A conclusive test of cold dark matter: no ifs or buts

Carlos S. Frenk
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University of Durham

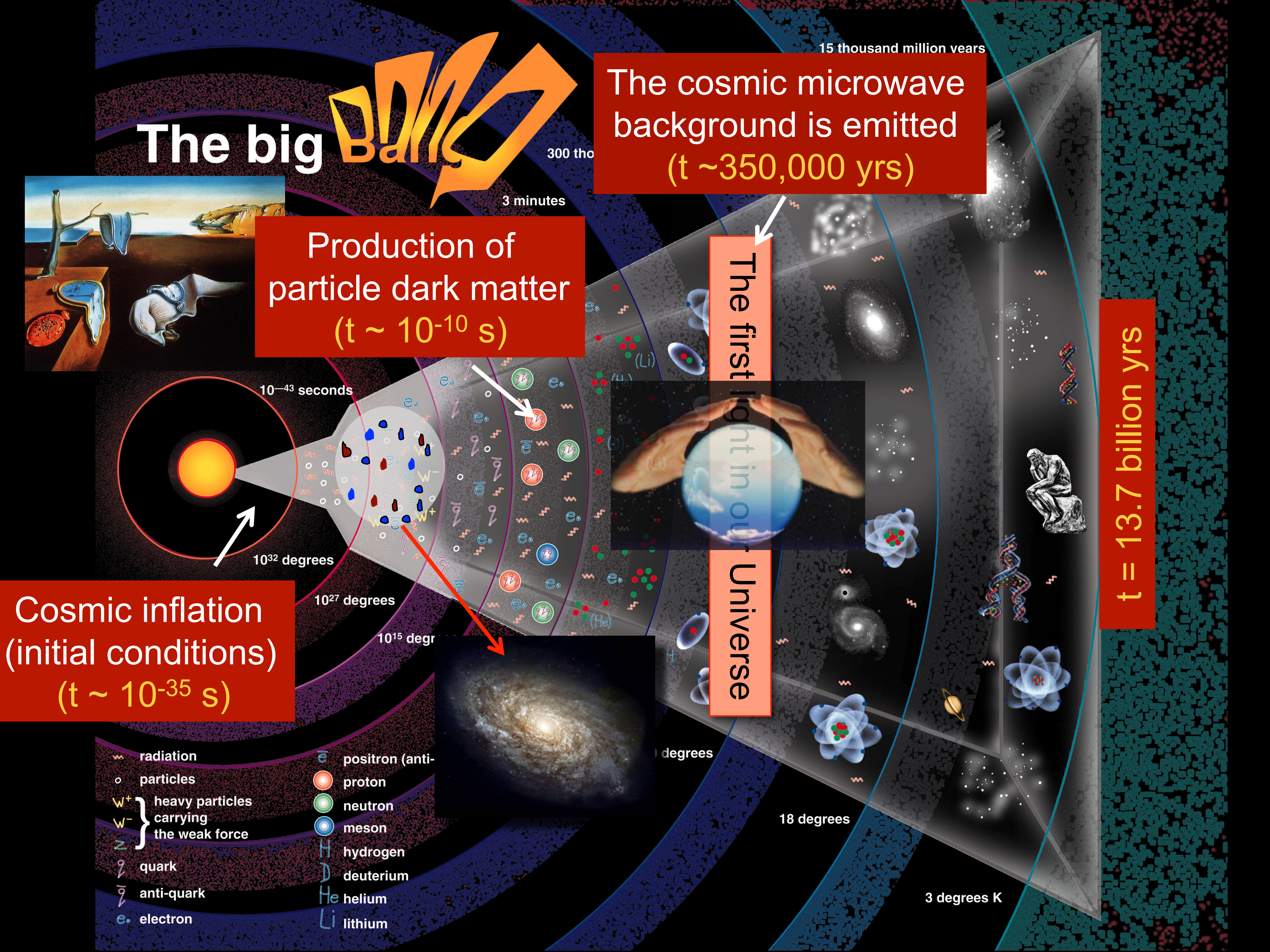
... or how to rule out CDM – or alternative models

The new Ogden Centre at Durham

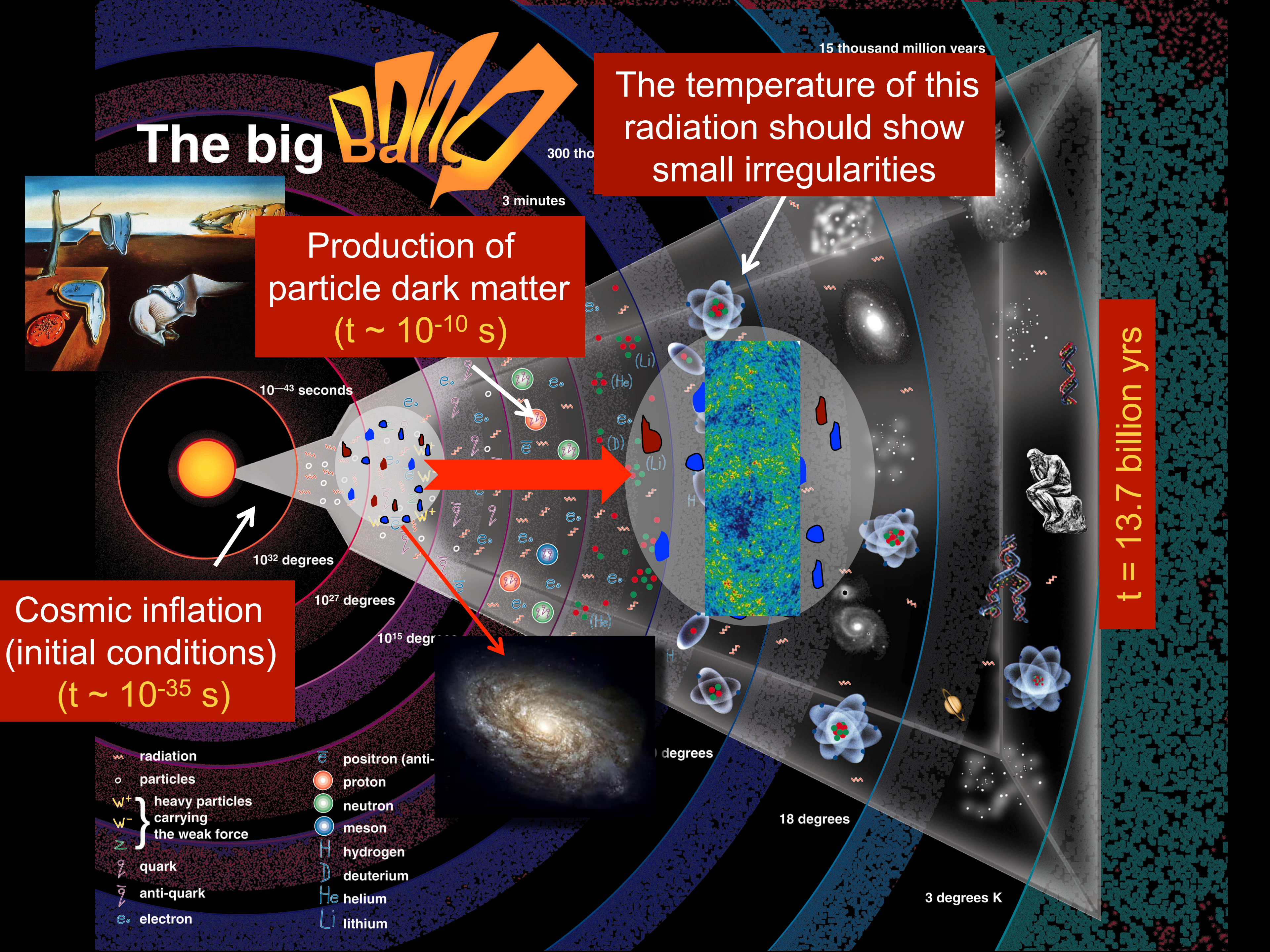
The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter



The big Bang
The cosmic microwave background is emitted
(t ~350,000 yrs)
Production of particle dark matter
(t ~ 10^-10 s)
Cosmic inflation (initial conditions)
(t ~ 10^-35 s)
The first light in our Universe
t = 13.7 billion yrs
15 thousand million years
300 tho
3 minutes
10—43 seconds
1032 degrees
1027 degrees
1015 degr
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium



The big Bang
The temperature of this radiation should show small irregularities
Production of particle dark matter
(t ~ 10-10 s)
Cosmic inflation (initial conditions)
(t ~ 10-35 s)
t = 13.7 billion yrs
15 thousand million years
3 minutes
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radiation
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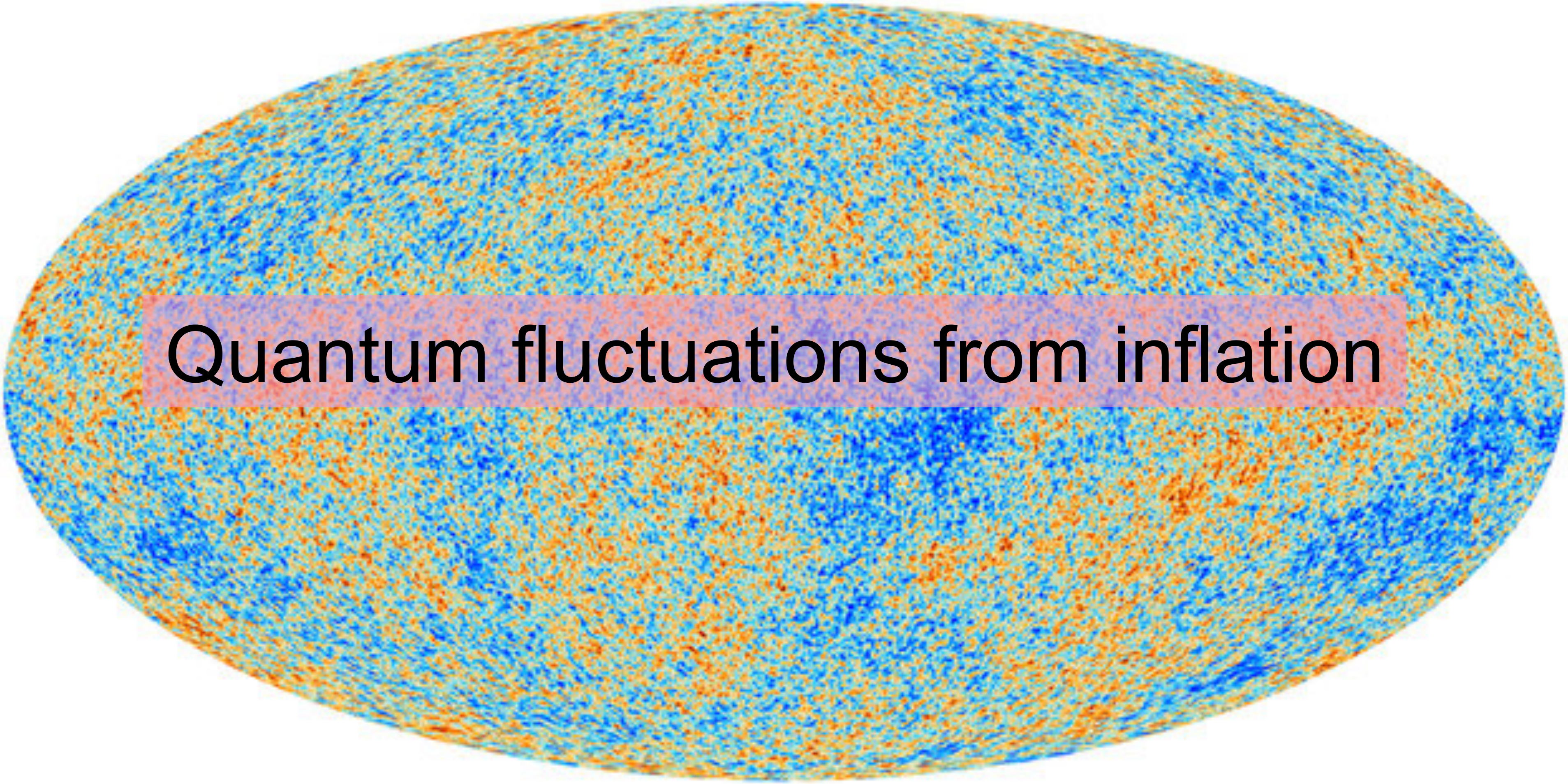
The initial conditions for galaxy formation



Temperature anisotropies in CMB

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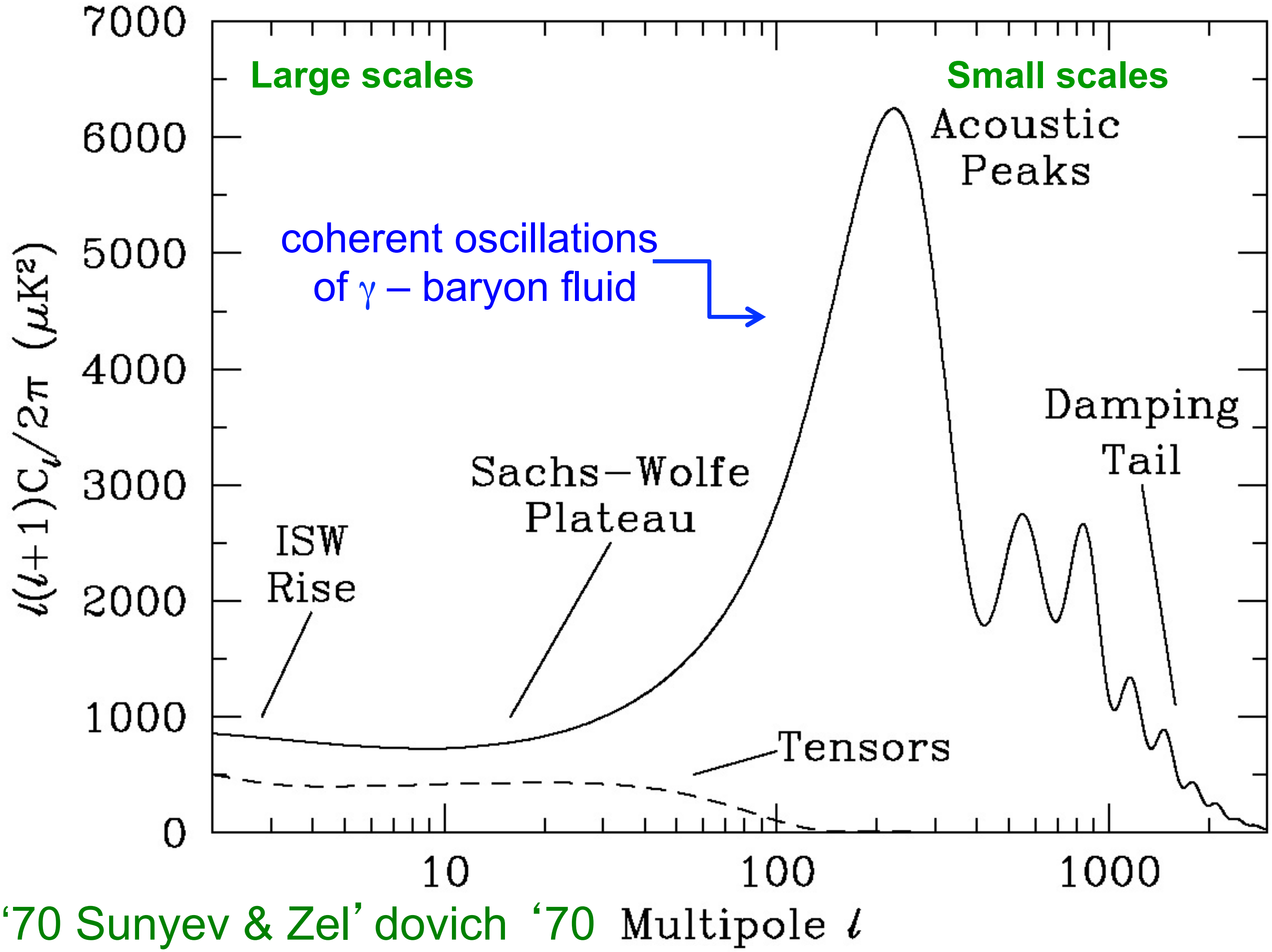
2D power spectrum



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

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

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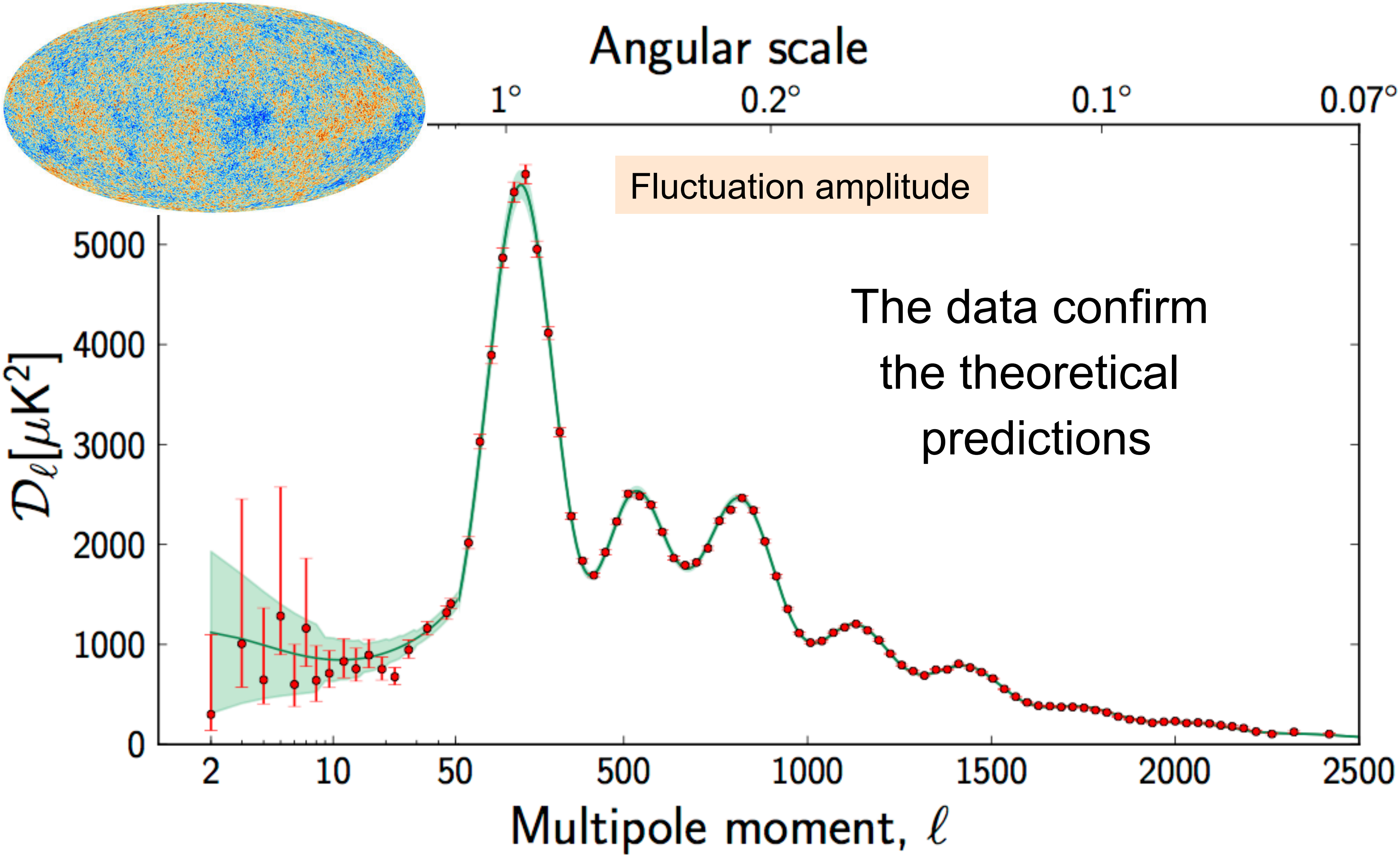
Planck: CMB temperature anisotropies



Planck coll. 2015

Univer

The six parameters of minimal ΛCDM model

6 mdoel parameters

		Planck+WP	
Parameter		Best fit	68% limits
$\Omega_b h^2$	Baryon density	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	Dark matter density	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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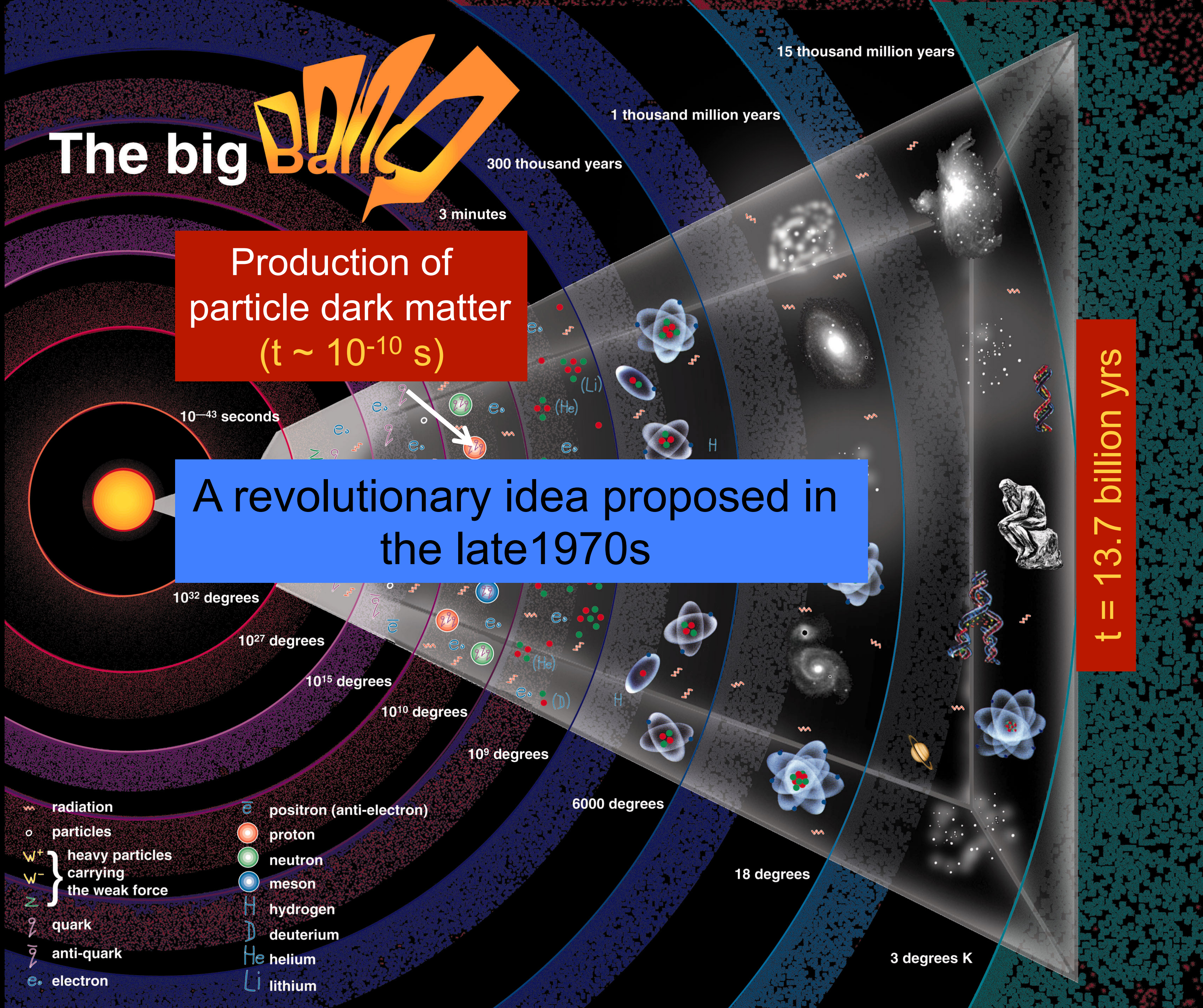

The big Bang
Production of particle dark matter (t ~ 10^-10 s)
A revolutionary idea proposed in the late1970s
t = 13.7 billion yrs
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees
109 degrees
6000 degrees
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radiation
particles
heavy particles carrying the weak force
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positron (anti-electron)
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meson
hydrogen
deuterium
helium
lithium

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 $S \simeq (E-E_0)^2$. 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 $S \simeq (E_0-E)\sqrt{(E_0-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

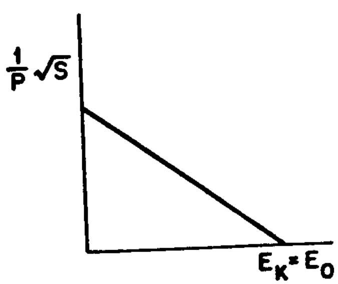


Fig. 1. Kurie plot for $M_\nu = 0$.

