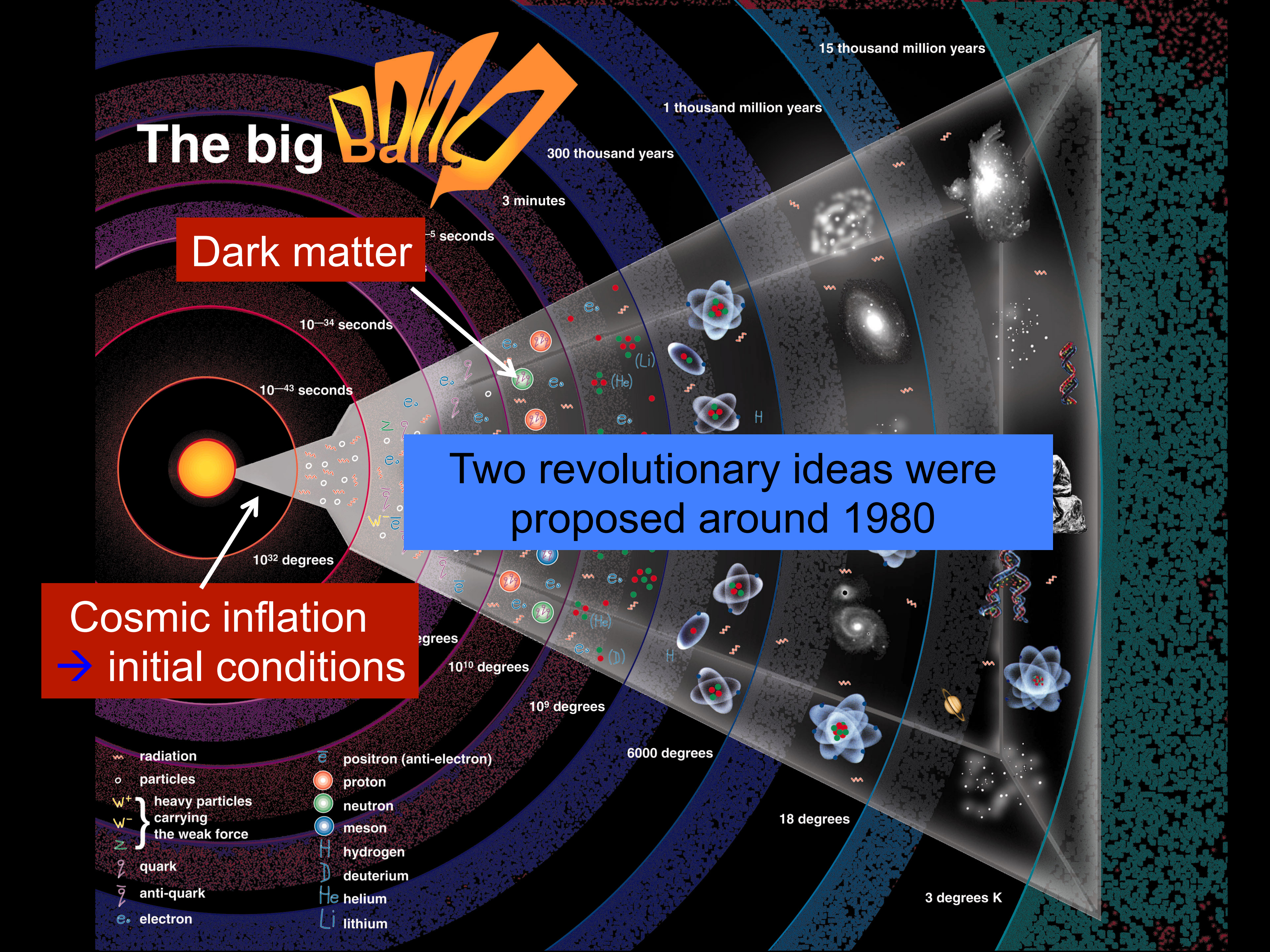
Looking for the identity of the dark matter in and around the Milky Way

Carlos S. Frenk
Institute for Computational Cosmology, Durham


The big Bang
Dark matter
Two revolutionary ideas were proposed around 1980
Cosmic inflation
→ initial conditions
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
seconds
10—34 seconds
10—43 seconds
10³² degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile ν majoron; KeVin	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

The dark matter power spectrum

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Free streaming →

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

for thermal relic

m_{CDM} ~ 100GeV

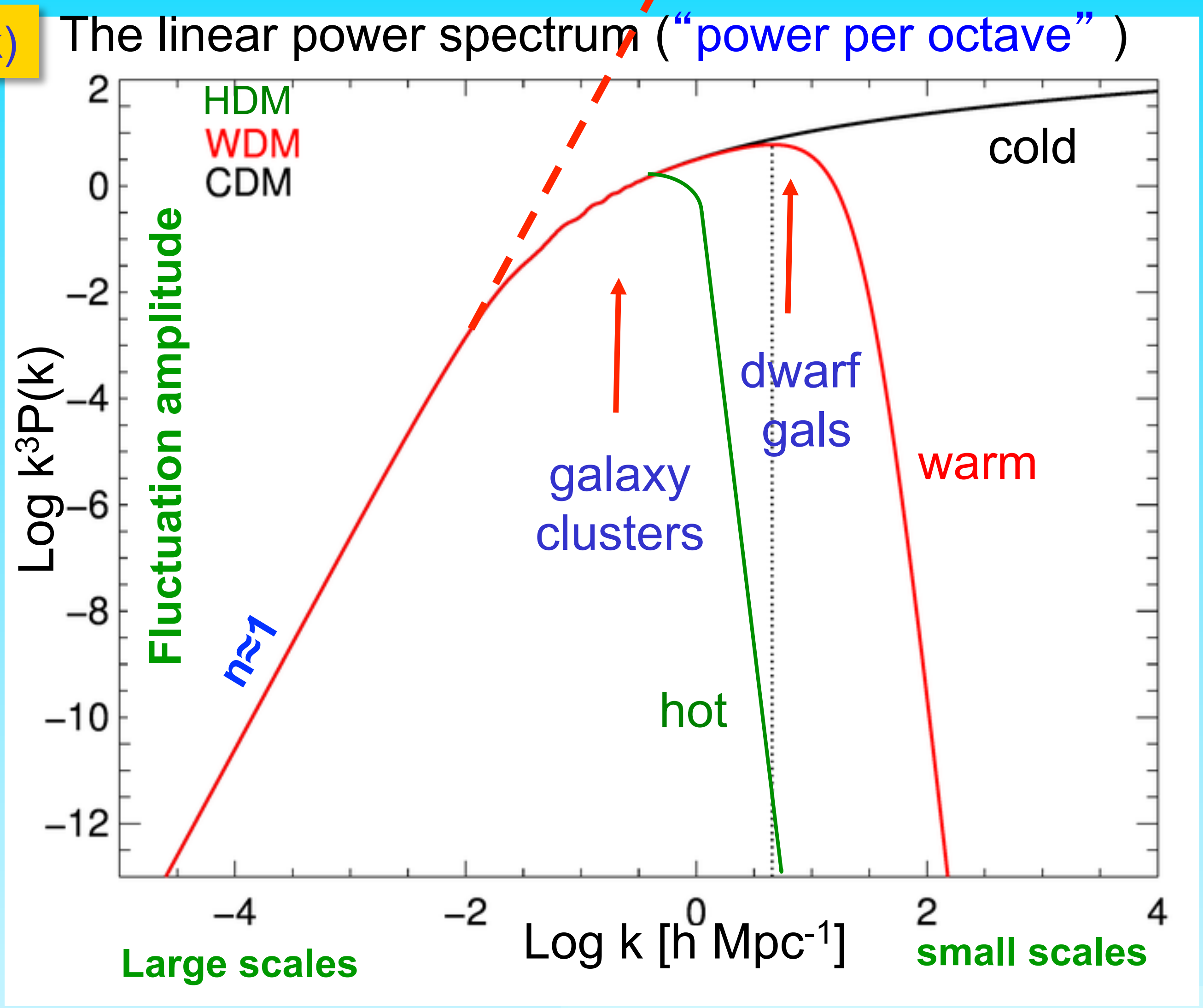
susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

sterile ν; M_{cut}~10^9 M_o

m_{HDM} ~ few eV

light ν; M_{cut}~10^{15} M_o



1980s:

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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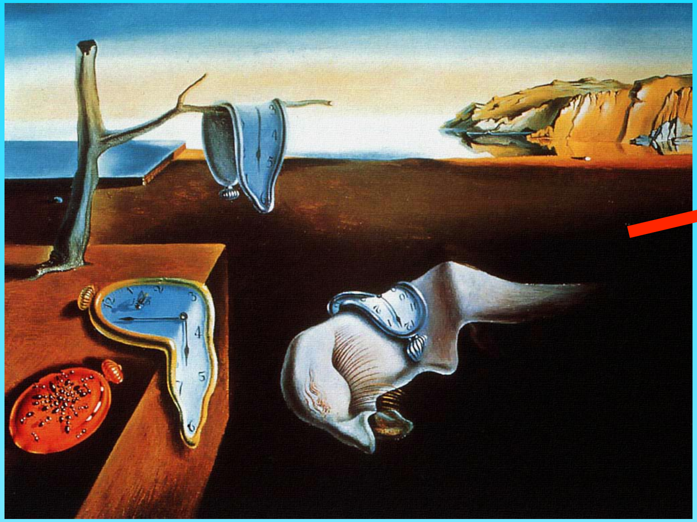
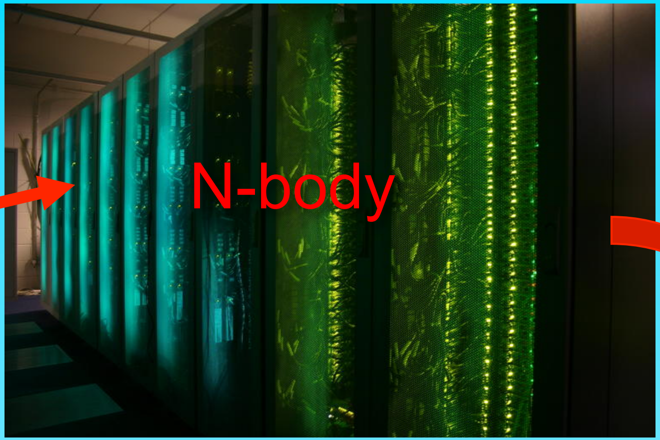
$t=10^{-35}$ seconds



"Cosmology machine"



$t=380{,}000$ yrs

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

Simulations

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

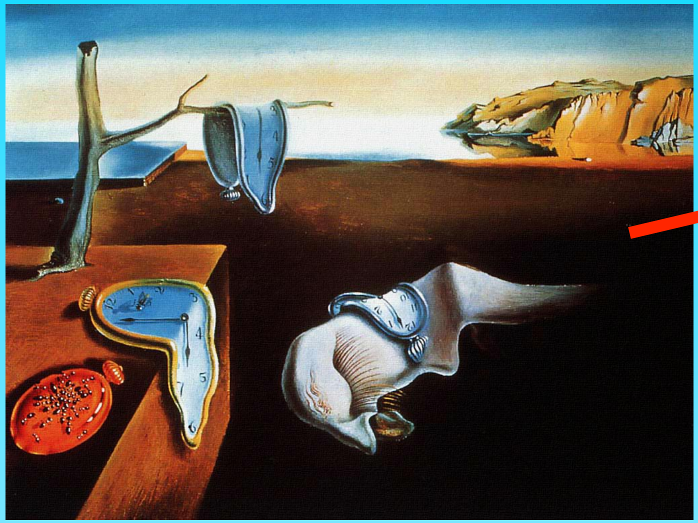
$t=13.8$ billion yrs

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

The formation of cosmic structure

University of Durham

$t=10^{-35}$ seconds



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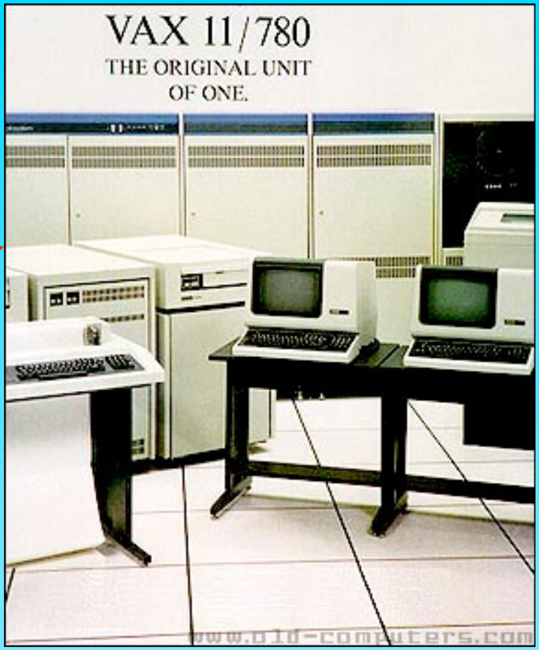
$\delta\rho/\rho \sim 10^{-5}$



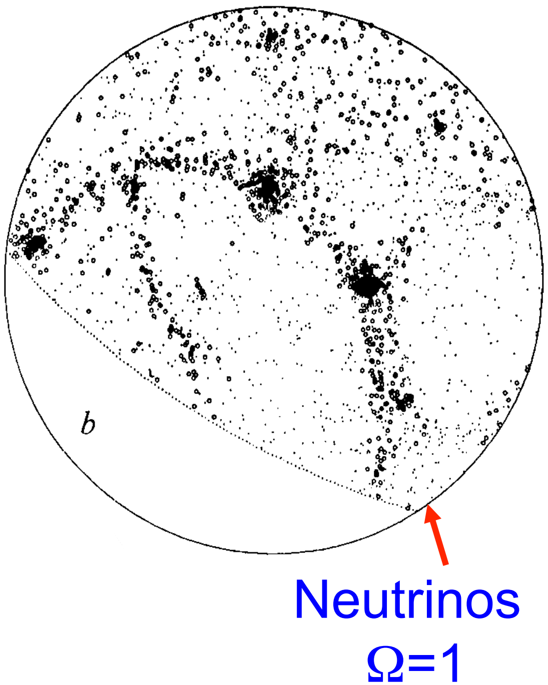
Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today

$t=13.8$ billion yrs

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

Institute for Computational Cosmology

Non-baryonic dark matter cosmologies



Frenk, White & Davis '83

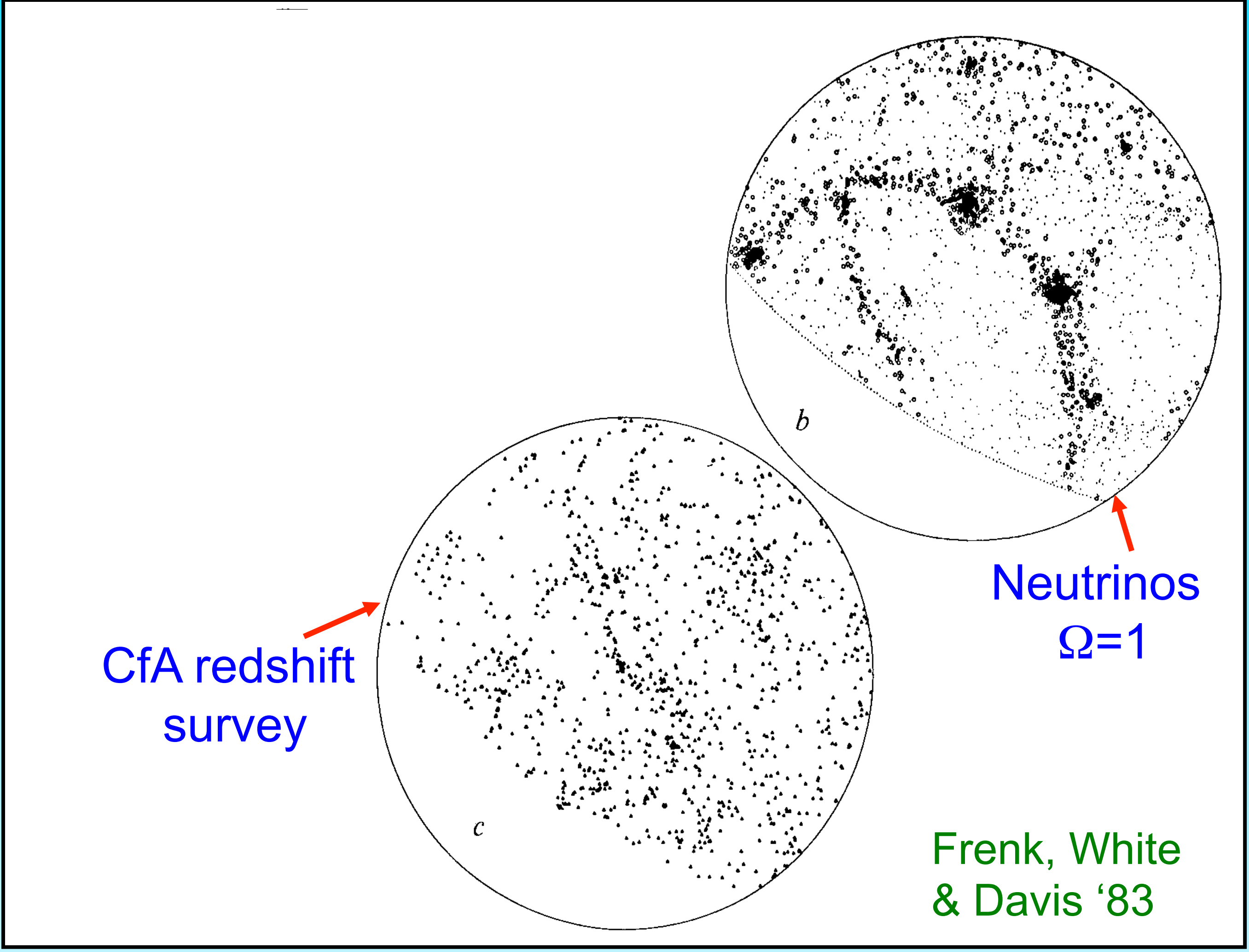
'85

Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clustring

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 10 ev



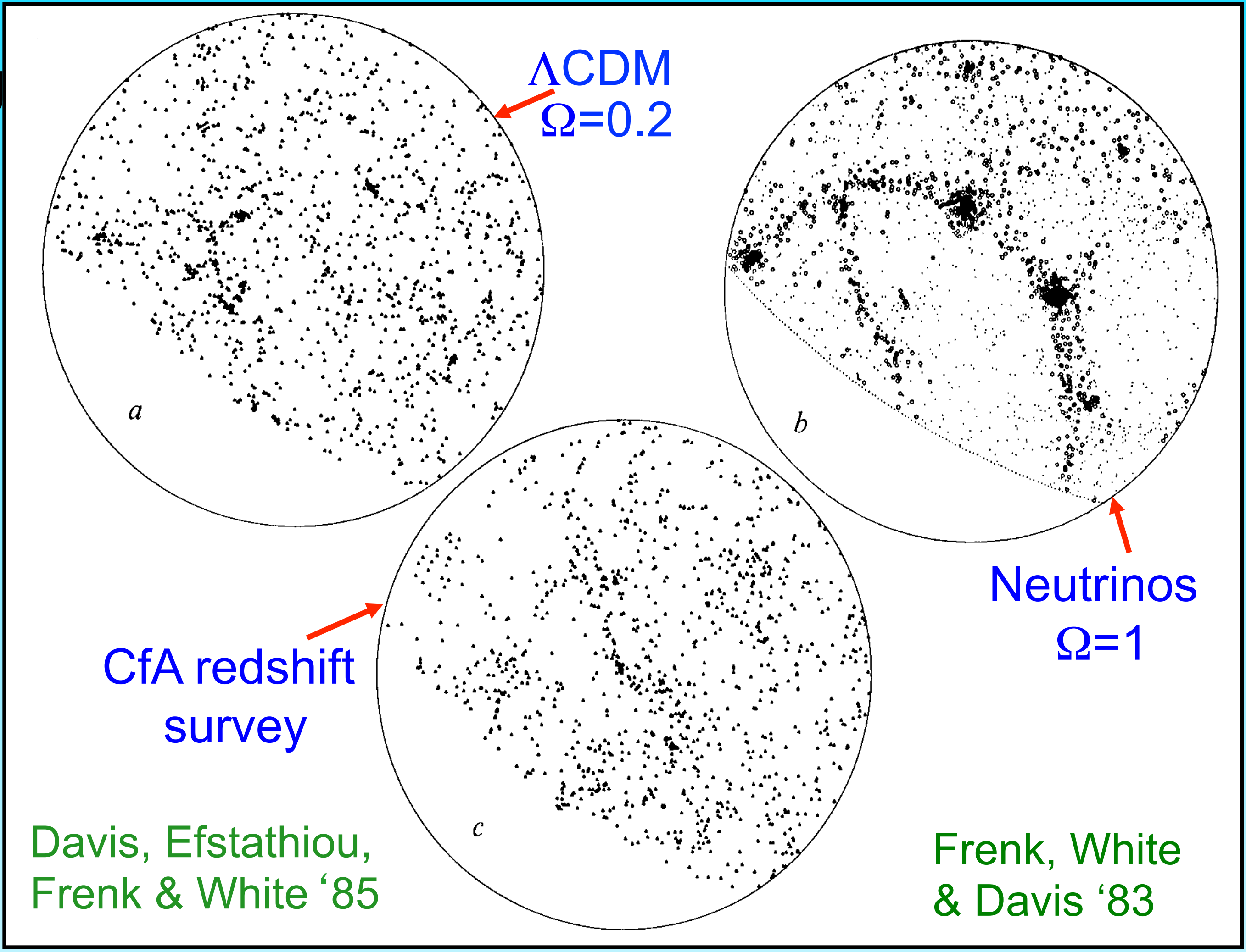
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust' ing

Neutrinos cannot make appreciable contribution to Ω → m_ν<< 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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Non-baryonic dark matter candidates

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

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ΛCDM model is an *a priori* implausible model!

… but makes definite predictions and is therefore testable

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The cold dark matter cosmogony

Main successes of the CDM cosmogony:

1. CMB temperature anisotropies

   (predicted 1982; discovered 1993)

2. Galaxy formation and clustering

(Clustering predicted early 80s; measured 90s: QDOT, APM, 2dFGRS, SDSS)

(Galaxy formation modelled/measured 90s: HST)

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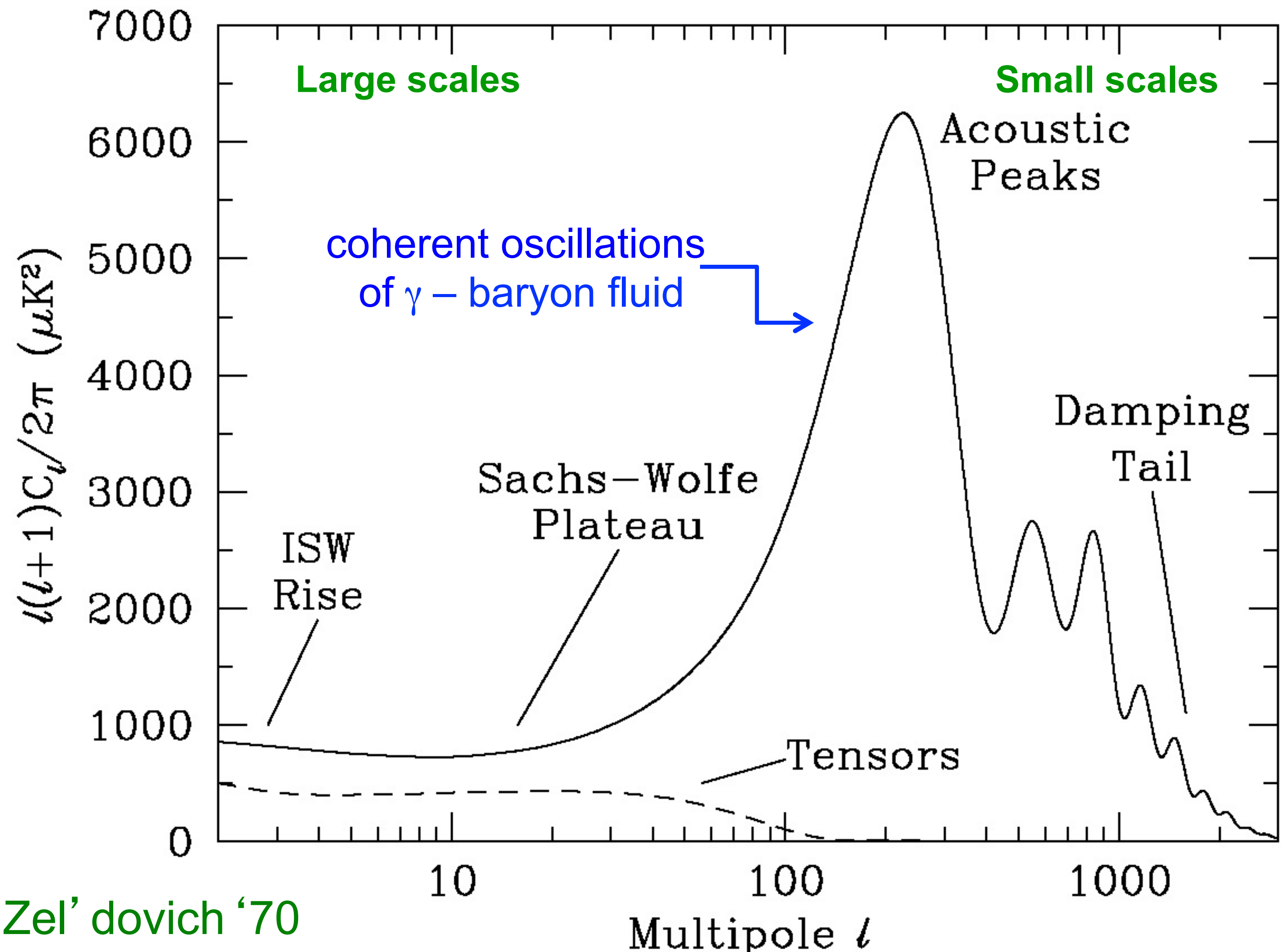
Temperature anisotropies in CMB

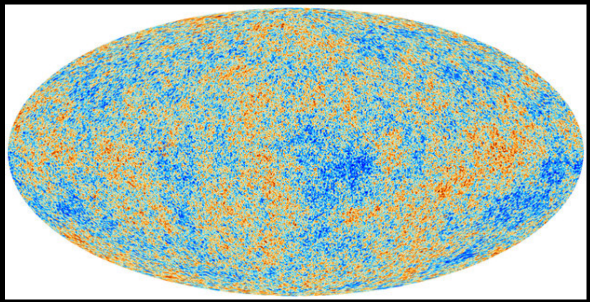
2D power spectrum



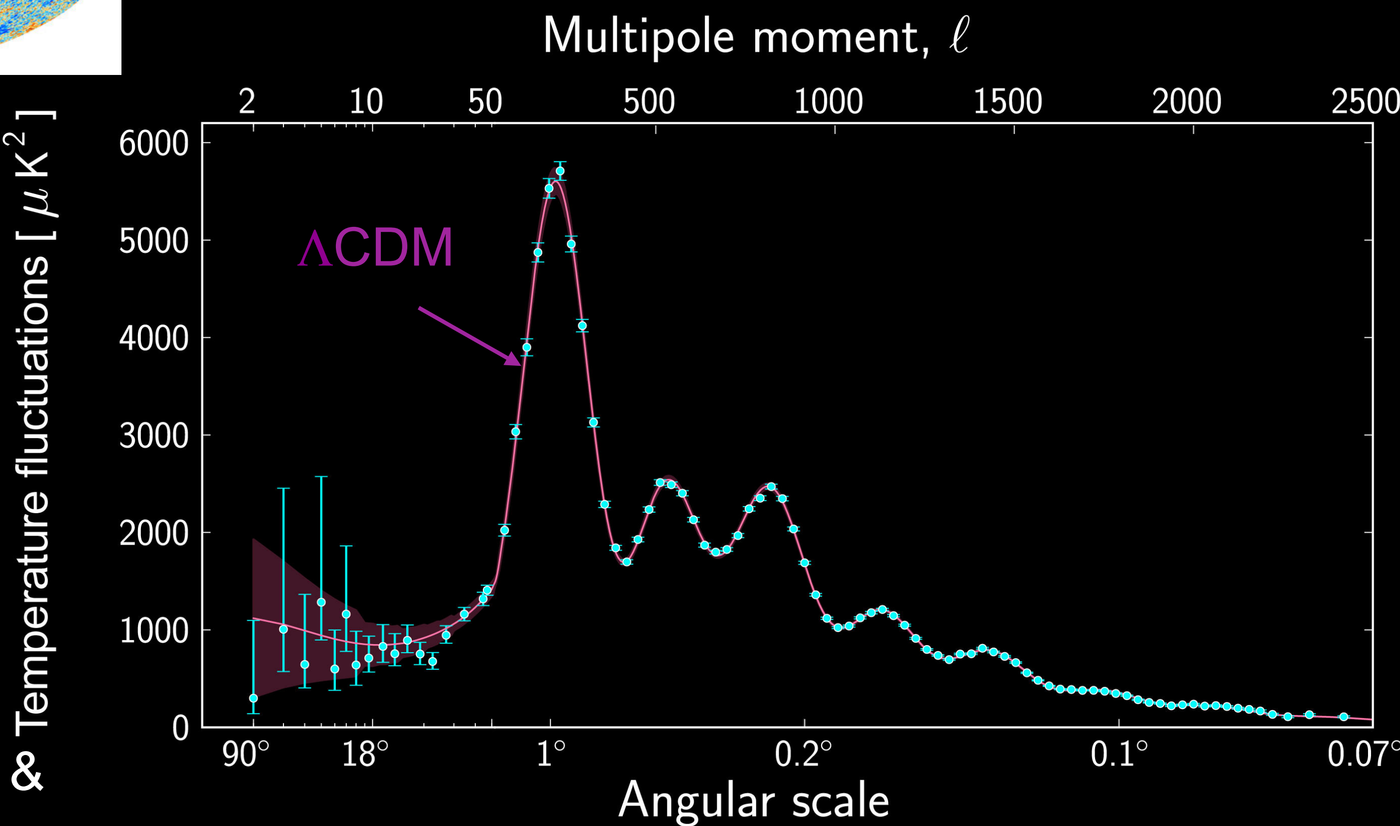
Sunyaev & Zel' dovich '70

Peebles & Yu '70; Peebles '82

Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000

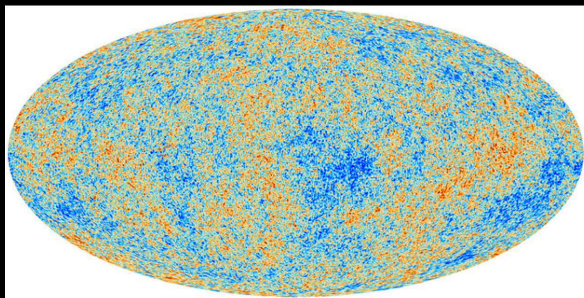


The data confirm the theoretical predictions (linear theory)

