

# Searching for the identity of the dark matter in our backyard

Carlos S. Frenk
Institute for Computational Cosmology,
Durham





## ... or how to rule out CDM

Carlos S. Frenk
Institute for Computational Cosmology,
Durham





## ... or many other possibilities

# Carlos S. Frenk Institute for Computational Cosmology, Durham

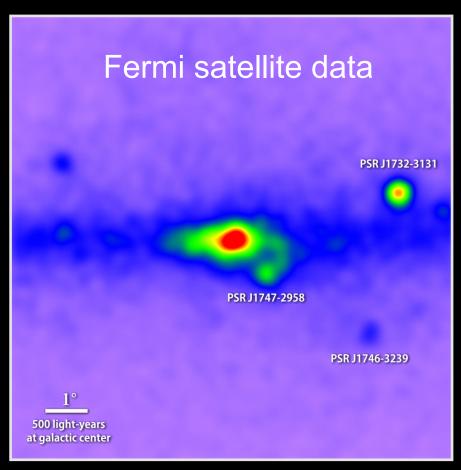


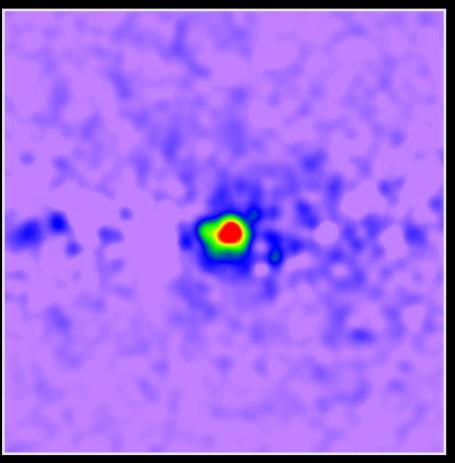
#### Cold dark matter

The Characterization of the Gamma-Ray Signal from the Central Milky Way:
A Compelling Case for Annihilating Dark Matter

Tansu Daylan,<sup>1</sup> Douglas P. Finkbeiner,<sup>1,2</sup> Dan Hooper,<sup>3,4</sup> Tim Linden,<sup>5</sup> Stephen K. N. Portillo,<sup>2</sup> Nicholas L. Rodd,<sup>6</sup> and Tracy R. Slatyer<sup>6,7</sup>

#### Uncovering a gamma-ray excess at the galactic center



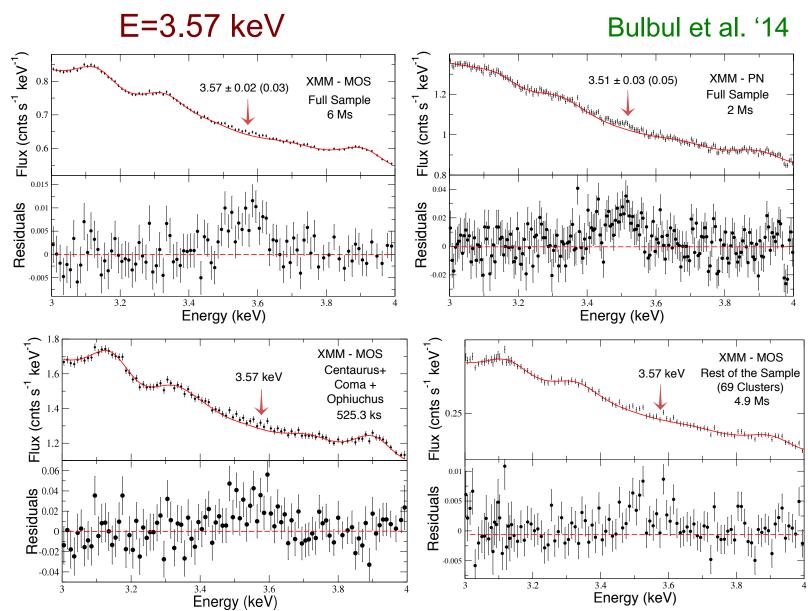


Unprocessed map of 1.0 to 3.16 GeV gamma rays

**Known sources removed** 



## Warm dark matter WDM decay line in 69 stacked clusters?

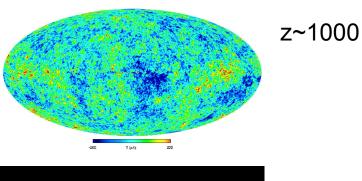


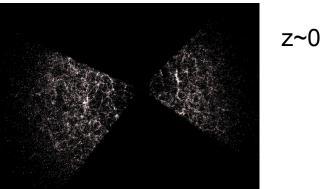


## Very unlikely that both are right!



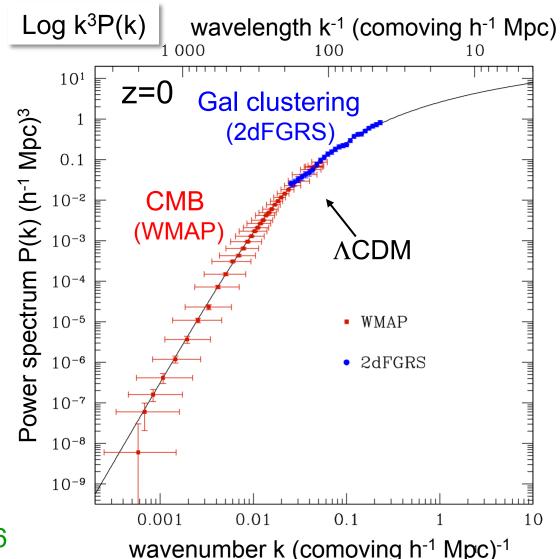
# The cosmic power spectrum: from the CMB to the 2dFGRS





→ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06





# The cosmic power spectrum: from the CMB to the 2dFGRS

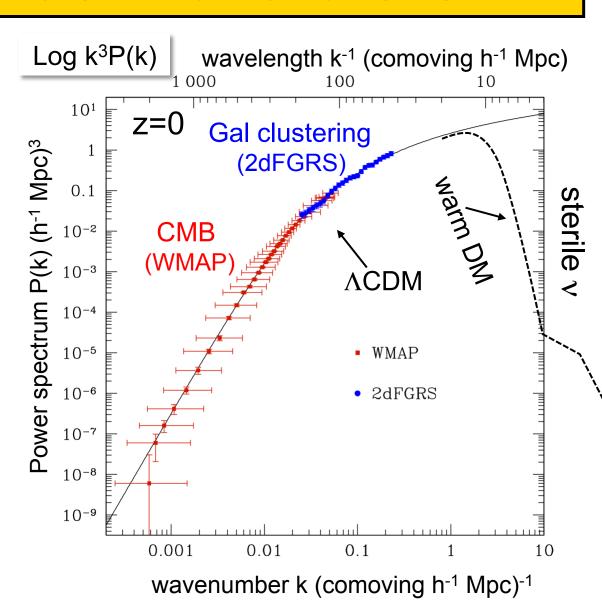
#### Free streaming →

 $\lambda_{cut} \; \alpha \; m_x^{-1}$ 

for thermal relic

 $m_{CDM} \sim 100 GeV$ susy;  $M_{cut} \sim 10^{-6} M_{o}$ 

 $m_{WDM} \sim \text{few keV}$ sterile v;  $M_{cut} \sim 10^9 M_o$ 





### Sterile neutrinos

#### Explain:

- Neutrino oscillations and masses
- Baryogenesis
- Absence of right-handed neutrinos in standard model
- Dark matter

#### Sterile neutrino minimal standard model (vNSM; Boyarski+ 09):

- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If  $\Omega_N = \Omega_{DM}$ , 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-rays decay

