Tests of ΛCDM

Carlos S. Frenk
Institute for Computational Cosmology, Durham

Using (sub)halos

University of Durham

The new Ogden Centre at Durham

University of Durham

Testing ΛCDM with (sub)halos

I. What do we know about subhalos in ΛCDM

- Abundance
- Radial distribution
- Structure

II. How can we use subhalos to test ΛCDM

- In the optical
- In gamma rays
- With gravitational lensing

Testing ΛCDM with (sub)halos

Subhalos are best studied with cosmological simulations

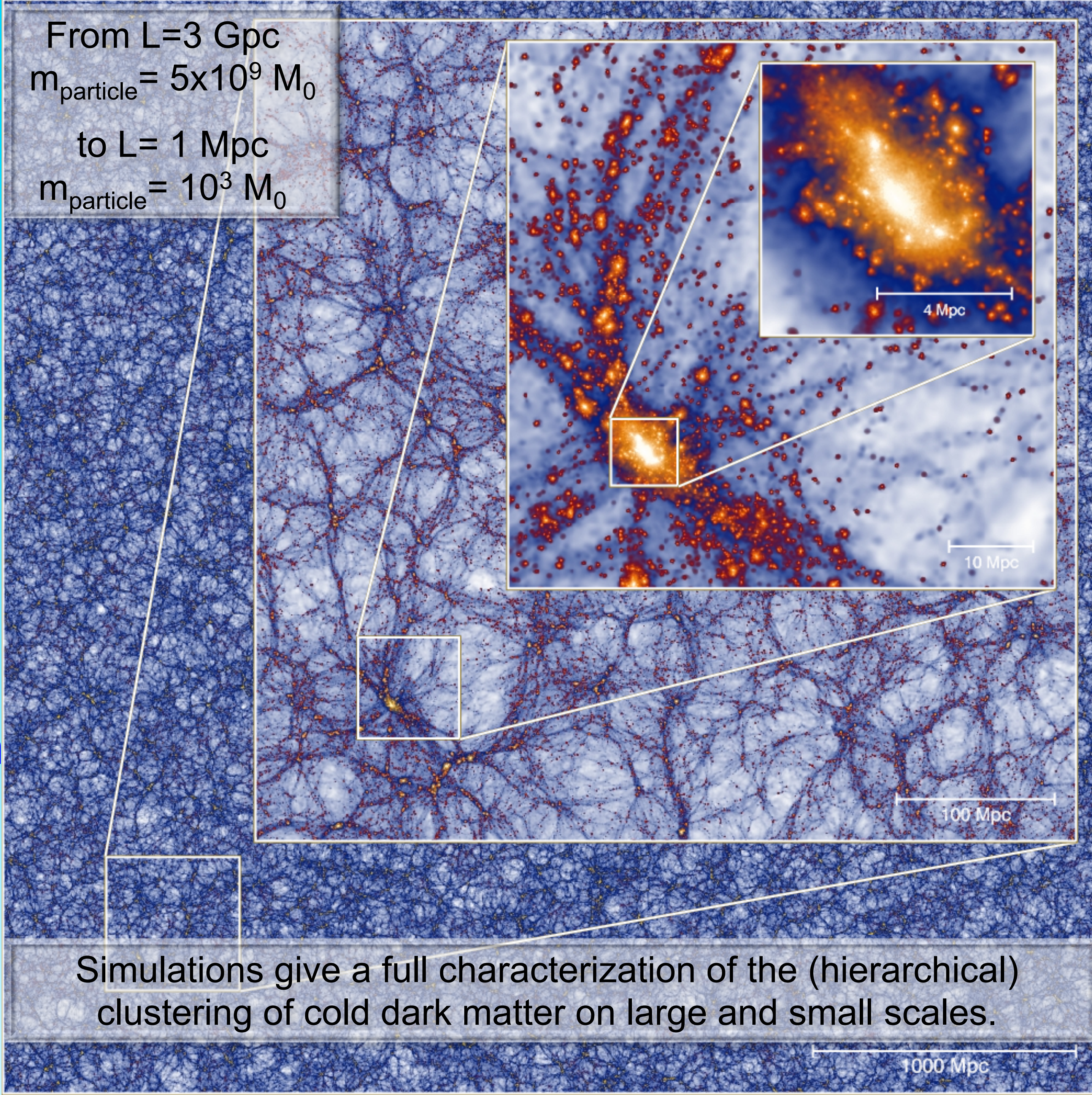
I. N-body simulations

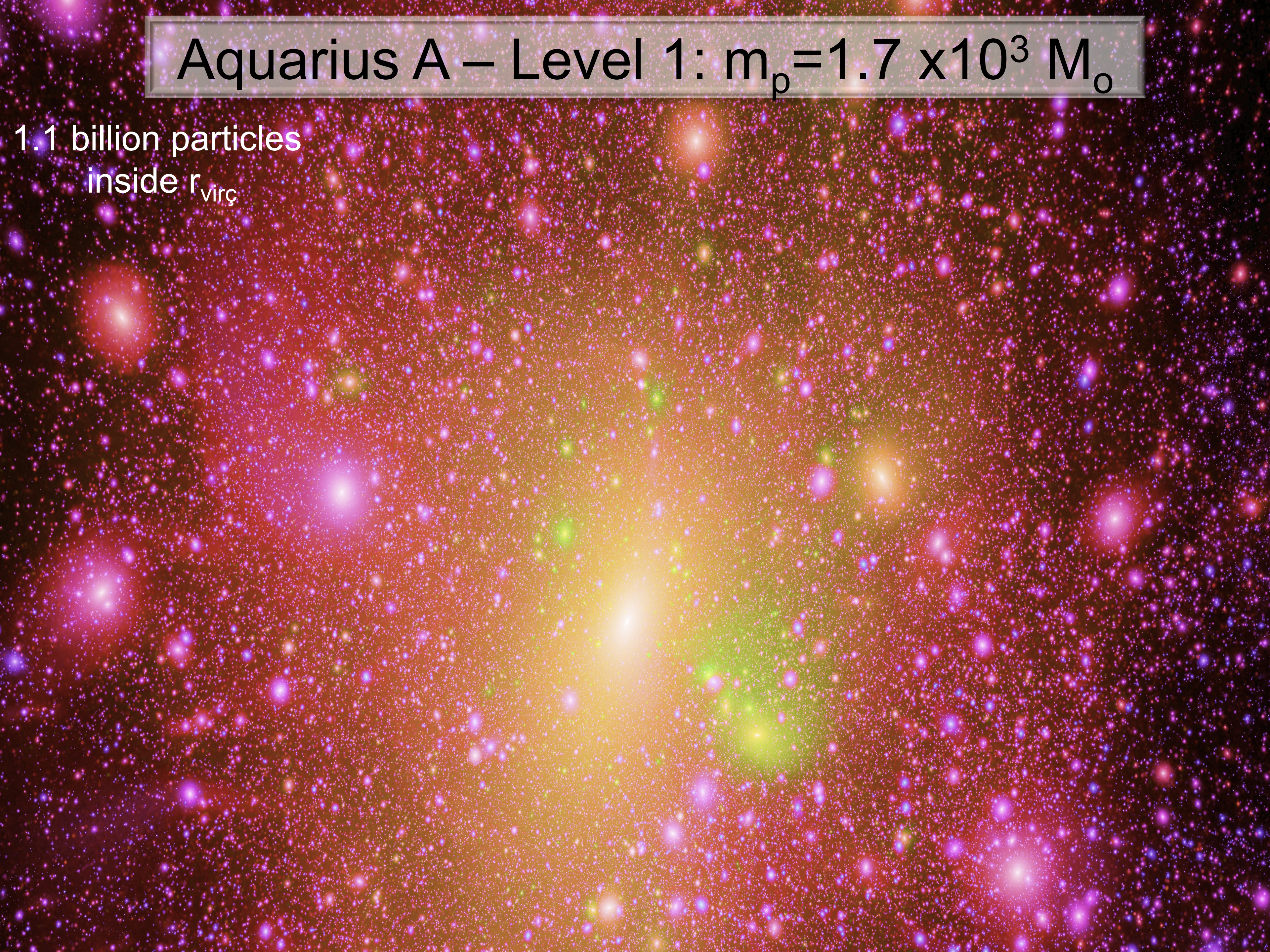
II. Hydrodynamical simulations

VIRGO

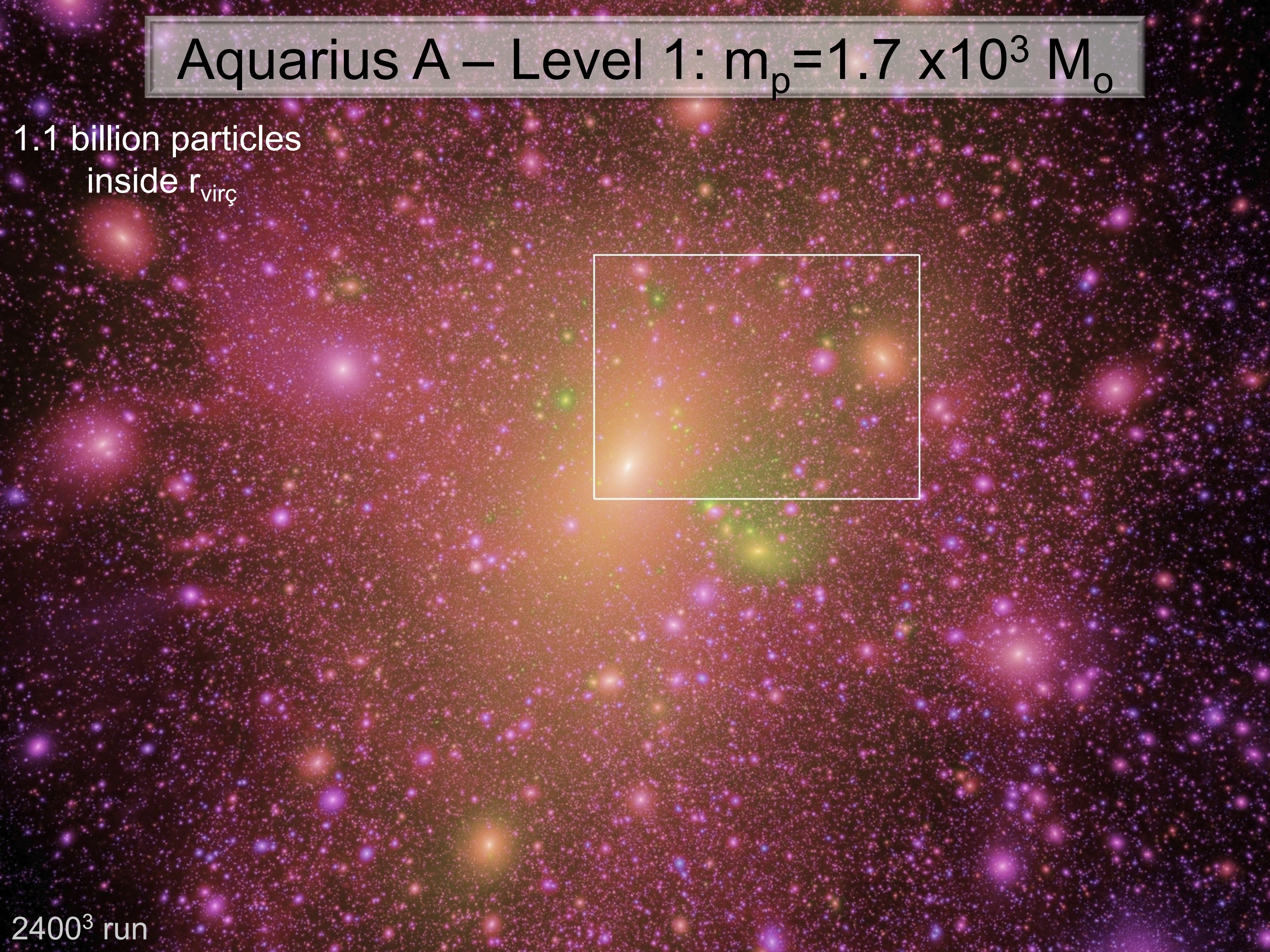
N-body simulations

The formation, evolution, abundance, clustering & structure of dark matter halos from CDM initial conditions is (almost) a solved problem




Aquarius A – Level 1: m_p=1.7 x10^3 M_o
1.1 billion particles
inside $r_{virç}$

Aquarius A – Level 1: m_p=1.7 x10^3 M_o



Aquarius A – Level 1: $m_p=1.7\ x10^3\ M_o$

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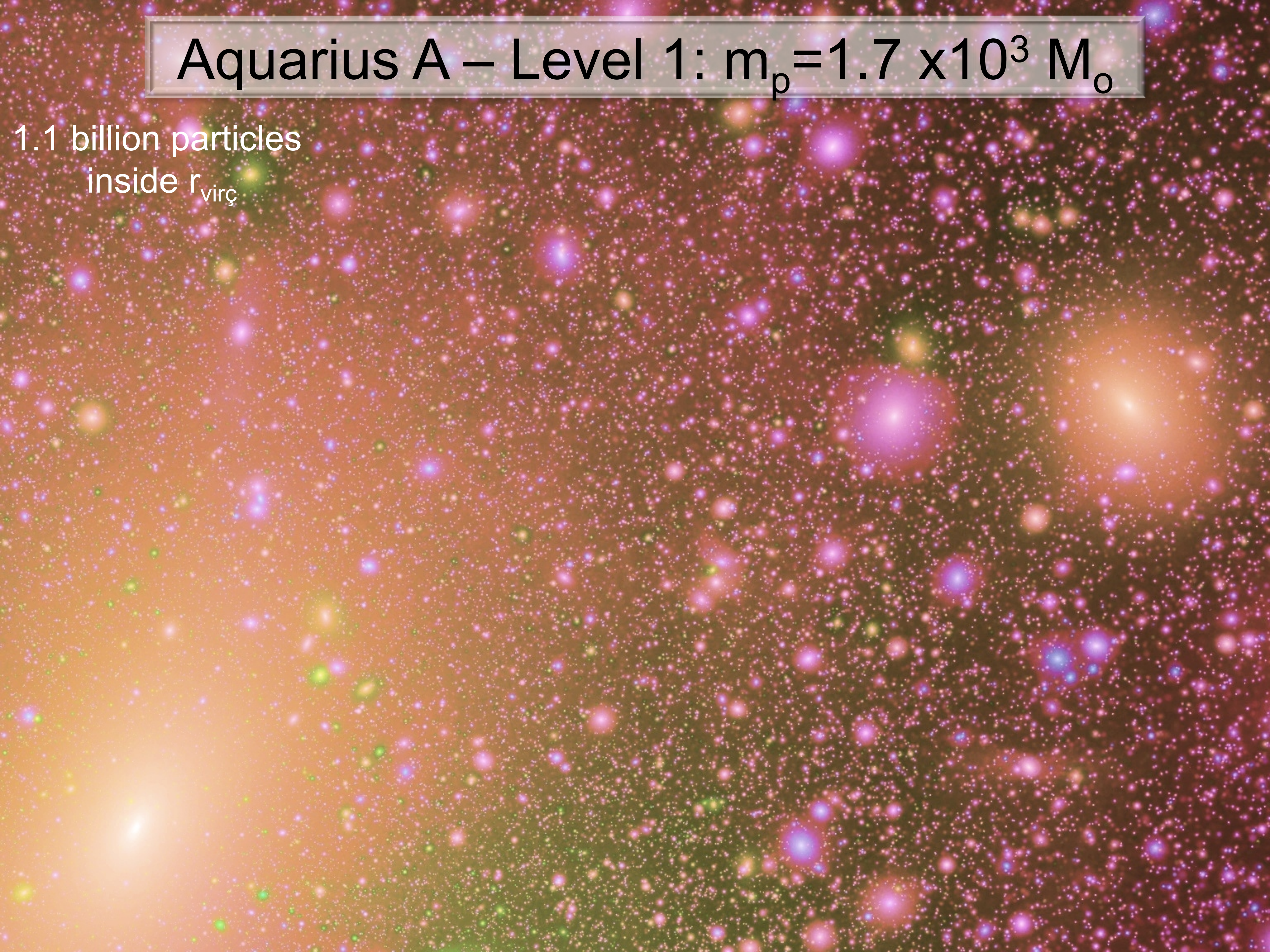
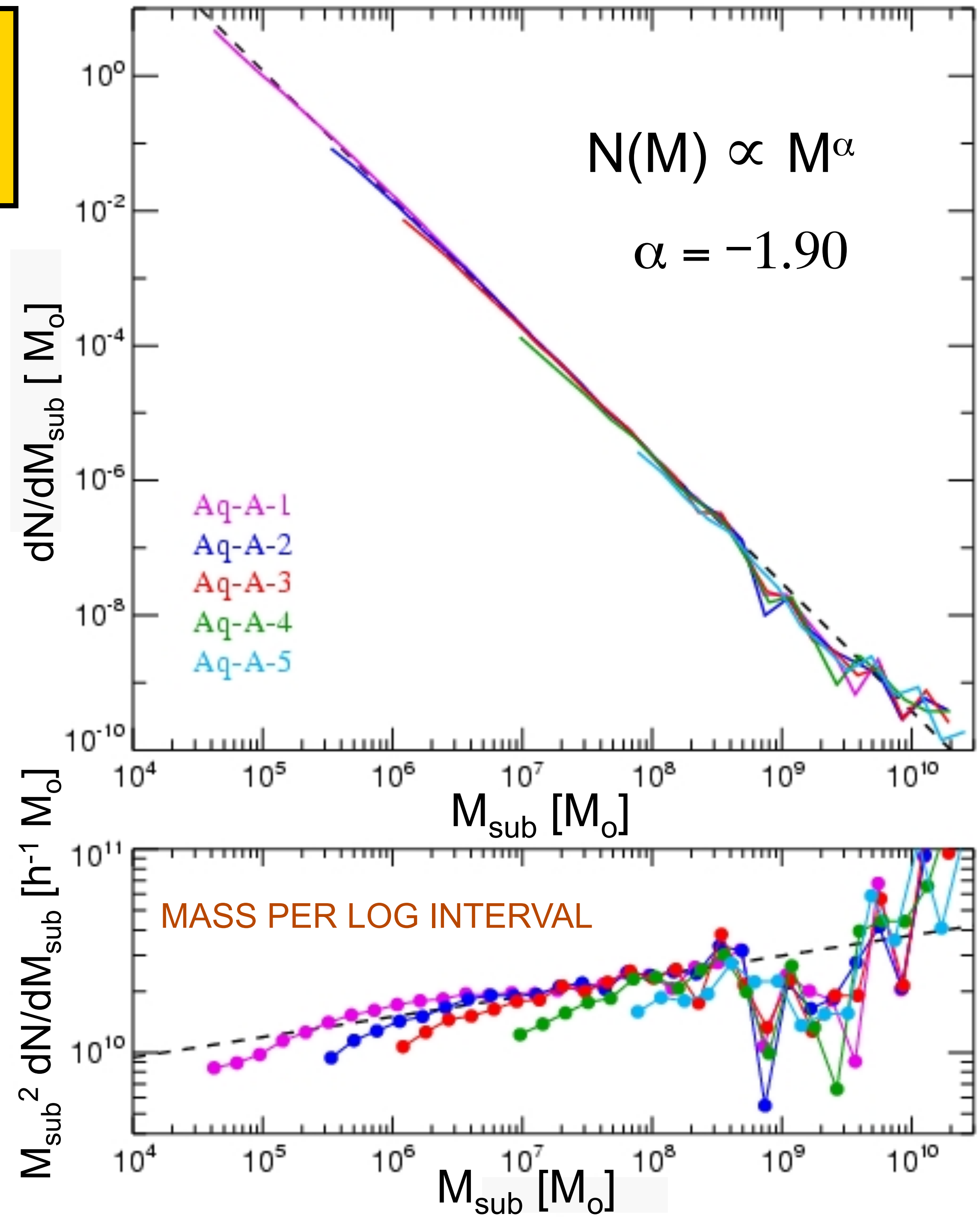


The mass function of substructures

- The subhalo mass function is shallower than M^2
- Subcritical slope → total mass in substructures converges at faint end
- Most of the substructure mass is in the few most massive halos

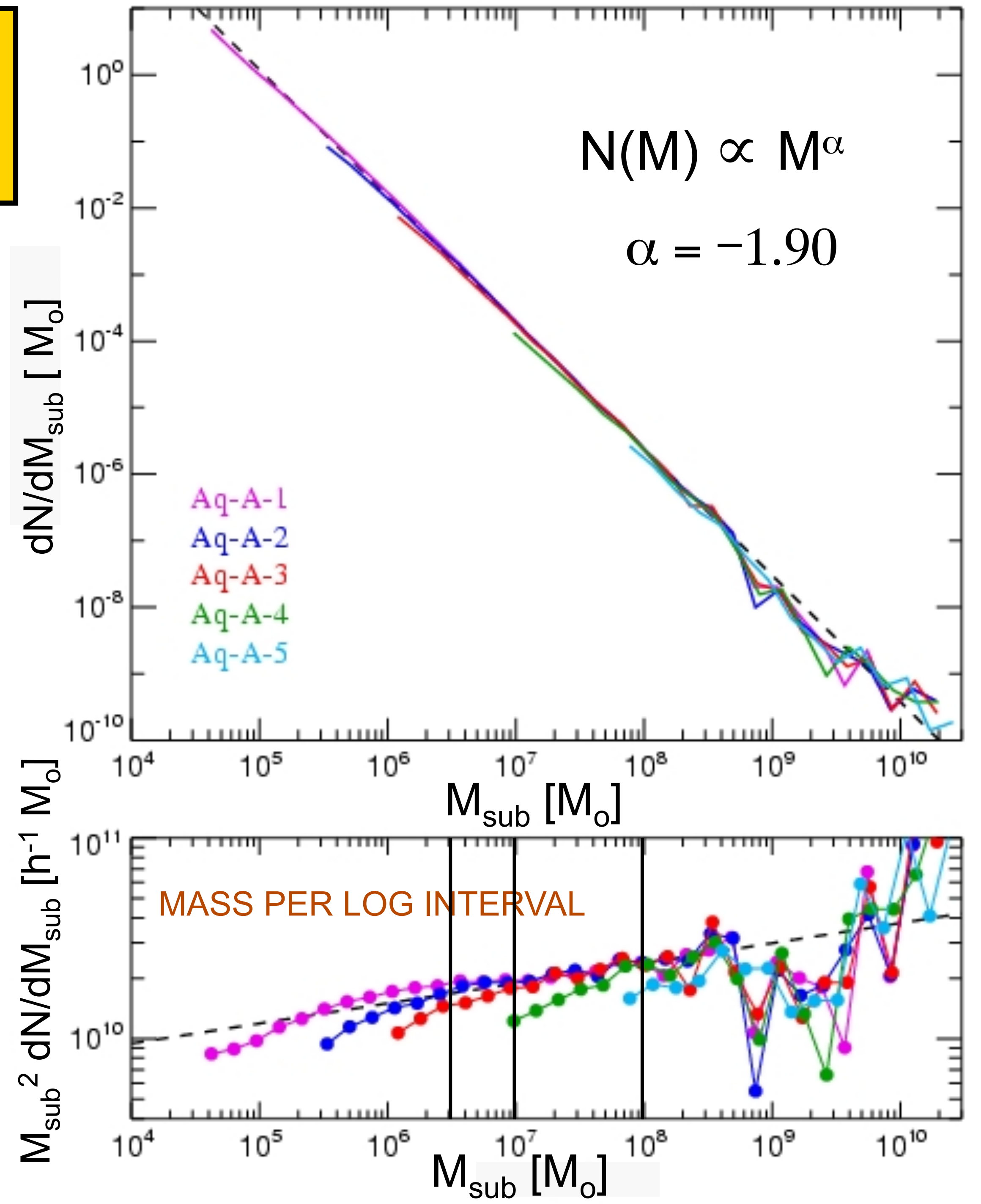
Virgo consortium '08



The mass function of substructures

The subhalo mass function is converged (to better than a few percent) for halos of >200 particles, even for moderate resolution, over a factor of 2000 in mass