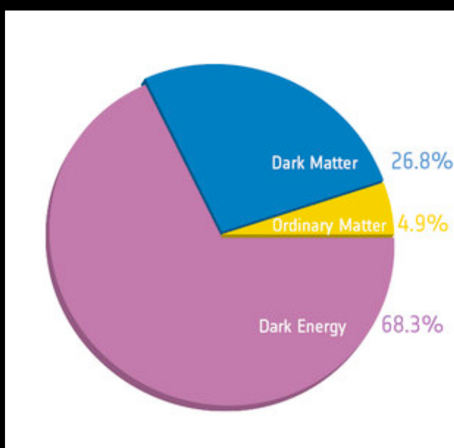
Peebles '82; Bond & Efstathiou '80s

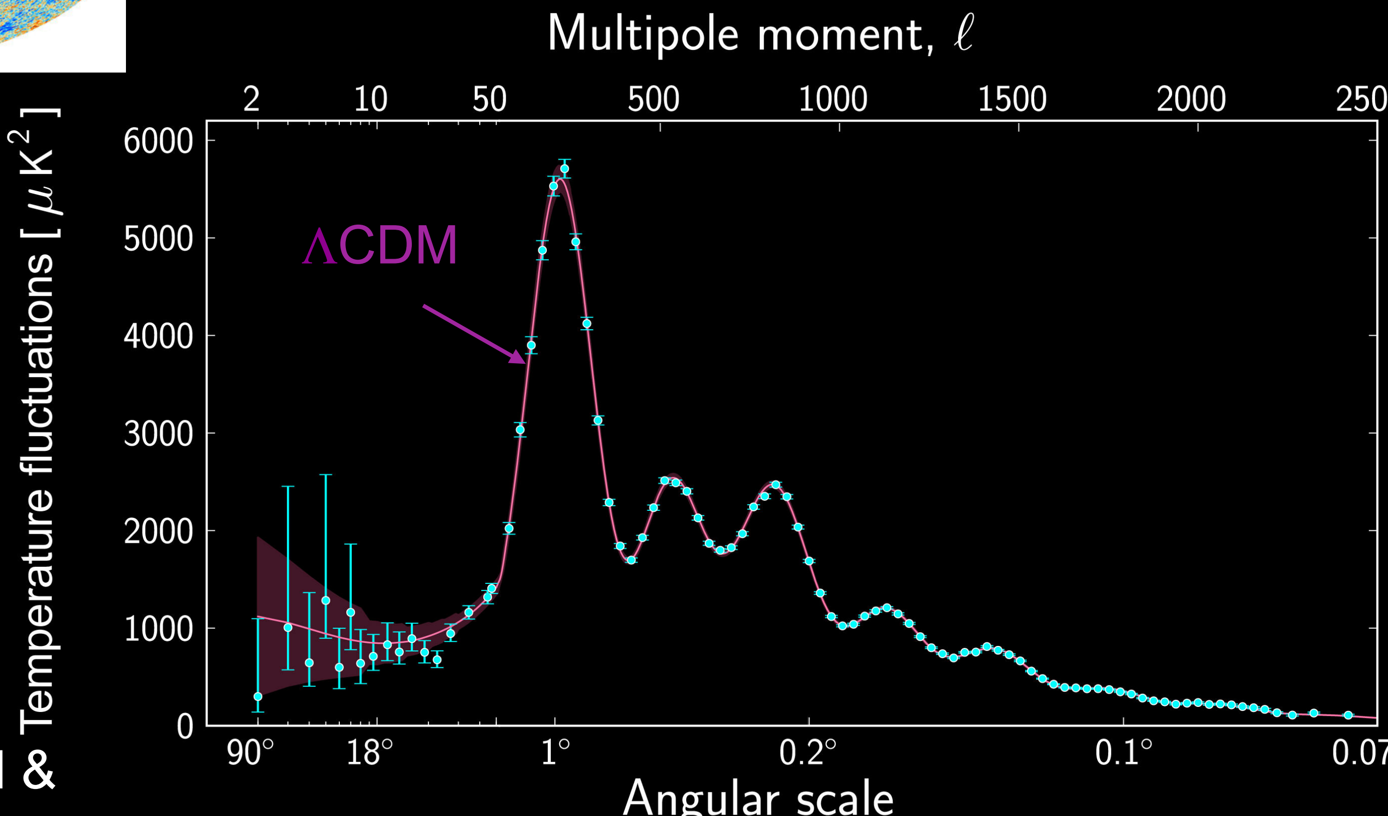
Planck collaboration '13

Planck temp anisotropies in CMB



Amplitude of fluctuations at z~ 1000





Peebles ' 82; Bond & Efstathiou '80s

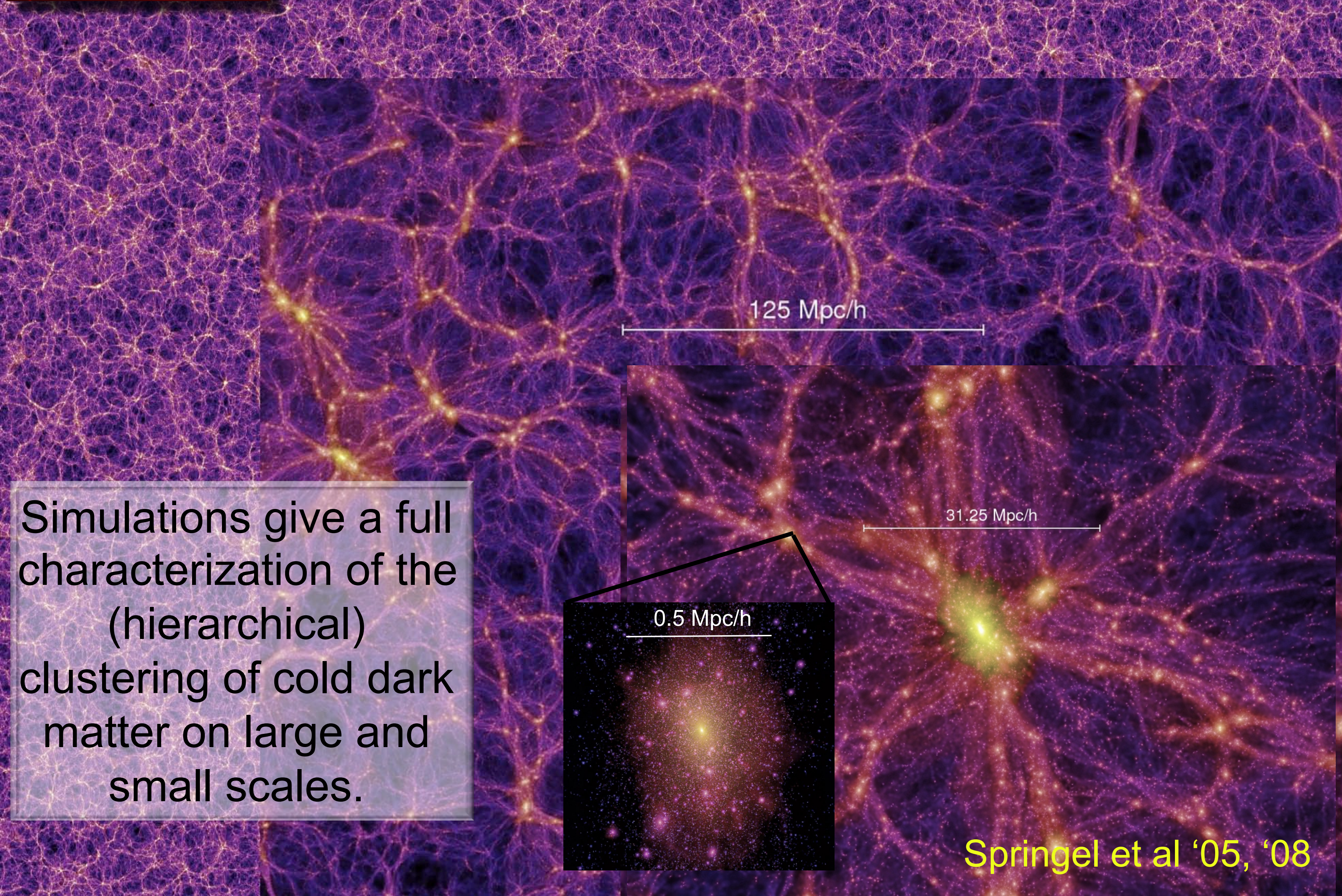
Planck collaboration '13

Galaxy formation & clustering

Two parts:

- Dark matter halo formation & clustering
- Gasdynamics, star formation, feedback, etc

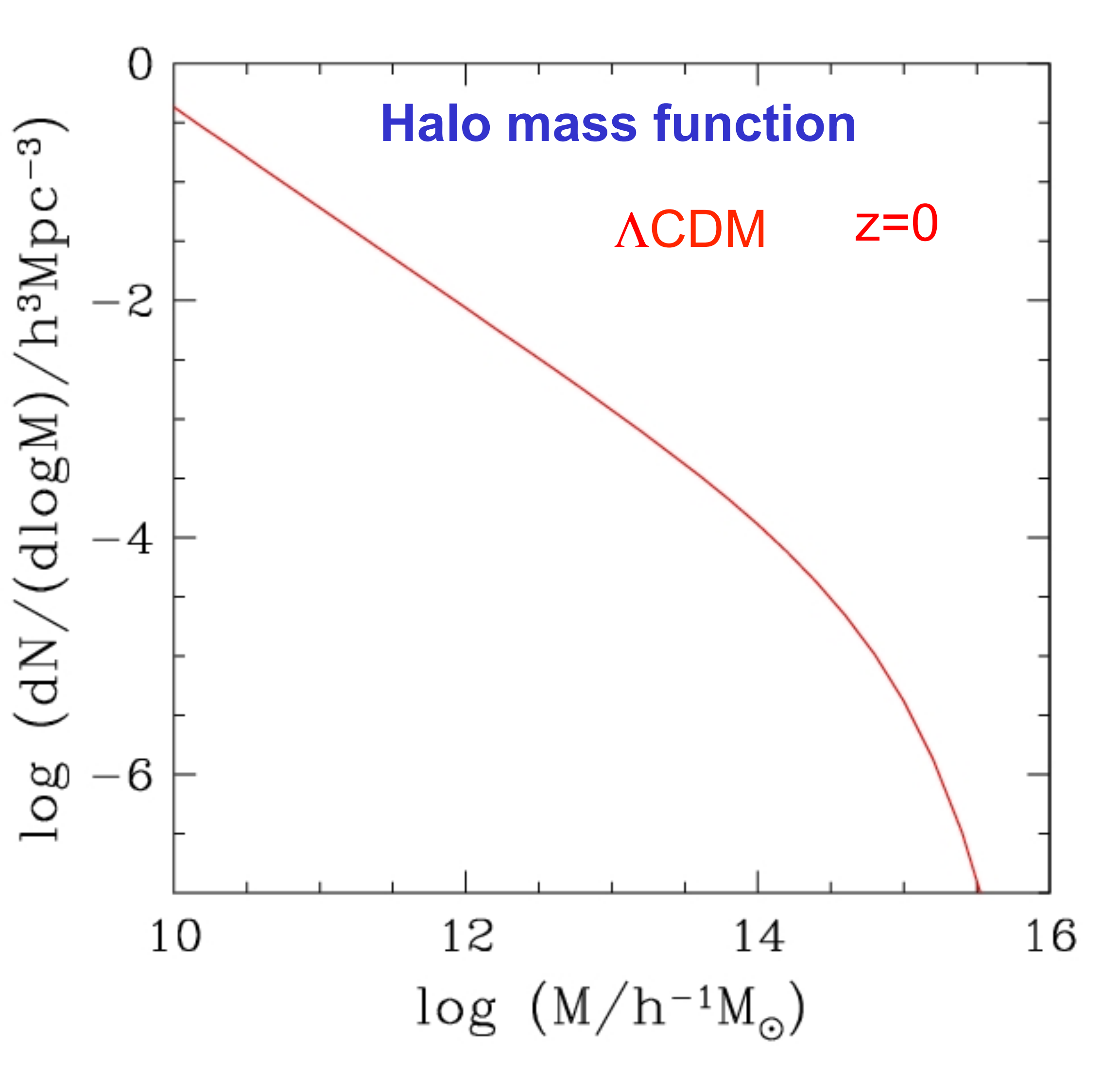
The Millennium/Aquarius simulation series



Simulations give a full characterization of the (hierarchical) clustering of cold dark matter on large and small scales.

Springel et al ‘05, ‘08

The Millennium/Aquarius simulation series

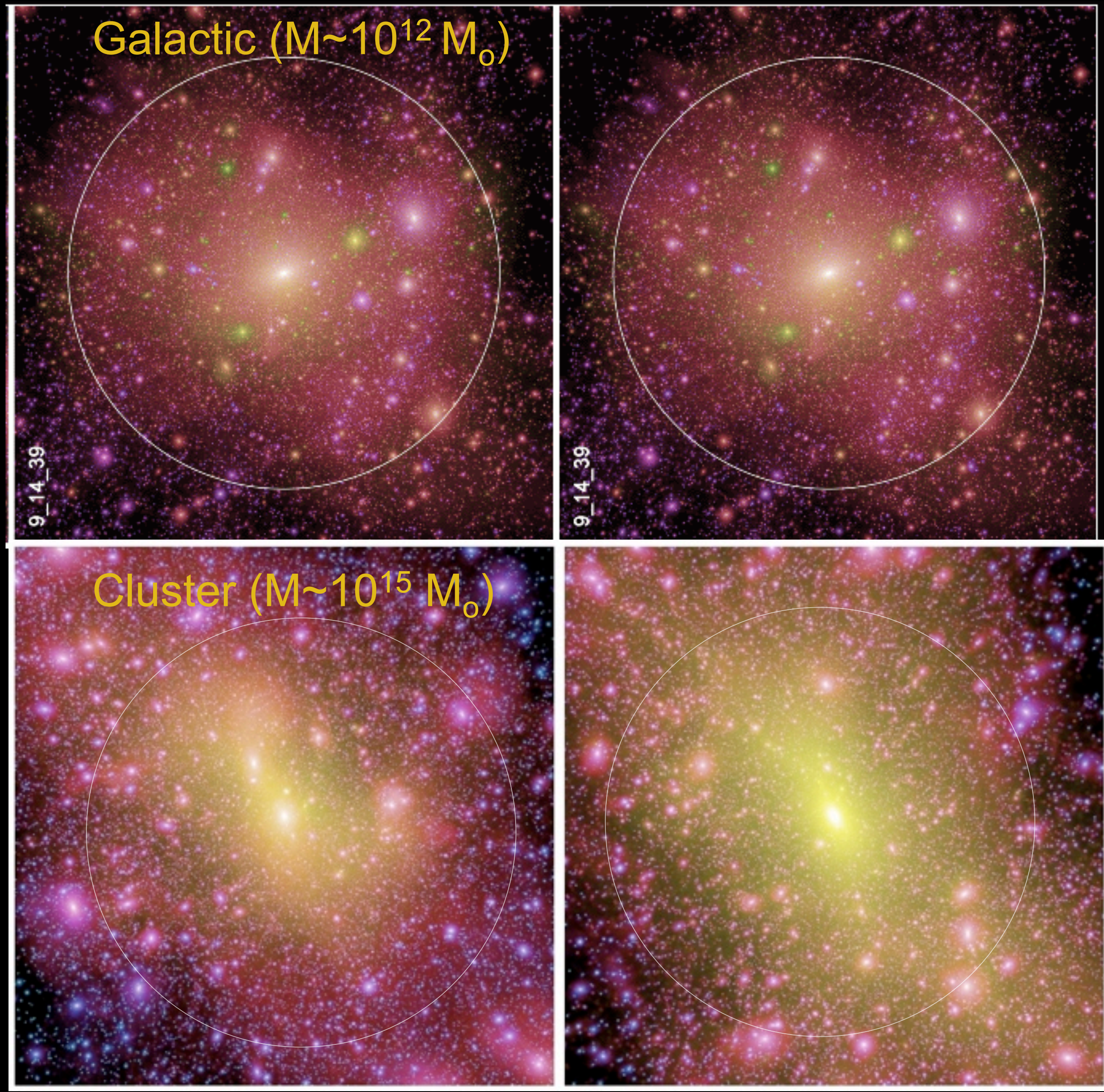


Springel et al '05, '08

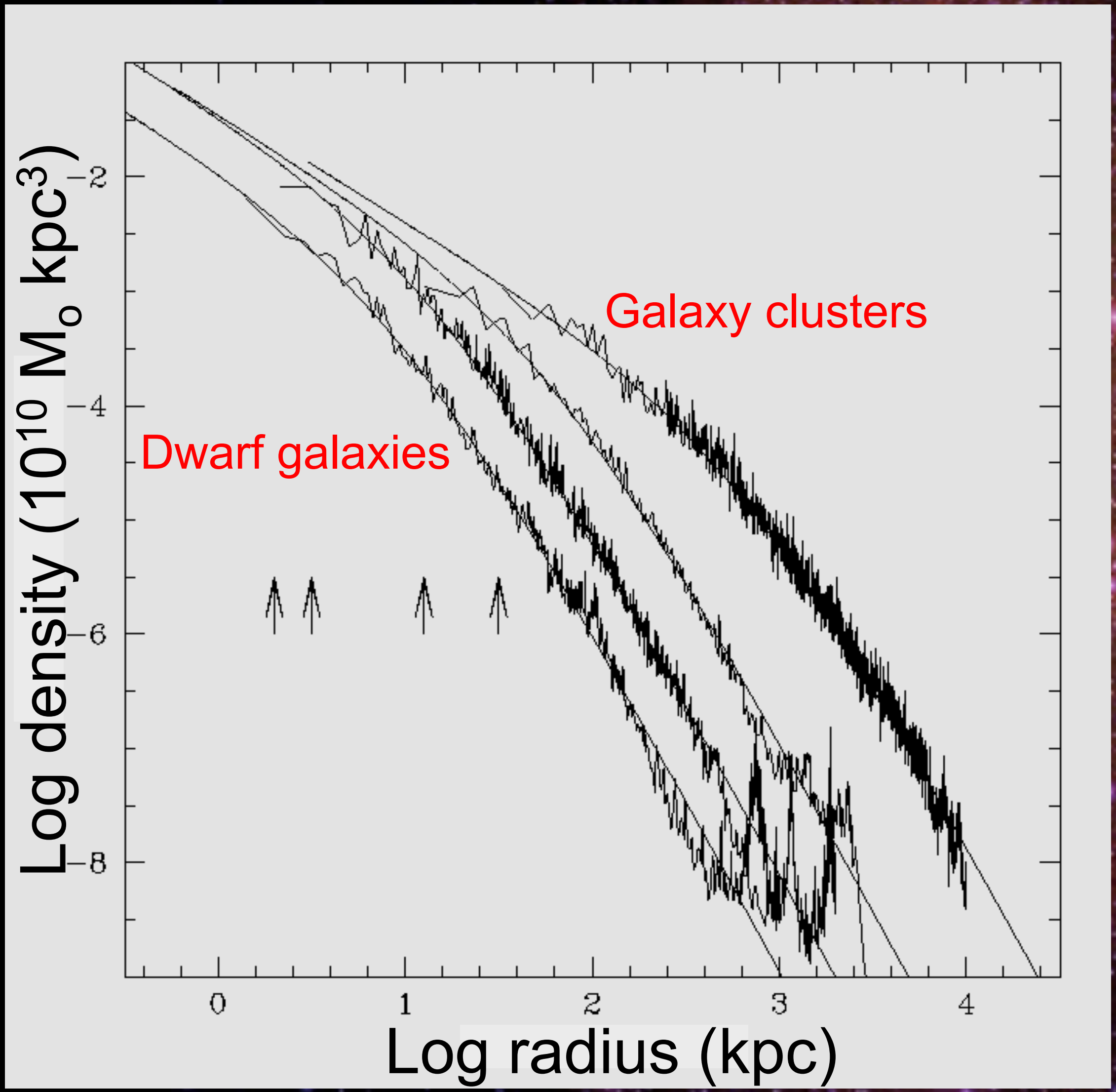
Aquarius (galactic) & Phoenix (cluster) halos

Self-similarity of CDM halos

The structure and substructure of CDM halos are approximately self-similar



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:

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

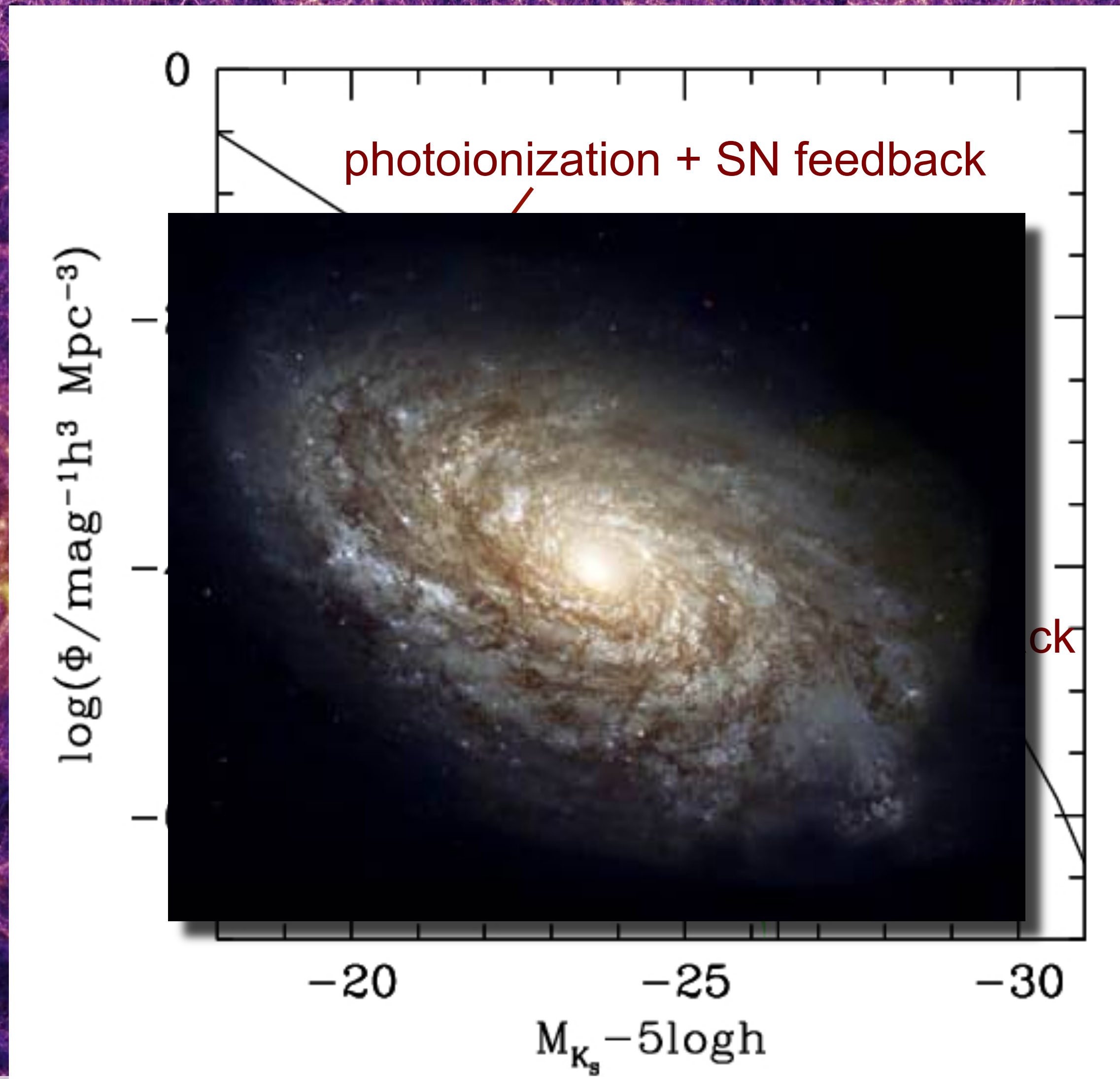
(Navarro, Frenk & White '97)

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

The Millennium/Aquarius simulation series

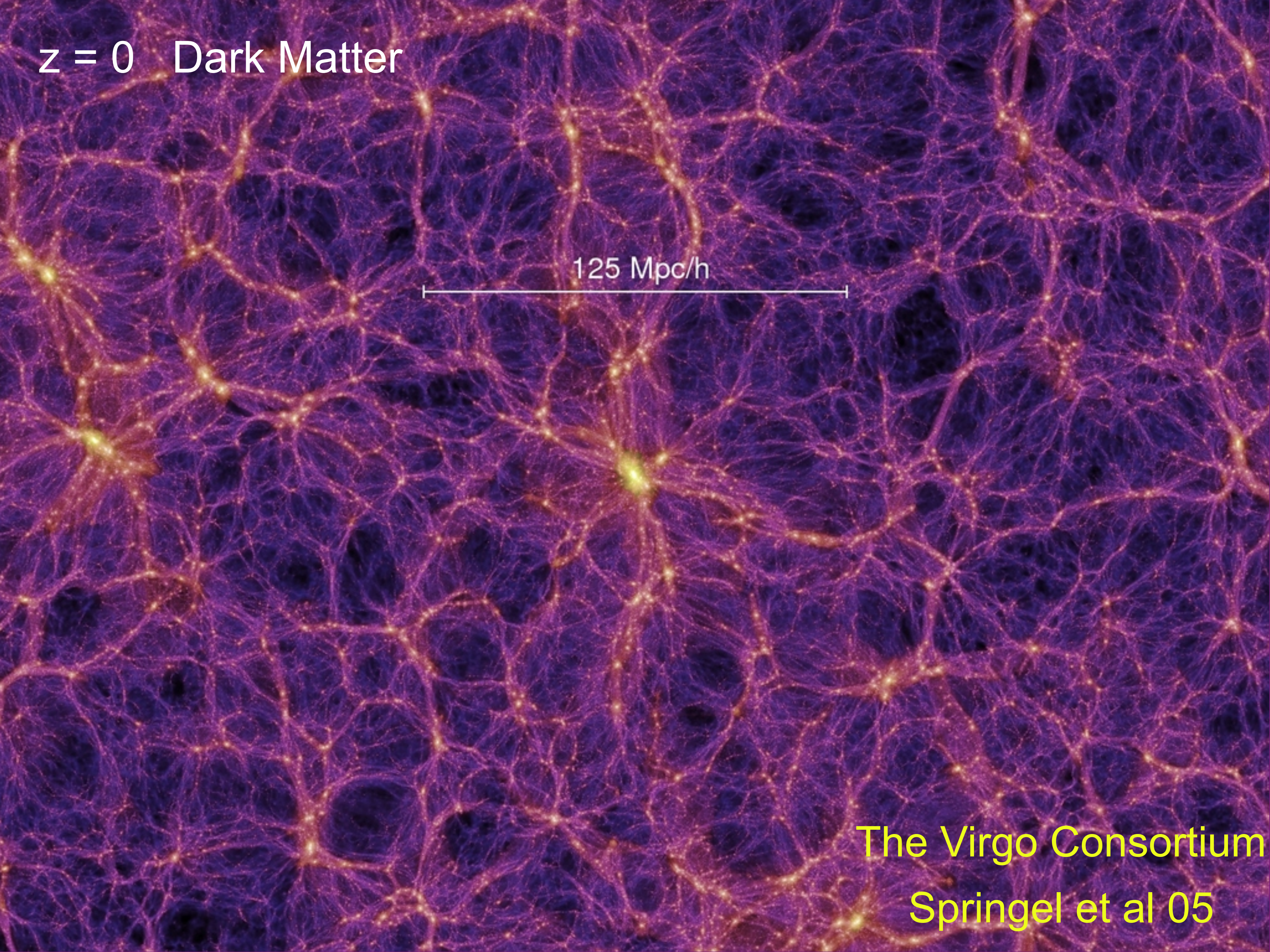
The halo mass function and the galaxy luminosity function have different shapes

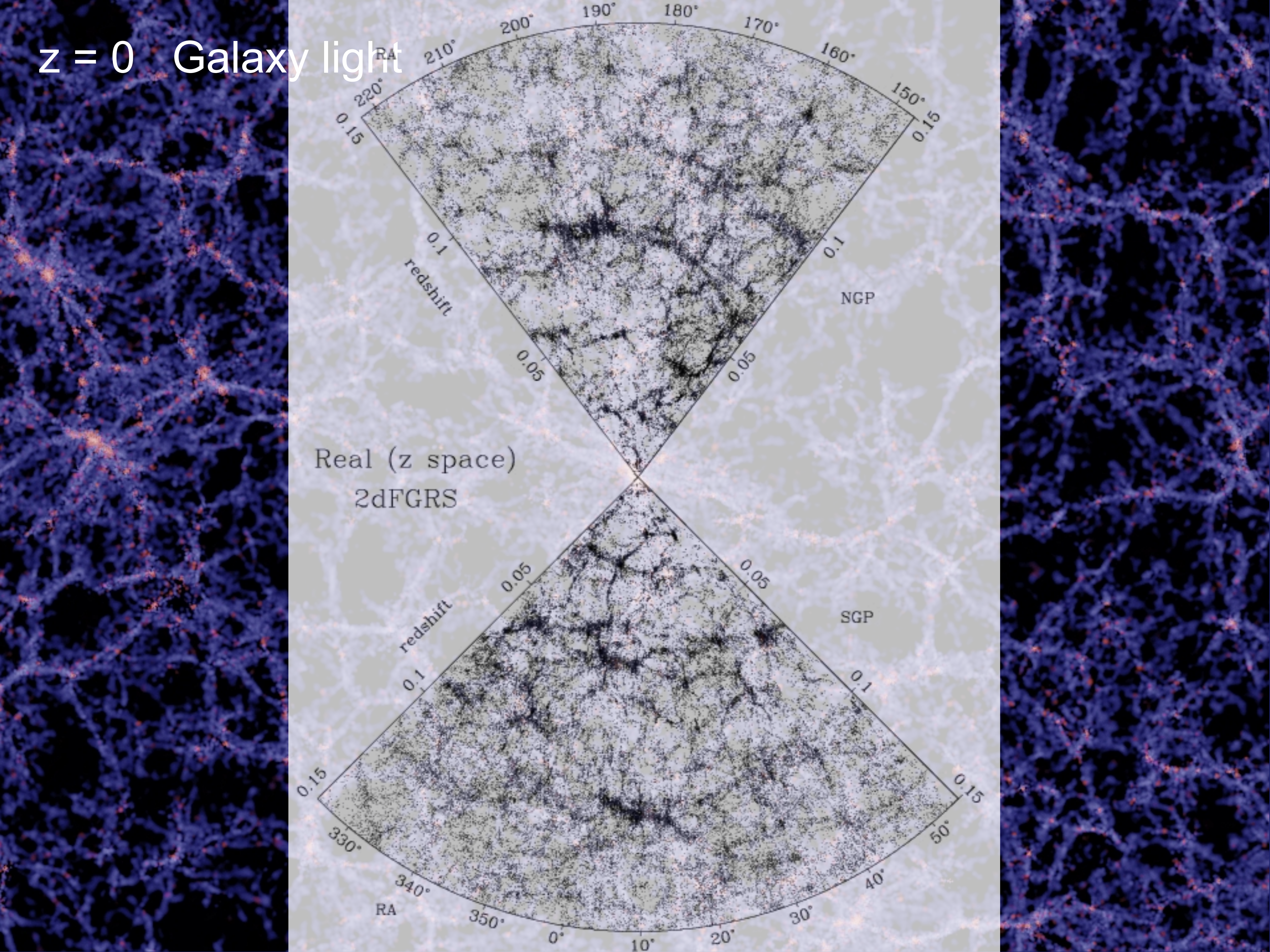
Complicated variation of M/L with halo mass



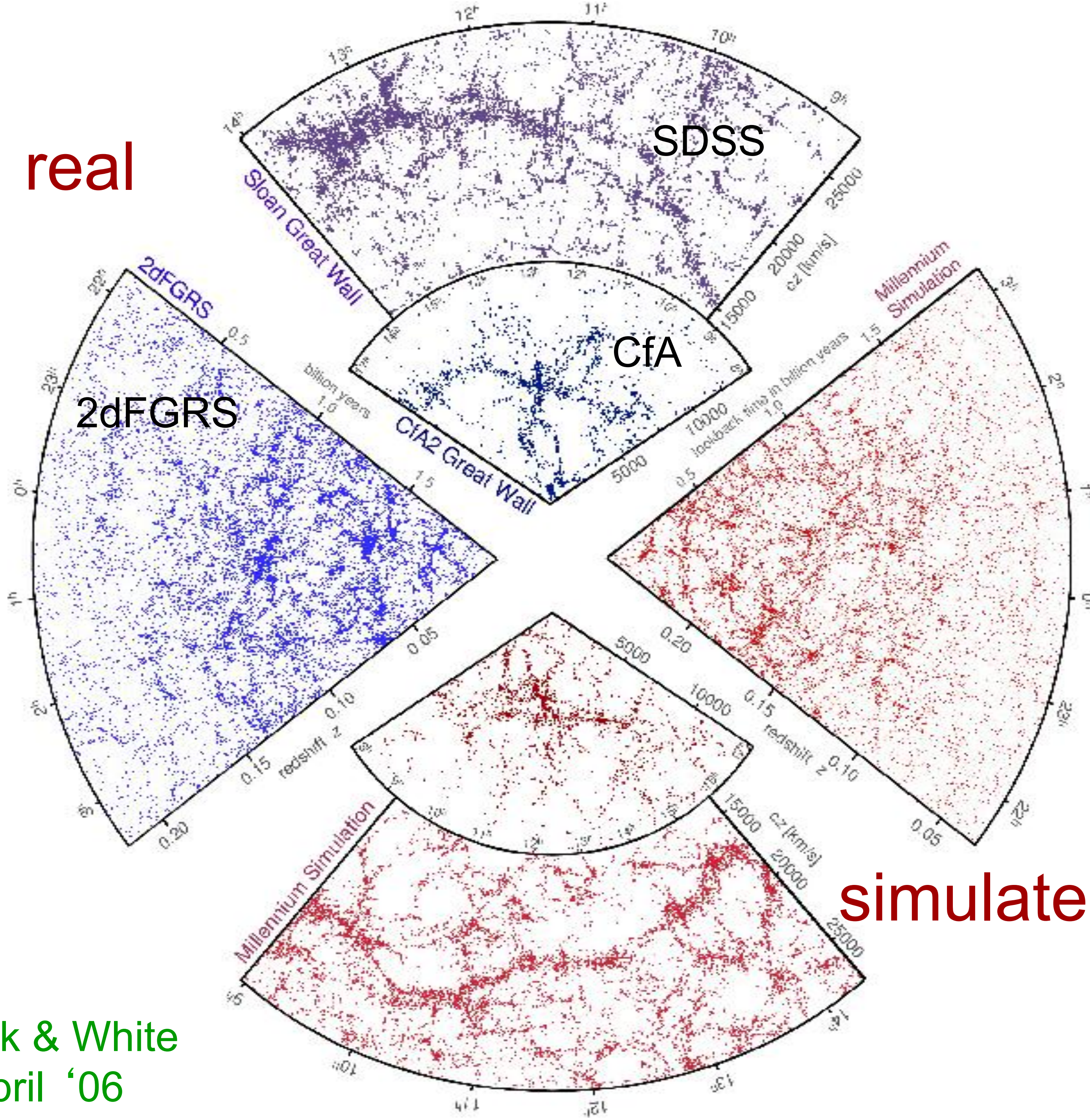
White & Frenk ‘91; Kauffmann et al ‘93; Cole et al ‘94, 00; Benson et al ’03; Croton et al ‘05; Bower et al. ’06

