

The standard model of cosmology

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Durham




... and how to rule it (or
alternatives) out

The Ogden Centre
at Durham



The Λ CDM model of cosmogony

Cosmological constant Cold dark matter



- *Ab initio*, **fully specified** model of **cosmic evolution** and the formation of cosmic structure
- Has strong **predictive** power and can, in principle, be **ruled out**
- Has made a number of **predictions** that were subsequently **verified** empirically (e.g. CMB, LSS, galaxy formation)
- Based on two heretical ideas that go back to the 1980s:

The big Bang



300 tho

3 minutes

15 thousand million years

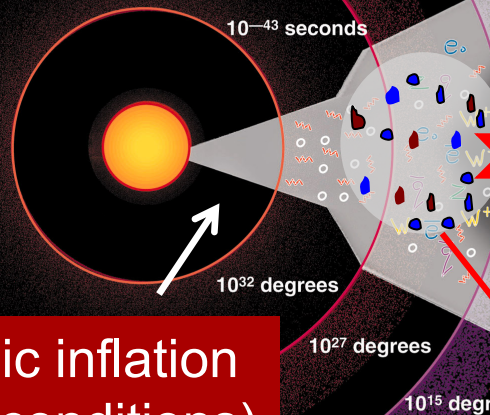
The cosmic microwave background is emitted
($t \sim 350,000$ yrs)

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

The first light in our Universe

$t = 13.7$ billion yrs

Cosmic inflation
(initial conditions)
($t \sim 10^{-35}$ s)



- radiation
- particles
- heavy particles carrying the weak force
- quark
- anti-quark
- electron
- positron (anti-proton)
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

degrees

18 degrees

3 degrees K

The big Bang



300 thousand

3 minutes

15 thousand million years

The temperature of this radiation should show small irregularities

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

10^{-43} seconds

10^{32} degrees

10^{27} degrees

10^{15} degrees

1 degrees

18 degrees

3 degrees K

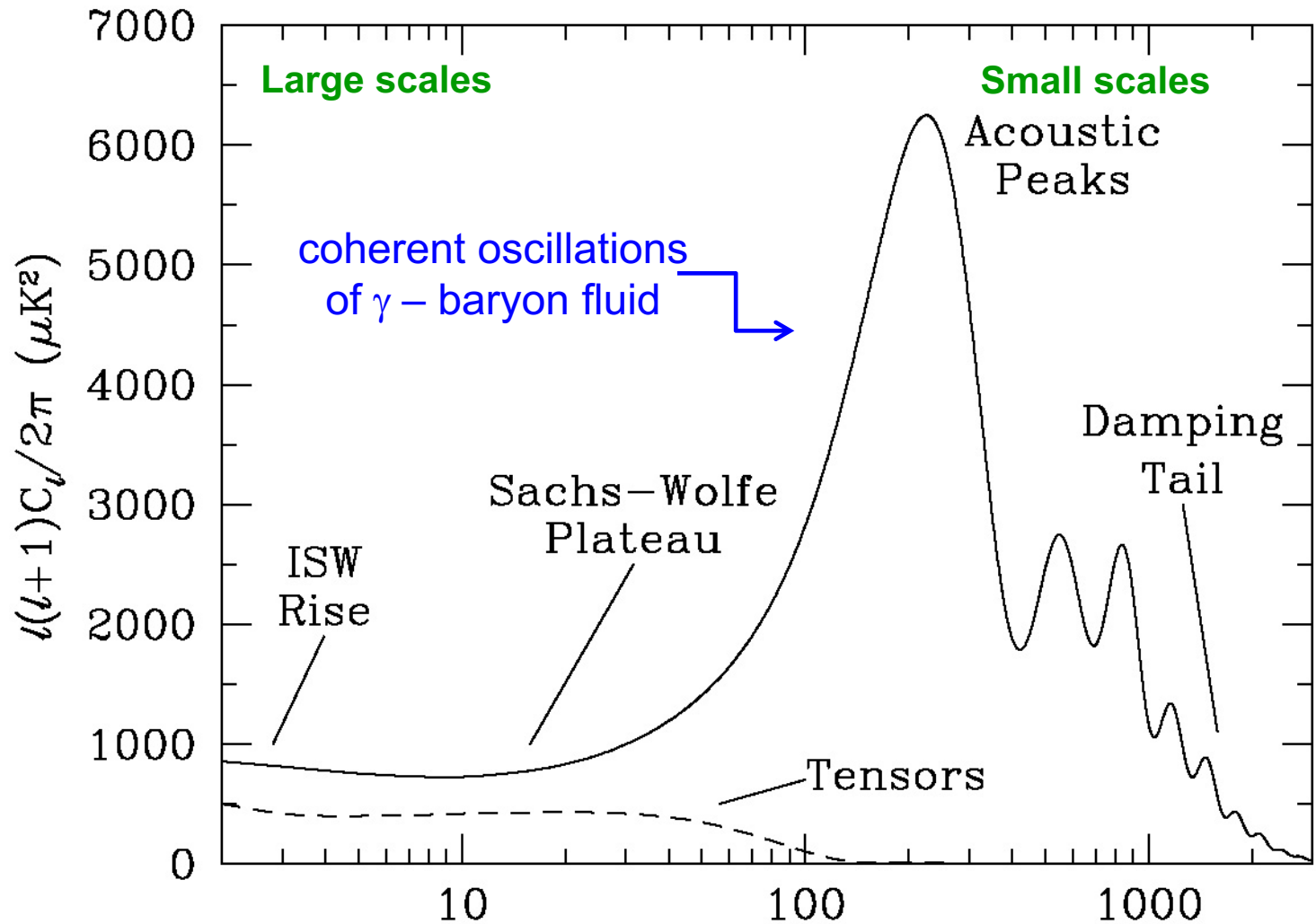
$t = 13.7$ billion yrs

Cosmic inflation
(initial conditions)
($t \sim 10^{-35}$ s)

- radiation
- particles
- W^+ heavy particles carrying the weak force
- W^-
- Z
- quark
- anti-quark
- electron
- positron (anti-proton)
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

Temperature anisotropies in CMB

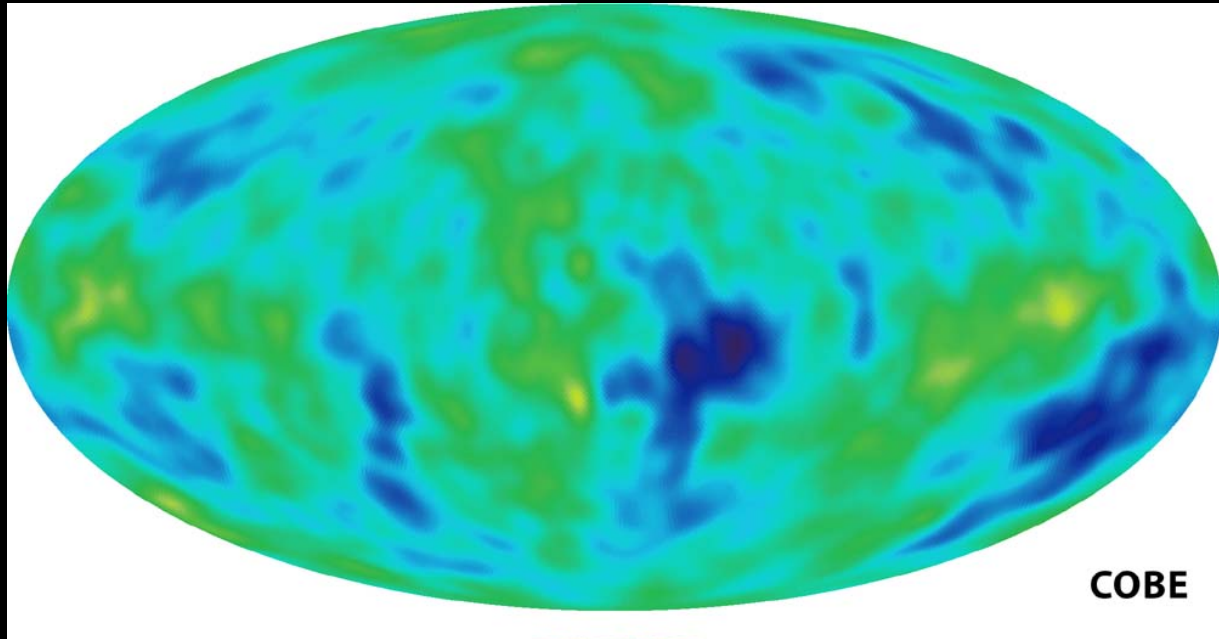
2D power spectrum



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

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

1992



The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

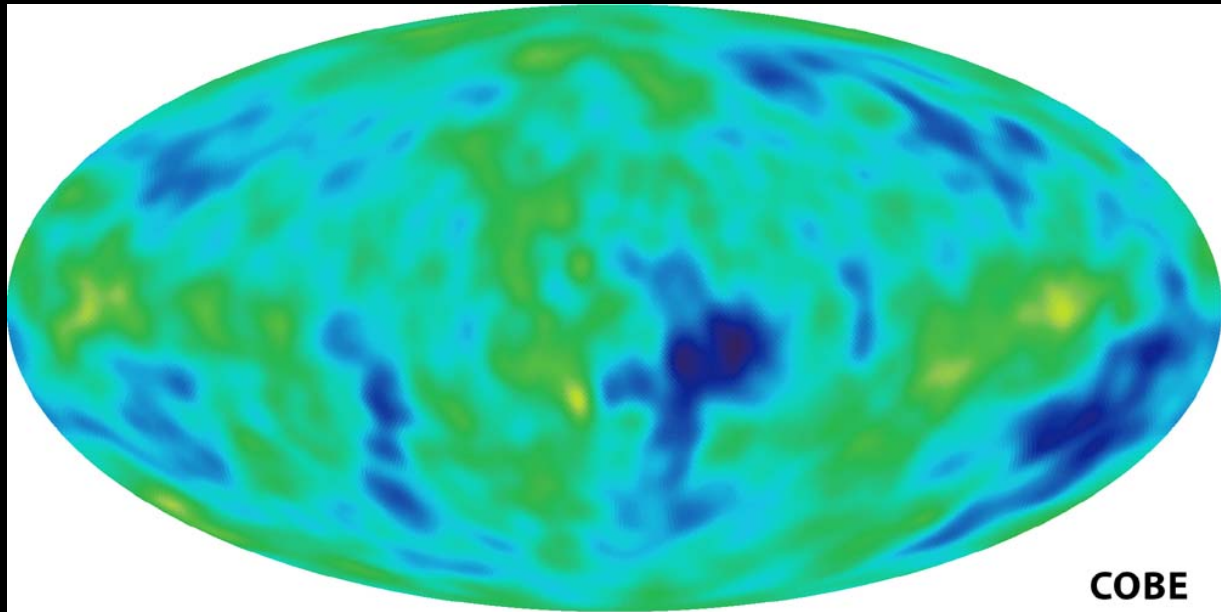
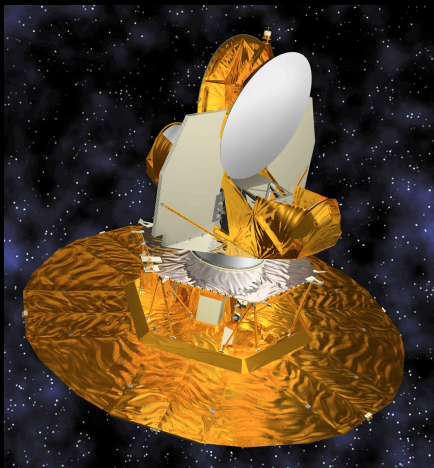
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions

The CMB

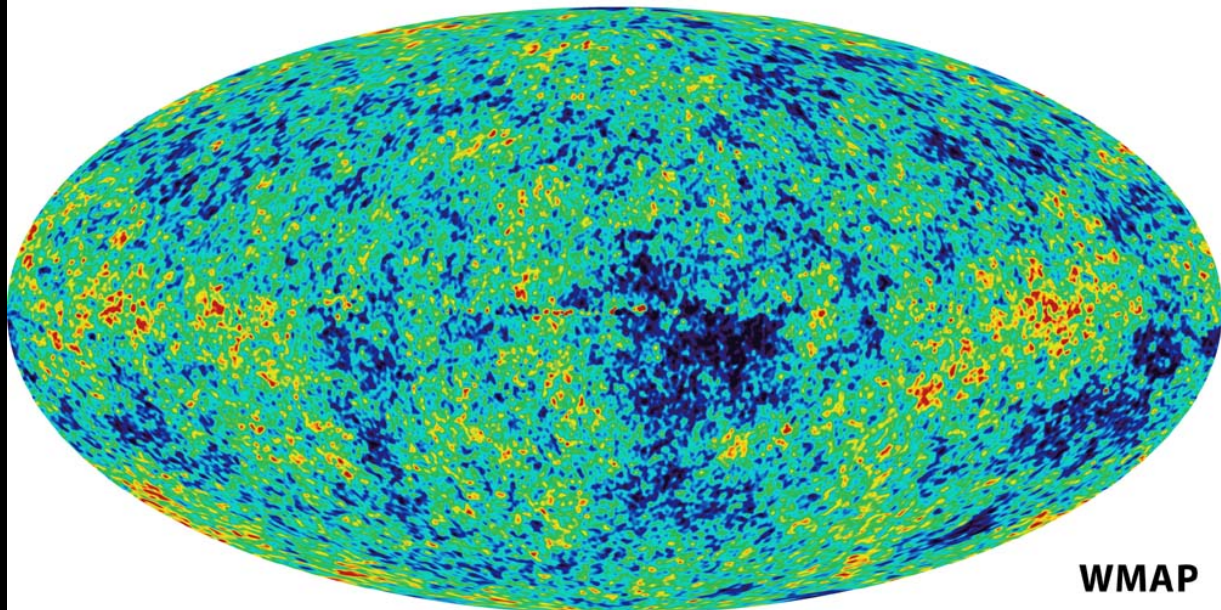
1992



2003



COBE



WMAP

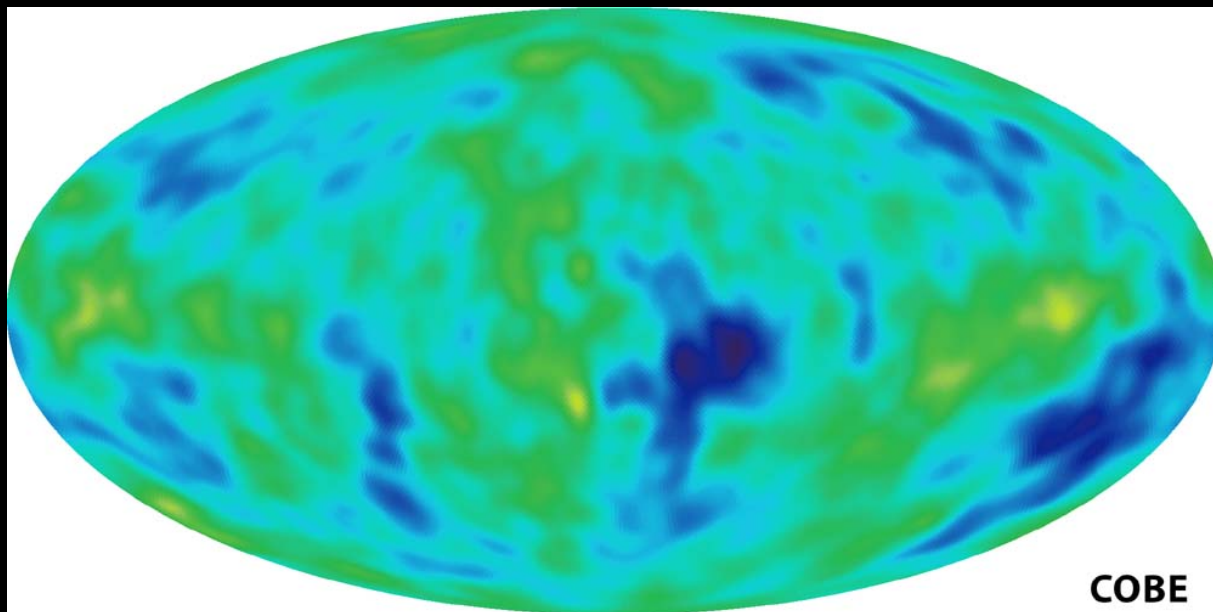
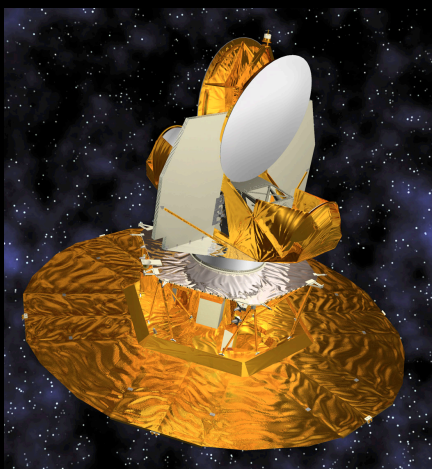
ICC

The CMB

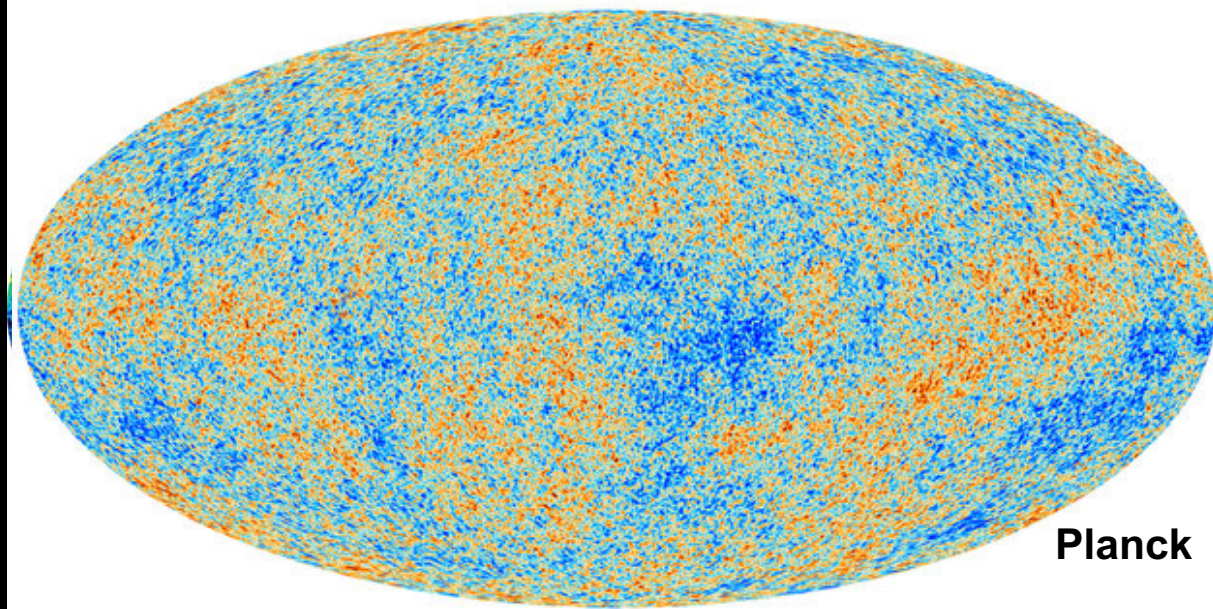
1992



2012



COBE



Planck

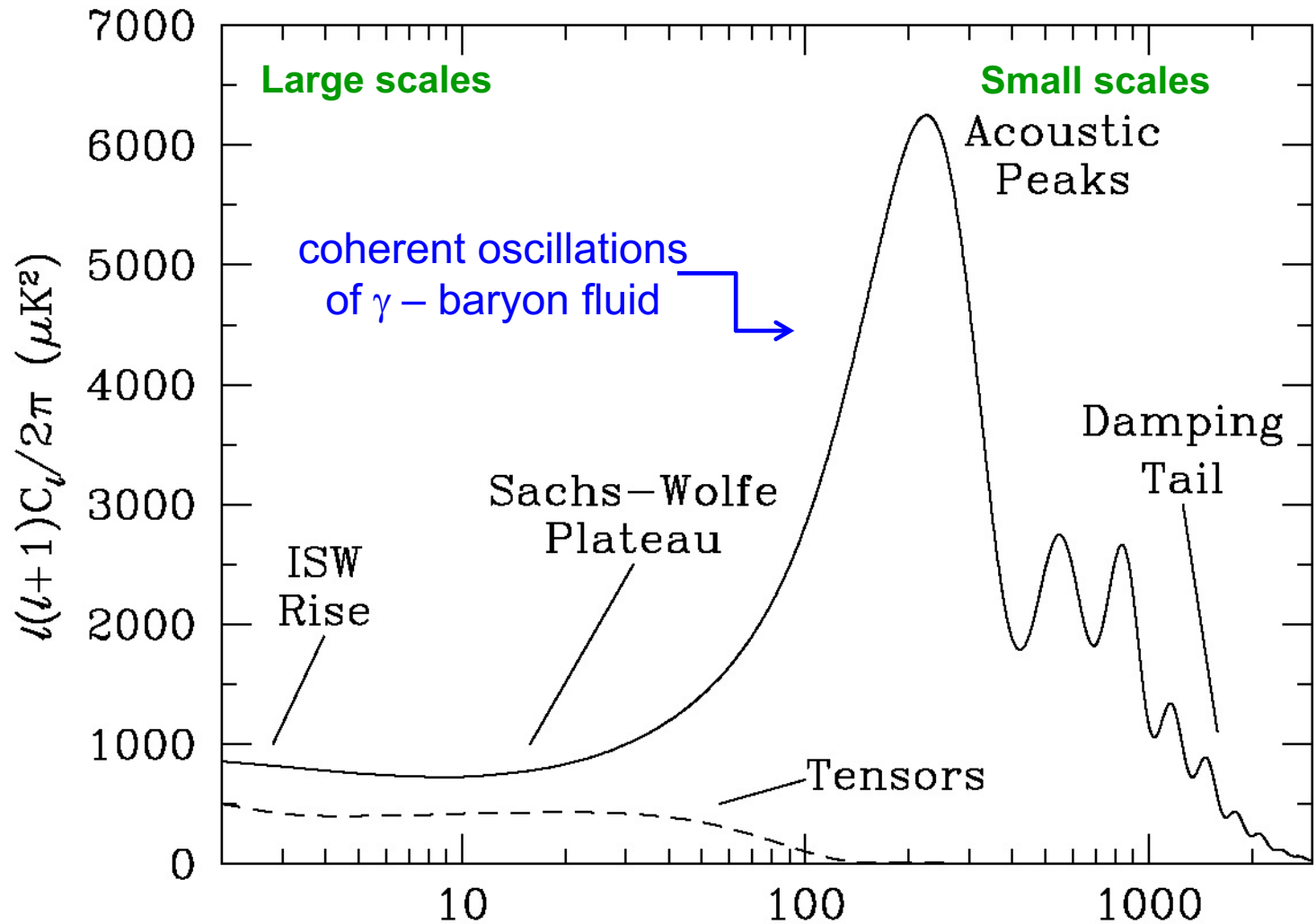
The initial conditions for galaxy formation



