How to rule out cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

... or other viable dark matter models

Non-baryonic dark matter candidates

From the 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

The dark matter power spectrum

Free streaming →

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

for thermal relic

m_{CDM} ~ 100GeV

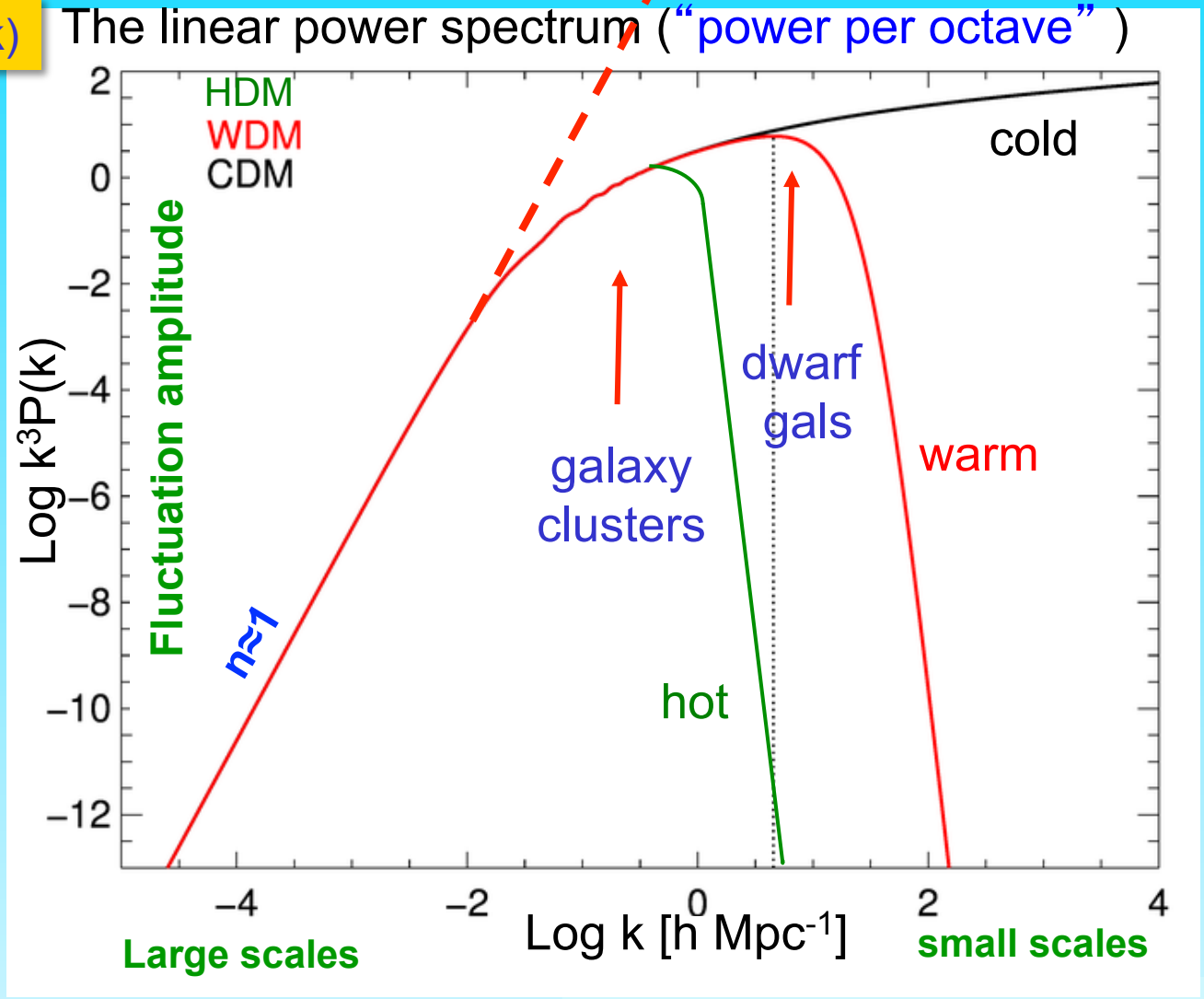
susy; $M_{cut} \sim 10^{-6} M_o$

m_{WDM} ~ few keV

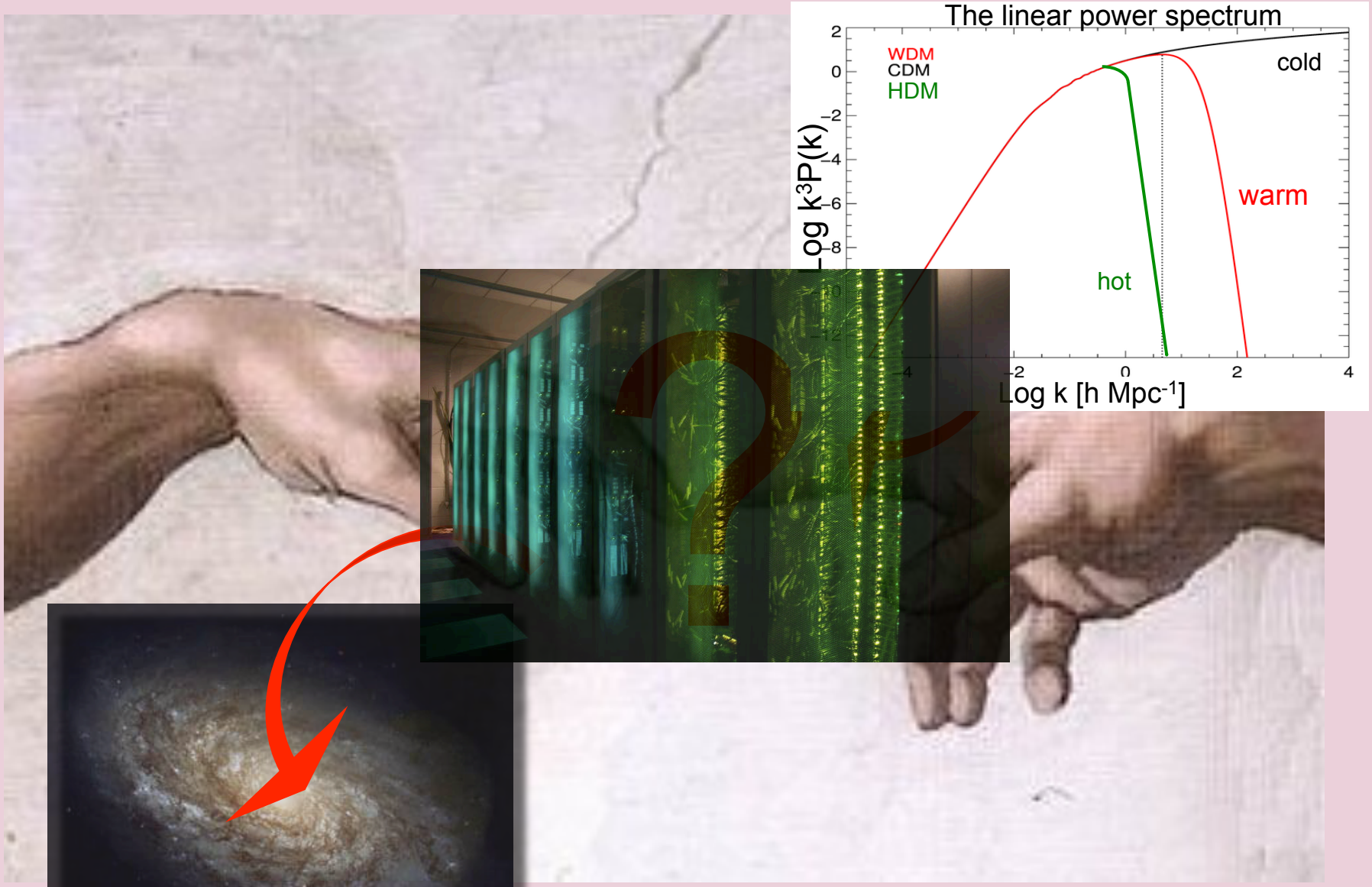
sterile ν; $M_{cut} \sim 10^{9} M_o$

m_{HDM} ~ few tens eV

light ν; $M_{cut} \sim 10^{15} M_o$



Non-linear evolution



University of Durham

Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann

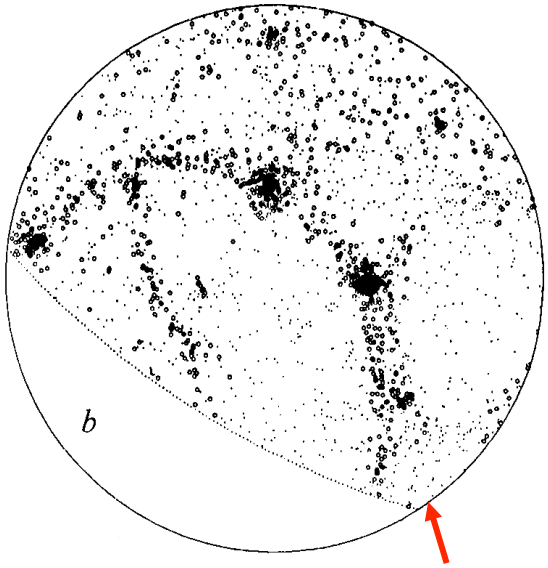
Poisson, Friedmann eqn

Radiative hydrodynamics

Subgrid astrophysics

How to make a virtual universe

Non-baryonic dark matter cosmologies



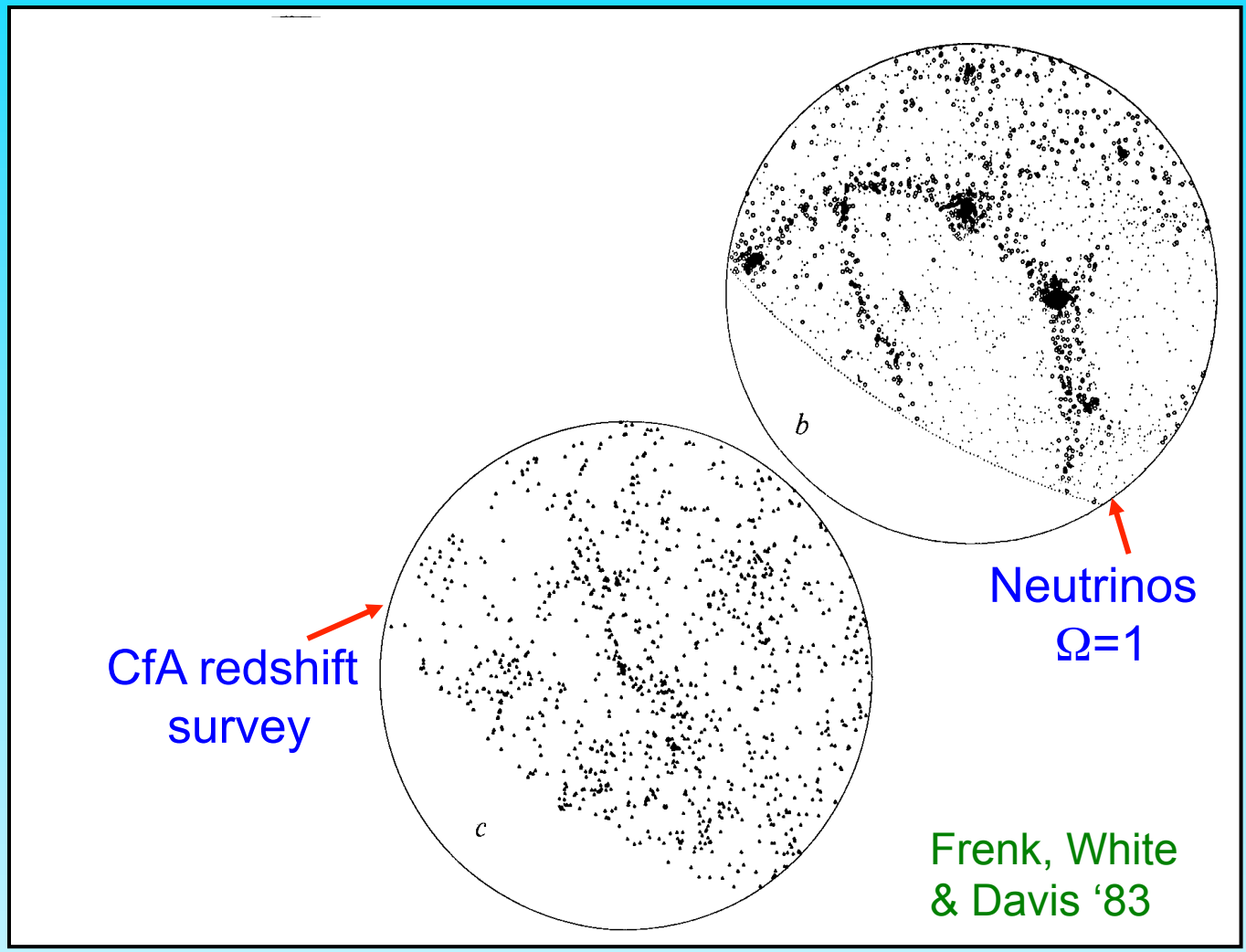
Neutrinos
Ω=1

Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → $m_\nu << 30$ ev



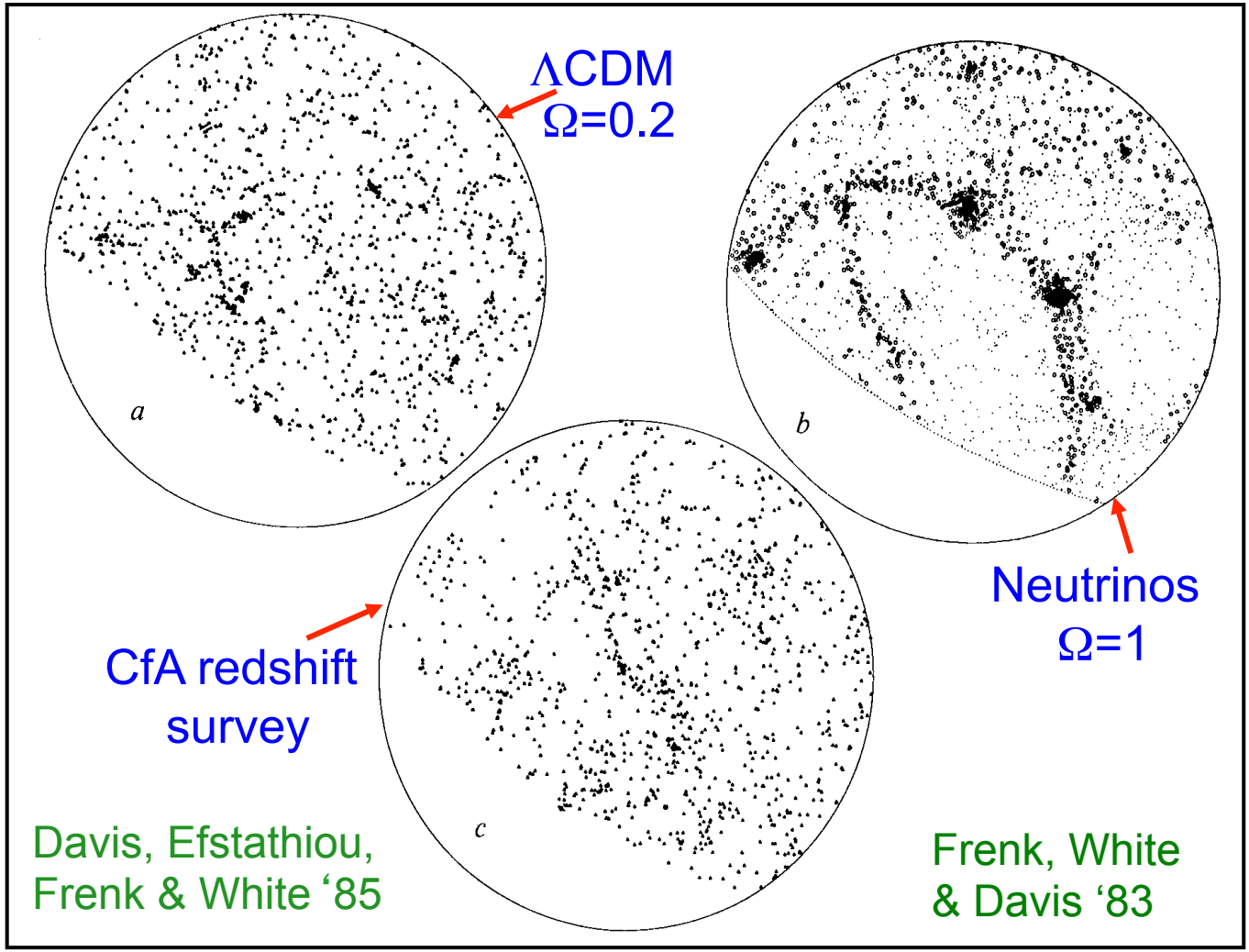
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → $m_\nu << 30$ ev

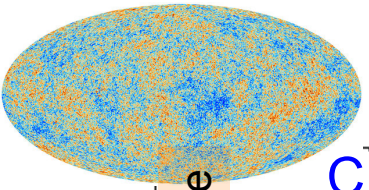
Early CDM N-body simulations gave promising results

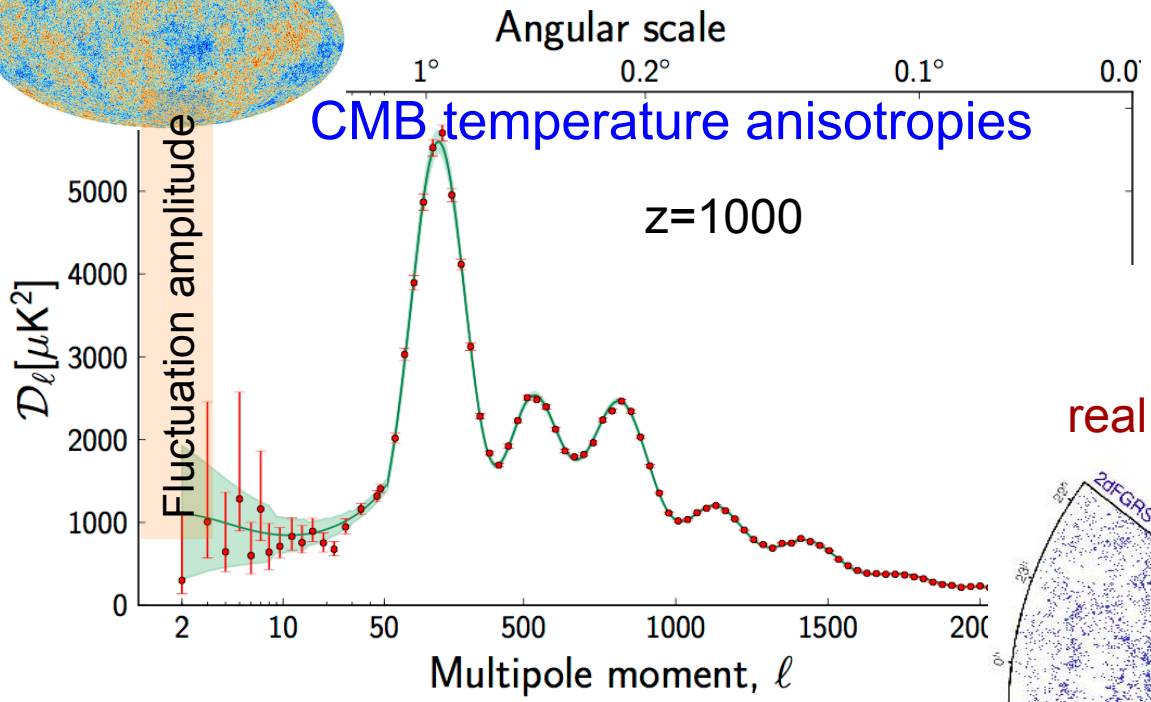
In CDM structure forms hierarchically



The ΛCDM model of cosmogony

Proposed in 1980s Now empirically supported by:



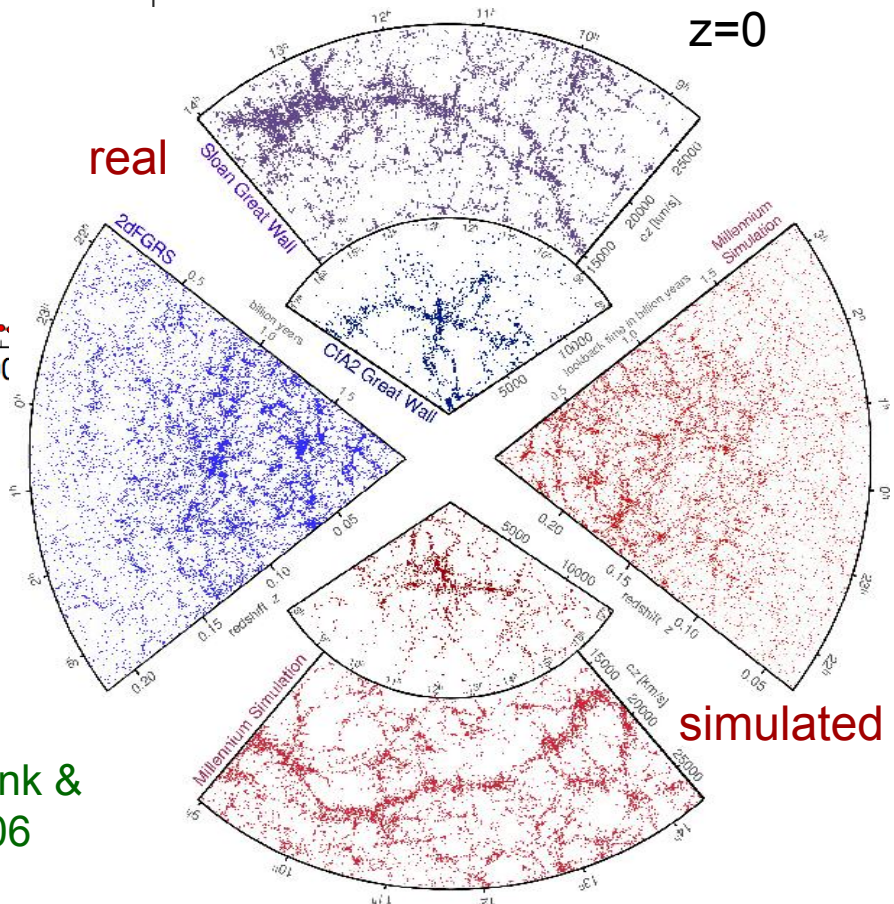


Planck coll. 2015

Galaxy clustering

z=0

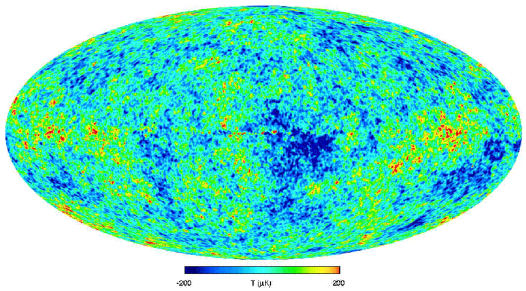
real



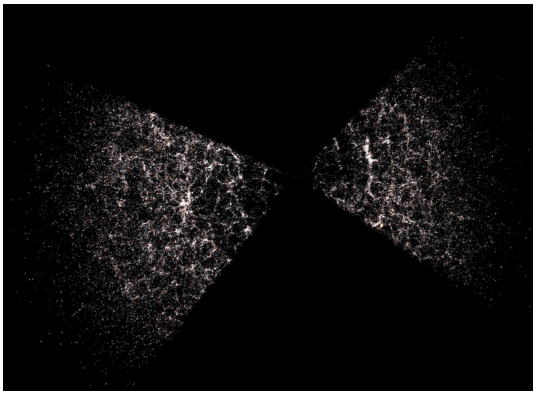
simulated

Springel, Frenk & White 2006

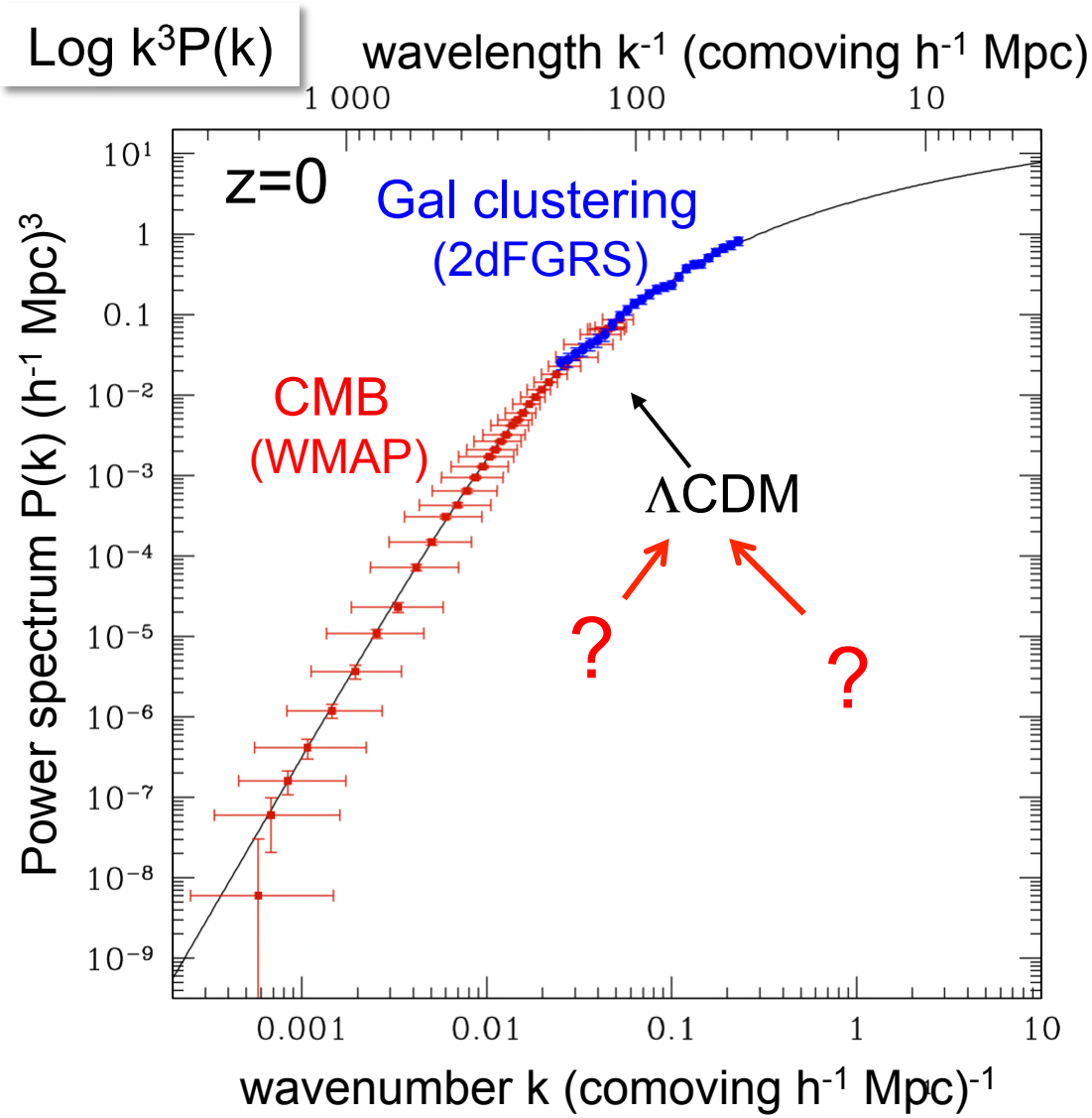
The cosmic power spectrum: from the CMB to the 2dFGRS



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 →

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

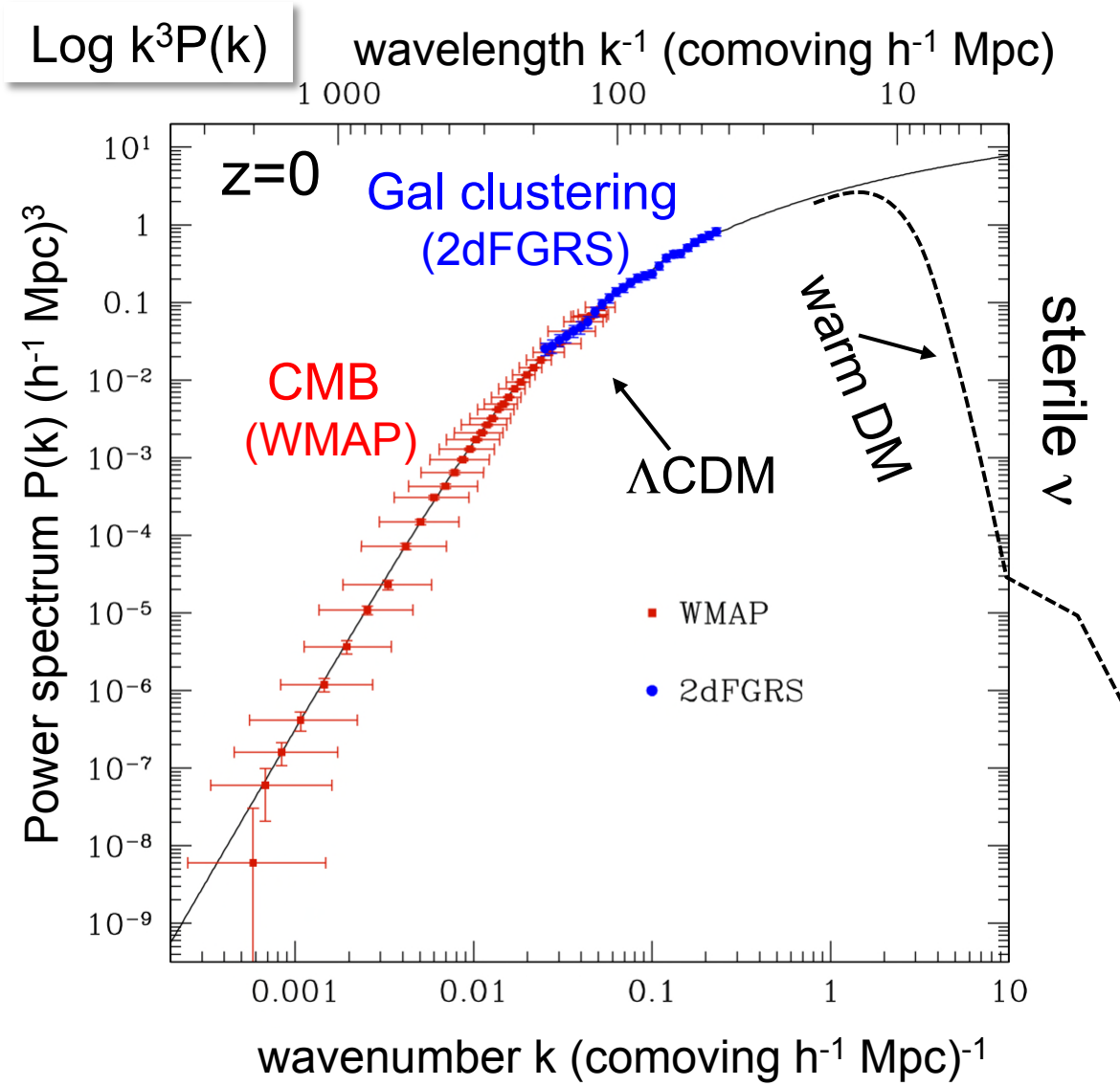
for thermal relic

$m_{CDM} \sim 100$GeV

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

- CDM: γ-ray excess from Galactic Center
- WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Very unlikely that both are right!

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

Free streaming →

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

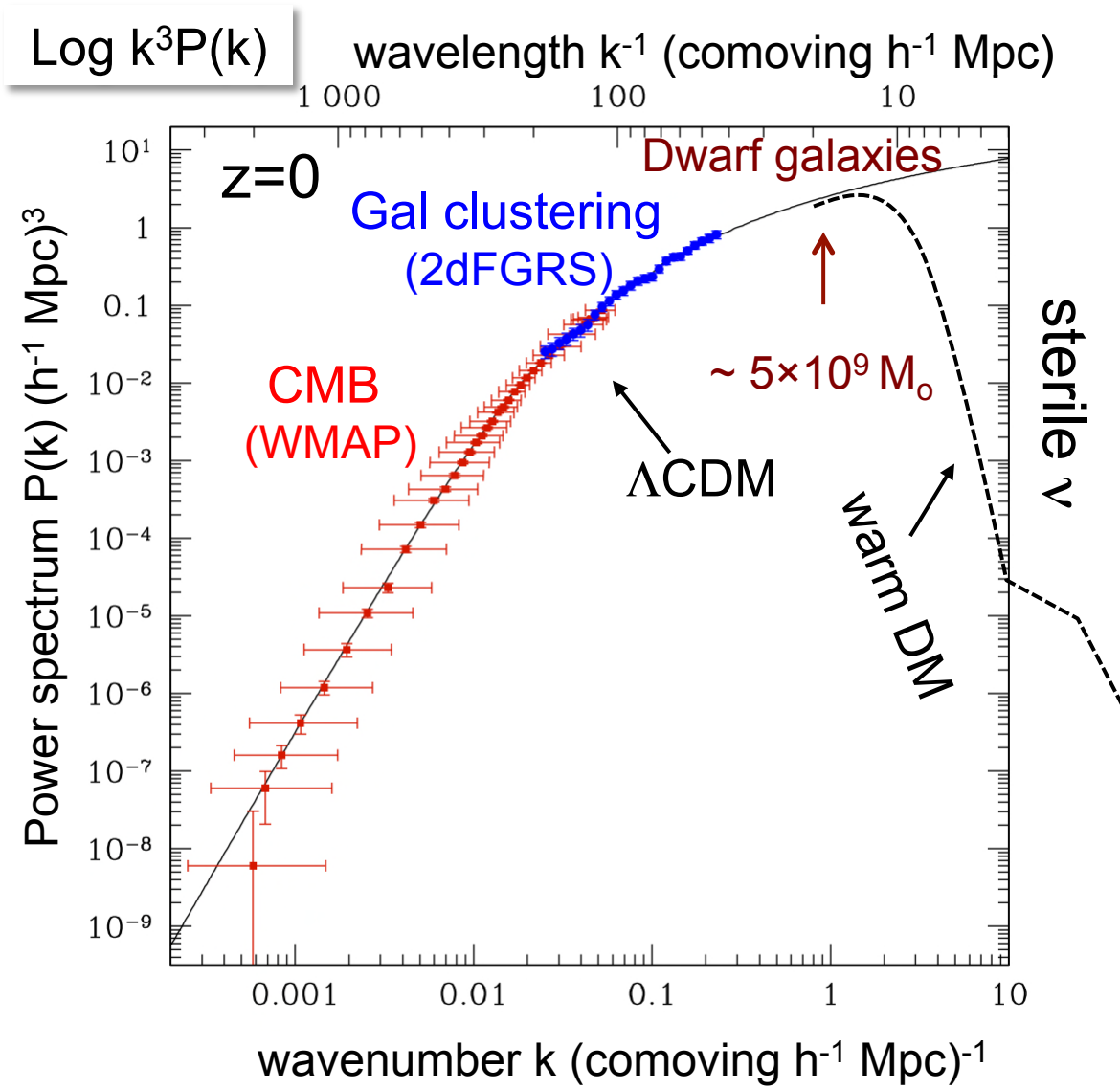
for thermal relic

$m_{CDM} \sim 100$GeV

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



Sterile neutrinos

Explain:

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

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

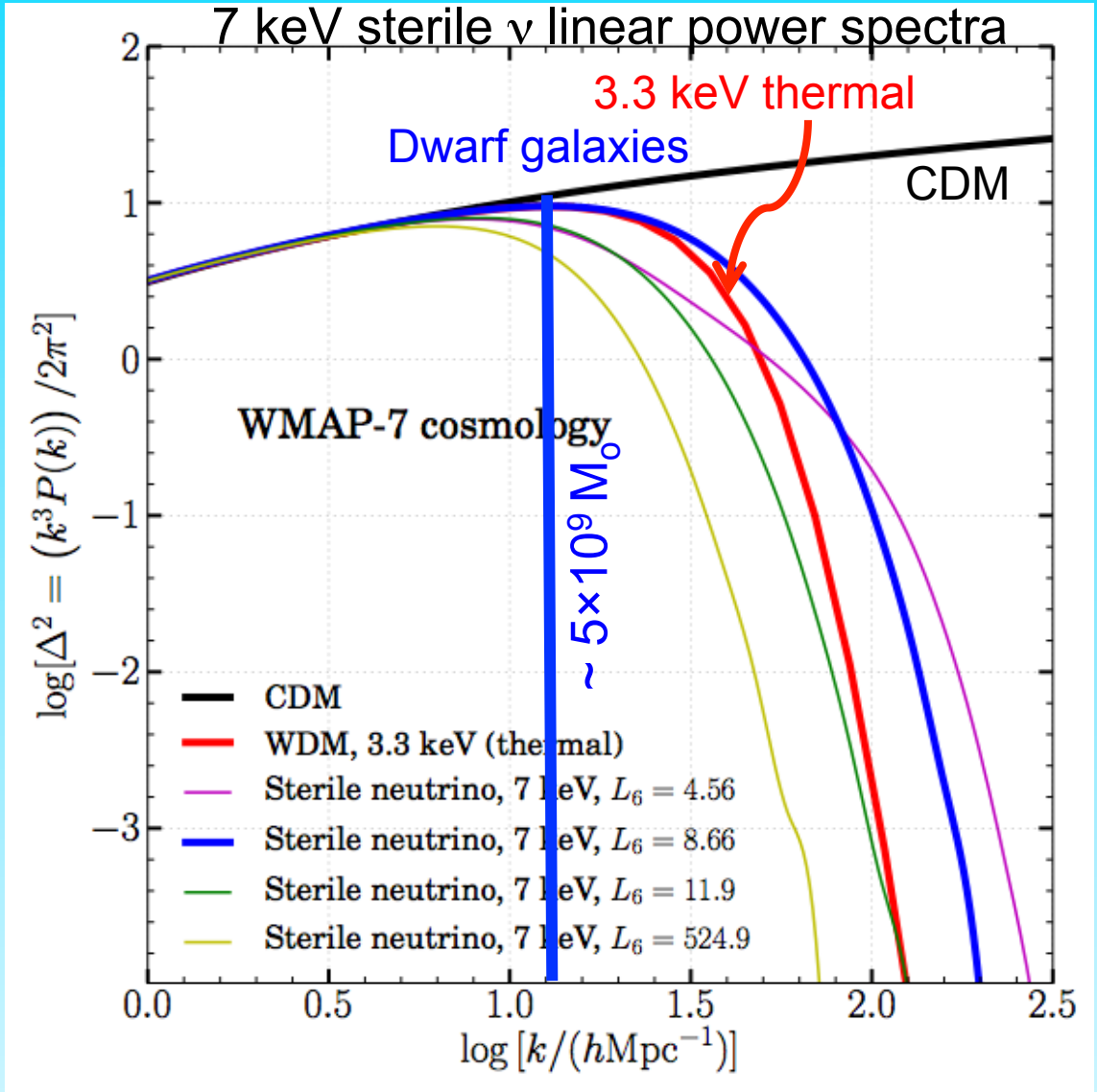
- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N=\Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-ray decay

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)

Lovell, Bose, CSF et al. 16



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

cold dark matter

warm dark matter

Obvious t

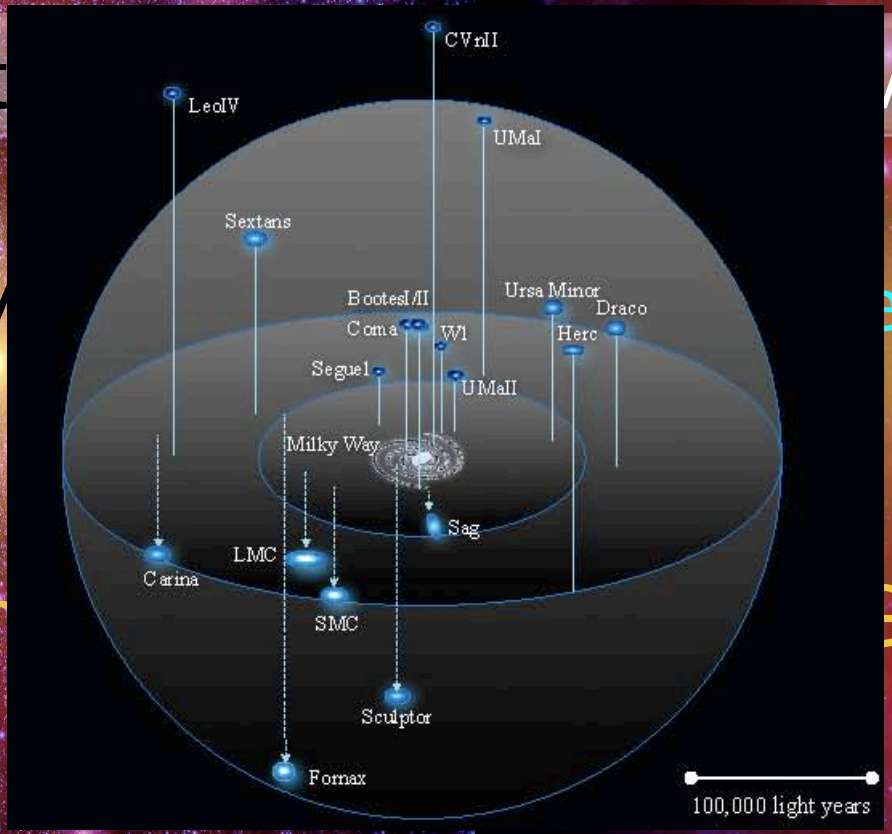
MW or M31

In the M

ered so far

Th

G!



