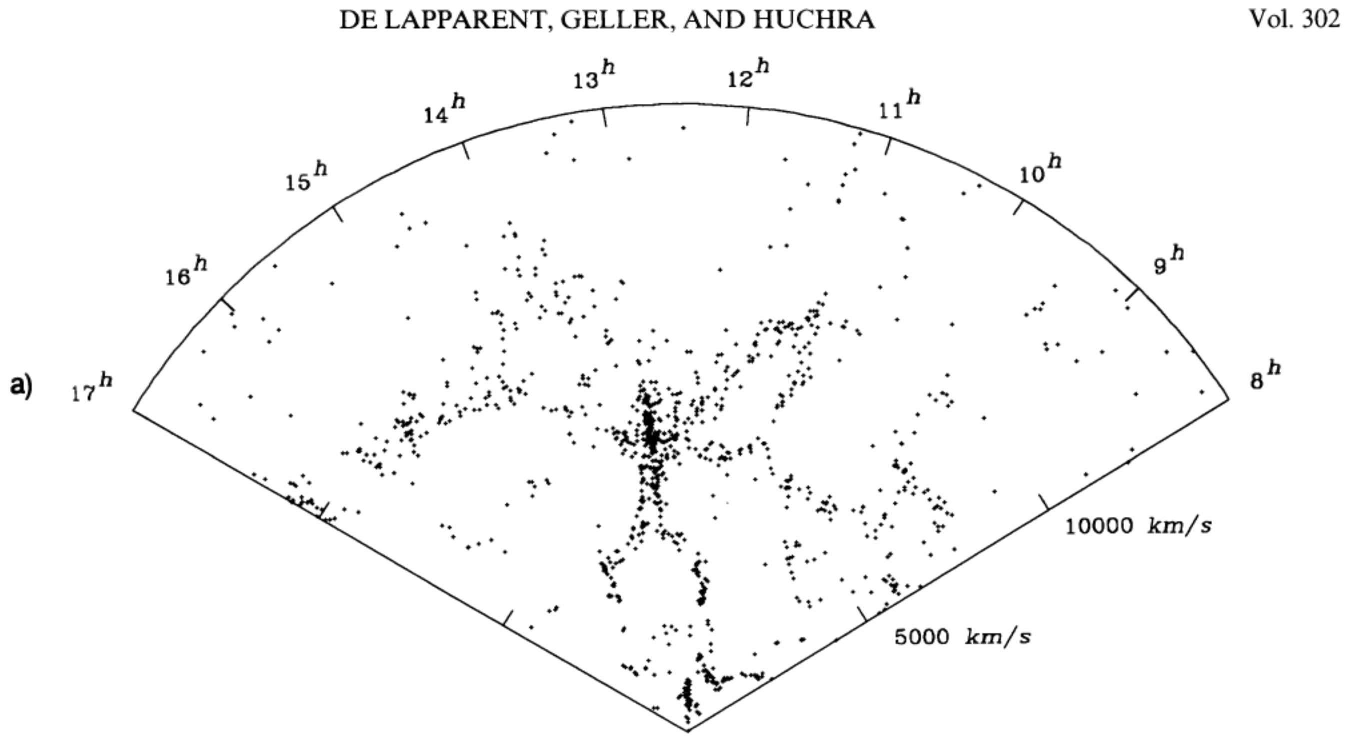
A conclusive test of cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

1980s


2020s

1980s



The CfA redshift survey

2020s

Galaxy distribution encodes info about dark matter and dark energy

DESi already has > 10 million spectra

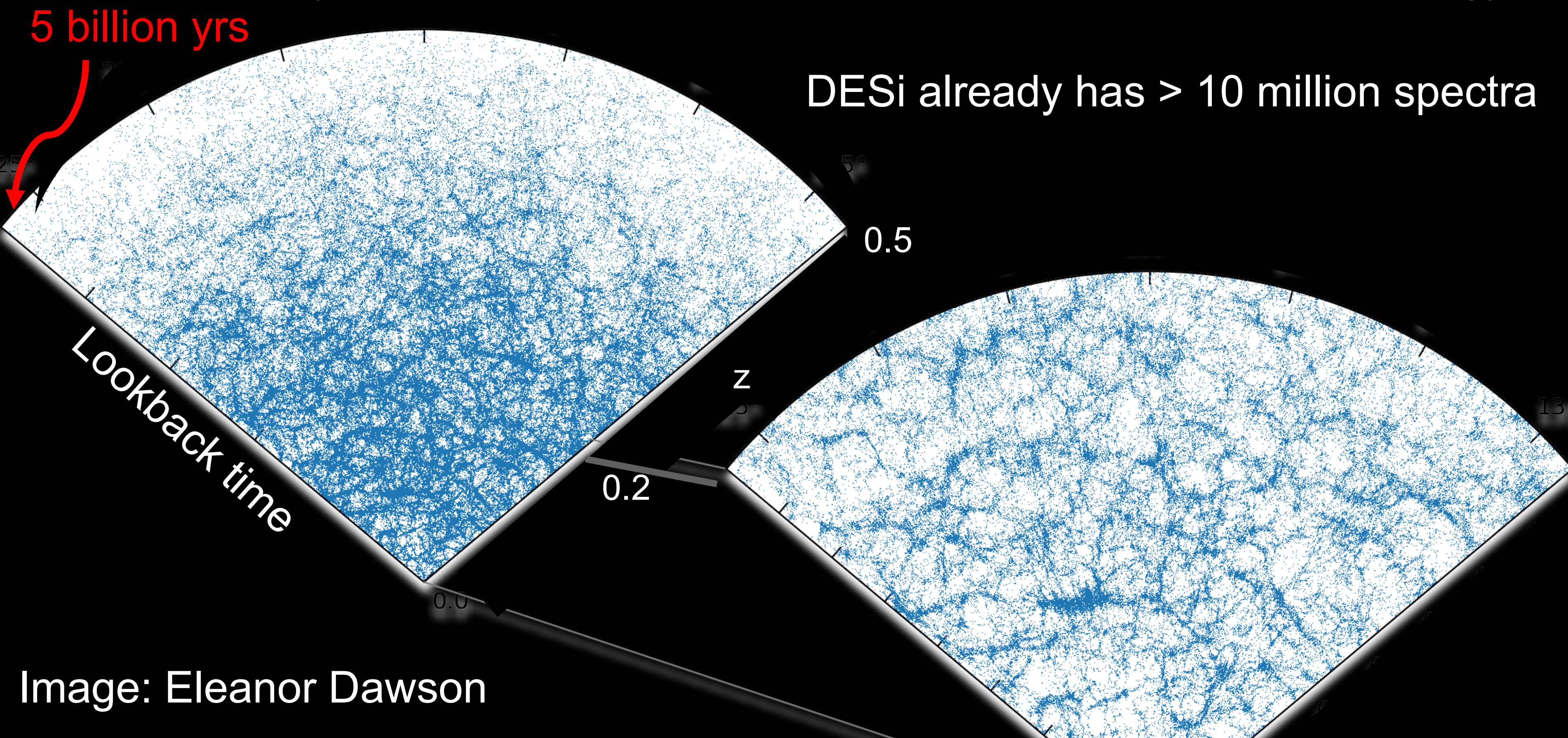
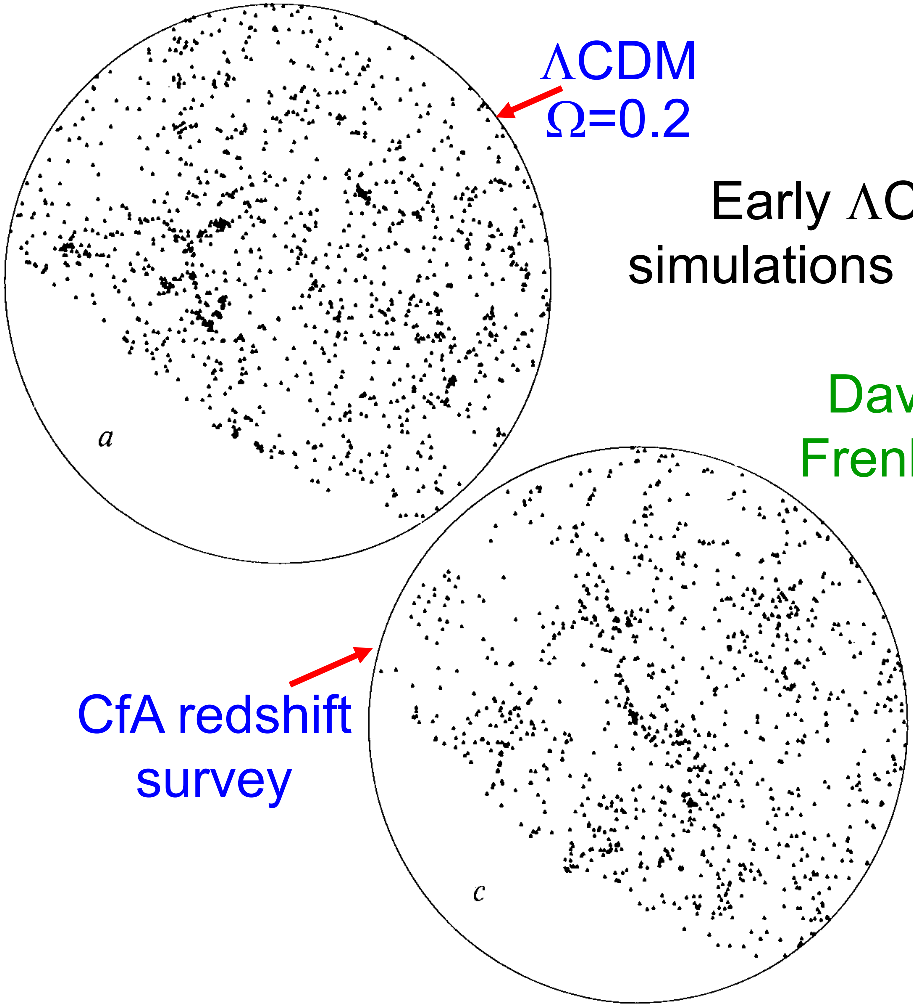


Image: Eleanor Dawson

University of Durham

1980s

The ΛCDM cosmology



ΛCDM
Ω=0.2

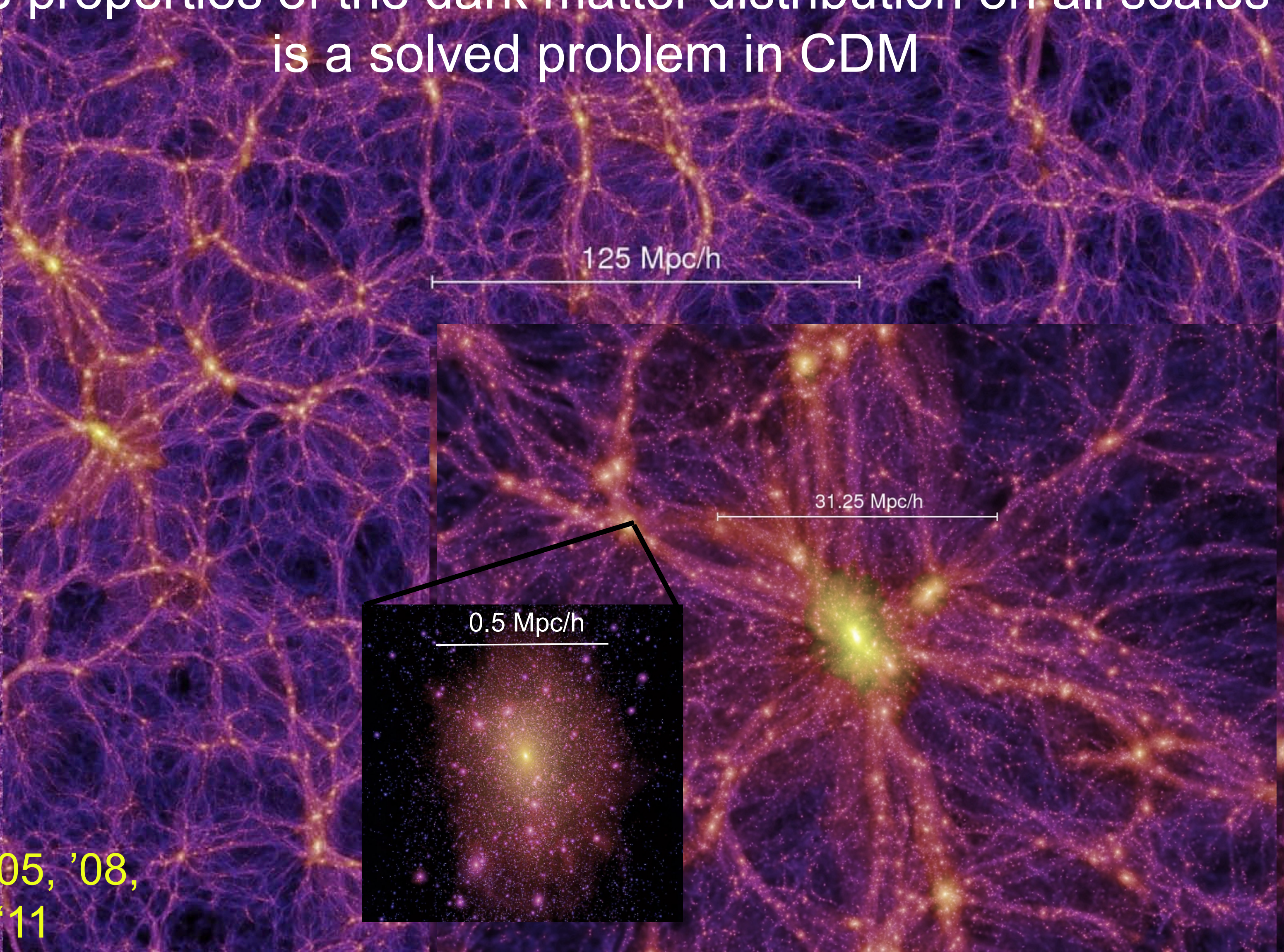
Early ΛCDM N-body simulations → realistic LSS

Davis, Efstathiou, Frenk & White 1985

CfA redshift survey

2020s

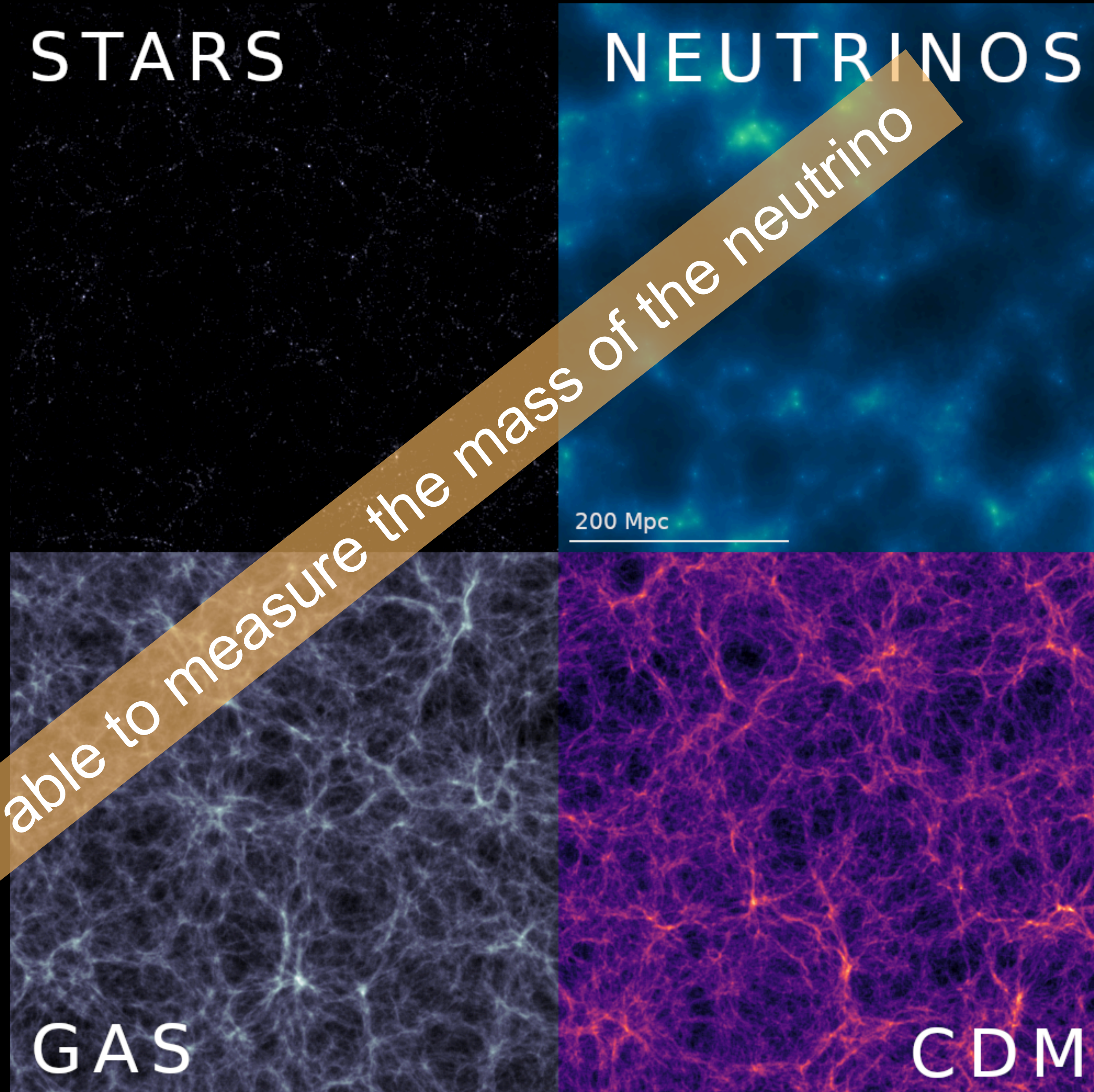
The properties of the dark matter distribution on all scales is a solved problem in CDM



