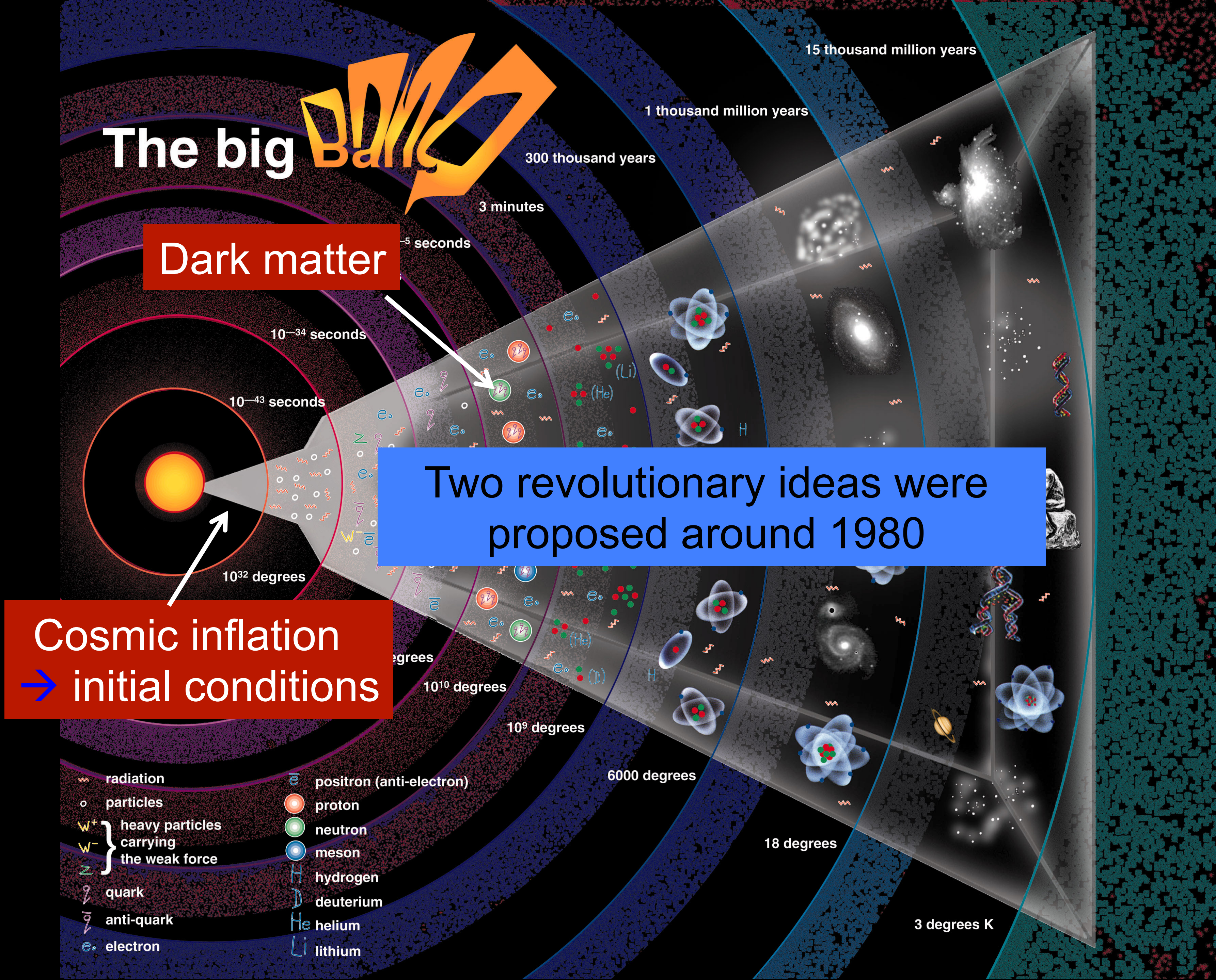
Roman Juszkiewicz (1952 – 2012)

Is CDM ruled out?

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
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 cosmologies

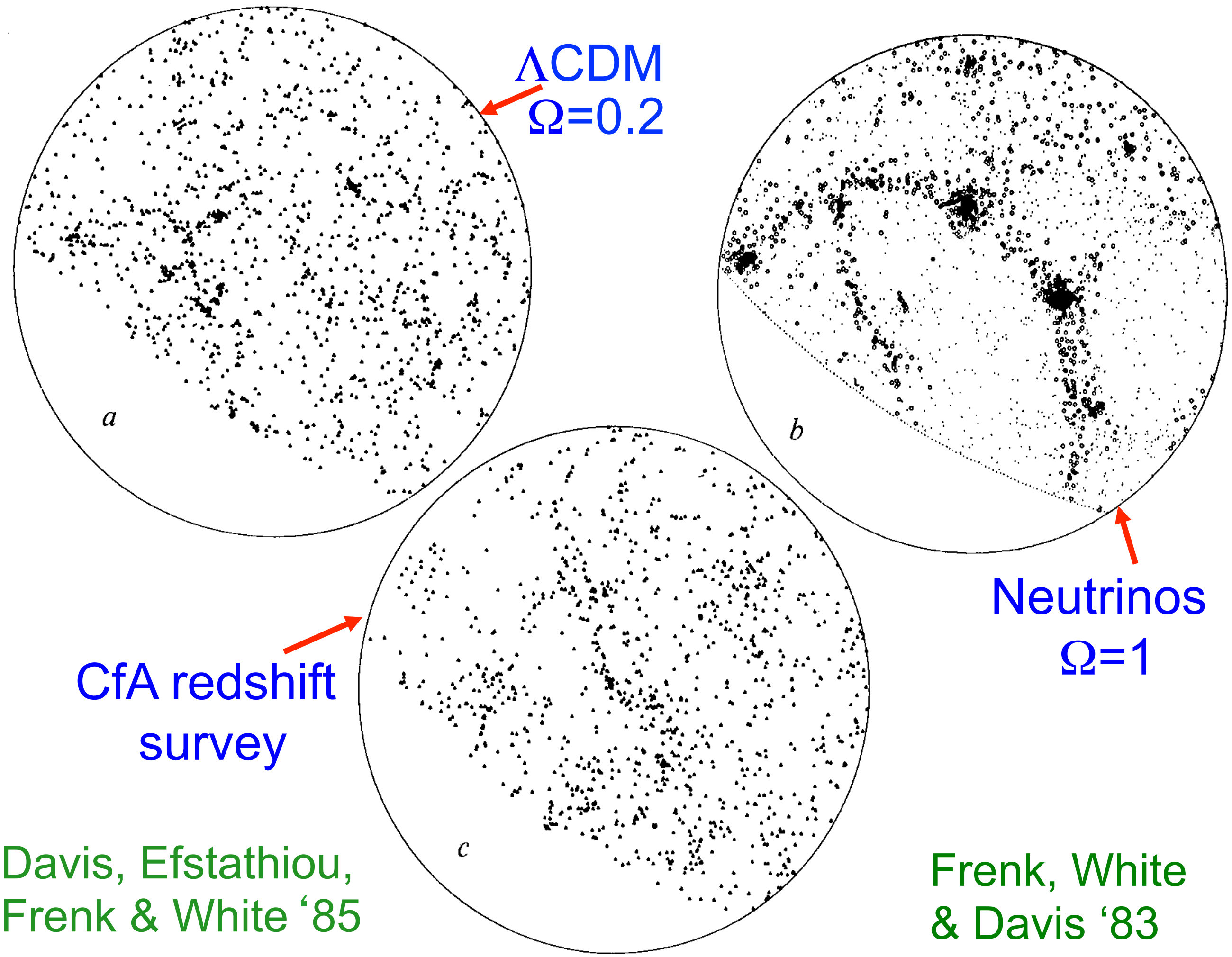
University of Durham

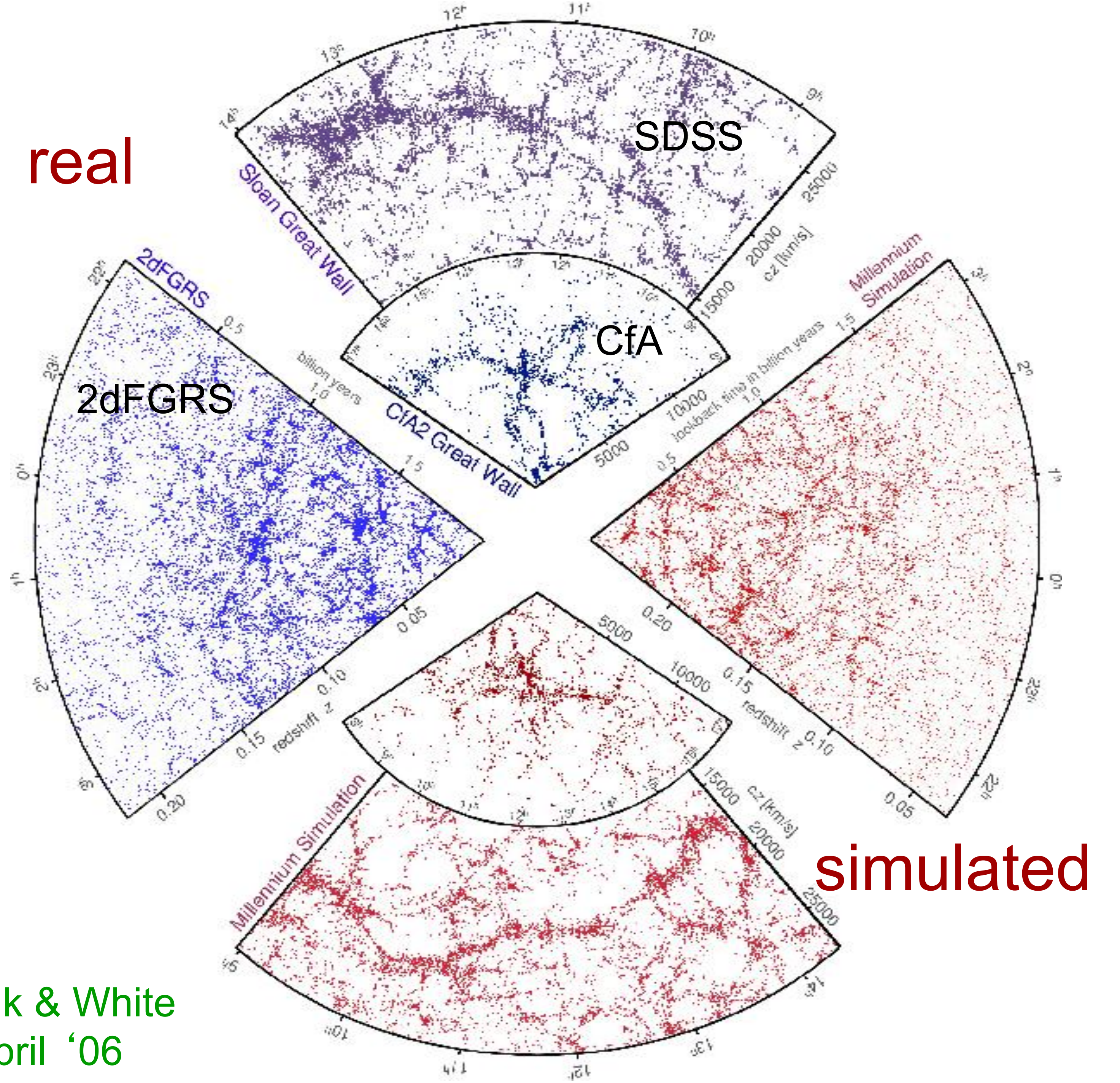
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

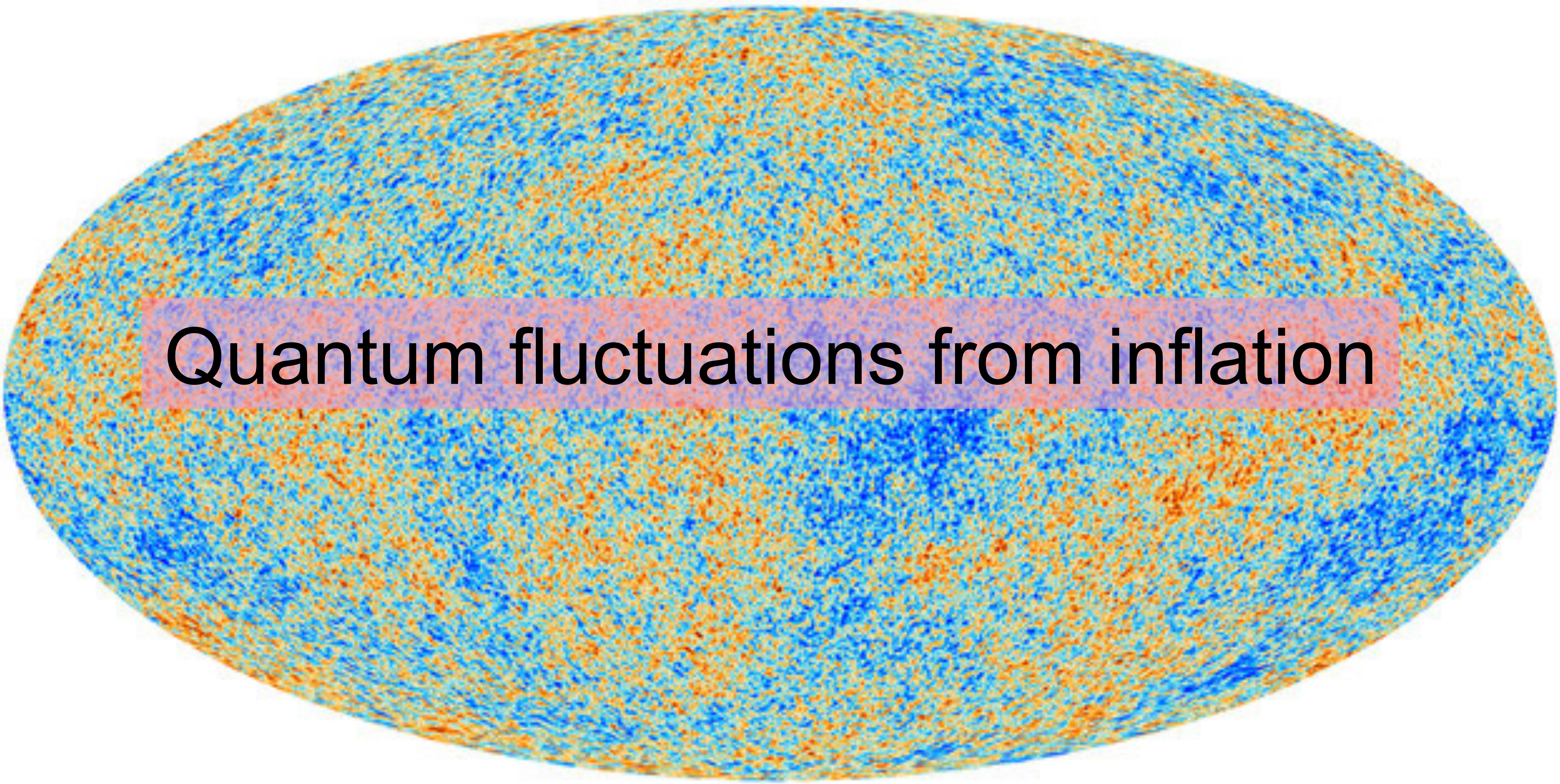




Springel, Frenk & White
Nature, April '06

University of Durham

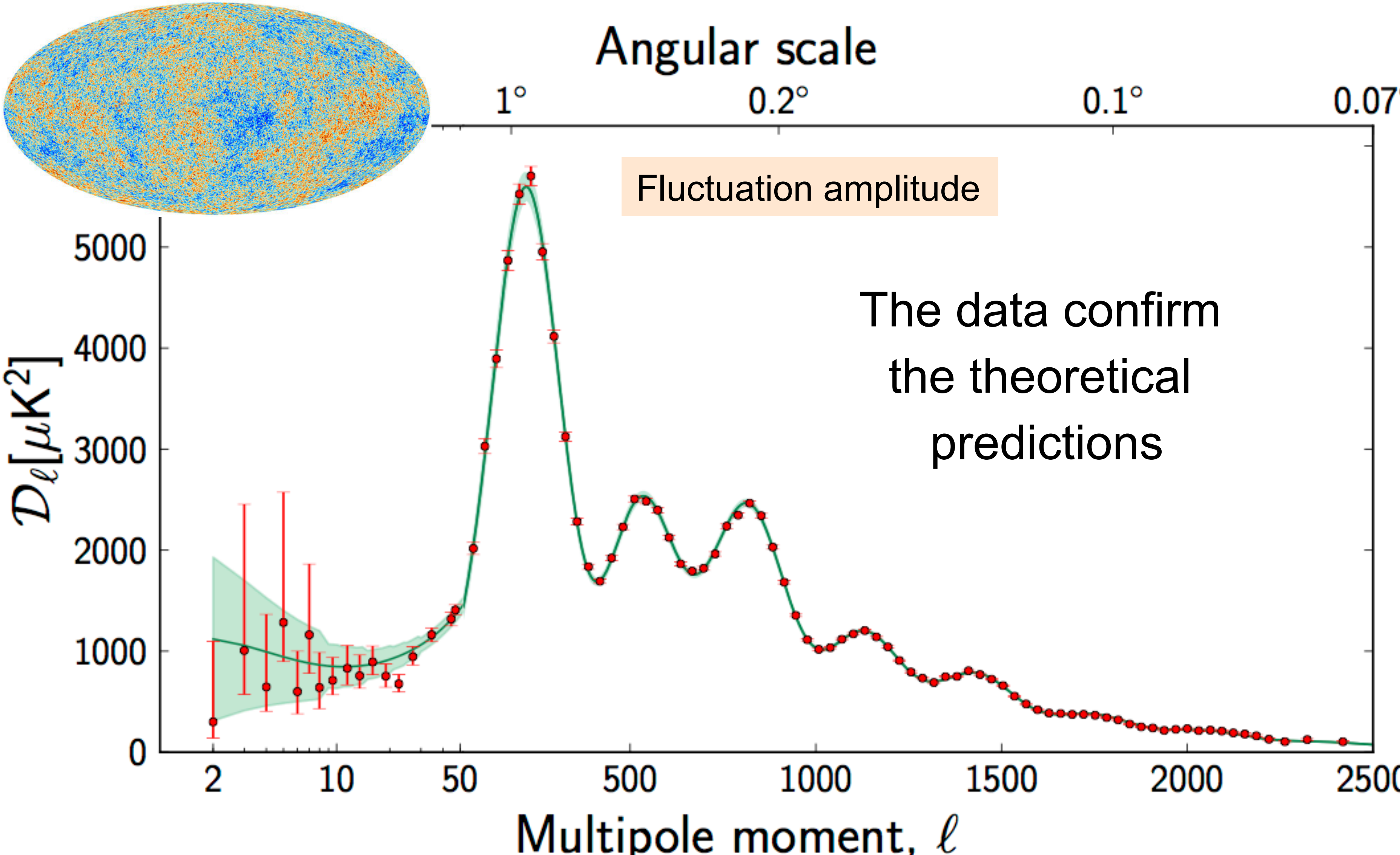
The initial conditions for galaxy formation



Quantum fluctuations from inflation

University of Durham

Planck: CMB temperature anisotropies



The data confirm the theoretical predictions

Planck coll. 2015

Institute for Computational Cosmology

The six parameters of minimal ΛCDM model

Univer

6 mdoel parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

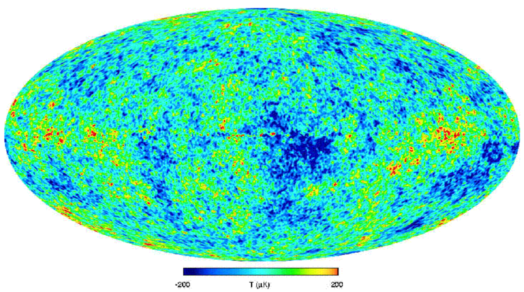
A 40σ detection of non-baryonic dark matter using only z=1000 data!

Planck collaboration ‘13

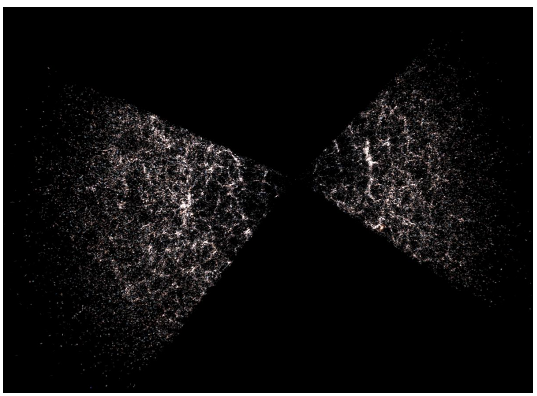
Institute for Computational Cosmology

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

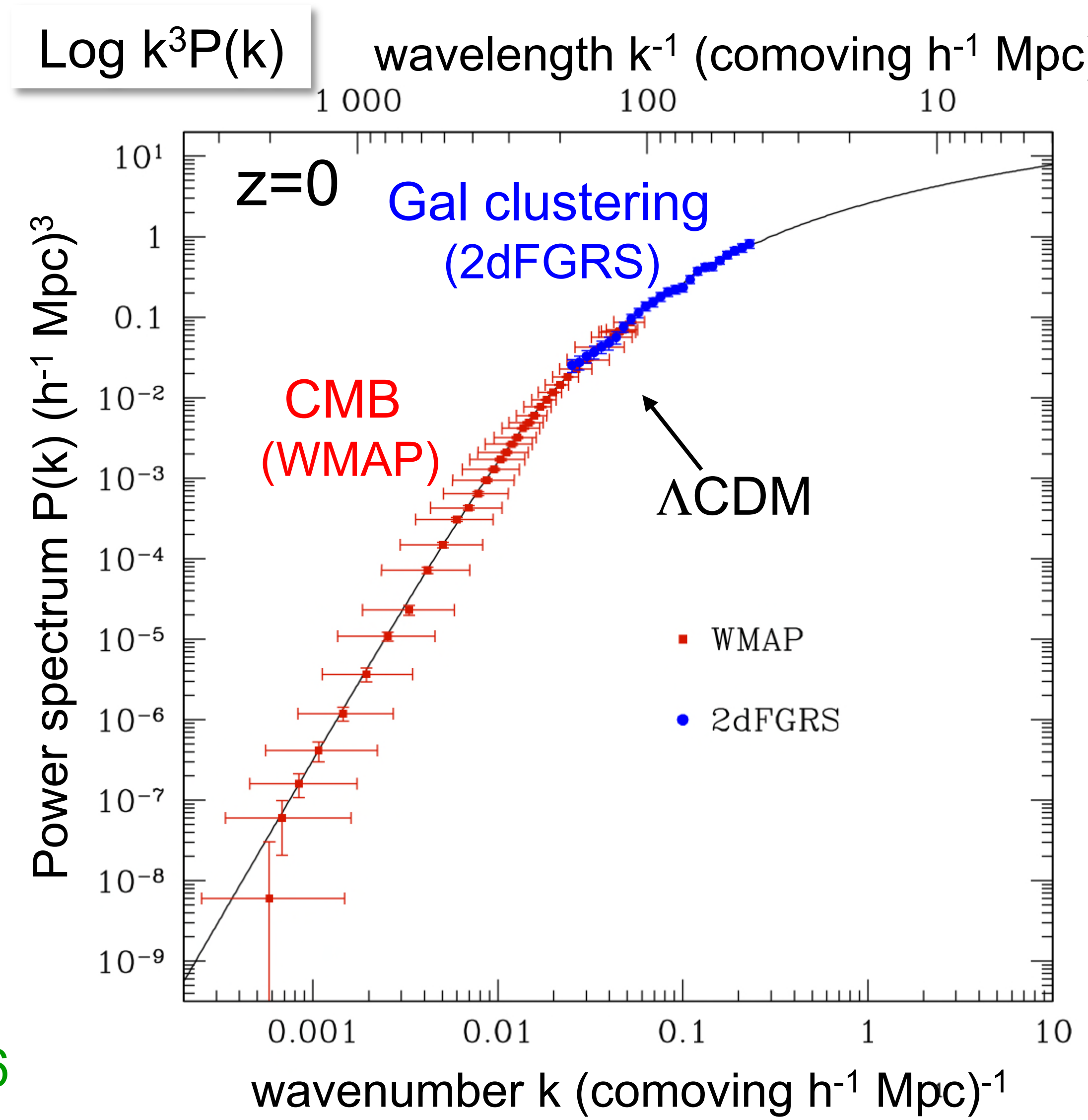
University of Durham



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 →

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

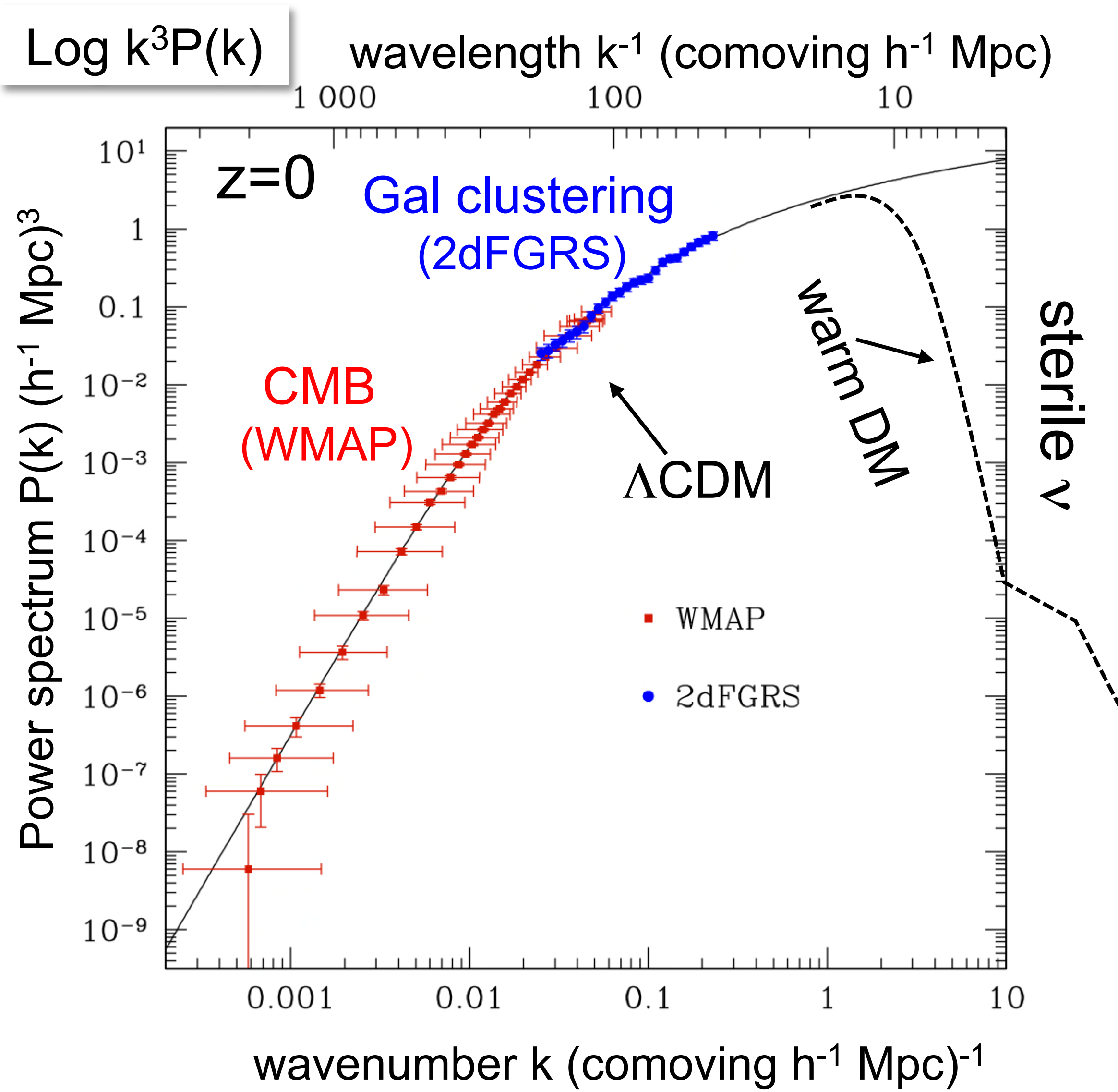
for thermal relic

$m_{CDM} \sim 100$GeV

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



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 I
Preprint typeset using LaTeX

DETECTION OF AN U

Esra Bulbul[1,2], M

[1] Har

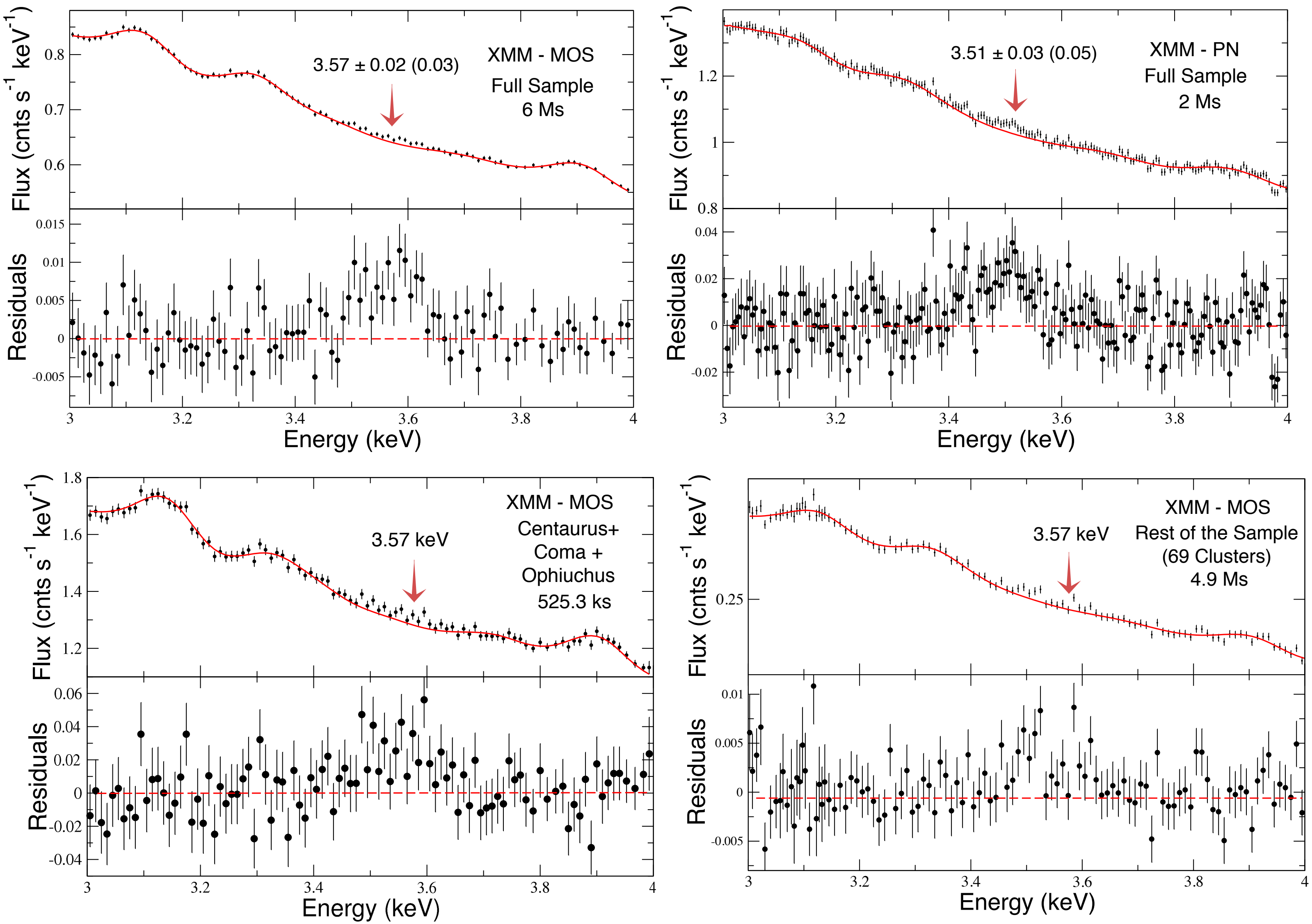
We detect a wea
spectrum of 73 g
independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra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

WDM decay line in 69 stacked clusters?

