How to rule out cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

... and other viable dark matter models

The new Ogden Centre at Durham

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

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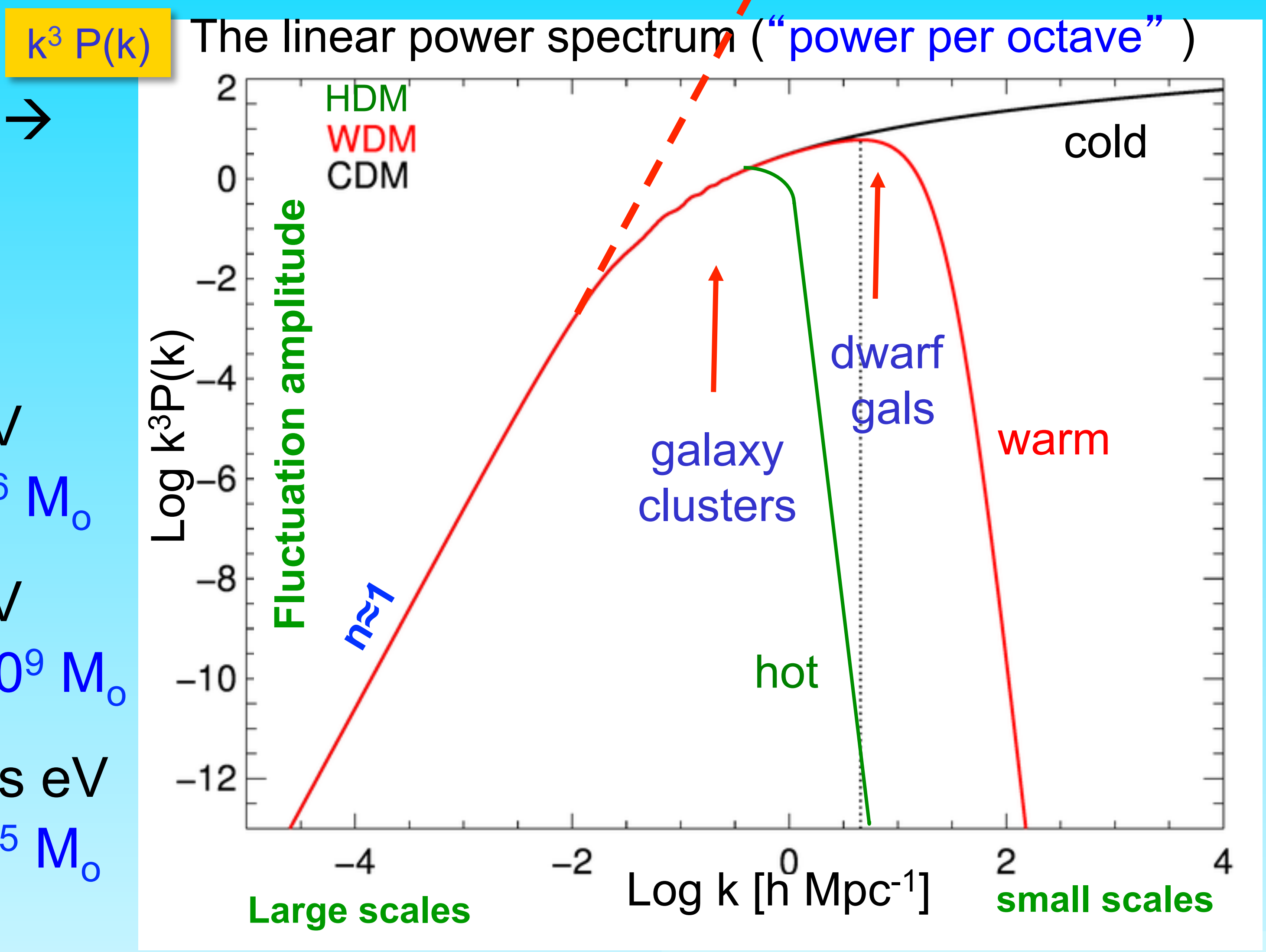
Free streaming →

$\lambda_{cut} \propto m_x^{-1}$
for thermal relic

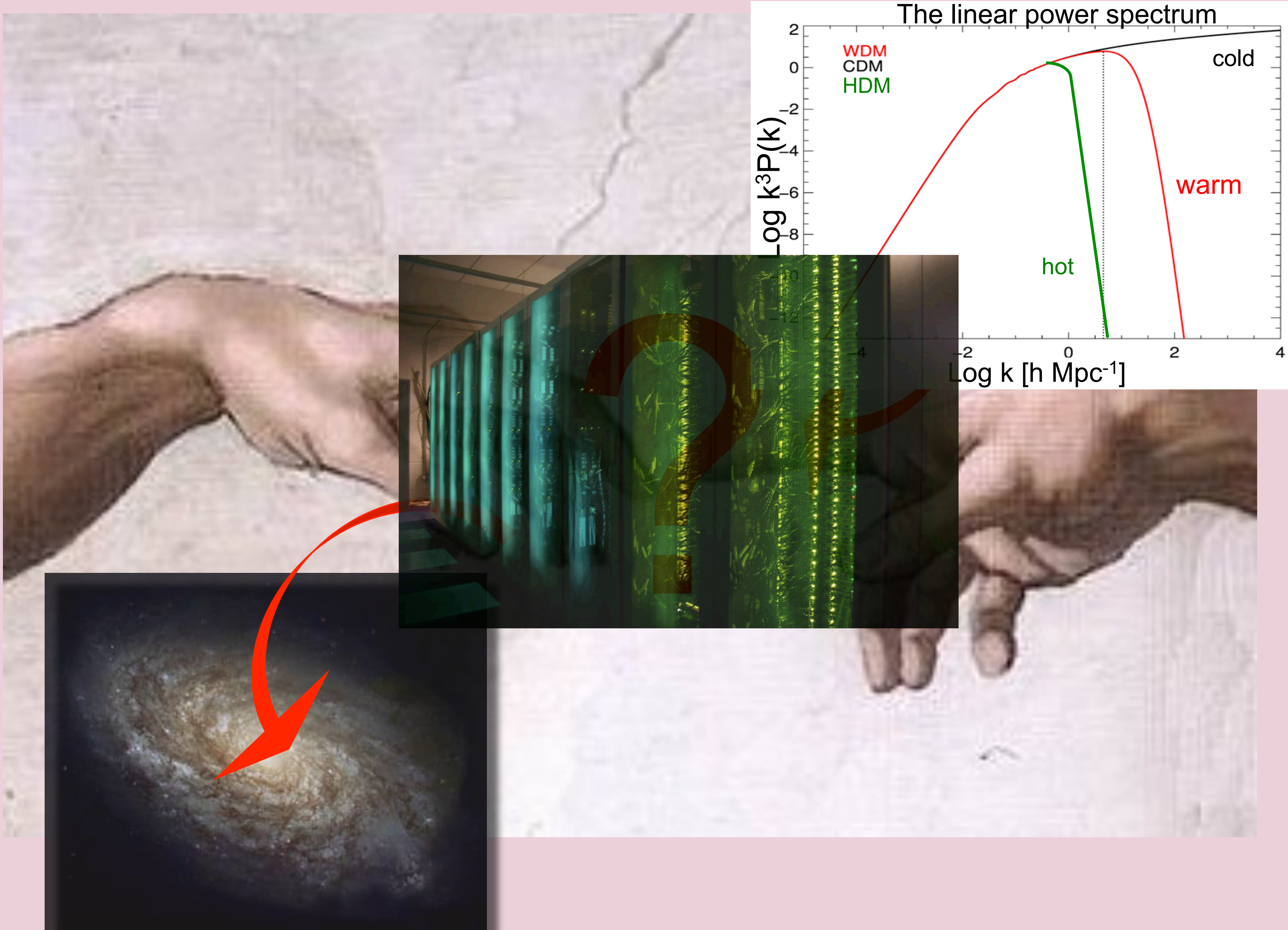
$m_{CDM} \sim$ 100GeV
susy; $M_{cut} \sim 10^{-6} M_o$

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

$m_{HDM} \sim$ few tens eV
light ν; $M_{cut} \sim 10^{15} M_o$



Non-linear evolution



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Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann

Poisson, Friedmann

Radiative hydrodynamics

Subgrid astrophysics

How to make a virtual universe

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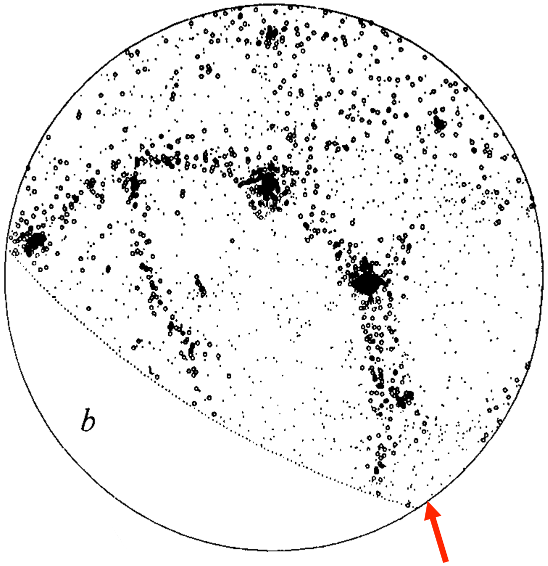
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

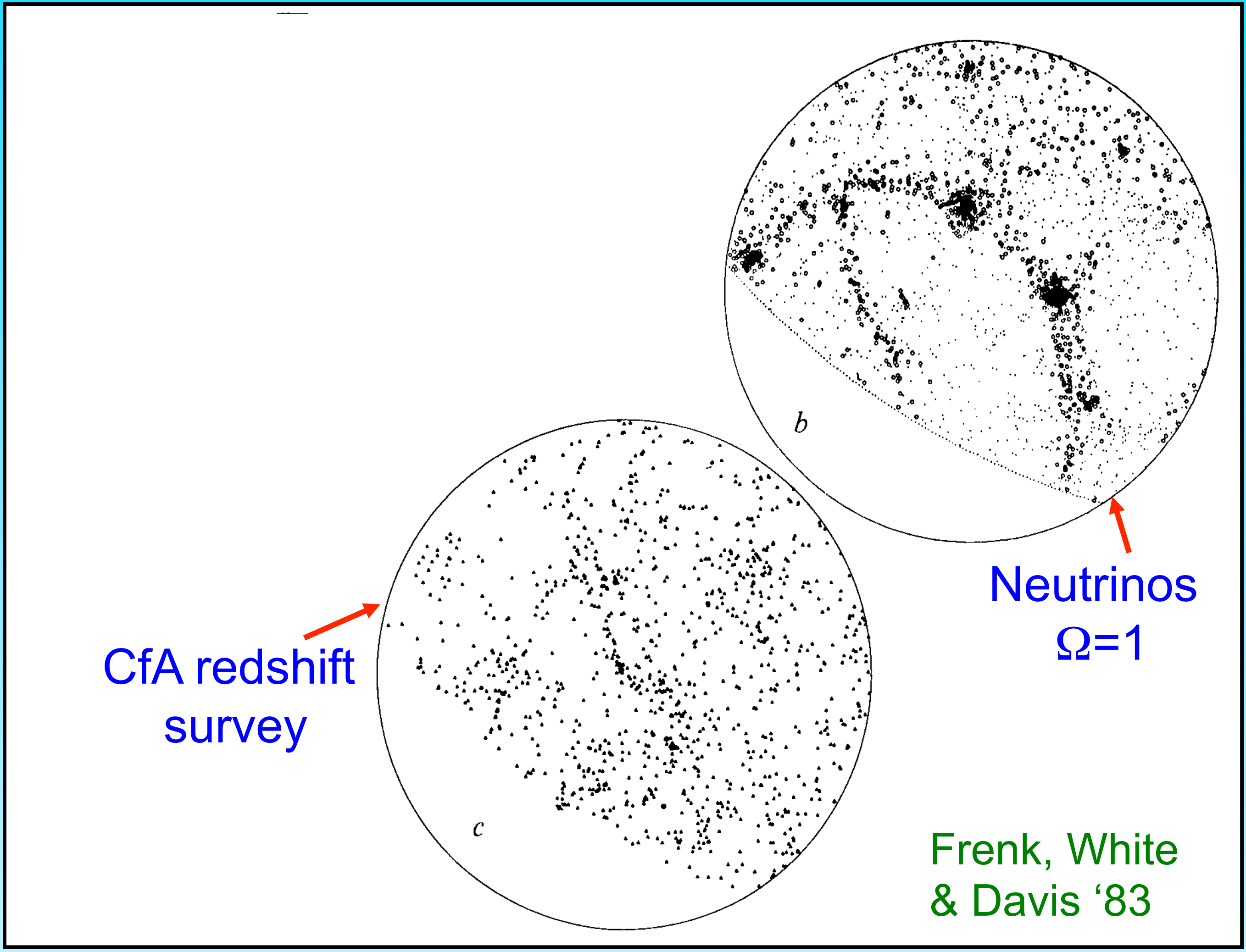
ICC
University of Durham

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev



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Non-baryonic dark matter cosmologies

