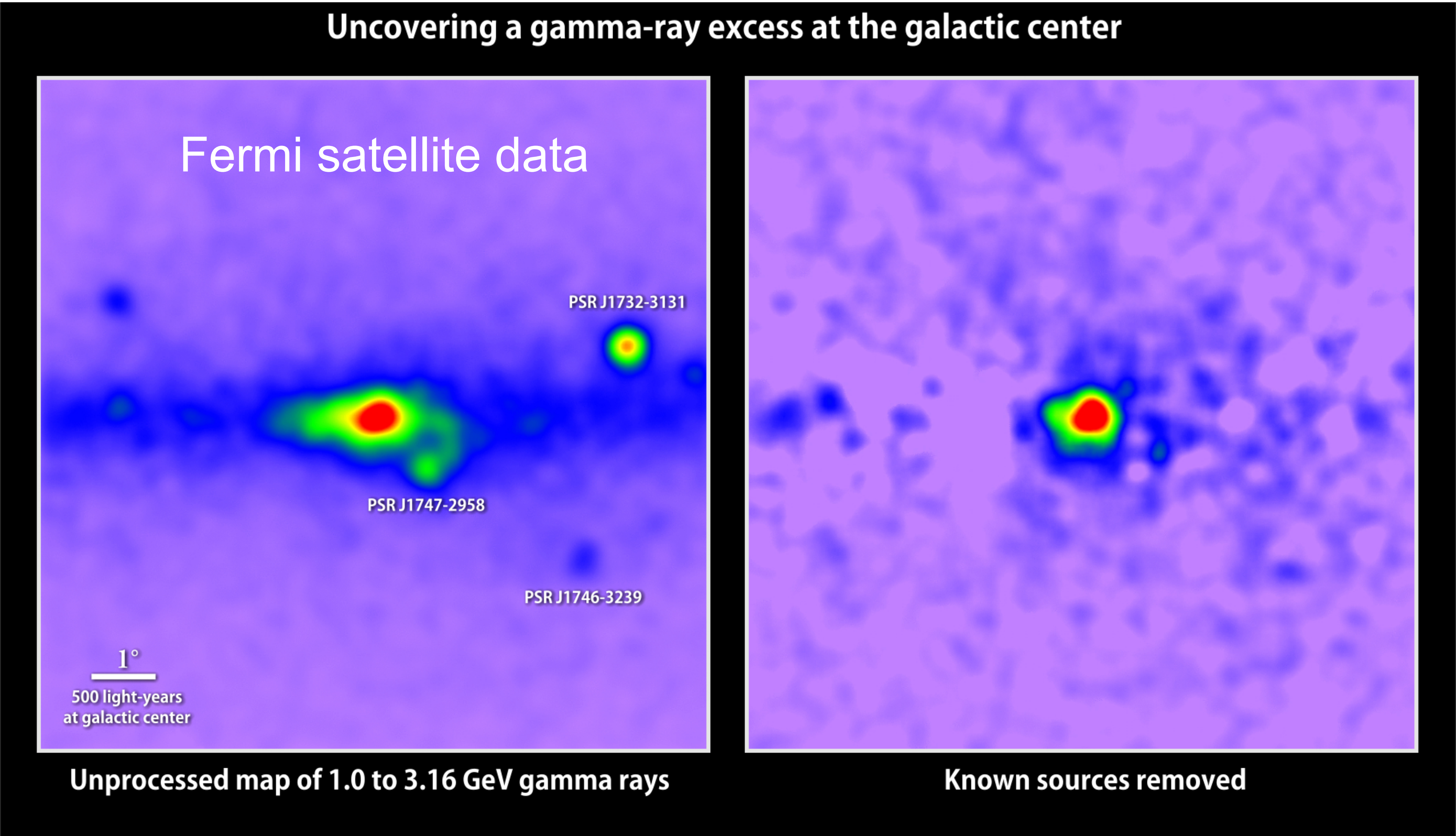
# Cold dark matter *vs* warm dark matter

*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,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]



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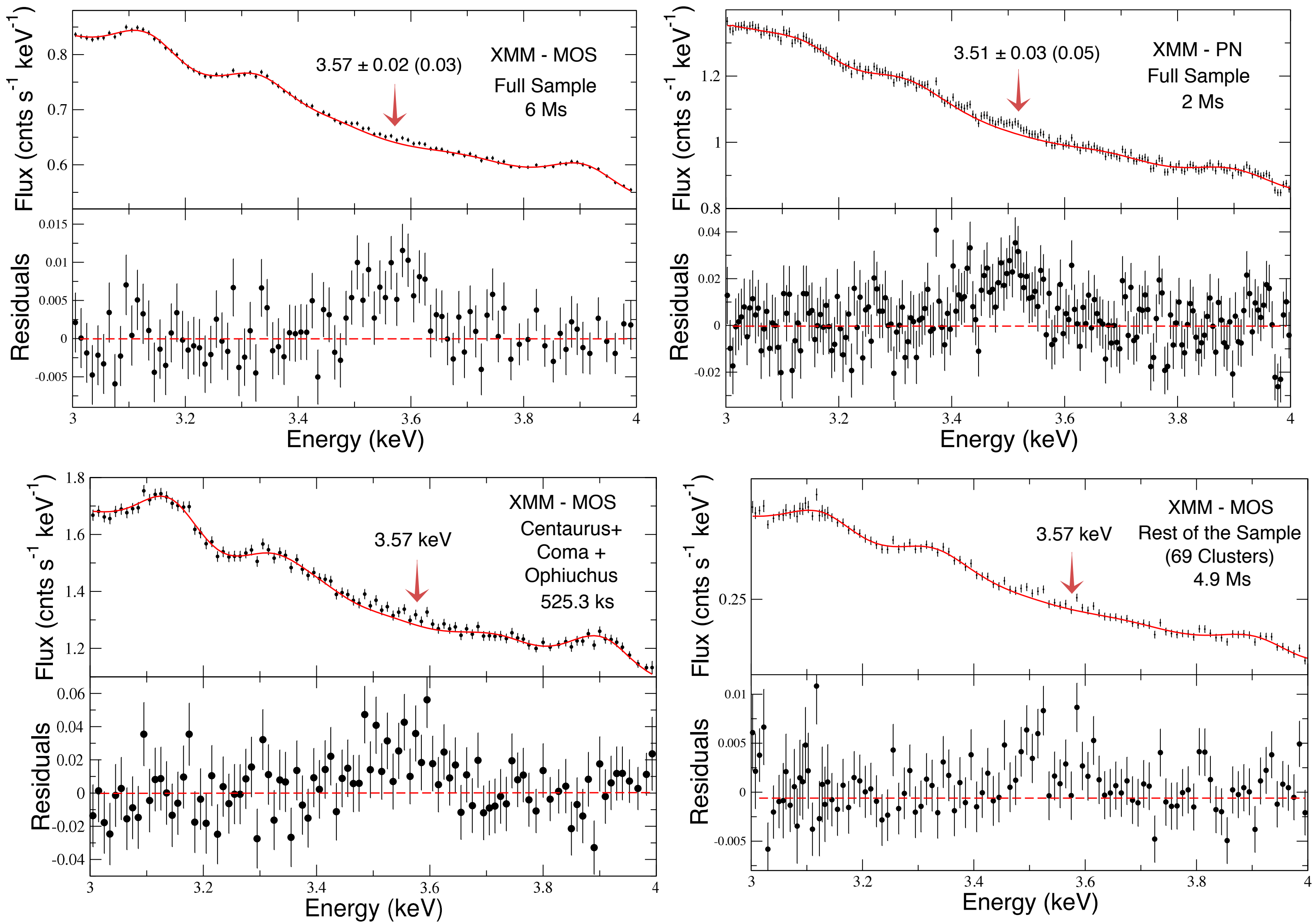
# Warm dark matter
# WDM decay line in 69 stacked clusters?

E=3.57 keV

Bulbul et al. '14



Very unlikely that both are right!

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

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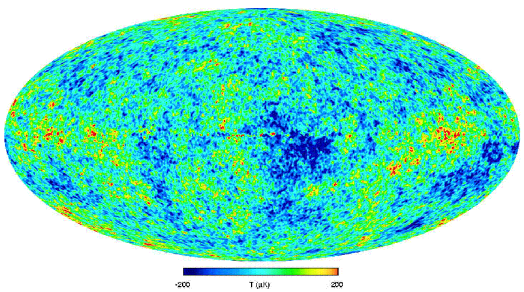
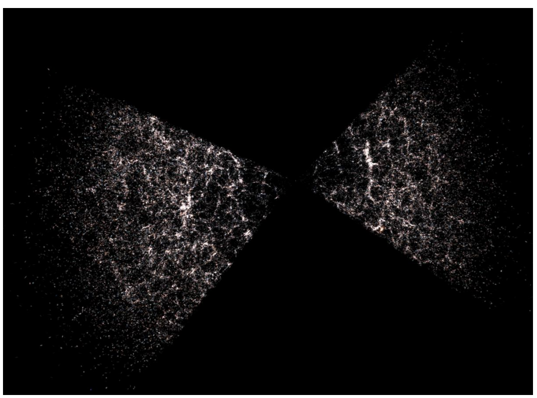
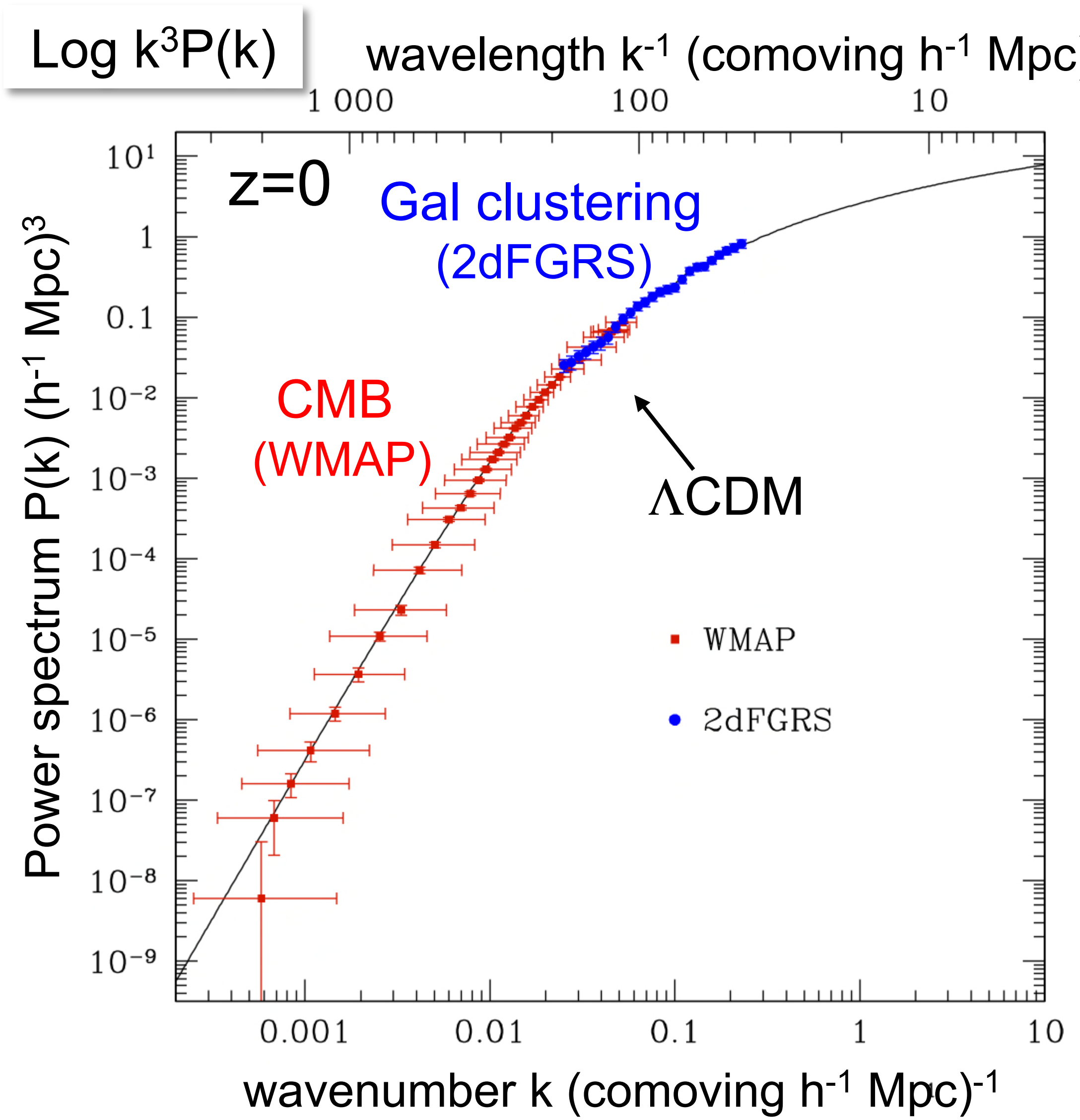


z~1000



z~0




⇒ 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 →

$\lambda_{cut}$ α $m_x^{-1}$

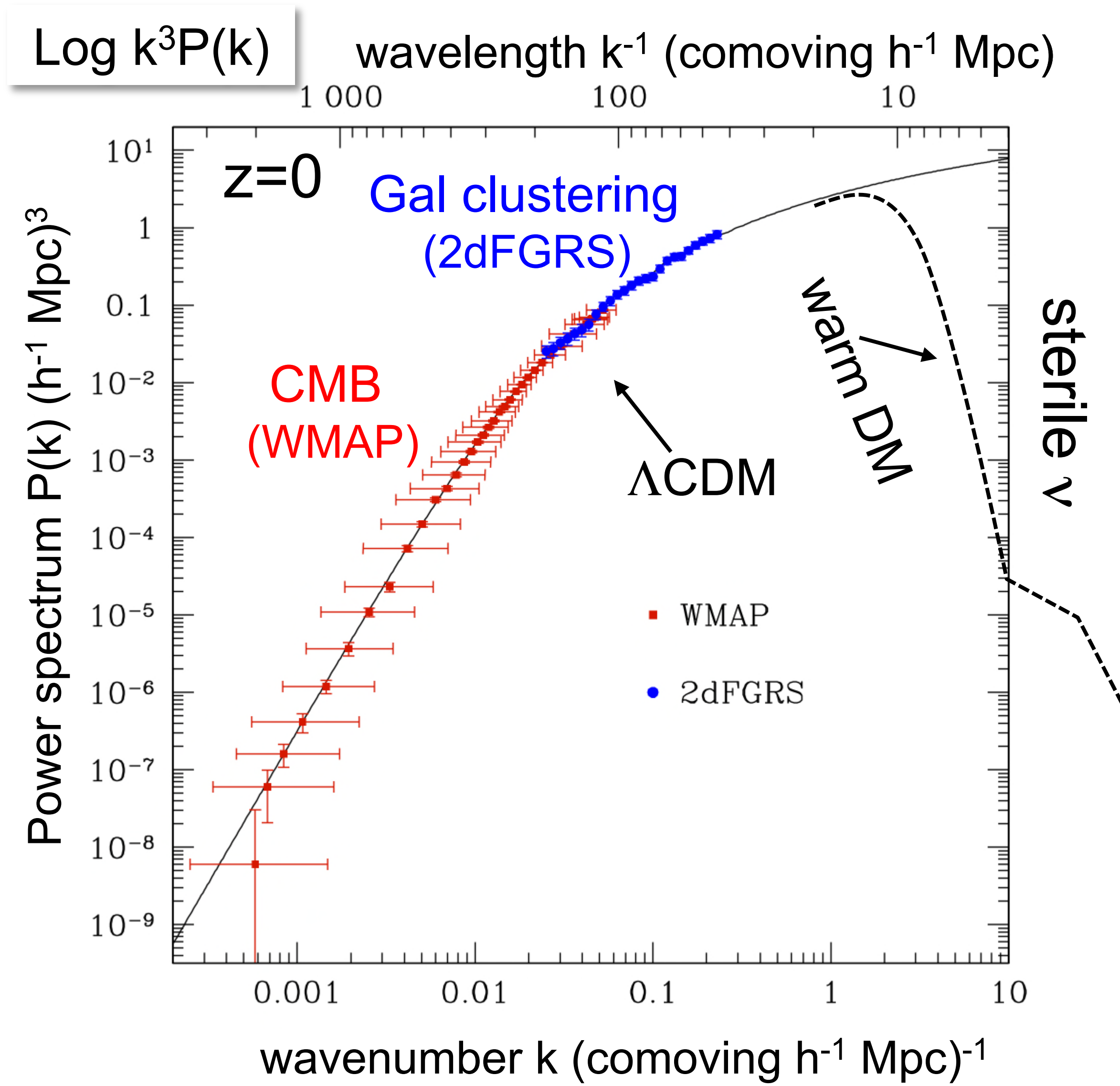
for thermal relic

$m_{CDM}$ ~ 100GeV

susy; $M_{cut}$ ~ $10^{-6}$ $M_o$

$m_{WDM}$ ~ few keV

sterile ν; $M_{cut}$~$10^9$ $M_o$



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# Sterile neutrinos

Explain:

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

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

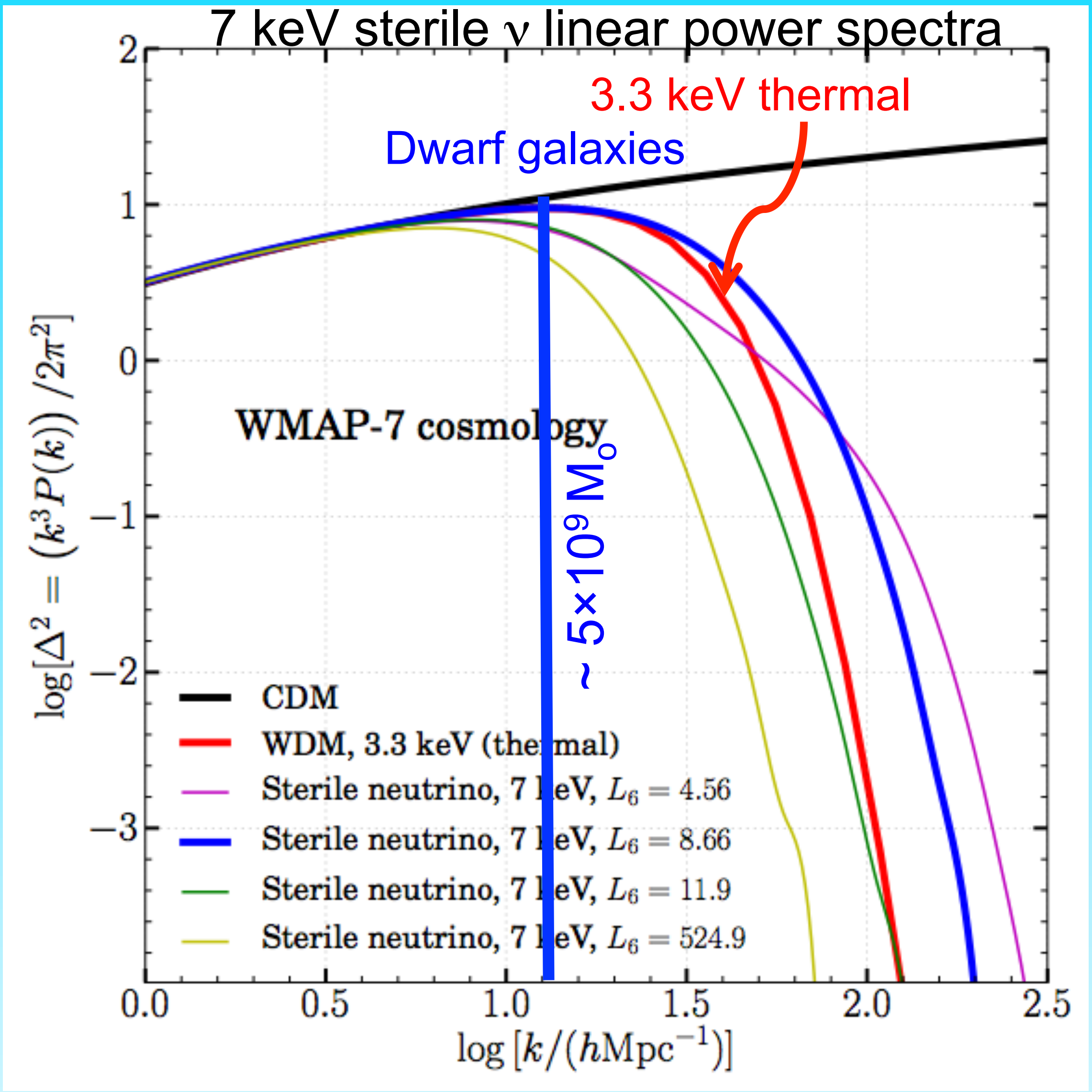
- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N = \Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-rays decay