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

Most subhalos never make a galaxy!

Because:

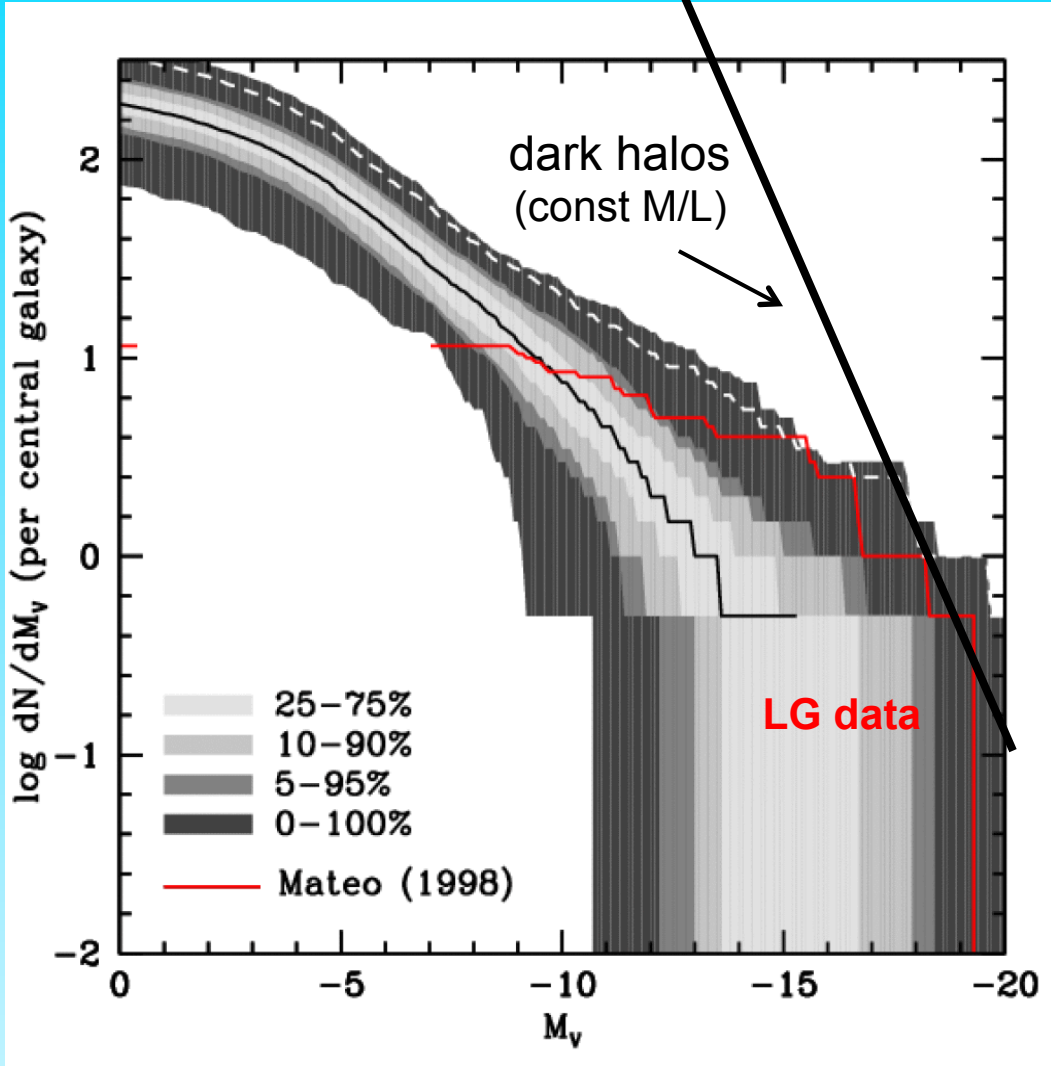
- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

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 (~10% of cases)



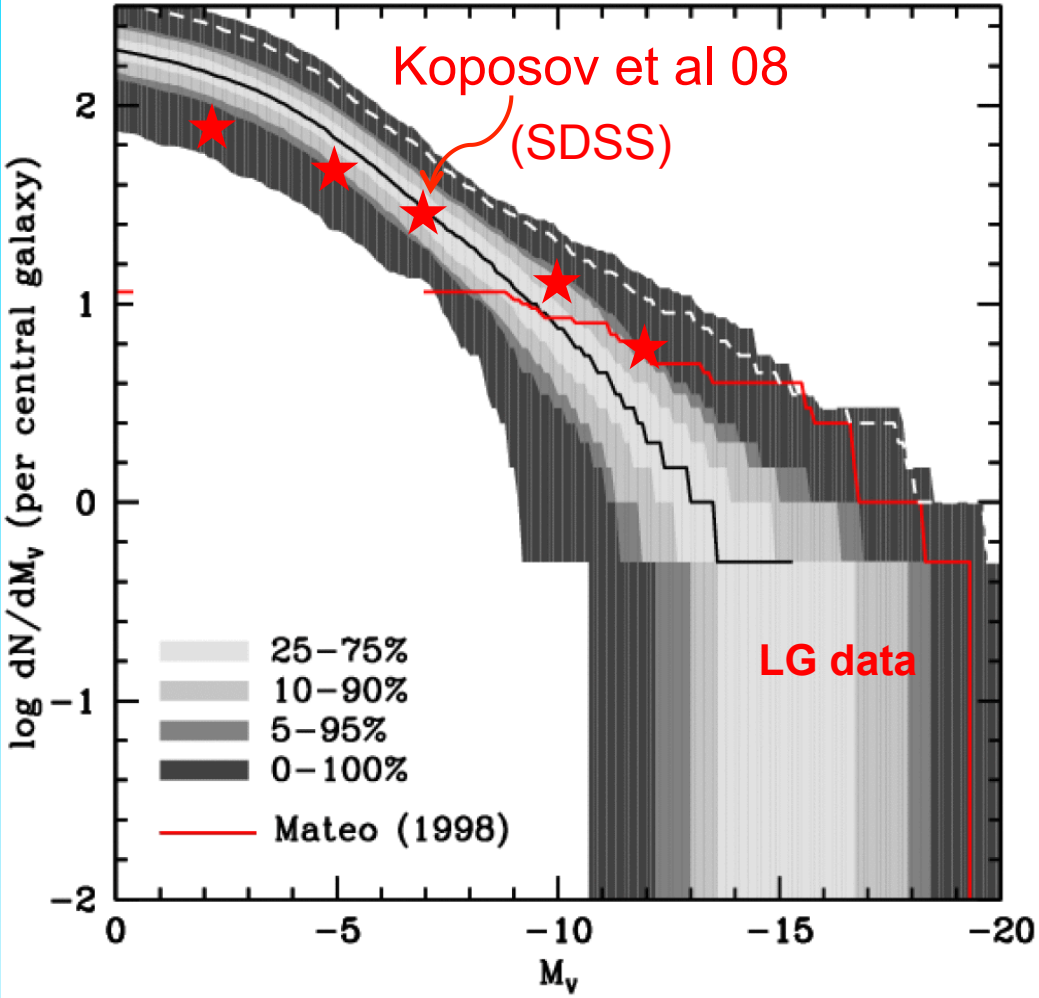
Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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 (~10% of cases)



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

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.

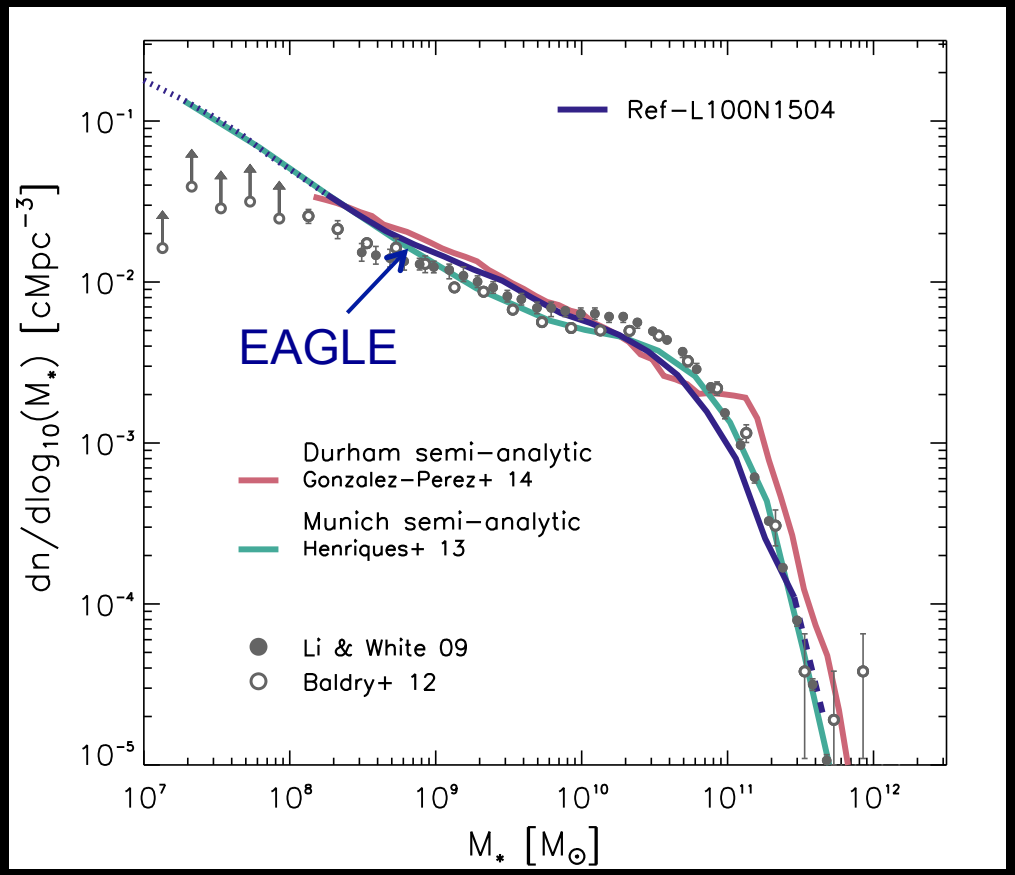
Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

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

Galaxy stellar mass function

Comparison to semi-analytic models



Schaye et al '15

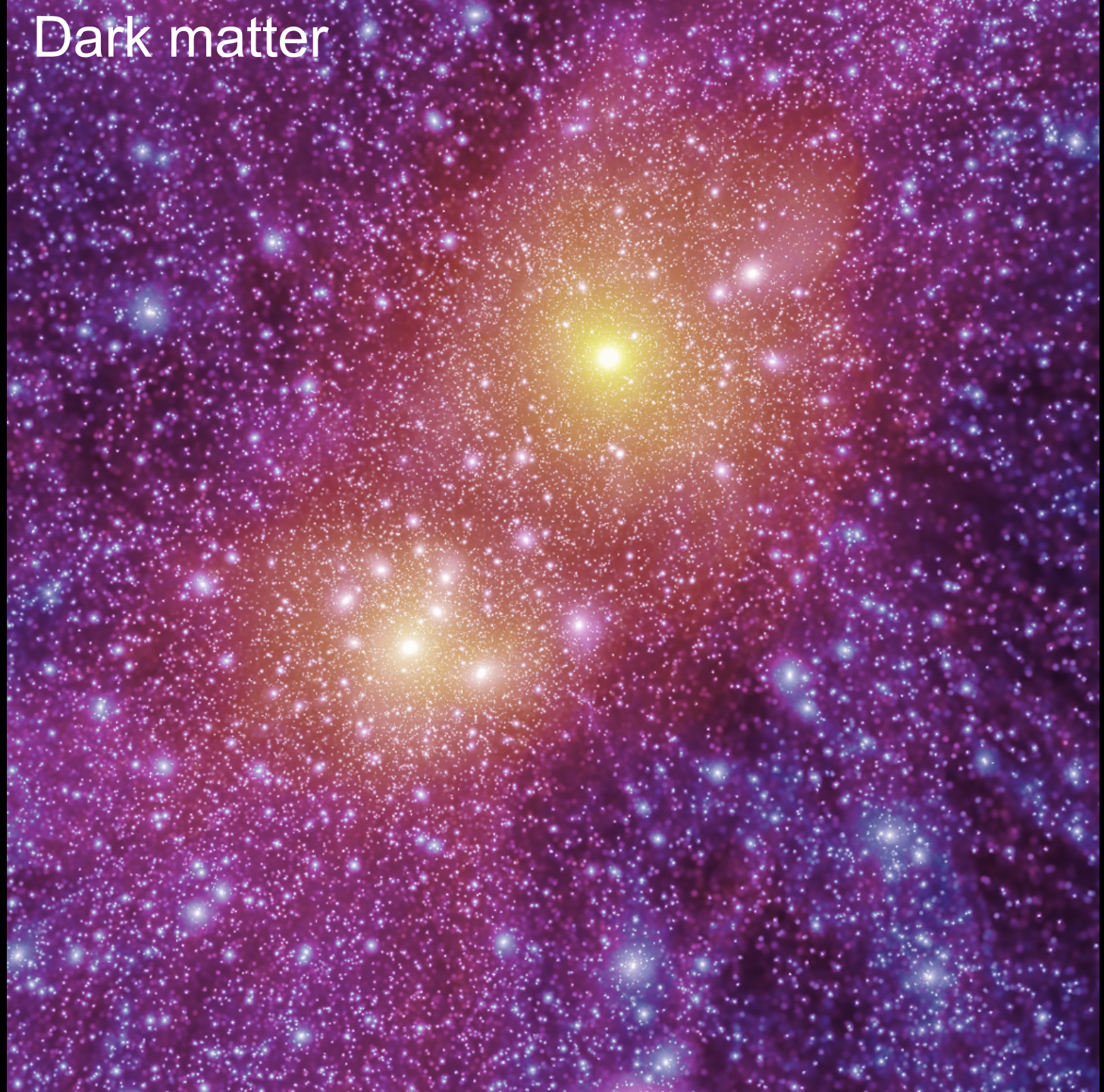
VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al ‘16



Stars

APOSTLE
EAGLE full hydro simulations

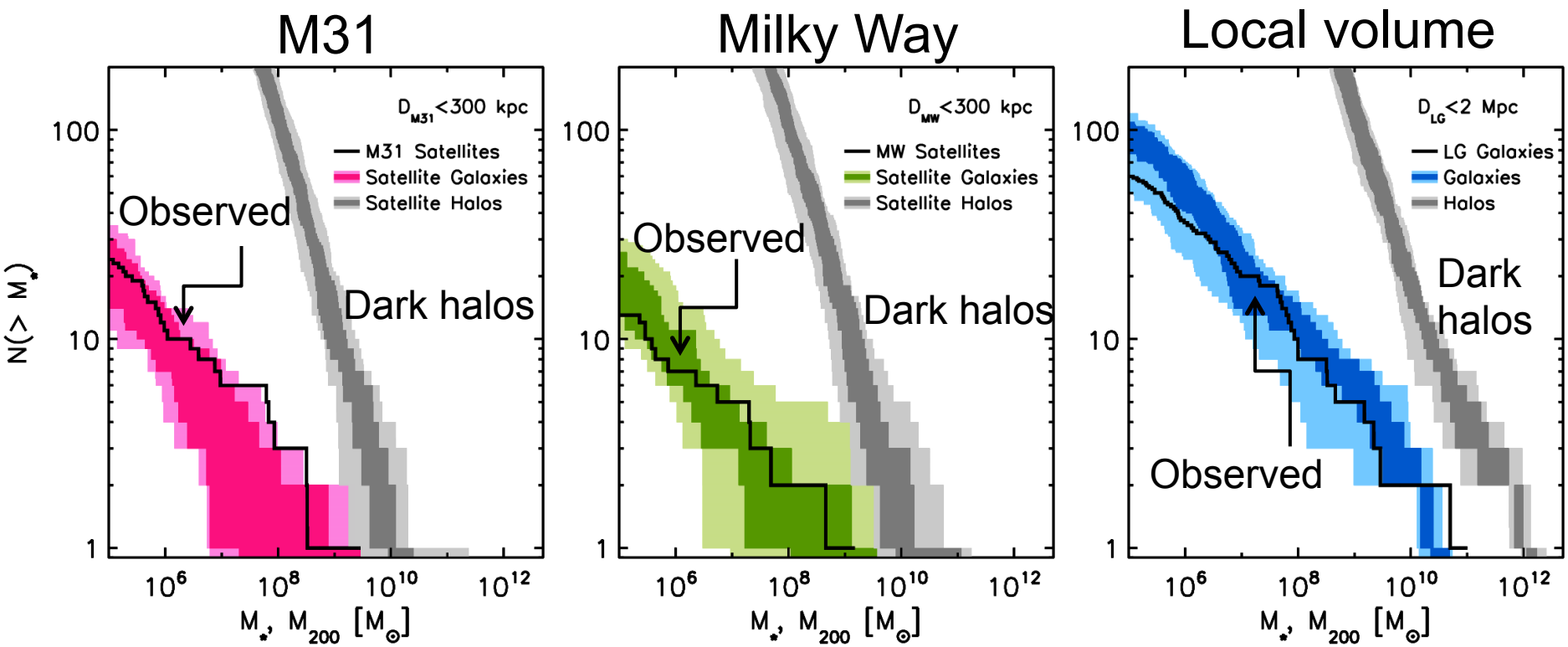
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation



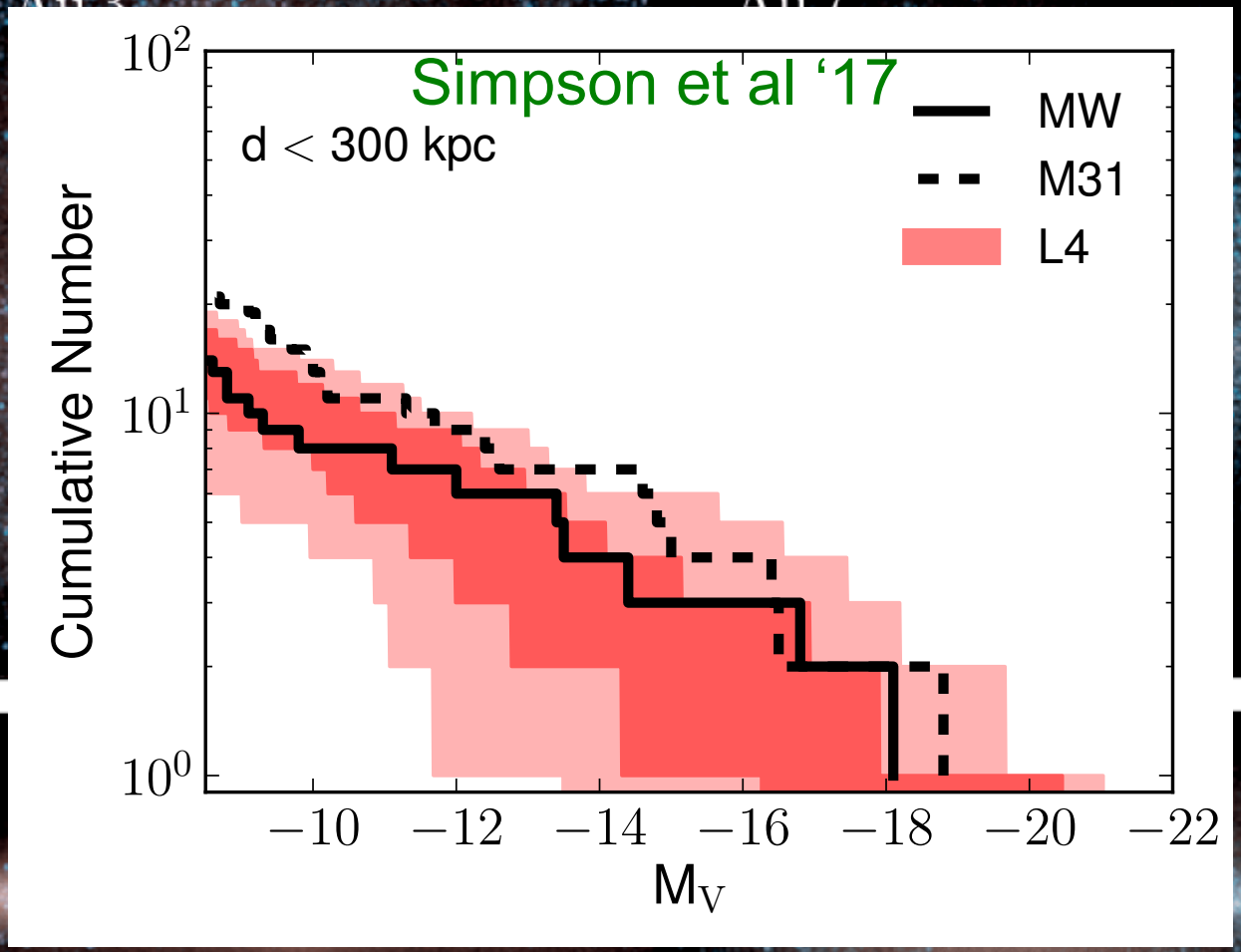
Sawala et al '16

The Auriga MW-like galaxies

Grand et al '16

30 very high res Arepo sims

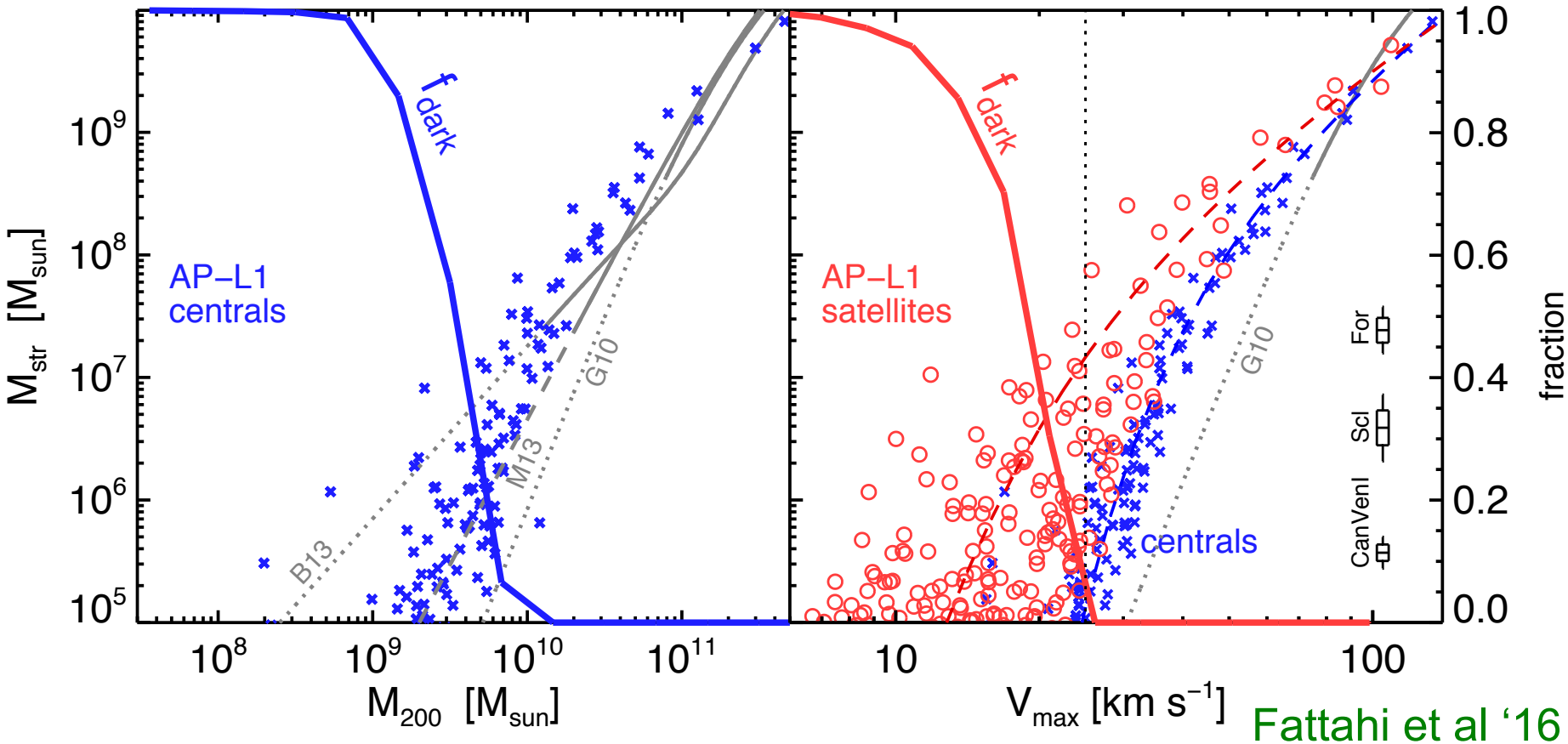
6 even higher res sims



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

Fraction of dark subhalos

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



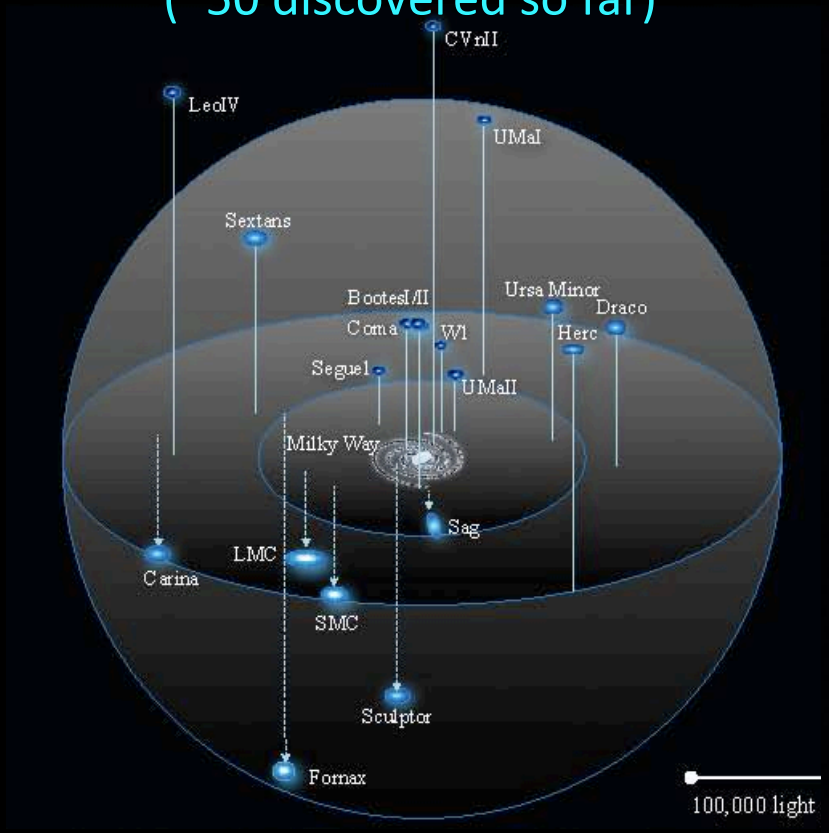
Fattahi et al '16

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

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

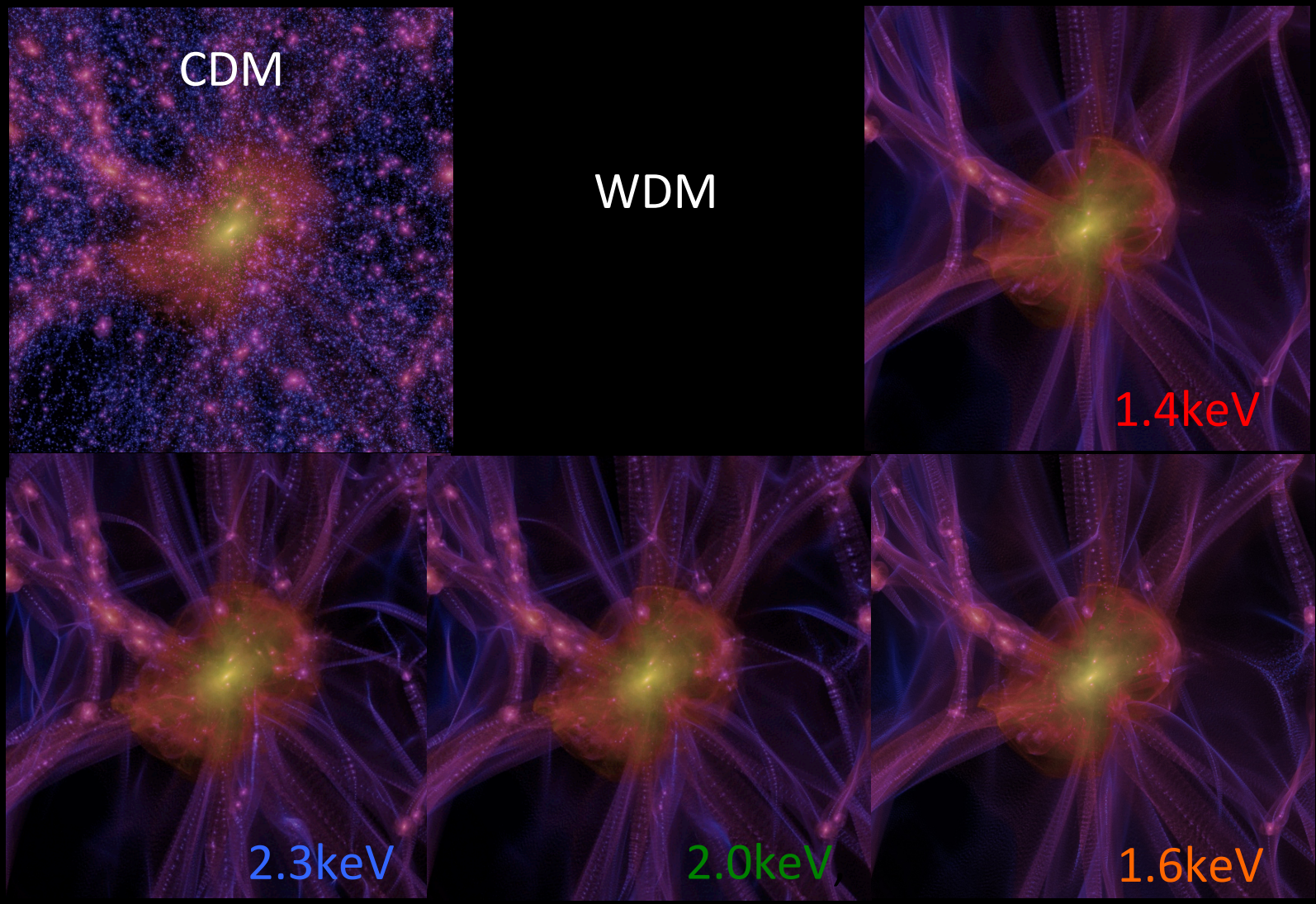
WDM

2.3 keV

2.0 keV

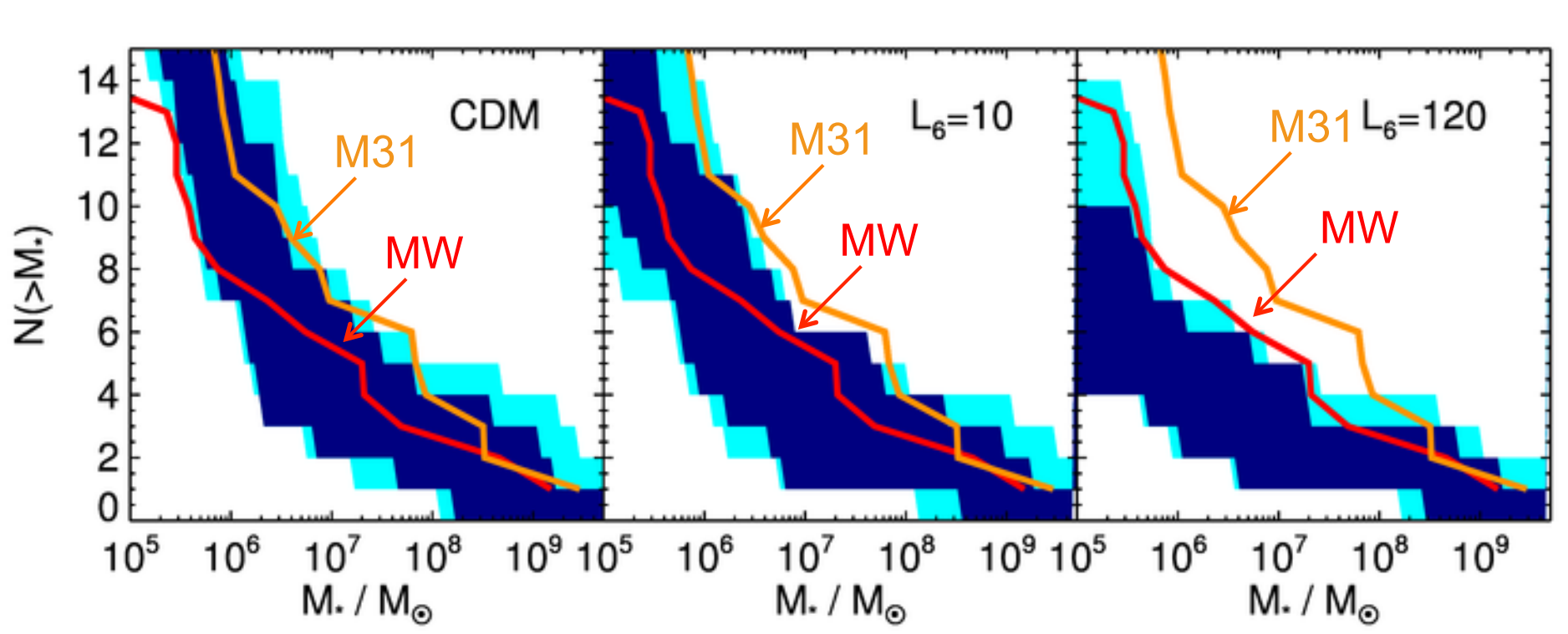
1.6 keV

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

When “baryon effects” are taken into account

→

Observed abundance of satellites is compatible with CDM but rules out some WDM models

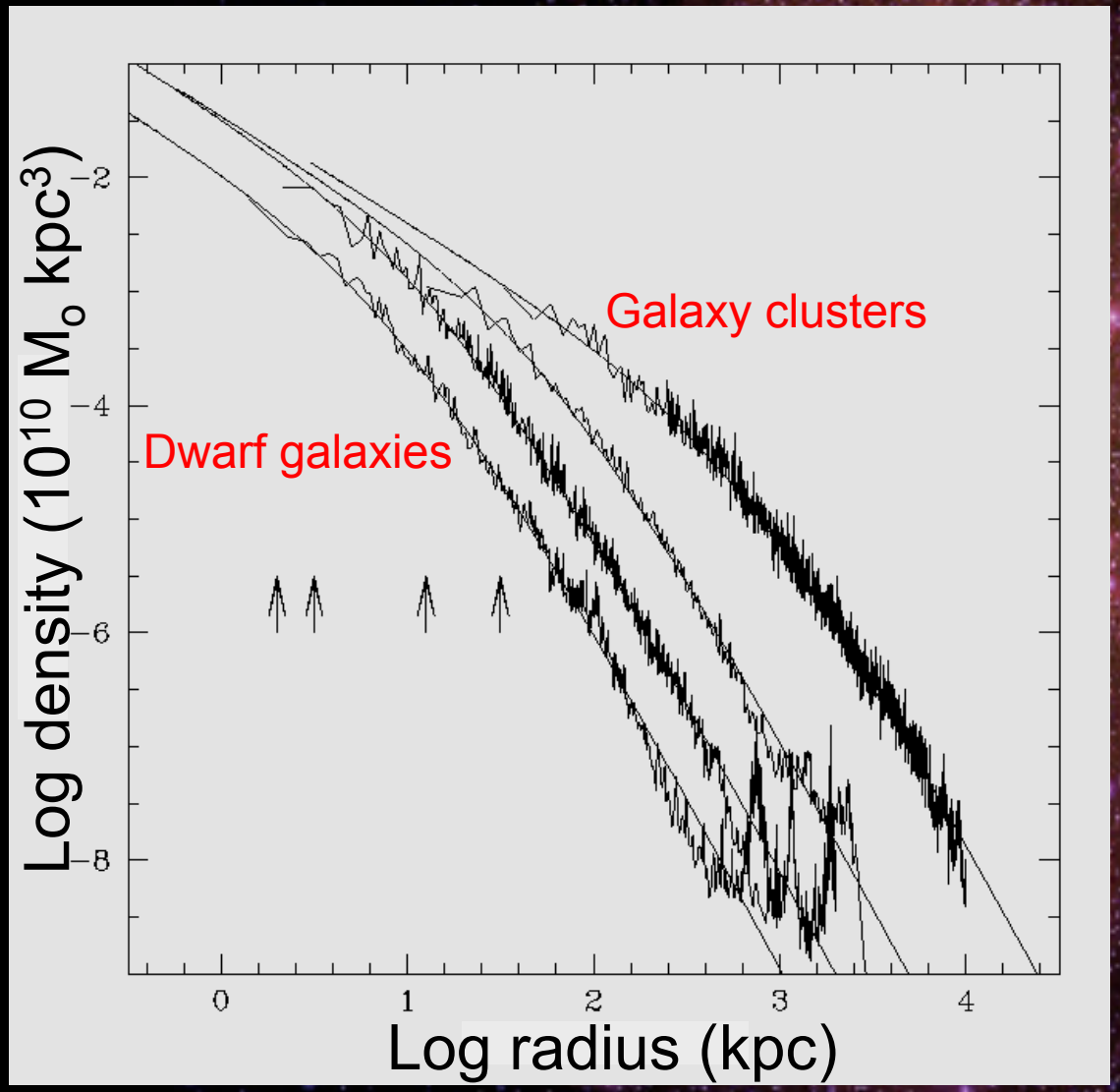
→

There is no such thing as the “satellite problem” in CDM!

