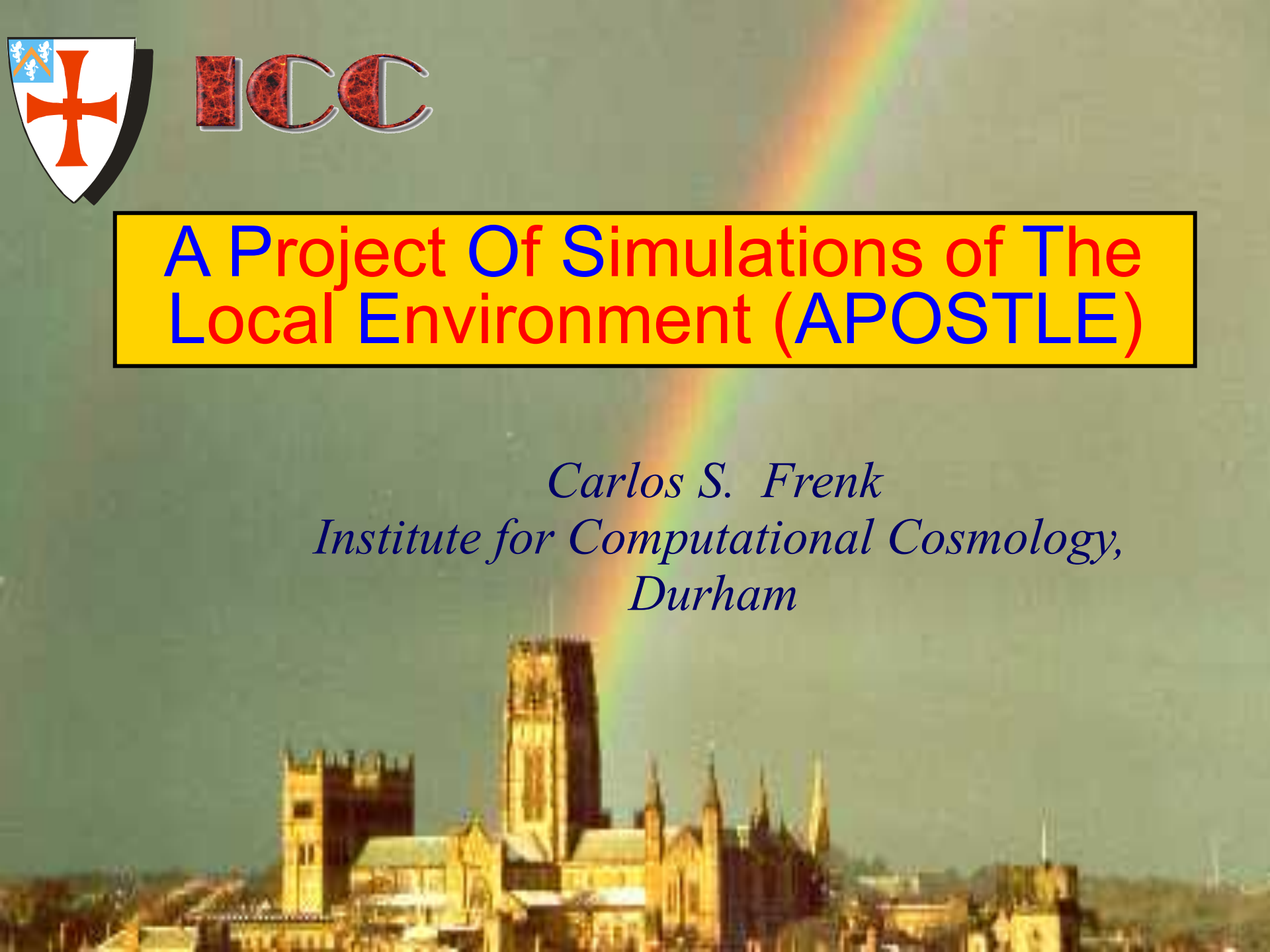


A Project Of Simulations of The Local Environment (APOSTLE)

Carlos S. Frenk
Institute for Computational Cosmology, Durham

VIRGO

icc.dur.ac.uk/Eagle

"Evolution and assembly of galaxies and their environment"

THE EAGLE PROJECT

Virgo Consortium

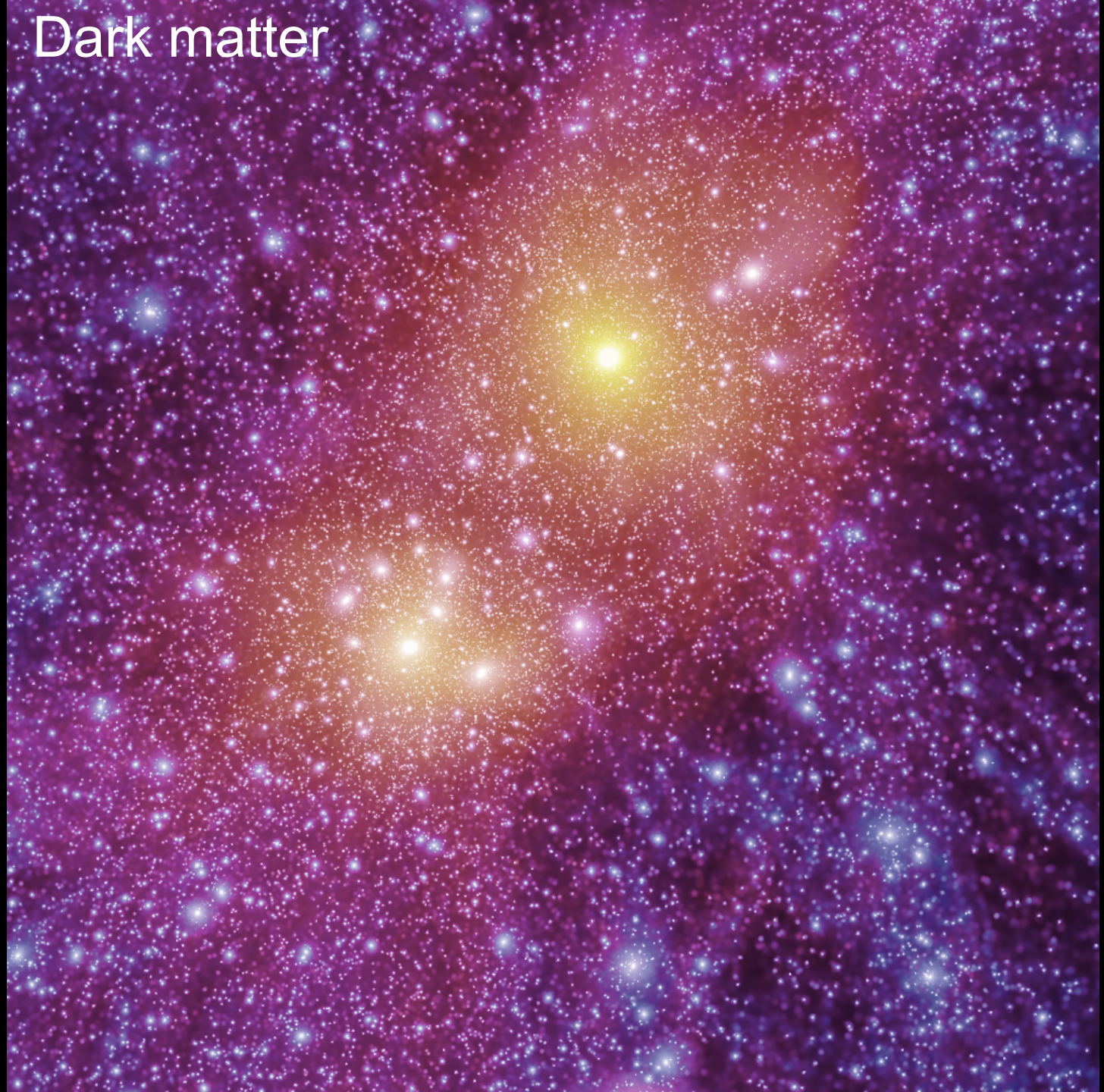
Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

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
&
WDM

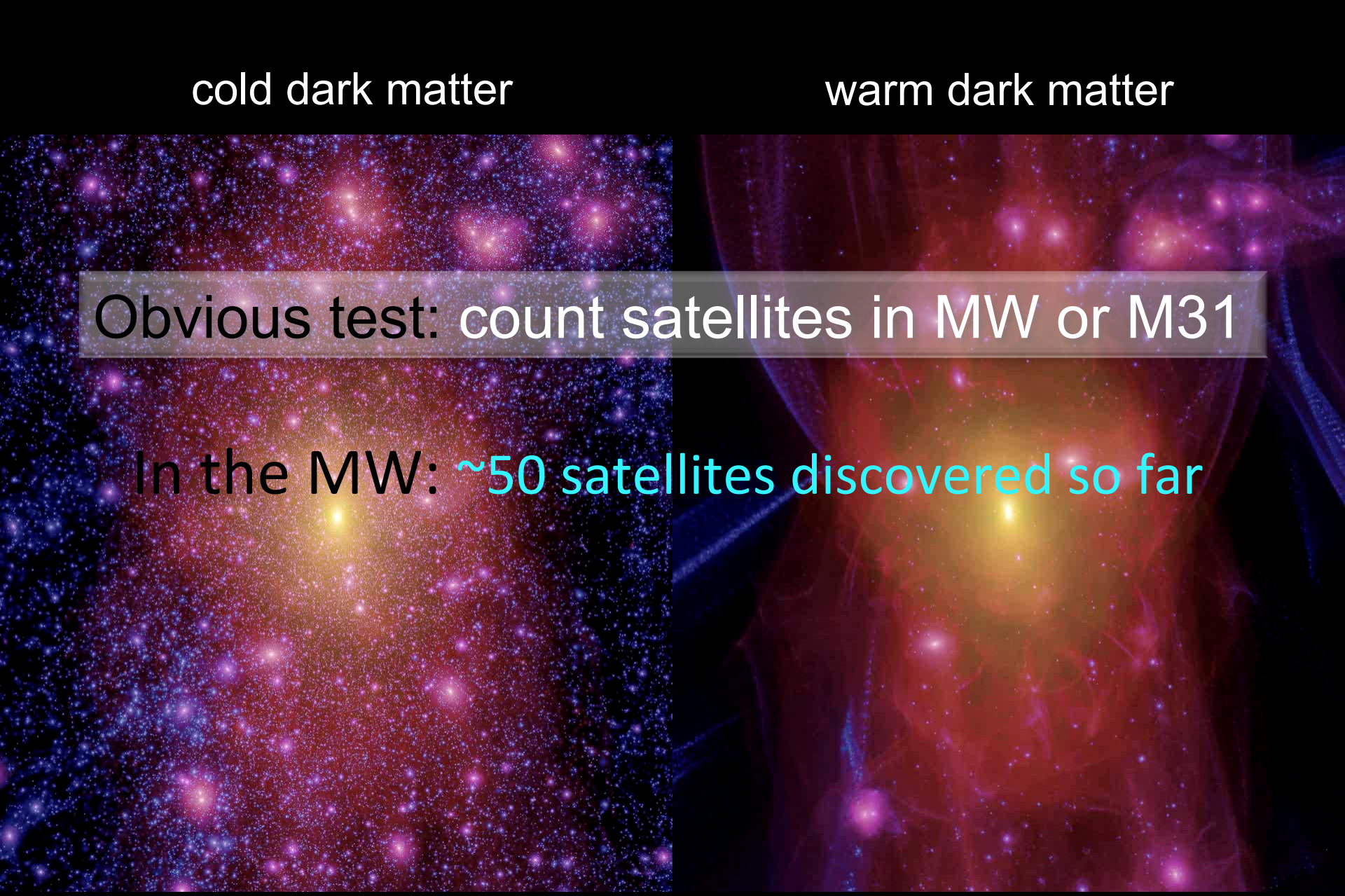
Sawala et al ’15
Fattahi et al ’15
Lovell et al’ 16

cold dark matter

warm dark matter

How can we distinguish between these?