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

- Thermal and resonant production mechanisms
- Resonant production depends on baryon asymmetry parameter, $L_6$
- Linear PS varies non-monothonically with $L_6$

Ly-α forest rules out thermal masses, mν<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

13.4 billion years ago

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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

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# The Copernicus Complexio (COCO) simulations

Hellwing et al. '15

WDM with thermal mass of 3.3 keV

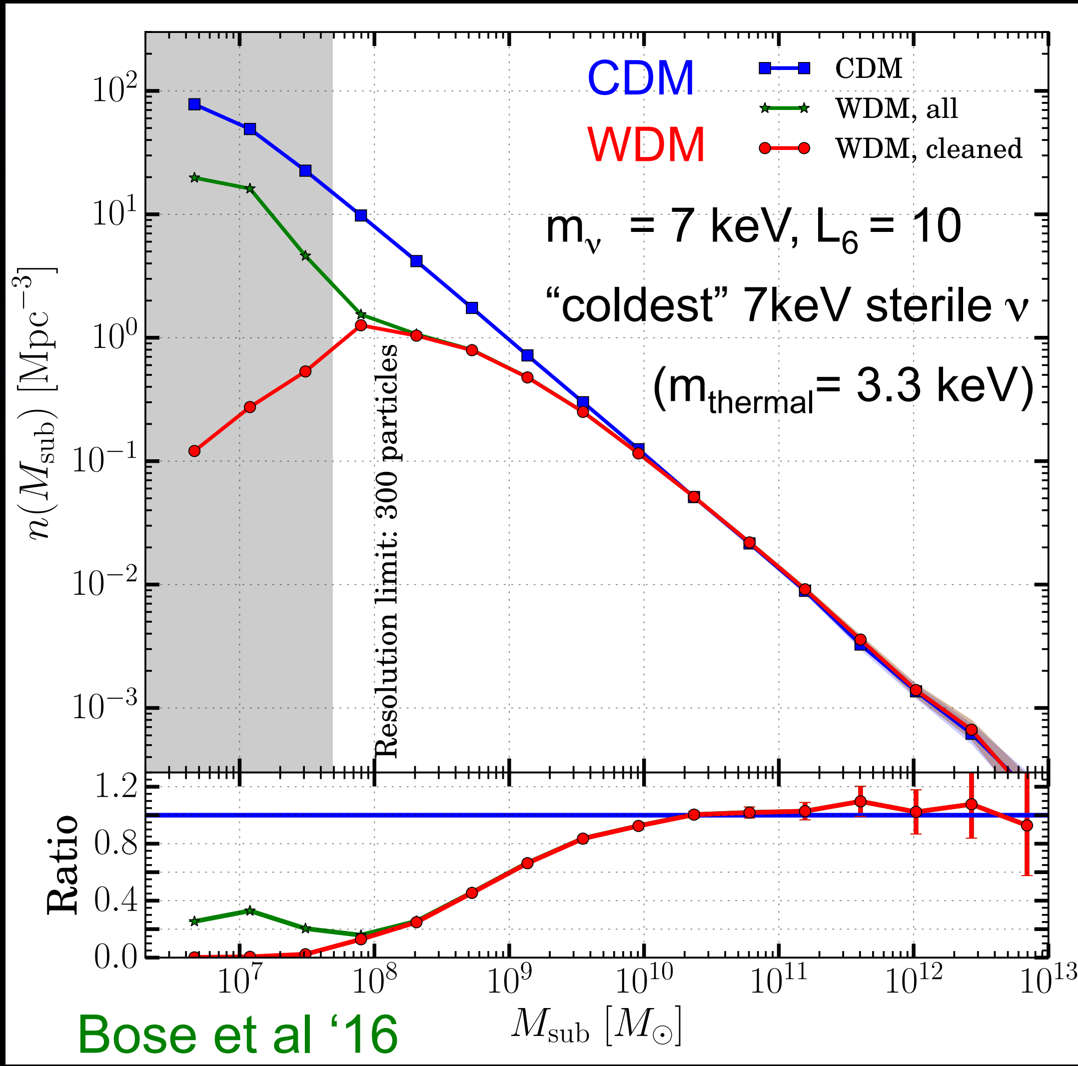
PS ≅ "coldest" ($L_6$ = 9) 7keV sterile neutrino

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

# The subhalo mass function

CDM

WDM

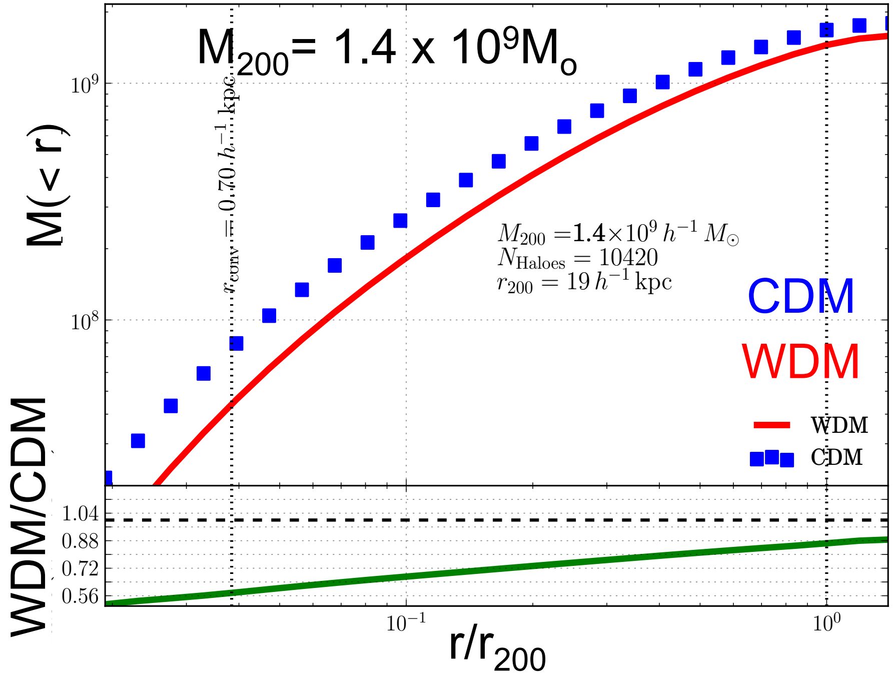


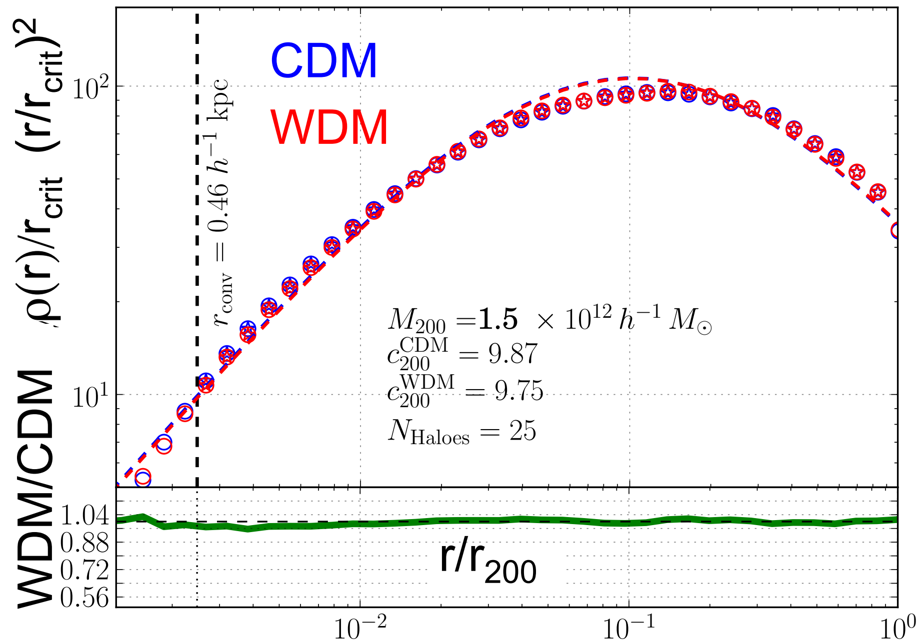

Already fewer WDM subhalos at $3 \times 10^9 M_o$

10 x fewer at $10^8 M_o$

# Halo density profiles

Profiles well fit by NFW for CDM and WDM




$\rho$(r) identical for ~$10^{12}M_o$

but lower central $\rho$ for ~$10^9$M

Bose et al ‘16

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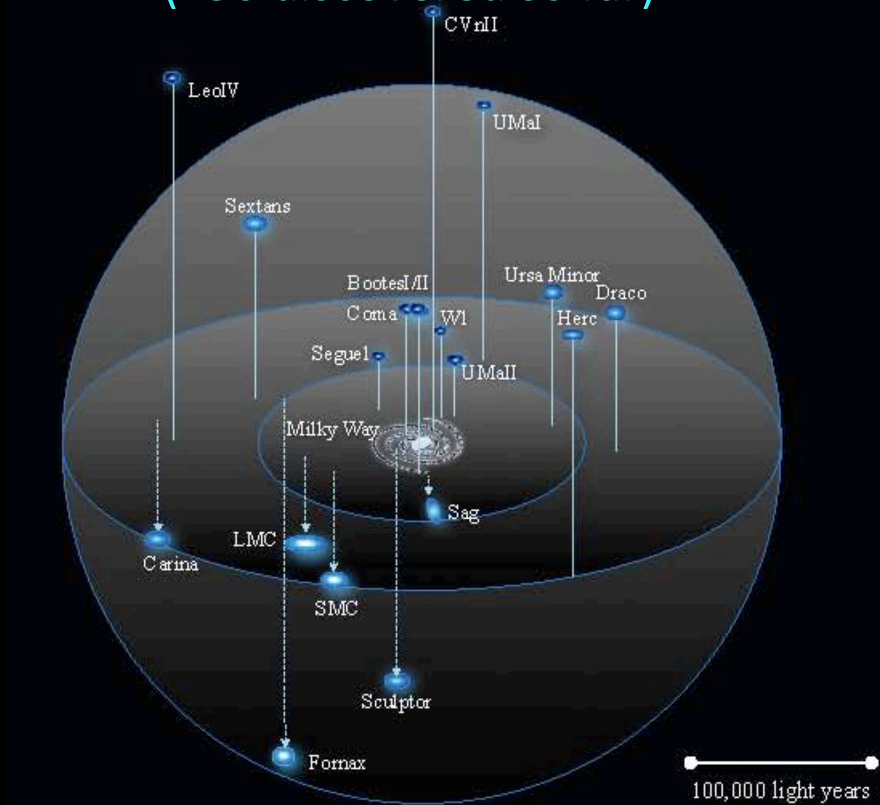
# Observational tests of CDM vs WDM

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 matter subhalos in CDM

(hundreds of thousands)

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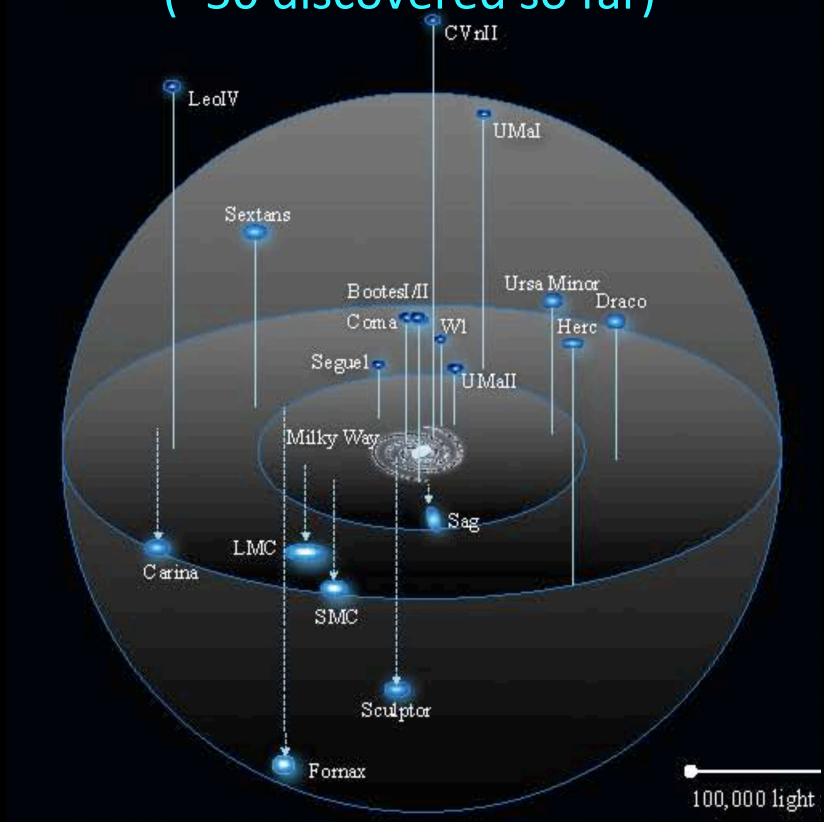



Dark matter subhalos in WDM

(a few tens)

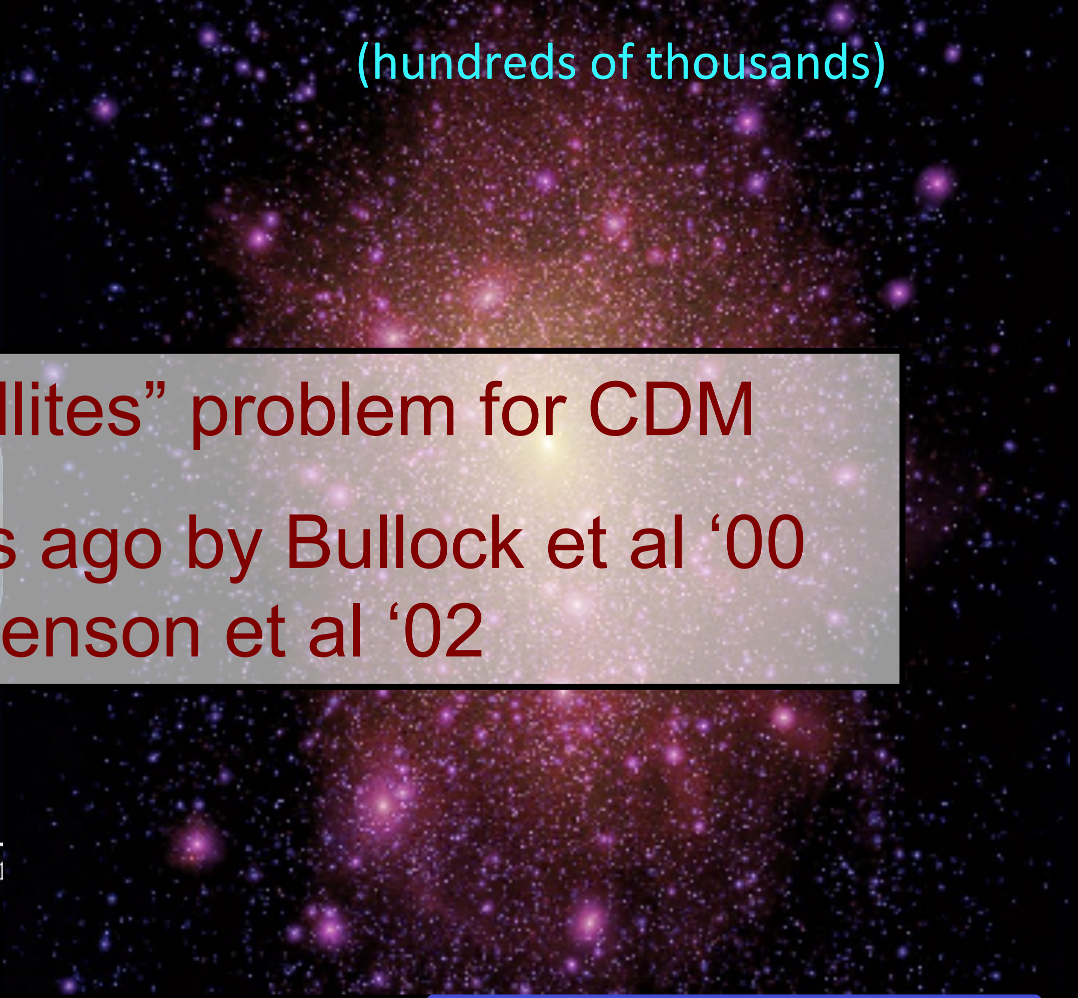
# The satellites of the MW and M31

The satellites of the MW

(~50 discovered so far)


Dark mattter subhalos in CDM

(hundreds of thousands)



"Missing satellites" problem for CDM

Solved 15 years ago by Bullock et al '00 and Benson et al '02

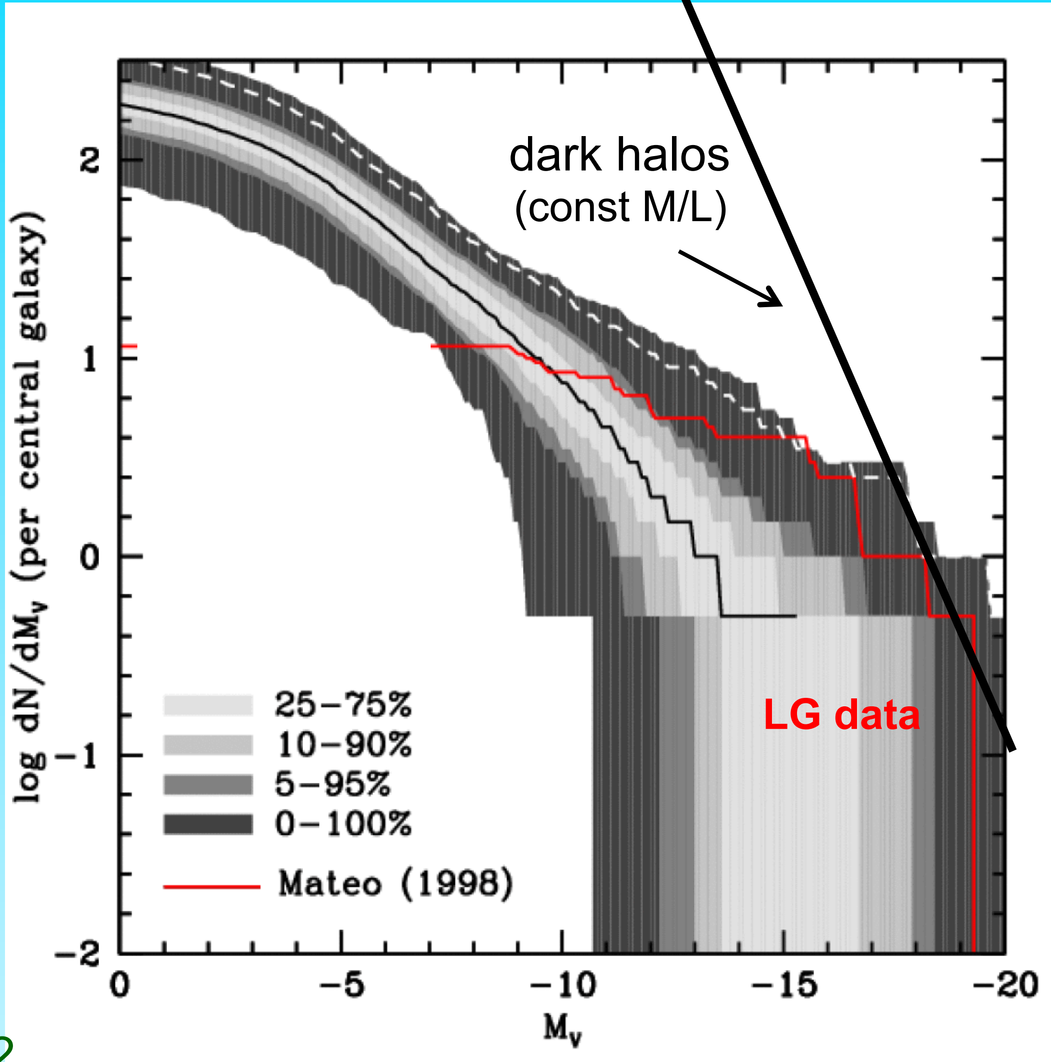
# Making a galaxy in a small halo is hard because:

- Reionization heats gas above $T_{vir}$, 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 $M_V$=-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 etal '93, Bullock etal '01)

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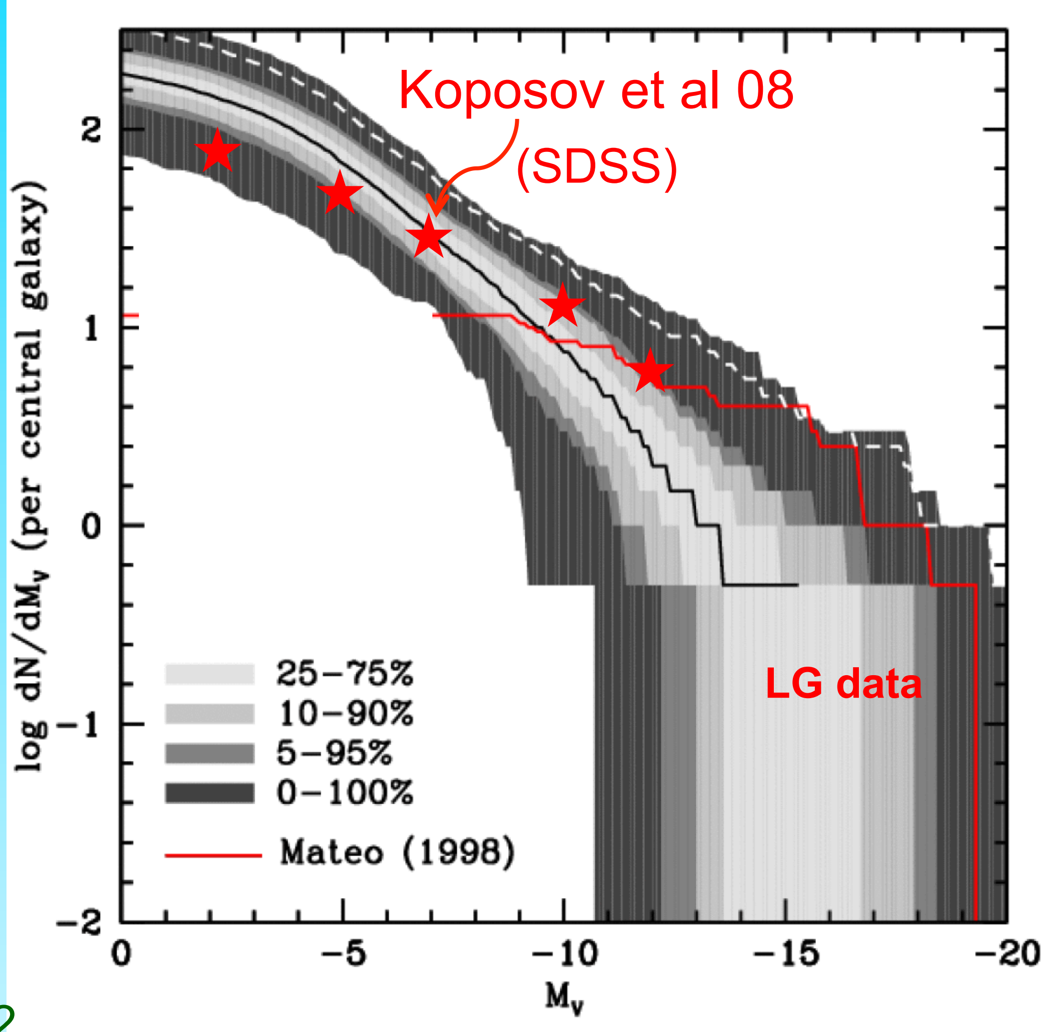
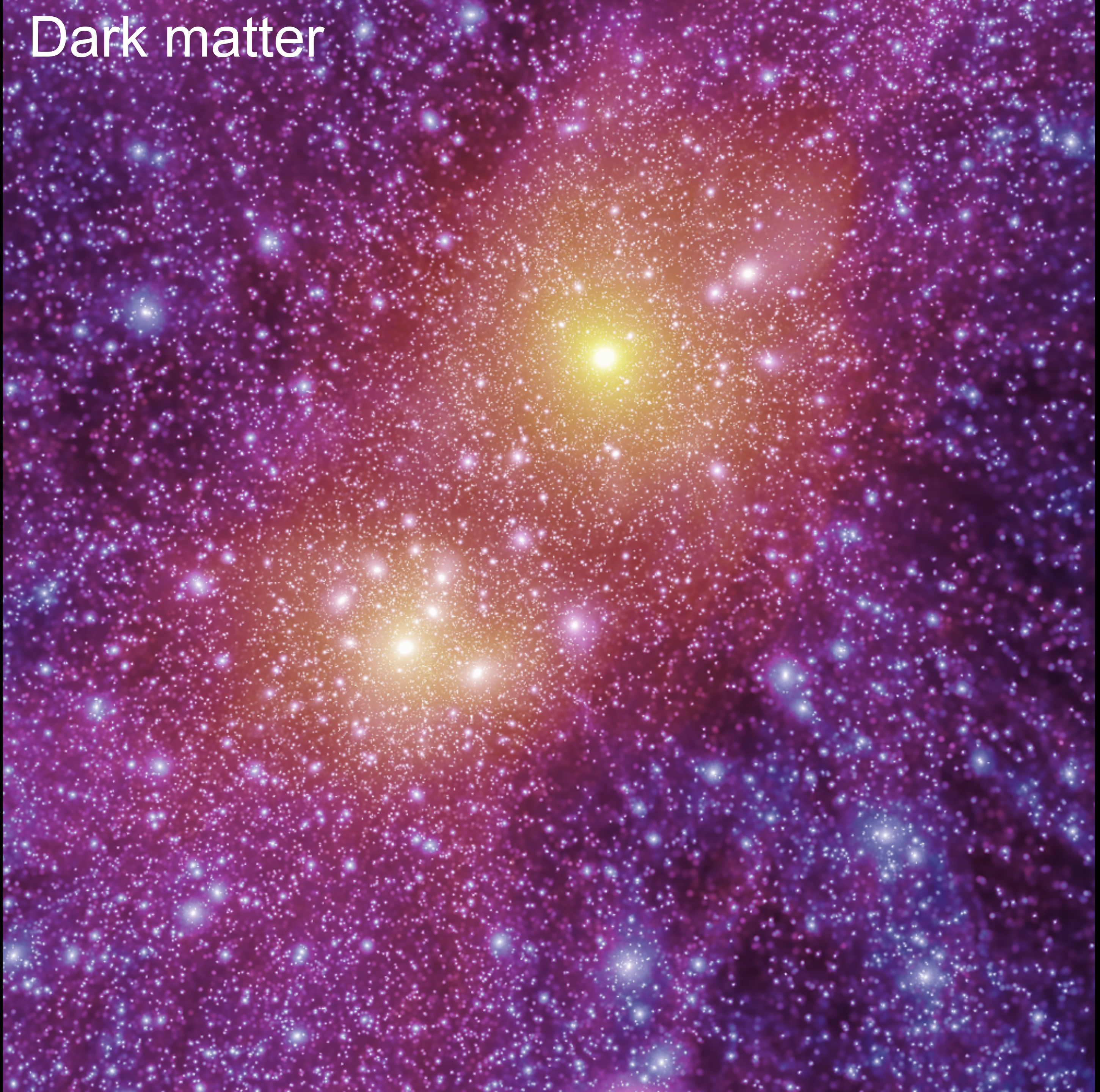



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

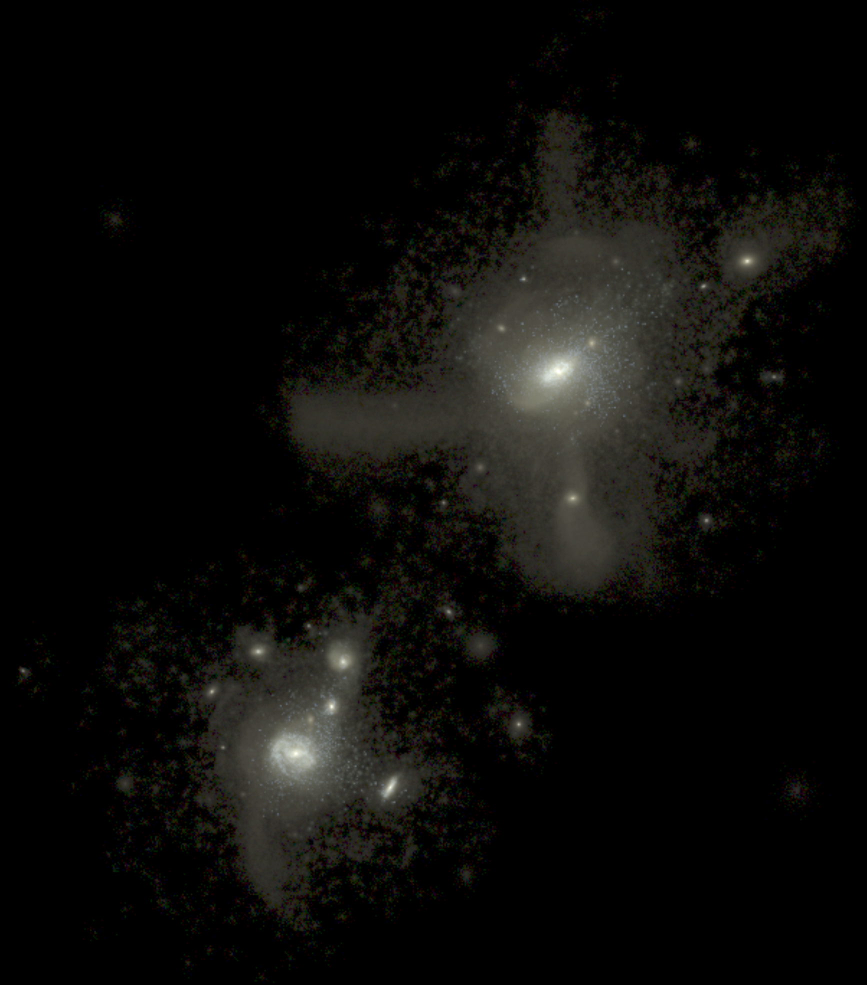



Sawala et al '15

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group



Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

# EAGLE Local Group simulation

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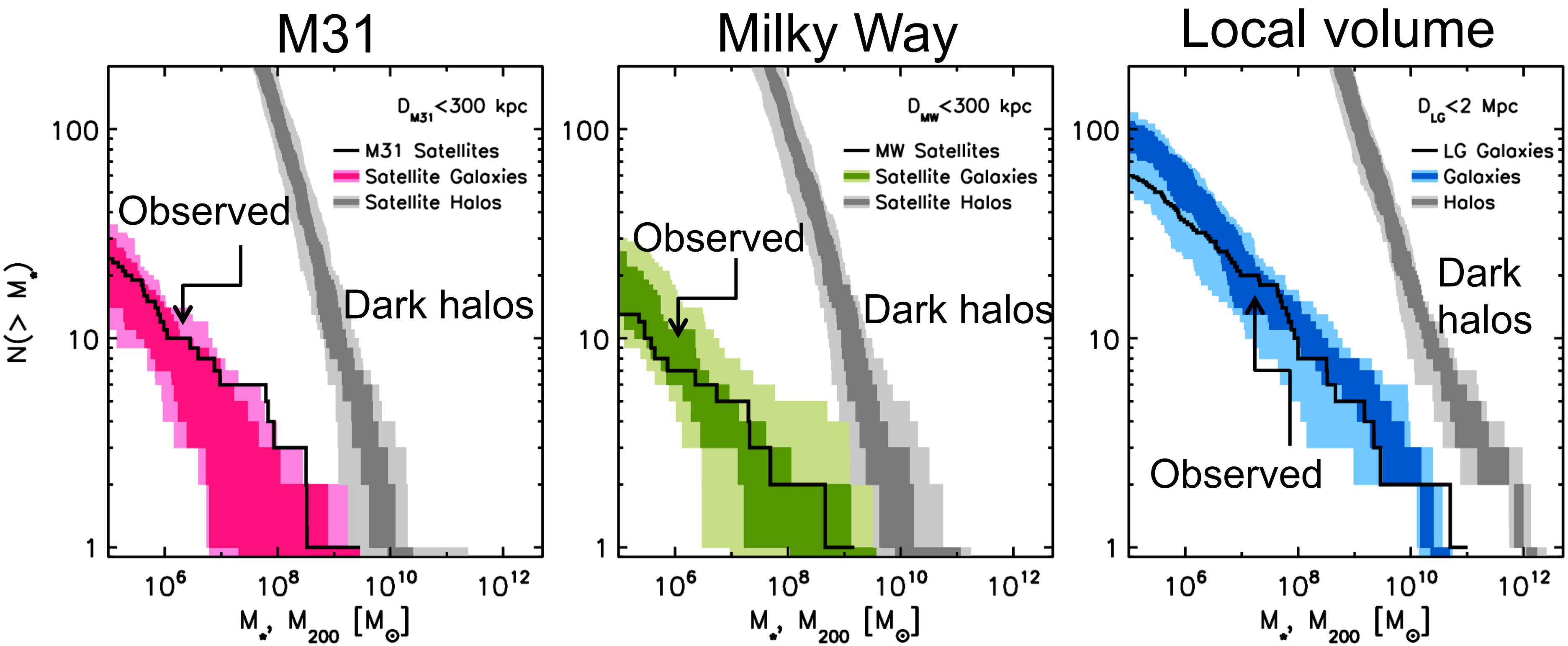
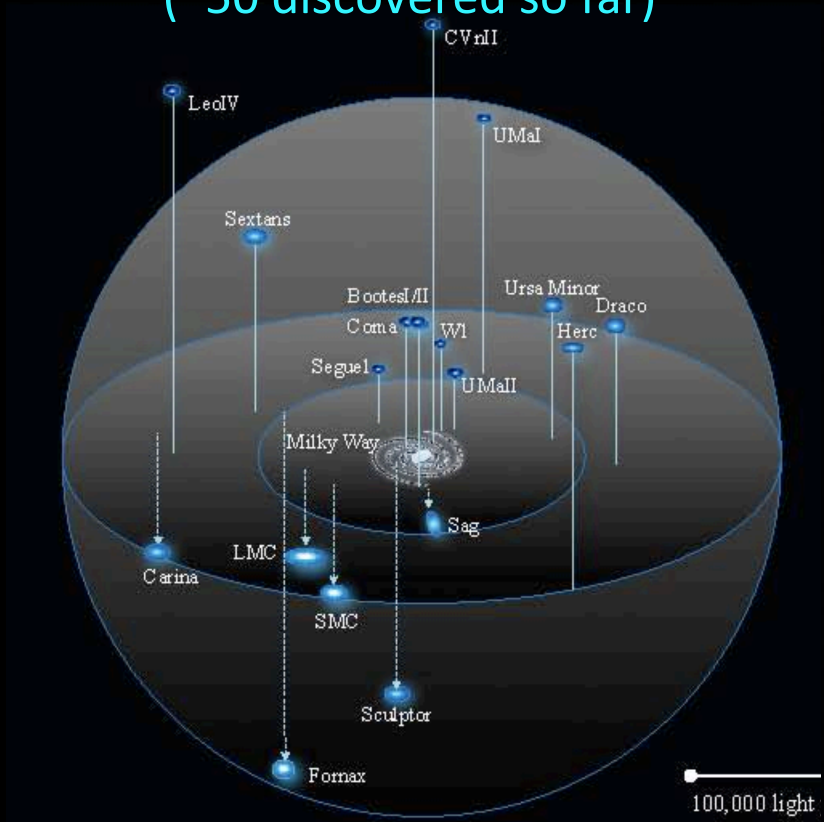



Sawala et al '15

# How about in WDM?

The satellites of the MW

(~50 discovered so far)

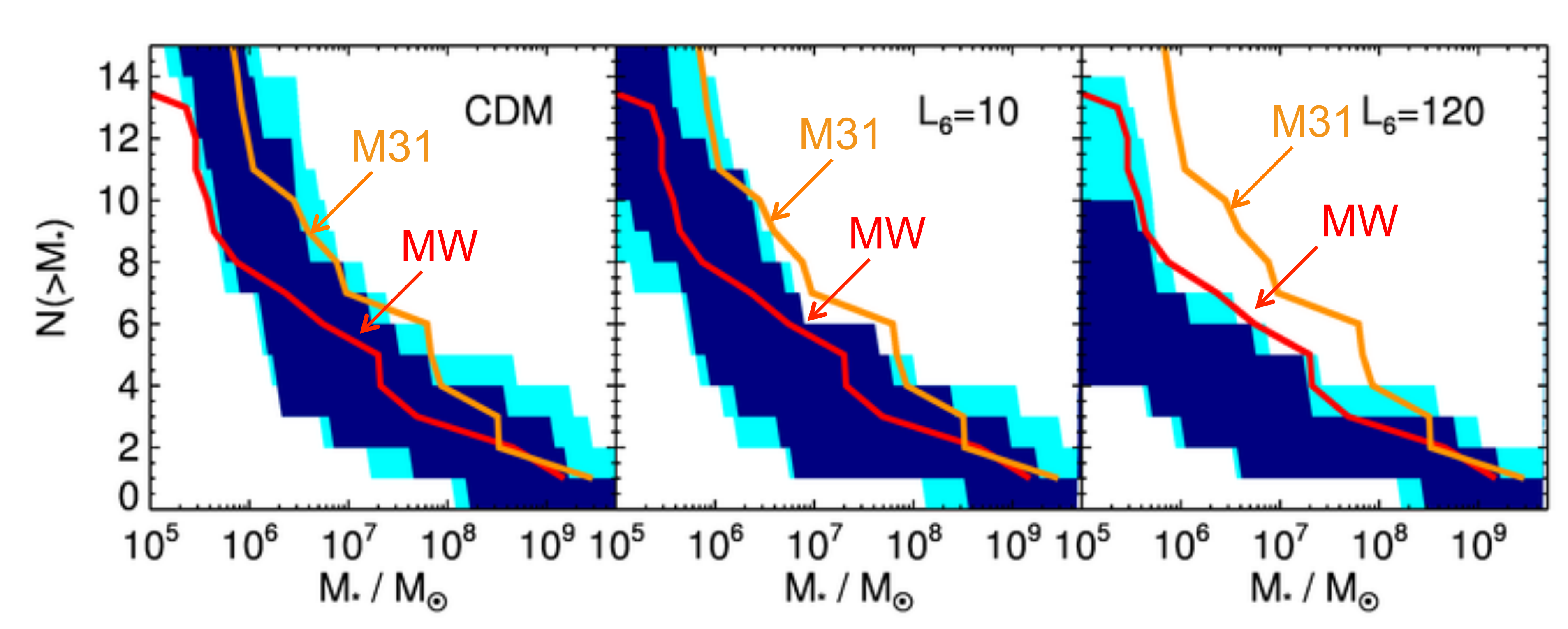



Dark matter subhalos in WDM

(a few tens)

