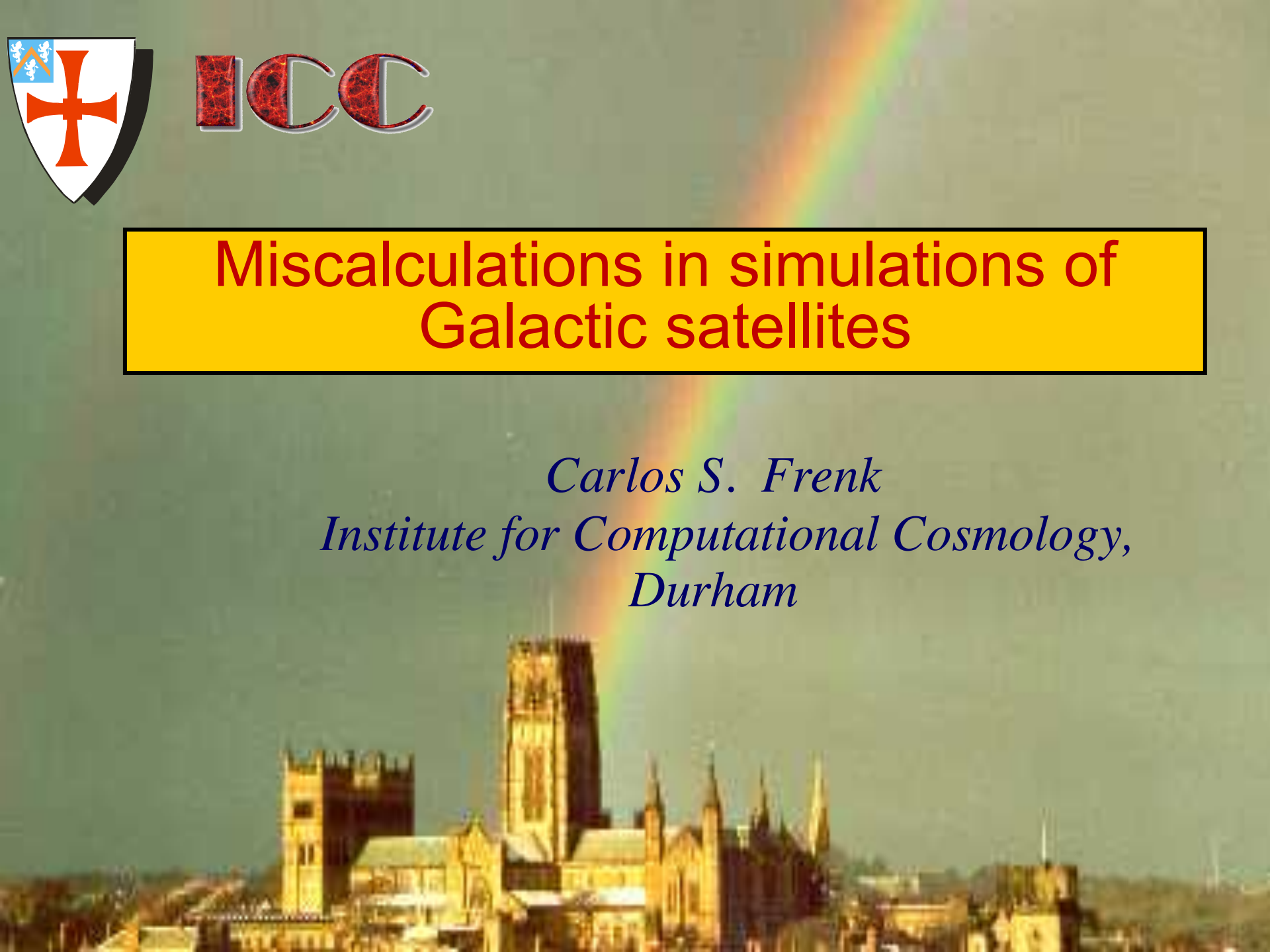

Miscalculations in simulations of Galactic satellites

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

The smallest galaxies

- Key to understanding galaxy formation
- May reveal the identity of the dark matter

The faintest dwarfs have ~10 – 10^5 M_o

→ can only be seen as satellites of the Milky Way

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The smallest galaxies

How much resolution is required to simulate the smallest galaxies?

Gas: the highest-resolution hydro galaxy simulations (Auriga, Apostle, Fire), have gas mass resolution ~10^4 M_o

→ Cannot study ultra-faint galaxies with current hydro simulations

Dark matter: resolution of ~10^5 M_o is enough

→ Can study ultra-faint galaxies with semi-analytic models

→ Galform

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A galaxy formation primer

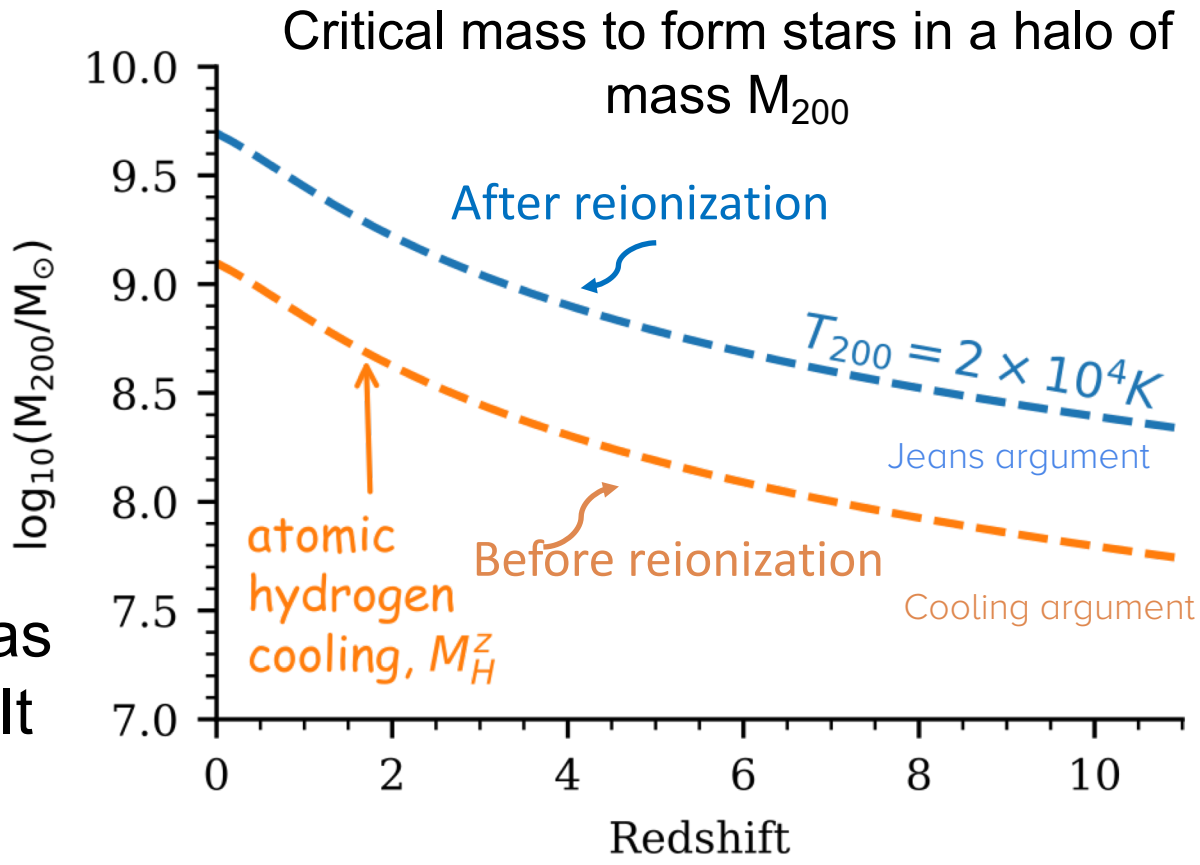
In which halos do galaxy form?