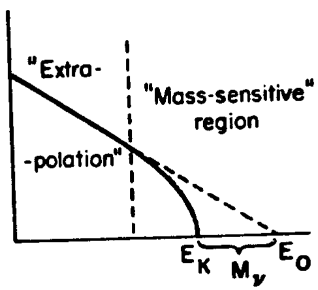
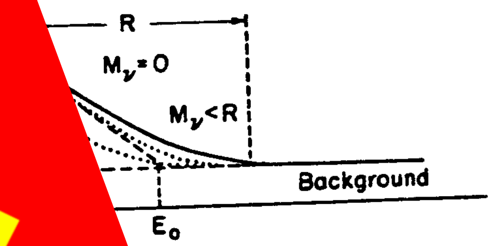


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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 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 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 $M_\nu = 100$ 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 $E_0 \sim 18.6$ 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.

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Non-baryonic dark matter candidates

From the early 1980s:

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

These possibilites can be tested with astrophysics

The dark matter power spectrum

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Free streaming →

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

for thermal relic

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

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

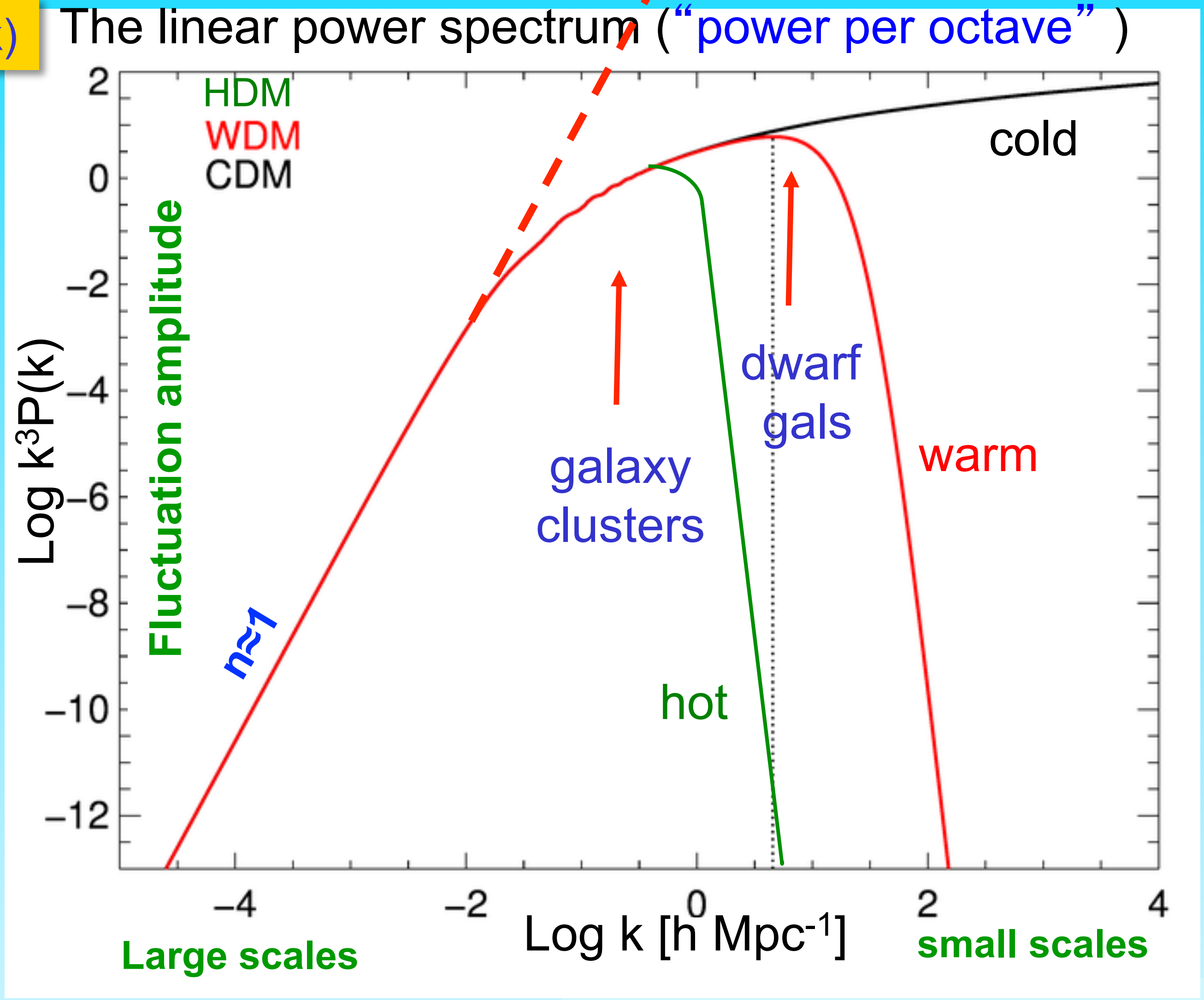
$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$

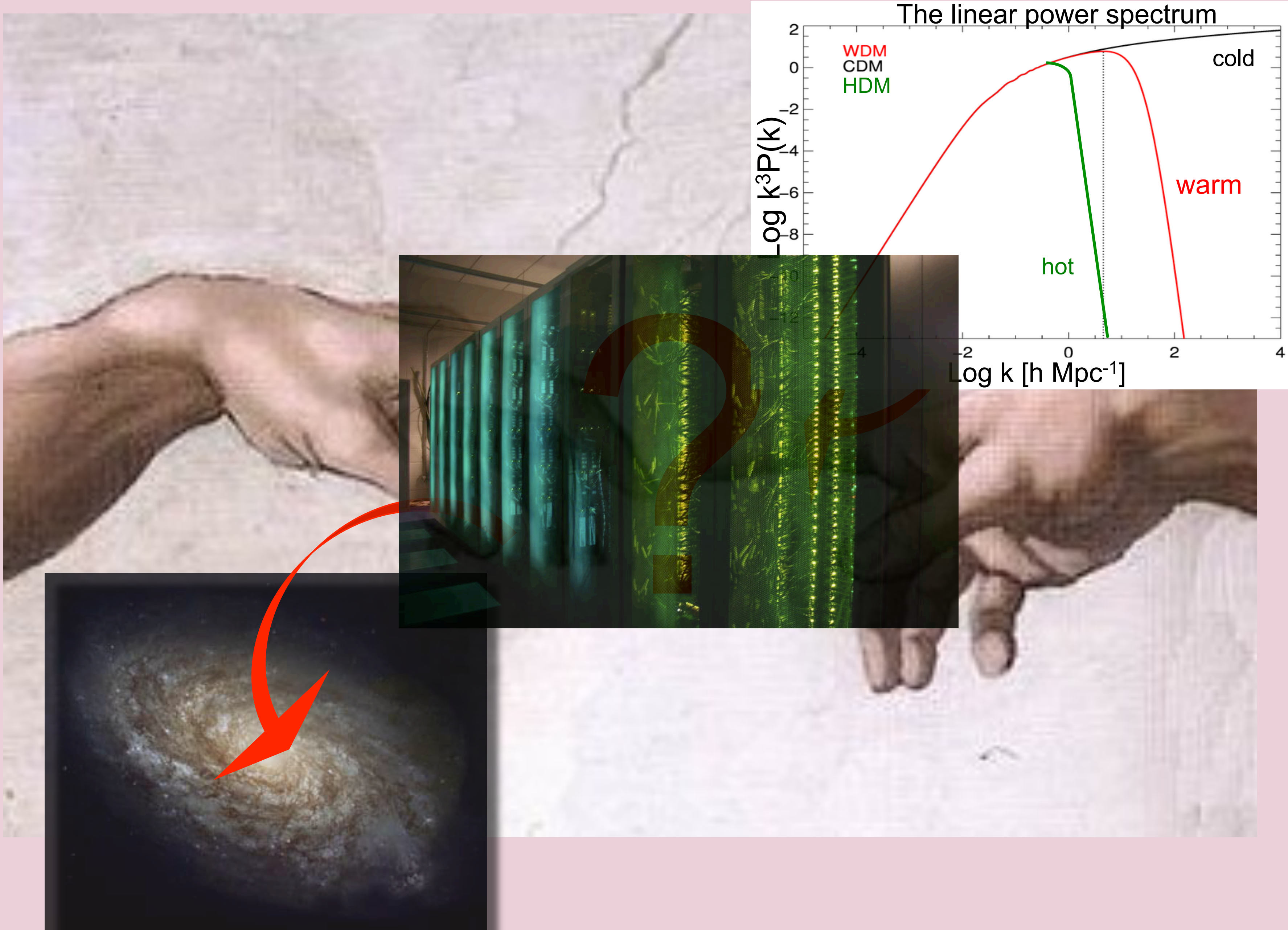
$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15}\ M_o$

$k^3\ P(k)$



Non-linear evolution



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Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann;
Poisson; Friedmann eqns;
Radiative hydrodynamics
Subgrid astrophysics

How to make a virtual universe

Institute for Computational Cosmology

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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

These possibilites can be tested with astrophysics

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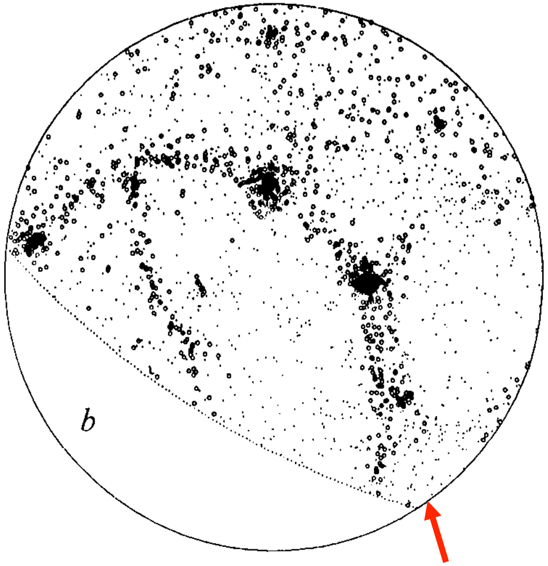
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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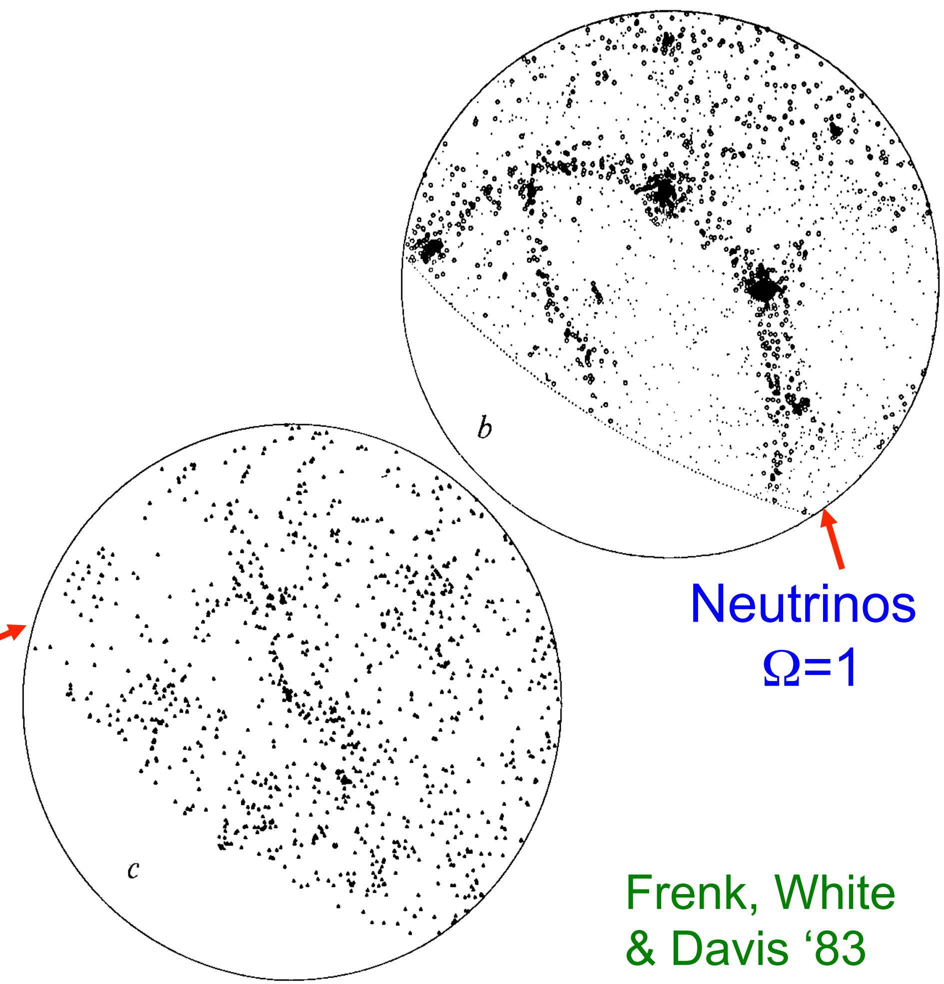
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν<< 30 ev



CfA redshift survey

Neutrinos
Ω=1

Frenk, White & Davis '83

Non-baryonic dark matter cosmologies

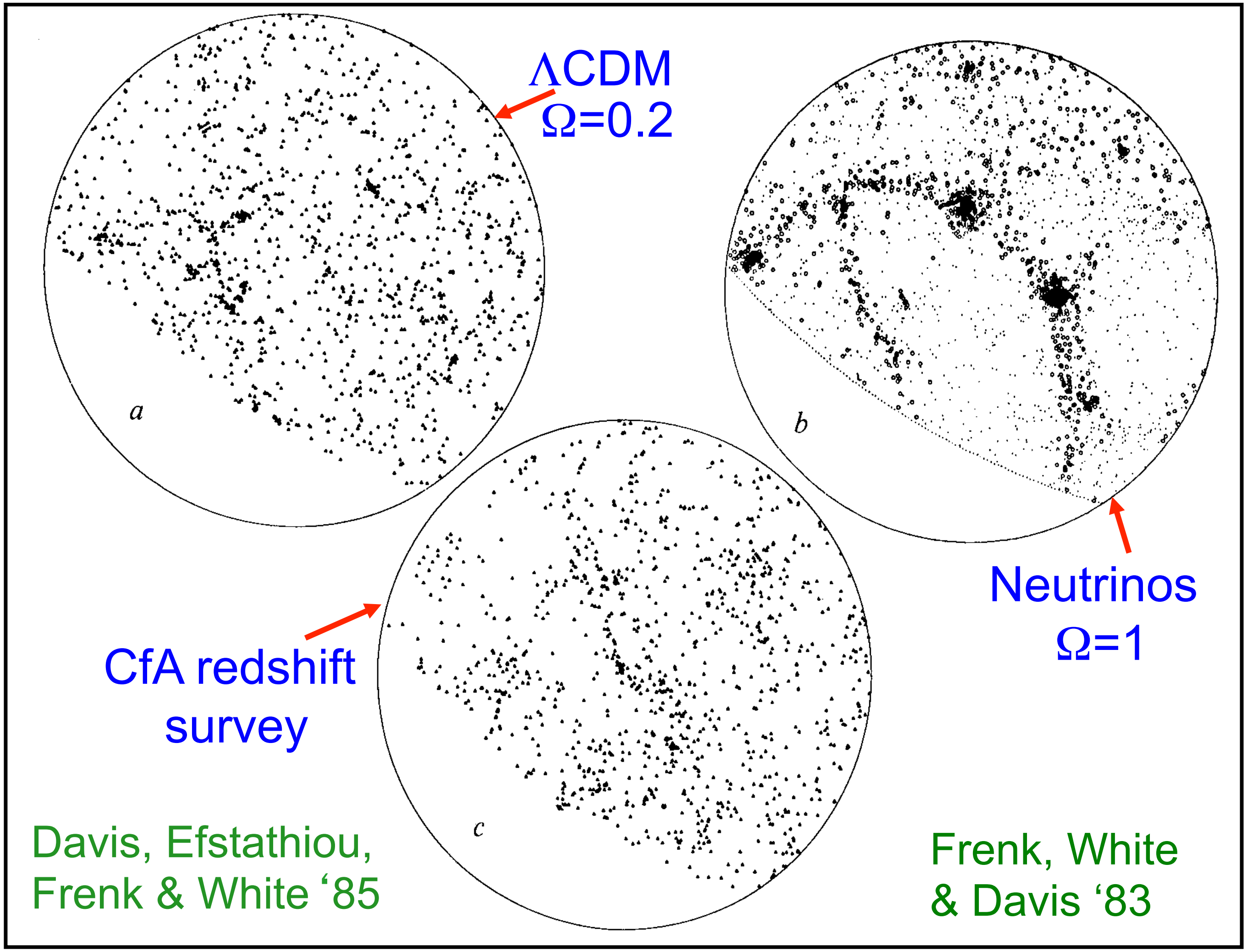
Neutrino DM → wrong clustering

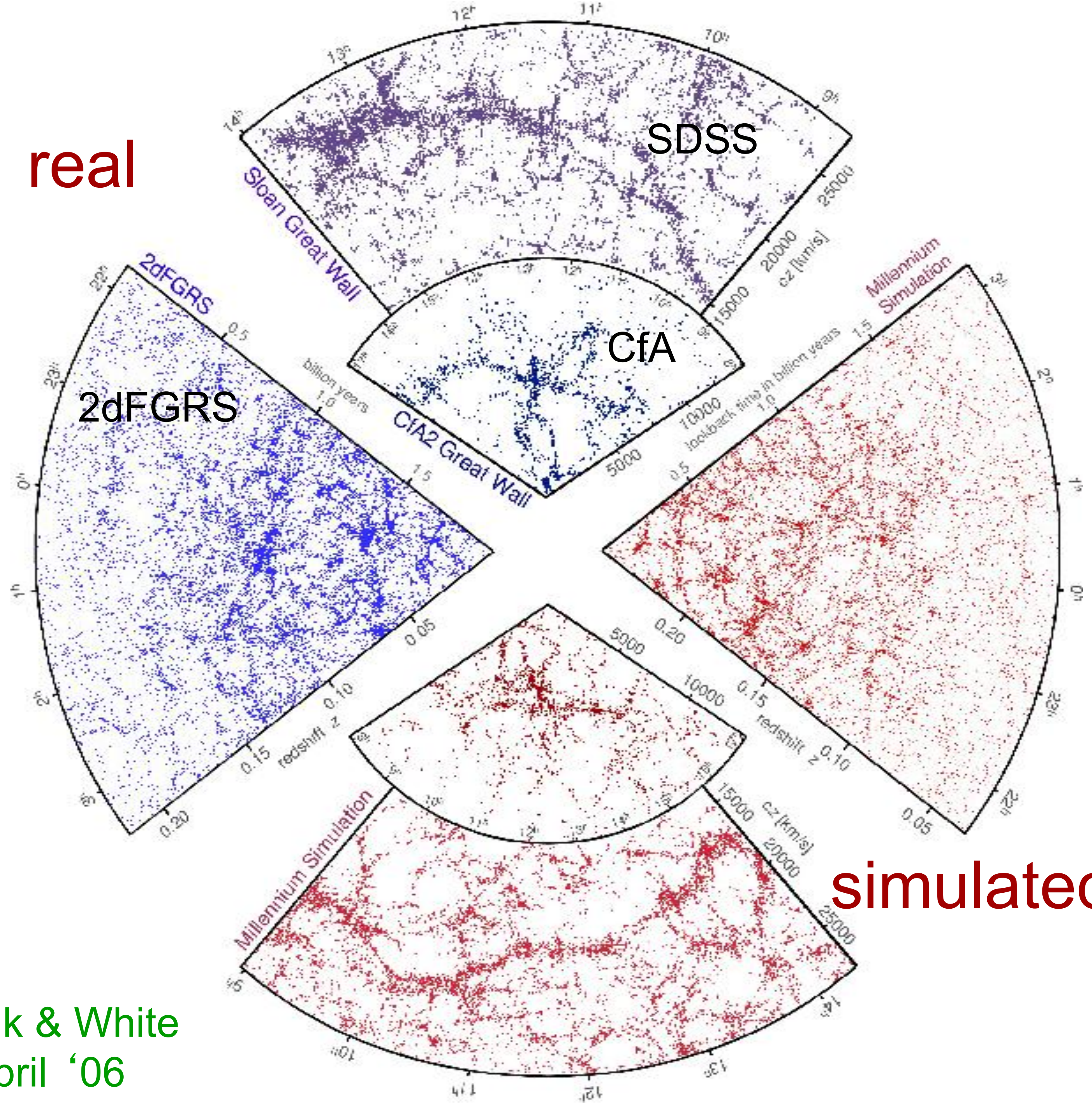
Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically





Springel, Frenk & White
Nature, April '06

The ΛCDM model of cosmogony

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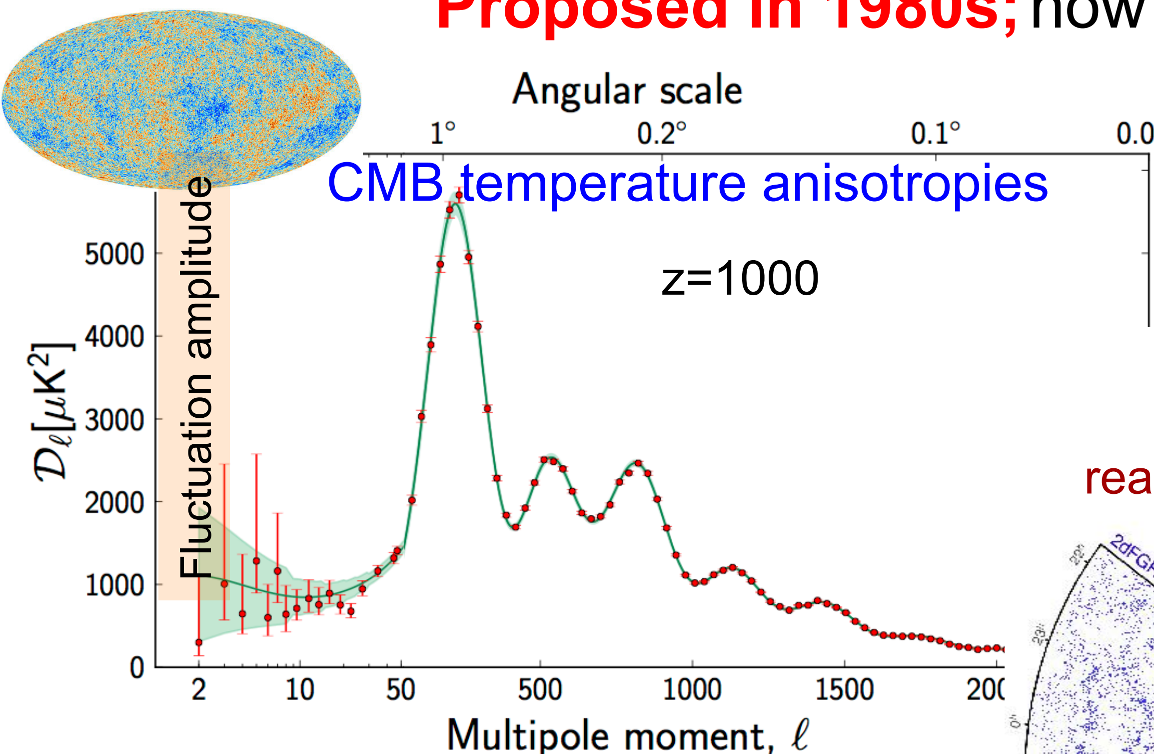
Proposed in 1980s; now empirically supported by:



CMB temperature anisotropies

Fluctuation amplitude

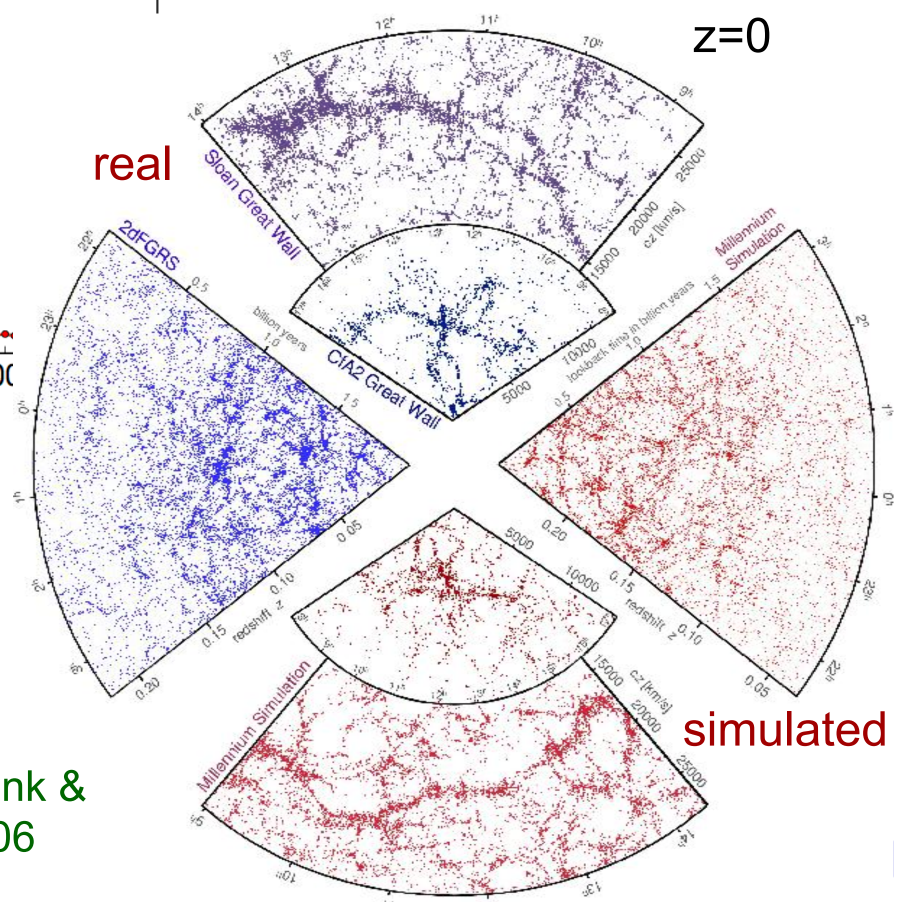
z=1000

Planck coll. 2015

Galaxy clustering

z=0

real



simulated

Springel, Frenk & White 2006

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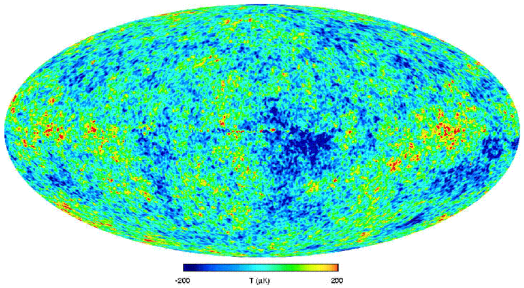
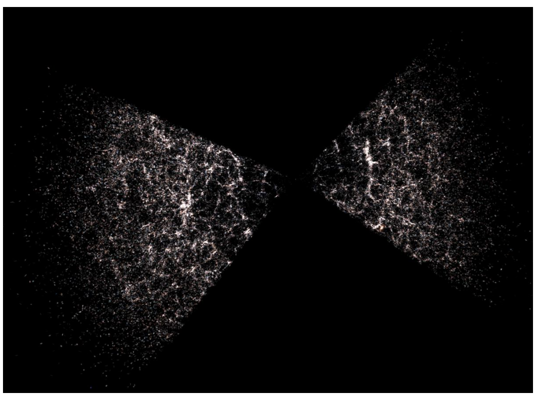
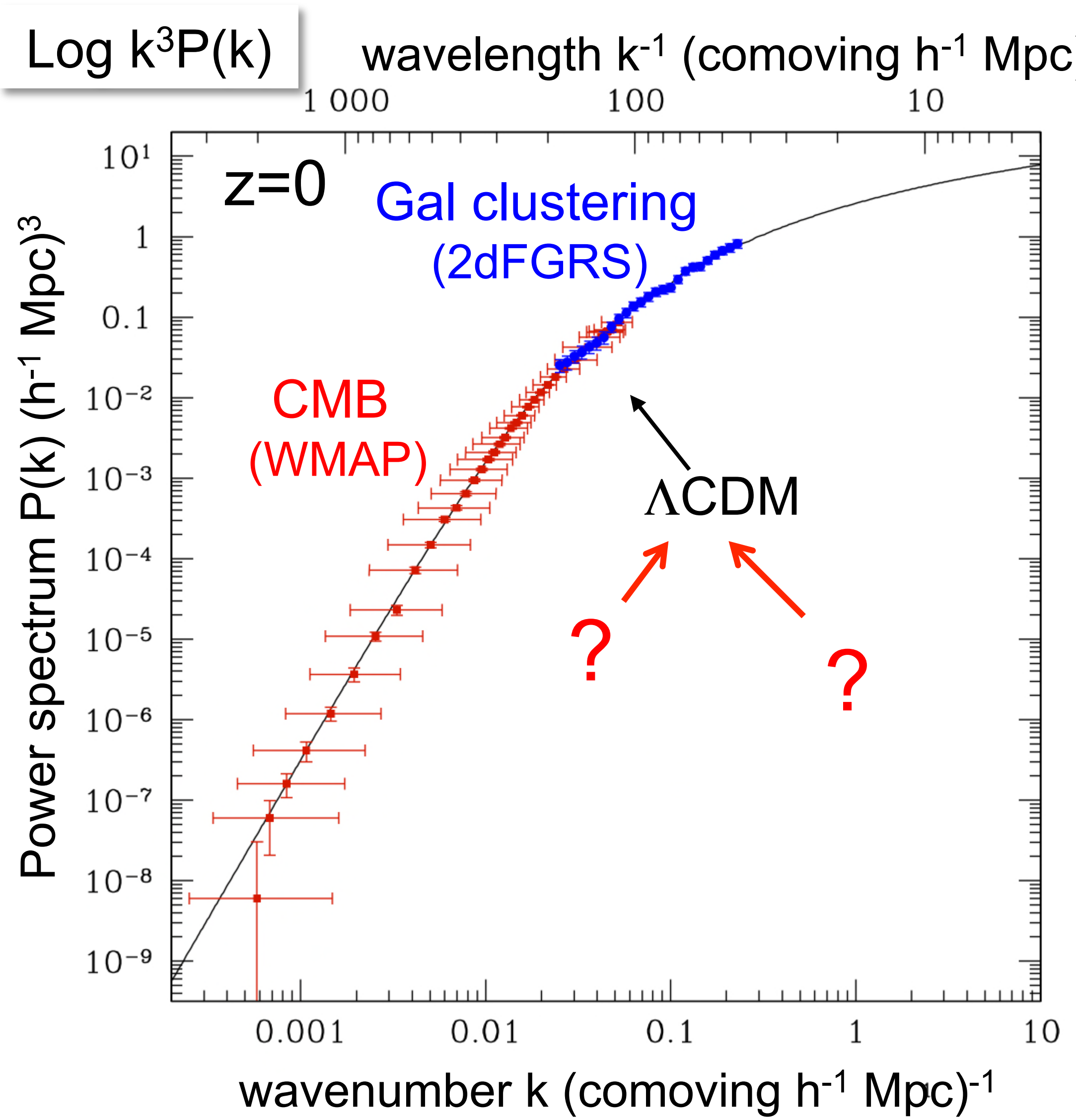
The cosmic power spectrum: from the CMB to the 2dFGRS

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

Free streaming →

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

for thermal relic

$m_{CDM} \sim 100$GeV

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

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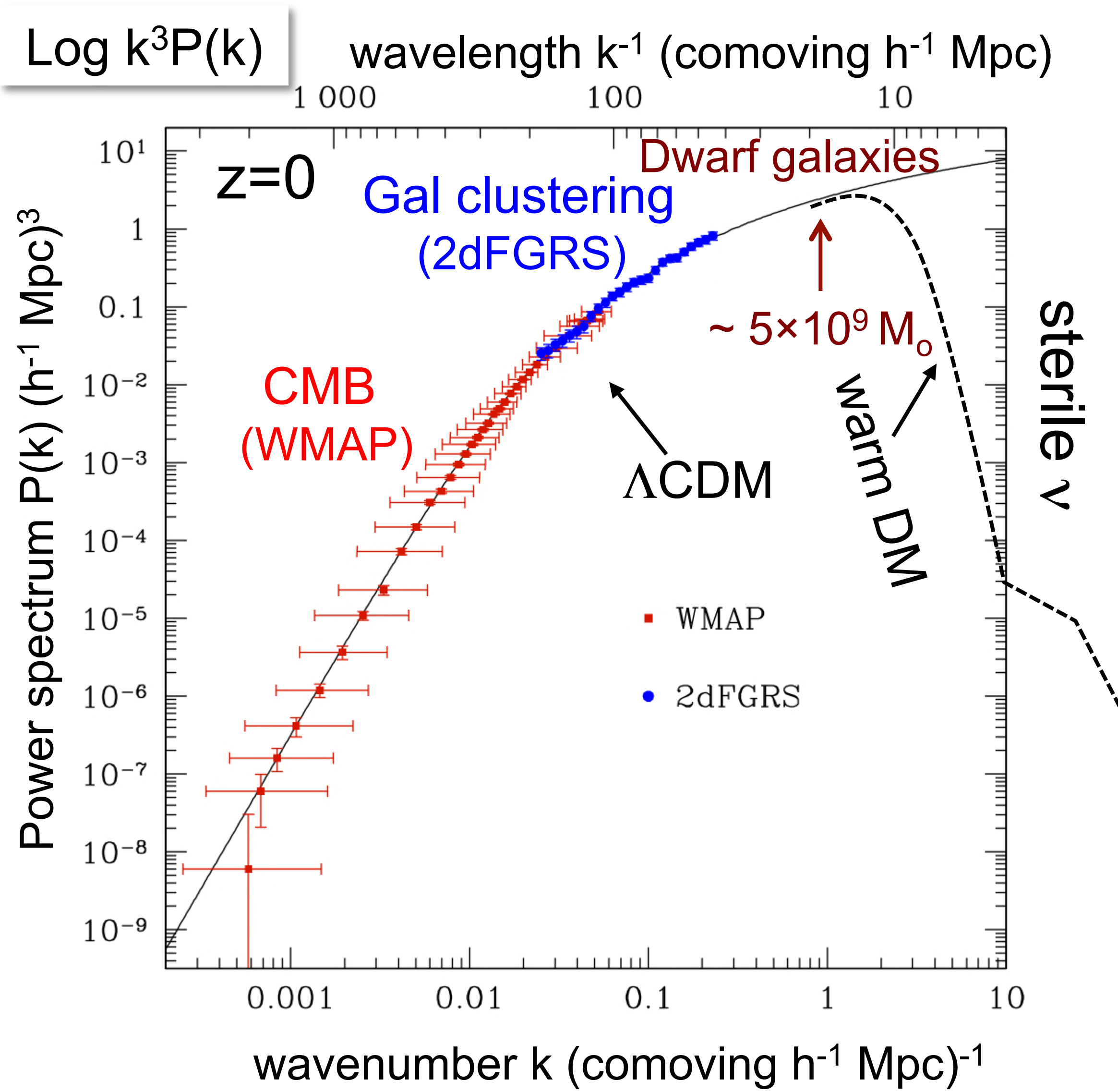


Both CDM & WDM compatible with CMB & galaxy clustering

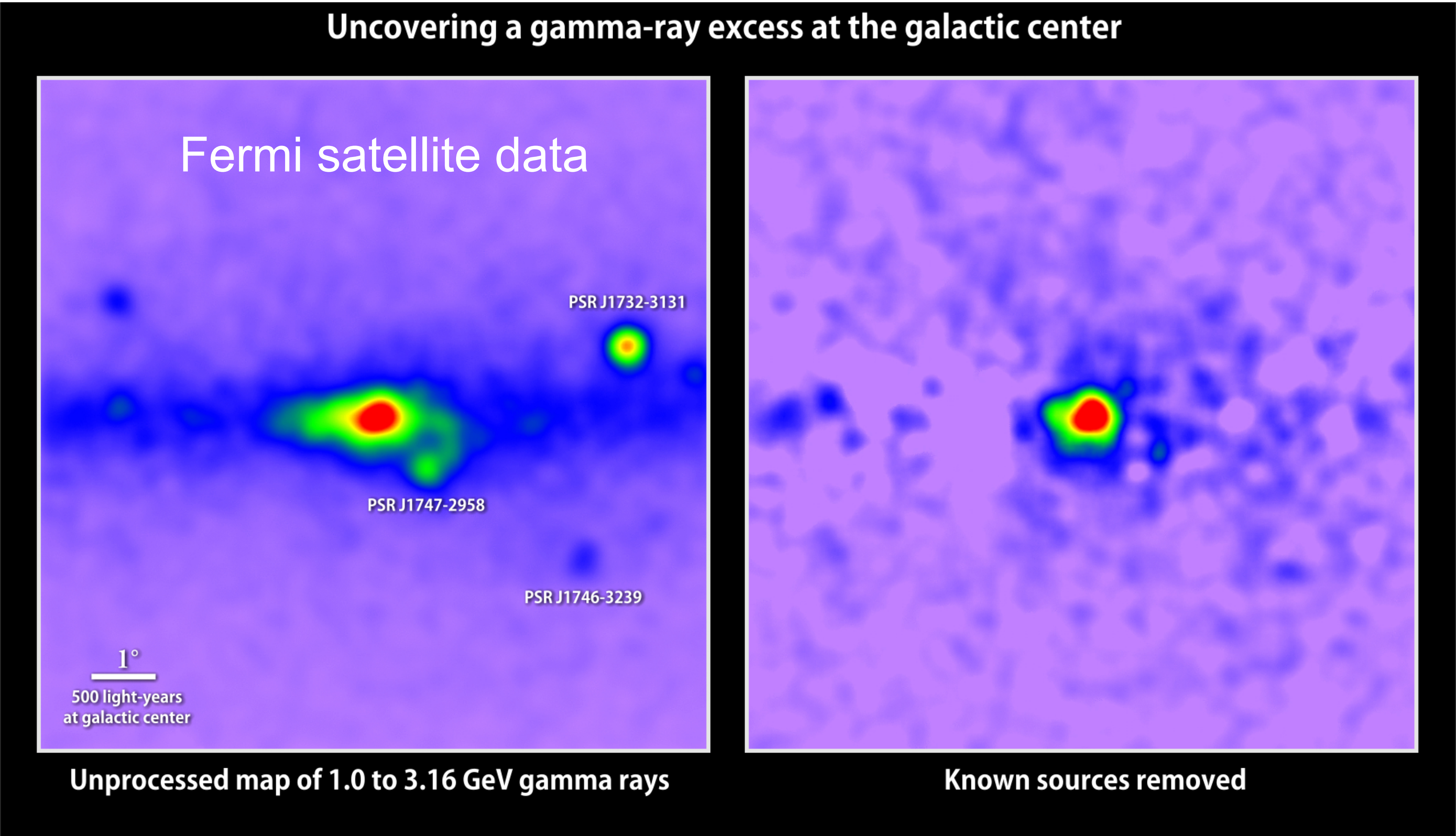
Claims that both types of DM have been discovered:

- CDM: γ-ray excess from Galactic Center
- 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?

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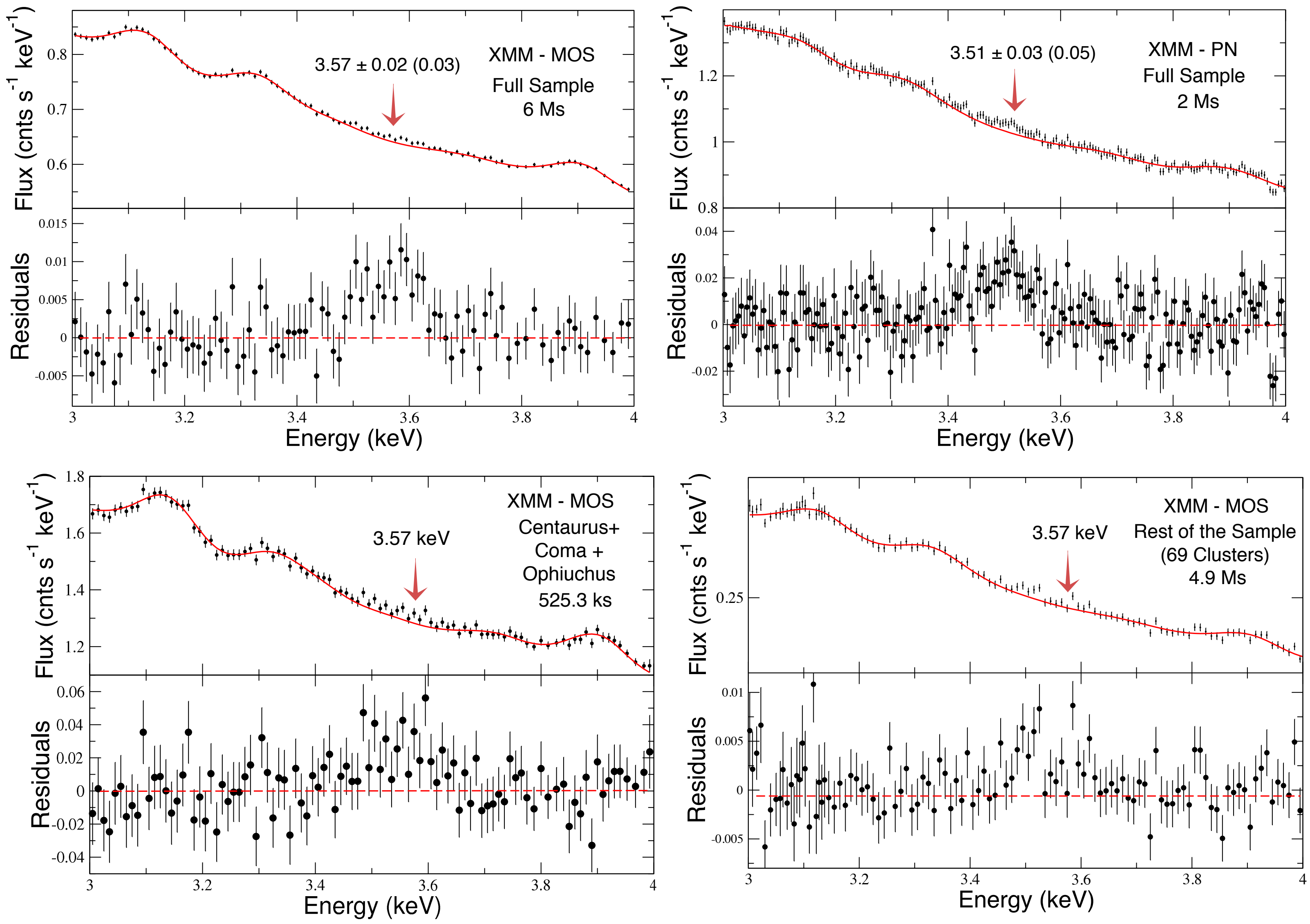
E=3.57 keV Bulbul et al. '14 See also Boyarsky et al. '14



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

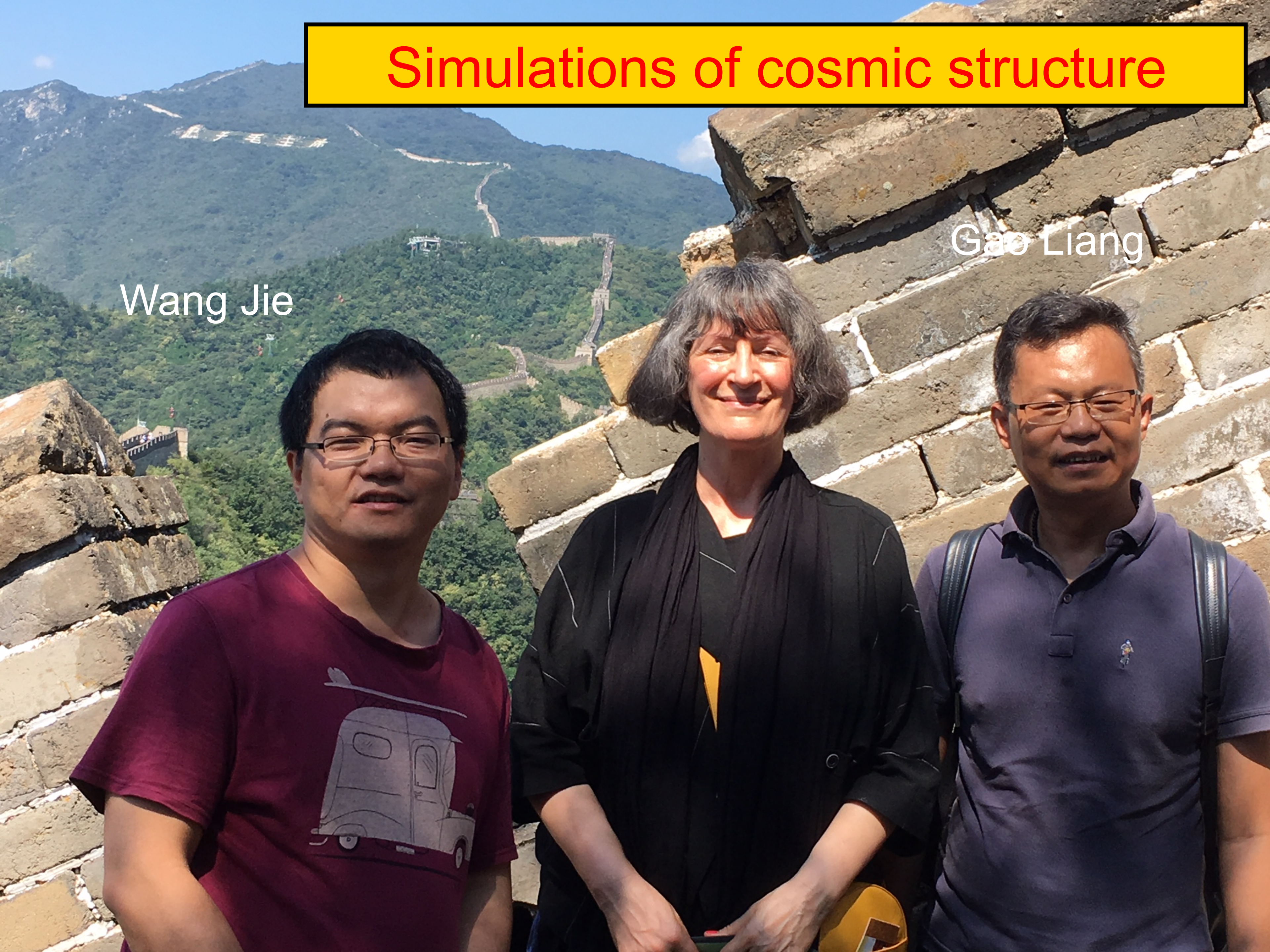
Very unlikely that both are right!