Springel et al '05, '08, Gao et al '11

Neutrinos make up < 1% of total dark matter

Can simulate their distribution with 1% accuracy



DESI may be able to measure the mass of the neutrino

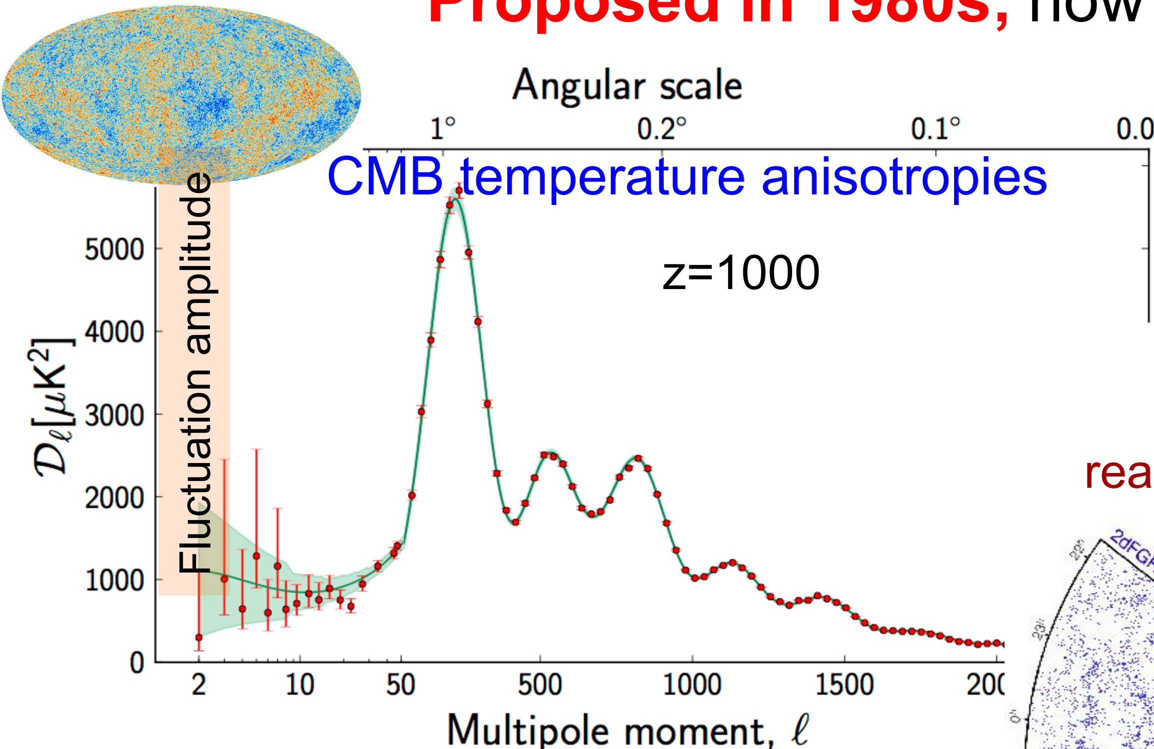
Elbers, Frenk, Jenkins, Li, Pascoli ‘23

The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:

CMB temperature anisotropies

z=1000

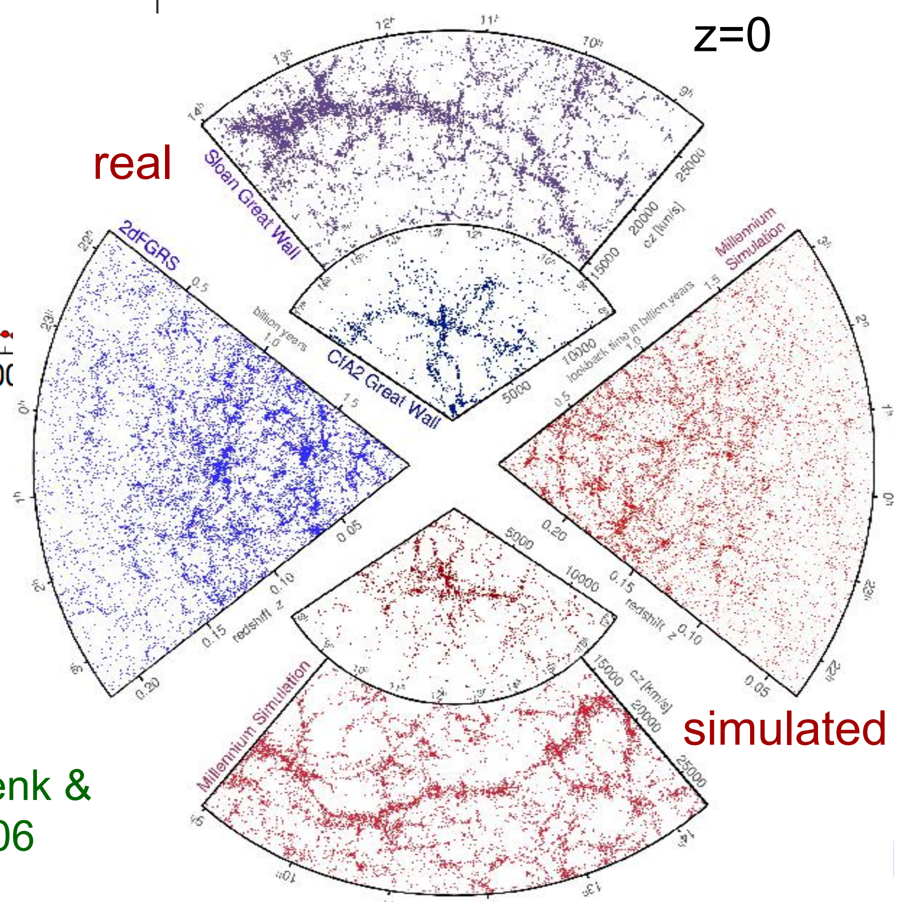


Planck coll. 2015

Galaxy clustering

z=0

real



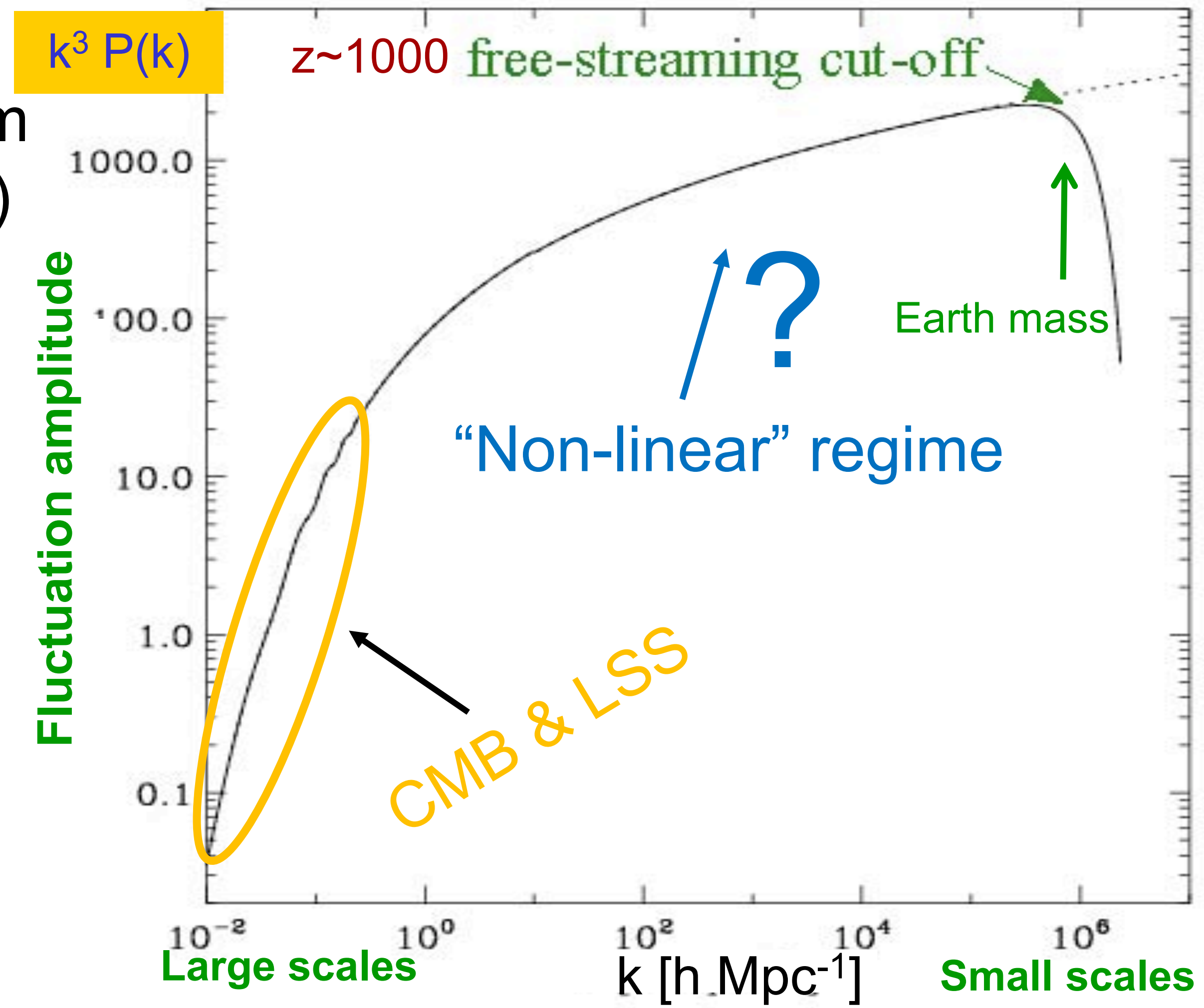
simulated

Springel, Frenk & White 2006

The cold dark matter power spectrum

Linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



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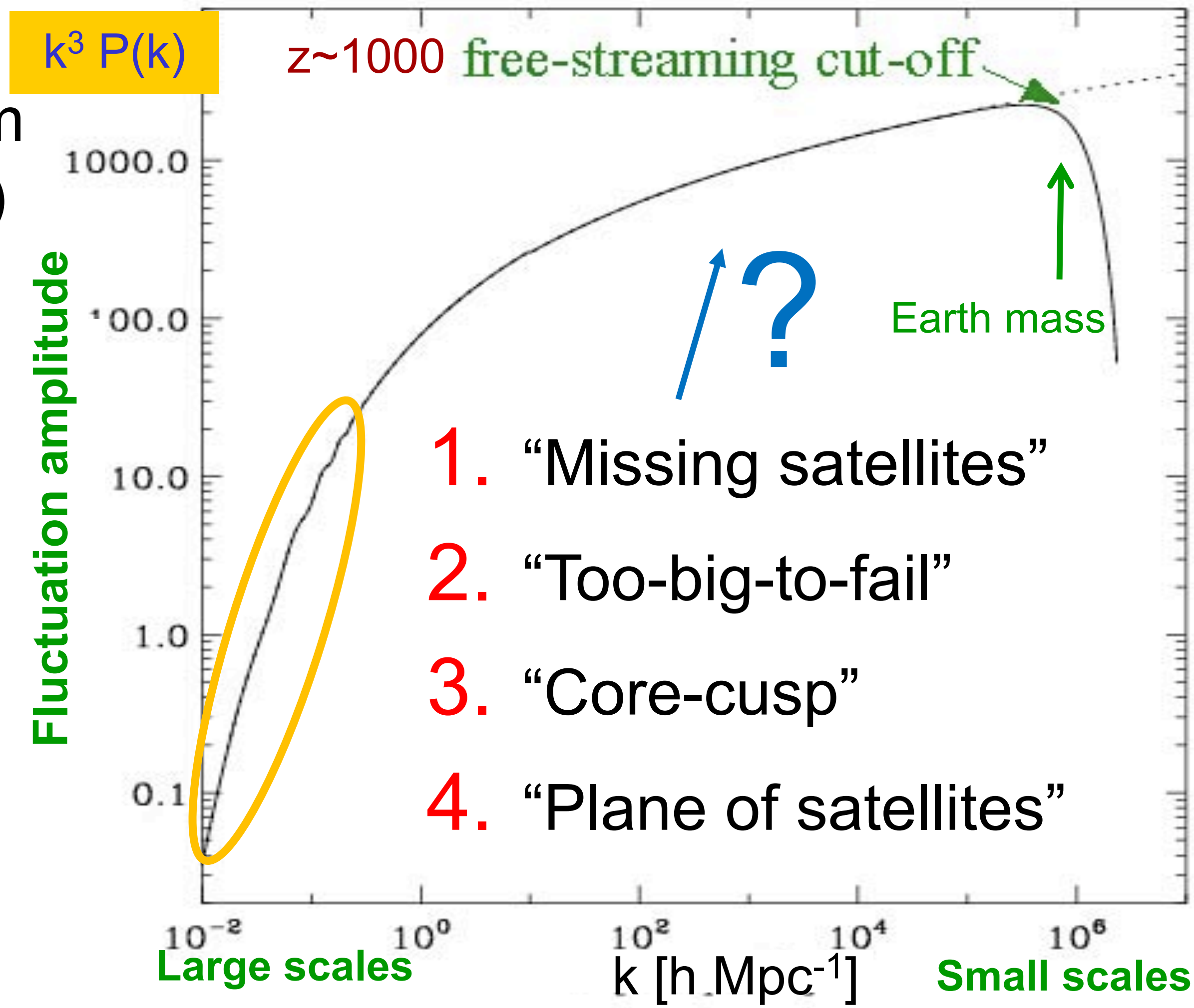

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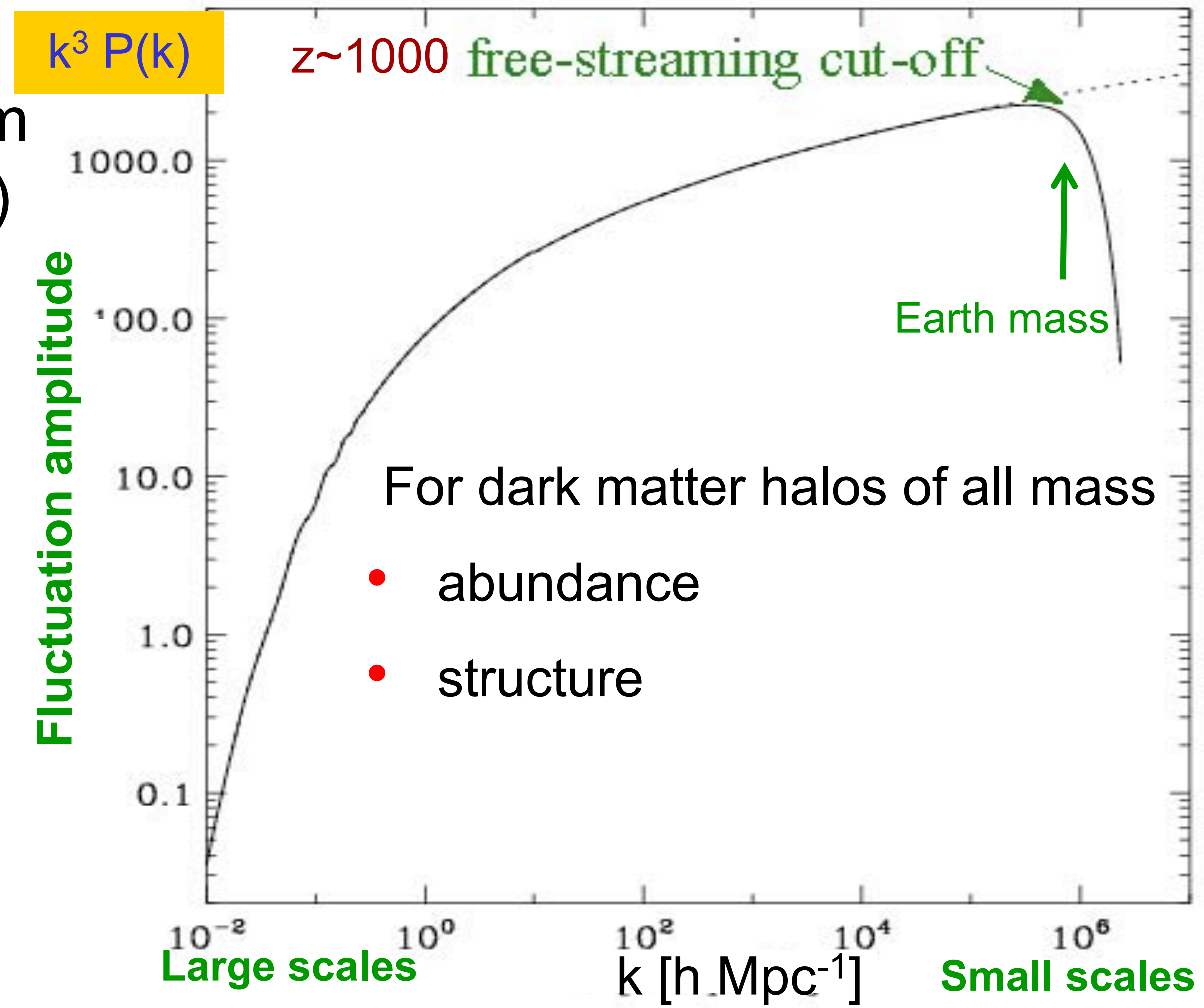