Quantum fluctuations from inflation

Temperature anisotropies in CMB

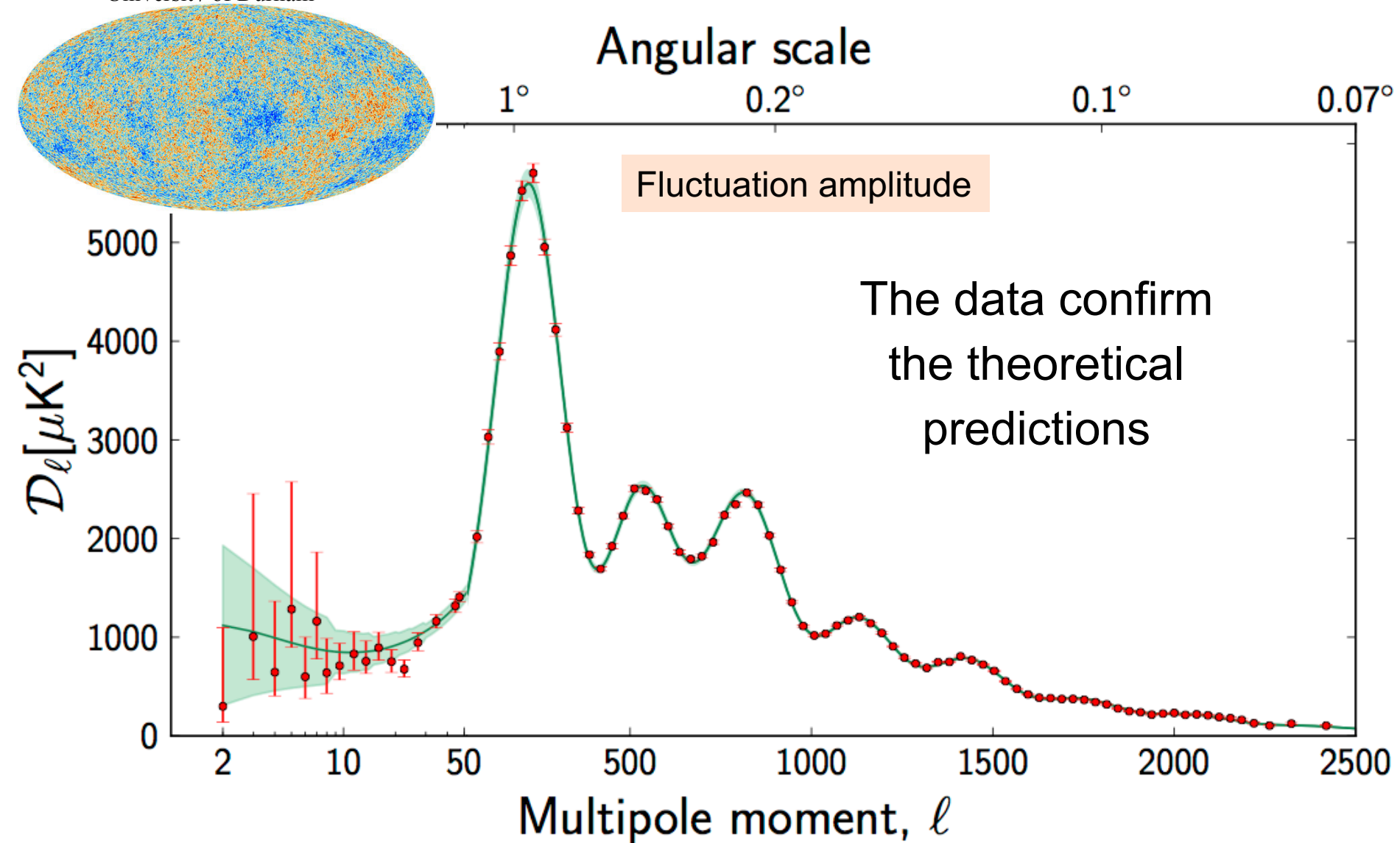
2D power spectrum



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

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

Planck: CMB temperature anisotropies



The six parameters of minimal Λ CDM model

		<i>Planck</i> +WP	
Parameter		Best fit	68% limits
6 model parameters	$\Omega_b h^2$. density of baryons .	0.022032	0.02205 ± 0.00028
	$\Omega_c h^2$. density of CDM .	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!

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	$10^{-5}\text{eV} - 100 \text{ GeV}$

The dark matter power spectrum

$k^3 P(k)$

The linear power spectrum (“power per octave”)

Free streaming →

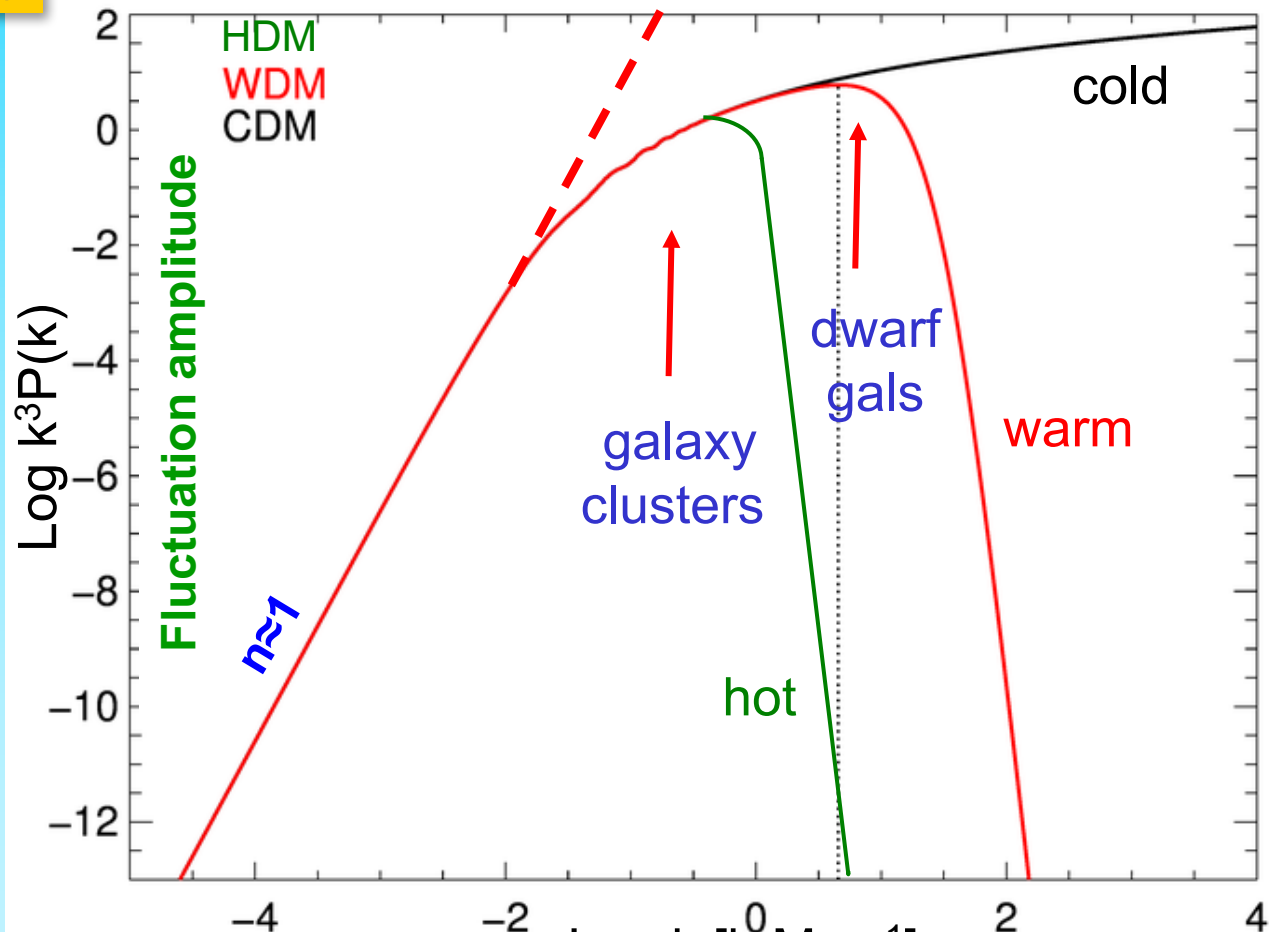
$$\lambda_{\text{cut}} \propto m_x^{-1}$$

for thermal relic

$m_{\text{CDM}} \sim 100 \text{ GeV}$
 susy; $M_{\text{cut}} \sim 10^{-6} M_{\odot}$

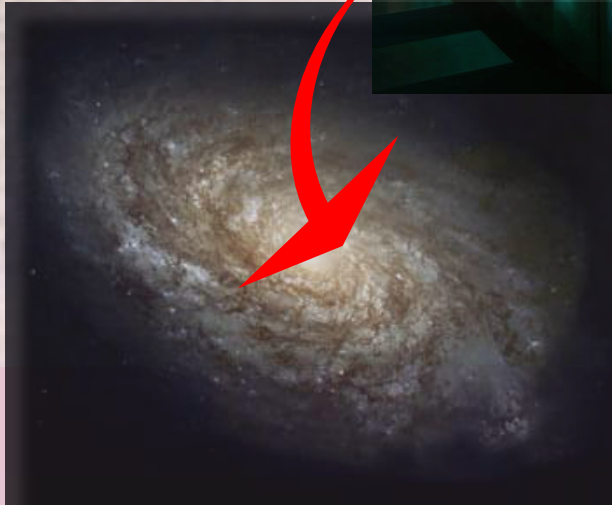
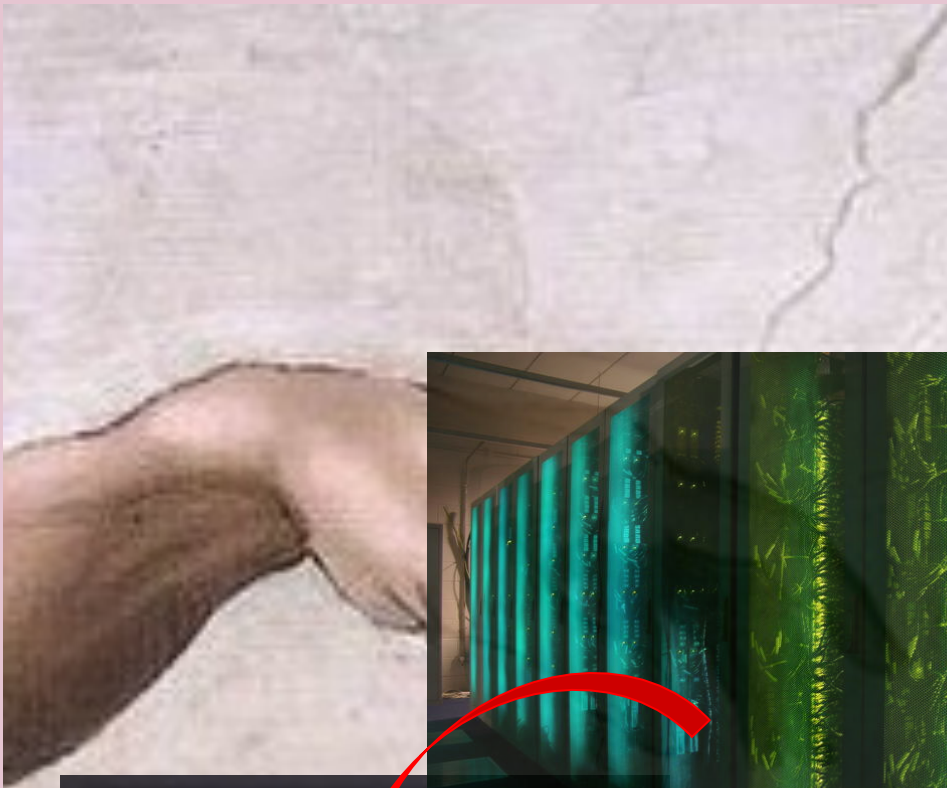
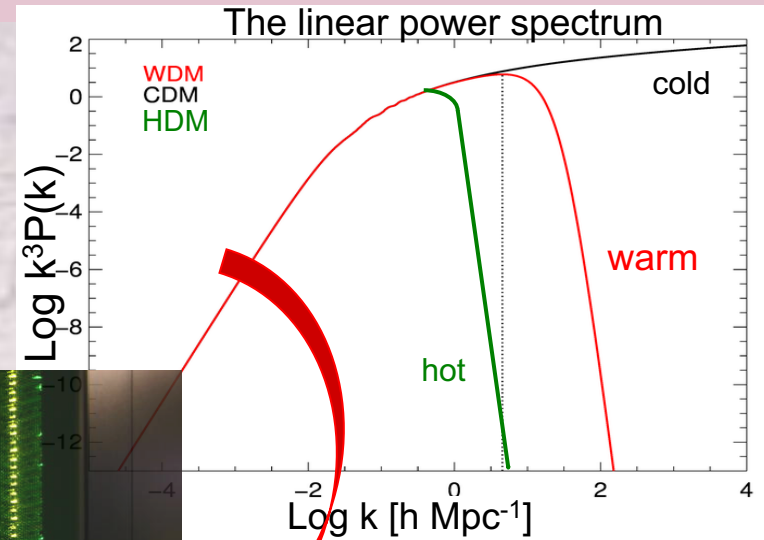
$m_{\text{WDM}} \sim \text{few keV}$
 sterile ν ; $M_{\text{cut}} \sim 10^9 M_{\odot}$

$m_{\text{HDM}} \sim \text{few tens eV}$
 light ν ; $M_{\text{cut}} \sim 10^{15} M_{\odot}$



These possibilities can be tested with astrophysics

Non-linear evolution

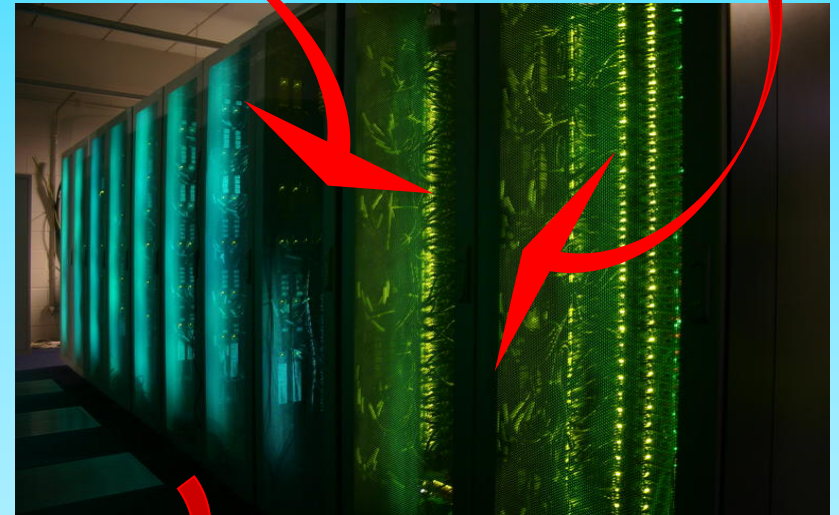


Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

Relevant equations:

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



How to make a virtual universe

Hot dark matter

-7-

LUBIMOV

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

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.

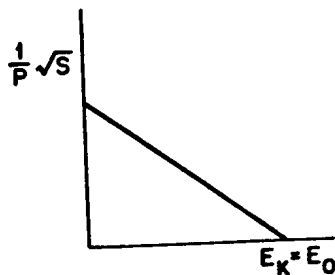


Fig. 1. Kurie plot for $M_\nu = 0$.

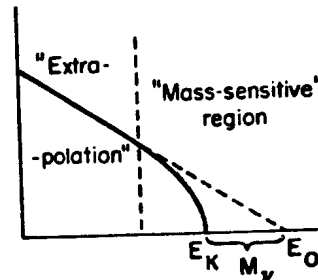
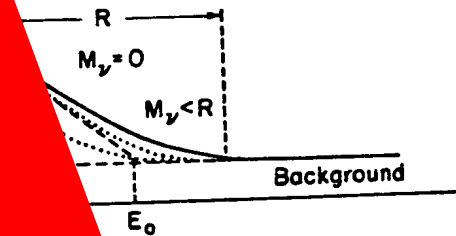


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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.



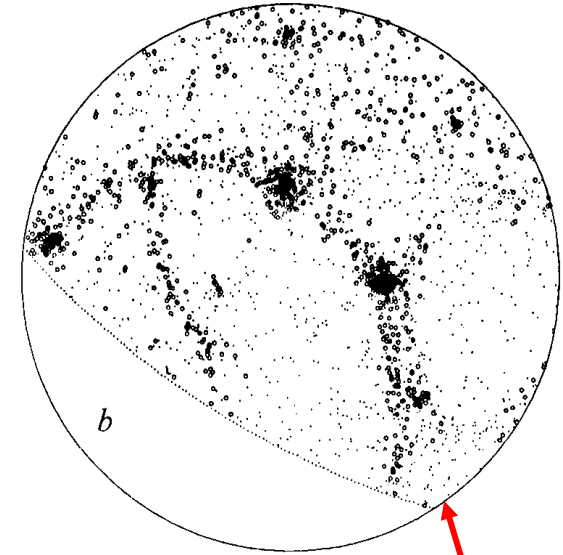
Realistic Kurie plot.

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 $M_\nu = 100$ eV we need resolution R , background Q , and statistics N . If $M_\nu = 30$ 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 $R \sim \Delta p/p \approx \text{const.}$). 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. Bergqvist (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. 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



