Are sterile neutrinos the dark matter? The way forward

ICC
University of Durham

The new Ogden Centre at Durham

University of Durham

The way forward

Detect the sterile neutrino and measure its mass

1. Direct production/detection

If sterile neutrinos mix with active neutrinos

Tritium β-decay – KATRIN

Sensitive in ev range

The way forward

Detect the sterile neutrino and measure its mass

1. Direct production/detection

If sterile neutrinos mix with active neutrinos

Tritium β-decay – KATRIN

2. Indirect detection

Decay of keV particle produces an X-ray line

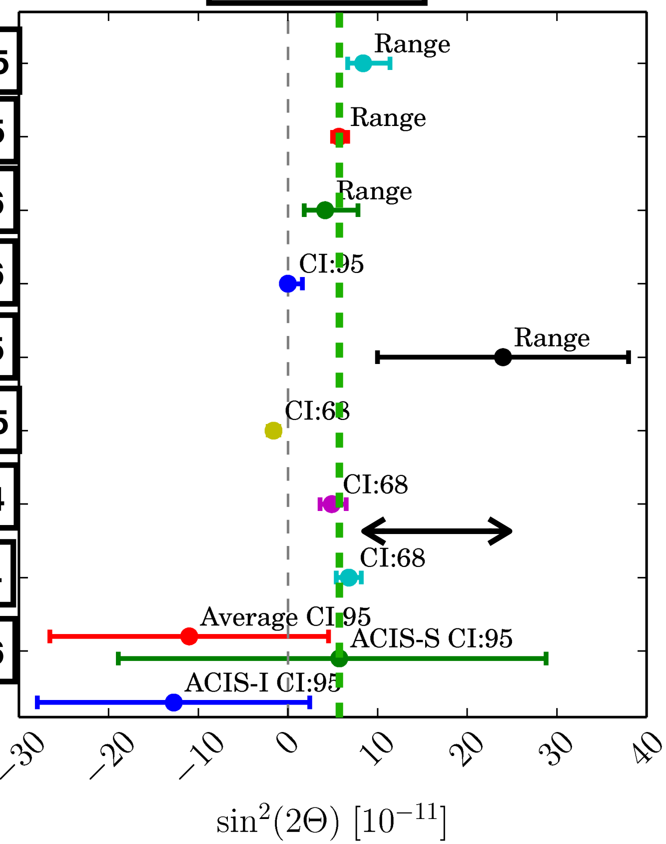
Detection of a 7 keV sterile neutrino?

Recent additional debates (– / +)

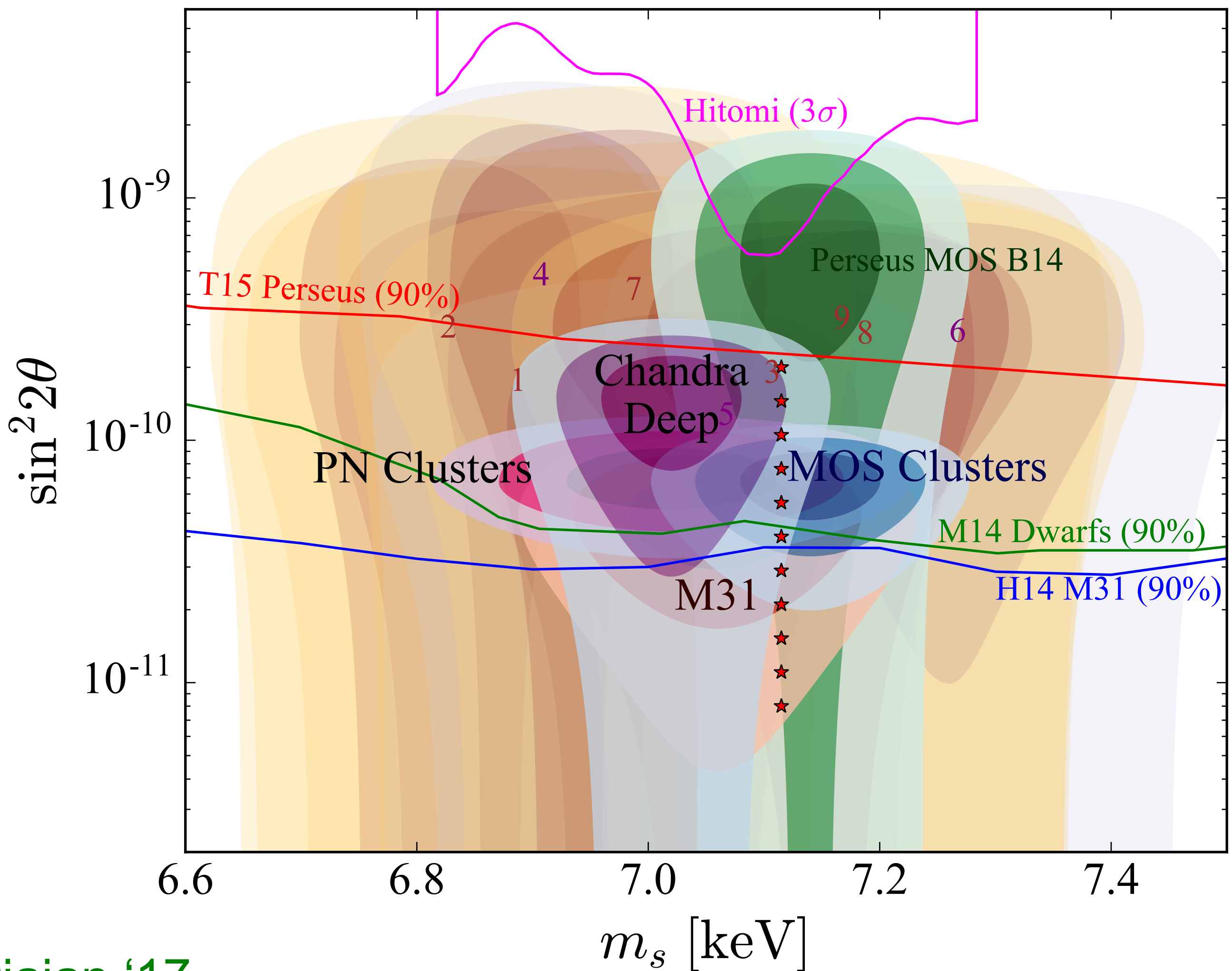
- Cappelluti+2017: Chandra Galactic halo
- Conlon+2017: AGN absorption line
- Neronov+2016: NuStar, COSMOS, ECDFS
- Malyshev+2014: dwarf spheroidal galaxies
- XMM Draco dwarf spheroidal galaxy
- Gu+2015/Shah+2016: Charge exchange
- The bananas debate: Potassium K, e.g. Jeltema&Profumo 2014
- Nature: dark matter evidence weakens

Consistency line (– / +)

- Bulbul+2016
- Franse+2016
- HITOMI Collaboration+2017
- Urban+2015
- Iakubovskyi+2015
- Boyarsky+2015
- Ruchayskiy+2016
- Jeltema+2016
- Jeltema+2015
- Anderson+2015
- Boyarsky+2014
- Bulbul+2014
- Hofmann+2016



Detection of a 7 keV sterile neutrino?



Abaziajan '17

The way forward

Detect the sterile neutrino and measure its mass

1. Direct detection

If sterile neutrinos mix with active neutrinos

Tritium β-decay – KATRIN

2. Indirect detection

Decay of keV particle produces an X-ray line

Future X-ray missions:

XARM – 2021 (replacement of Hitomi (with soft/X-ray spectrometer 0.3-12 keV – 5-7 ev spectral resolution)

Athena – 2028 (0.5-12 keV; high resolution – 2.5 ev spectral resolution; large area)

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The way forward

Astrophysical constraints

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

Astrophysical constraints

Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

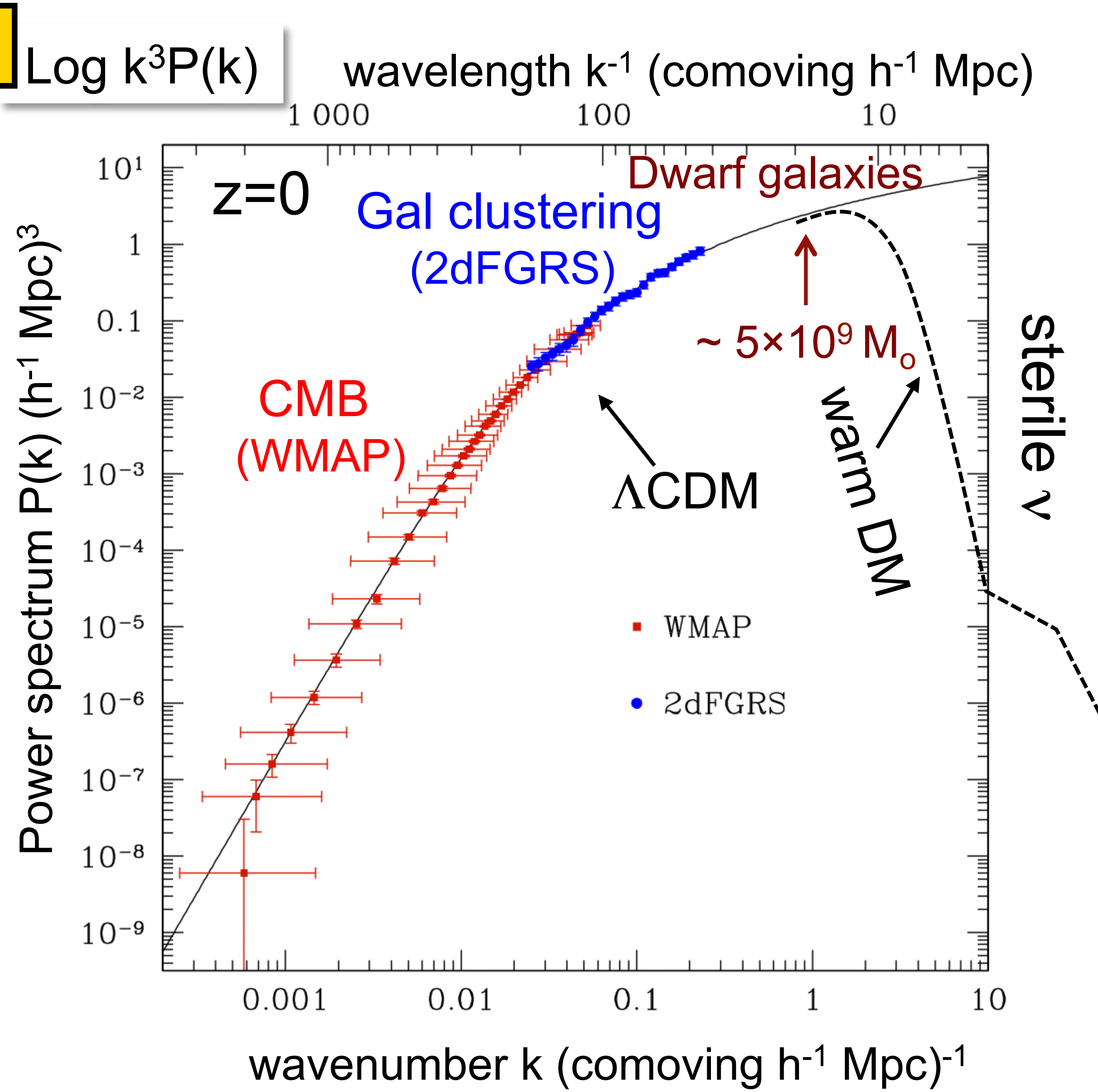
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Astrophysical key to identity of dark matter

→Subgalactic scales

(strongly non-linear)

Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

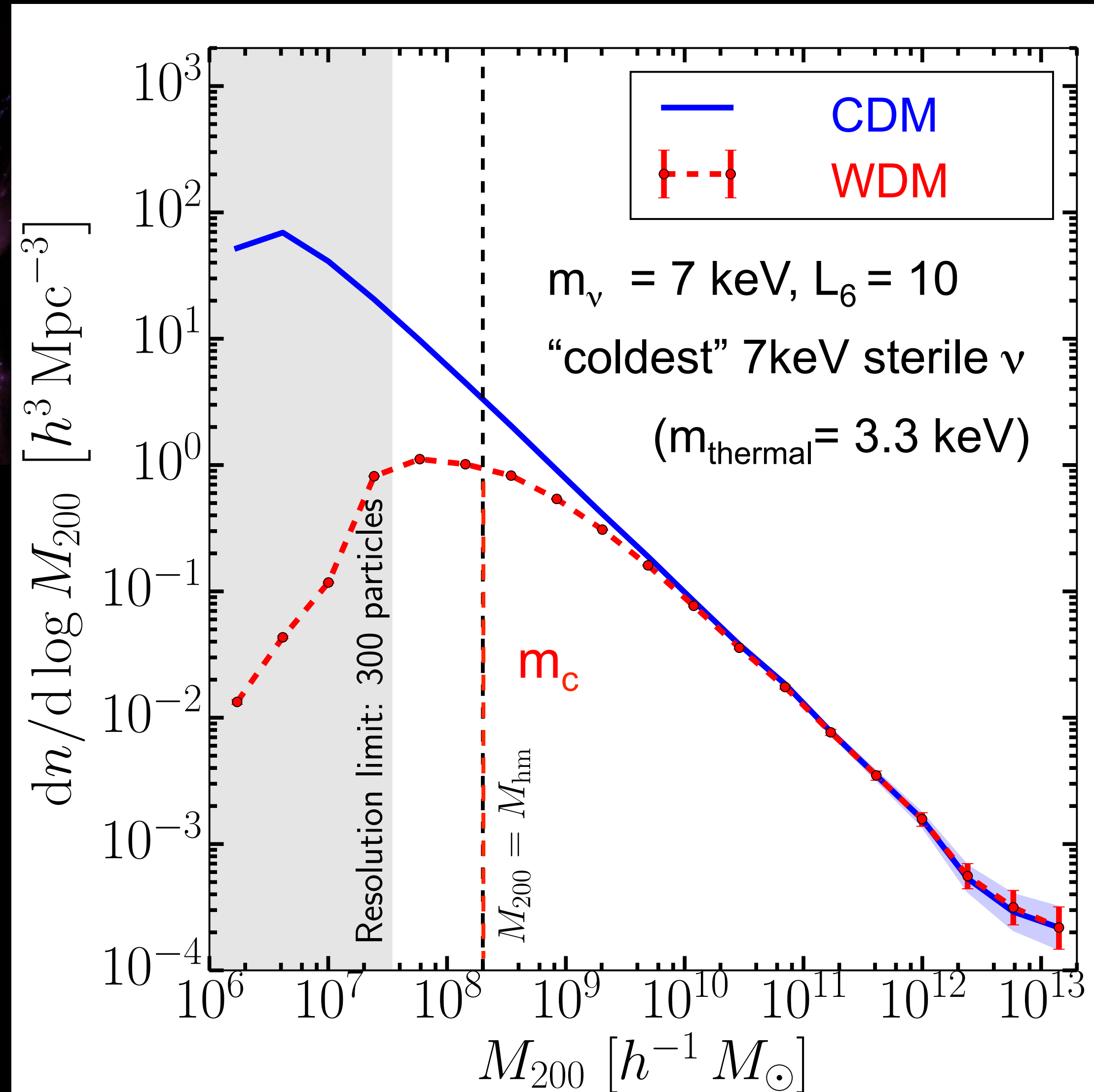
Institute for Computational Cosmology

cold dark matter warm dark matter

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

The subhalo mass function

CDM WDM



1.5 x fewer WDM subhalos at 10^9 M_o

3x fewer at 2×10^8 M_o

Bose, CSF et al '16

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…

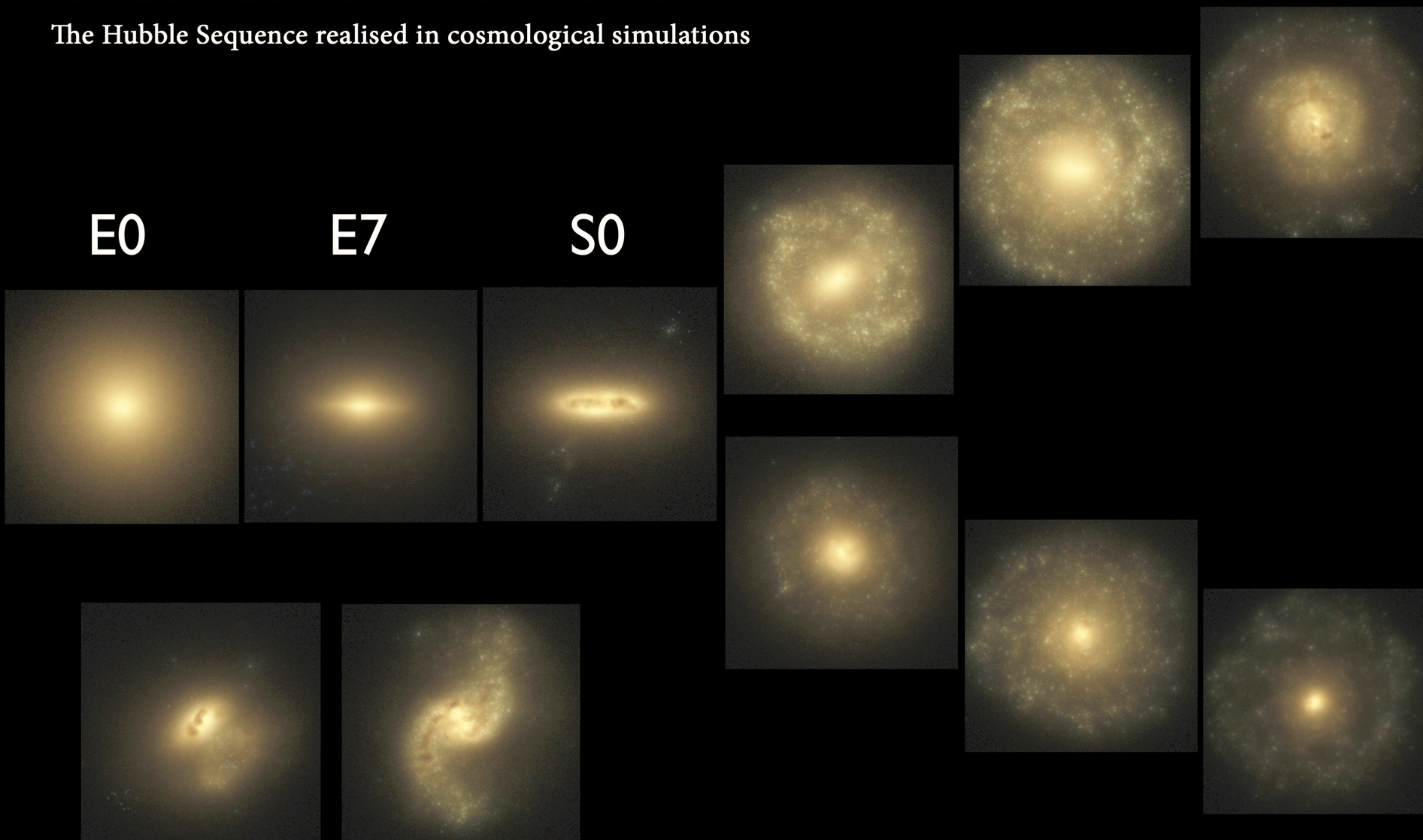
Durham University VIRGO ICC DiRAC PRACE

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

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

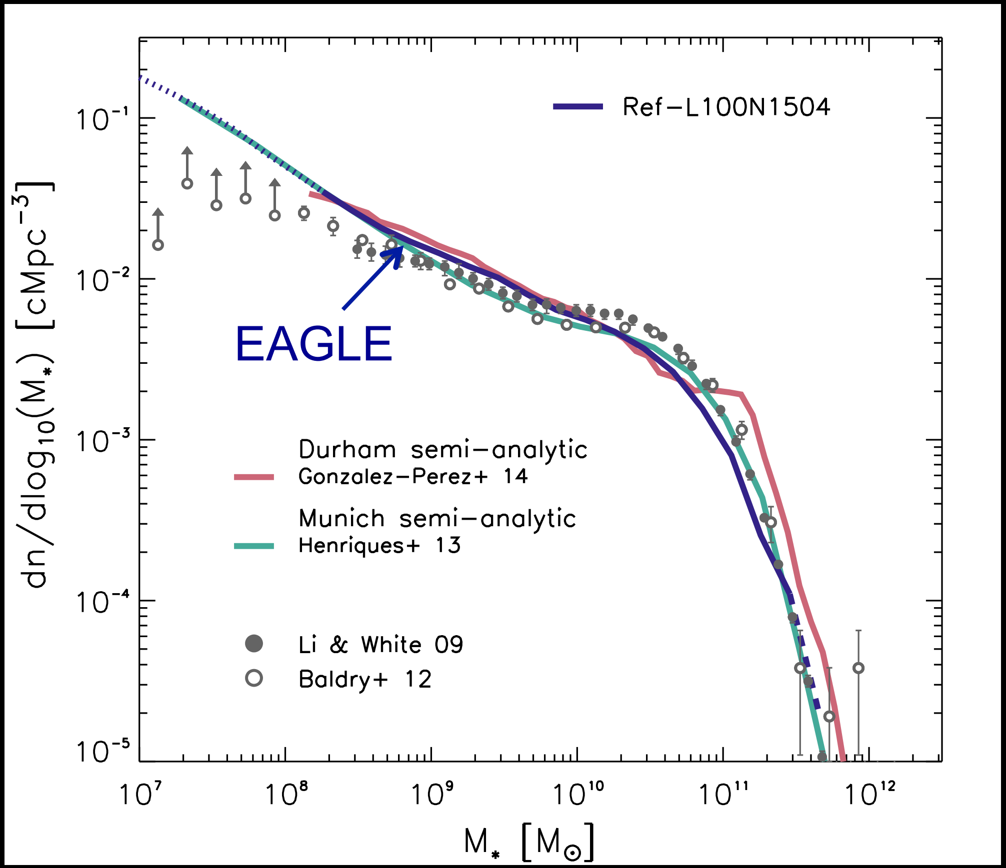
The Hubble Sequence realised in cosmological simulations



Trayford et al '15

Galaxy stellar mass function

Comparison to semi-analytic models



Schaye et al ‘15

Fraction of dark subhalos

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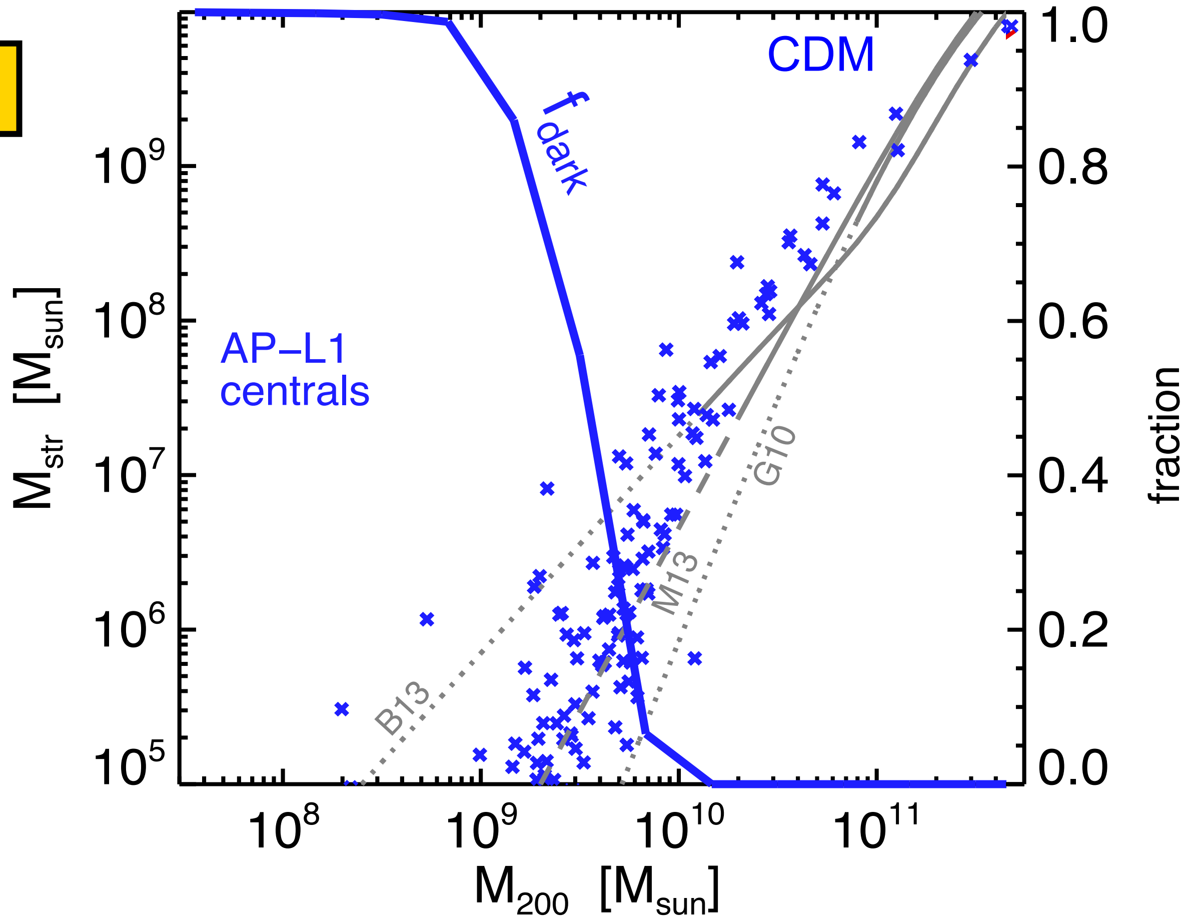
APOSTLE