University of Durham

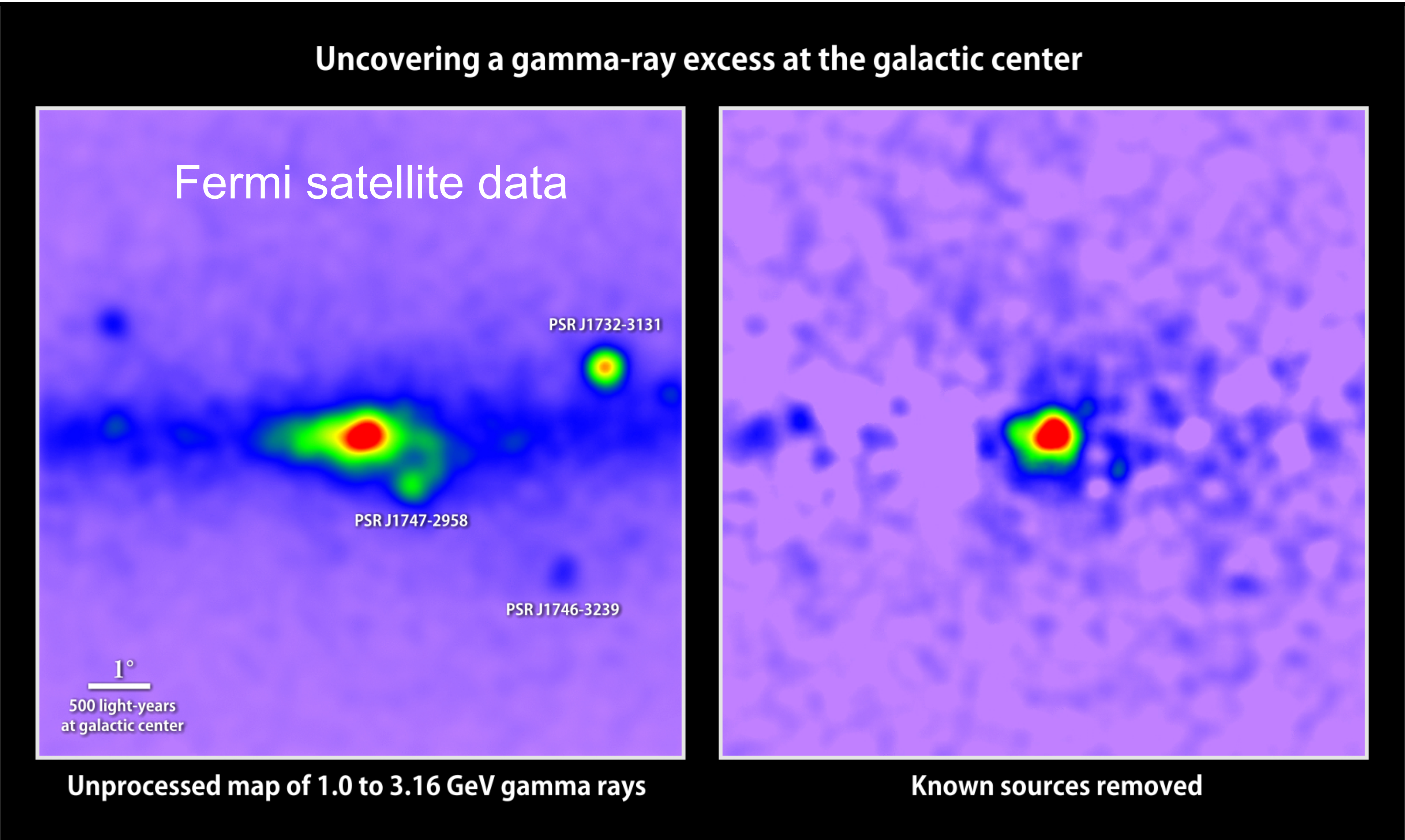
E=3.57 keV

Bulbul et al. '14

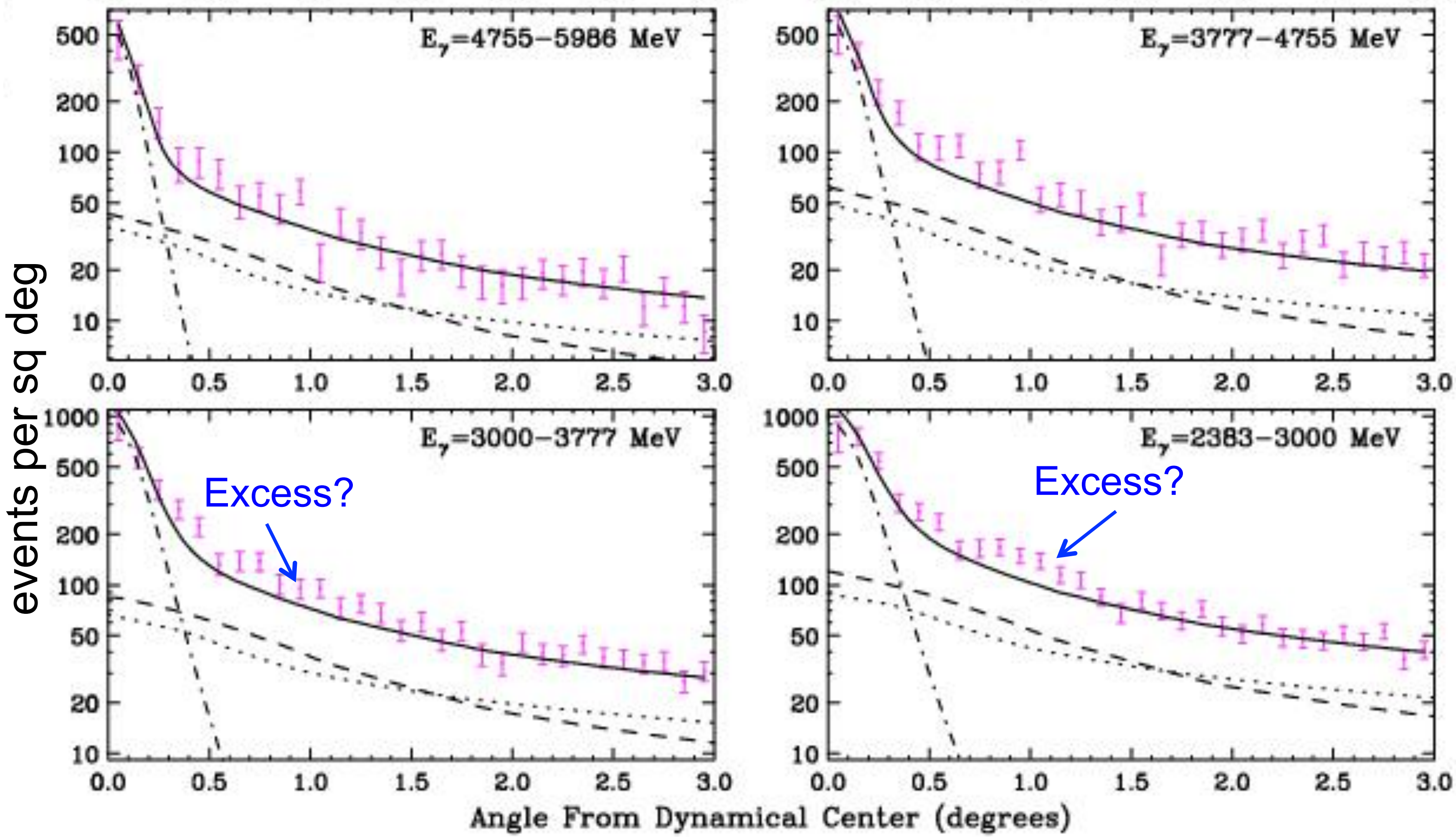


The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

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]



Annihilation radiation from the Galactic Centre?



Hooper & Goodenough '11

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for thermal relic

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

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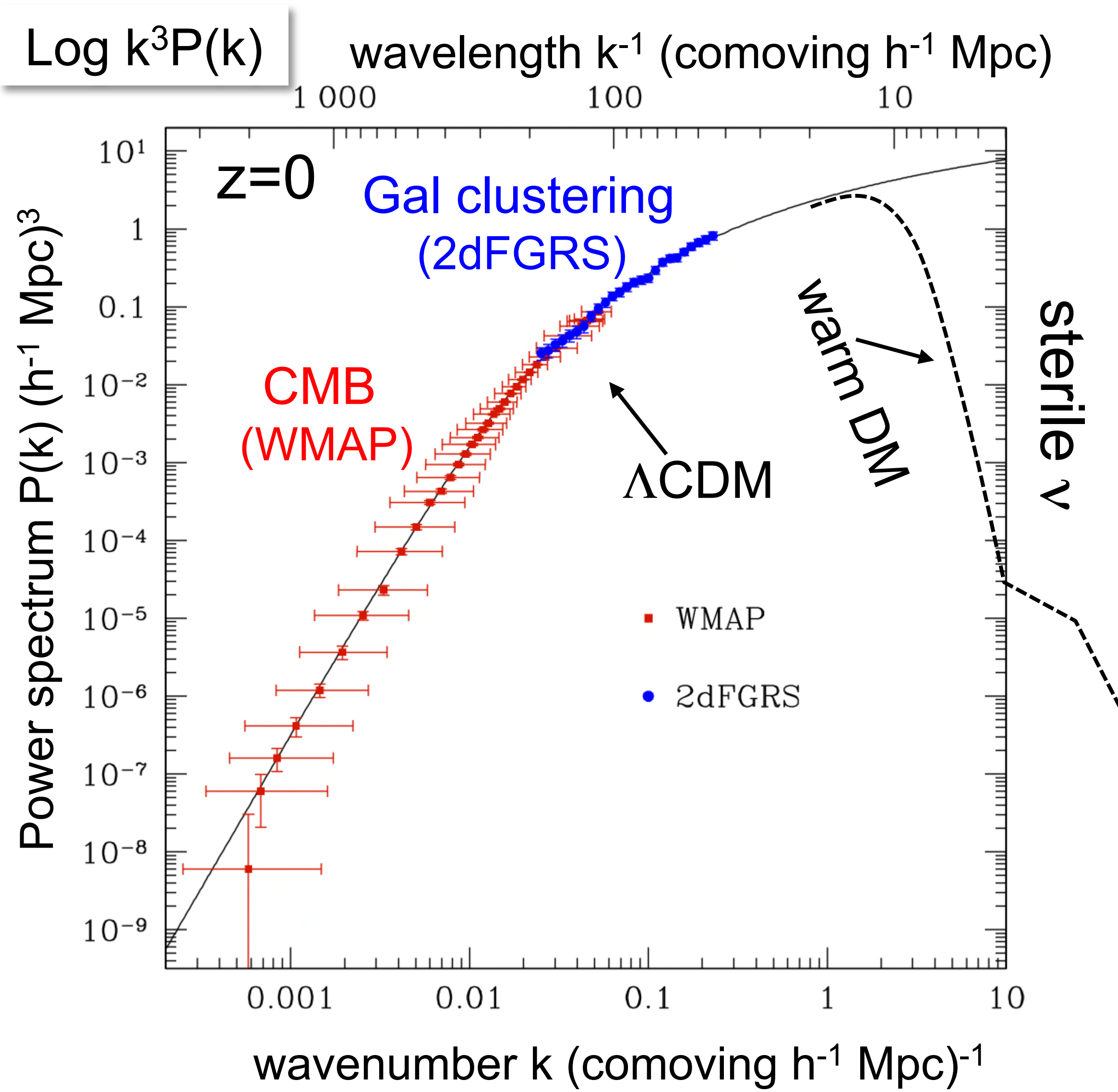
sterile ν; M_{cut}~10^9 M_o



Astrophysical key to identity of dark matter:

→Subgalactic scales

(strongly non-linear)

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

University of Durham

Four problems on small scales

Traditionally ascribed to CDM:

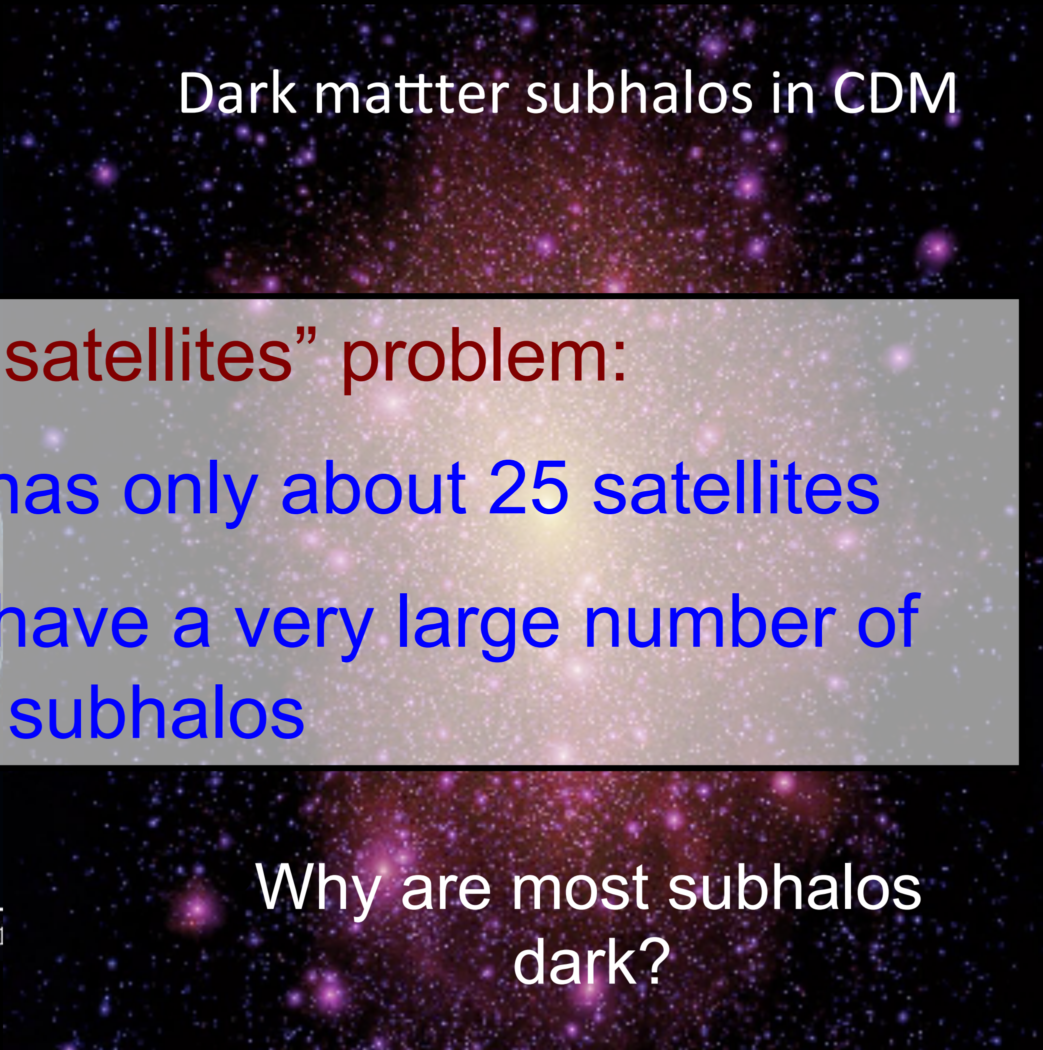
1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “core-cusp” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?

The “missing satellites” problem in CDM

The satellites of the MW

Dark matter 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?

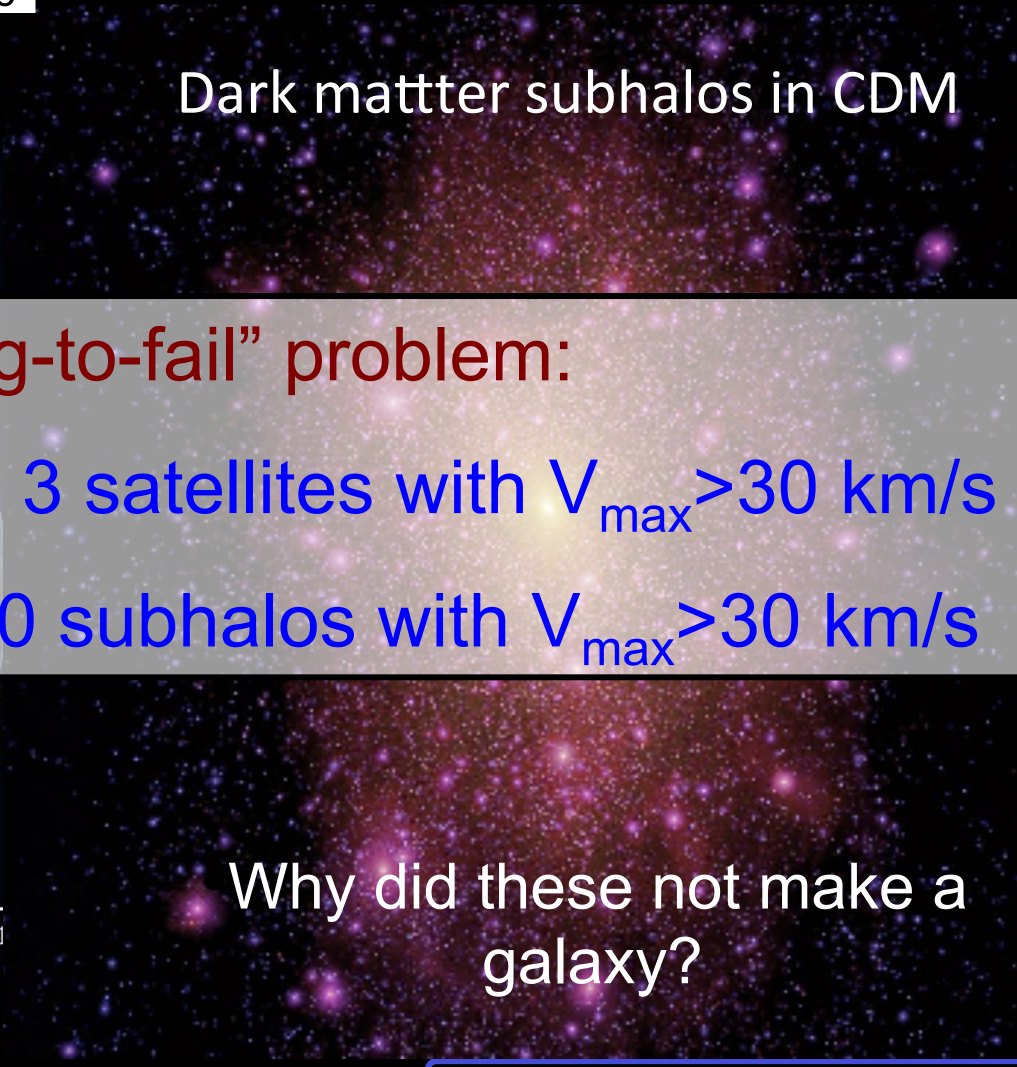
The “too-big-to-fail” problem

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

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

The satellites of the MW

Dark mattter subhalos in CDM



“Too-big-to-fail” problem:

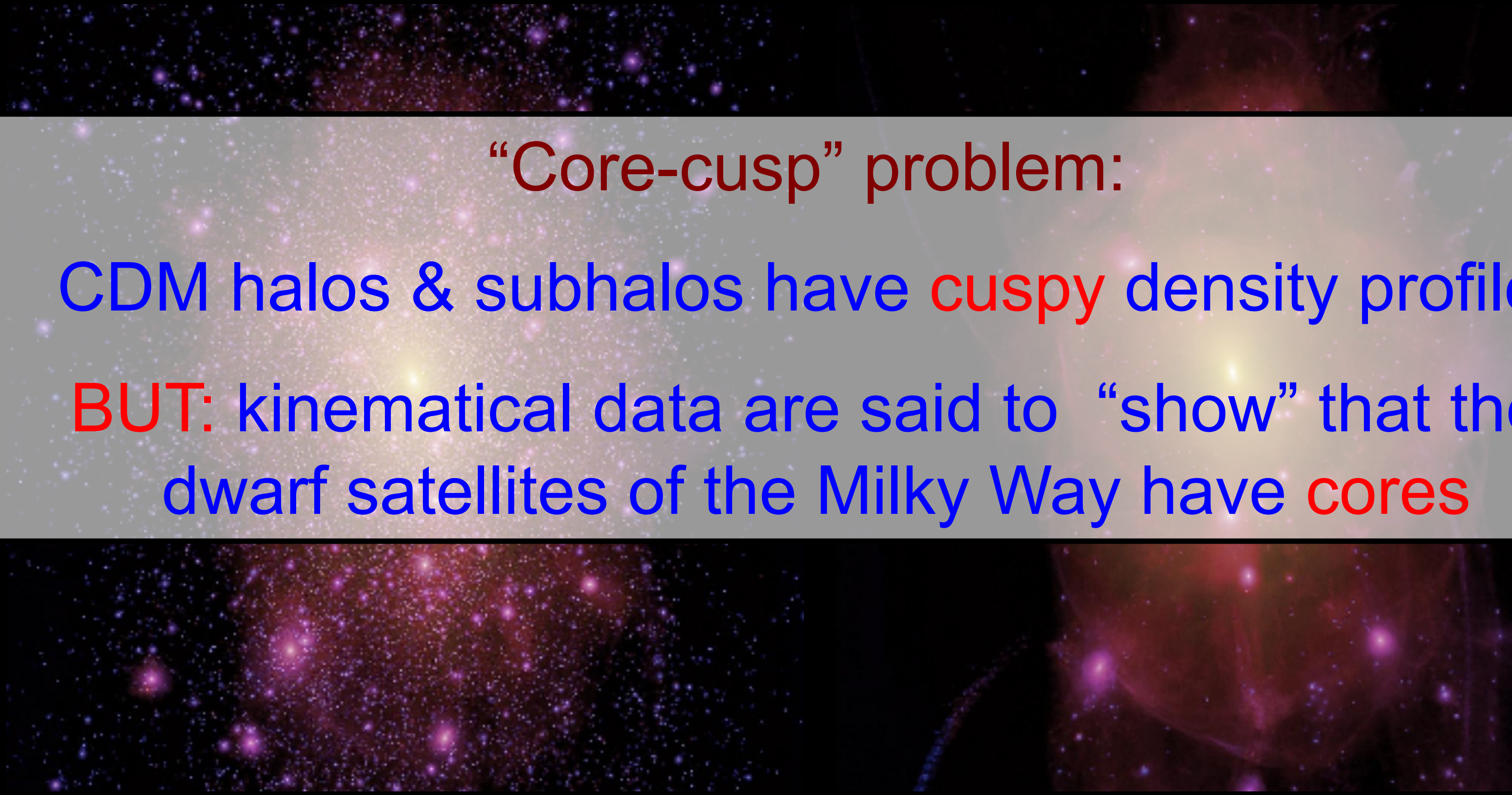
Milky way has only 3 satellites with V_{max}>30 km/s

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

Why did these not make a galaxy?

The core-cusp problem

cold dark matter | warm dark matter



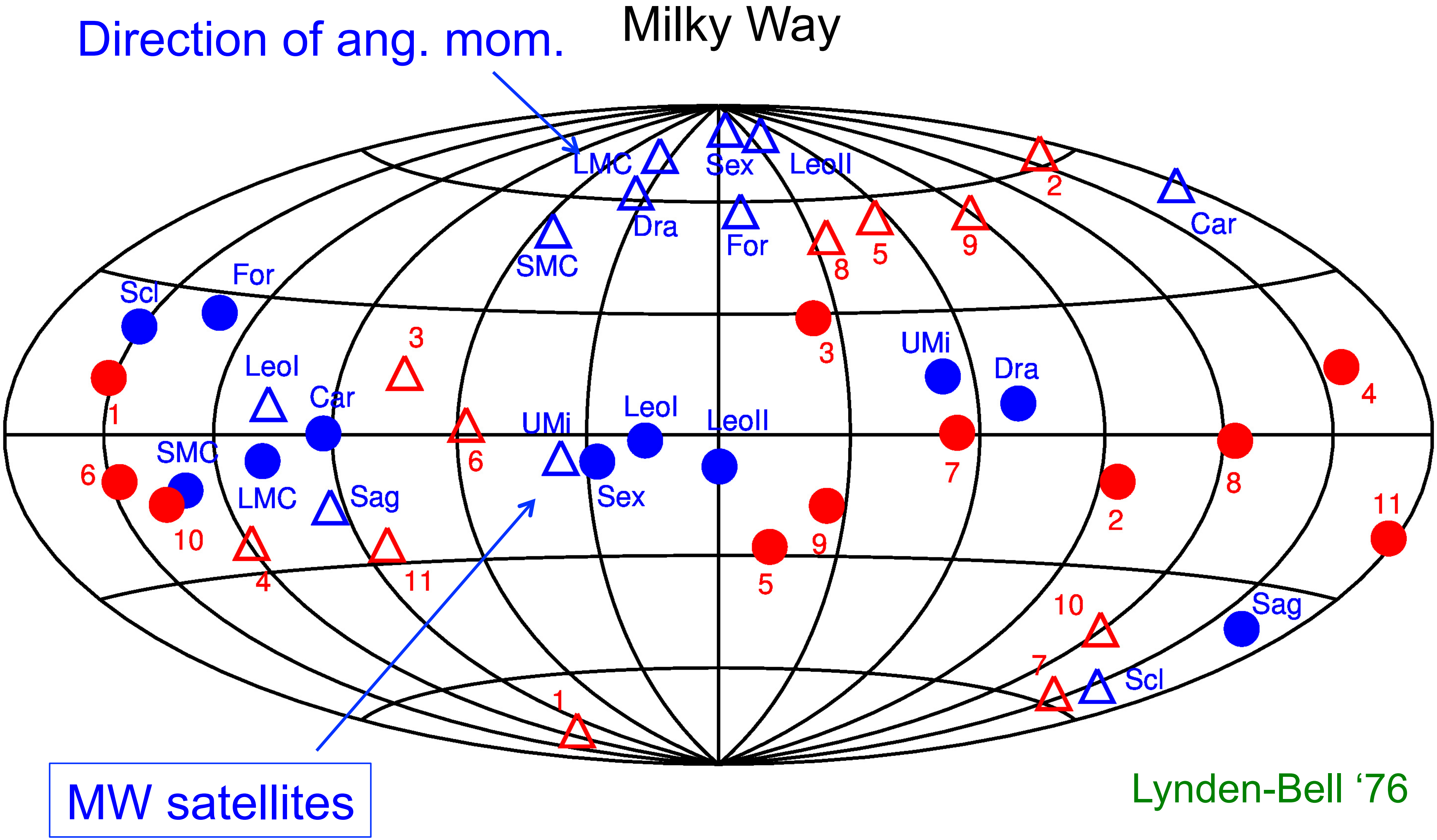
"Core-cusp" problem:

CDM halos & subhalos have cuspy density profiles

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

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

The "satellite disk" problem

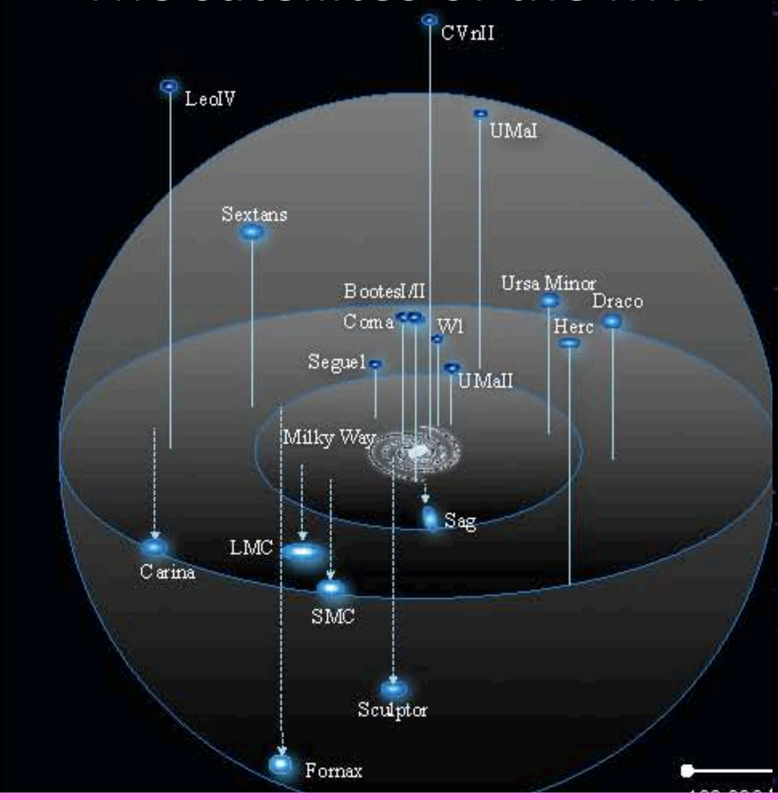


Lynden-Bell '76

Does warm dark matter also suffer from these four “problems”?