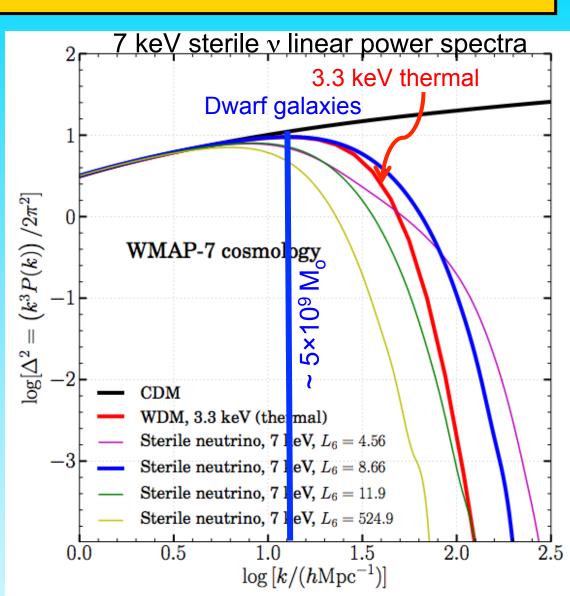


# Primordial P(k) for 7 keV sterile neutrino models

- Thermal and resonant production mechanisms
- Resonant production depends on baryon asymmetry parameter, L<sub>6</sub>
- Linear PS varies nonmonothonically with L<sub>6</sub>

Ly- $\alpha$  forest rules out thermal masses, mv<3.3 keV (Viel + '13)

Bose, Lovell 'et al. 16





## Astrophysical key to identity of dark matter:

Subgalactic scales

(strongly non-linear)



Cold Dark Matter

Warm Dark Matter

cold dark matter warm dark matter How can we distinguish between these?

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



## Observational tests of CDM vs WDM

- I. The abundance of satellite galaxies in MW/M31
- II. The structure of galactic satellites (too-big-to-fail)
- III. The abundance of dark halos and subhalos



# The Copernicus Complexio (COCO) simulations

Hellwing et al. '15

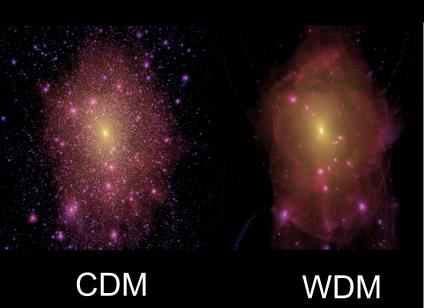
WDM with thermal mass of 3.3 keV

PS = "coldest" ( $L_6 = 9$ ) 7keV sterile neutrino

Ruling this out  $\rightarrow$  rules out all 7keV sterile  $\nu$  models!

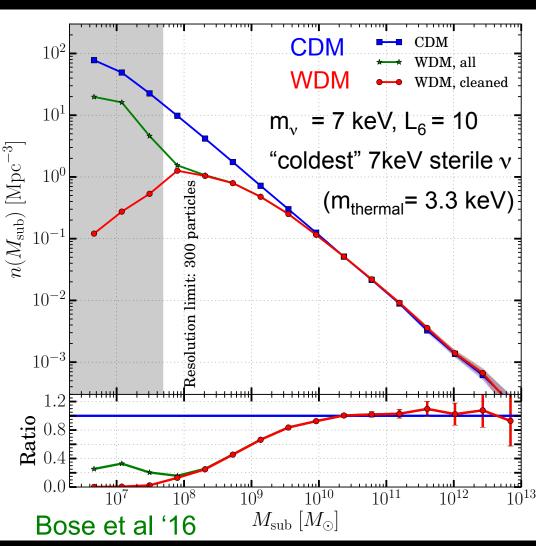


### The subhalo mass function



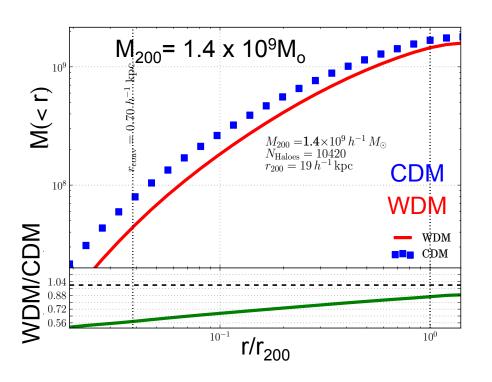
Already fewer WDM subhalos at 3x10<sup>9</sup>M<sub>o</sub>

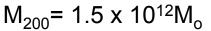
10 x fewer at 108M<sub>o</sub>

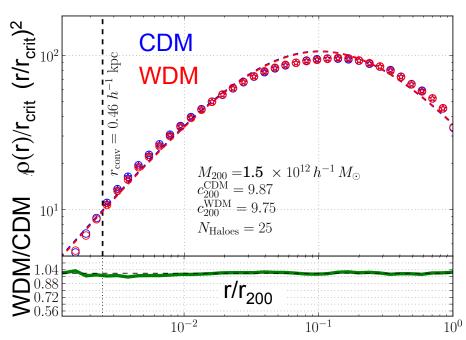


## Halo density profiles

## Profiles well fit by NFW for CDM and WDM







 $\rho$ (r) identical for ~10<sup>12</sup>M<sub>o</sub> but lower central  $\rho$  for ~10<sup>9</sup>M

Bose et al '16

**Institute for Computational Cosmology** 



## Observational tests of CDM vs WDM

- I. The abundance of satellite galaxies in MW/M31
- II. The structure of galactic satellites (too-big-to-fail)
- III. The abundance of dark halos and subhalos



## Observational tests of CDM vs WDM

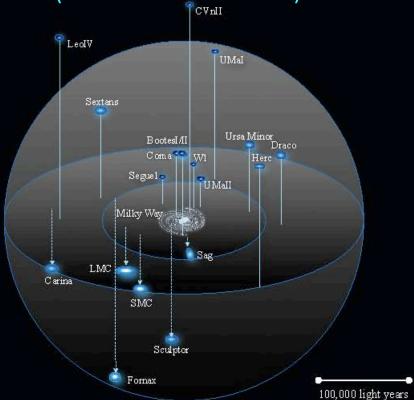
I. The abundance of satellite galaxies in MW/M31



## The satellites of the MW and M31

#### The satellites of the MW

(~50 discovered so far)



#### Dark mattter subhalos in CDM

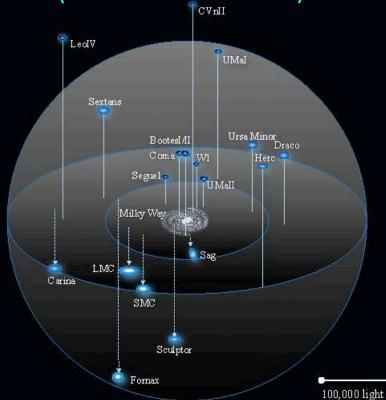
(hundreds of thousands)



## The satellites of the MW and M31

#### The satellites of the MW

(~50 discovered so far)

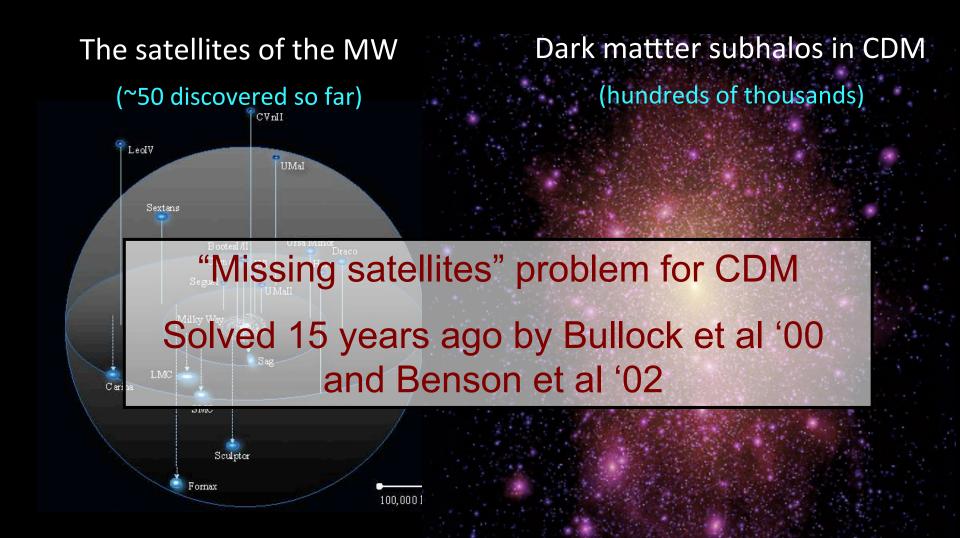


#### Dark mattter subhalos in WDM

(a few tens)



