Clues to the identity of the dark matter in the Milky Way

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cold dark matter

warm dark matter

Both CDM & WDM compatible with CMB & galaxy clustering

There are claims that both types of DM have been discovered

- CDM: γ-ray excess from Galactic Center
- WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12 cold dark matter | warm dark matter

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Boyarski & Ruchayskiy ‘12

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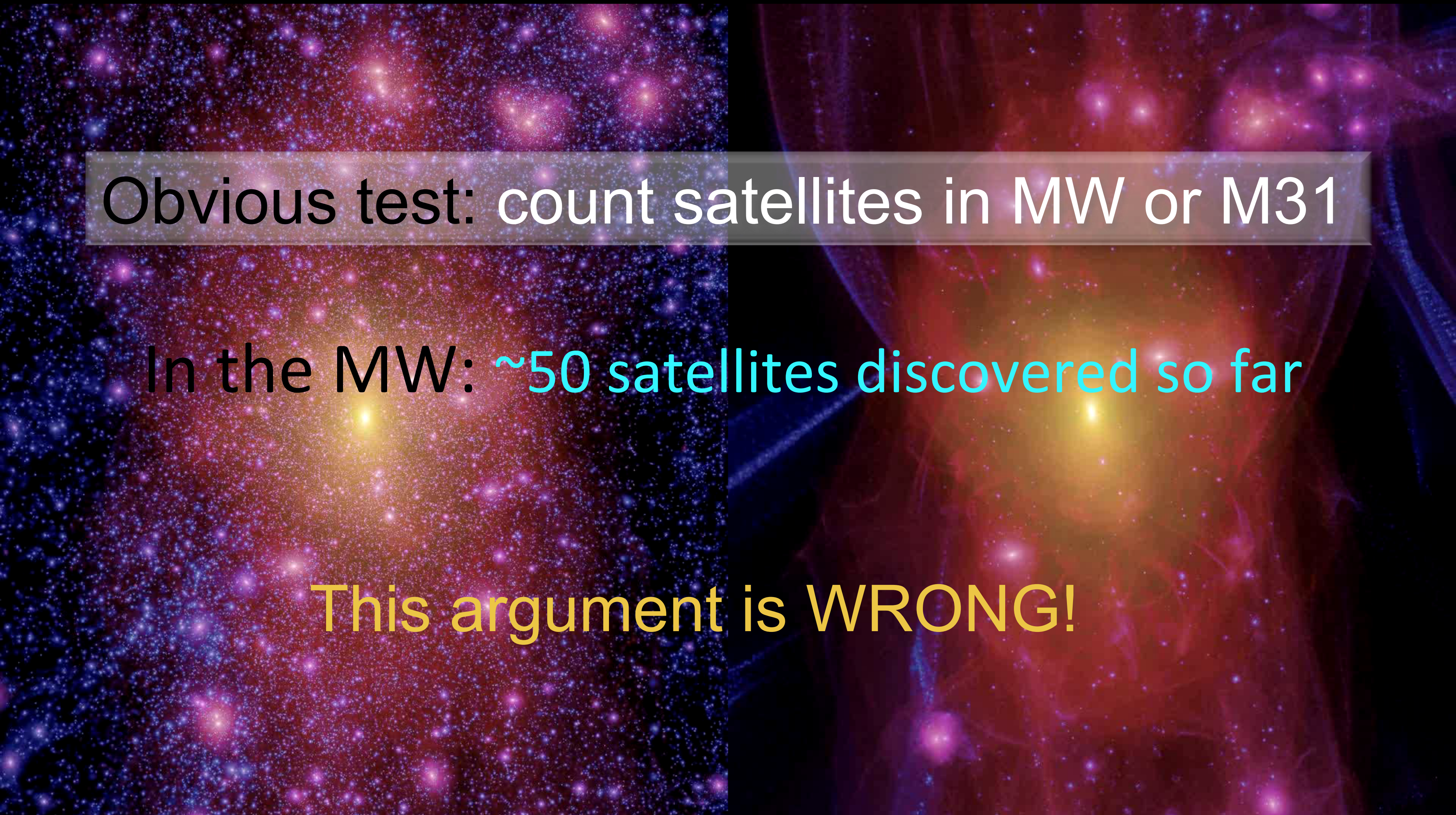


Obvious test: count satellites in MW or M31

In the MW: ~50 satellites discovered so far

This argument is WRONG!

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

Most subhalos never make a galaxy!

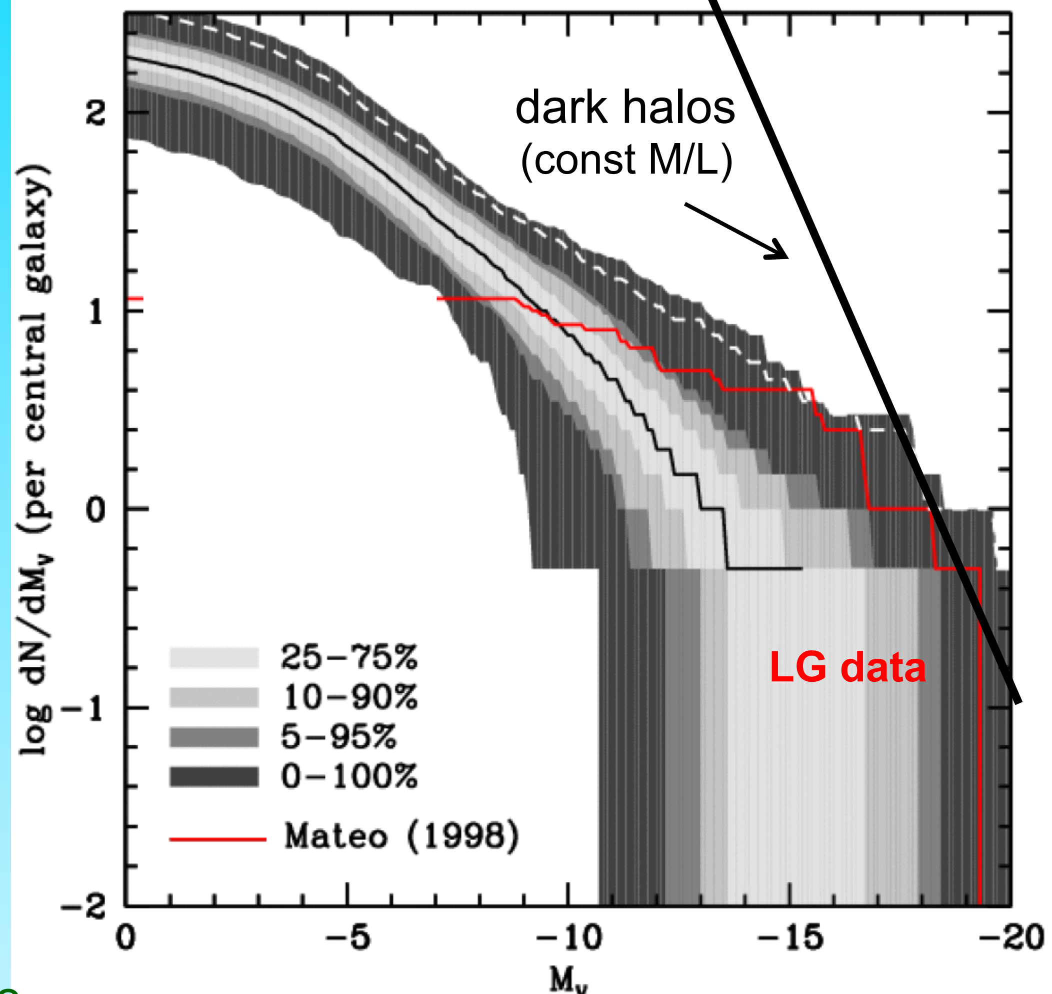
Because:

- Reionization heats gas above T_{vir}, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

University of Durham

- 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 '00)

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Luminosity Function of Local Group Satellites

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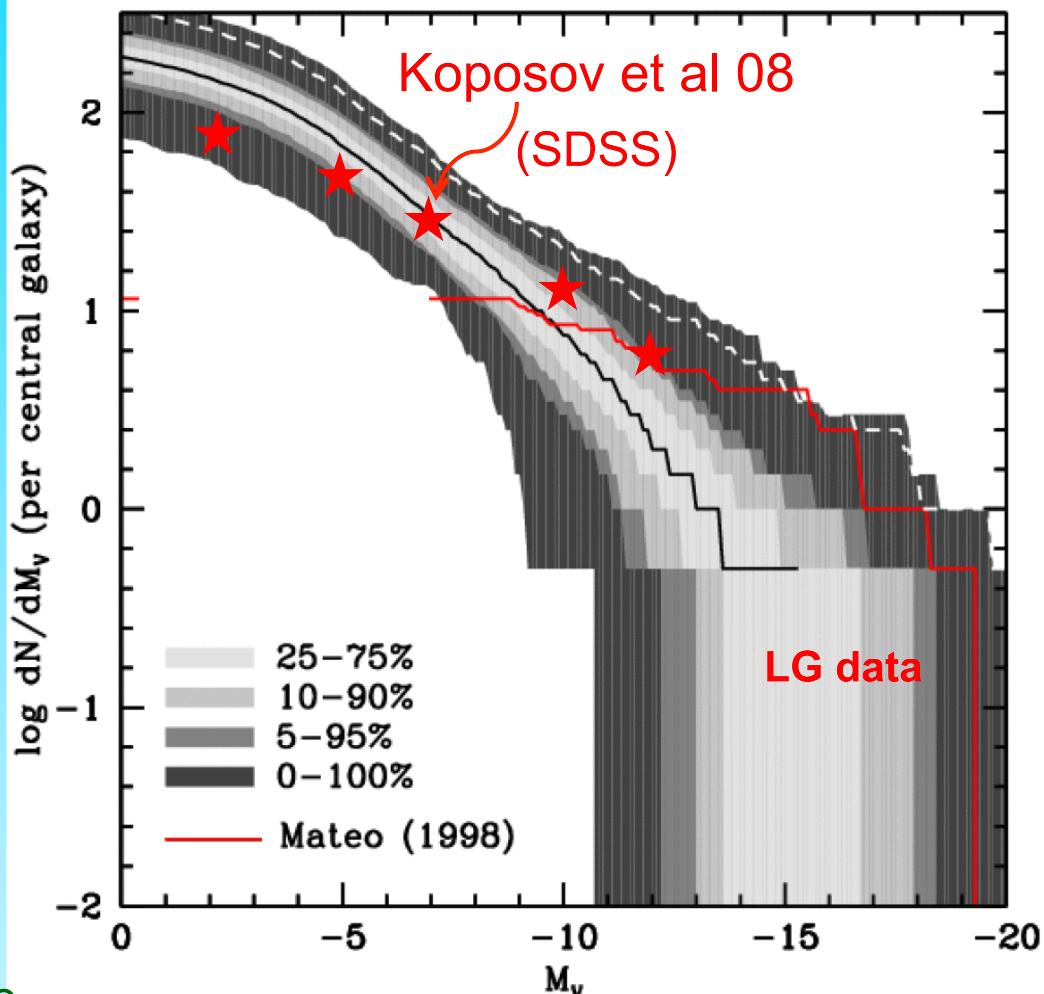