Springel et al ‘05, ‘08


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


z = 0 Galaxy light
Real (z space)
2dFGRS
NGP
SGP
redshift
RA
0.05
0.1
0.15
150°
160°
170°
180°
190°
200°
210°
220°
330°
340°
350°
0°
10°
20°
30°
40°
50°

real



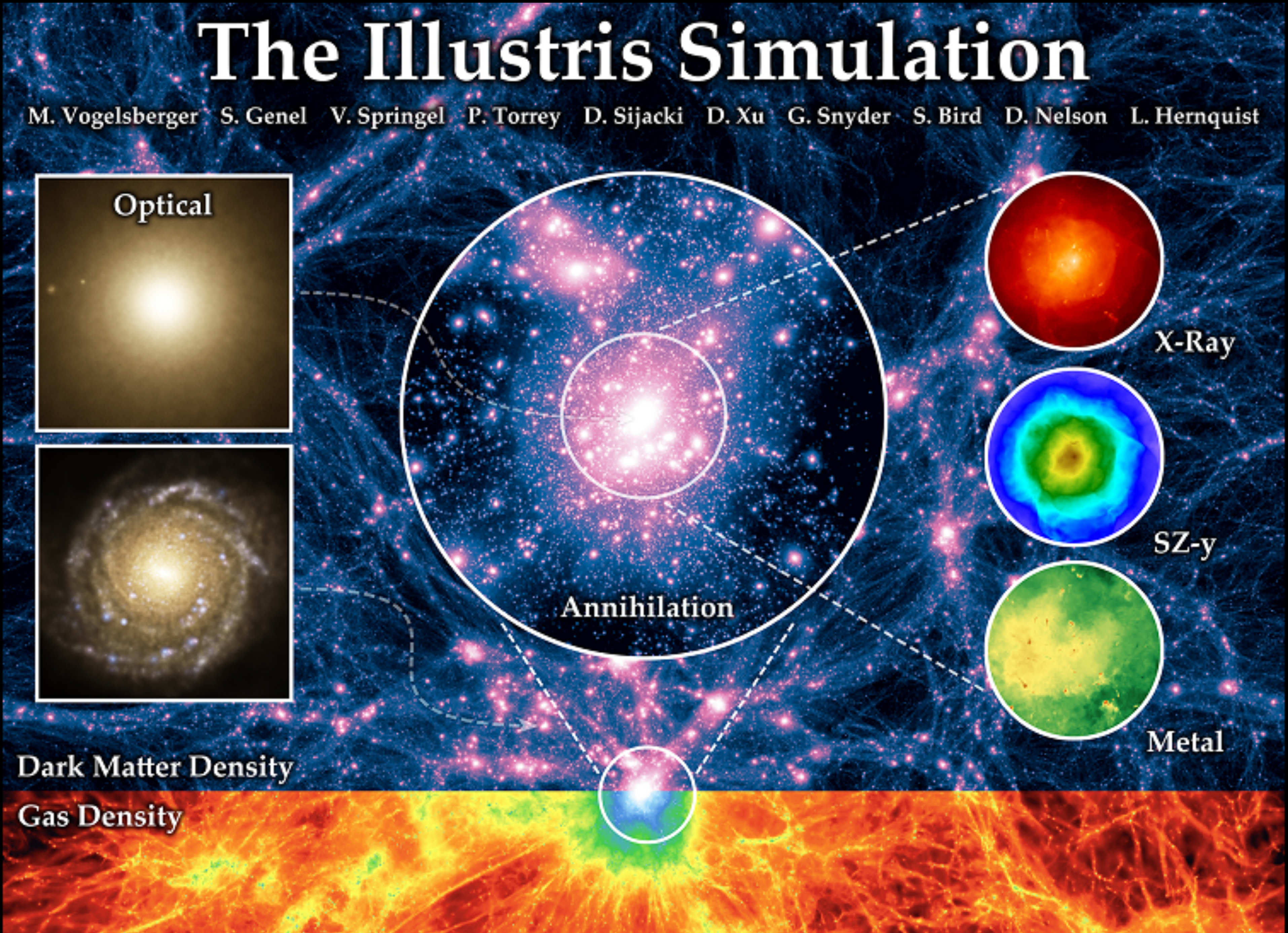
simulated

Springel, Frenk & White
Nature, April '06

Gas simulations of galaxy populations

- New generation of gasdynamic simulations of cosmologically representative volumes (~100 Mpc)^3 produce realistic galaxies

- Slower, much less resolution/volume than semianalytics but do not assume spherical symmetry and follow evol. of gas in detail


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Annihilation
Metal
Dark Matter Density
Gas Density

The “Evolution and assembly of galaxies and their environment” **(EAGLE)** simulation project

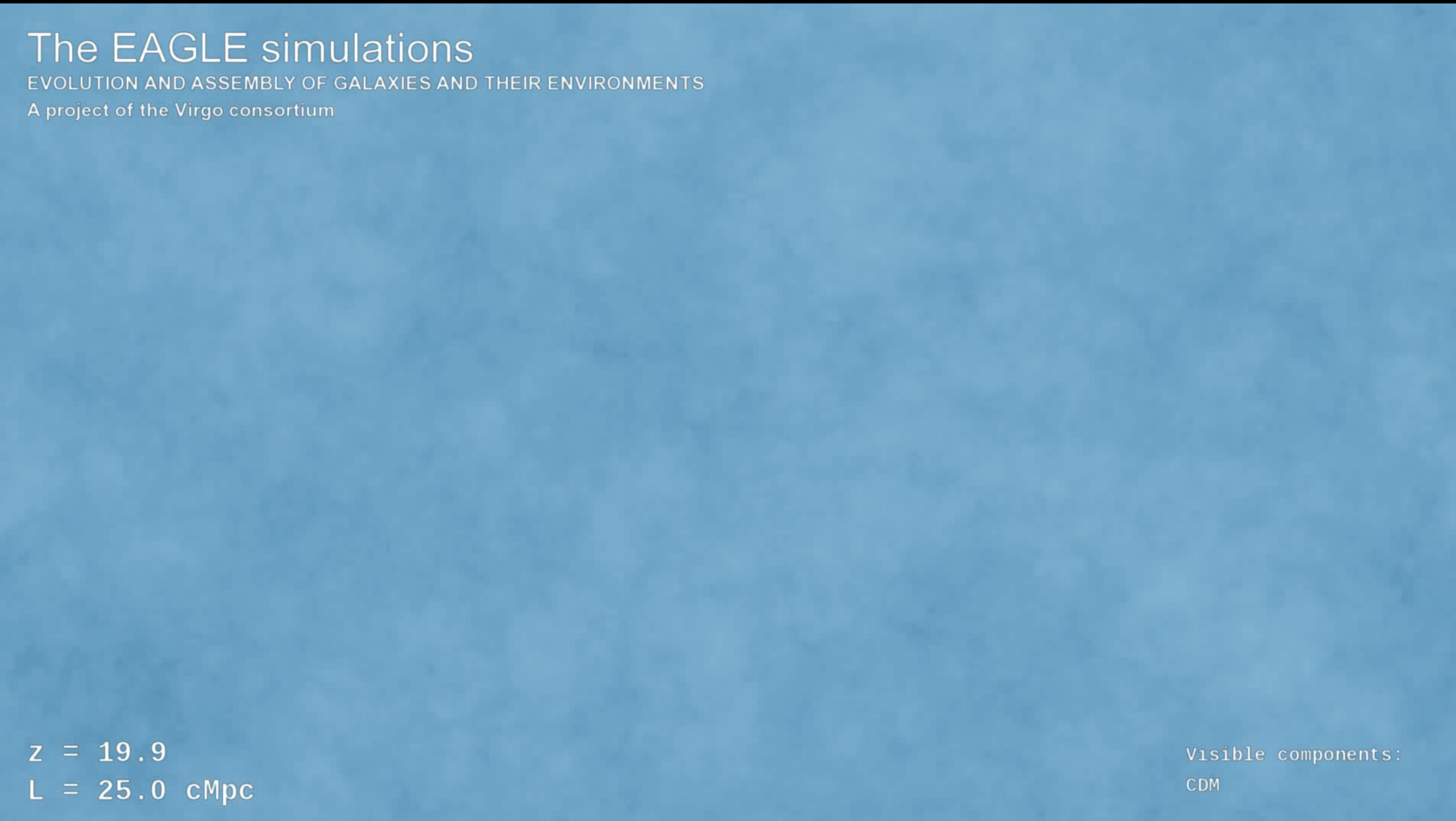
Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

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

+ Virgo Consortium

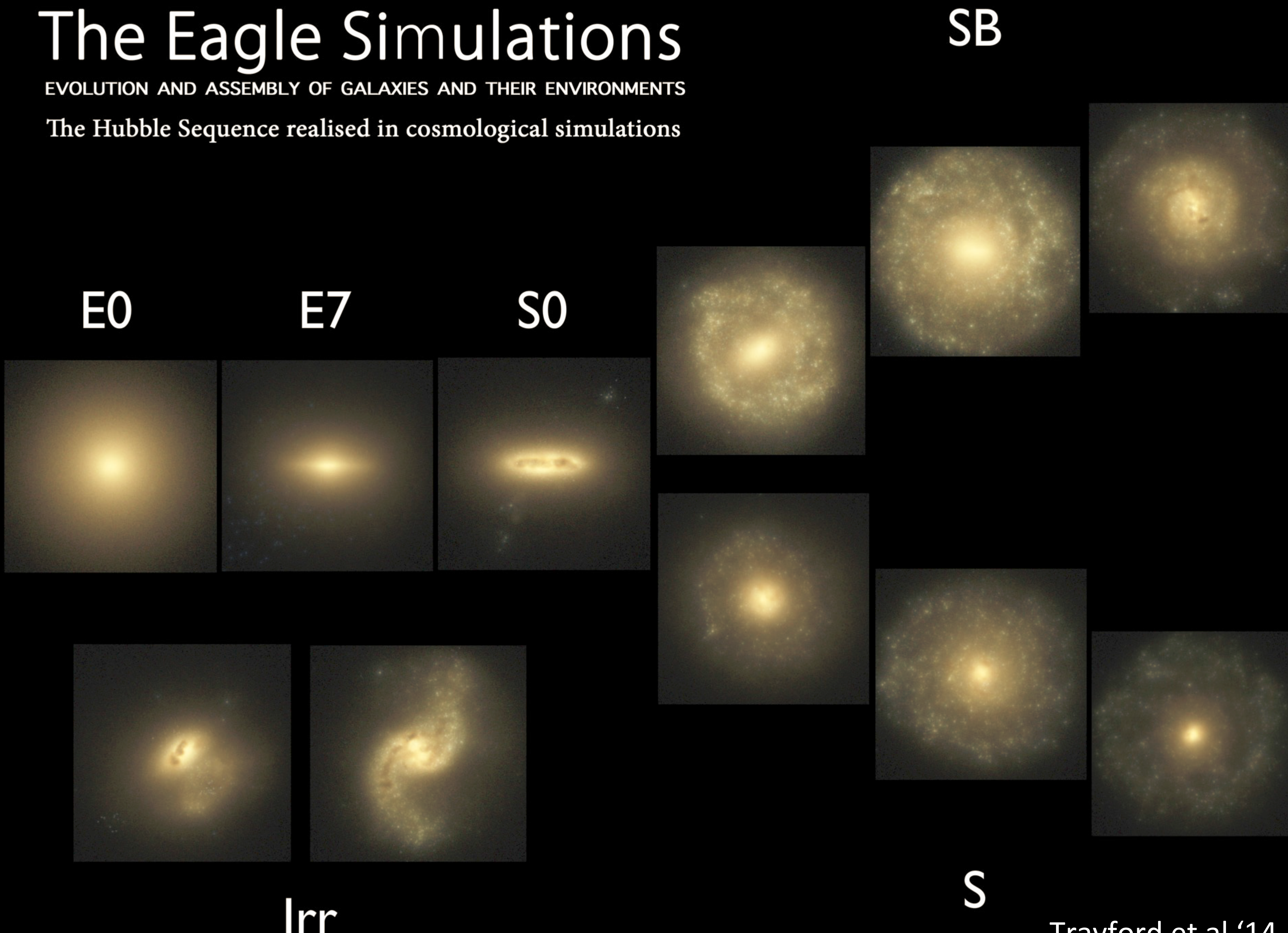
NAM 2014


The EAGLE simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo consortium
z = 19.9
L = 25.0 cMpc
Visible components:
CDM

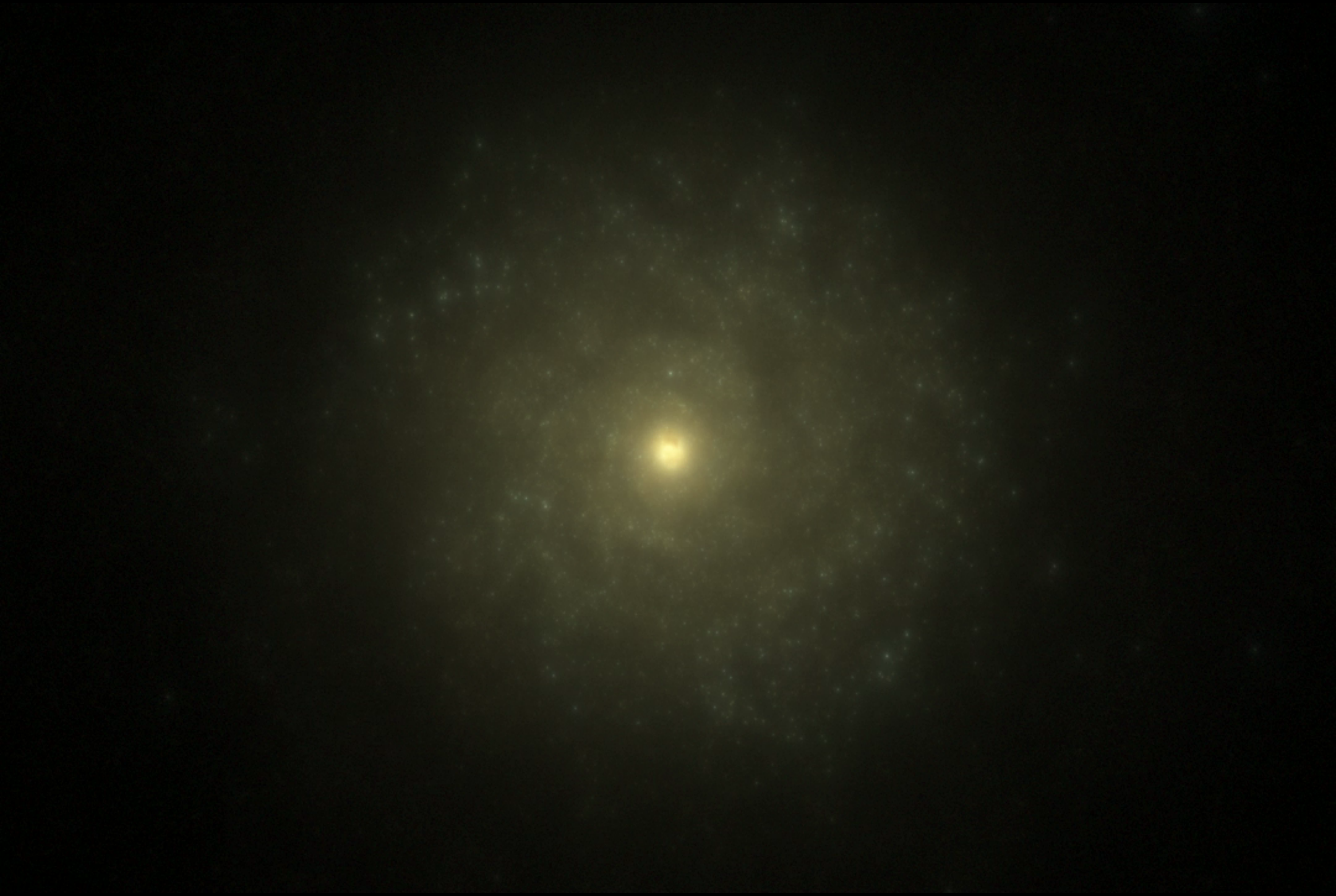
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



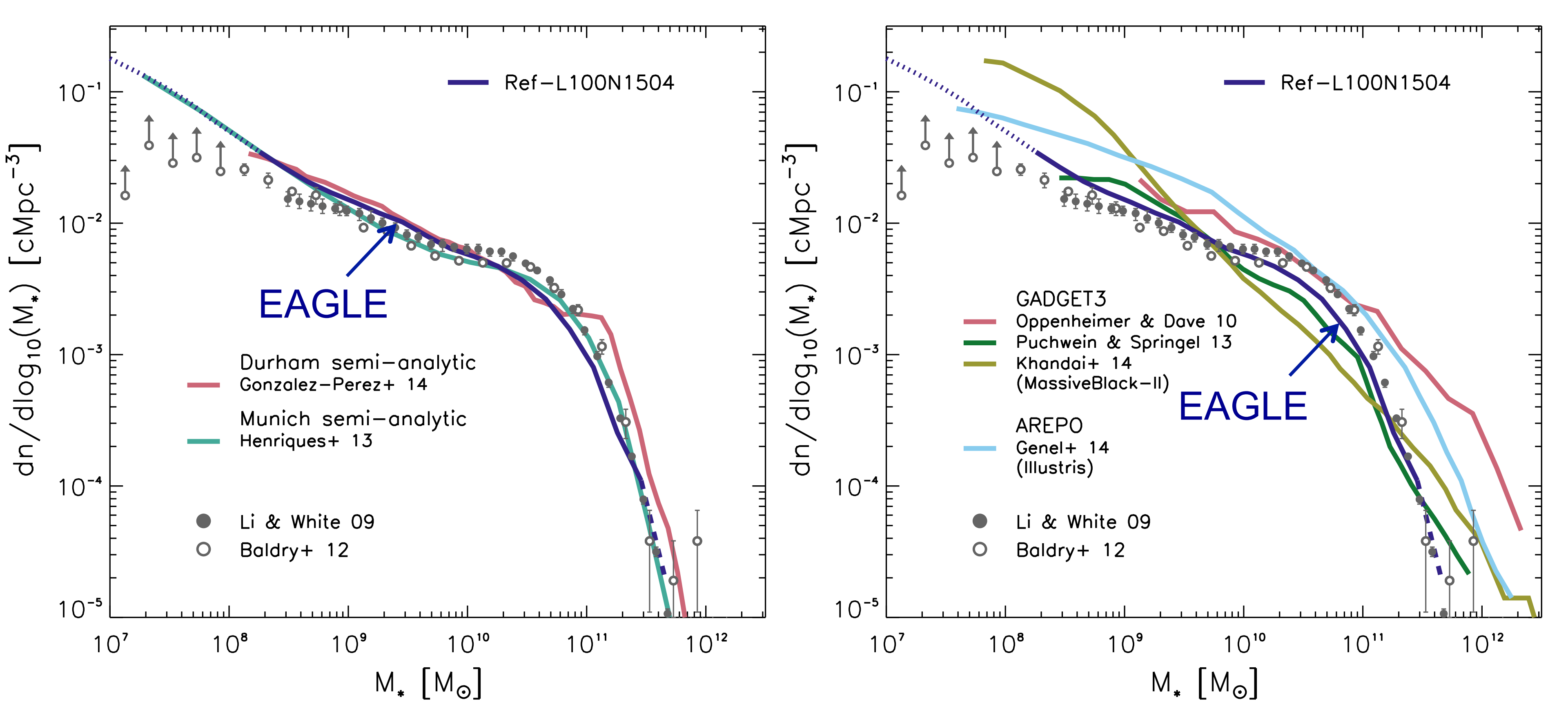
Trayford et al '14



Galaxy stellar mass function

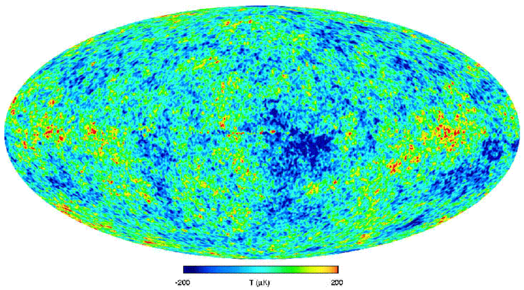
Semi-analytic models

Hydrodynamic simulations

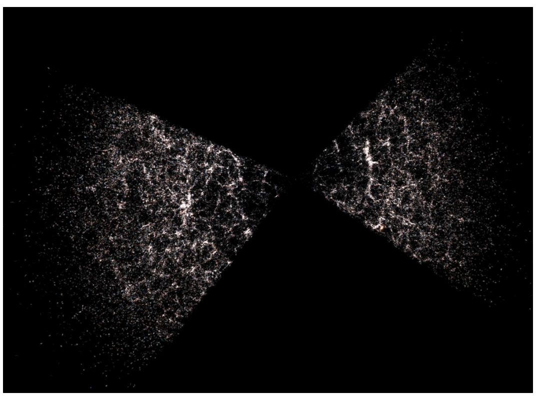


The cosmic power spectrum: from the CMB to the 2dFGRS

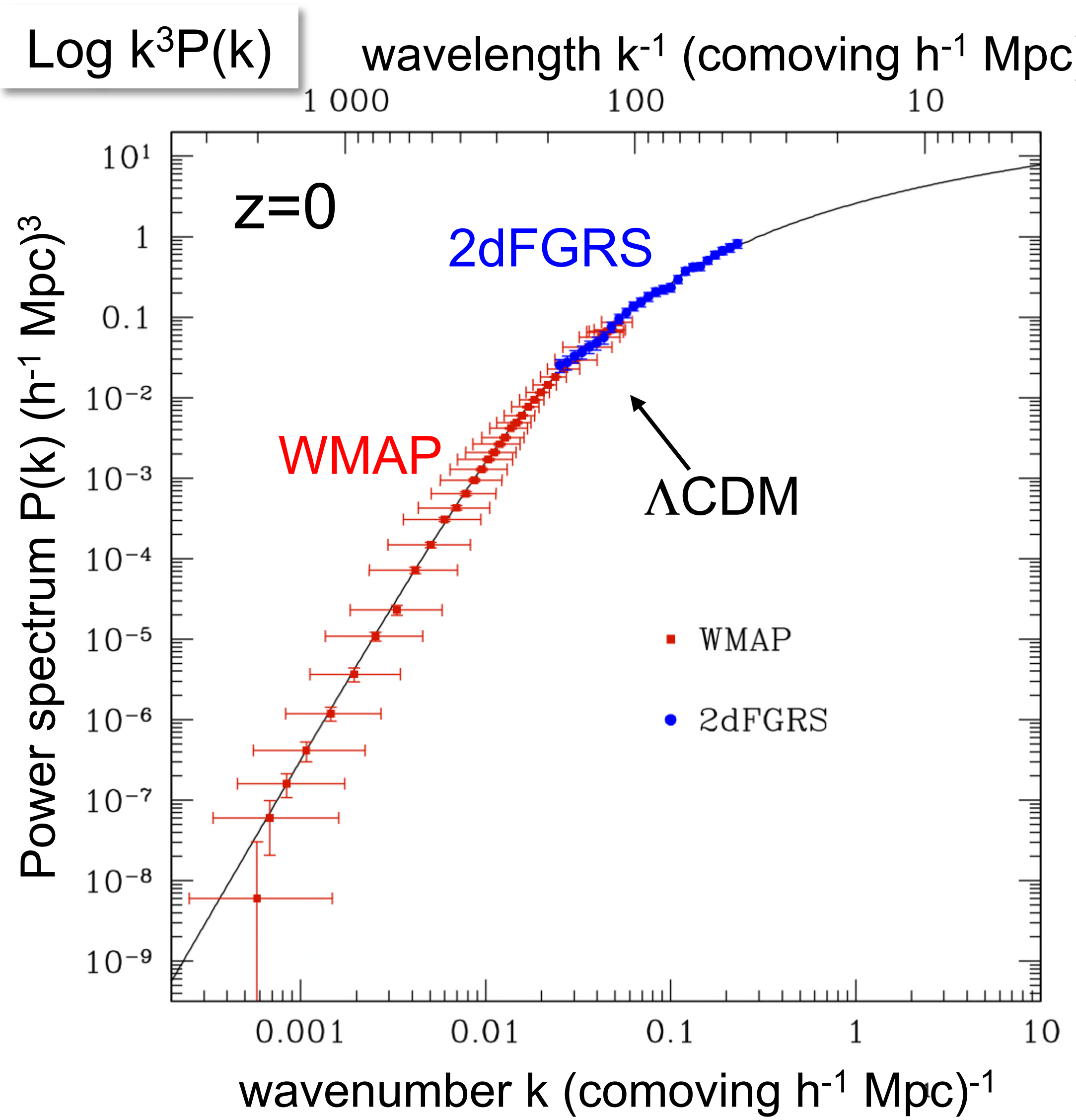
University of Durham



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

University of Durham

Free streaming →

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

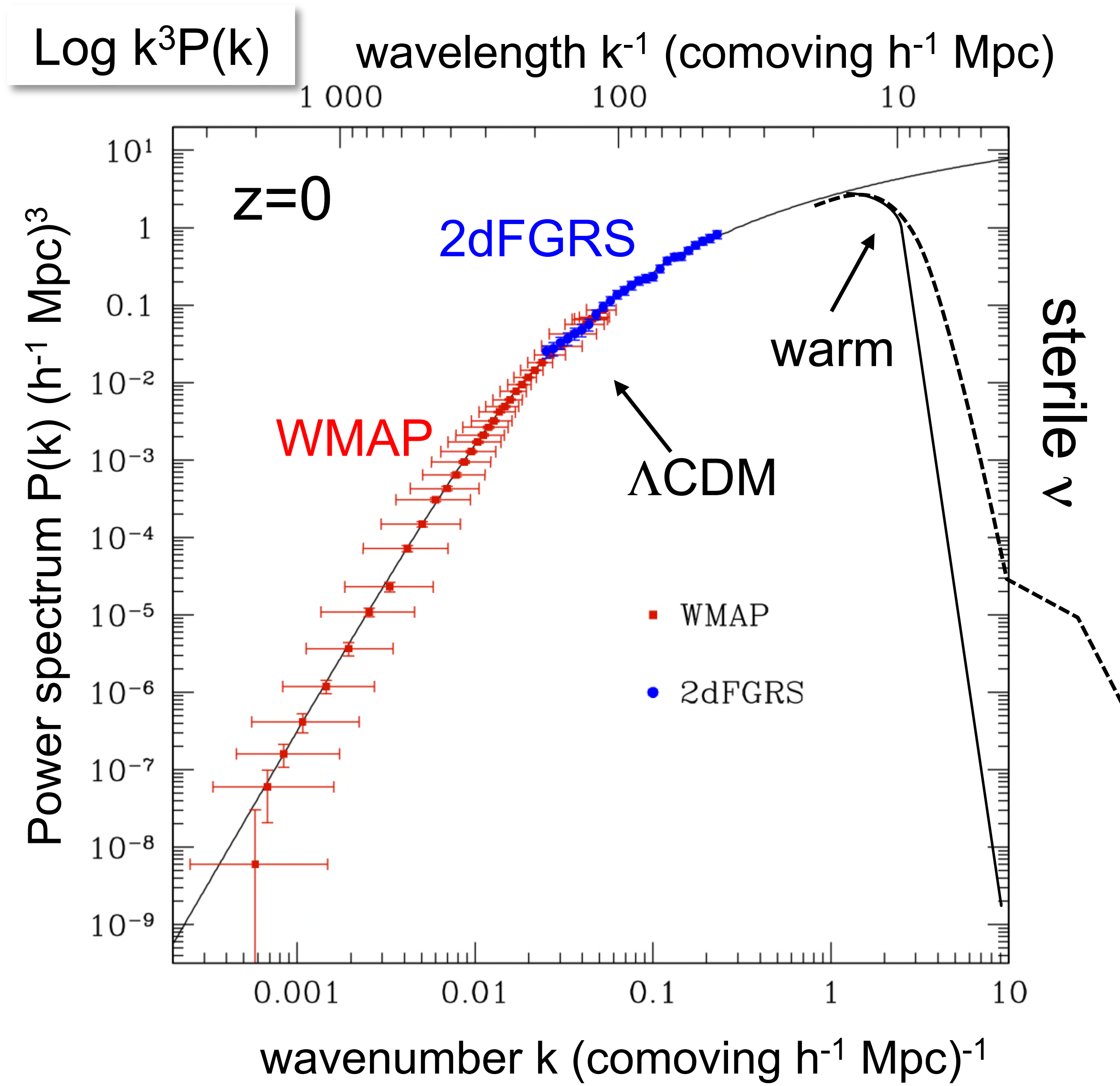
for thermal relic

$m_{CDM} \sim 100GeV$

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

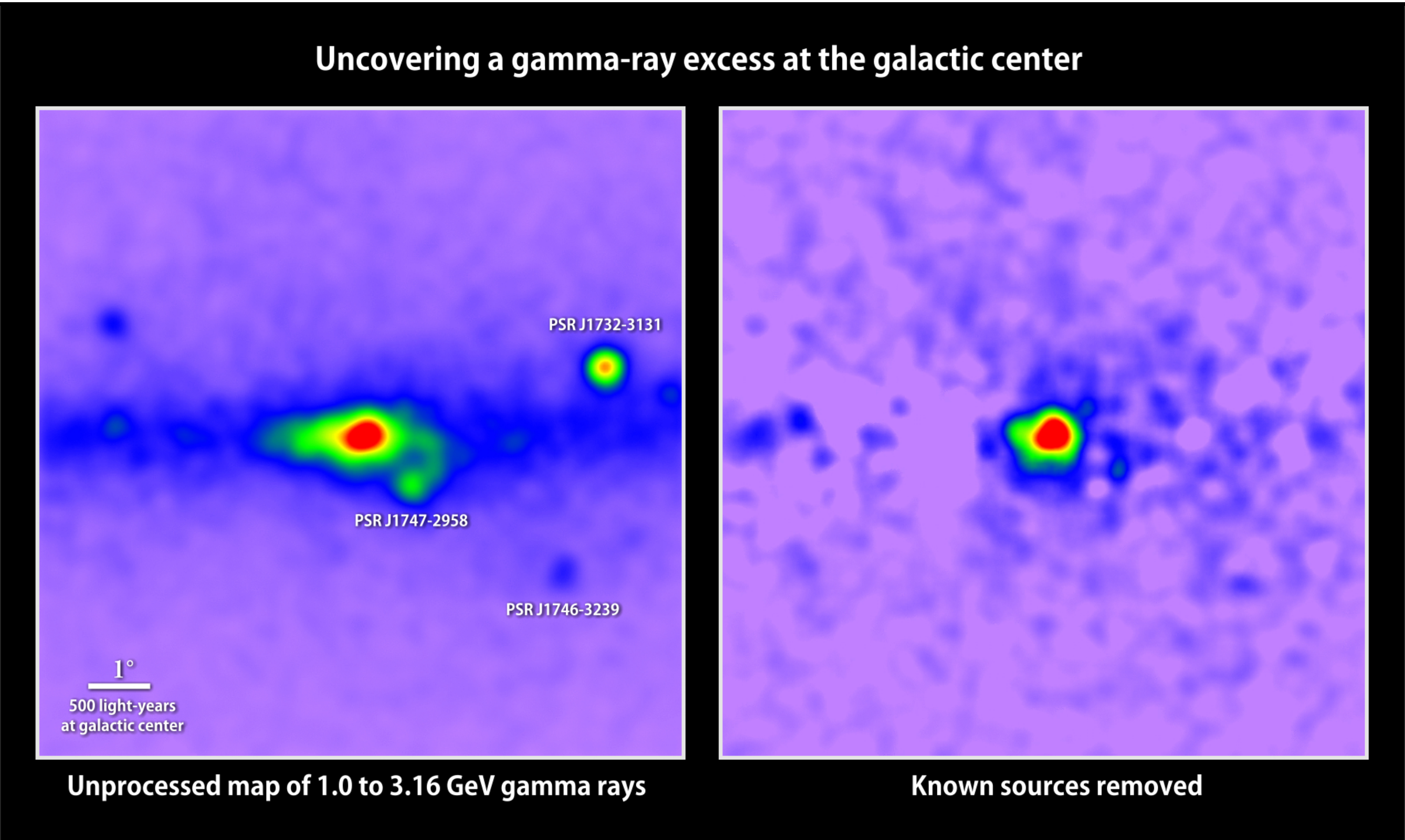
$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]