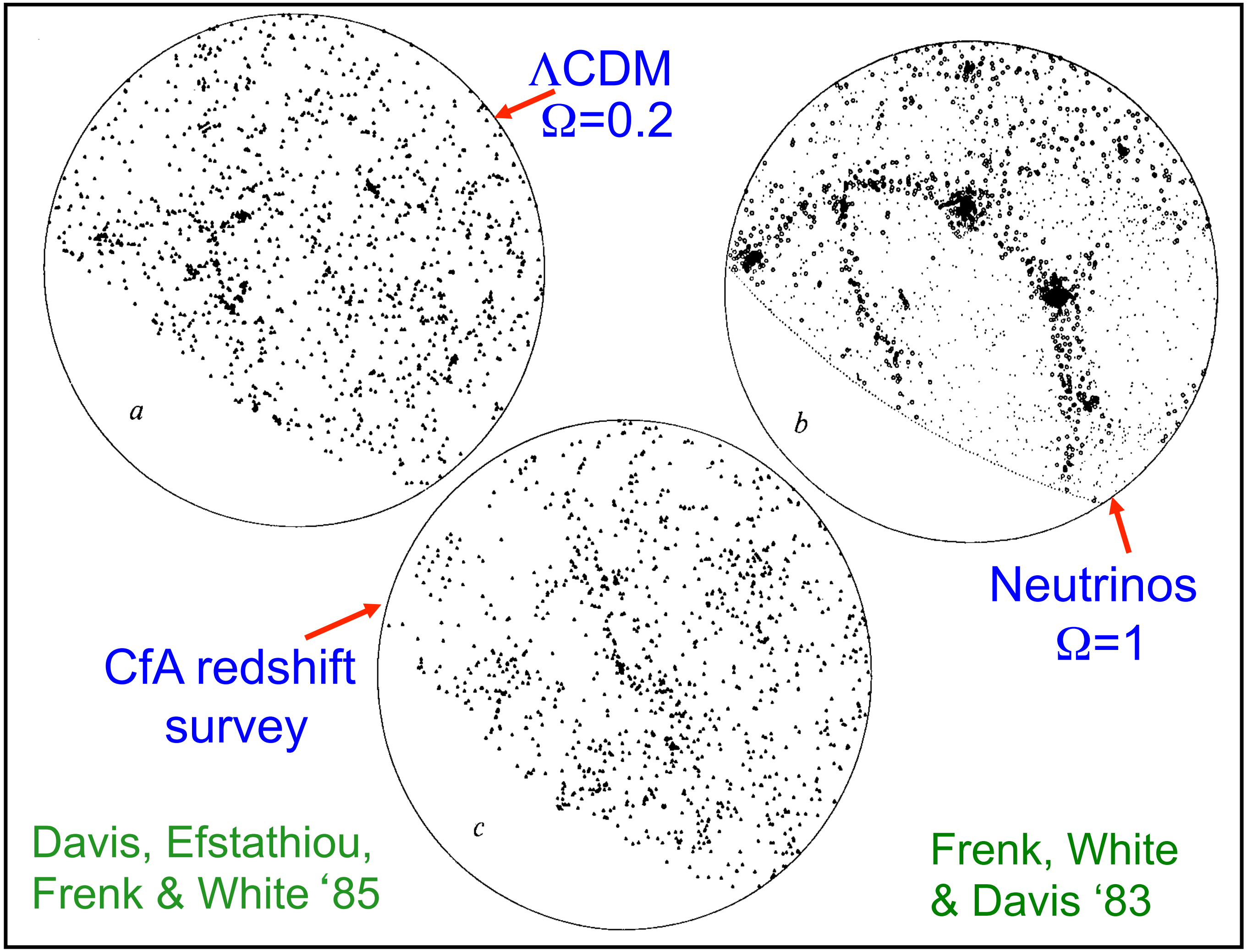
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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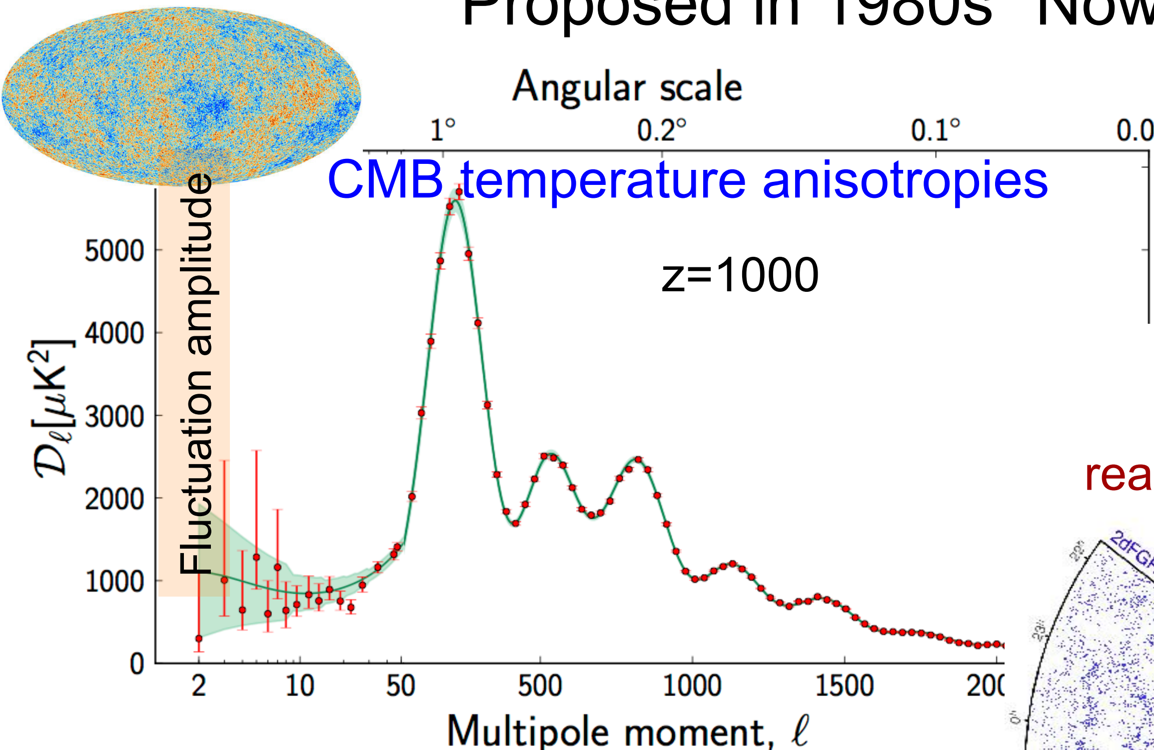
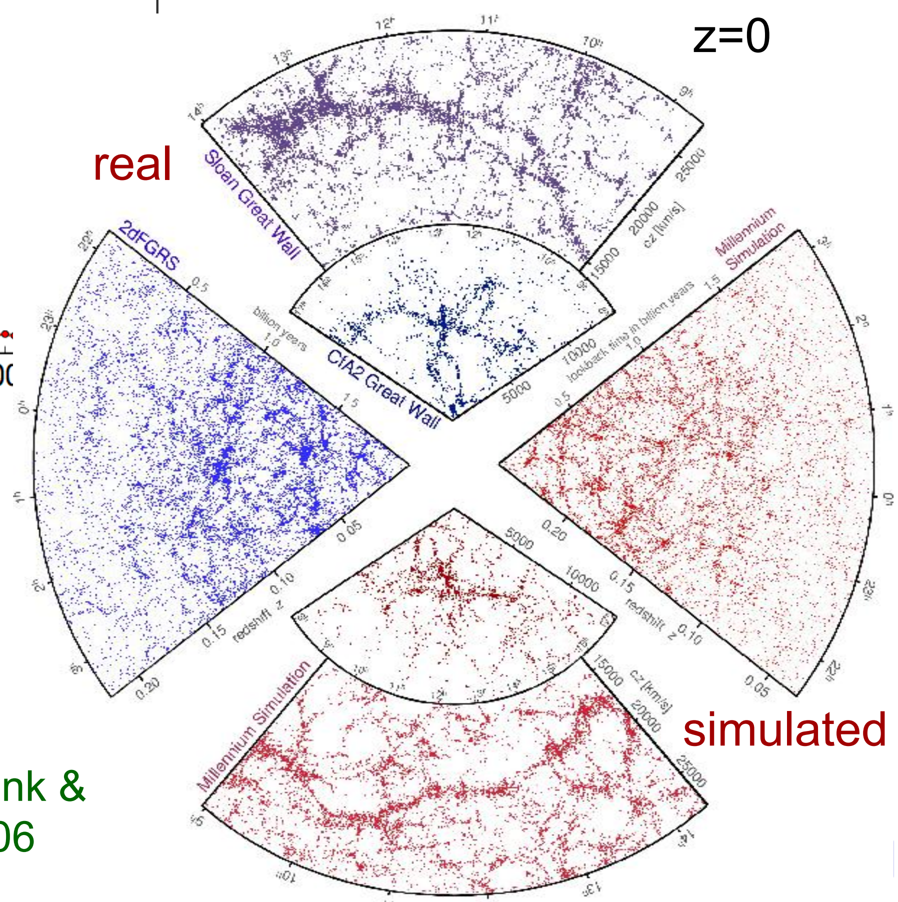
The ΛCDM model of cosmogony

Proposed in 1980s   Now empirically supported by:



Planck coll. 2015

Galaxy clustering



Springel, Frenk & White 2006

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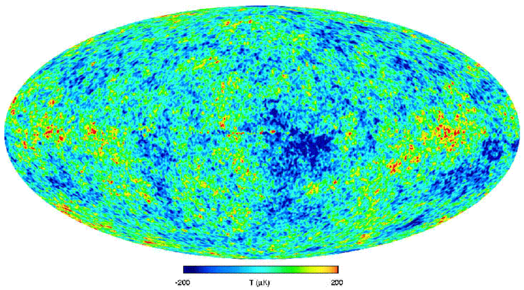
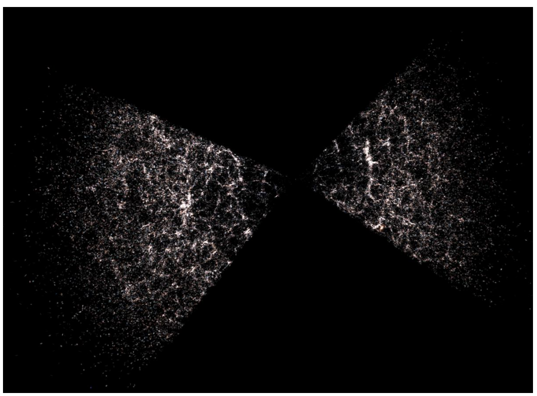
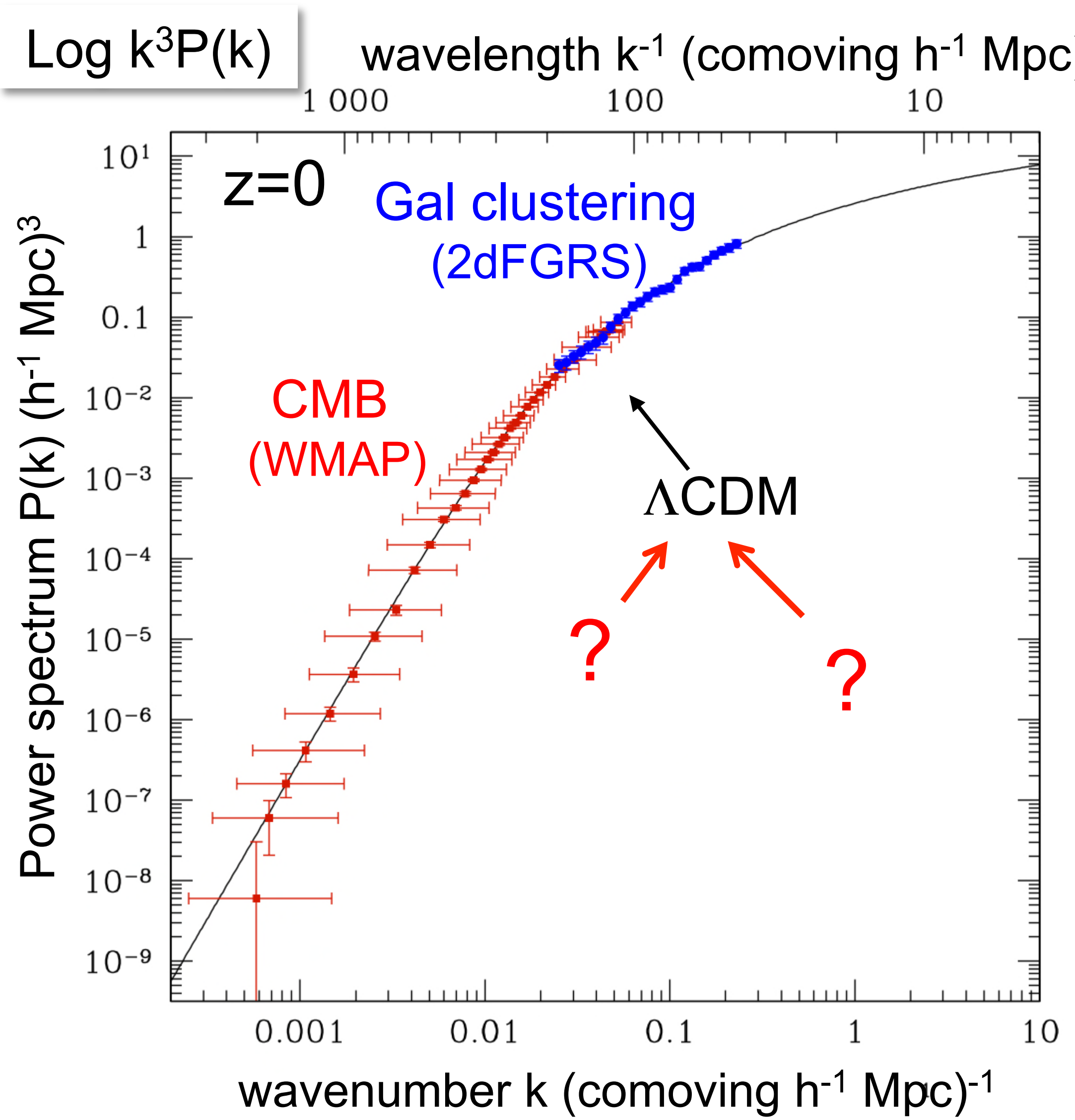
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

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

Free streaming →

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for thermal relic

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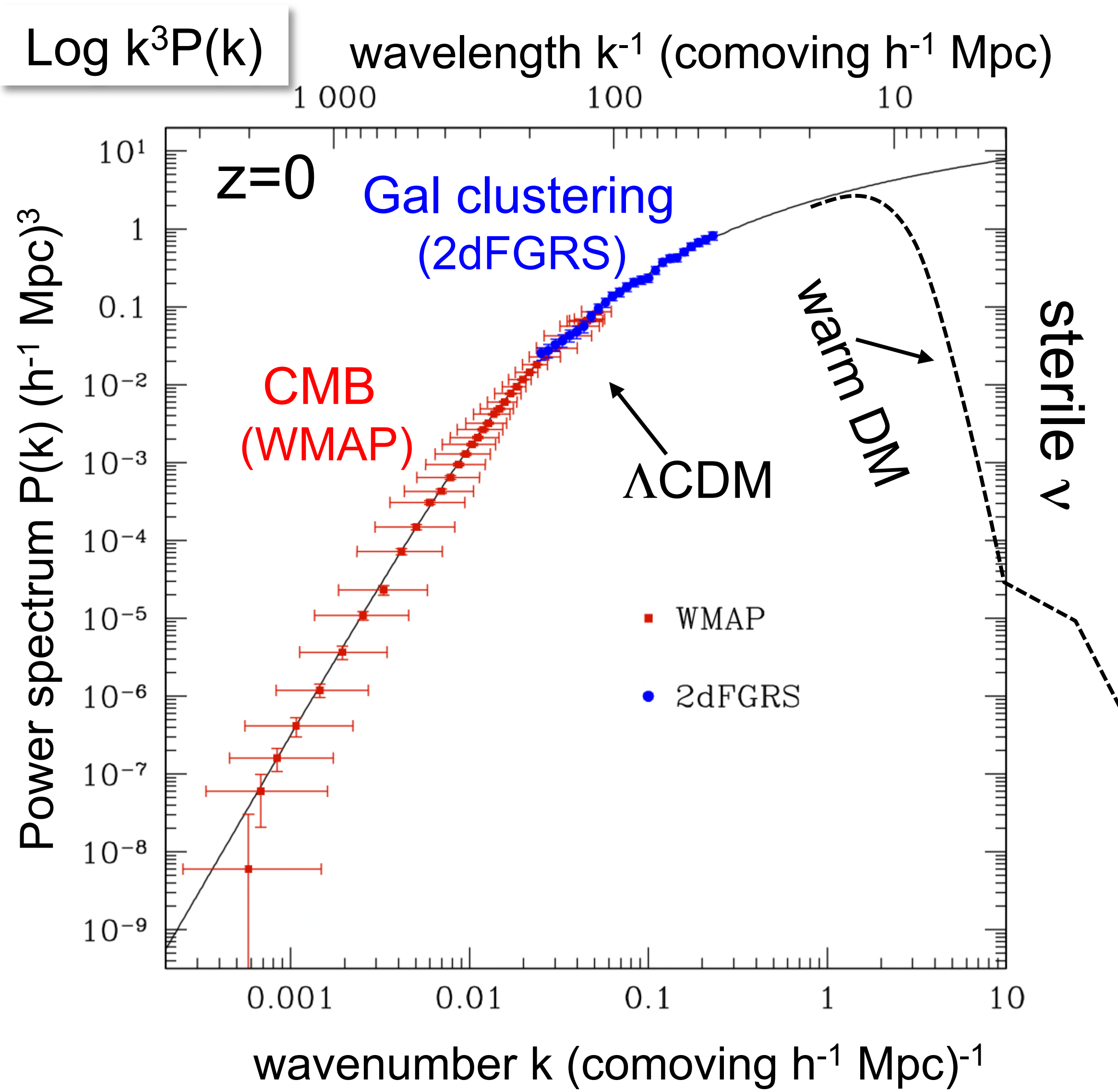

Both CDM & WDM compatible with CMB & galaxy clustering

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 →

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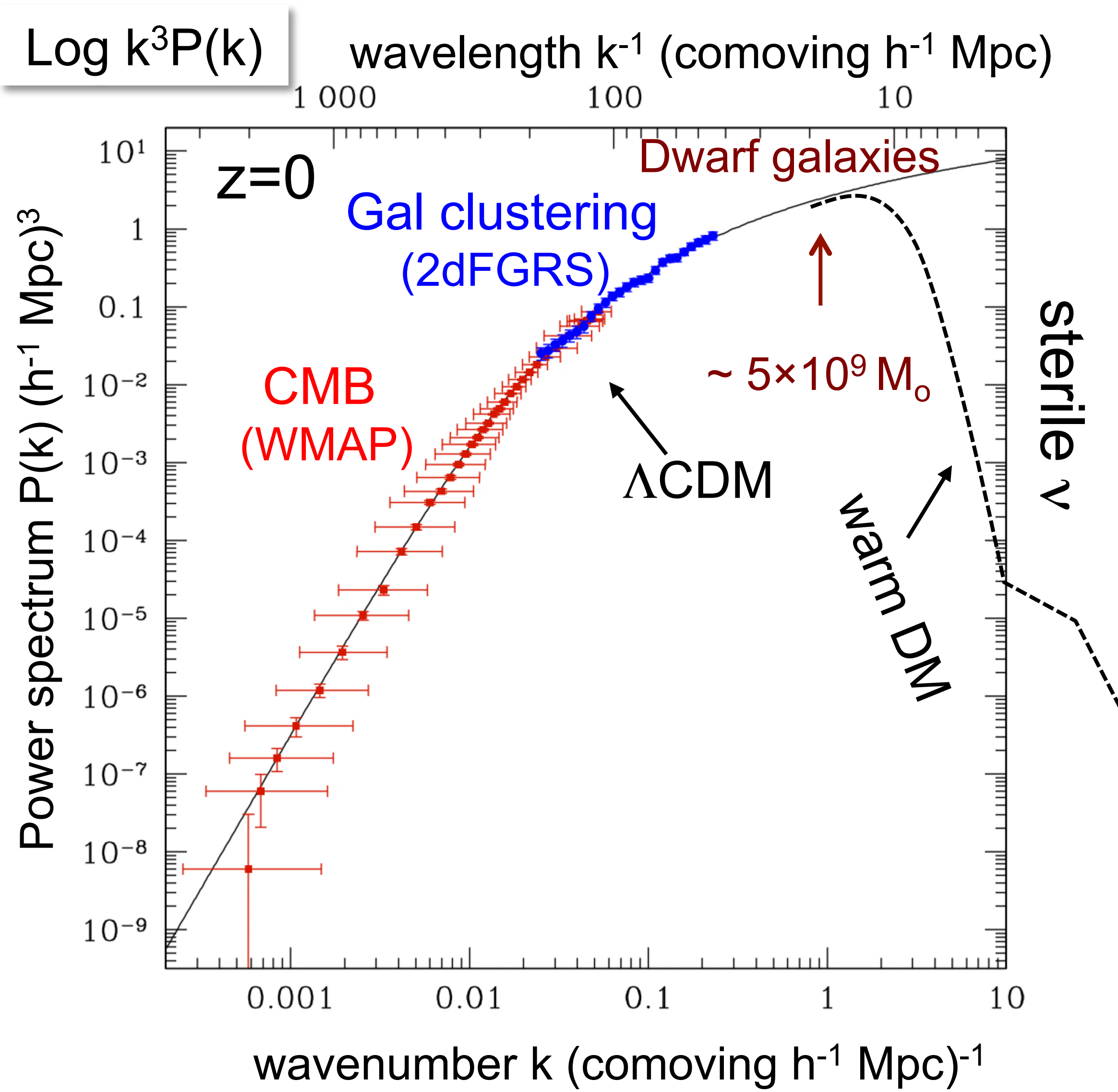