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VIRGO

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

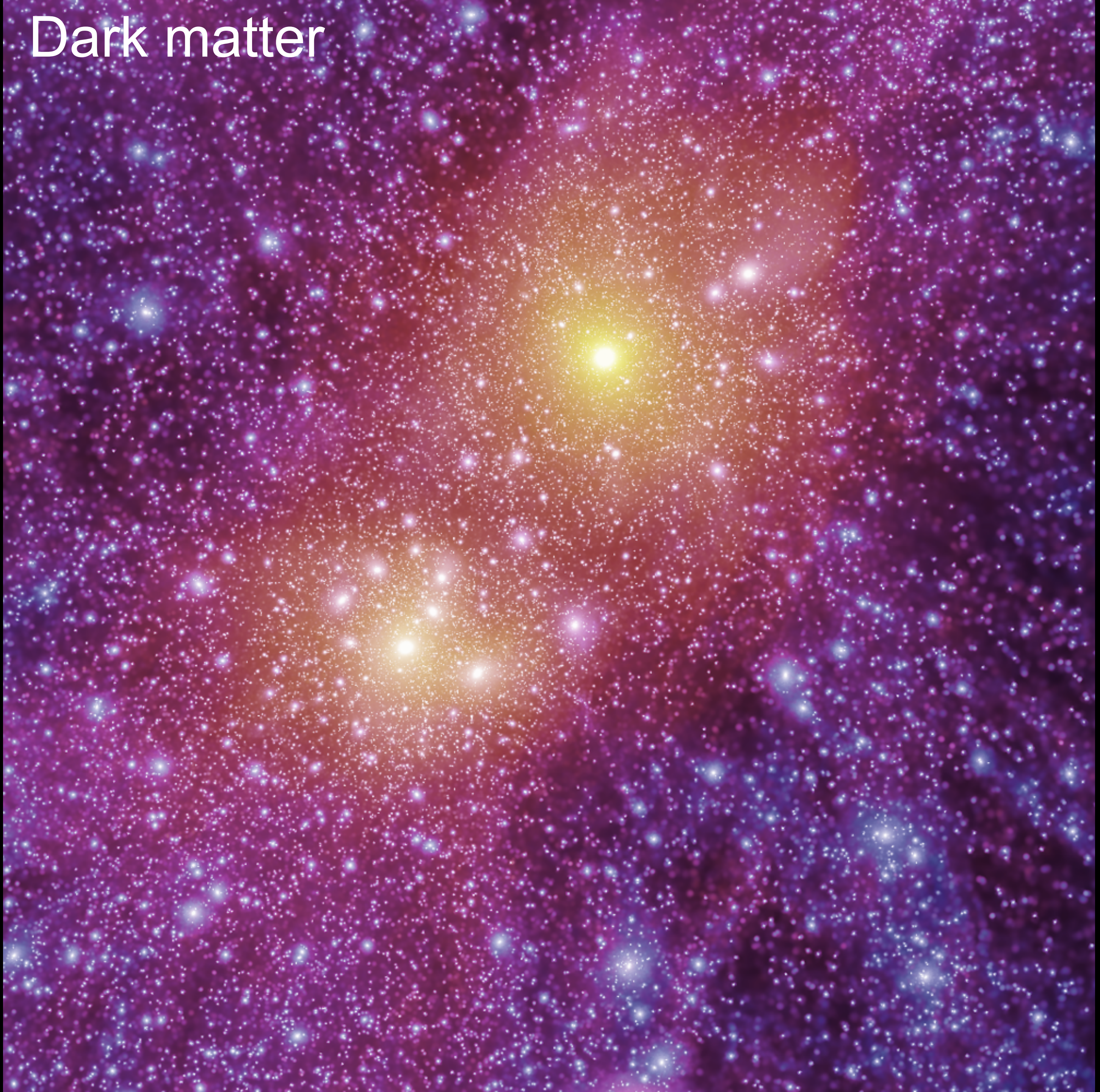
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