The halo mass function

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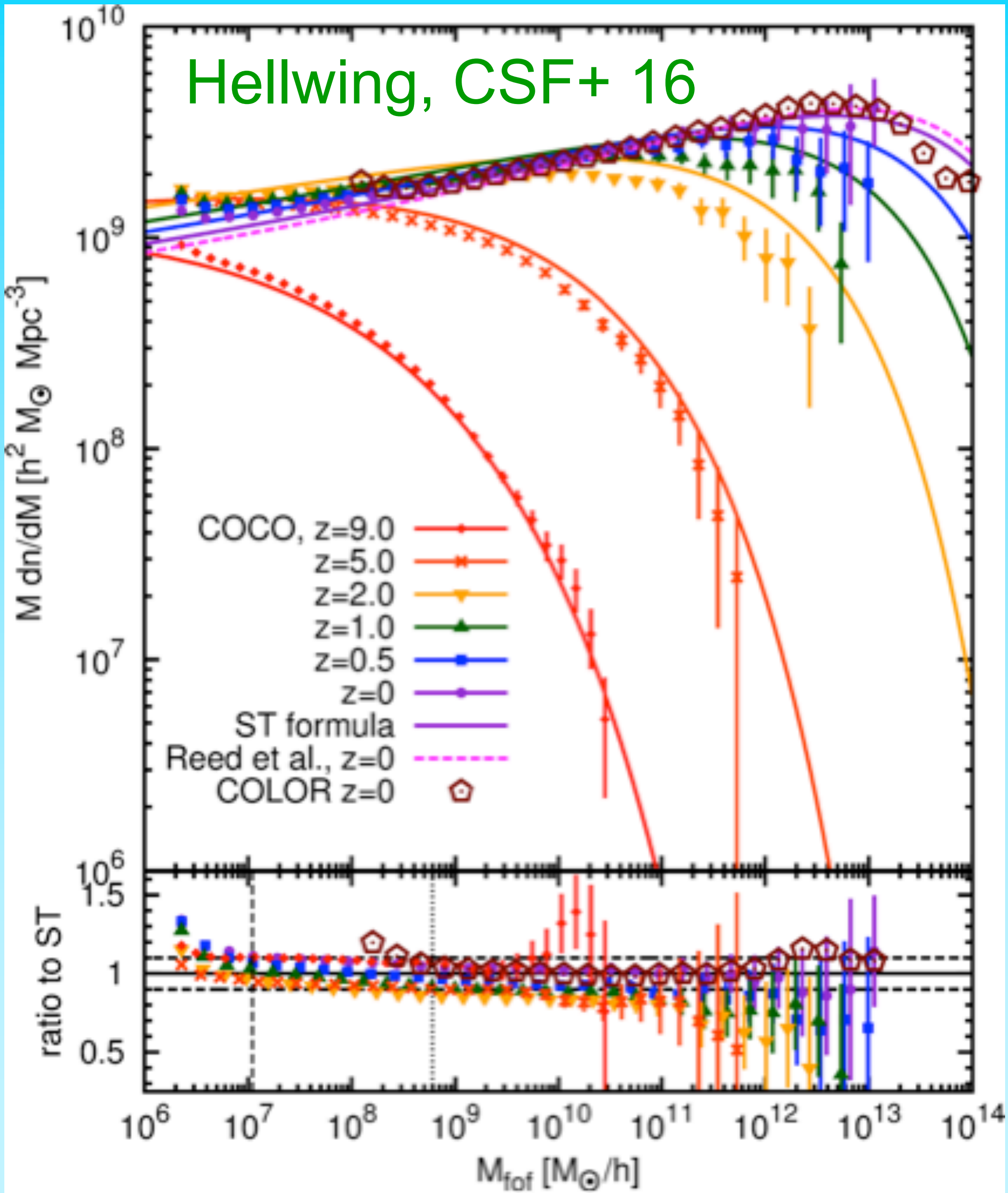
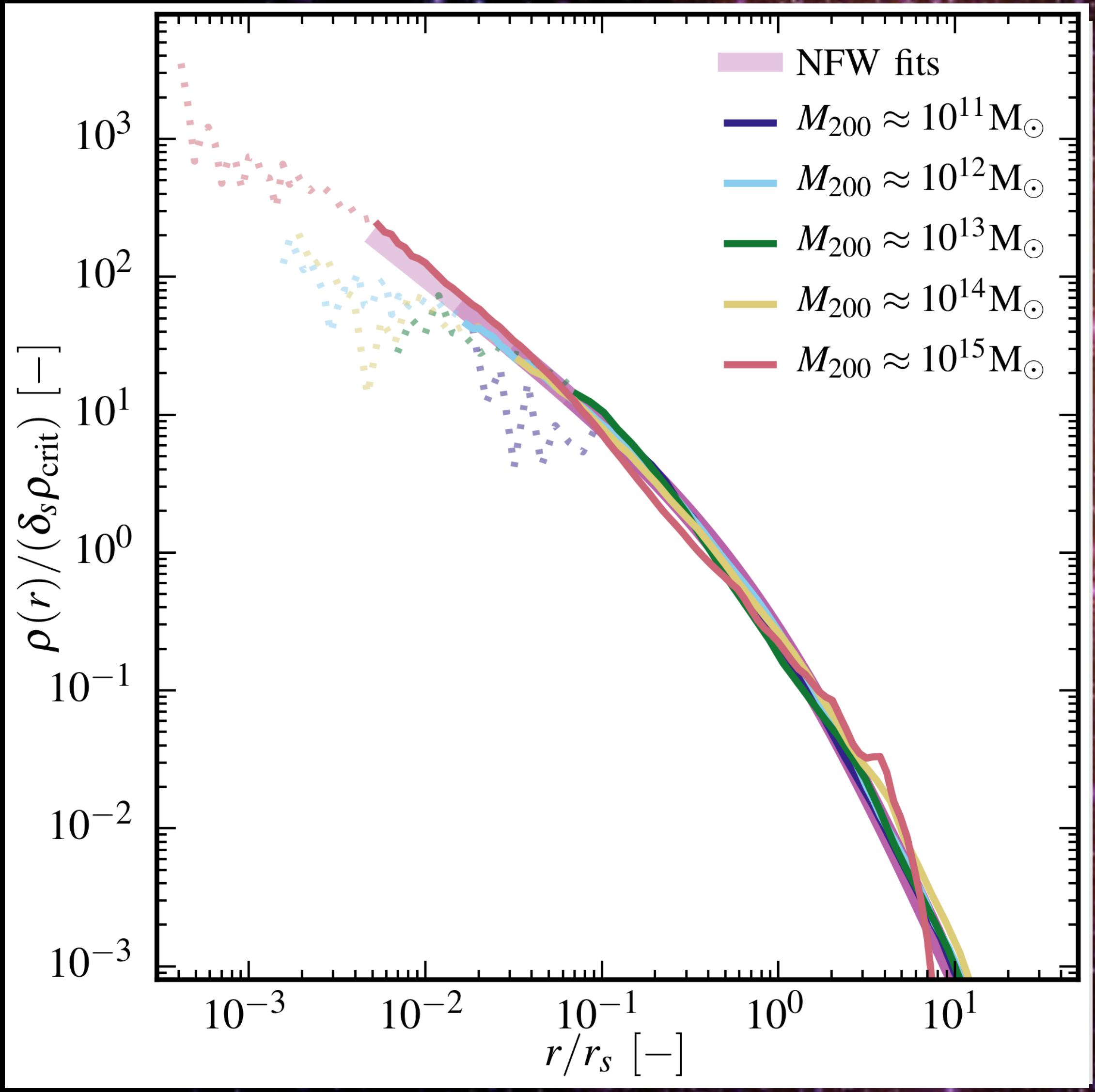
Until recently, halo mass function known from
$10^6 – 10^{15}$ M_o
from hi-z to z=0



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:

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

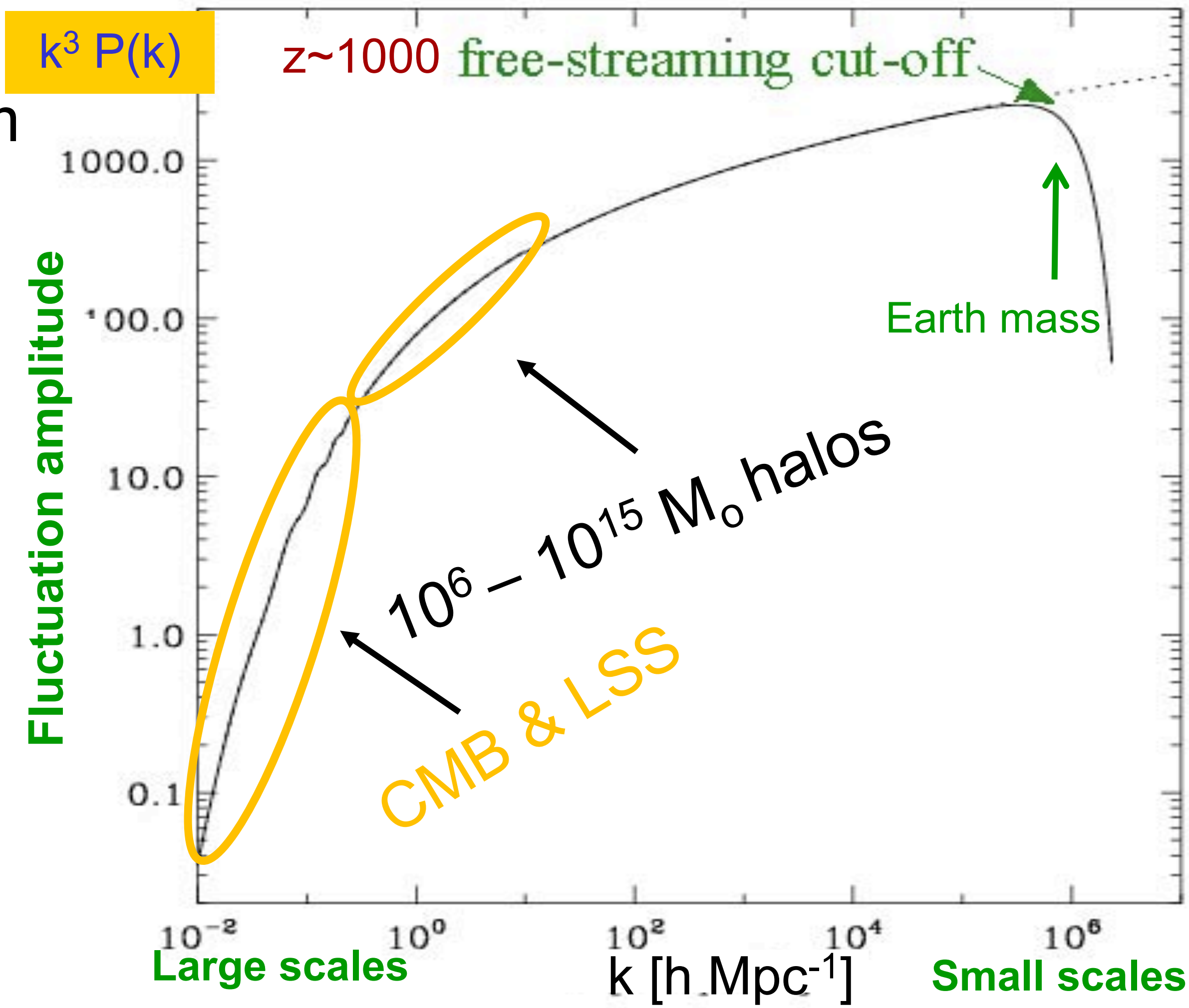
(Navarro, Frenk & White ’97)

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

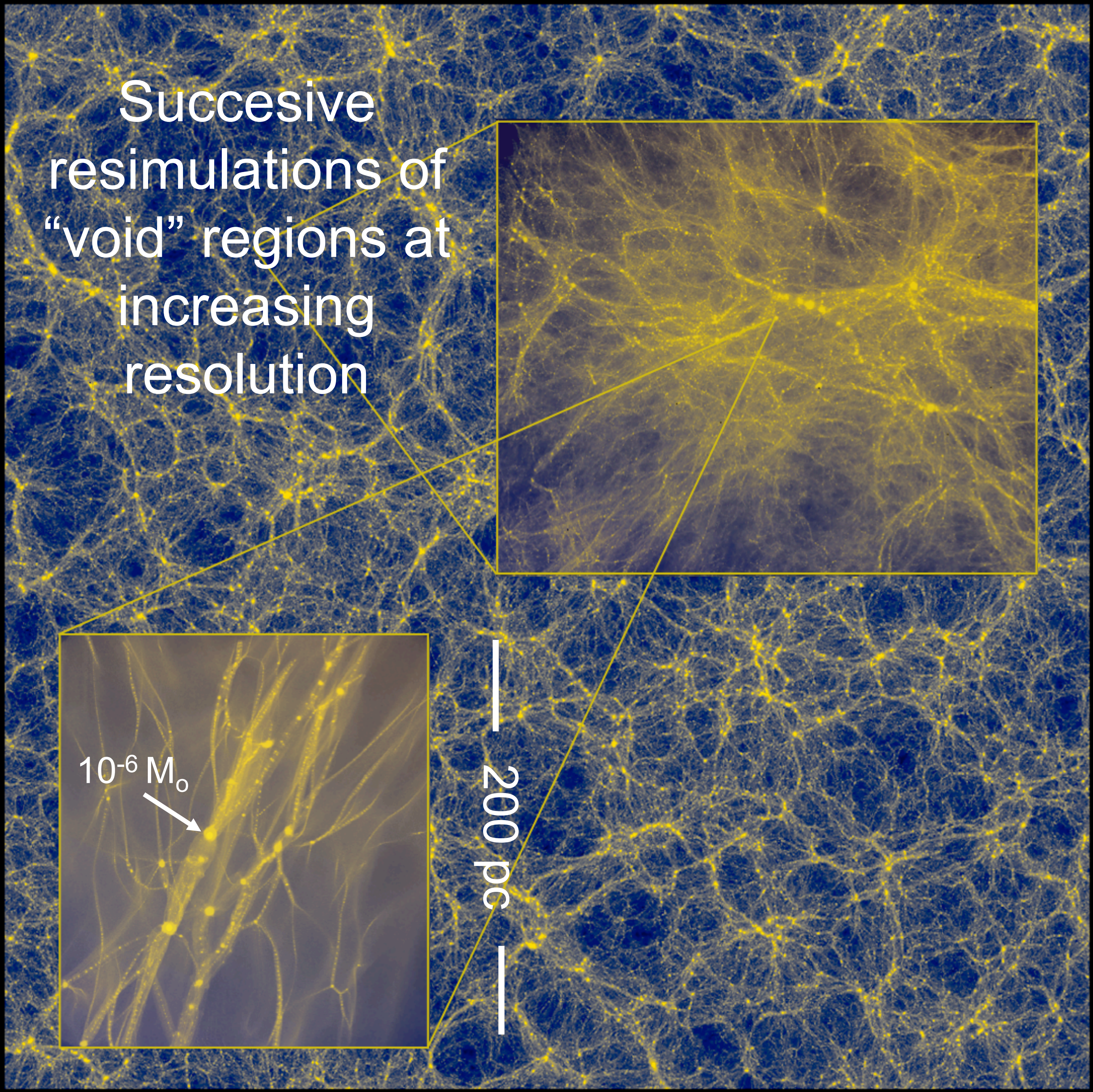
The cold dark matter power spectrum

Linear power spectrum ("power per octave")

