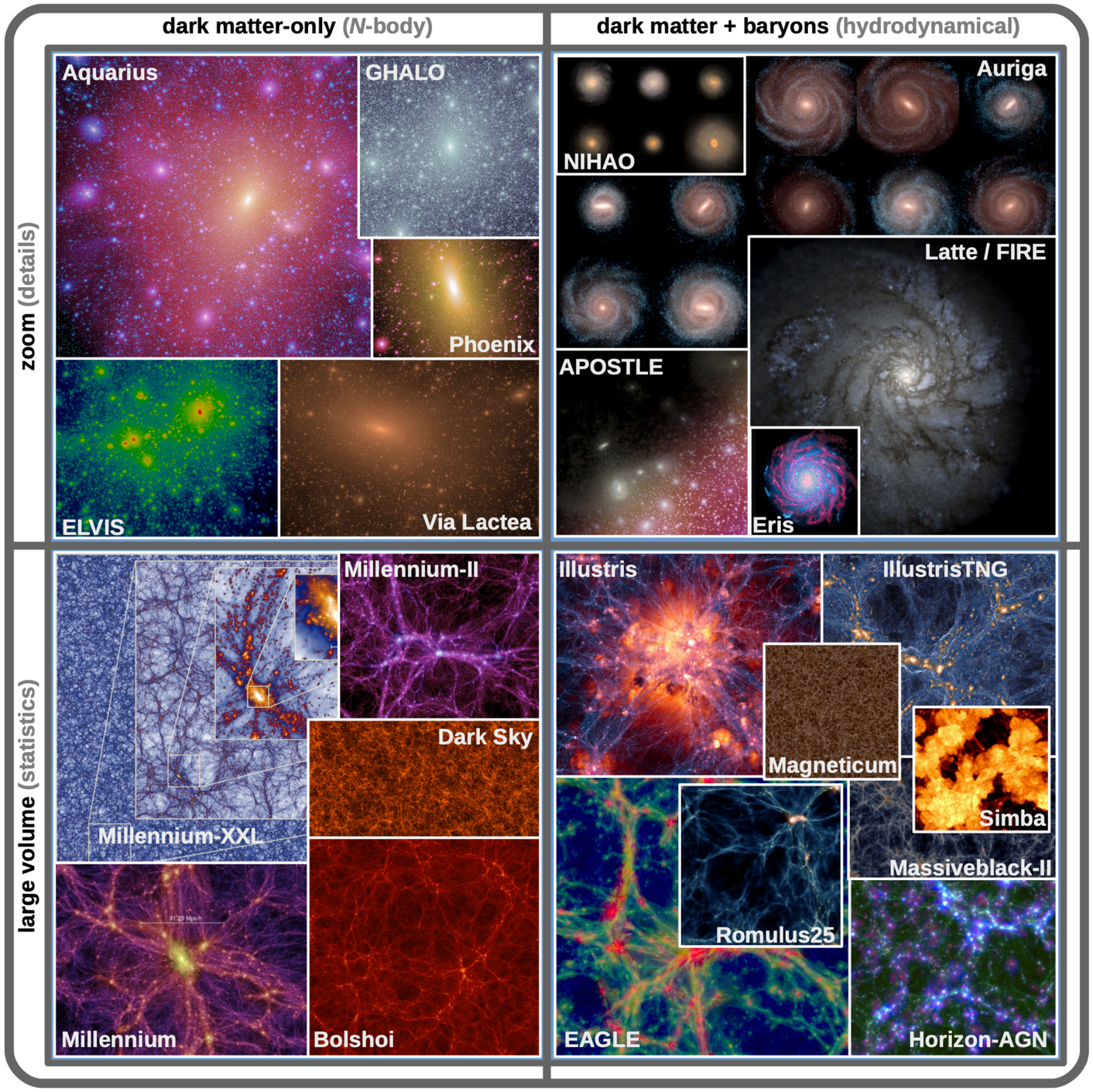


Fig. 7.16 Time evolution in the Millennium-II simulation. The most massive halo in the simulation is shown at four different redshifts, and three spatial resolutions. The thickness of the slices from left to right is 15, 10, and $6h^{-1}$ Mpc, respectively. Source: M. Boylan-Kolchin et al. 2009, *Resolving cosmic structure formation with the Millennium-II Simulation*, MNRAS 398, 1150, p. 1155, Fig. 2. Reproduced by permission of Oxford University Press on behalf of the Royal Astronomical Society

Examples of Cosmological Simulations

- Millennium I / II
- Illustris / TNG
- Zoom Simulations
- CLUES/Hestia (constrained simulations)

Fig. by Vogelsberger et al. (2020)



Examples of Cosmological Simulations

- Millennium I / II
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- CLUES/Hestia (constrained simulations)

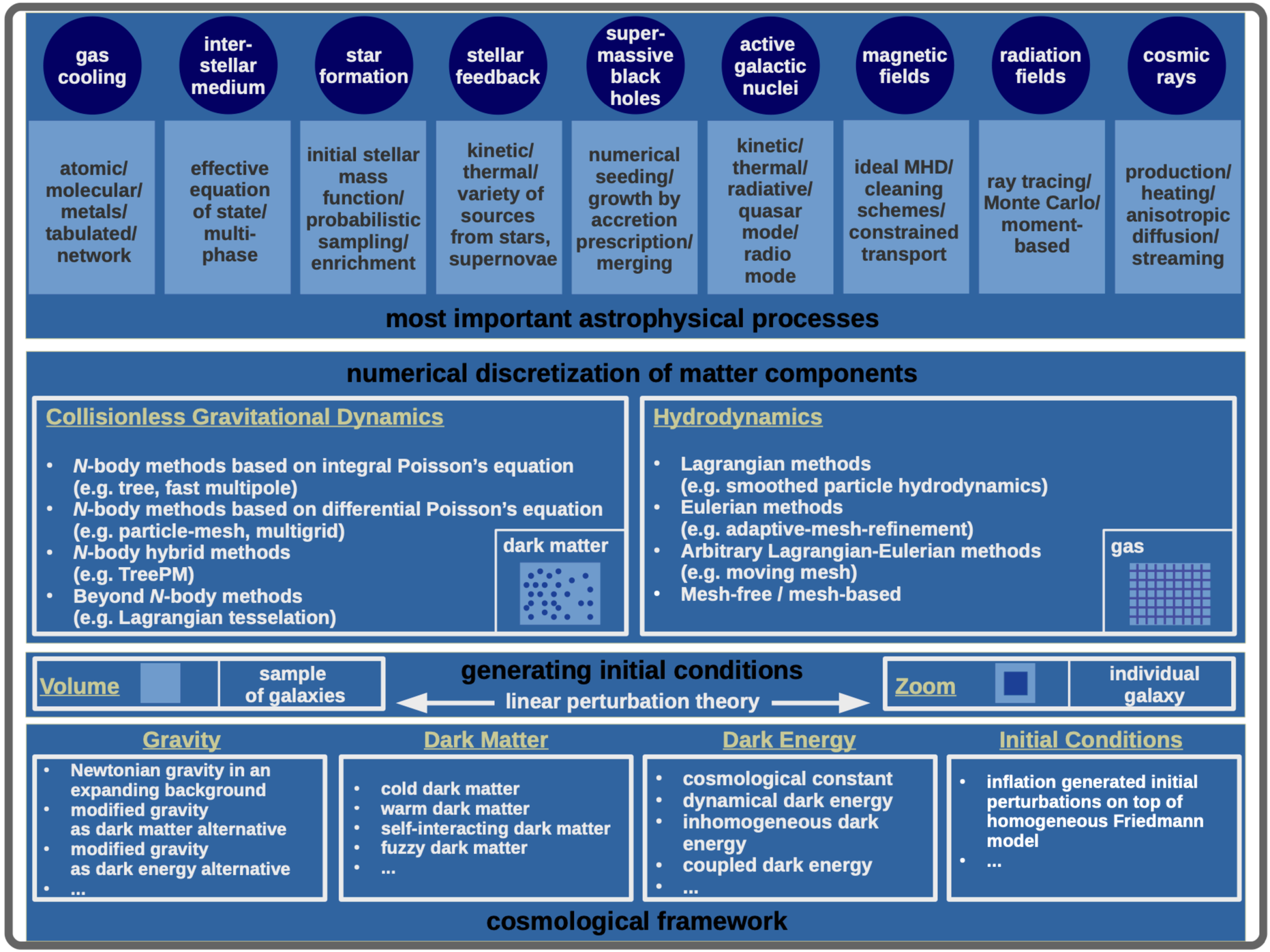
Tab. by Vogelsberger et al. (2020)

Table 2: Recent structure and galaxy formation simulations

simulation	volume	method[a]	mass resolution[b]	spatial resolution[c]	primary reference
	[Mpc^3]		[$M_\odot$]	[kpc]	
dark matter-only					
Millennium	685^3	TreePM	$1.2\times10^9/-$	6.85/–	Springel et al. (2005b)[368]
Millennium-2	137^3	TreePM	$9.4\times10^6/-$	1.37/–	Boylan-Kolchin et al. (2009)[369]
Horizon 4π	2740^3	PM/ML	$7.7\times10^9/-$	10.41/–	Teyssier et al. (2009)[370]
Bolshoi	357^3	PM/ML	$1.9\times10^8/-$	1.43/–	Klypin et al. (2011)[371]
Full Universe Run	29167^3	PM/ML	$1.4\times10^{12}/-$	55.6/–	Alimi et al. (2012)[372]
Millennium-XXL	4110^3	TreePM	$8.5\times10^9/-$	13.7/–	Angulo et al. (2012)[82]
MultiDark	1429^3	PM/ML	$1.2\times10^{10}/-$	10/–	Prada et al. (2012)[373]
Dark Sky	11628^3	Tree/FM	$5.7\times10^{10}/-$	53.49/–	Skillman et al. (2014)[54]
ν^2GC	1647^3	TreePM	$3.2\times10^8/-$	6.28/–	Ishiyama et al. (2015)[374]
Q Continuum	1300^3	TreePM/P^3M	$1.5\times10^8/-$	2.82/–	Heitmann et al. (2015)[84]
OuterRim	4225^3	TreePM/P^3M	$2.6\times10^9/-$	6.0/–	Habib et al. (2016)[46]
EuclidFlagship	20000^3	Tree/FM	$10^9/-$	5/–	Potter et al. (2017)[47]
Aquarius	zoom	TreePM	$1.7\times10^3/-$	0.02/–	Springel et al. (2008)[104]
Via Lactea II	zoom	Tree	$4.1\times10^3/-$	0.04/–	Diemand et al. (2008)[375]
GHALO	zoom	Tree	$1.0\times10^3/-$	0.06/–	Stadel et al. (2009)[376]
CLUES	zoom	TreePM	$3.4\times10^5/-$	0.21/–	Libeskind et al. (2010)[377]
Phoenix	zoom	TreePM	$8.7\times10^5/-$	0.21/–	Gao et al. (2012)[105]
ELVIS	zoom	TreePM	$1.9\times10^5/-$	0.14/–	Garrison-Kimmel et al. (2014)[378]
COCO	zoom	TreePM	$1.6\times10^5/-$	0.33/–	Hellwing et al. (2016)[379]
+ baryons					
Illustris	107^3	TreePM+MMFV	$6.7\times10^6/1.3\times10^6$	1.42/0.71	Vogelsberger et al. (2014)[149]
Horizon-AGN	142^3	PM/ML+AMR	$8.0\times10^7/1.0\times10^7$	1.0/1.0	Dubois et al. (2014)[380]
EAGLE	100^3	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	Schaye et al. (2015)[124]
MassiveBlack-2	143^3	TreePM+SPH	$1.6\times10^7/3.2\times10^6$	2.64/2.64	Khandai et al. (2015)[381]
Bluetides[d]	574^3	TreePM+SPH	$1.7\times10^7/3.4\times10^6$	0.24/0.24	Feng et al. (2016)[382]
Magneticum	68^3	TreePM+SPH	$5.3\times10^7/1.1\times10^7$	1.4/0.7-1.4	Bocquet et al. (2016)[85]
MUFASA	74^3	TreePM+MLFM	$9.6\times10^7/1.8\times10^7$	0.74/0.74	Daveé et al. (2016)[383]
BAHAMAS	571^3	TreePM+SPH	$5.5\times10^9/1.1\times10^9$	0.25/0.25	McCarthy et al. (2017)[384]
Romulus25	25^3	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	Tremmel et al. (2017)[385]
IllustrisTNG[e]	111^3	TreePM+MMFV	$7.5\times10^6/1.4\times10^6$	0.74/0.19	Springel et al. (2018)[87]
Simba[f]	147^3	TreePM+MLFM	$1.4\times10^8/2.7\times10^7$	0.74/0.74	Davé et al. (2019)[182]
Eris	zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	0.12/0.12	Guedes et al. (2011)[349]
VELA	zoom	PM/ML + AMR	$8.3\times10^4/1.9\times10^5$	0.03/0.03[g]	Ceverino et al. (2014)[386]
NIHAO	zoom	Tree+SPH	$3.4\times10^3/6.2\times10^2$	0.12/0.05	Wang et al. (2015)[125]
APOSTLE	zoom	TreePM+SPH	$5.0\times10^4/1.0\times10^4$	0.13/0.13	Sawala et al. (2016)[387]
Latte/FIRE	zoom	TreePM+MLFM	$3.5\times10^4/7.1\times10^3$	0.02/0.001	Wetzel et al. (2016)[352]
Auriga	zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	0.18/0.18[h]	Grand et al. (2017)[297]
MACSIS	zoom	TreePM+SPH	$6.4\times10^9/1.2\times10^9$	5.77/5.77	Barnes et al. (2017)[388]
Cluster-EAGLE	zoom	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	Barnes et al. (2017)[126]
The Three Hundred Project	zoom	TreePM+SPH	$1.9\times10^9/3.5\times10^8$	9.59/9.59	Cui et al. (2018)[389]
FABLE	zoom	TreePM+MMFV	$8.1\times10^7/1.5\times10^7$	4.15/4.15	Henden et al. (2018)[390]
RomulusC	zoom	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	Tremmel et al. (2019)[391]

Modern Simulations

- Vogelsberger et al. (2020)
- Many different aspects consider e.g. baryonic processes.



Identification of Dark Matter Halos in Simulations

Simulation in its simplest form only provides position and velocity coordinates of dark matter particles. Need to identify dark matter halos to measure their individual properties and determine statistical distributions.

Different algorithms exist. Two main categories:

- Bound particles: based on positions and velocities, identify all particles that are gravitationally bound to the same over-density.
- Friends-of-friends: identify all particles with separation < some fraction *b* of the mean particle separation (*b* ~ 0.2 → characteristic density ~200 critical density).

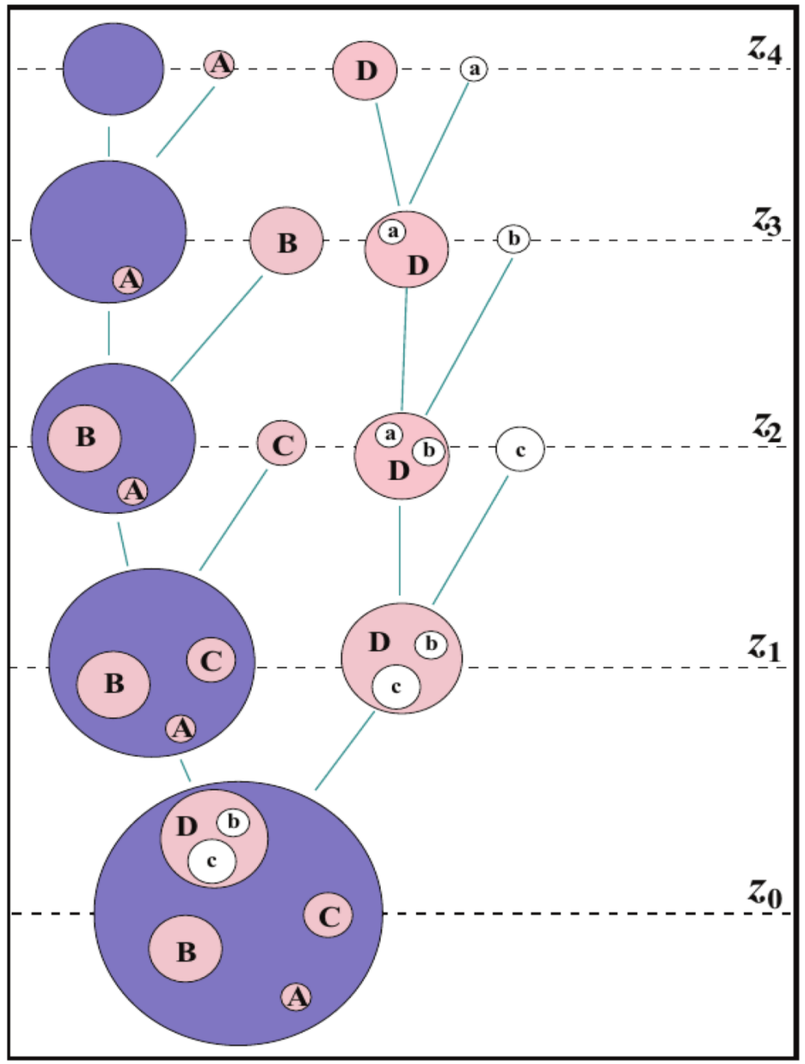
Properties of Dark Matter Halos

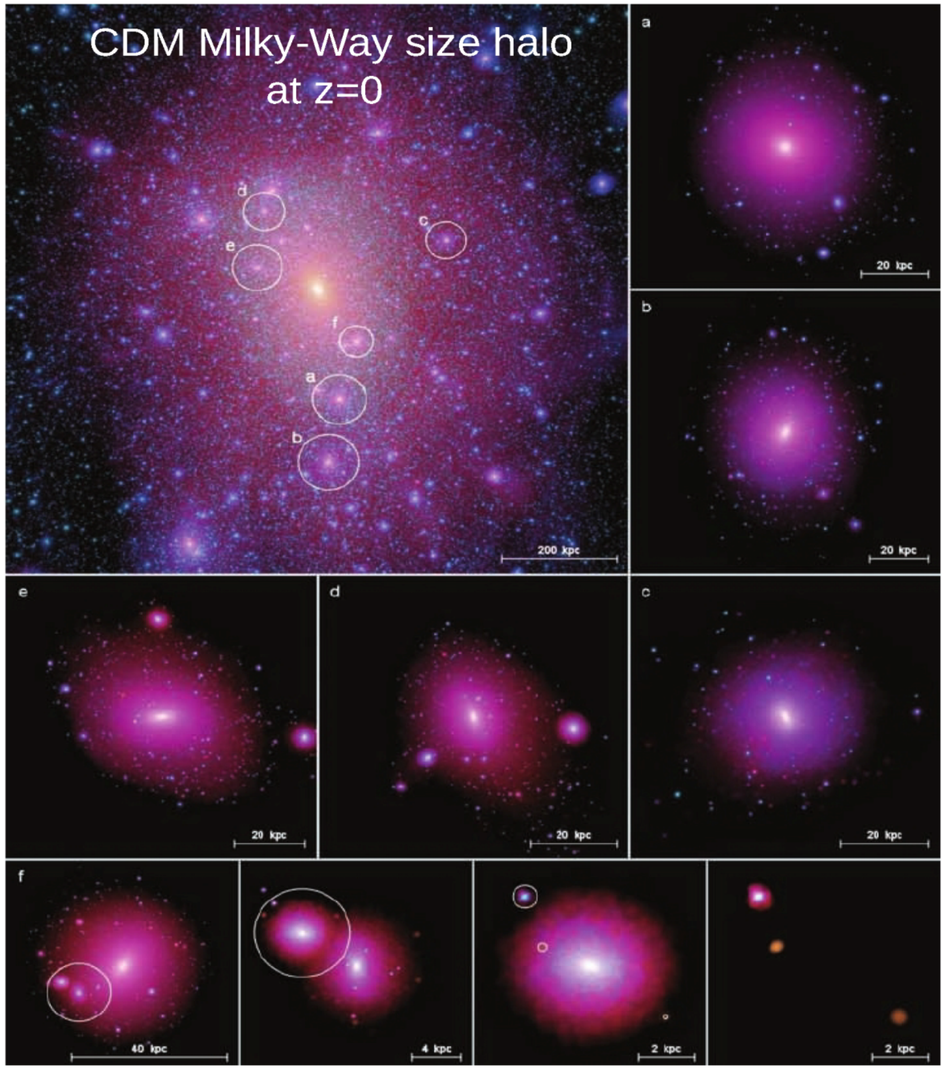
- The density profile of halos averaged over spherical shells seems to have a universal functional form:
- NFW profile (Navarro, Frenk & White 1996): $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

  r_s: characteristic radius, where slope of profile changes from $\rho \propto r^{-1}$ to $\rho \propto r^{-3}$.
- Implies high-density cusp of dark matter in the center.
- Many other halo profile fitting functions exist, e.g. Einasto profile, some of which provide a better match to simulations.

