How to rule out cold dark matter

Carlos S. Frenk
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… or interesting alternatives

University of Durham
ICC

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The new Ogden Centre at Durham

The dark matter power spectrum

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Free streaming →

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

for thermal relic

$m_{CDM} \sim 100GeV$

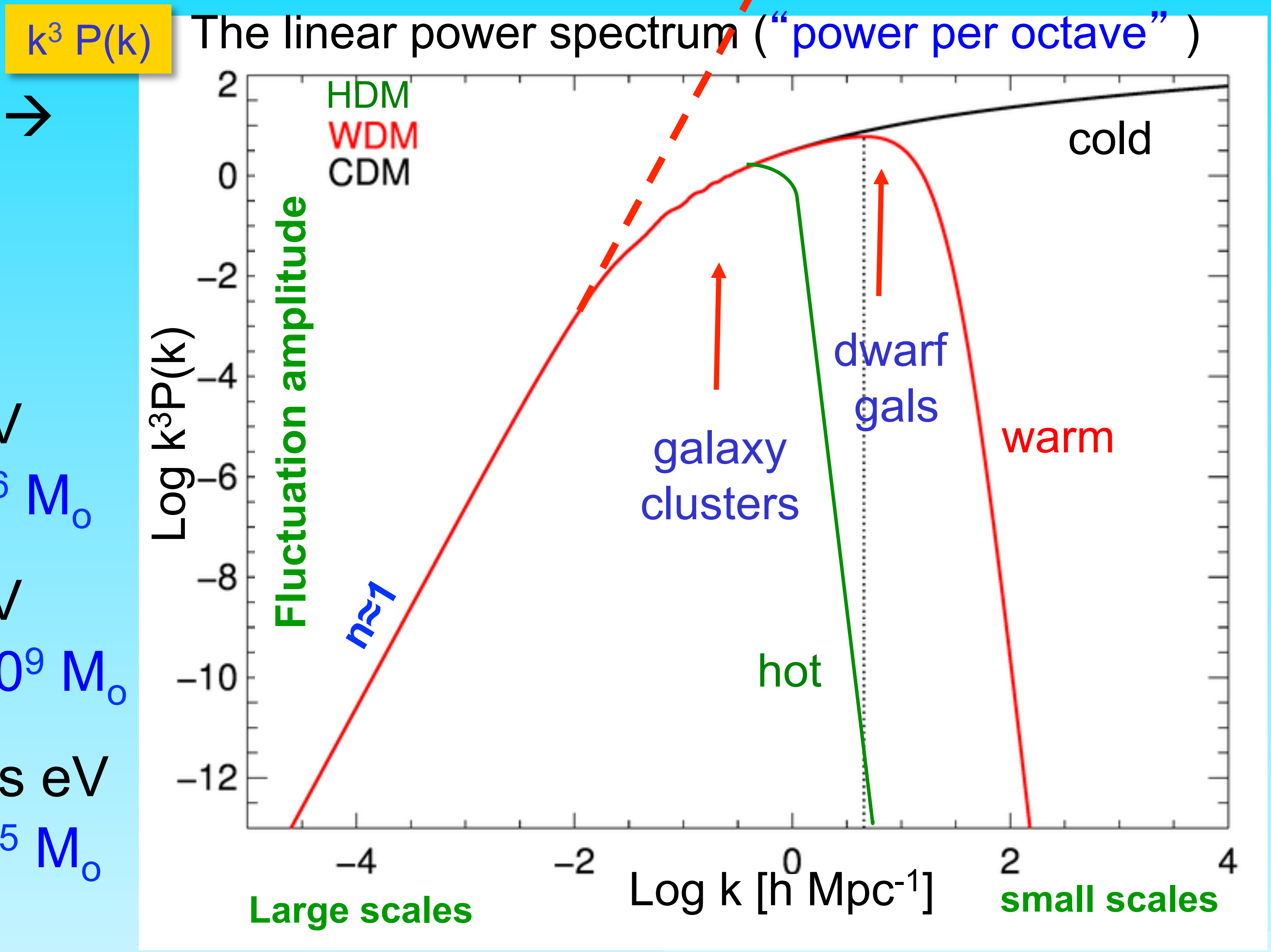
susy; $M_{cut} \sim 10^{-6} M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$

$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15} M_o$



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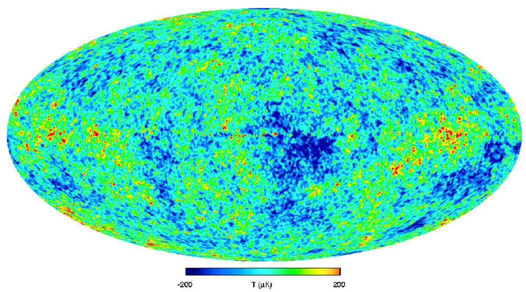
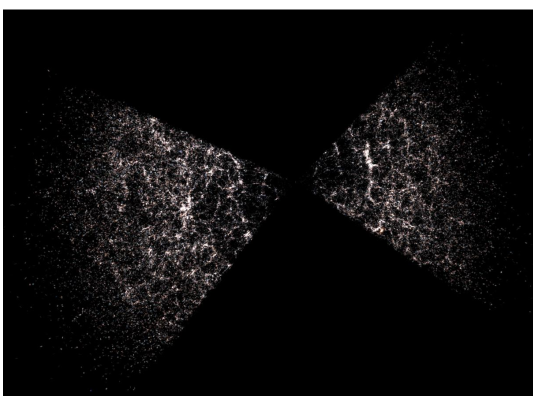
The cosmic power spectrum: from the CMB to the 2dFGRS



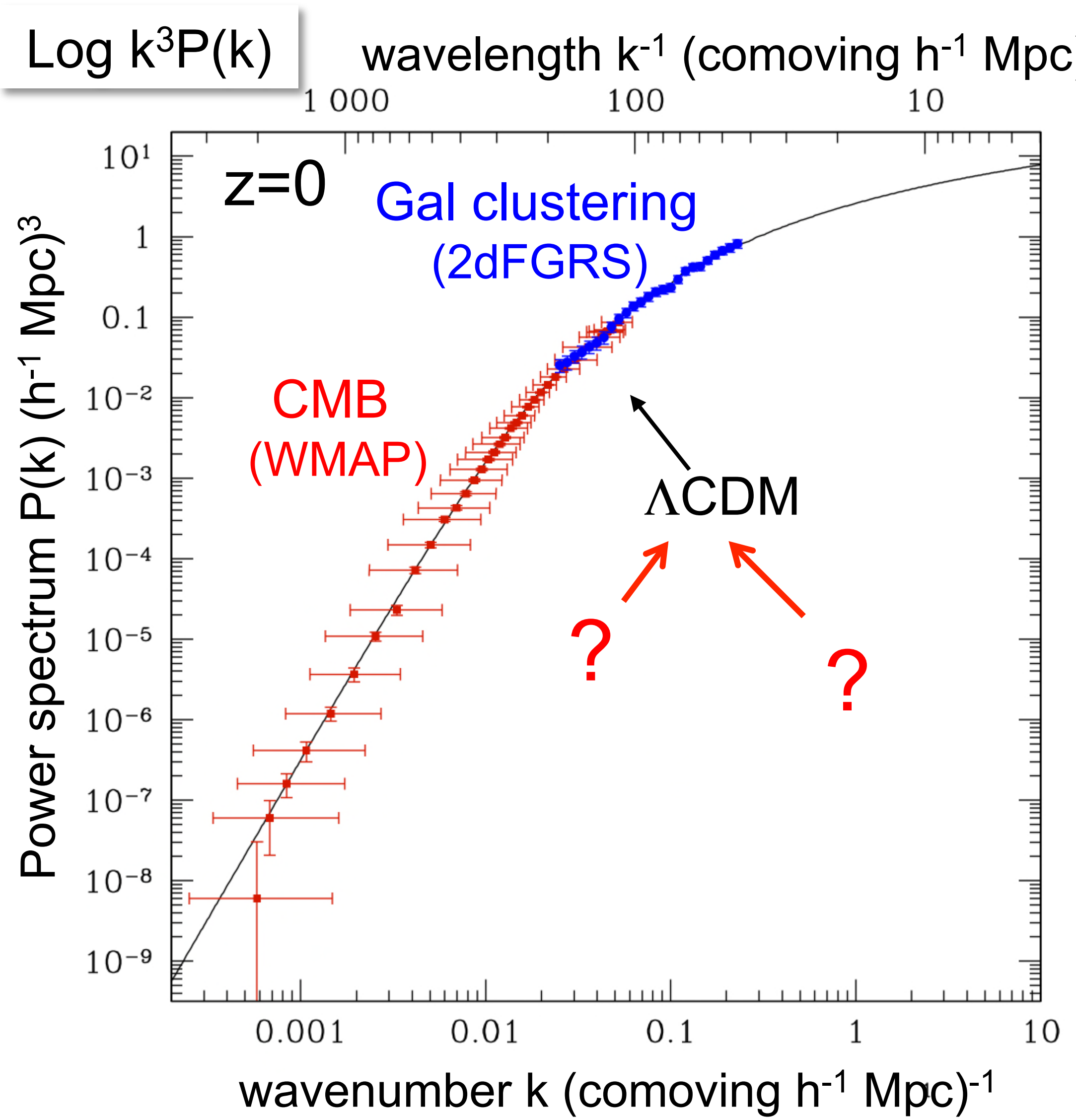
z~1000



z~0

$\Rightarrow$ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



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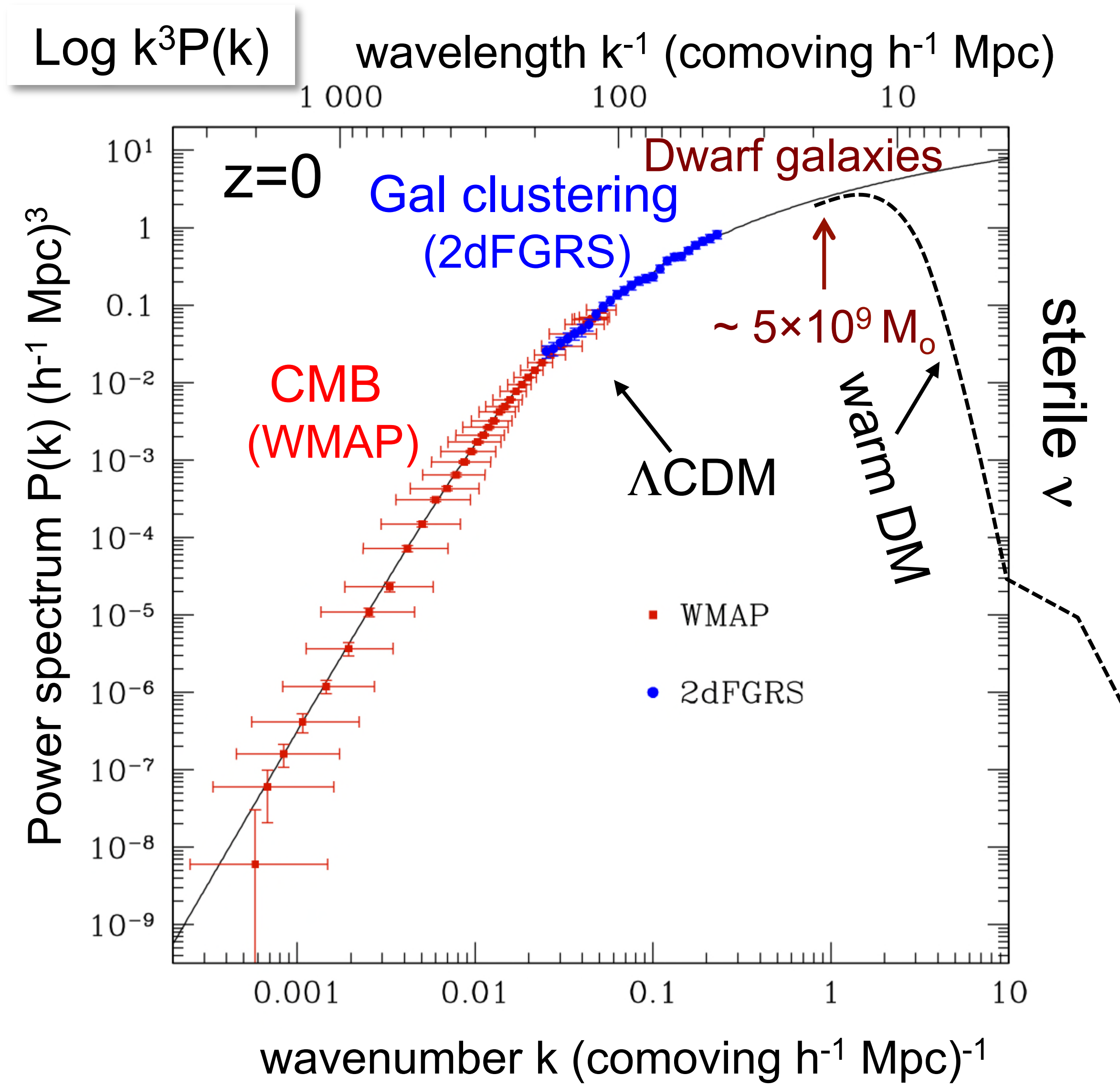

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Sterile neutrinos

Explain:

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

Sterile neutrino minimal standard model (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

