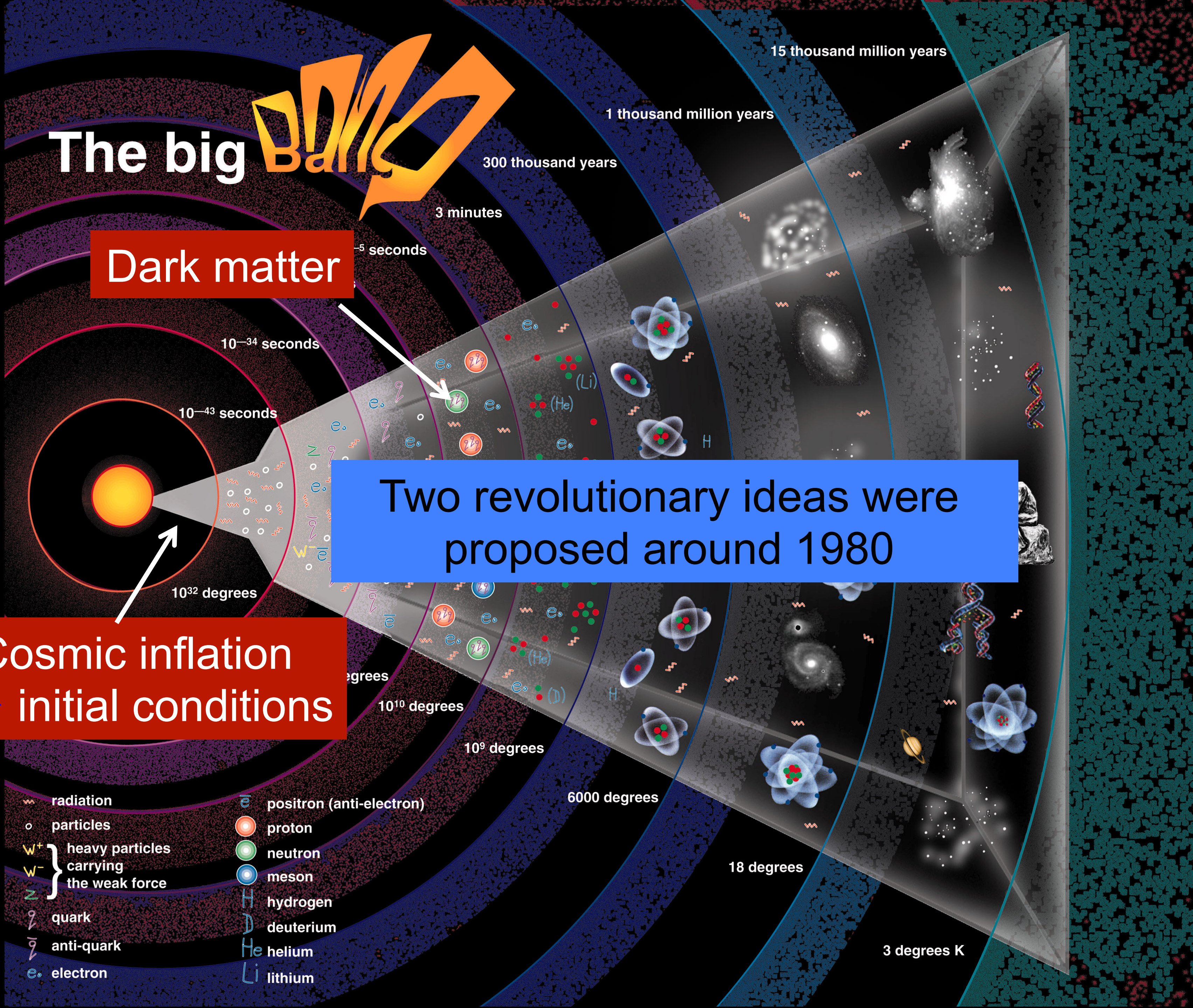
Clues to the identity of dark matter from simulations and observations

Carlos S. Frenk
Institute for Computational Cosmology,
Durham

Two revolutionary ideas were proposed around 1980

Dark matter

Cosmic inflation
→ initial conditions



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Non-baryonic dark matter candidates

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

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The dark matter power spectrum

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

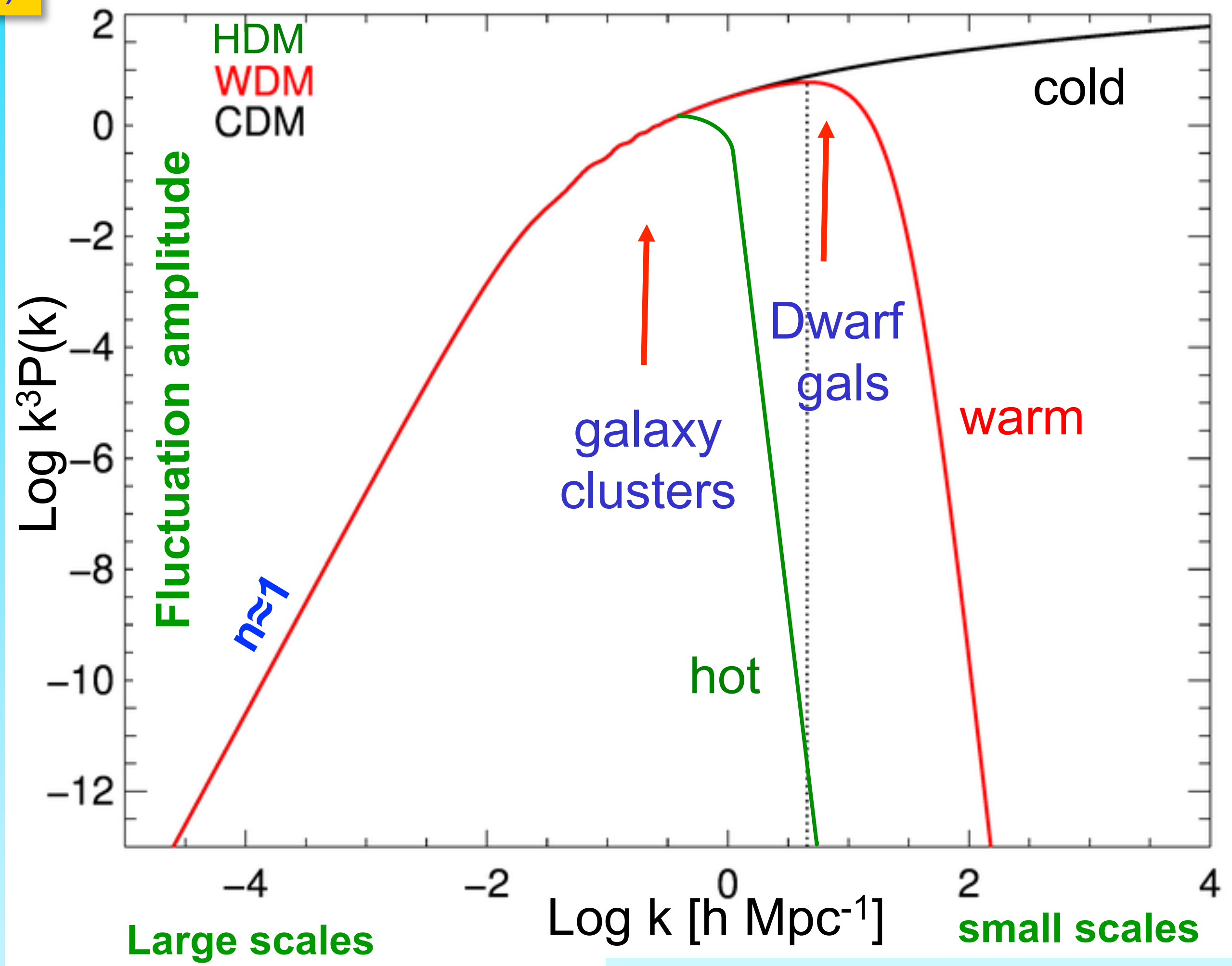
sterile ν; $M_{cut} \sim 10^{9}\ M_o$

$m_{HDM} \sim$ few eV

light ν; $M_{cut} \sim 10^{15}\ M_o$

$k^3\ P(k)$

The linear power spectrum ("power per octave")



For the first time in Cosmology → a well-defined theory of the initial conditions for the formation of cosmic structure

The formation of cosmic structure

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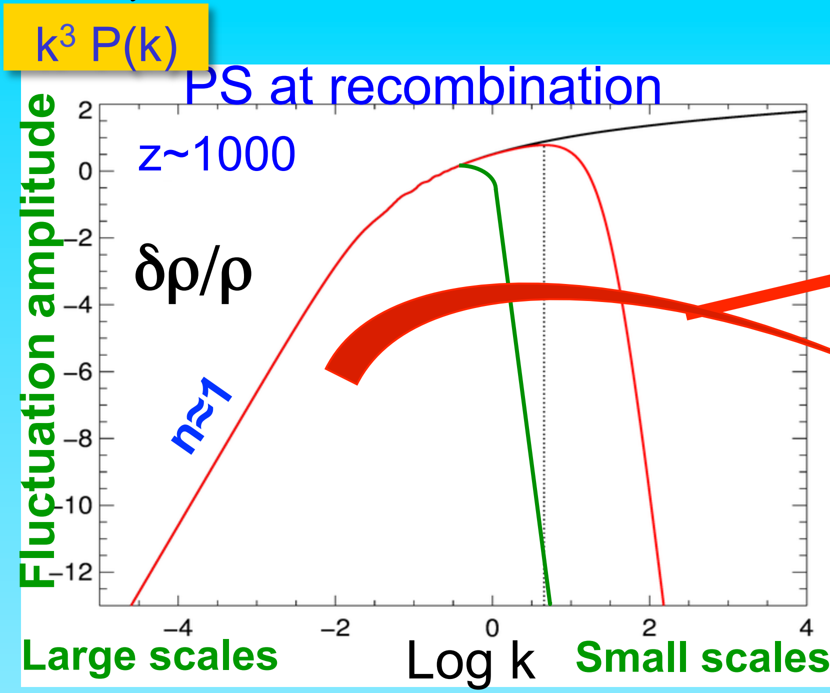
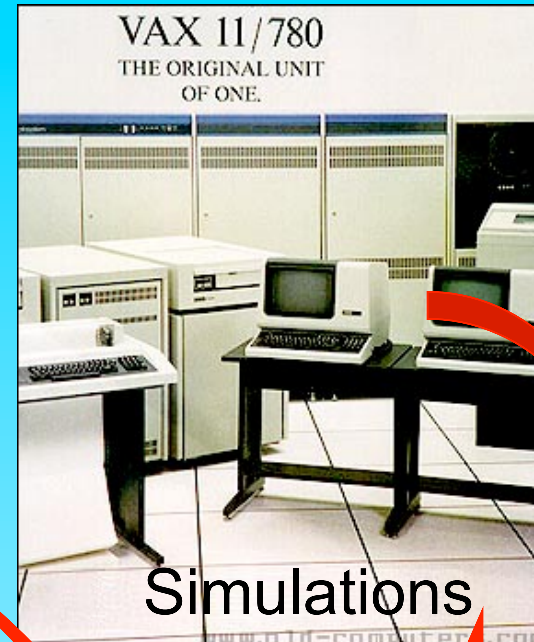


t=380,000 yrs

$\delta\rho/\rho \sim 10^{-5}$



Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

t=14.1billion yrs

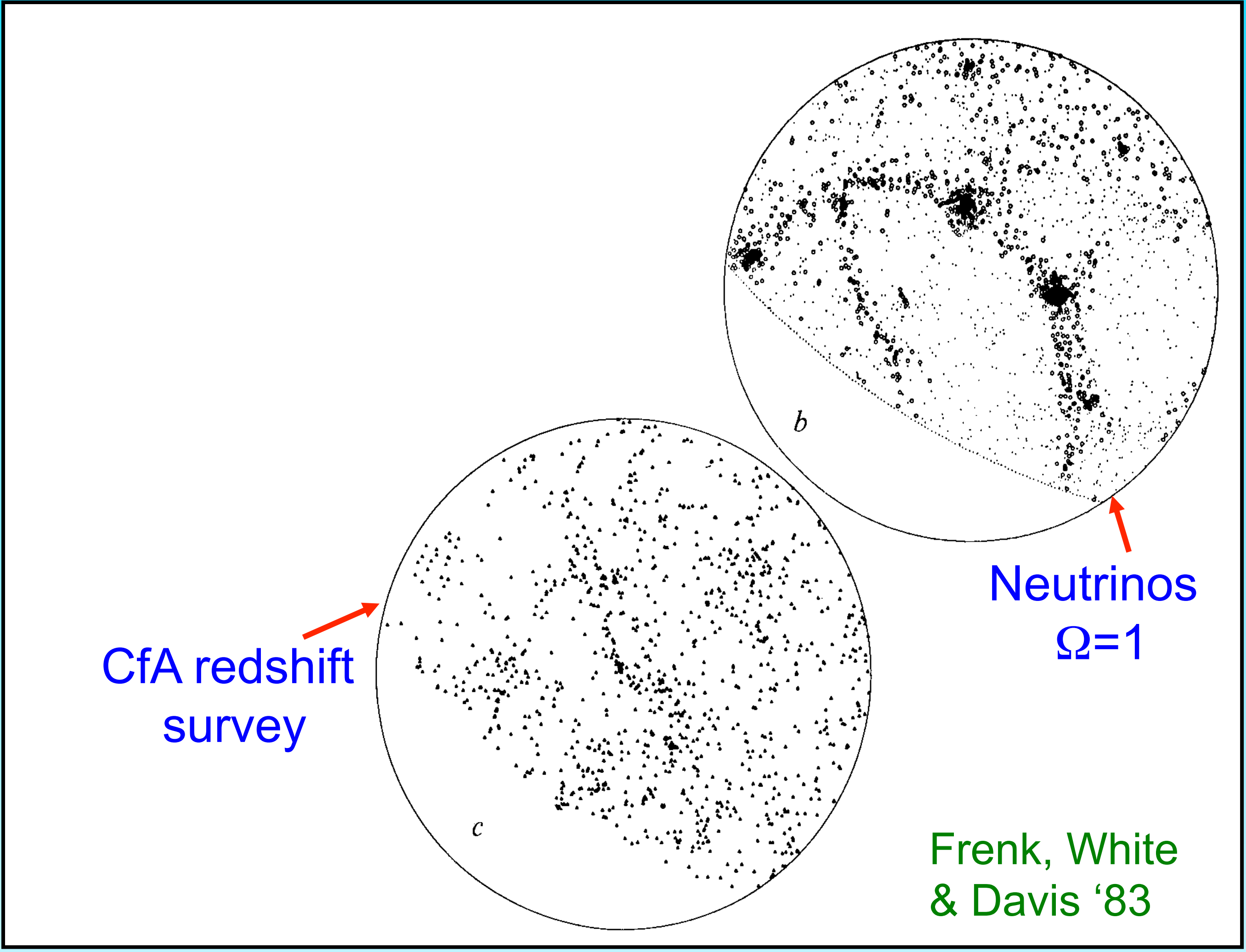
$\delta\rho/\rho \sim 1-10^{6}$

Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev



Non-baryonic dark matter cosmologies

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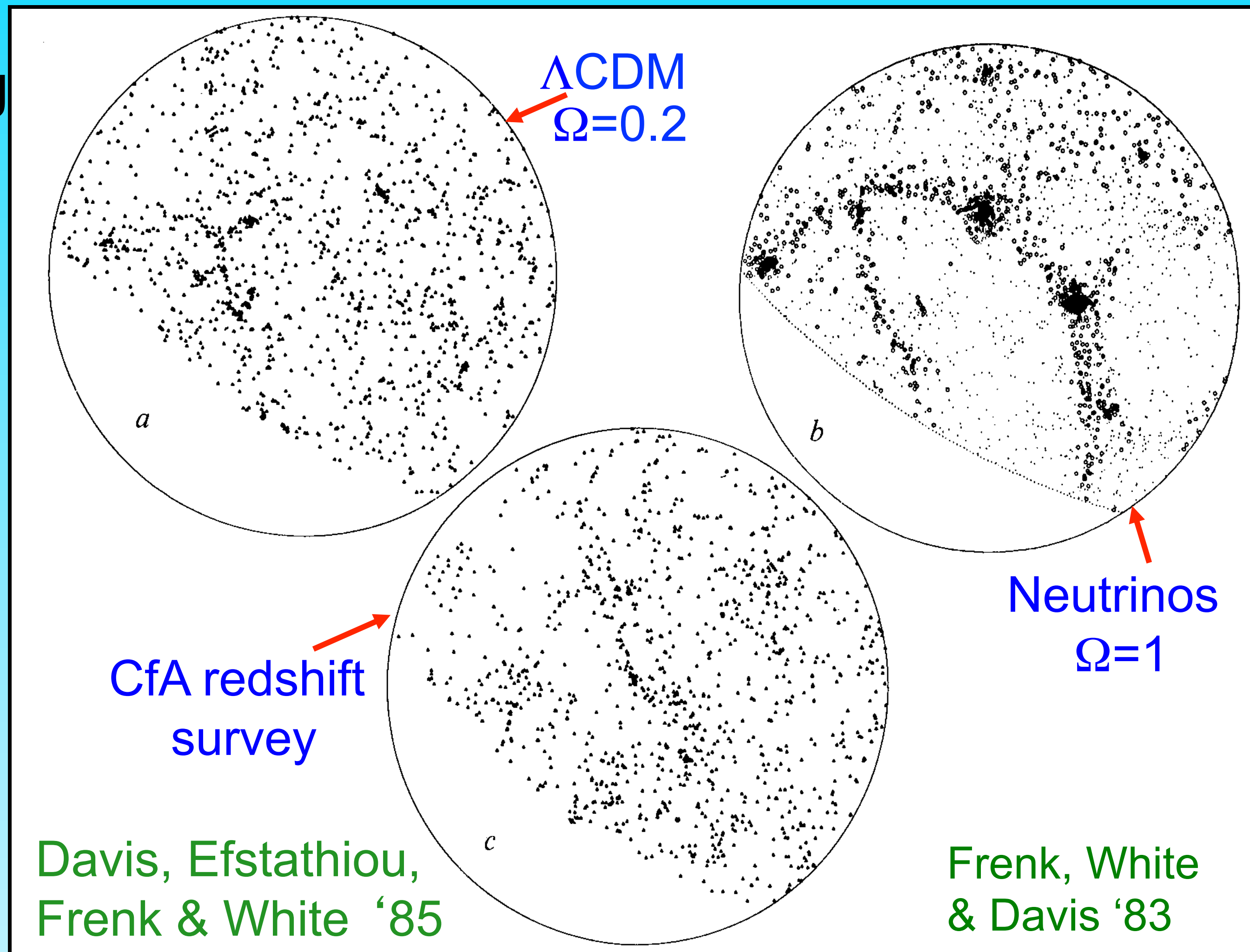
→ m_ν << 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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cold	axion neutralino	10^{-5}eV- >100 GeV

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warm	sterile neutrino majoron; KeVino	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

The cold dark matter cosmogony

Main successes of the CDM cosmogony:

1. CMB temp. anisotropies: predicted 1981; discovered 1993
2. Galaxy formation and evolution (modelled early 90s; 1991 -)
3. Galaxy clustering (predicted early 80s; measured 1990- QDOT, APM, 2dFGRS, SDSS)

Temperature anisotropies in CMB

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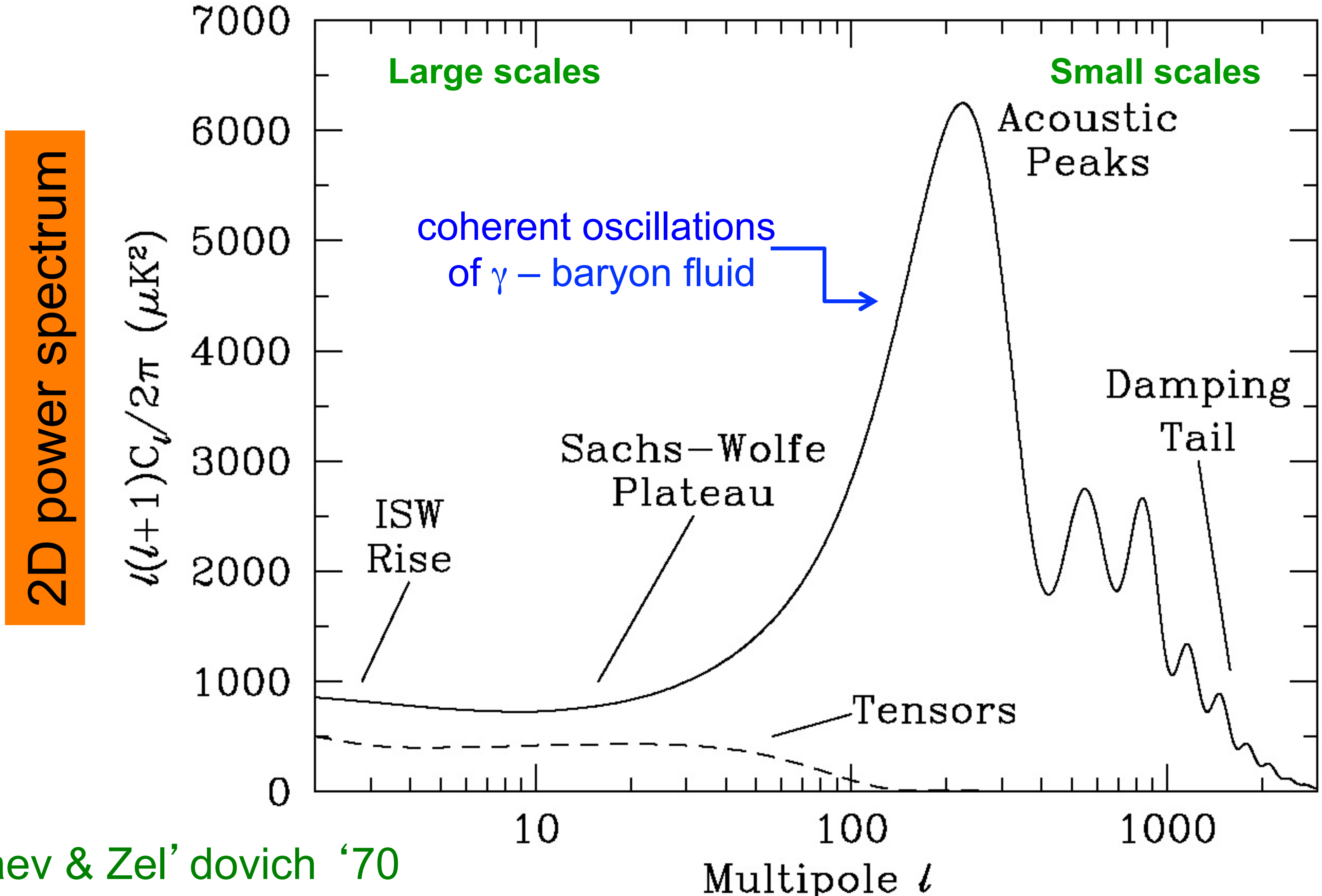
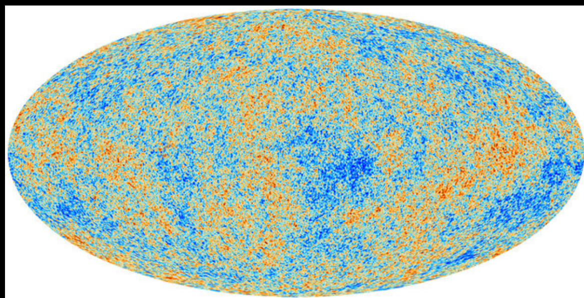
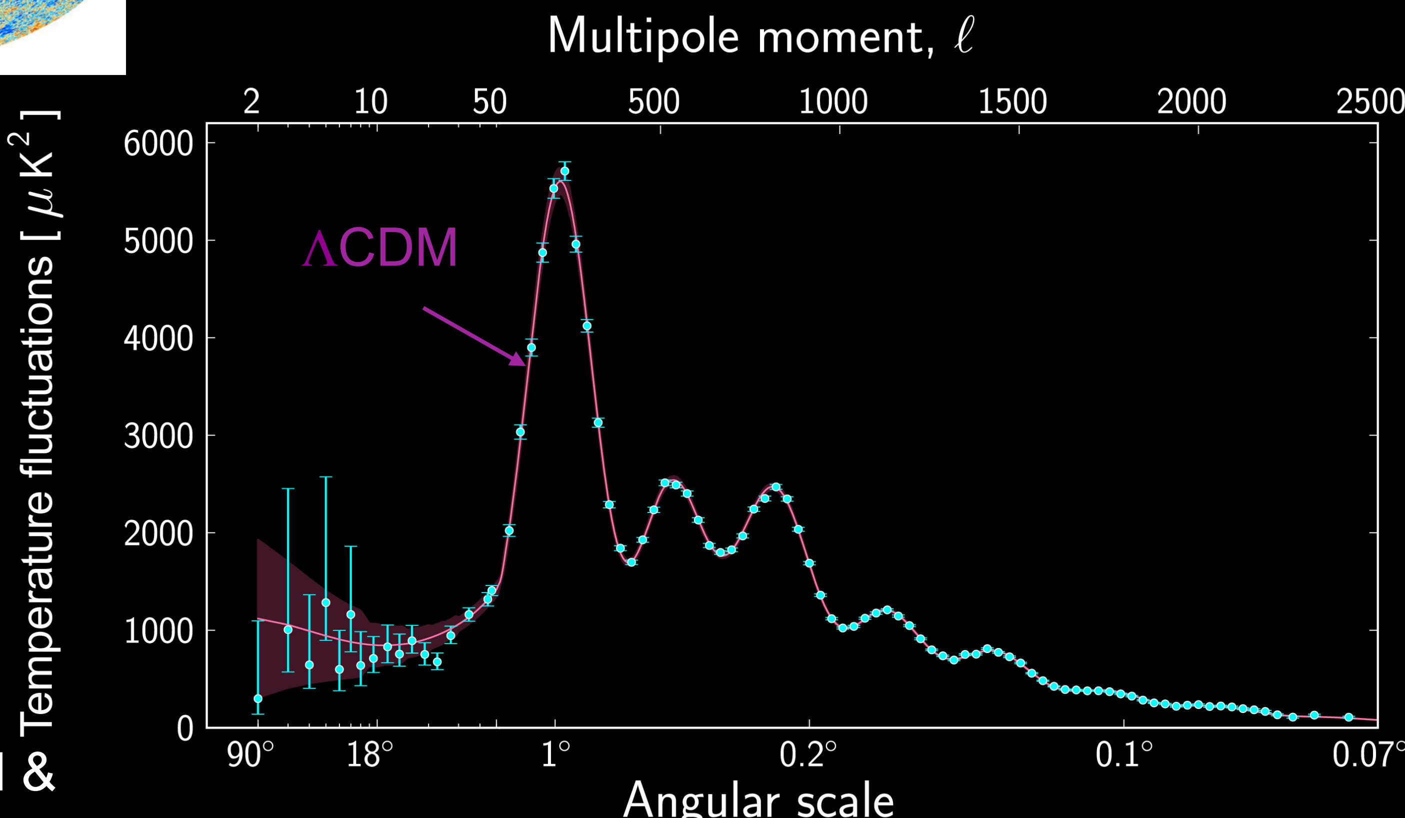