Virgo consortium '08



The substructure V_{max} function

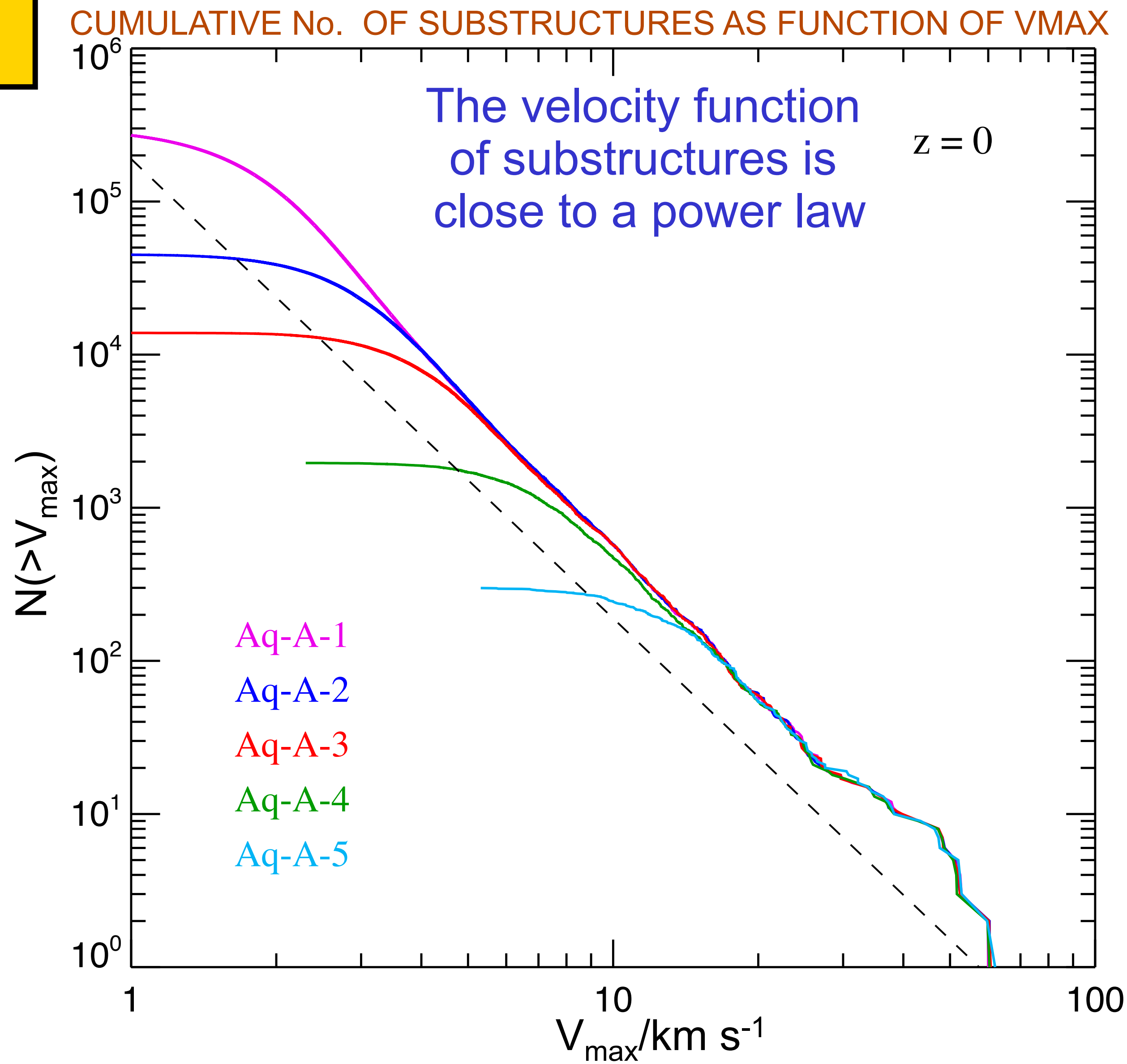
V_{max} mass function is also well converged for halos of >200 particles

Level 1 → converged results for

V_{max} > 1.5 km/s

r_{max} > 165 pc

Springel et al. '08



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The mass fraction in substructures

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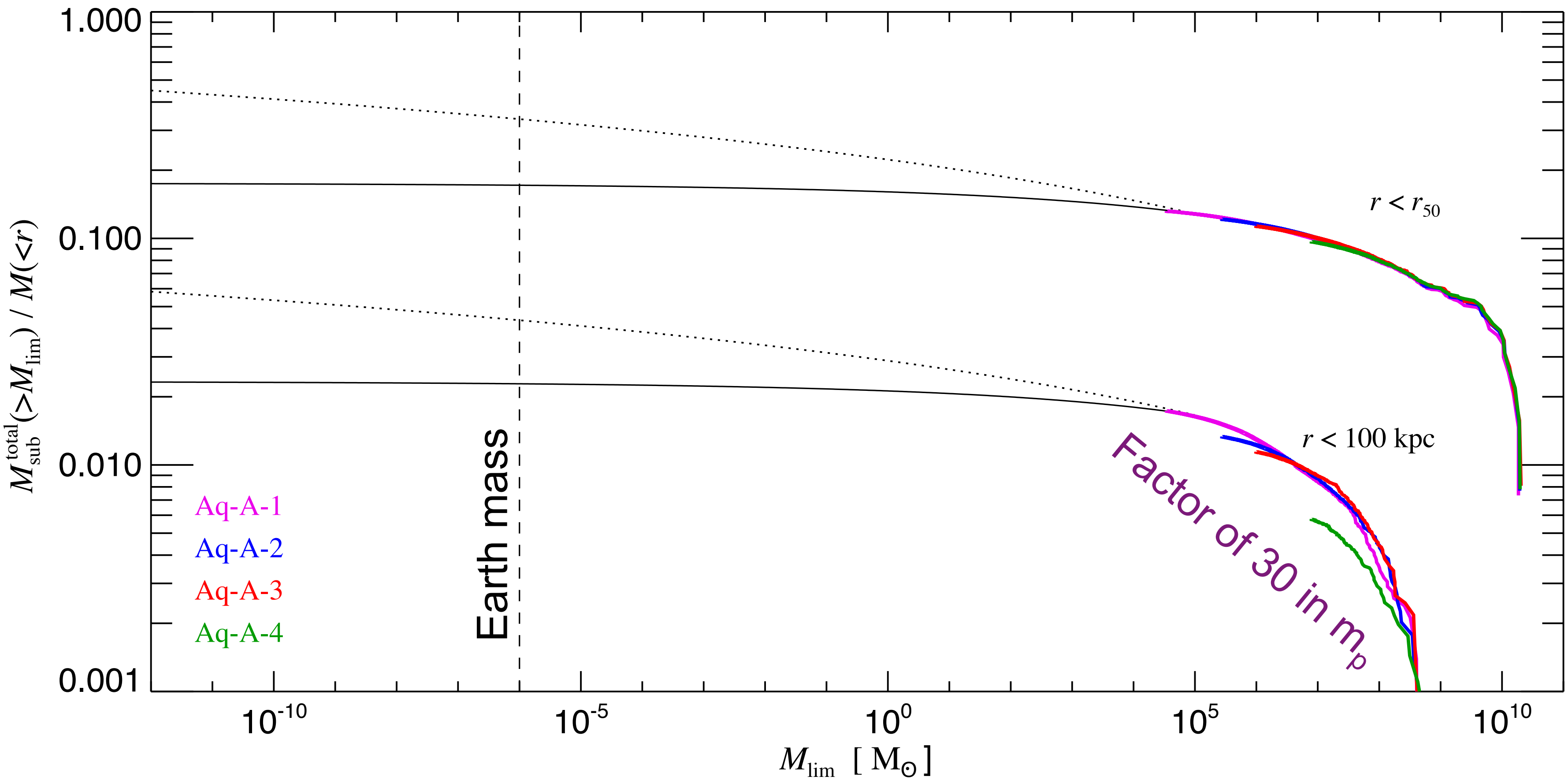

The mass fraction in substructure is well converged over a factor of 30 in mass resolution

Springel et al. ‘08

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Subhalo density profiles

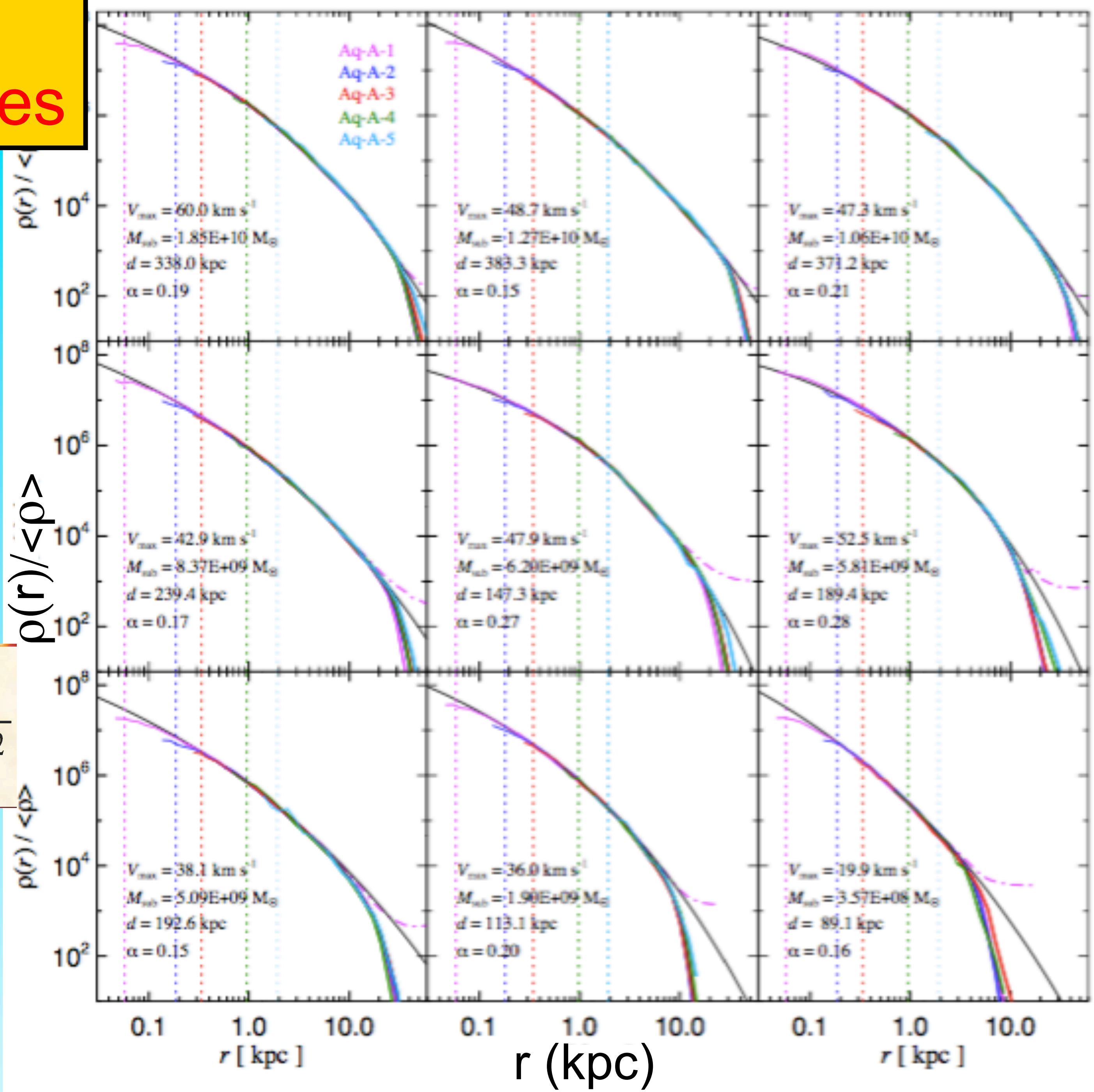
Converged beyond Power et al radius

Well fit by NFW

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

or Einasto profiles

Springel et al. '08



VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and their environment”

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

Durham University VIRGO ICC DiRAC PRACE

The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

Effects of baryons in subhalos

Baryon effects:

I. Light up some subhalos by star formation

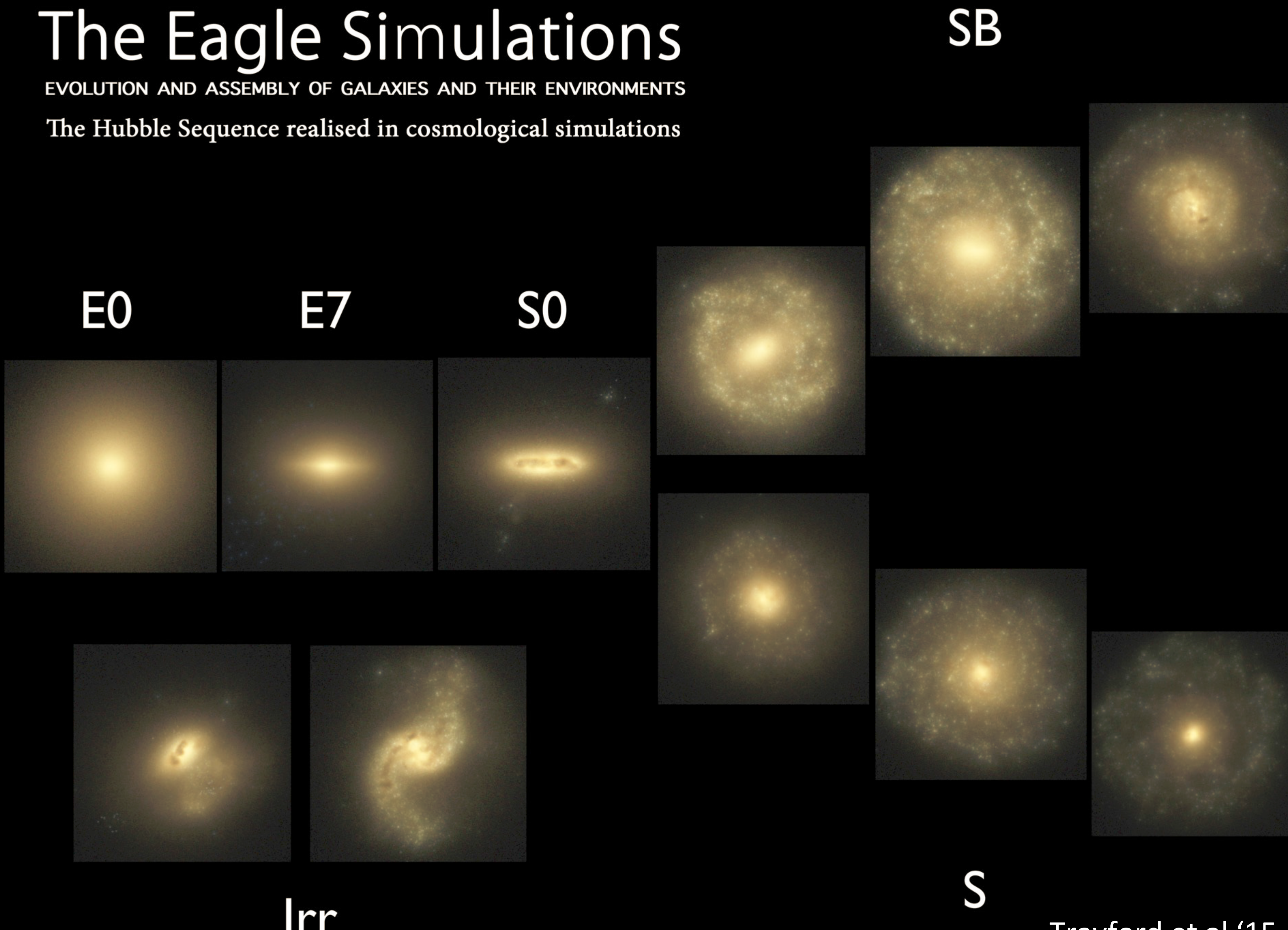
II. Change their inner structure slightly

III. Central galaxy can destroy small subhalos

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

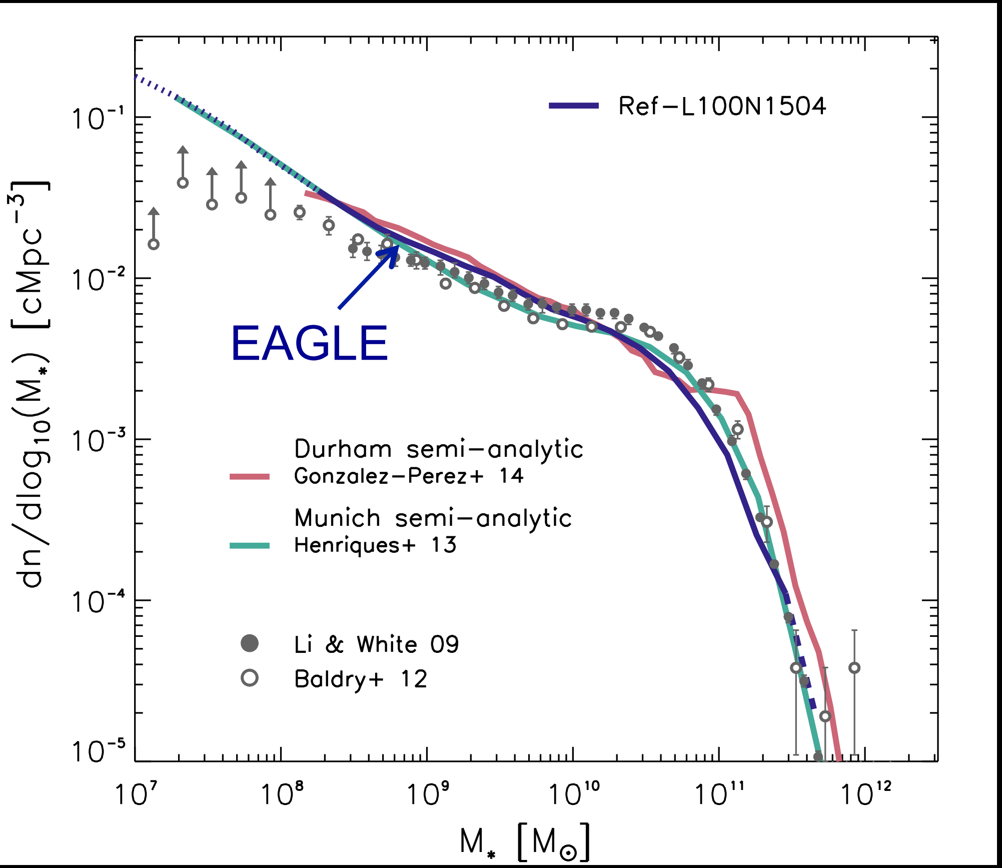
The Hubble Sequence realised in cosmological simulations



Trayford et al ‘15

Galaxy stellar mass function

Comparison to semi-analytic models



Schaye et al '15

Most subhalos never make a galaxy!

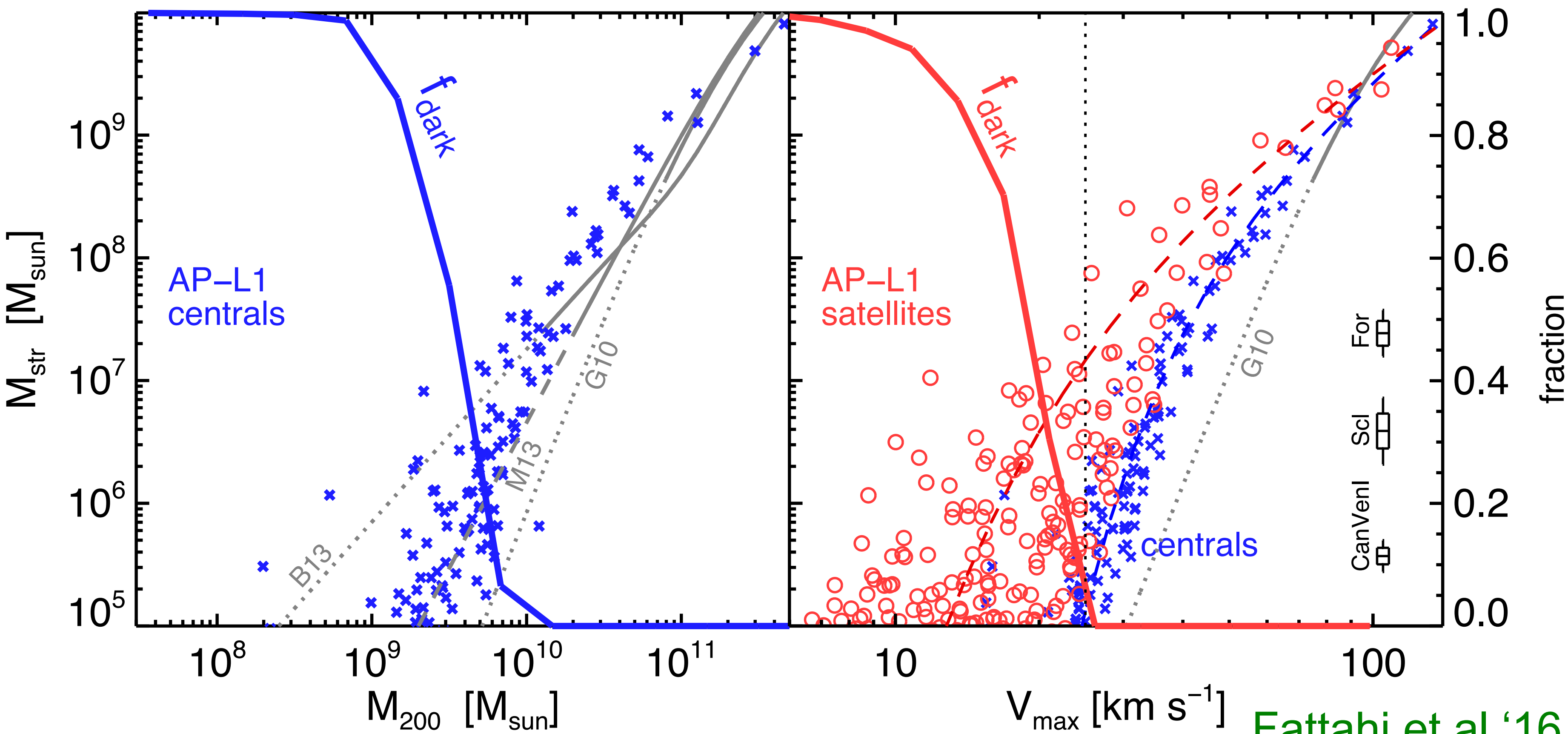
Because:

- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

Fraction of dark subhalos

University of Durham

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



Fattahi et al '16

All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

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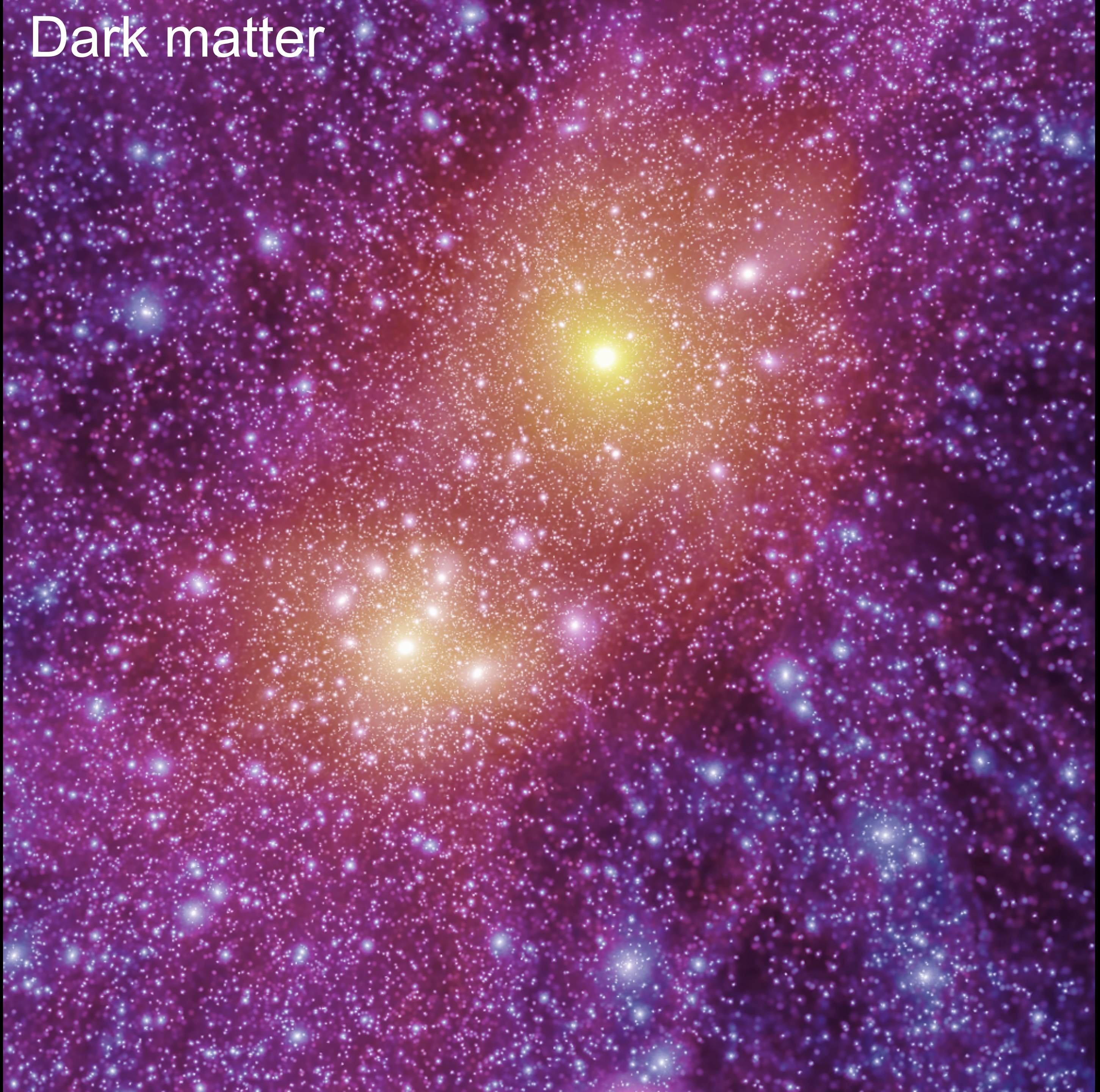
VIRGO

Local Group

APOSTLE
EAGLE full
hydro
simulations

CDM

Sawala et al ‘16

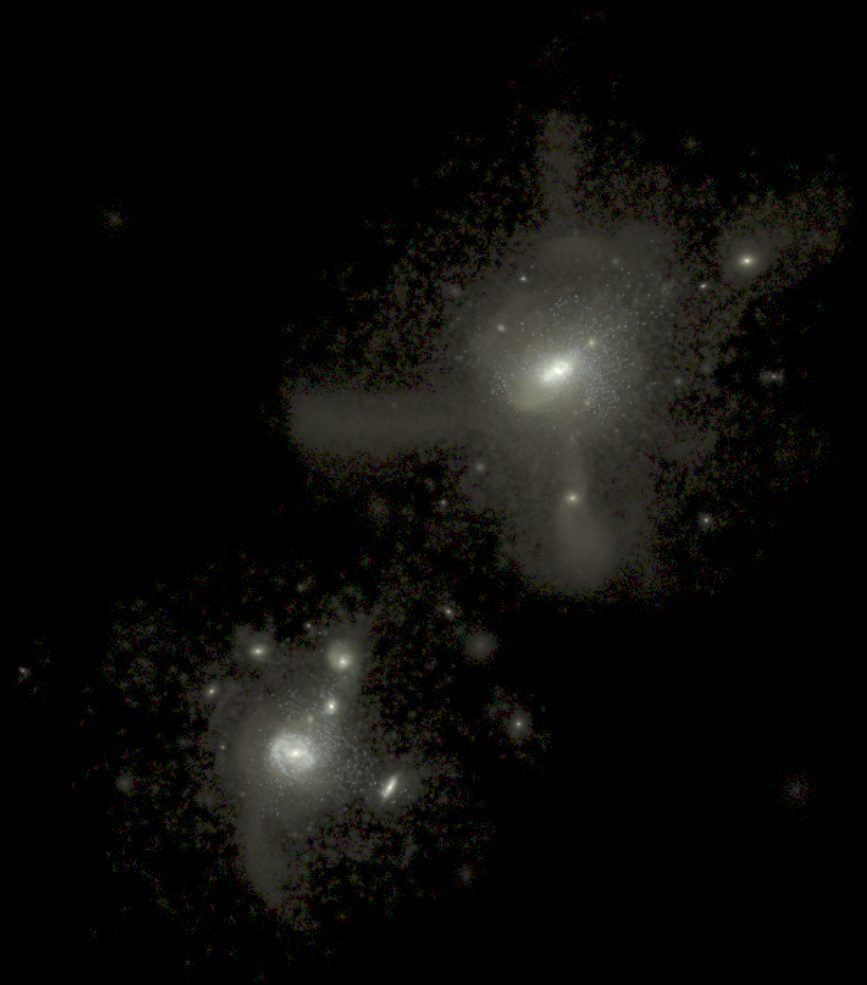


Stars

Local Group

APOSTLE EAGLE full hydro simulations

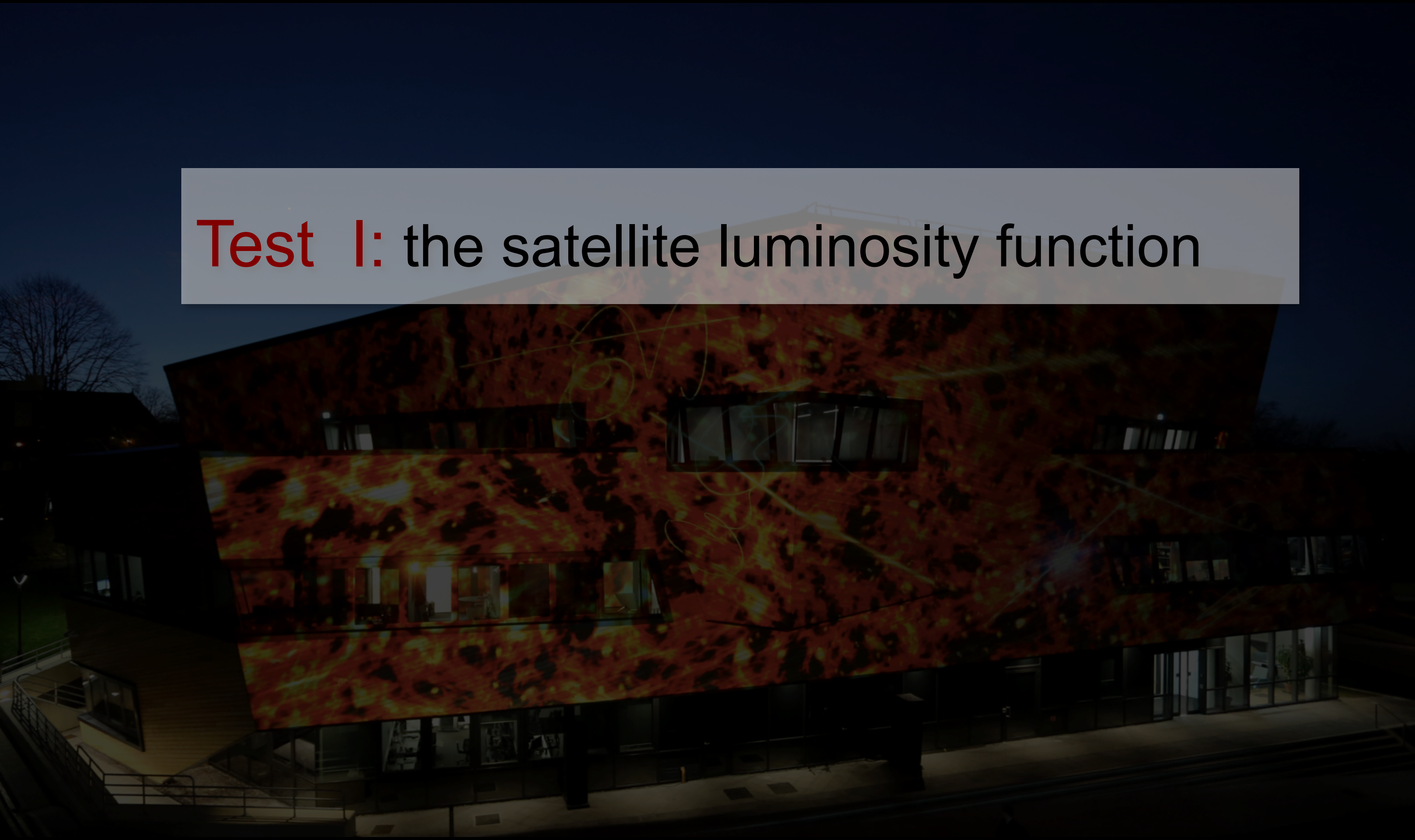
Stars



Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

Tests of ΛCDM with subhalos

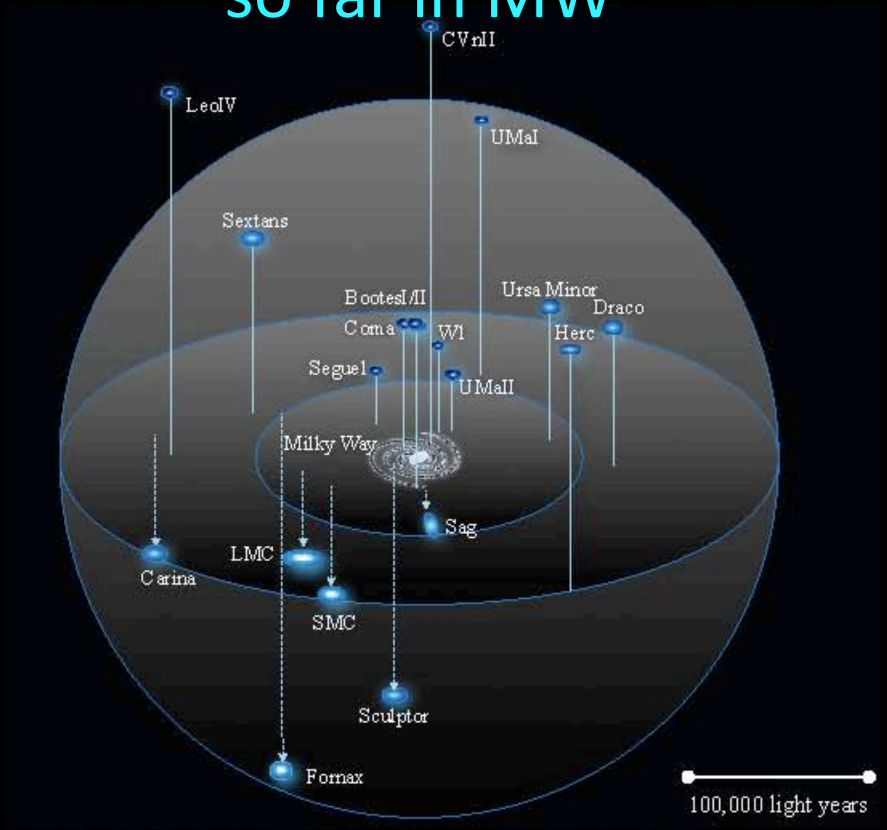


Test I: the satellite luminosity function

The satellites of the Milky Way

cold dark matter

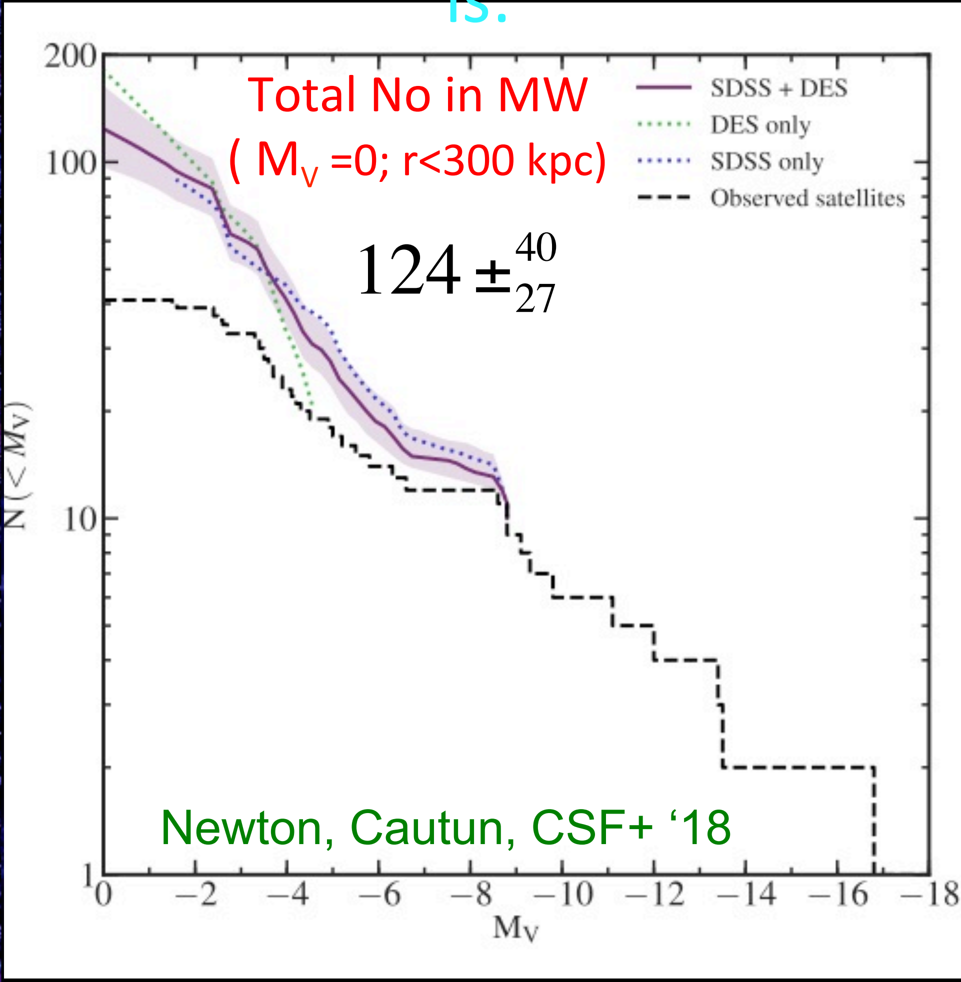
~50 satellites discovered so far in MW



The satellites of the Milky Way

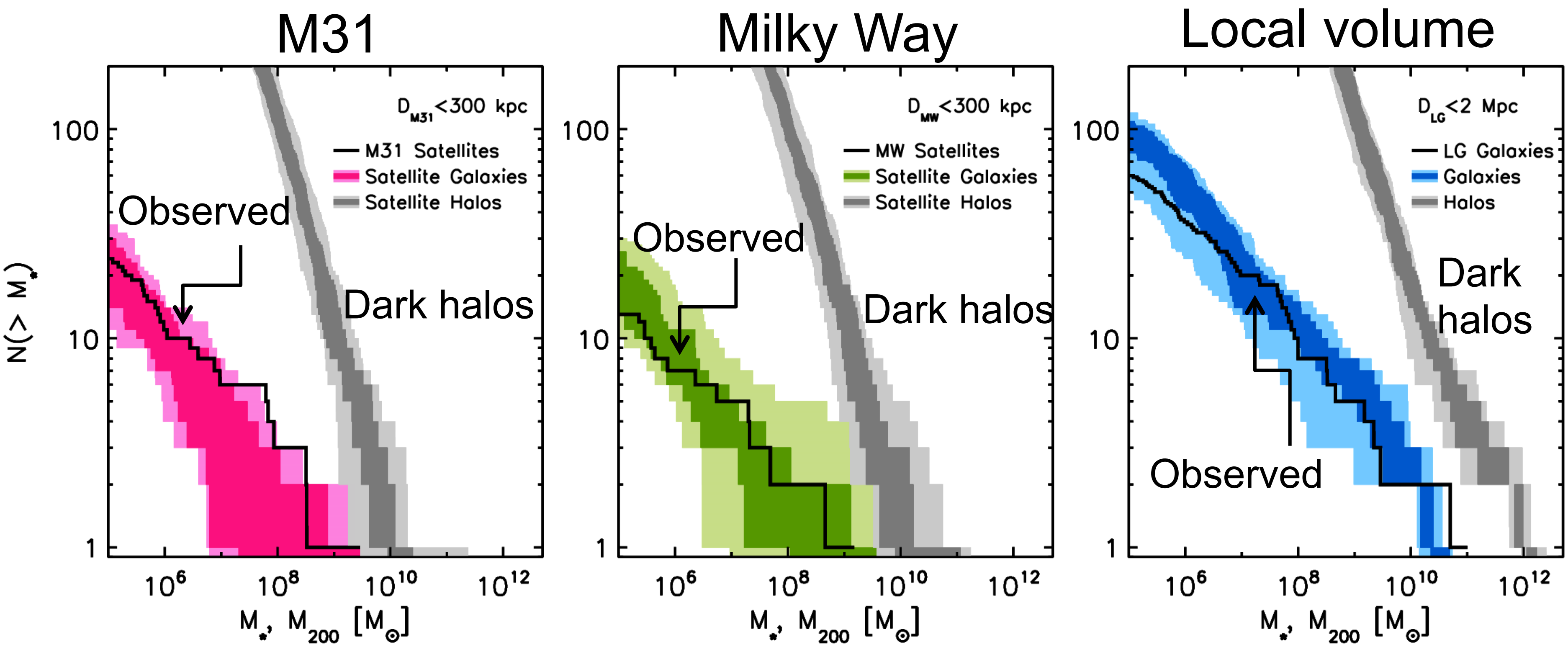
cold dark matter

Total No in MW (to M_V =0) is:



EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

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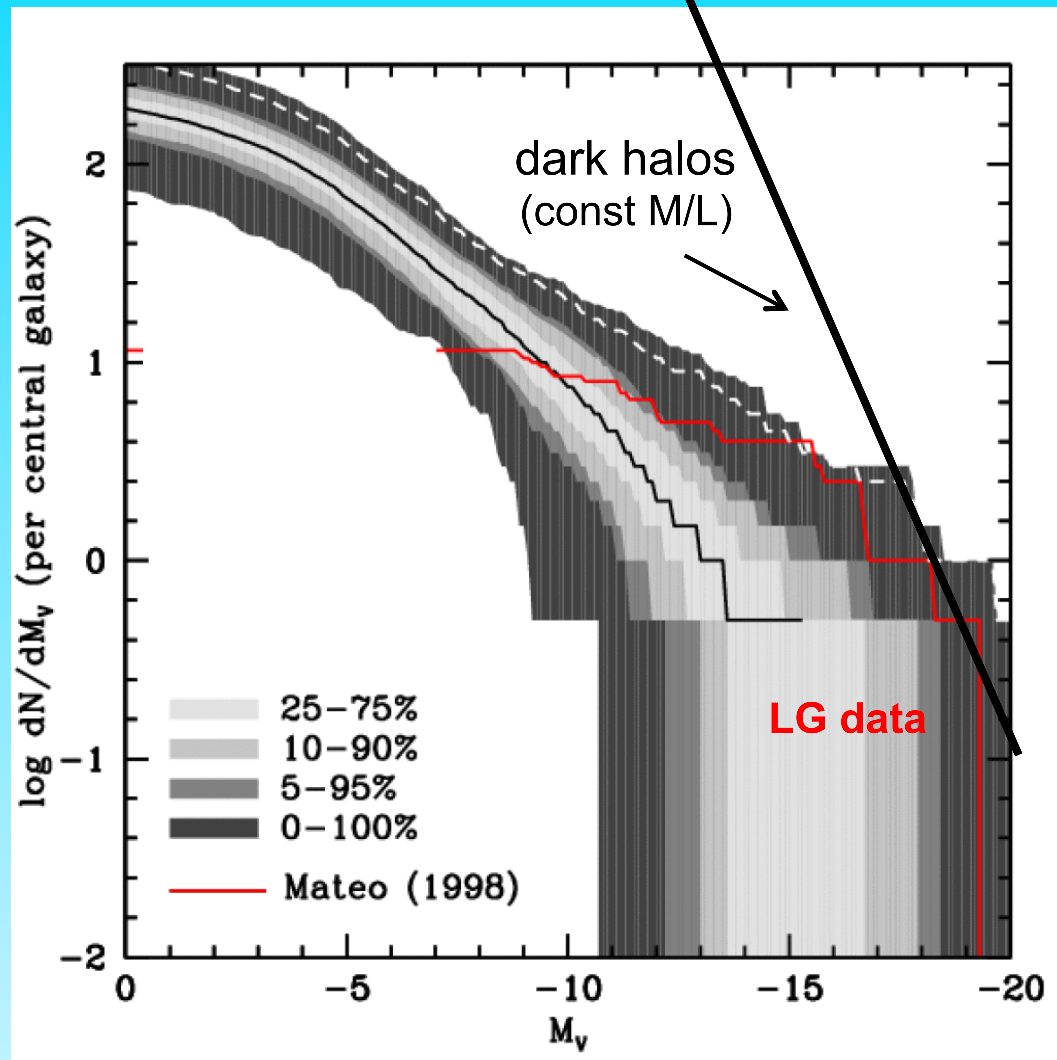
Luminosity Function of Local Group Satellites

- 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 (~10% of cases)



Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

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Luminosity Function of Local Group Satellites