## The satellites of the MW and M31



#### Making a galaxy in a small halo is hard because:

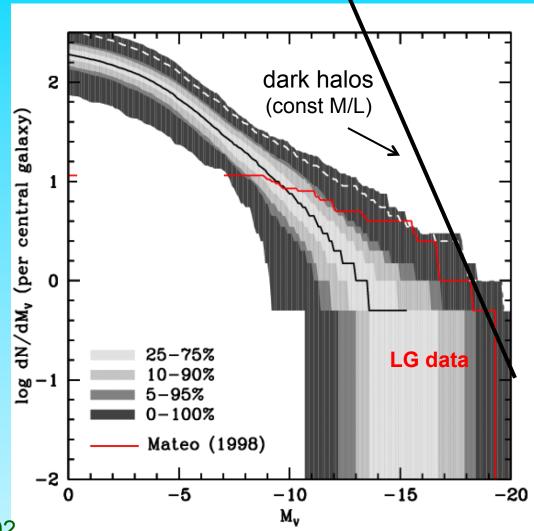
- Reionization heats gas above T<sub>vir</sub>, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels residual gas

Most subhalos never make a galaxy!



# Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M<sub>V</sub>=-9 and V<sub>cir</sub> > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)

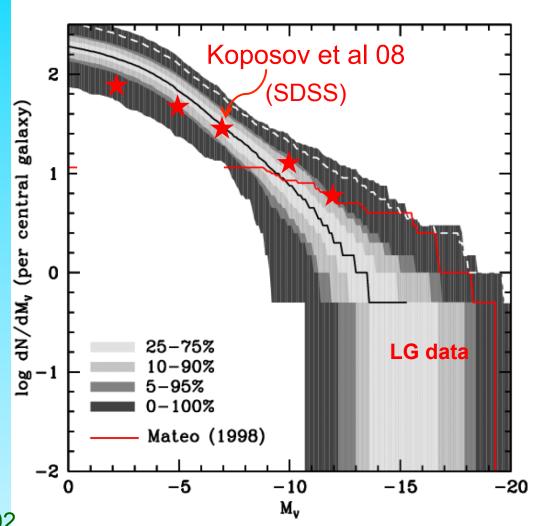


Benson, Frenk, Lacey, Baugh & Cole '02 (see also Kauffman etal '93, Bullock etal '01)



# Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M<sub>V</sub>=-9 and V<sub>cir</sub> > 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 etal '93, Bullock etal '01)

**Institute for Computational Cosmology** 

"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...



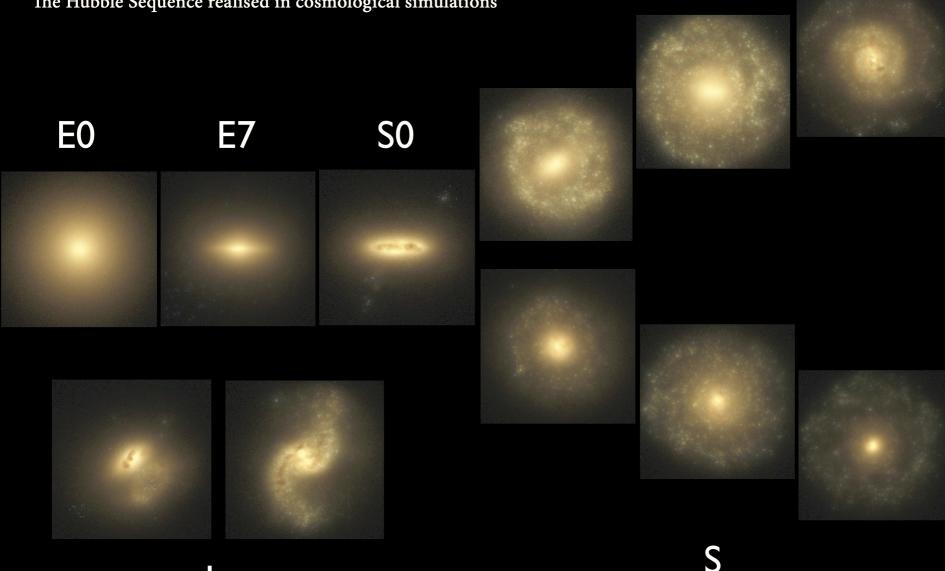




## The Eagle Simulations

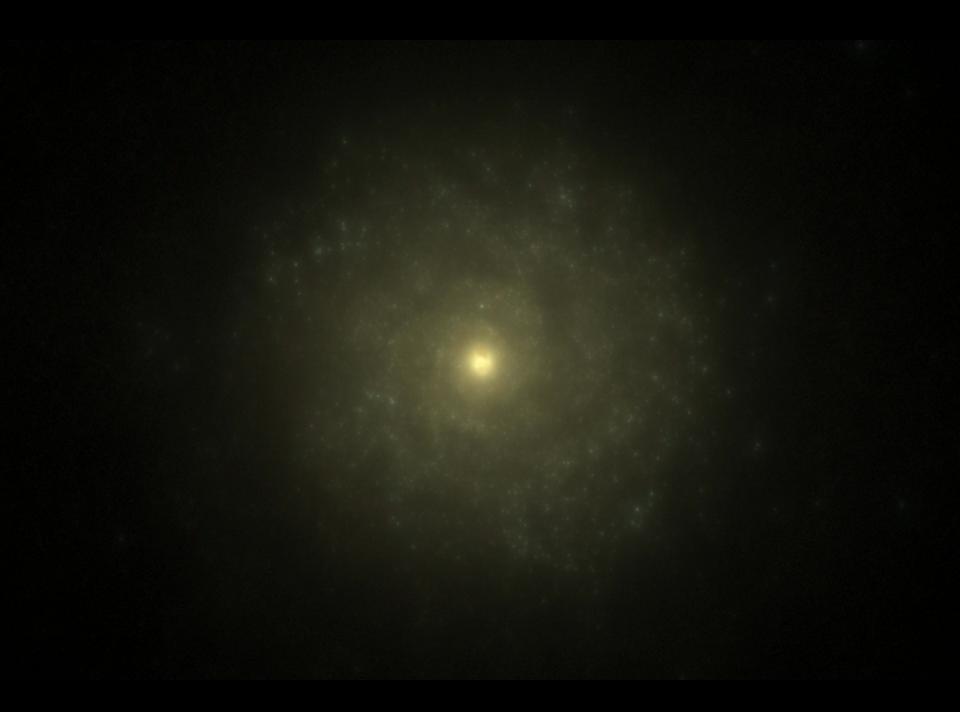
**EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS** 