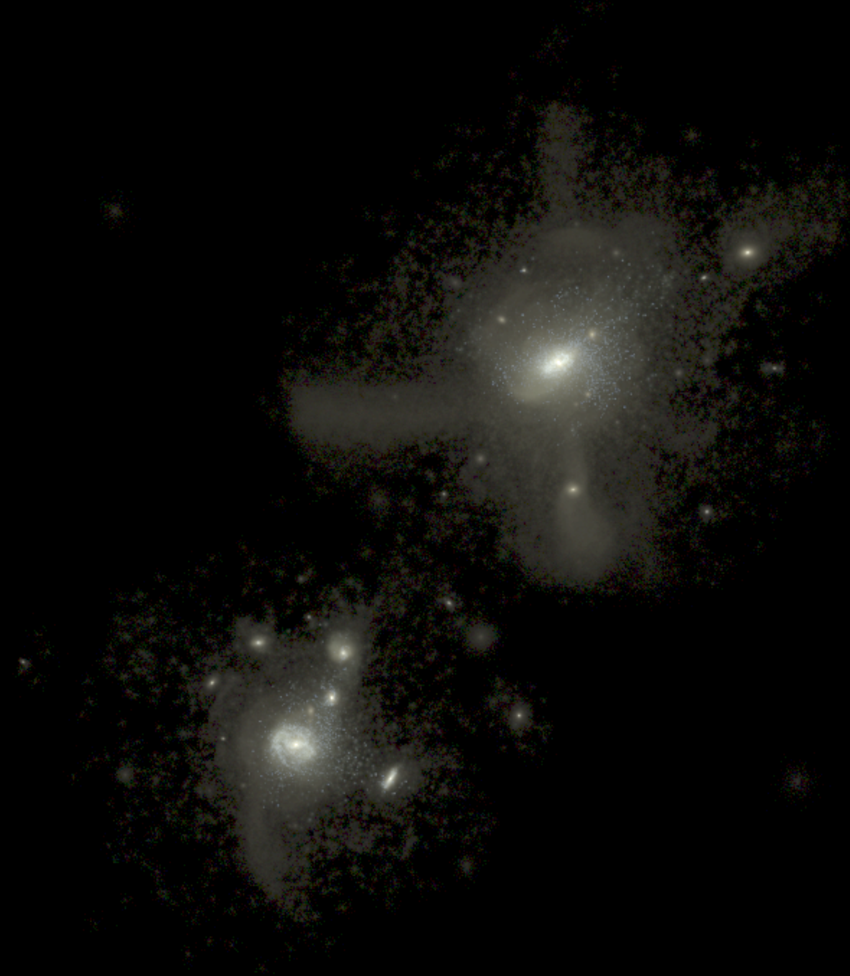


Sawala et al ‘15

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

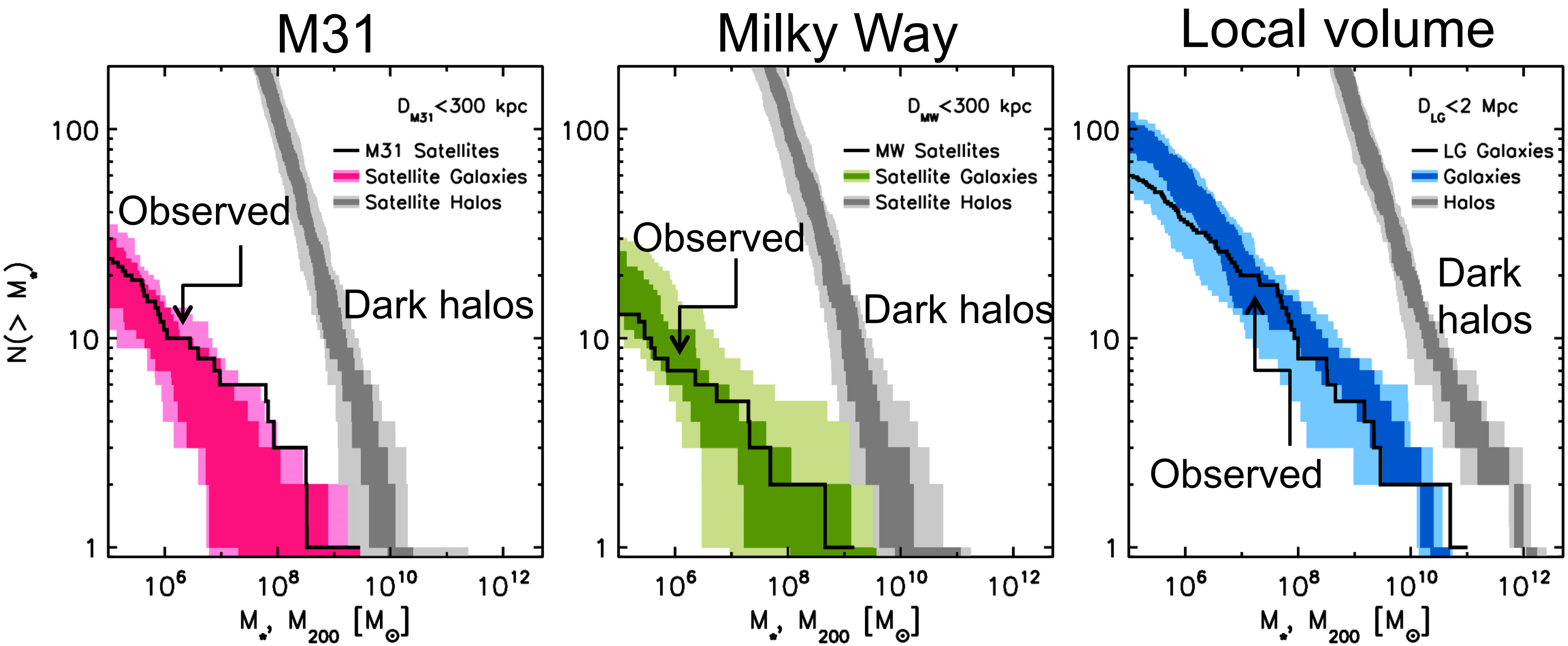


Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

EAGLE Local Group simulation

University of Durham



Sawala et al '15

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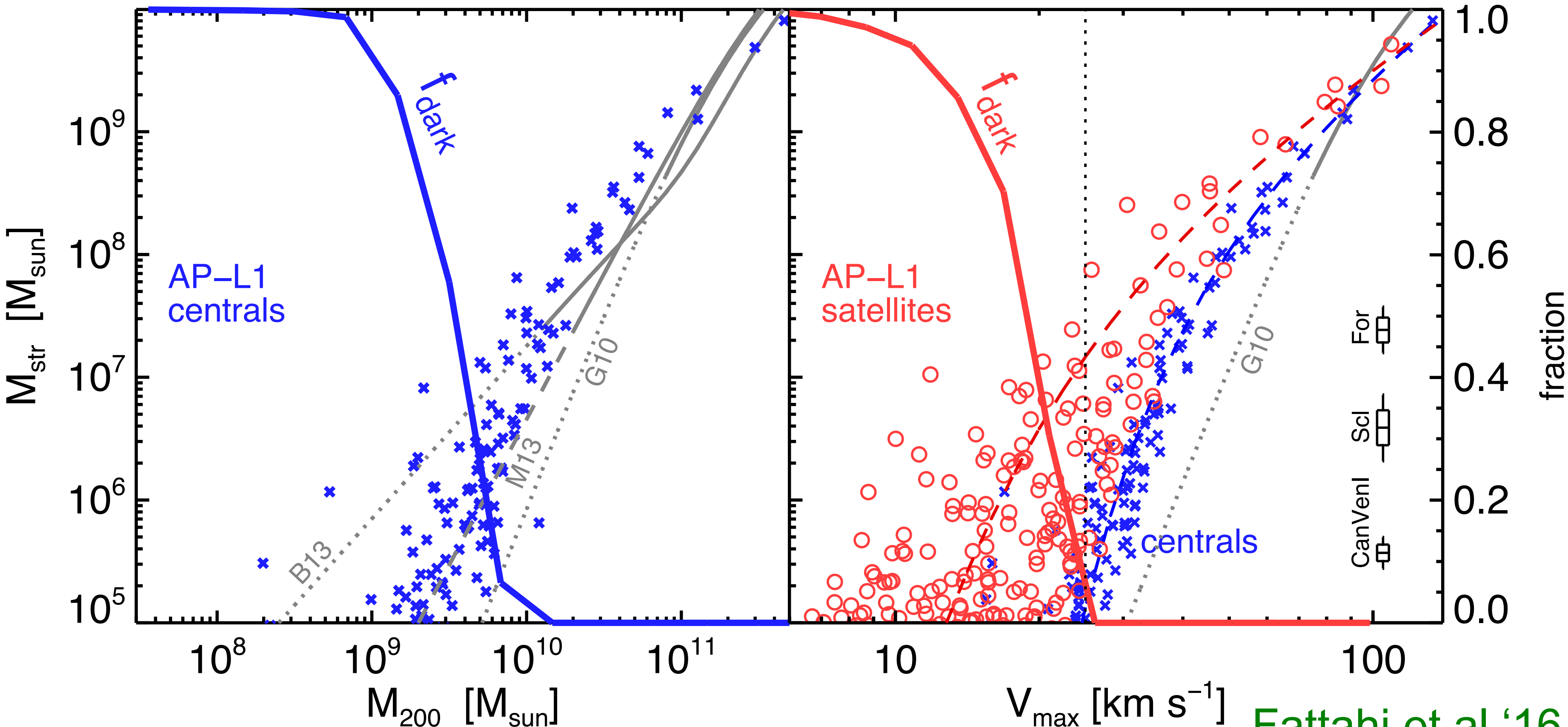
Fraction of dark subhalos

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



Fattahi et al '16

All halos of mass < $10^9 M_o$ or V_{max} < 7 km/s are dark

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

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

"Too-big-to-fail" problem in CDM:

N-body CDM sims produce too many massive subhalos (e.g. >10 with V_{max}>30 km/s)

BUT: Milky Way has only 3 sats with V_{max}>30 km/s

Why did the big subhalos not make a galaxy?

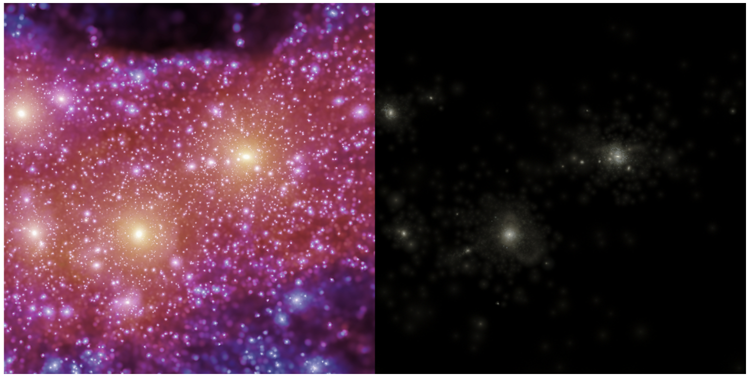
To-big-to-fail in CDM: baryon effects

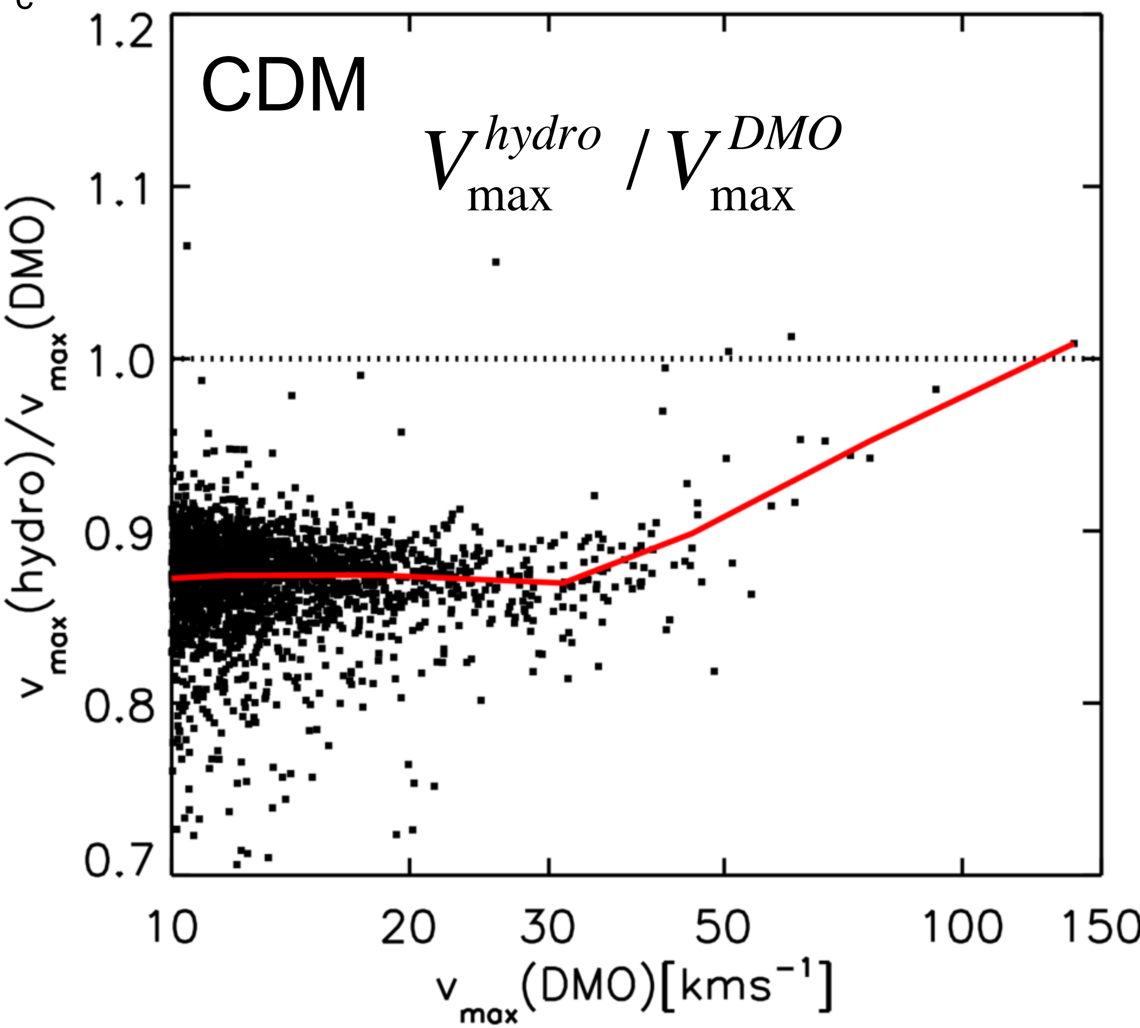
University of Durham

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala et al. '13, '15

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Too-big-to-fail: the baryon bailout

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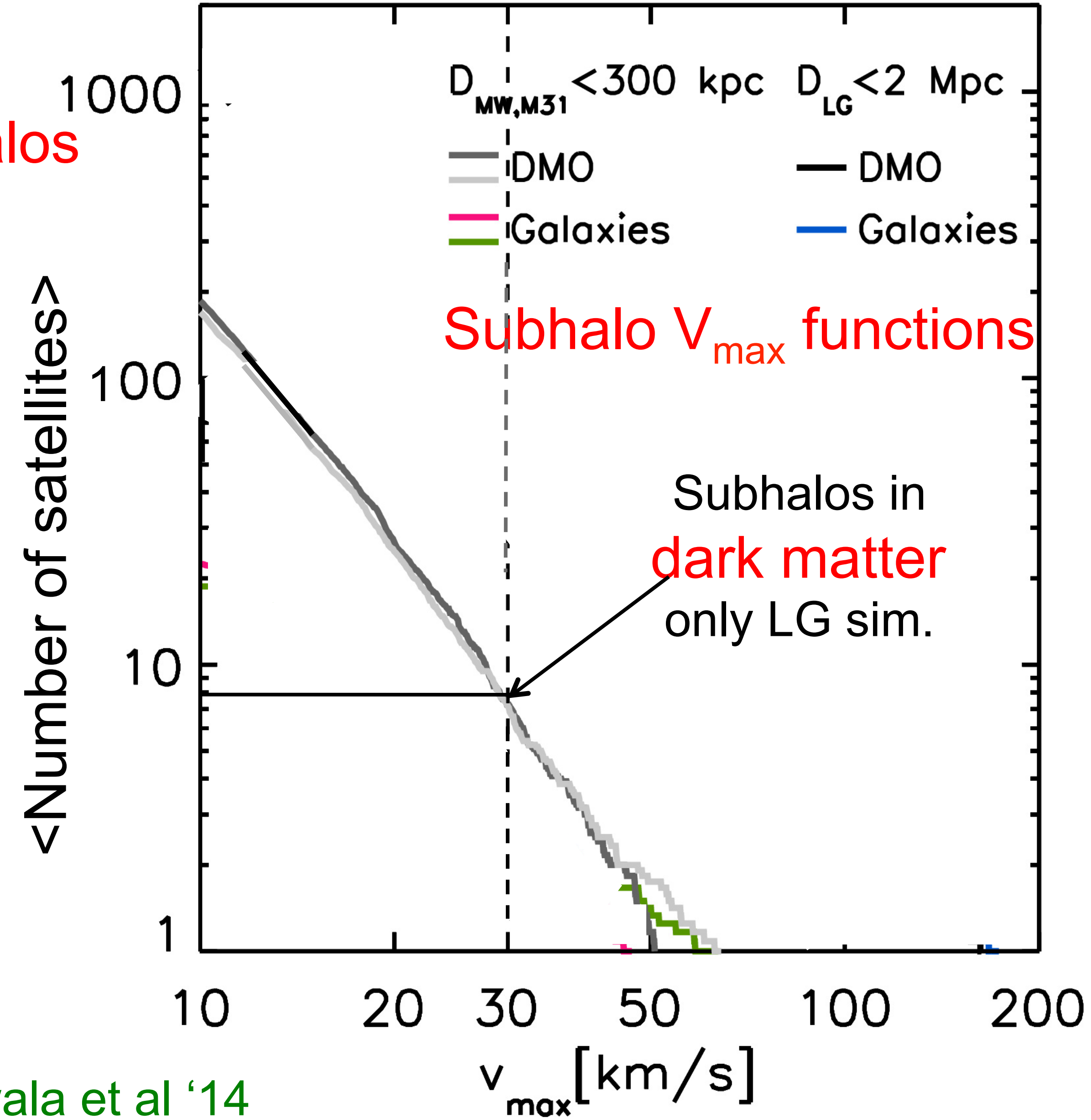
DM only sims → ~10 halos with V_{max}> 30 km/s