Sunyaev & Zel'dovich '70
Peebles & Yu '70; Peebles '82

Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000



The data confirm the theoretical predictions (linear theory)

Peebles ’82; Bond & Efstathiou ‘80s

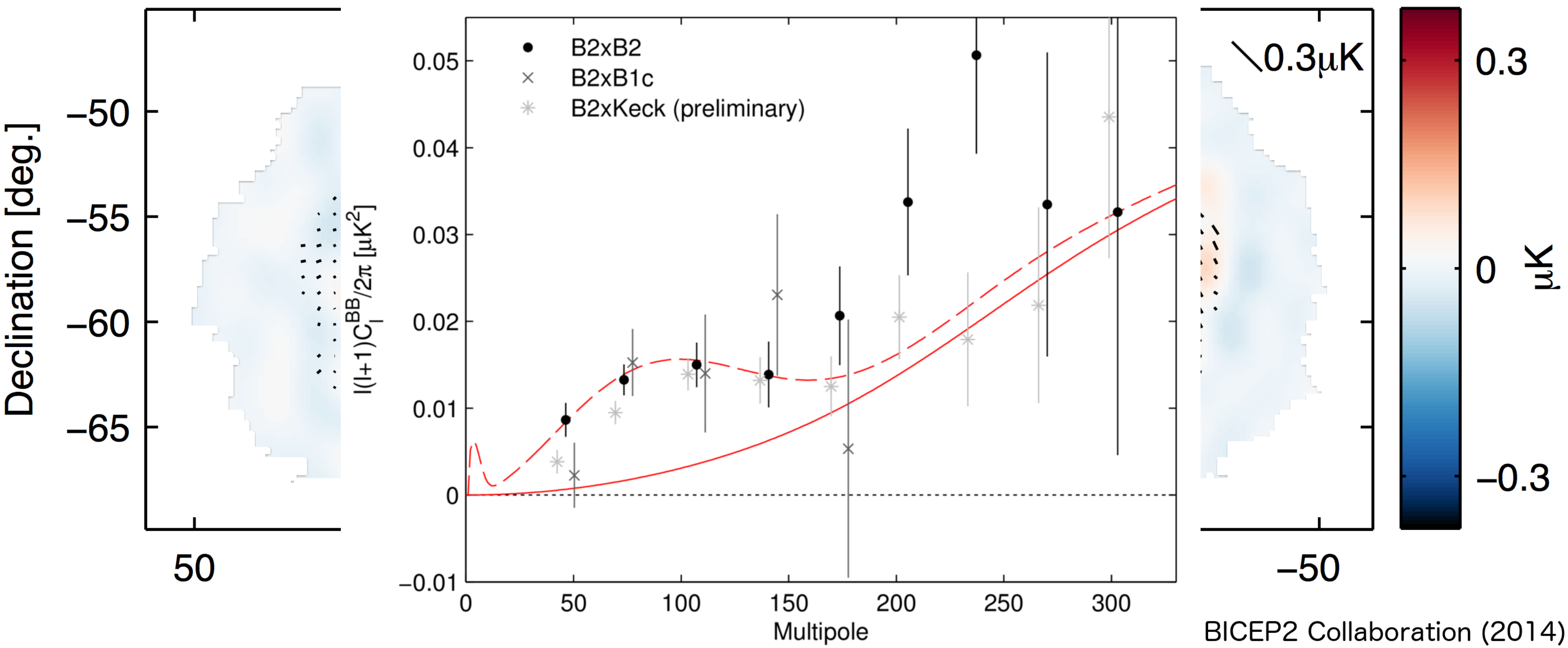
Planck collaboration ‘13

Detection of B-mode polarization?

Gravitational waves are a fundamental prediction of inflation

They induce B-mode polarization in the CMB at low l

BICEP2: B signal



BICEP2 Collaboration (2014)

Ade et al. '14

Volume 91B, number 1 PHYSICS LETTERS 24 March 1980

A NEW TYPE OF ISOTROPIC COSMOLOGICAL MODELS WITHOUT SINGULARITY

A.A. STAROBINSKY
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England [1]
and The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR [2]

The important property of all nonsingular models with the initial superdense de Sitter state is that, as shown in ref. [8], such a large amount of relic gravitational waves is generated by one-loop processes in these models (in particular, in the range $1-10^{-5}$ Hz) that predictions of the semiclassical theory and the very existence of this state can be experimentally verified in the near future. Adopting such a model, one should also call for some mechanism of baryon-number generation because initial symmetry requires zero initial values of all charges.

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The galaxy luminosity function

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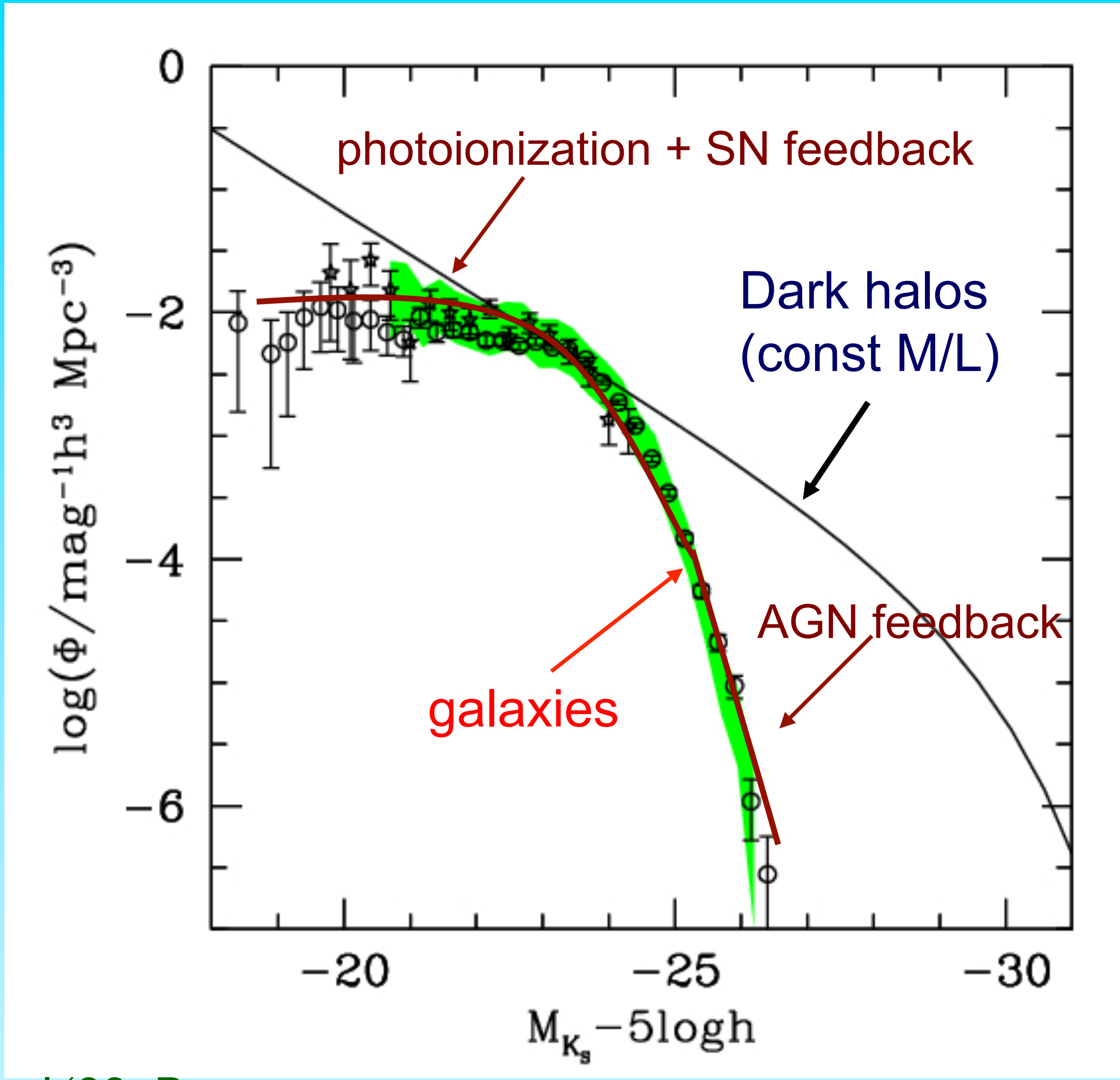
The halo mass function and the galaxy luminosity function have different shapes

⇨

Galaxy luminosity not just $\propto$ halo mass

Complicated variation of M/L with halo mass



White & Frenk ‘91; Kauffmann et al ‘93; Benson et al ’03; Croton et al ‘05; Bower et al. ’06

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Star forming galaxies

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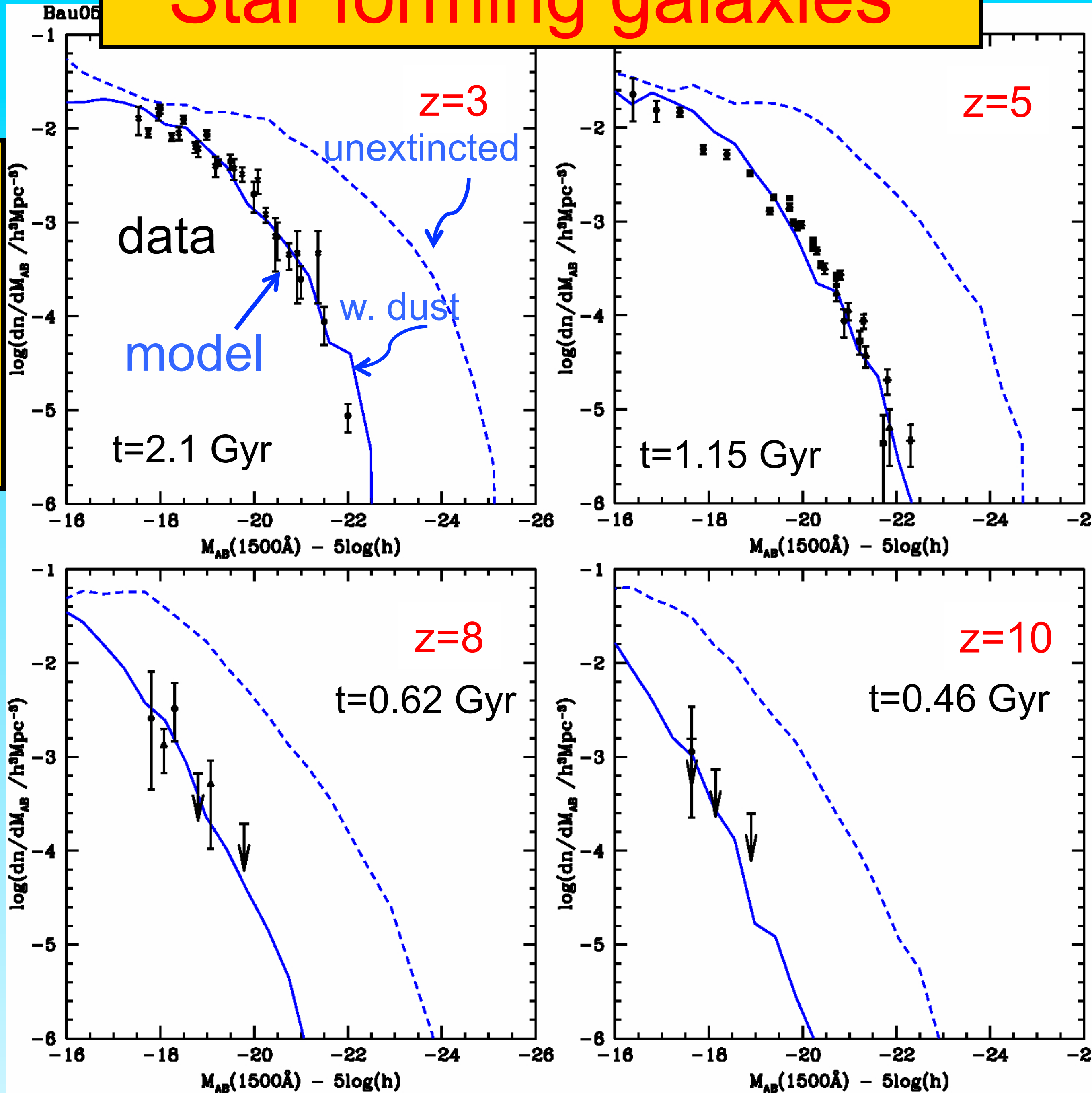
Evolution of Lyman-break galaxy lum. function



Lacey, Baugh, Frenk, Benson '12

The cold dark matter cosmogony

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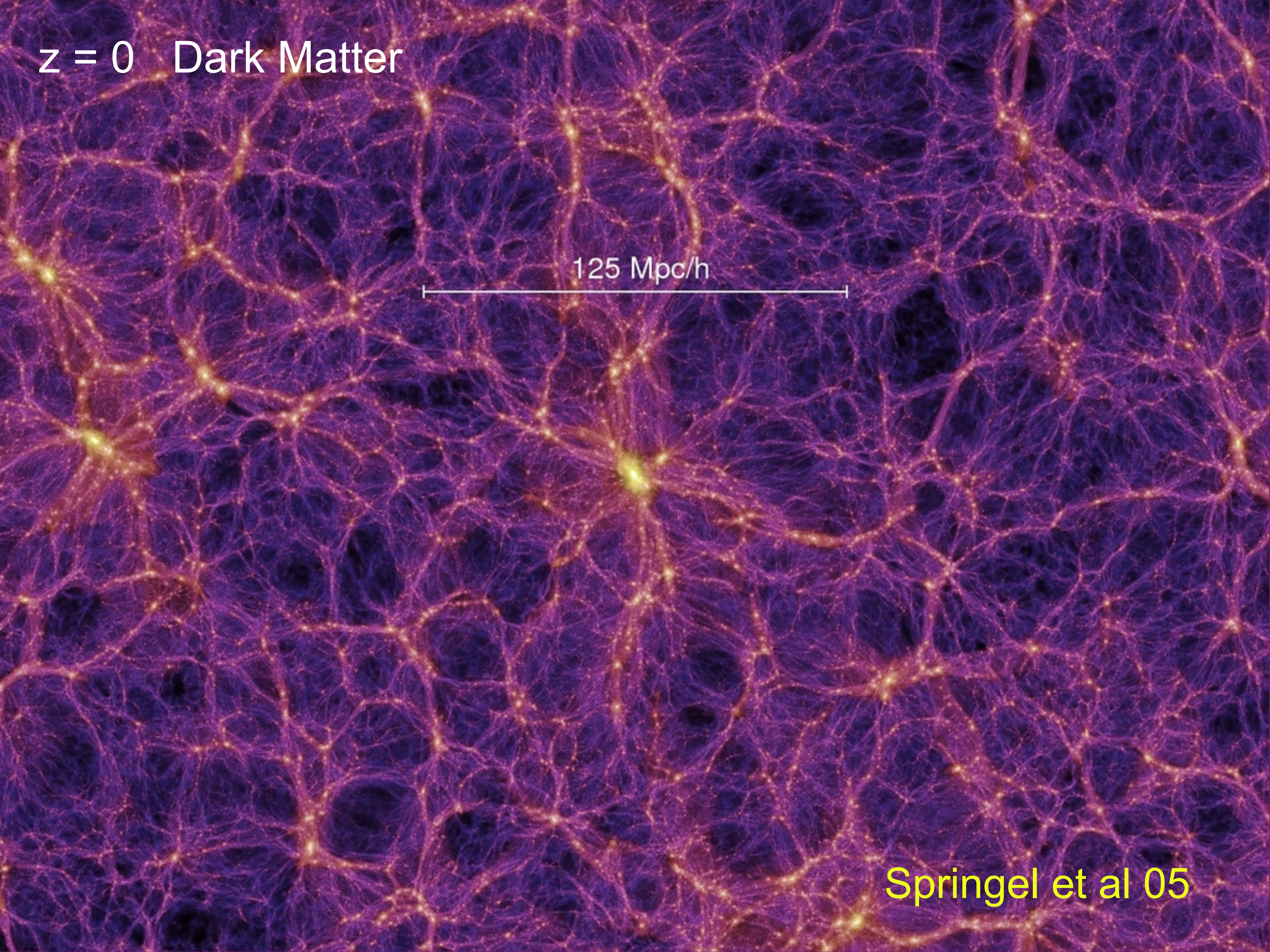
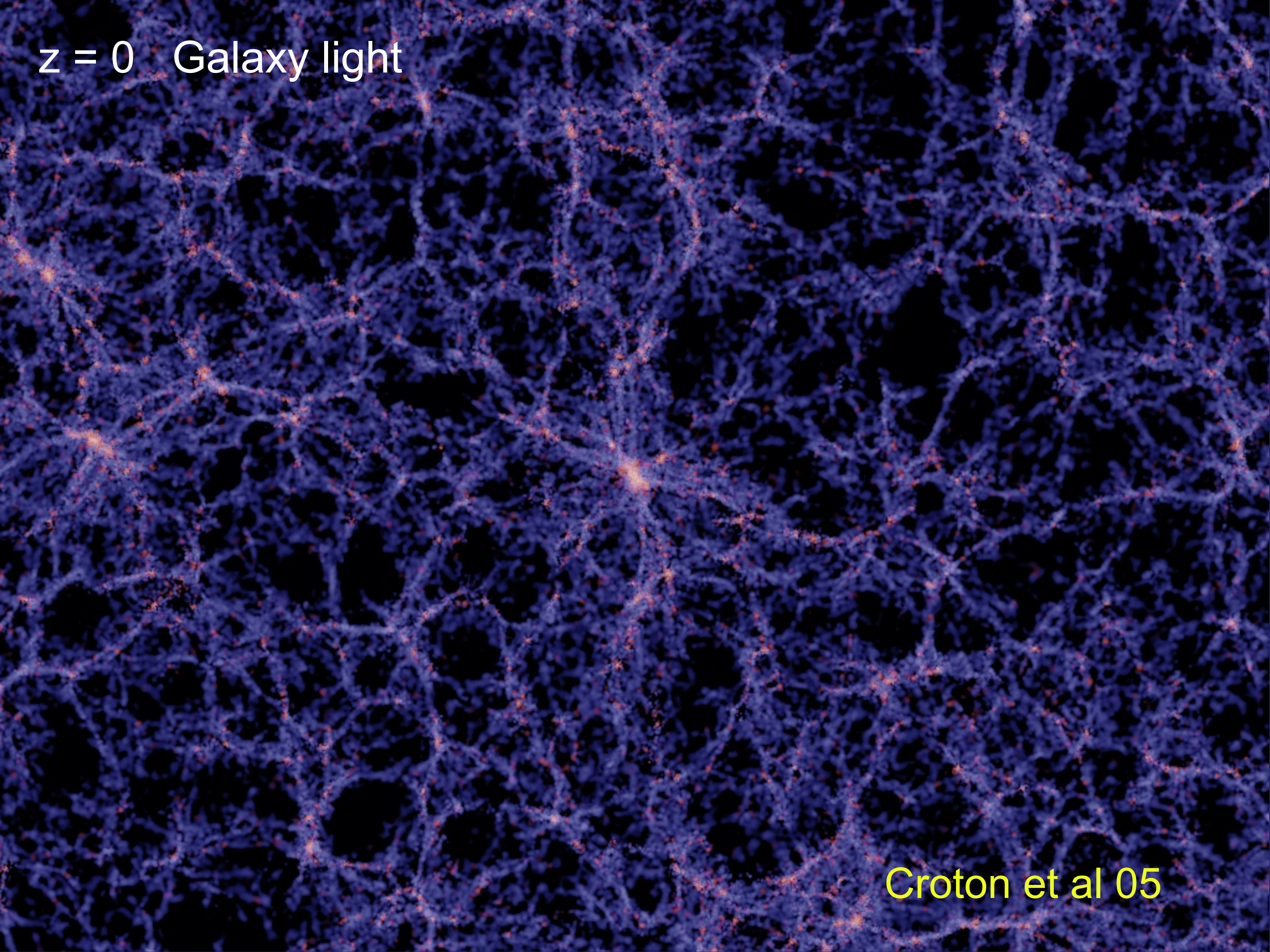
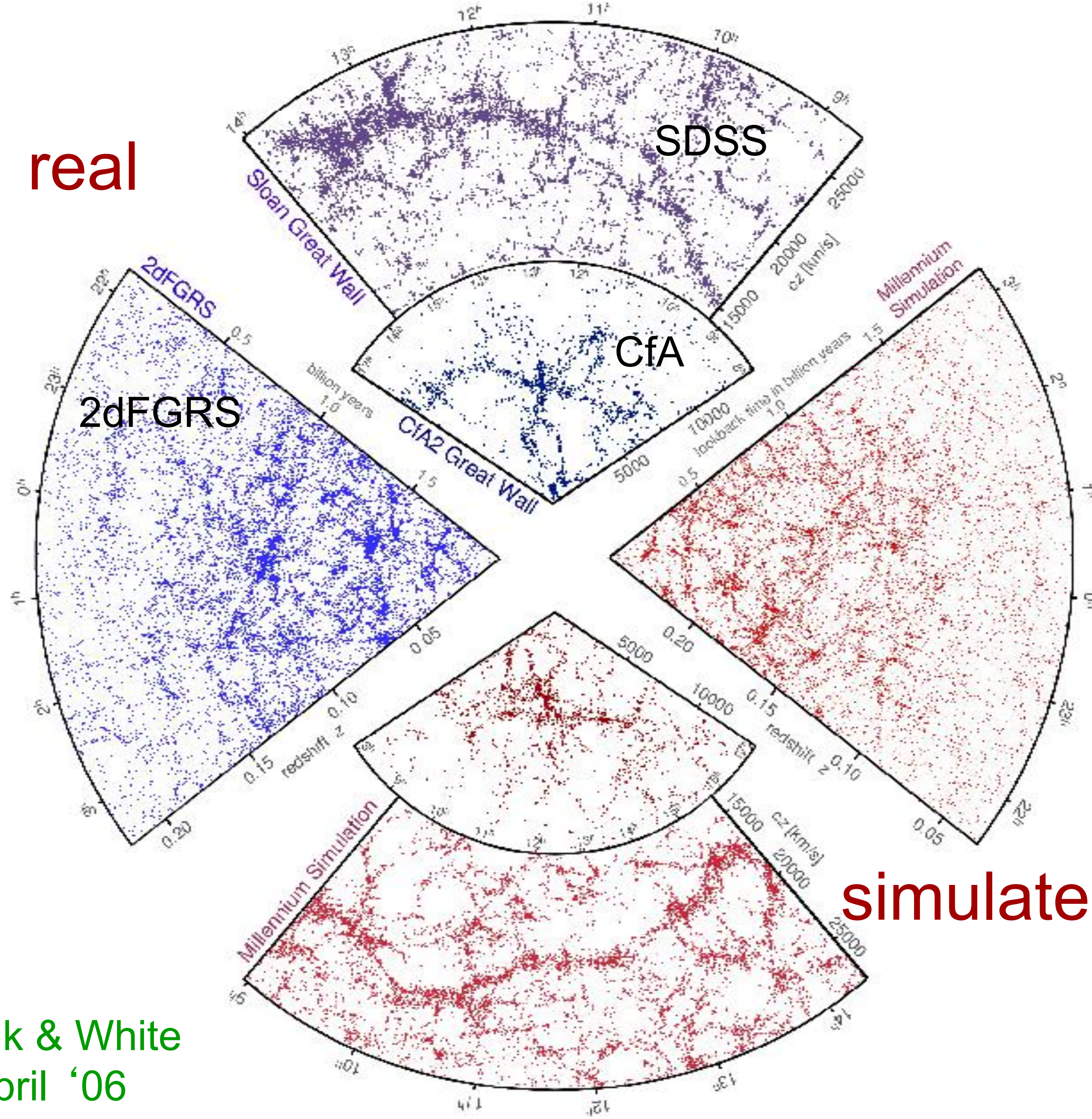

