A conclusive test of cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

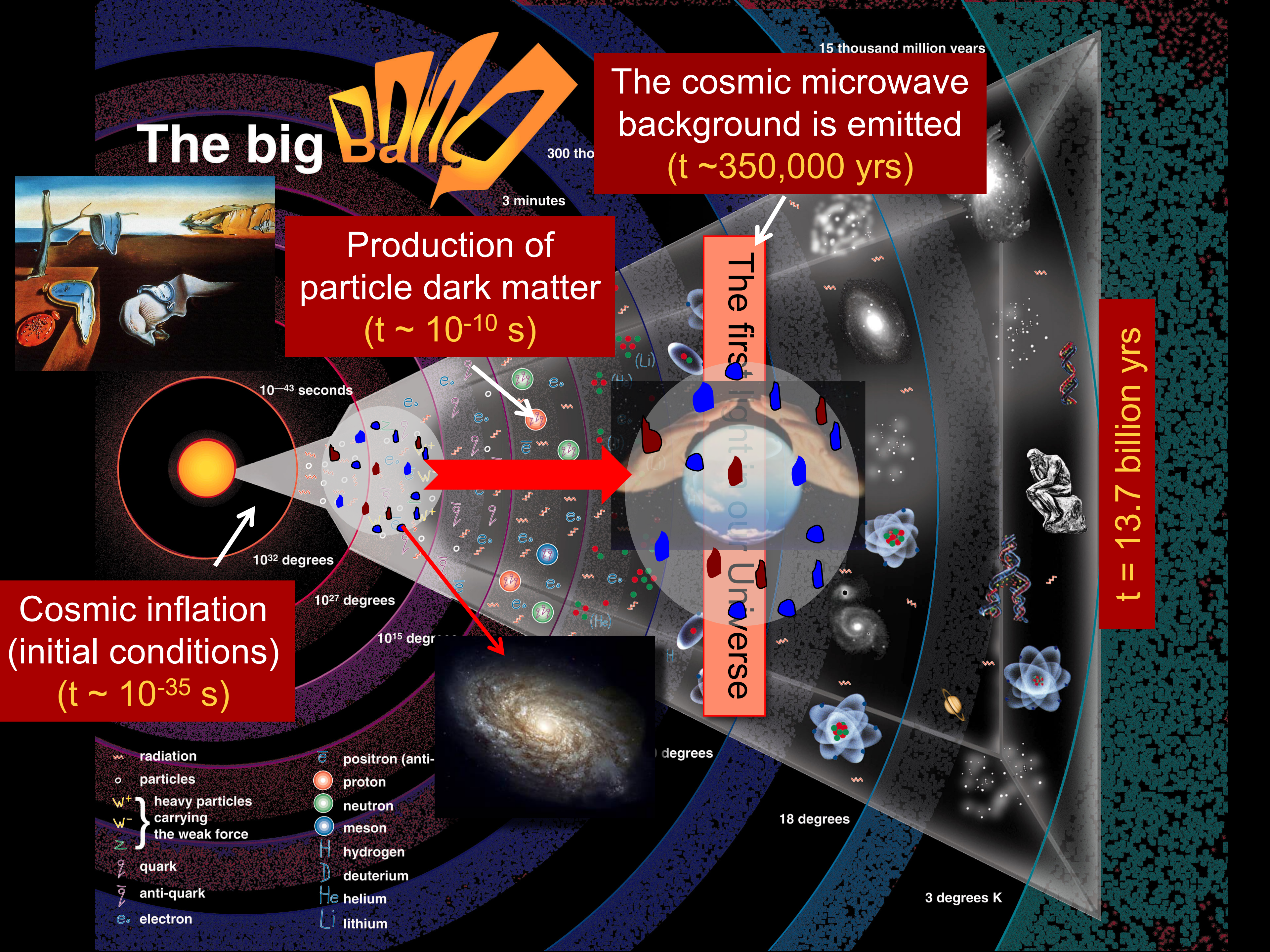
University of Durham

The ΛCDM model of cosmogony

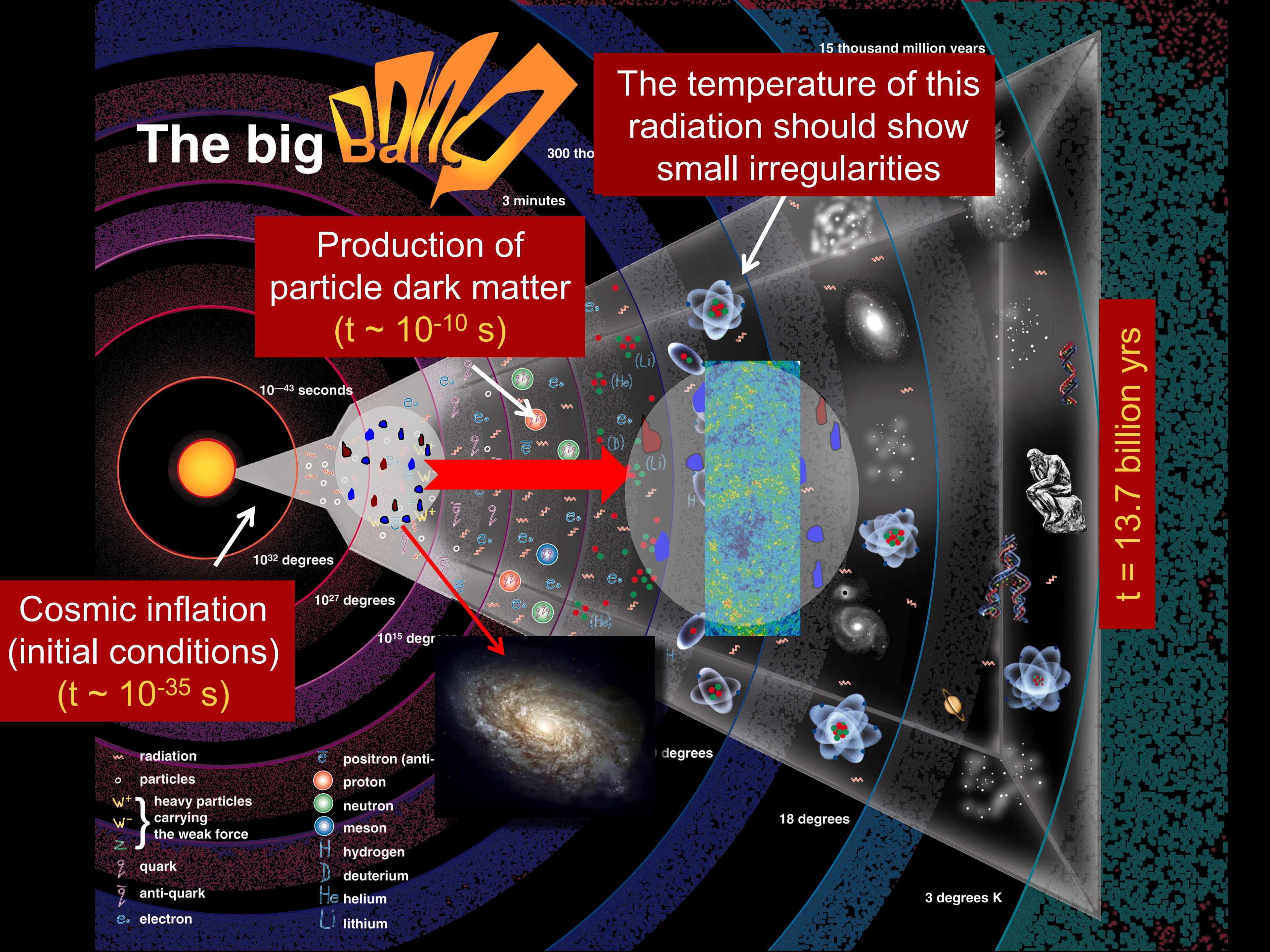
Cosmological constant

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



The big Bang
15 thousand million years
300 tho
3 minutes
The temperature of this radiation should show small irregularities