ICC
University of Durham

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 F
Preprint typeset using LaTeX

DETECTION OF AN U

ESRA BULBUL[1,2], M
[1] Har

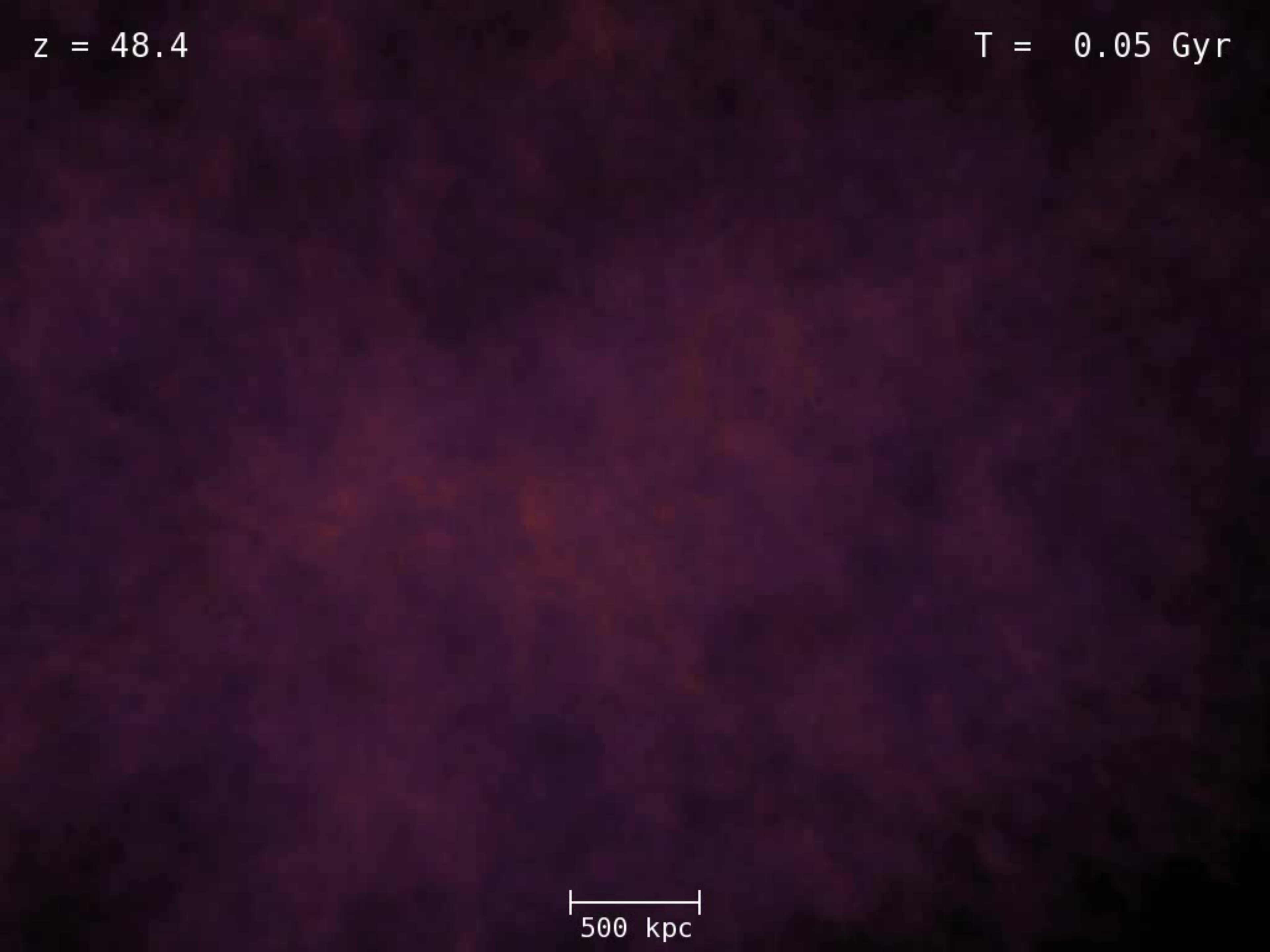
We detect a wea spectrum of 73 g independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra 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

20 minutes to here

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 '12

Four problems on small scales

Traditionally ascribed to CDM:

1. The “core-cusp” problem
2. The “missing satellites” problem
3. The “too-big-to-fail” problem
4. The “satellite disk” problem

CDM ruled out?

Four problems on small scales

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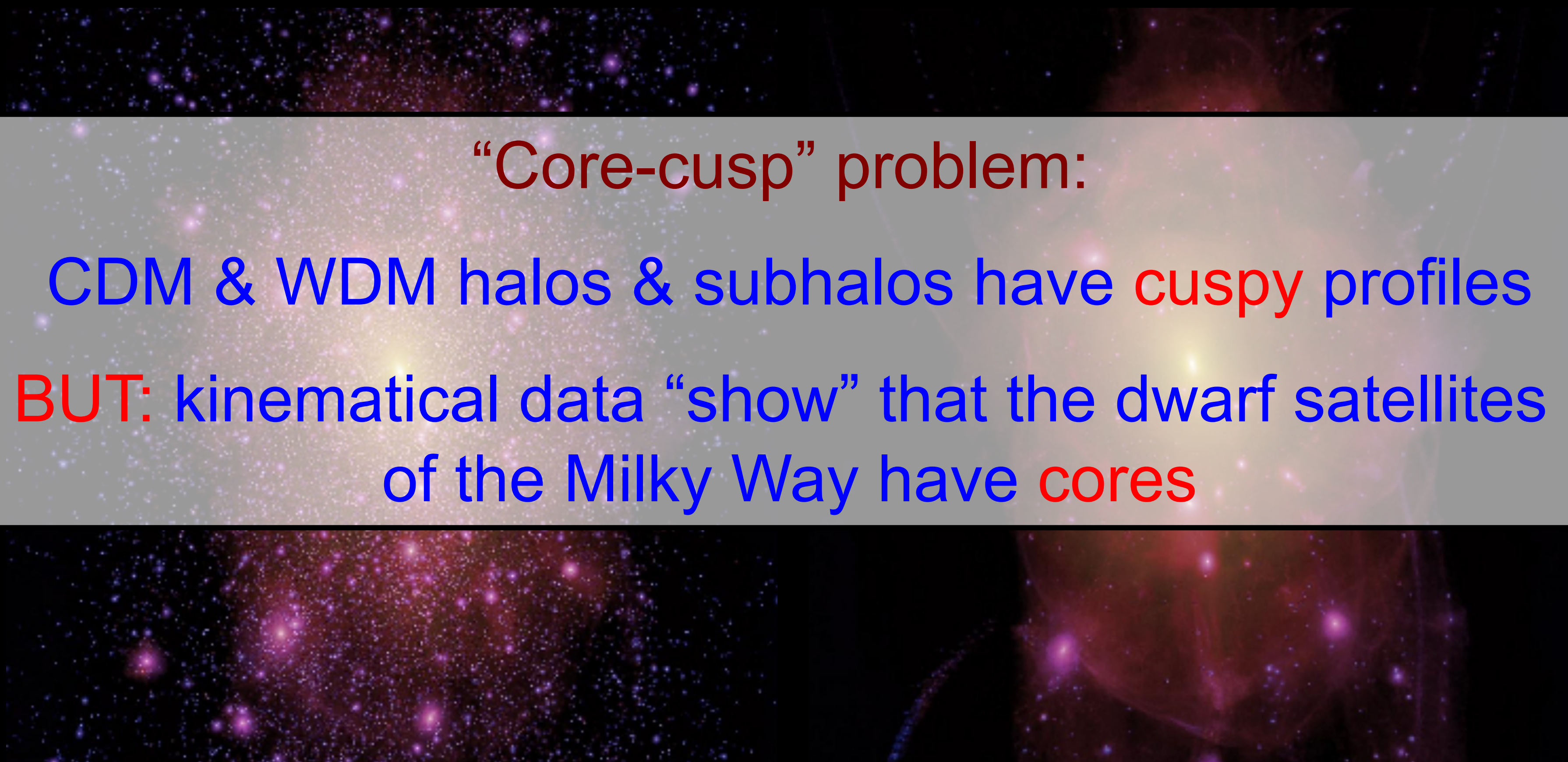
Can these help distinguish between CDM & WDM?

The core-cusp problem

cold dark matter

warm dark matter



"Core-cusp" problem:

CDM & WDM halos & subhalos have cuspy profiles

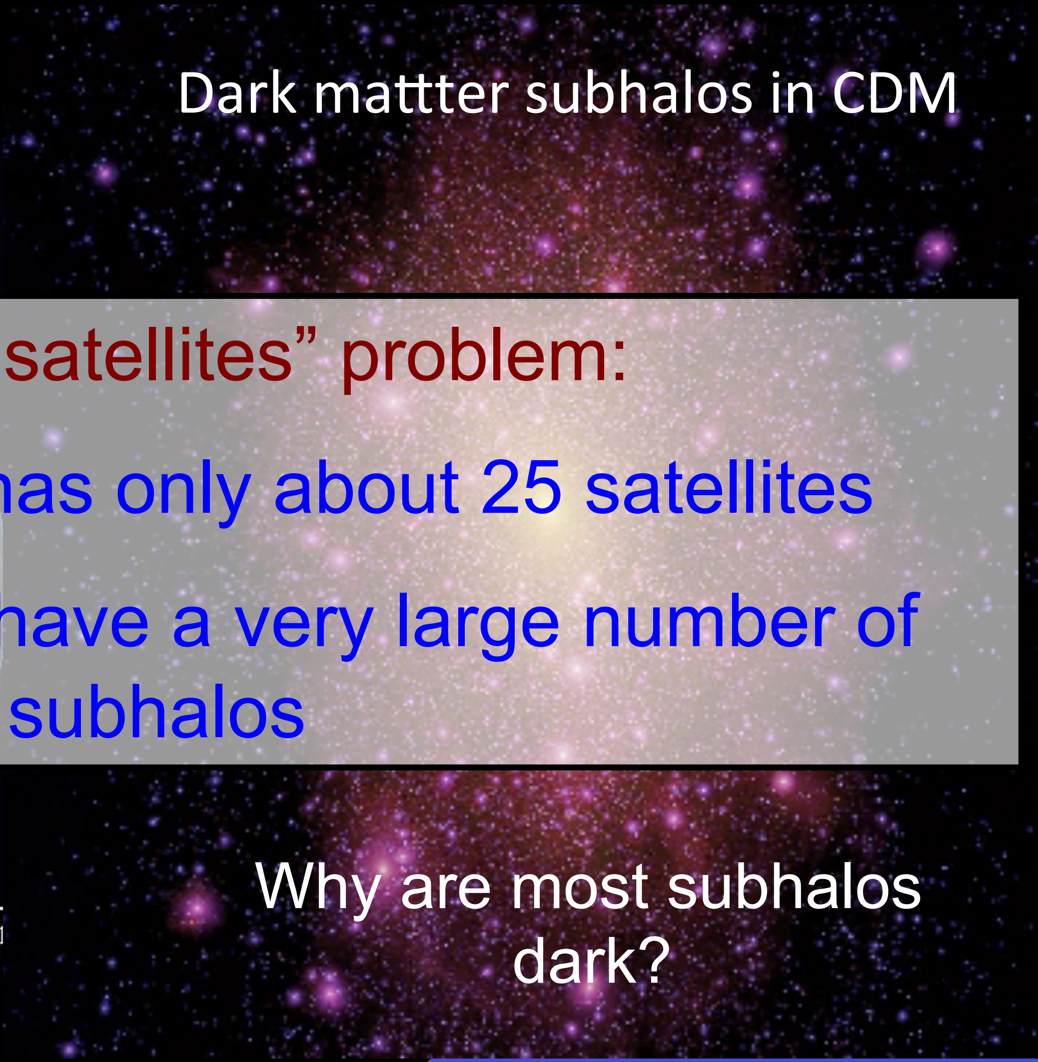
BUT: kinematical data "show" that the dwarf satellites of the Milky Way have cores

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

The “missing satellites” problem in CDM

The satellites of the MW

Dark mattter subhalos in CDM



“Missing satellites” problem:

The Milky way has only about 25 satellites

BUT: CDM halos have a very large number of subhalos

Why are most subhalos dark?

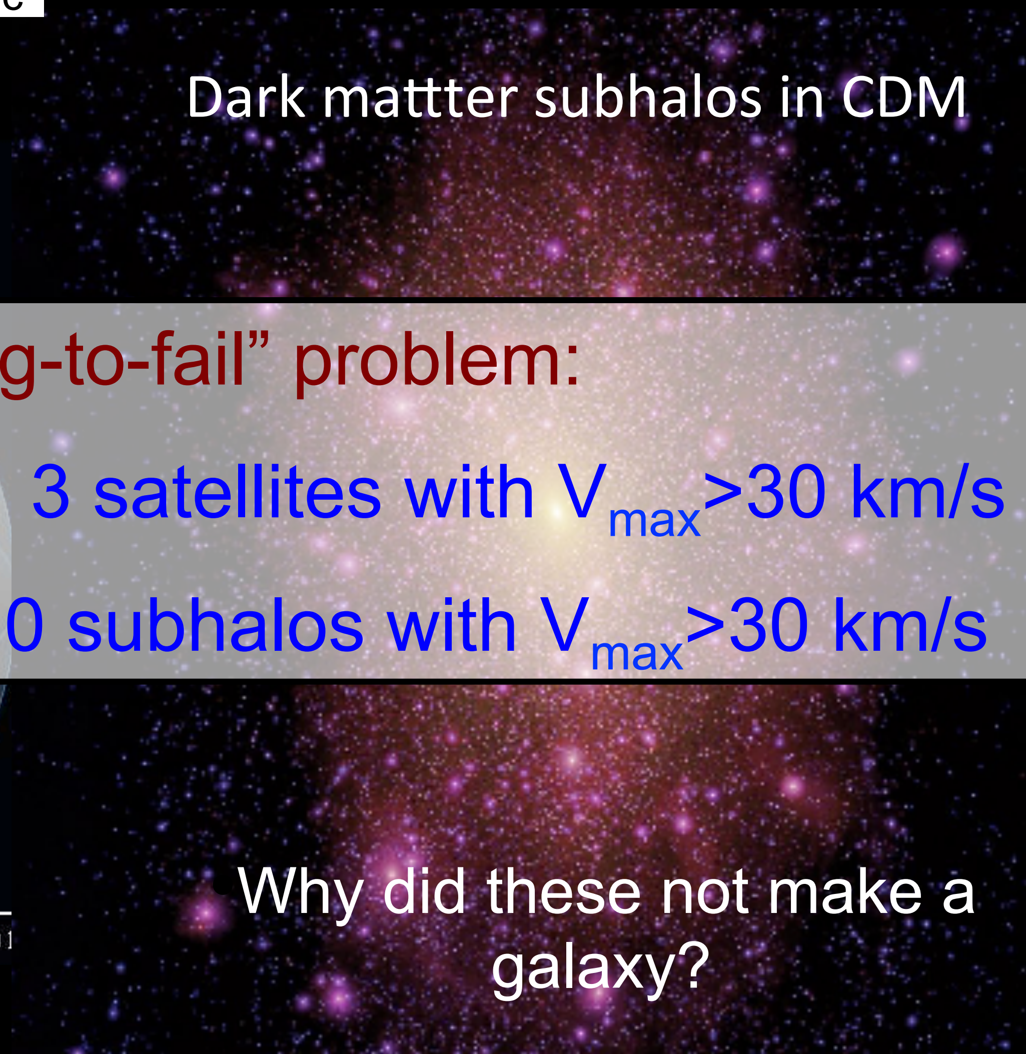
The "too-big-to-fail" problem

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

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

The satellites of the MW

Dark mattter subhalos in CDM



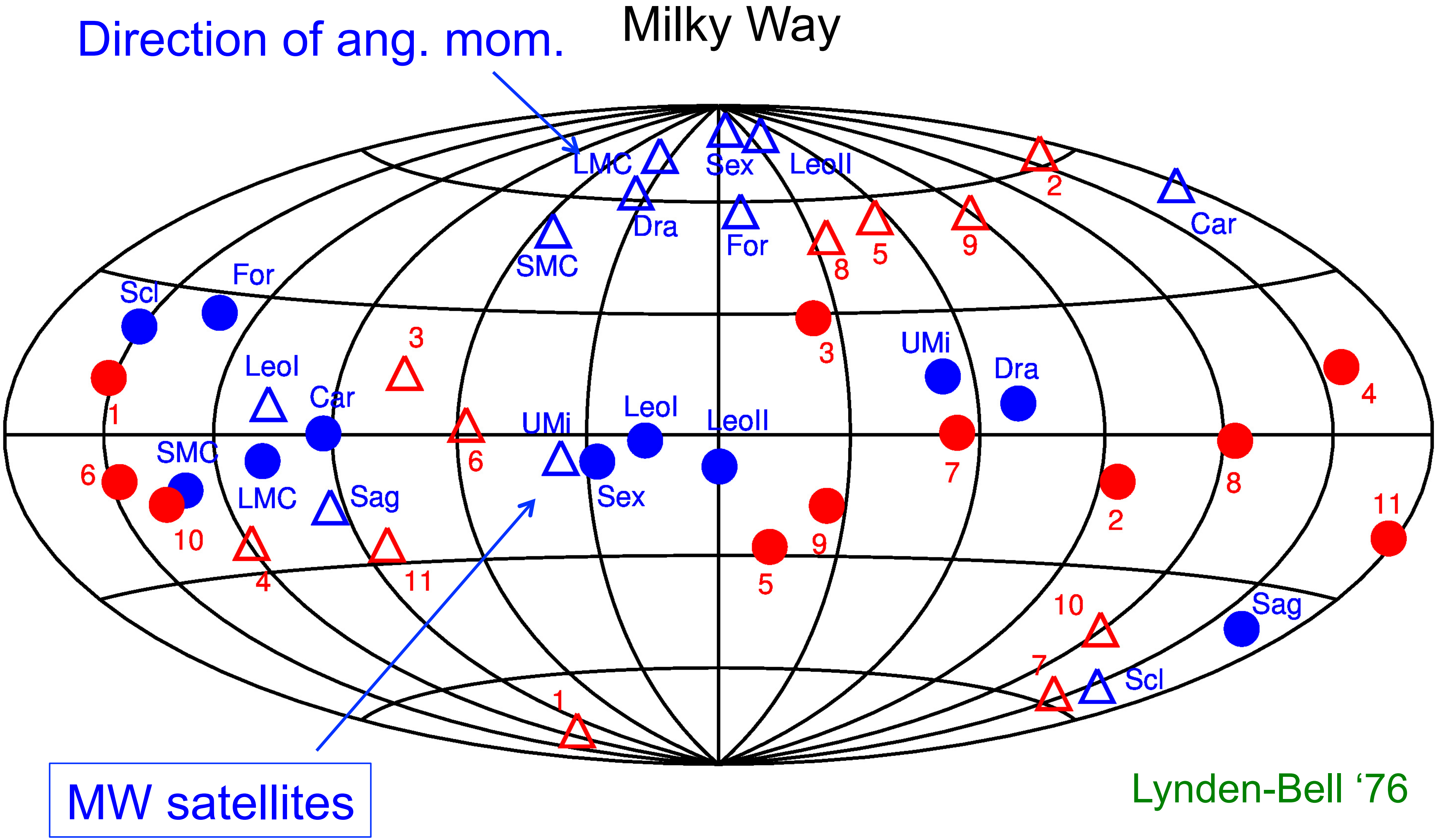
"Too-big-to-fail" problem:

Milky way has only 3 satellites with V_{max}>30 km/s

BUT: CDM has ~10 subhalos with V_{max}>30 km/s

Why did these not make a galaxy?

The "satellite disk" problem



Lynden-Bell '76

University of Durham

Four problems on small scales

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University of Durham

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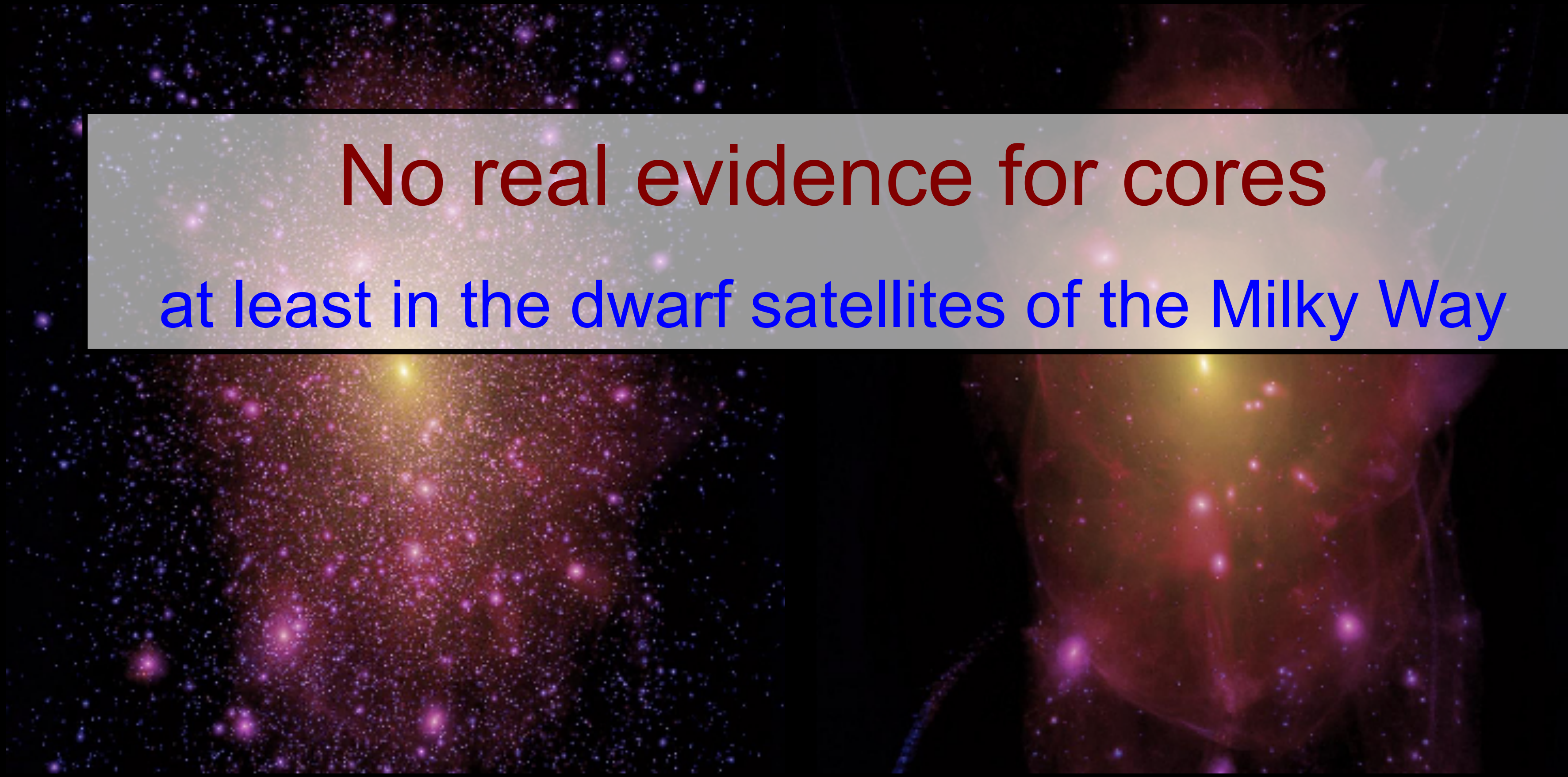
Can these help distinguish between CDM & WDM?

The core-cusp problem

cold dark matter | warm dark matter



No real evidence for cores

at least in the dwarf satellites of the Milky Way

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

Dwarf galaxies around the Milky Way

Many claims that dwarf spheroidal satellites have density cores

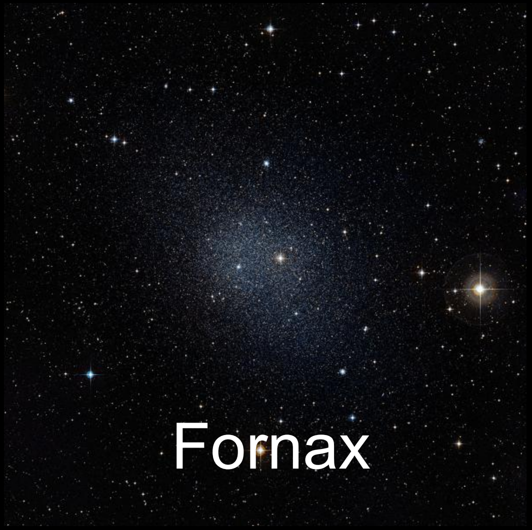
- e.g. Gilmore et al. ’07, Kuzio de Naray ’08 and many more

Sextans

Carina

Sagittarius

Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

University of Durham

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

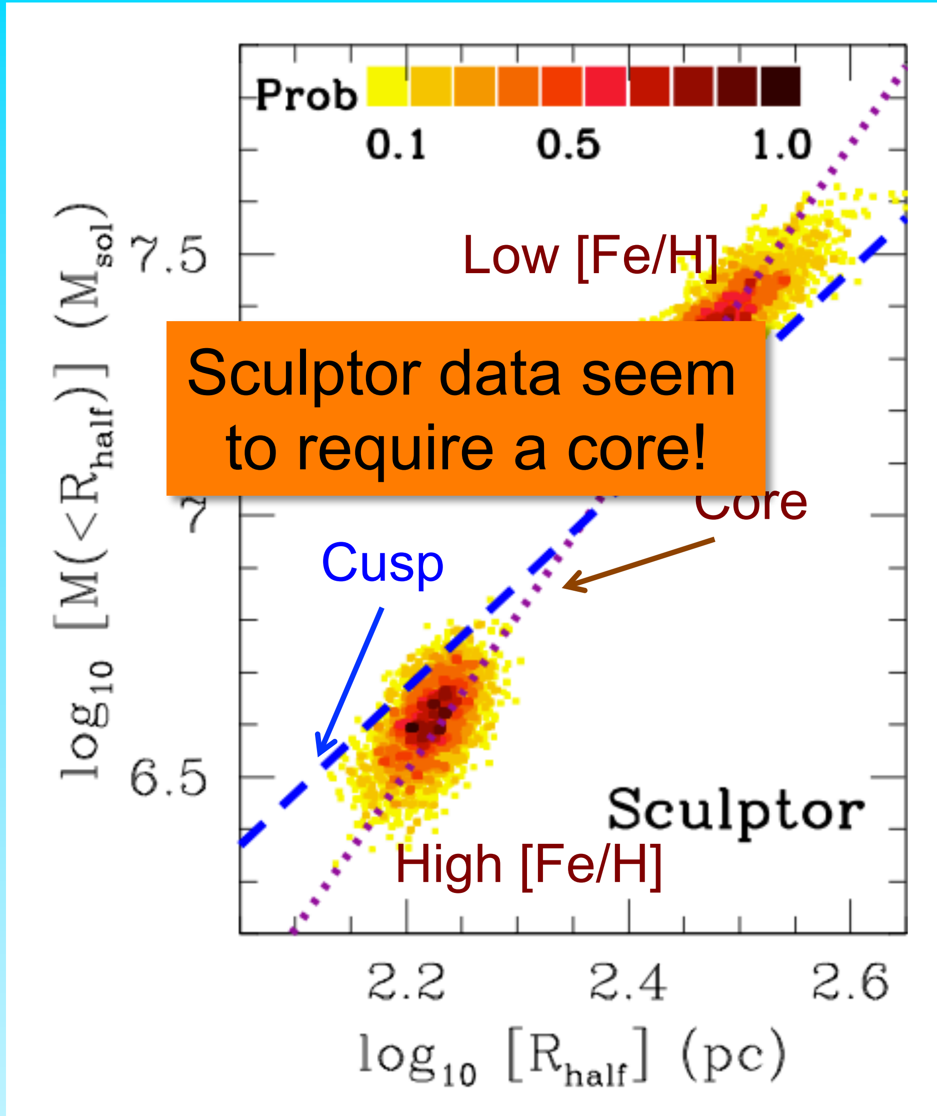
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

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

Walker '10; Wolf et al '10→

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

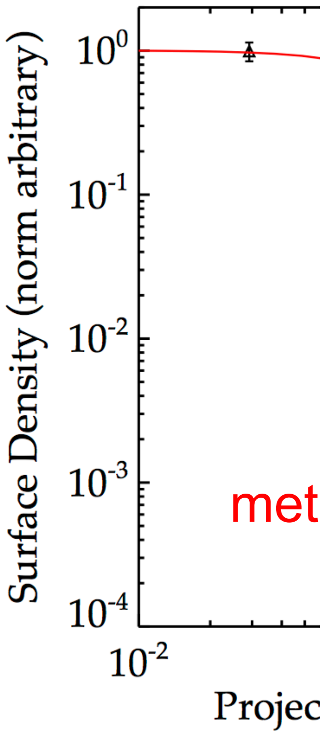


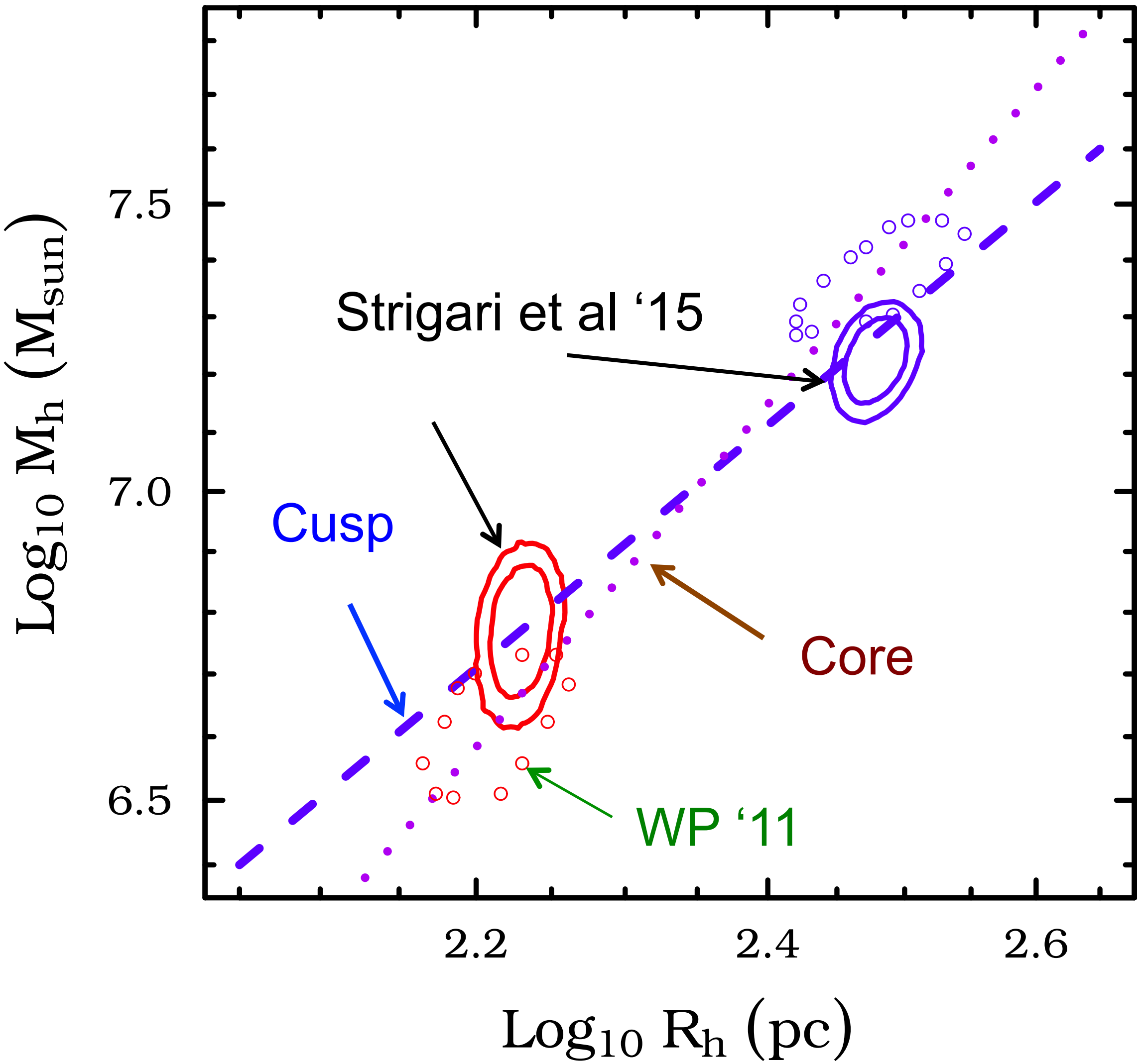
Walker & Peñarrubia '11

The DM halo of the Sculptor dwarf

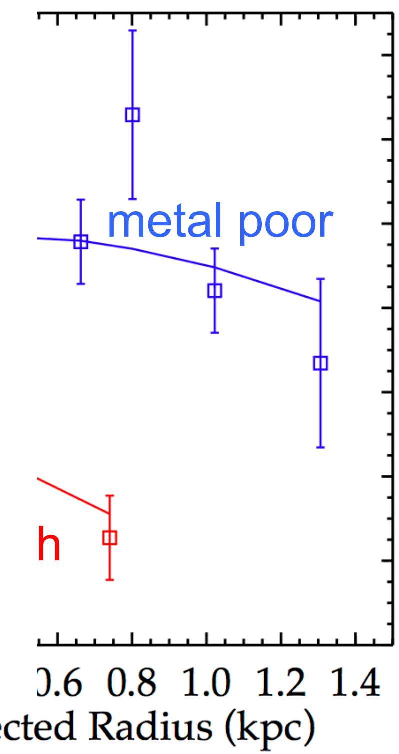
University of Durham

Distribution function analysis





y dispersion



Data cons
eq

Strigari, Fre...