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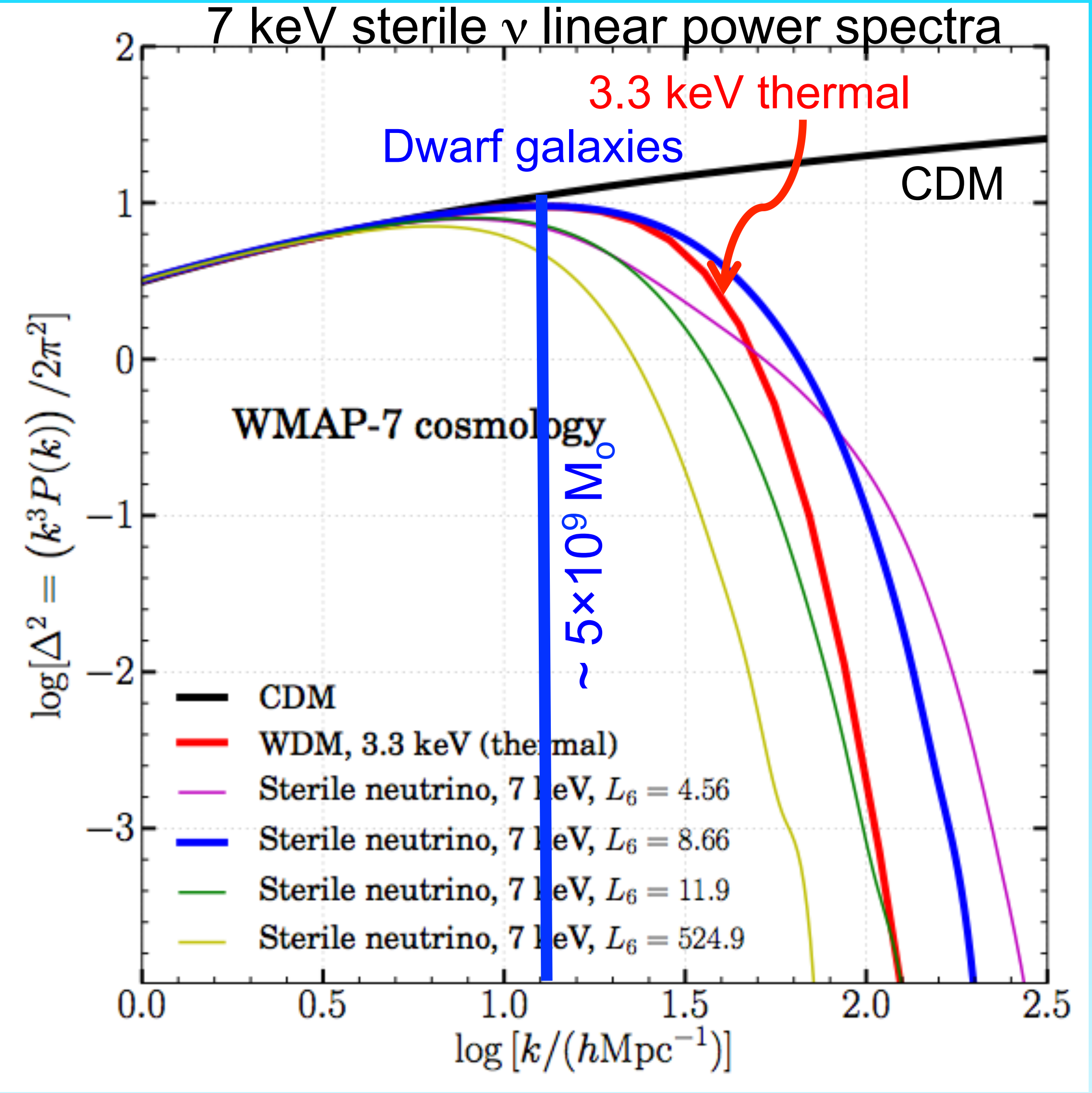
- Thermal and resonant production mechanisms
- Resonant production depends on lepton asymmetry parameter, L_6
- Linear PS varies non-monothonically with L_6

Ly-α forest rules out thermal masses, mν<3.3 keV (Viel + '13)

Lovell, Bose, CSF et al. 16



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!

Cold Dark Matter	Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter warm dark matter

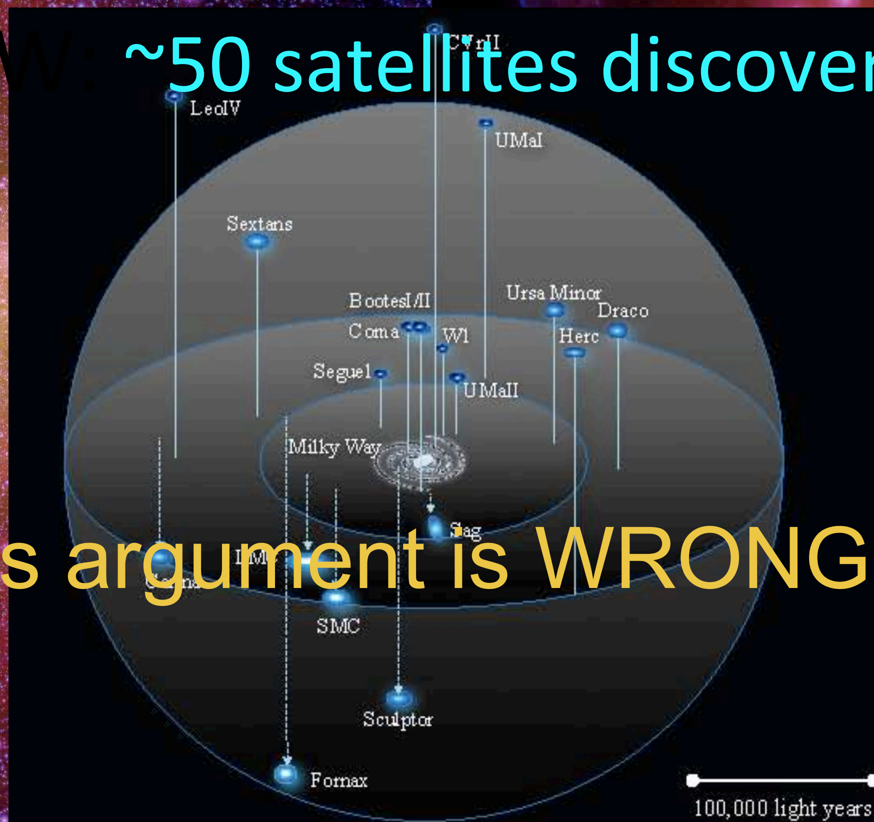
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31

In the MW: ~50 satellites discovered so far



This argument is WRONG!

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

Most subhalos never make a galaxy!

Because:

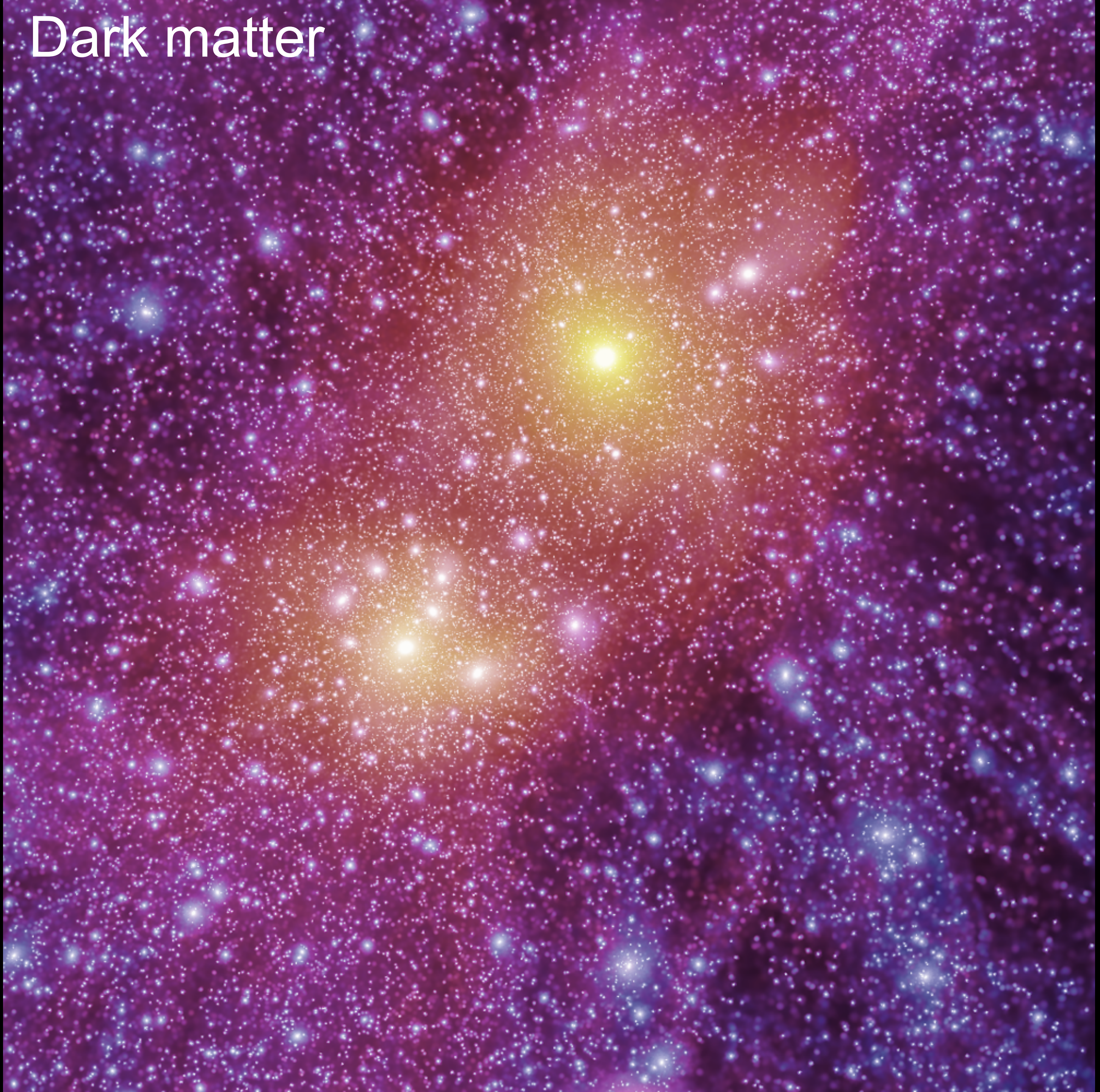
- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

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

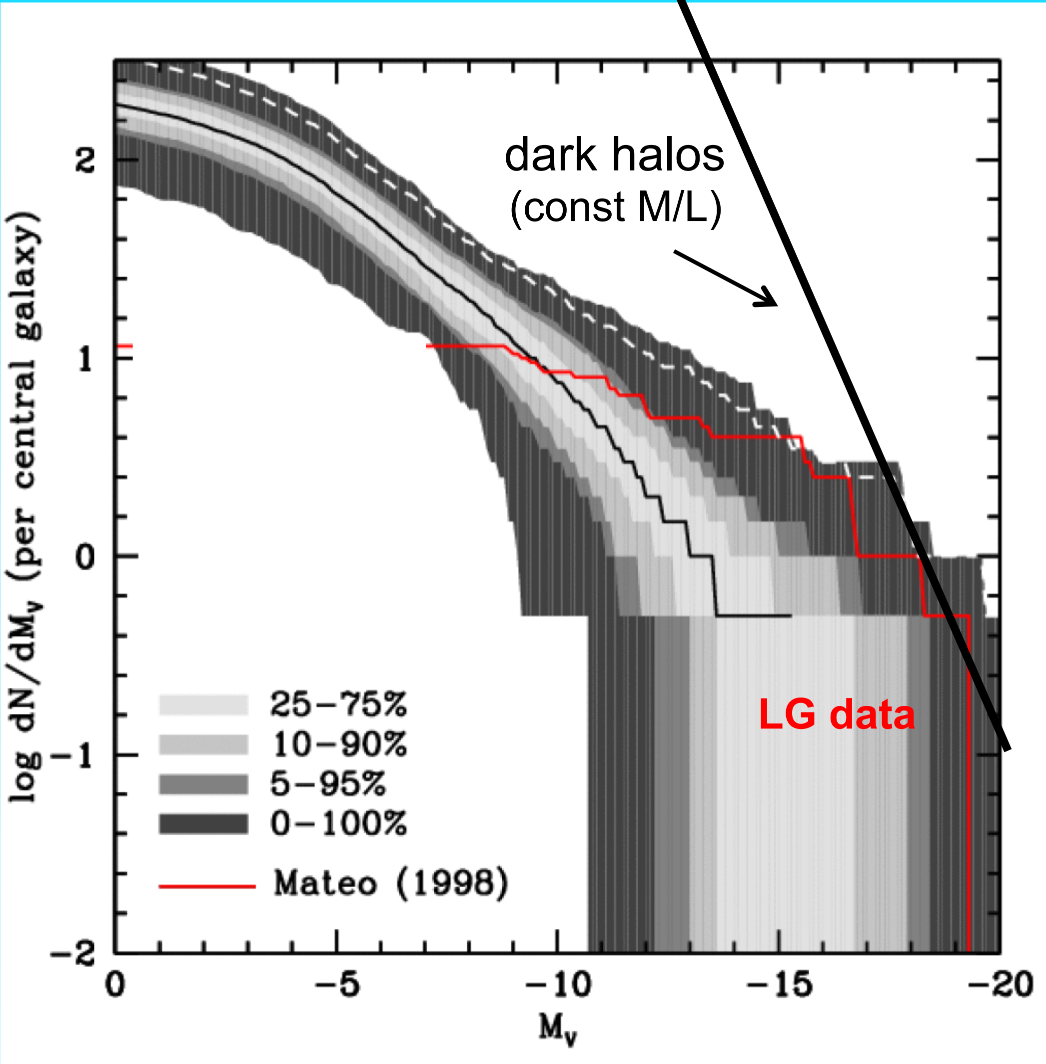
Sawala et al ‘16

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)

