A conclusive test of cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

Fundamental predictions of ΛCDM

→ Primordial PS of density perturbations + random phases

Linear regime: cosmic microwave background

Evolved non-linear regime: dark matter halos →

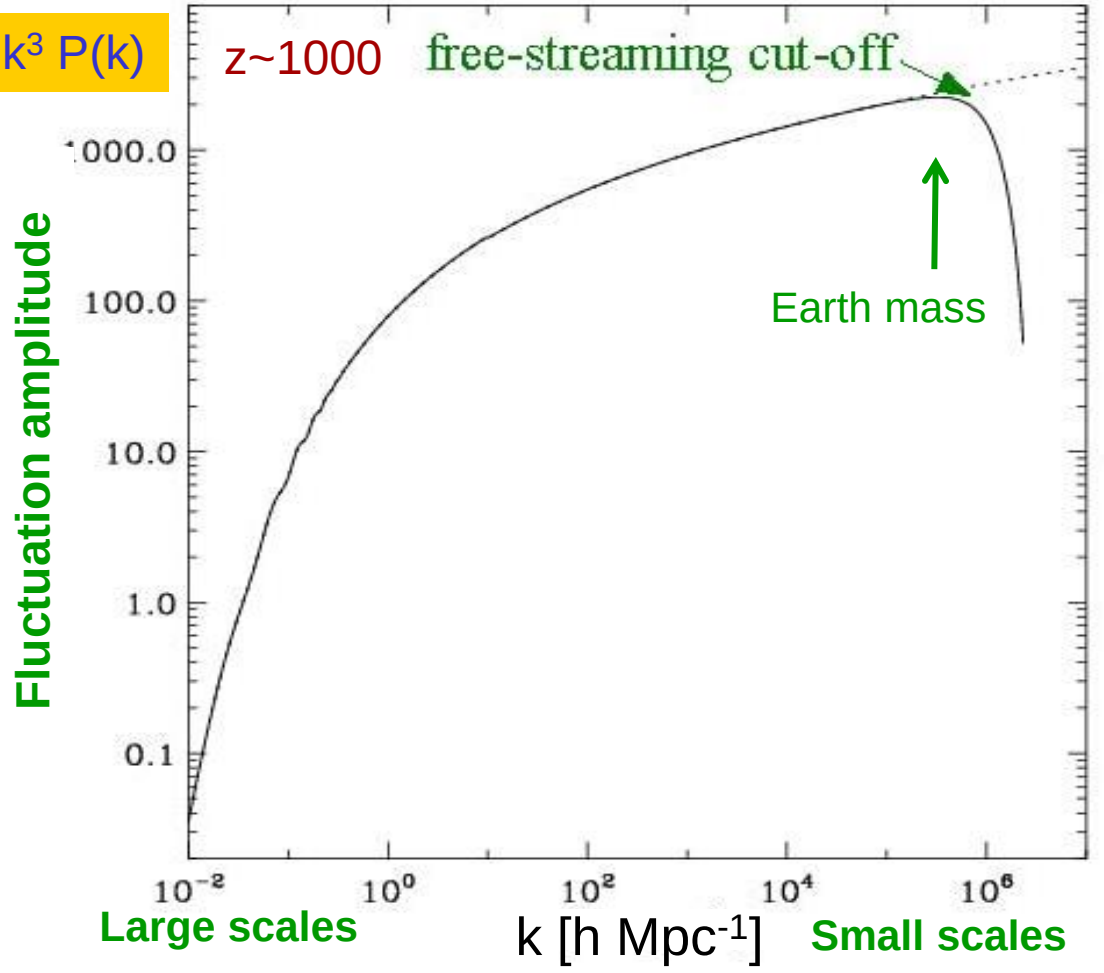
- abundance
- structure
- clustering

University of Durham

The cold dark matter power spectrum

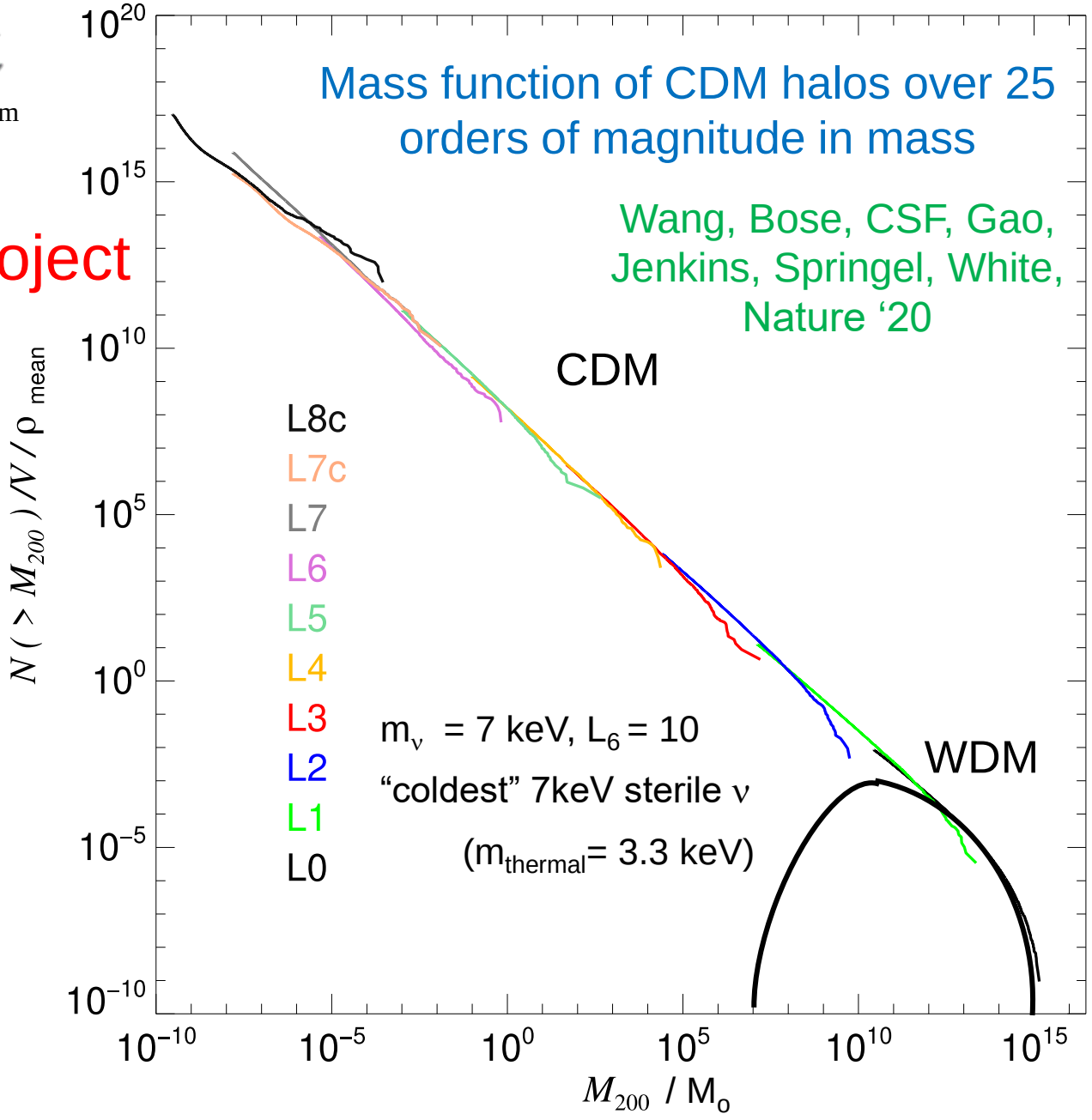
The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04

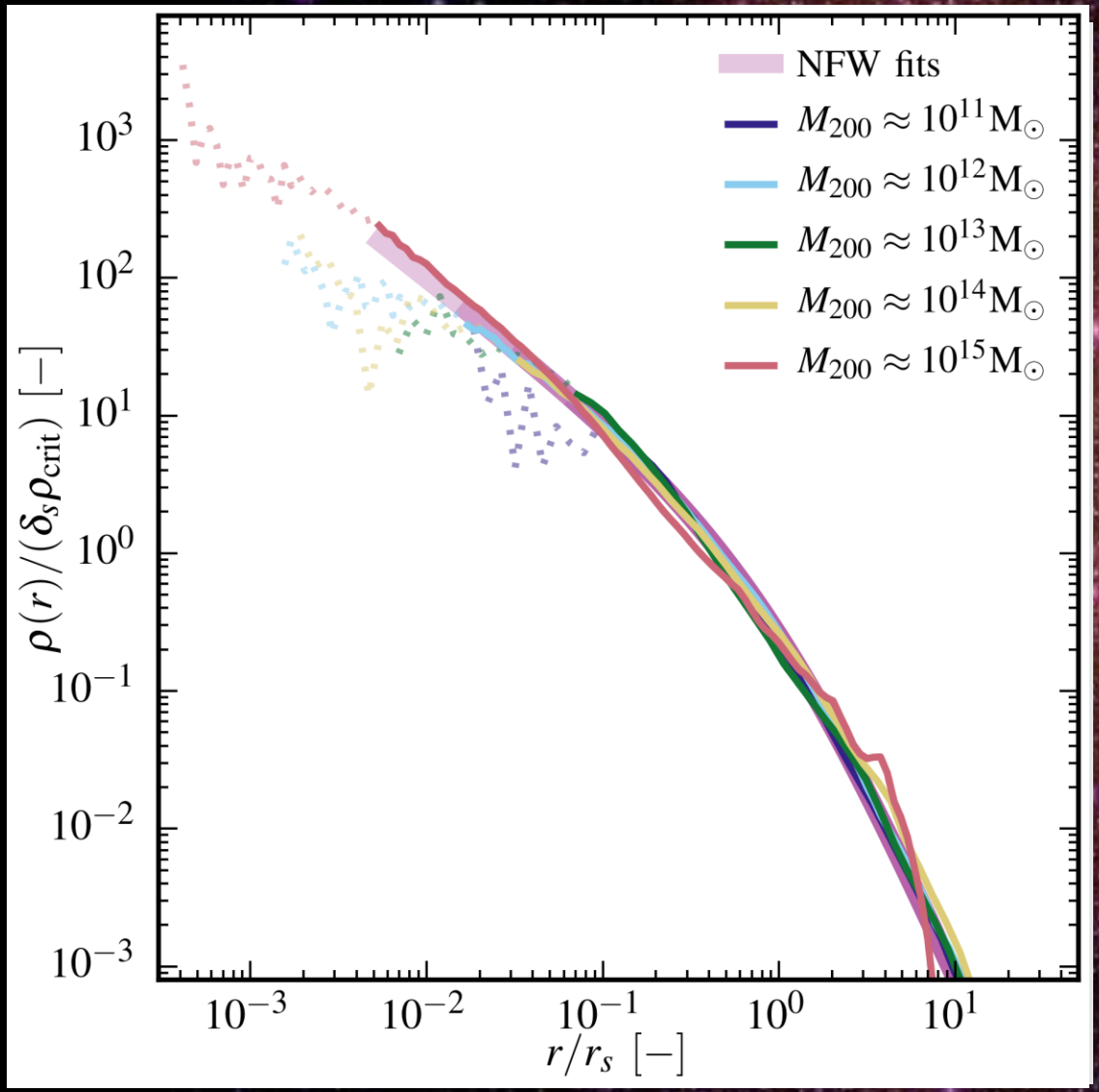


University of Durham

The VVV project



The density profile of cold dark matter halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are “cuspy” - no `core’ near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