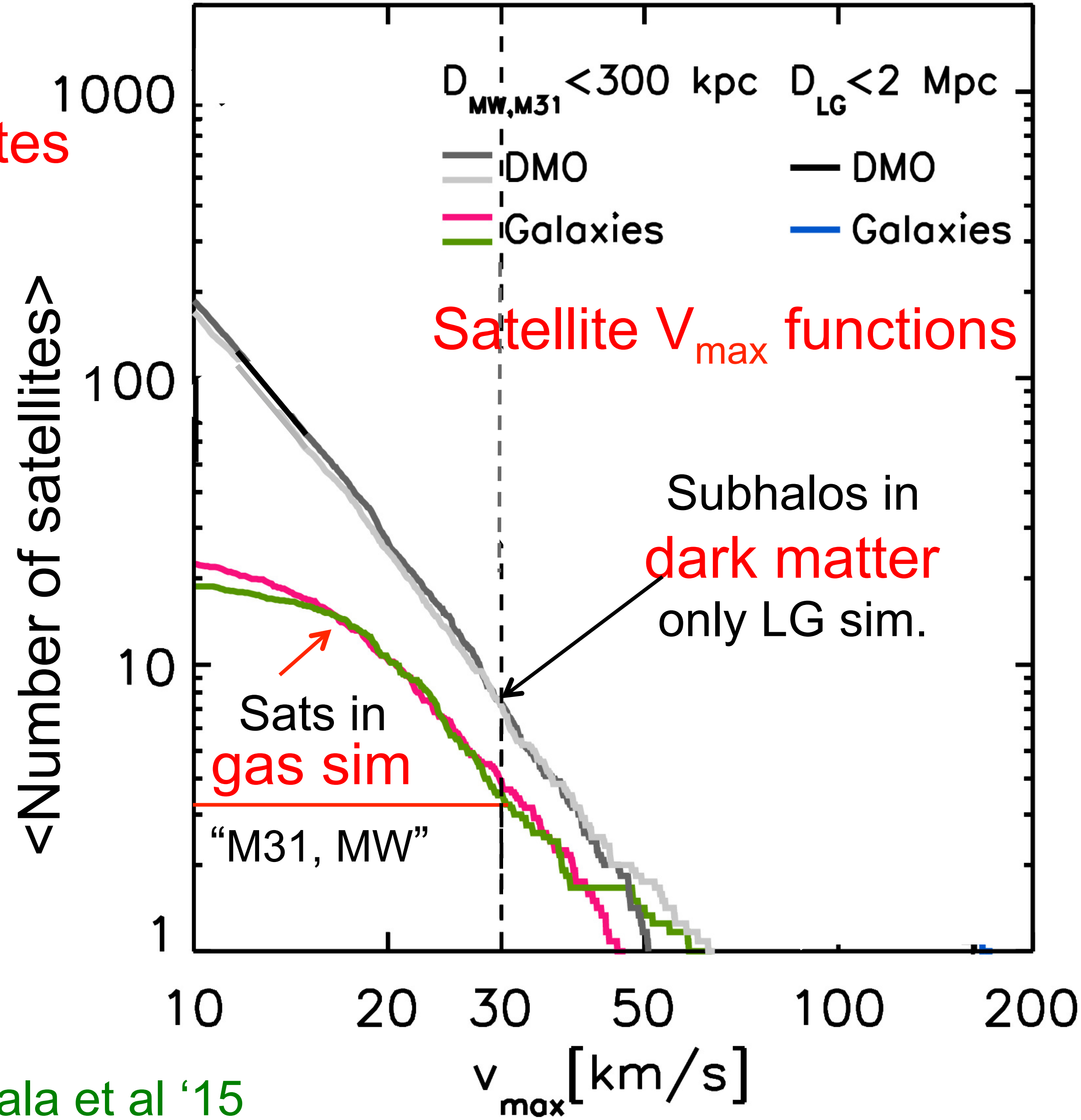


Sawala et al '14

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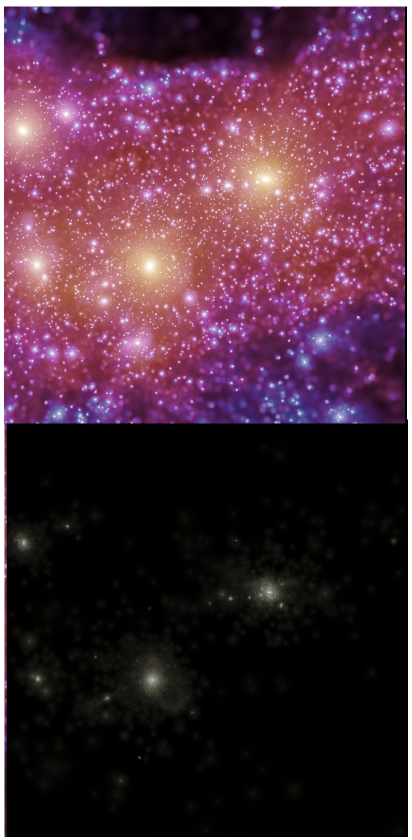
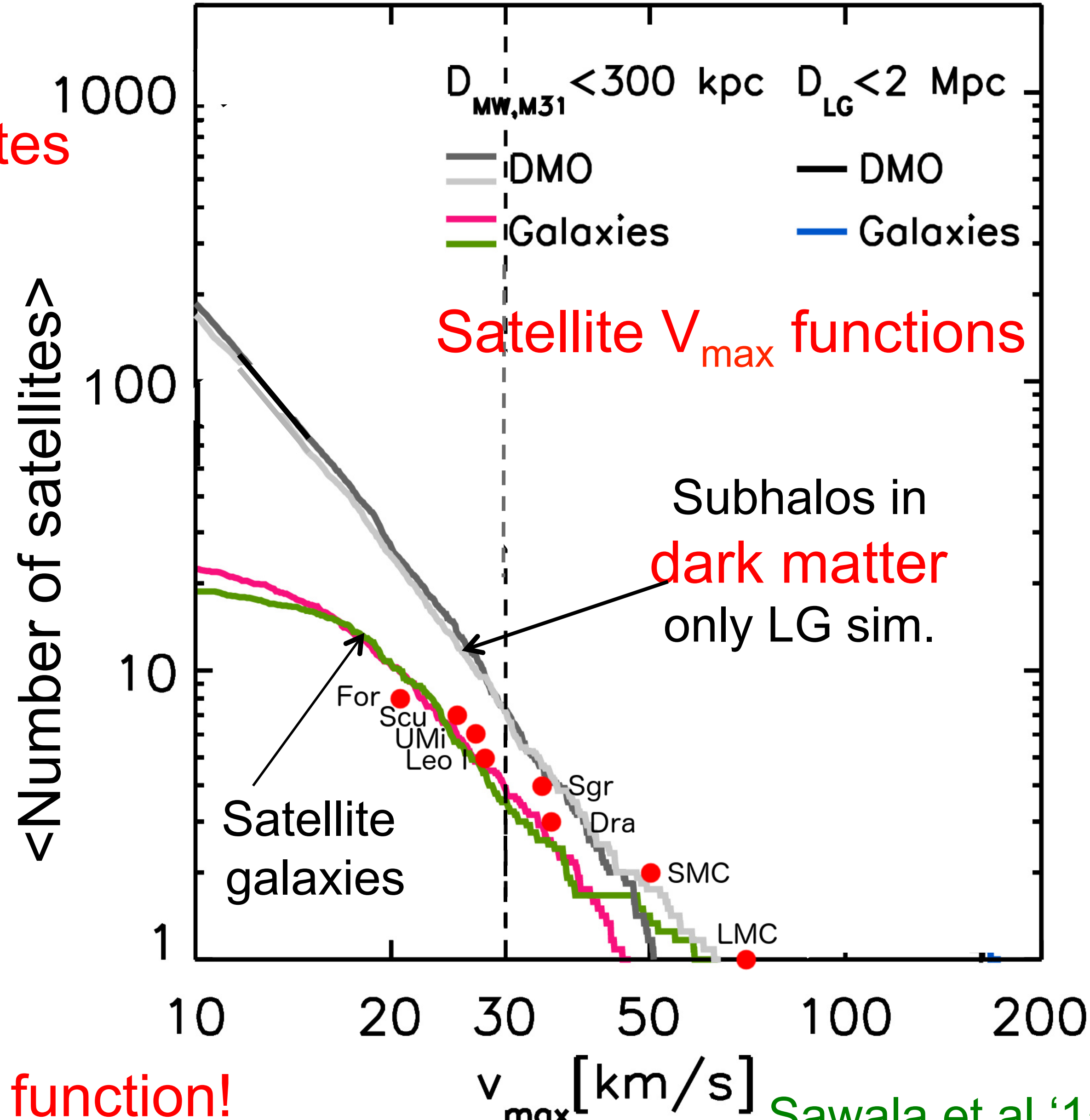
Hydro sims → ~3 satellites
with V_{max}> 30 km/s





… and with correct V_{max} function!

