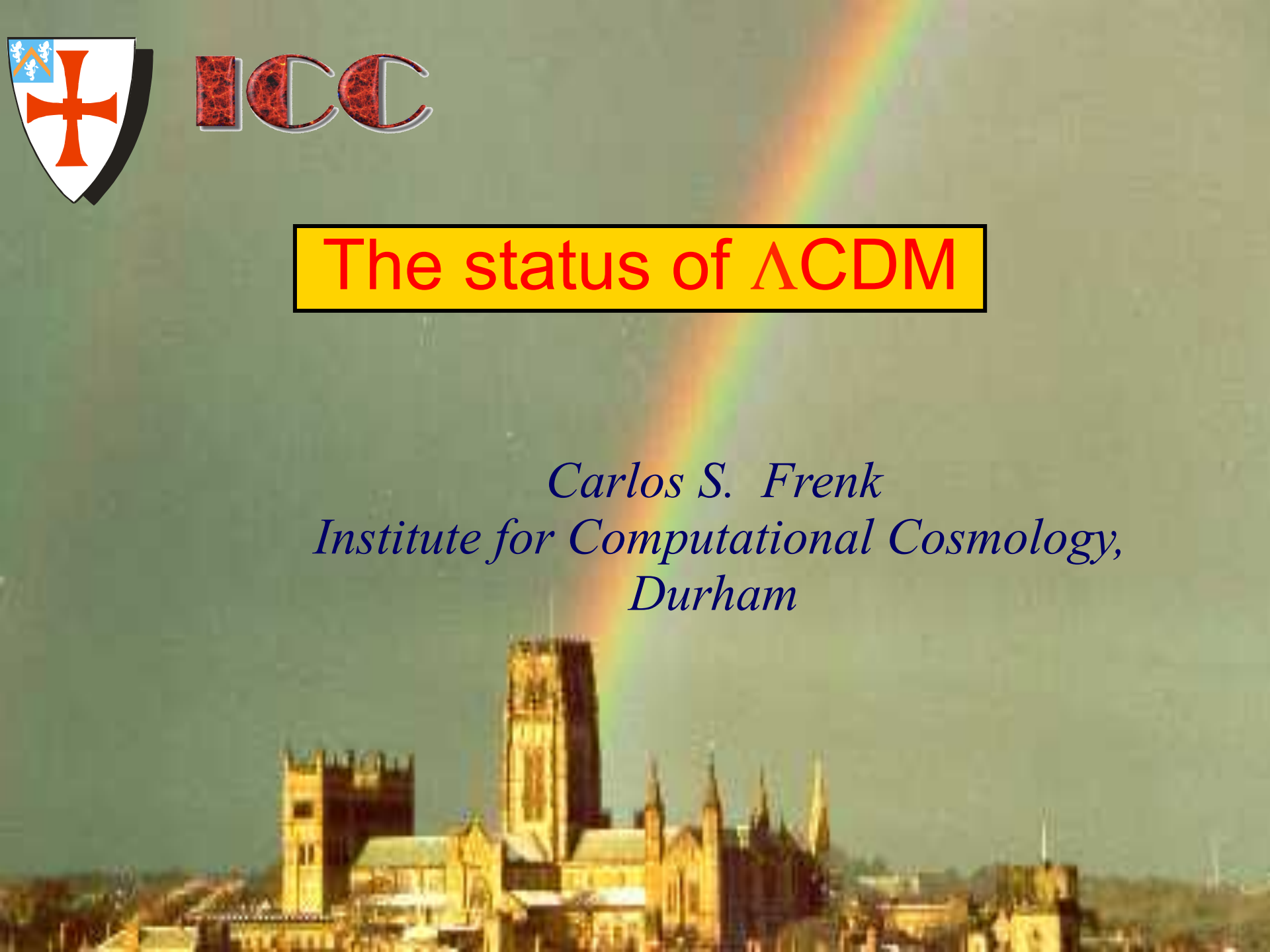

The status of ΛCDM

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

Axions could be cold dark matter

The new Ogden Centre at Durham

And cold dark matter is supposed to be in crisis!

Should you stop working on classical axions?

No, but there is a conclusive test of CDM

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CDM in "crisis"

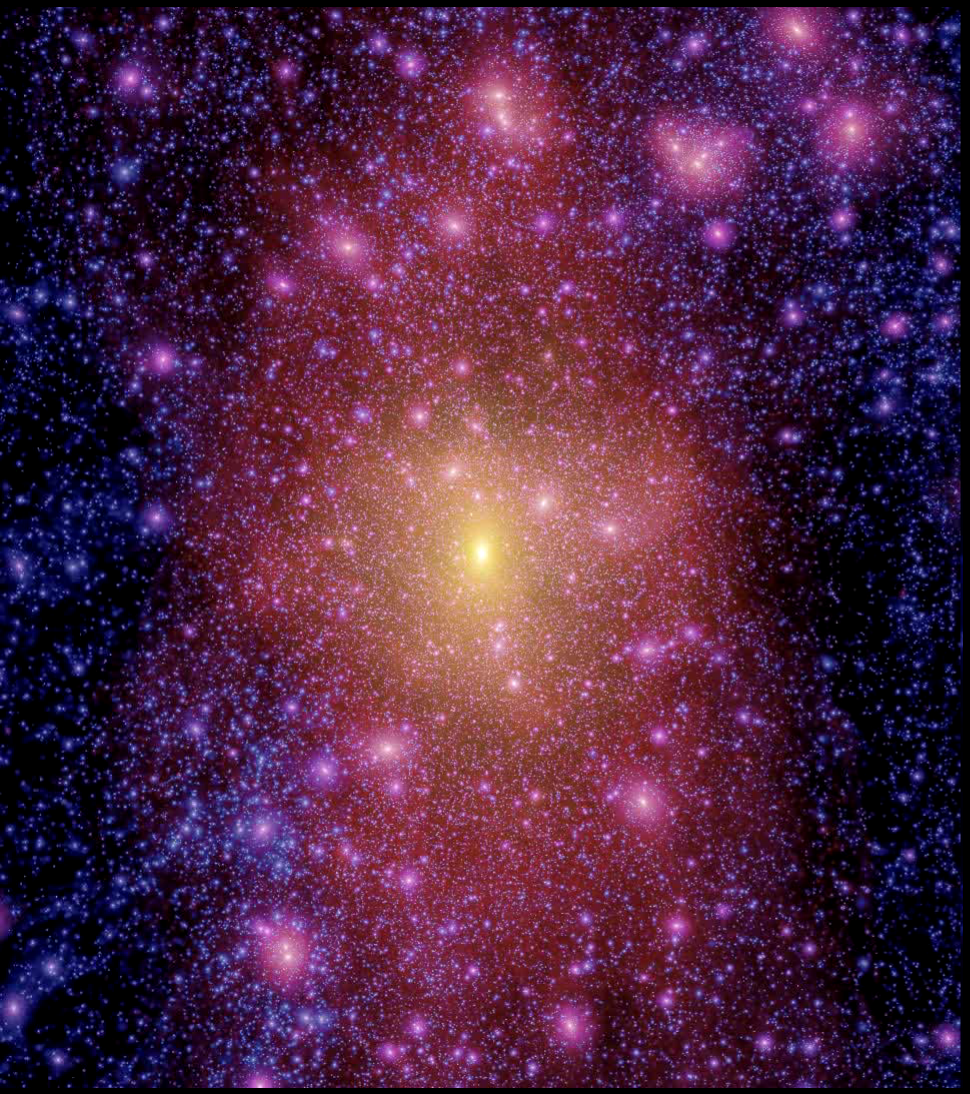
Four problems of CDM:

1. The "missing satellites" problem
2. The "too-big-to-fail" problem
3. The "plane of satellites" problem
4. The "core-cusp" problem

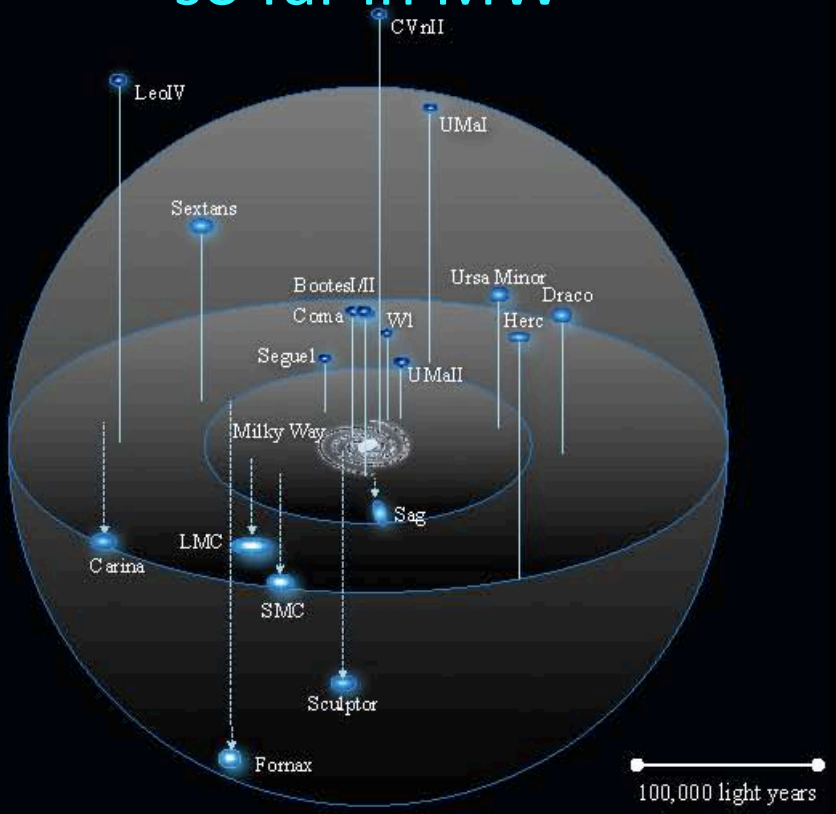
See Sawala, CSF + 16 (arXiv:1511.01098)