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Sterile neutrinos

Explain:

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

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

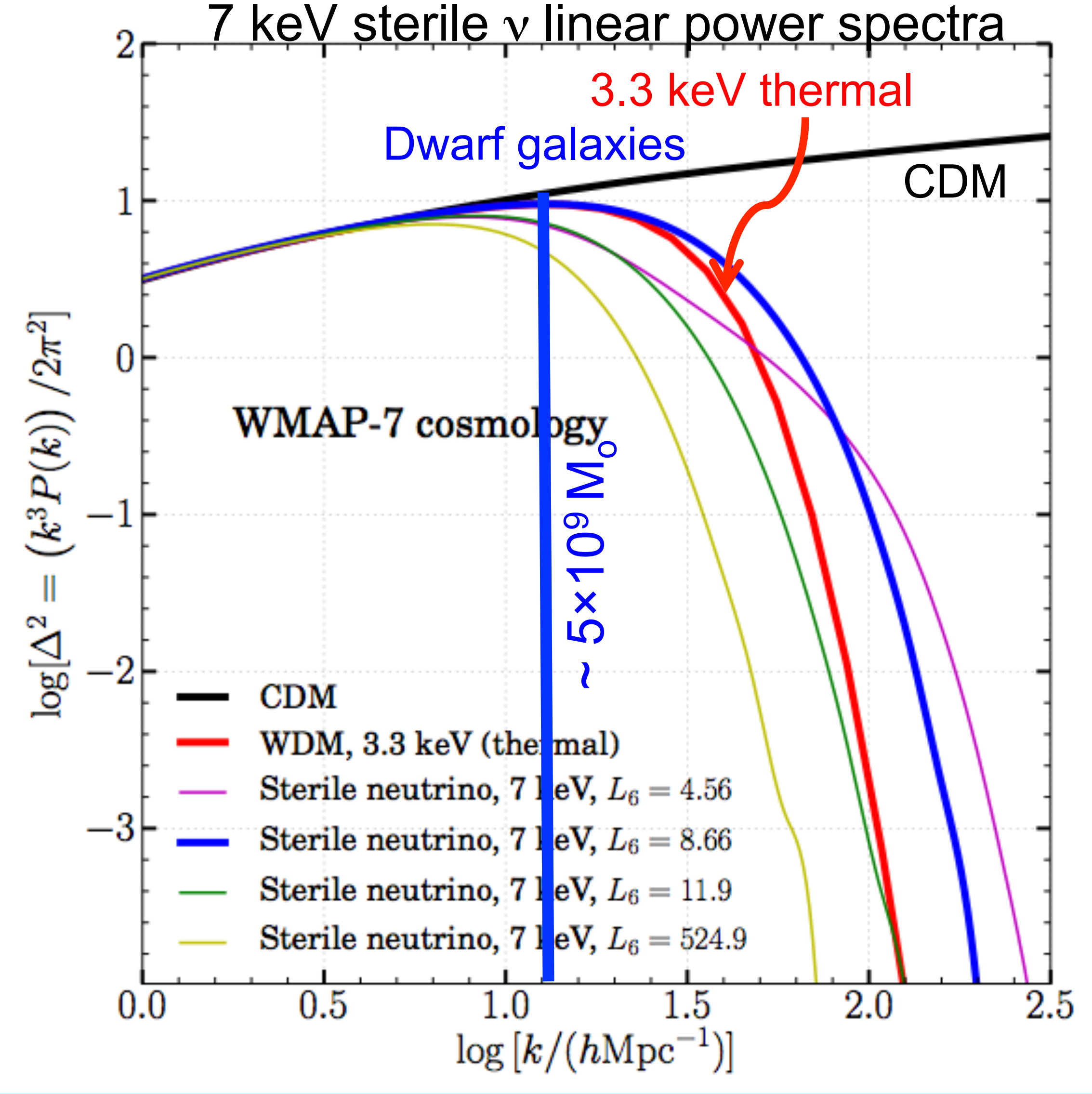
- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N = \Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-ray decay

Primordial P(k) for 7 keV sterile neutrino models

- 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

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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

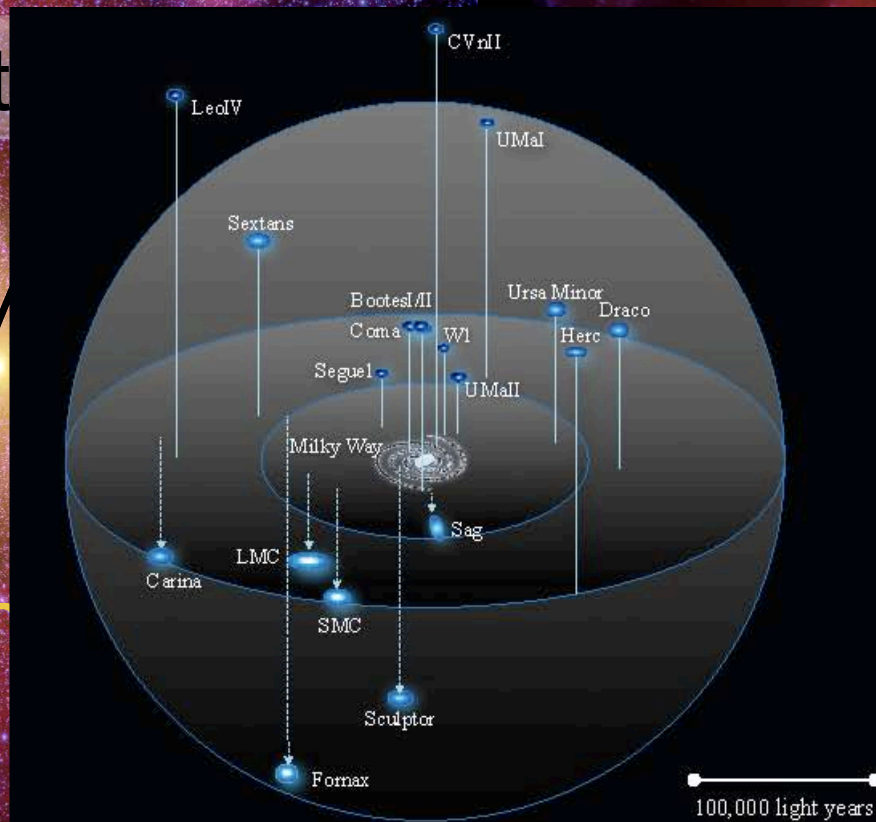
MW or M31

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

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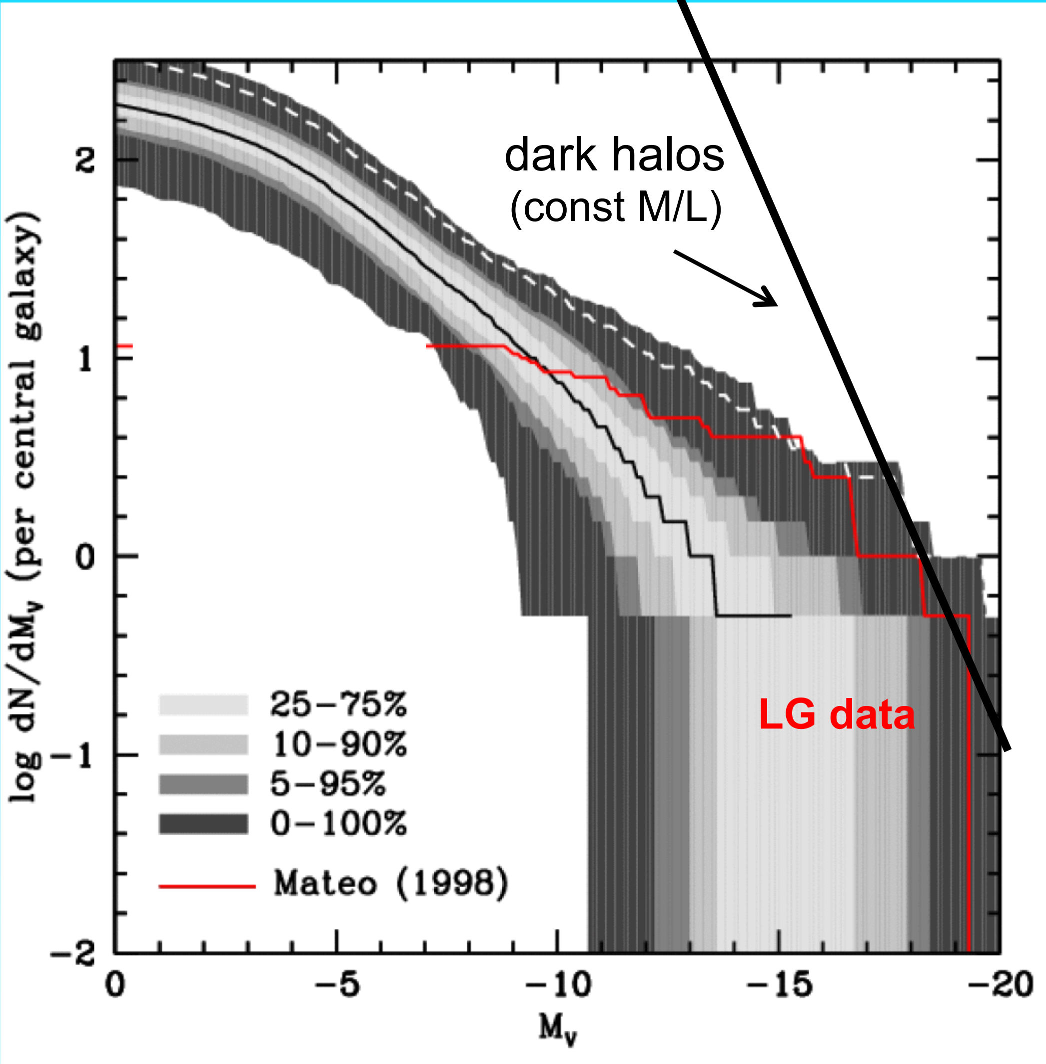
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~10% of cases)



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

Luminosity Function of Local Group Satellites

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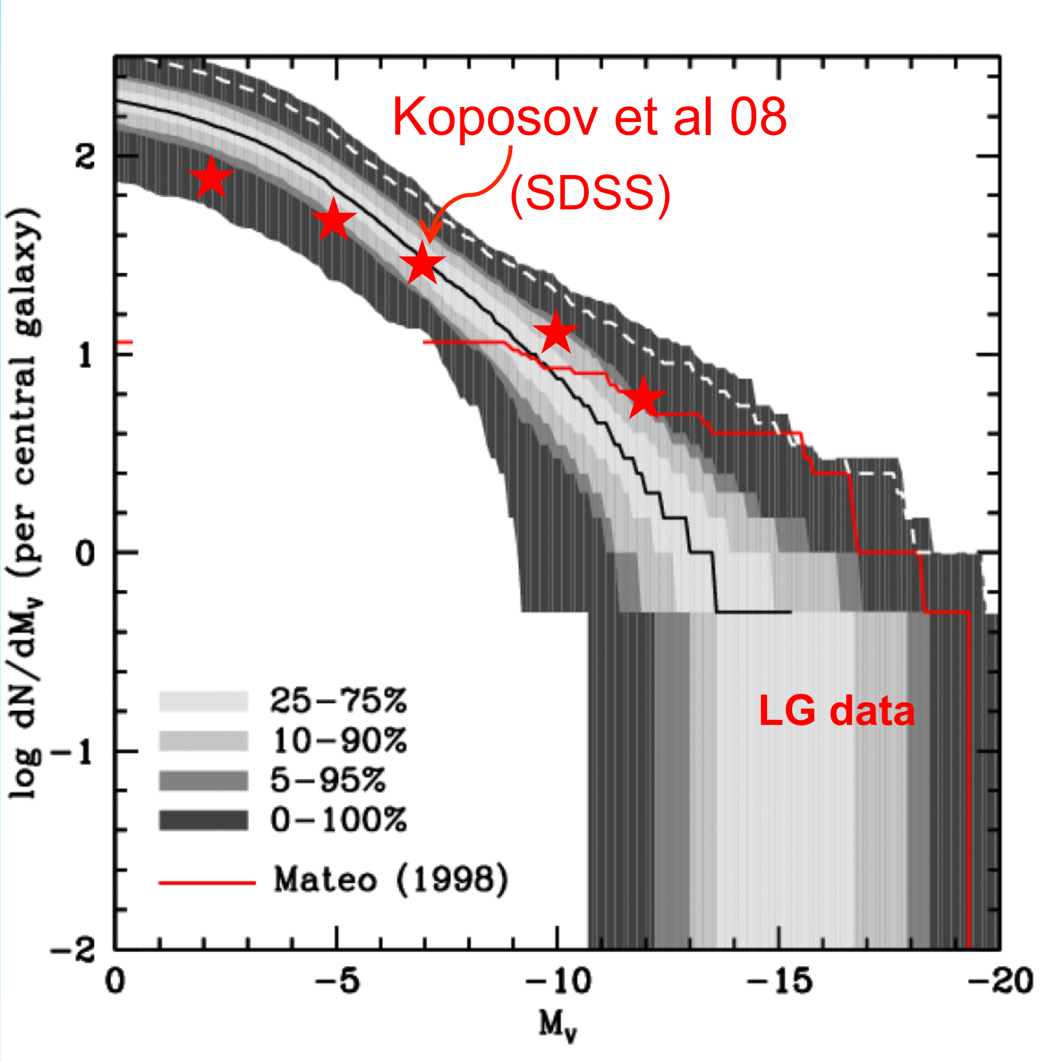


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

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.