Astrophysical key to identity of dark matter

→Subgalactic scales

(strongly non-linear)

Simulations of cosmic structure



ICC

Cold Dark Matter | Warm Dark Matter

13.4 billion years ago

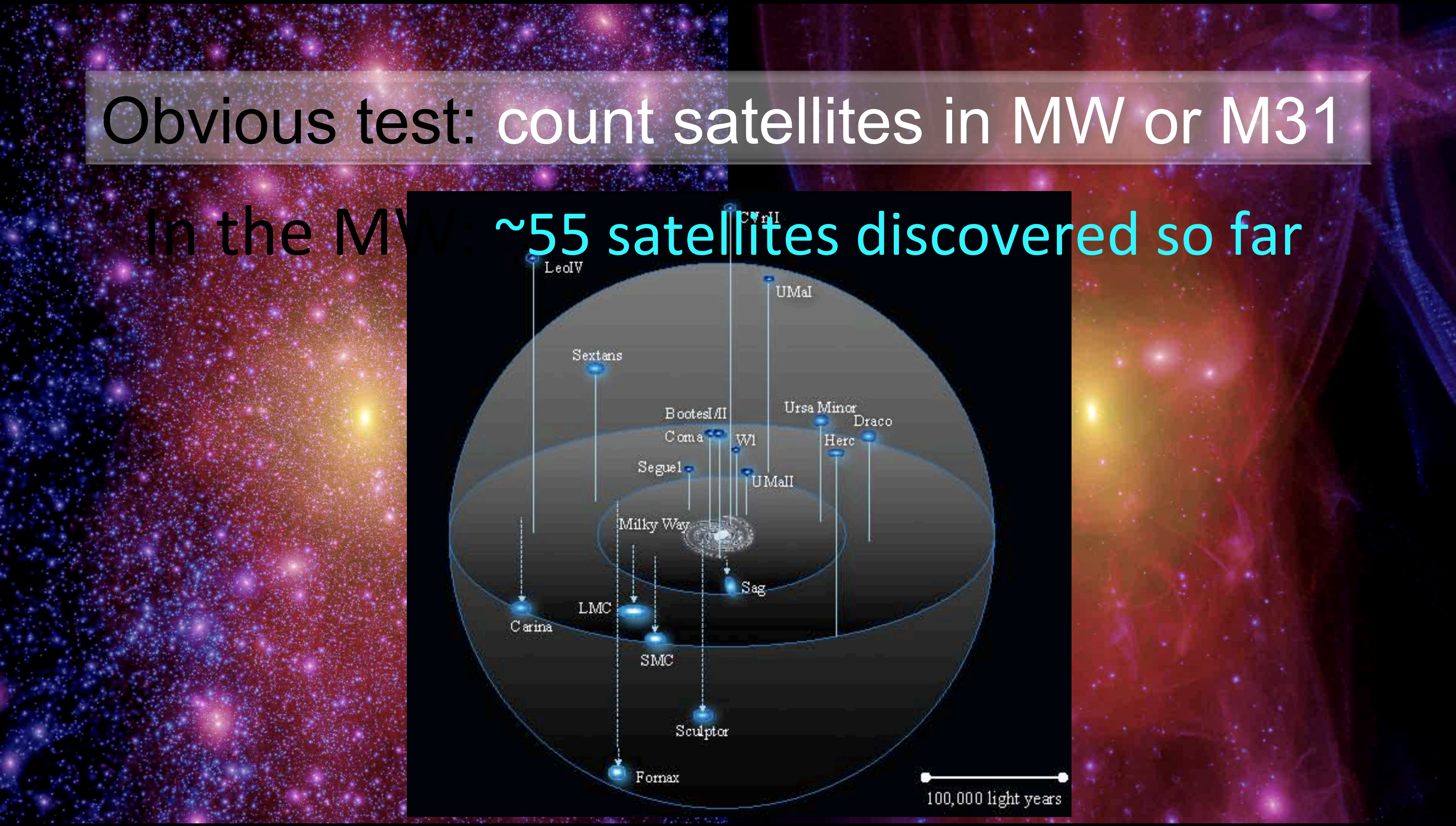
Institute for Computational Cosmology

cold dark matter warm dark matter

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

cold dark matter

warm dark matter



Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far

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

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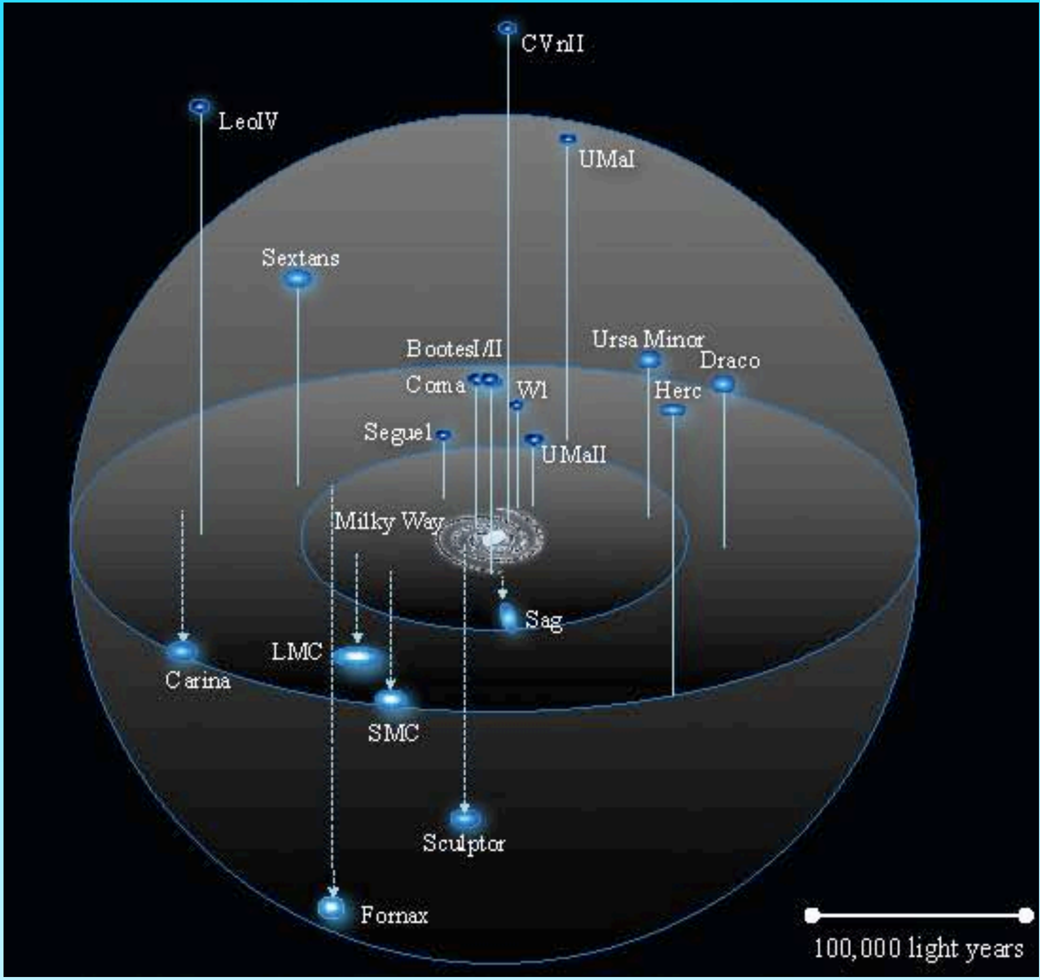
The MW satellite luminosity function

~55 satellites discovered so far in MW



About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)

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The MW satellite luminosity function

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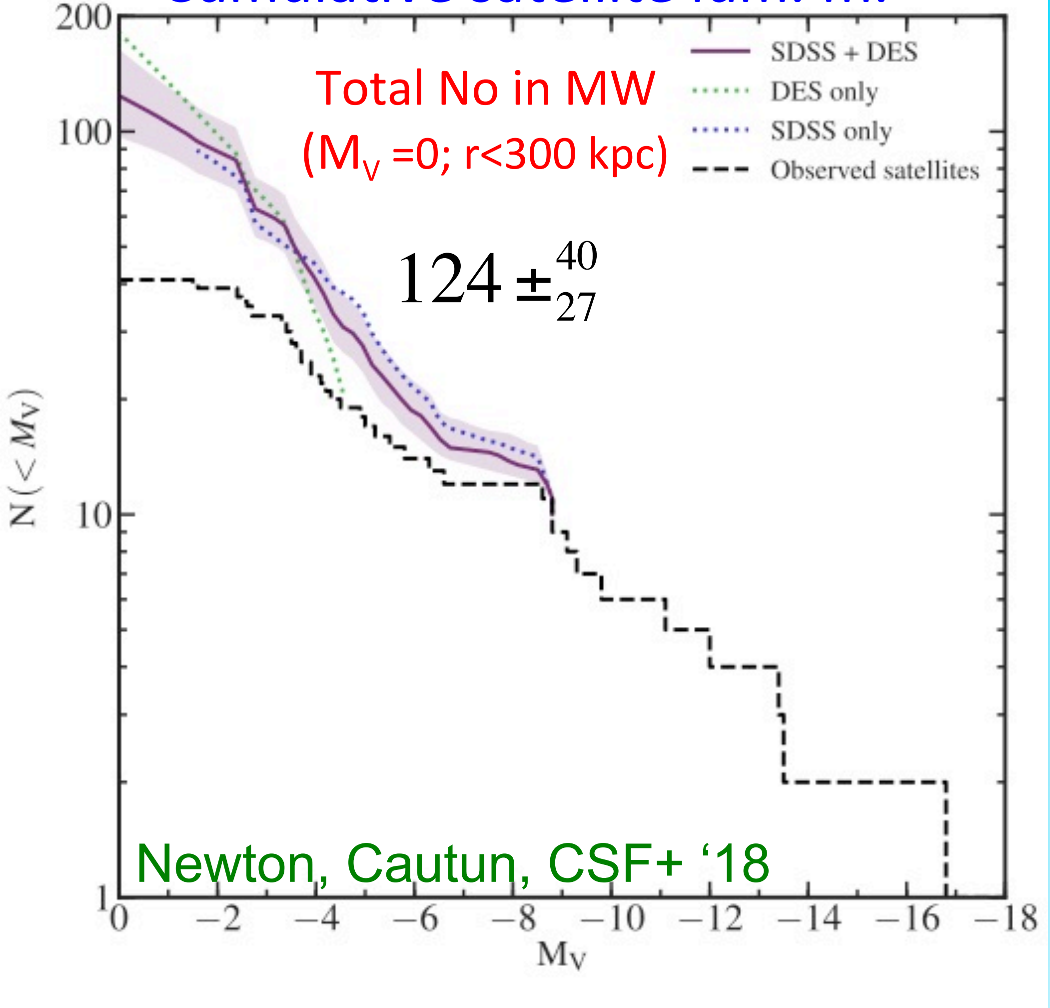
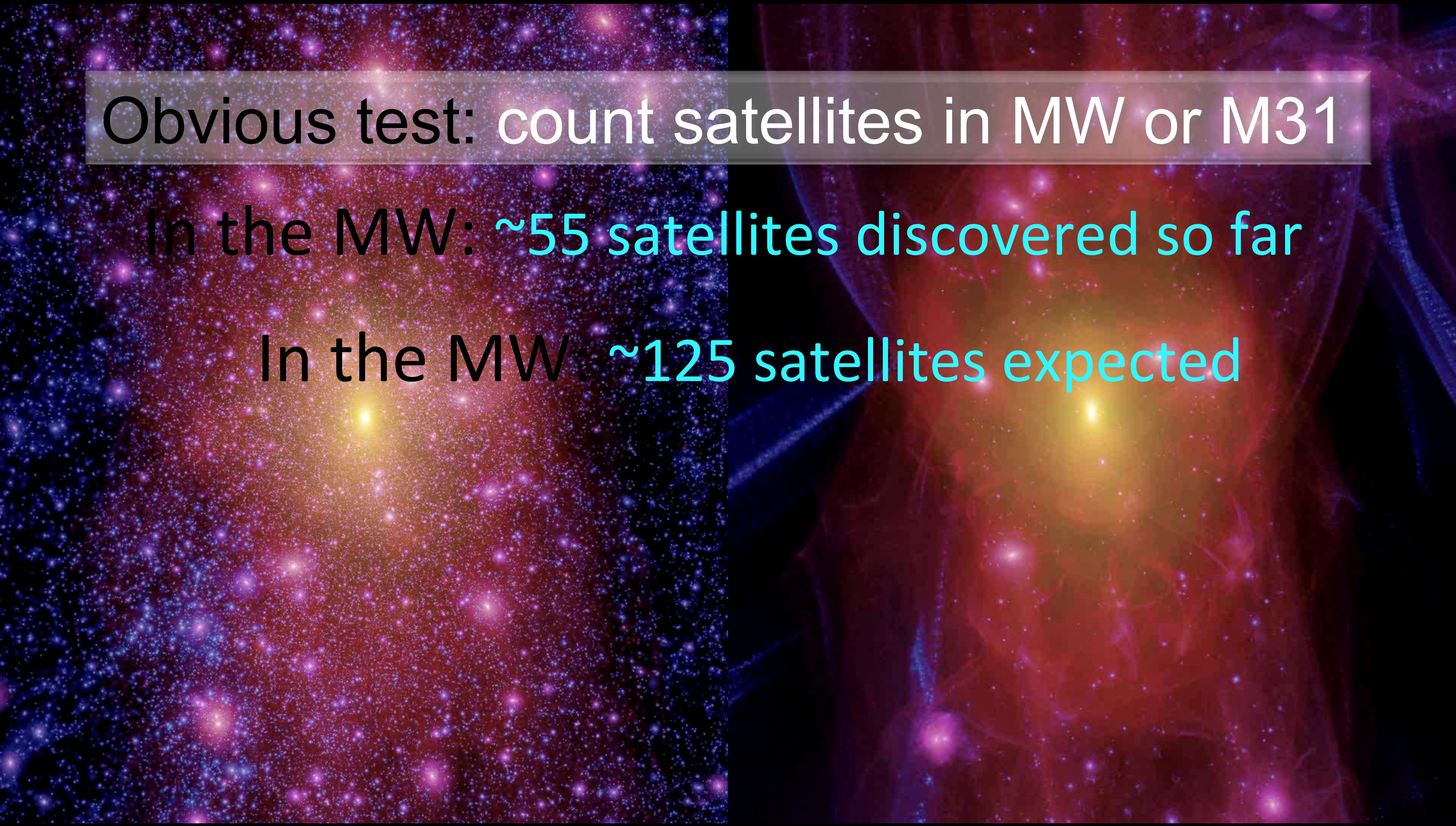
Cumulative satellite lum. fn.



cold dark matter   warm dark matter



Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far

In the MW: ~125 satellites expected

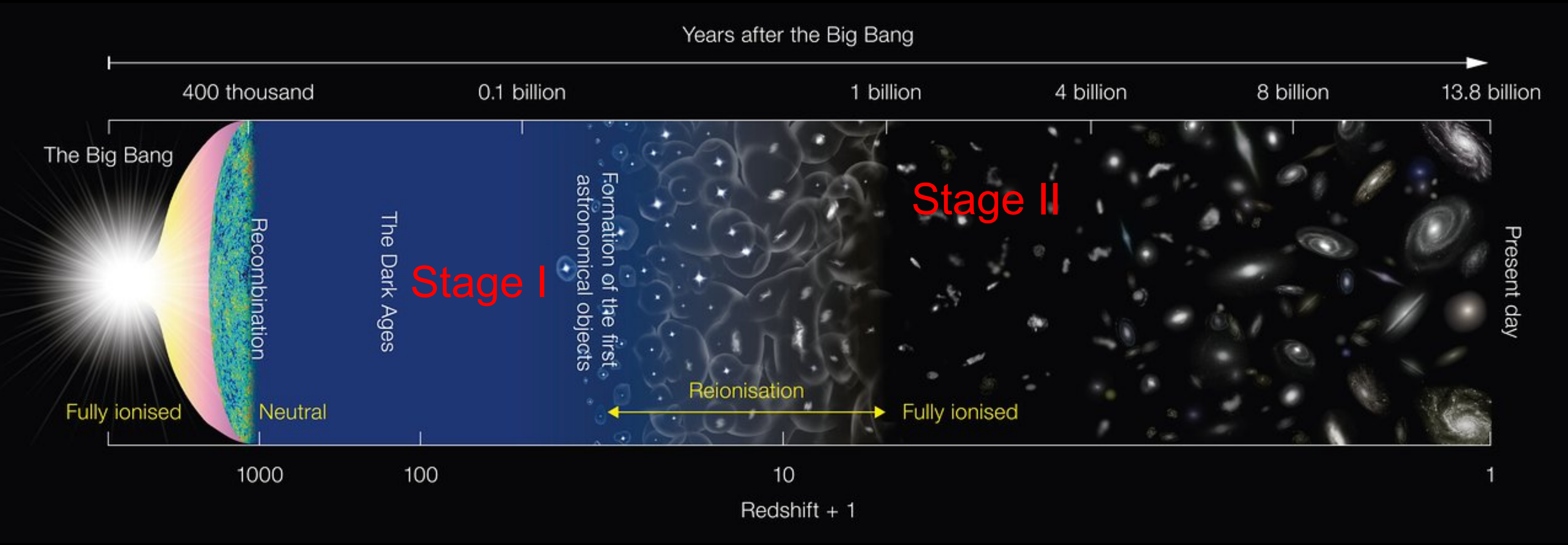
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '12

cold dark matter　　　　warm dark matter

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


Most subhalos never make a galaxy!