Assumes a 100GeV wimp
Green et al '04

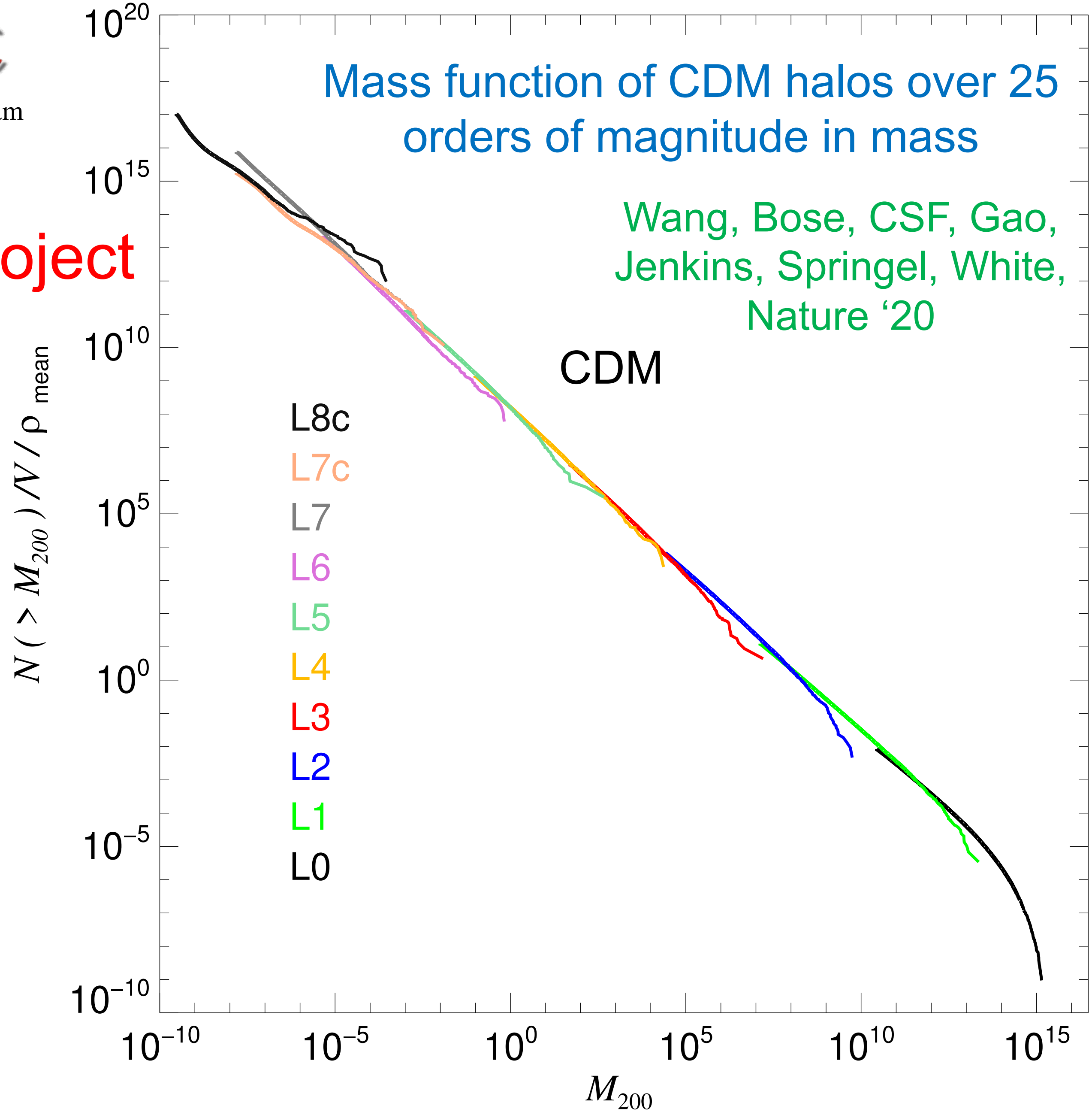


The number of dark matter halos from Earth mass to clusters



Wang, Bose, CSF, Gao, Jenkins, Springel, White, Nature ‘20

The VVV project



Density profile shapes

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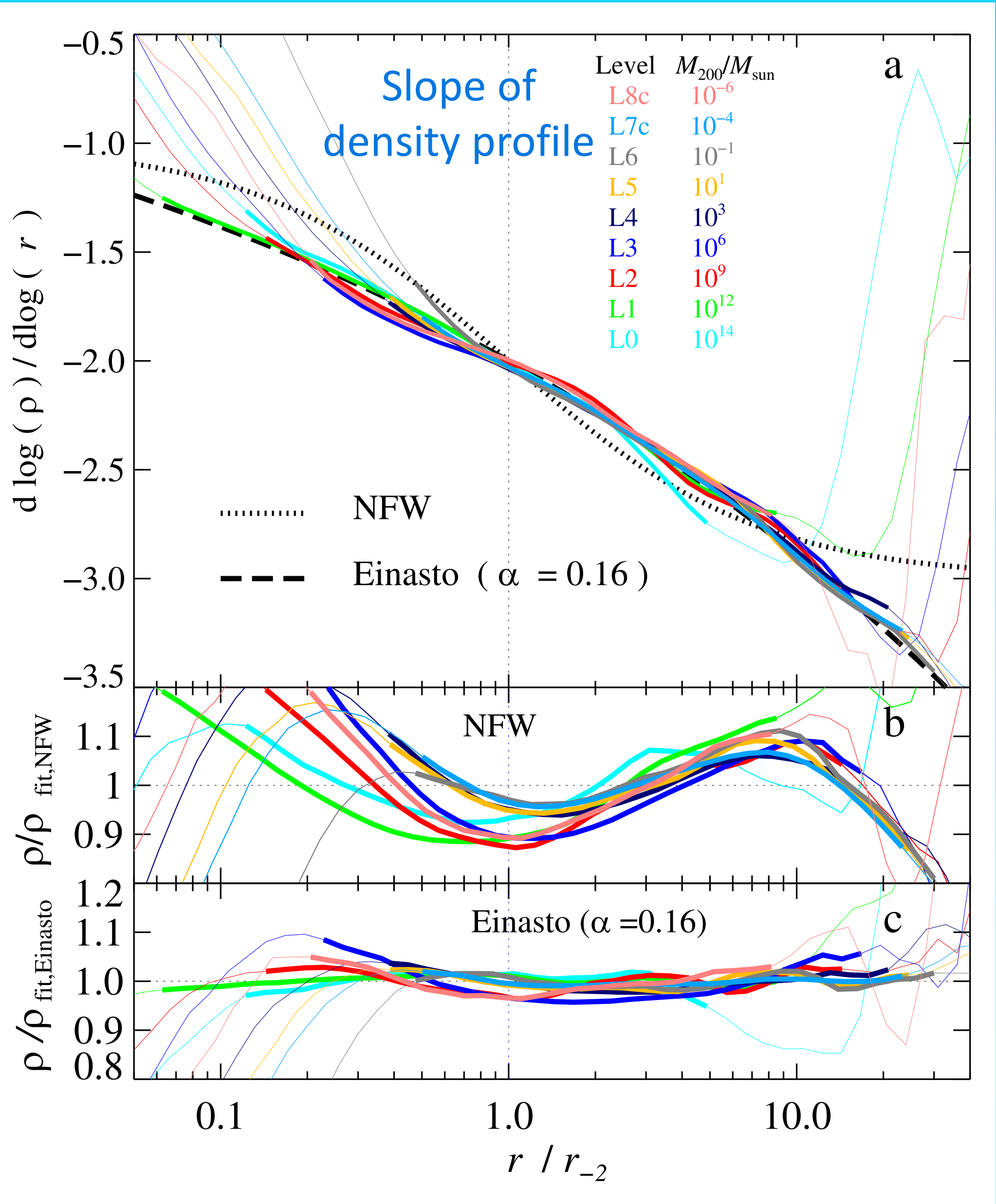
Over 20 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (α =0.16) to within 7%



Wang, Bose, CSF + '20

ICC

We know abundance & structure of halos of ALL masses

How many make a galaxy?

Flammarion 1888: tete des etoiles

A galaxy formation primer

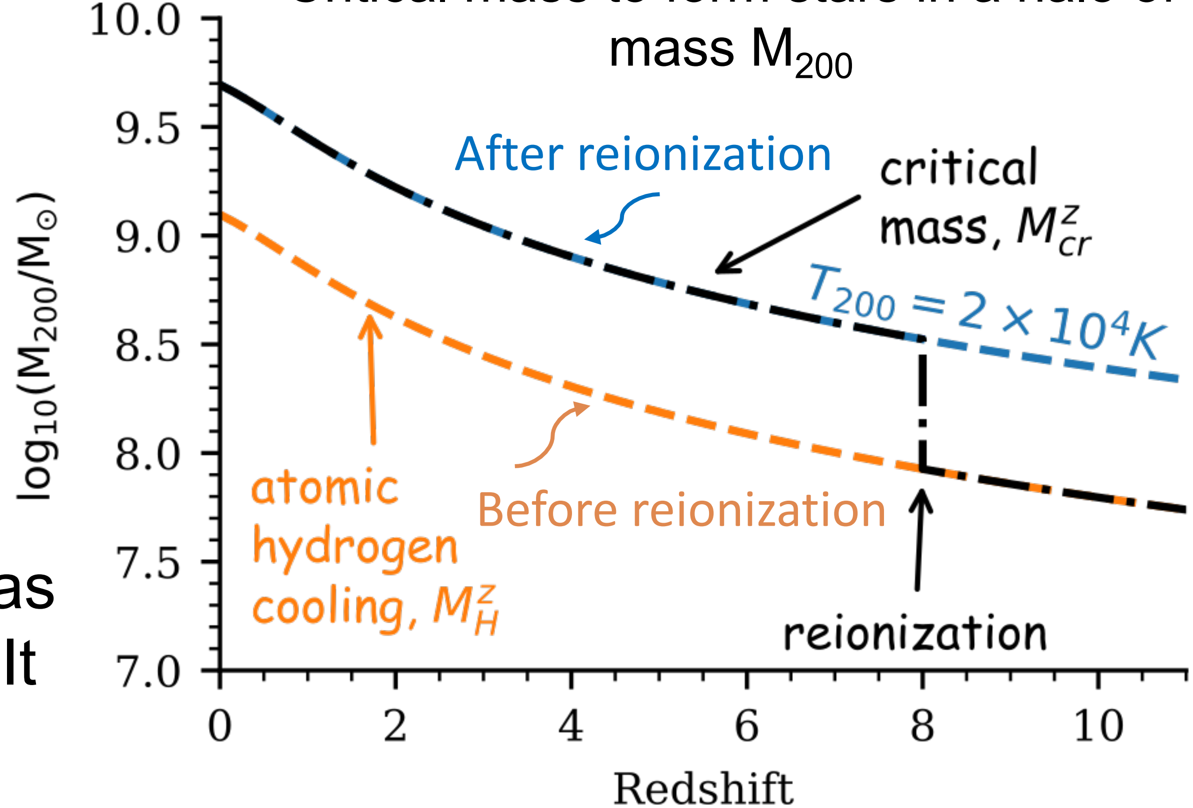
1. Before reionization, stars can only form if atomic H cooling is effective: → T>7000 K

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

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

$T_{vir} > T_{IGM} = 2\mathrm{x}10^4$ K

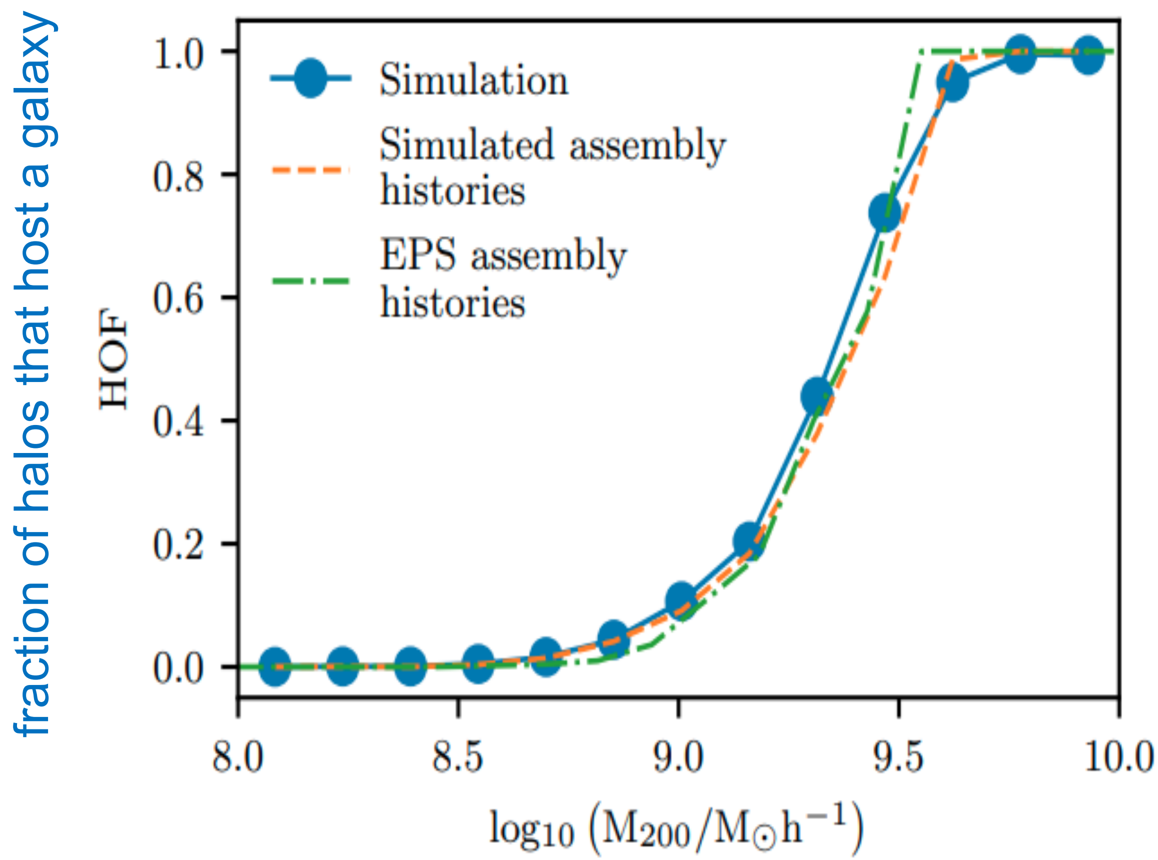
Critical mass to form stars in a halo of mass M_{200}