1. Before reionization, stars can only form if atomic H cooling is effective: → T>7000 K

$$M_H^z \sim (4 \times 10^7\ M_\odot) \left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2x10^4$ K



Benitez-Llambay & CSF '20

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A galaxy formation primer

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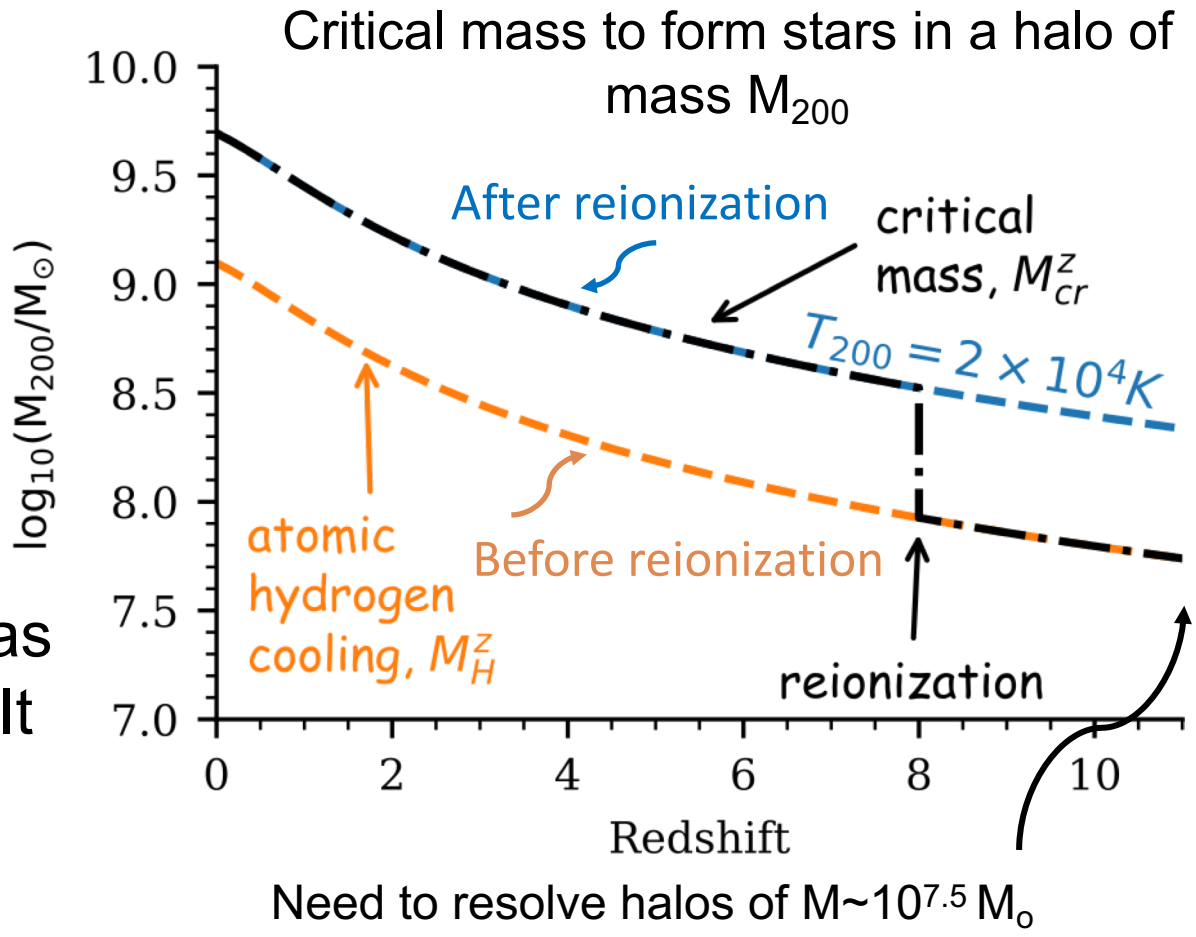

Need to resolve halos of M~10$^{7.5}$ M$_o$

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A galaxy formation primer

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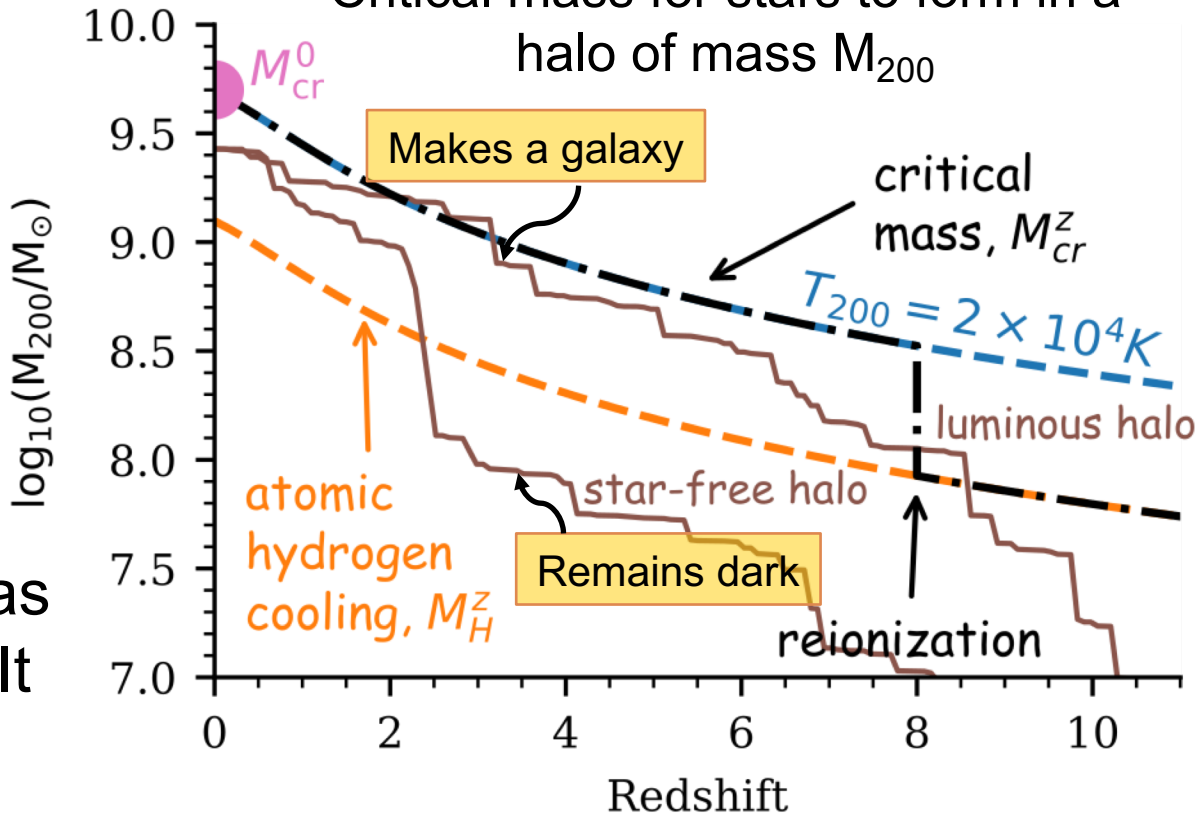
Critical mass for stars to form in a halo of mass M_{200}



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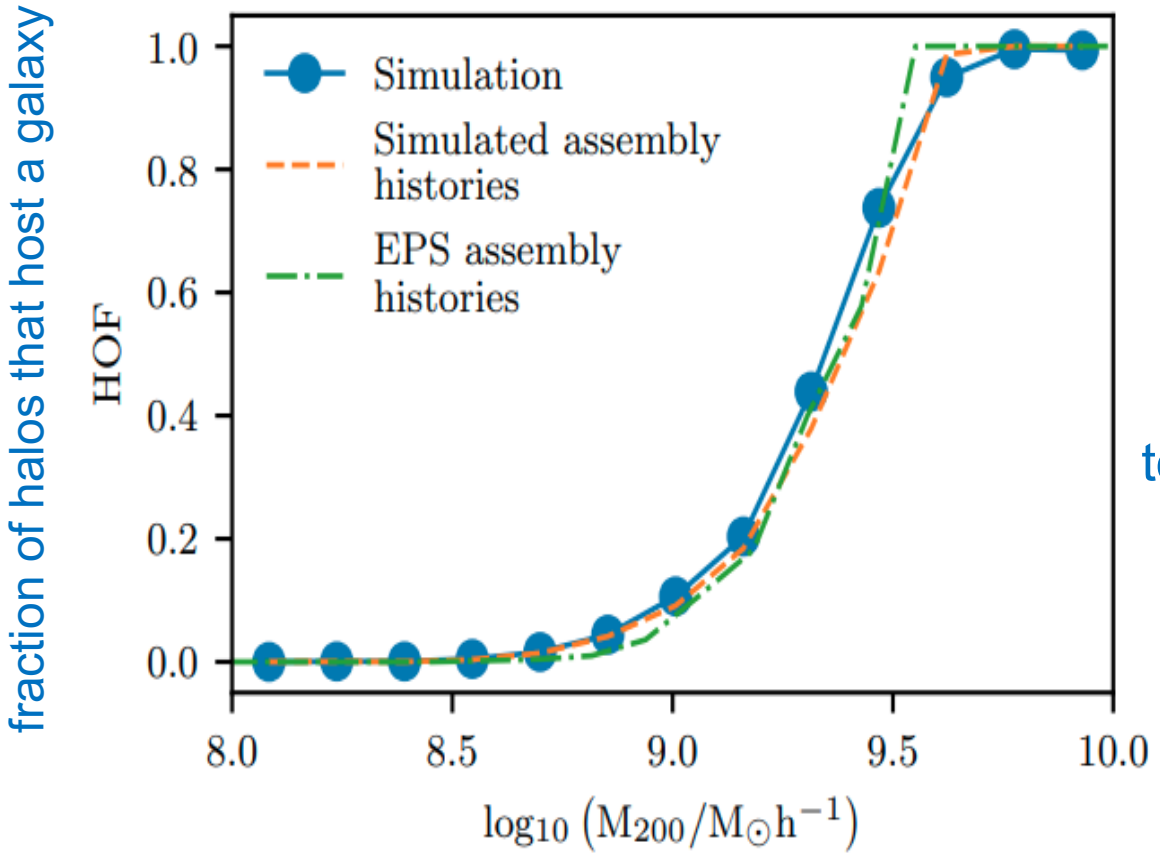
A galaxy formation primer