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

$V_{max} = \max V_c$

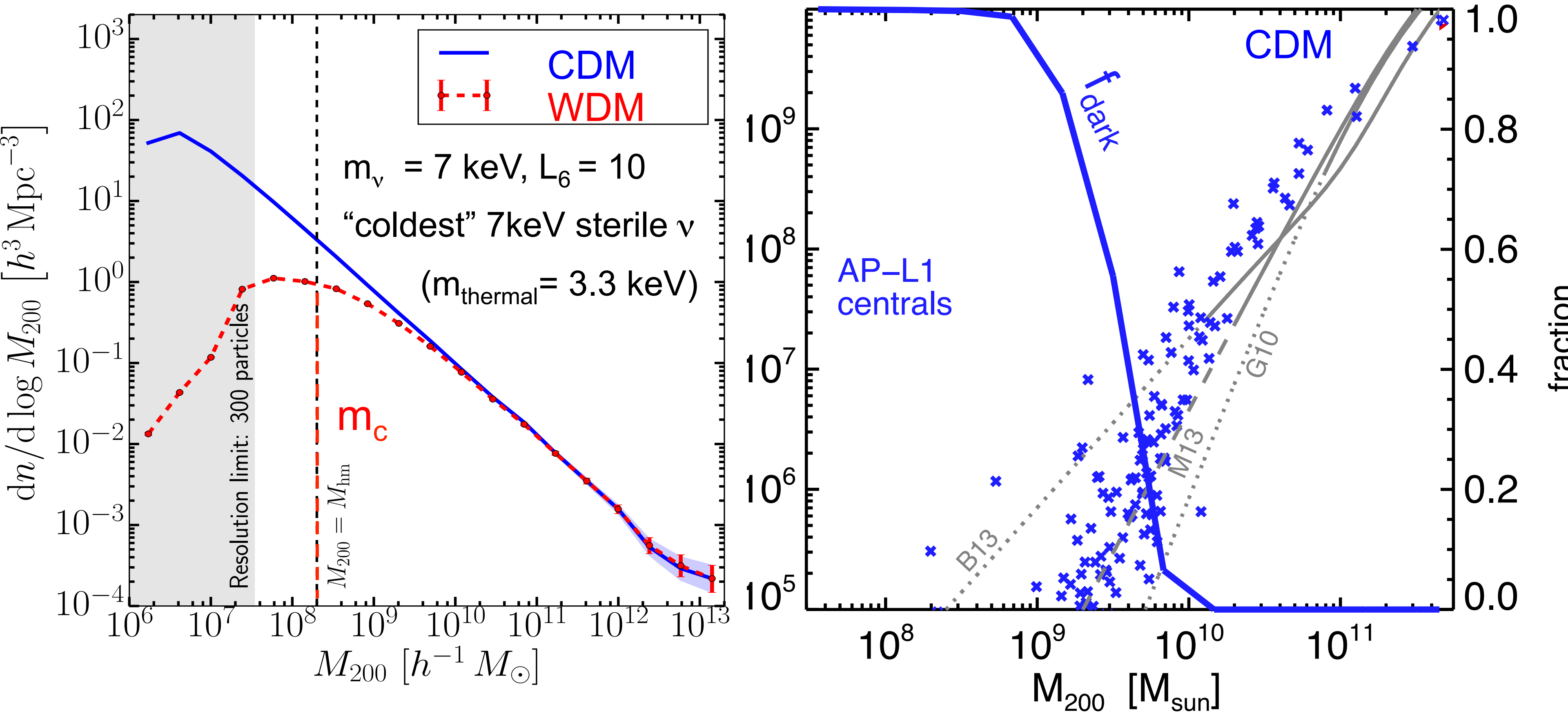


All halos of mass $< 5\times10^8 M_o$ or $V_{max} < 7$ km/s are dark ($m_* < 10^4 M_o$)

Sawala et al '16; Fattahi et al '16

Institute for Computational Cosmology

Fraction of dark subhalos



All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

Differences between WDM and CDM mostly involve dark halos

Sawala et al '16; Fattahi et al '16

Observational tests of CDM vs WDM

I. The abundance of satellite galaxies in MW/M31

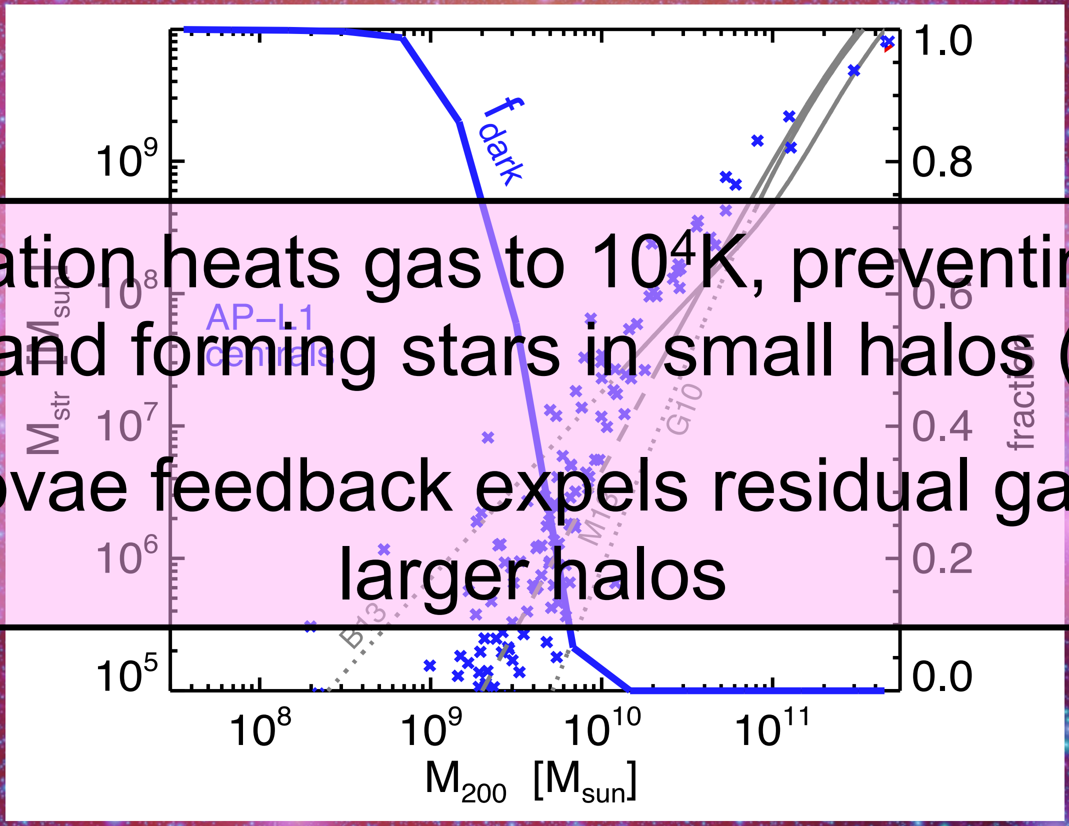
II. Halo structure: cores vs cusps

Iii. The abundance of dark halos and subhalos

Most subhalos never make a galaxy!

Because:

- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos



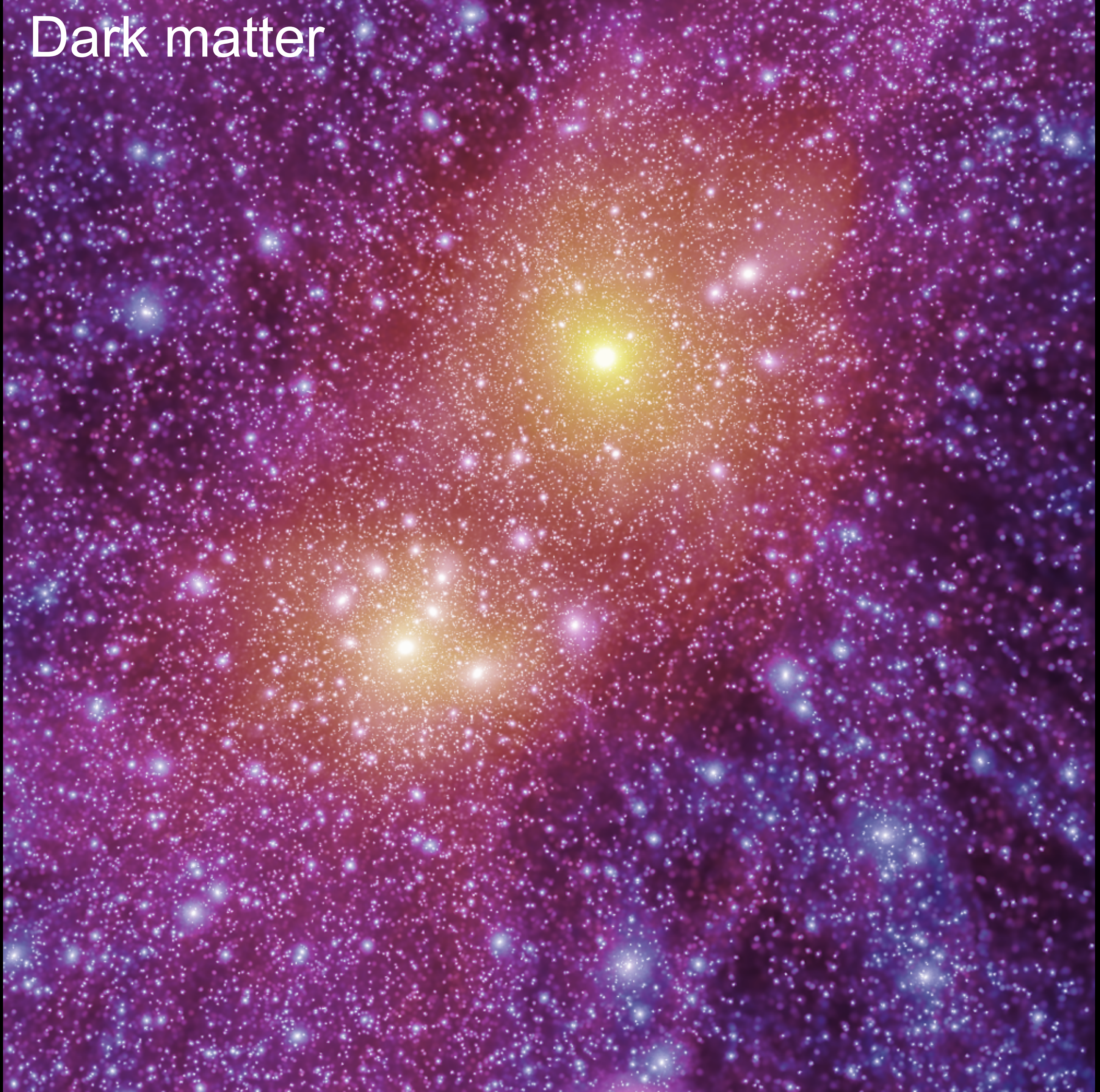
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



Stars

VIRGO

APOSTLE
EAGLE full
hydro
simulations

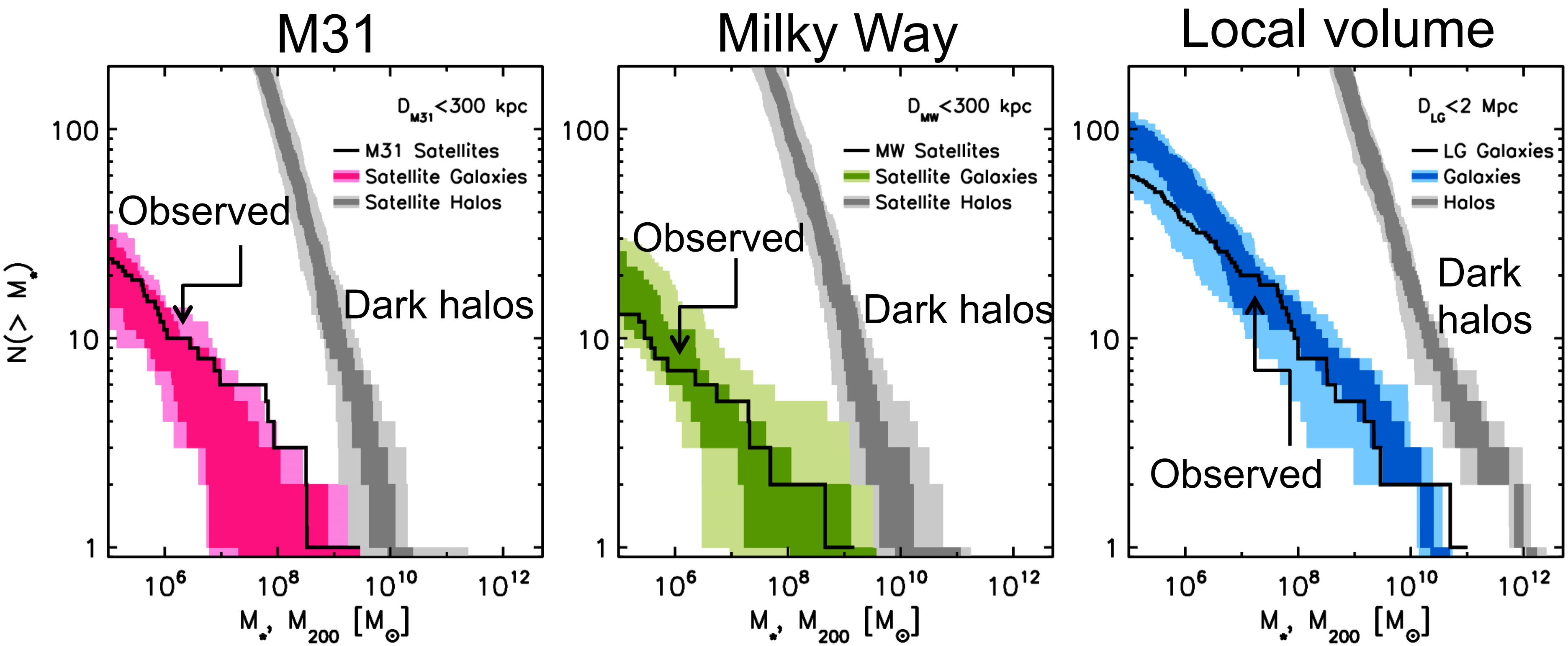
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation



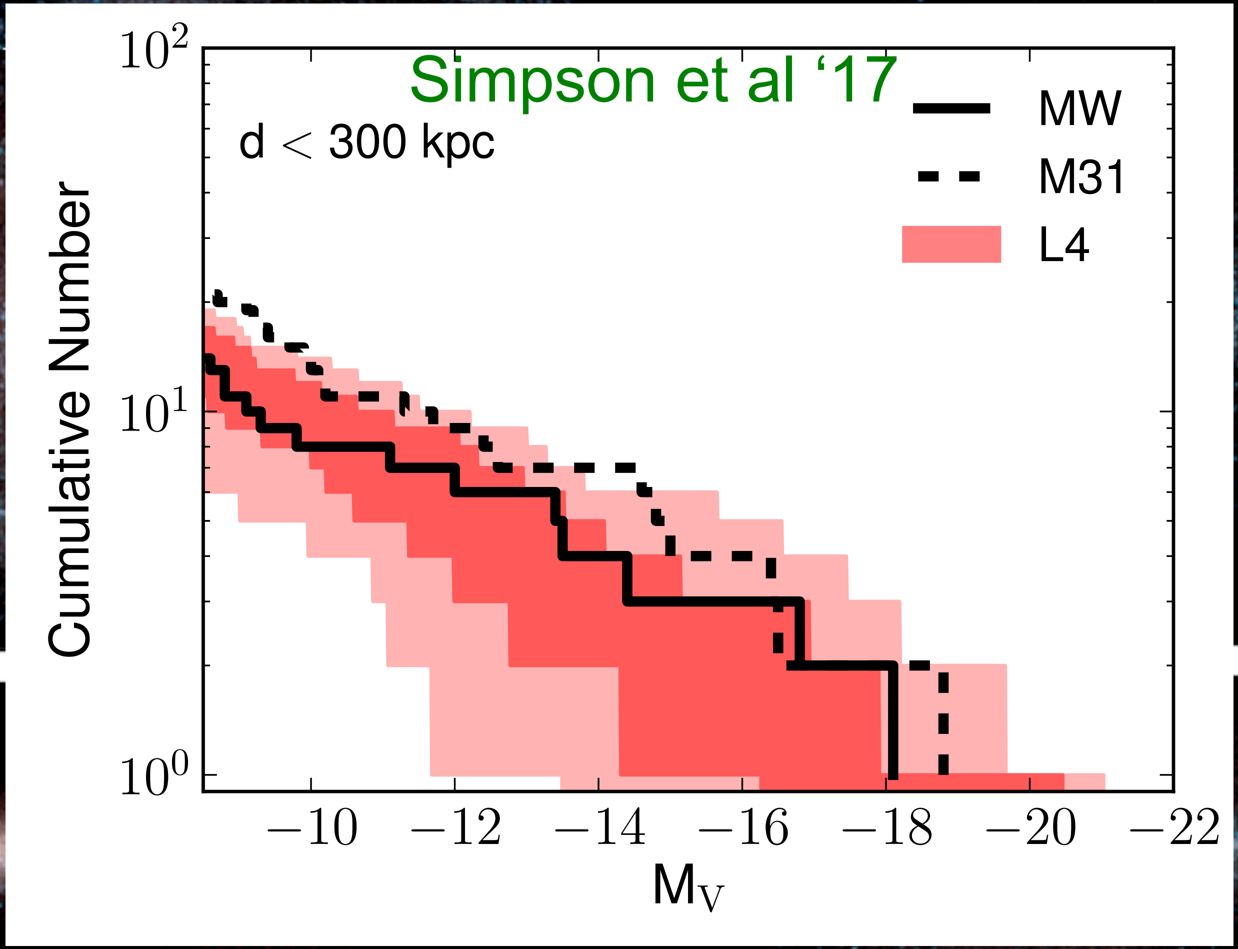
Sawala, CSF et al '16

The Auriga MW-like galaxies

Grand et al '16

30 very high res Arepo sims

6 even higher res sims



D. Campbell
C. Frenk
F. Gomez
R. Grand
A. Jenkins
F. Marinacci
R. Pakmor
V. Springel
S. White

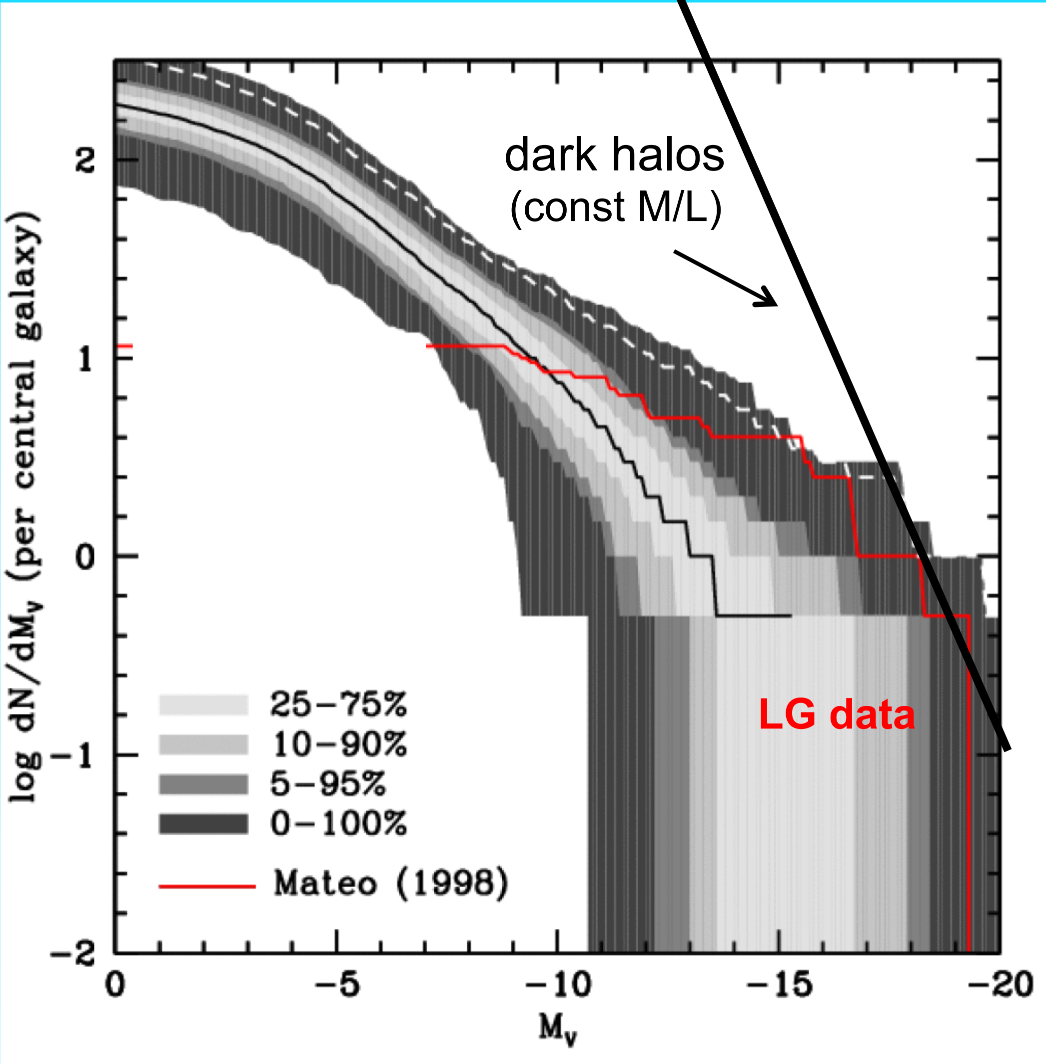
Luminosity Function of Local Group Satellites

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 (~10% of cases)



Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

Luminosity Function of Local Group Satellites

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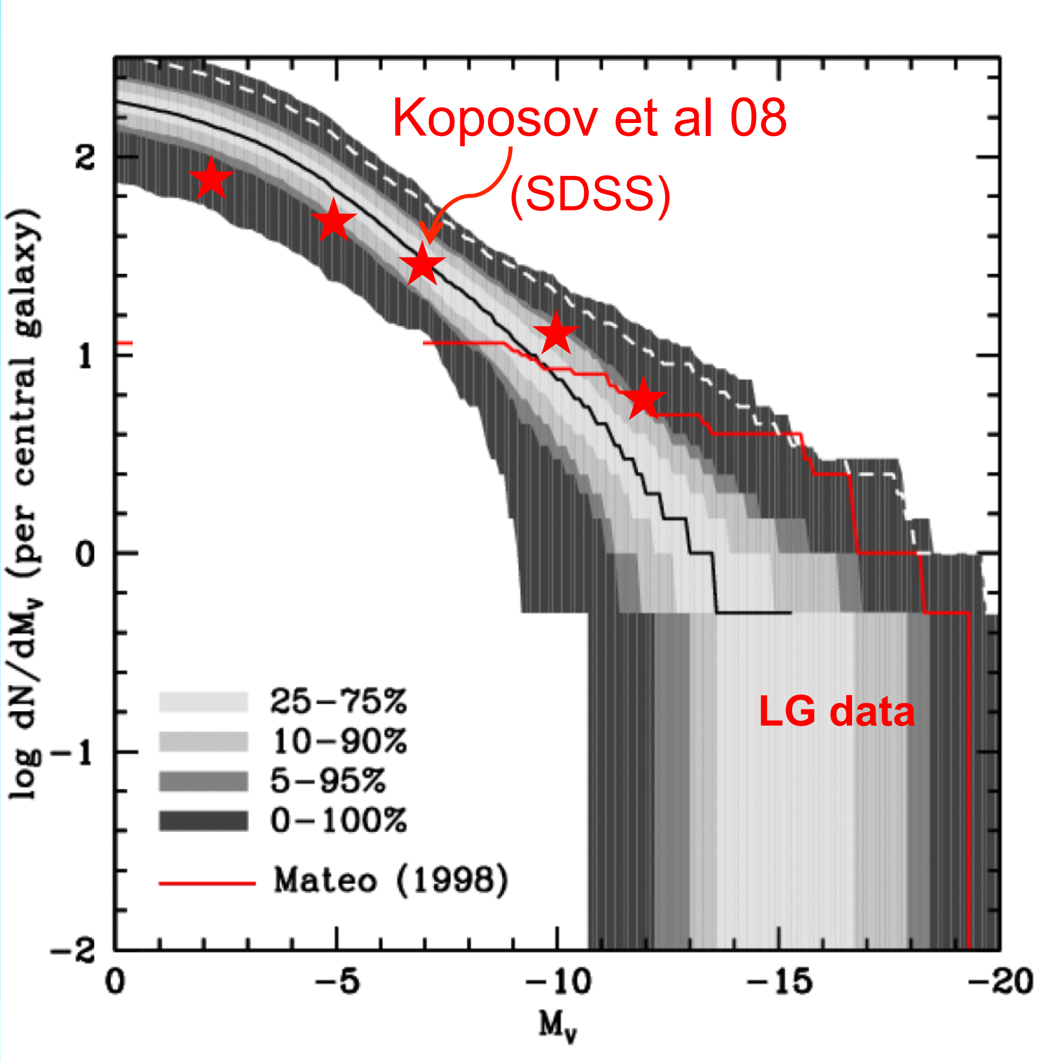
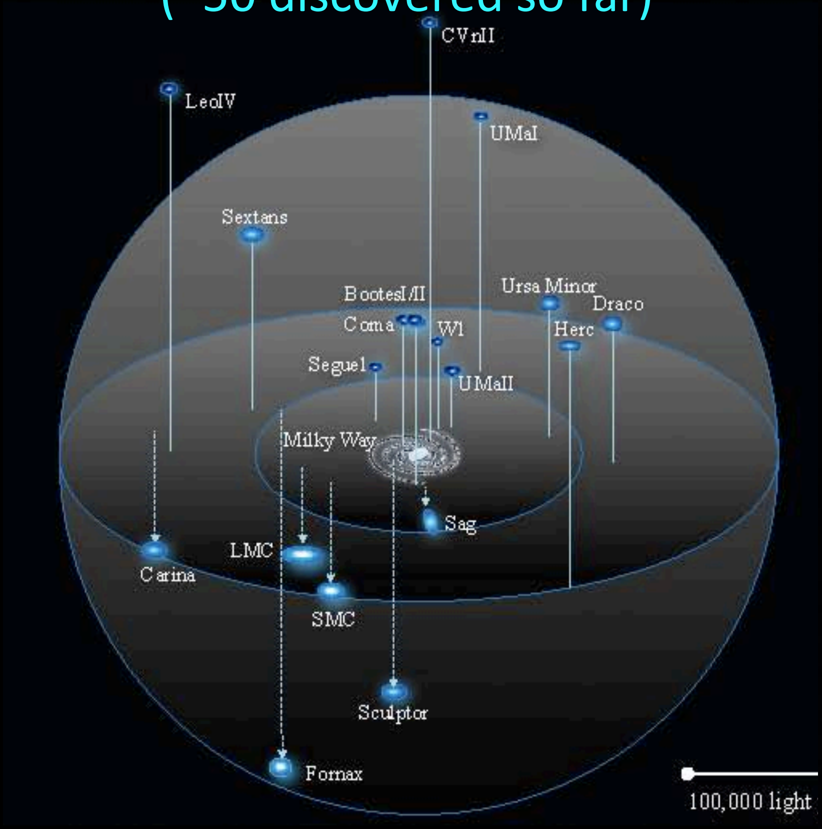


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

How about in WDM?

The satellites of the MW

(~50 discovered so far)



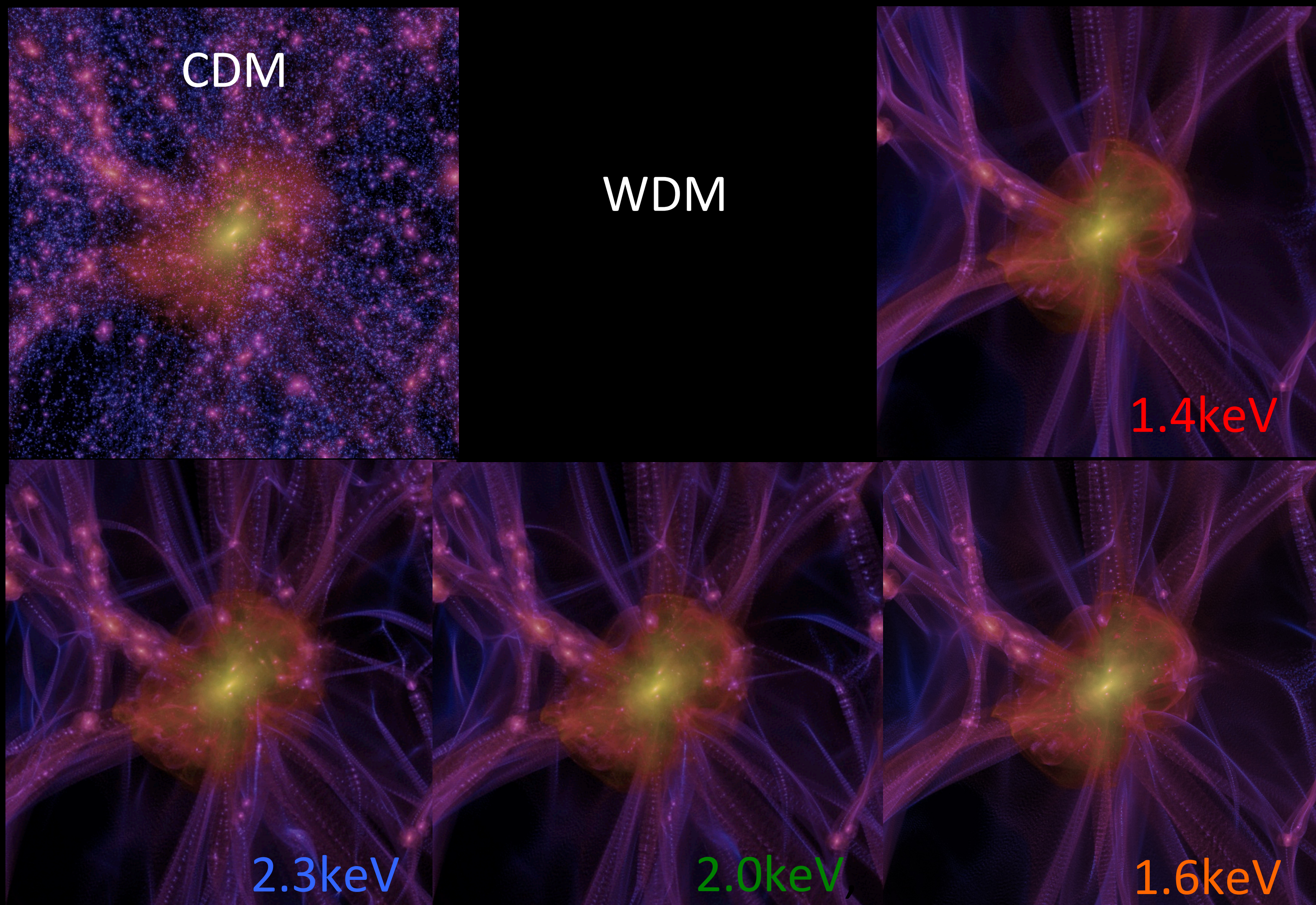
Dark mattter subhalos in WDM

(a few tens)

Warm DM: different ν mass

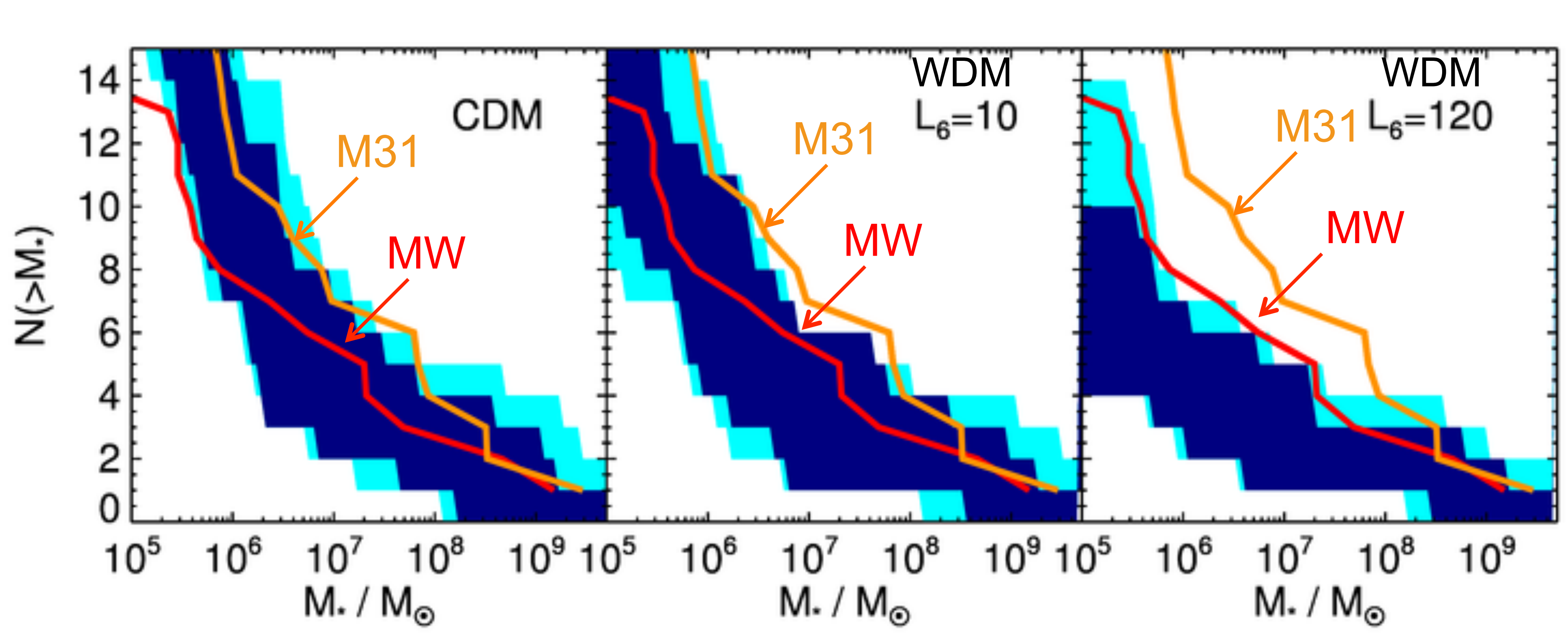
z=3

WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



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

Limits on sterile ν mass

University of Durham

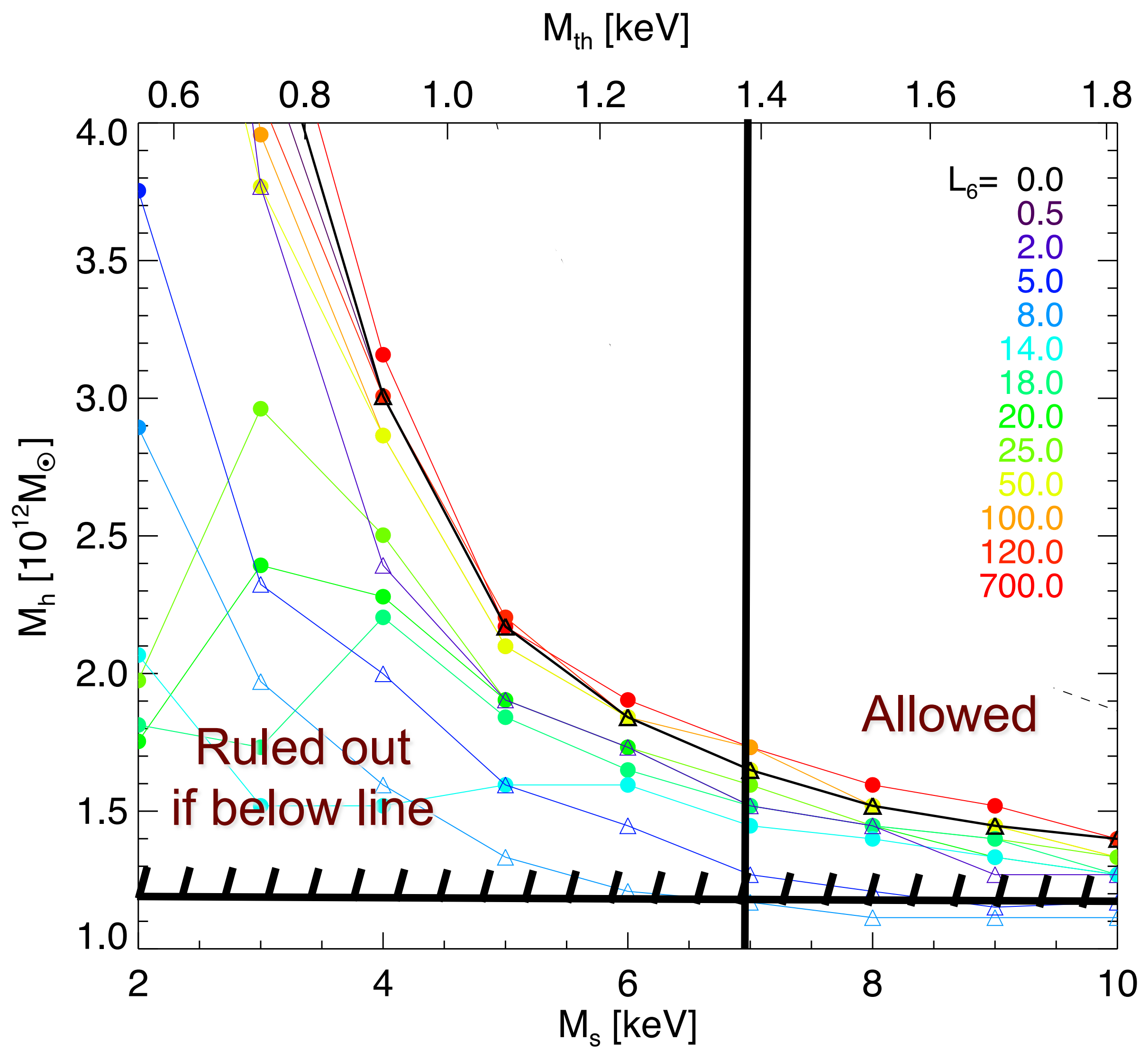
In WDM, no. of sats depends:

- Particle mass
- MW halo mass

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

→

7keV sterile ν ruled out



Lovell et al '16

All we have achieved by counting satellite galaxies is to rule out a few WDM models!

Does the inner structure of satellites help?

Core vs cusp "problem"

University of Durham

Evidence for warm dark matter!

THE ASTROPHYSICAL JOURNAL, 663:948–959, 2007 July 10

THE OBSERVED PROPERTIES OF DARK MATTER ON SMALL SPATIAL SCALES

GERARD GILMORE,[1] MARK I. WILKINSON,[1,2] ROSEMARY F. G. WYSE,[3] JAN T. KLEYNA,[4] ANDREAS KOCH,[5,6]
N. WYN EVANS,[1] AND EVA K. GREBEL[6,7]

ABSTRACT

dark matter in star clusters. We present a synthesis of recent photometric and kinematic data for several of the most dark-matter dominated galaxies. There is

of $\sim 15\mathrm{km\,s^{-1}}$. In two dSphs there is evidence that the density profile is shallow (cored) in the inner regions, and so far none of the dSphs display kinematics

which require the presence of an inner cusp. The maximum central dark matter density derived is model dependent, but is likely to have a mean value (averaged over a volume of radius 10pc) of $\sim 0.1\,M_\odot\,\mathrm{pc}^{-3}$ (about $5\mathrm{GeV/c^2\ cm^{-3}}$) for our proposed cored dark mass distributions (where it is similar to the mean value),

smaller systems containing dark matter are not observed. These values provide new information into the nature of the dominant form of dark matter.

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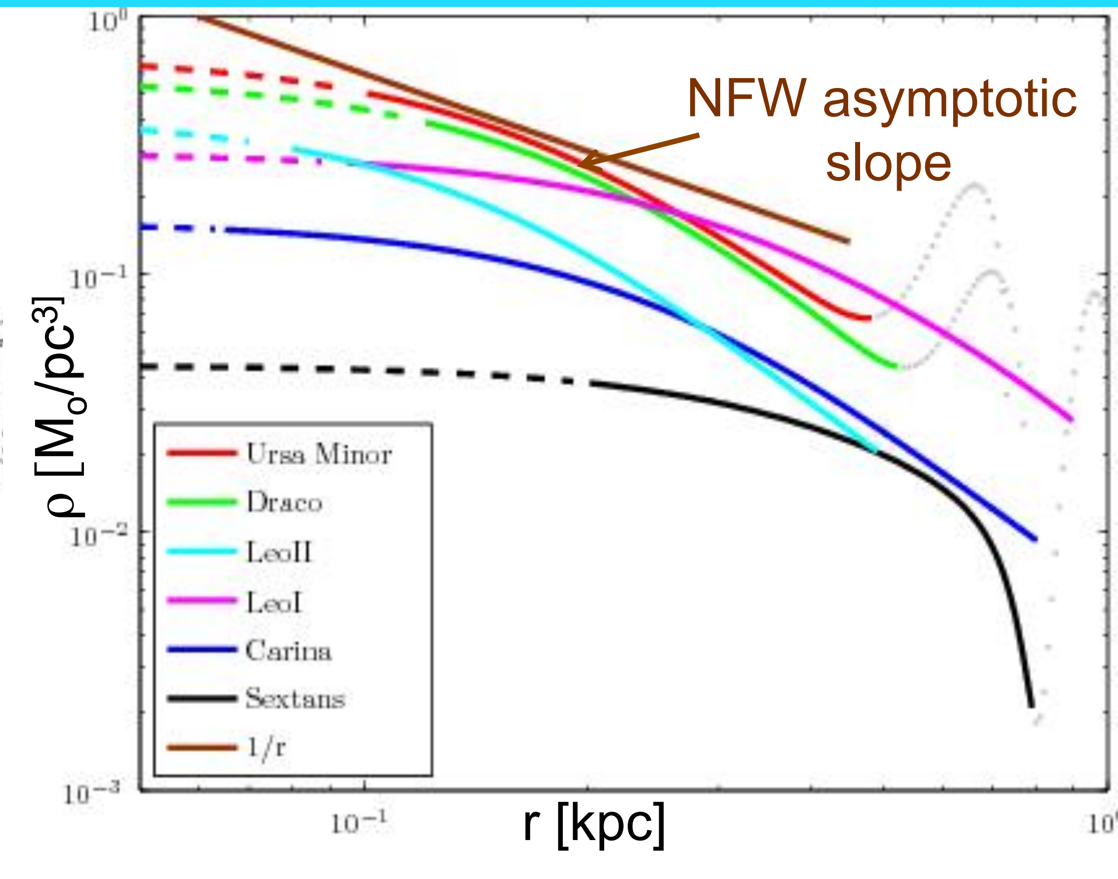
The DM halos of dwarf spheroidals

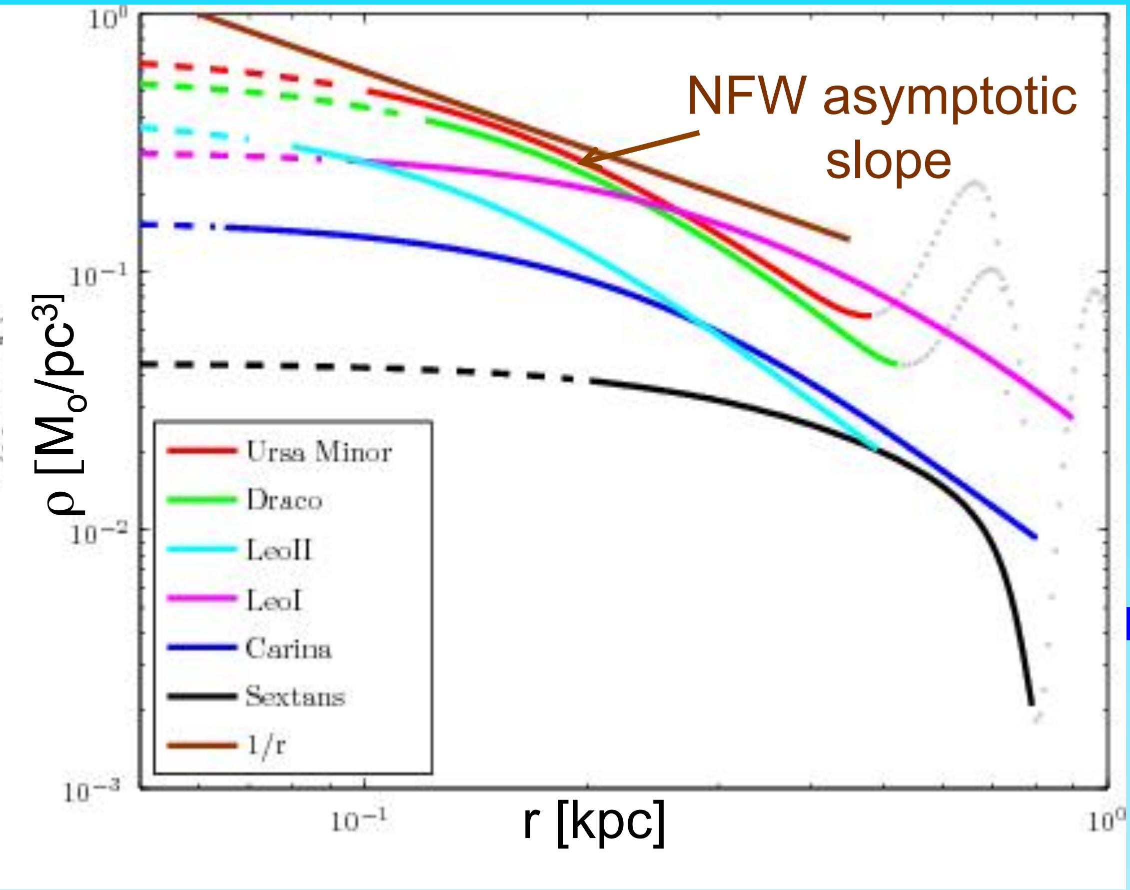


Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc…"

