Clues to the identity of the dark matter in our local neighbourhood

Carlos S. Frenk
Institute for Computational Cosmology, Durham

... and how to rule out CDM (or other models)

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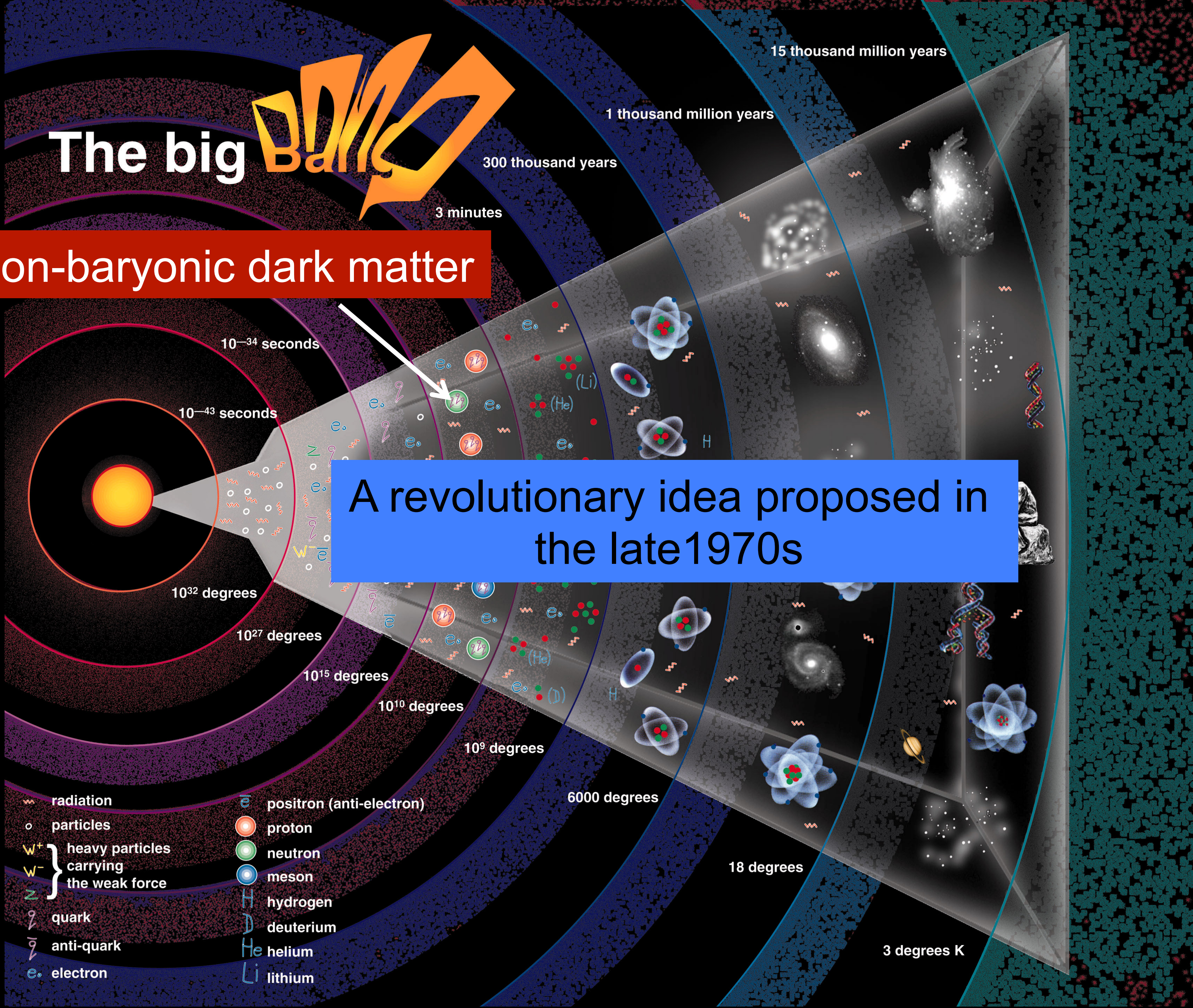
The big Bang
Non-baryonic dark matter
A revolutionary idea proposed in the late1970s
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—34 seconds
10—43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

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Non-baryonic dark matter candidates

From the 1980s:

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

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The dark matter power spectrum

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Free streaming →

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

for thermal relic

$m_{CDM} \sim 100GeV$

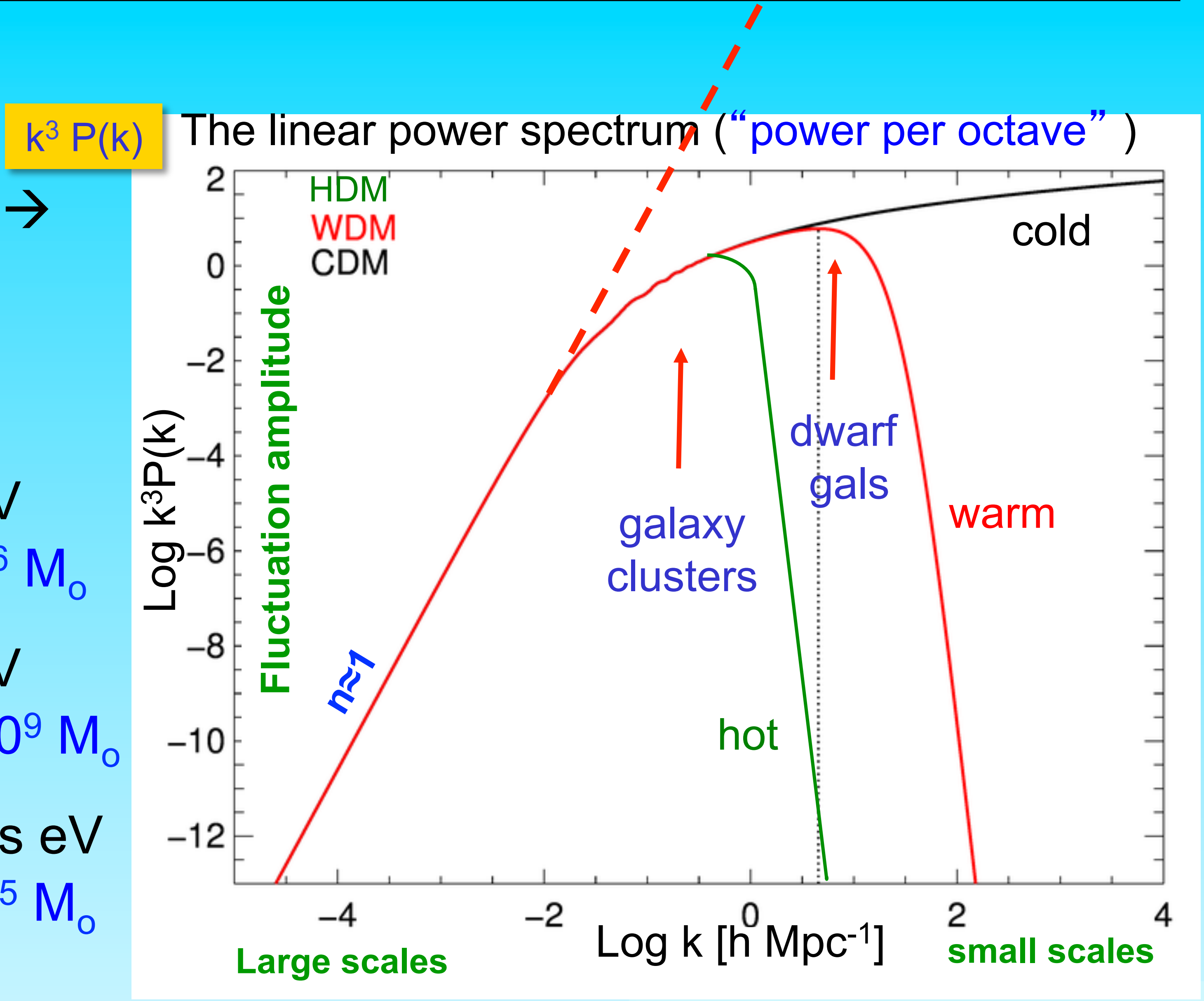
susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$

$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15}\ M_o$



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Non-baryonic dark matter candidates

From the 1980s:

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

Hot dark matter

$m_\nu = 30$ ev → $\Omega = 1$

1981

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 ($E_{3\,max}$ ≅ 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.

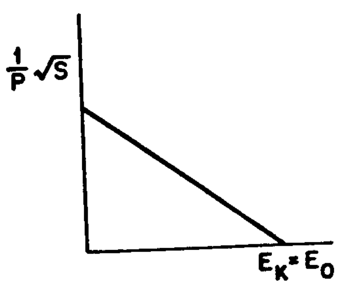


Fig. 1. Kurie plot for $M_\nu = 0$.

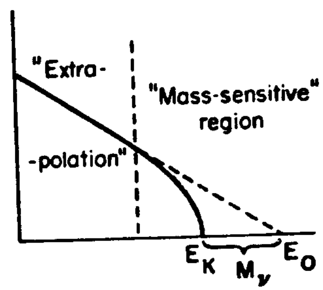
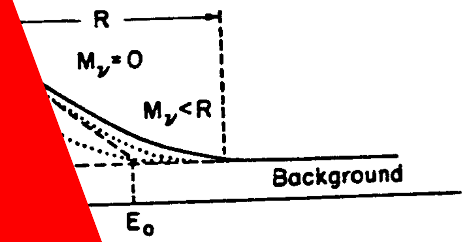


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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.

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



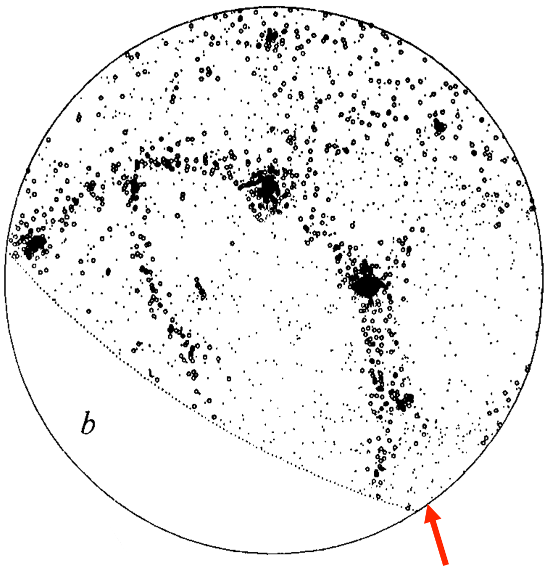
...ealistic Kurie plot.

...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 nucleus, and simple theoretical interpretation, 3) highly reduced 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



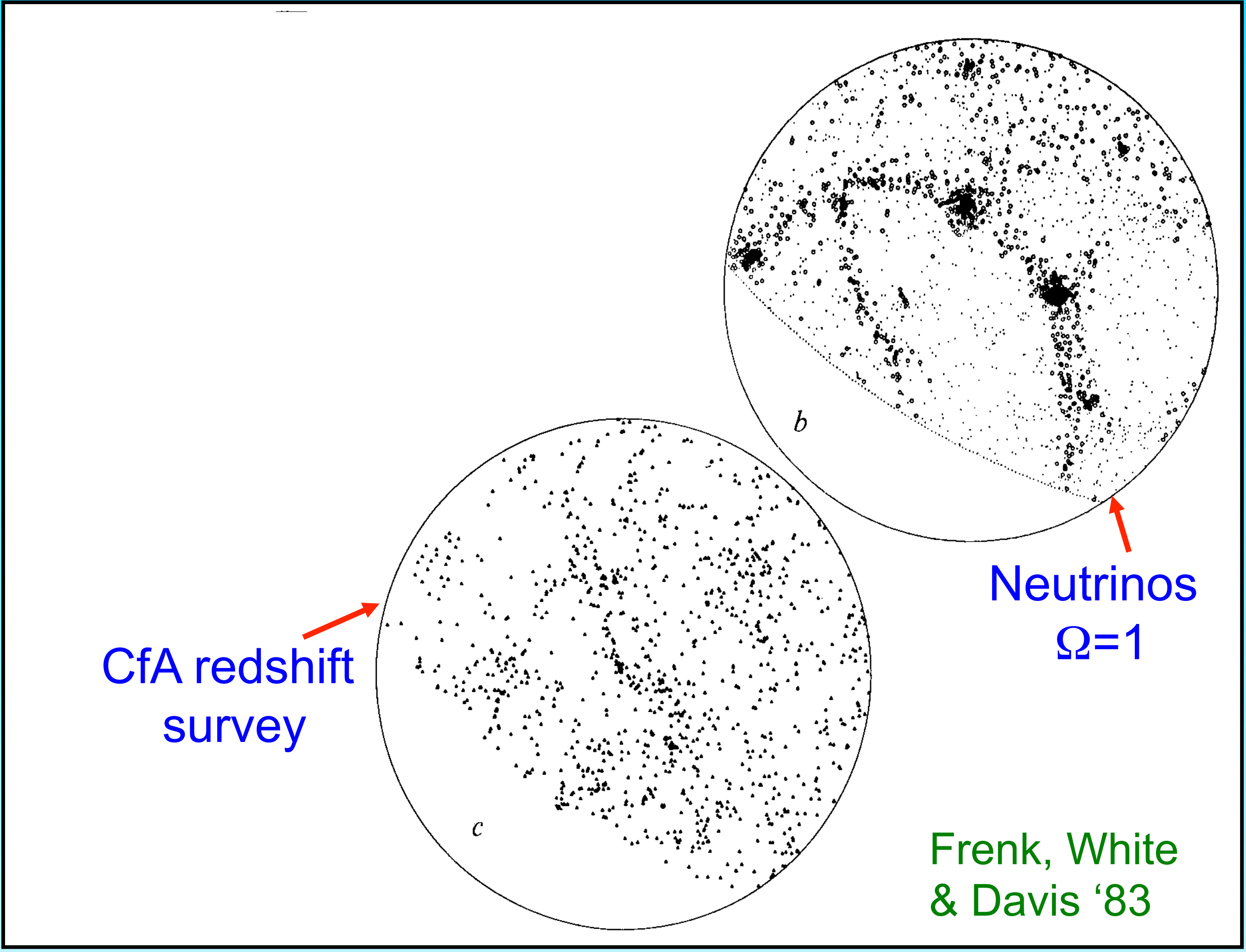
Neutrinos
$\Omega=1$

Frenk, White
& Davis ‘83

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

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



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Non-baryonic dark matter cosmologies

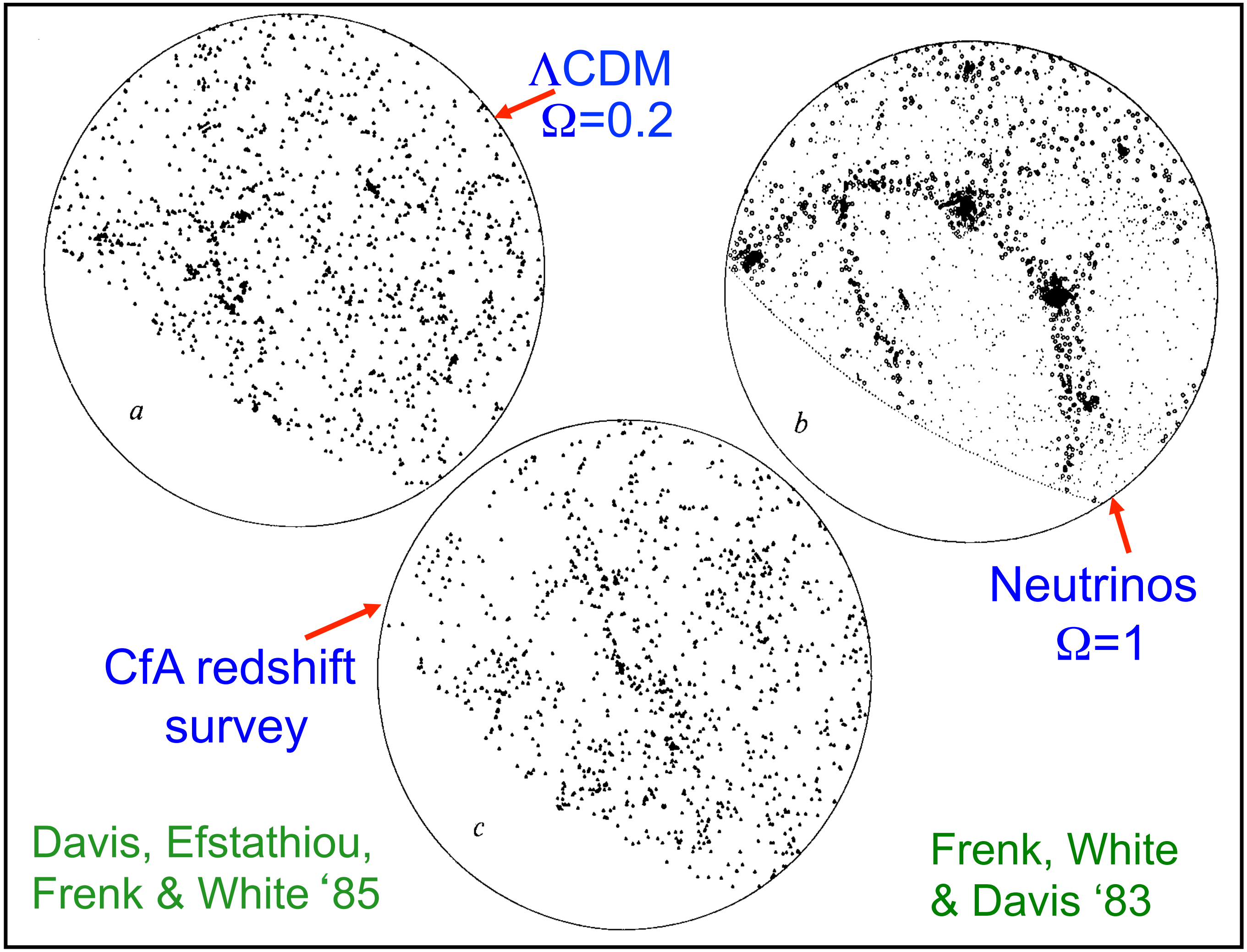
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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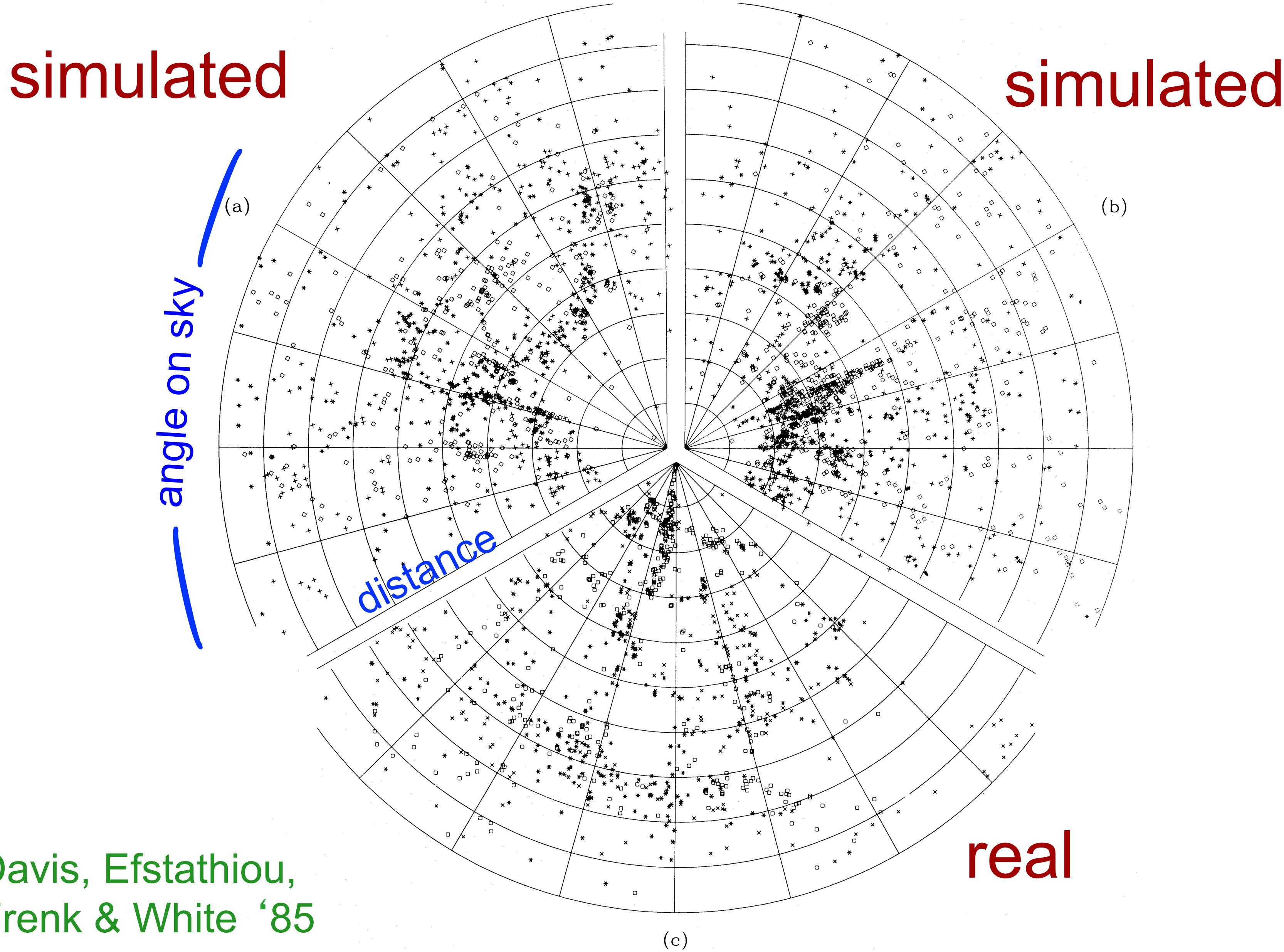
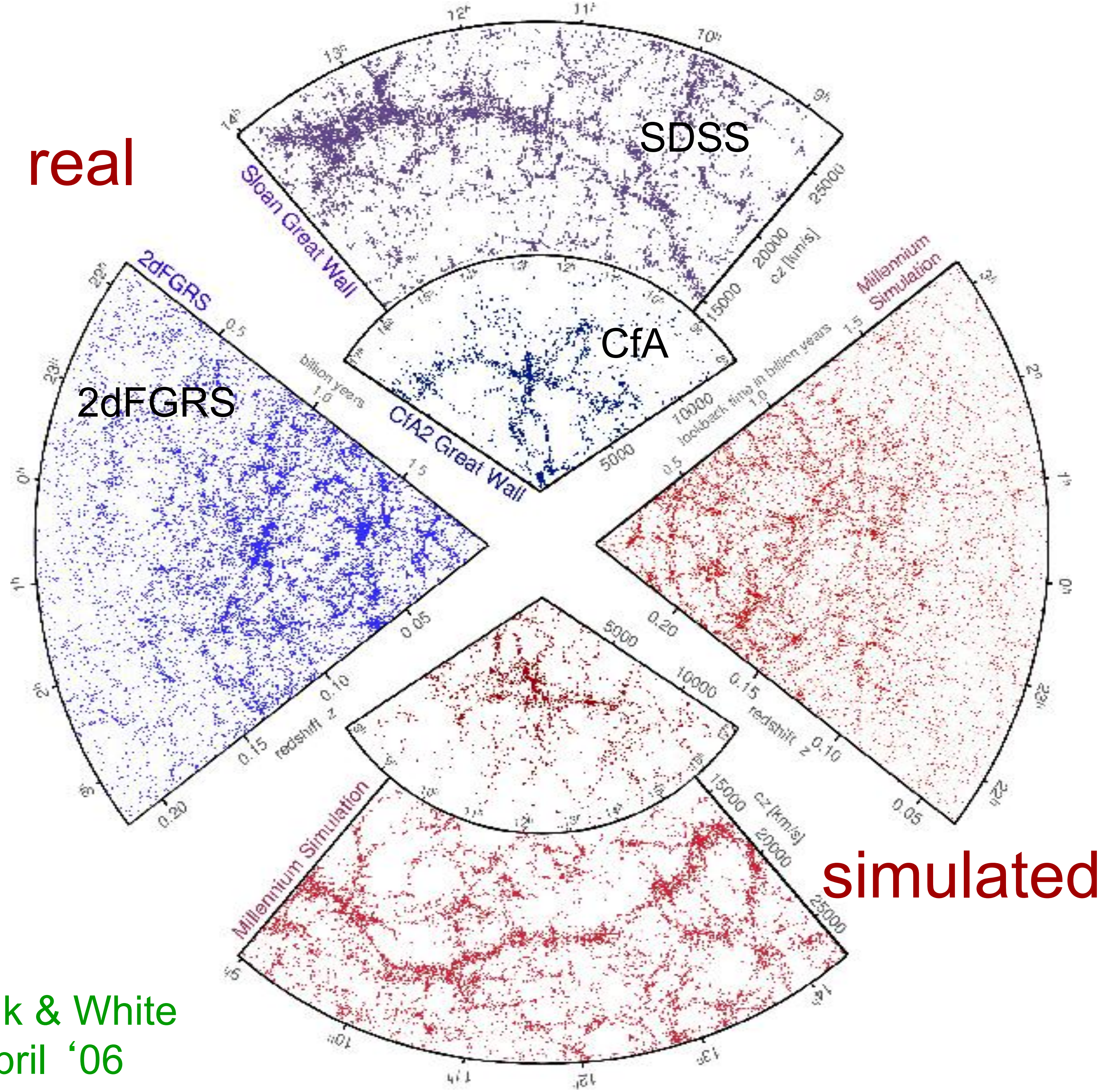
Early simulations of ΛCDM