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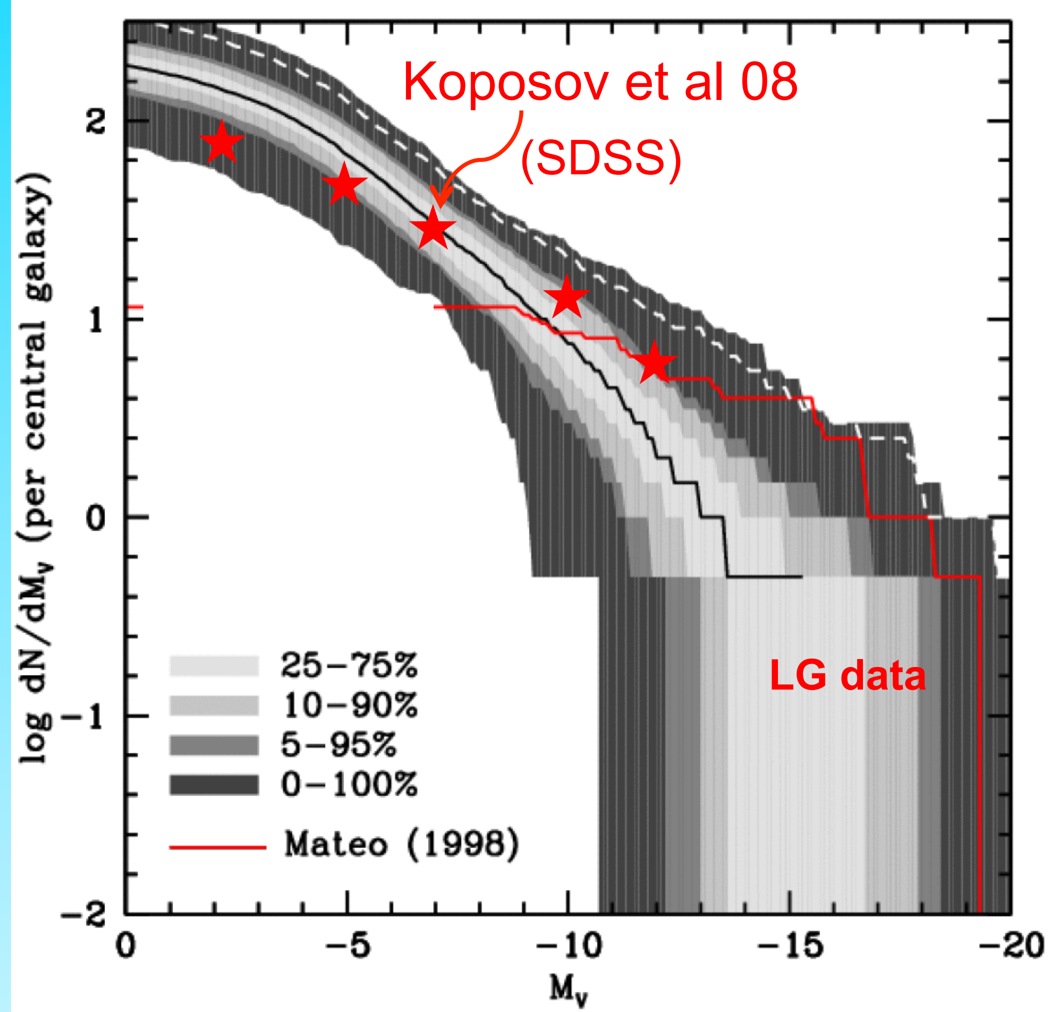

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EAGLE Local Group simulation

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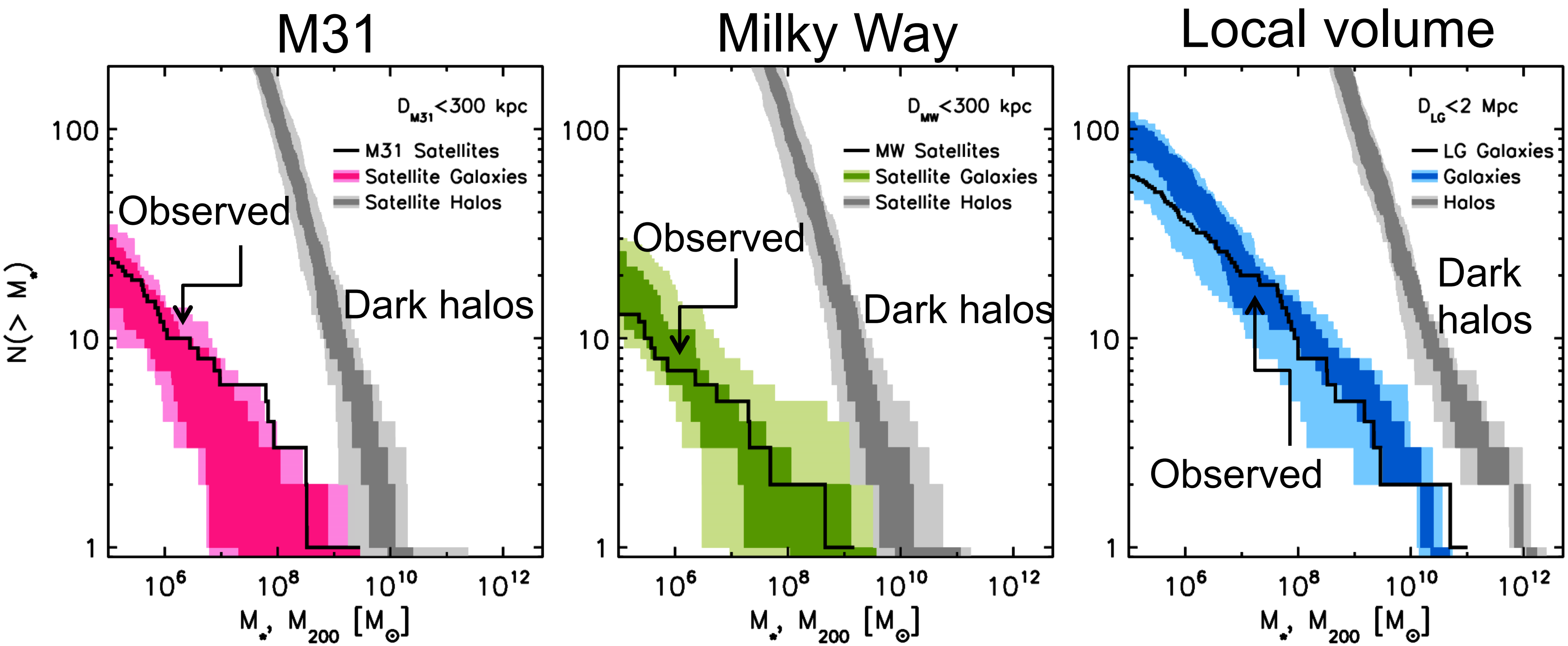

Sawala, CSF et al '16

Fraction of dark subhalos

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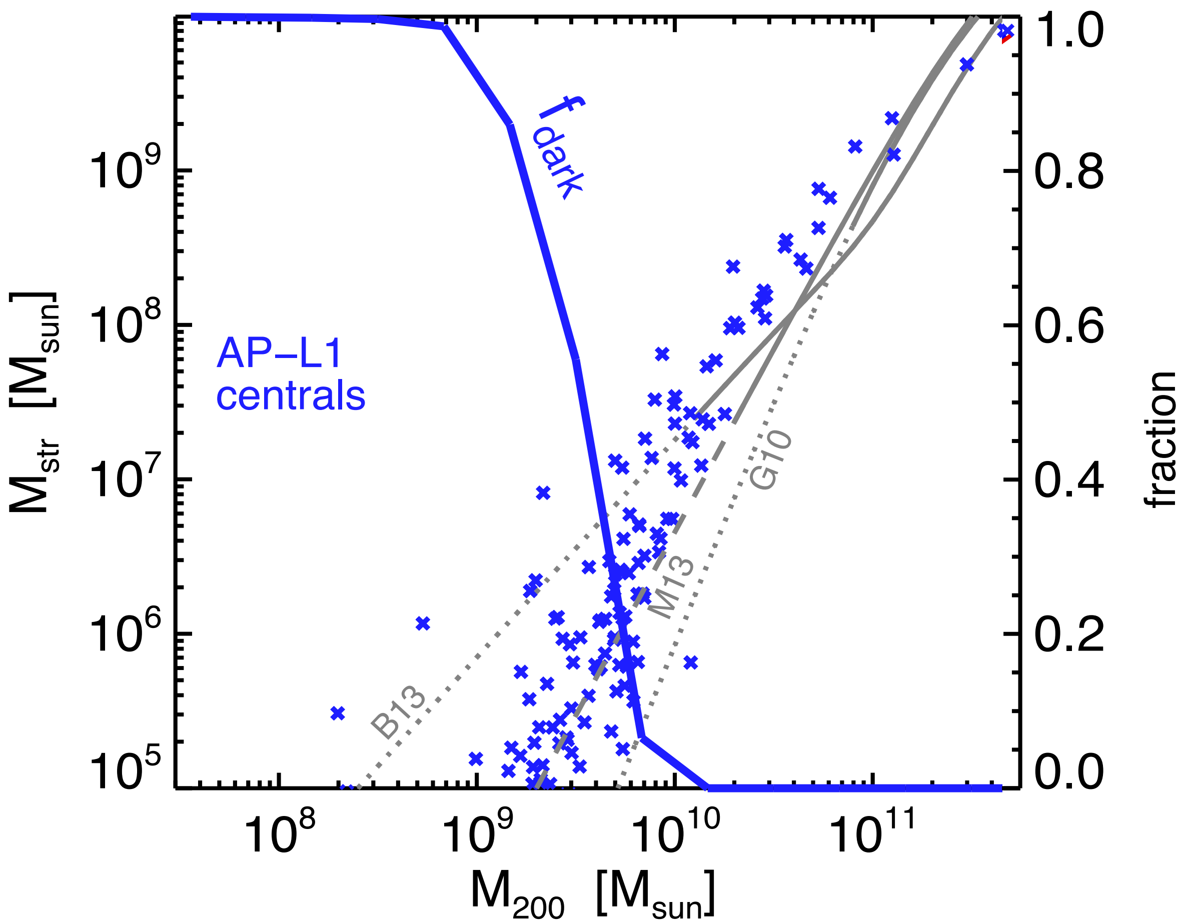
$$V_c = \sqrt{\frac{GM}{r}}$$

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



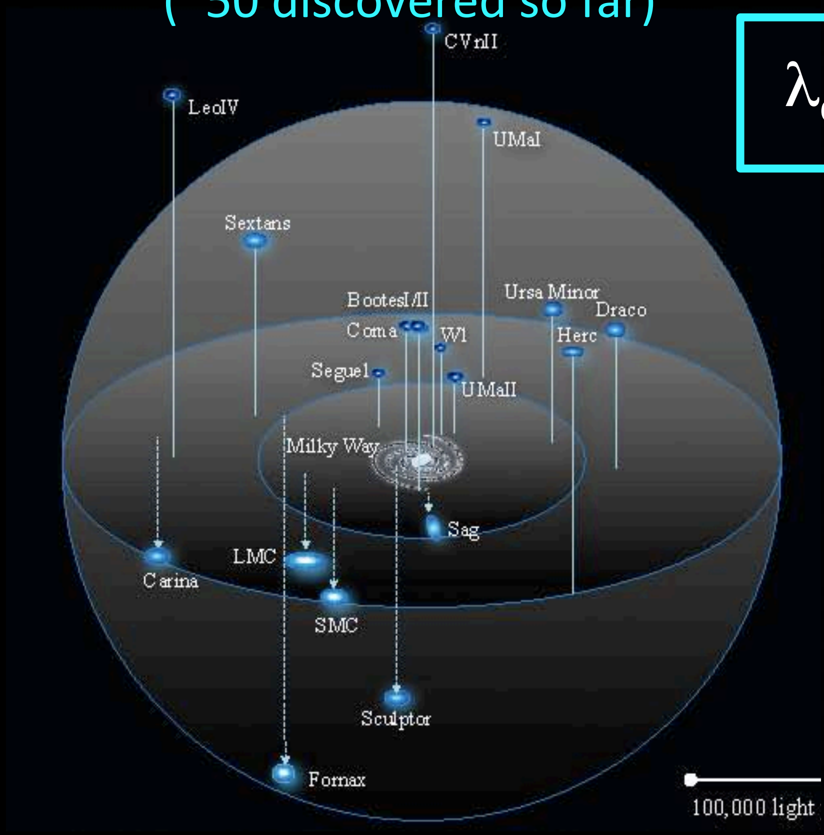
All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

Fattahi et al '16

How about in WDM?