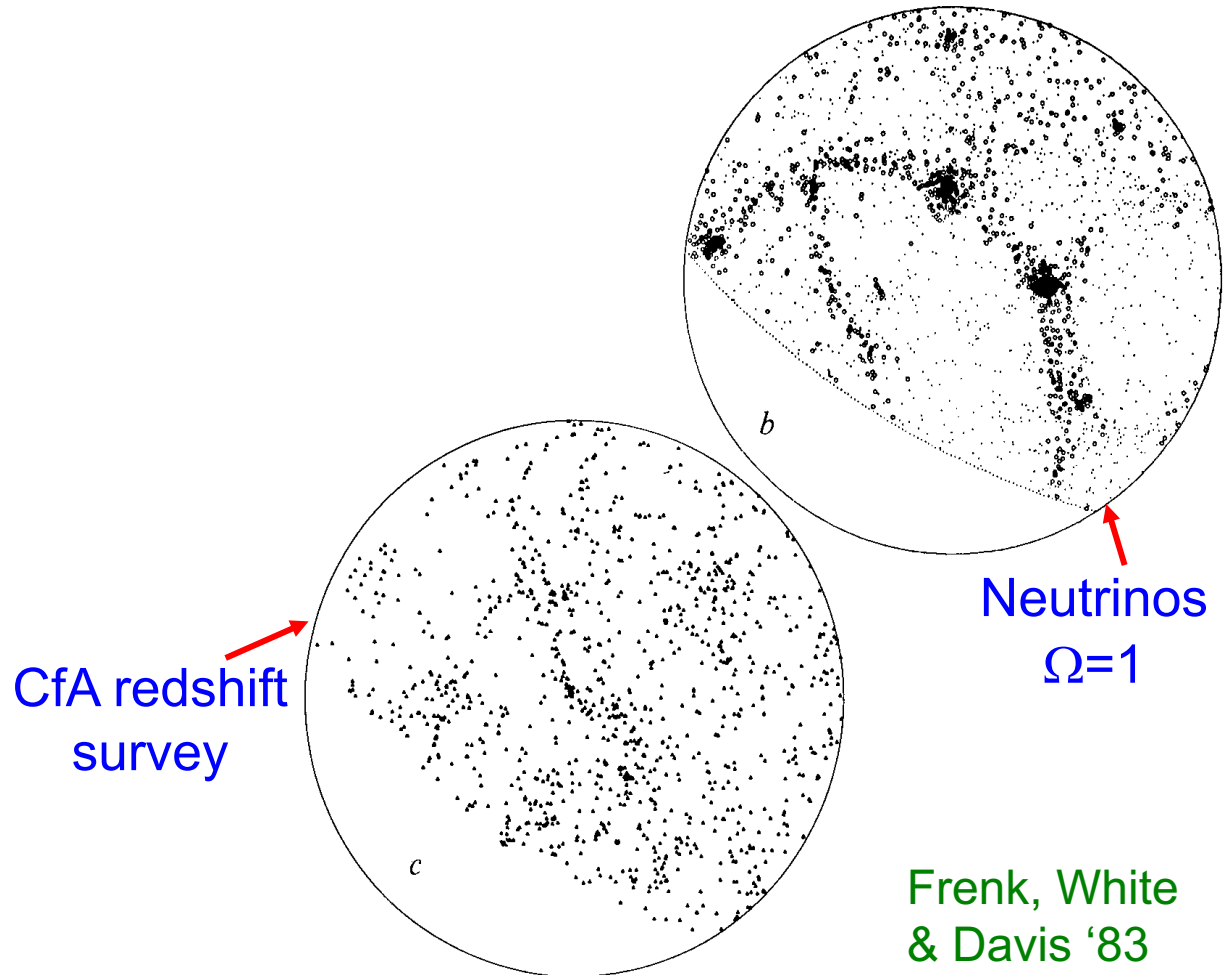
Neutrinos
 $\Omega=1$

Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

Neutrino DM →
wrong clustering

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



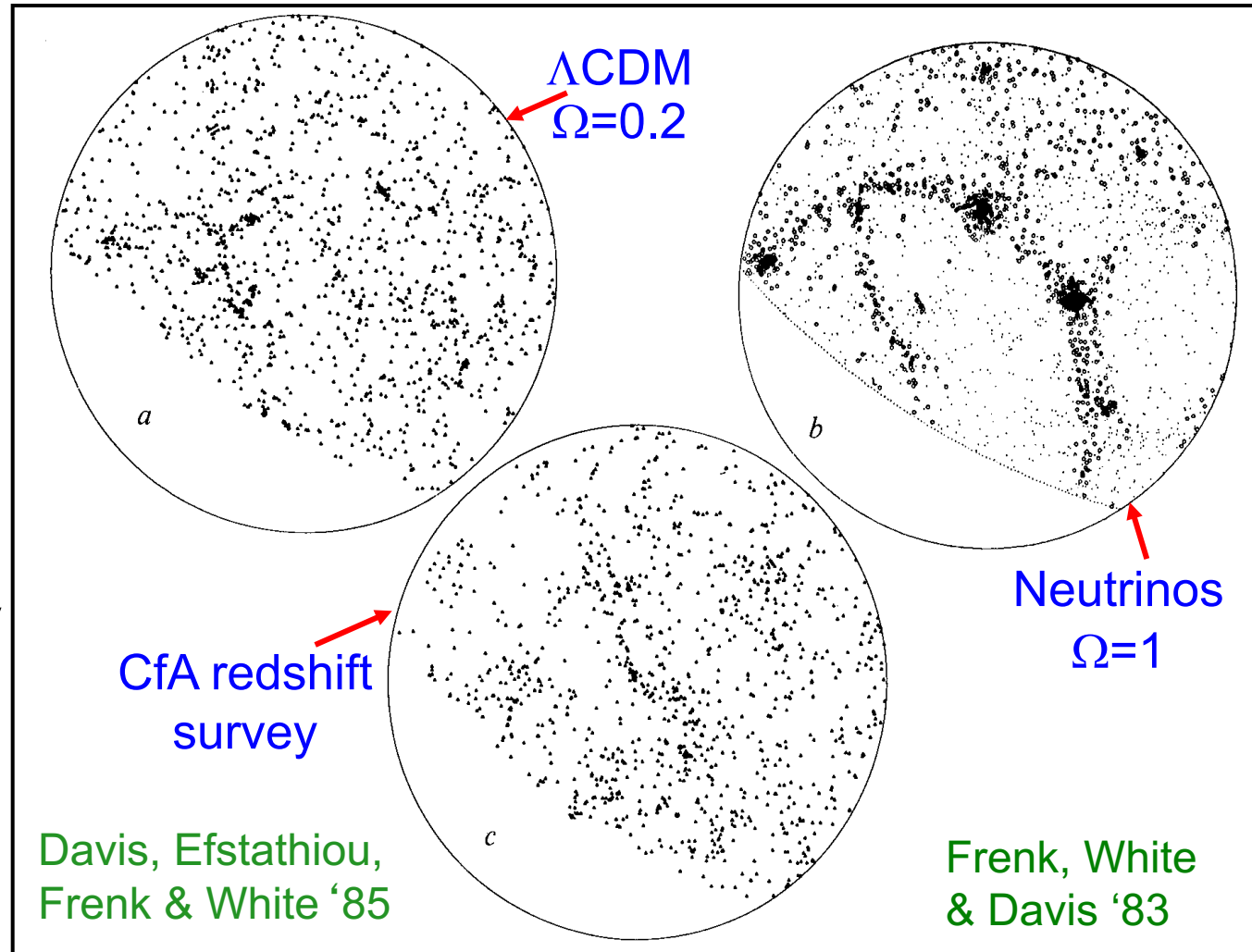
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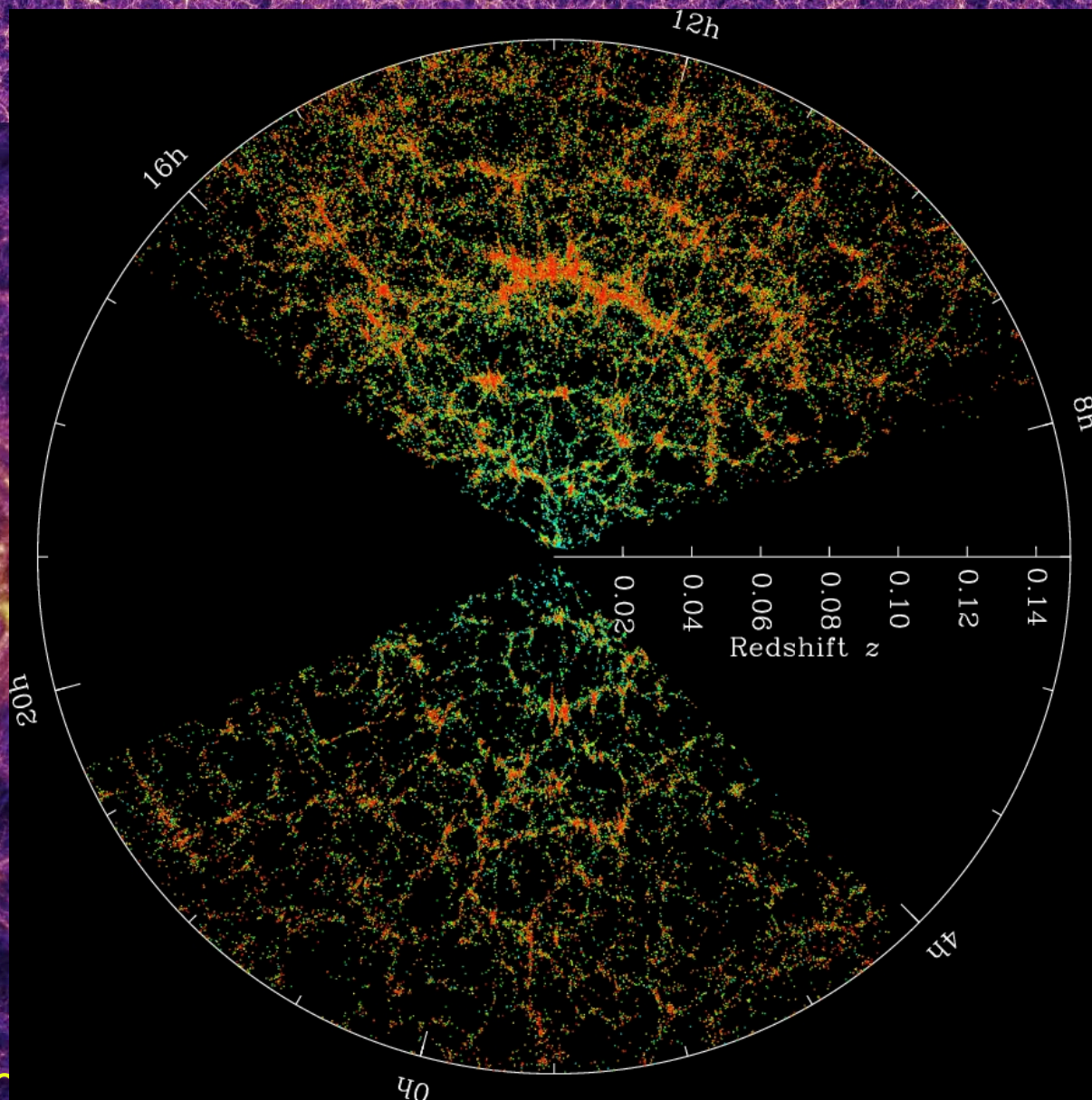
Early CDM N-body
simulations gave
promising results

In CDM structure
forms hierarchically



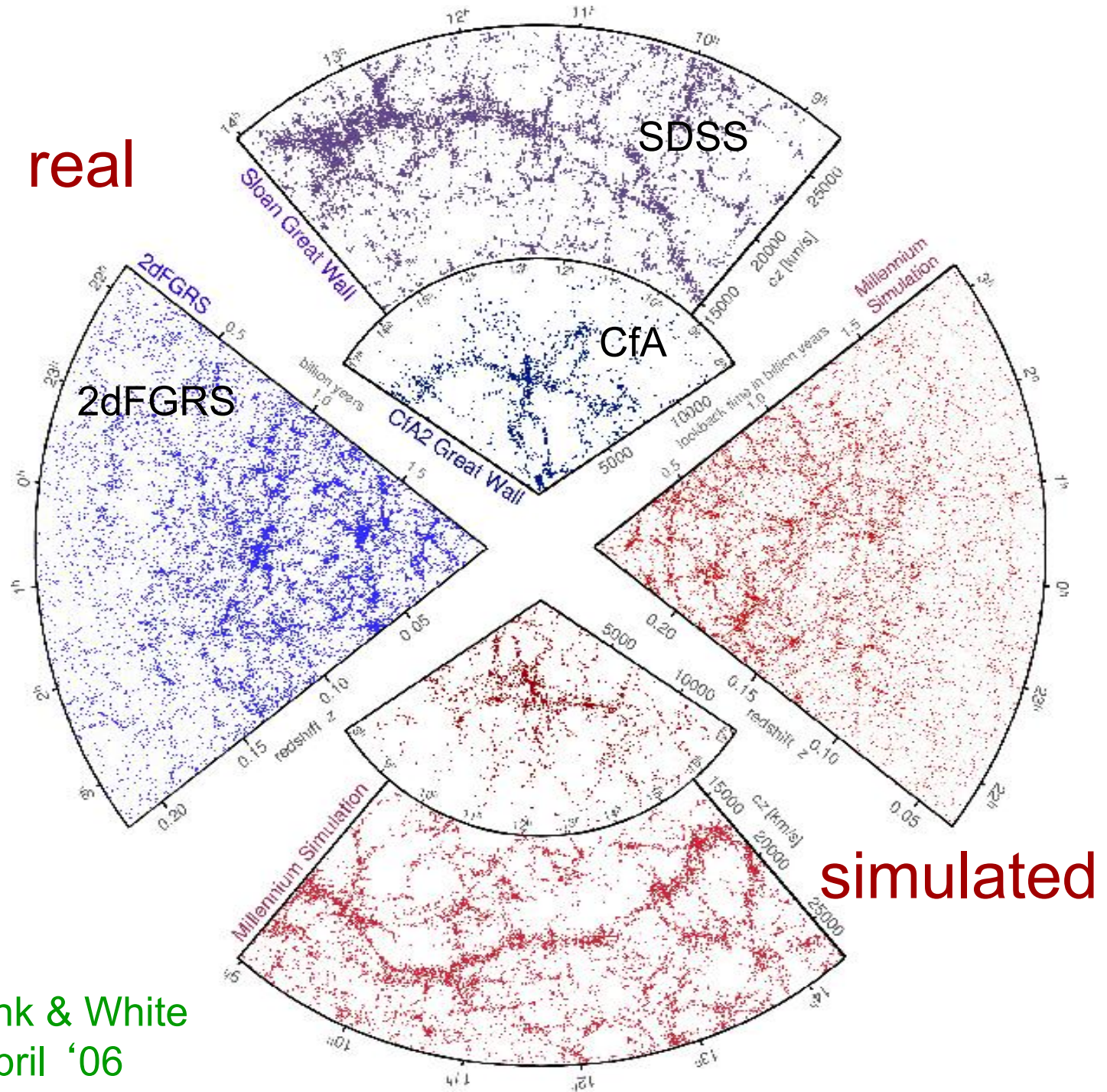
VIRGO

The Millennium/Aquarius/Phoenix simulation series



Springel et al '05, '06,
Gao et al '11

real

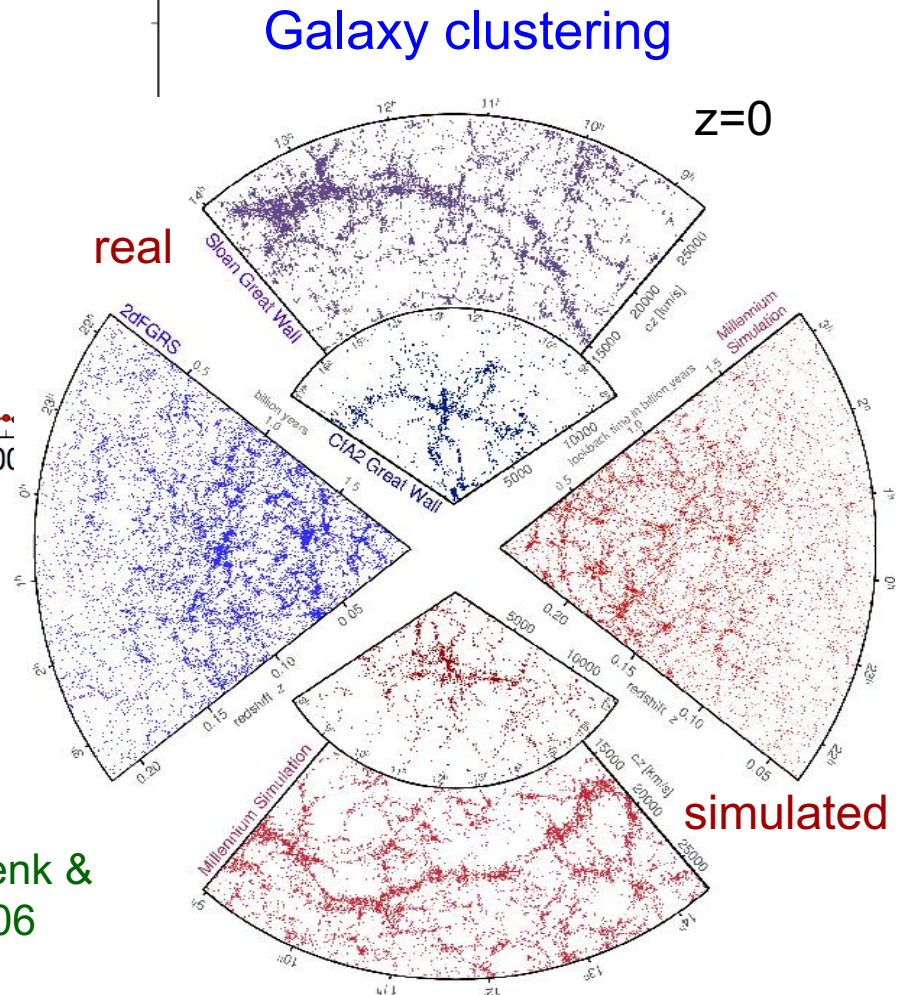
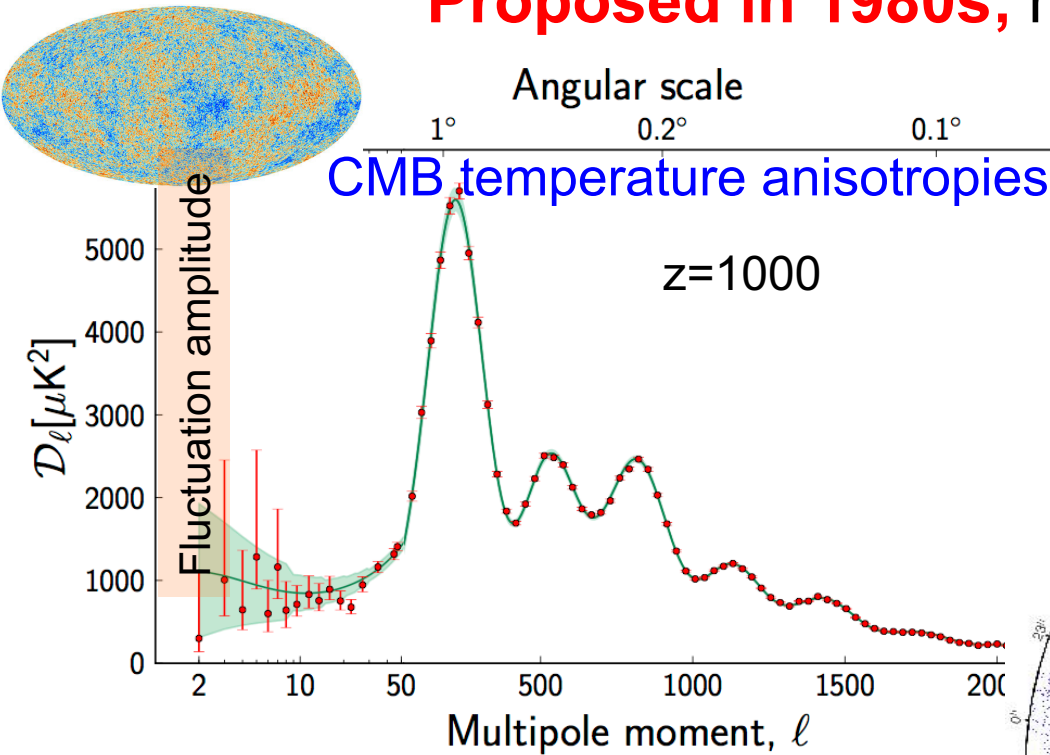


simulated

Springel, Frenk & White
Nature, April '06

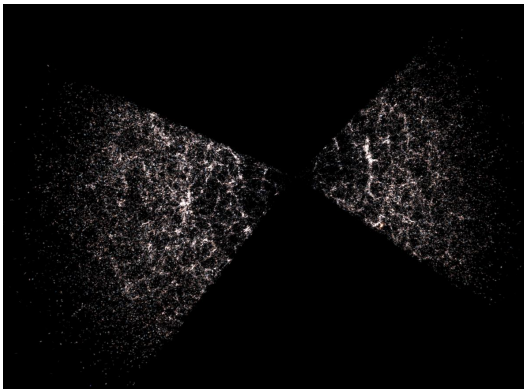
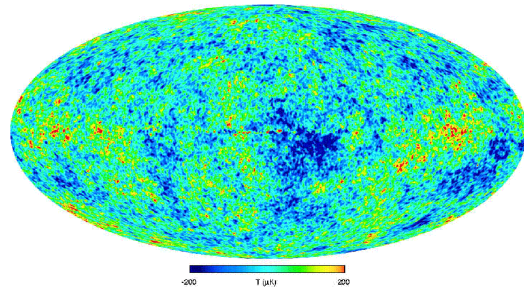
The Λ CDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Springel, Frenk &
White 2006

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



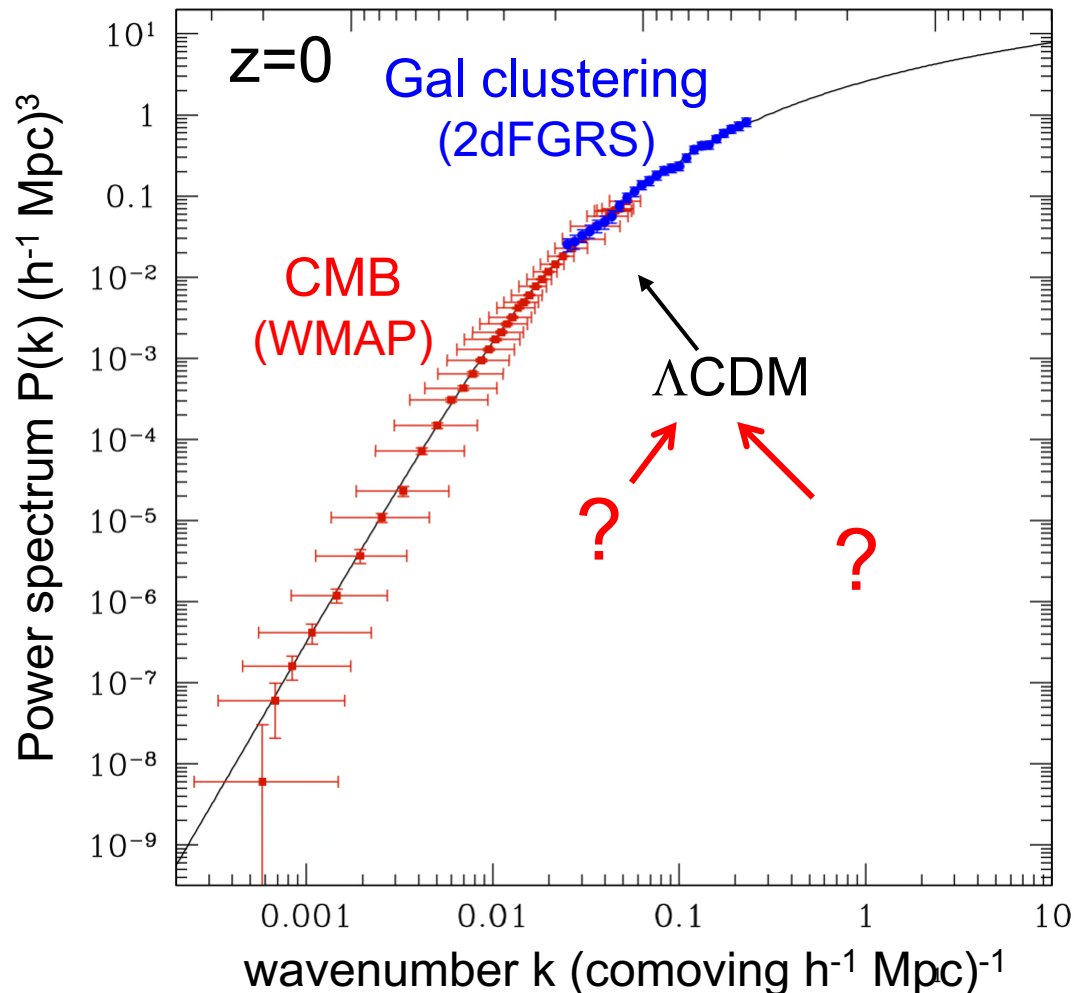
⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

$z \sim 1000$

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

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



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

Free streaming →

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

for thermal relic

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

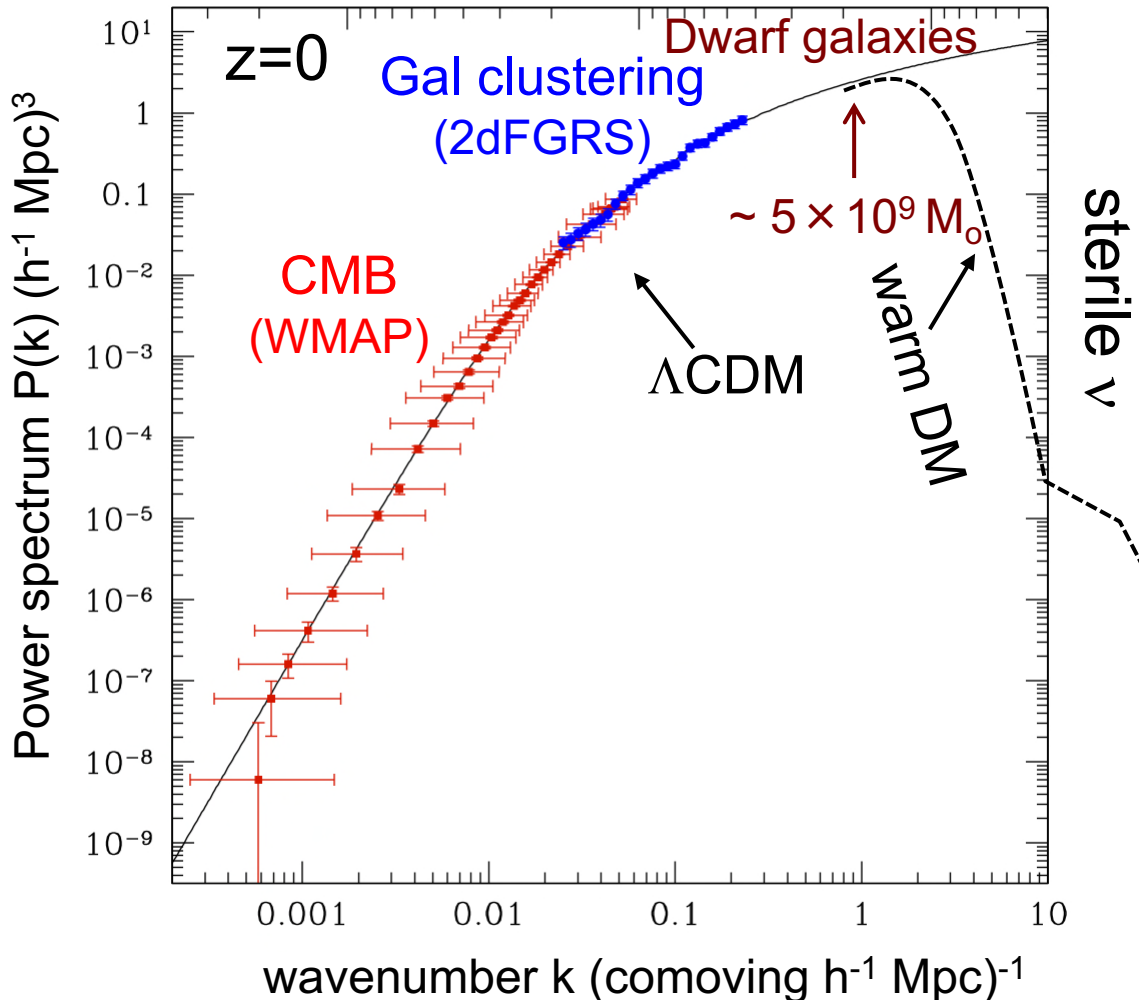
$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

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

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

Log $k^3 P(k)$

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



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 by X-ray decay



Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

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

Cold dark matter

Annihilation radiation from the Galactic Centre?

