

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

How can we distinguish between these?

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
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

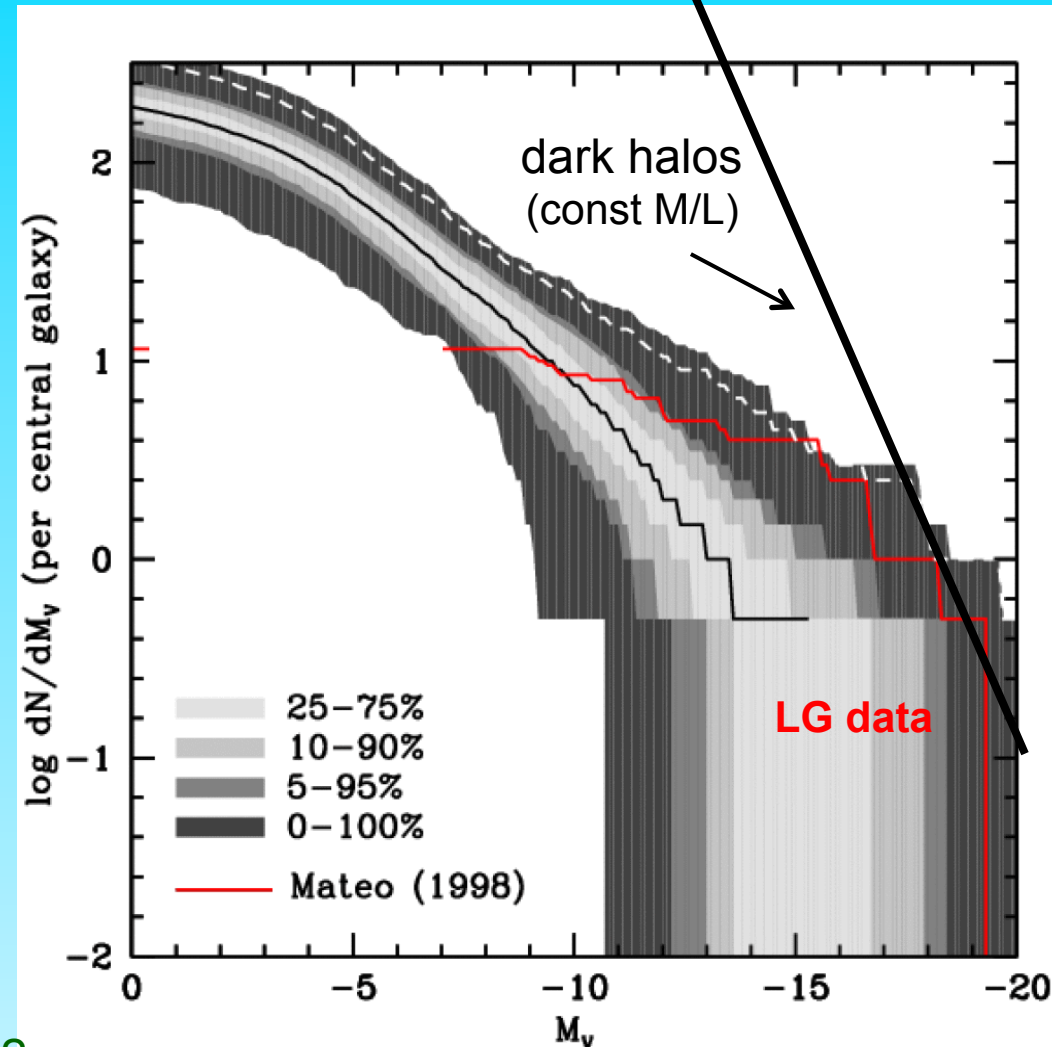
Most subhalos never make a galaxy!

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

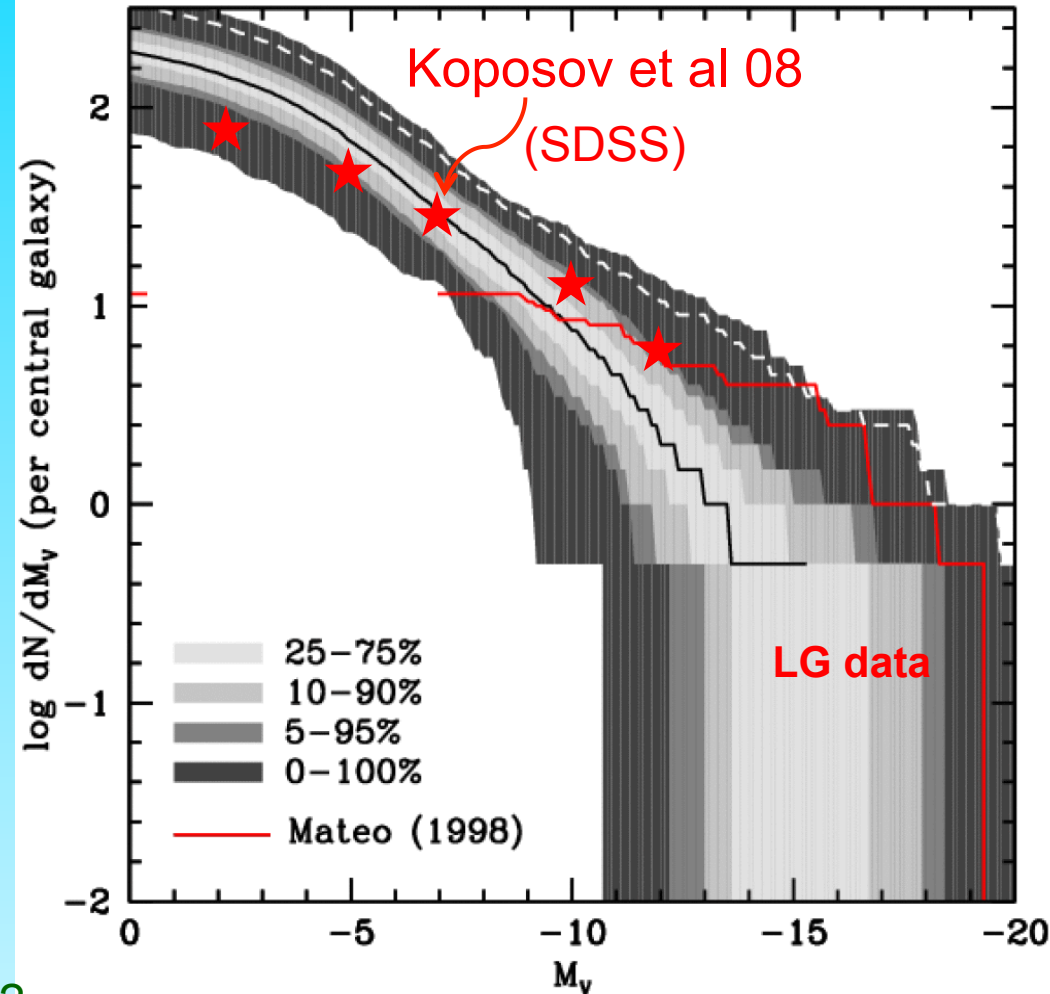
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

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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...