Subhalos and Hierarchical Merging

"Merger Tree"





Three tests:

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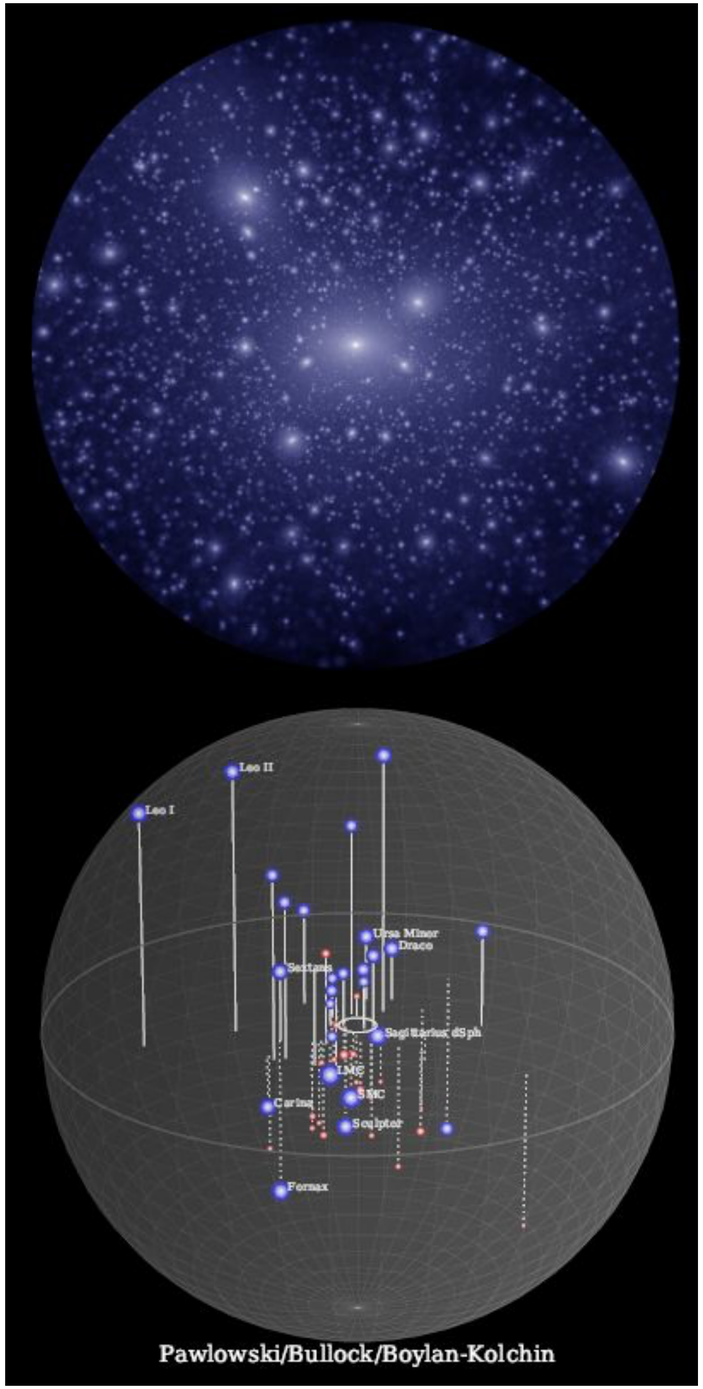
The Missing Satellite Galaxies Problem

Observation (1999): only 11 luminous satellite galaxies around the Milky Way.

Dark Matter Simulations: hundreds of dark matter subhalos of comparable mass.



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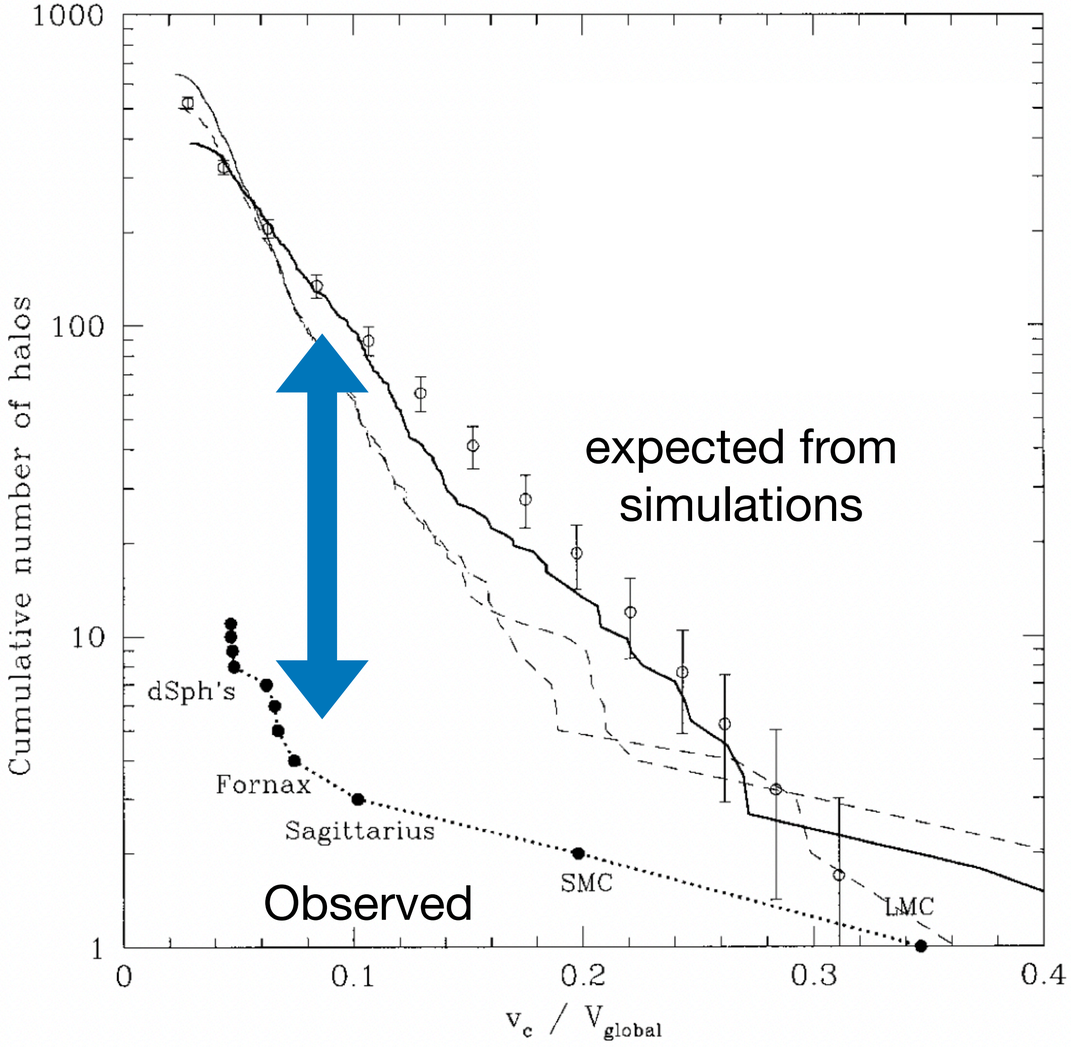
- Moore et al. (1999): »Dark Matter Substructure within Galactic Halos« The Astrophysical Journal, 524, L19.
- Klypin et al. (1999): »Where are the Missing Galactic Satellites?«, The Astrophysical Journal, 522, 82.



Possible Solutions to the Missing Satellites Problem

1. We did not yet **find all satellite galaxies**.
2. Many dark matter subhalos **do not contain a luminous galaxy**.
3. There are indeed less sub halos then predicted.
   → The **cold dark matter model is wrong**.

Testing Cosmological Expectations with Satellite Galaxy Systems

Duhem-Quine Thesis: unambiguous falsifications of scientific hypotheses impossible because empirical tests require background assumptions
→ the blame can be placed on one of these "auxiliary" hypotheses.

Testing Cosmological Expectations with Satellite Galaxy Systems

- Predictions on galaxy scales via numerical simulations involve

Underlying ΛCDM Model + **Implementation of Baryonic Physics**

- Found a mismatch between observation and expectation?
  → ΛCDM ruled out! 😱 Or maybe just due to incorrectly approximated physics? 🤔

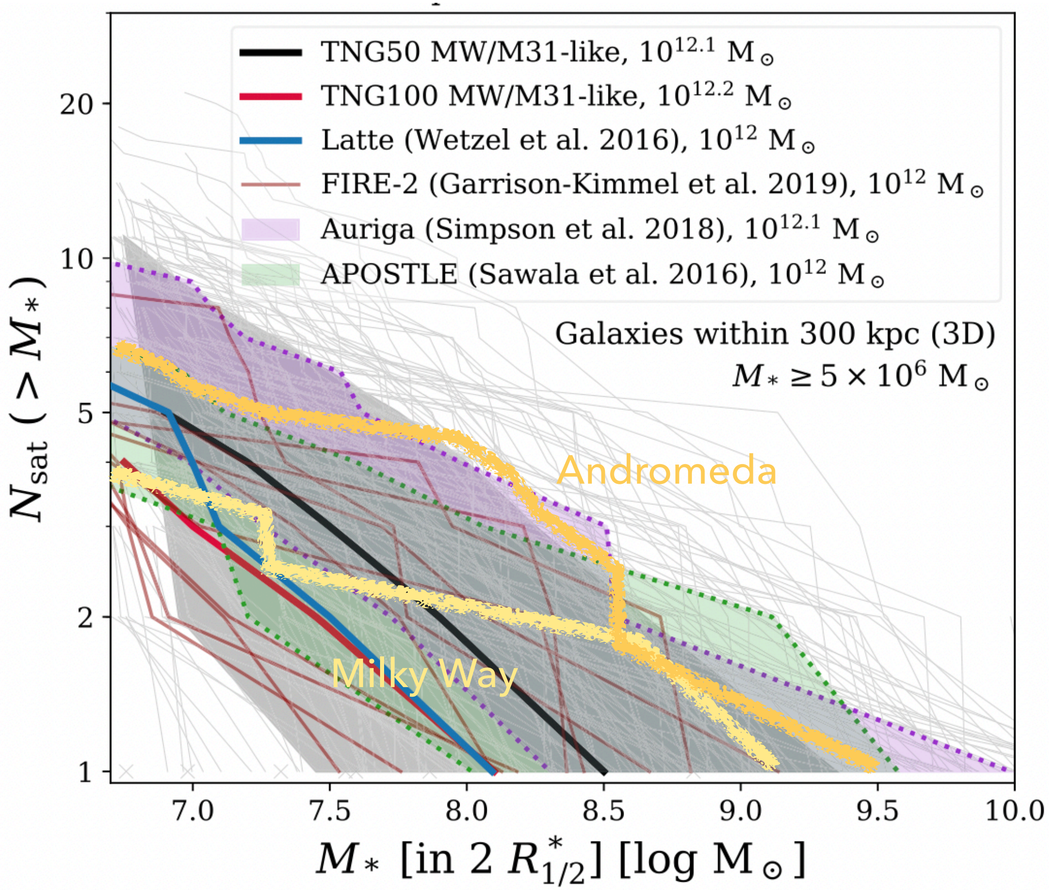
Need to consider to what degree predictions might be affected by details of baryonic physics.

Likely Solution: Baryonic Physics

- Better than counting: compare **satellite galaxy luminosity function** with simulation expectations.
- Modern simulations account for **baryonic effects which can prevent subhalos from forming stars,** i.e. dark matter subhalos do not all host a luminous galaxy.
- Simulations generally agree with each other and with number of satellites in Local Group.

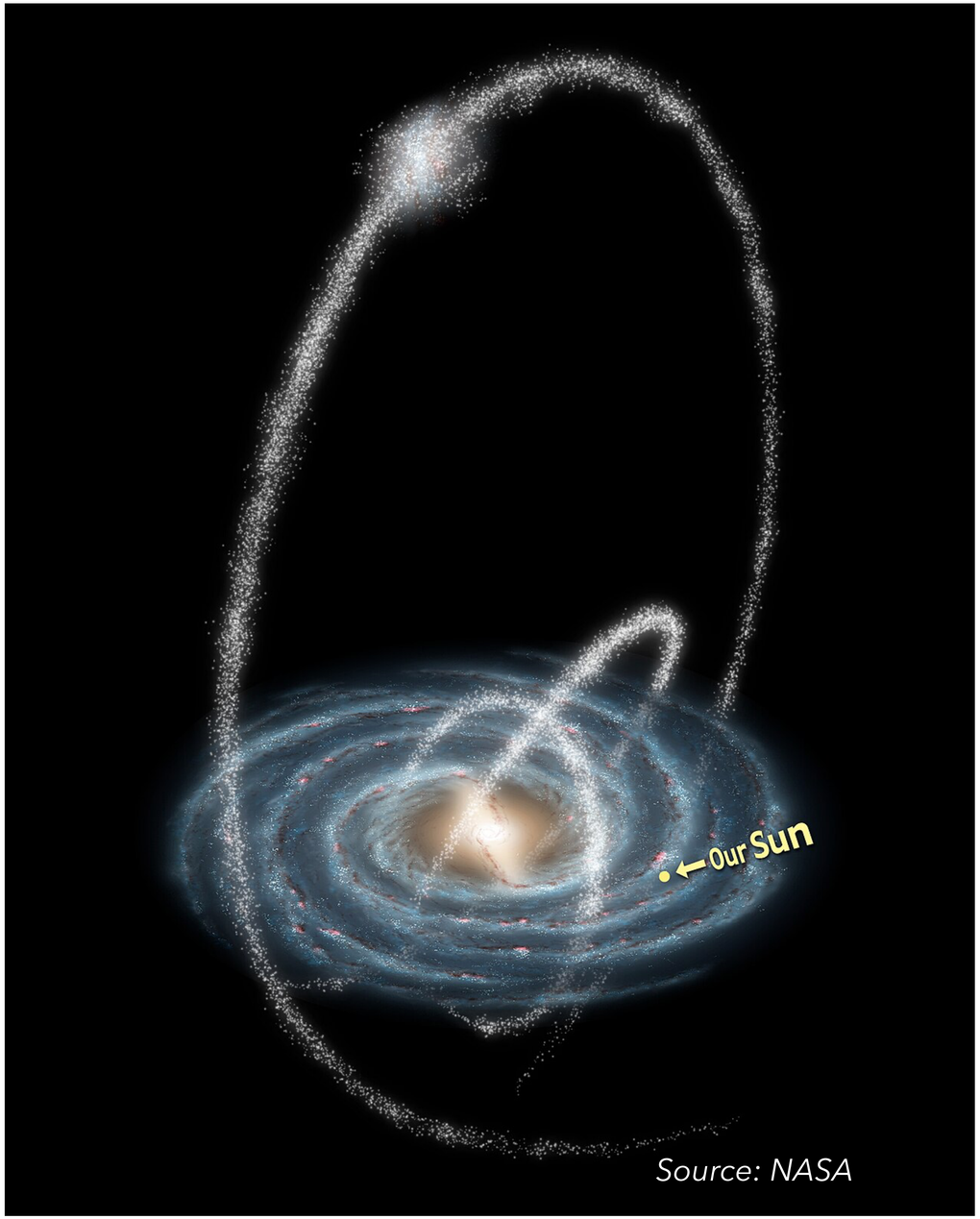
➡ **Missing Satellites Problem solved! (?)**

Stellar mass functions from various simulation (Engler et al. 2021)



Not all subhalos contain a luminous galaxy

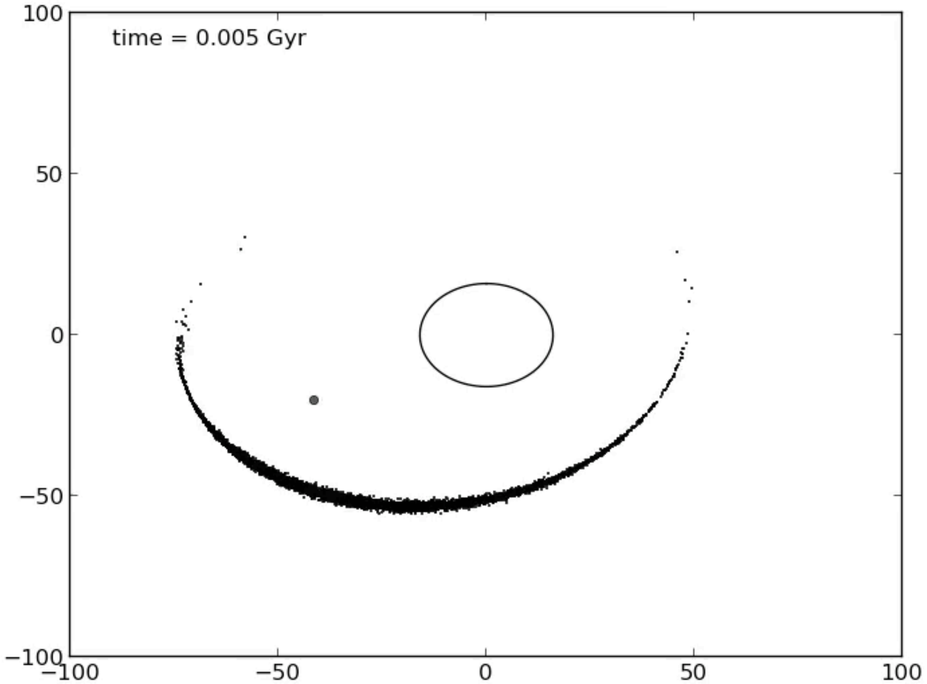
- **Prediction of this solutiono:** there are purely dark subhalos.
- Clear proof of such an object would strongly support validity of cold dark matter model.
- **Possible evidence:** Gaps in stellar streams.