University of Durham

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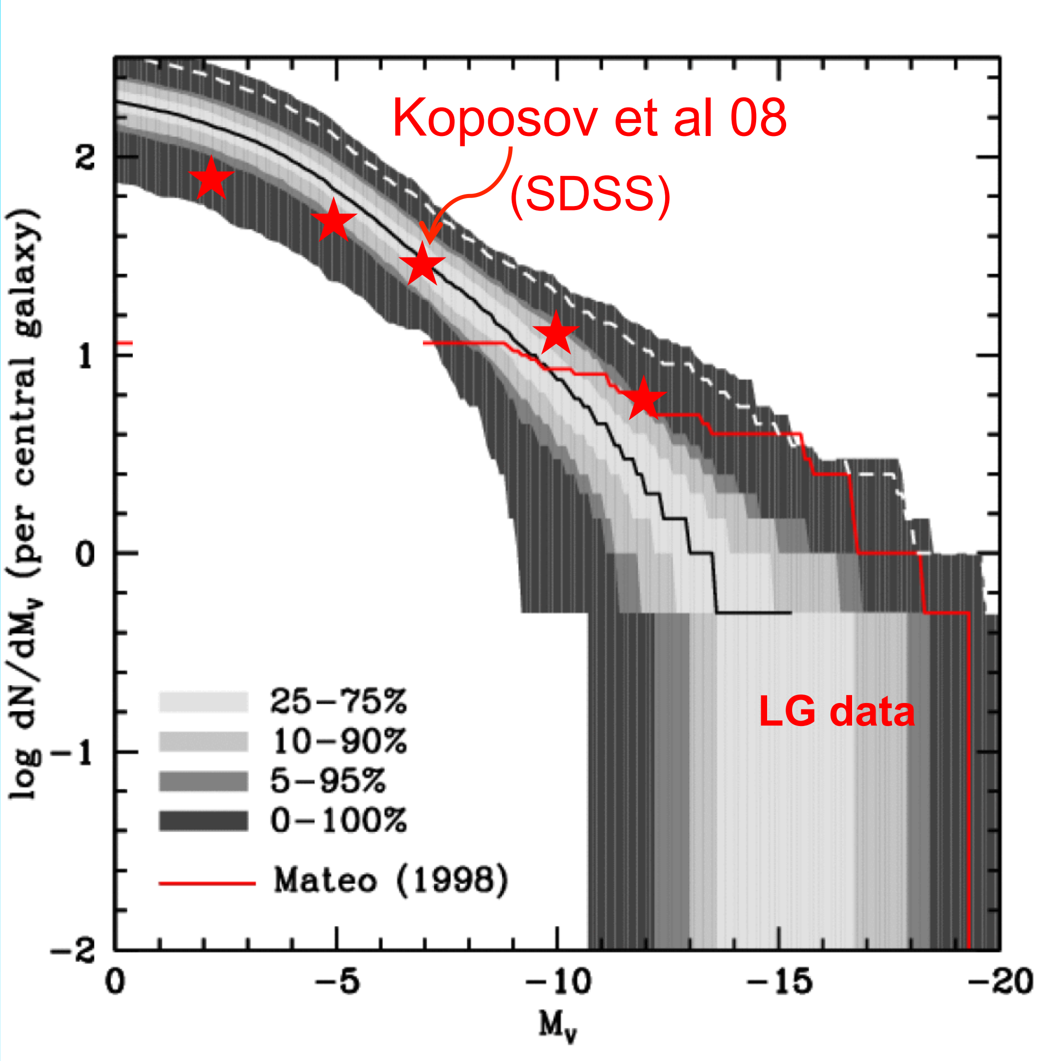

Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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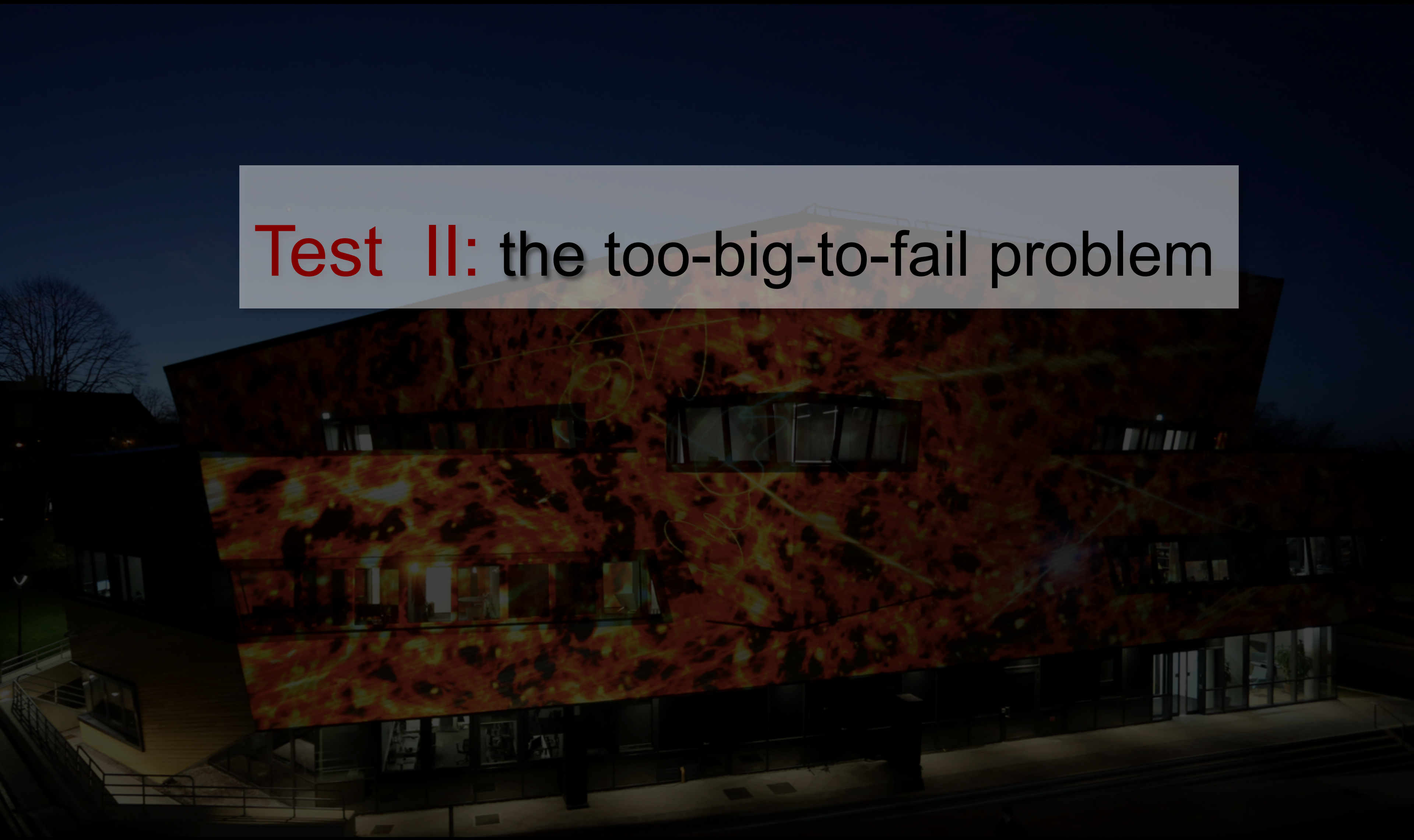
Observed abundance of satellites is compatible with CDM

→

There is no such thing as the "satellite problem" in CDM!

Tests of ΛCDM with subhalos



Test II: the too-big-to-fail problem

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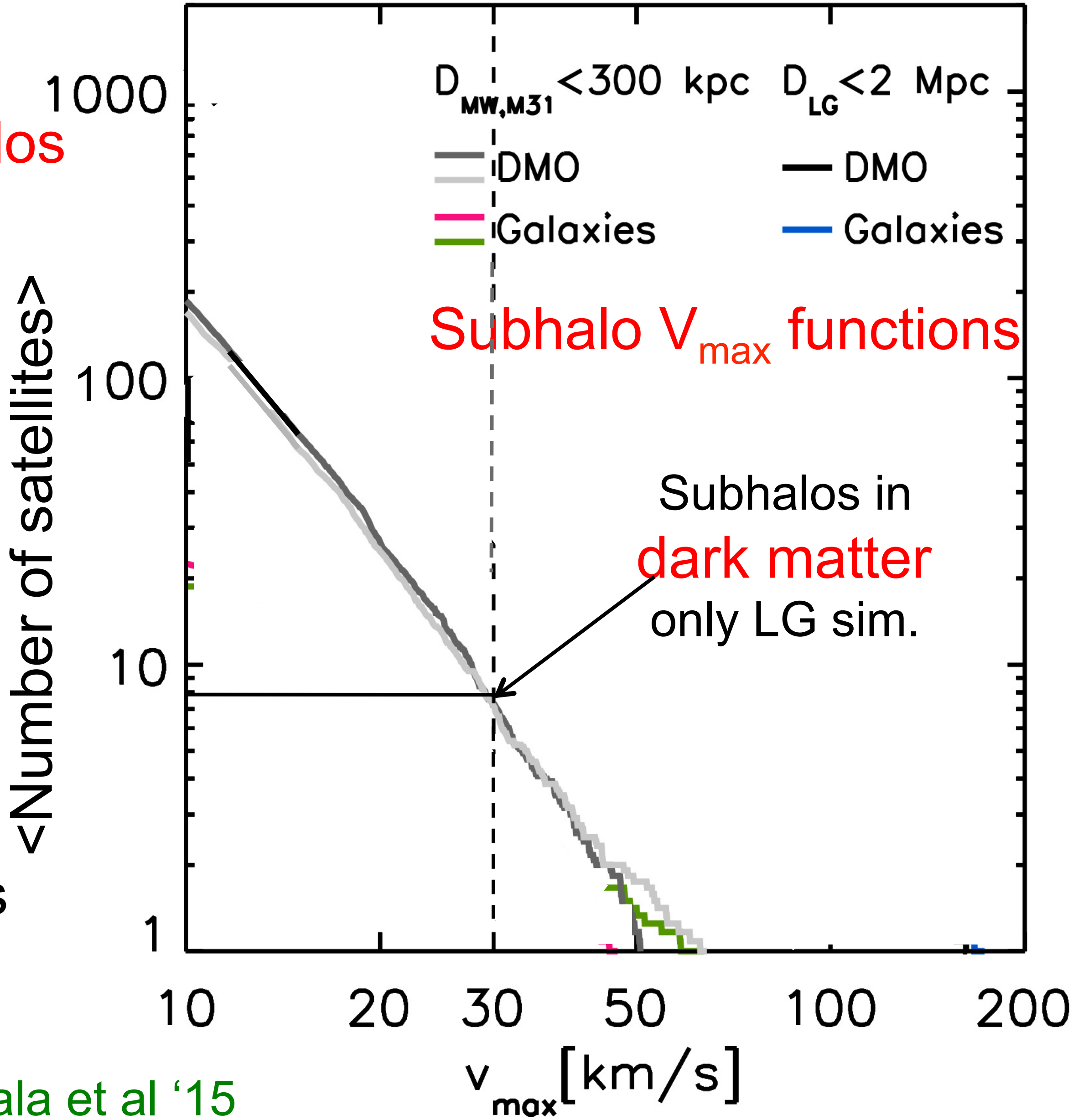
Too-big-to-fail: the baryon bailout

DM only sims → ~10 halos with V_{max}> 30 km/s

But MW has only 3: LMC, SMC, Sagittarius



Sawala et al '15

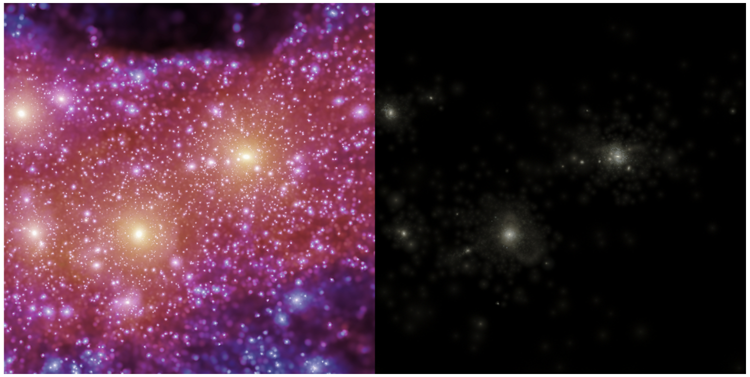
Baryon effects on halo structure

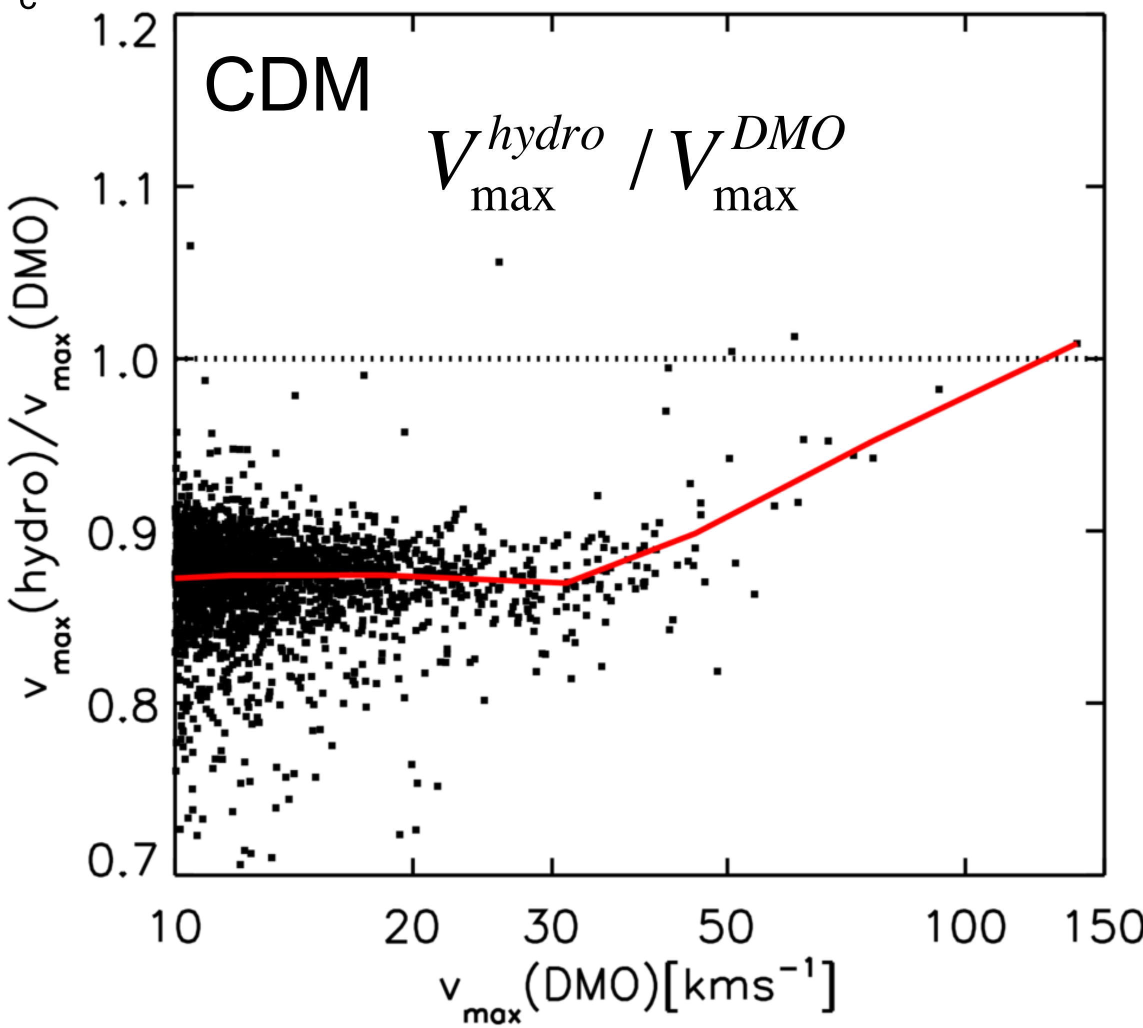
University of Durham

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala, CSF + ‘13, ’15

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Too-big-to-fail: the baryon bailout

University of Durham

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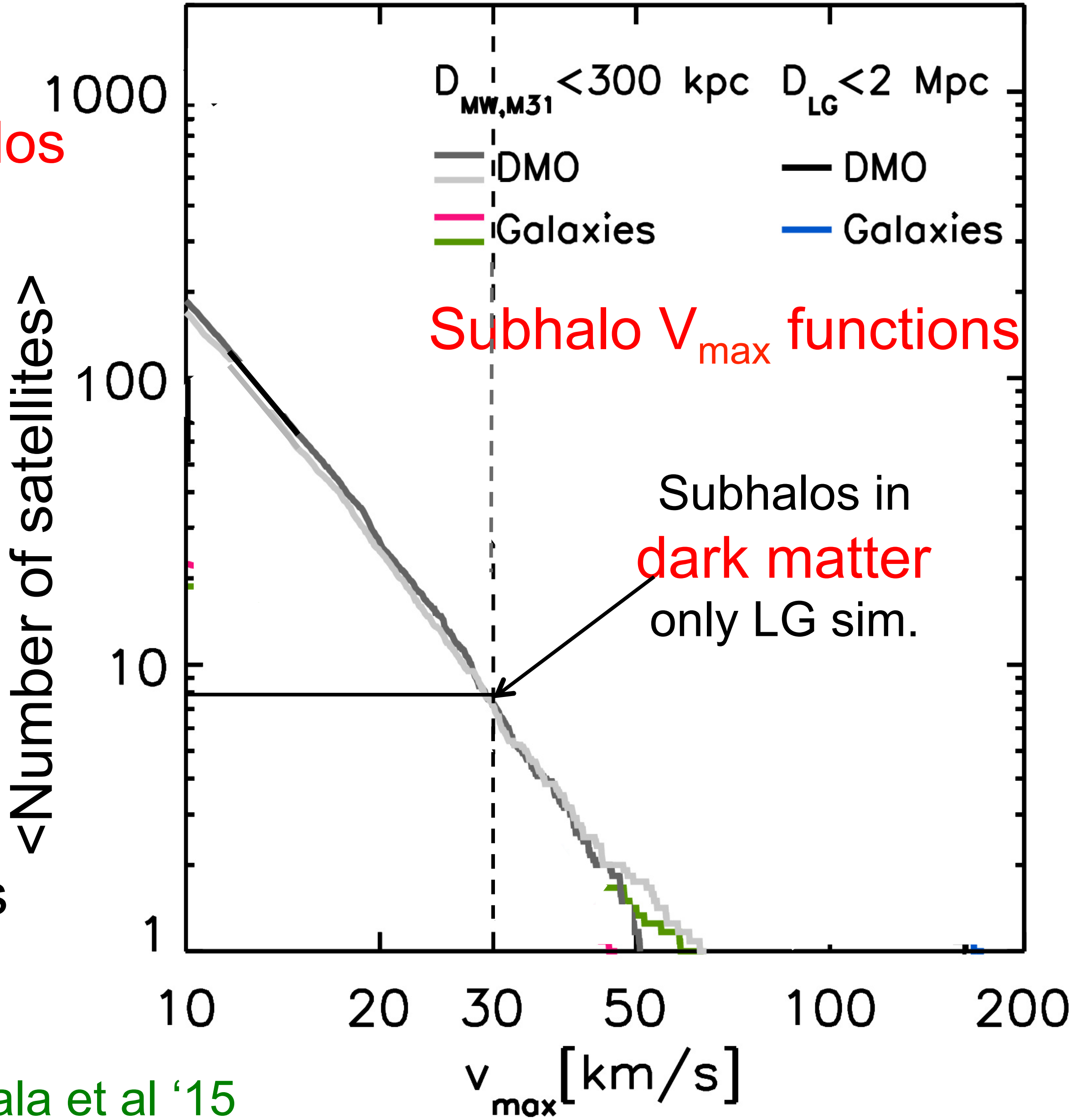
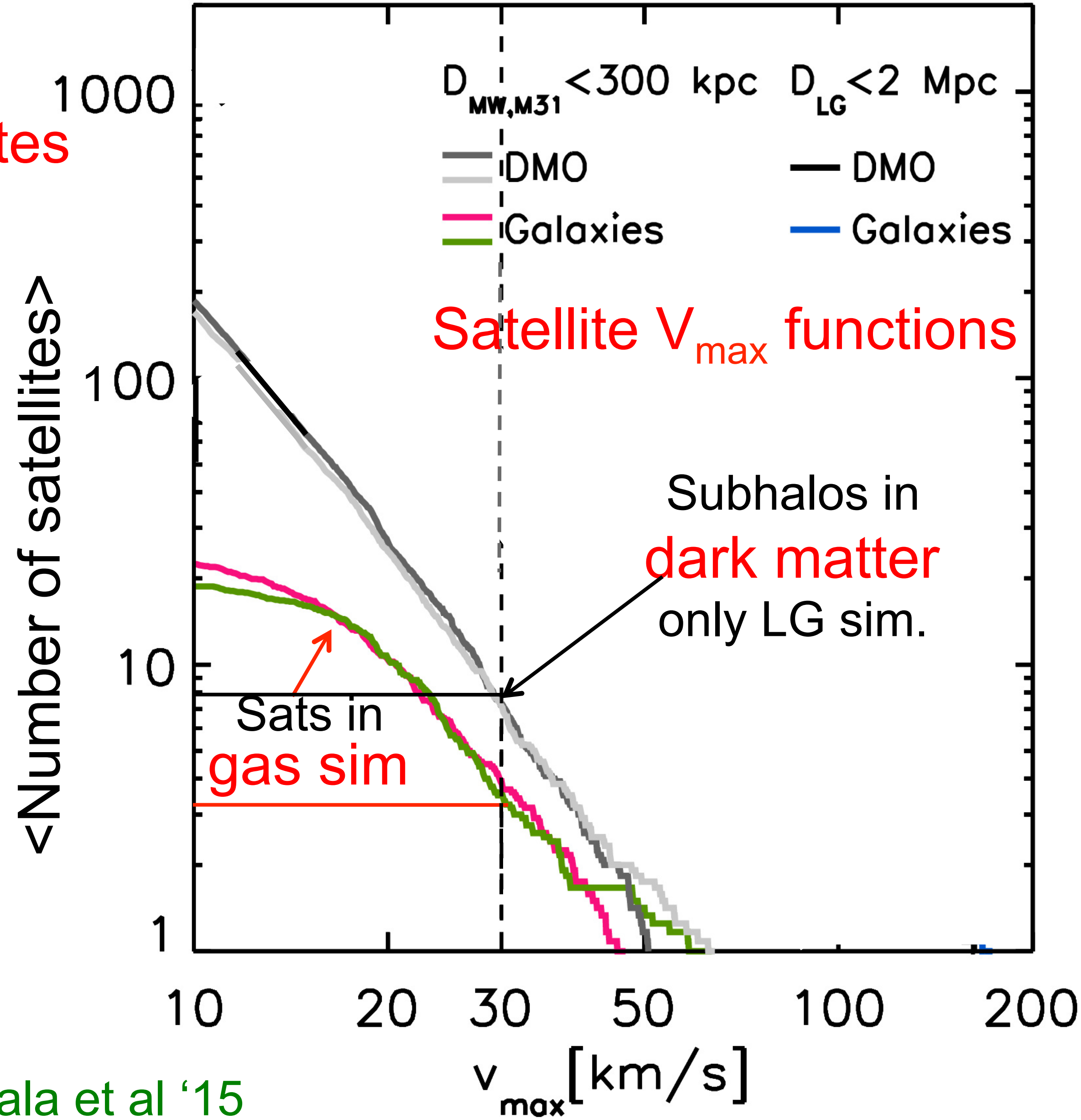


Sawala et al '15

Too-big-to-fail: the baryon bailout

University of Durham

Hydro sims → ~3 satellites with V_{max}> 30 km/s



Sawala et al '15

Too-big-to-fail: the baryon bailout

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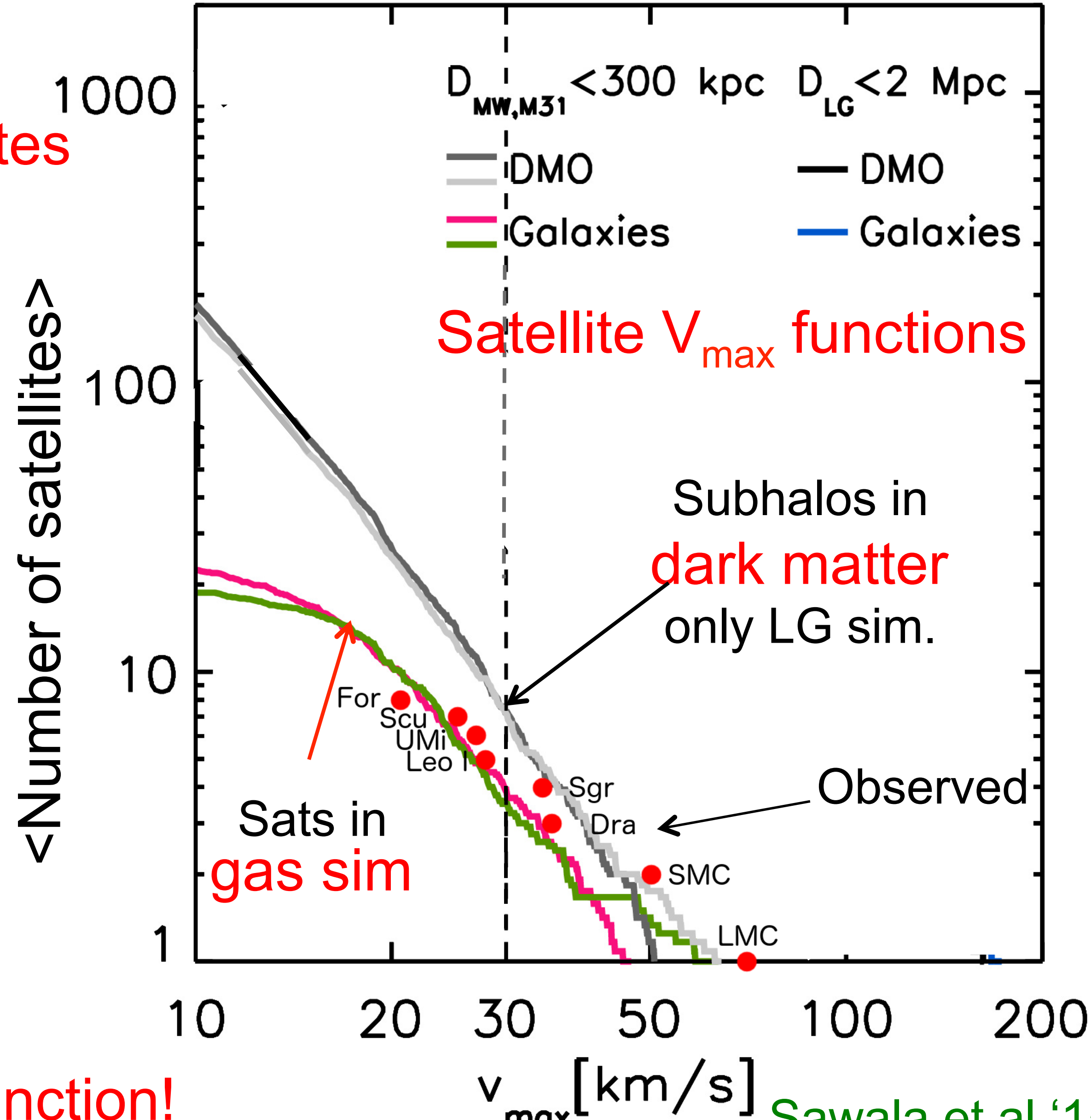


. and with correct V_{max} function!

Sawala et al '15

Tests of ΛCDM with subhalos

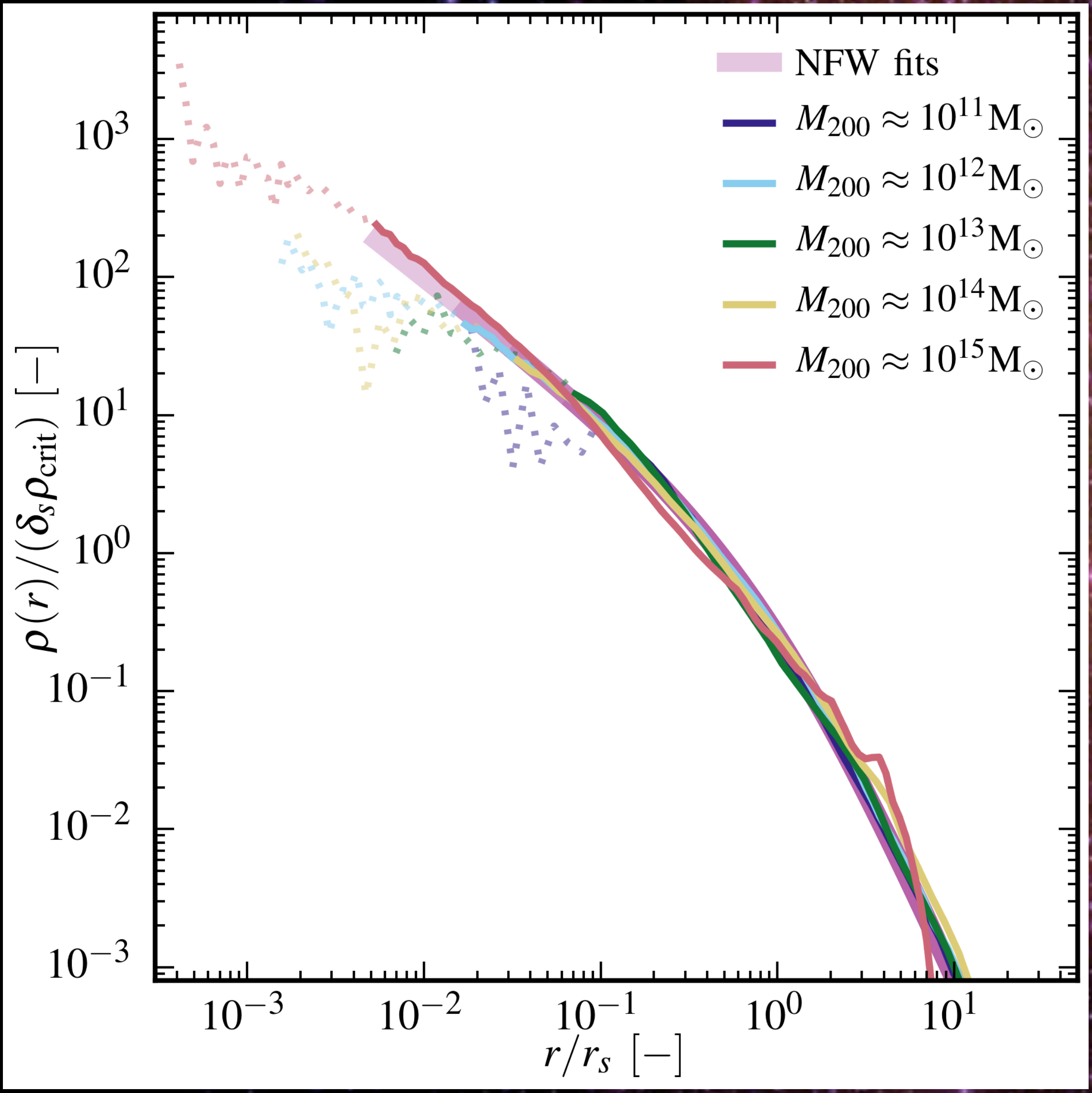
Test III: inner density profile (core/cusp problem)

Dark matter halos: cores or cusps?

Two myths

- The DM halos of observed dwarfs have central cores
- Hydro simulations of dwarfs produce cores if they have bursty star formation

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)

Does Nature have them?

Sawala et al '15

The density profile of halos/subhalos

Two main approaches:

I. Stellar dynamics

II. Gas rotation curves

The DM halo of the Sculptor dwarf

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Sculptor has two stellar pops:

(i) centrally concentrated, high [Fe/H]

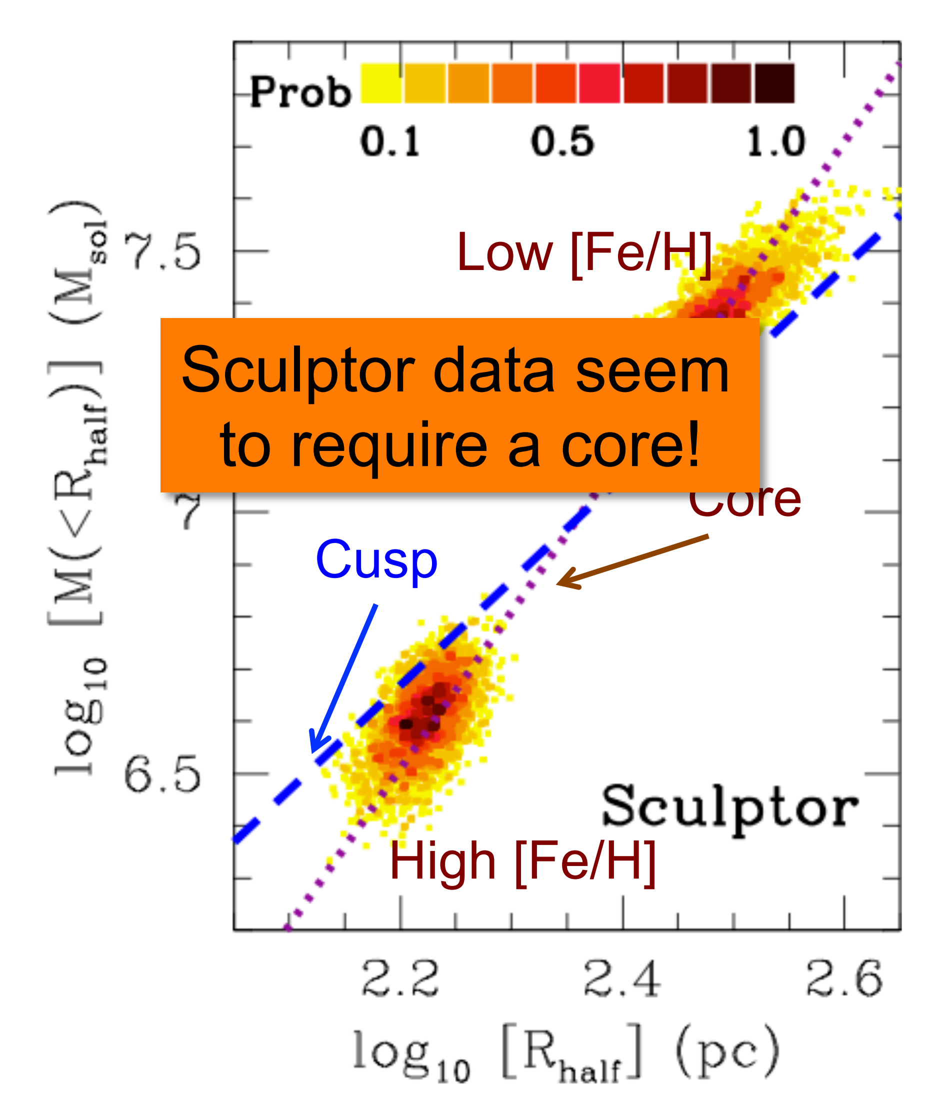
(ii) extended, low [Fe/H]

$$M(<r) = \mu \frac{r < \sigma_{los}^{2} >}{G}$$

$r = r_{1/2}$

Walker '10; Wolf et al '10→

if $r=r_{1/2}$, $\mu=2.5$, independently of model assumptions!



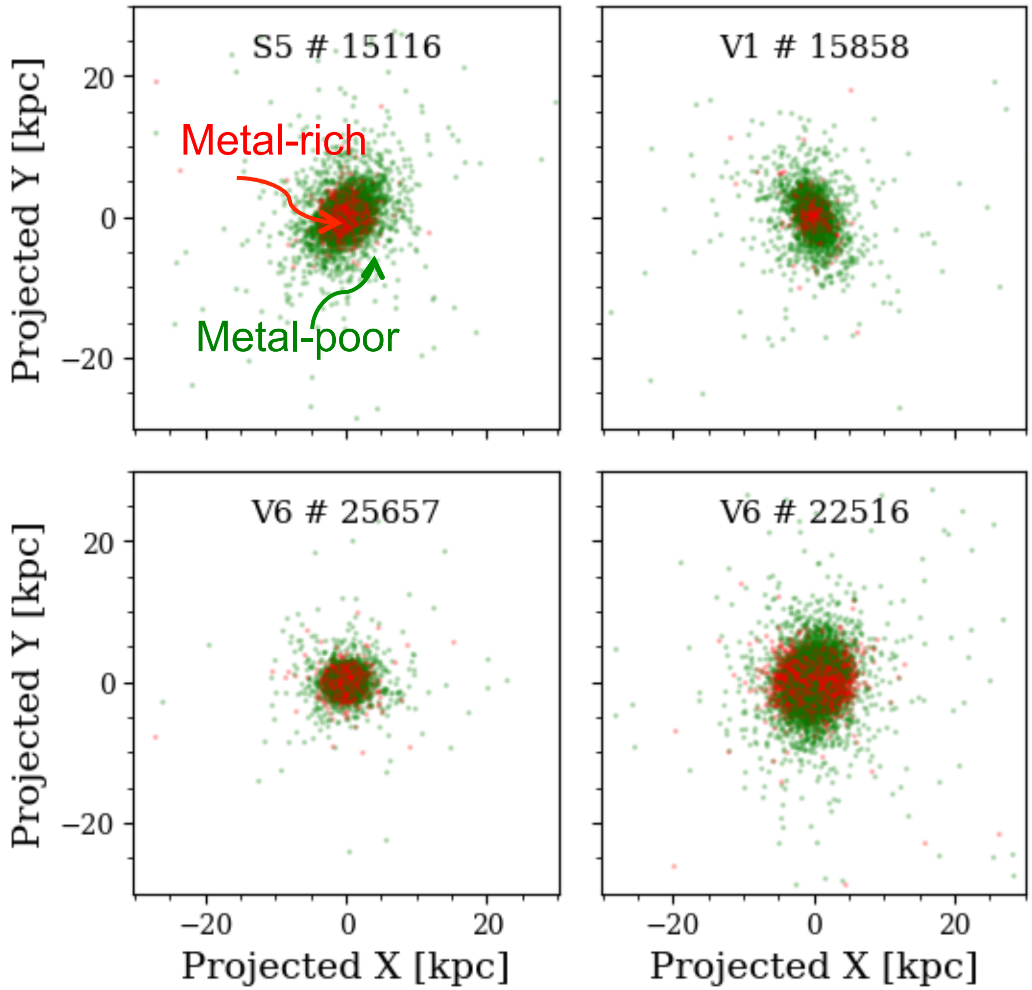
Sculptor data seem to require a core!

Walker & Peñarrubia '11

Apostle: satellites w. 2-metalicity pops

Wolf/Walker mass estimator assumes equilibrium and spherical symmetry

The stellar populations are not spherical and the shapes of the two can be different



Campbell, CSF+ 16,
Genina, Benitez-Llambay, CSF + ‘17

Apostle: satellites w. 2-metalicity pops

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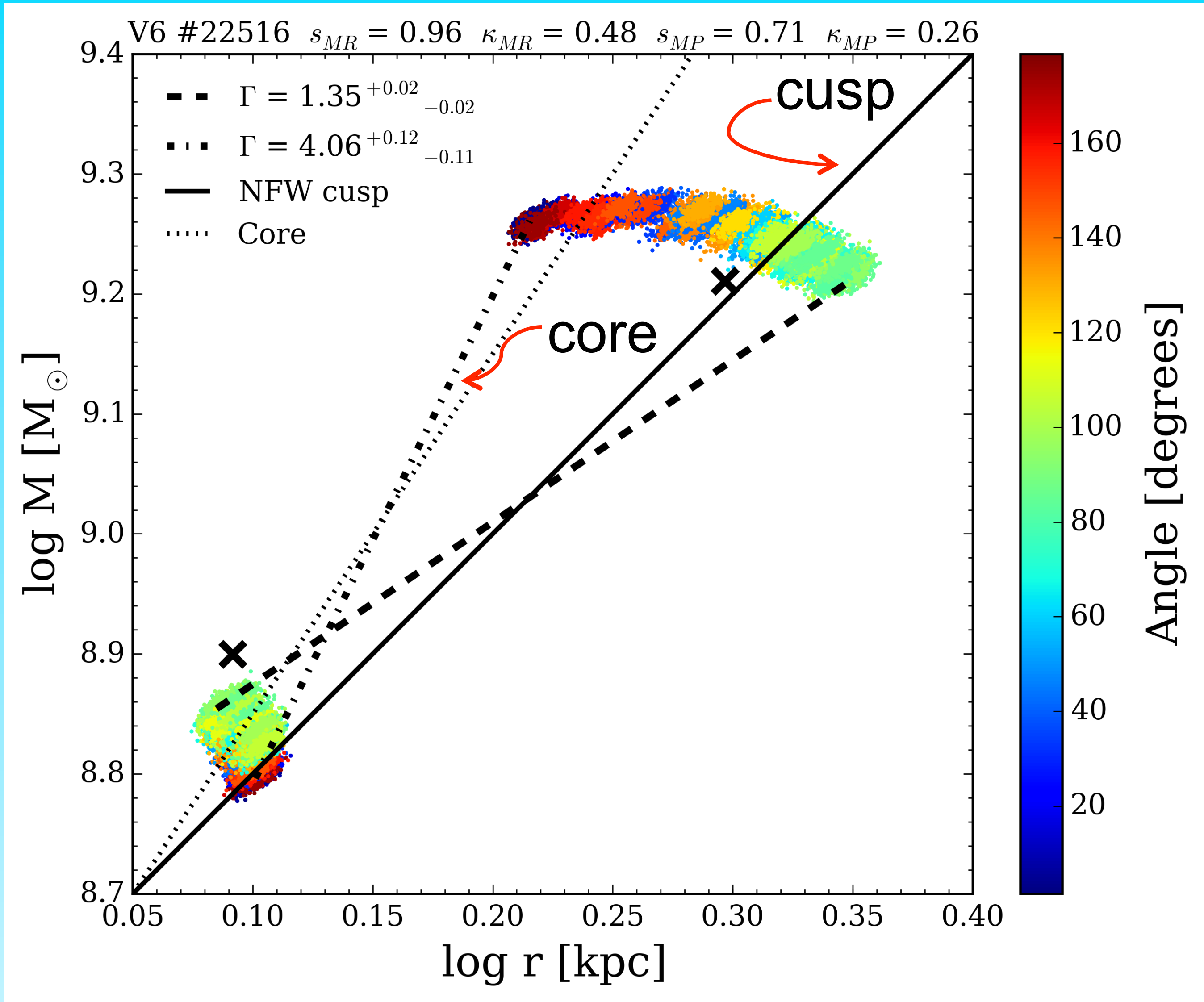
The inferred slope (core or cusp) depends on the viewing angle!



Gennina, Benitez-Llambay, CSF + '17

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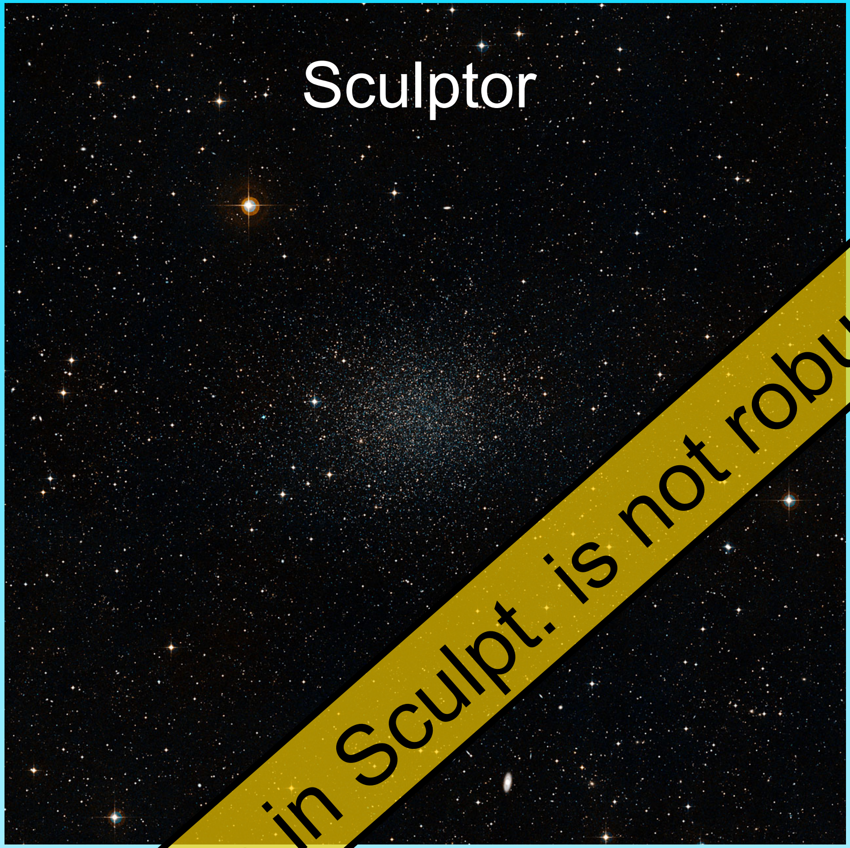
The DM halo of the Sculptor dwarf

$$M(<r) = \mu \frac{r < \sigma_{los}^{2} >}{G}$$

Key assumption of mass estimator:

spherical symmetry

Is Sculptor spherical?



WP11 core in Sculpt. is not robust

Genina, CSF et al '17

Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

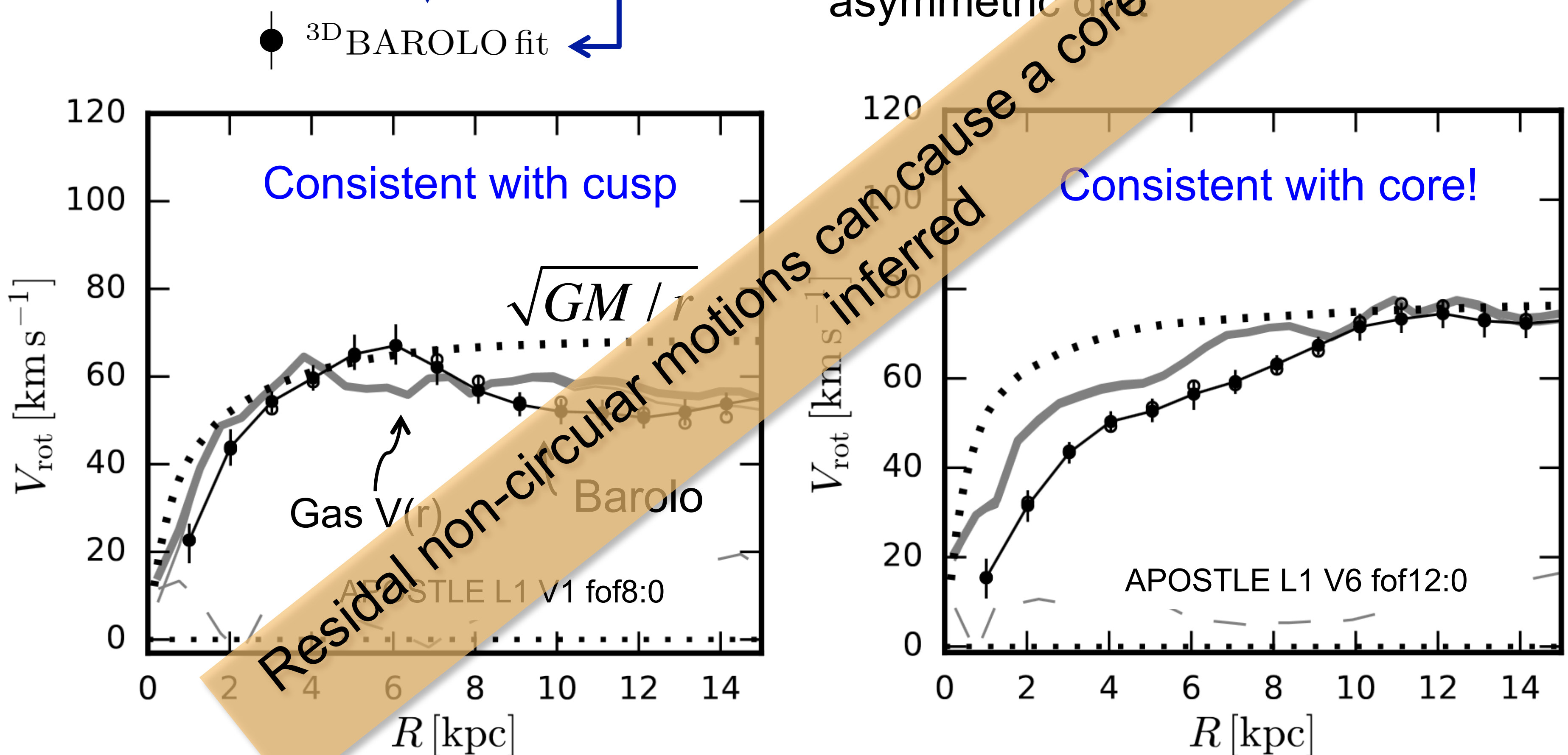
Rotation curves of 2 APOSTLE dwarfs

University of Durham

APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{v}}$

Tilted-ring model corrected for asymmetric drift



Residual non-circular motions can cause a core to be incorrectly inferred

Oman et al '18; Marasco et al '18

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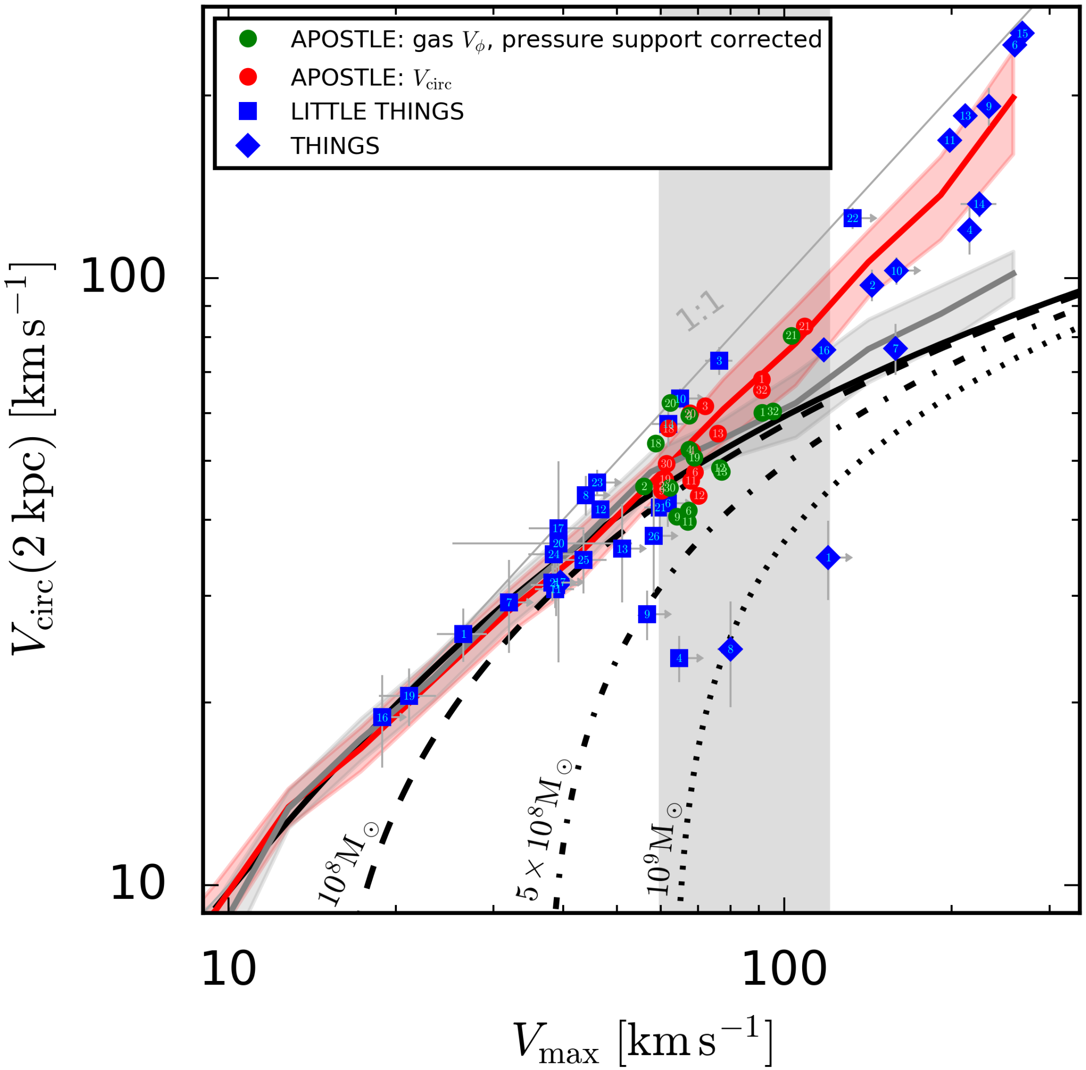
The diversity of rotation curves



Oman+ '17

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The diversity of rotation curves

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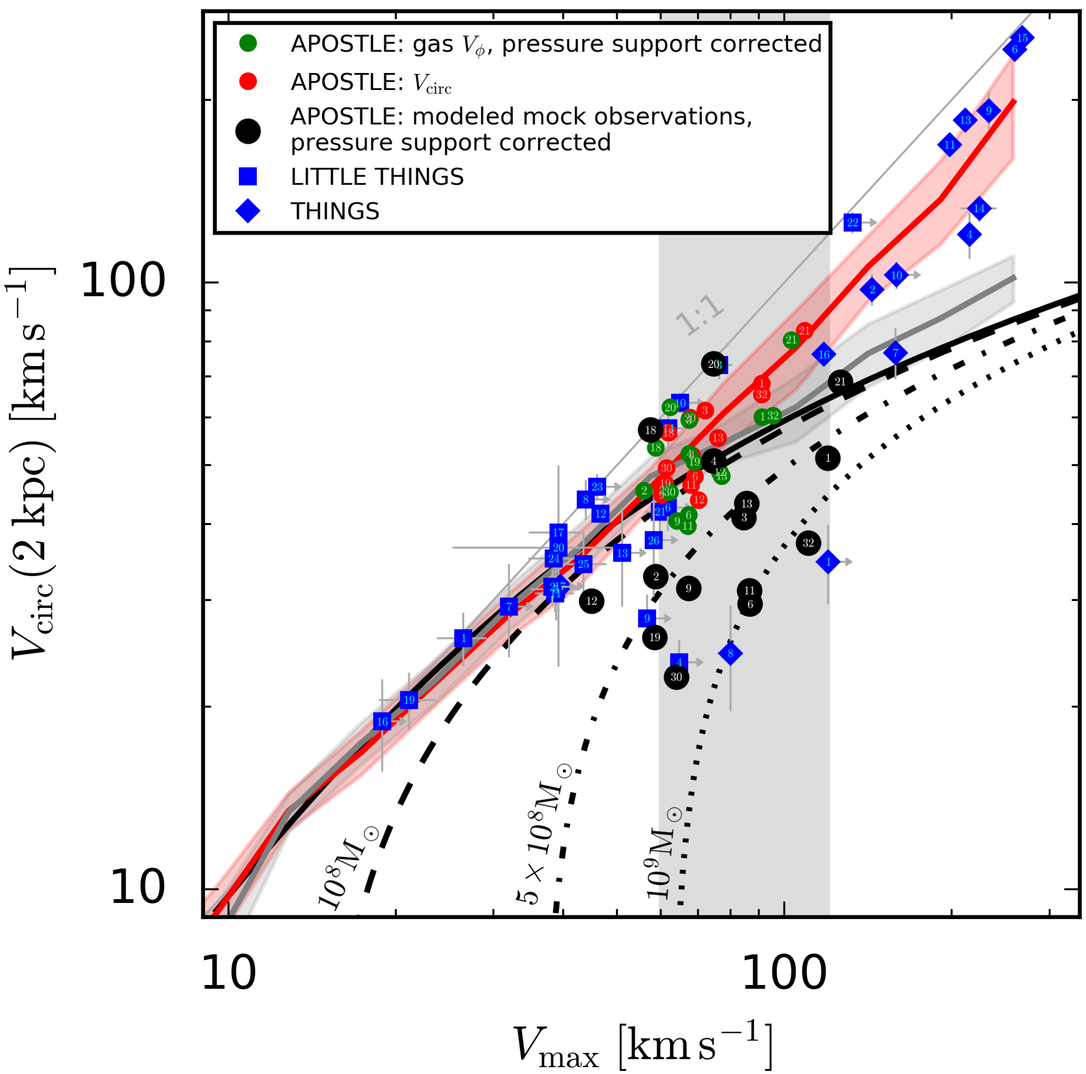

Oman+ '17

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But, if cores were found in galaxies would that rule out CDM and WDM?

The physics of core formation

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)

The cores of dwarf galaxy haloes L75

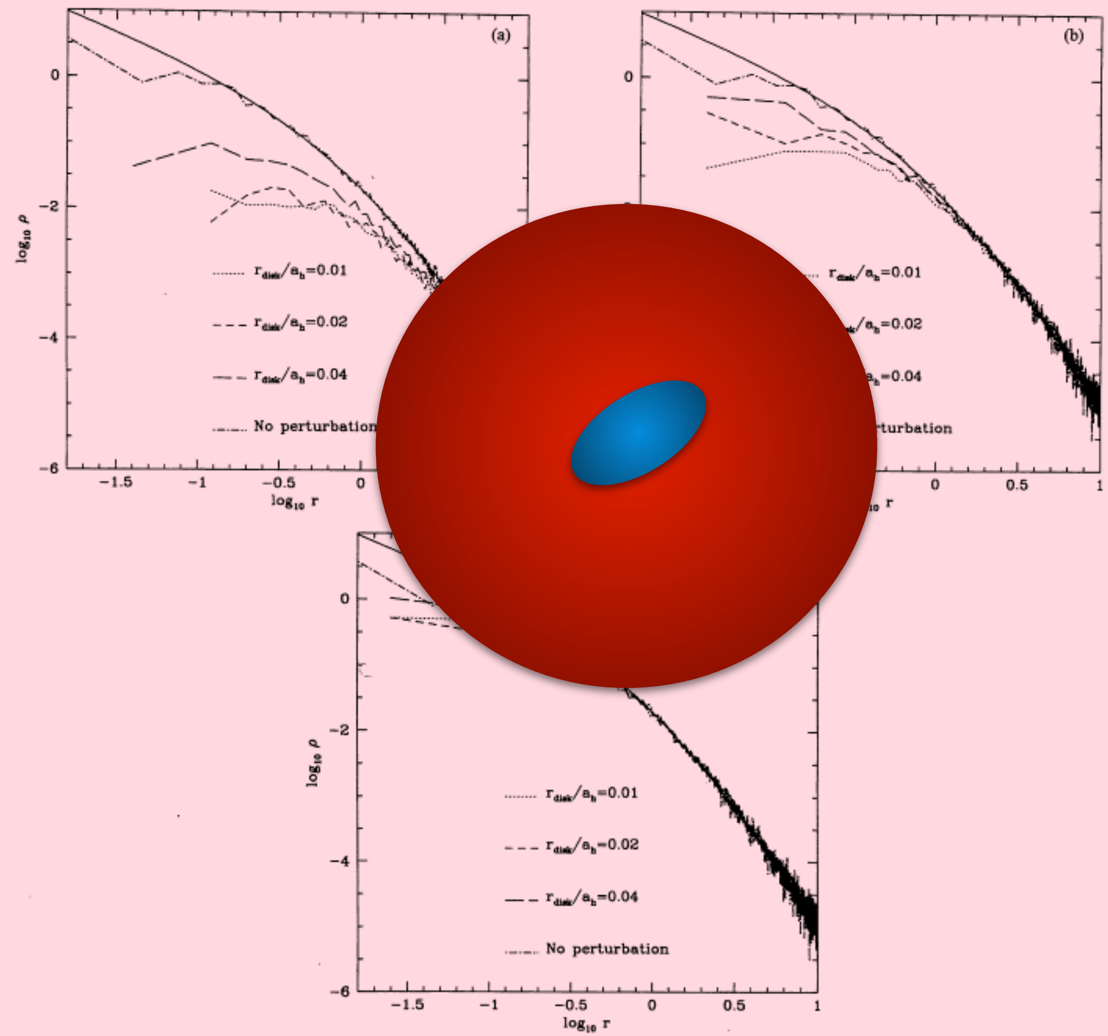


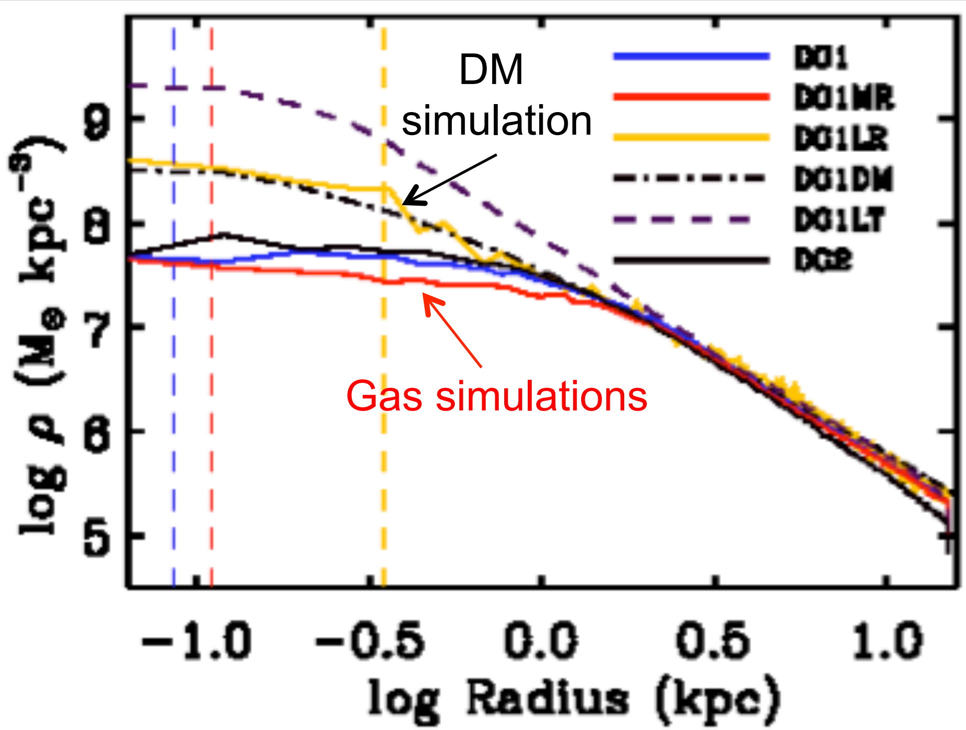
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{disc} = 0.2$.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

Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

→ High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy



Governato et al. '12

Pontzen et al. '12

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Cores or cusps in simulations?

Depends on details of how star formation is modelled
(subgrid physics)

Key parameter: gas density threshold for star formation

High density → NEF mechanism

Low density → not enough central gas density to perturb DM

Cores or cusps in simulations?

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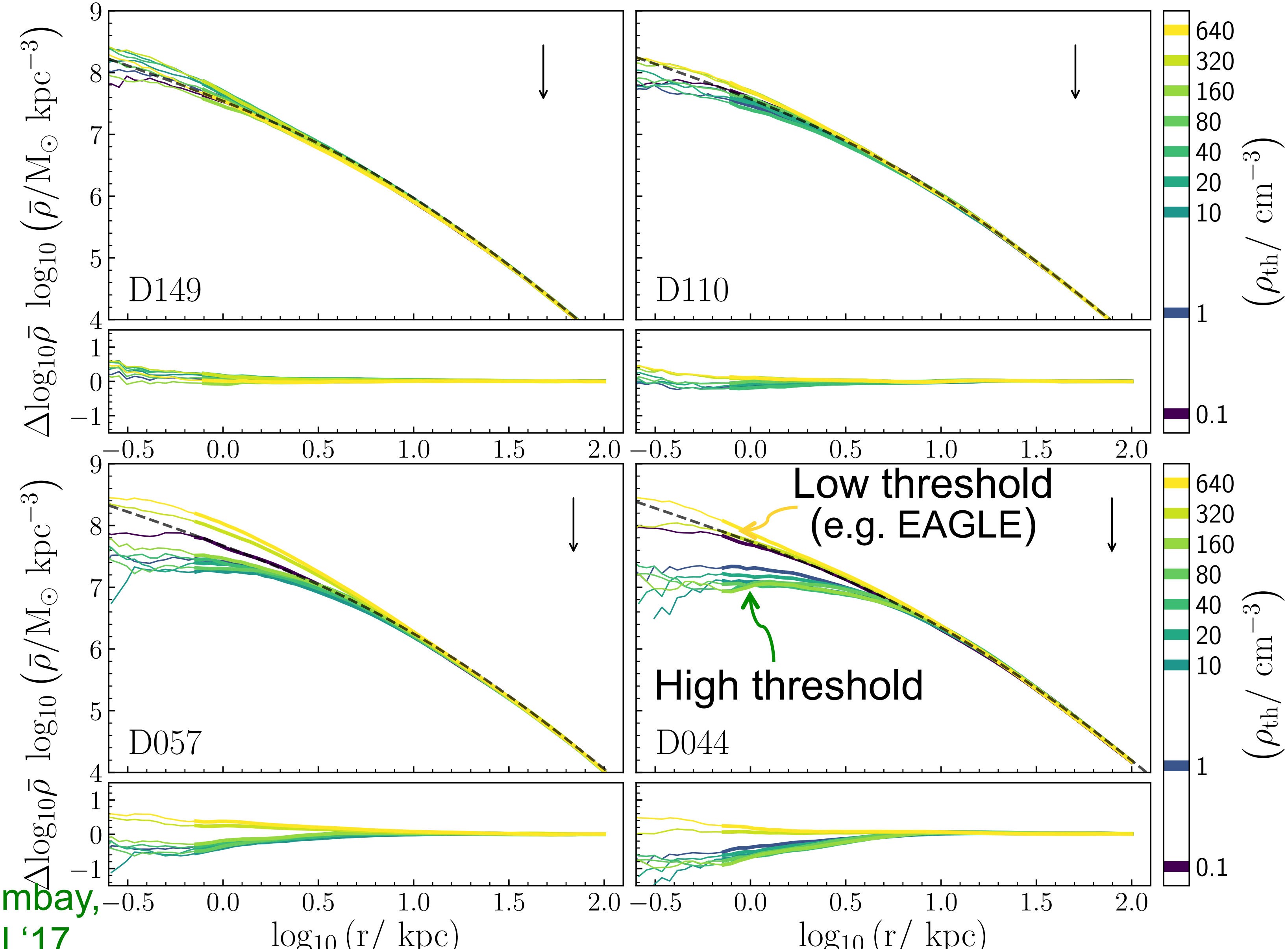

Benitez-Llambay, CSF et al '17

There is NO strong evidence for cores in dwarf galaxies

(Existing data are consistent with either cusps or cores)

But in any case cores can be easily created by baryon effects

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Tests of ΛCDM with subhalos

I. What do we know about subhalos in ΛCDM (and ΛWDM)

- Abundance
- Radial distribution
- Structure

II. How can we use subhalos to test ΛCDM

- In the optical
- In gamma rays
- With gravitational lensing

Tests of ΛCDM with subhalos

Test IV: γ-ray annihilation radiation

A blueprint for detecting CDM

University of Durham

Supersymmetric particles annihilate and lead to production of γ-rays which may be observable by FERMI

Intensity of annihilation radiation at ***x*** depends on:

$$\int \rho^2(\boldsymbol{x}) \, \langle \sigma v \rangle \, dV$$

halo density at ***x*** — cross-section

For a smooth NFW profile: $L \propto \frac{V^4_{\max}}{r_{\max}}$

Milky Way halo seen in DM annihilation radiation

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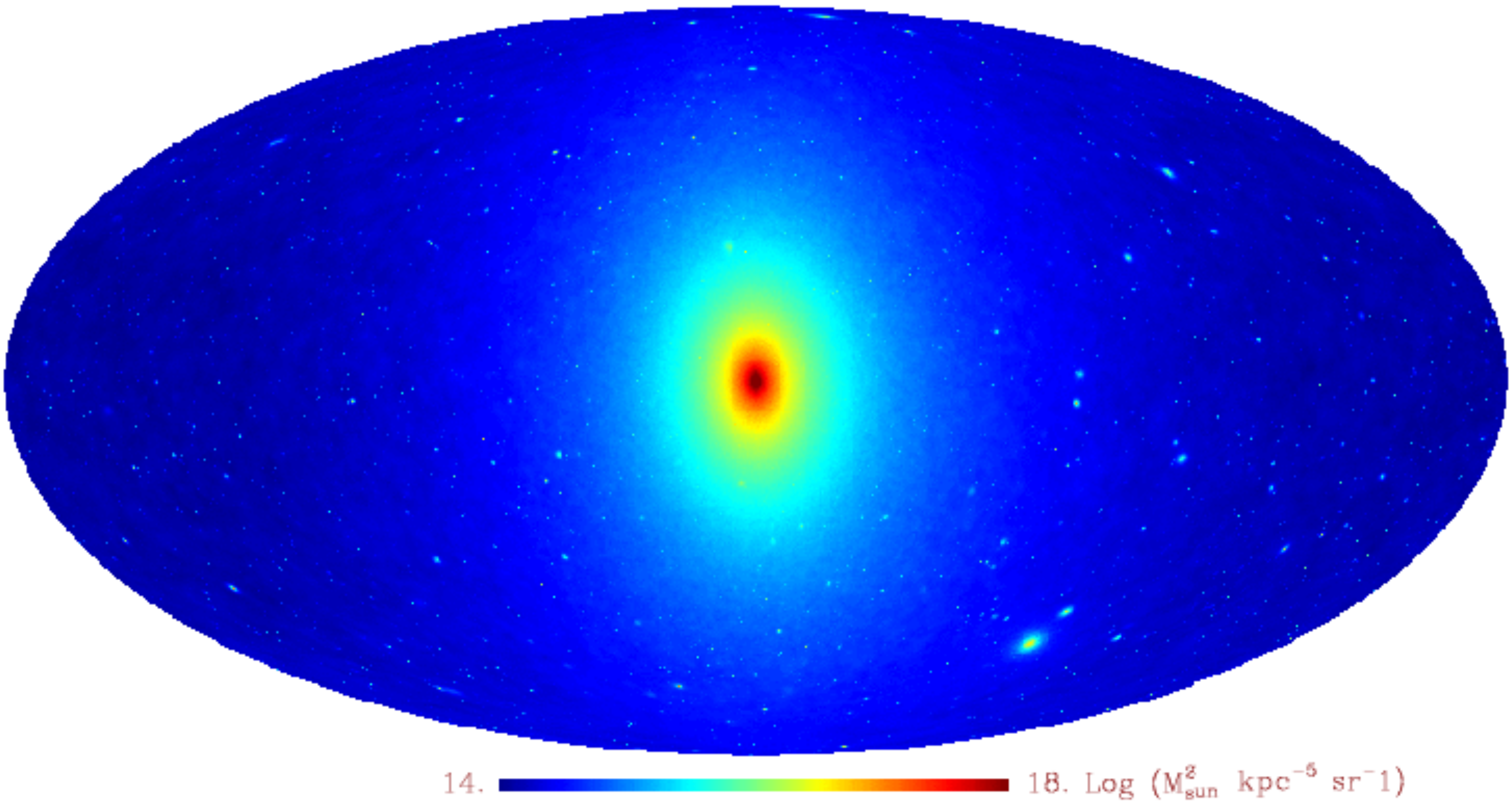
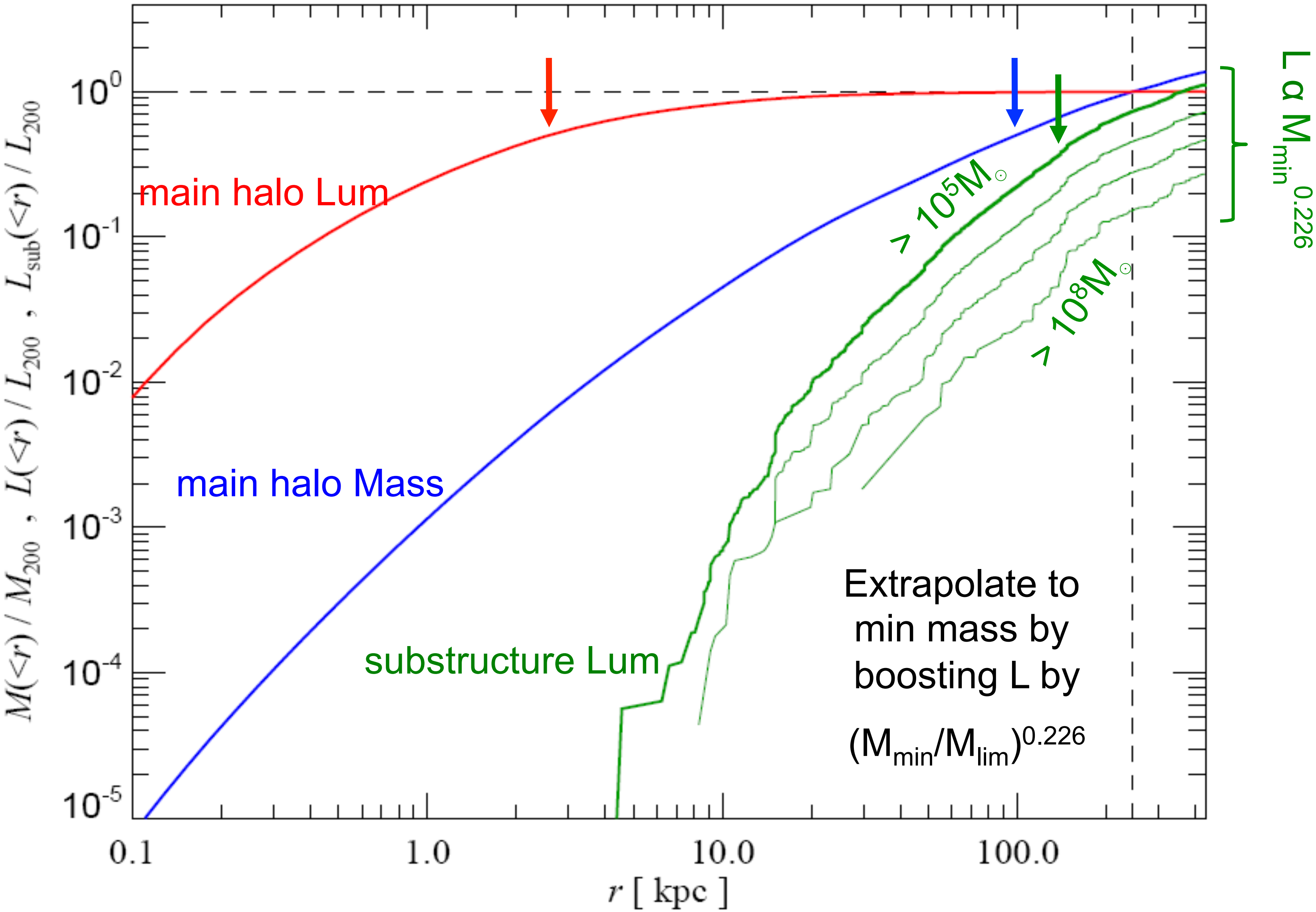
Aquarius simulation



Springel + '08b

University of Durham

Mass and annihilation radiation profiles of a MW halo



A blueprint for detecting halo CDM

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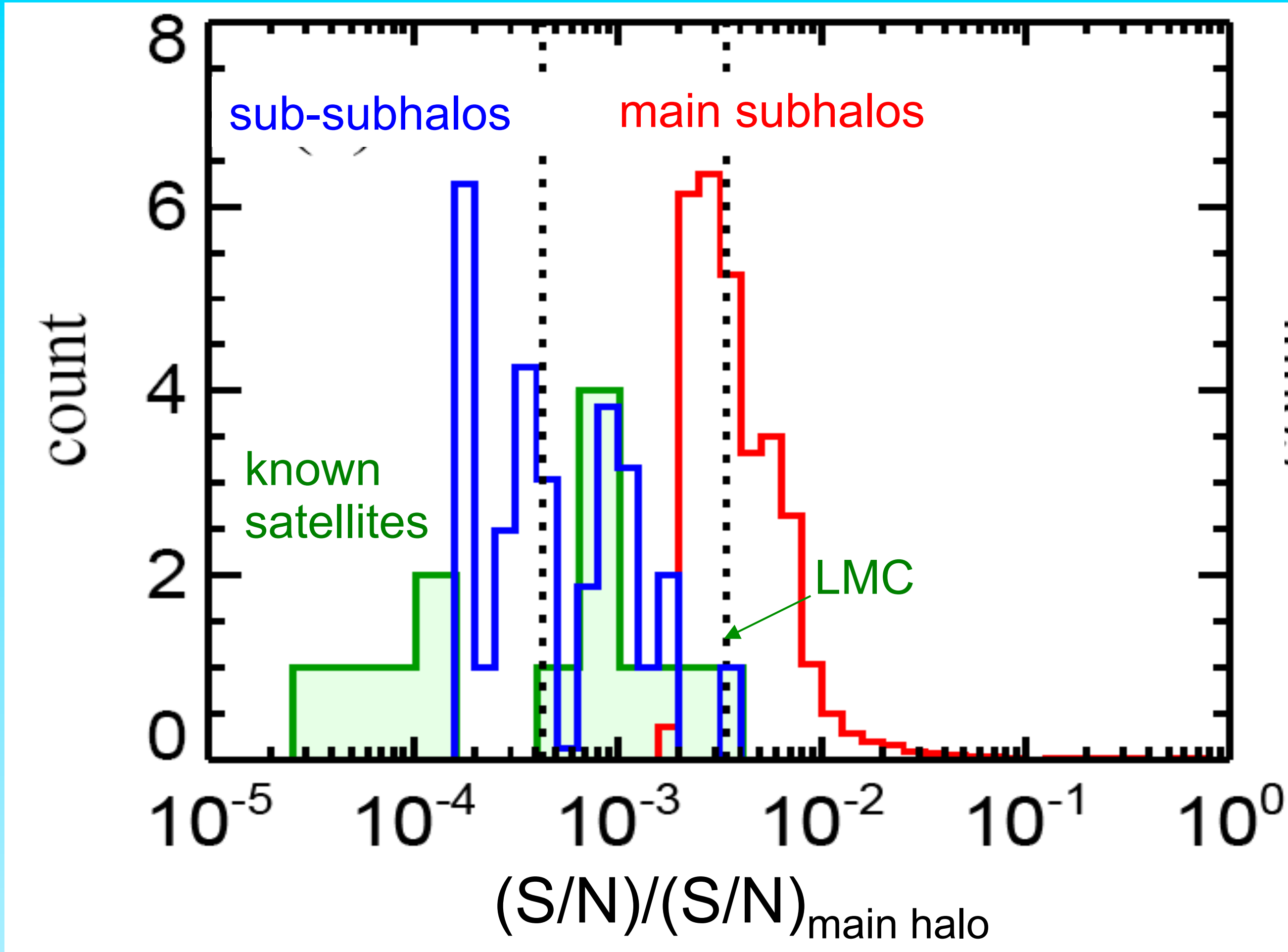
Springel + '08b

S/N for detecting subhalos in units of that for detecting the main halo

30 highest S/N objects, assuming use of optimal filters



- Highest S/N subhalos have 1% of S/N of main halo
- Highest S/N subhalos have 10 times S/N of known satellites
- Substructure of subhalos has no influence on detectability

Can CDM be ruled out?

Yes !

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Tests of ΛCDM with subhalos

Test V: strong gravitational lensing

The satellites of the Milky Way

cold dark matter

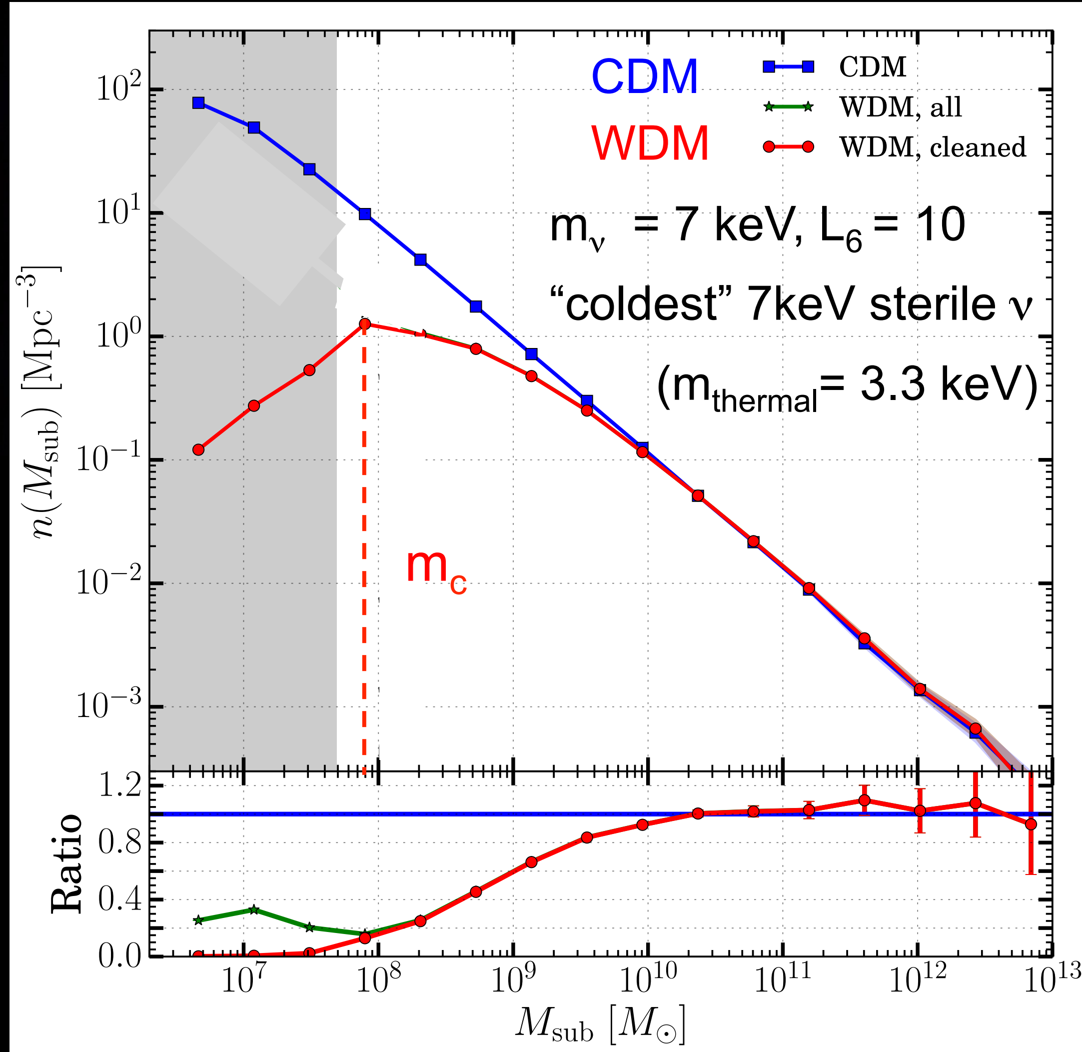
The key prediction of CDM is that there should be a very large number of small dark matter halos, too small to have made a galaxy.

cold dark matter　　　　warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

The subhalo mass function

CDM WDM



3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

Bose, CSF et al ‘16

Can we distinguish CDM/WDM?