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

Does the inner structure of satellites help?

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)

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


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

How about baryon effects?

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

How about baryon effects?

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*

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.

Baryon effects in the MW satellites

University of Durham

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

The cores of dwarf galaxy haloes L75

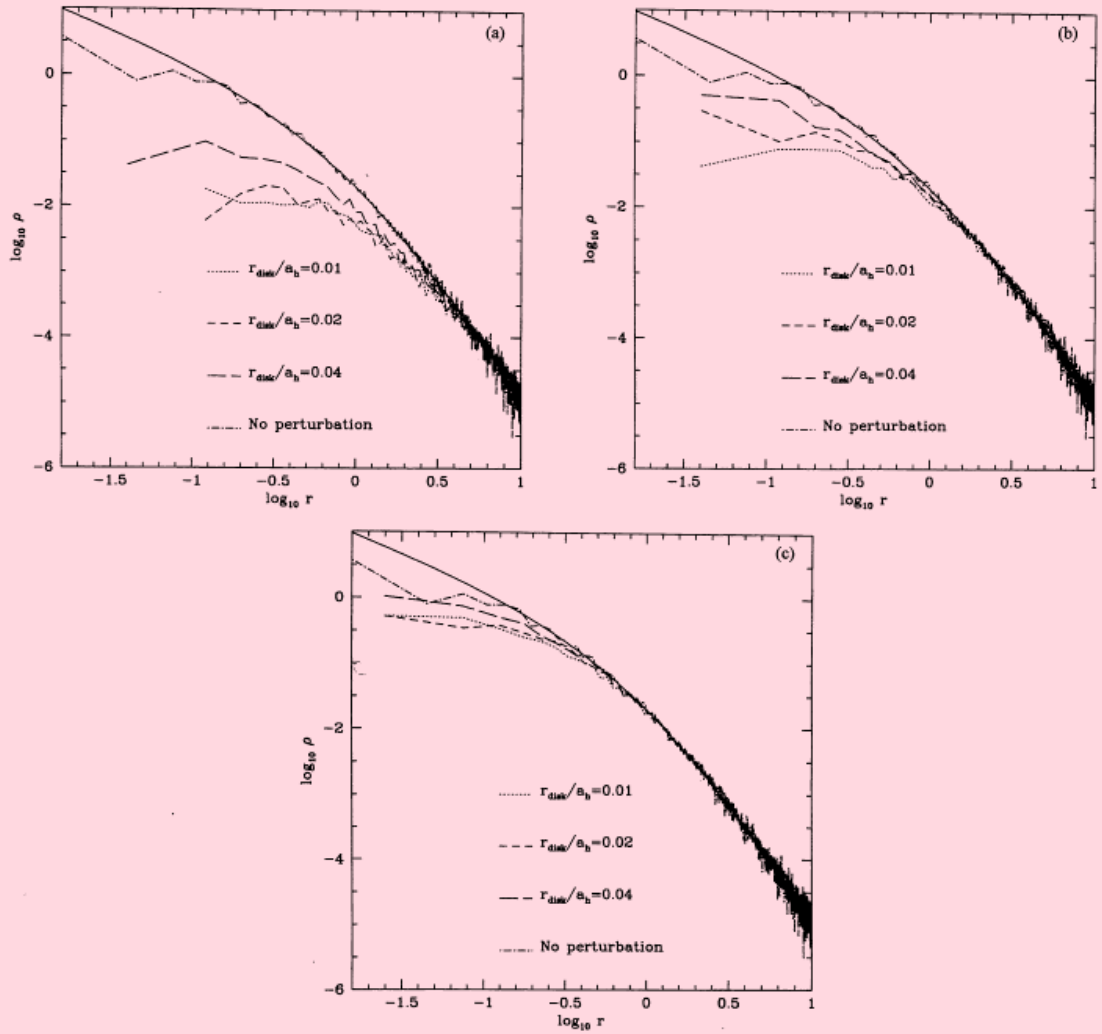


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

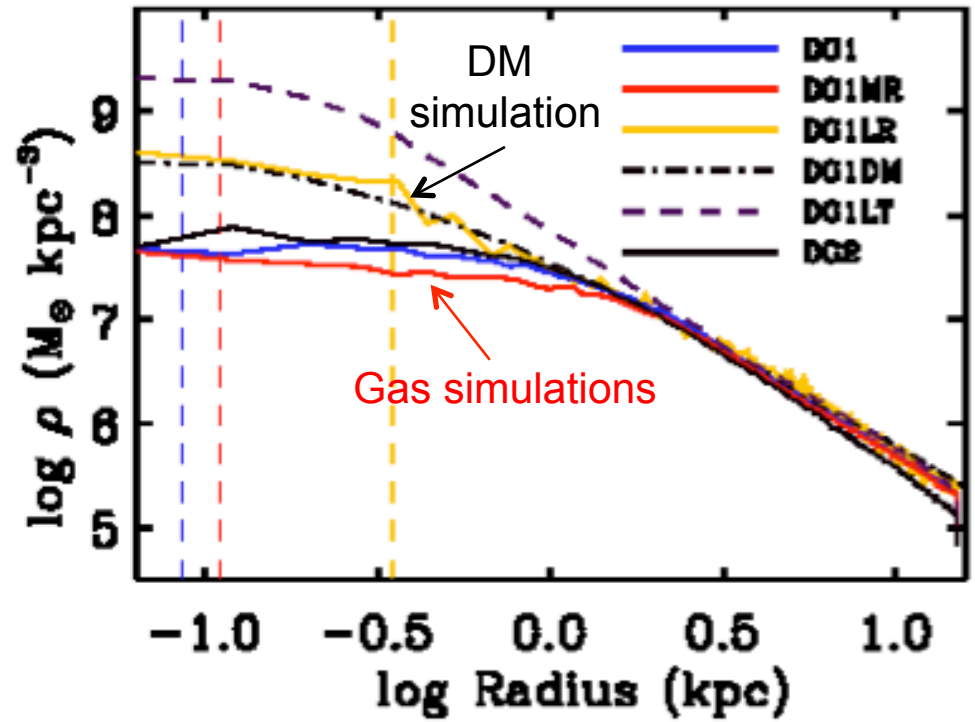
Cores in dwarf galaxy simulations

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



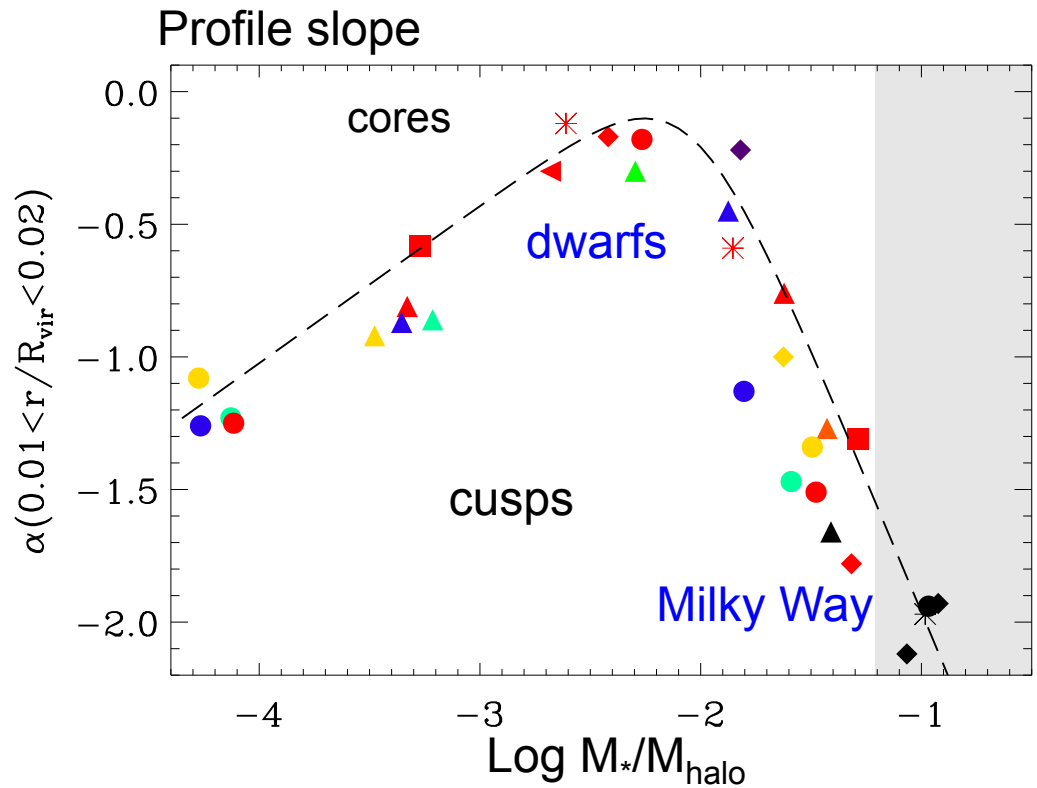
Governato et al. '12

Pontzen et al. '12

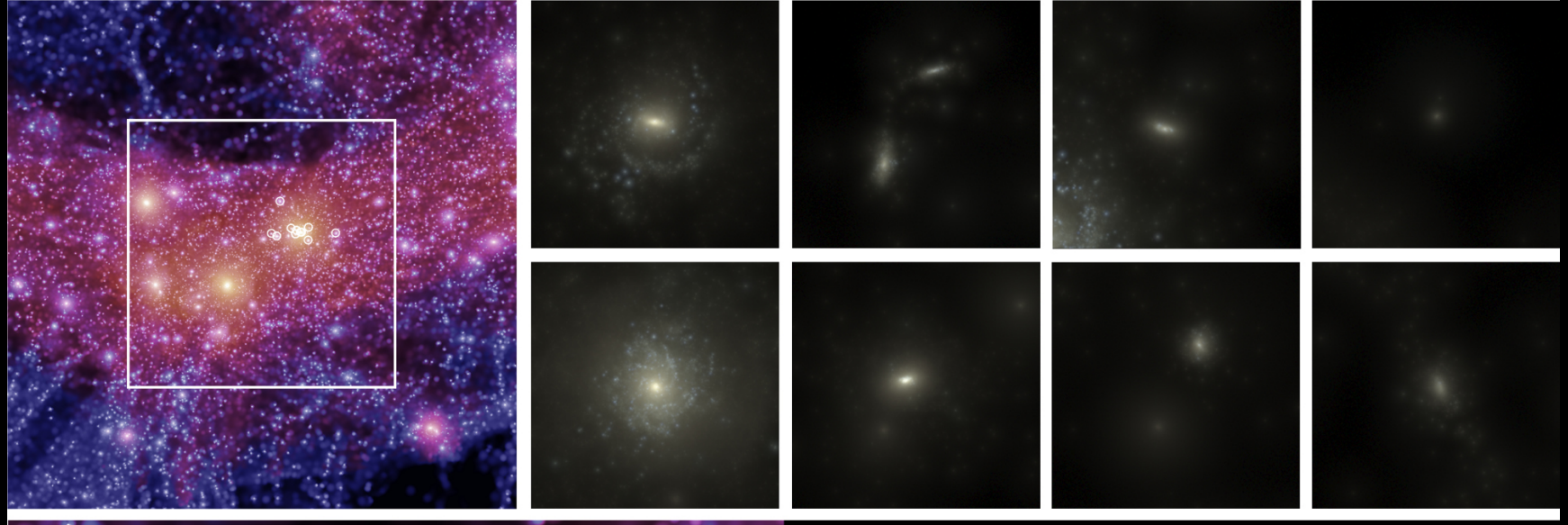
Cores in dwarf galaxy simulations

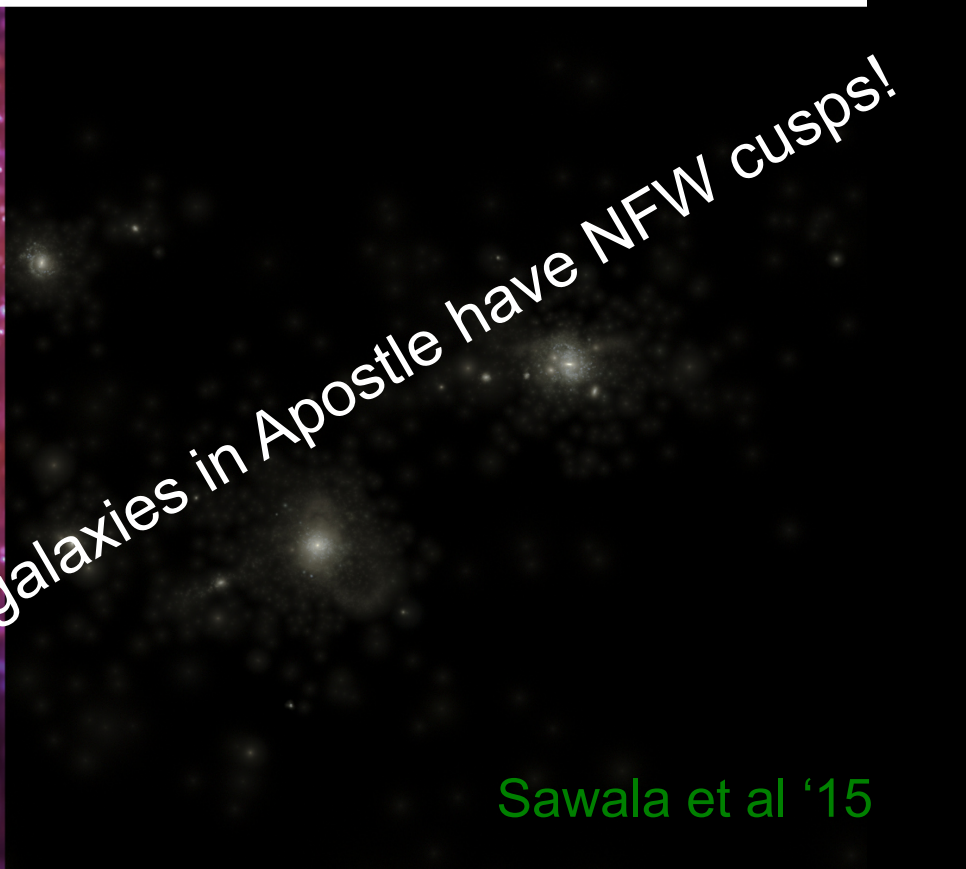
Cores may only form in a limited range of galaxy masses

- Galaxy too small → not enough energy
- Galaxy to large → potential well too deep



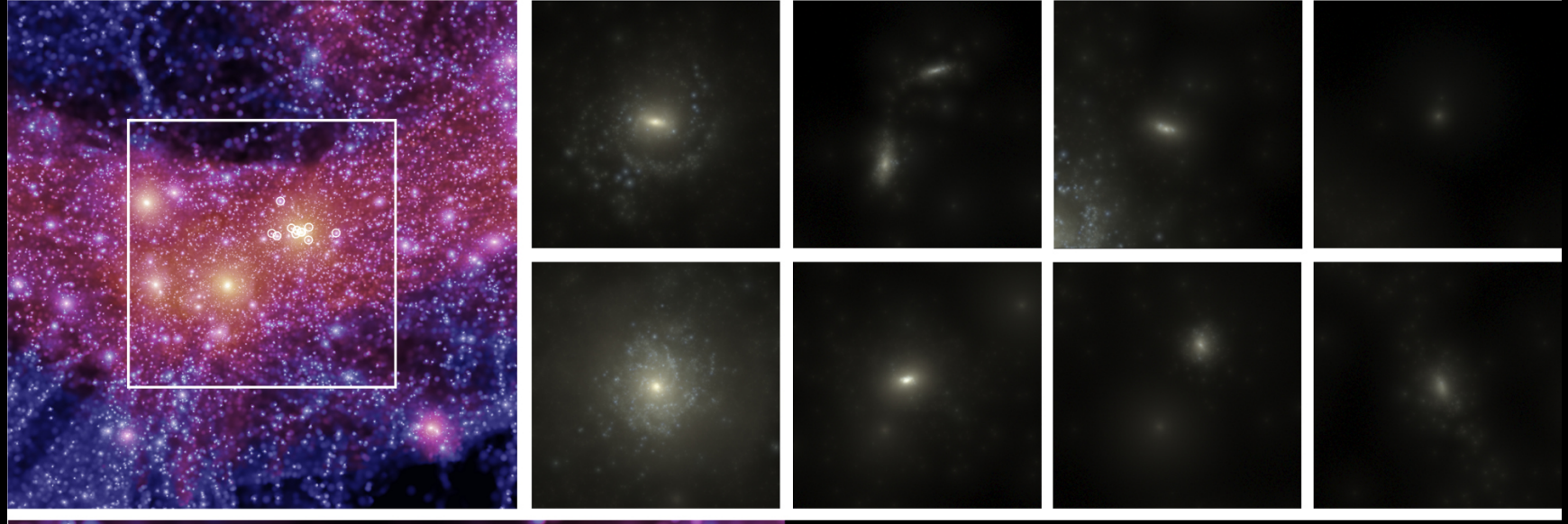
Di Cintio et al. ’14





Dwarf galaxies in Apostle have NFW cusps!

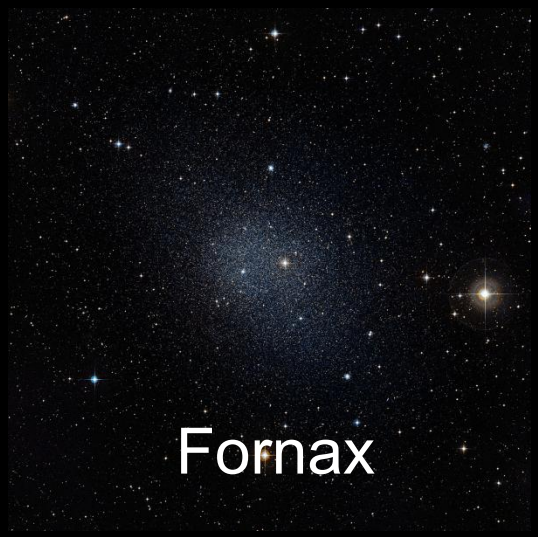
Sawala et al ‘15



Does Nature have them?