The Hubble Sequence realised in cosmological simulations



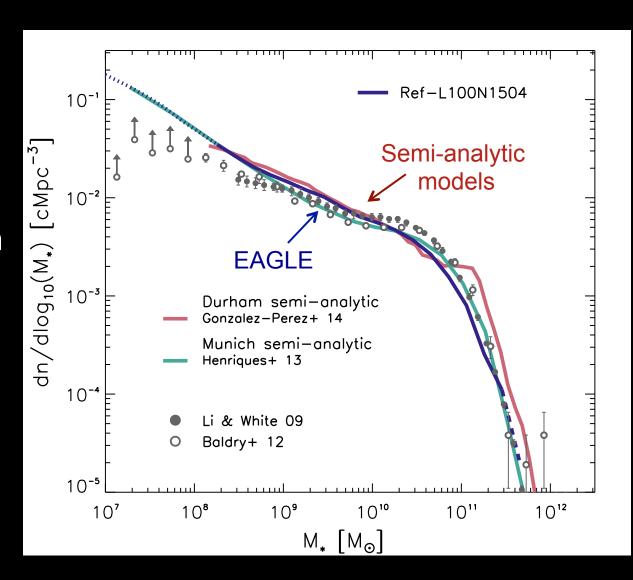
Trayford et al '15

SB



## Galaxy stellar mass function

Eagle gives a good match to observed stellar mass fn over 5 orders of magnitude in stellar mass



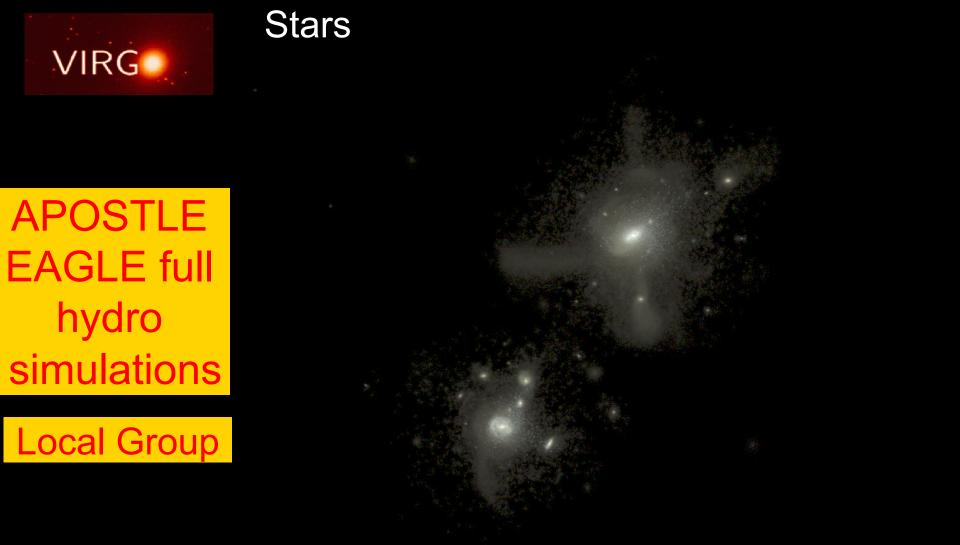
VIRG

APOSTLE
EAGLE full
hydro
simulations

**Local Group** 

Sawala et al '15



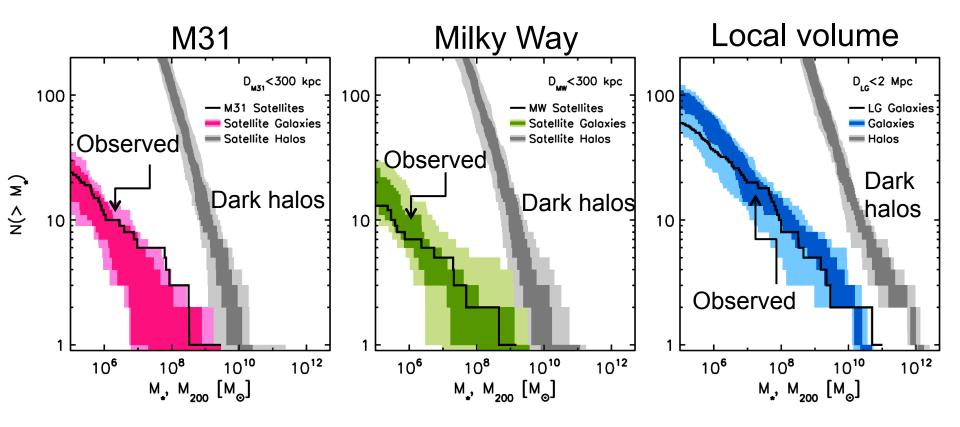


Far fewer satellite galaxies than CDM halos

Sawala et al '15



## **EAGLE Local Group simulation**

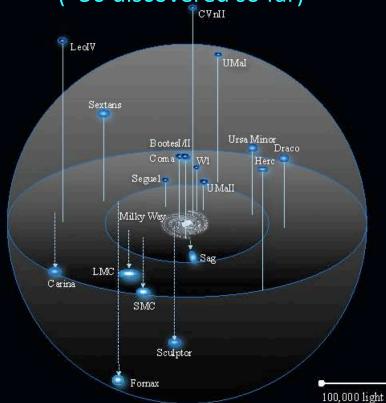




## How about in WDM?

#### The satellites of the MW

(~50 discovered so far)



#### Dark mattter subhalos in WDM

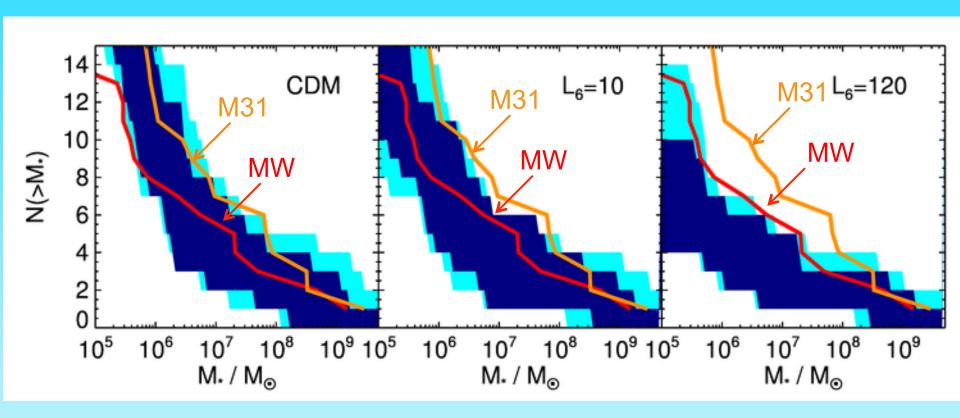
(a few tens)



# Luminosity Function of Local Group Satellites in WDM

From "Warm Apostle:" 7keV sterile v

 $M_h \sim 10^{12} M_o$ 



Lovell et al. '16

**Institute for Computational Cosmology** 



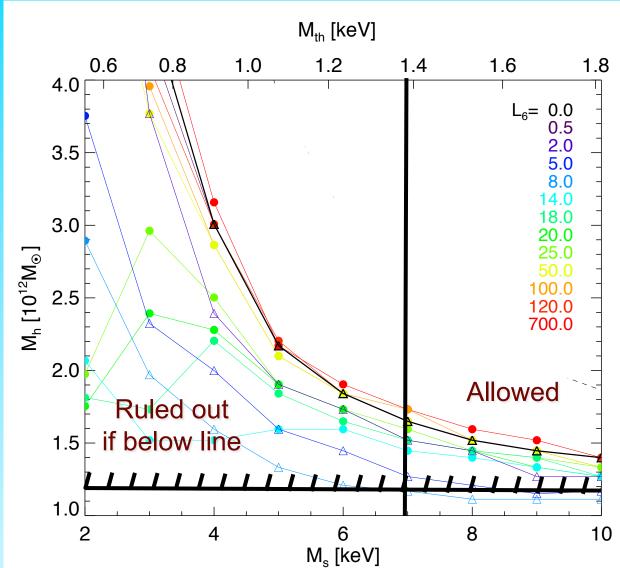
### Limits on sterile v mass

In WDM, no. of sats depends:

- Particle mass
- MW halo mass

If  $M_{halo}$ <1.2 x 10<sup>12</sup>  $M_{o}$ 

7keV sterile √ ruled out



Lovell et al '16



## Observational tests of CDM vs WDM

- I. The abundance of satellite galaxies in MW/M31
- II. The structure of galactic satellites (too-big-to-fail)
- III. The abundance of dark halos and subhalos



## Observational tests of CDM vs WDM

II. The structure of galactic satellites (too-big-to-fail)



### The strucure of satellite halos

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

$$V_{max} = max V_{c}$$

The satellites of the MW

Dark mattter subhalos in CDM

"Too-big-to-fail" problem:

N-body CDM sims produce too many massive subhalos (e.g. >10 with V<sub>max</sub>>30 km/s)

BUT: Milky Way has only 3 sats with V<sub>max</sub>>30 km/s



Why did these not make a galaxy?