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



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

cold dark matter

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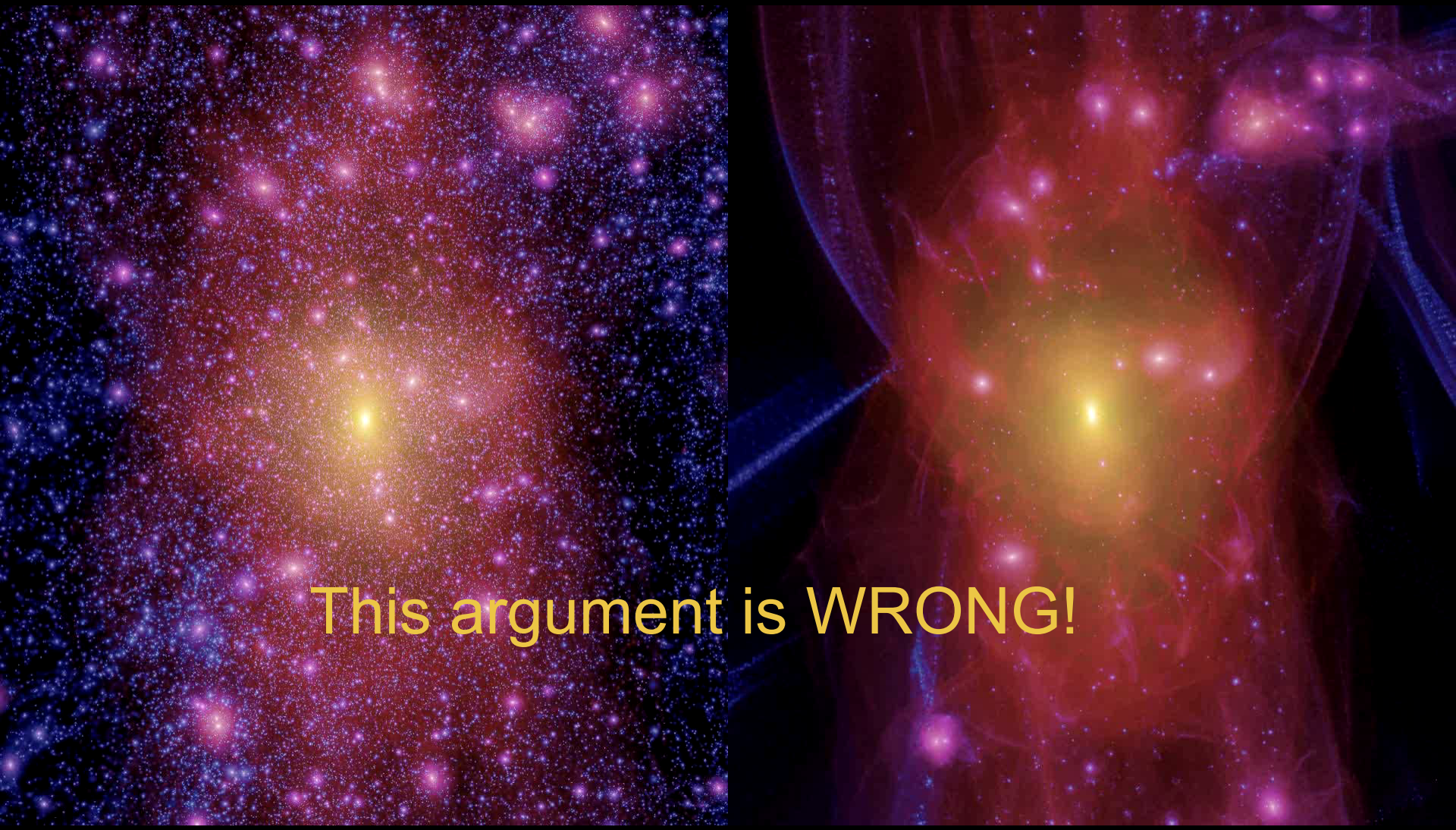

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

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

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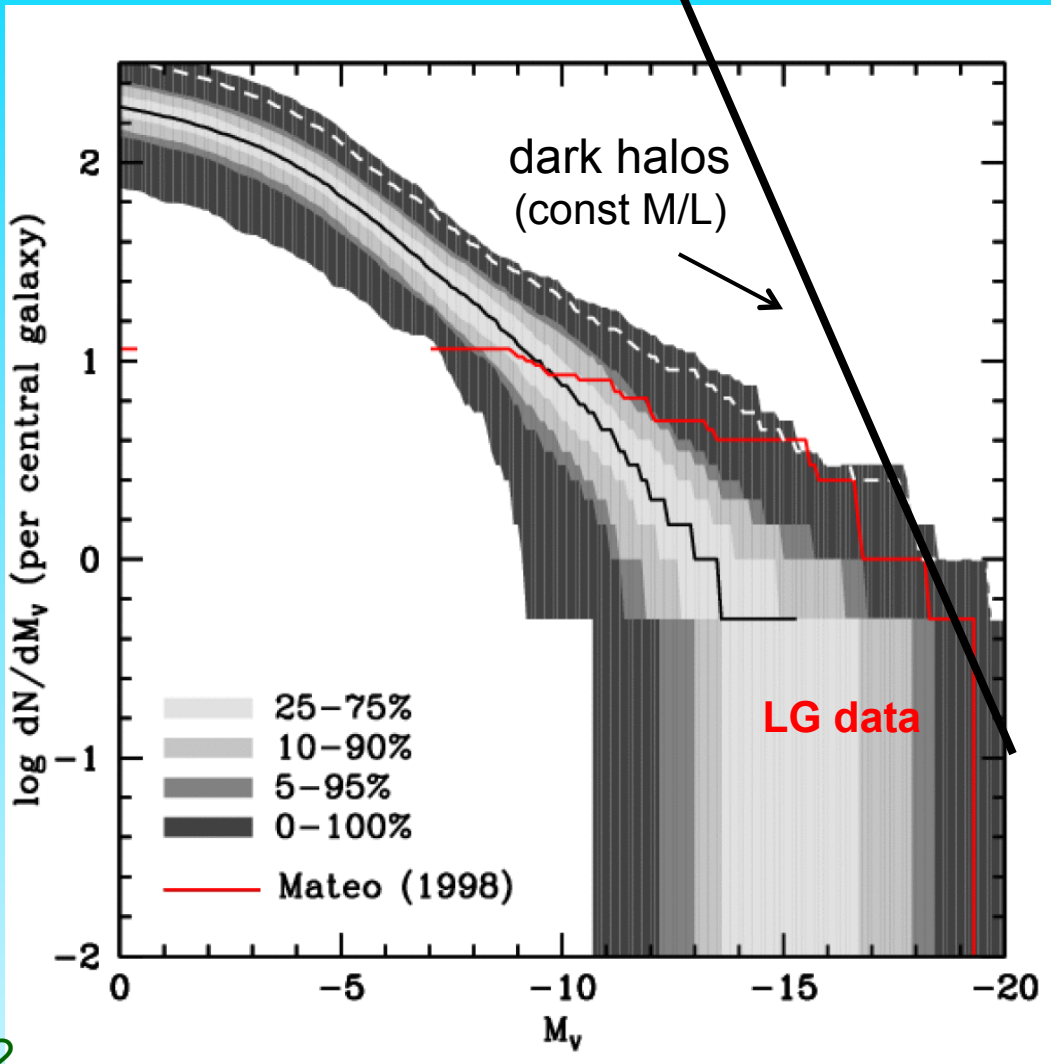
Luminosity Function of Local Group Satellites

- 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 (~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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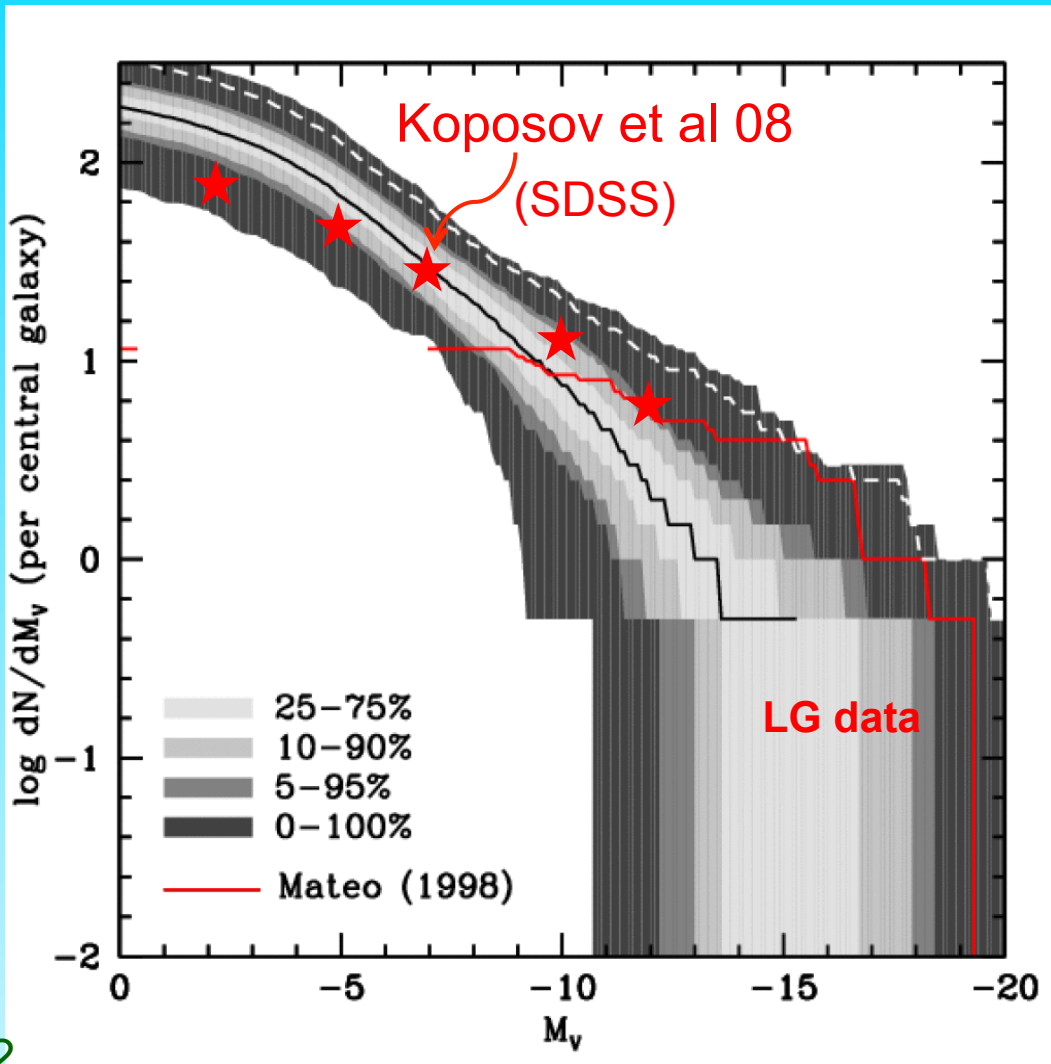

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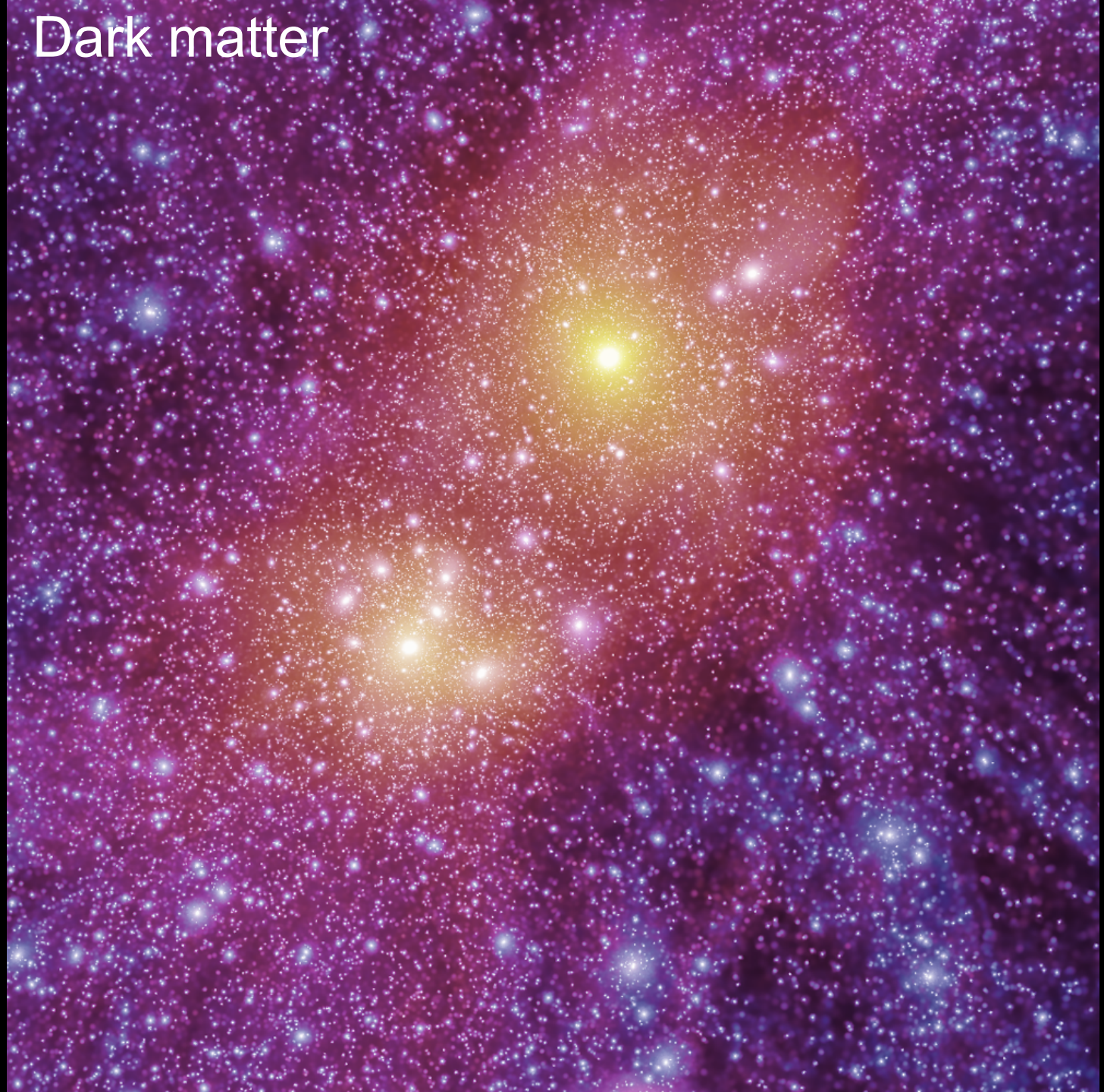