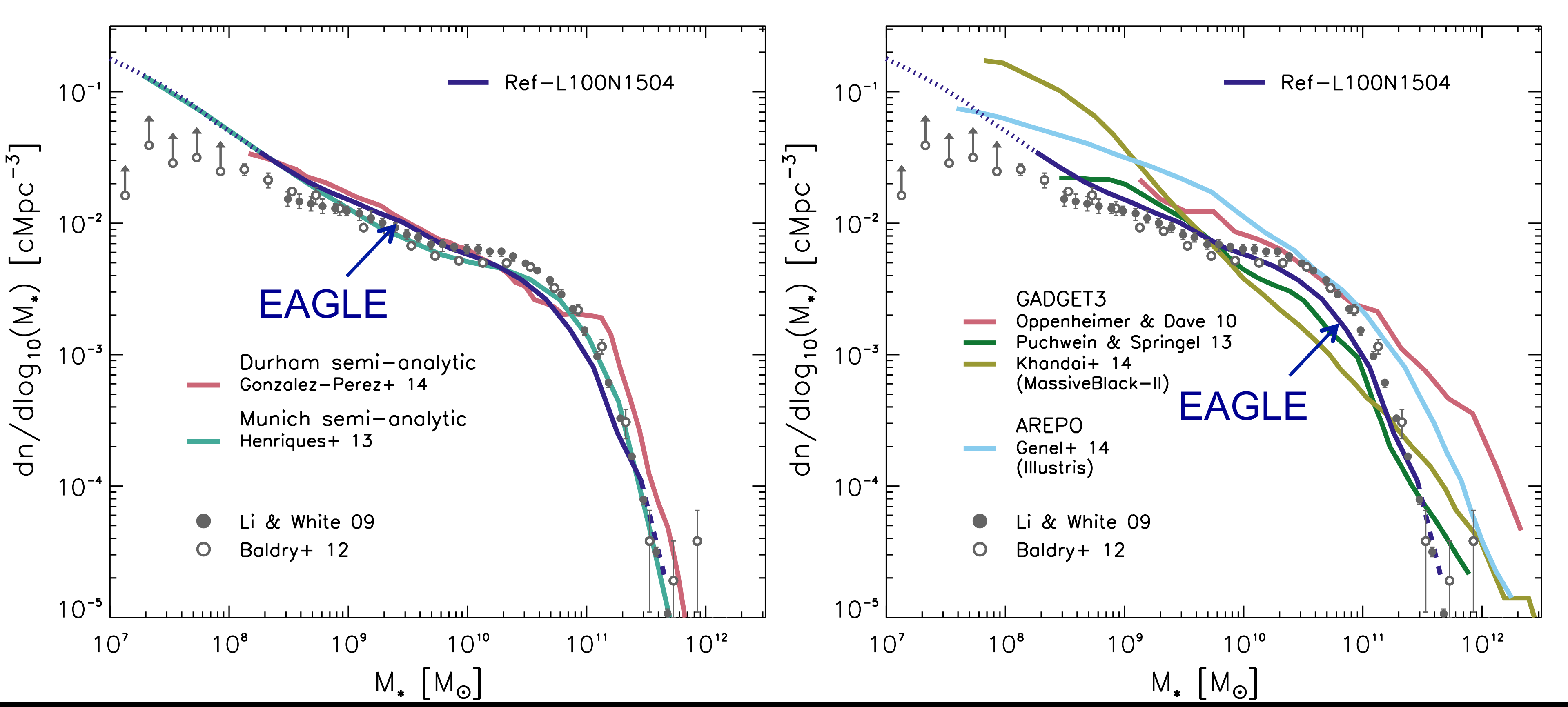
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

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

Galaxy stellar mass function

Comparison to semi-analytic models

Comparison to other Hydro simulations

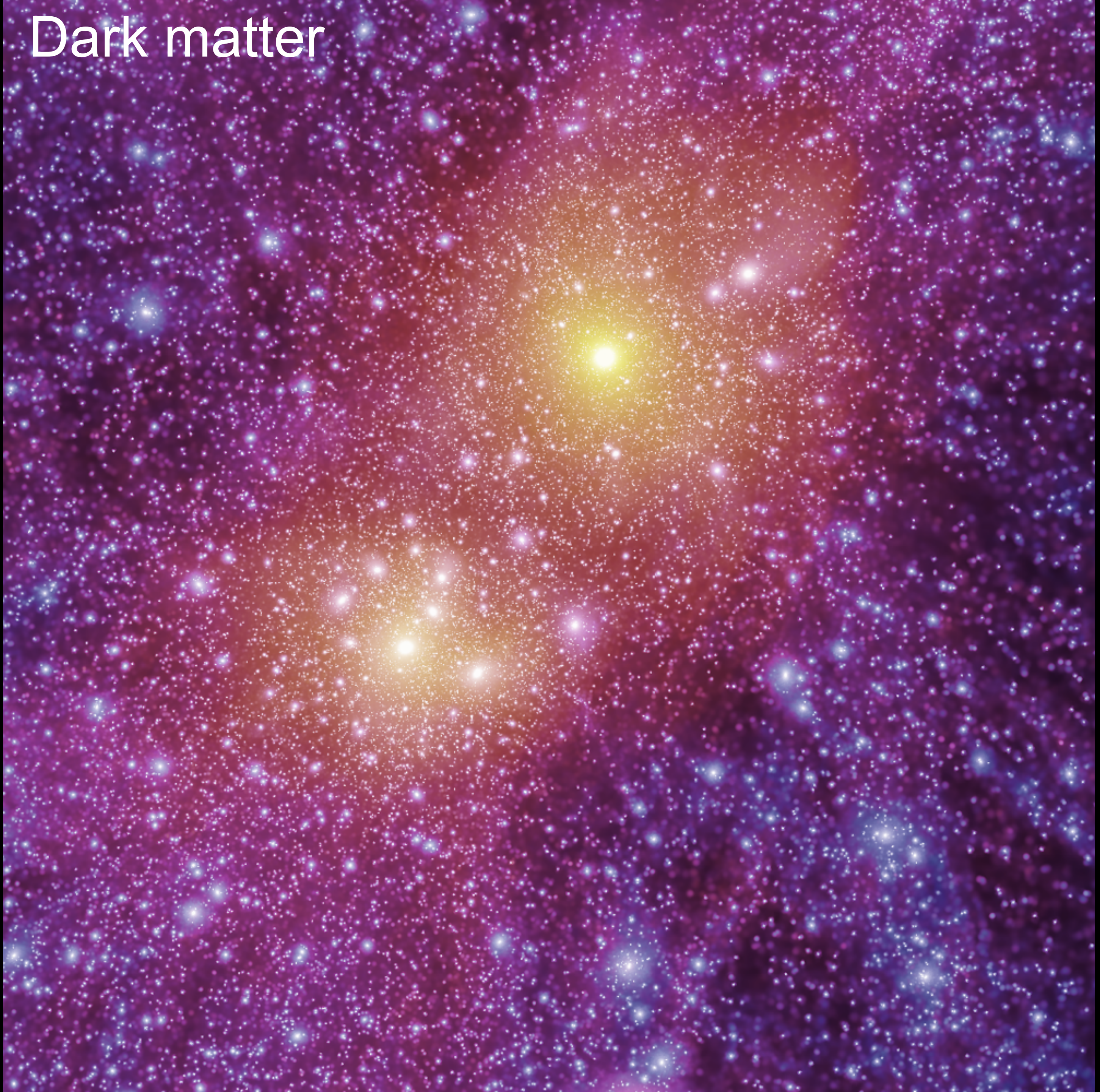


APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



Stars

APOSTLE
EAGLE full
hydro
simulations

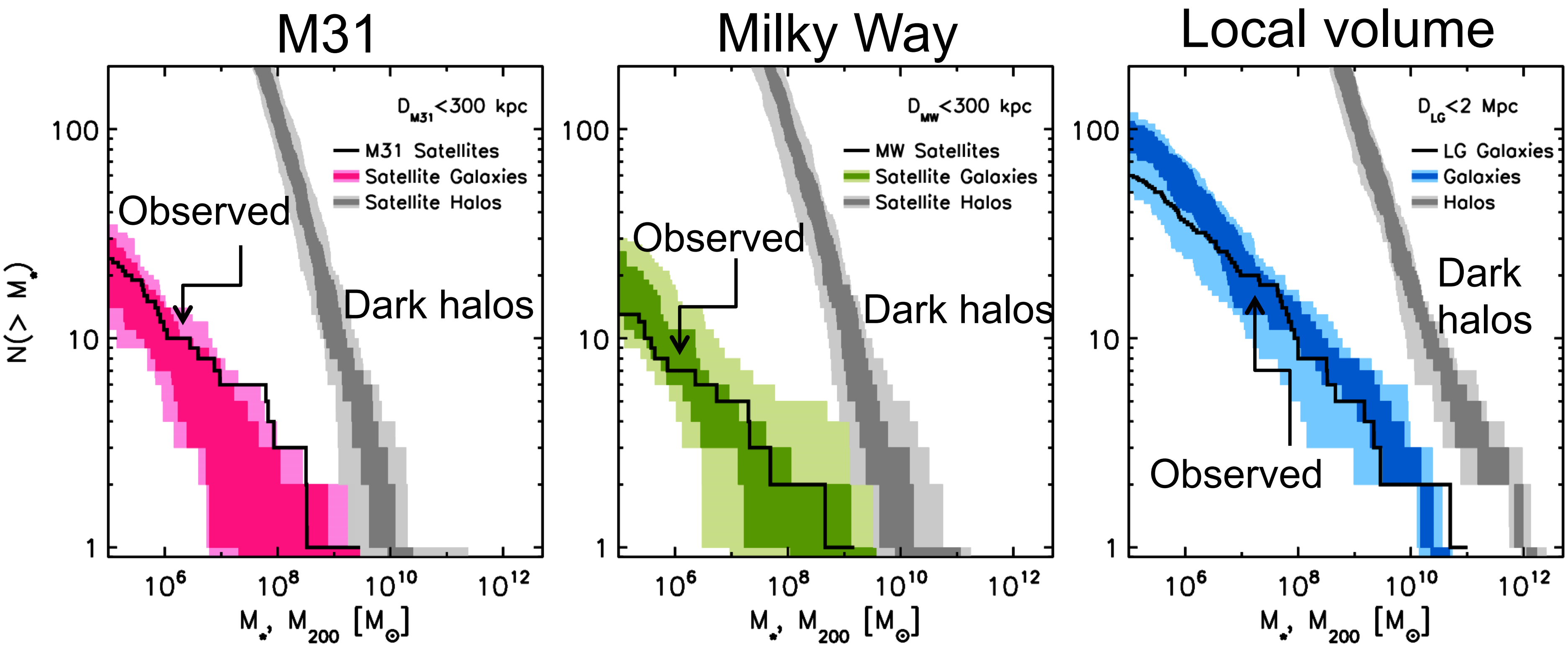
Local Group

Stars

Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation



Sawala et al ‘16

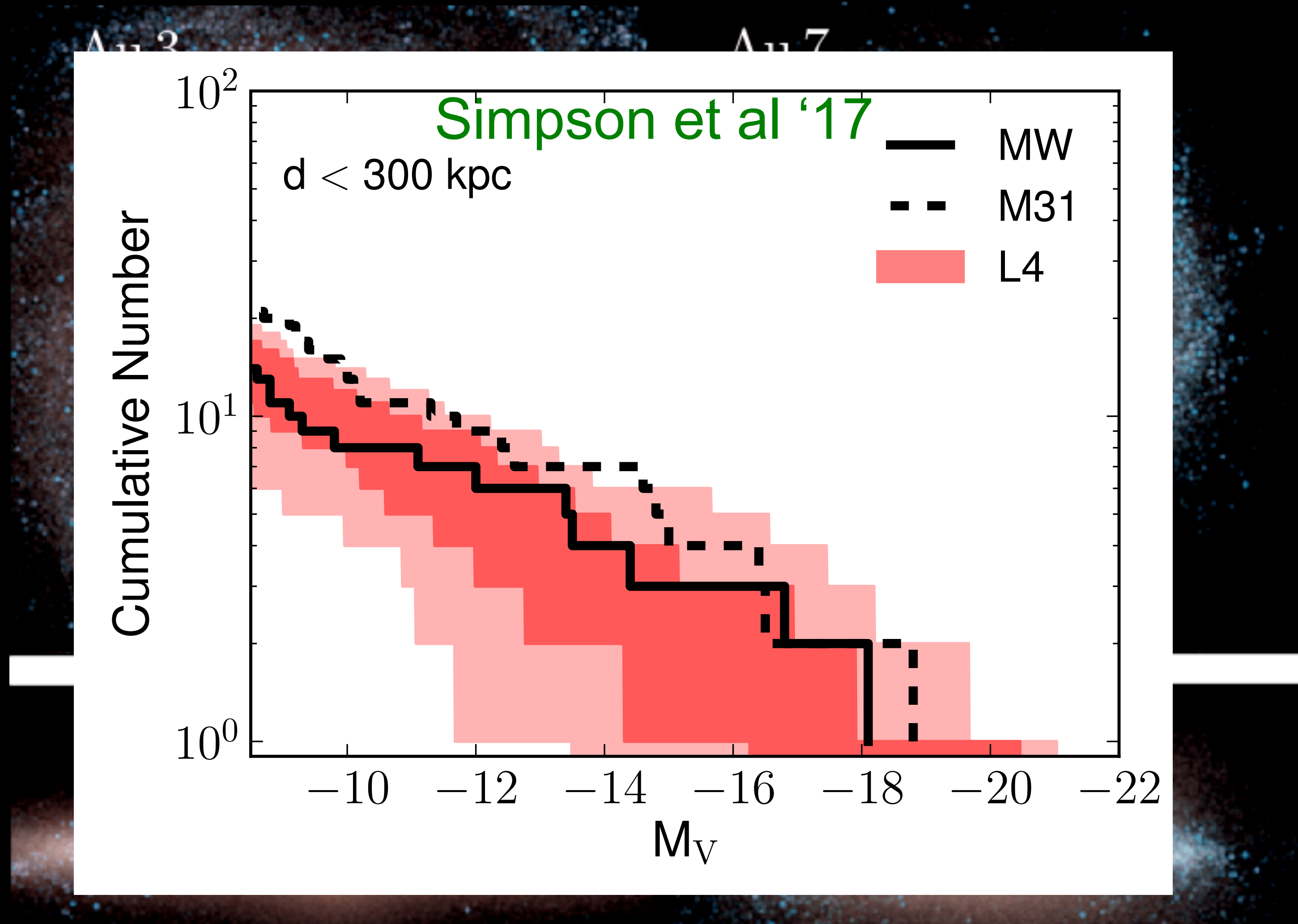
The Auriga MW-like galaxies

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

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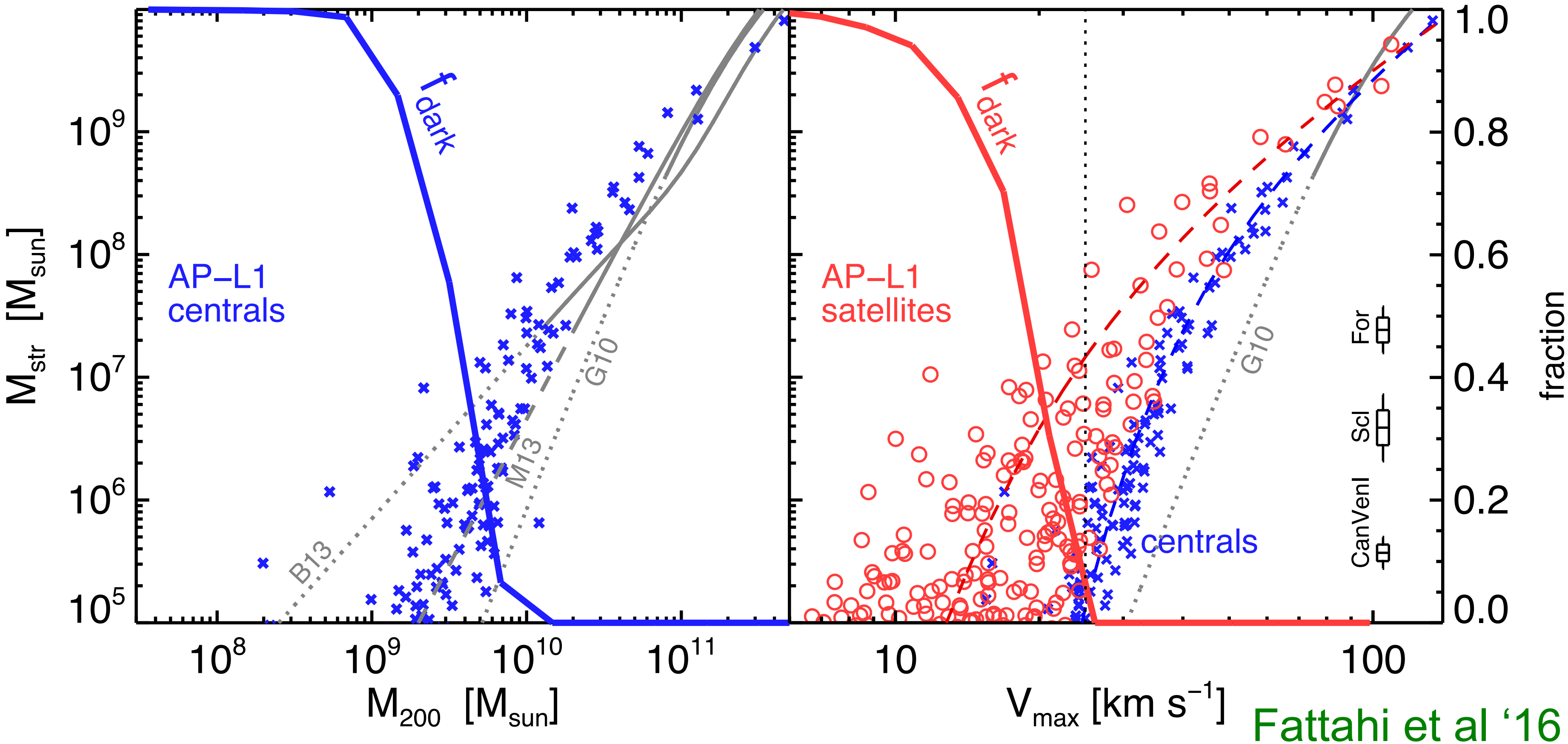
$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{max} = \max V_c$$



Fattahi et al '16

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

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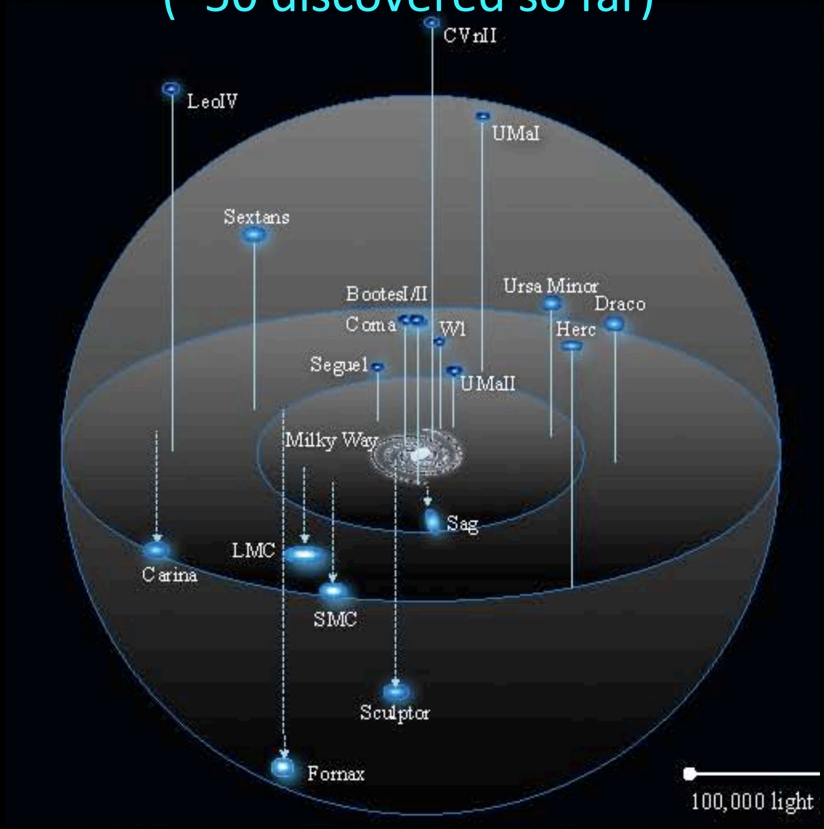
How about in WDM?