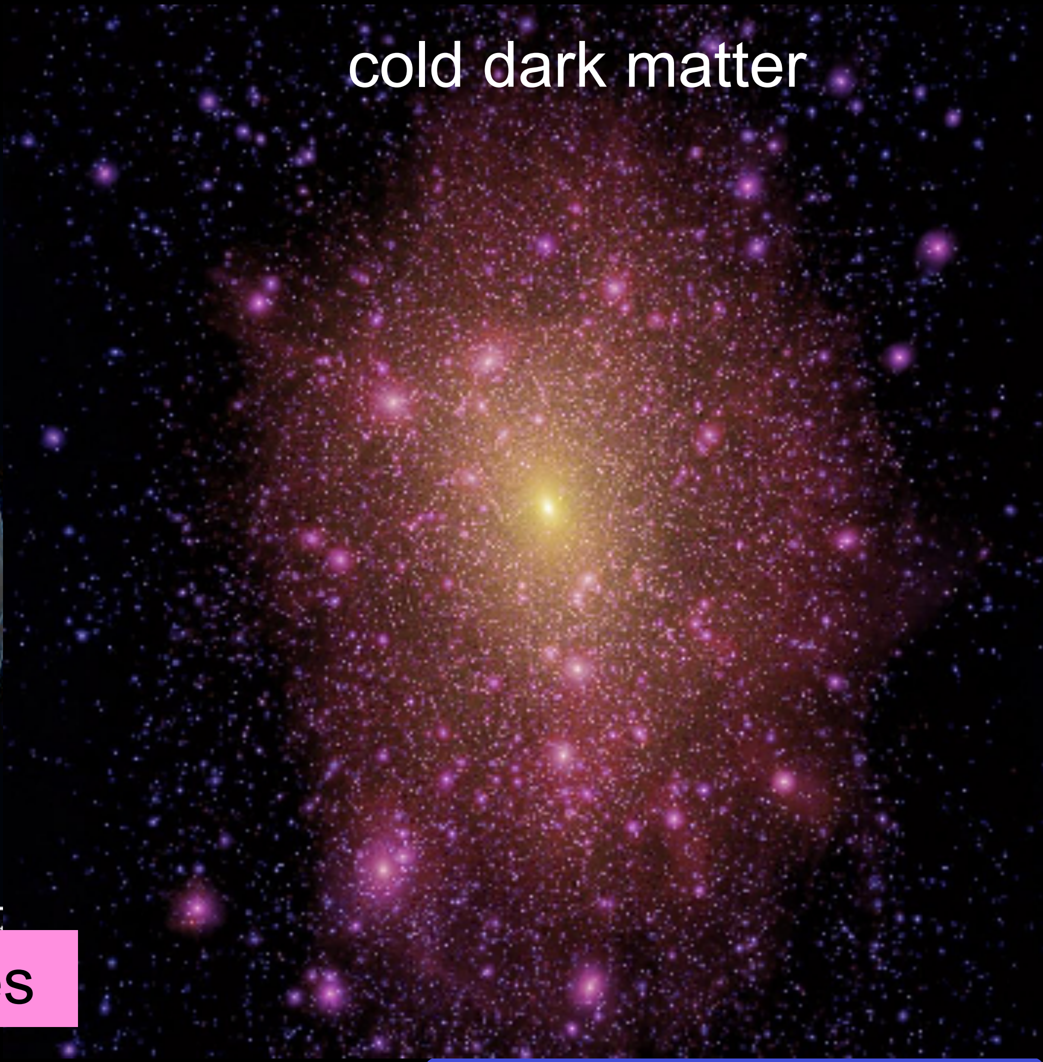
The "missing satellites" problem

The satellites of the MW



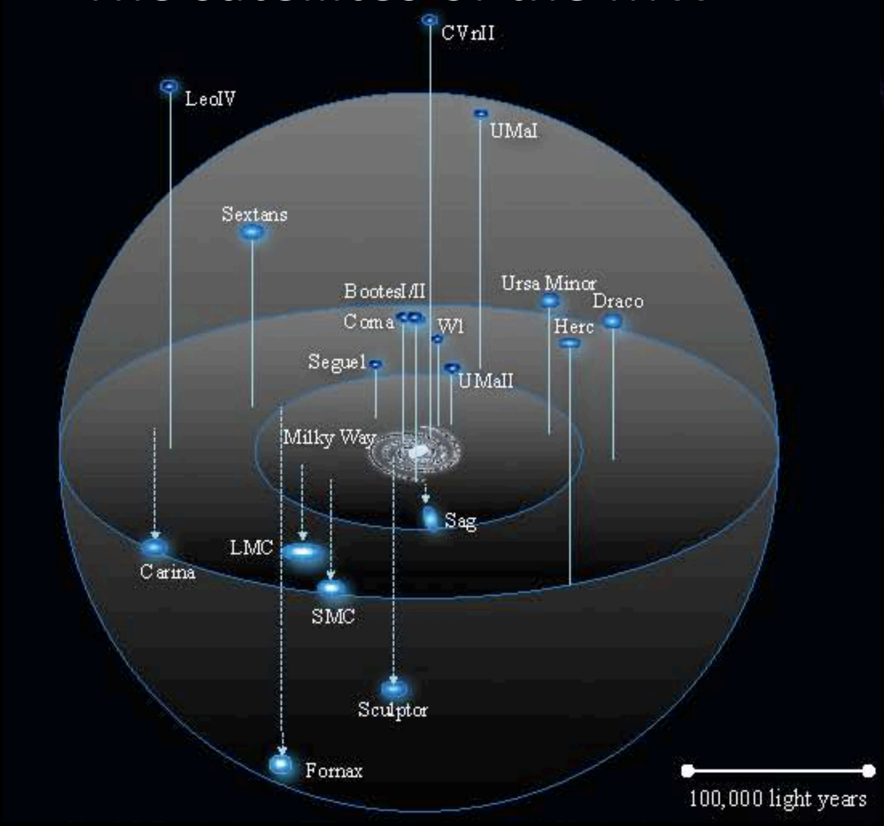
MW has only ~25 satellites

cold dark matter

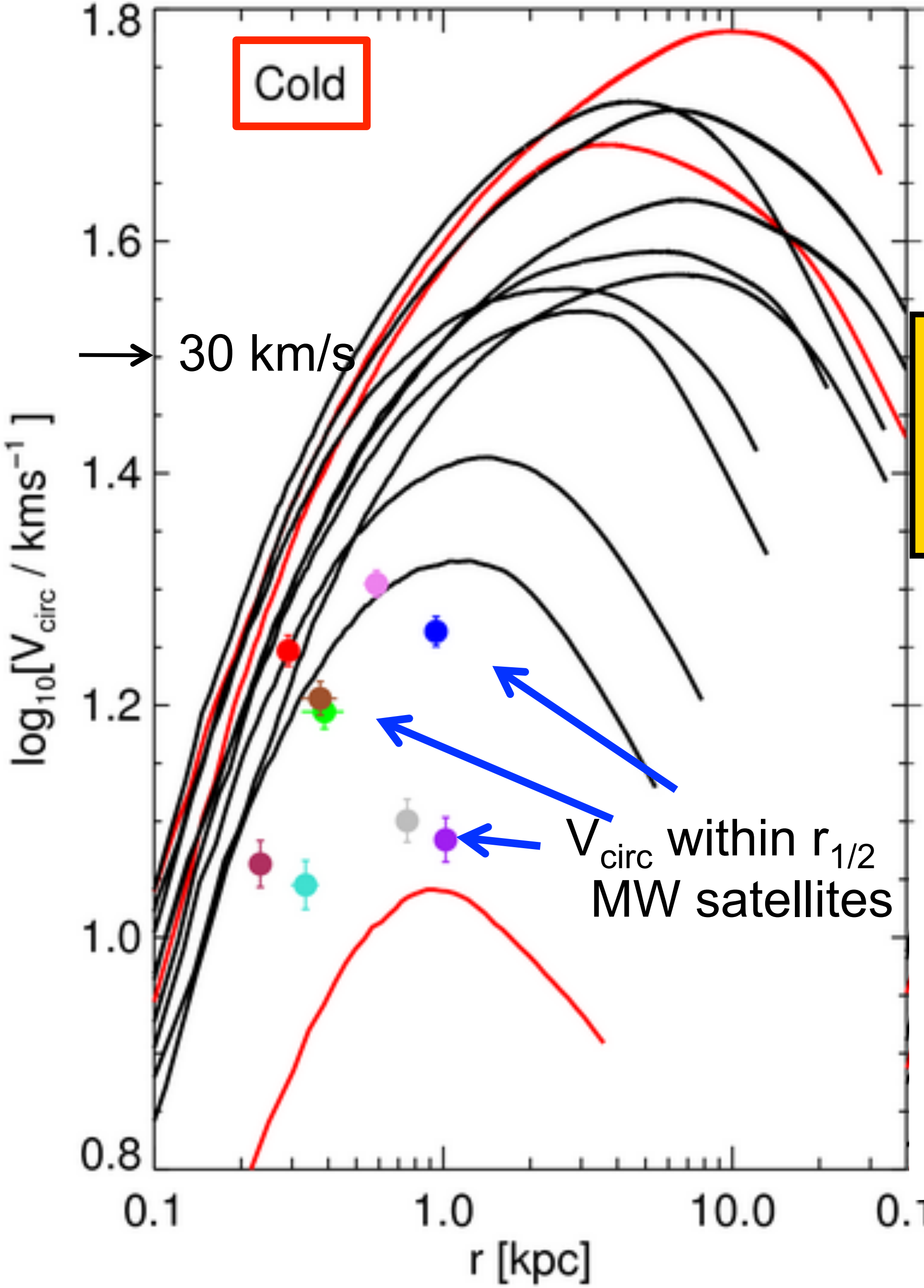


The “missing satellites” problem

The satellites of the MW



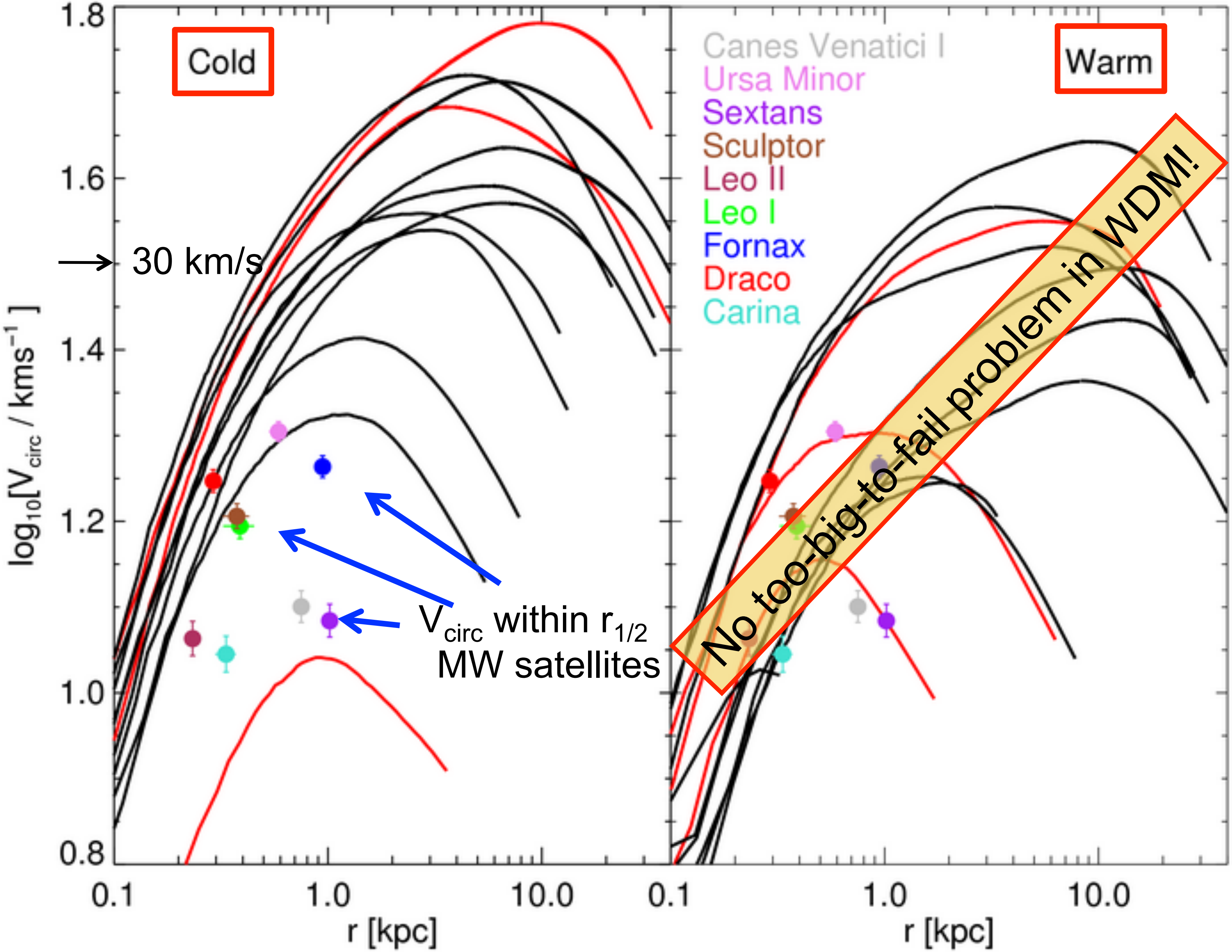
warm dark matter



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

The "too-big-to-fail" problem

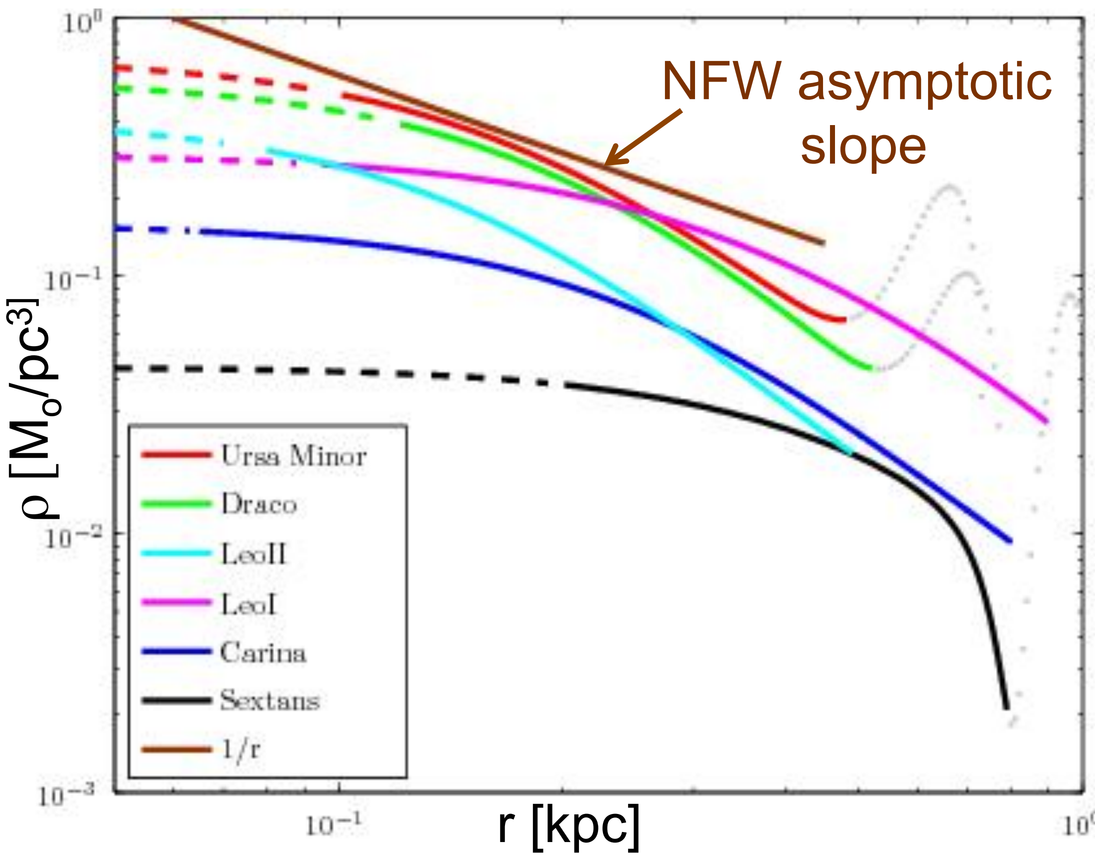
Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '11



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

The DM halos of dwarf spheroidals

University of Durham



Gilmore etal '07

Inferred density profiles for 6 dwarf spheroidals

"… the central DM density profile is typically cored, not cusped, with scale sizes never less than a few hundred pc …"

"… (keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here."

Institute for Computational Cosmology

Some of these arguments are WRONG!

University of Durham

Four problems on small scales

Traditionally ascribed to CDM:

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University of Durham

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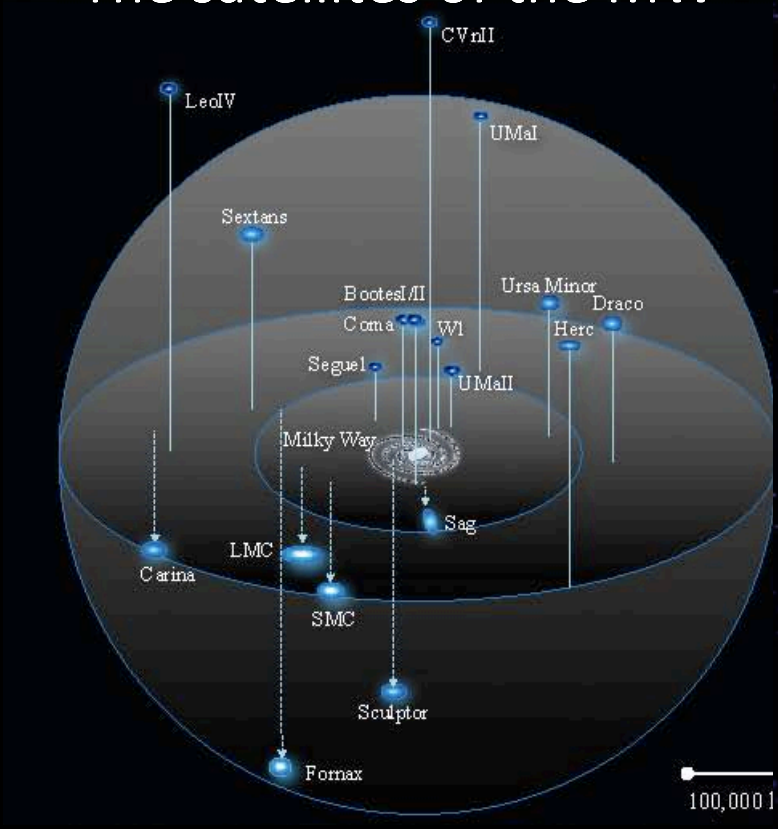
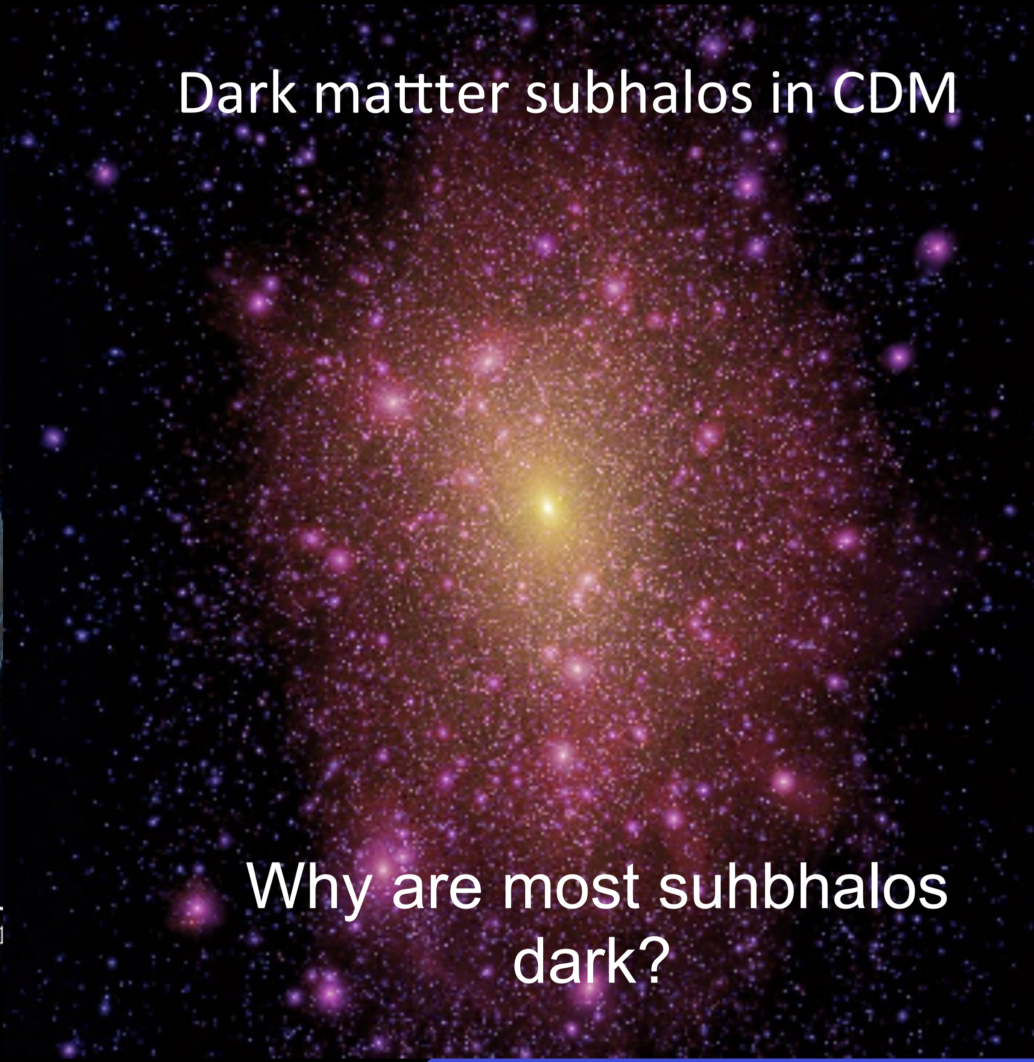


Dark mattter subhalos in CDM



Why are most suhbhalos dark?

Making a galaxy in a small halo is hard because:

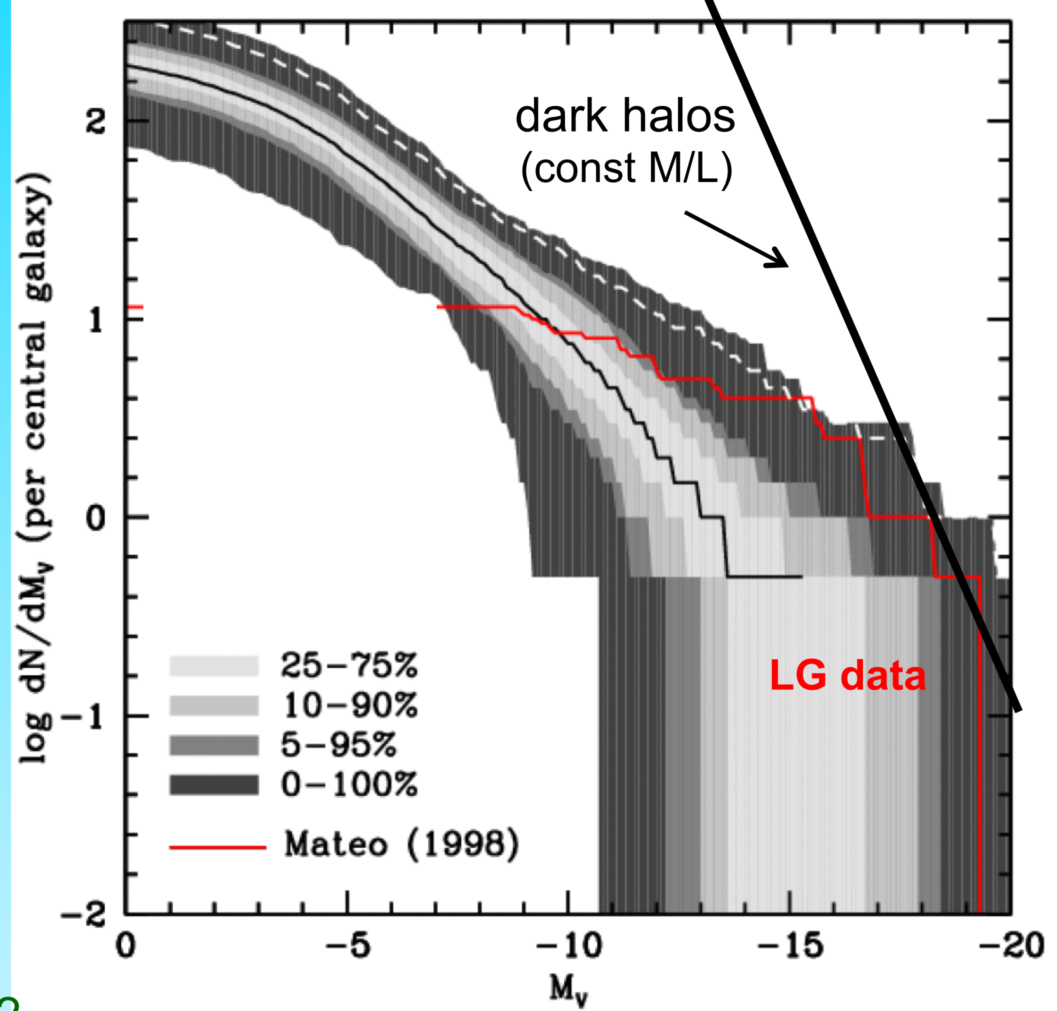
- Reionization heats gas above T_{vir}, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels residual gas

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)