Halo Occupation Fraction (HOF): fraction of halos of a given mass TODAY that host a galaxy



Halos of $M<3\times10^8 M_o$ today have NO galaxy

Halos of $M>5\times10^9 M_o$ today all have a galaxy

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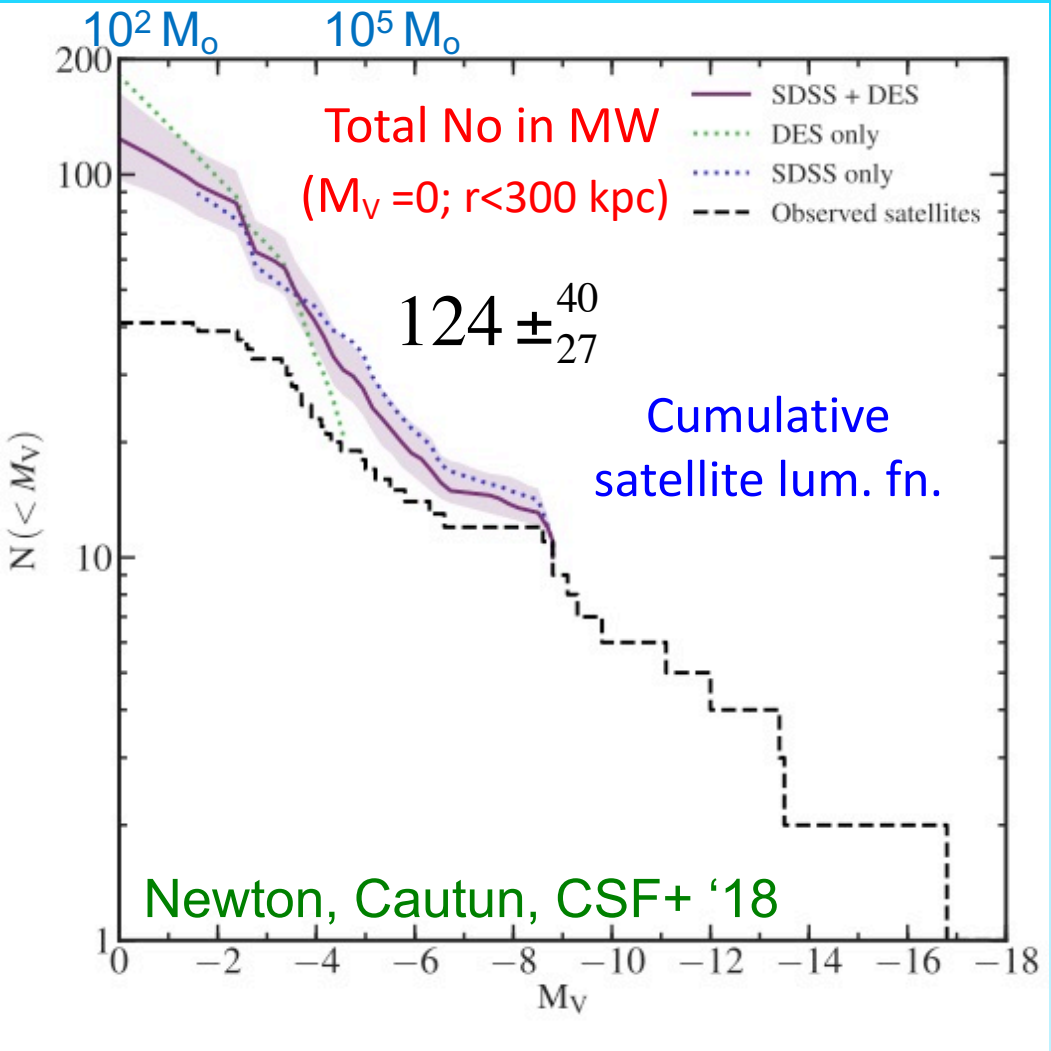
The MW satellite luminosity function

About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)



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The MW satellite luminosity function

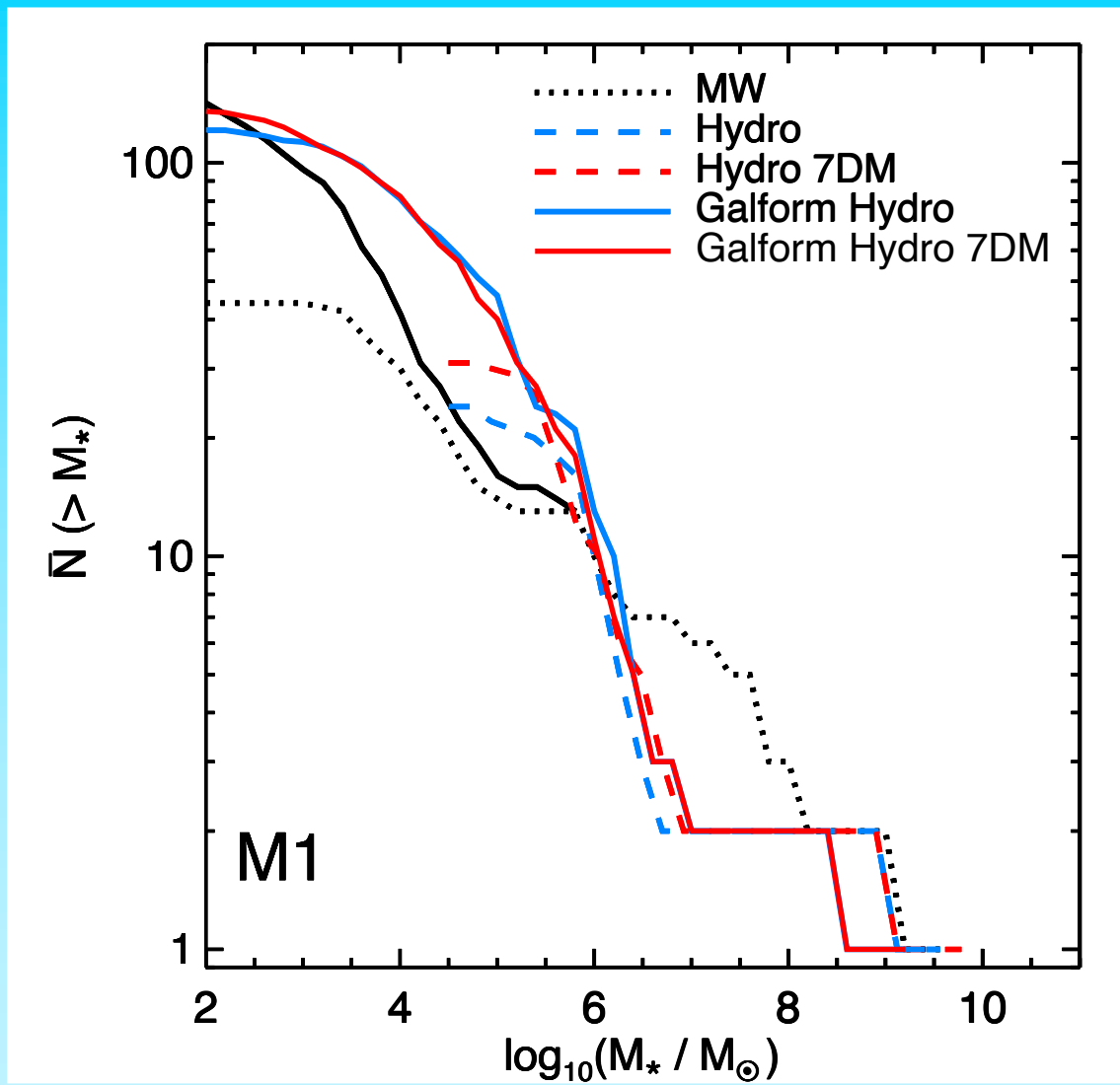
Comparison of hdyro simulations and Galform