Production of particle dark matter (t ~ 10-10 s)
10—43 seconds
1032 degrees
1027 degrees
1015 degr
degrees
18 degrees
3 degrees K
Cosmic inflation (initial conditions) (t ~ 10-35 s)
t = 13.7 billion yrs
radiation
particles
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Temperature anisotropies in CMB

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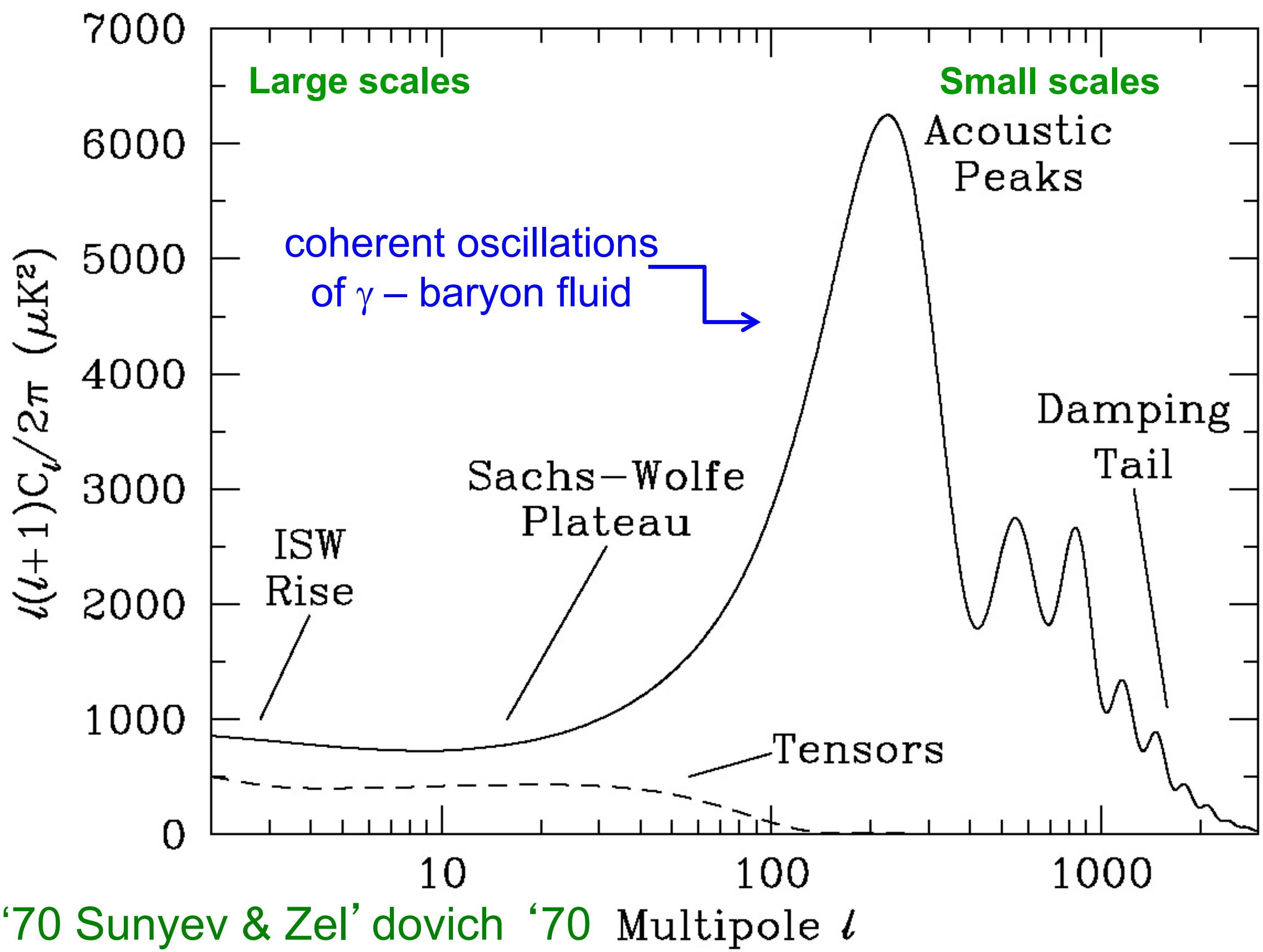
2D power spectrum