Sawala et al '15

No oo-big-to-fail problem in CDM

→

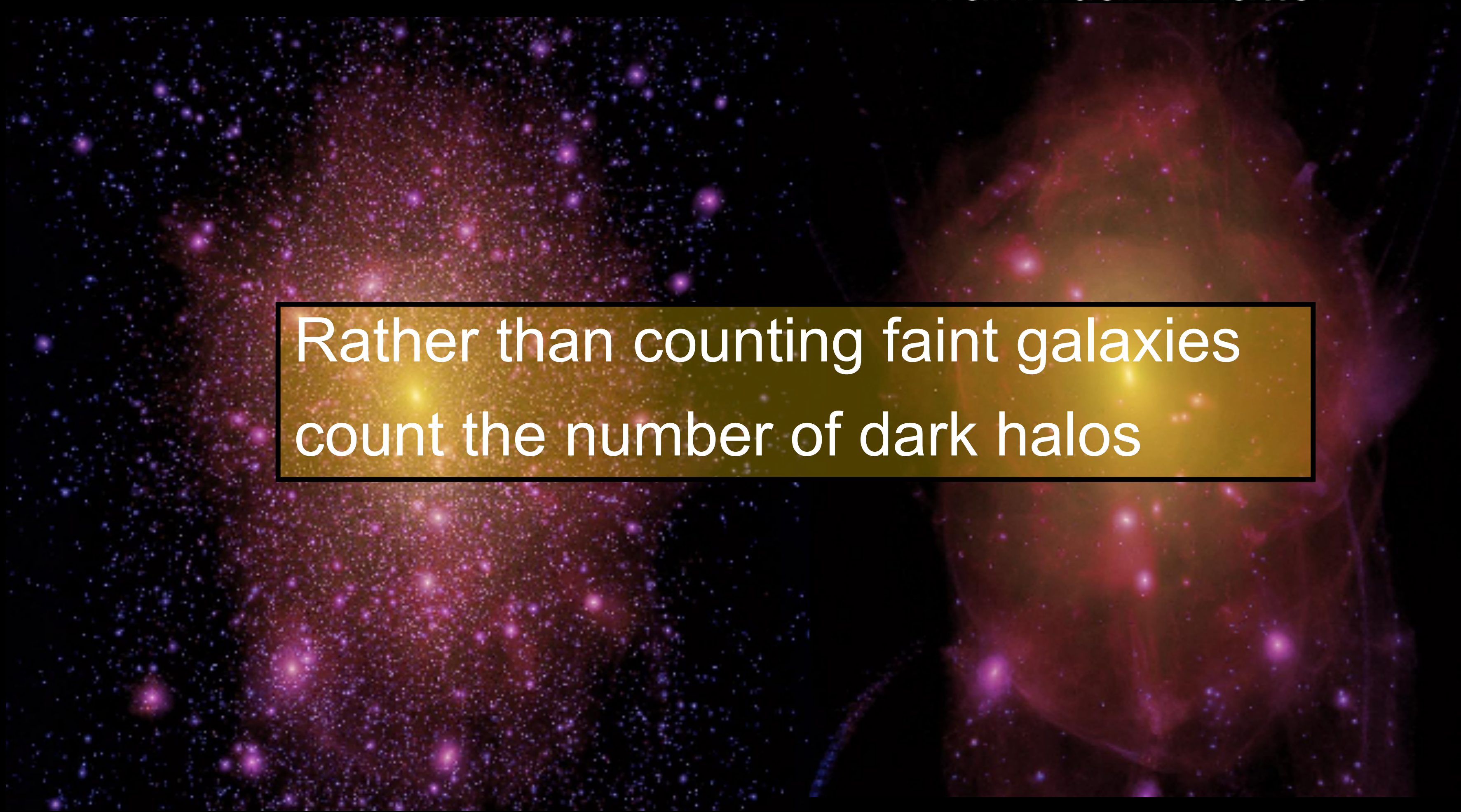
When "baryon effects" are included

So, we can’t distinguish CDM from WDM by counting satellite galaxies

There is no need for despair: there is a way to distinguish them

Can we distinguish CDM/WDM?

cold dark matter | warm dark matter



Rather than counting faint galaxies count the number of dark halos

Can we distinguish CDM/WDM?

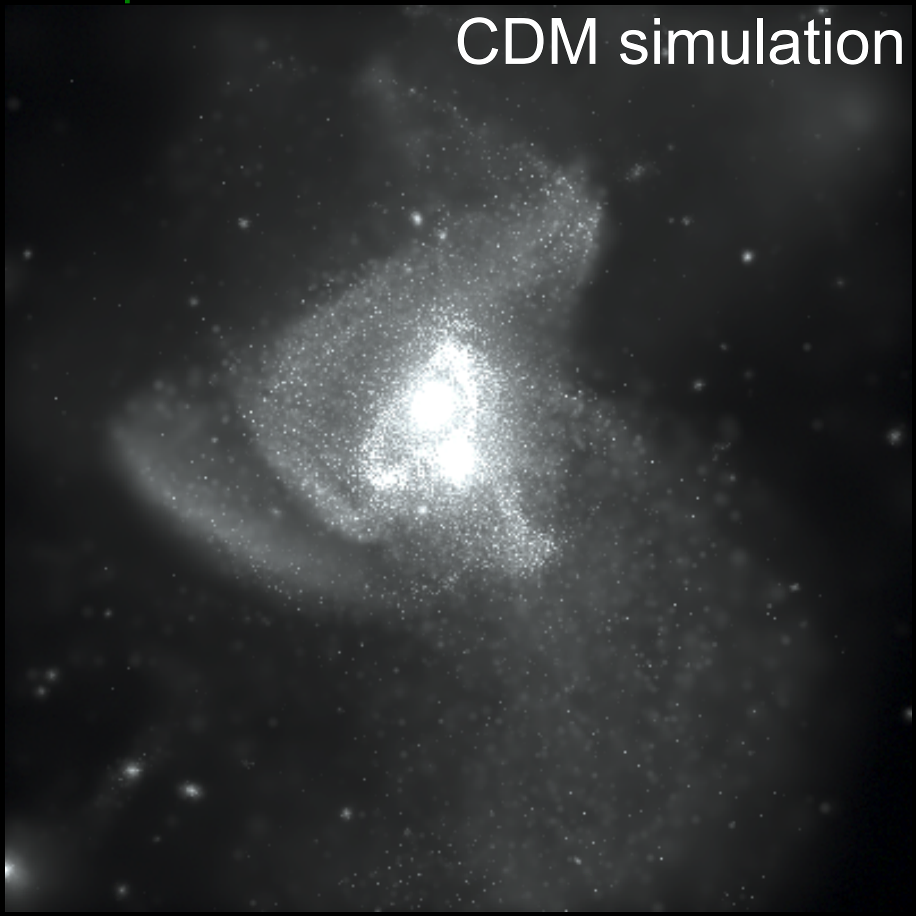
cold dark matter

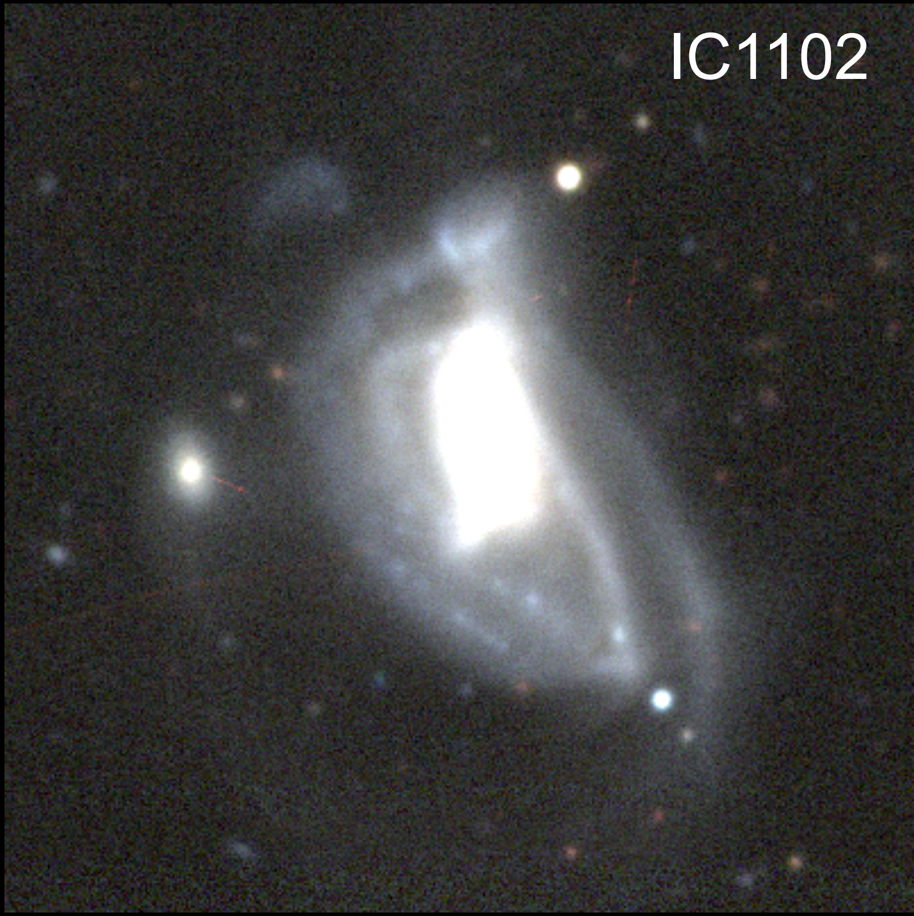
warm dark matter

1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing

Can we distinguish CDM/WDM?