The satellites of the MW

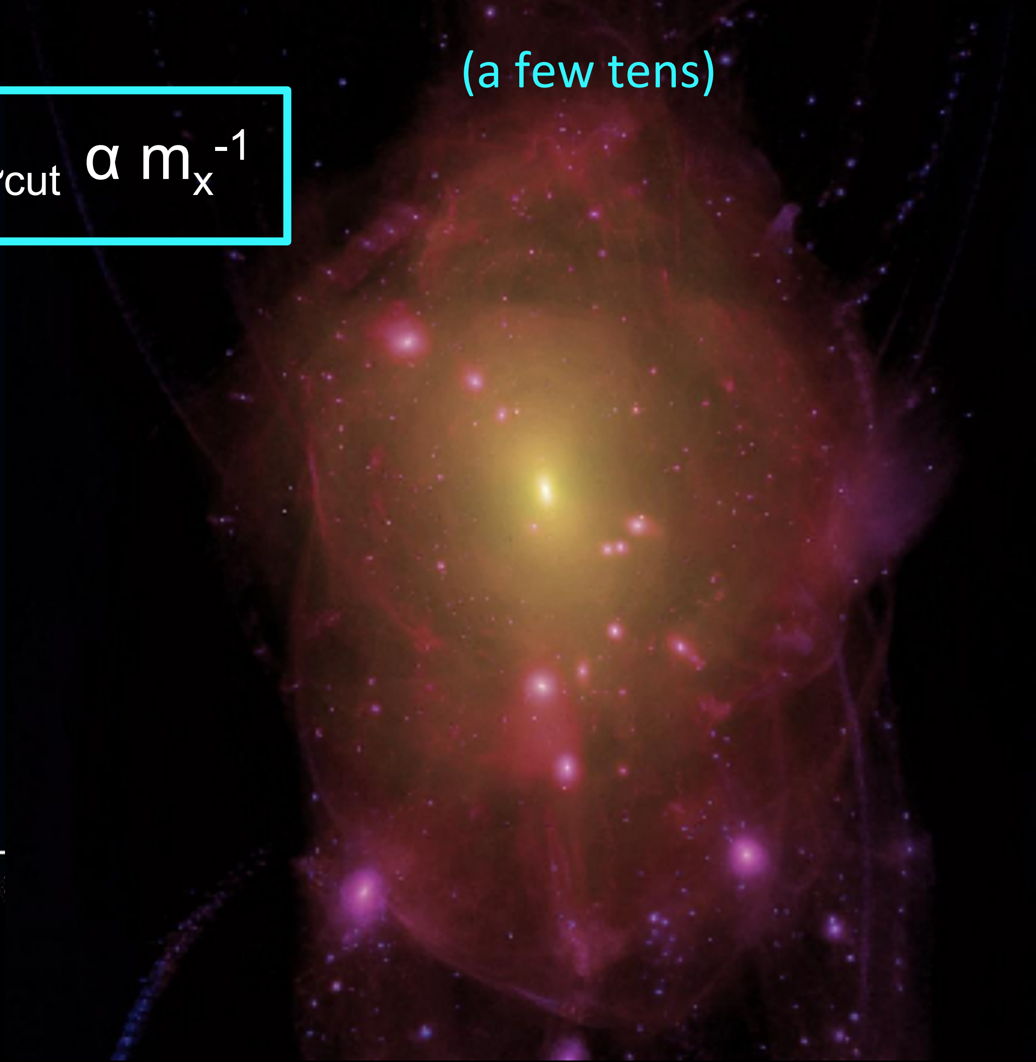
(~50 discovered so far)



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

Dark matter subhalos in WDM

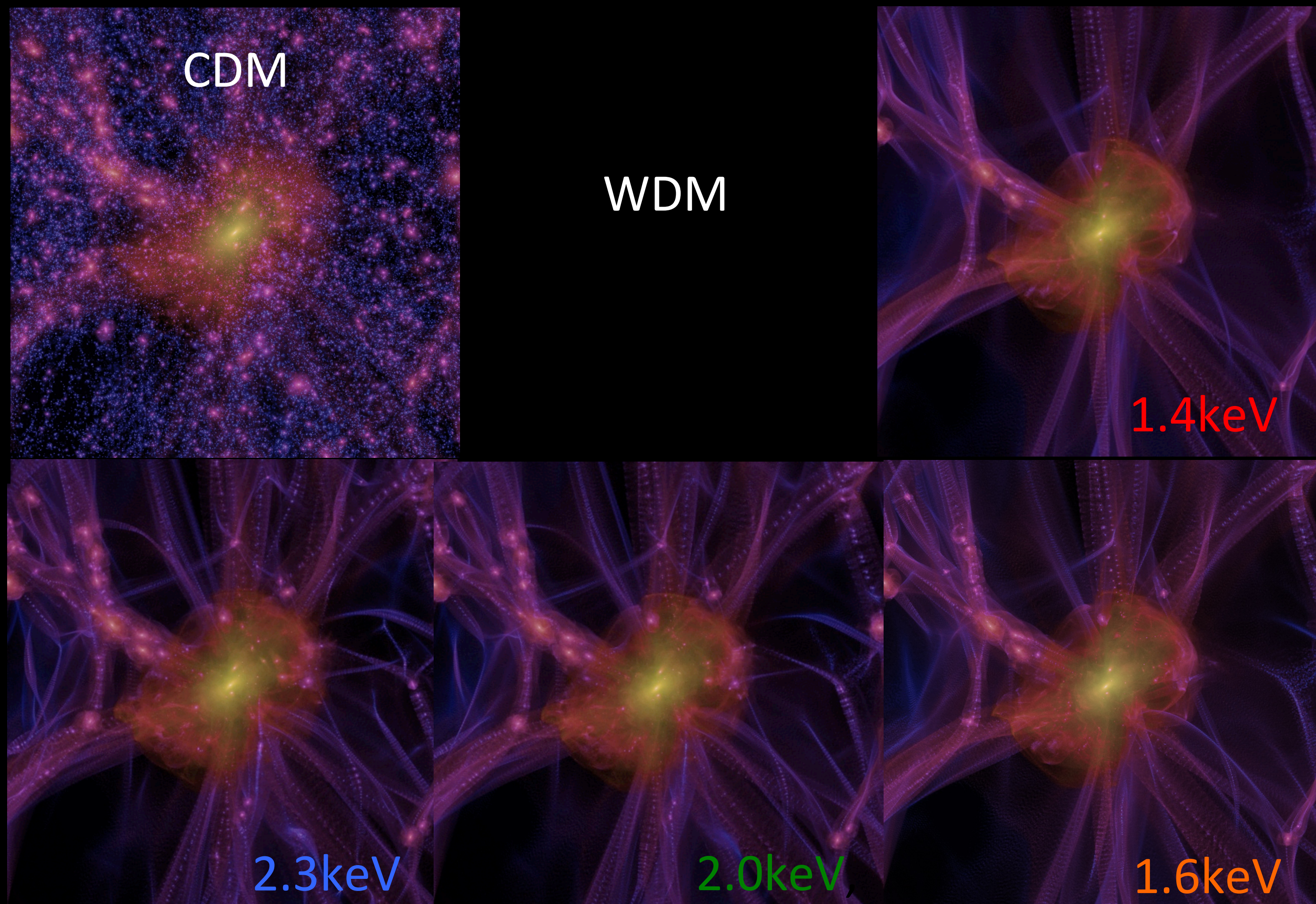
(a few tens)



Thermal warm DM: different ν mass

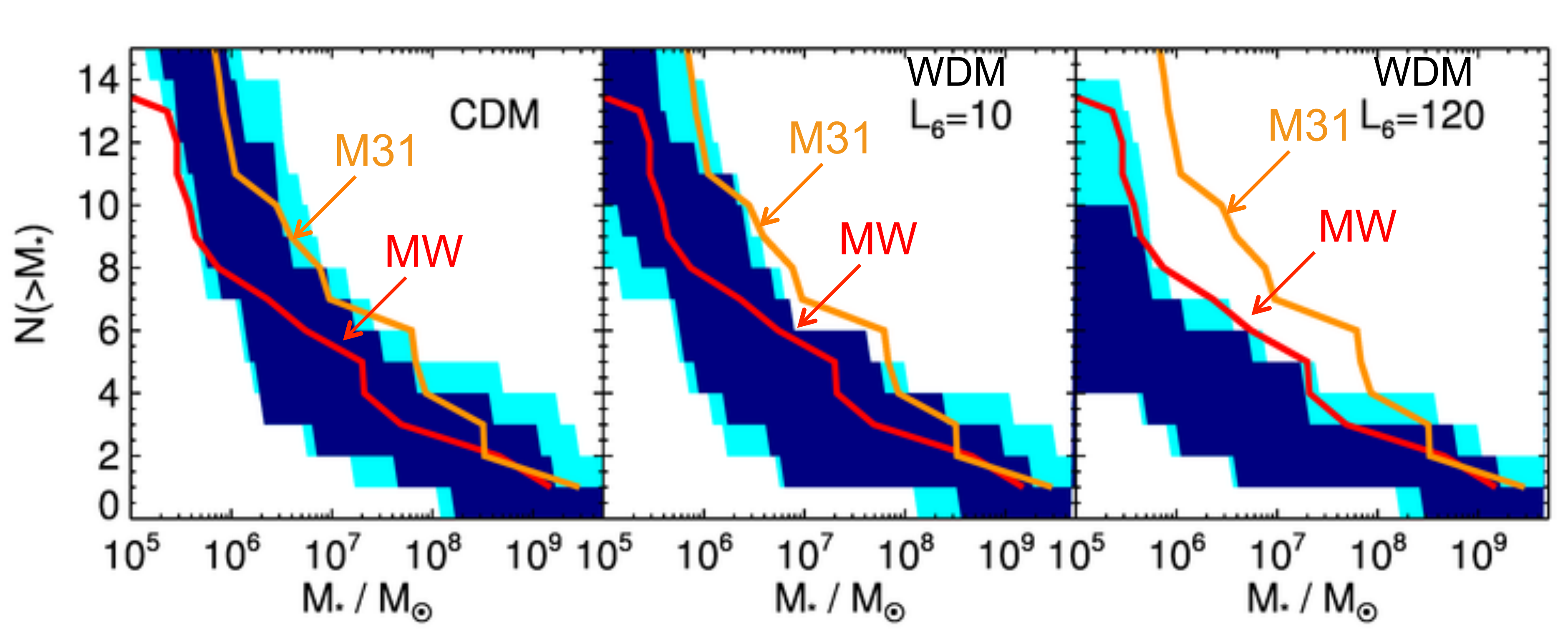
z=3

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 νMSM $M_h \sim 10^{12} M_o$



→ Can rule out parts of sterile ν parameter space

Lovell et al. '16

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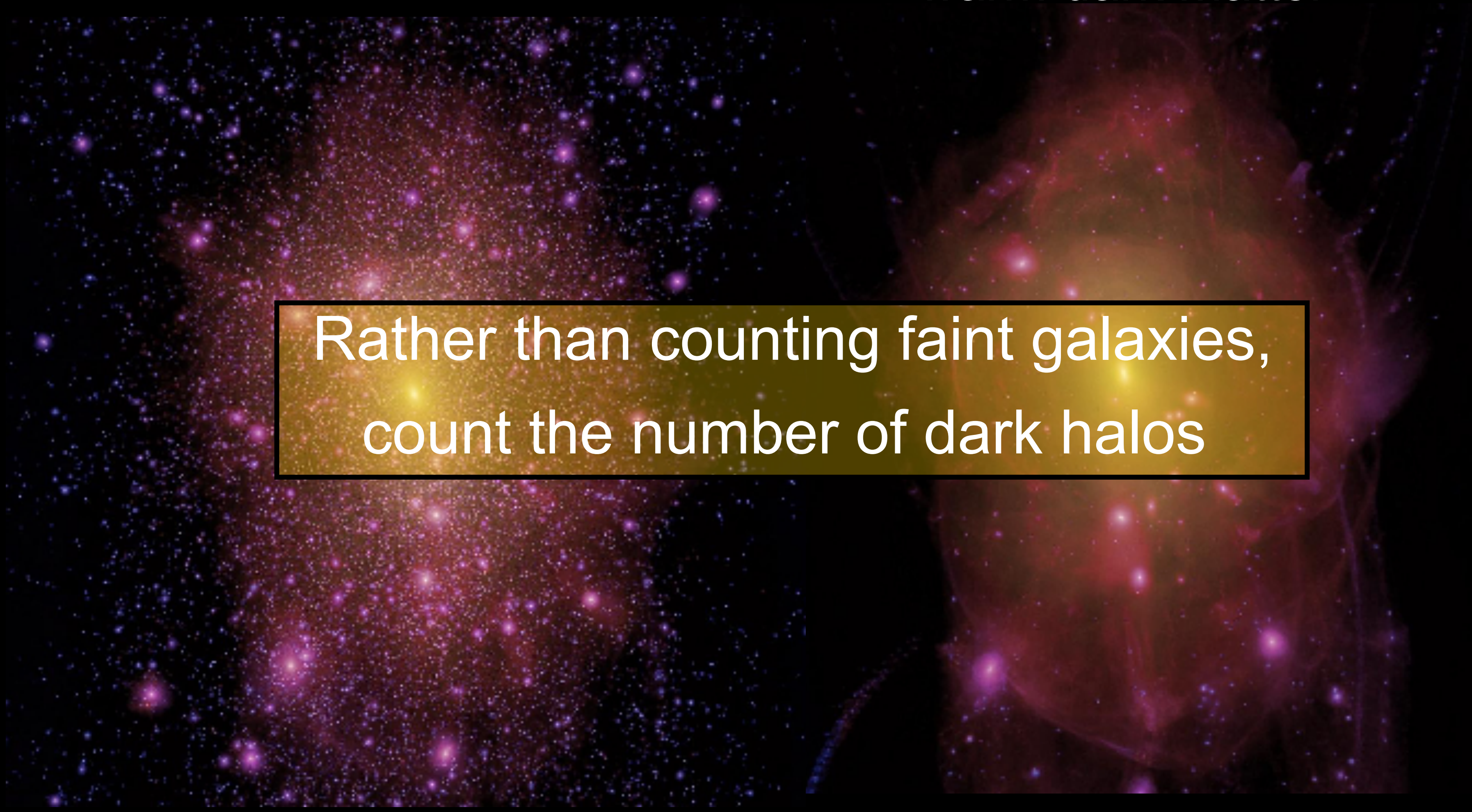
Is there any way can distinguish CDM from WDM?