The “Magpie” project: Eagle resimulations of MW analogues

Gas mass ~10^5 M_o

DM mass ~10^6 M_o

~10^5 M_o (7DM)



Shao, Cautun, Frenk ‘22

The importance of "orphan" galaxies

Orphan galaxies: satellites that lost their halos due to resolution effects

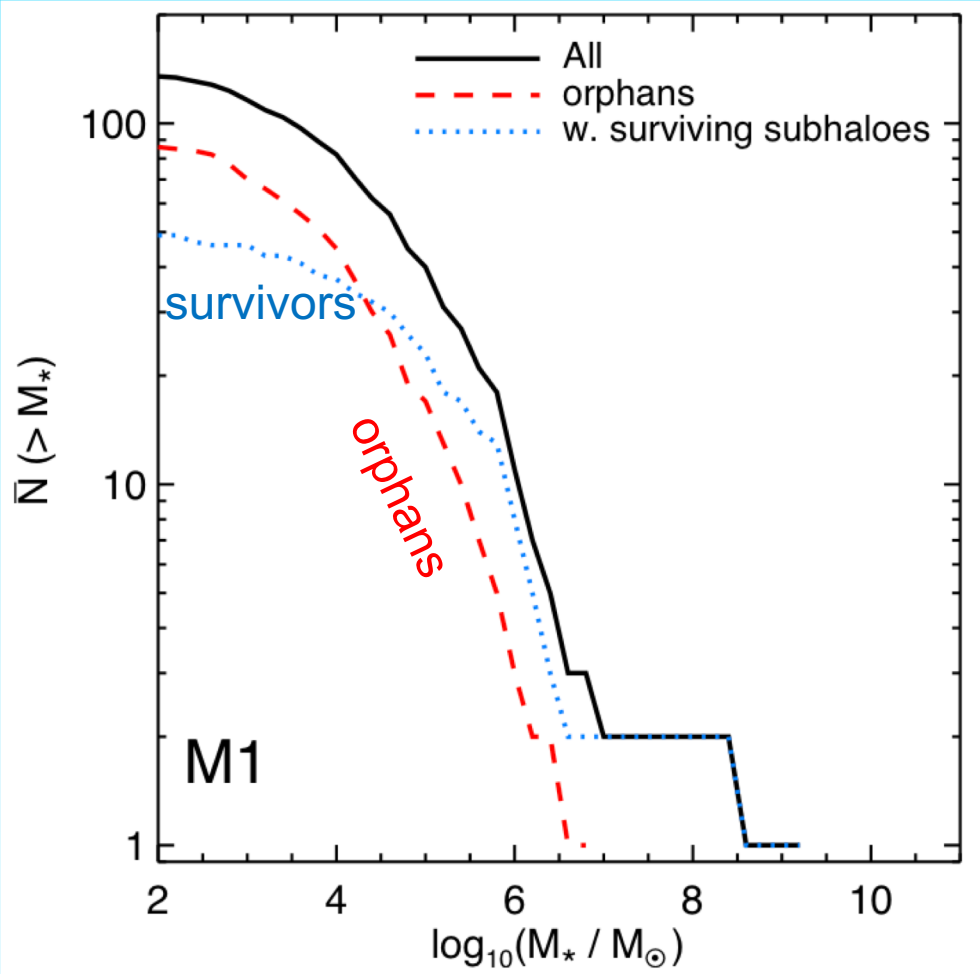
Galform applied to the Magpie hydro simulation merger trees

Magpie:

Gas mass ~10^5 M_o

DM mass ~10^6 M_o

~10^5 M_o (7DM)



- ~2/3 of ultrafaints are orphans
- Even relatively bright satellites can be orphans

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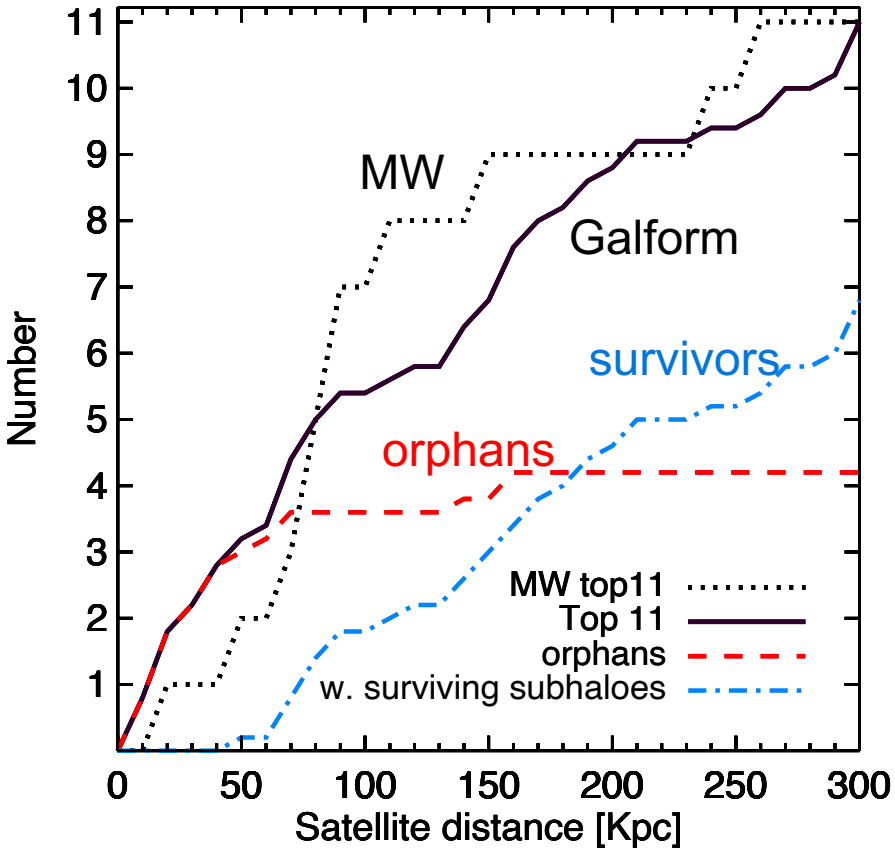
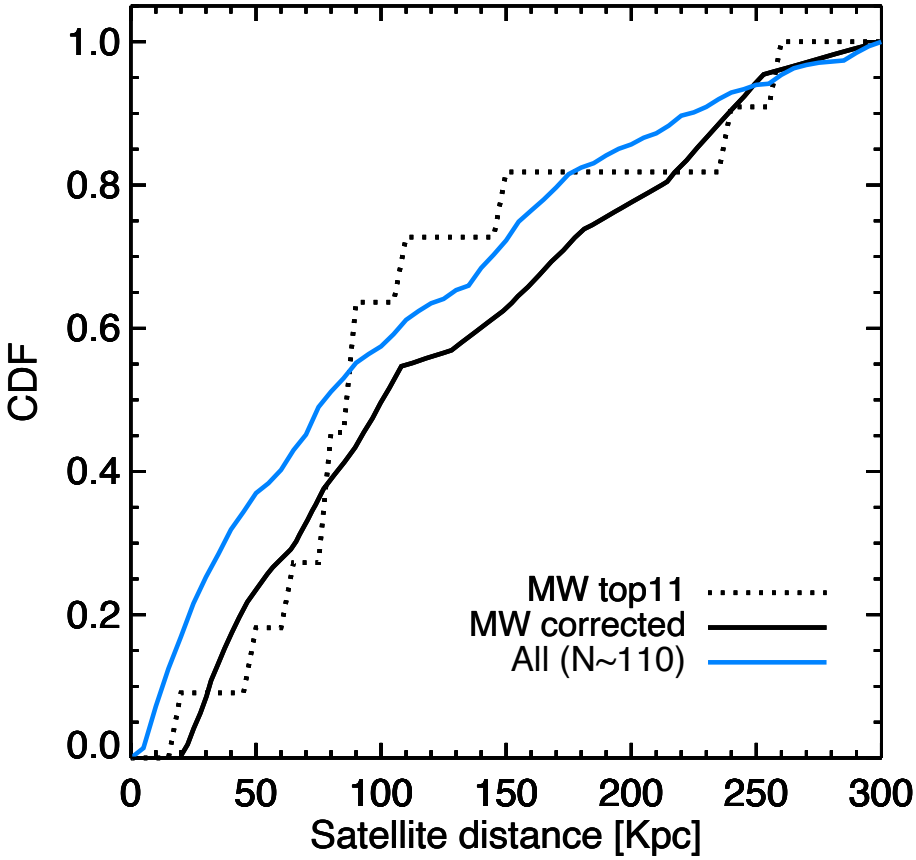
The MW satellite radial distribution

Where are the orphans?