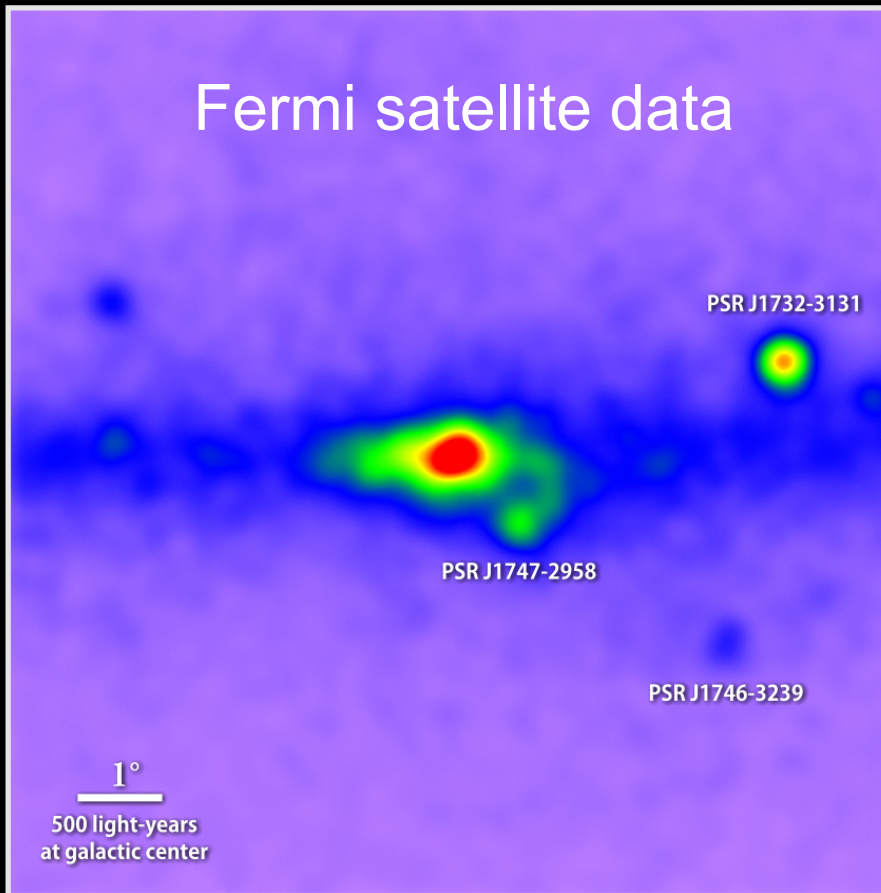
Cold dark matter

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

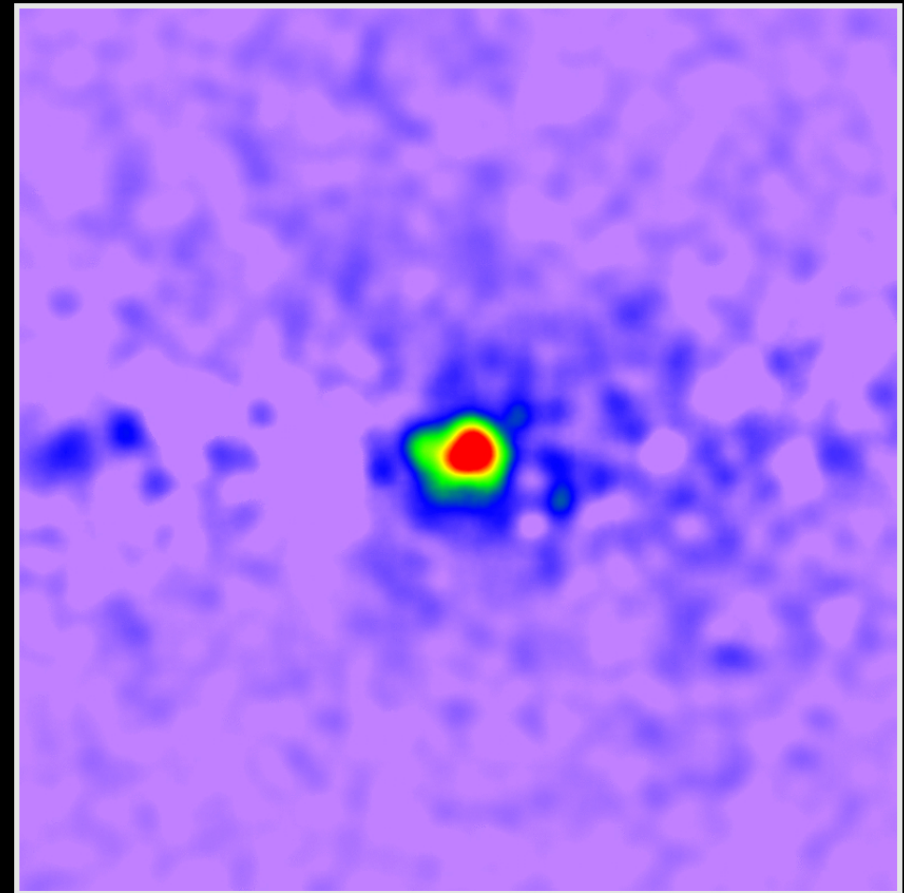
Tansu Daylan,¹ Douglas P. Finkbeiner,^{1,2} Dan Hooper,^{3,4} Tim Linden,⁵
Stephen K. N. Portillo,² Nicholas L. Rodd,⁶ and Tracy R. Slatyer^{6,7}

Uncovering a gamma-ray excess at the galactic center

Fermi satellite data



Unprocessed map of 1.0 to 3.16 GeV gamma rays



Known sources removed

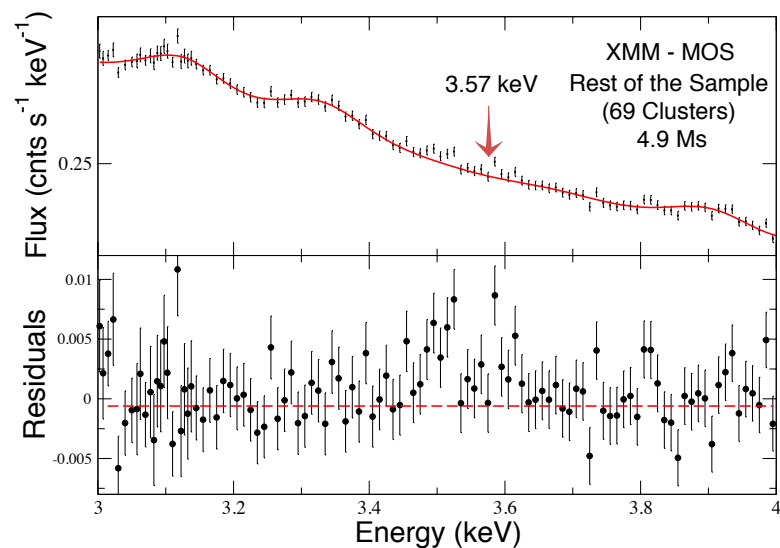
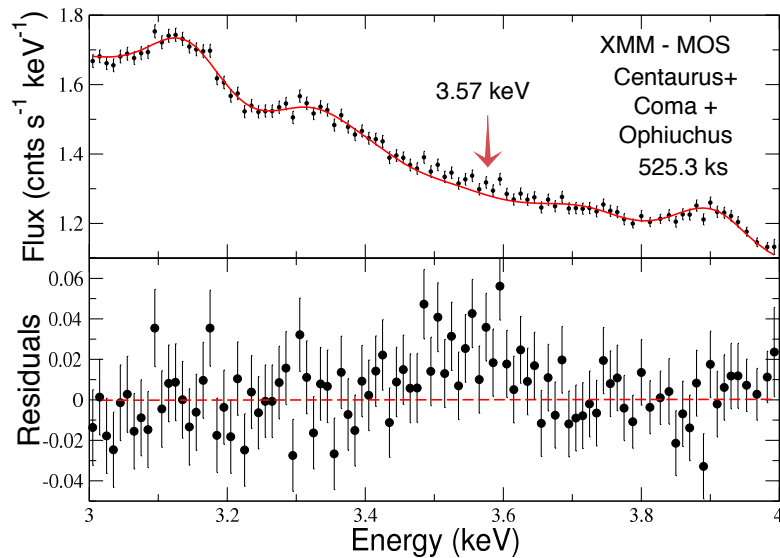
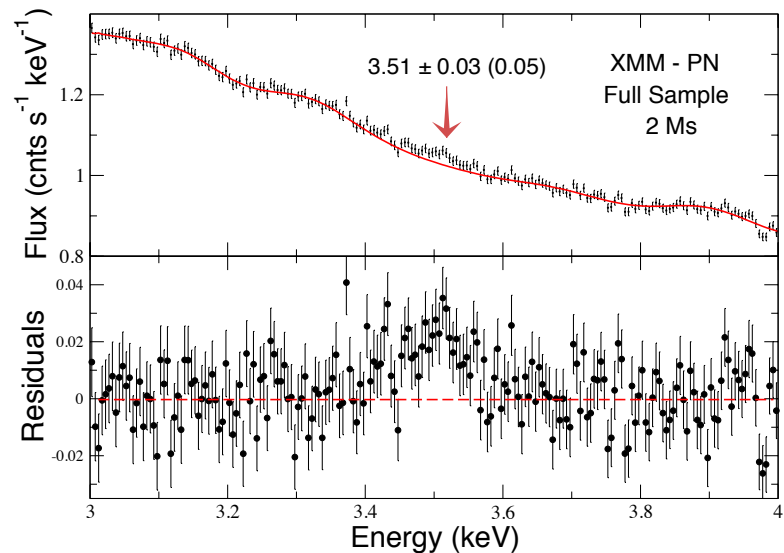
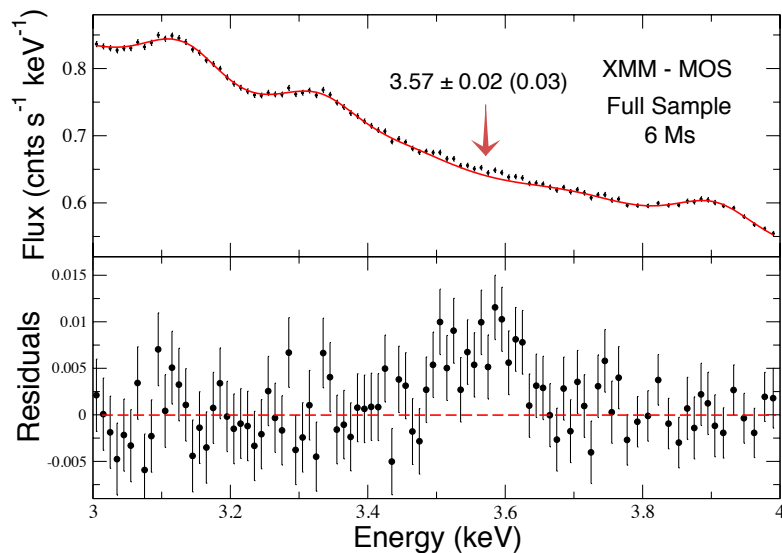
Warm dark matter

Decay line at 3.51 keV in galaxies and clusters

Warm dark matter WDM decay line in 69 stacked clusters?

$E=3.57$ keV

Bulbul et al. '14 See also Boyarsky et al. '14





Both CDM & WDM compatible with CMB & galaxy clustering

Claims that both types of DM have been discovered:

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

Very unlikely that both are right!



The identity of the dark matter is encoded
in dwarf galaxies and in the halo of the MW
(strongly non-linear regime)

Three problems of CDM on small scales

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

Other dark matter particle candidates

Postulated largely to solve the perceived “small-scale crisis” of CDM

- Self-interacting dark matter (SIDM)
- Axion-like particles (ALPS)
- “Fuzzy dark matter” (e.g extremely light bosons)




Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

cold dark matter

warm dark matter



How can we distinguish between these?

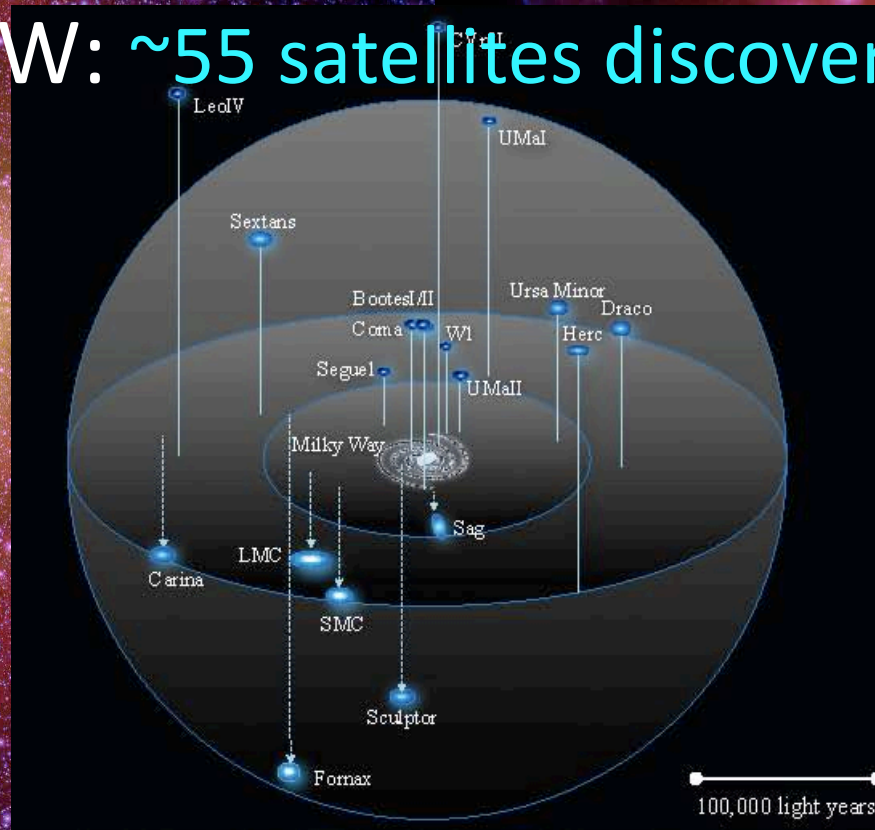
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far

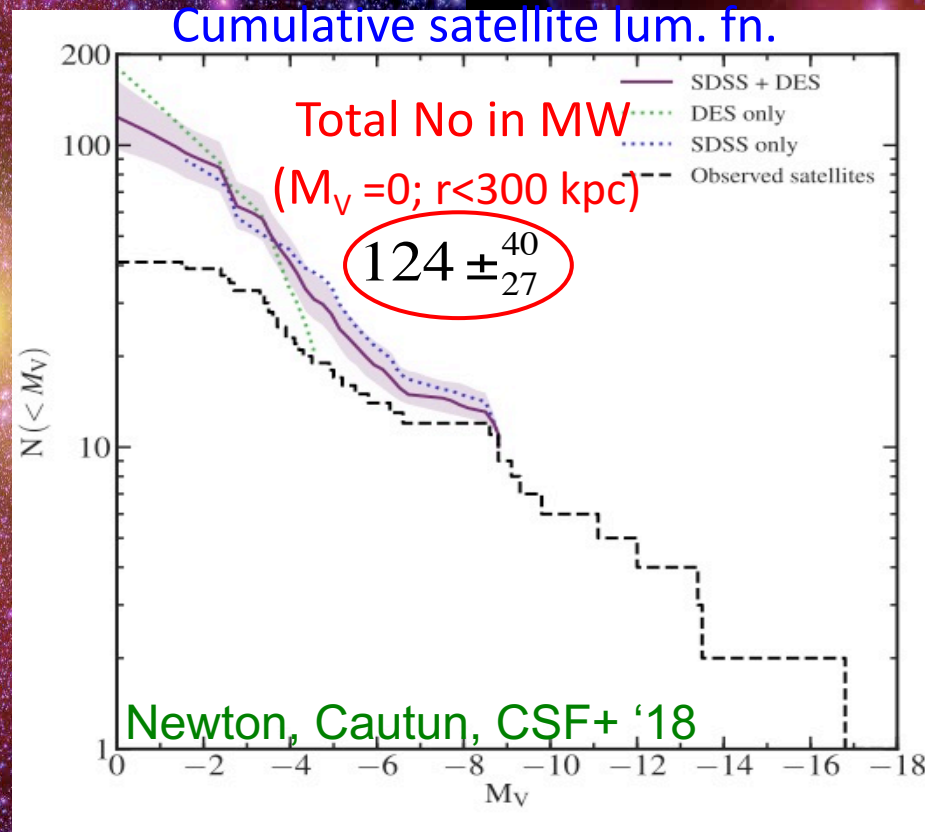


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
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cold dark matter

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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
~125 satellites expected

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

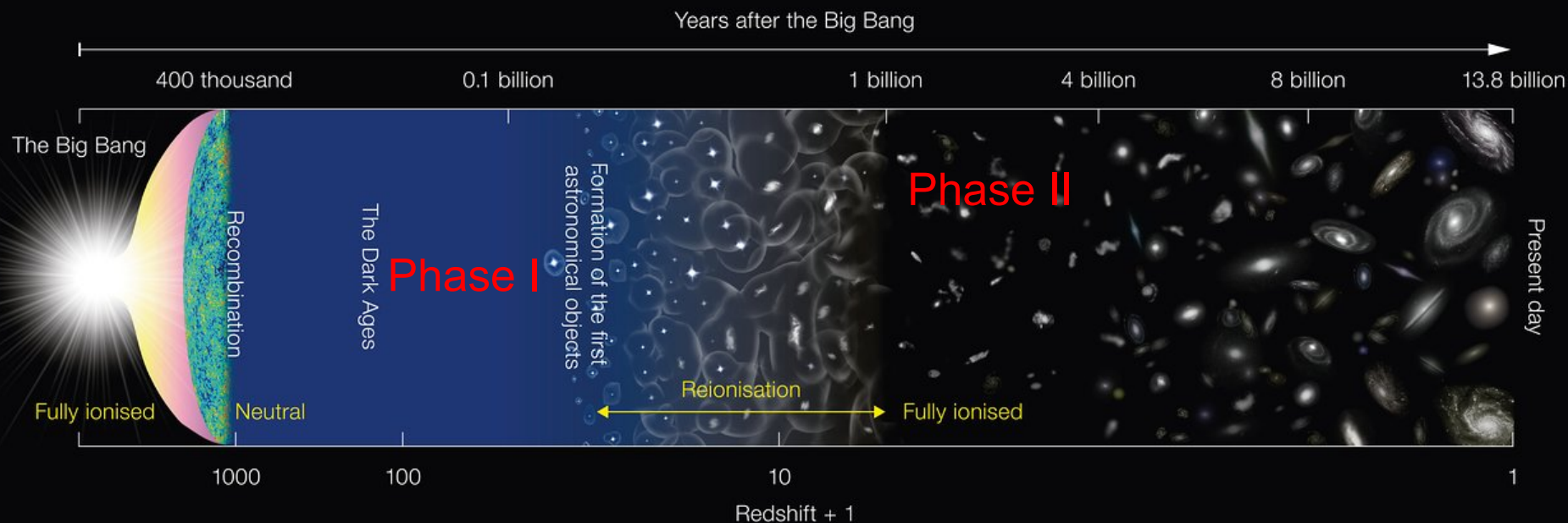
This argument (“missing satellites”) is **WRONG!**

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

A dense field of stars in space, with a bright yellow star in the center and a text box overlaid.

Most subhalos never make a galaxy!

The two phases of galaxy formation



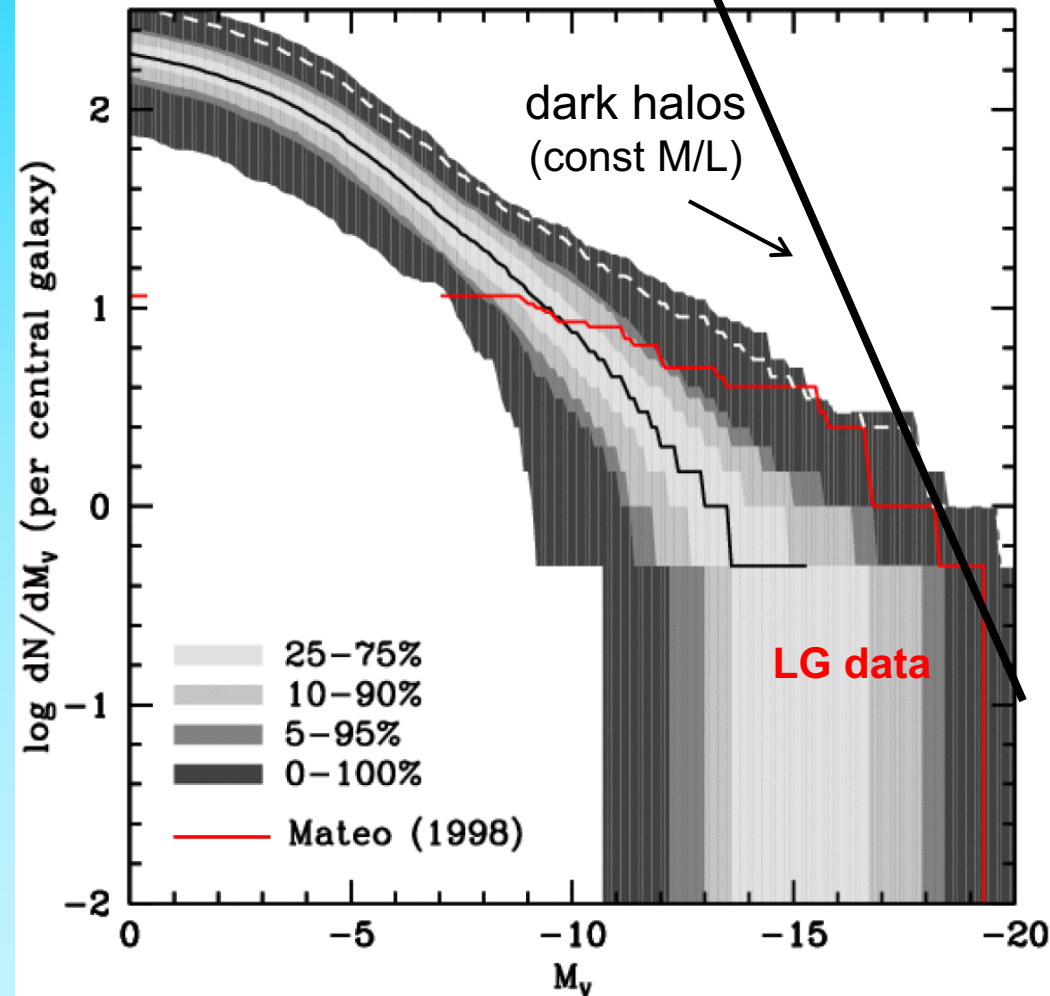
Phase I: Galaxies begin to form during the “dark ages”

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

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

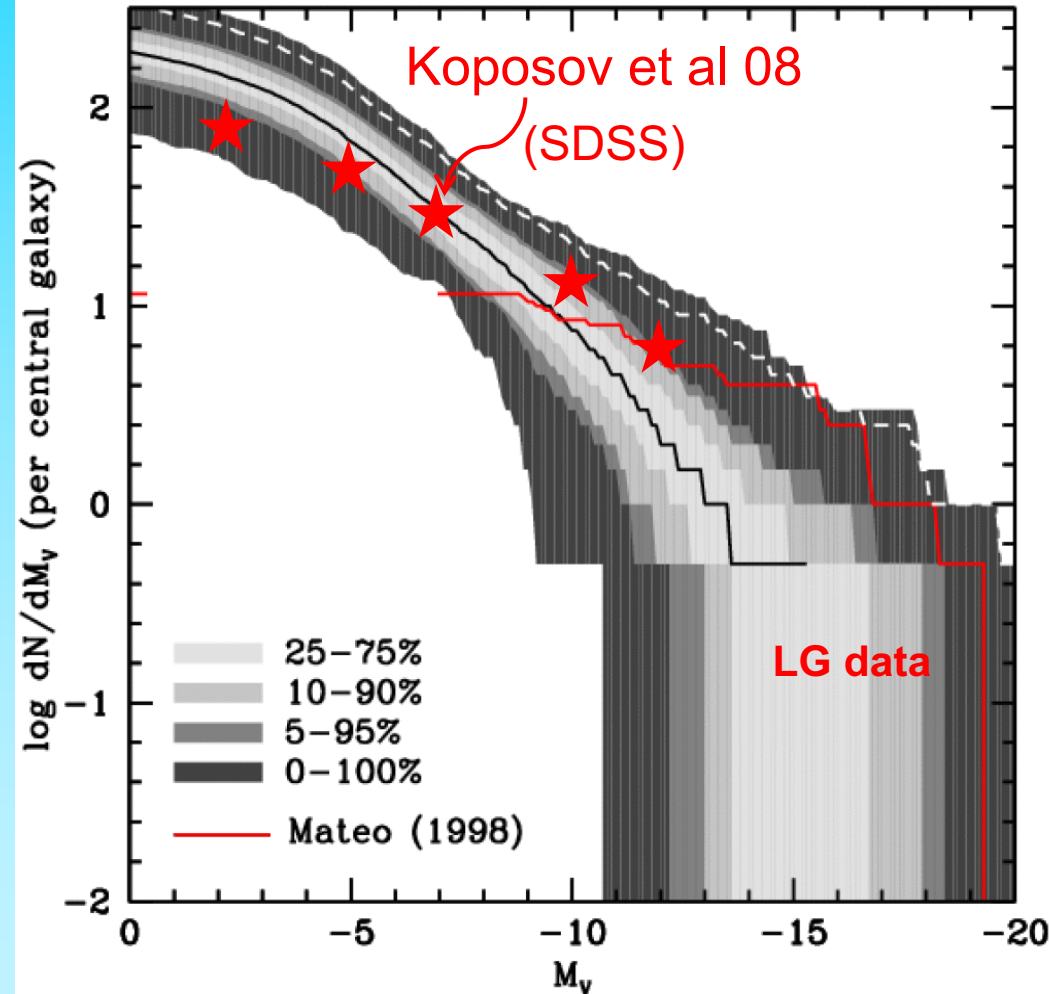
Luminosity Function of Local Group Satellites