VIRG

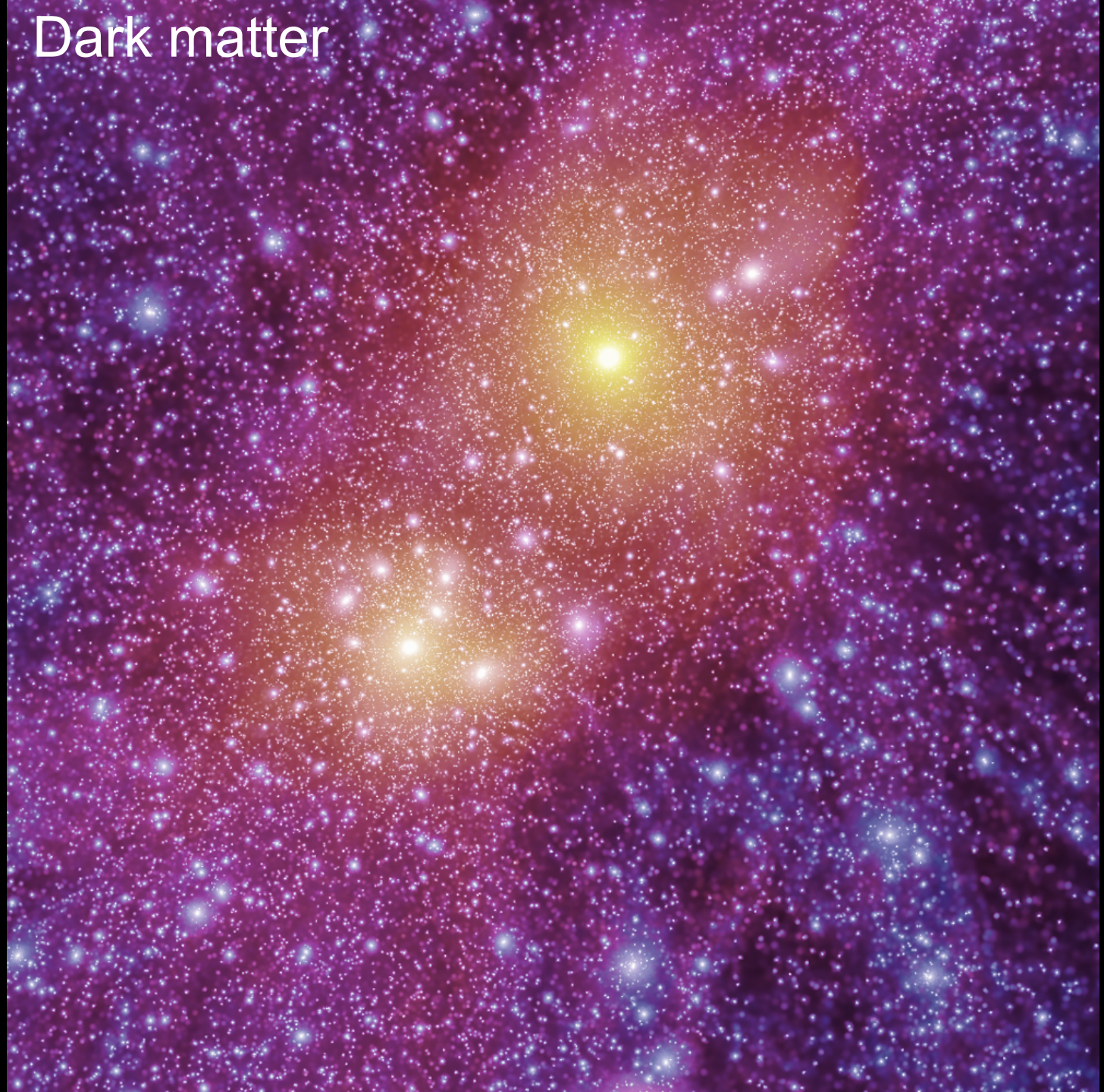
Dark matter

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al '15



Stars

VIRG

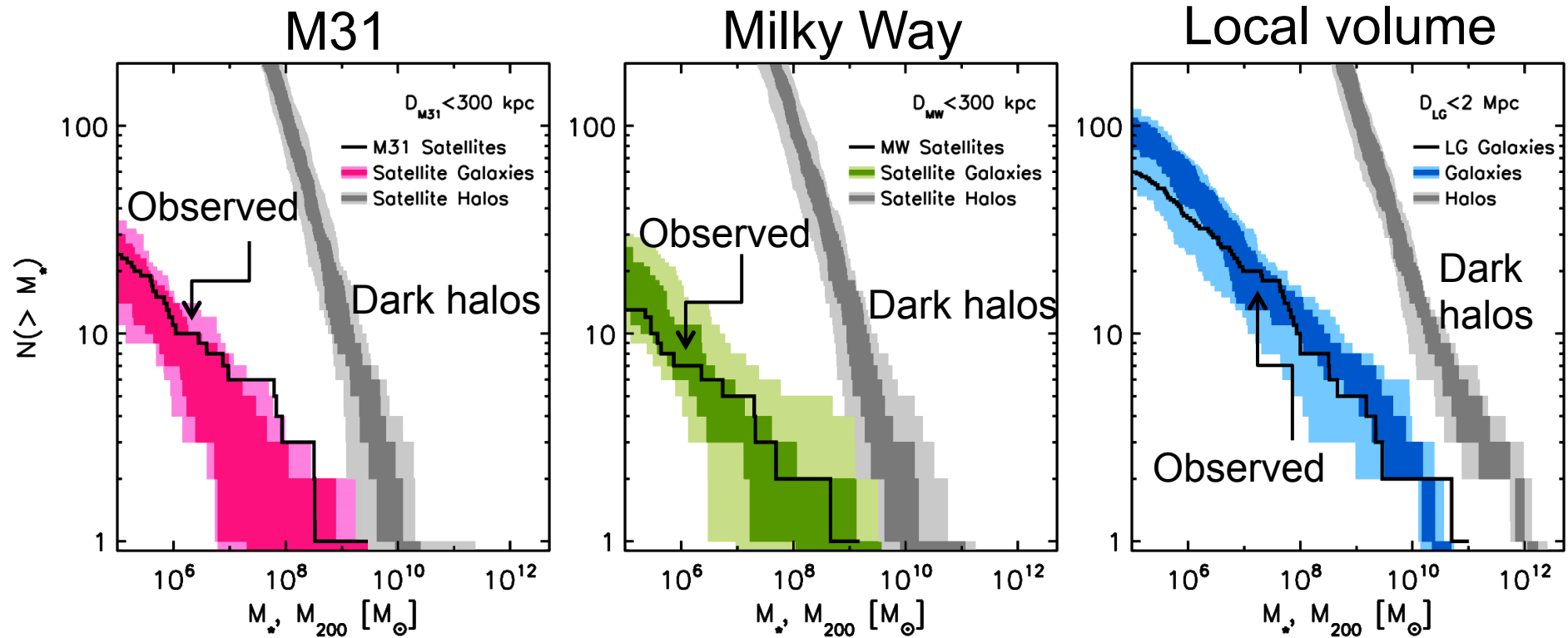
APOSTLE
EAGLE full
hydro
simulations

Local Group

Far fewer satellite galaxies than CDM halos

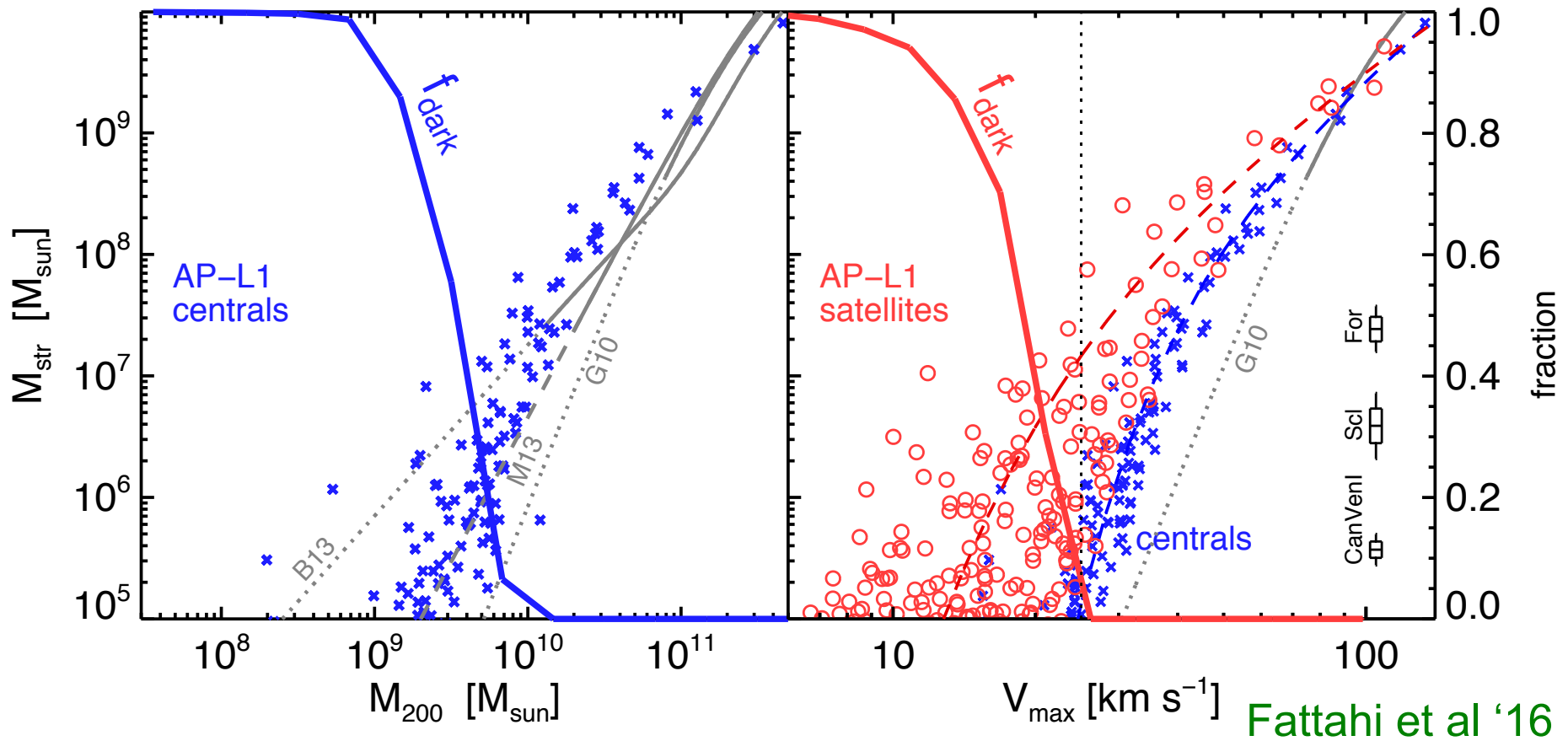
Sawala et al '15

EAGLE Local Group simulation



Fraction of dark subhalos

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



Fattahi et al '16

All halos of mass $< 10^9 M_{\odot}$ or $V_{\max} < 7 \text{ km/s}$ 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