VIRGO

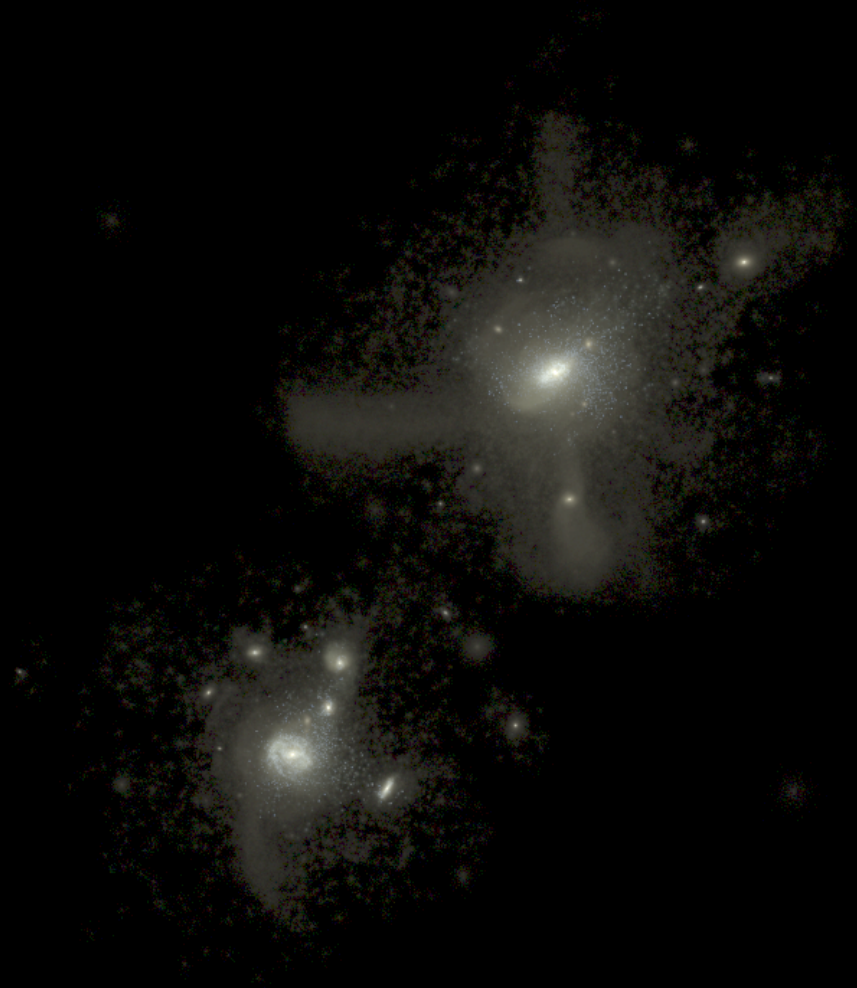
APOSTLE
EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘15

Stars



APOSTLE
EAGLE full hydro simulations

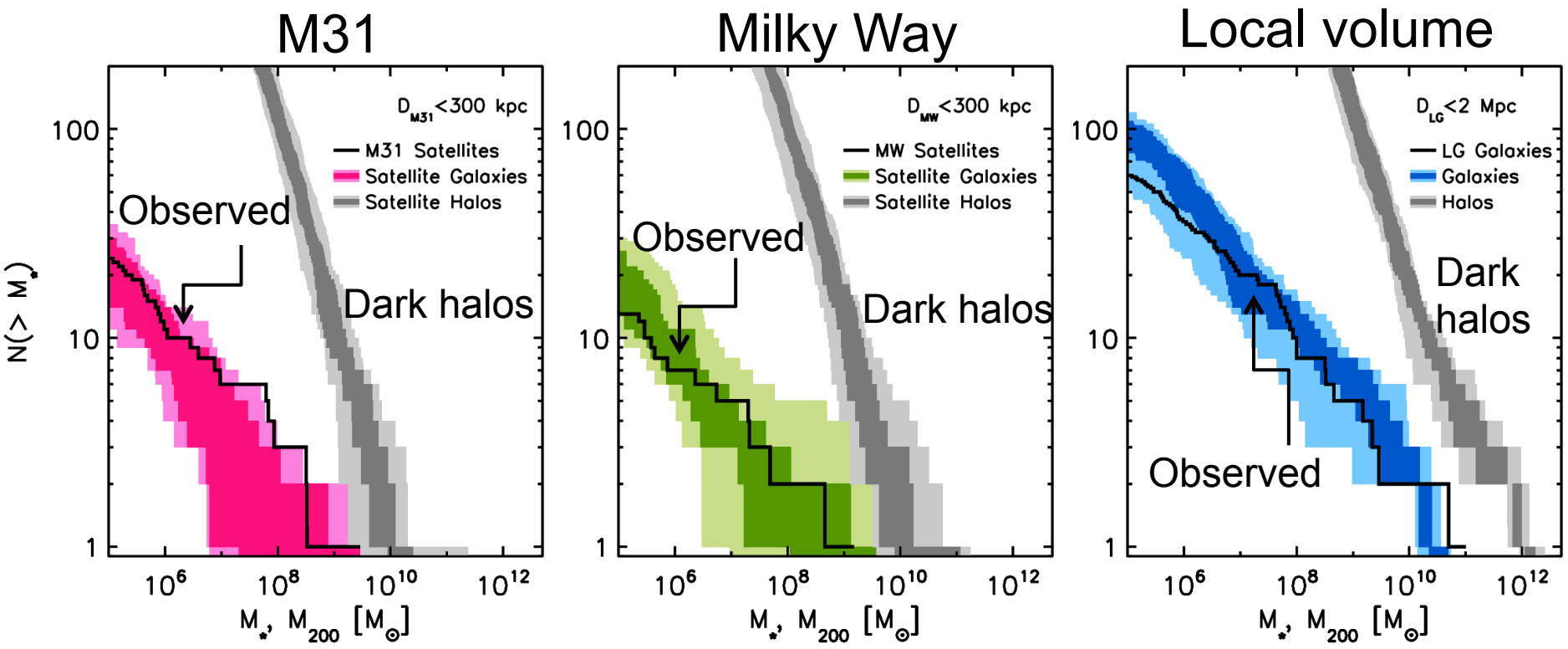
Local Group

Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

University of Durham

EAGLE Local Group simulation



Sawala et al '15

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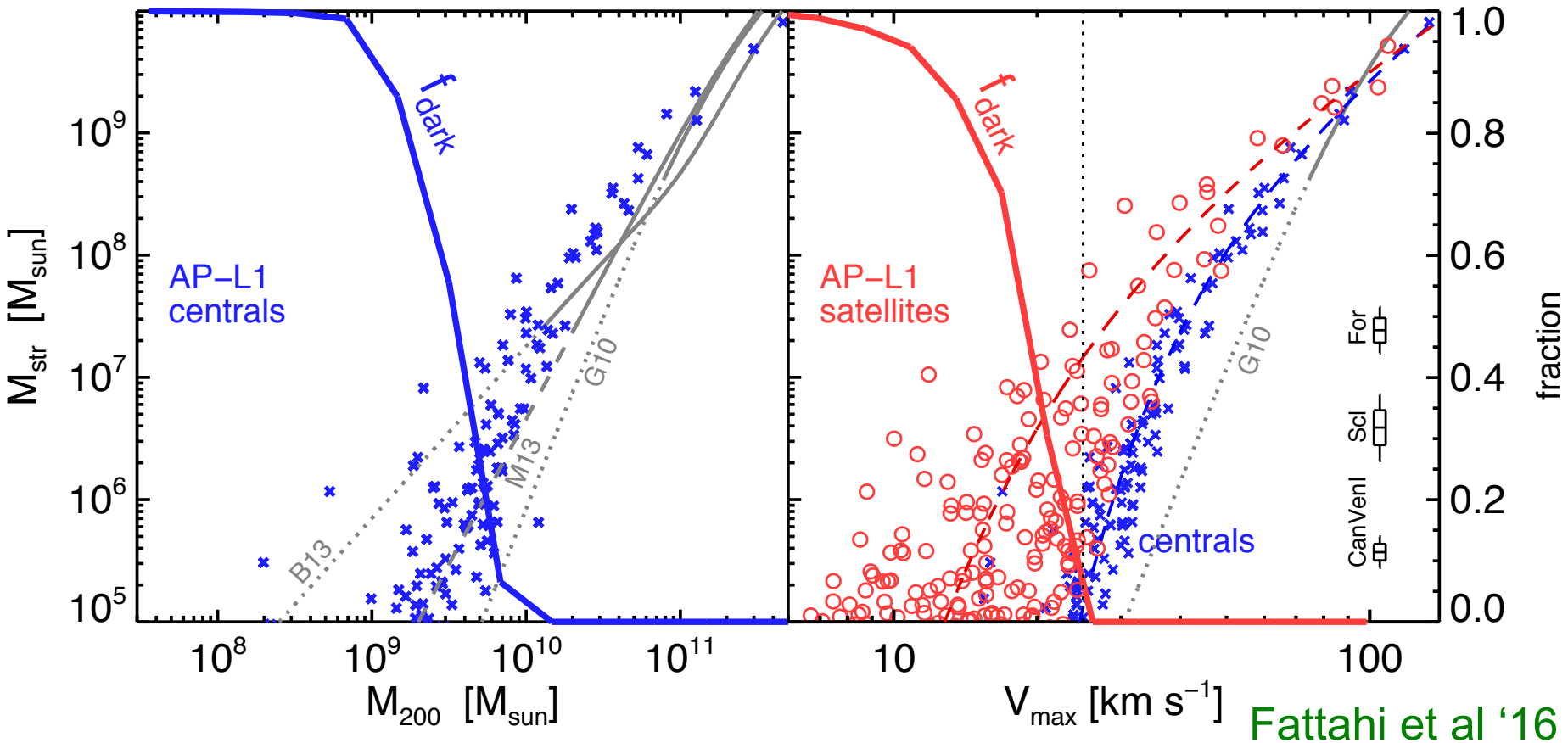
Fraction of dark subhalos

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



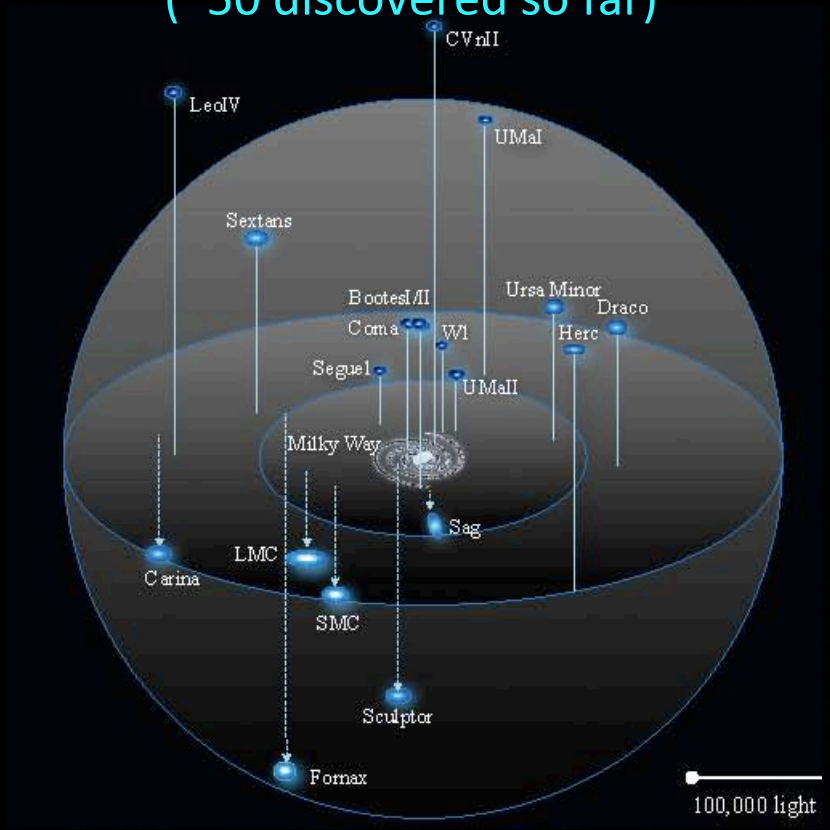
Fattahi et al '16

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

How about in WDM?

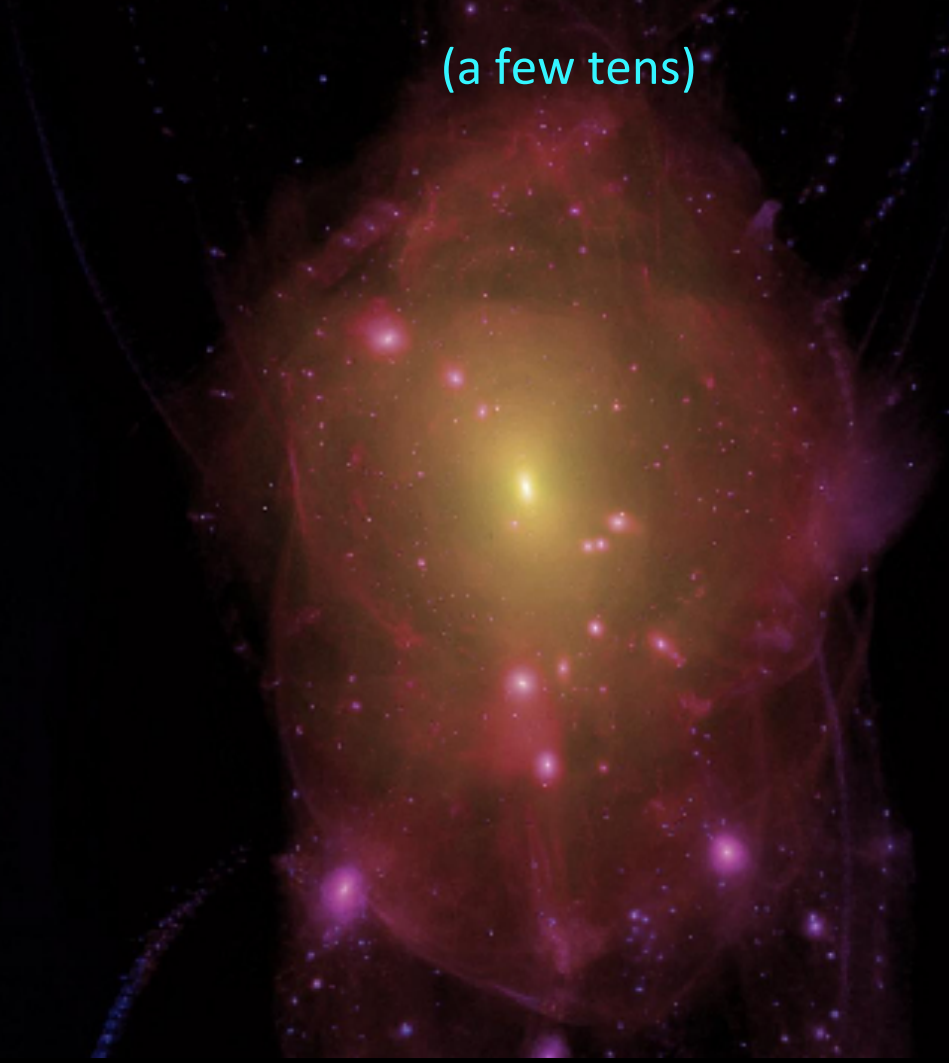
The satellites of the MW

(~50 discovered so far)