- 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 (~10% of cases)



Luminosity Function of Local Group Satellites

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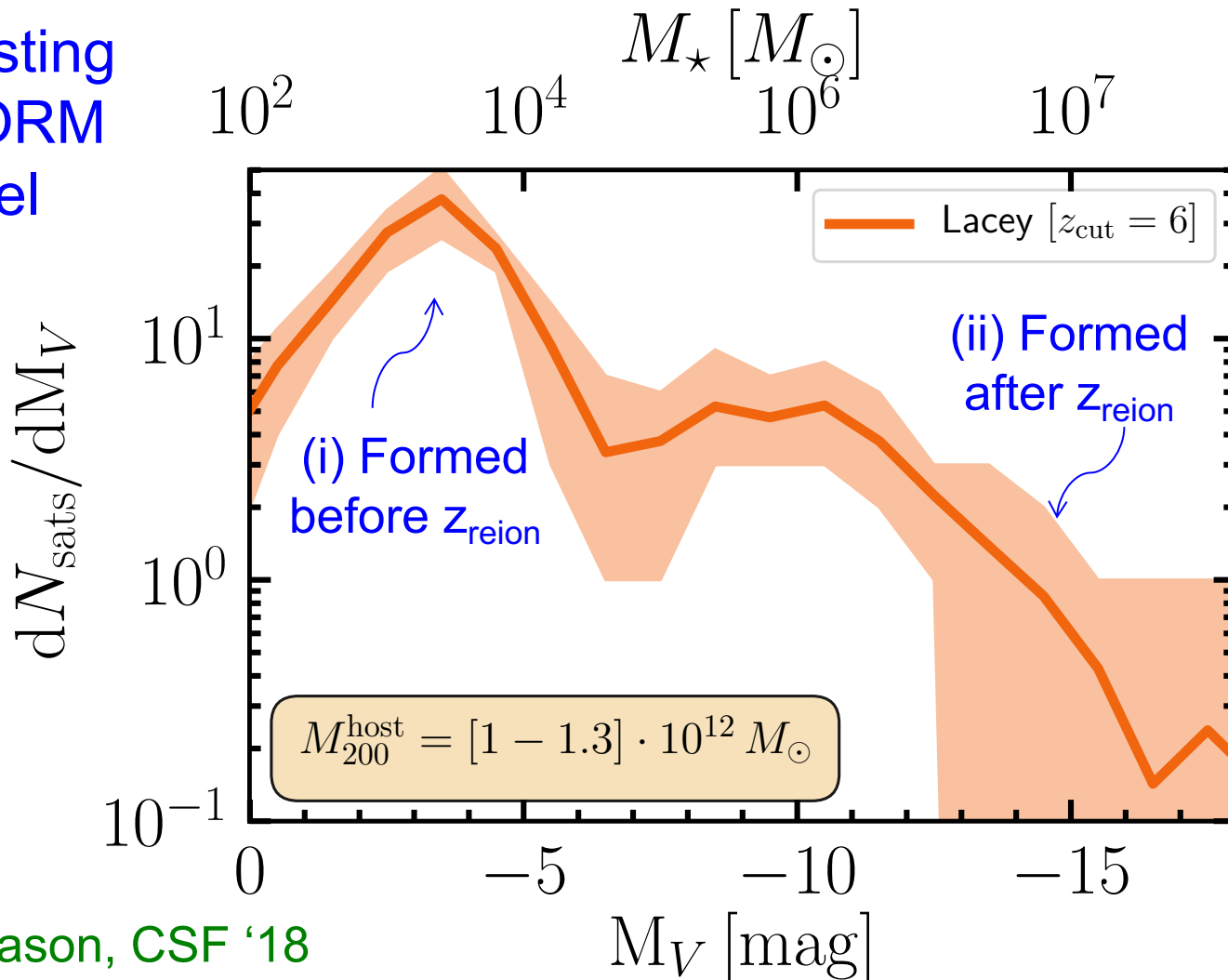


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

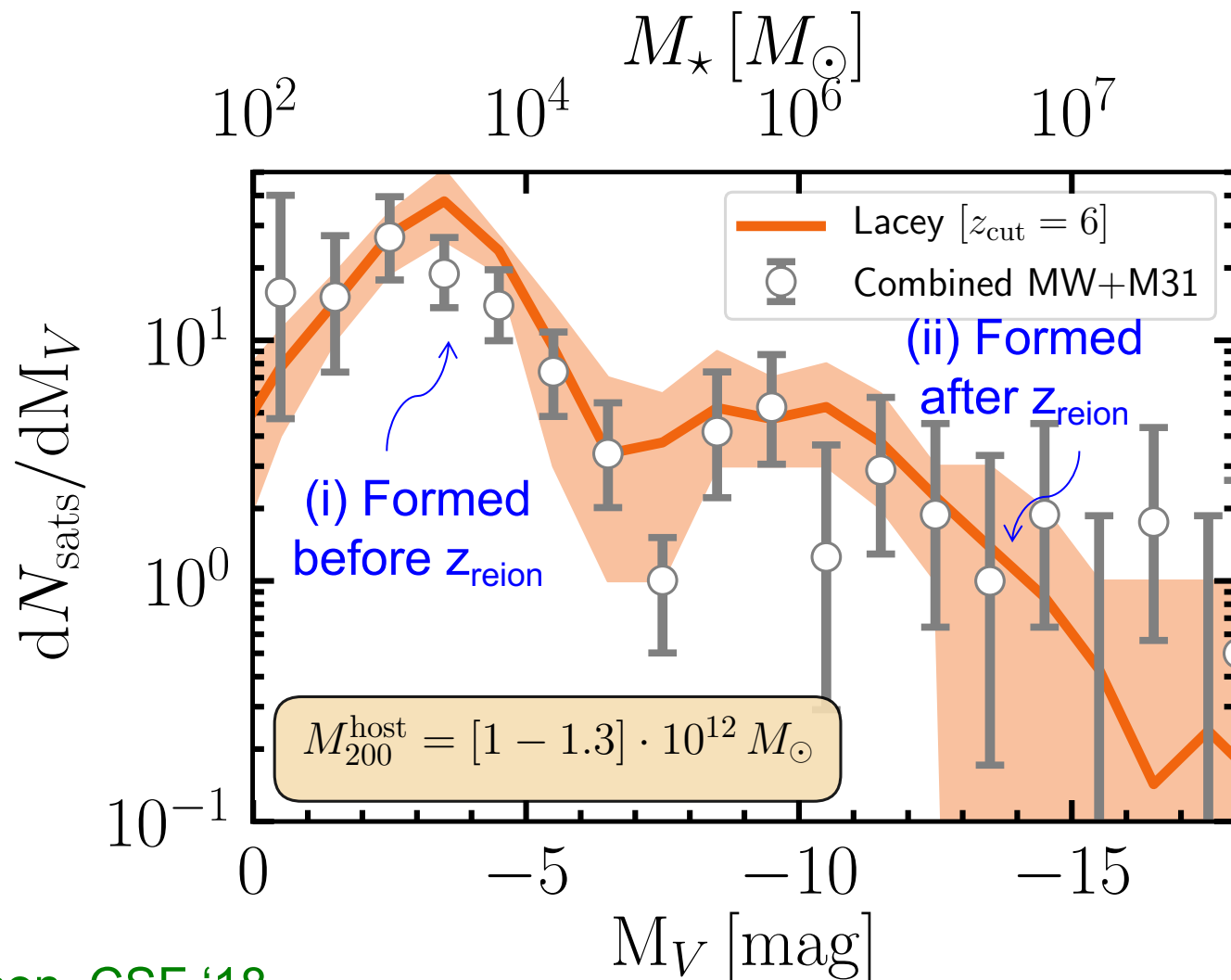
The satellite luminosity function

Two populations of sats formed: (i) before and (ii) after reionization

Pre-existing
GALFORM
model



Theory vs data





VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and
their environment”

THE EAGLE PROJECT

Virgo Consortium

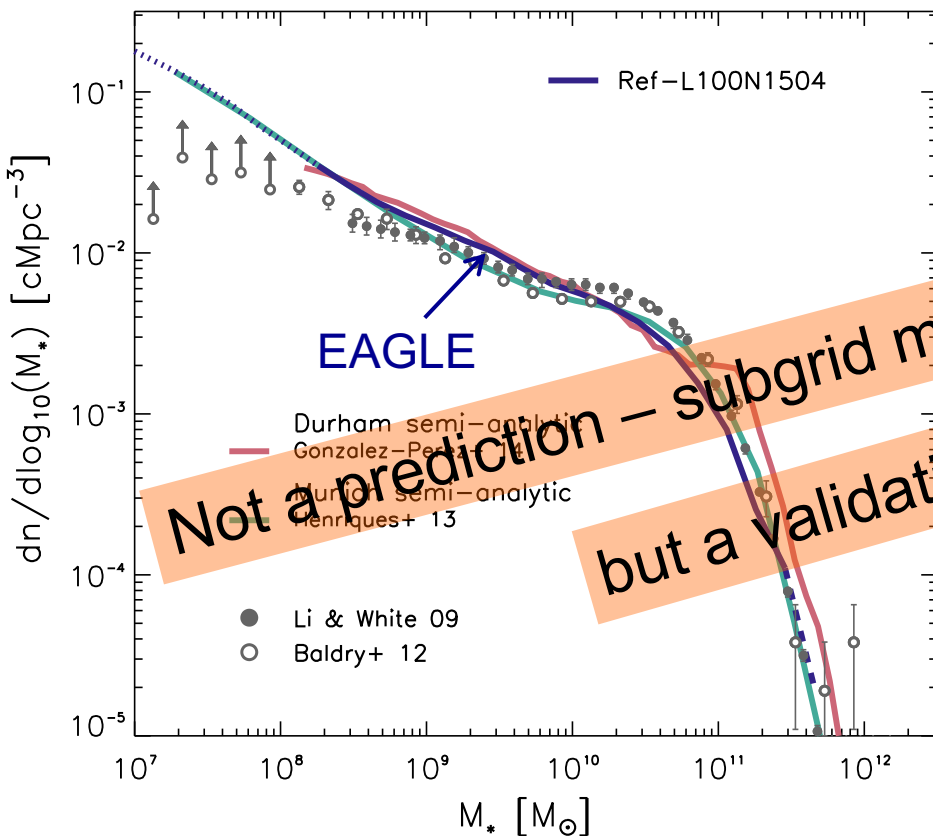
Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

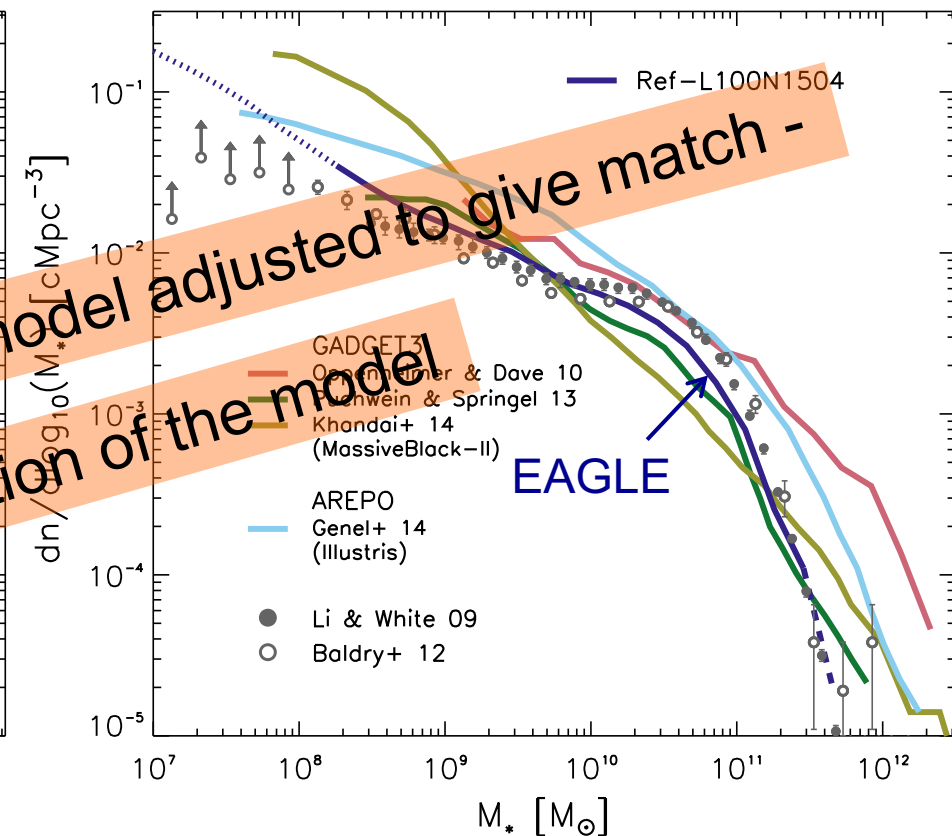
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...

Galaxy stellar mass function

Comparison to semi-analytic models



Comparison to other Hydro simulations



The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

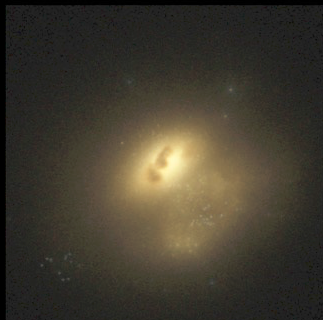
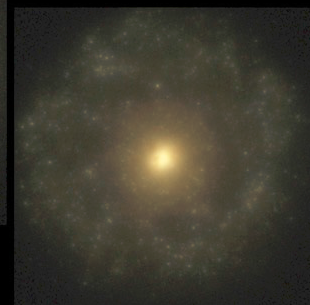
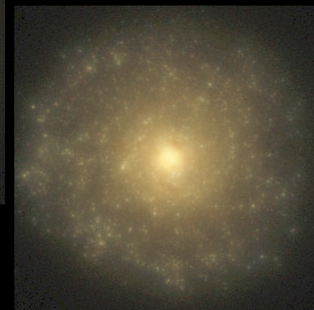
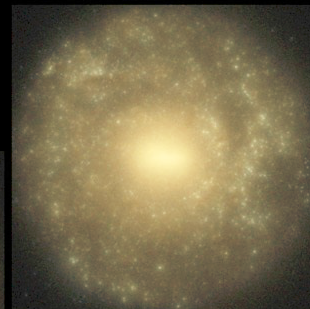
The Hubble Sequence realised in cosmological simulations

E0

E7

S0

SB



Irr

S

Trayford et al '15

VIRG

Dark matter

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al '16



Stars

VIRG

APOSTLE
EAGLE full
hydro
simulations

Local Group

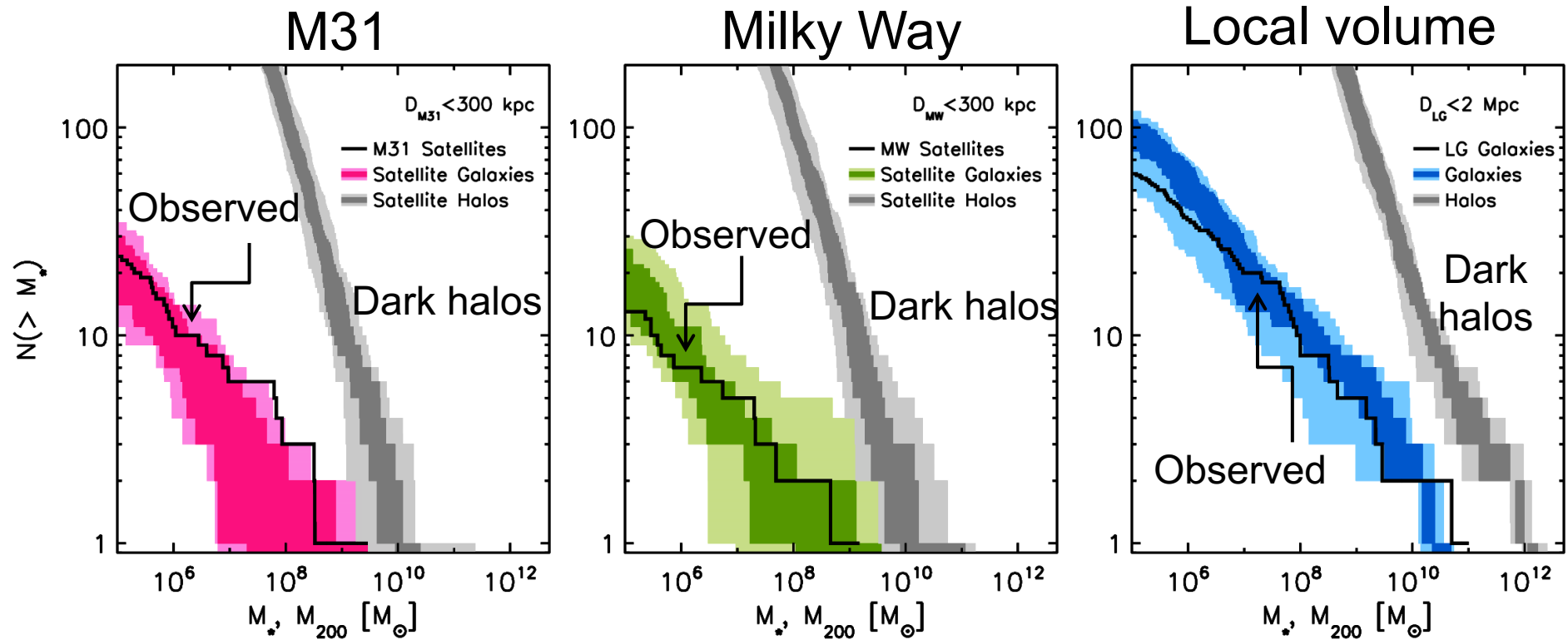
Stars

Far fewer satellite galaxies than CDM halos

Sawala et al '16



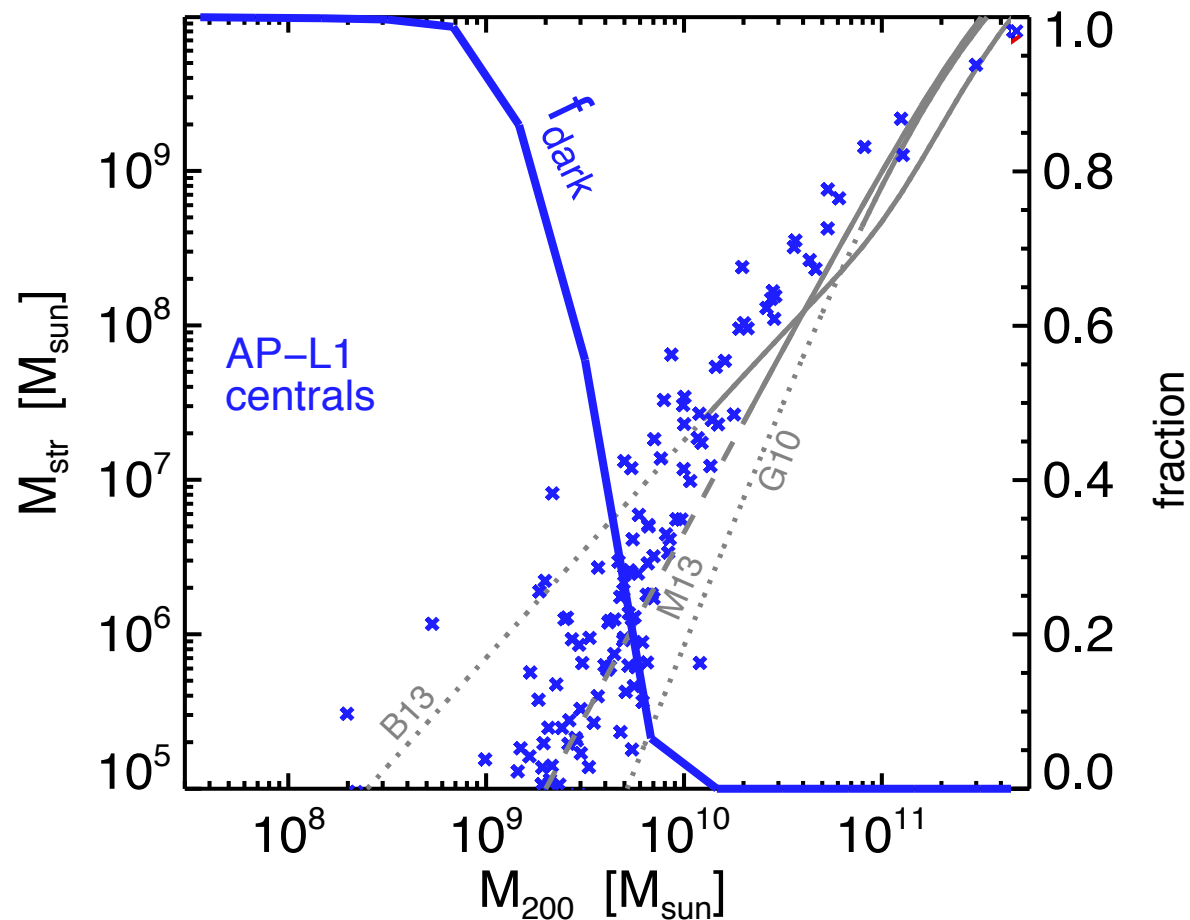
EAGLE Local Group simulation



Fraction of dark halos

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

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



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

When “baryon effects” are
taken into account



Observed abundance of satellites
is compatible with CDM

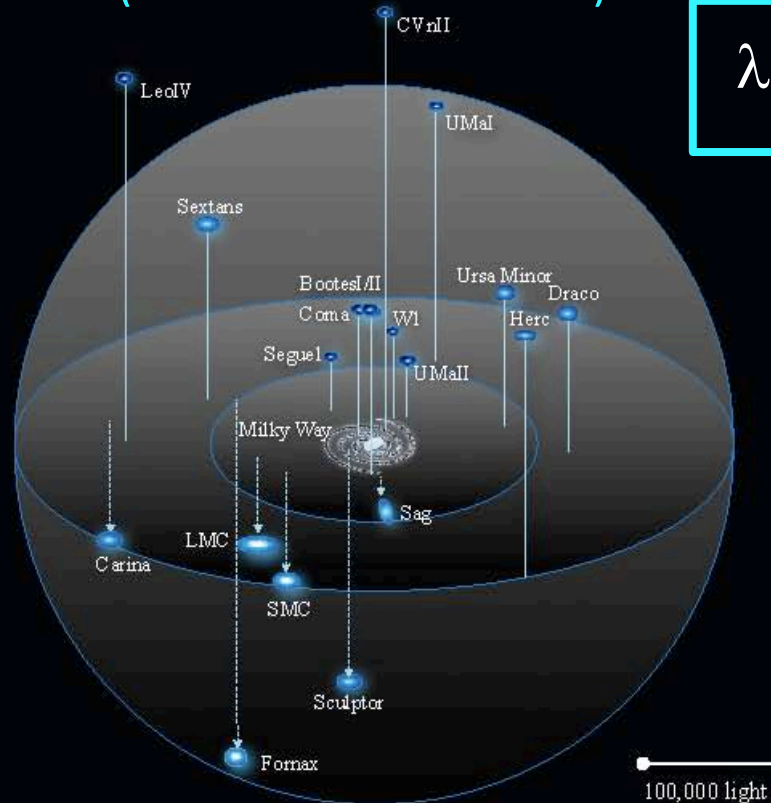


There is no such thing as the
“satellite problem” in CDM!