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

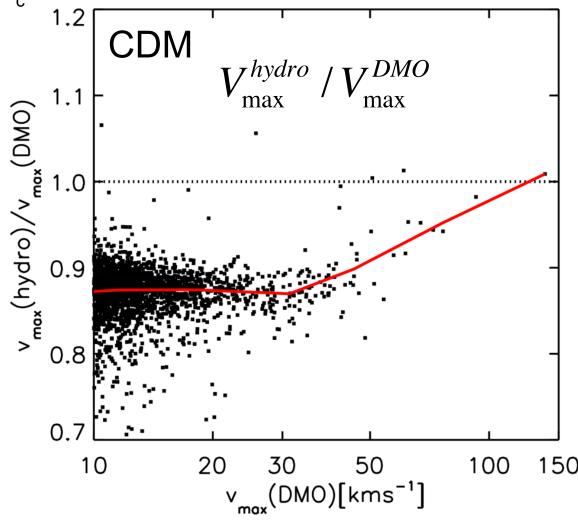
$$V_c = \sqrt{\frac{GM}{r}}$$

$$V_{max} = max V_{c}$$

Reduction in V<sub>max</sub> due to SN feedback:

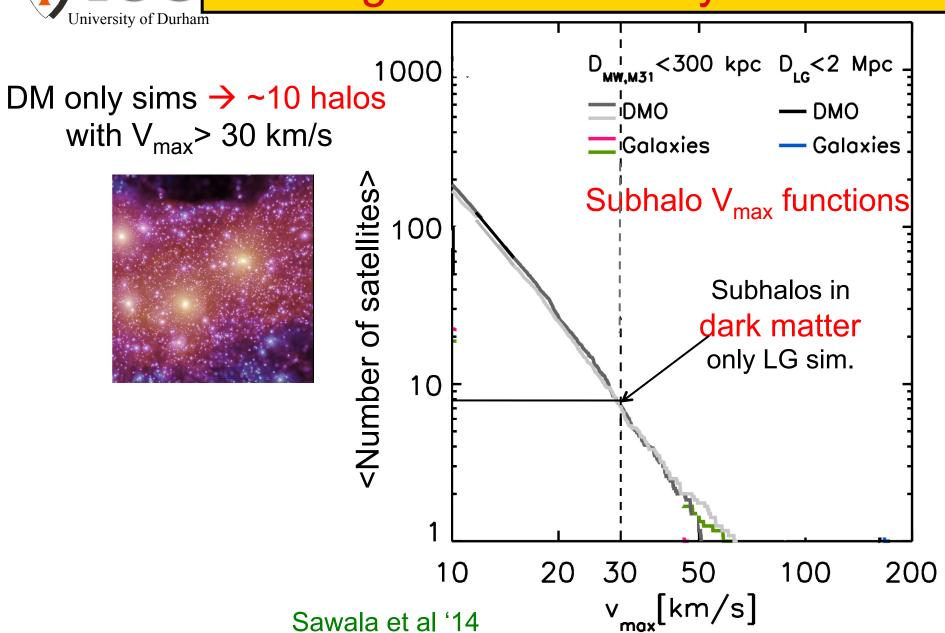
→ Lowers halo mass & thus halo growth rate





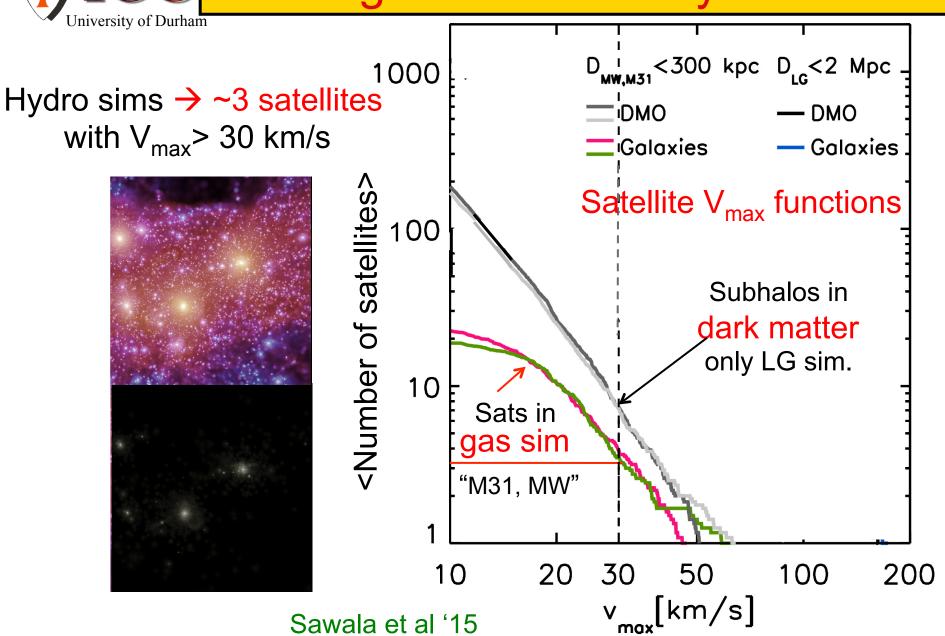


## Too-big-to-fail: the baryon bailout



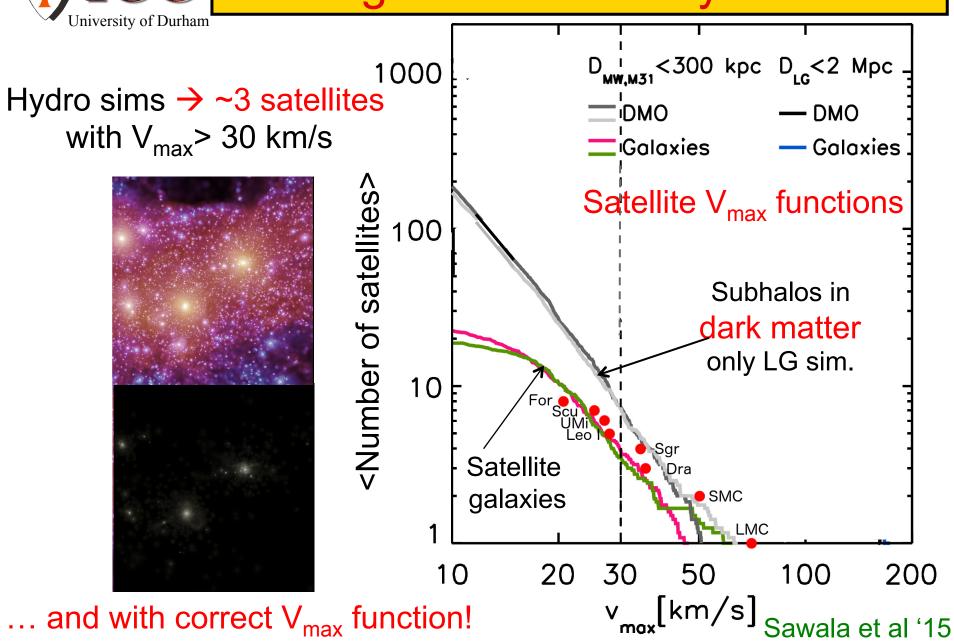


## Too-big-to-fail: the baryon bailout





## Too-big-to-fail: the baryon bailout





## Too-big-to-fail problem in CDM



Solved by "baryon effects"