University of Durham

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

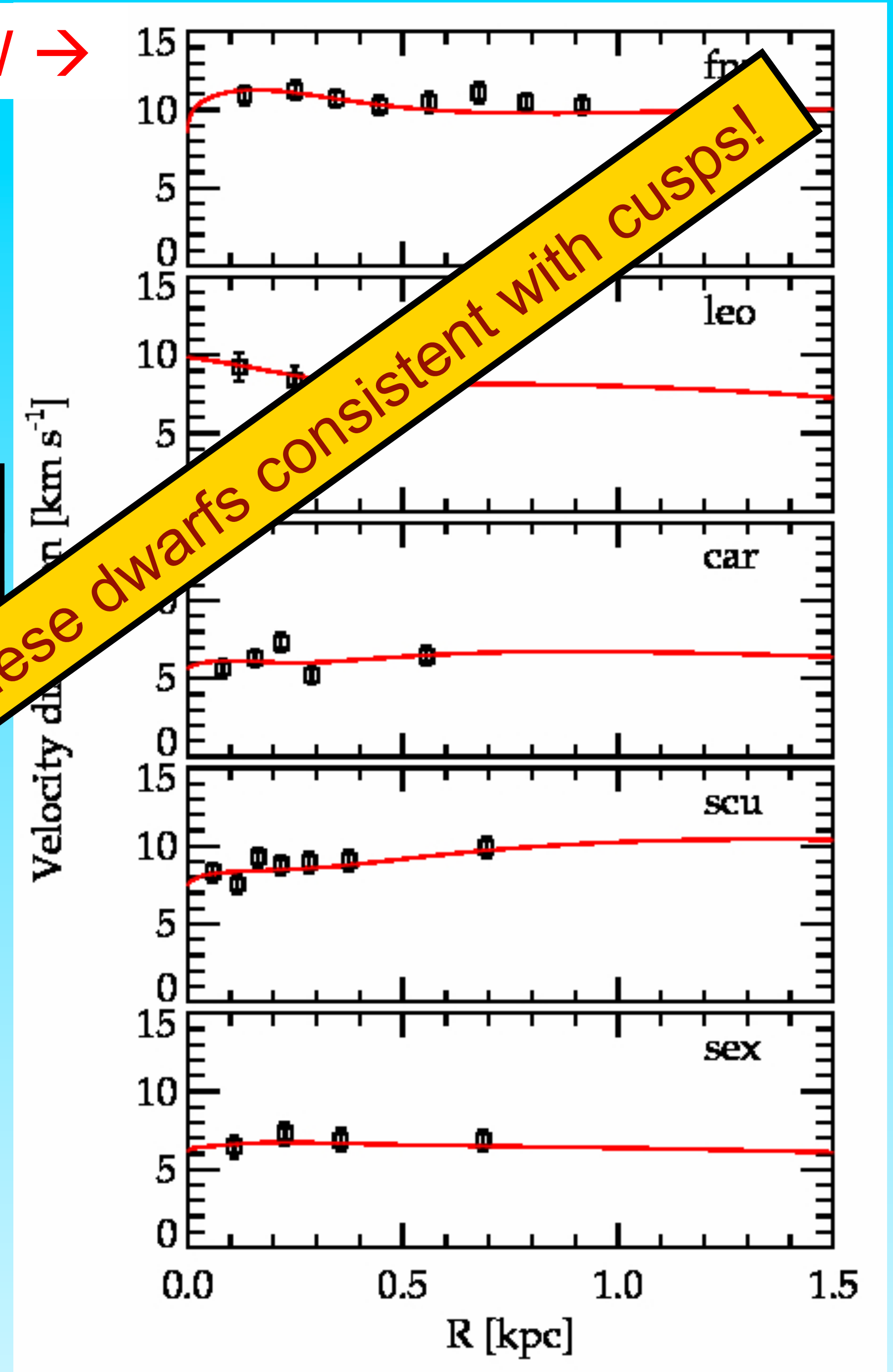
Cuspy!

vel. an...py

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

Strigari, Frenk & White '10

Photometric and kinematical data for these dwarfs consistent with cusps!

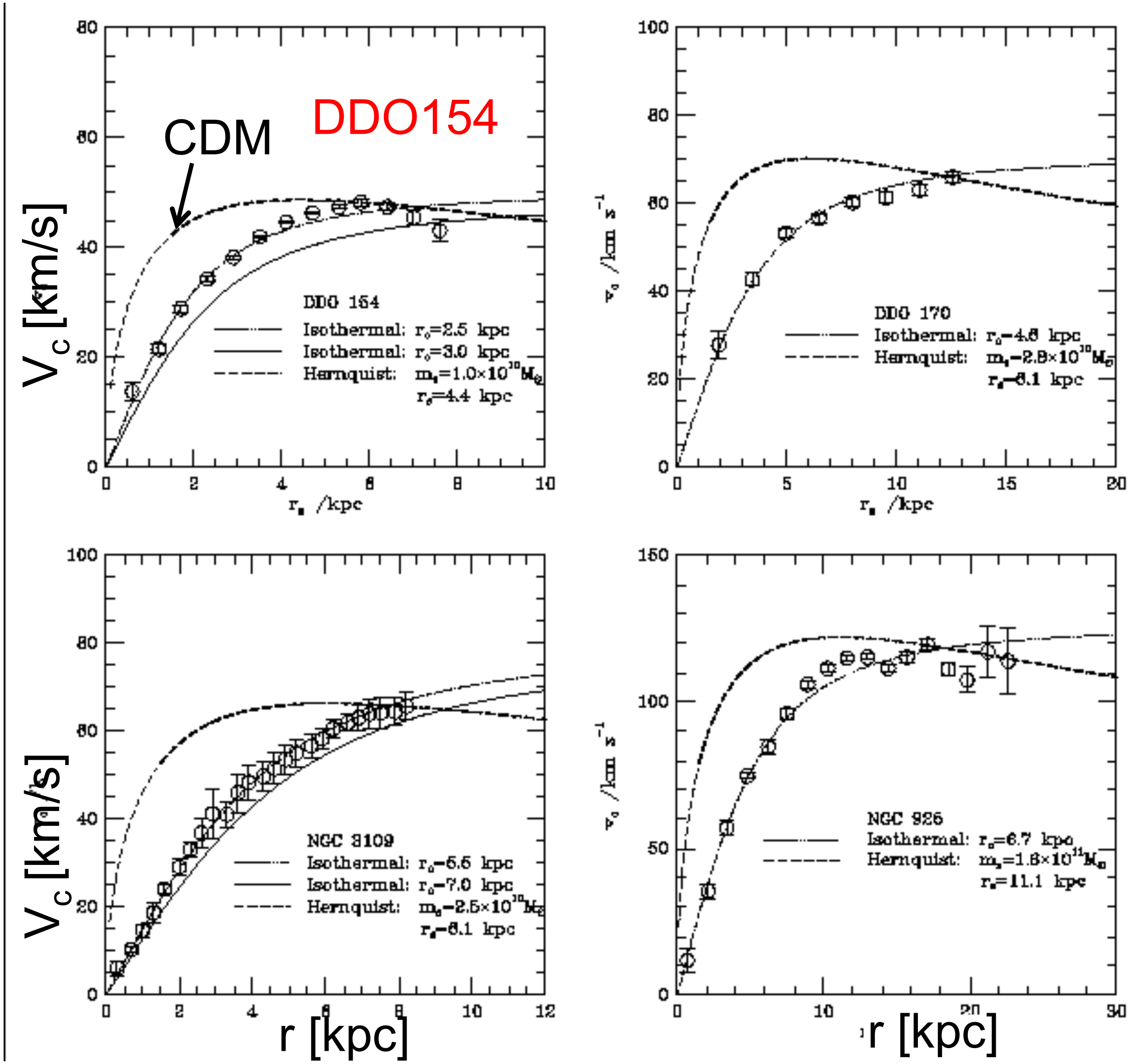


Cores or cusps in the dwarf sph. satellites of the MW?

When sufficiently general models are considered, even best data cannot distinguish cores from NFW cusps

University of Durham

Cores in field dwarf galaxies



Moore '94

Hα rotation curves

→ core radii

Institute for Computational Cosmology

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*

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

Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

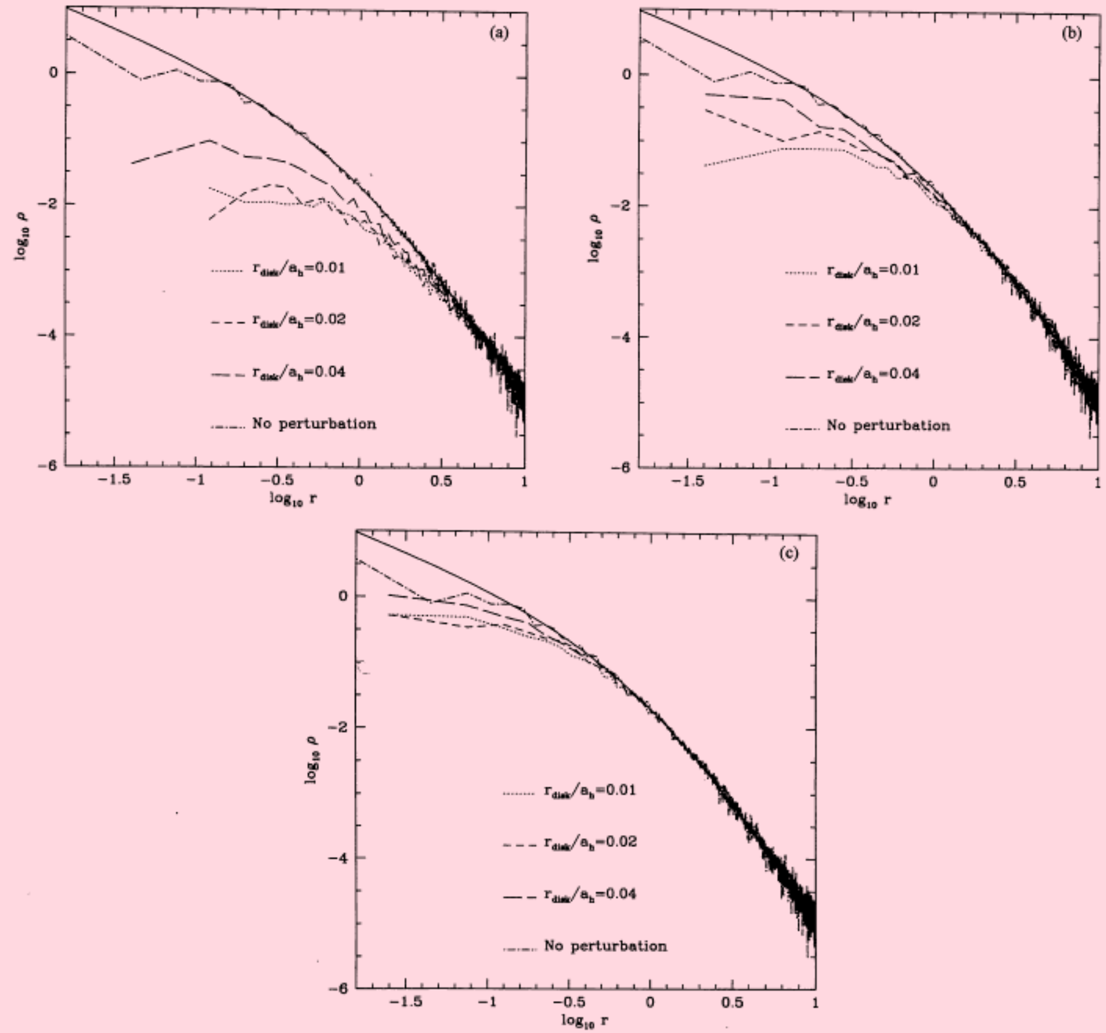
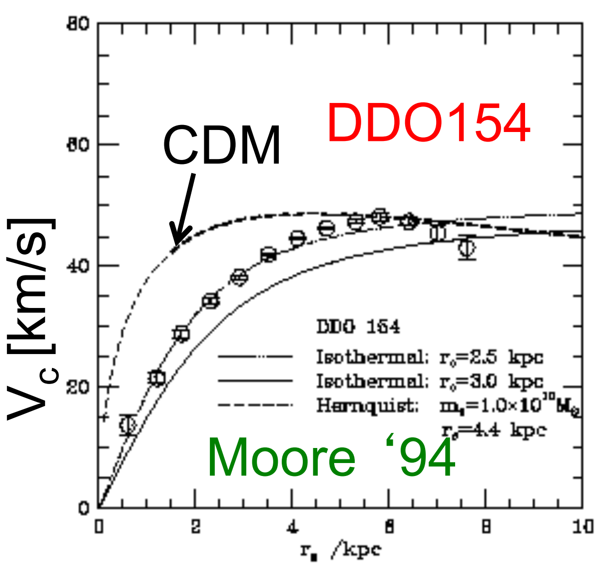
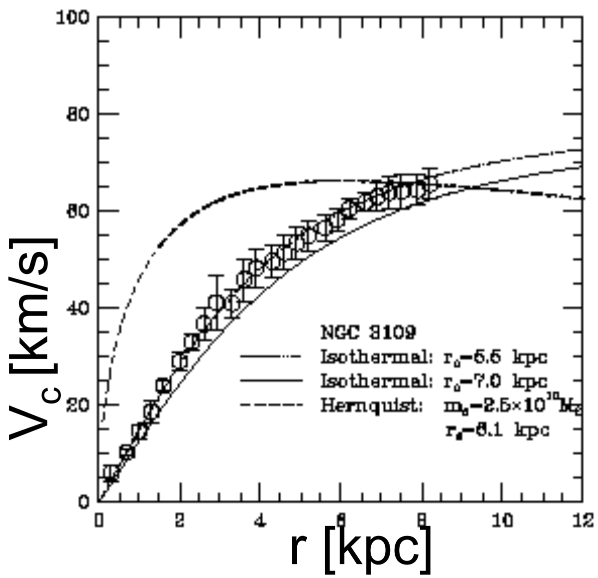


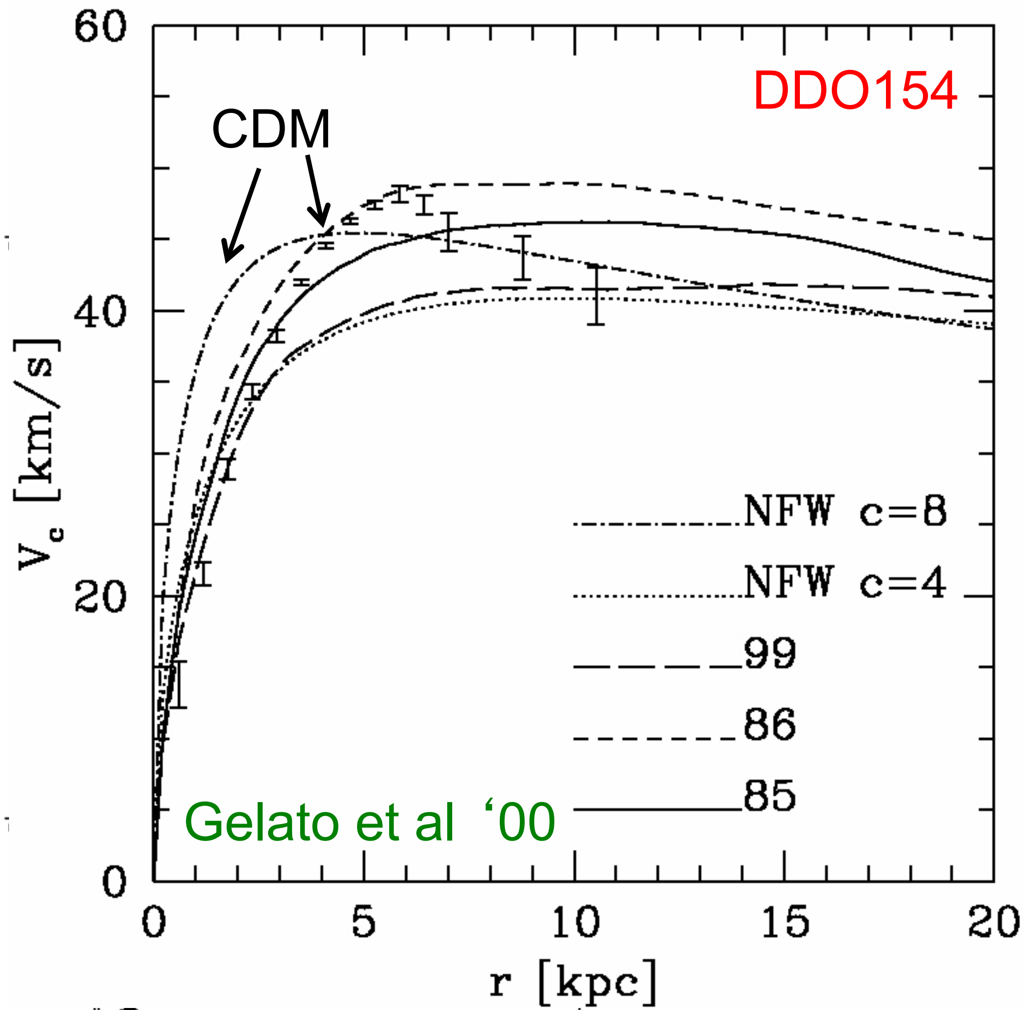
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

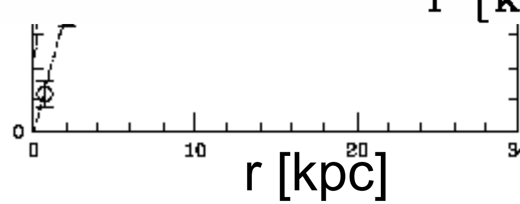
Cores in dwarf galaxies

University of Durham



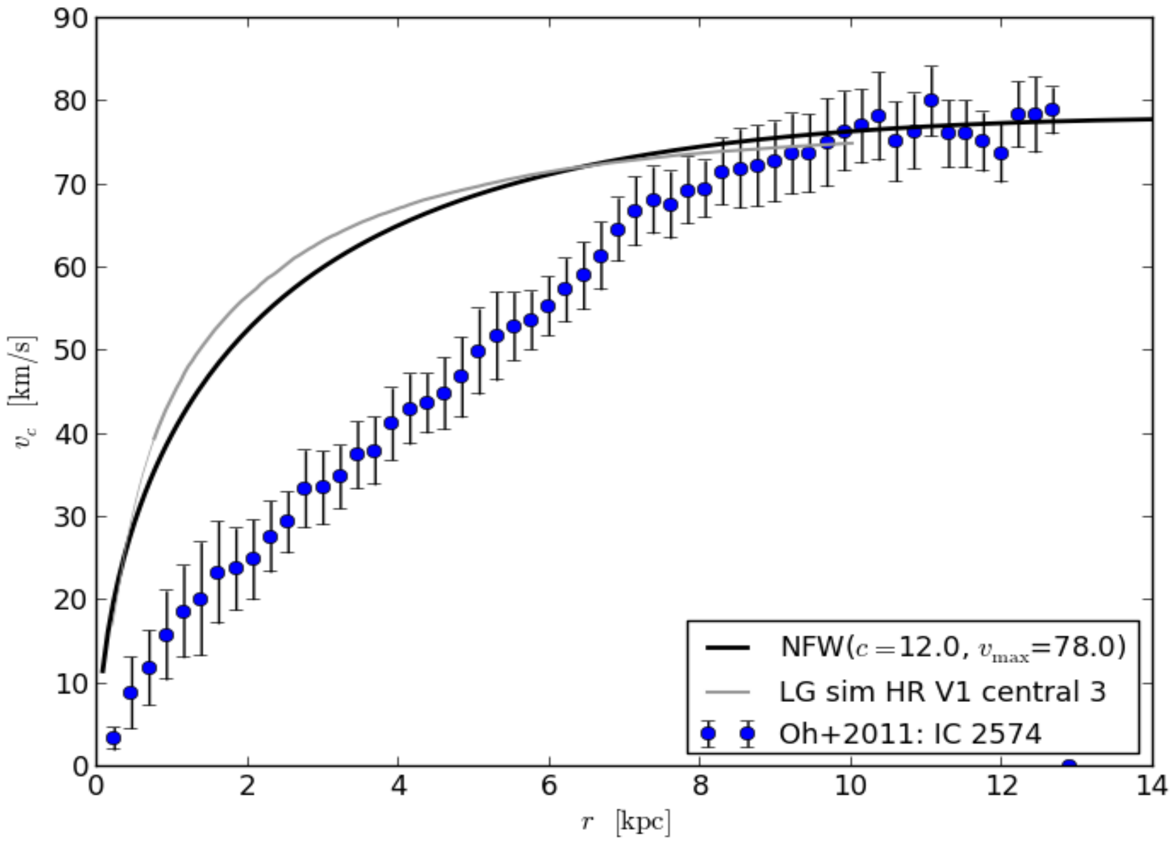






Cores in dwarf galaxies

Can this explain extreme cases like IC2574 → r_{core}= 5kpc?



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35 minutes to here

Four problems on small scales

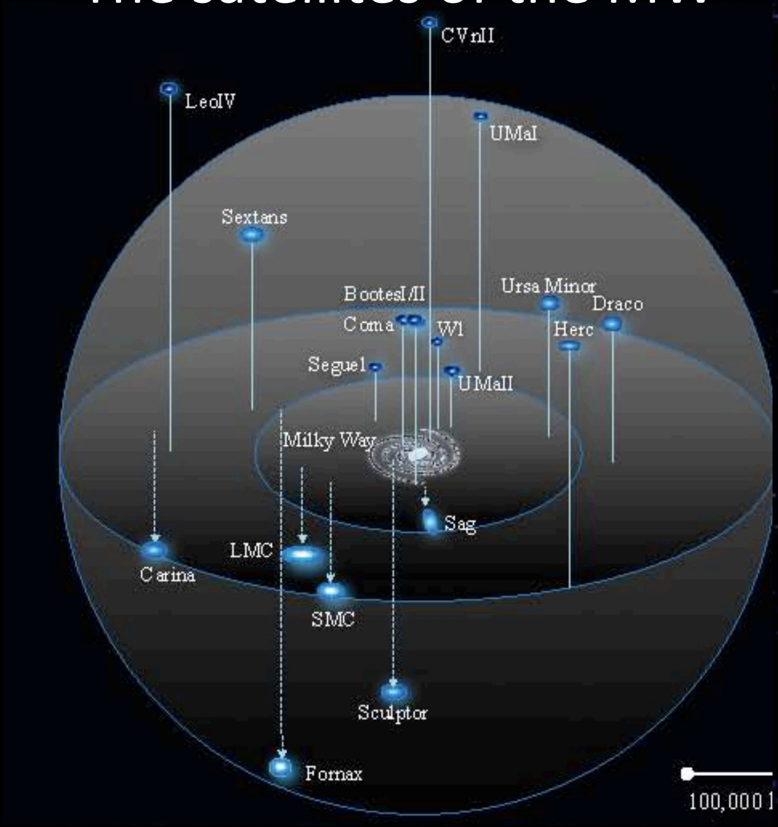
Traditionally ascribed to CDM:

1. The "core-cusp" problem
2. The "missing satellites" problem
3. The "too-big-to-fail" problem
4. The "satellite disk" problem

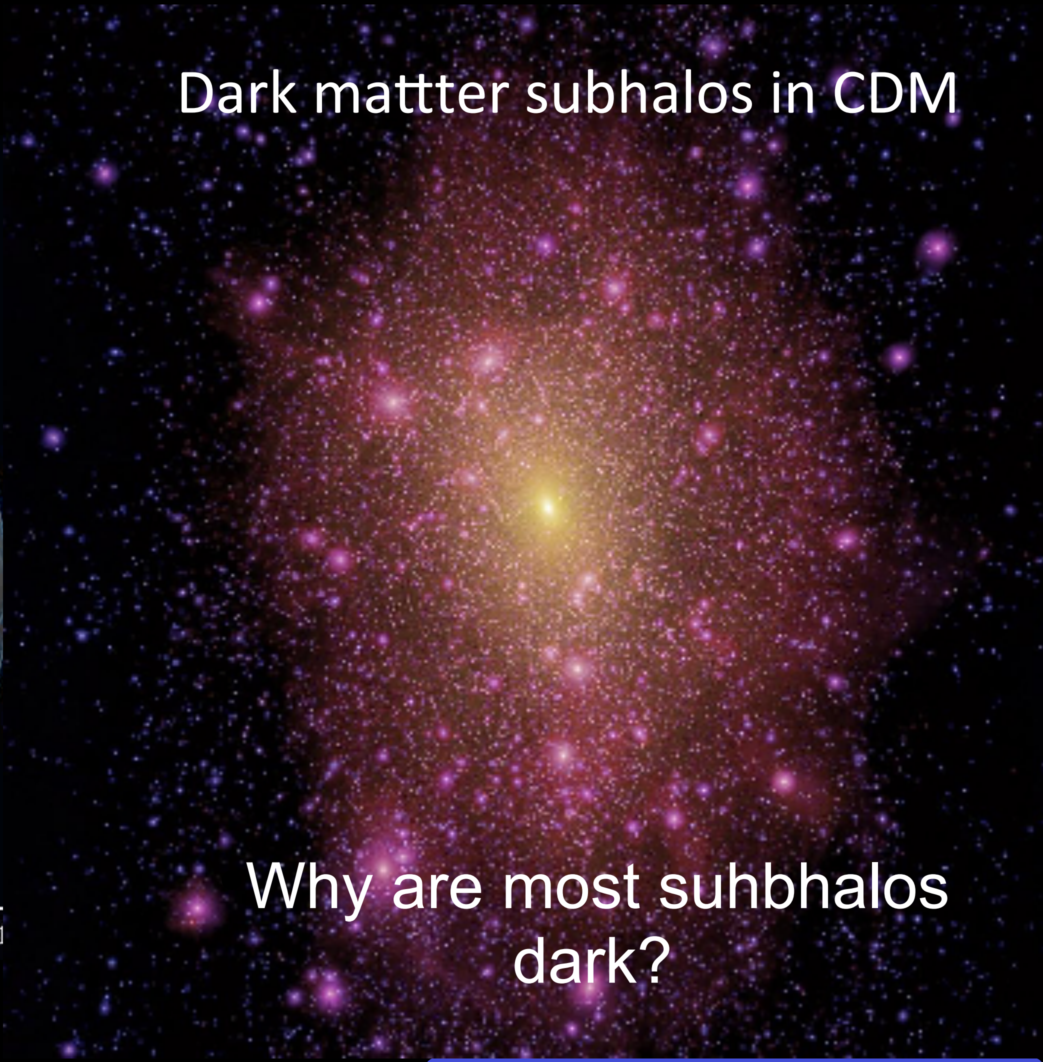
Can these help distinguish between CDM & WDM?

The "missing satellites" problem in CDM

The satellites of the MW



Dark mattter subhalos in CDM



Why are most suhbhalos dark?

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 residual gas

Most subhalos never make a galaxy!