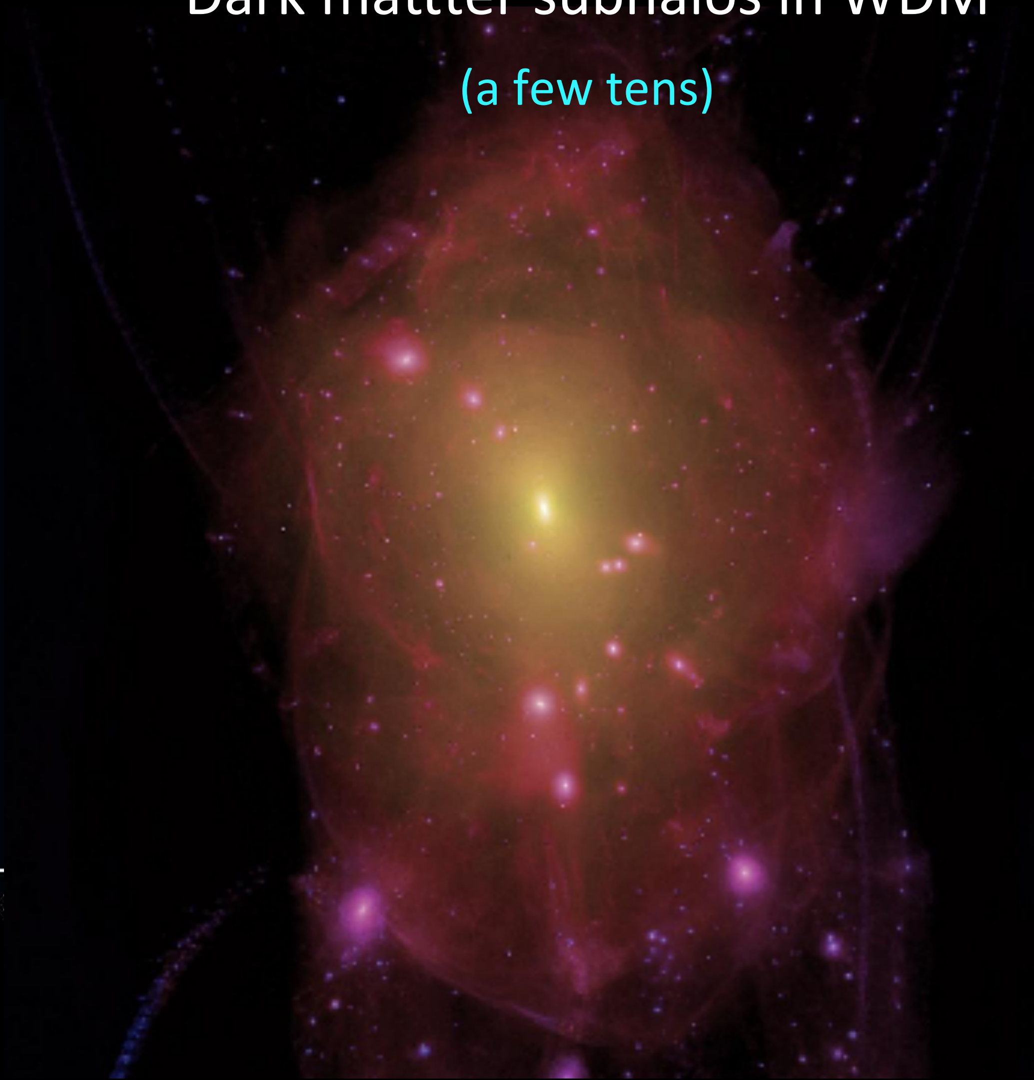
The satellites of the MW

(~50 discovered so far)



Dark mattter subhalos in WDM

(a few tens)



Warm DM: different ν mass

z=3

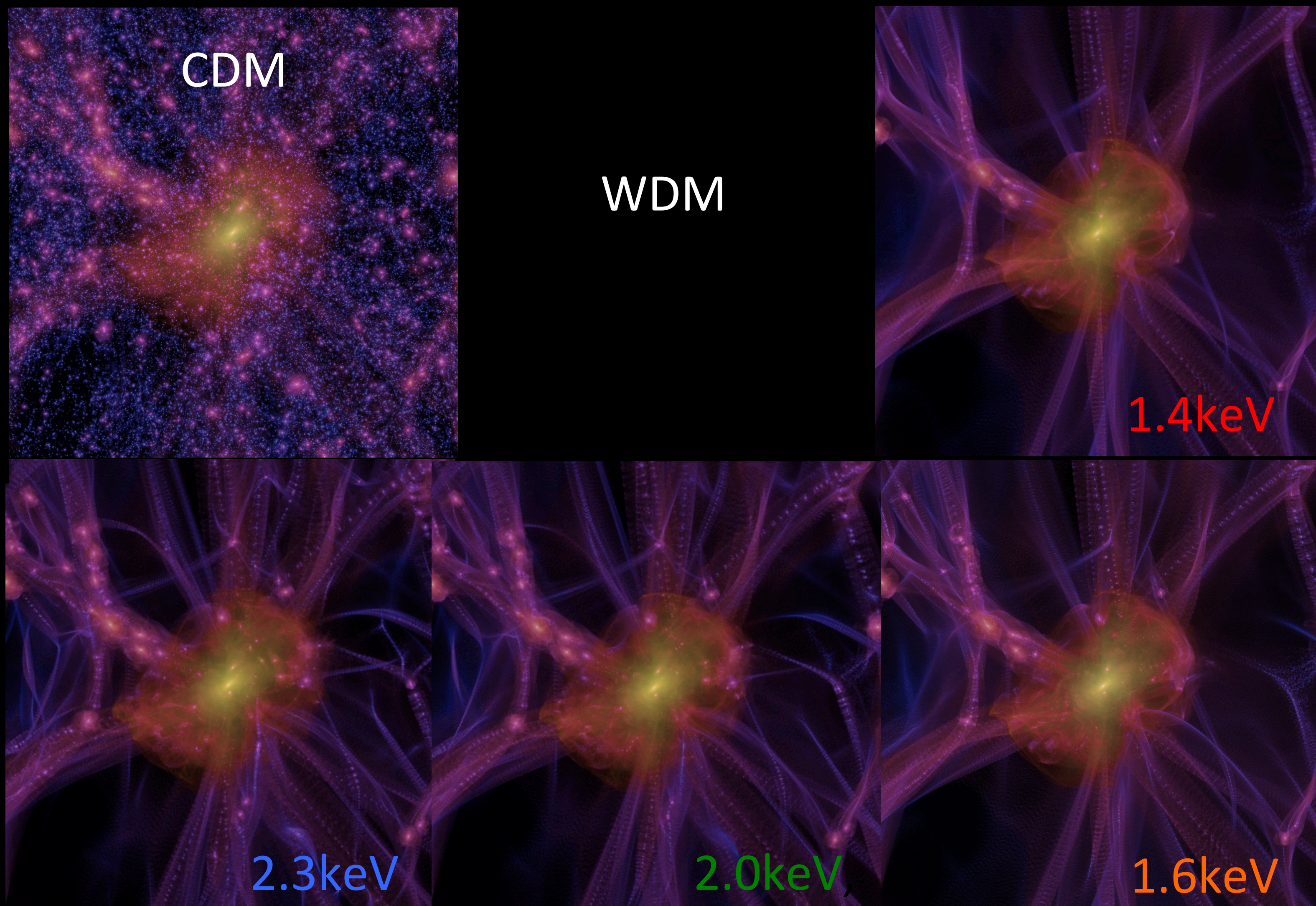
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



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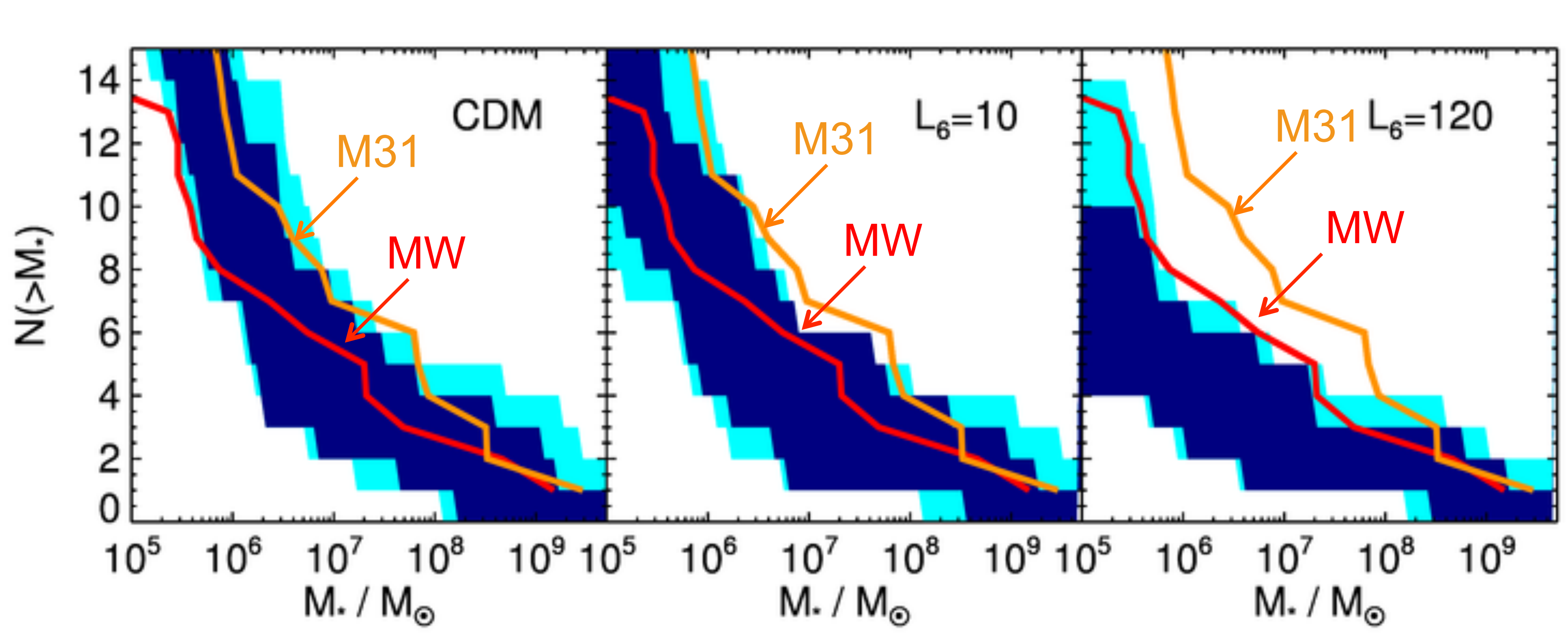
Luminosity Function of Local Group Satellites in WDM

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

→

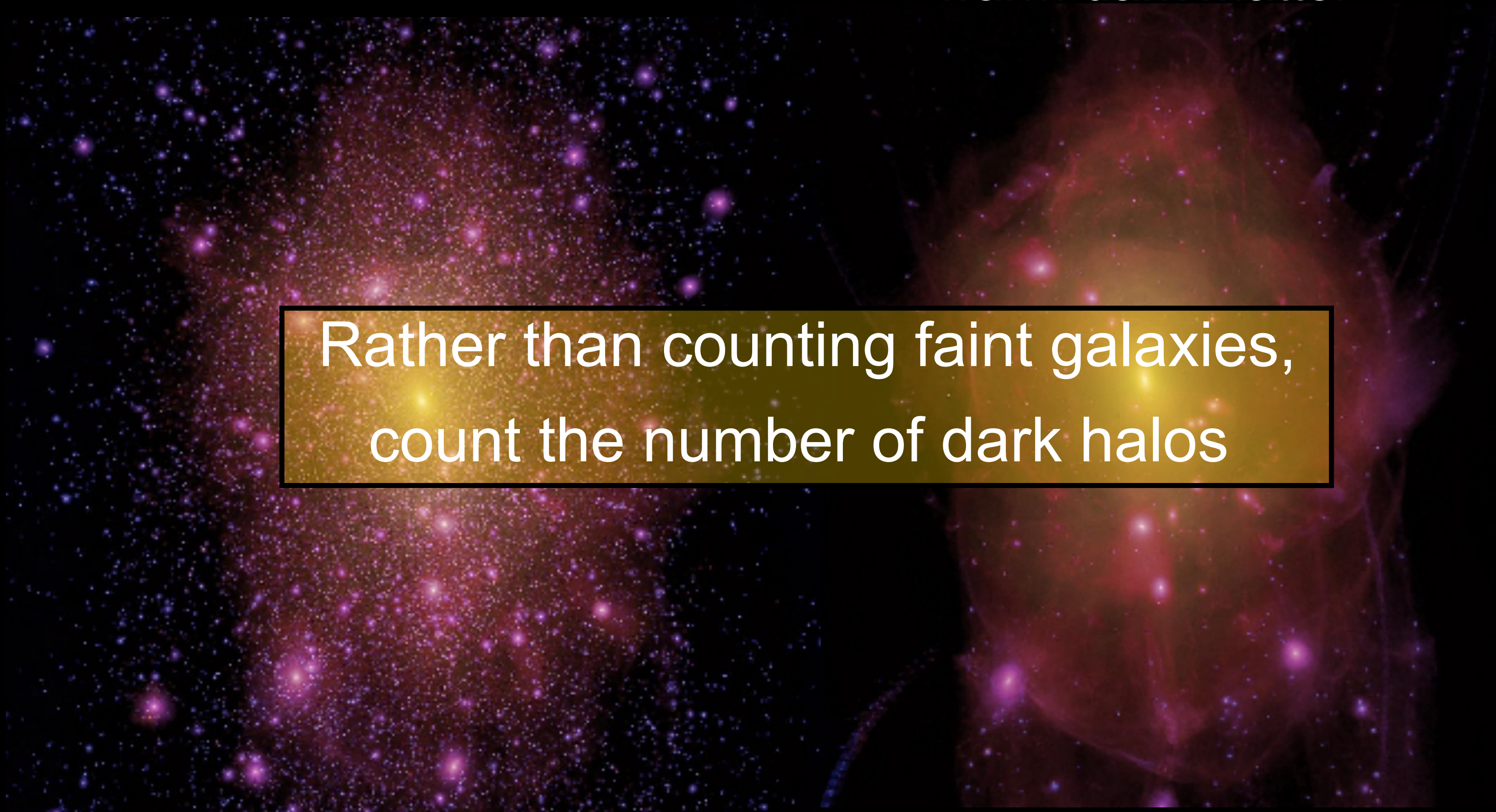
There is no such thing as the “satellite problem” in CDM!

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?