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

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

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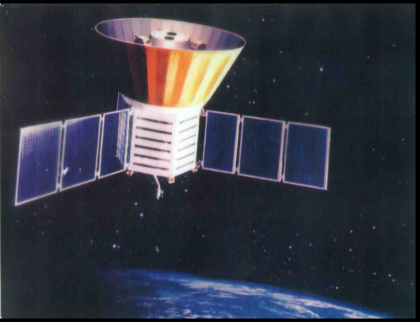
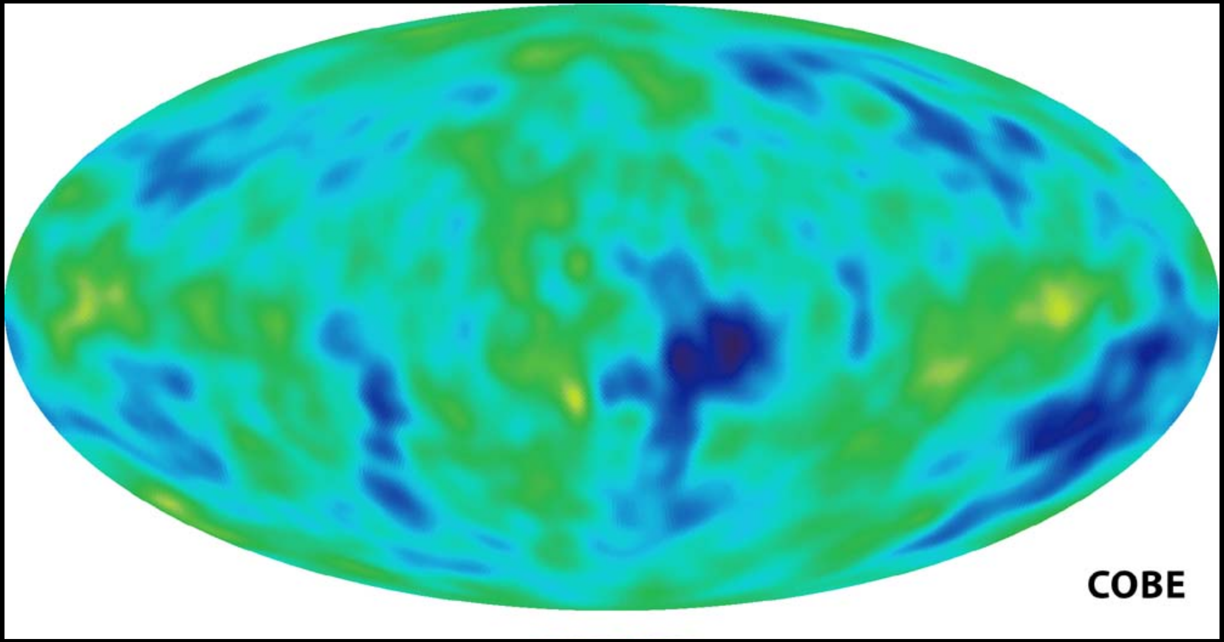
The CMB

1992



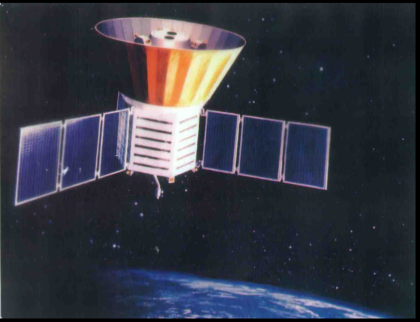


The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

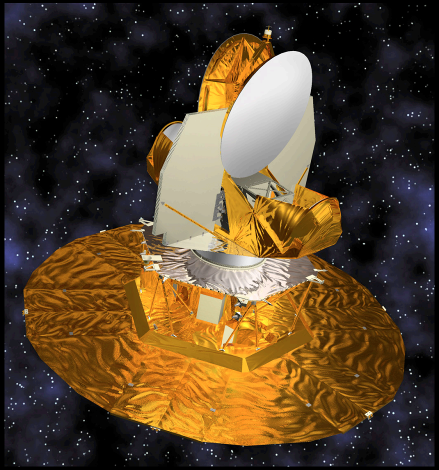
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions

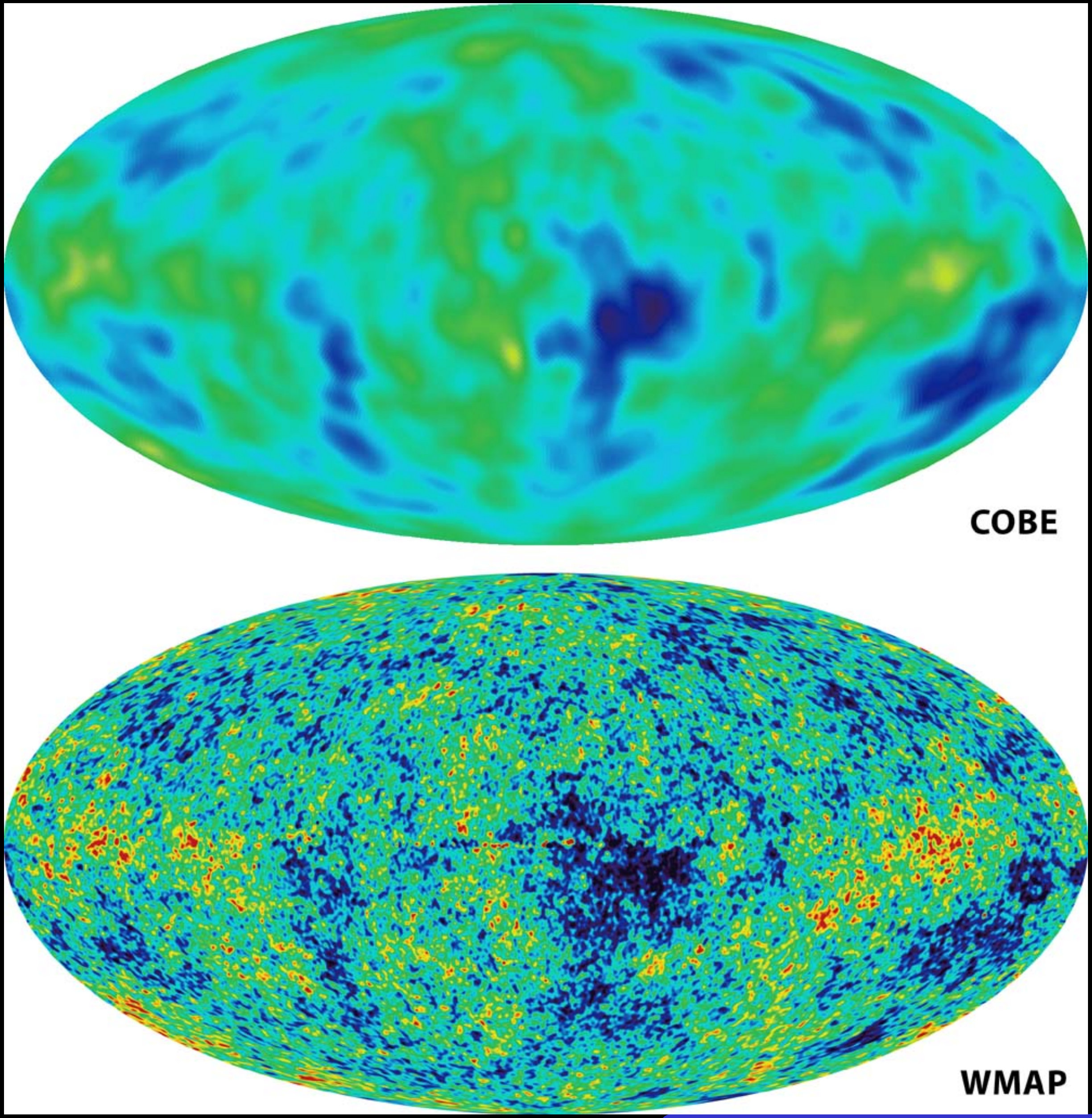
The CMB

1992



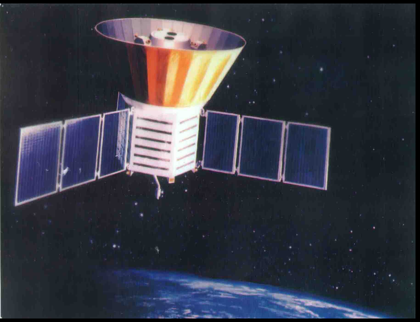
2003



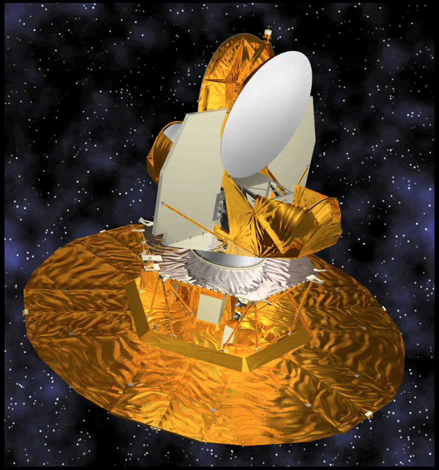


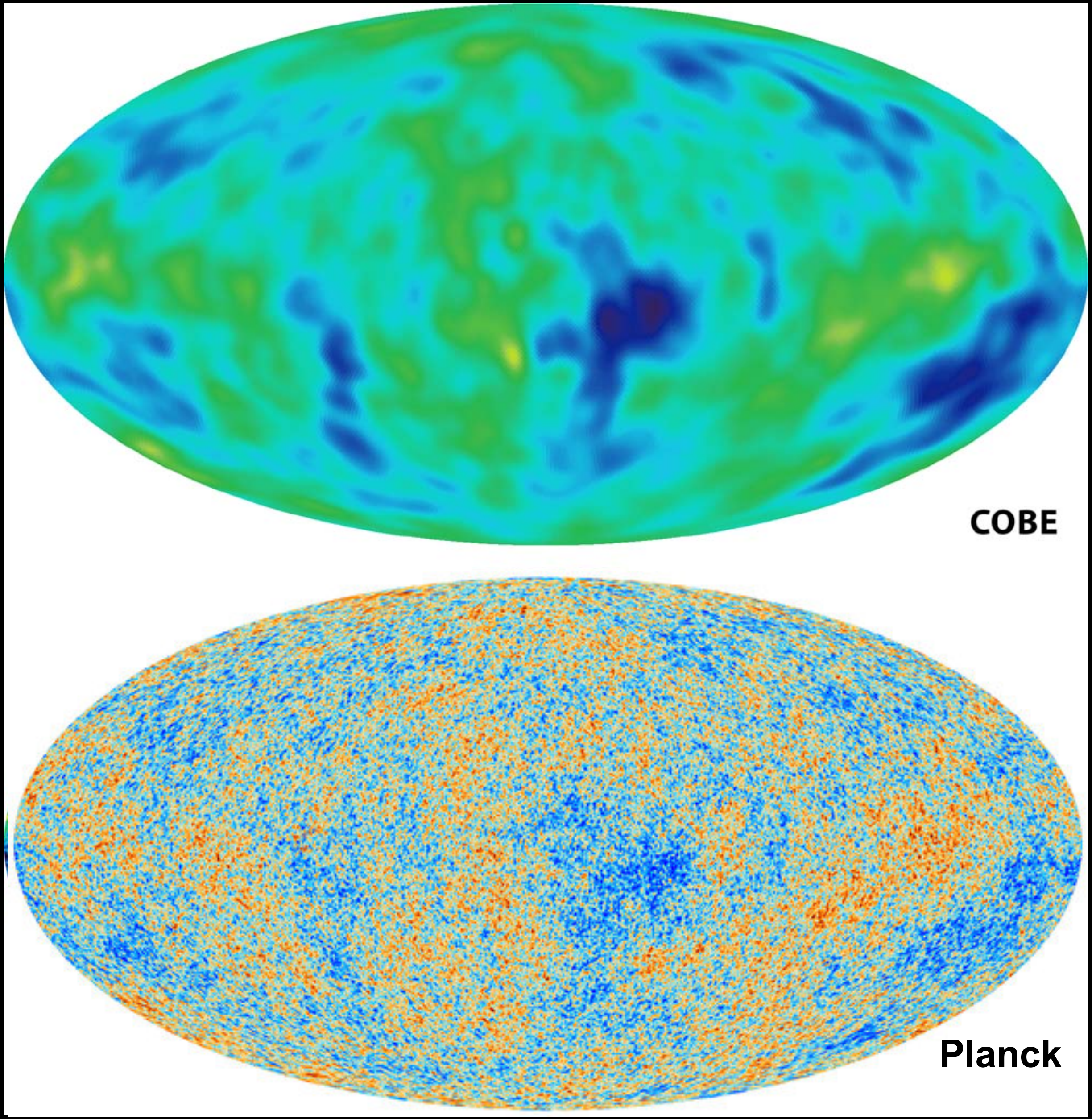
The CMB

1992



2012