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

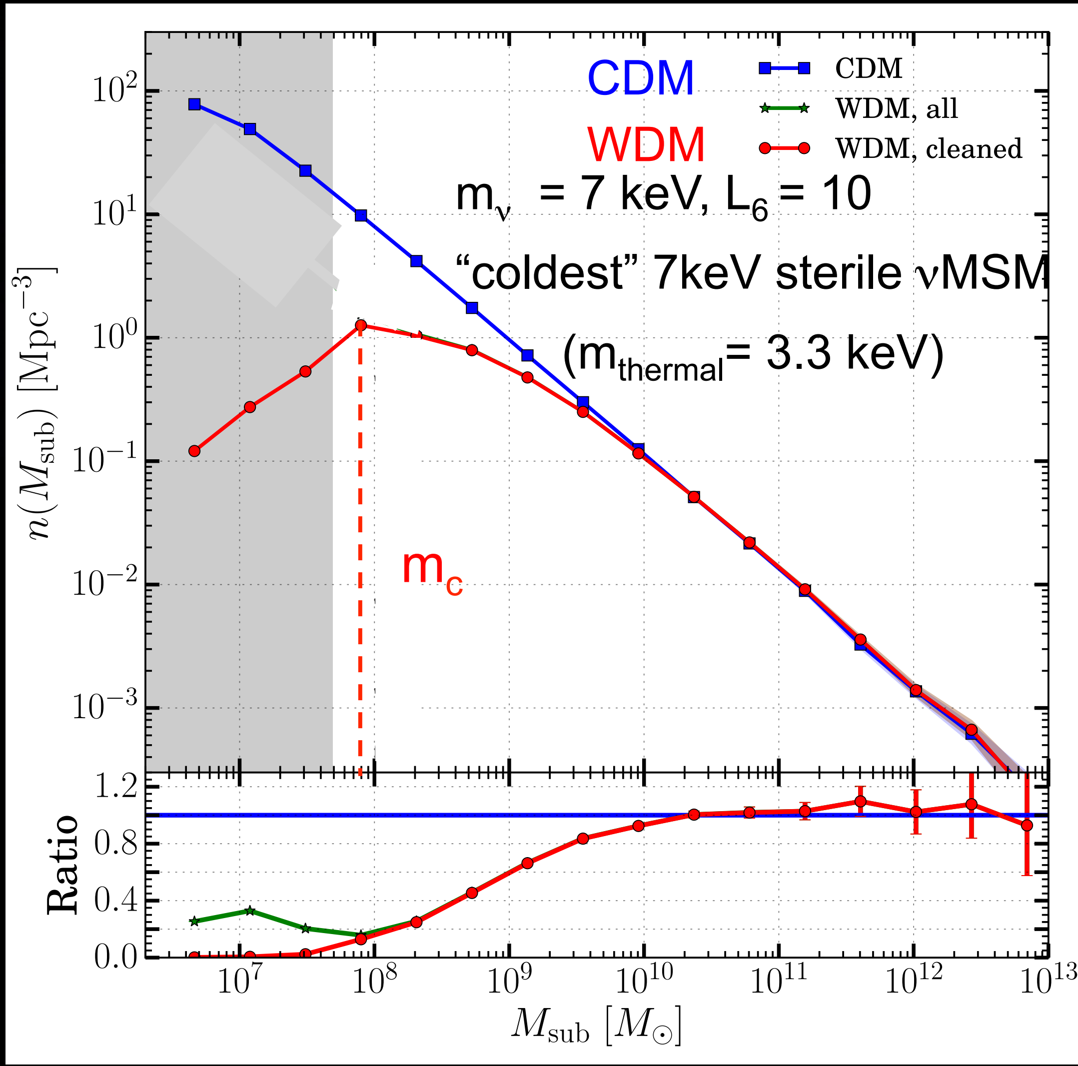
Can we distinguish CDM/WDM?

cold dark matter | warm dark matter



The subhalo mass function

CDM   WDM



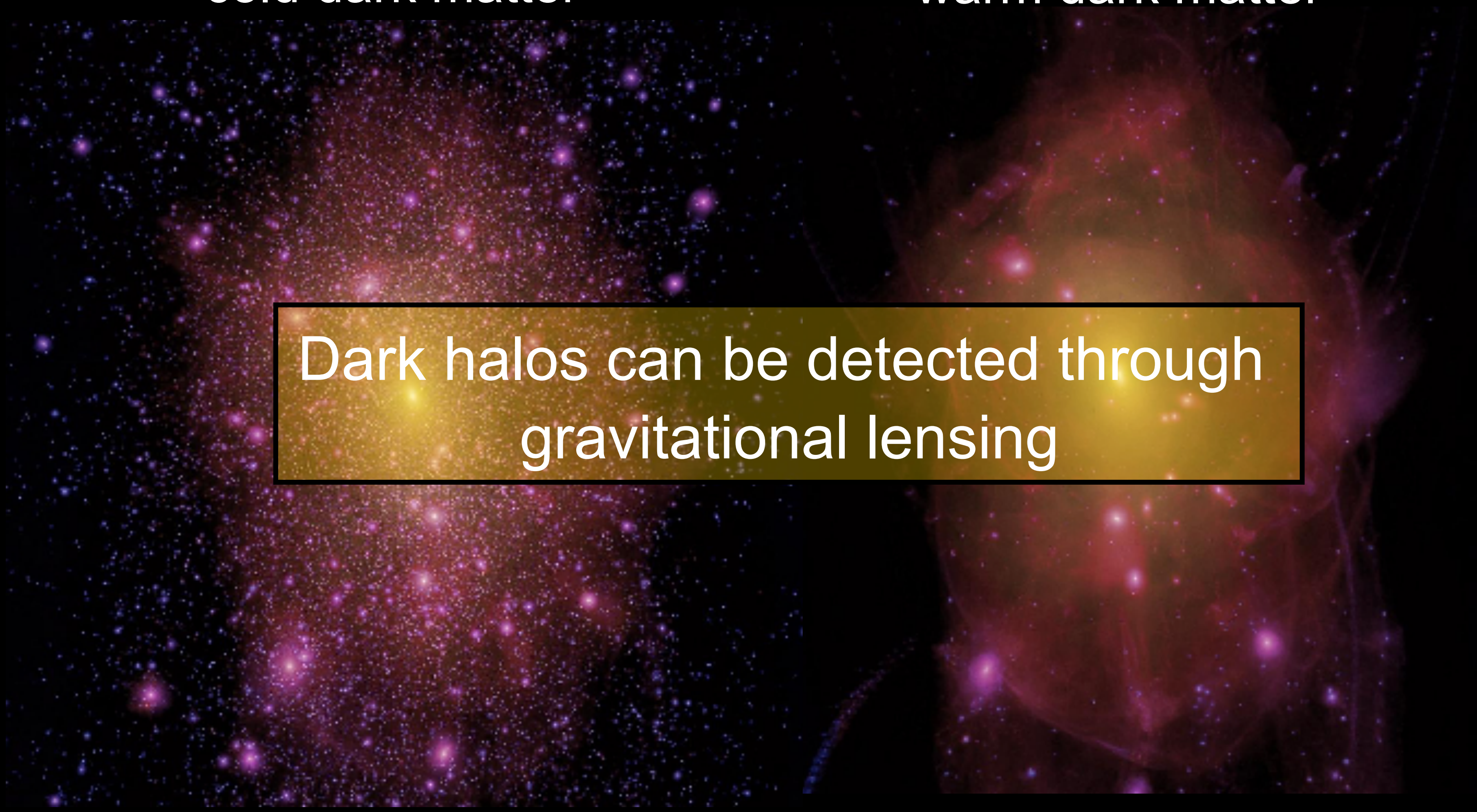
3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

Bose, CSF et al '16

Can we distinguish CDM/WDM?