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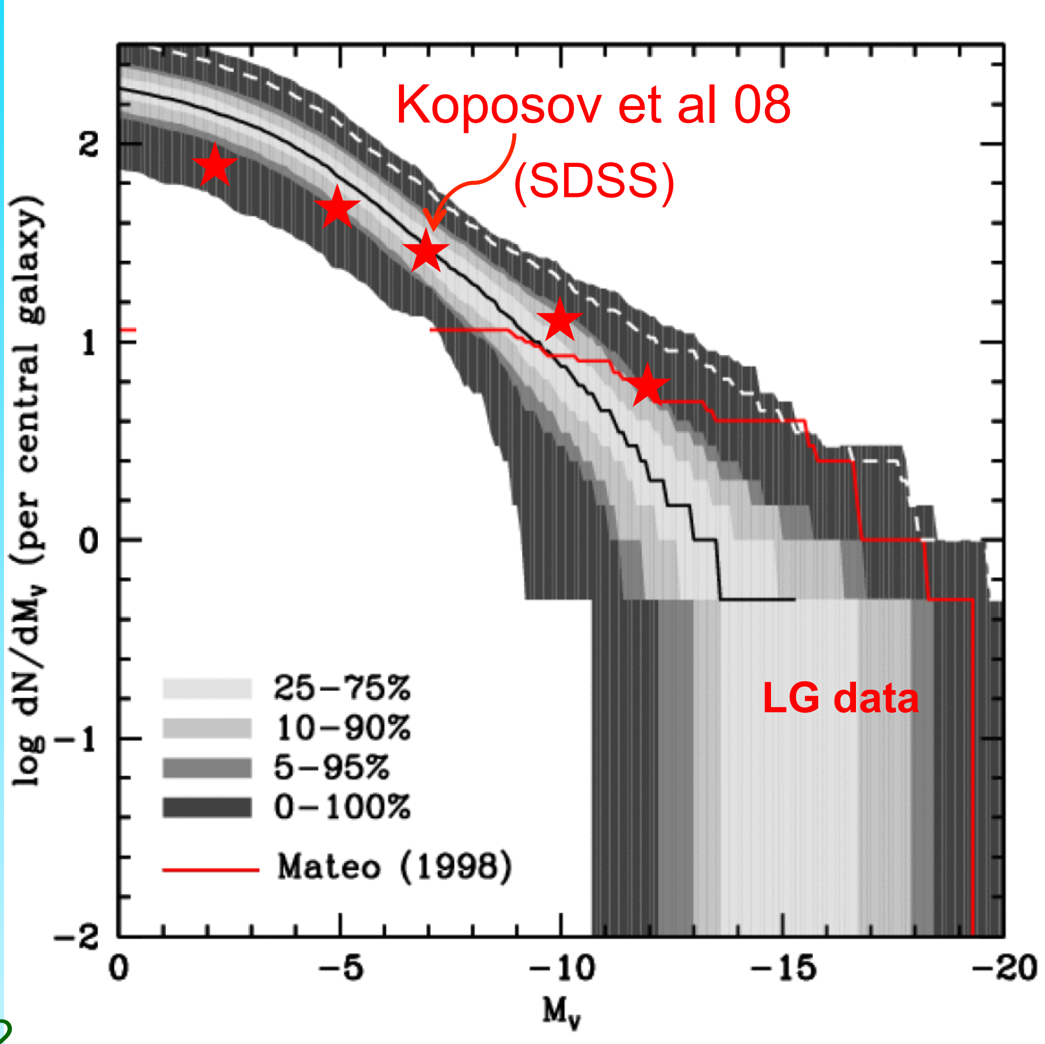


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

VIRGO

EAGLE full hydro simulations

Local Group

Sawala et al ‘15

Far fewer satellite galaxies than CDM halos

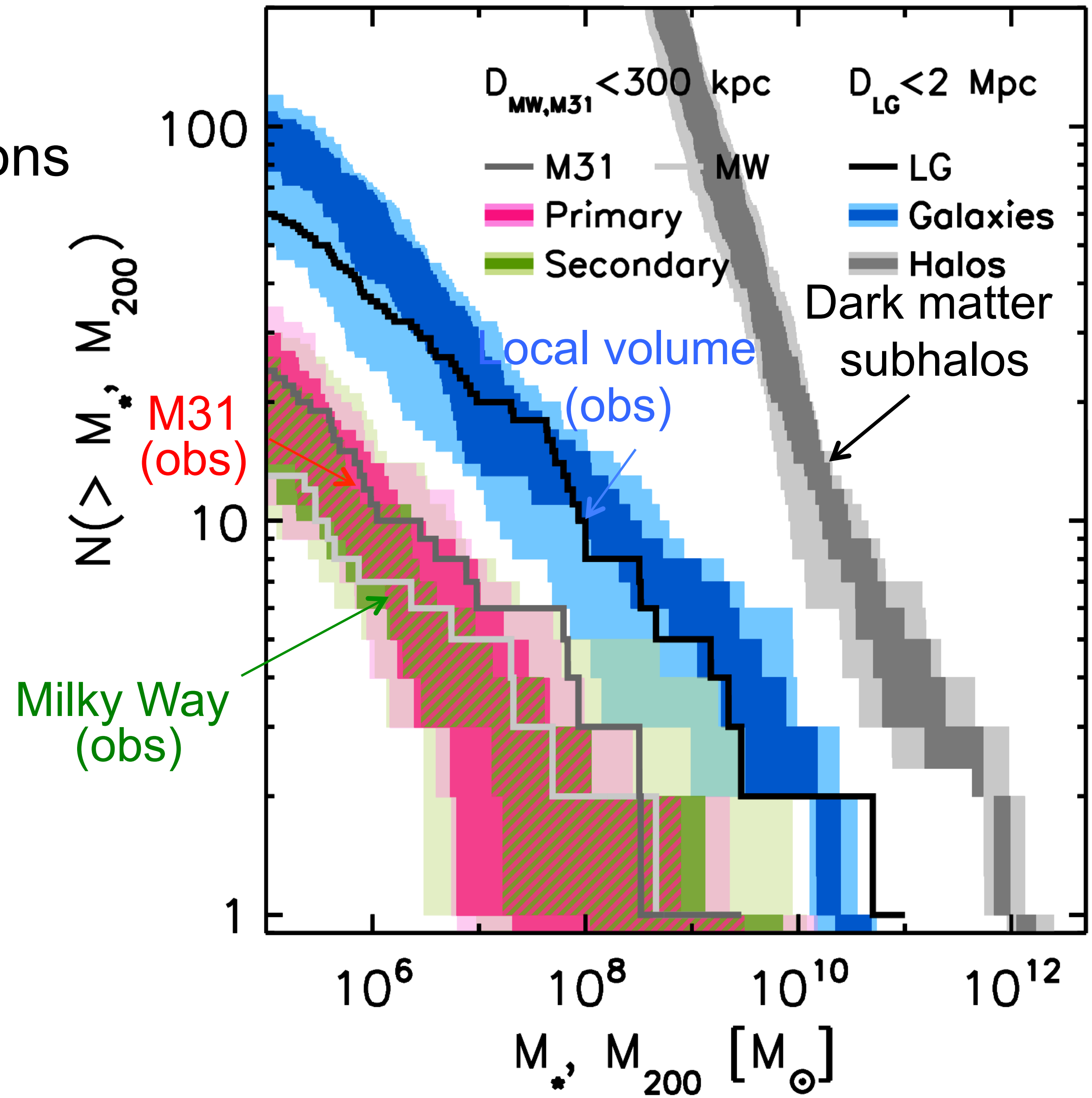
EAGLE full hydro simulations

Local Group

Sawala et al '15

EAGLE Local Group simulation

Stellar mass functions



Sawala et al '15

Is there a "satellite problem" in CDM?

No, when galaxy formation is taken into account!

Is there a “satellite problem” in WDM?

Potentially!

Warm DM: different ν mass

z=3

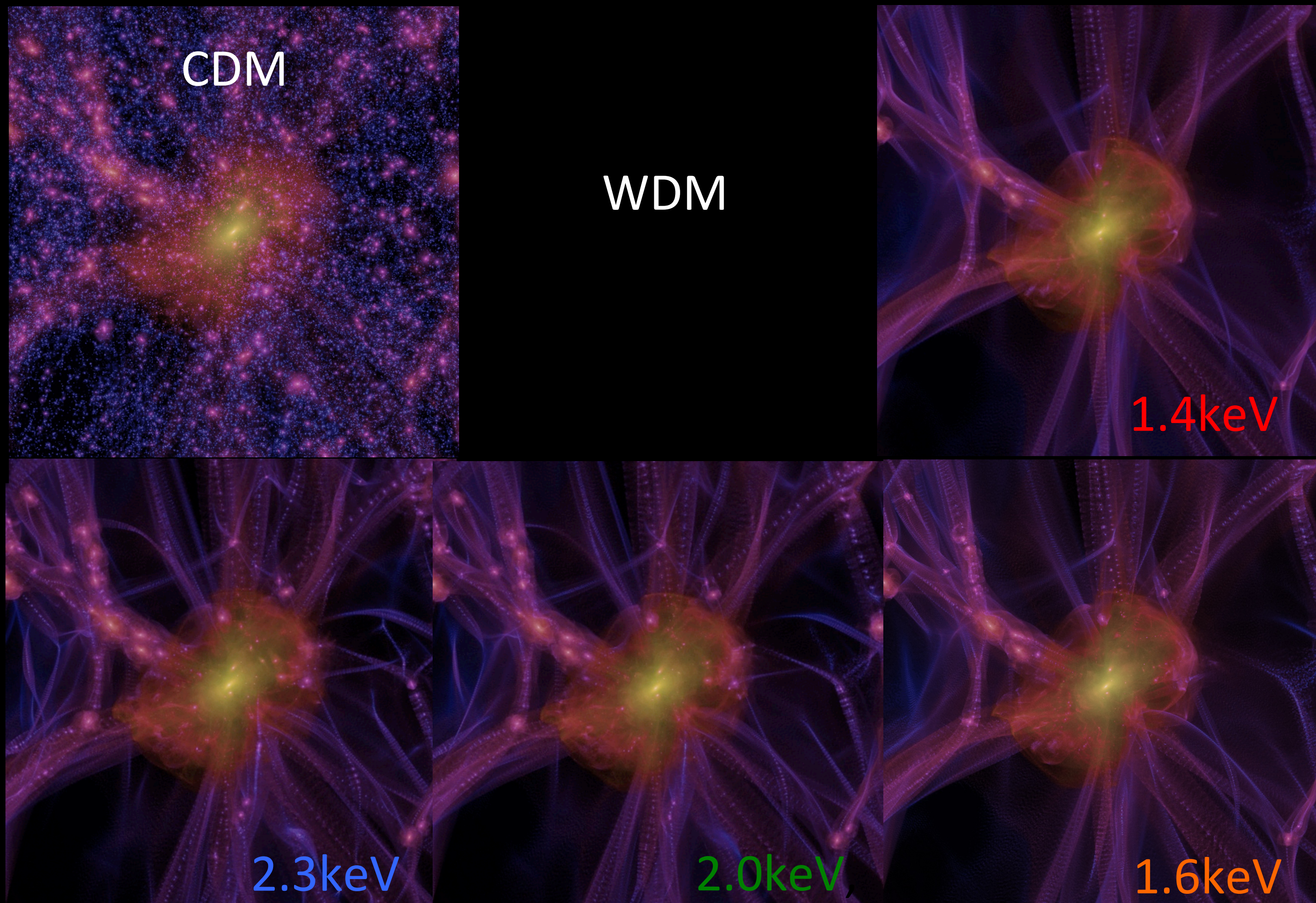
WDM

2.3 keV

2.0 keV

1.6 keV

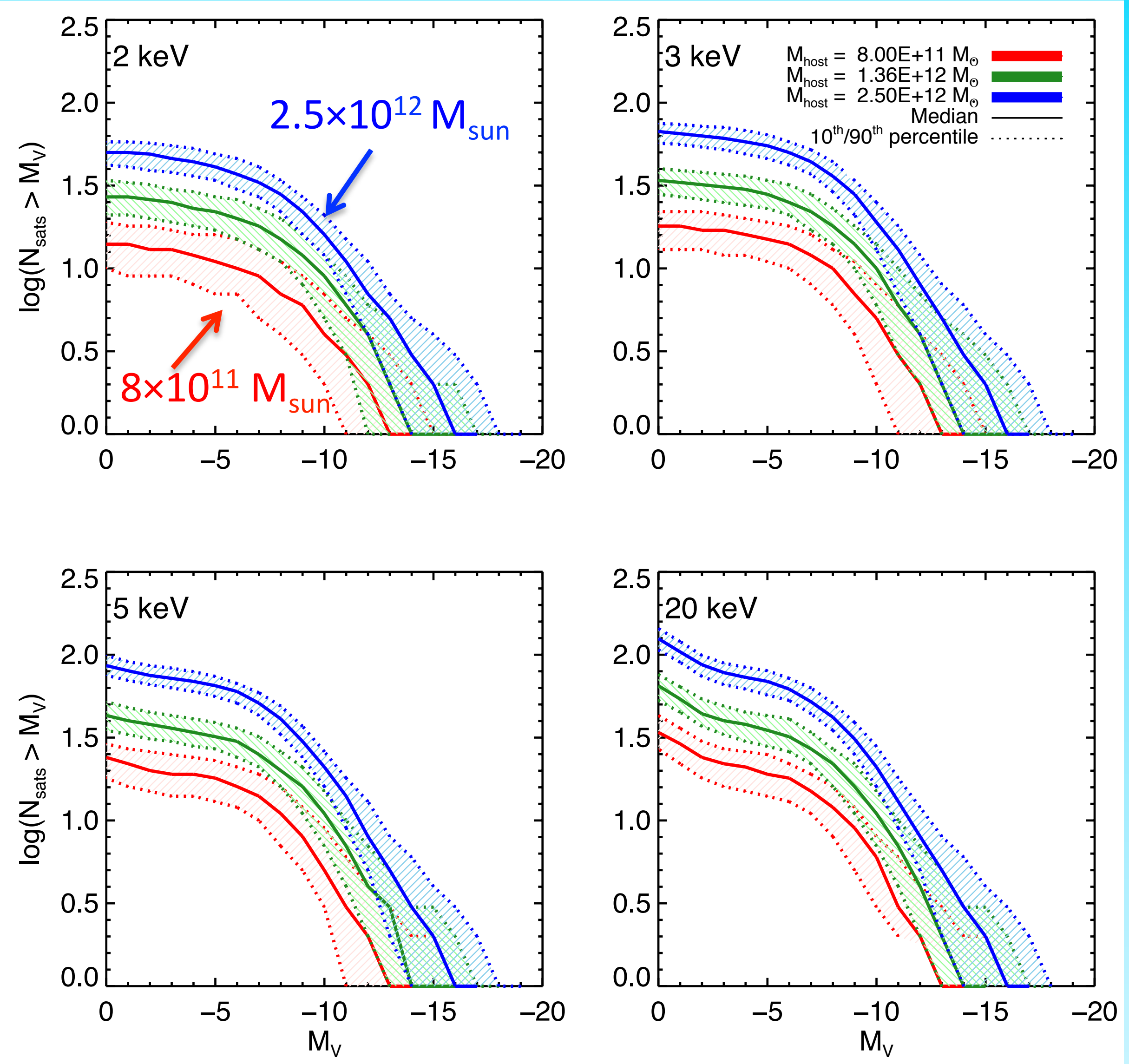
1.4 keV



Luminosity Function of Local Group Satellites in WDM

No of sats ↗ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

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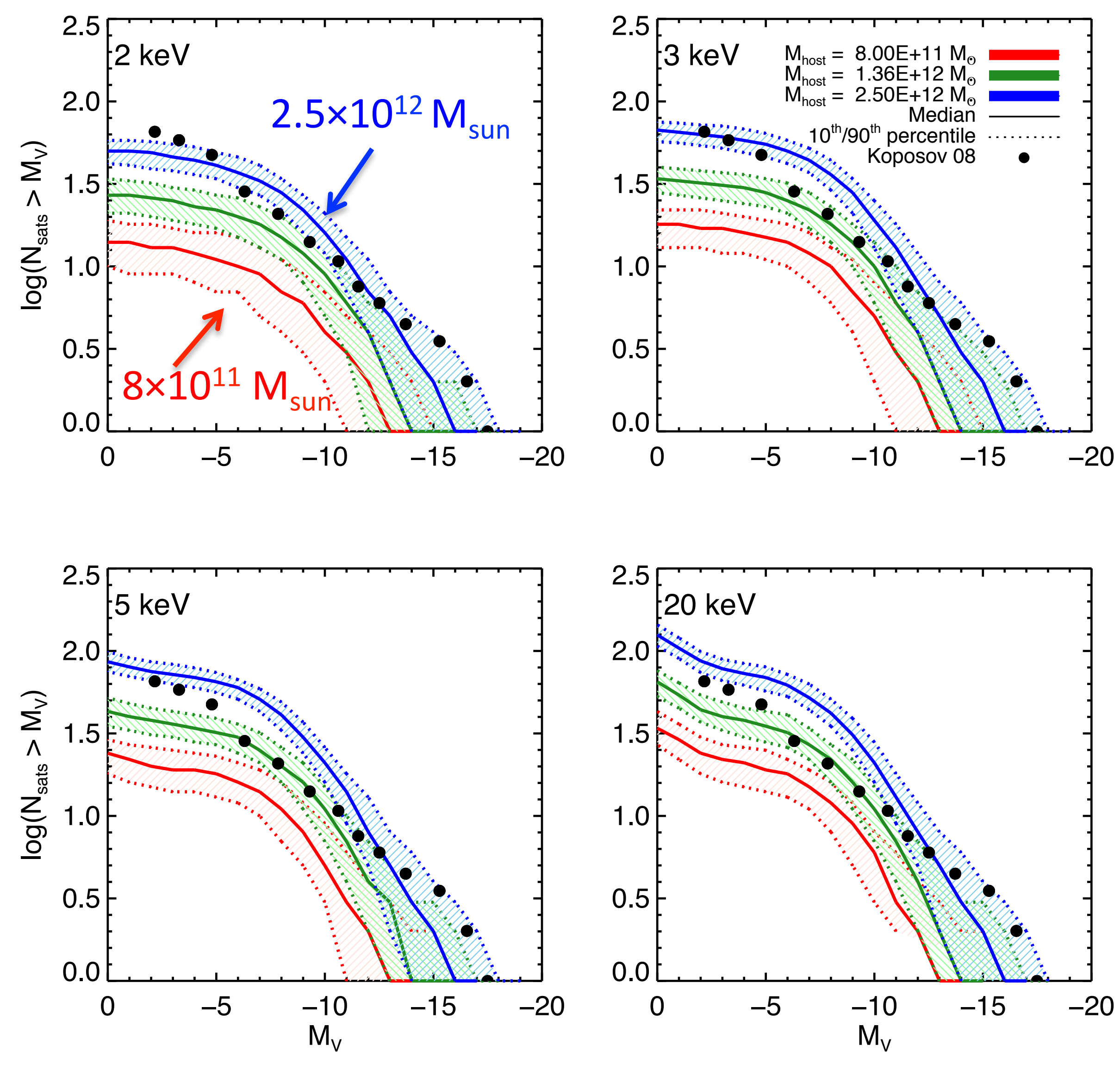


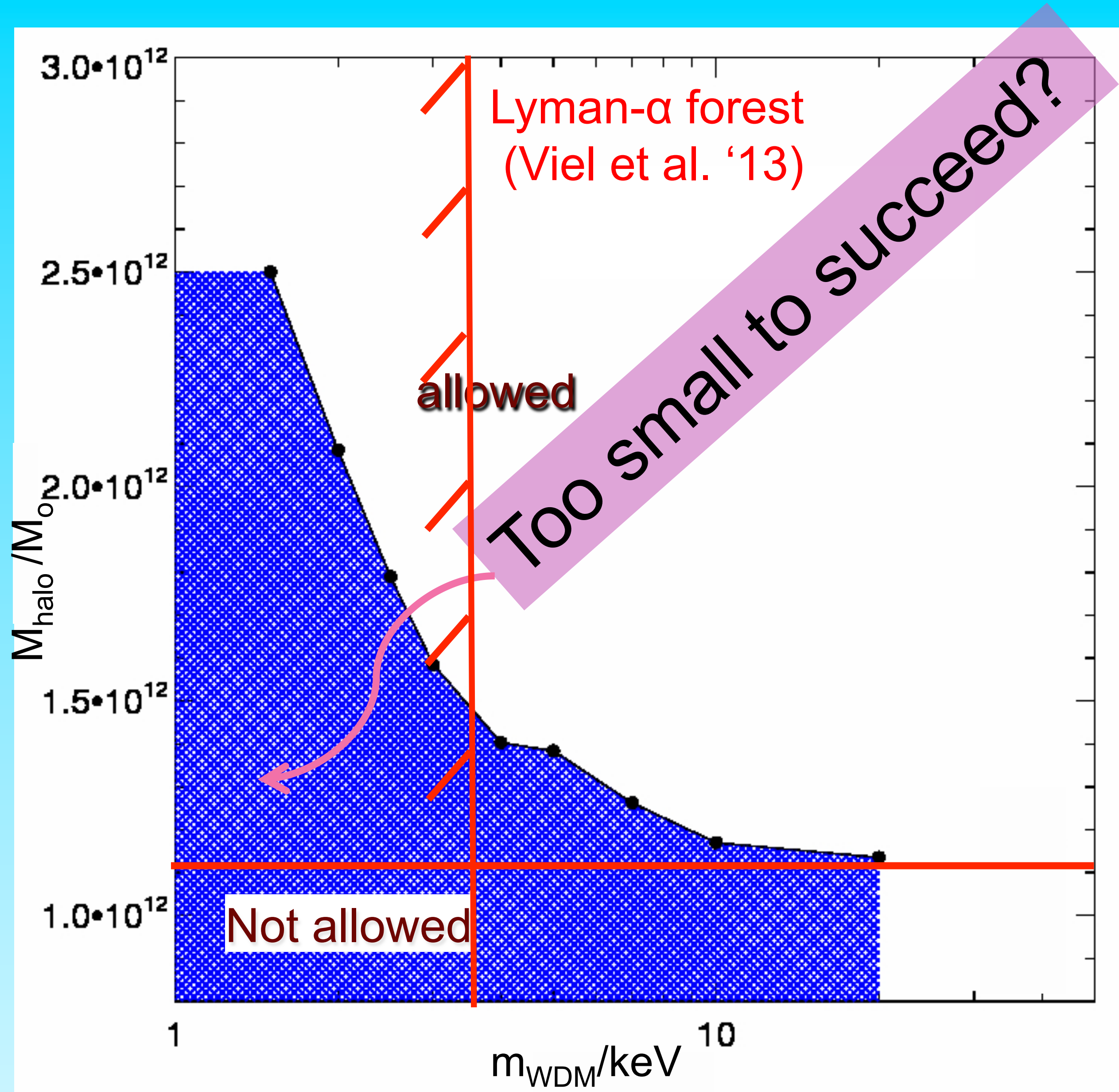
Kennedy, Cole & Frenk '13

Limits on WDM particle mass

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

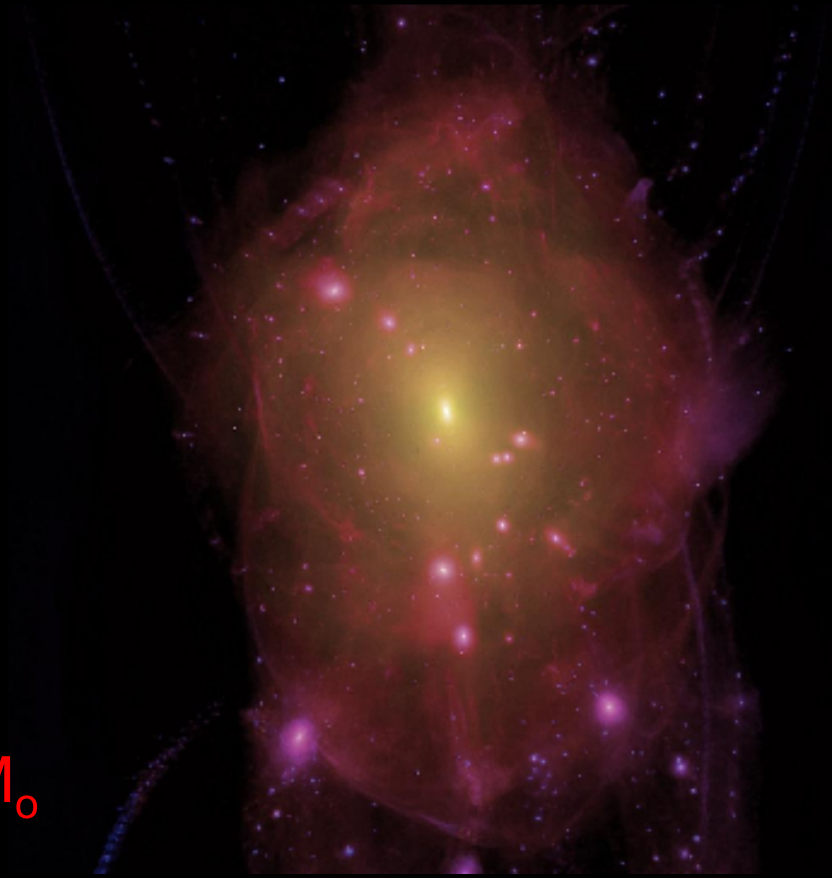
For standard galaxy formation model, WDM ruled out if $M_{halo} < 1.1 \times 10^{12}\ M_o$

Kennedy, Cole & Frenk ‘14



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

University of Durham

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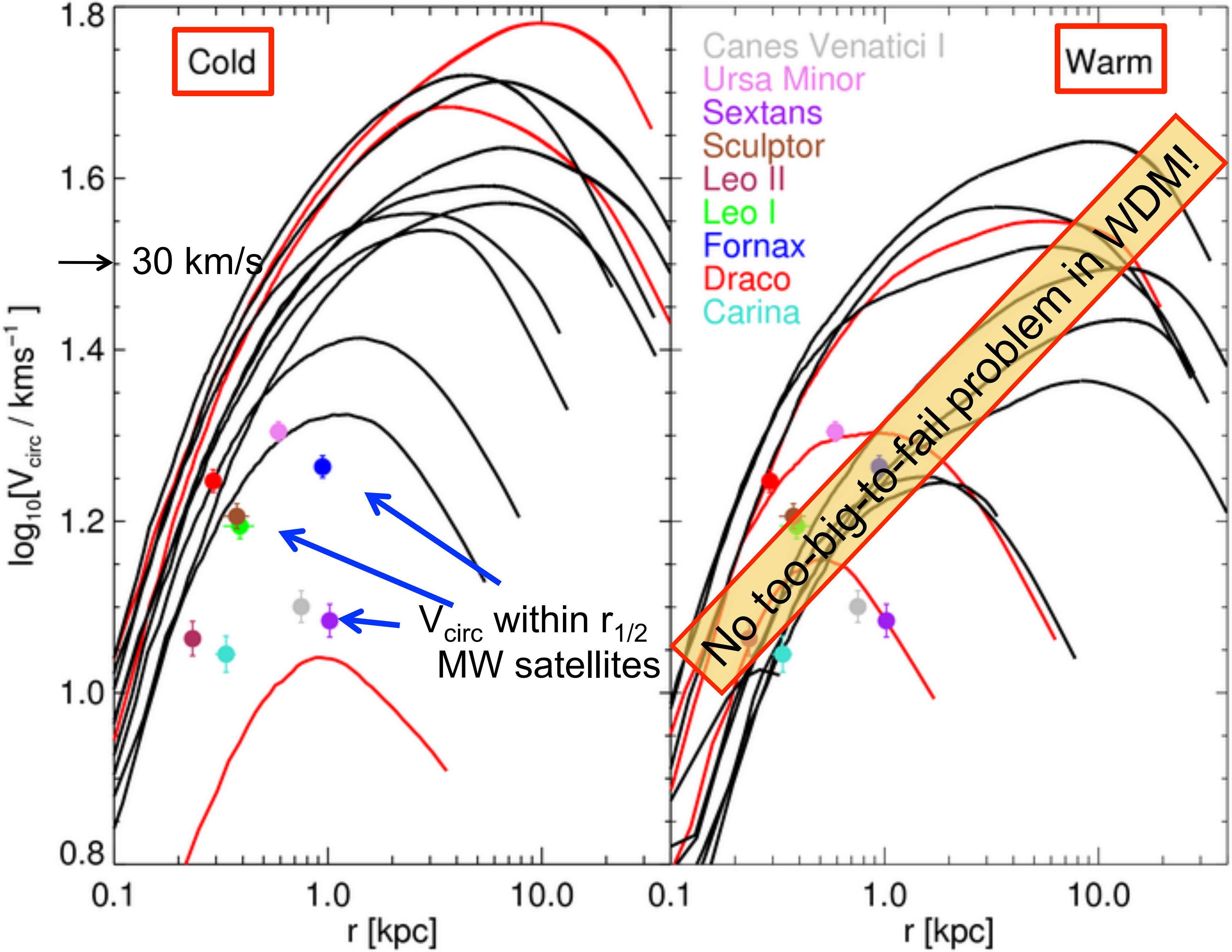

Cold
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Canes Venatici I
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30 km/s
V_{circ} within $r_{1/2}$
MW satellites
No too-big-to-fail problem in WDM!
$\log_{10}[V_{circ} / \mathrm{kms}^{-1}]$
r [kpc]
0.1
1.0
10.0
0.8
1.0
1.2
1.4
1.6
1.8