The DM halos of dwarf spheroidals



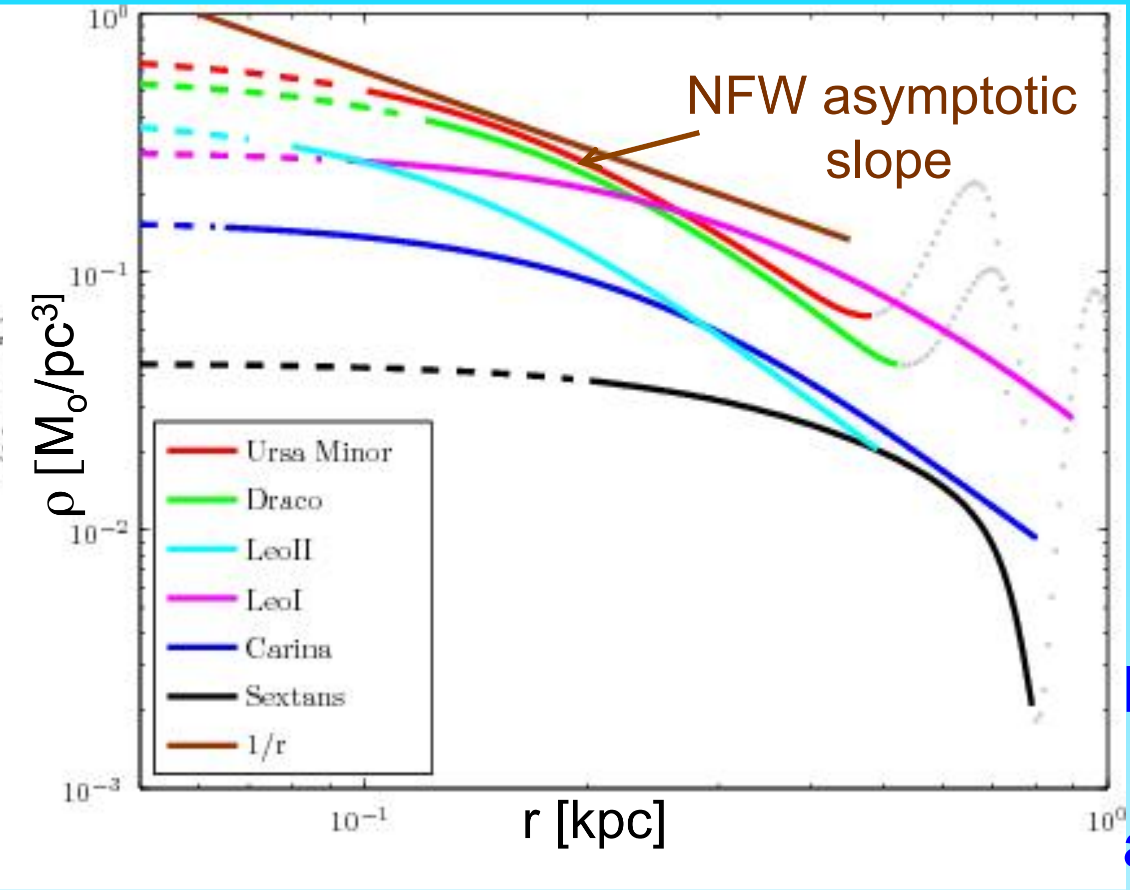
Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"…maximum central dark matter density … has a mean value of ~0.1 M_o/pc^3 (about 5 $GeV/c^2\ cm^{-3}$) …"

The DM halos of dwarf spheroidals

University of Durham

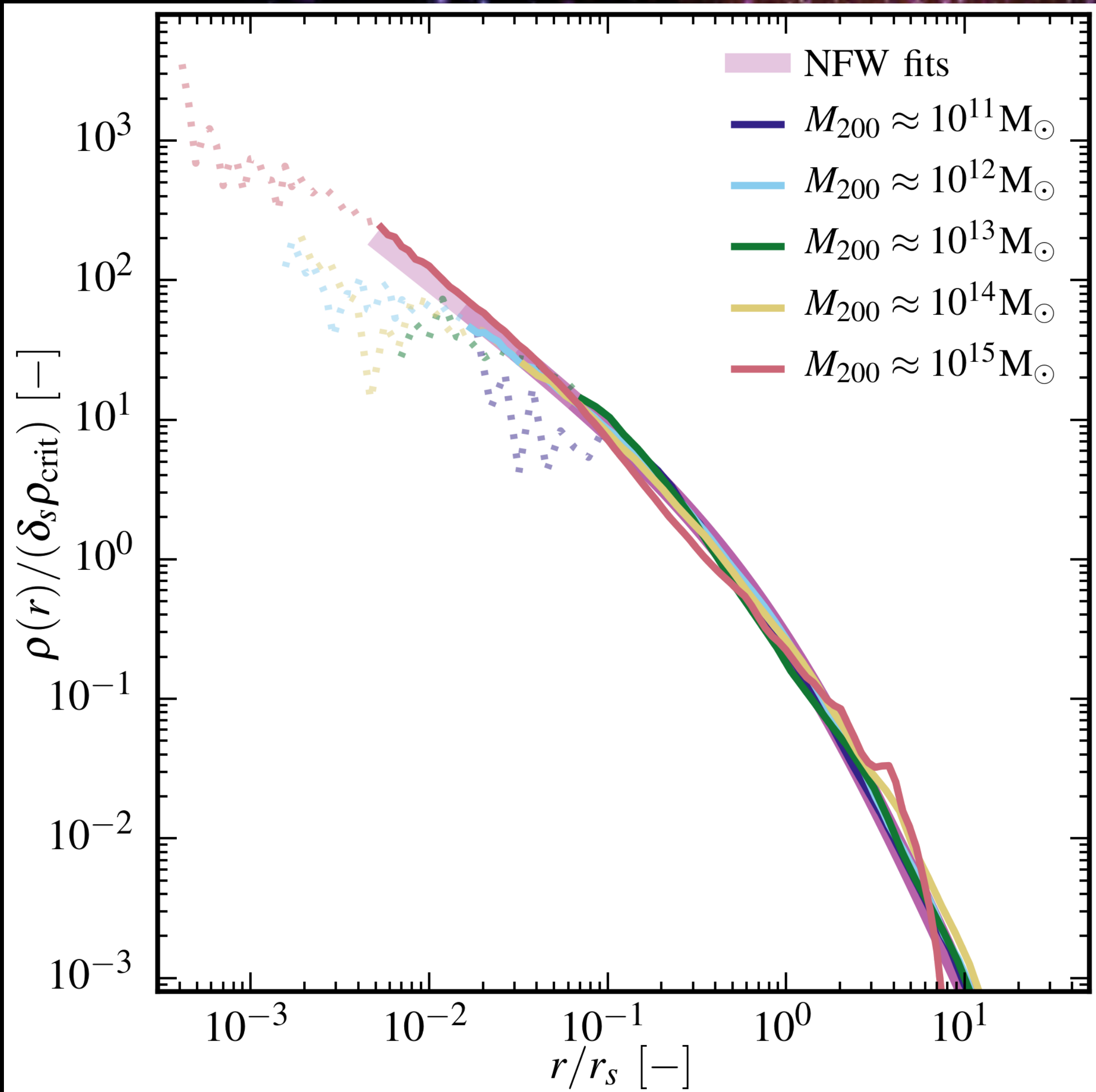


Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"… Rather interestingly, intermediate-mass (keV) sterile neutrino particles have been discussed … as relevant in just the spatial and density range we have derived here…"

The Density Profile of Cold Dark Matter Halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

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

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger δ)

How about in WDM?

cold dark matter

warm dark matter

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

Density profiles of WDM halos

WDM particles have significant thermal velocities at early times

Since the phase-space density cannot increase, shouldn't this produce a uniform density core?

Core radii in WDM halos

The thermal velocities of WDM particles induce cores.

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Shao, Gao, Theuns, Frenk '13

Maccio et al.'12

Core radii in WDM halos

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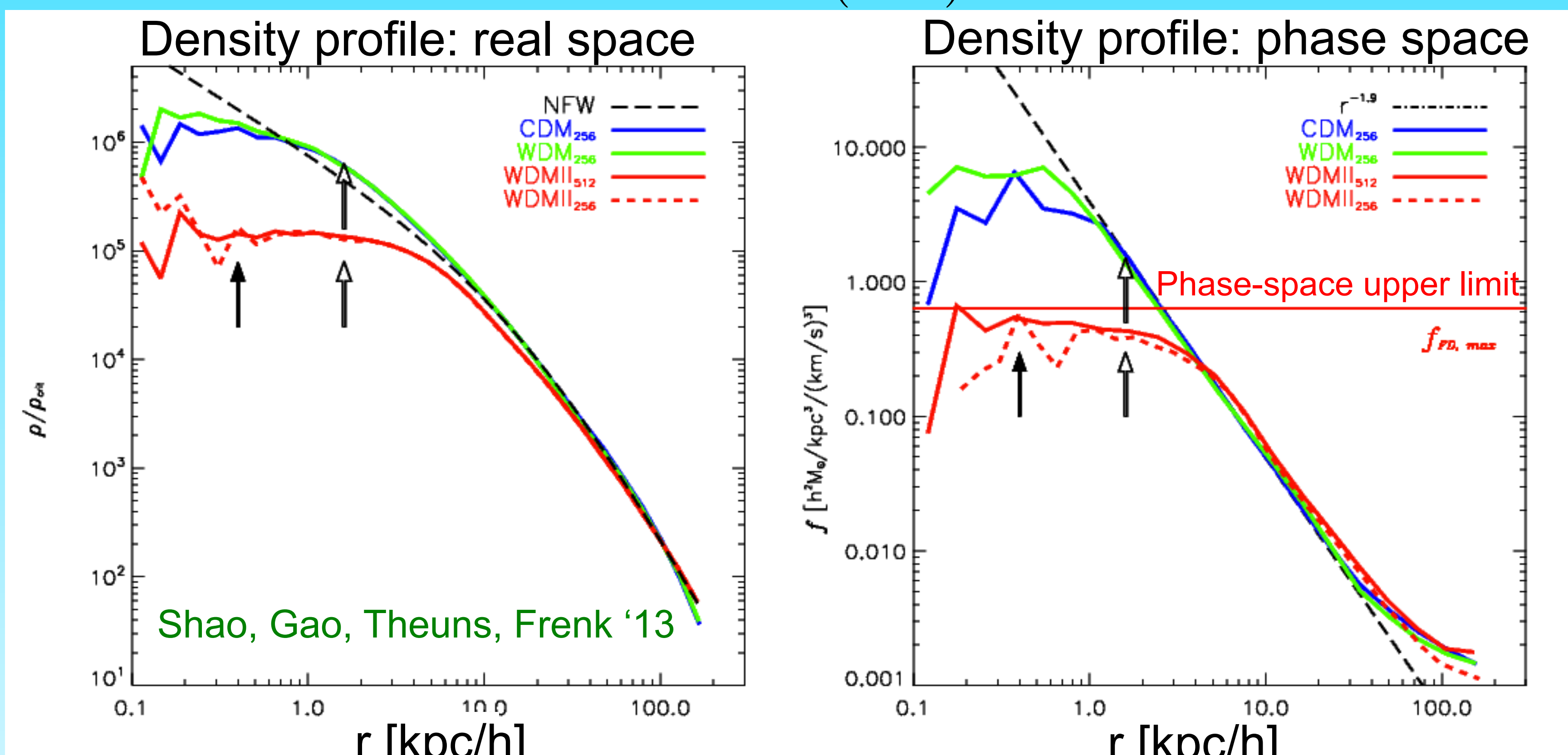


Core radii in WDM halos

University of Durham

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

By requiring $f = f_{FD}$

$$m_x^4 = \frac{6(2\pi\hbar)^3}{(2\pi)^{5/2} g G \sigma r_h^2}$$

Shao, Gao, Theuns, Frenk '13

University of Durham

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Phase space arguments → $$r_c = \frac{pc}{\left(\frac{m_x c^2}{8.2keV}\right)^2 \left(\frac{\sigma}{km/s}\right)^{1/2} \left(\frac{g}{2}\right)^{1/2}}$$

core radius

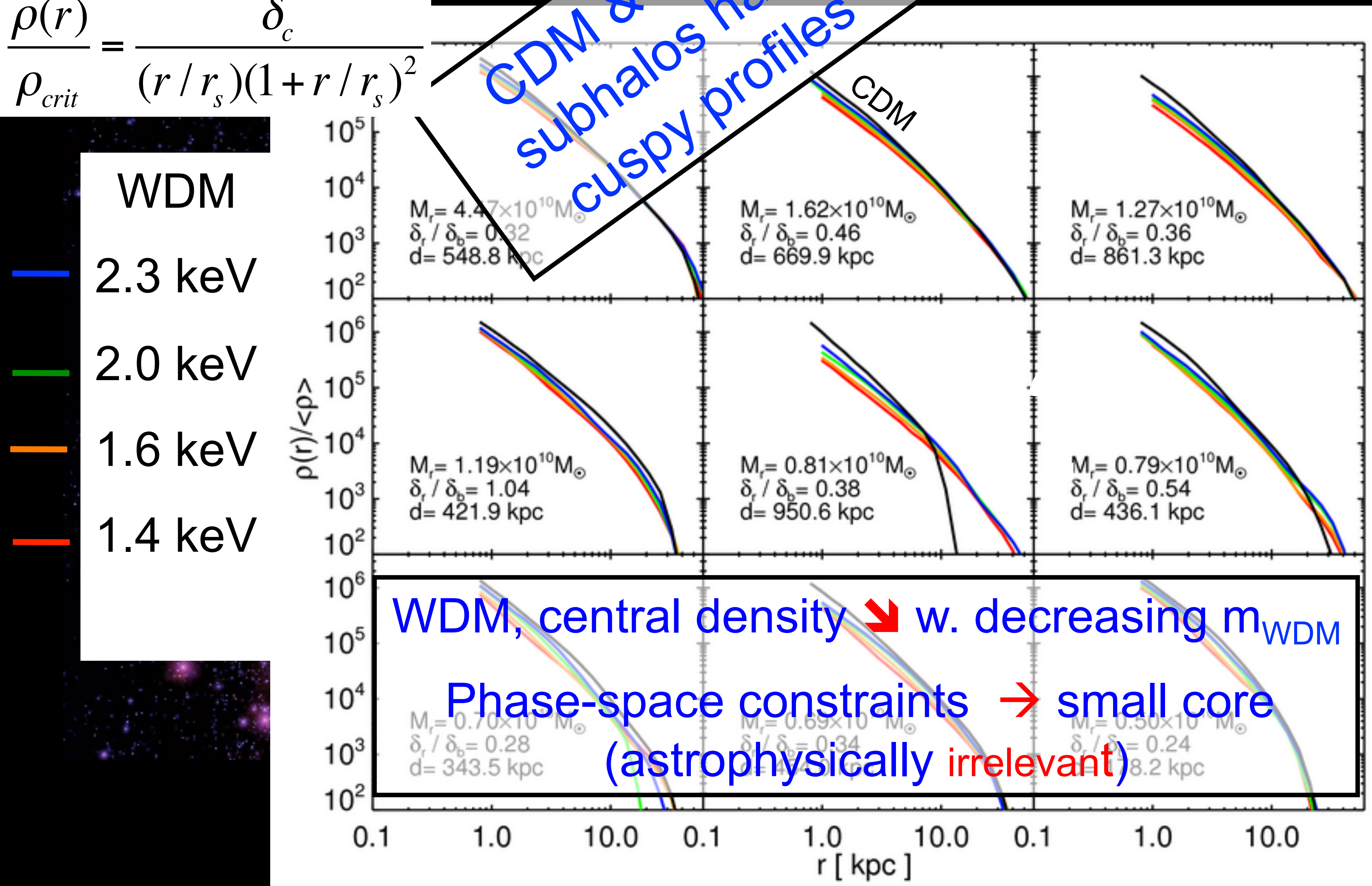
For m_{WDM} > 1.5 keV, core radii in WDM models are < 10pc →

core radii NOT relevant in WDM even in dwarf gals

Shao, Gao, Theuns, Frenk '13
see also Maccio et al '12

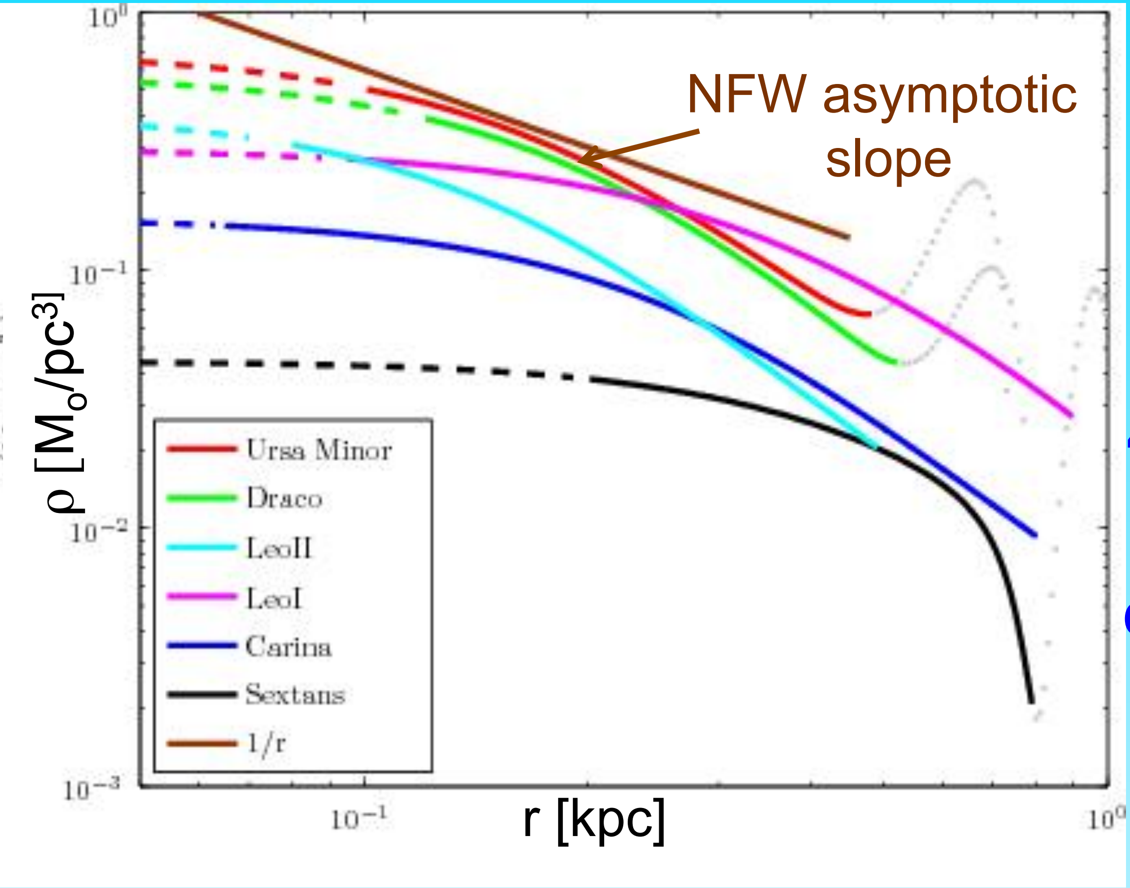
The core-cusp problem

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



The DM halos of dwarf spheroidals

University of Durham



Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc…"

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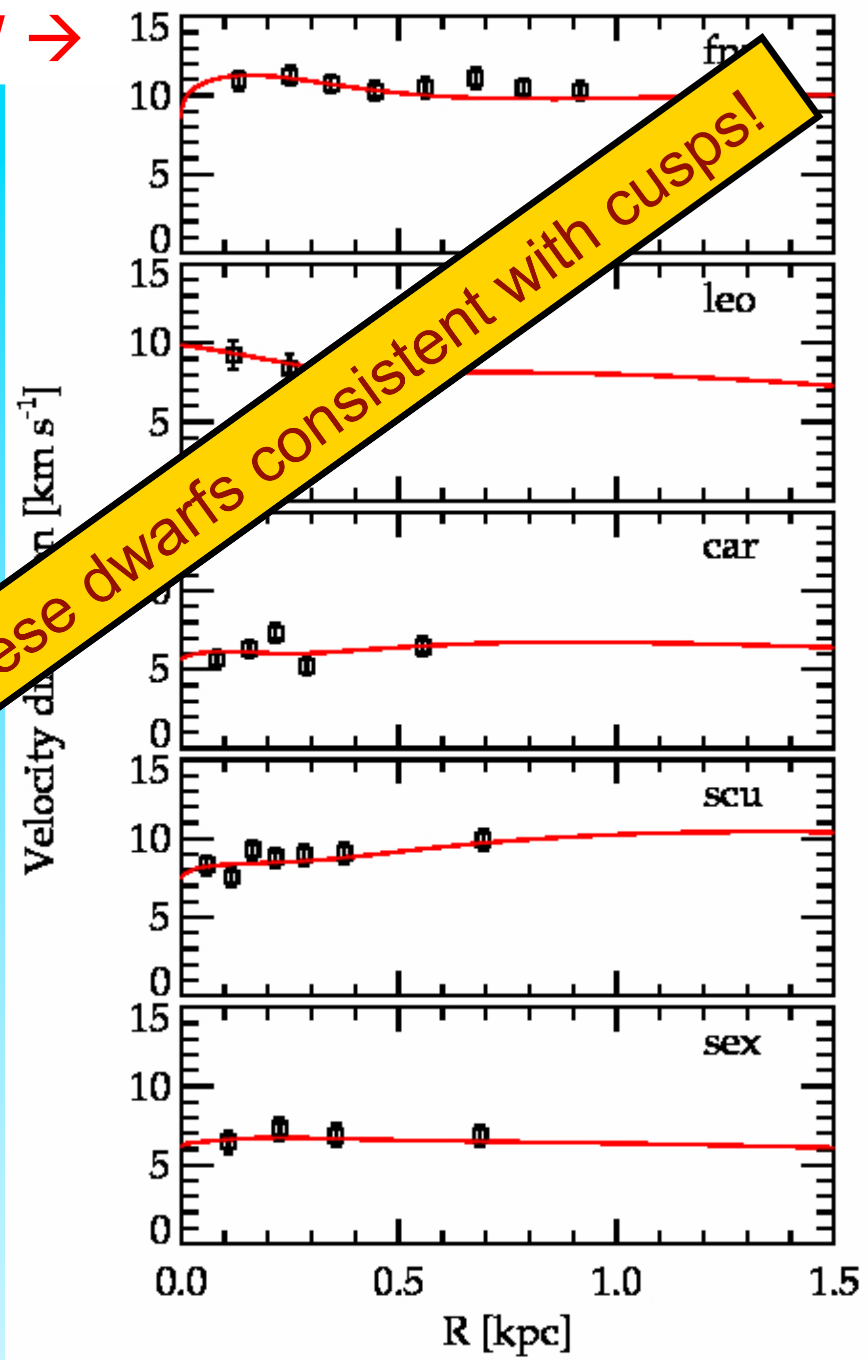
Fits assuming NFW →



Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim

Cuspy!

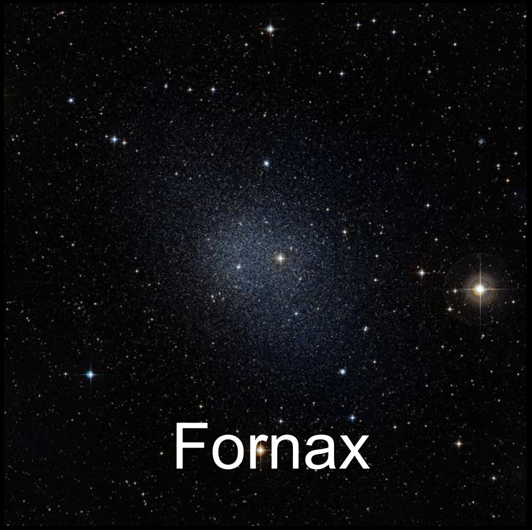
vel. an... py

- Assume isotropi... ts
- Solve for σ...
- Com... with observed σ_r (r)
- ... best fit" subhalo

Photometric and kinematical data for these dwarfs consistent with cusps!