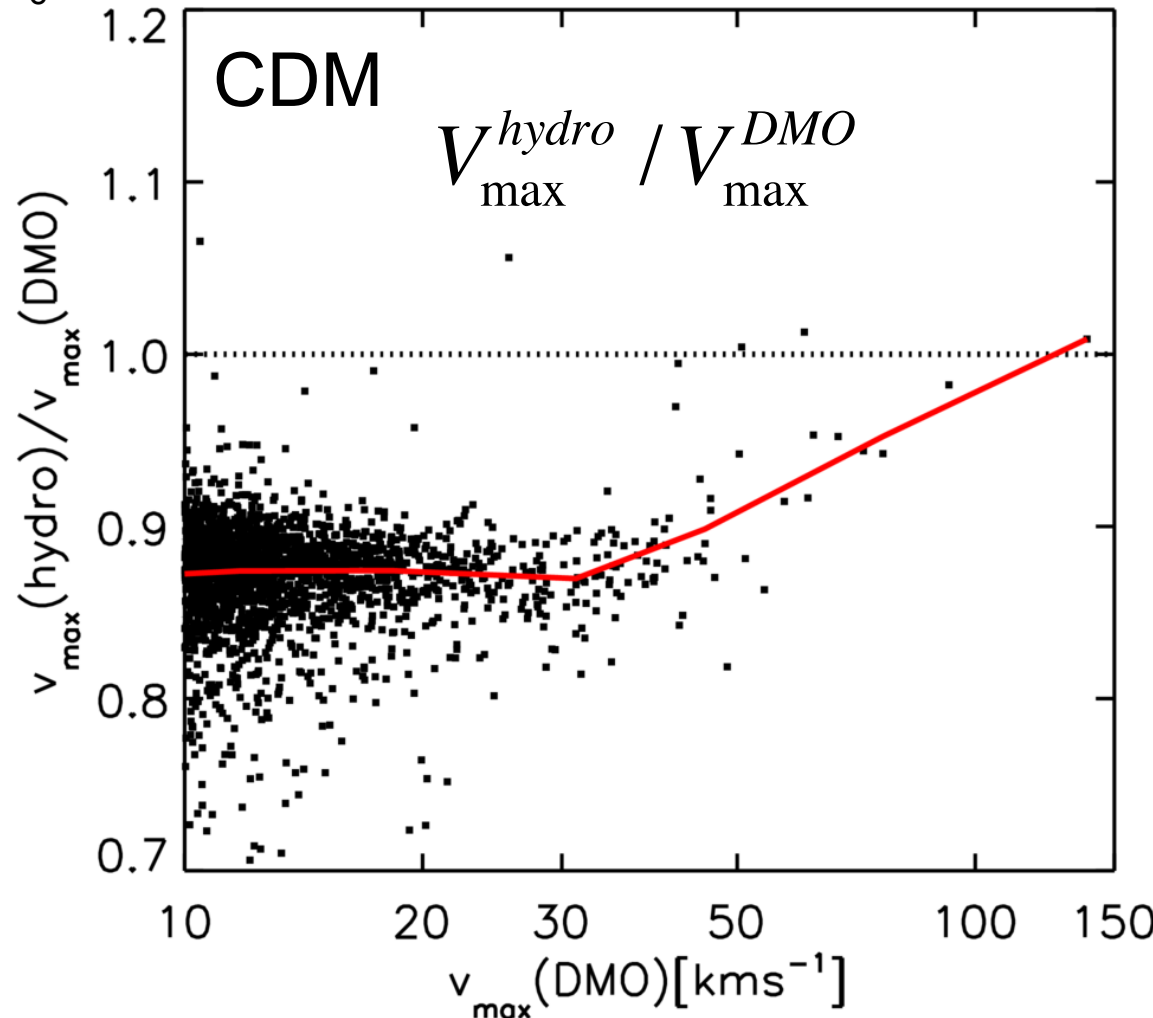
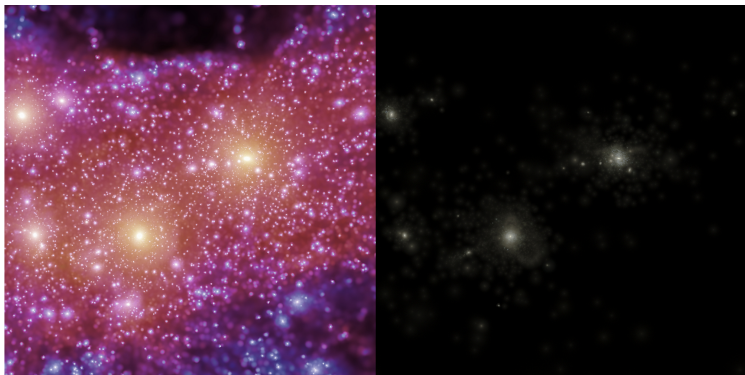
Why did the big subhalos
not make a galaxy?

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

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

Reduction in $V_{\max}$ due to
SN feedback:

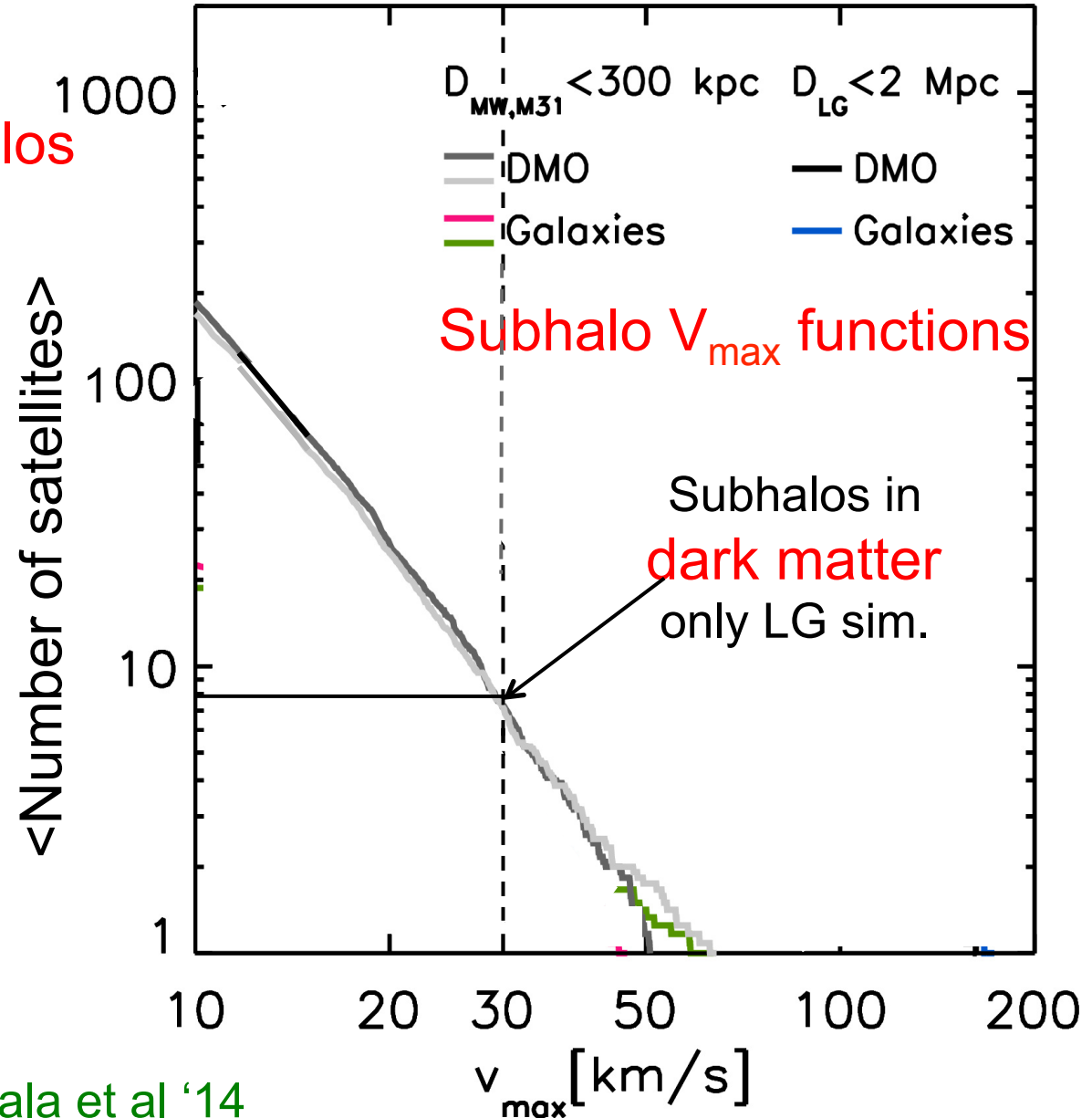
→ Lowers halo mass &
thus halo growth rate