Dark mattter subhalos in WDM

(a few tens)



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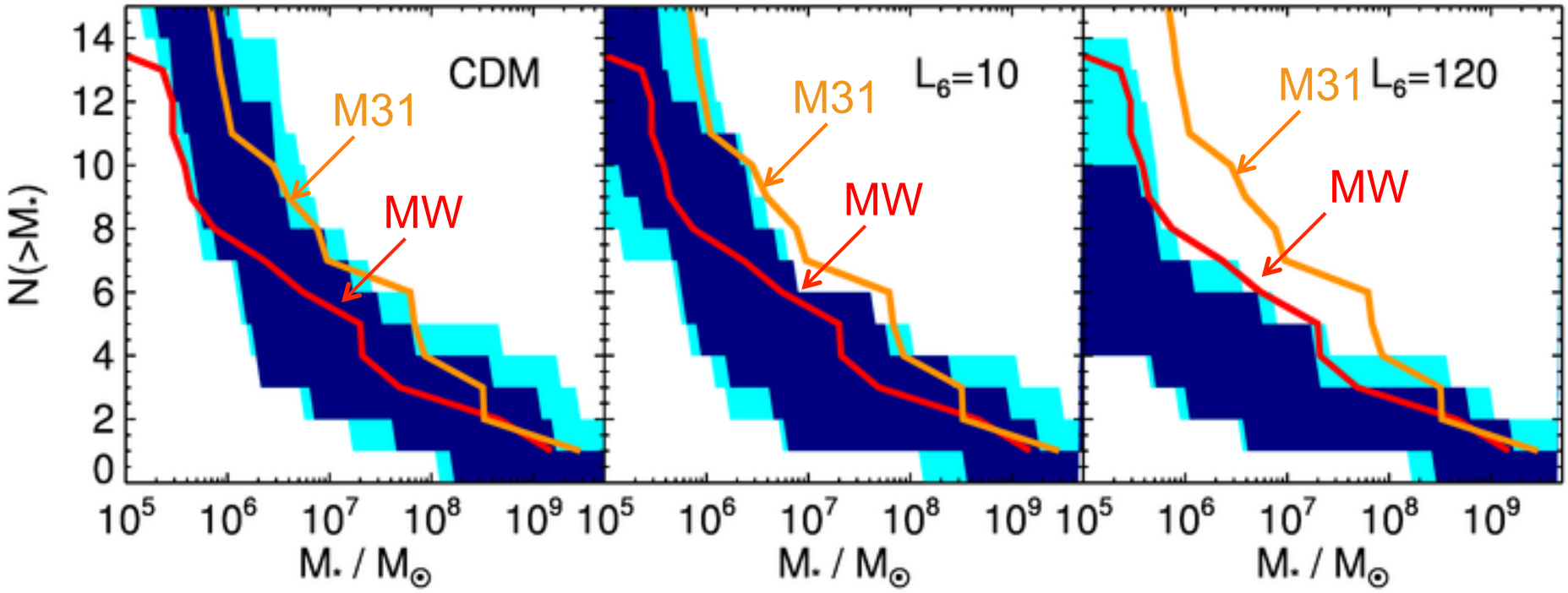
Luminosity Function of Local Group Satellites in WDM

From "Warm Apostle:" 7keV sterile ν $M_h \sim 10^{12} M_o$



Lovell et al. '16

Institute for Computational Cosmology

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

$V_{max} = \max V_c$

"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

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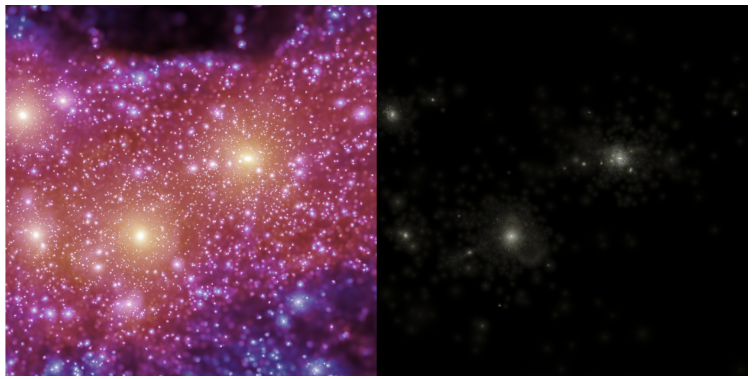
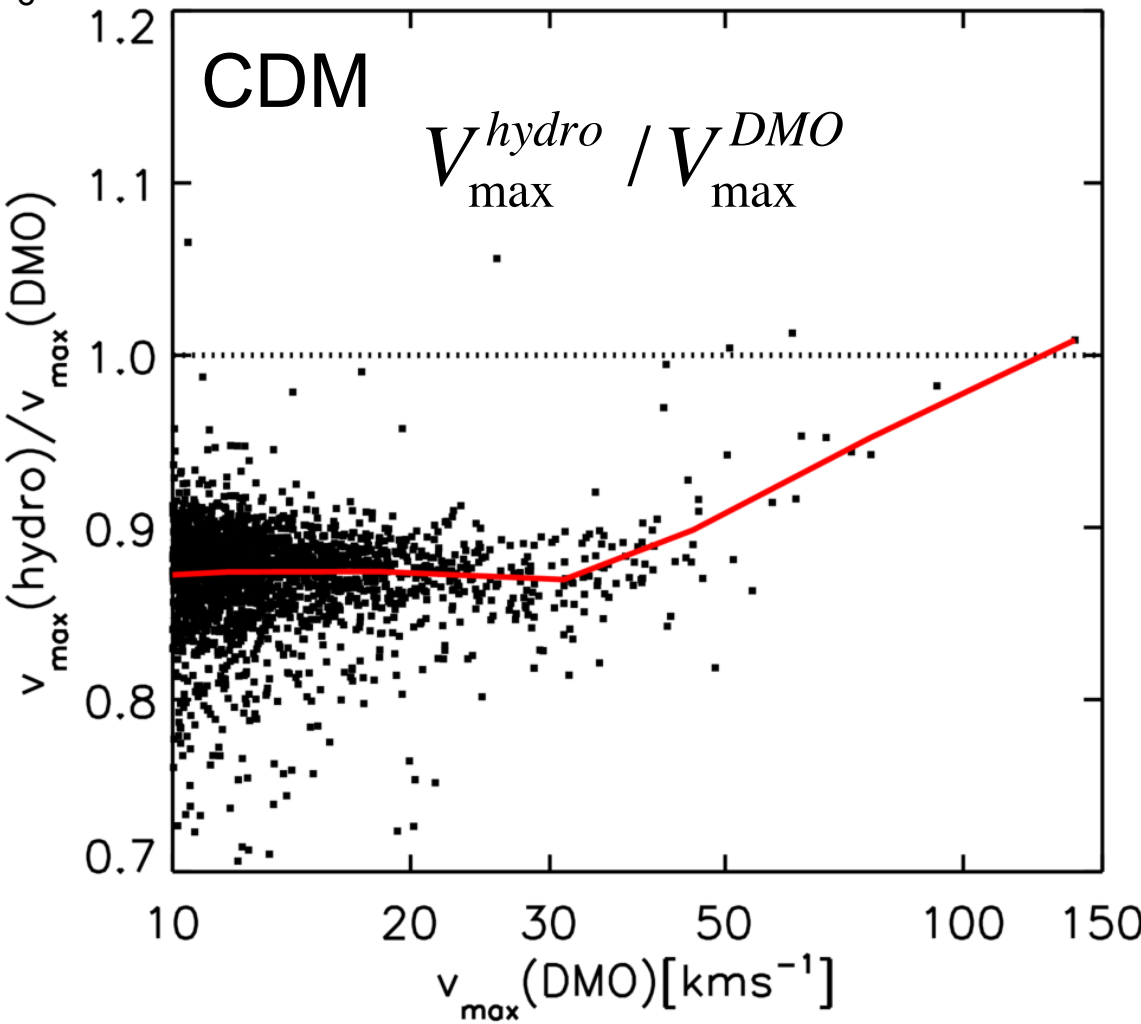
$$V_c = \sqrt{\frac{GM}{r}}$$

$V_{max} = \max V_c$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala et al. '13, '15

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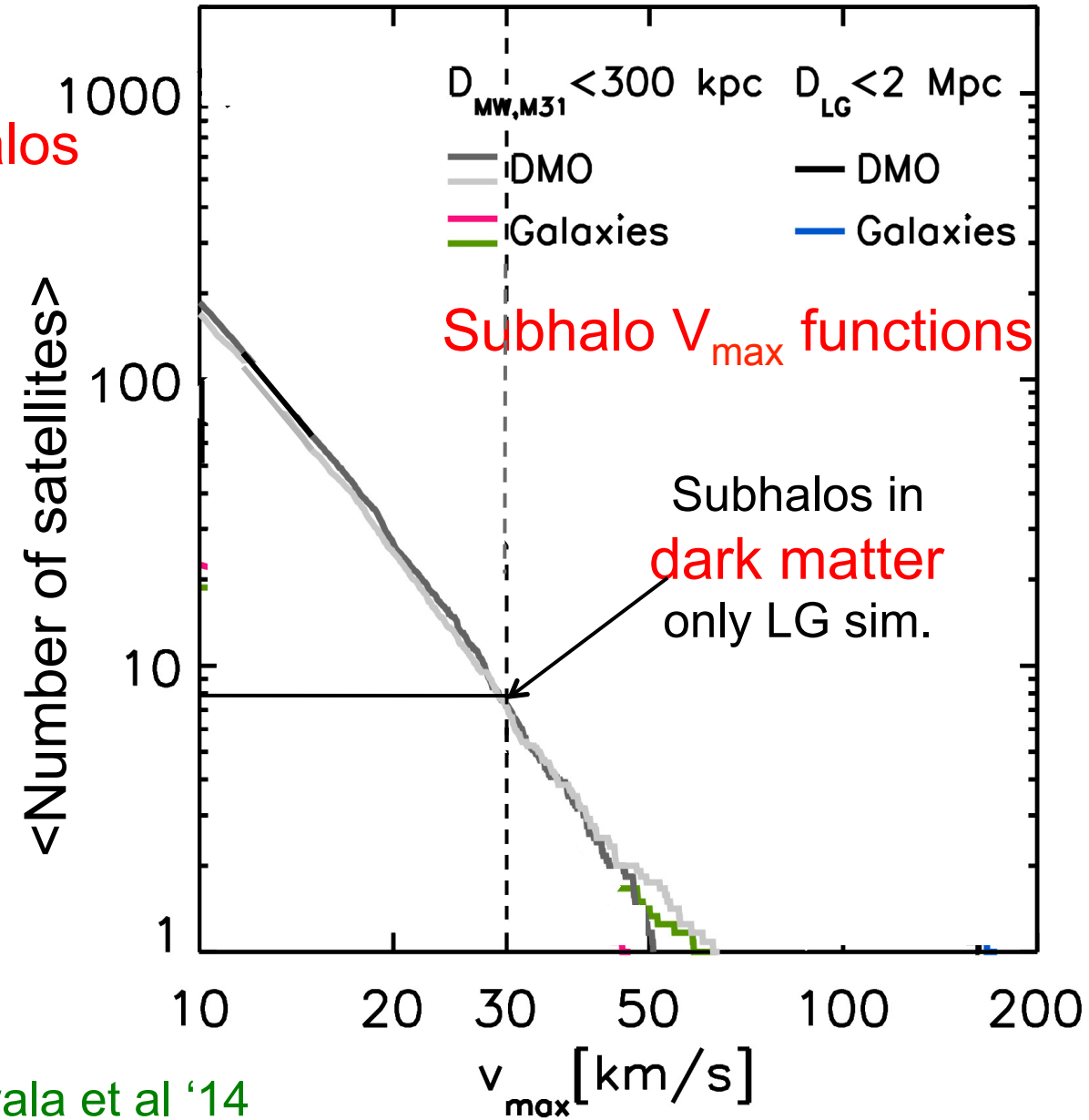
Too-big-to-fail: the baryon bailout