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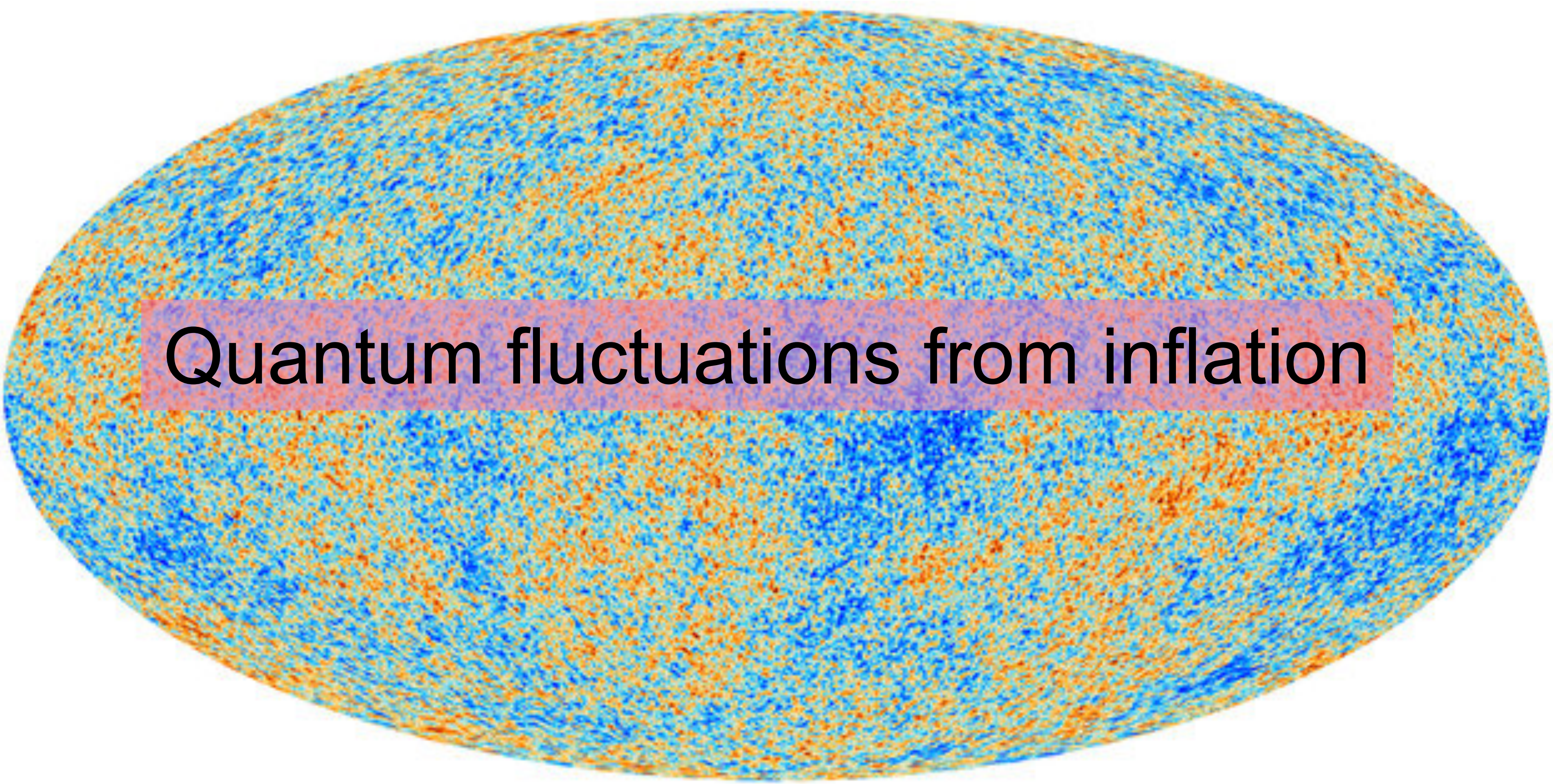
The initial conditions for galaxy formation



Planck collaboration ‘13

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Temperature anisotropies in CMB