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The plane of satellites in the MW

Sibelius project

Constrained realizations of the local universe (w. BORG & SWIFT)

Till Sawala, Marius Cautun, Carlos Frenk, John Helly, Jens Jasche, Adrian Jenkins, Peter Johansson, Guilhem Lavaux, Stuart McAlpine, Matthieu Schaller

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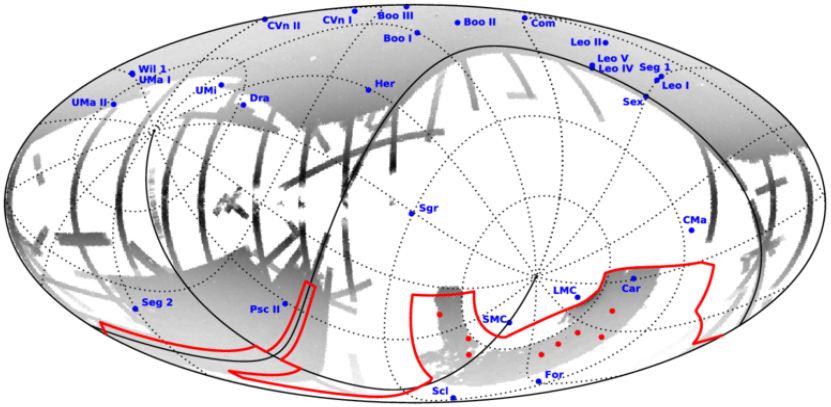
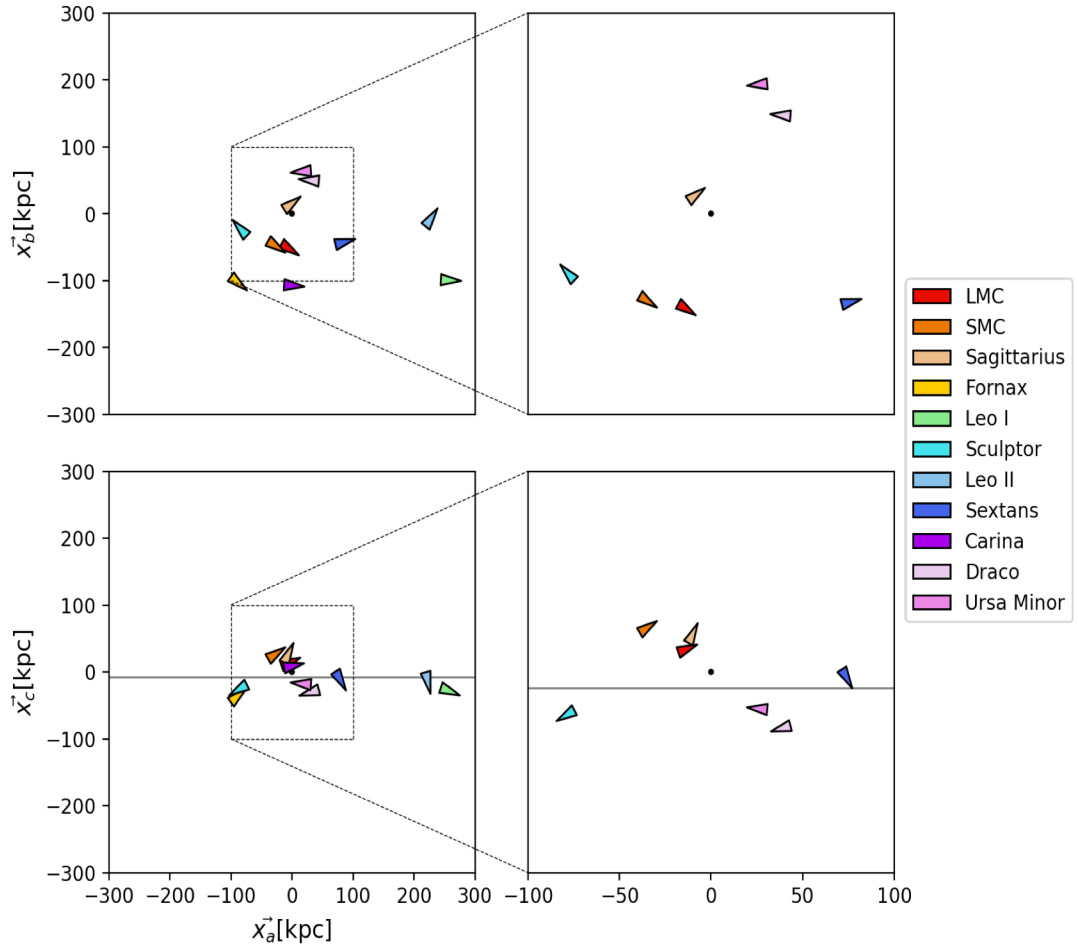
The plane of satellites in the MW

Problem: the 11 "classical" Milky Way satellites are in a thin, possibly rotating plane (Lynden-Bell 1976)



Bechtol+ 2015



Sawala, Cautun, CSF et al '22

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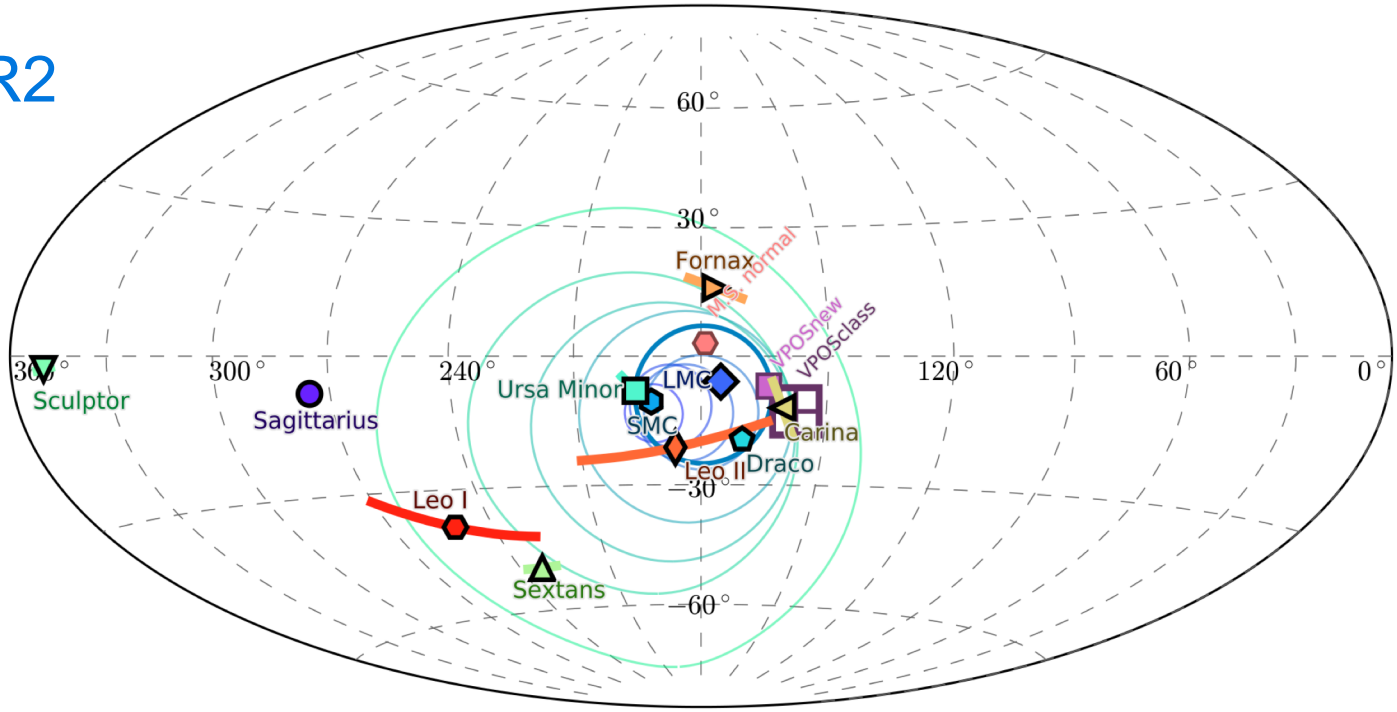
The plane of satellites in the MW