z = 0 Dark Matter
125 Mpc/h
Springel et al 05


z = 0 Galaxy light
Croton et al 05

real



simulated

Springel, Frenk & White
Nature, April ‘06

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

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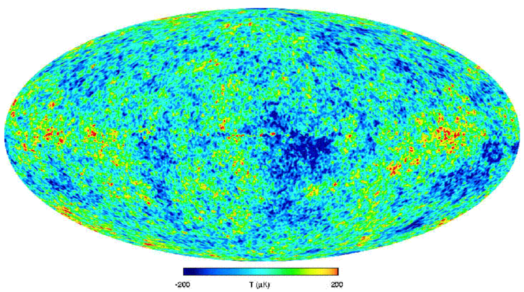
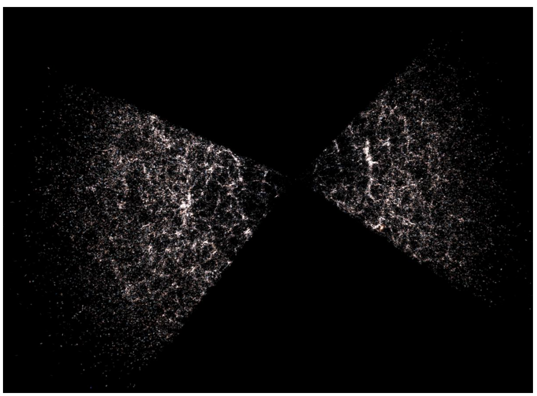
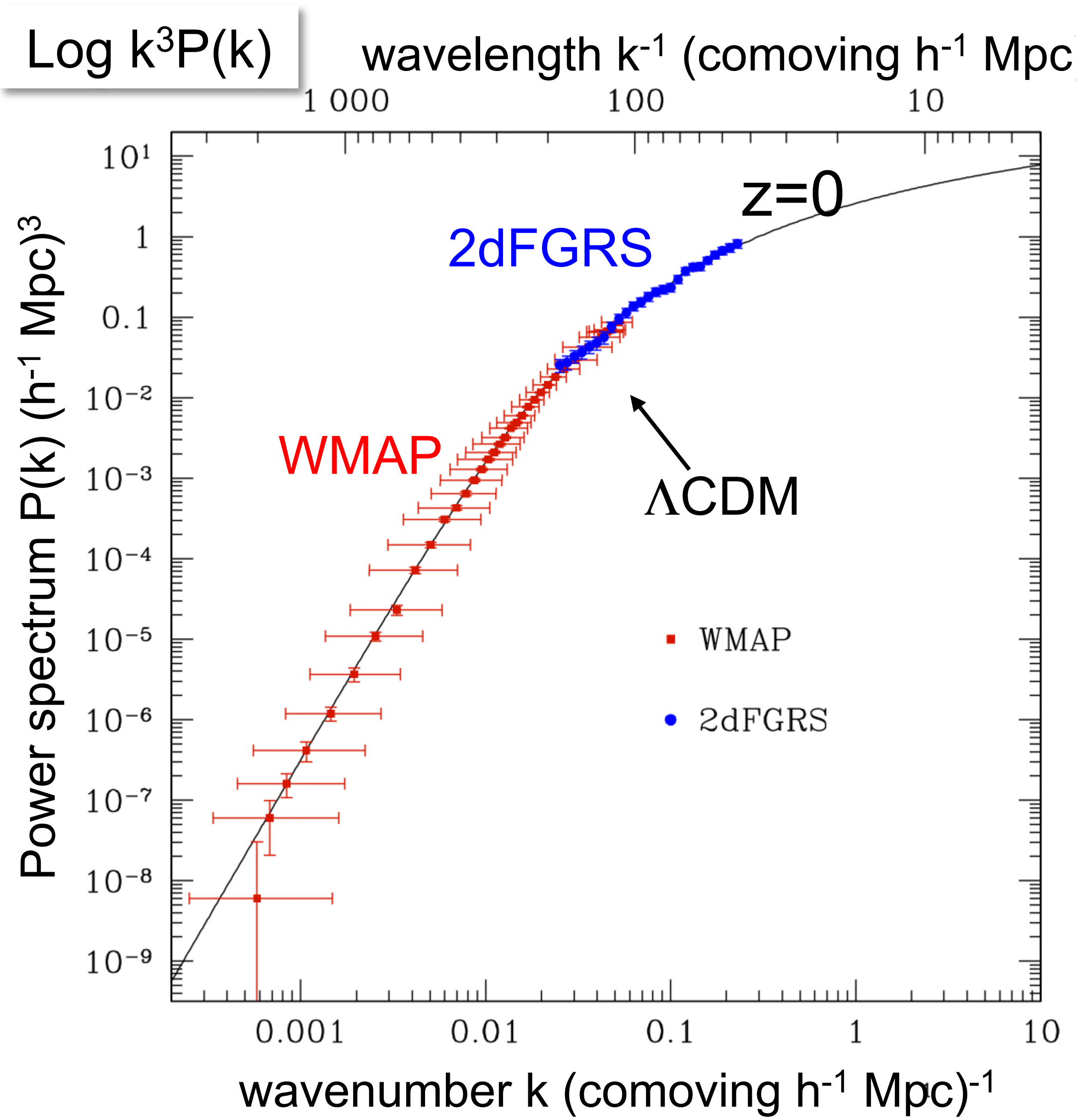


z~1000



z~0



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

Sanchez et al 06

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

Free streaming →

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

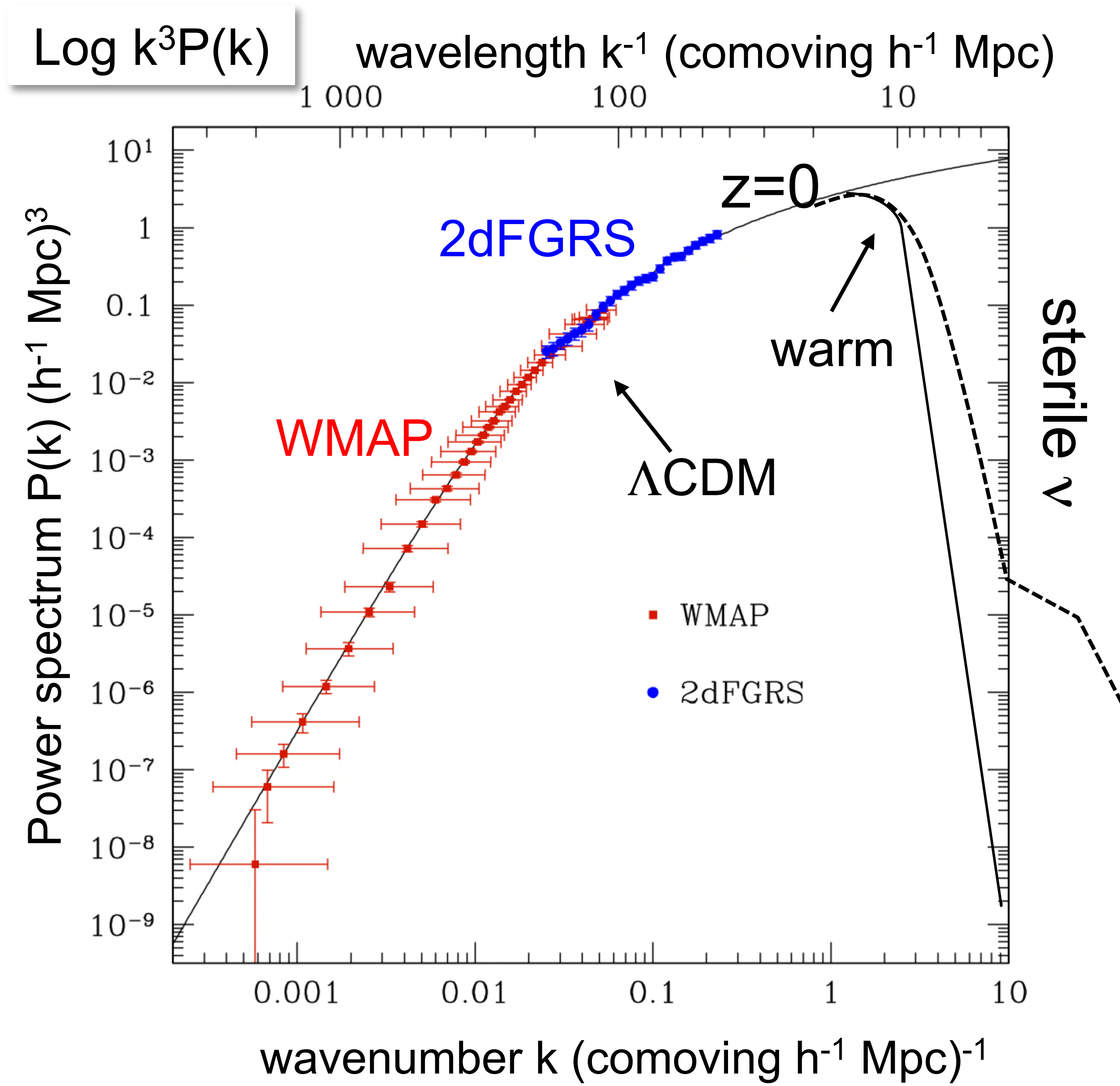
for thermal relic

$m_{CDM} \sim 100\text{GeV}$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



The ν minimal standard model

- Neutrino Minimal Standard Model (νMSM) proposed to explain neutrino masses (Asaka & Shaposhnikov '05; Boyarski, Ruchowskyi)

- Adds three sterile neutrinos to the SM. The lightest of these would be the dark matter

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

Free streaming →

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

for thermal relic

$m_{CDM} \sim$ 100GeV

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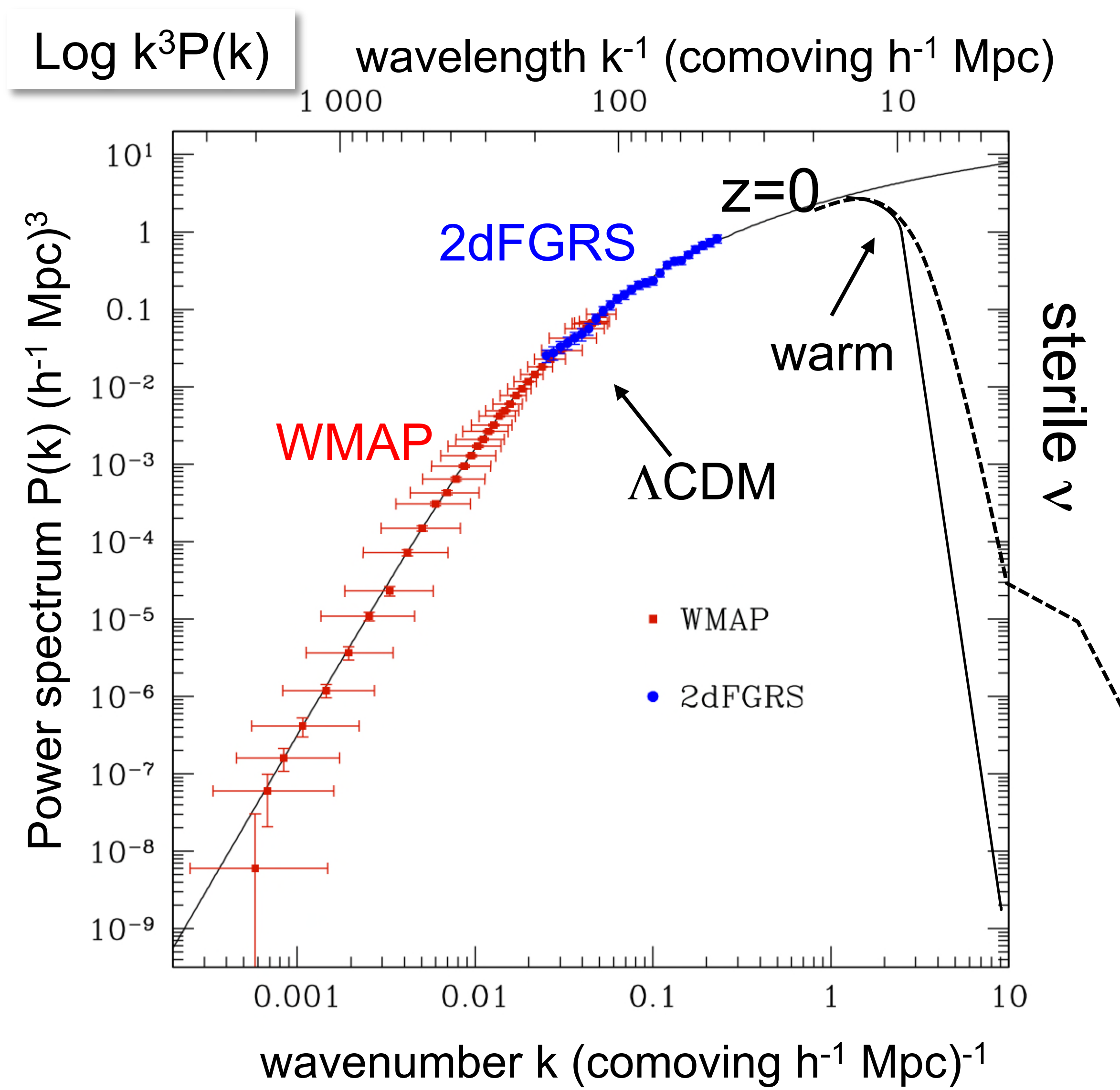

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An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine

[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

SUBMITTED TO APJ, 2014 I
Preprint typeset using LATEX

DETECTION OF AN U

ESRA BULBUL[1,2], M

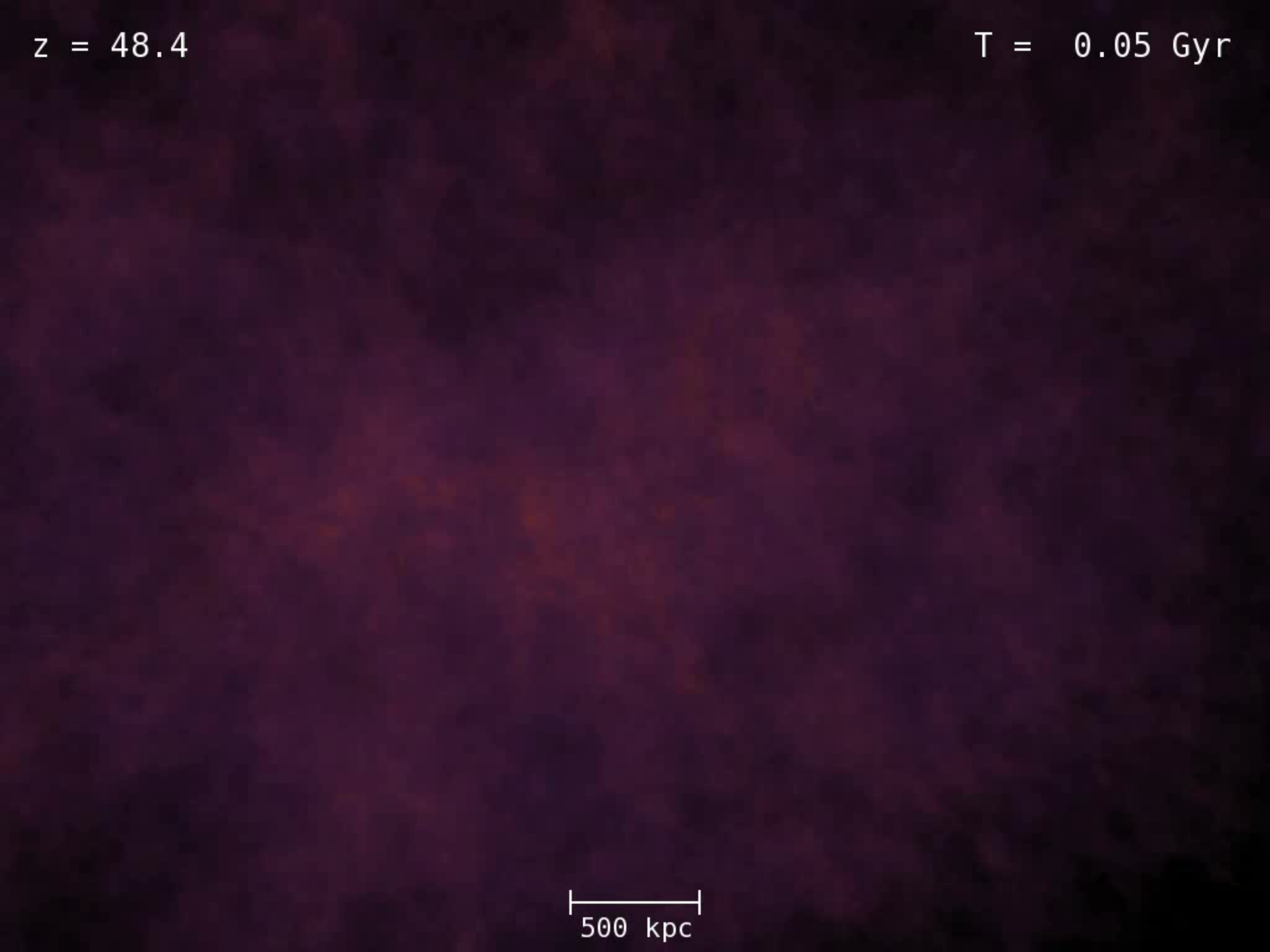
[1] Har

We detect a wea
spectrum of 73 g
independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based

Astrophysical key to identity of dark matter:

→Subgalactic scales

(strongly non-linear)


z = 48.4
T = 0.05 Gyr
500 kpc

Cold Dark Matter Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter

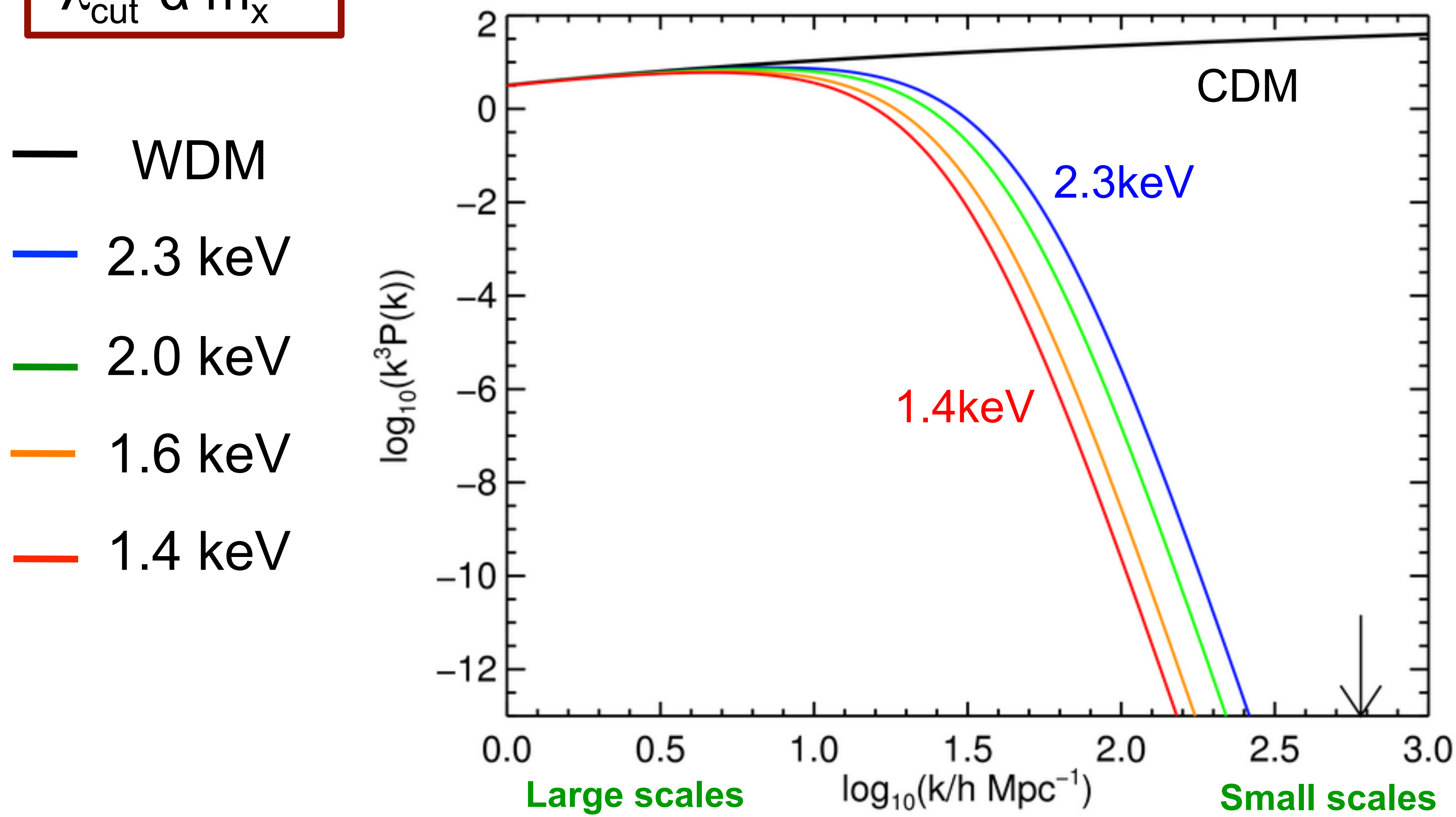
warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘14

Warm DM: different ν mass

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

The linear power spectrum ("power per octave")



Lovell et al '14

Institute for Computational Cosmology

Warm DM: different ν mass

z=3

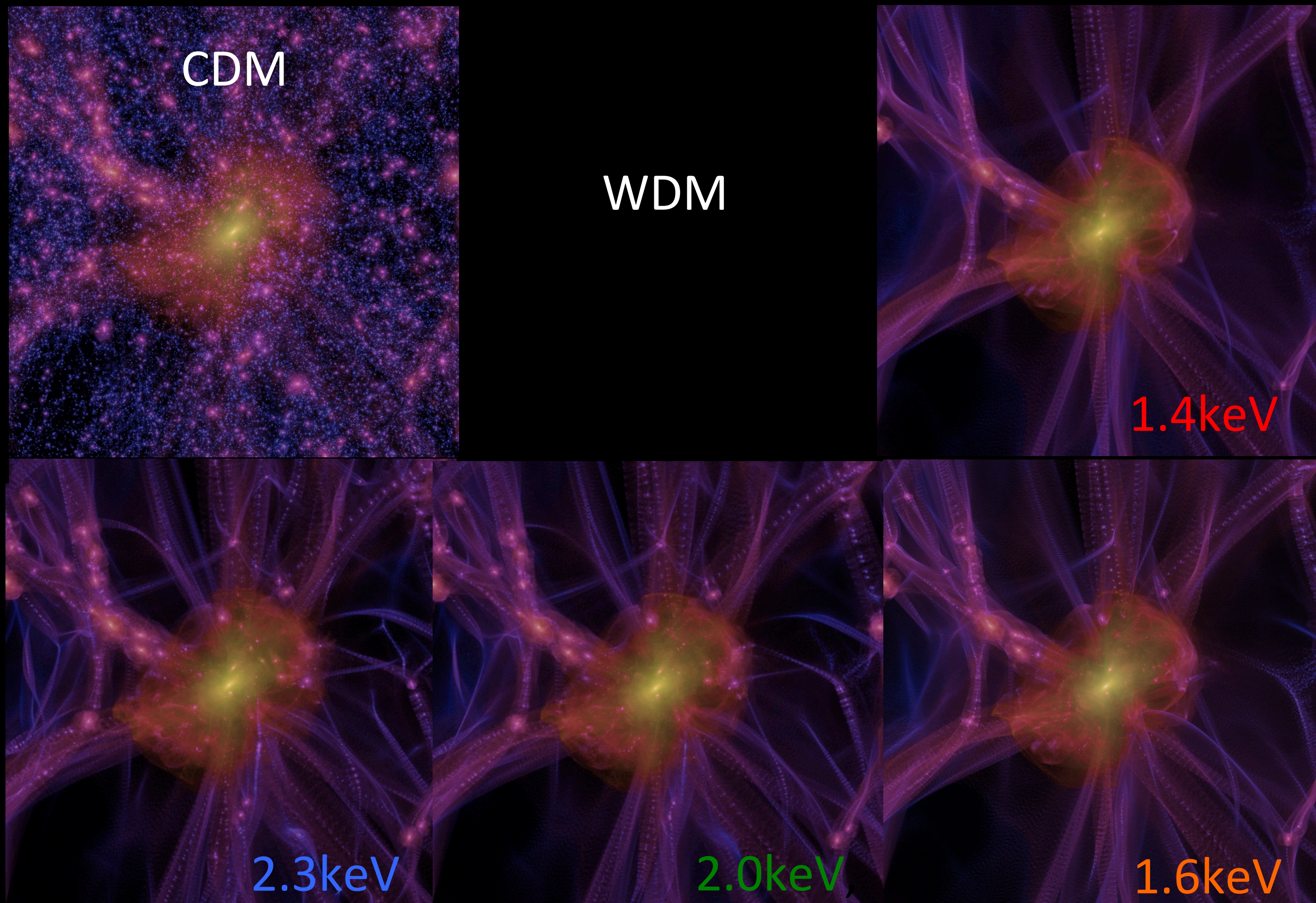
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



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N-body simulations: CDM *vs* WDM

Simulations make 2 important predictions on galactic scales:

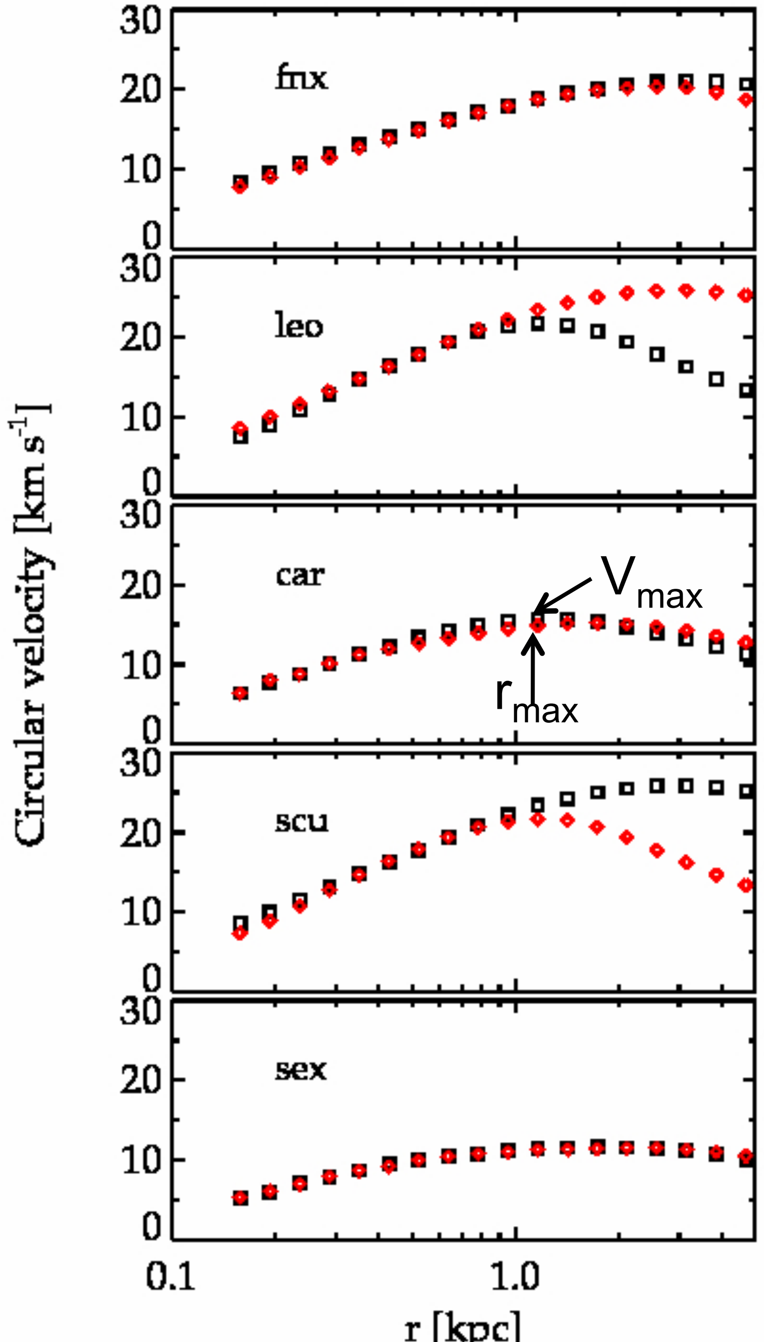
Cold dark matter

- Large number of self-bound substructures (10% of mass) survive
- The main halo and its subhalos have "cuspy" density profiles

Warm dark matter

- Far fewer self-bound substructures (5% of mass) survive
- Main halo profile identical to CDM; subhalos still "cuspy" but less concentrated than in CDM