Sawala et al. '13, '15

Too-big-to-fail: the baryon bailout

DM only sims $\rightarrow$ **~ 10 halos**
with $V_{\max} > 30$ km/s

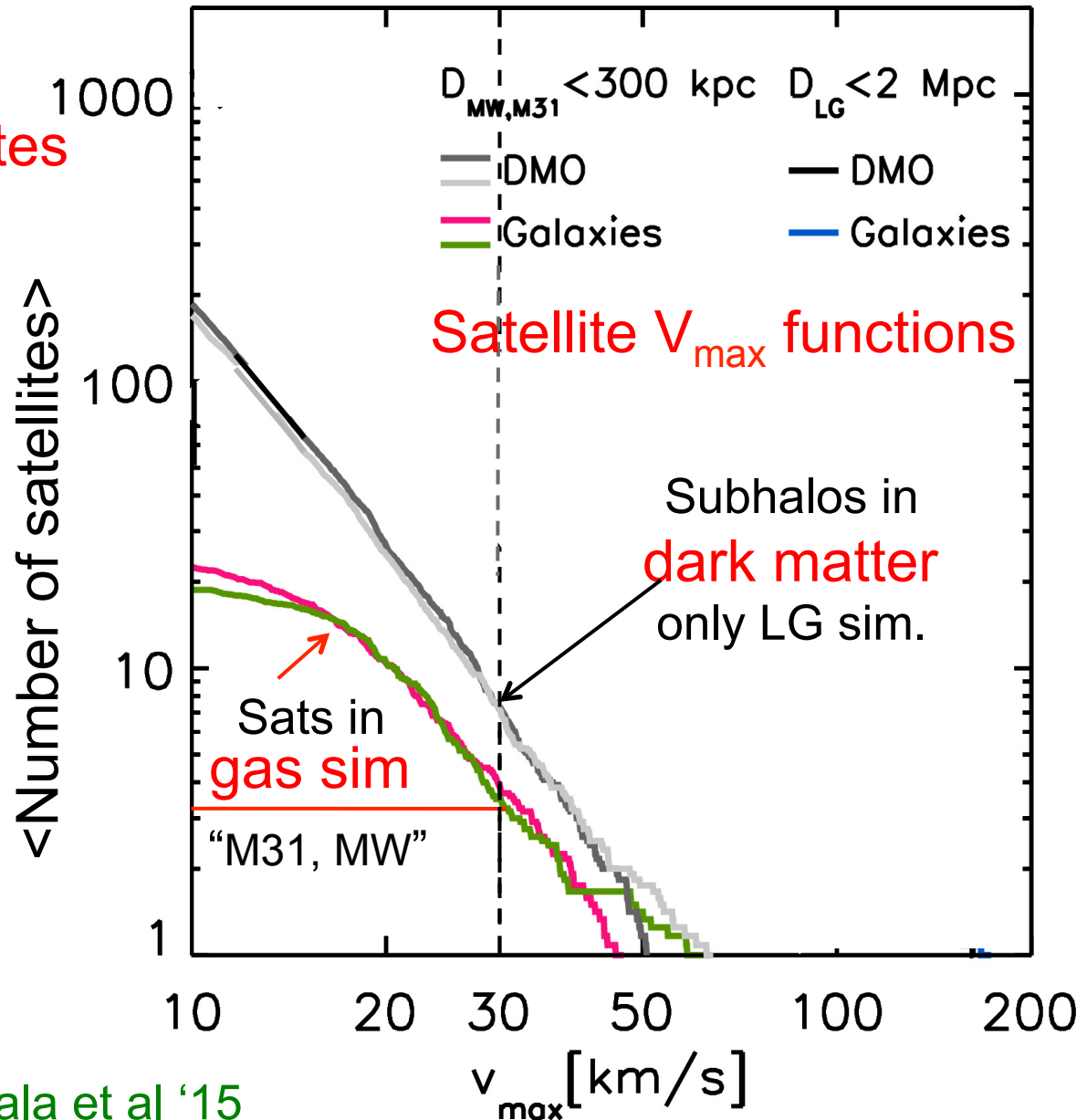


Too-big-to-fail: the baryon bailout

Hydro sims $\rightarrow$ **~3 satellites**
with $V_{\max} > 30$ km/s

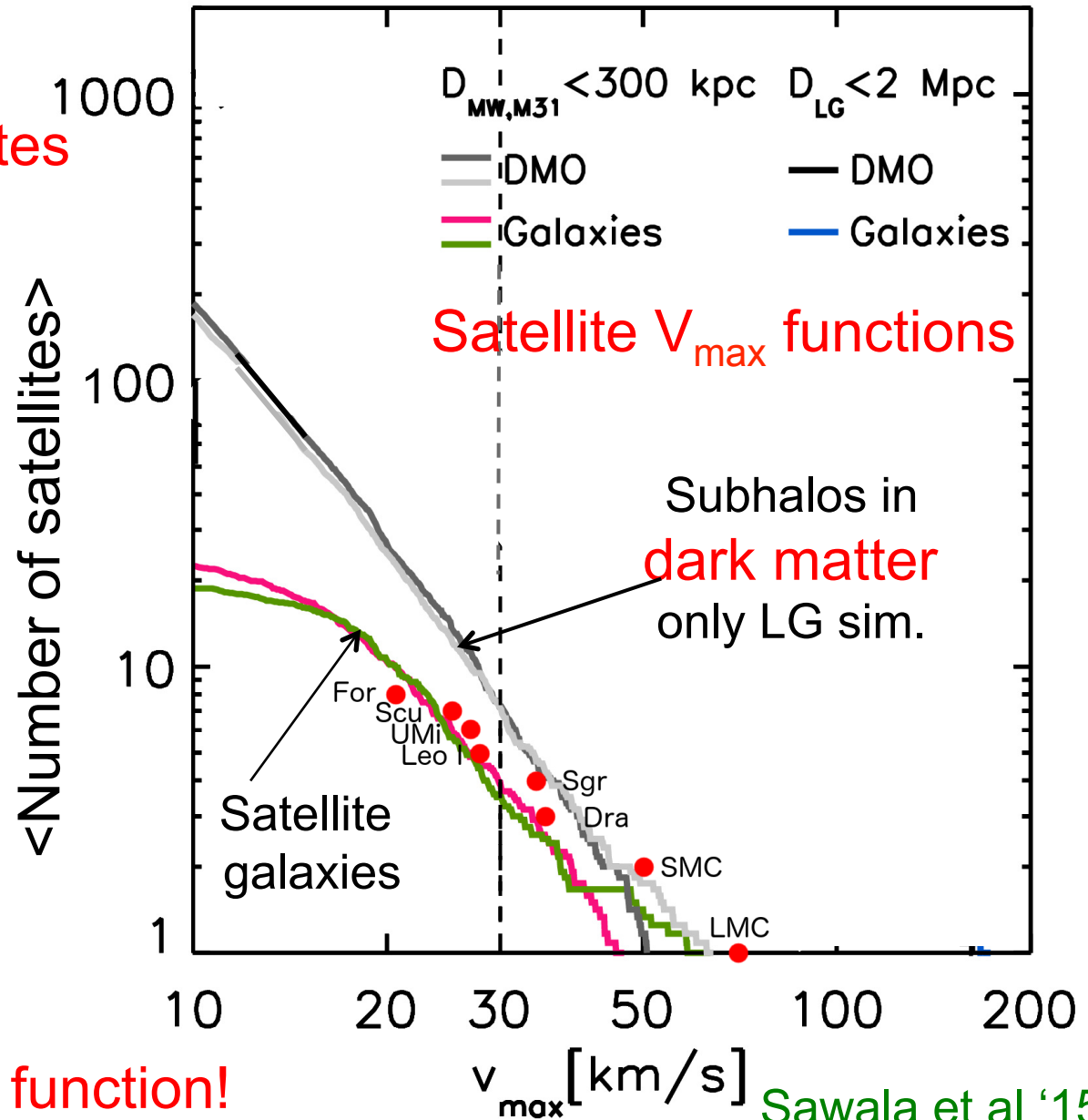


Sawala et al '15



Too-big-to-fail: the baryon bailout

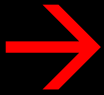
Hydro sims $\rightarrow$ **~ 3 satellites**
with $V_{\max} > 30$ km/s



... and with correct $V_{\max}$ function!



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?

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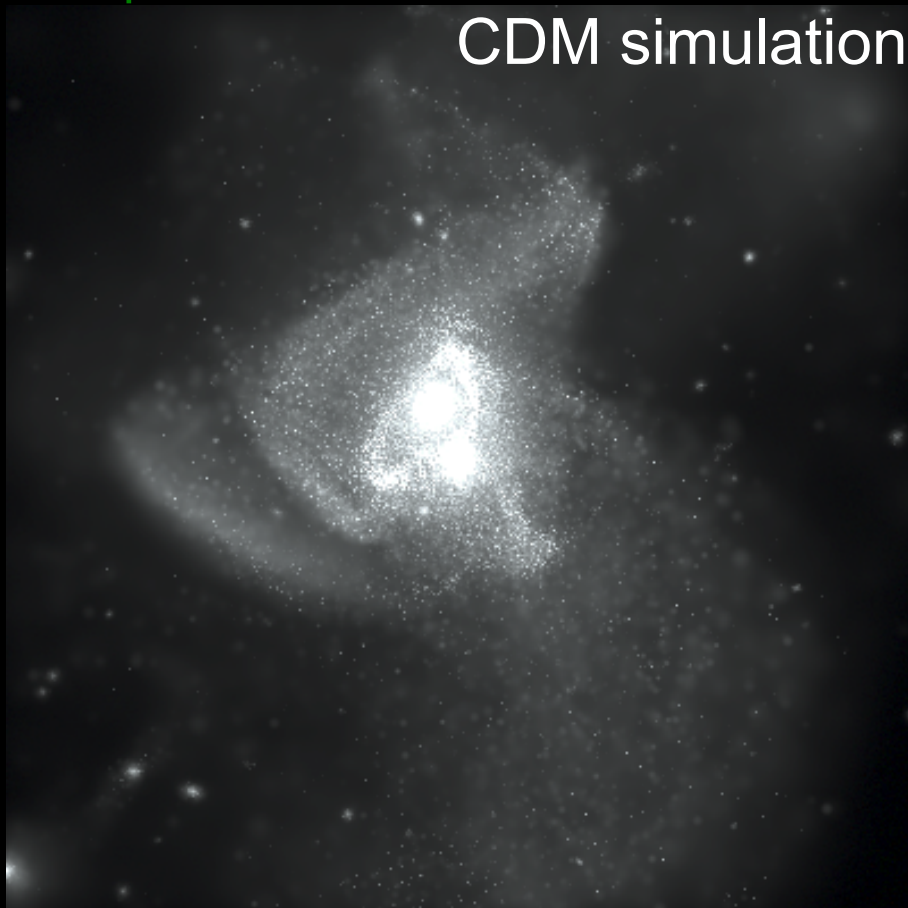
1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing



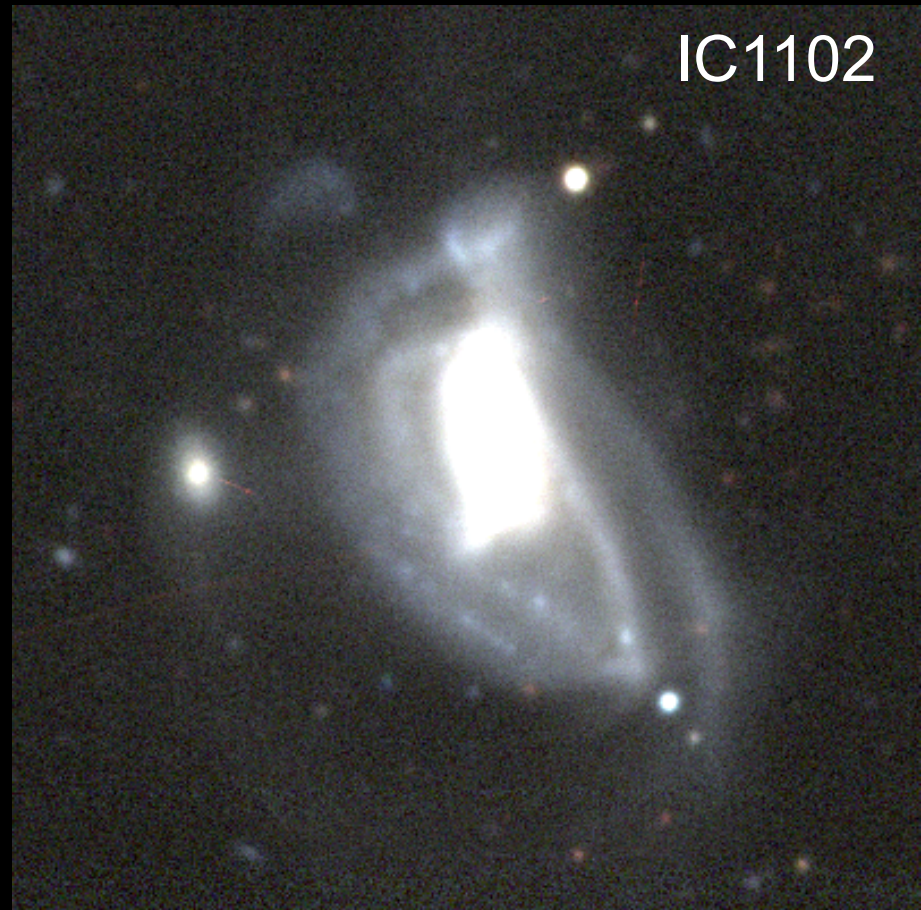
Can we distinguish CDM/WDM?