Strigari, Frenk & White '10

Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

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

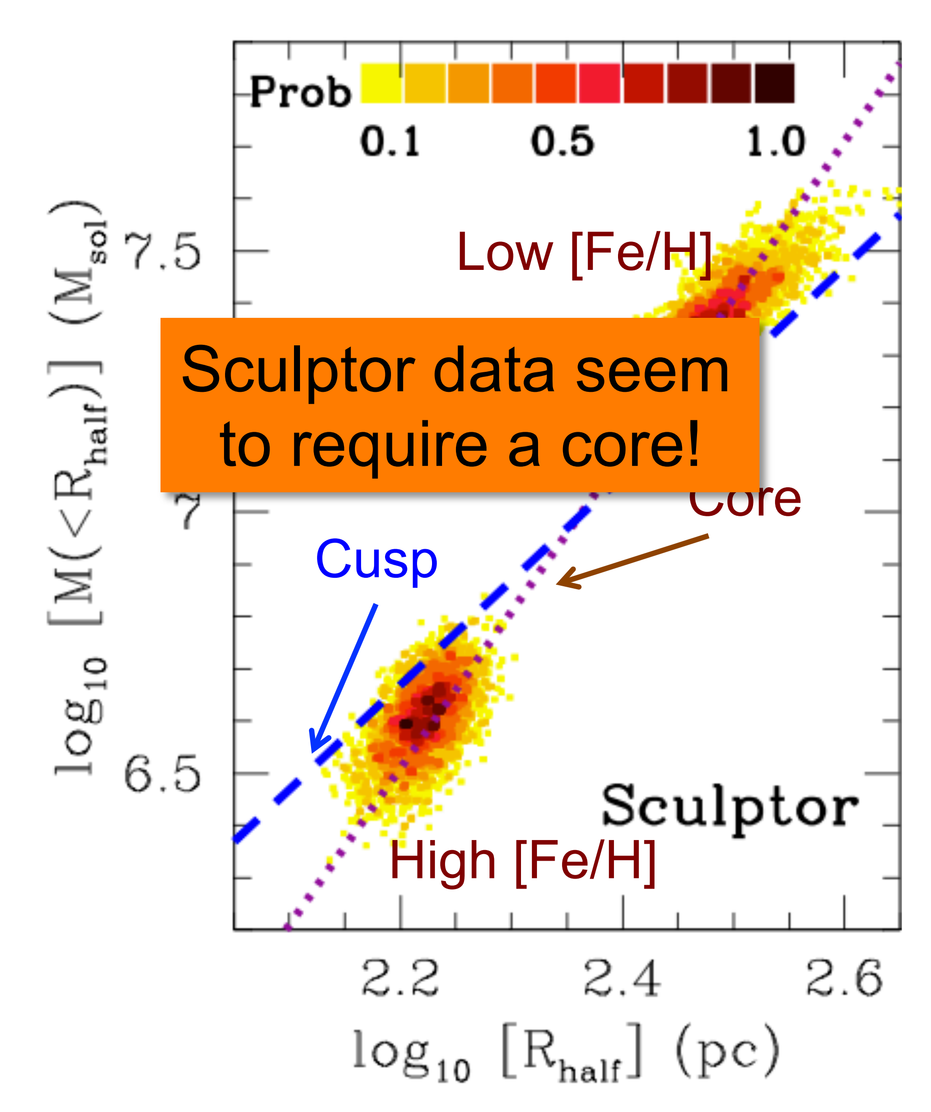
(ii) extended, low [Fe/H]

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

$r=r_{1/2}$

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

The DM halo of the Sculptor dwarf

Strigari, Frenk & White '15

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $$\rho(r) = \frac{\rho_s}{x(1+x)^2}$$

For each population: $$f(E,J) = g(J)h(E),$$

Parametrize: $$g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^{\alpha}$$

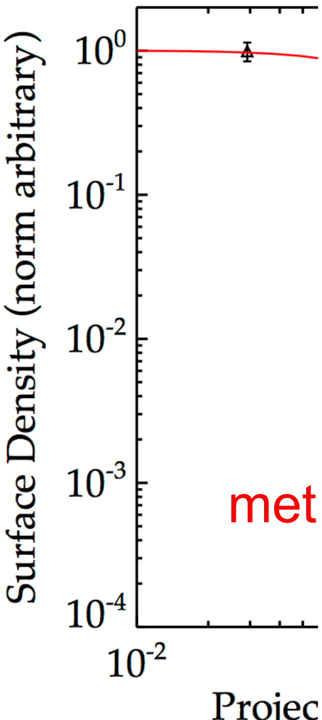
$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for} E \geq \Phi_{lim}, \end{cases}$$

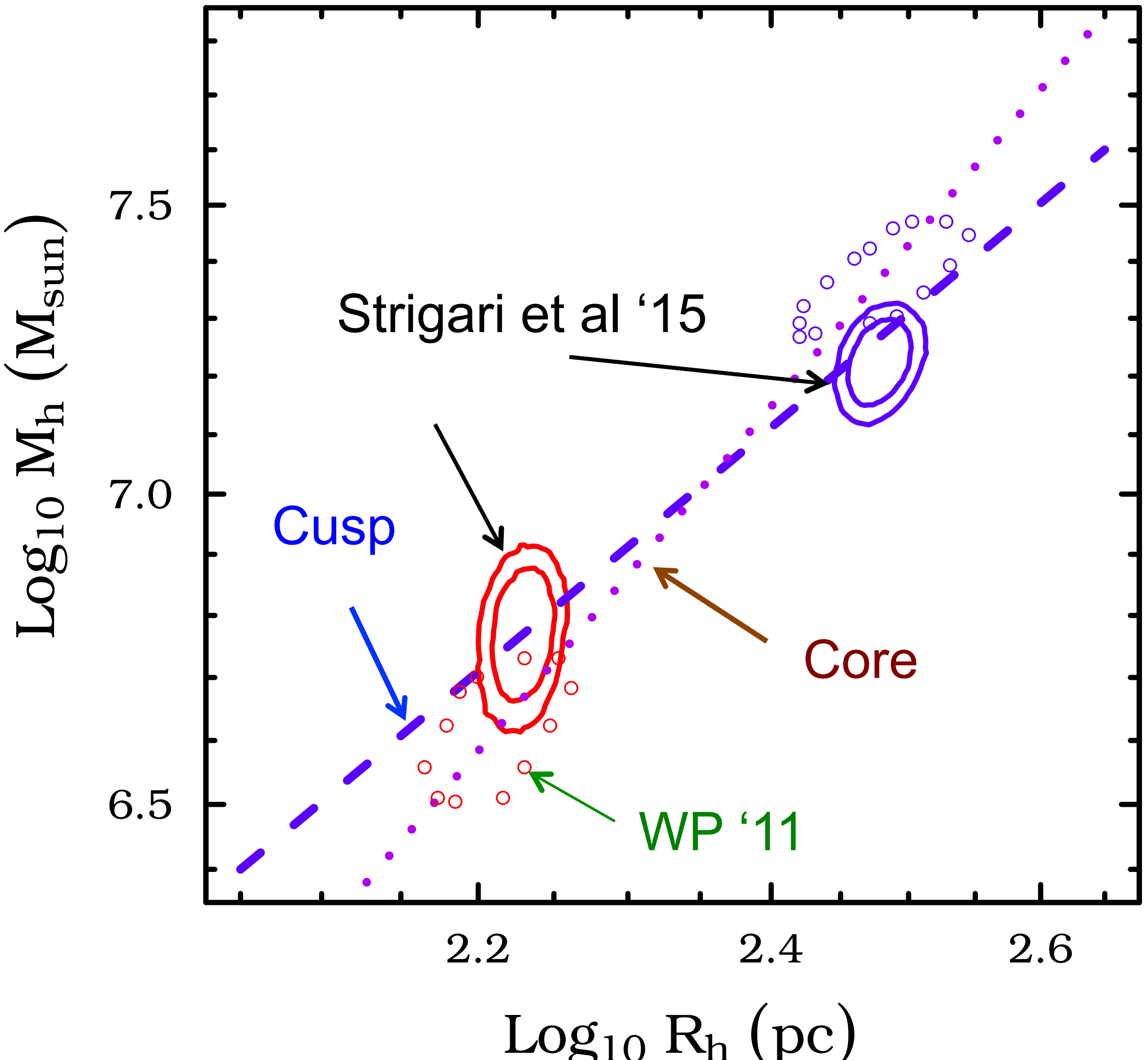
Find best-fit parameters using MCMC

University of Durham

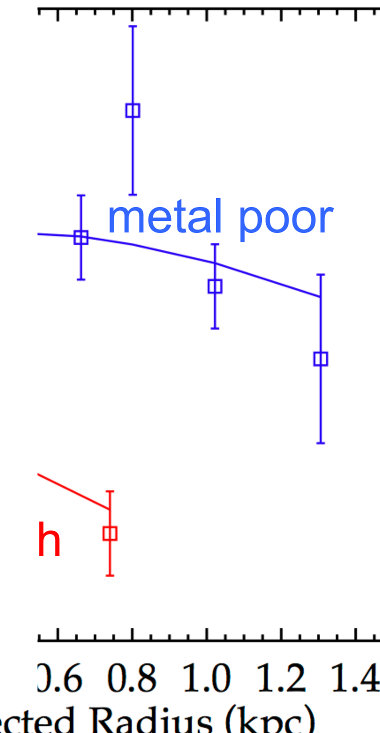
The DM halo of the Sculptor dwarf

Distribution function analysis





y dispersion



Data cons

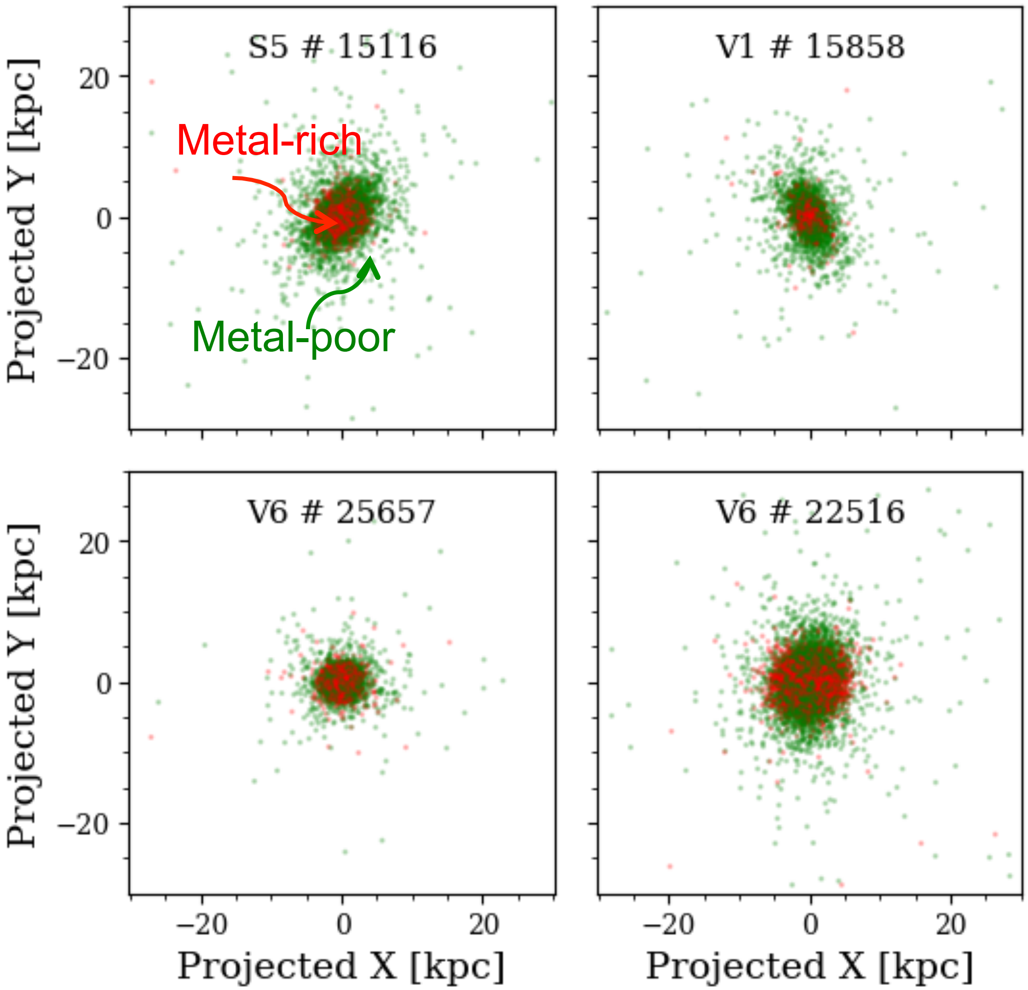
eq

Strigari, Frenk & White '15

Apostle: satellites w. 2-metalicity pops

University of Durham

The stellar populations are not spherical and the shapes of the two can be different



Gennina, Benitez-Llambay, CSF + '17

Institute for Computational Cosmology

The DM halo of the Sculptor dwarf

University of Durham

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

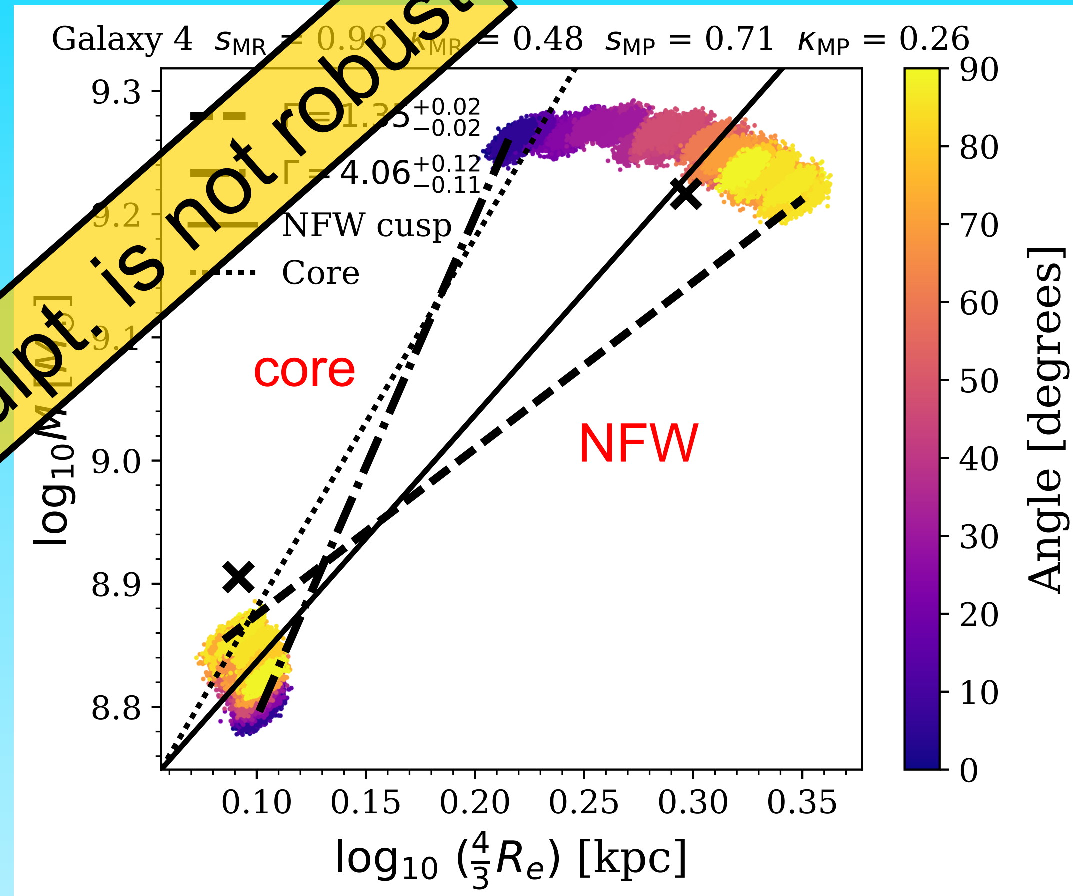
Key assumption of mass estimator:

spherical symmetry

Most satellites in apostle are elongated!

WP11 core in Sculpt. is not robust

View galaxy from different directions



You can infer any slope, from NFW to core depending on viewing angle!

Genina, Benitez-Llambay, CSF + ‘17

Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

University of Durham

Rotation curves of 2 APOSTLE dwarfs

APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{v}}$

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit

Let's apply this to APOSTLE galaxies by making a mock 2D velocity field and analysing it just as the real data

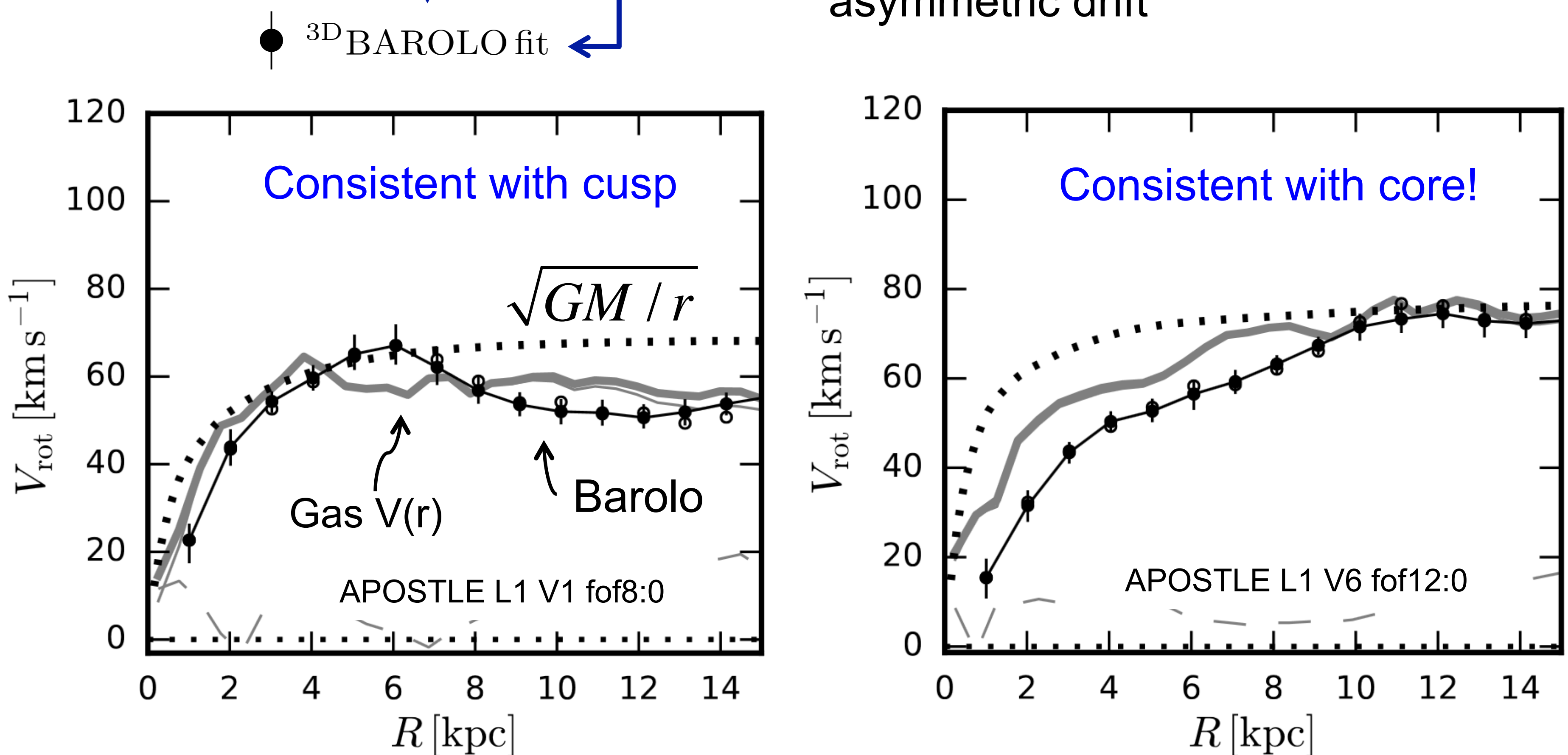
Rotation curves of 2 APOSTLE dwarfs

University of Durham

APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{r}}$

Tilted-ring model corrected for asymmetric drift



Oman et al '17; Marasco et al '17

How about baryon effects?

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]

[1]*Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA*
[2]*Physics Department, University of Durham, South Road, Durham DH1 3LE*

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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

Parry, CSF et al. '11
Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

Navarro, Eke, Frenk '96

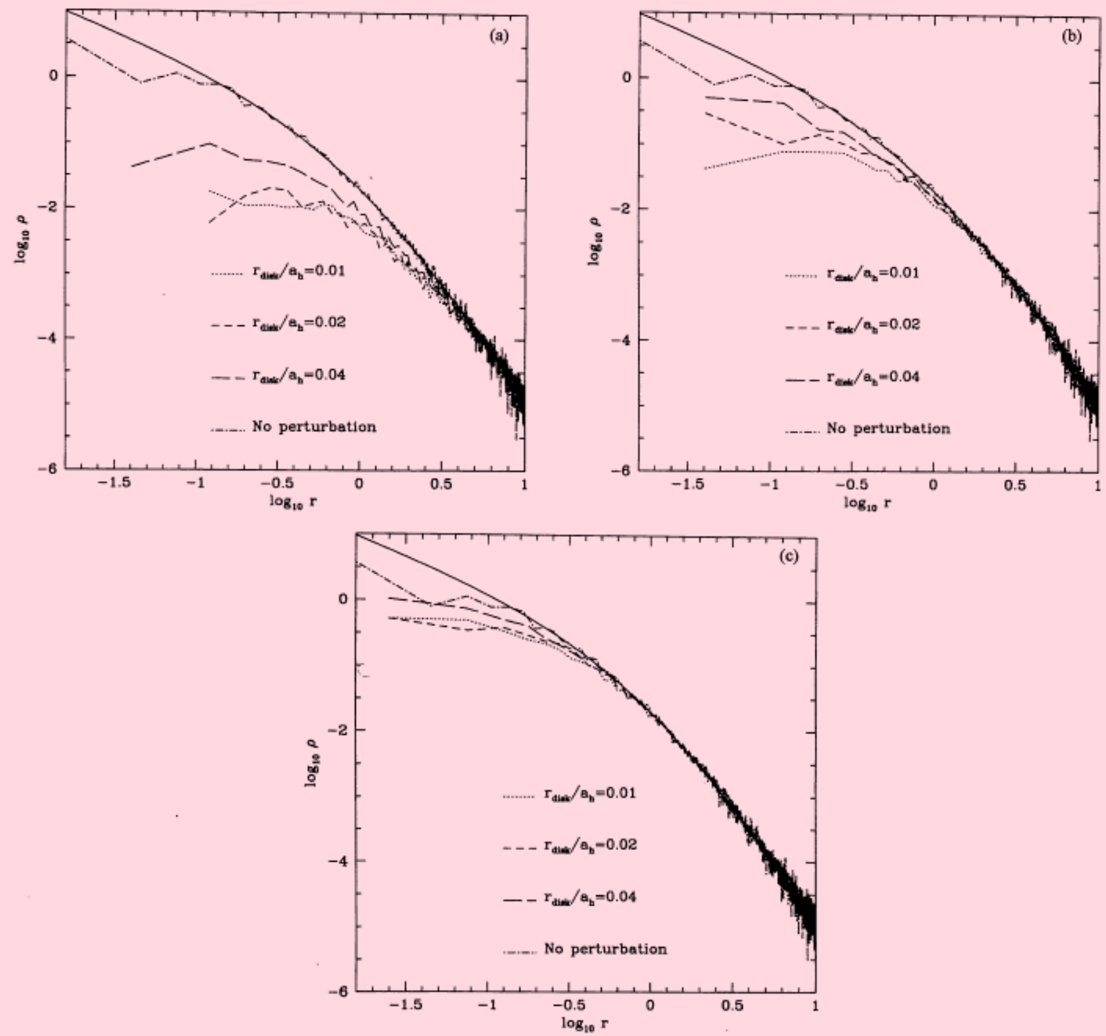

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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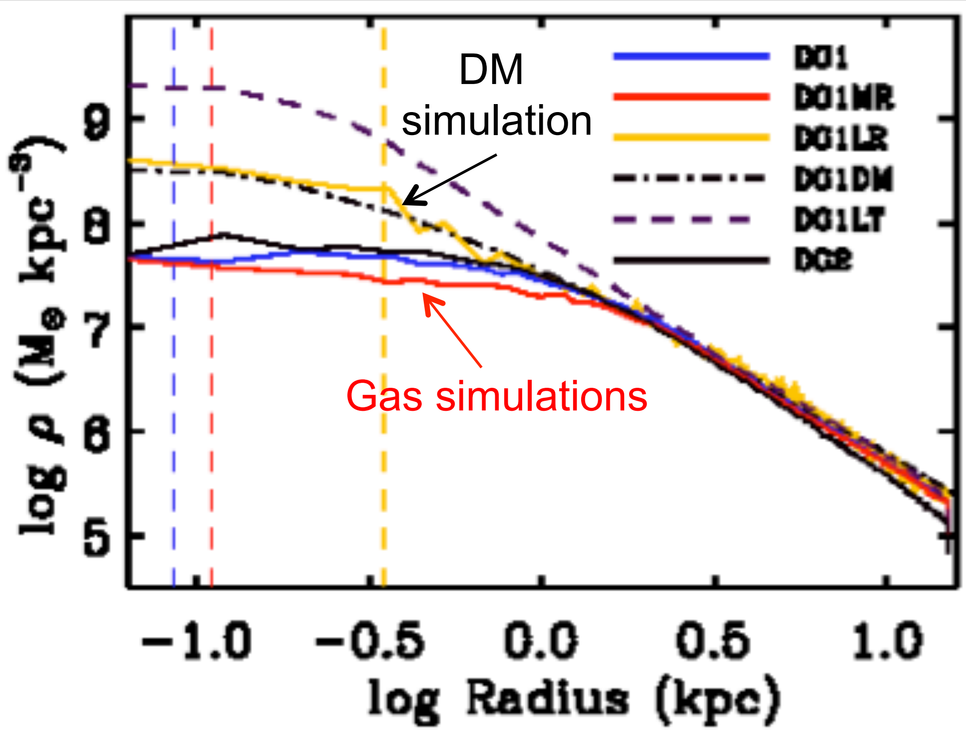
Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