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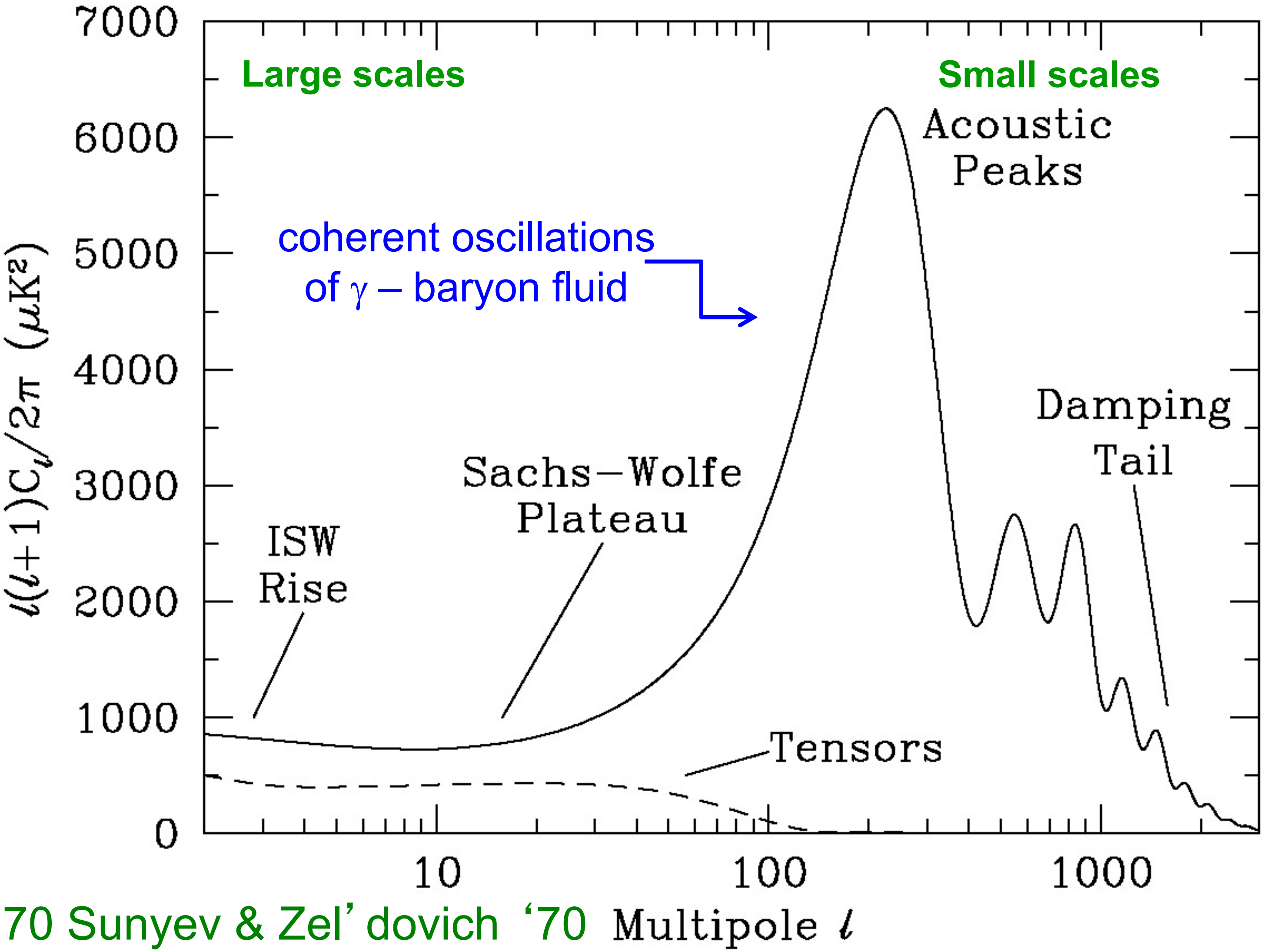
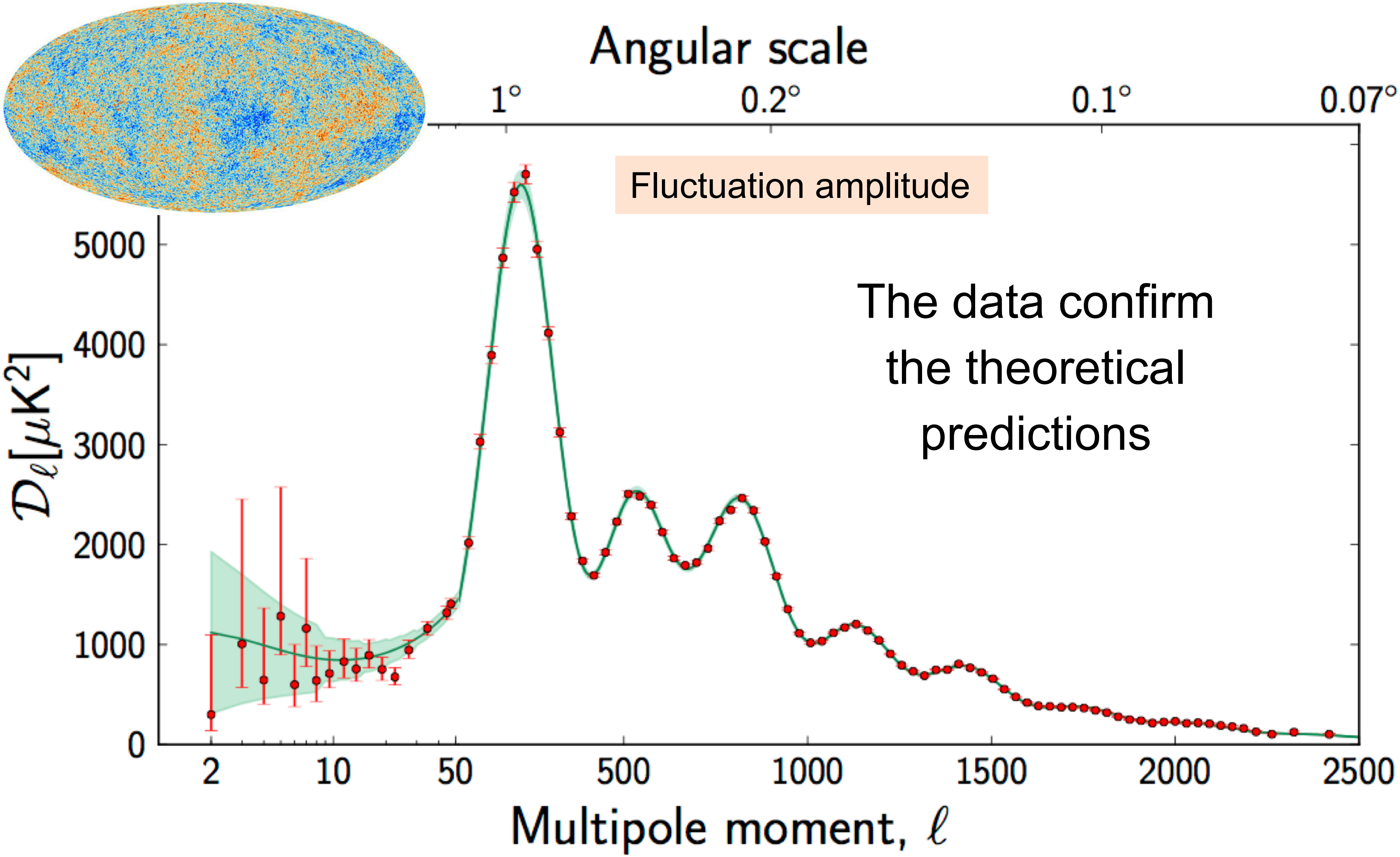
2D power spectrum



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

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

Planck: CMB temperature anisotropies



Planck coll. 2015

The six parameters of minimal ΛCDM model

Univer

6 model parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$ 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!