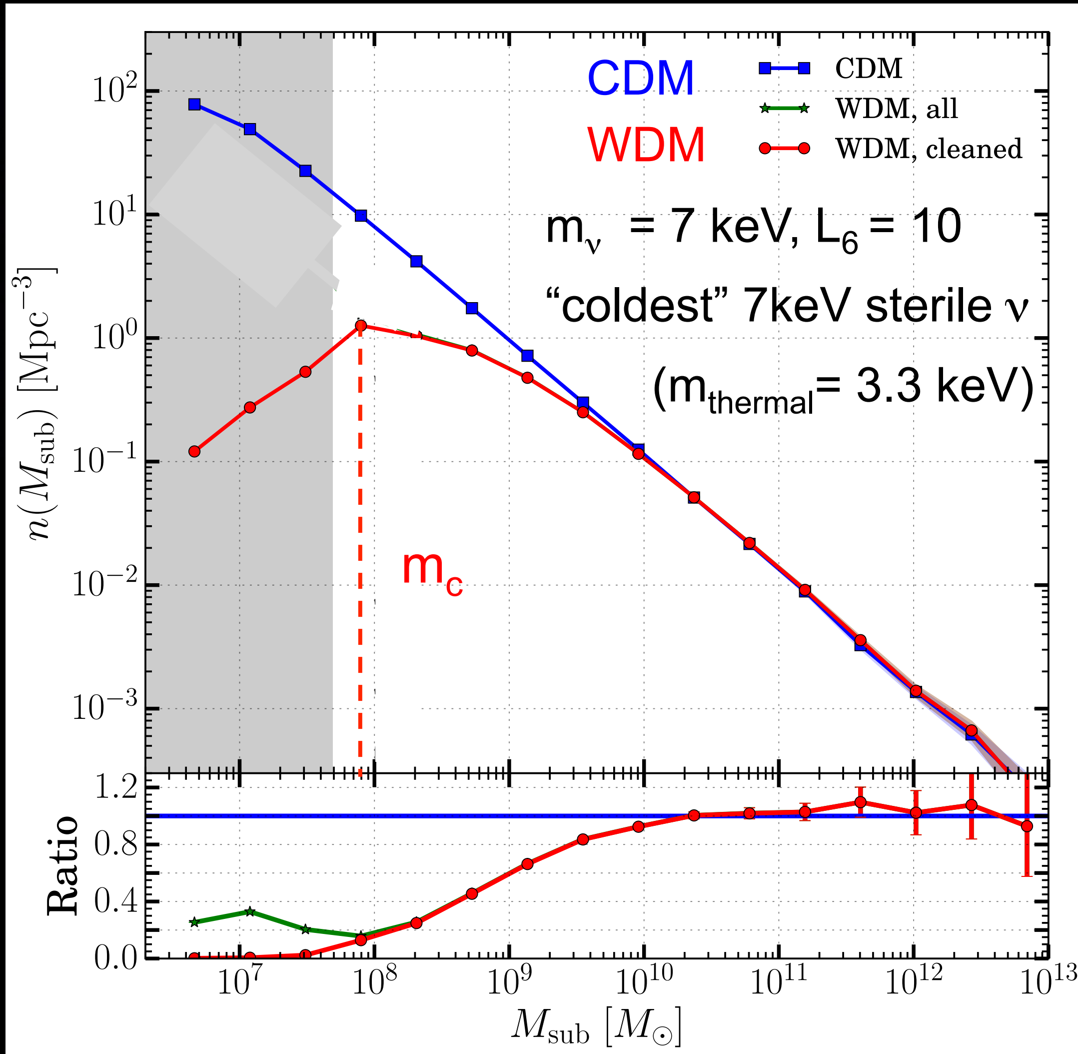
cold dark matter | warm dark matter



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

The subhalo mass function

CDM WDM



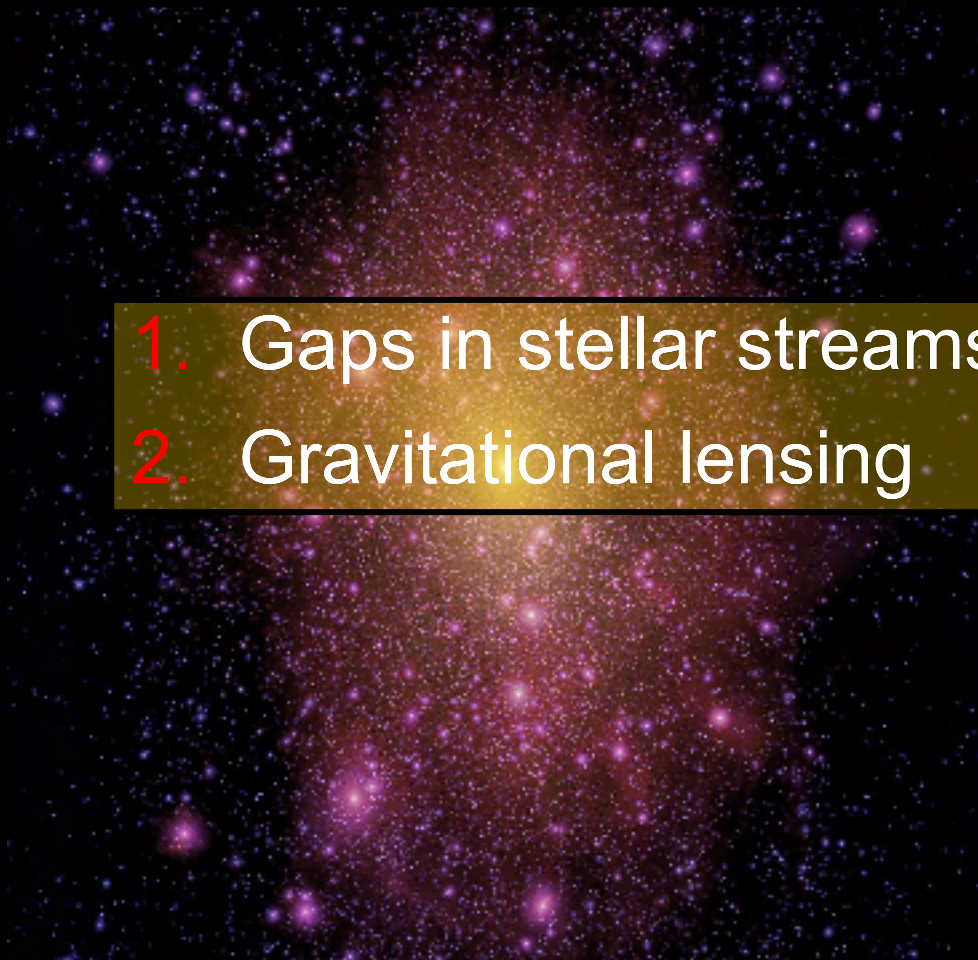
3 x fewer WDM subhalos at $3x10^9$ M_o

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

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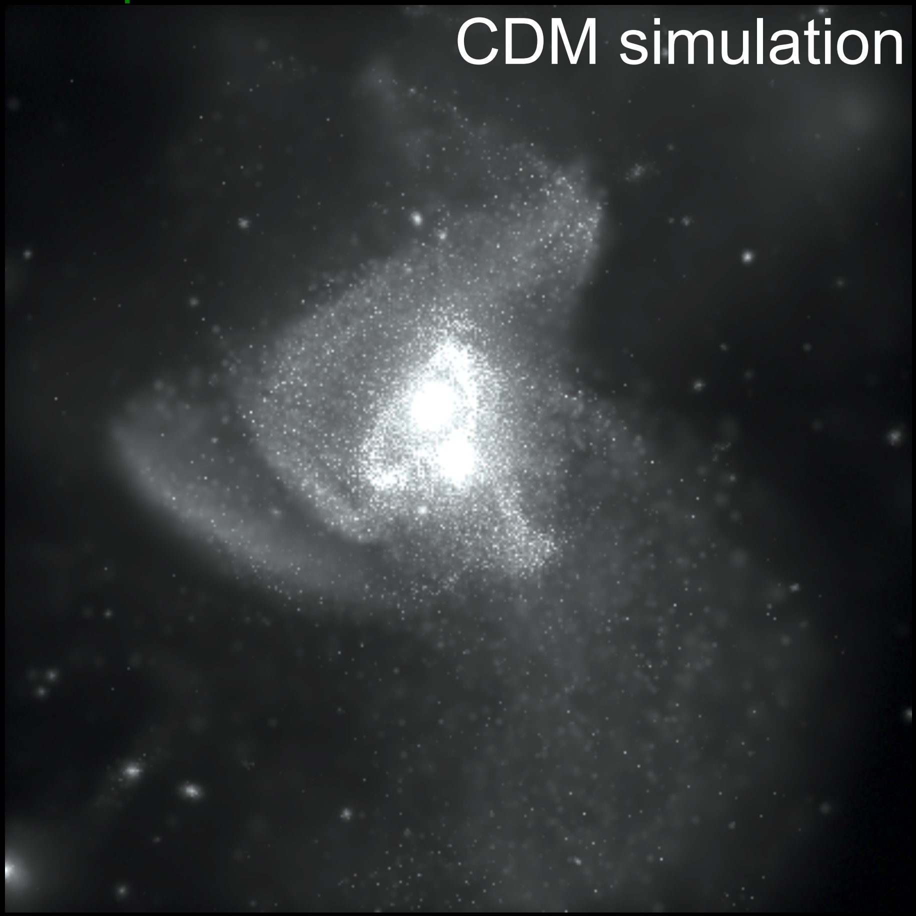
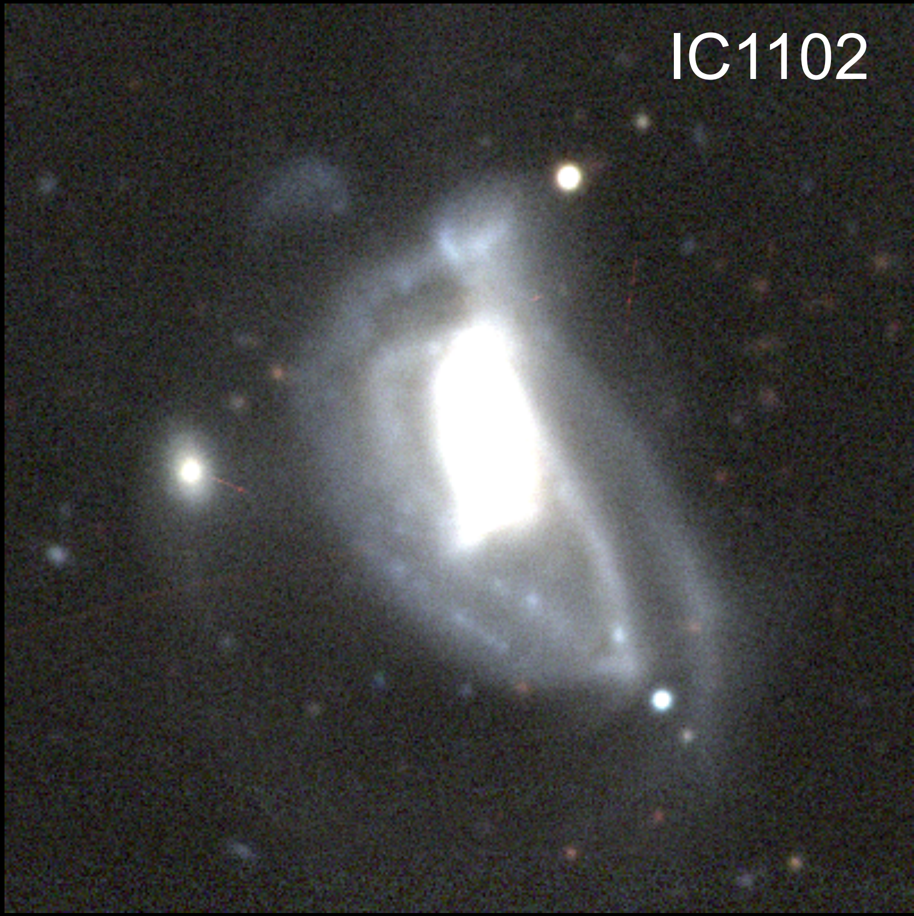
Can we distinguish CDM/WDM?

Cooper et al '16





Subhalos crossing a cold tidal stream can produce a gap

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

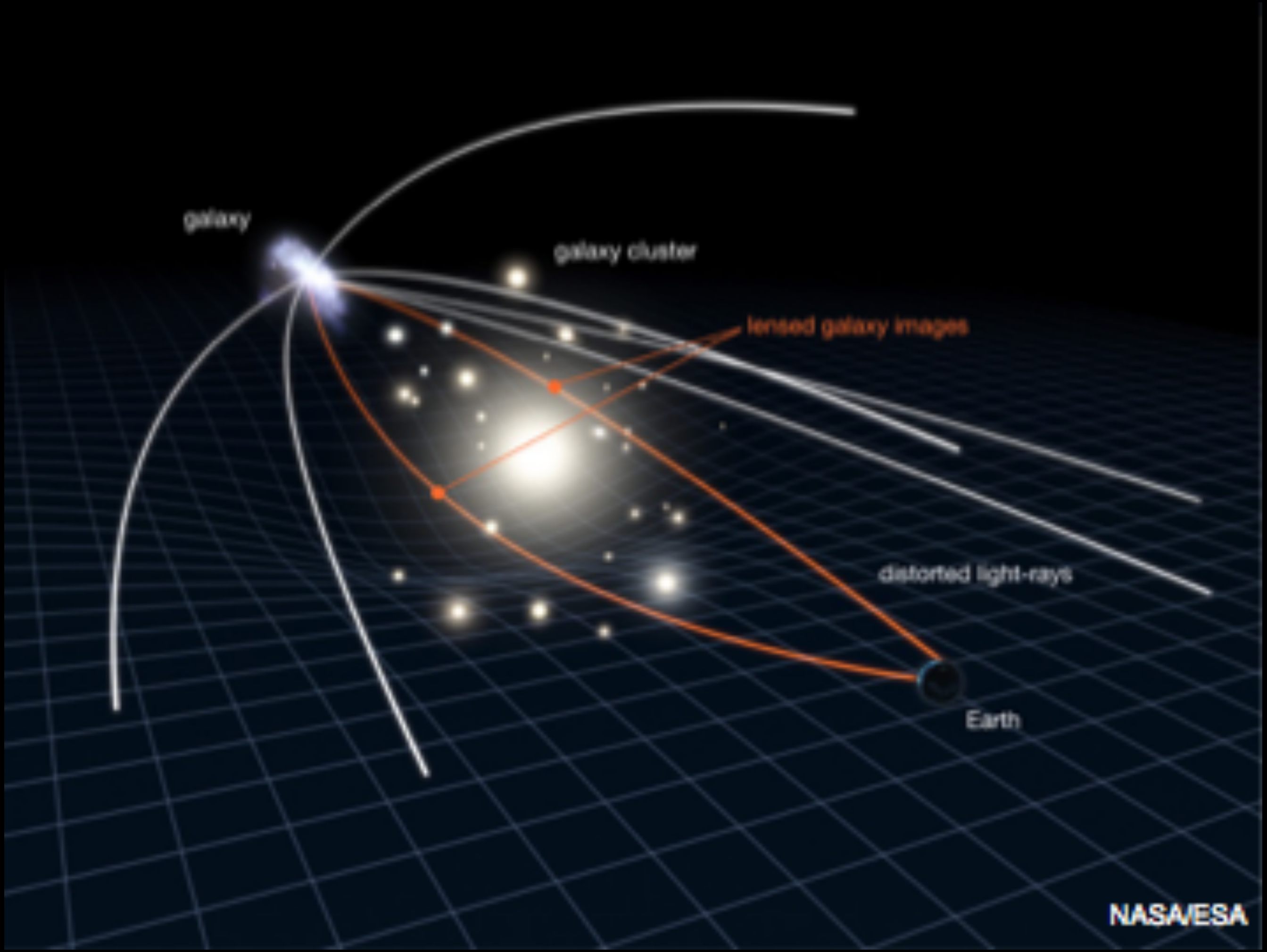
Can we distinguish CDM/WDM?

