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DWARF GALAXIES IN LCDM:

INTERNAL STRUCTURE, DUST EMISSION, AND DISTRIBUTION AROUND HOSTS

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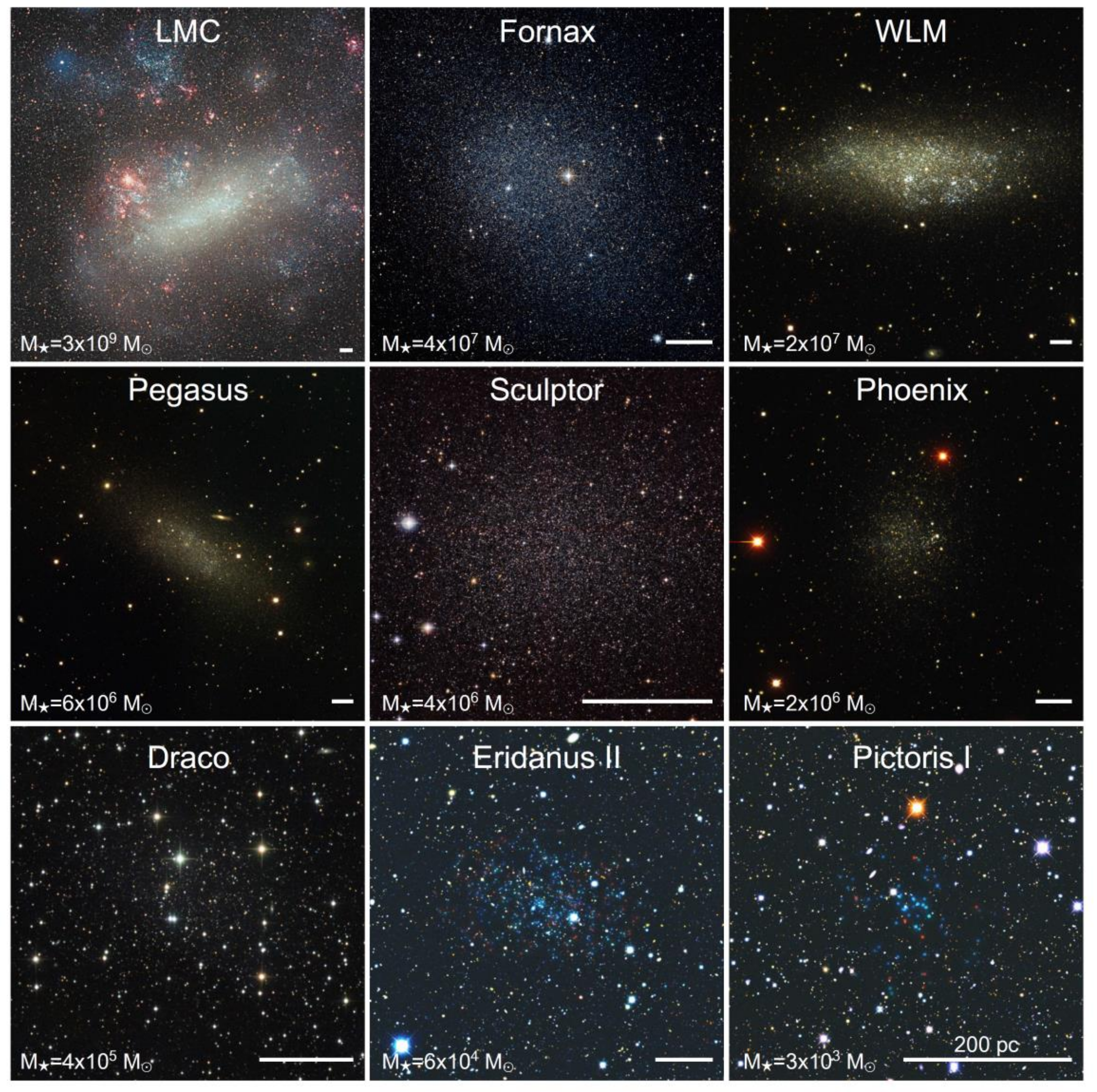
M87; Credit: ESO

Observed dwarf galaxies present very diverse and puzzling properties.

Some Local Group dwarf galaxies



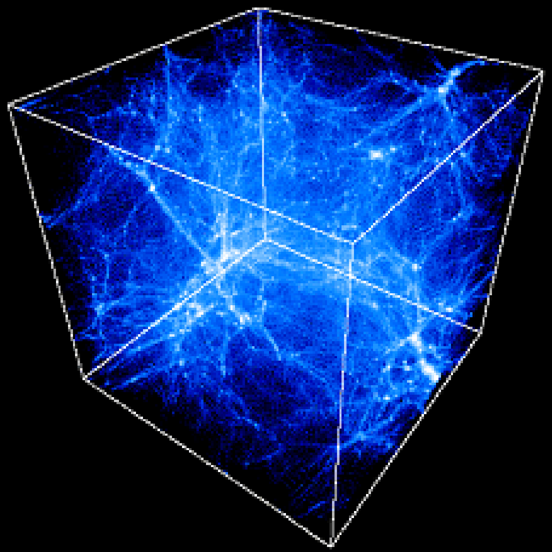
DWARF=
- Dark matter dominated
- Low mass
- Low metallicity

But…

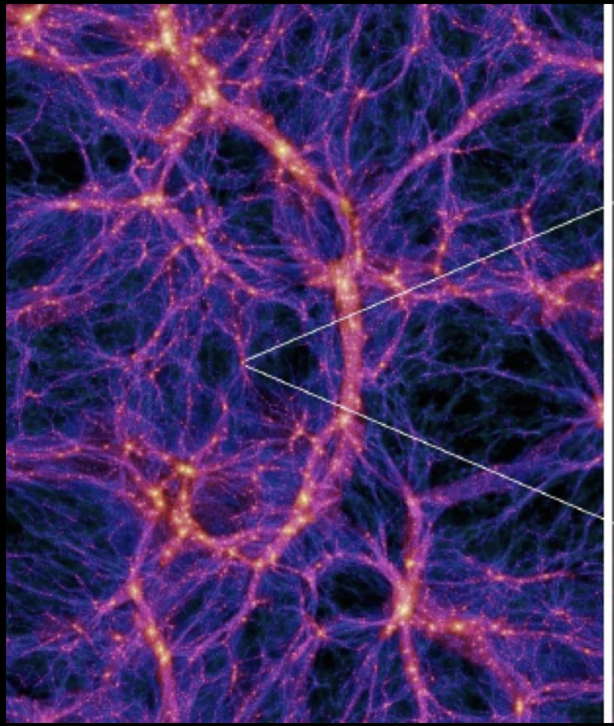
- ❑ Very diverse morphologies, sizes, emission, star formation histories, internal mass distribution, spatial distribution, …
- ❑ Some properties disagree with LCDM theoretical predictions obtained from cosmological simulations ('small scale problems in LCDM')

(See eg Bullock&Boylan-Kolchin17)

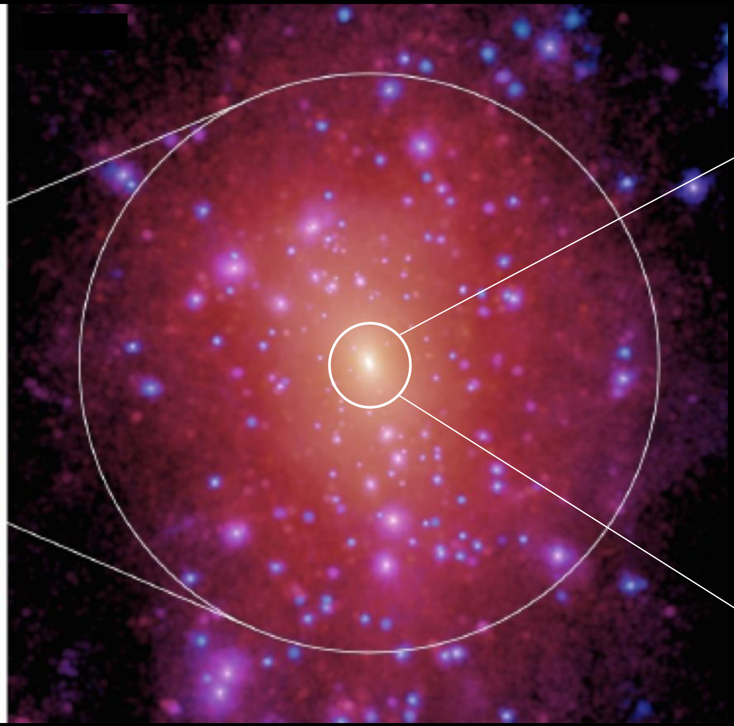
Zoom-in cosmological hydrodynamical (DM, gas and stars) simulations of galaxy formation as tools to understand dwarf galaxy formation/evolution in a LCDM context: High resolution to focus on smallest scales