Benitez-Llambay & CSF '20

A galaxy formation primer

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

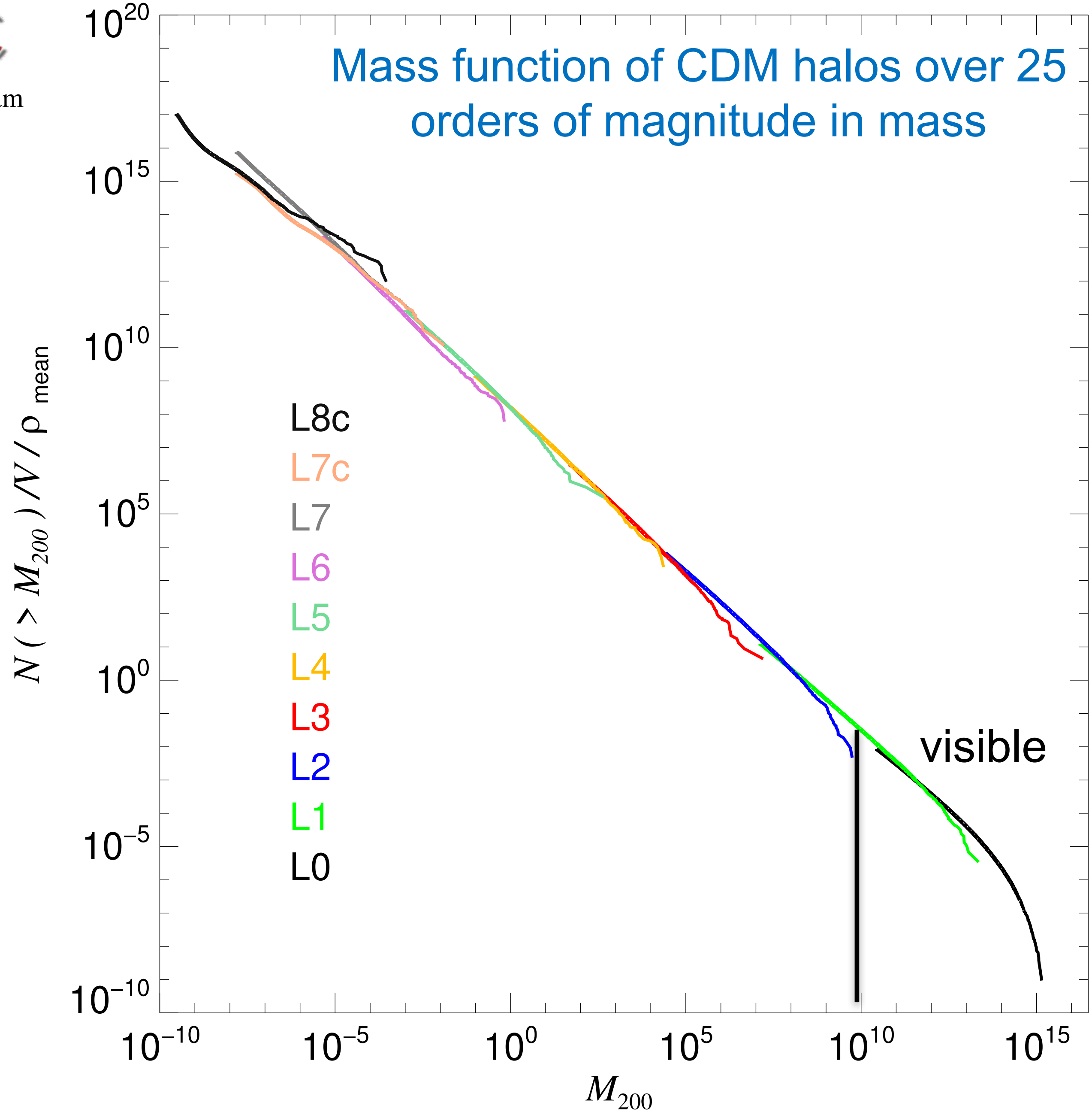


$M<3x10^8 M_o$ → dark

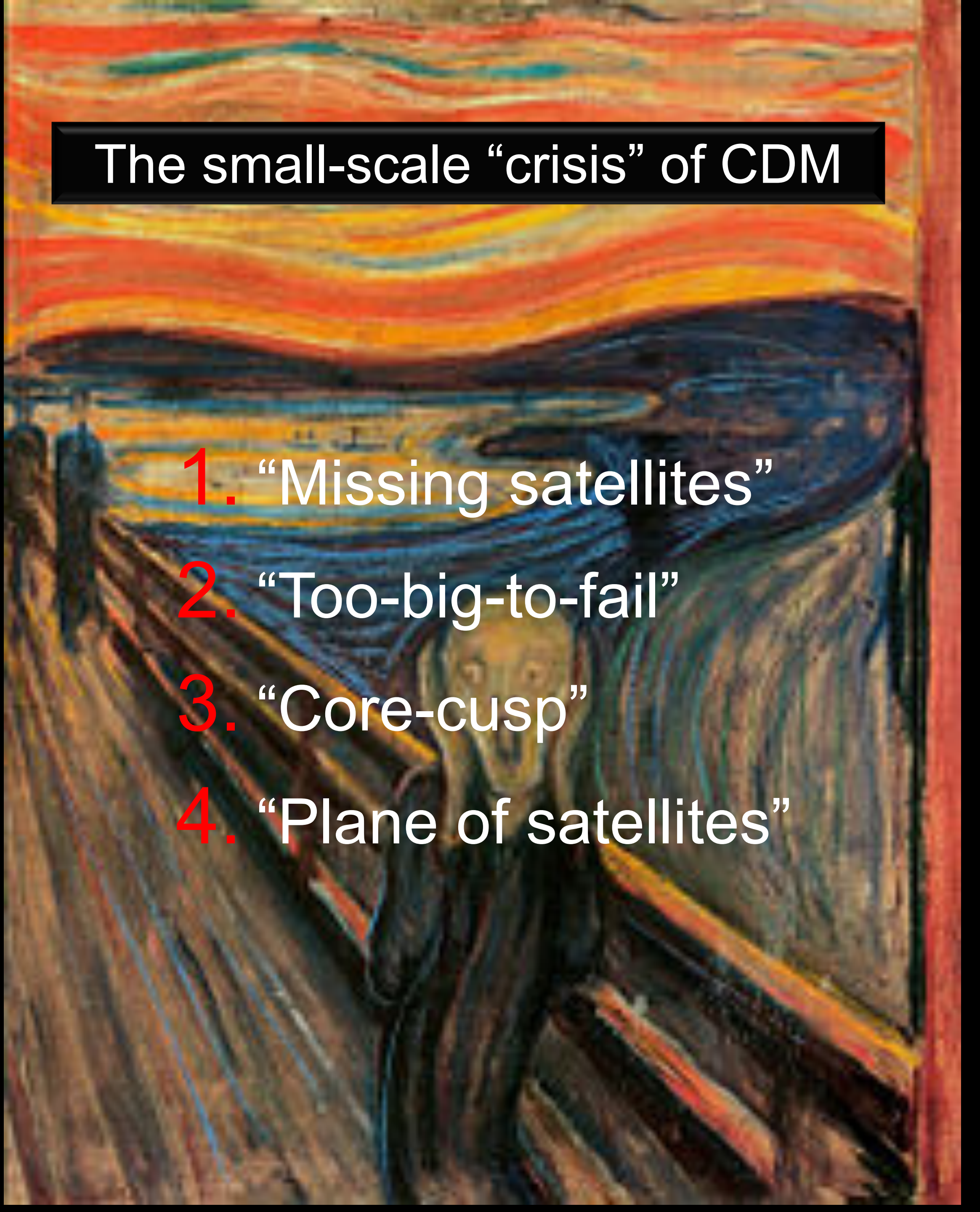
$M>3x10^9 M_o$ → visible

Benitez-Llambay & CSF '20

Institute for Computational Cosmology

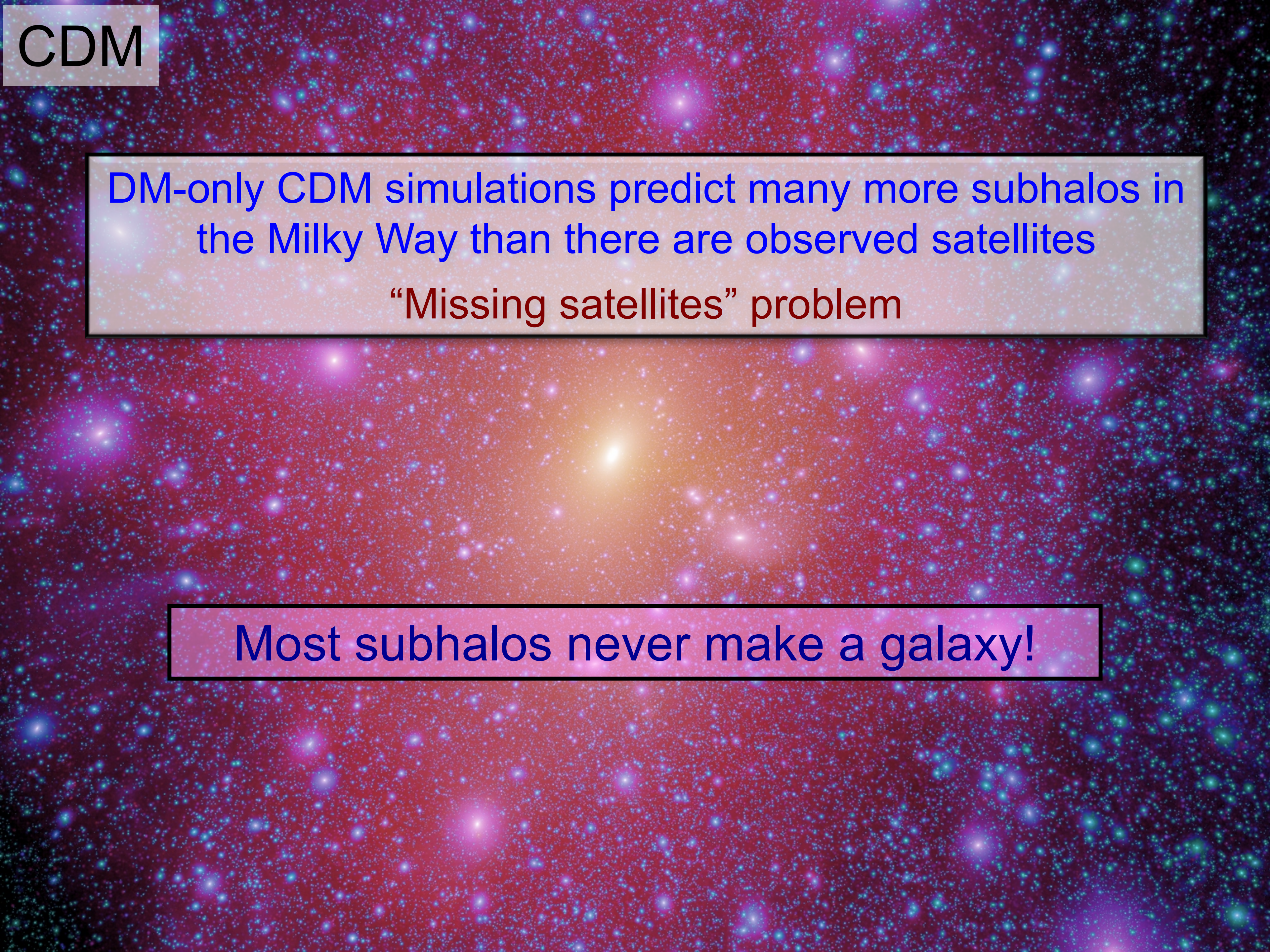


Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020



The small-scale “crisis” of CDM

1. “Missing satellites”
2. “Too-big-to-fail”
3. “Core-cusp”
4. “Plane of satellites”


CDM
DM-only CDM simulations predict many more subhalos in the Milky Way than there are observed satellites
“Missing satellites” problem
Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

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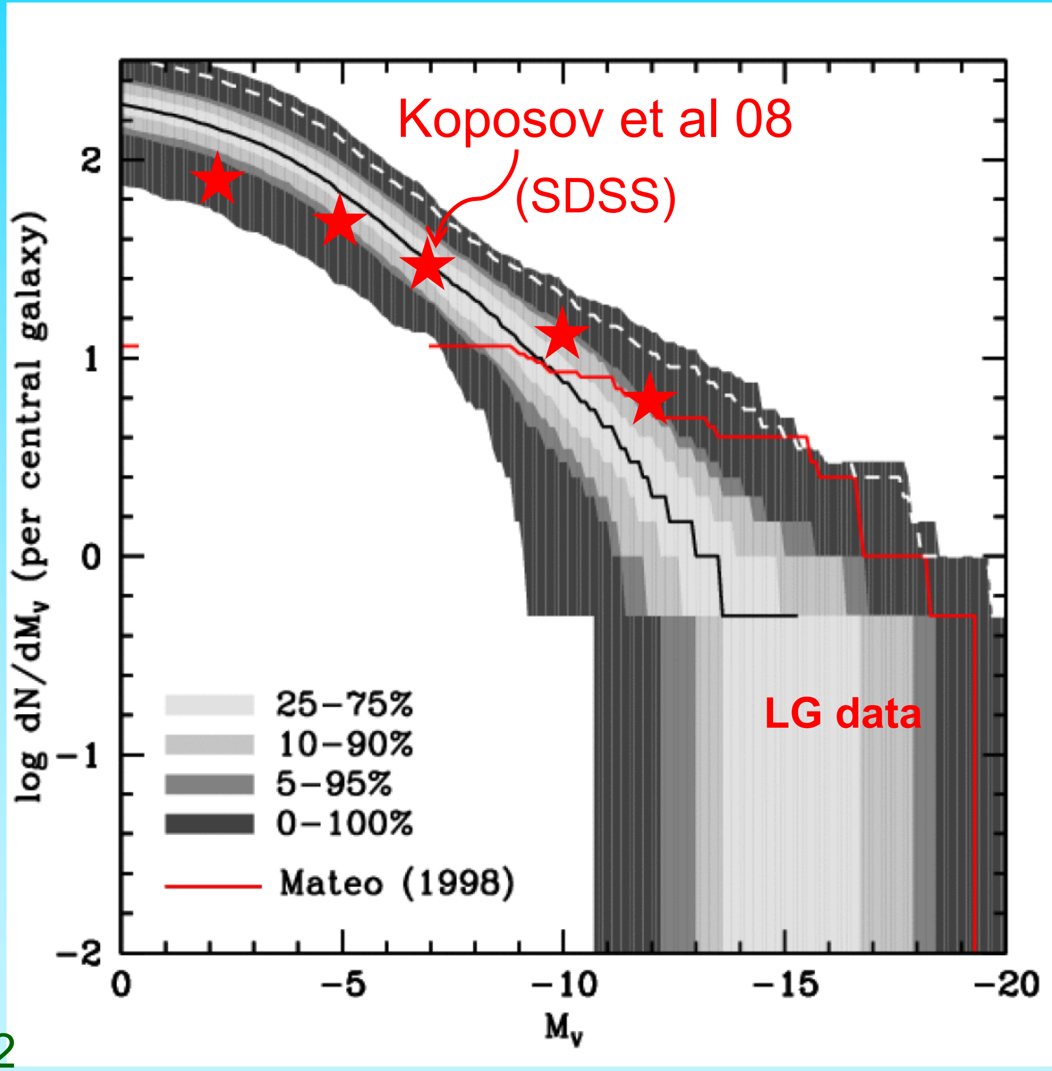
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



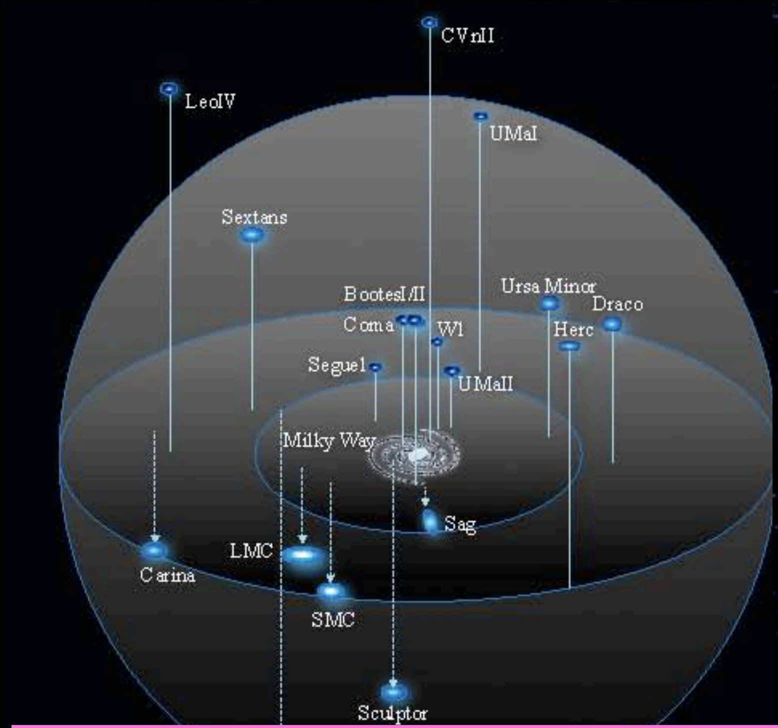
Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

The "too-big-to-fail" problem

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

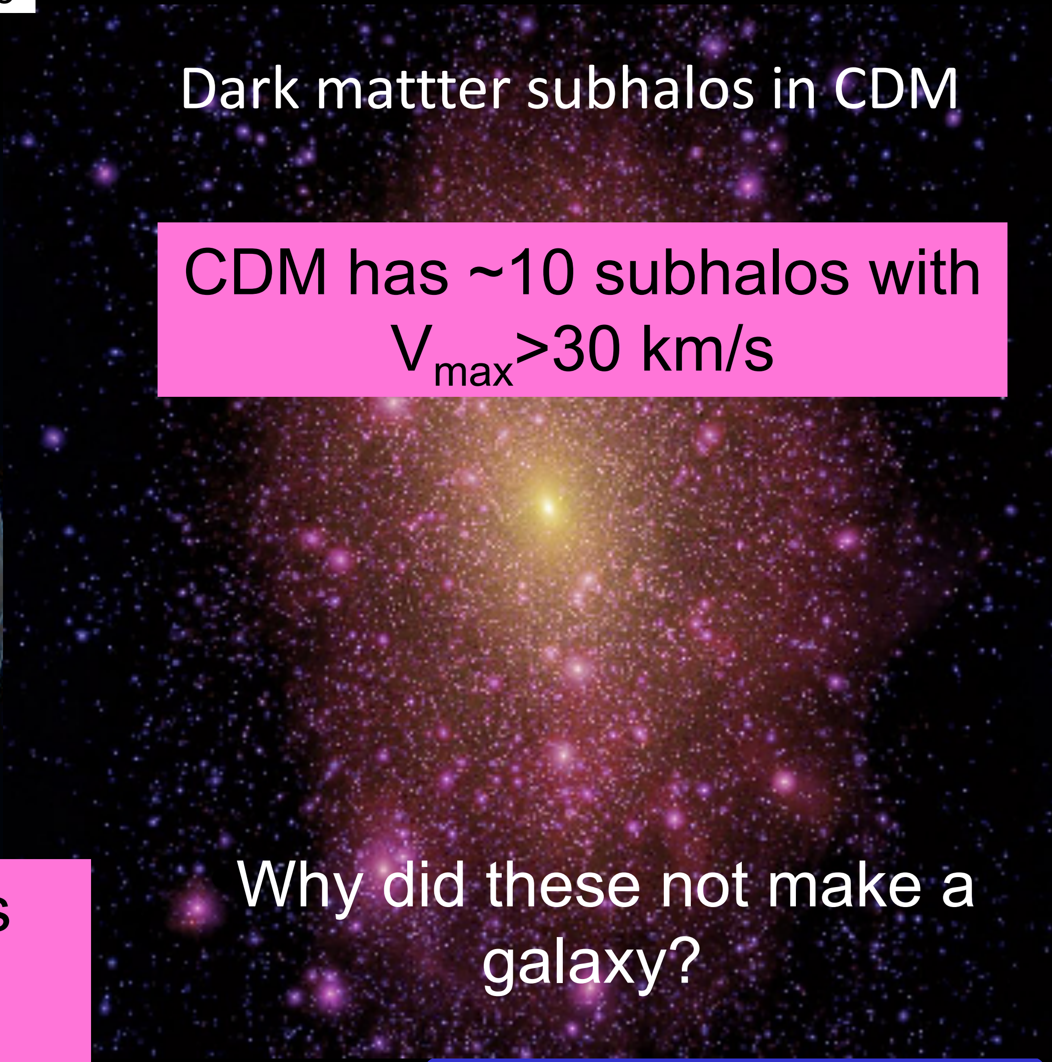
$$V_{max} = \max V_c$$

The satellites of the MW



MW has only 3 satellites with V_{max}>30 km/s
(LMC, SMC, Sgr)

Dark matter subhalos in CDM



CDM has ~10 subhalos with V_{max}>30 km/s

Why did these not make a galaxy?

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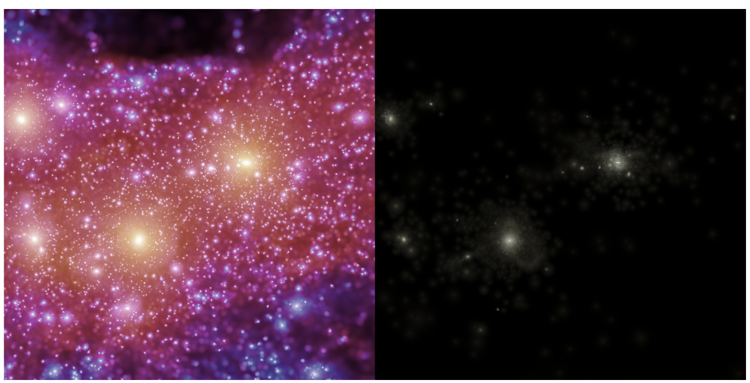
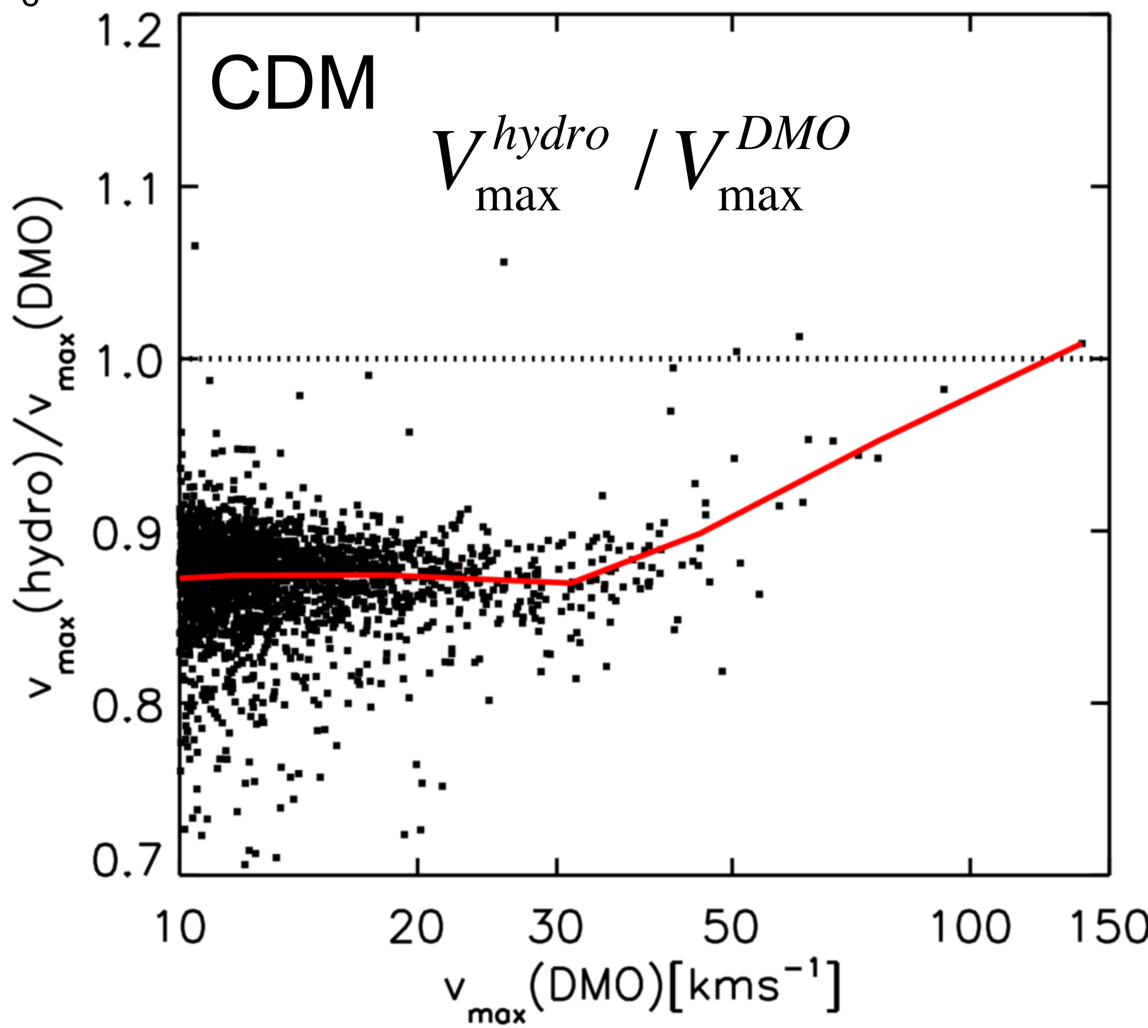
Too-big-to-fail in CDM: baryon effects

$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala, CSF et al. '13, '15

The core/cusp "problem"