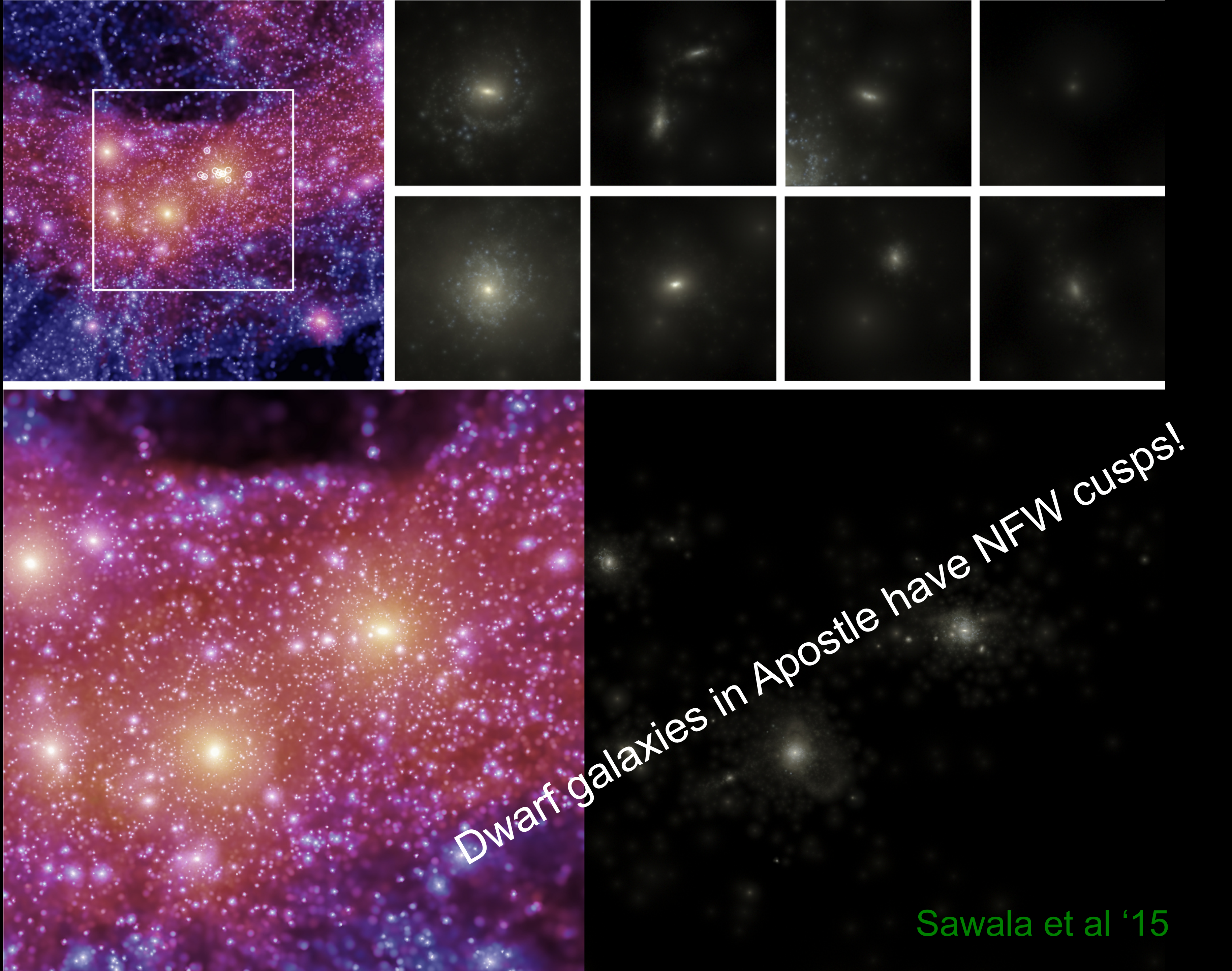
EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

→ Sudden repeated removal of gas transfers binding energy



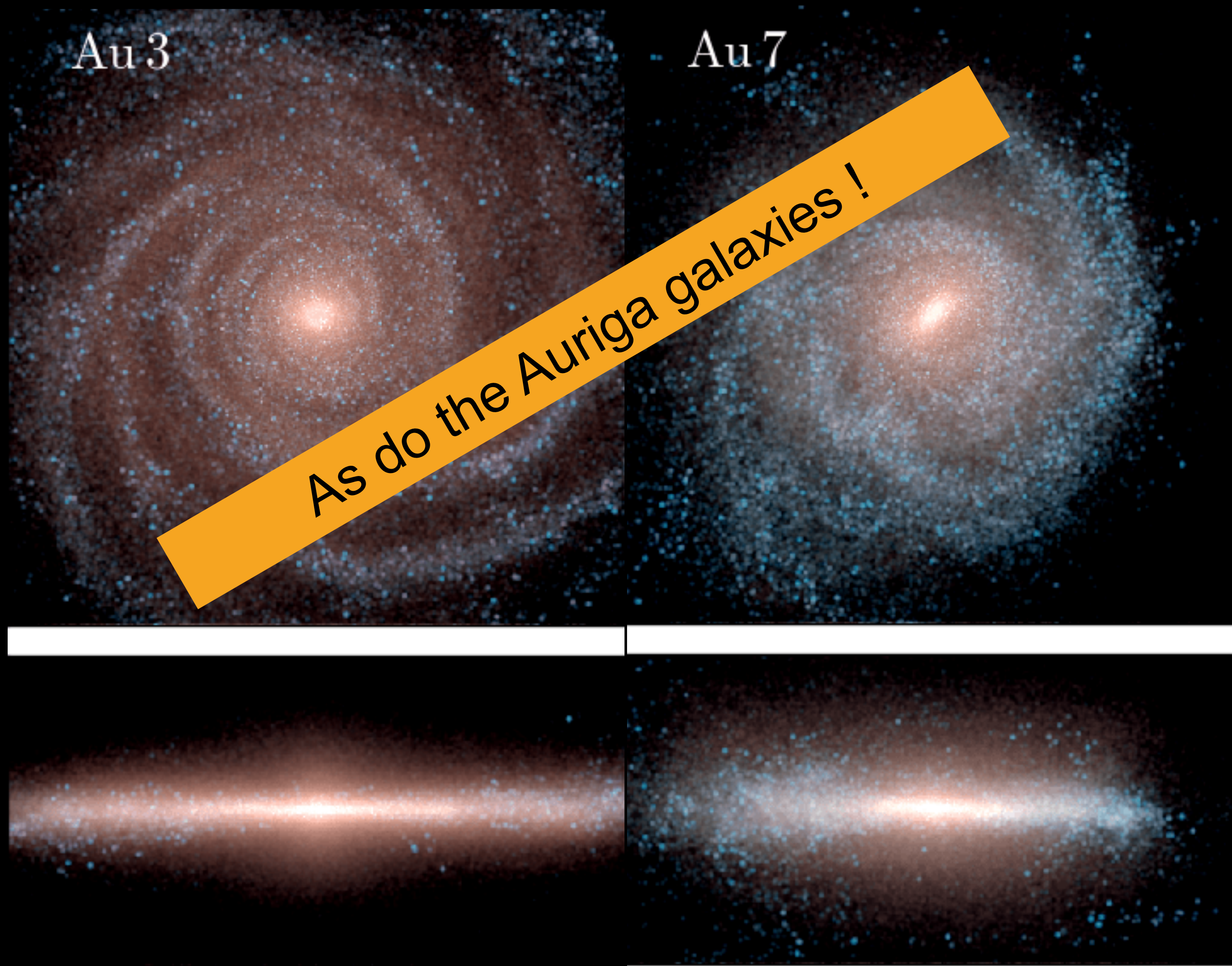
Governato et al. '12
Pontzen et al. '12


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

The Auriga MW-like galaxies

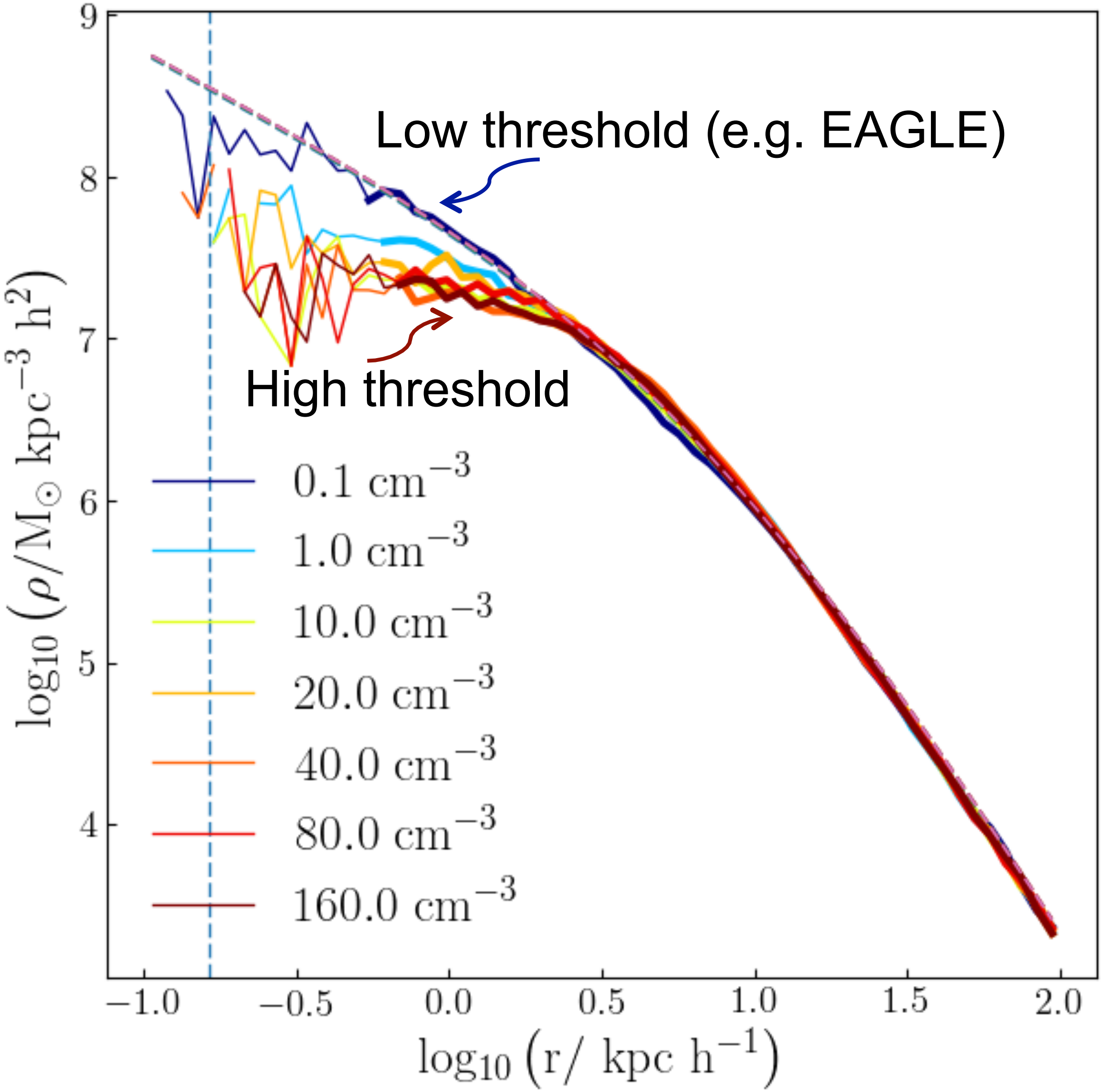
30 very high res Arepo sims

6 even higher res sims



D. Campbell
C. Frenk
F. Gomez
R. Grand
A. Jenkins
F. Marinacci
R. Pakmor
V. Springel
S. White

Cores or cusps in simulations?



Benitez-Llambay, CSF et al '17

Conclusions from halo structure

Cores in WDM are too small(< 10 pc) to be relevant

No evidence for cores in dwarf galaxies → inferred 'cores' due to systematics in analysis of stellar dynamics and HI rotation curves:

If cores exist → can be produced by baryon effects

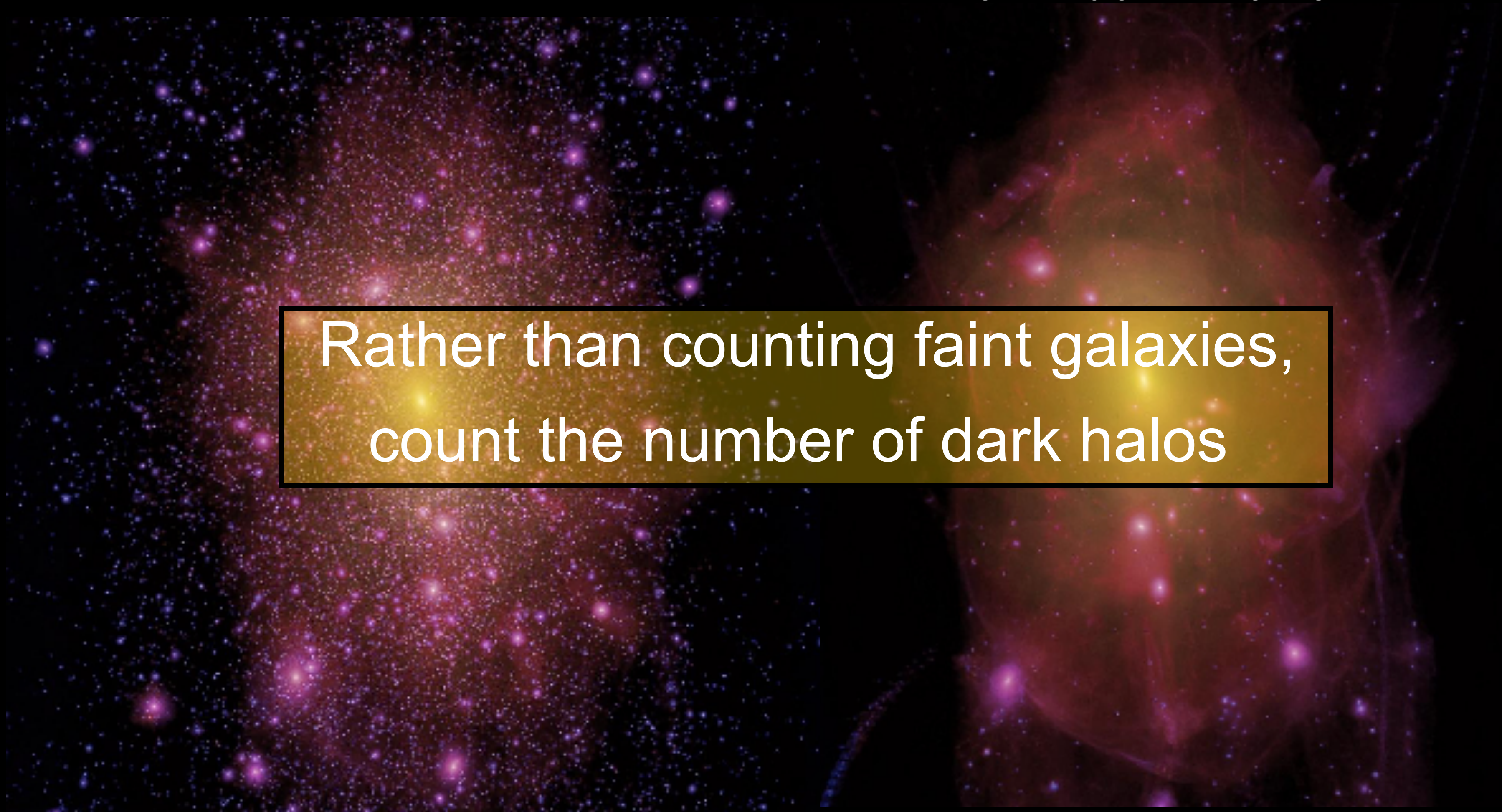
Is there any way can distinguish CDM from WDM?