The structure of the Milky Way satellites

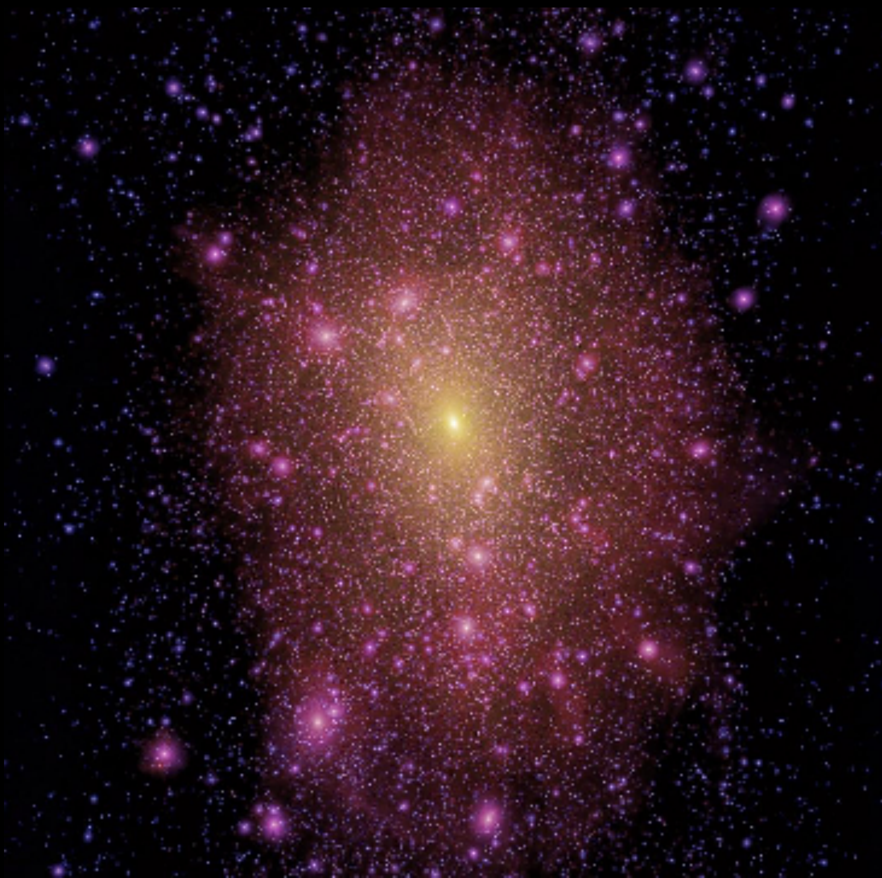


$$V_c = \sqrt{\frac{GM}{r}} \qquad V_{\max} = \max V_c$$

Strigari, Frenk & White 2010

Subhalo abundance

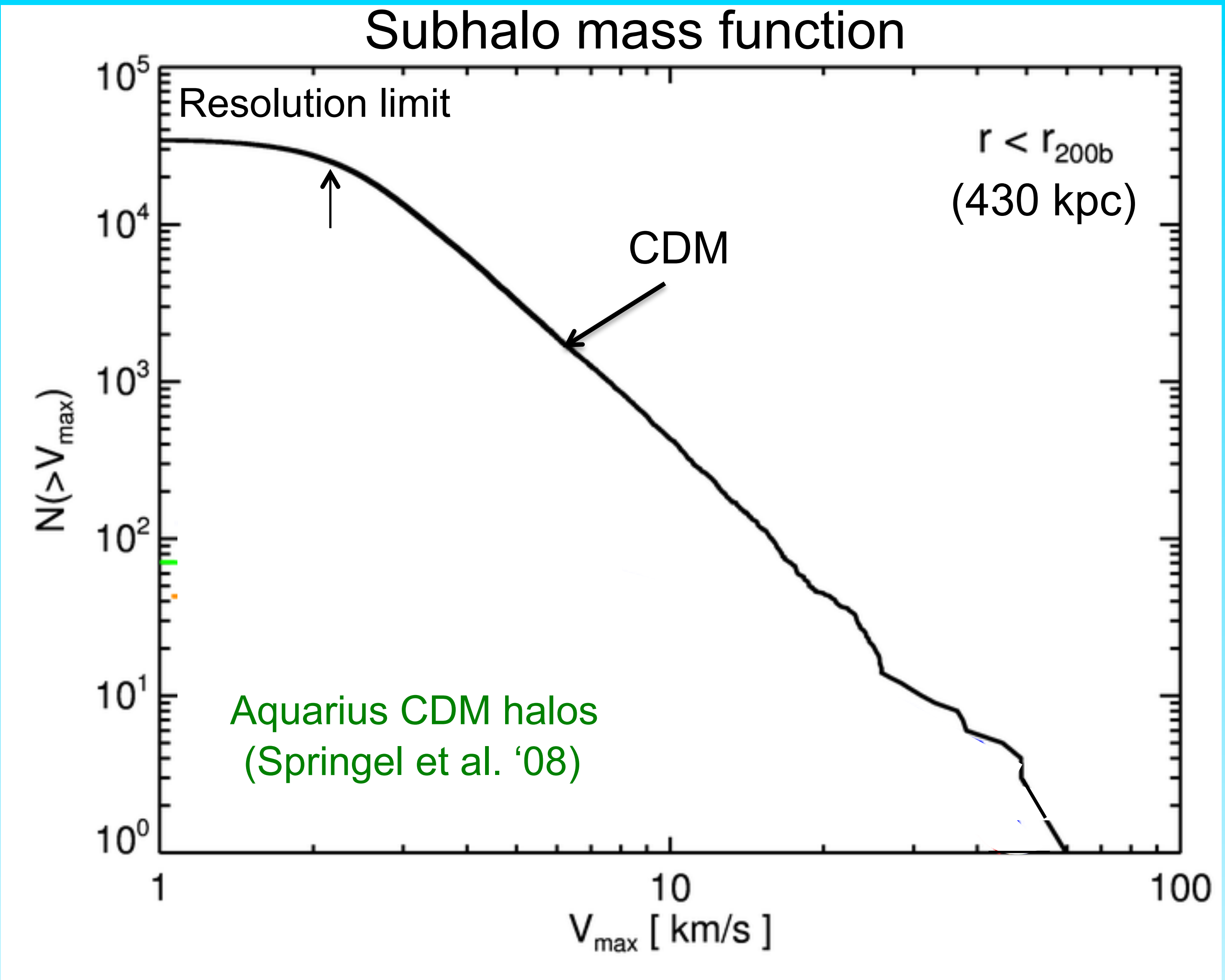
cold dark matter



warm dark matter

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

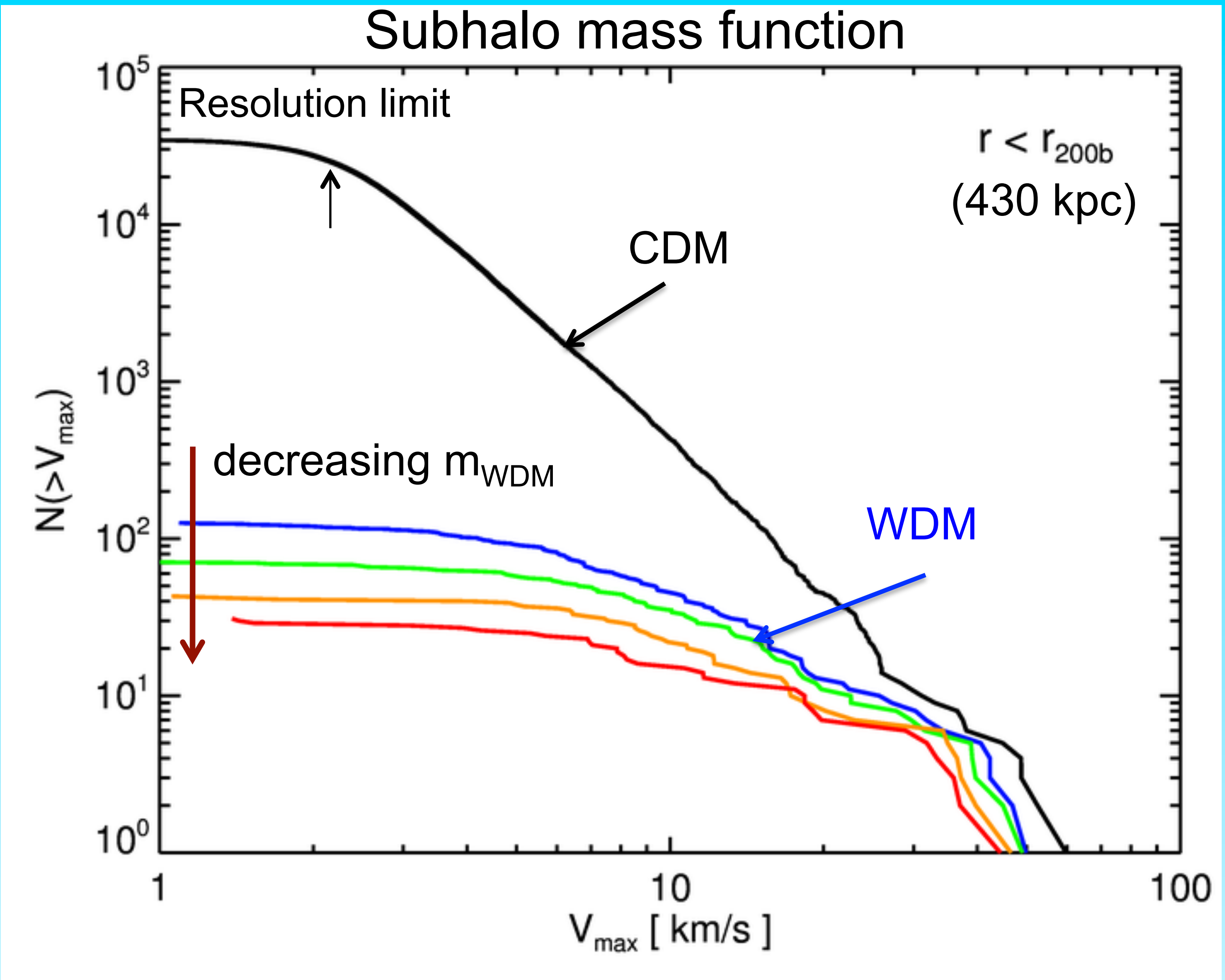
The mass function of substructures



Lovell et al '14

The mass function of substructures

University of Durham

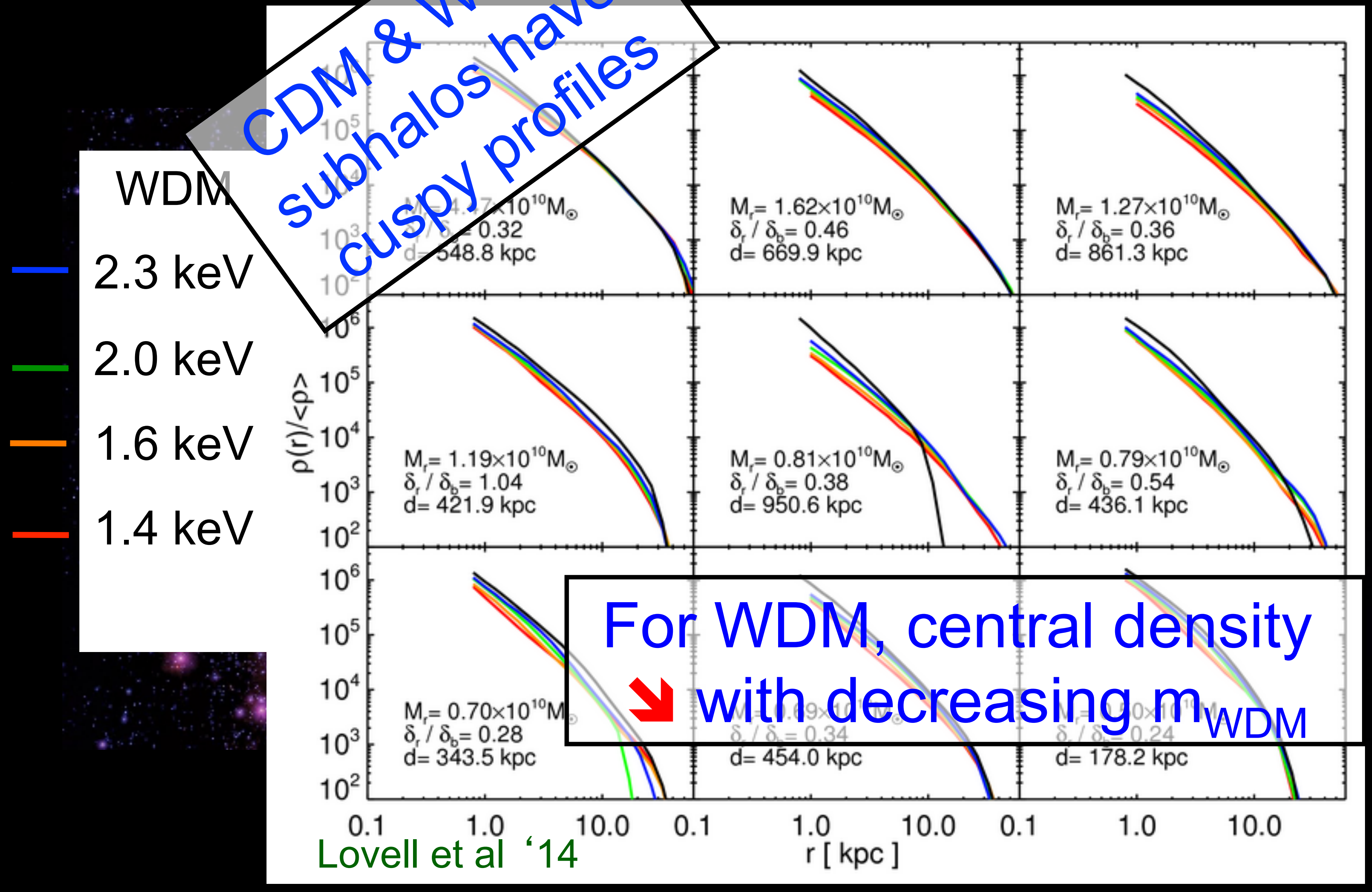


WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV

No of suhalos ↗ with m_{WDM}

Lovell et al ‘14

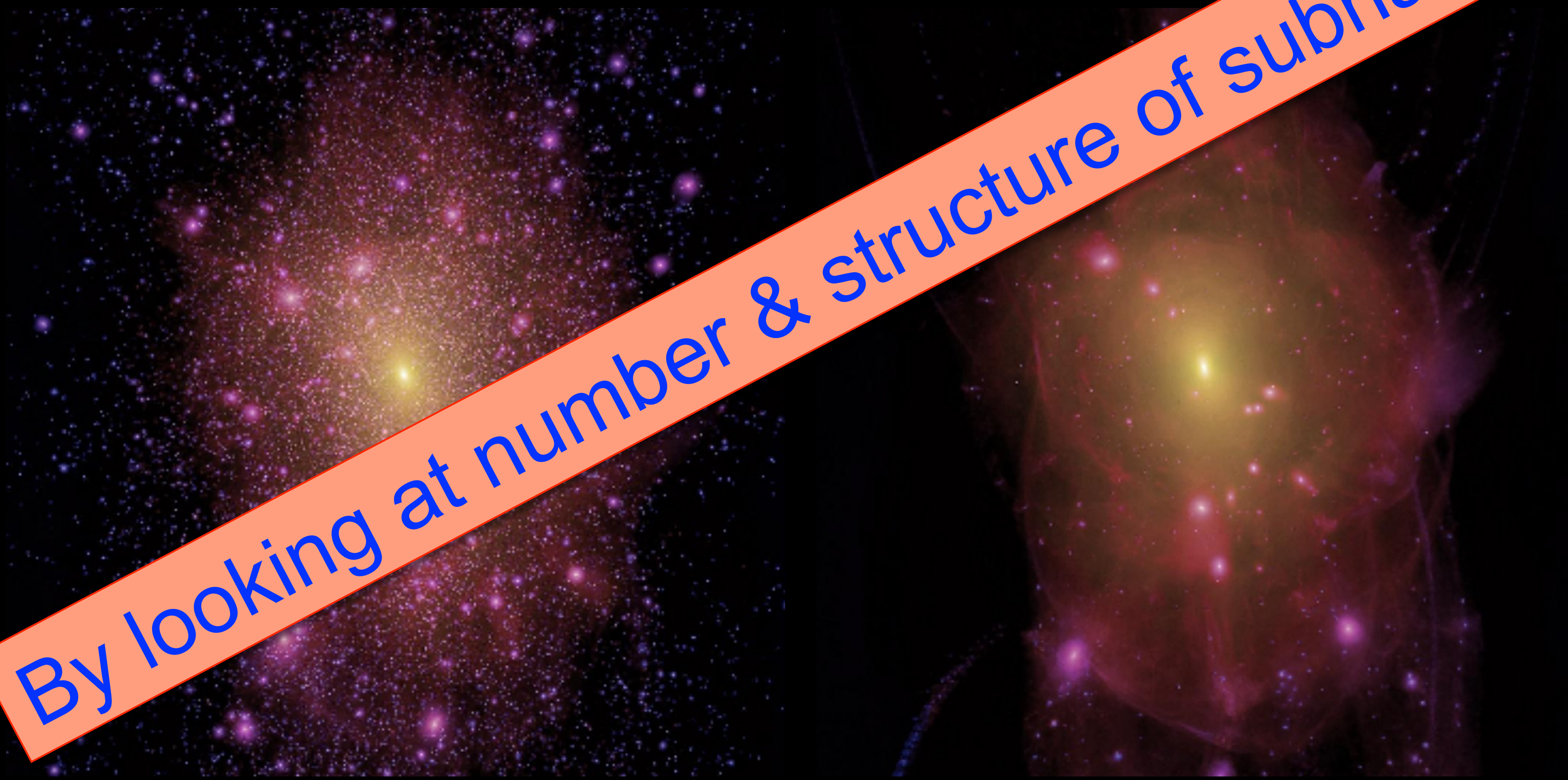
Subhalo density profiles



How can we distinguish between CDM & WDM ?

Subhalo abundance

cold dark matter | warm dark matt

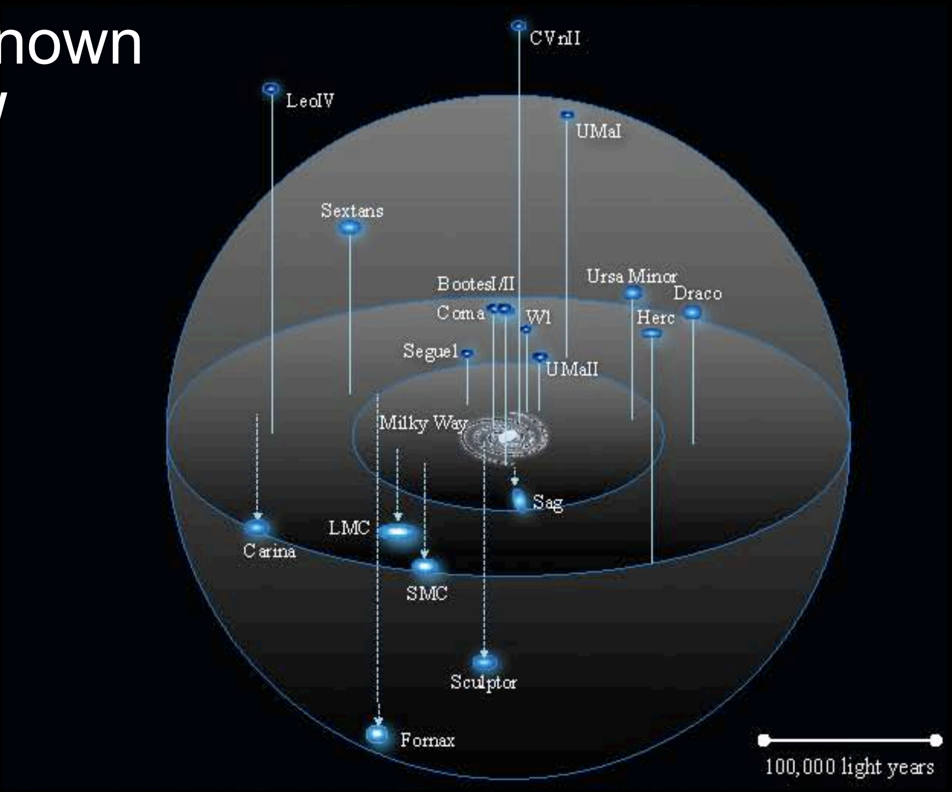


By looking at number & structure of subhalos

Lovell, Frenk, Eke, Gao, Jenkins, Theuns ’12, ‘13

The satellites of the Milky Way

~25 satellites known
in the MW



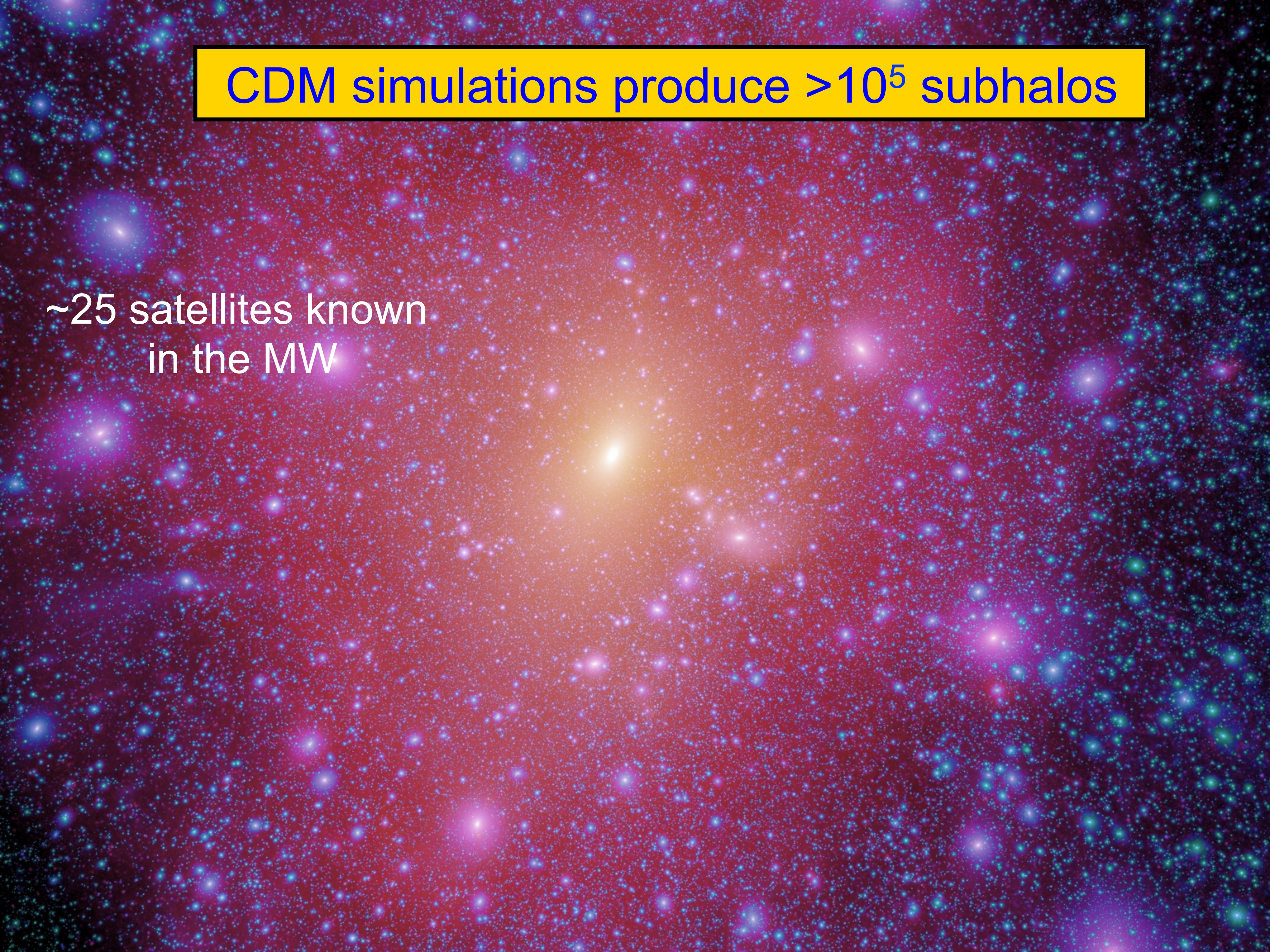
Subhalo abundance

cold dark matter

warm dark matter

Lovell, Frenk, Eke, Gao, Jenkins, Theuns ’12, ‘14

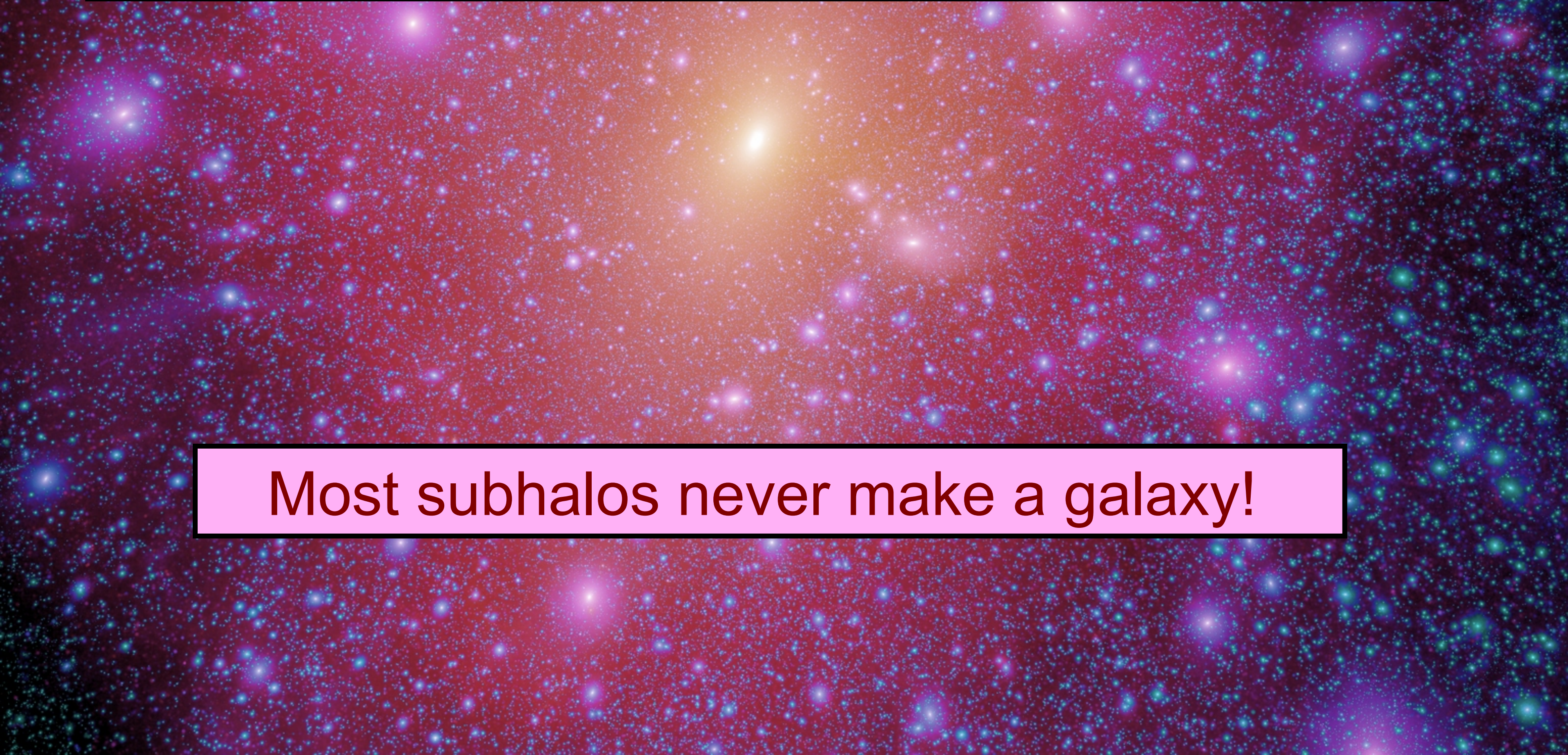
CDM simulations produce $>10^5$ subhalos