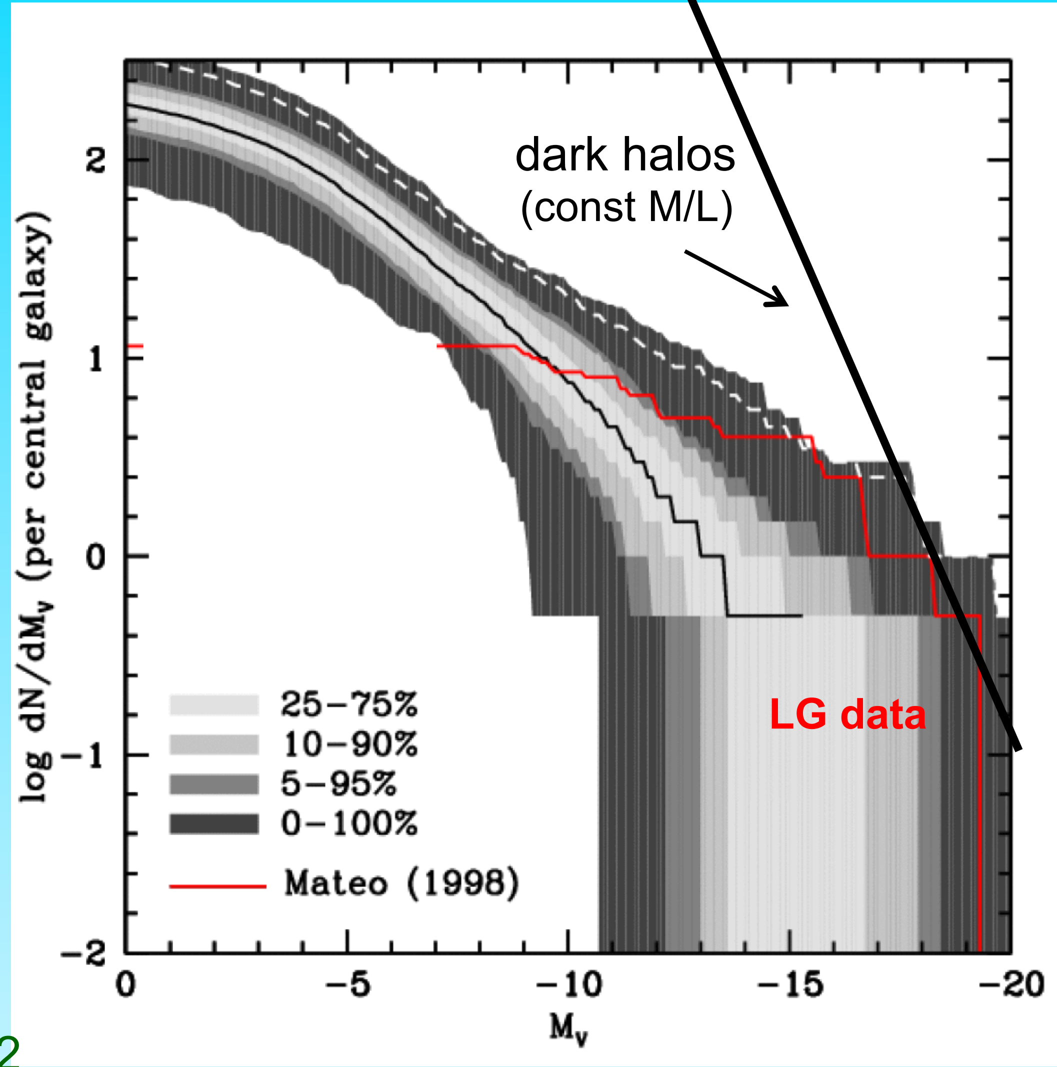
Luminosity Function of Local Group Satellites

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 (~2% of cases)



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

University of Durham

Luminosity Function of Local Group Satellites

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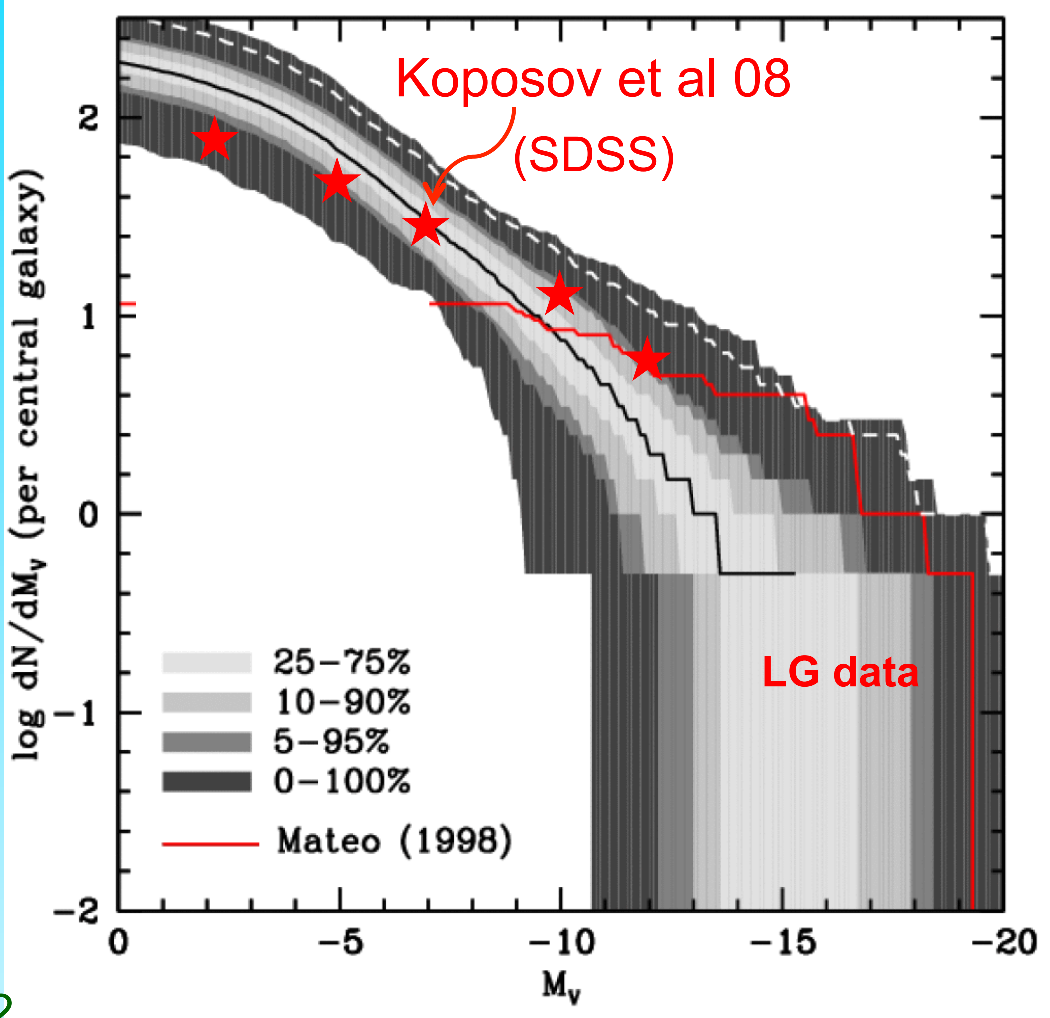


Benson, Frenk, Lacey, Baugh & Cole '02 (see also Kauffman etal '93, Bullock etal '01)

VIRGO

The "Evolution and assembly of galaxies and their environment" (EAGLE) simulation project

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…

+ Virgo Consortium

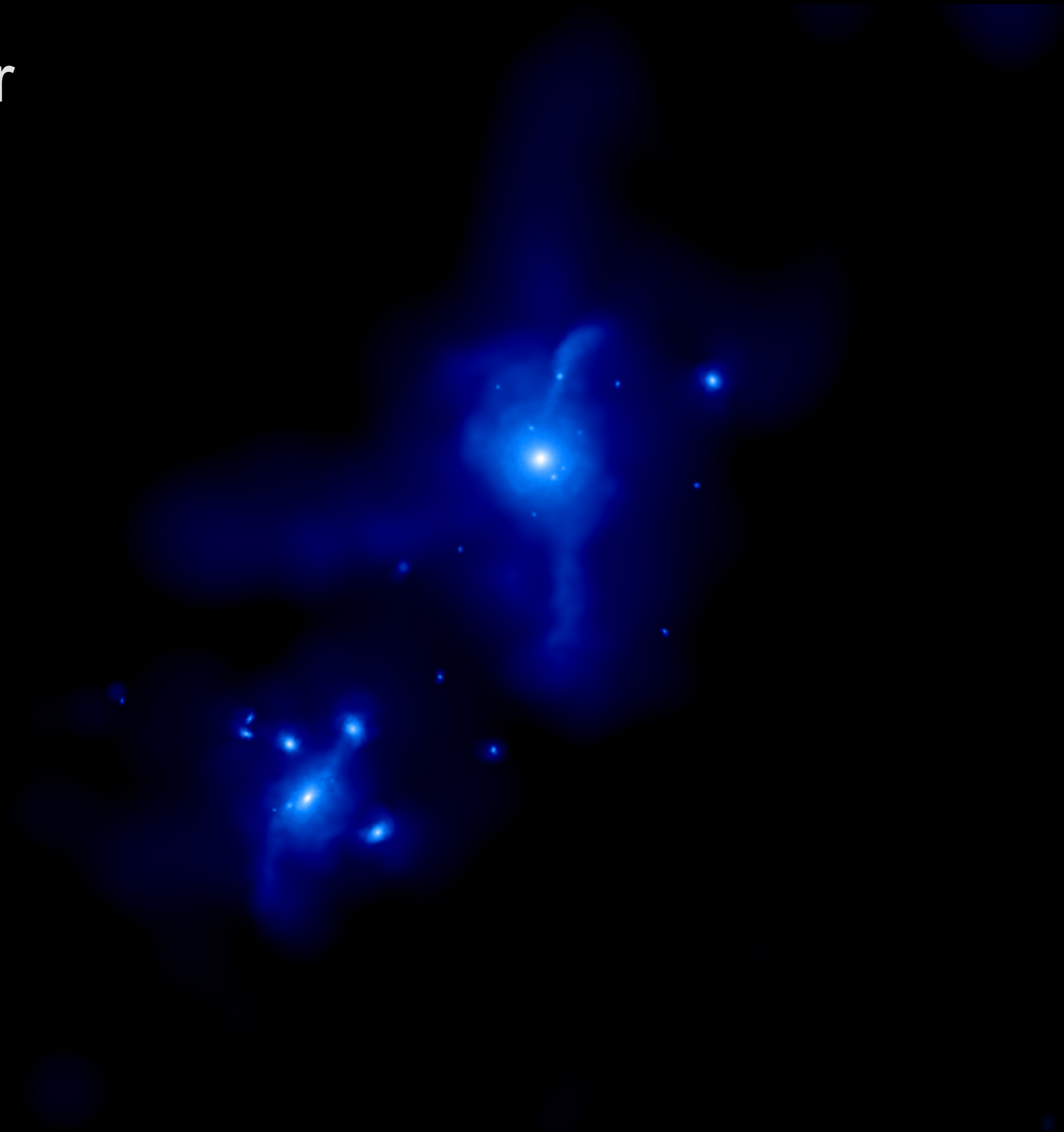
NAM 2014

DiRAC

ICC Institute for Computational Cosmology

PRACE

EAGLE full hydro Local Group simulations



VIRGO

EAGLE full hydro simulations

Local Group

Sawala et al ‘14

Far fewer satellite galaxies than CDM halos

EAGLE full hydro simulations

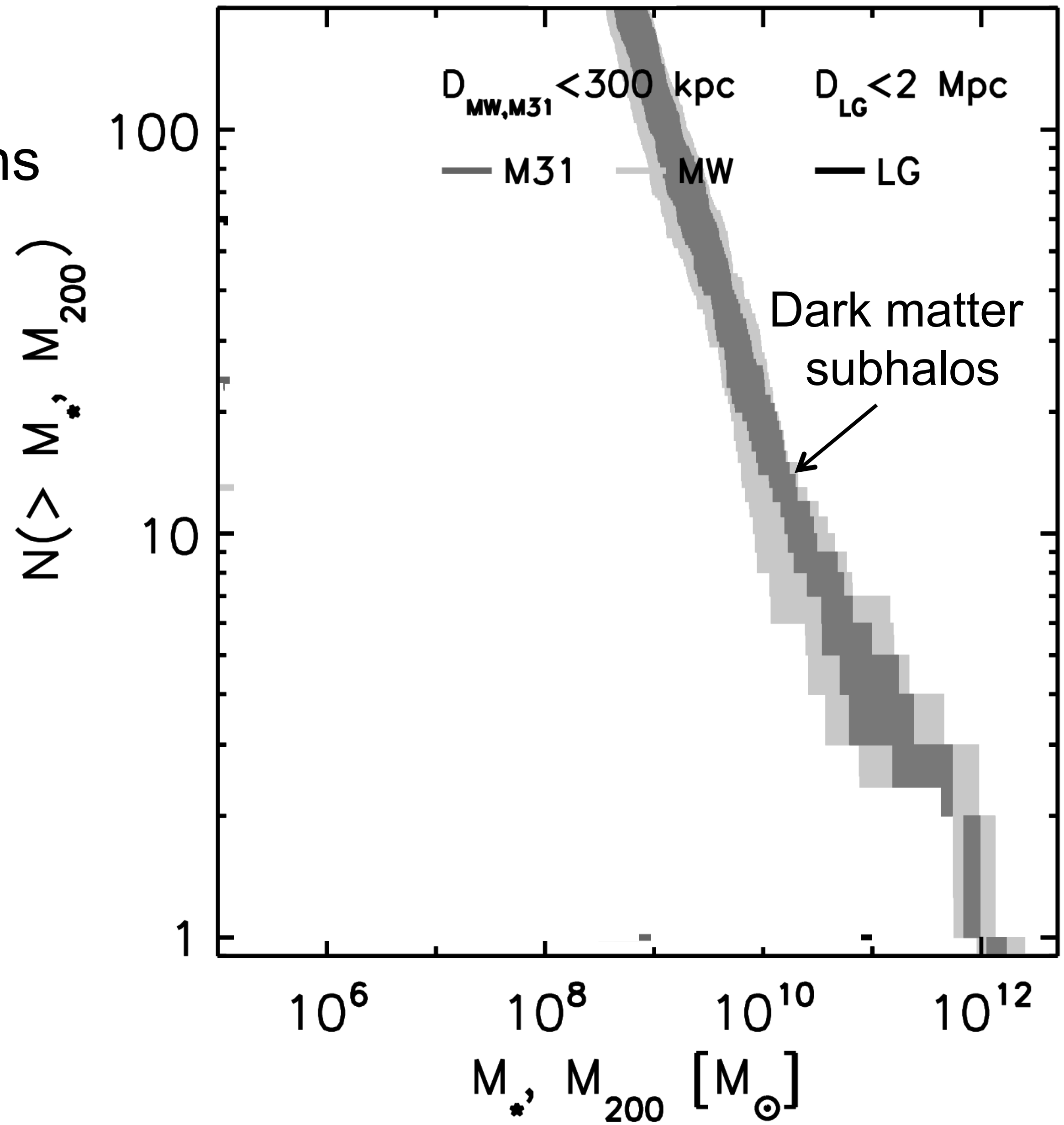
Local Group

Sawala et al ‘14

EAGLE Local Group simulation

University of Durham

Subhalo mass functions

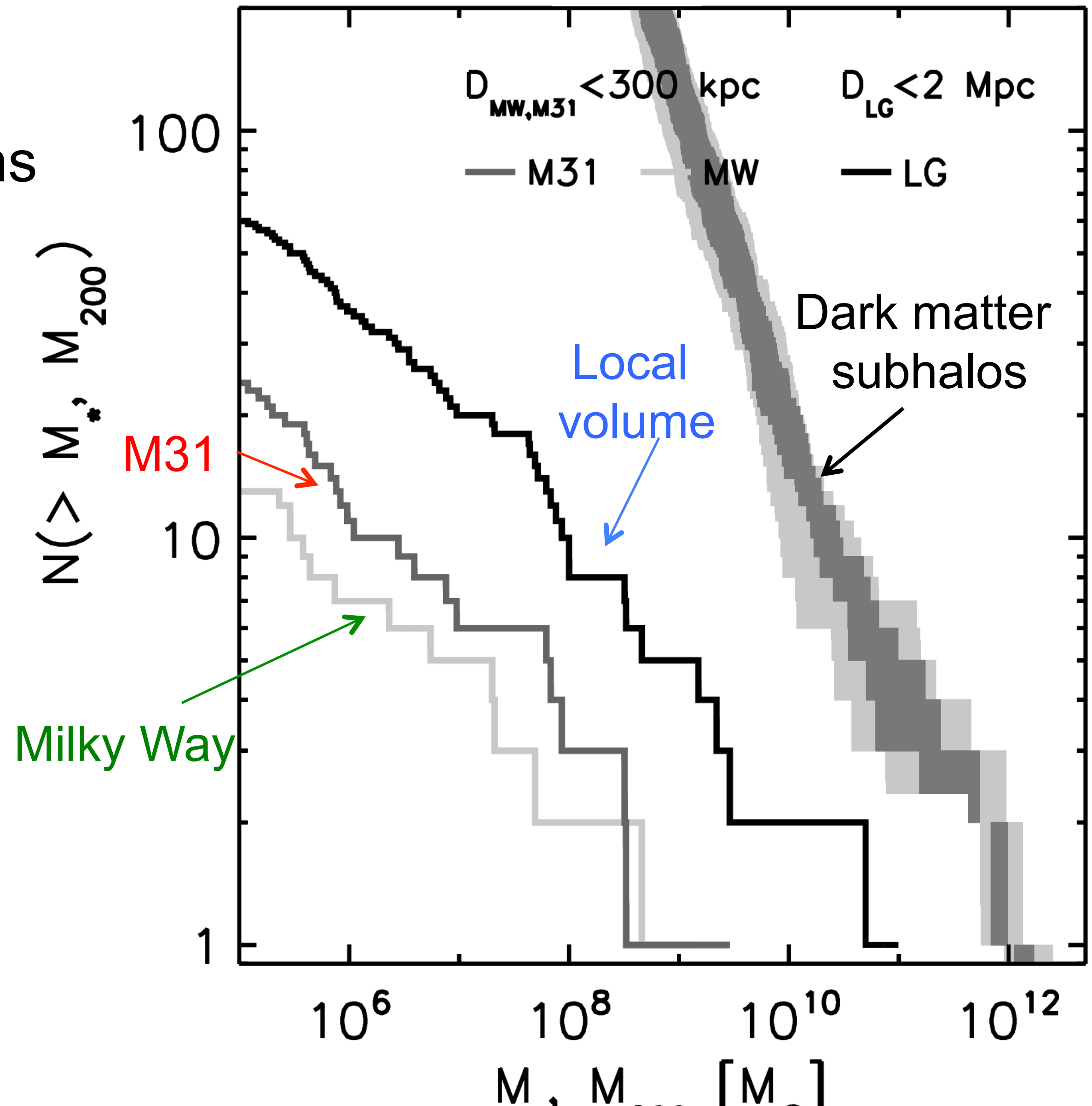


Sawala et al '14

University of Durham

EAGLE Local Group simulation

Stellar mass functions

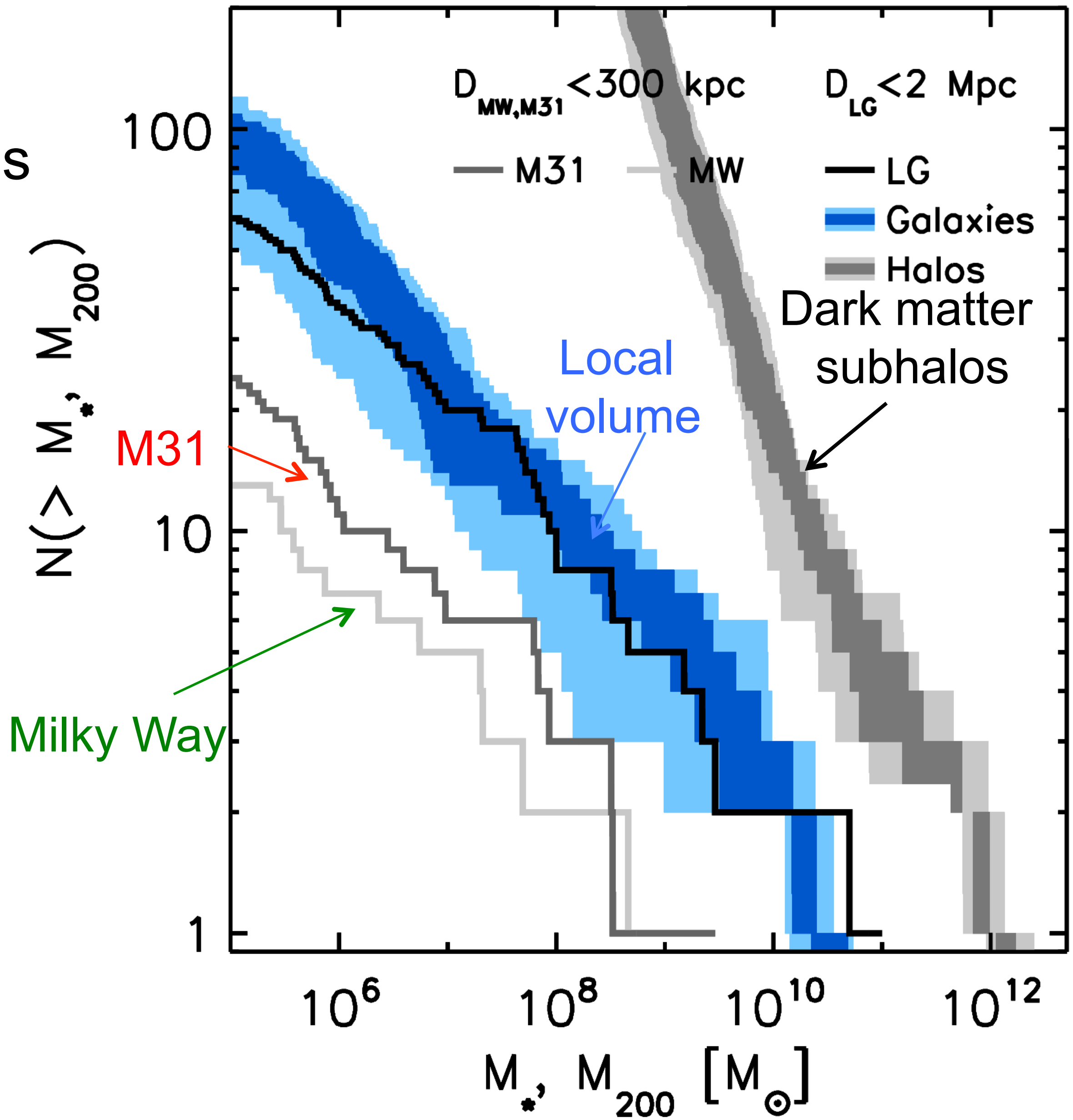


Sawala et al '14

EAGLE Local Group simulation

University of Durham

Stellar mass functions

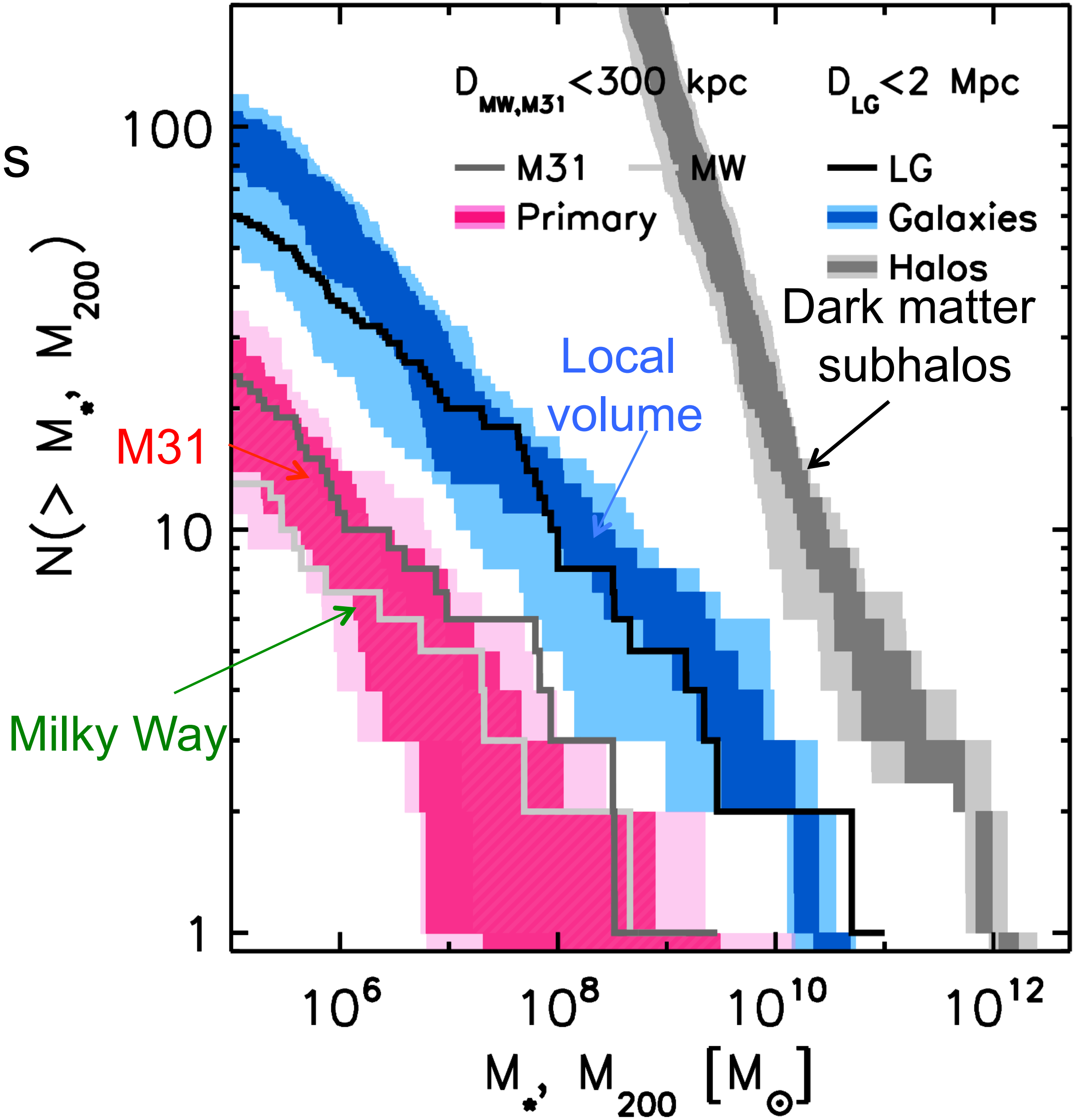


Sawala et al '14

EAGLE Local Group simulation

University of Durham

Stellar mass functions

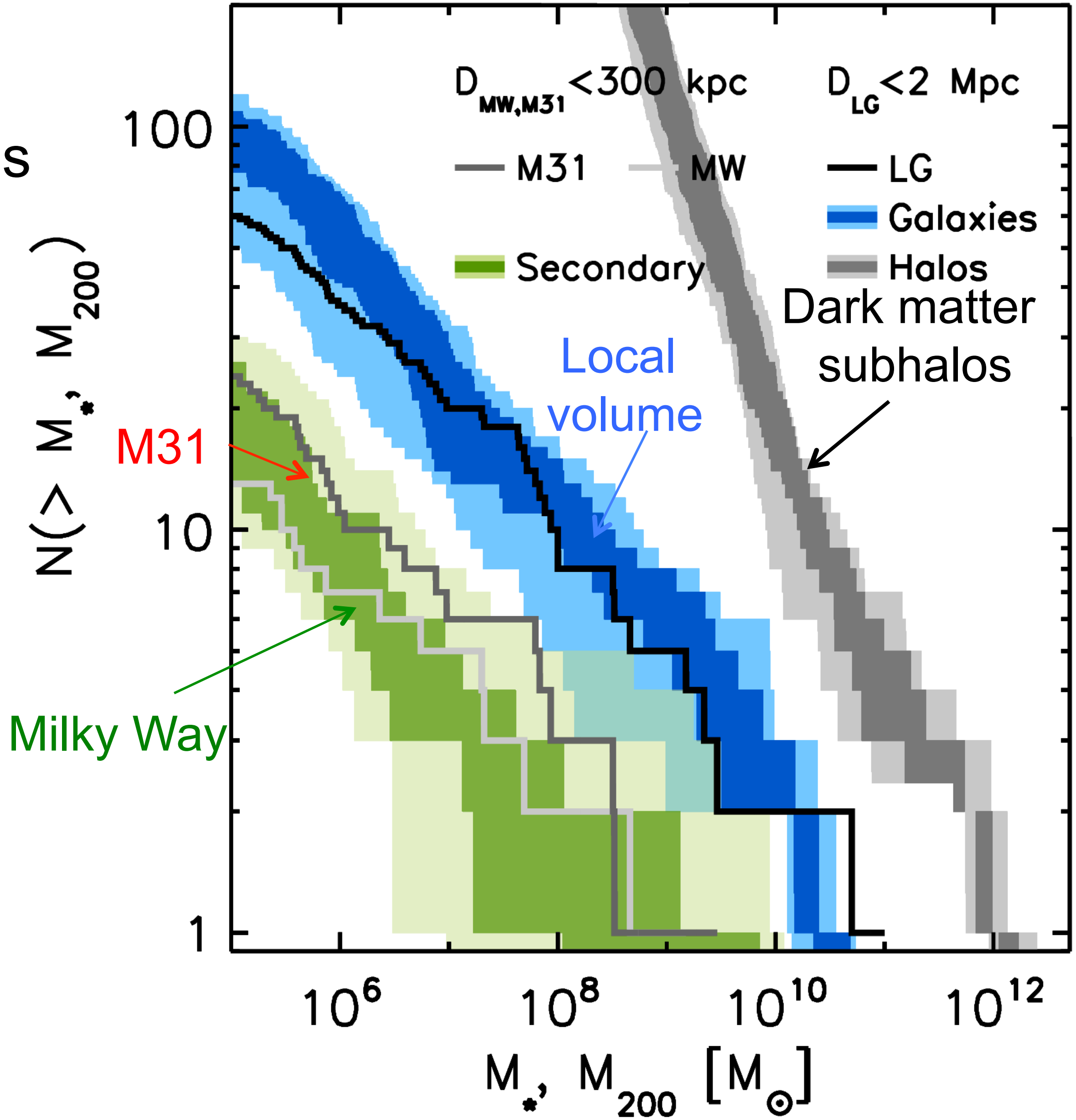


Sawala et al ‘14

EAGLE Local Group simulation

University of Durham

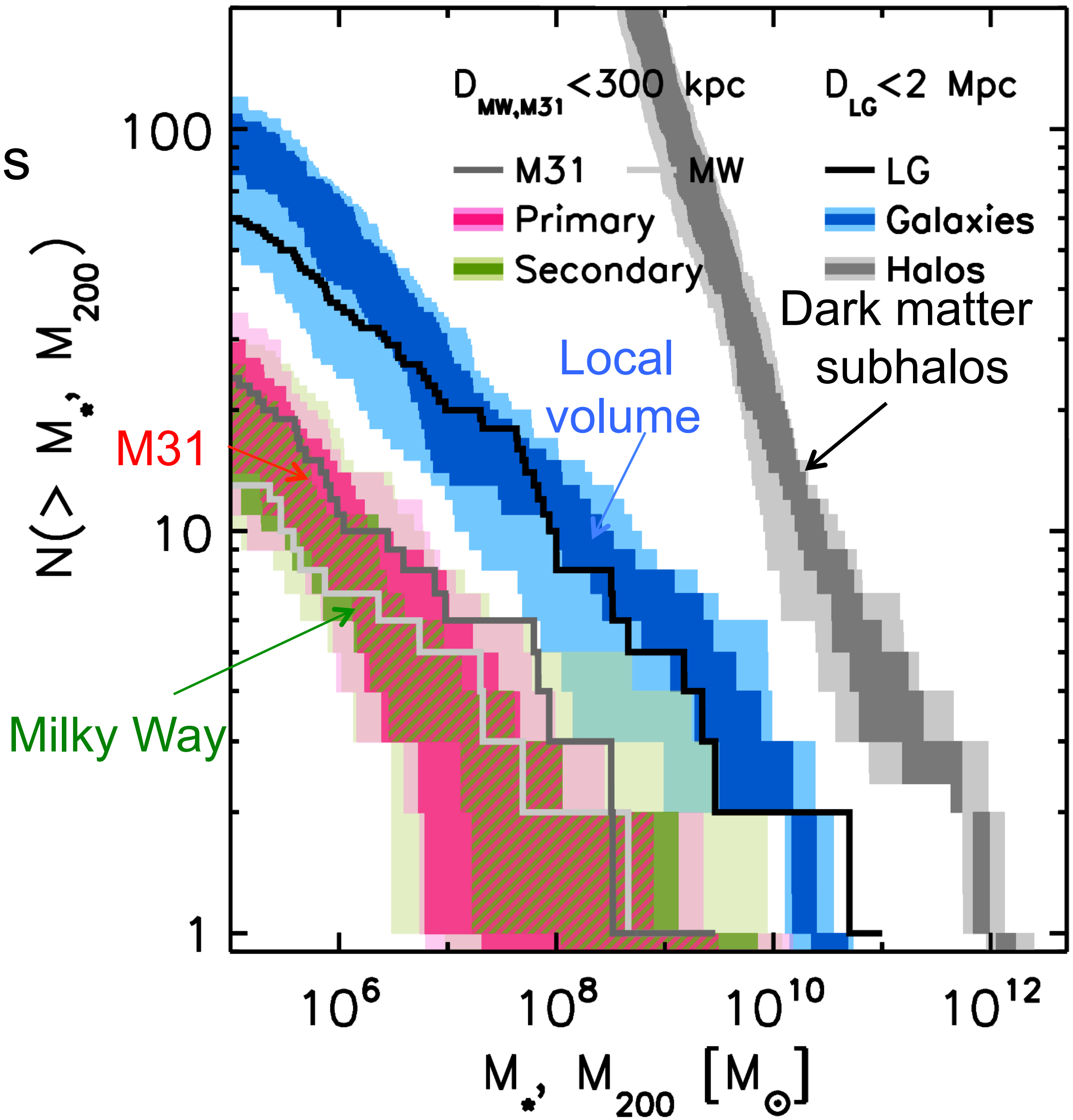
Stellar mass functions



Sawala et al '14

EAGLE Local Group simulation

Stellar mass functions



Sawala et al '14

Is there a “satellite problem” in CDM?

No, when galaxy formation is taken into account!