The satellites of the Milky Way

cold dark matter



~50 satellites discovered so far in MW

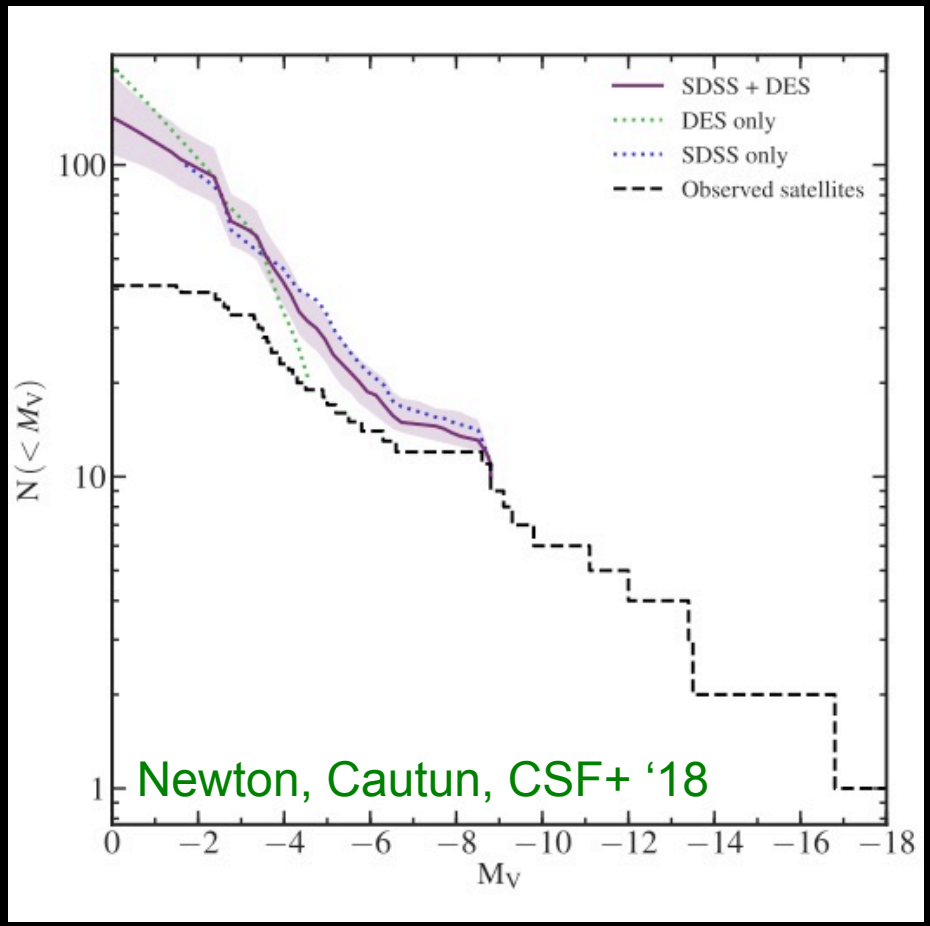


The satellites of the Milky Way

cold dark matter

Total N in MW (to M_V =0) is

$142 \pm {}^{53}_{34}$



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

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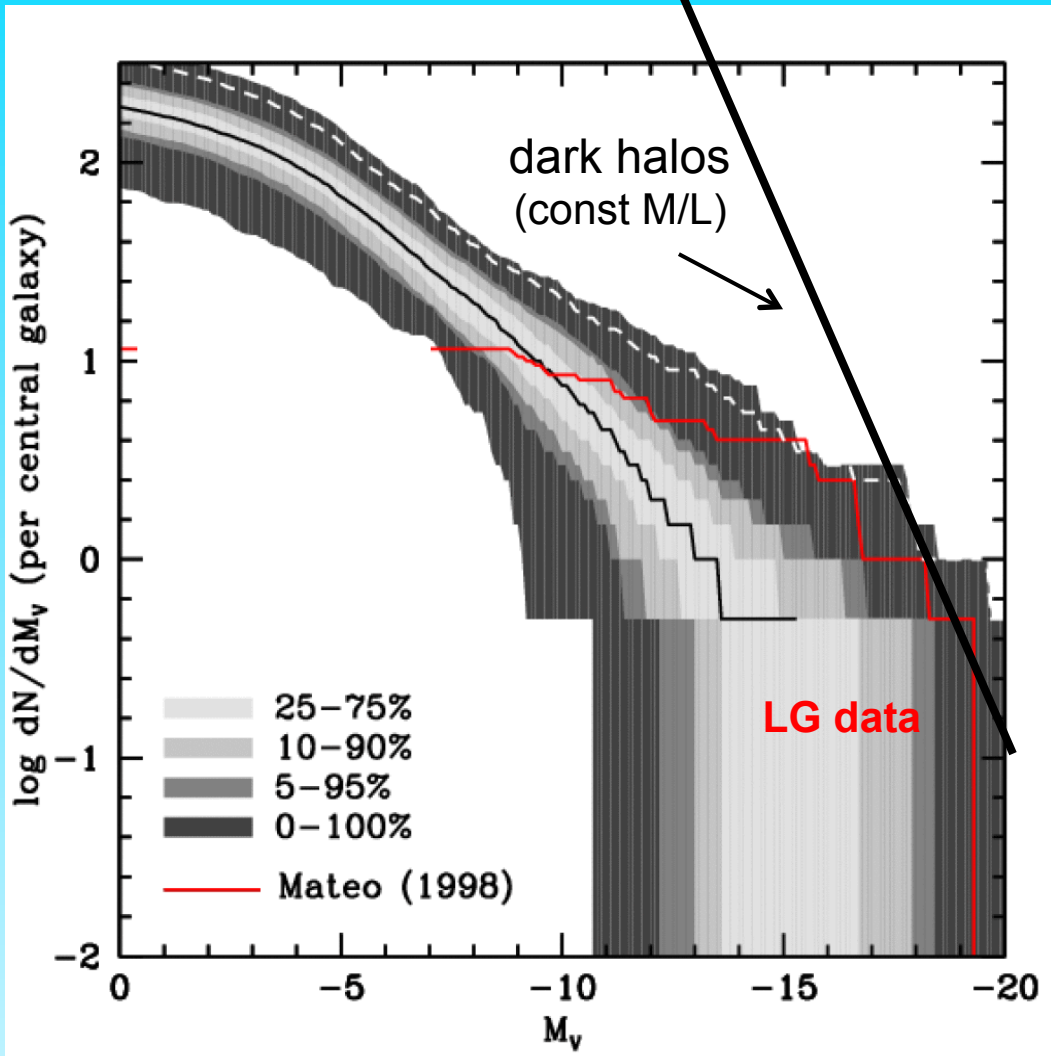
Luminosity Function of Local Group Satellites

- 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

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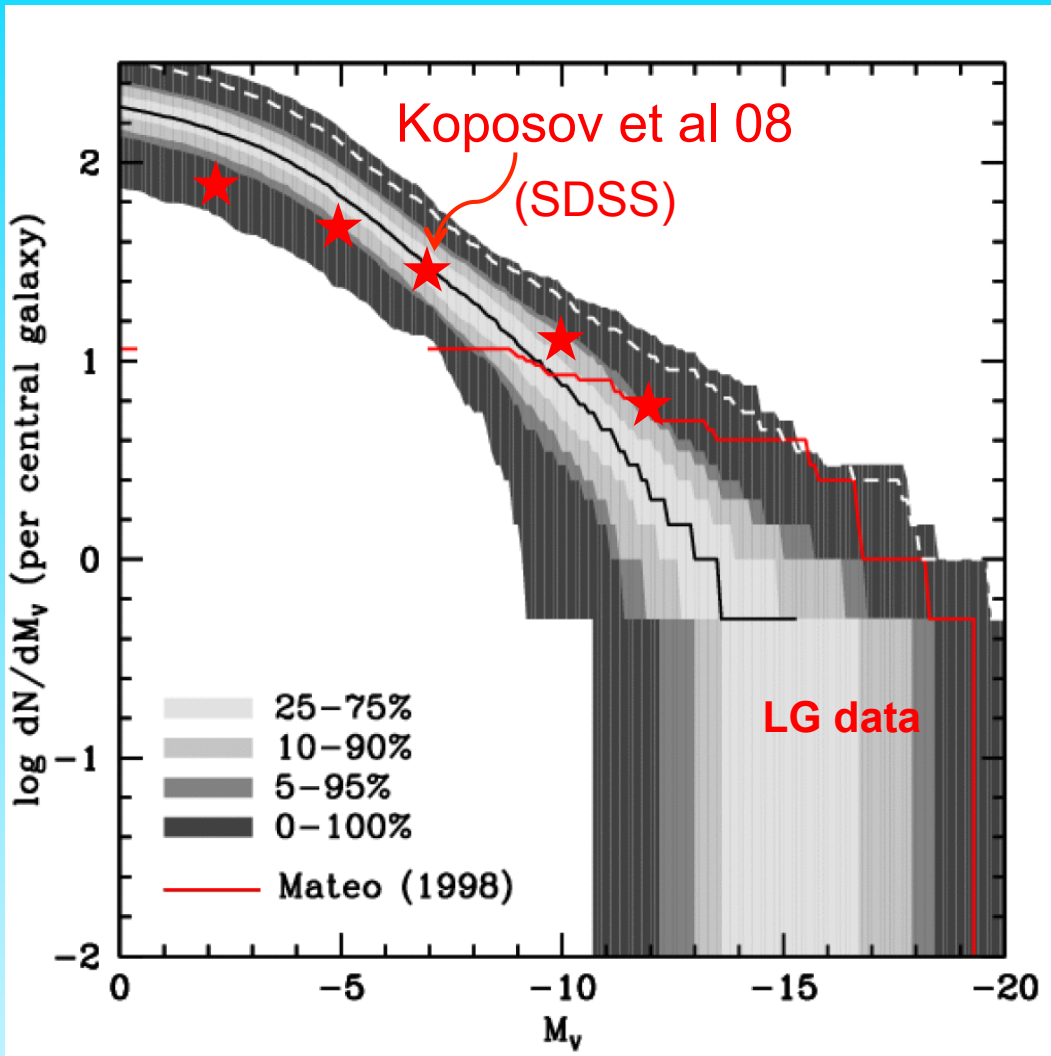


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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...

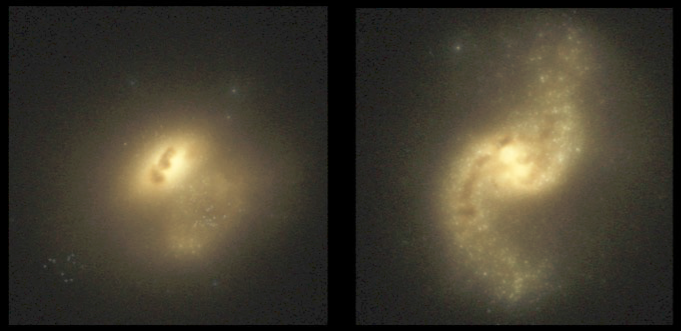
Durham University VIRGO ICC DiRAC PRACE

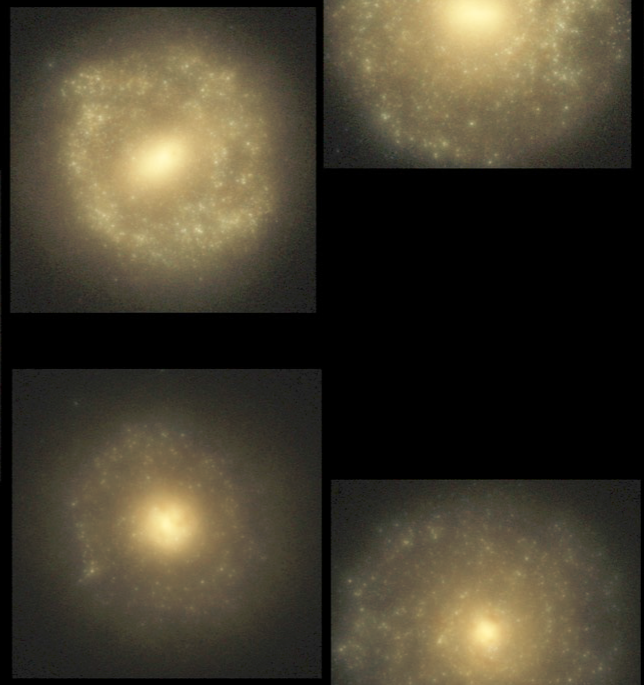
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

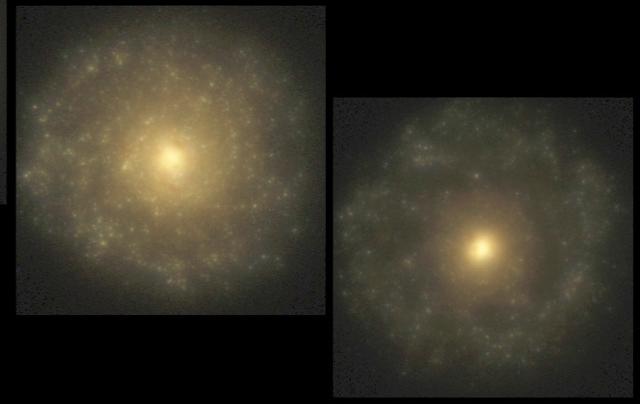
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

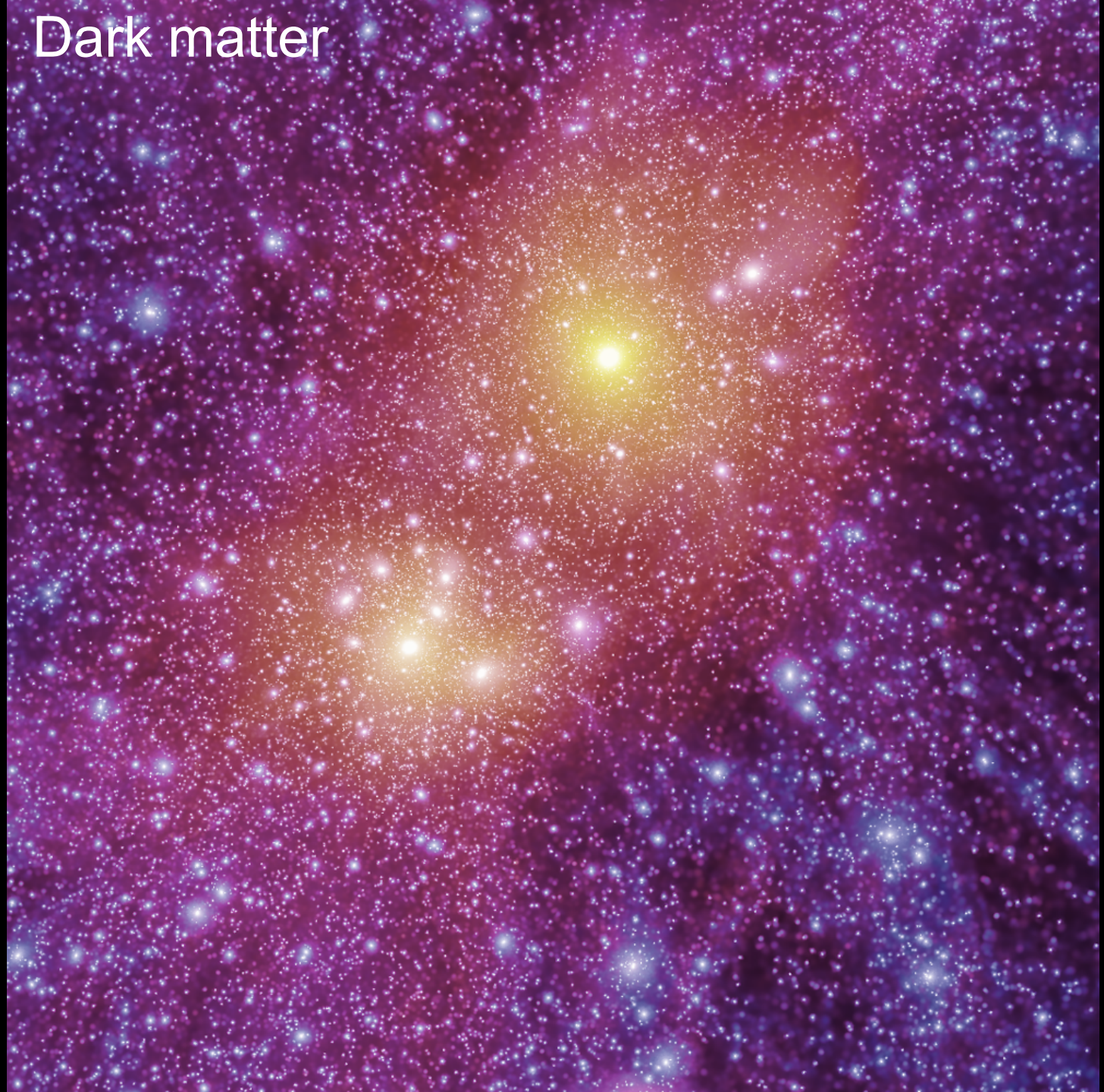
The Hubble Sequence realised in cosmological simulations