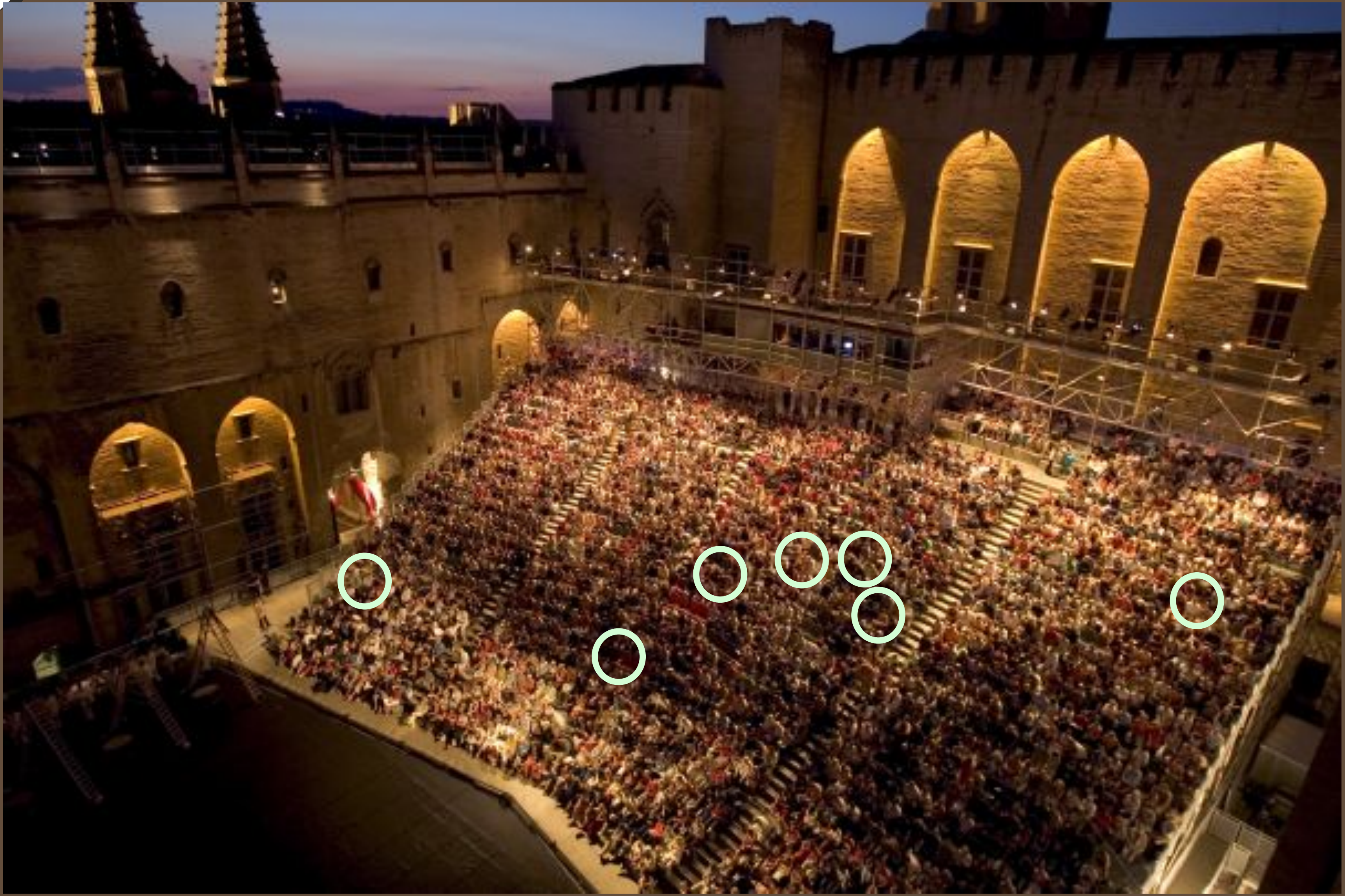
Making a galaxy in a small halo is hard because:

Reionization heats gas above $T_{vir,}$ preventing it from cooling and forming stars in small halos

- Supernovae feedback expels gas



Most subhalos never make a galaxy!

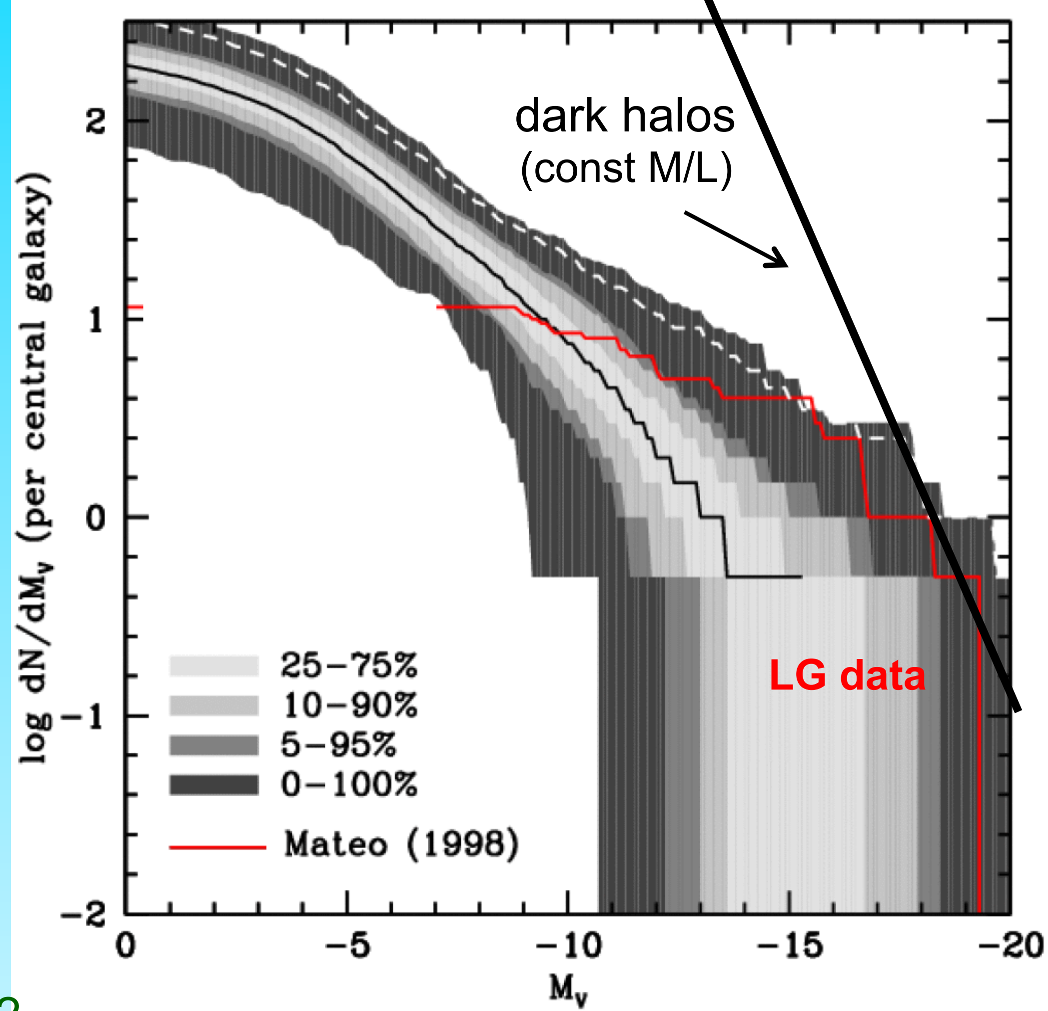


Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s

- Model predicts many, as yet undiscovered, faint satellites

- LMC/SMC should be rare (~2% of cases)



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

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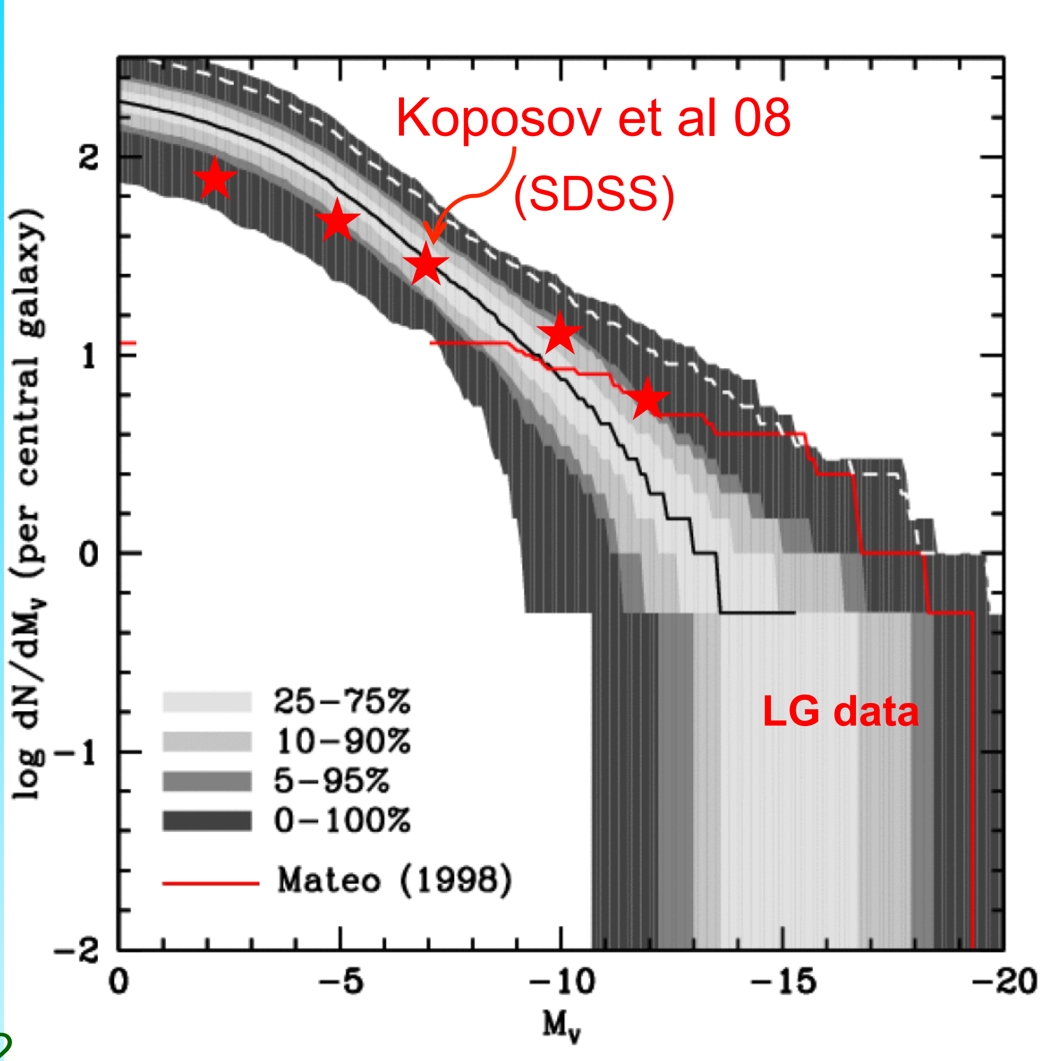

Benson, Frenk, Lacey, Baugh & Cole '02
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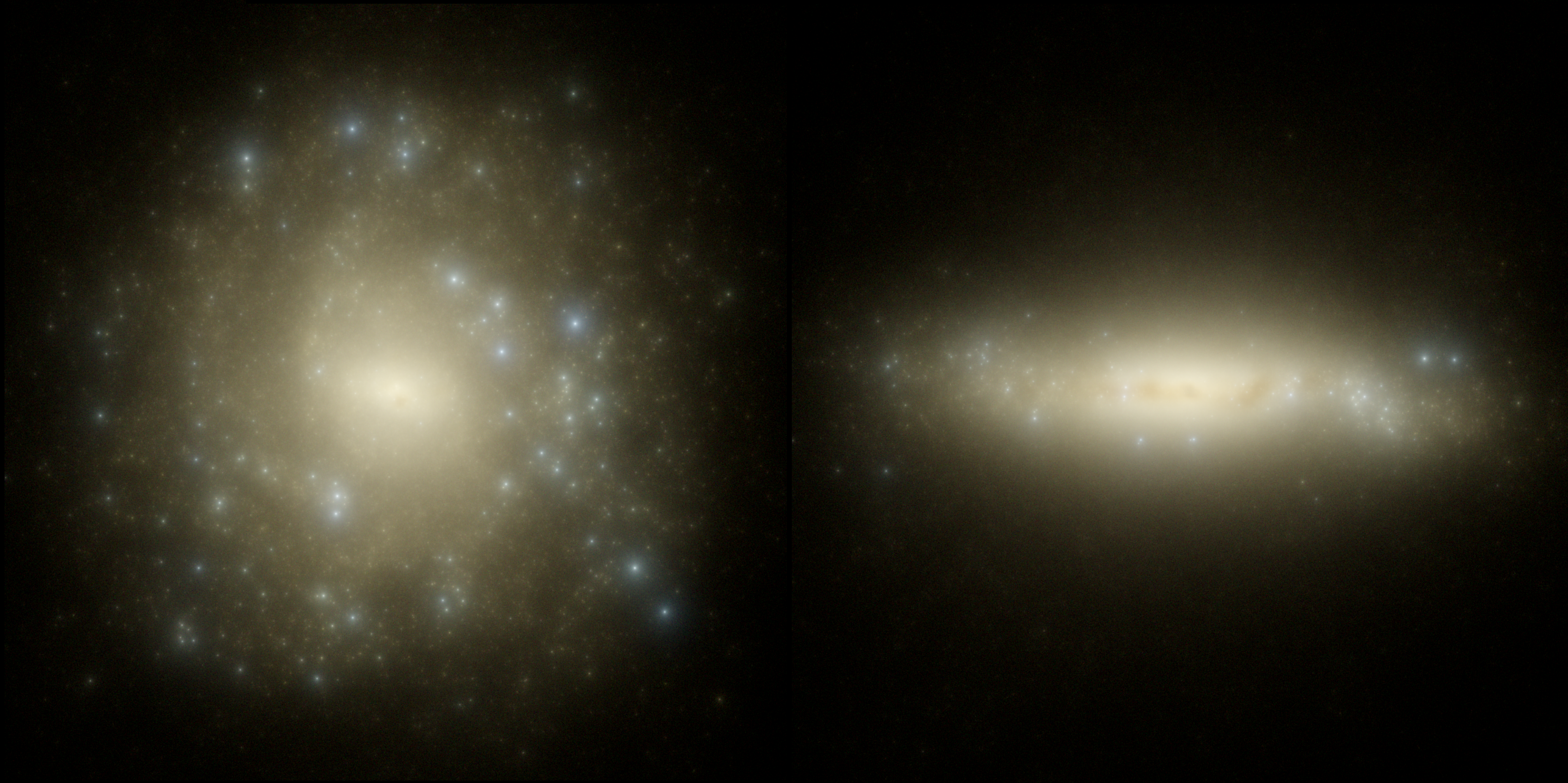
Hydrodynamic simulations

Eagle (Evolution and Assembly of galaxies and their environment)



Virgo consortium – Schaye et al '14; Sawala et al '14

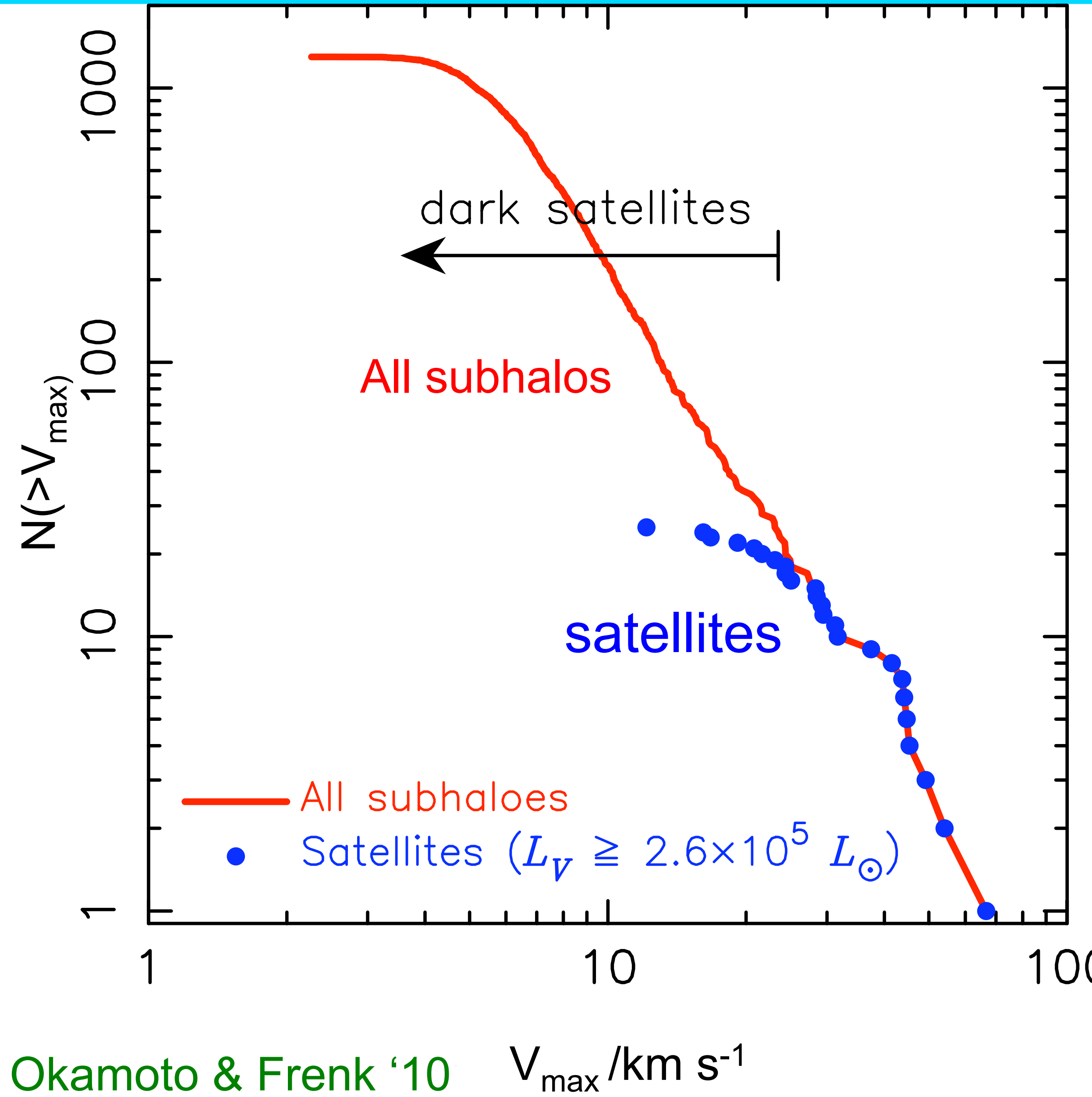
Circular velocity functions

University of Durham

Full hydro simulations

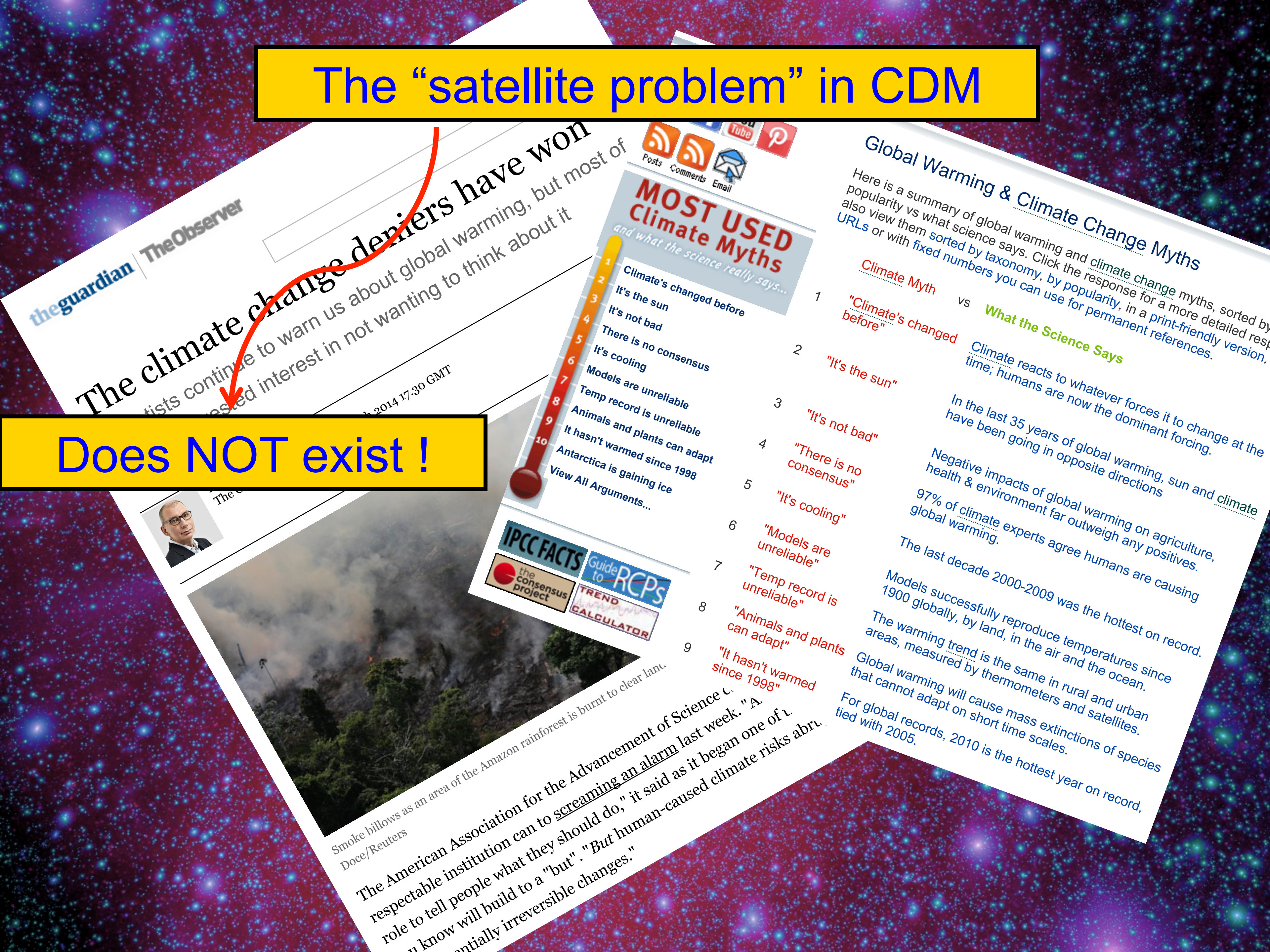
Okamoto & Frenk '10

- All subhalos with v_c > 20 km/s make a satellite of $L > 2.6 \times 10^5 L_o$
- Satellite formation inhibited in subhalos of v_{max} < 20 km/s today (12 km/s at z=9)



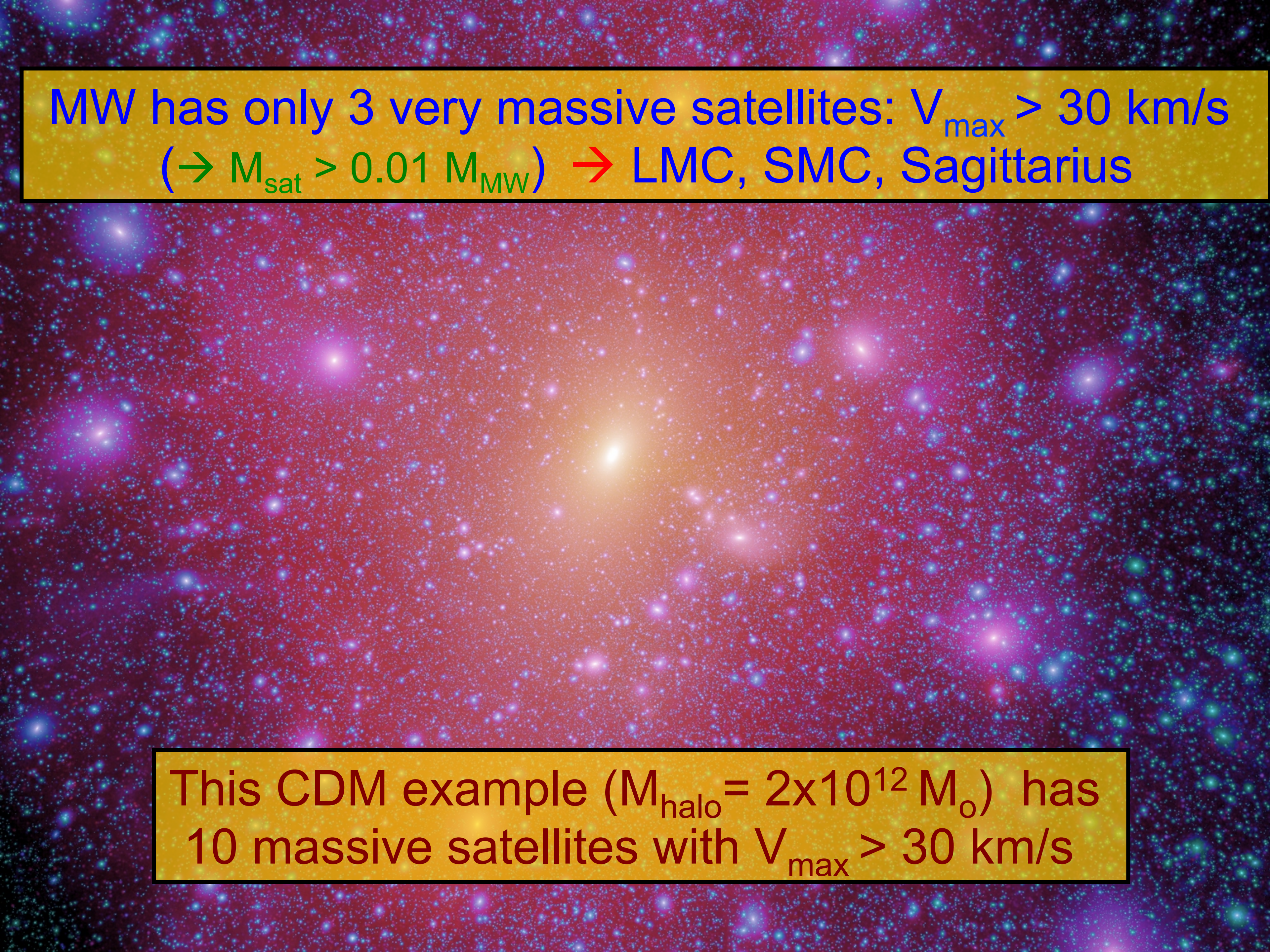
Okamoto & Frenk '10

The “satellite problem” in CDM



Does NOT exist !