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

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

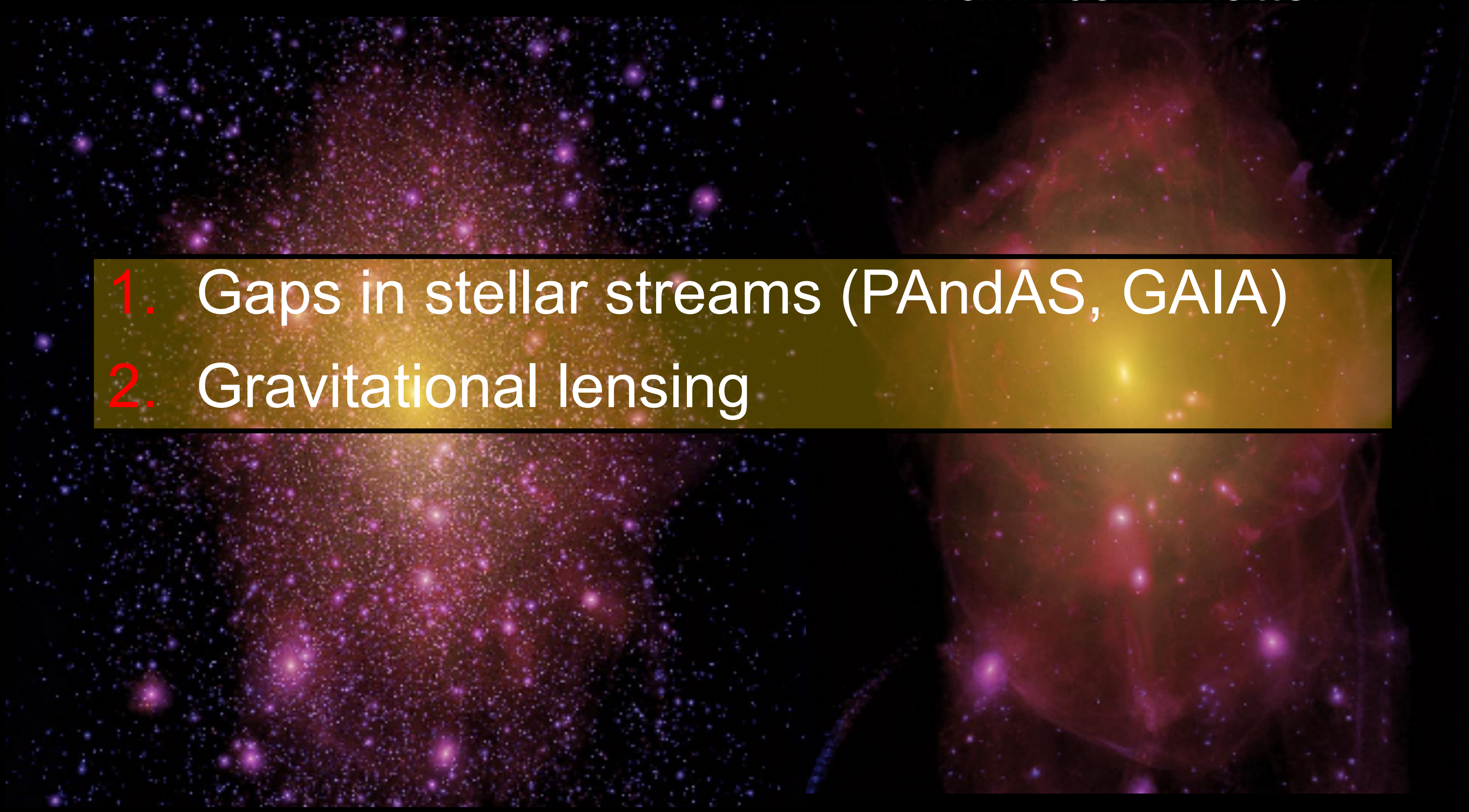


Rather than counting faint galaxies, count the number of dark halos

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

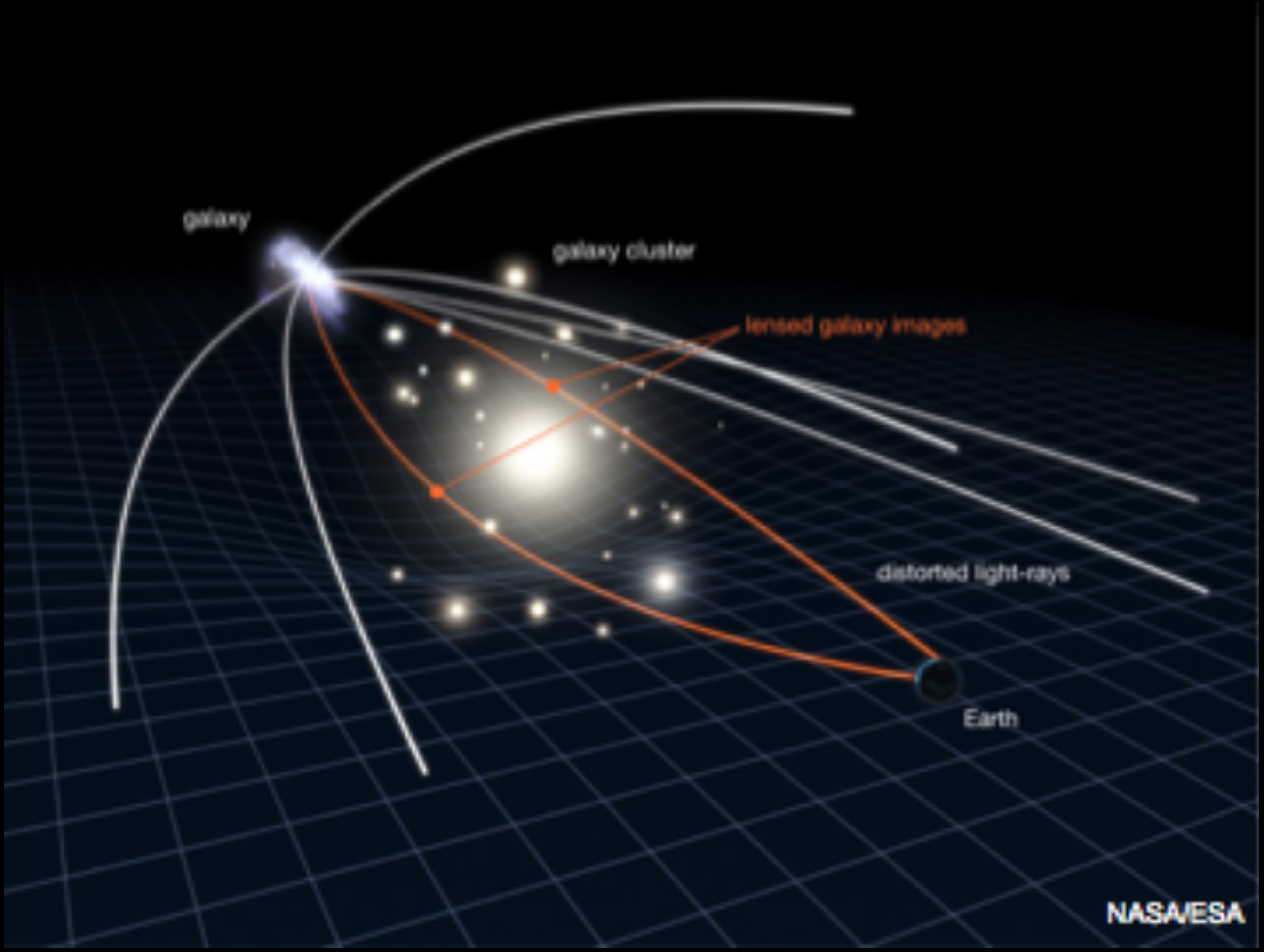


1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing

Gravitational lensing: Einstein rings

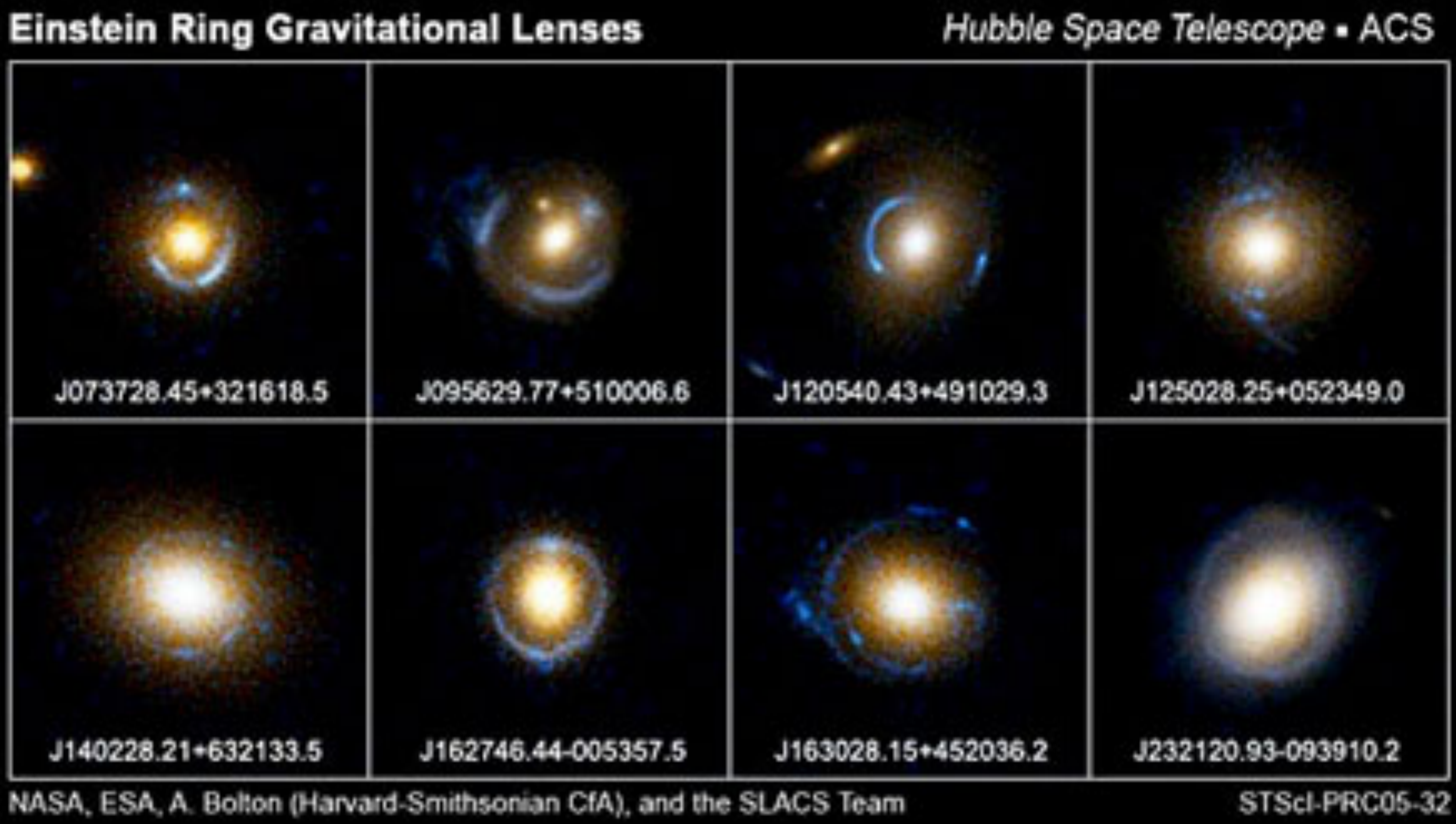
How to rule out CDM or WDM
(or both)

Gravitational lensing: Einstein rings

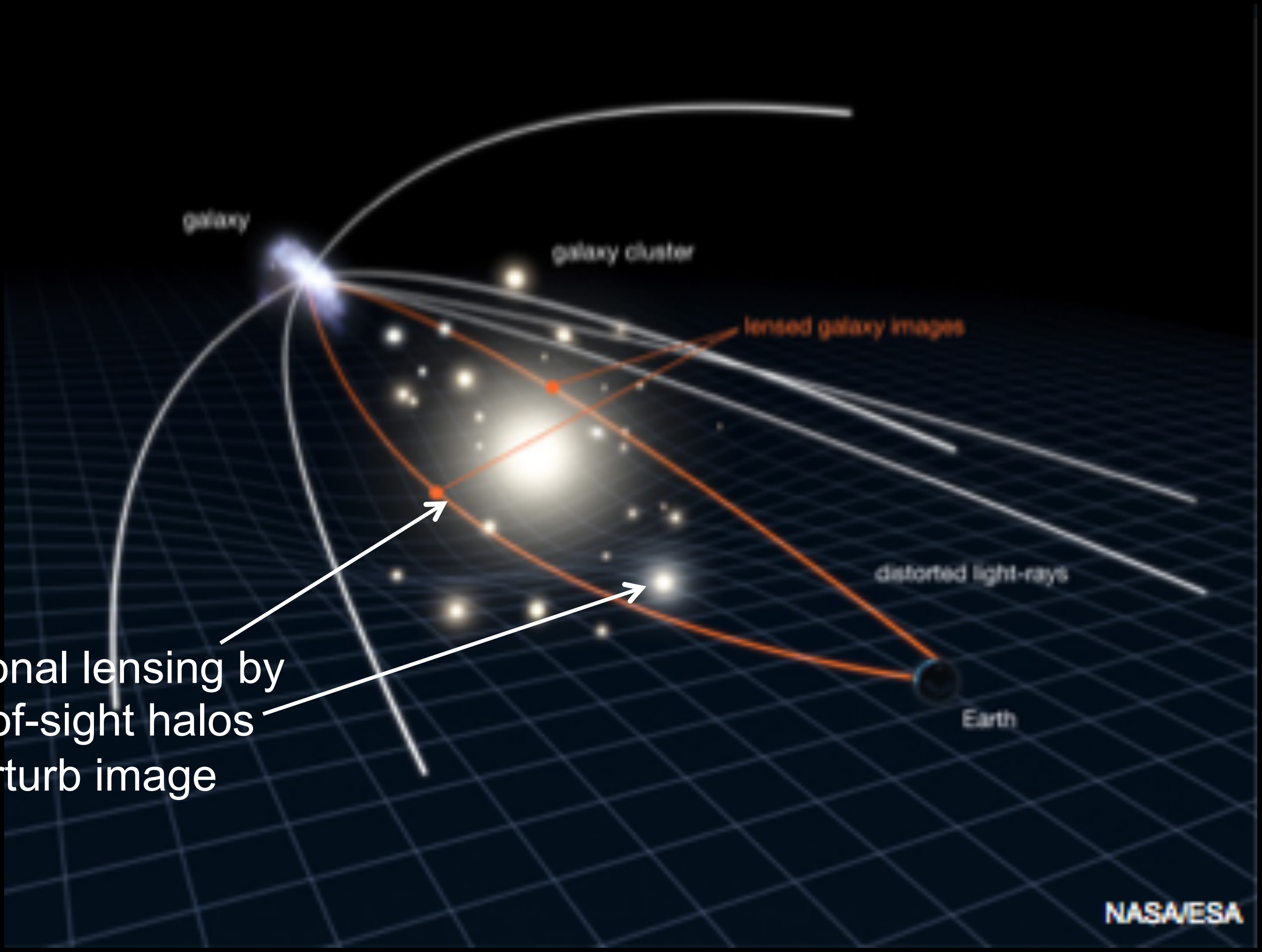


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings



Additional lensing by line-of-sight halos perturb image

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

Detecting substructures with strong lensing

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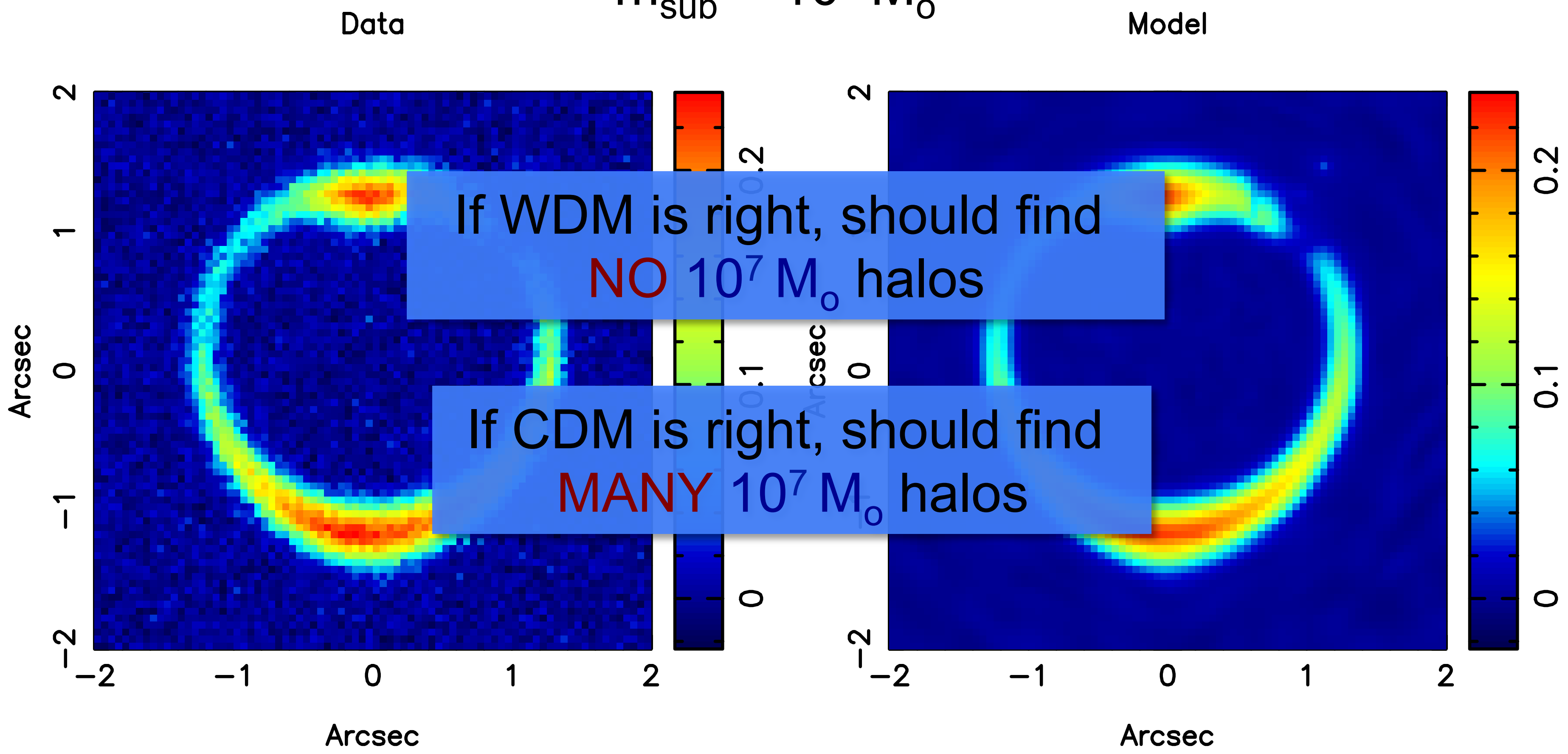
Vegetti & Koopmans '09

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



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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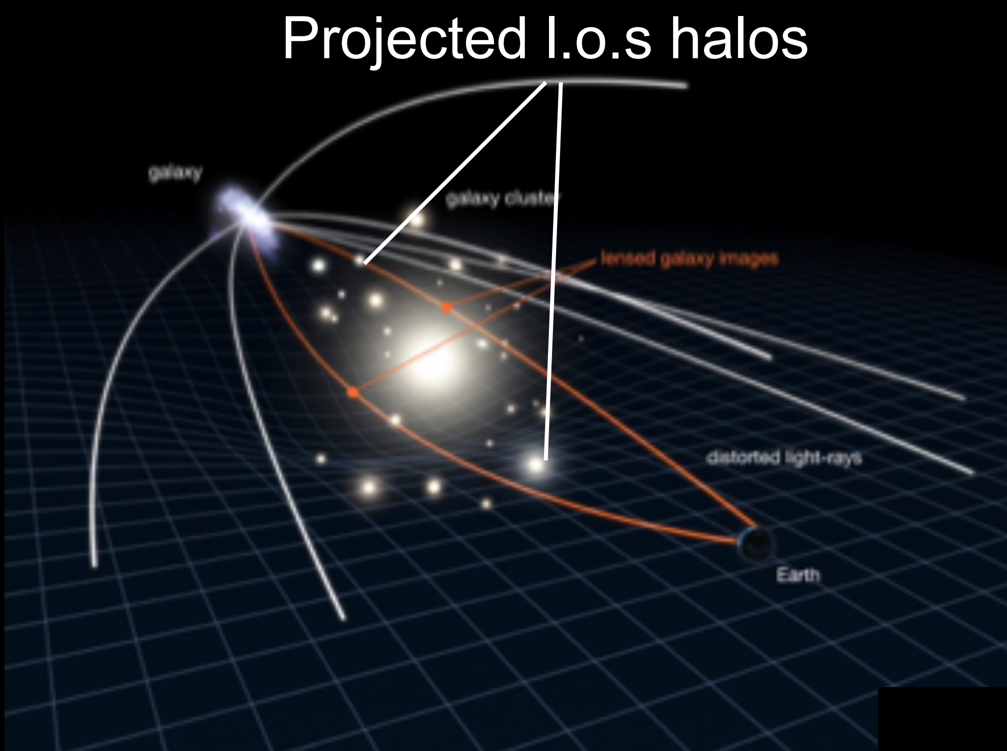
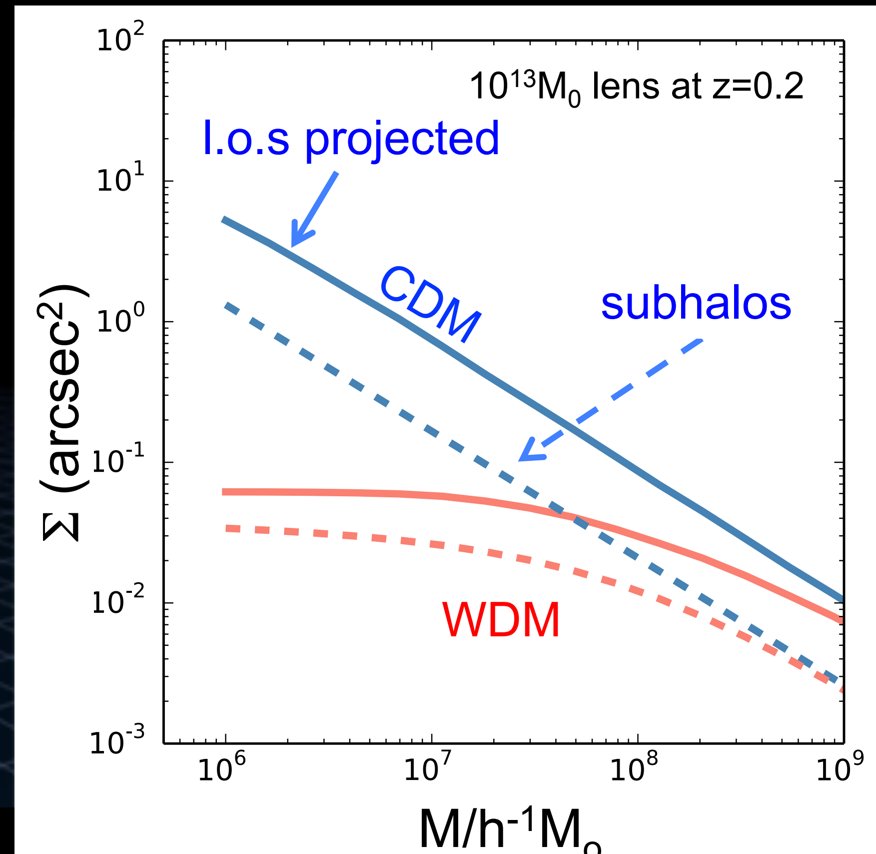
Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?



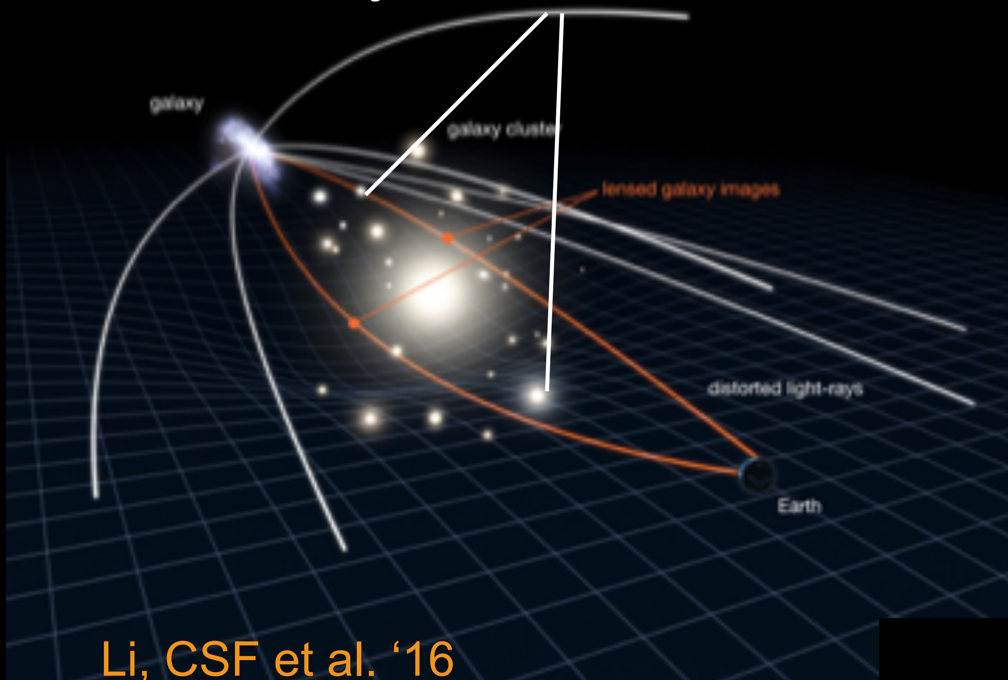


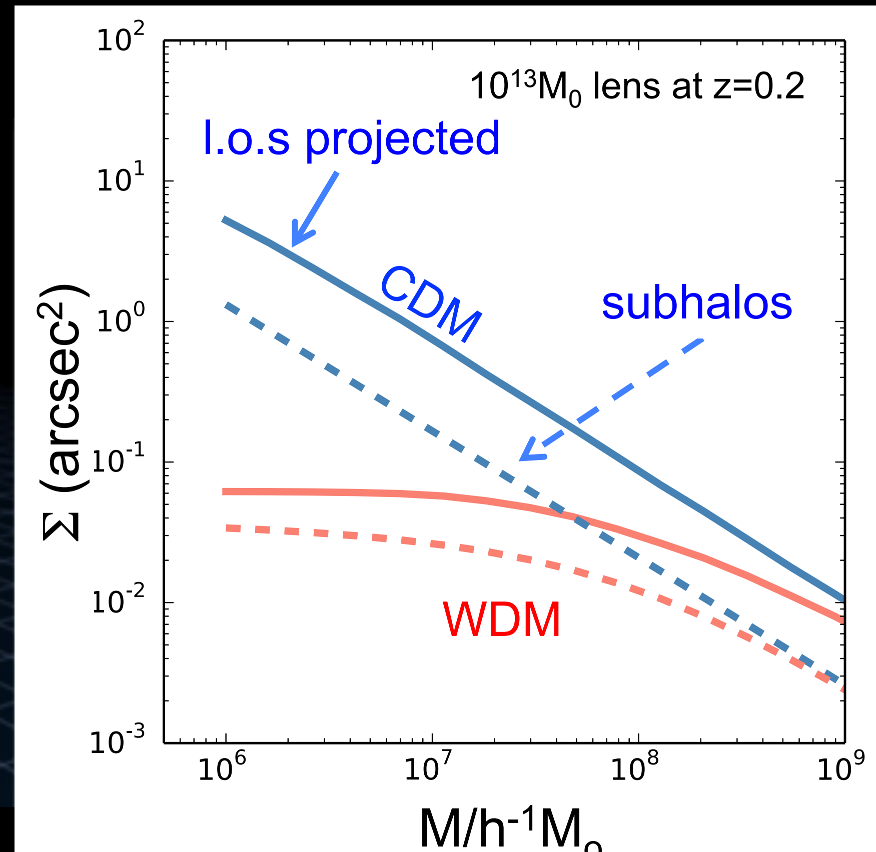
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. ‘16

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?