Large volume dark matter-only cosmological box



A small region centered in a main halo is selected…



…and resimulated at high resolution

m_{dm}~10^6 Msol

...including hydrodynamics

m_{gas} ~10^4 Msol

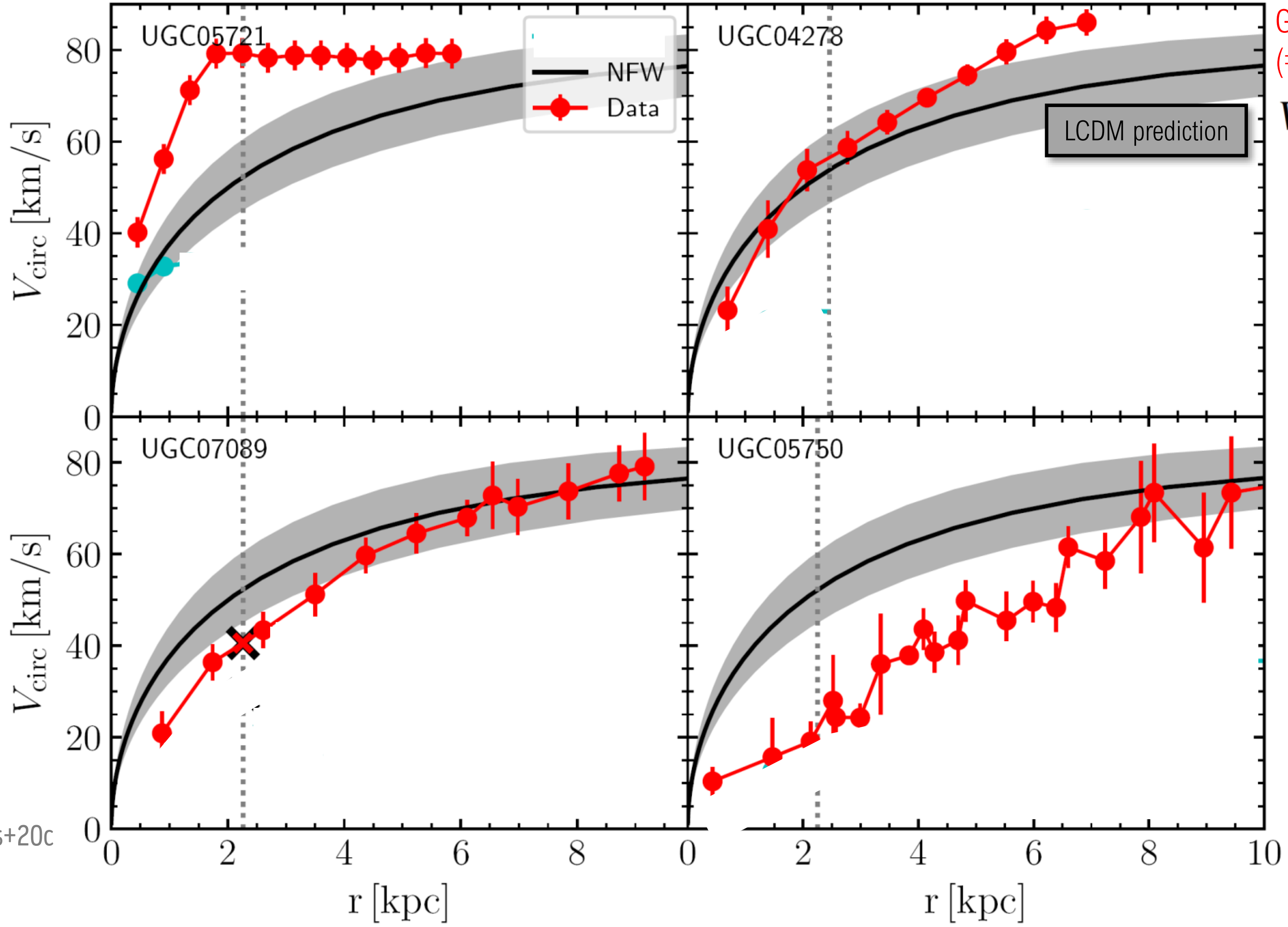
- CLUES Project (Yepes+14), MagICC Project (Brook+12), NIHAO Project (Wang+15), PDEVA-5004 (Domenech-Moral+12), Aquarius-Cα (Springel+08,Tissera+)

1. INTERNAL STRUCTURE OF DWARF GALAXIES

LCDM predicts a unique rotation curve for galaxies of a same mass scale. However, observed rotation curves of dwarf galaxies reveal a diversity of shapes.

DIVERSITY OF DWARF GALAXY ROTATION CURVES: THE 'CUSP-CORE' PROBLEM.

Sharply-rising rotation curves may arise from baryon accumulation in the inner regions: 'cusps'



Santos-Santos+20c

Galaxies with same Vmax~80 km/s (=similar halo mass)

$$V_{\mathrm{circ-spherical}}(r) = \sqrt{\frac{GM(<r)}{r}}$$

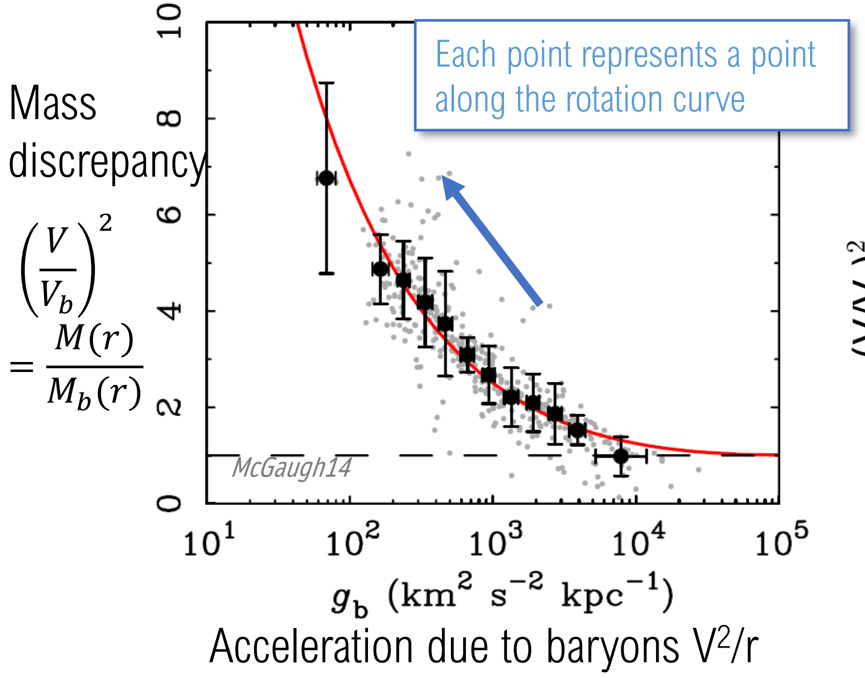
Galaxies with inner velocities below the LCDM expectation imply a ***deficit of mass***; a 'core' in the DM distribution

Diversity can be achieved by feedback-driven baryonic outflows that lead to the expansion of the dark matter halo

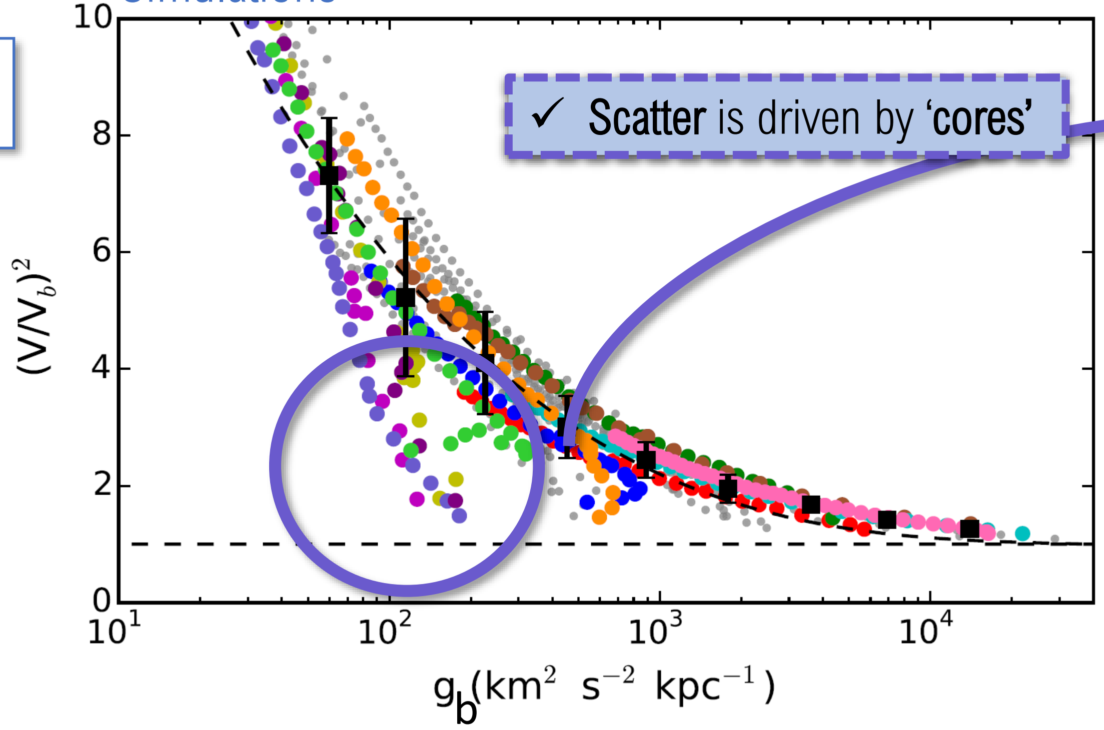
Pontzen&Governato+12

THE MASS DISCREPANCY – ACCELERATION RELATION (+SCATTER) IS REPRODUCIBLE IN LCDM (Santos-Santos+16)