## Too-big-to-fail in WDM

Dark mattter subhalos in WDM

In WDM models that match satellite LF there is **no** too-big-to-fail problem

- Halos are less dense than in CDM (later formation)
- V<sub>max</sub> reduction due to baryons

(a few tens)



## Observational tests of CDM vs WDM

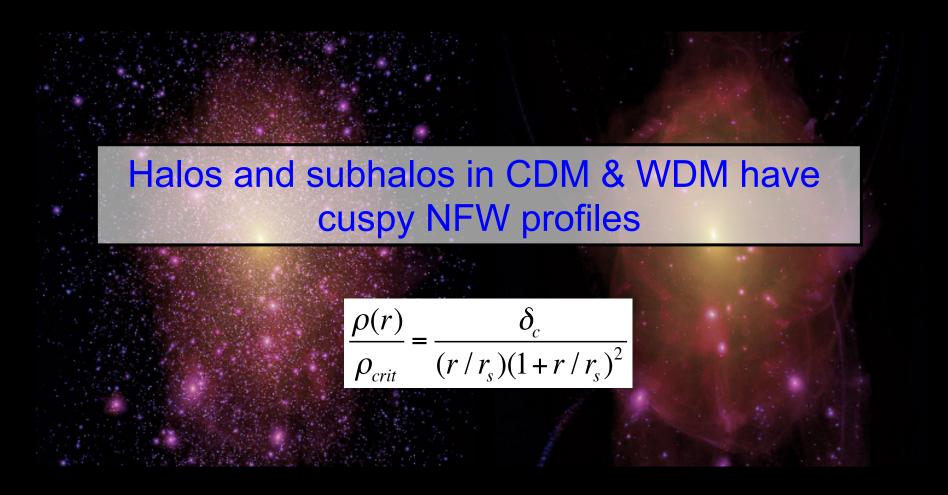
II. The structure of galactic satellites (too-big-to-fail)



## The core-cusp problem

cold dark matter

warm dark matter



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



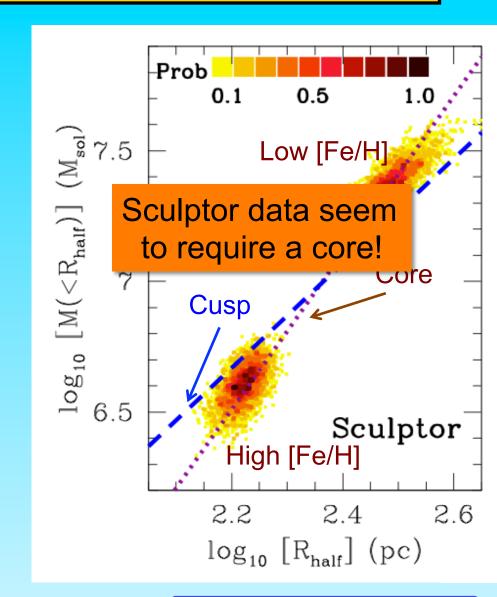
## The DM halo of the Sculptor dwarf

#### Sculptor has two stellar pops:

- (i) centrally concentrated, high [Fe/H]
- (ii) extended, low [Fe/H]

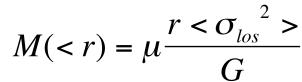
$$M(< r) = \mu \frac{r < \sigma_{los}^{2} >}{G}$$

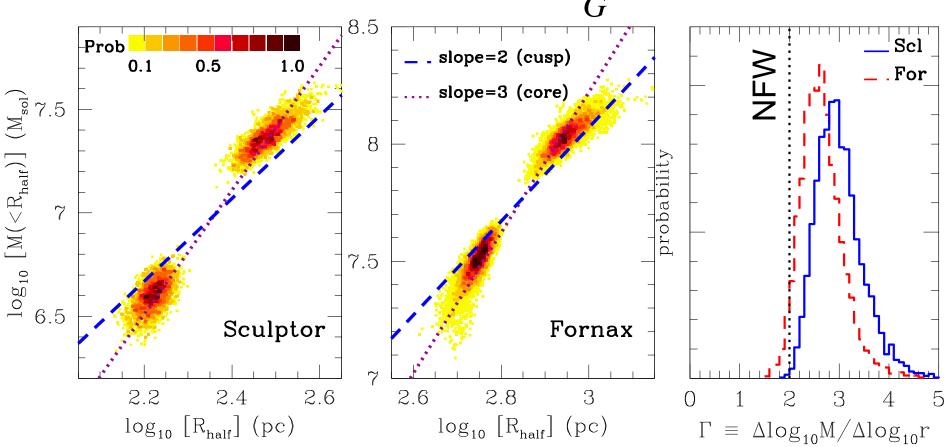
Walker '10; Wolf et al '10→
if r=r<sub>1/2</sub>, μ=2.5, independently of model assumptions!





## Cusps in Sculptor and Fornax





NFW ruled out at

>96% Fornax

>99% Sculptor

Walker & Peñarrubia (2011)



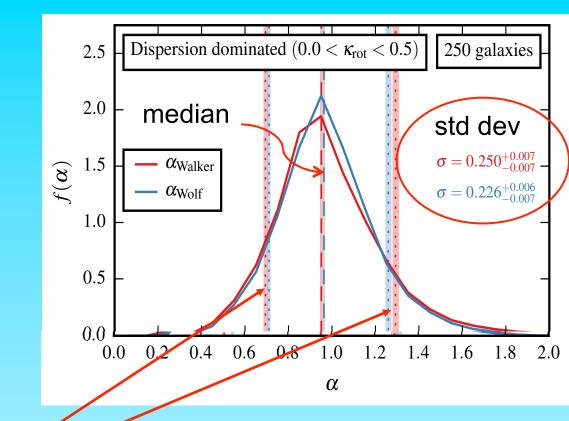




### Uncertainties in the Walker/Wolf estimator

$$\alpha_{\text{Walker}} = \frac{2.5G^{-1}\sigma_{\text{los}}^2R_{\text{e}}}{M(< R_{\text{e}})}$$

$$\alpha_{\text{Wolf}} = \frac{4G^{-1}\sigma_{\text{los}}^2 R_{\text{e}}}{M(<4R_{\text{e}}/3)}$$