The two stages of galaxy formation



Stage I: Galaxies begin to form during the “dark ages”

First stars reionize H and heat it up to 10^4K → prevents gas from cooling in halos of “T_{vir}” < 10^4K – galaxy formation is interrupted

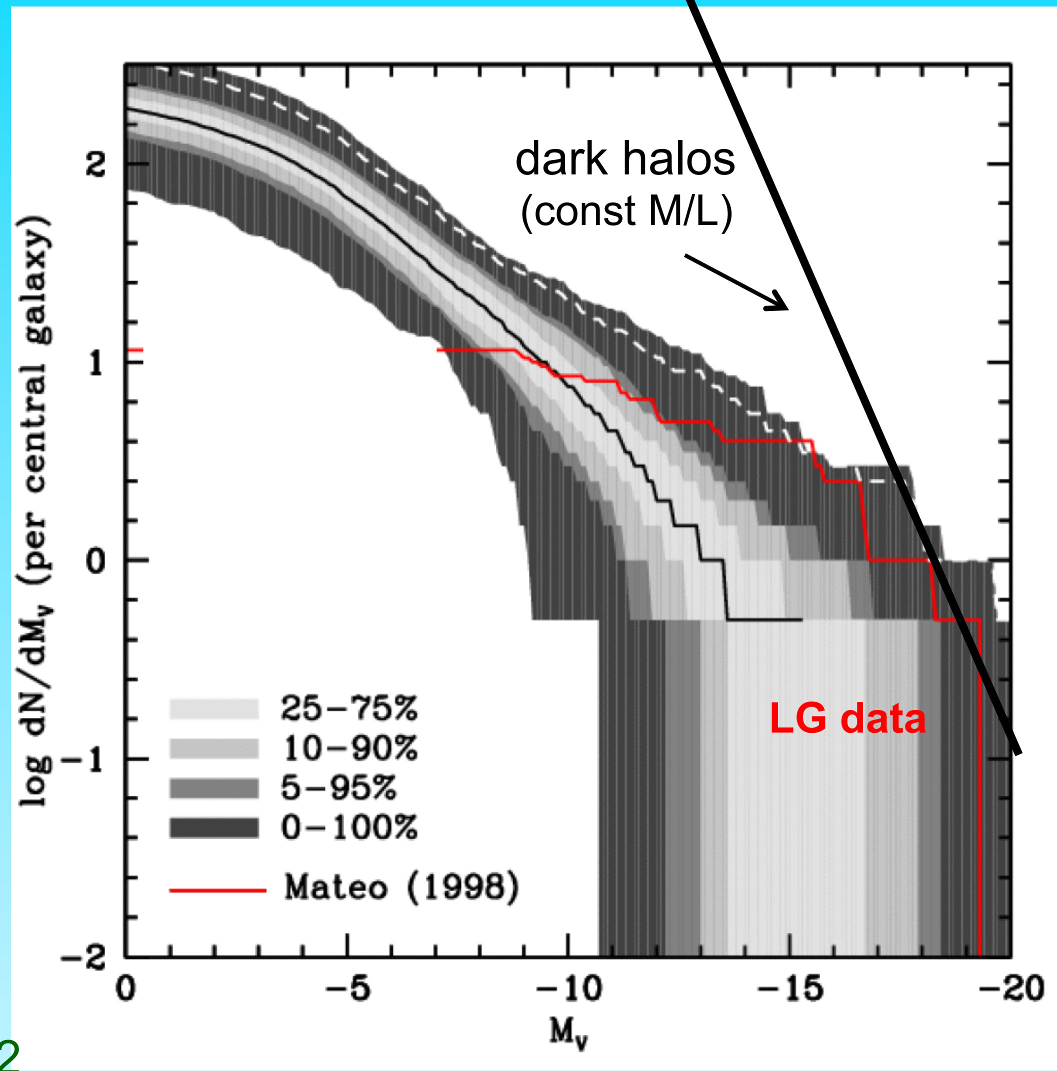
Stage II: Halos with “T_{vir}” > 10^4K form → galaxy formation resumes

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

Luminosity Function of Local Group Satellites

University of Durham

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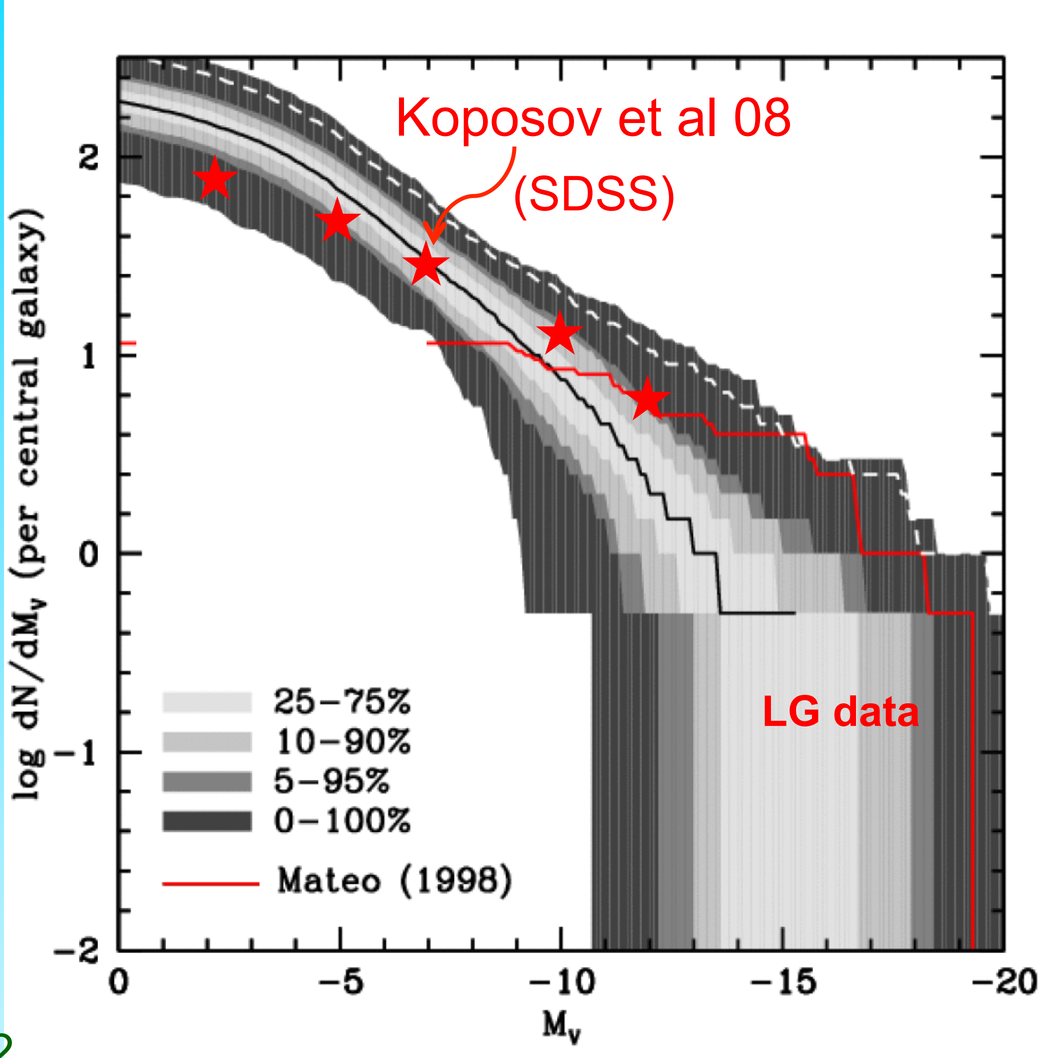


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman et al ’93, Bullock et al ’01)

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…

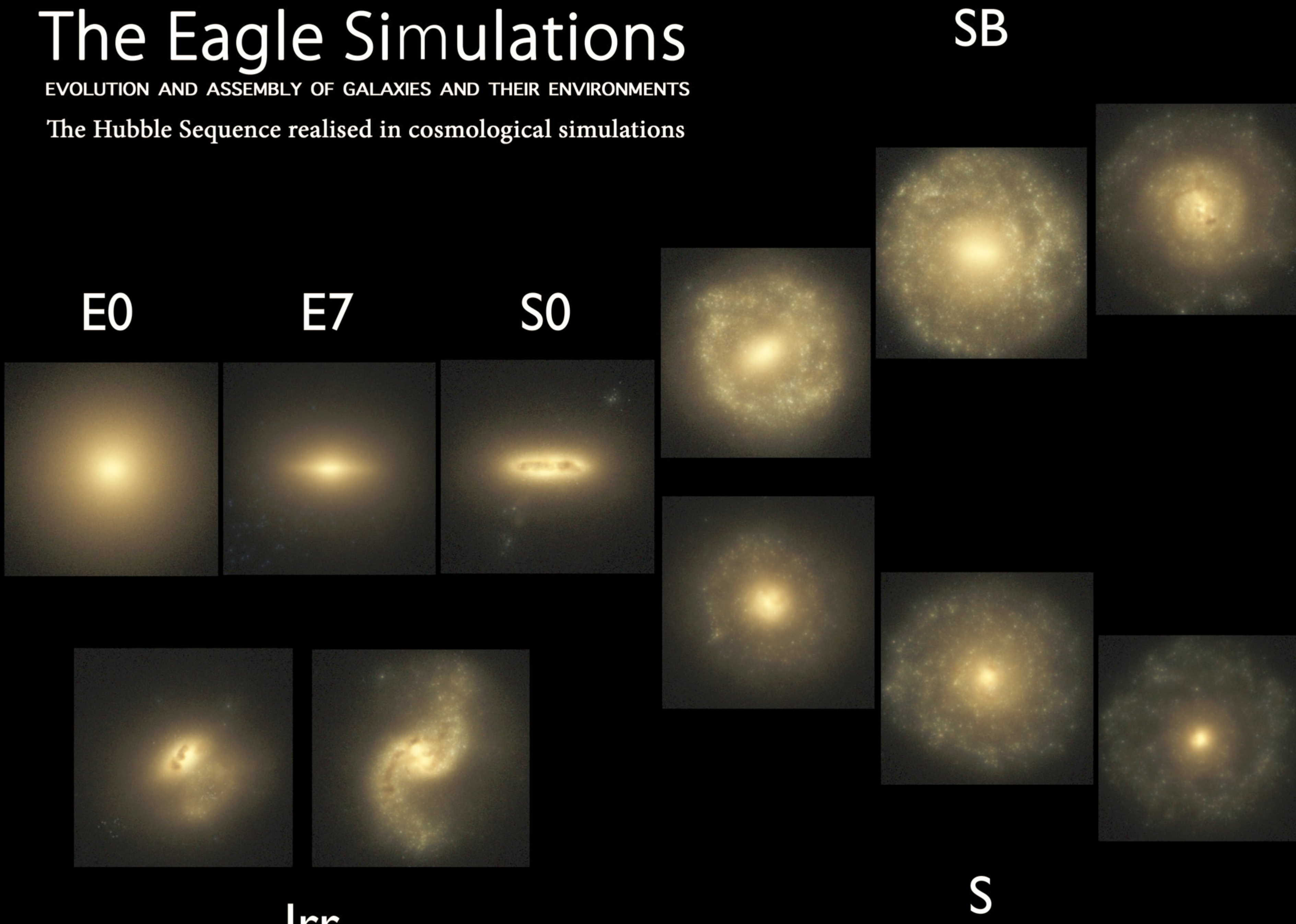
Durham University VIRGO ICC DiRAC PRACE

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

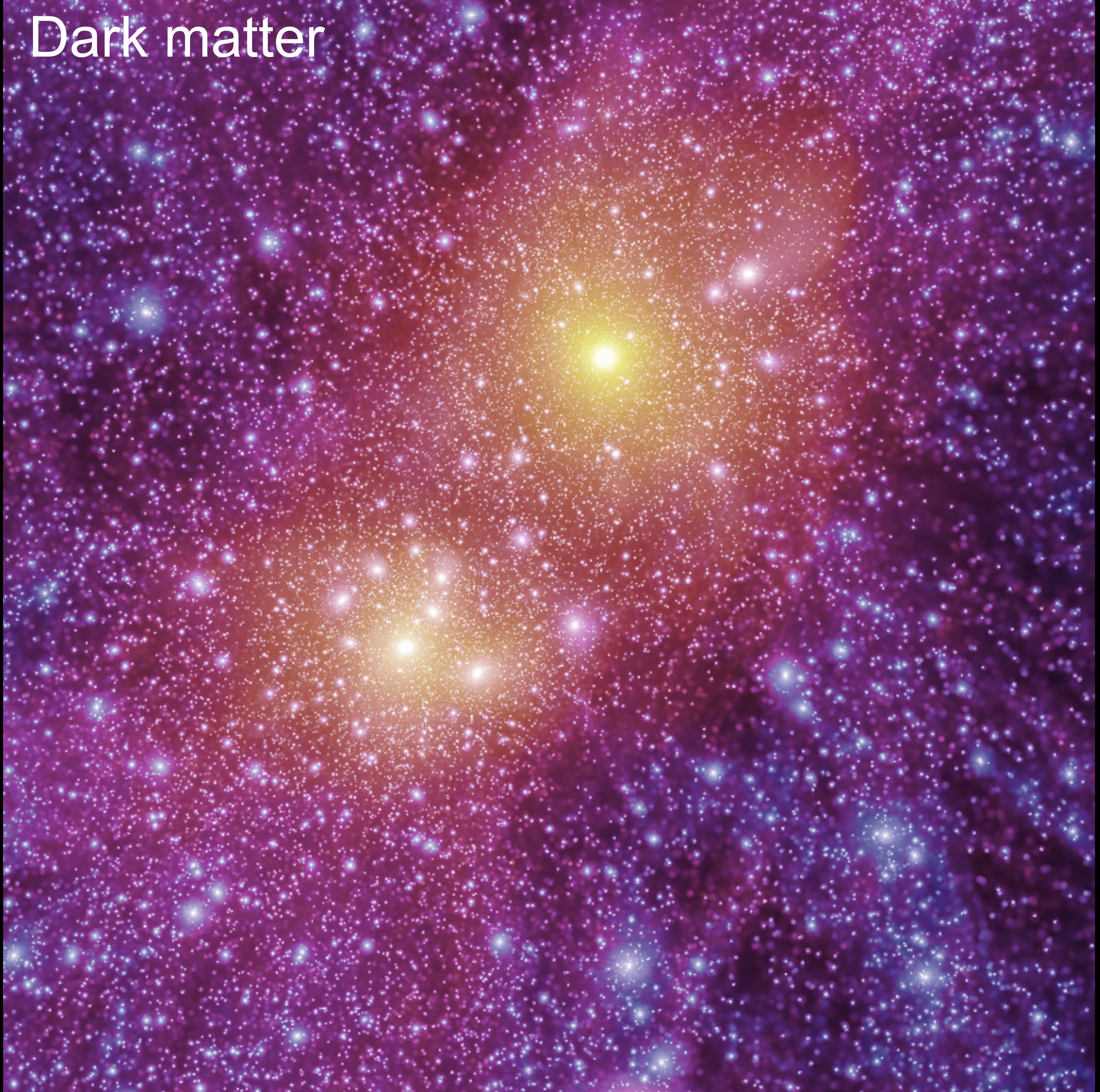
VIRGO

APOSTLE
EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16



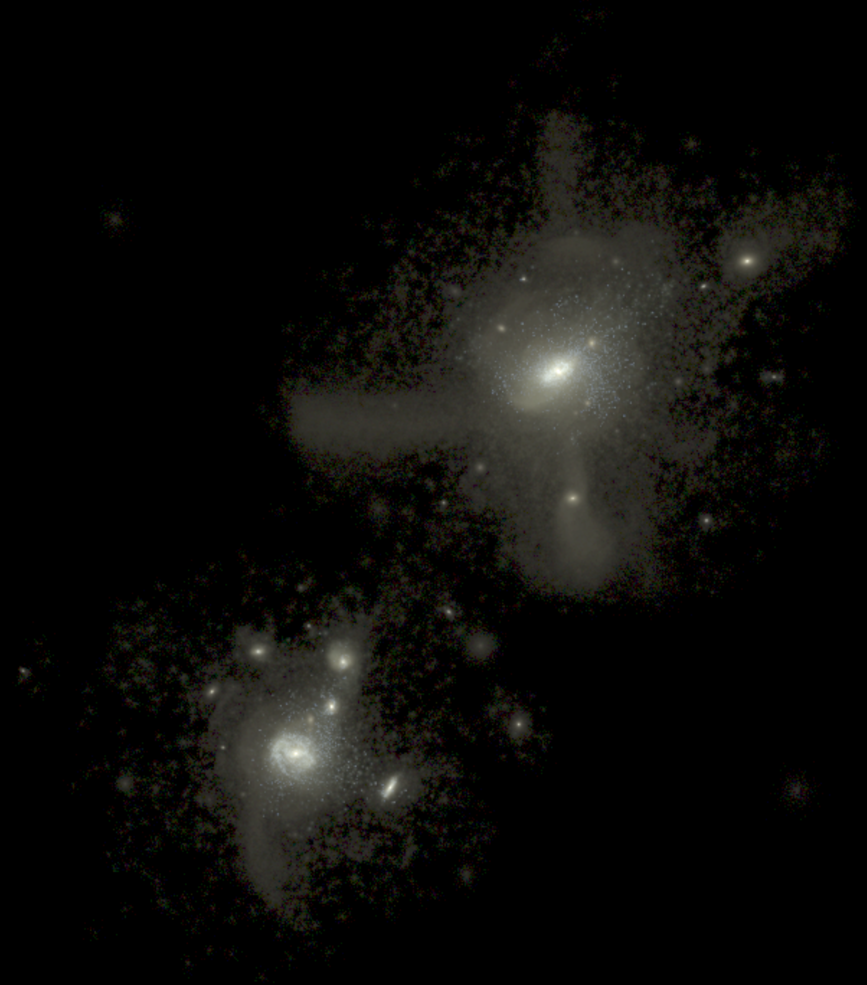
VIRGO

Stars

APOSTLE EAGLE full hydro simulations

Local Group

CDM



Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

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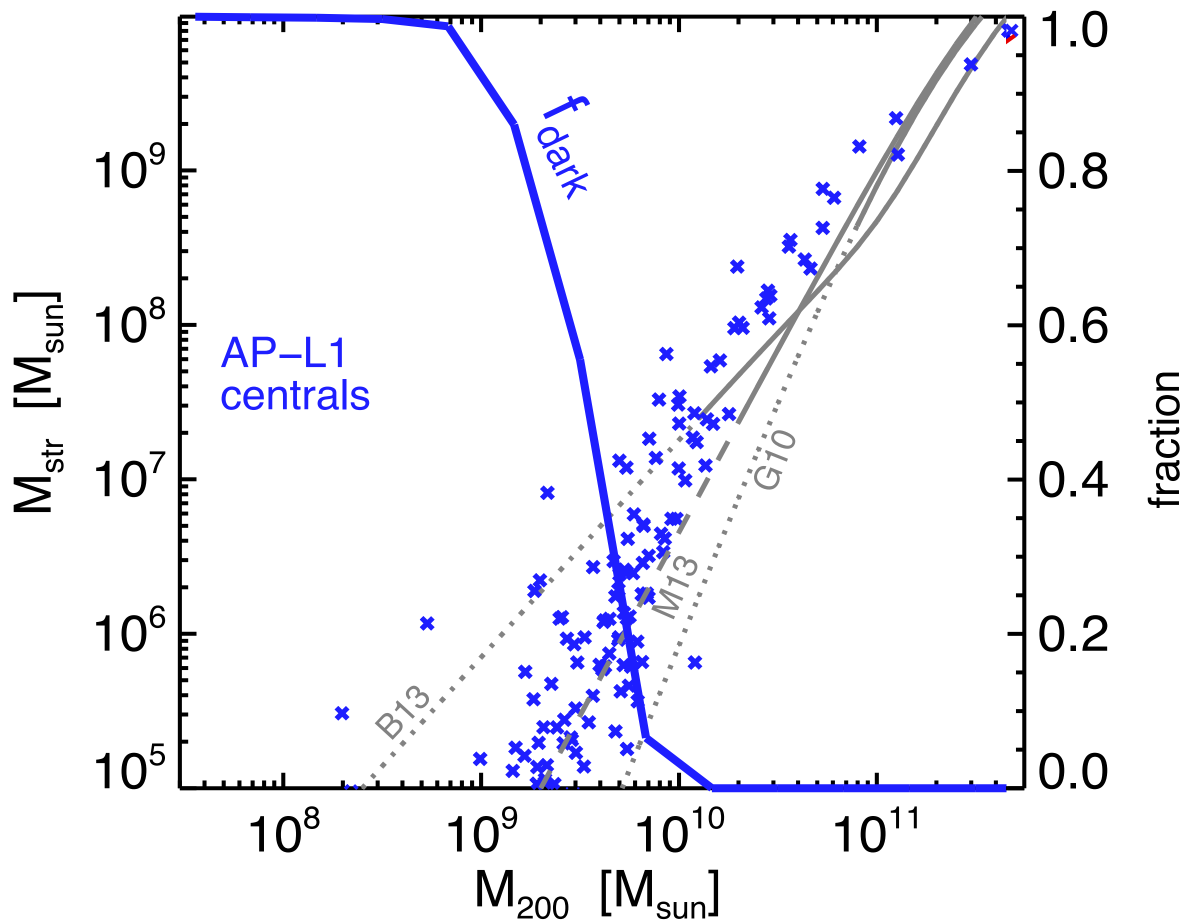
Fraction of dark subhalos

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

$V_{max} = \max V_c$



All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

Fattahi et al '16

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EAGLE Local Group simulation

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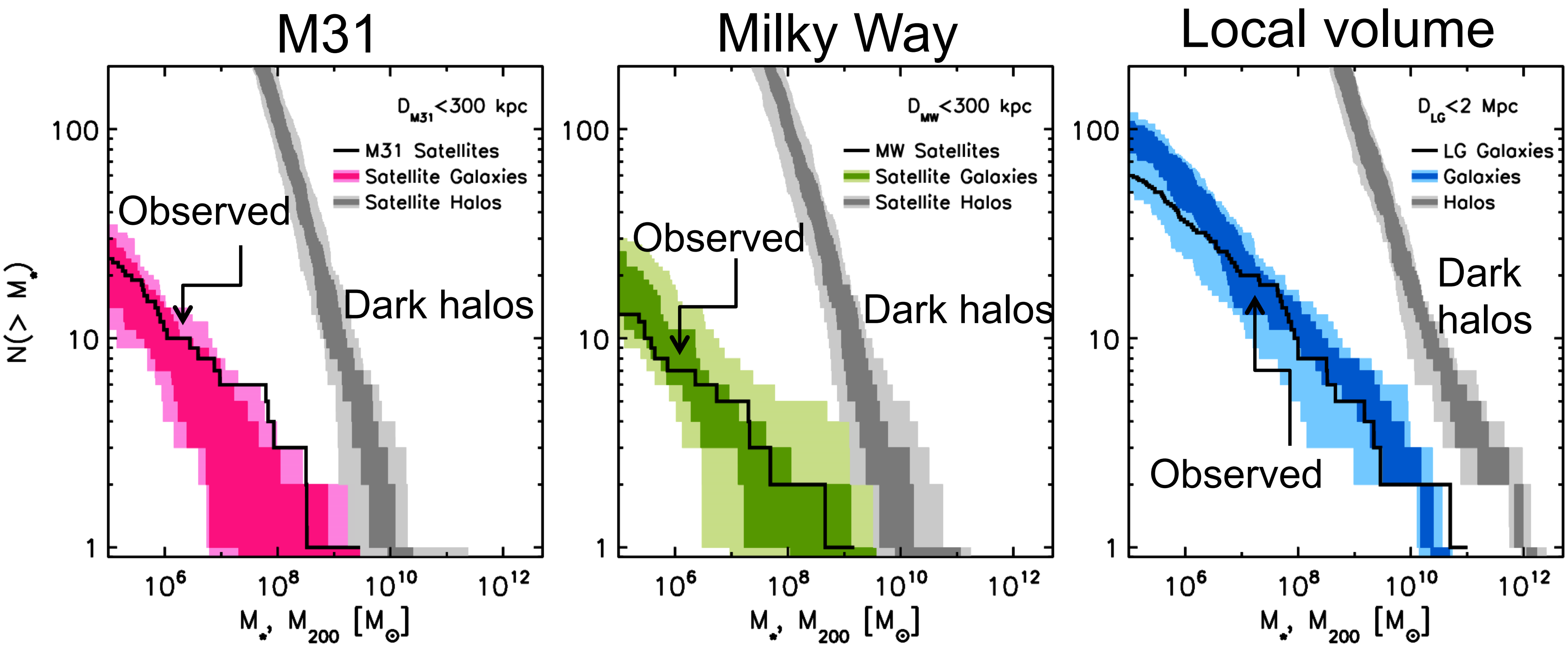


Sawala et al '16

When "baryon effects" are taken into account

→

Observed abundance of satellites is compatible with CDM

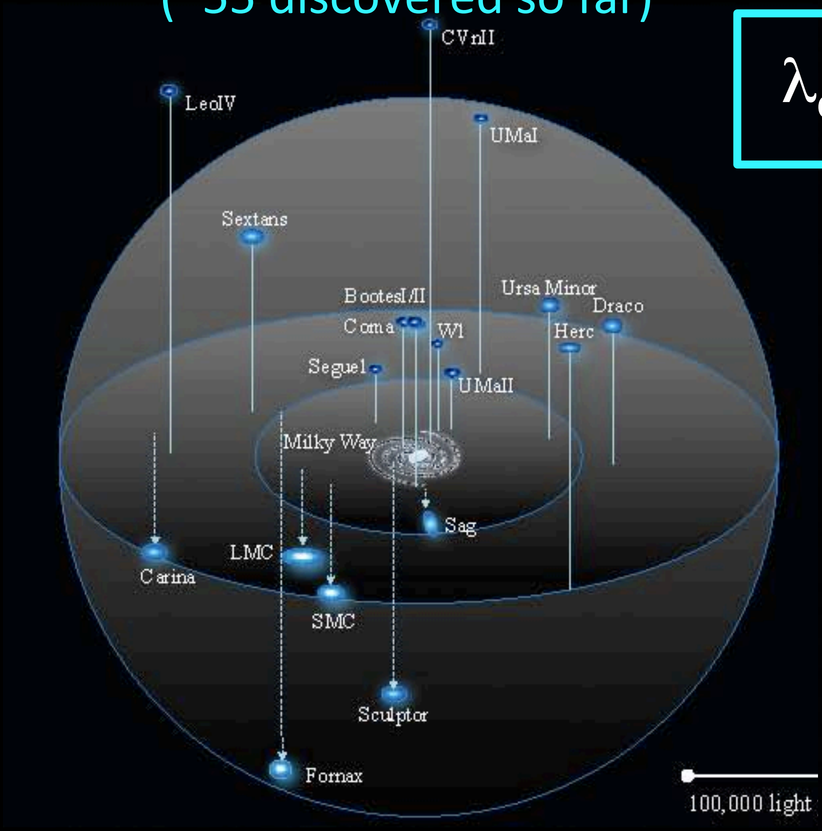
→

There is no such thing as the "satellite problem" in CDM!