Sawala et al ‘15

Dwarf galaxies around the Milky Way




Sextans


Sagittarius

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

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

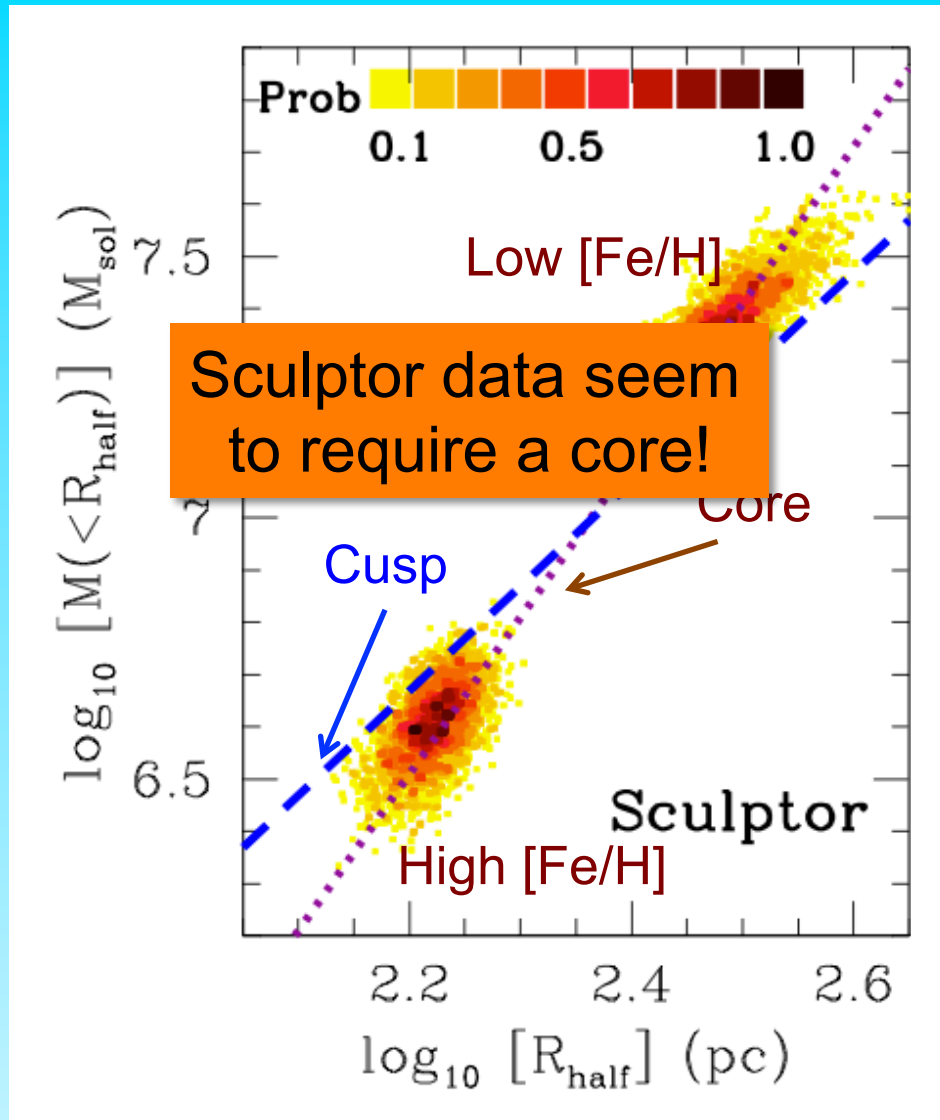
(ii) extended, low [Fe/H]

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

$r = r_{1/2}$

Walker '10; Wolf et al '10→

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



Walker & Peñarrubia '11

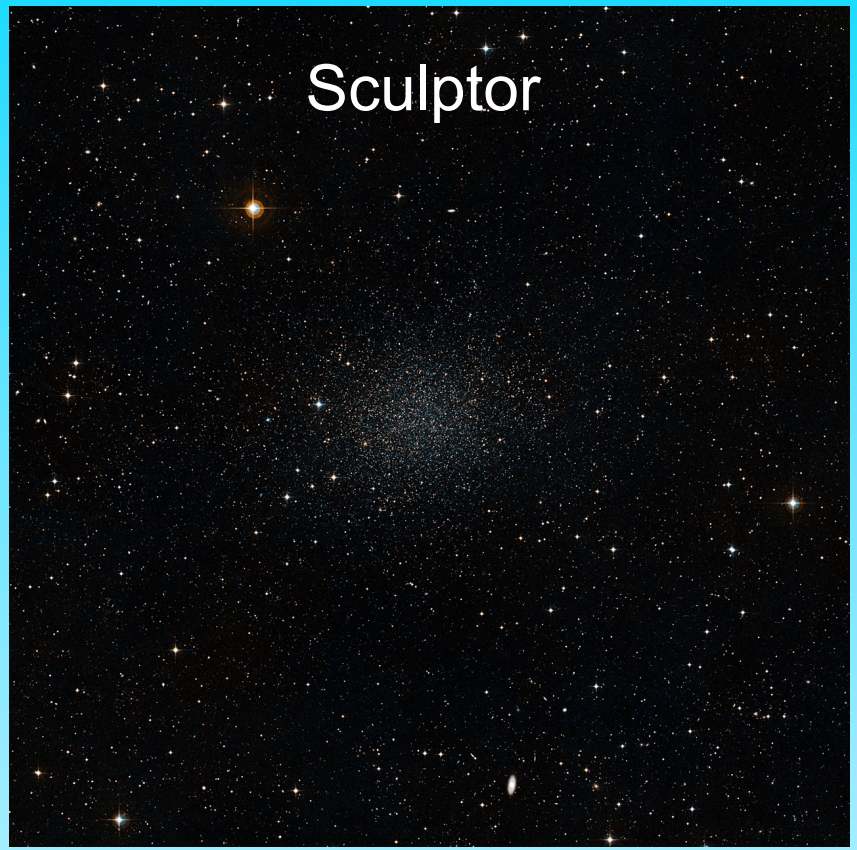
The DM halo of the Sculptor dwarf

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

Key assumption of mass estimator:

spherical symmetry

Is Sculptor spherical?

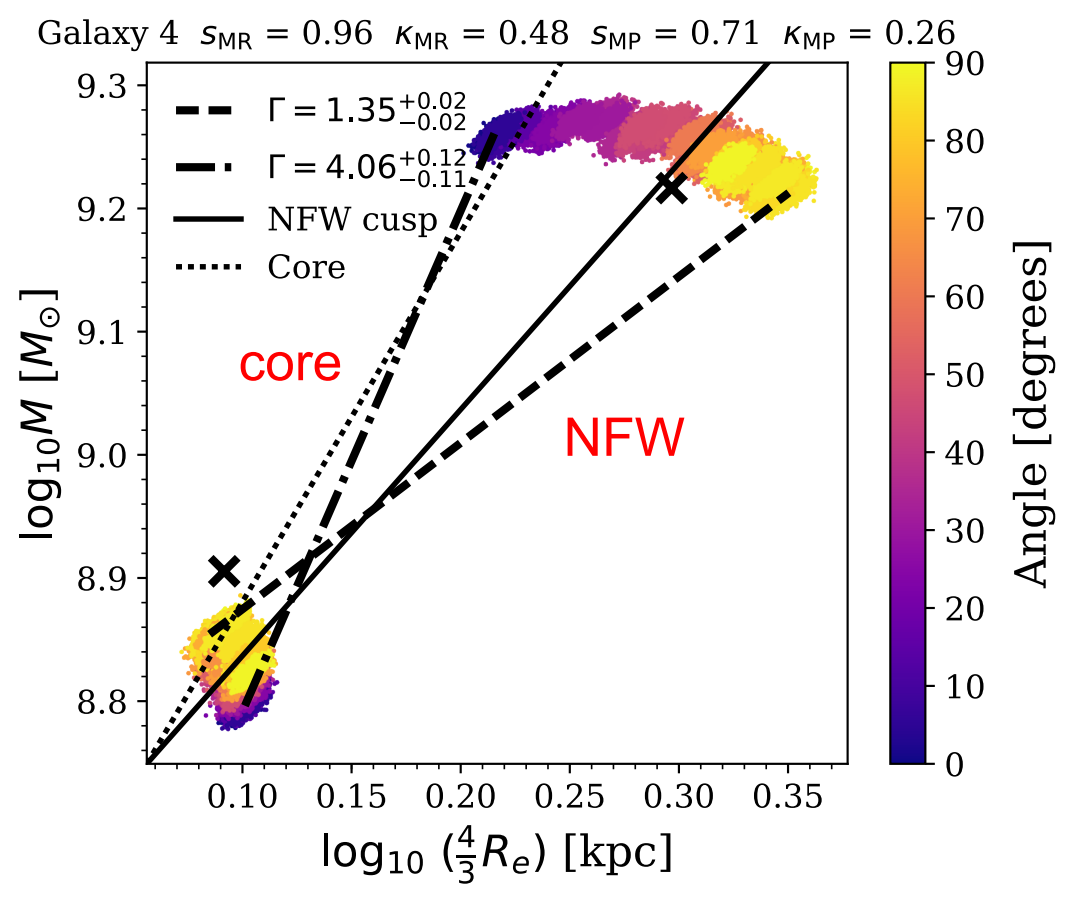


Genina, CSF et al '17

The DM halo of the Sculptor dwarf

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

View galaxy from different directions



Key assumption of mass estimator:

spherical symmetry

Most satellites in apostle are elongated!

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

Genina, CSF et al '17

Institute for Computational Cosmology

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

Rotation curves of 2 APOSTLE dwarfs

APOSTLE galaxies all have NFW cusps

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

↓

Tilted-ring model corrected for asymmetric drift

← ^{3D}BAROLO fit

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

↓

^{3D}BAROLO fit ← Tilted-ring model corrected for asymmetric drift

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

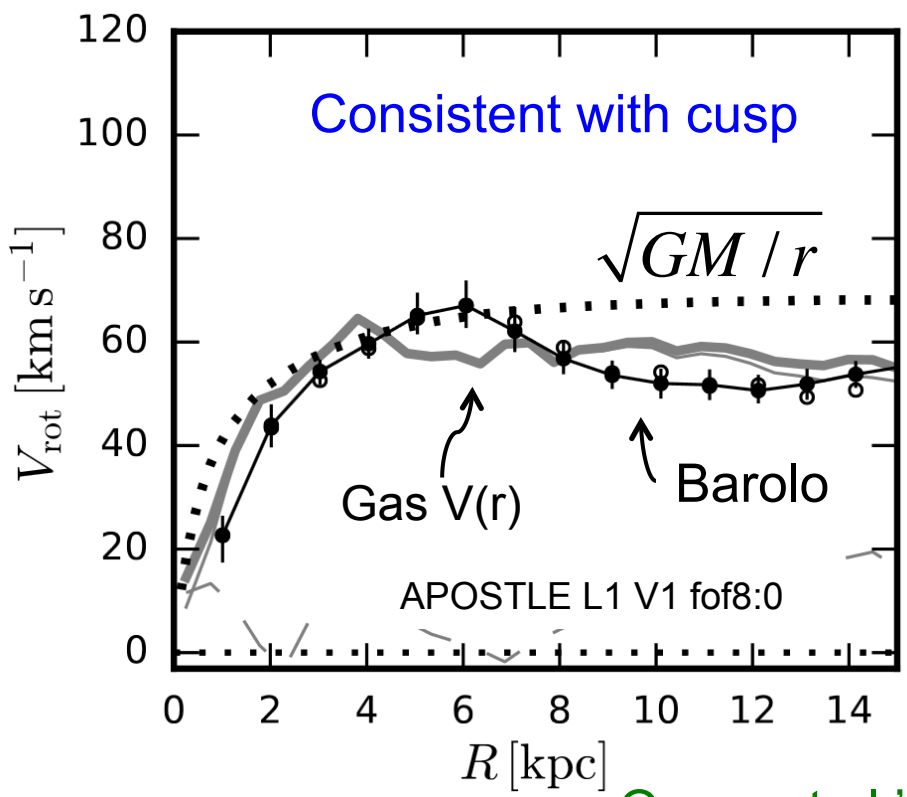
Rotation curves of 2 APOSTLE dwarfs

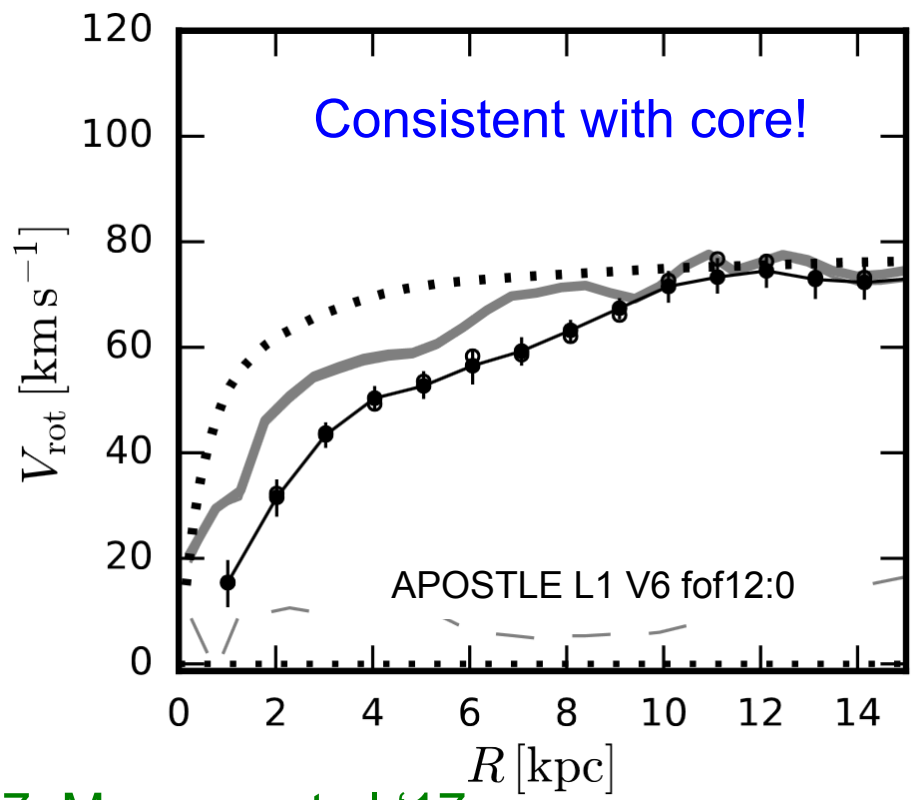
APOSTLE galaxies all have NFW cusps

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





Oman et al '17; Marasco et al '17

Conclusions from halo structure

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

There is NO evidence for cores in dwarf galaxies

Existing data are consistent with either cusps or cores

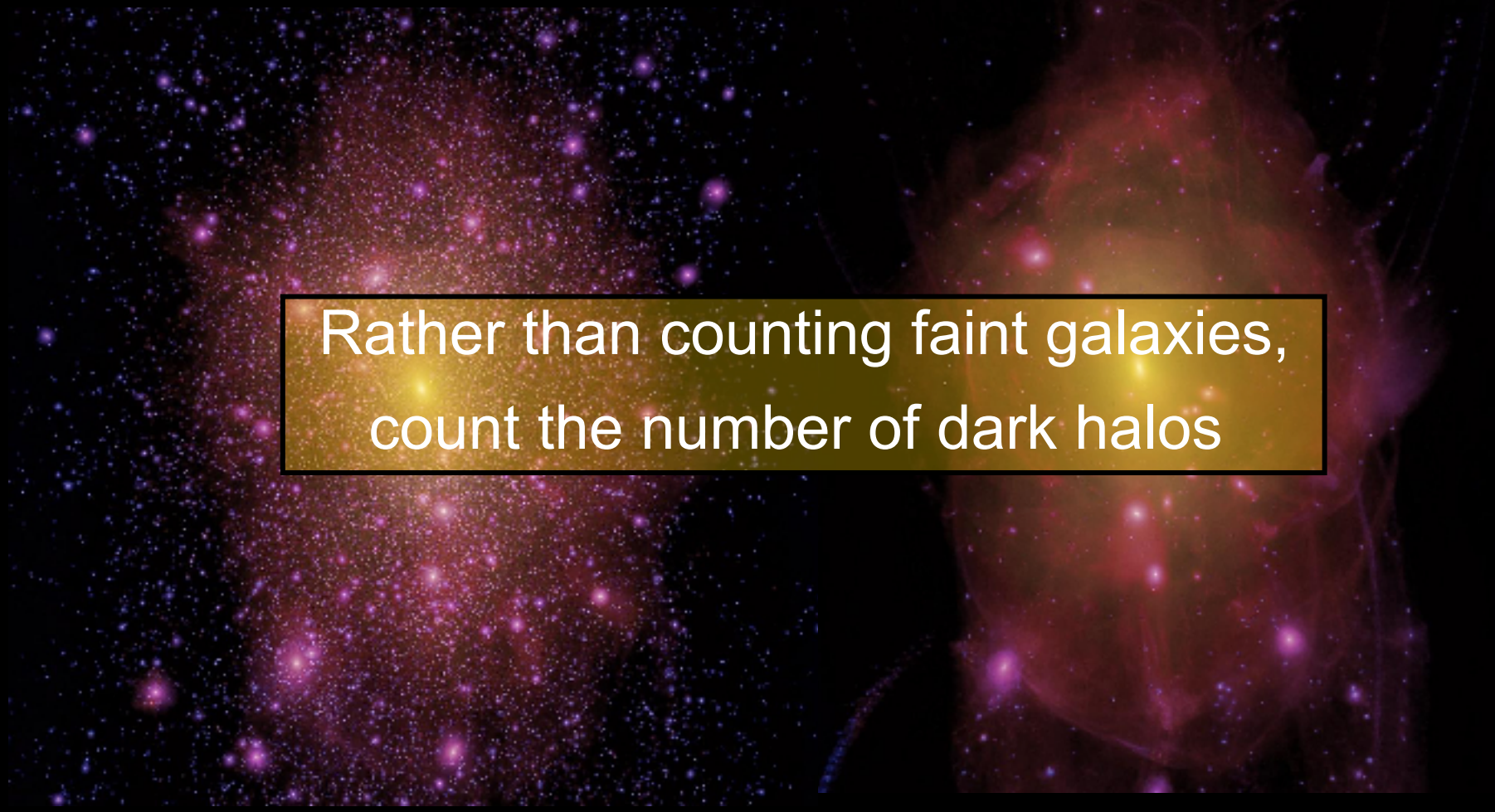
So, we can’t distinguish CDM from WDM by counting satellite galaxies

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

Can we distinguish CDM/WDM?