Warm vs cold dark matter subhalos

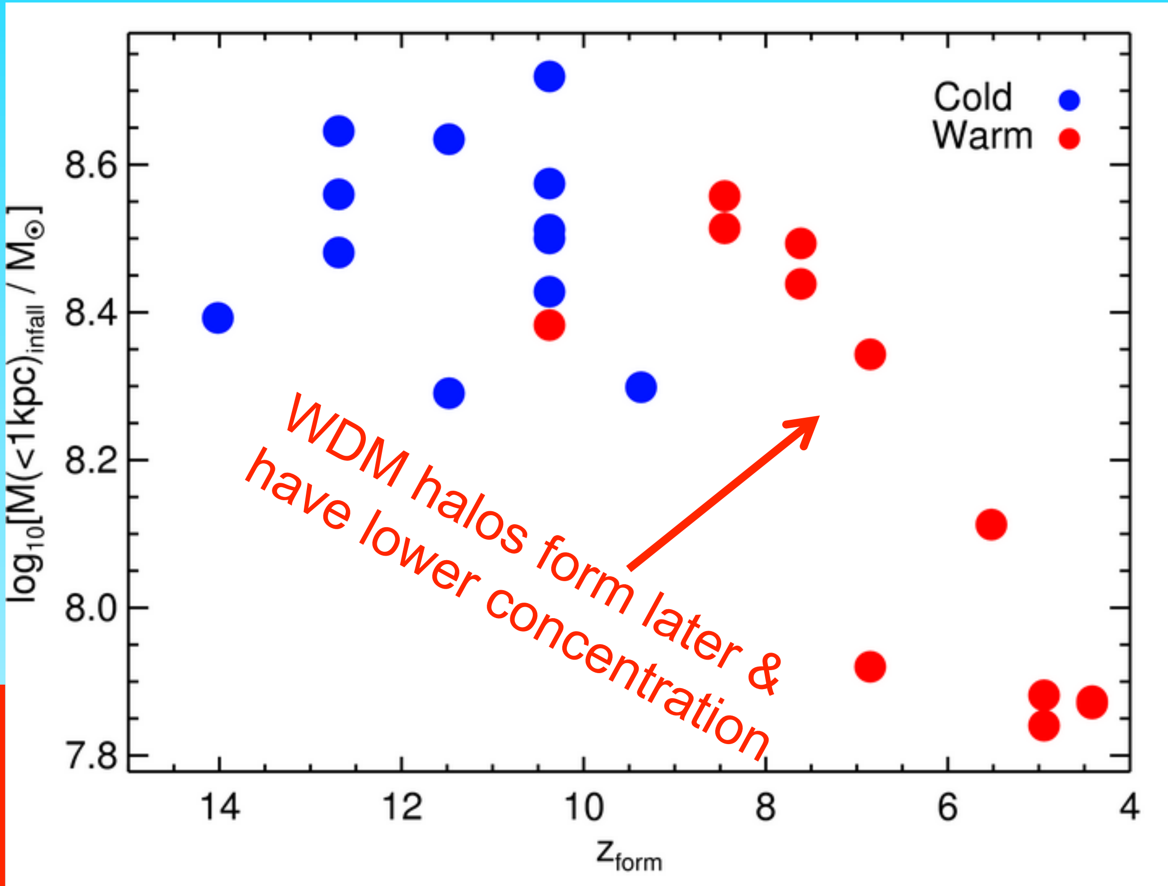
University of Durham

"Formation redshift"
→ z at which M_{halo} first exceeded $M_{infall}(<1kpc)$

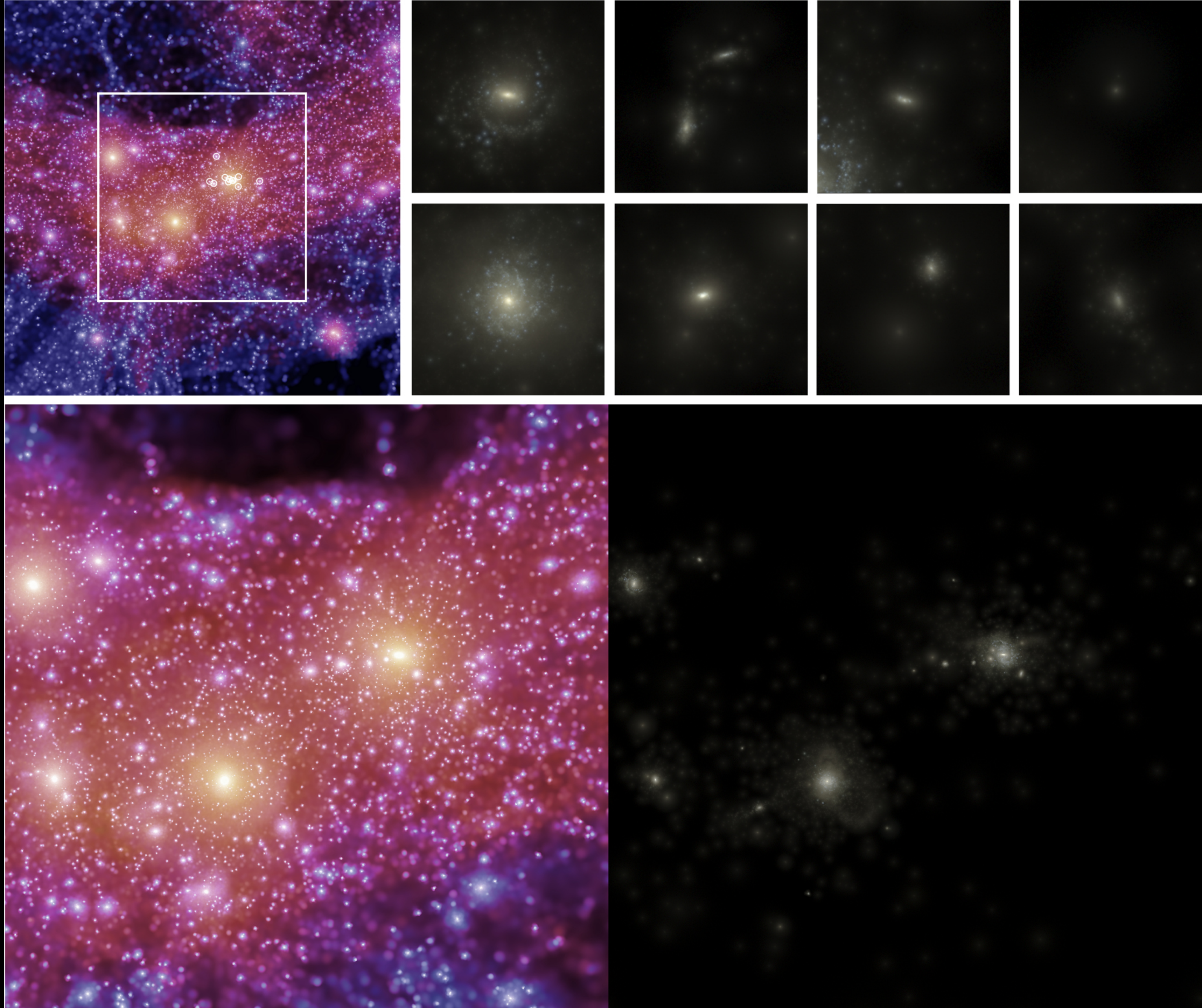
WDM halos form later & have lower central masses than their CDM counterparts!

→

WDM subhalos are still cuspy but are less concentrated than CDM subhalos



Lovell, Eke, Frenk, Gao, Jenkins et al '11



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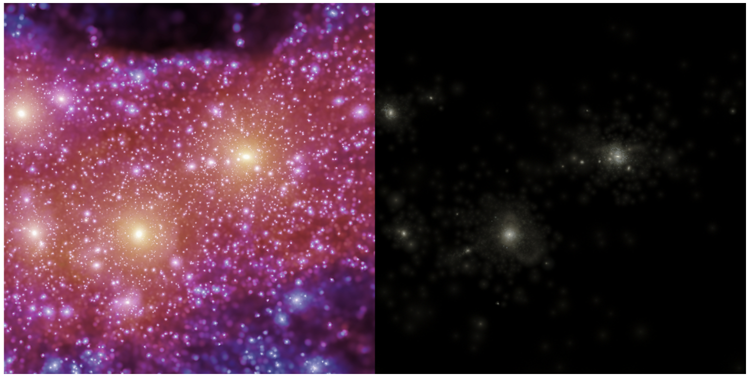
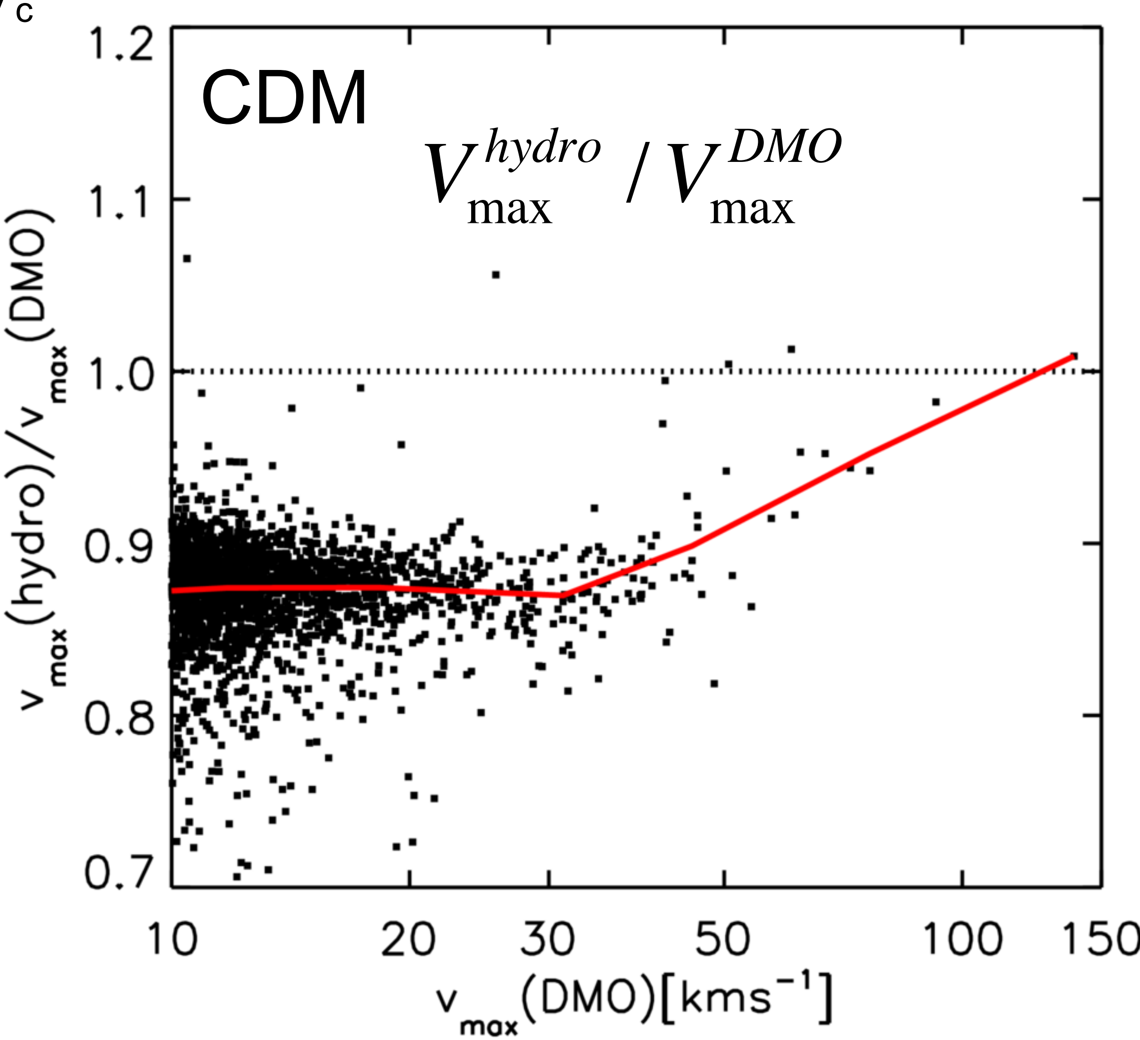
To-big-to-fail in CDM: baryon effects

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate



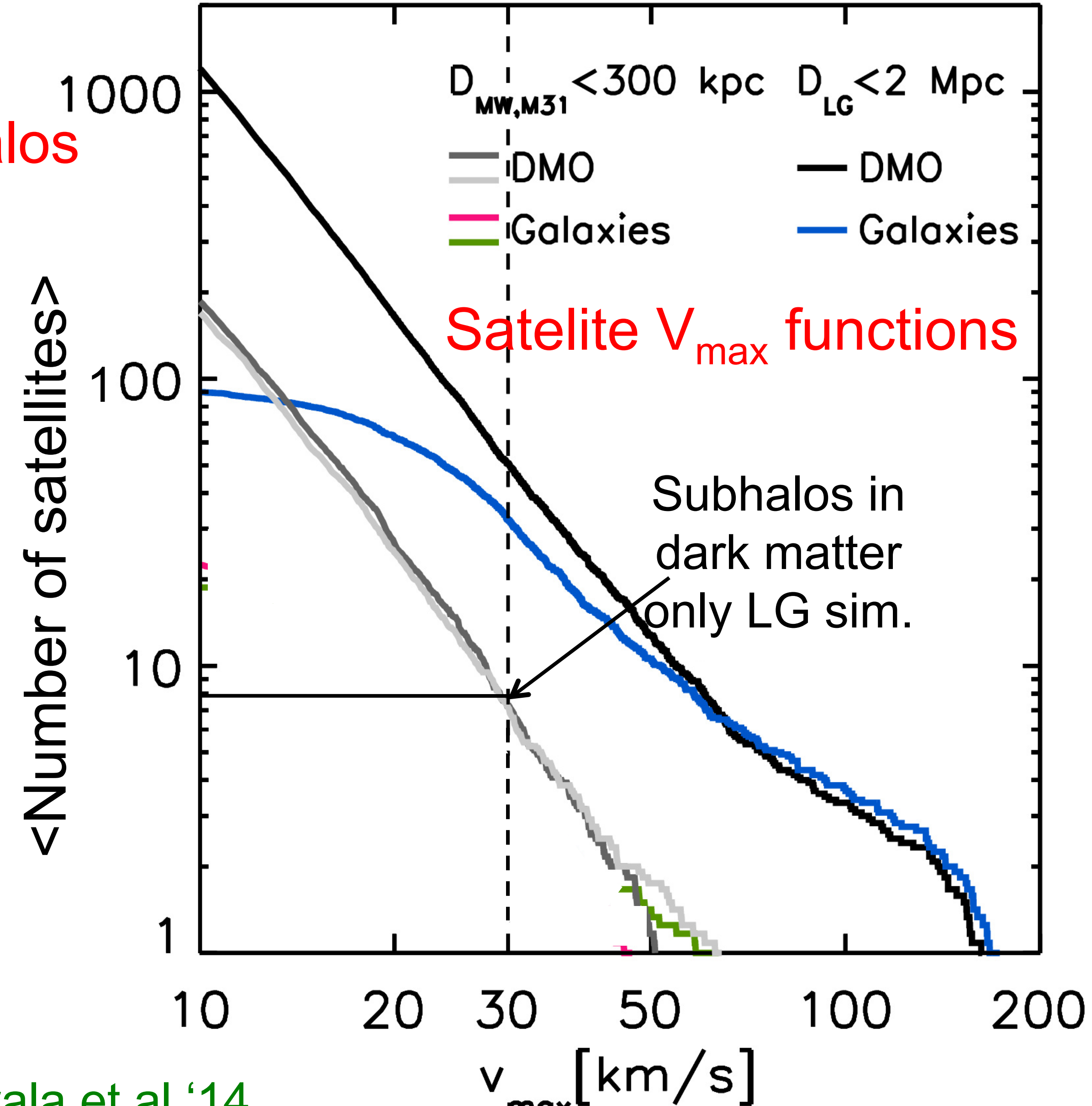


Sawala et al. '13, '15

Too-big-to-fail: the baryon bailout

University of Durham

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

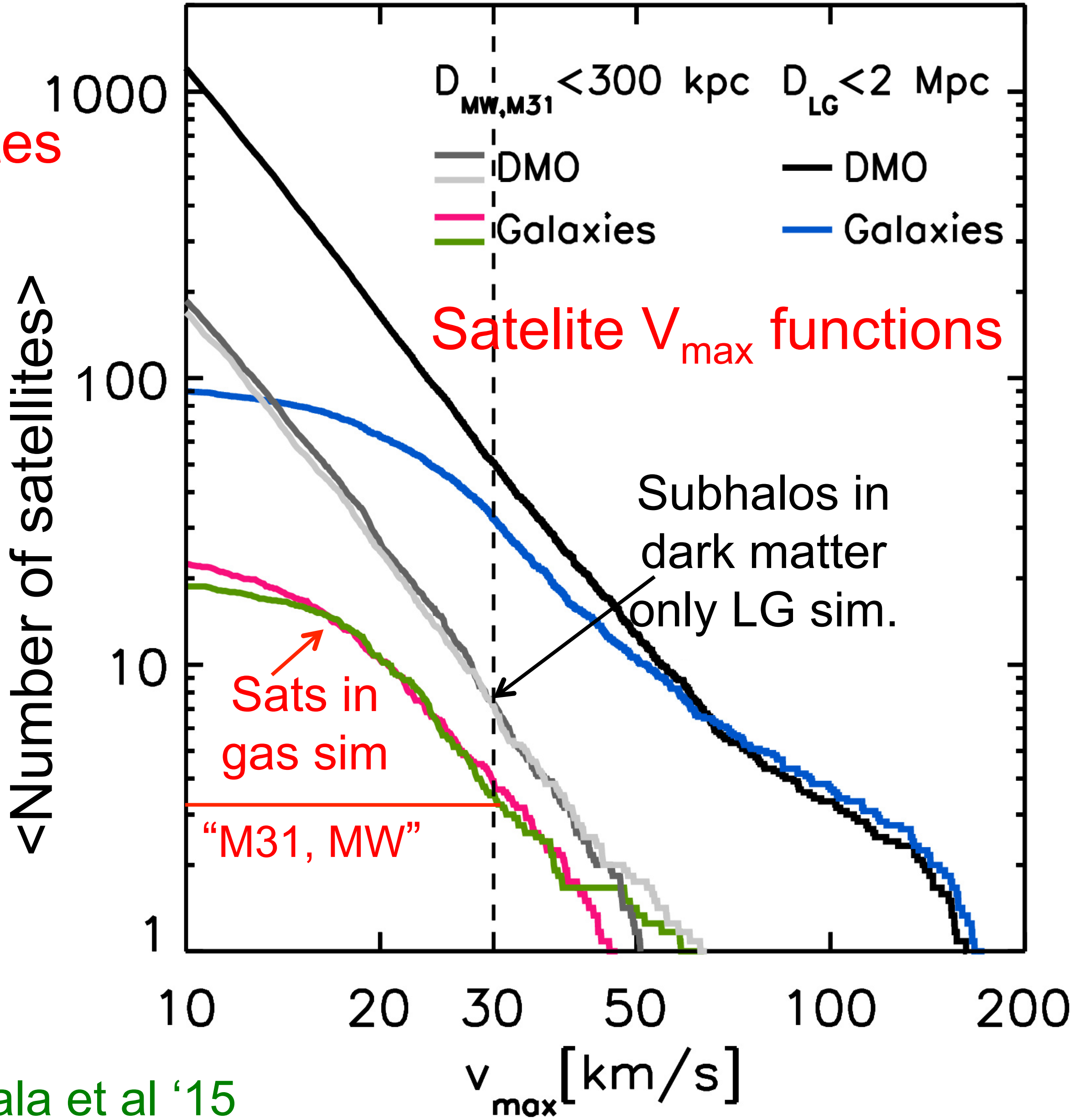


Sawala et al '14

Too-big-to-fail: the baryon bailout

University of Durham

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



Sawala et al '15

Too-big-to-fail: the baryon bailout

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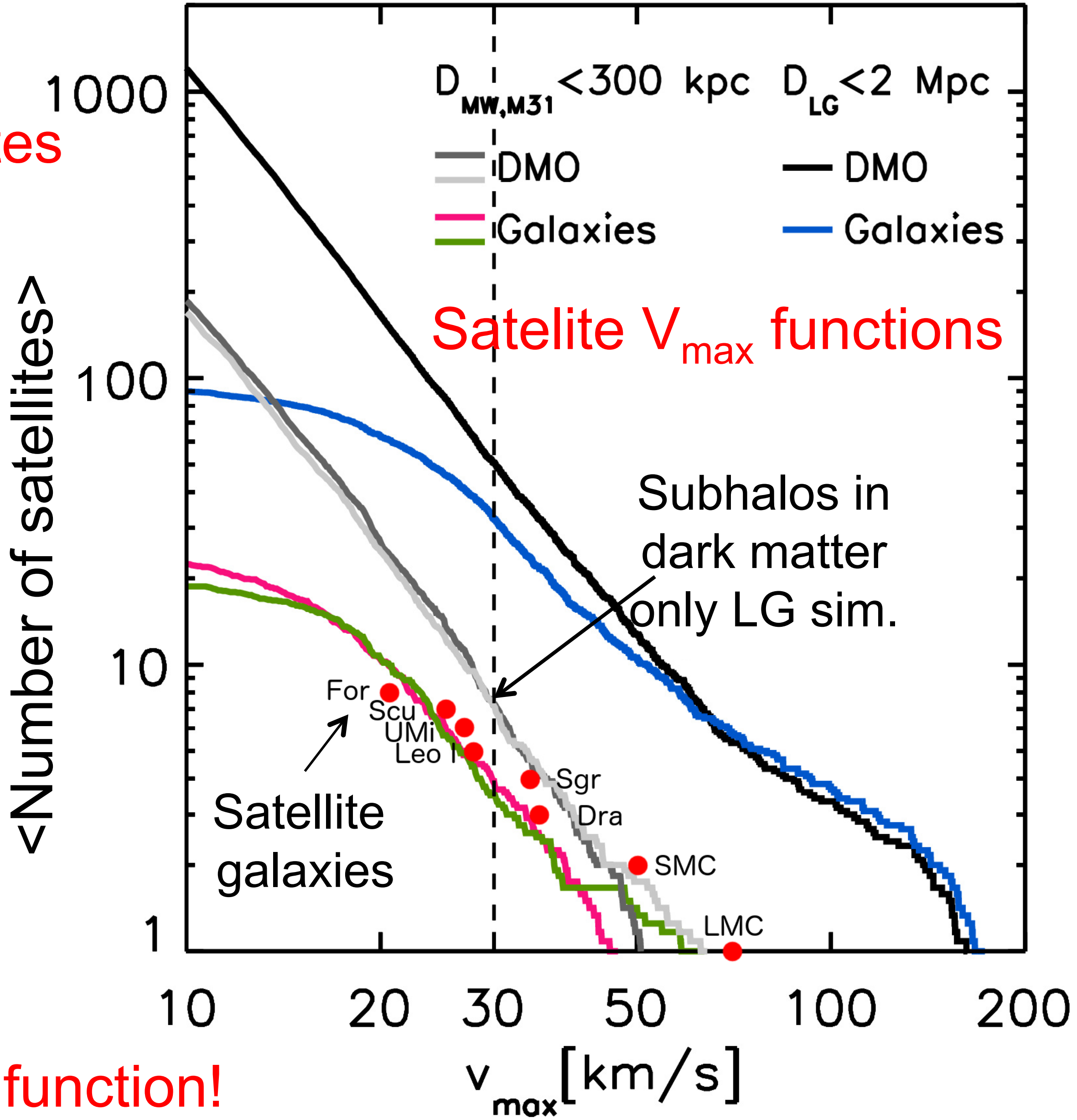


… and with correct V_{max} function!

Is there a "too-big-to-fail" problem in WDM?

No

Is there a “too-big-to-fail” problem in CDM?

No, when galaxy formation is taken into account!

University of Durham

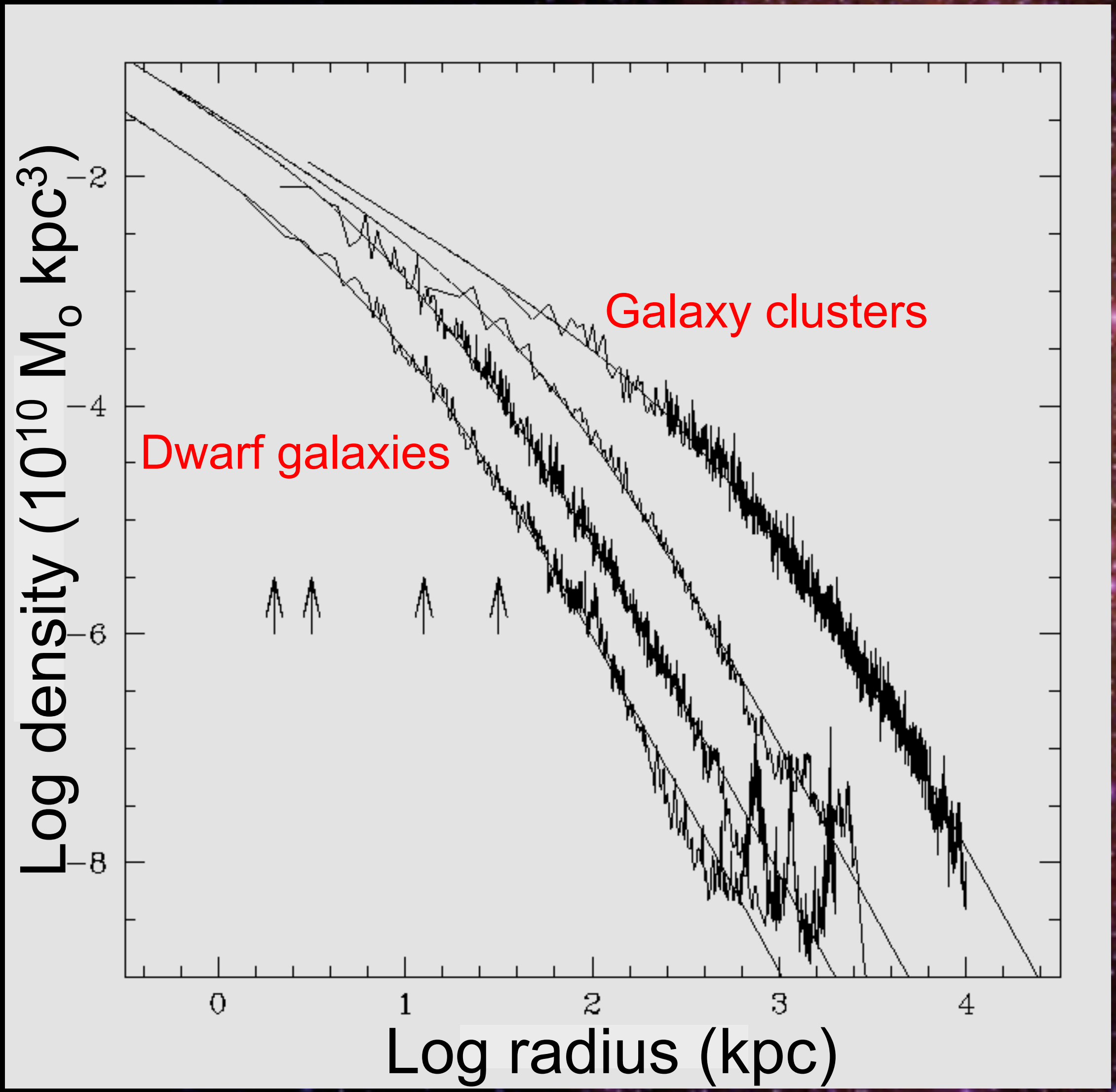
Four problems on small scales

Traditionally ascribed to CDM:

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

Can these help distinguish between CDM & WDM?

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)


Dwarf galaxies in Eagle have NFW cusps!
Sawala et al '15

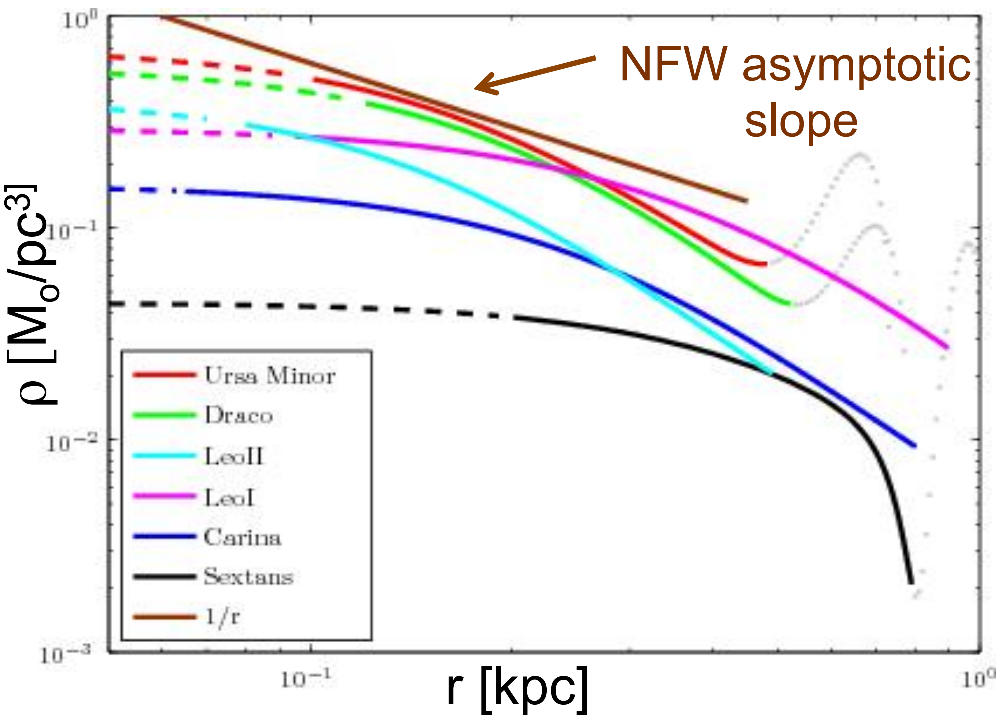
Evidence for warm dark matter?