Source: NASA

Not all subhalos contain a luminous galaxy

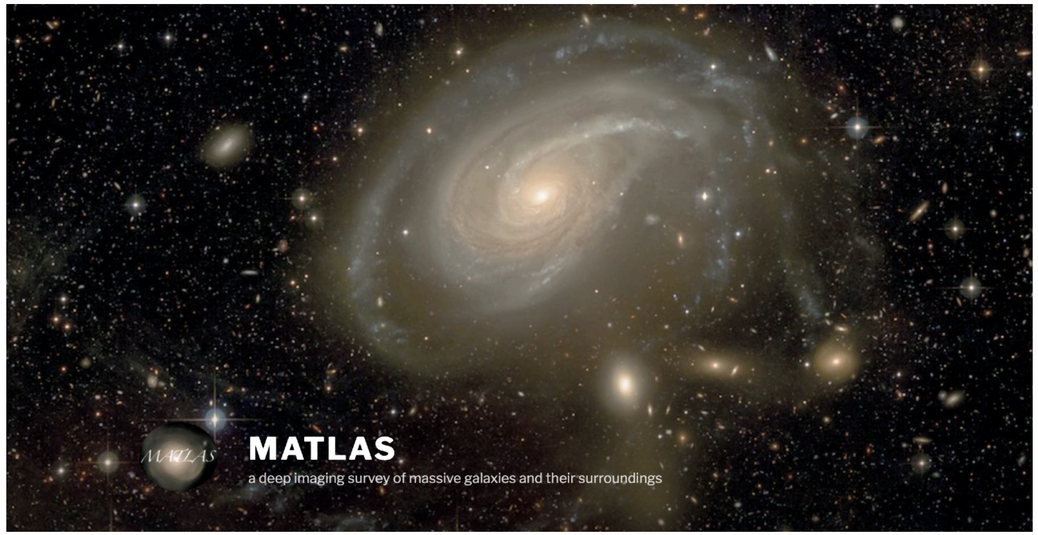
- **Prediction of this solutiono:** there are purely dark subhalos.
- Clear proof of such an object would strongly support validity of cold dark matter model.
- **Possible evidence:** Gaps in stellar streams.
- But complications: e.g. luminous satellites and GCs, as well as MW bar and giant molecular clouds can have a similar effect.



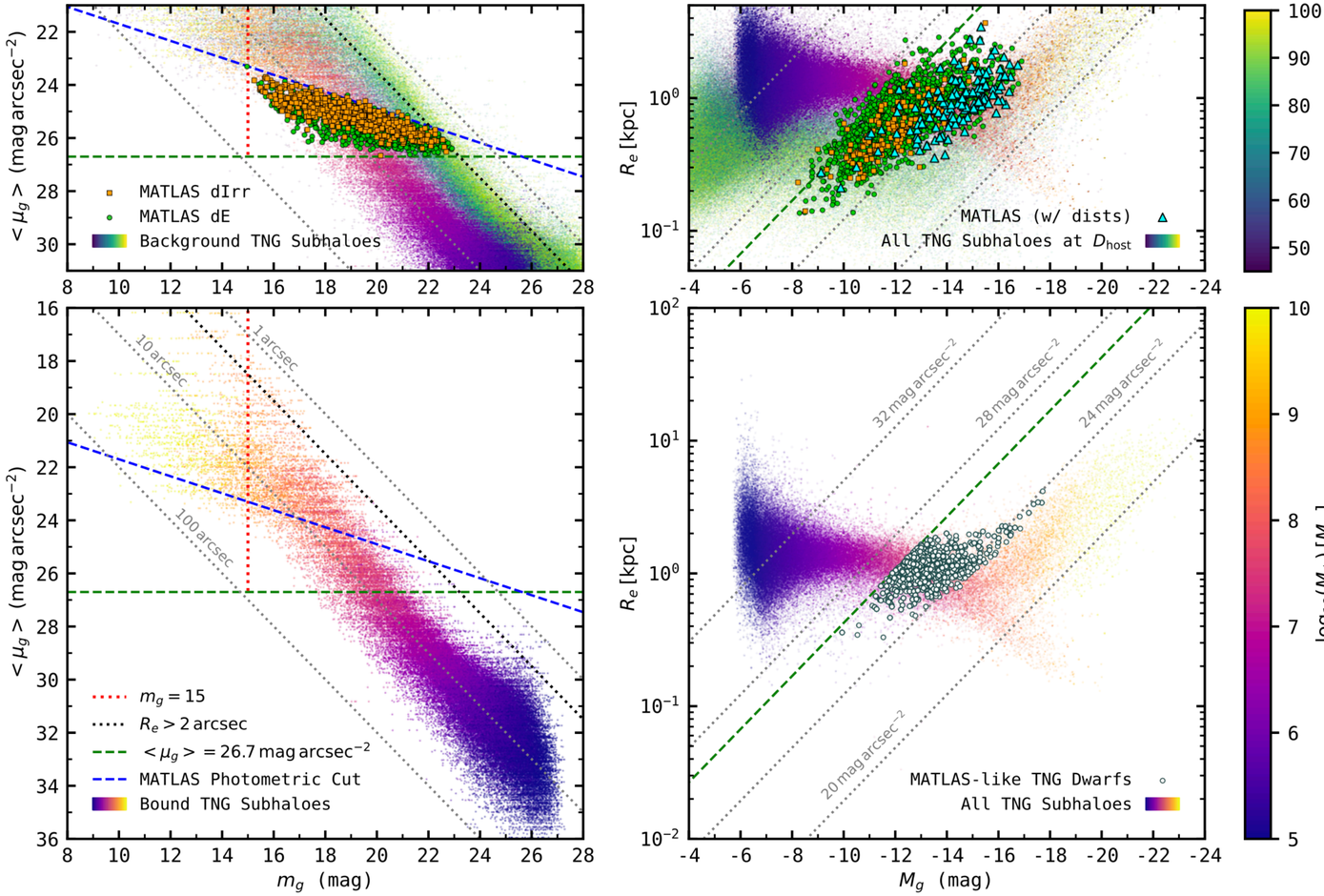
Source: A. Helmi, video at https://www.astro.rug.nl/~ahelmi/dev/videos.php

A too-many-satellites problem?

MATLAS fields: 48 fields around isolated galaxies.
We "mock-observe" TNG50 to find analogs for comparison.
→ ***6σ discrepancy*** in dwarf galaxy counts!



Kanehisa, K. J., et al.: A&A, 686, A280 (2024)



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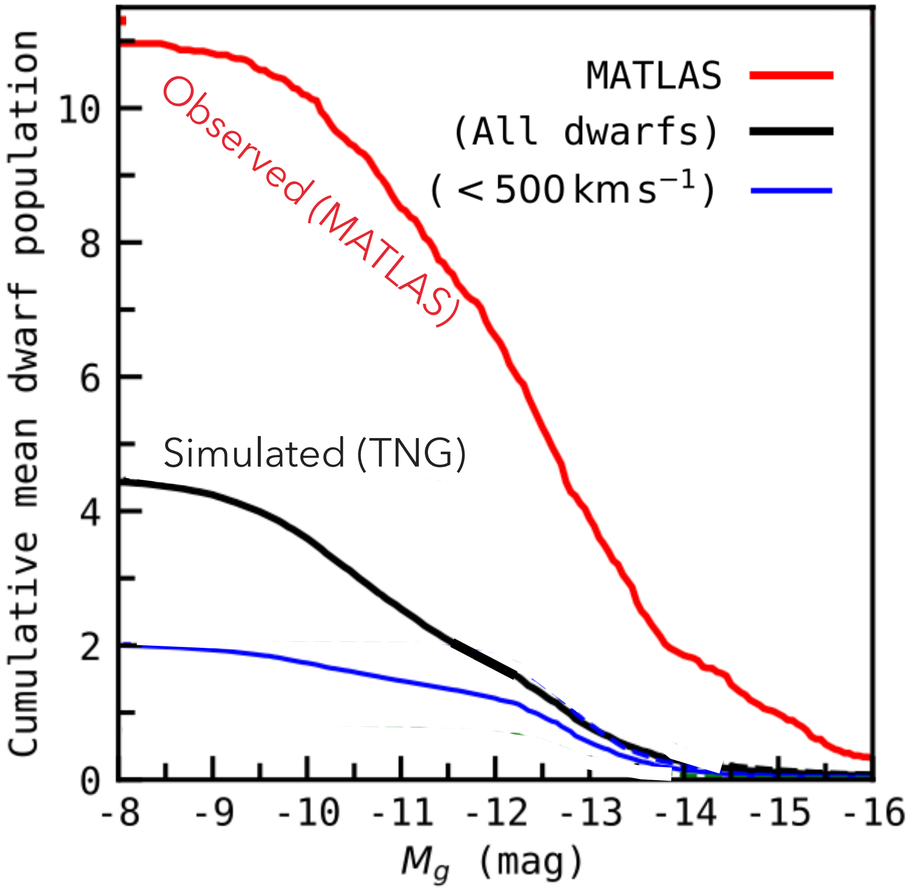
Did we focus too much on the Local Group?
Let's look at some other systems:

MATLAS (Kanehisa, Pawlowski et al. 2024)



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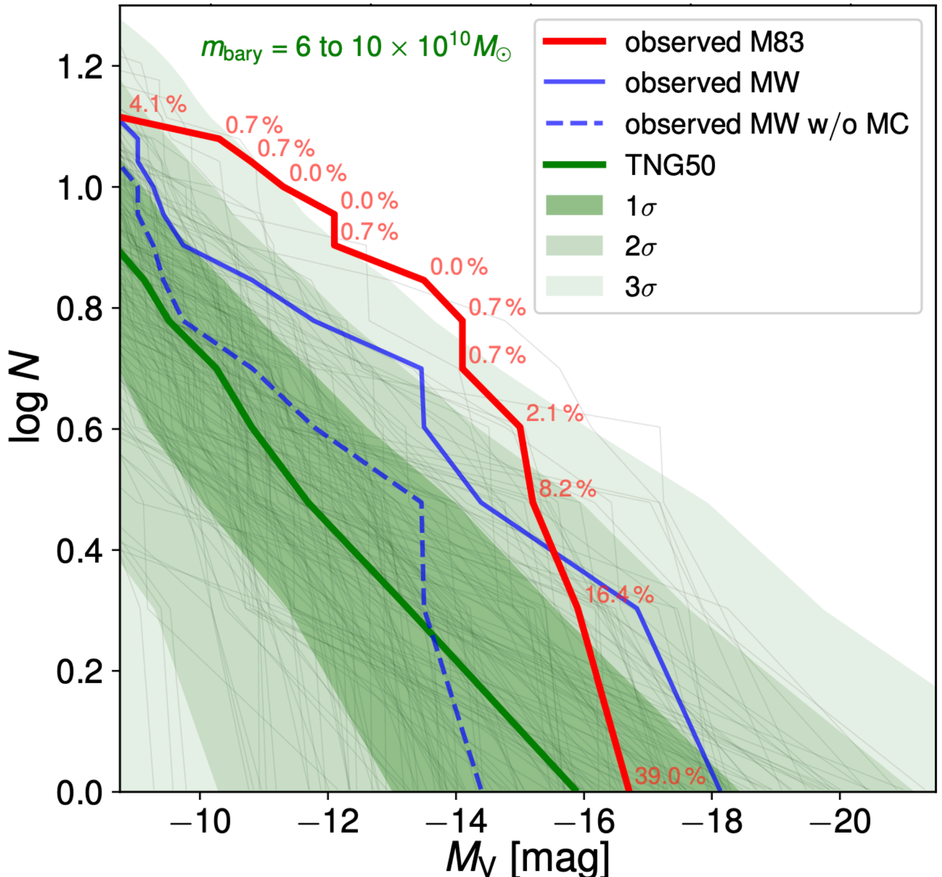
- **M83:** one specific galaxy of MW mass where we find too many satellites: 3-5 σ discrepancy

M83 (Müller, Pawlowski et al. 2024)



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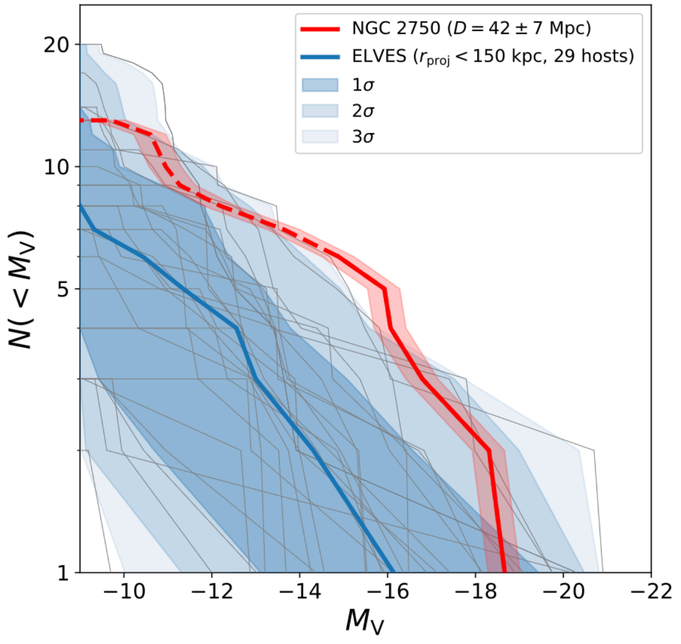
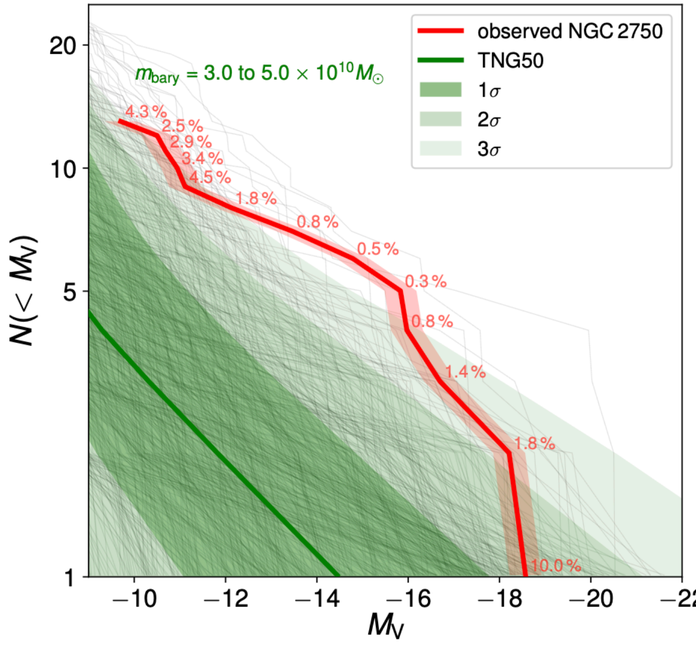
- **NGC 2750:** also shows an excess of bright satellites.

NGC 2750 (Taibi, Pawlowski et al. 2025)





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- **NGC 2750:** also shows an excess of bright satellites.

Need to be cautious when assessing apparent solutions: might be tailored to the Local Group.

Three tests:

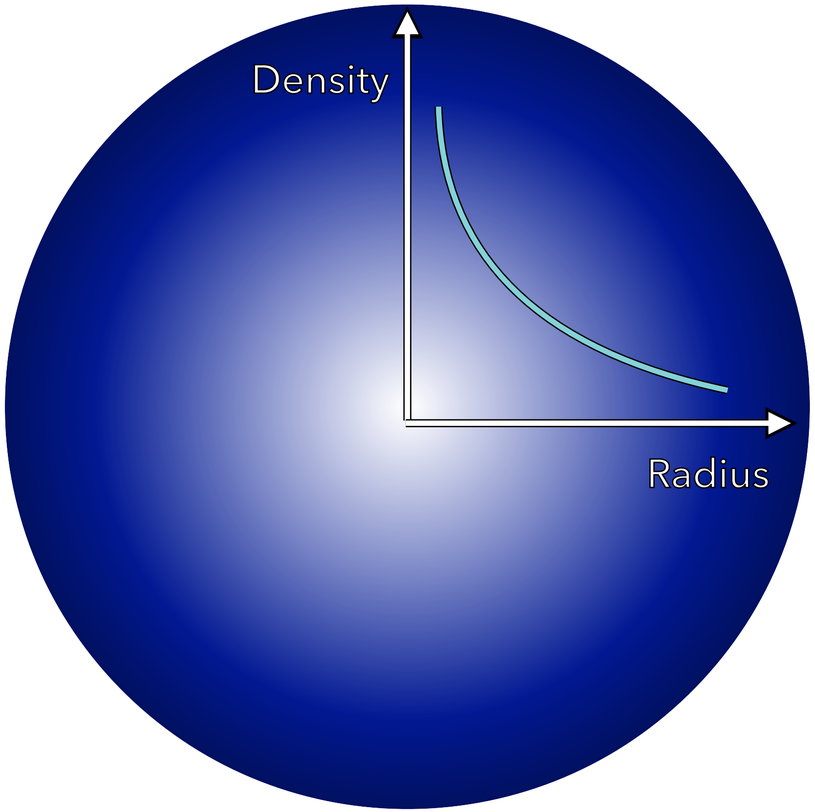
- How many satellite galaxies are there?
- How does dark matter distribute in dwarf galaxies?
- How do satellites distribute and move around hosts?