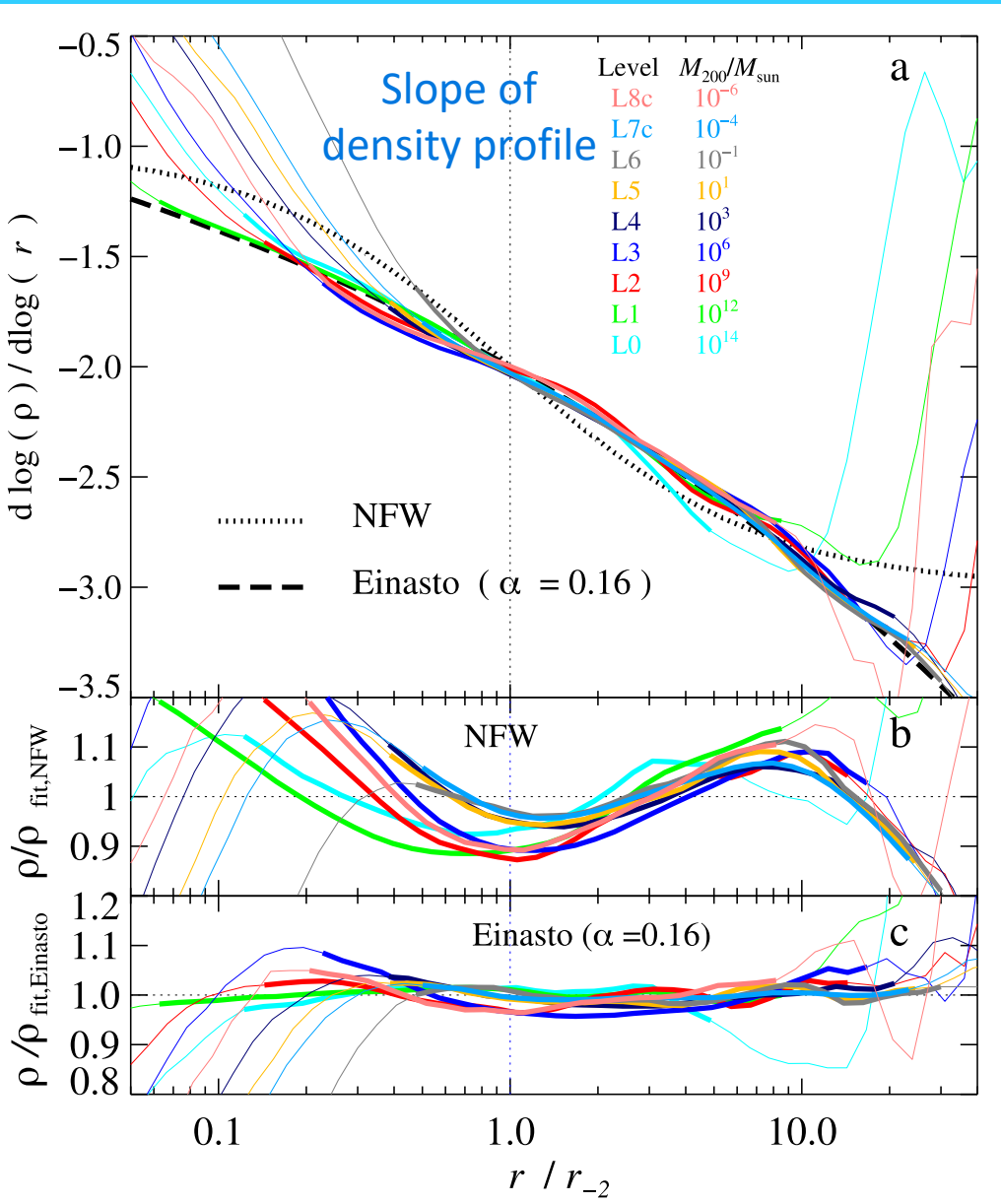
(Navarro, Frenk & White ’97)

More massive halos and halos that form earlier have higher densities (bigger δ)

University of Durham

Density profile shapes

Over 20 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (α =0.16) to within 7%



Wang, Bose, CSF + '20

University of Durham

The small-scale “crisis”: four problems

		“Solved” in:	
1.	“Missing satellites”	2002	Baryon effects
2.	“Too-big-to-fail”	2015	
3.	“Core-cusp”	1996	
4.	“Plane of satellites”	2022	

CDM

DM-only CDM simulations predict many more subhalos in the Milky Way than there are observed satellites

"Missing satellites" problem

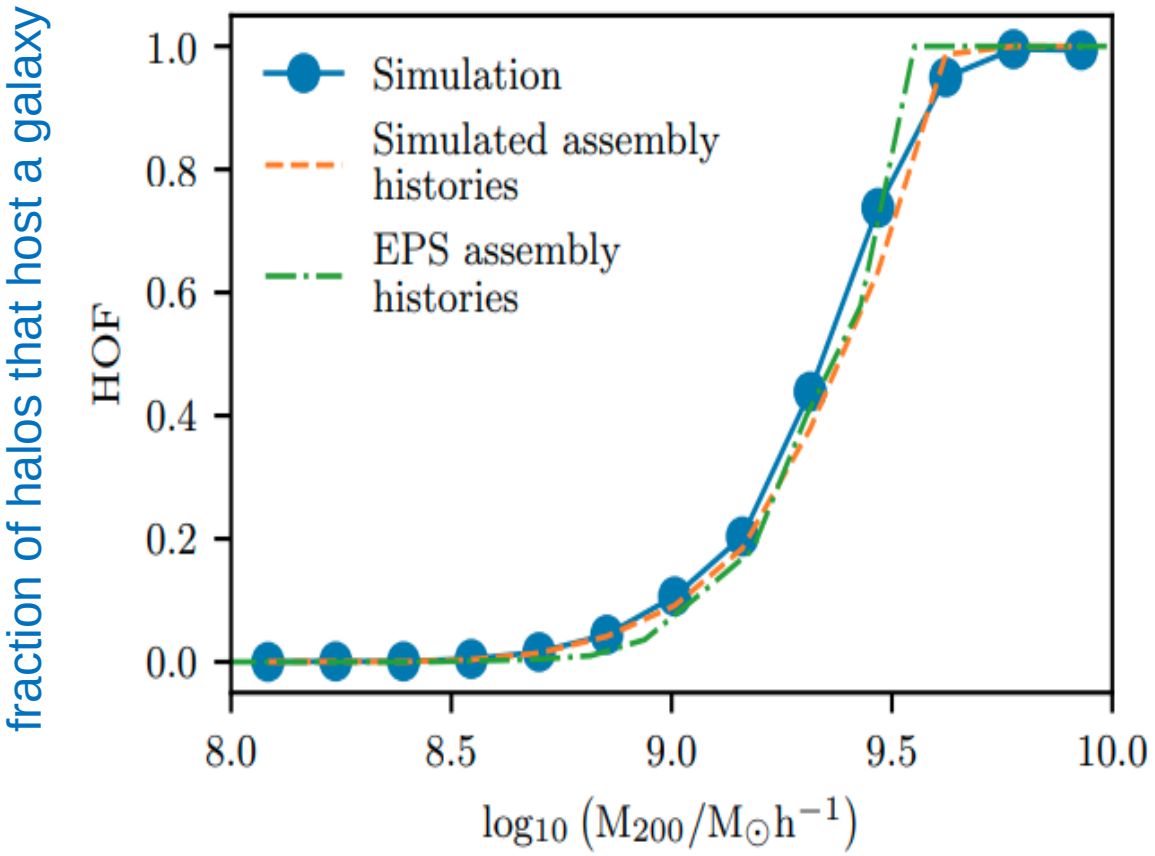
This argument is WRONG!

Most subhalos never make a galaxy!