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



Sawala et al '14

Too-big-to-fail: the baryon bailout

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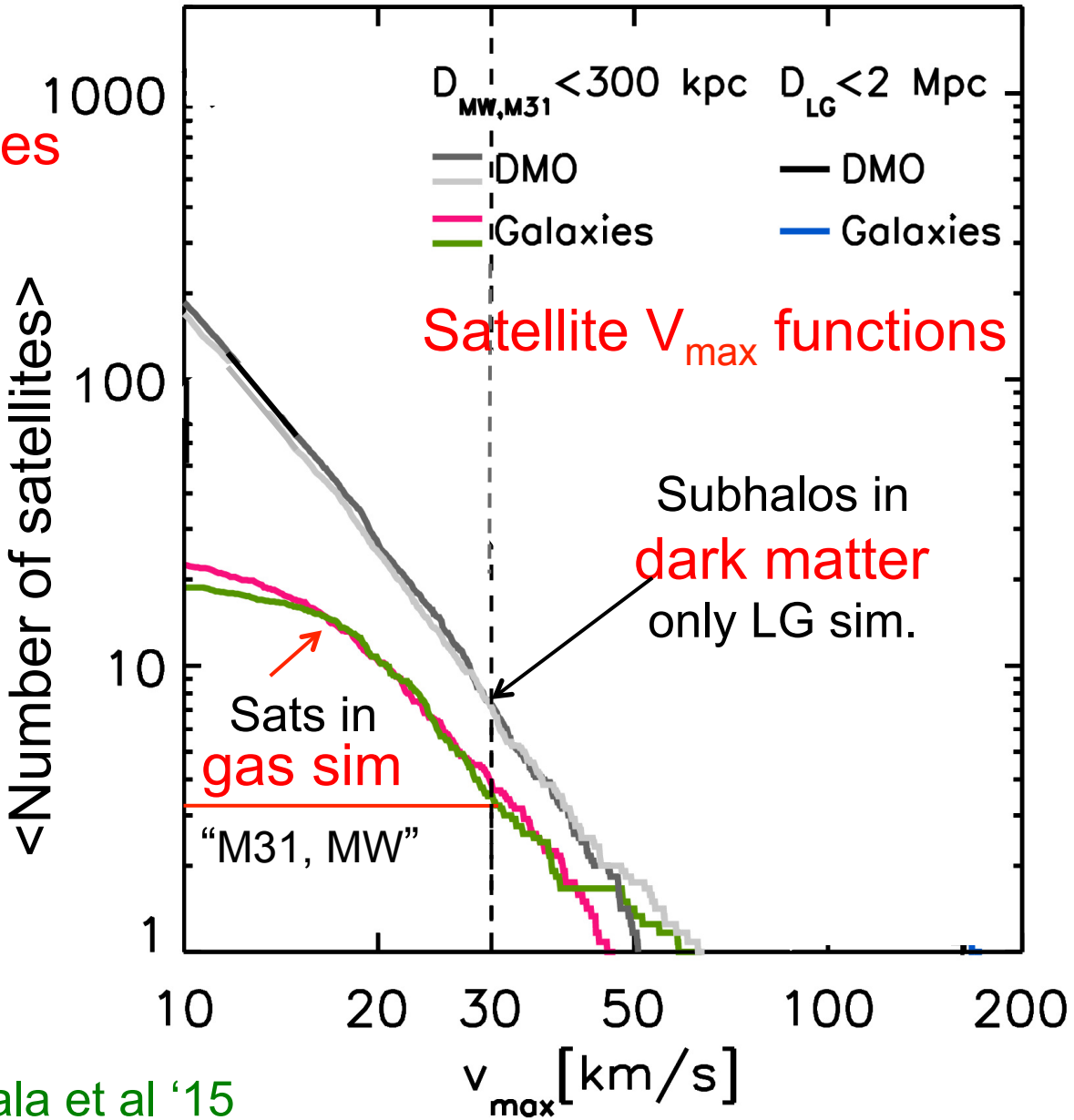
Hydro sims → ~3 satellites with V_{max}> 30 km/s



Sawala et al '15

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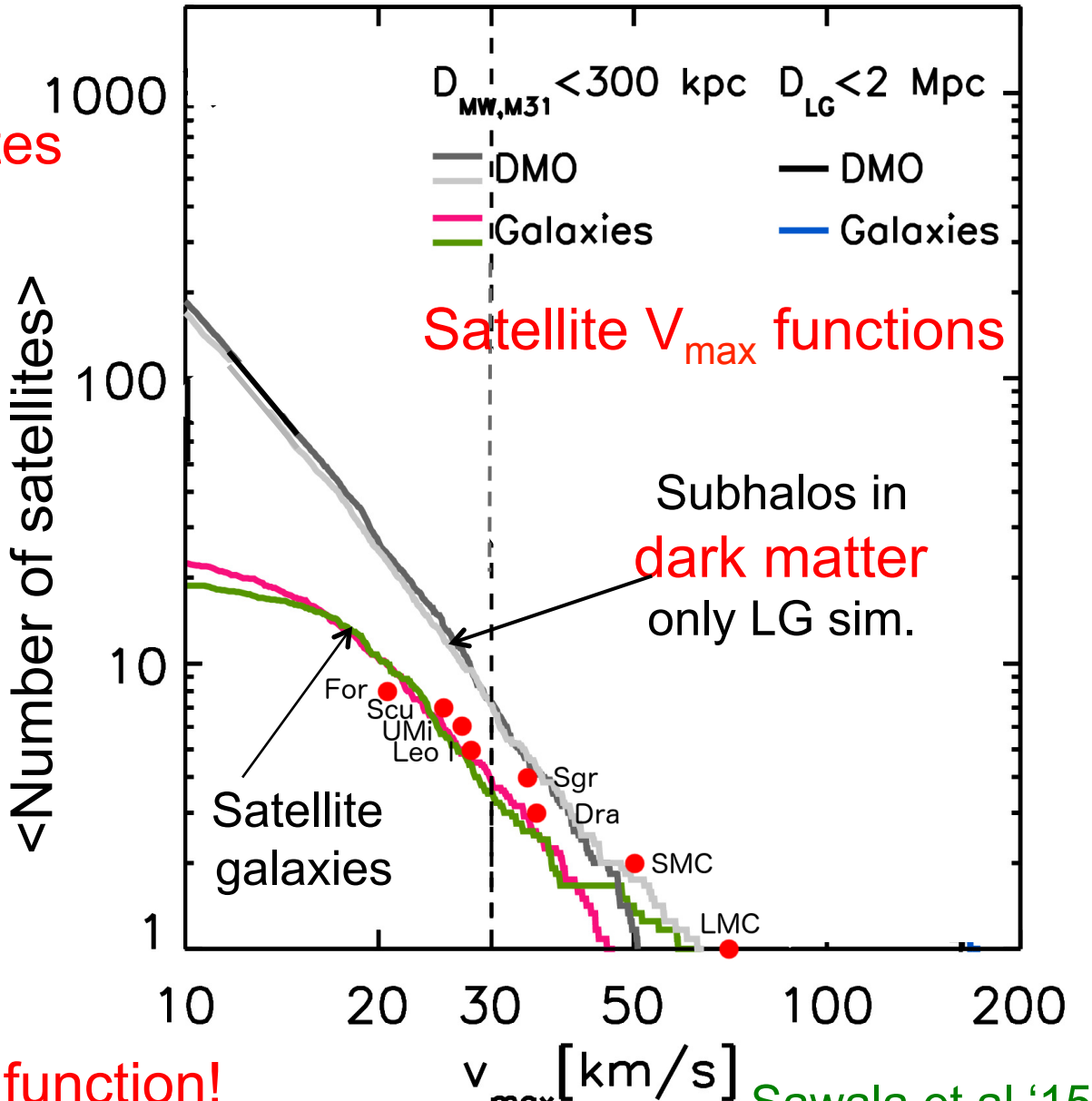
Too-big-to-fail: the baryon bailout

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



… and with correct V_{max} function!

Sawala et al '15

No too-big-to-fail problem in CDM

→

When “baryon effects” are included

The core-cusp problem

cold dark matter

warm dark matter

Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

Lovell, Eke, Frenk, Gao, Jenkins, Theuns ‘12


ICC
$\rho(r) = \frac{\rho_0}{\frac{r}{r_0}\left(1+\frac{r}{b}\right)^2}$

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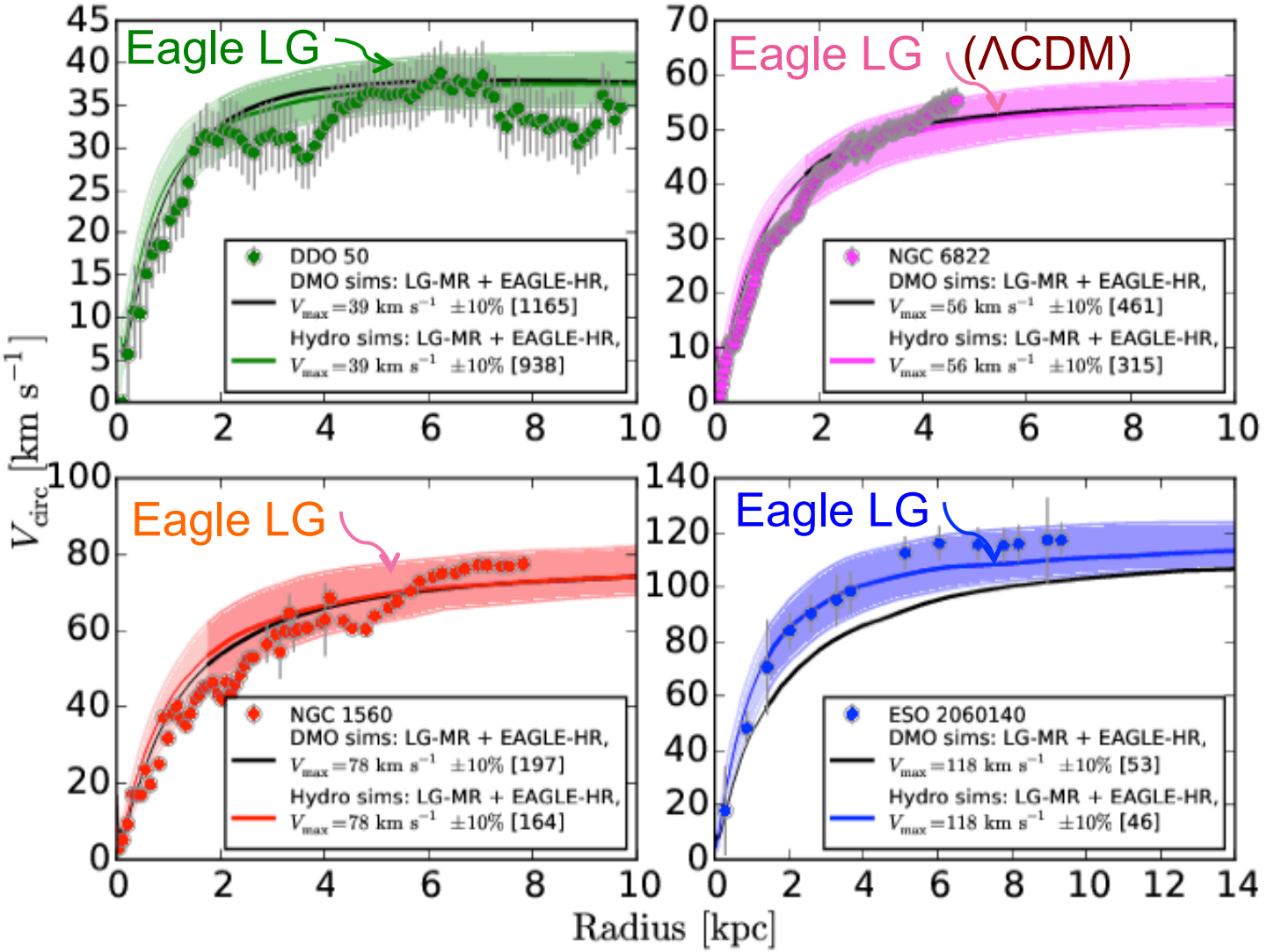
The diversity of gal rotation curves

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L_*)



Oman, Navarro, Frenk et al. '15

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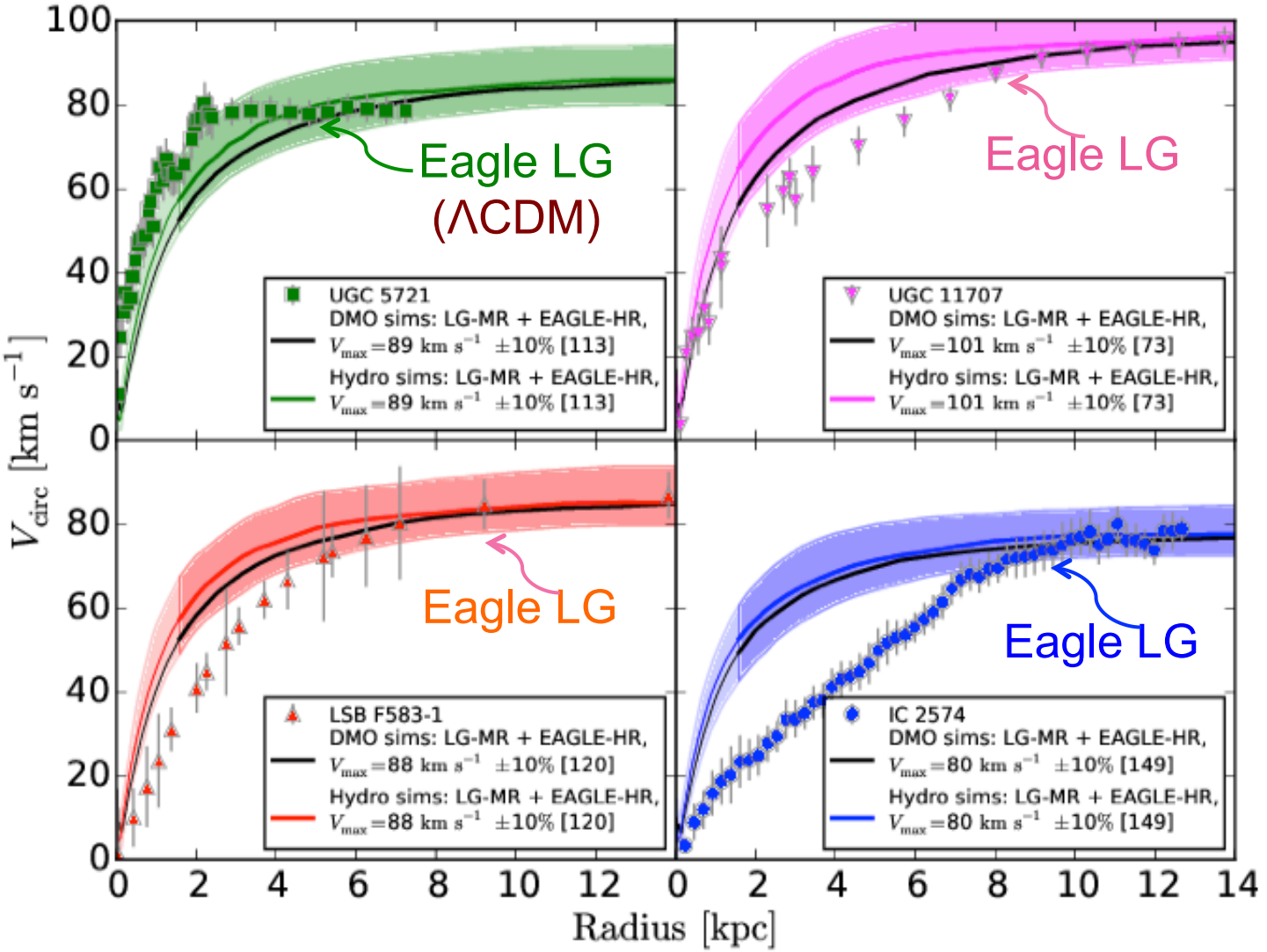
The diversity of gal rotation curves

Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L_*)



Oman et al. '15

University of Durham

Rotation curves of 2 APOSTLE dwarfs

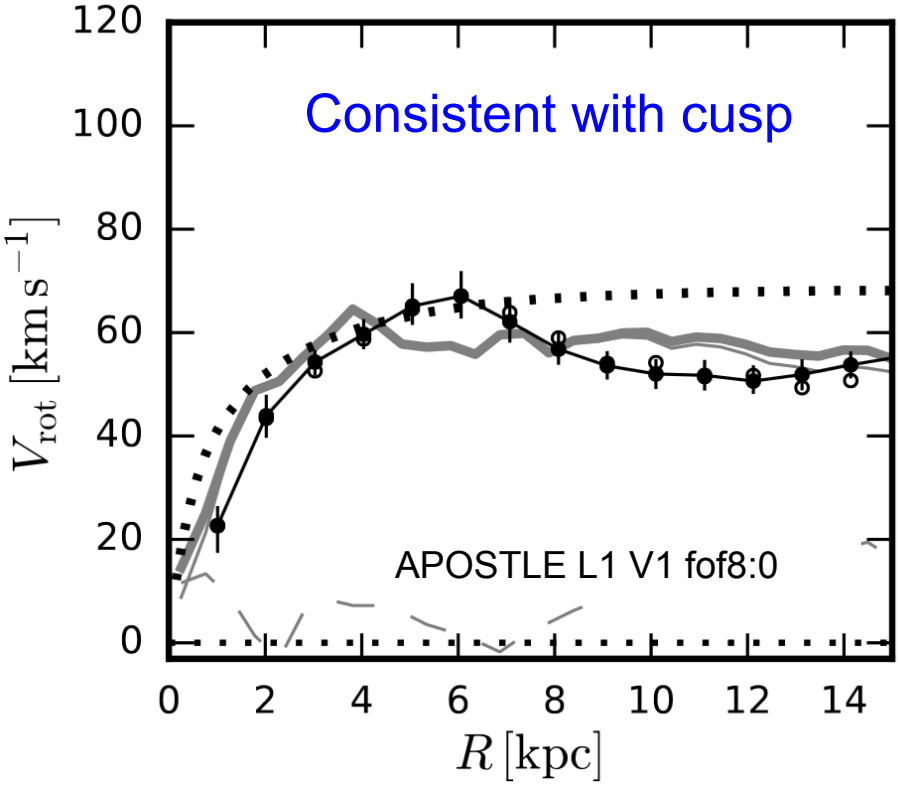
APOSTLE galaxies all have NFW cusps

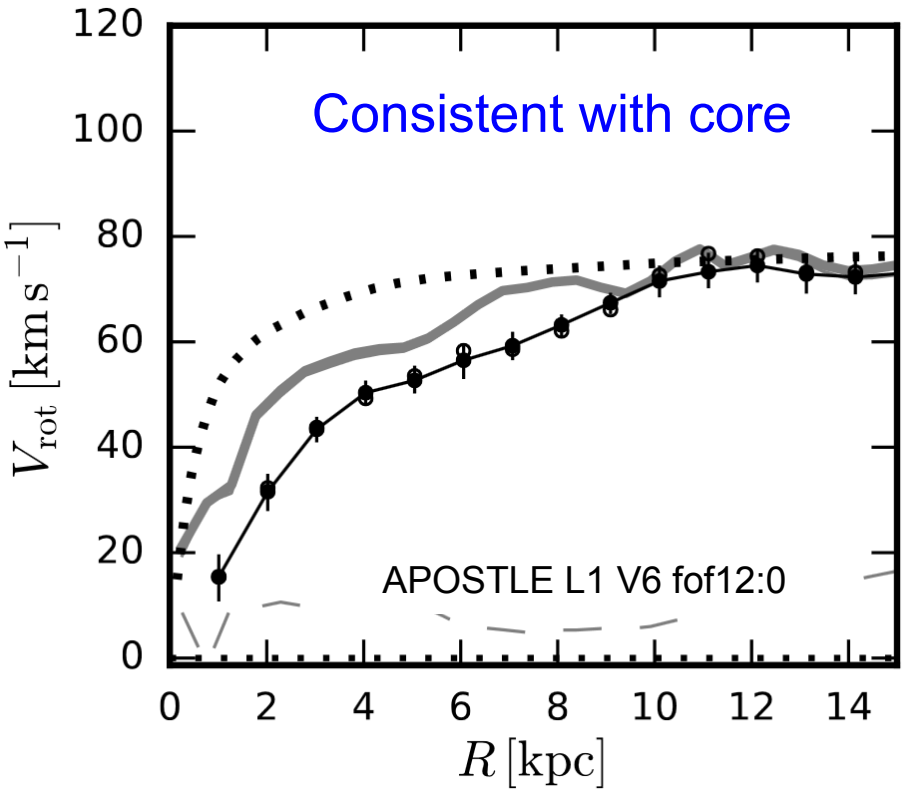
$V_c = \sqrt{\frac{GM(<r)}{r}}$

gas $V_\phi(r)$

^{3D}BAROLO fit

Tilted-ring model corrected for asymmetric drift





Oman et al '17

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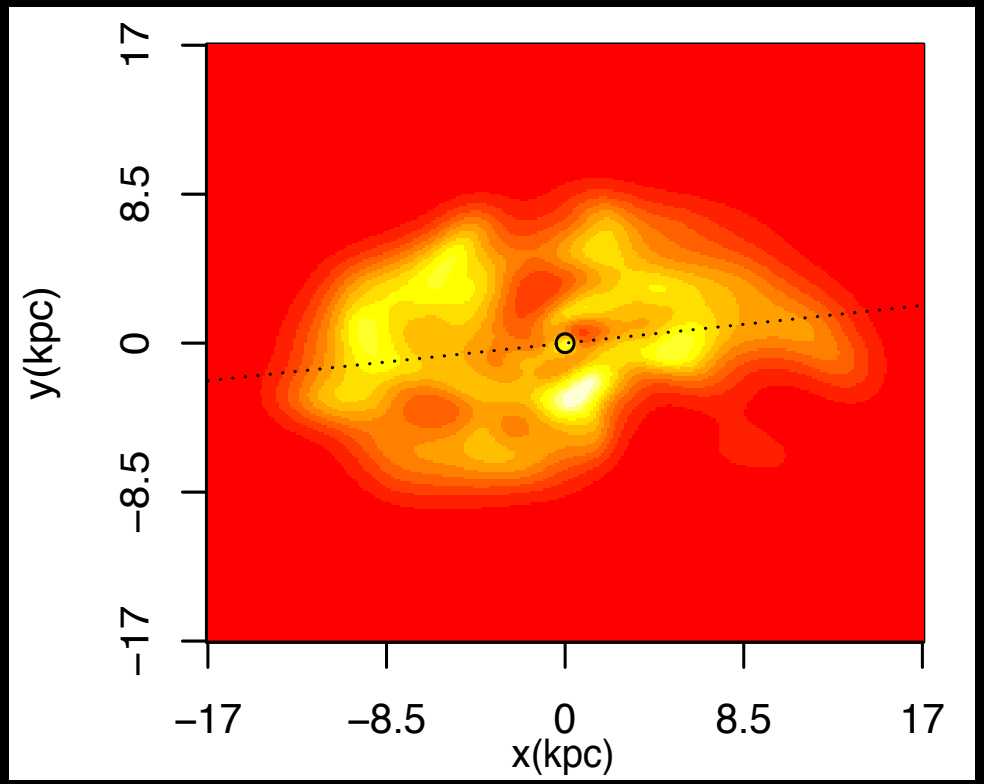
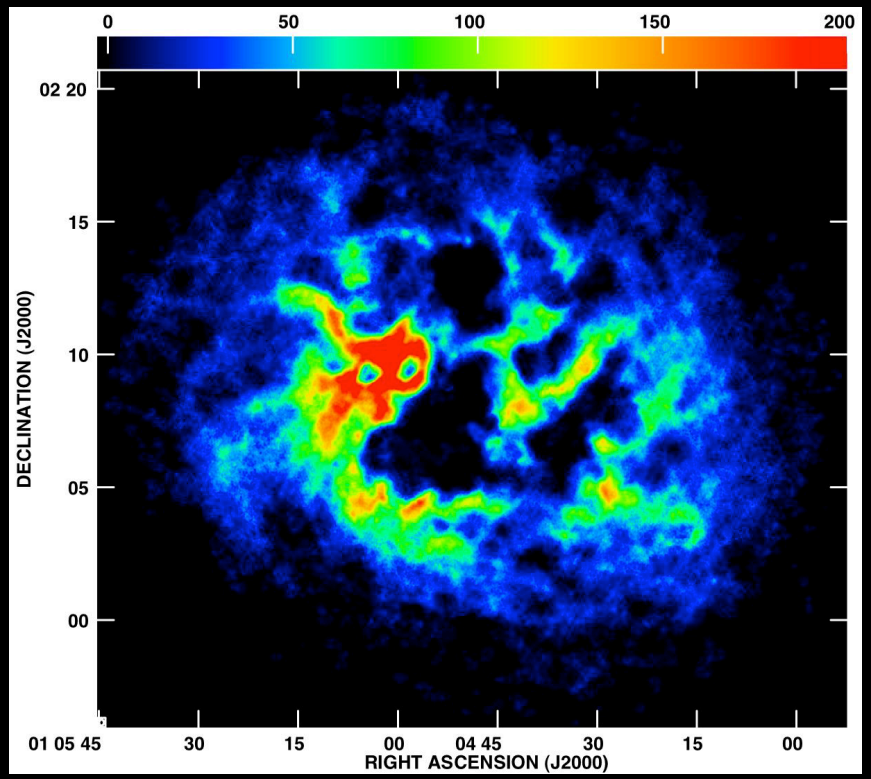
Rotation curves of APOSTLE dwarfs

Holes in APOSTLE due to supernovae explosions

APOSTLE dwarf



IC 1613 Little THINGS



Hague et al ‘16

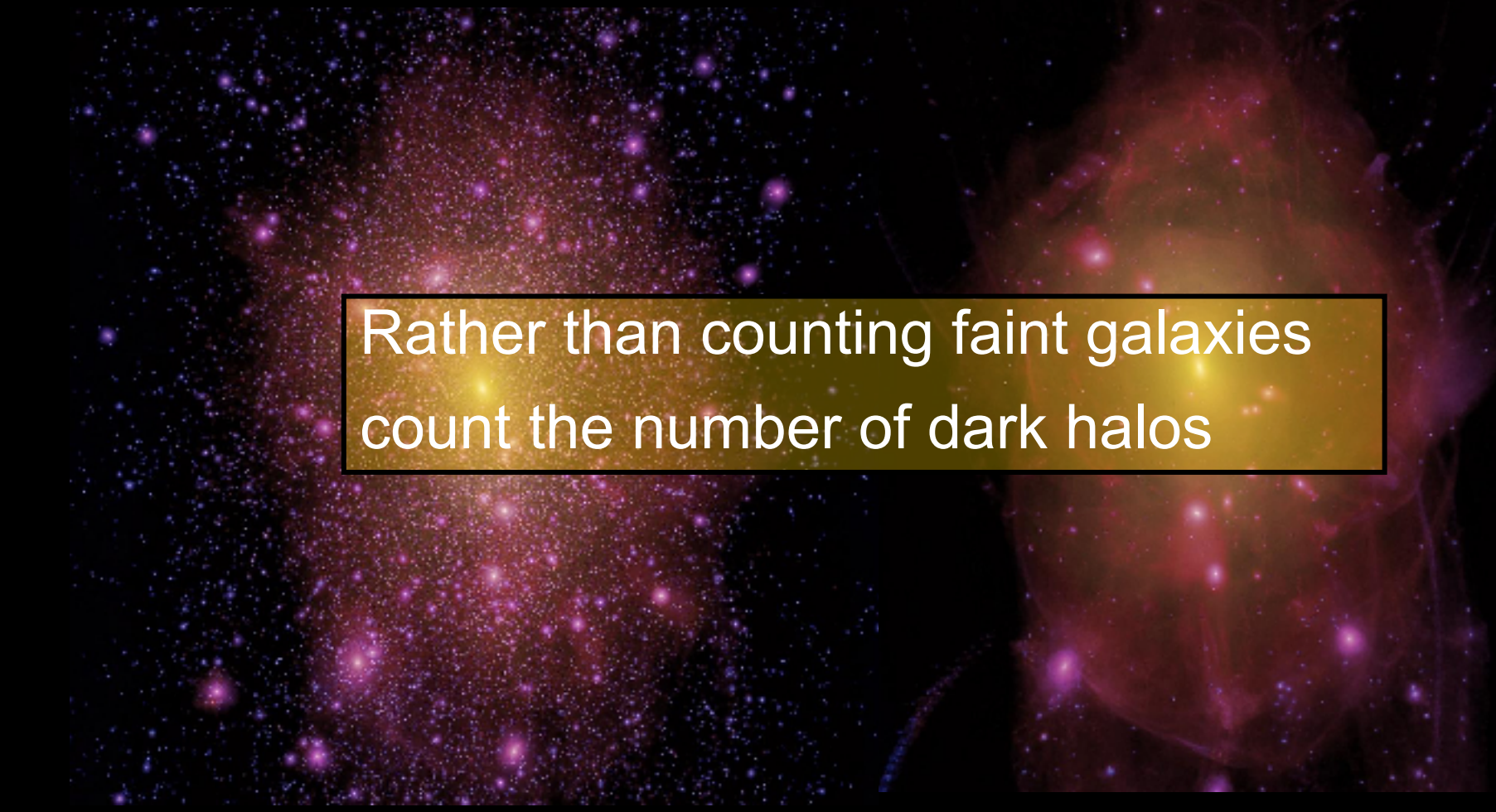
So, we can't distinguish CDM from WDM by counting satellite galaxies