cold dark matter

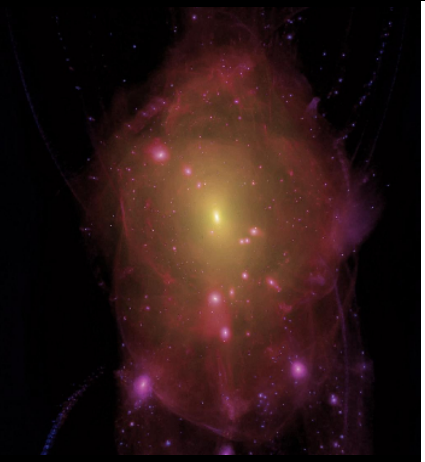
warm dark matter



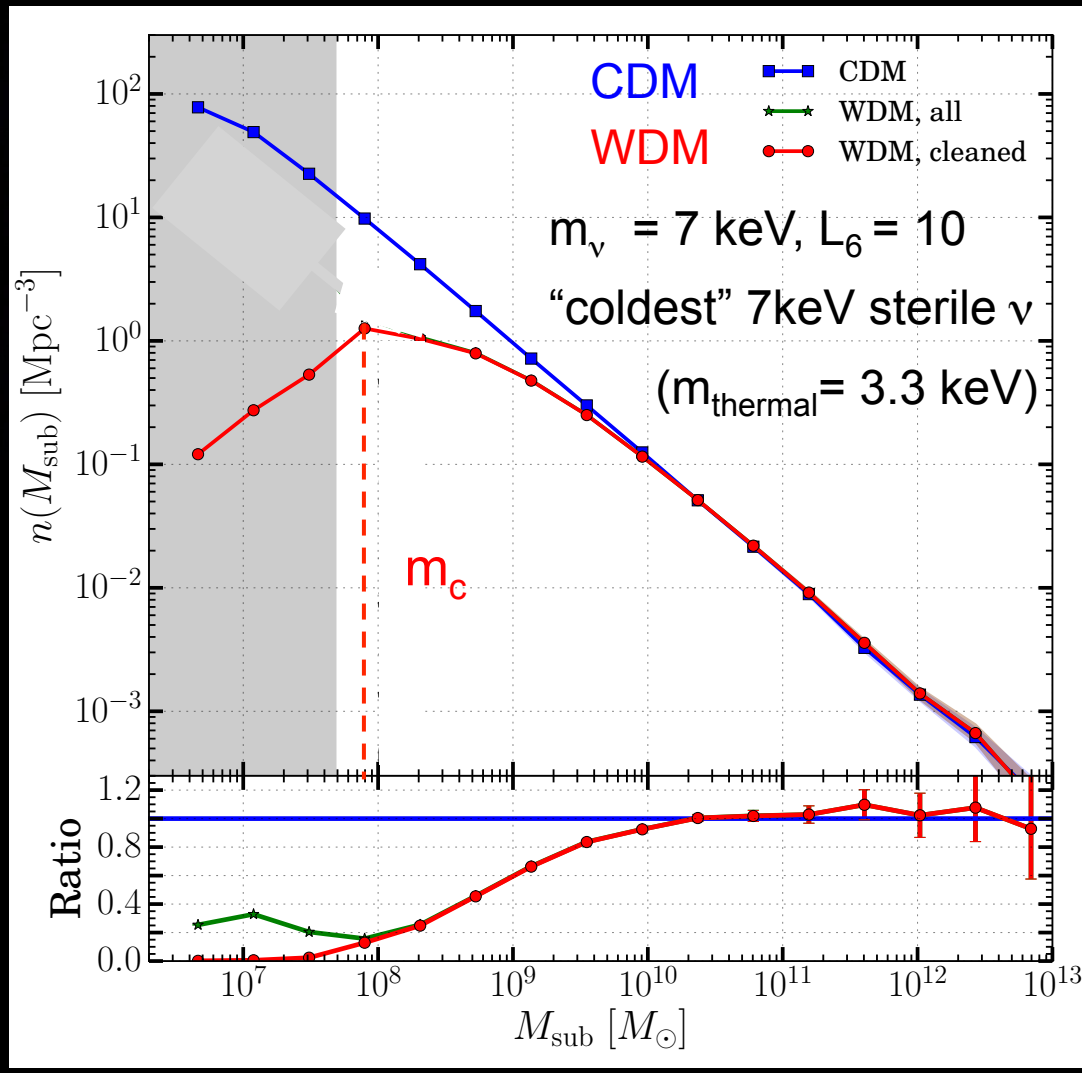
Rather than counting faint galaxies, count the number of dark halos

The subhalo mass function

CDM



WDM



3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

Bose, CSF et al '16

Can we distinguish CDM/WDM?

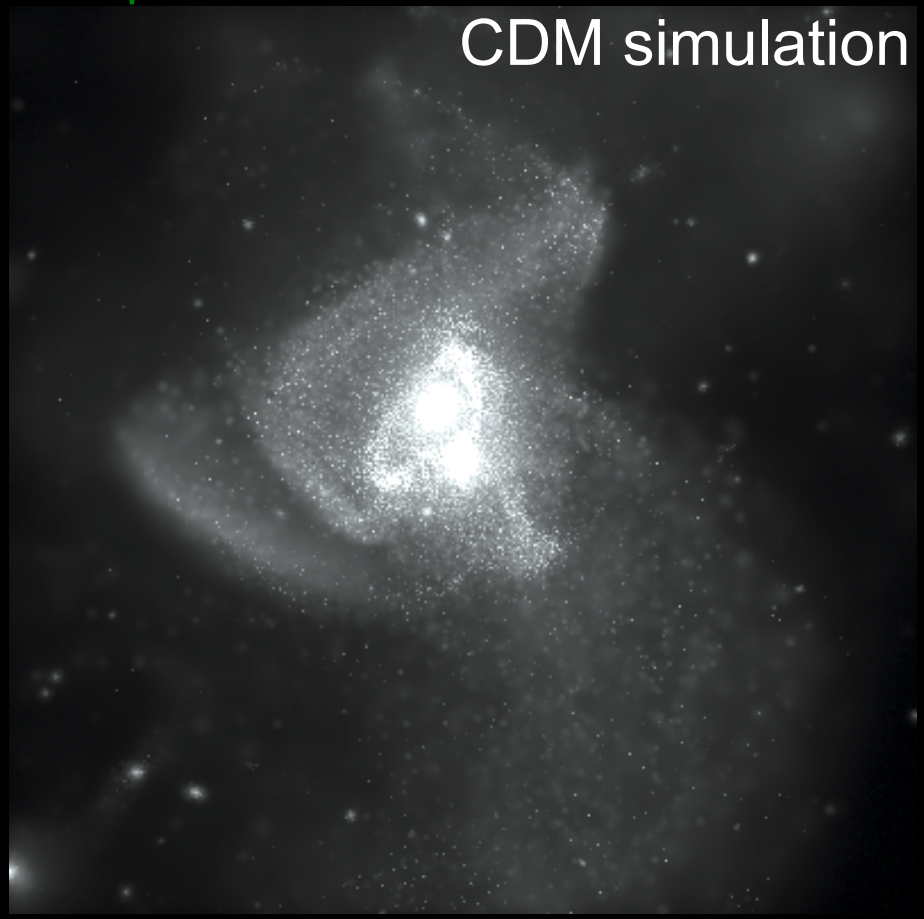
cold dark matter

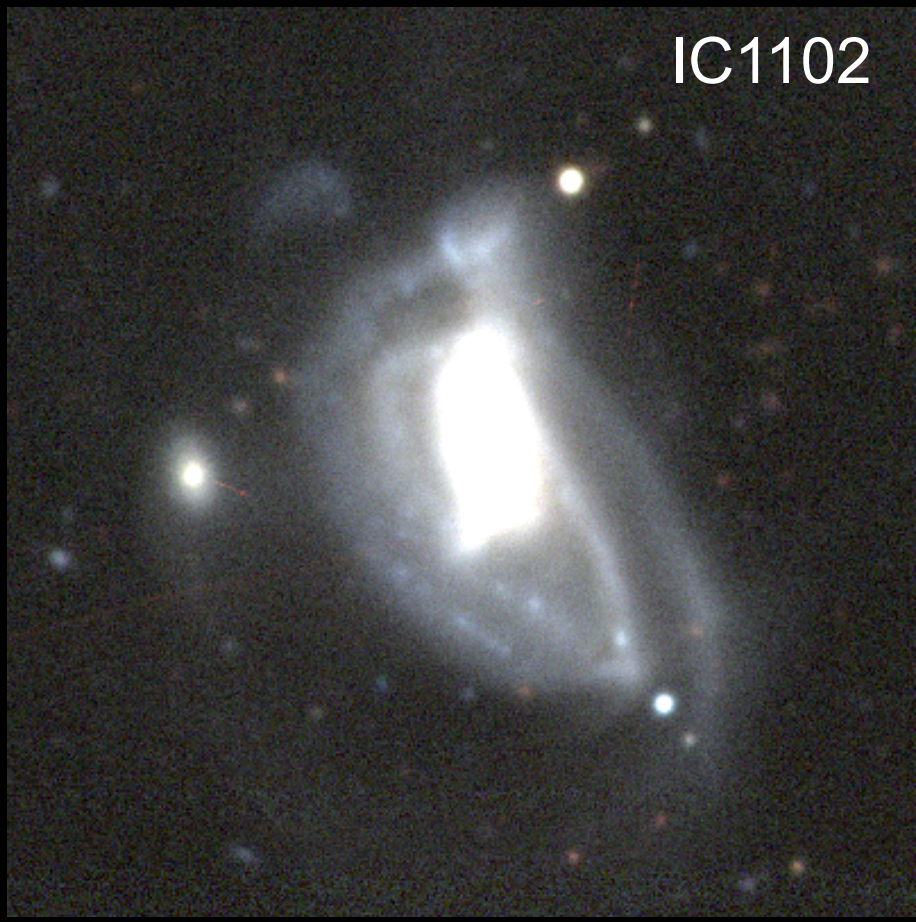
warm dark matter

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

Can we distinguish CDM/WDM?

Cooper et al '16





Subhalos crossing a cold tidal stream can produce a gap

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

Can we distinguish CDM/WDM?