How about in WDM?

The satellites of the MW

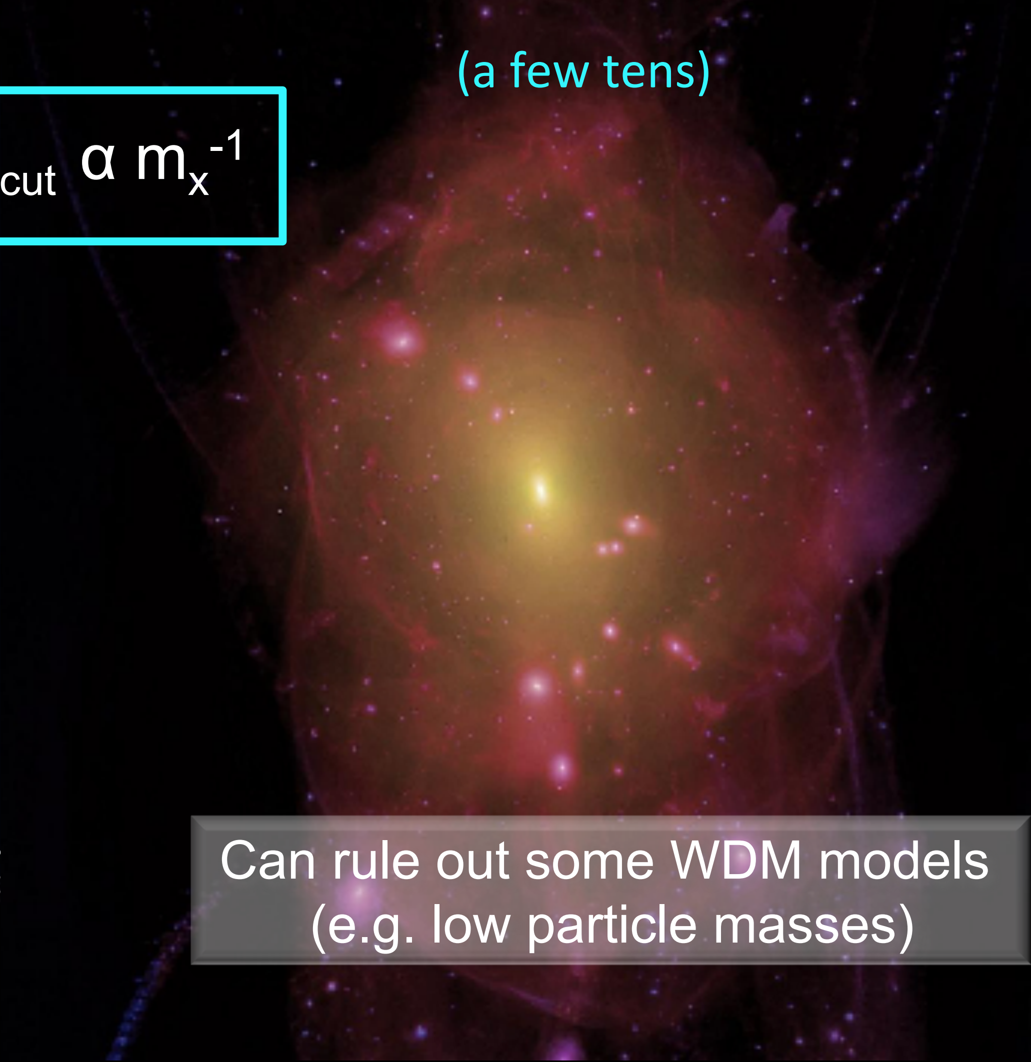
(~55 discovered so far)



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

Dark matter subhalos in WDM

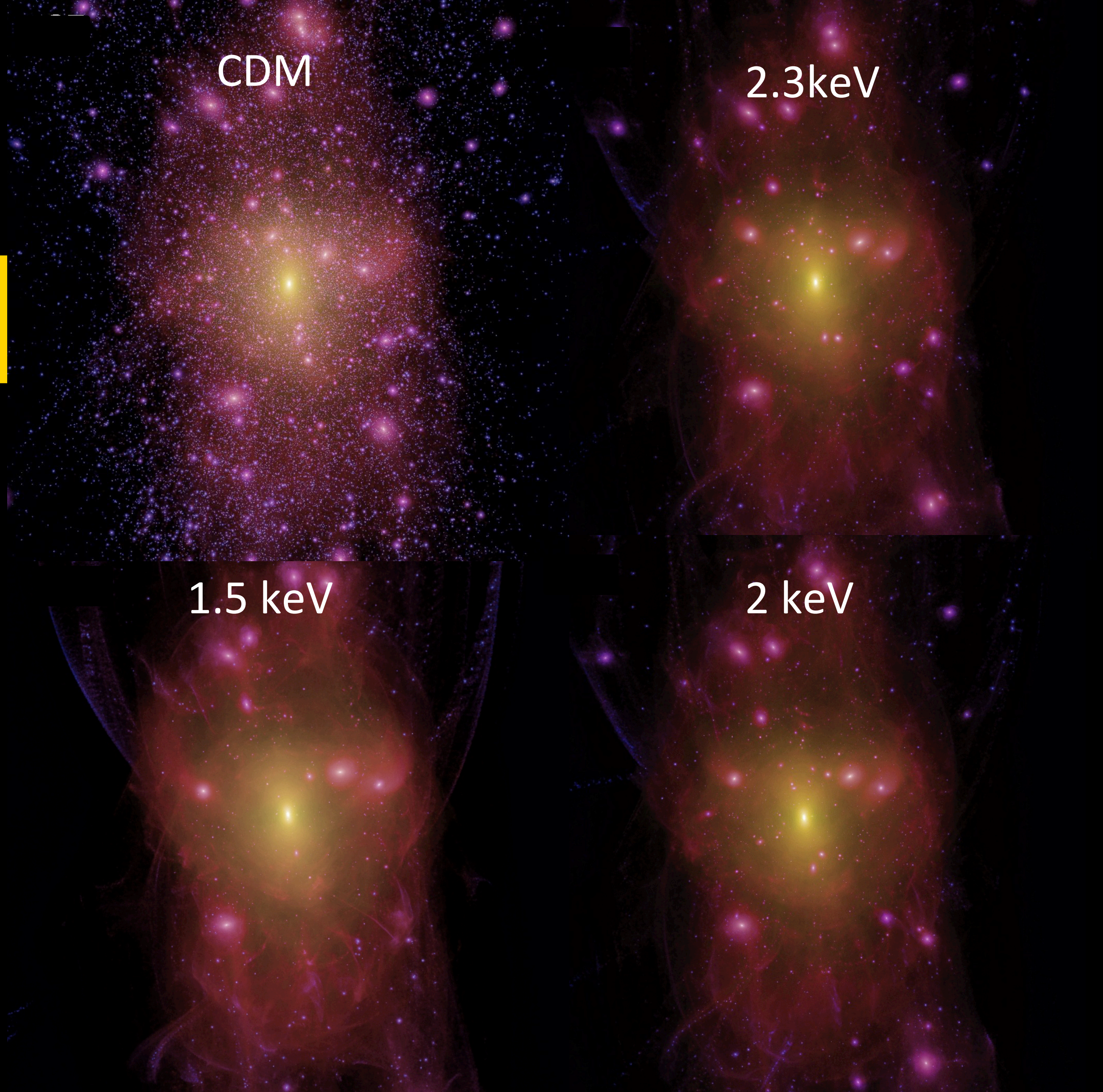
(a few tens)



Can rule out some WDM models (e.g. low particle masses)

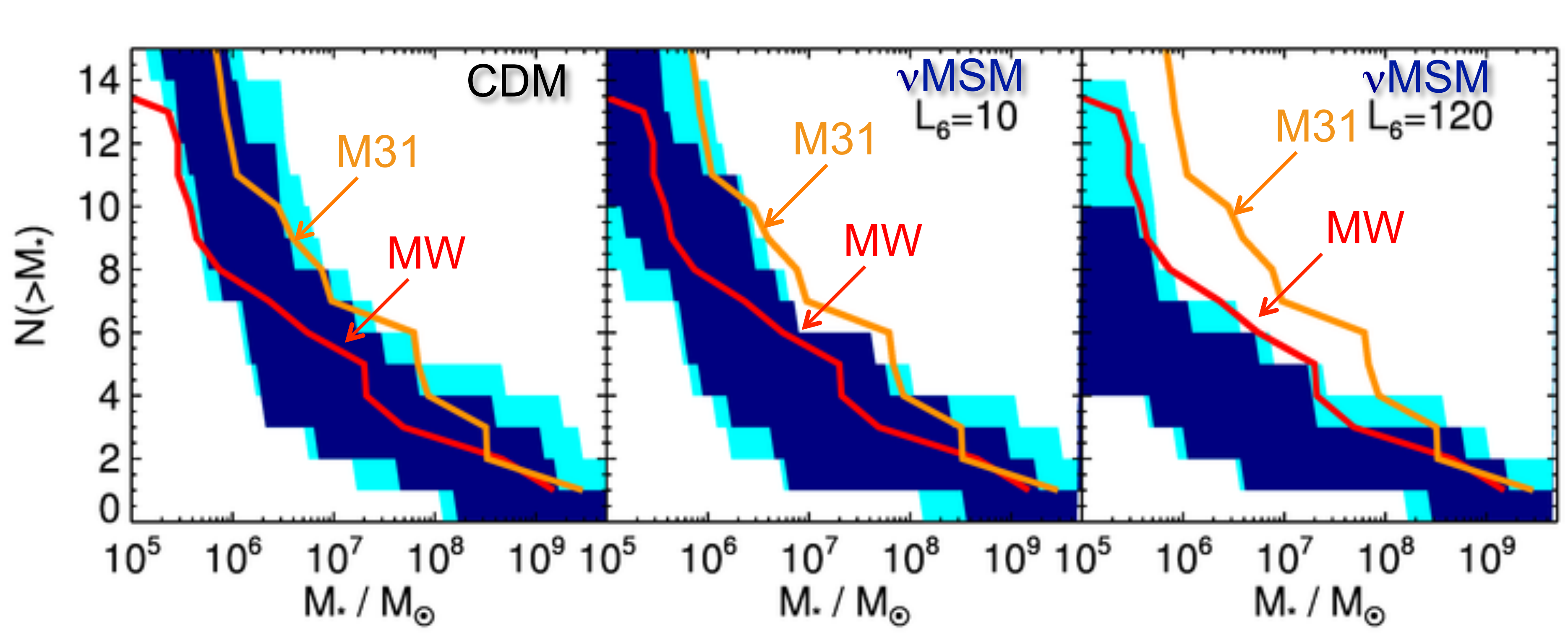
Warm DM: different ν mass

WDM
2.3 keV
2.0 keV
1.5 keV



Luminosity Function of Local Group Satellites in WDM

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



Lovell et al. '16

Mon. Not. R. Astron. Soc. 283, L72–L78 (1996)

How about baryon effects?

The cores of dwarf galaxy haloes

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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.

The physics of core formation

Cusps → cores

Perturb central halo region by growing a galaxy adiabatically and removing it suddenly (Navarro, Eke & Frenk '96)

Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

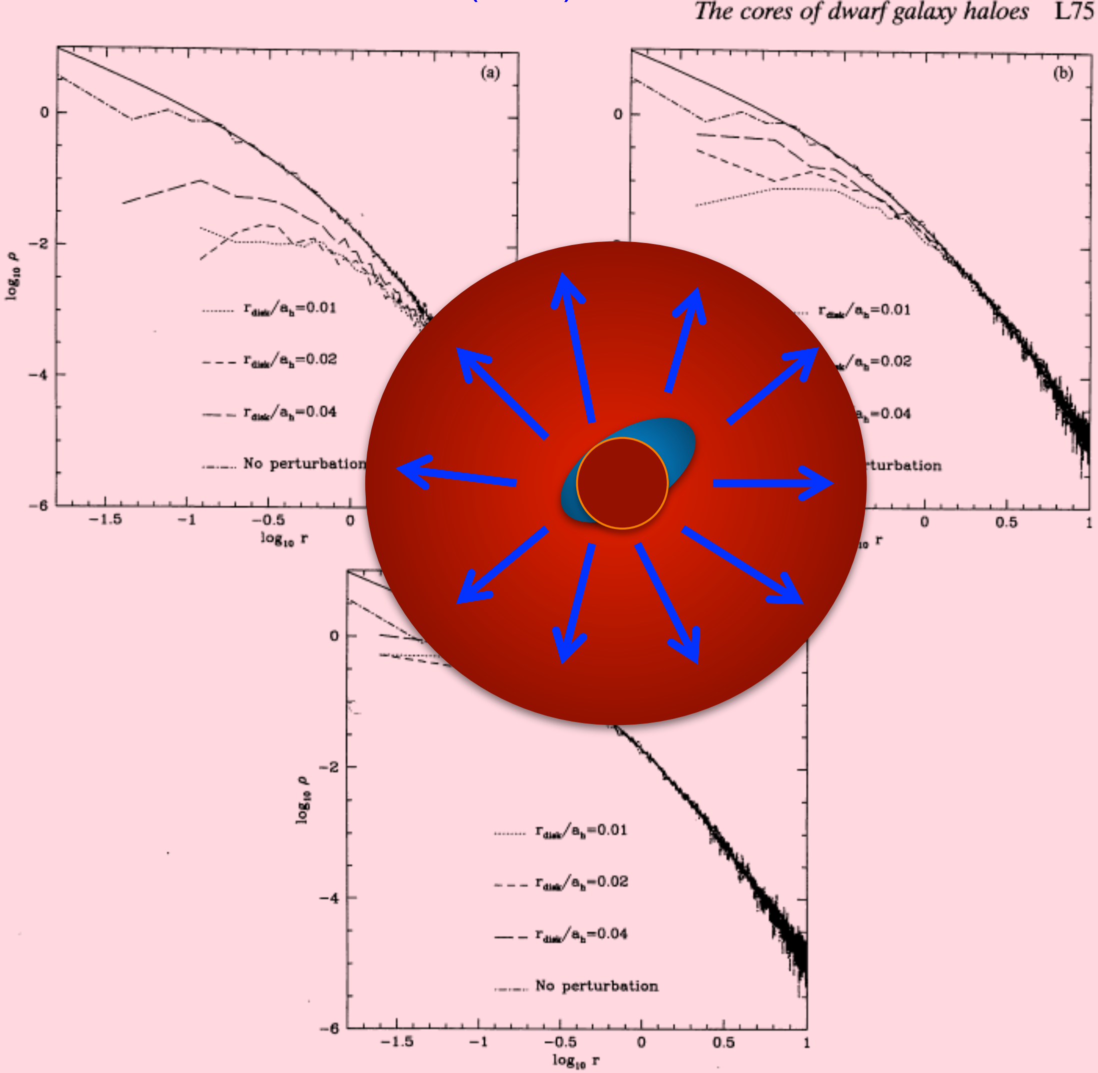


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

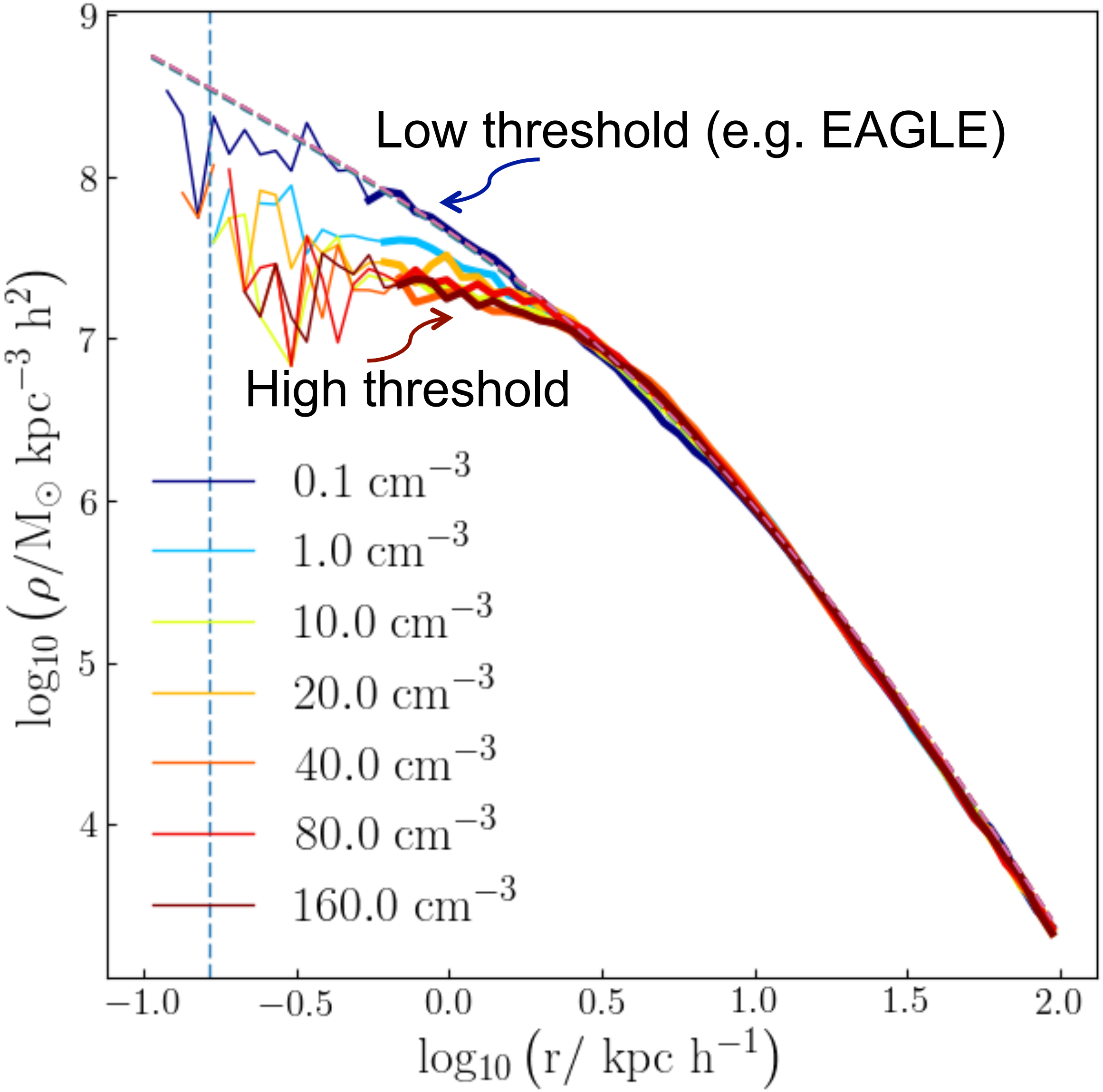
Core formation

In the absence of a treatment of the (multi-phase) interstellar medium, need a “subgrid” model for star formation

Key parameter: gas density threshold for star formation

Physically meaningless

Cores or cusps in simulations?