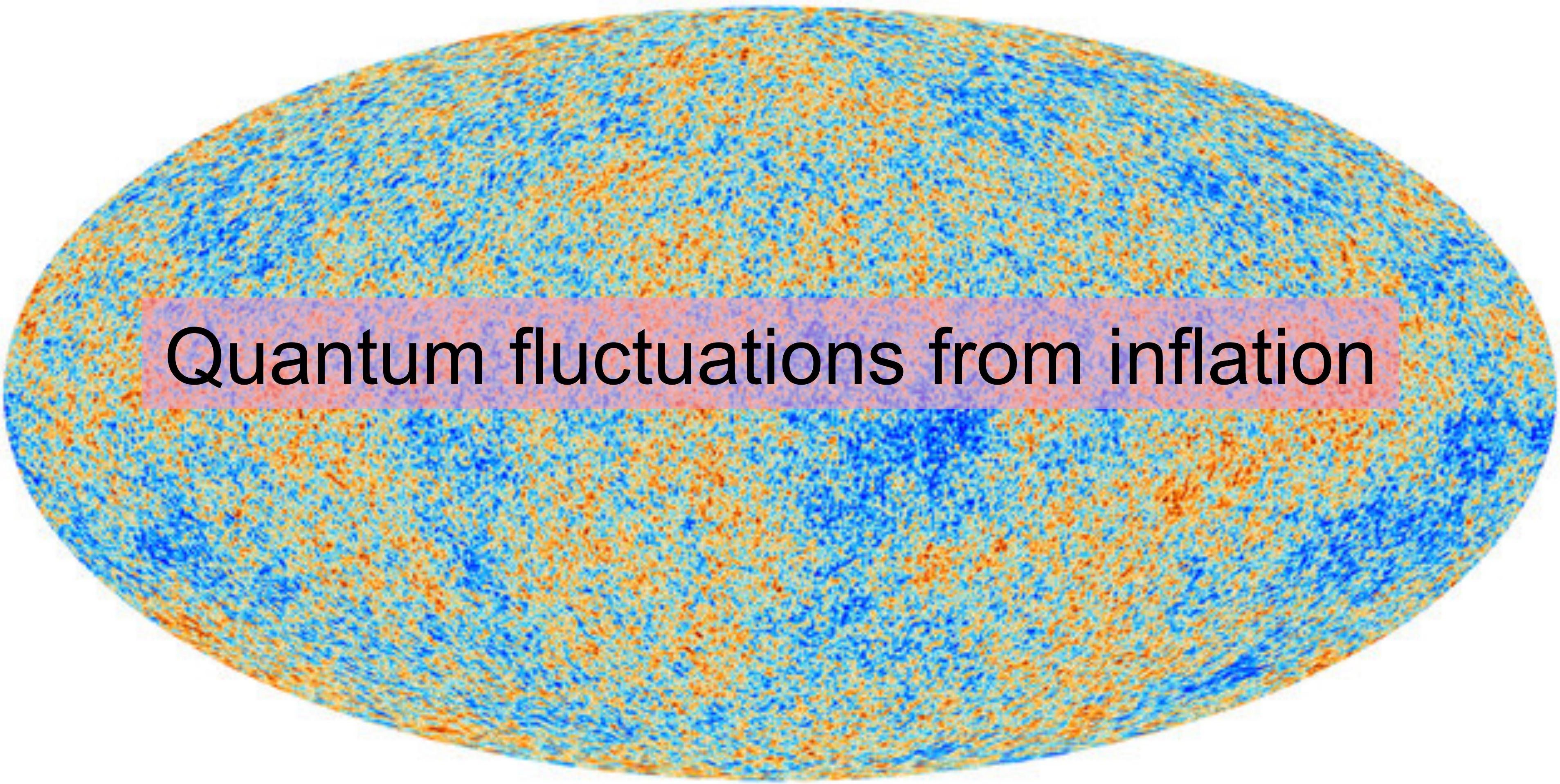


Davis, Efstathiou, Frenk & White '85



Springel, Frenk & White
Nature, April ‘06

The initial conditions for galaxy formation



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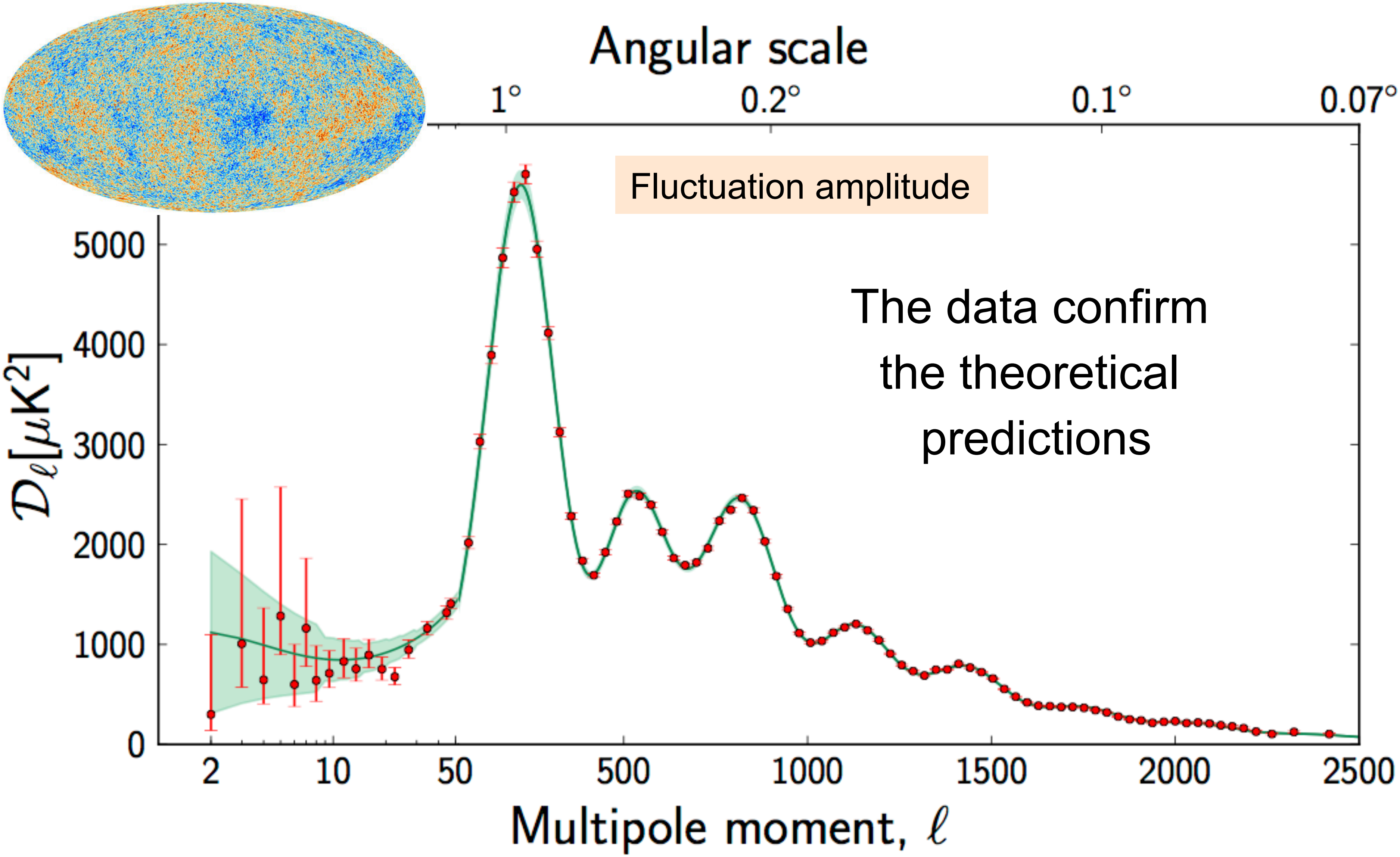
Planck: CMB temperature anisotropies



Planck collaboration 2015

Univer

The six parameters of minimal ΛCDM model

6 mdoel parameters

Parameter	*Planck*+WP 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

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

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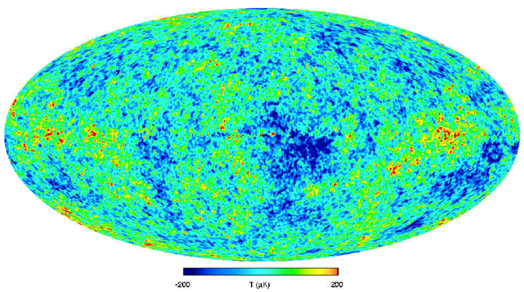
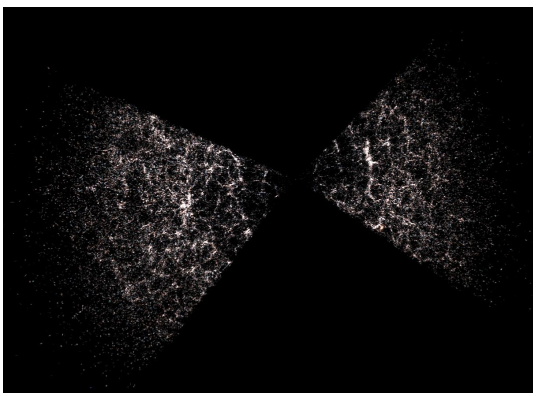
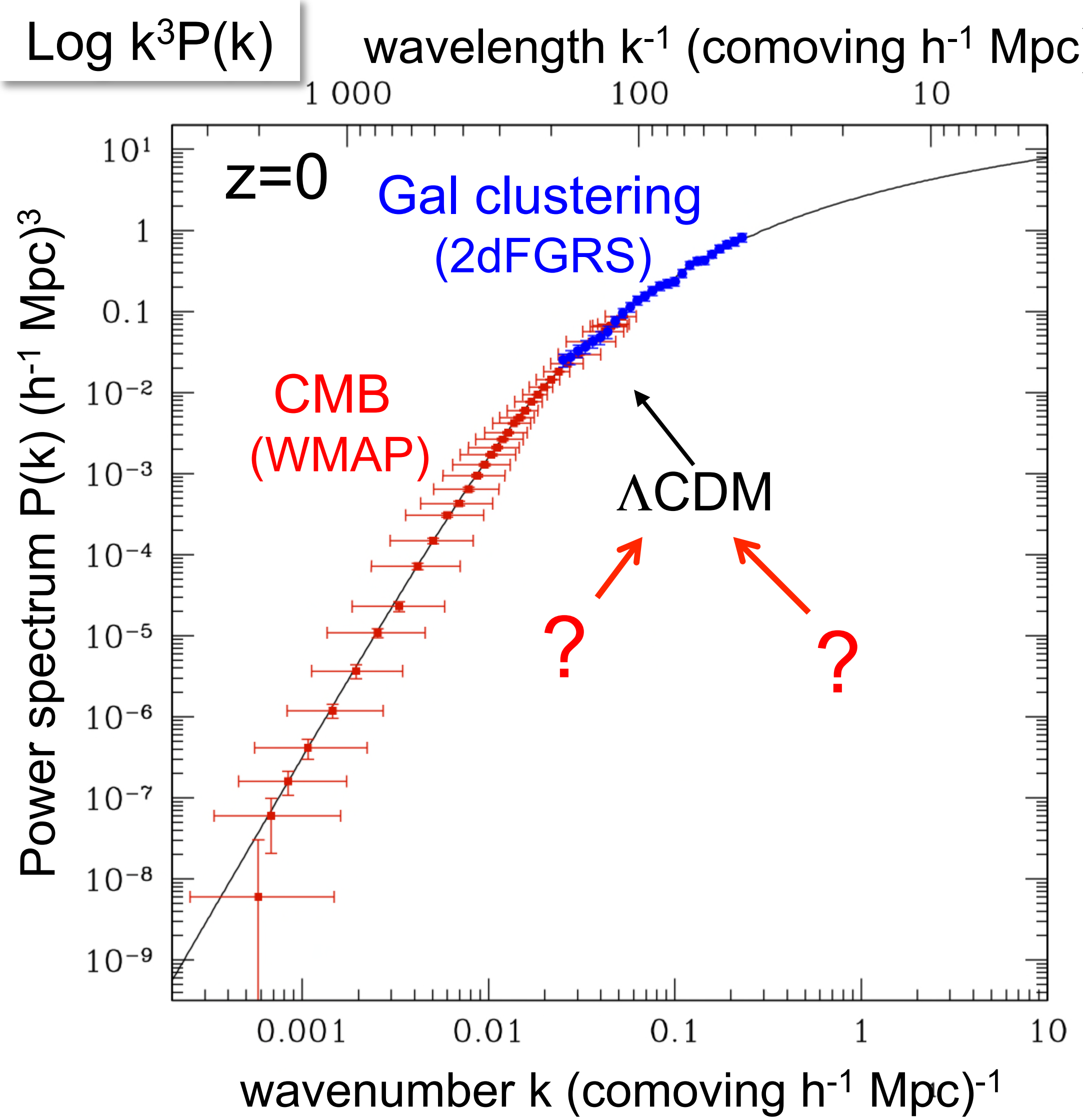


z~1000



z~0

Log $k^3P(k)$



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

Sanchez et al 06

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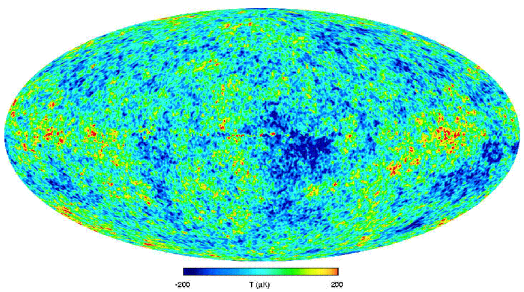
The cosmic power spectrum: from the CMB to the 2dFGRS



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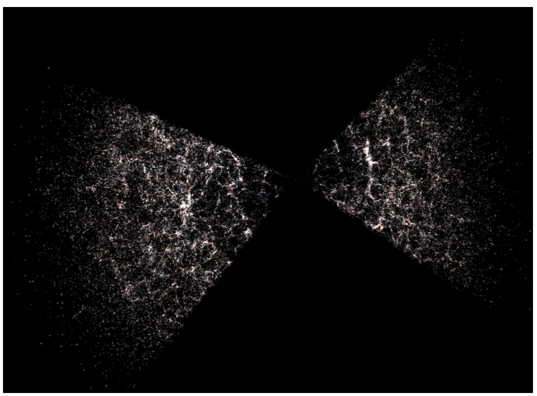
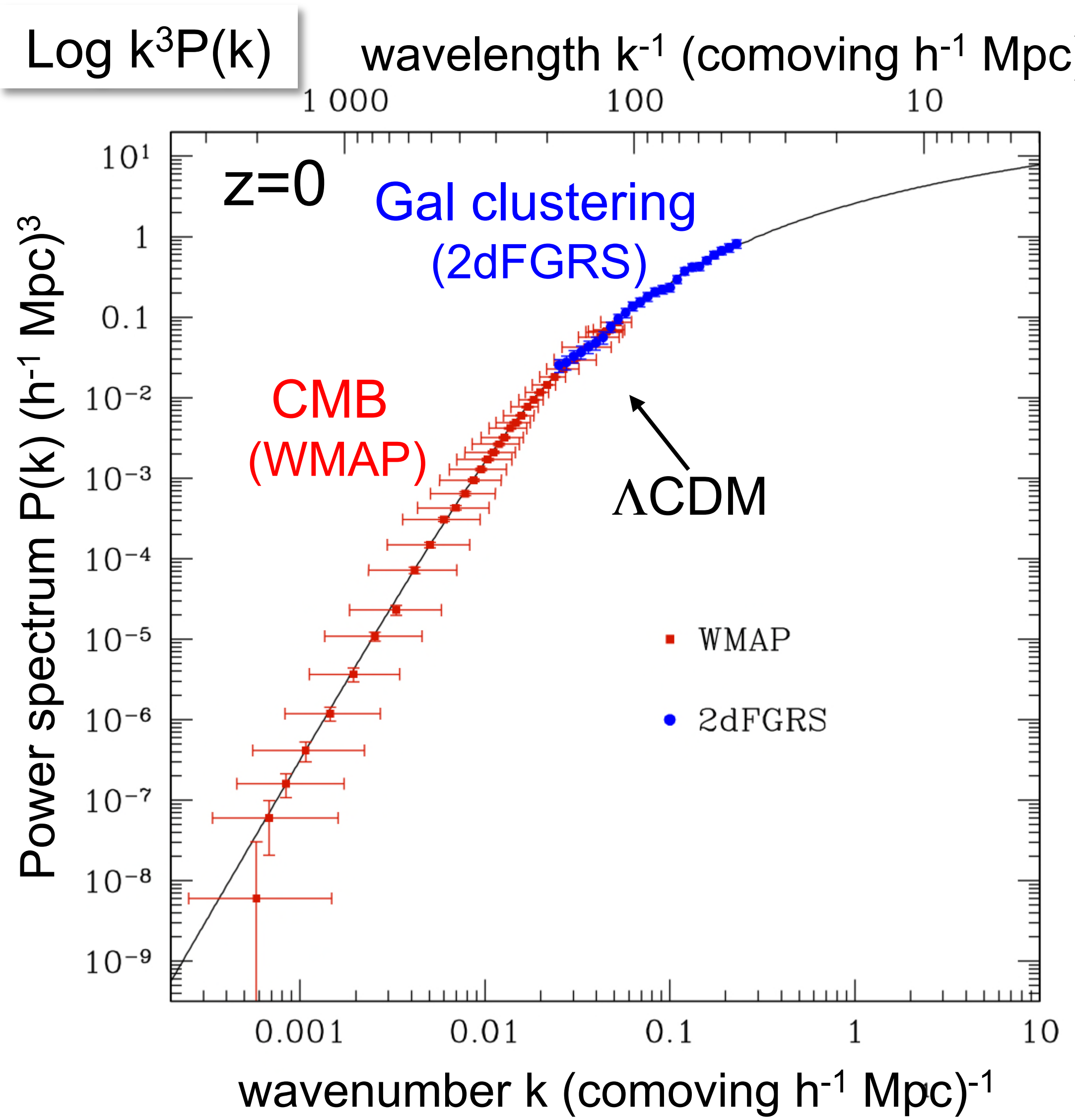


z~0



$\Rightarrow$ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

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

Free streaming →

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

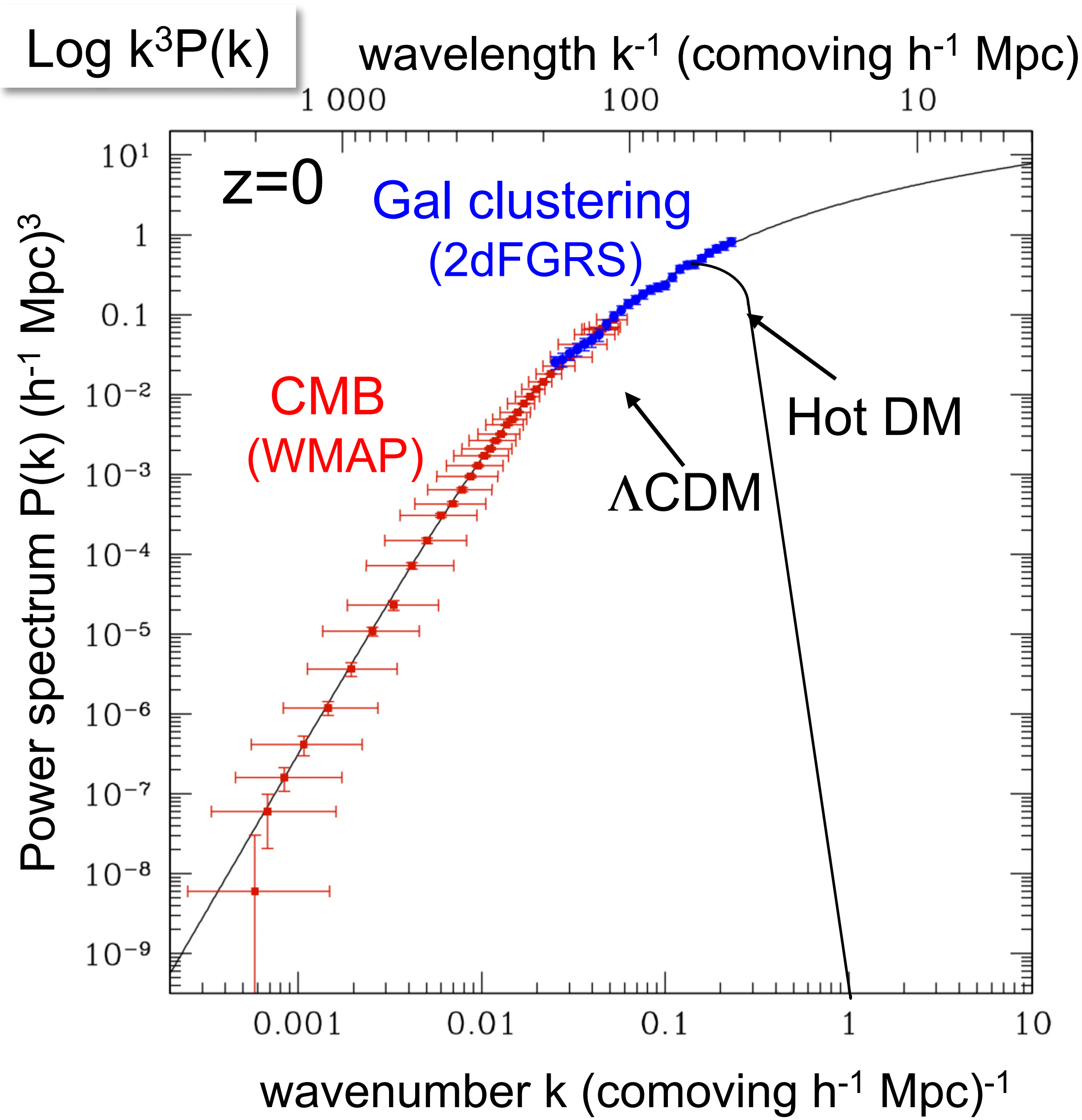
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



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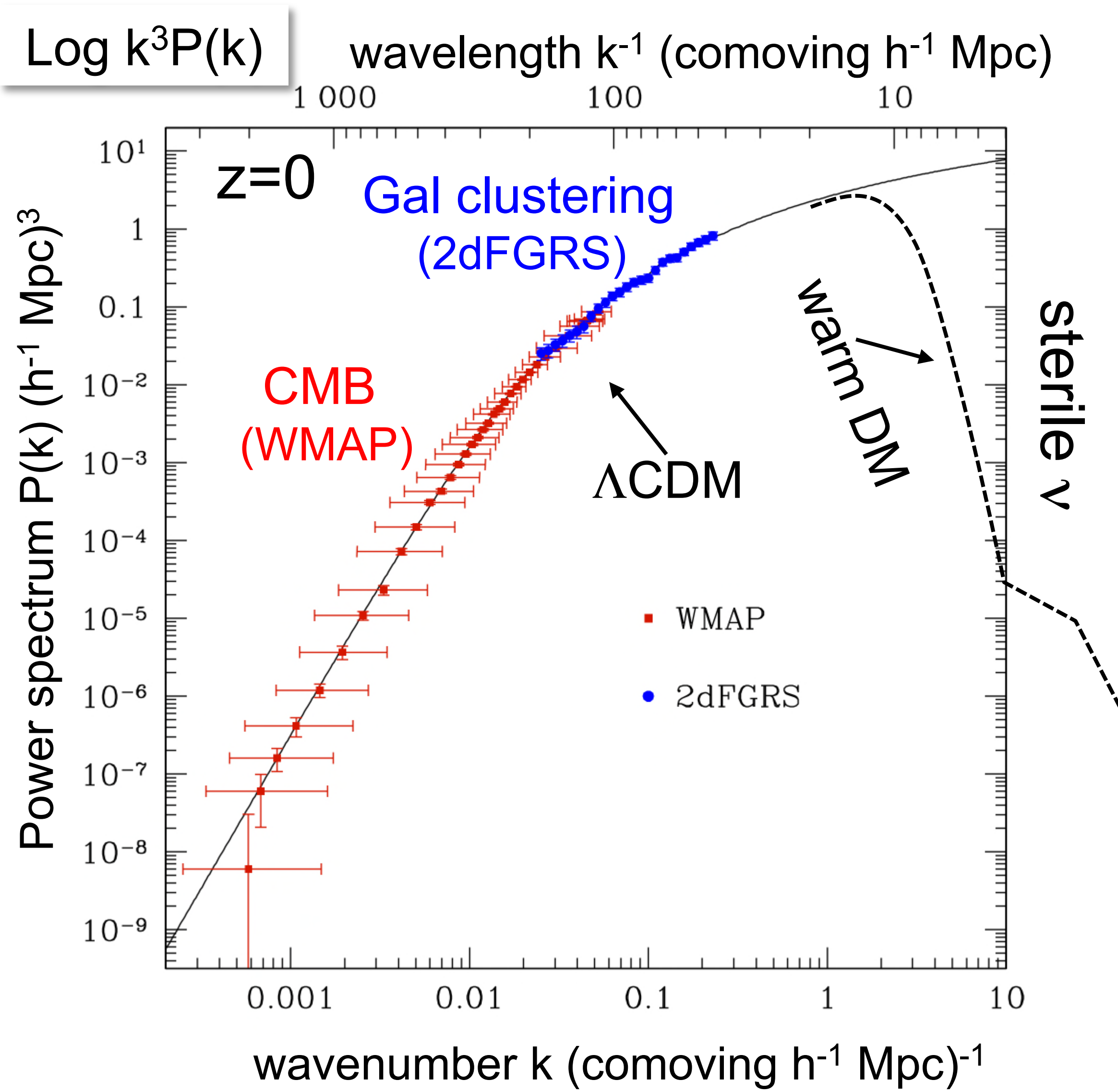


Both CDM & WDM compatible with CMB & galaxy clustering

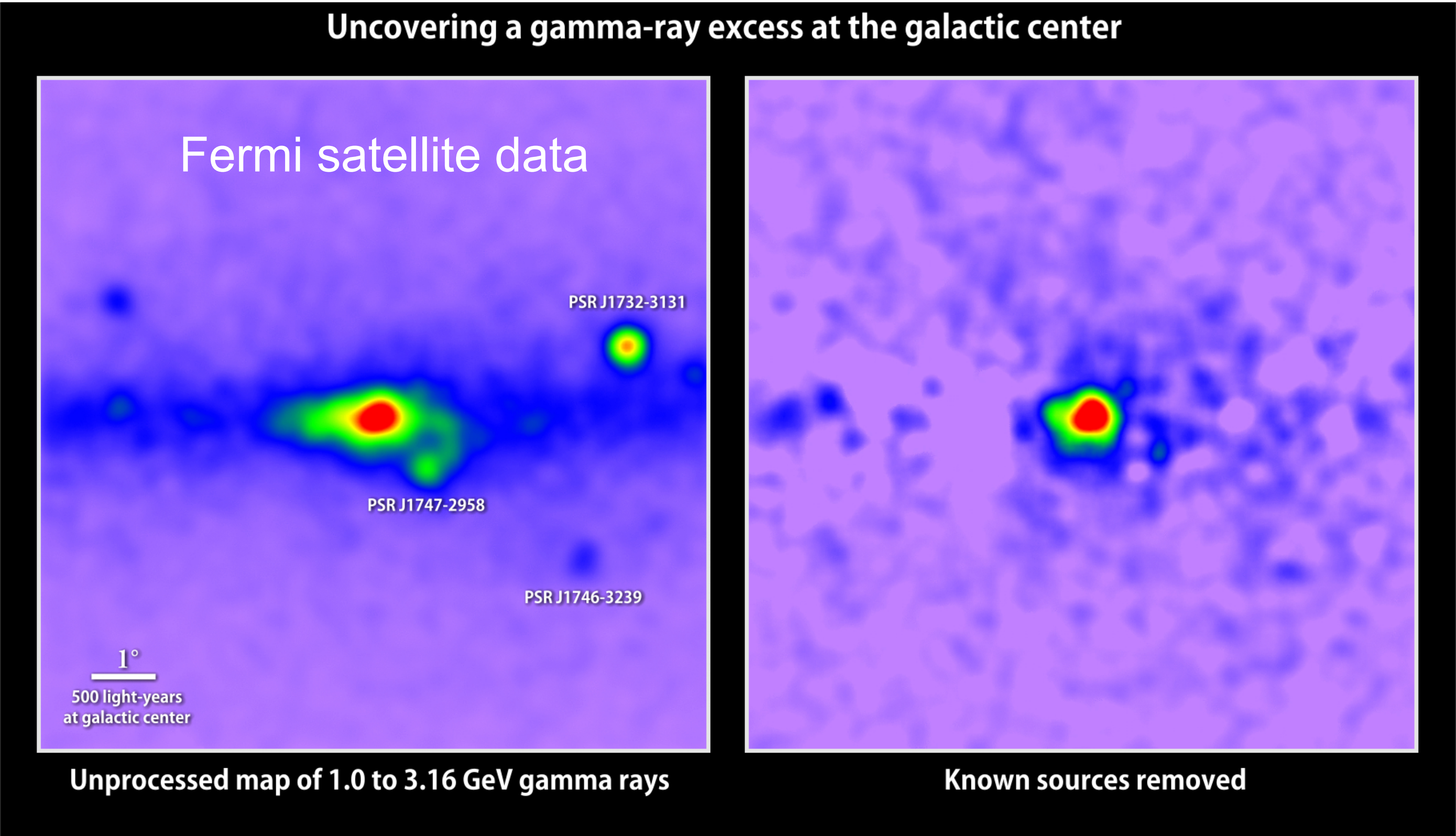
Claims that both types of DM have been discovered:

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

Cold dark matter

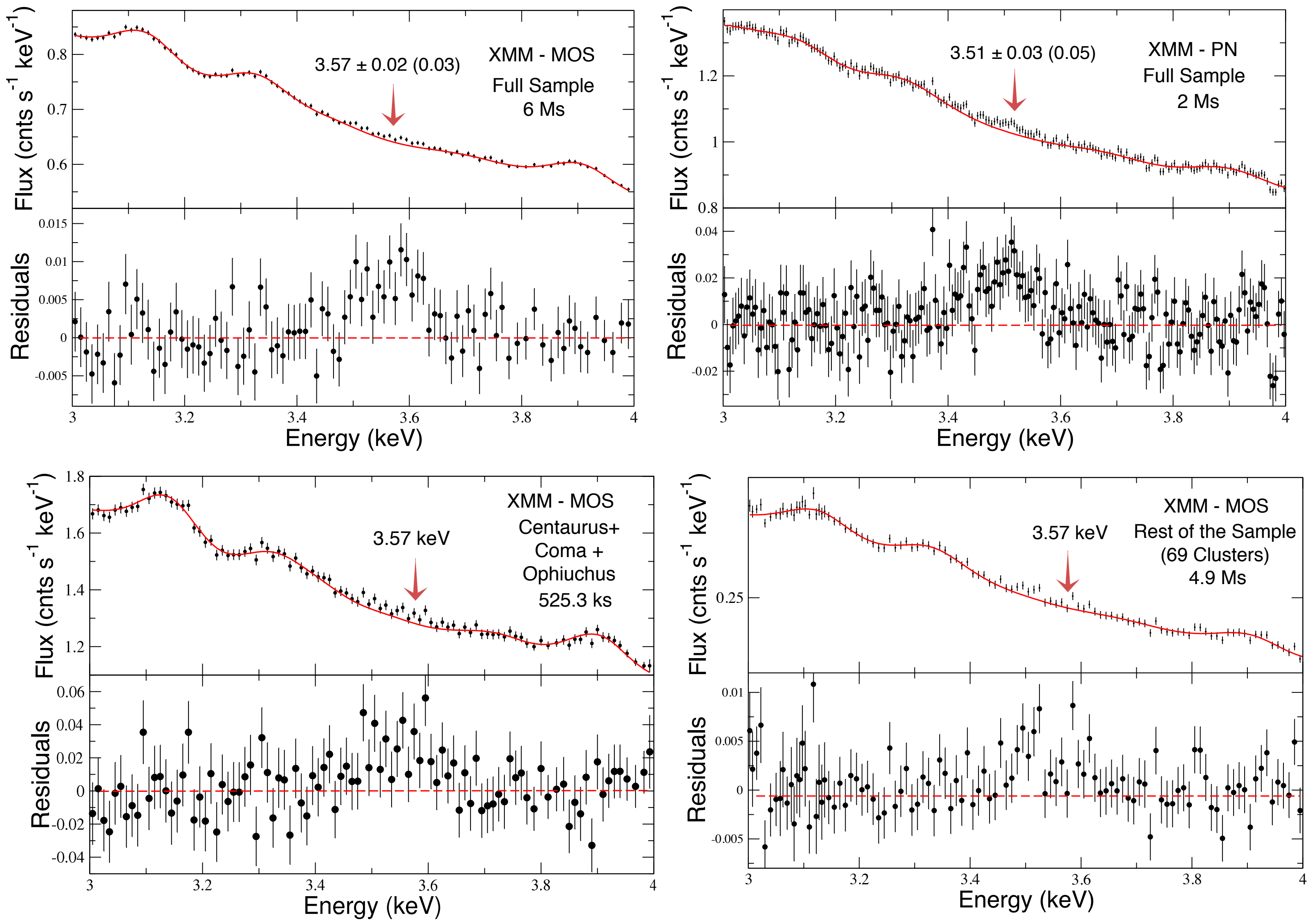
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

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
WDM decay line in 69 stacked clusters?

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



Very unlikely that both are right!

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Sterile neutrinos

Explain:

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

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

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

Primordial P(k) for 7 keV sterile neutrino models

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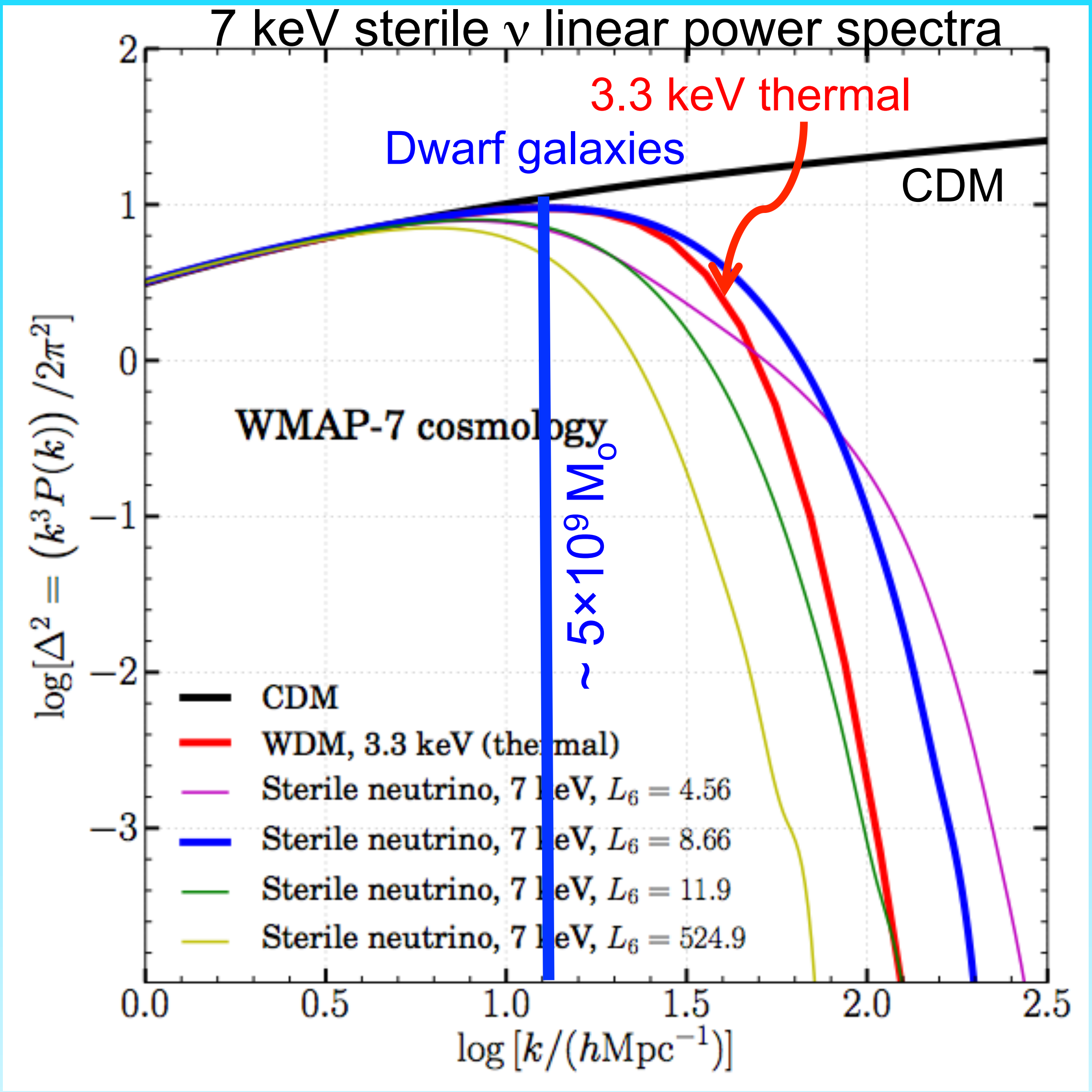
- Thermal and resonant production mechanisms
- Resonant production depends on baryon asymmetry parameter, L_6
- Linear PS varies non-monothonically with L_6

Ly-α forest rules out thermal masses, mν<3.3 keV (Viel + '13)

Lovell, Bose, CSF et al. 16



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

cold dark matter

warm dark matter

Obvious t

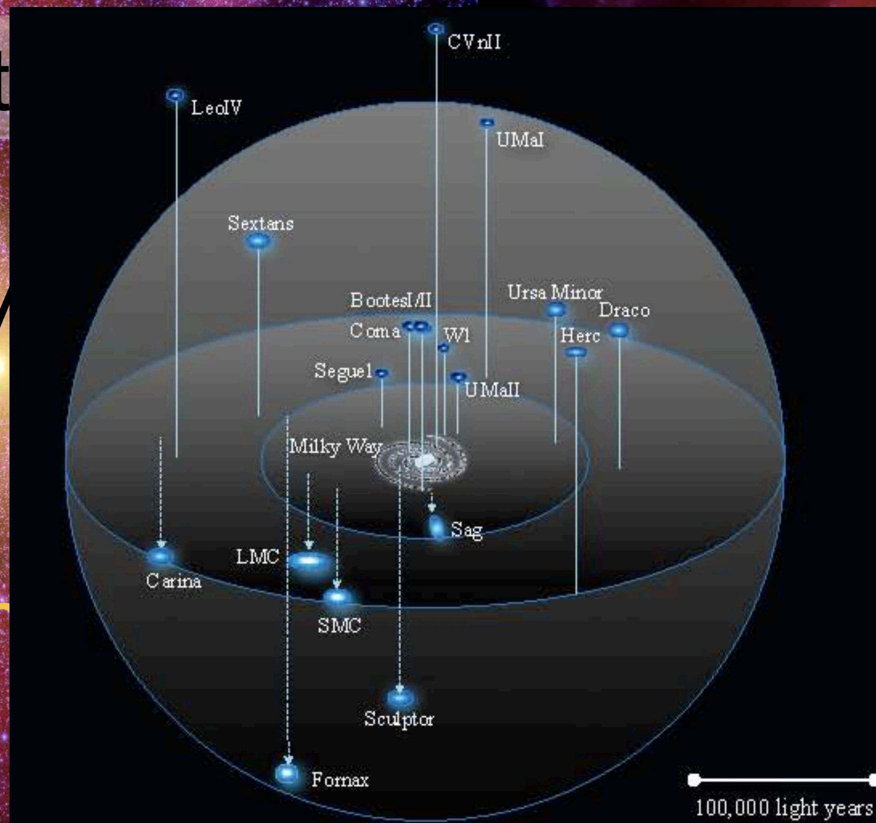
MW or M31

In the M

ered so far

Th

G!



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

Most subhalos never make a galaxy!

Because:

- Reionization heats gas to ~10^4K, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

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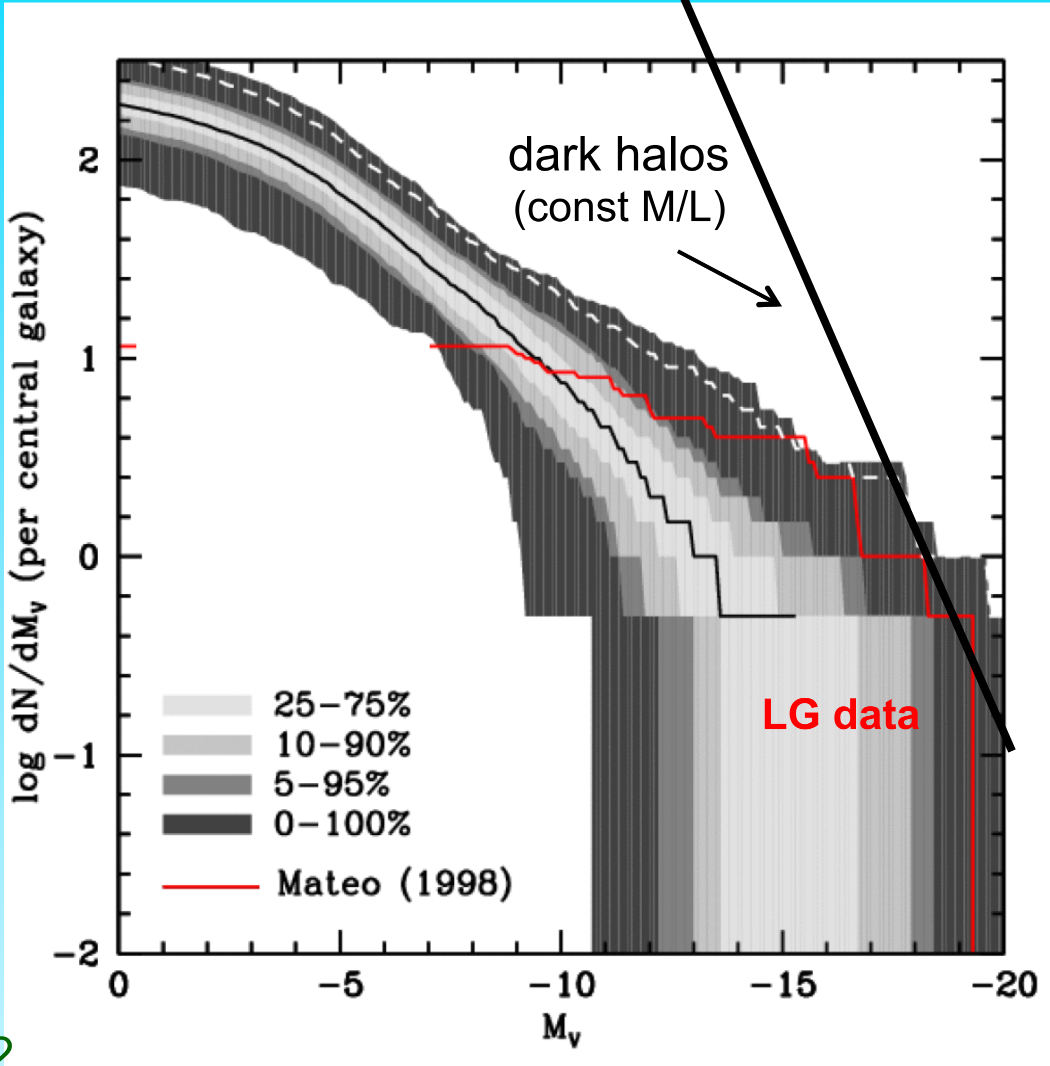
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

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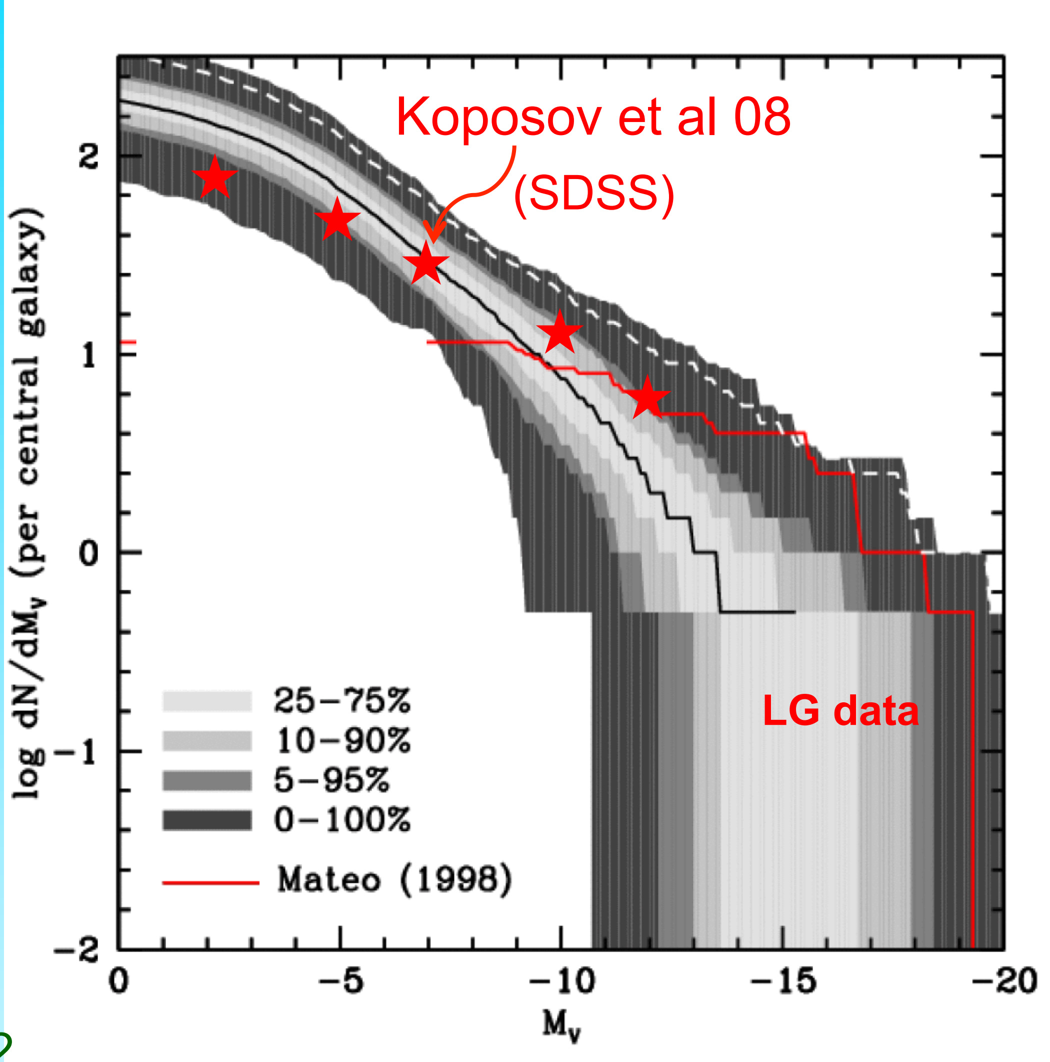


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman etal ’93, Bullock etal ’01)

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...

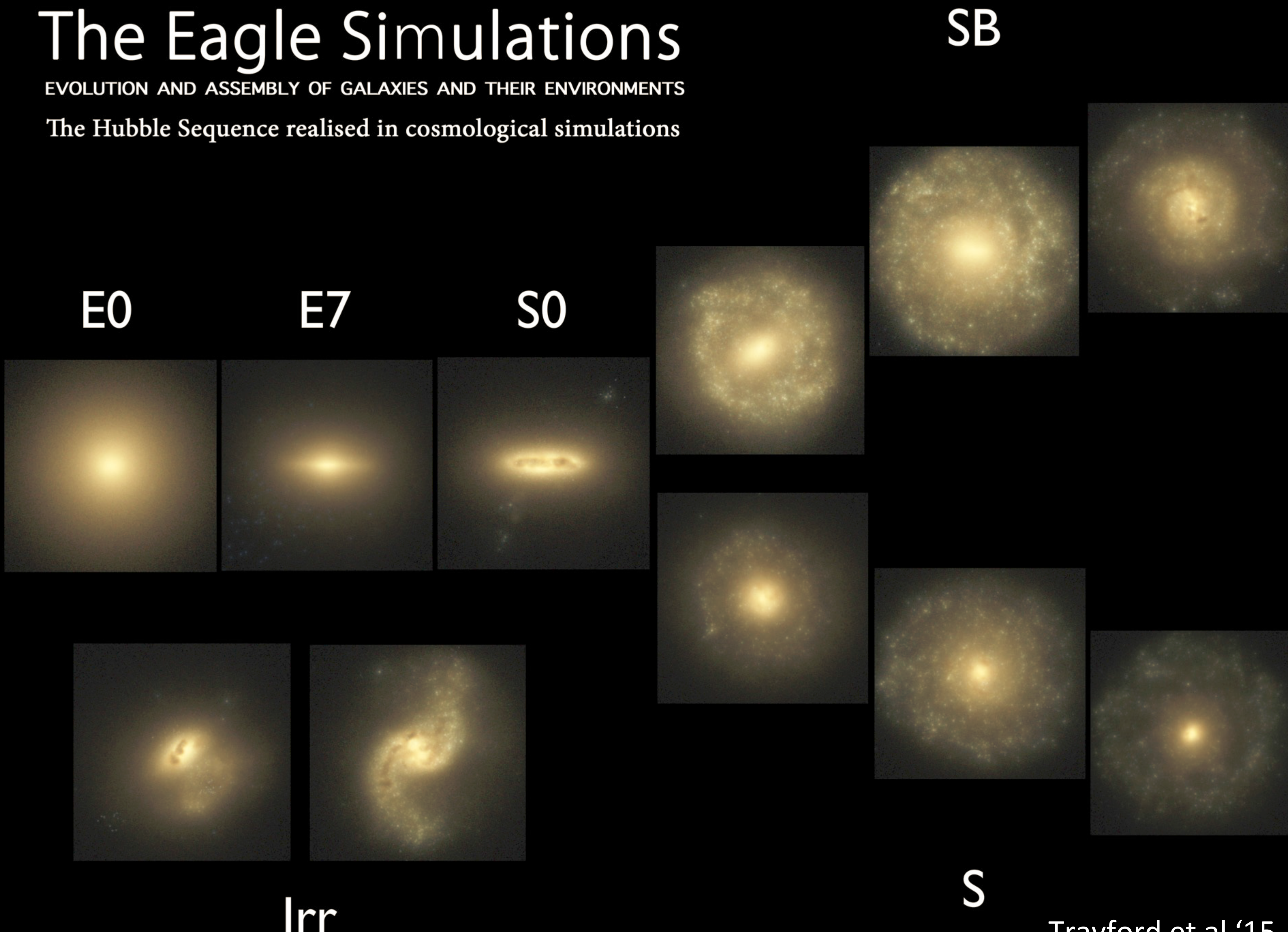
Durham University VIRGO ICC DiRAC PRACE

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

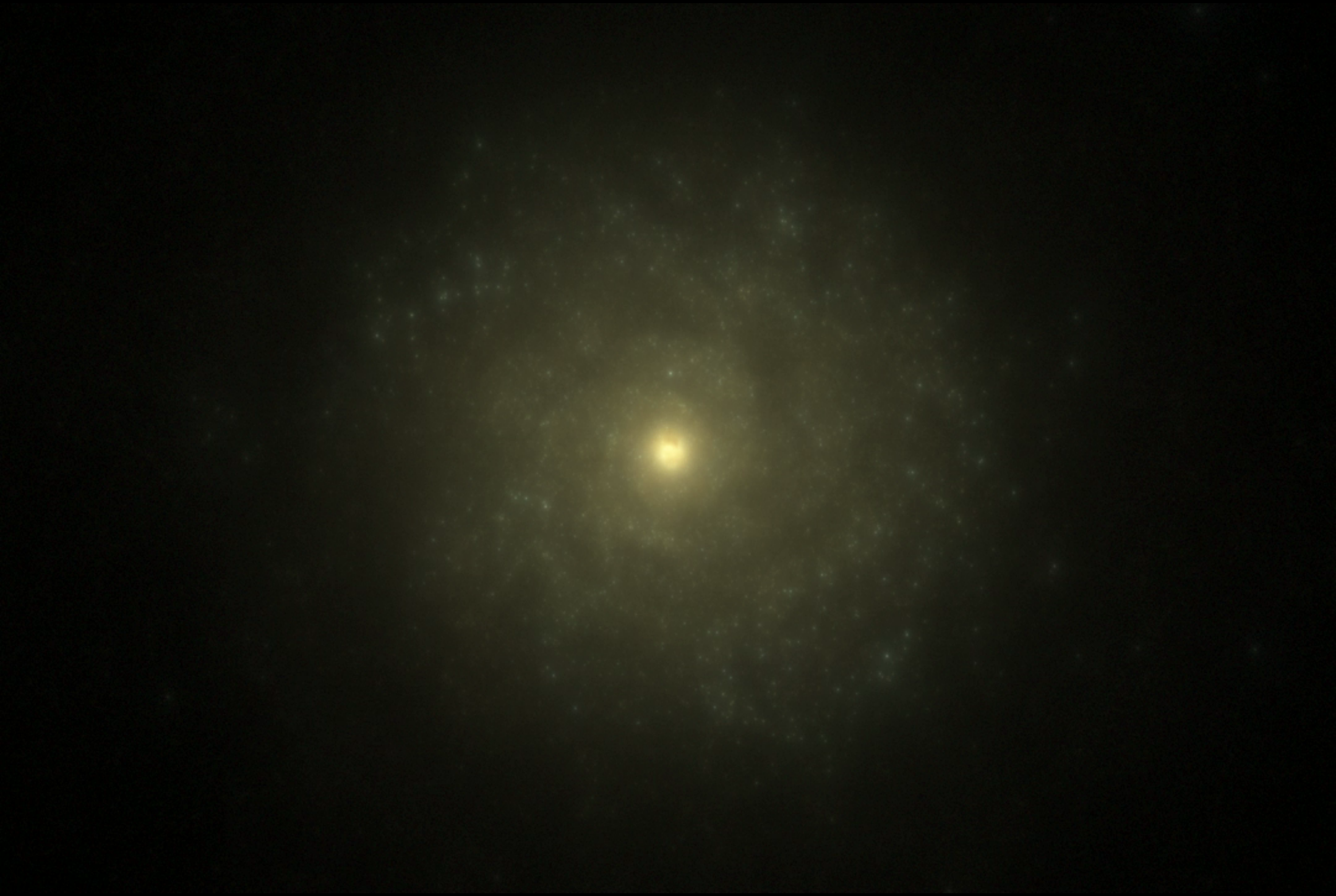
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford et al '15



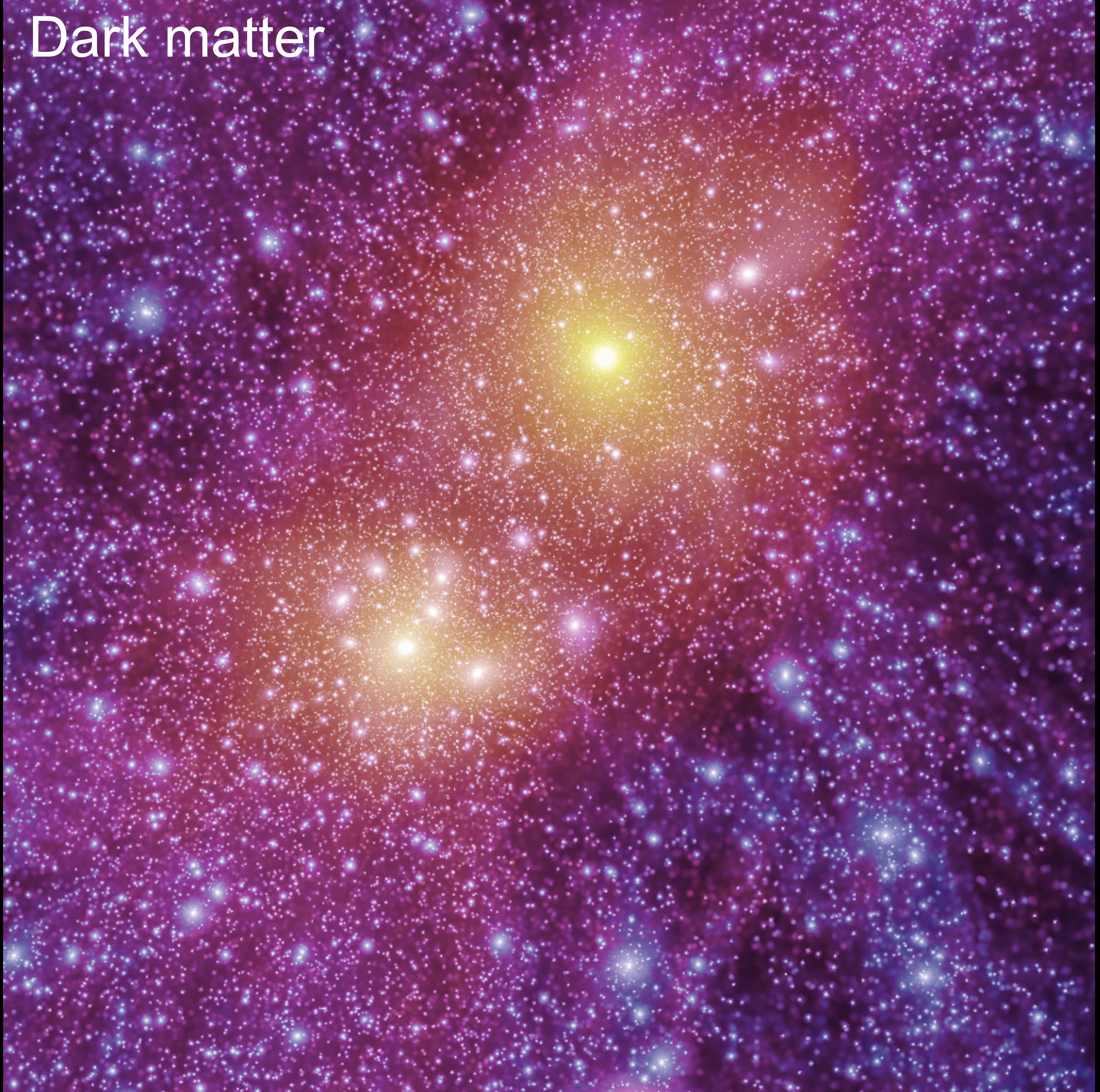
VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al ‘15



Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Far fewer satellite galaxies than CDM halos

Sawala et al ‘15

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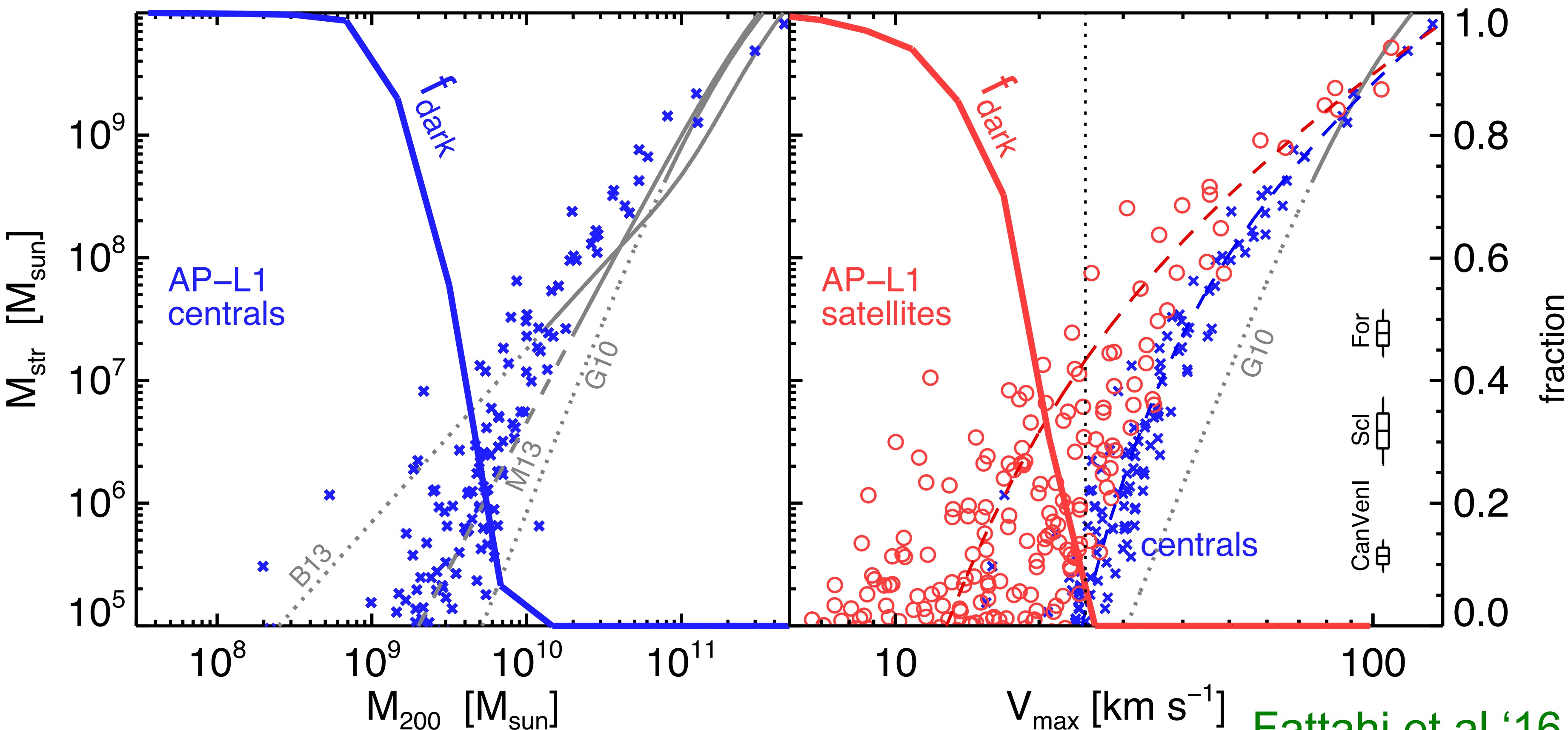
Fraction of dark subhalos

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



Fattahi et al '16

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

EAGLE Local Group simulation

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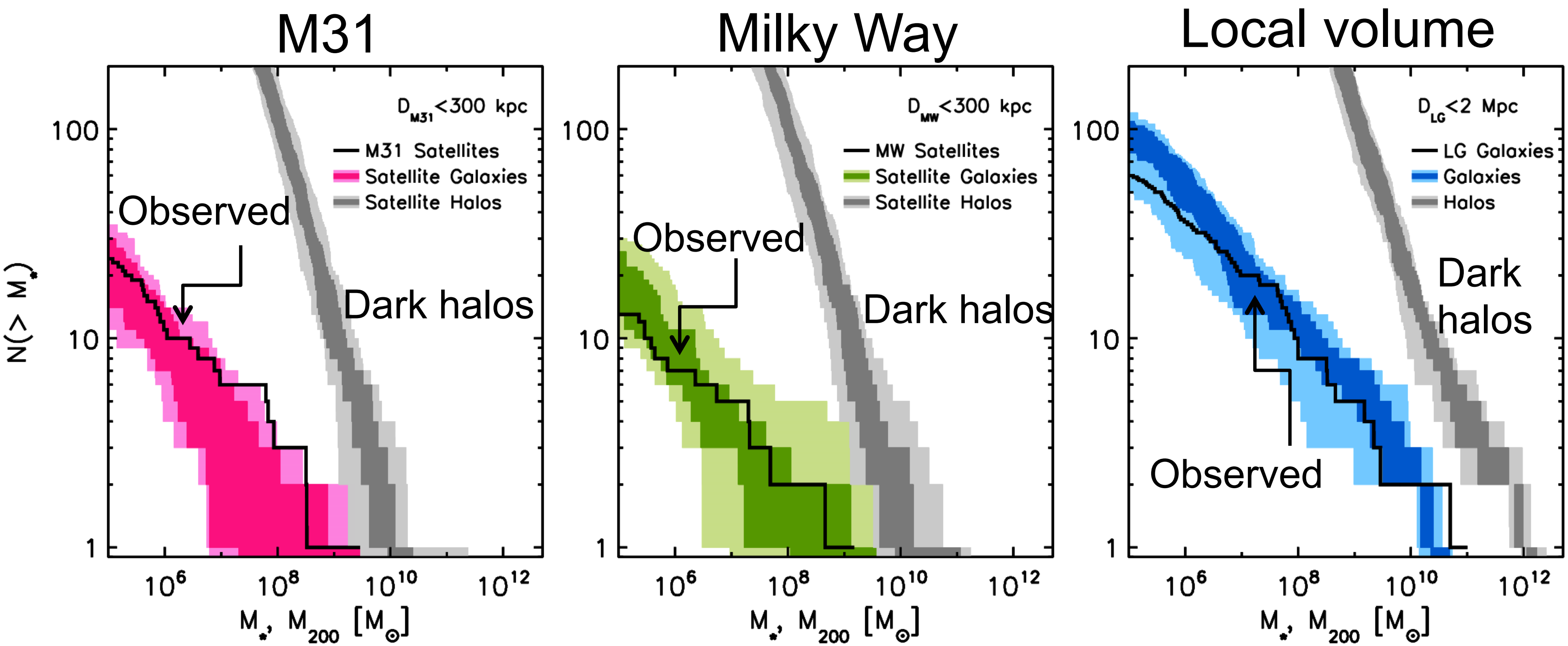

Sawala et al '15

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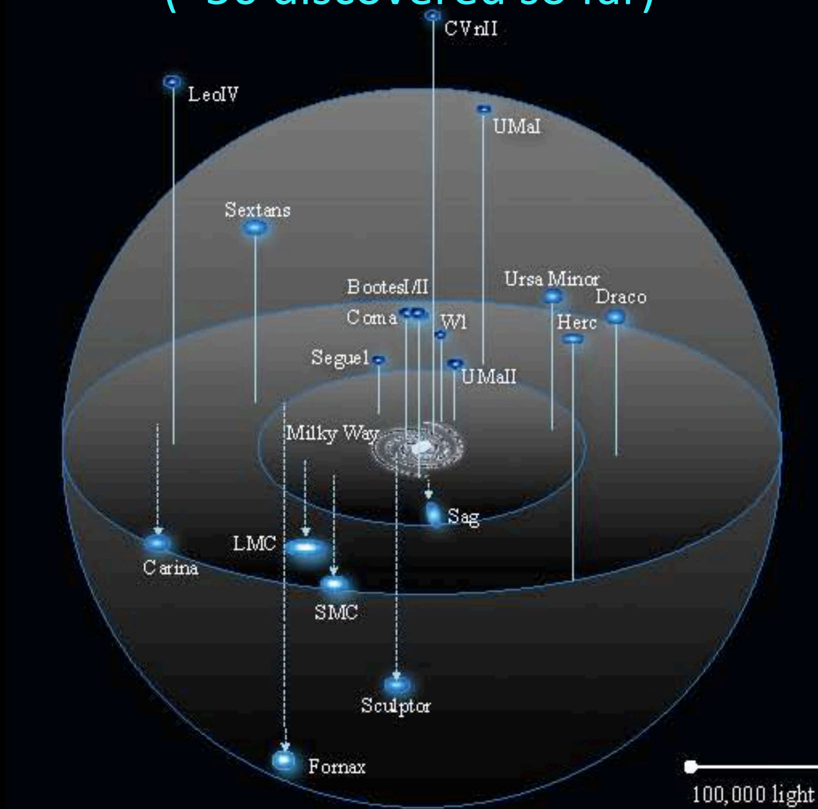
How about in WDM?

The satellites of the MW

(~50 discovered so far)



Dark matter subhalos in WDM

(a few tens)

Primordial P(k) for 7 keV sterile neutrino models

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- Thermal and resonant production mechanisms
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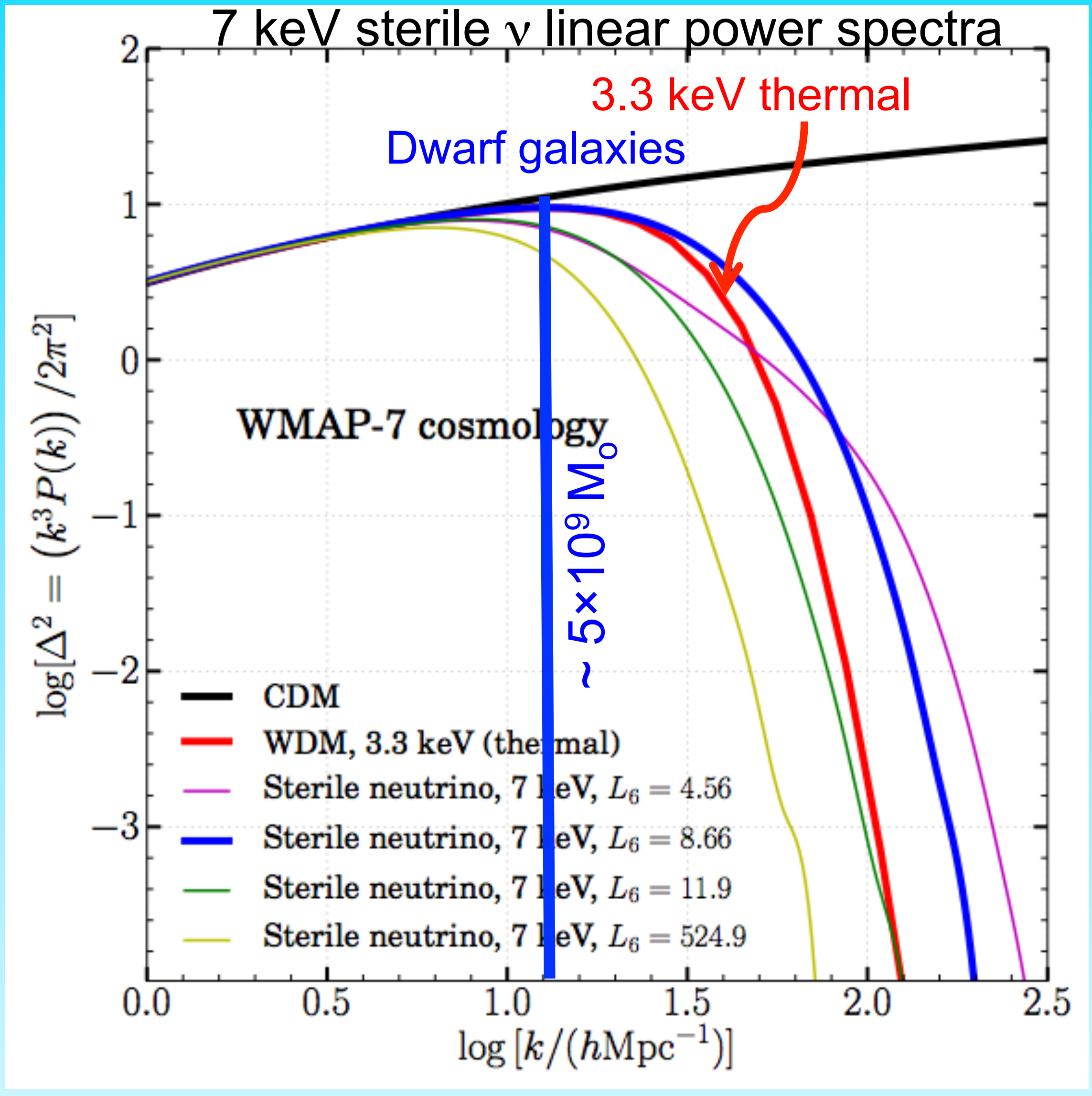
- Linear PS varies non-monothonically with L_6

Ly-α forest rules out thermal masses, mν<3.3 keV (Viel + '13)

Bose, Lovell ' et al. 16



Warm DM: different ν mass

z=3

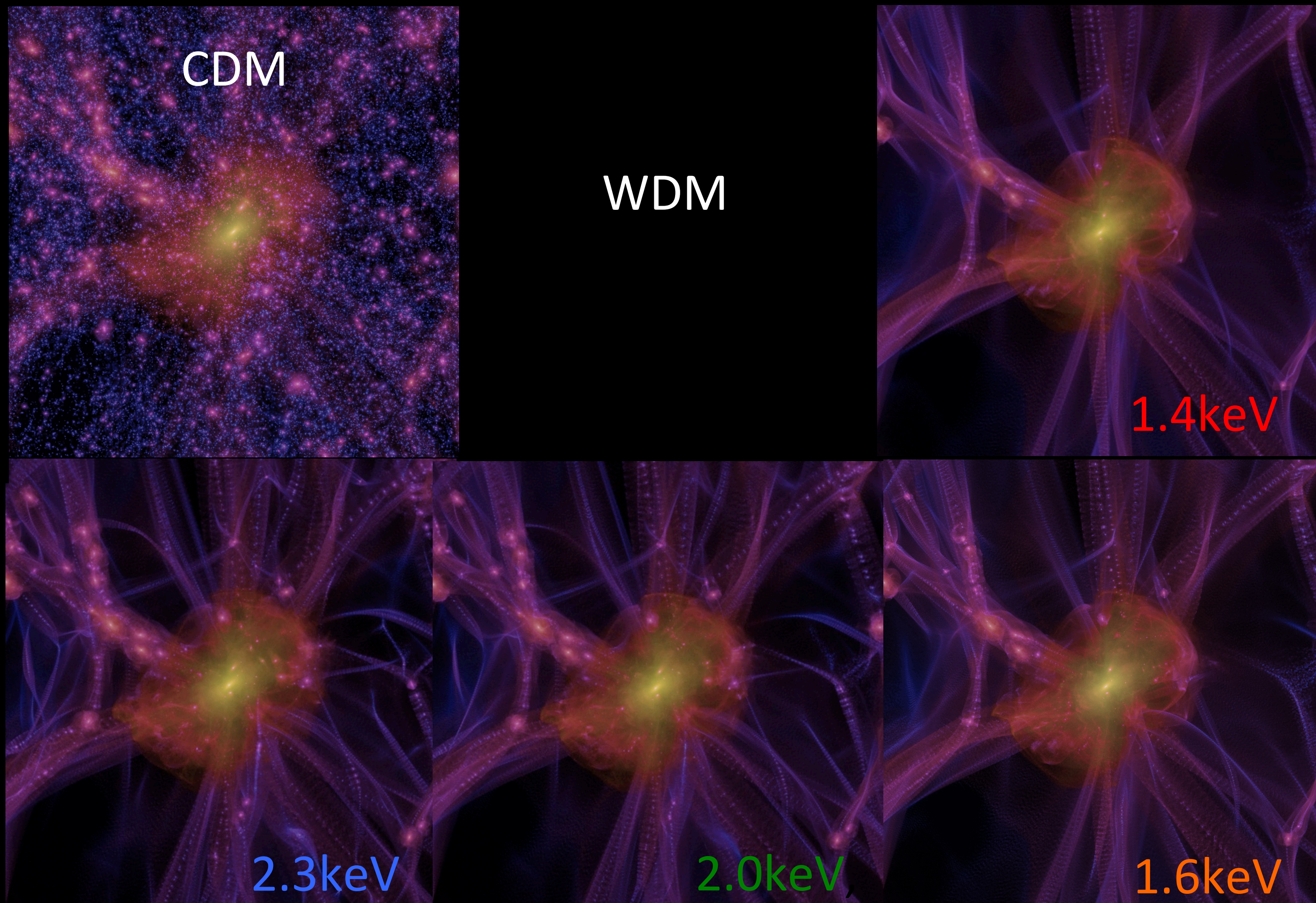
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Luminosity Function of Local Group Satellites in WDM

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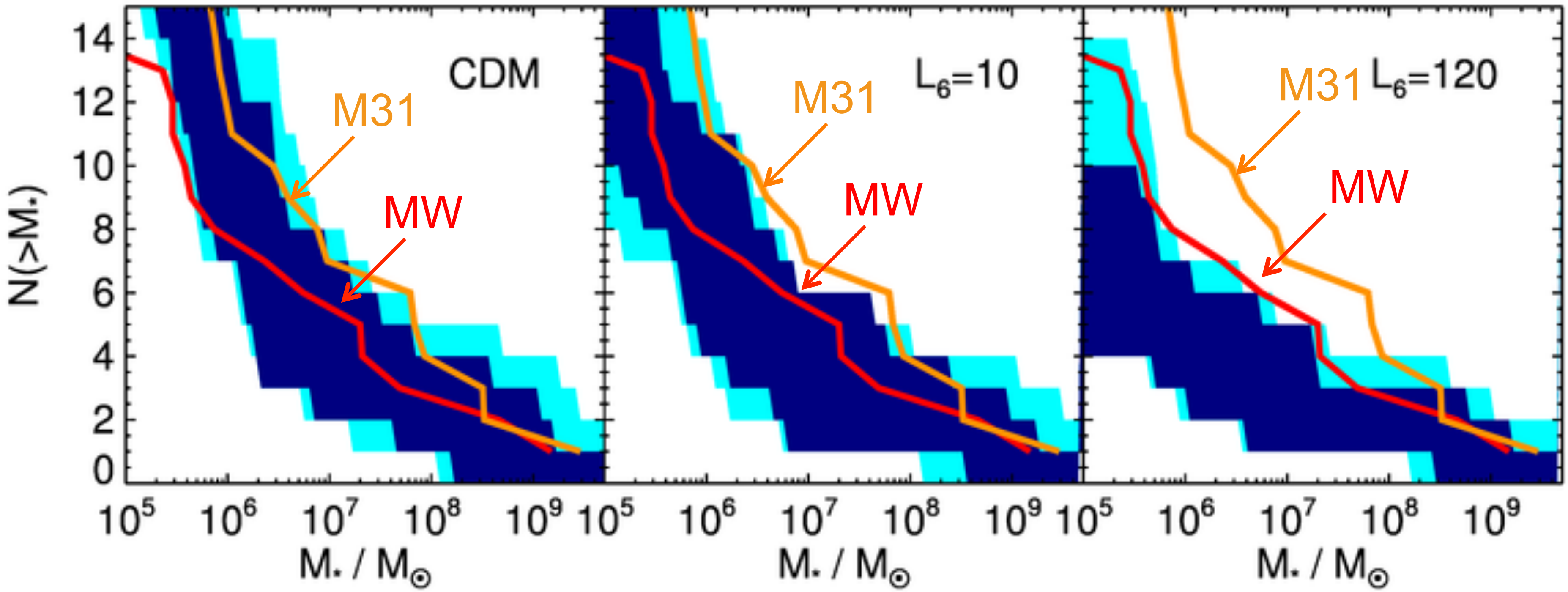
From "Warm Apostle:" 7keV sterile ν $M_h \sim 10^{12} M_o$



Lovell et al. '16

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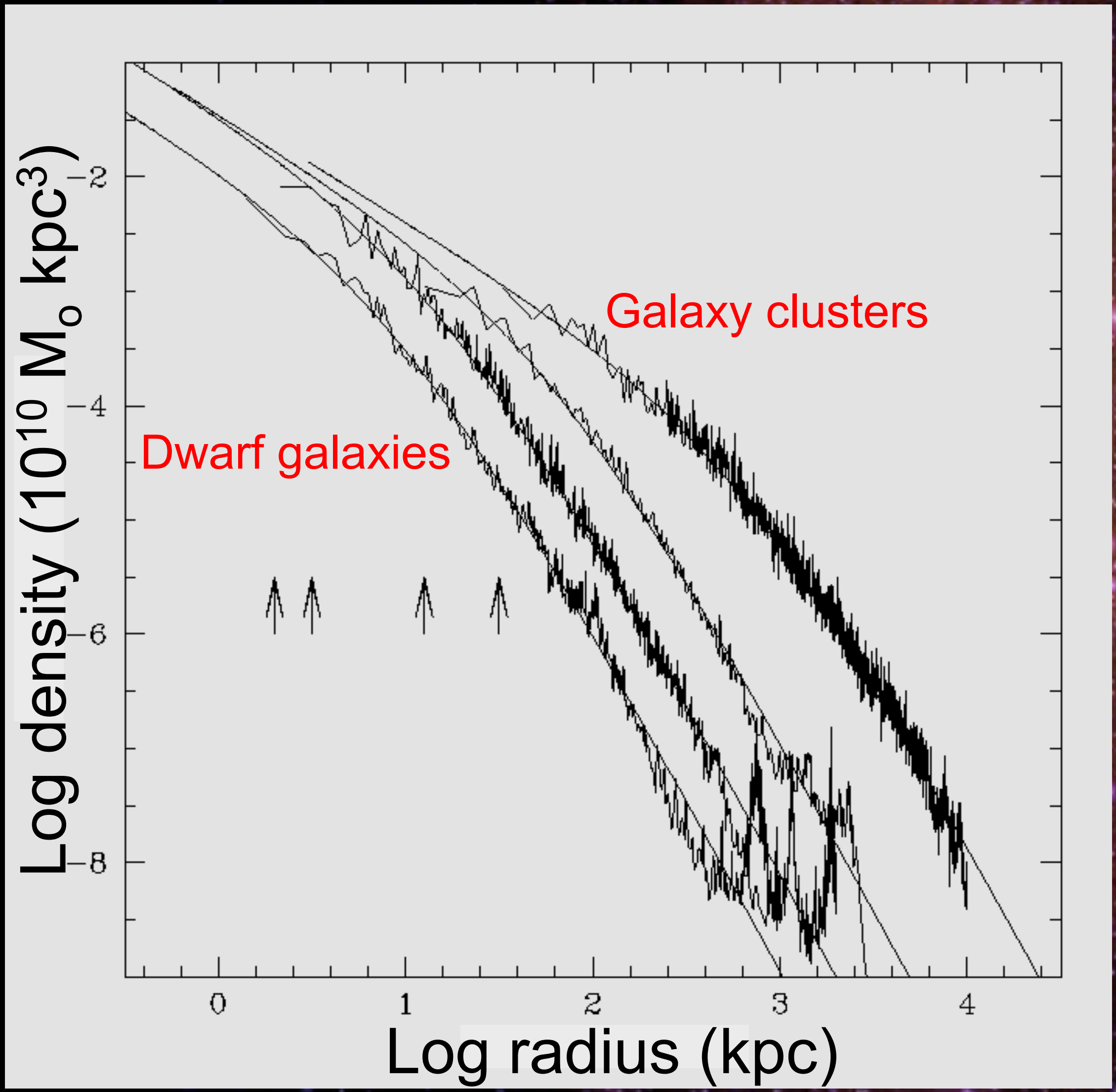
Conclusions from counting satellites

No “satellite problem” in CDM (when galaxy formation physics is taken into account)

Can rule out a subset of WDM models which do not produce enough satellites

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:

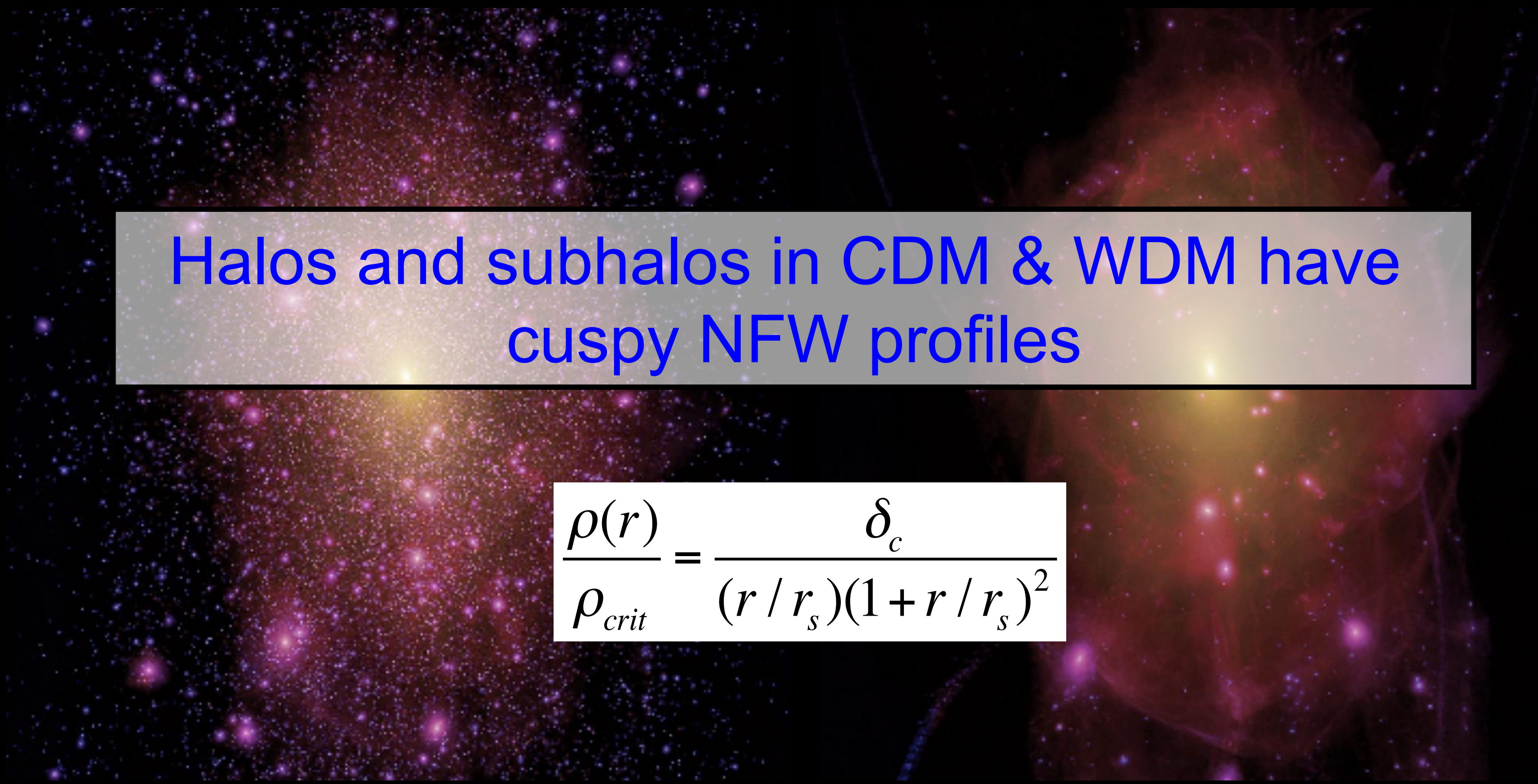
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(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

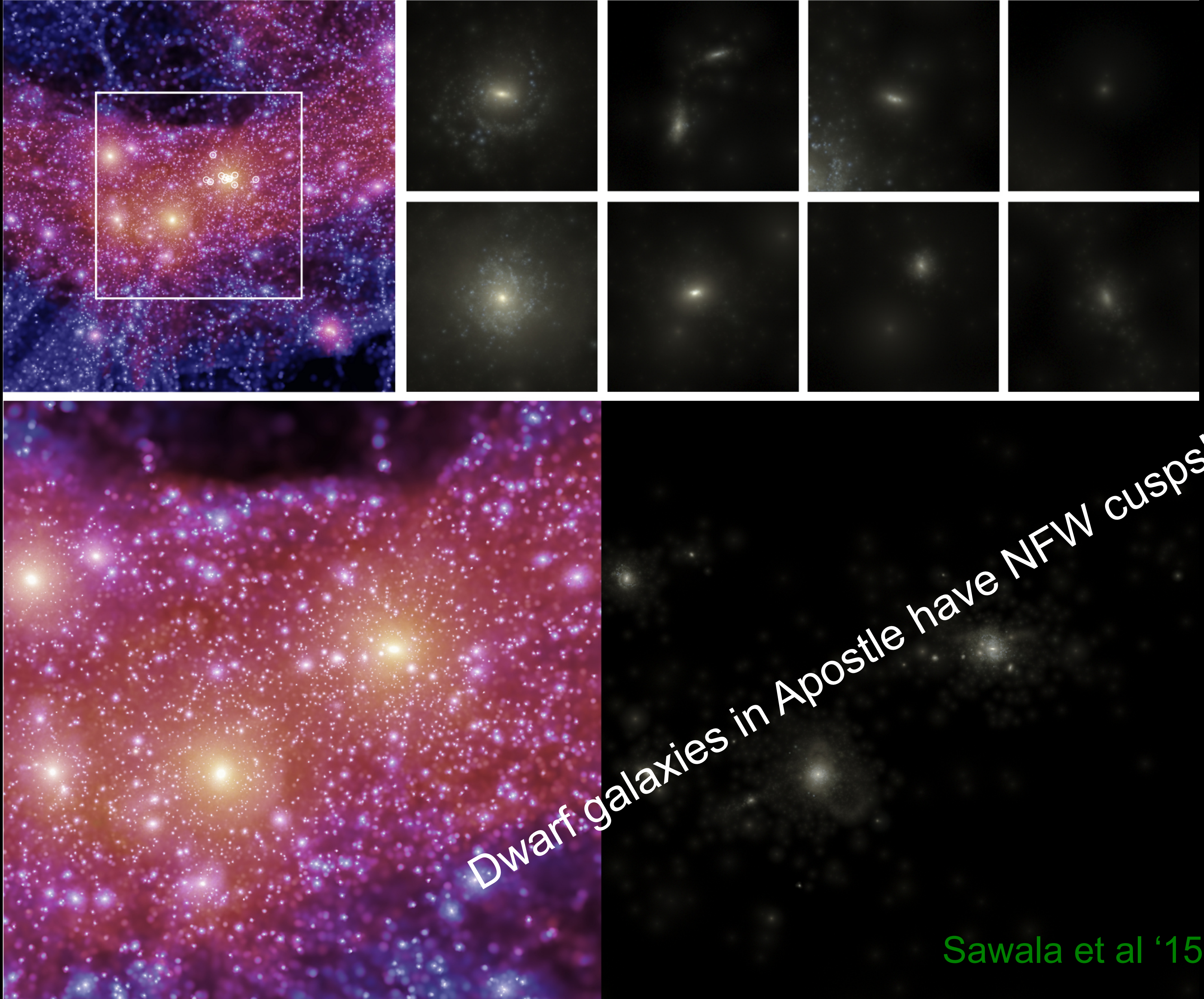


Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

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

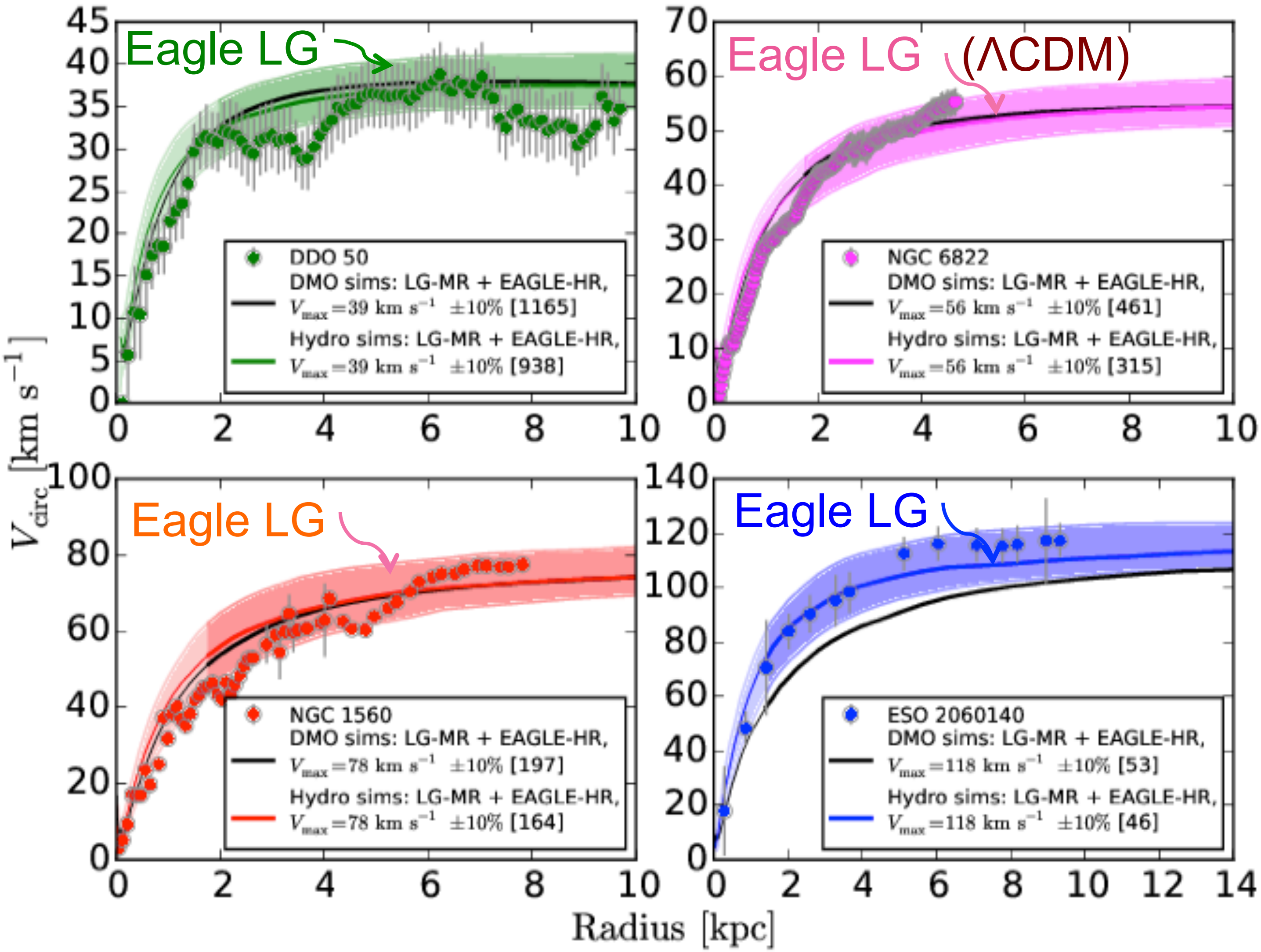
University of Durham

The diversity of gal rotation curves

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

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L_*)



Oman, Navarro, Frenk et al. '15

Institute for Computational Cosmology

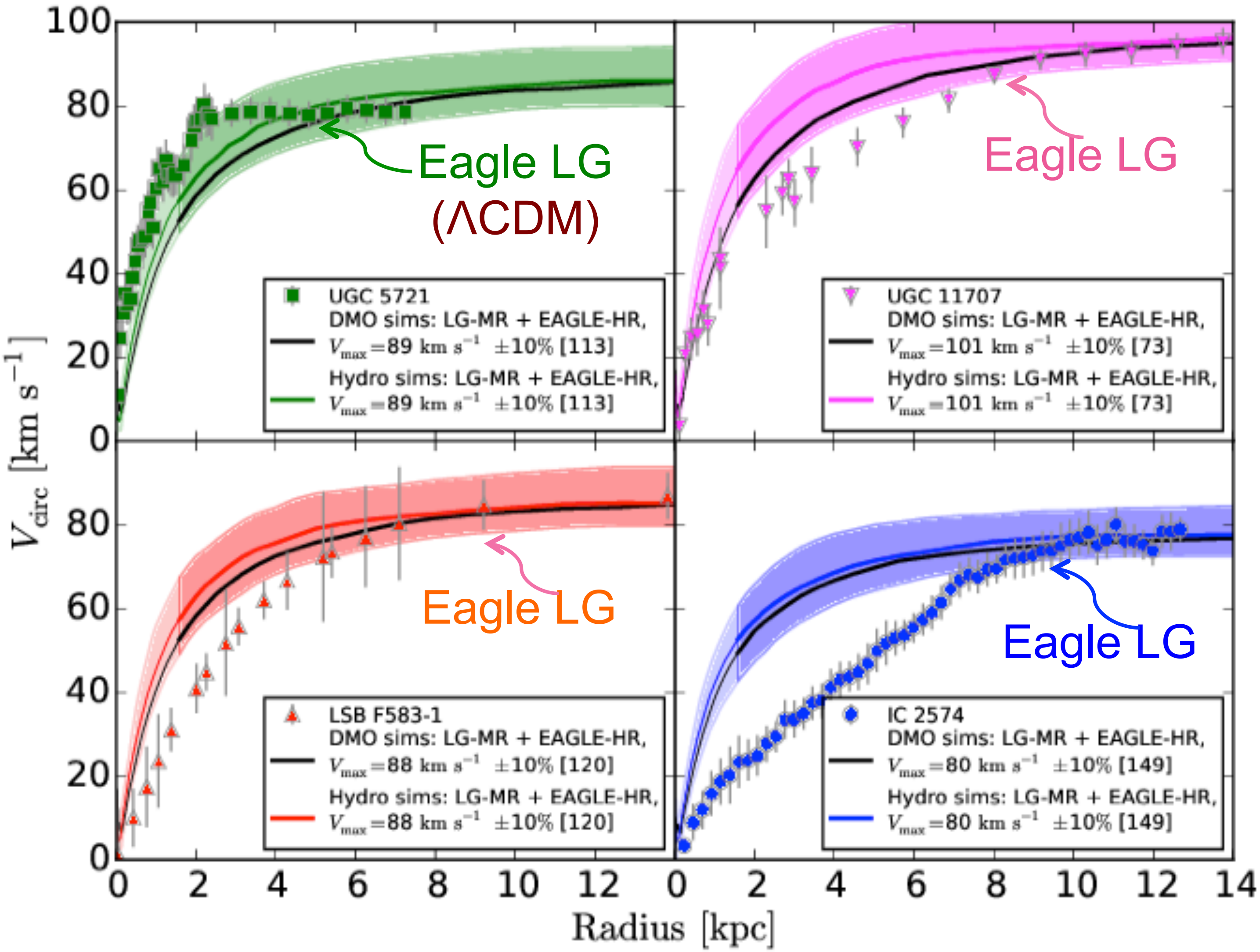
University of Durham

The diversity of gal rotation curves

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

Four rotation curves that are NOT well fit by ΛCDM

(from dwarfs to ~L_*)



Oman, Navarro, Frenk et al. ‘15

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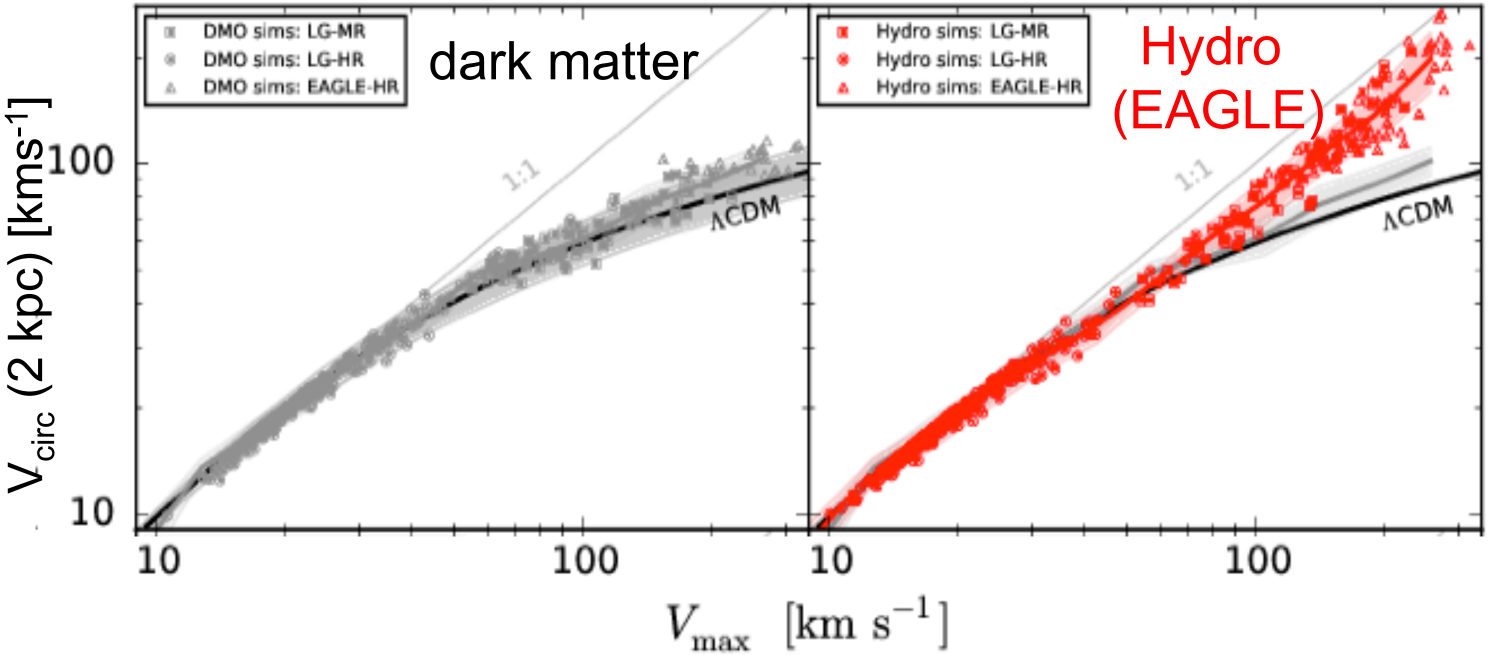
The diversity of gal. rotation curves

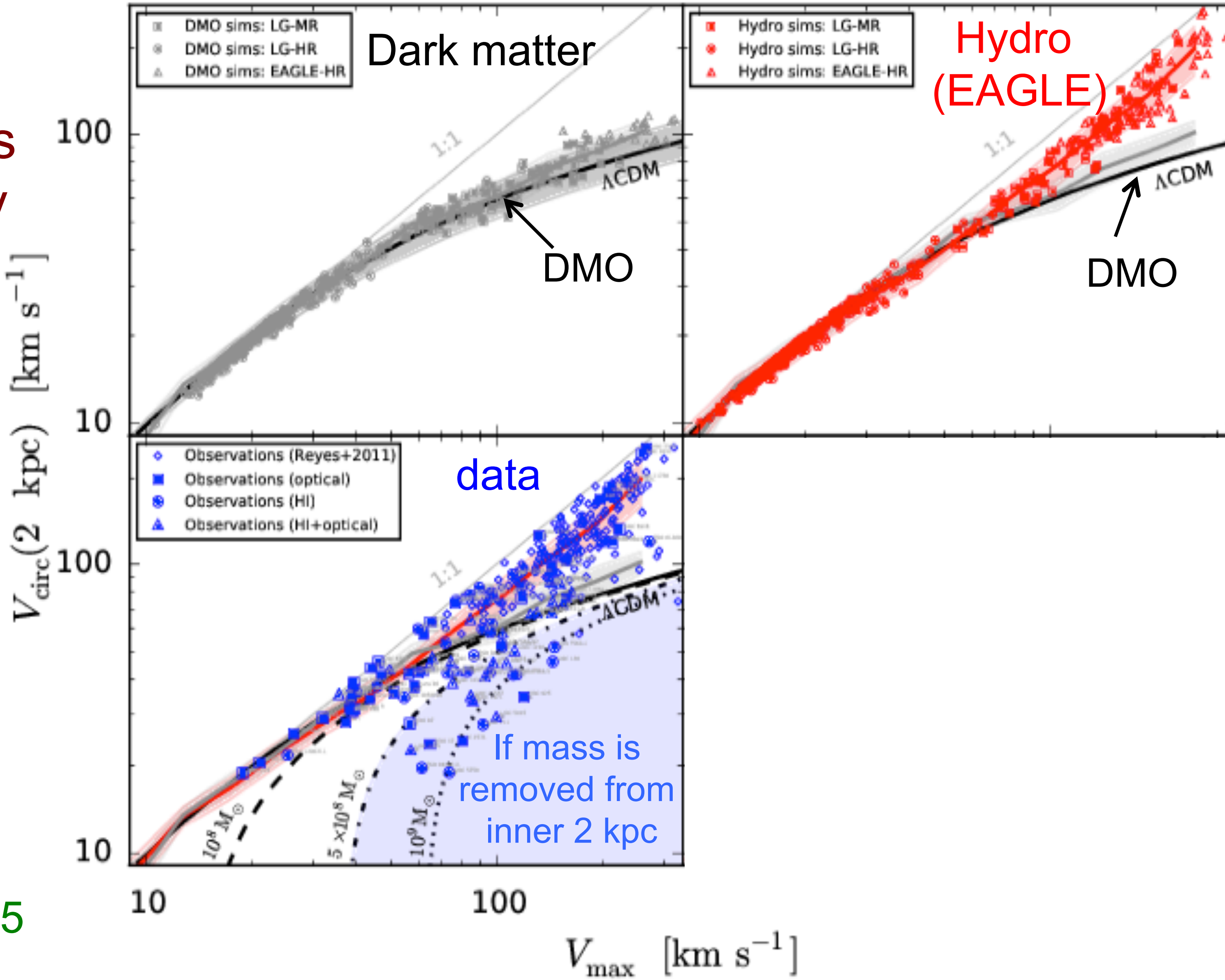


Oman et al. '15

The diversity of gal rotation curves

University of Durham

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



Oman et al. '15

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]

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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

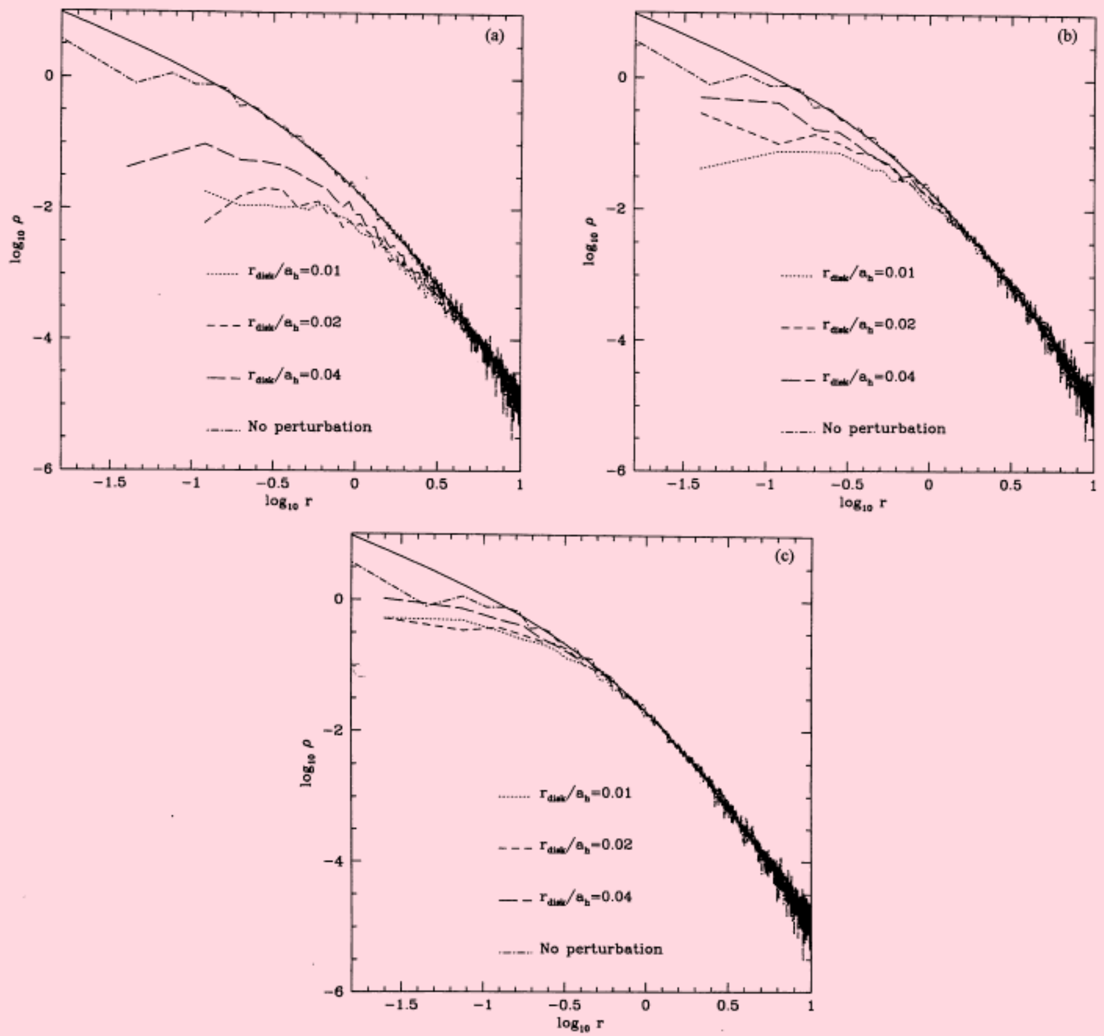


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

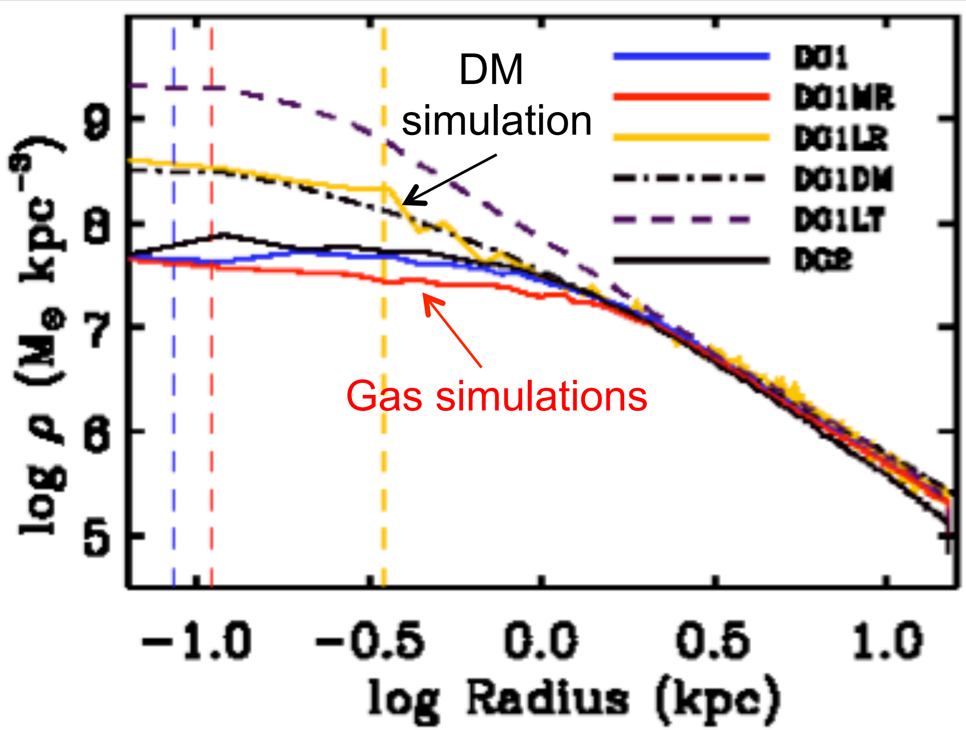
Cores in dwarf galaxy simulations

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

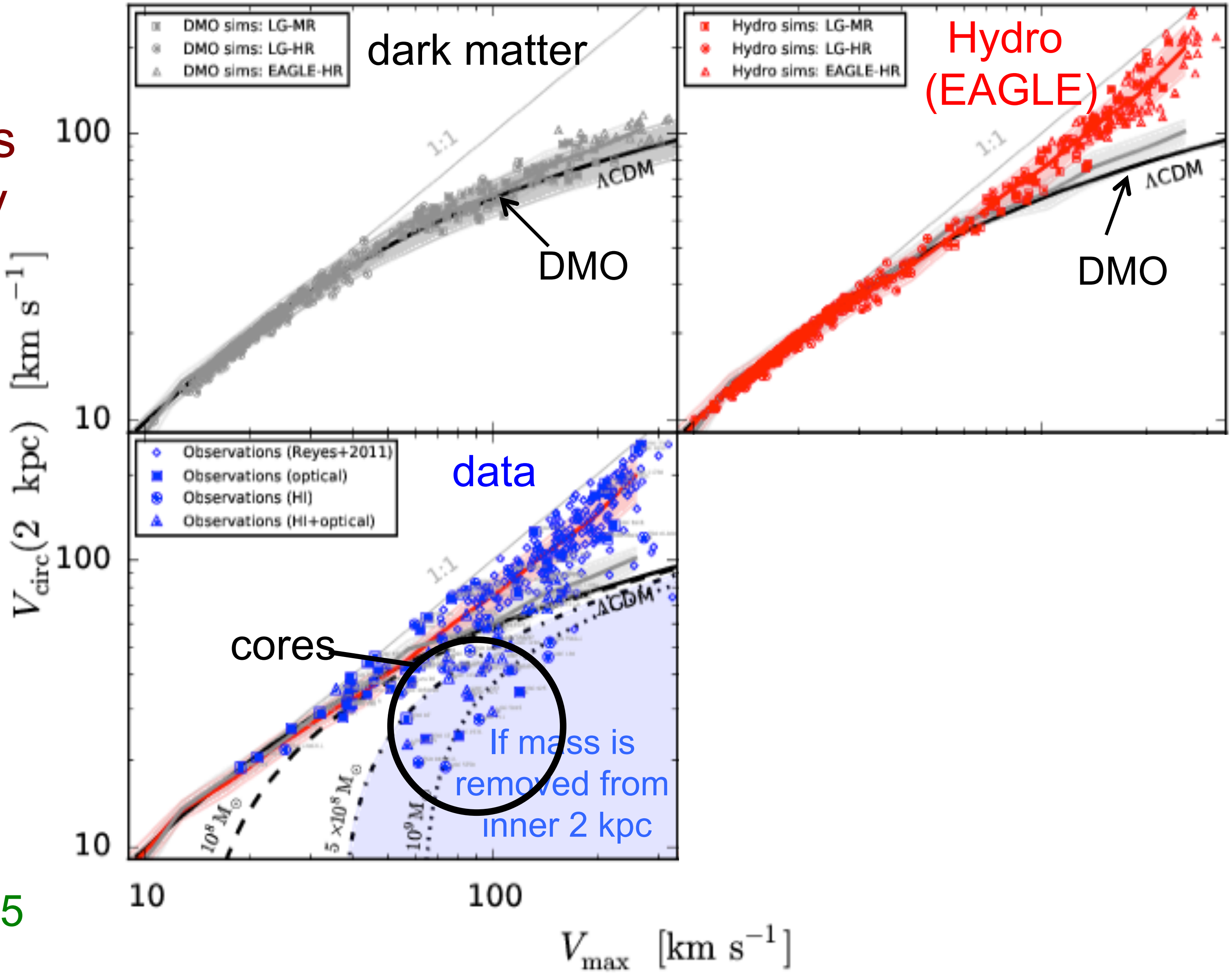


Governato et al. '10
Pontzen et al. '11

The diversity of gal rotation curves

University of Durham

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



Oman et al. '15

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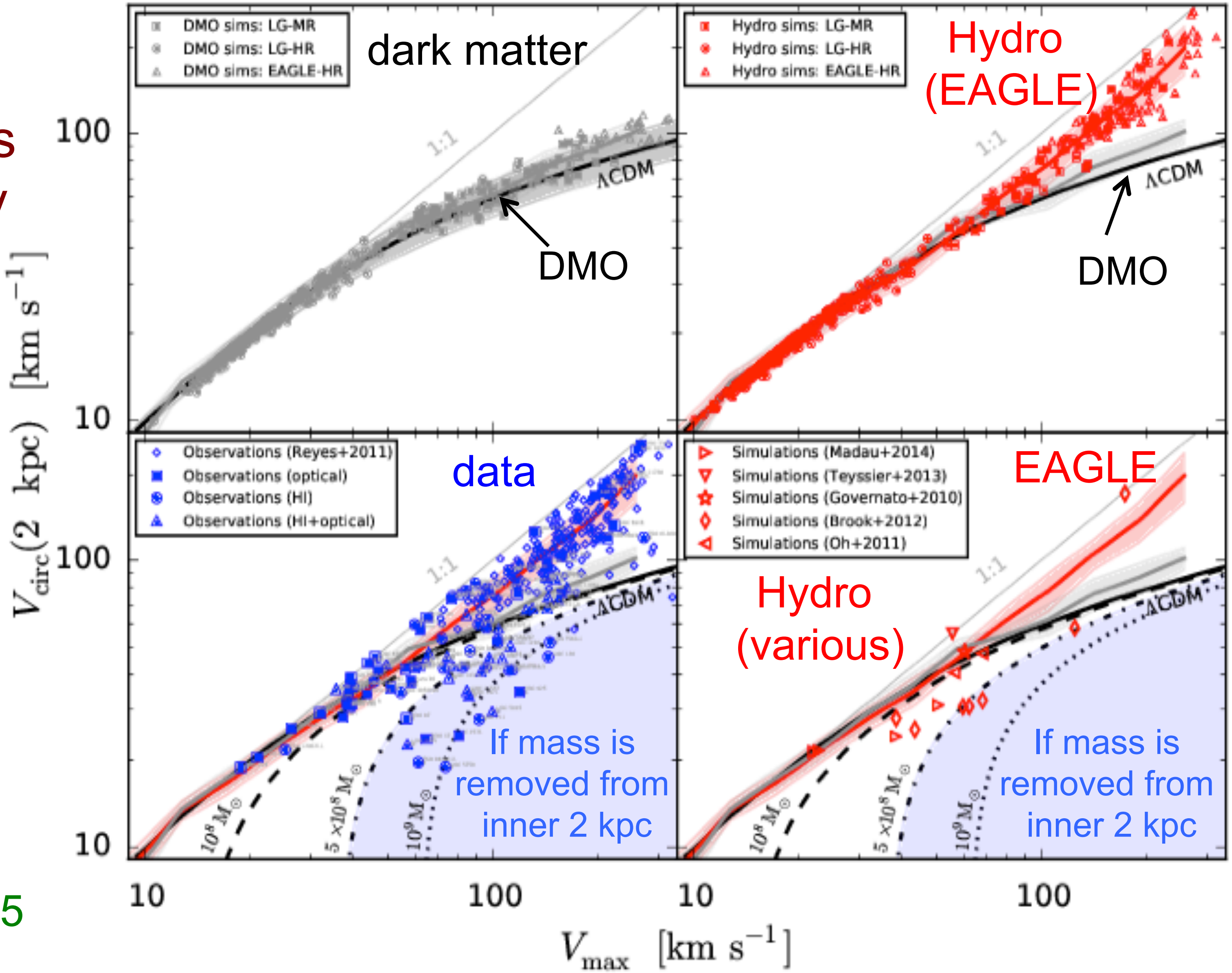

Oman et al. '15

The diversity of gal rotation curves

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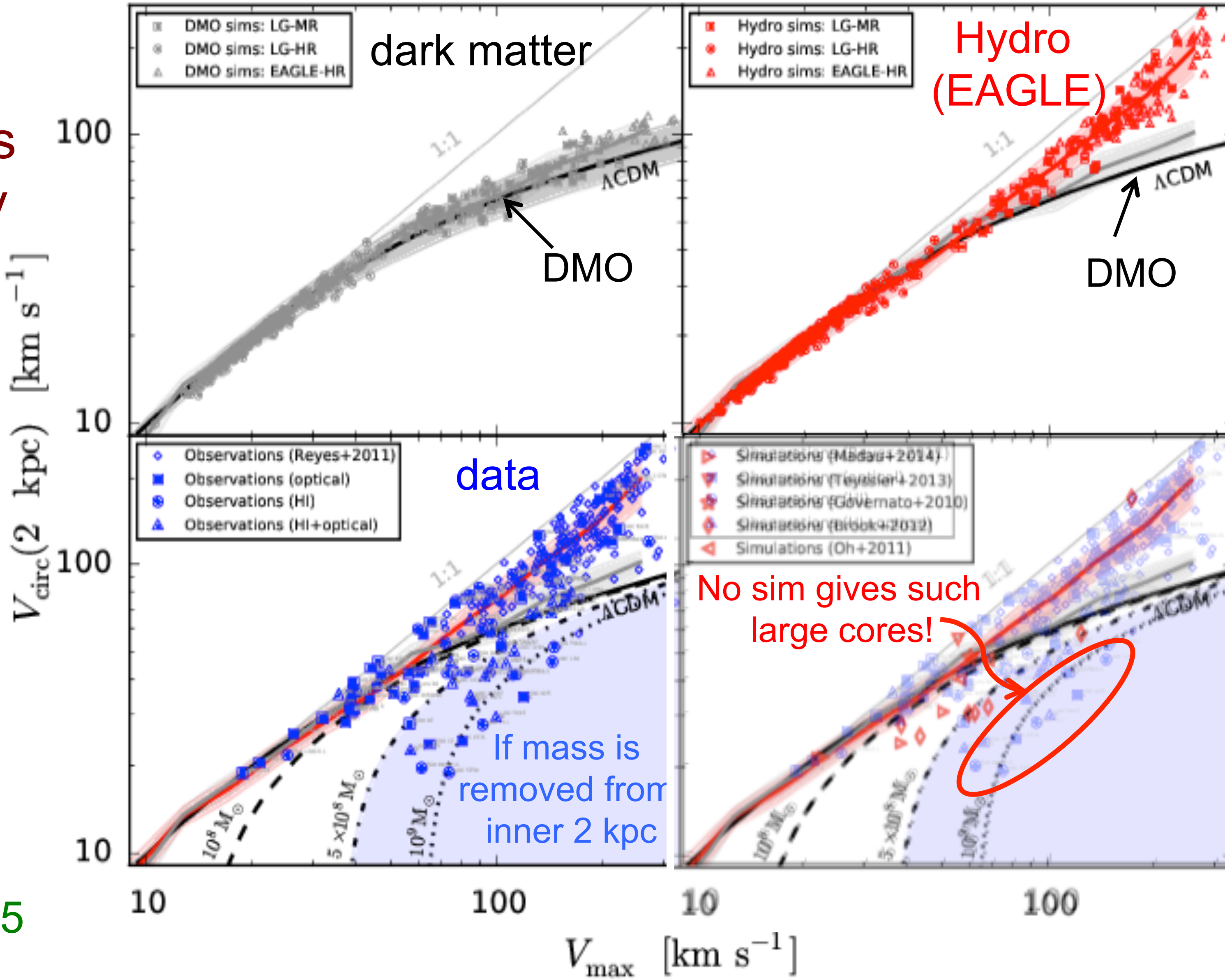
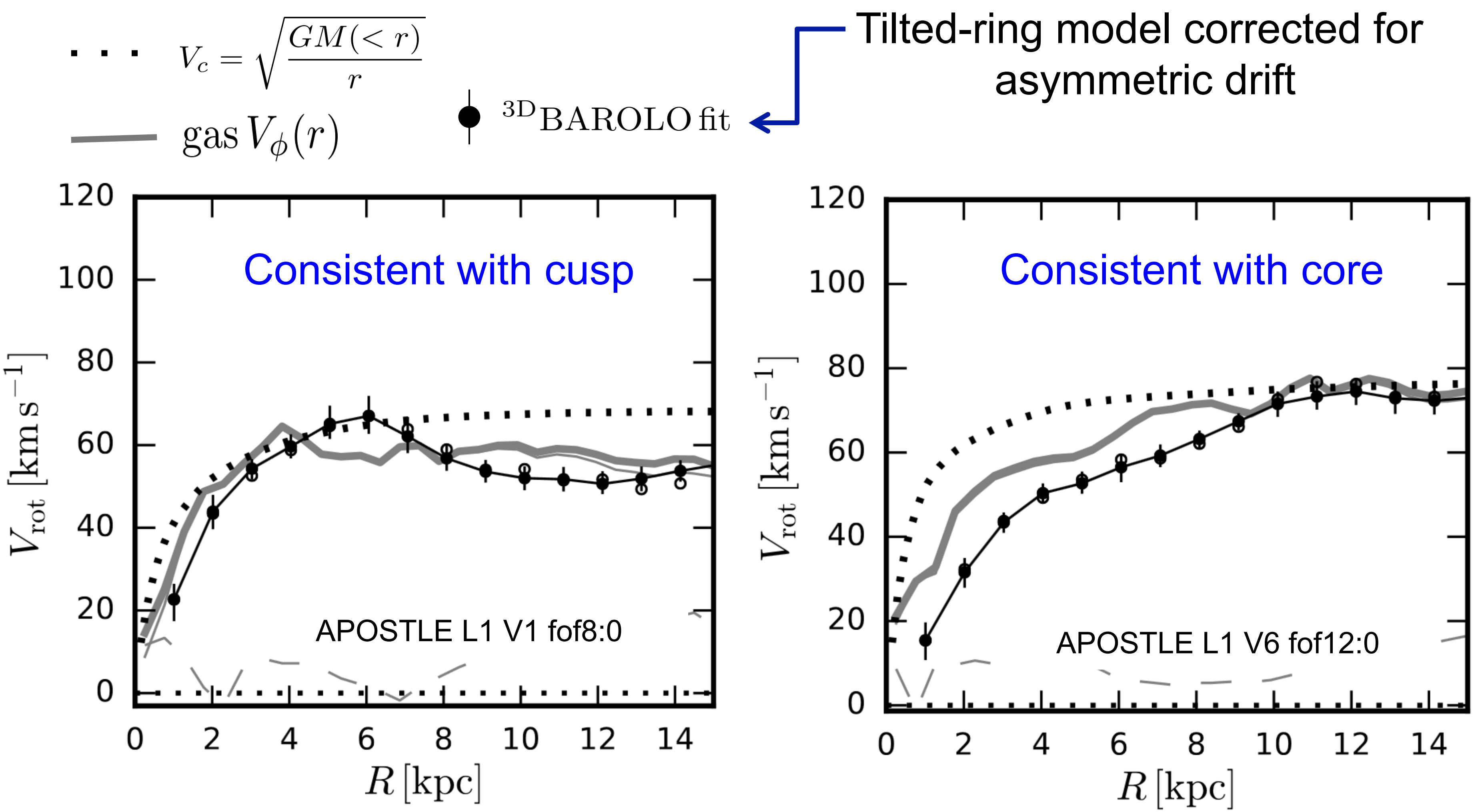


Oman et al. '15

Rotation curves of 2 APOSTLE dwarfs

University of Durham

APOSTLE galaxies all have NFW cusps



Oman et al ‘17

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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

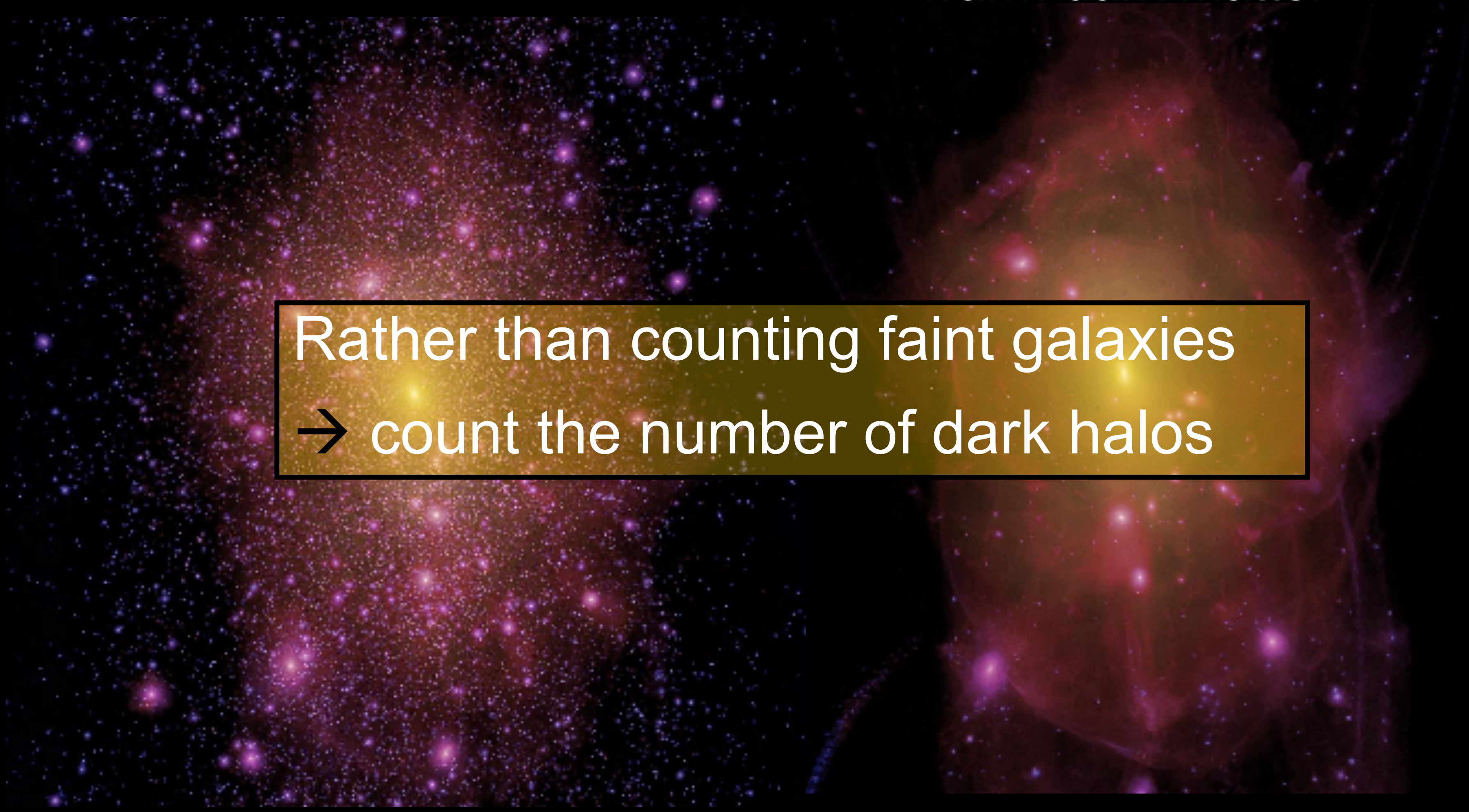
AND/OR (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect.

So, we can't distinguish CDM from WDM by counting satellite galaxies or by their structure

There is no need for despair: there is a way to distinguish them

Can we distinguish CDM/WDM?

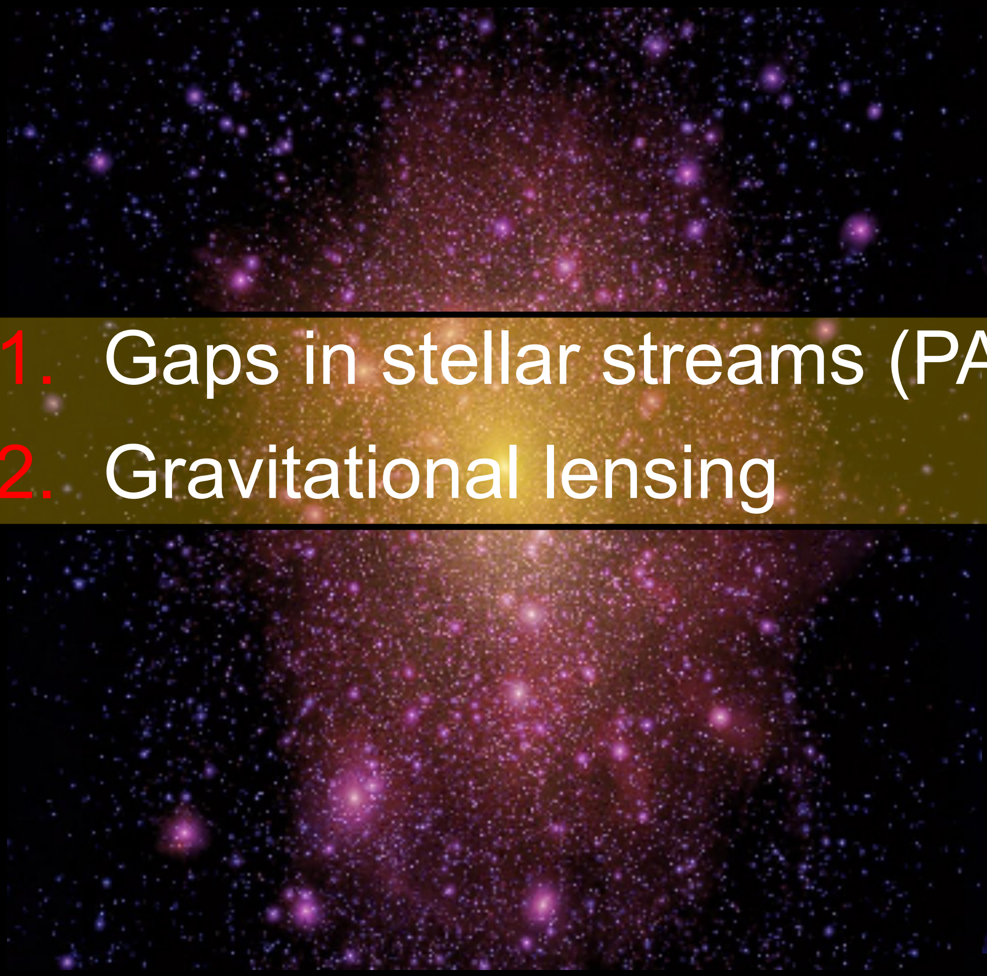
cold dark matter | warm dark matter



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

Can we distinguish CDM/WDM?

cold dark matter

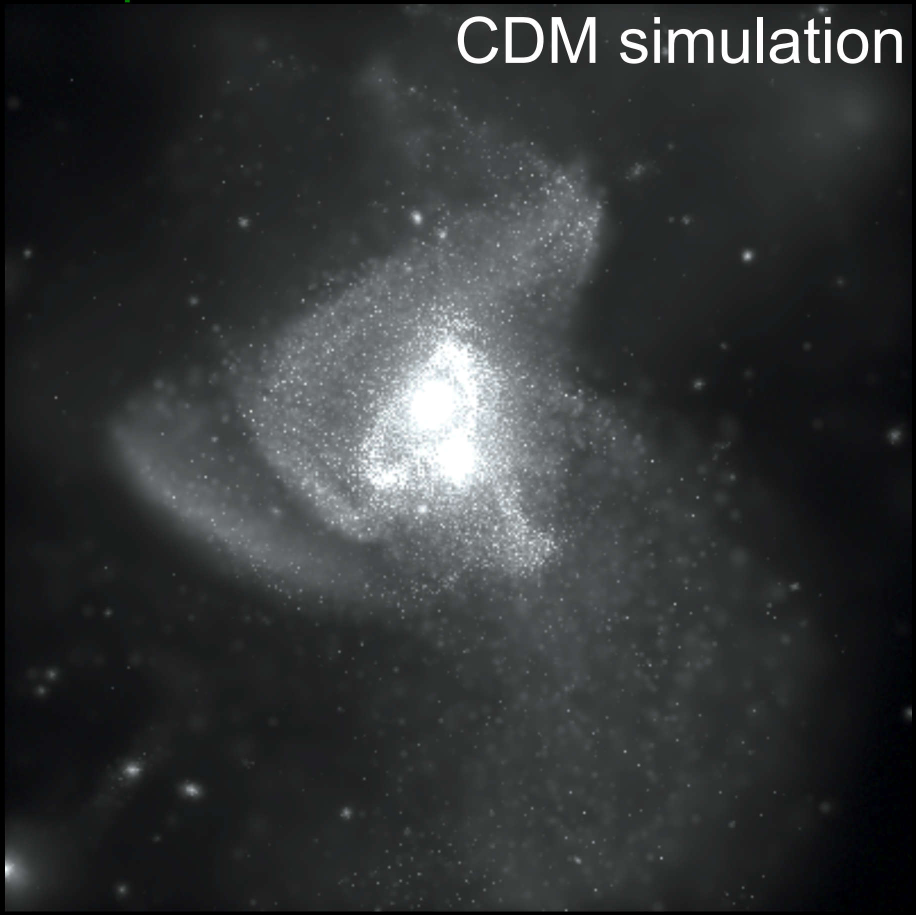


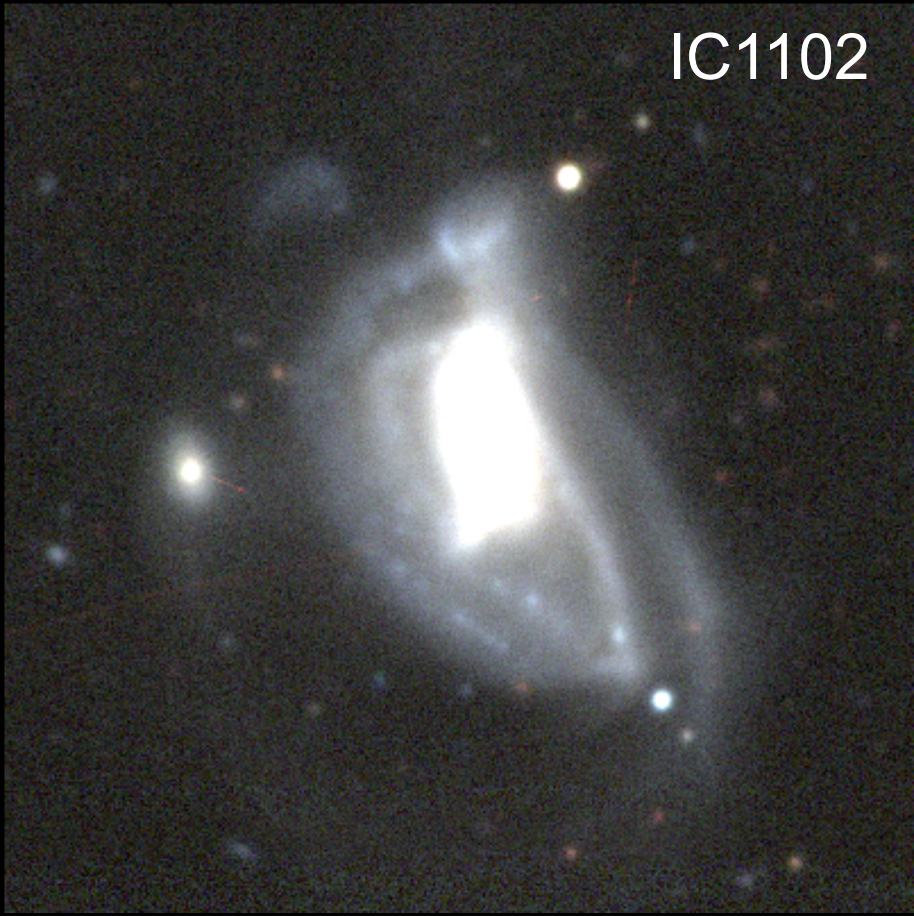
warm dark matter

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

Can we distinguish CDM/WDM?

Cooper et al '16

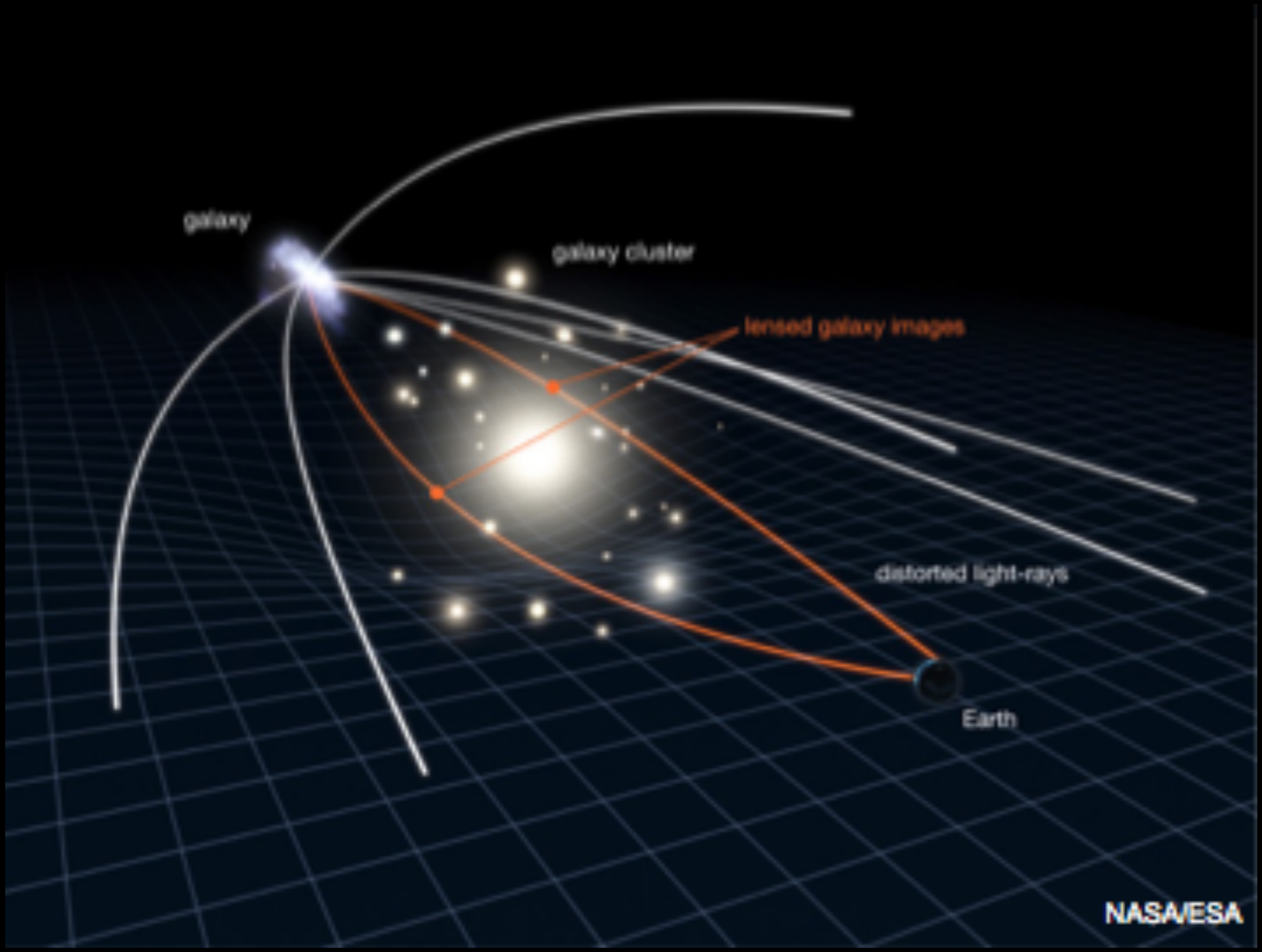




Subhalos crossing a cold tidal stream can produce a gap

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

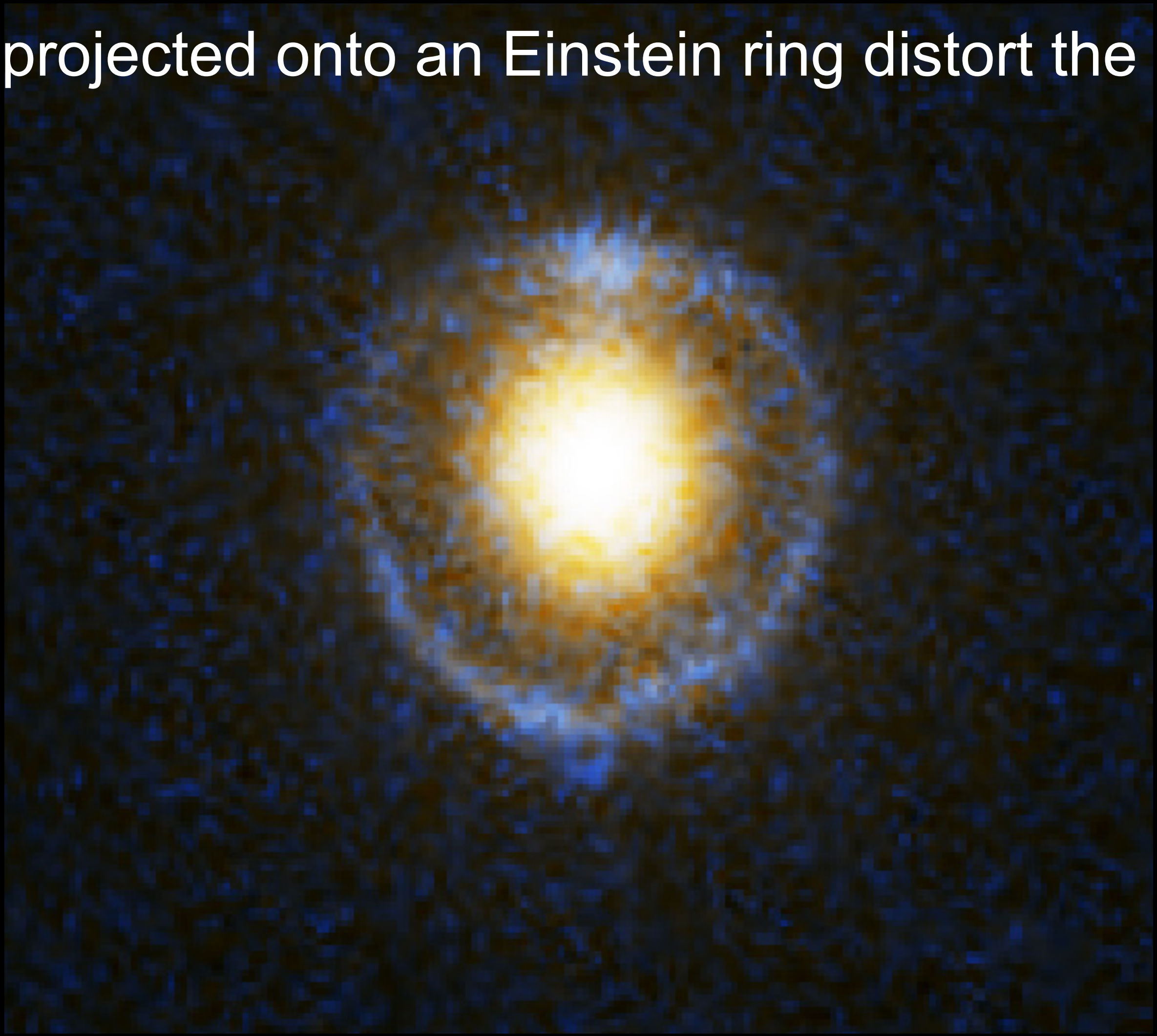
Gravitational lensing: Einstein rings



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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



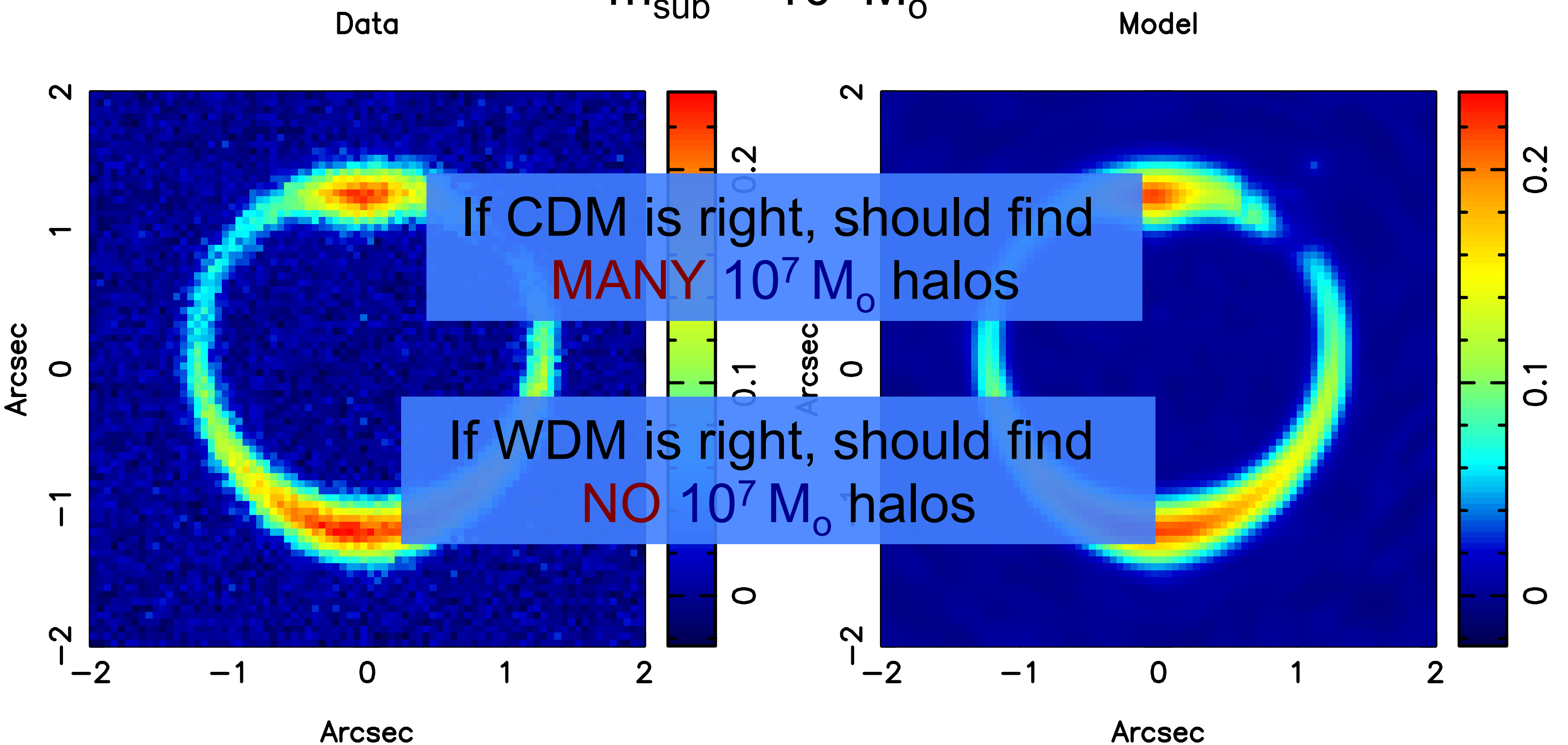
Vegetti & Koopmans '09

University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$



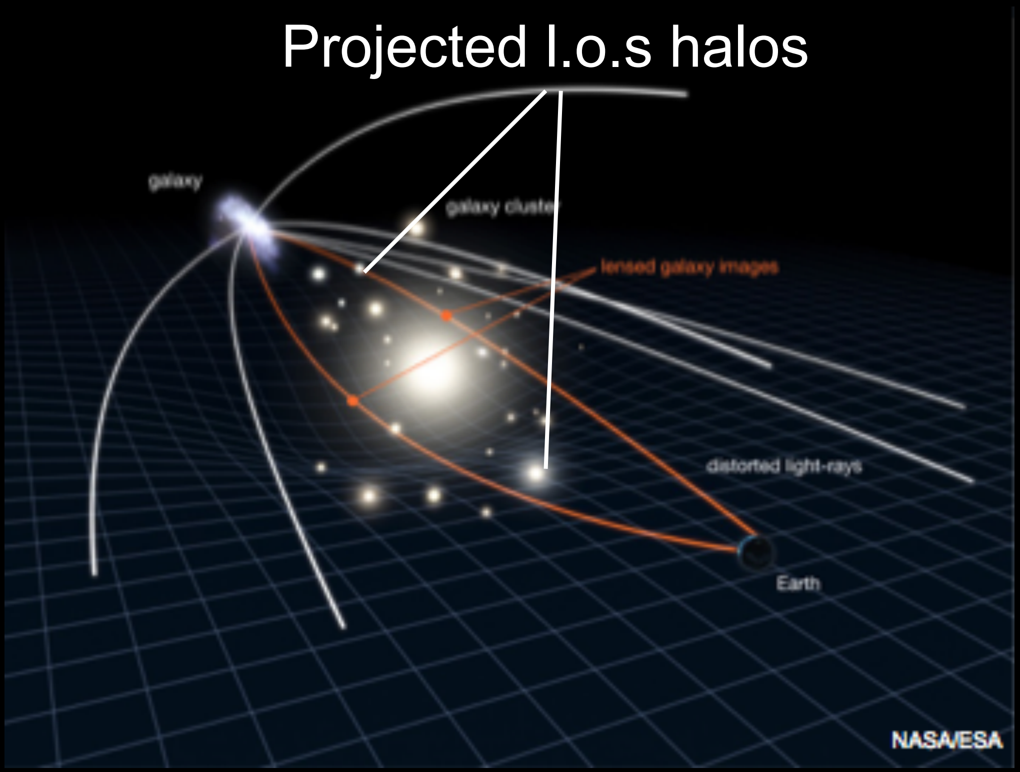
If CDM is right, should find MANY $10^7 M_o$ halos

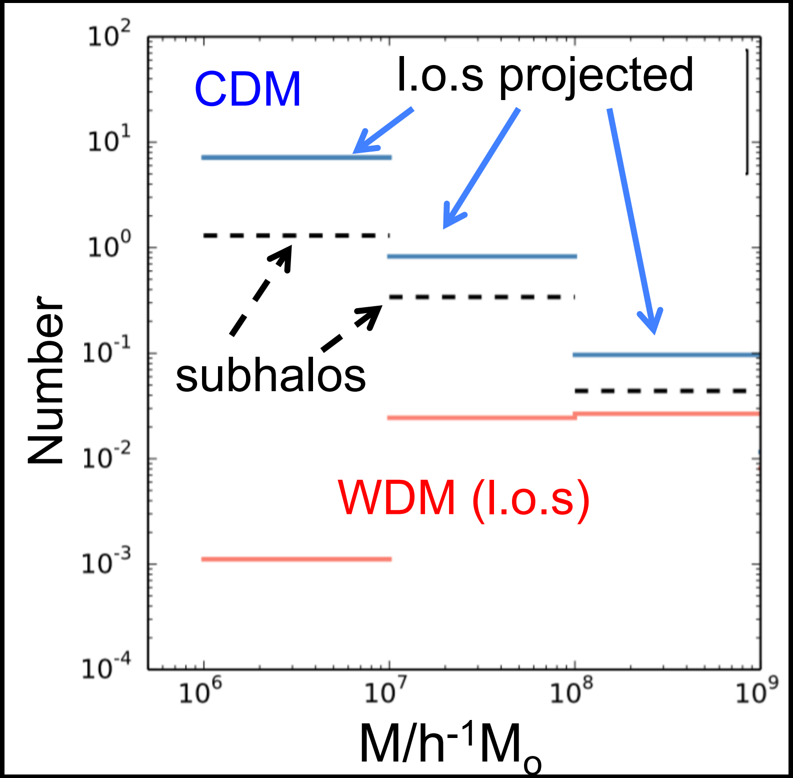
If WDM is right, should find NO $10^7 M_o$ halos

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

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens





The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16

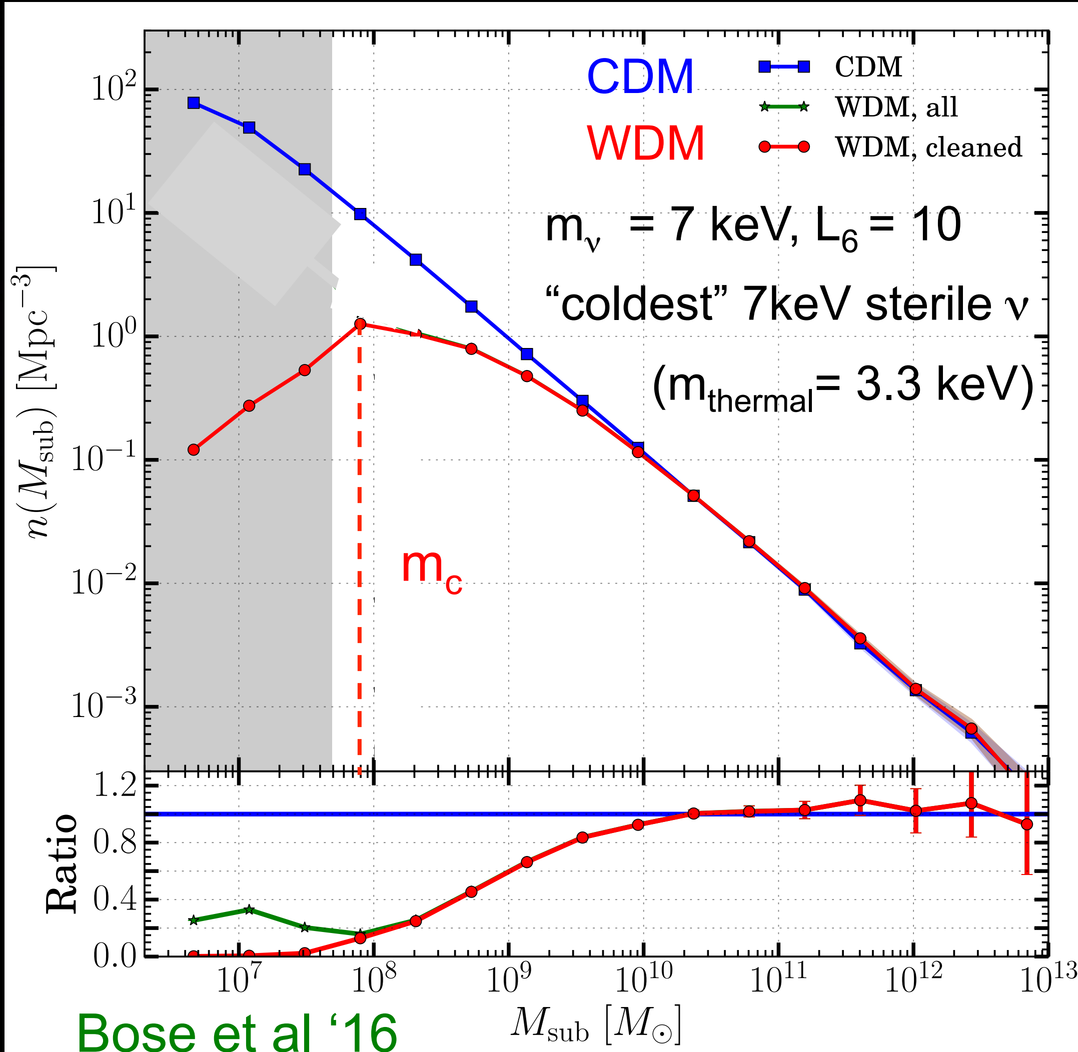
The subhalo mass function

CDM

WDM

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

10 x fewer at 10^8M_o



Bose et al '16

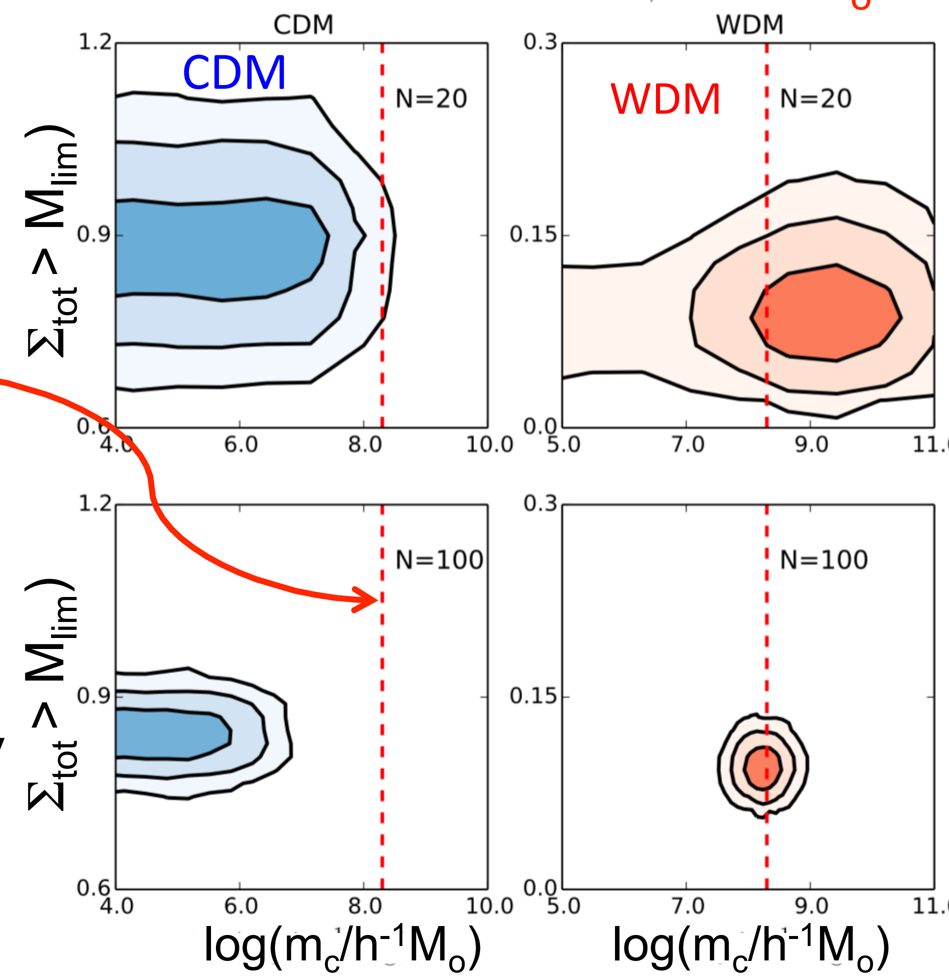
Detecting substructures with strong lensing

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

m_c= halo cutoff mass

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

Detection limit = 10^7 $h^{-1}M_o$



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

- If DM is CDM → rule out 7 keV sterile ν at many σ
- If DM is 7 keV sterile ν → rule out CDM at 3σ!

Li, CSF et al ‘16

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Strong gravitational lensing could rule out CDM within the next few years!!!

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. Presence of cores debatable; could be due to baryons
3. Strong gravitational lensing can distinguish CDM/WDM

-- and could rule out CDM!