# Luminosity Function of Local Group Satellites in WDM

From "Warm Apostle:" 7keV sterile ν




Lovell et al. '16

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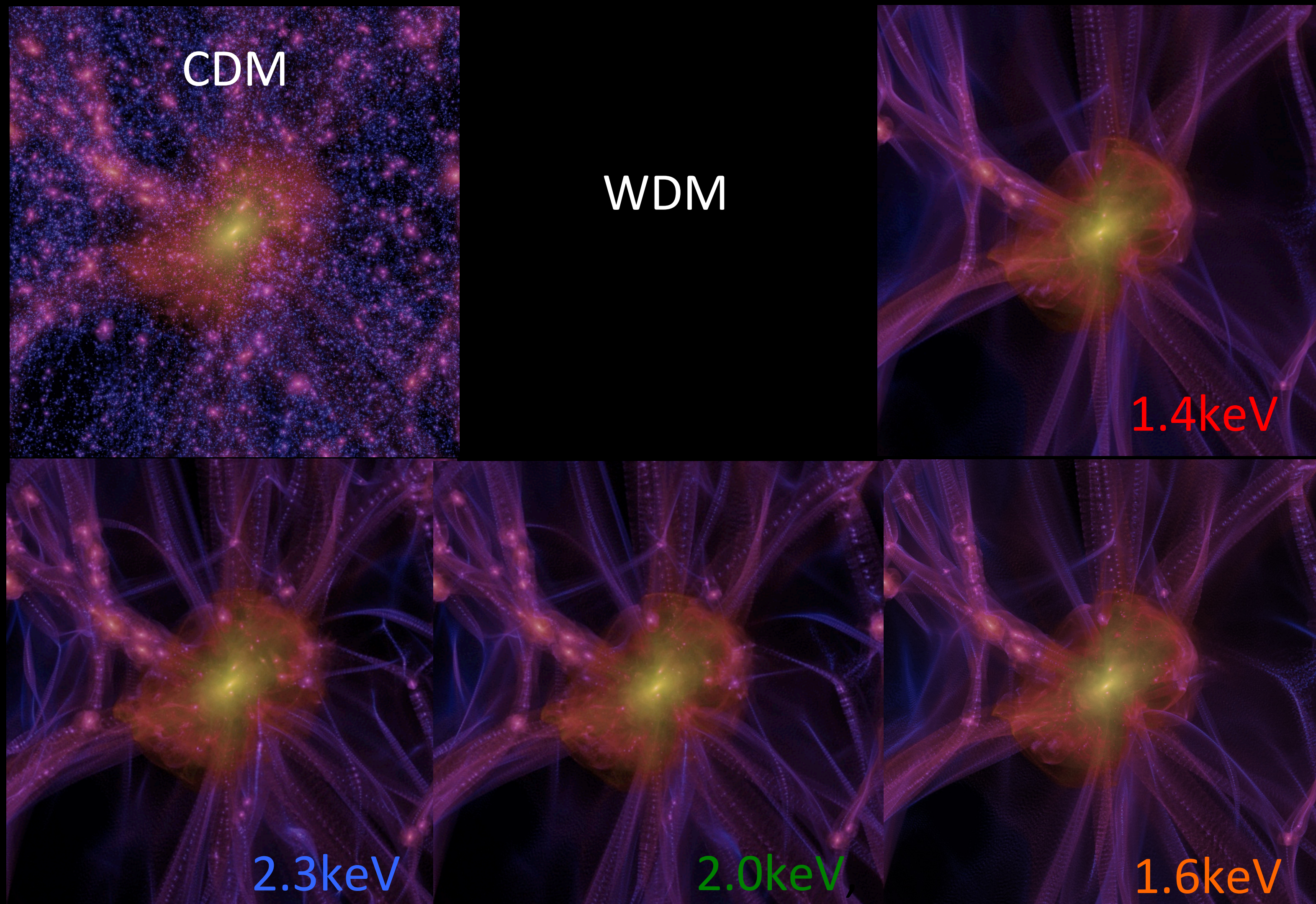
# Warm DM: different ν mass

z=3

WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



# Limits on sterile ν mass

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In WDM, no. of sats depends:

- Particle mass
- MW halo mass

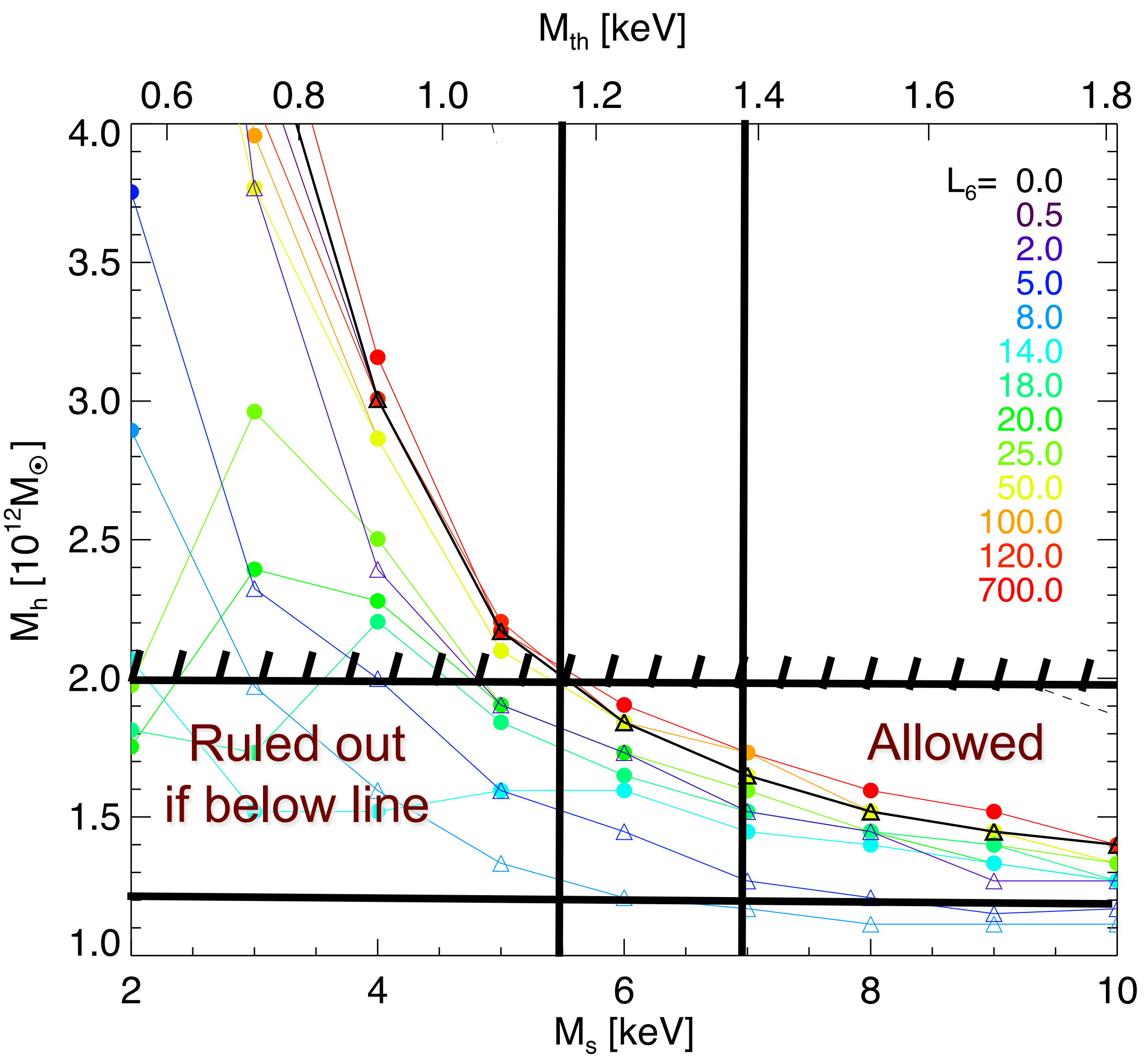
7 keV sterile ν requires

$M_{halo} > 1.2 \times 10^{12}\ M_o$

For $M_{halo} < 2 \times 10^{12}\ M_o$

$m_\nu > 5.5$ keV

Lovell et al '16



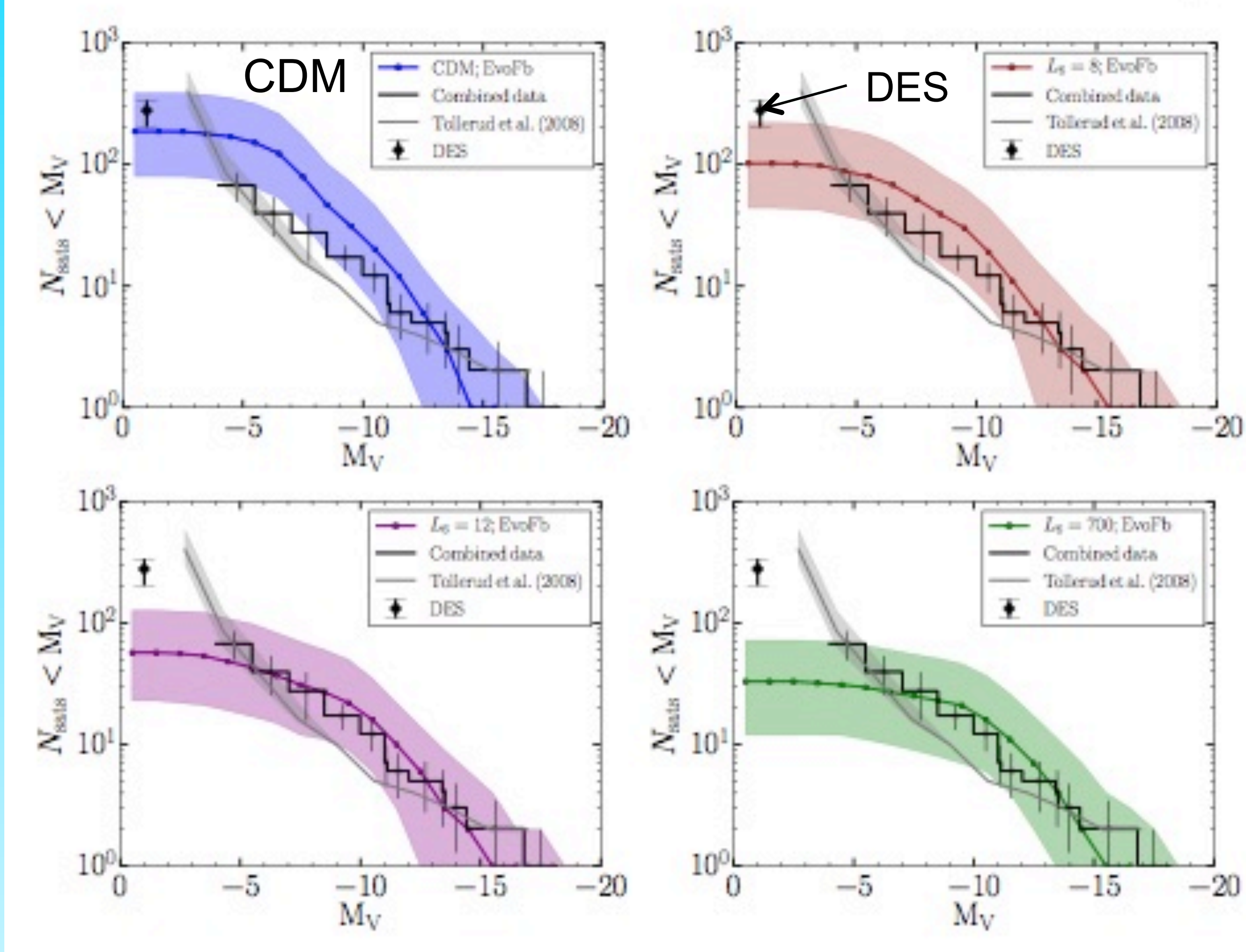
# Luminosity function of MW satellites in WDM

7 KeV sterile ν; $M_{halo} \sim 1 \times 10^{12} M_o$

Sterile ν models consistent with data for classical satellites

Most sterile ν models ruled out by DES satellites!

Bose et al. ‘16

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# Observational tests of CDM vs WDM

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# Observational tests of CDM vs WDM

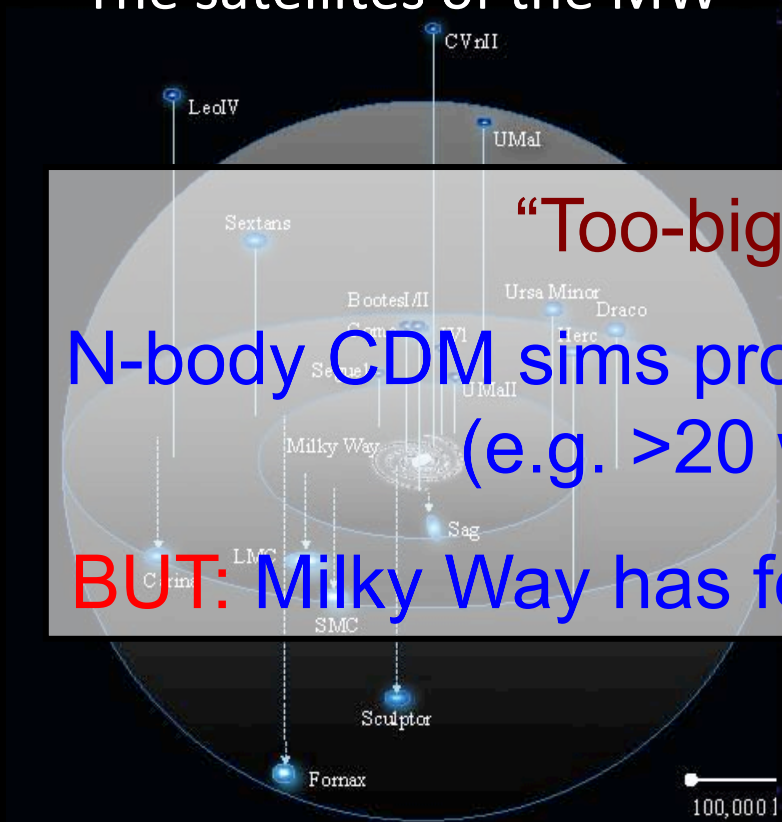
II. The structure of galactic satellites (too-big-to-fail)

# The strucure of satellite halos

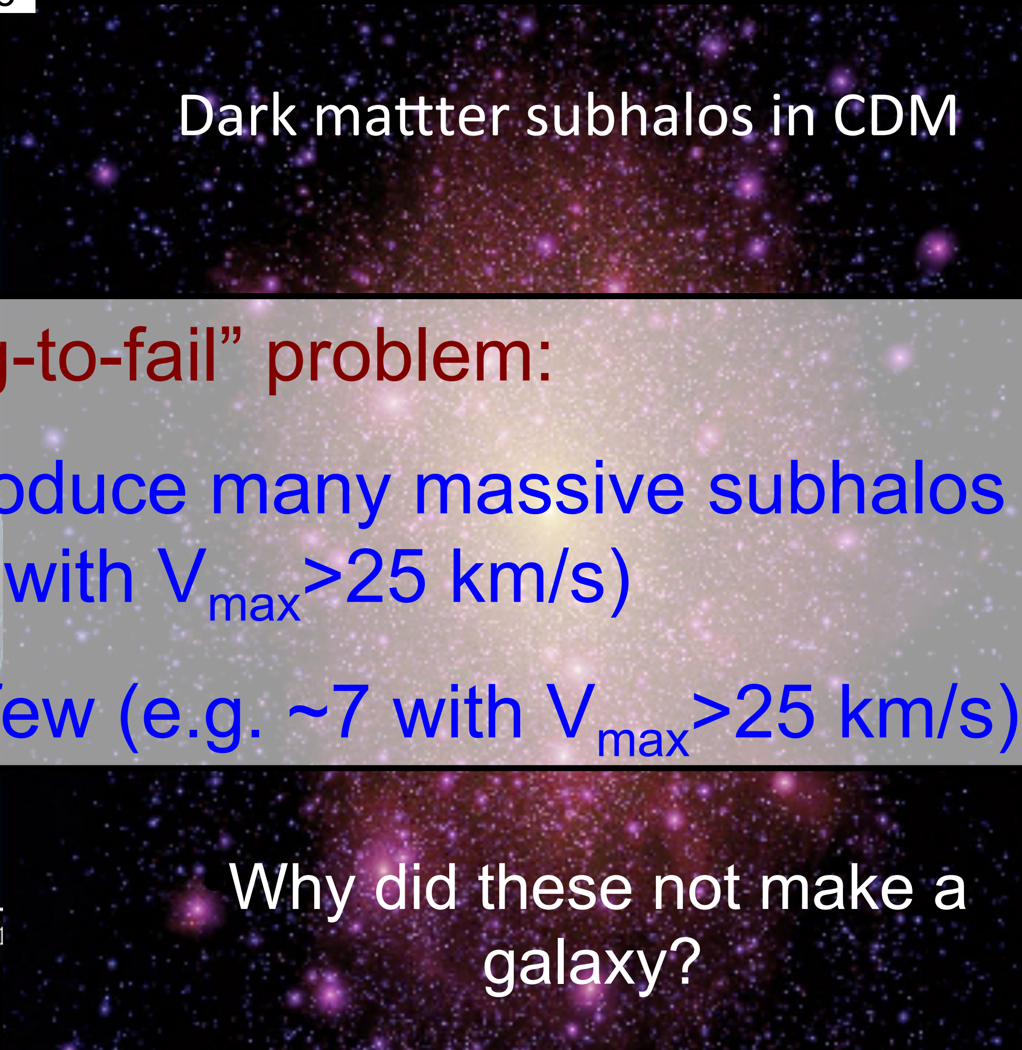
$$V_c = \sqrt{\frac{GM}{r}}$$

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

The satellites of the MW




Dark matter subhalos in CDM



“Too-big-to-fail” problem:

N-body CDM sims produce many massive subhalos (e.g. >20 with $V_{max}$>25 km/s)

BUT: Milky Way has few (e.g. ~7 with $V_{max}$>25 km/s)

Why did these not make a galaxy?