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

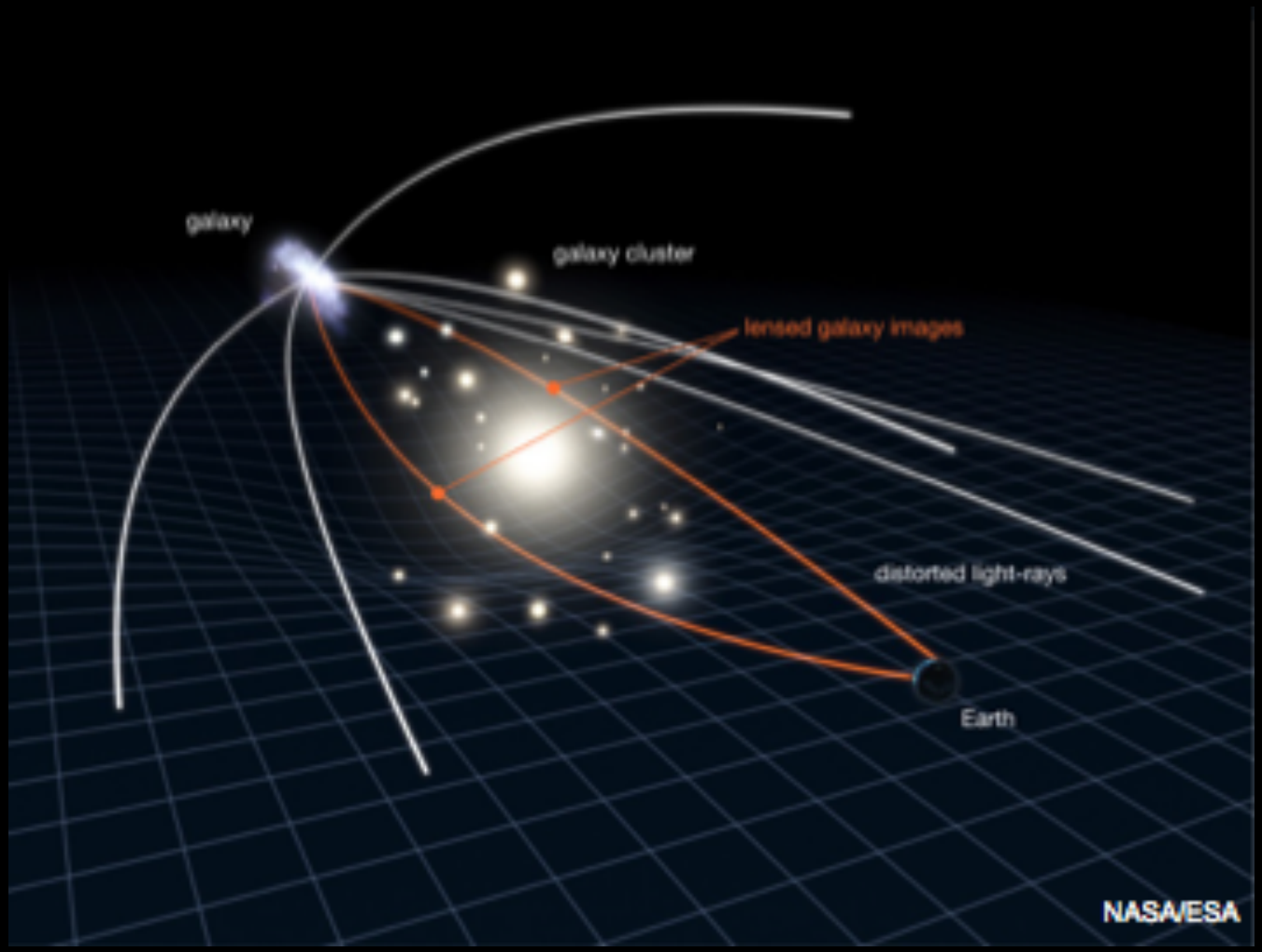
Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