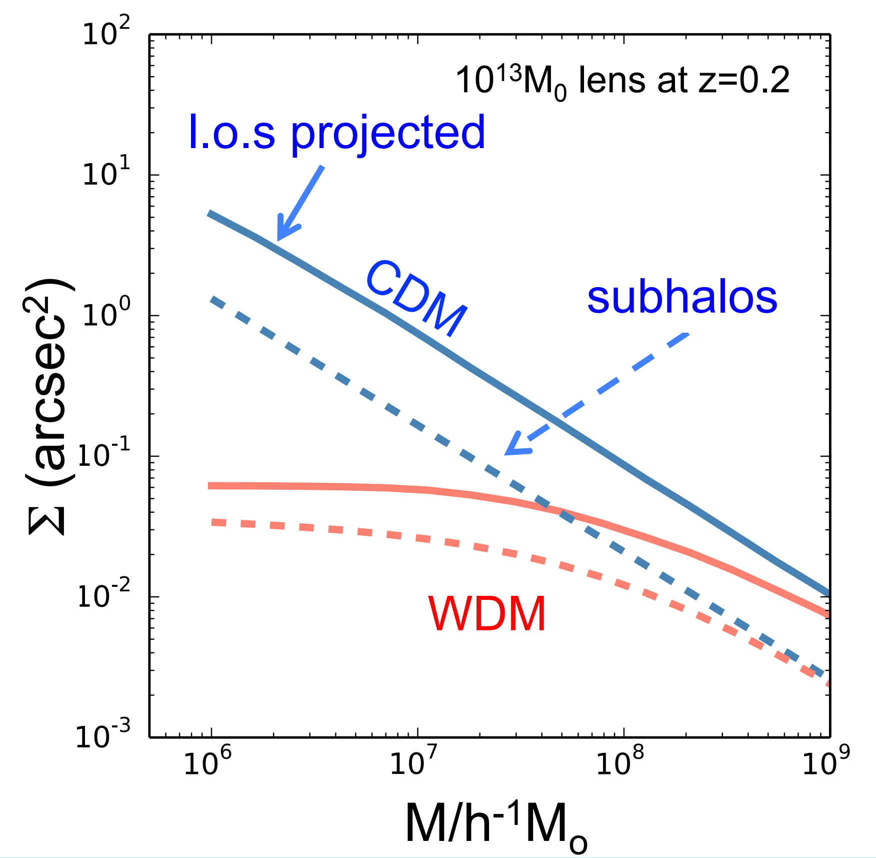


→ This is the cleanest possible test: it depends ONLY on the small-mass end of the "field" halo mass function which we know how to calculate and is unaffected by baryons

Gravitational lensing: Einstein rings

For SLAC (lenses ~z=02):

- Subhalos ~20% of signal in CDM
- Subhalos ~50% of signal in WDM



Interaction with central galaxy can destroy subhalos

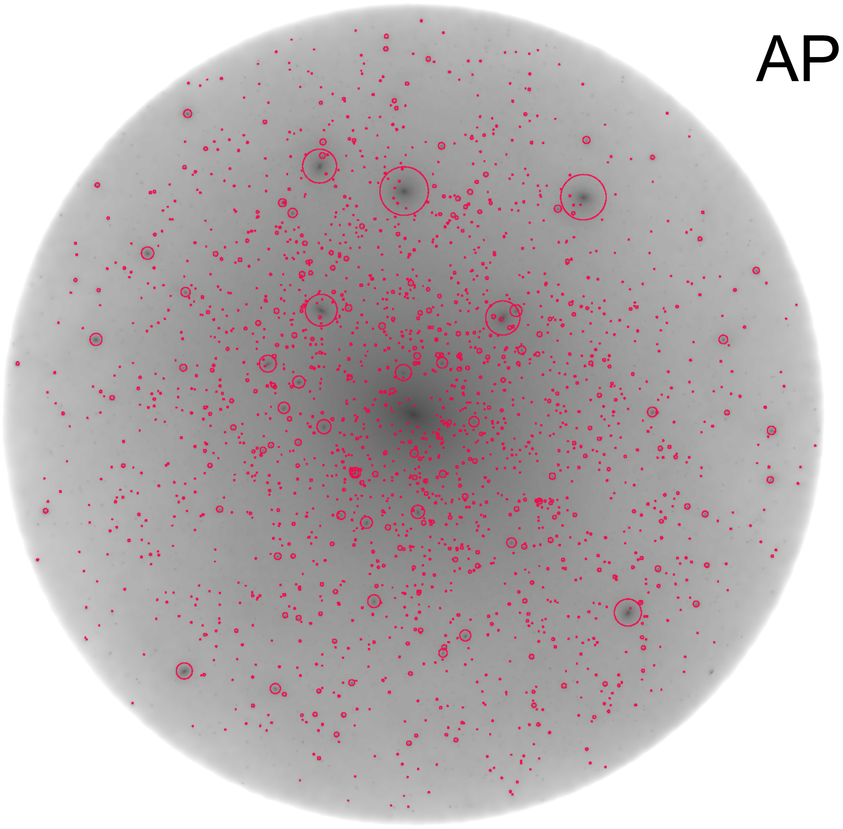
Sawala et al '17

Richings et al '17

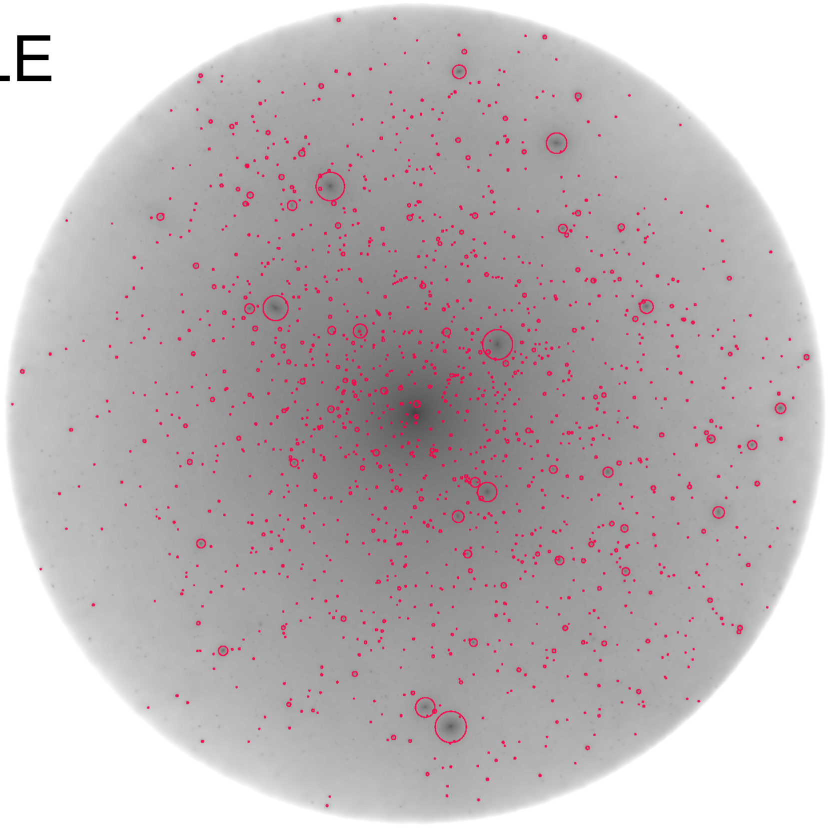
University of Durham

Destruction of dark substructures by galactic baryons

APOSTLE



Dark matter only simulation

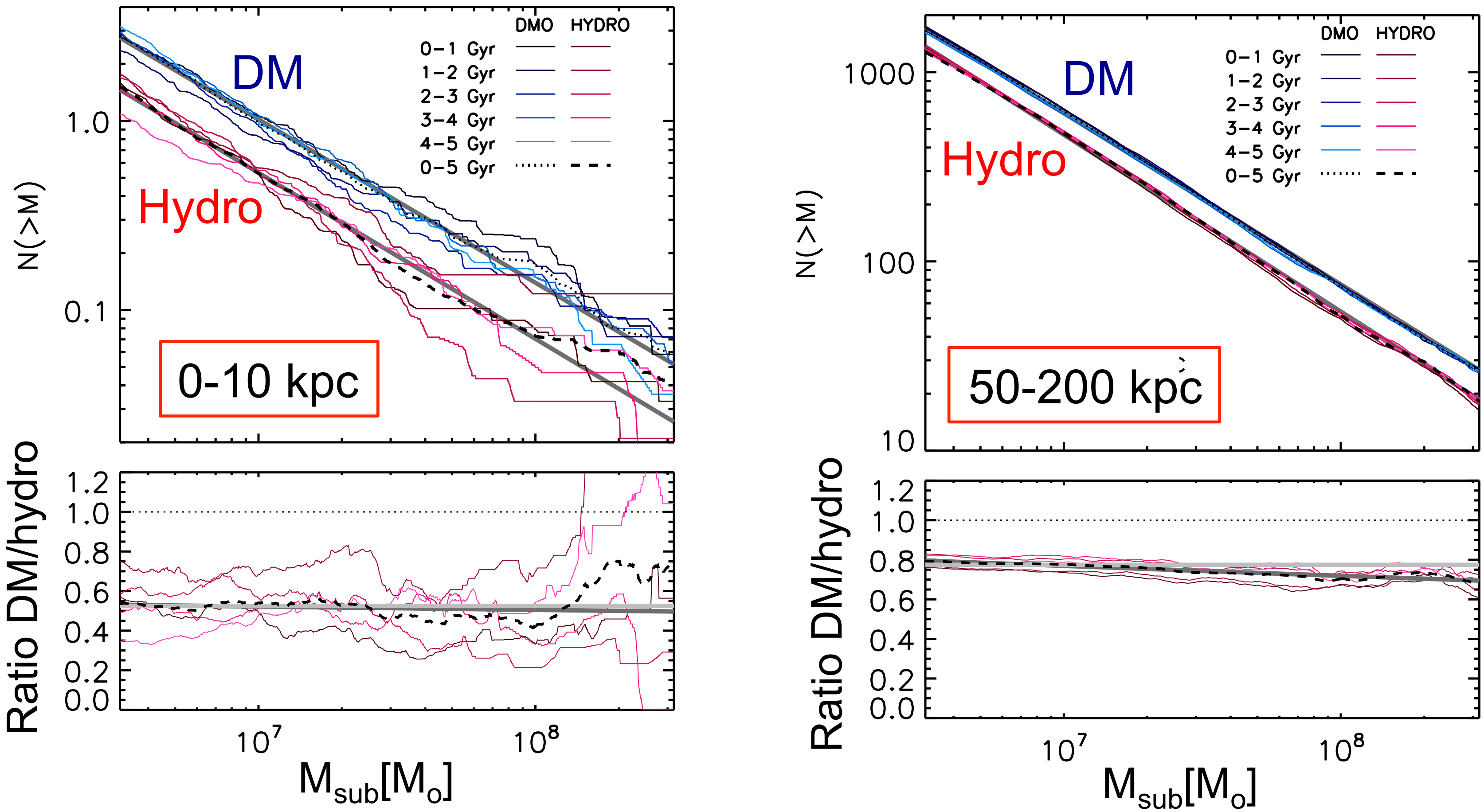


Hydrodynamic simulation

Sawala et al '17

Institute for Computational Cosmology

Destruction of dark substructures by galactic baryons



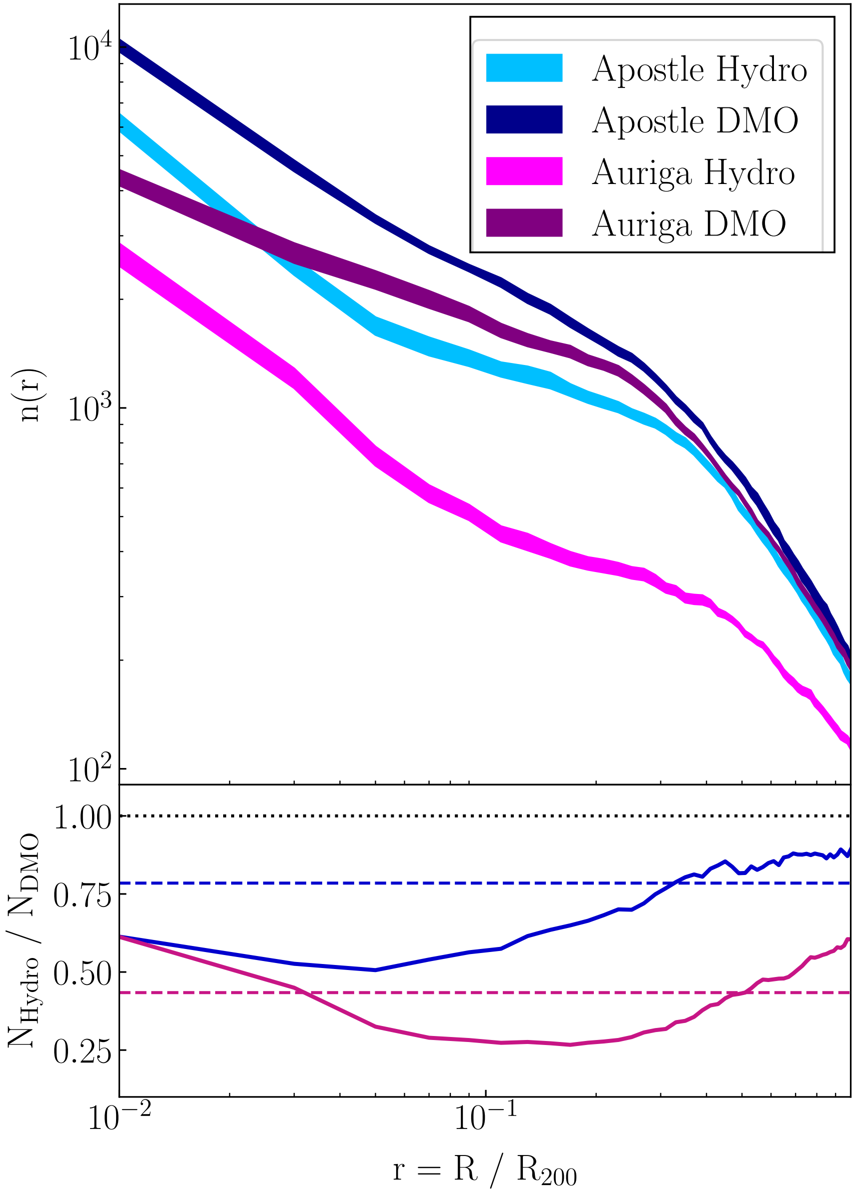
- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
- 20% " 50-200 kpc "

Sawala et al '16

APOSTLE/AURIGA

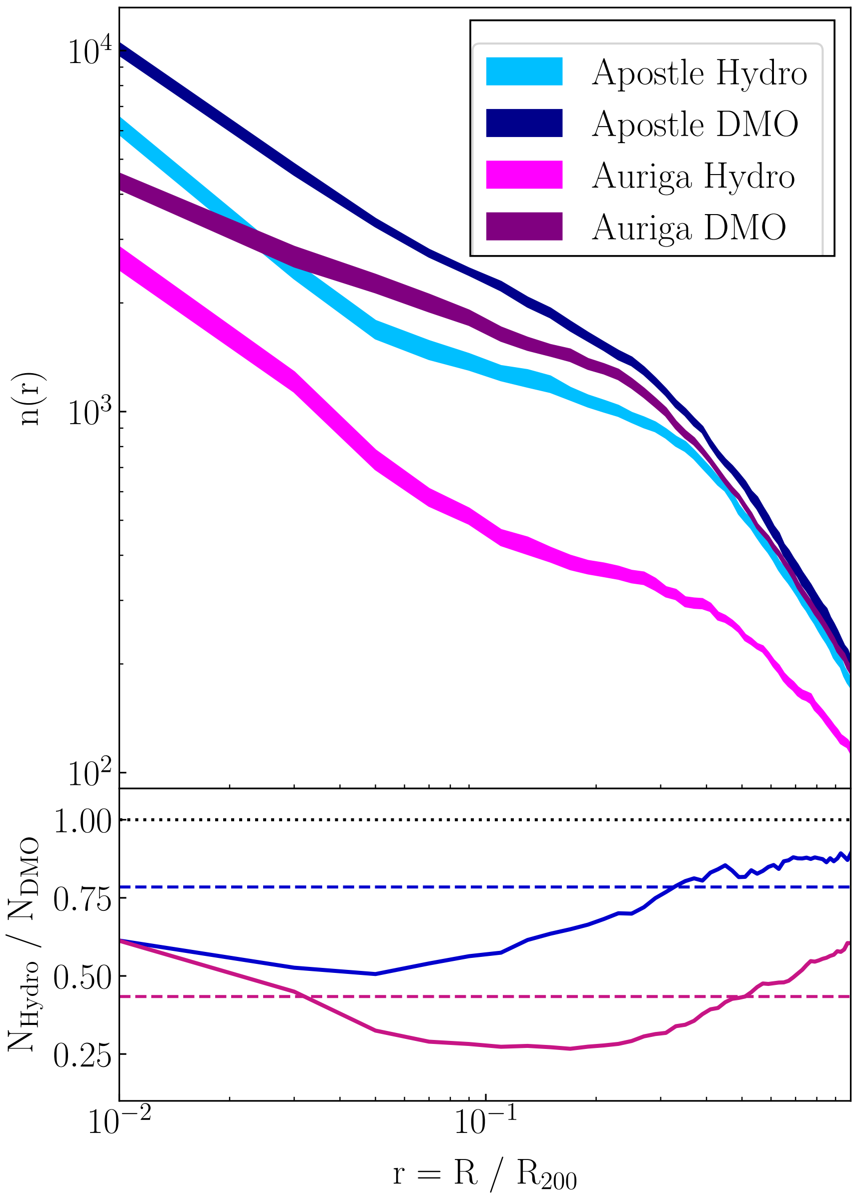
J. Richings+ '18

$10^{6.5}$ - $10^{8.5}$ $M_\odot$

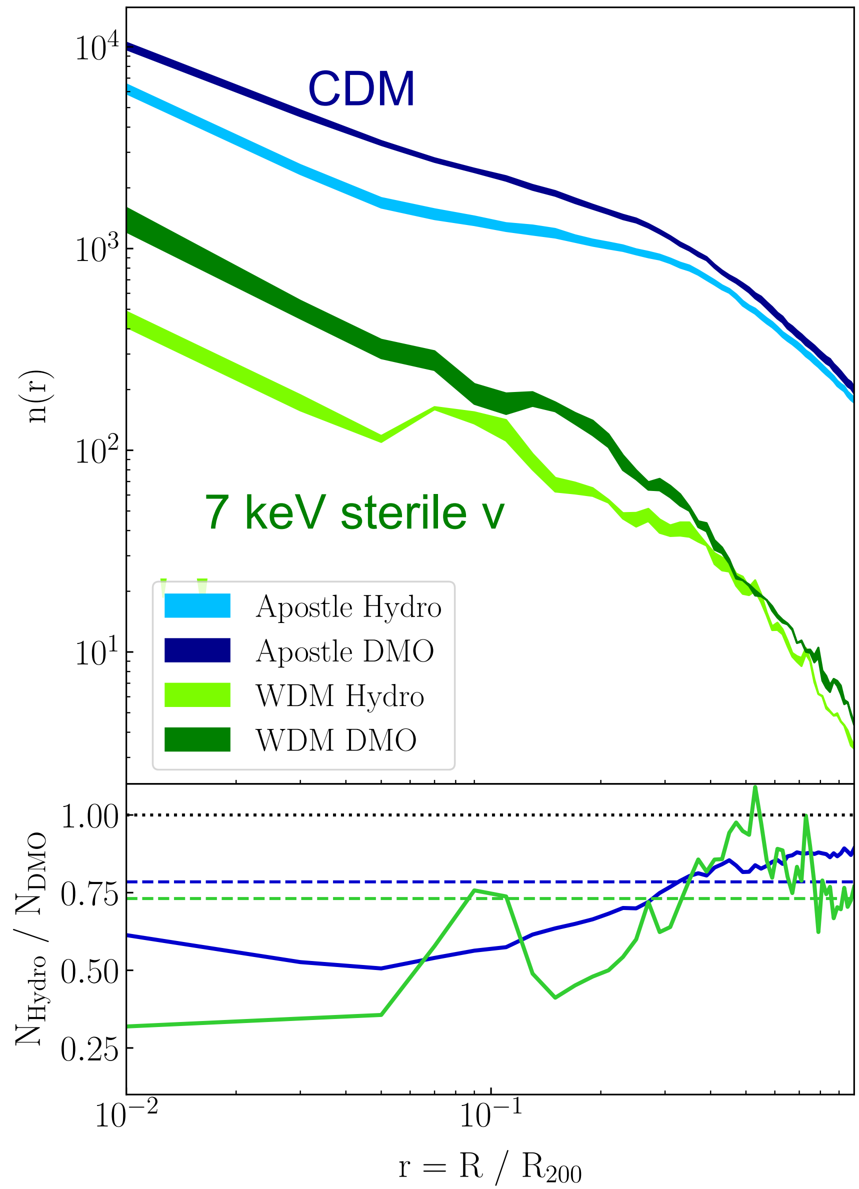


APOSTLE/AURIGA J. Richings+ ‘18 CDM/WDM

$10^{6.5}$ - $10^{8.5}$ $M_\odot$



$10^{6.5}$ - $10^{8.5}$ $M_\odot$



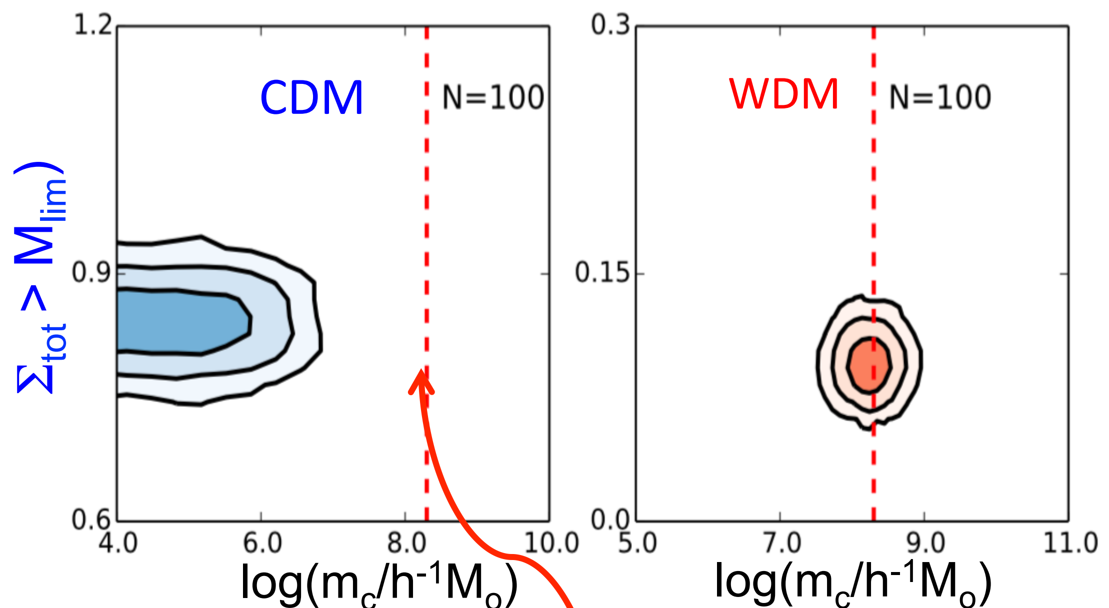
Detecting substructures with strong lensing

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

m_c= halo cutoff mass

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

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



m_c= halo cutoff mass

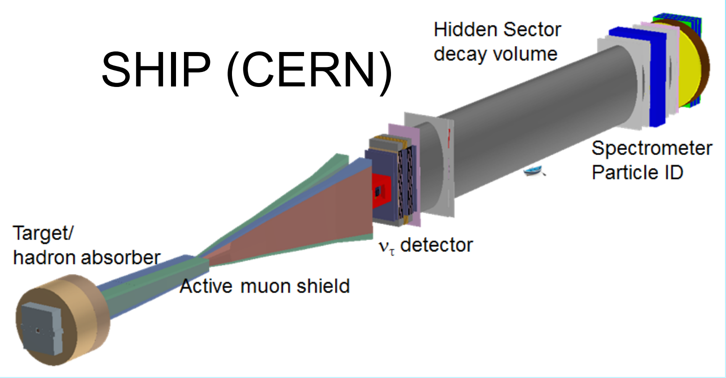
$m_c = 1.3 \times 10^8\ h^{-1}M_o$ for coldest 7 keV sterile neutrino

- If DM is 7 keV sterile ν → exclude CDM at >>σ!
- If DM is CDM → exclude 7 keV sterile ν at >>σ

Li, CSF et al '16

The way forward

	Timeline
1. Confirm the 3.5 keV line	
→ Micro-X or XARM may do it	→ 2021
2. Detect mass function cutoff	
→ Einstein ring distortions may do it	→ 2020
→ Gaps in streams	→ 2020
→ Lyman-α forest may also do it	?
3. Produce/detect particles in lab	→ 2025



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. Halos < ~$5.10^8 M_0$ are dark; halos >$10^{10} M_0$ are bright

   (abundance matching fails for halos <$10^{10} M_0$)
3. No evidence for cores but baryon effects can make them
4. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!