# To-big-to-fail problem in CDM

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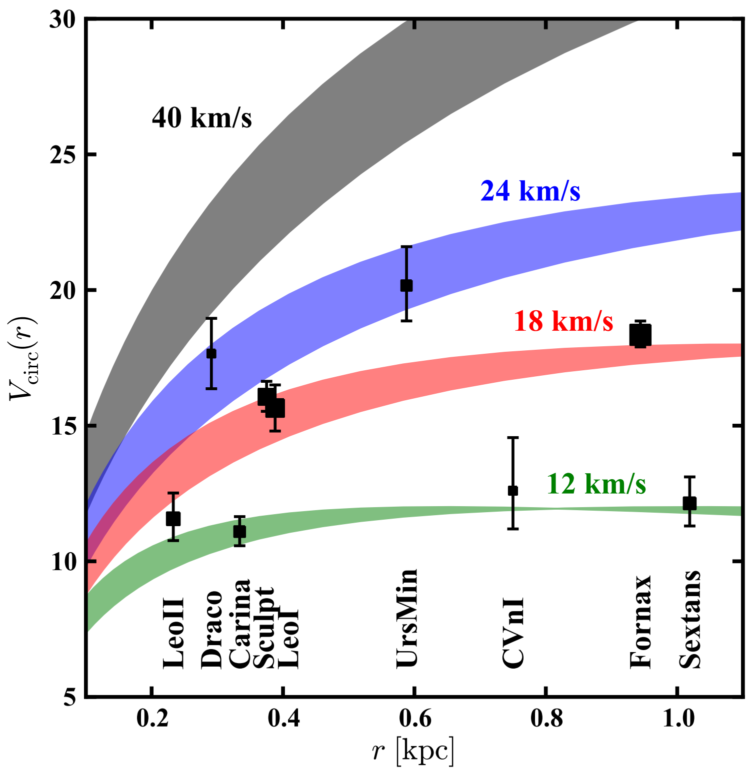
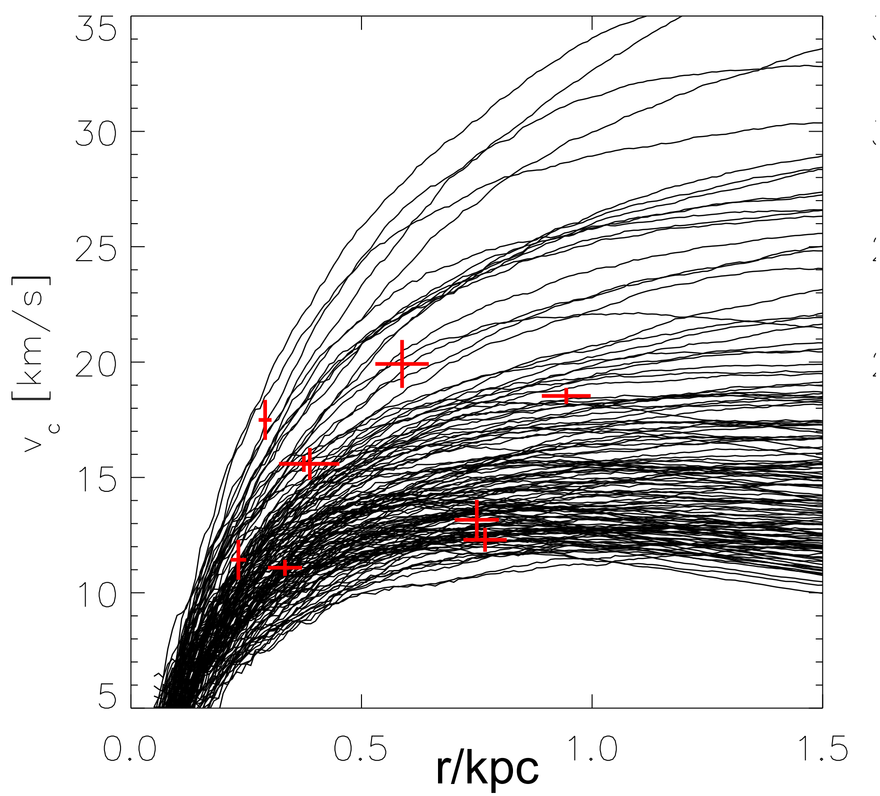
$$V_c = \sqrt{\frac{GM}{r}}$$

"Aquarius" N-body sim




Boylan-Kolchin et al '12

Apostle dark-matter only




Sawala et al '16

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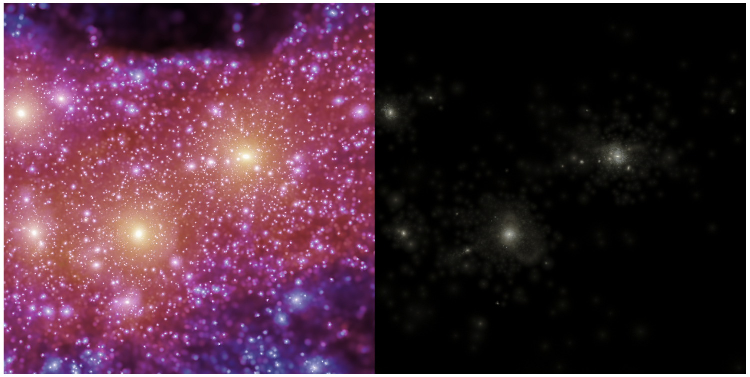
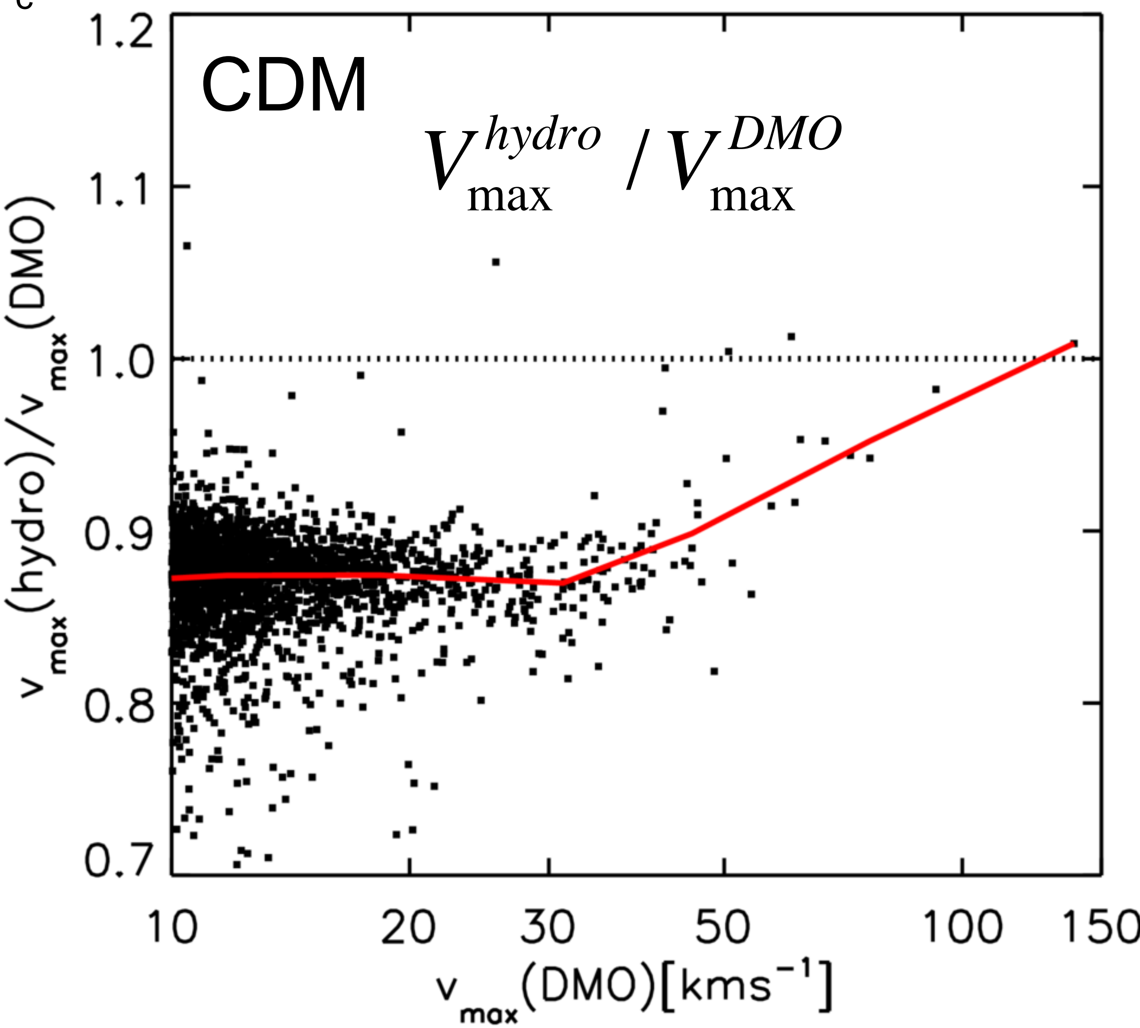
# To-big-to-fail in CDM: baryon effects

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

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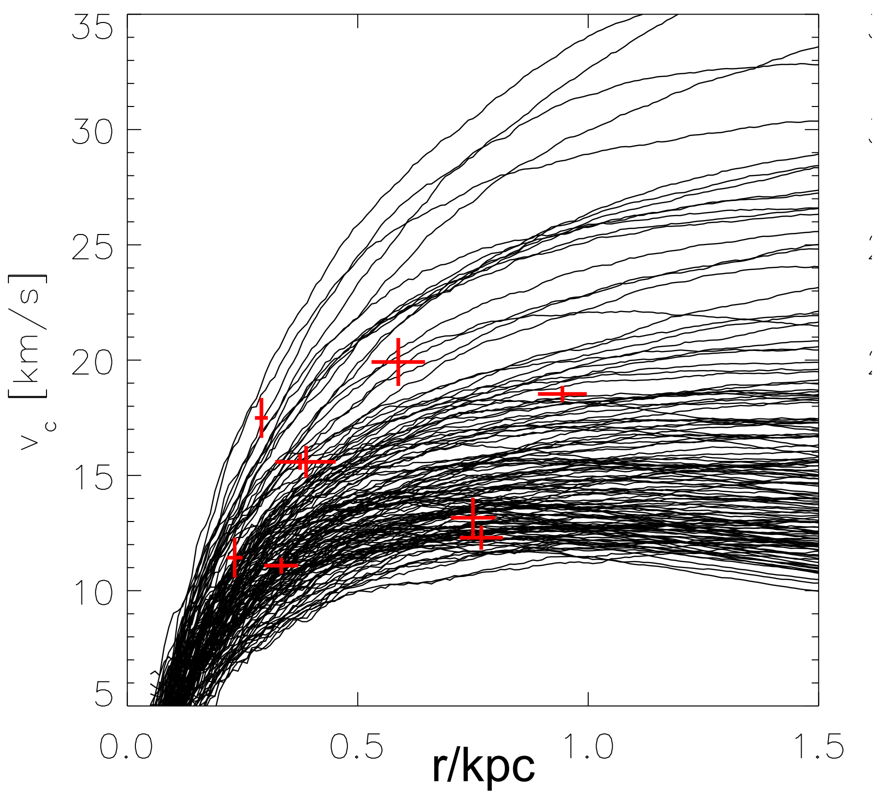
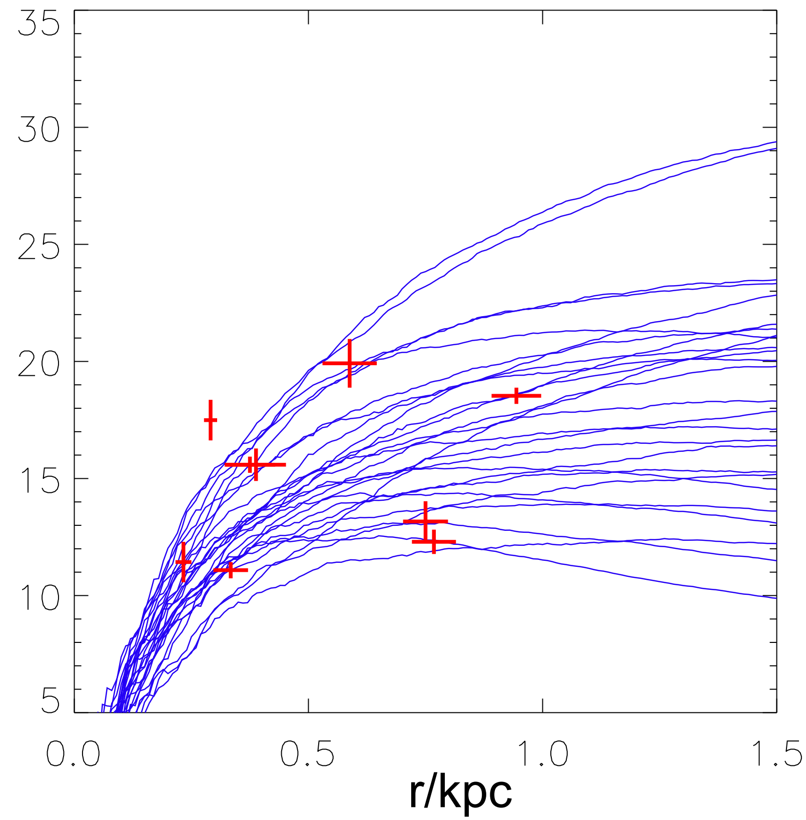
$$V_c = \sqrt{\frac{GM}{r}}$$

Apostle dark-matter only




Apostle with baryons




Sawala et al '16

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

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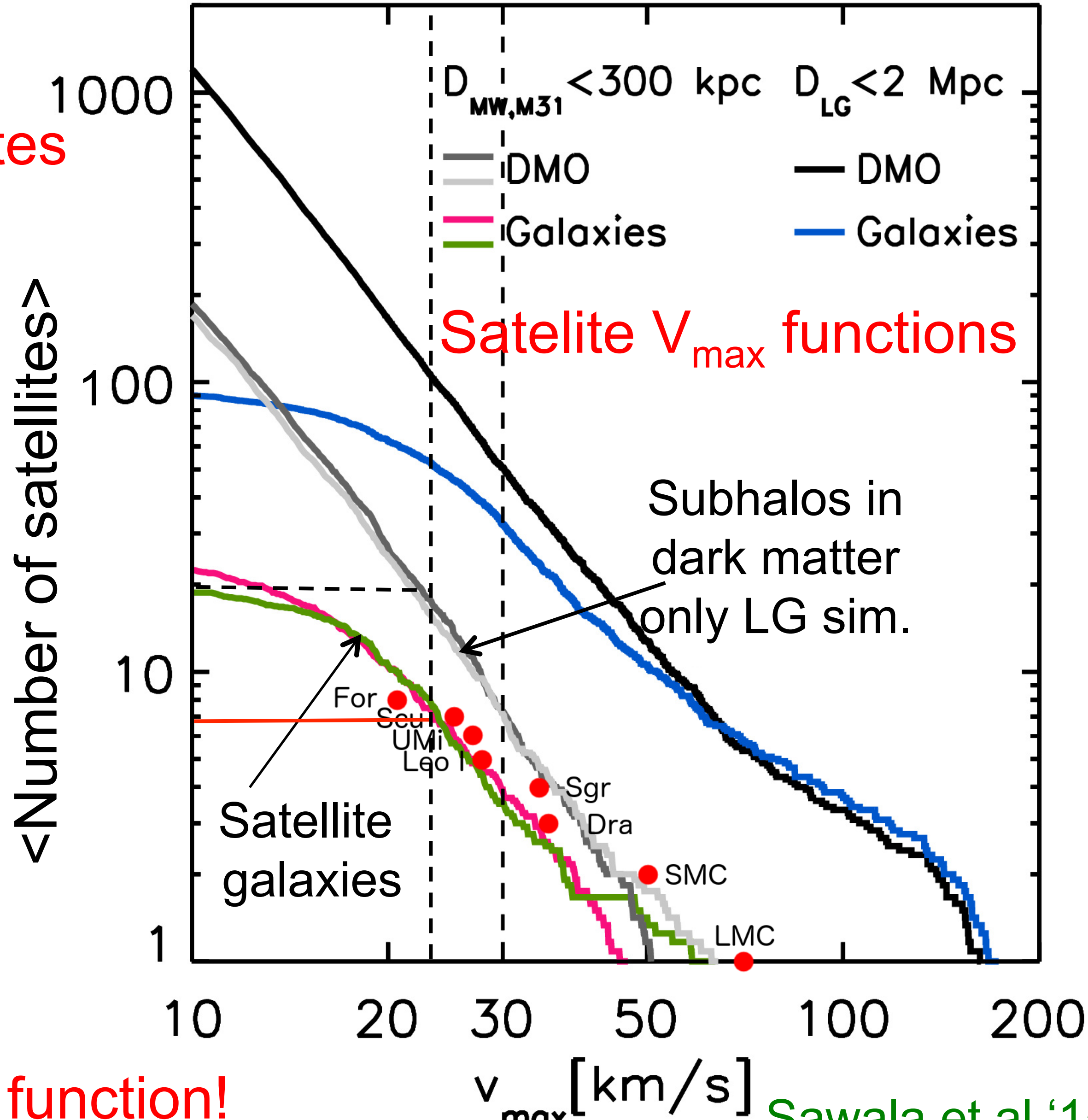
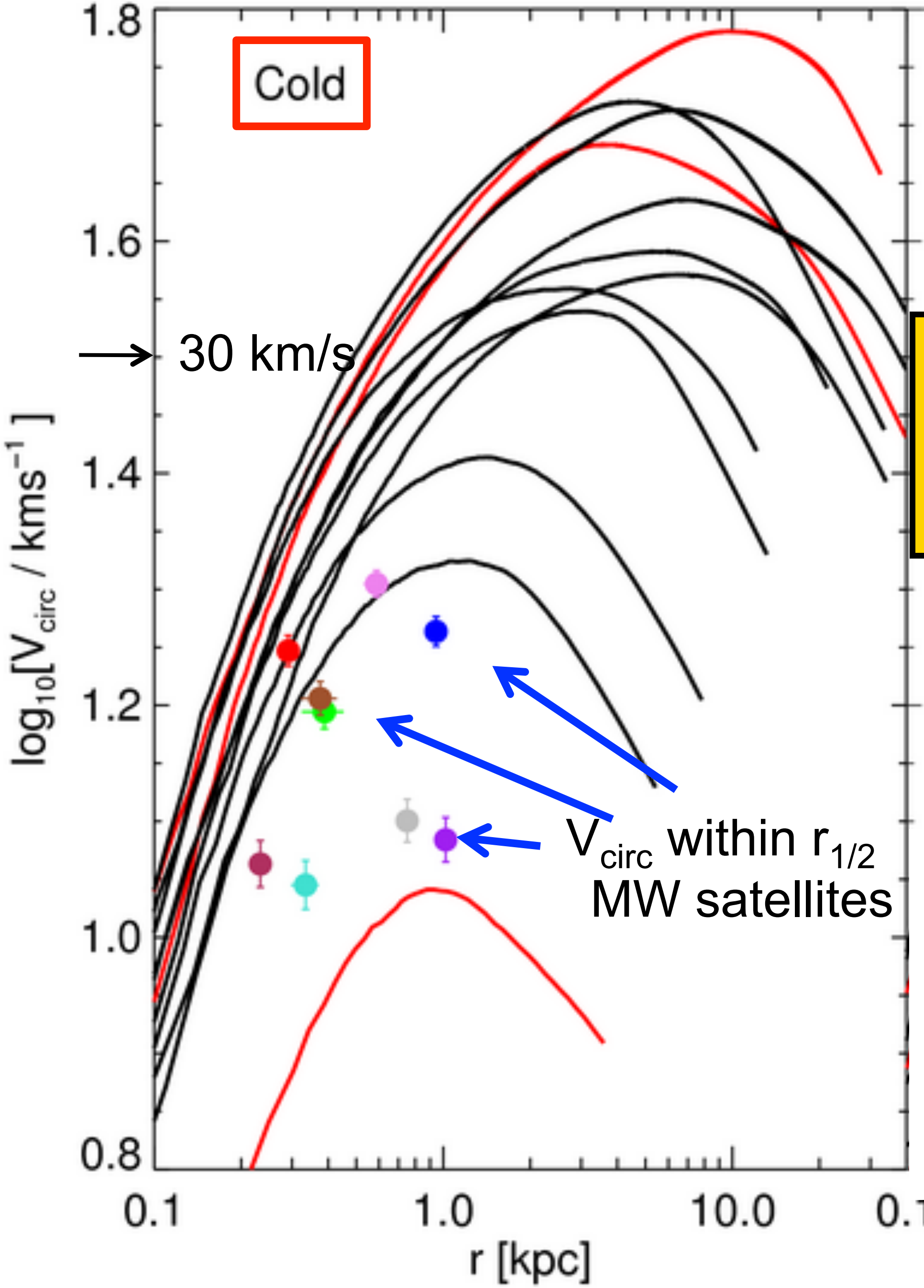
Hydro sims → ~3 satellites with $V_{max}$> 30 km/s




… and with correct $V_{max}$ function!