University of Durham

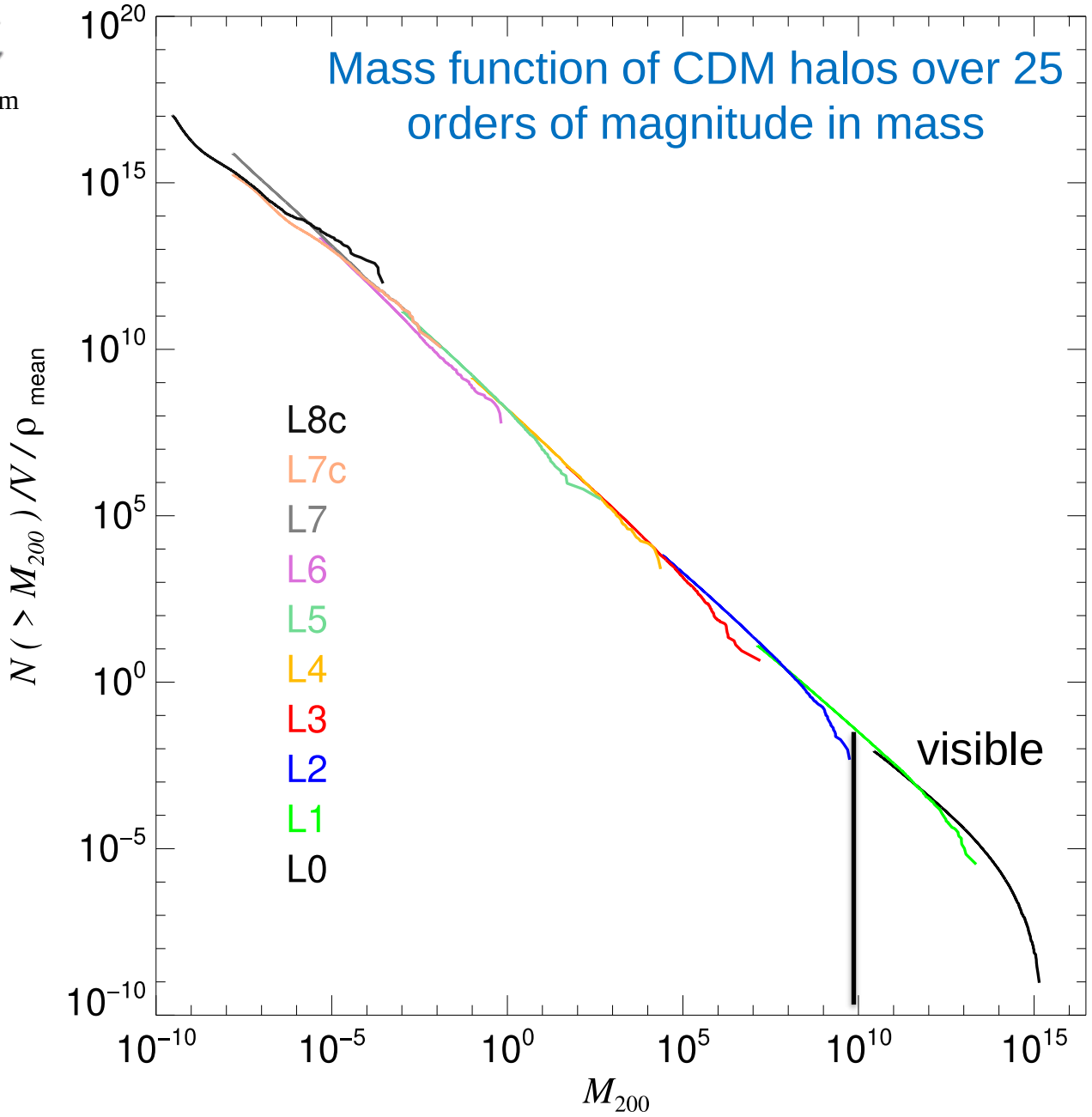
A galaxy formation primer

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



Benitez-Llambay & CSF ‘20

University of Durham

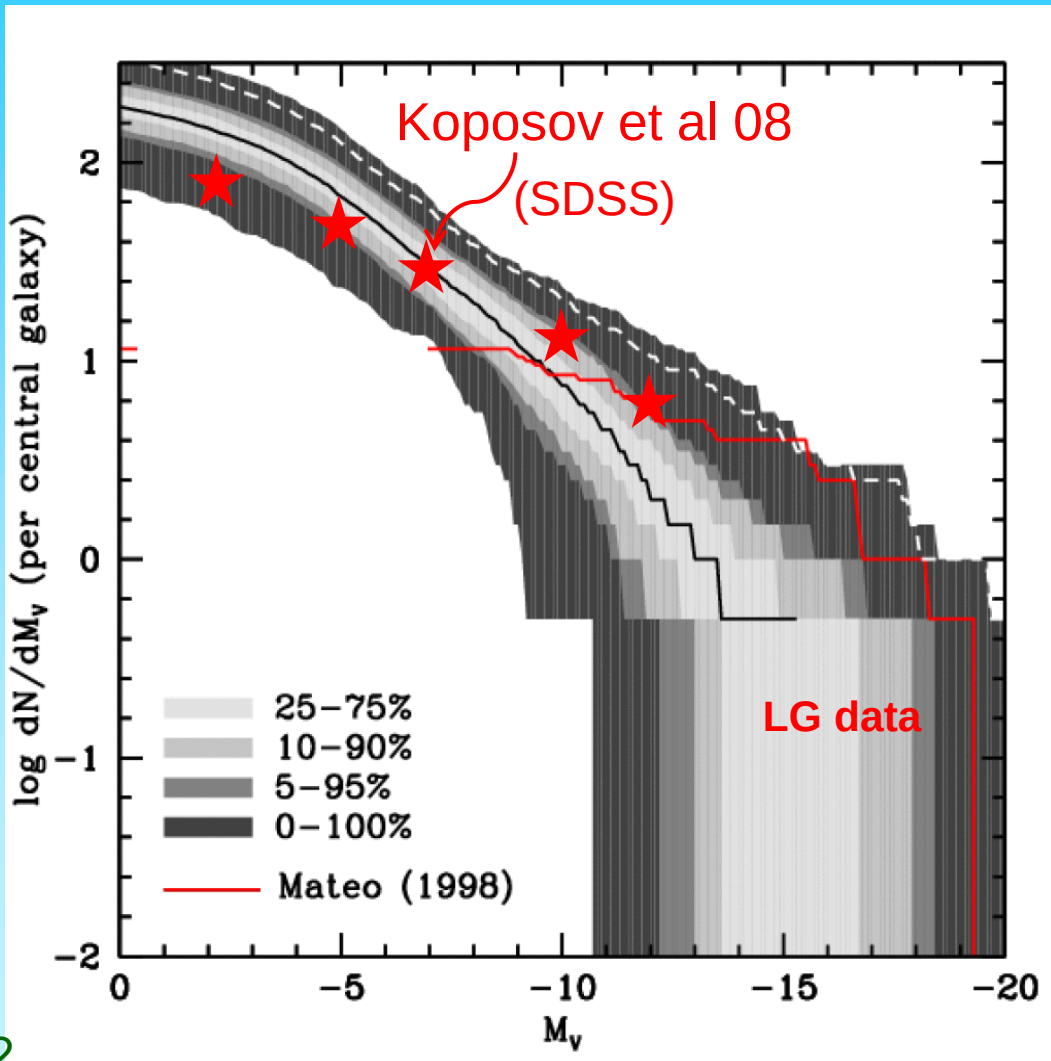


Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

University of Durham

Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

Too-big-to-fail problem

CDM DM-only simulations make ~10 subhalos with V_{max}>30 km/s

MW has only 3 satellites with V_{max}>30 km/s

(LMC, SMC, Sgr)

Too-big-to-fail in CDM: baryon effects

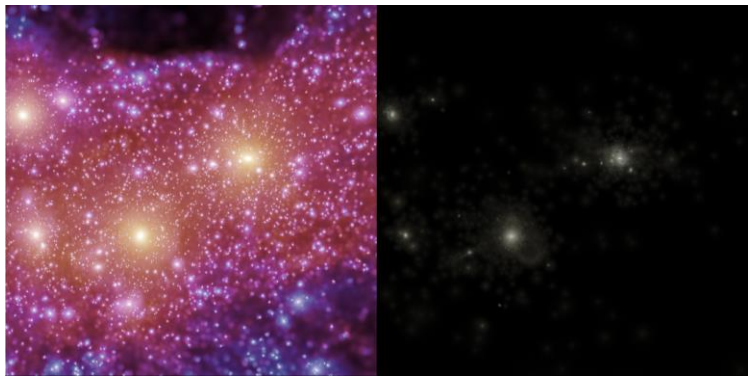
University of Durham

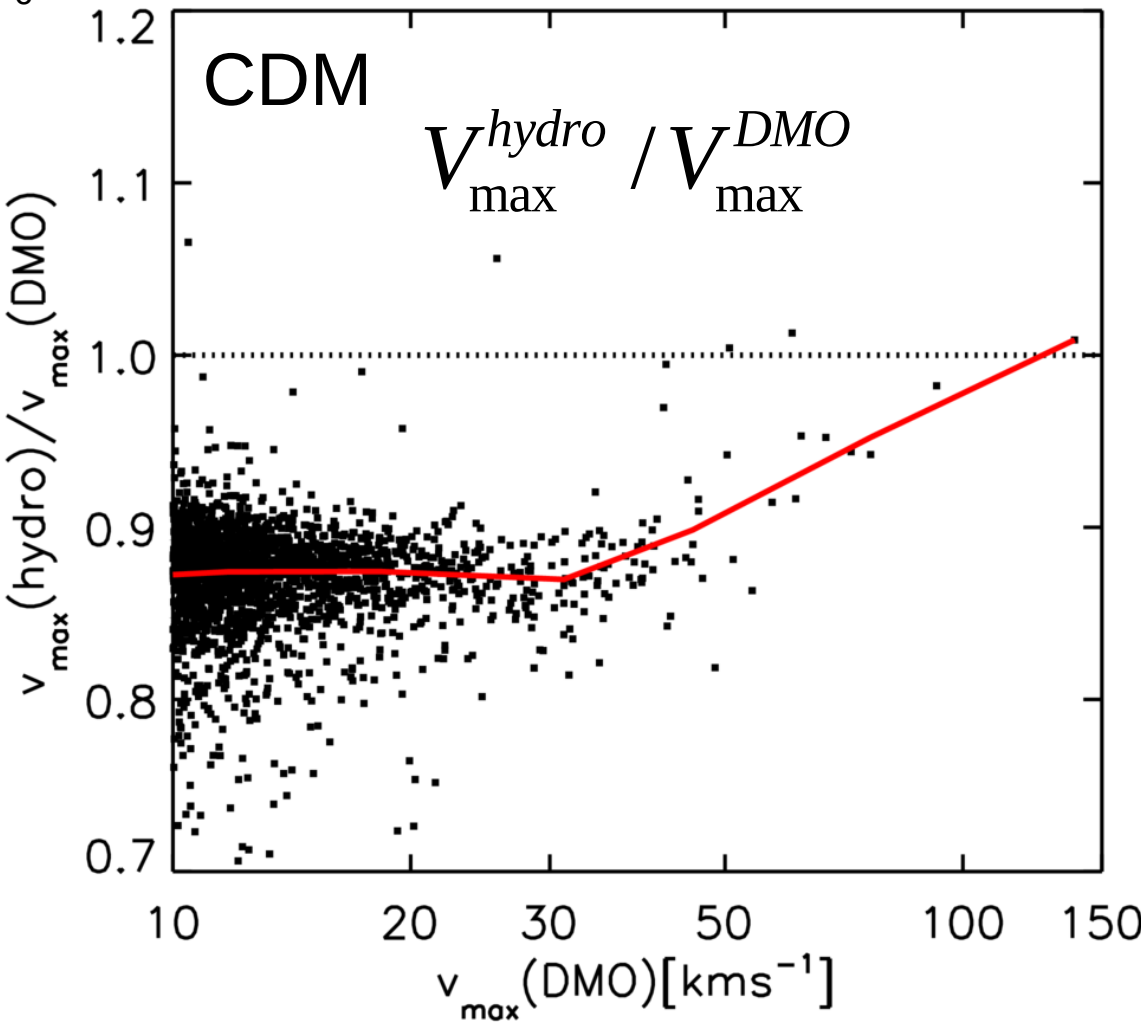
$$V_c = \sqrt{\frac{GM}{r}}$$

$V_{max} = \max V_c$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala, CSF et al. '13, '15

University of Durham

DMO simulations predict NFW profiles

The physics of core formation

DMO simulations predict NFW profiles

Cusps → cores

Perturb central halo region by growing a galaxy adiabatically and removing it suddenly (Navarro, Eke & Frenk '96)

Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

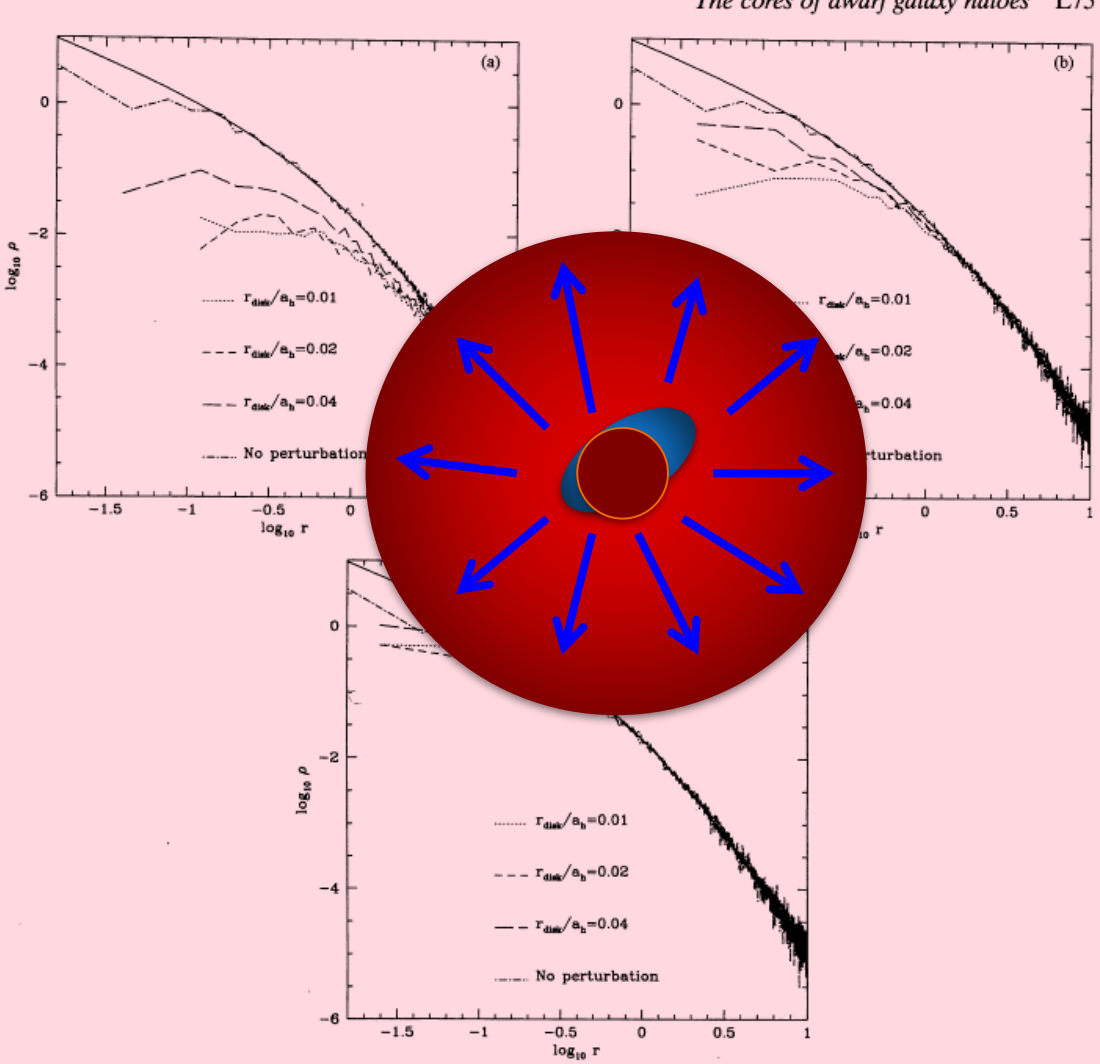
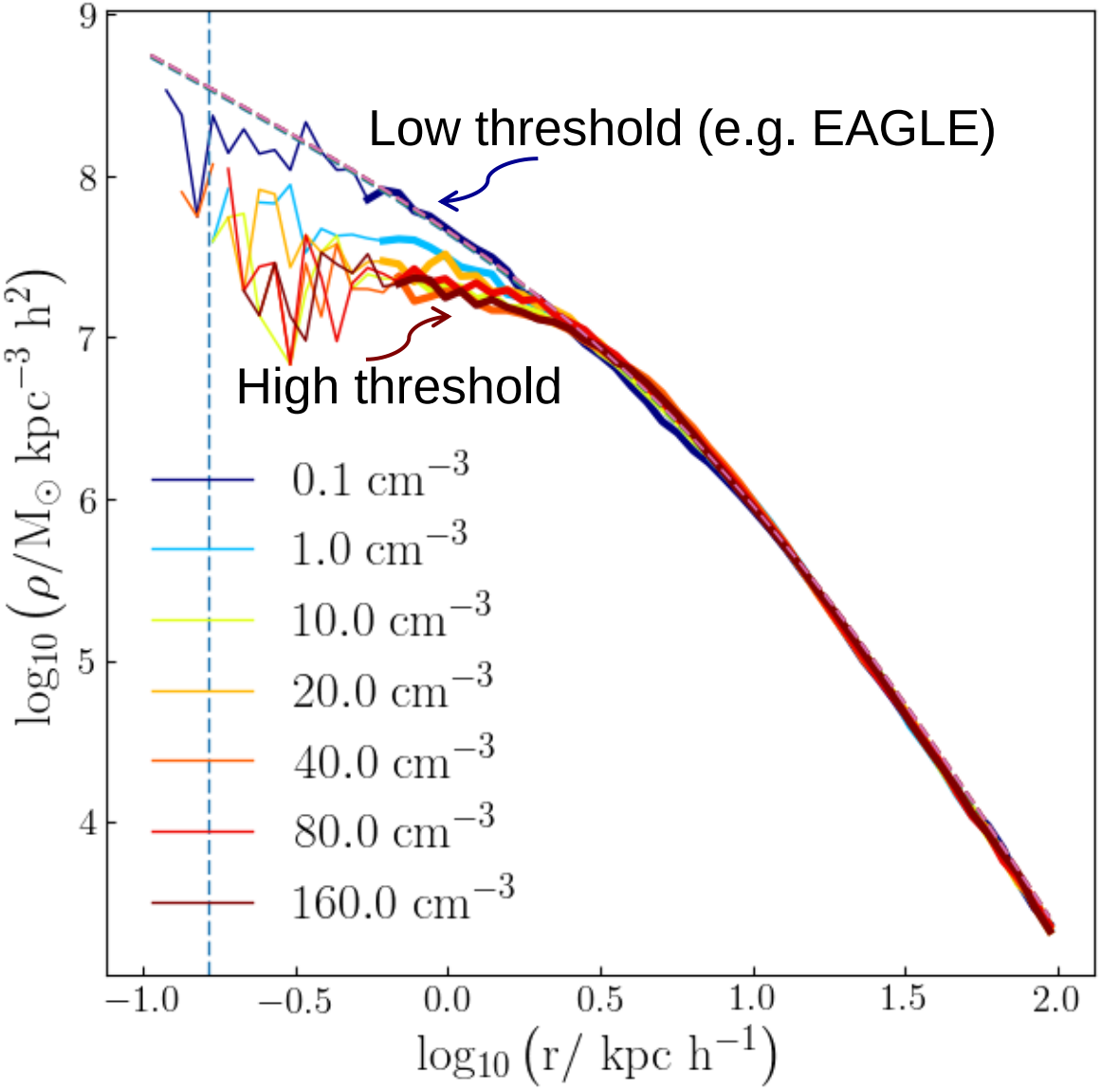


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$. (b) $M_{disc}=0.1$. (c) $M_{disc}=0.05$.

University of Durham

Cores or cusps in simulations?

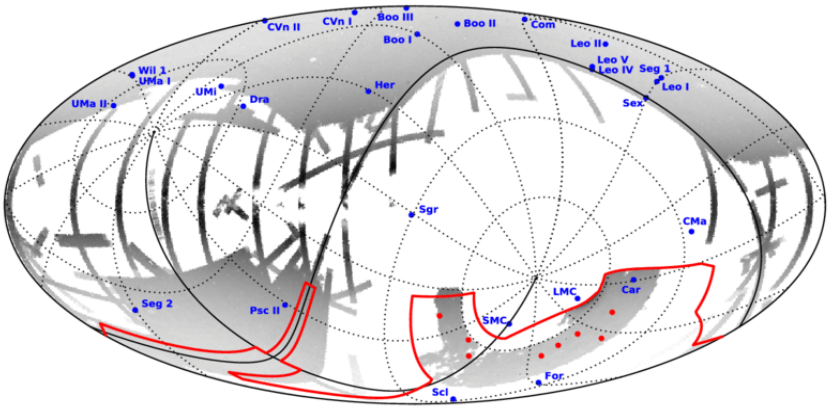


Benitez-Llambay, CSF et al ‘19

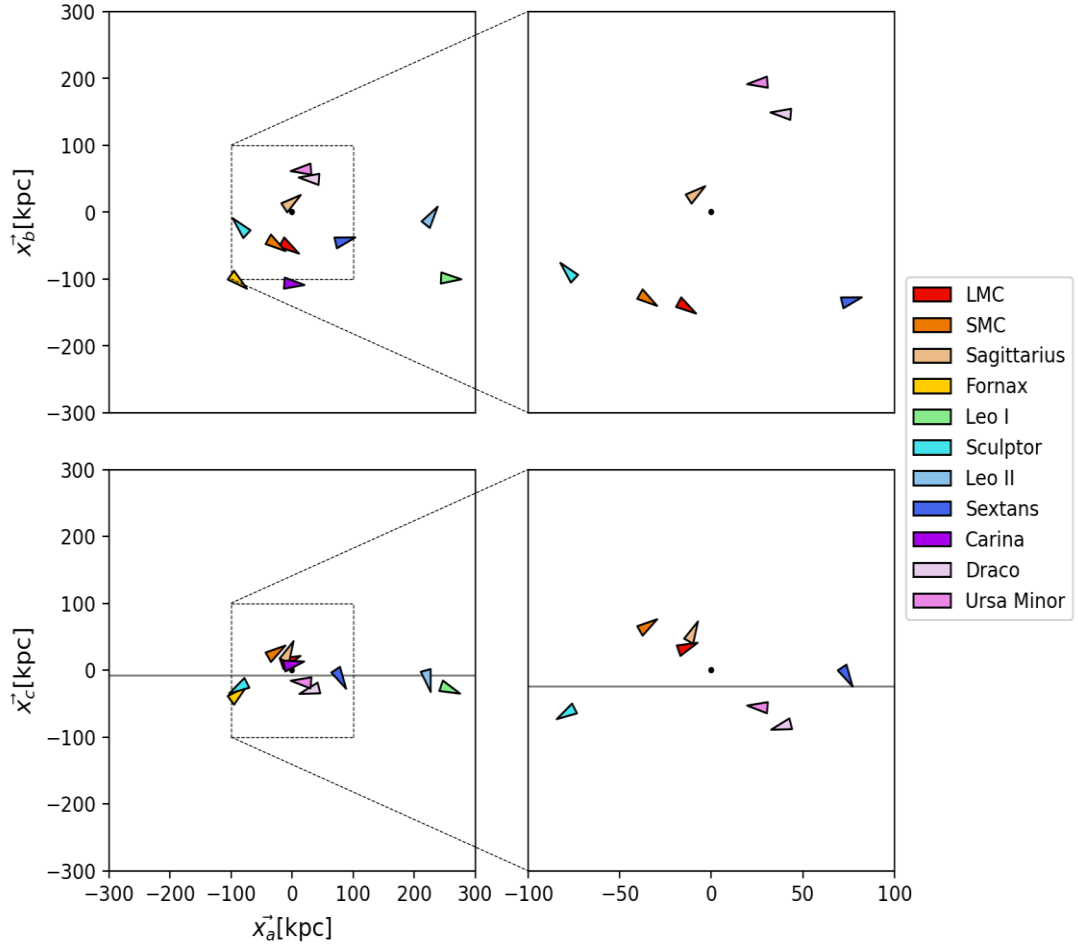
University of Durham

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

Institute for Computational Cosmology

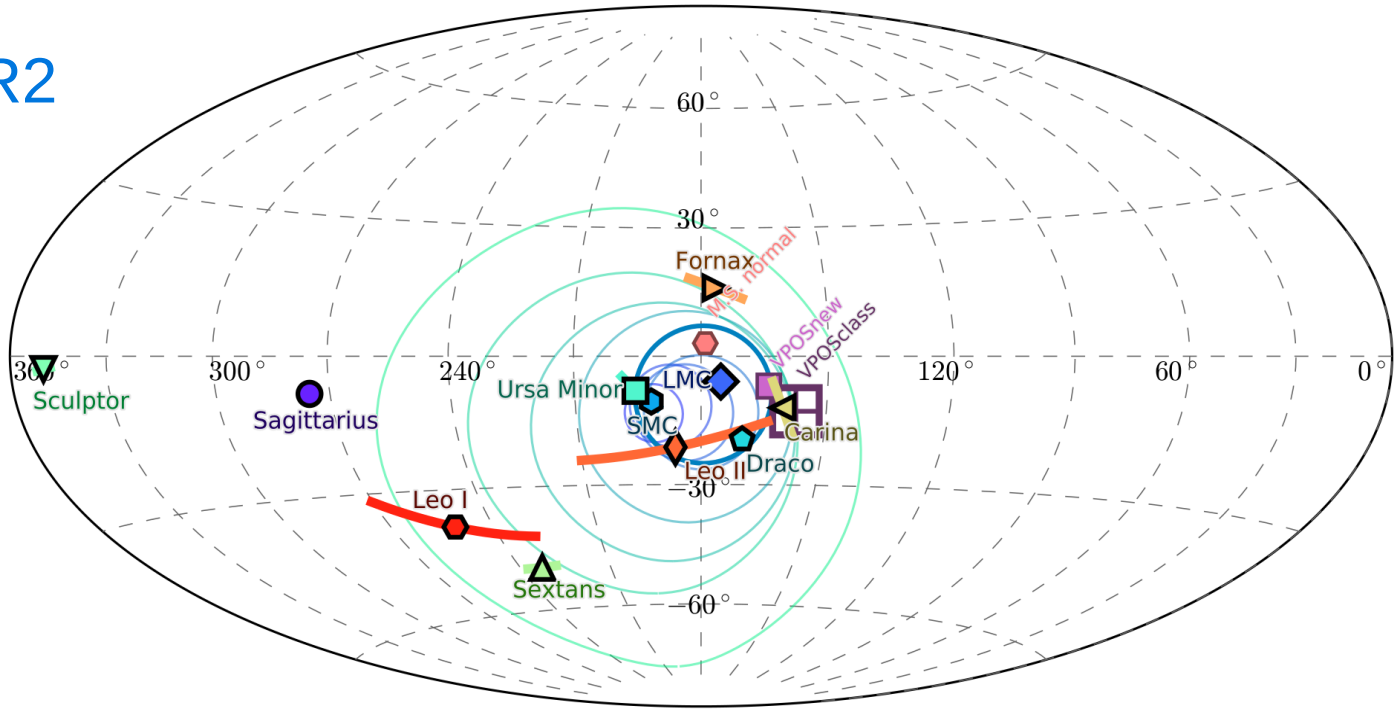
University of Durham

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

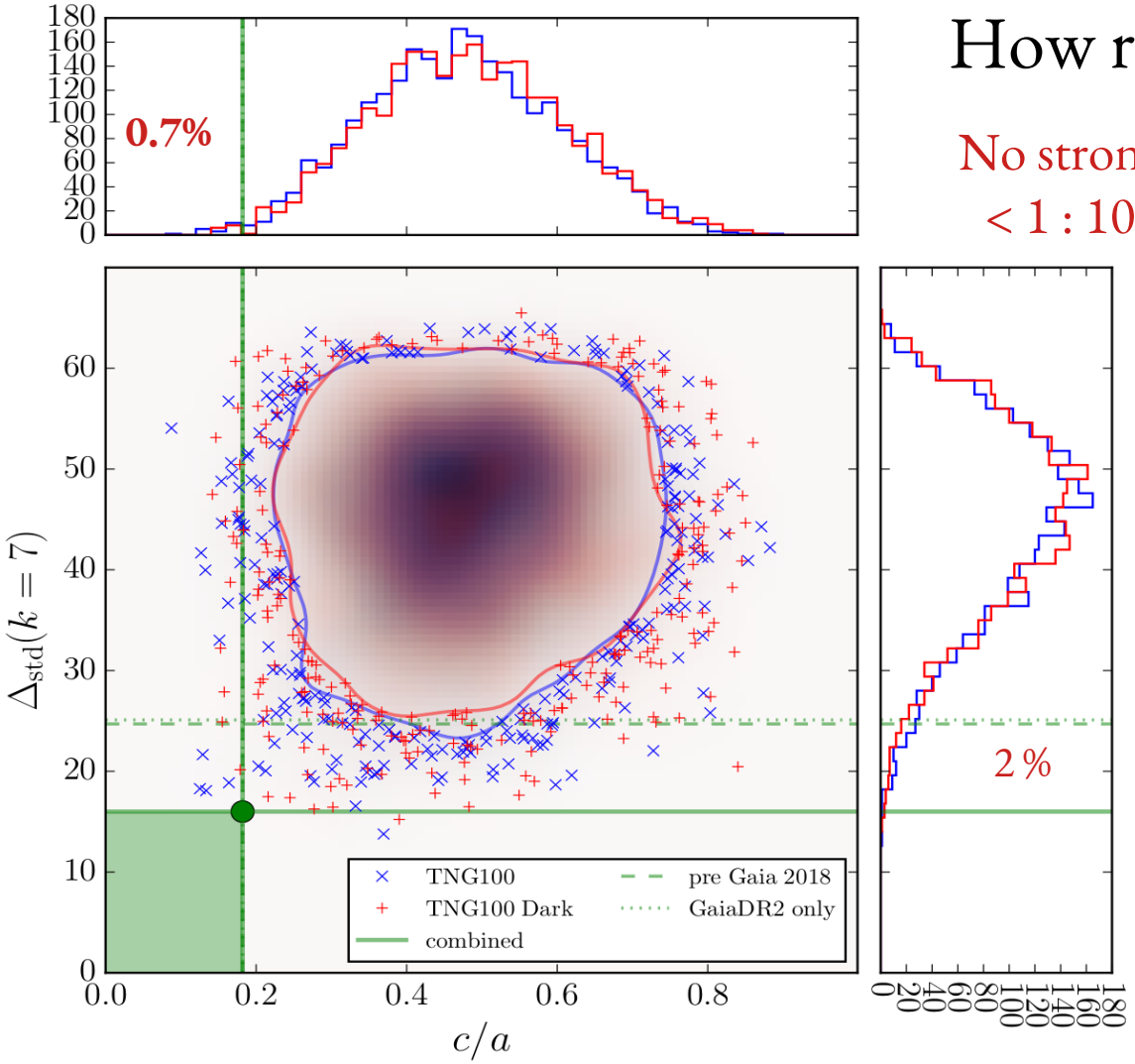
GAIA DR2



Pawlowski & Kroupa (2020)

University of Durham

The plane of satellites in the MW



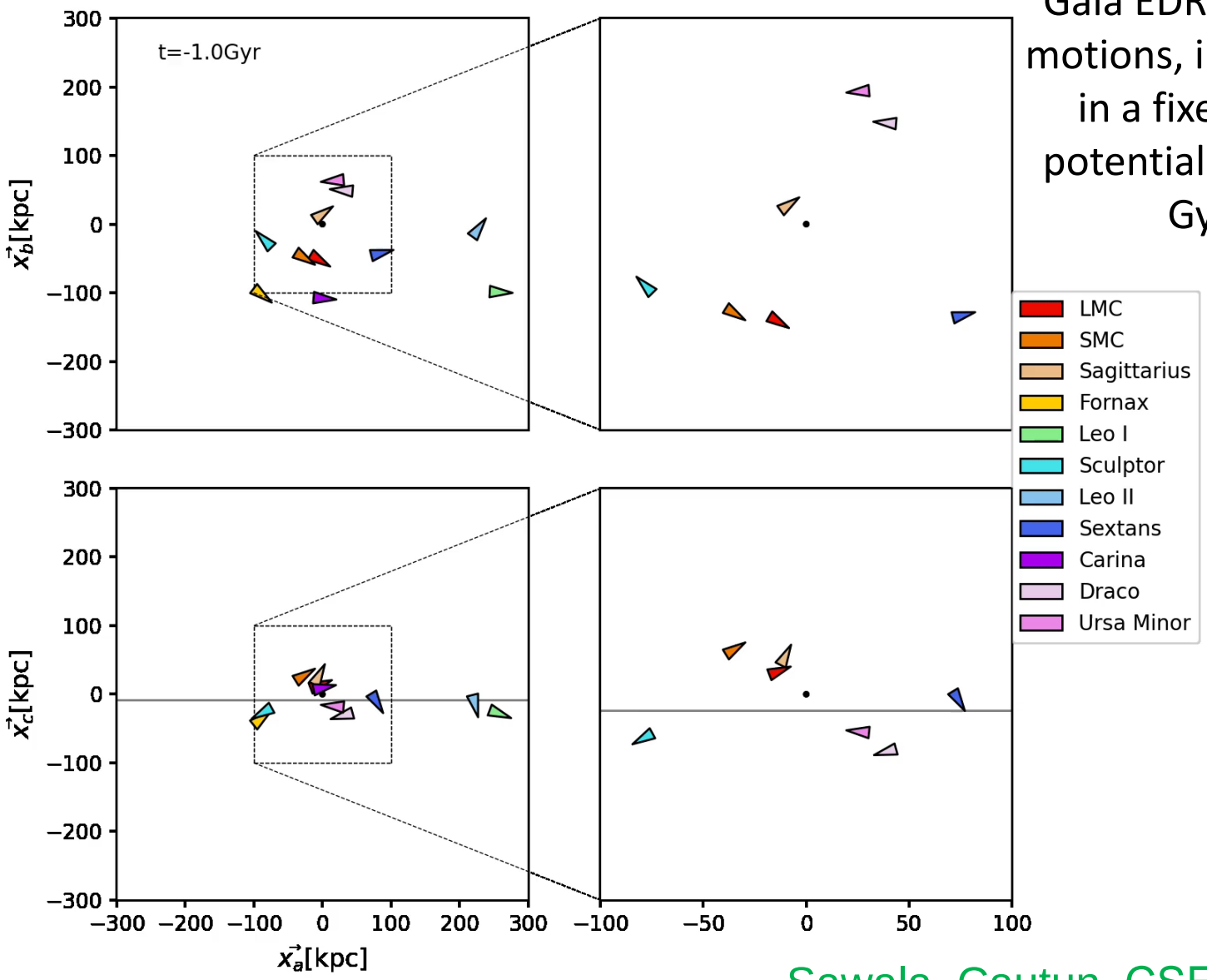
How rare is it?

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

Eigenvalues of inertia tensor

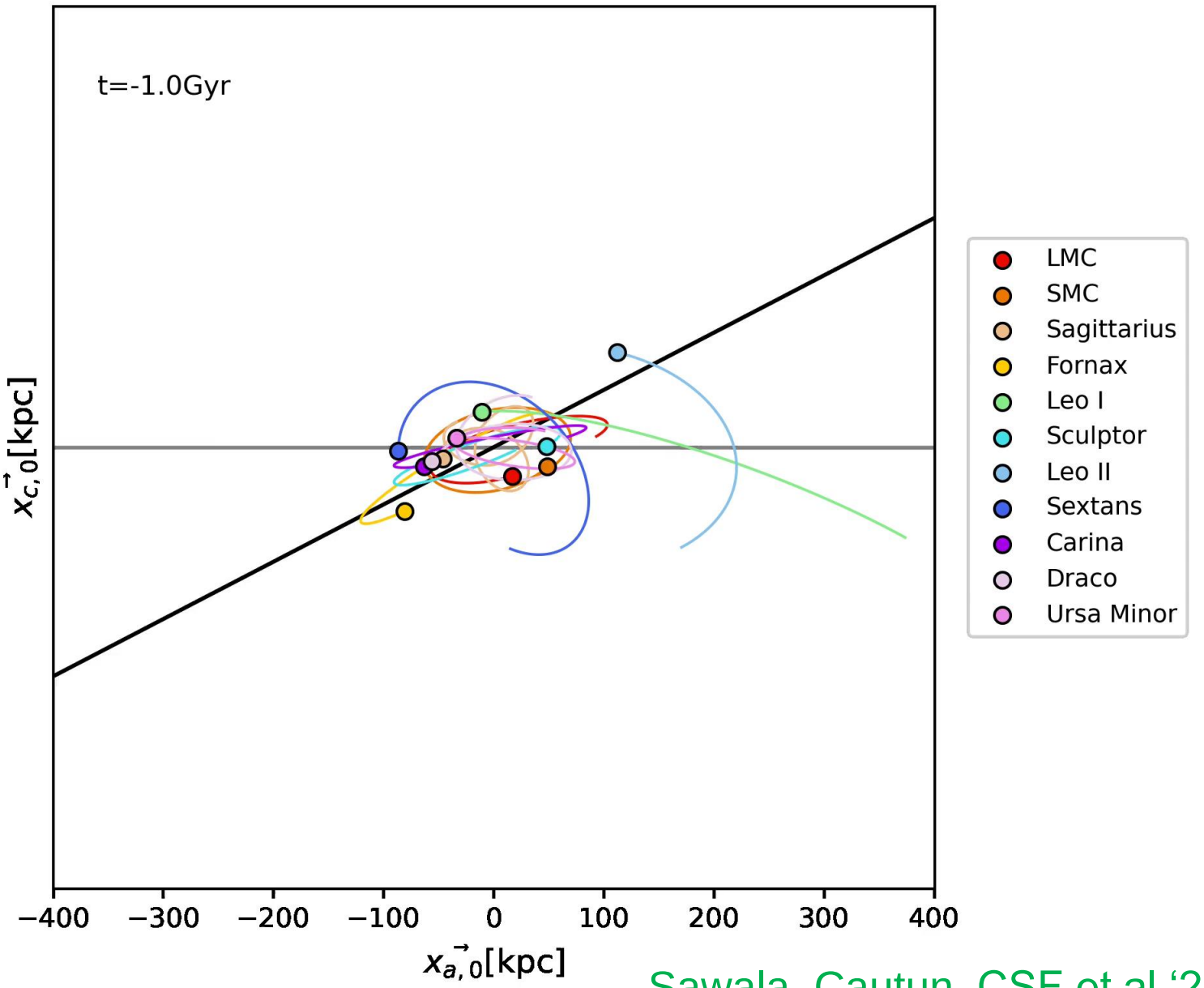
a>b>c

Pawlowski & Kroupa (2020)



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

Sawala, Cautun, CSF et al '22

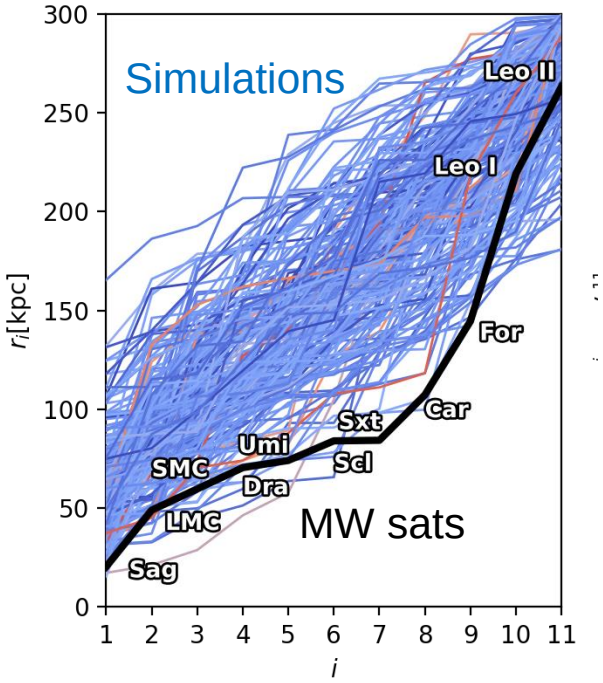


Sawala, Cautun, CSF et al ‘22

University of Durham

The plane of satellites in the MW

Radius of i^{th} closest satellite



100 ΛCDM N-body simulations of Local Group analogues: $m_p=1x10^6M_o$

MW "Satellites" top-11 ranked by v_{peak}

Limited resolution → satellites in inner regions artificially disrupted

→ need to follow "orphan" galaxies

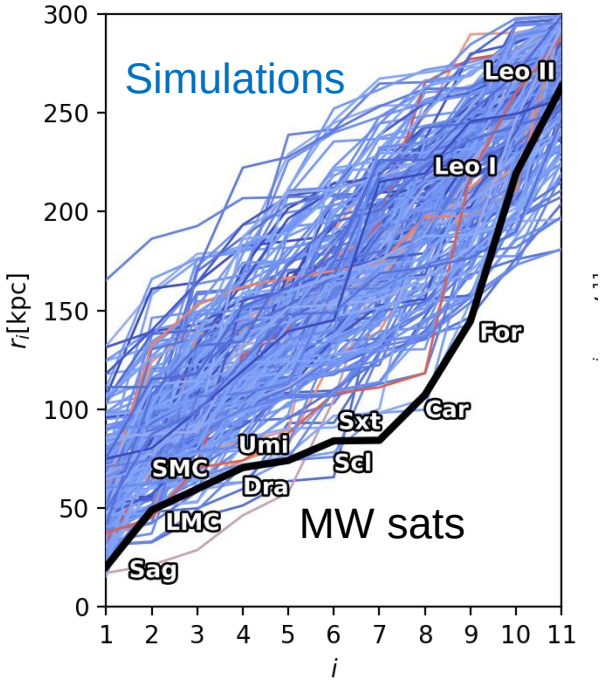
Sawala, Cautun, CSF et al '22

Institute for Computational Cosmology

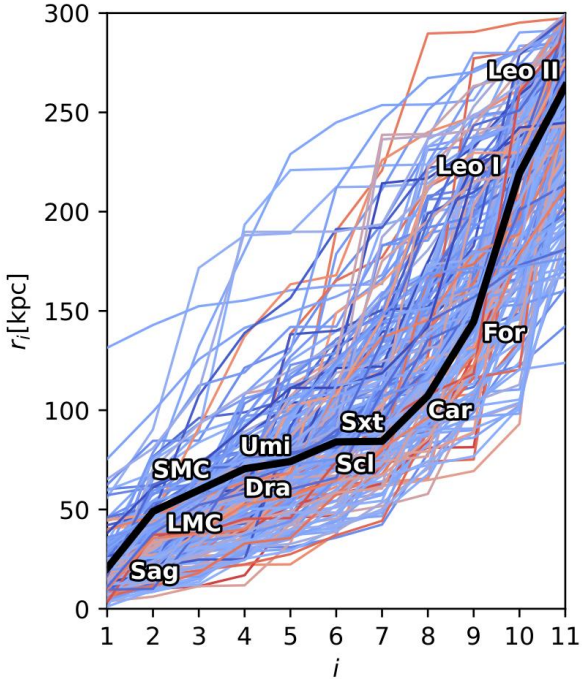
University of Durham

The plane of satellites in the MW

Radius of i^{th} closest satellite



Including orphans



Including “orphan” satellites reproduces radial distribution & reduces c/a

Sawala, Cautun, CSF et al ‘22

Institute for Computational Cosmology

University of Durham

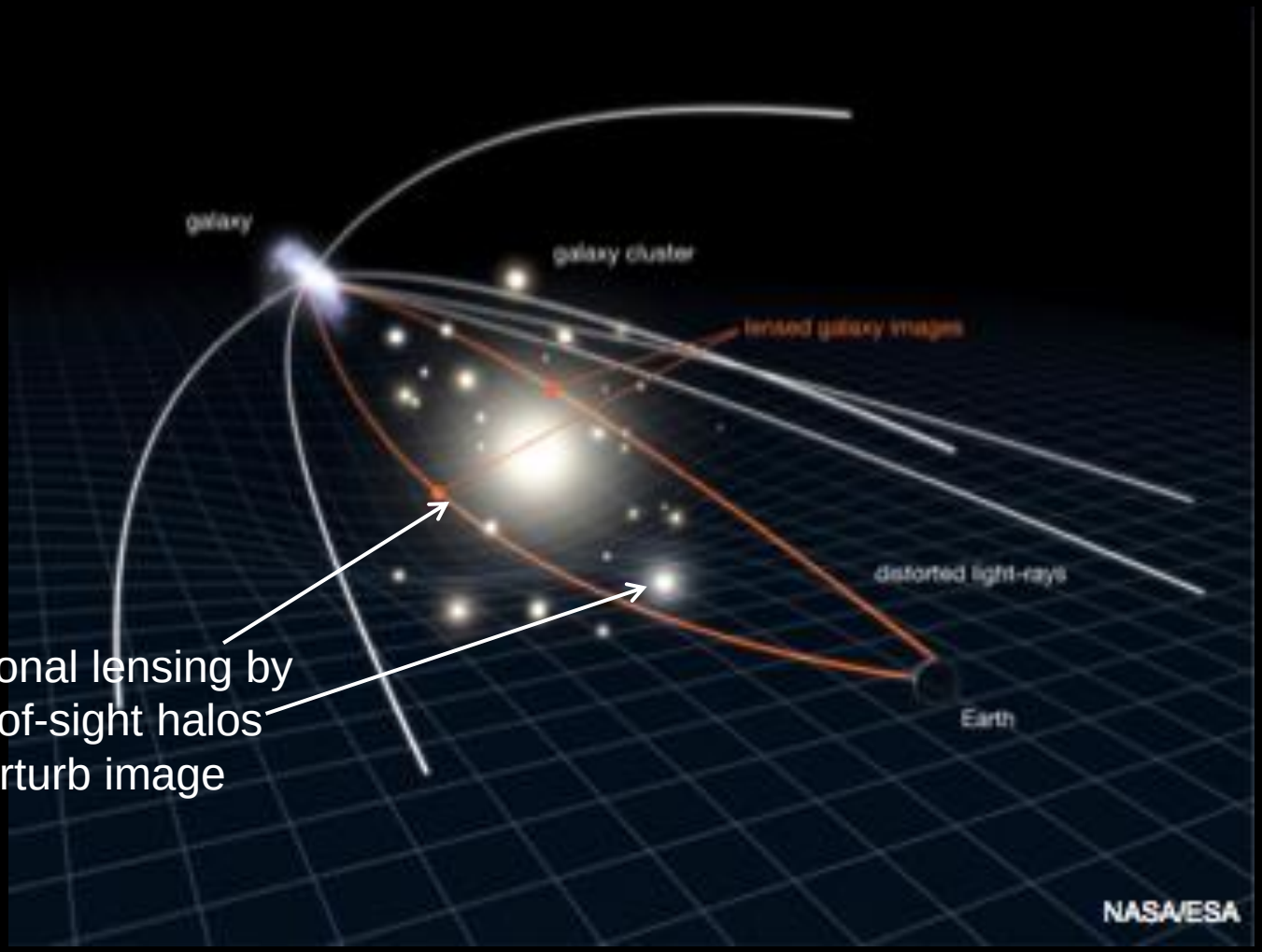
The rotating plane of satellites

What about the clustered poles?

- Complete sample of subhaloes (with orphans)
- Look elsewhere effect

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

Gravitational lensing: Einstein rings

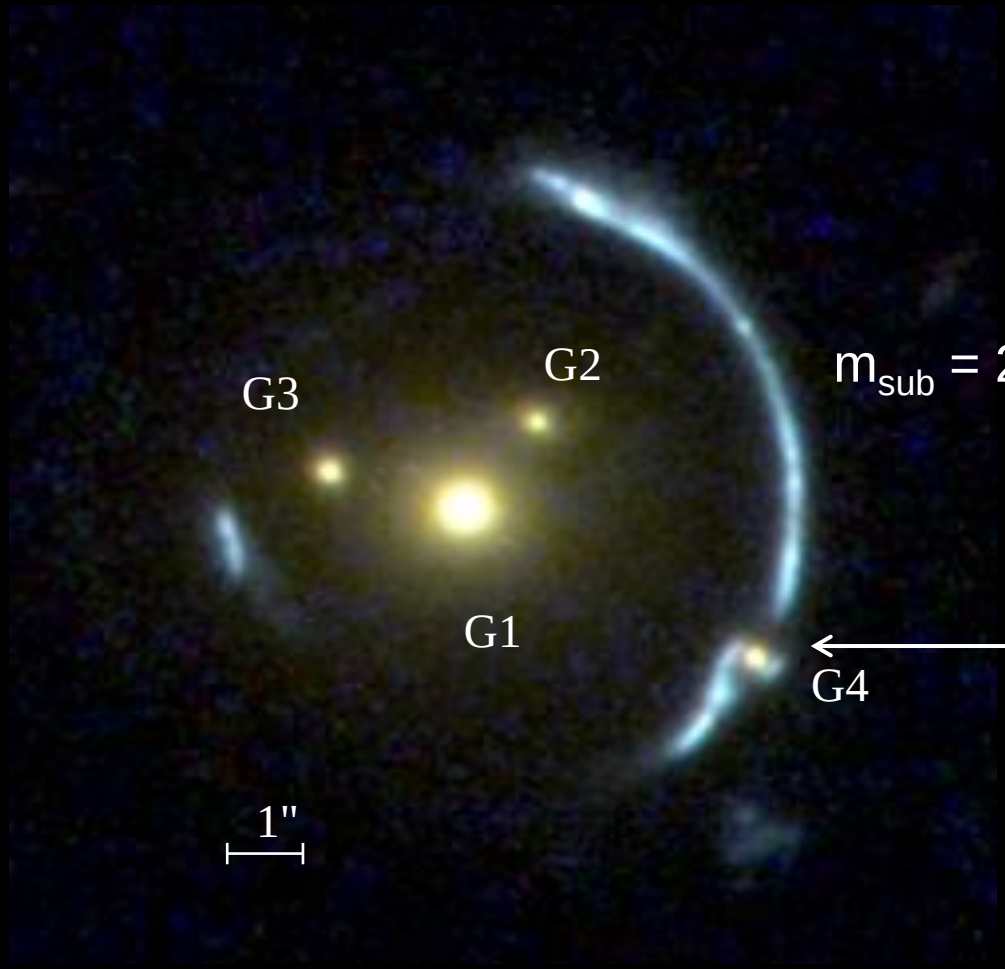


Additional lensing by line-of-sight halos perturb image

When the source and the lens are well aligned → strong arc or an Einstein ring

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



Vegetti et al ‘10

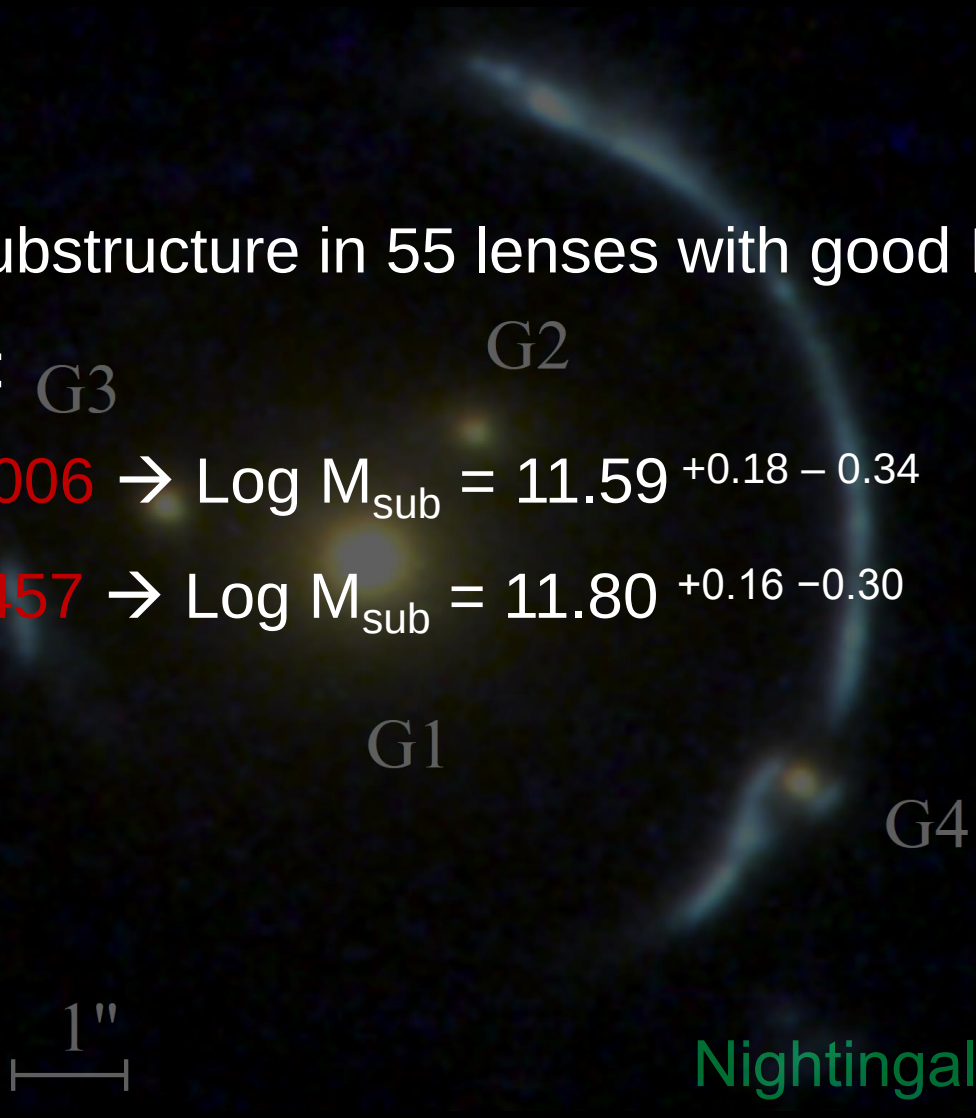
Gravitational lensing: substructures

Searched for substructure in 55 lenses with good HST imaging

→ 2 detections:

SLACS0946+1006 → Log M_{sub} = 11.59 $^{+0.18}$ $_{-0.34}$

BELLS1226+5457 → Log M_{sub} = 11.80 $^{+0.16}$ $^{-0.30}$



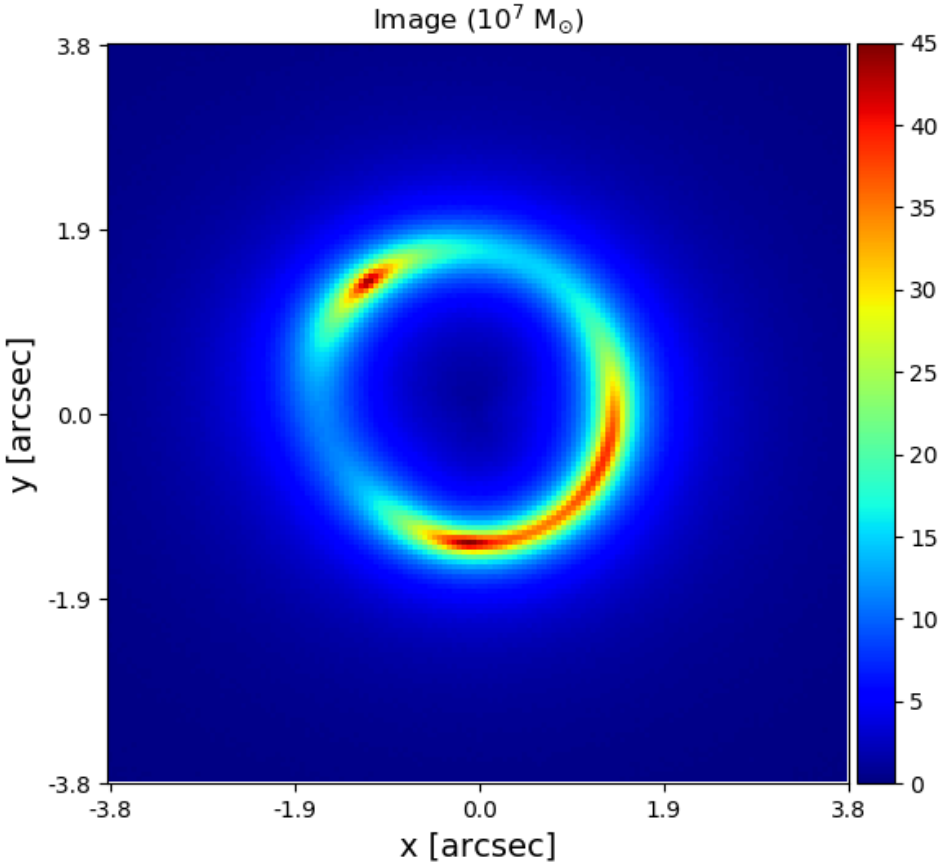
Nightingale + ‘22

University of Durham

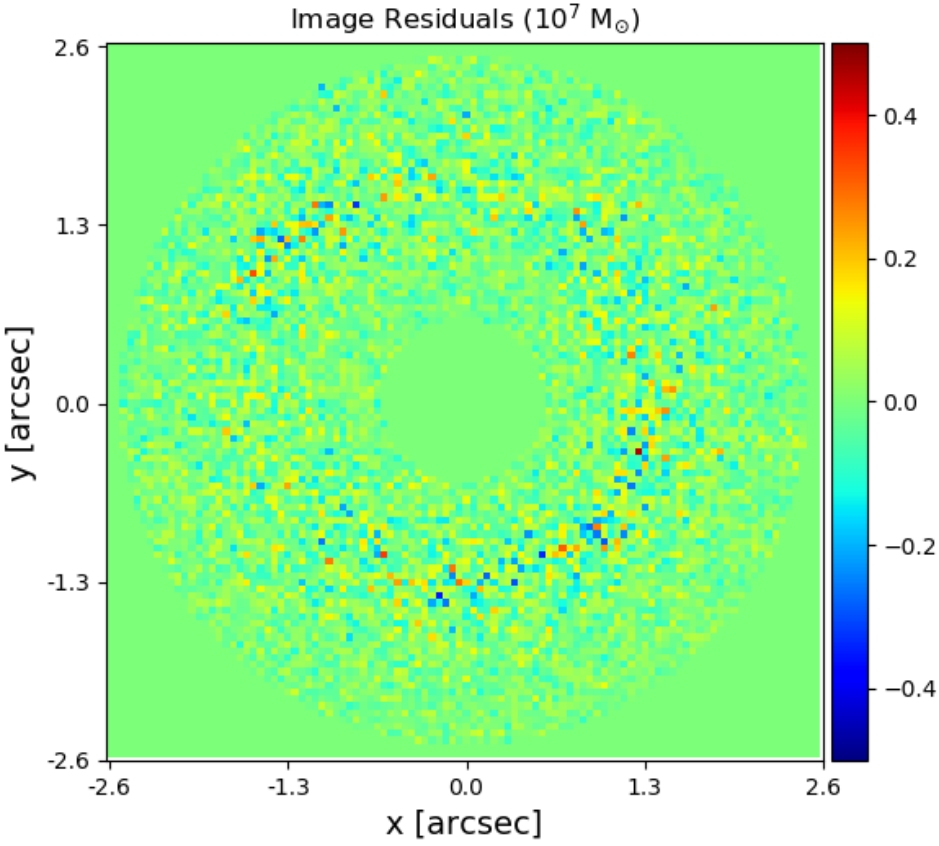
Strong lensing: detecting small halos

HST "data": z_{source}=1; z_{lens}=0.2 10^7 M_o halo – NOT so easy to spot

Image



Residuals (image – smooth model)



He, Li, CSF et al '19

Conclusions

- Can test ΛCDM in non-linear regime
- Halo abundance, structure, clustering known from 10^{-6} – 10^{15} M_o

  - Missing satellites
  - Too-big-to-fail
  - Core/cusp

  → "Solved" by baryon effects

  - Plane of satellites

    → Plane is transient

    → MW plane not rare

- Definitive test of ΛCDM → dark subhalos → strong lensing