Cooper et al '16

CDM simulation



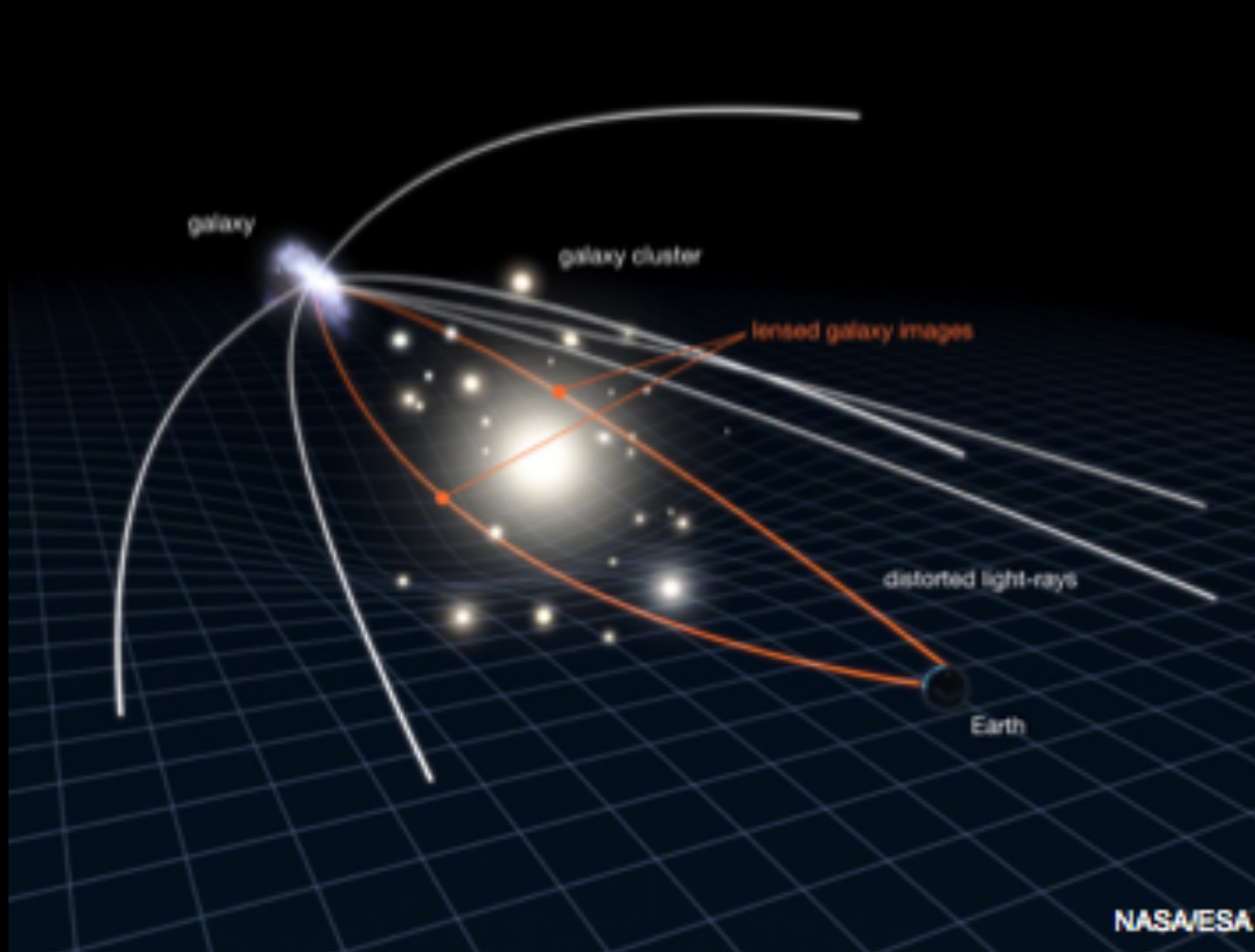
IC1102



Subhalos crossing a cold tidal stream can produce a gap

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

Gravitational lensing: Einstein rings

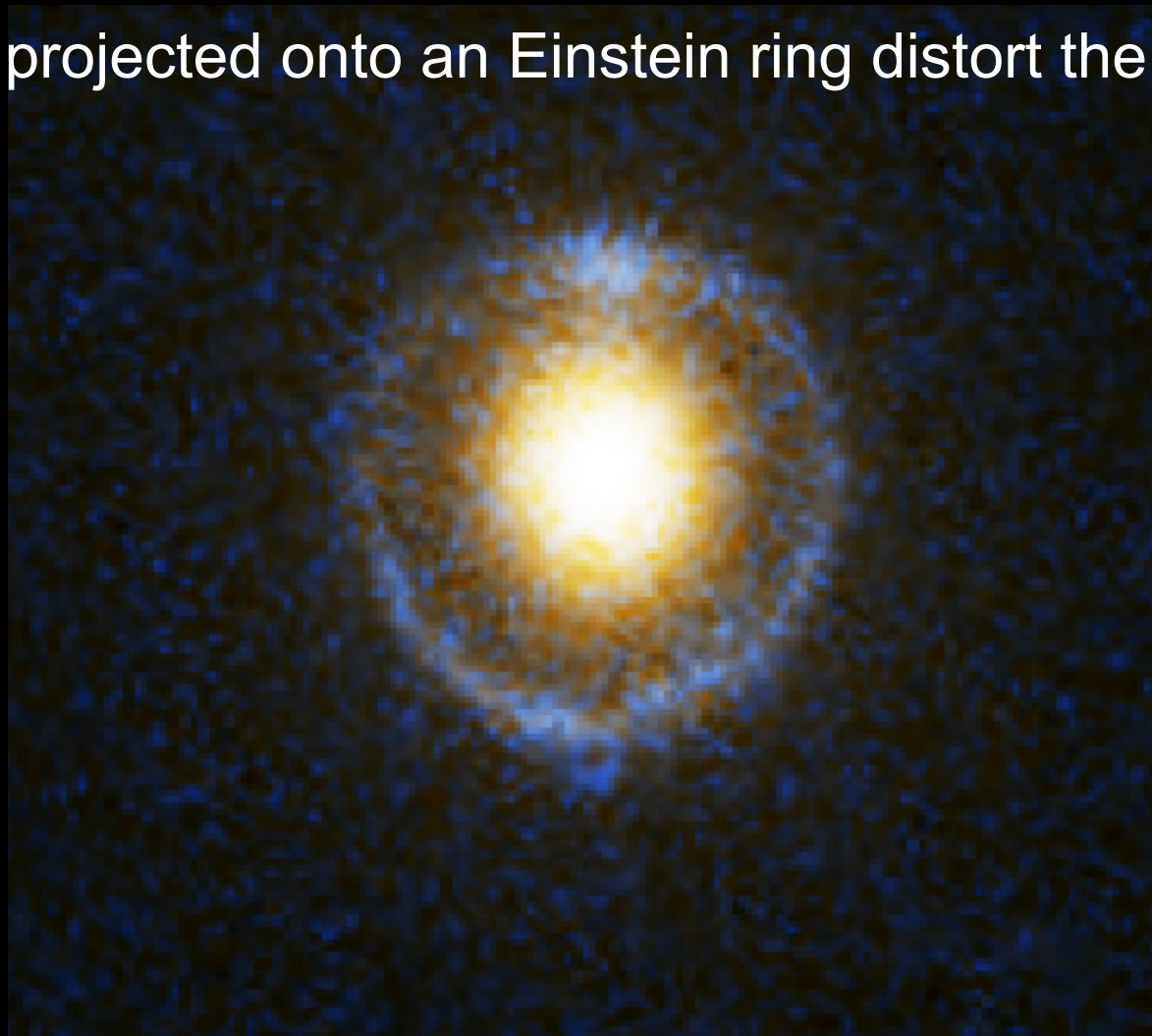


When the source and the lens are well aligned → strong arc of an Einstein ring



Gravitational lensing: Einstein rings

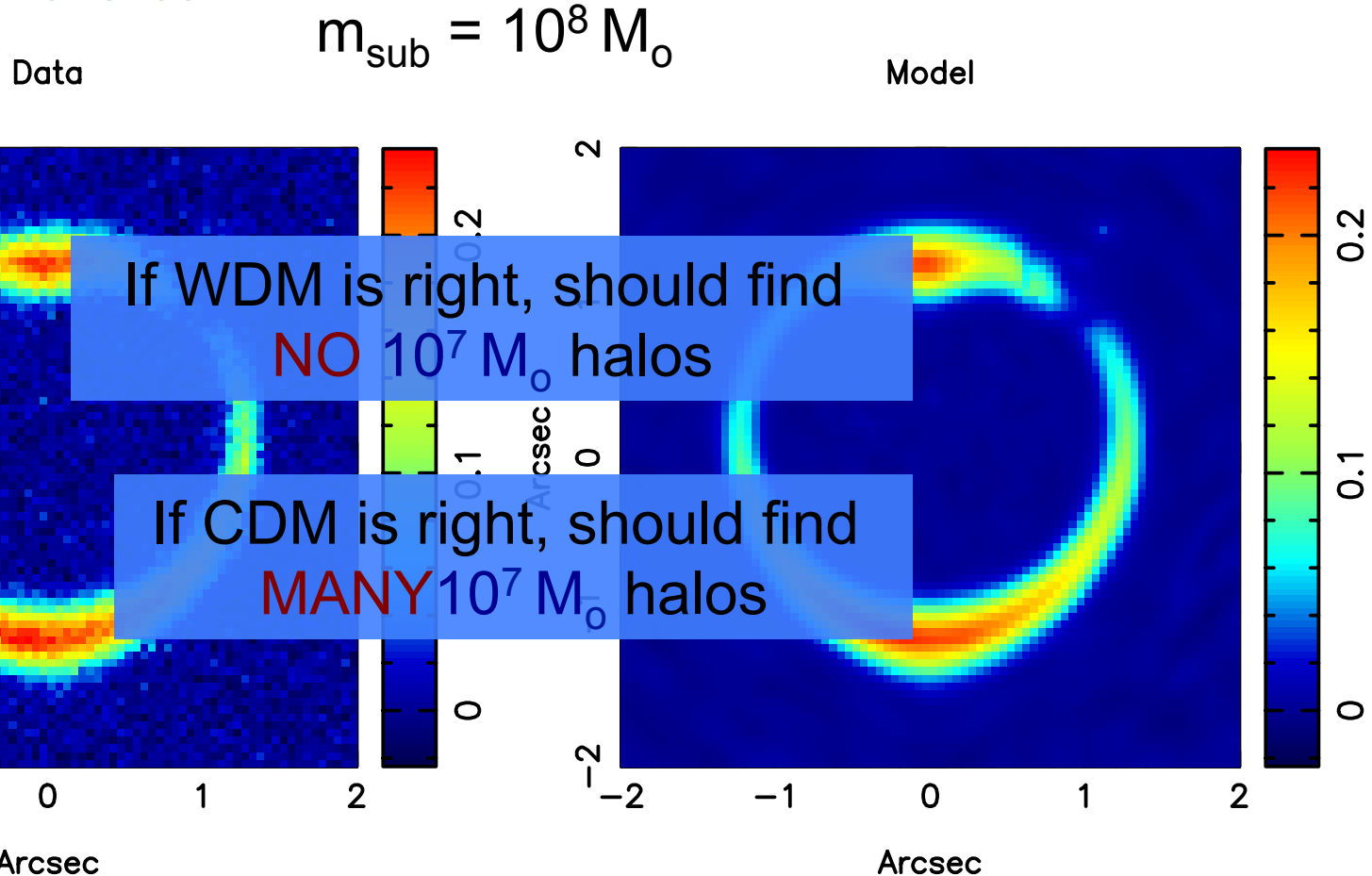
Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans '09

Detecting substructures with strong lensing

Vegetti & Koopmans '09



Can detect subhalos as small as $10^7 M_{\odot}$

Gravitational lensing: Einstein rings

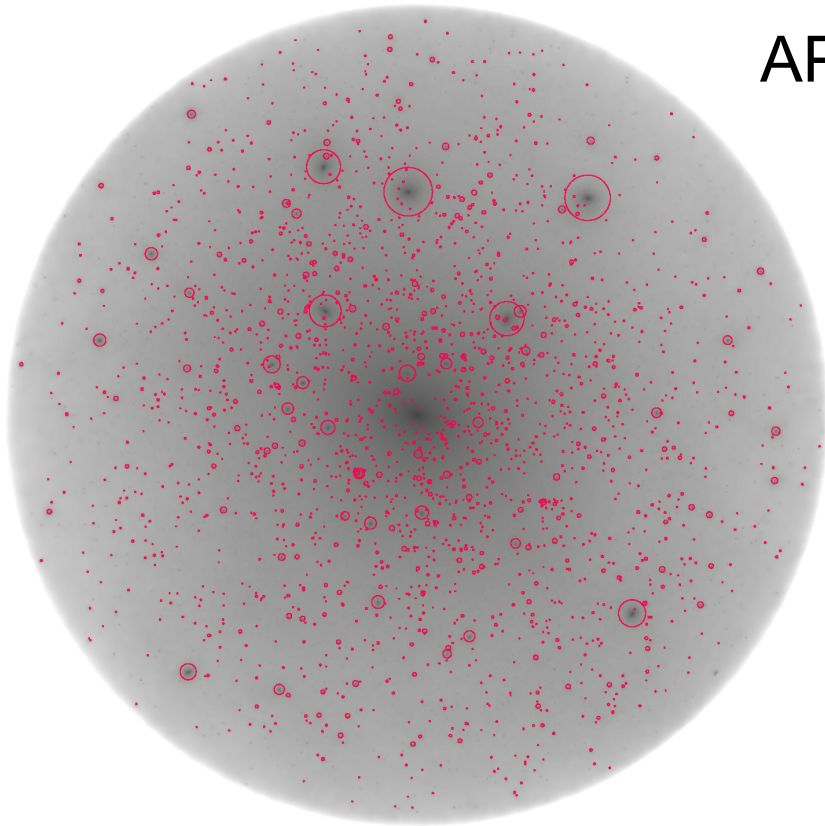
Two important considerations:

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

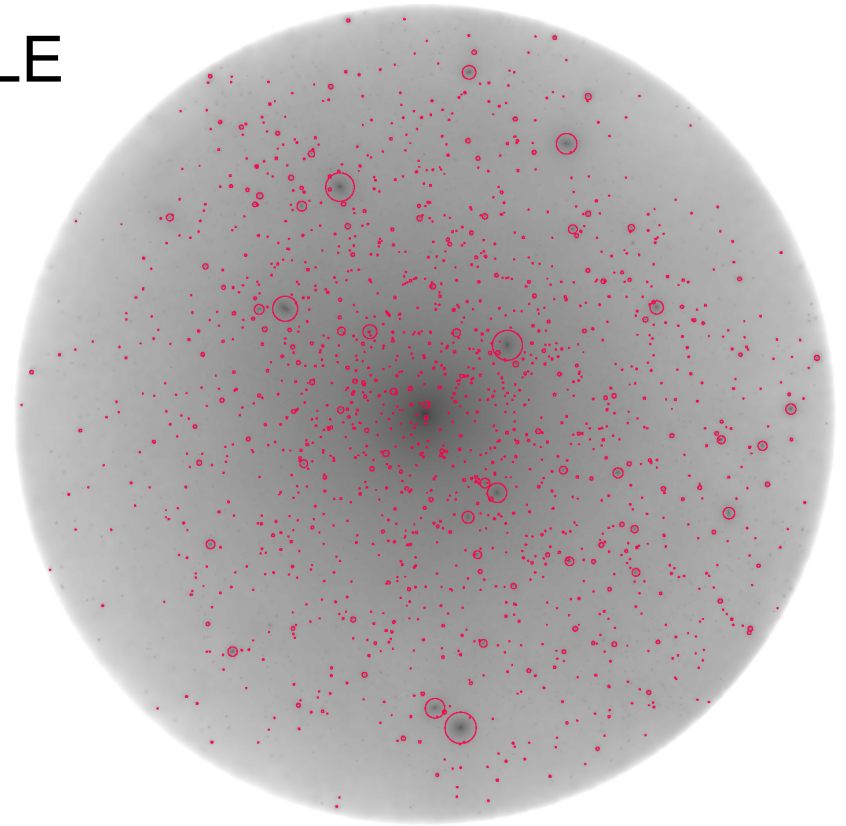


Destruction of dark substructures by galactic baryons

APOSTLE

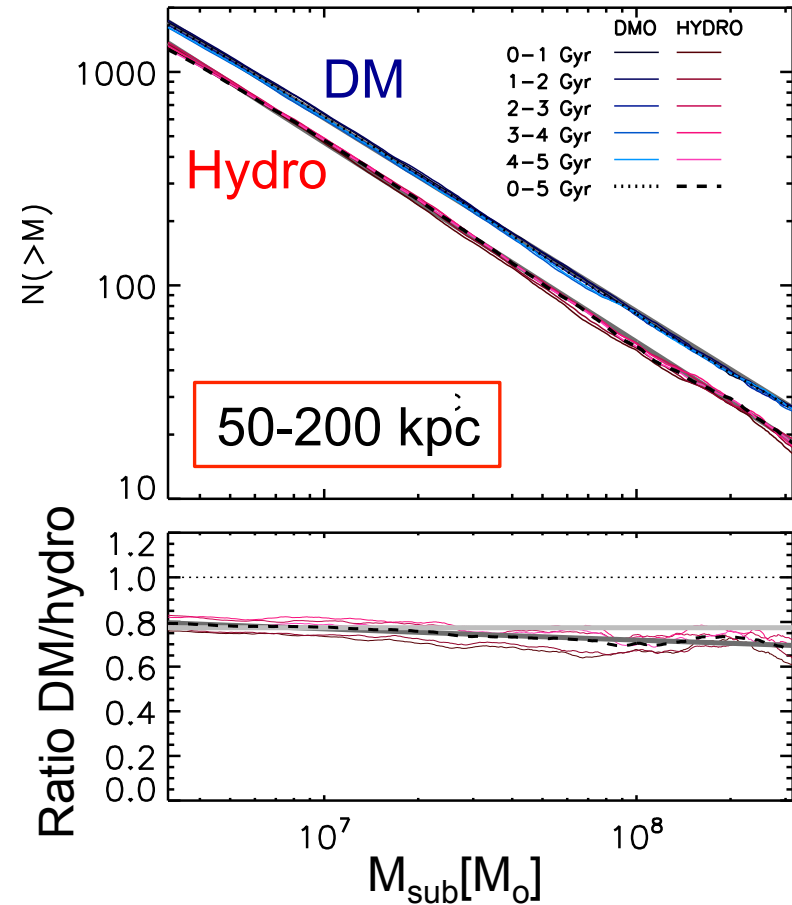
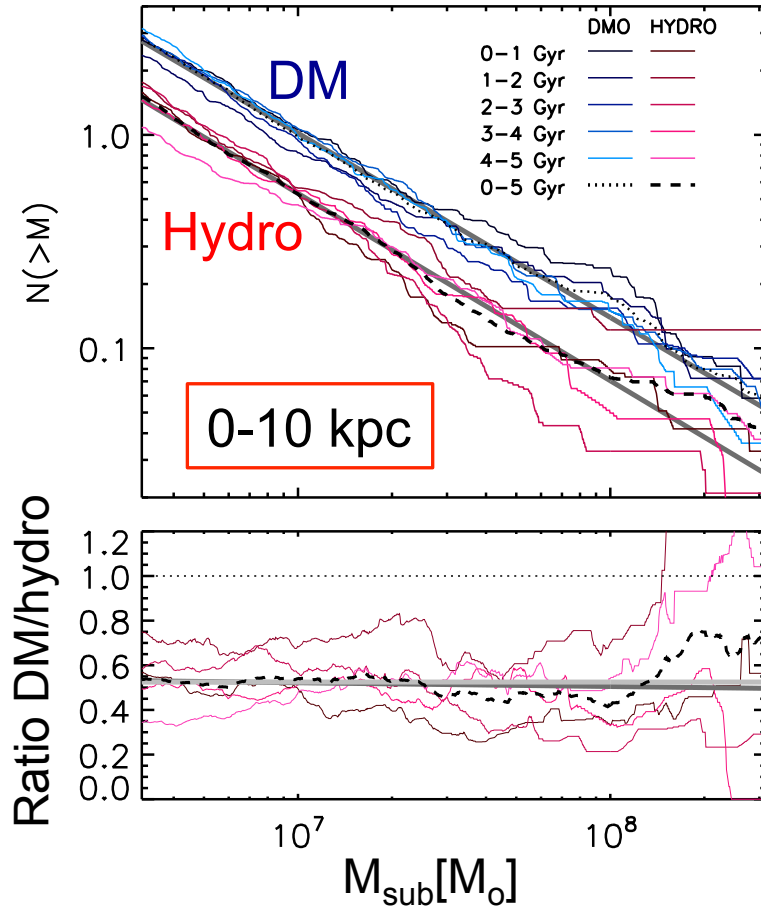


Dark matter only simulation



Hydrodynamic simulation

Destruction of dark substructures by galactic baryons

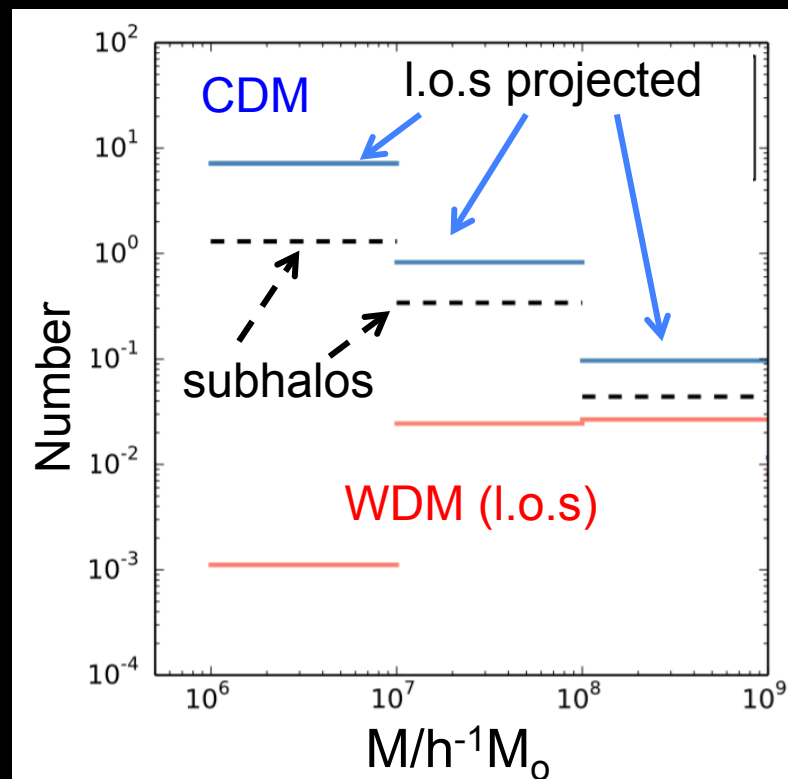
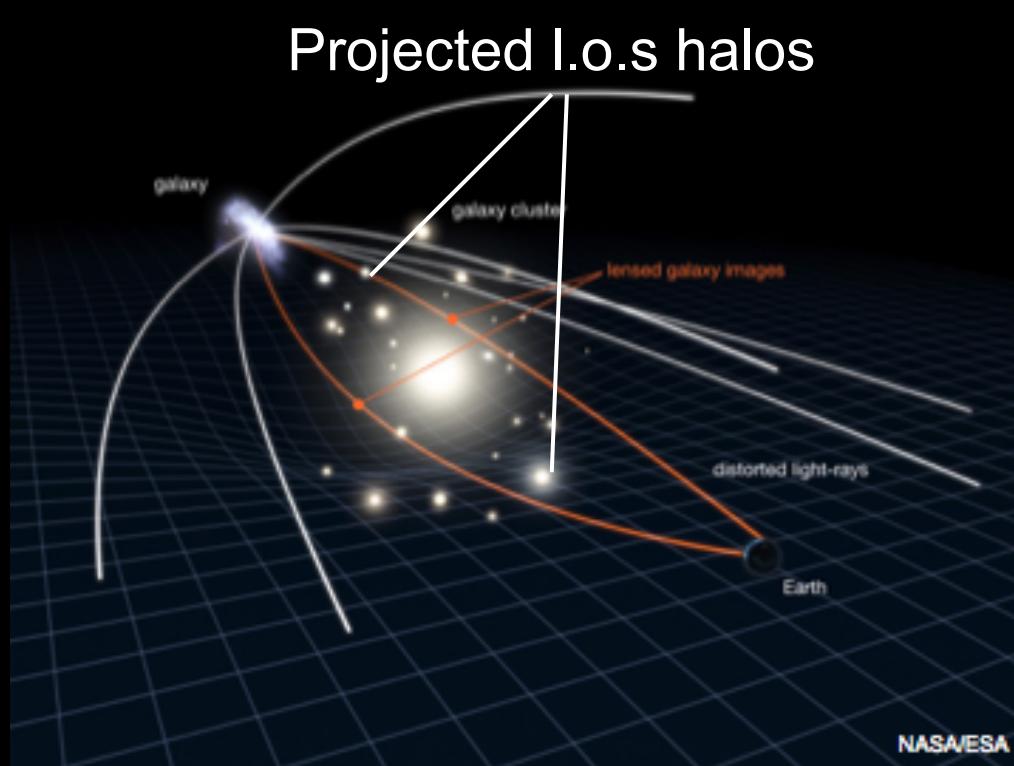


- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
 - 20% “ 50-200 kpc “
- Sawala et al '16

Substructures vs interlopers

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

Projected l.o.s halos



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

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)

The subhalo mass function

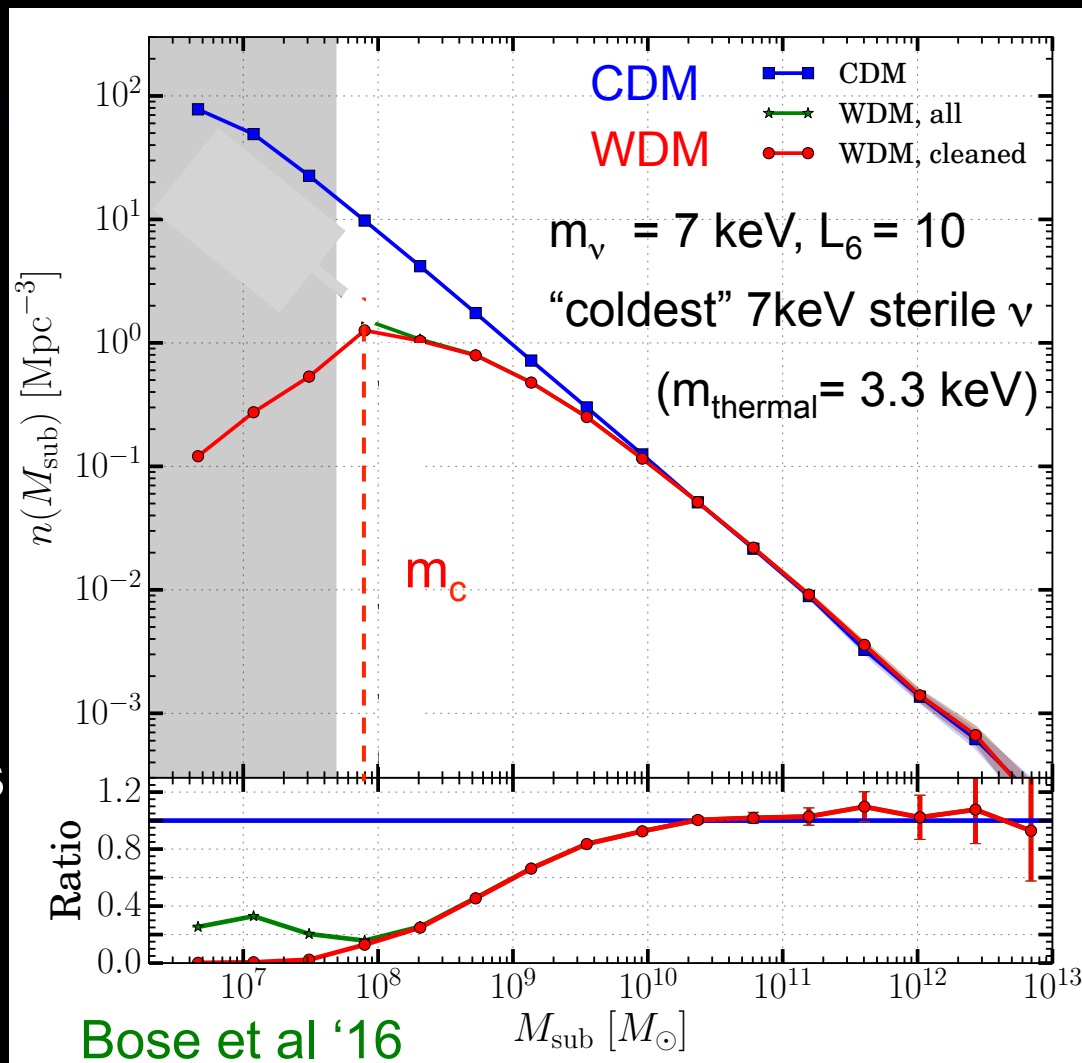


CDM

WDM

Already fewer WDM subhalos
at $3 \times 10^9 M_\odot$

10 x fewer at $10^8 M_\odot$



Detecting substructures with strong lensing

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

m_c = halo cutoff mass

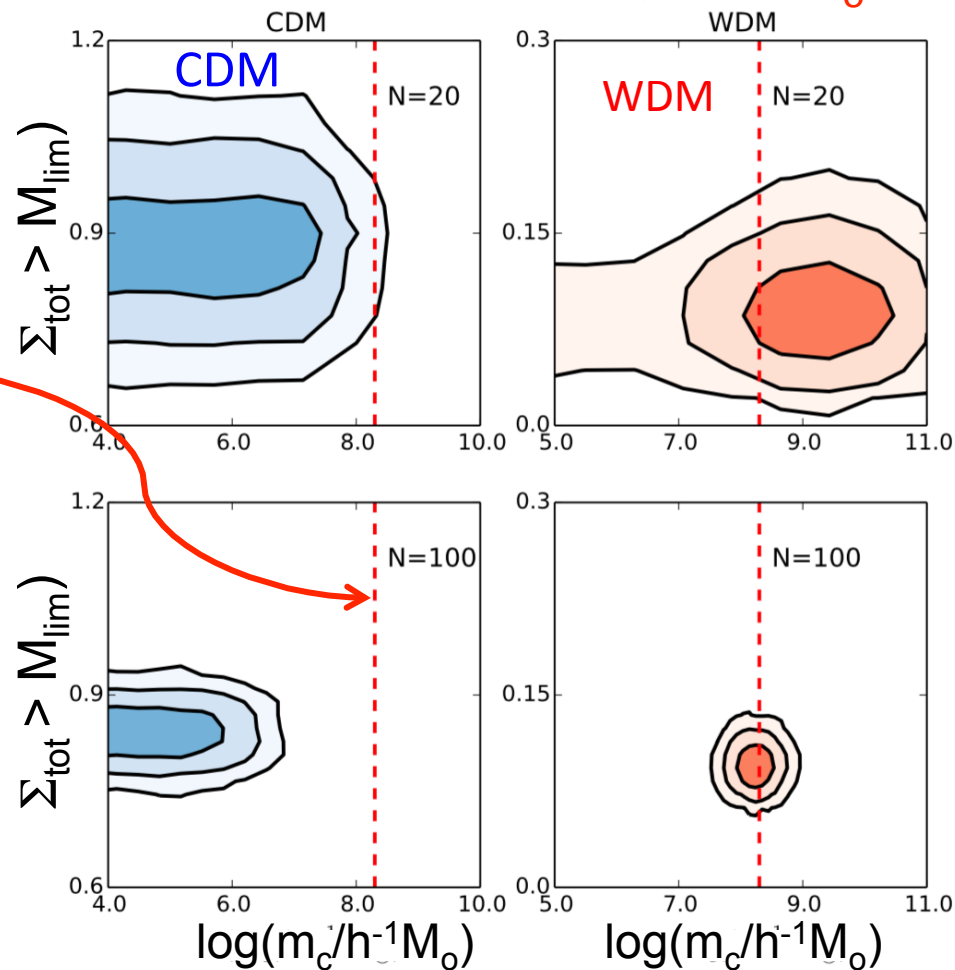
$m_c = 1.3 \times 10^8 h^{-1} M_\odot$ for coldest 7 keV sterile neutrino

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

- If DM is CDM $\rightarrow$ rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile $\nu \rightarrow$ rule out CDM at 3σ !

Li, CSF et al '16

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





Conclusions

- Λ CDM: great **success** on scales $> 1\text{Mpc}$: CMB, LSS, gal evolution
- But on these scales **Λ CDM** 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 gravitational lensing can distinguish CDM/WDM
(and could rule out CDM!)