How about in WDM?

The satellites of the MW

(~55 discovered so far)



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

Dark matter subhalos in WDM

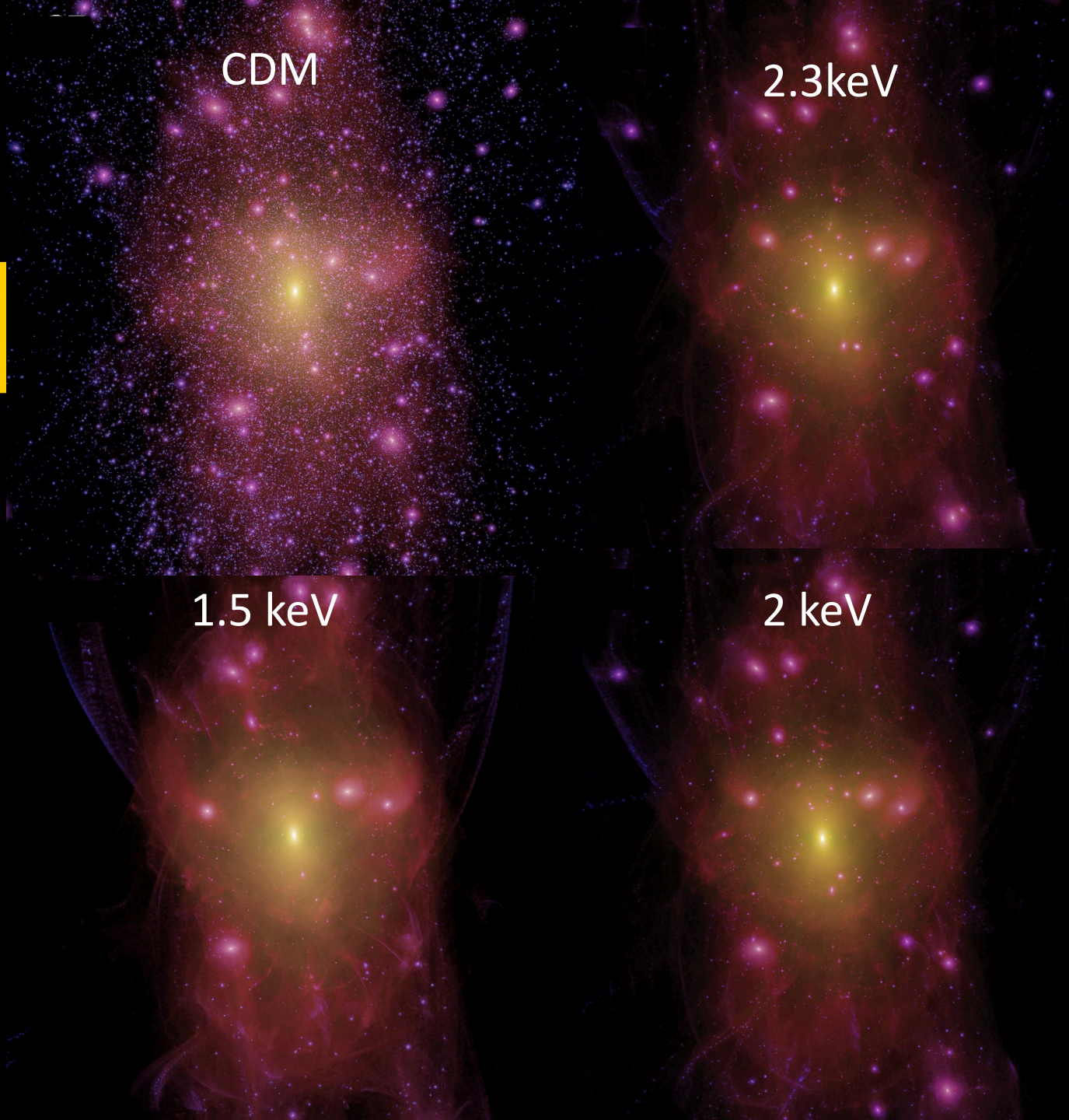
(a few tens)

Can rule out low WDM
particle masses



Warm DM:
different ν mass

- WDM
- 2.3 keV
- 2.0 keV
- 1.5 keV

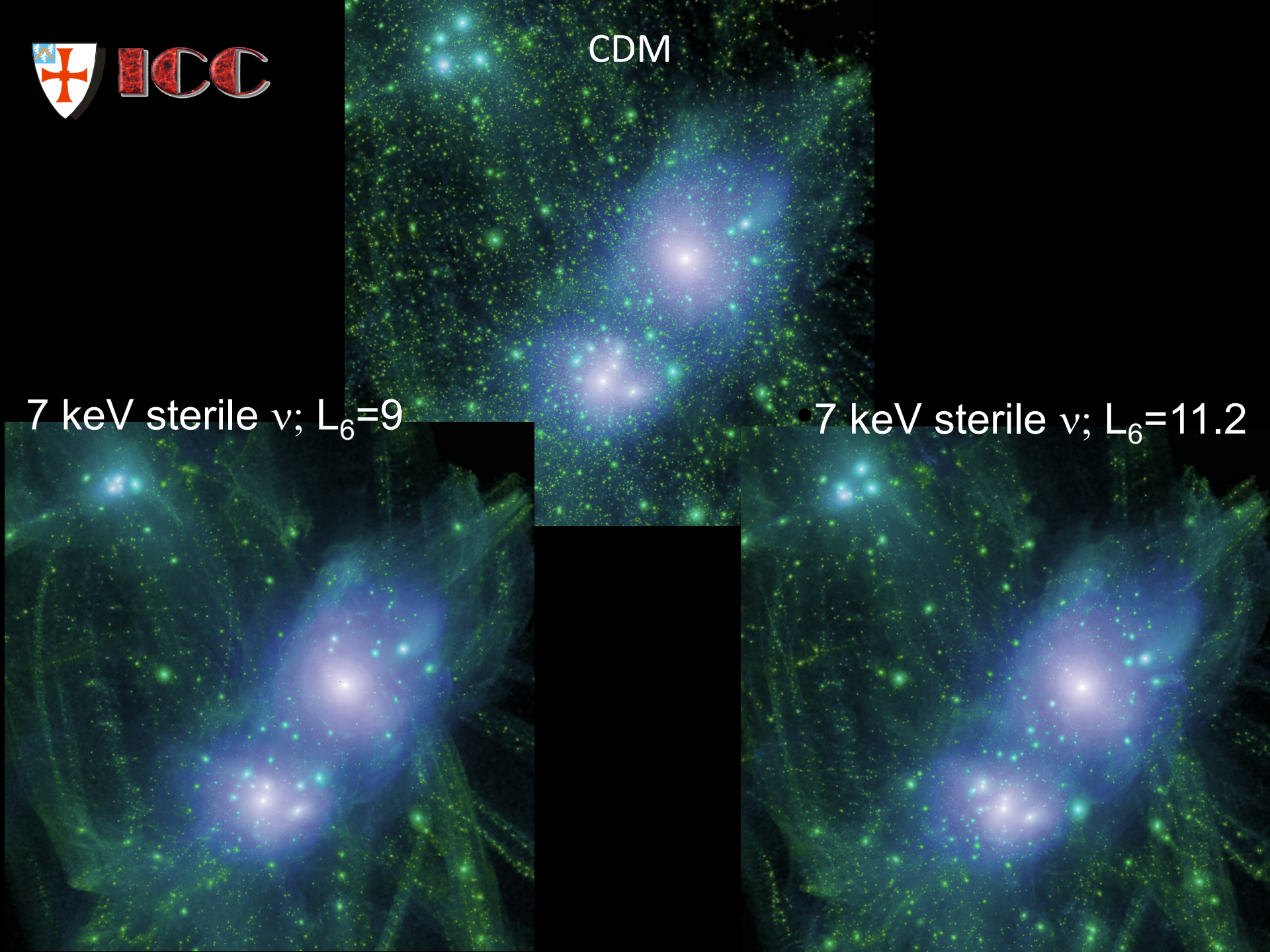




CDM

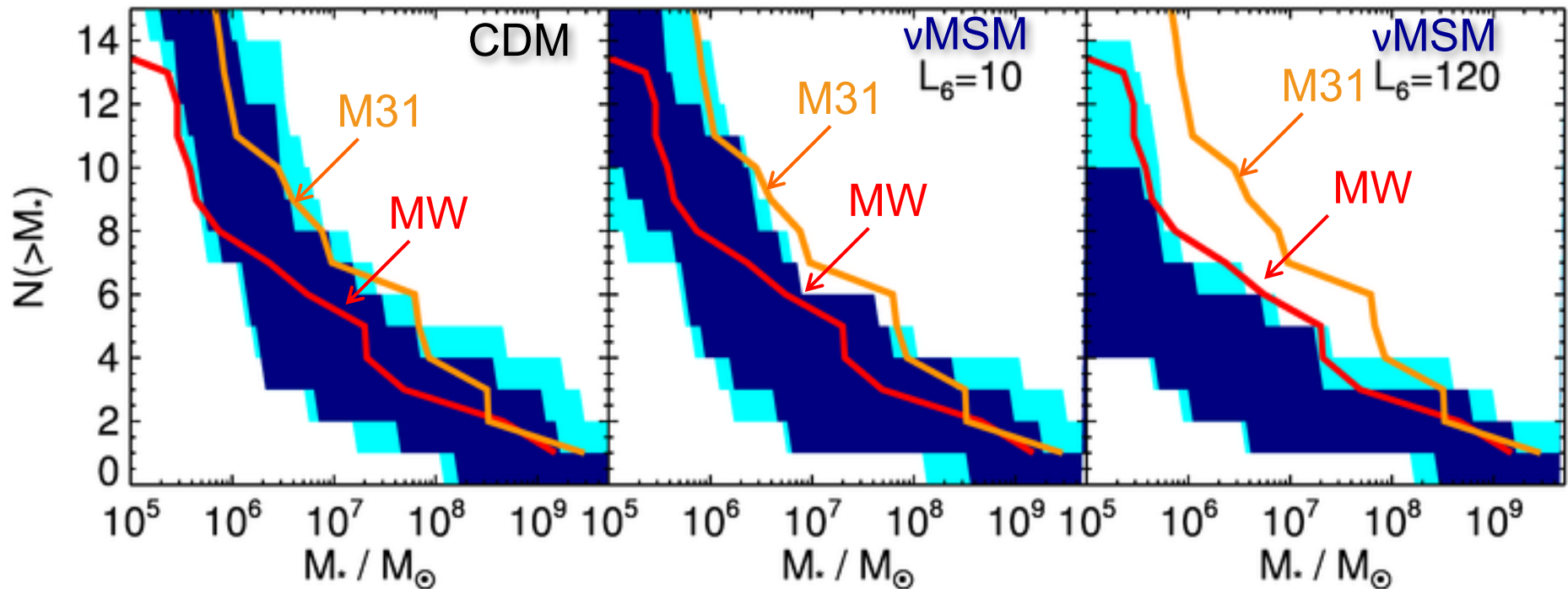
7 keV sterile ν ; $L_6=9$

• 7 keV sterile ν ; $L_6=11.2$



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



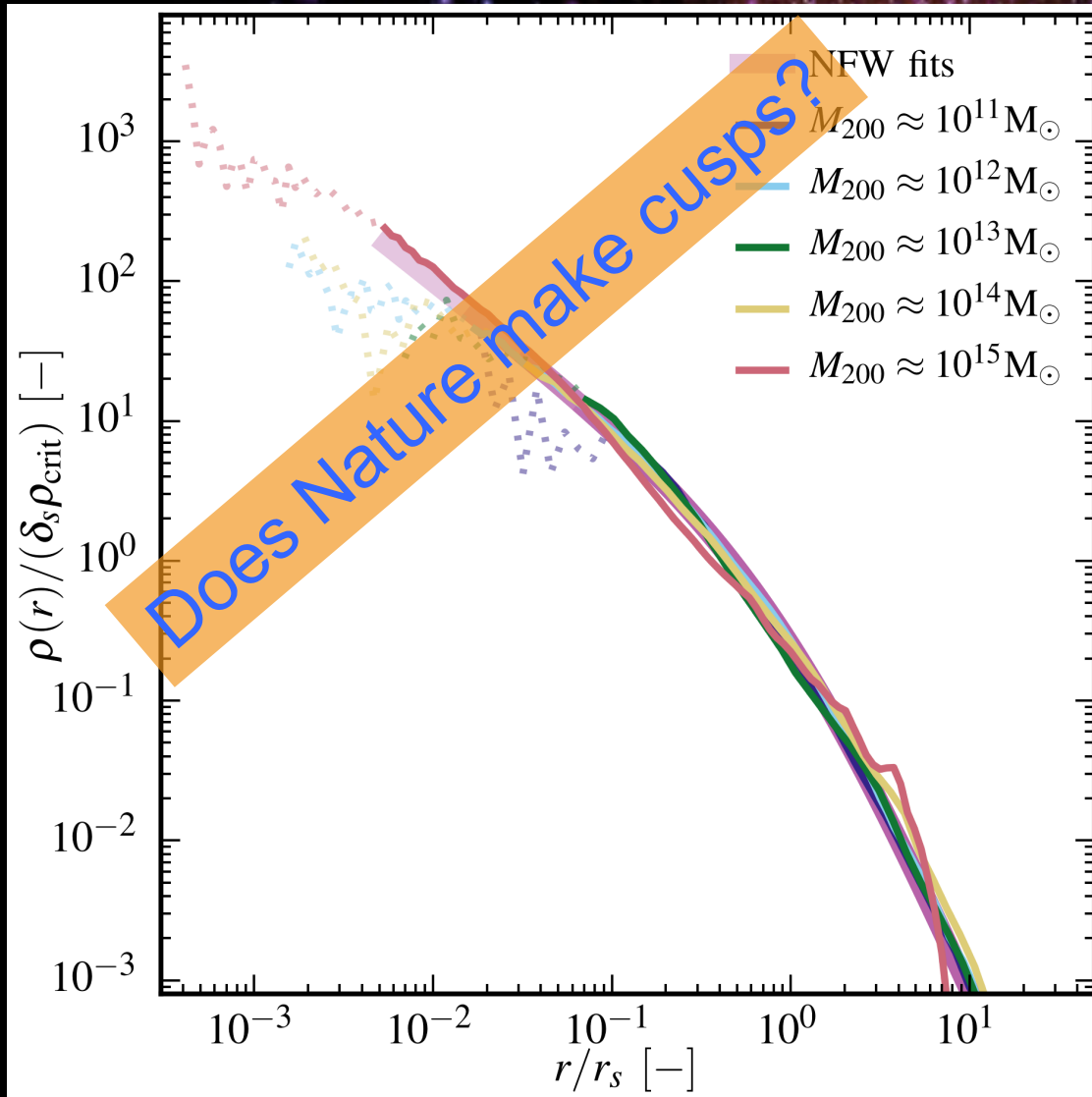
Can't rule out CDM (or
WDM) by counting the
satellites of the Milky Way

Does the inner
structure of satellites
help?

→ The core/cusp problem



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:

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

(Navarro, Frenk & White '97)

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



Cores or cusps in nature?



↓
Cores

↓
Cusps

No convincing evidence for cores in observed galaxies



But if cores were found in halos, would
this rule out CDM (and WDM)?



But, if cores were
found to exist in
galaxies, would
this rule out CDM
(& WDM)?

No!



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)

The cores of dwarf galaxy haloes L75

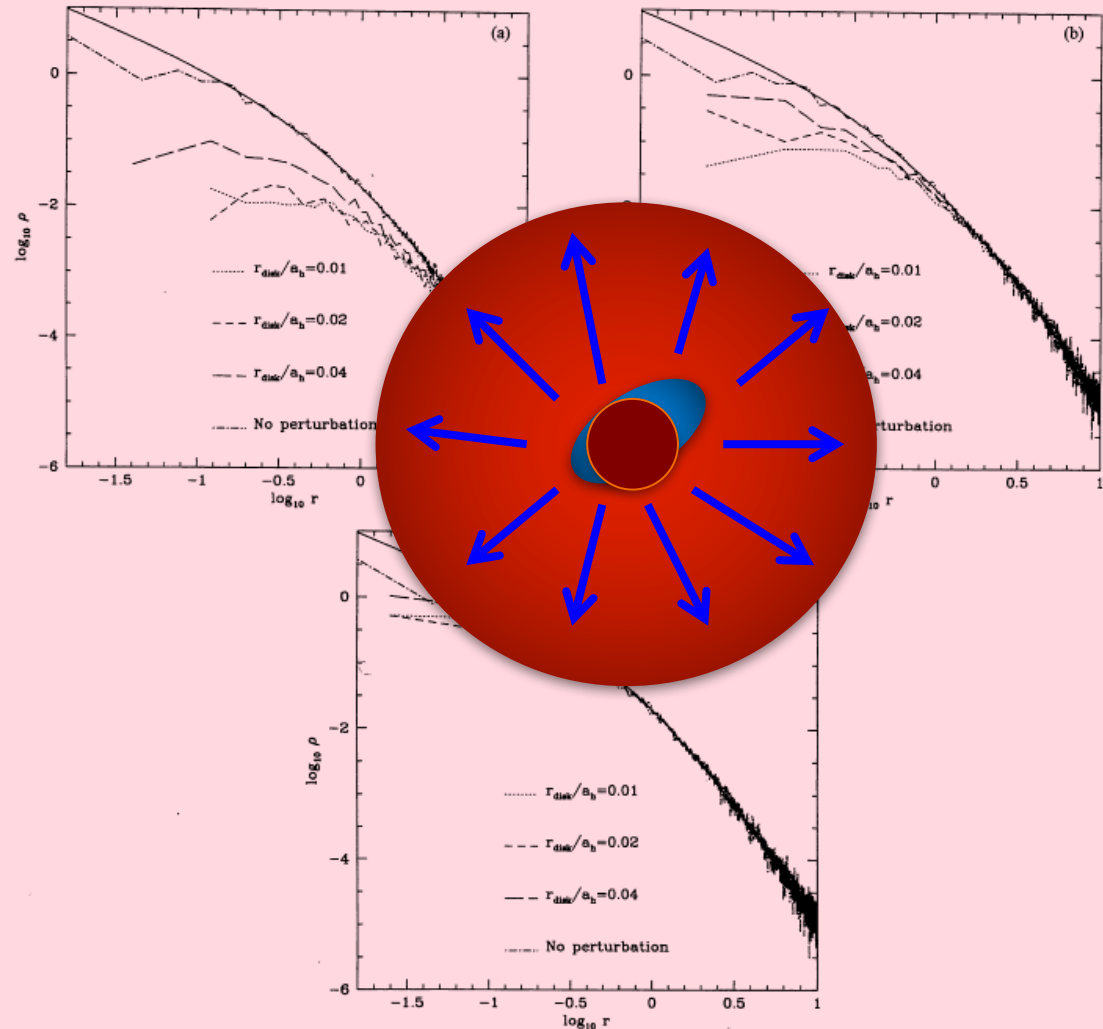


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{\text{disc}}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

Core formation

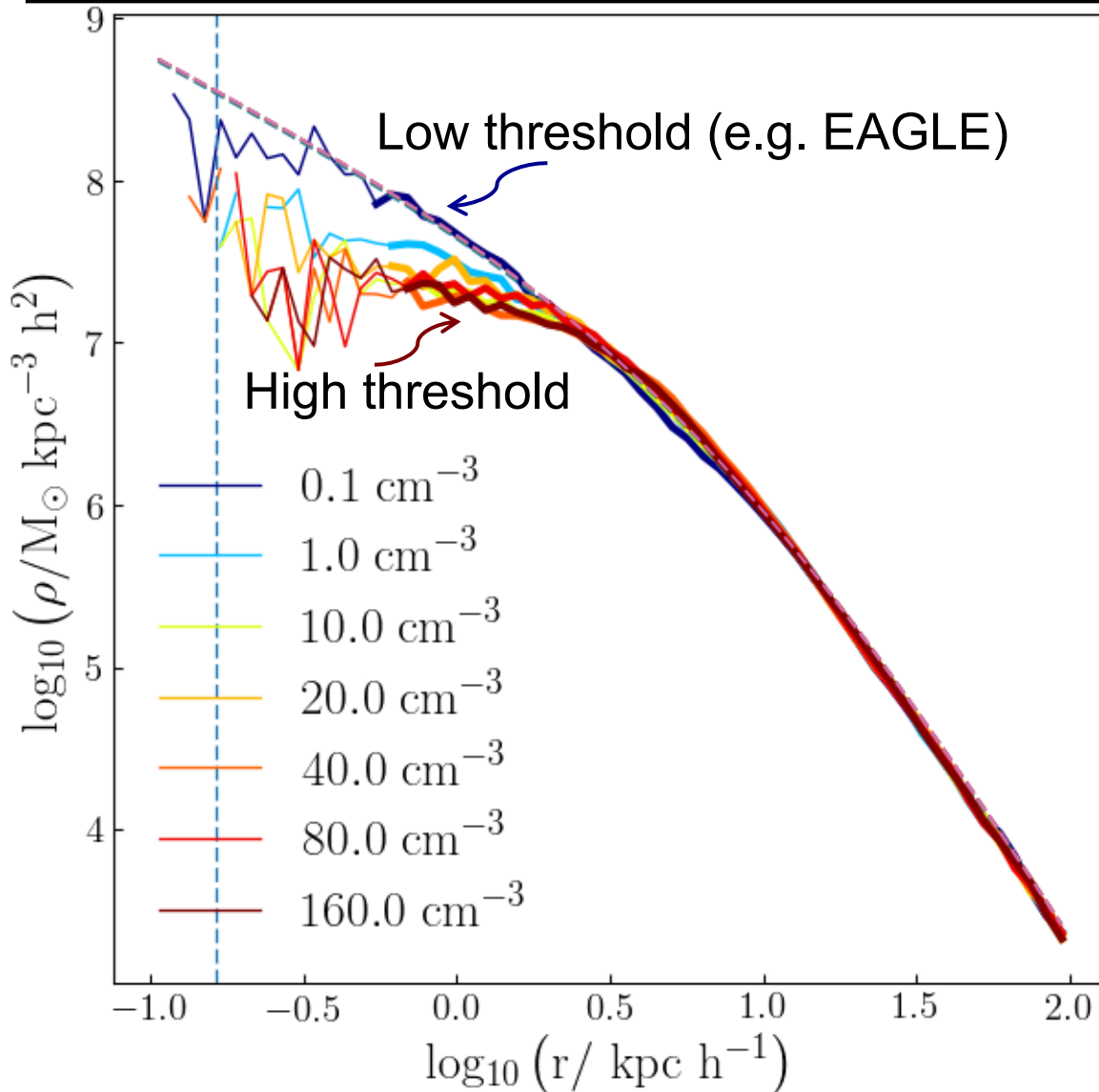
In the absence of a treatment of the (multi-phase) interstellar medium, need a “subgrid” model for star formation

Key parameter: gas density threshold for star formation



Physically meaningless

Cores or cusps in simulations?





Cores in halos can be generated by “baryon effects”

Is there any way can distinguish CDM from WDM?

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





Can we distinguish CDM/WDM?