cold dark matter | warm dark matter

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

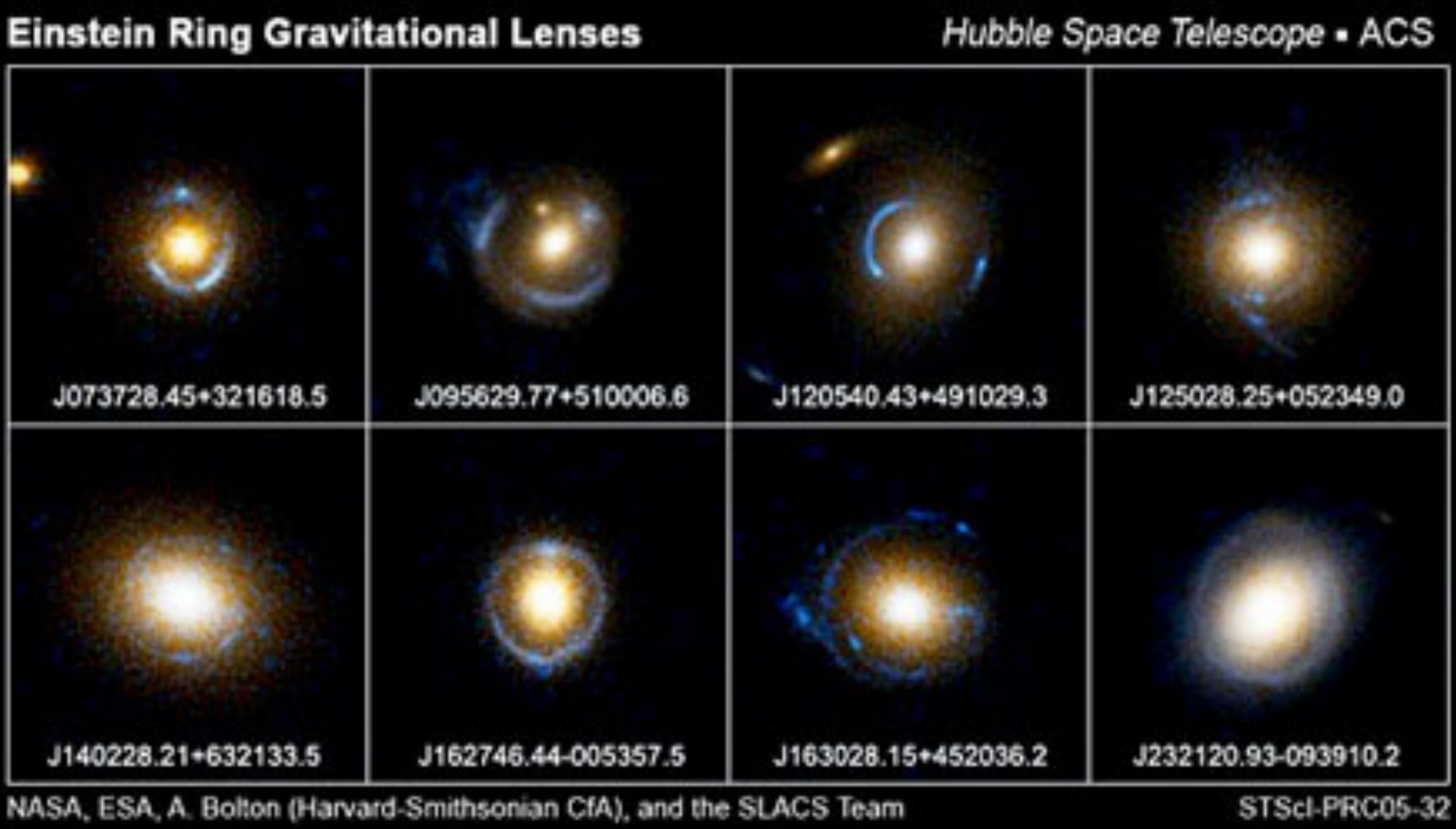
How to rule out CDM

Gravitational lensing: Einstein rings

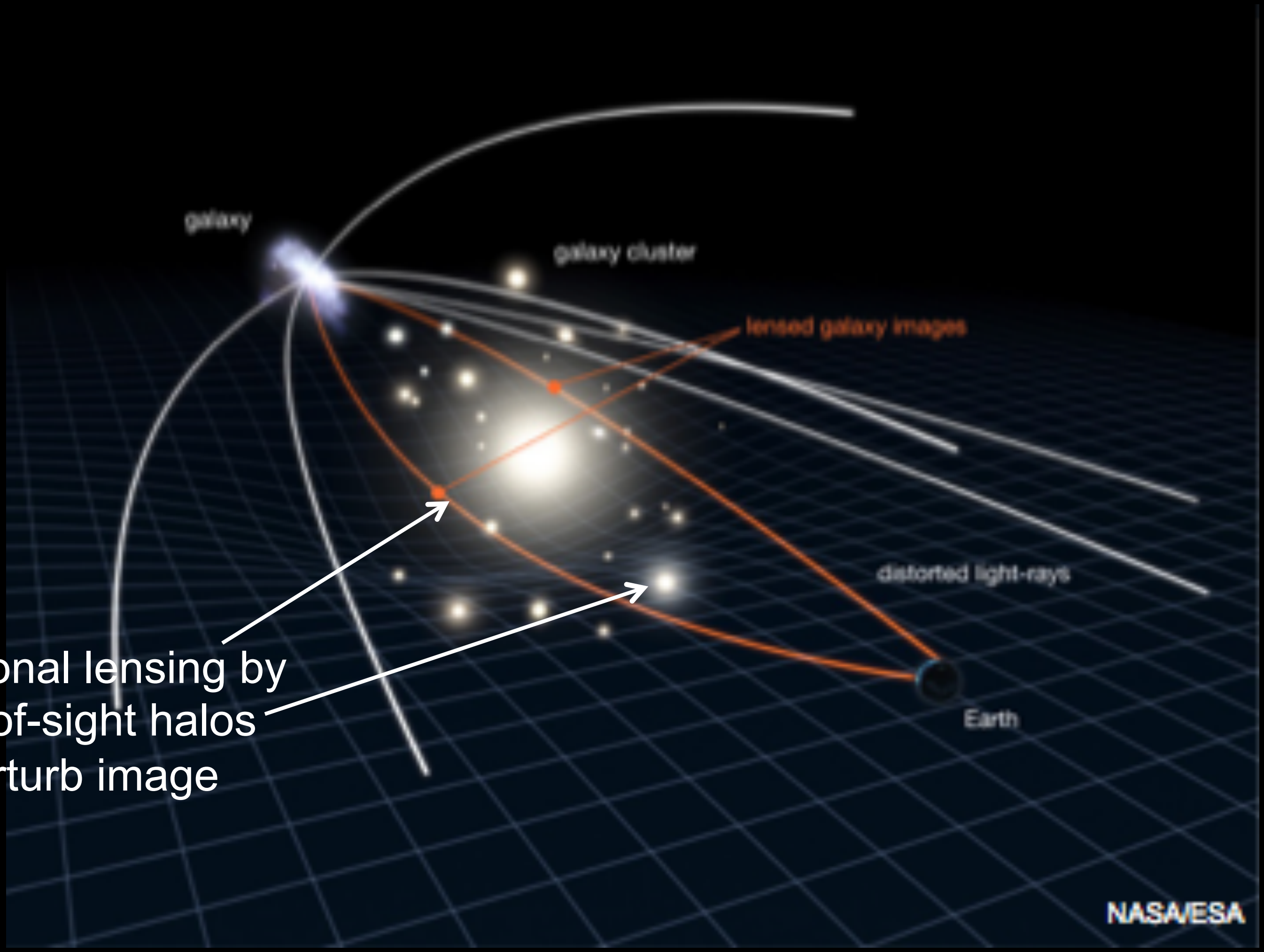


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



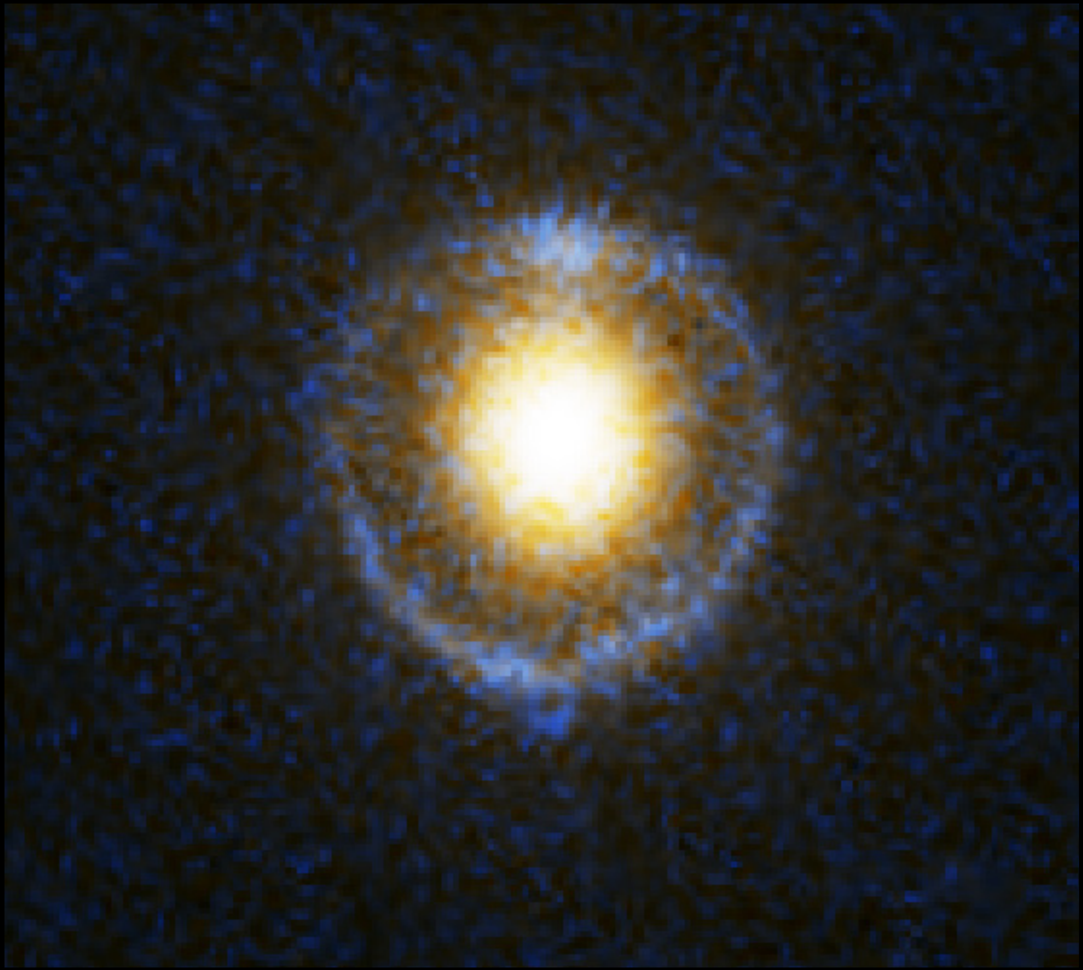
Gravitational lensing: Einstein rings



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



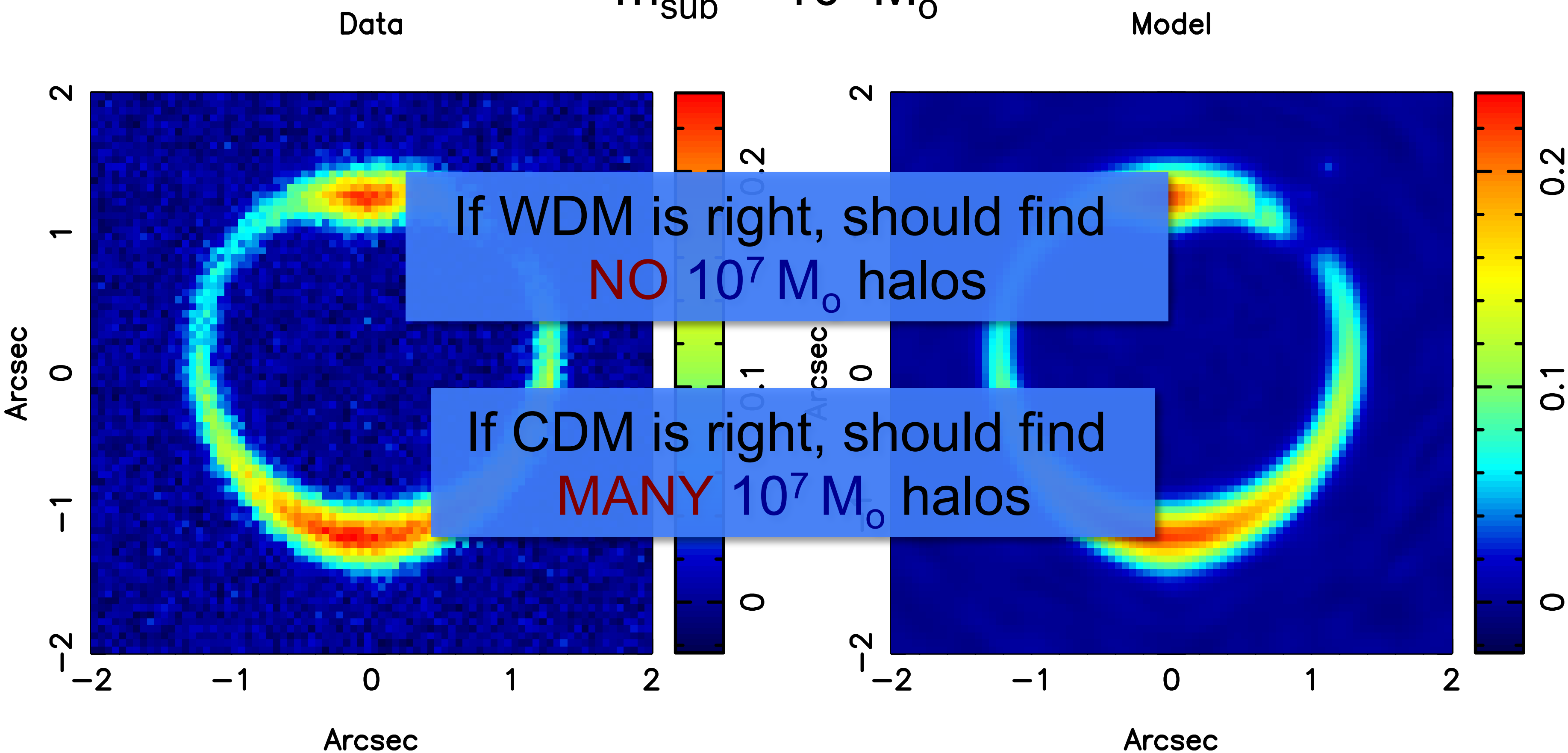
Vegetti & Koopmans '09

University of Durham

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 $10^7 M_o$

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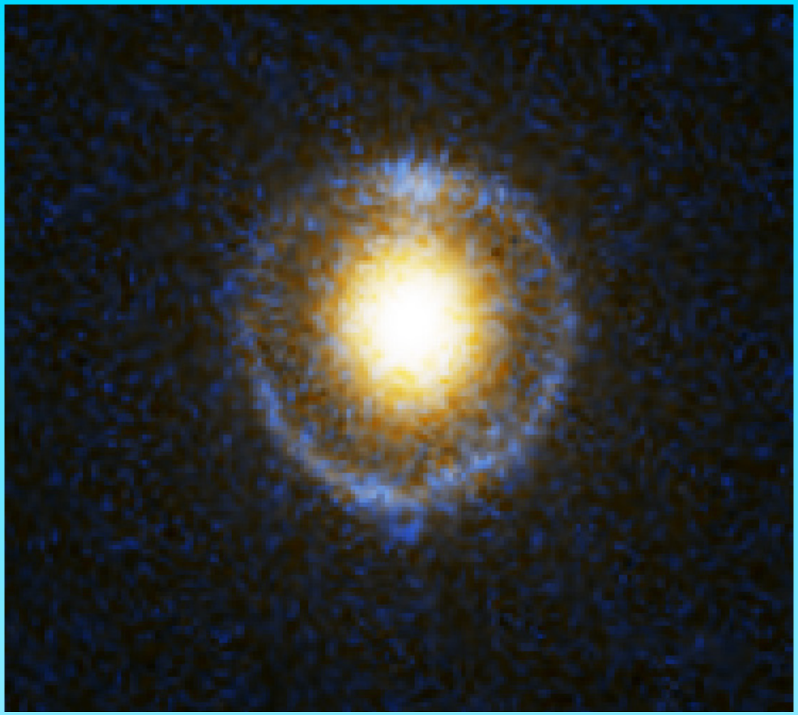
Gravitational lensing: Einstein rings



Two important considerations:

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

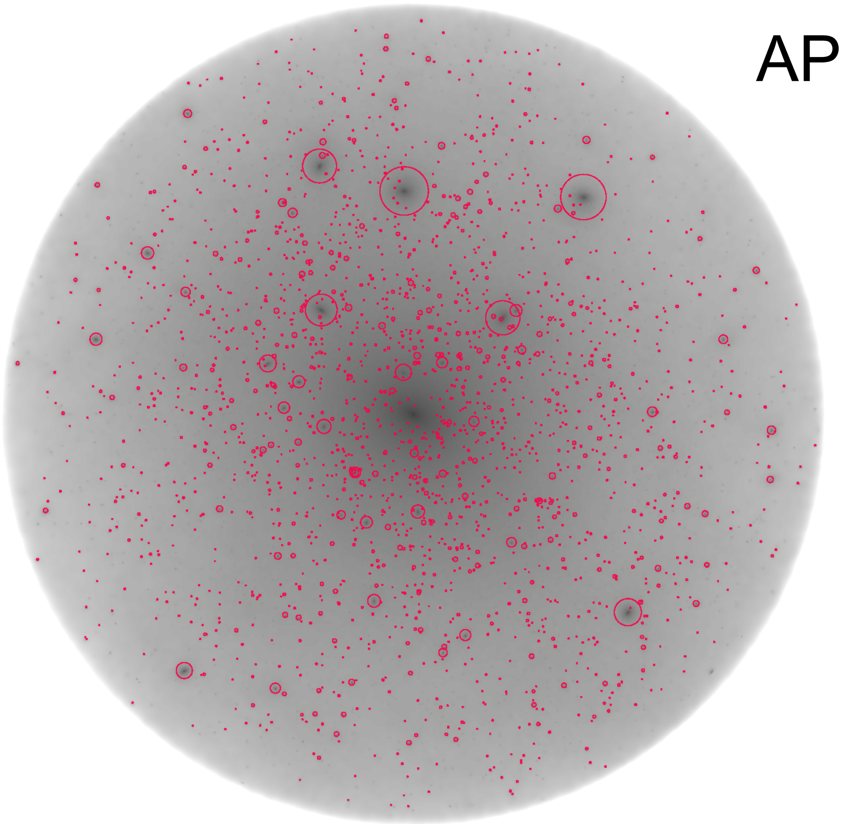
Sawala et al '17

Richings et al '17

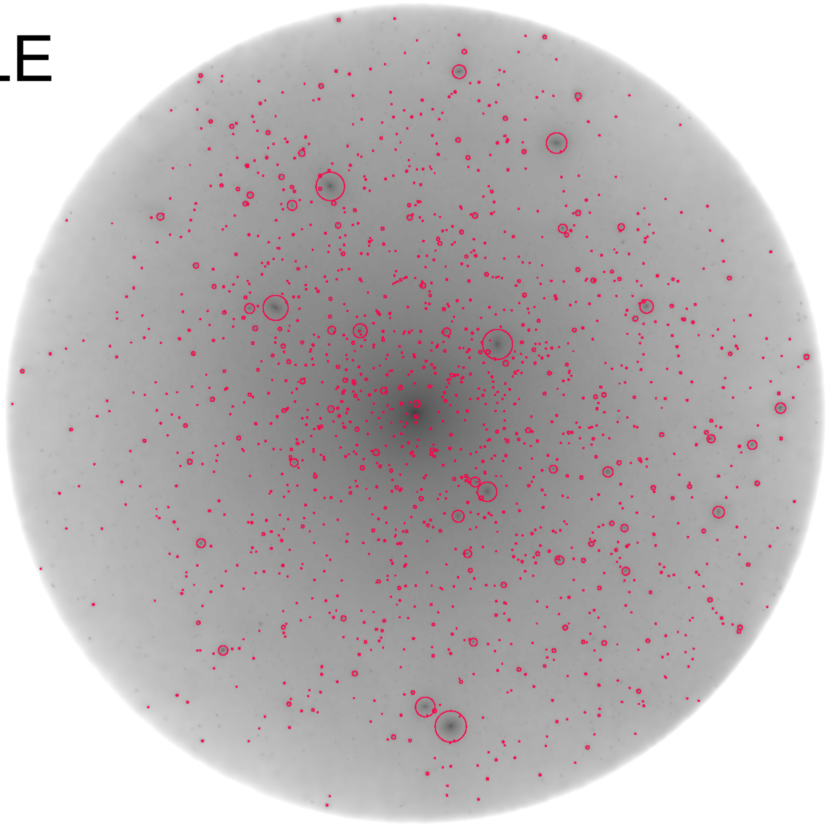
Destruction of dark substructures by galactic baryons