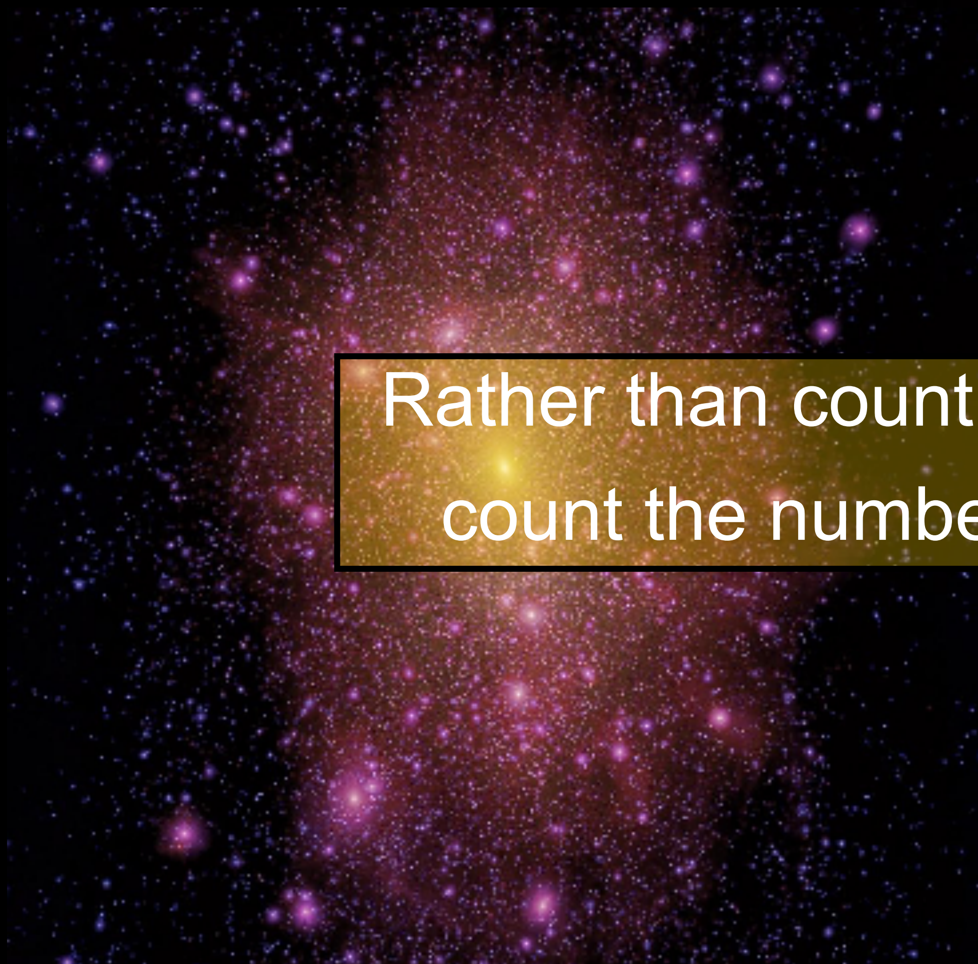
Benitez-Llambay, CSF et al '17

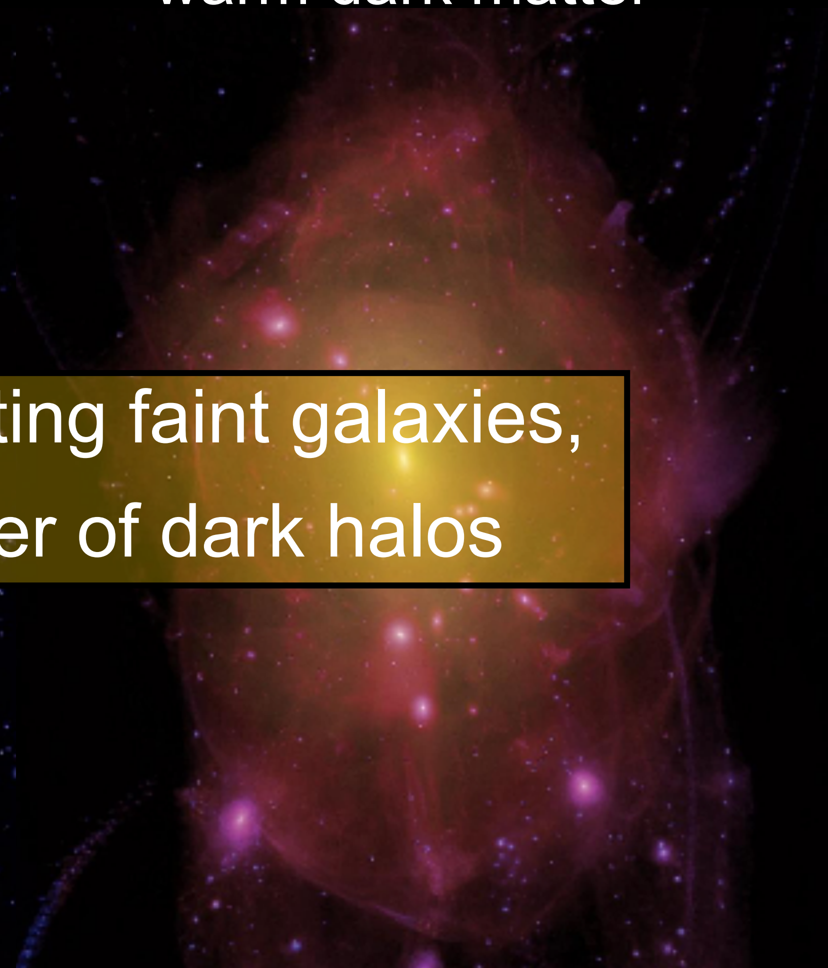
So, we can't distinguish CDM from WDM by counting satellite galaxies or by their structure

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

Can we distinguish CDM/WDM?

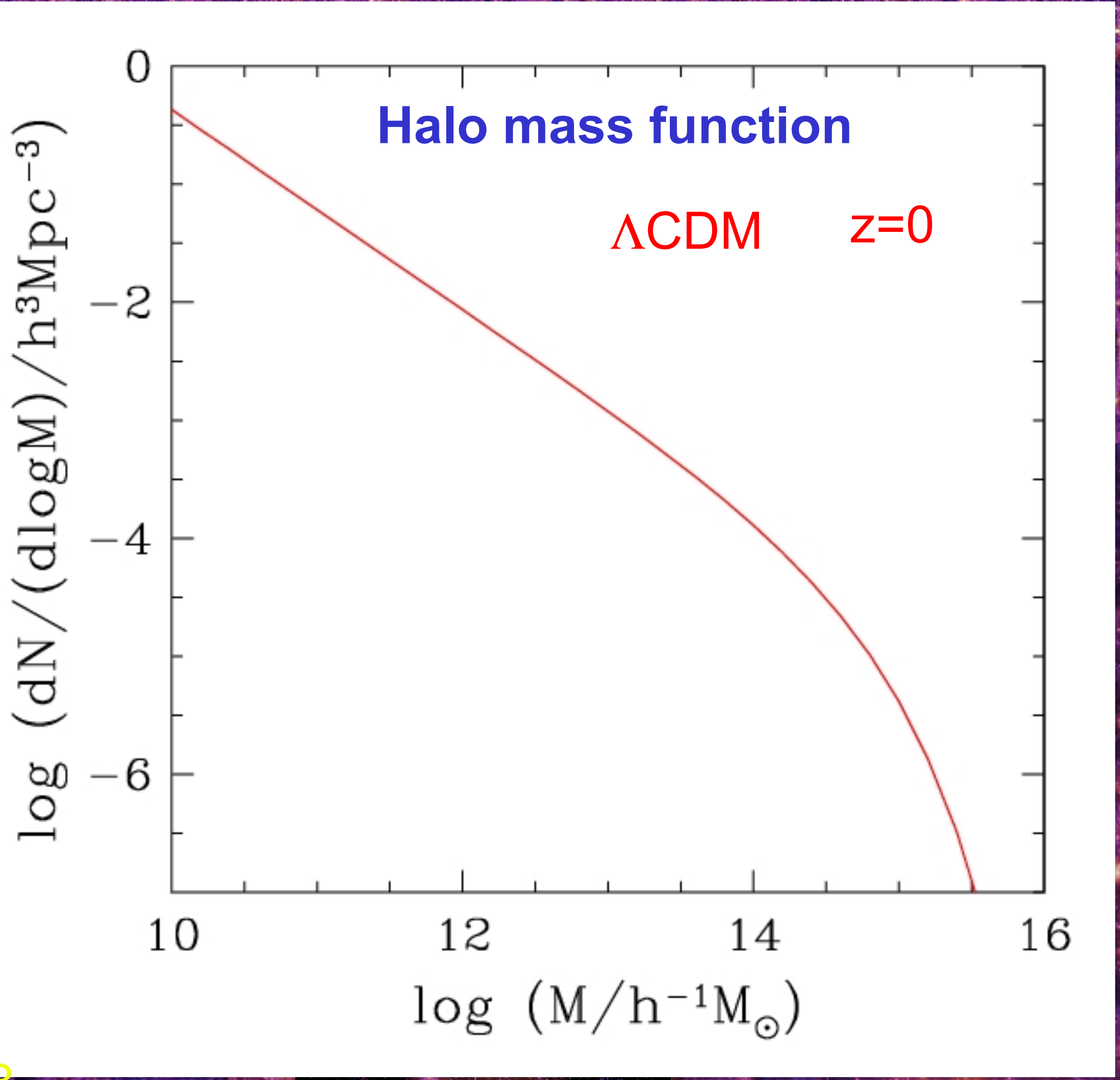
cold dark matter | warm dark matter





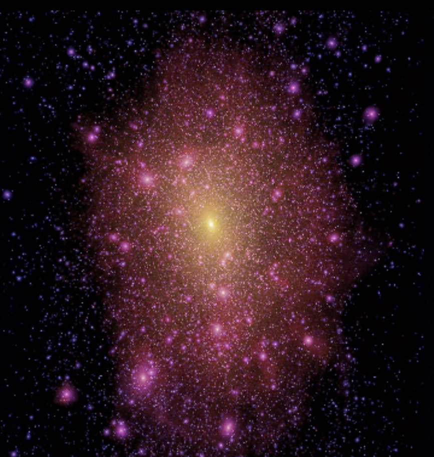
Rather than counting faint galaxies, count the number of dark halos

The Millennium/Aquarius/Phoenix simulation series



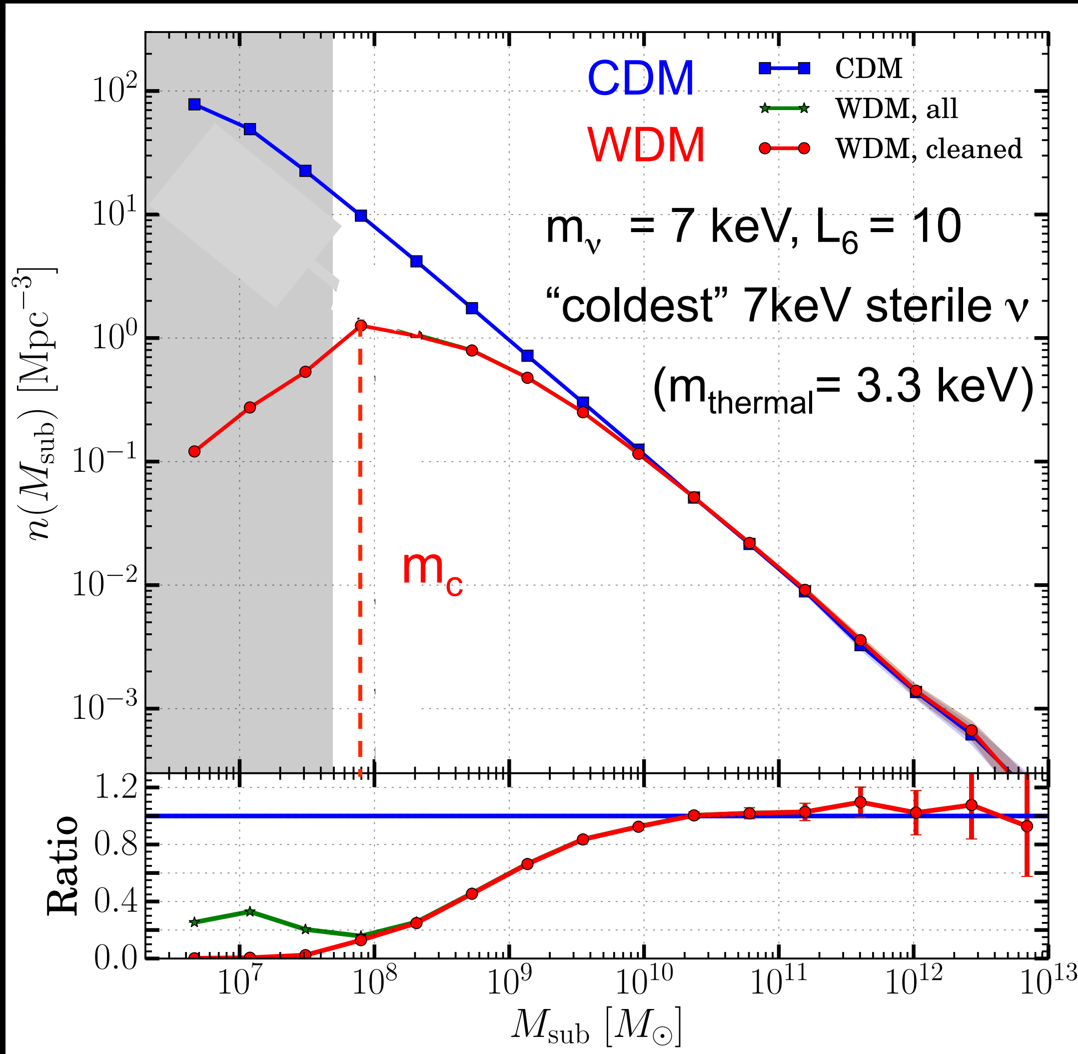
Springel et al '05, '08,
Gao et al '11

The halo 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

Can we distinguish CDM/WDM?