Planck collaboration ‘13

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Non-baryonic dark matter candidates

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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

The dark matter power spectrum

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Free streaming →

$\lambda_{cut} \propto m_x^{-1}$ for thermal relic

$m_{CDM} \sim 100GeV$

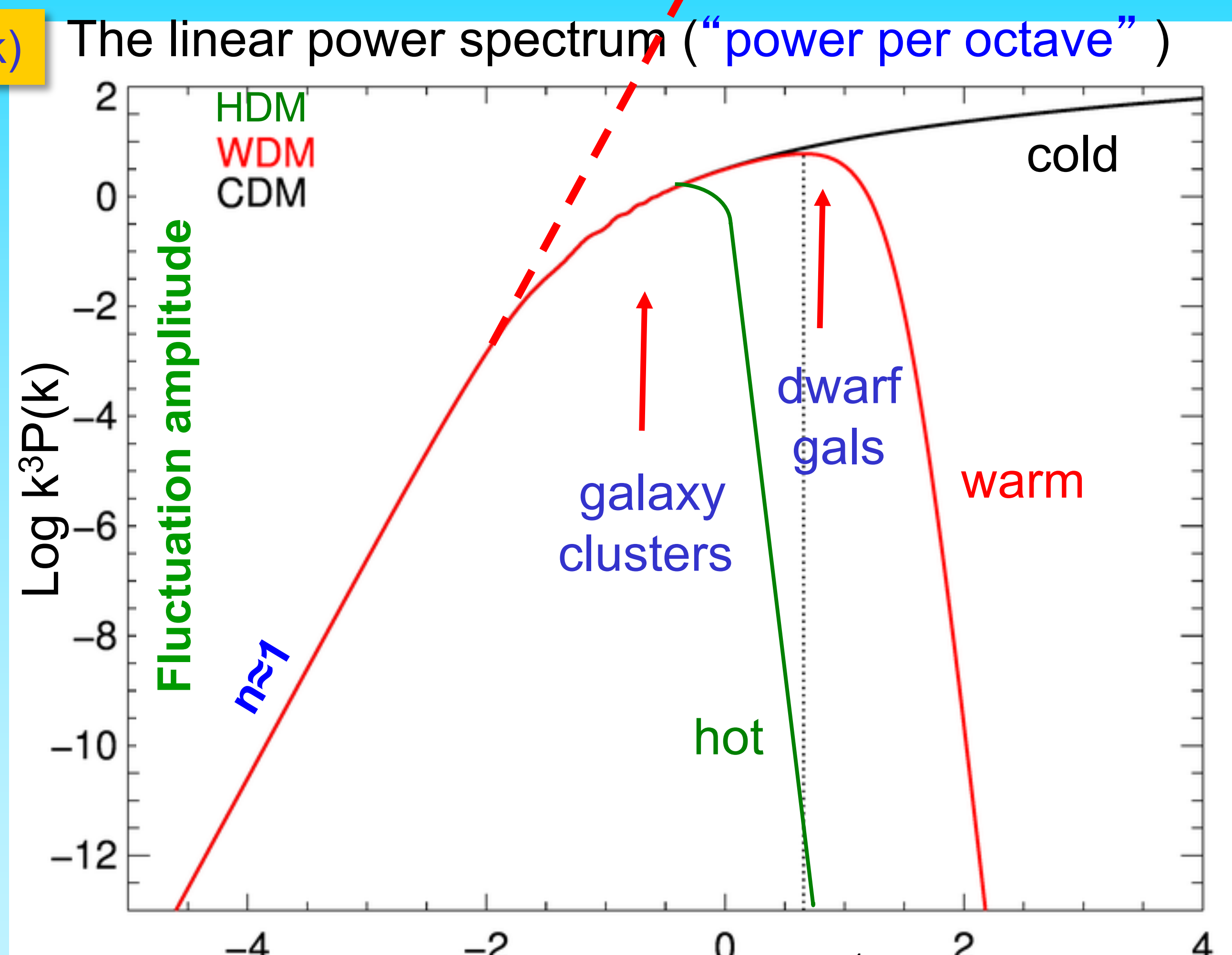
susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$

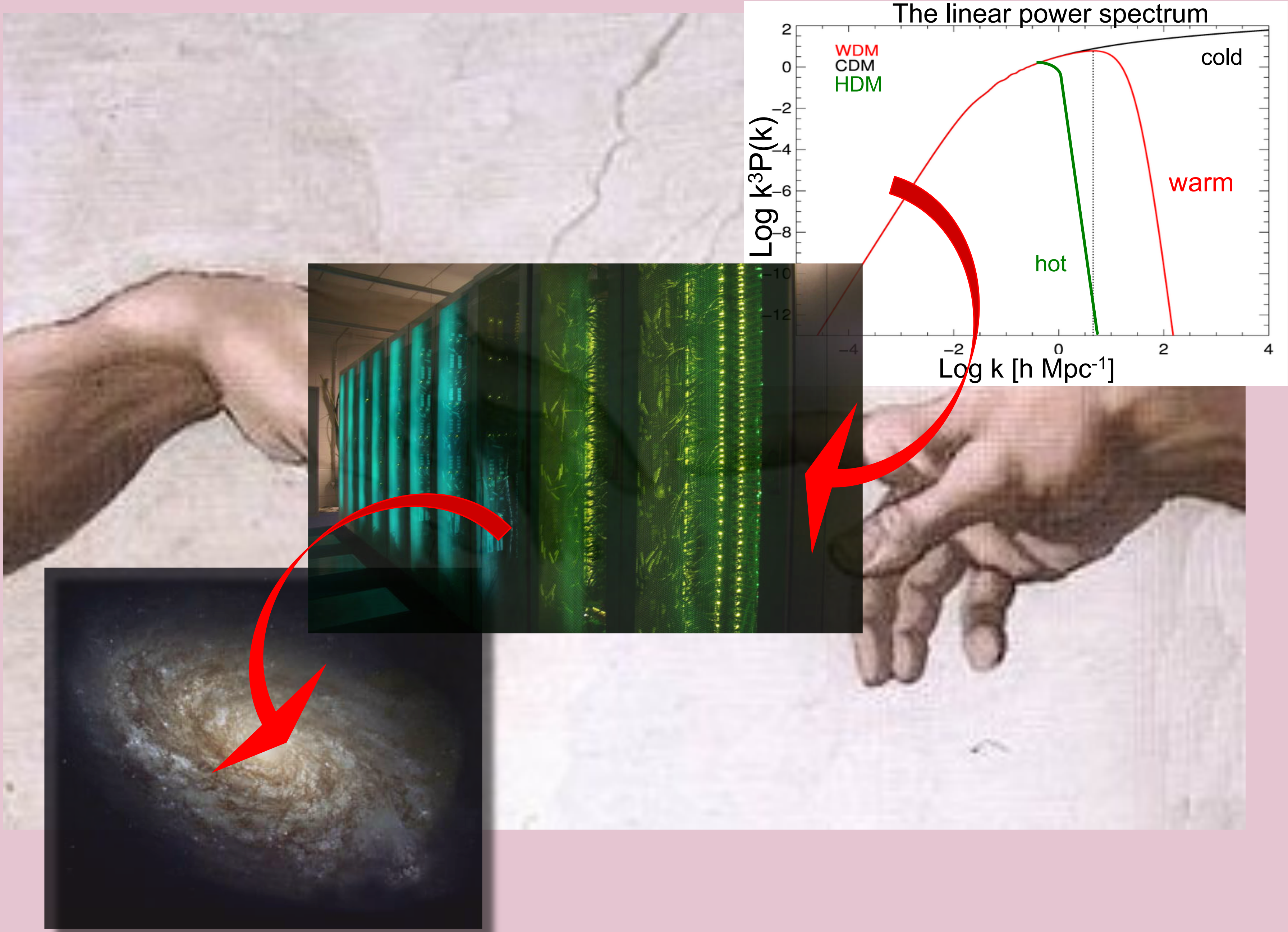
$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15}\ M_o$