ICC

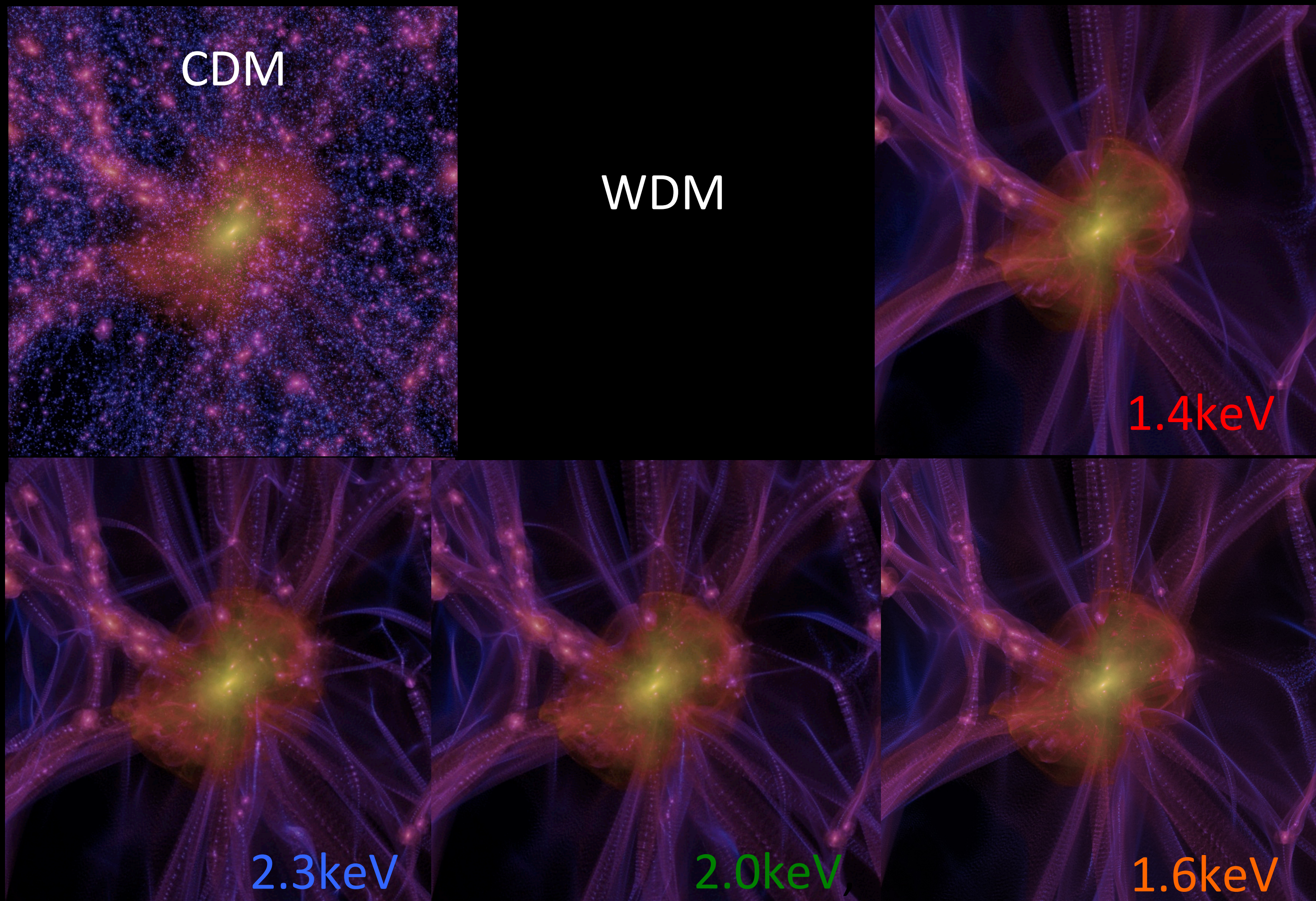
Is there a “satellite problem” in WDM?

Potentially!

Warm DM: different ν mass

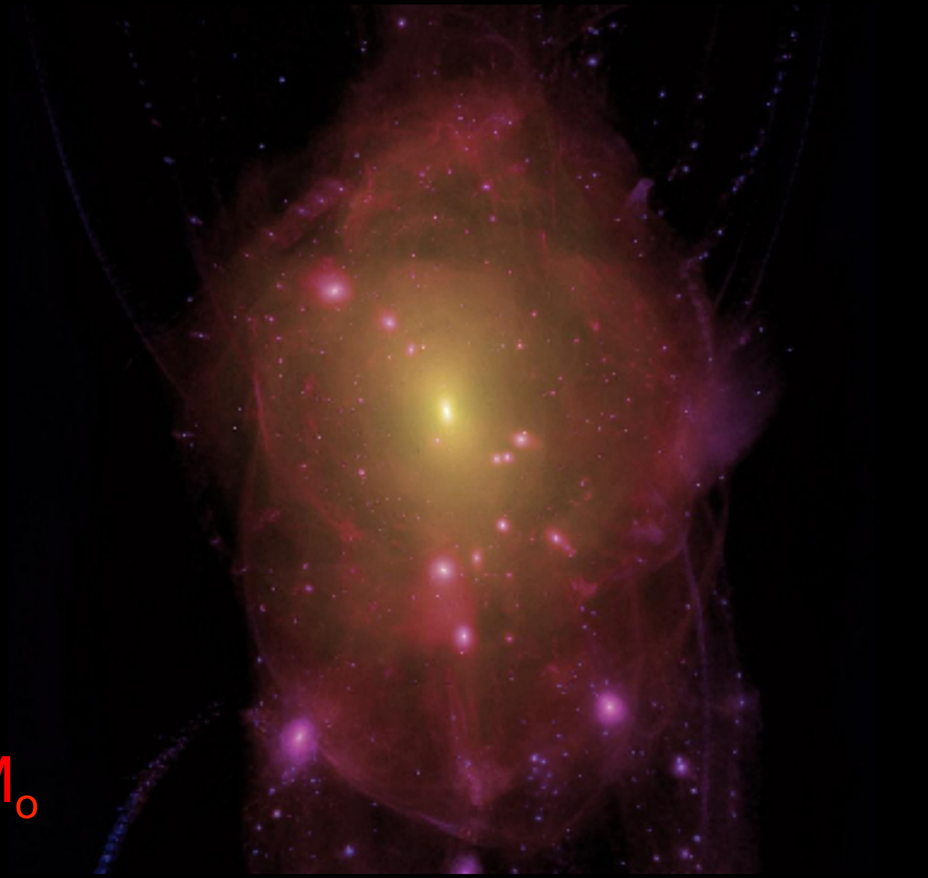
z=3

WDM
- 2.3 keV
- 2.0 keV
- 1.6 keV
- 1.4 keV



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 $m_{wdm} > 3$ keV

➔ lower limit $M_{halo} > 1.1 \times 10^{12}\, M_o$

Kennedy, Cole & Frenk '13

45 minutes to here

Four problems on small scales

Traditionally ascribed to CDM:

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3. The "too-big-to-fail" problem
4. The "satellite disk" problem

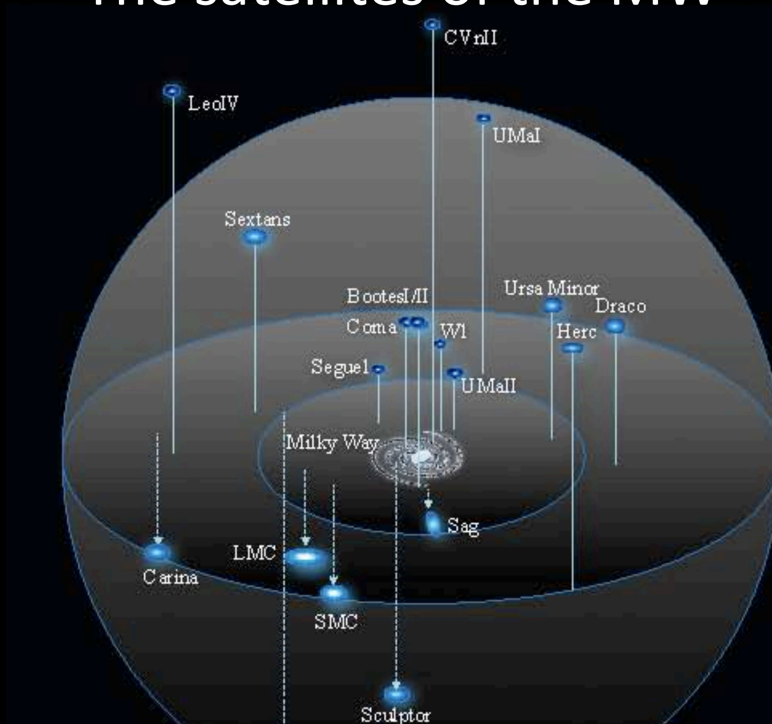
Can these help distinguish between CDM & WDM?

The "too-big-to-fail" problem

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

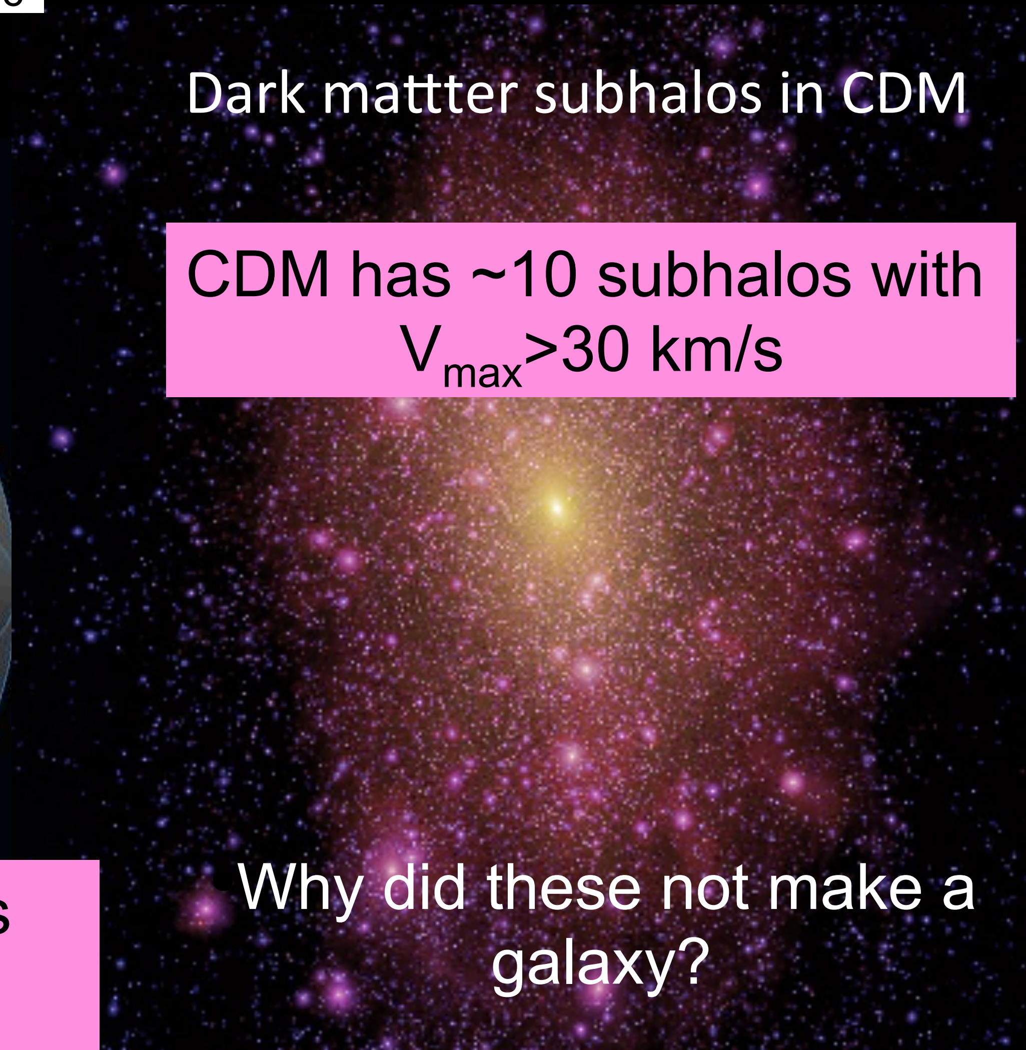
$$V_{max} = \max V_c$$

The satellites of the MW



MW has only 3 satellites with V_{max}>30 km/s

(LMC, SMC, Sgr)



Dark mattter subhalos in CDM

CDM has ~10 subhalos with V_{max}>30 km/s

Why did these not make a galaxy?

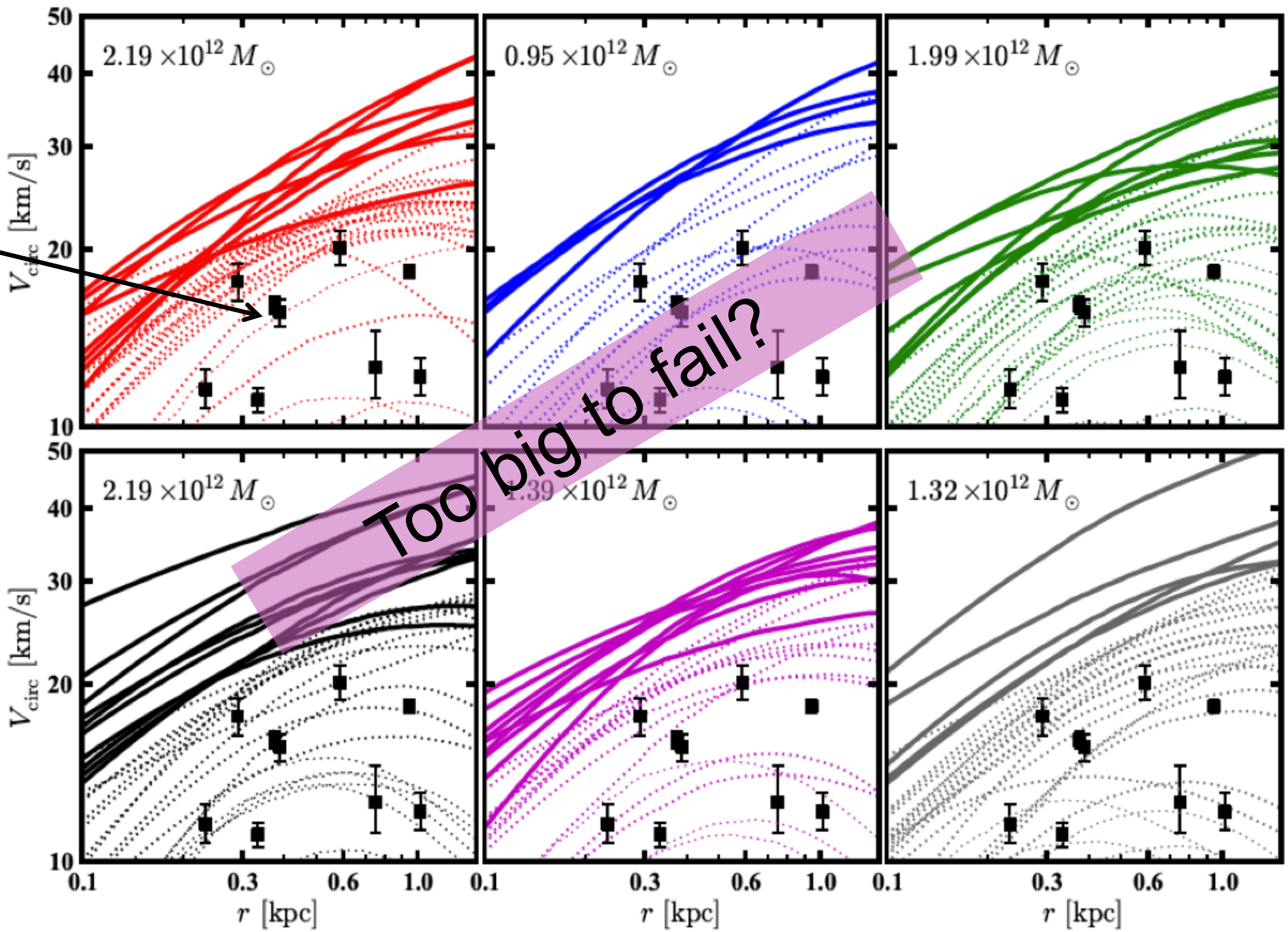
Rotation curves of Aquarius subhalos

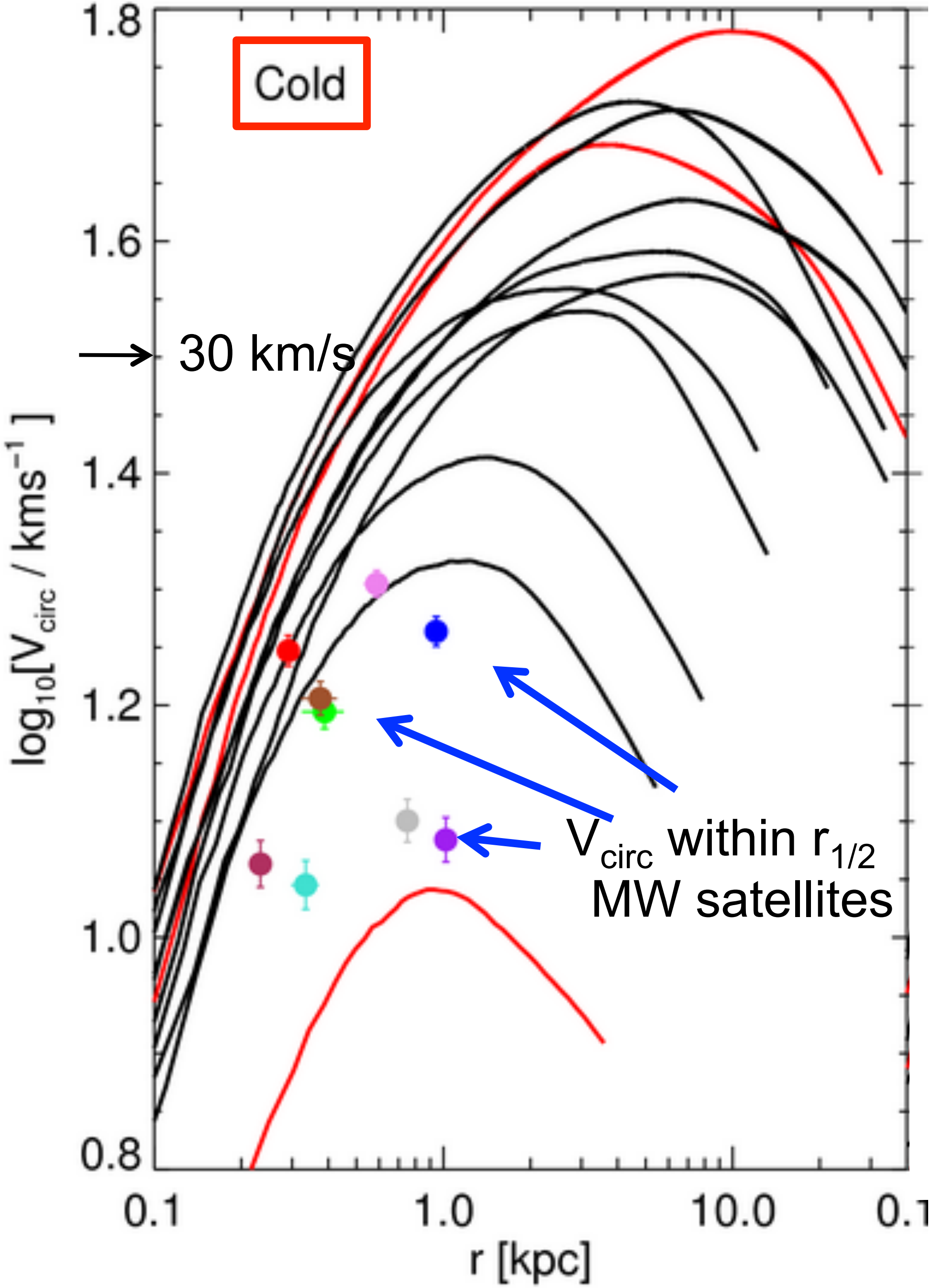
Boylan-Kolchin et al. ‘11

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

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

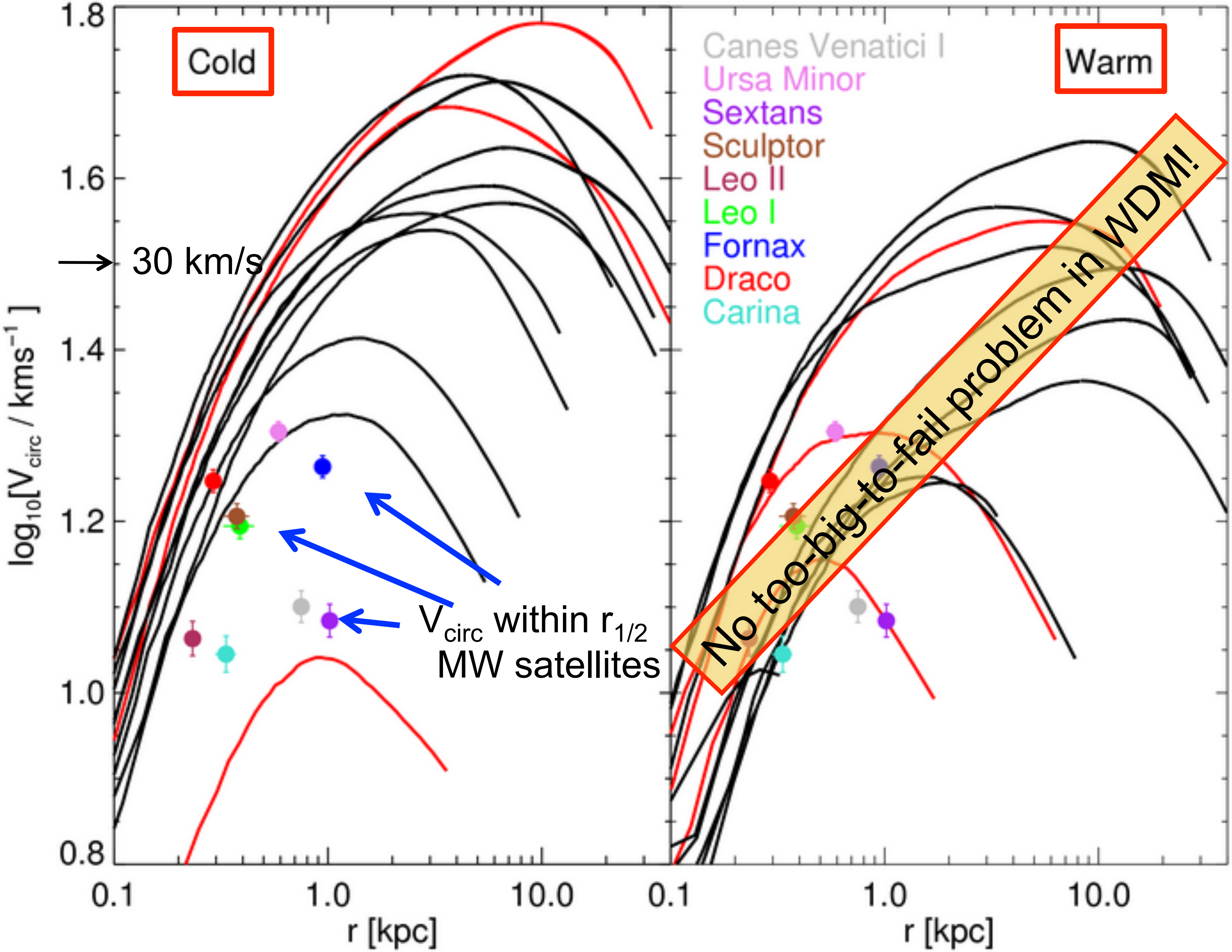
Excludes LMC, SMC, Sagittarius





$$V(r)_c = \sqrt{\frac{GM(r)}{r}}$$

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


Cold
Warm
30 km/s
Canes Venatici I
Ursa Minor
Sextans
Sculptor
Leo II
Leo I
Fornax
Draco
Carina
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

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

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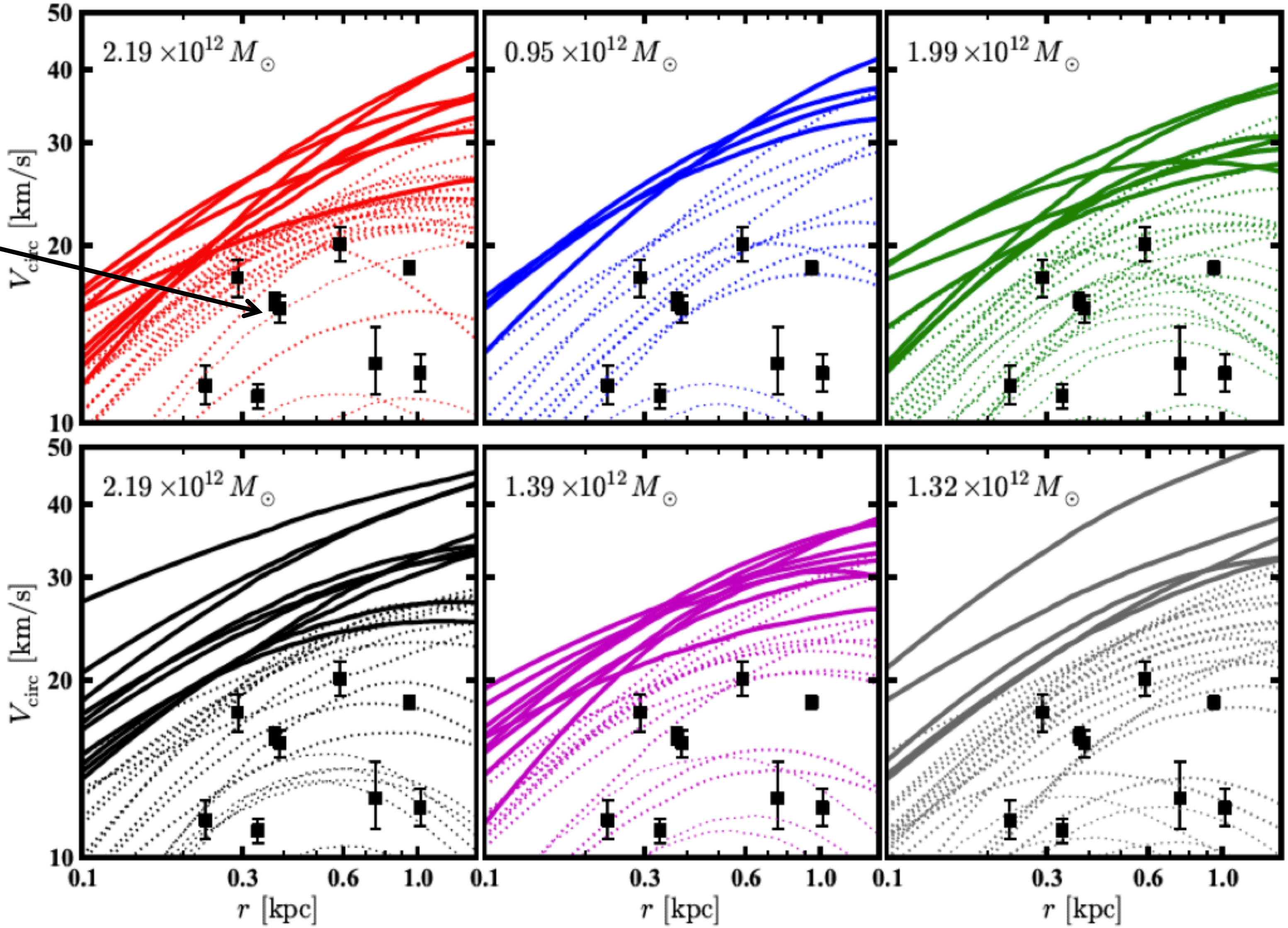