Cooper et al ‘16

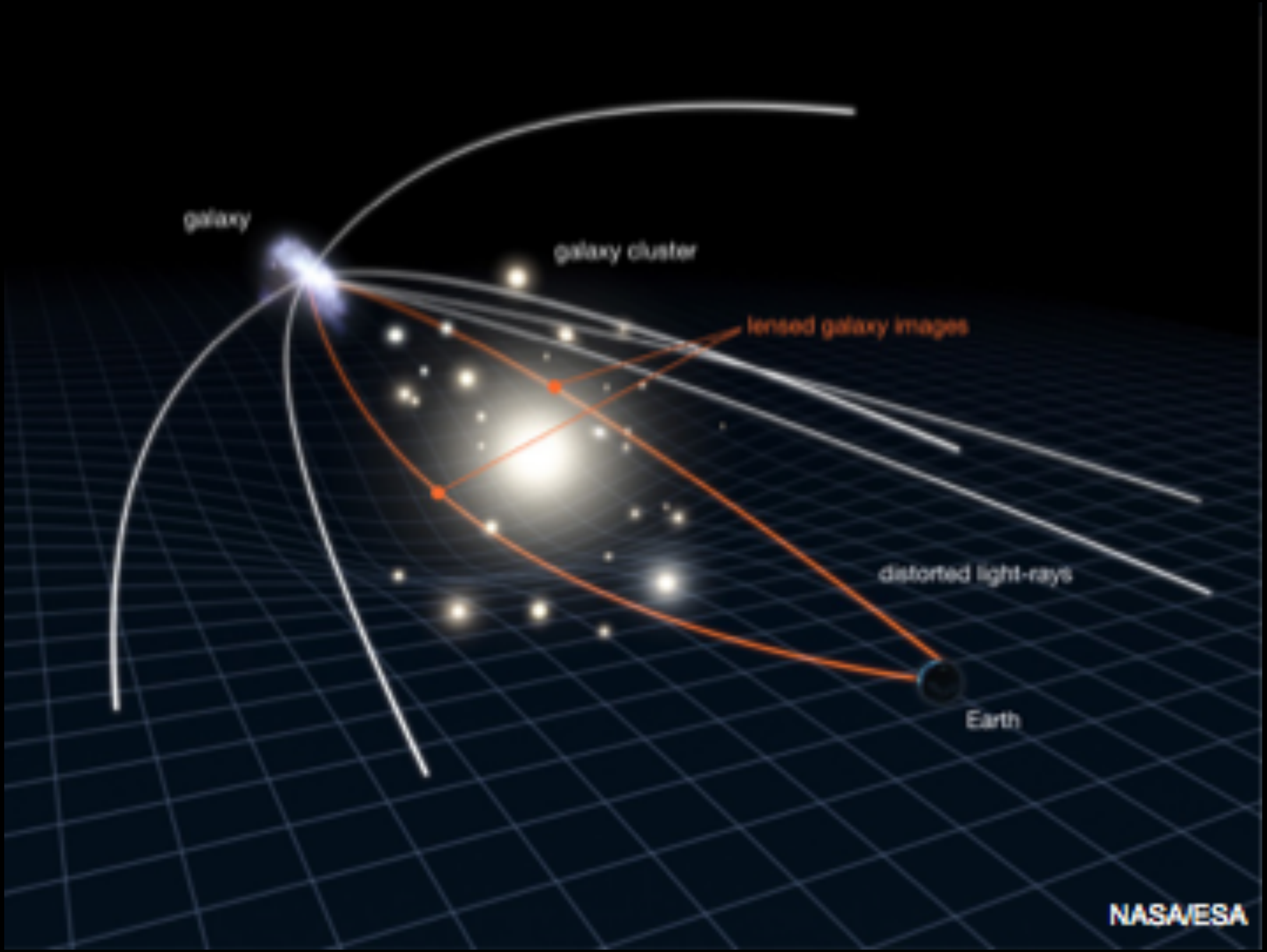




Subhalos crossing a cold tidal stream can produce a gap

Globular cluster streams (e.g. Pal 5) may be best

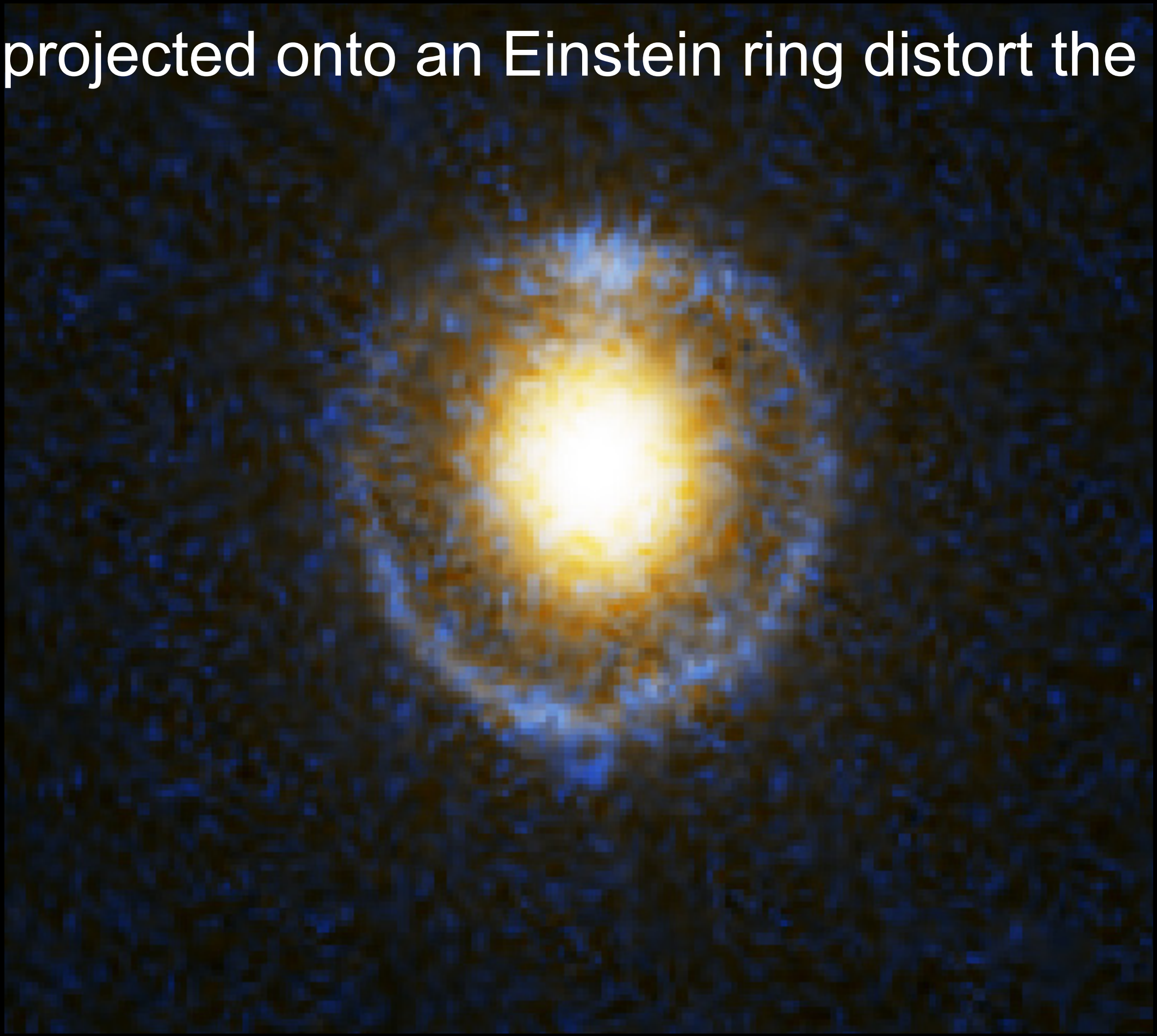
Gravitational lensing: Einstein rings



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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



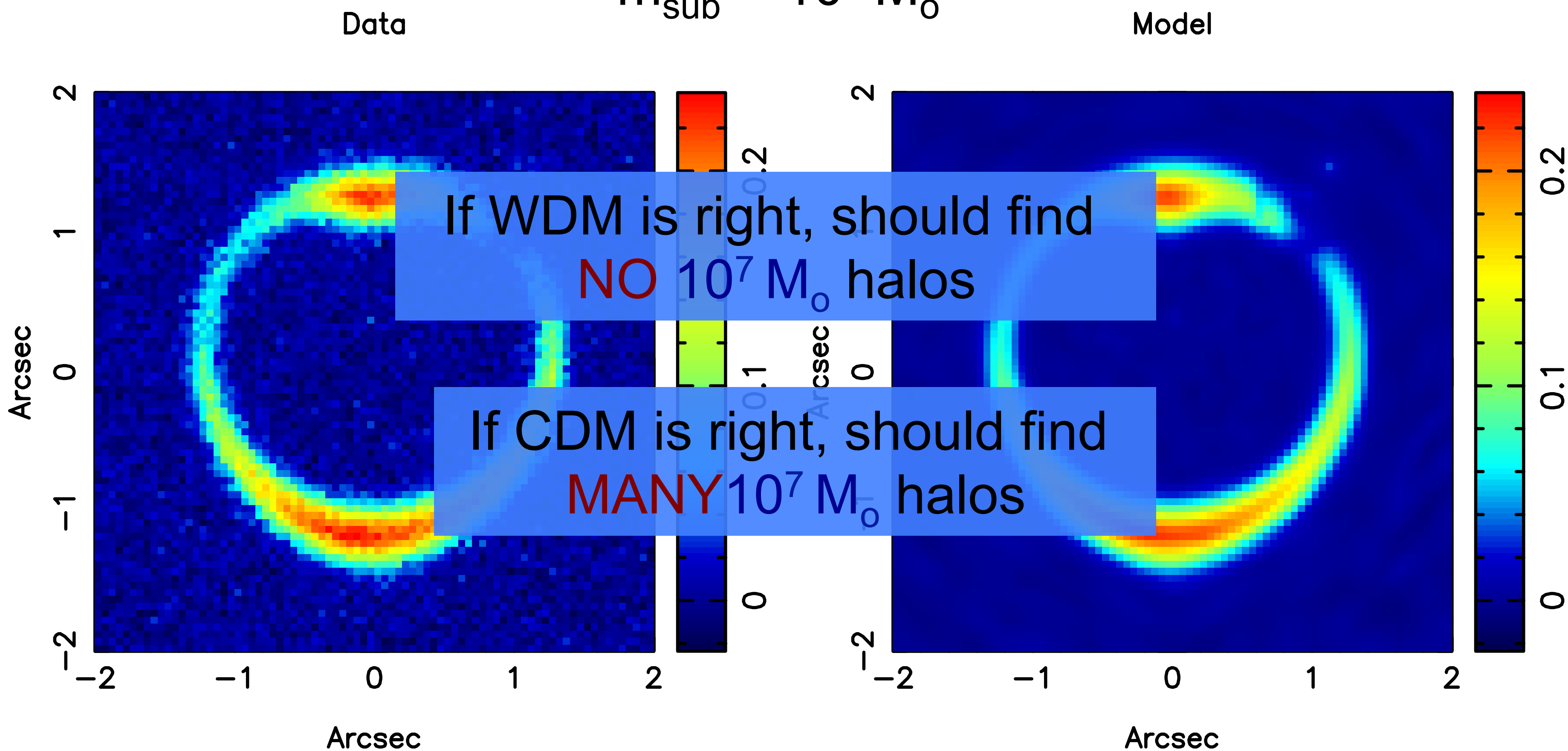
Vegetti & Koopmans ‘09

ICC University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$

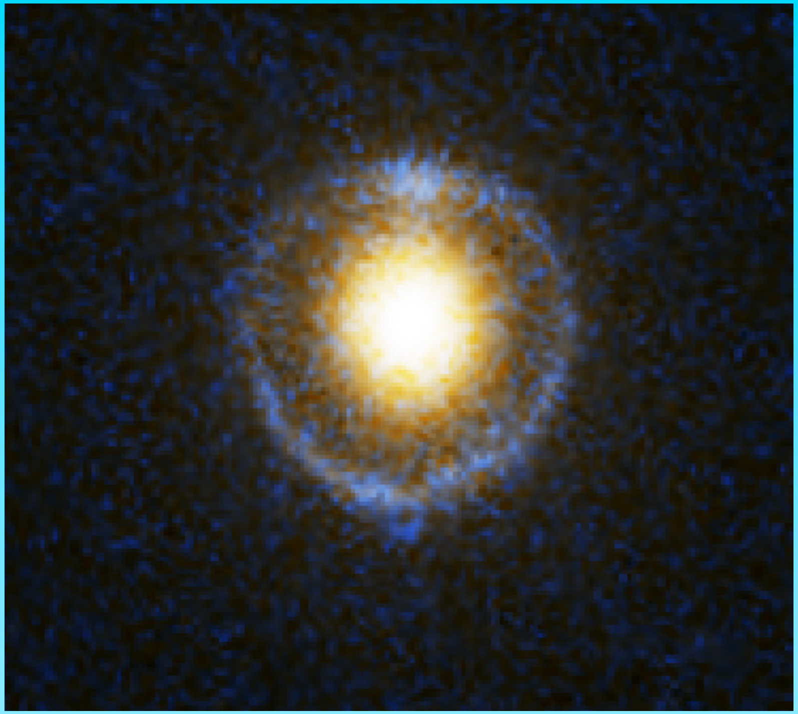


If WDM is right, should find NO $10^7 M_o$ halos

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

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

Gravitational lensing: Einstein rings



Two important considerations:

- The central galaxy can destroy subhalos
- Line-of-sight projected halos also lens