University of Durham

The Astrophysical Journal, 663:948–959, 2007 July 10

THE OBSERVED PROPERTIES OF DARK MATTER ON SMALL SPATIAL SCALES

Gerard Gilmore,[1] Mark I. Wilkinson,[1,2] Rosemary F. G. Wyse,[3] Jan T. Kleyna,[4] Andreas Koch,[5,6]
N. Wyn Evans,[1] and Eva K. Grebel[6,7]



Inferred density profiles for 6 dwarf spheroidals

"…dark matter forms cored mass distributions, with a core scale length of greater than about 100pc, and always has a maximum central density in a narrow range…"

"…(keV) sterile neutrino particles have been discussed as relevant in just the spatial and density range we have derived here."

Density profiles of WDM halos

WDM particles have significant thermal velocities at early times

Since the phase-space density cannot increase, shouldn't this produce a uniform density core?

Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Shao, Gao, Theuns, Frenk ' 13

Maccio et al.'12

Core radii in WDM halos

University of Durham

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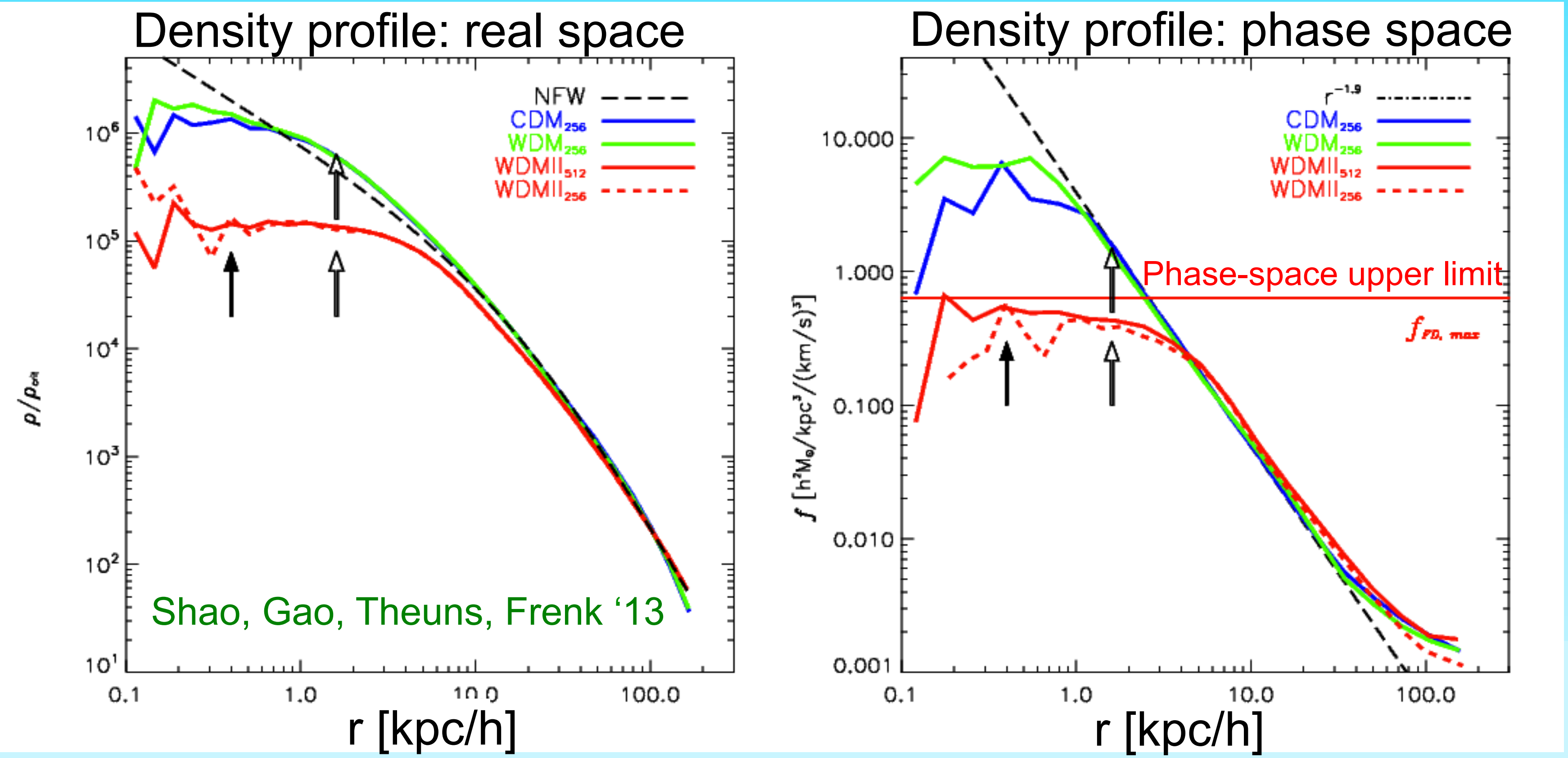

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Core radii in WDM halos

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

By requiring $f = f_{FD}$

$$m_x^4 = \frac{6(2\pi\hbar)^3}{(2\pi)^{5/2} g G \sigma r_h^2}$$

Shao, Gao, Theuns, Frenk ' 13

Core radii in WDM halos

University of Durham

The thermal velocities of WDM particles induce cores

Liouville's theorem → upper bound on fine-grained ph. space den.

$$f_{FD} = \frac{g m_x^4}{2(2\pi\hbar)^3}.$$

Phase space arguments →

$$r_c = \frac{pc}{\left(\frac{m_x c^2}{8.2keV}\right)^2 \left(\frac{\sigma}{km/s}\right)^{1/2} \left(\frac{g}{2}\right)^{1/2}}$$

core radius

For m_{WDM} > 1.5 keV, core radii in WDM models are < 10pc →

core radii NOT relevant in WDM even in dwarf gals

Shao, Gao, Theuns, Frenk '13
see also Maccio et al '12

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The core-cusp problem

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

CDM & WDM subhalos have cuspy profiles

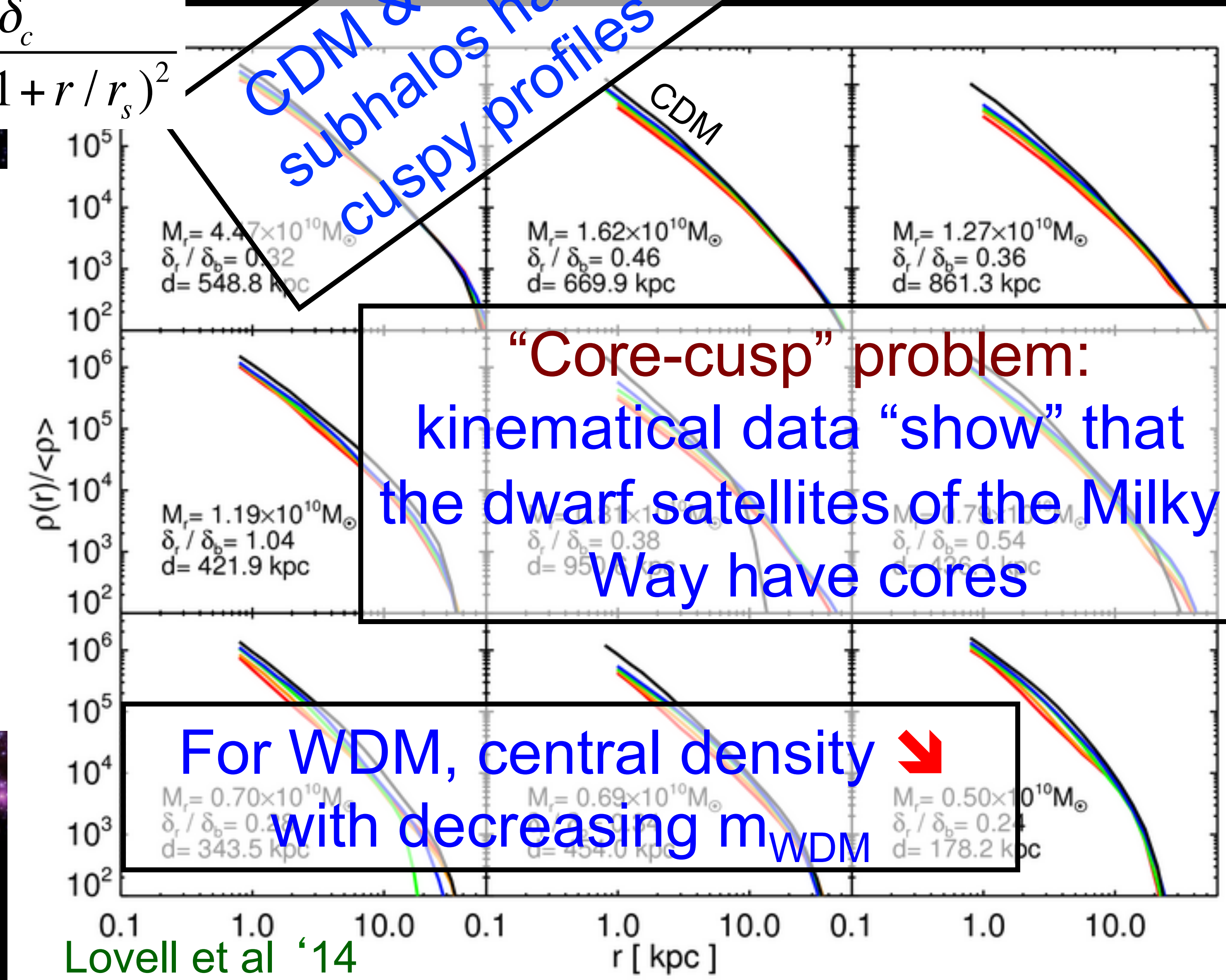
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Lovell et al '14

"Core-cusp" problem: kinematical data "show" that the dwarf satellites of the Milky Way have cores

For WDM, central density ↘ with decreasing m_{WDM}

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

Fornax

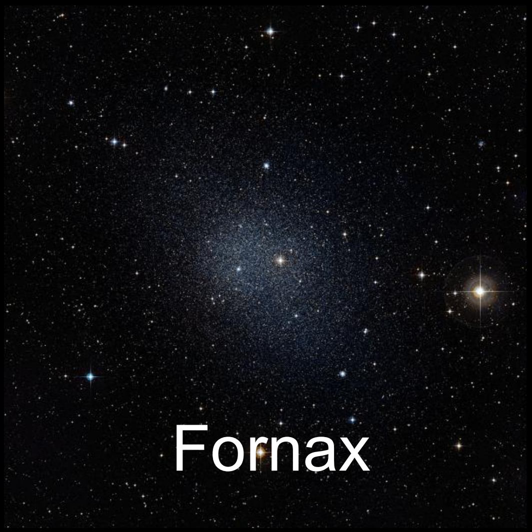
Sculptor

Sextans

Carina

Sagittarius

Dwarf galaxies around the Milky Way



Sextans

Carina

Sagittarius

The DM halo of the Sculptor dwarf

University of Durham

Sculptor has two stellar pops:

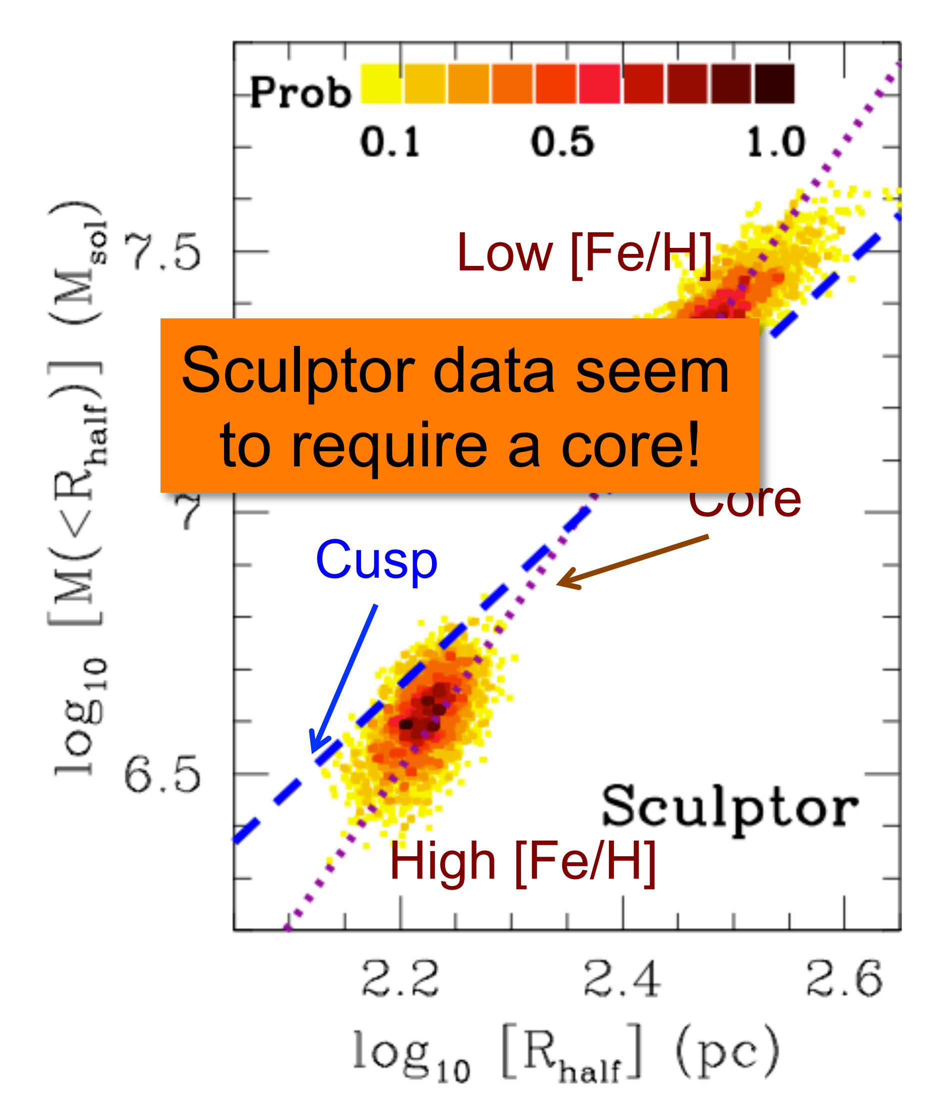
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

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

Walker '10; Wolf et al '10→

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



Walker & Peñarrubia '11

University of Durham

The DM halo of the Sculptor dwarf

Strigari, Frenk & White '15

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $$\rho(r) = \frac{\rho_s}{x(1+x)^2}$$

For each population: $$f(E,J) = g(J)h(E),$$

Parametrize: $$g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^{\alpha}$$

$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for} E \geq \Phi_{lim}, \end{cases}$$

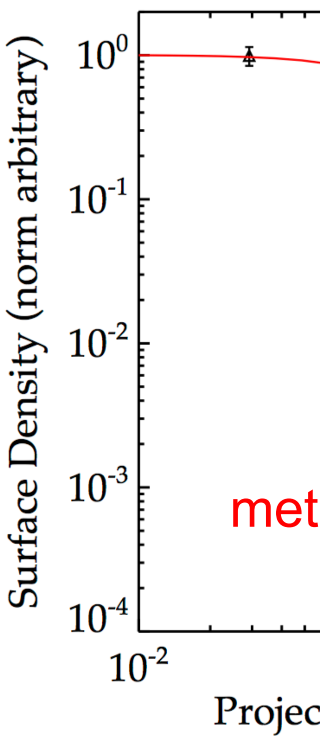
Find best-fit parameters using MCMC

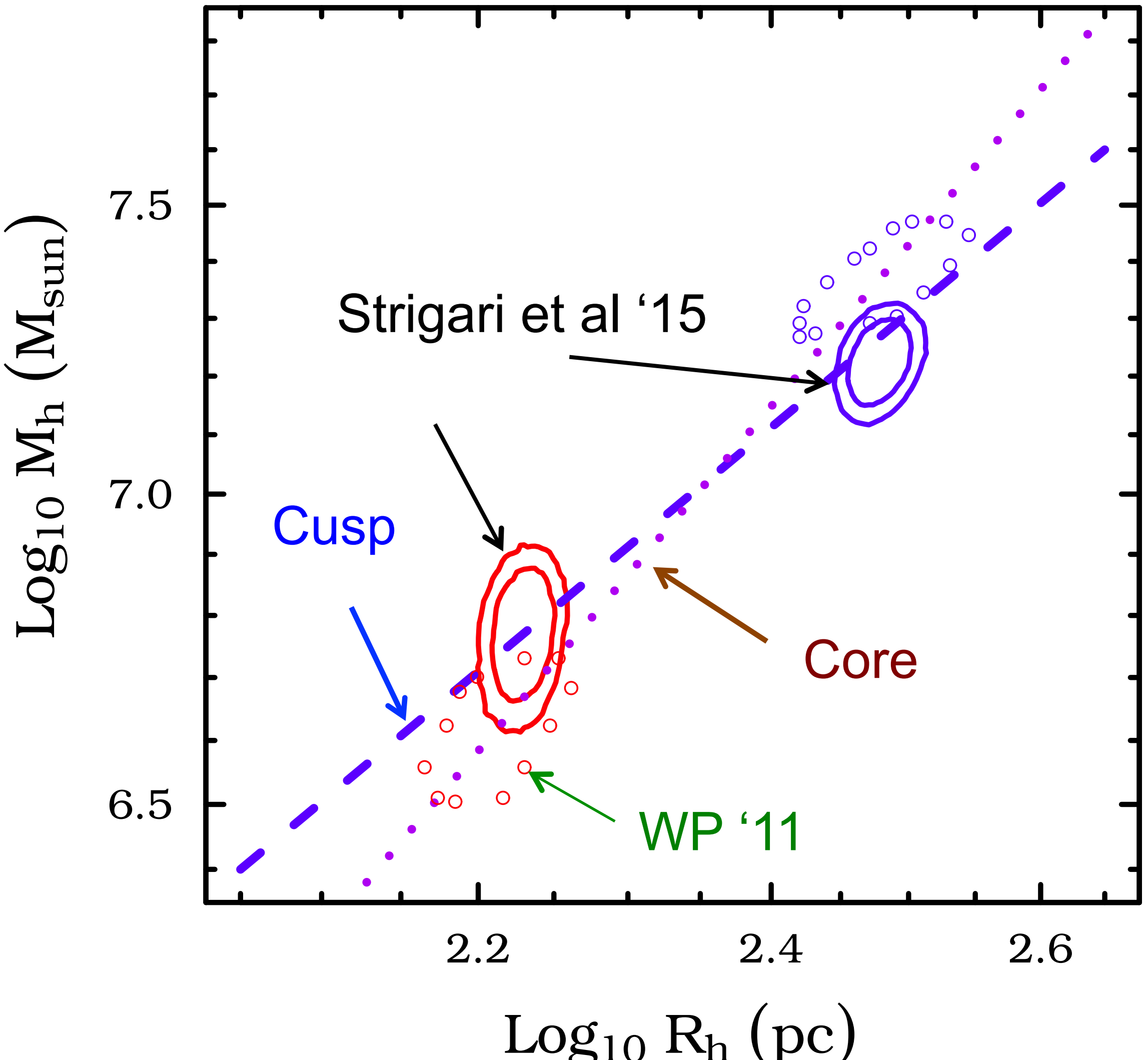
Institute for Computational Cosmology

The DM halo of the Sculptor dwarf

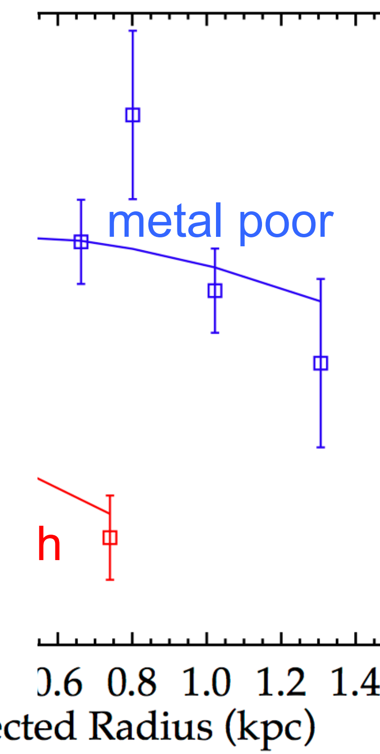
University of Durham

Distribution function analysis





y dispersion



Data cons
eq

Strigari, Frenk & White '15

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

When sufficiently general models are considered, even best kinematical data cannot distinguish cores from NFW cusps in the dwarf spheroidal satellites of the Milky Way

How about in field dwarf galaxies?

Data are not as detailed, but some dwarfs have disks:

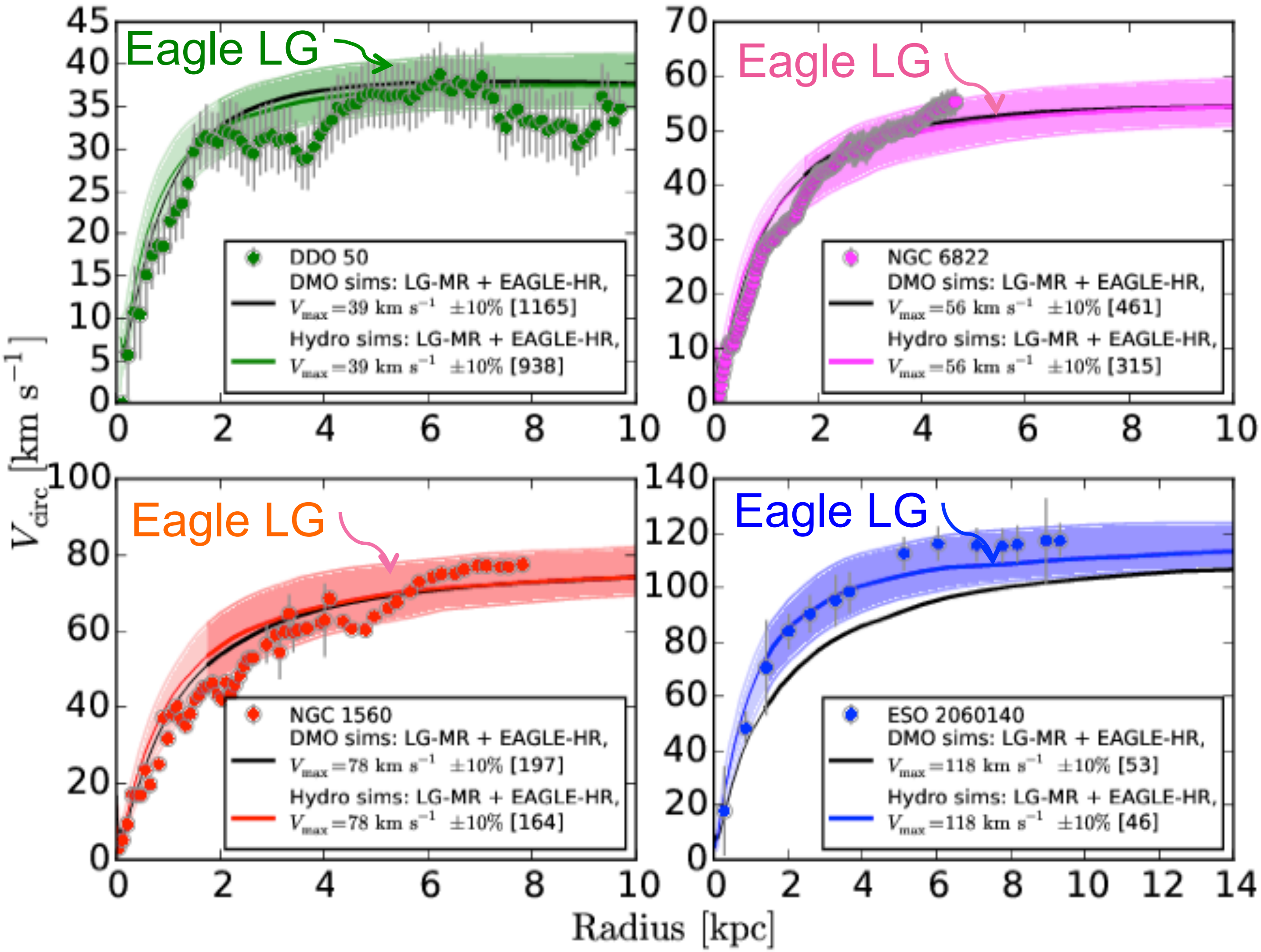
(i) Rotation curves

(ii) 2D velocity fields

The diversity of gal rotation curves

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)

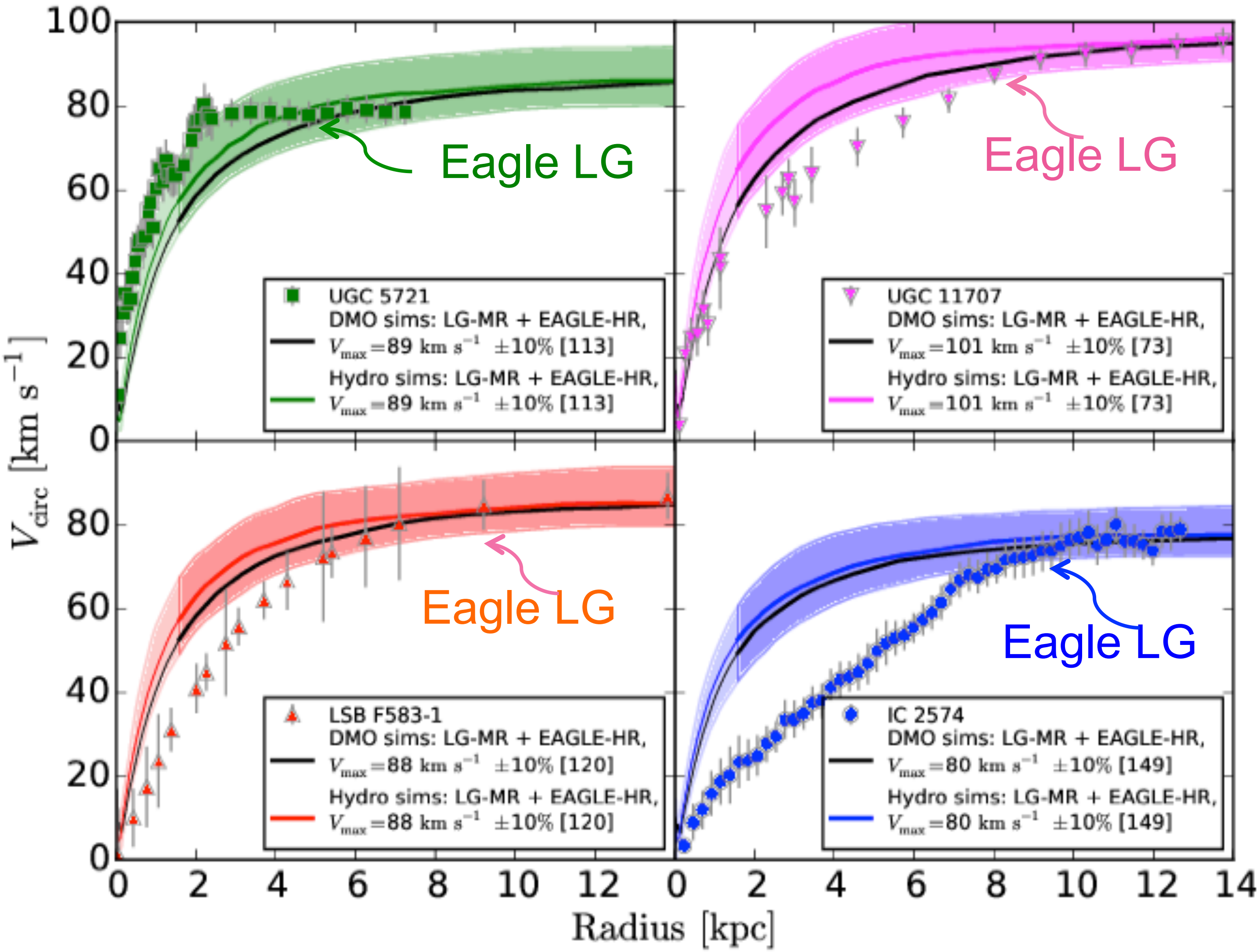


Oman, Navarro, Frenk et al. '15

The diversity of gal rotation curves

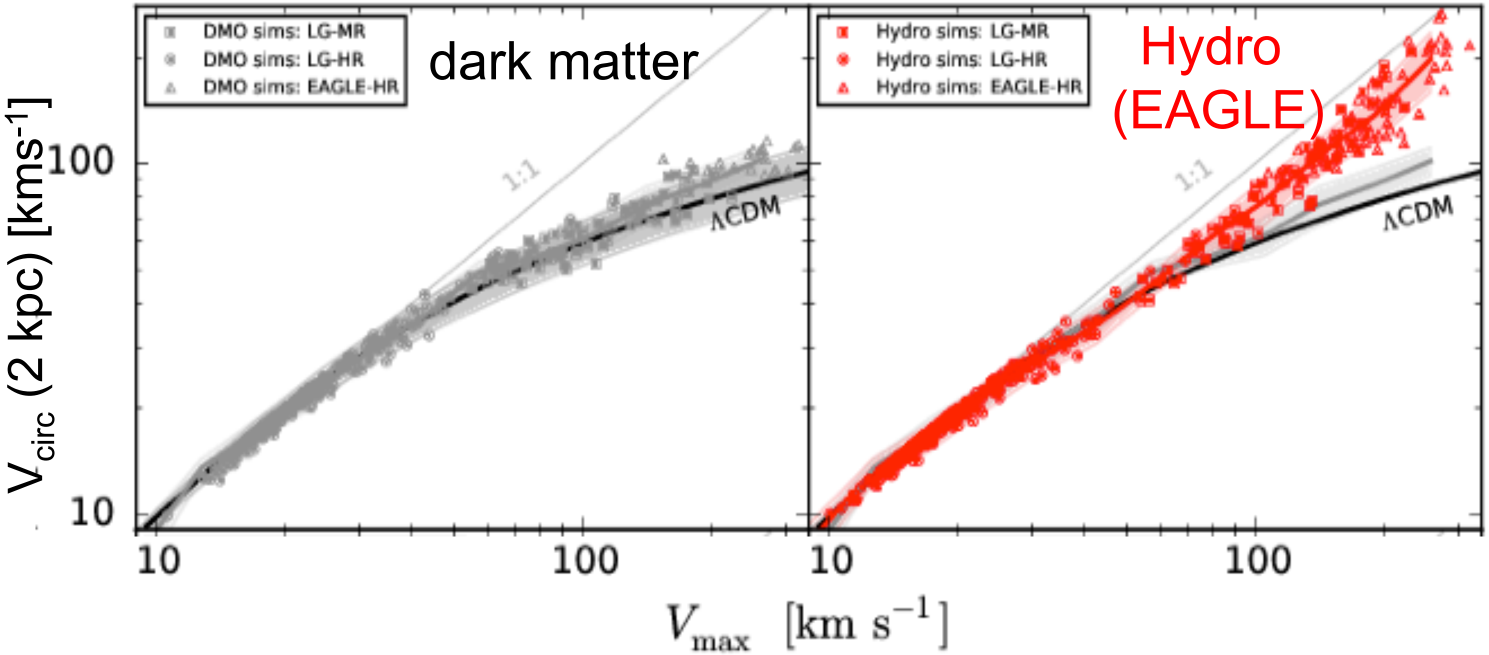
Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L$_*$)



