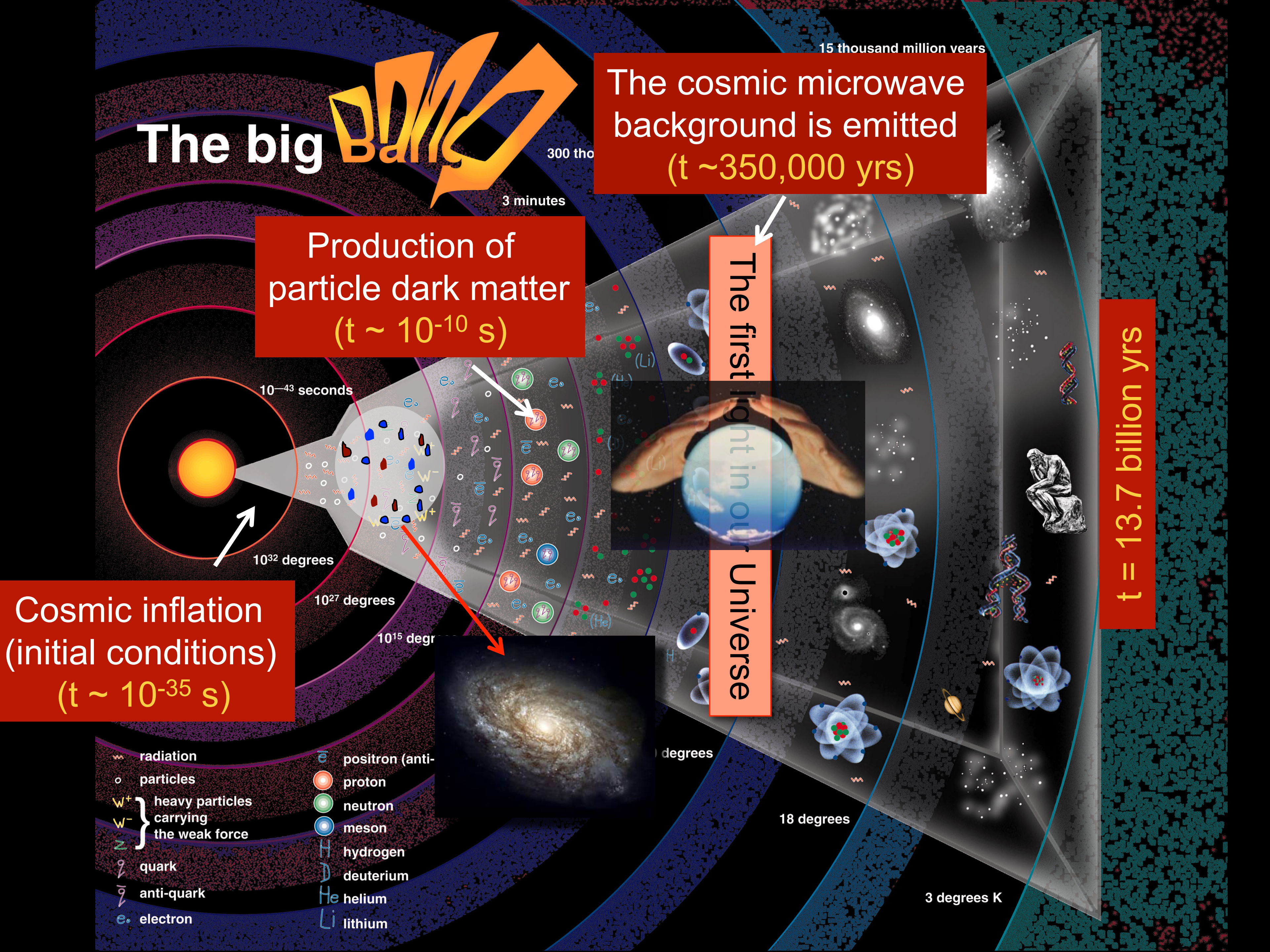
The identity of the dark matter is written on the sky

Carlos S. Frenk
Institute for Computational Cosmology, Durham

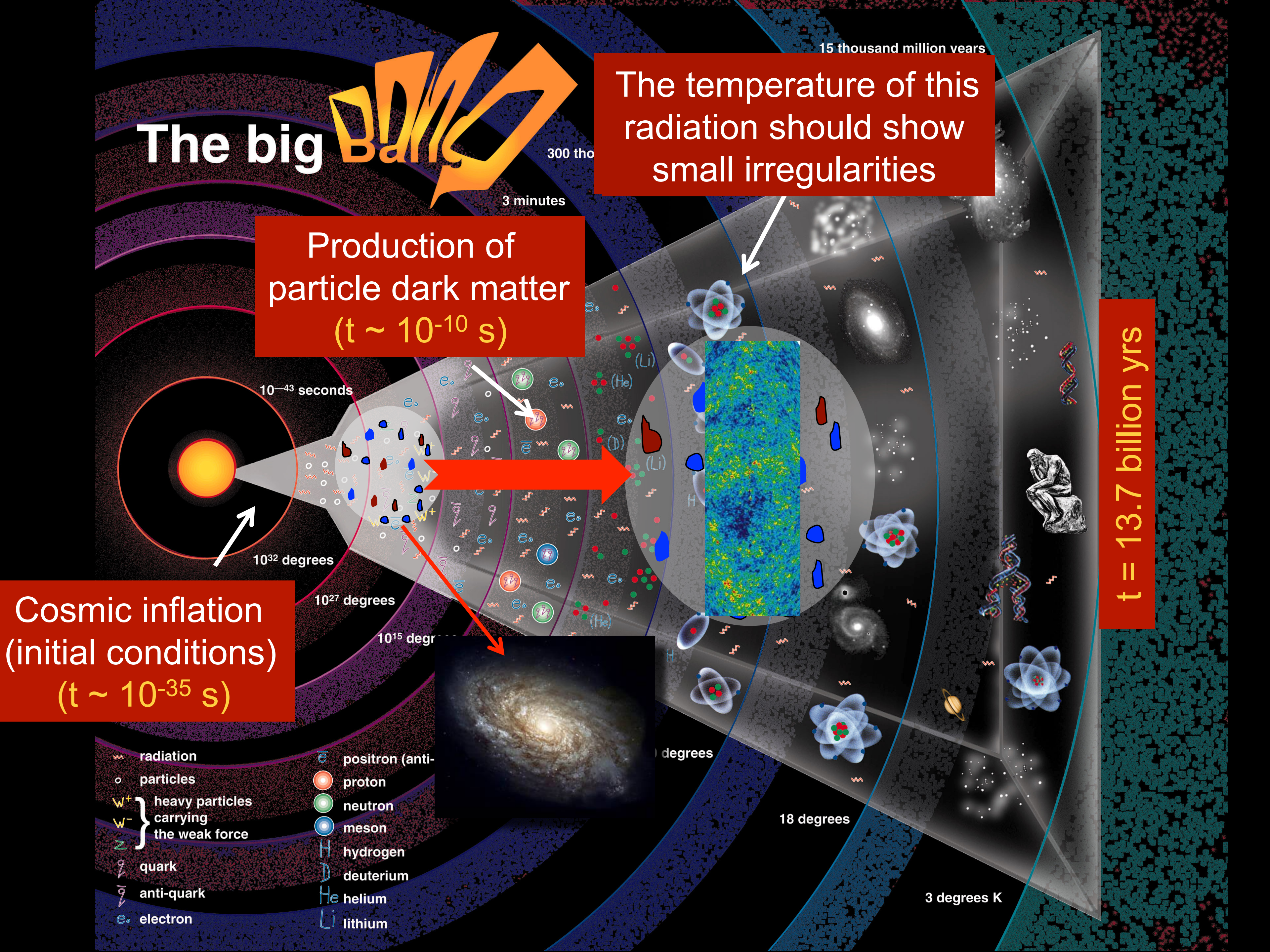
The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter



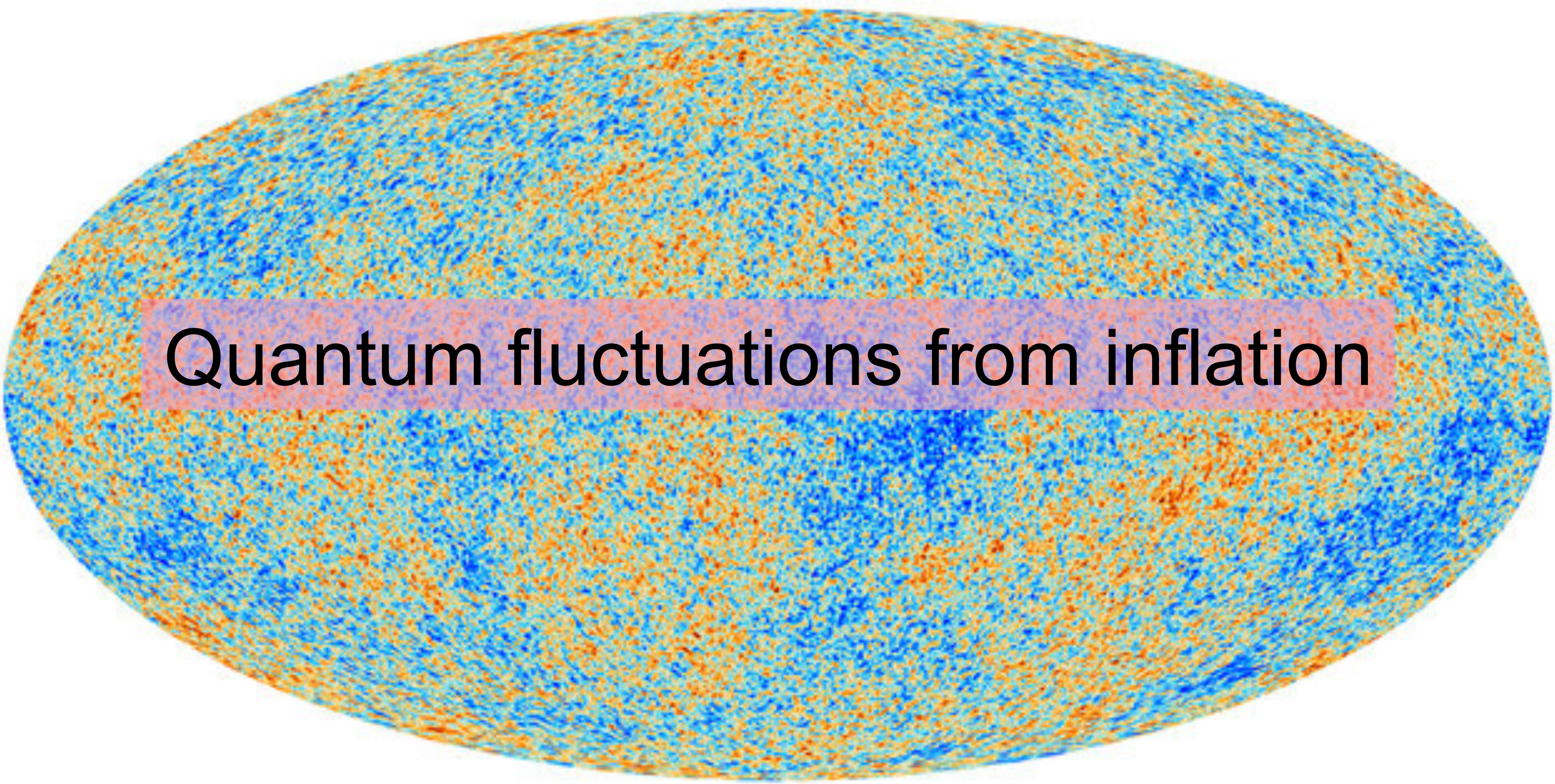
The big Bang
15 thousand million years
300 tho
3 minutes
The cosmic microwave background is emitted
(t ~350,000 yrs)
Production of particle dark matter
(t ~ 10^-10 s)
The first light in our Universe
t = 13.7 billion yrs
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degr
degrees
18 degrees
3 degrees K
Cosmic inflation
(initial conditions)
(t ~ 10^-35 s)
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium



The big Bang
15 thousand million years
The temperature of this radiation should show small irregularities
3 minutes
Production of particle dark matter (t ~ 10^{-10} s)
10^{-43} seconds
10^{32} degrees
10^{27} degrees
Cosmic inflation (initial conditions) (t ~ 10^{-35} s)
18 degrees
3 degrees K
t = 13.7 billion yrs
radiation
particles
W^+ W^- Z heavy particles carrying the weak force
quark
anti-quark
electron
proton
neutron
meson
hydrogen
deuterium
helium
lithium

University of Durham

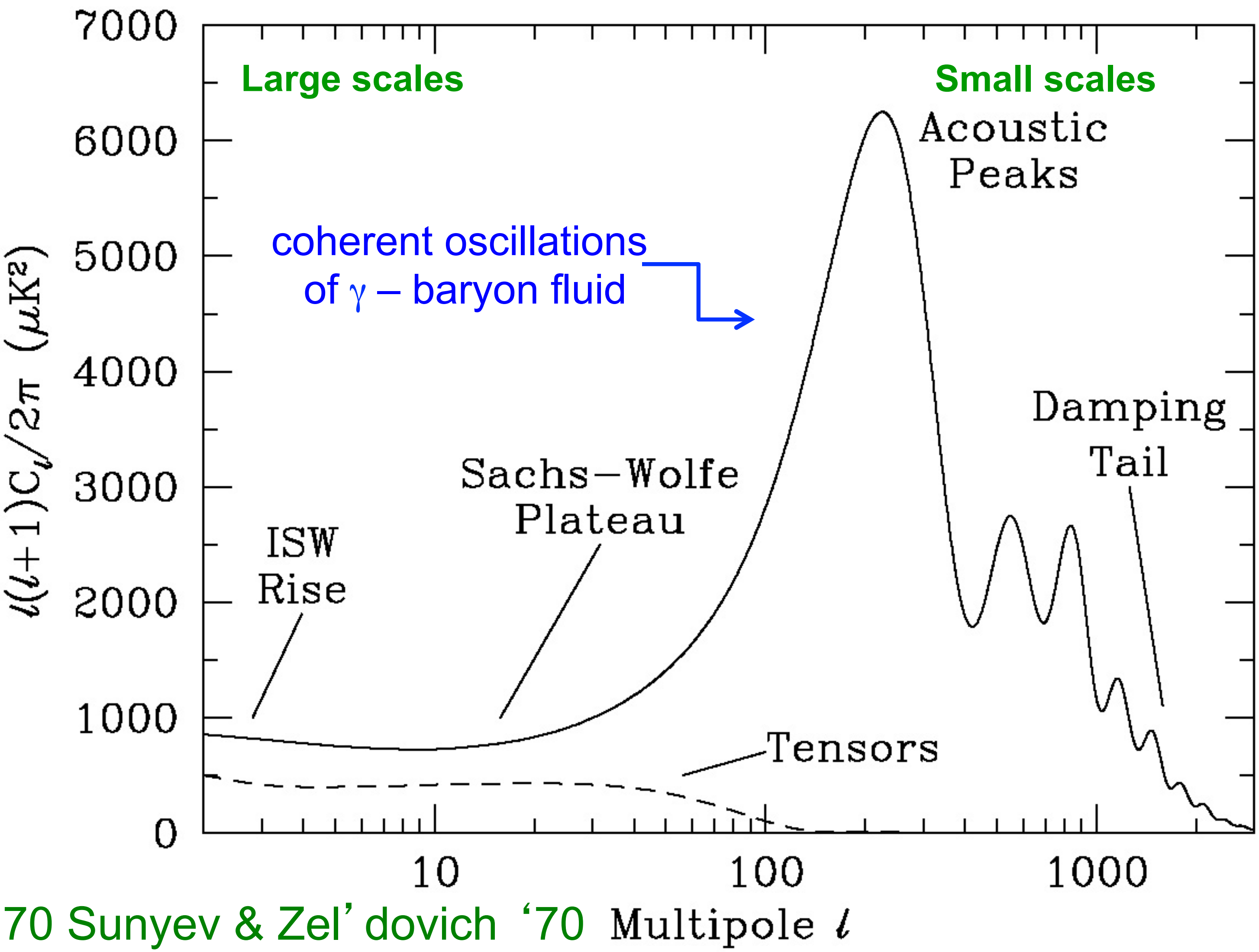
The initial conditions for galaxy formation



Temperature anisotropies in CMB

University of Durham

2D power spectrum



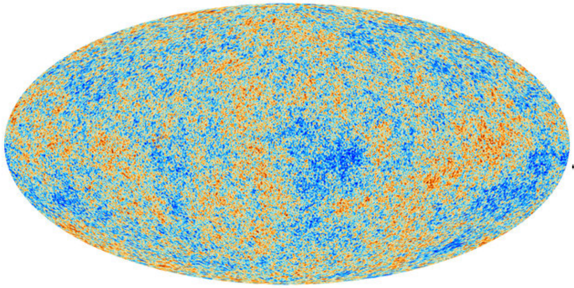
Peebles & Yu '70 Sunyev & Zel'dovich '70

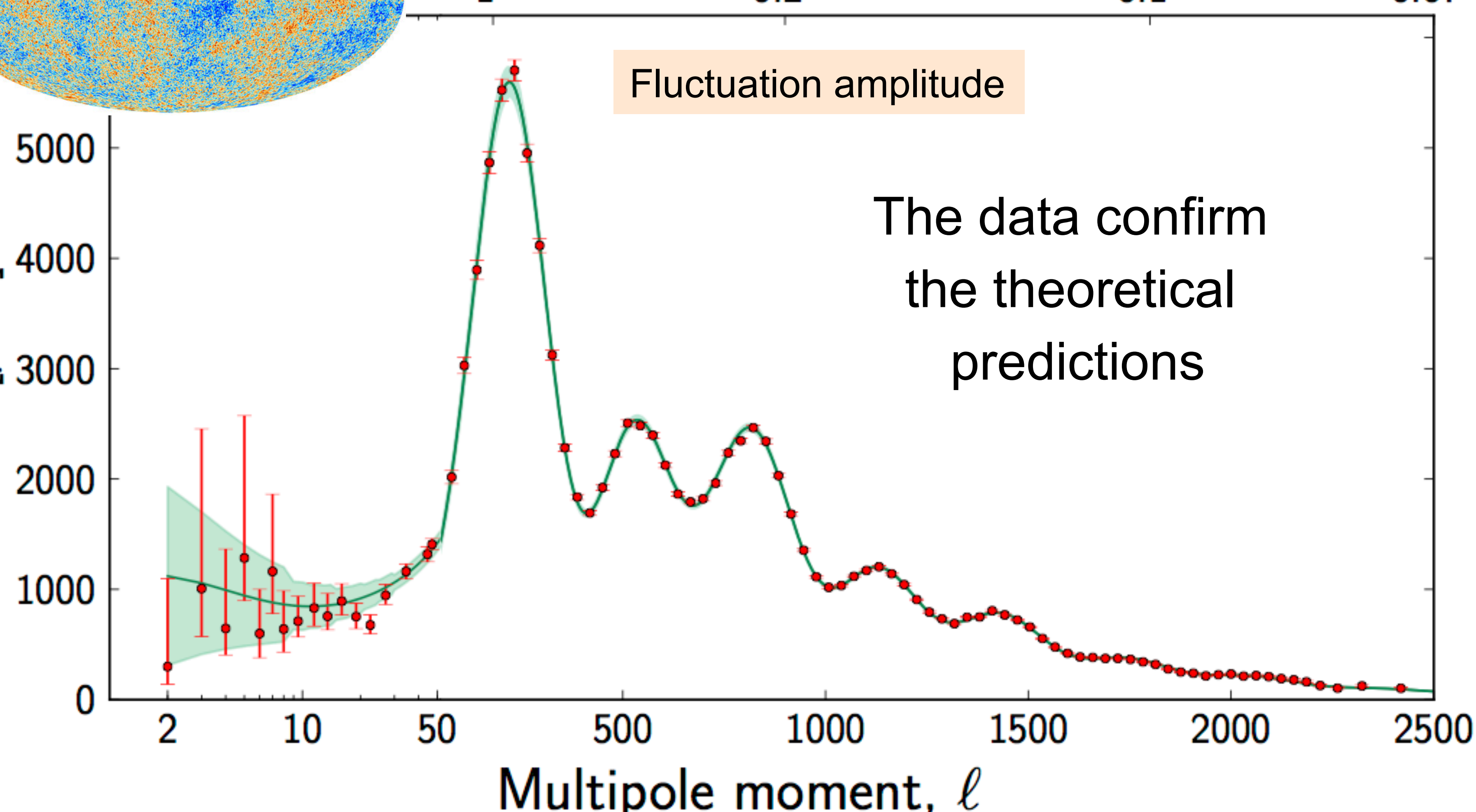
For CDM: Peebles '82; Bond &Efstathiou '84

Institute for Computational Cosmology

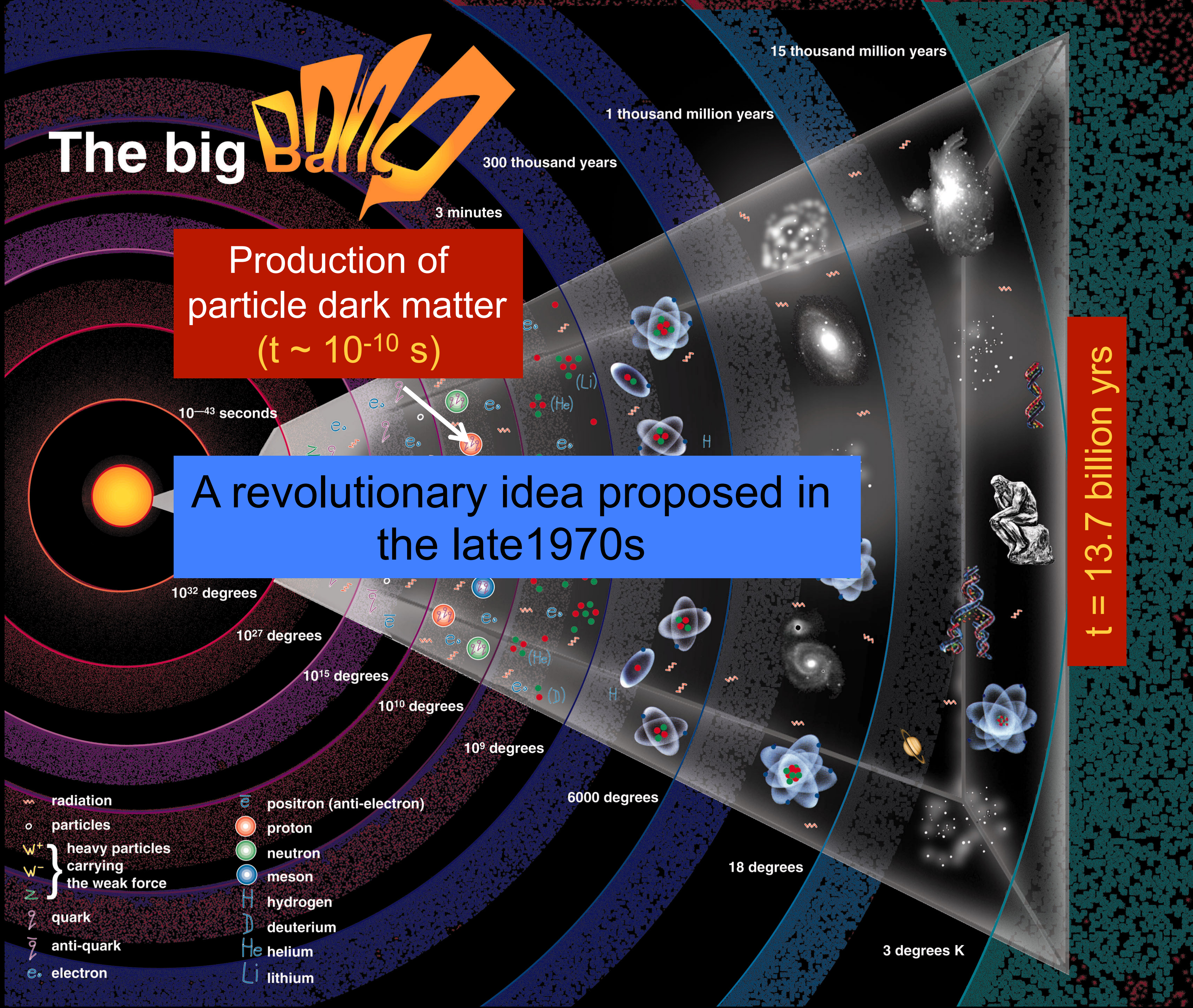
University of Durham ICC

Planck: CMB temperature anisotropies





Planck coll. 2015



Production of particle dark matter ($t \sim 10^{-10}$ s)

A revolutionary idea proposed in the late1970s

t = 13.7 billion yrs

Non-baryonic dark matter candidates

From the 1980s:

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

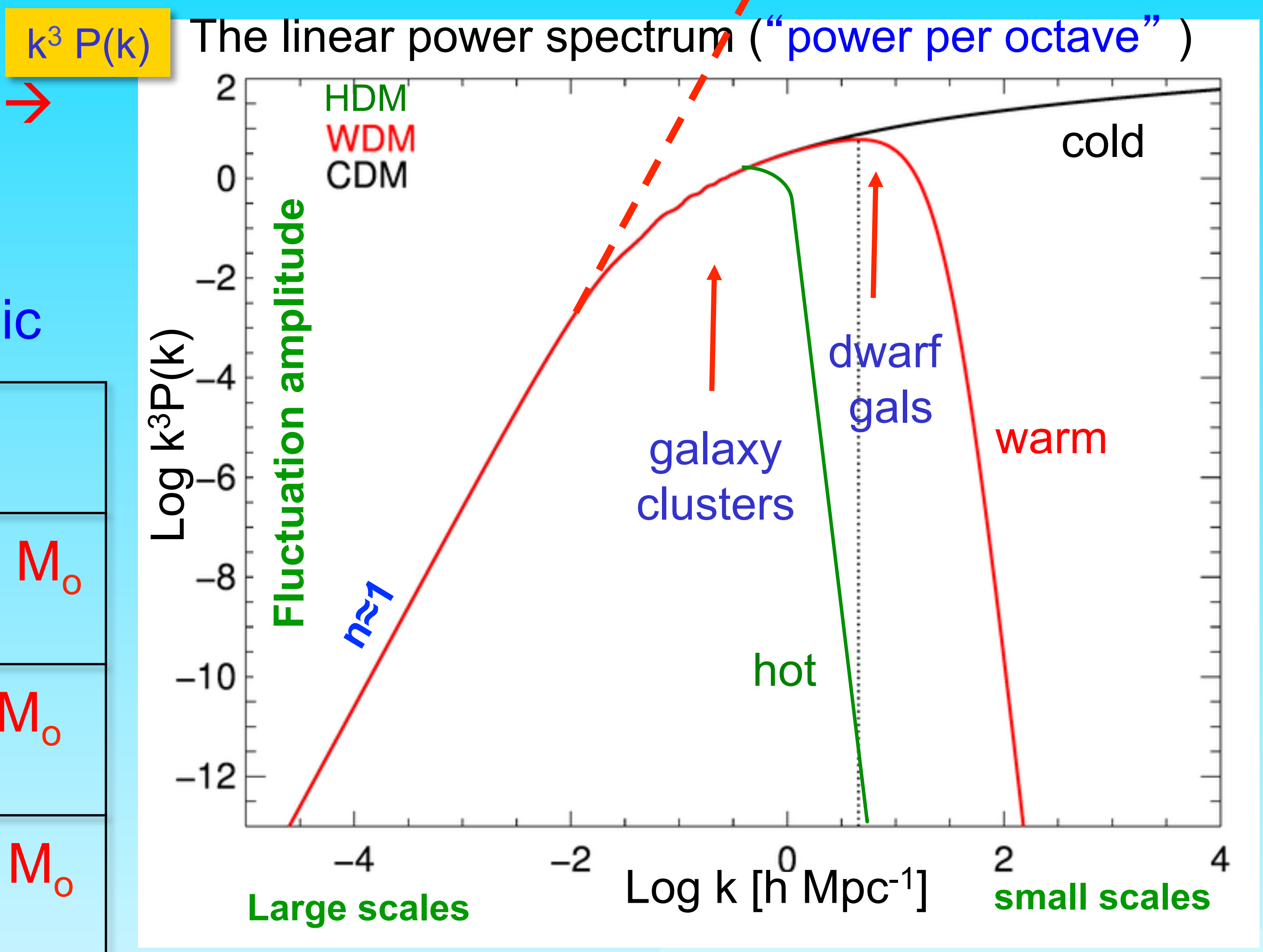
The dark matter power spectrum

Free streaming →

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

for a thermal relic

Type	M_{cut}
Hot	~10^{15} M_o
Warm	~10^{9} M_o
Cold	~10^{-6} M_o



University of Durham

Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann

Poisson, Friedmann

Radiative hydrodynamics

Subgrid astrophysics

How to make a virtual universe

Institute for Computational Cosmology

Hot dark matter

1981

$m_\nu = 30$ ev $\rightarrow \Omega = 1$

HAS THE NEUTRINO A NON-ZERO REST MASS?*
(Tritium β-Spectrum Measurement)

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov
Institute for Theoretical and Experimental Physics, Moscow, U.S.S.R.

V. Kosik
Institute of Molecular Genetics, Moscow, U.S.S.R.

ABSTRACT

The high energy part of the β-spectrum of tritium in the v... molecule was measured with high precision by a toroidal β-spect... meter. The results give evidence for a non-zero electron anti- neutrino mass.

Fifty years ago Pauli introduced the neutrino to explain the β-spectrum shape. Pauli made the first estimate of the neutrino mass ($E_{3\,max} \cong$ nuclei mass defect): it should be very small or maybe zero. Up to now the study of the β-spectrum shape is the most sensitive, direct method of neutrino mass measurement.

For allowed β-transitions, if $M_\nu = 0$, then $S \simeq (E-E_o)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_o$ (total β-transition energy). If $M_\nu \neq 0$, then $S \simeq (E_o-E)\sqrt{(E_o-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

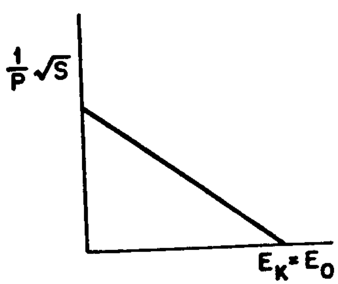


Fig. 1. Kurie plot for $M_\nu = 0$.

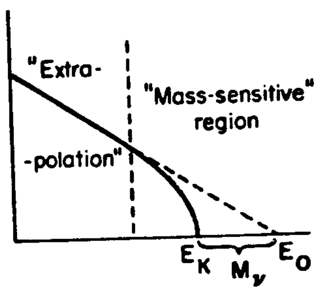
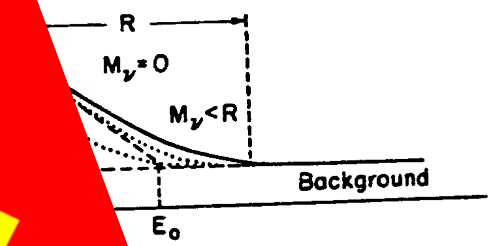


Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_o from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_o - E_k$. Qualitatively, $M_\nu \neq 0$ if the β-spectrum near the end-point runs below the extrapolated curve.

*Paper presented by Oleg Egorov.

I... things are more complicated. The apparatus reso- ...rongly affects the spectrum endpoint and rather ...e spectrum slope.



...ealistic Kurie plot.

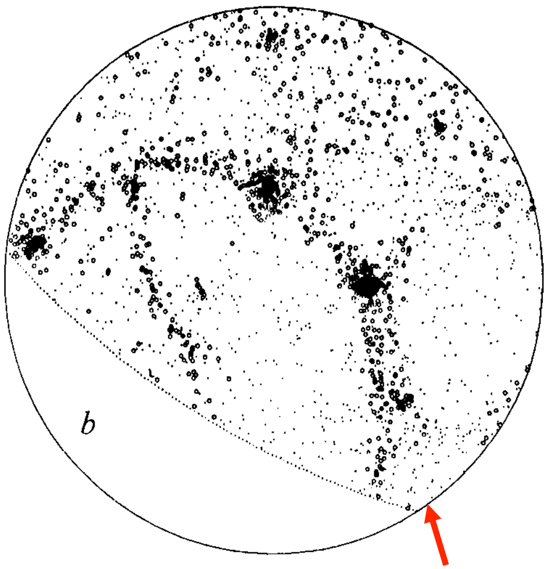
...extrapolation. However, we are unable ..., then once again the lack of counts near the ... indicate that $M_\nu \neq 0$. If $M_\nu \leq R$, the changes due to ...mass and the influence of R are indistinguishable. For M_ν ...ermination the knowledge of R is compulsory. The background de- termines the statistical accuracy near the endpoint, i.e., in the region of the highest sensitivity to the ν mass. So: 1) R should be $\sim M_\nu$, 2) the smaller M_ν is, the smaller the background ($\sim M_\nu^2$) must be and the higher the statistics ($\sim M_\nu^{-3}$) must be. For example, suppose that for $M_\nu = 100$ eV we need resolution R, background Q, and statistics N. If $M_\nu = 30$ eV, to achieve the same ΔM/M they should be R/3, Q/10, and N × 30, respectively.

The shorter the β-spectrum, the less it is spread due to R (as $R \sim \Delta p/p$ = const.). A classical example is ^3H β-decay, which has 1) the smallest $E_o \sim 18.6$ keV, 2) an allowed β-transition, simple theoretical interpretation, 3) highly reduced nucleus, and simple radioactivity. The first experiments with ^3H were by S. Curran et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^3H gas in a proportional counter, they obtained $M_\nu \leq 1$ keV. Further progress required magnetic spectrometer development. This allowed the resolution to be improved considerably, and L. Langer and R. Moffat (1952) obtained $M_\nu \leq 250$ eV. The best value was obtained by K. Bergkvist (1972): $R \sim 50$ eV and $M_\nu \leq 55$ eV.

The ITEP spectrometer is of a new type: ironless, with toroidal magnetic field (E. Tretyakov, 1973). The principle of the toroidal magnetic field focusing systems was proposed by V. Vladimirsky et al. (An example is a "Horn" of ν-beams.) It turns out that a rectilinear conductor (current) has a focusing ability for particles emitted perpendicular to the rotation axis. This system has infinite periodical focusing structure. The ITEP spectrometer is based on this principle.

Non-baryonic dark matter cosmologies

University of Durham



Neutrinos
$\Omega=1$

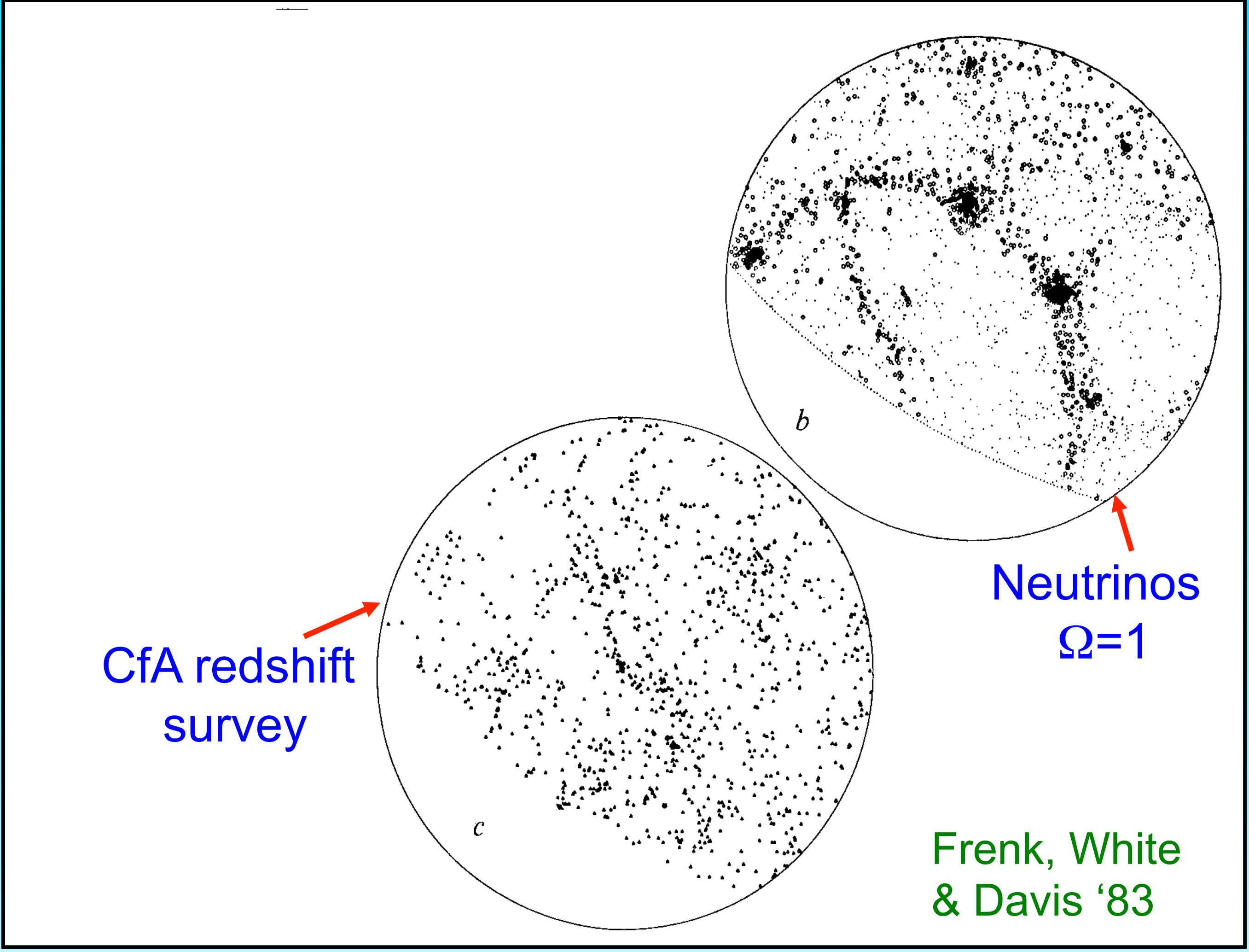
Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev



University of Durham

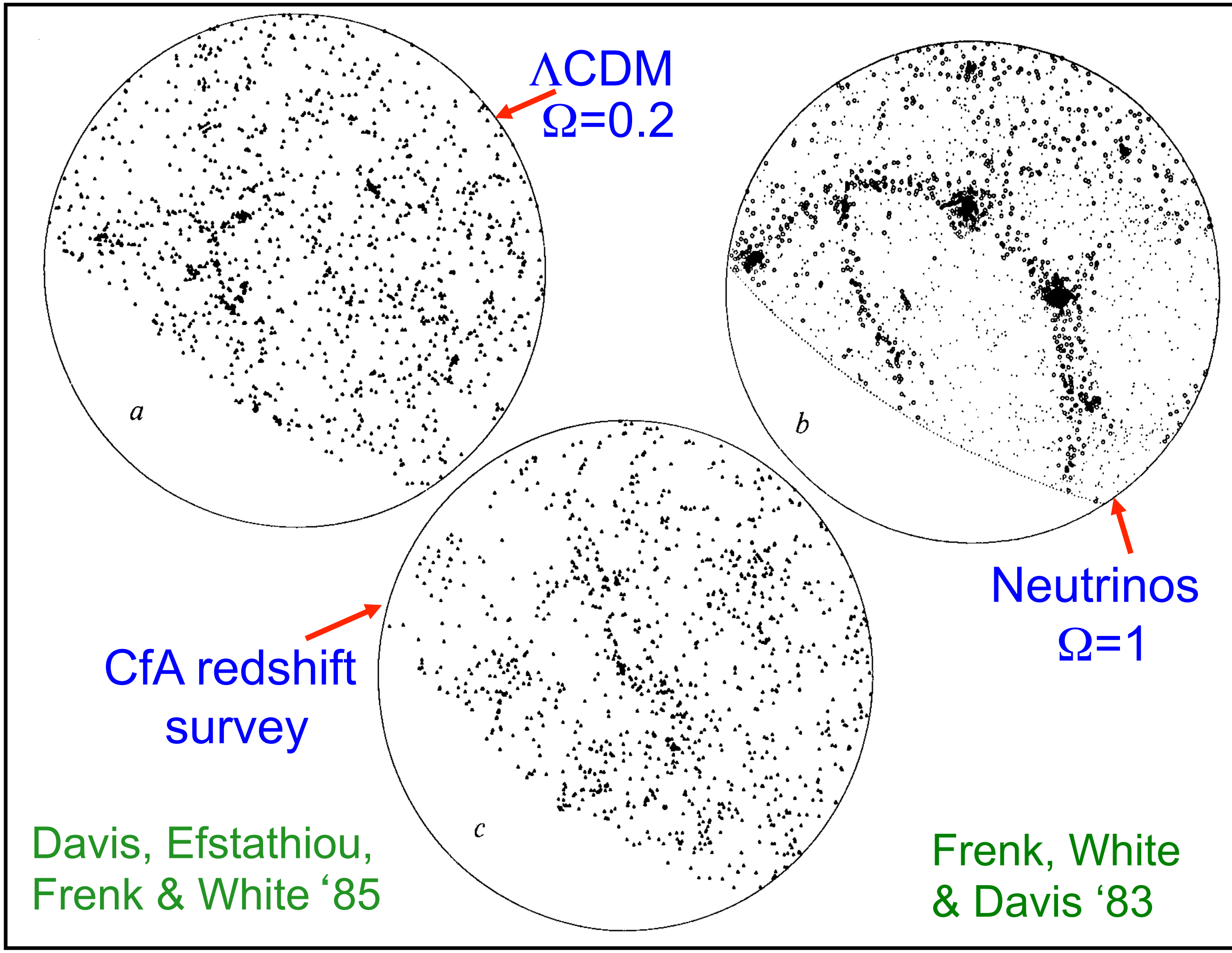
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

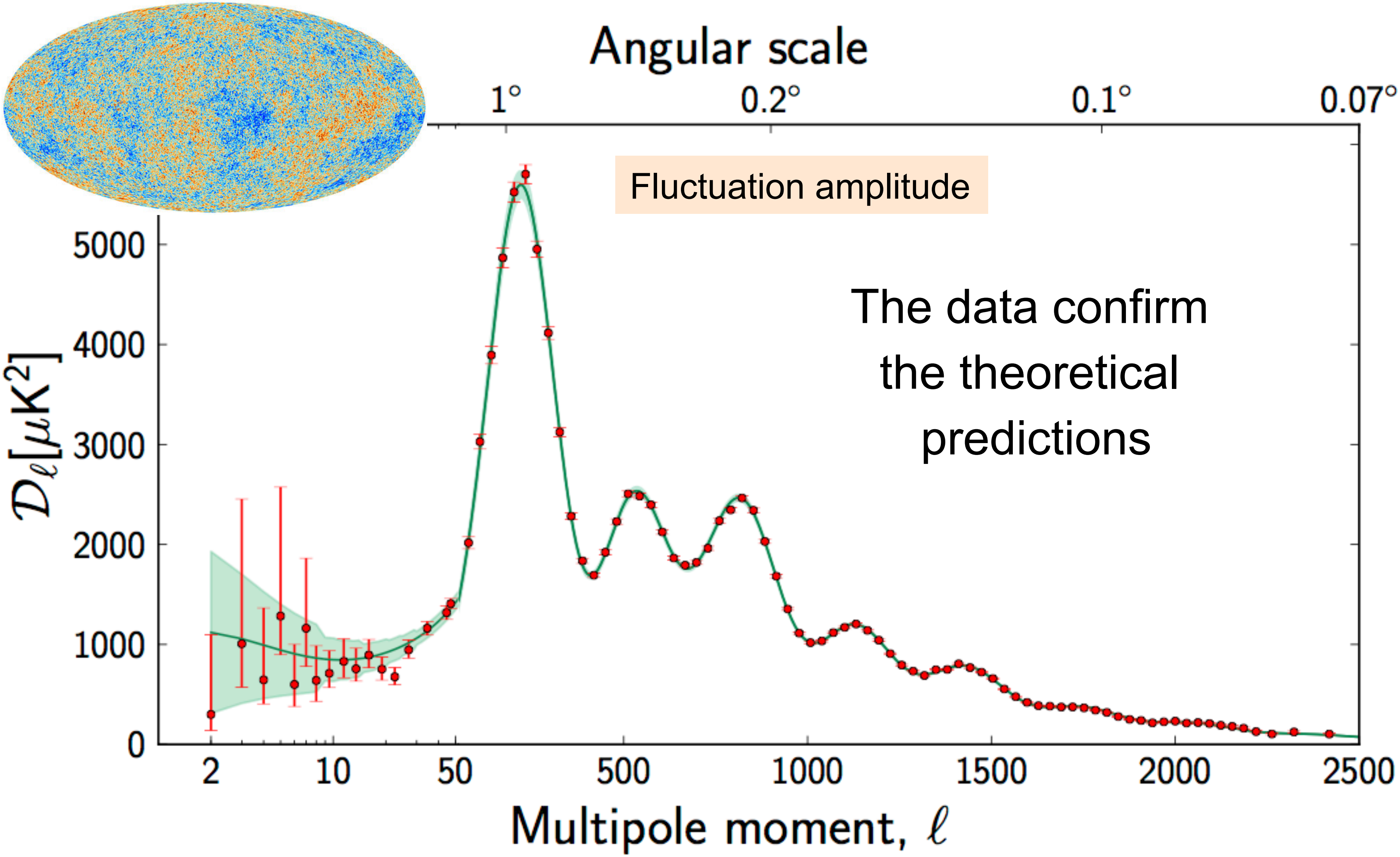
Neutrinos cannot make appreciable contribution to Ω → $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Planck: CMB temperature anisotropies



Planck coll. 2015

The six parameters of minimal ΛCDM model

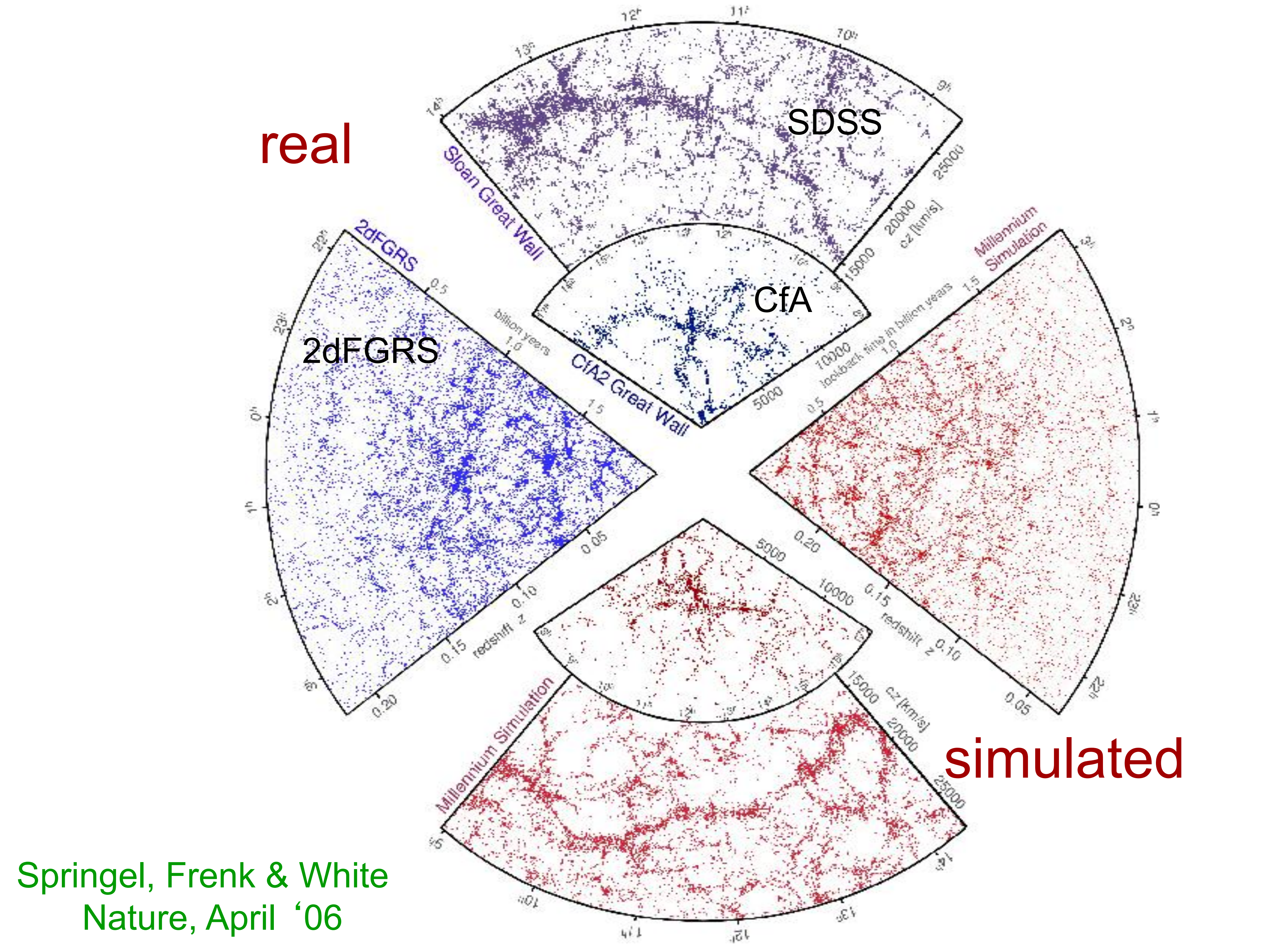
Univer

6 mdoel parameters

	Planck+WP	
Parameter	Best fit	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	$3.089^{+0.024}_{-0.027}$

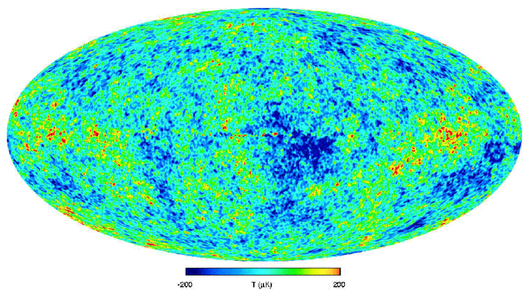
A 40σ detection of non-baryonic dark matter using only z=1000 data!

Planck collaboration ‘13

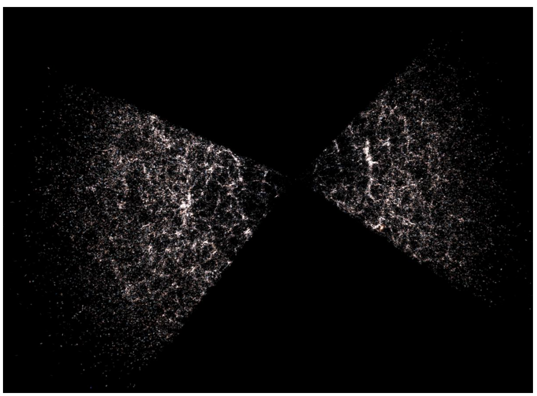

real
SDSS
Sloan Great Wall
CfA
CfA2 Great Wall
2dFGRS
2dFGRS
Millennium Simulation
Millennium Simulation
simulated
lookback time in billion years
redshift z
cz [km/s]
billion years
Springel, Frenk & White
Nature, April '06

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

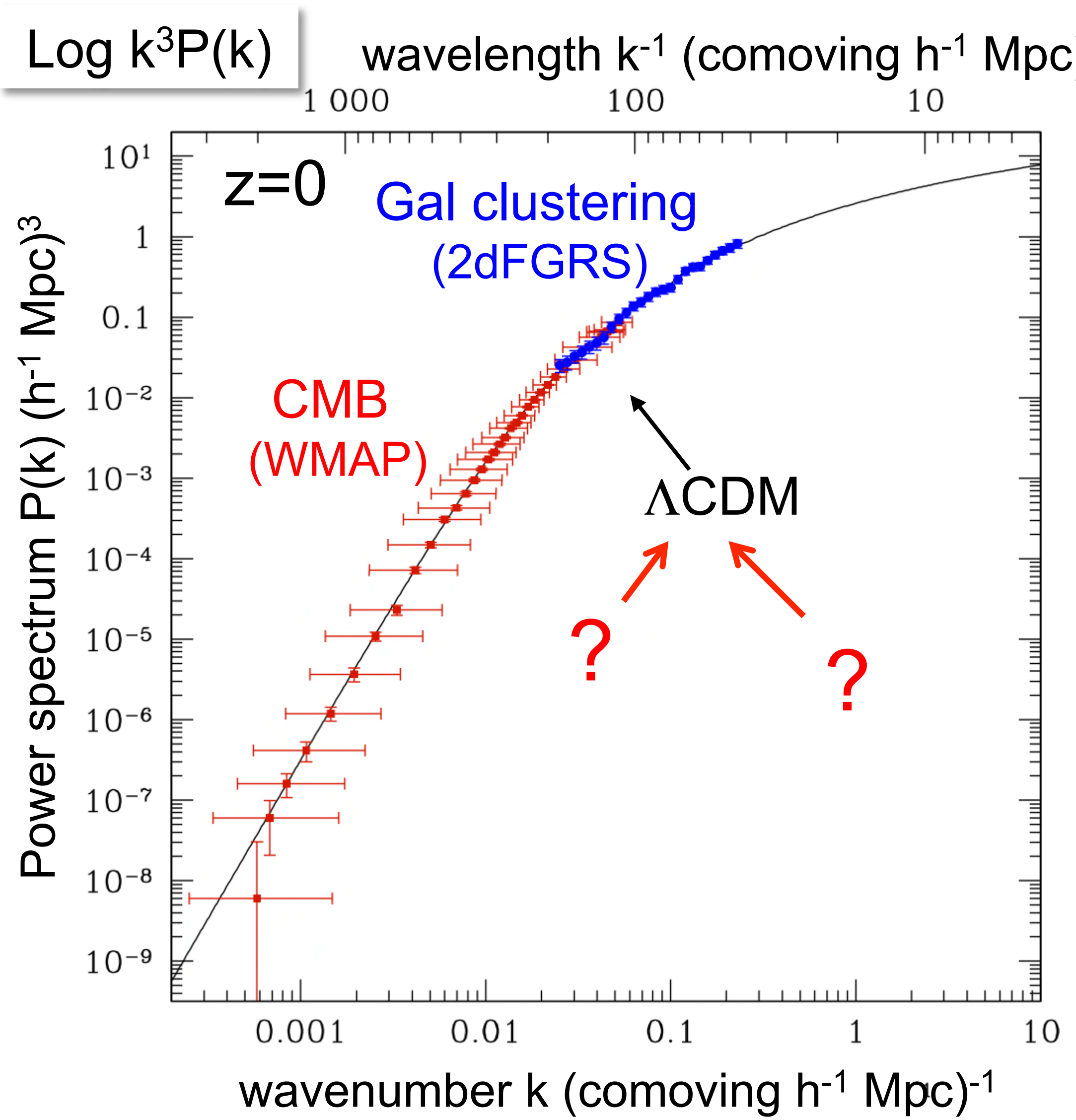
University of Durham



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 →

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

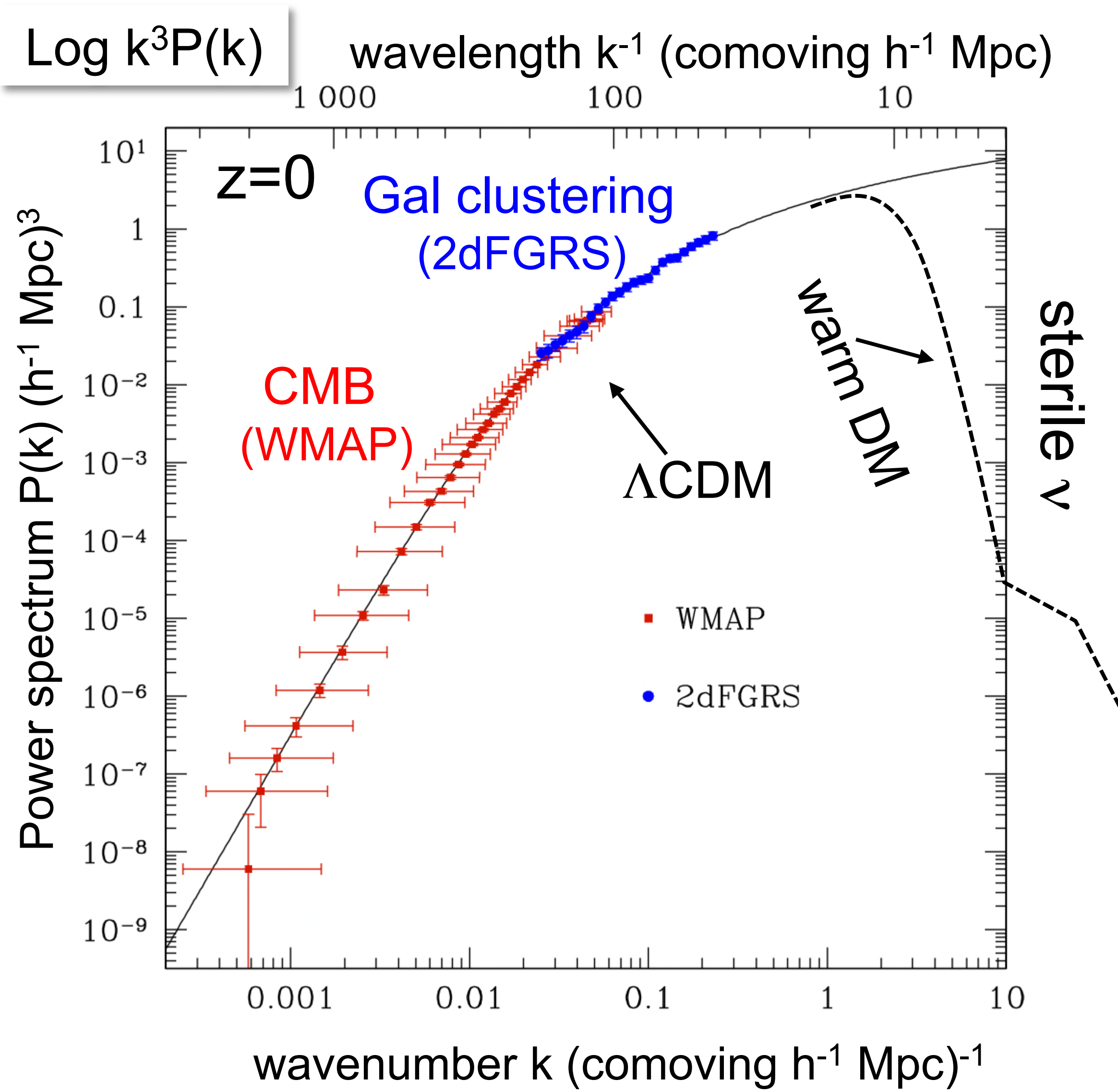
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

- CDM: γ-ray excess from Galactic Center
- WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

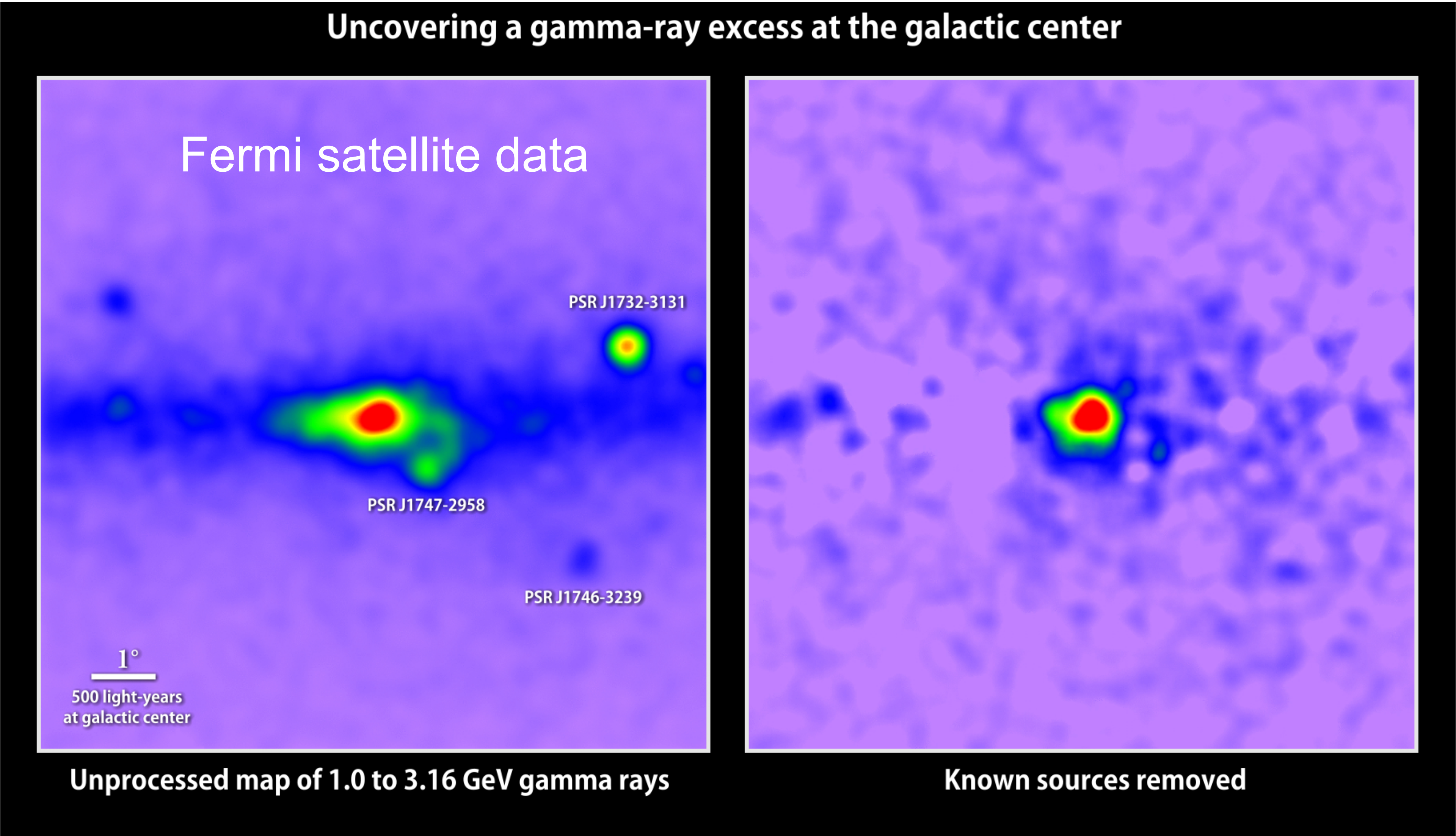
Cold dark matter

Annihilation radiation from the Galactic Centre?

Cold dark matter

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]



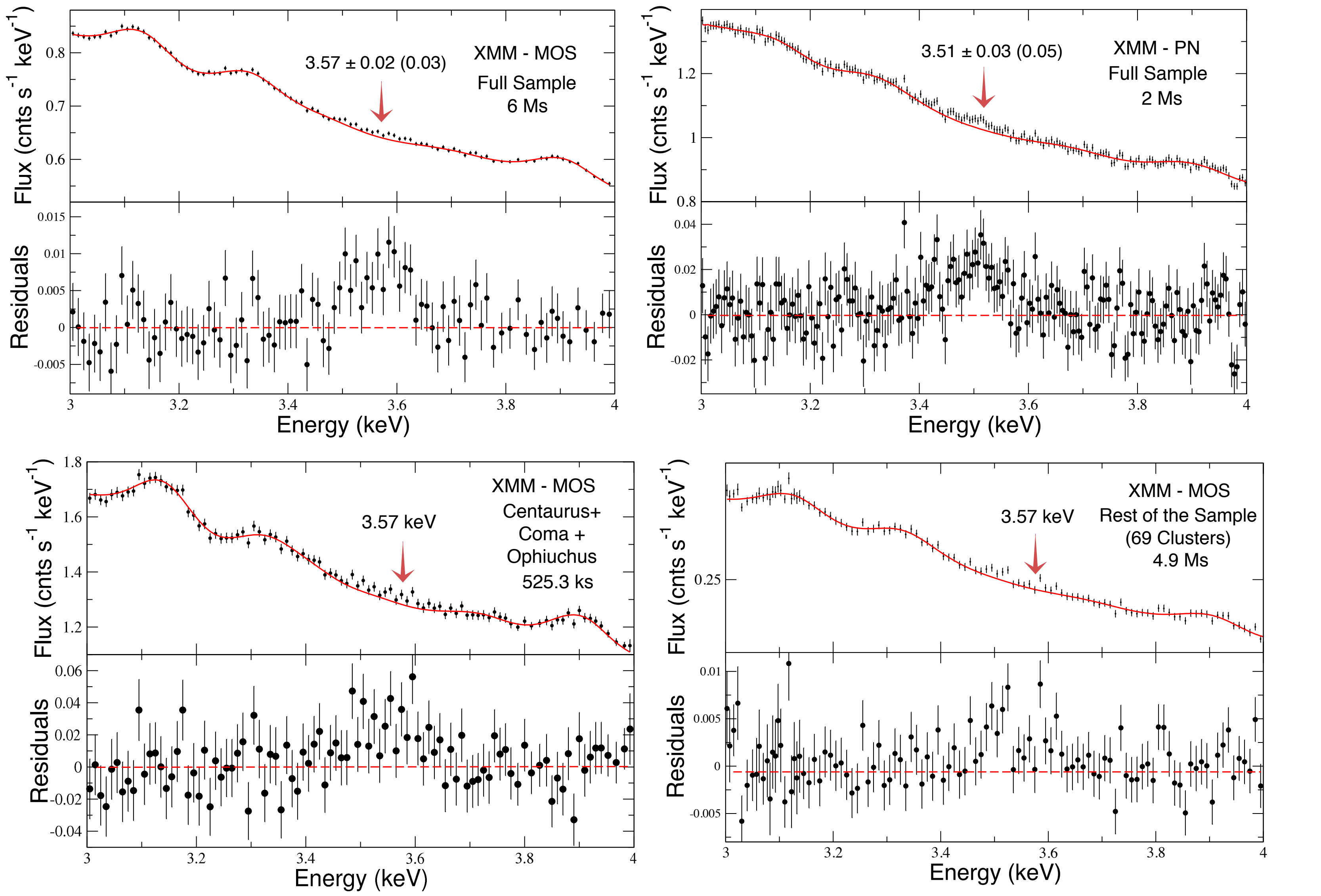
Warm dark matter

Decay line at 3.51 keV in galaxies and clusters

University of Durham

Warm dark matter
WDM decay line in 69 stacked clusters?

E=3.57 keV   Bulbul et al. '14   See also Boyarsky et al. '14



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

- CDM: γ-ray excess from Galactic Center
- WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Very unlikely that both are right!

Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter | warm dark matter

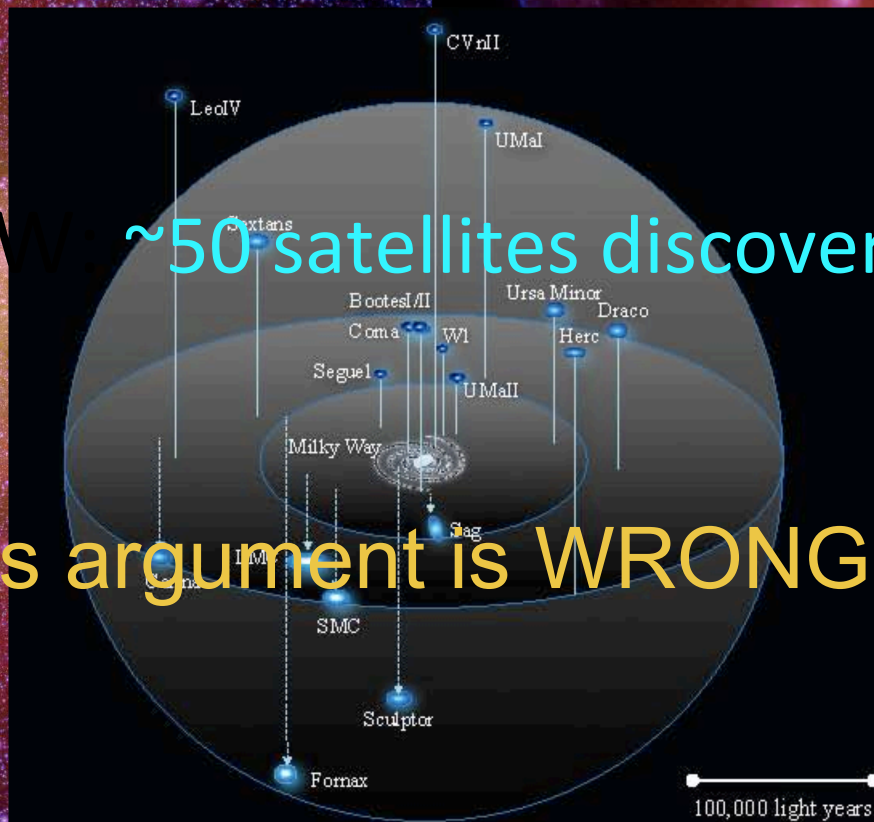
How can we distinguish between these?

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

cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31



In the MW: ~50 satellites discovered so far

This argument is WRONG!

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

Most subhalos never make a galaxy!

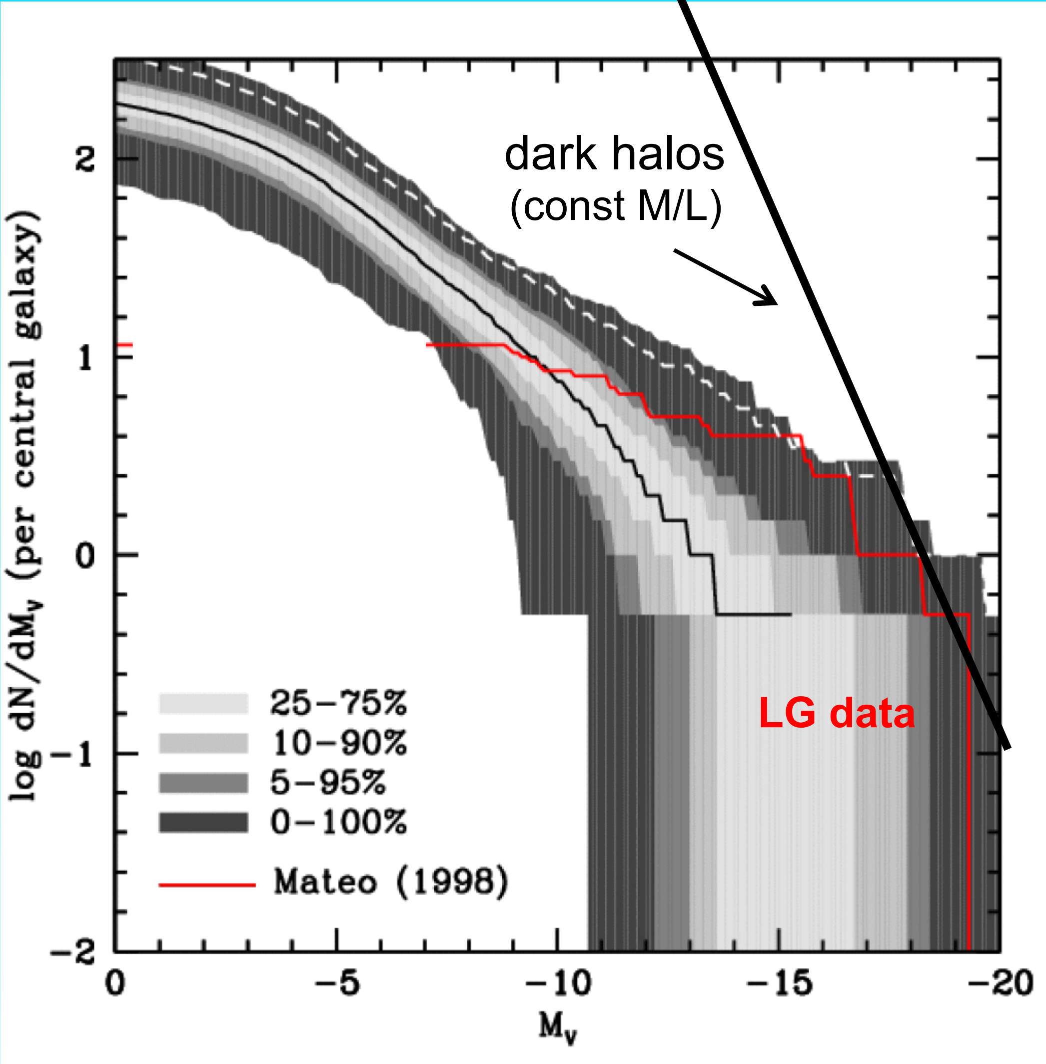
Because:

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

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)



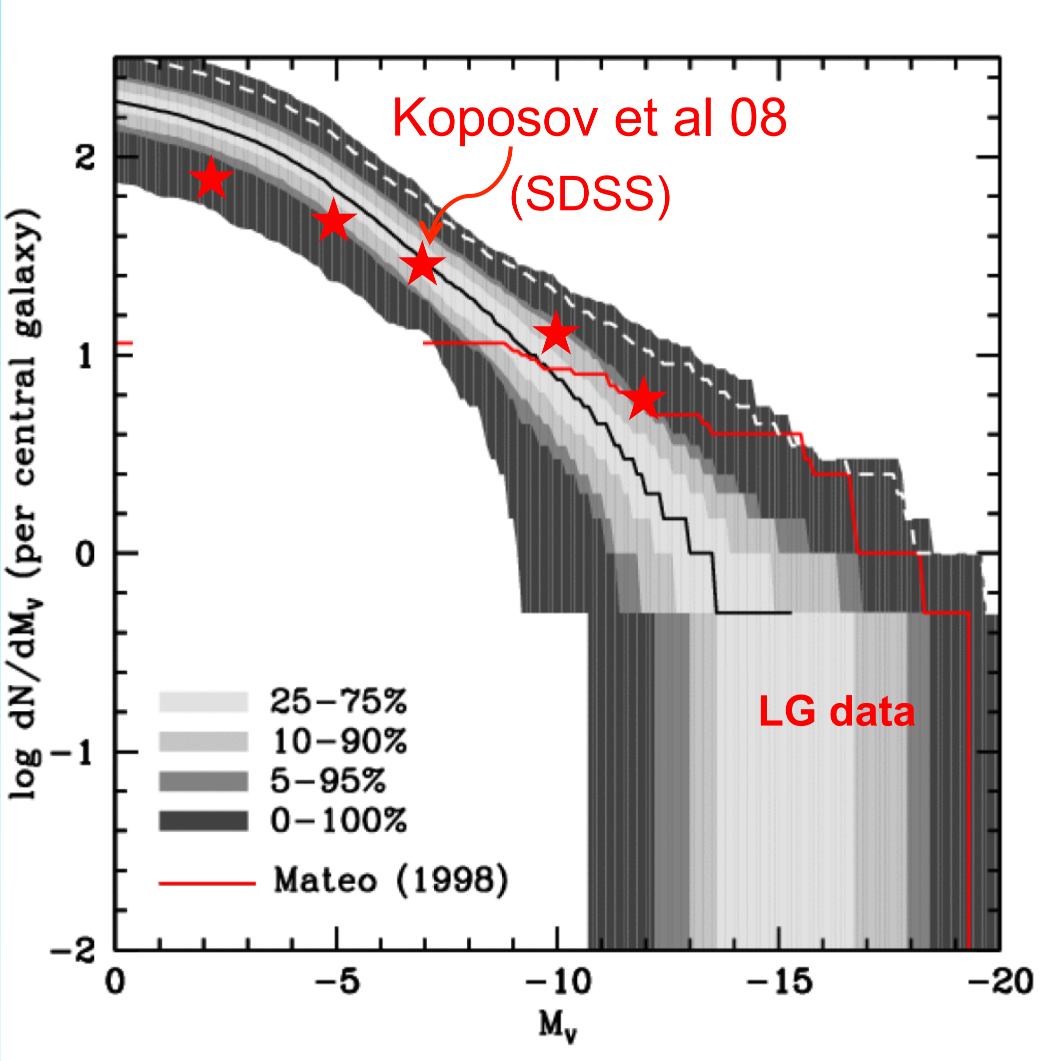
Benson, csf, Lacey, Baugh & Cole ’02
(see also Kauffman et al ’93, Bullock et al ’00)

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, csf, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock etal '01)

VIRGO

icc.dur.ac.uk/Eagle

"Evolution and assembly of galaxies and their environment"

THE EAGLE PROJECT

Virgo Consortium

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

Leiden: Rob Crain, Joop Schaye.

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

Durham University VIRGO ICC DiRAC PRACE

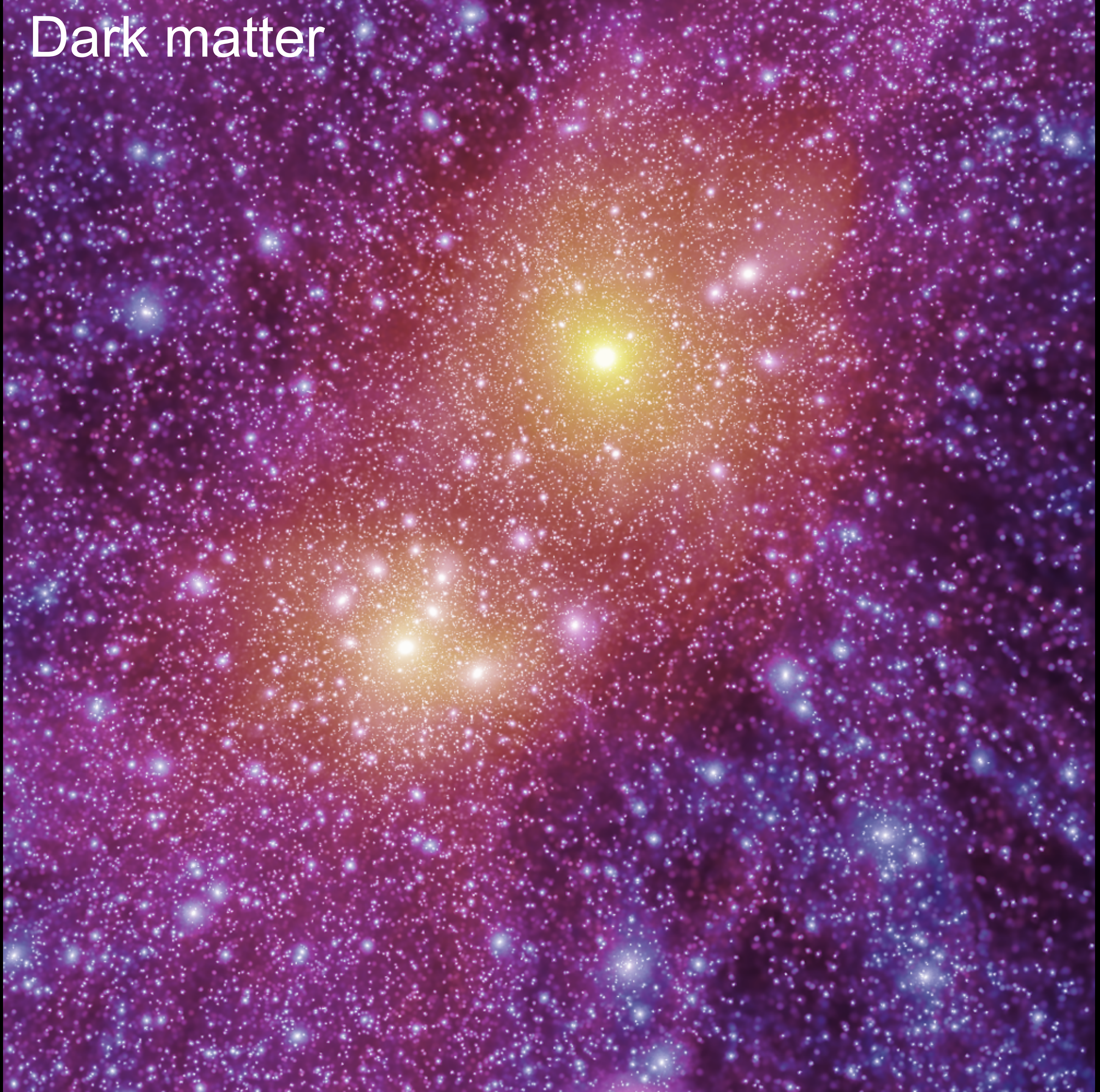
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

APOSTLE EAGLE full hydro simulations

Local Group

CDM

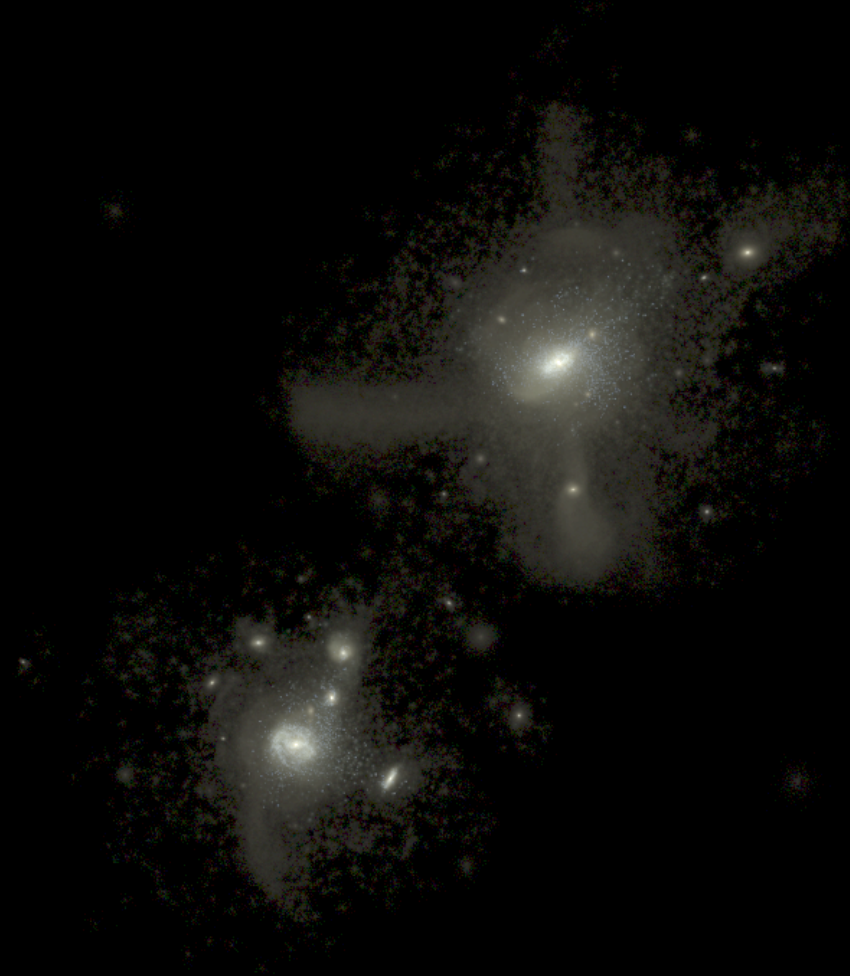
Sawala, csf et al '15



Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

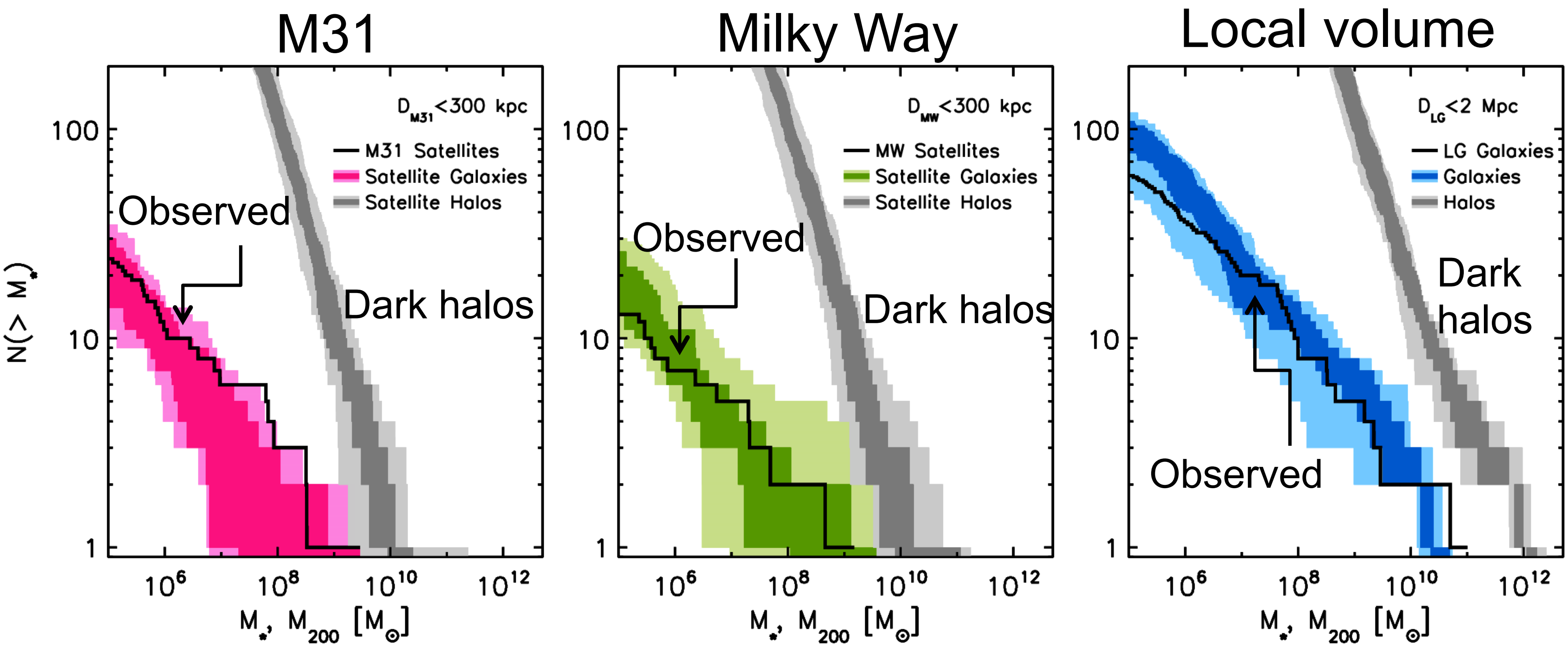


Far fewer satellite galaxies than CDM halos

Sawala, csf
et al ‘15

EAGLE Local Group simulation

University of Durham

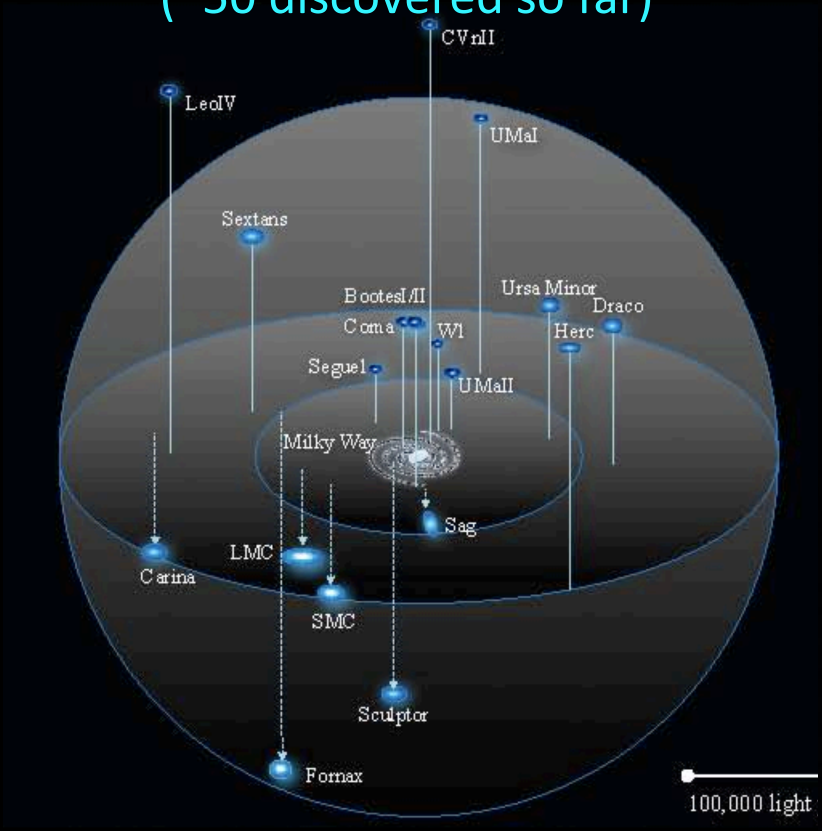


Sawala, csf et al '15

How about in WDM?

The satellites of the MW

(~50 discovered so far)



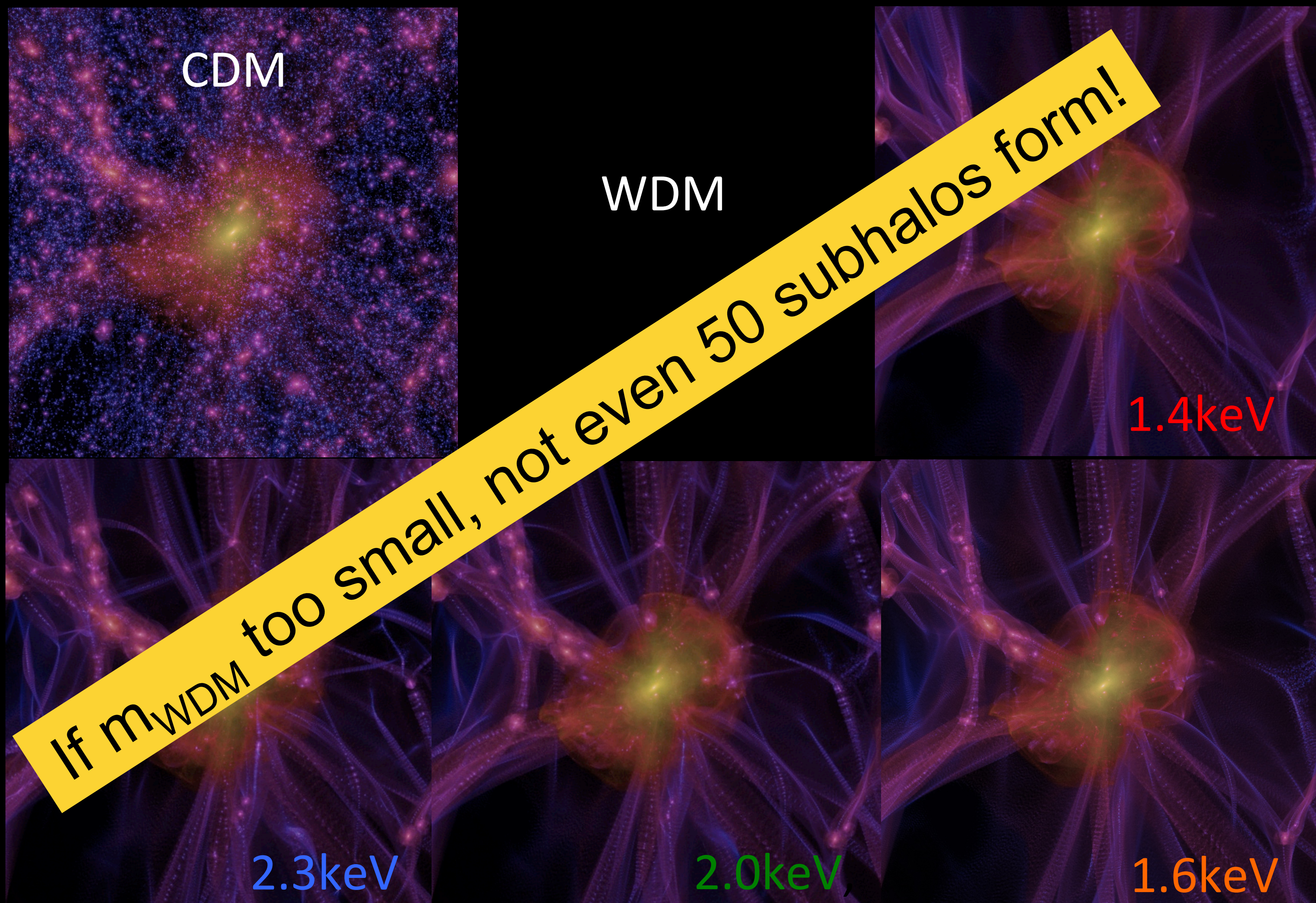
Dark mattter subhalos in WDM

(a few tens)

Warm DM: different ν mass

z=3

WDM
2.3 keV
2.0 keV
1.6 keV
1.4 keV



When "baryon effects" are taken into account

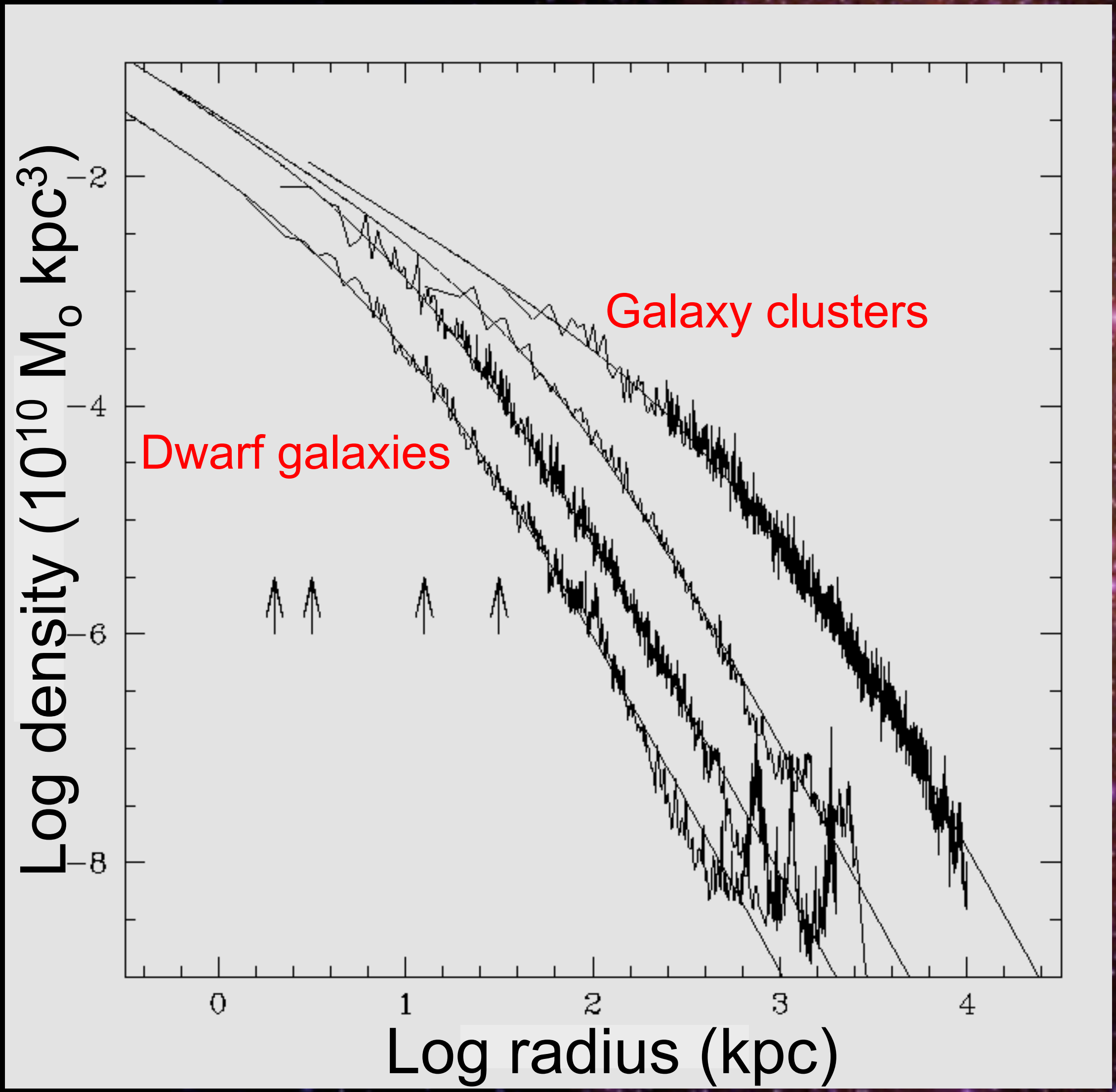
→

Observed abundance of satellites is compatible with CDM but rules out some WDM models

All we have achieved by counting satellite galaxies is to rule out a few WDM models!

Does the inner structure of satellites help?

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:

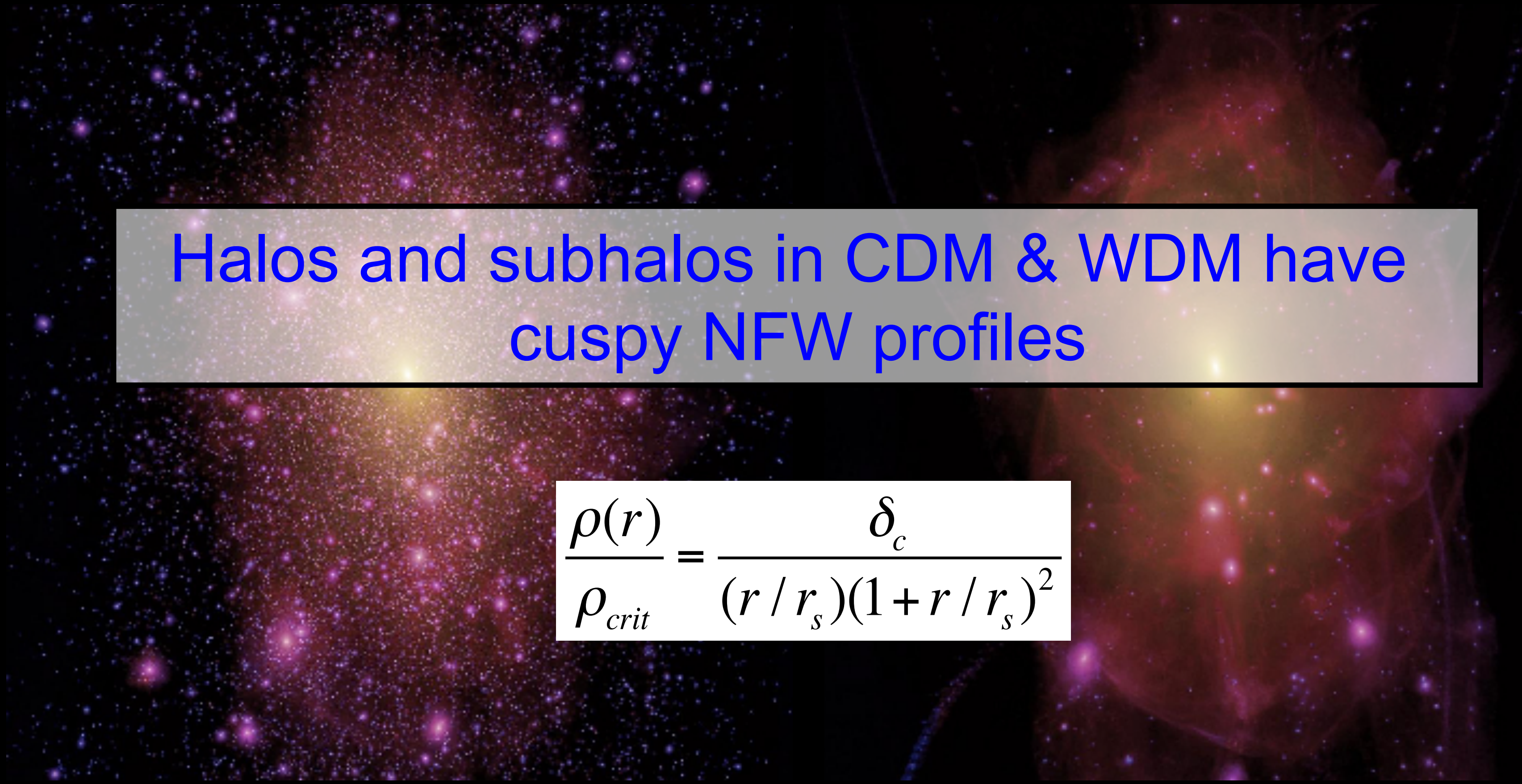
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

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

The core-cusp problem

cold dark matter | warm dark matter

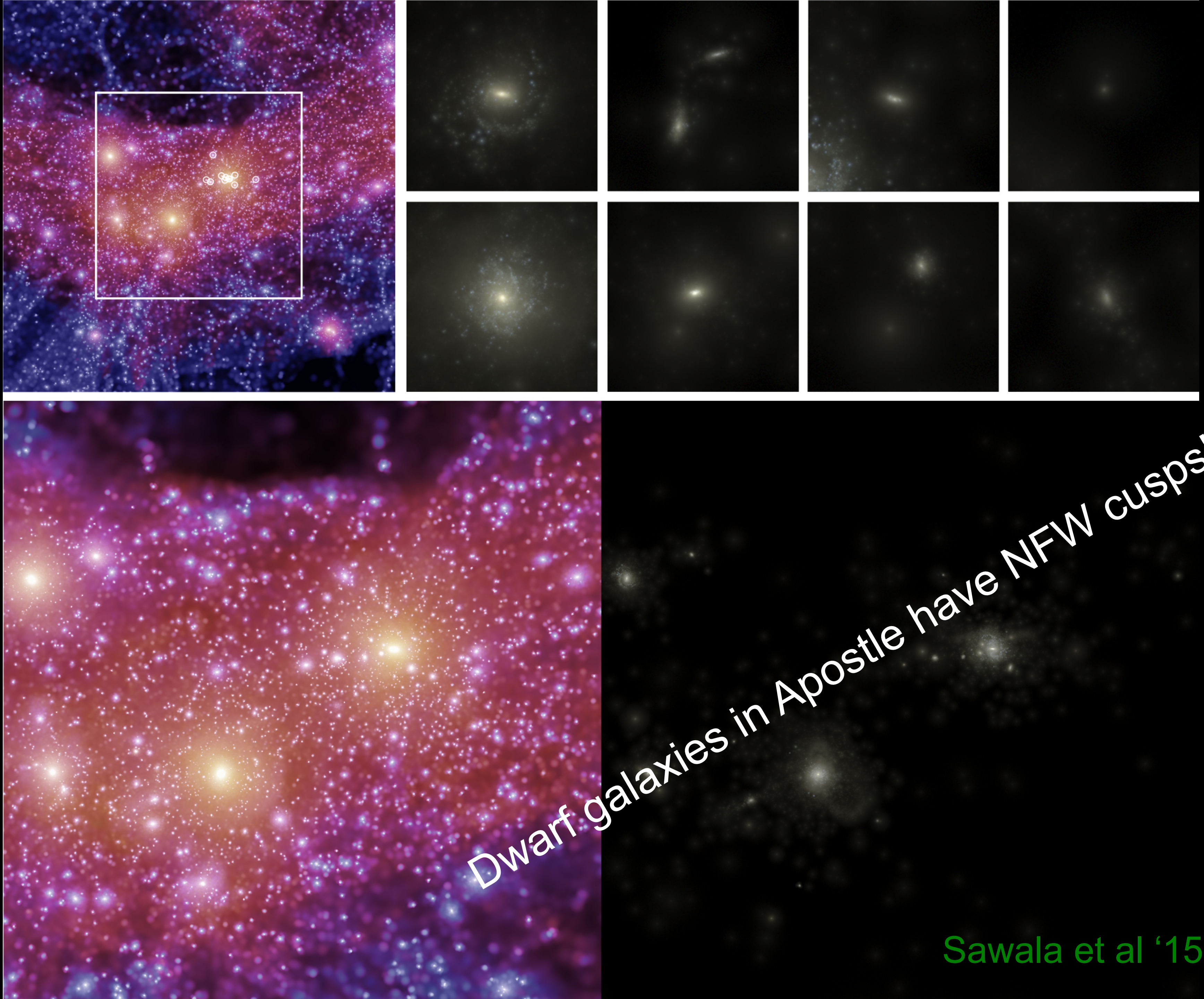


Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

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

ICC


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

Does Nature have them?

Sawala et al '15

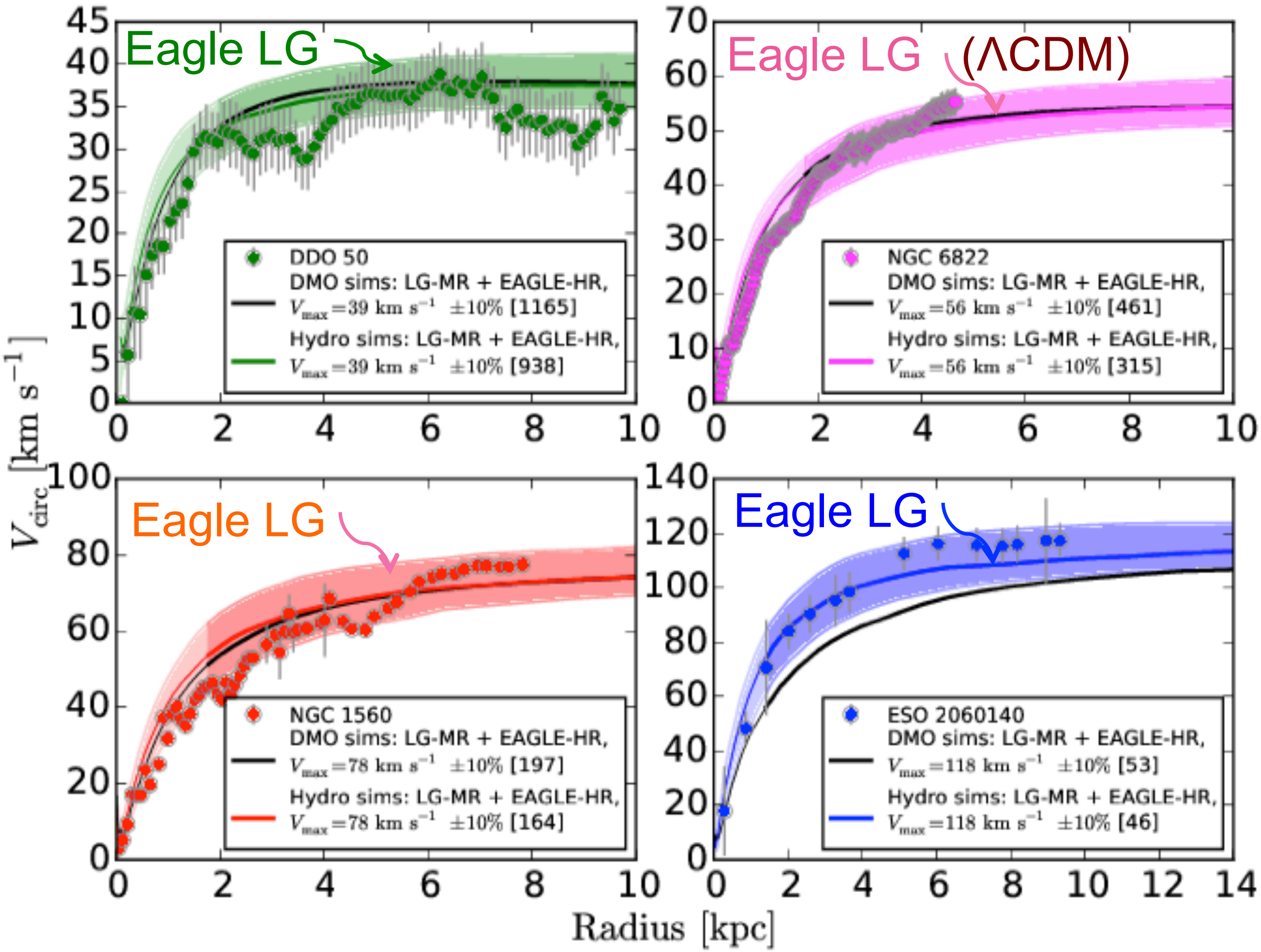
The diversity of gal rotation curves

University of Durham

$$V_{circ} = \sqrt{\frac{GM}{r}}$$

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)



Oman, Navarro, Frenk et al. '15

Institute for Computational Cosmology

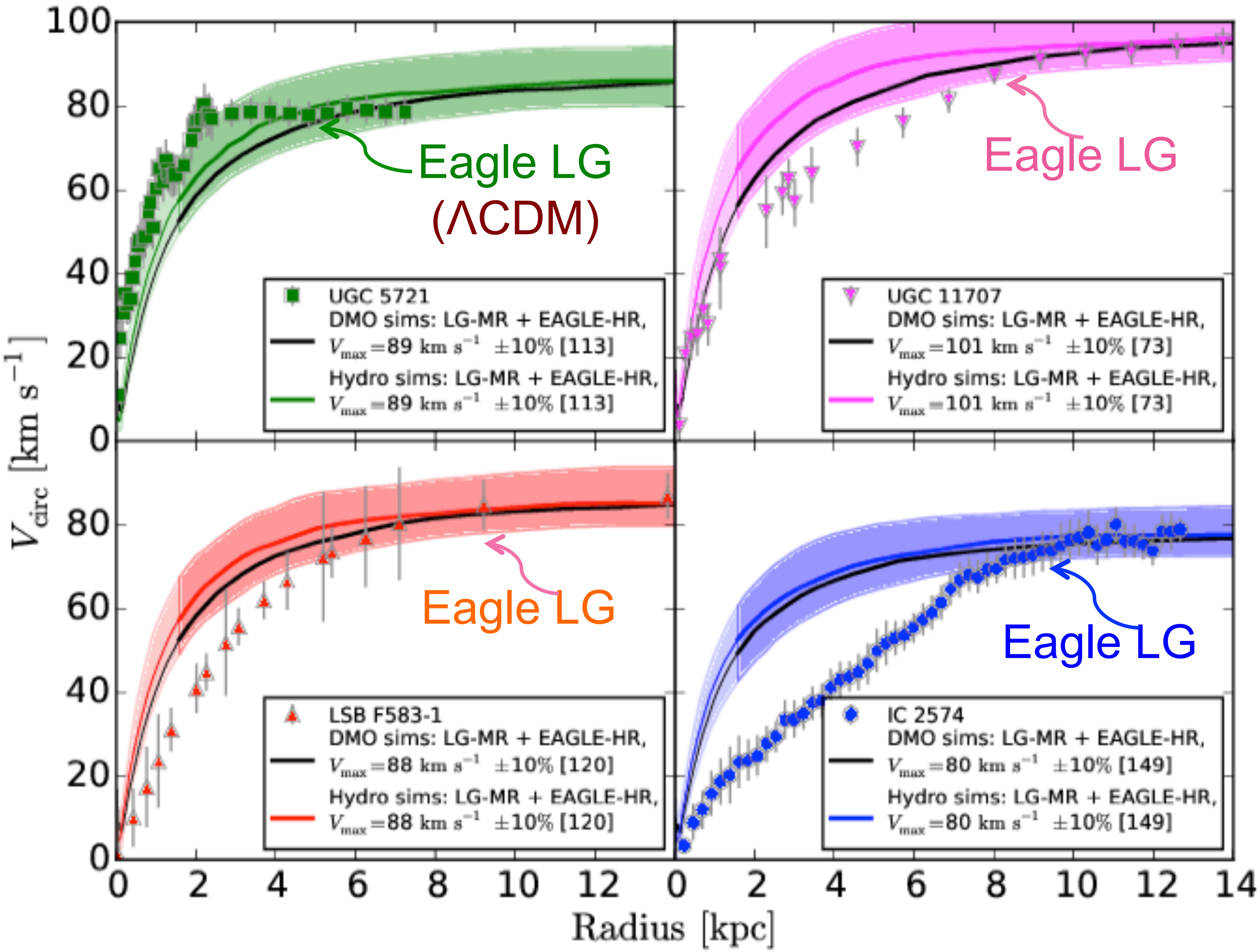
The diversity of gal rotation curves

University of Durham

$$V_{circ} = \sqrt{\frac{GM}{r}}$$

Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L_*)



Oman, Navarro, Frenk et al. '15

Does IC2574 rule out CDM (and WDM)?

Or are there 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

Parry, CSF et al. '11
Governato et al. '12
Pontzen & Governato '12
Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

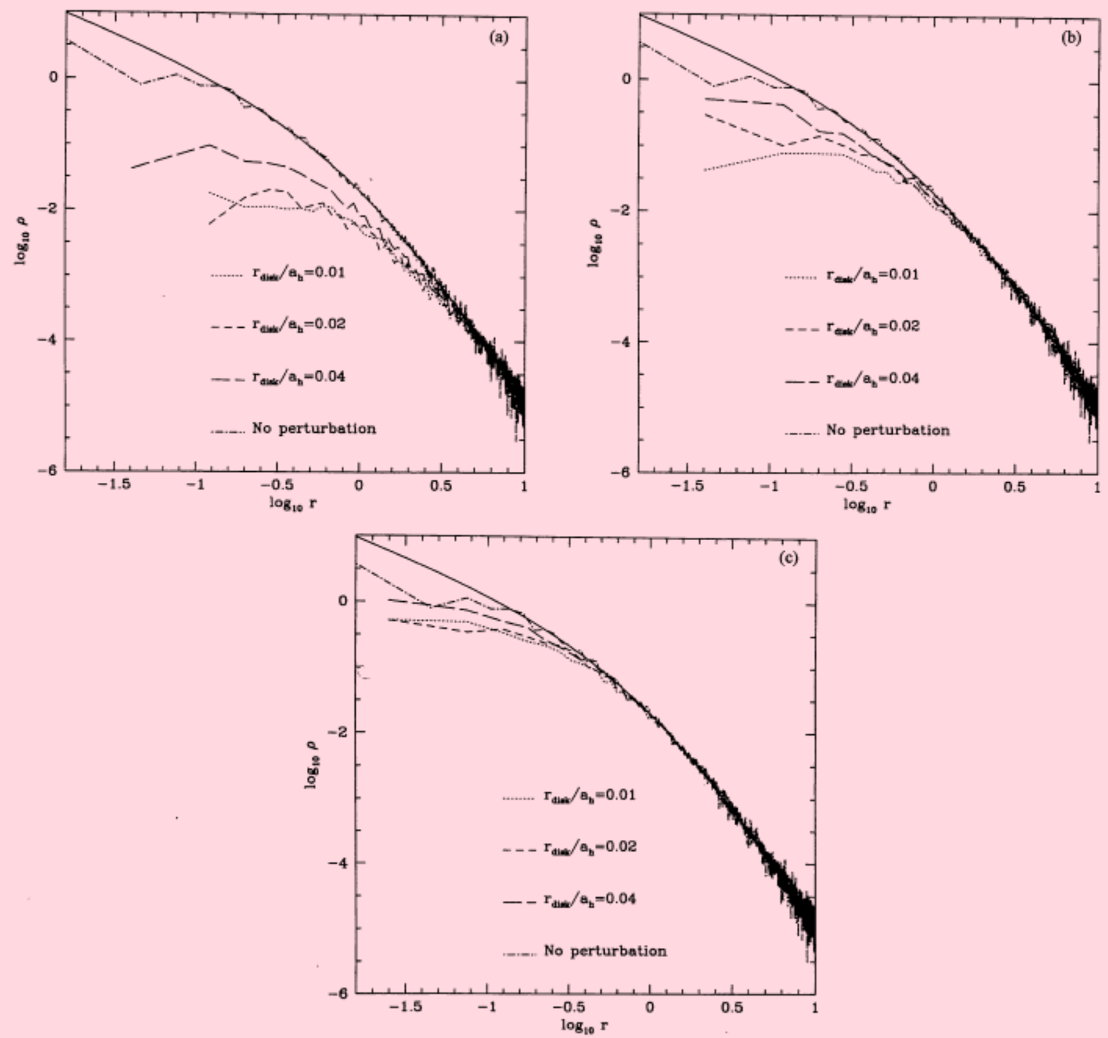


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

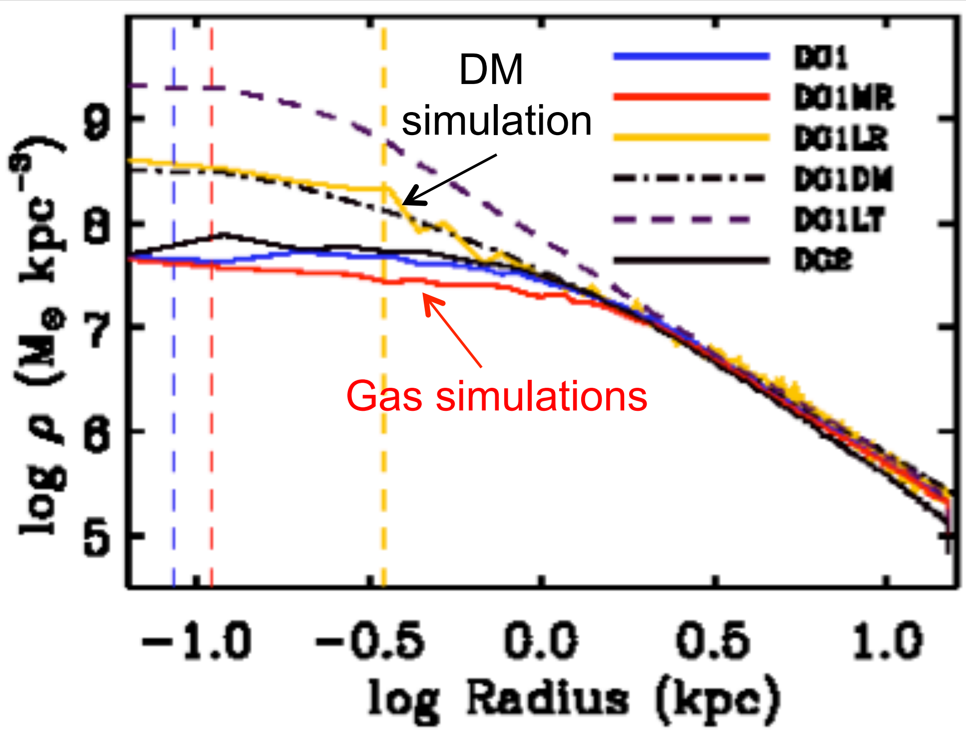
Cores in dwarf galaxy simulations

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



Parry, csf et al '11, Governato et al. '12
Pontzen et al. '12

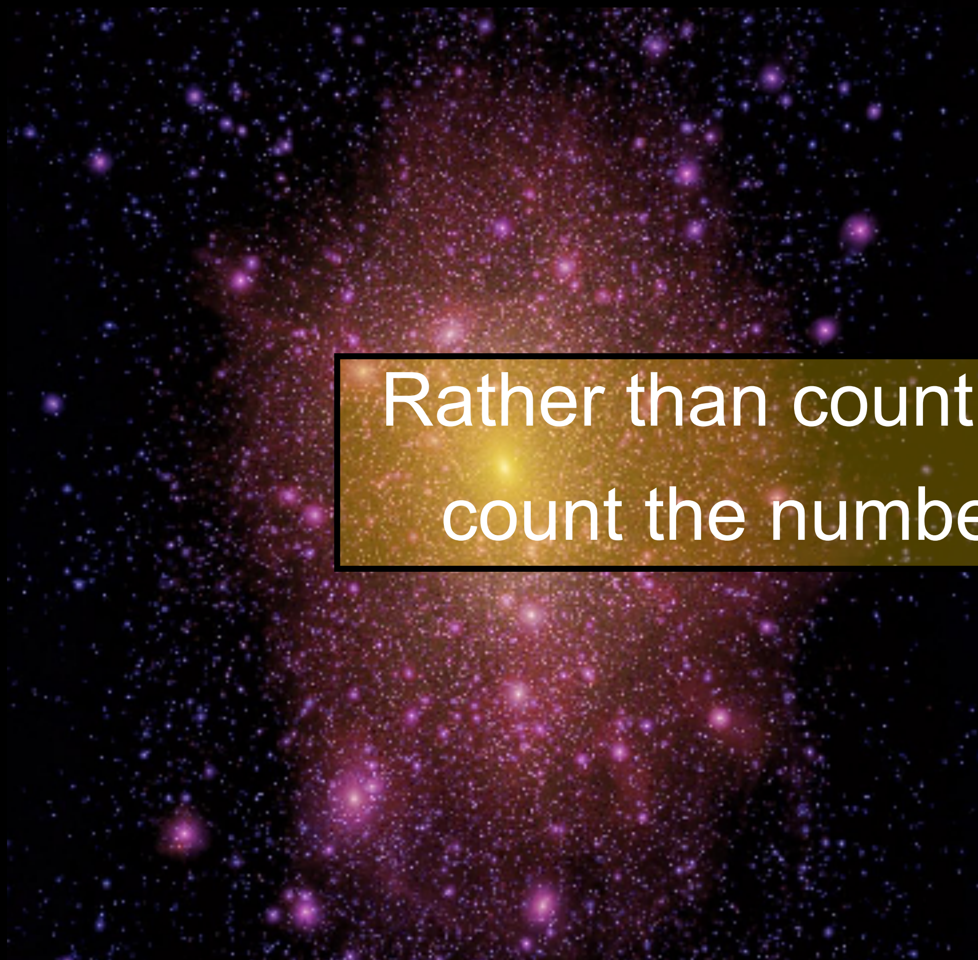
All we achieved by counting satellite galaxies is to rule out a few WDM models

The inner structure of satellites doesn't help to distinguish either

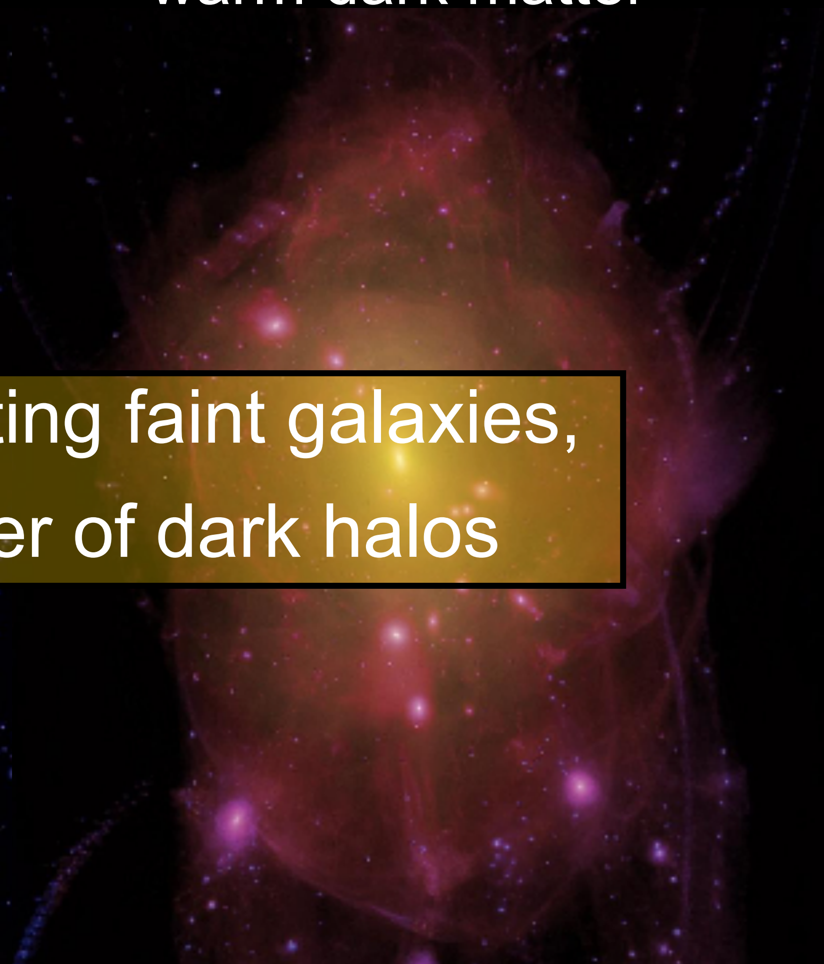
Anything else?

Can we distinguish CDM/WDM?

cold dark matter



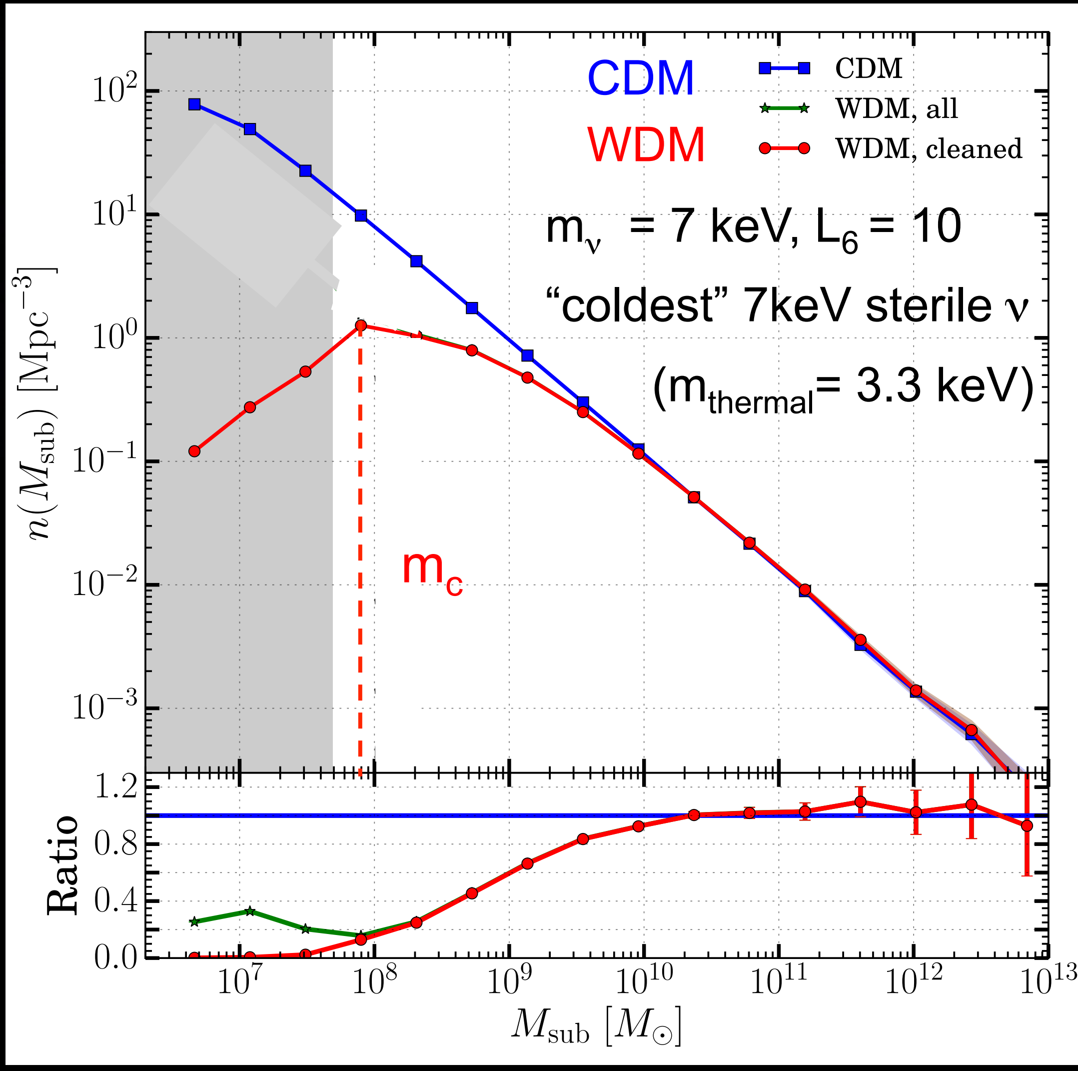
warm dark matter



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

The subhalo mass function

CDM WDM



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

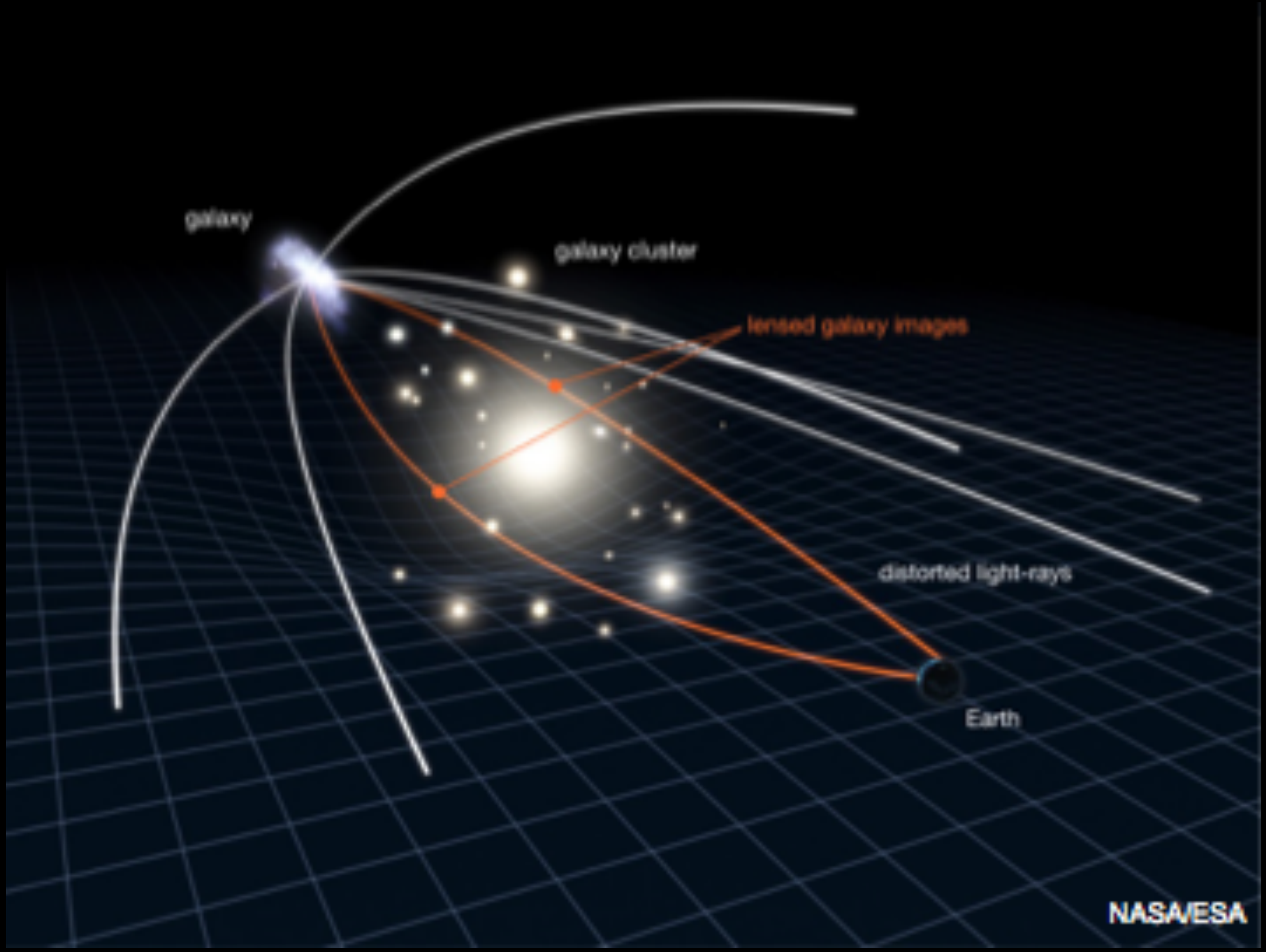
10 x fewer at 10^8 M_o

Bose, CSF et al '16

Gravitational lensing: Einstein rings

How to rule out CDM

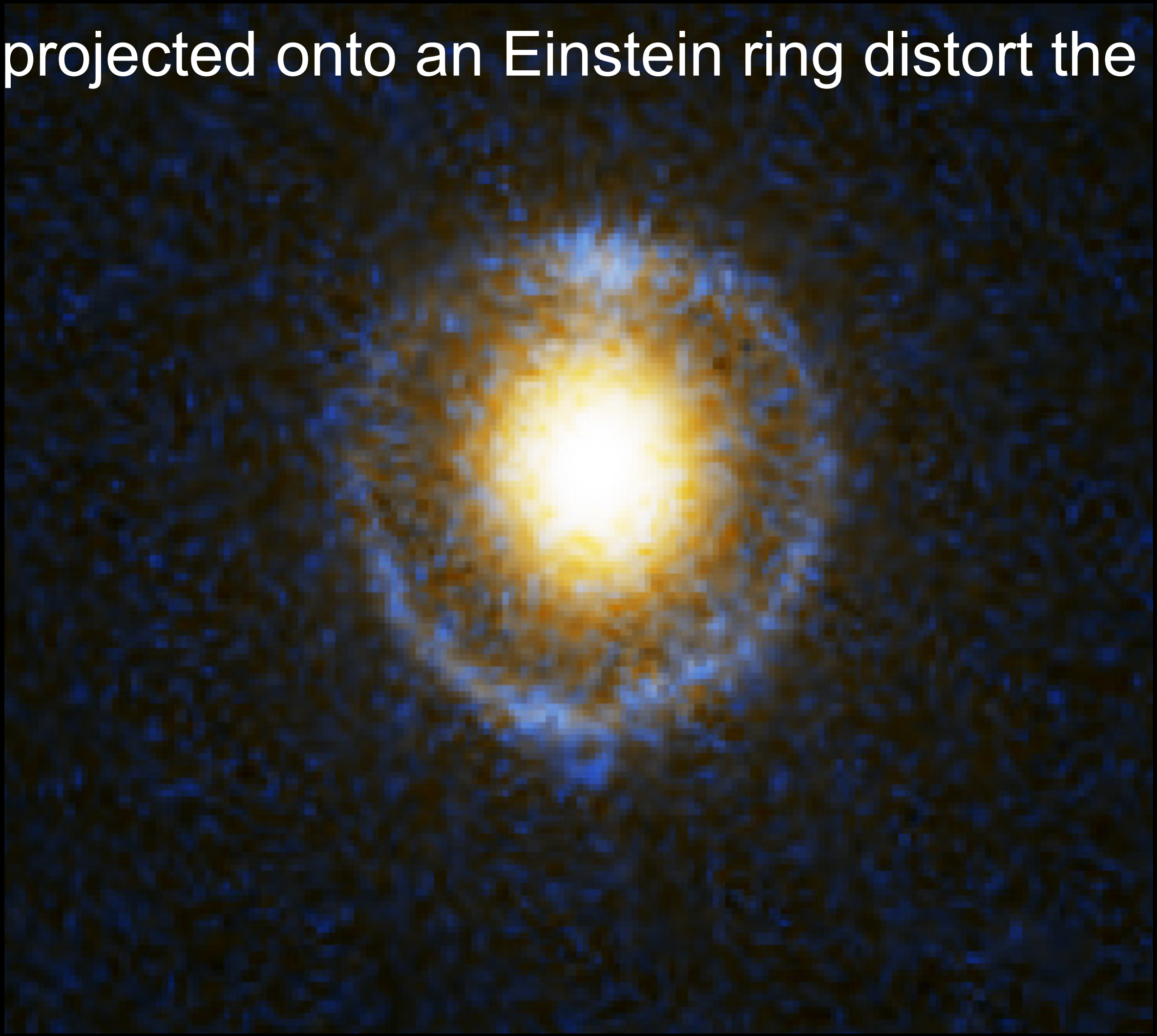
Gravitational lensing: Einstein rings



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

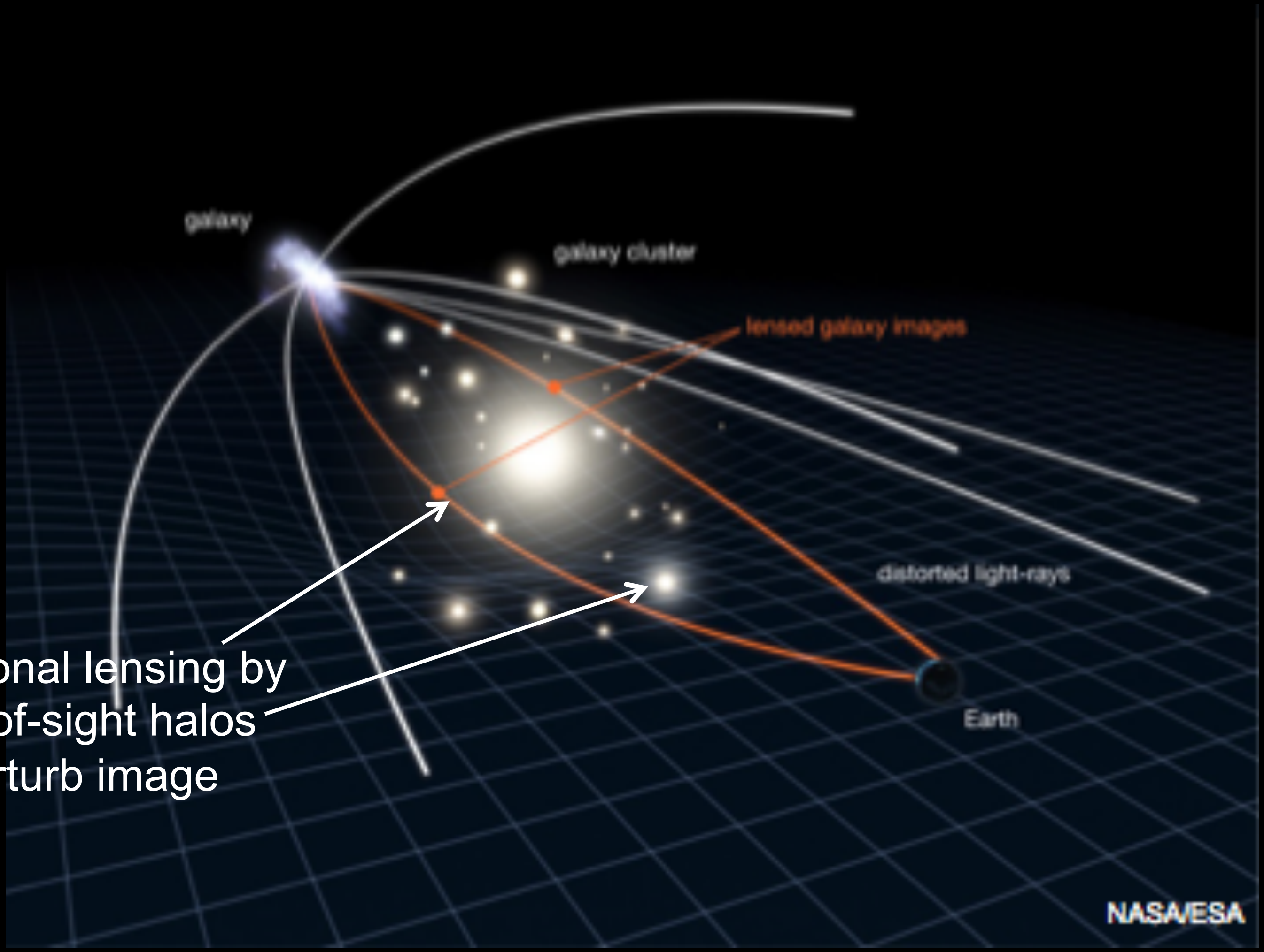
Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans ‘09

Gravitational lensing: Einstein rings



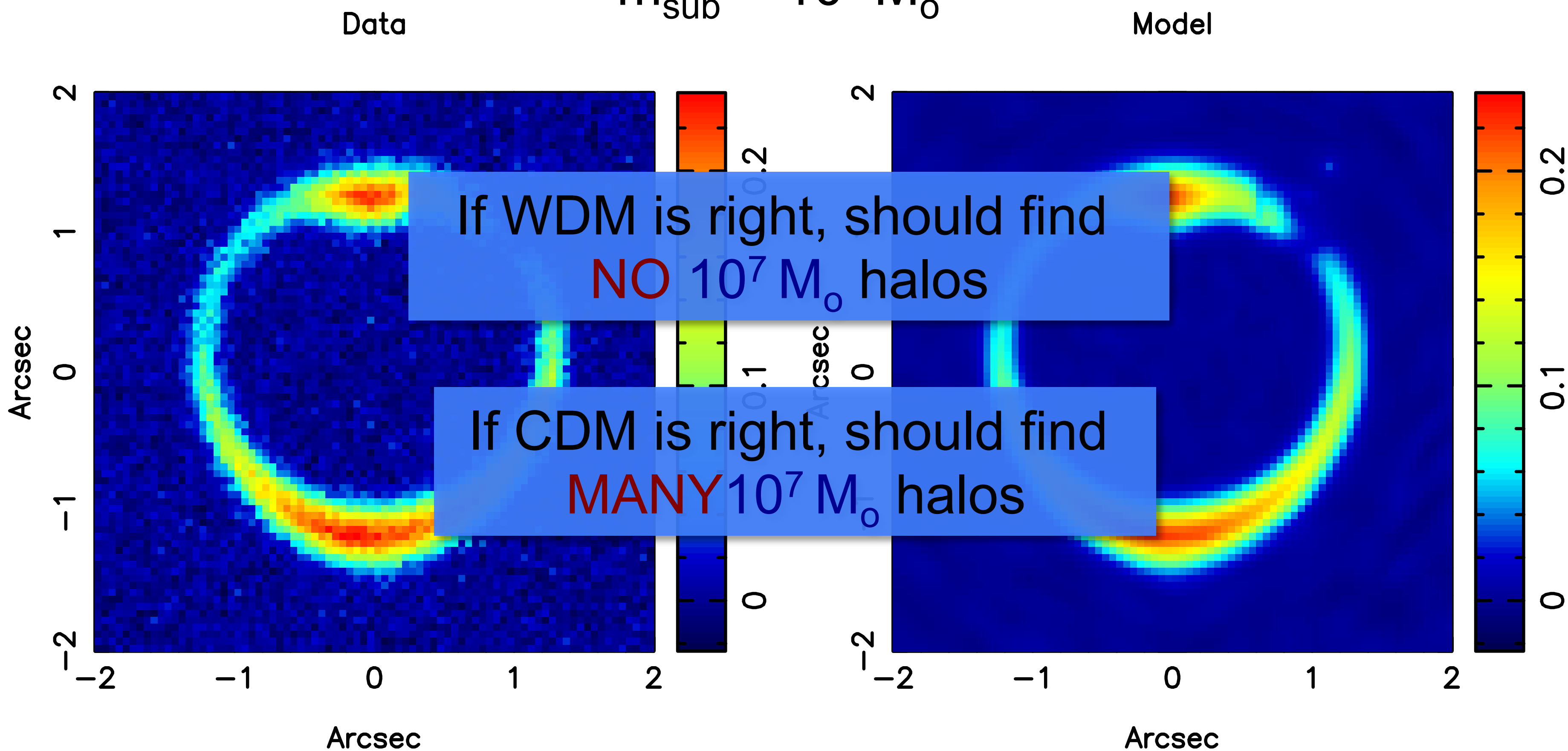
Additional lensing by line-of-sight halos perturb image

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

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8\,M_o$



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

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

Can detect subhalos as small as $10^7\,M_o$

University of Durham

Detecting substructures with strong lensing

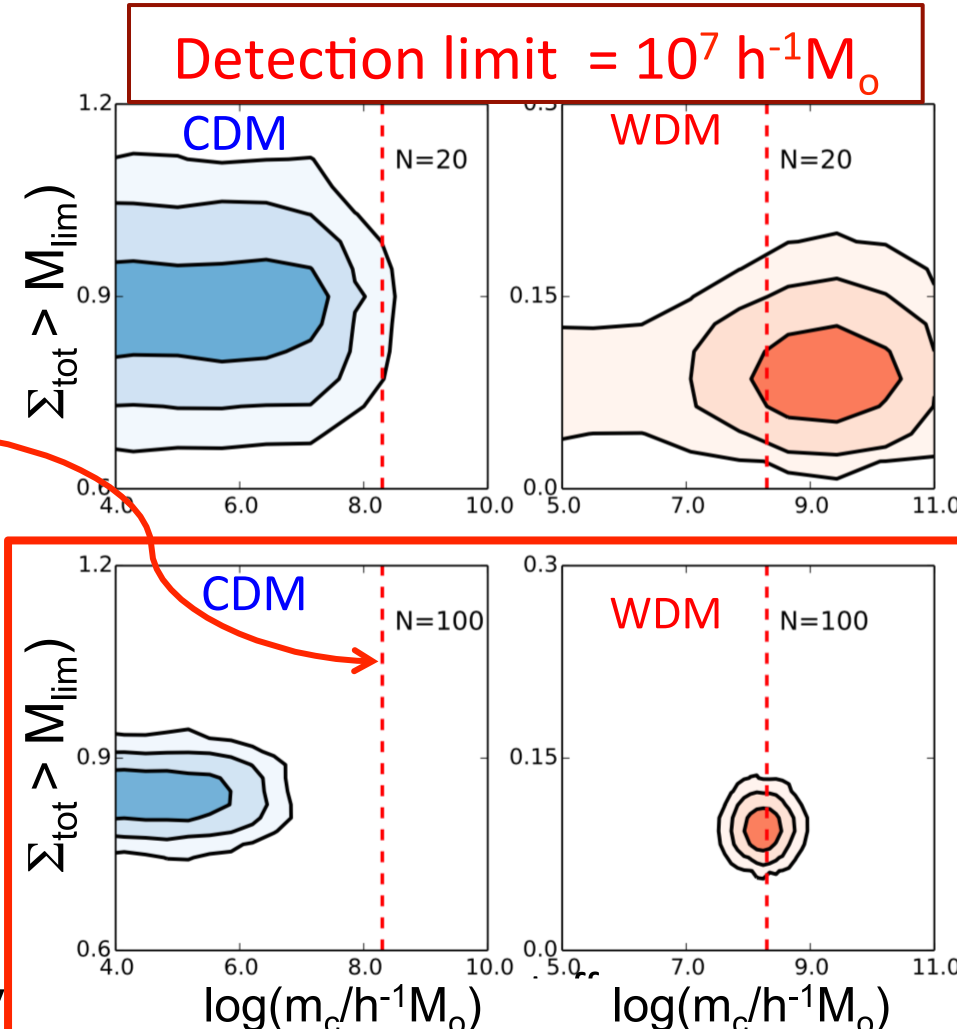
Σ_{tot}= projected halo number density within Einstein ring

m_c= halo cutoff mass

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

100 Einstein ring systems and detection limit: $m_{low} = 10^7\ h^{-1}M_o$

- If DM is 7 keV sterile ν → rule out CDM at many σ!
- If DM is CDM → rule out 7 keV sterile ν at many σ



Li, CSF et al '16

Conclusions

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

1. Counting faint galaxies cannot distinguish CDM/WDM
2. Cores can be easily produced by baryon effects
3. Strong gravitational lensing can distinguish CDM/WDM

   (and could rule out CDM!)