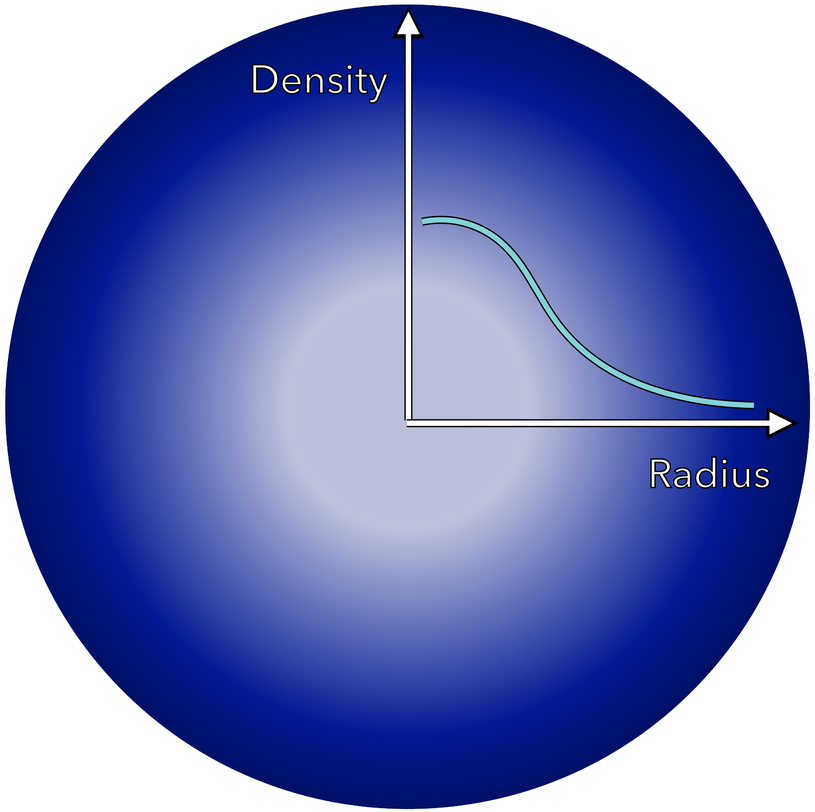
Distribution of Dark Matter in Dwarf Galaxies: too little DM in center

- Simulations predict NFW profile $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

Prediction: central density peak in dark matter halos

Observation: Core of constant density in center off many galaxies





Cusp-Core Problem

- Dark Matter simulations predict a high-density "cusp" of dark matter in the center of a halo.
- Some observed galaxies instead show rotation curves that rise more slowly, indicating a close-to constant density "core" of dark matter in their centers.

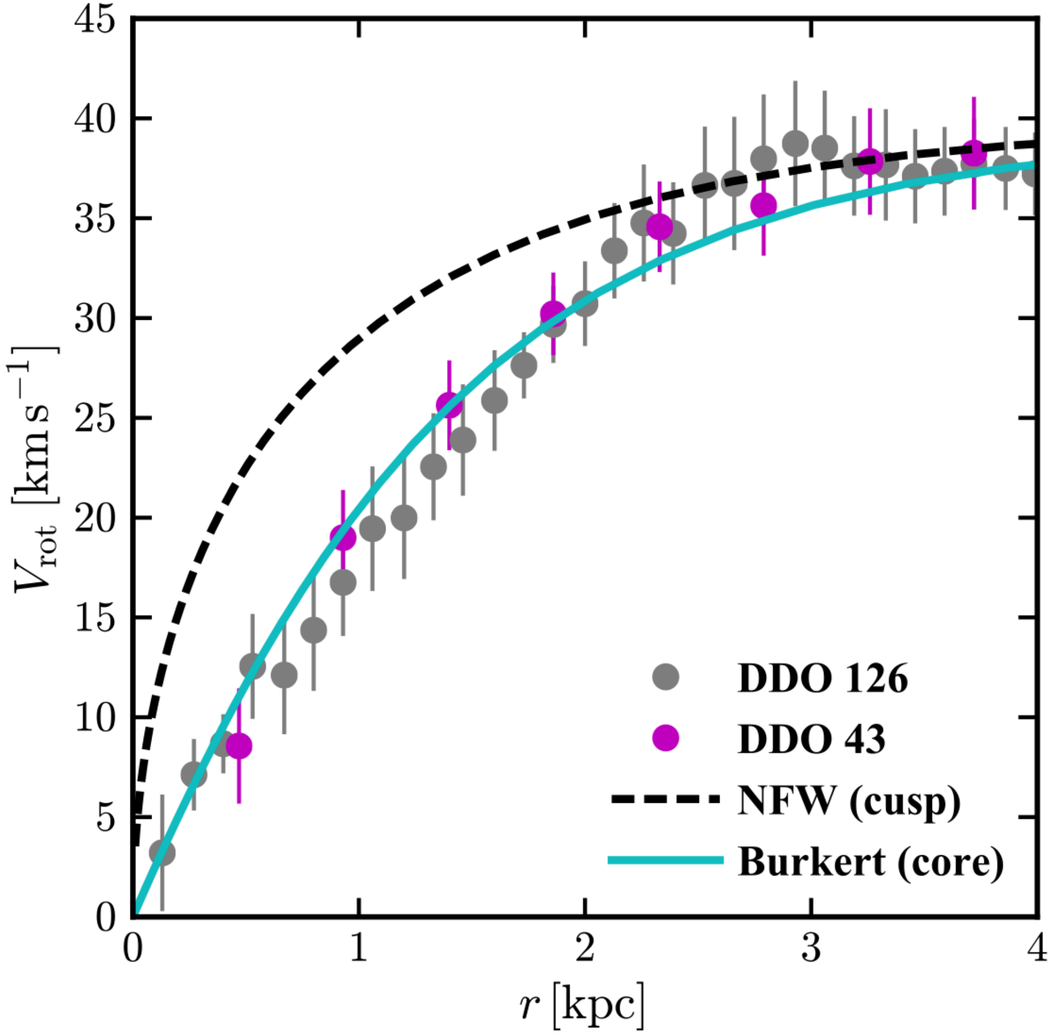


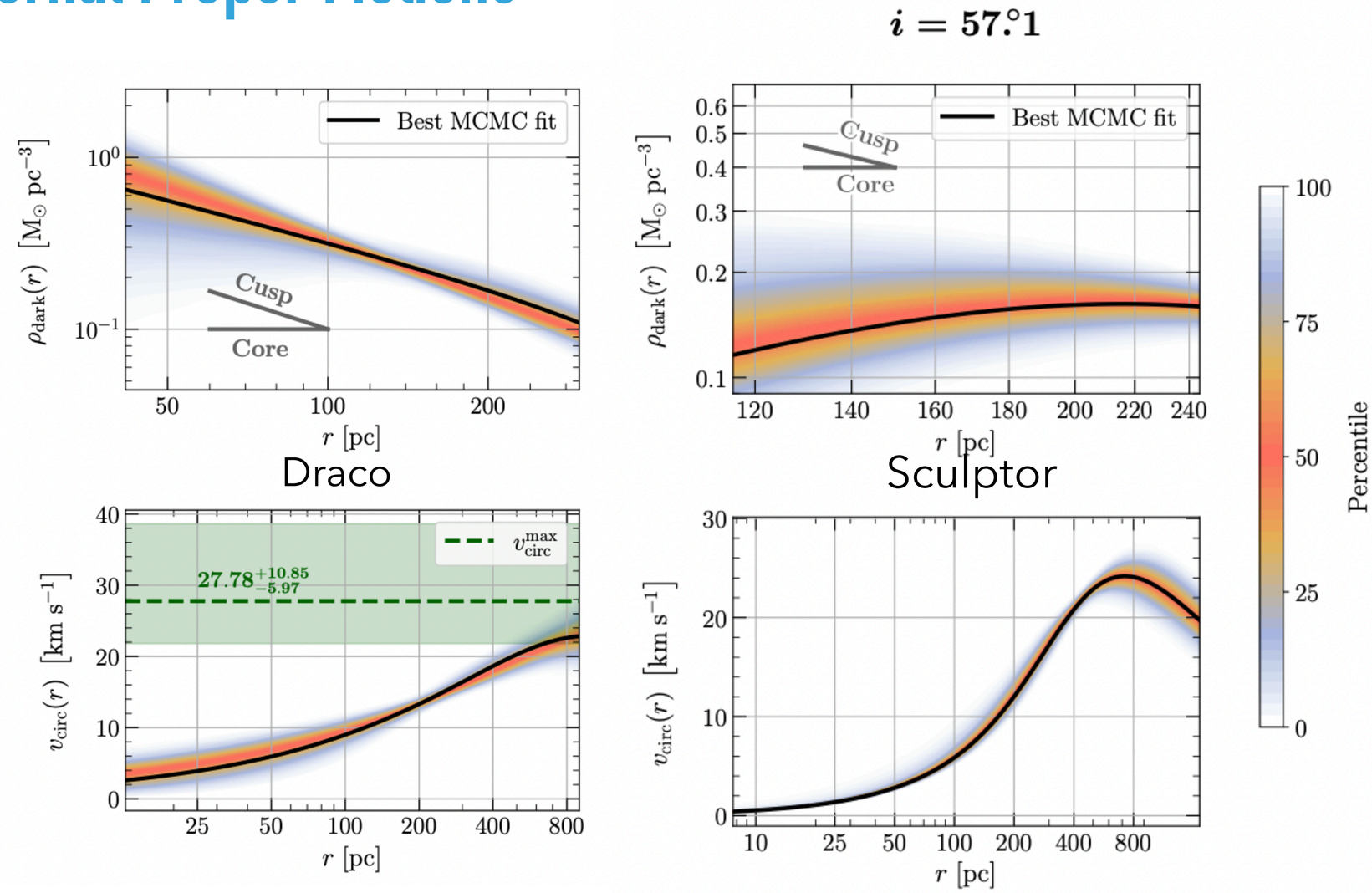
Figure 9

The Cusp-Core problem. The dashed line shows the naive ΛCDM expectation (NFW, from dark-matter-only simulations) for a typical rotation curve of a $V_{\rm max} \approx 40\,{\rm km\,s^{-1}}$ galaxy. This rotation curve rises quickly, reflecting a central density profile that rises as a cusp with $\rho \propto 1/r$. The data points show the rotation curves of two example galaxies of this size from the LITTLE THINGS survey (Oh et al. 2015)), which are more slowly rising and better fit by a density profil with a constant density core (Burkert 1995, cyan line).

Bullock & Boylan-Kolchin (2017)

Cusp-Core Problem With Internal Proper Motions

- Left: inferred density profile and circular velocity of the Draco dwarf galaxy (Vitral et al. 2024).
- Right: inferred density profile and circular velocity of the Sculptor dwarf galaxy (Vitral et al. 2025).



Bullock & Boylan-Kolchin (2017)

Too-Big-To-Fail Problem

- One would expect that the most massive dark subhaloes contain the most luminous satellite galaxies.
- However, the most luminous observed MW satellites seem to live in lower-density dark matter halos than expected from simulations of MW-like hosts.

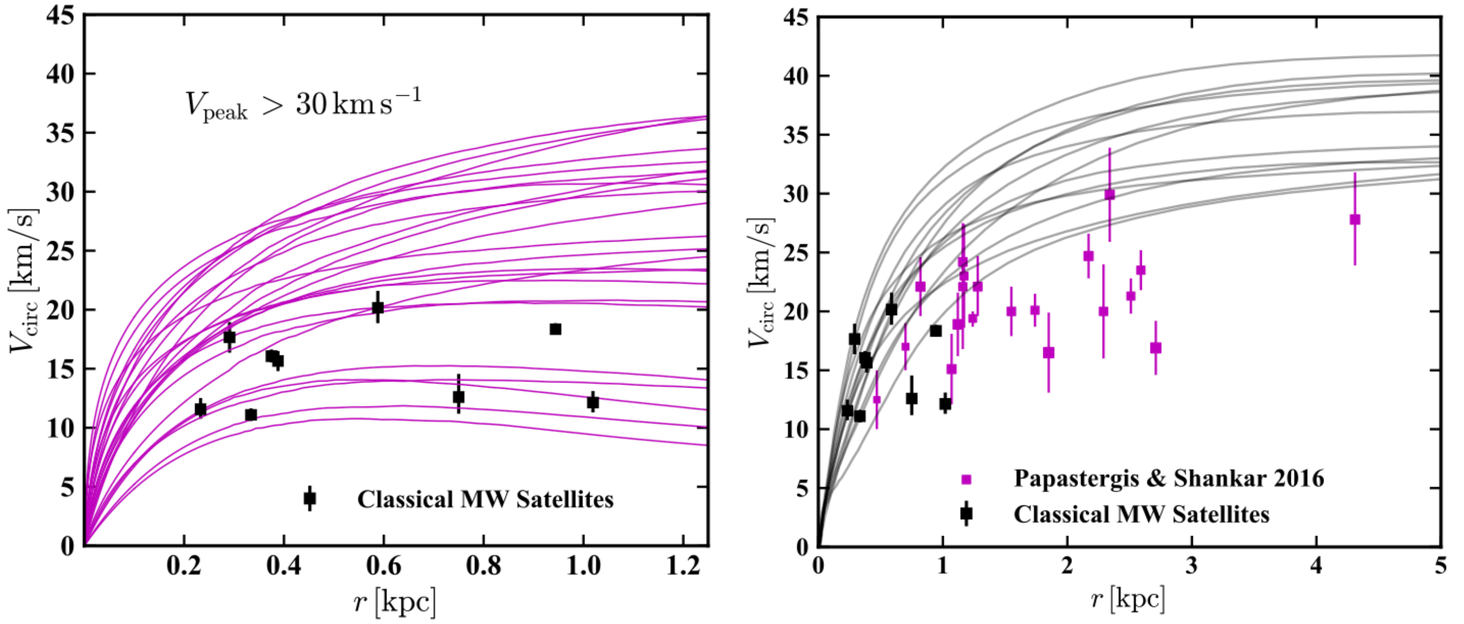


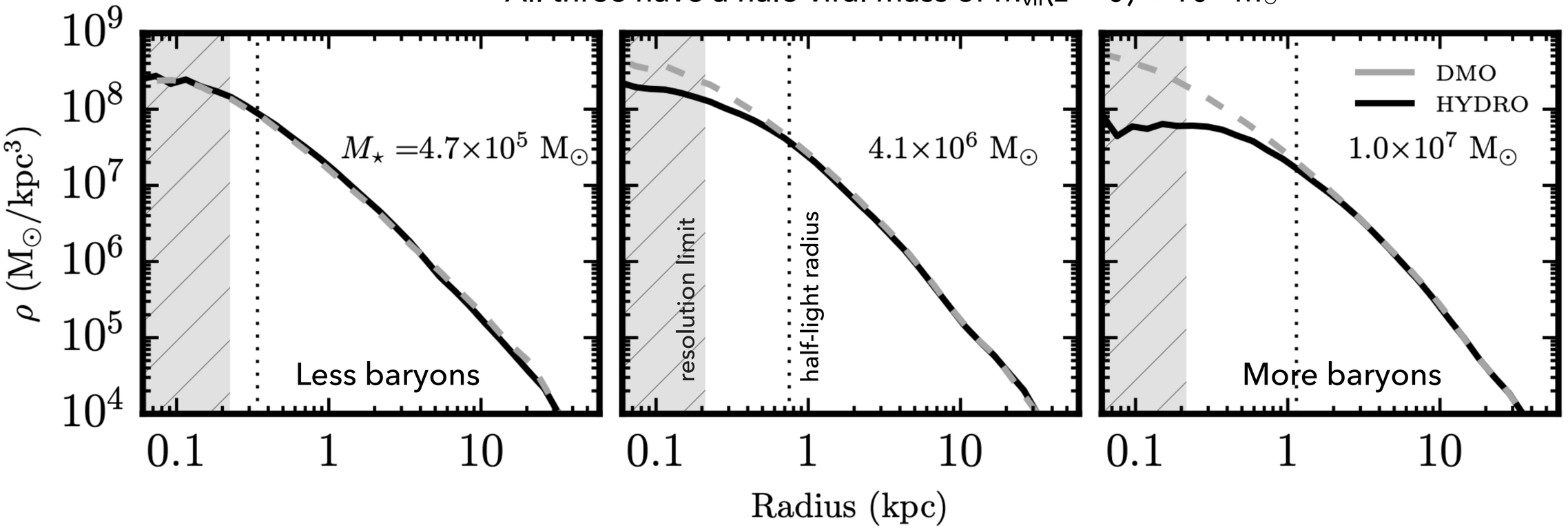
Figure 10

The Too-Big-to-Fail Problem. *Left:* Data points show the circular velocities of classical Milky Way satellite galaxies with $M_\star \simeq 10^{5-7} M_\odot$ measured at their half-light radii $r_{1/2}$. The magenta lines show the circular velocity curves of subhalos from one of the (dark matter only) Aquarius simulations. These are specifically the subhalos of a Milky Way-size host that have peak maximum circular velocities $V_{\rm max} > 30\,{\rm km\,s^{-1}}$ at some point in their histories. Halos that are this massive are likely resistant to strong star formation suppression by reionization and thus naively too big to have failed to form stars (modified from Boylan-Kolchin, Bullock & Kaplinghat 2012). The existence of a large population of such satellites with greater central masses than any of the Milky Way's dwarf spheroidals is the original Too-Big-to-Fail problem. *Right:* The same problem – a mismatch between central masses of simulated dark matter systems and observed galaxies – persists for field dwarfs (magenta points), indicating it is not a satellite-specific process (modified from Papastergis & Ponomareva 2017). The field galaxies shown all have stellar masses in the range $5.75 \leq \log_{10}(M_\star/M_\odot) \leq 7.5$. The gray curves are predictions for ΛCDM halos from the fully self-consistent hydrodynamic simulations of Fitts et al. (2016) that span the same stellar mass range in the simulations as the observed galaxies.

Bullock & Boylan-Kolchin (2017)

Resolving the Core–Cusp Problem: Baryonic Feedback Affecting Inner DM Slope

All three have a halo viral mass of $M_{vir}(z = 0) \approx 10^{10} M_\odot$



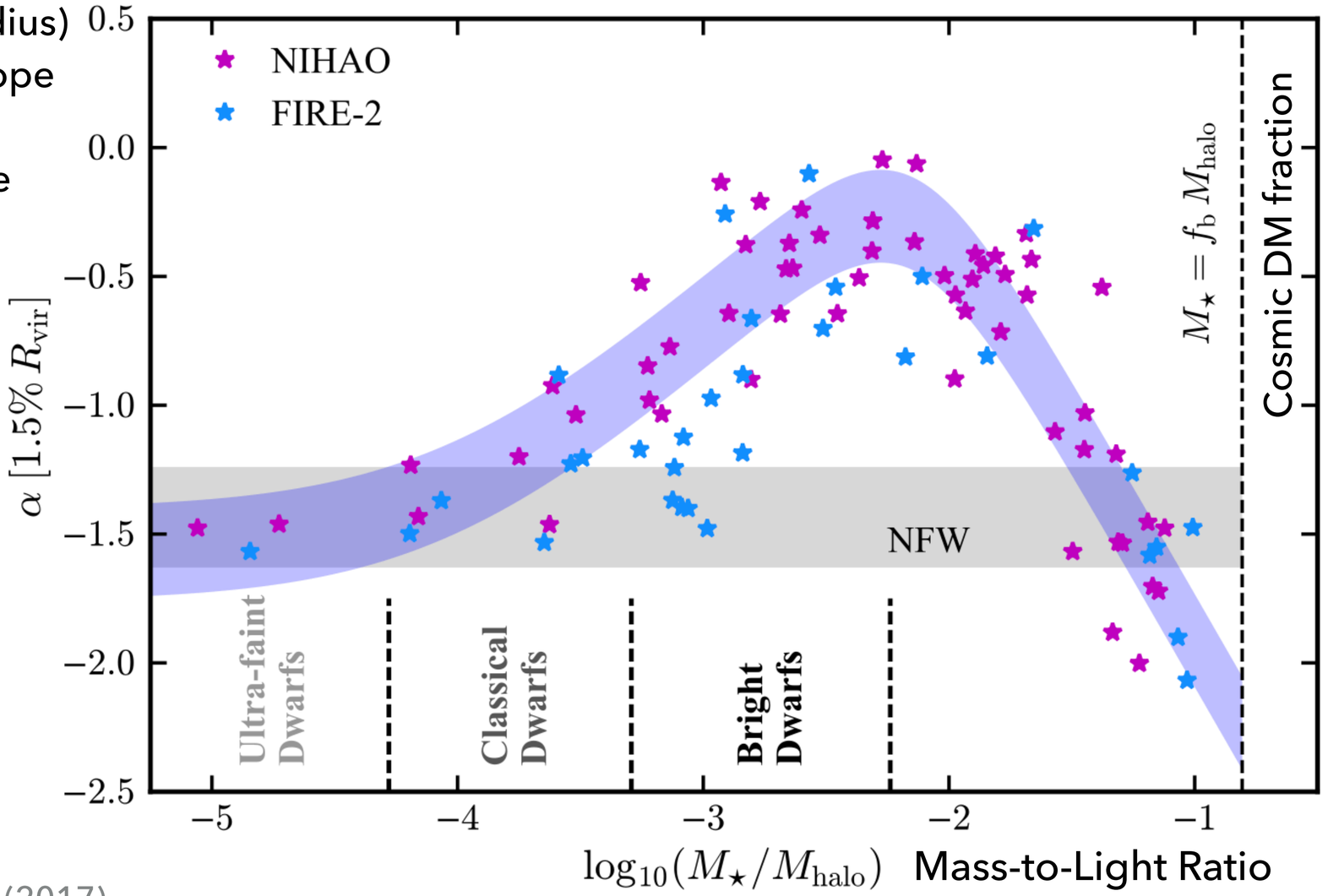
Bullock & Boylan-Kolchin (2017)

Resolving the Core–Cusp Problem: Baryonic Feedback Affecting Inner DM Slope

Inner (1.5% or viral radius) dark matter density slope

α ≈ 0: dark matter core

α < -0.8: cusp



Expected range from dark-matter-only simulations

Bullock & Boylan-Kolchin (2017)

Possible Solutions by (Small) Modifications to Nature of DM

- Baryonic physics might solve many problems, but another possibility is that maybe dark matter is not “cold” but “warm”, or “self-interacting”.
- Can help solve e.g. missing satellites or core-cusp problems.
- Tailored to not affect large-scale structure, but also does not address satellite planes problem.

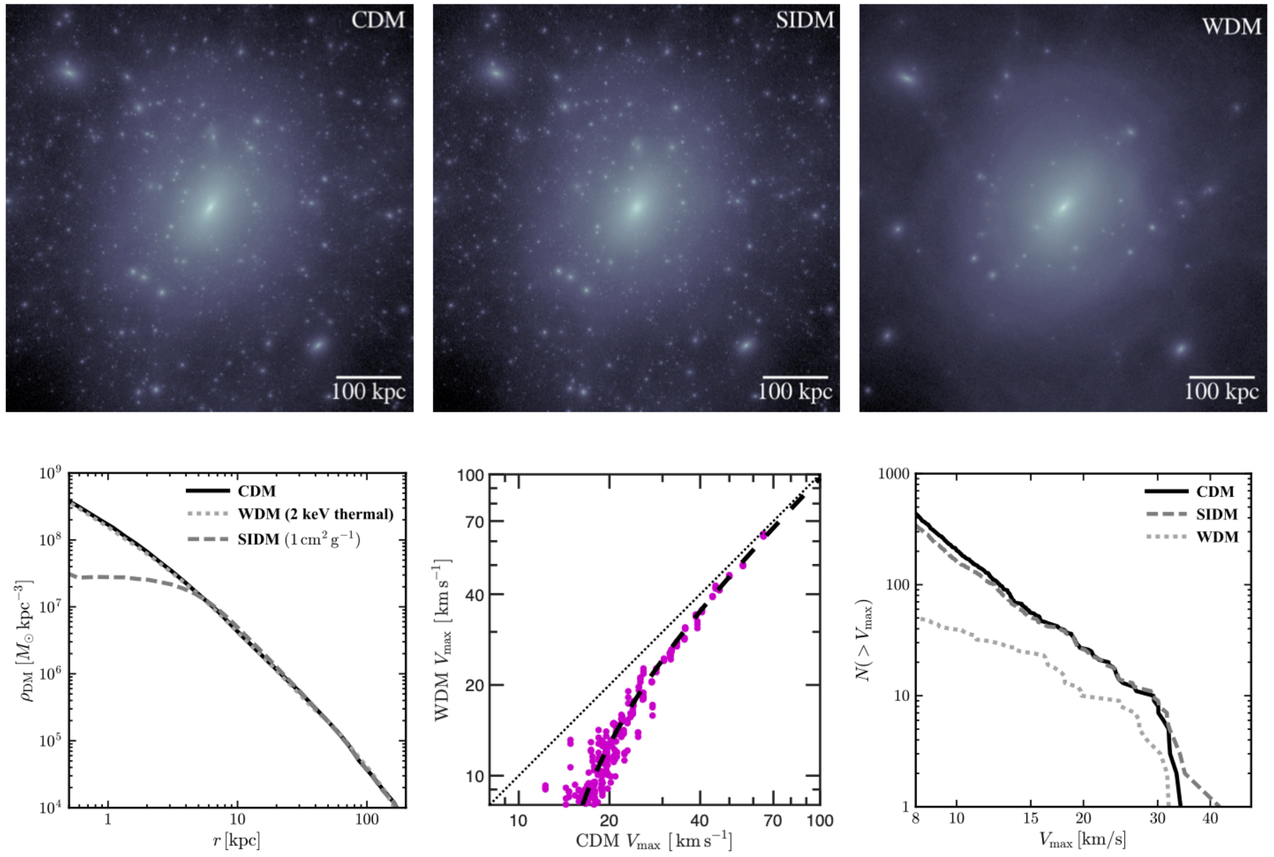


Figure 15

Dark matter phenomenology in the halo of the Milky Way. The three images in the upper row show the same Milky-Way-size dark matter halo simulated with CDM, SIDM ($\sigma/m = 1$ cm^2/g), and WDM (a Shi-Fuller resonant model with a thermal equivalent mass of 2 keV). The left panel in the bottom row shows the dark matter density profiles of the same three halos while the bottom-right panel shows the subhalo velocity functions for each as well. The middle panel on the bottom shows that while the host halos have virtually identical density structure in WDM and CDM, individual subhalos identified in both simulations smaller $V_{\rm max}$ values in WDM (Bozek et al. 2016). This effect can explain the bulk of the differences seen in the $V_{\rm max}$ functions (bottom right panel). Note that SIDM does not reduce the abundance of substructure (unless the power spectrum is truncated) but it does naturally produce large constant-density cores in the dark matter distribution. WDM does not produce large constant-density cores at Milky Way-mass scales but does result in fewer subhalos near the free-streaming mass and reduces $V_{\rm max}$ of a given subhalo (through reduced concentration) near the half-mode mass ($M_{\rm halo} \lesssim 10^{10}\,M_\odot$ for the plotted 2 keV thermal equivalent model).

Bullock & Boylan-Kolchin (2017)

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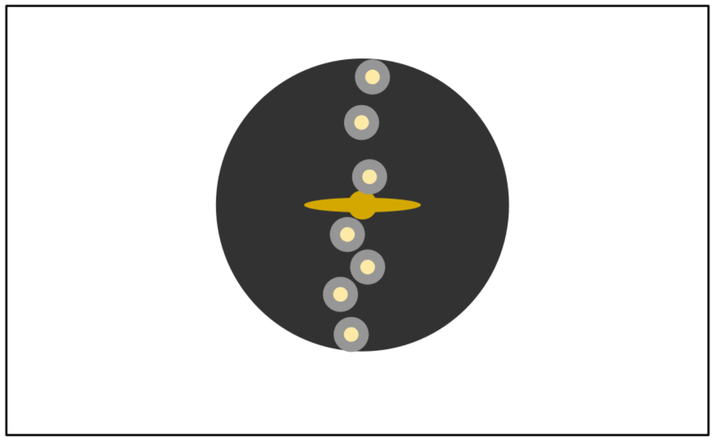
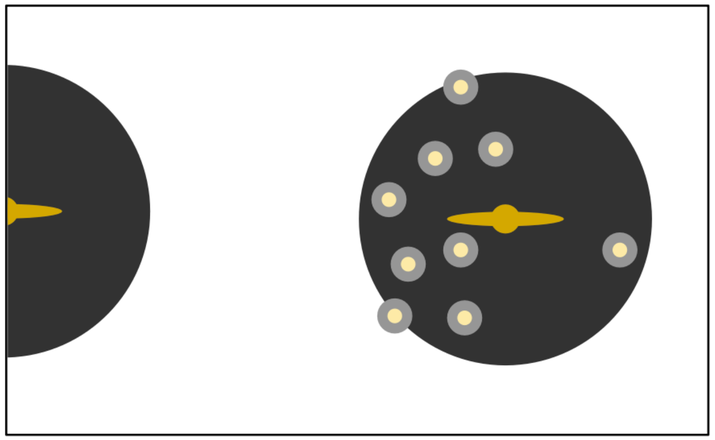
Phase-Space Pecularities in Satellite Galaxy Systems

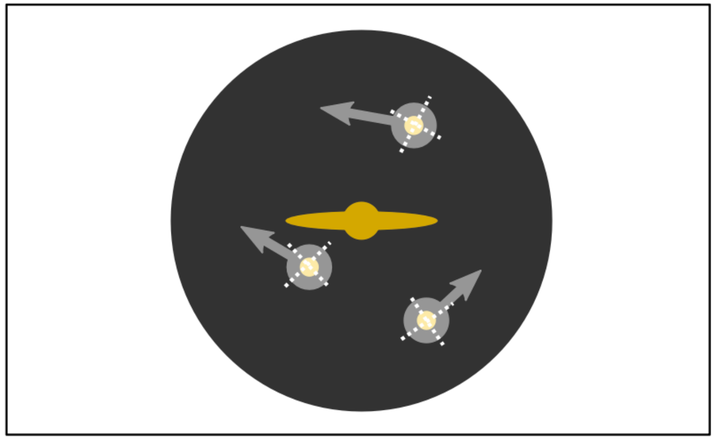
Plane of Satellites



Lopsidedness

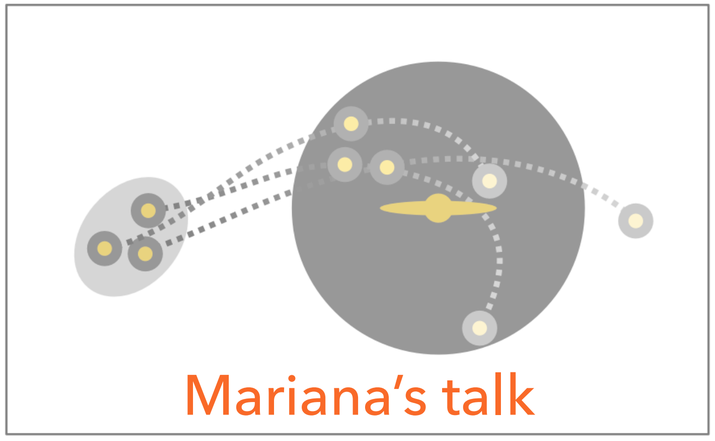


Tangential Velocity Excess

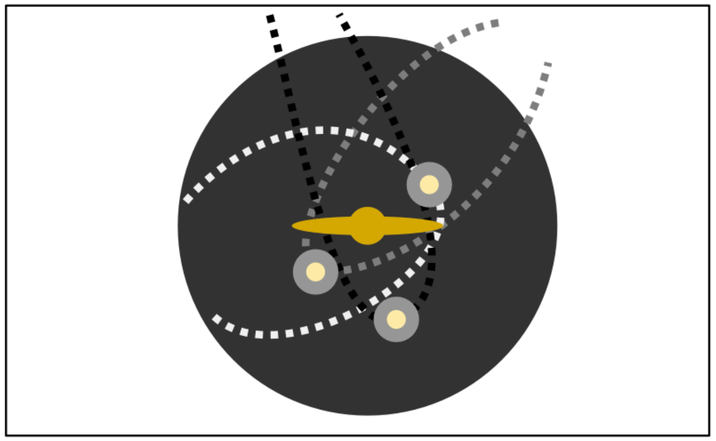


Satellite Pairs

Group Infall



Pericenter Excess

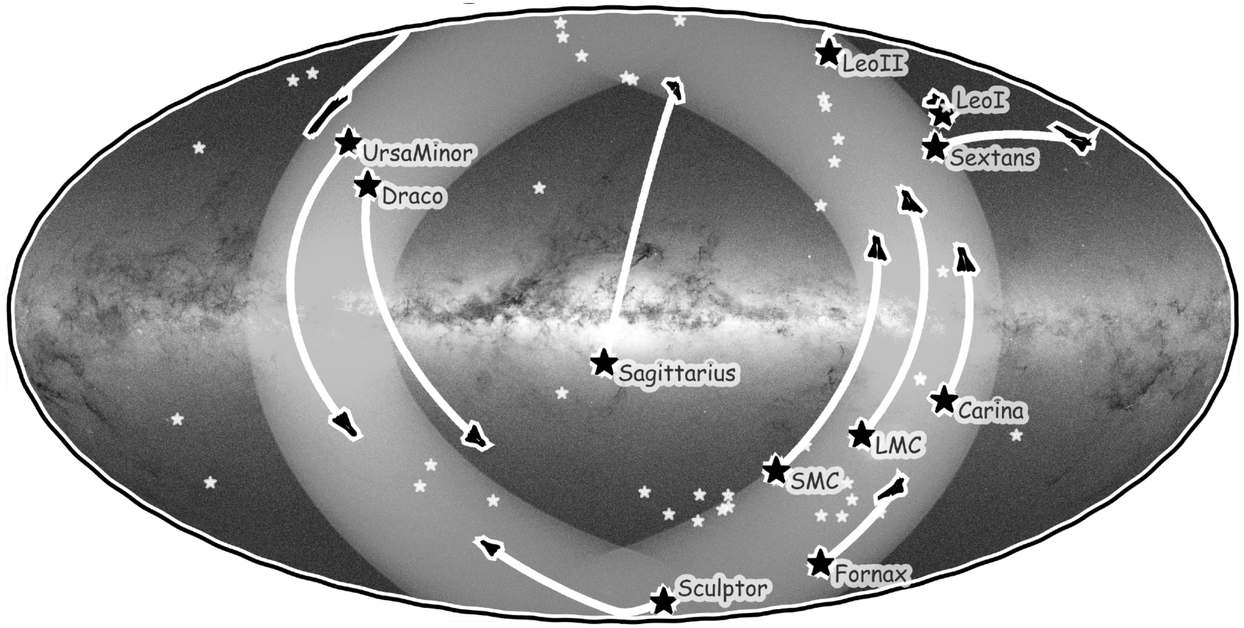


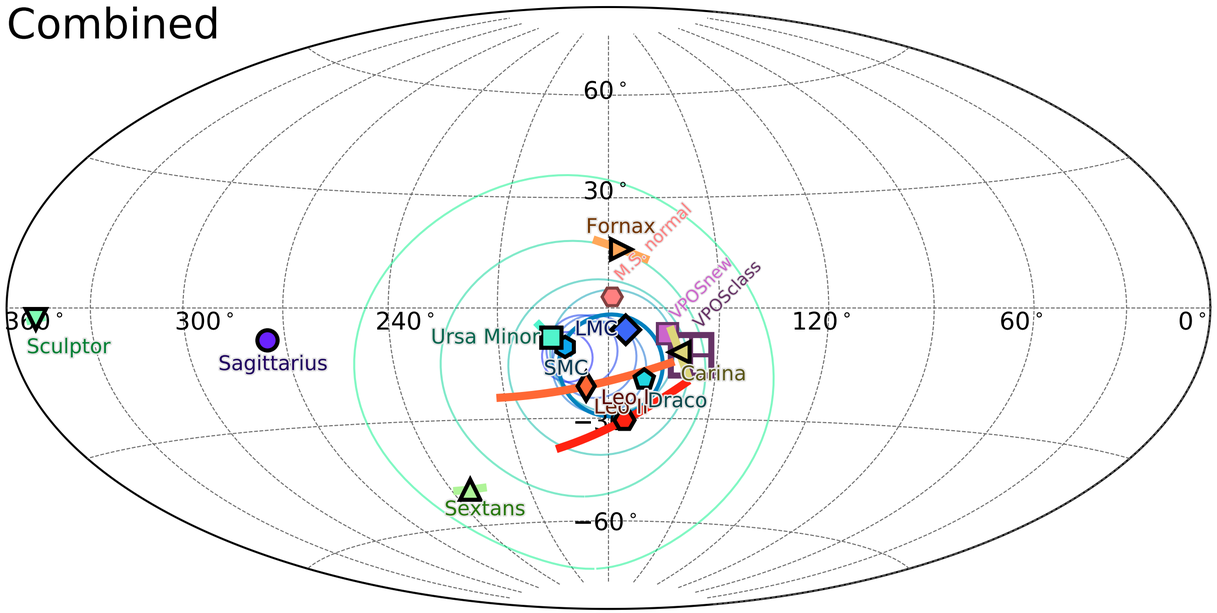
Simulation of the formation of a Milky-Way-like galaxy(dark matter only)

Quelle: https://www.caterpillarproject.org/

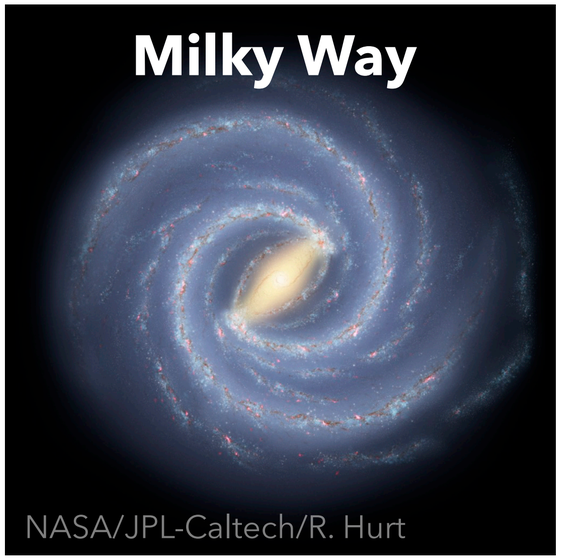
Planes of Satellite Galaxies Problem

- ΛCDM predicts that subhaloes are approximately randomly distributed around a host and move in largely random directions.
- Observed satellite galaxies of the Milky Way show a surprising degree of correlation: arranged in flattened distribution, and a preference to co-orbit along this.
- This is what I've done most of my work on, so I could give a whole lecture series on just this topic … ;-)



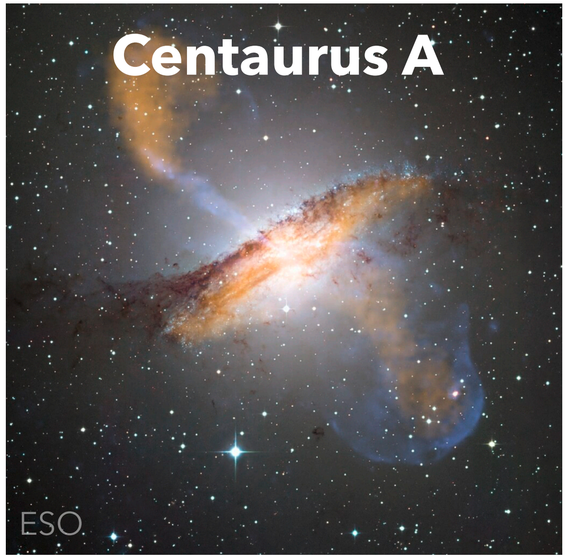


Best-Studied Observed Cases of Satellite Galaxy Planes



From my review (Pawlowski, 2021)

Casetti-Dinescu, Pawlowski et al. (2025)



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Pawlowski et al. (2024)

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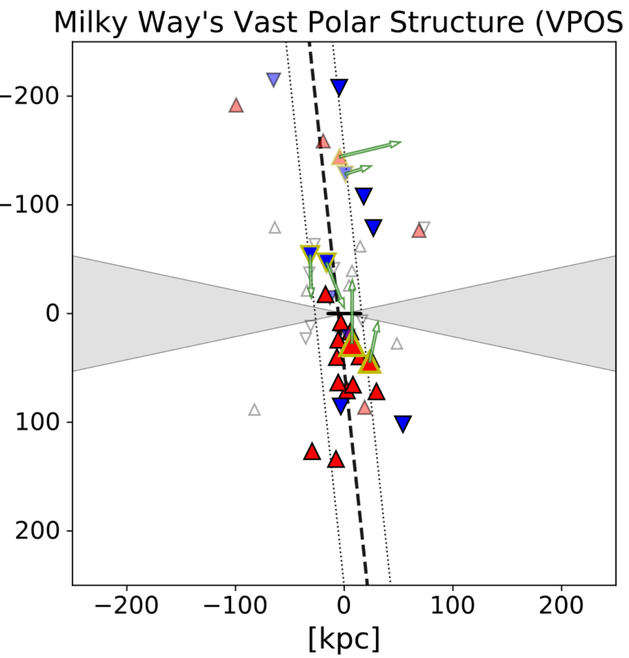

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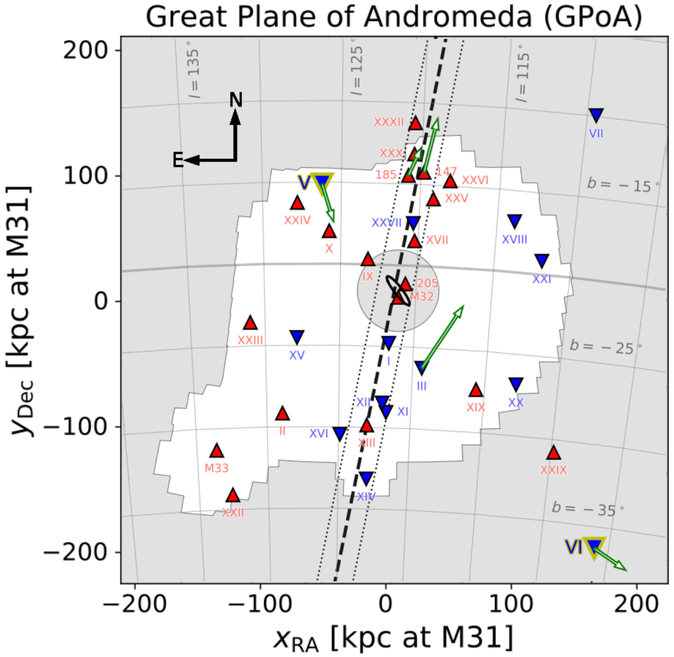

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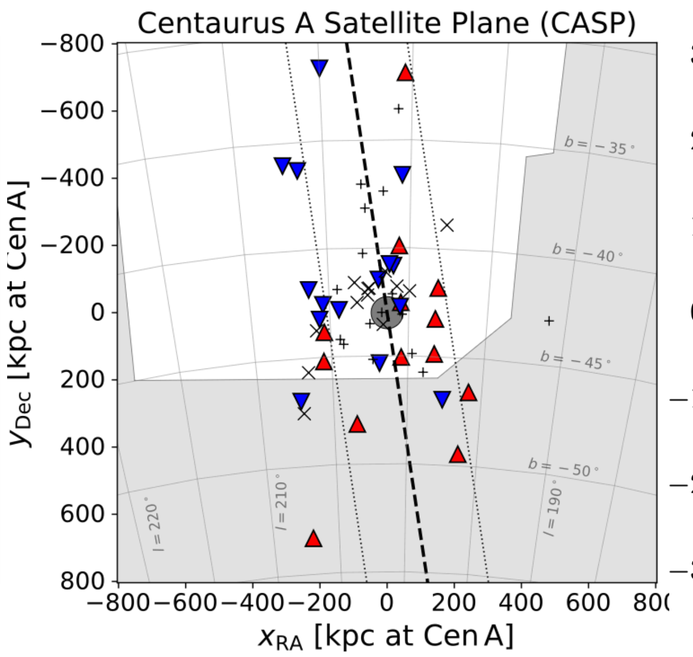
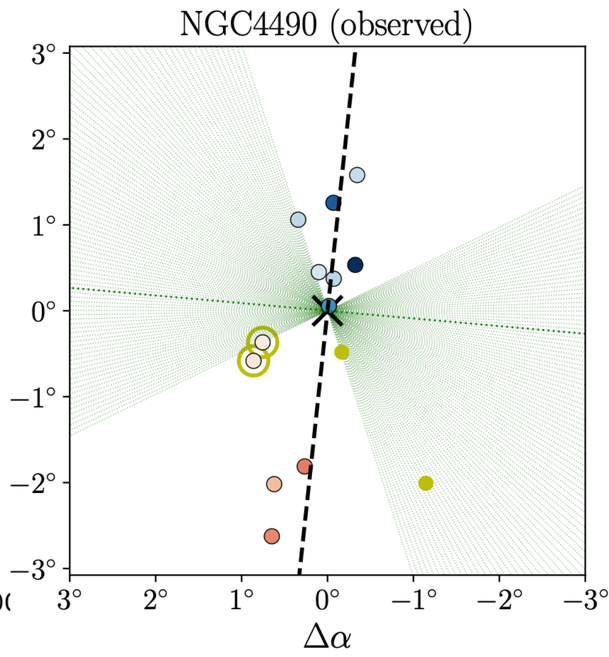


From my review (Pawlowski, 2021)



Pawlowski et al. (2024)

proper motions
→ 3D velocities
→ orbital poles align

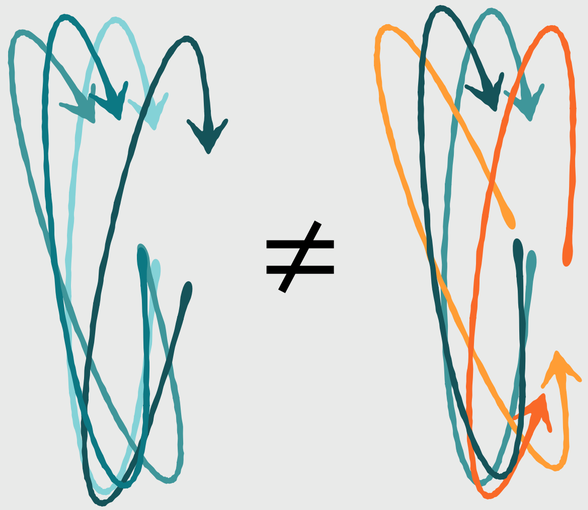
Key Characteristics of Satellite Planes

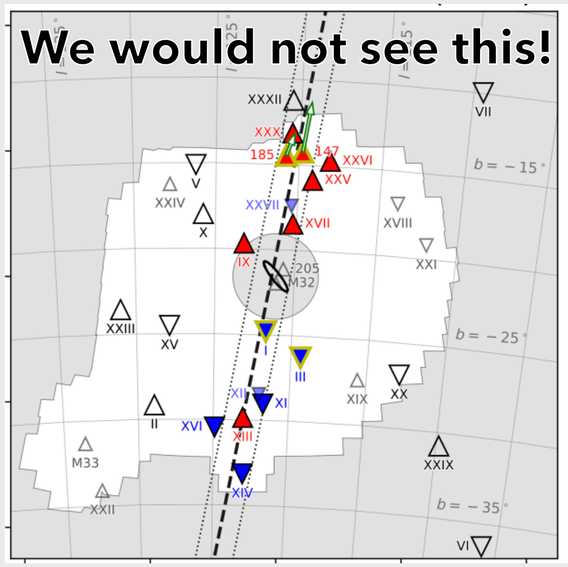
Flattening + **Kinematic Coherence**

e.g. absolute rms height or minor-to-major axis ratio

Rotating (≠ just moving in plane) → aligned angular momenta!

ΛCDM comparisons that require
only motion along plane
(not common direction)
over-estimate frequency of analogs





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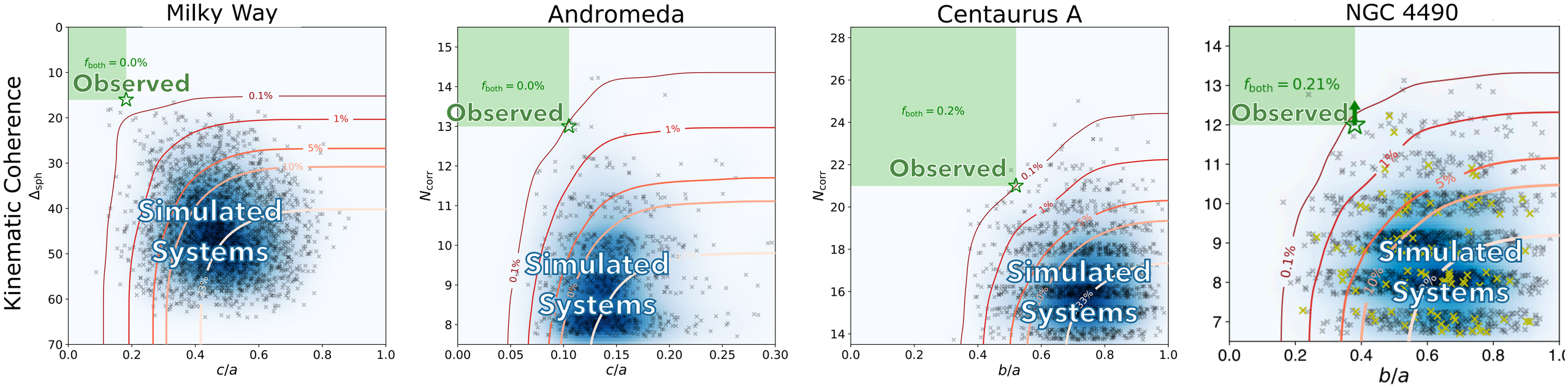

From my review (Pawlowski, 2021)

Flattening of Satellite Distribution

Pawlowski et al. (2024)

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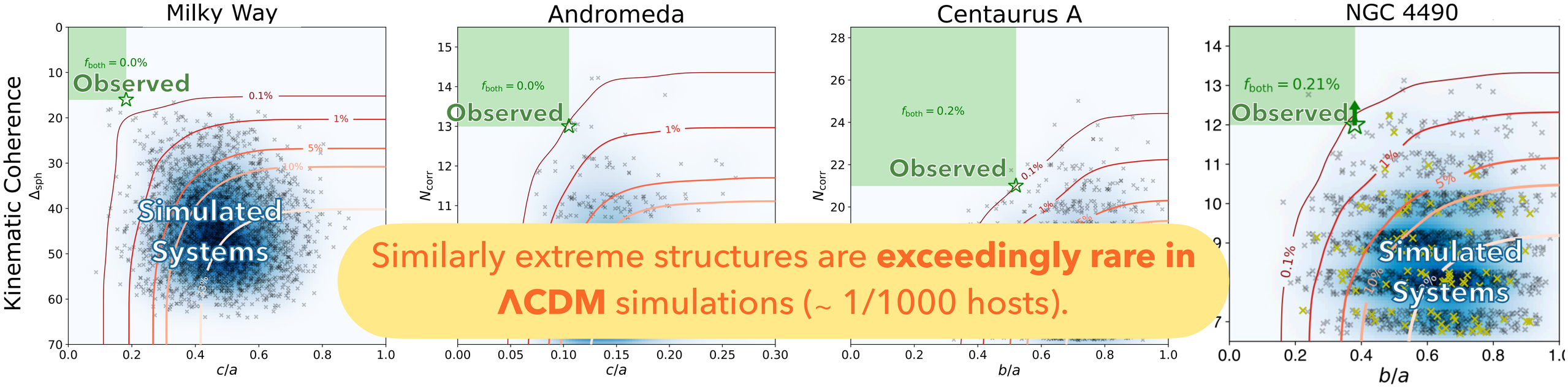


Similarly extreme structures are **exceedingly rare in ΛCDM** simulations (~ 1/1000 hosts).

From my review (Pawlowski, 2021)

Flattening of Satellite Distribution

Pawlowski et al. (2024)

Testing Cosmological Expectations with Satellite Galaxy Systems

- Predictions on galaxy scales via numerical simulations involve

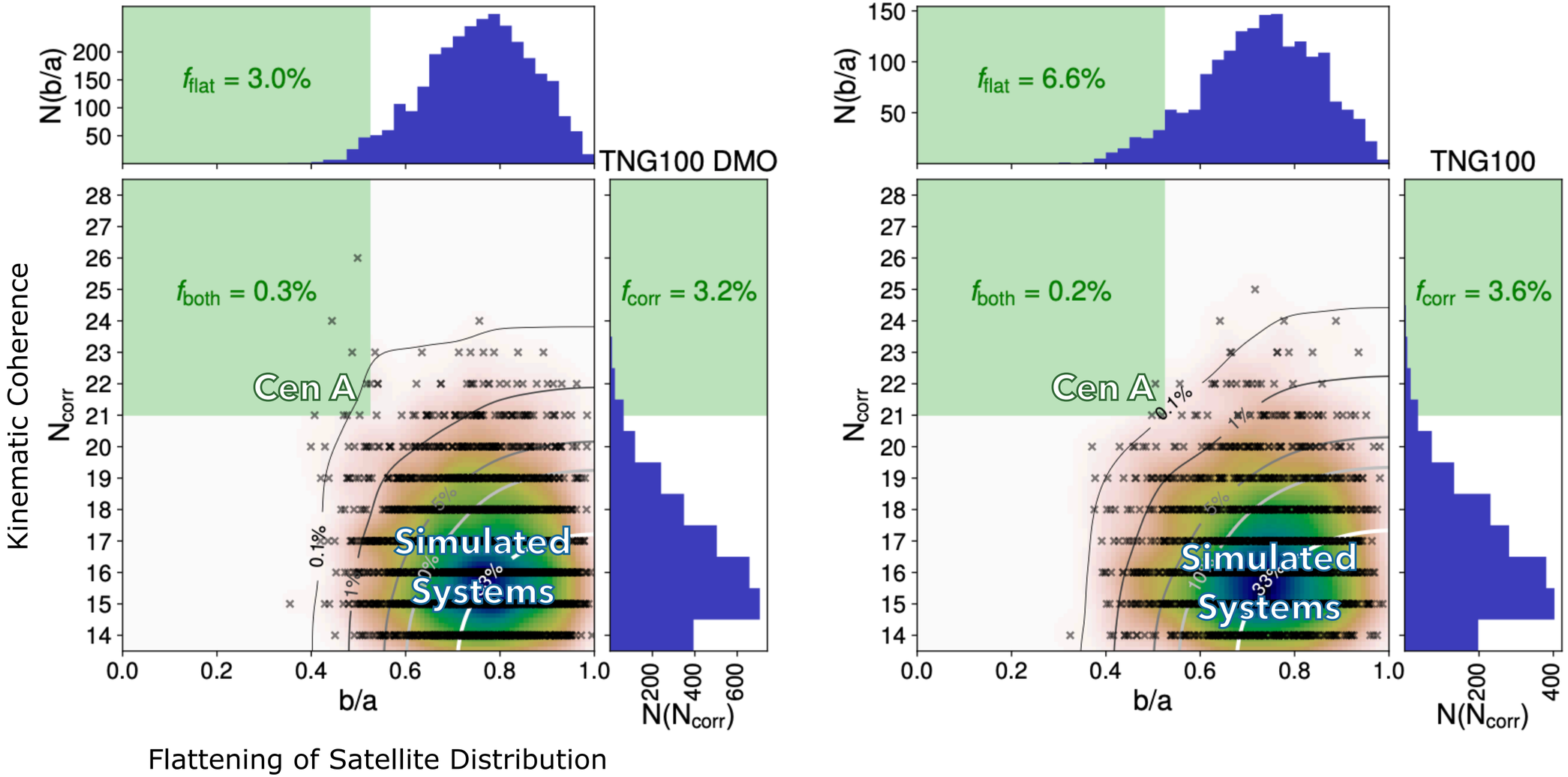
Underlying ΛCDM Model + **Implementation of Baryonic Physics**

- Found a mismatch between observation and expectation?
  → ΛCDM ruled out! 😱 Or maybe just due to incorrectly approximated physics? 🤔

Need to consider to what degree predictions might be affected by details of baryonic physics.