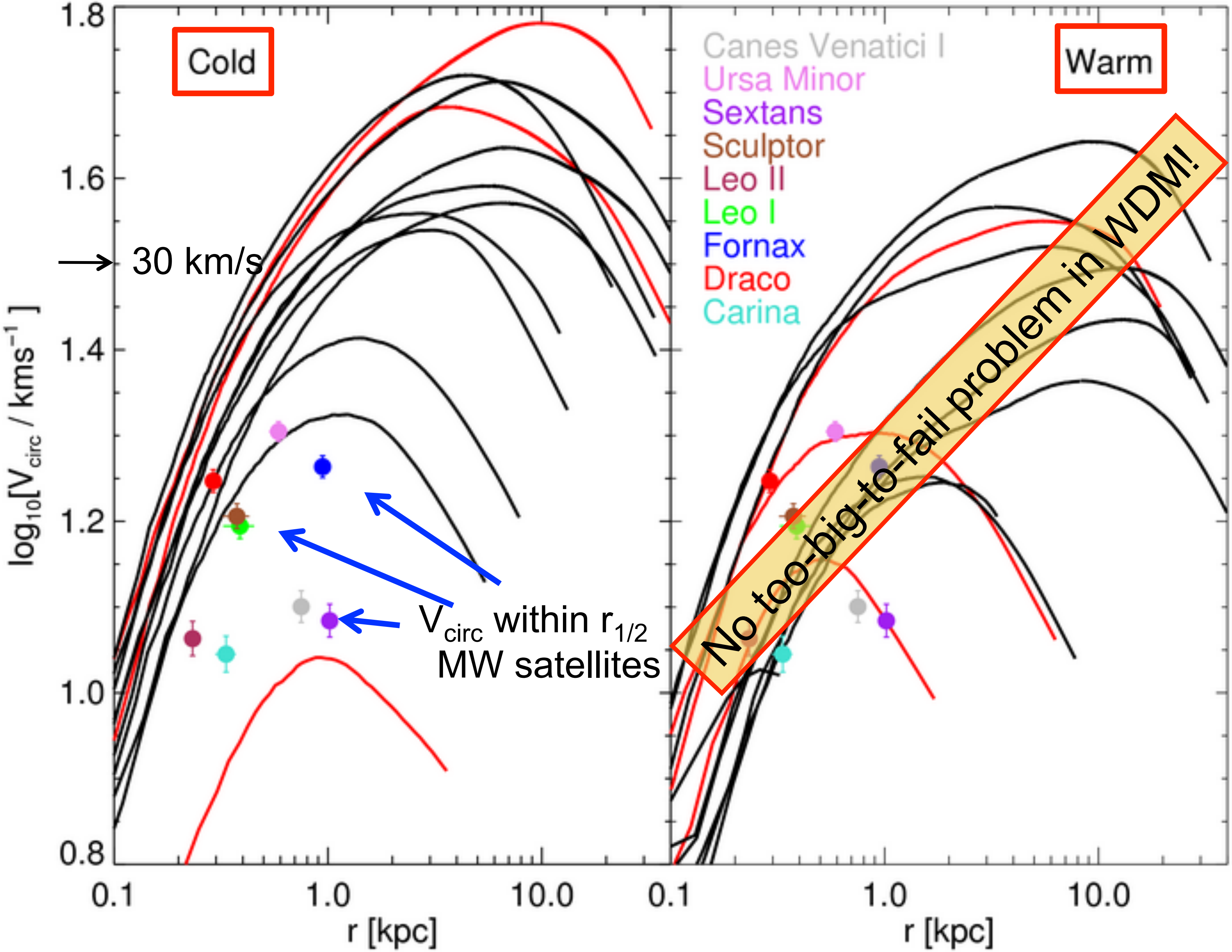
Sawala et al '15




$$V(r)_c = \sqrt{\frac{GM(r)}{r}}$$

# The "too-big-to-fail" problem

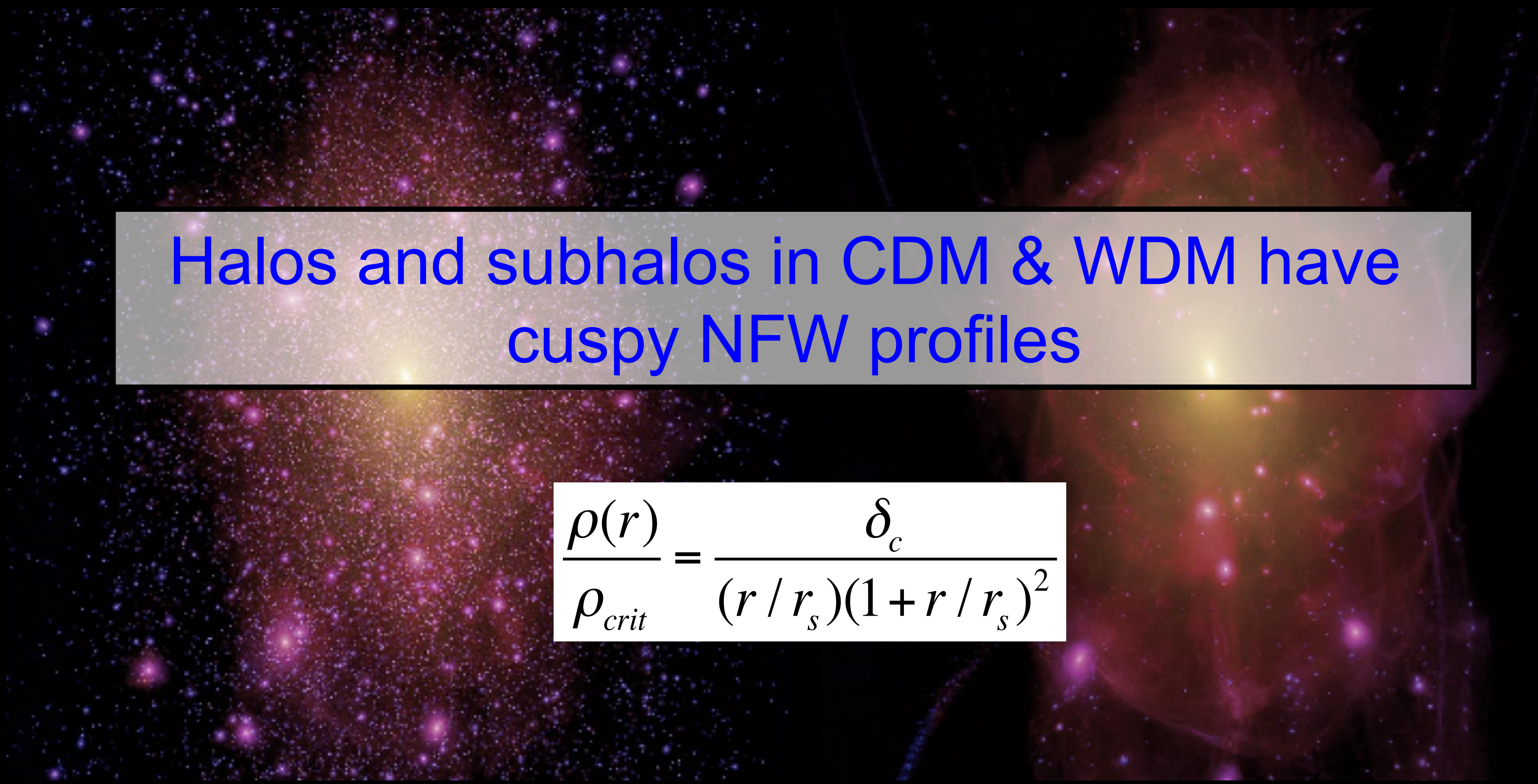
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '11



Cold
Warm
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
30 km/s
$V_{circ}$ within $r_{1/2}$
MW satellites
No too-big-to-fail problem in WDM!
$\log_{10}[V_{circ}$ / kms$^{-1}$]
r [kpc]
1.8
1.6
1.4
1.2
1.0
0.8
0.1
1.0
10.0

# 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


Dwarf galaxies in Eagle have NFW cusps!
Sawala et al '15

# The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

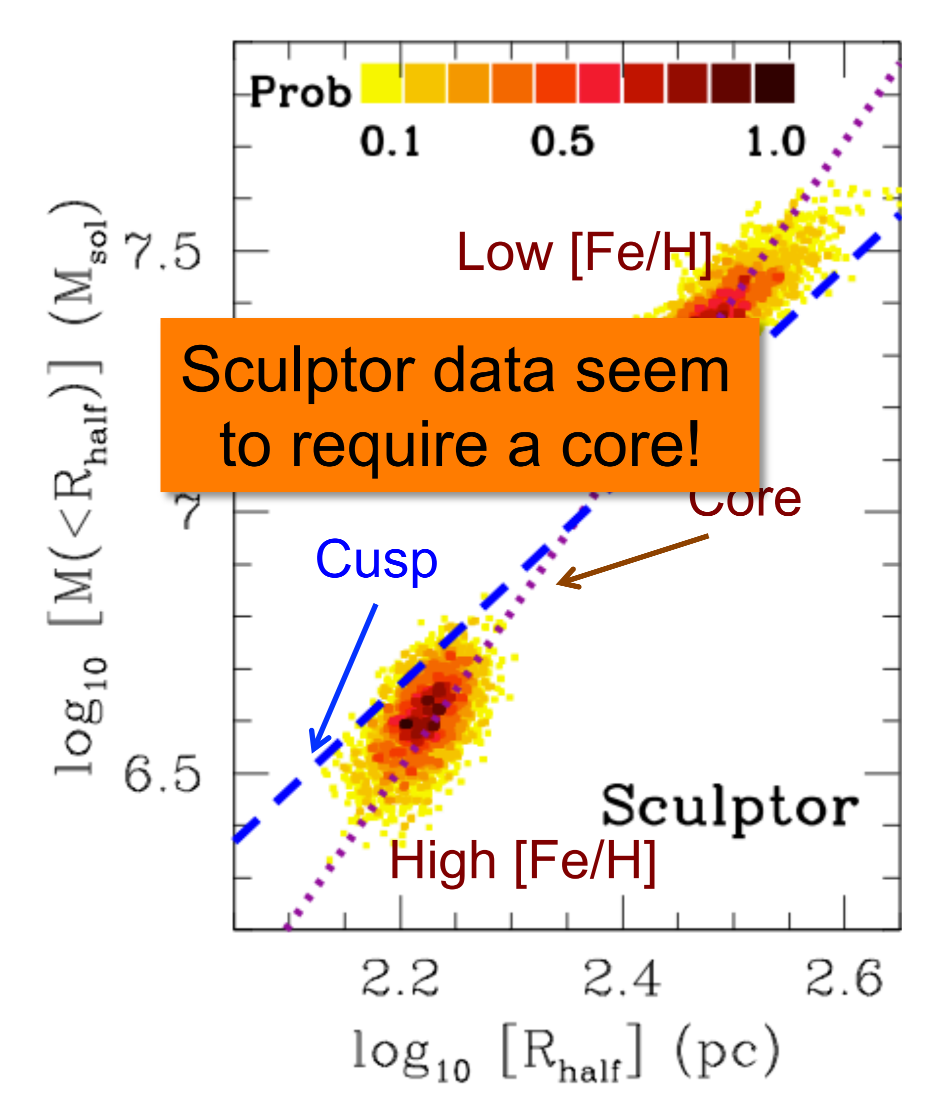
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

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

Walker '10; Wolf et al '10→

if $r=r_{1/2}$, $\mu=2.5$, independently of model assumptions!



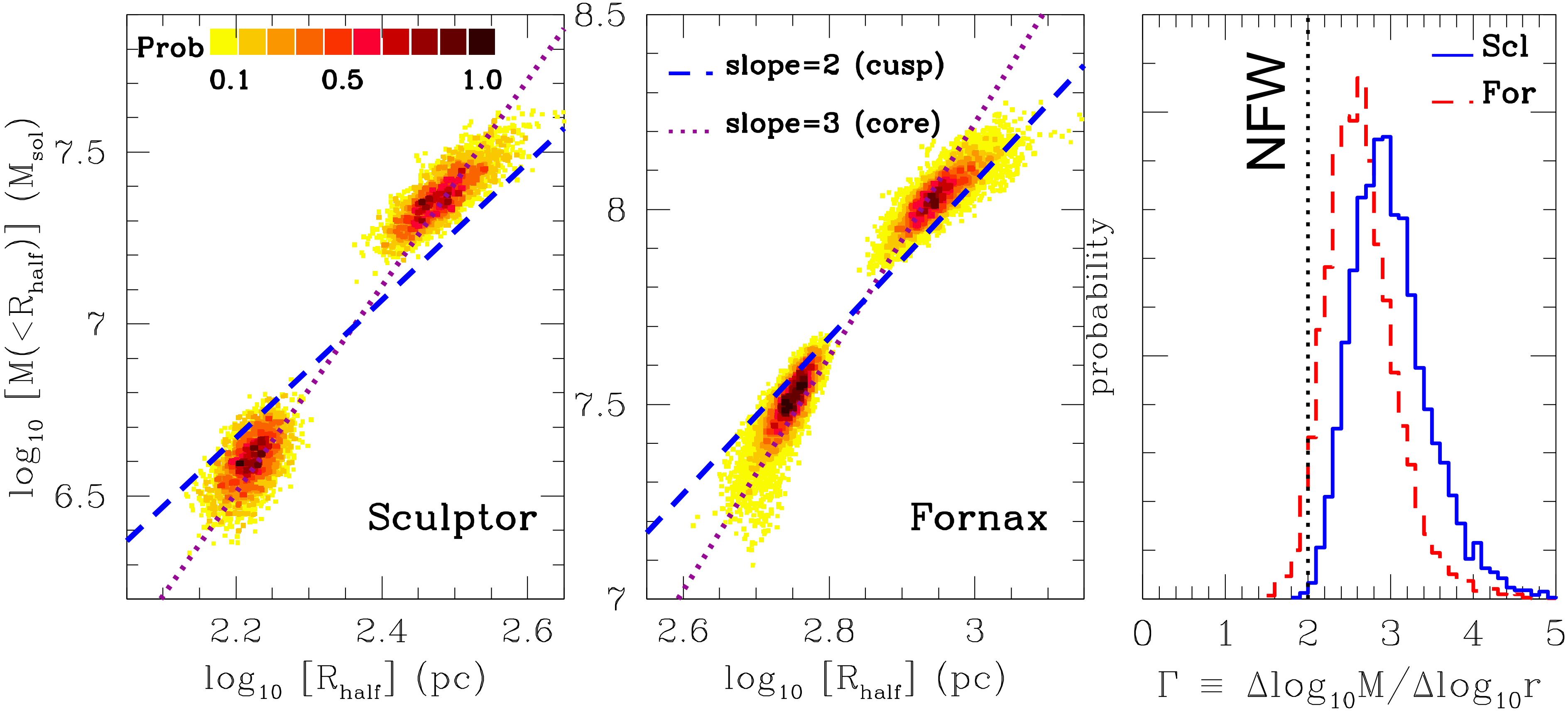

Sculptor data seem to require a core!

Walker & Peñarrubia '11

University of Durham

# Cusps in Sculptor and Fornax

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




NFW ruled out at { >96% Fornax, >99% Sculptor }

Walker & Peñarrubia (2011)

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How well does the Walker/Wolf estimator work?
Sawala et al ‘15

# Uncertainties in the Walker/Wolf estimator

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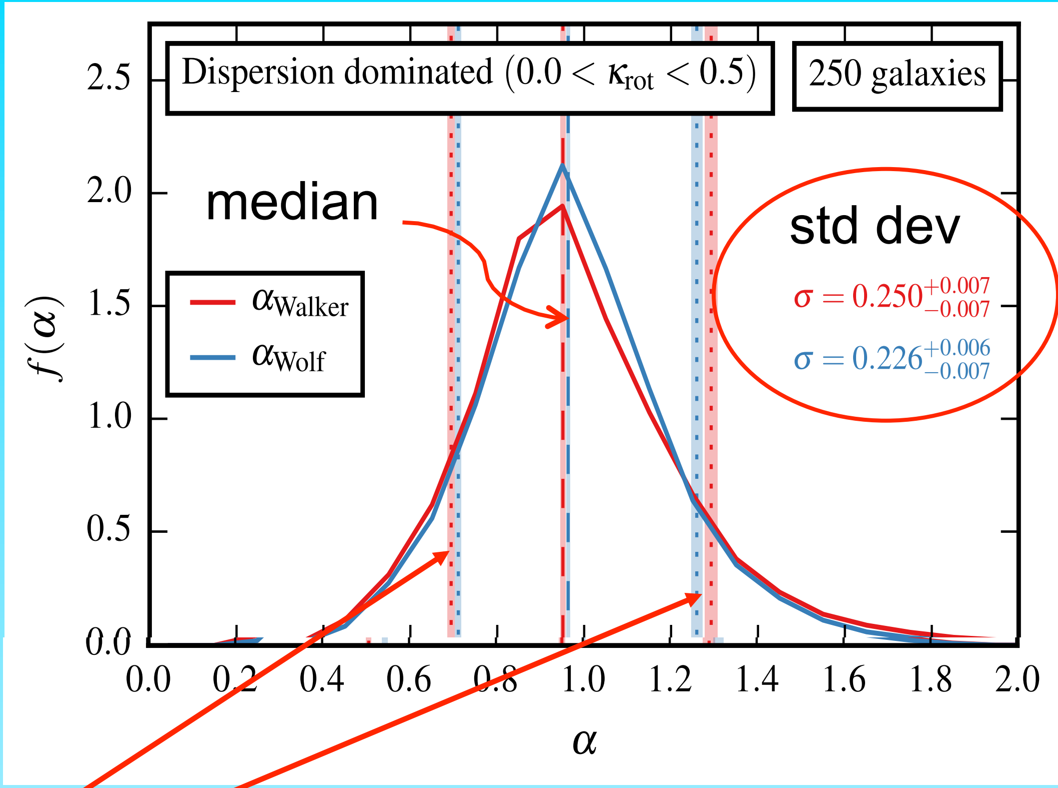
$$\alpha_{\mathrm{Walker}} = \frac{2.5G^{-1}\sigma_{\mathrm{los}}^2 R_{\mathrm{e}}}{M(<R_{\mathrm{e}})}$$

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




10th and 90th percentiles

$$\alpha = \frac{M_{\mathrm{estimated}}}{M_{\mathrm{true}}}$$

$$\int f(\alpha)\,\mathrm{d}\alpha = 1$$

Campbell et al. '16

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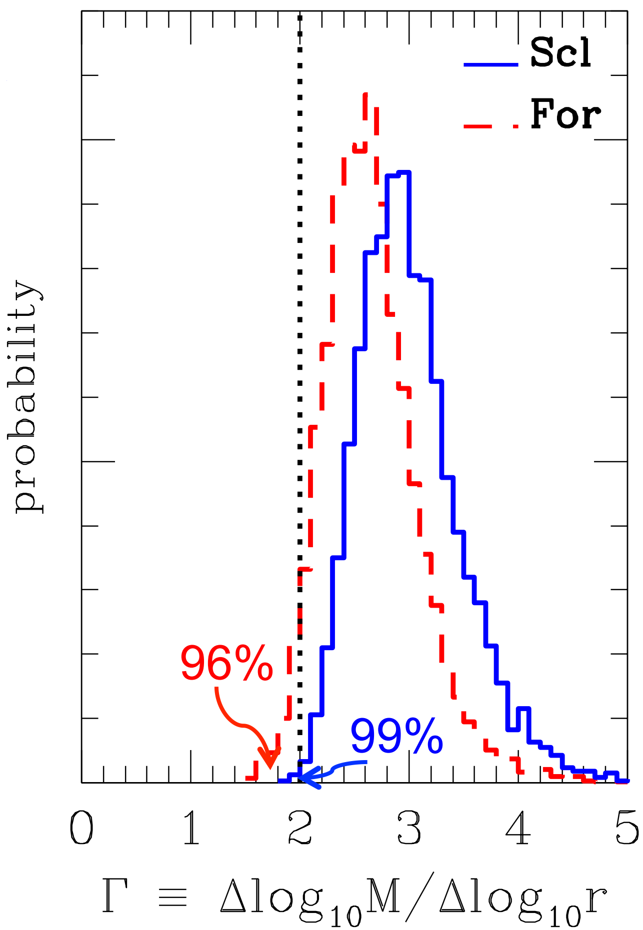
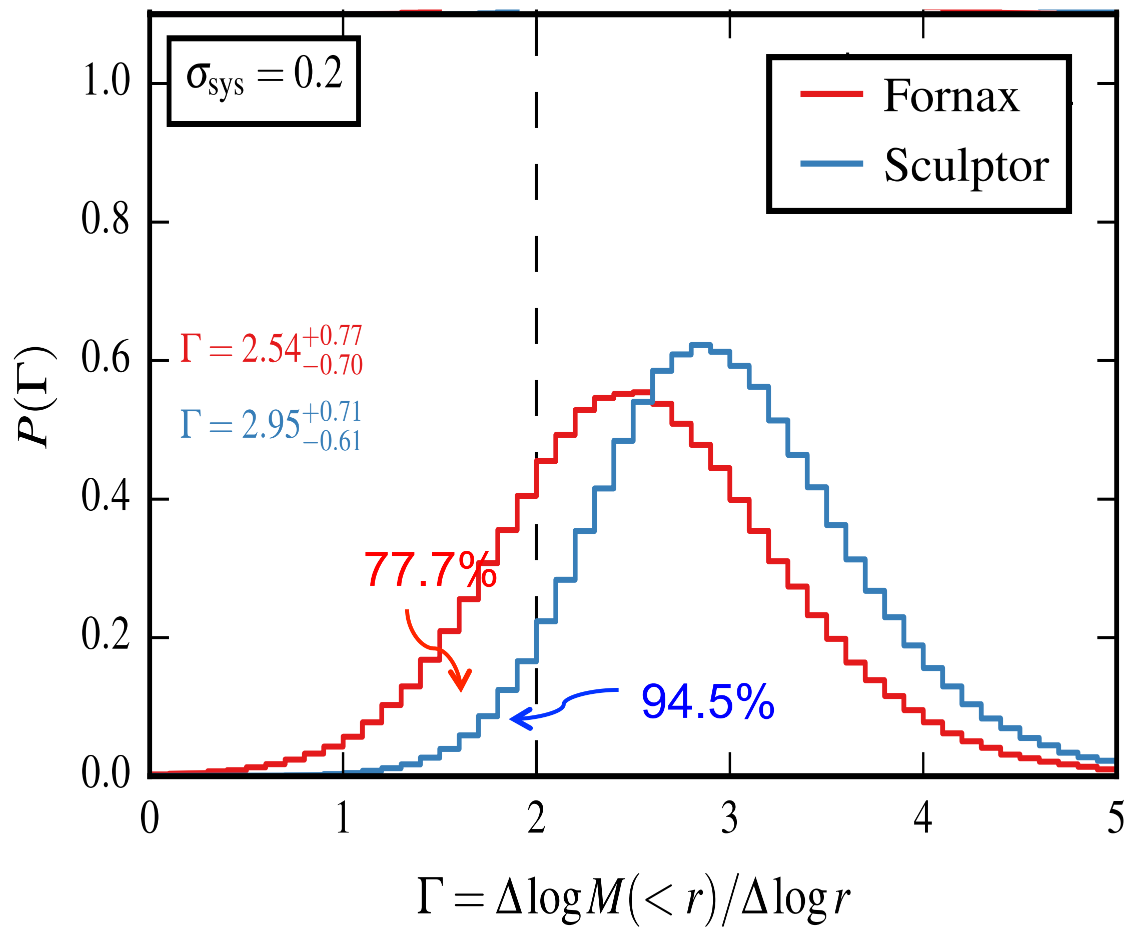
# The DM density profile of Sculptor