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

Gravitational lensing: Einstein rings

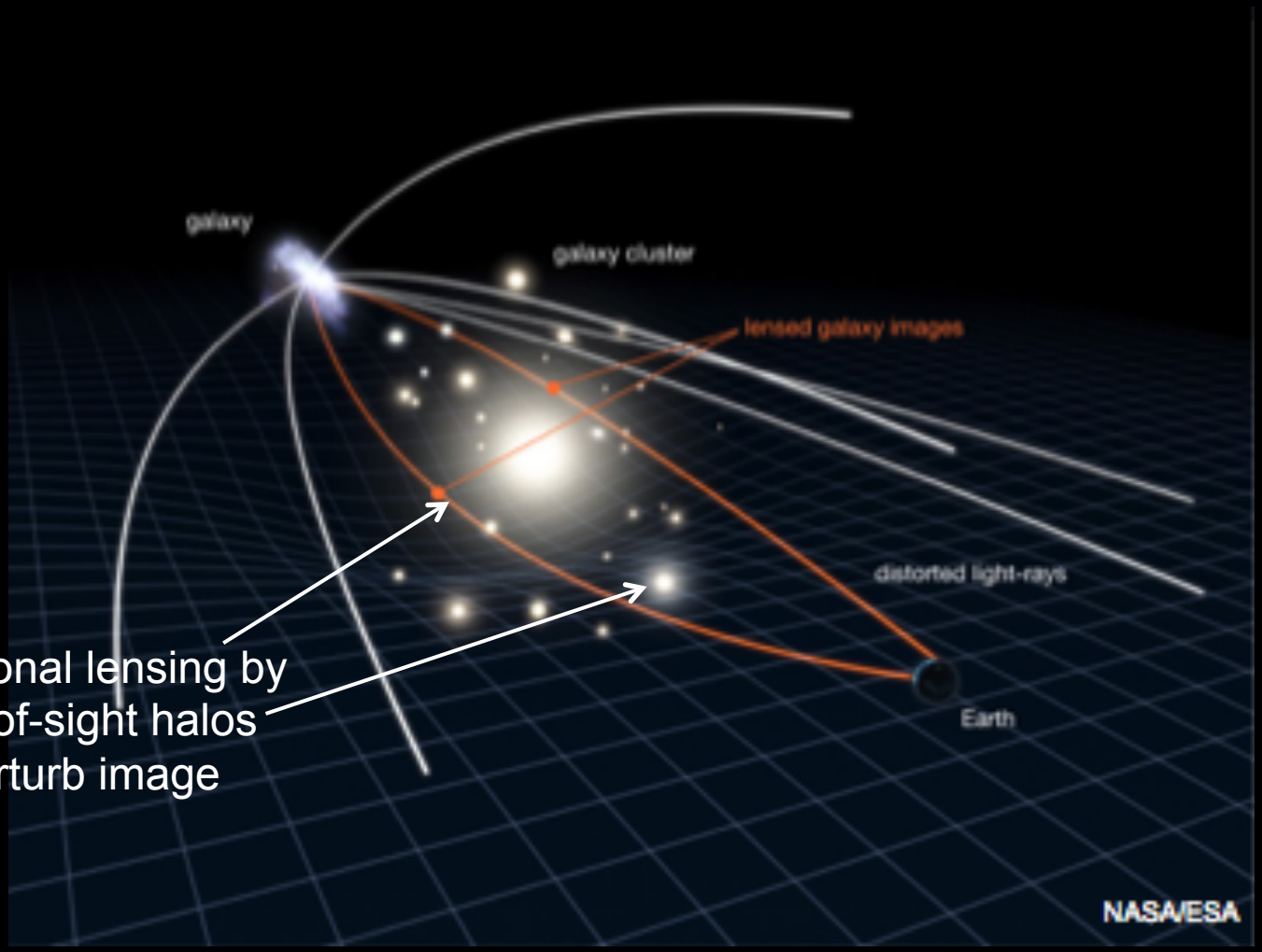


When the source and the lens are well aligned → strong arc of an Einstein ring

Gravitational lensing: Einstein rings

Vegetti & Koopmans ‘09

Gravitational lensing: Einstein rings

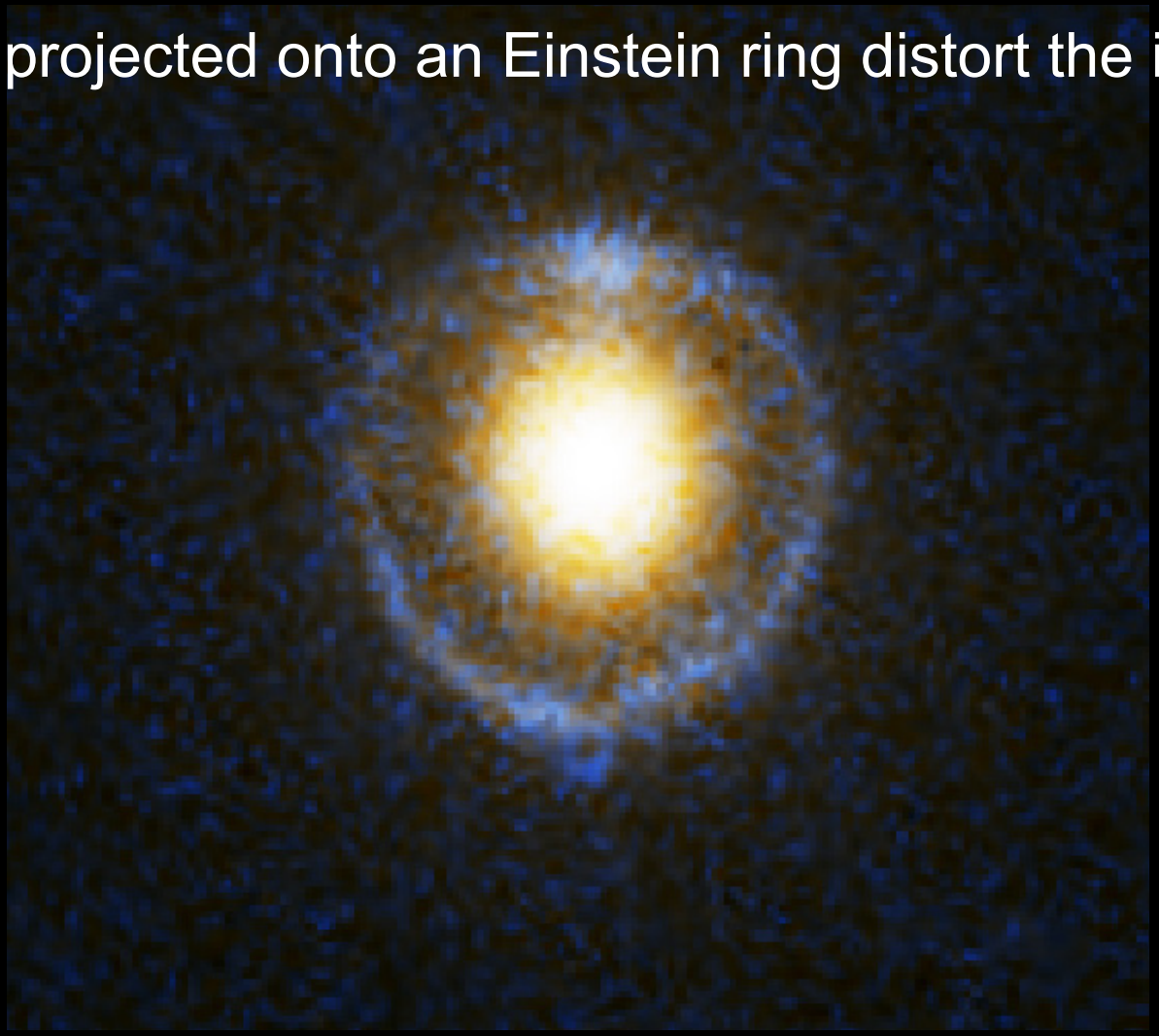


Additional lensing by line-of-sight halos perturb image

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



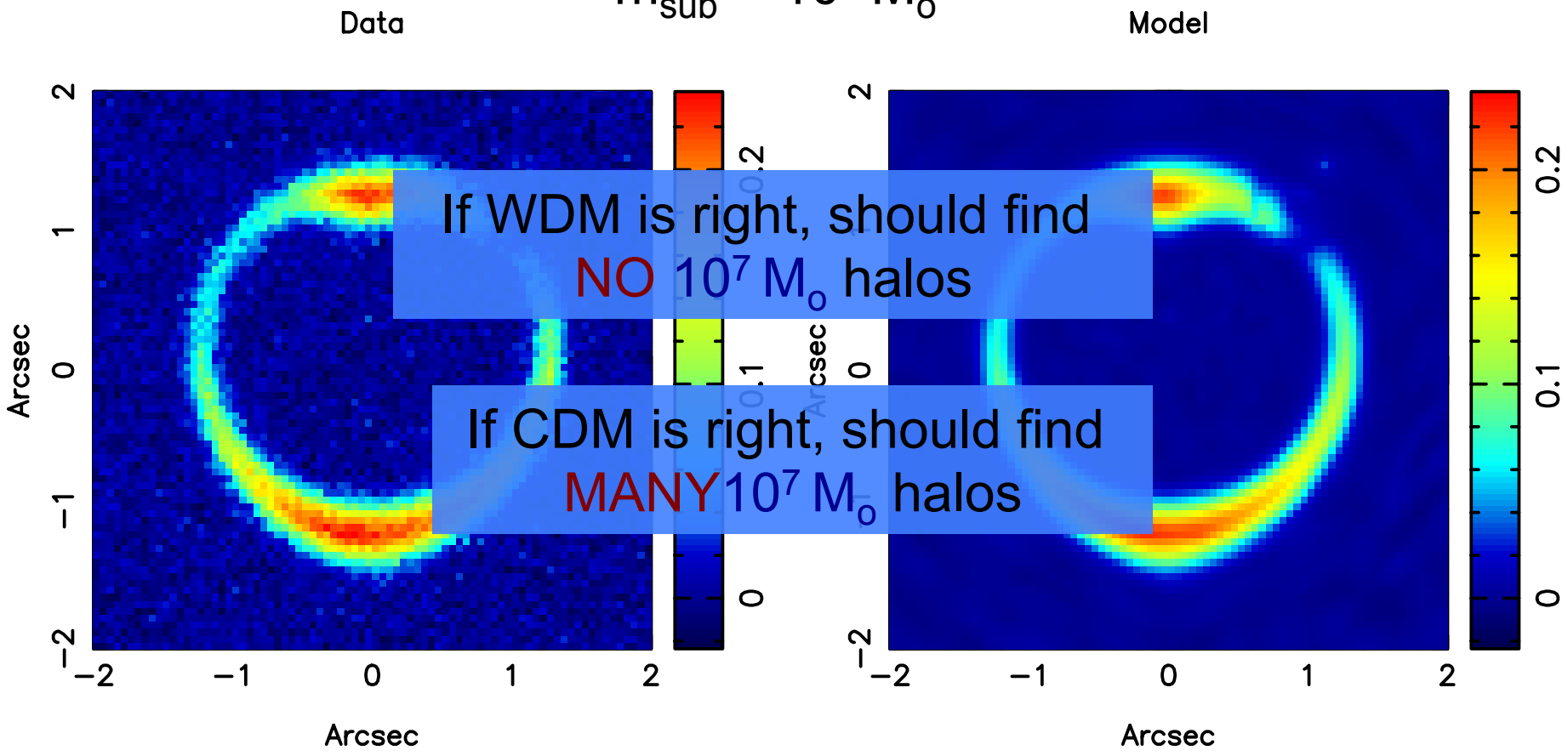
Vegetti & Koopmans ‘09

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 $10^7\ M_o$

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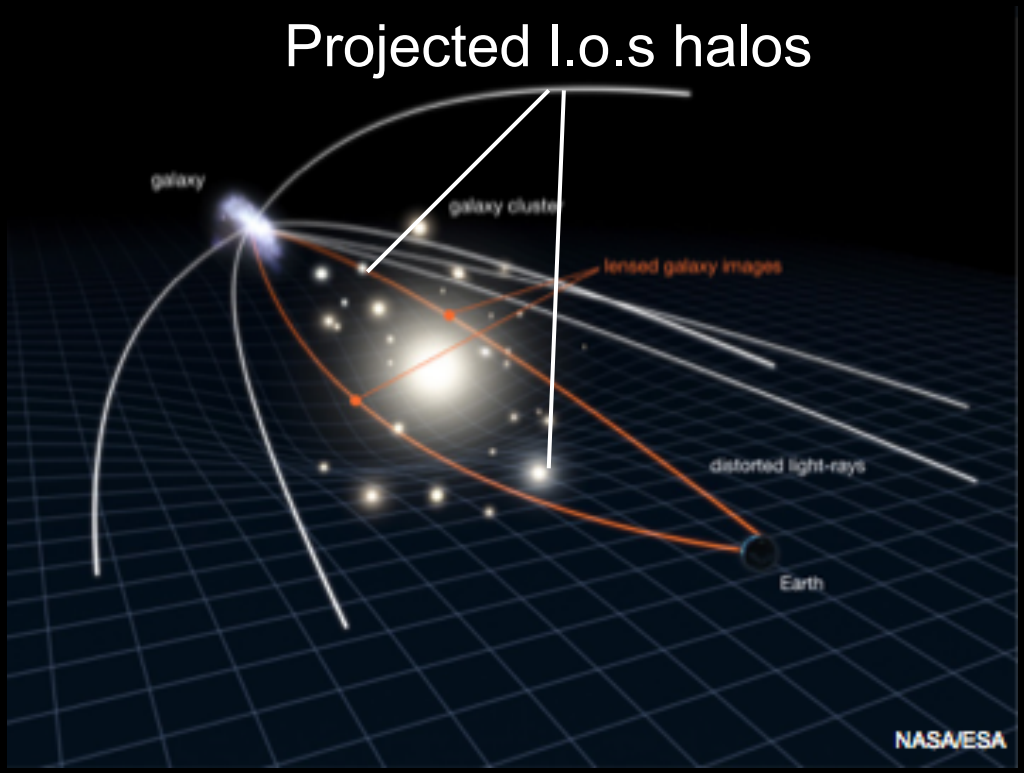
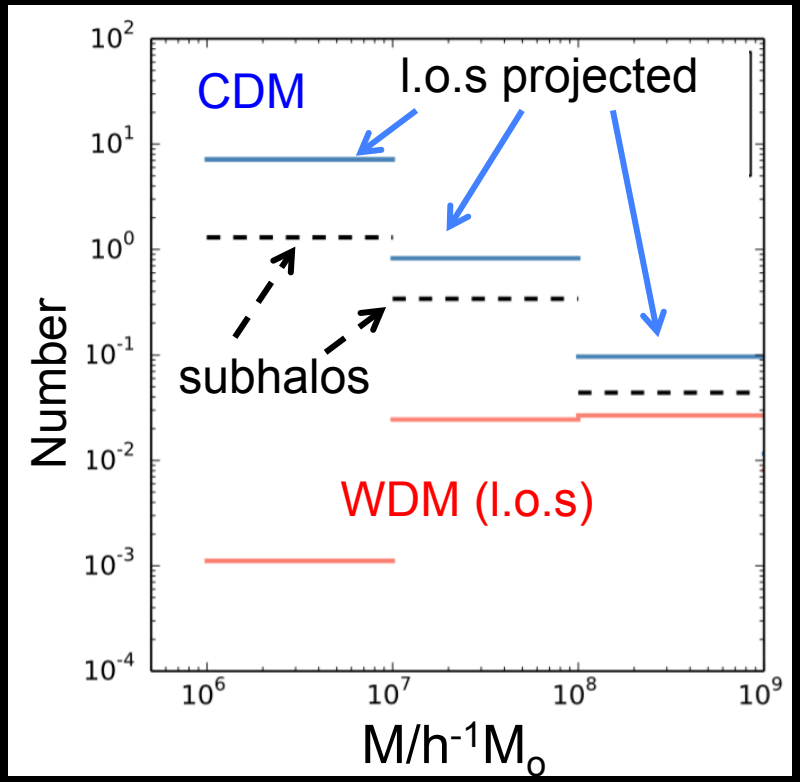
Substructures vs interlopers

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



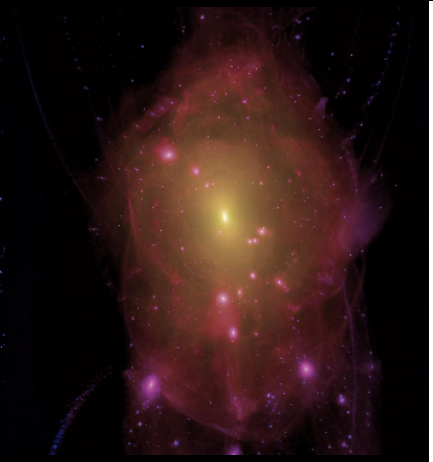


The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. ‘16

The halo mass function

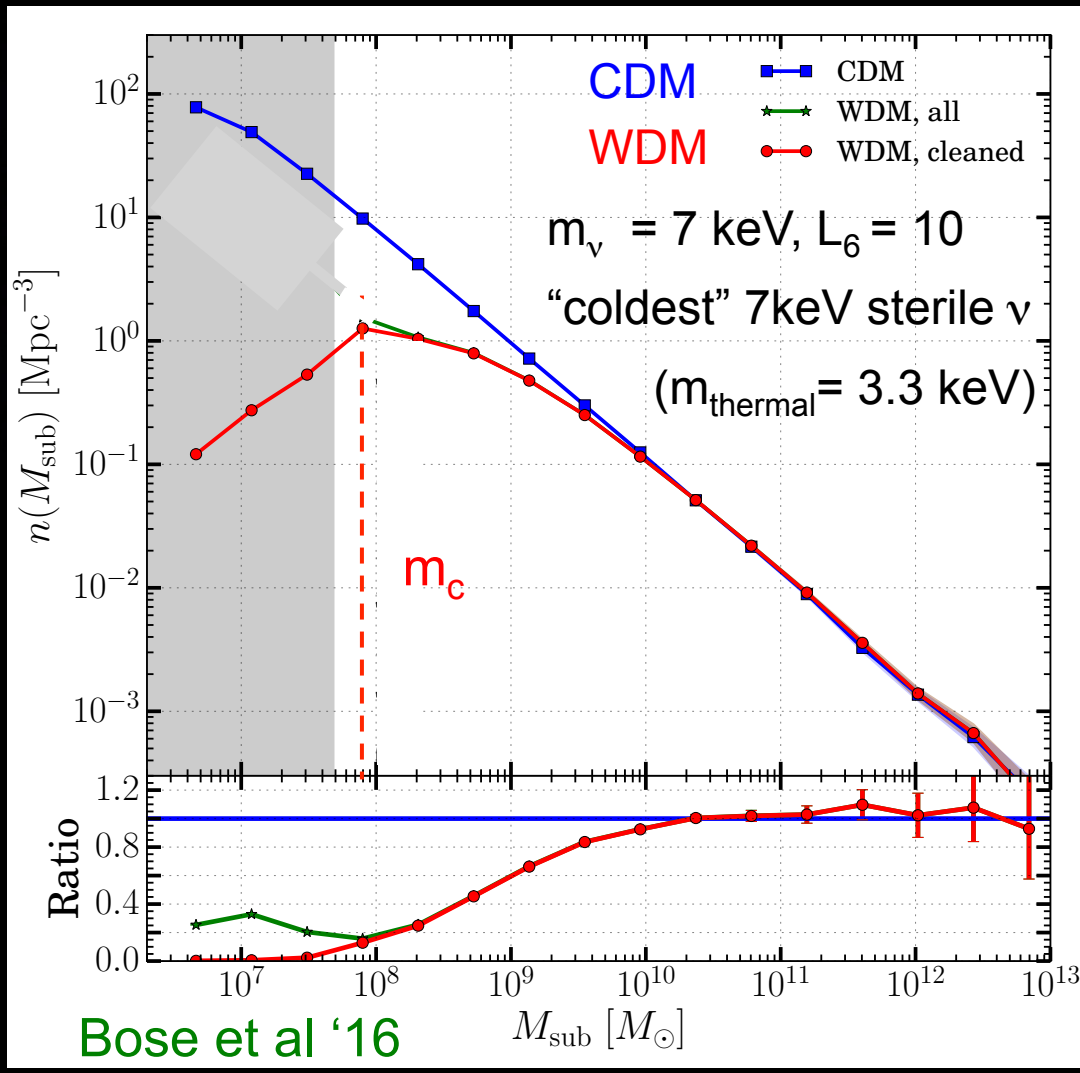
CDM



WDM

Already fewer WDM halos at $3 \times 10^9 M_o$

10 x fewer at $10^8 M_o$



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Detecting substructures with strong lensing

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

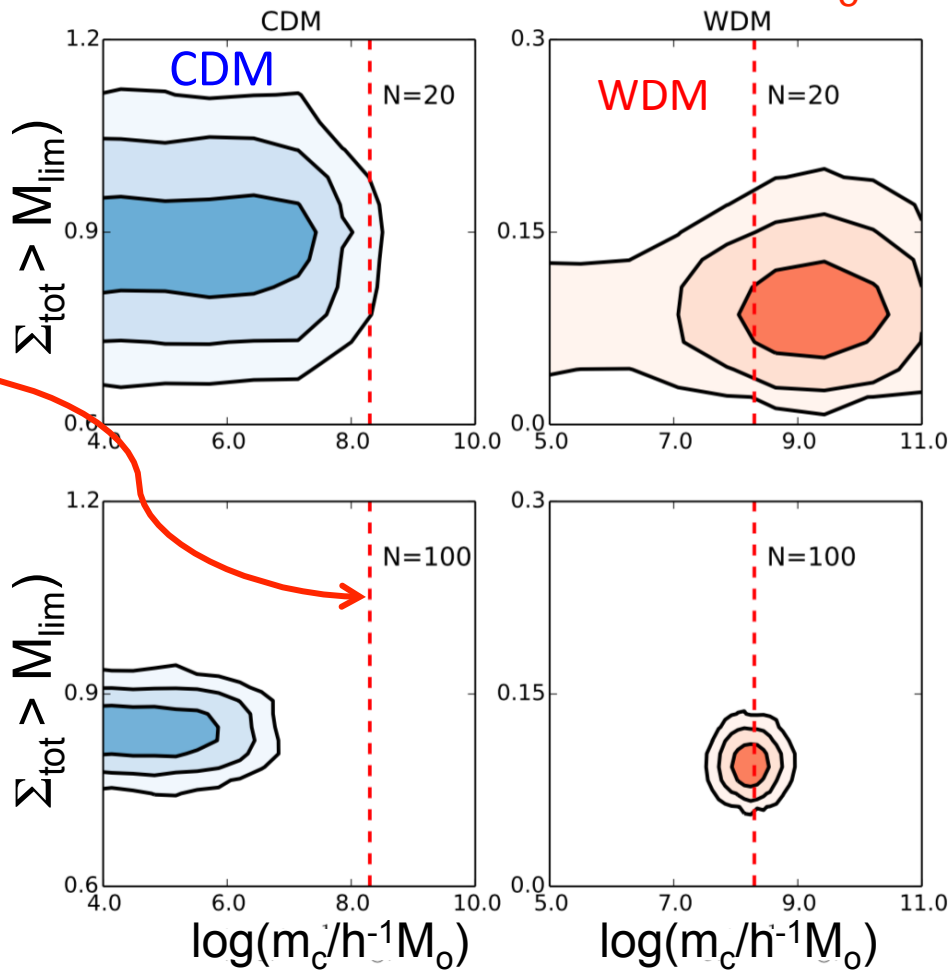
m_c= halo cutoff mass

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. Some “observed” cores may be artefacts
4. Strong gravitational lensing can distinguish CDM/WDM

(and could rule out CDM!)