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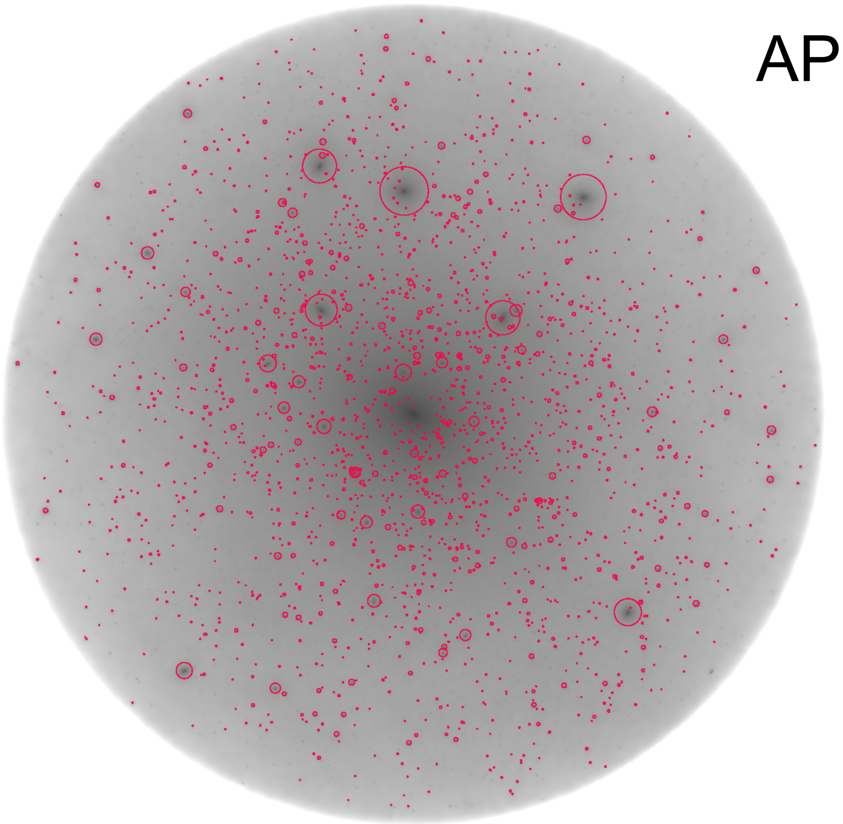
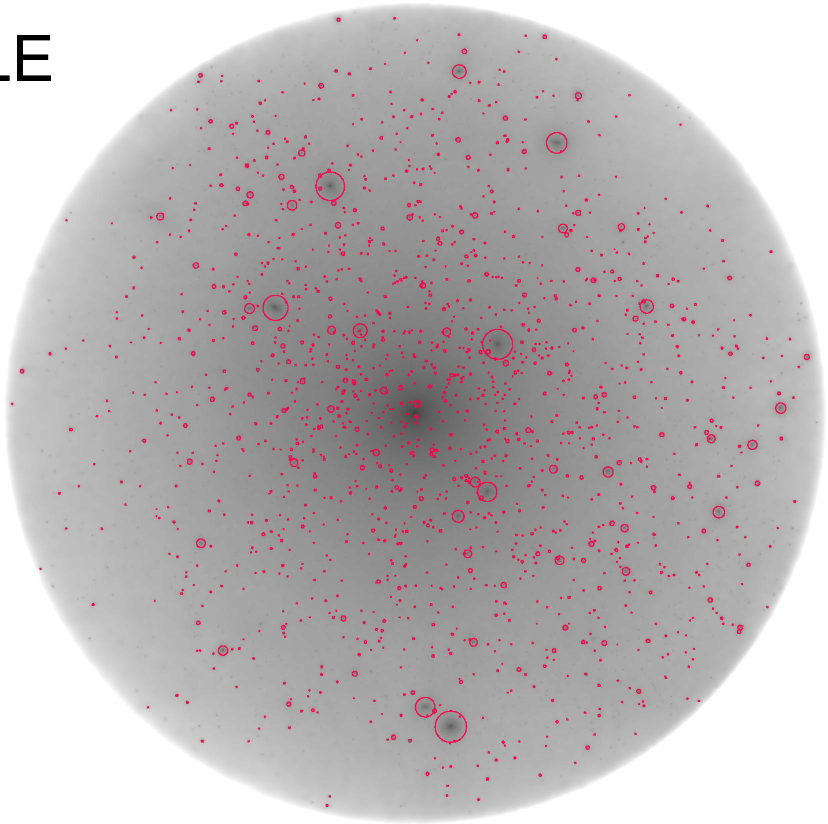
Destruction of dark substructures by galactic baryons

APOSTLE



Dark matter only simulation



Hydrodynamic simulation

Sawala et al '16

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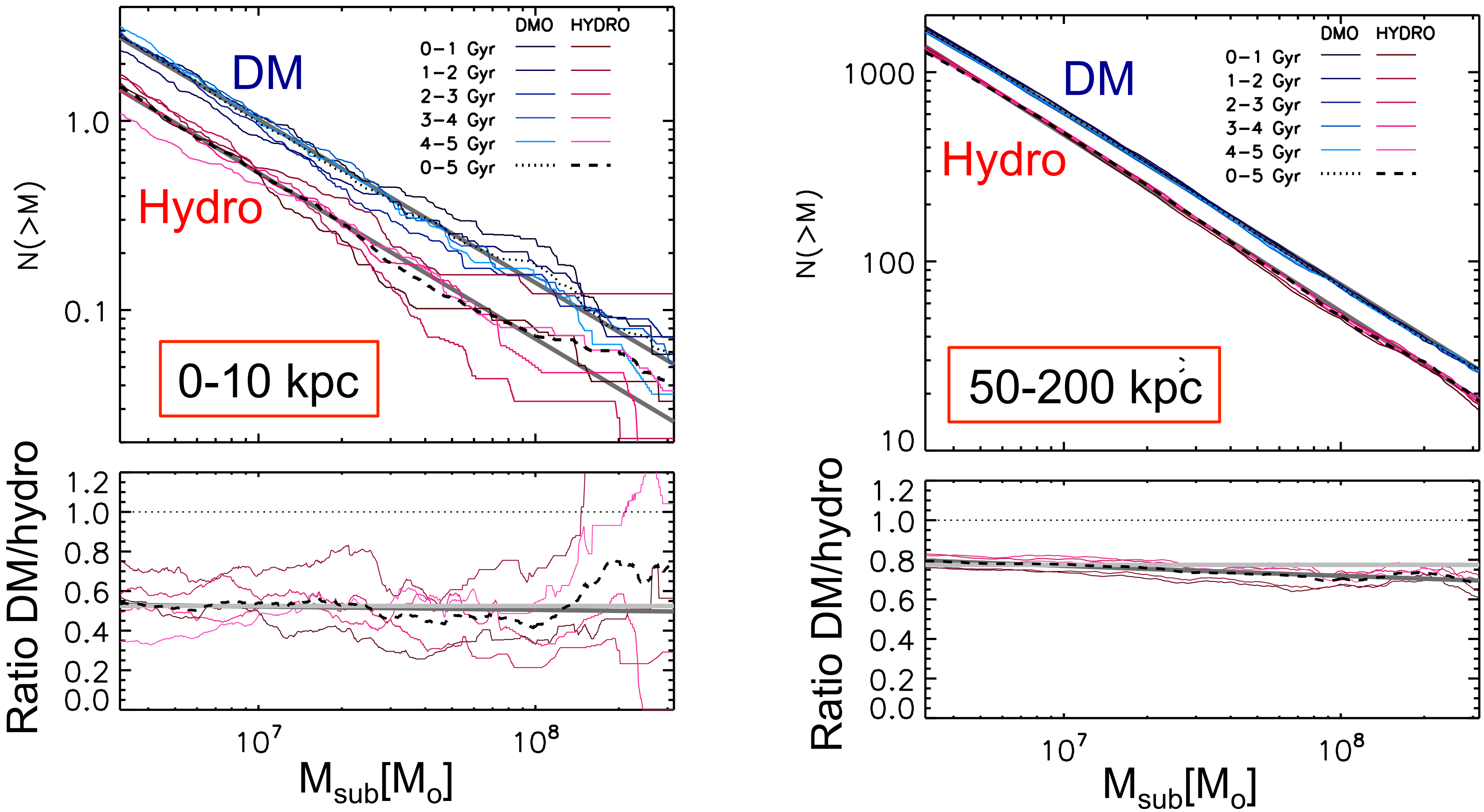
Destruction of dark substructures by galactic baryons

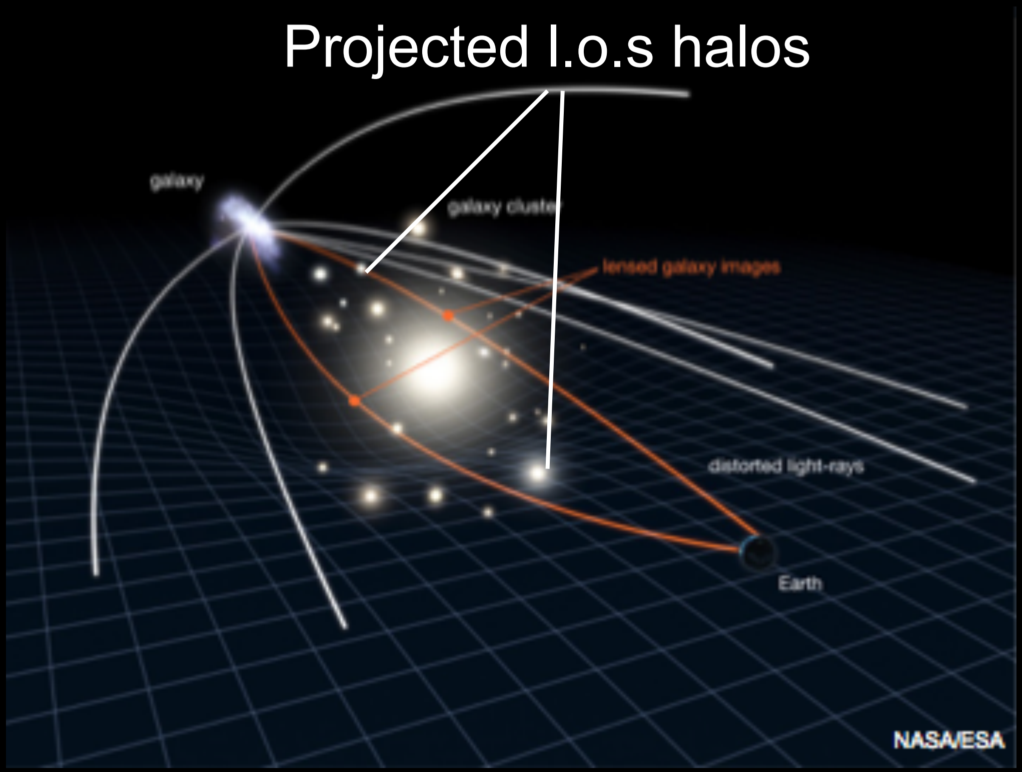


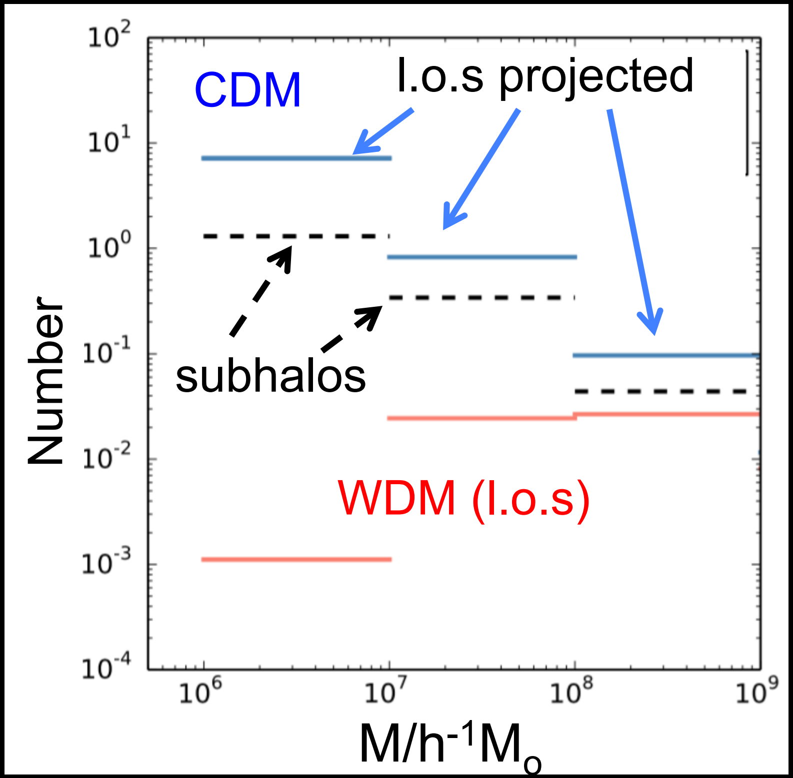
- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
- 20% " 50-200 kpc "