The plane could be a spinning disk

The orbital poles of 7 of the 11 satellites are clustered

GAIA DR2



Pawlowski & Kroupa (2020)

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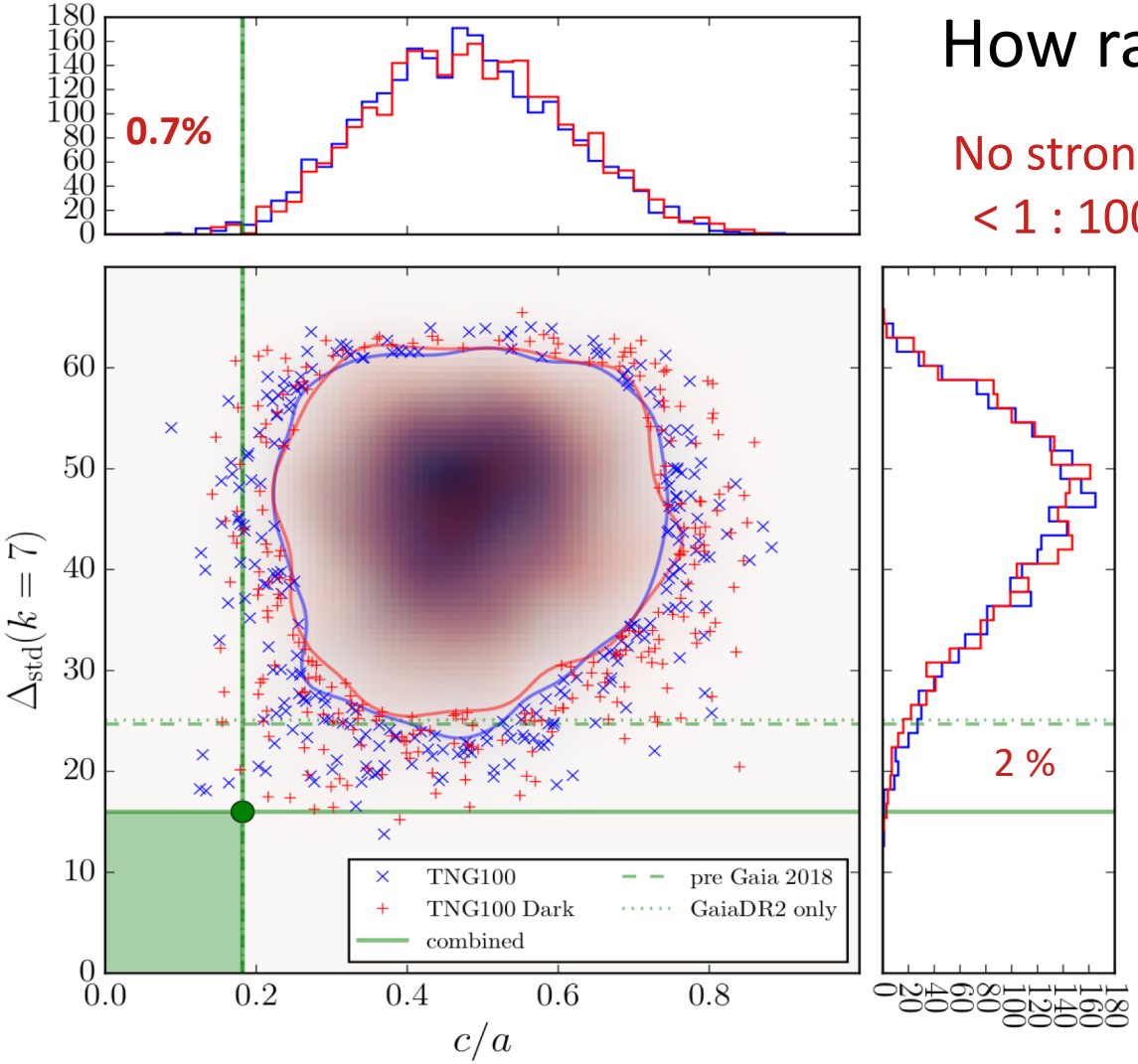
The plane of satellites in the MW



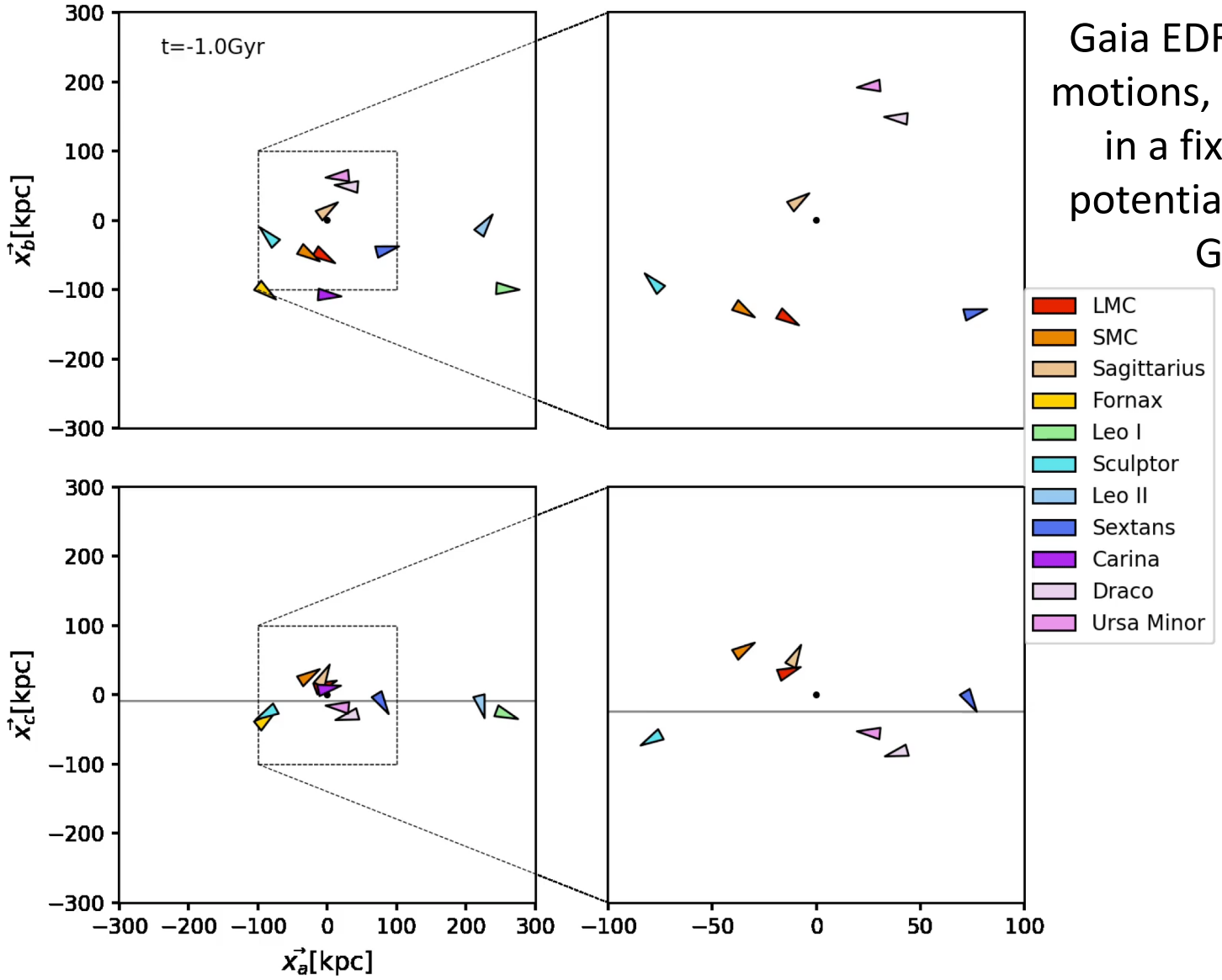
How rare is it?

No strong correlation –
< 1 : 100,000 chance?