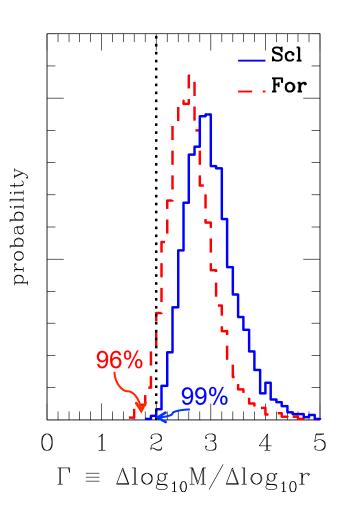
10th and 90th percentiles

$$lpha = rac{M_{
m estimated}}{M_{
m true}}$$

$$\int f(\alpha) \, \mathrm{d} \alpha = 1$$
 Campbell et al. '16

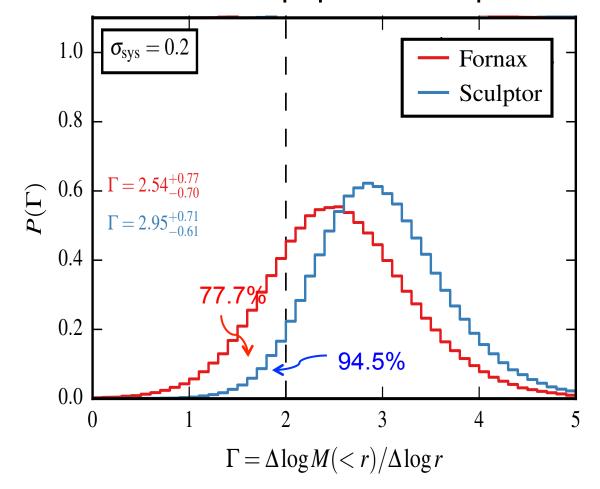


## The DM density profile of Sculptor



Walker & Peñarrubia '11

include scatter of 20% on each mass and assume the 2 pops are independent



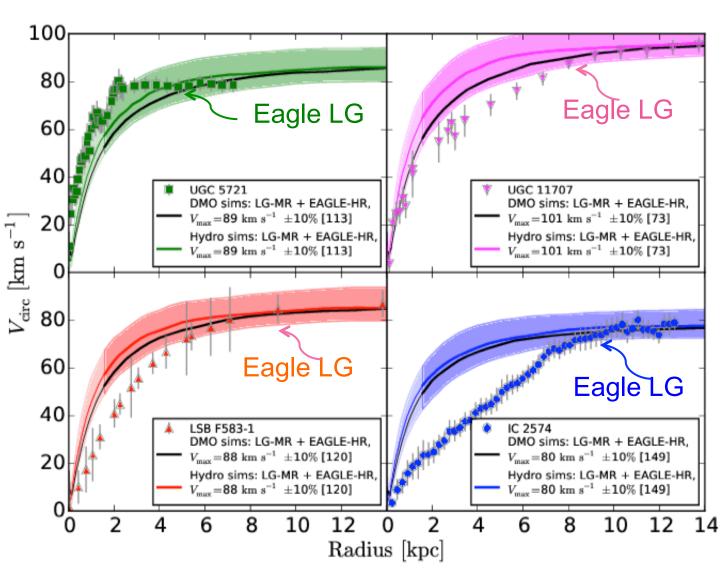
Campbell et al. '16



## The diversity of gal rotation curves

Four rotation curves that are NOT well fit by ΛCDM

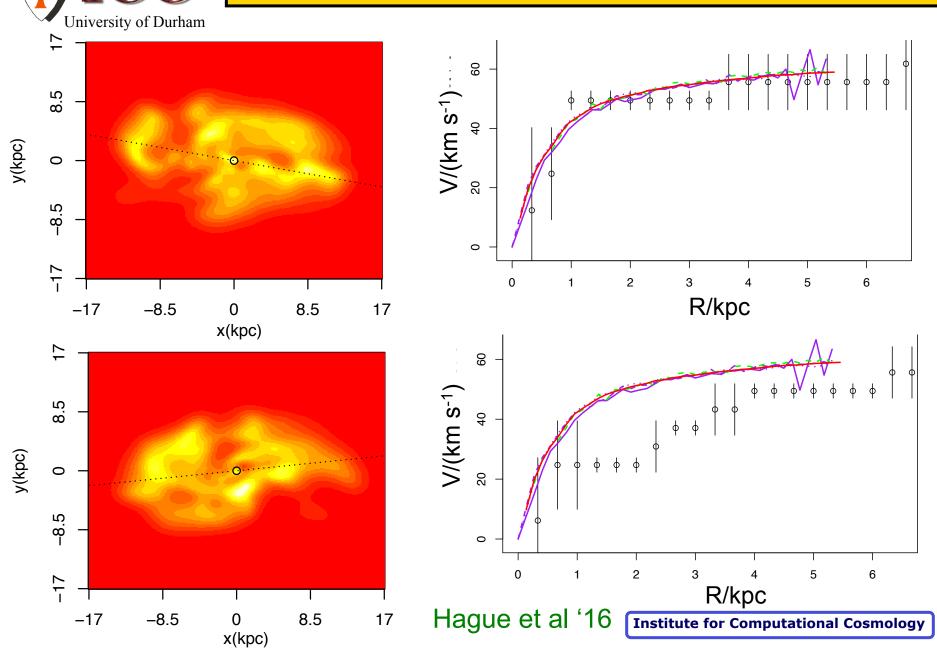
(from dwarfs to ~L<sub>\*</sub>)



Oman et al. '15

## University of Durham

### Rotation curves of APOSTLE dwarfs





## Cores or cusps?

Core are generally thought to exist in some galaxies

But, do they???

And if they exist, do they tell us anything about dark matter?

#### The cores of dwarf galaxy haloes

Julio F. Navarro, 1,2 ★ Vincent R. Eke2 and Carlos S. Frenk2

Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

#### ABSTRACT

We use N-body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

<sup>&</sup>lt;sup>1</sup>Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA

<sup>&</sup>lt;sup>2</sup>Physics Department, University of Durham, South Road, Durham DH1 3LE

## University of Durham

### Baryon effects in the MW satellites

Let gas cool and condense to the galactic centre

- → gas self-gravitating
- → star formation/burst

Rapid ejection of gas during starburst  $\rightarrow$  a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12 Pontzen & Governato '12 Brooks et al. '12

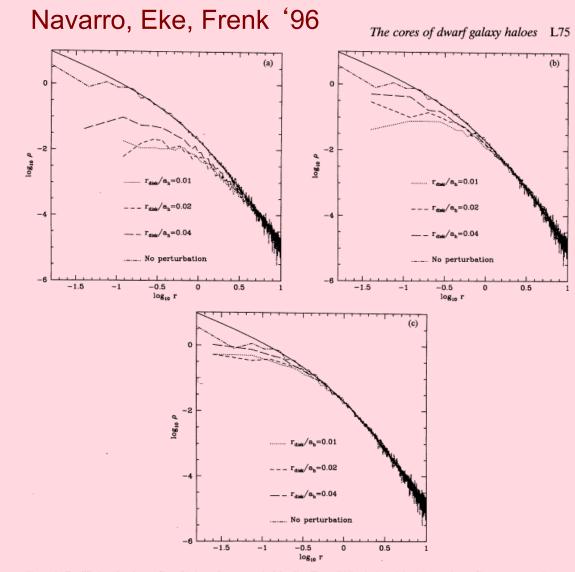


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at t = 200. (a)  $M_{\rm disc} =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



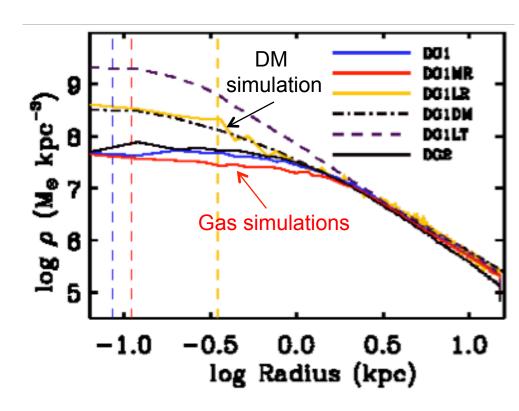
## Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