cold dark matter

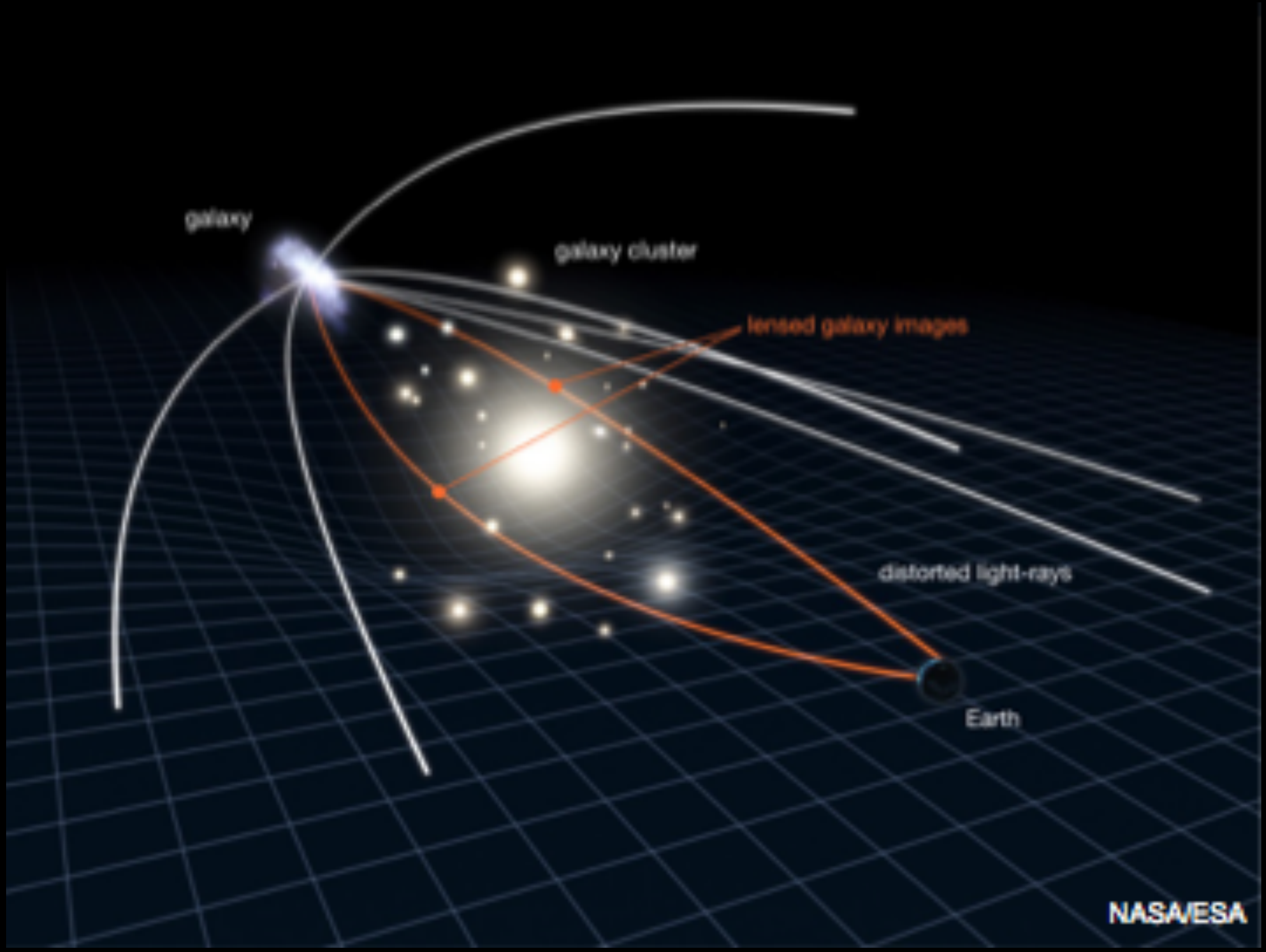
warm dark matter

Dark halos can be detected through gravitational lensing

Gravitational lensing: Einstein rings

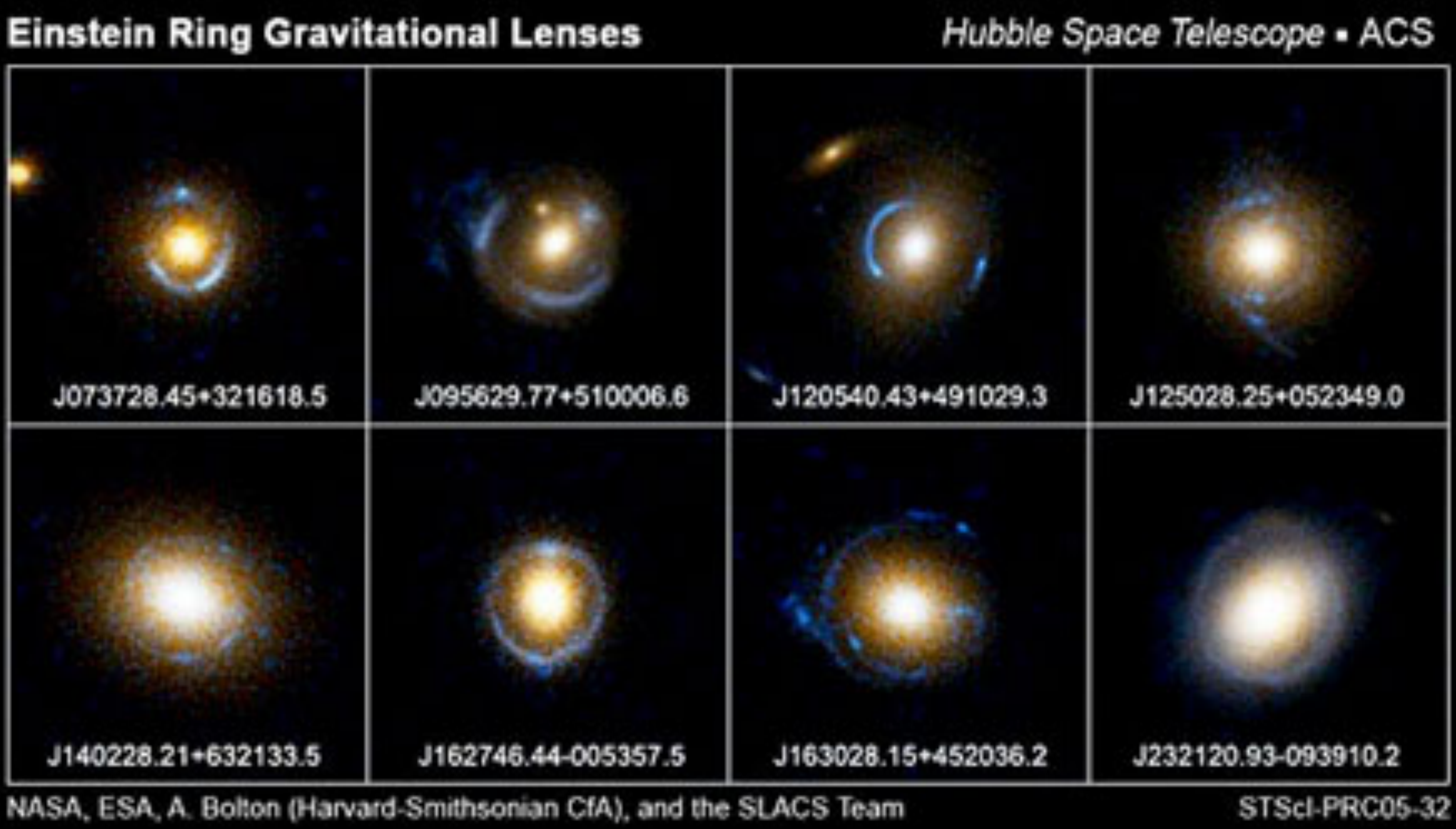
How to rule out CDM

Gravitational lensing: Einstein rings

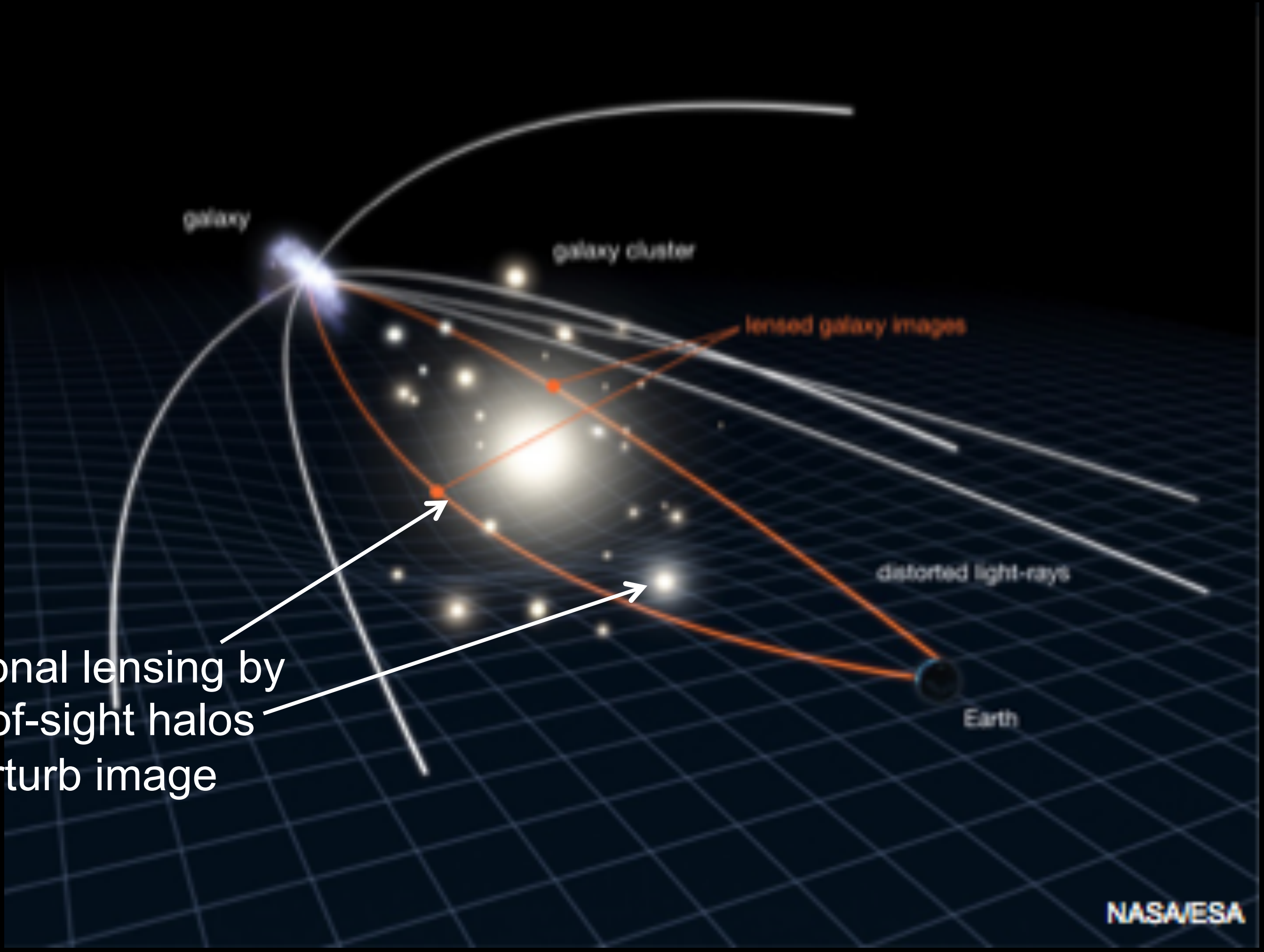


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

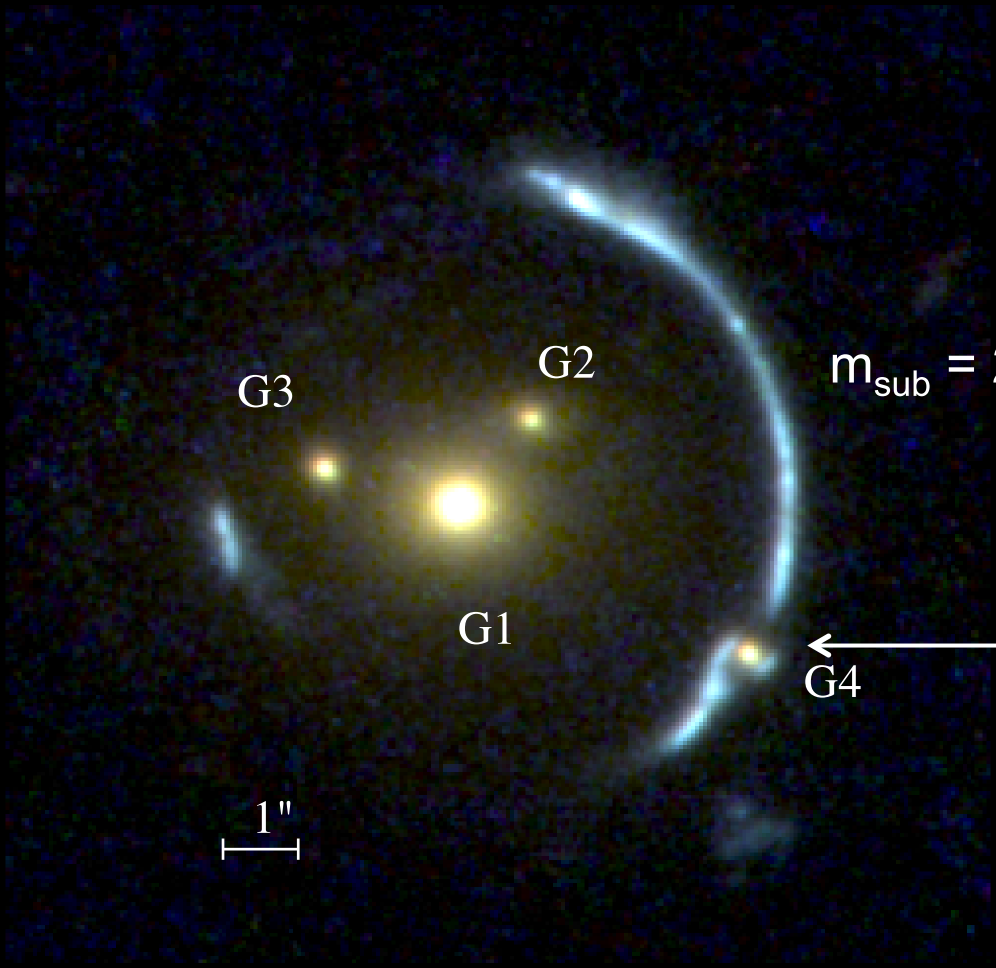


Additional lensing by line-of-sight halos perturb image

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

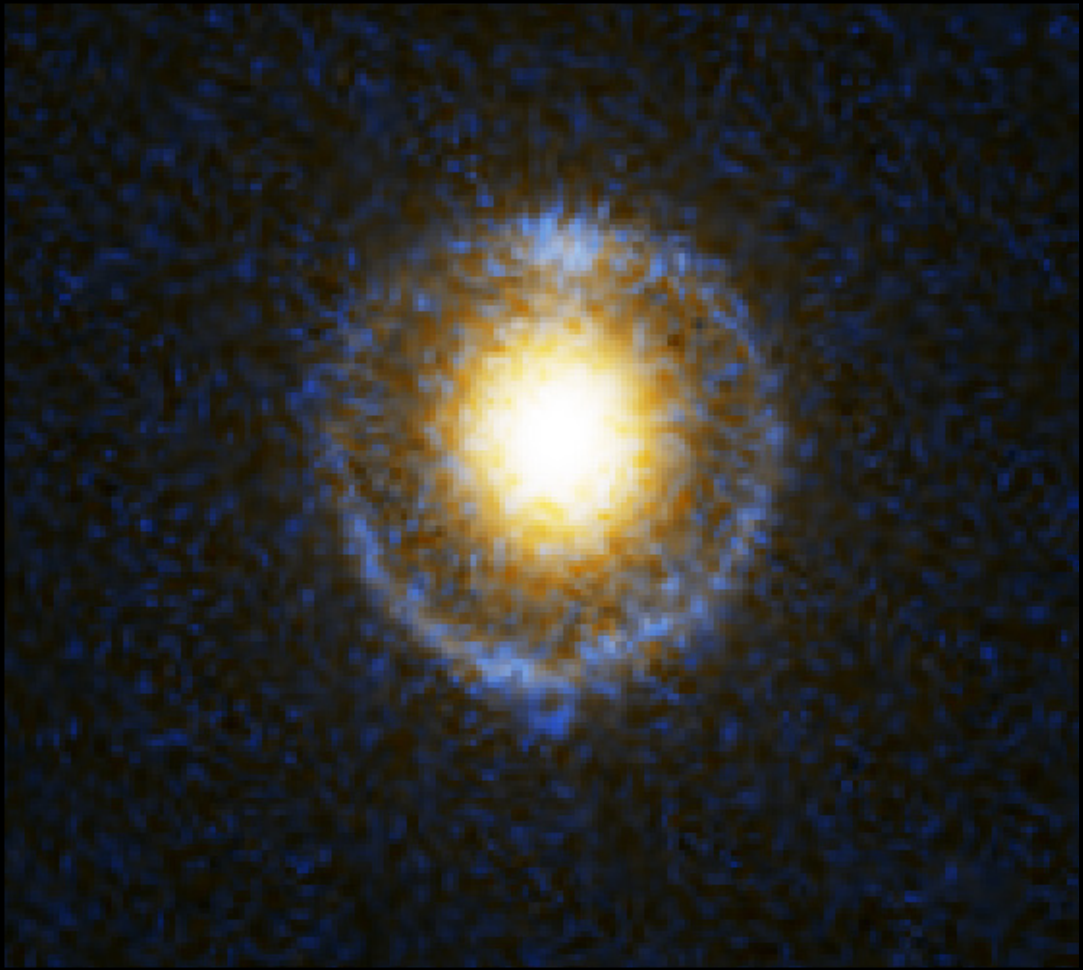


$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al ‘10

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image

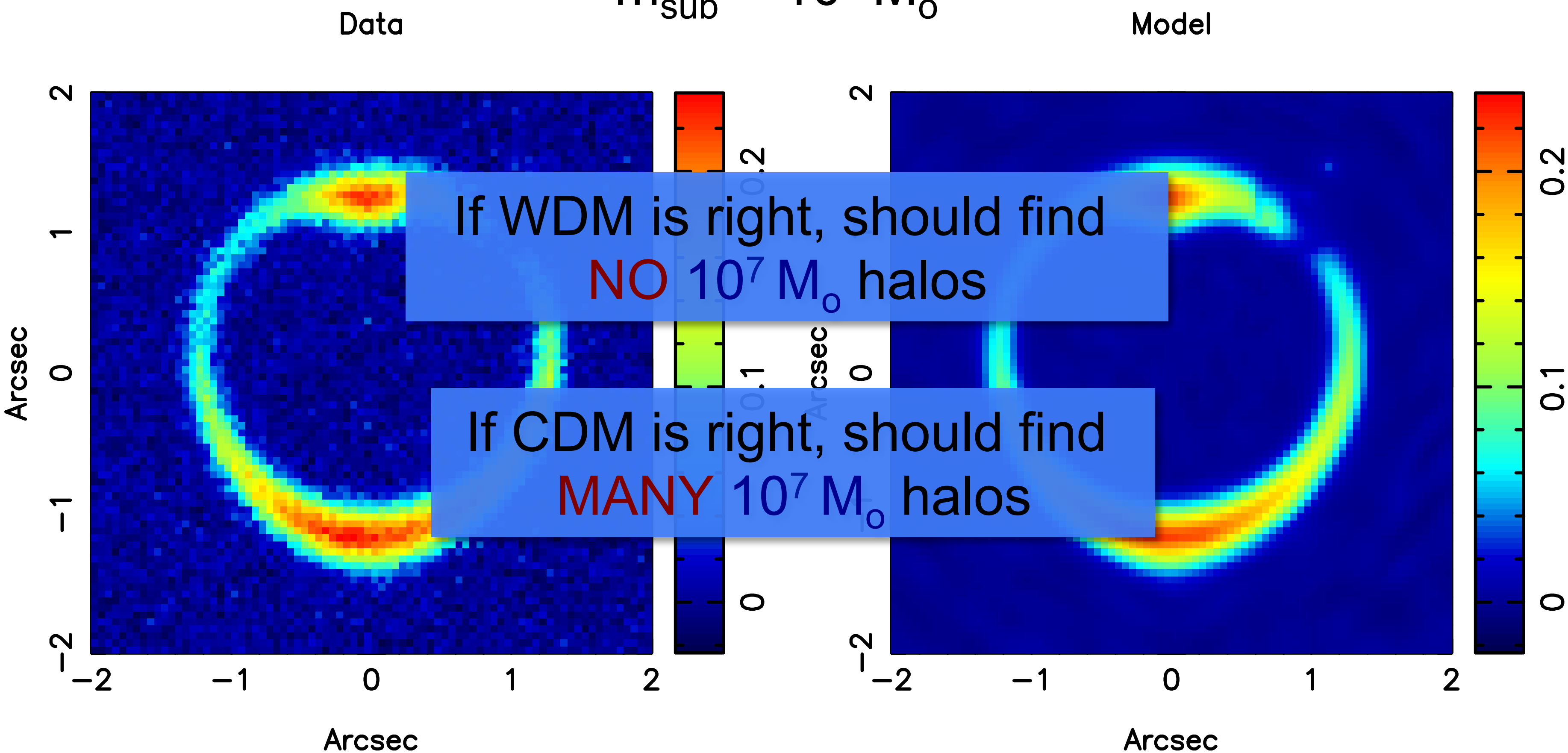


Vegetti & Koopmans ‘09

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$



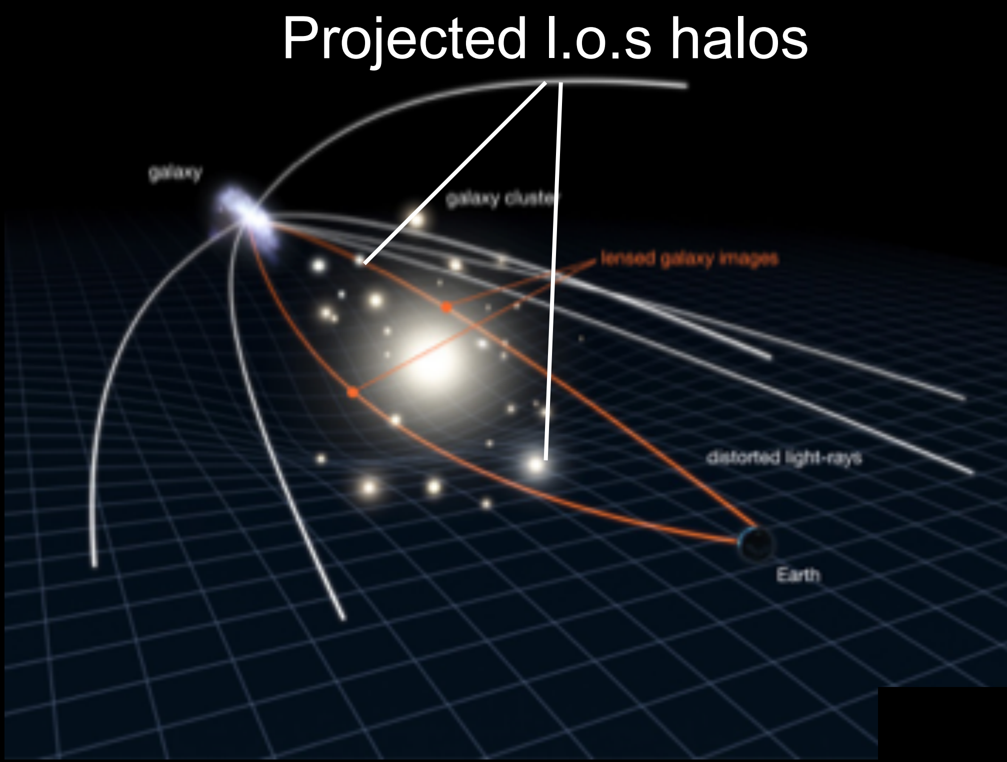
If WDM is right, should find NO $10^7 M_o$ halos

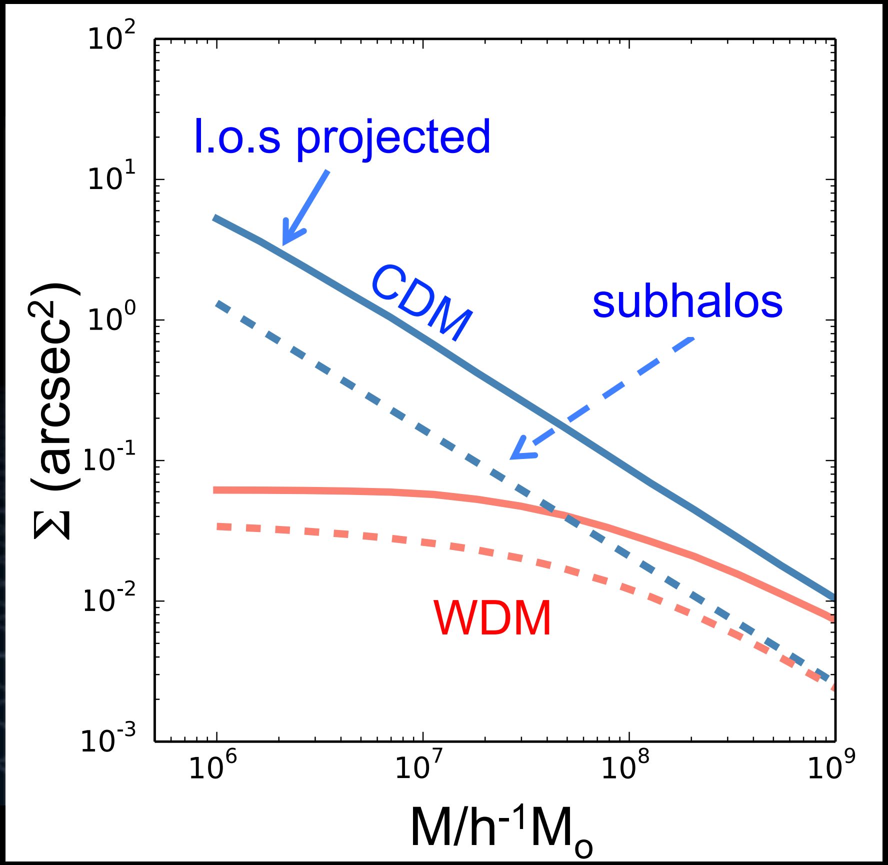
If CDM is right, should find MANY $10^7 M_o$ halos

Can detect subhalos as small as $10^7 M_o$

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?



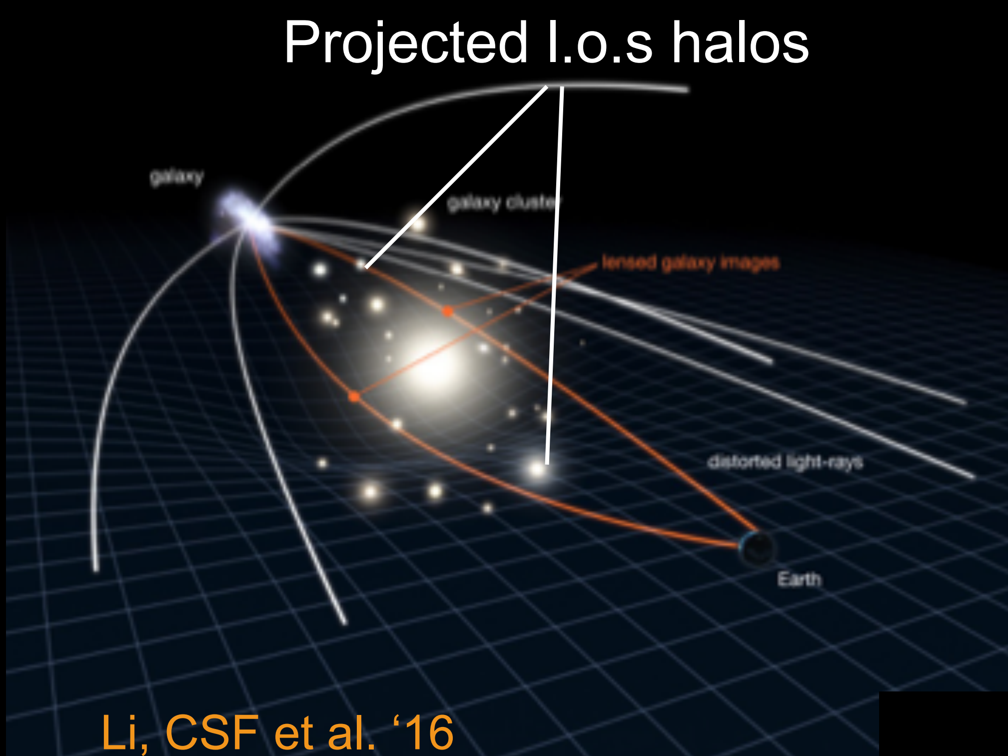


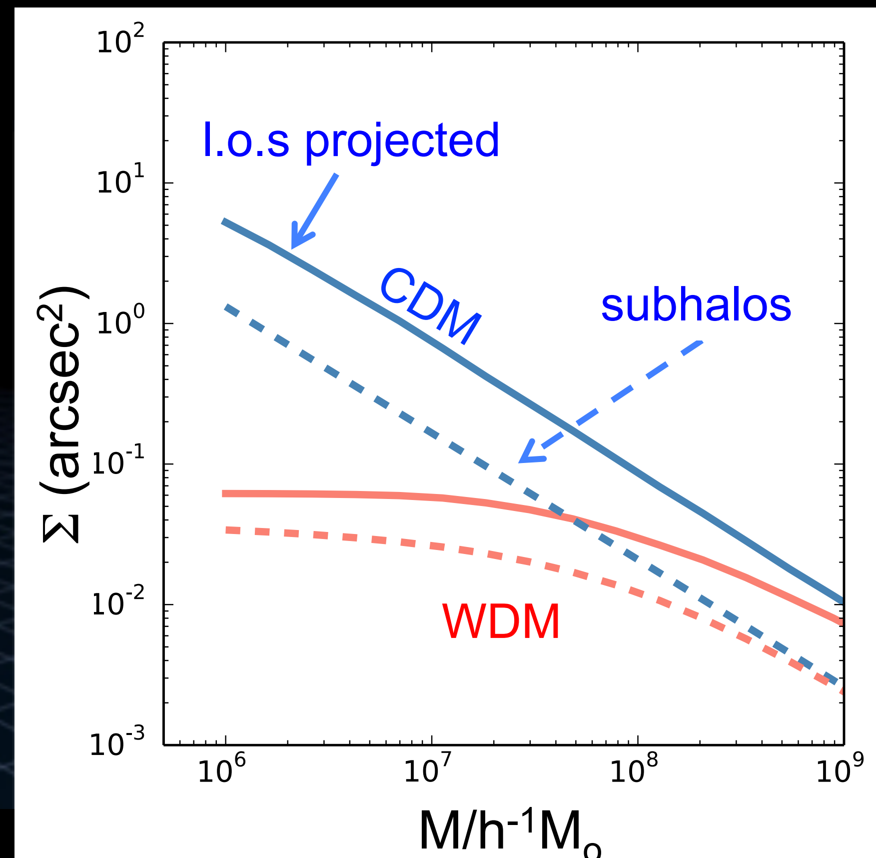
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16; see also Despali et al. '18

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?





→ This is the cleanest possible test: it depends ONLY on the small-mass end of the "field" halo mass function which we know how to calculate and is unaffected by baryons

Detecting substructures with strong lensing

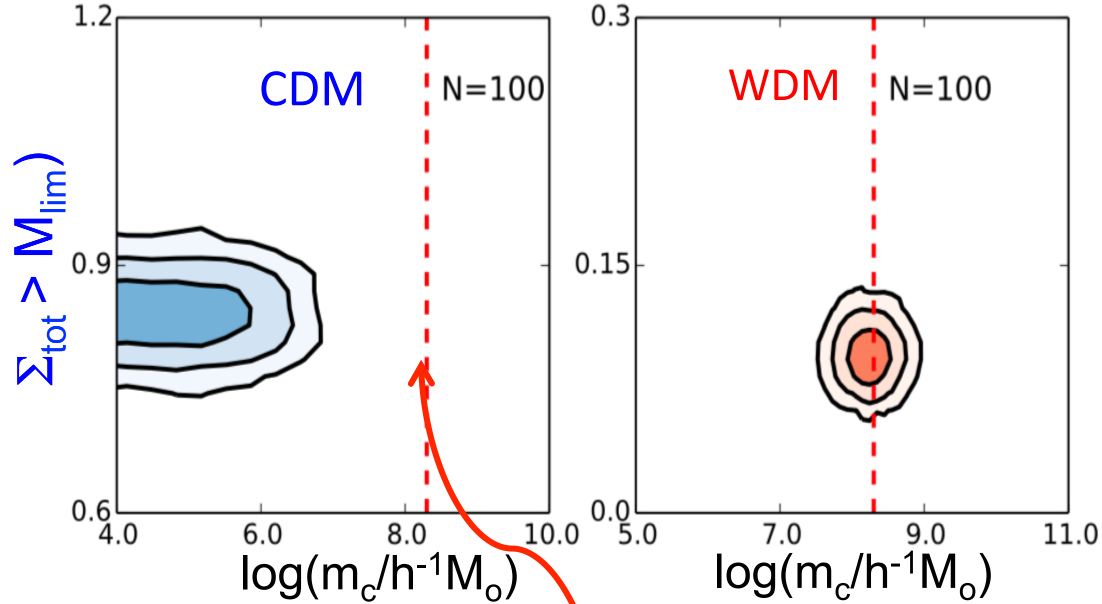
University of Durham

Σ_{tot}= projected halo number density within Einstein ring

m_c= halo cutoff mass

100 Einstein ring systems and detection limit: $m_{low} = 10^7\ h^{-1}M_o$

Detection limit $= 10^7\ h^{-1}M_o$



m_c= halo cutoff mass

$m_c = 1.3 \times 10^8\ h^{-1}M_o$ for coldest 7 keV sterile neutrino

- If DM is 7 keV sterile ν → exclude CDM at >>σ!
- If DM is CDM → exclude 7 keV sterile ν at >>σ

Li, CSF et al '16

Institute for Computational Cosmology

Conclusions

Five tests of ΛCDM using subhalos

… of which only one is conclusive and possible

1. The satellite luminosity function: OK for CDM & WDM
2. Too-big-to-fail: OK for CDM & WDM
3. Core/cusp: no evidence for cores but can be produced by baryon effects: OK for CDM & WDM
4. γ-ray annihilation radiation: potentially conclusive
5. Distortions of strong gravitational lenses: conclusive & possible, but involves l.o.s halos, not subhalos