University of Durham

APOSTLE



Dark matter only simulation



Hydrodynamic simulation

Sawala et al ‘17

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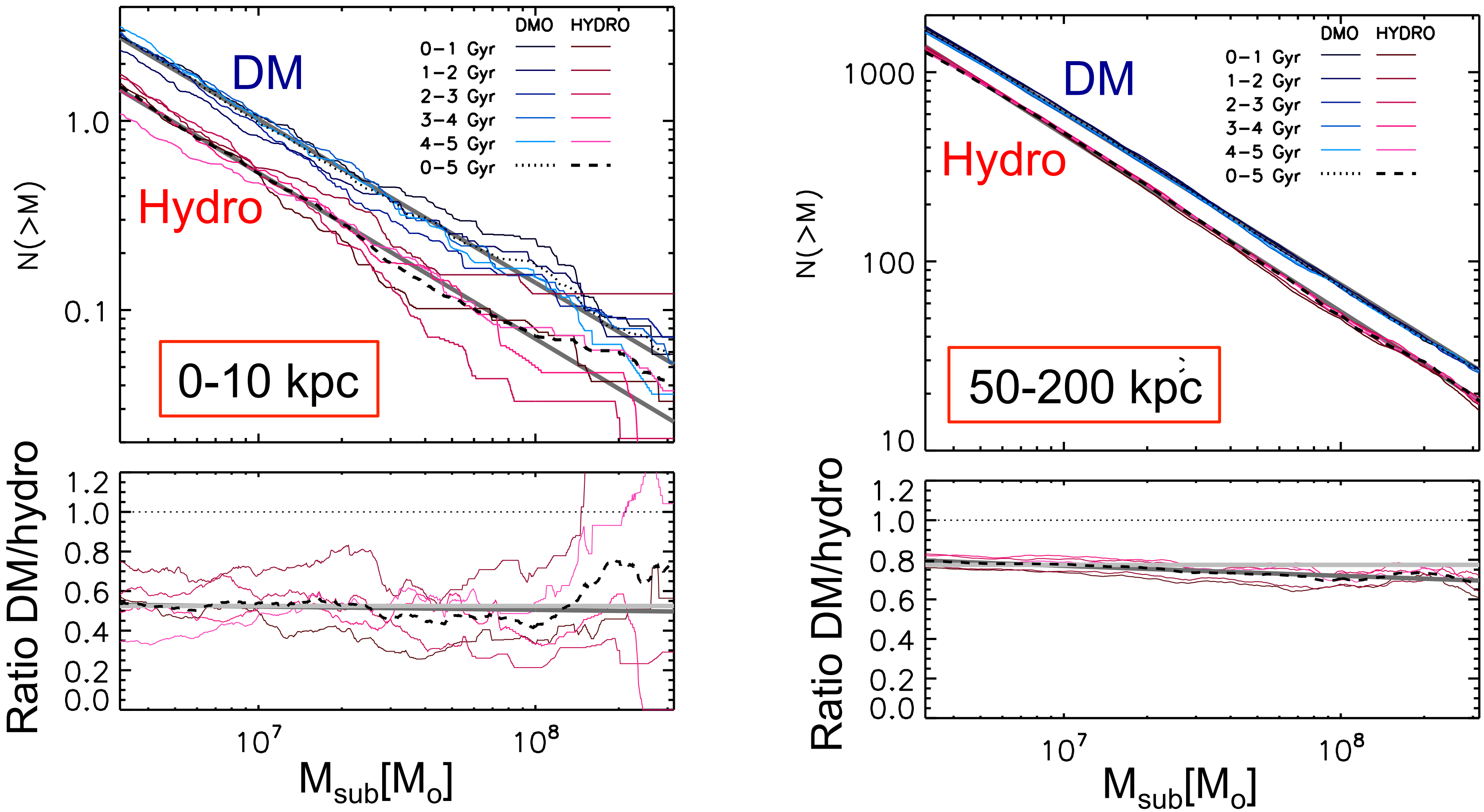
Destruction of dark substructures by galactic baryons

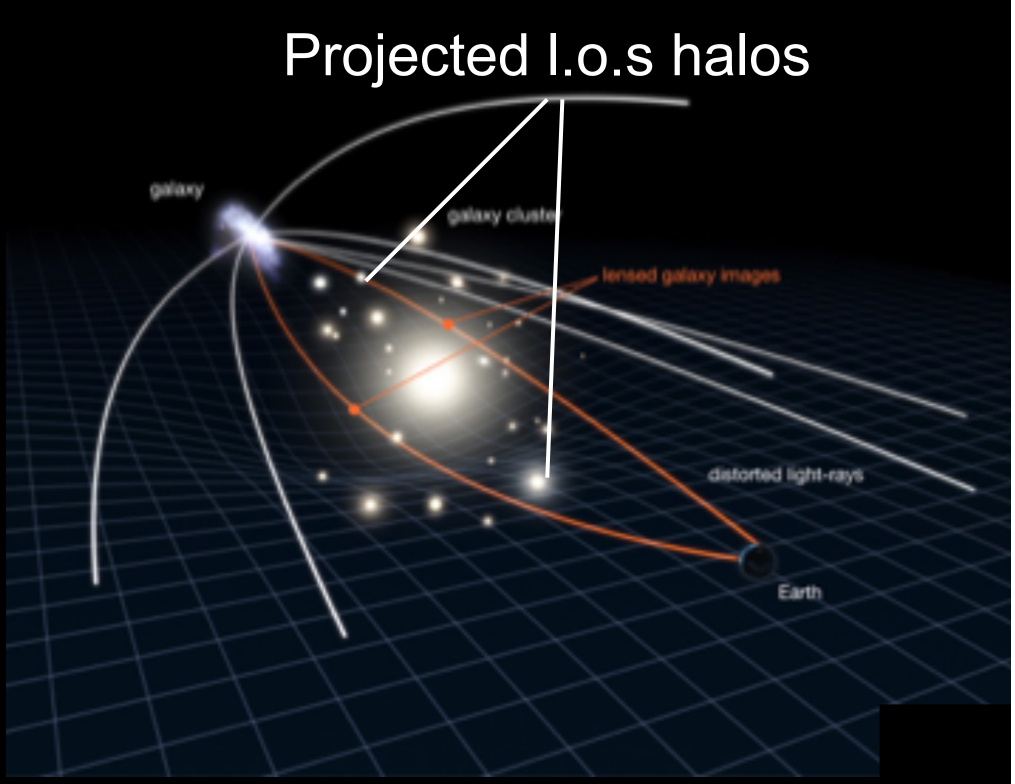


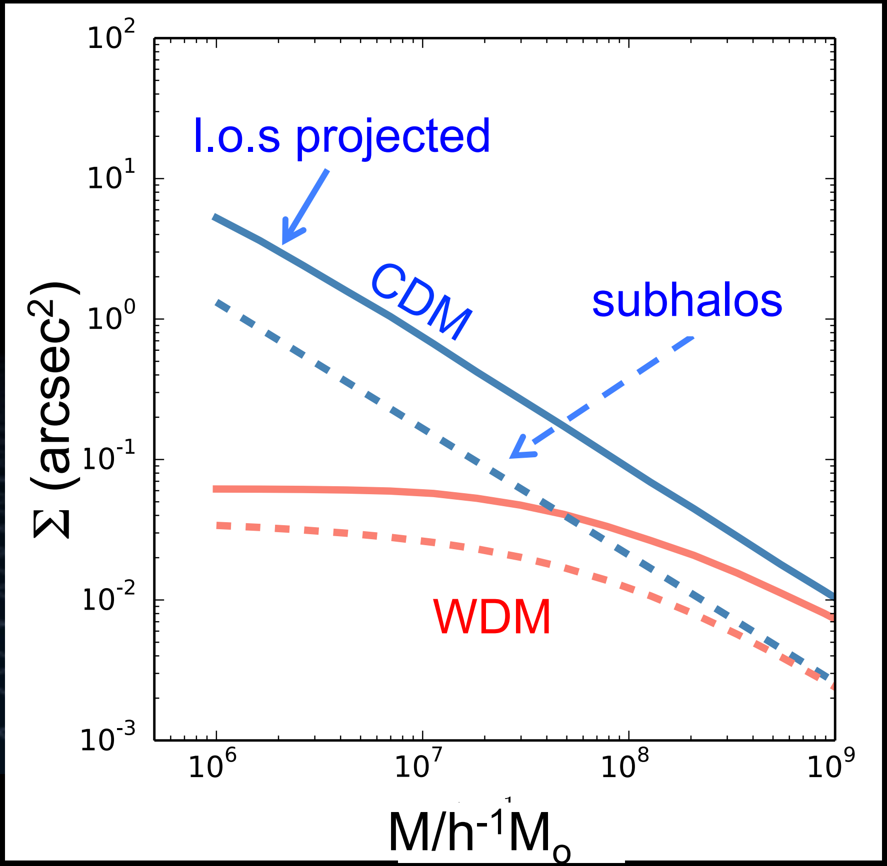
- 40% of subhalos in 0-10 kpc destroyed by interaction w. galaxy
- 20% " 50-200 kpc

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

Gravitational lensing: Einstein rings

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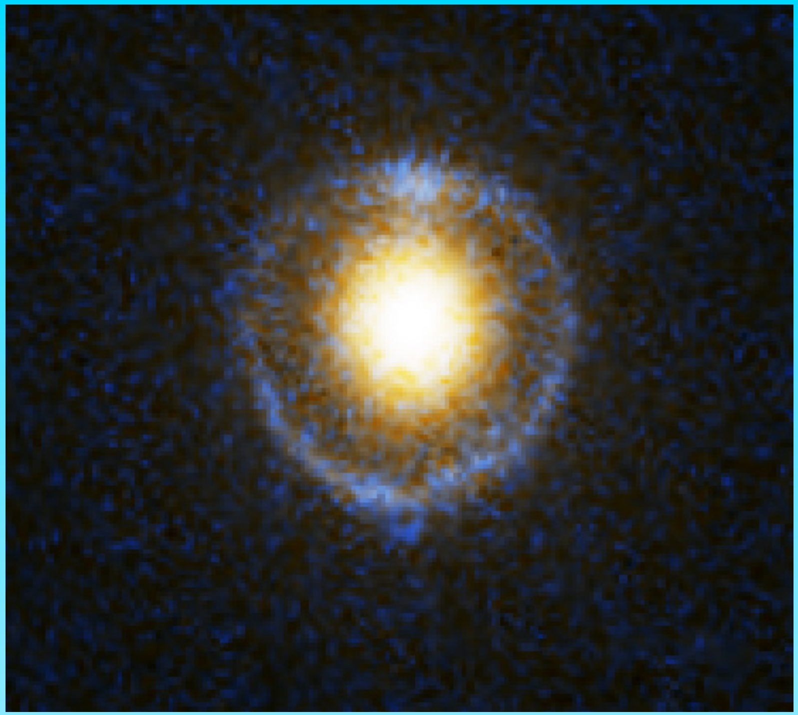

Two key considerations:

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

Answer:

- Central galaxy destroys ~40% of halos within Einstein ring (Sawala et al. ‘17)
- Projected halos dominate the strong lensing signal (Li et al ‘16)

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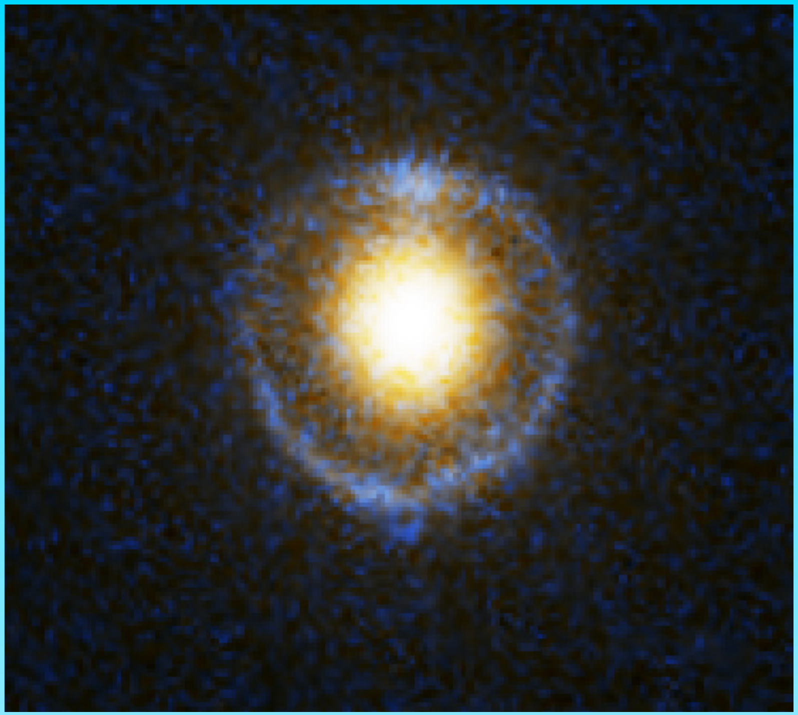
Gravitational lensing: Einstein rings



Two key considerations:

- The central galaxy can destroy subhalos
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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

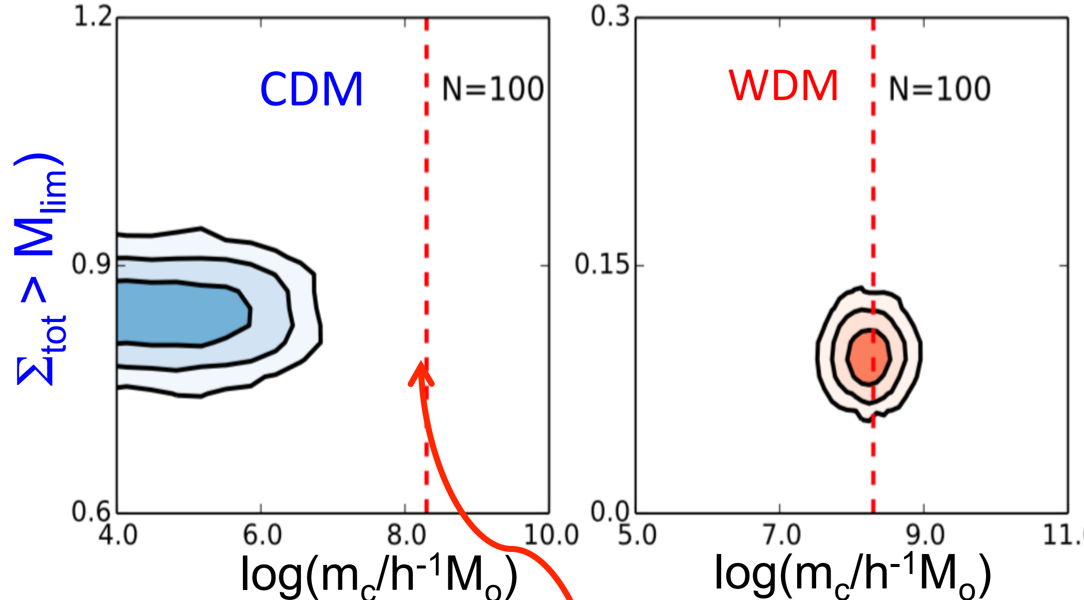
University of Durham

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

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

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

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
- 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. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!