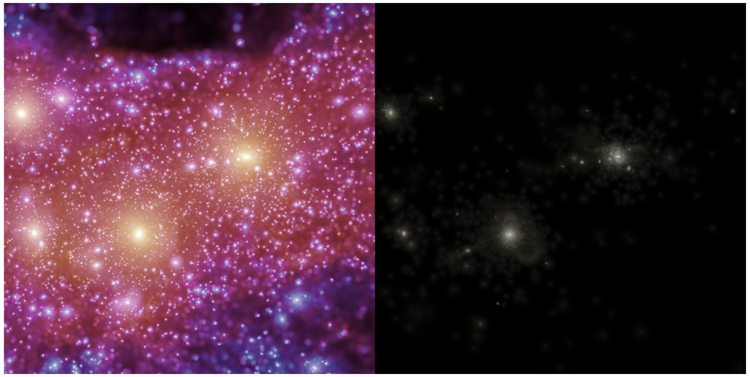
To-big-to-fail in CDM: baryon effects

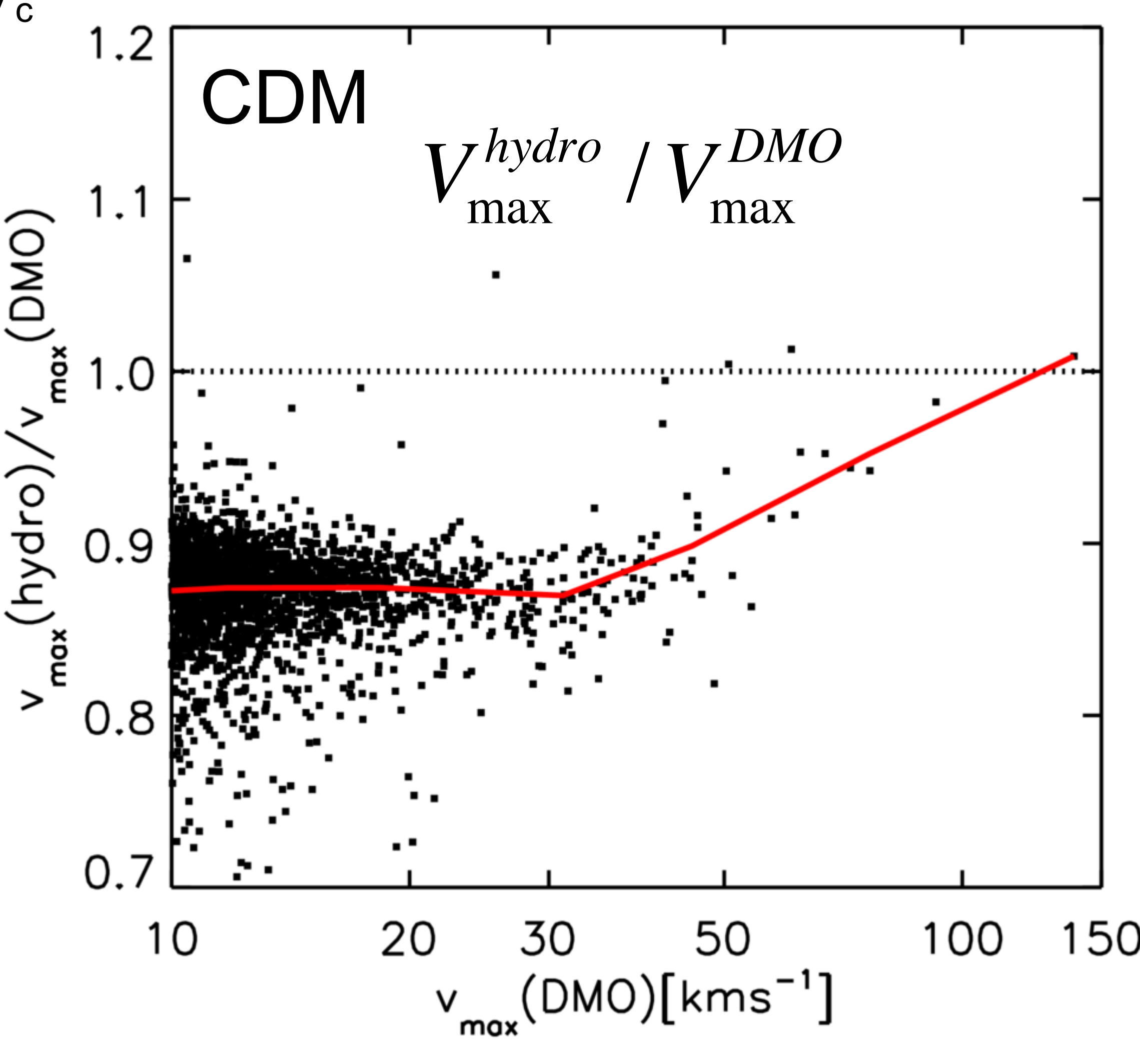
University of Durham

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





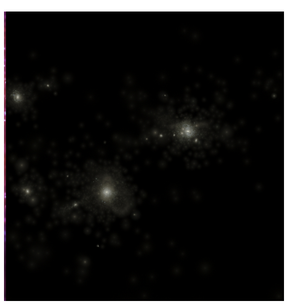
Sawala et al. '13, '14

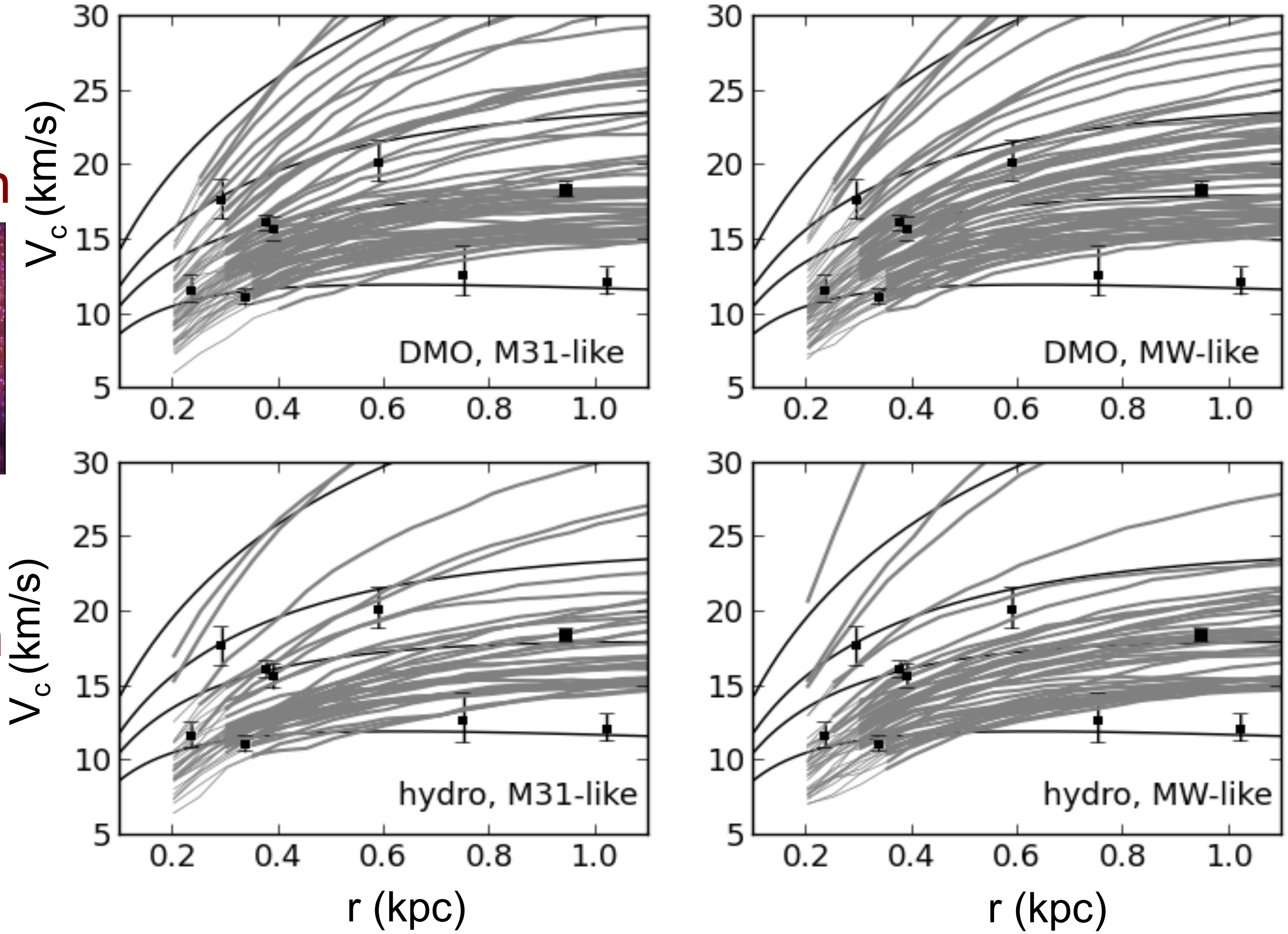
University of Durham

Too-big-to-fail: the baryon bailout

DM-only simulation

Gas simulation





Sawala et al. '14

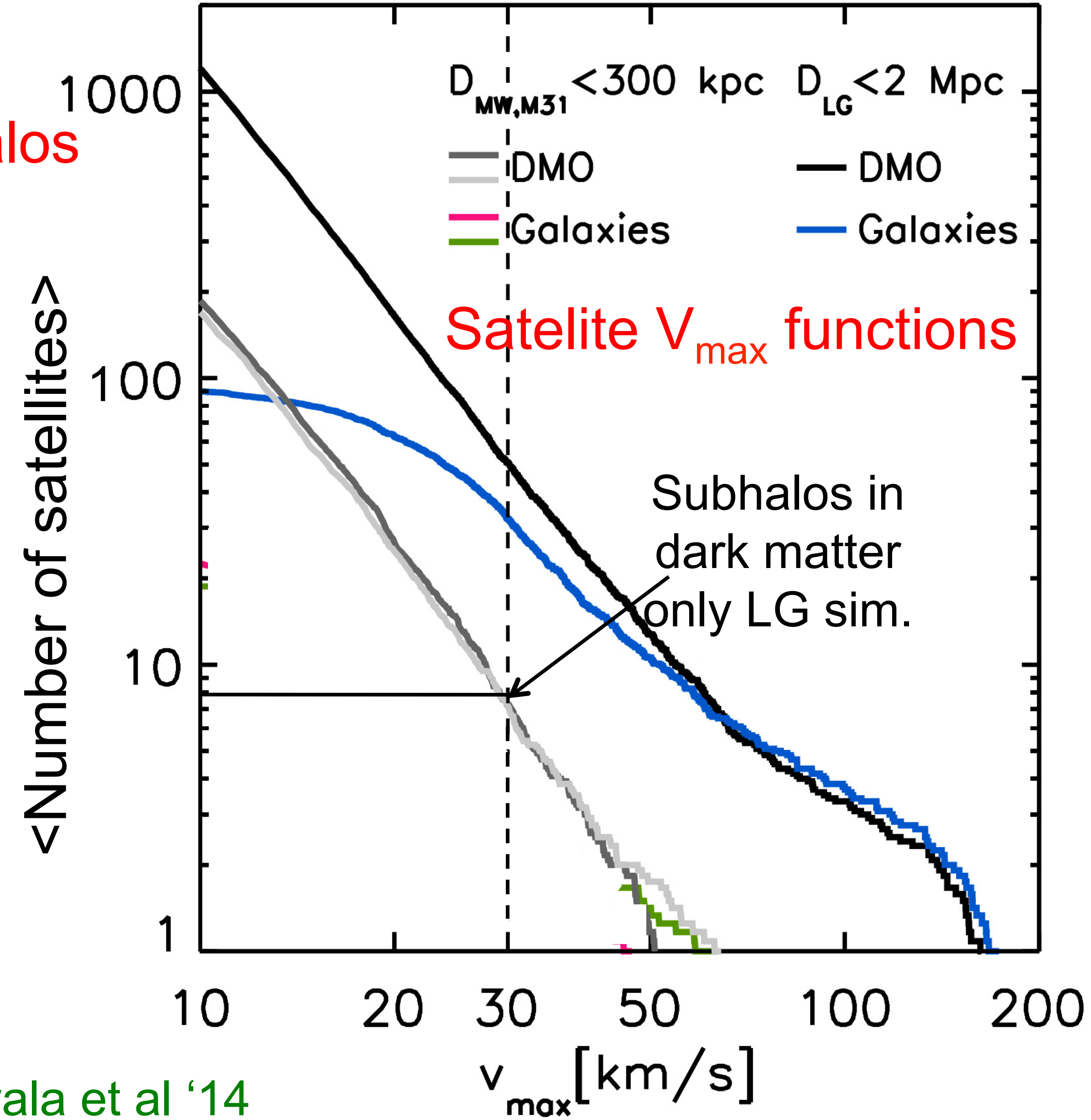
Number of subhalos of given V_{max} is greatly reduced in gas simulations

Institute for Computational Cosmology

Too-big-to-fail: the baryon bailout

University of Durham

DM only sims → ~10 halos with V_{max}> 30 km/s

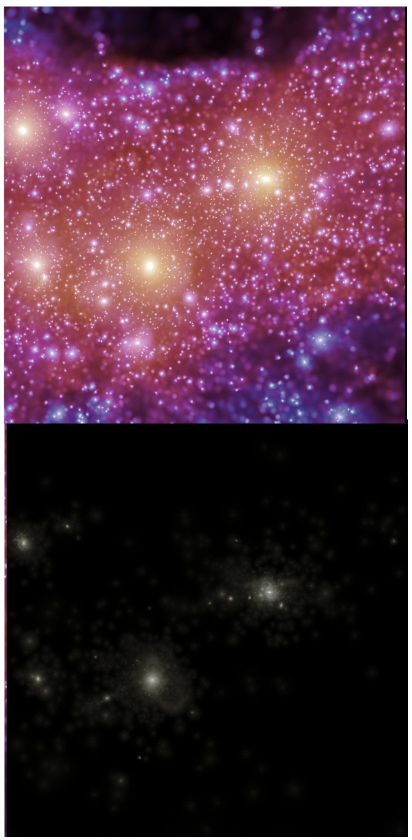


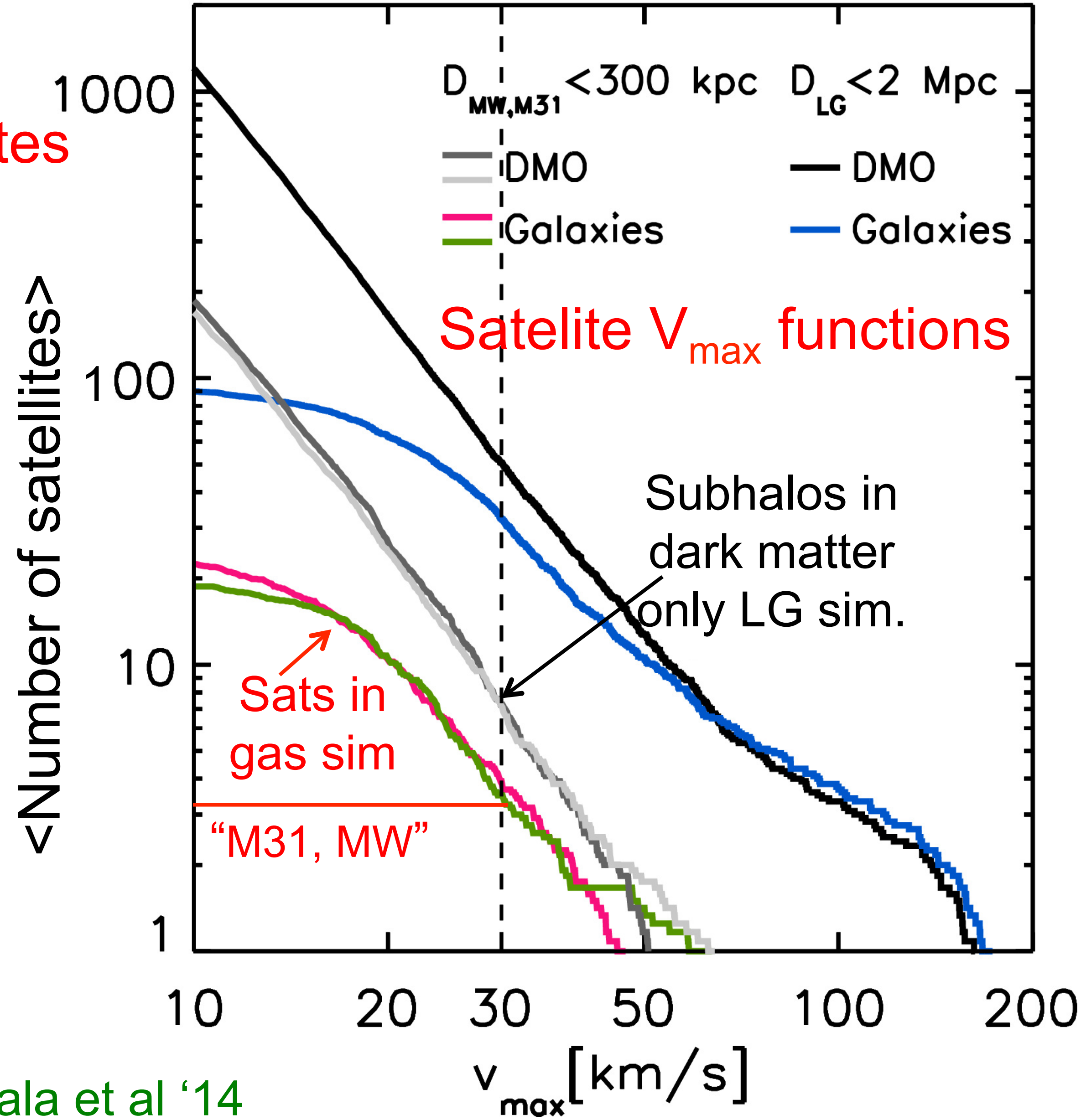
Sawala et al '14

Too-big-to-fail: the baryon bailout

University of Durham

Hydro sims → ~3 satellites with V_{max}> 30 km/s





Sawala et al '14

Too-big-to-fail: the baryon bailout

University of Durham

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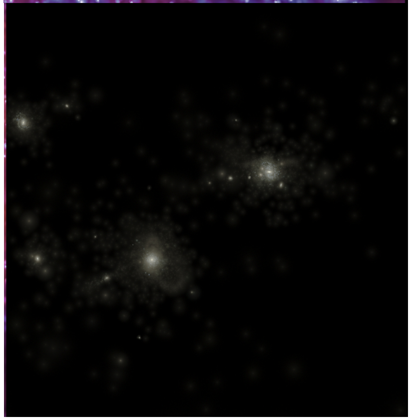
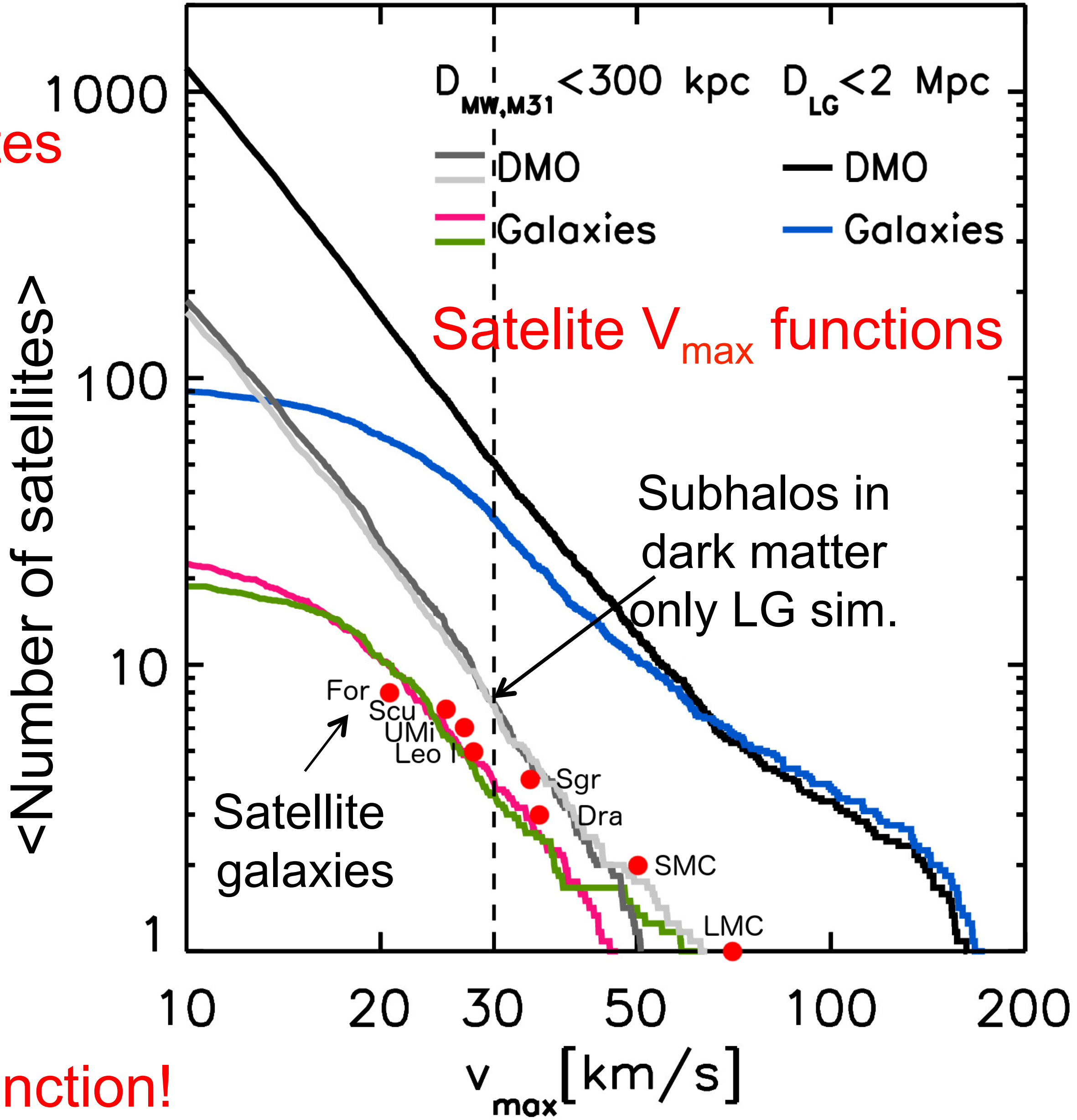




. and with correct V_{max} function!

Four problems on small scales

University of Durham

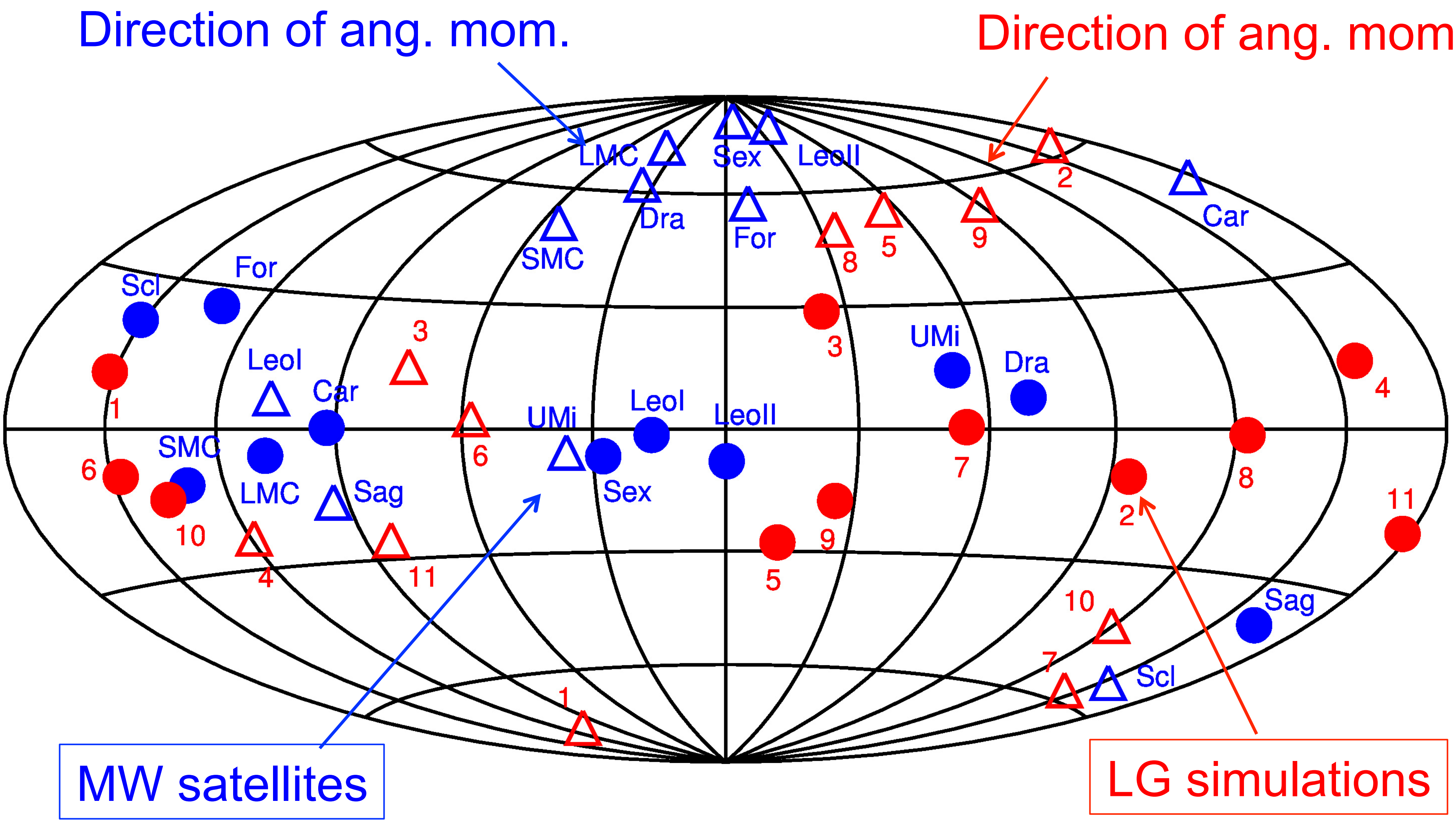
Traditionally ascribed to CDM:

1. The "core-cusp" problem
2. The "missing satellites" problem
3. The "too-big-to-fail" problem
4. The "satellite disk" problem

Can these help distinguish between CDM & WDM?

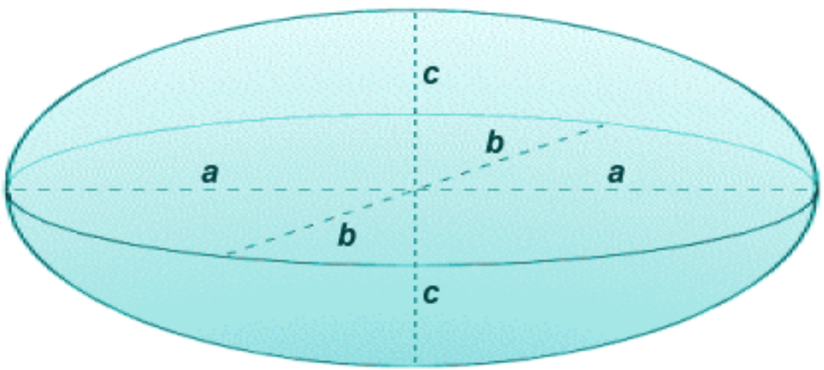
ICC
University of Durham

The “satellite disk” problem



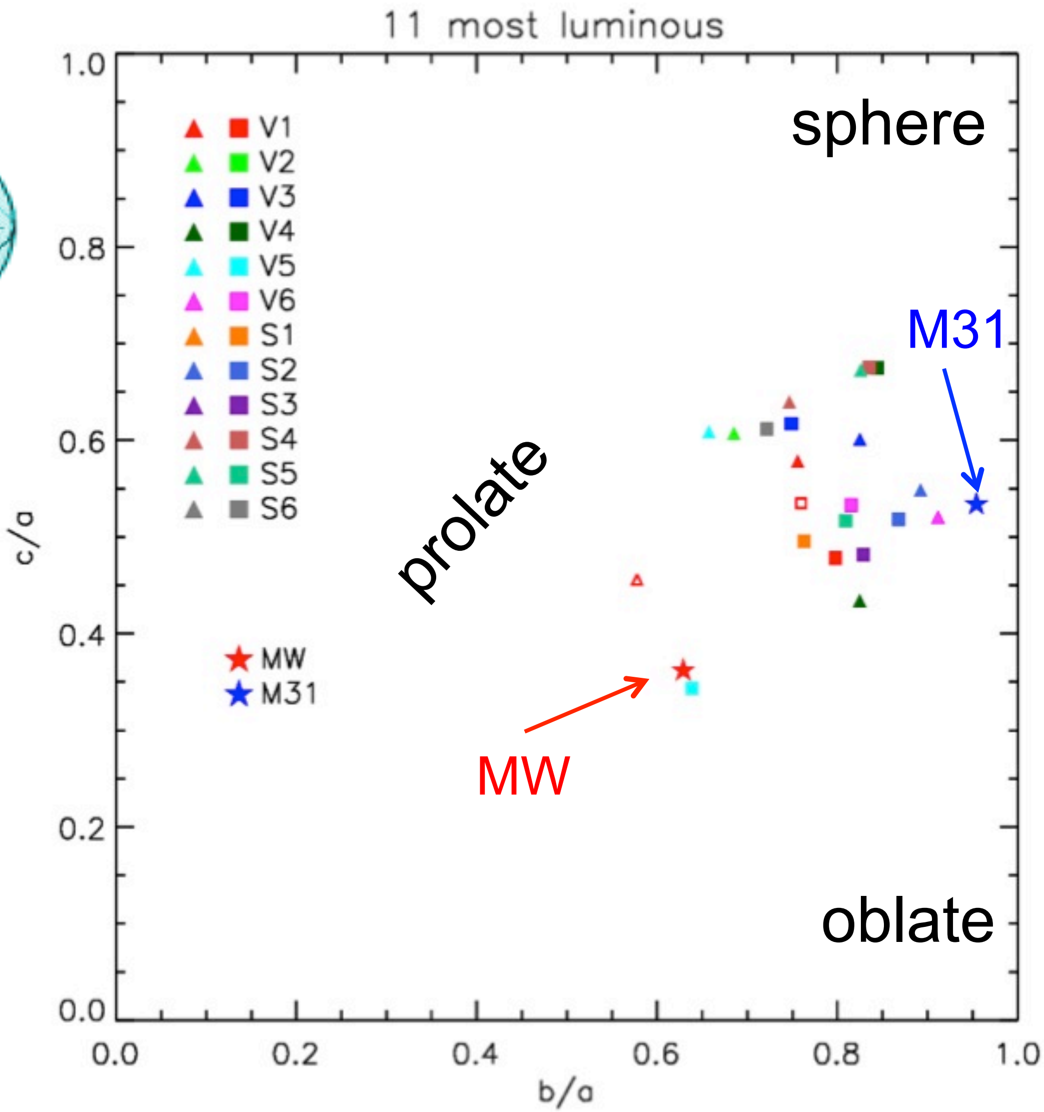
Lynden-Bell ‘76

The “satellite disk” problem



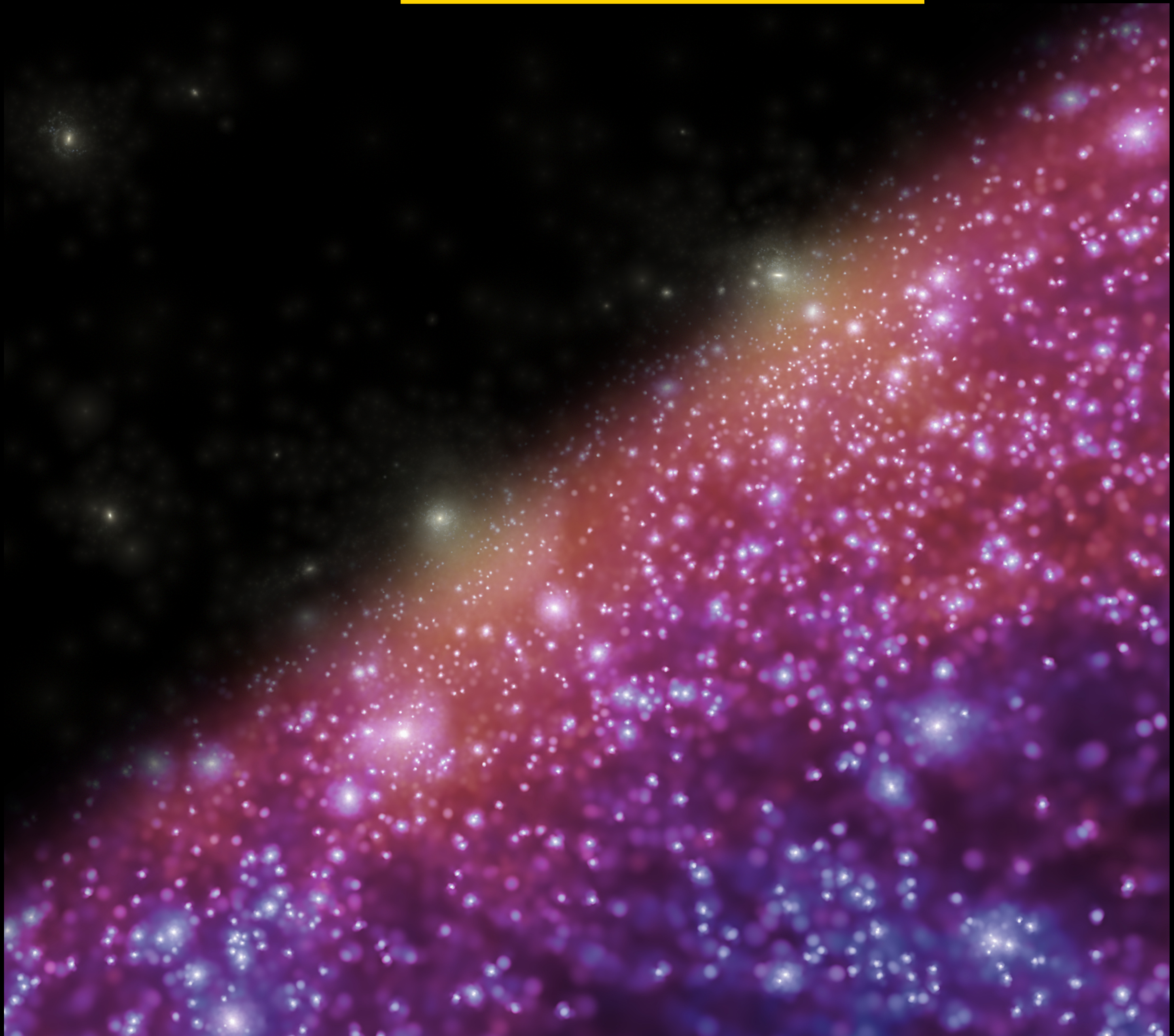
11 brightest satellites in MW make up a “great pancake”

1/12 LG simulations ≅ MW



Libeskind et al ’05; Wang et al ’12; Ibata ‘14

Conclusions



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

Four "problems" on small scales:

1. Core-cusp: Not a problem? (Baryon effects?)
2. Abundance of sats: CDM OK; WDM OK if m_{WDM}> 3 KeV
3. Too-big-to-fail: CDM, WDM OK
4. Disk of satellites: CDM, WDM OK

Conclusions

The four "problems" of CDM on small scales identified in dark matter only simulations:

1. Core-cusp
2. Missing satellites
3. Too-big-to-fail
4. Disk of satellites

Are not there when when galaxy formation is taken into account!

University of Durham

The identity of the dark

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

CDM

Submitted to ApJ, 2014 February 10
Preprint typeset using LaTeX style emulateapj v. 04/17/13

WDM

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra B... Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]

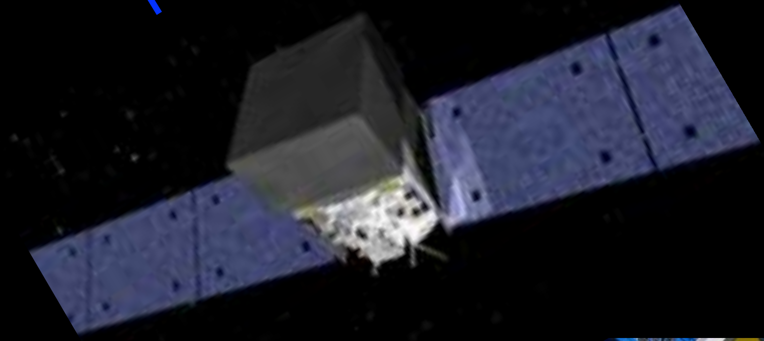
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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

Cosmology

Cold dark matter ?

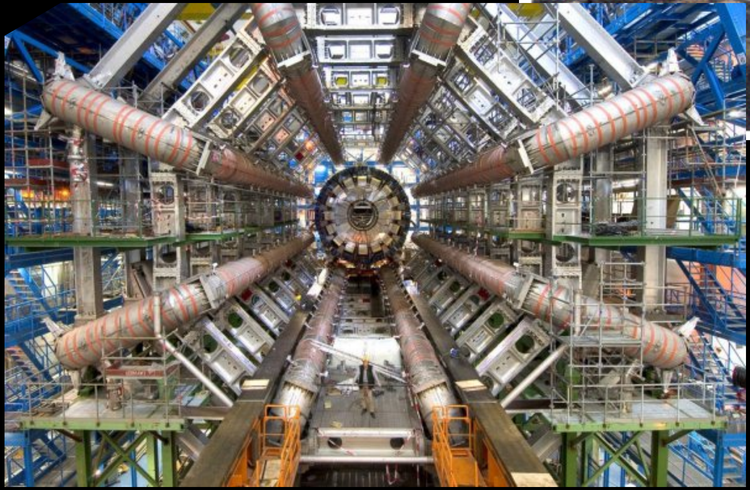
Fermi



Annihilation radiation

Direct detection

UK DM search
(Boulby mine)



Evidence for SUSY

ICC

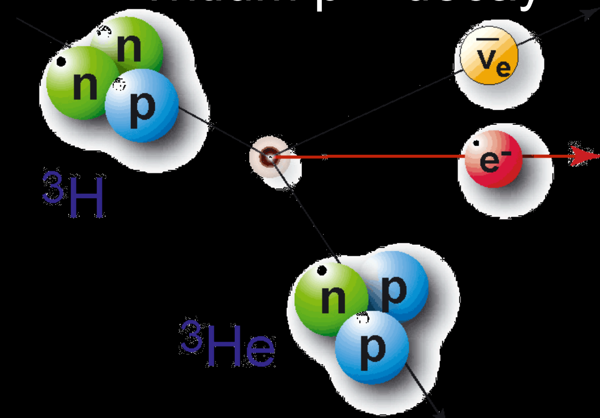
Warm dark matter ?

Sterile neutrino detection possible

Decay line in X-rays

Constellation X

Tritium β - decay



KATRIN
Karlsruhe Tritium Neutrino Experiment

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

1. Dark subhalos (gravitational lensing)
2. Subhalo structure (stellar kinematics)
3. Stellar streams (stellar surveys – PAndAS, GAIA)