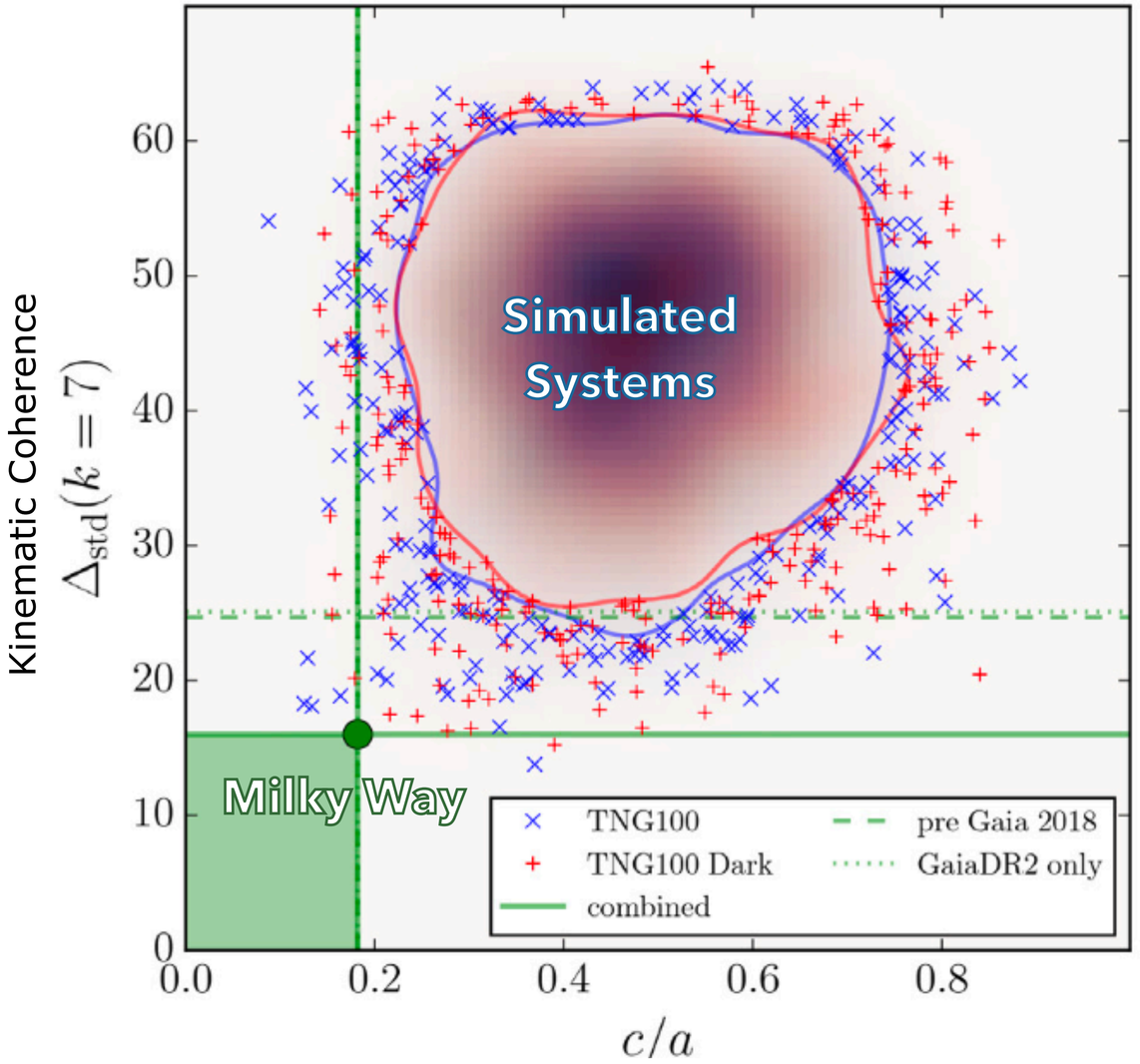
Dark Matter Only (left) vs. Hydrodynamical (right) Simulations: Similar Tension with Cen A

Müller, Pawlowski et al. 2021



Flattening of Satellite Distribution

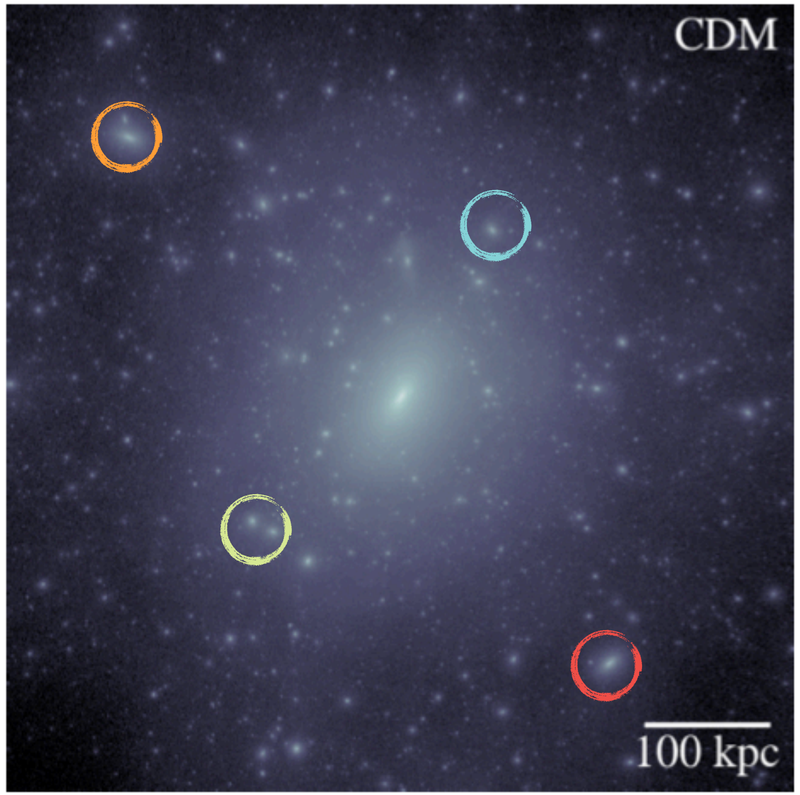
Dark Matter Only vs. Hydrodynamical Simulations: Similar Tension with Milky Way



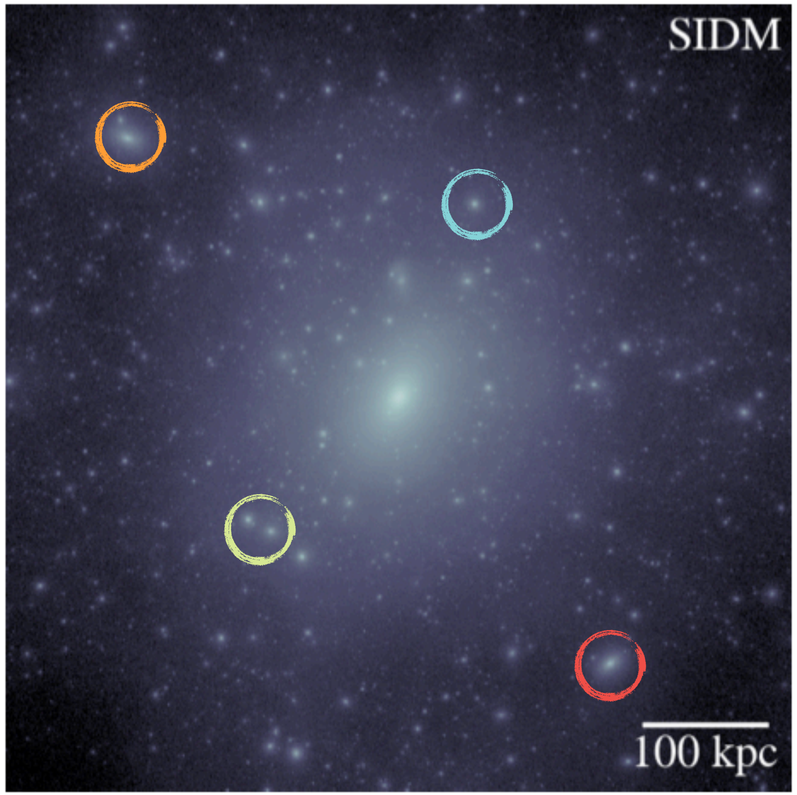
Pawlowski & Kroupa 2020

Distribution of satellite galaxies is very similar in different dark matter models

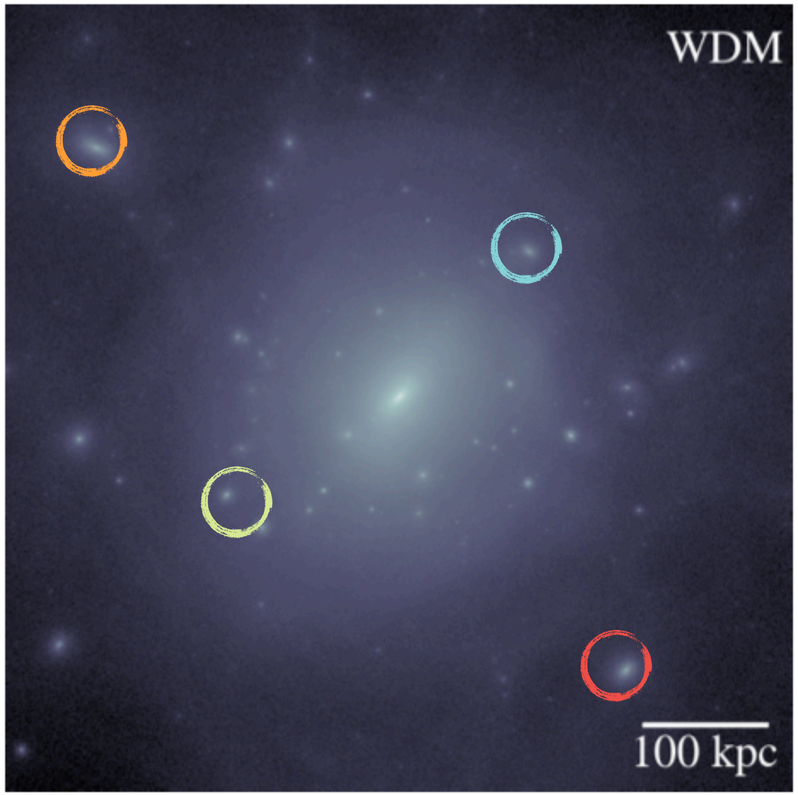
Soumya's talk



Cold Dark Matter



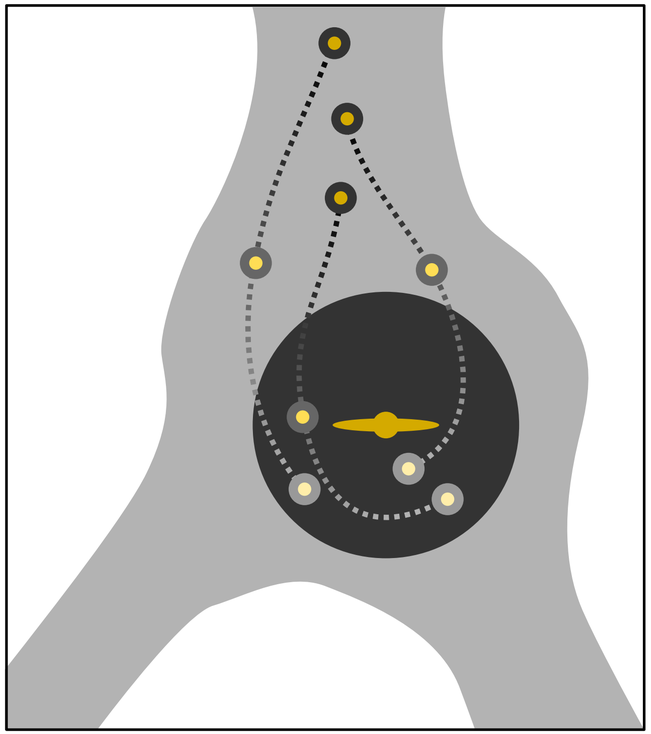
Self-Interacting Dark Matter



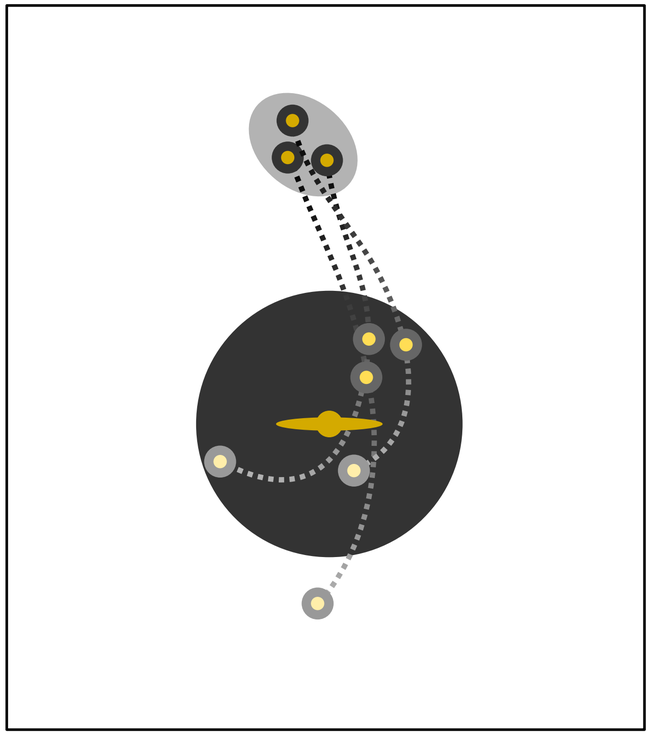
Warm Dark Matter

POSSIBLE ORIGINS OF SATELLITE PHASE-SPACE CORRELATIONS

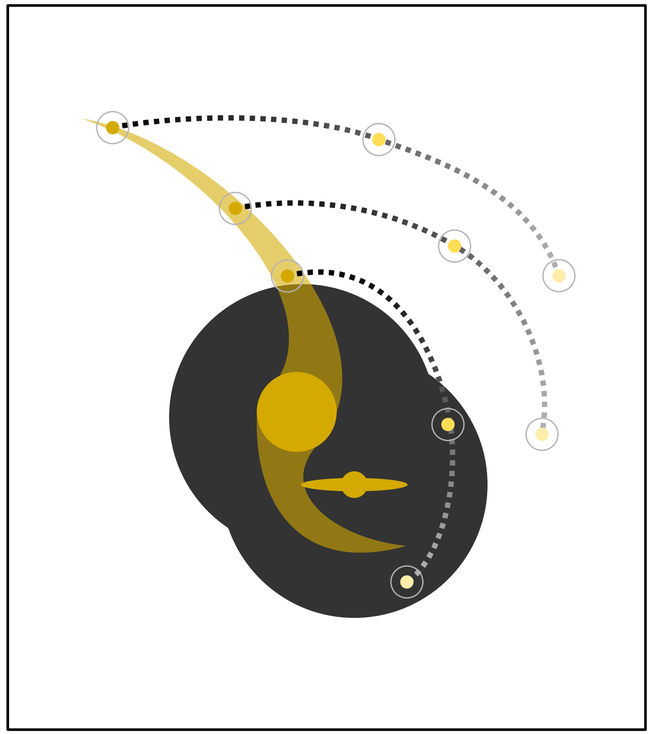
Filamentary Accretion



Group Infall



Tidal Dwarf Galaxies

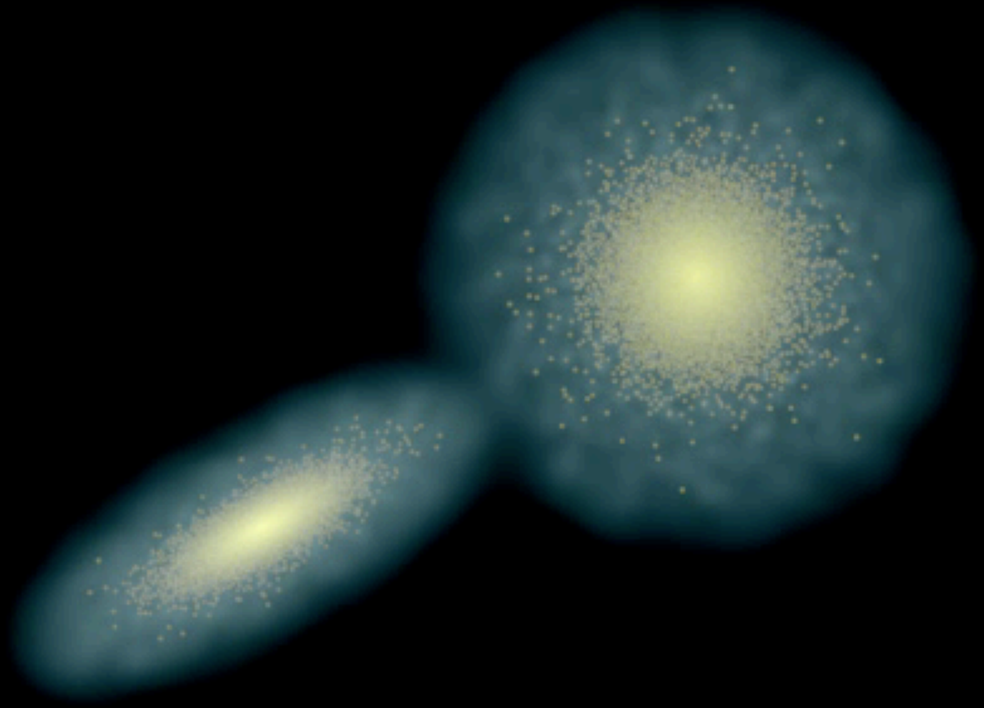


Pawlowski (2018)

Tides in Galaxies

Video at https://esahubble.org/videos/heic0810d/

Visualization: F. Summers (STScI). Simulation: C. Mihos (CWRU) & L. Hernquist (Harvard)



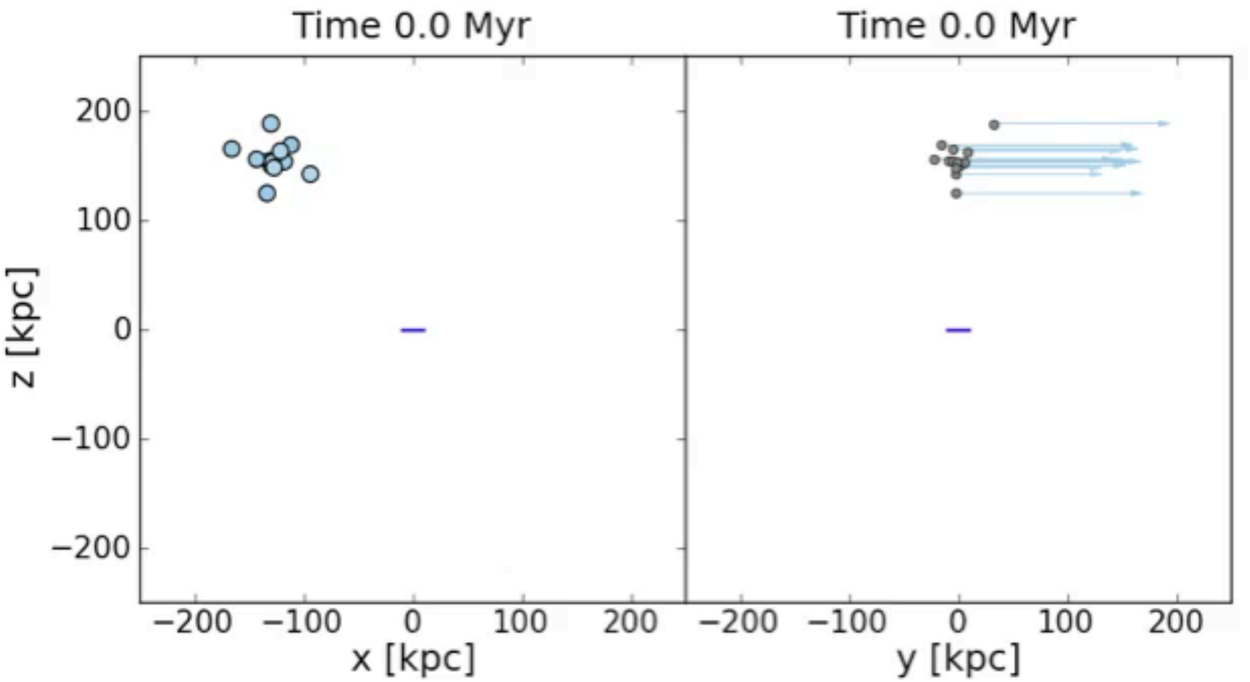
© Markus Wetzstein

Group Infall

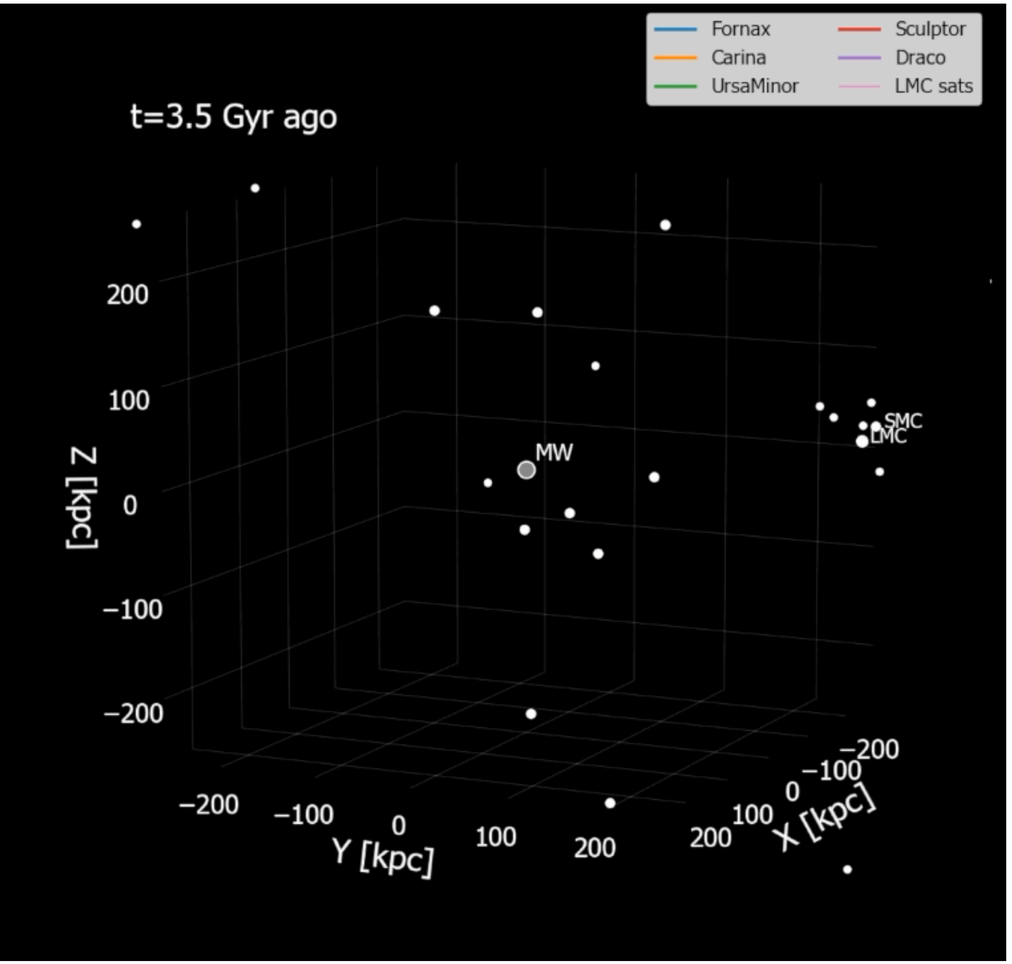
Accretion of satellite galaxies in groups can result in orbital correlation (e.g. Li & Helmi, 2008):

+ Group shares similar orbits, disperses along common plane, but initial group needs to be compact (Metz et al. 2009: conflict with observations).

+ Some subhalos in ΛCDM simulations are accreted in groups, but effect already self-consistently included in simulations.



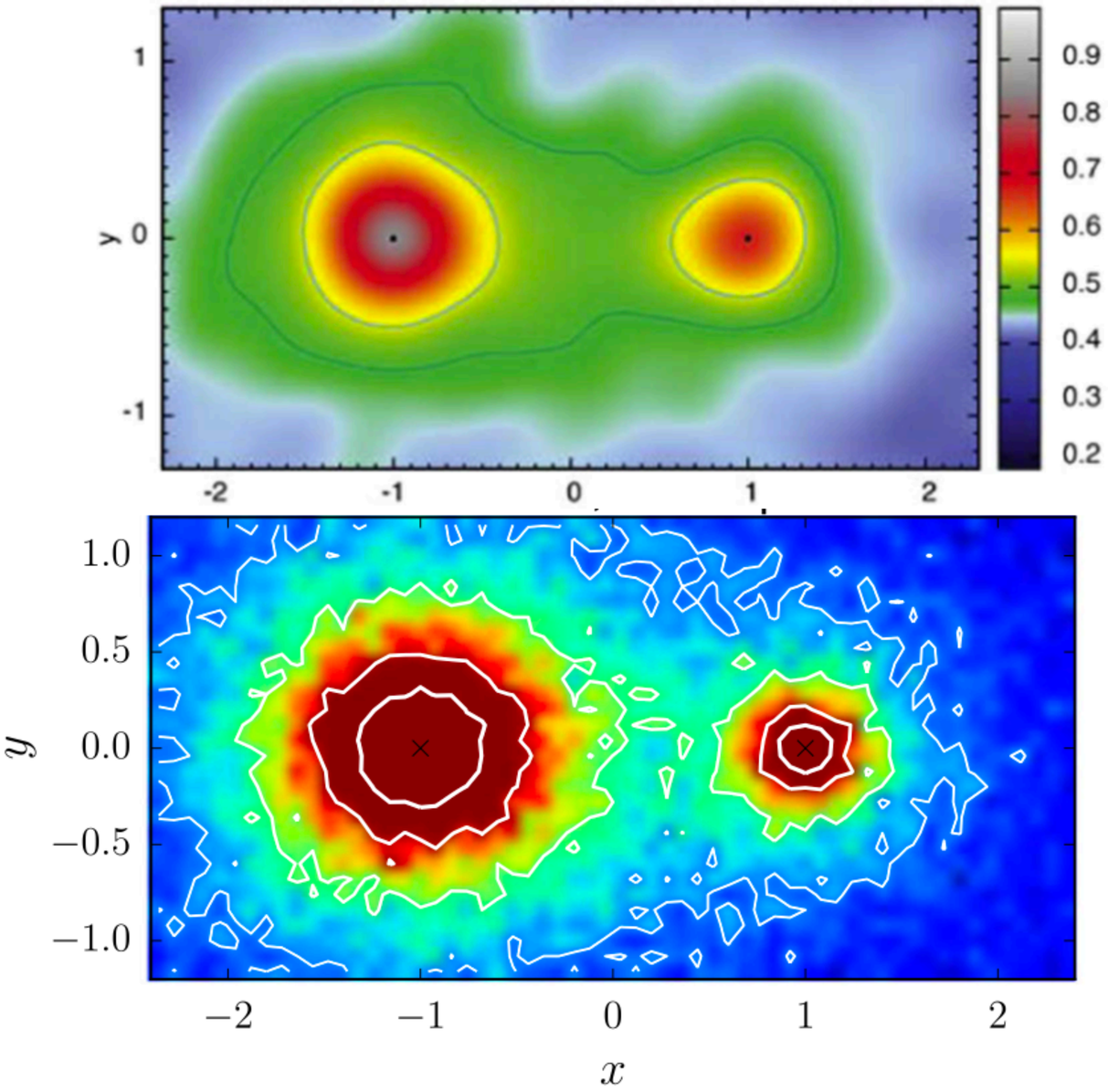
Group Infall



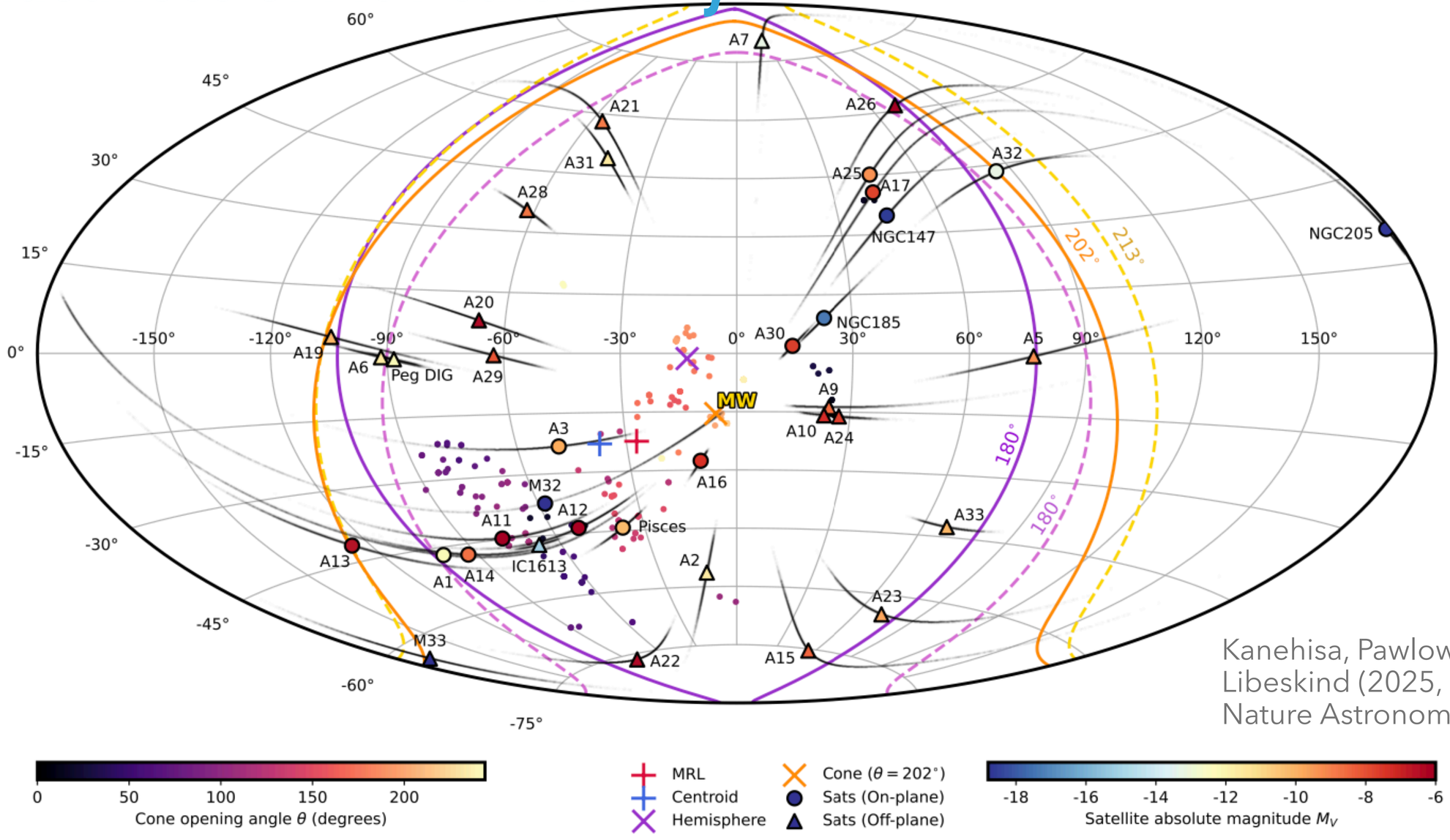
- Too many groups fall in over the lifetime of a halo, and groups consist of small number of galaxies only.
- Satellites brought in along with LMC can be identified (e.g. Patel et al. 2020), but no clear evidence that any classical MW dSphs were LMC satellites.
- Vasiliev (2023): If LMC on second infall, some on-plane satellites could have been stripped from LMC at its first passage.

Lopsided Satellite Systems

- **Satellites** in stacked SDSS satellite-host systems **show** 8% **overabundance towards partner** host (Libeskind et al. 2016).
- **Similar** degree of **overabundance found in cosmological simulations** (Pawlowski et al. 2017). So, not an issue for ΛCDM?
- SDSS **only** allows to **compare a few brightest satellites** and stacked distributions.
  What about in-depth comparison of M31 to cosmological expectations?



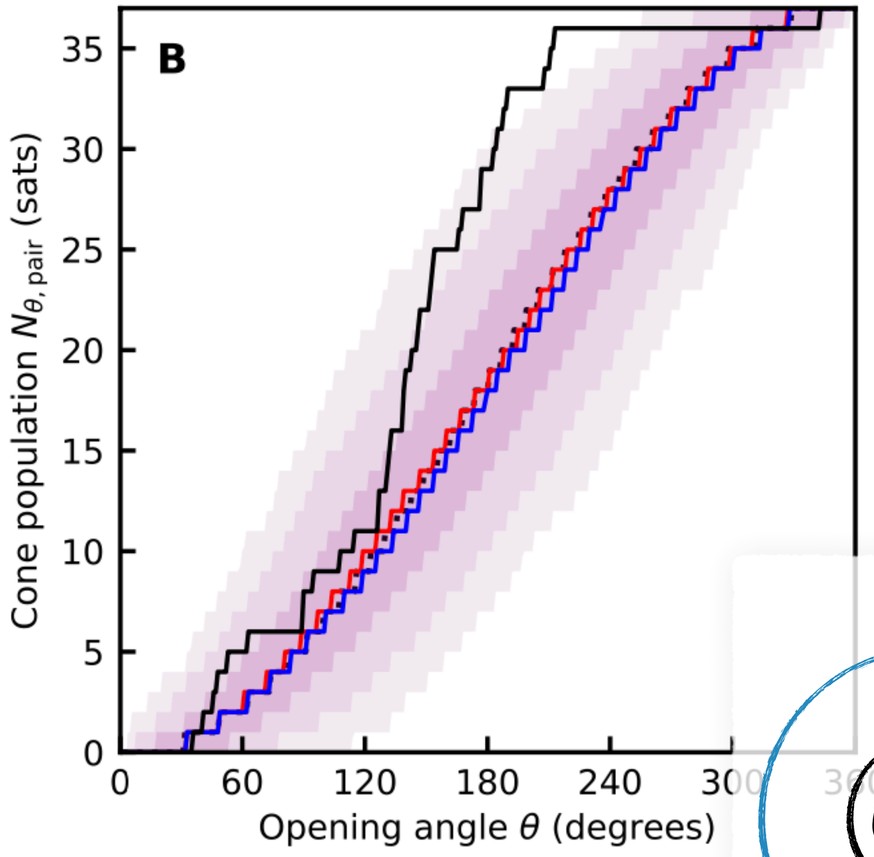
Lopsidedness of M31 satellite system



Kanehisa, Pawlowski & Libeskind (2025, Nature Astronomy)

Lopsidedness of M31 satellite system

- Andromeda's satellites have long been known to preferentially lie on the side facing the MW.
- Modern distance measurements show **all but one of 37 satellites contained within 107° of MW**.
- Comparison to cosmological simulations (IllustrisTNG, EAGLE) show: **less than 0.4% of simulated analogs are as extreme!**
- **In conjunction with** its **satellite plane**, this paints the **Andromeda system** as **an extreme outlier** in the prevailing **cosmological paradigm**.



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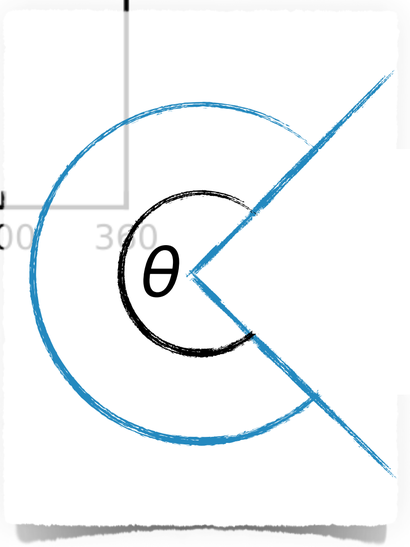

Summary

Need numerical simulations to make predictions on dwarf galaxy scales.

Several “Small-Scale Challenges” were identified over the years: Missing Satellites, Core-Cusp, Too-big-to-fail, Planes of Satellites.

Many small-scale problems can be addressed by adequately modelling baryonic physics in simulations. But tricky to get right (e.g. over-solved missing satellites?).

Issues of phase-space correlations (e.g. planes of satellite galaxies) are more robust against details of baryonic physics → remain a challenge for cosmology.

Literature

Reviews:

- Bullock & Boylan-Kolchin (2017): “Small-Scale Challenges to the ΛCDM Paradigm”, ARA&A, 55, 343.
- Sales et al. (2022): “Baryonic solutions and challenges for cosmological models of dwarf galaxies”, Nature Astronomy, 6, 897.
- Pawlowski (2018): “The planes of satellite galaxies problem, suggested solutions, and open questions”, MPLA, 3330004
- Pawlowski (2021): “Phase-Space Correlations among Systems of Satellite Galaxies”, Galaxies, 9, 66.