Observations



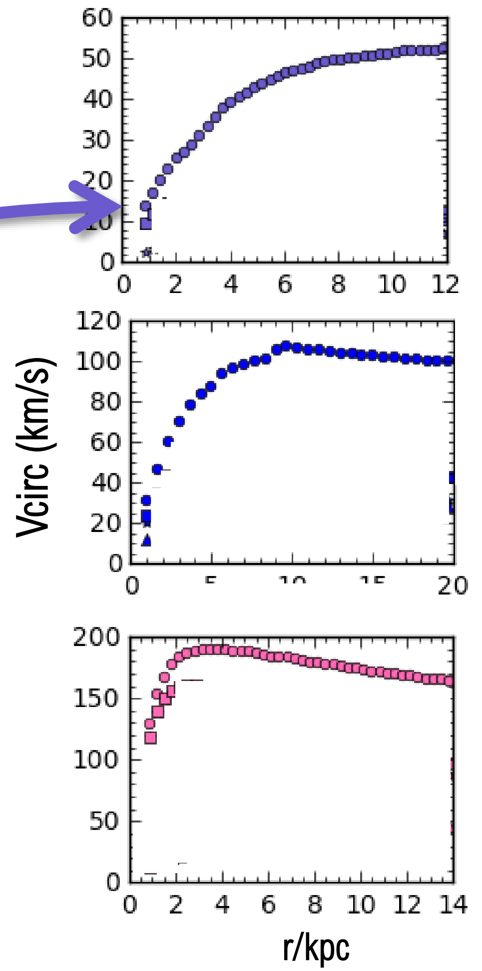
Simulations



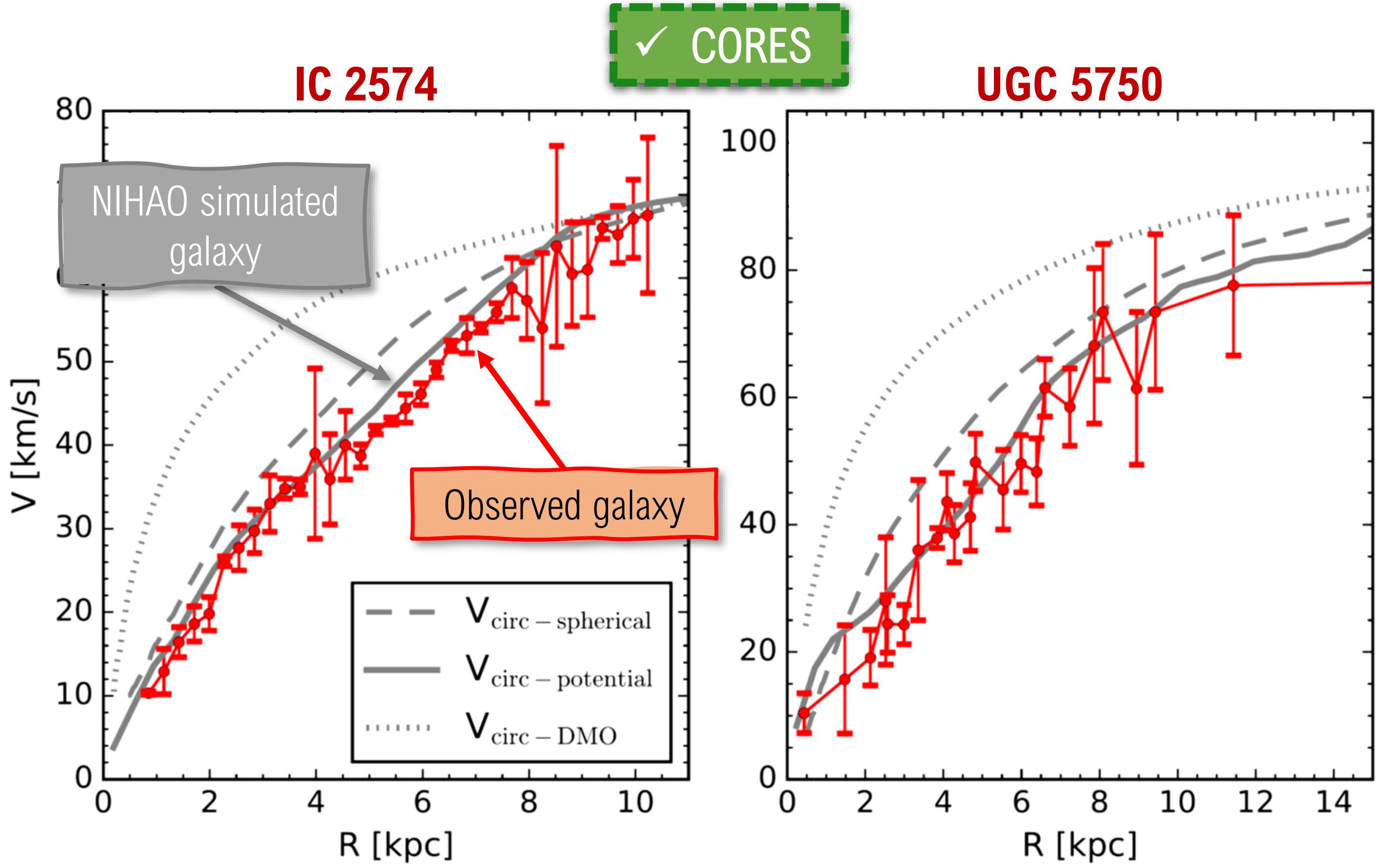
✓ The MDAR arises naturally in LCDM

Examples of rotation curves of MaGICC simulated galaxies

See Stinson+13,Brook+14

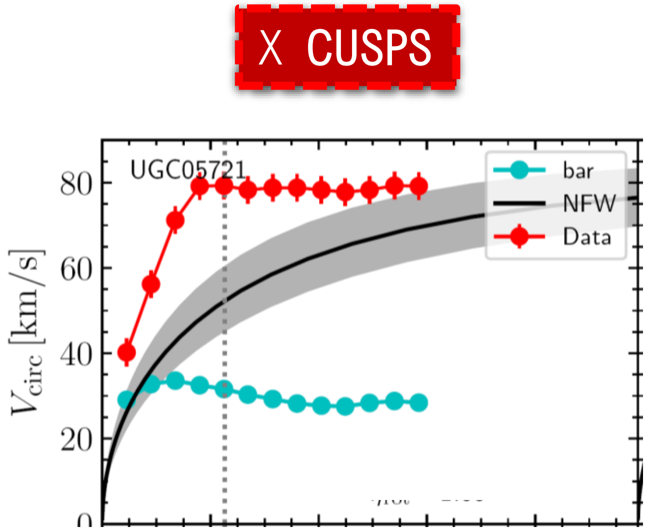


Dark matter halo expansion in LCDM can reproduce the most extreme slowly-rising rotation curves observed (i.e. largest cores) Santos-Santos+18



Circular velocity computed from the 'true' gravitational potential (instead of assuming spherical symmetry)

$$V_{\mathrm{circ-potential}} = \sqrt{R \frac{\partial \Phi}{\partial R}}_{z=0}$$



The **cuspiest cases remain a problem** for galaxy formation models that allow for DM halo expansion

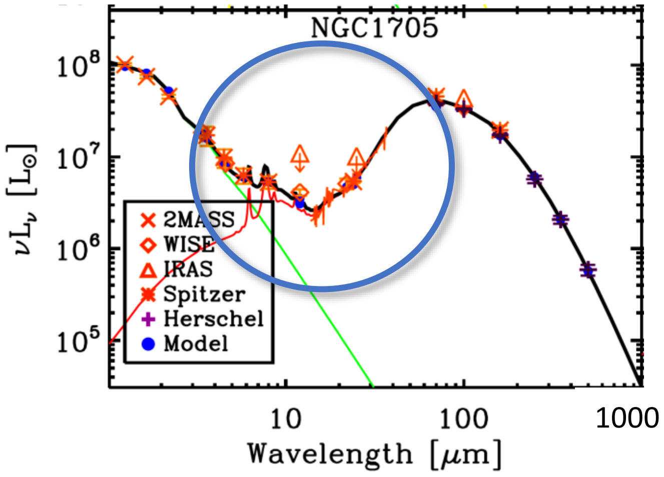
(see Santos-Santos,Navarro et al. 2020c)

2. DUST EMISSION IN DWARF GALAXIES

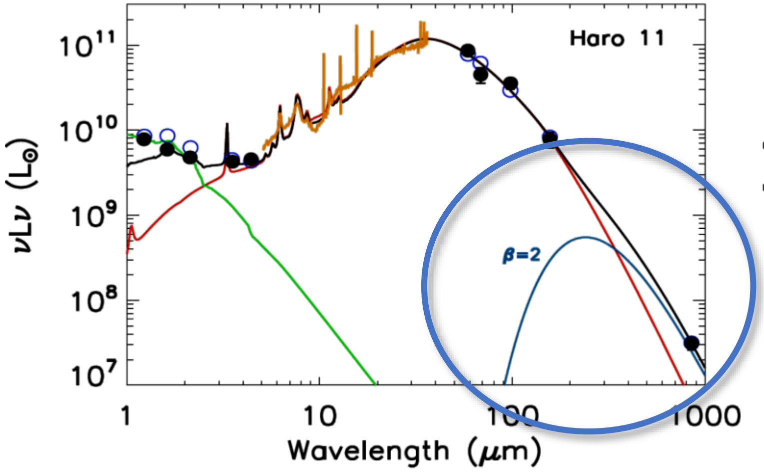
Recent *Herschel* observations of dwarf galaxies show a diversity of submm-IR SED shapes, as compared to massive galaxies

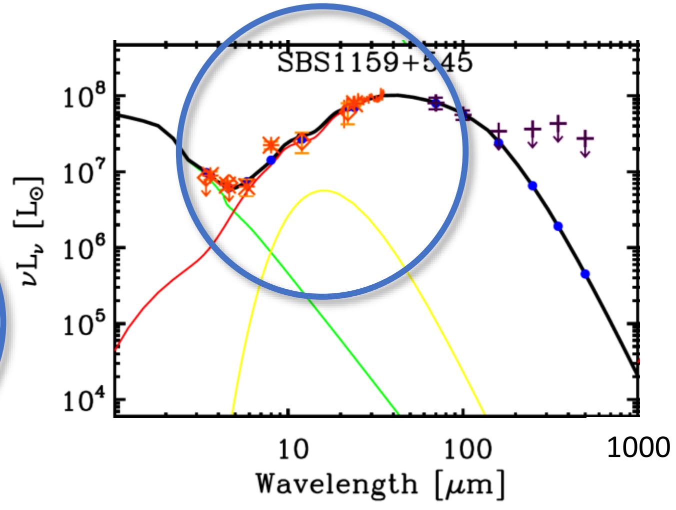
INFRARED SPECTRAL ENERGY DISTRIBUTIONS

Remy-Ruyer+15: DGS



Galametz+09





Low intensity of PAH bands

Excess of submm emission

Broadening of the IR peak

- Dwarf galaxies show particular spectral features → **'special' DUST emission**
- Current models invoke the need for extra dust components but cannot give a physical explanation

The interplay of molecular clouds and cirrus (dense and diffuse dust phases), as modeled in ***GRASIL-3D***, can explain the characteristic SED features observed in dwarf galaxies.