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




Walker & Peñarrubia '11




Campbell et al. '16

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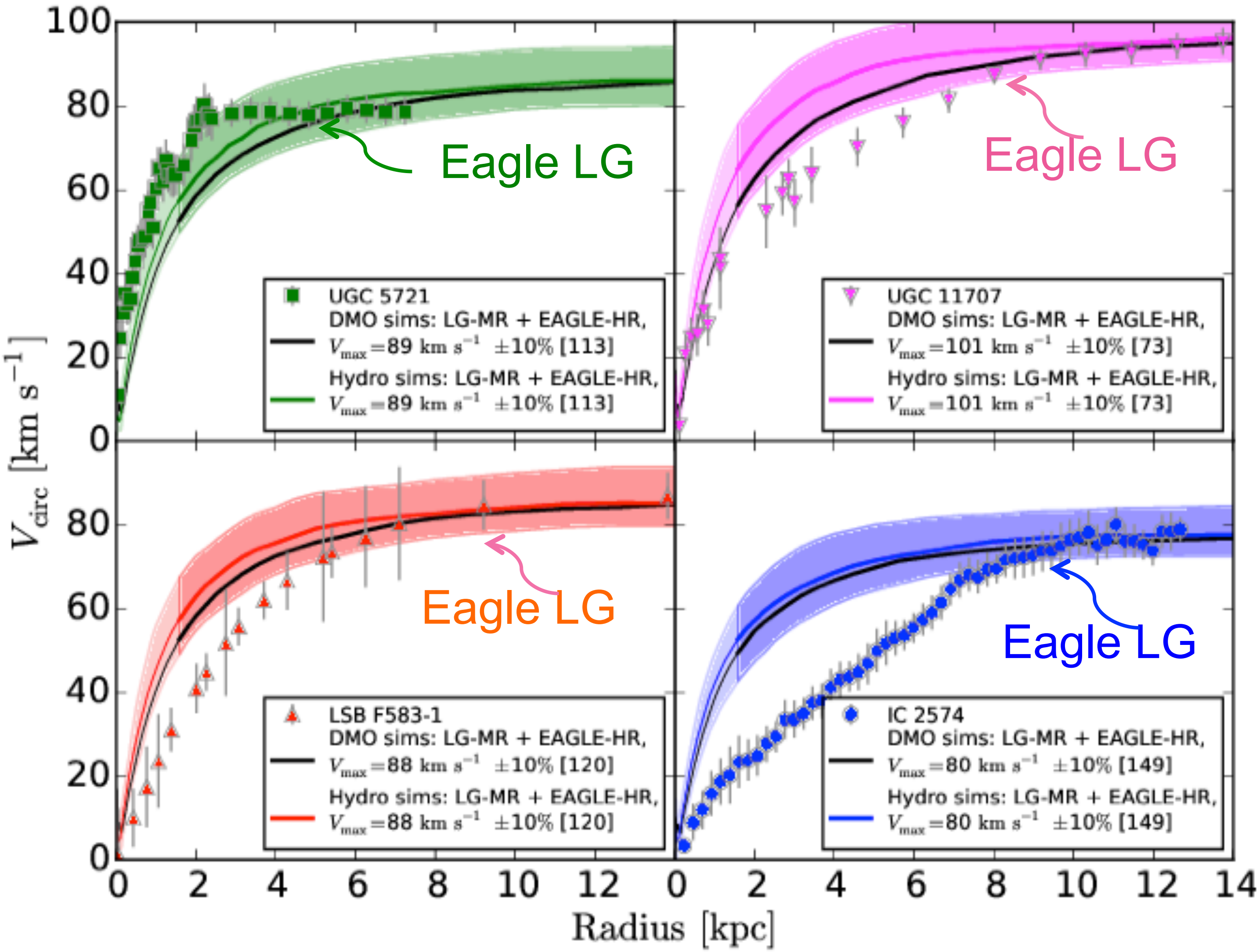
# The diversity of gal rotation curves

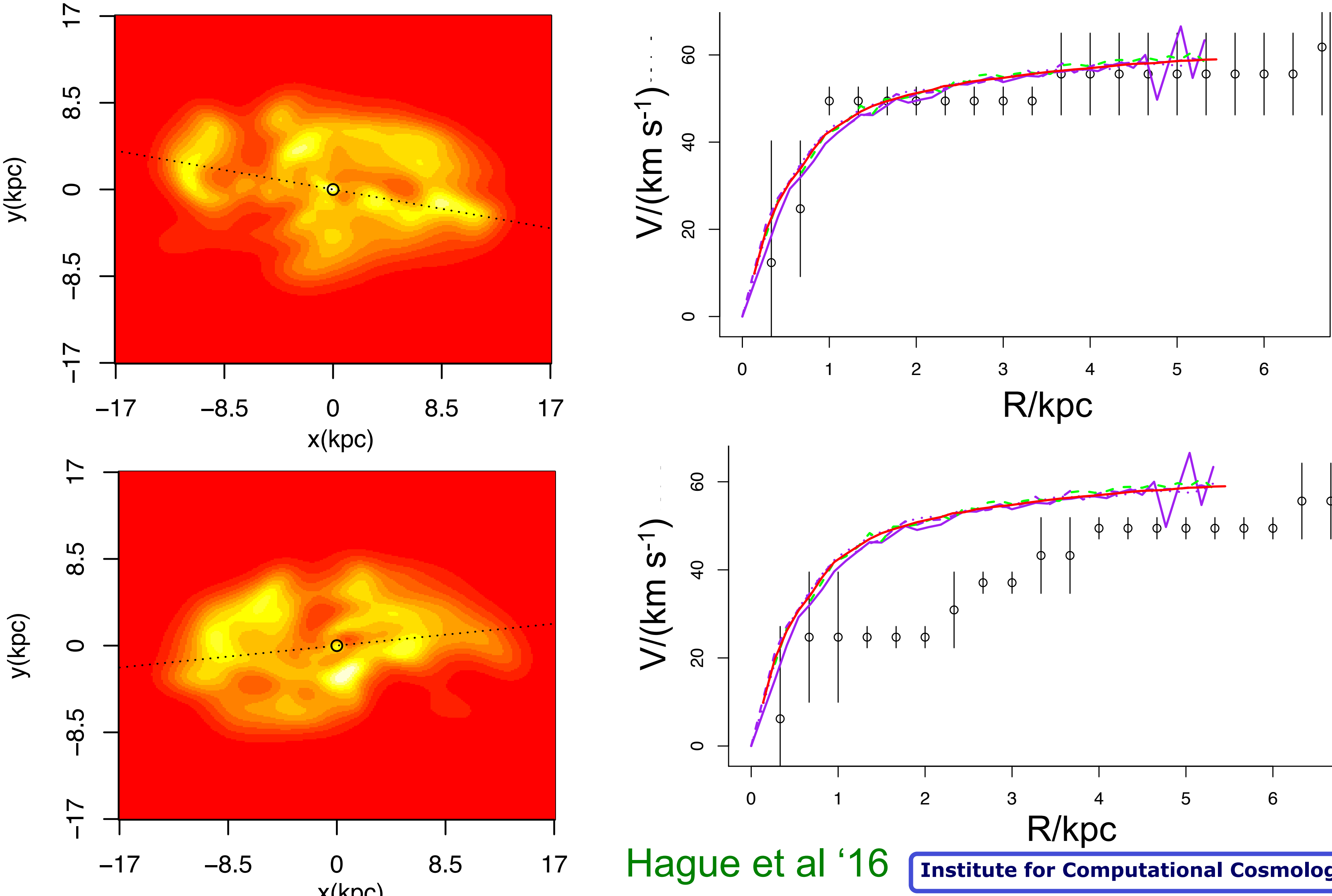
Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L*)




Oman et al. '15

# Rotation curves of APOSTLE dwarfs




Hague et al ‘16

Mon. Not. R. Astron. Soc. 283, L72–L78 (1996)

# The cores of dwarf galaxy haloes

Julio F. Navarro,[1,2]★ Vincent R. Eke[2] and Carlos S. Frenk[2]

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**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.

# Baryon effects in the MW satellites

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Let gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

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

Navarro, Eke, Frenk '96



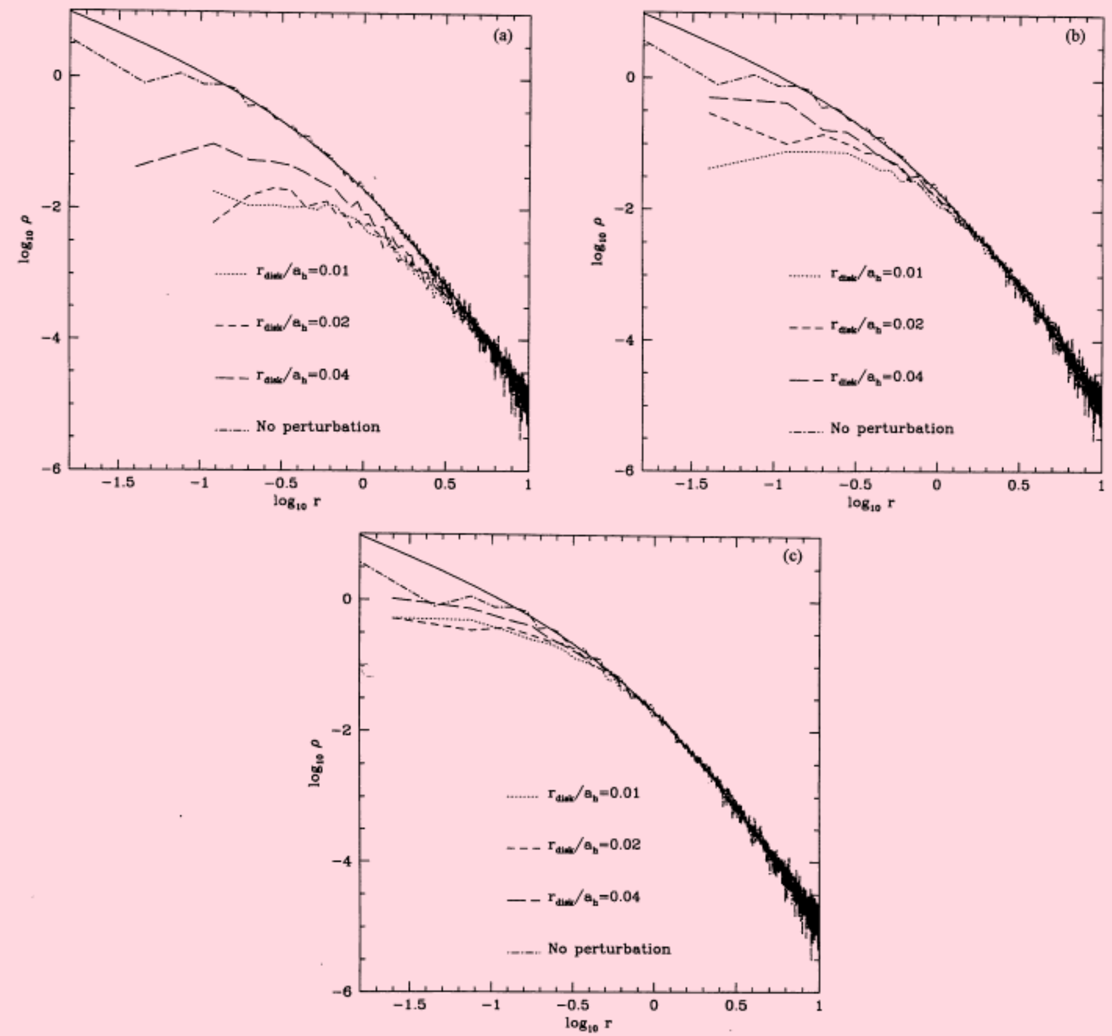



**Figure 3.** Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

# Cores in dwarf galaxy simulations

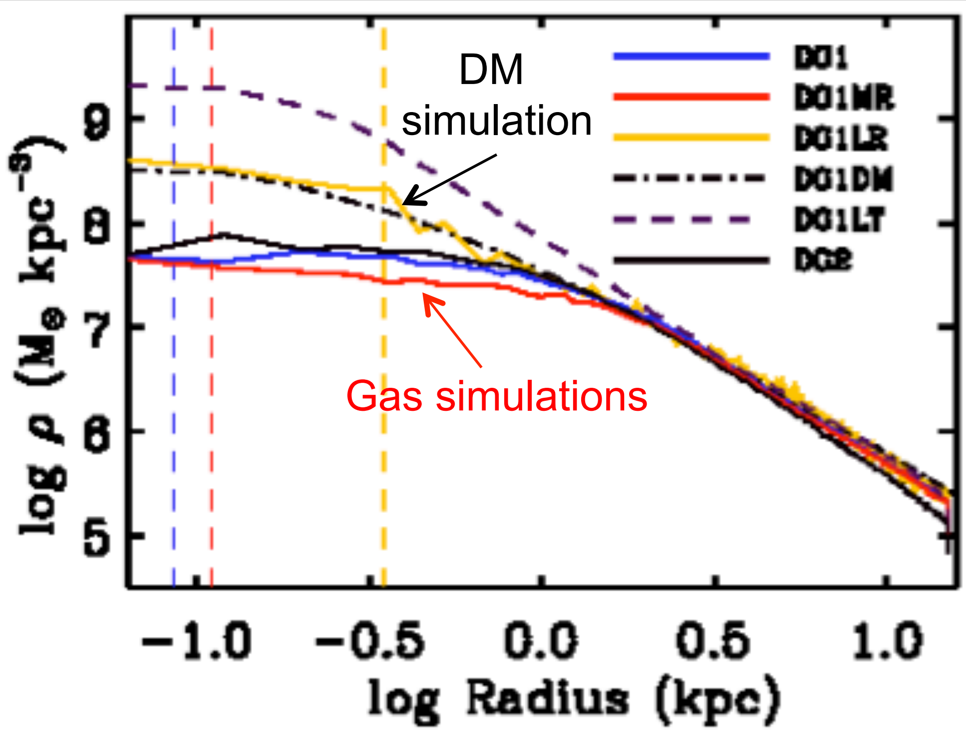
University of Durham

Governato et al. assume high density threshold for star formation

EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

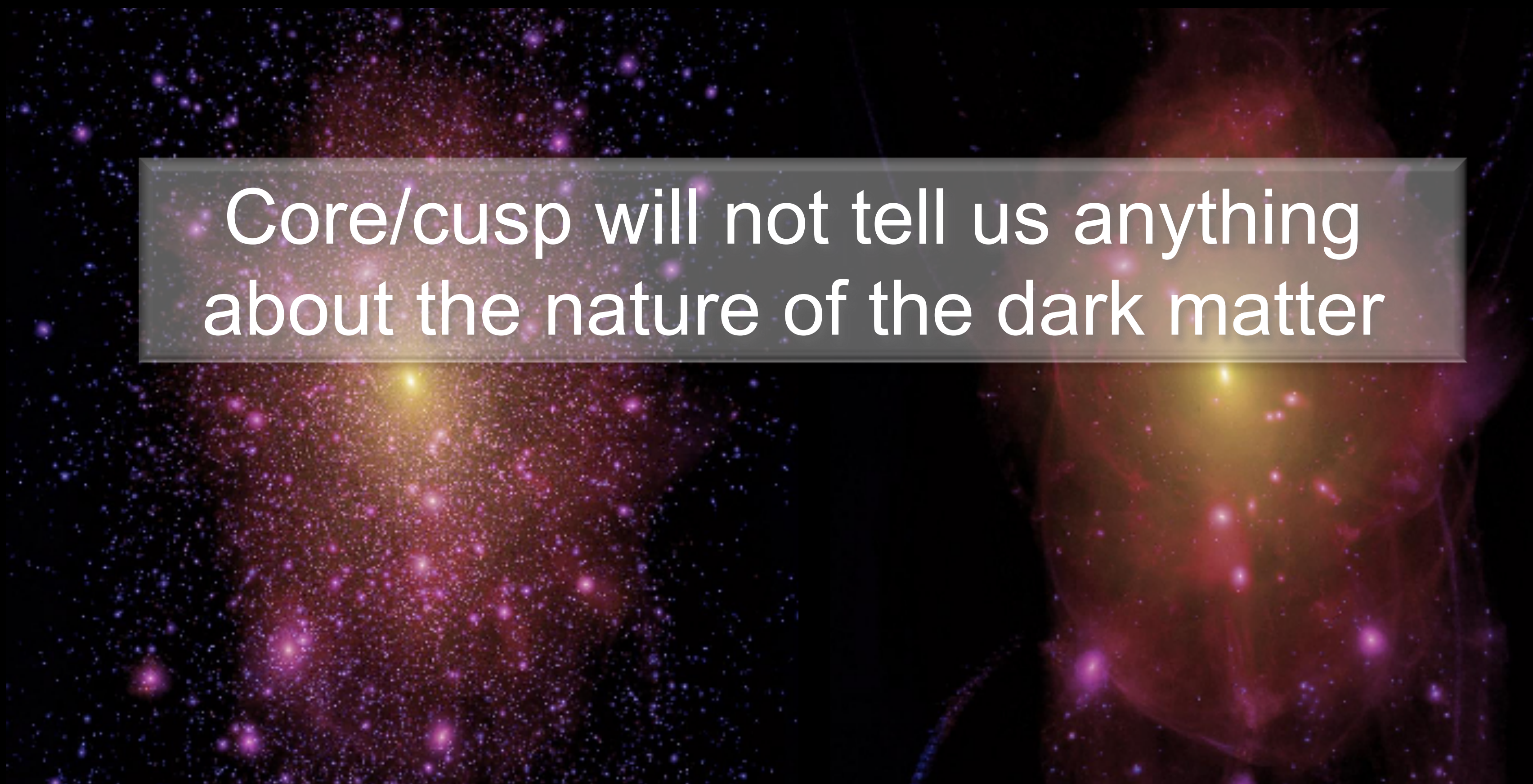
→ Sudden repeated removal of gas transfers binding energy