cold dark matter | warm dark matter

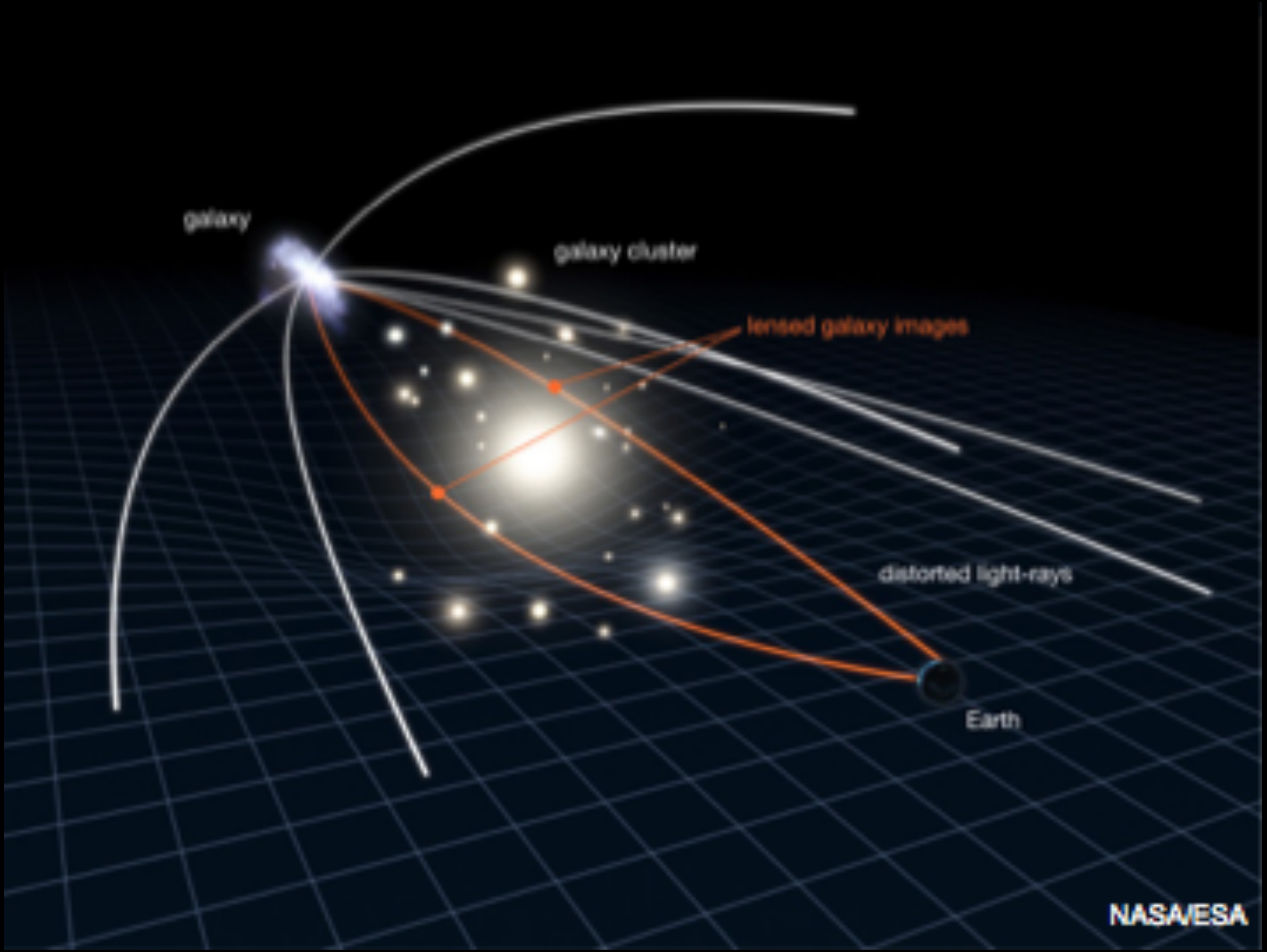


Dark halos can be detected through gravitational lensing

Gravitational lensing: Einstein rings

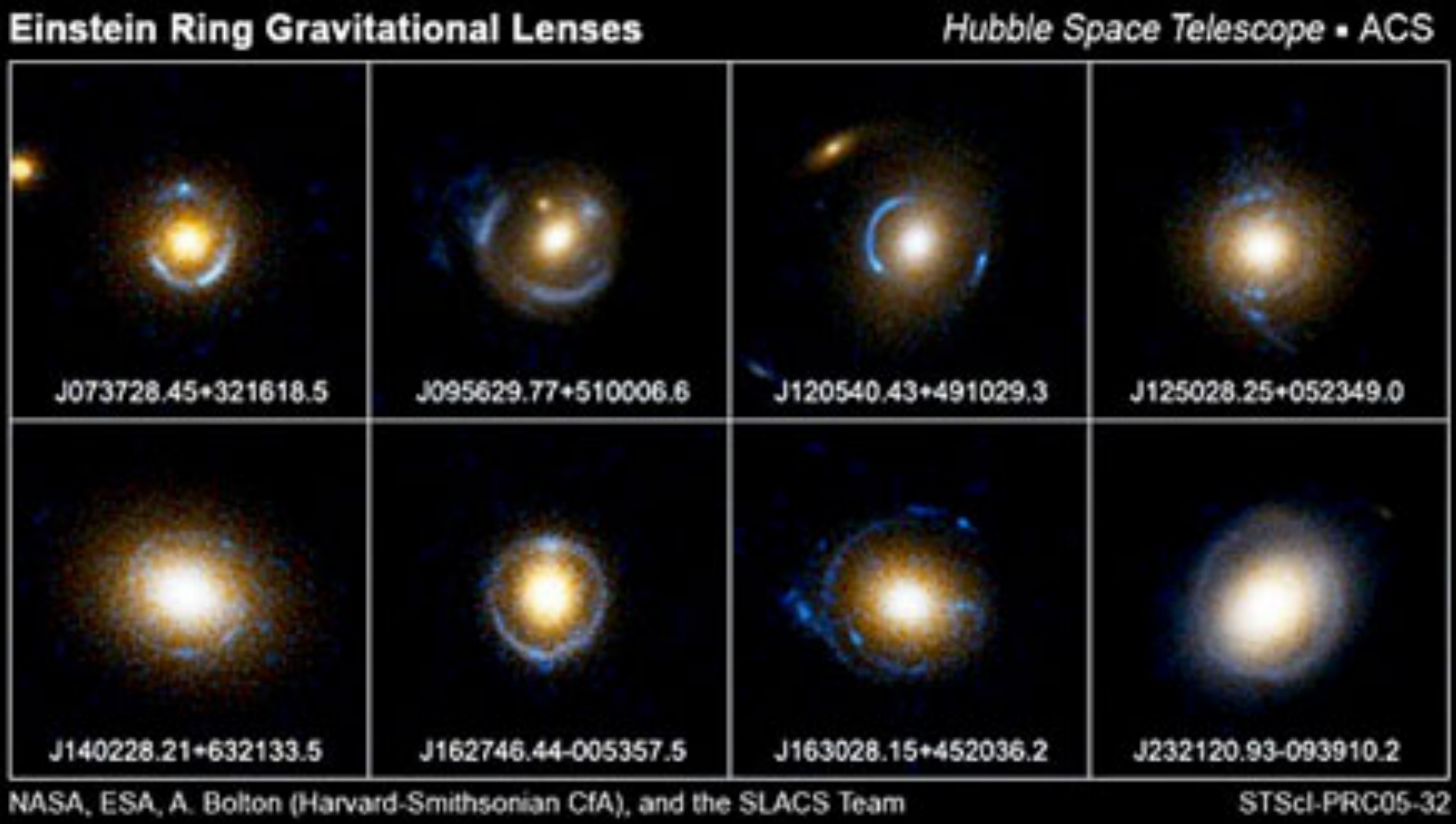
How to rule out CDM

Gravitational lensing: Einstein rings

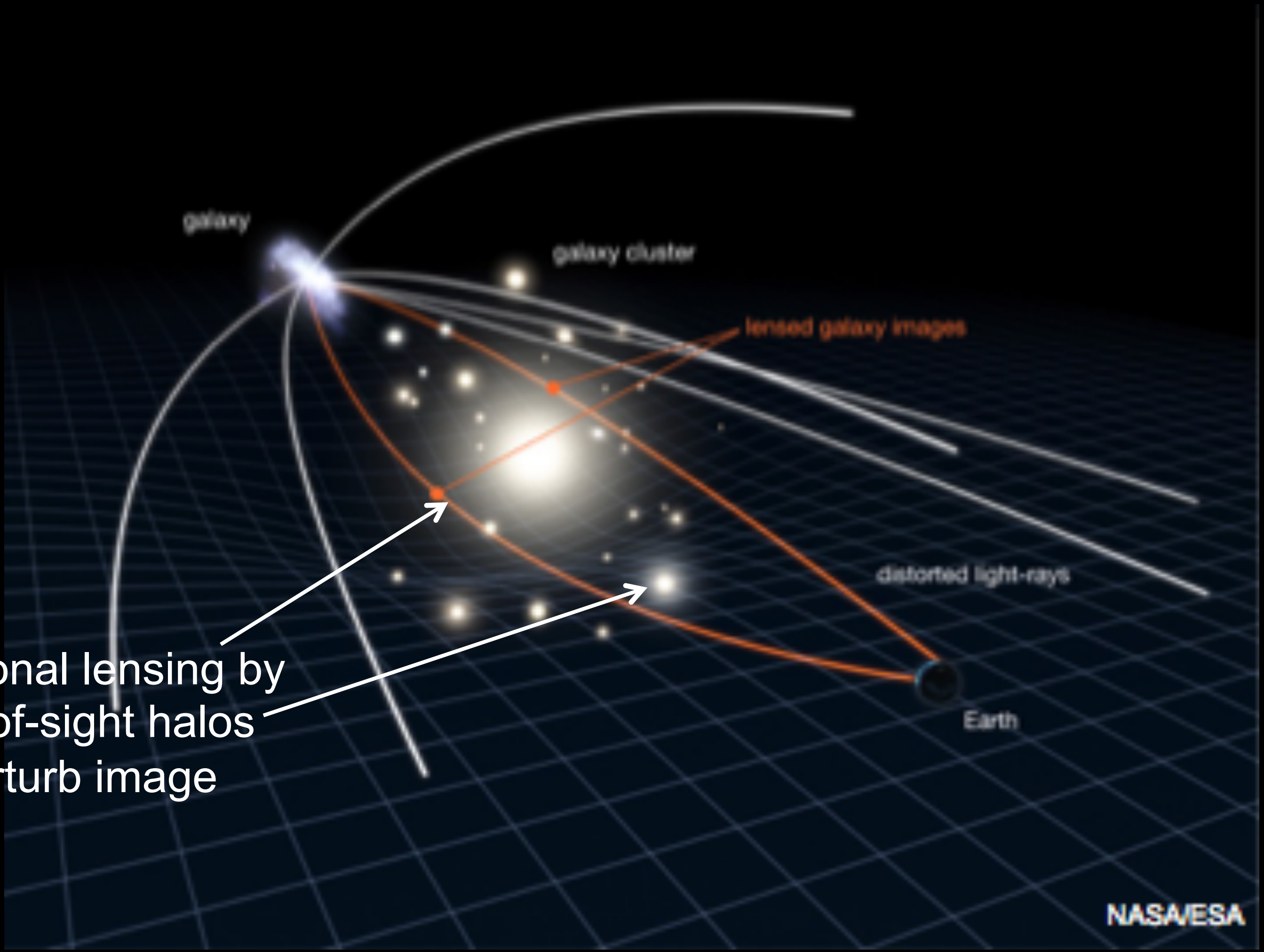


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



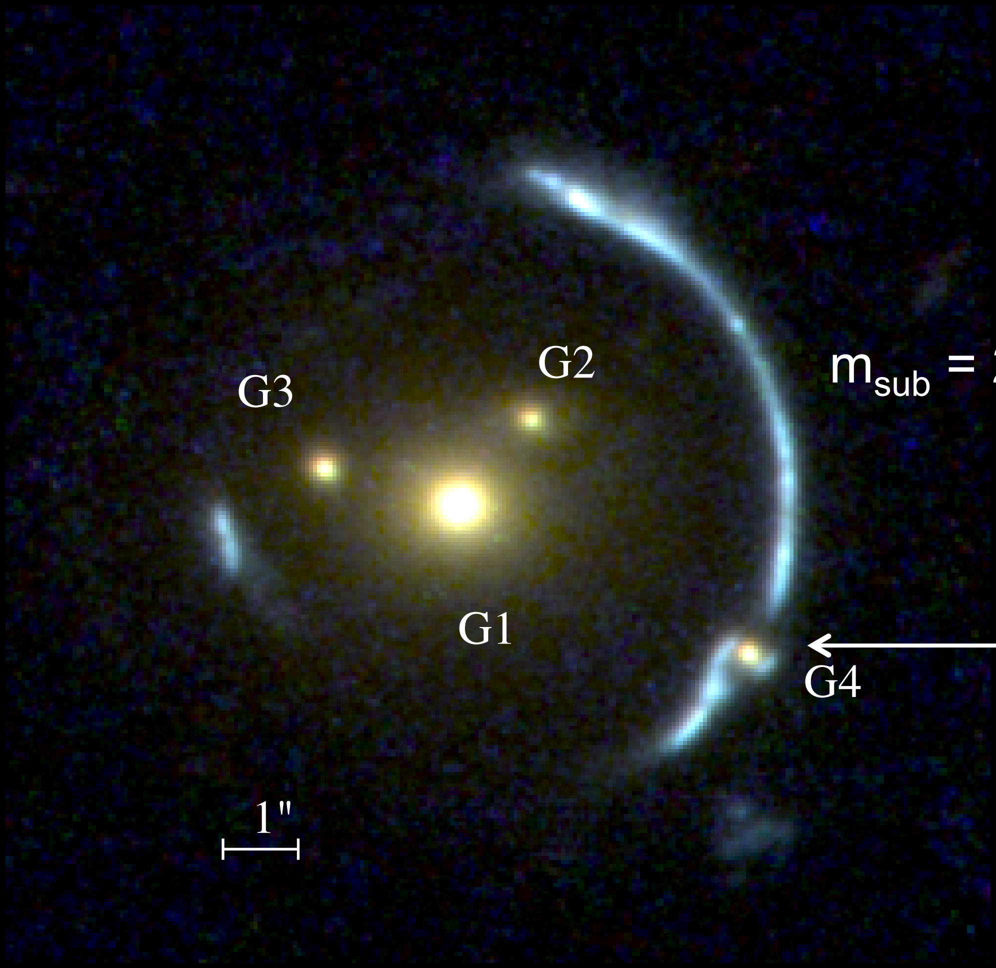
Gravitational lensing: Einstein rings



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

Gravitational lensing: Einstein rings

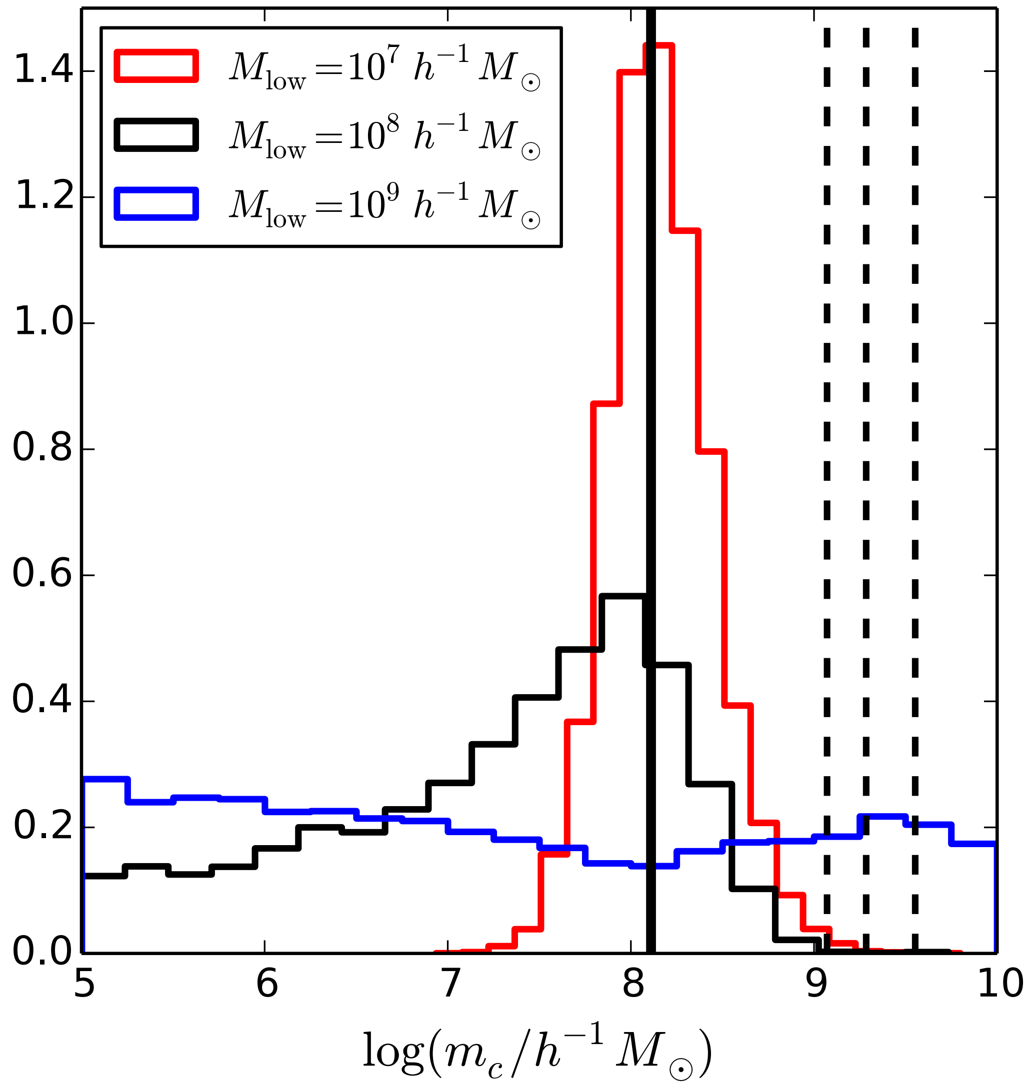
Halos projected onto an Einstein ring distort the image



$m_{sub} = 2.8 \times 10^{10}\, M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings



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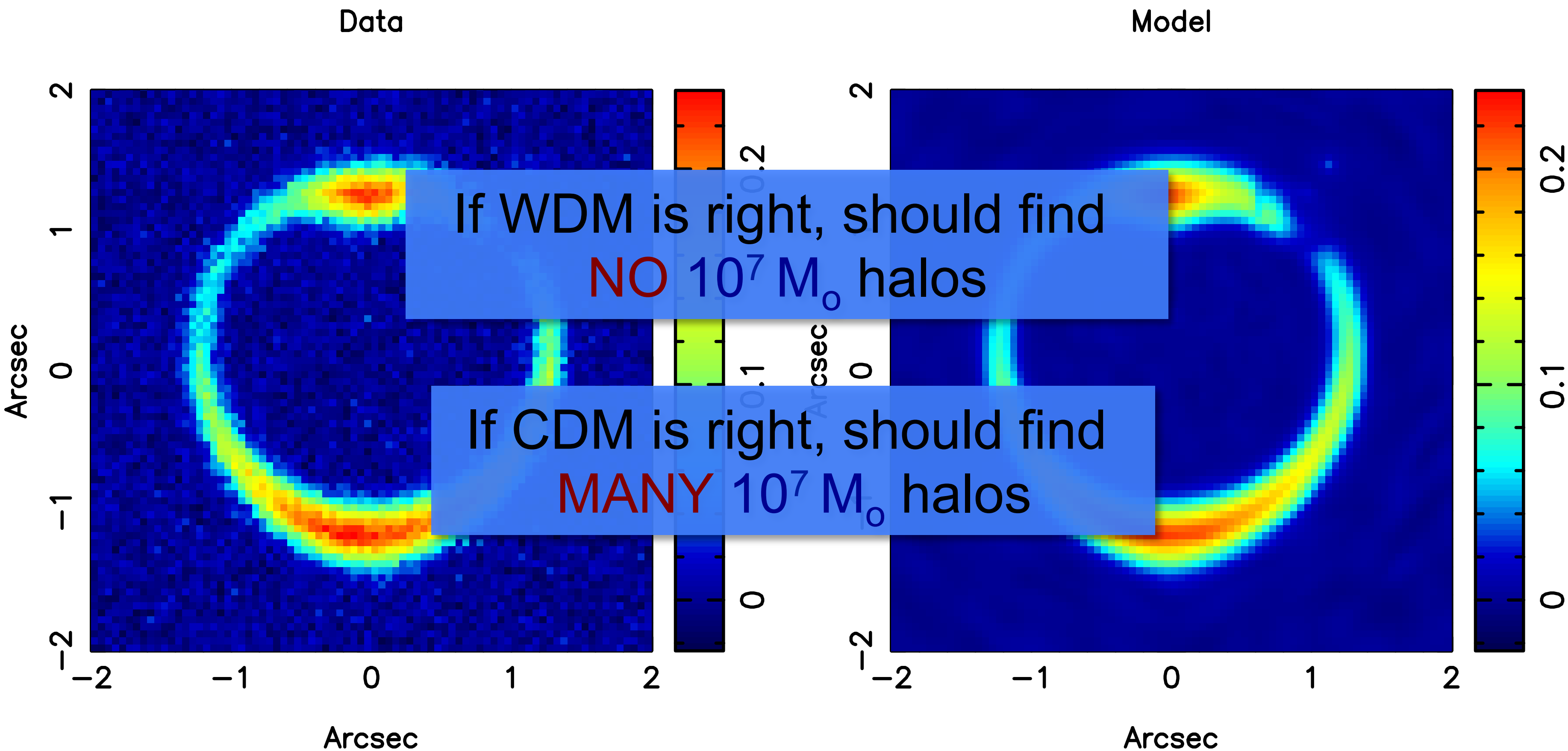
Detecting substructures with strong lensing

Can detect subhalos as small as $10^7 - 10^8 M_o$

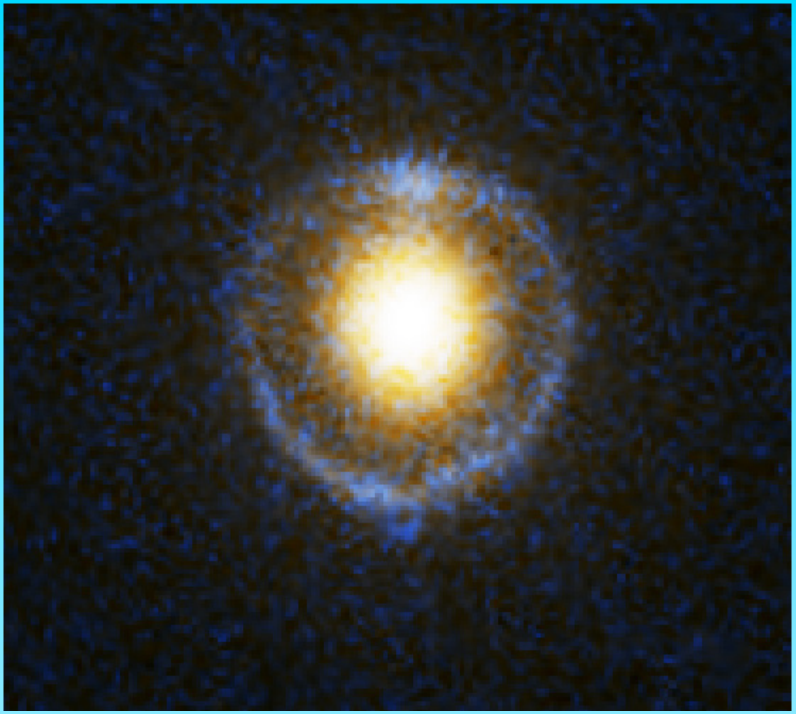


If WDM is right, should find NO 10^7 M_o halos

If CDM is right, should find MANY 10^7 M_o halos

Vegetti & Koopmans ‘09

Gravitational lensing: Einstein rings



Two important considerations:

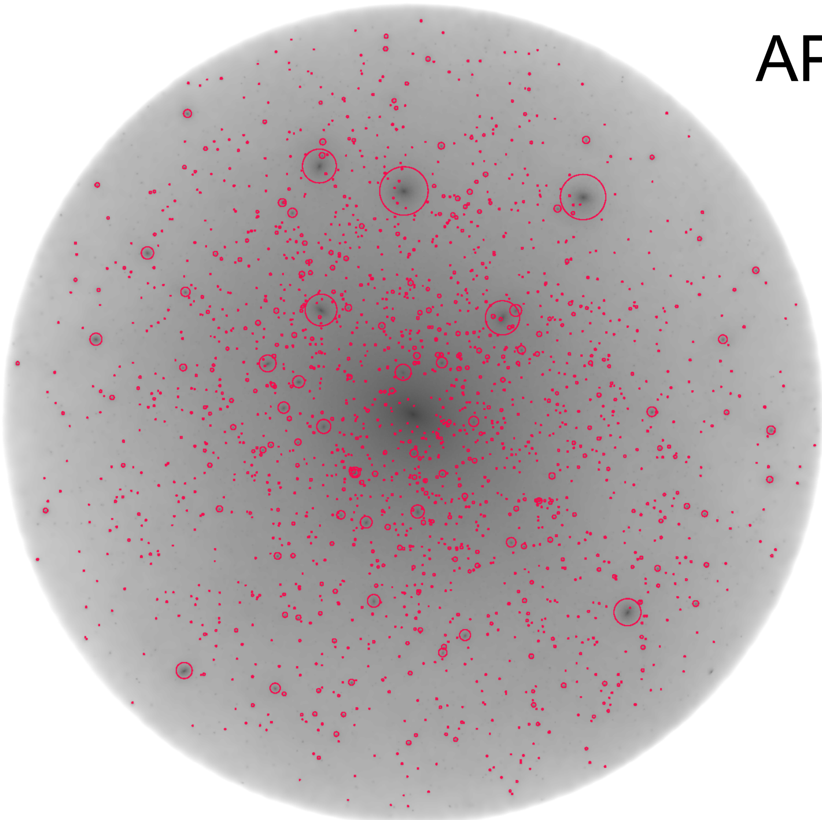
- The central galaxy can destroy subhalos
- Both subhalos and line-of-sight projected halos lens