Oman et al. '15

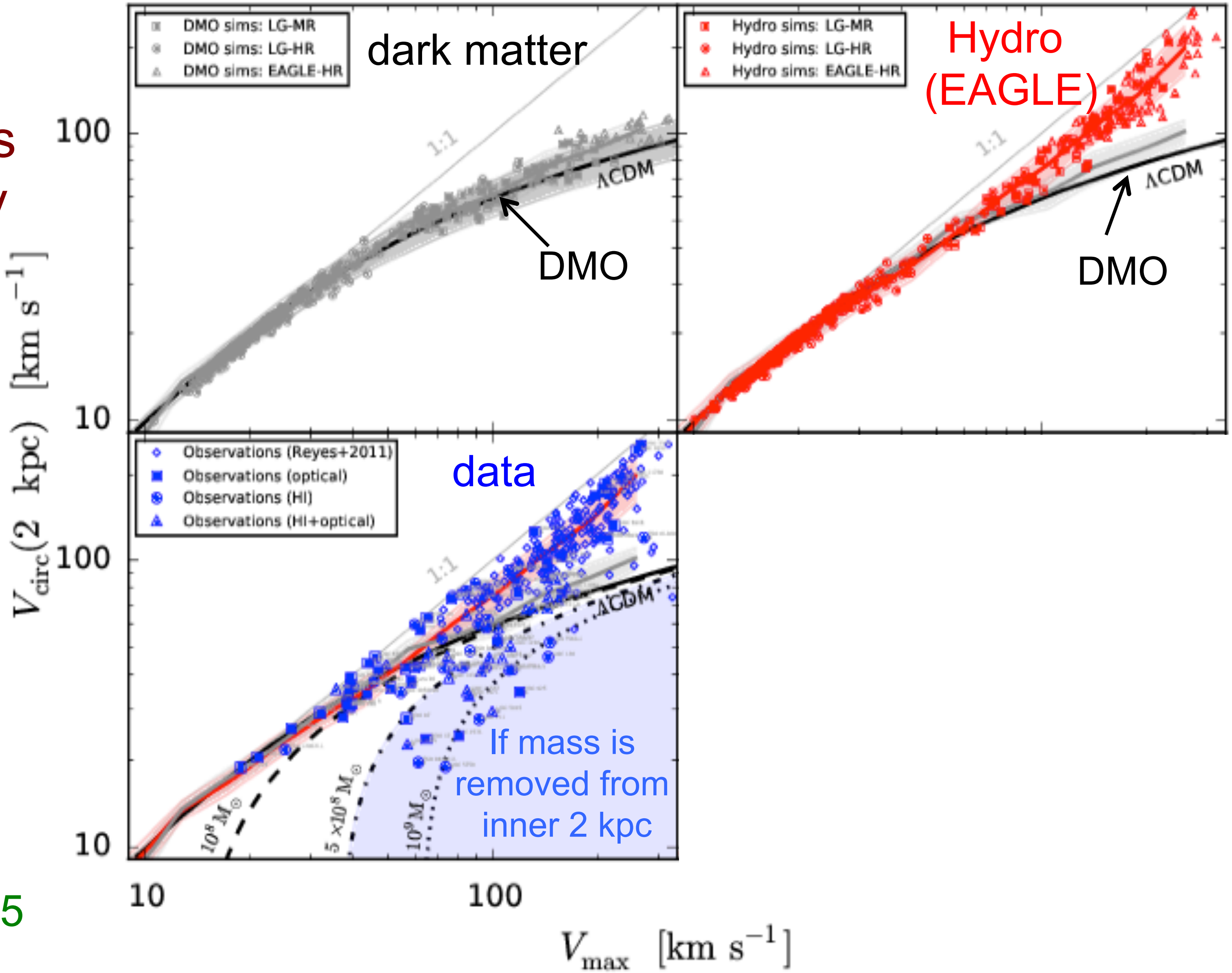
The diversity of gal rotation curves



Oman et al. '15

The diversity of gal rotation curves

Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

Are there other baryon effects that could make cores but are not present in Eagle?

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

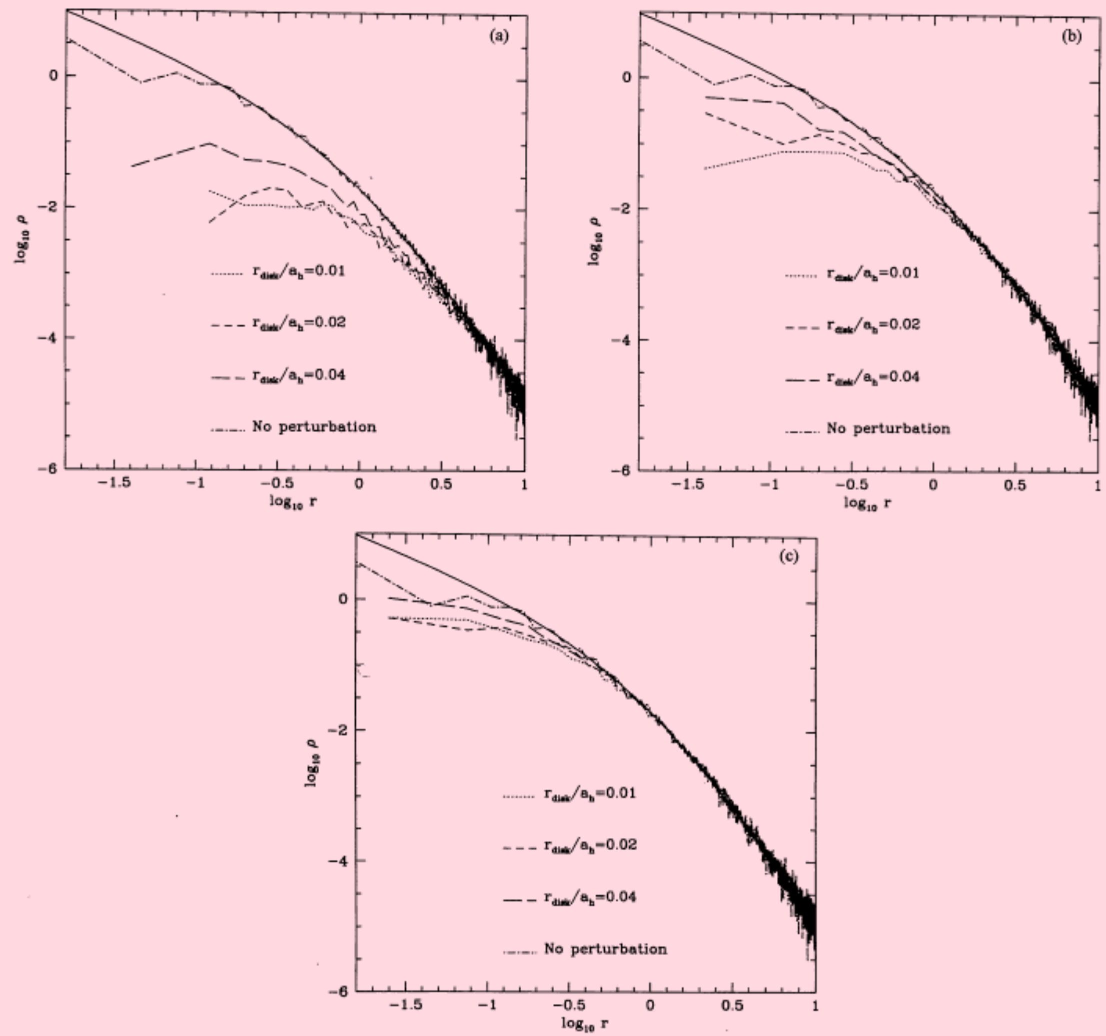


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

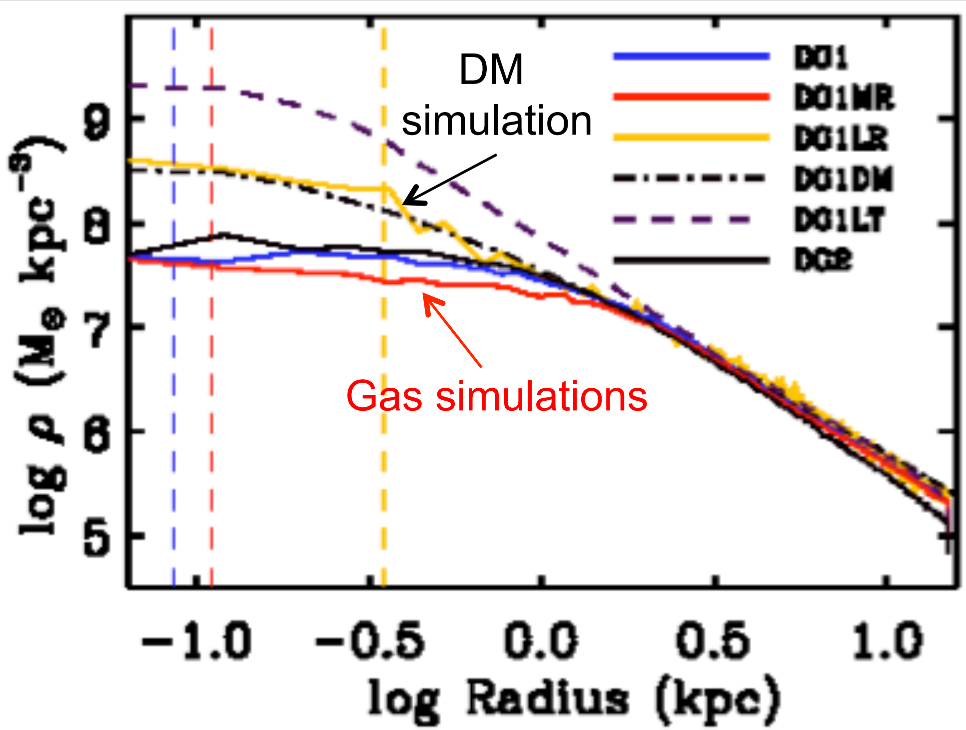
Cores in dwarf galaxy simulations

Governato et al. assume high density threshold for star formation

EAGLE does not

→ High threshold allows large gas mass to accumulate in centre

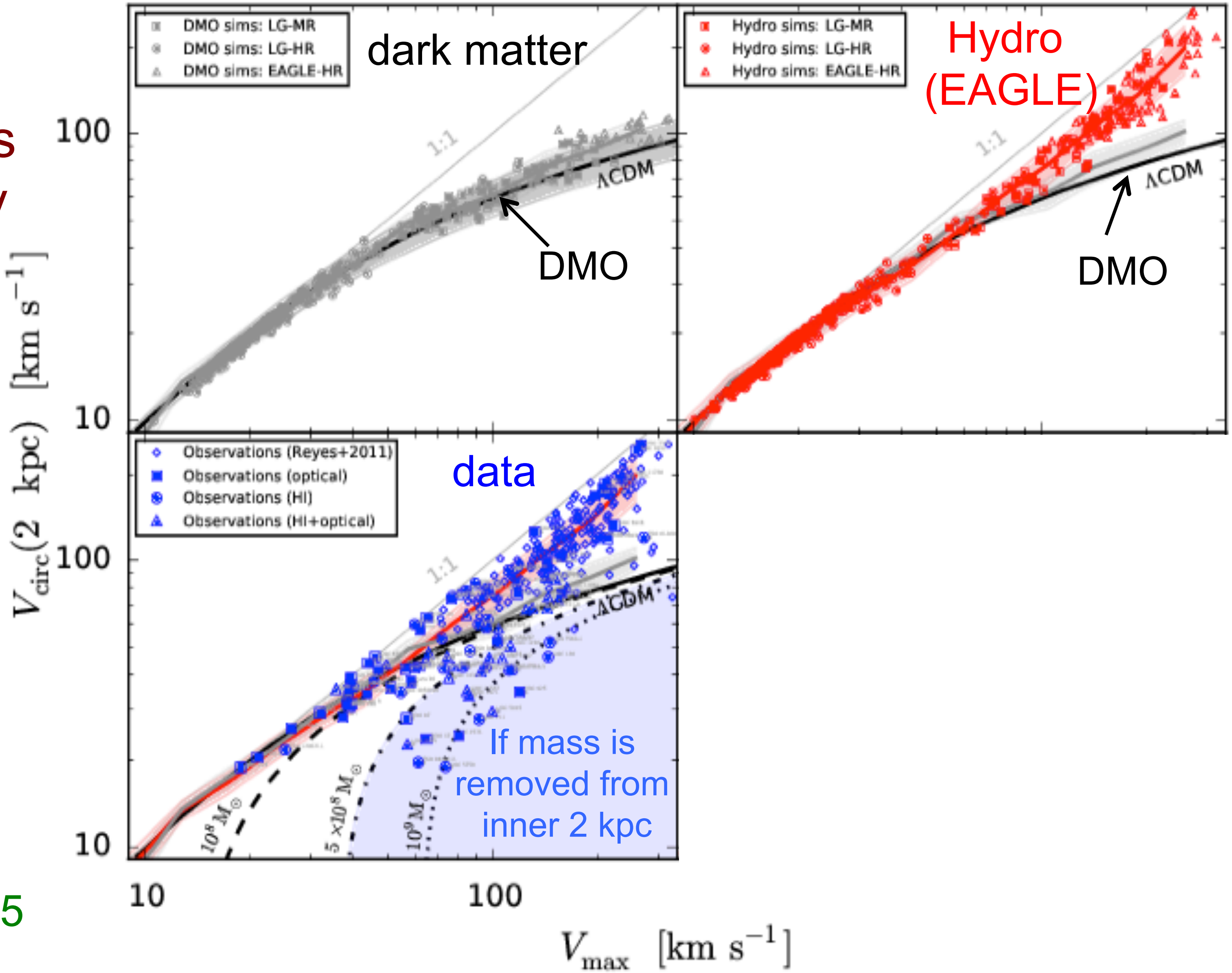
→ Sudden repeated removal of gas transfers binding energy



Governato et al. '10
Pontzen et al. '11

The diversity of gal rotation curves

Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

The diversity of gal rotation curves

University of Durham

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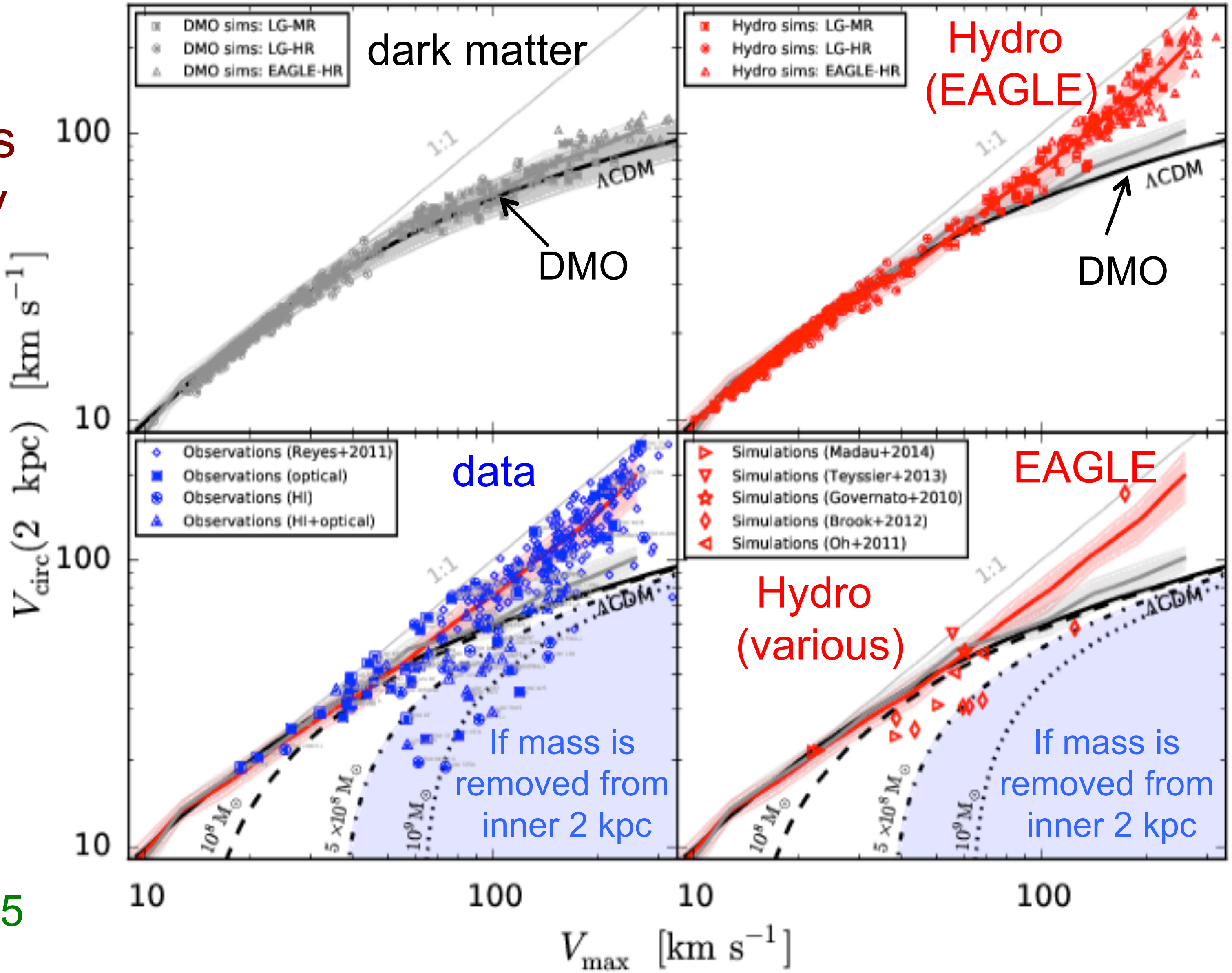


Oman et al. '15

Cores or cusps in dwarf gals?

- Some dwarfs have rotation curves that agree well with EAGLE
- Others have inner mass deficits compared to ΛCDM expectation
- In many cases, inner deficit much larger than seen in simulations that make cores

EITHER (i) dark matter more complex than in any current model

OR (ii) current simulations fail to reproduce effects of baryons on inner regions of dwarfs

AND/OR (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect.

Four problems on small scales

University of Durham

Traditionally ascribed to CDM:

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

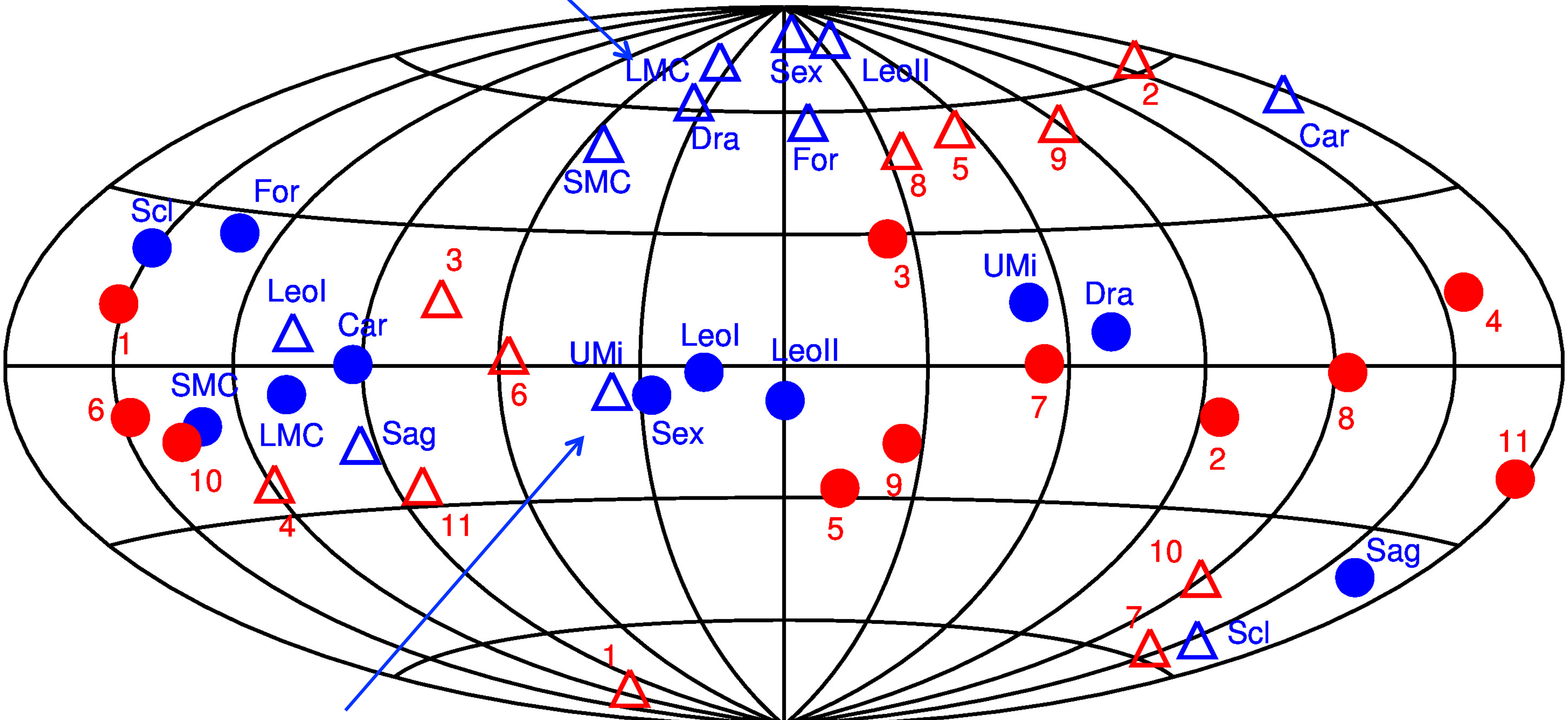
Can these help distinguish between CDM & WDM?

The “satellite disk” problem

University of Durham

Direction of ang. mom.

Milky Way



MW satellites

Lynden-Bell ‘76

Sawala et al ‘15

Institute for Computational Cosmology

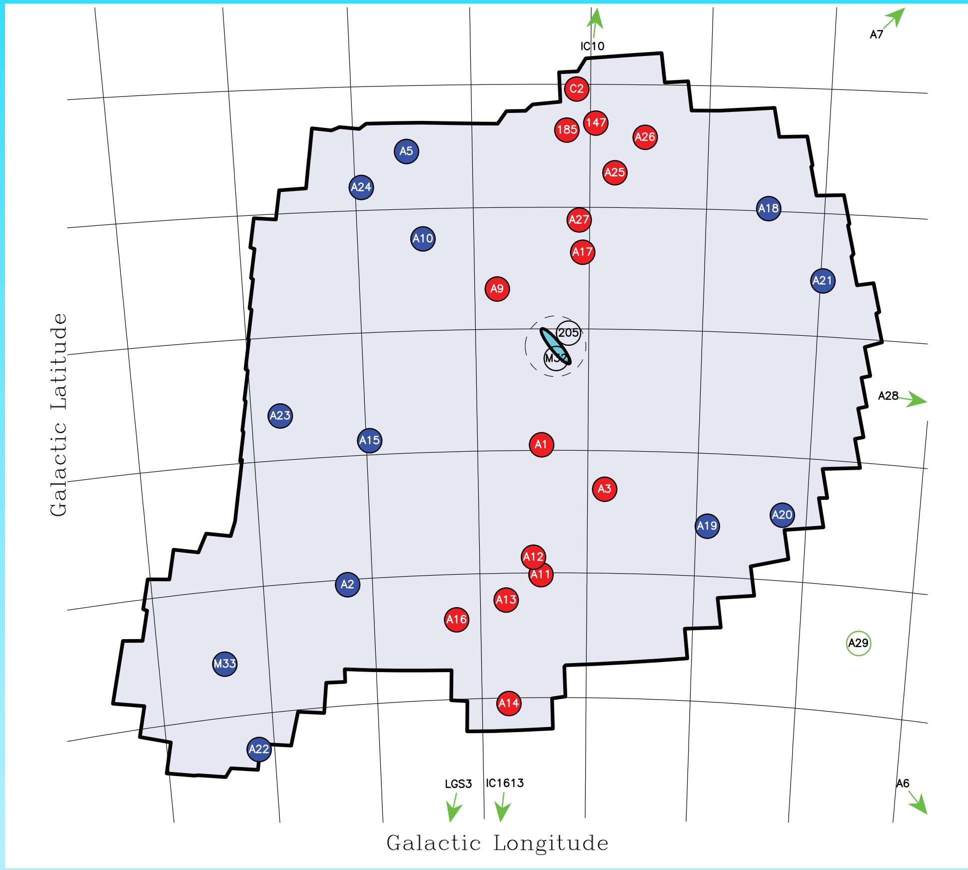
The curious case of a thin, “rotating” plane of sats in M31

University of Durham

Ibata et al ‘13 found a plane of 15 satellites in Andromeda (out of 27) of which 13 have the same sense of rotation

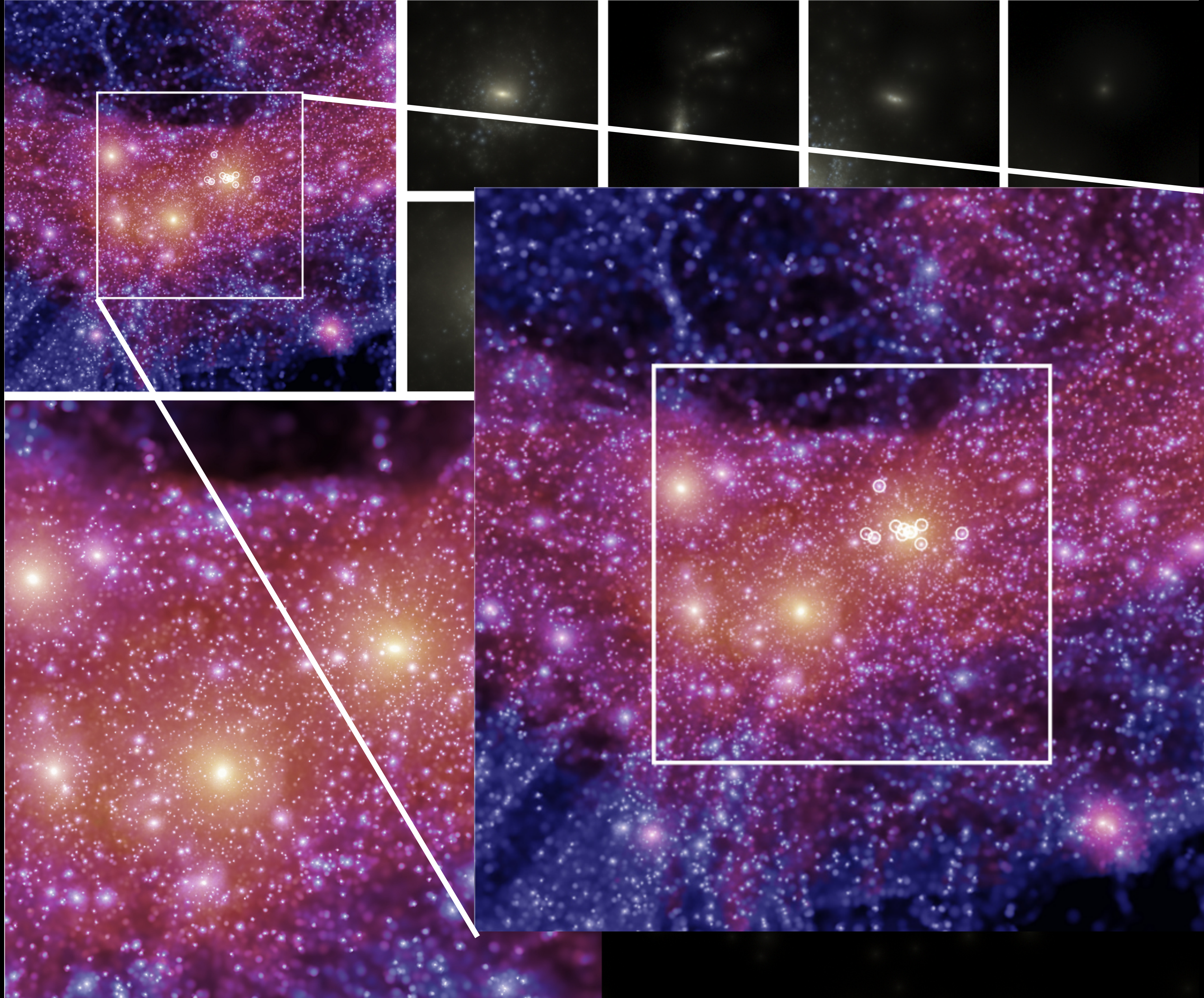
They claim a 4.3σ detection

“We find that 0.04% of host galaxies [in Millennium II] display satellite alignments that are at least as extreme as the observations, when we consider their extent, thickness, and number of members rotating in the same sense.”