Trayford et al ‘15



VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al ‘16

Stars

APOSTLE
EAGLE full hydro simulations

Local Group

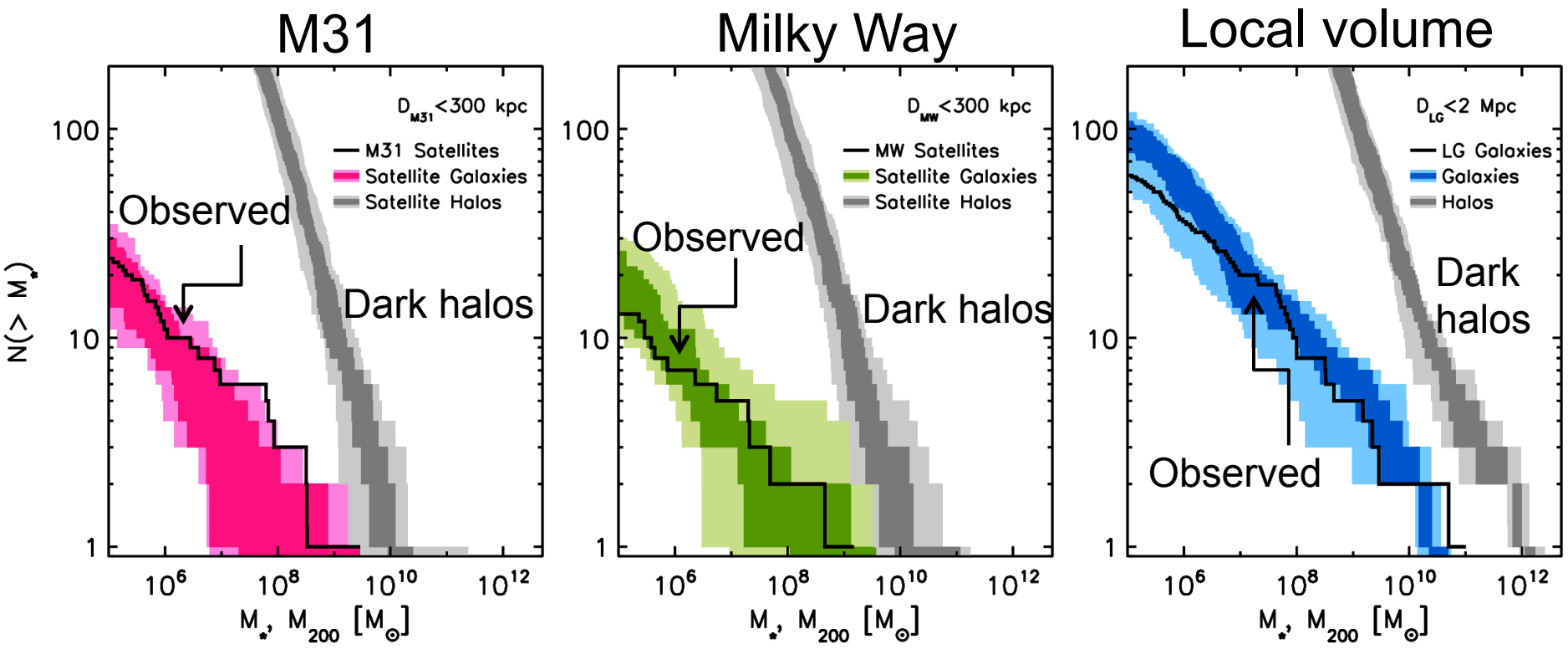
Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

University of Durham

EAGLE Local Group simulation



Sawala, CSF et al '16

Institute for Computational Cosmology

When “baryon effects” are taken into account

→

Observed abundance of satellites is compatible with CDM

→

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

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CDM in "crisis"

Four problems of CDM:

1. ~~The "missing satellites" problem~~
2. The "too-big-to-fail" problem
3. The "plane of satellites" problem
4. The "core-cusp" problem

See Sawala, CSF + 16 (arXiv:1511.01098)

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

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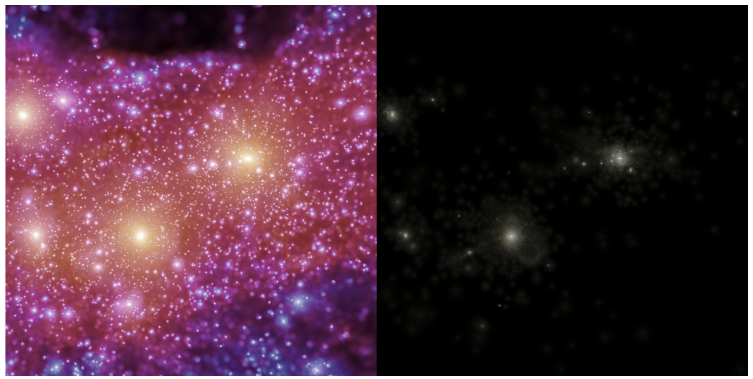
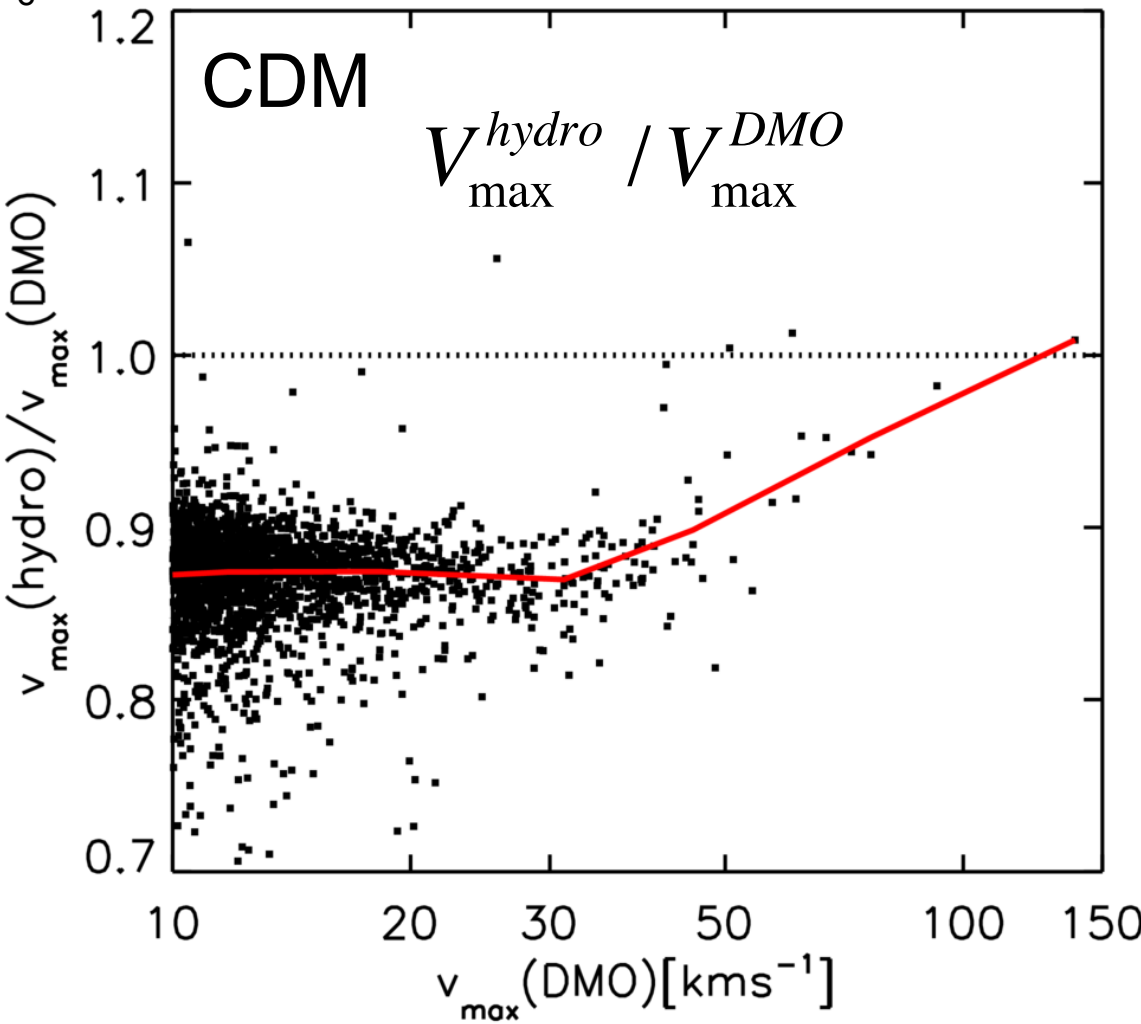
$$V_c = \sqrt{\frac{GM}{r}}$$

$V_{max} = \max V_c$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala, CSF +. '13, '15

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CDM in "crisis"

Four problems of CDM:

1. ~~The "missing satellites" problem~~
2. ~~The "too-big-to-fail" problem~~
3. ~~The "plane of satellites" problem~~

→ Solved by doing the statistics properly
(Cautun, CSF+ '17)

See Sawala, CSF + 16 (arXiv:1511.01098)

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CDM in "crisis"

Four problems of CDM:

1. ~~The "missing satellites" problem~~
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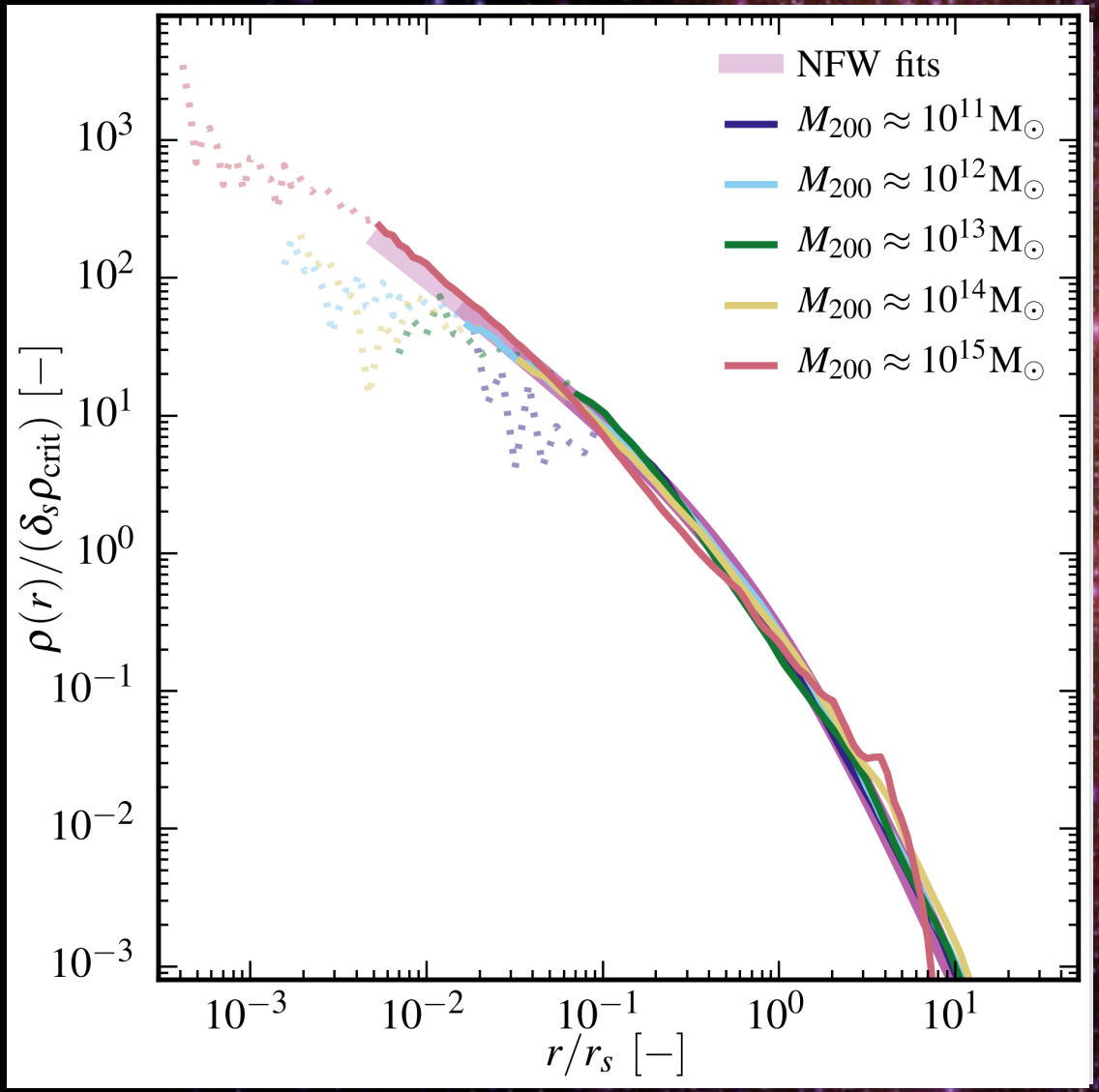
4. The "core-cusp" problem