Sawala et al ’17

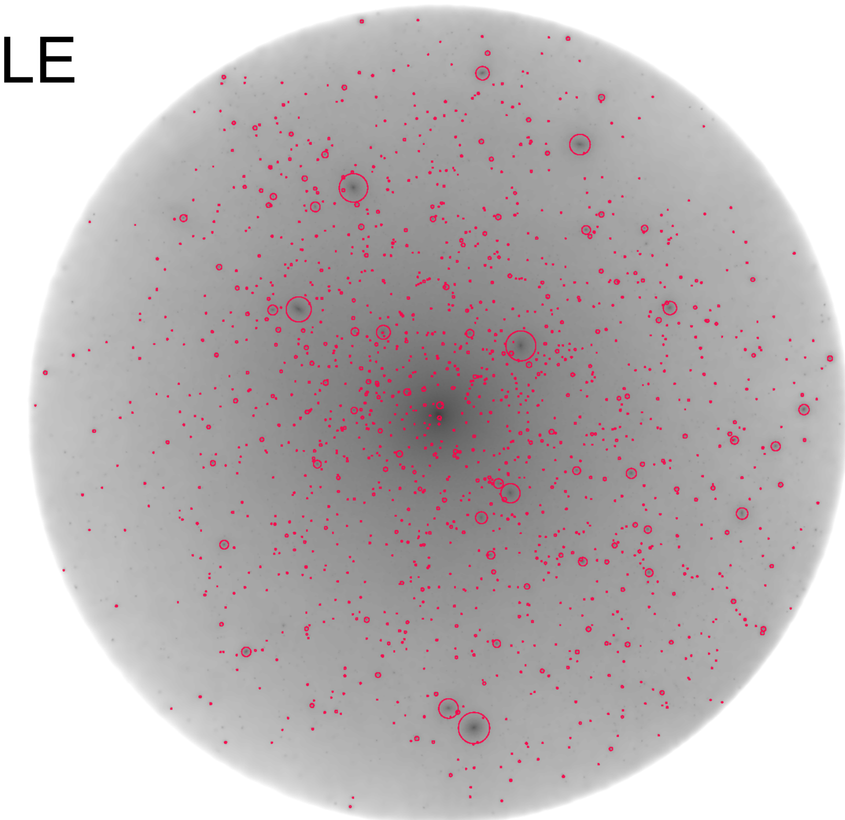
Richings et al ‘17

Destruction of dark substructures by galactic baryons

APOSTLE



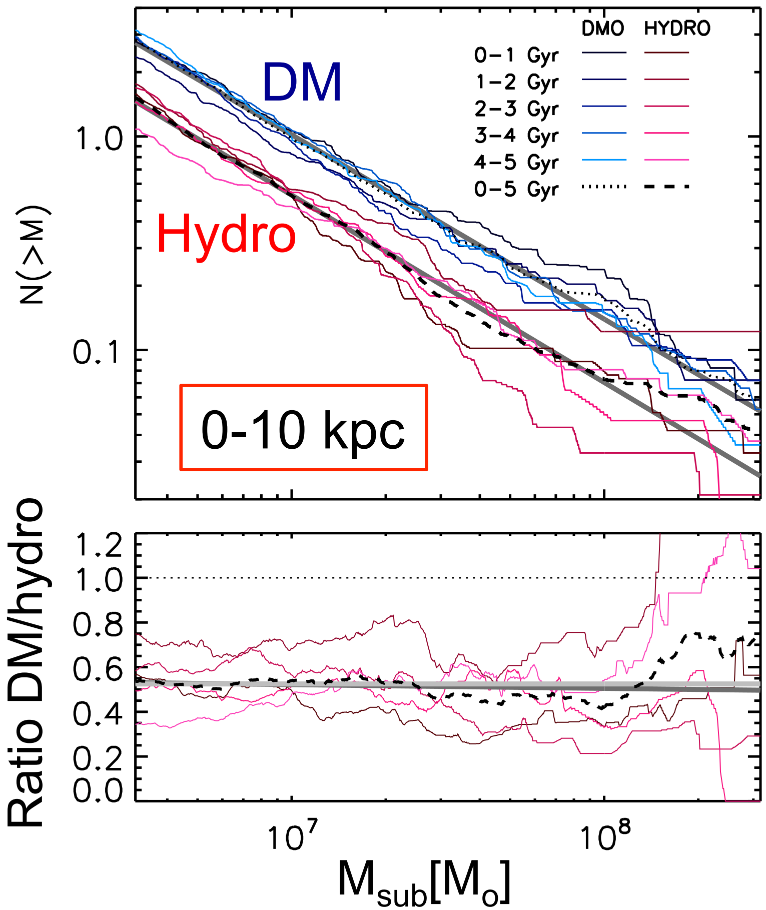
Dark matter only simulation

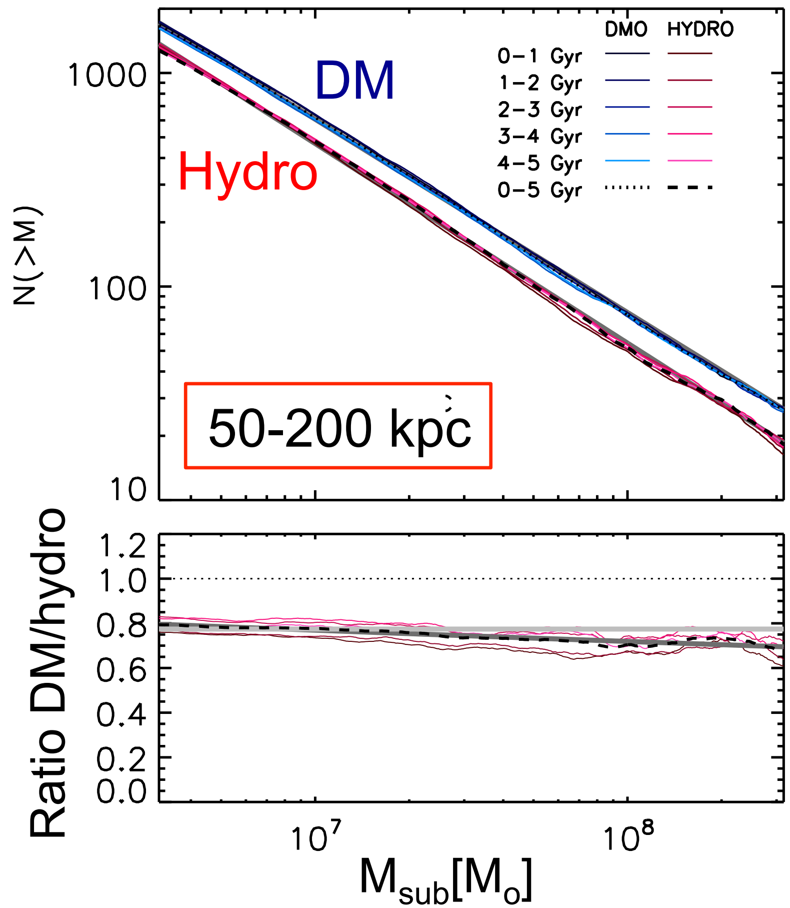


Hydrodynamic simulation

Sawala et al '17

Destruction of dark substructures by galactic baryons



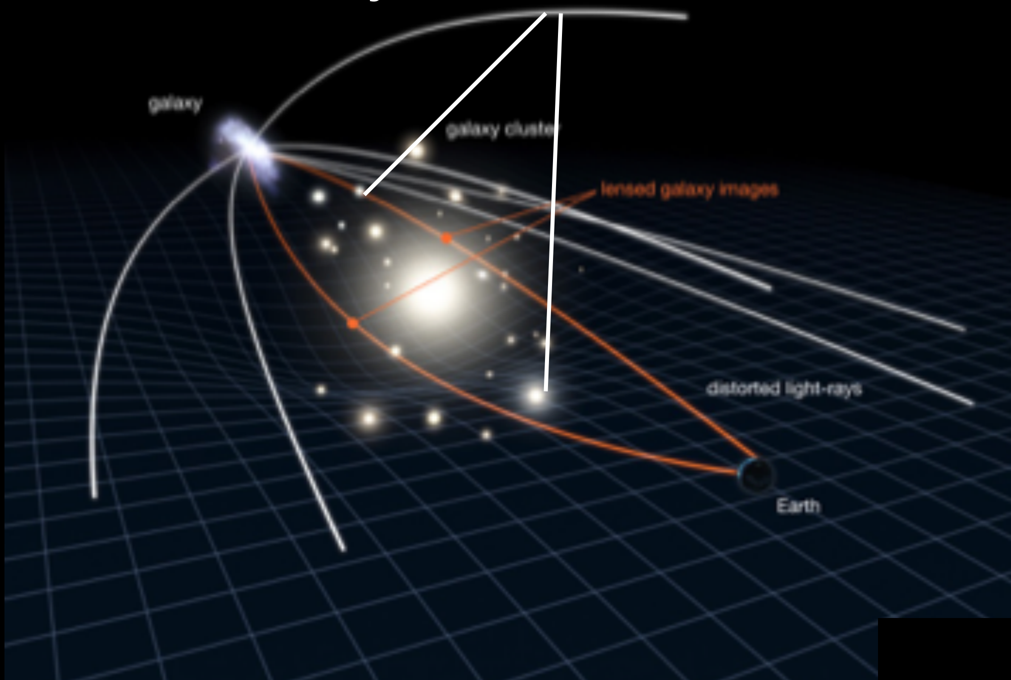


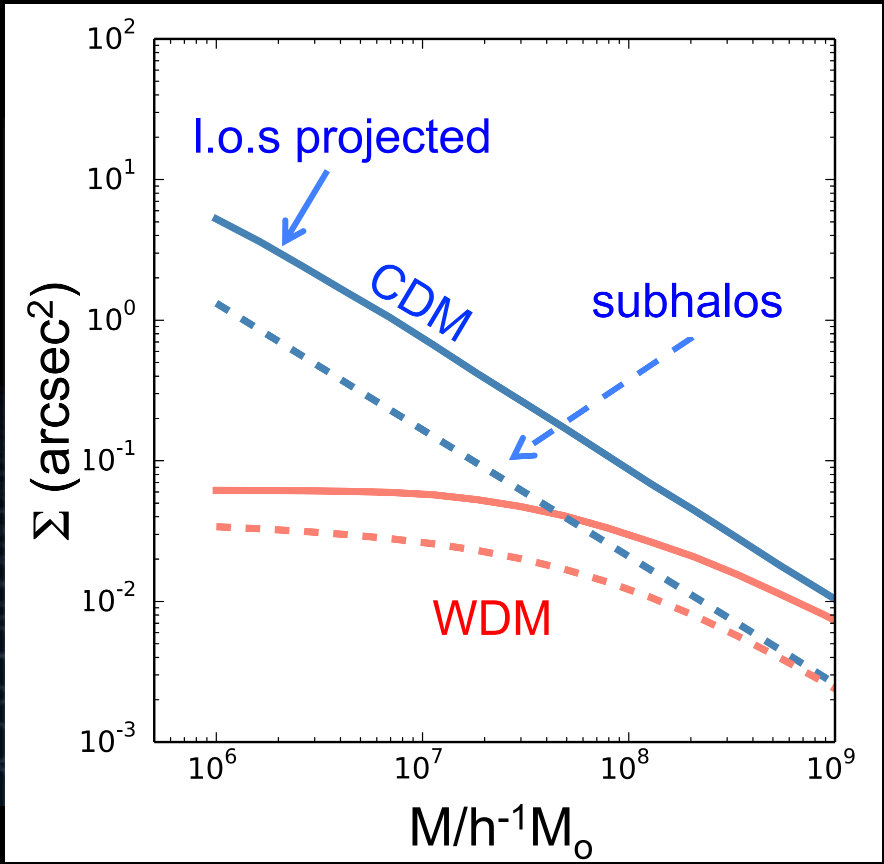
- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
- 20% " 50-200 kpc

Sawala et al '17

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

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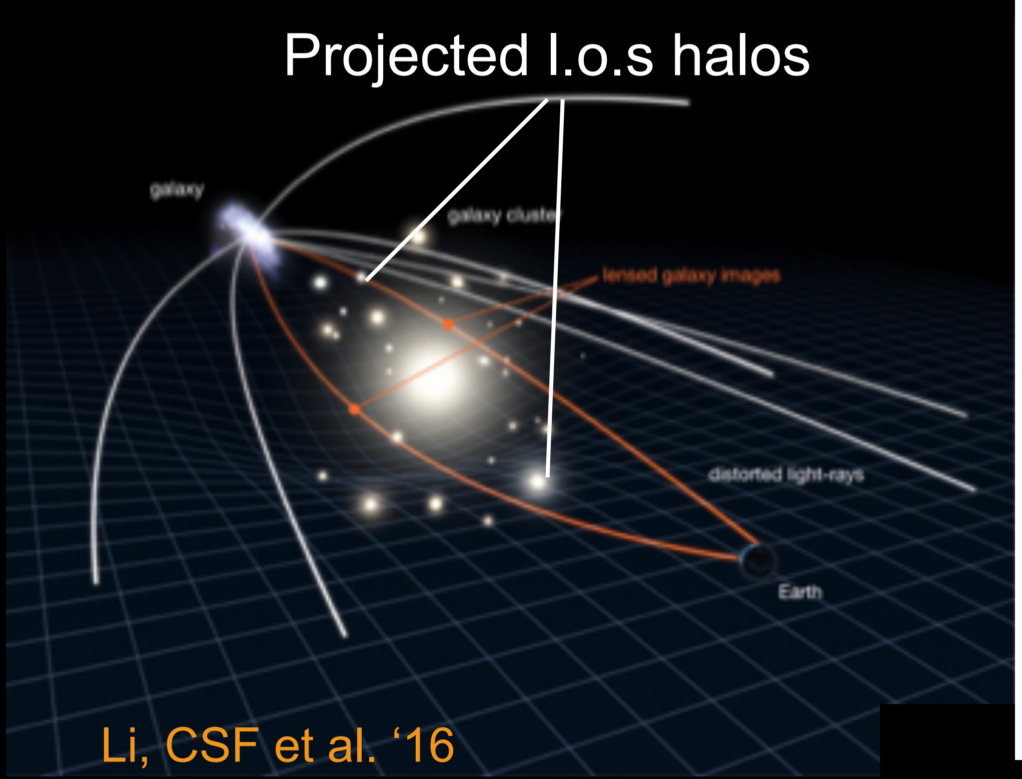
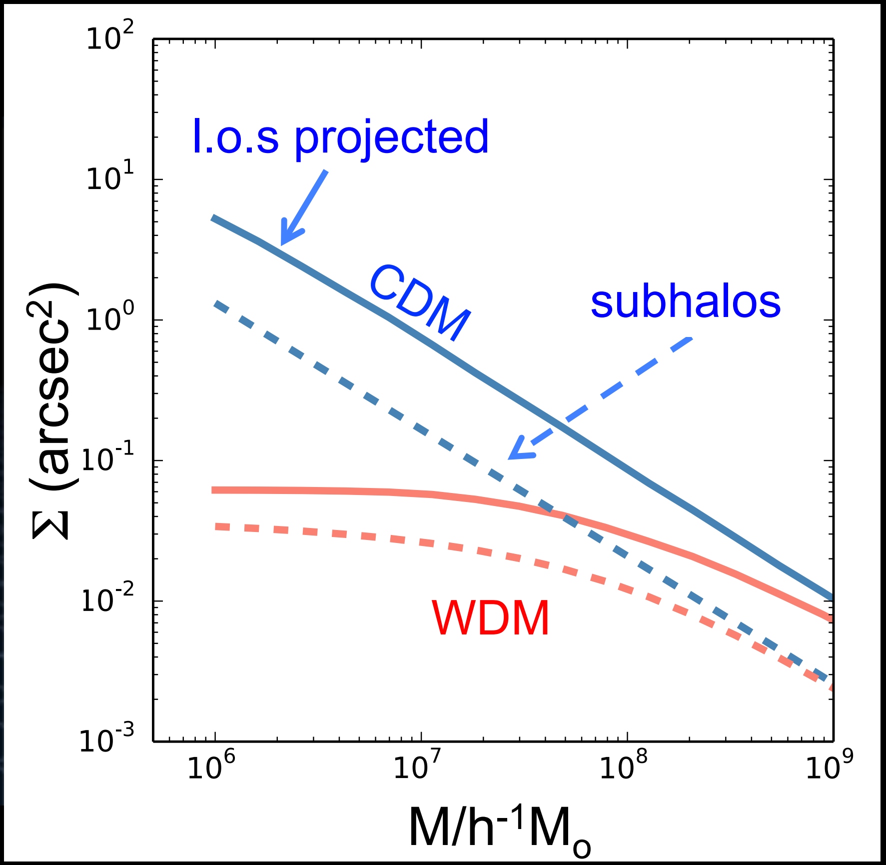




→ This is the cleanest possible test: it depends ONLY on the small-mass end of the “field” halo mass function which we know how to calculate and is unaffected by baryons

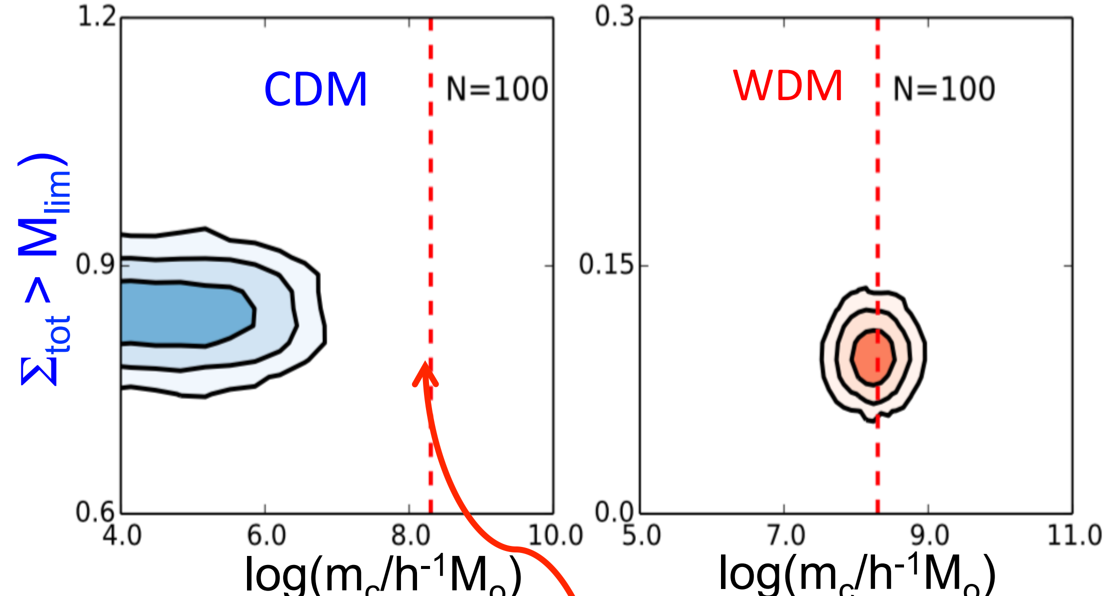
Detecting substructures with strong lensing

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 in ν

MSM 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

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Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- But on these scales ΛCDM cannot be distinguished from WDM
- CDM → many small ($<10^8 M_0$) halos; WDM → only a few

1. Halos < $\sim 5.10^8 M_0$ are dark; halos $>10^{10} M_0$ are bright
2. → Counting satellites won't work!
3. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM

→ and can potentially rule out CDM!