DMO simulations predict NFW profiles

But some galaxies are inferred to have cores

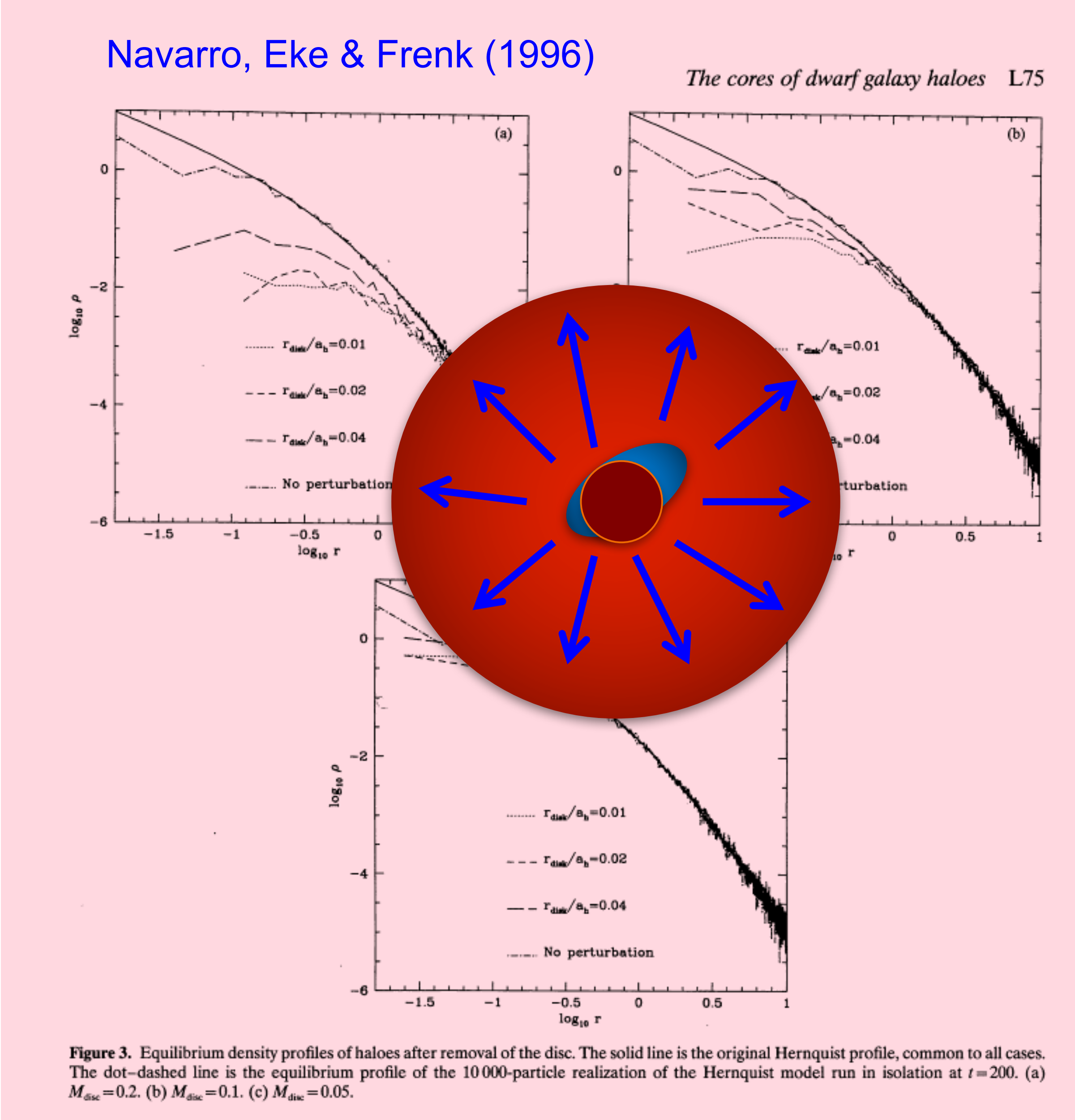
The core/cusp “problem”

DMO simulations predict NFW profiles

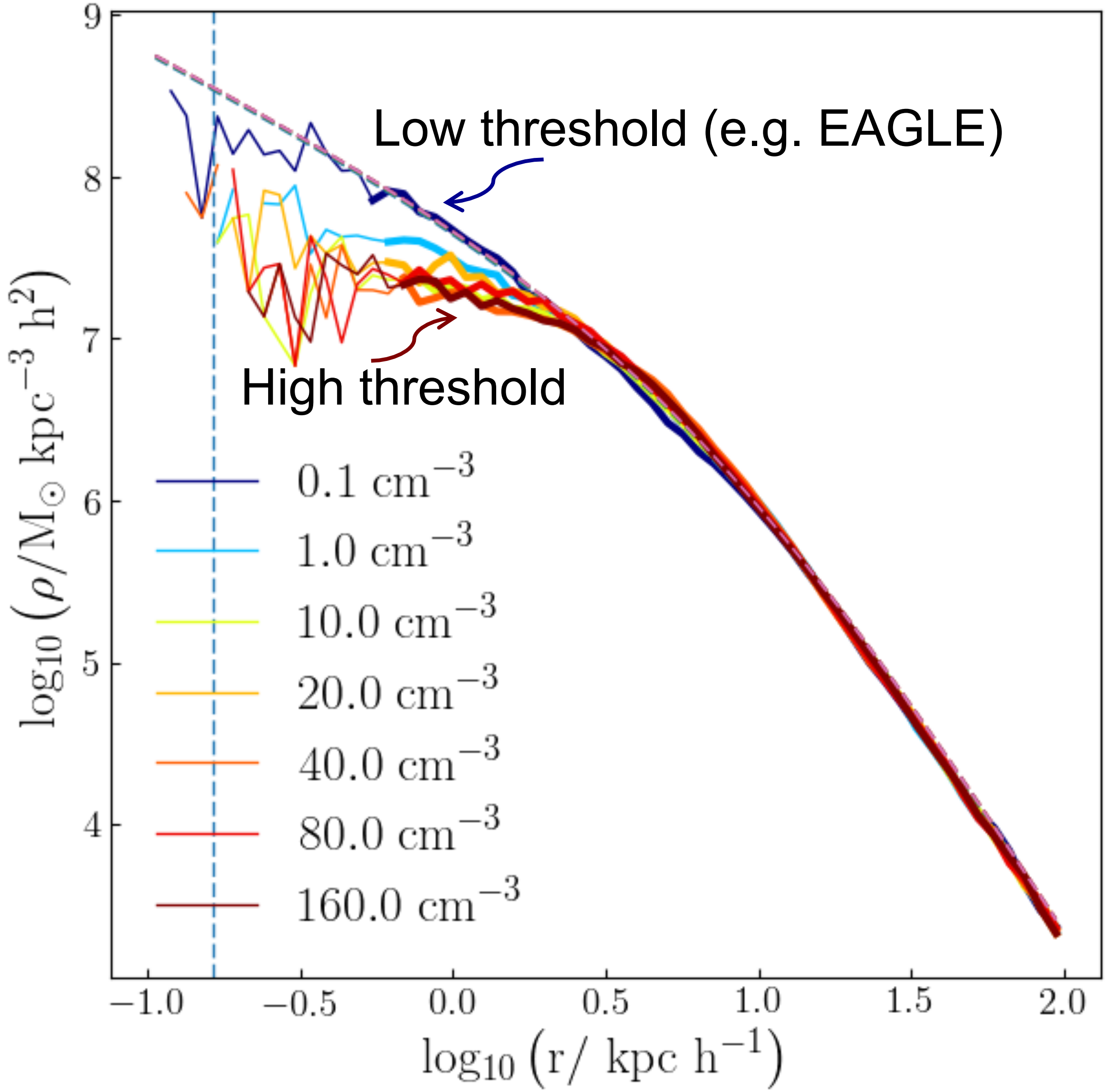
Cusps → cores

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)



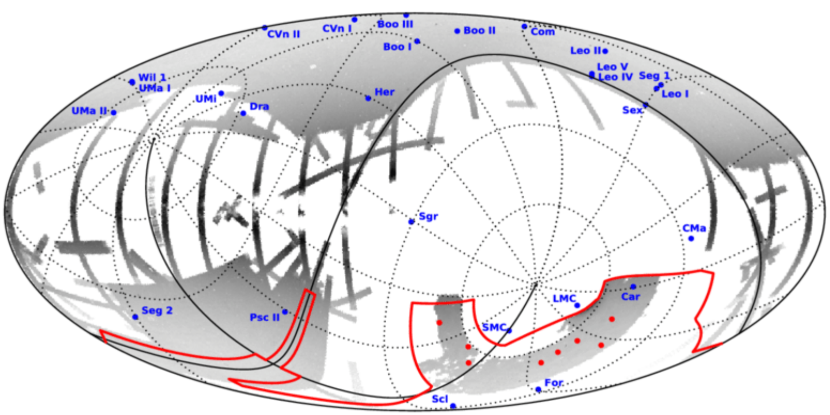
Cores or cusps in simulations?



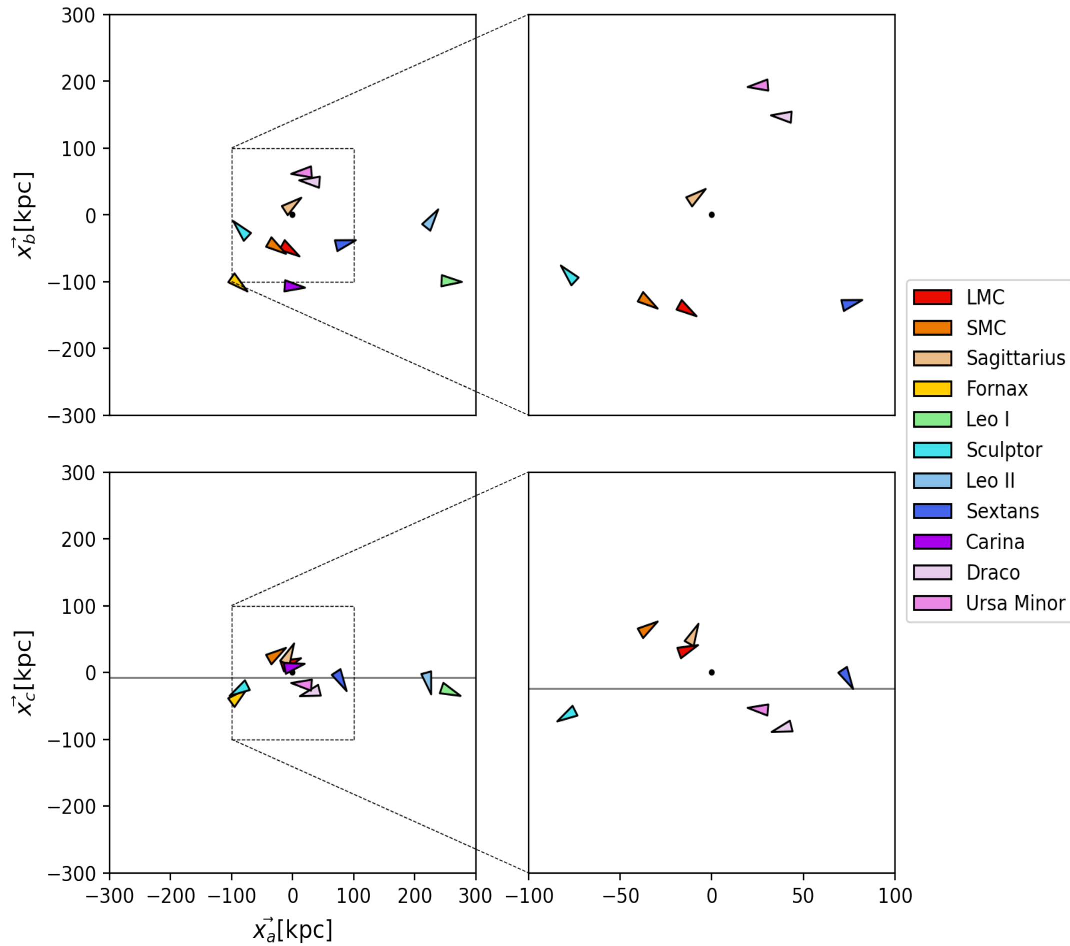
Benitez-Llambay, CSF et al '19

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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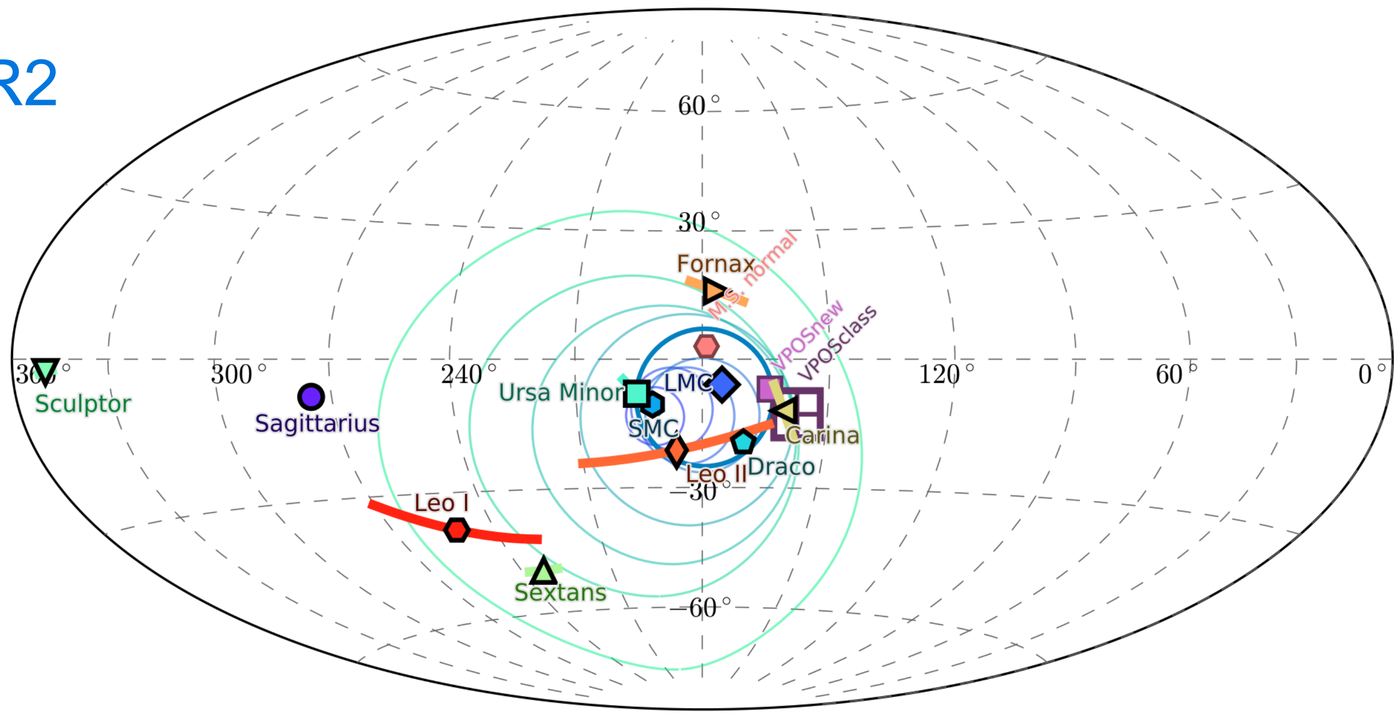
The plane of satellites in the MW

The plane could be a spinning disk

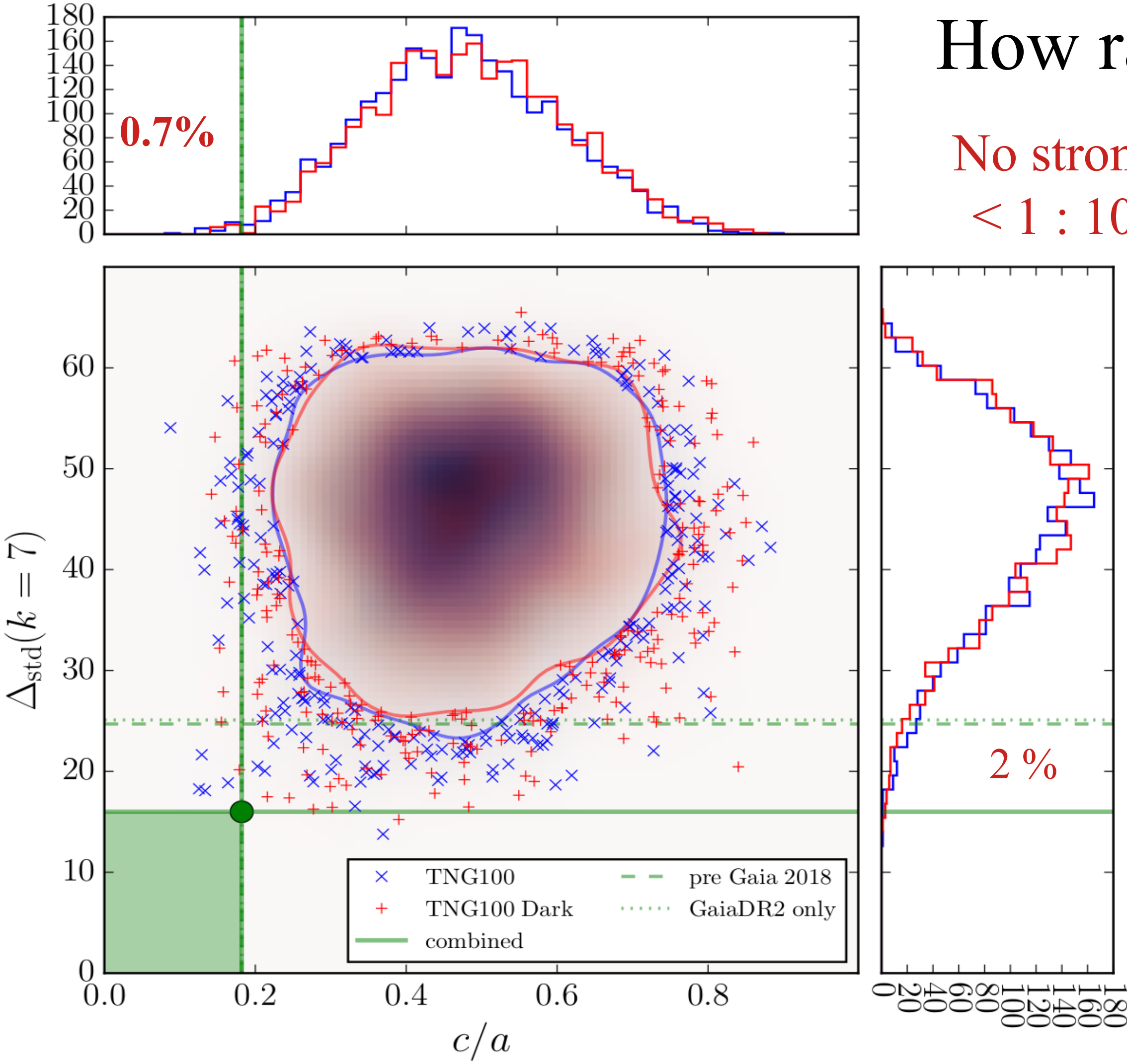
The orbital poles of 7 of the 11 satellites are clustered

GAIA DR2



Pawlowski & Kroupa (2020)

The plane of satellites in the MW



How rare is it?