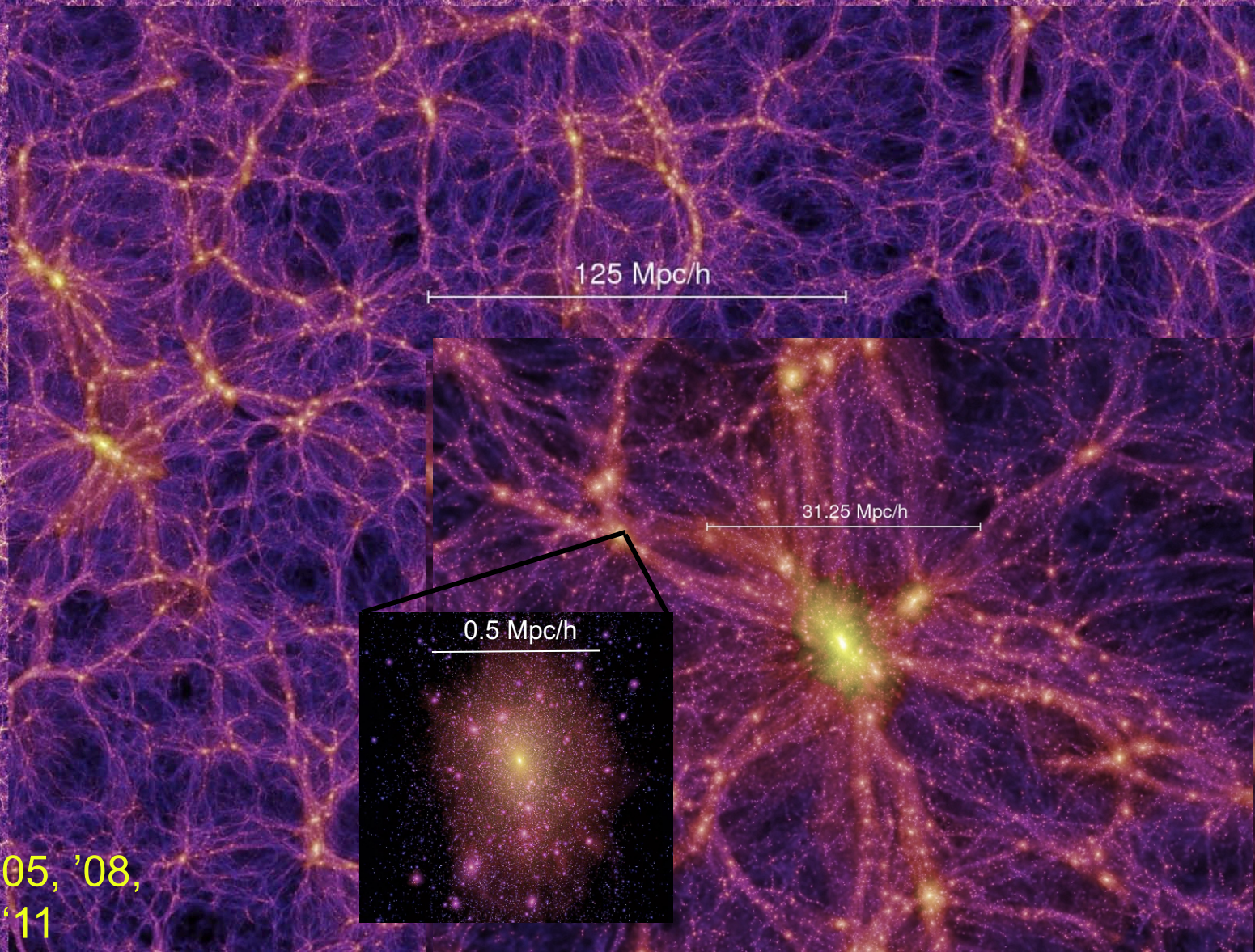
cold dark matter

warm dark matter

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

VIRGO

The Millennium/Aquarius/Phoenix simulation series



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

The subhalo mass function

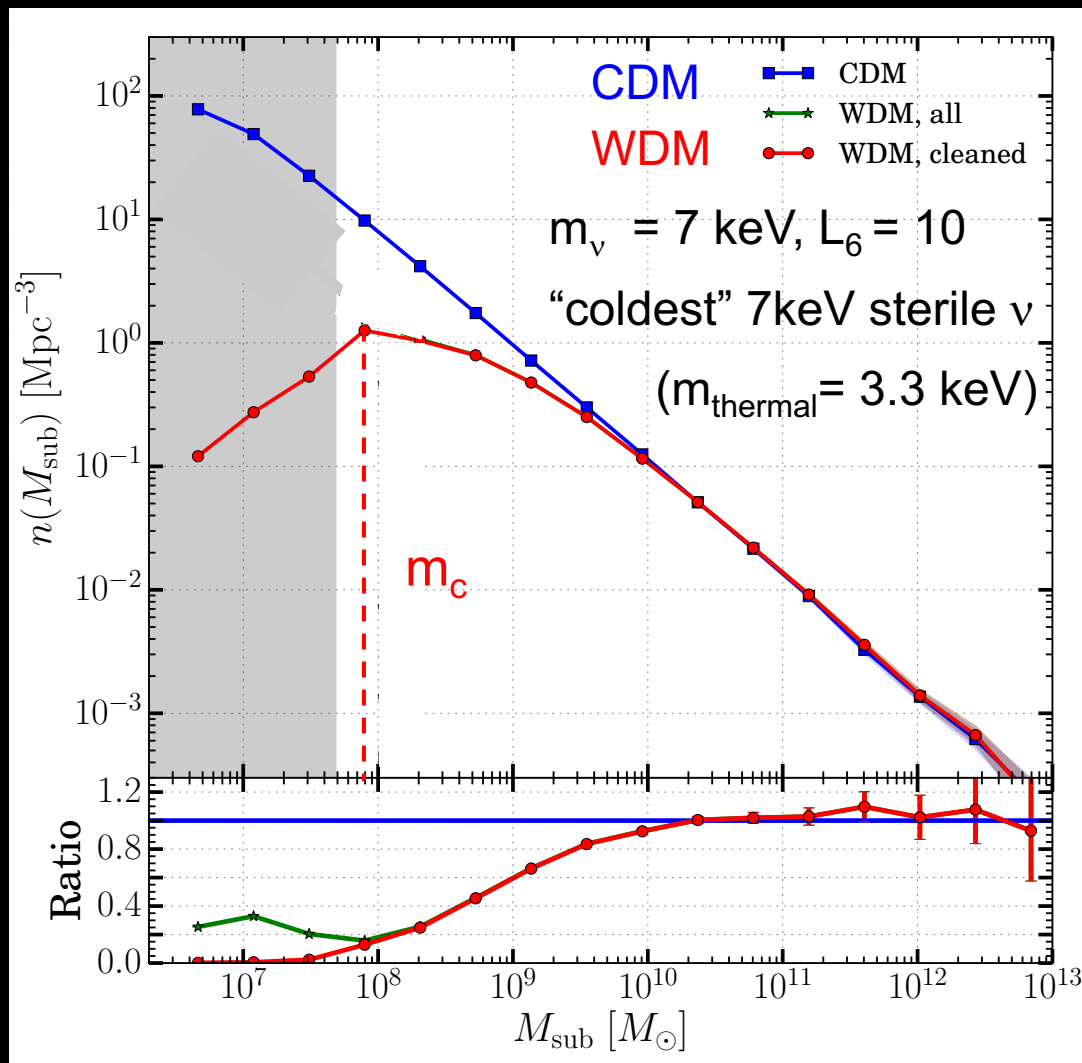


CDM

WDM

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

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





Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

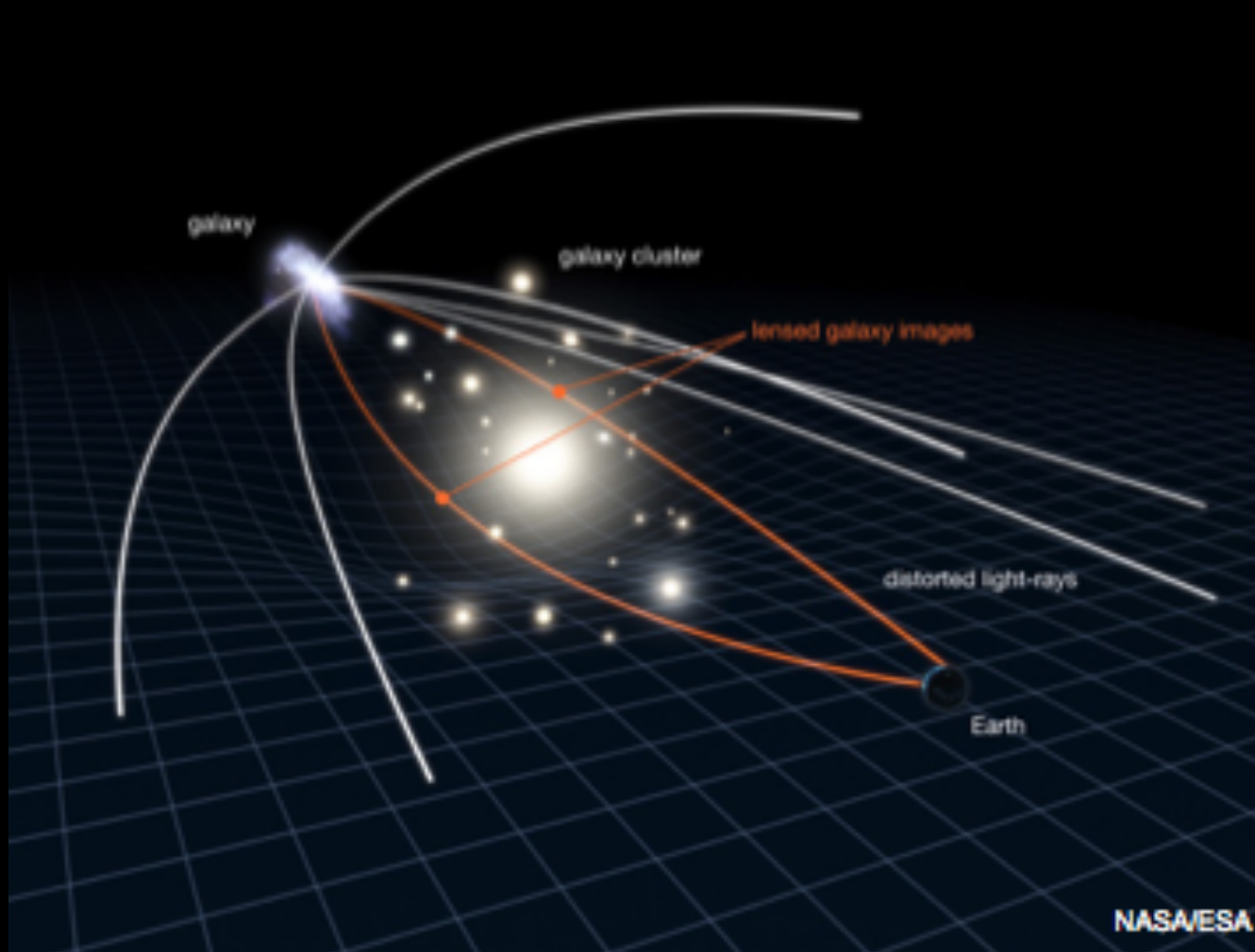
Dark halos can be detected through
gravitational lensing