MW has only 3 very massive satellites: V_{max} > 30 km/s
(→ M_{sat} > 0.01 M_{MW}) → LMC, SMC, Sagittarius


MW has only 3 very massive satellites: V_{max} > 30 km/s
(→ M_{sat} > 0.01 M_{MW}) → LMC, SMC, Sagittarius
This CDM example (M_{halo}= 2x10^{12} M_o) has
10 massive satellites with V_{max} > 30 km/s

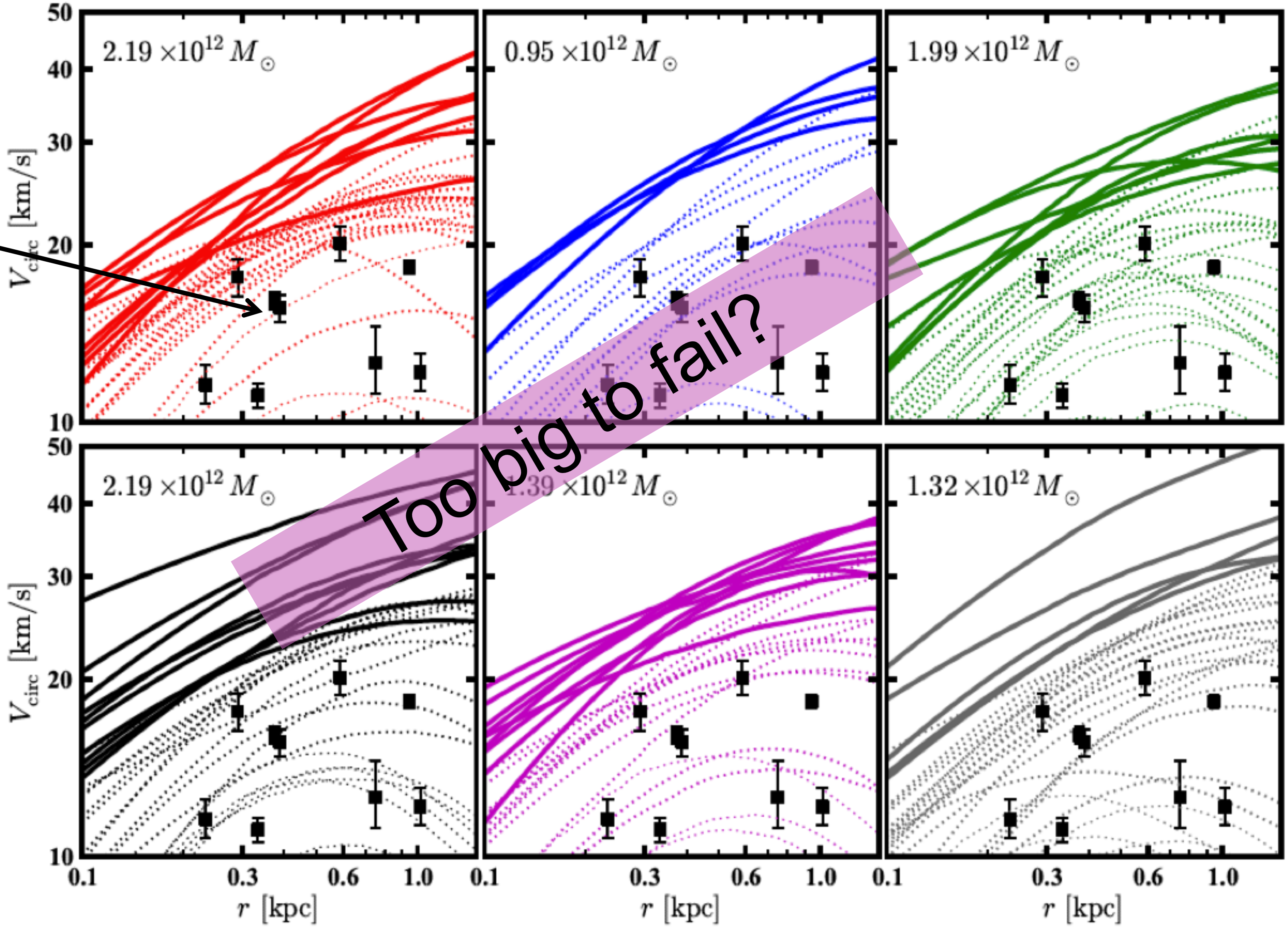
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

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

9 dwarf satellites of Milky Way: mass within half-light radius

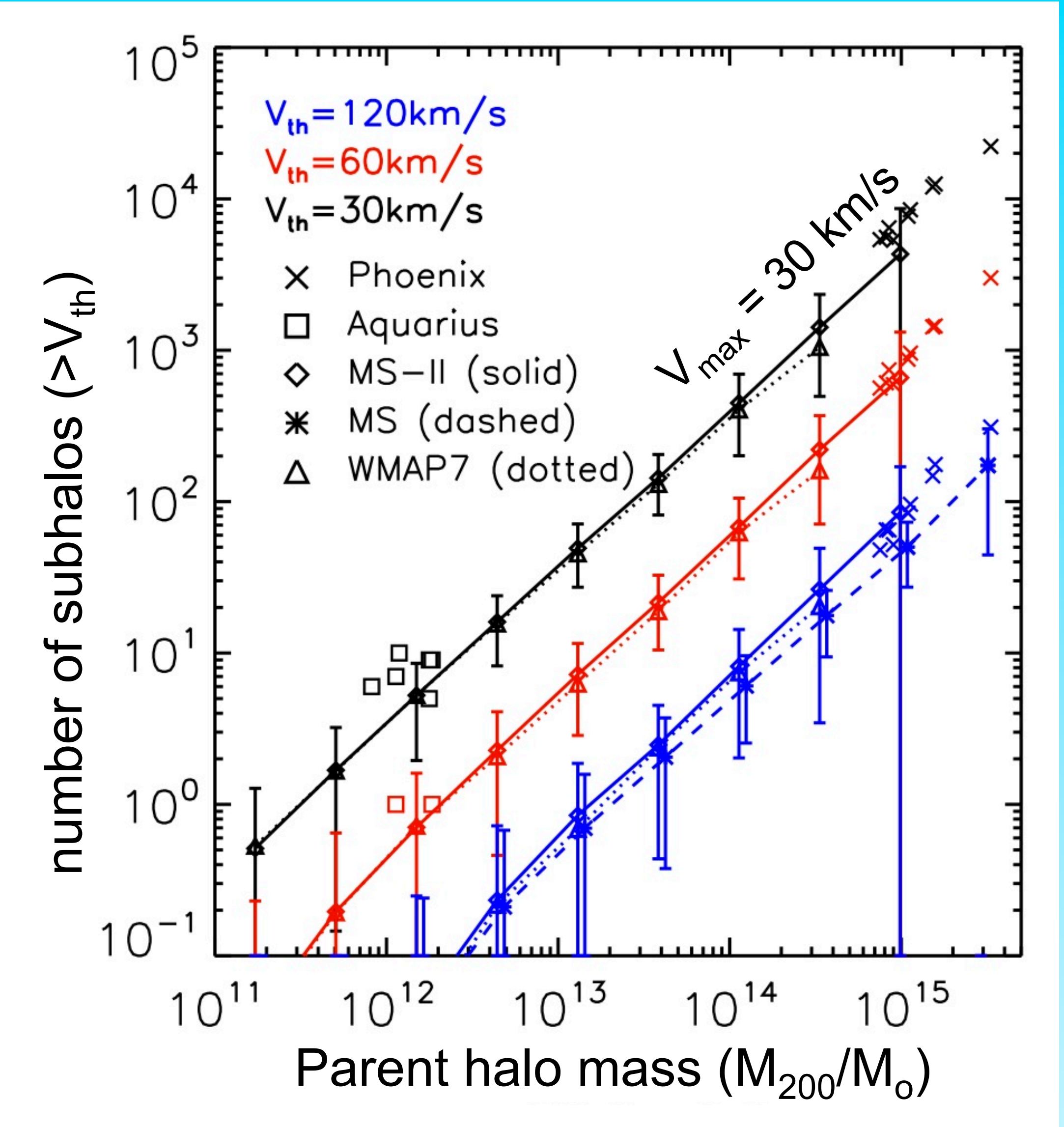
Excludes LMC, SMC, Sagittarius



Number of massive subhalos

Number of massive subhalos increases rapidly with halo mass

→ Milky Way halo mass cannot be too large if CDM is right!



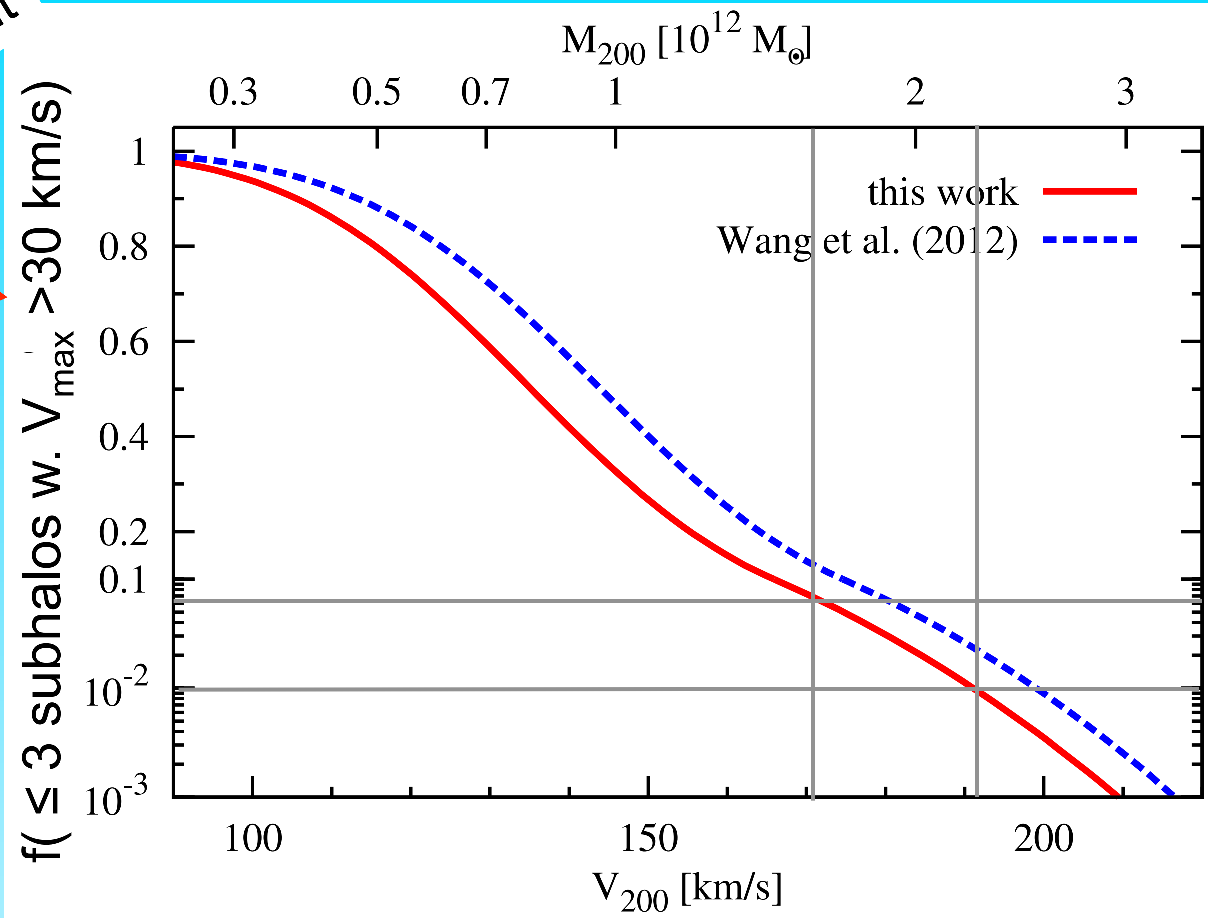
Wang, Frenk, Navarro, Gao '12

University of Durham

Probability of massive subhalos

Probability of
having at ...
subhal... with
V... 30 km/s

1 – prob. that ΛCDM is ruled out



Depends strongly on M_{200} (and V_{cut})

CDM requires

$M_{halo} < 1.5\mathrm{x}10^{12} M_o$
(95% confidence)

If mass of MW halo
$>2.2\mathrm{x}10^{12} M_o$ pure CDM
is ruled out (99% conf)

Wang, Frenk, Navarro, Gao '12
Cautun, Frenk, van den Weygaert, Hellwing '14

Institute for Computational Cosmology

Rotation curves of Aquarius subhalos

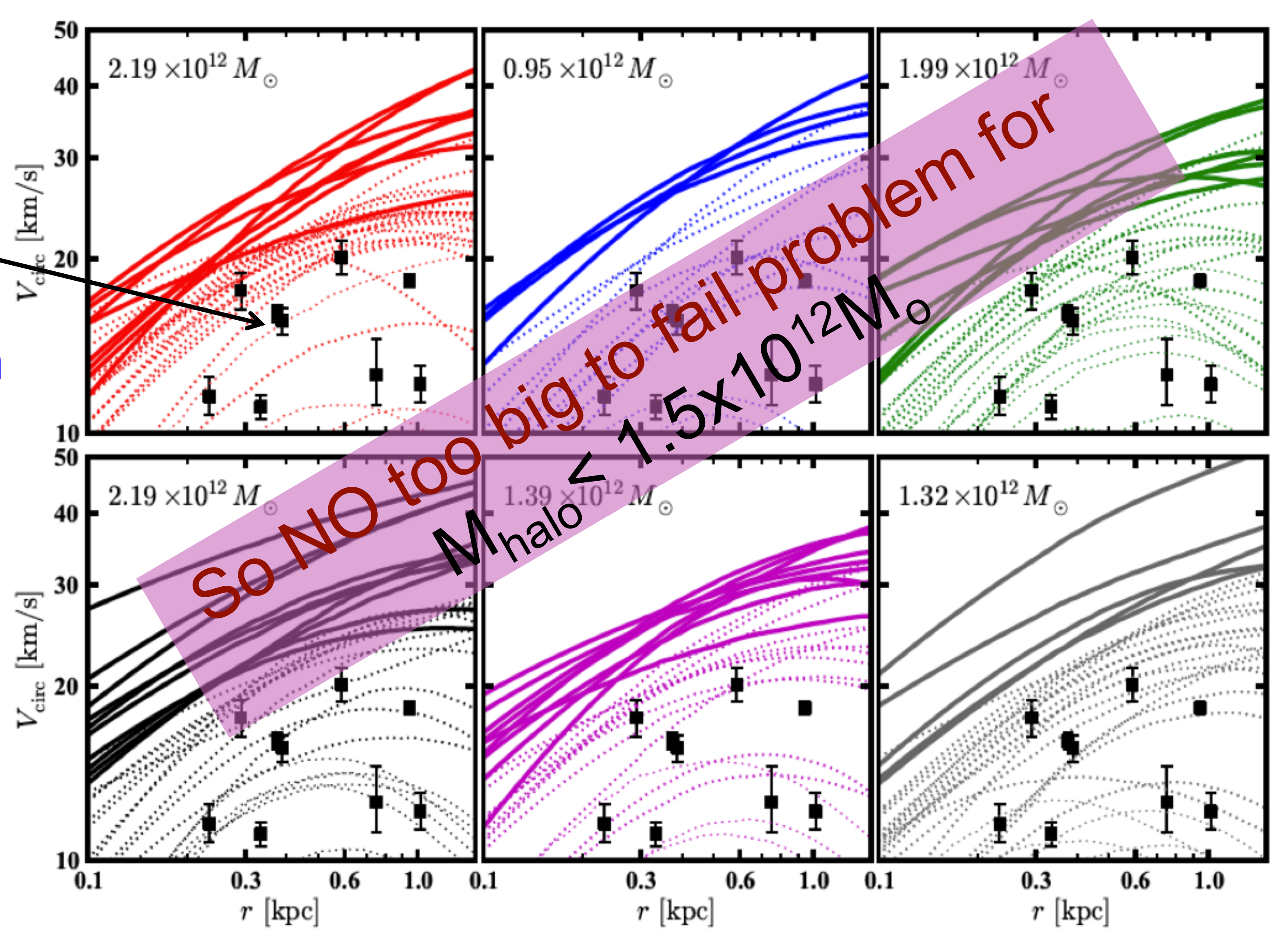
University of Durham

Boylan-Kolchin et al. '11

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

9 dwarf satellites of Milky Way: mass within half-light radius

Excludes LMC, SMC, Sagittarius



Cosmology on small scales

- The number of satellites (the "satellite problem")
- The structure of satellites (the "too-big-to-fail" problem)

How about WDM?

Tests of the nature of the DM

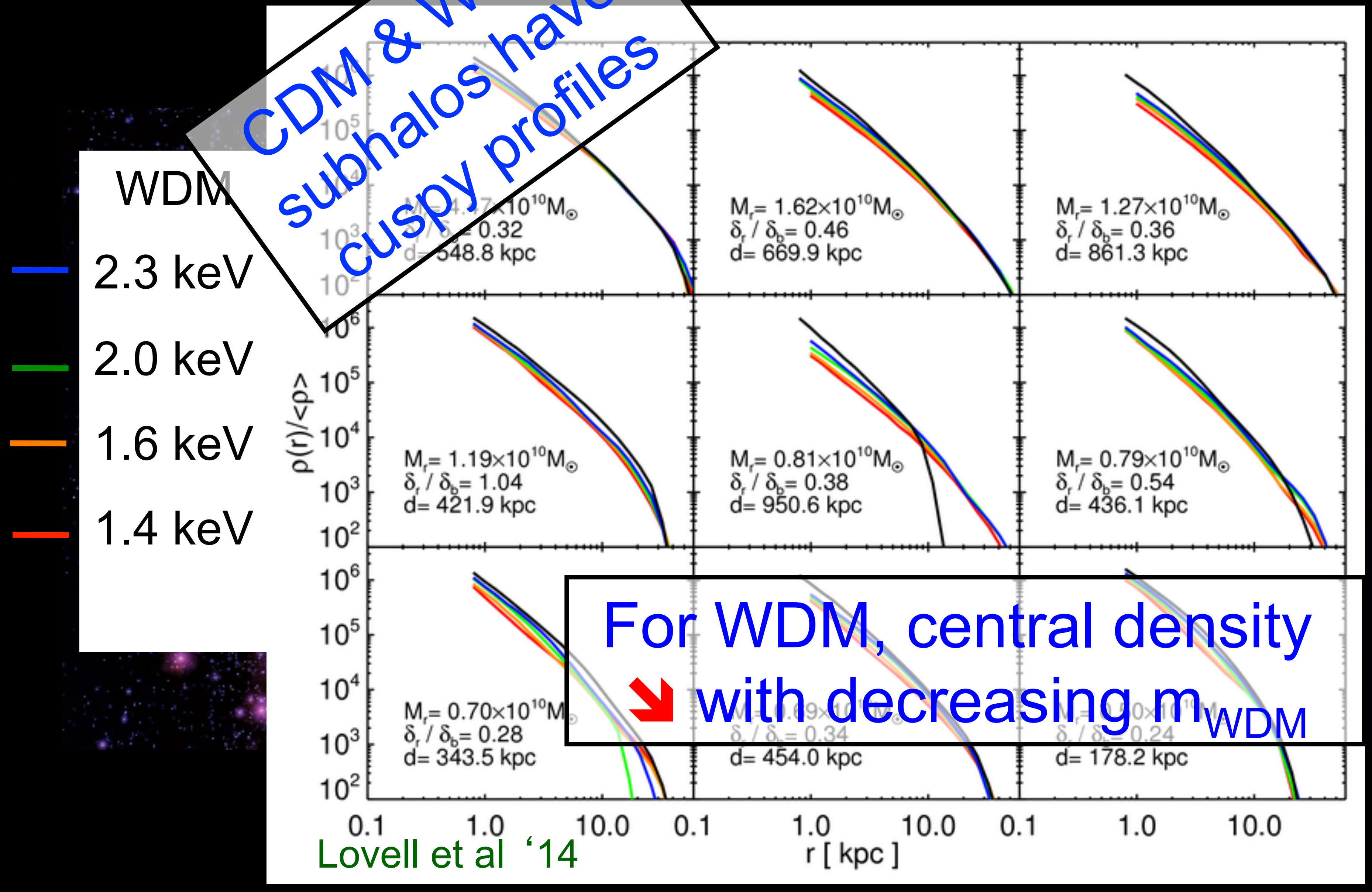
cold dark matter

warm dark matter

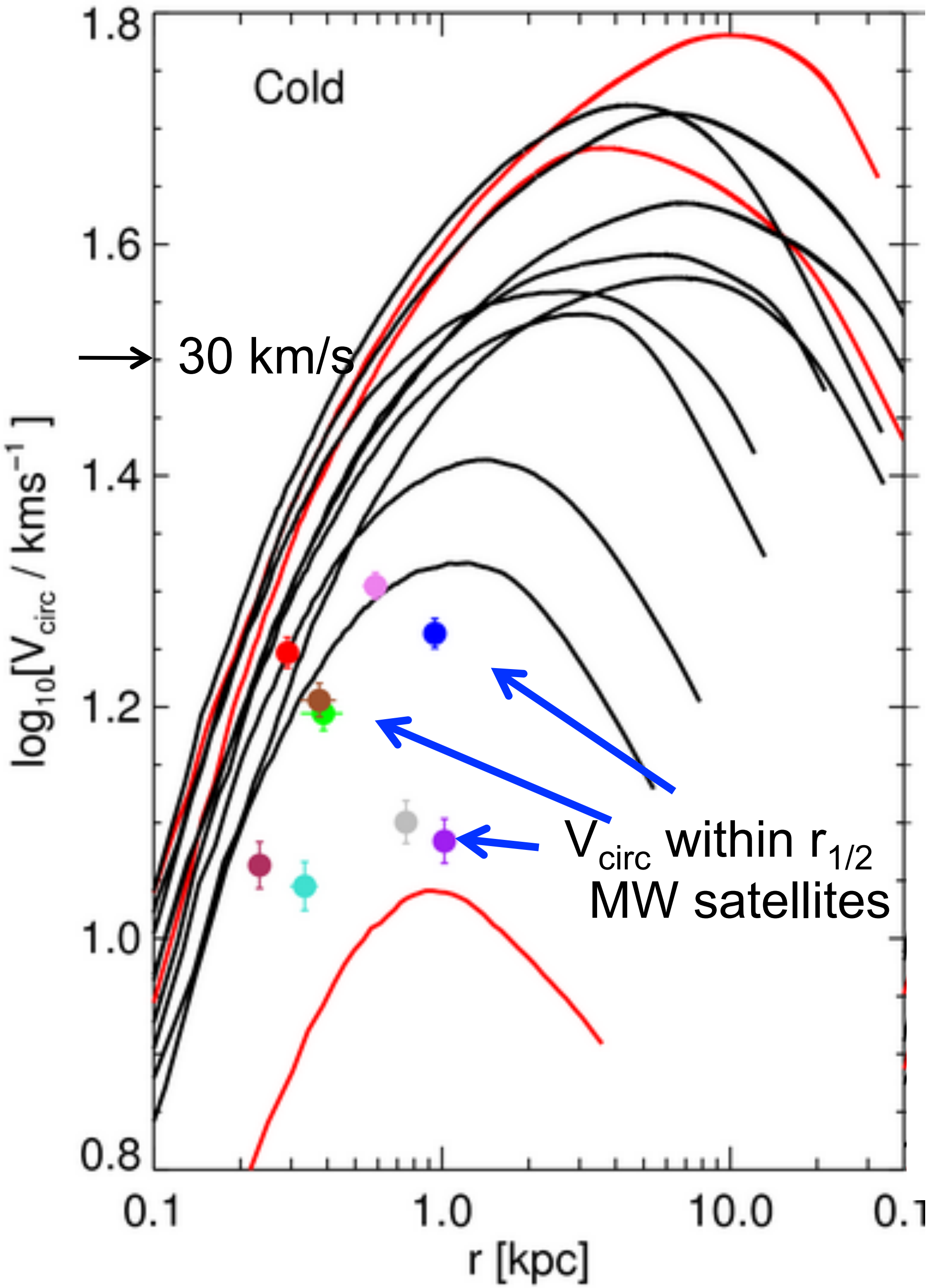
WDM does not suffer from the "too-big-to-fail problem

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

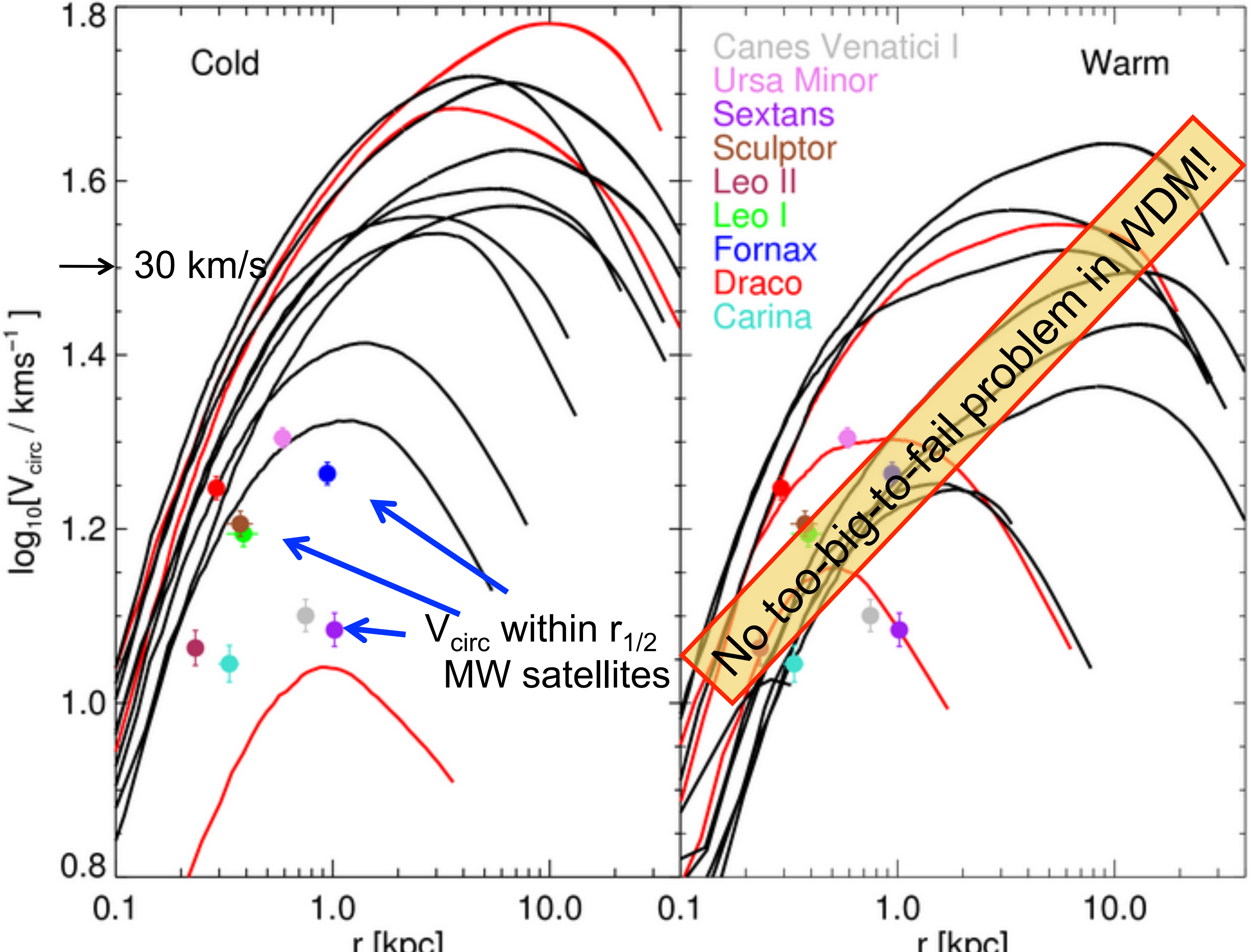
Subhalo density profiles



Lovell et al '14



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



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

Cosmology on small scales

- The number of satellites (the "satellite problem")
- ✔ The structure of satellites (the "too-big-to-fail" problem)

How about WDM?