Eigenvalues of inertia tensor

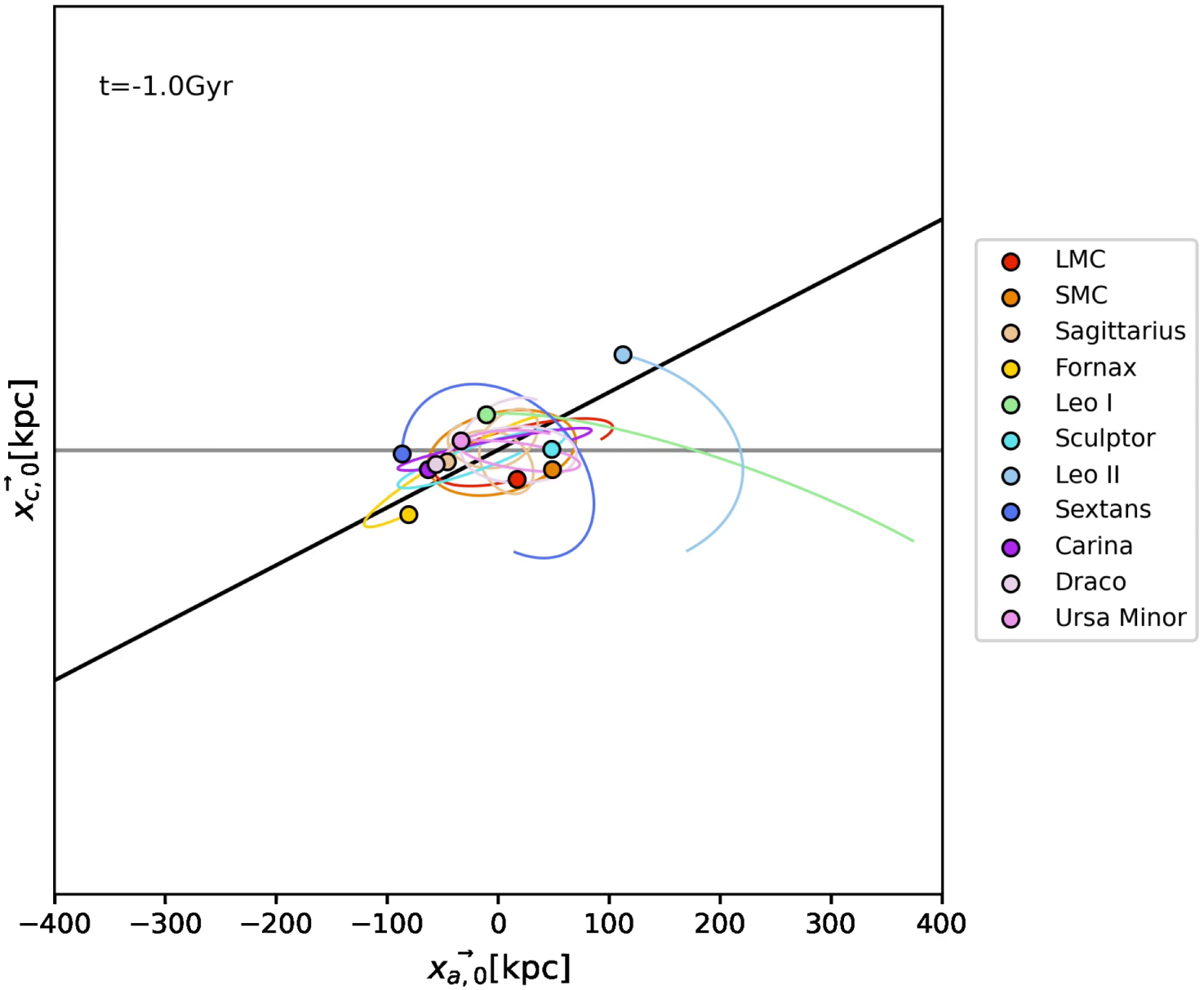
a>b>c

Pawlowski & Kroupa (2020)



Gaia EDR3 proper motions, integrated in a fixed MW potential for +/- 1 Gyr.

Sawala, Cautun, CSF et al ‘22


t=-1.0Gyr
LMC
SMC
Sagittarius
Fornax
Leo I
Sculptor
Leo II
Sextans
Carina
Draco
Ursa Minor
−400
−300
−200
−100
0
100
200
300
400
$x_{a,0}^{\vec{}}$[kpc]
$x_{c,0}^{\vec{}}$[kpc]

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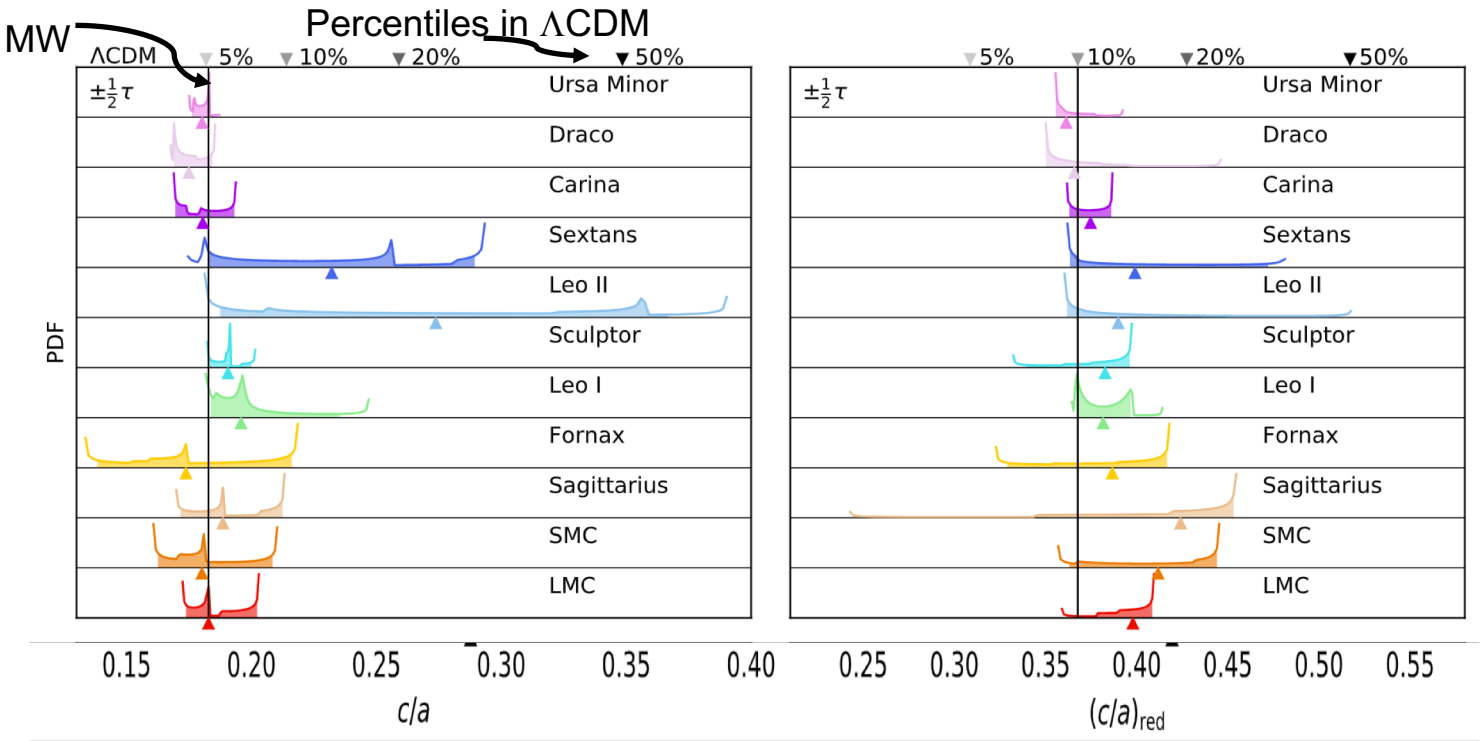
The plane of satellites in the MW



Each satellite integrated for one orbital period, with the other 10 satellites fixed