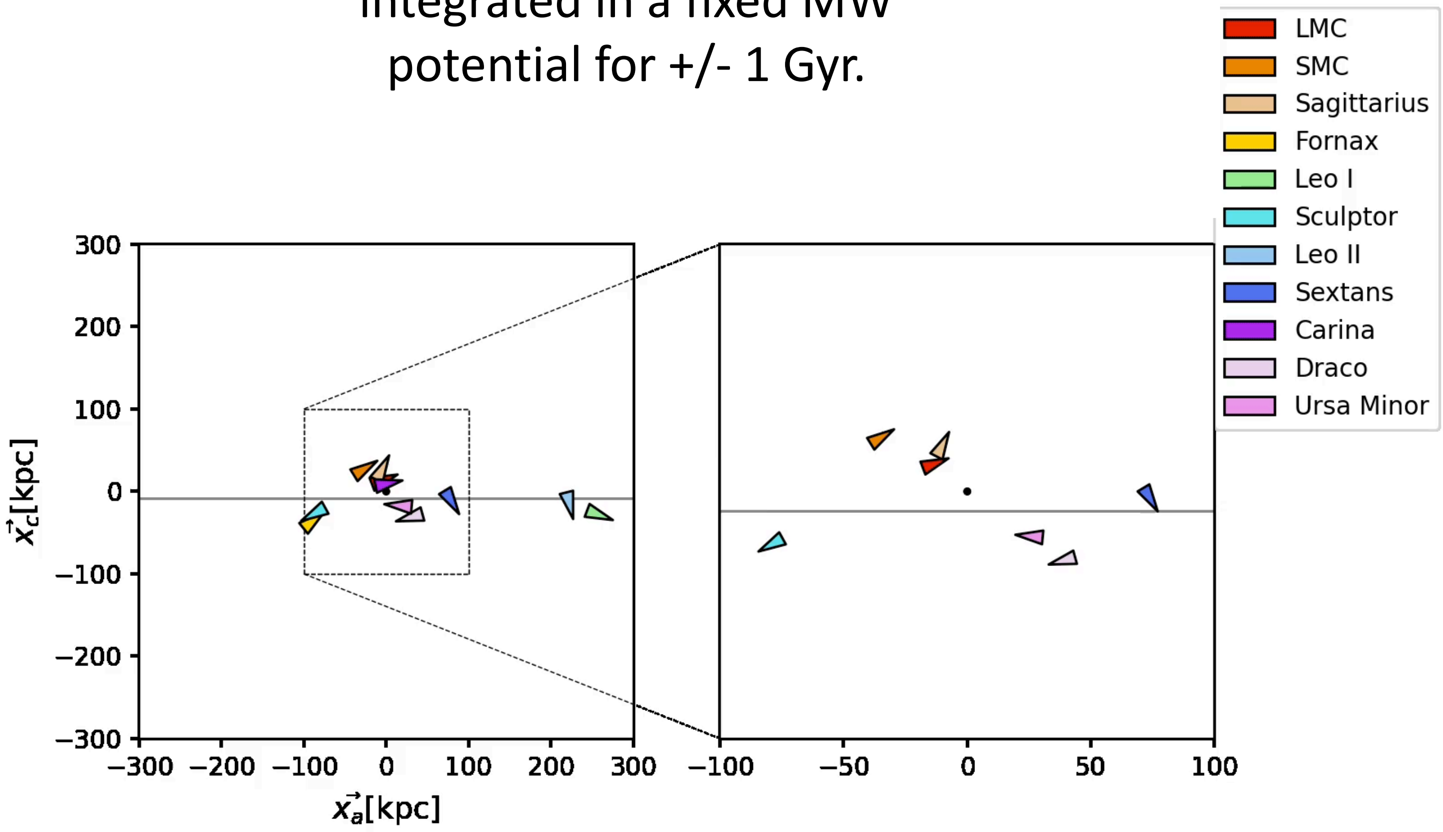
No strong correlation –
< 1 : 100,000 chance?

Eigenvalues of inertia tensor

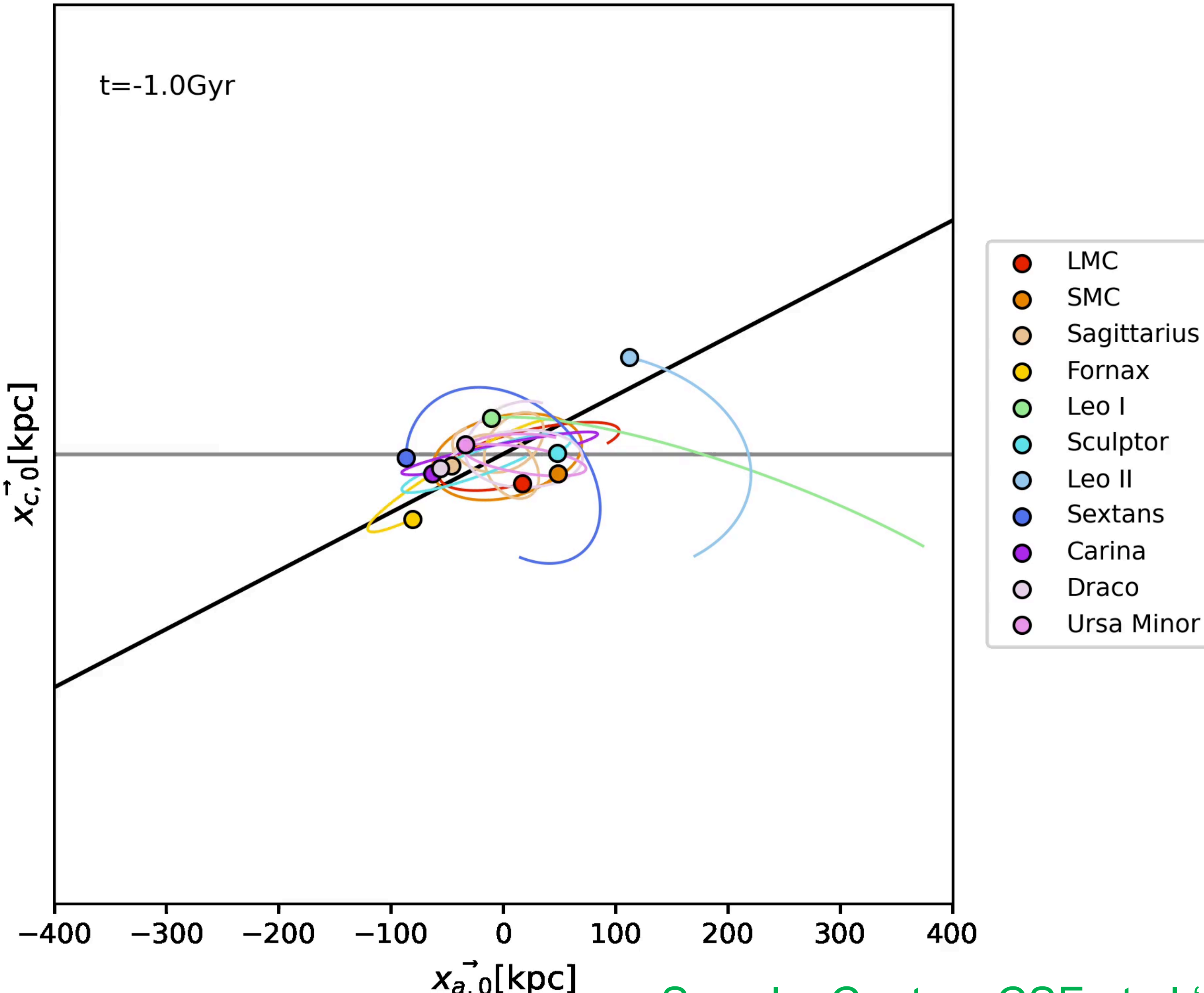
a>b>c

Pawlowski & Kroupa (2020)

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



Sawala, Cautun, CSF et al ‘23



Sawala, Cautun, CSF et al '22

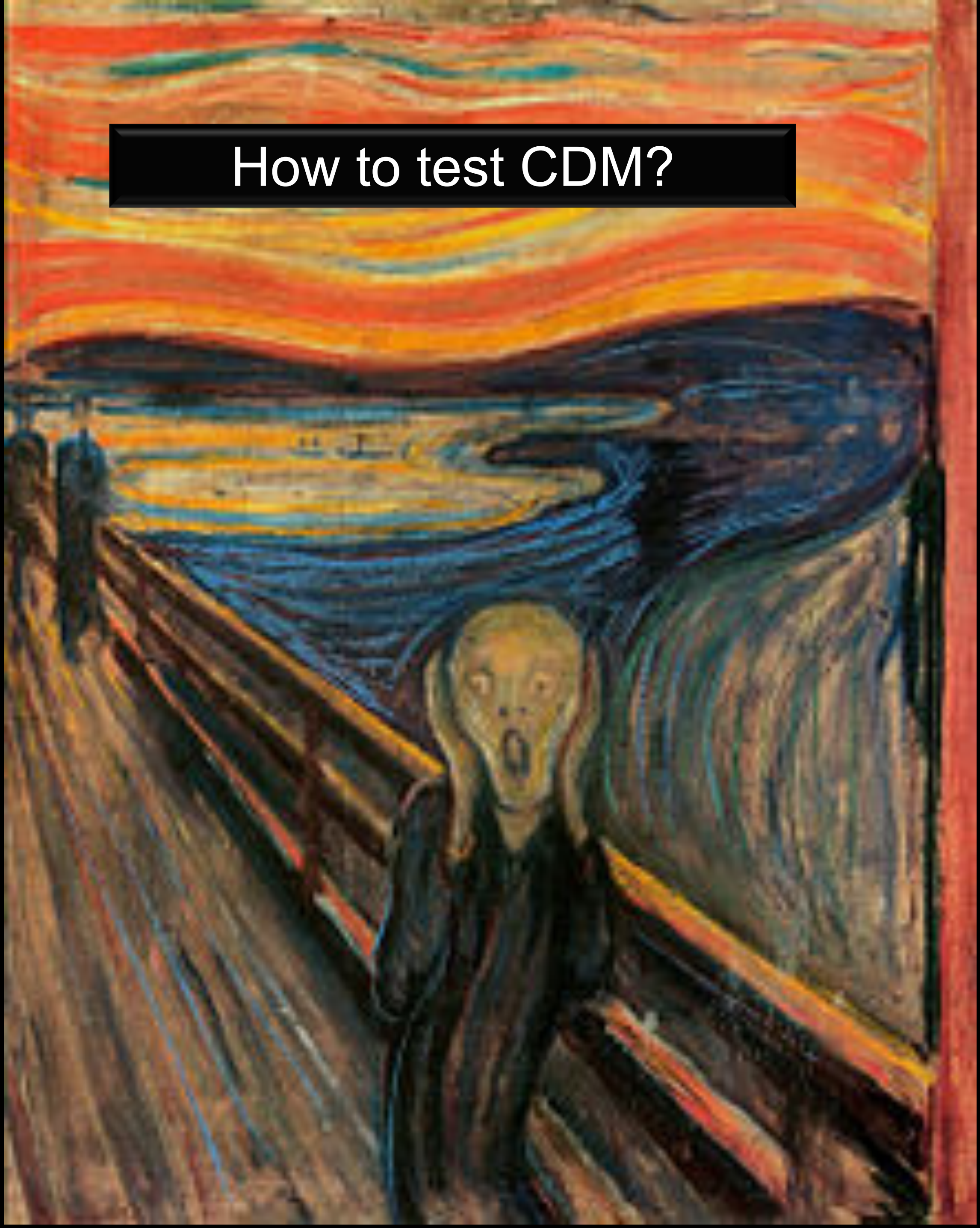
The rotating plane of satellites

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

We have 5/200 (2.5%) more clustered than the MW (compared to 0.04%)

Still rare, but not *astronomically* unlikely.

How to test CDM?



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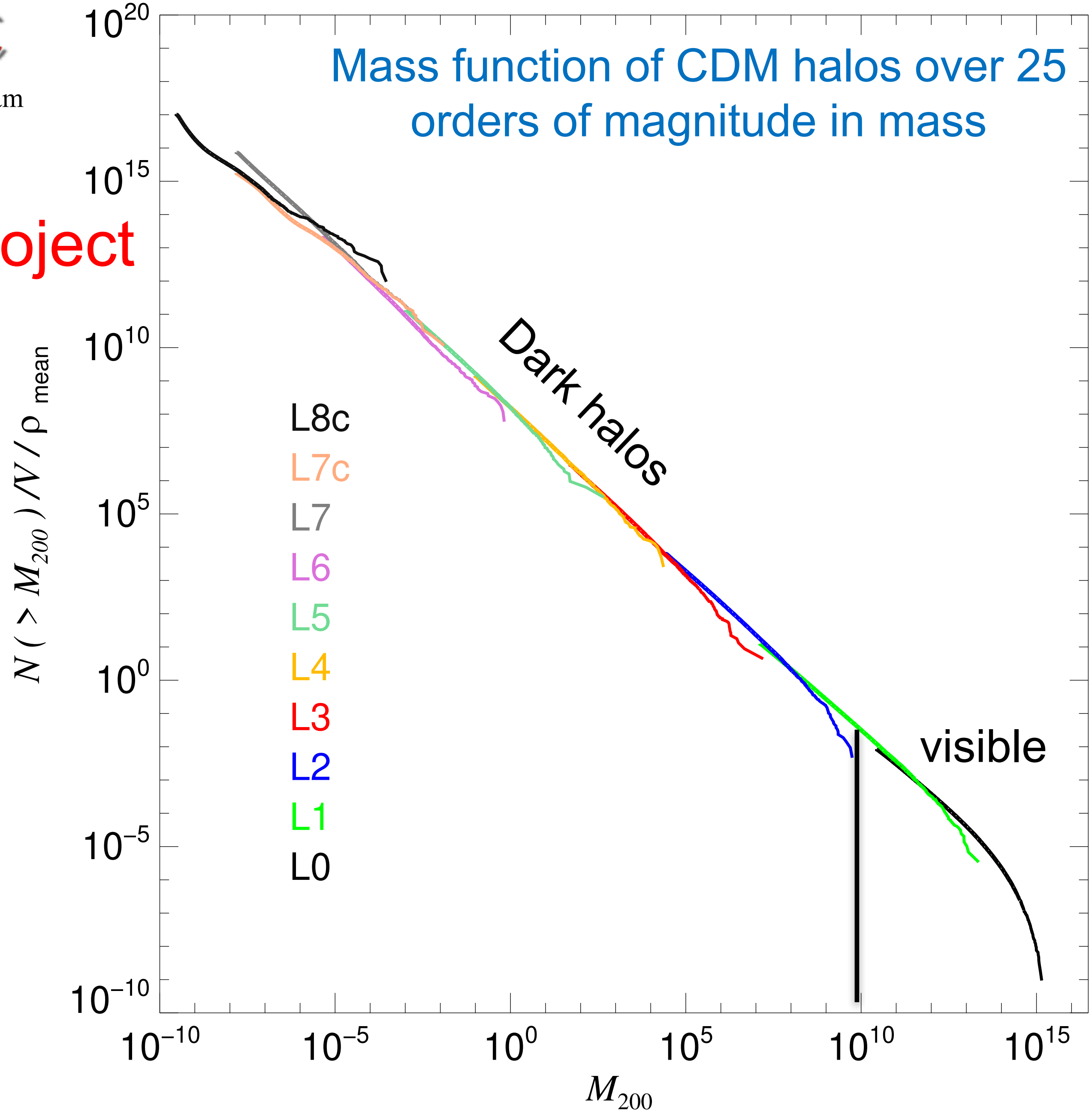
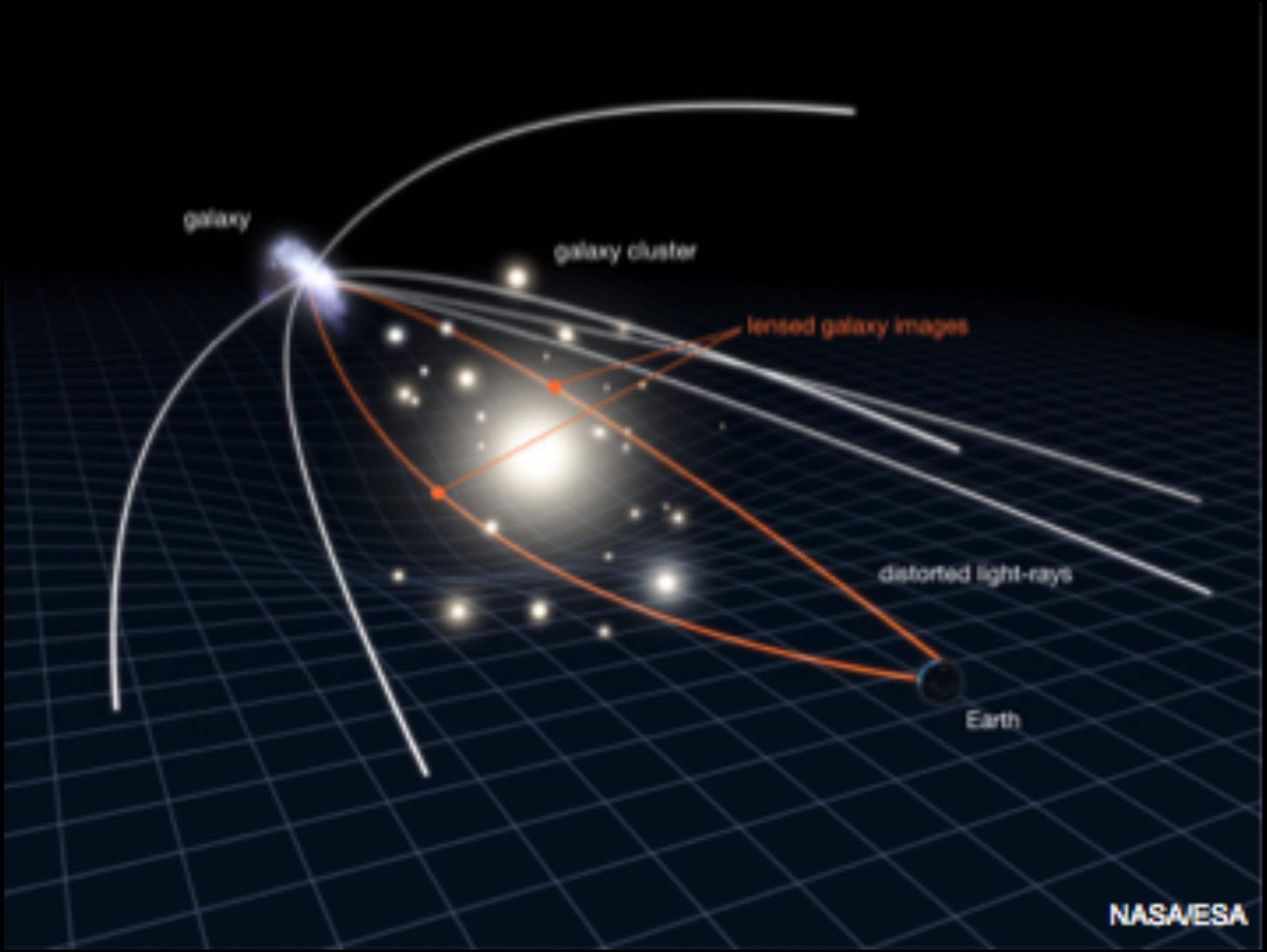
The VVV project