Warm DM: different ν mass

z=3

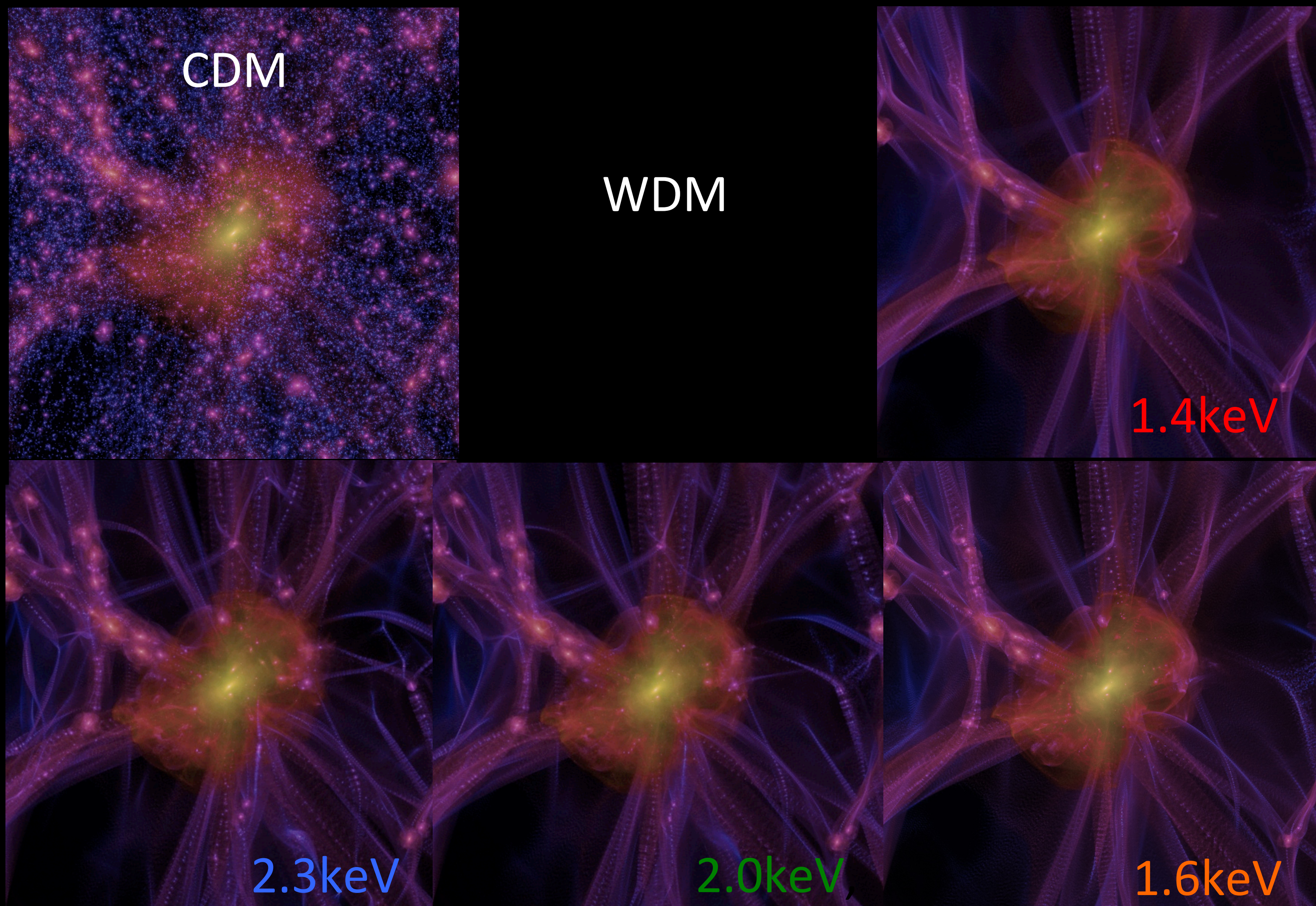
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



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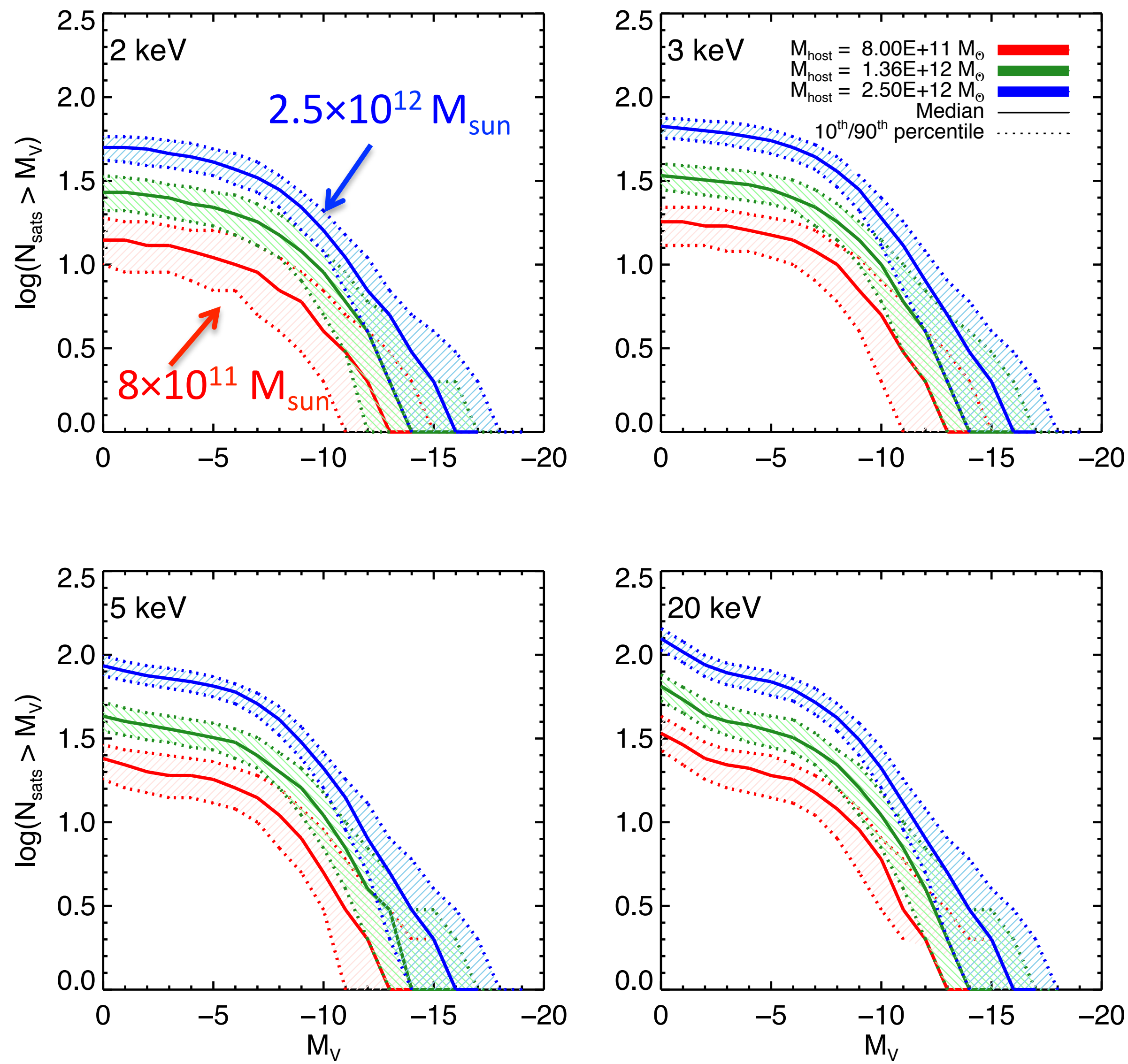
Luminosity Function of Local Group Satellites in WDM

No of sats ↗ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

University of Durham

Luminosity Function of Local Group Satellites in WDM

No of sats ↗ with:

- host halo mass
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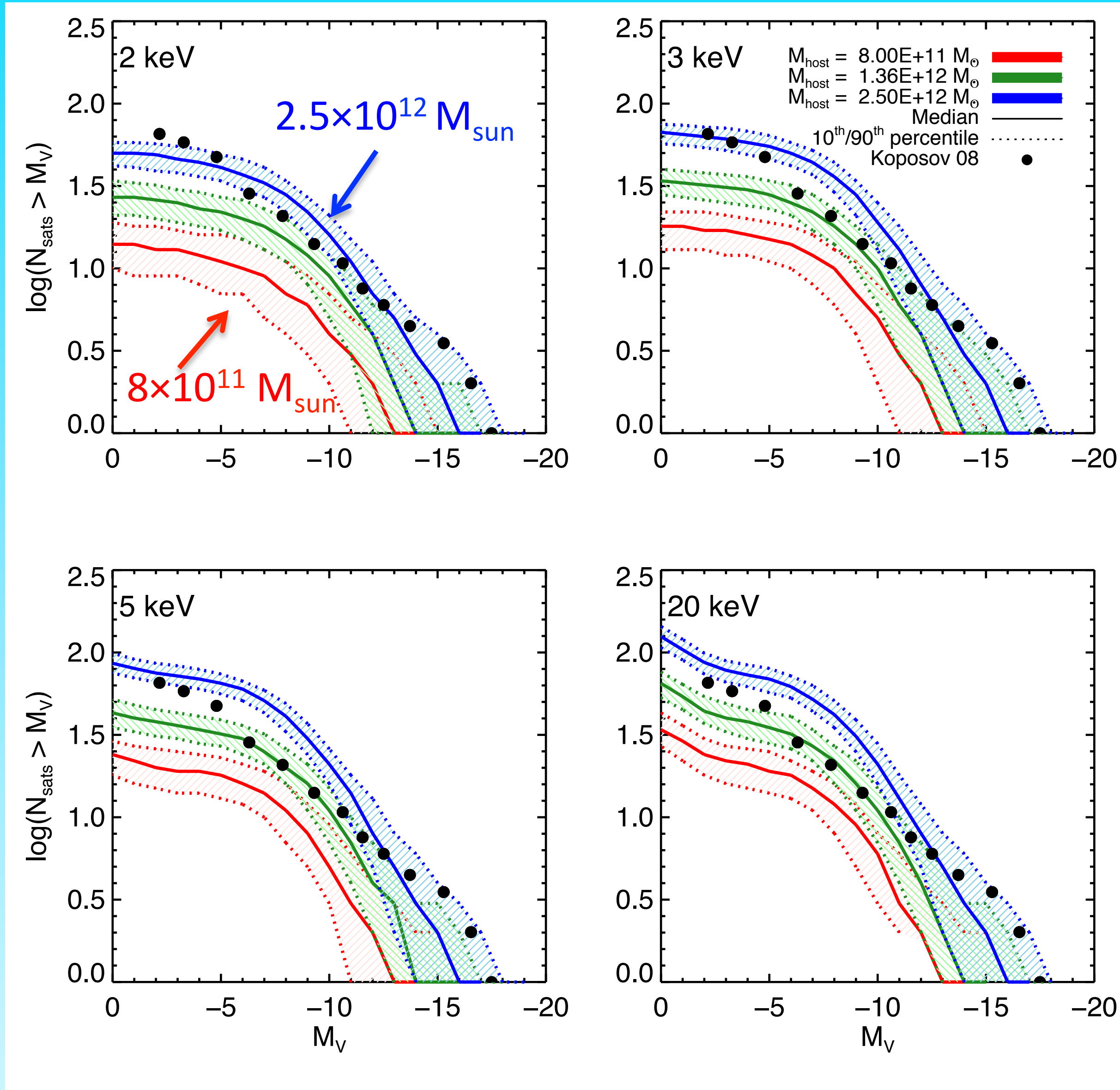

Kennedy, Cole & Frenk '13

Tests of the nature of the DM

warm dark matter

If the halo mass is too small and/or the WDM particle mass is too small, there will not be enough subhalos to account for the observed satellites!

➔ lower limit on m_{wdm}

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

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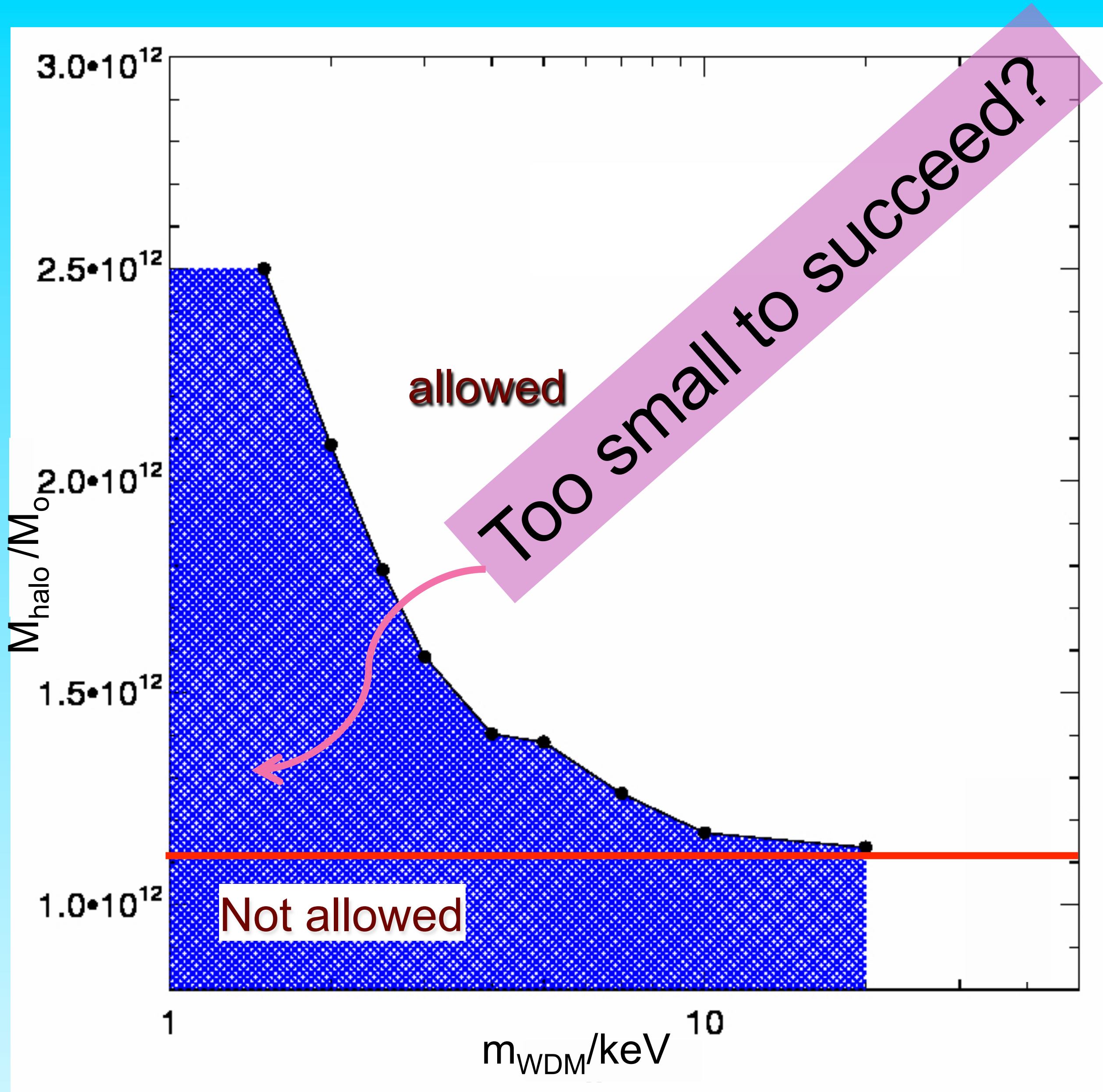
Limits on WDM particle mass

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{halo} < 1.1 \times 10^{12}\ M_o$

Kennedy, Cole & Frenk '14



Limits on WDM particle mass

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Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

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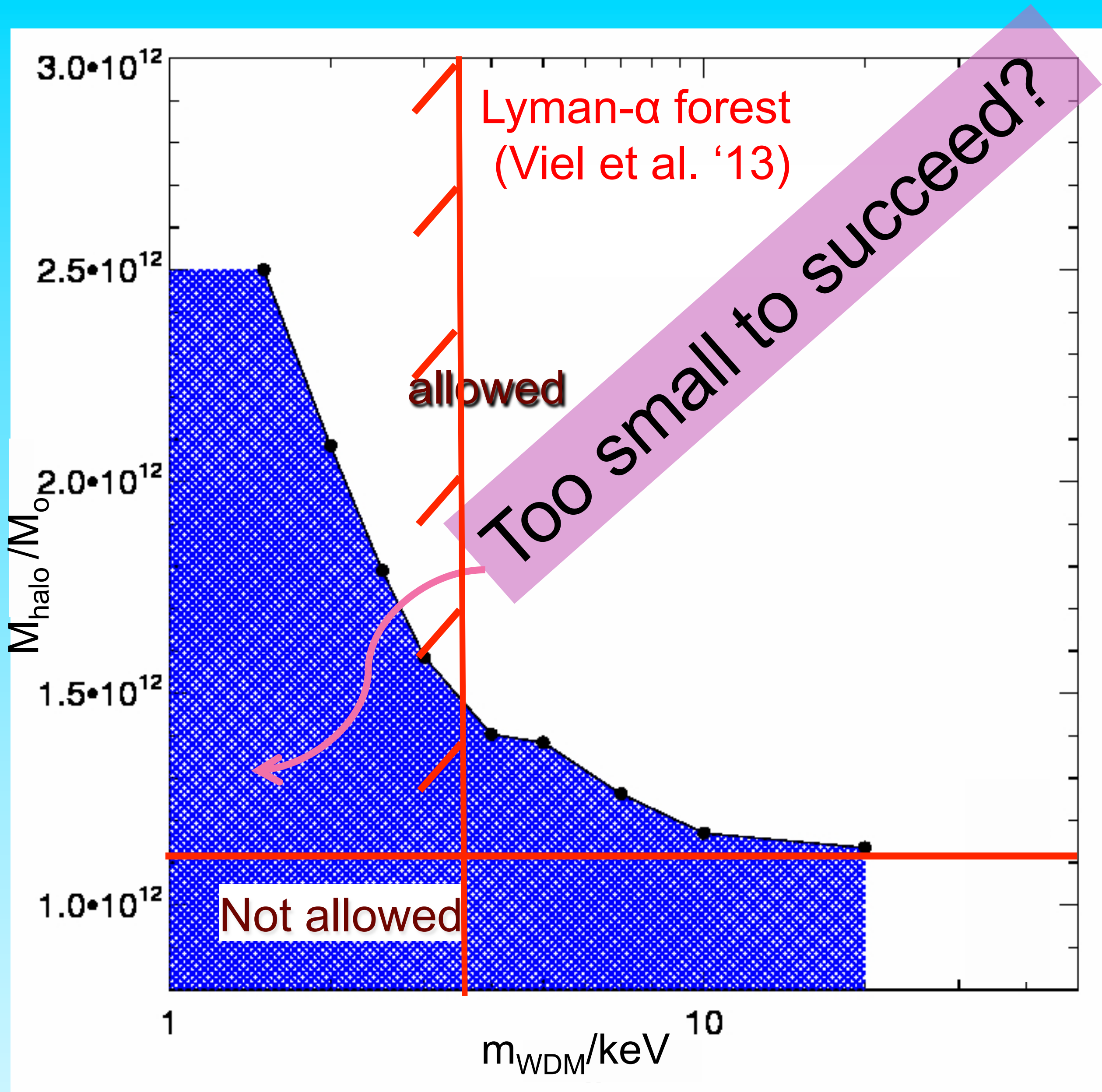
Kennedy, Cole & Frenk '14



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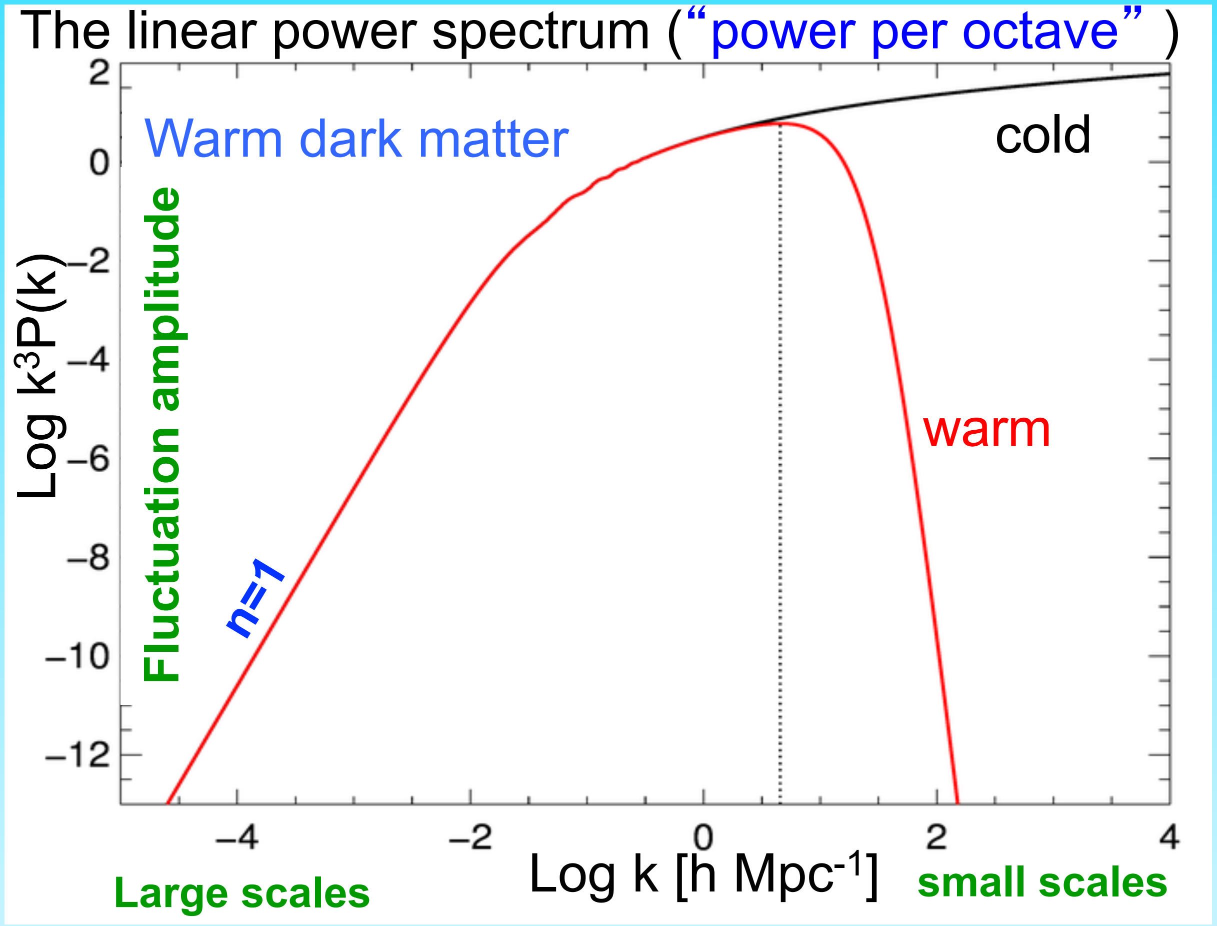
Estimates of the MW halo mass