Gravitational lensing: Einstein rings

How to rule out CDM

Gravitational lensing: Einstein rings

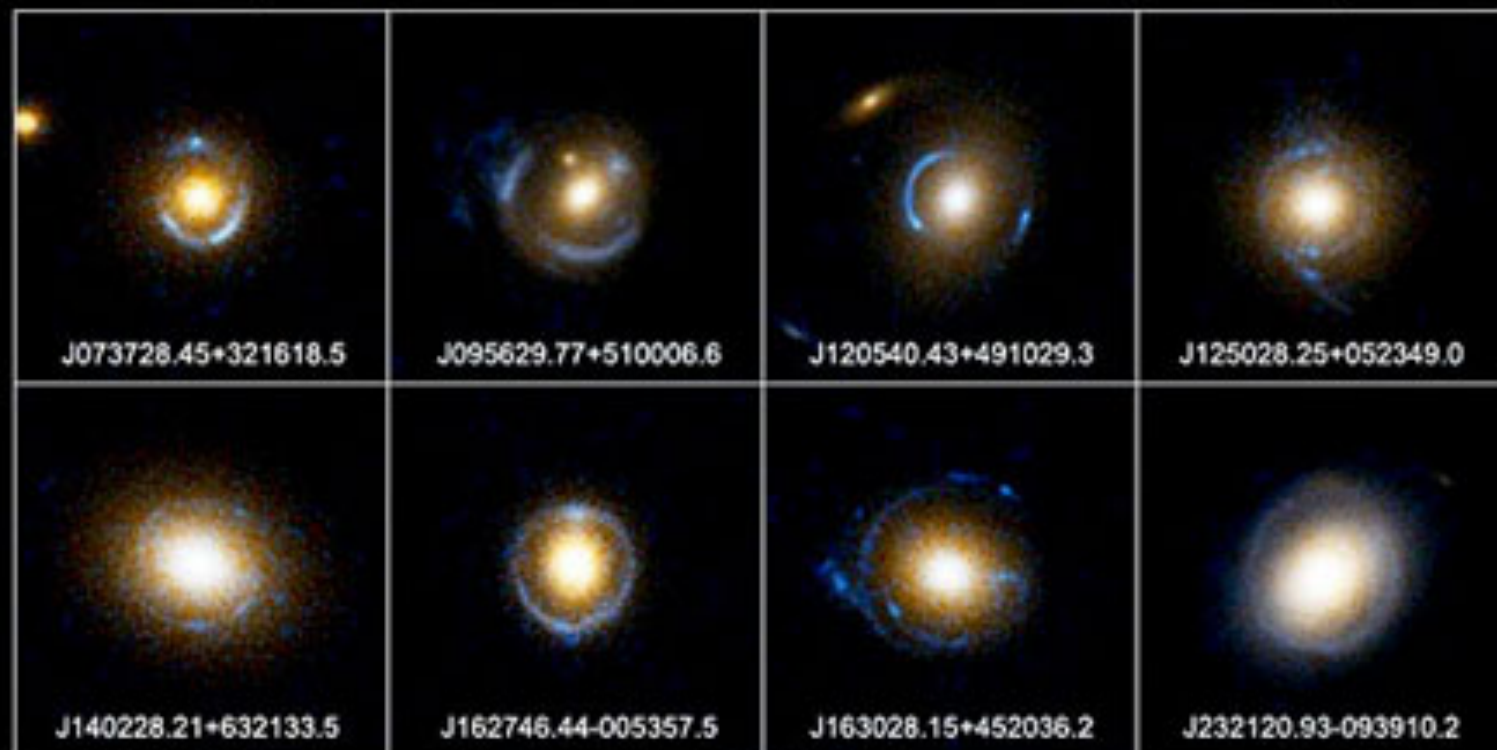


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses

Einstein Ring Gravitational Lenses

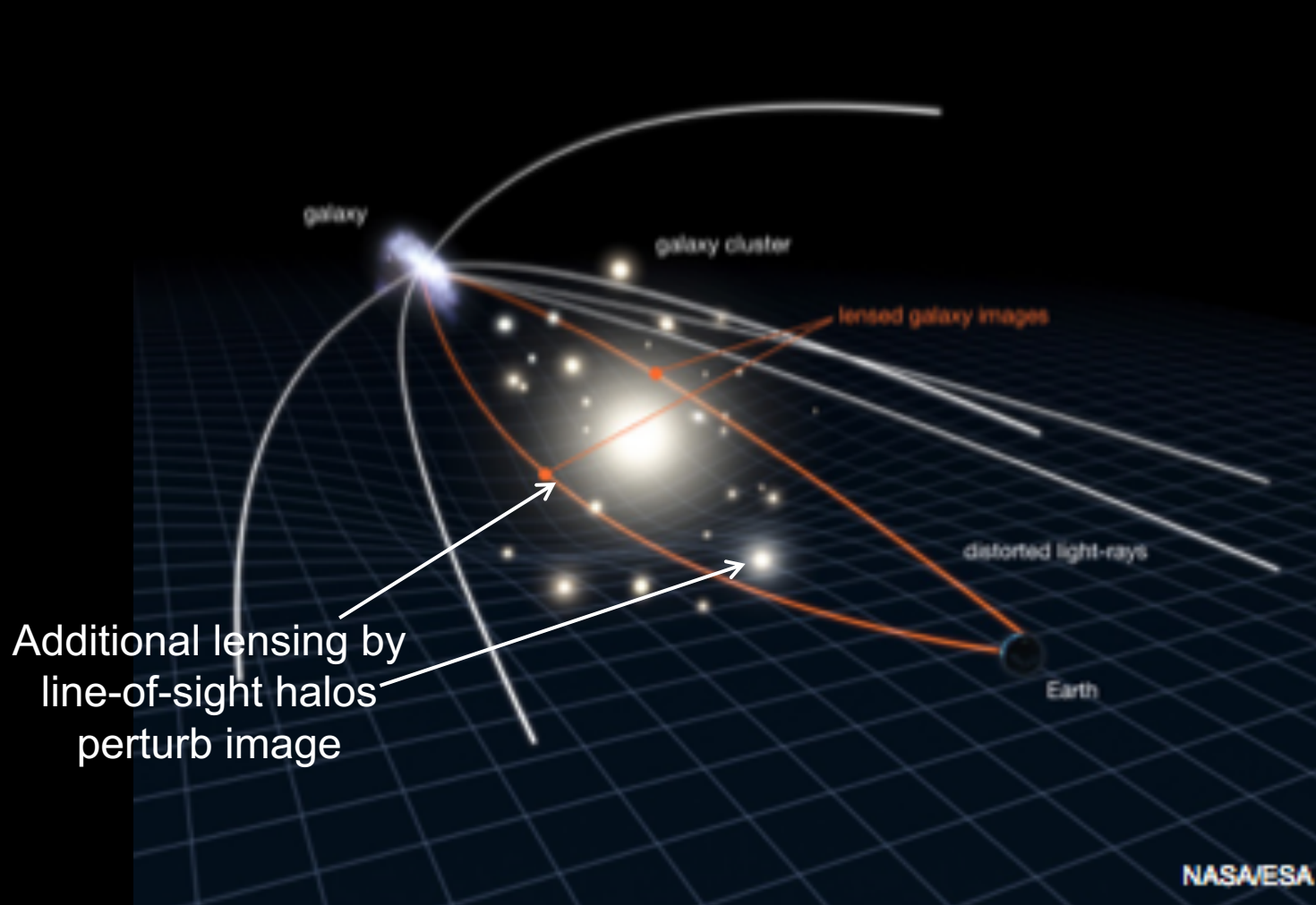
Hubble Space Telescope • ACS



NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

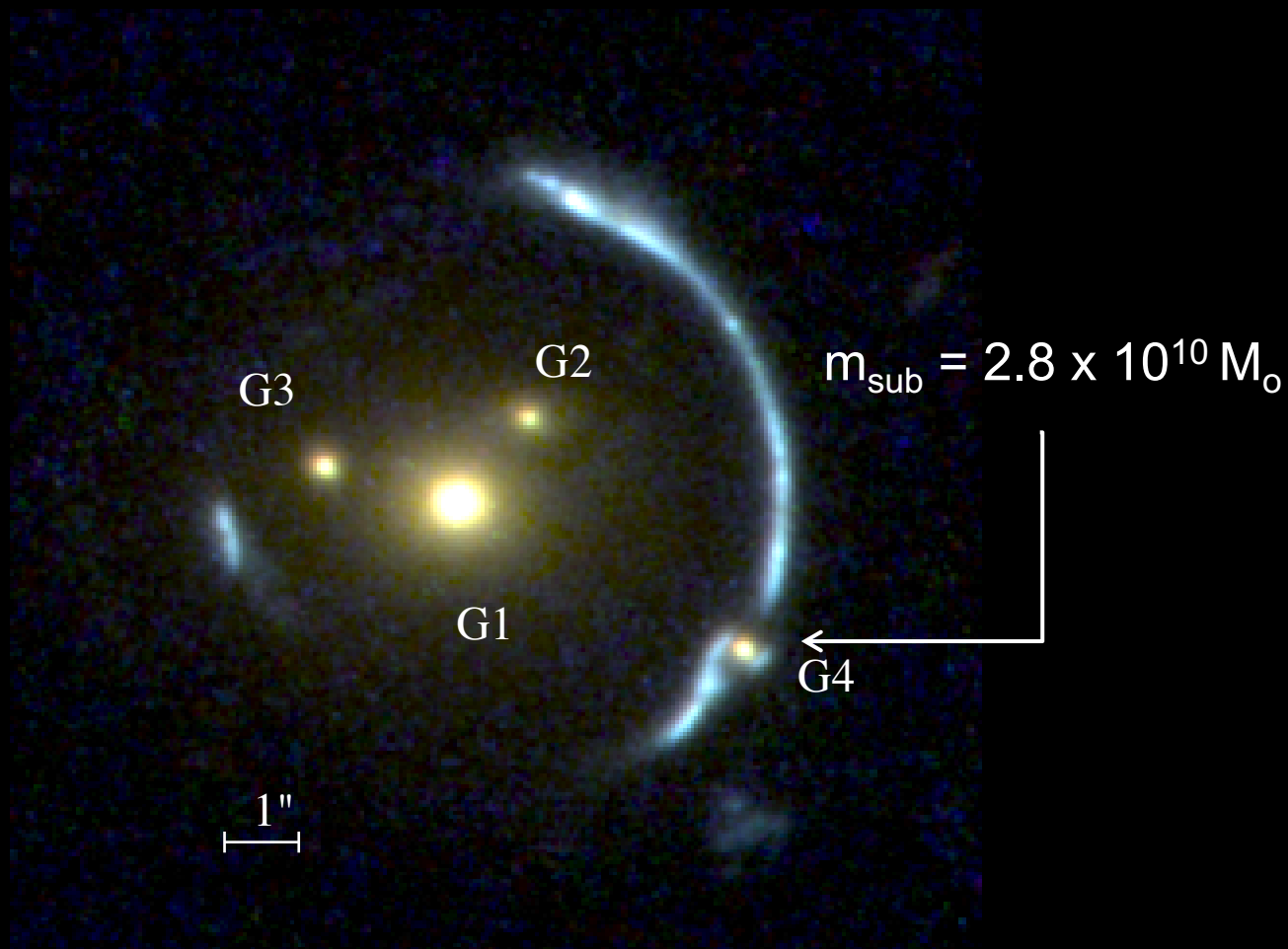
Gravitational lensing: Einstein rings



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 et al '10



Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans '09

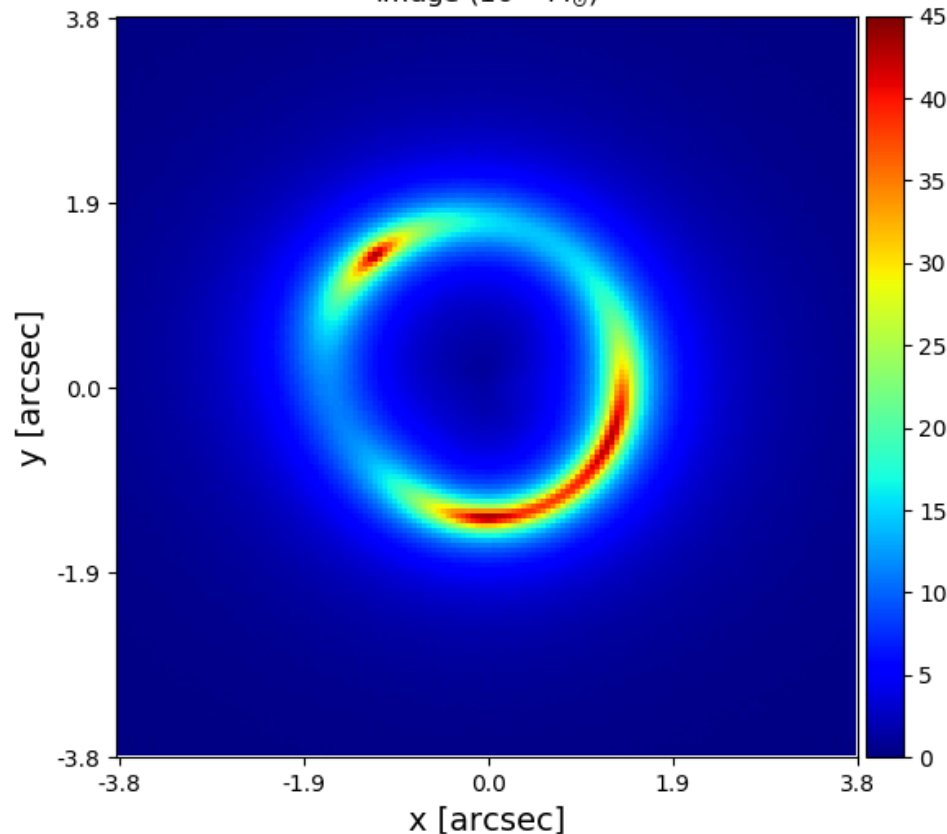
Gravitational lensing: Einstein rings

HST “data”: $z_{\text{source}}=1$; $z_{\text{lens}}=0.2$

$10^{10}M_{\odot}$ halo – **easy to spot**

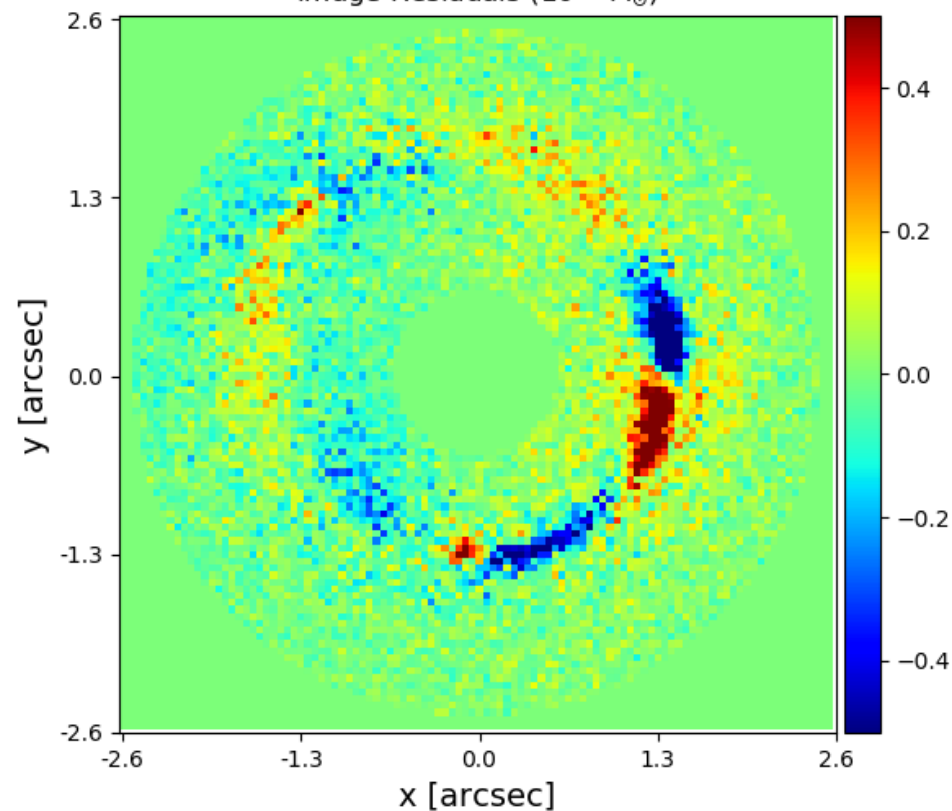
Image

Image ($10^{10} M_{\odot}$)



Residuals

Image Residuals ($10^{10} M_{\odot}$)

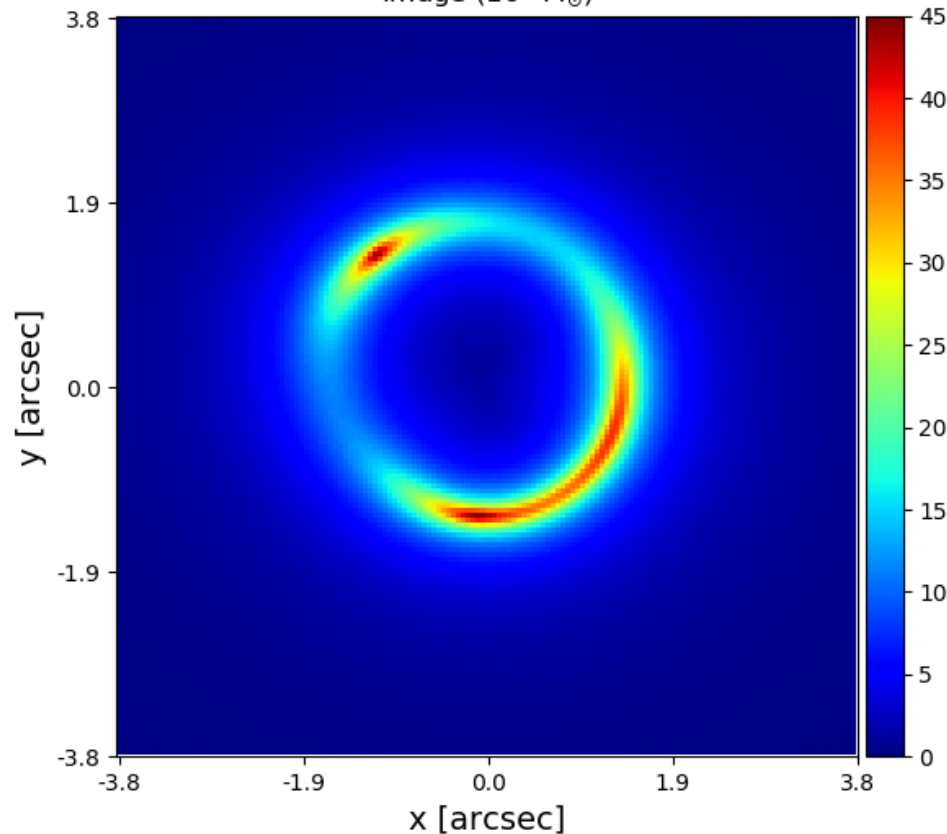


Gravitational lensing: Einstein rings

HST “data”: $z_{\text{source}}=1$; $z_{\text{lens}}=0.2$ $10^7 M_{\odot}$ halo – NOT so easy to spot

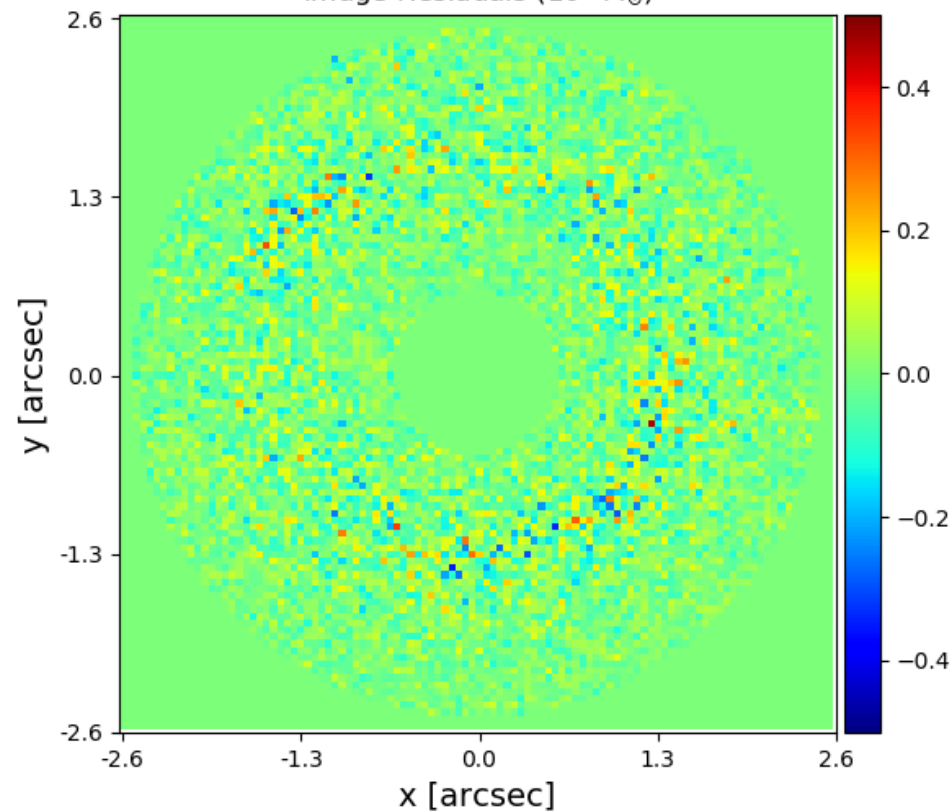
Image

Image ($10^7 M_{\odot}$)



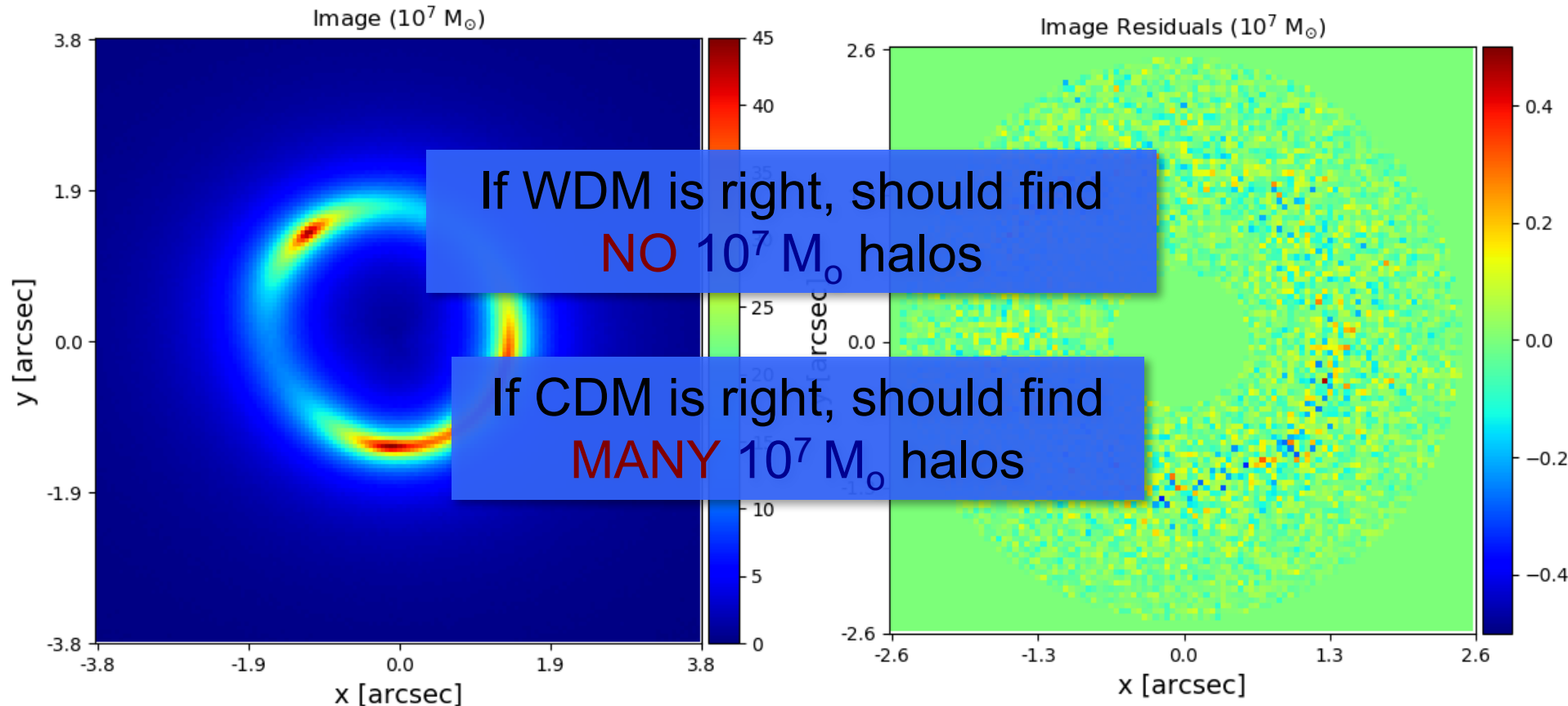
Residuals

Image Residuals ($10^7 M_{\odot}$)



Detecting substructures with strong lensing

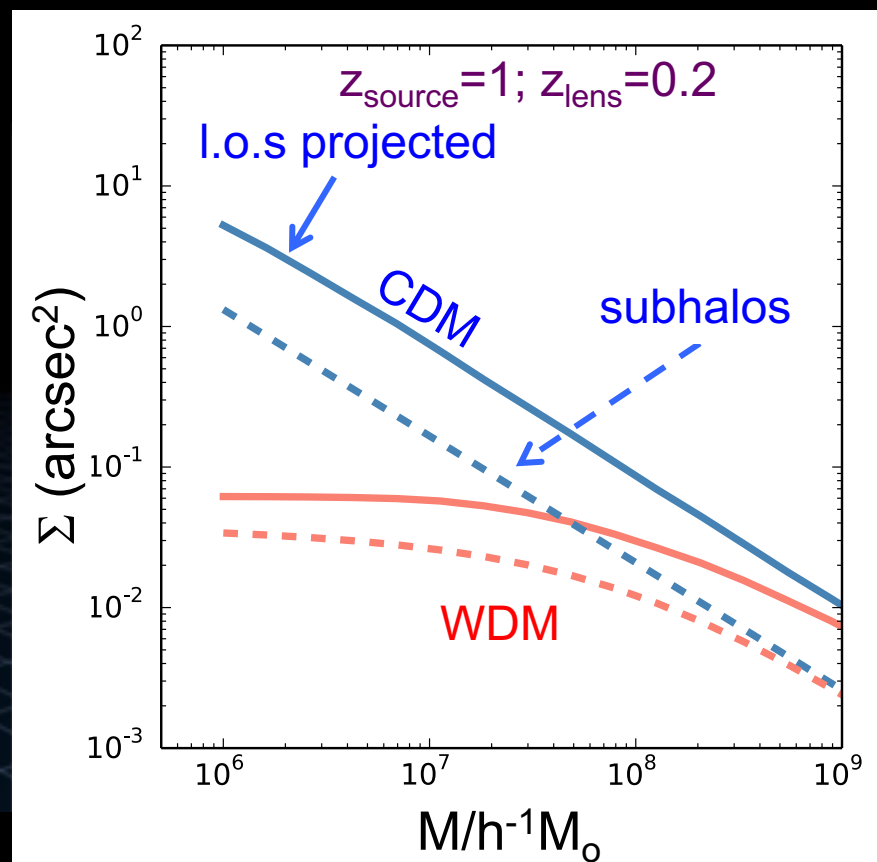
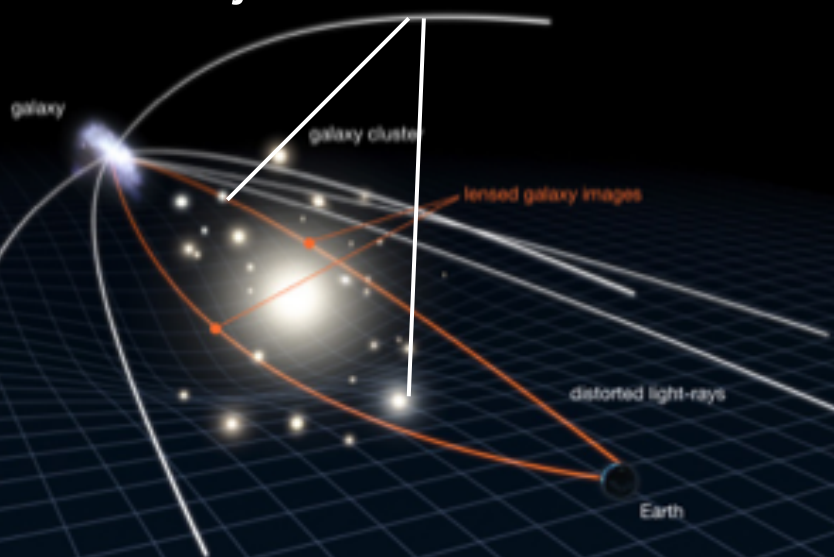
Can detect subhalos as small as $10^7 - 10^8 M_\odot$



Substructures vs interlopers

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

Projected l.o.s halos

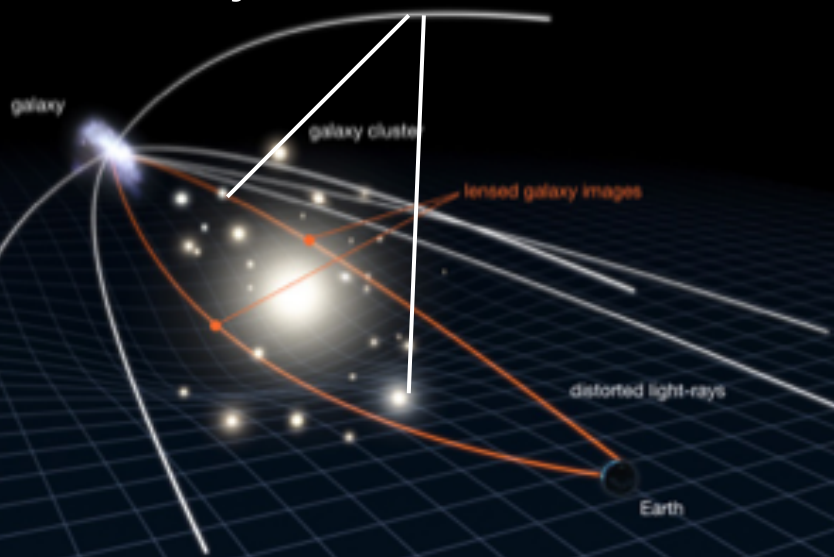


The number of line-of-sight haloes is larger than that of subhaloes

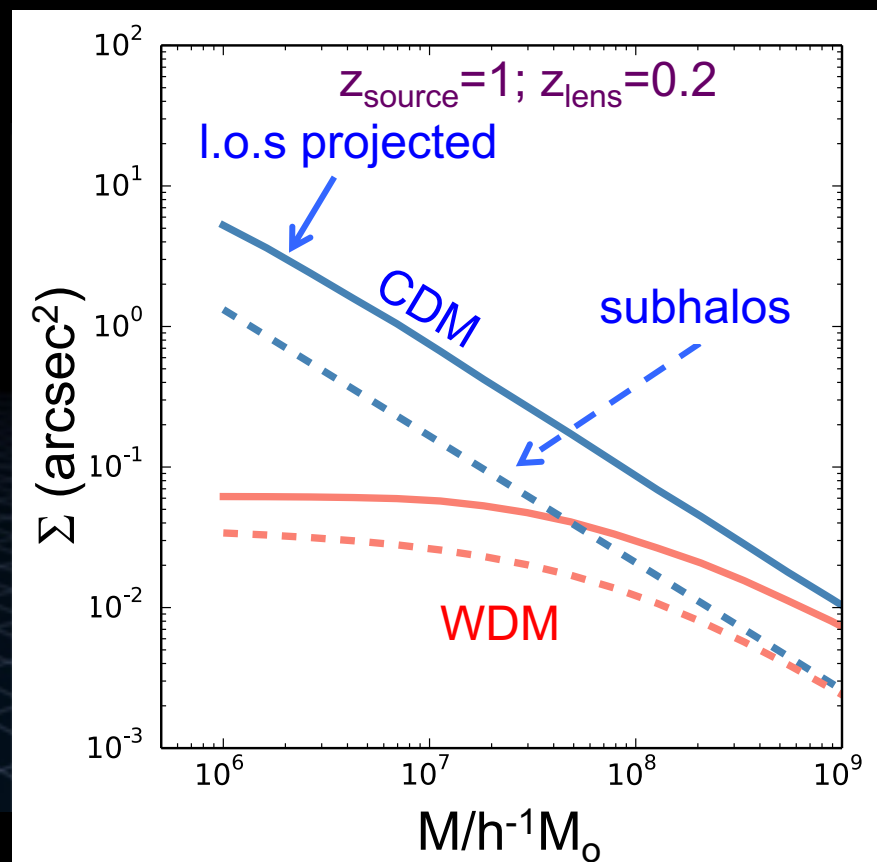
Substructures vs interlopers

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

Projected l.o.s halos



Li, CSF et al. '16



→ 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**

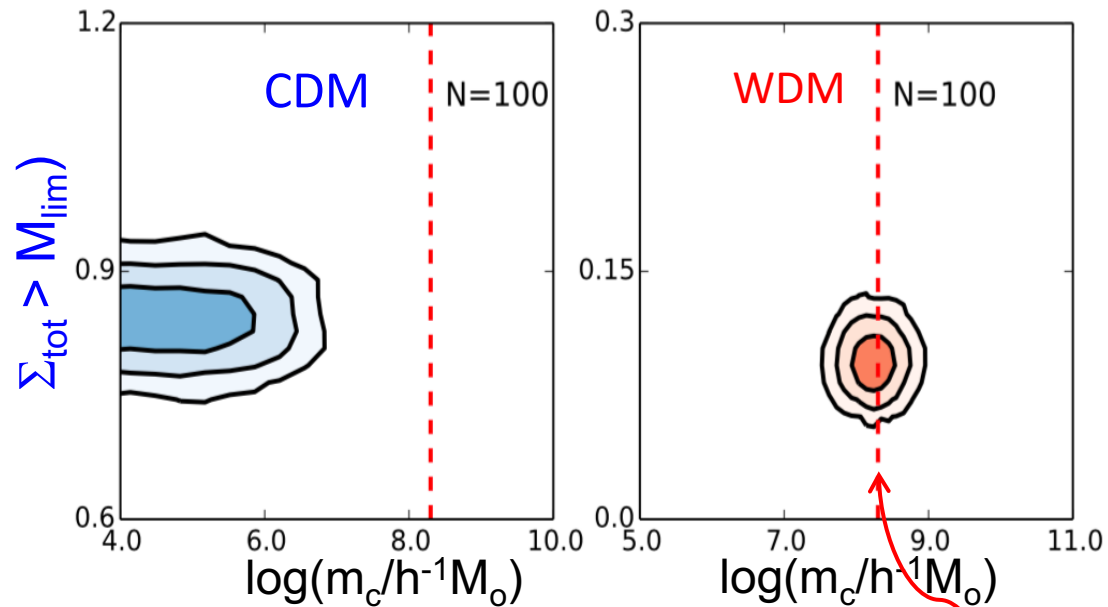
Detecting substructures with strong lensing

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

m_c = halo cutoff mass

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

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



m_c = halo cutoff mass

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

- If DM is 7 keV sterile $\nu \rightarrow$ **exclude** CDM at $\gg \sigma$!
- If DM is CDM \rightarrow **exclude** 7 keV sterile ν at $\gg \sigma$



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. CDM makes many small subhalos but most ($\sim 5 \cdot 10^8 M_\odot$) are dark \rightarrow **No satellite problem** in CDM or WDM
 2. No evidence for cores; **baryon effects** can make them \rightarrow **No “core/cusp” problem** in CDM or WDM
 3. Distortions of **strong** gravitational **lenses** offer a **clean test** of CDM vs WDM \rightarrow and can potentially **rule out CDM!**