See Sawala, CSF + 16 (arXiv:1511.01098)

The Density Profile of Cold Dark Matter Halos



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

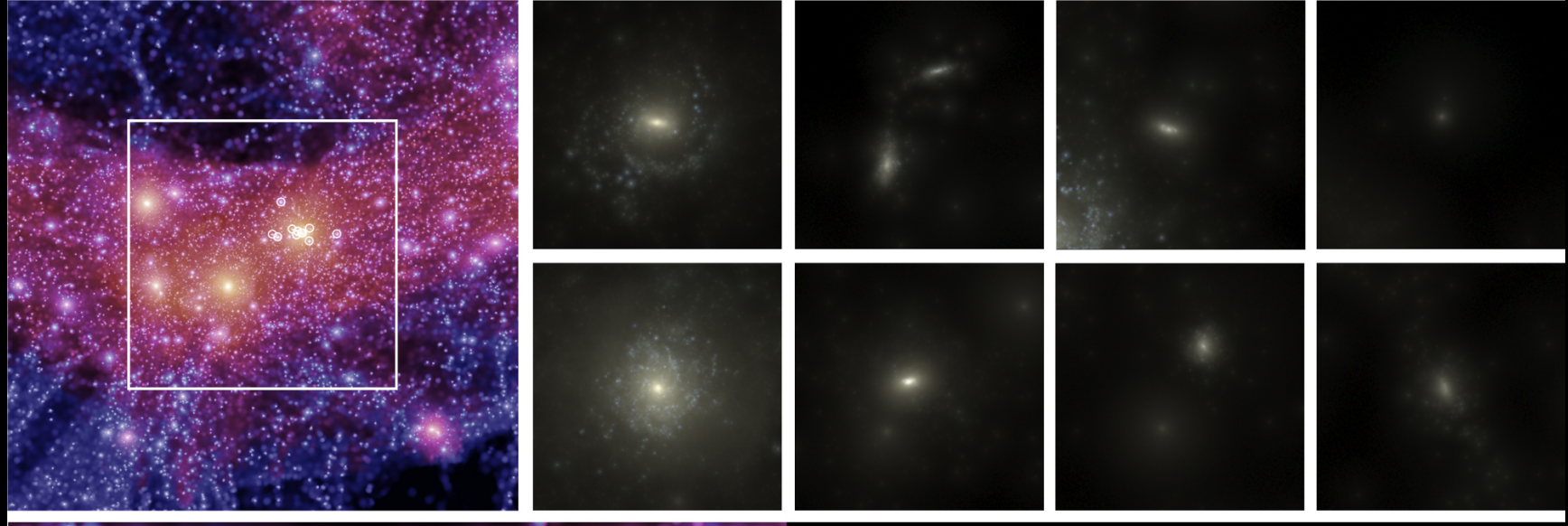
Density profiles are “cuspy” - no `core’ near the centre

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

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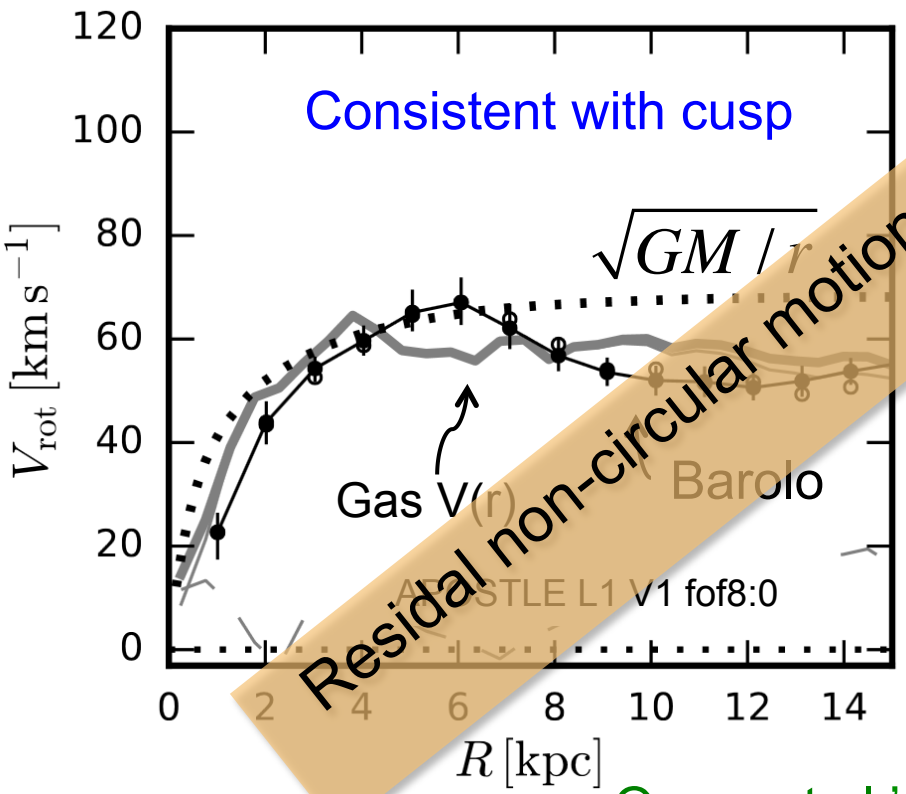
Rotation curves of 2 APOSTLE dwarfs

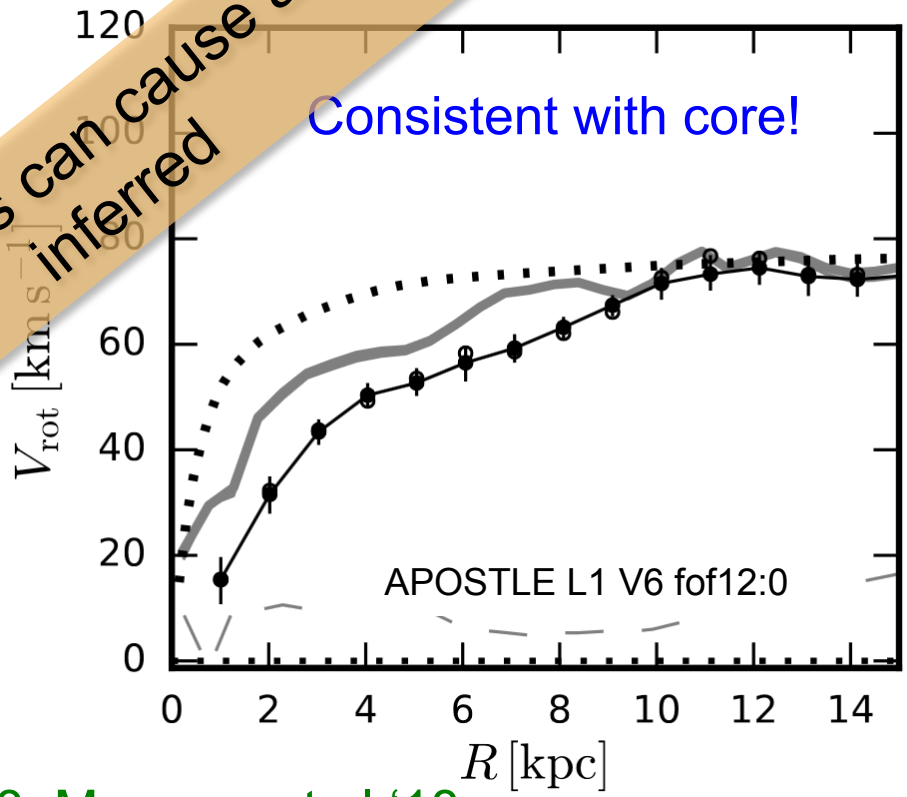
APOSTLE galaxies all have NFW cusps

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

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit





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

Oman et al '18; Marasco et al '18

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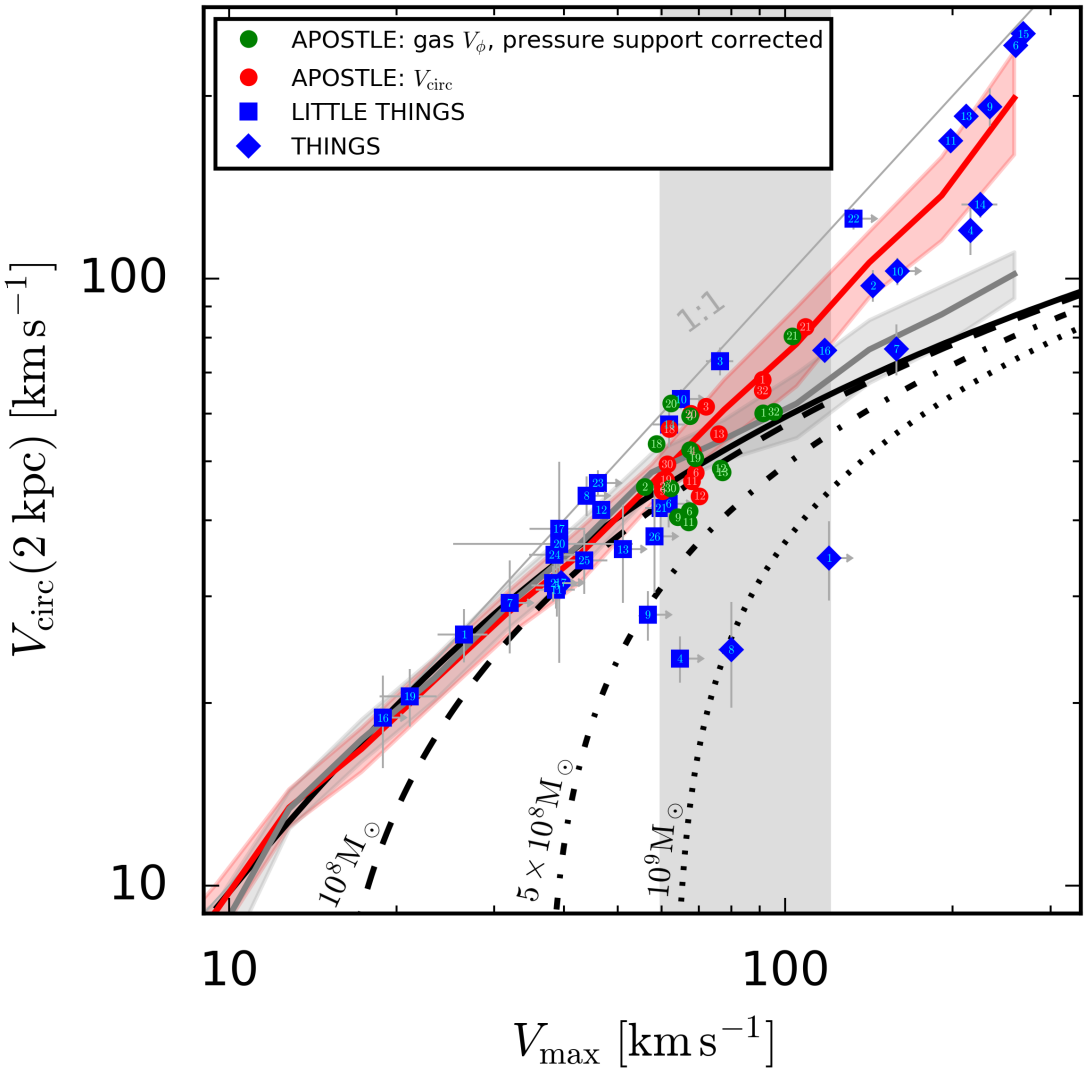
The diversity of rotation curves