- Li & White → $M_{200} = 2.4\times10^{12}\,M_o$; $M_{200} > 8\times10^{11}\,M_o$ at 95% CL
- Guo et al → $8\times10^{11}\,M_o < M_{200} < 4.7\times10^{12}\,M_o$
- Deason et al → $5\times10^{11}\,M_o < M_{150kpc} < 1\times10^{12}\,M_o$
- Xue et al → $8\times10^{11}\,M_o < M_{100} < 1.3\times10^{12}\,M_o$
- Battaglia et al → $6\times10^{11}\,M_o < M_{100} < 3\times10^{12}\,M_o$

Warm dark matter



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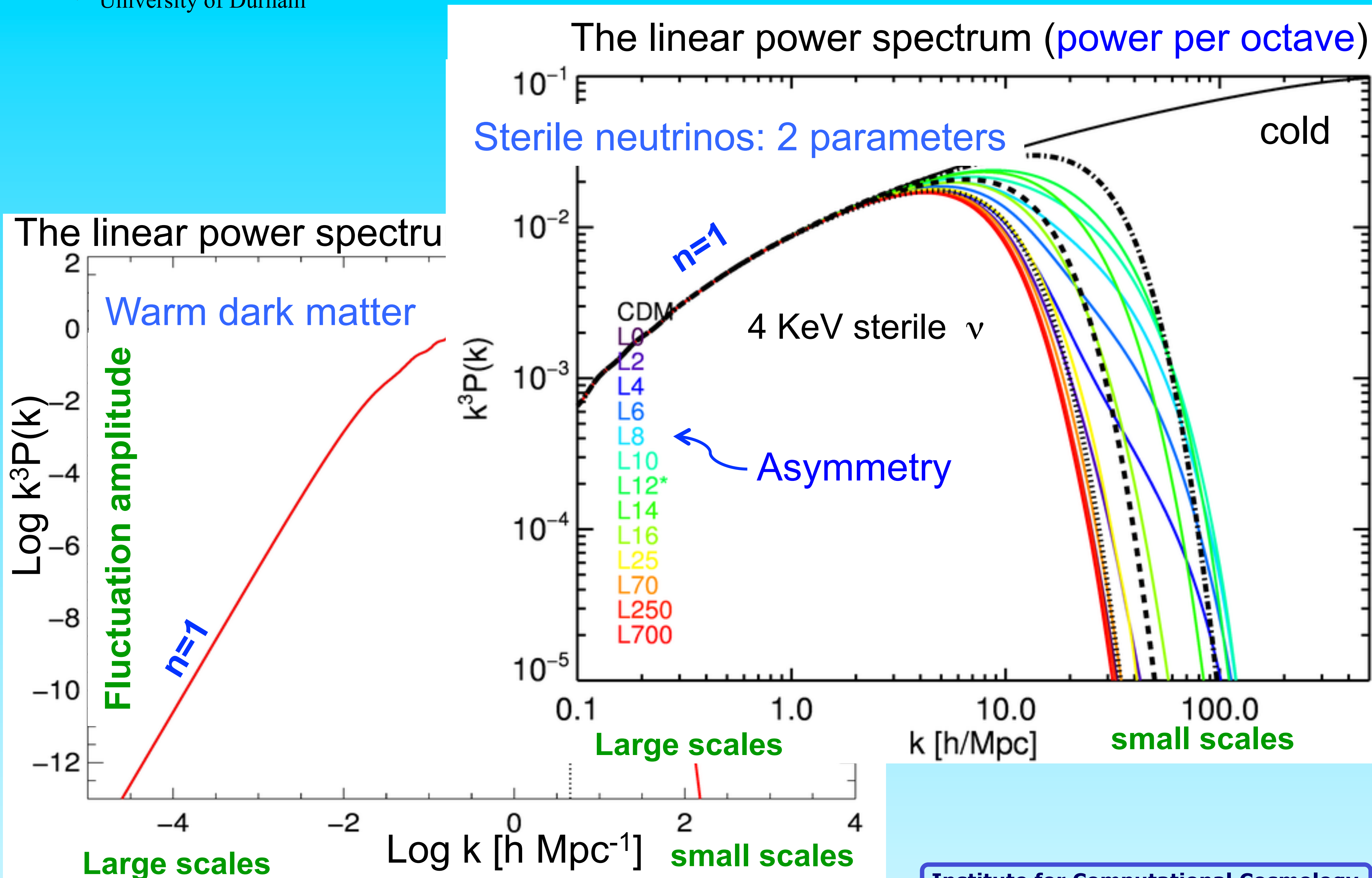
Sterile neutrinos



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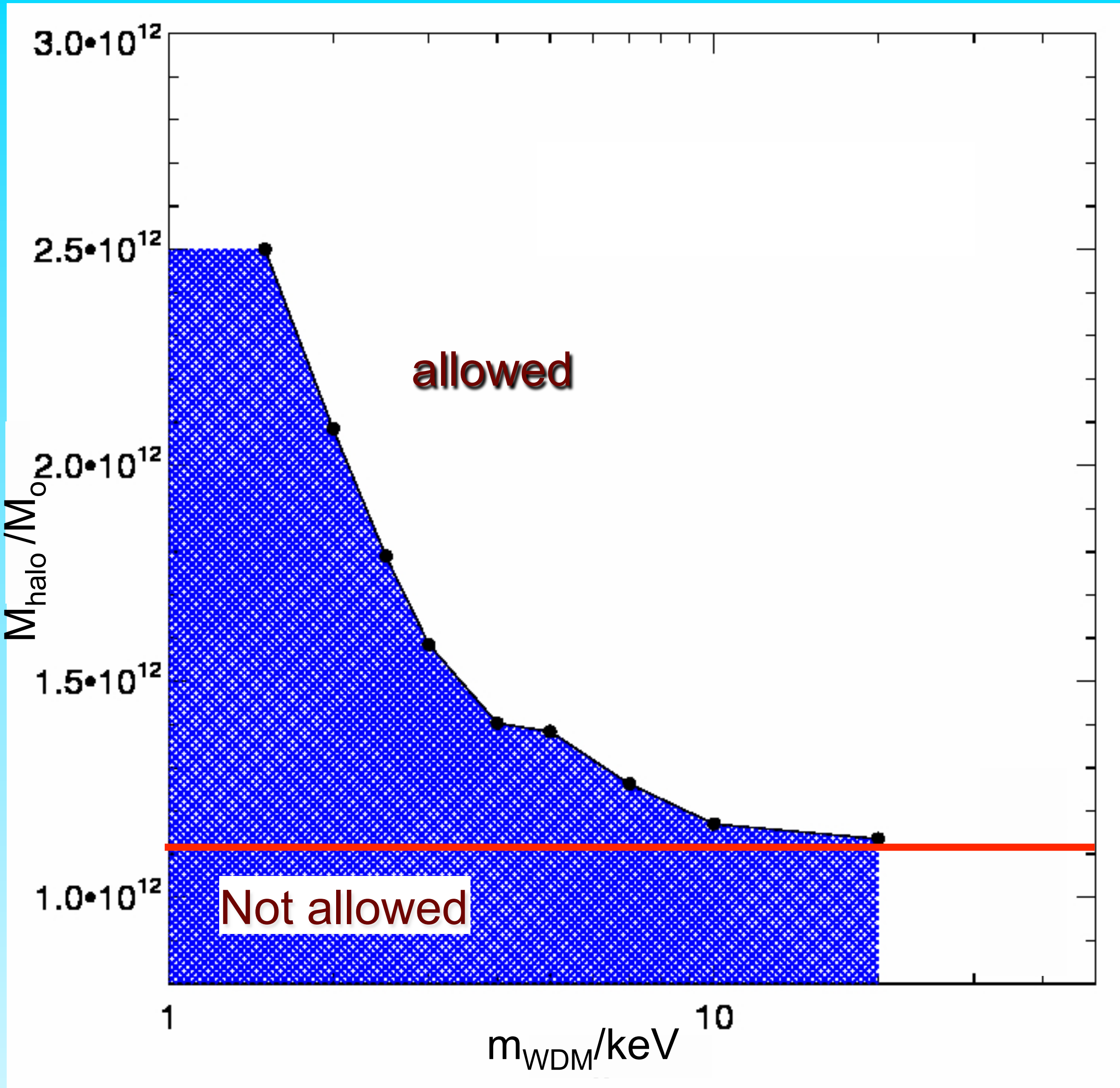
Limits on WDM particle mass

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{halo}<1.1\times10^{12}\ M_o$

Kennedy, Cole & Frenk '14



Limits on sterile neutrino mass

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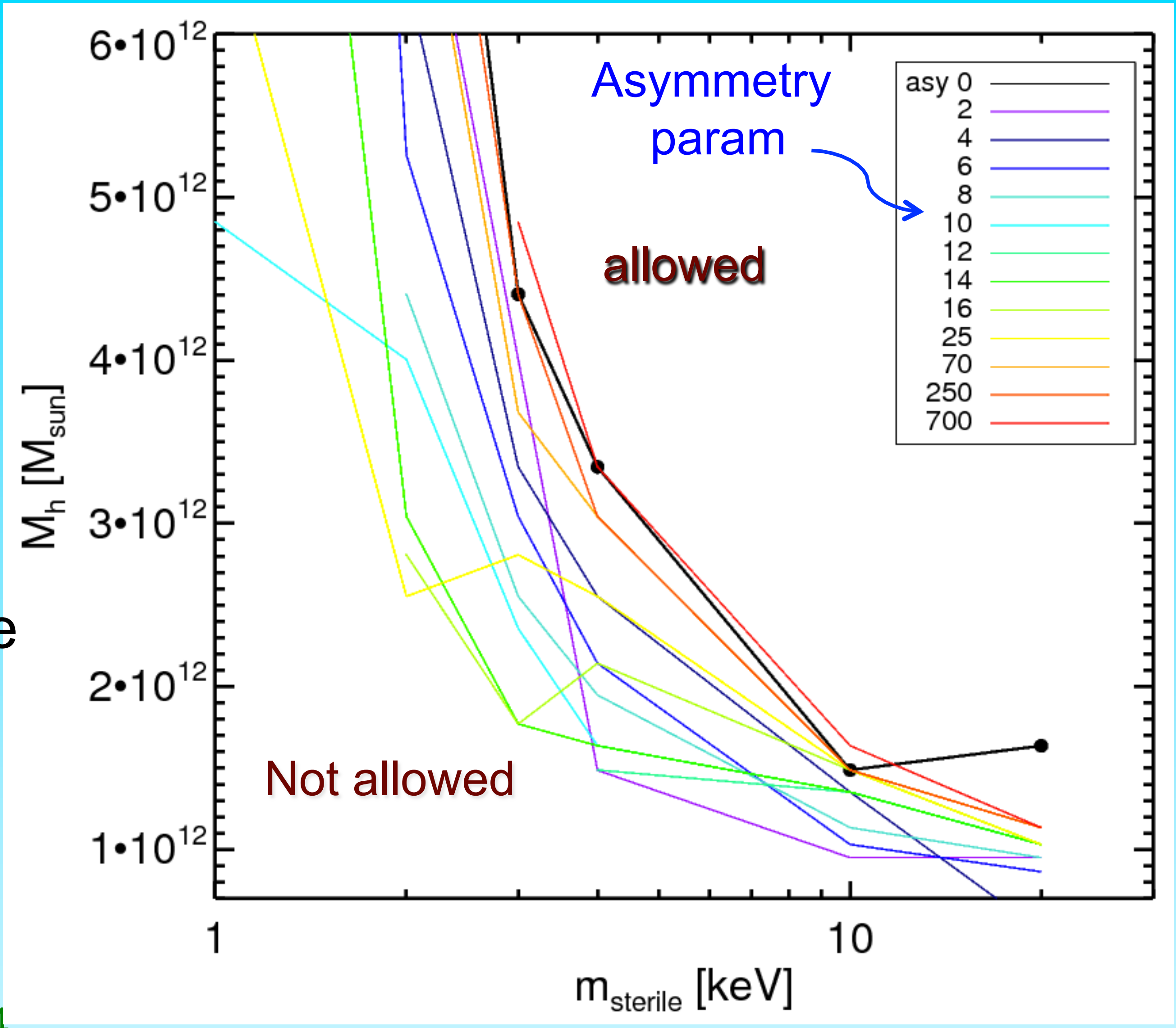
In νMSM, the mass power spectrum can be described by 2 params: m_ν and an asymmetry param.

The constraints on the mass generally become weaker



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Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Unless baryon effects are important

Ruled out unless $M_{halo} < 1.5 \times 10^{12} M_o$

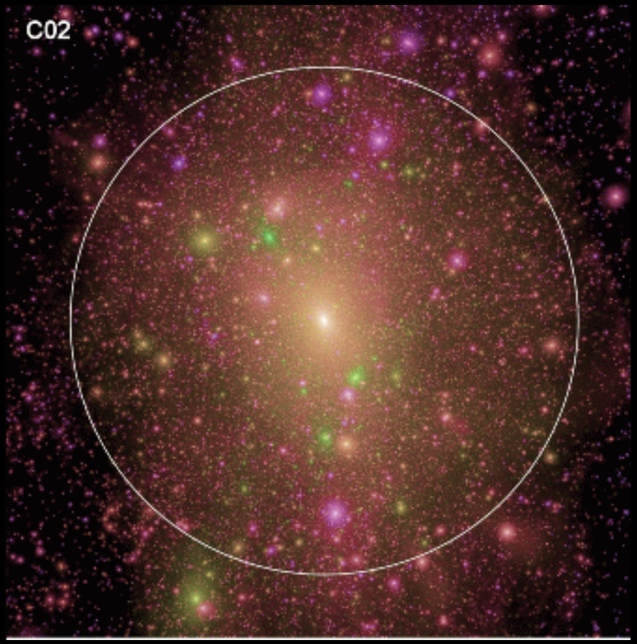
(from abundance of massive satellites)

Warm dark matter :

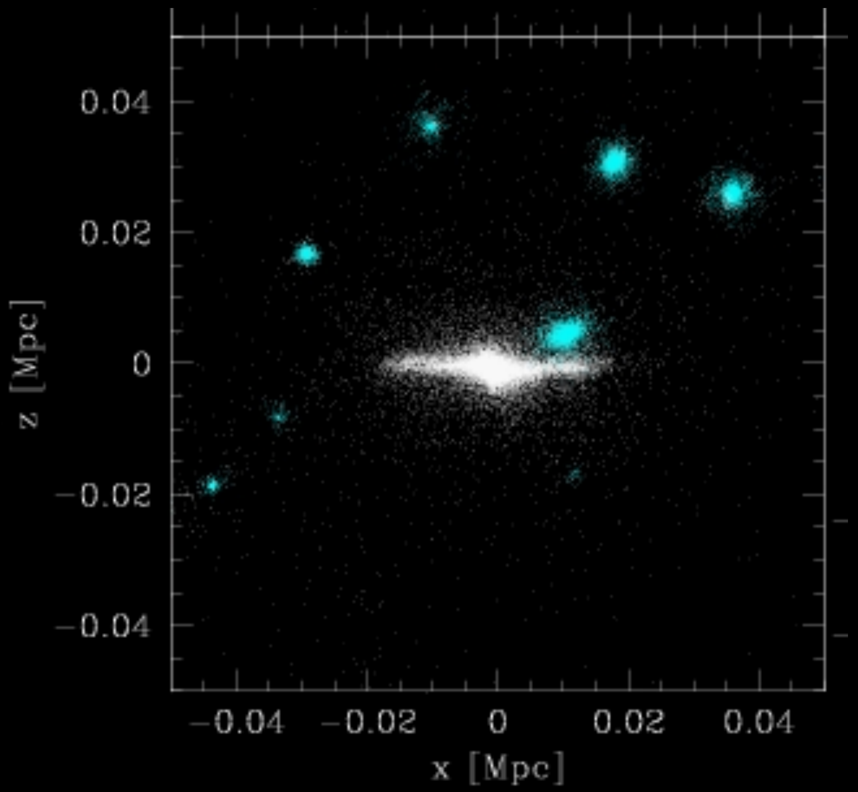
Ruled out unless $M_{halo} > 1.2 \times 10^{12} M_o$

(from abundance of satellites)

The satellites of the Milky Way

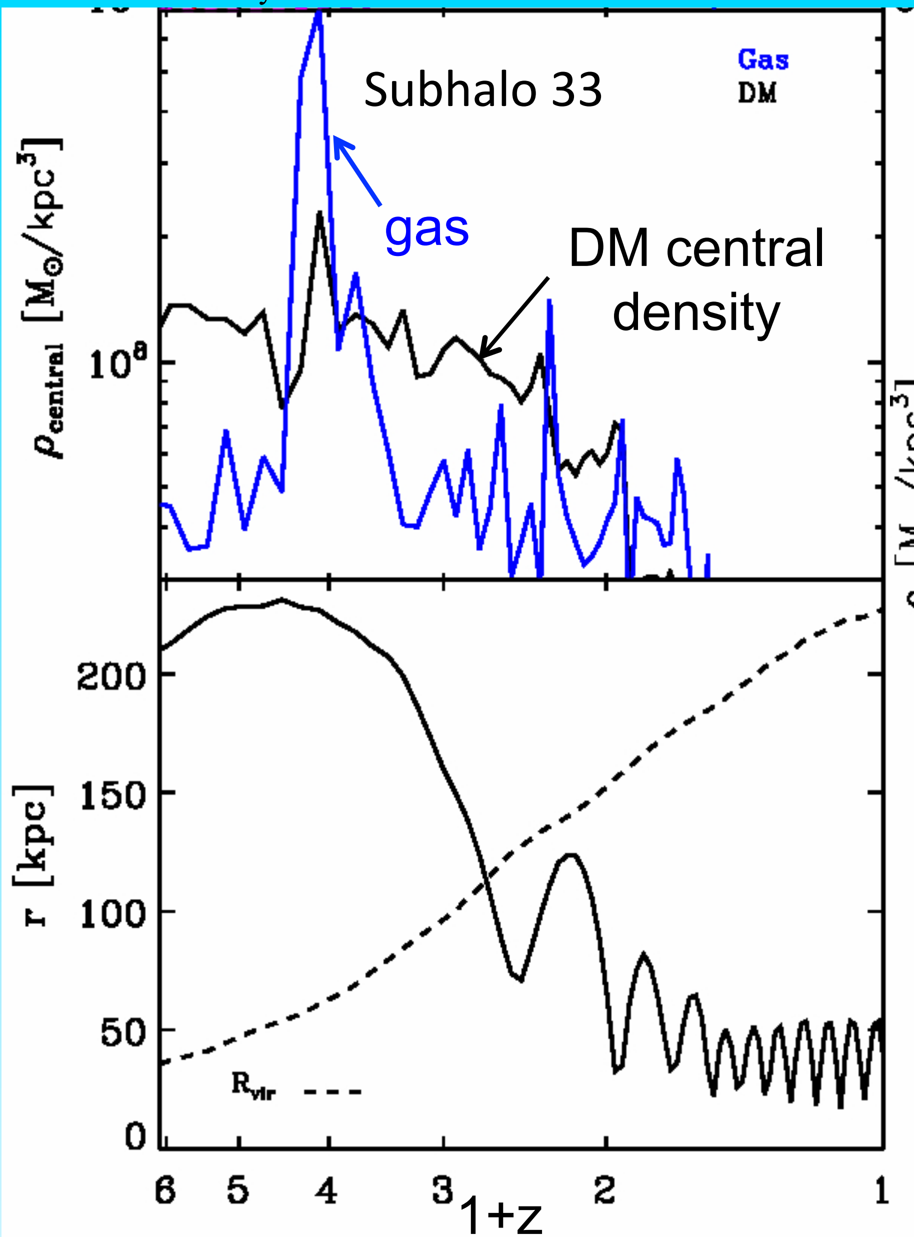


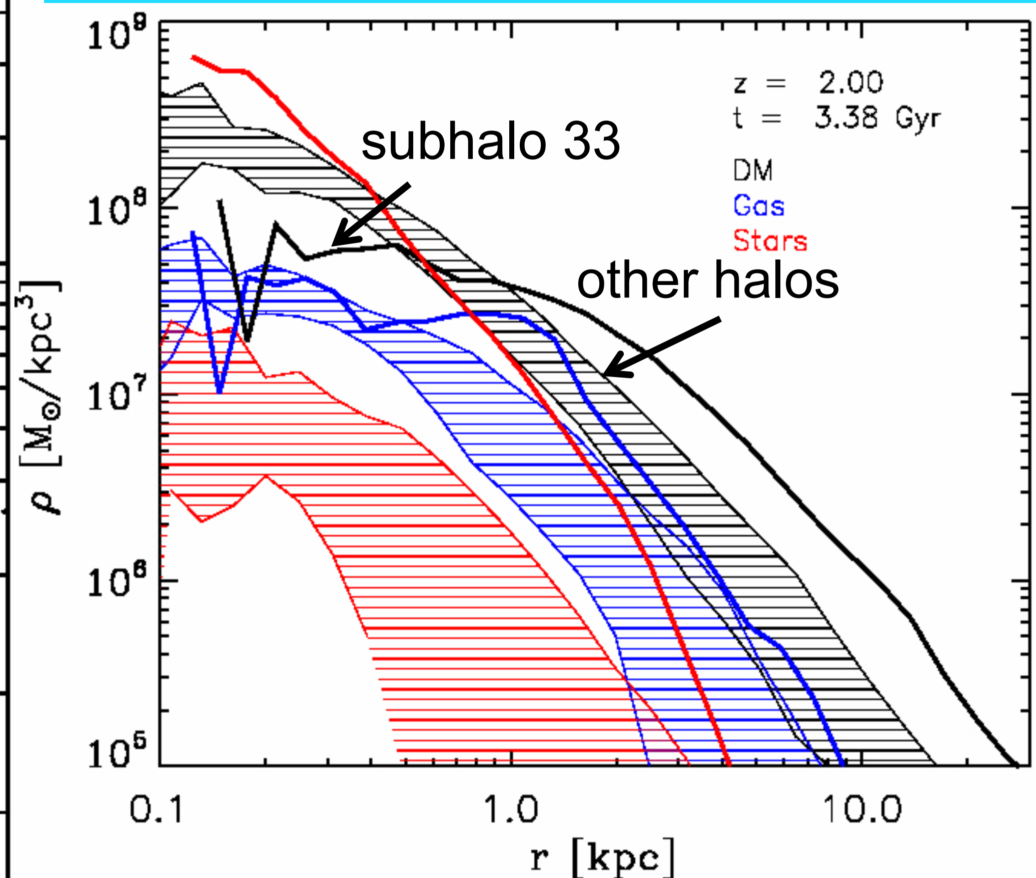
SPH simulations of galaxy formation in one of the Aquarius halos



Parry, Eke, Frenk & Okamoto '11

Baryon effects in the MW satellites





Parry, Eke & Frenk '11

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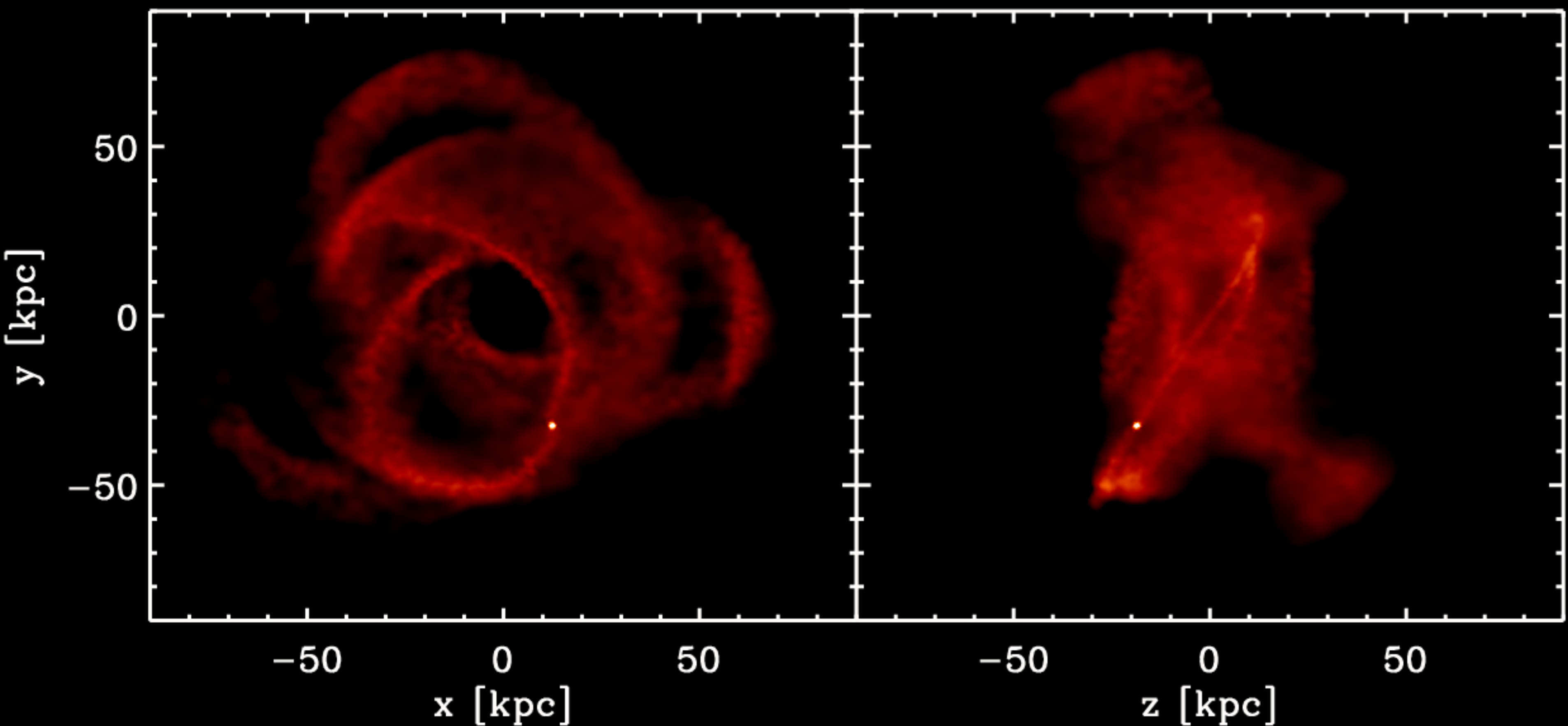
Baryon effects in the MW satellites

Subhalo 33



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DM & sats of the MW: conclusions

Abundance and kinematics of MW sats set strong constraints on nature of dark matter

Key properties of sat system:
- Luminosity function
- Abundance of most massive sats

Model	Sat Lum Fn	Massive sats	Comments
CDM	OK	$M_{halo} < 1.5 \times 10^{12}\ M_o$	? Unless baryon effects reduce central density
WDM	$M_{halo} > 1.2 \times 10^{12}\ M_o$	OK	+ X-ray constraint $M_{halo} > 1.5 \times 10^{12}\ M_o$ $m_x < 5 keV$