cold dark matter

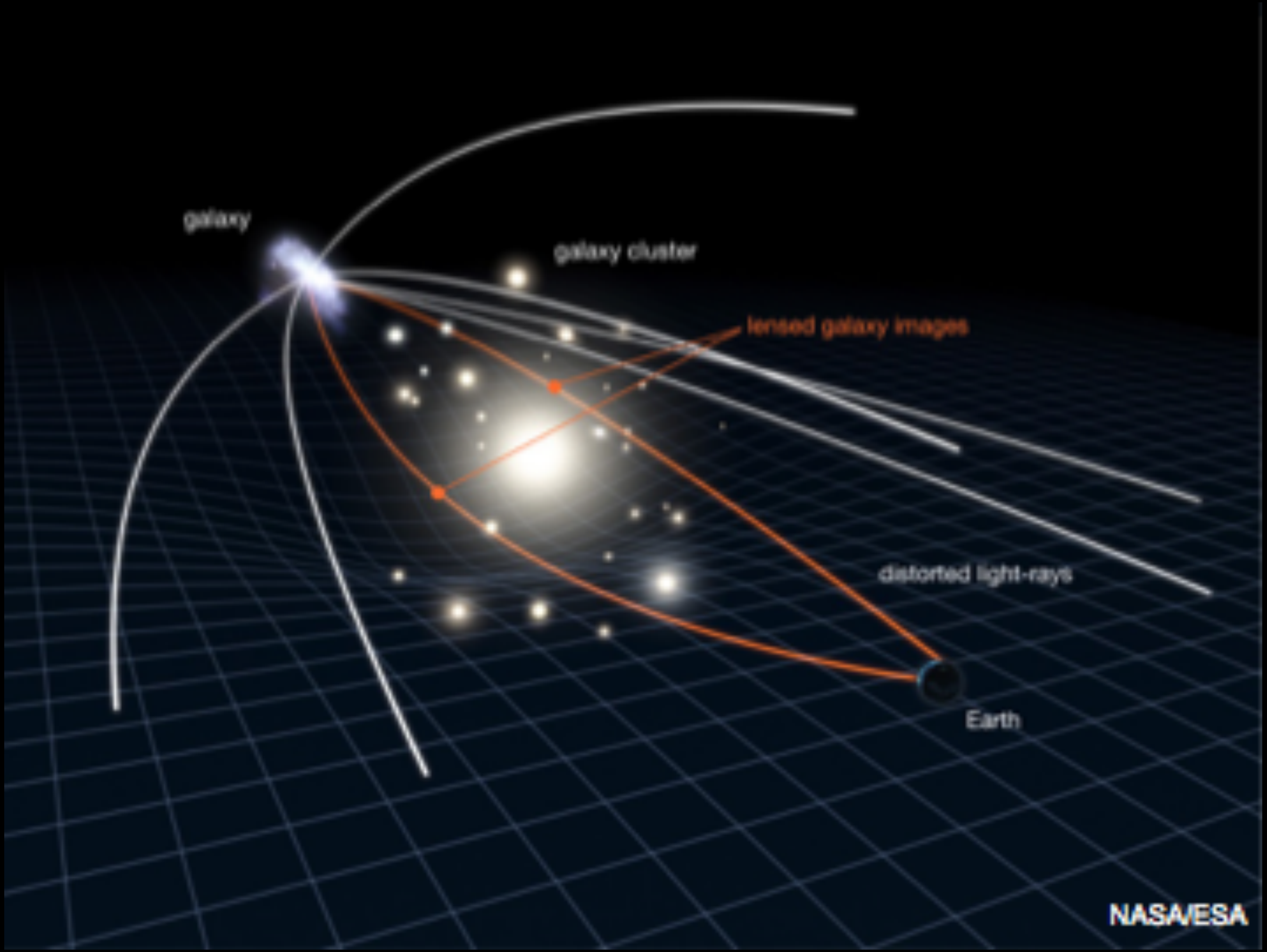
warm dark matter

Gravitational lensing

Gravitational lensing: Einstein rings

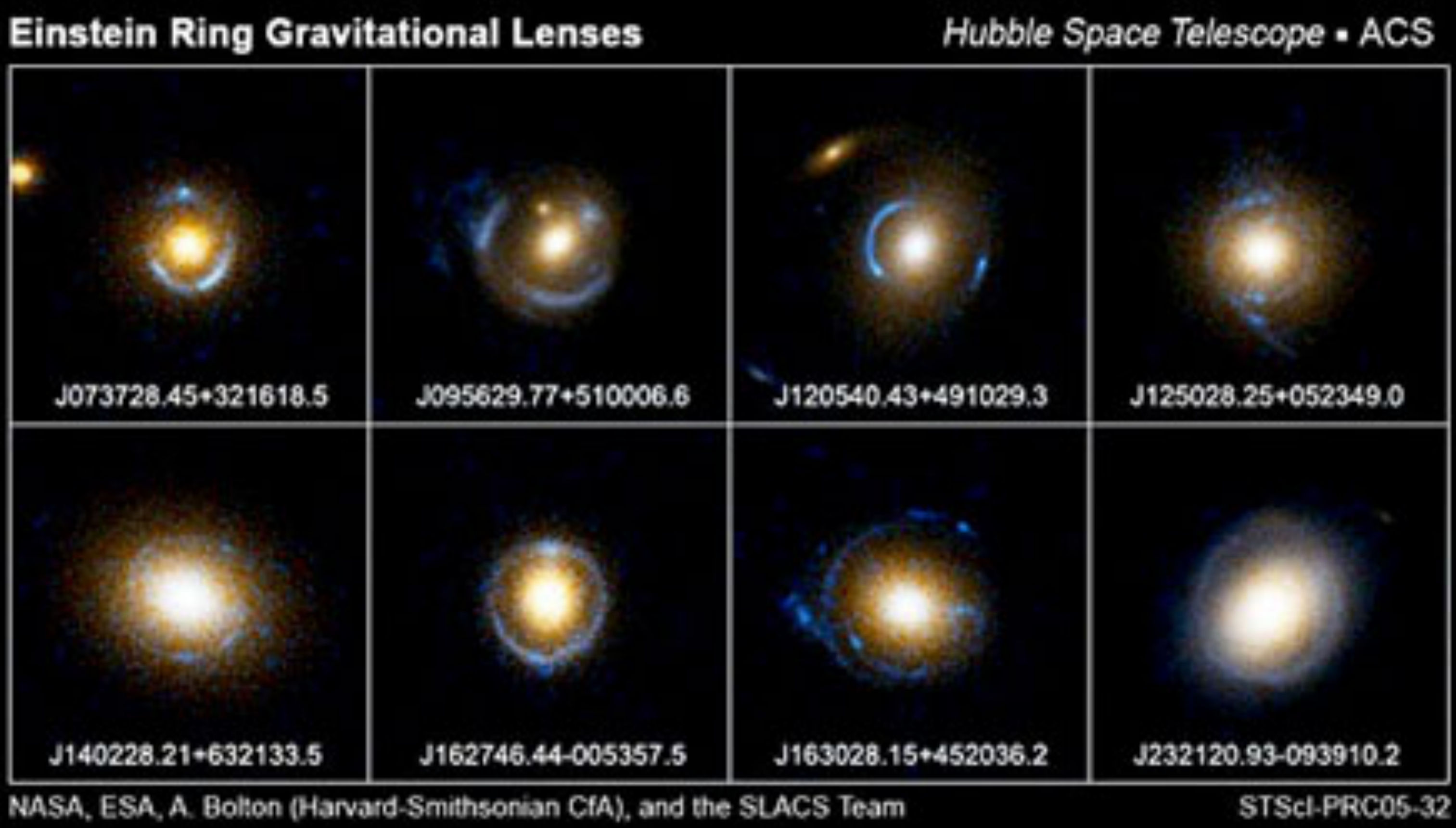
How to rule out CDM

Gravitational lensing: Einstein rings

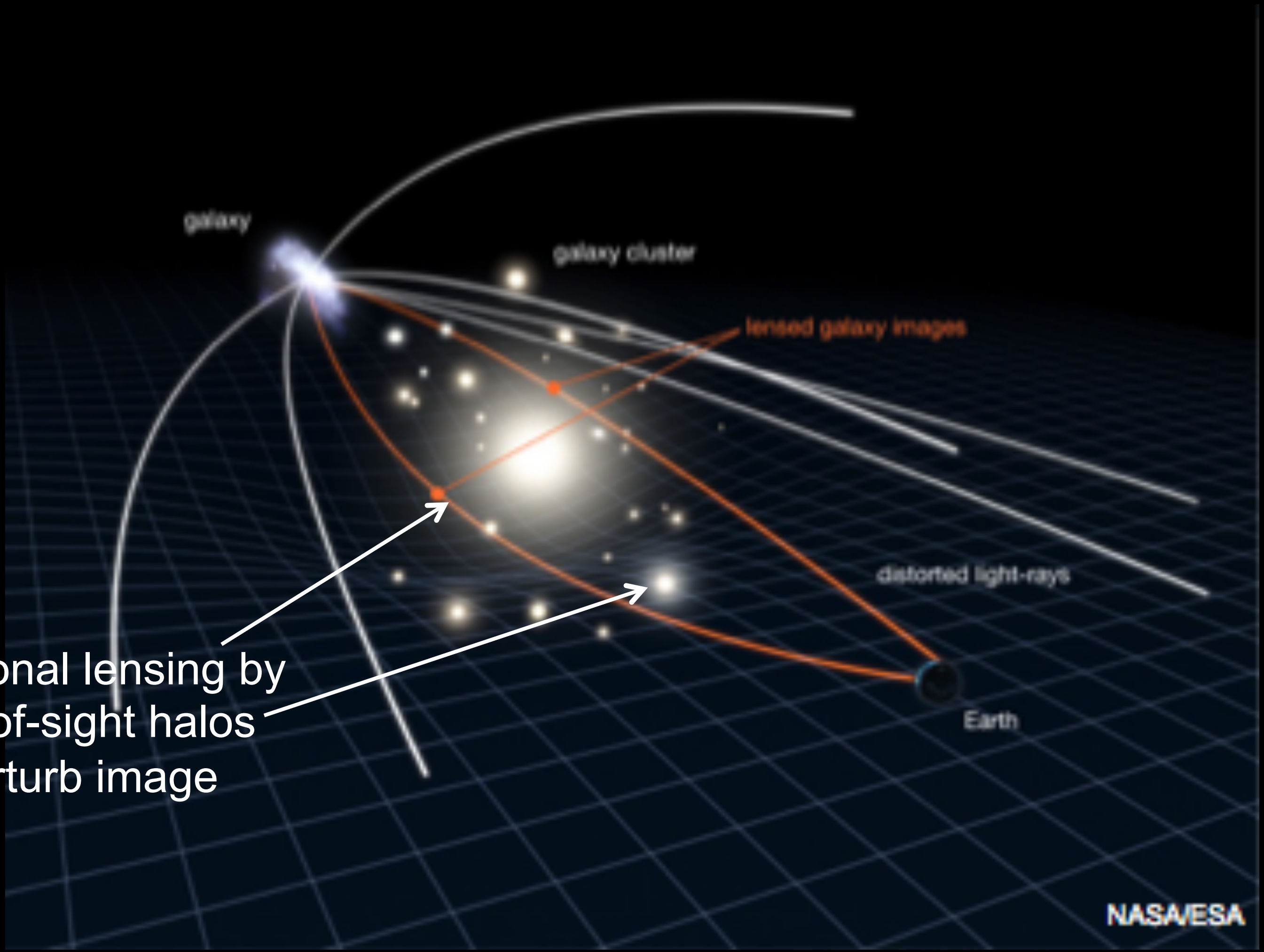


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

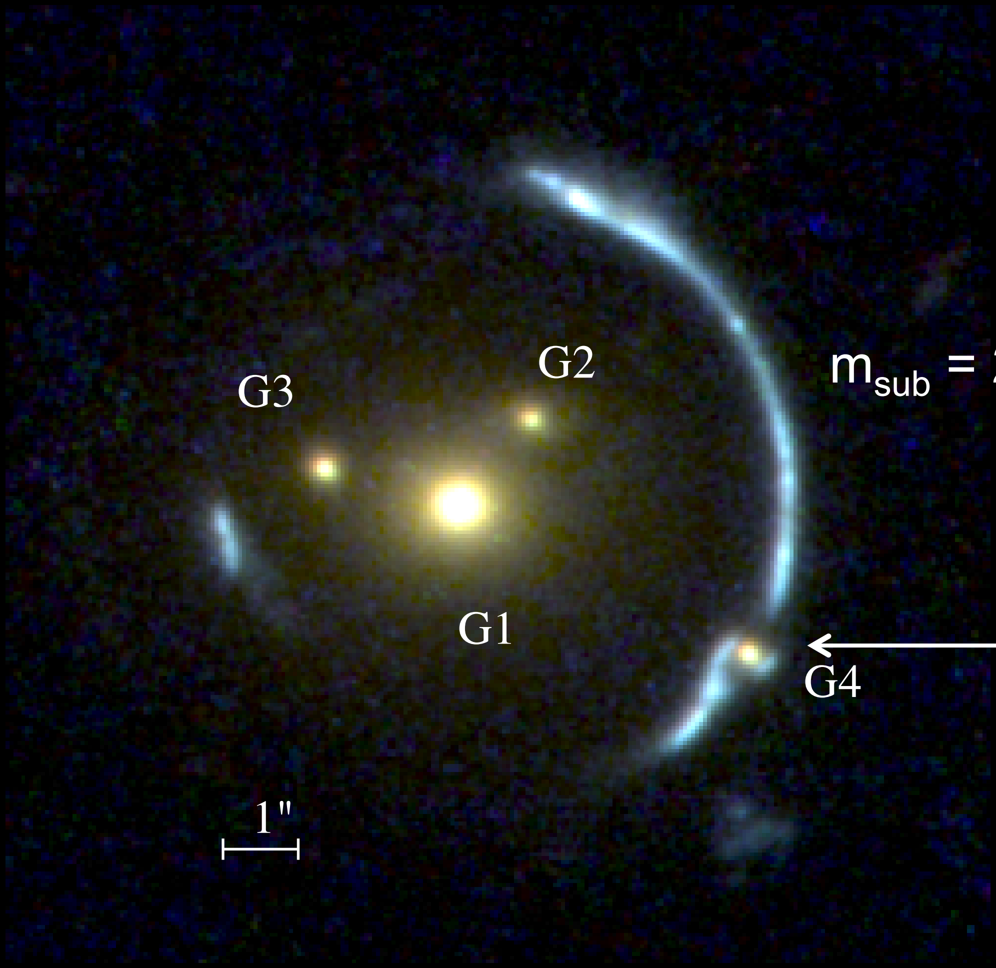


Additional lensing by line-of-sight halos perturb image

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

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image

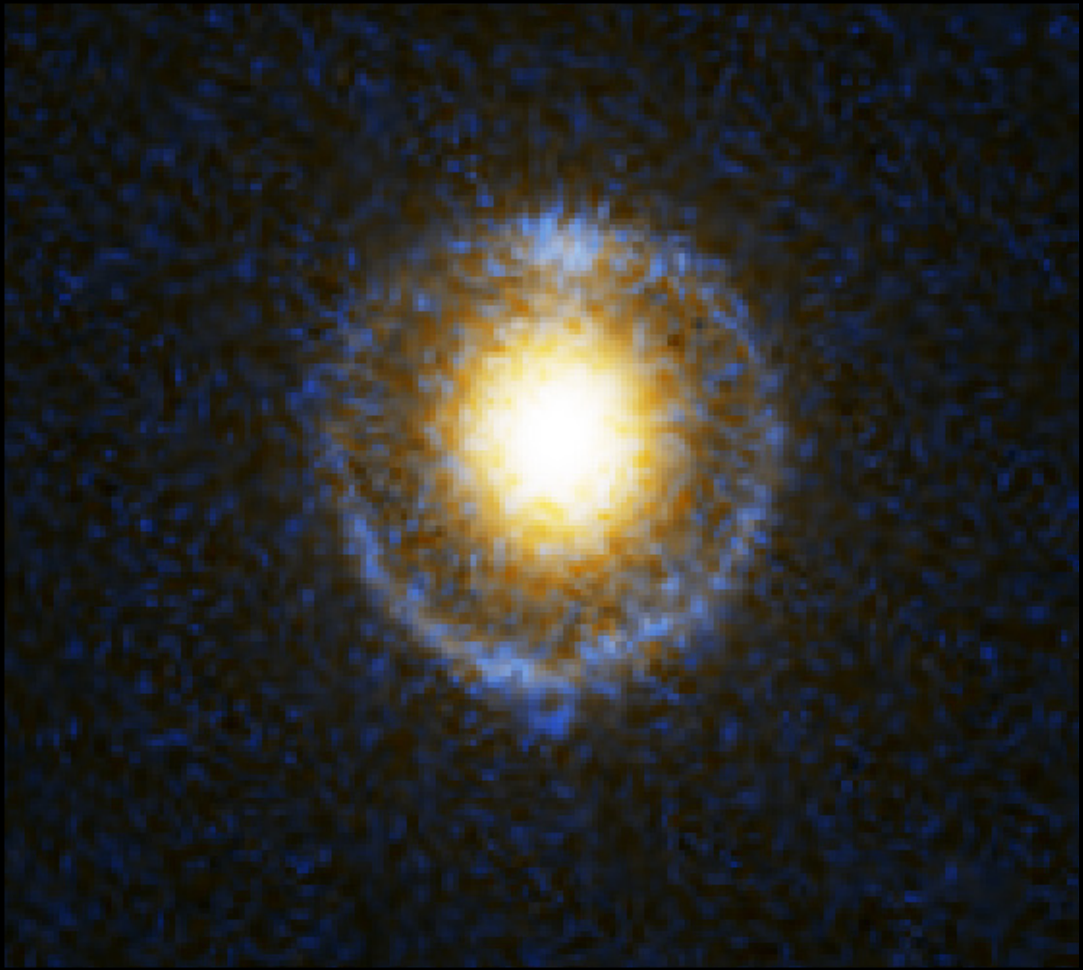


$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



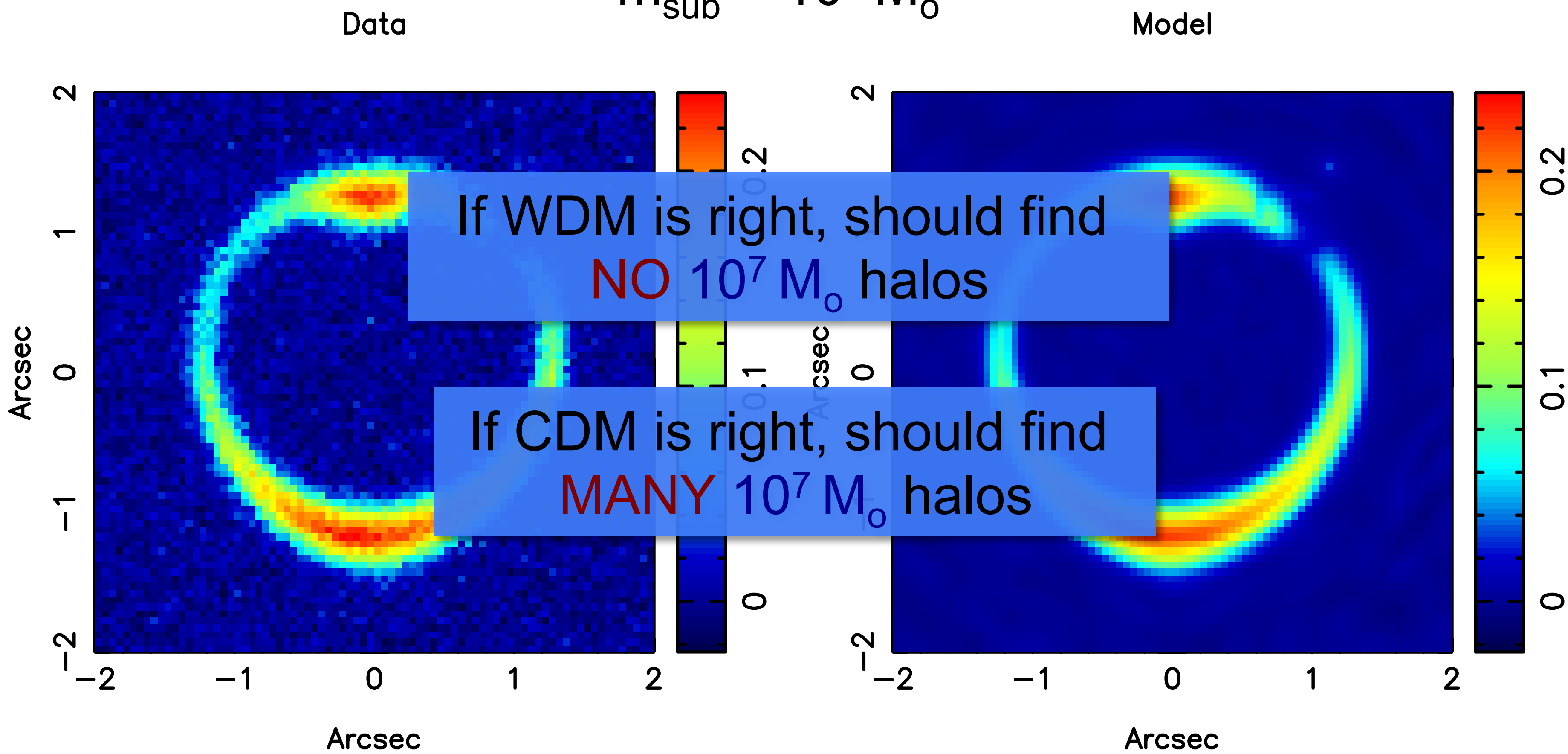
Vegetti & Koopmans '09

University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$



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

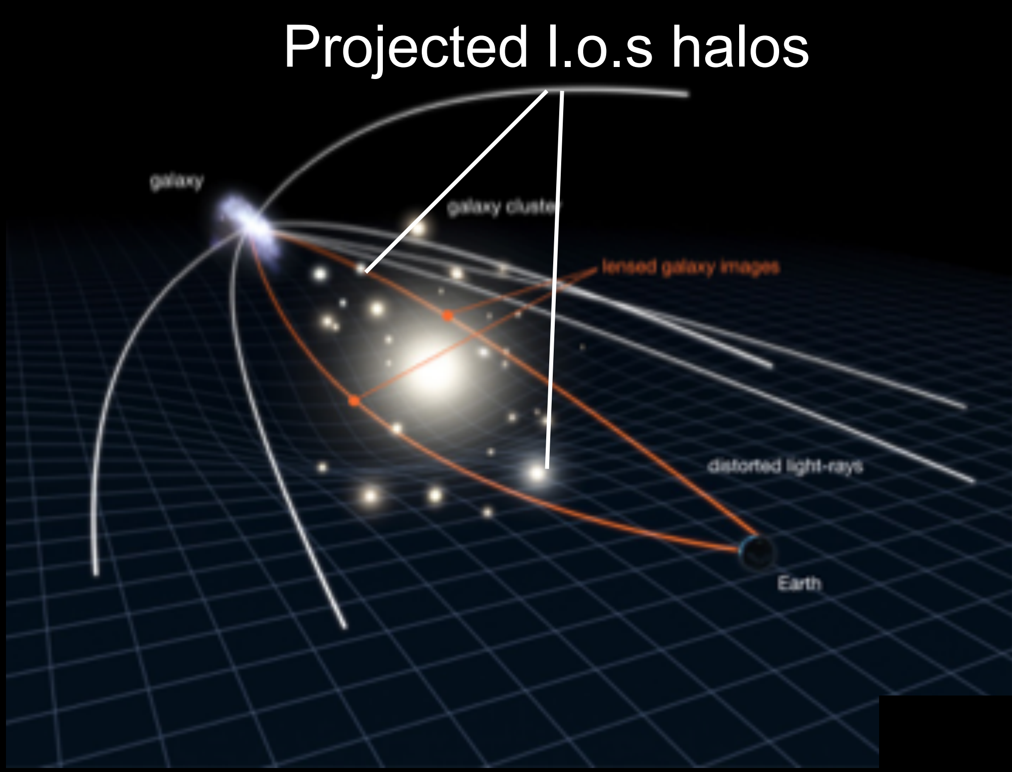
If CDM is right, should find MANY $10^7 M_o$ halos

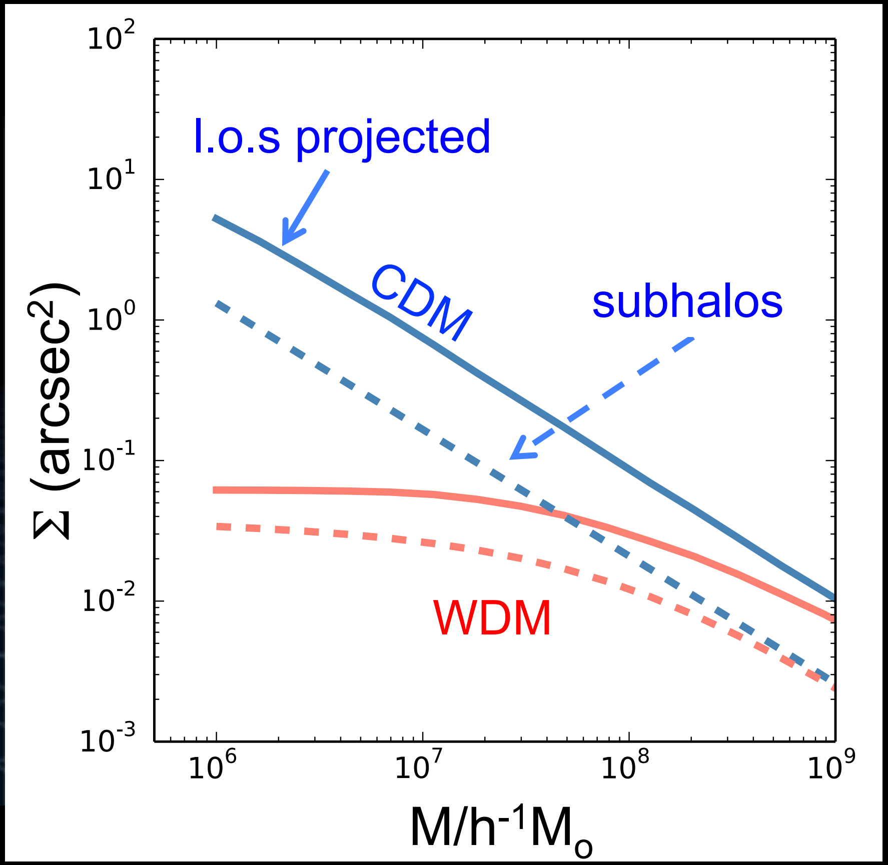
Can detect subhalos as small as $10^7 M_o$


Ran Li
OCT
HSBC
BEA

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?



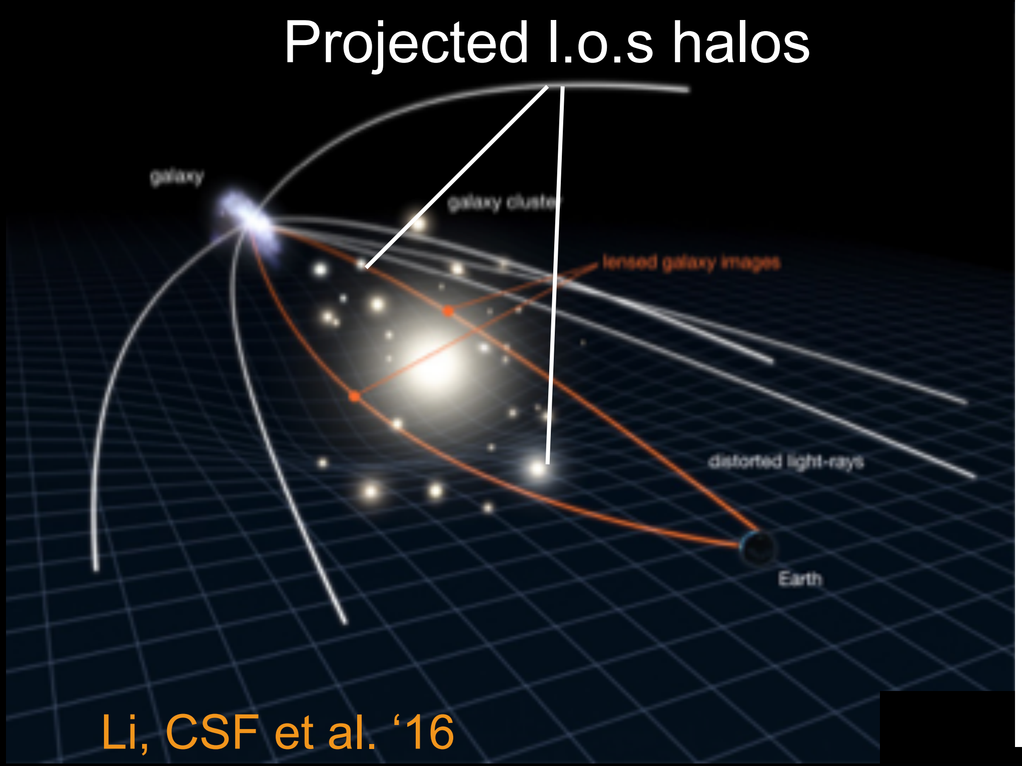


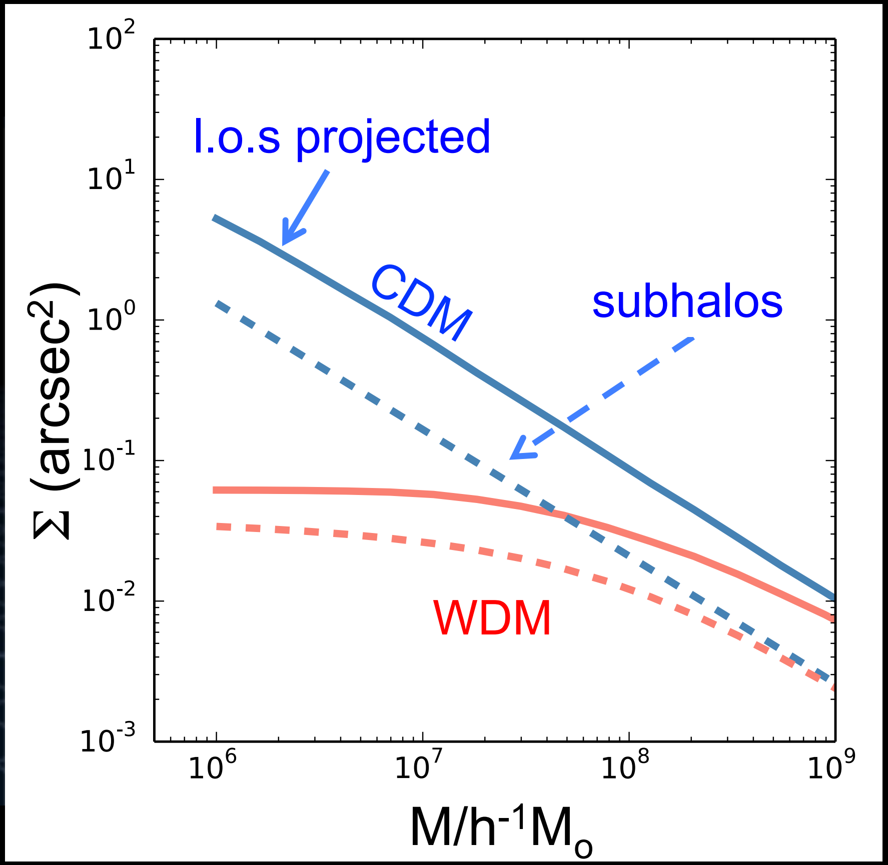
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16; see also Despali et al. '18

Substructures vs interlopers

Subhalos & halos projected along the l.o.s both lens: who wins?





→ This is the cleanest possible test: it depends ONLY on the small-mass end of the "field" halo mass function which we know how to calculate and is unaffected by baryons

Detecting substructures with strong lensing

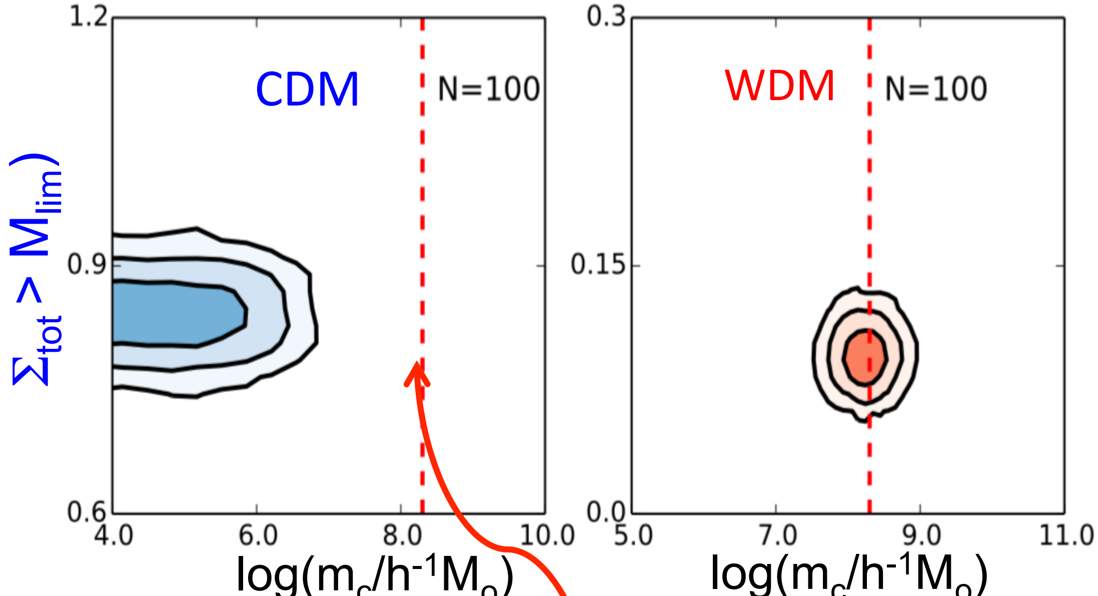
University of Durham

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

m_c= halo cutoff mass

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

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



m_c= halo cutoff mass

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

- If DM is 7 keV sterile ν → exclude CDM at >>σ!
- If DM is CDM → exclude 7 keV sterile ν at >>σ

Li, CSF et al '16

Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution
- Λ makes little difference to formation of cosmic structure
- But the identity of DM makes a big difference on small scales

1. CDM makes many small subhalos but most ($<5.10^8 M_0$) are dark → No satellite problem in CDM or WDM
2. No evidence for cores; baryon effects can make them → No "core/cusp" problem in CDM or WDM
3. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!