Oman+ ‘17

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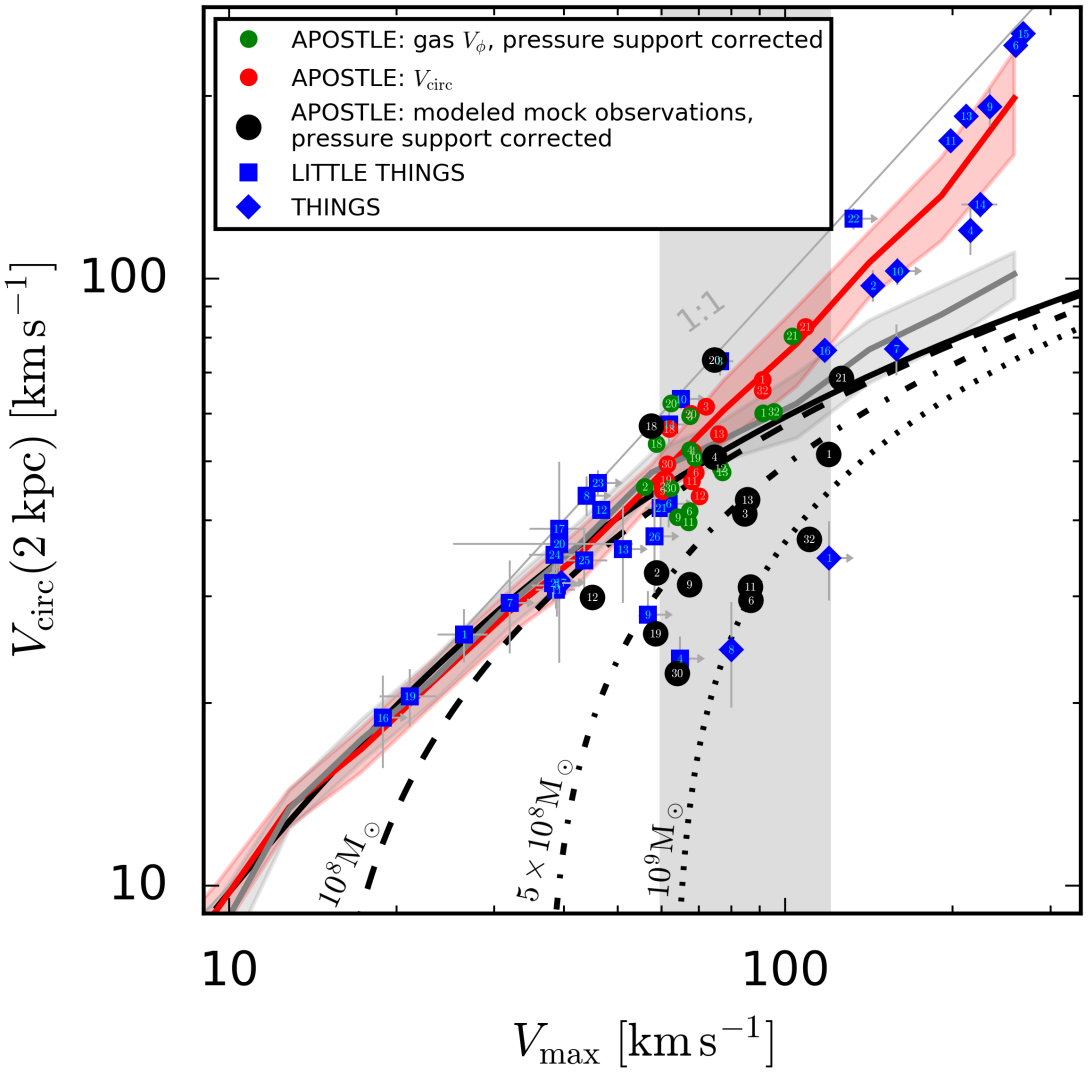
The diversity of rotation curves



Oman+ ‘17

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)

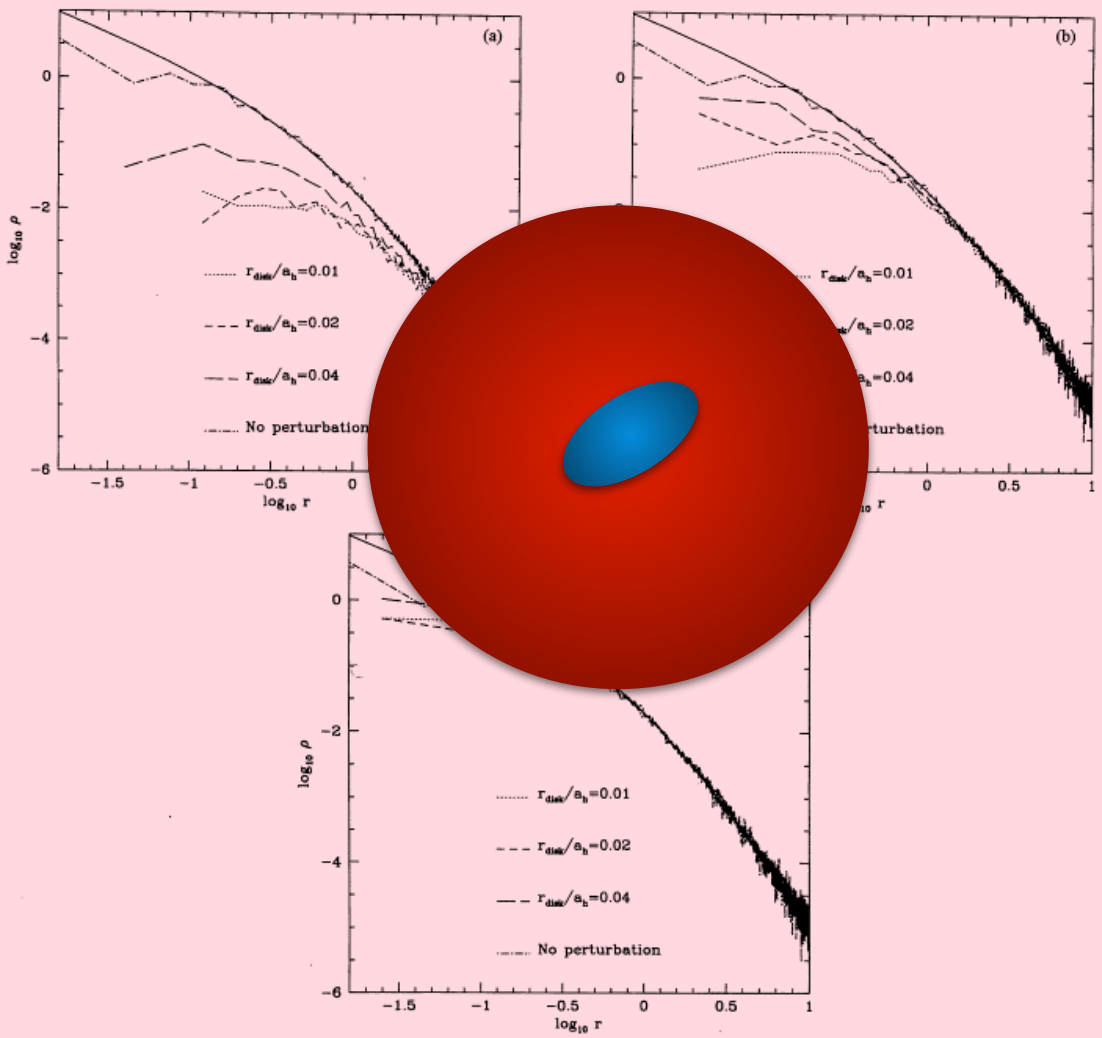


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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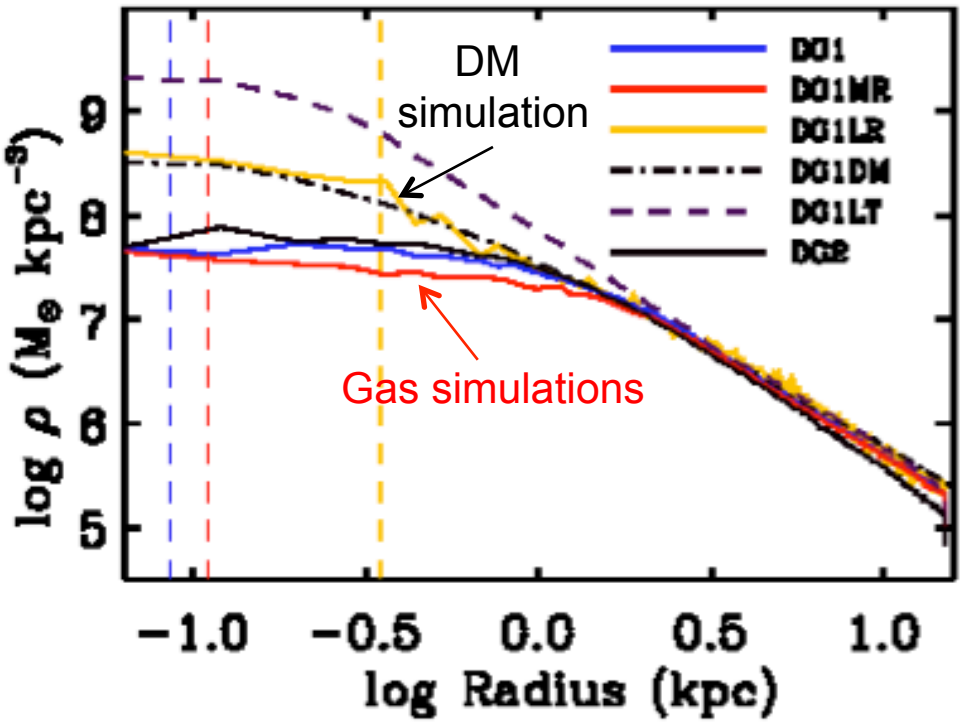
Cores in dwarf galaxy simulations

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

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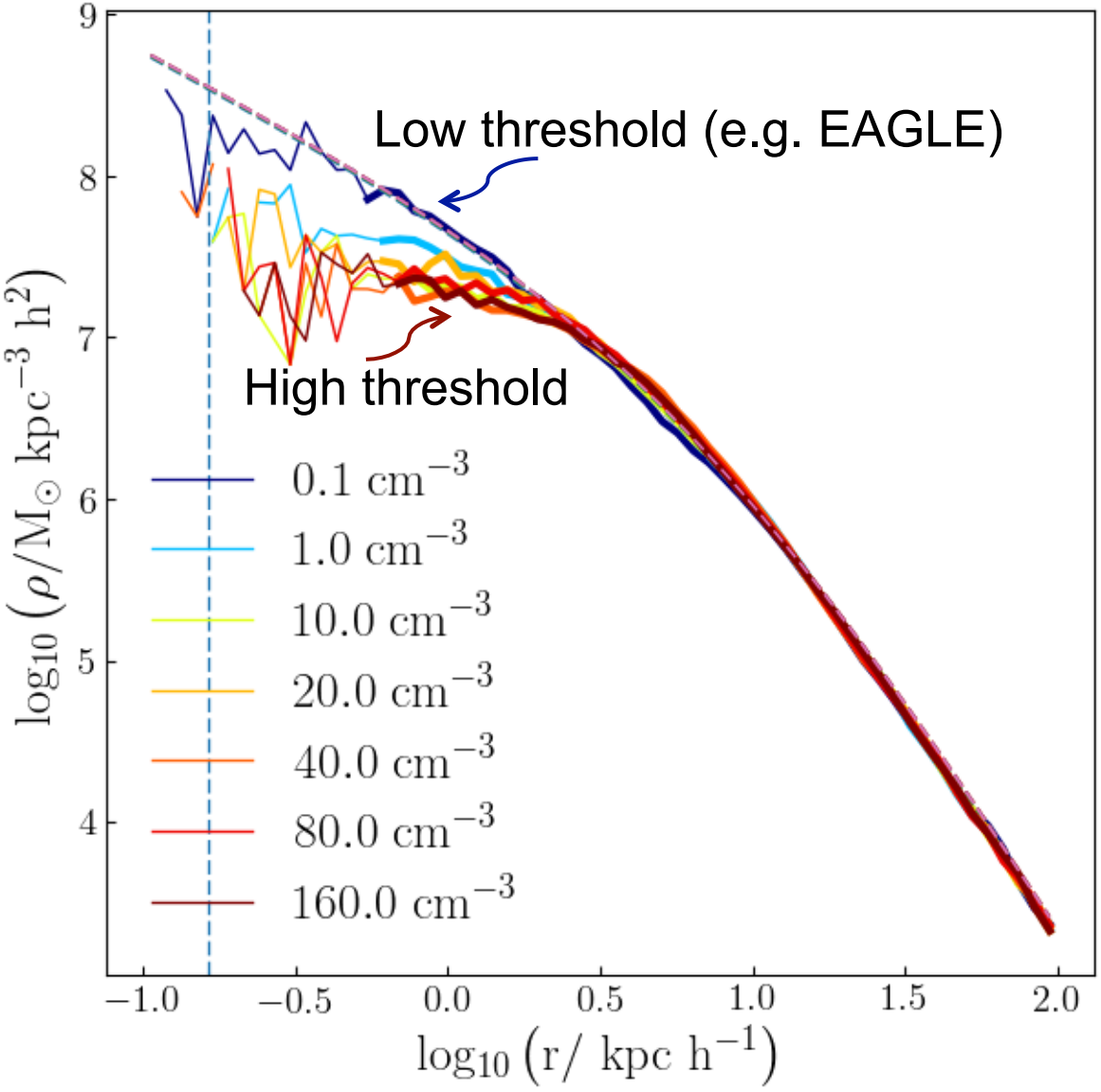
Cores or cusps in simulations?



Benitez-Llambay, CSF et al ‘17

Institute for Computational Cosmology

There is NO 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

Can CDM be ruled out?

Yes !