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

cold dark matter

warm dark matter

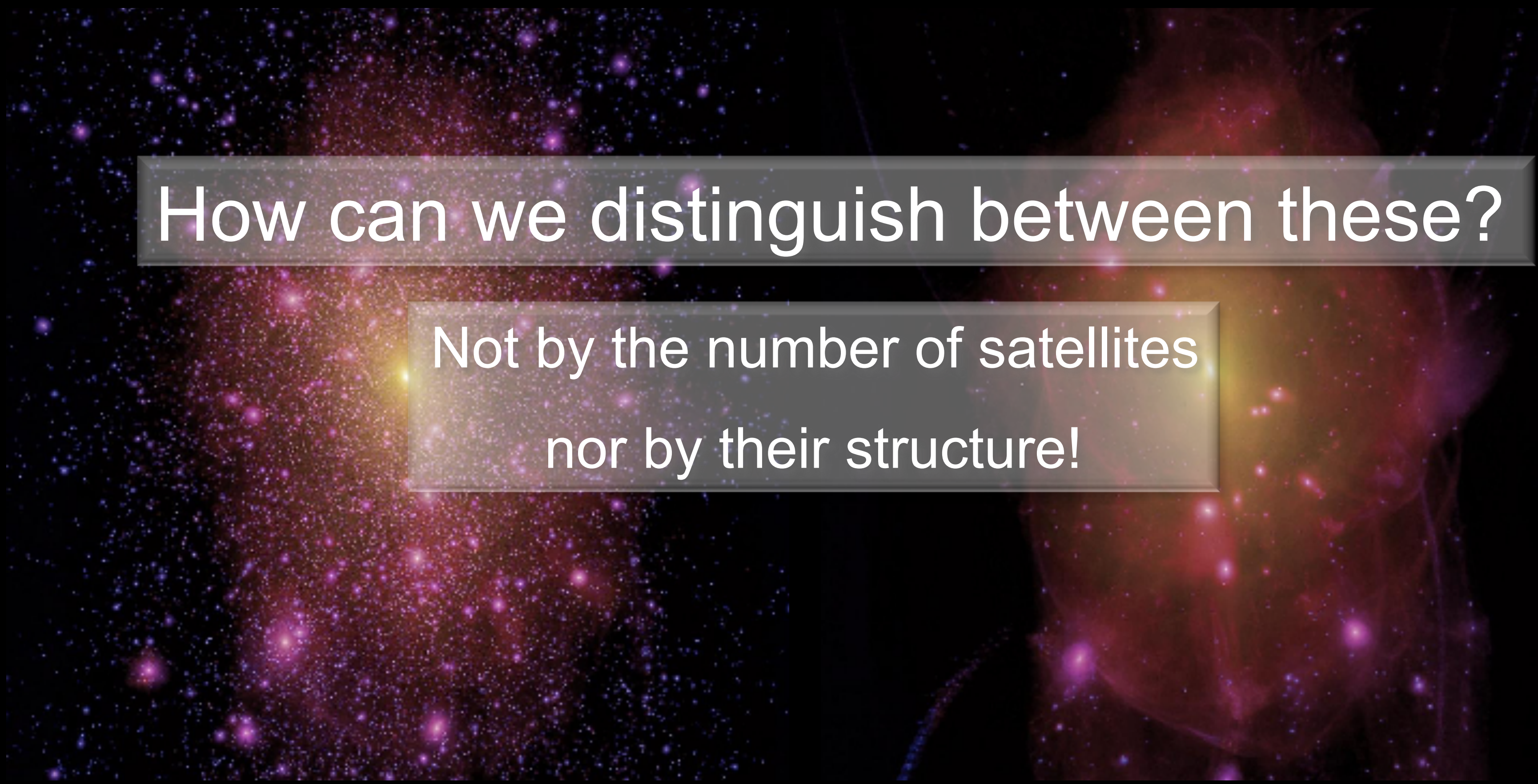


Core/cusp will not tell us anything about the nature of the dark matter

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)

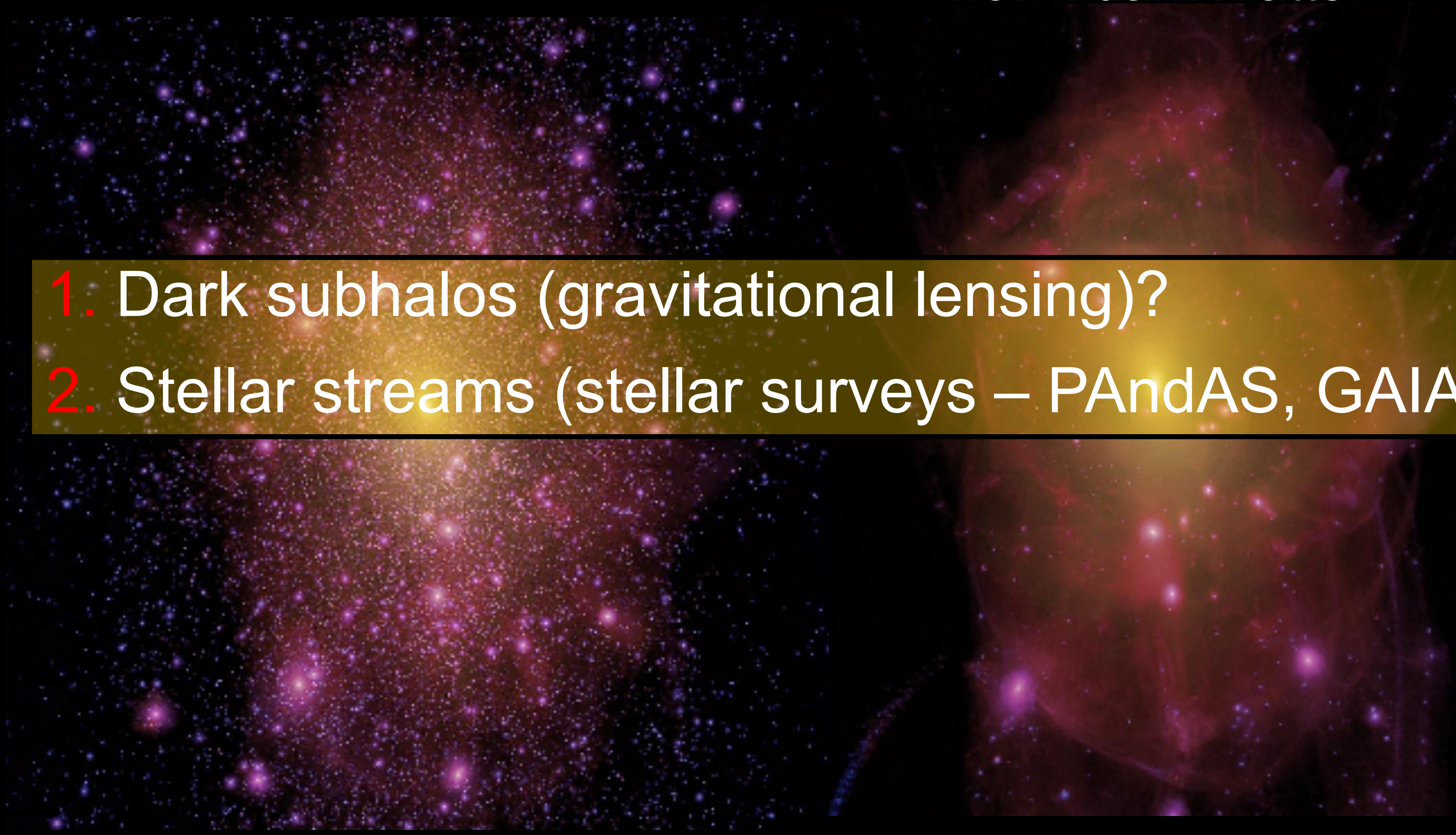
III. The abundance of dark halos and subhalos

# Observational tests of CDM vs WDM

III. The abundance of dark halos and subhalos

# Can we distinguish CDM/WDM?

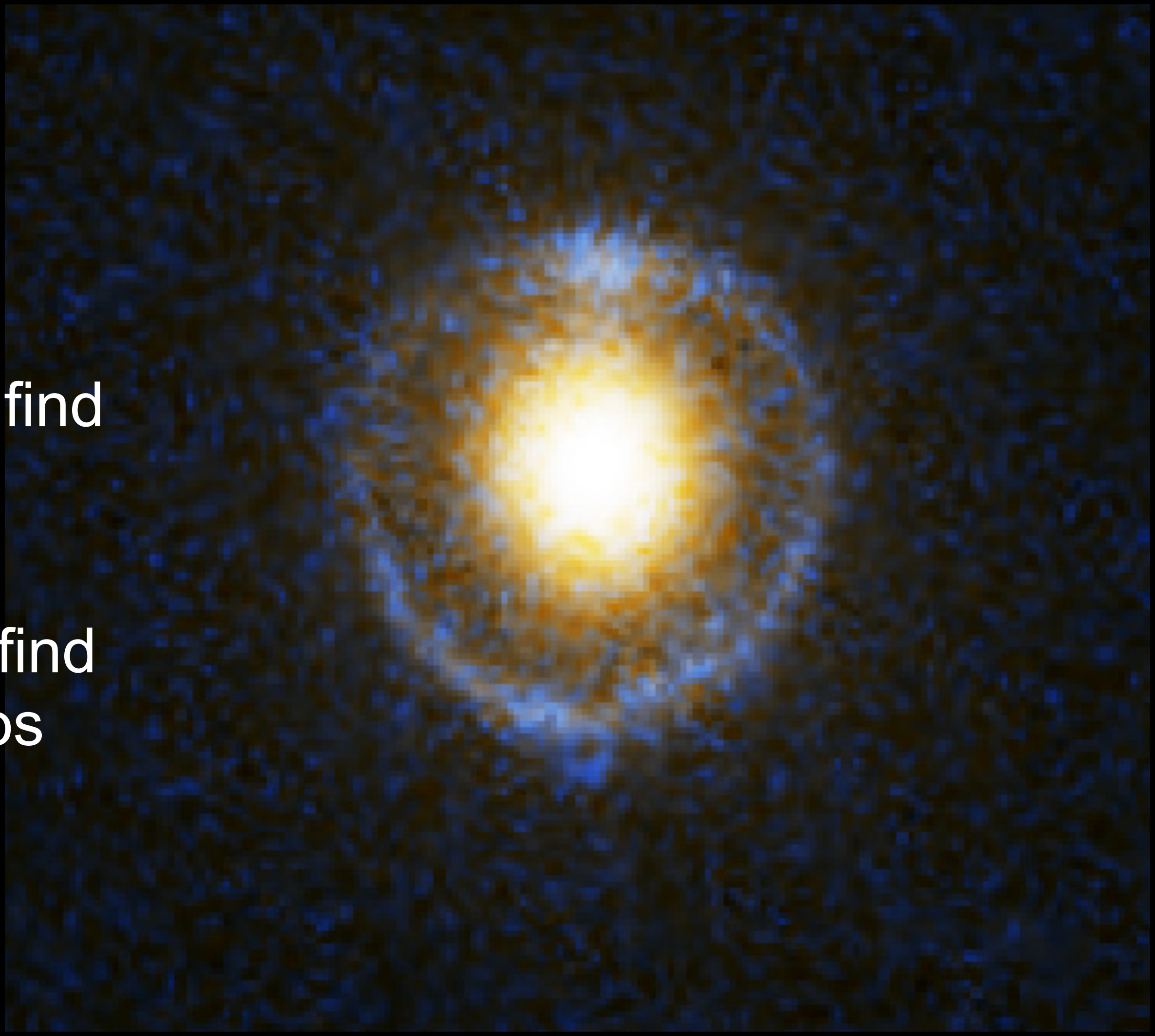
cold dark matter | warm dark matter



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

# Gravitational lensing: Einstein rings

Substructures distort
Einstein rings



If WDM is right, should find
NO small subhalos

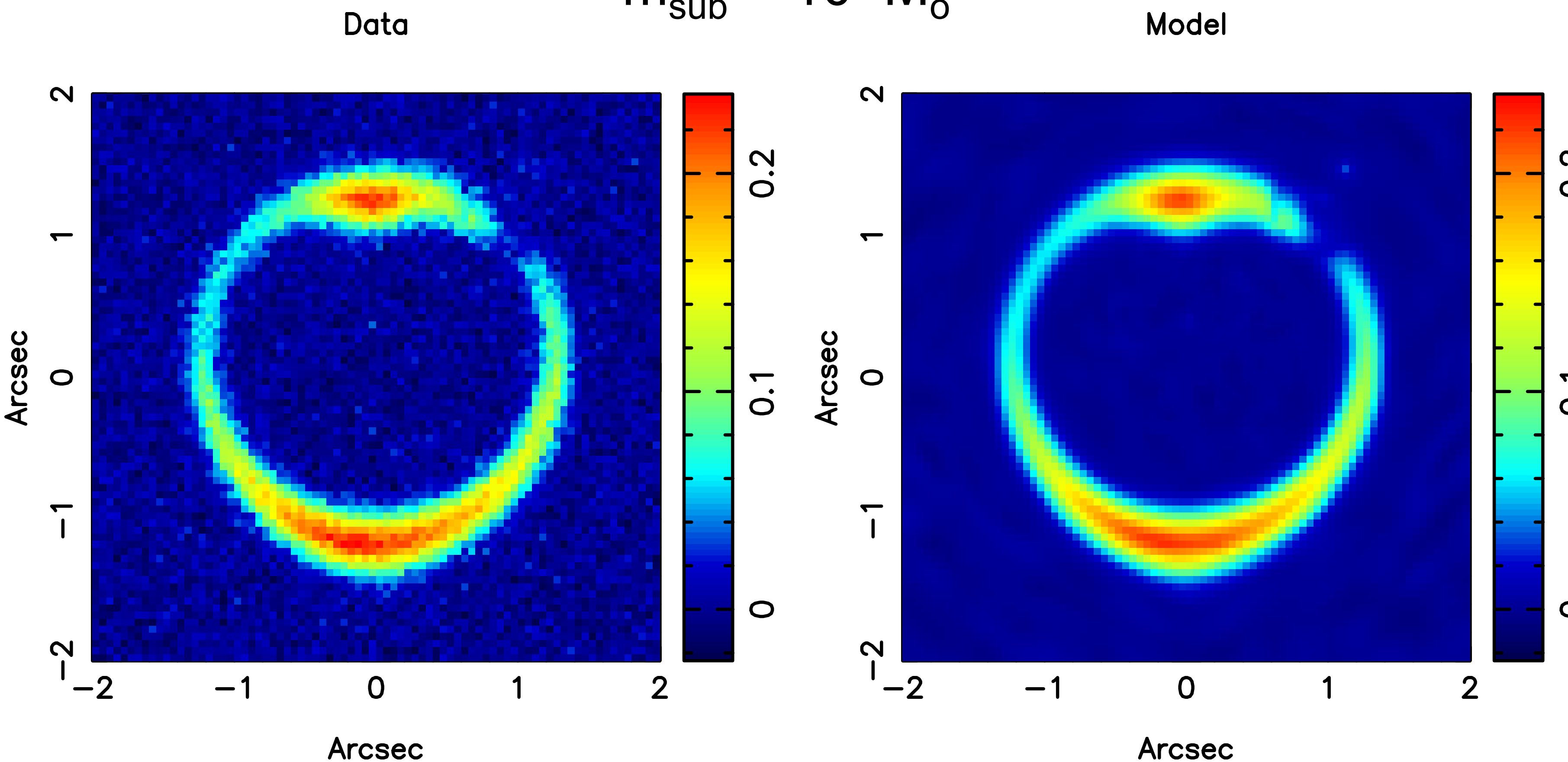
If CDM is right, should find
MANY small subhalos

Vegetti & Koopmans '09

University of Durham

# Detecting substructures with strong lensing

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




Vegetti & Koopmans '09

Institute for Computational Cosmology

# Detecting substructures with strong lensing

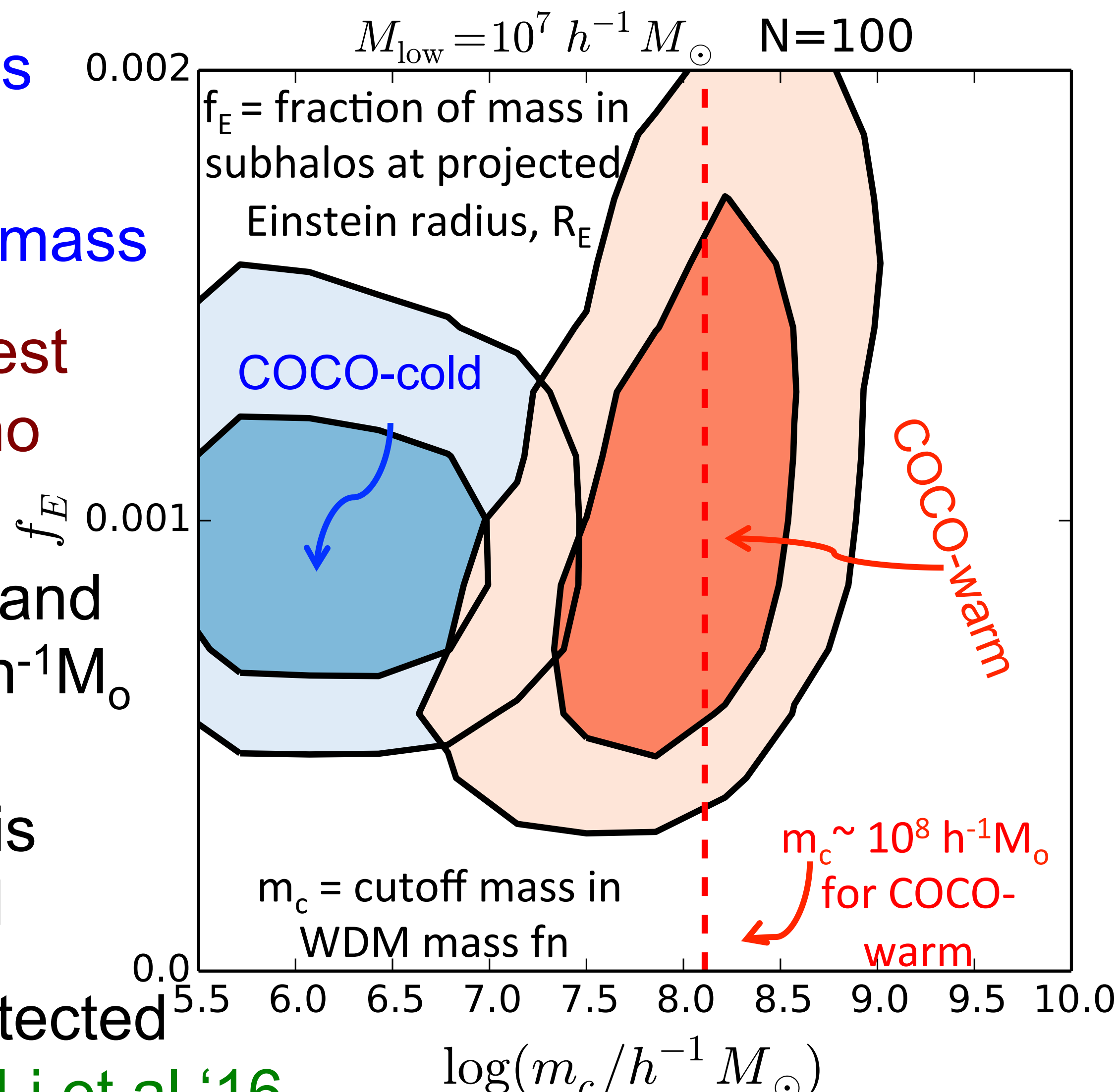
University of Durham

$f_E$ = fraction of mass in subs within Einstein ring

$m_c$ = characteristic subhalo mass

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

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




- If cutoff in mass function is detected → rule out CDM
- If small subhaloes are detected → rule out WDM

Li et al ‘16

# Conclusions

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

| | CDM | WDM |
|---|---|---|
| 1. The satellites luminosity function | ✓ | ✓ |
| 2. The $V_{max}$ fn (“too-big-to-fail”) | ✓ | ✓ |
| 3. Core or cusps in halos | – | – |
| 4. Subhalo mass fn– strong lensing | ? | ? |