Sawala et al '16

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens





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

Li, CSF et al. '16

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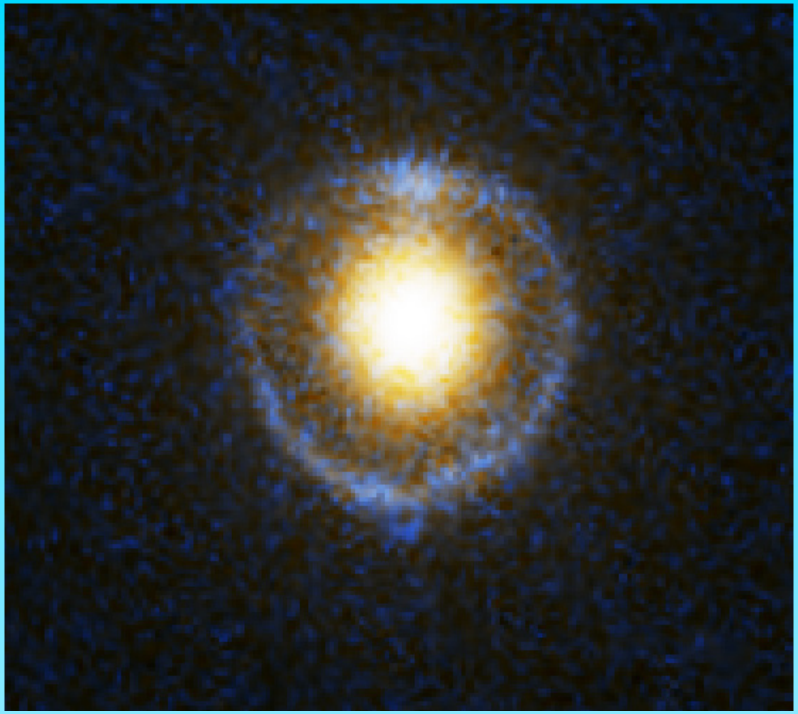
Gravitational lensing: Einstein rings



Two key considerations:

- The central galaxy can destroy subhalos
- Line-of-sight projected halos also lens

Answer:

- Central galaxy destroys ~40% of halos within Einstein ring (Sawala et al. ‘16)
- Projected halos dominate the strong lensing signal (Li et al ‘16)

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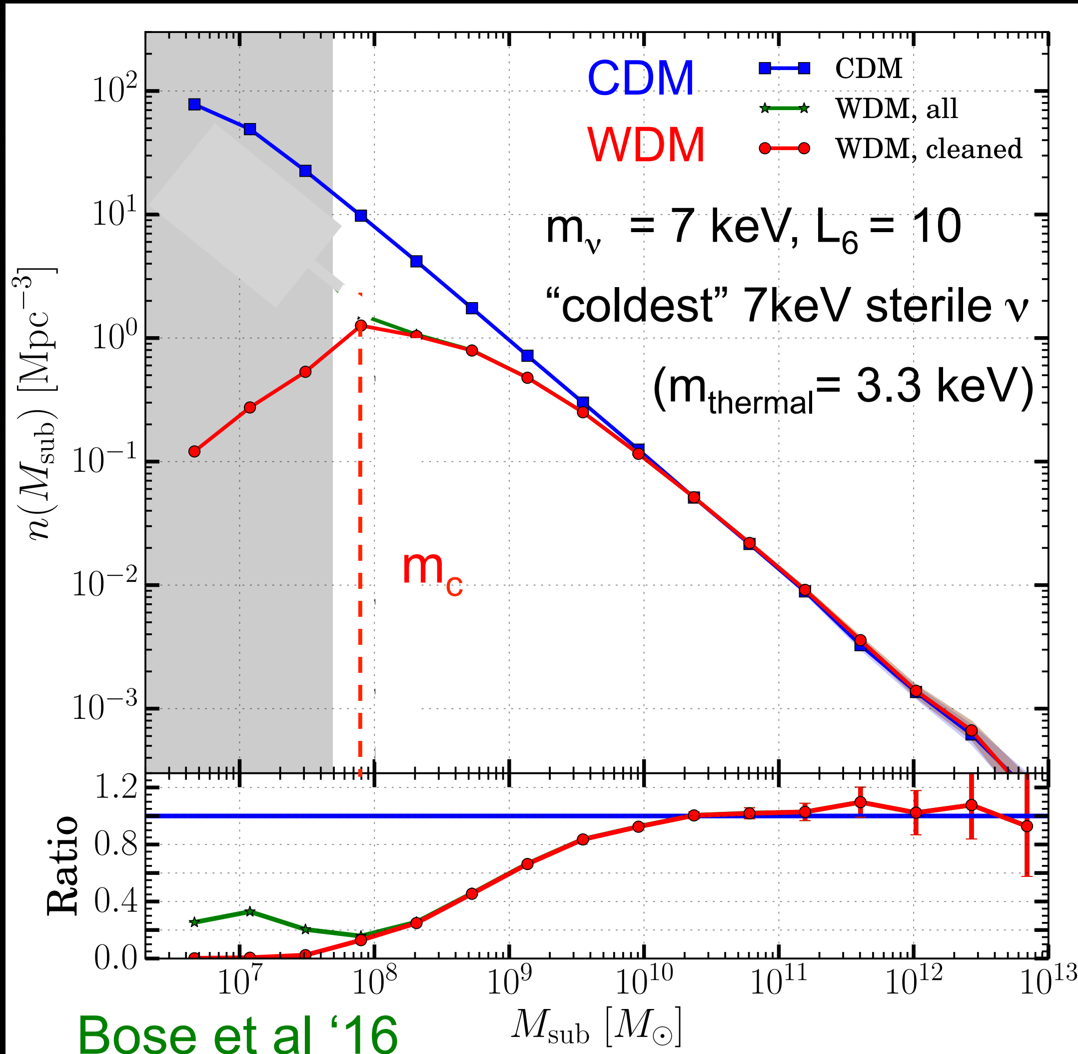
The subhalo mass function

CDM

WDM

Already fewer WDM subhalos at $3\times10^9 M_o$

10 x fewer at $10^8 M_o$



Detecting substructures with strong lensing

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

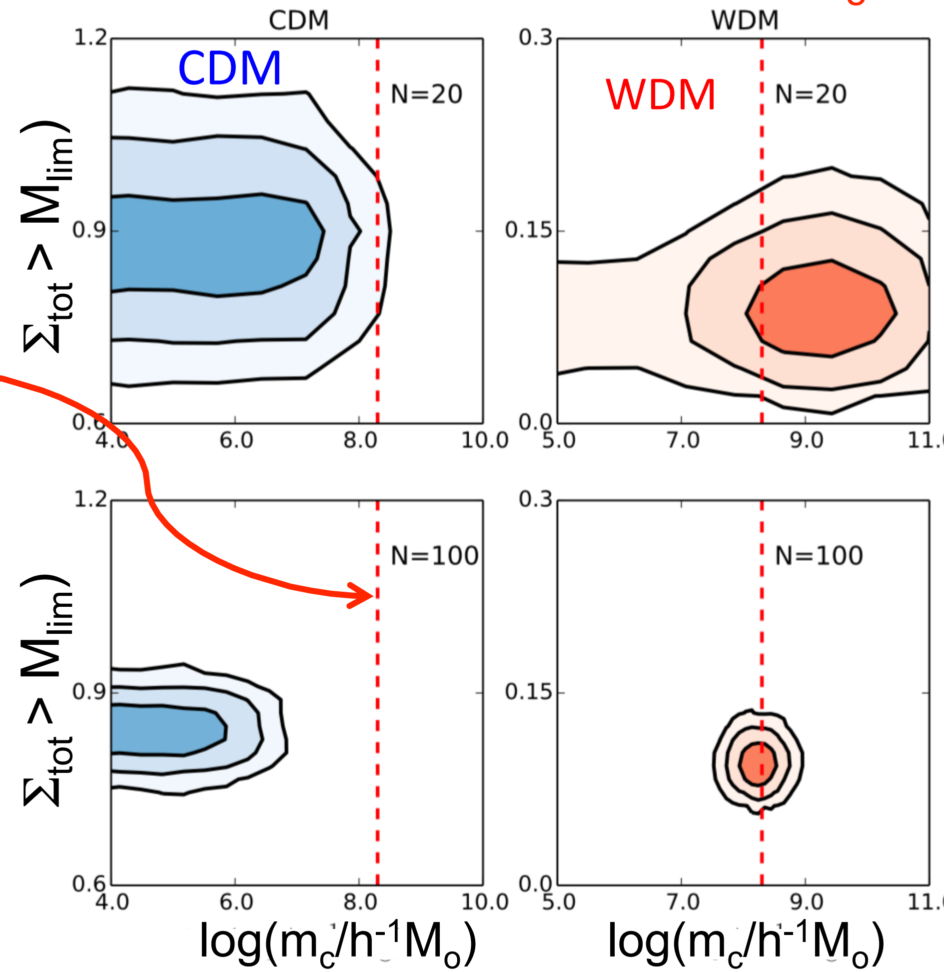
m_c= halo cutoff mass

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

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

- If DM is CDM → rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile ν → rule out CDM at 3σ!

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



Li, CSF et al '16

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Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- But on these scales ΛCDM cannot be distinguished from WDM
- The identity of the DM makes a big difference on small scales

1. Counting faint galaxies cannot distinguish CDM/WDM
2. No too-big-to-fail when baryon effects are included
3. Strong graviational lensing can distinguish CDM/WDM

   (and could rule out CDM!)