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

Can we distinguish CDM/WDM?

cold dark matter

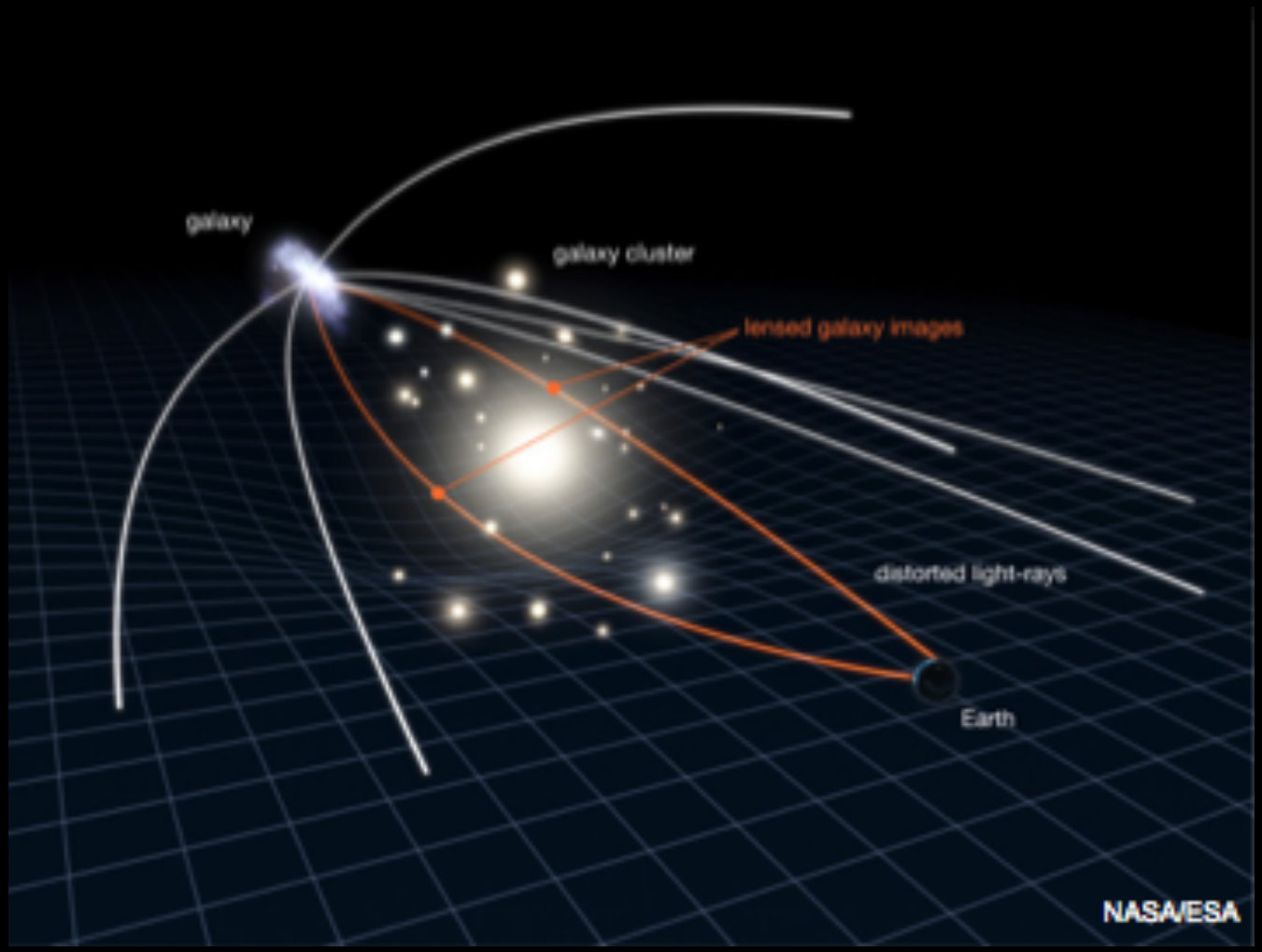
warm dark matter

Dark halos can be detected through gravitational lensing

Gravitational lensing: Einstein rings

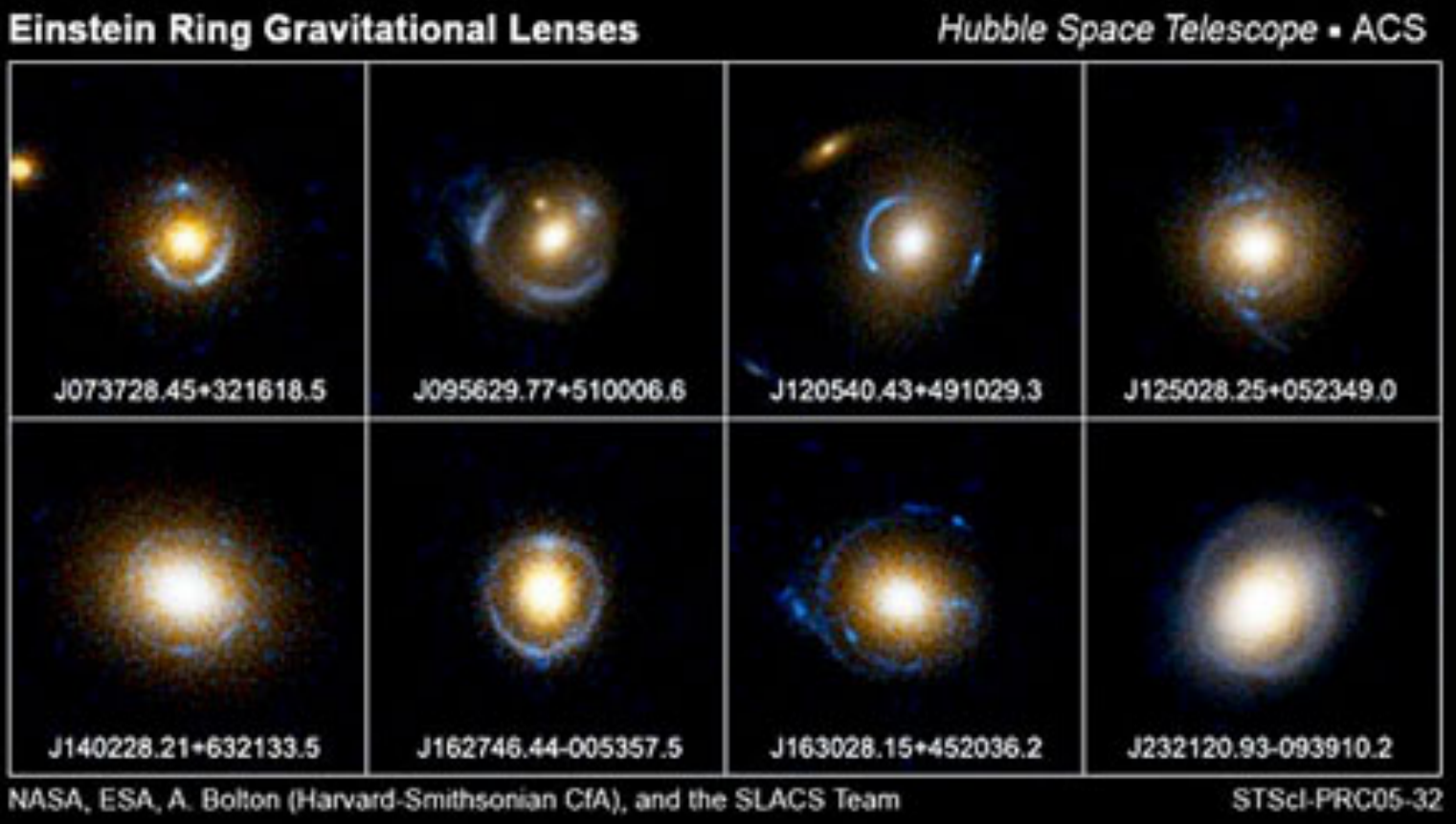
How to rule out CDM

Gravitational lensing: Einstein rings

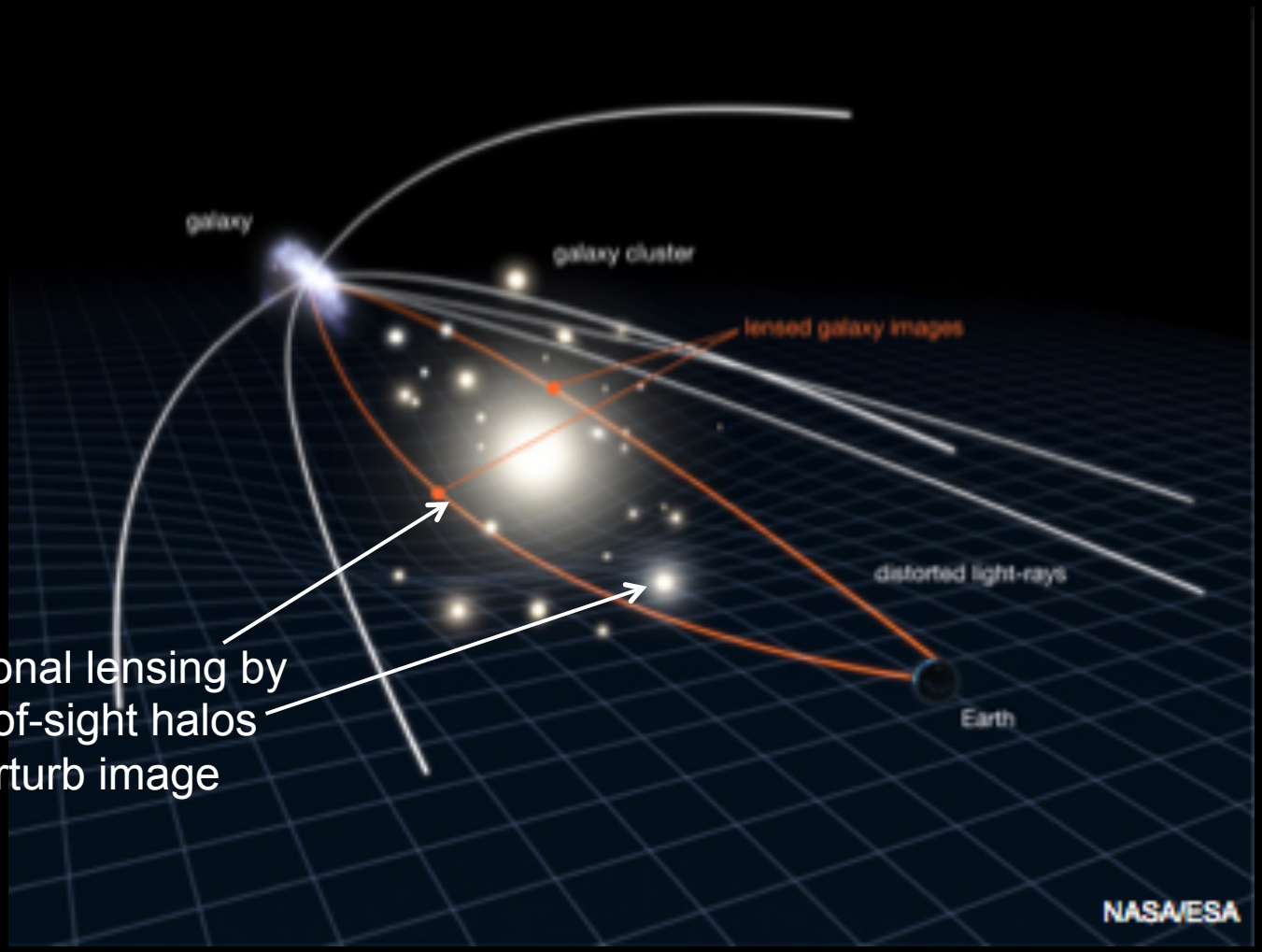


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

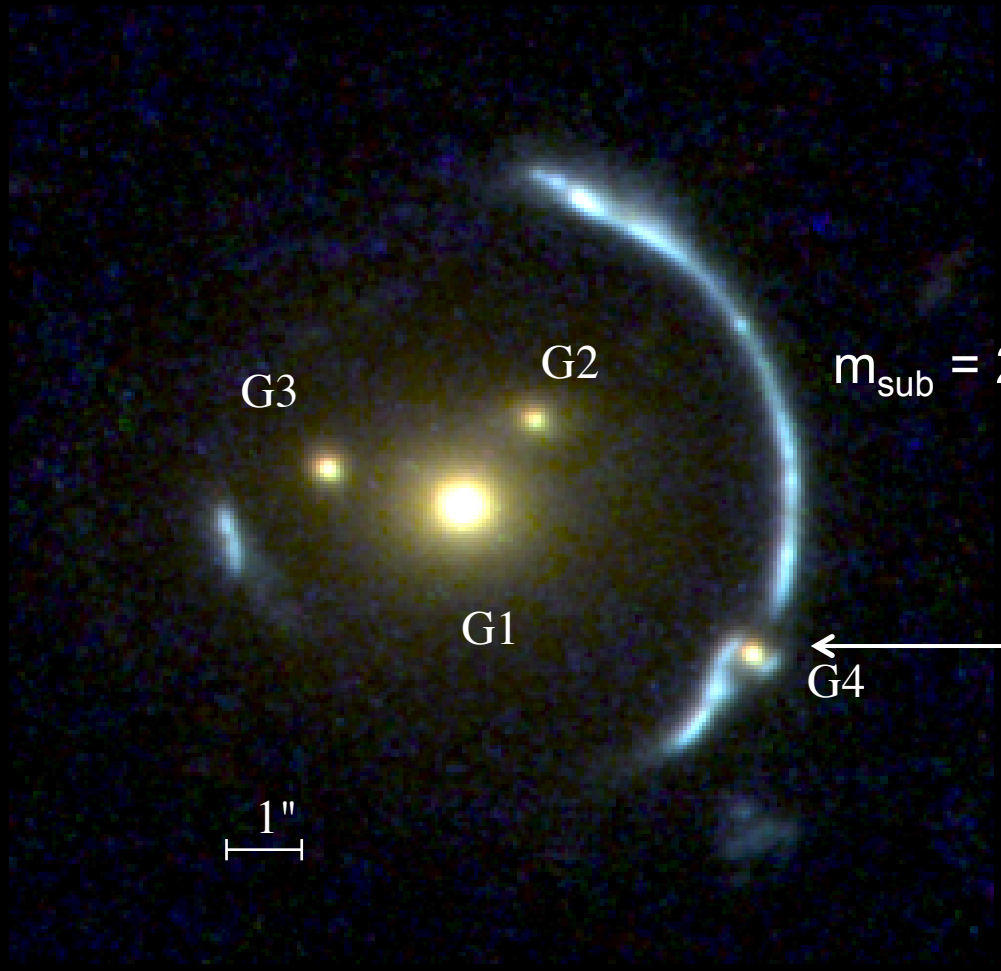


Additional lensing by line-of-sight halos perturb image

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

Gravitational lensing: Einstein rings

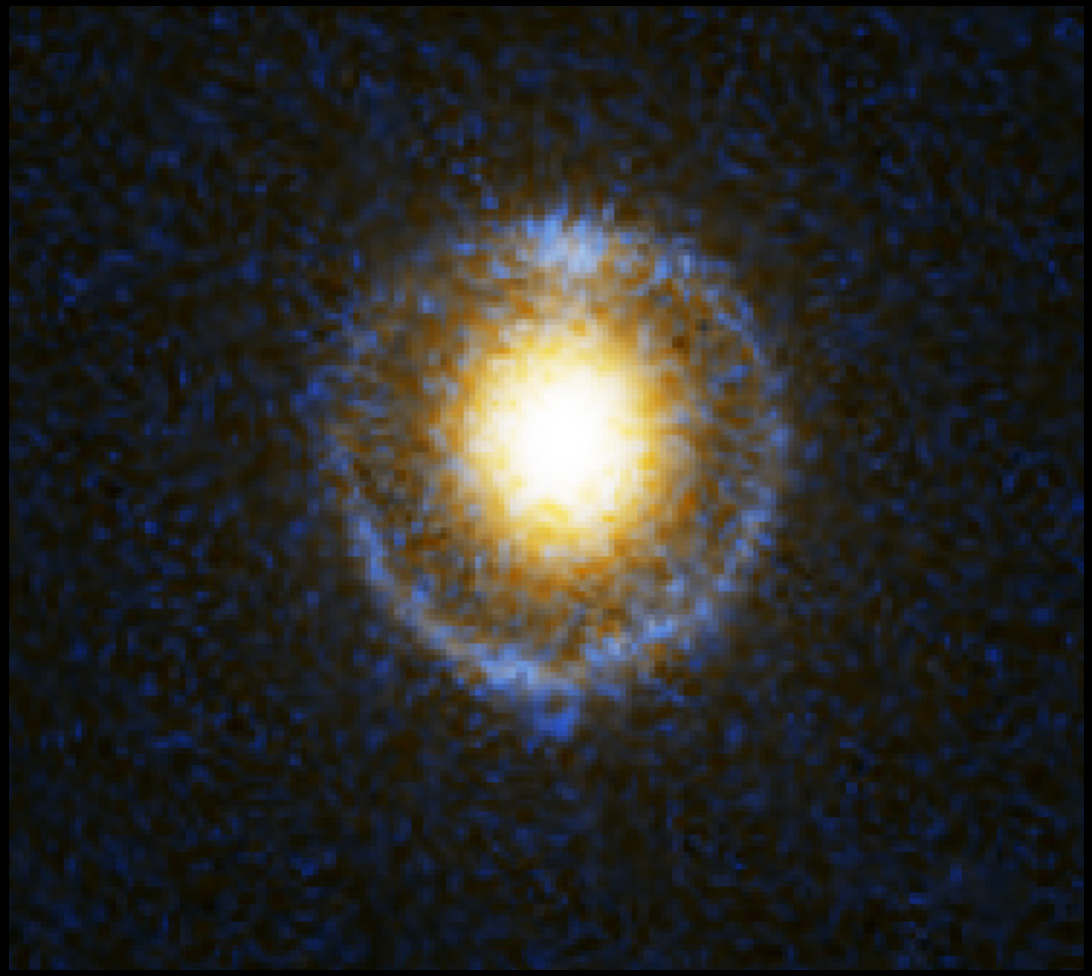
Halos projected onto an Einstein ring distort the image



Vegetti et al ‘10

Gravitational lensing: Einstein rings

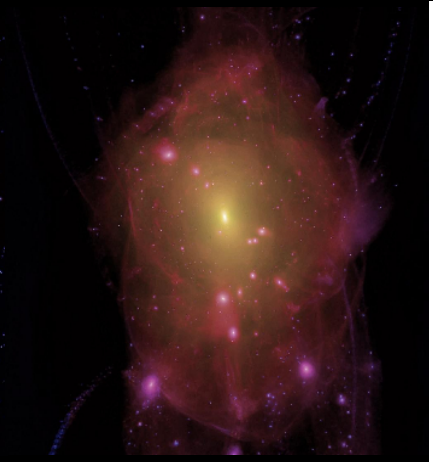
Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans ‘09