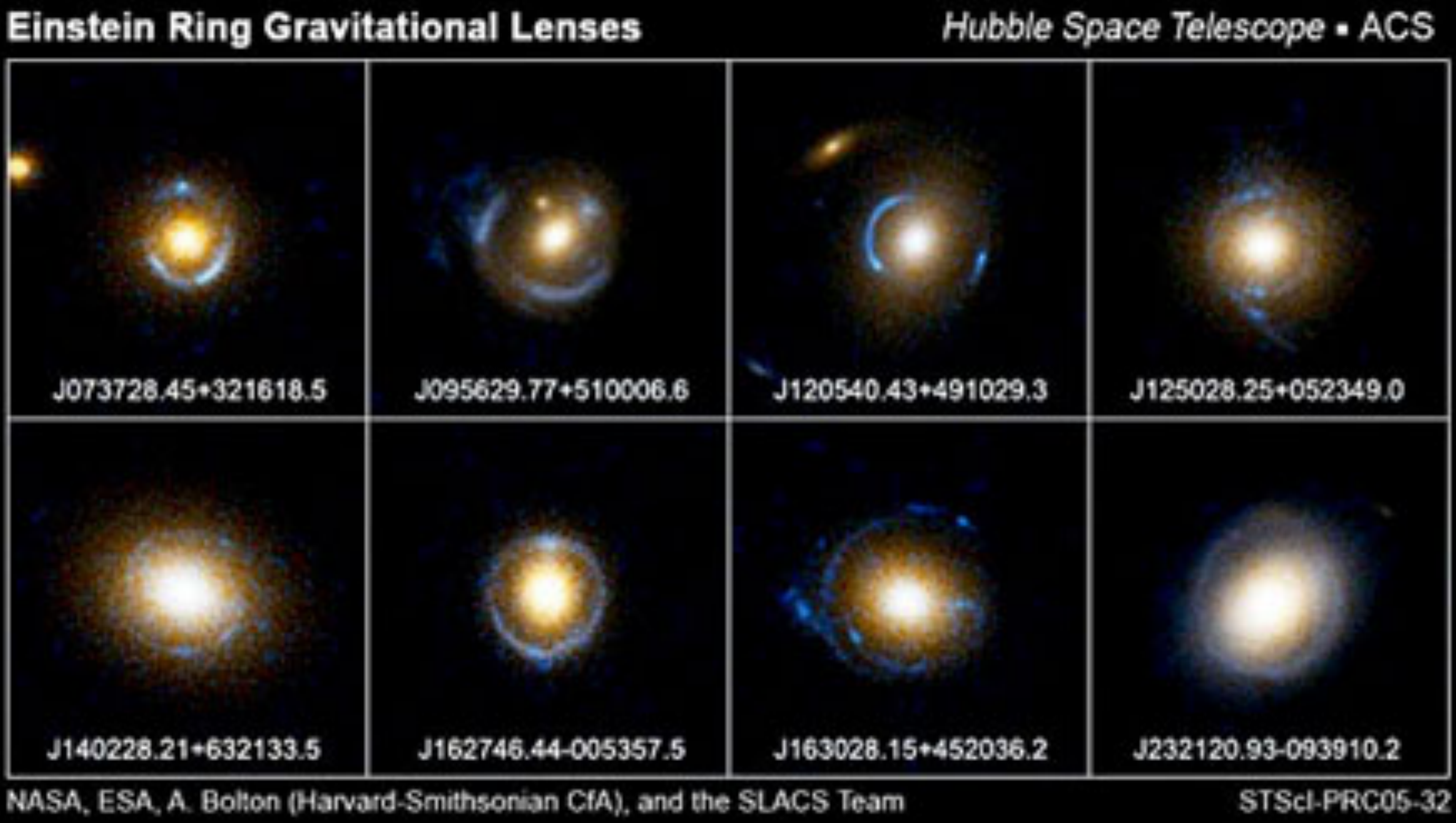
Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

Gravitational lensing: Einstein rings



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

SLAC sample of strong lenses



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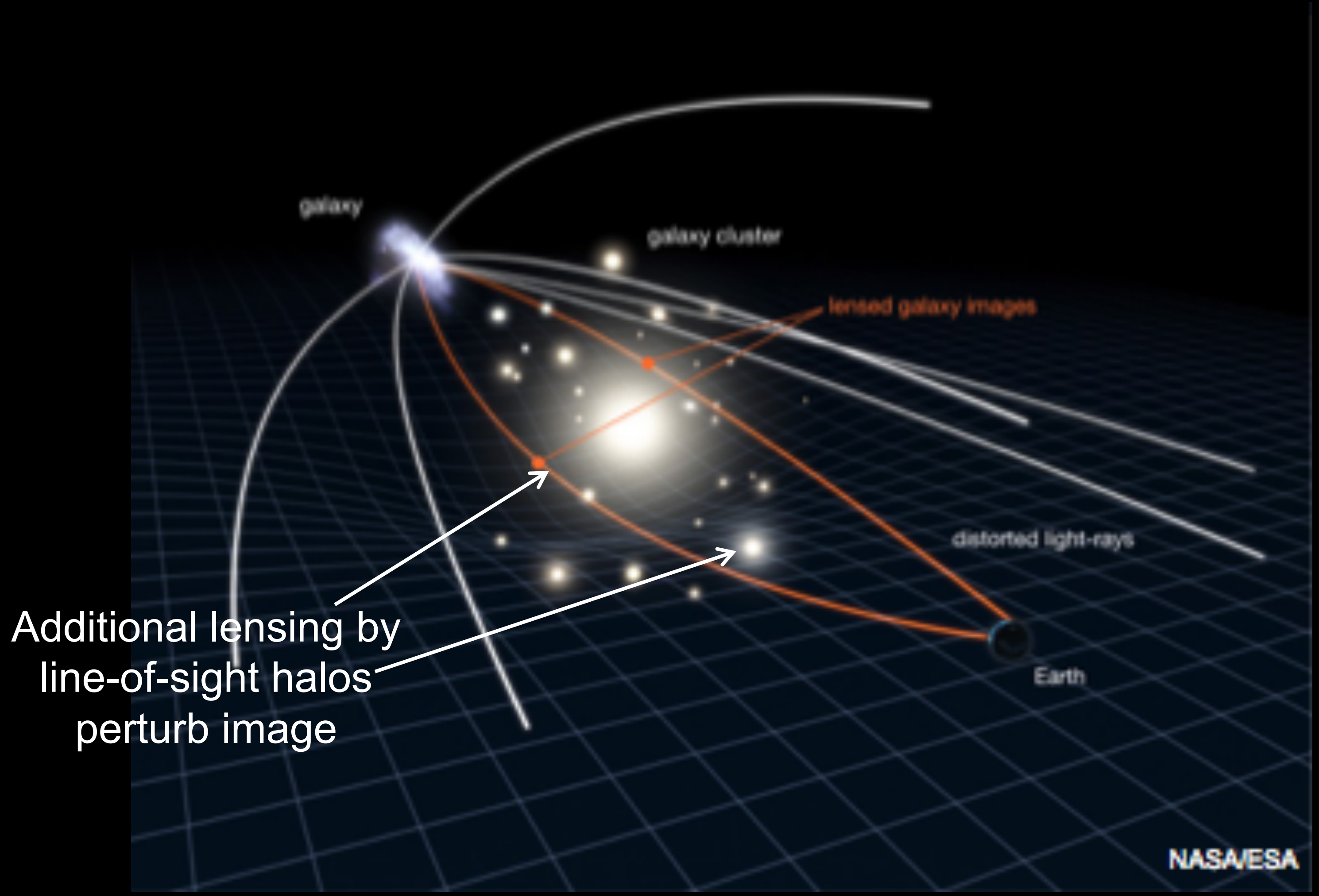


When the source and the lens are well aligned → strong arc or an Einstein ring

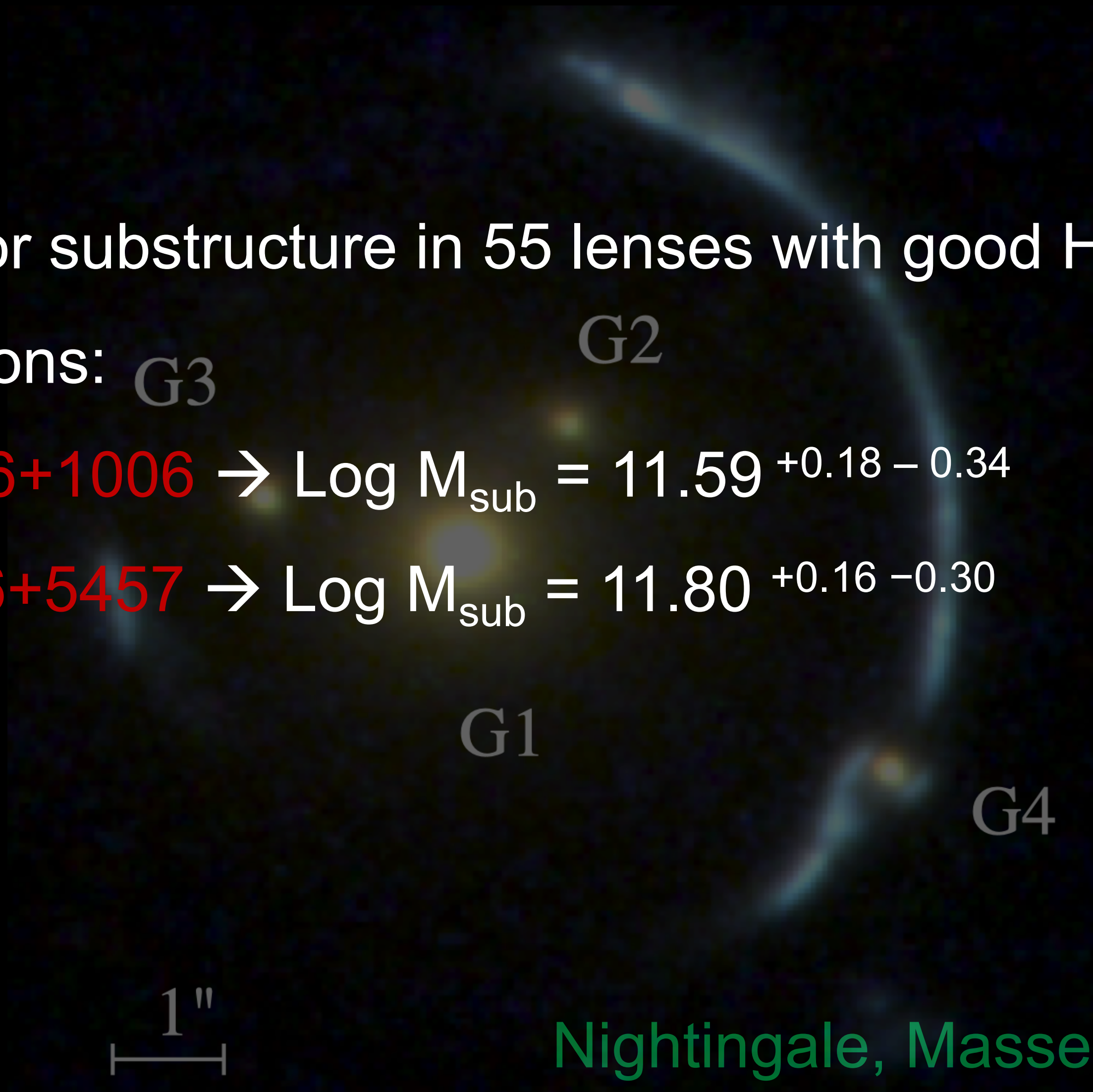
Gravitational lensing: substructures

Searched for substructure in 55 lenses with good HST imaging

→ 2 detections:

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

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



Nightingale, Massey, CSF+ '22

Strong lensing: detecting small halos

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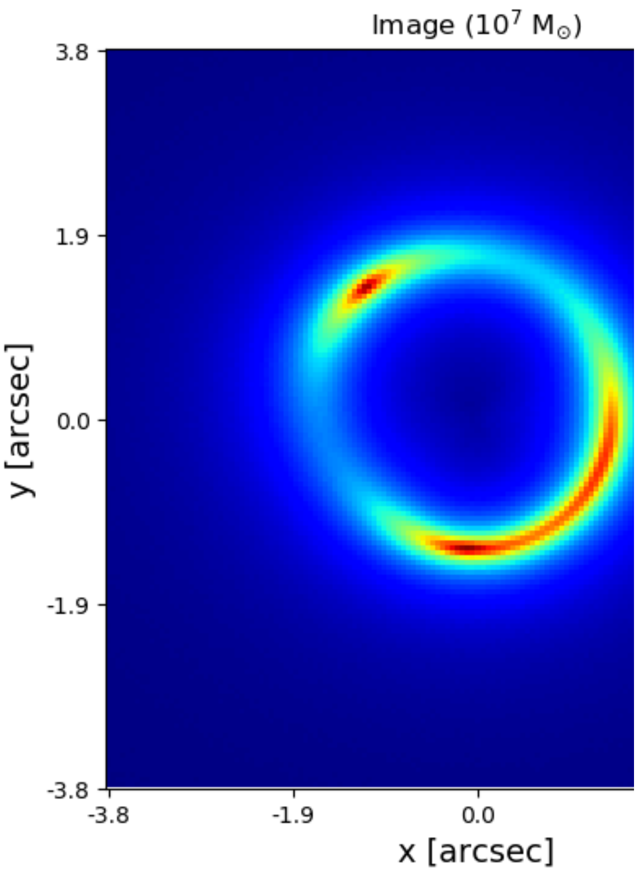
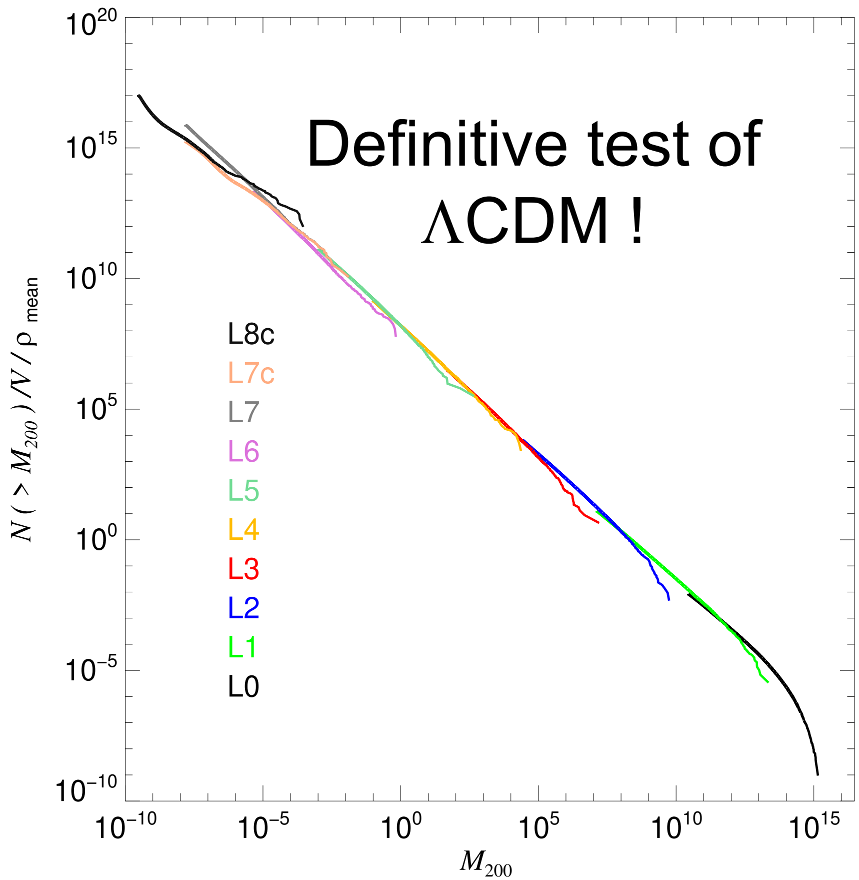
HST “data”: z_{source}=1; z_{lens}=0.2 10^7 M_o halo – NOT so easy to spot

Image





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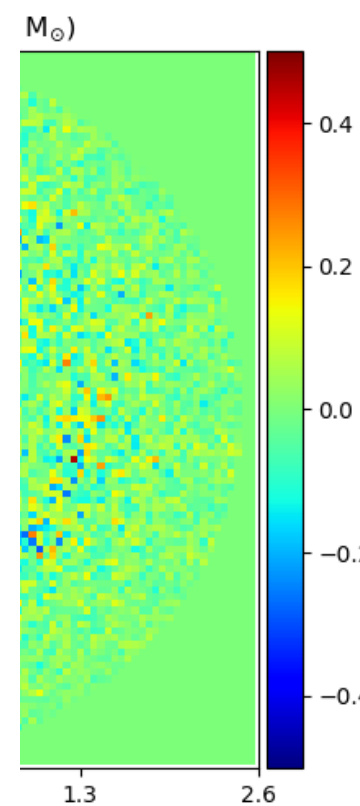

He, Li, CSF et al ‘19

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

HAPPY BIRTHDAY celebration !