Santos-Santos+17

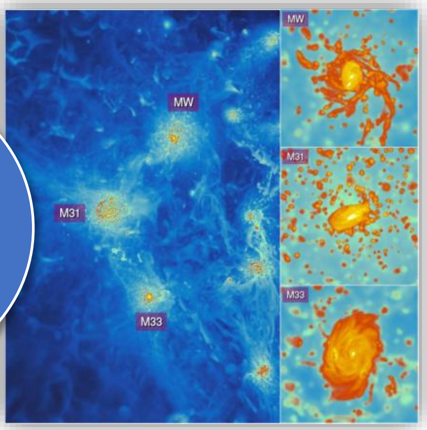
GRASIL-3D radiative transfer code

Dominguez-Tenreiro+14

- **Separate treatment: dense & diffuse gas phase**
- Age-dependent dust reprocessing of stellar populations
- Detailed Dust model
- D/G ∝ Z^{α}, and PAH abund. as observed in dwarfs
- RT solved in a grid

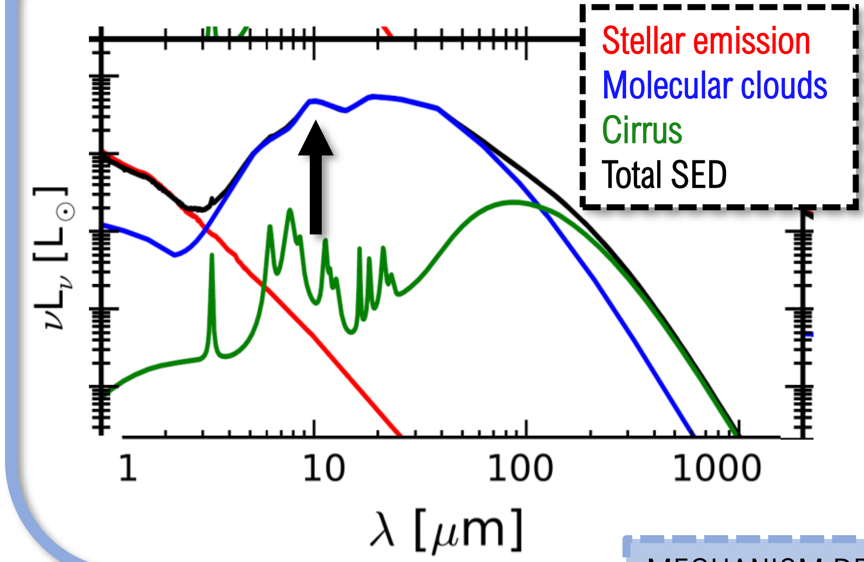
\+

Star-forming dwarfs from CLUES

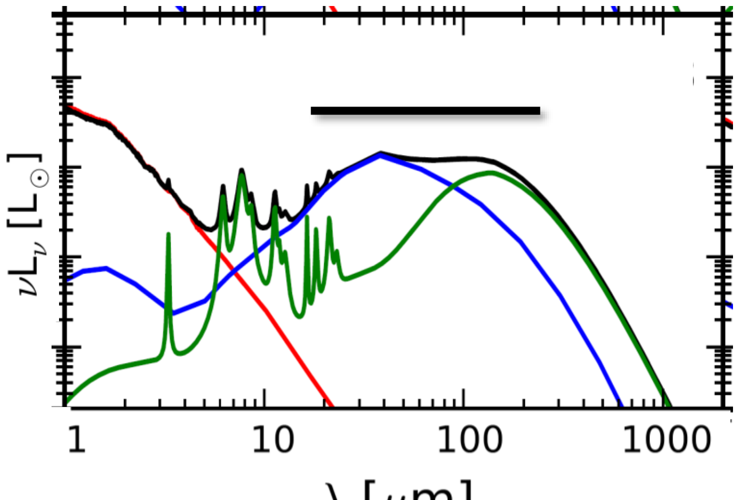


=

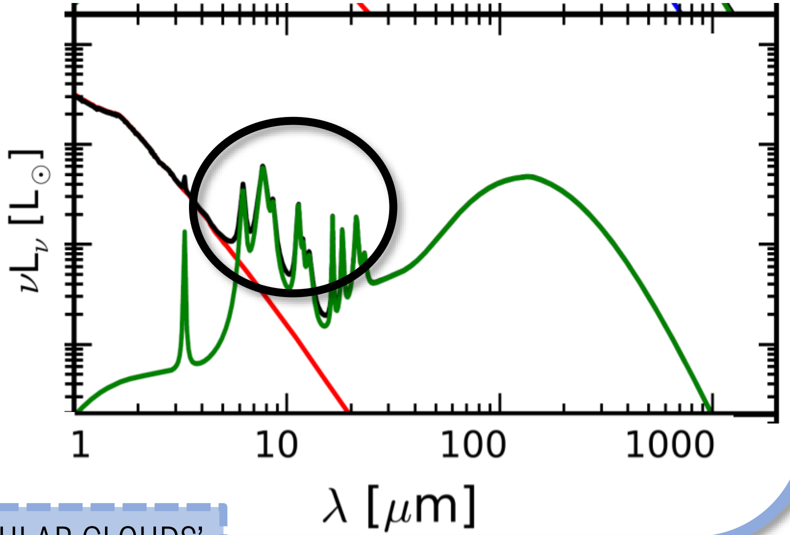
a) MC emission dominates:



b) Two dust components of similar intensity:



c) No (or very weak) MC emission:



MECHANISM DRIVING DIVERSITY: AMOUNT OF ENERGY ABSORBED BY 'MOLECULAR CLOUDS'

3. Planes of satellites around disc galaxies

Satellite galaxies are spatially distributed in planes around the Milky Way and Andromeda

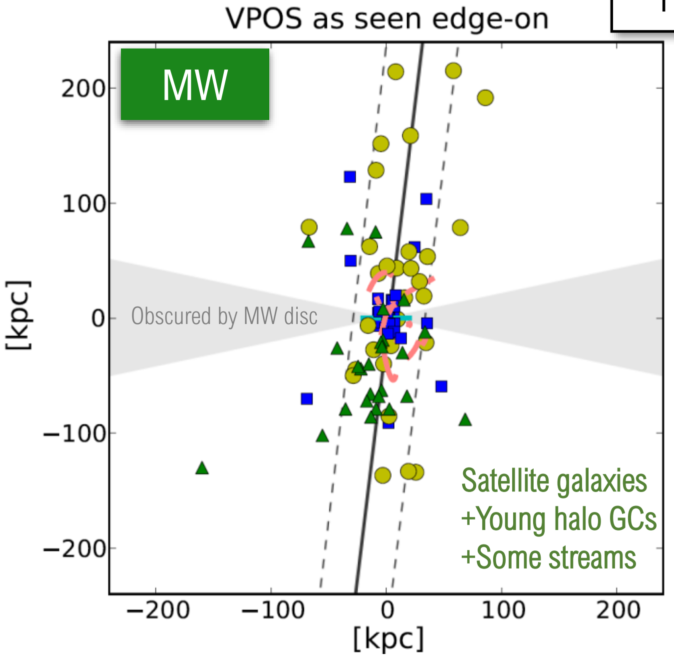
MW: “Vast Polar Structure”
M31: “Great Plane of Andromeda”
(Pawlowski+13)

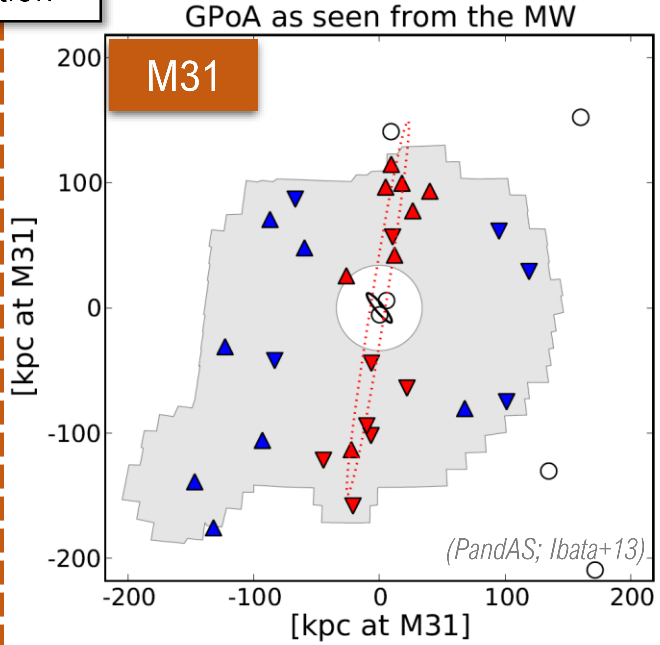
Planes of satellites in CenA, M101 group?
(Tully+15, Muller+18)

- Planes of satellites as those observed are not frequent in DM-only large-volume cosmological LCDM simulations
  (Pawlowski+14,Cautun+15)

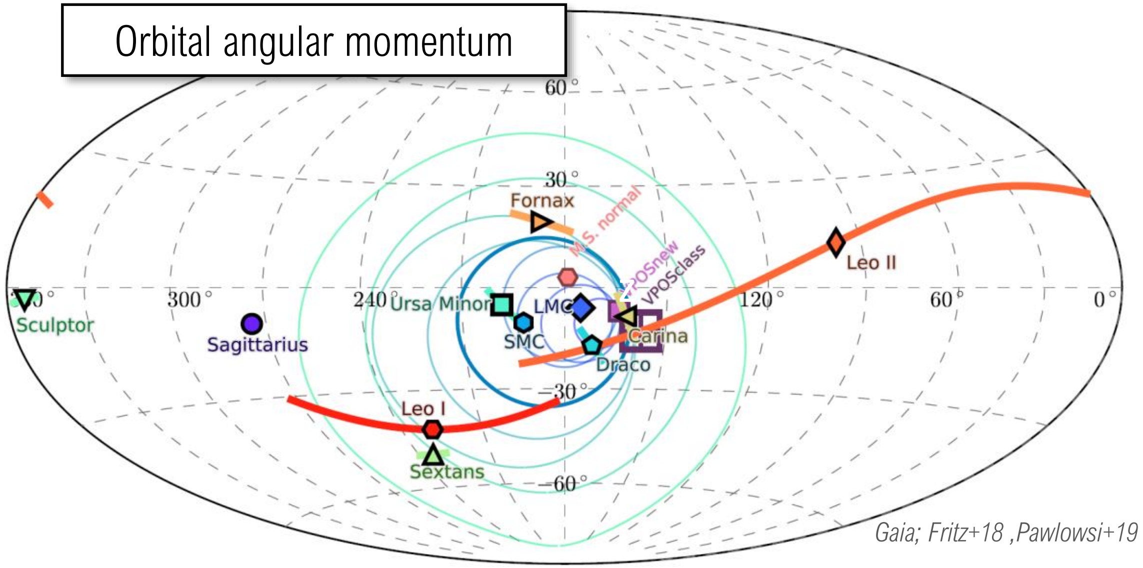
- Do they form in hydro-simulations of disc galaxies? What are their characteristics and trends?
  (see Gillet+15, Ahmed+16, Maji+17, Garaldi+18)

Position



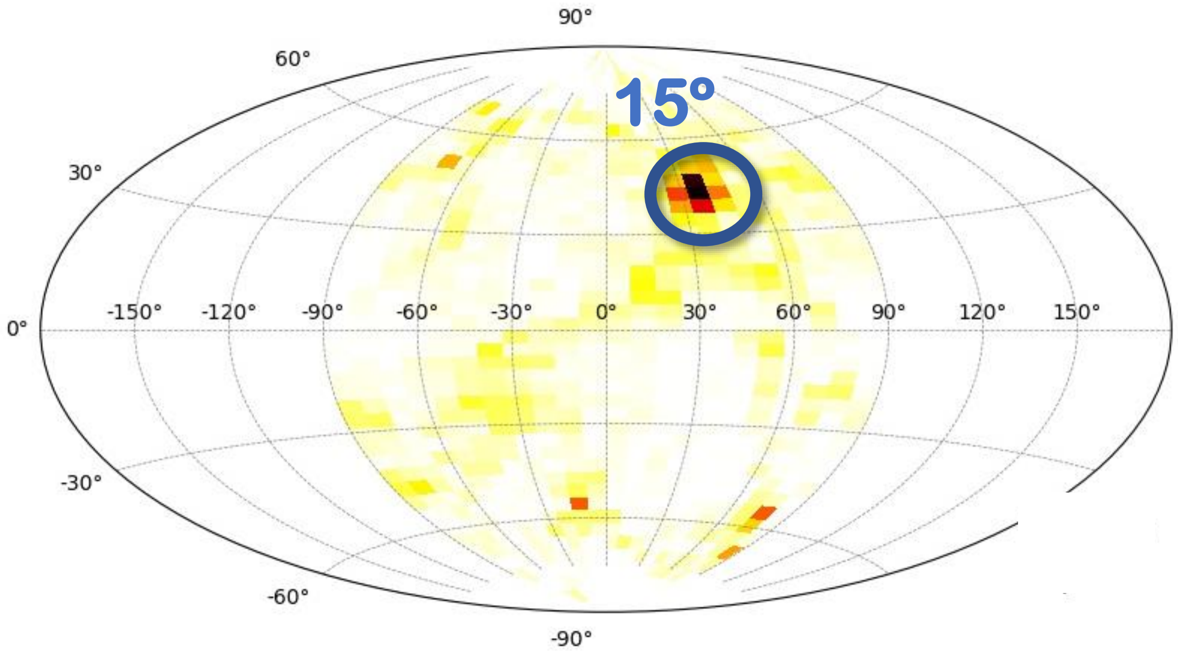


Orbital angular momentum



A method to identify predominant planar arrangements of satellites in both observational data or simulations: "4-galaxy-normal density plots" Pawlowski+13, Santos-Santos+20a,b

1. Fit a plane (Tensor of Inertia; Metz+07) to every possible combination of 4 different satellites out of Ntot
2. Draw the density map with the projection of "4-galaxy-normals" ; weighted by $\log\left(\frac{a+b}{c}\right)$
3. Identify location of high-density peaks
4. For each peak: Count satellites contributing to 4-galaxy-normals placed within 15º from peak.
5. Order satellites by weighted-counts
6. New: Fit plane to group of N_{sat} satellites as ordered by contribution: N_{sat} = 7,8,9…N_{tot}



Santos-Santos+20 a,b

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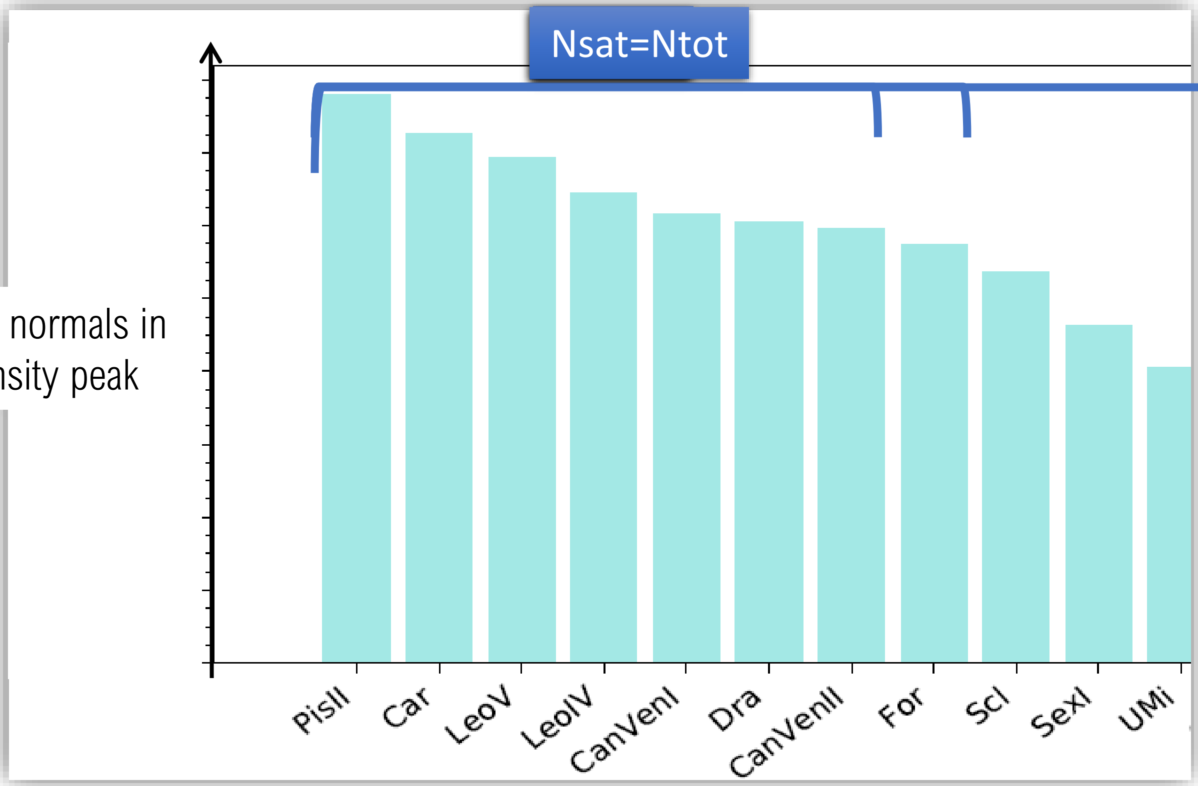
Nsat=Ntot

Contribution to normals in direction of density peak



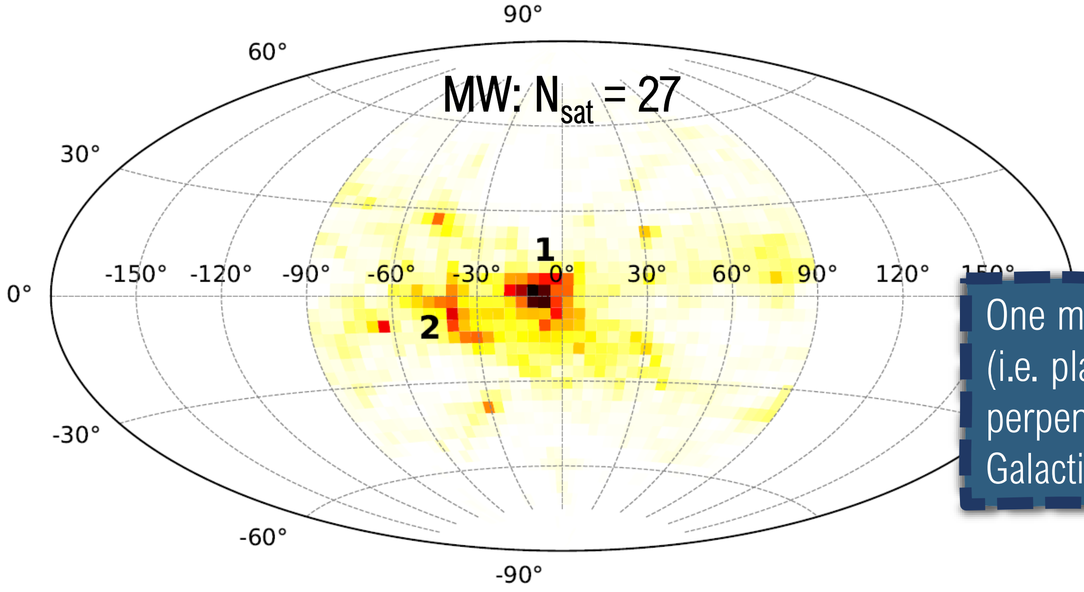
We obtain a collection of planes, each with different N_{sat} .

Santos-Santos+20 a,b

Identifying predominant planar spatial alignments of satellites

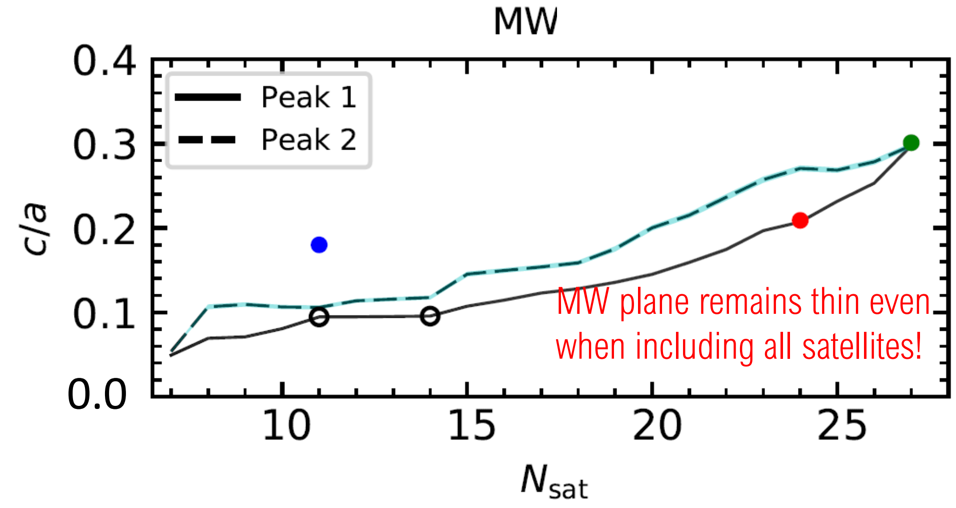
Santos-Santos+20a

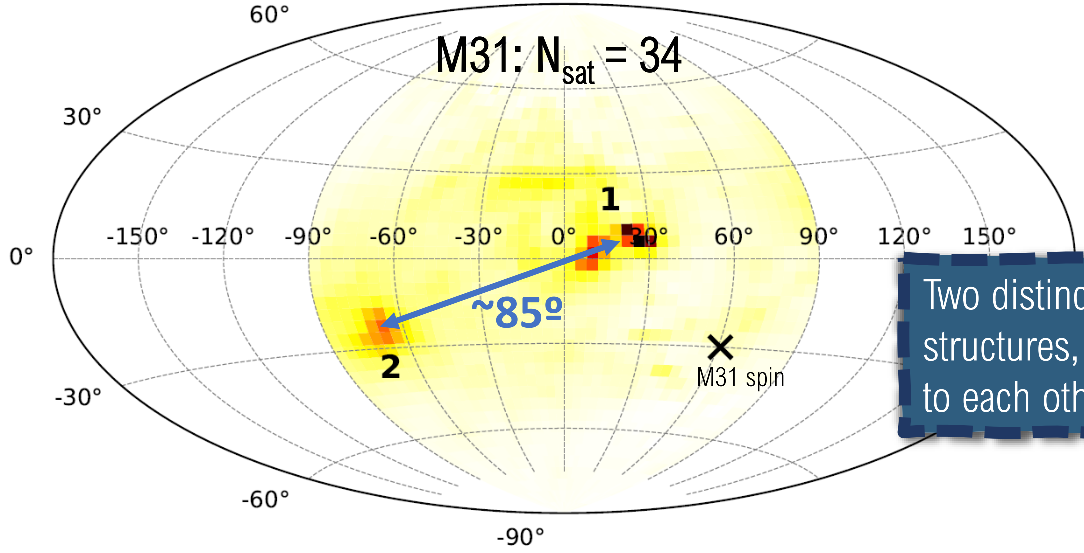
APPLICATION TO MW/M31 DATA



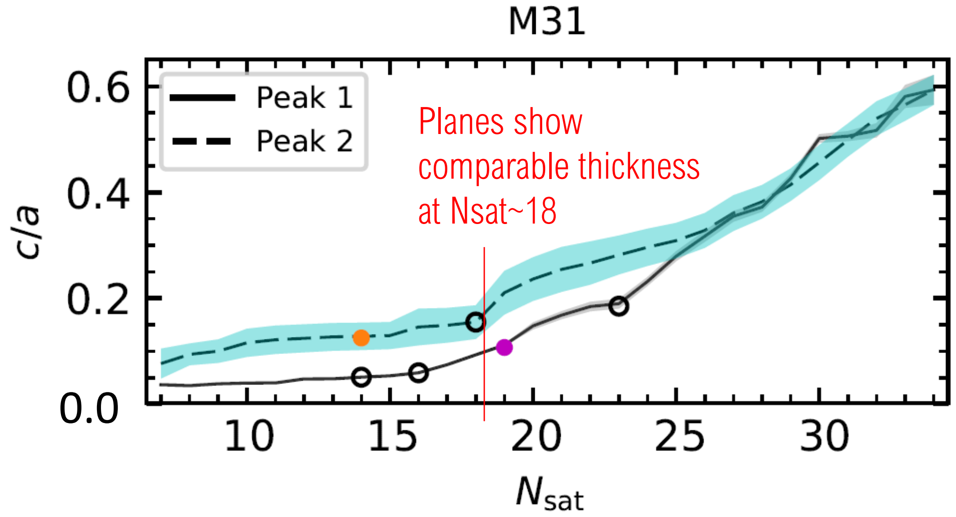
One main overdensity (i.e. planar structure); perpendicular to the Galactic disc

Thickness of the planar structure as a function of the number of satellites involved



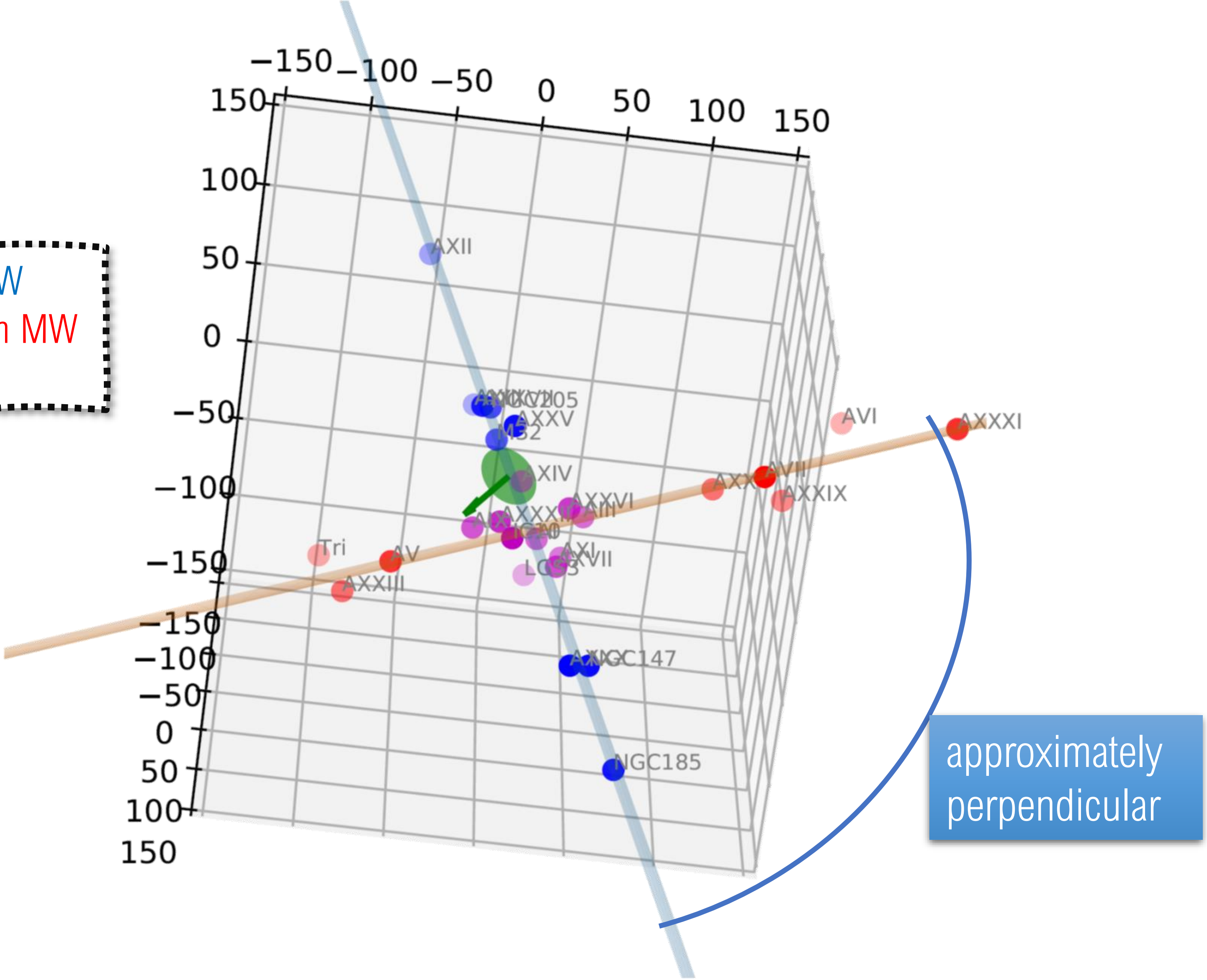


Two distinct planar structures, perpendicular to each other



There are two perpendicular planes of satellites in Andromeda, with similar ‘qualities’ (i.e., number of satellites involved, thickness) Santos-Santos+20a

Peak 1 (GPoA; Nsat=19) Observed edge-on from MW
Peak 2 (New plane; Nsat=18) Observed face-on from MW
Common satellites (Nsat=10)



Planes of satellites around LCDM simulated disc galaxies

SATELLITES ARE SPATIALLY ORGANIZED IN PLANES DURING THE ENTIRE EVOLUTION OF THE SYSTEM Santos-Santos+20b

PDEVA-5004

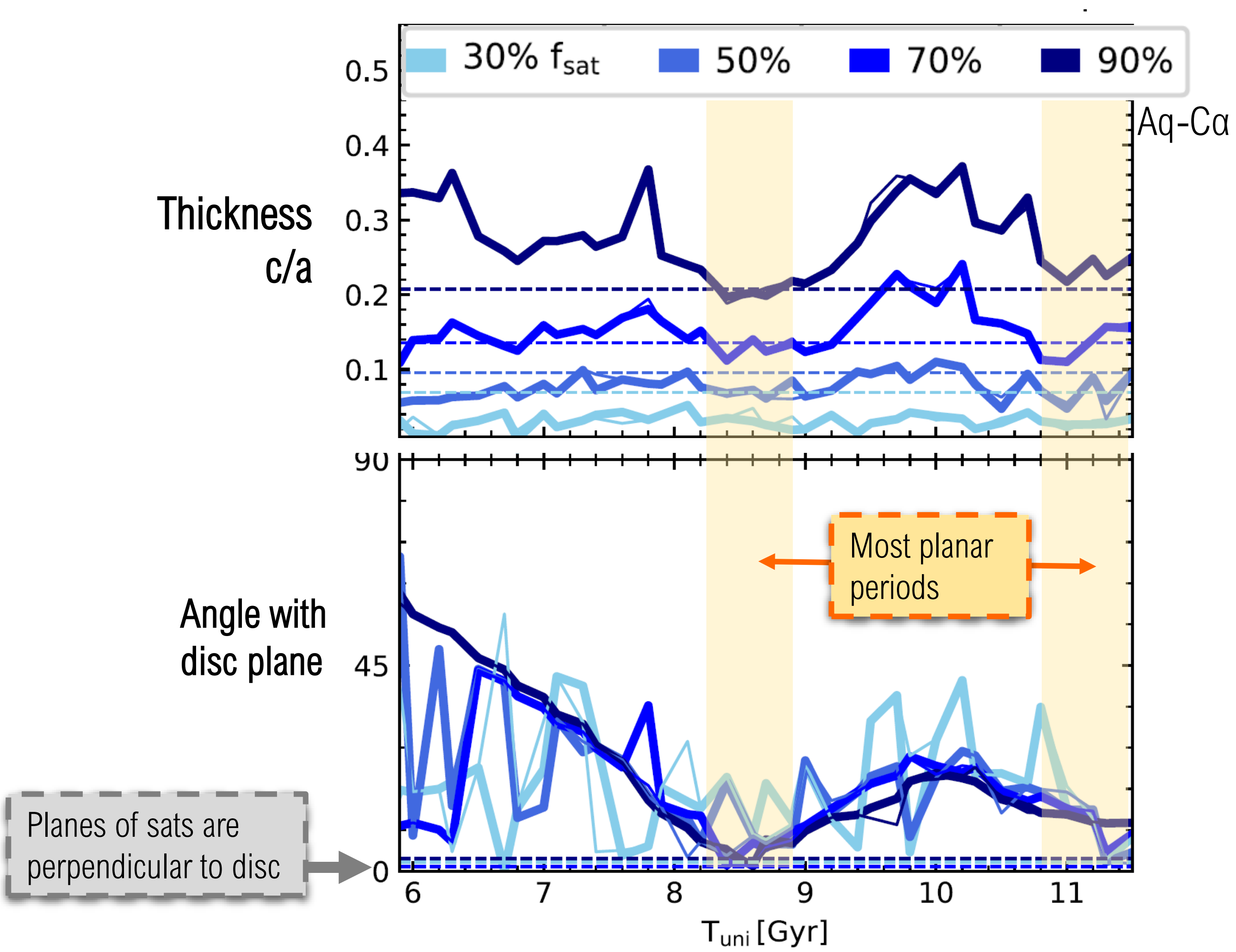
Serna+03,Domenech-Moral+12; Dominguez-Tenreiro+15

Aquarius-Cα

Springel+08, Pedrosa&Tissera15

- ✓ Thin stellar disks
- ✓ High number of satellite galaxies (~30)
- ✓ Quiet merger history after virialization

Thinnest plane found at given time including certain fraction of satellites



Planes of satellites around LCDM simulated disc galaxies

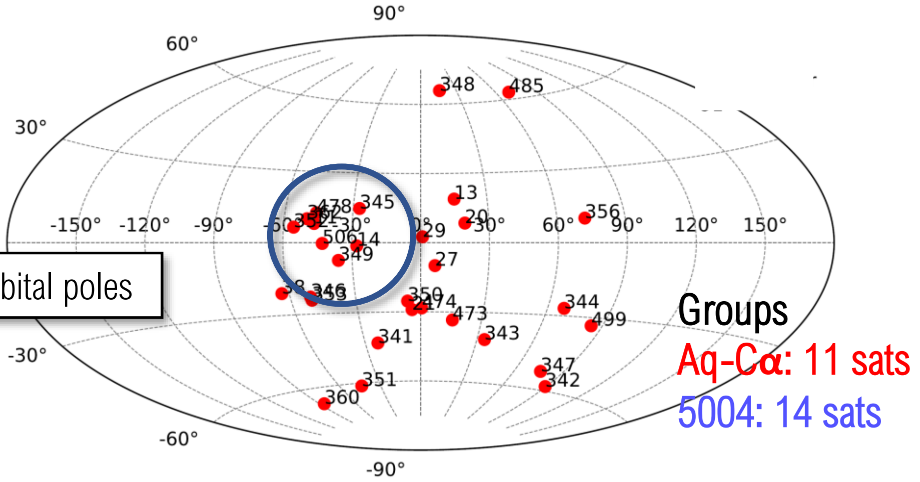
CO-ORBITING SATELLITES DEFINE TIME-PERSISTENT PLANES Santos-Santos et al. In prep

❑ Group of **co-orbiting satellites:** aligned orbital poles

Different to the rest of satellites:

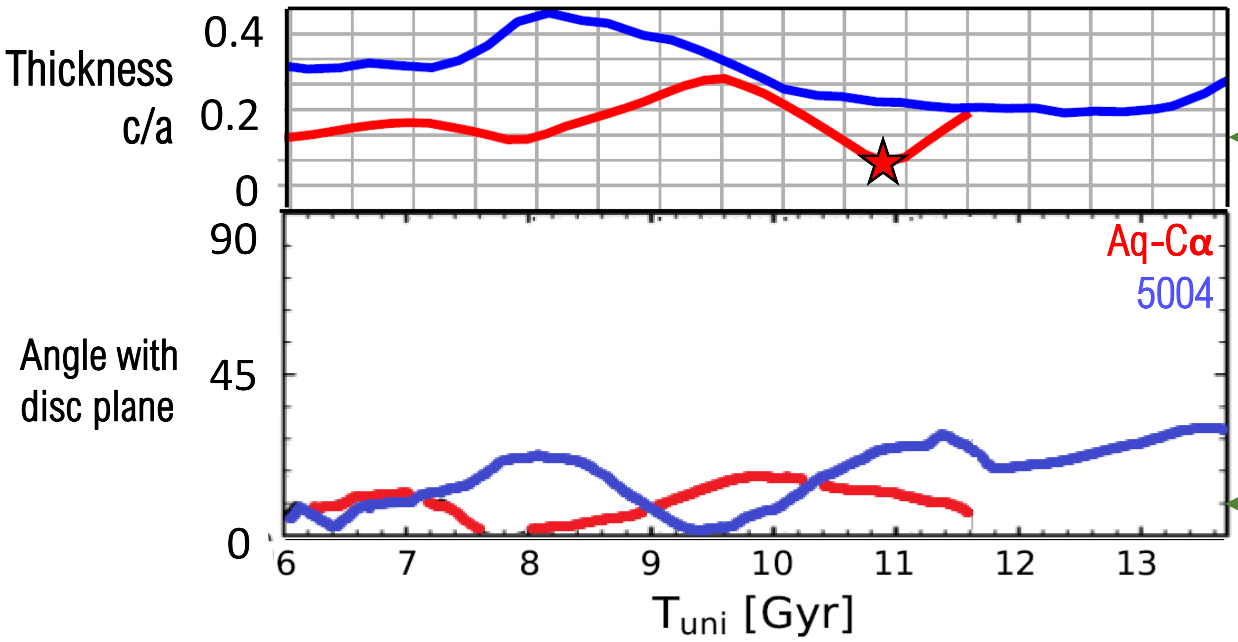
- Higher specific orb.ang.mom
- Orbit at larger radial distances from host
- Orbit more perpendicularly to galactic disk

Projection of orbital poles



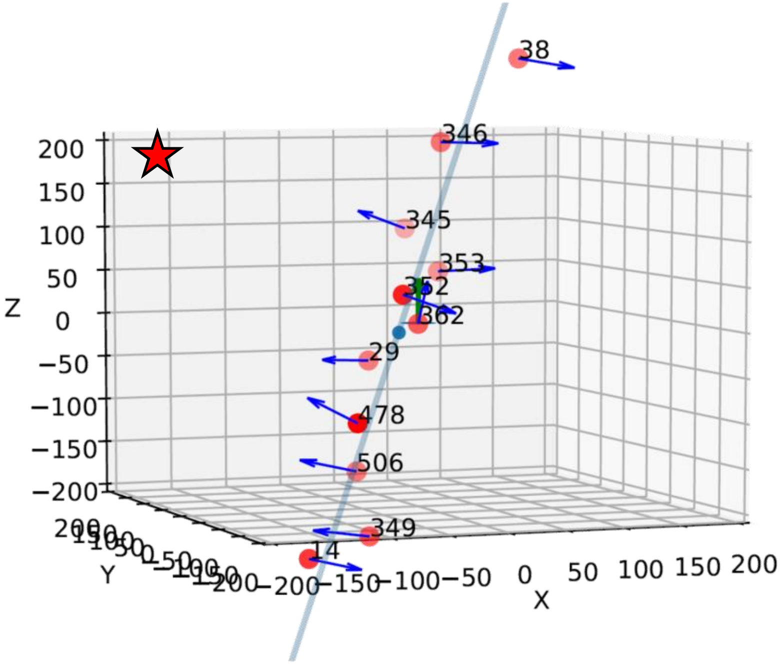
Groups
Aq-Cα: 11 sats
5004: 14 sats

Time evolution of the plane of co-orbiting satellites

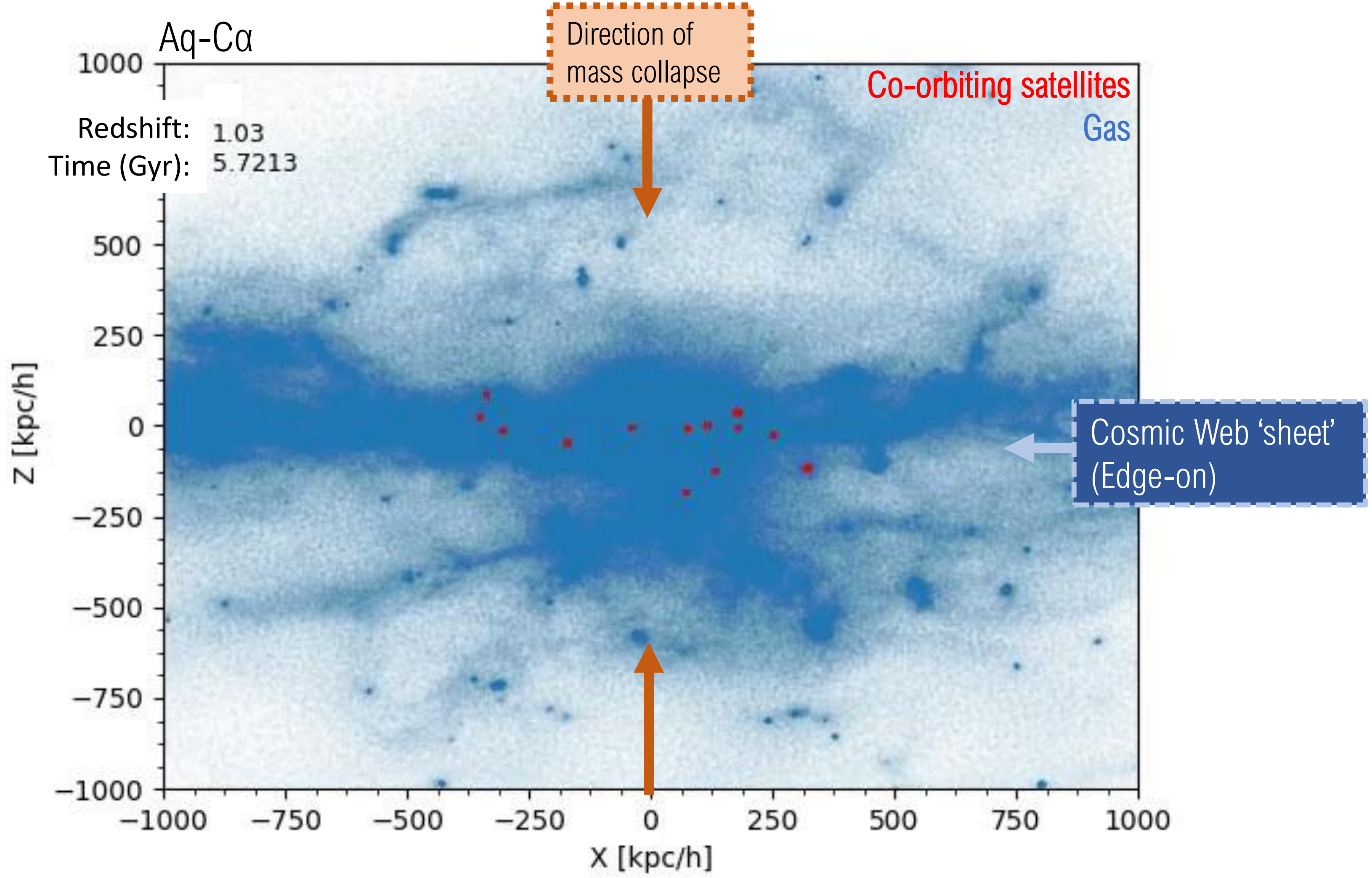


Thin at all times

mostly perpendicular to disc



What is the origin of persistent planes of satellites? Links to the Local cosmic web



Plane of co-orbiting satellites coincides with plane of local Cosmic Web at high-redshift, where mass is accumulating at large scales

- Local Cosmic Web defines, at high-z, the common dynamical properties of kinematically-coherent satellites

  See also Libeskind+12,14,15

- **Overall quiet merger history** allows some of these satellites to conserve their original orbital angular momentum→ persistent plane

Conclusions of this thesis:

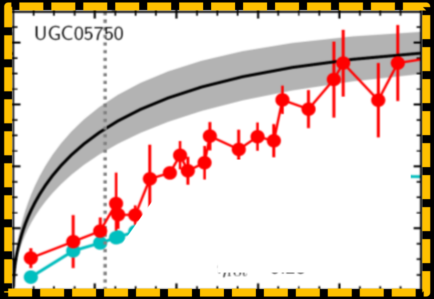
- Dark matter halo expansion can increase the diversity of rc shapes within a lcdm context. In particular, it allows to recover the largest cores observed and can explain the scatter of the mass discrepancy-acceleration relation.

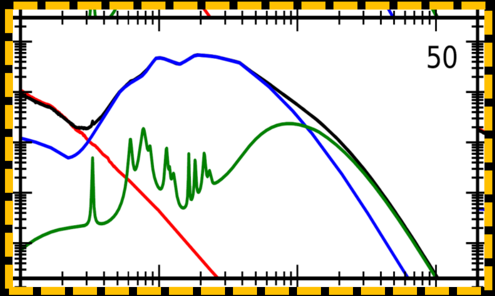
- The particular IR SED features observed in dwarf galaxies can be explained by the two-component dust model in GRASIL-3D (consisting of dense molecular clouds and diffuse cirrus).

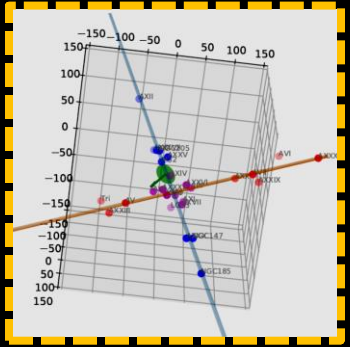
- There is a second plane of satellites in M31 that is similar in thickness to the GPoA and perpendicular to it.

- Satellites around simulated MW-type disc galaxies with quiet merger histories are organized in planar structures. During certain periods of cosmic evolution these are very thin and mostly perpendicular to the galaxy disc.

- Groups of co-orbiting satellites are found around simulated disc galaxies. These define planes of satellites that are persistent in time. Their origin may be linked to the local cosmic web at high redshift.







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M87; Credit: ESO