The subhalo mass function

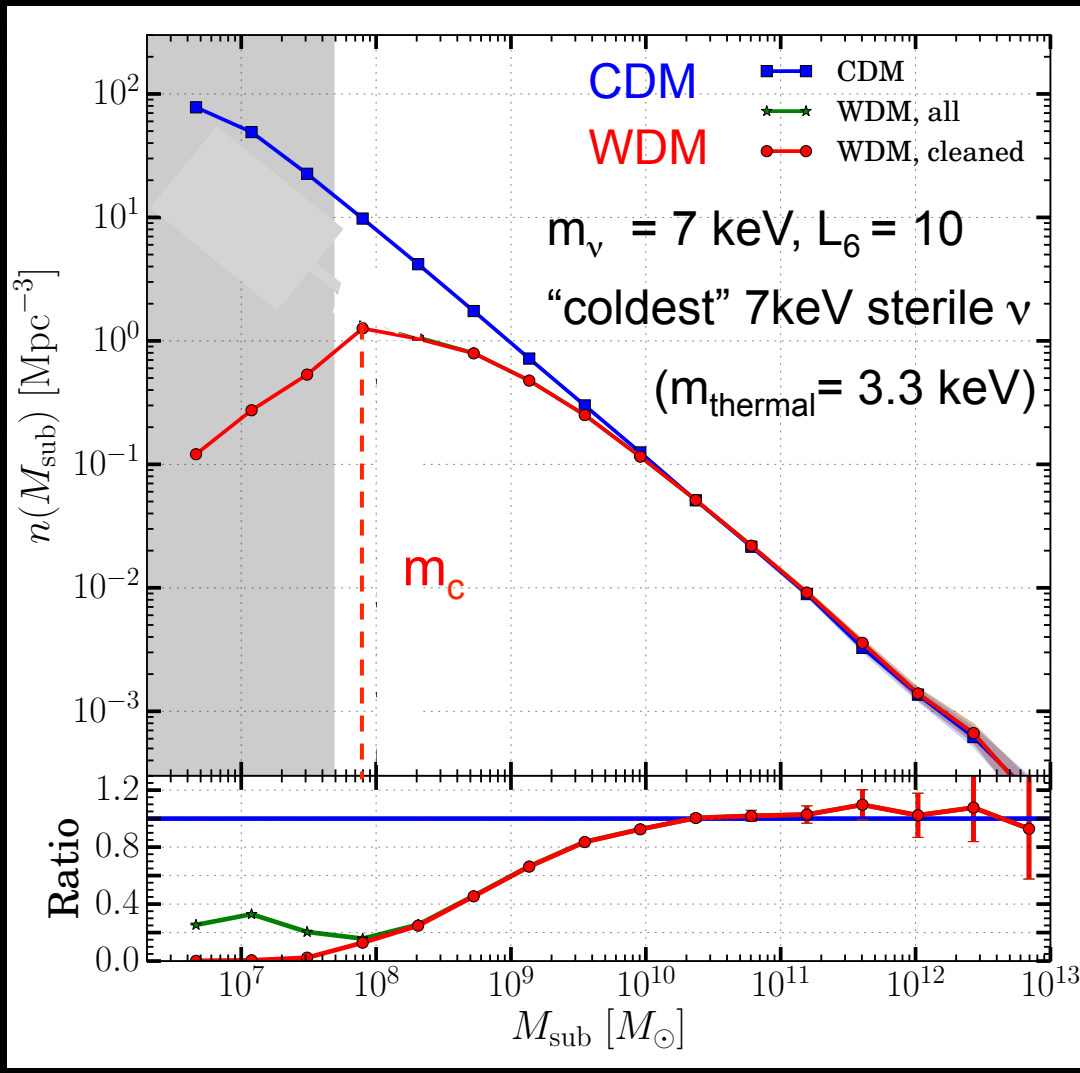
CDM



WDM

3 x fewer WDM subhalos at $3 \times 10^9\ M_o$

10 x fewer at $10^8\ M_o$



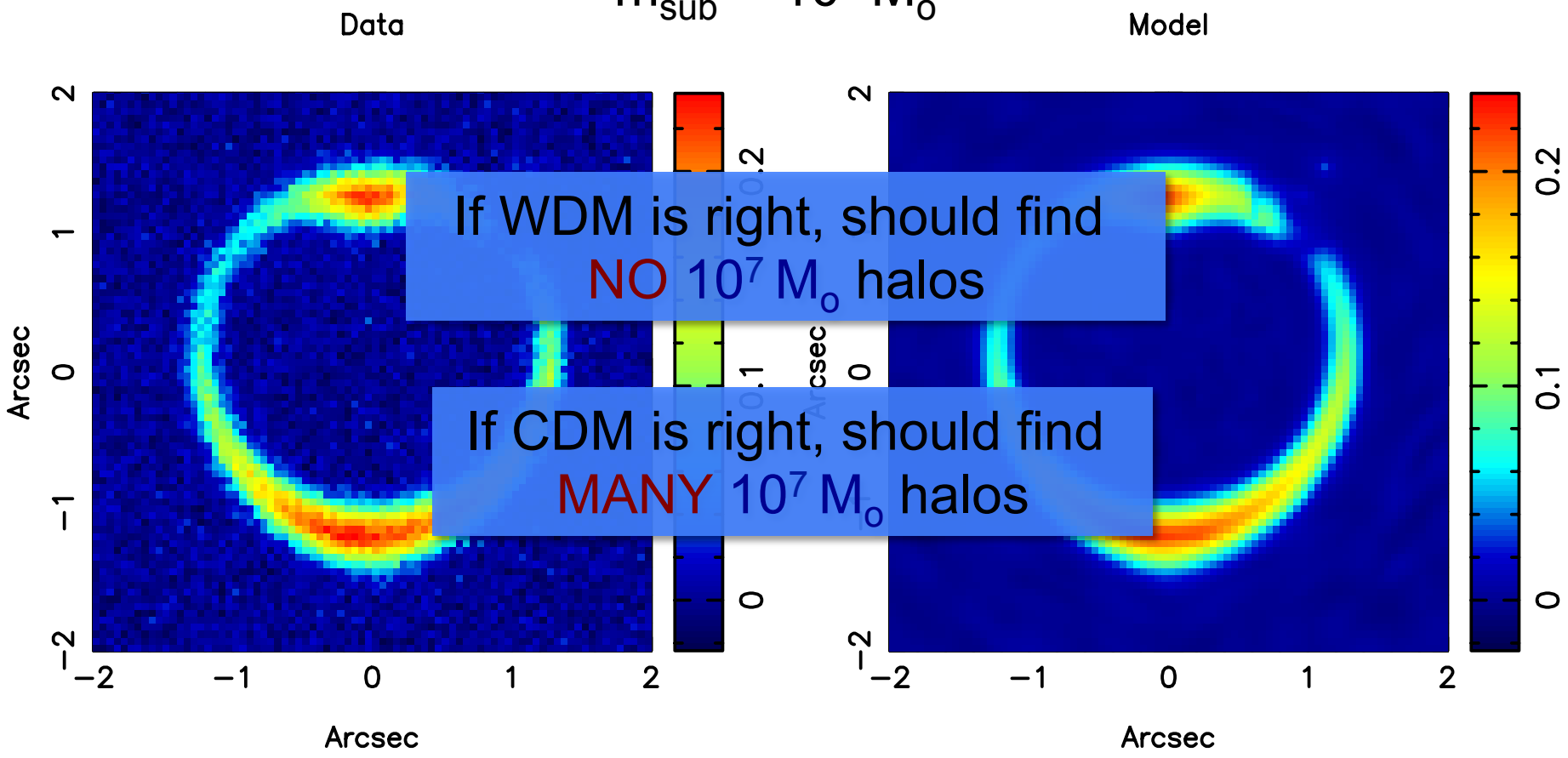
Bose, CSF et al '16

University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8\ M_o$



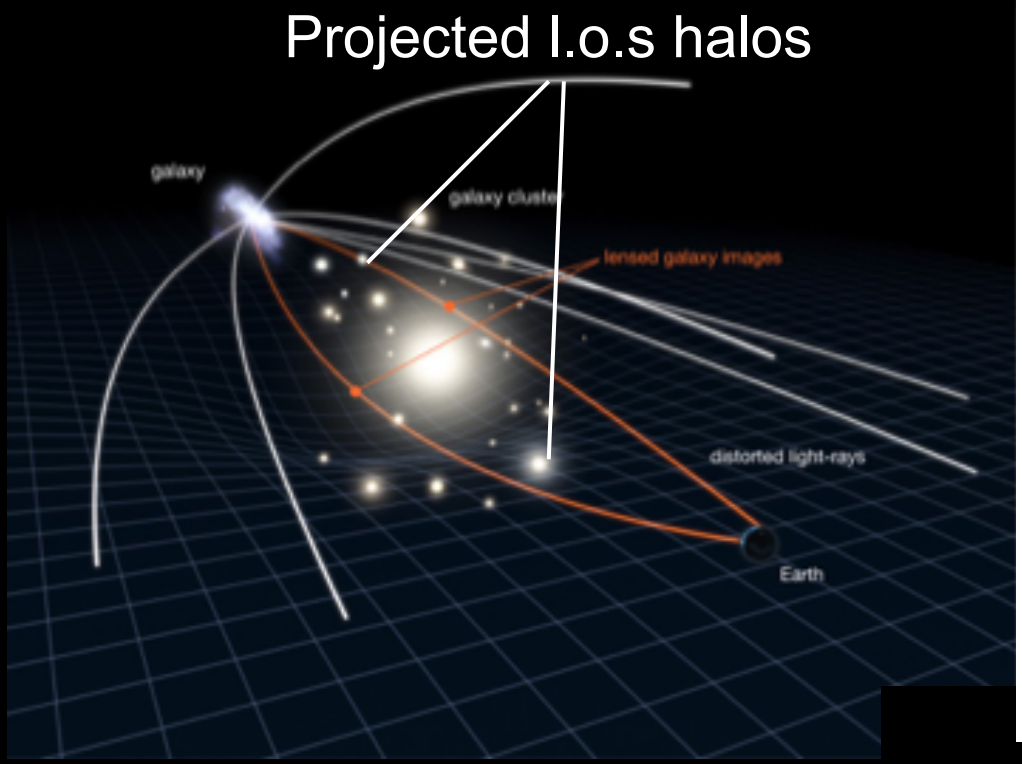
If WDM is right, should find NO $10^7\ M_o$ halos

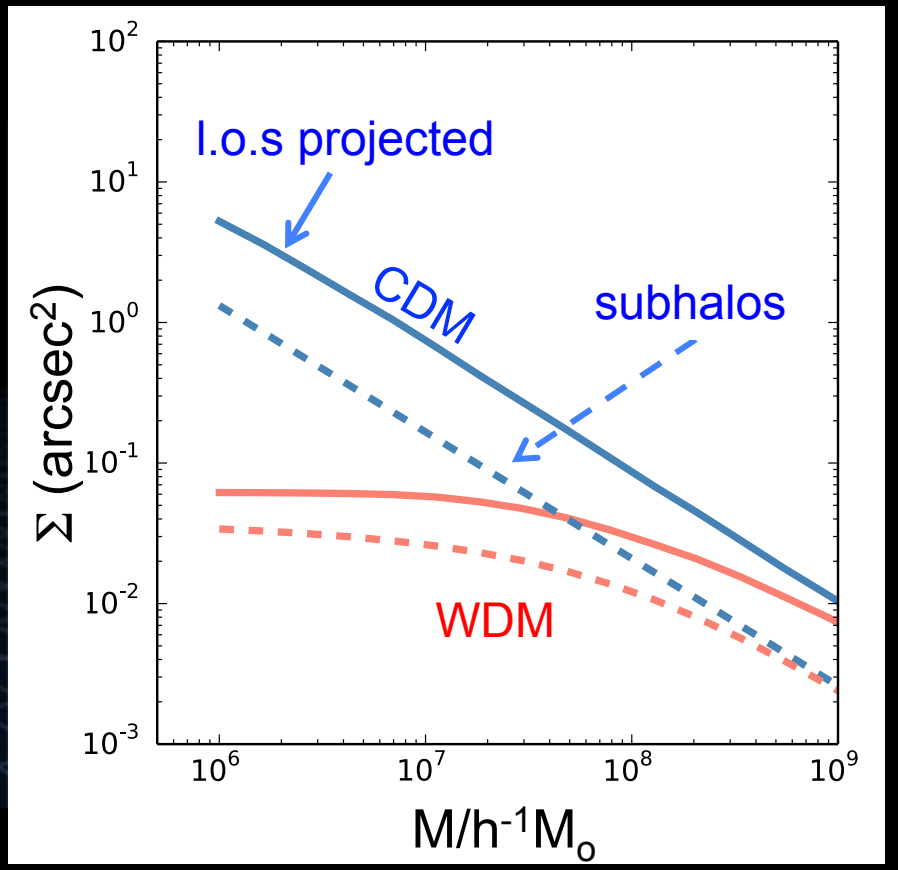
If CDM is right, should find MANY $10^7\ M_o$ halos

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?



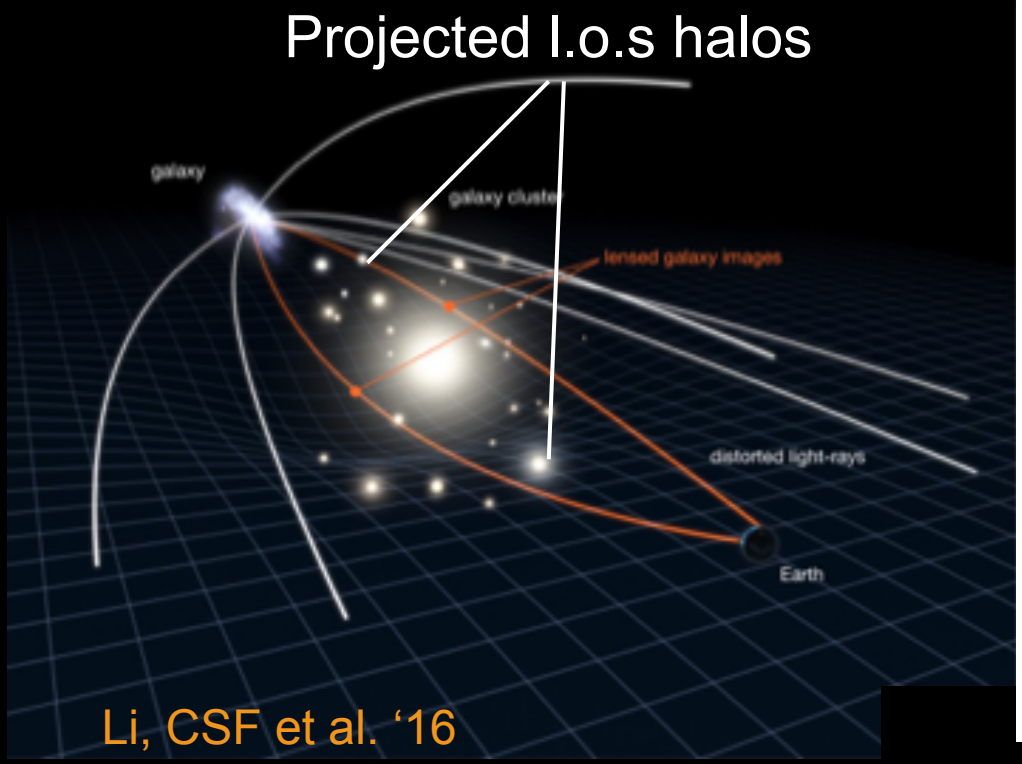


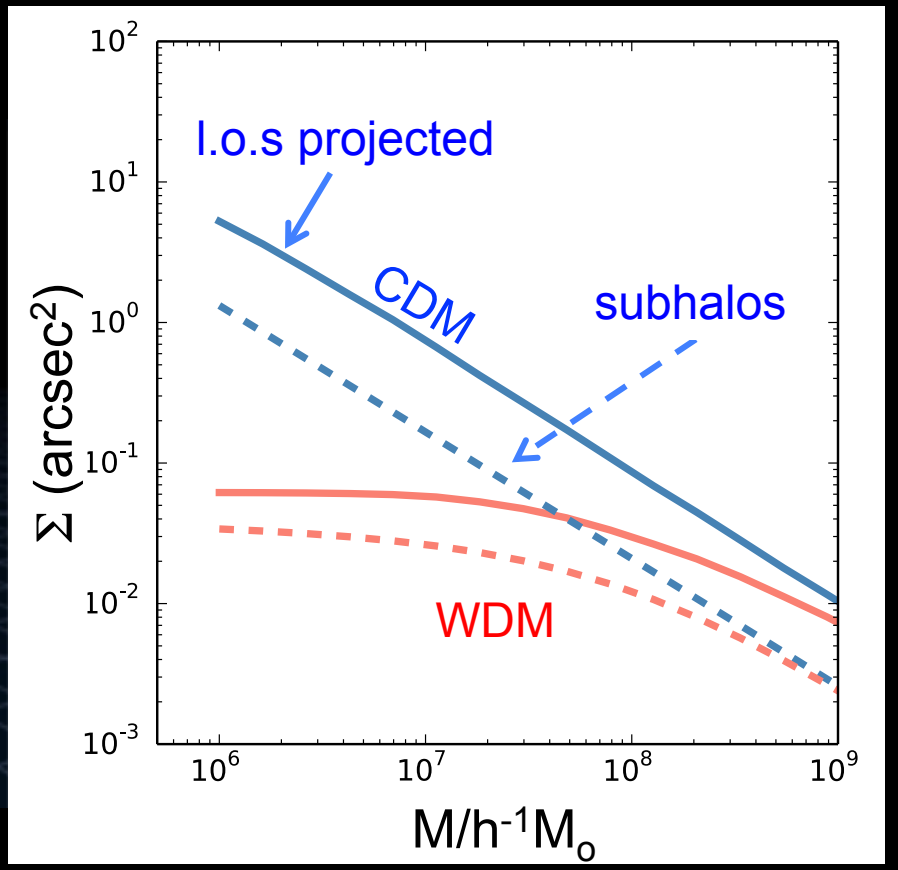
The number of line-of-sight haloes is larger than that of subhaloes