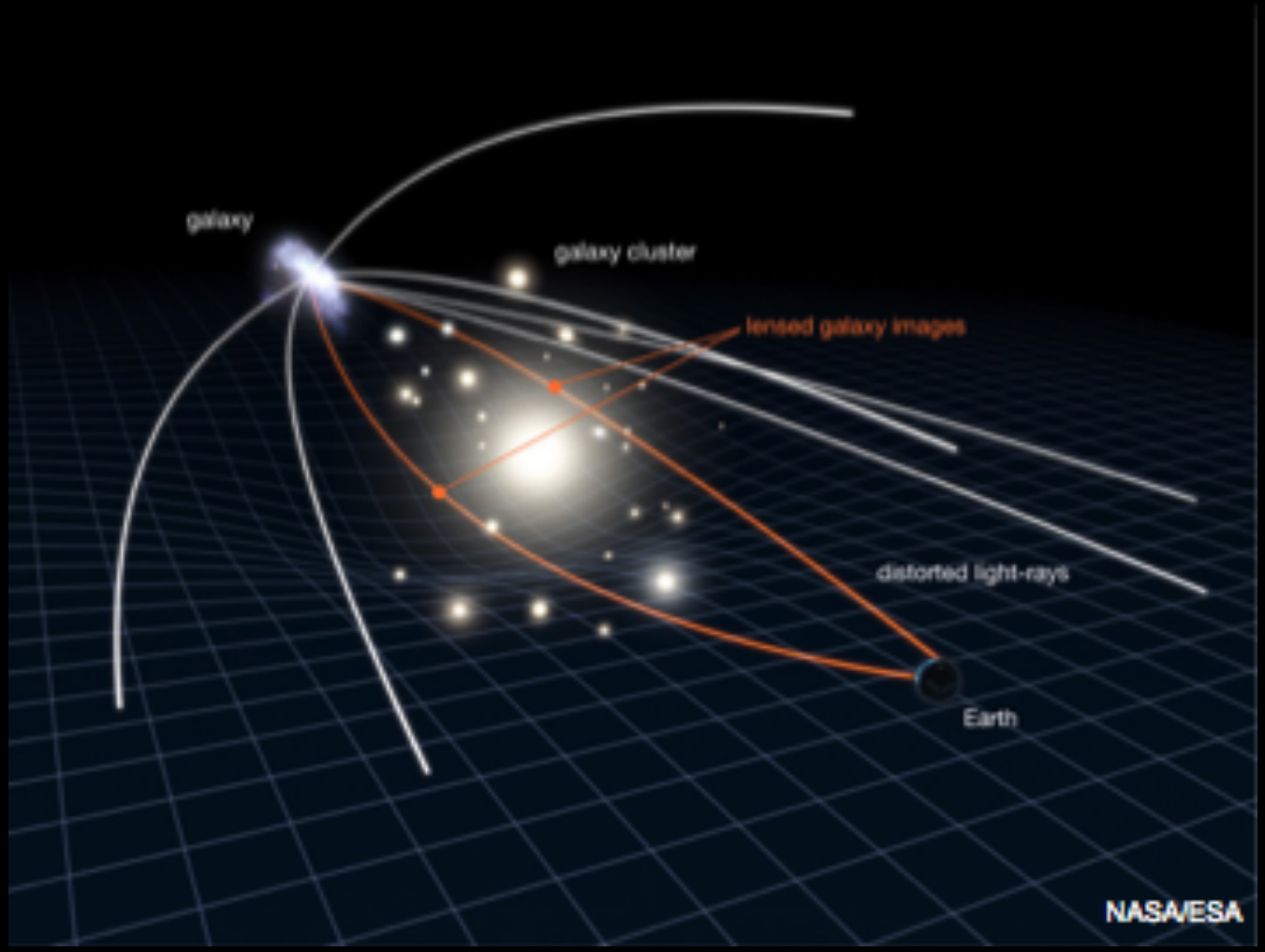
cold dark matter

warm dark matter

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

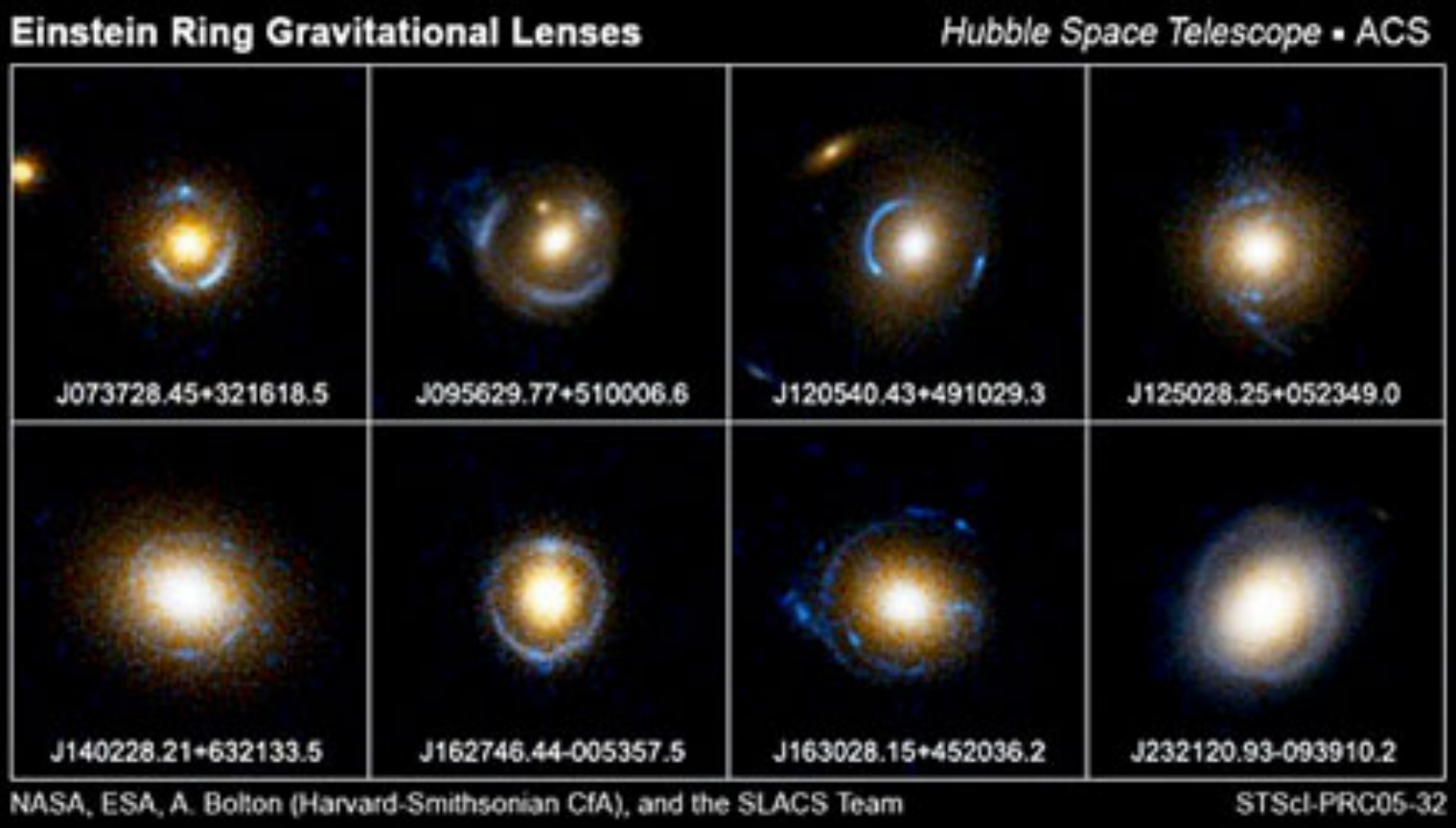
How to rule out CDM

Gravitational lensing: Einstein rings

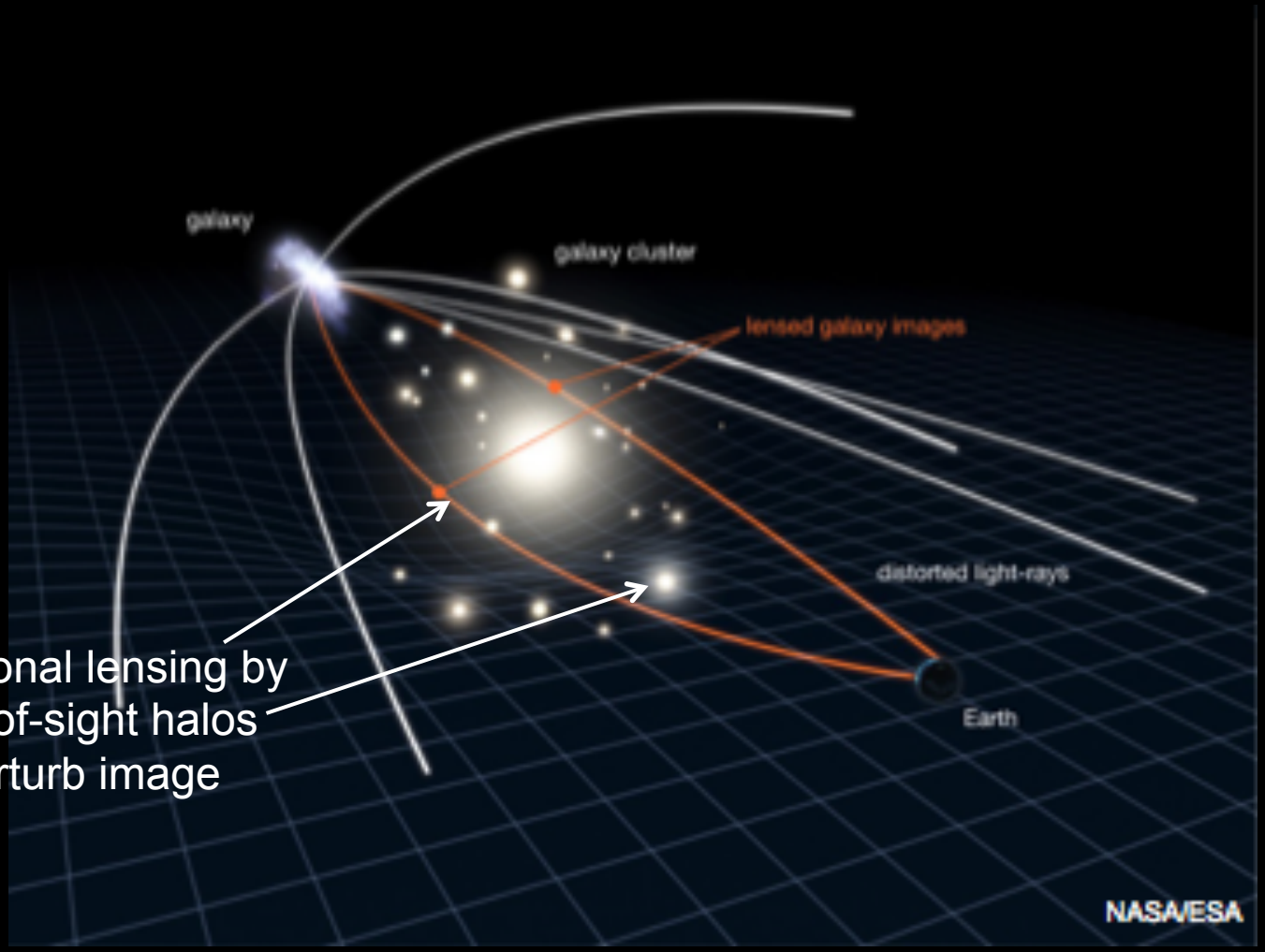


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

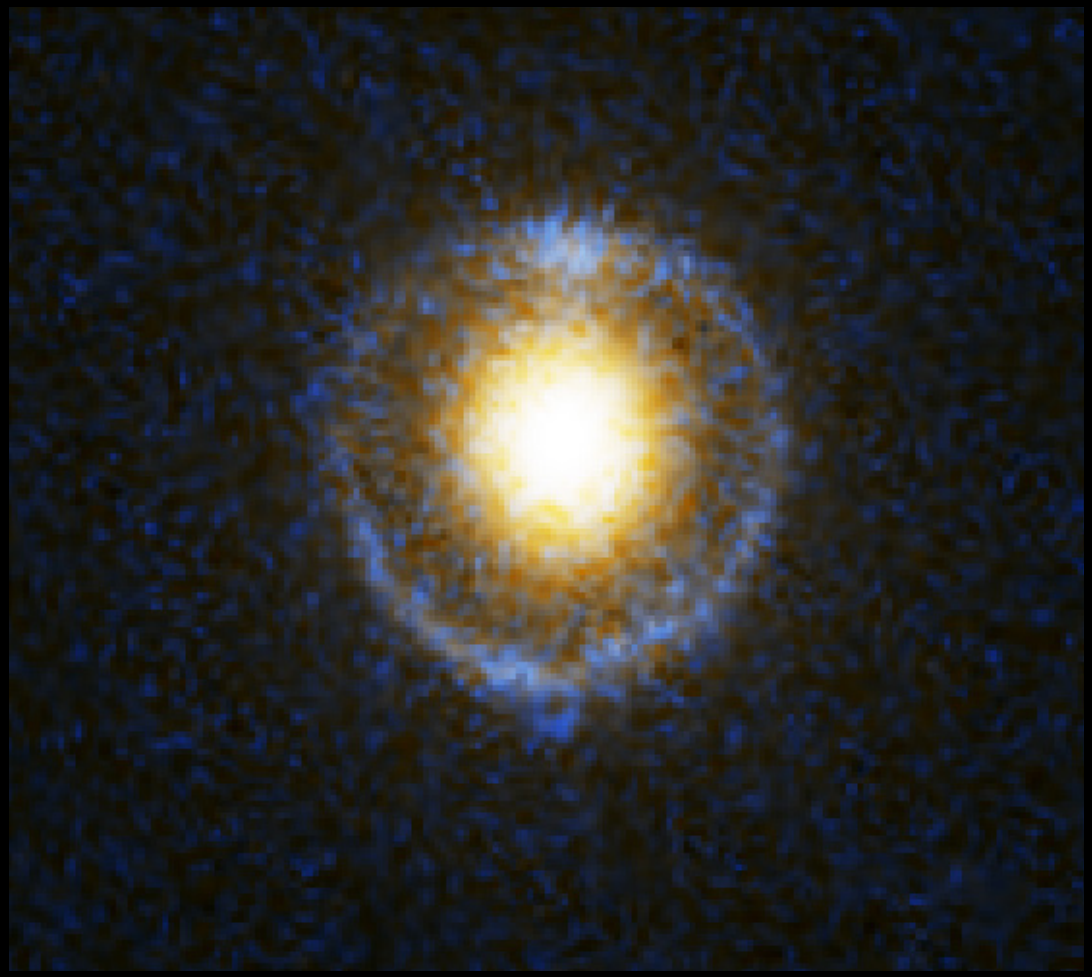


Additional lensing by line-of-sight halos perturb image

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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image

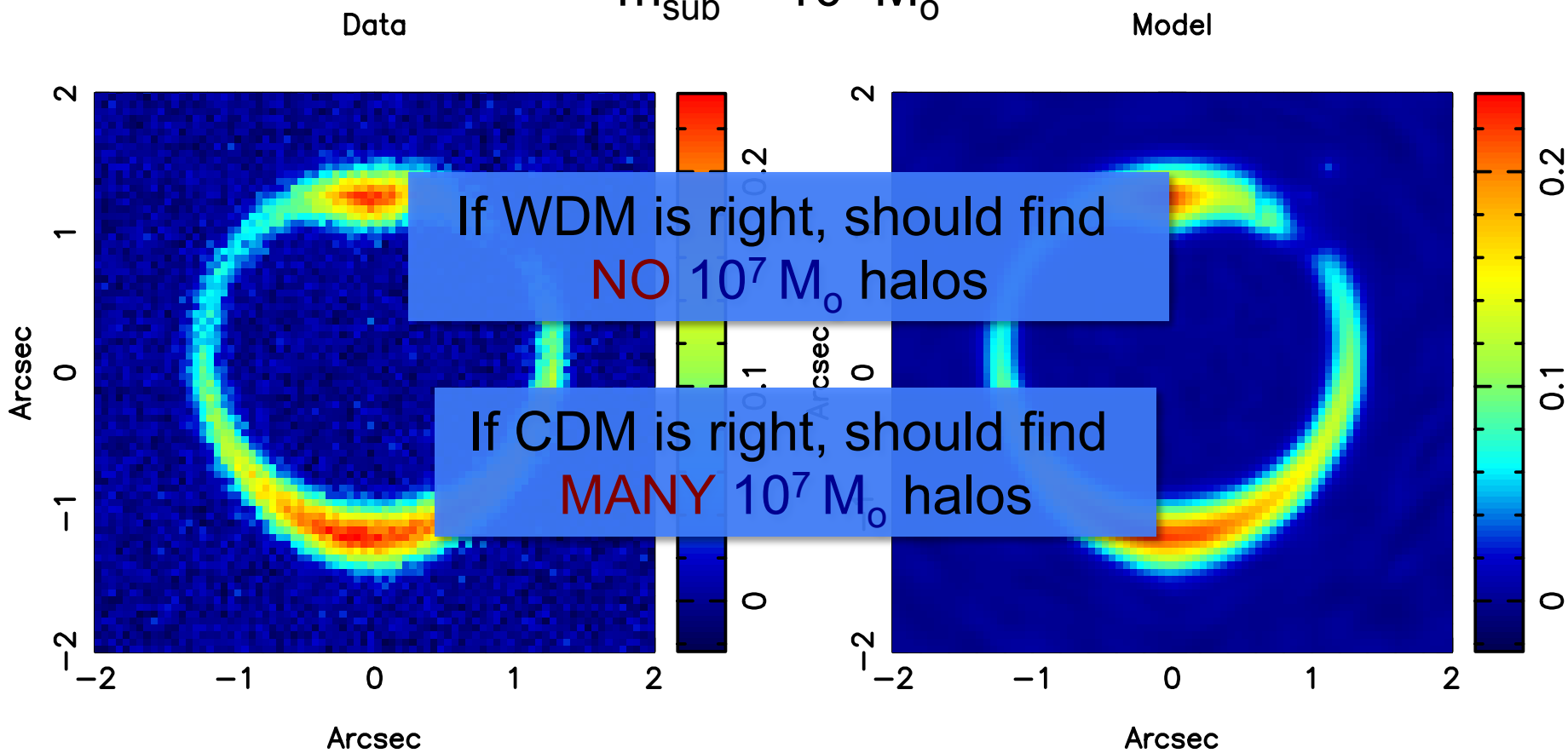


Vegetti & Koopmans '09

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

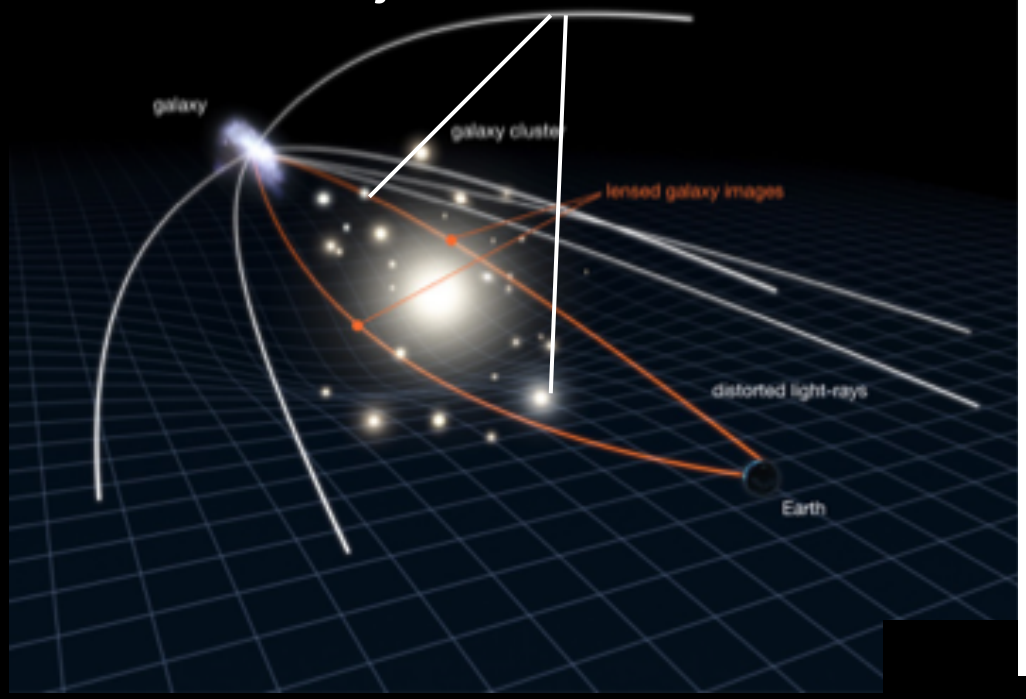
Can detect subhalos as small as $10^7 M_o$

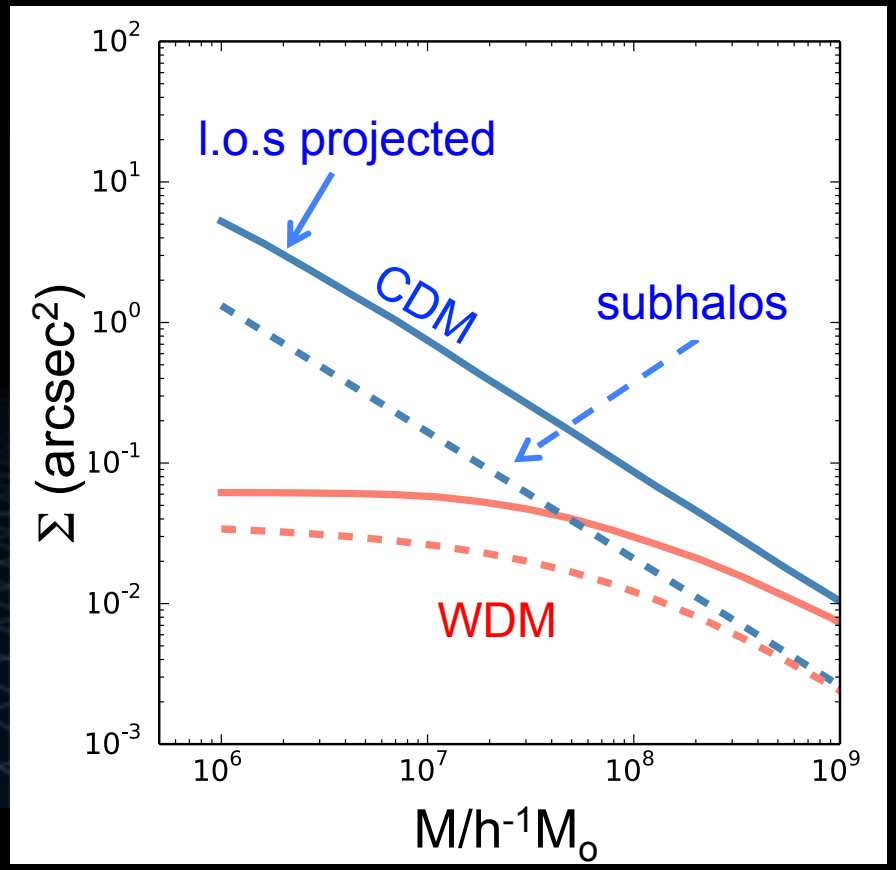
Institute for Computational Cosmology

Substructures vs interlopers

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

Projected l.o.s halos





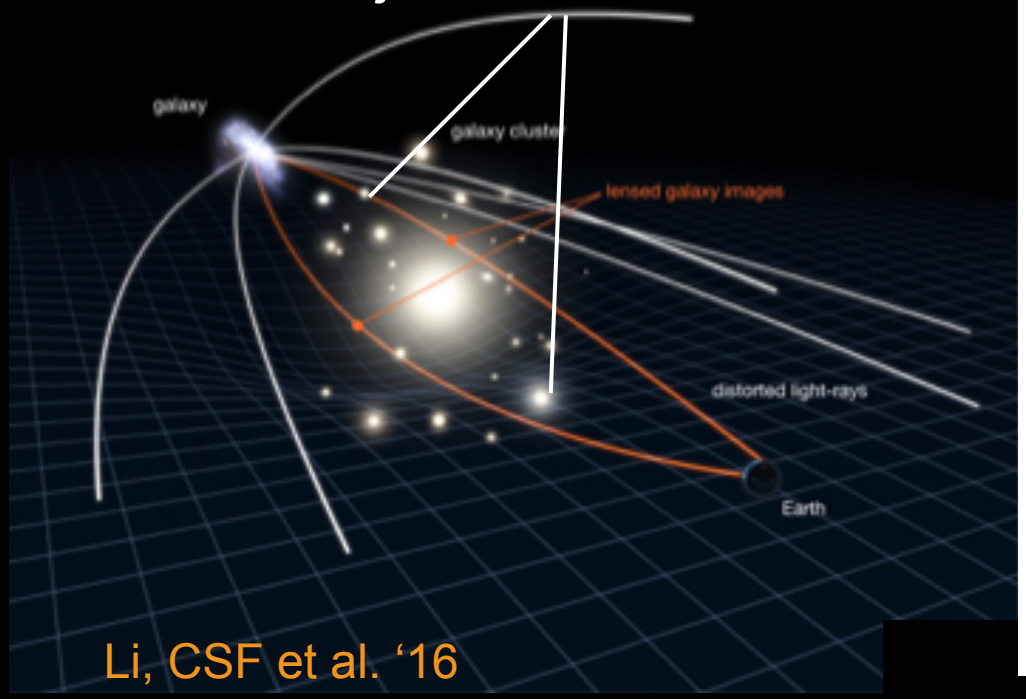
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16

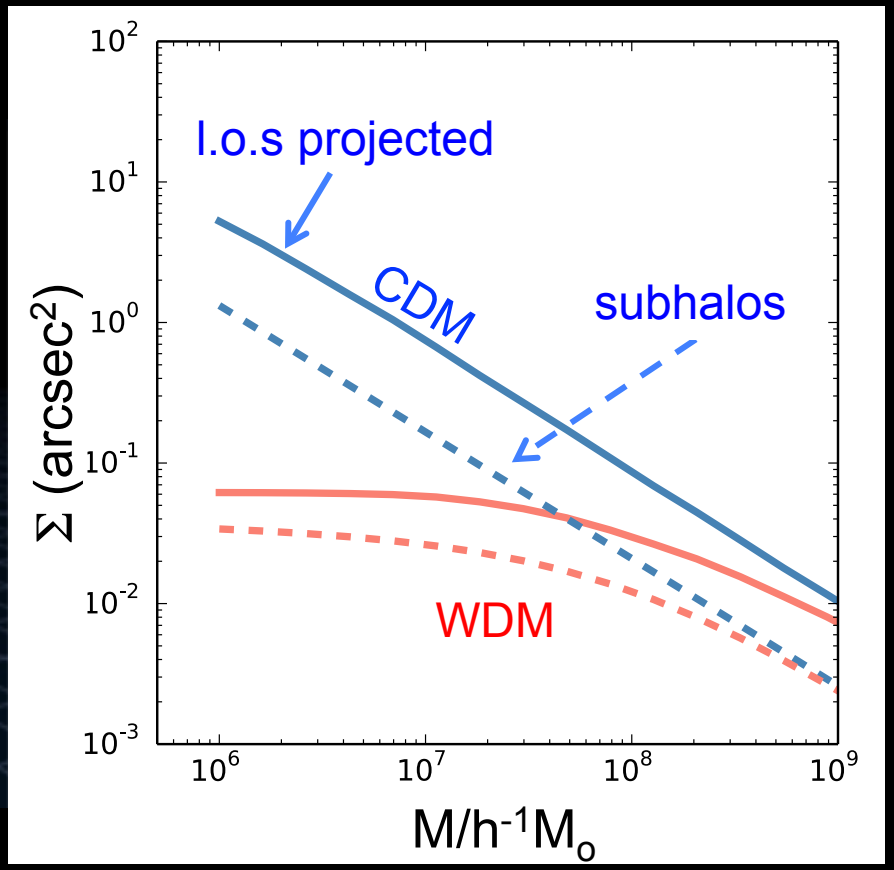
Substructures vs interlopers

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

Projected l.o.s halos



Li, CSF et al. '16



→ 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

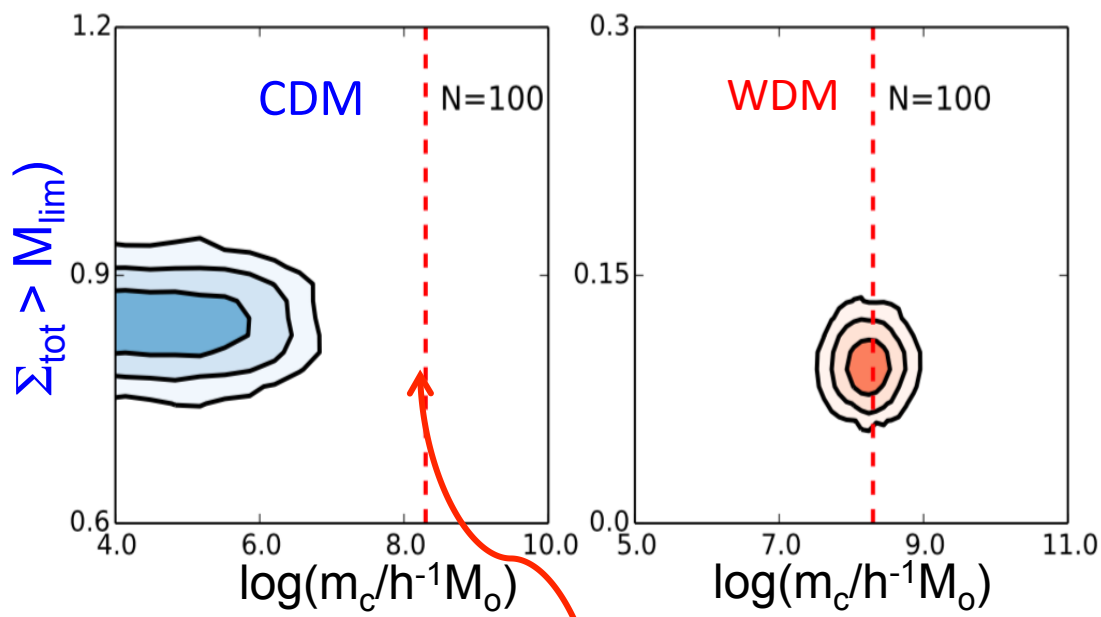
Detecting substructures with strong lensing

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

Institute for Computational Cosmology

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!