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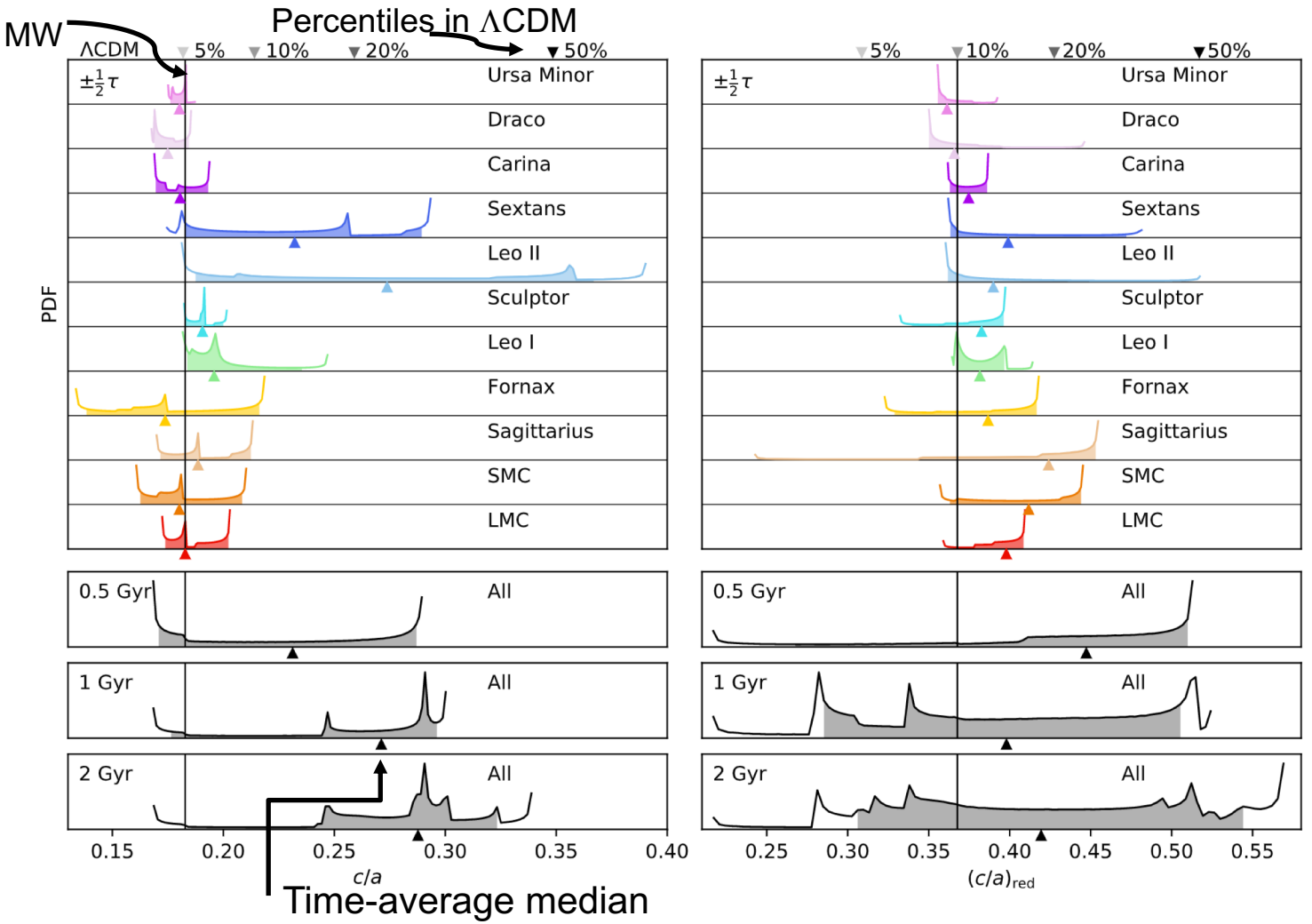
The plane of satellites in the MW



Each satellite integrated for one orbital period, with the other 10 satellites fixed

Simultaneously integrated over the past 0.5, 1 and 2 Gyr.

The present values of c/a and $(c/a)_{red}$ of the MW are unusually low – **for the MW**!

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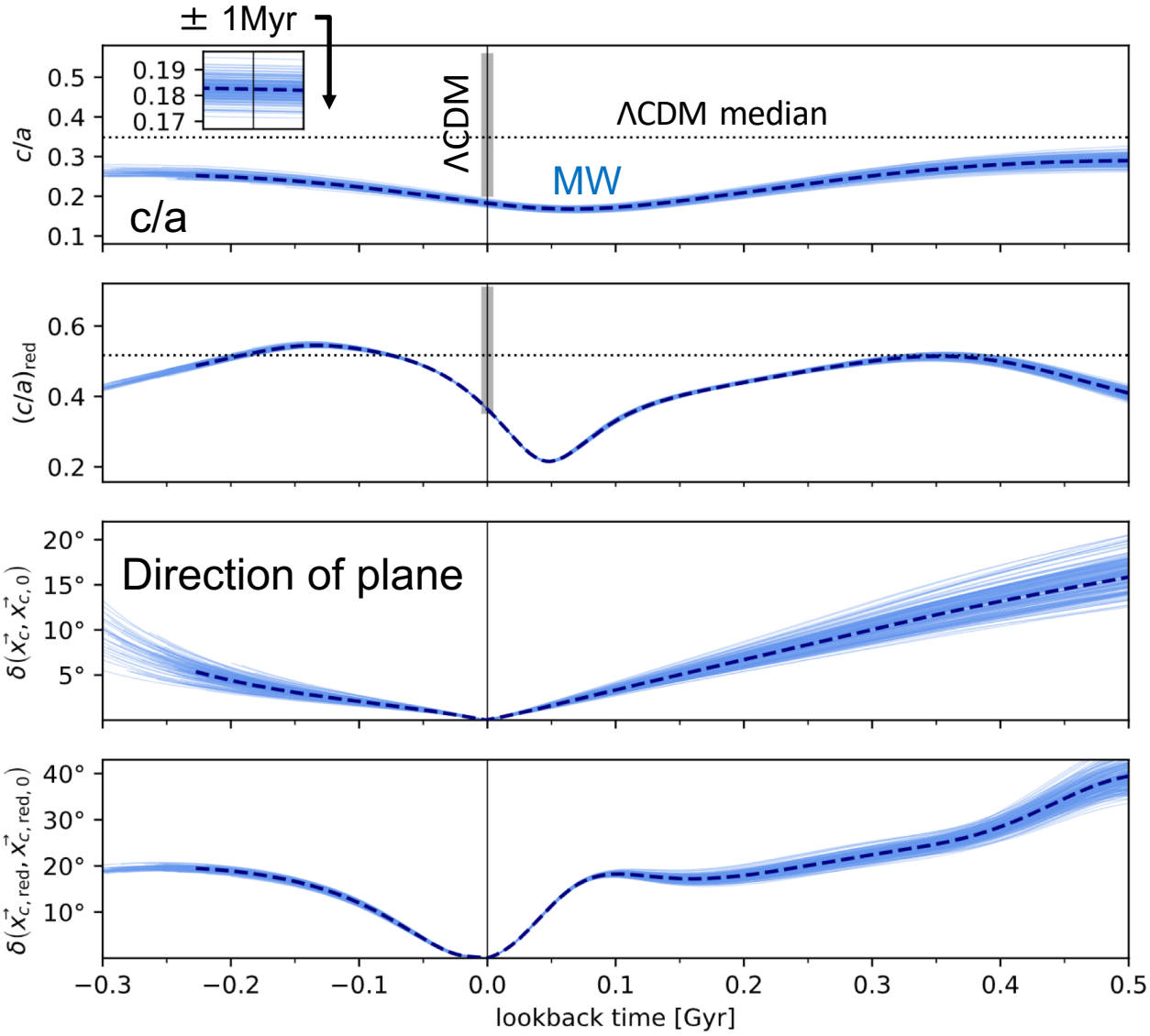
Evolution of the plane of satellites

MW "plane of satellites" is just as transient as equally flattened distributions in our simulations

The plane of satellites is tilting



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The rotating plane of satellites

What about the clustered poles?

- Gaia EDR3: 23 degrees (not 16)
- Look elsewhere effect
- Complete sample of subhaloes (with orphans)

We have 5/200 (2.5%) more clustered than the MW (compared to 0.04%)
Still rare, but not *astronomically* unlikely.

Conclusions

- The smallest galaxies (10 --10^5M) key to gal formation & DM
- Beyond reach of current hydro simulations
- But can be modelled with SA models in DM sims of moderate res.

➢ Orphans are important even at hi res. With orphans:

1. Galform simulations agree with MW sat lum fn and radial distribution → No "too many satellites" problem

2. Flattening (c/a) of MW plane and alignment of orbital poles are not unusual in ΛCDM

➢ The MW plane of satellites is transient → will get fatter in 0.5Gyrs!