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

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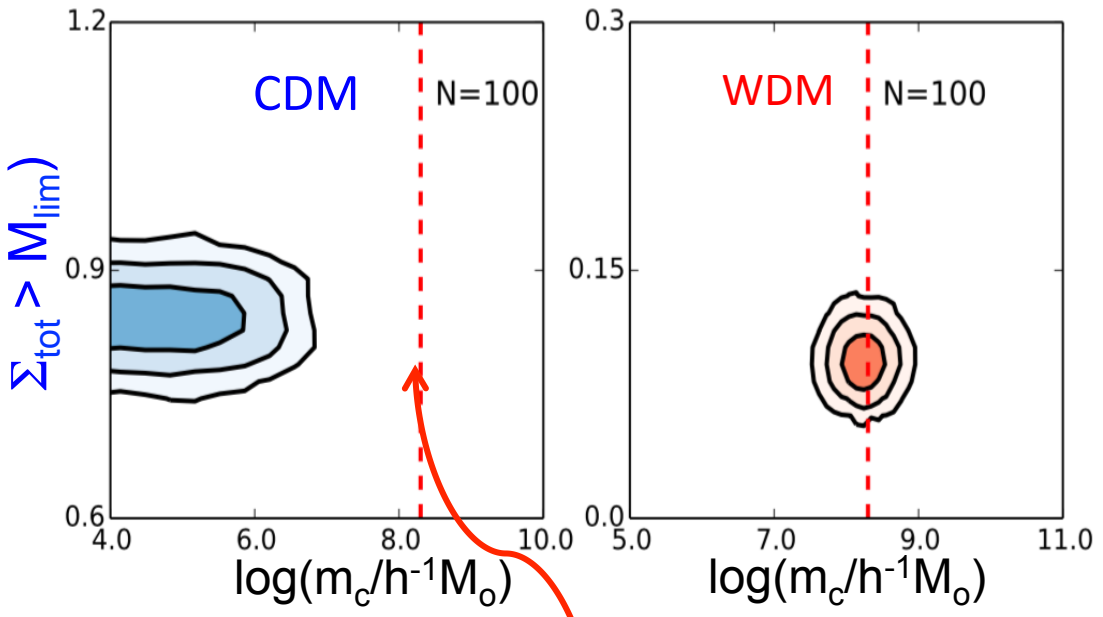
Detecting substructures with strong lensing

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

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Conclusions

The CDM small-scale "CRISIS" (a time of intense difficulty or danger)

What crisis?

1. The interpretation of astronomical observations is hard → be skeptical!

2. Consider new particle dark matter candidates that are motivated by physics, not by trying to solve non-existent astronomical problems

* Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM