



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

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

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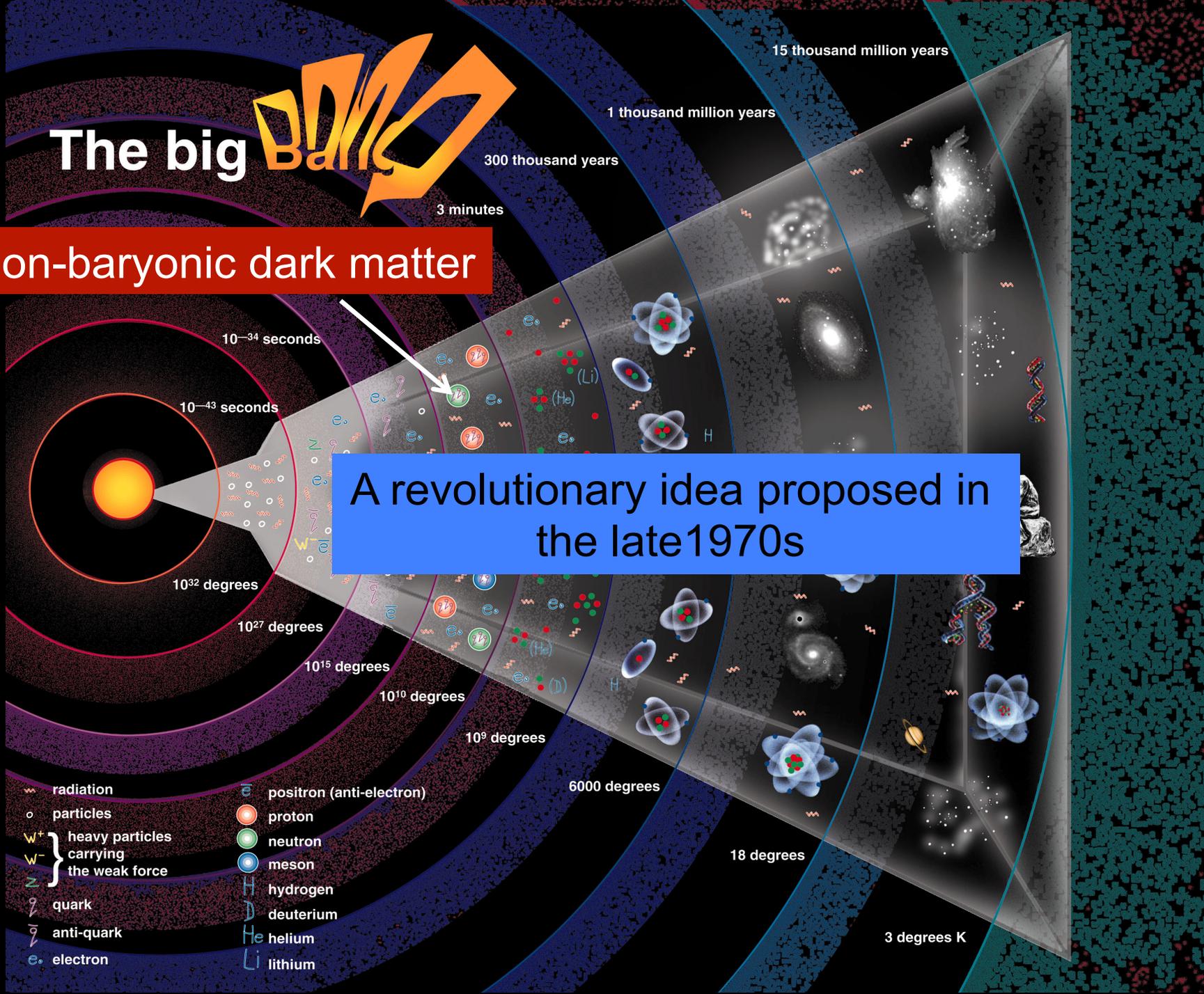


The big Bang



Non-baryonic dark matter

A revolutionary idea proposed in the late 1970s



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

The dark matter power spectrum

$k^3 P(k)$

The linear power spectrum (“power per octave”)

Free streaming \rightarrow

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

for thermal relic

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

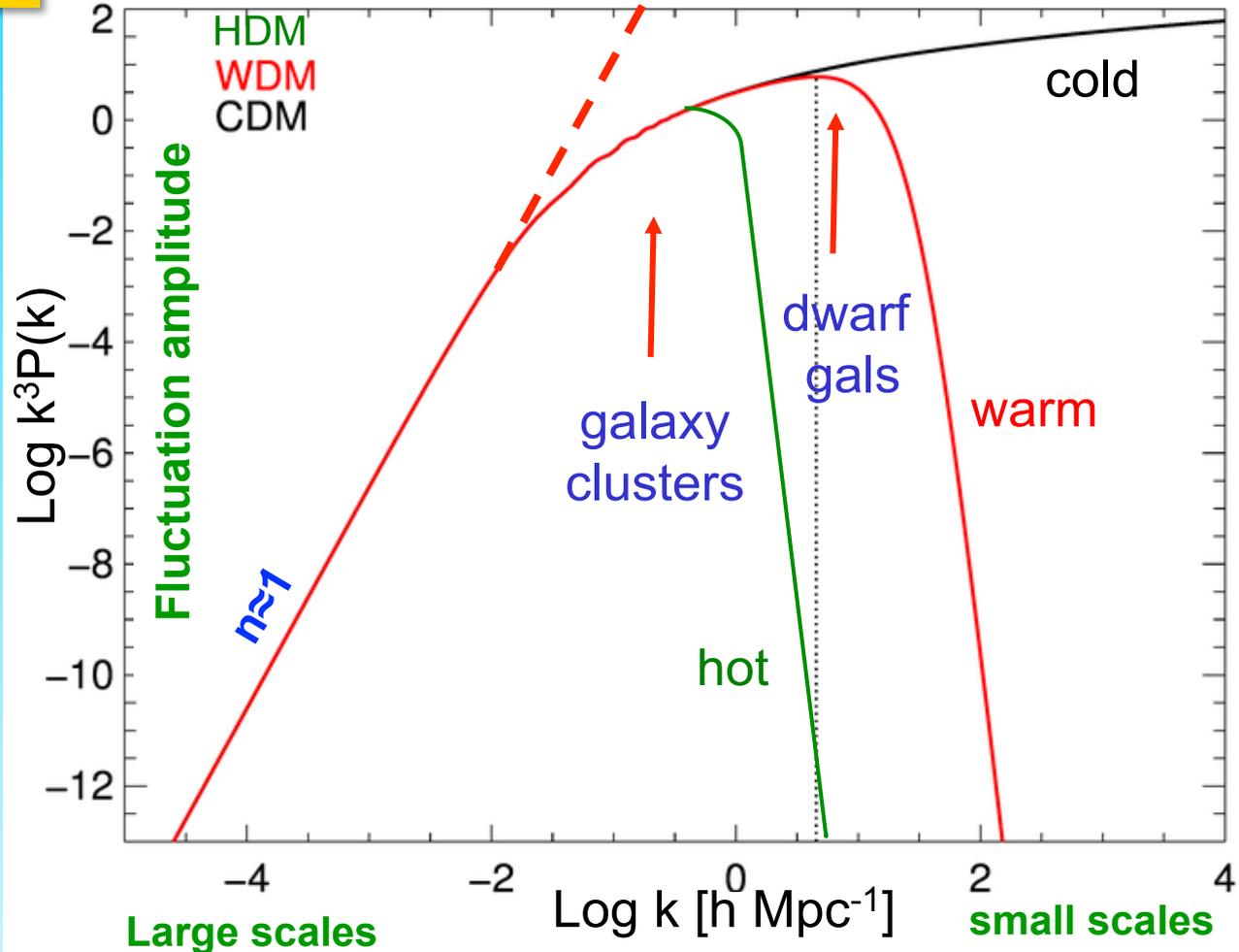
$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

$$m_{\text{WDM}} \sim \text{few keV}$$

$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$

$$m_{\text{HDM}} \sim \text{few tens eV}$$

$$\text{light } \nu; M_{\text{cut}} \sim 10^{15} M_{\odot}$$



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

$m_\nu = 30 \text{ eV} \rightarrow \Omega = 1$

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 molecule was measured with high precision by a toroidal β -spectrometer. 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 ($E_\beta \text{ max} \approx$ 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 $S \approx (E - E_0)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_0$ (total β -transition energy). If $M_\nu \neq 0$, then $S \approx (E_0 - E) \sqrt{(E_0 - E)^2 - M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

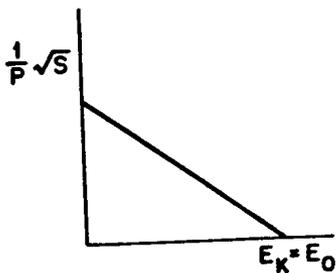


Fig. 1. Kurie plot for $M_\nu = 0$.

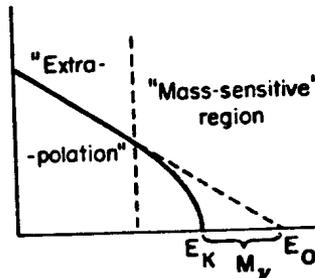


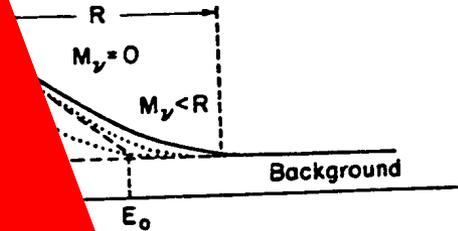
Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_0 from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_0 - E_k$. Qualitatively, $M_\nu \neq 0$ if the β -spectrum near the endpoint runs below the extrapolated curve.

* Paper presented by Oleg Egorov.



things are more complicated. The apparatus resolution strongly affects the spectrum endpoint and rather the spectrum slope.



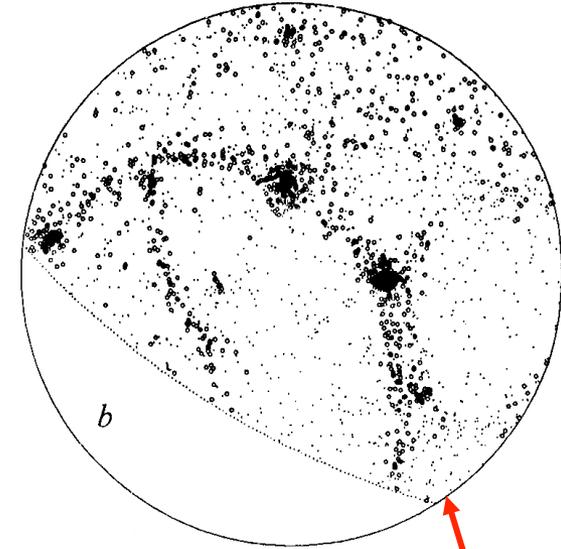
Realistic Kurie plot.

...extrapolation. However, we are unable to determine M_ν , then once again the lack of counts near the endpoint indicate that $M_\nu \neq 0$. If $M_\nu \leq R$, the changes due to M_ν and the influence of R are indistinguishable. For $M_\nu > R$, the determination of the knowledge of R is compulsory. The background determines 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 $M_\nu = 100 \text{ eV}$ we need resolution R , background Q , and statistics N . If $M_\nu = 30 \text{ eV}$, to achieve the same $\Delta M/M$ they should be $R/3$, $Q/10$, and $N \times 30$, respectively.

The shorter the β -spectrum, the less it is spread due to R (as $R \sim \Delta p/p = \text{const.}$). A classical example is ^3H β -decay, which has 1) the smallest $E_0 \sim 18.6 \text{ keV}$, 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 $M_\nu \leq 1 \text{ keV}$. Further progress required magnetic spectrometer development. This allowed the resolution to be improved considerably, and L. Langer and R. Moffat (1952) obtained $M_\nu \leq 250 \text{ eV}$. The best value was obtained by K. Bergkvist (1972): $R \sim 50 \text{ eV}$ and $M_\nu \leq 55 \text{ eV}$.

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. Vladimirovsky 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



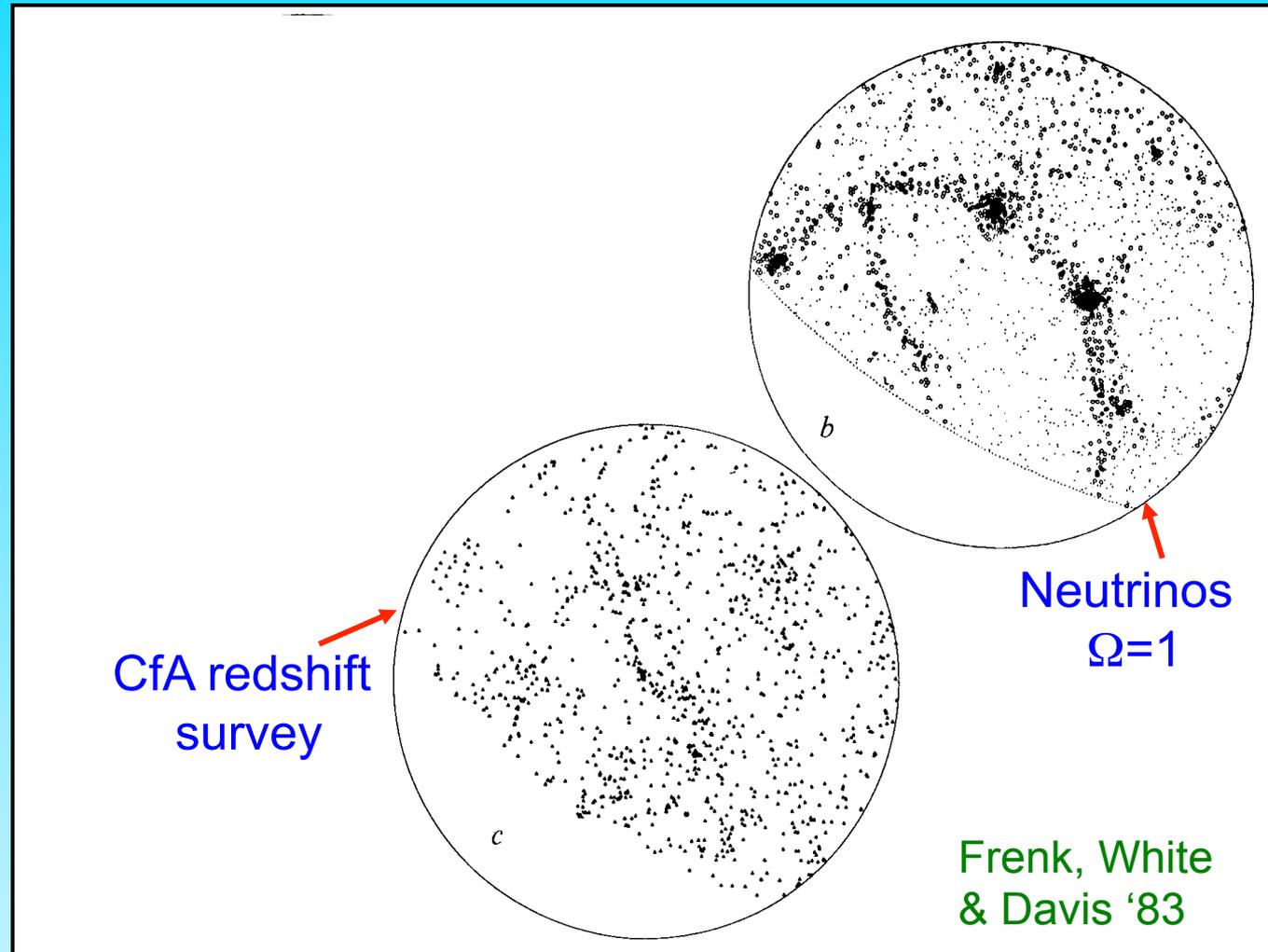
Neutrinos
 $\Omega=1$

Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM \rightarrow
wrong clustering

Neutrinos cannot
make appreciable
contribution to Ω
 $\rightarrow m_\nu \ll 30 \text{ eV}$



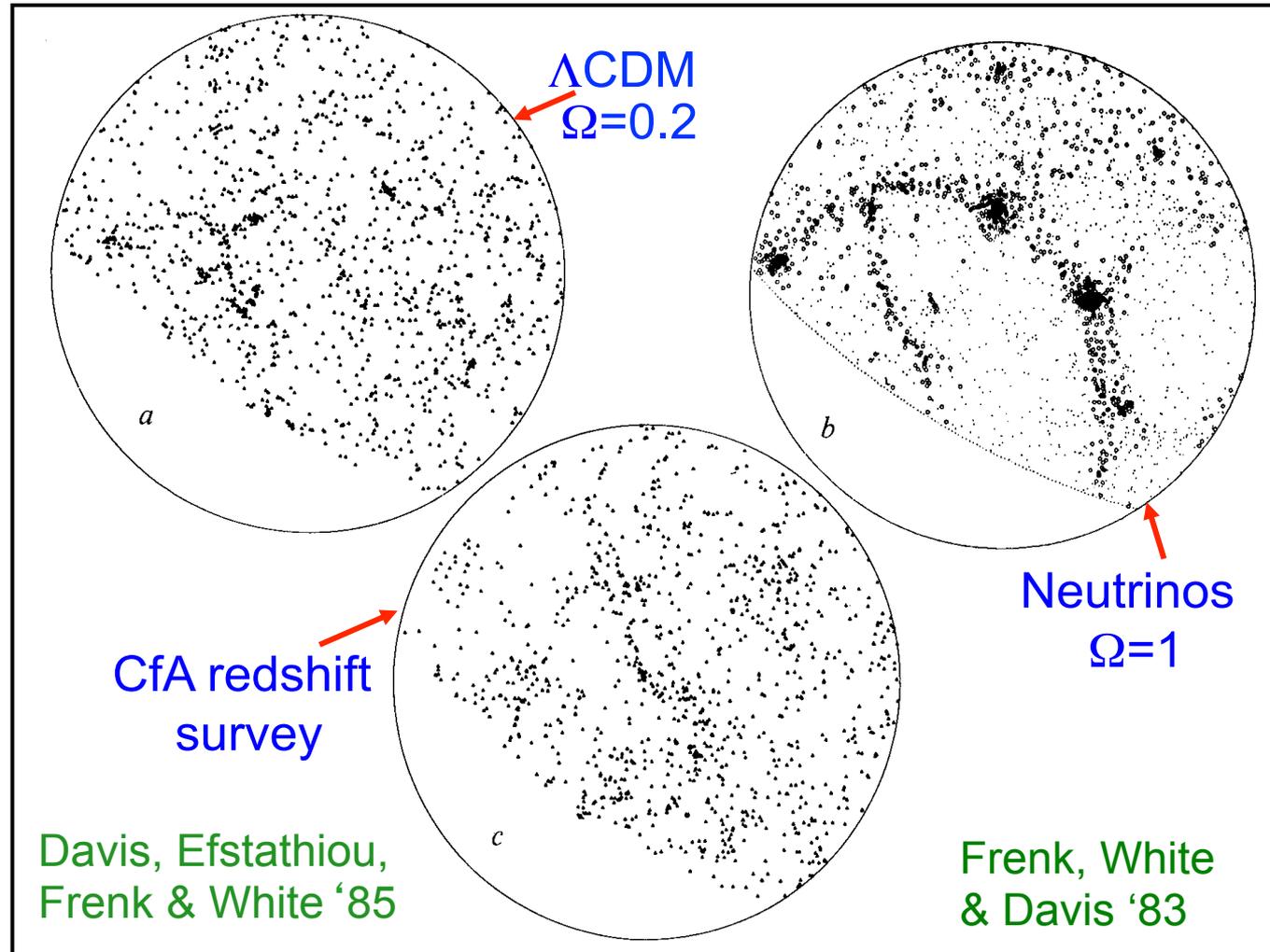
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Early CDM N-body
simulations gave
promising results

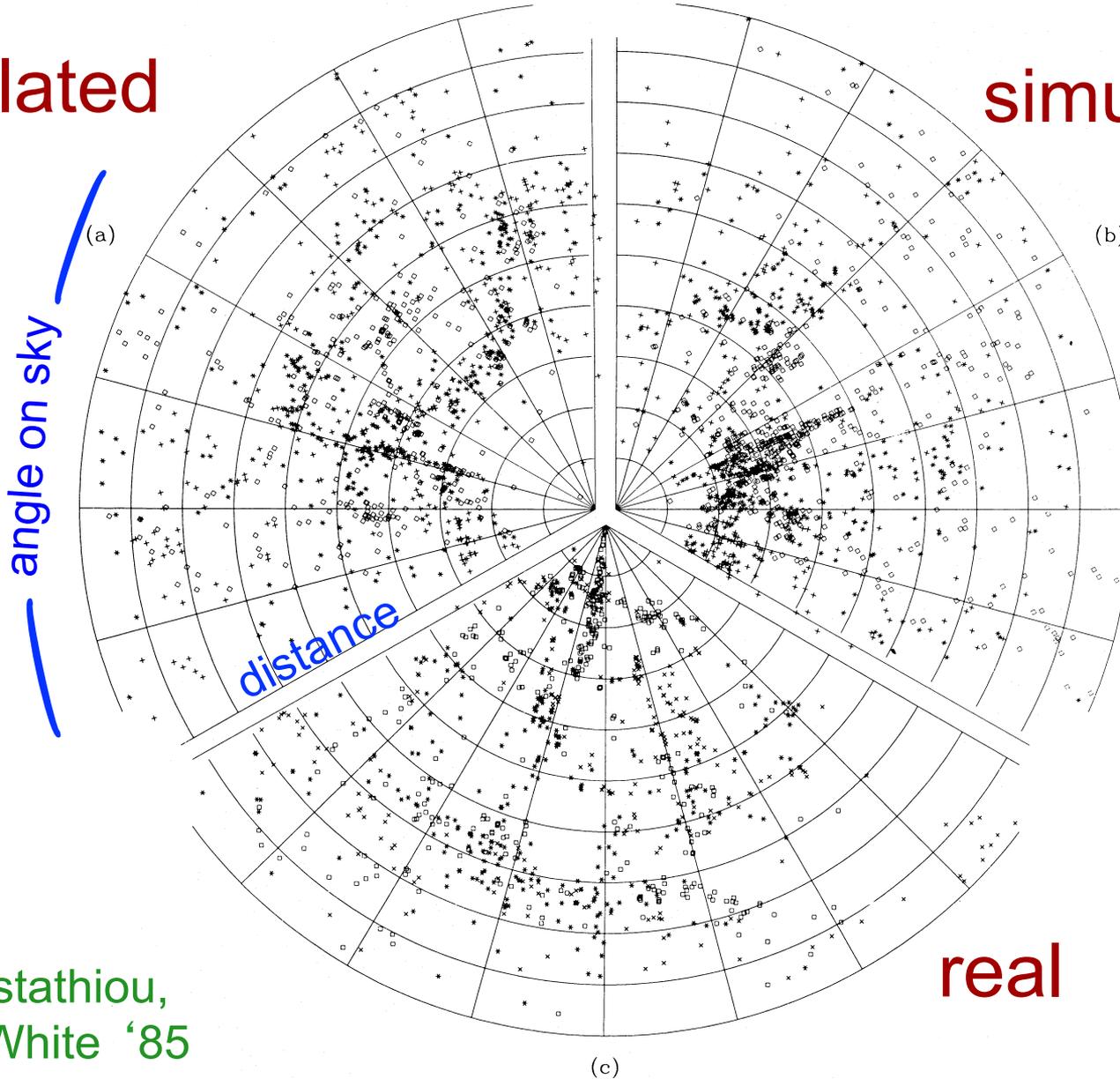
In CDM structure
forms hierarchically



Early simulations of Λ CDM

simulated

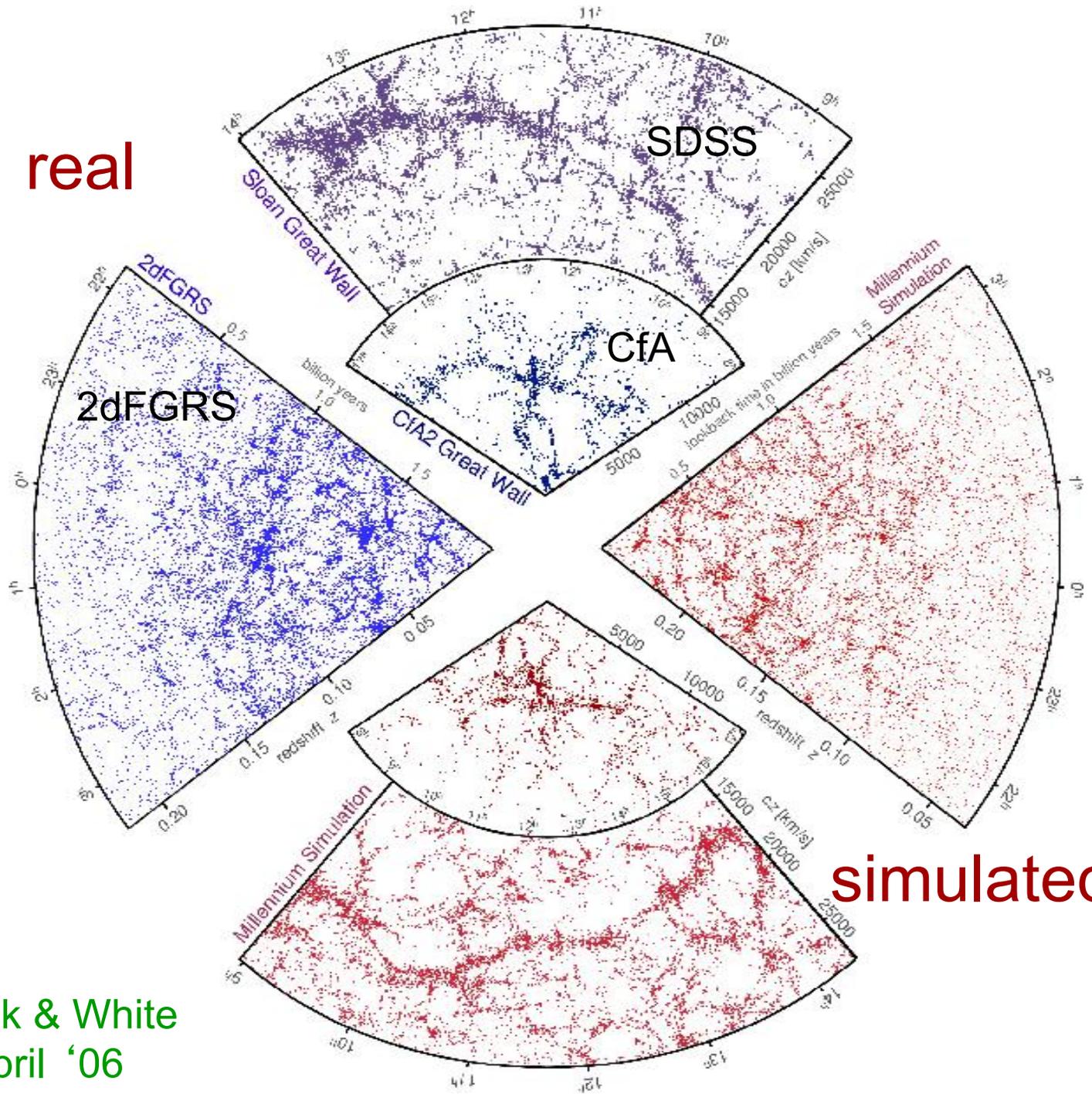
simulated



Davis, Efstathiou,
Frenk & White '85

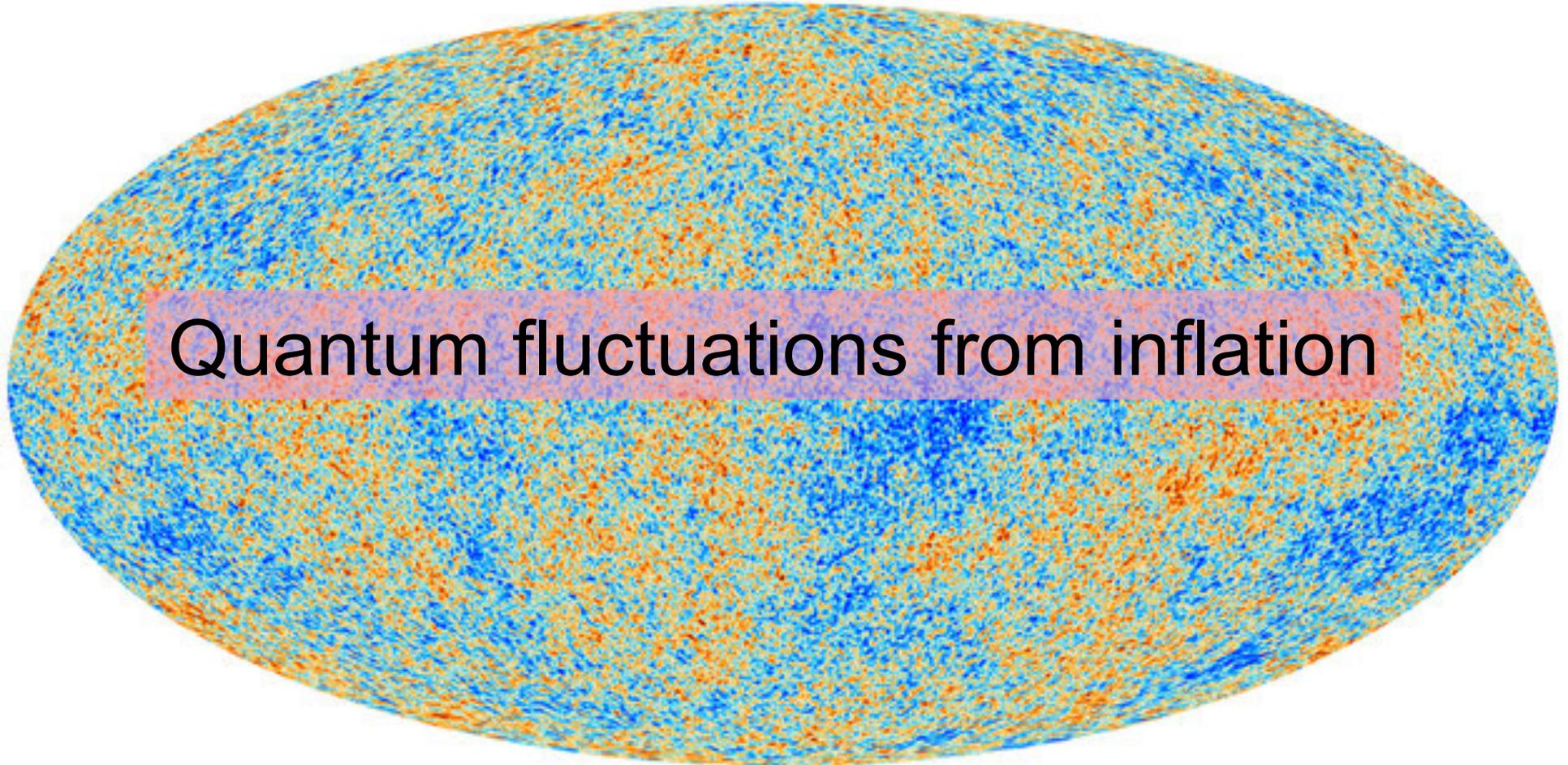
real

real



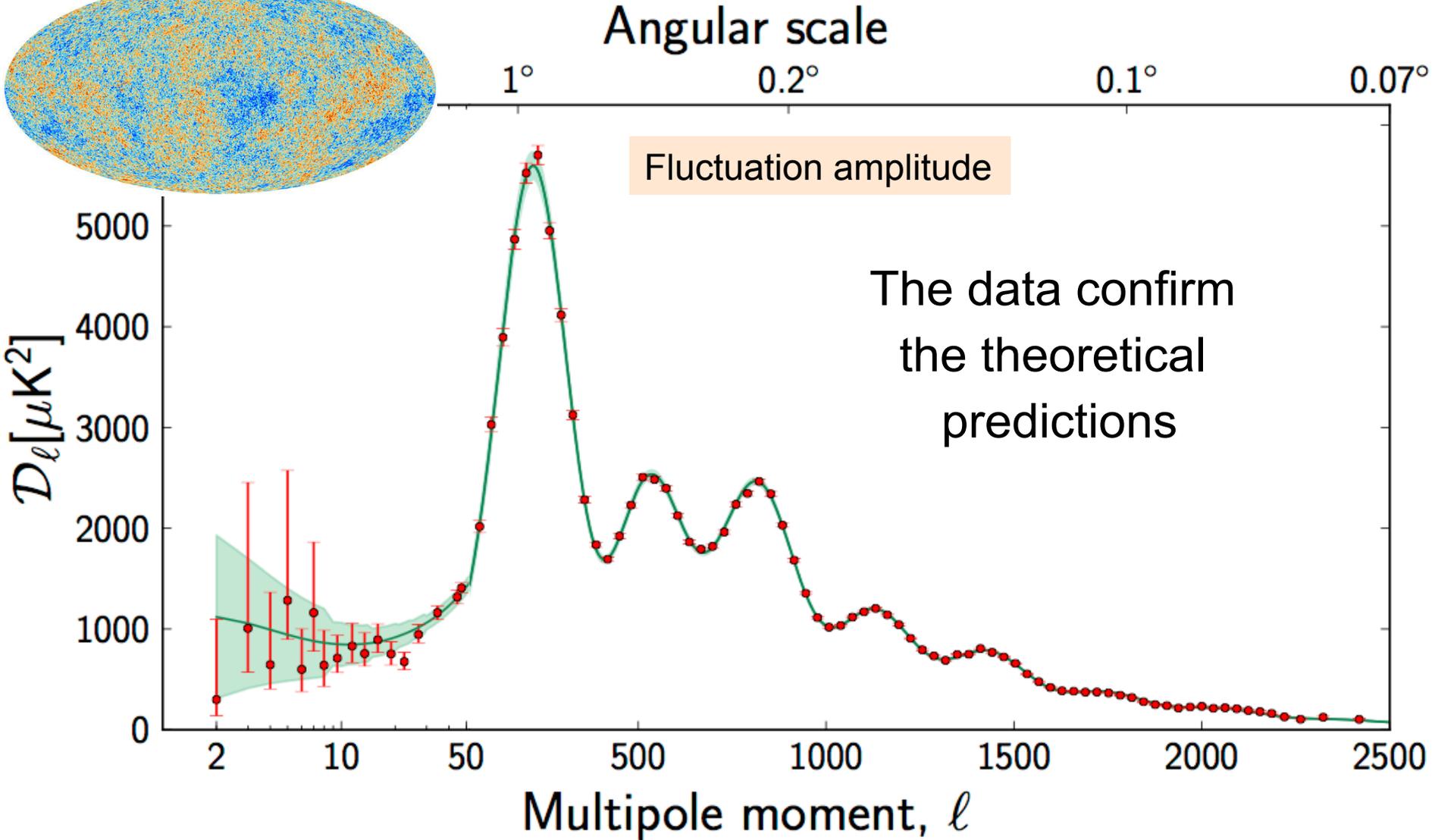
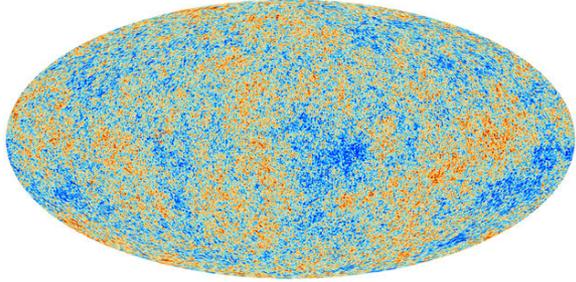
simulated

The initial conditions for galaxy formation



Quantum fluctuations from inflation

Planck: CMB temperature anisotropies





The six parameters of minimal Λ CDM model

Univer

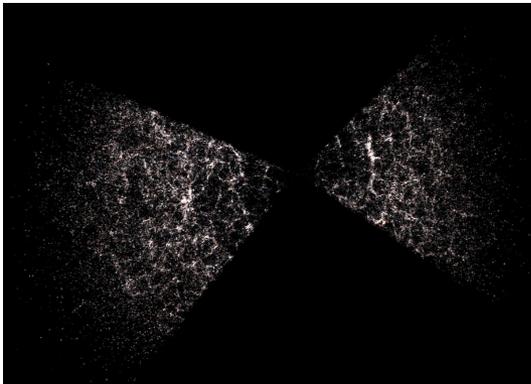
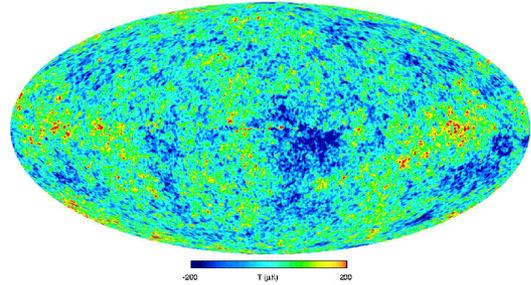
Planck+WP

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	$3.089^{+0.024}_{-0.027}$

6 model parameters

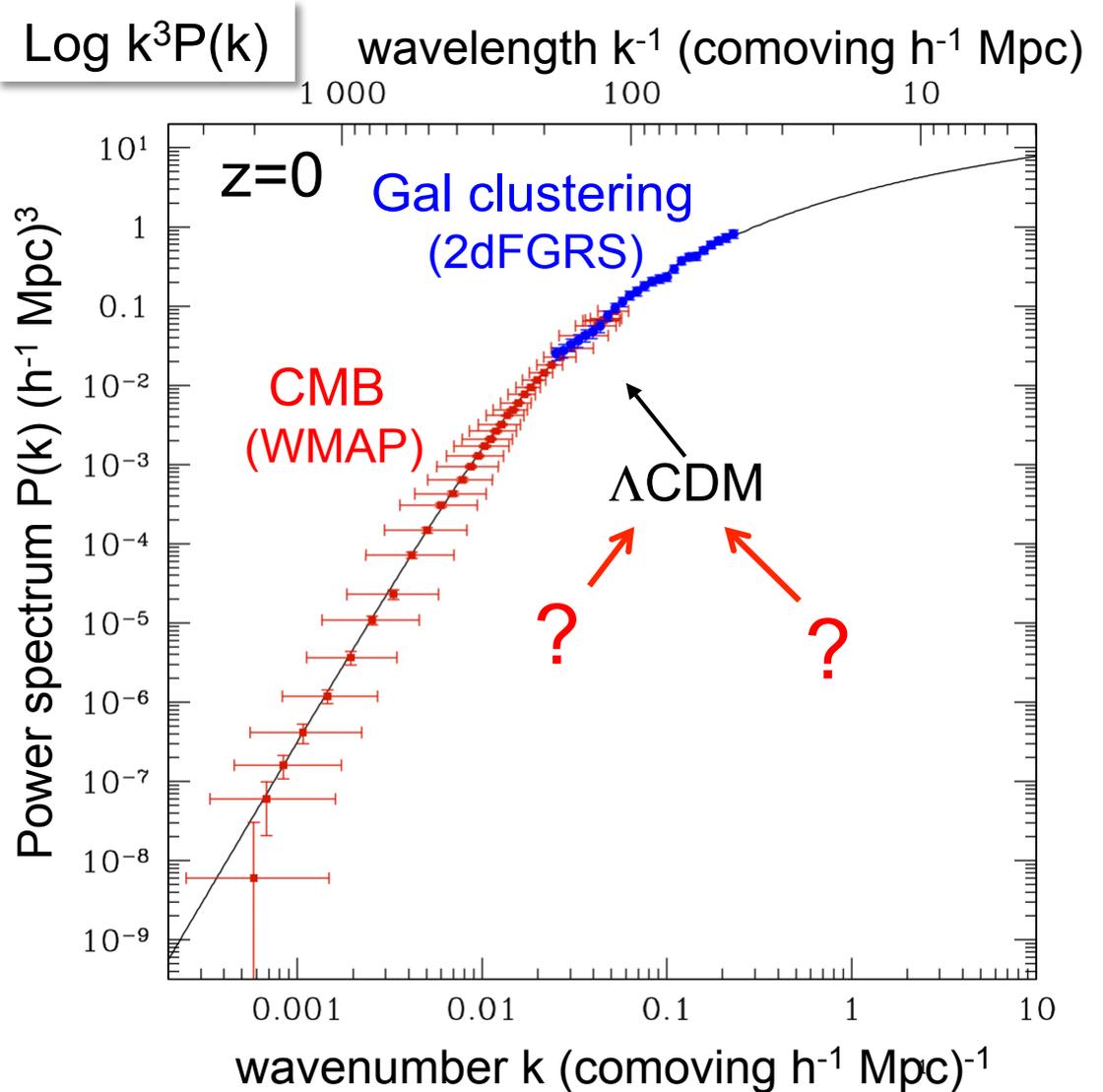
A 40σ detection of non-baryonic dark matter using only $z=1000$ data!

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

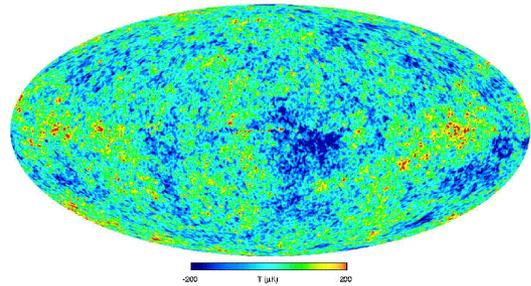


⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



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

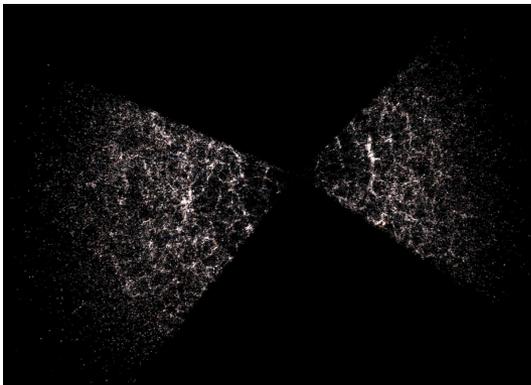


$z \sim 1000$

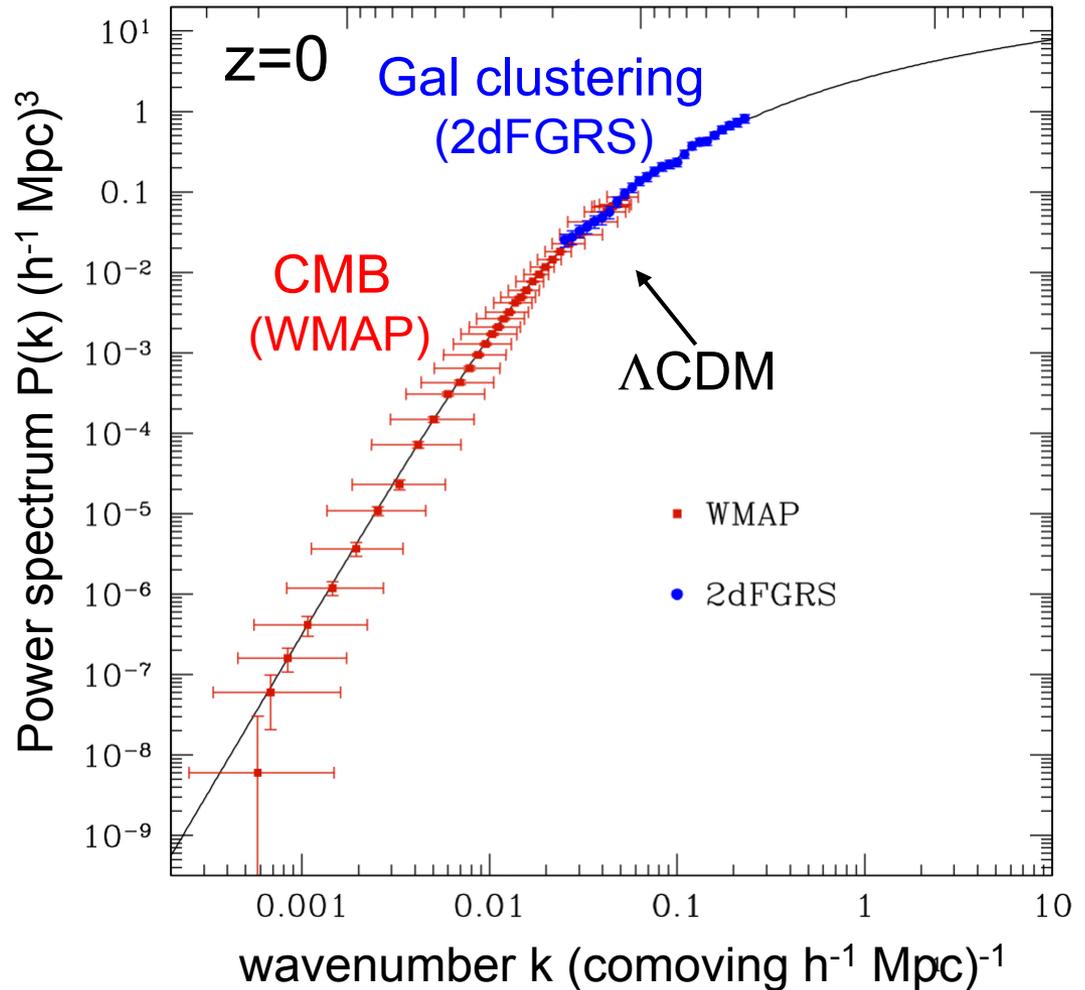
$\text{Log } k^3 P(k)$

wavelength k^{-1} (comoving h^{-1} Mpc)

1 000 100 10



$z \sim 0$



⇒ Λ CDM 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 \rightarrow

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

for thermal relic

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

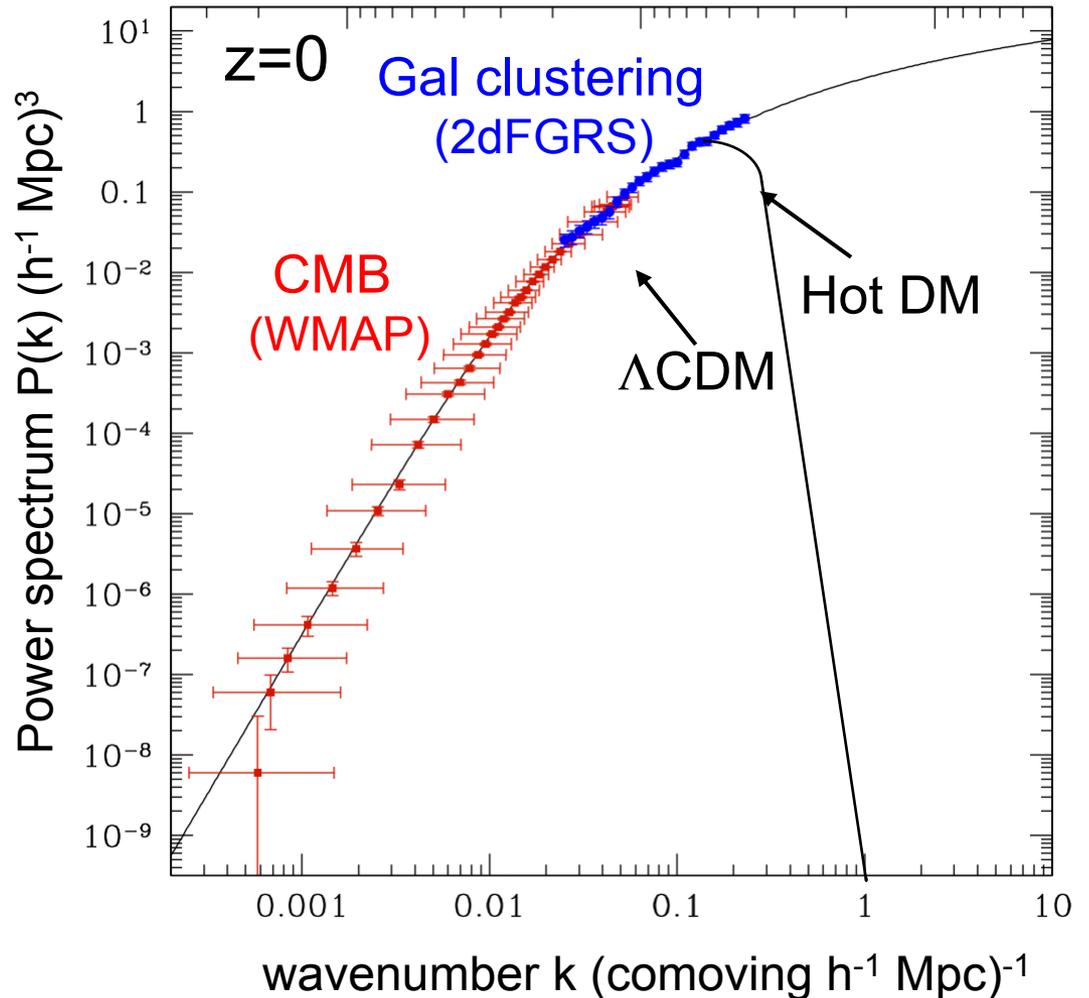
$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

$$m_{\text{WDM}} \sim \text{few keV}$$

$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$

Log $k^3 P(k)$ wavelength k^{-1} (comoving h^{-1} Mpc)

1 000 100 10



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

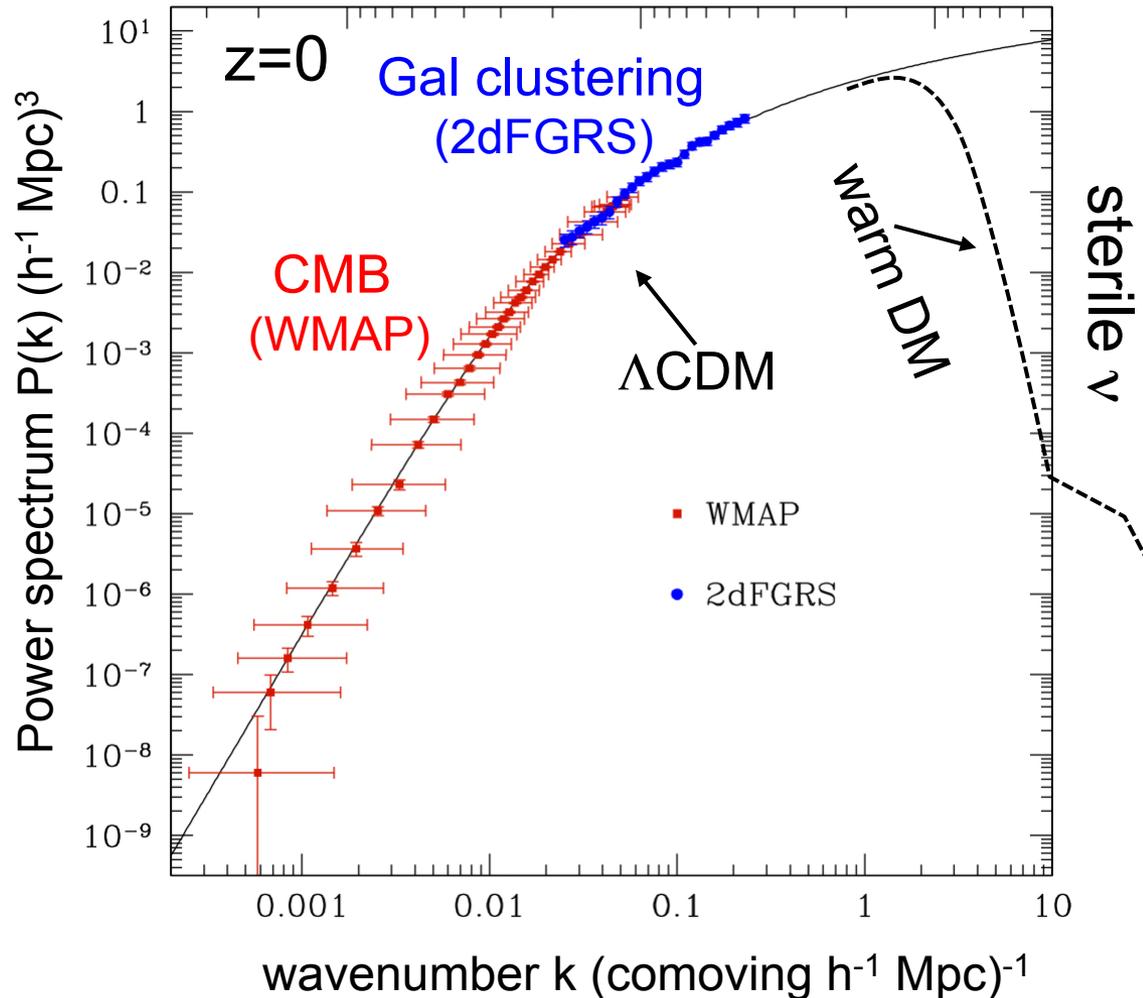
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 sterile ν ; $M_{\text{cut}} \sim 10^9 M_{\odot}$

$\text{Log } k^3 P(k)$ wavelength k^{-1} (comoving $h^{-1} \text{ Mpc}$)
 1 000 100 10





Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

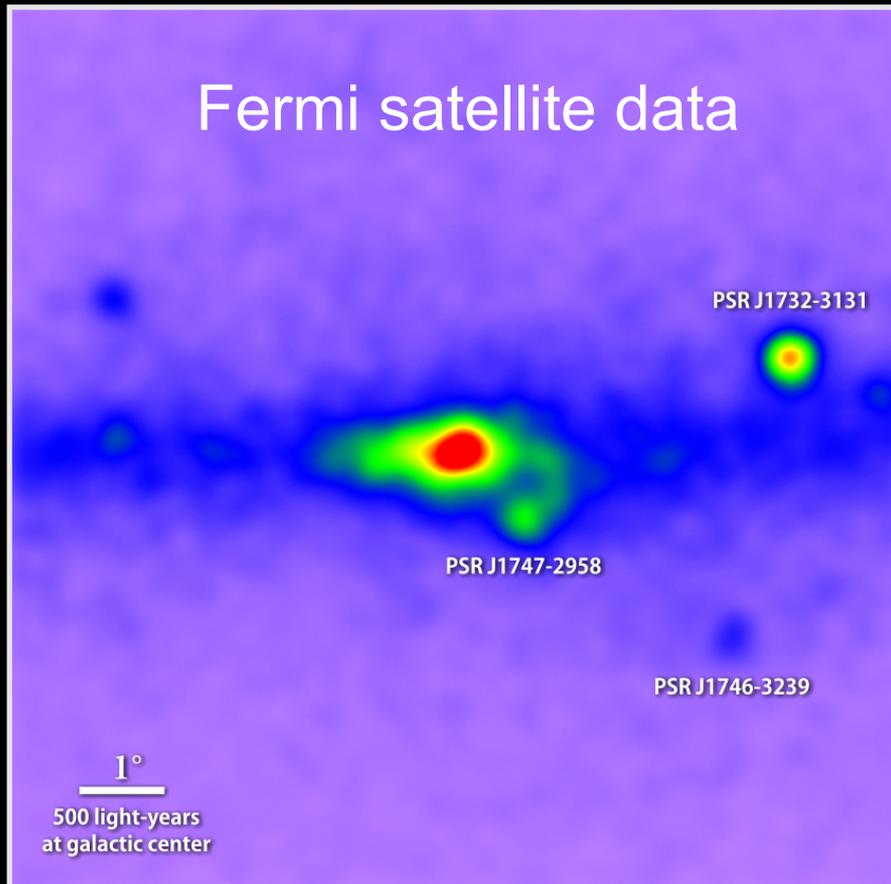
- ◆ CDM: γ -ray excess from Galactic Centre
- ◆ WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Cold dark matter

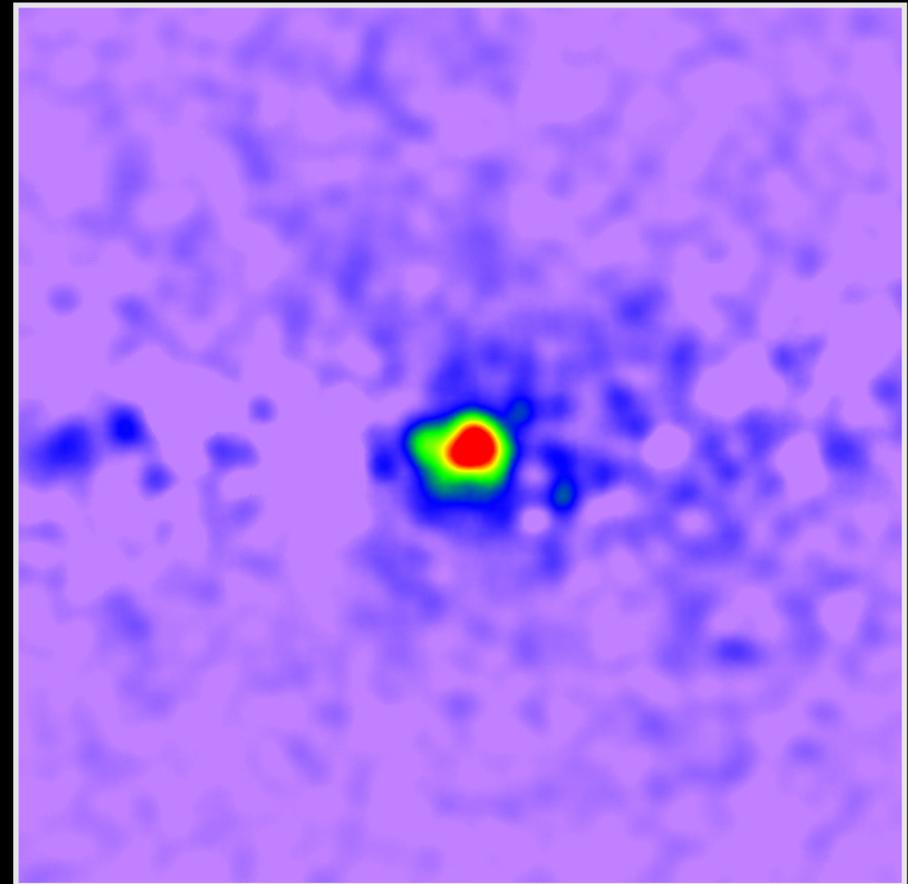
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

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}

Uncovering a gamma-ray excess at the galactic center



Unprocessed map of 1.0 to 3.16 GeV gamma rays

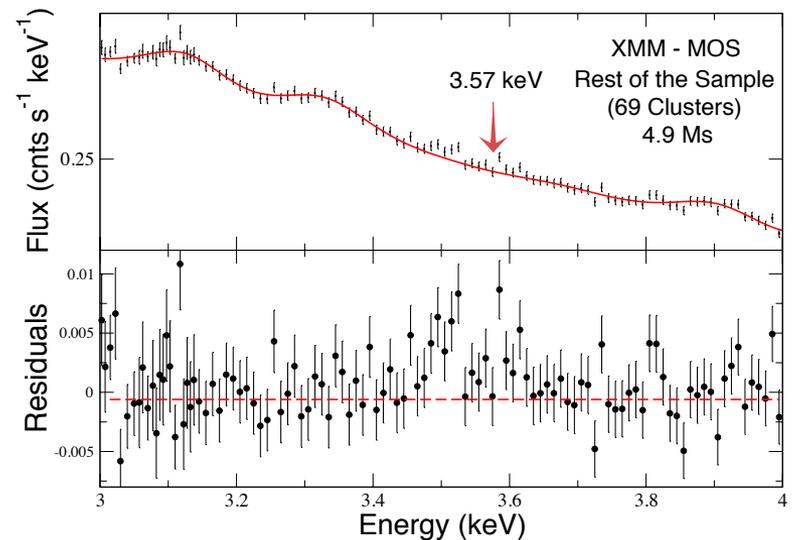
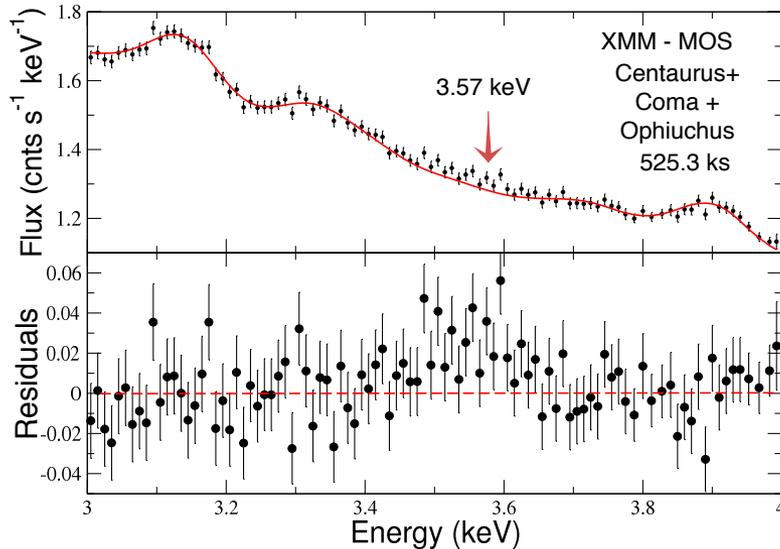
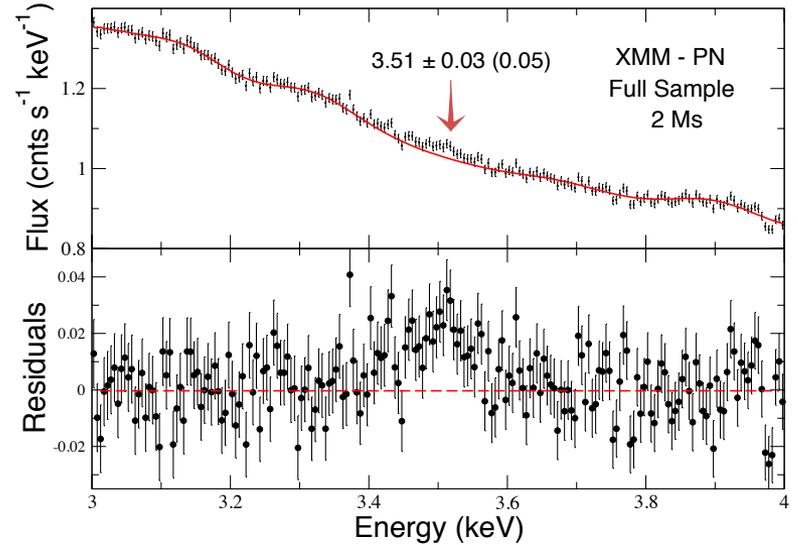
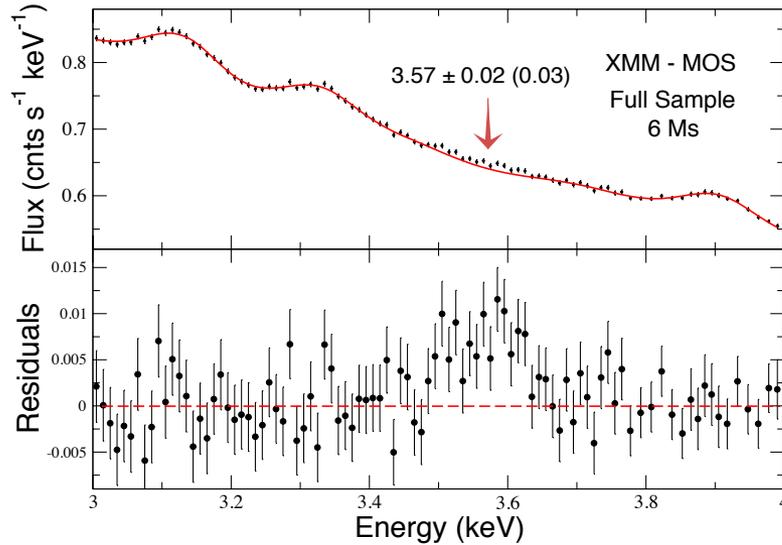


Known sources removed

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!

Sterile neutrinos

Explain:

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

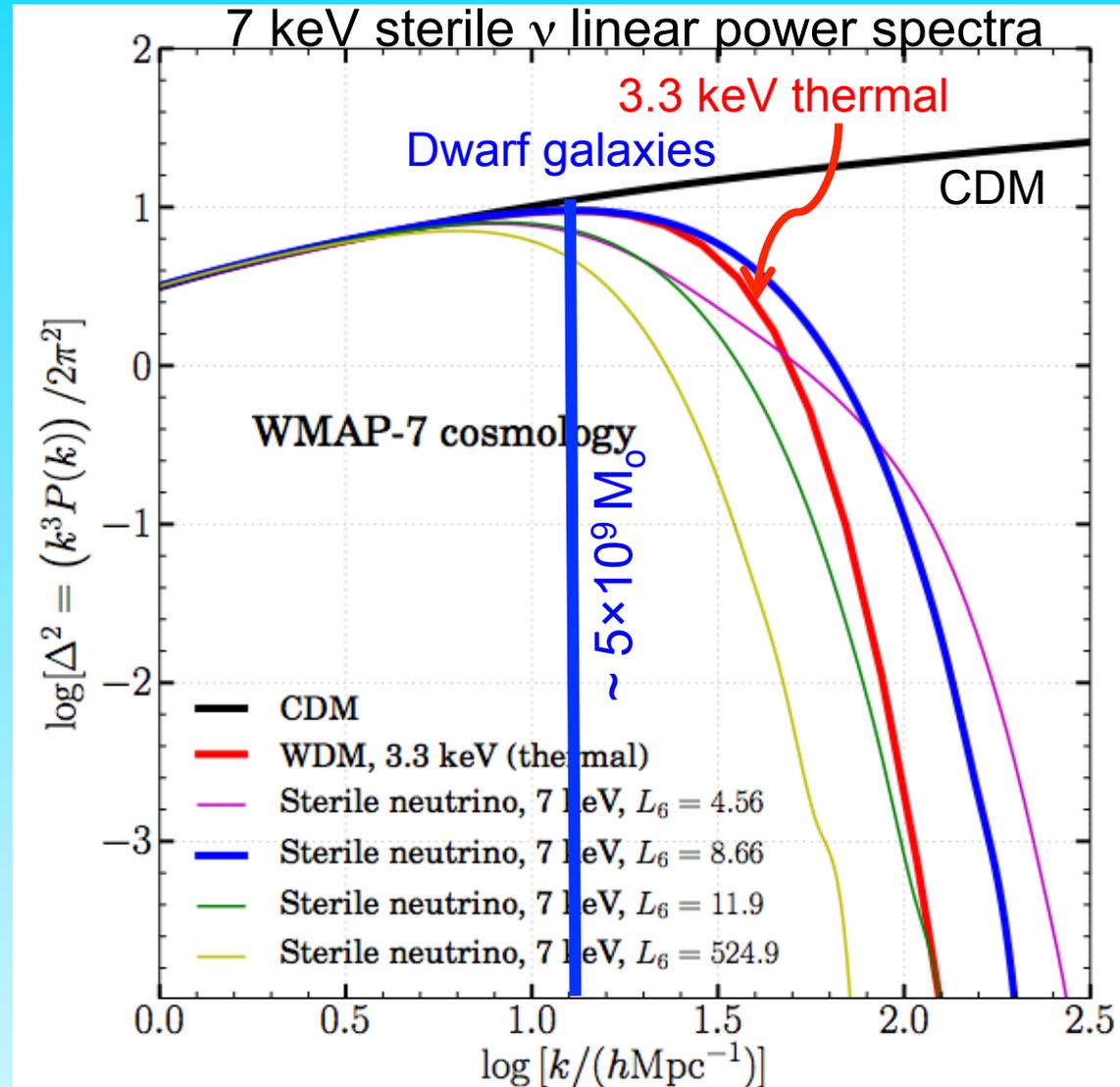
Sterile neutrino minimal standard model (ν MSM; Boyarski+ 09):

- 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

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

Ly- α forest rules out thermal masses, $m_\nu < 3.3$ keV (Viel + '13)





Astrophysical key to identity of dark matter:

→ Subgalactic scales
(strongly non-linear)



Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

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 to

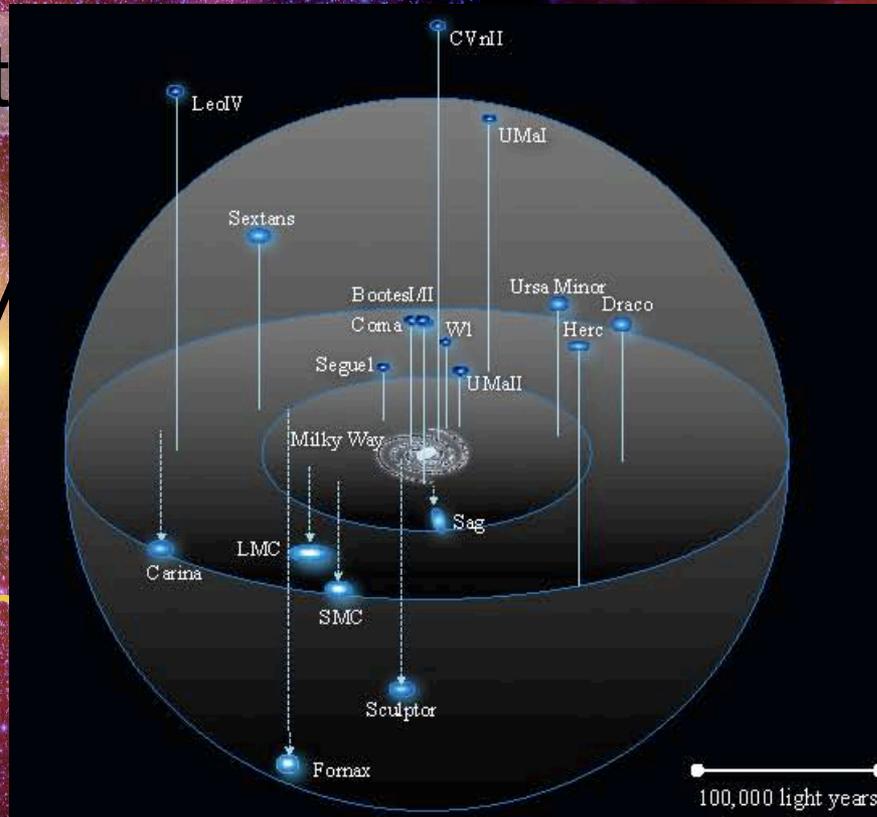
MW or M31

In the M

ered so far

Th

G!



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

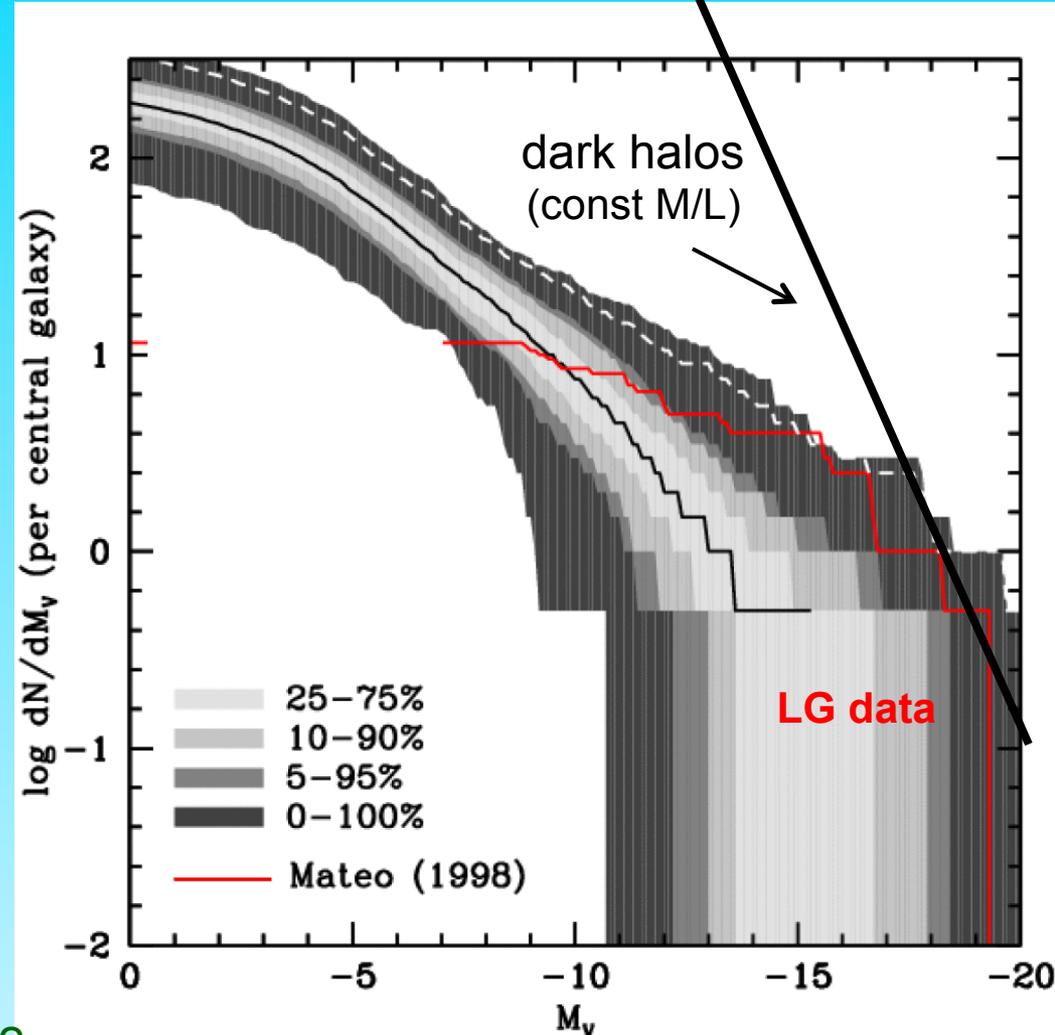
Most subhalos never make a galaxy!

Because:

- Reionization heats gas to $\sim 10^4\text{K}$, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

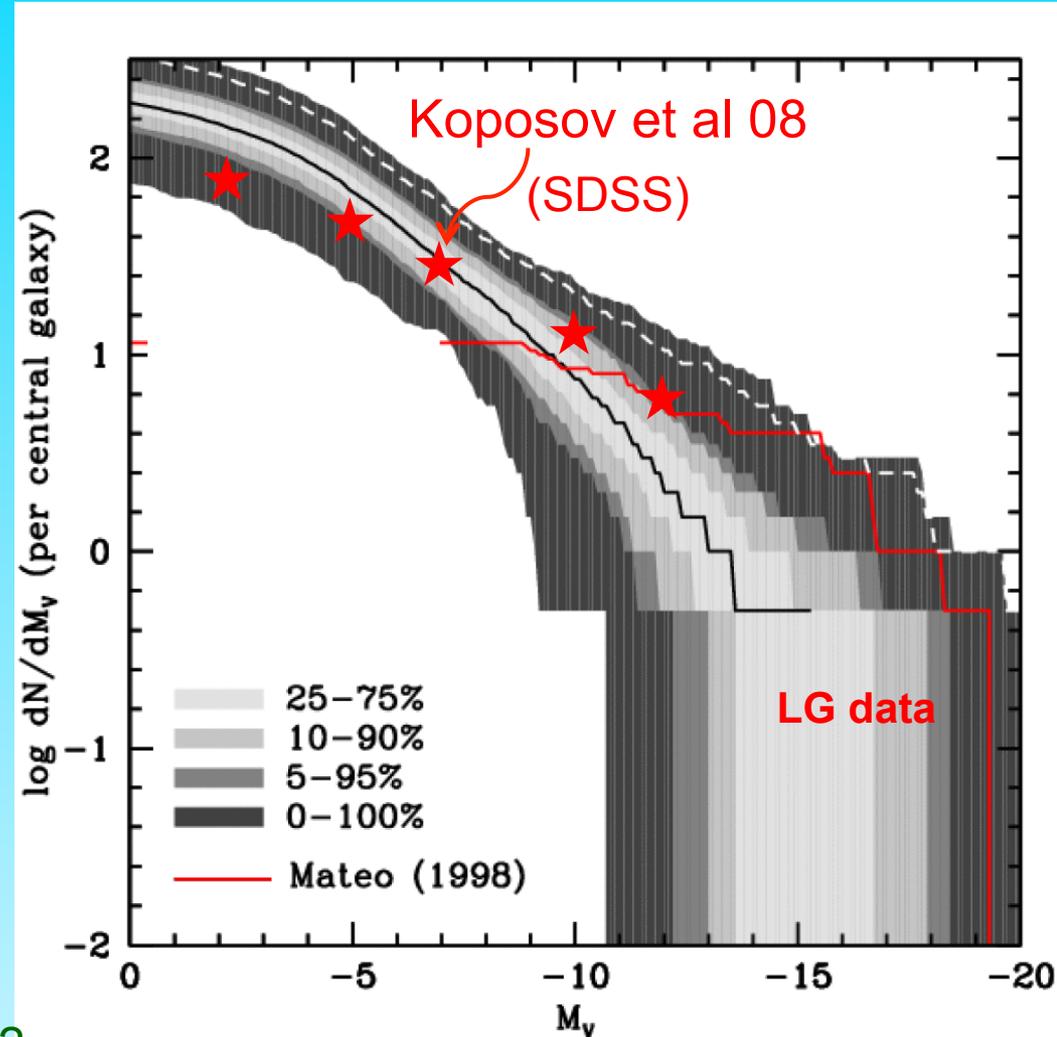
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

Luminosity Function of Local Group Satellites

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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...

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

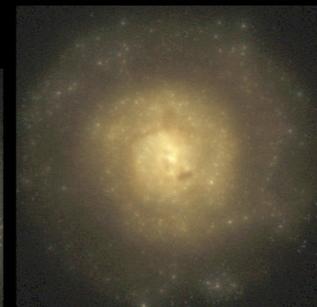
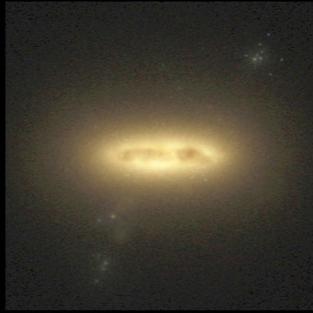
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



Irr

S

Trayford et al '15

Dark matter

VIRG

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al '15



Stars

VIRG

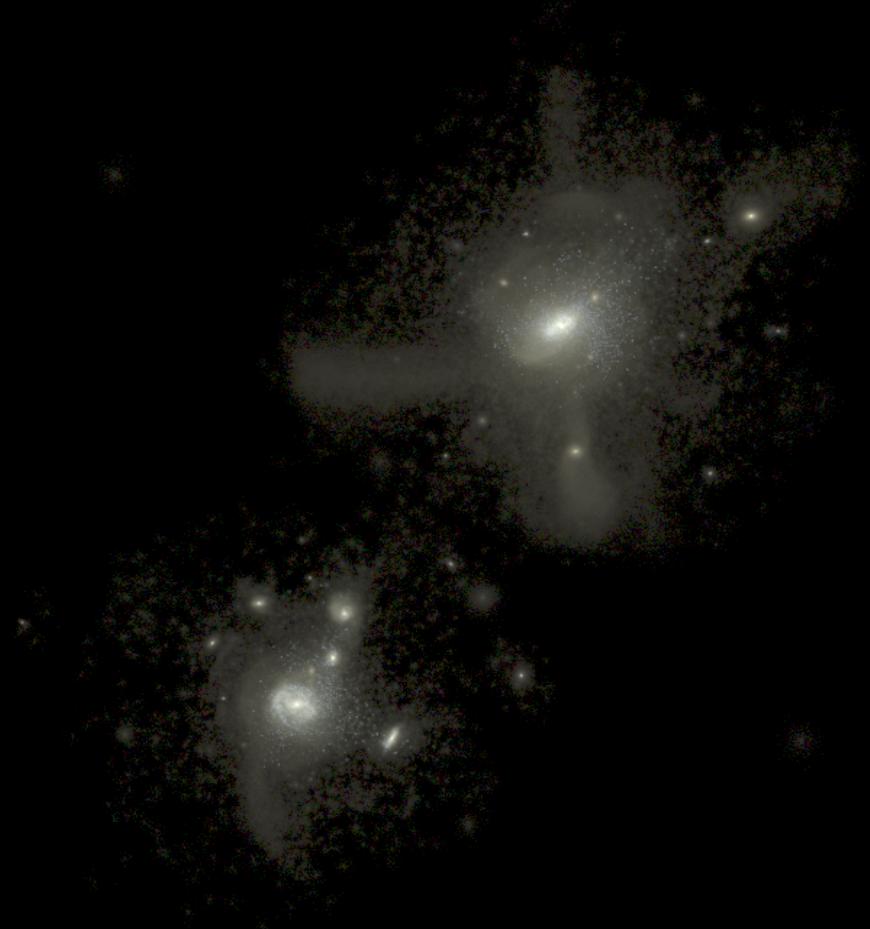


APOSTLE
EAGLE full
hydro
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Local Group

CDM

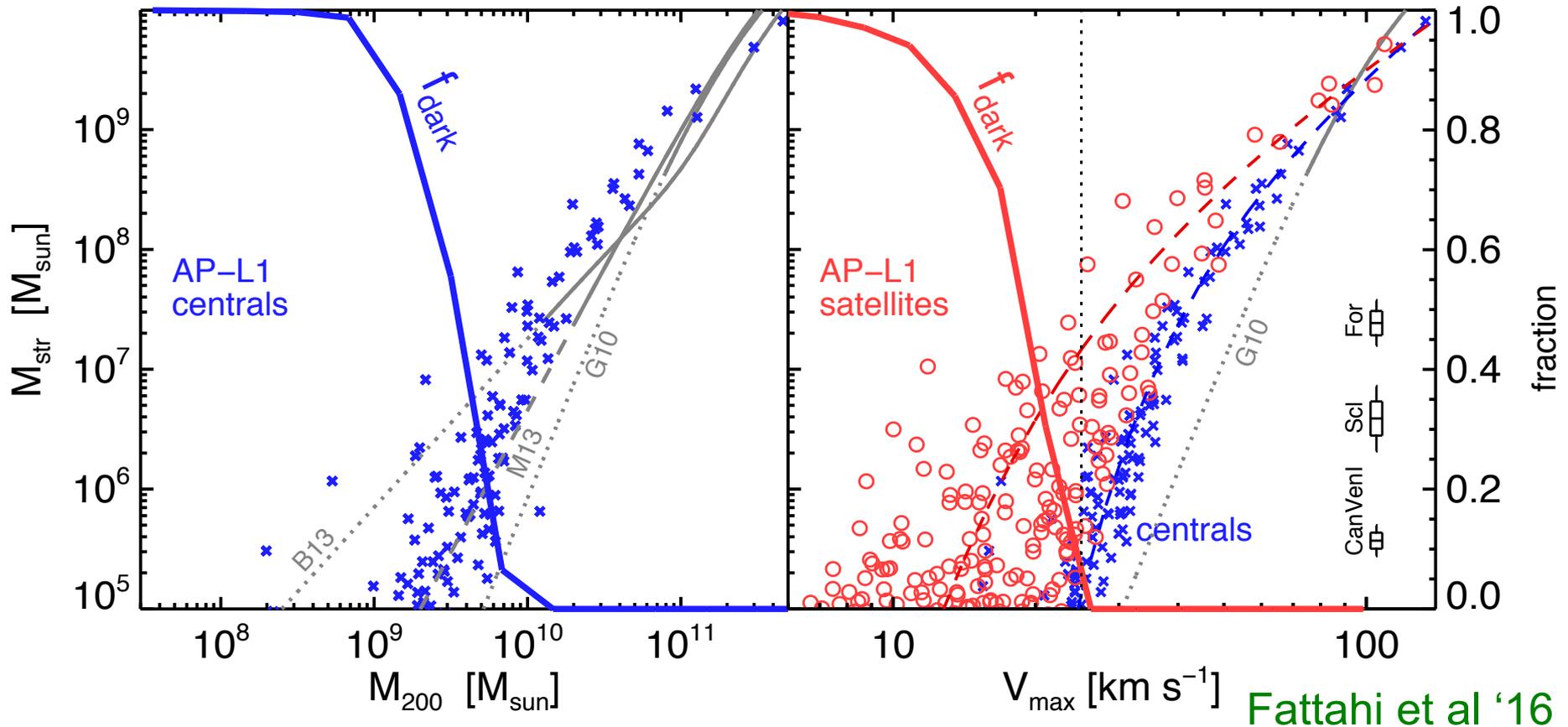
Far fewer satellite galaxies than CDM halos



Sawala et al '15

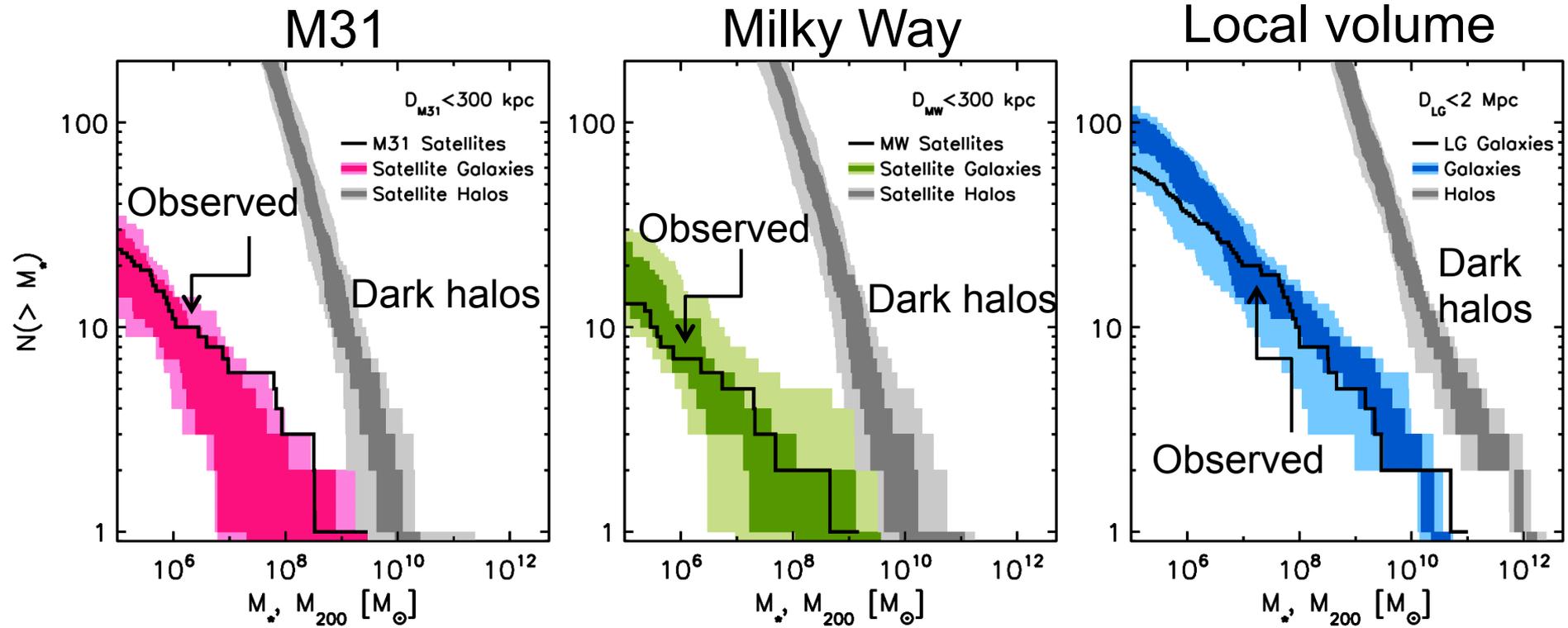
Fraction of dark subhalos

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



Fattahi et al '16

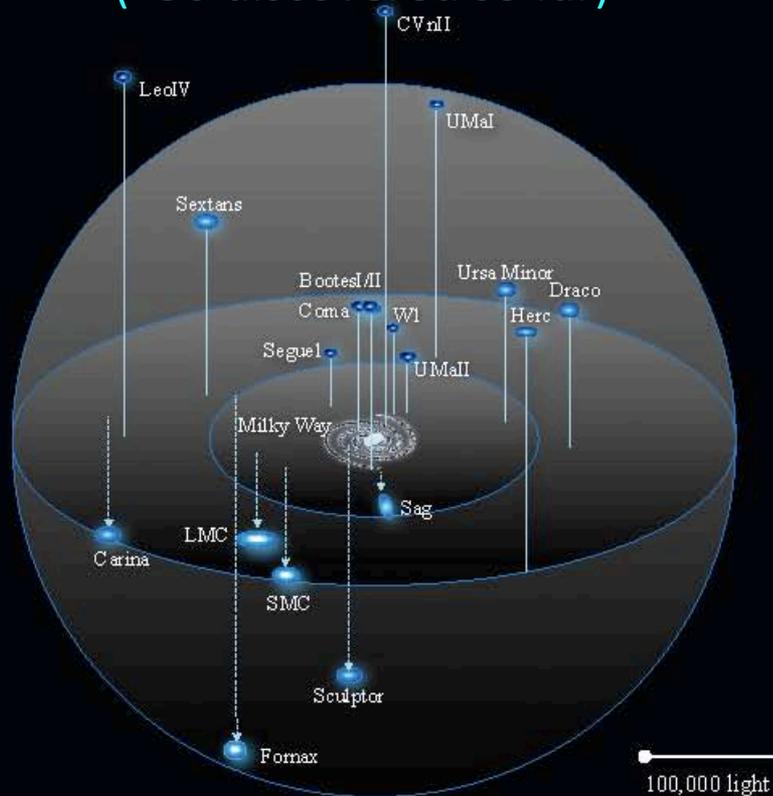
All halos of mass $< 5 \times 10^8 M_{\odot}$ or $V_{\max} < 7 \text{ km/s}$ are dark



How about in WDM?

The satellites of the MW

(~50 discovered so far)



Dark matter subhalos in WDM

(a few tens)

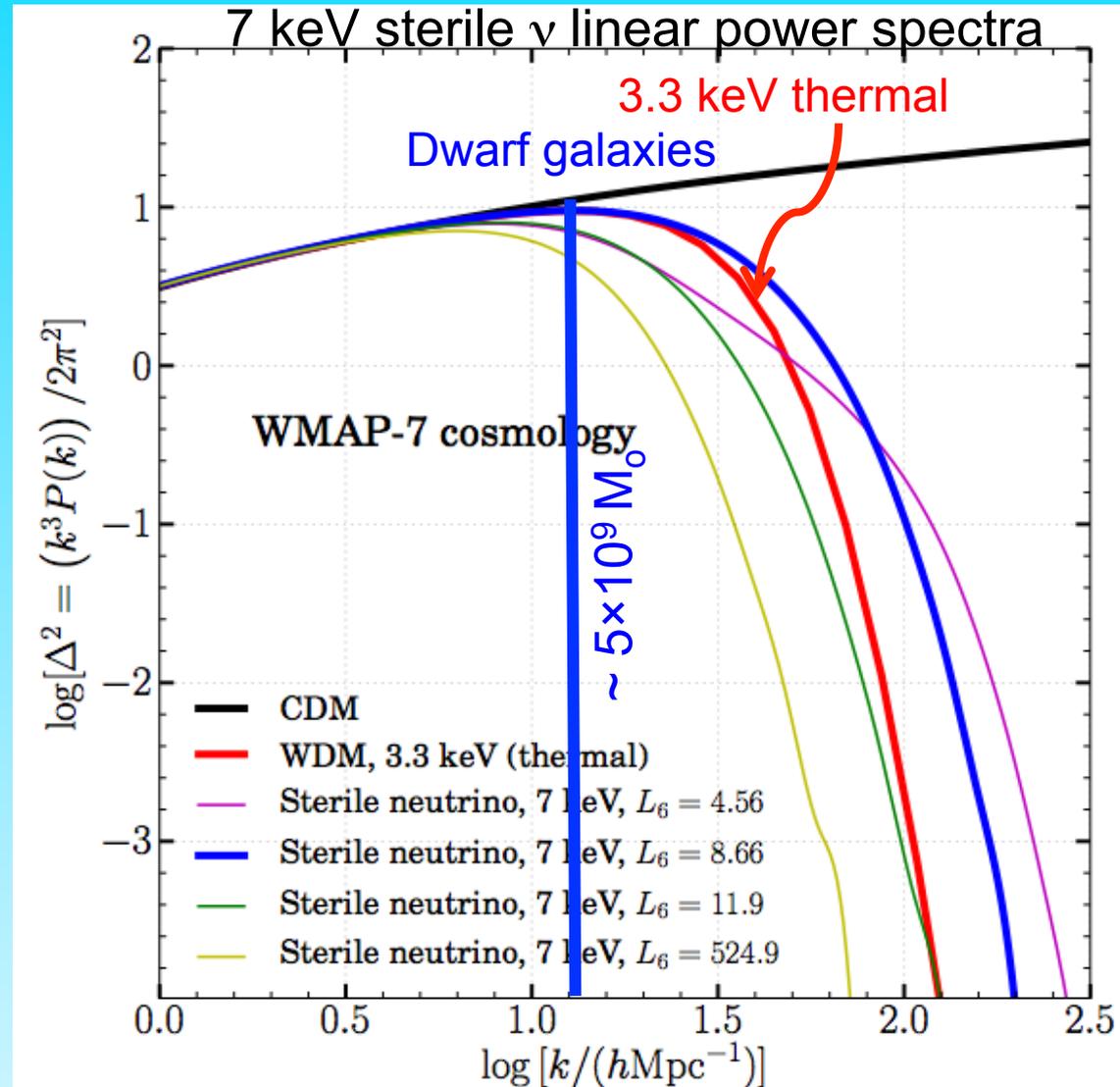


Primordial $P(k)$ for 7 keV sterile neutrino models

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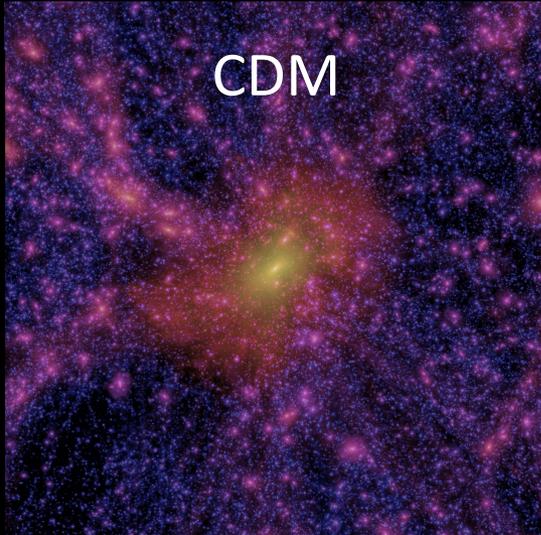
Bose, Lovell et al. 16



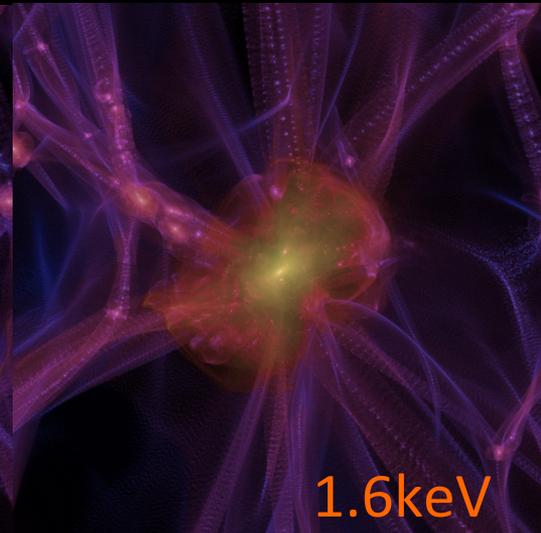
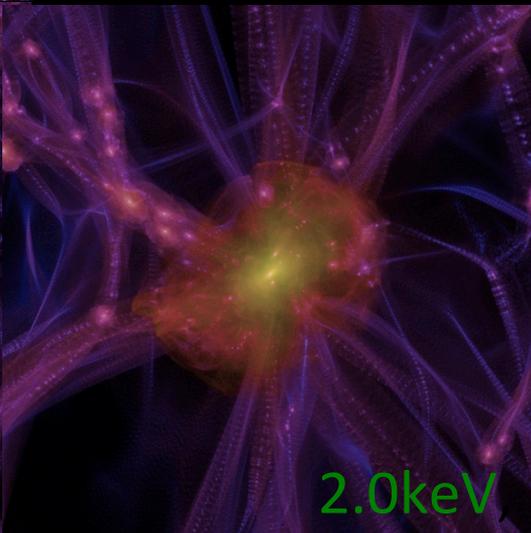
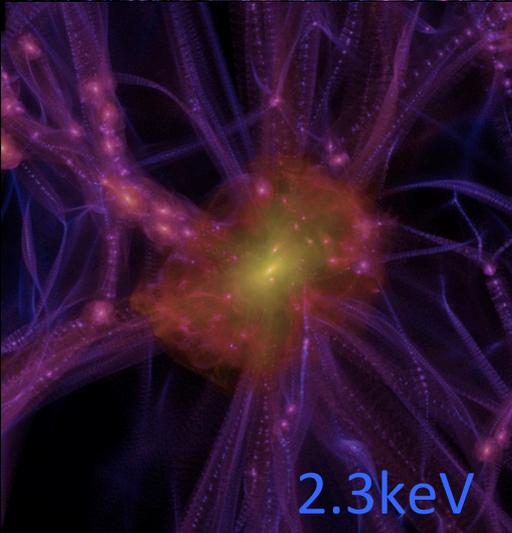
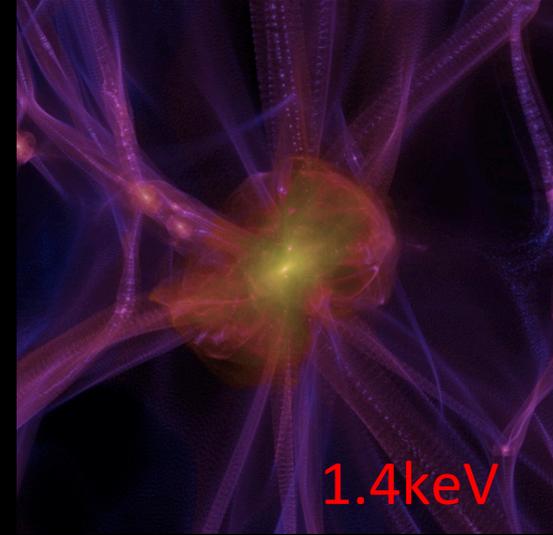
Warm DM: different ν mass

$z=3$

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



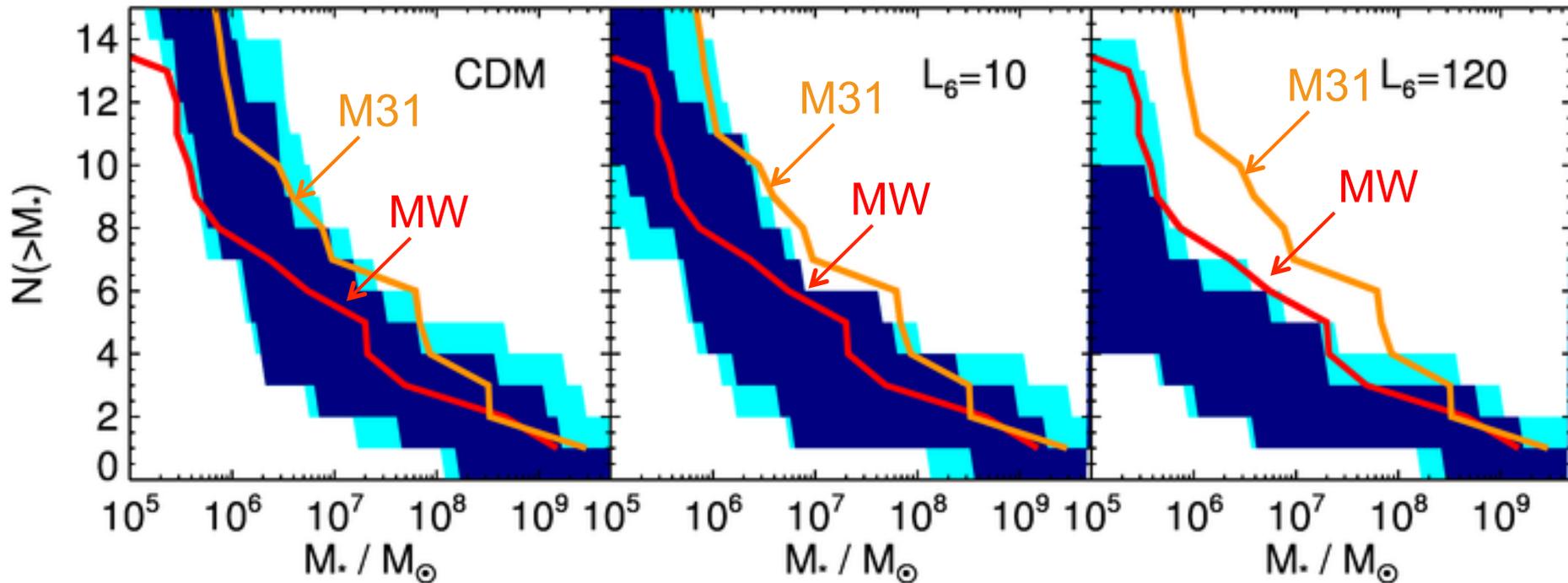
WDM



Luminosity Function of Local Group Satellites in WDM

From “Warm Apostle:” 7keV sterile ν

$M_h \sim 10^{12} M_\odot$



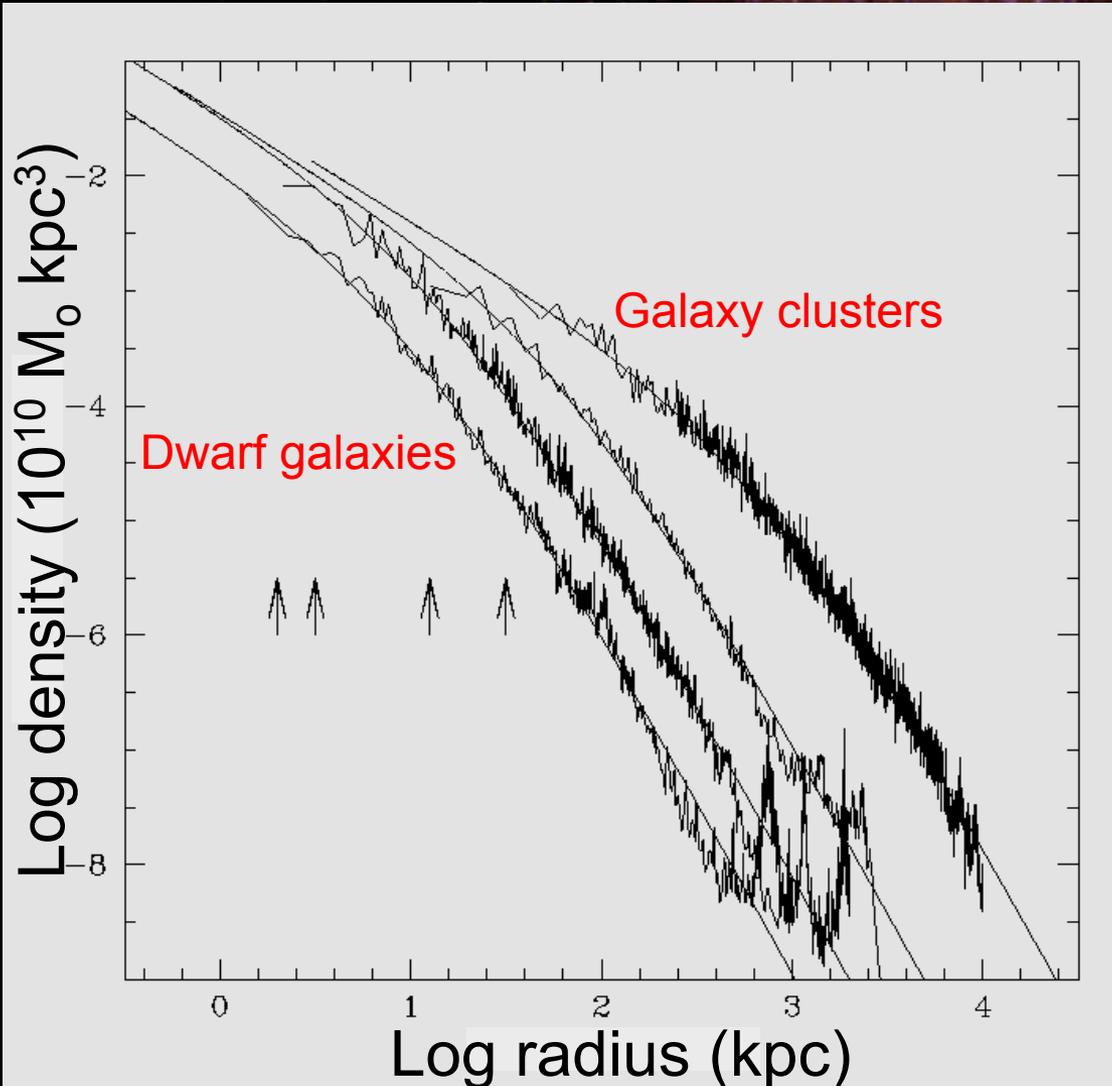
Lovell et al. '16

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

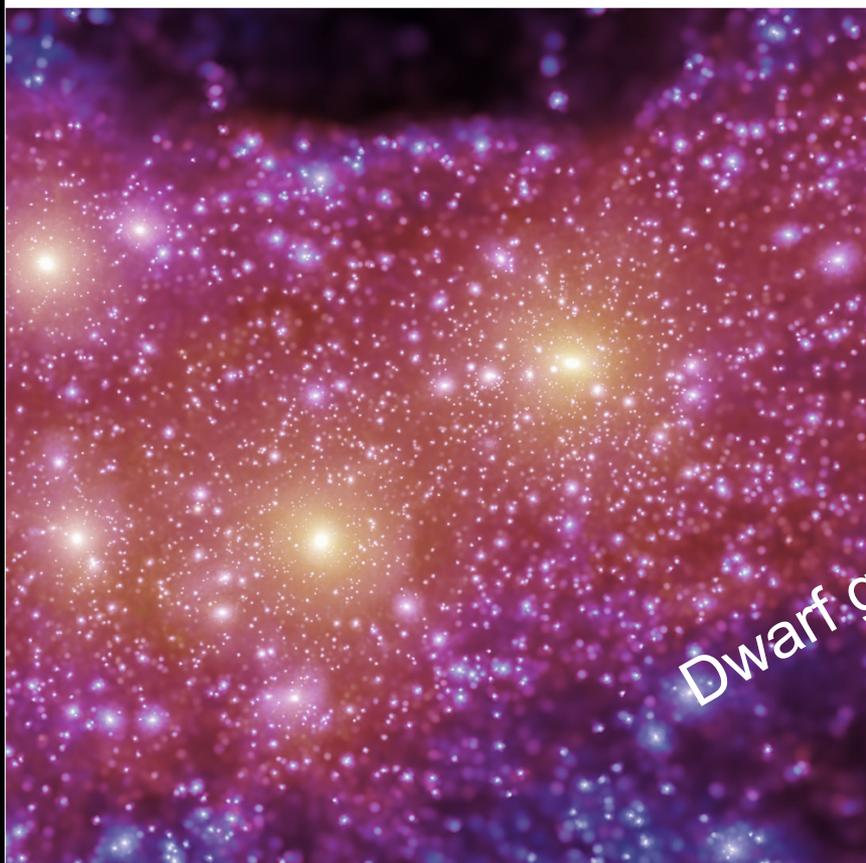
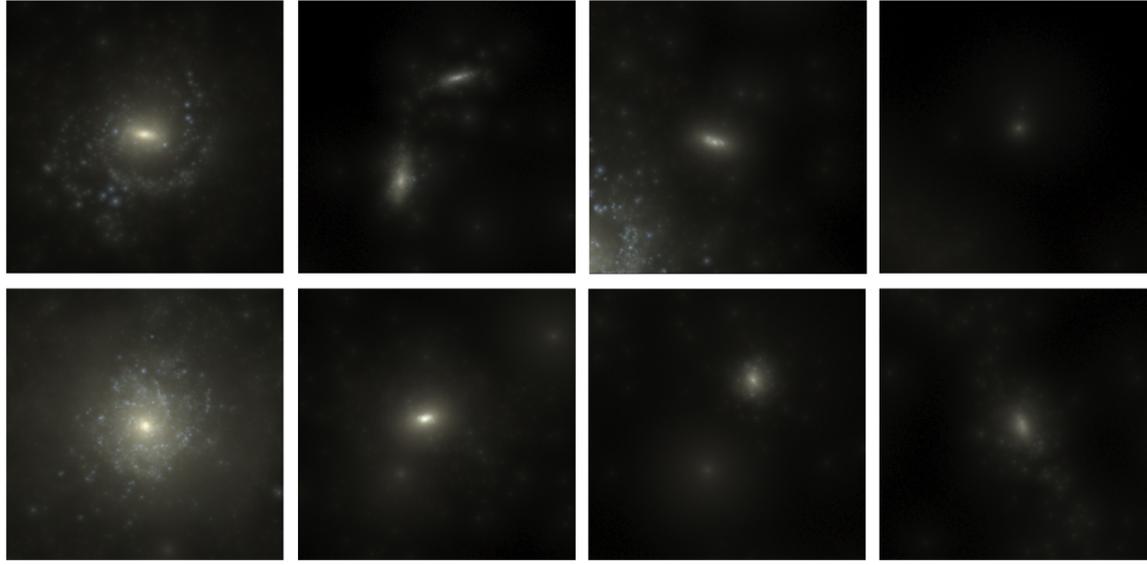
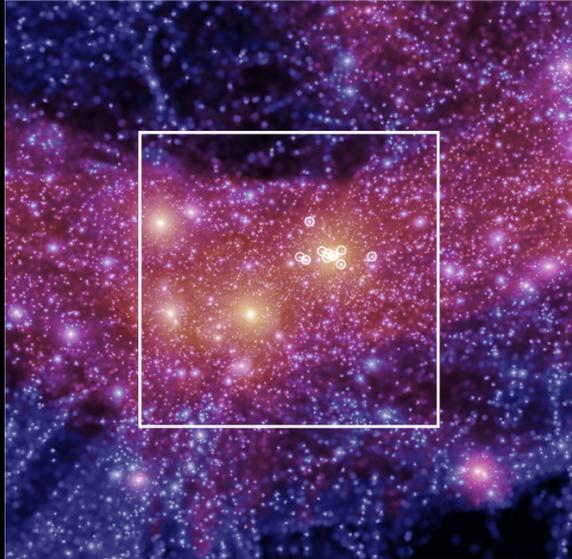
warm dark matter

Halos and subhalos in CDM & WDM have cuspy NFW profiles

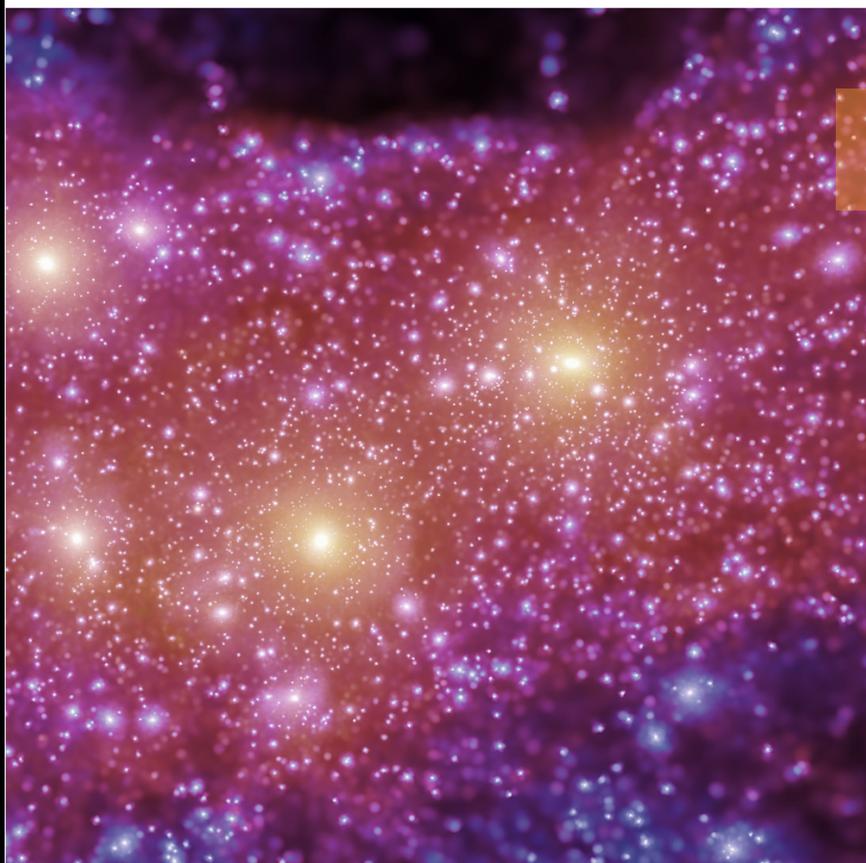
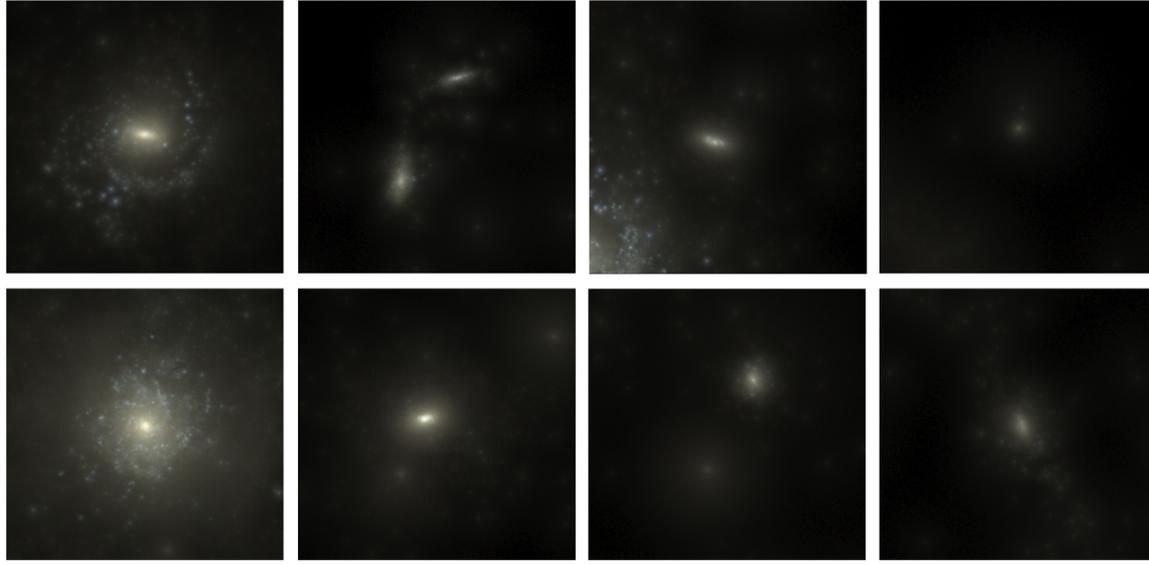
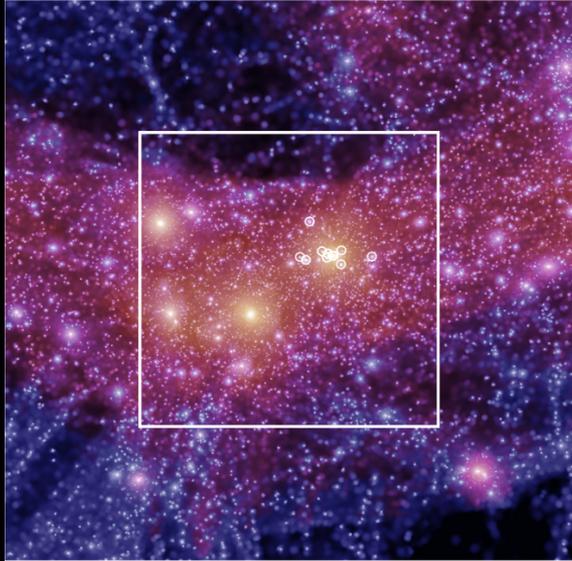
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

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





Dwarf galaxies in Apostle have NFW cusps!



Does Nature have them?



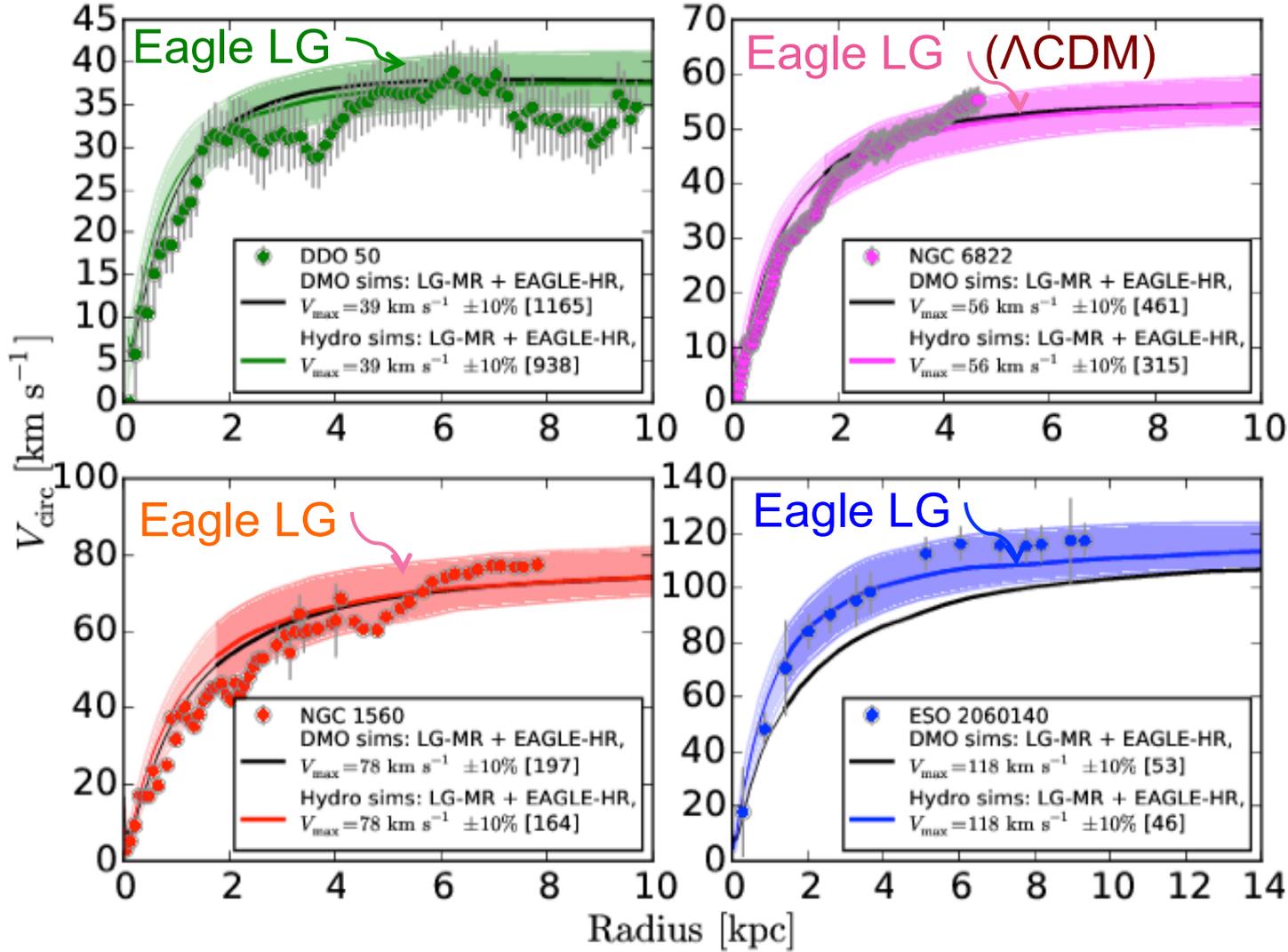
Sawala et al '15

The diversity of gal rotation curves

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

Four rotation curves that are well fit by Λ CDM

(from dwarfs to $\sim L_*$)

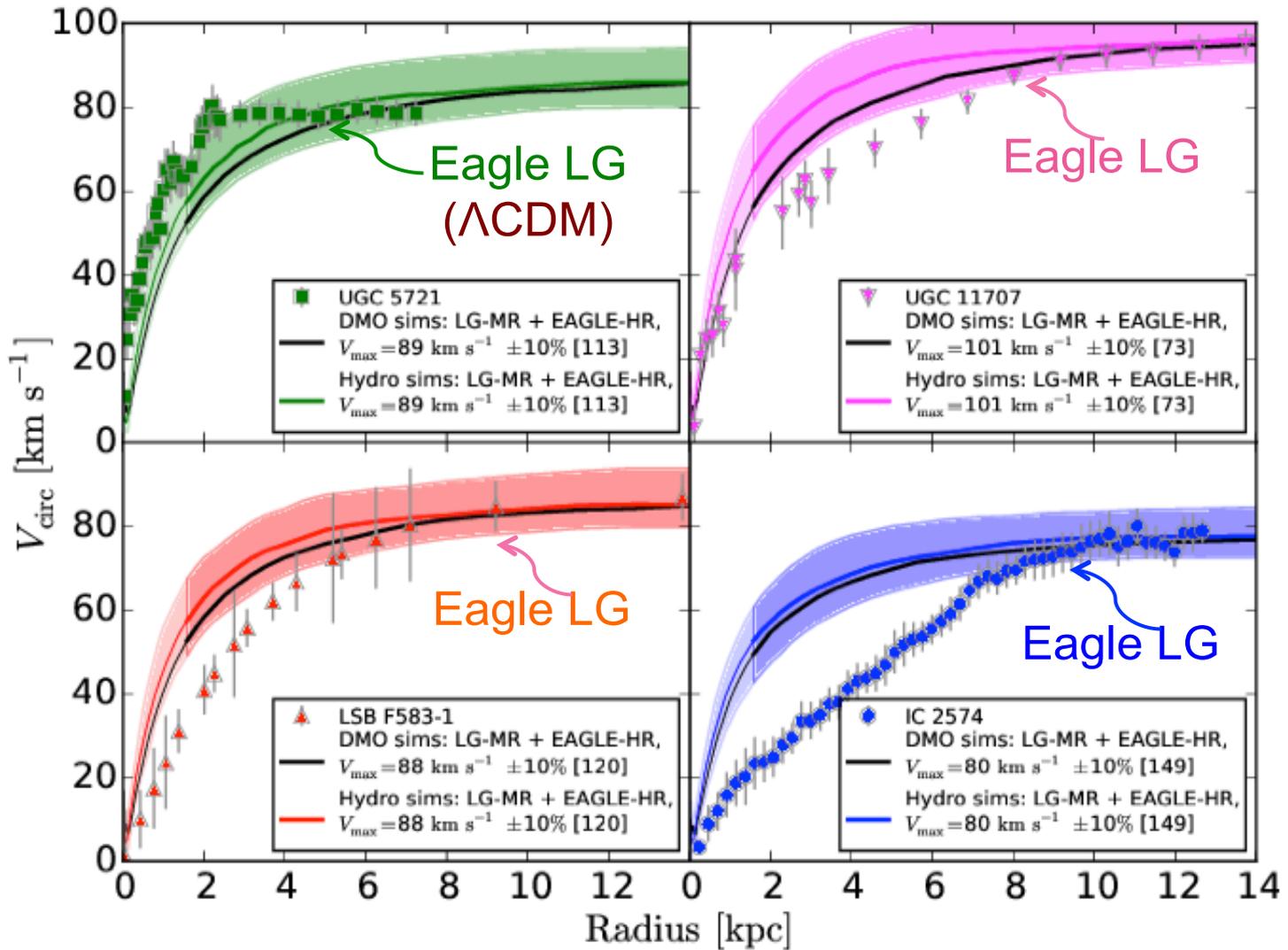


The diversity of gal rotation curves

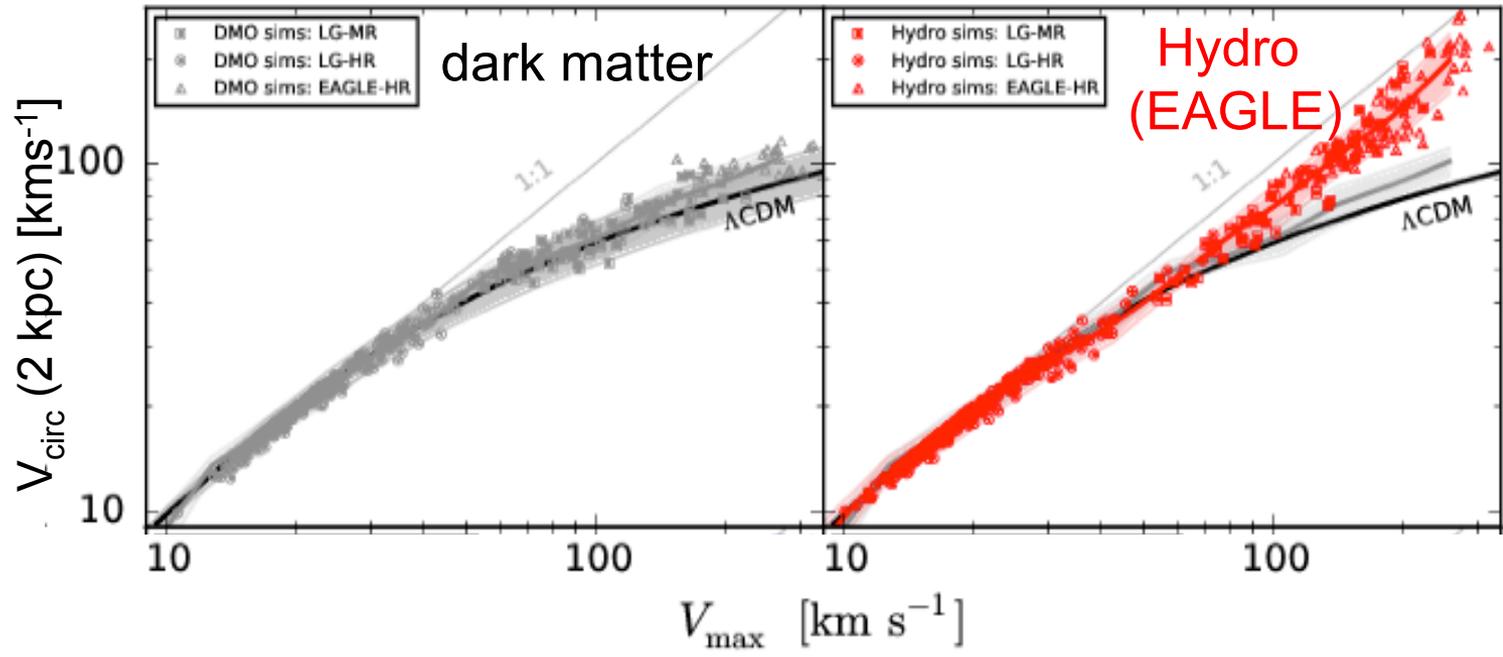
$$V_{circ} = \sqrt{\frac{GM}{r}}$$

Four rotation curves that are NOT well fit by Λ CDM

(from dwarfs to $\sim L_*$)

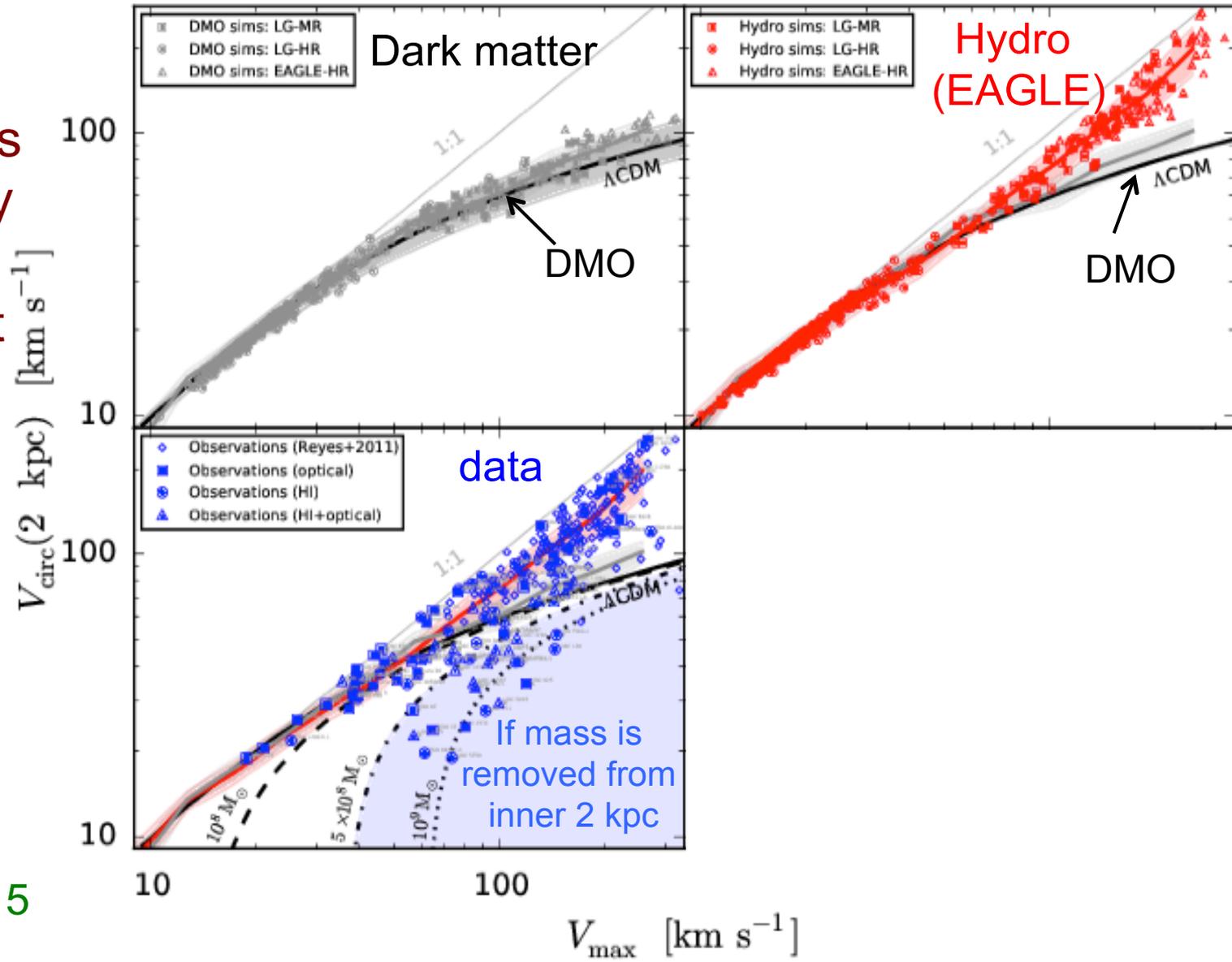


The diversity of gal. rotation curves



The diversity of gal rotation curves

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





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

The cores of dwarf galaxy haloes

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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.

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

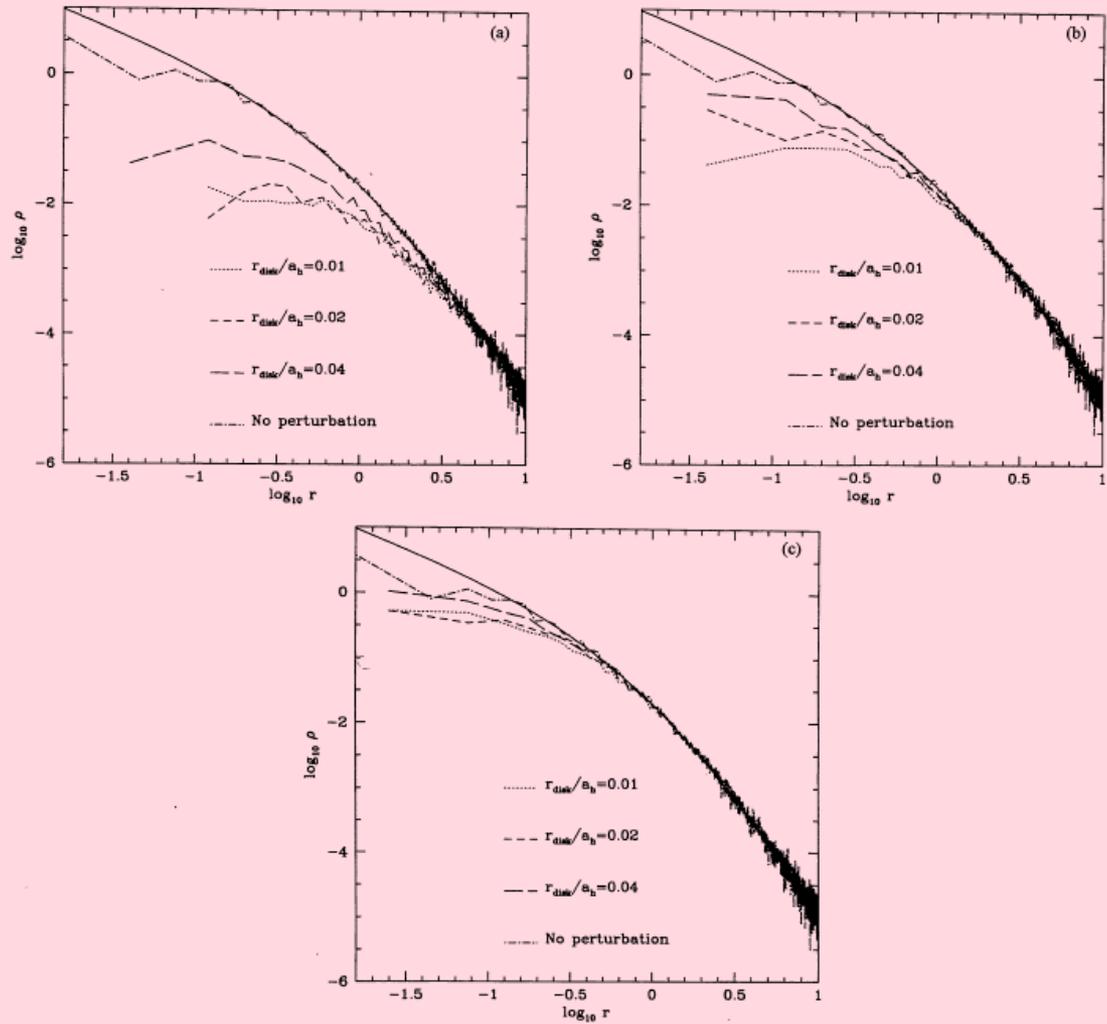


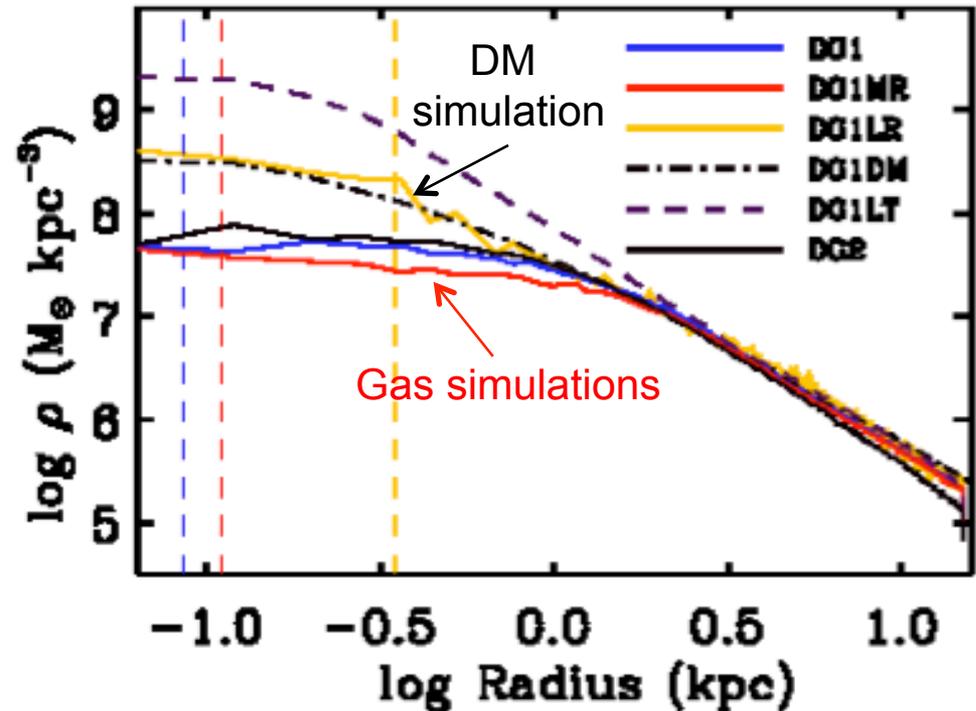
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$.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

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

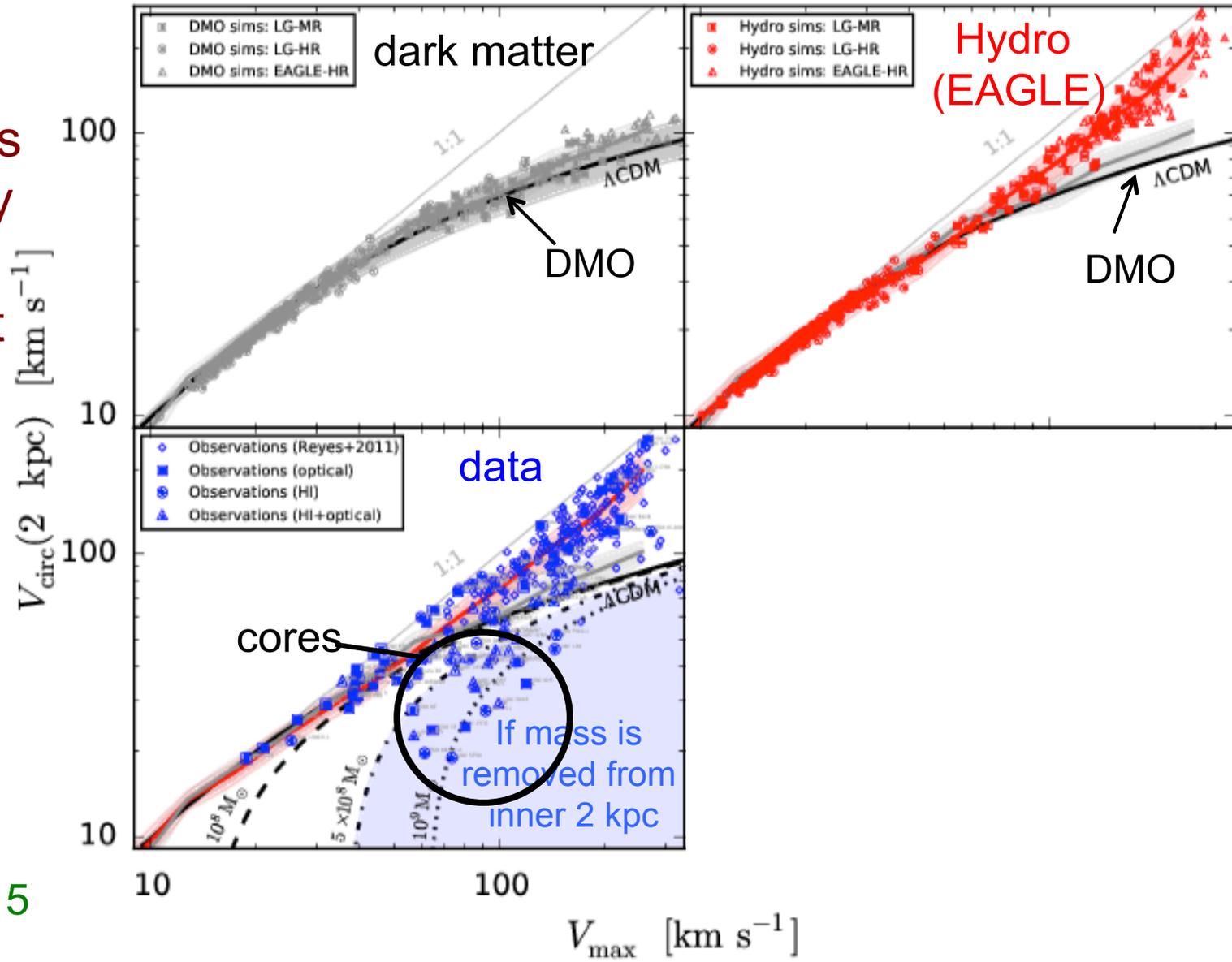


Governato et al. '10

Pontzen et al. '11

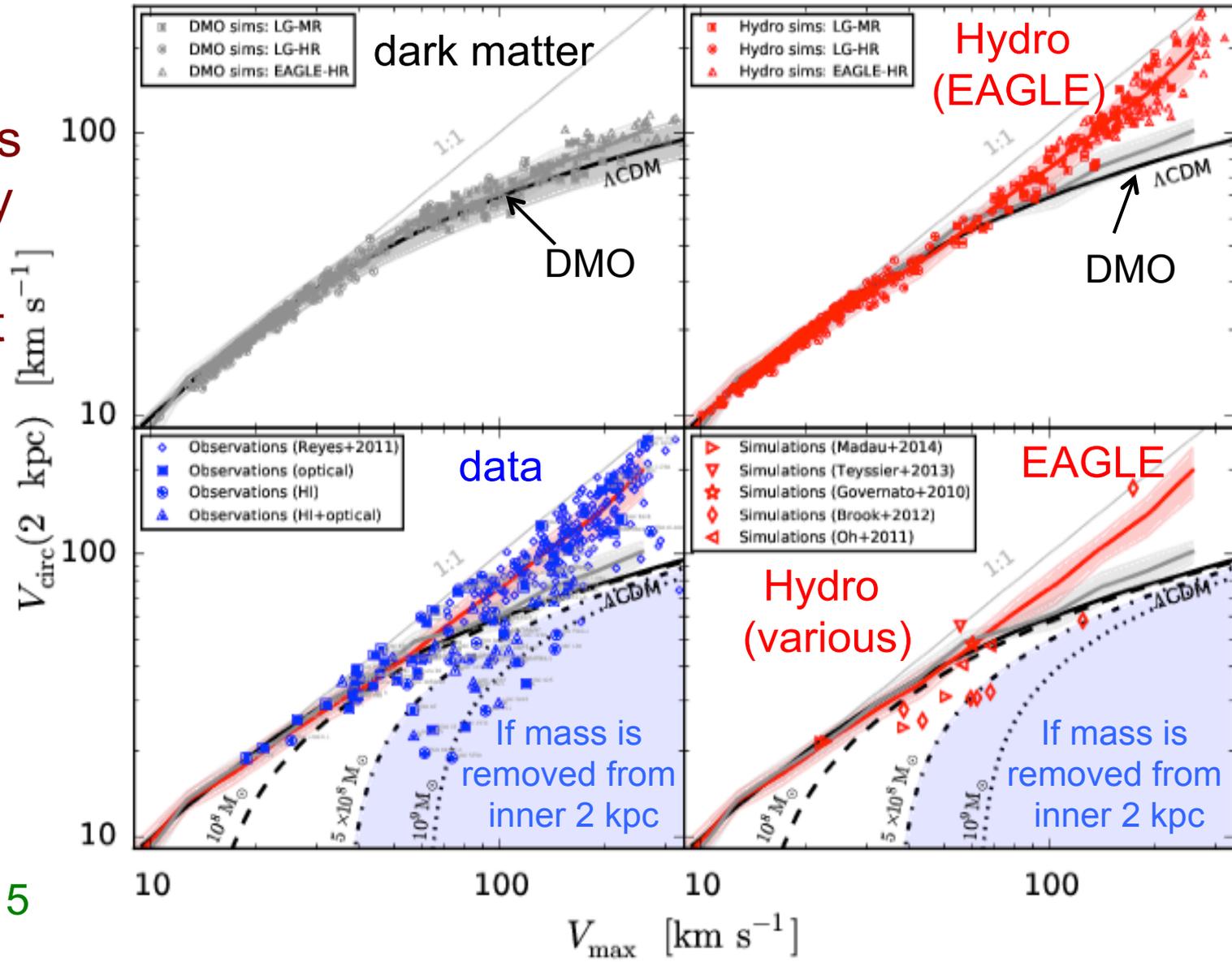
The diversity of gal rotation curves

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



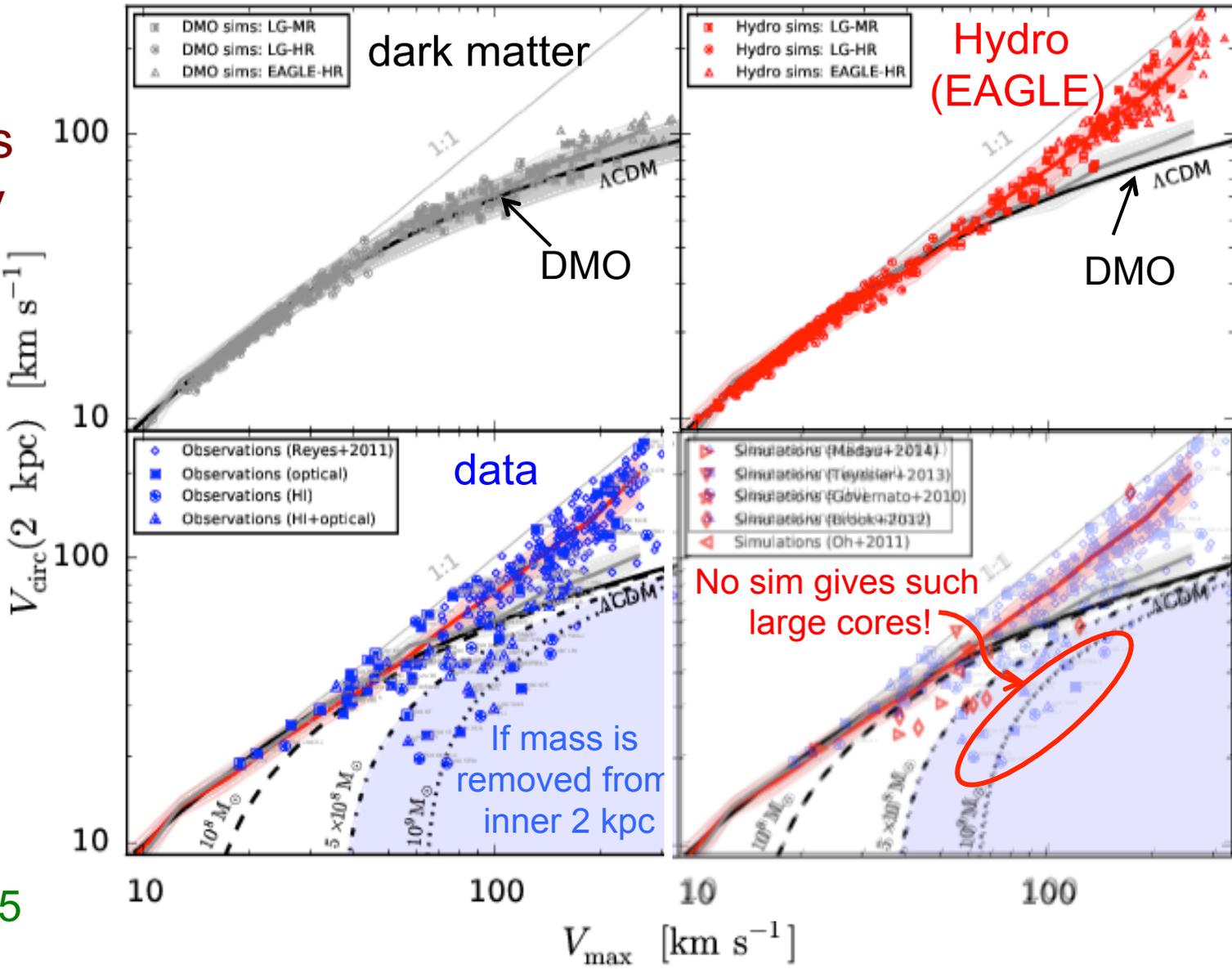
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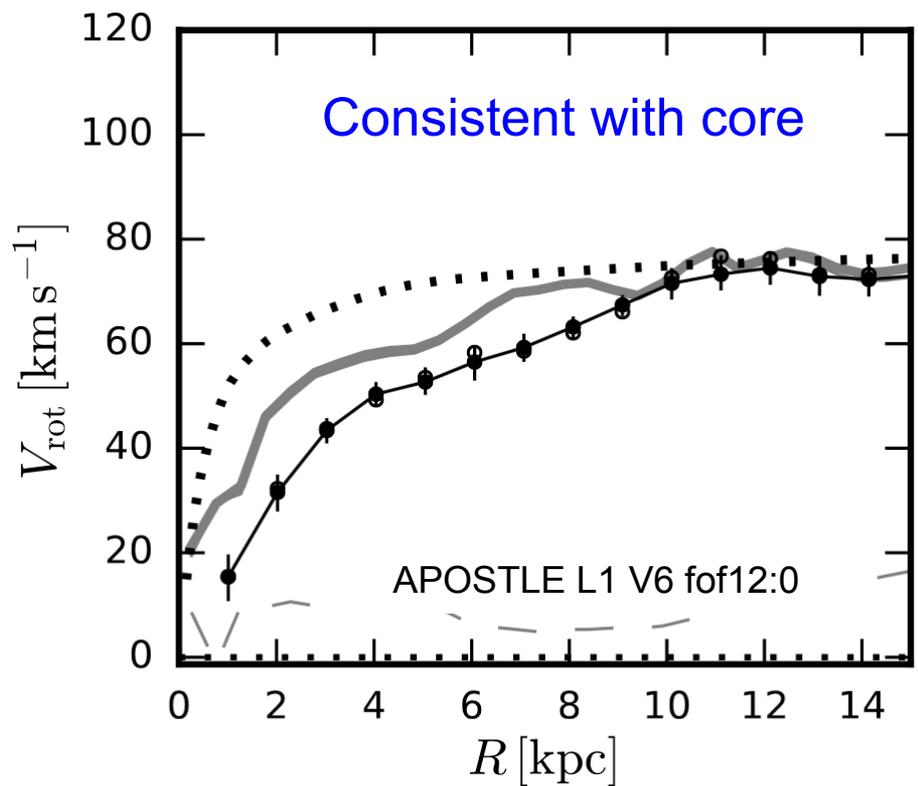
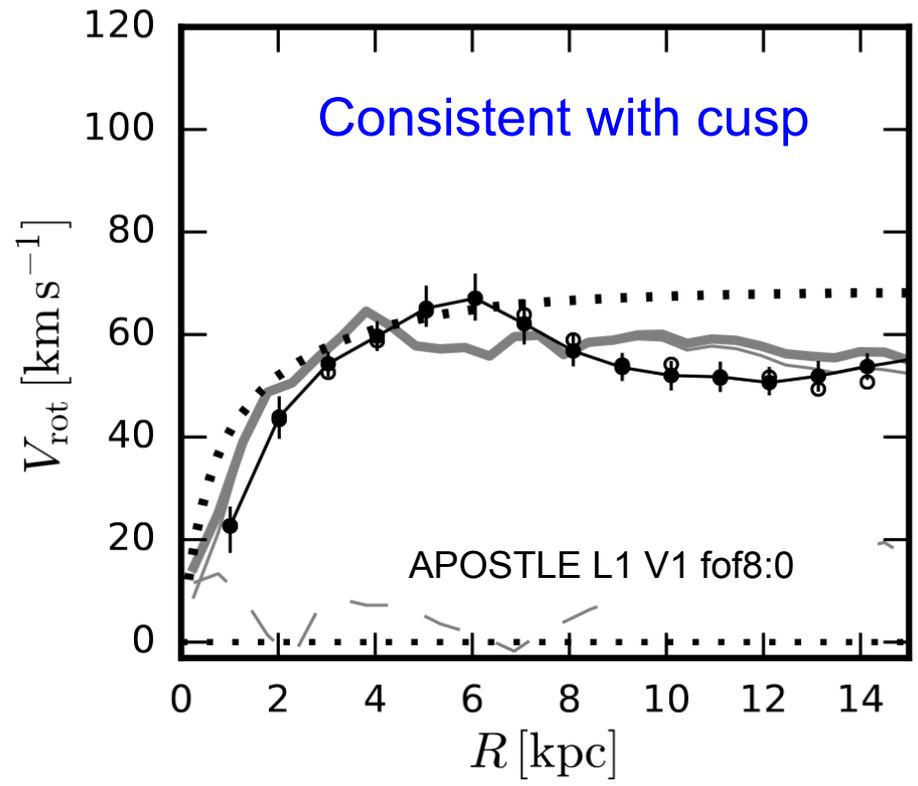


Rotation curves of 2 APOSTLE dwarfs

APOSTLE galaxies all have NFW cusps

$\cdots V_c = \sqrt{\frac{GM(< r)}{r}}$
 — gas $V_\phi(r)$ ● 3D BAROLO fit

Tilted-ring model corrected for asymmetric drift





Cores or cusps in dwarf gals?

- Some dwarfs have rotation curves that agree well with EAGLE
- Others have inner mass deficits compared to Λ CDM 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

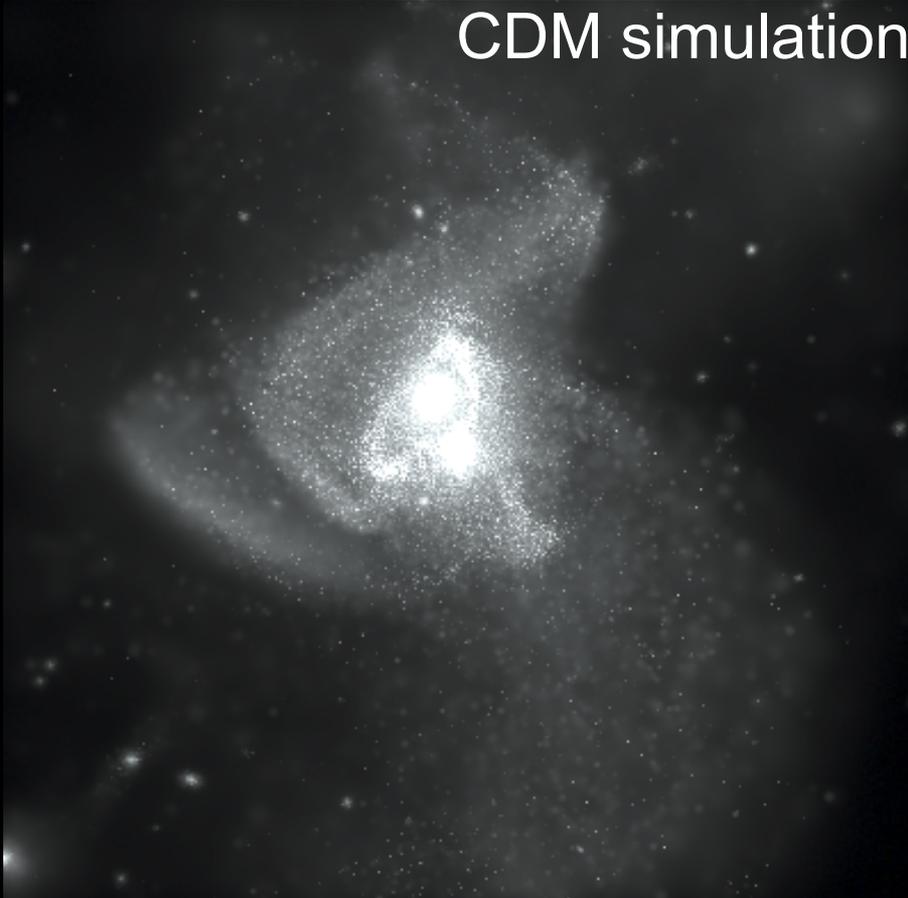
1. Gaps in stellar streams (PAndAS, GAIA)
2. Gravitational lensing



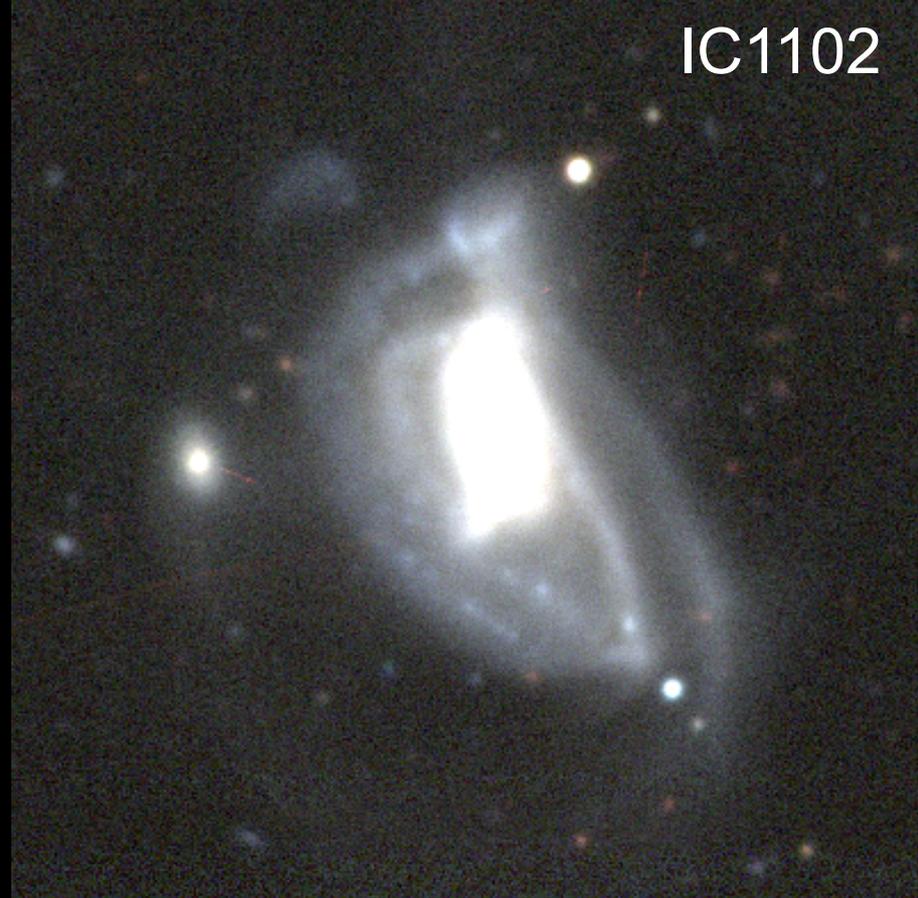
Can we distinguish CDM/WDM?

Cooper et al '16

CDM simulation



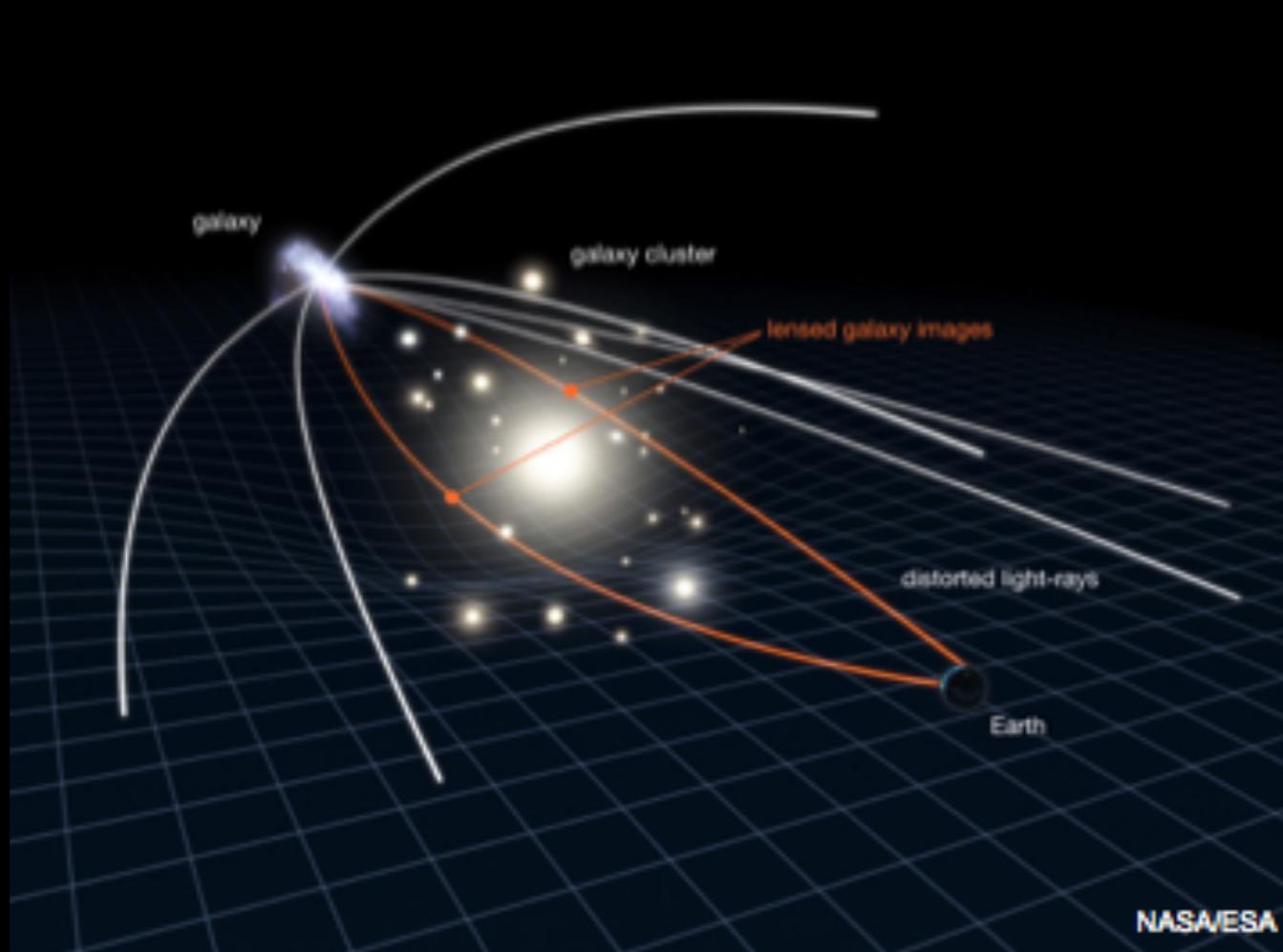
IC1102



Subhalos crossing a cold tidal stream can produce a gap

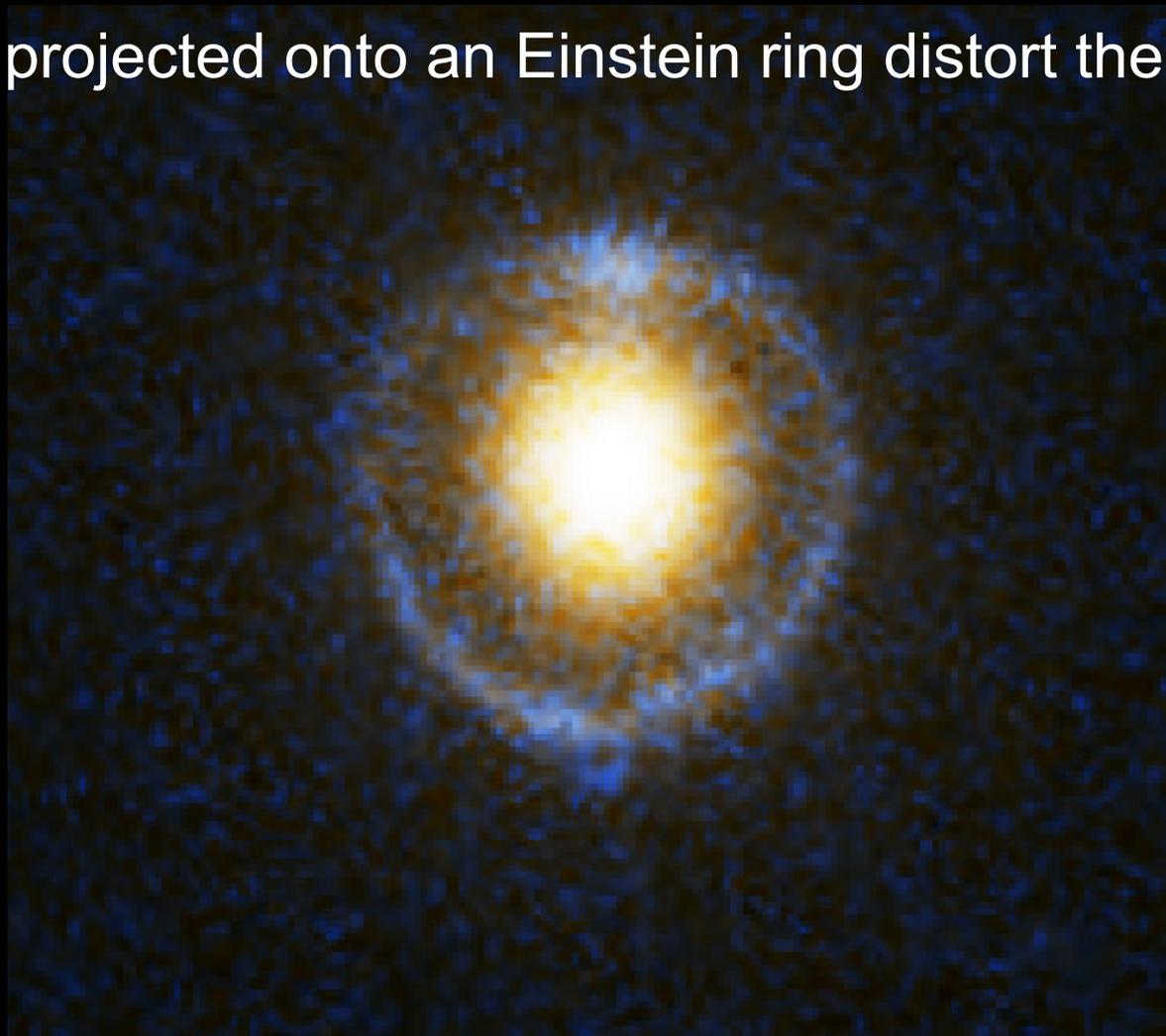
Globular cluster streams (e.g. Pal 5) may be best

Gravitational lensing: Einstein rings



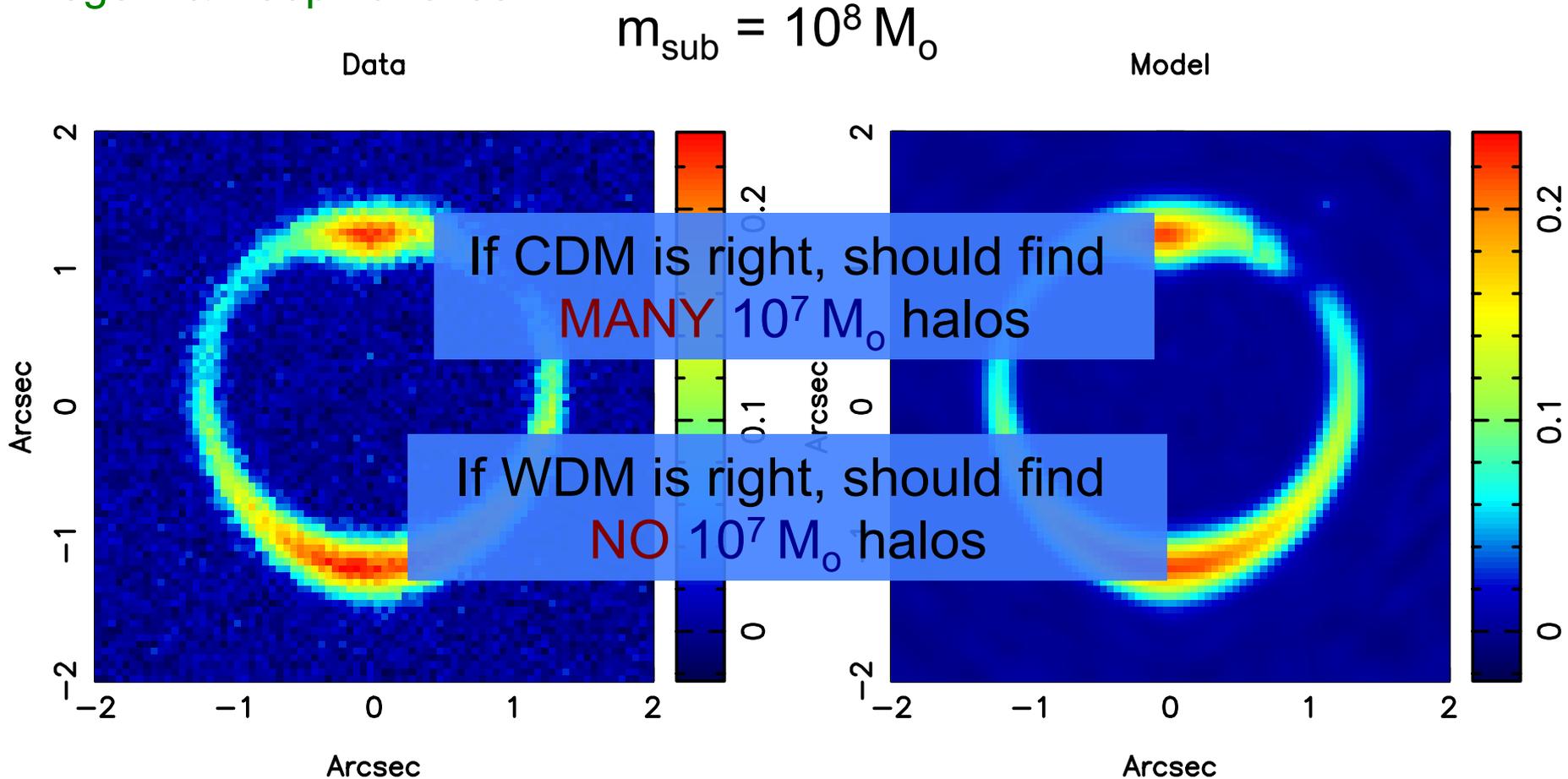
When the source and the lens are well aligned → strong arc or an Einstein ring

Halos projected onto an Einstein ring distort the image



Detecting substructures with strong lensing

Vegetti & Koopmans '09

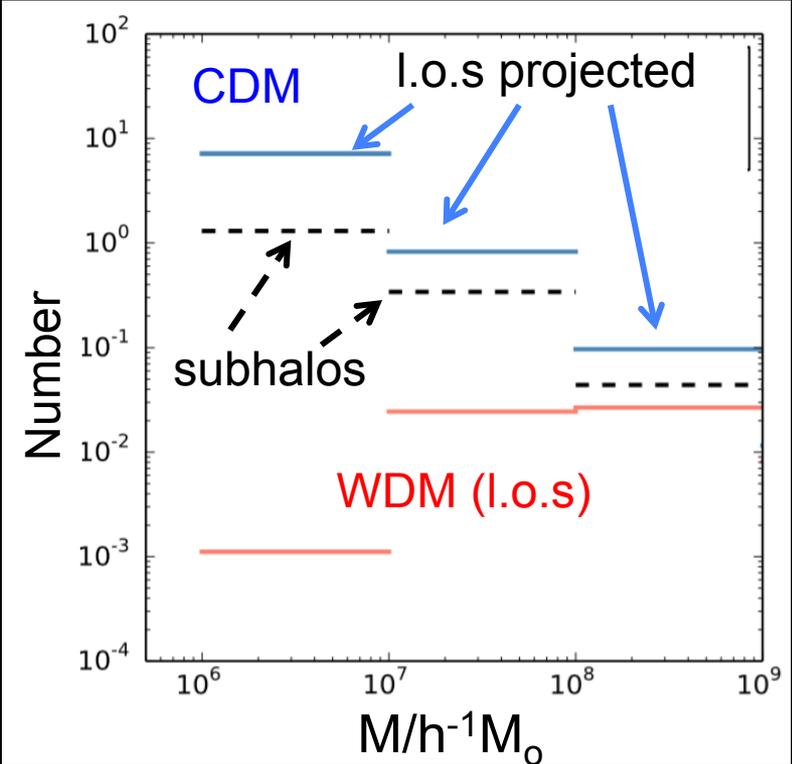
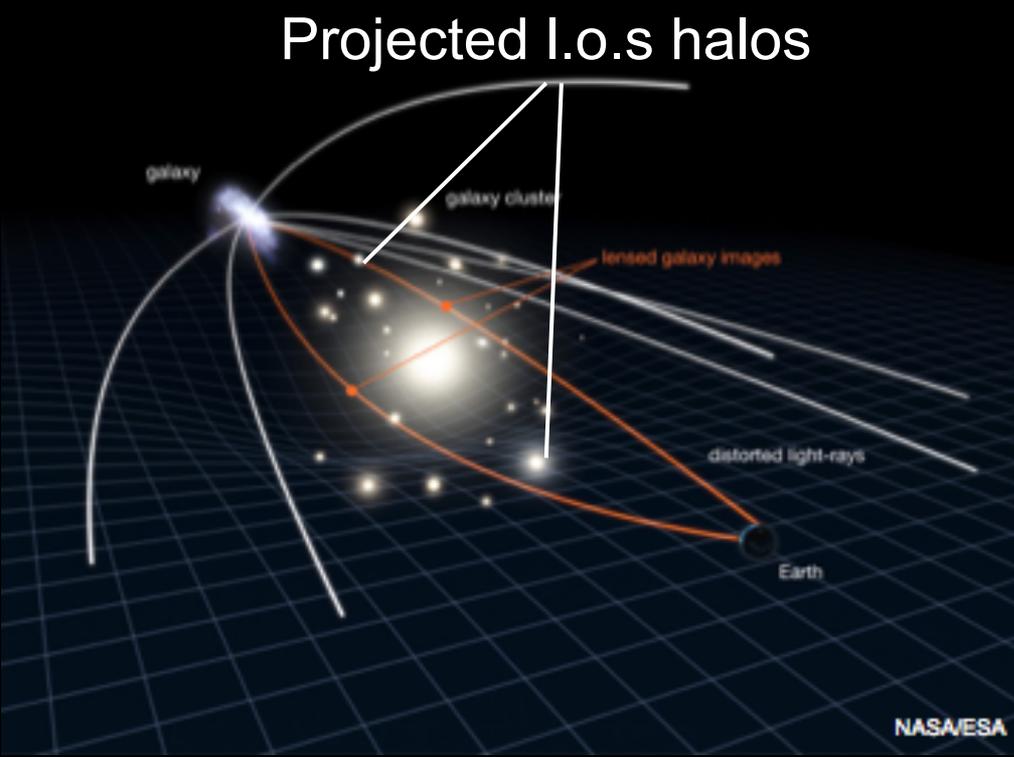


Can detect subhalos as small as $10^7 M_{\odot}$

Substructures vs interlopers

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

Projected l.o.s halos



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

The subhalo mass function

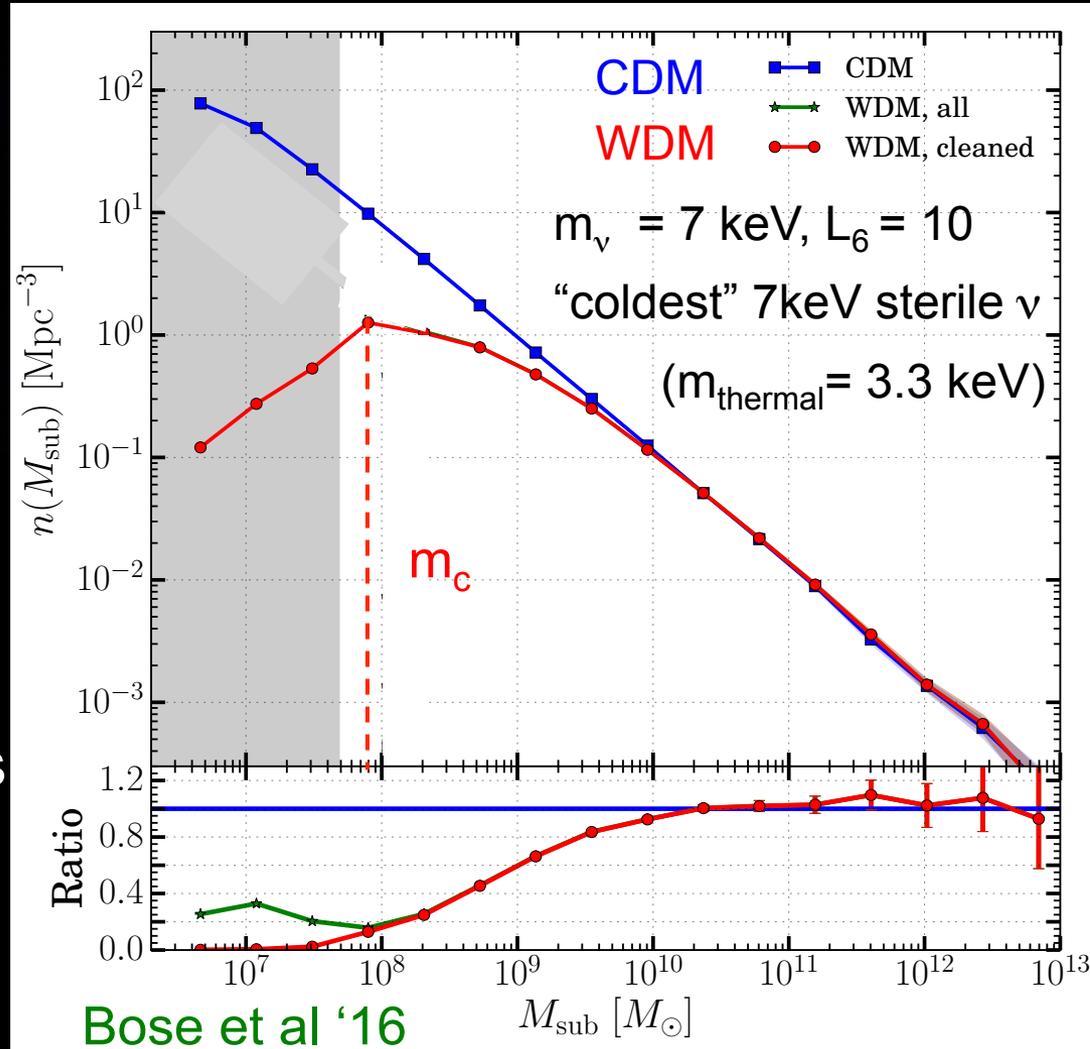


CDM

WDM

Already fewer WDM subhalos
at $3 \times 10^9 M_\odot$

10 x fewer at $10^8 M_\odot$



Detecting substructures with strong lensing

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

m_c = halo cutoff mass

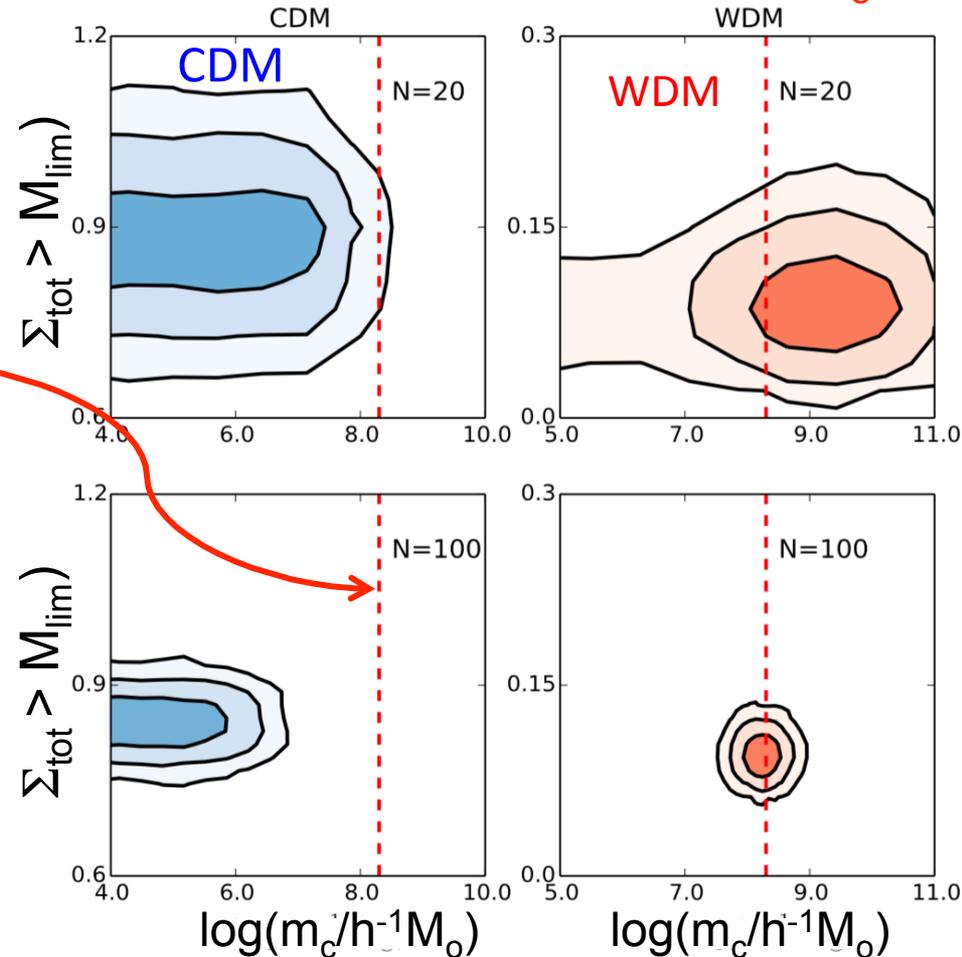
$m_c = 1.3 \times 10^8 h^{-1} M_\odot$ for coldest 7 keV sterile neutrino

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

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

Li, CSF et al '16

Detection limit = $10^7 h^{-1} M_\odot$





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





Conclusions

- Λ CDM: great **success** on scales $> 1\text{Mpc}$: CMB, LSS, gal evolution
 - But on these scales Λ CDM 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!