Ibata et al ‘13

Institute for Computational Cosmology



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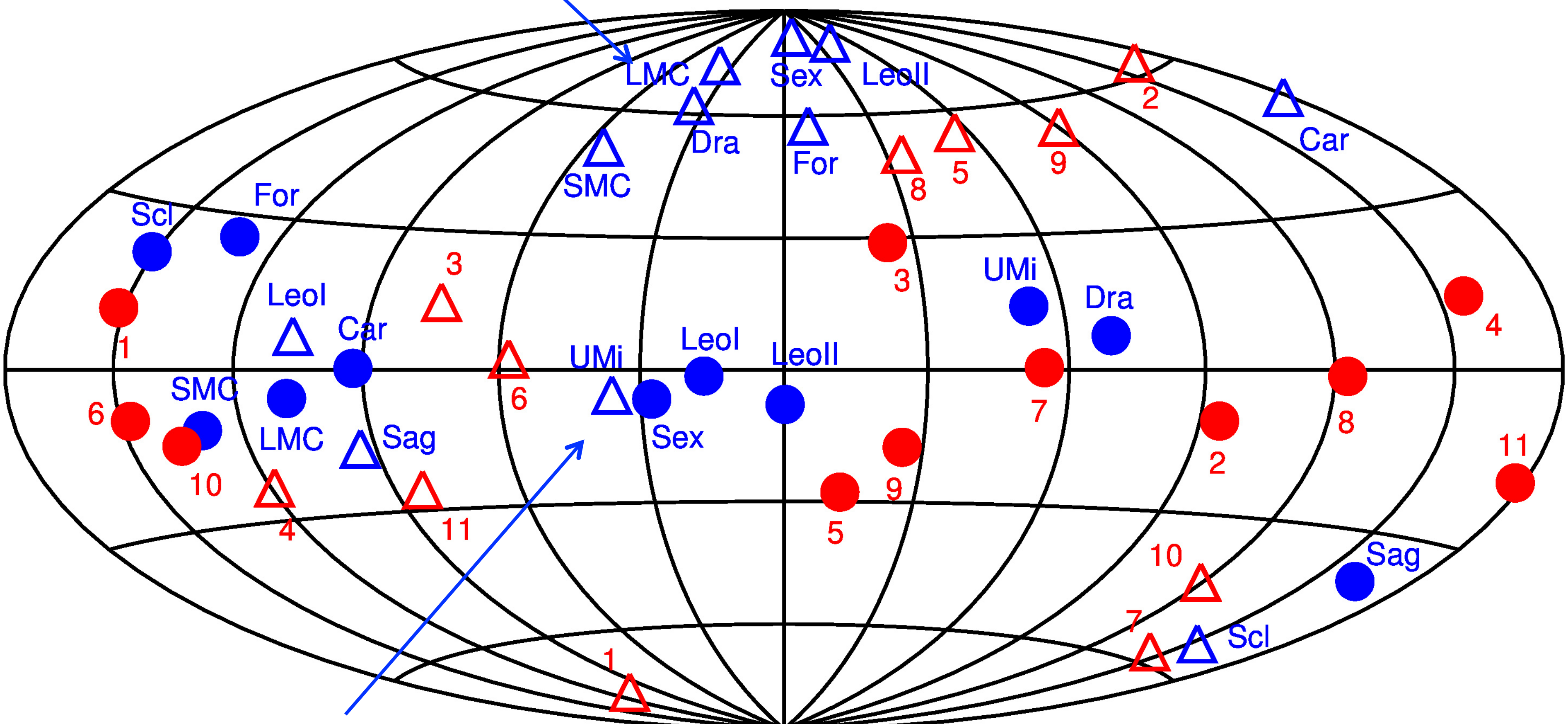
The “satellite disk” problem

Direction of ang. mom.

Milky Way



MW satellites

Lynden-Bell ‘76

Sawala et al ‘15

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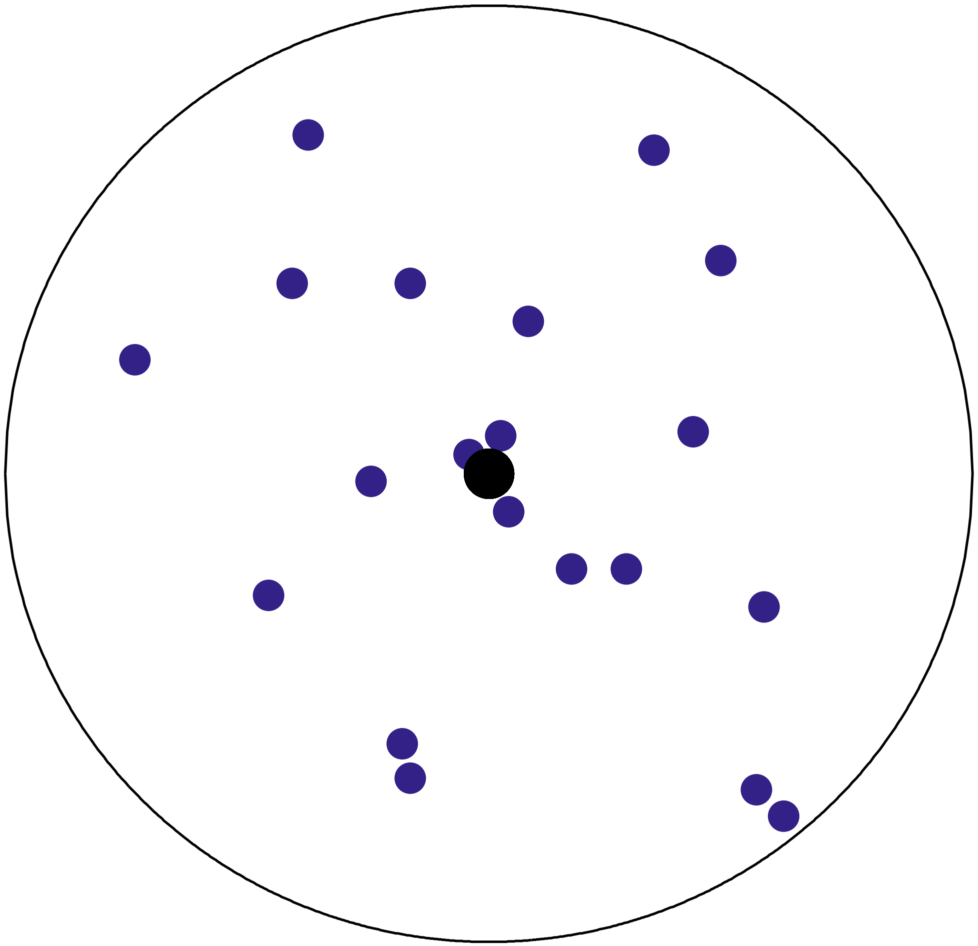
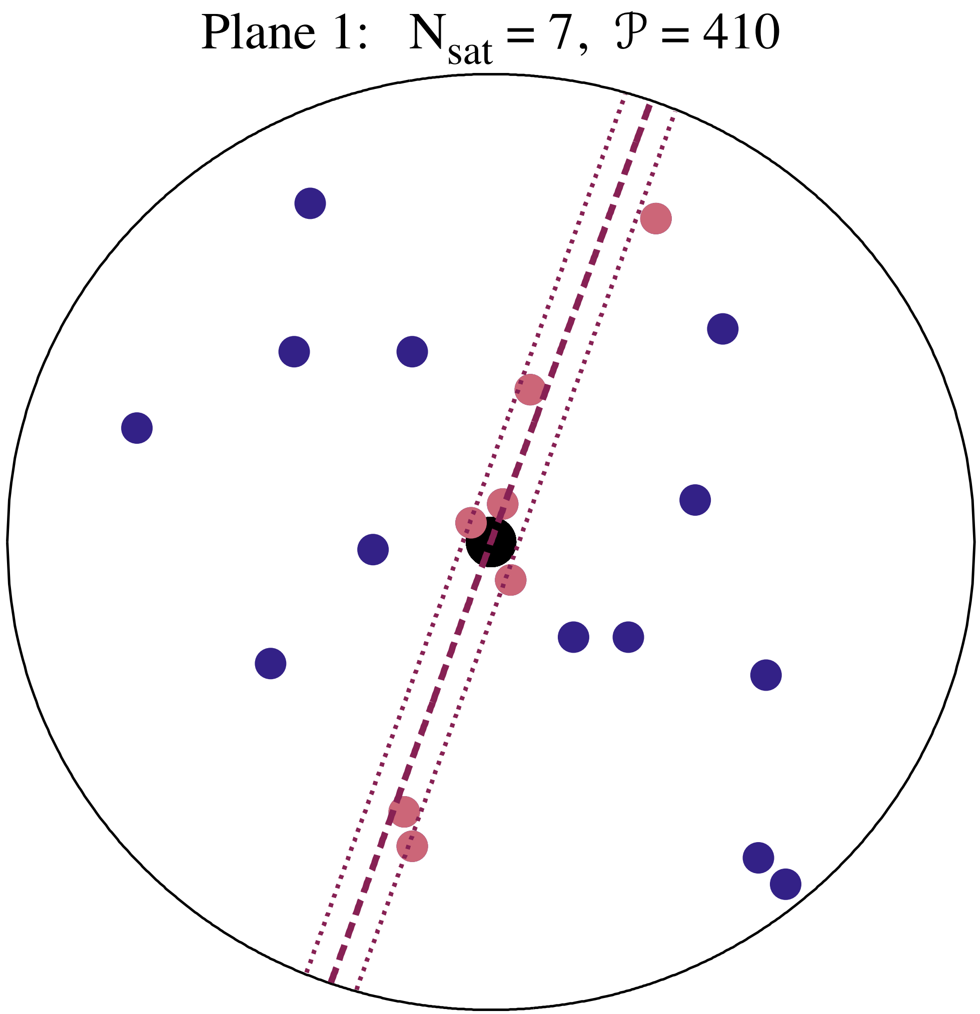
Finding disks of satellites



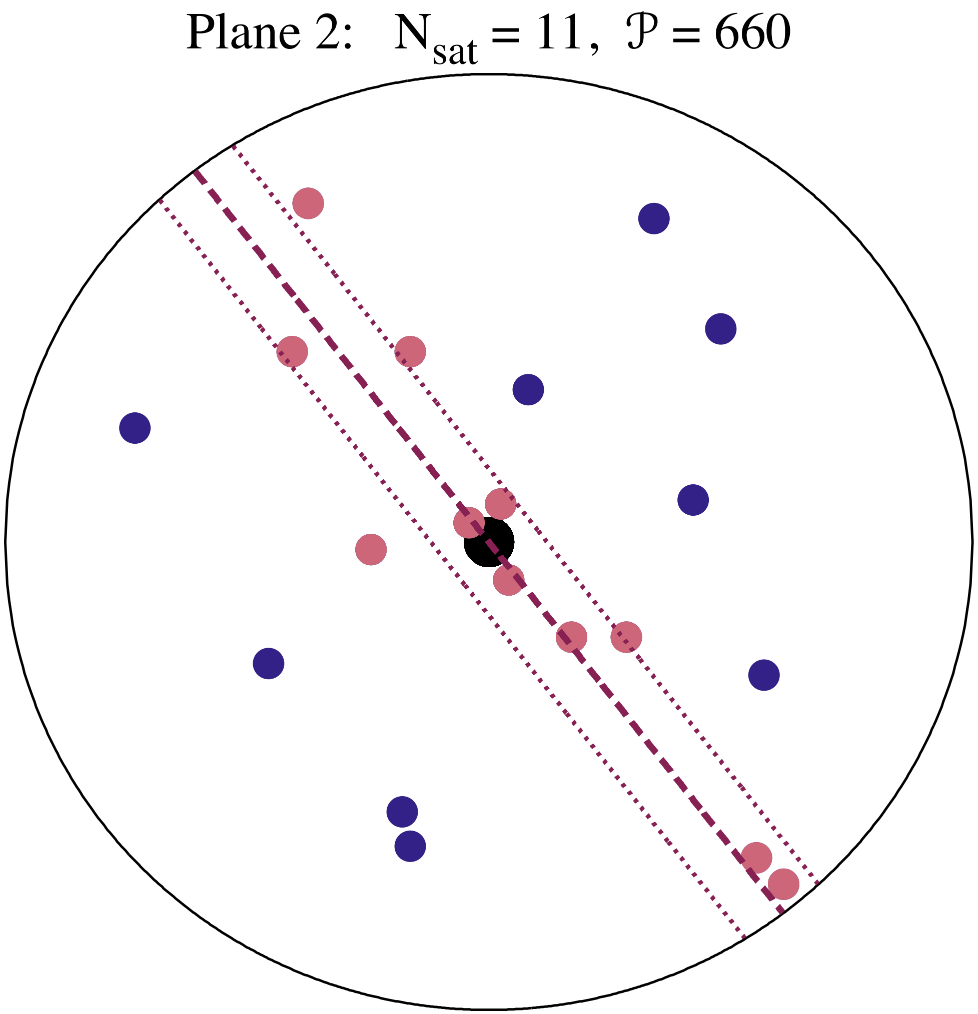
Cautun et al. ‘15

Finding disks of satellites



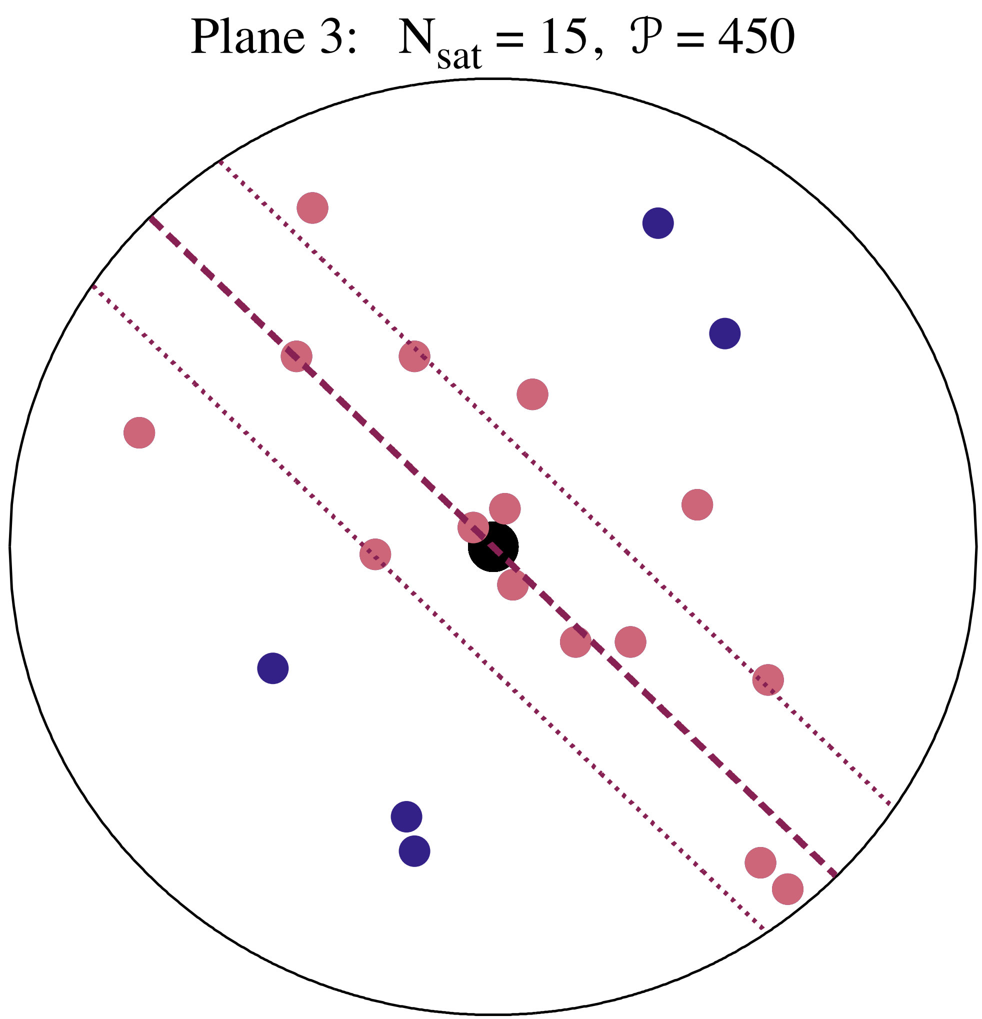
Cautun et al. '15

Finding disks of satellites



Cautun et al. '15

Finding disks of satellites



Cautun et al. '15

The "satellite disk" problem

Prominence of a plane = $\frac{1}{\text{Probability of finding plane in random distr}}$

Prominence of plane thiner than $r_\perp$ having N_{sat} galaxies

$$\mathcal{P}^{\text{plane i}}_{\text{spatial}} = \frac{1}{p\left(\leqslant r_{\perp;\, i} \mid N_{\text{sat; i}}\right)}$$

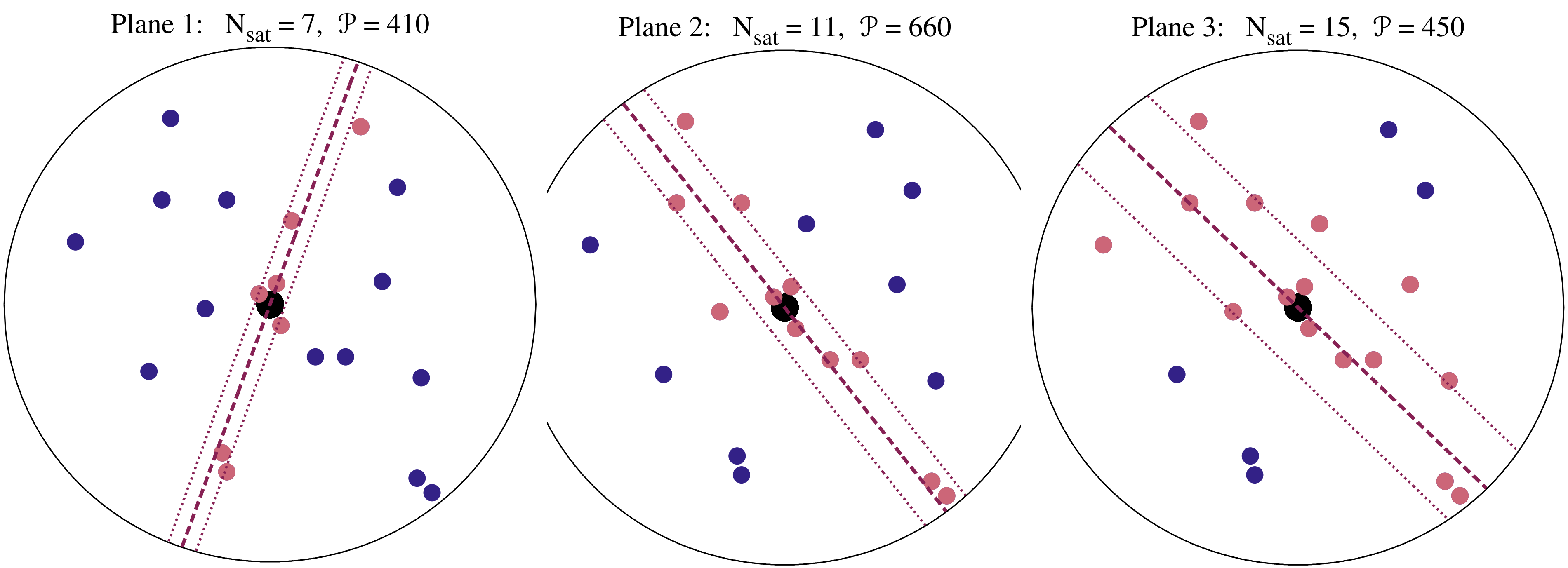
Prominence of plane of N_{sat} gals, N same sense of rotation

$$\mathcal{P}^{\text{plane i}}_{\text{2D-kin}} = \frac{1}{p\left(\geqslant N_{\text{s.s.r.; i}} \mid N_{\text{sat; i}}\right)}$$

$$\mathcal{P}^{\text{rarest}}_{\text{spatial}} = \max_{\text{all planes i}} \left[\mathcal{P}^{\text{plane i}}_{\text{spatial}} \right] ;$$

Cautun et al '15

Finding disks of satellites

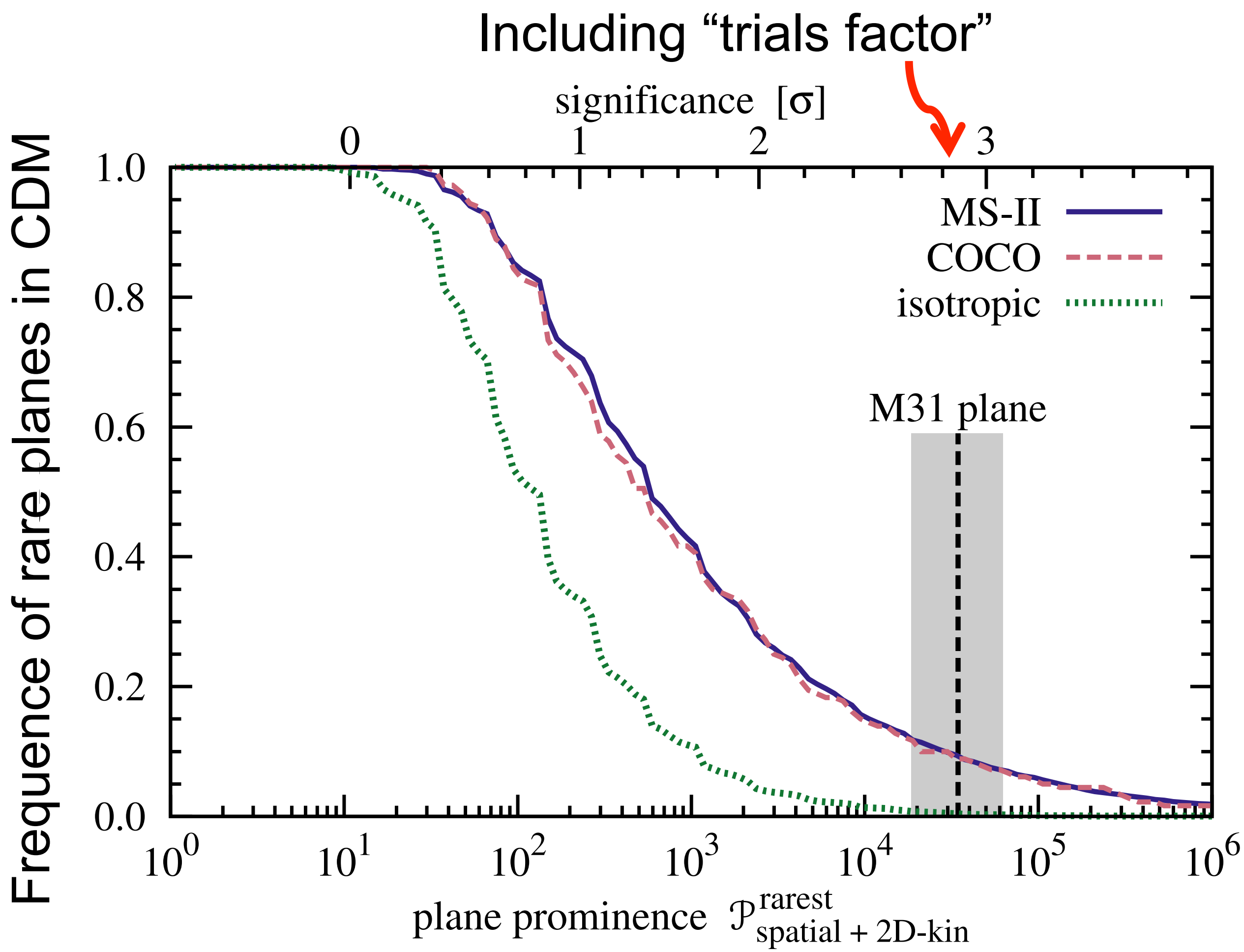


Cautun, Bose, CSF et al ‘15

The significance of Ibata's plane

University of Durham

- Significance of Ibata's plane is reduced by x100 when trials factor is included
- 8.8% of halos in ΛCDM simulation have even more prominent disks than Ibata's



In random distribution, 1 in 30,000 chance of finding a plane of 15 sats (out of 27) as thin found by Ibata et al., with at least 13 having same sense of rotation

Cautun et al '15

Conclusions

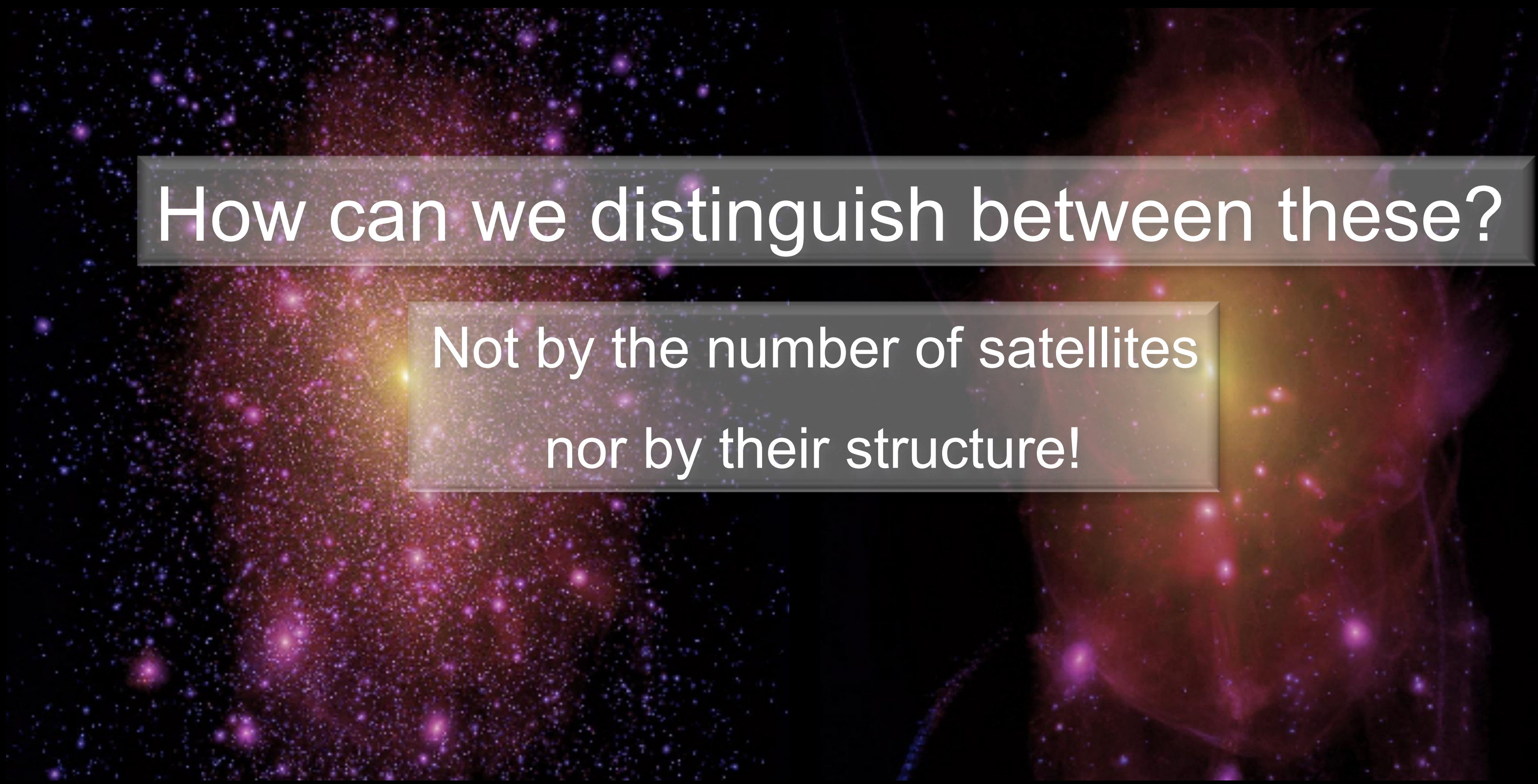
- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- But on these scales ΛCDM cannot be distinguished from WDM
- The identity of the DM makes a big difference on small scales

Four "problems" on small scales:

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

cold dark matter

warm dark matter



How can we distinguish between these?

Not by the number of satellites

nor by their structure!

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

Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

1. Dark subhalos (gravitational lensing)?
2. Stellar streams (stellar surveys – PAndAS, GAIA)?