EAGLE does not

High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy



Governato et al. '10 Pontzen et al. '11



cold dark matter

warm dark matter

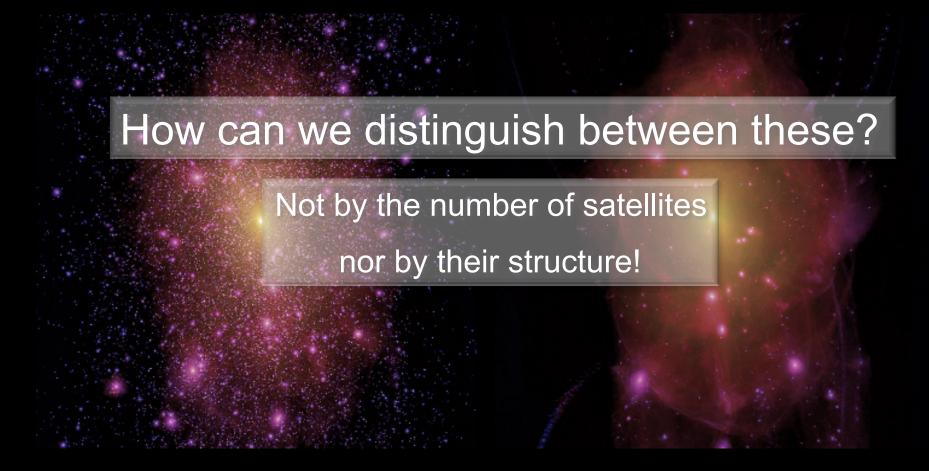
Core/cusp will not tell us anything about the nature of the dark matter

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



cold dark matter

warm dark matter



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







## Observational tests of CDM vs WDM

- I. The abundance of satellite galaxies in MW/M31
- II. The structure of galactic satellites (too-big-to-fail)
- III. The abundance of dark halos and subhalos



## Observational tests of CDM vs WDM

III. The abundance of dark halos and subhalos



## Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

- 1. Dark subhalos (gravitational lensing)?
- Stellar streams (stellar surveys PAndAS, GAIA)?

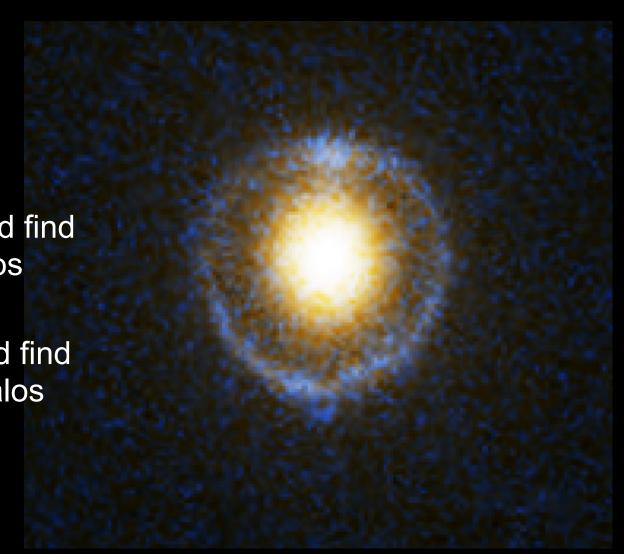


## Gravitational lensing: Einstein rings

Substructures distort Einstein rings

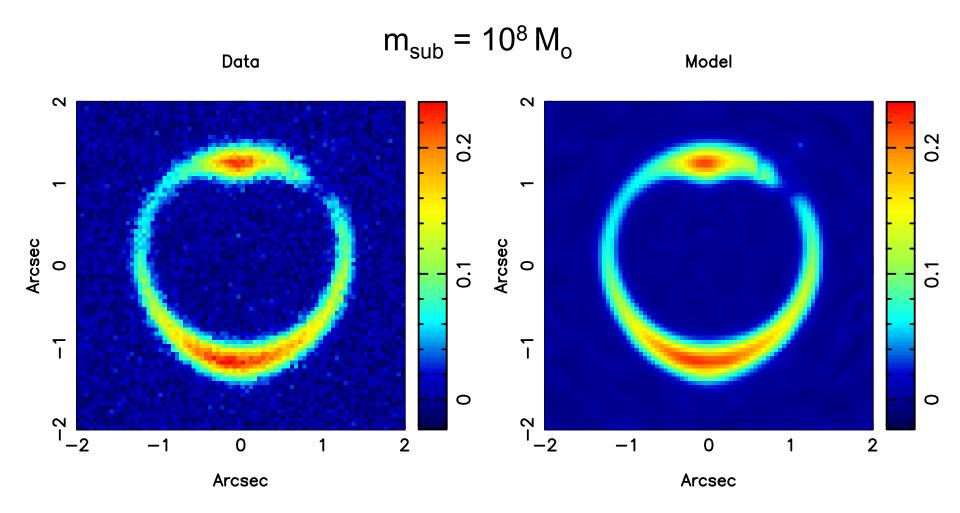
If WDM is right, should find NO small subhalos

If CDM is right, should find MANY small subhalos





# Detecting substructures with strong lensing



Vegetti & Koopmans '09



# Detecting substructures with strong lensing

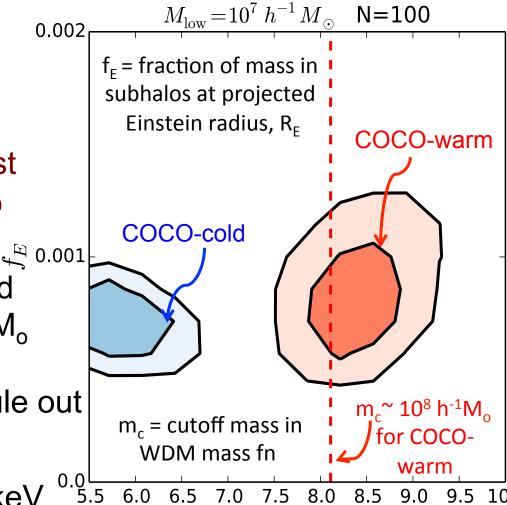
f<sub>E</sub> = fraction of mass in subs
 within Einstein ring

m<sub>c</sub>= subhalo cutoff mass

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

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

- If DM is 7 keV sterile v → rule out CDM at 3σ!
- If DM is CDM → rule out 7 keV <sup>0.0</sup>5.5
   sterile v at many σ Li et al '16



 $\log(m_c/h^{-1}M_{\odot})$ 



## Gravitational lensing: Einstein rings

#### Two subtleties:

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

#### **Answer:**



- Central galaxy destroys ~30% of halos within Einstein ring (Sawala et al. '16)
- Projected halos dominate the strong lensing signal (Li et al '16)



# Detecting substructures with strong lensing

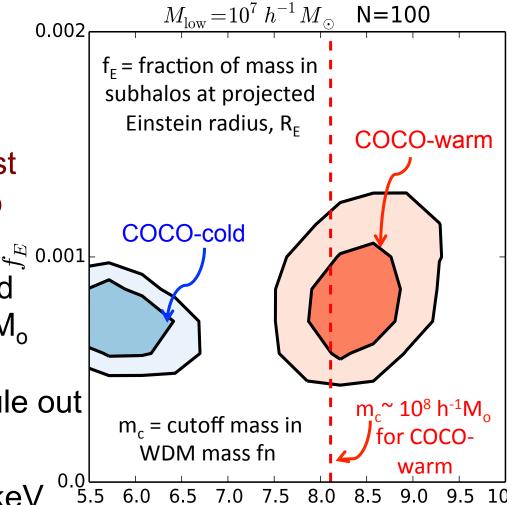
f<sub>E</sub> = fraction of mass in subs
 within Einstein ring

m<sub>c</sub>= subhalo cutoff mass

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

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

- If DM is 7 keV sterile v → rule out CDM at 3σ!
- If DM is CDM → rule out 7 keV <sup>0.0</sup>5.5
   sterile v at many σ Li et al '16



 $\log(m_c/h^{-1}M_{\odot})$ 



## Conclusions

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

1. The satellites luminosity function	<b>/</b>	<b>✓</b>
2. The V <sub>max</sub> fn ("too-big-to-fail")	J	
3. Core or cusps in halos	-	_
4. Subhalo mass fn– strong lensing	?	?