These possibilites can be tested with astrophysics

Non-linear evolution



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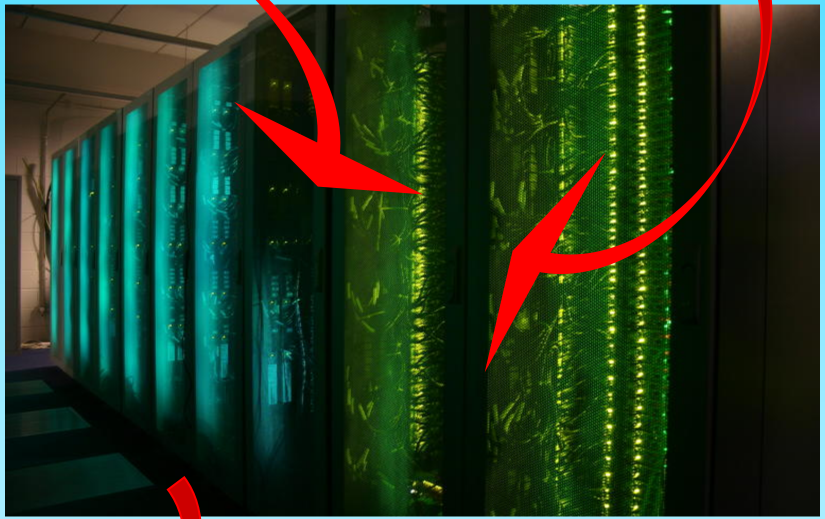
Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

Relevant equations:

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



How to make a virtual universe

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Hot dark matter

m_ν = 30 ev → Ω = 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 ($E_{\beta\,max}$ ≅ 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.

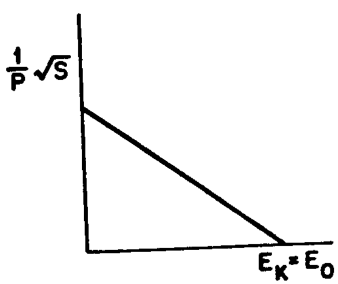


Fig. 1. Kurie plot for $M_\nu = 0$.

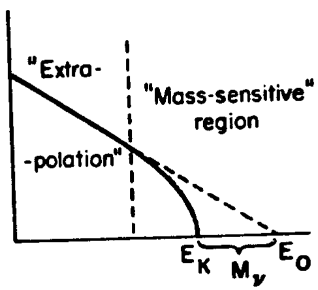
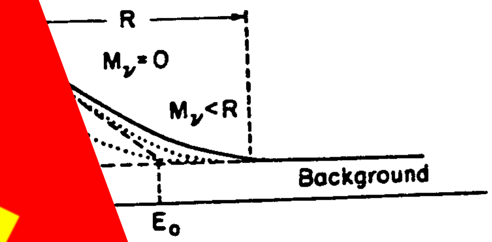


Fig. 2. Kurie plot for $M_\nu \neq 0$.

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 de- termines the statistical accuracy near the endpoint, i.e., in the region of the highest sensitivity to the ν mass. So: 1) R should be $\sim M_\nu$, 2) the smaller M_ν is, the smaller the background ($\sim M_\nu^2$) must be and the higher the statistics ($\sim M_\nu^{-3}$) must be. For example, suppose that for M_ν = 100 eV we need resolution R, background Q, and statistics N. If M_ν = 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 ∿ Δp/p = const.). A classical example is ^3H β-decay, which has 1) the smallest E_0 ∿ 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 reso- lution 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 ∿ 50 eV and $M_\nu \leq 55$ eV.

The ITEP spectrometer is of a new type: ironless, with toroi- dal magnetic field (E. Tretyakov, 1973). The principle of the tor- oidal 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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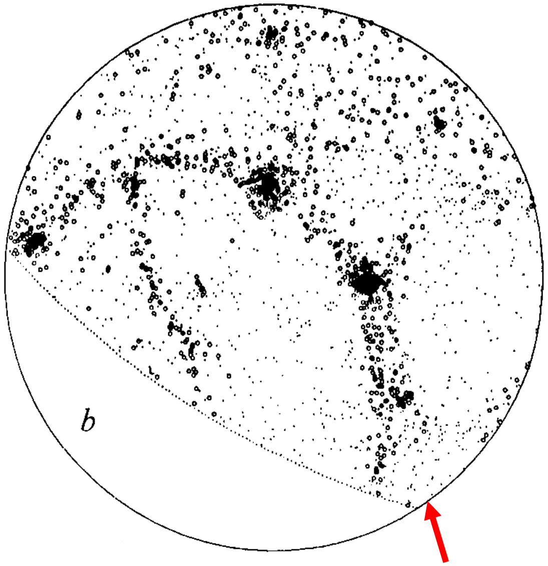
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White
& Davis '83

Non-baryonic dark matter cosmologies

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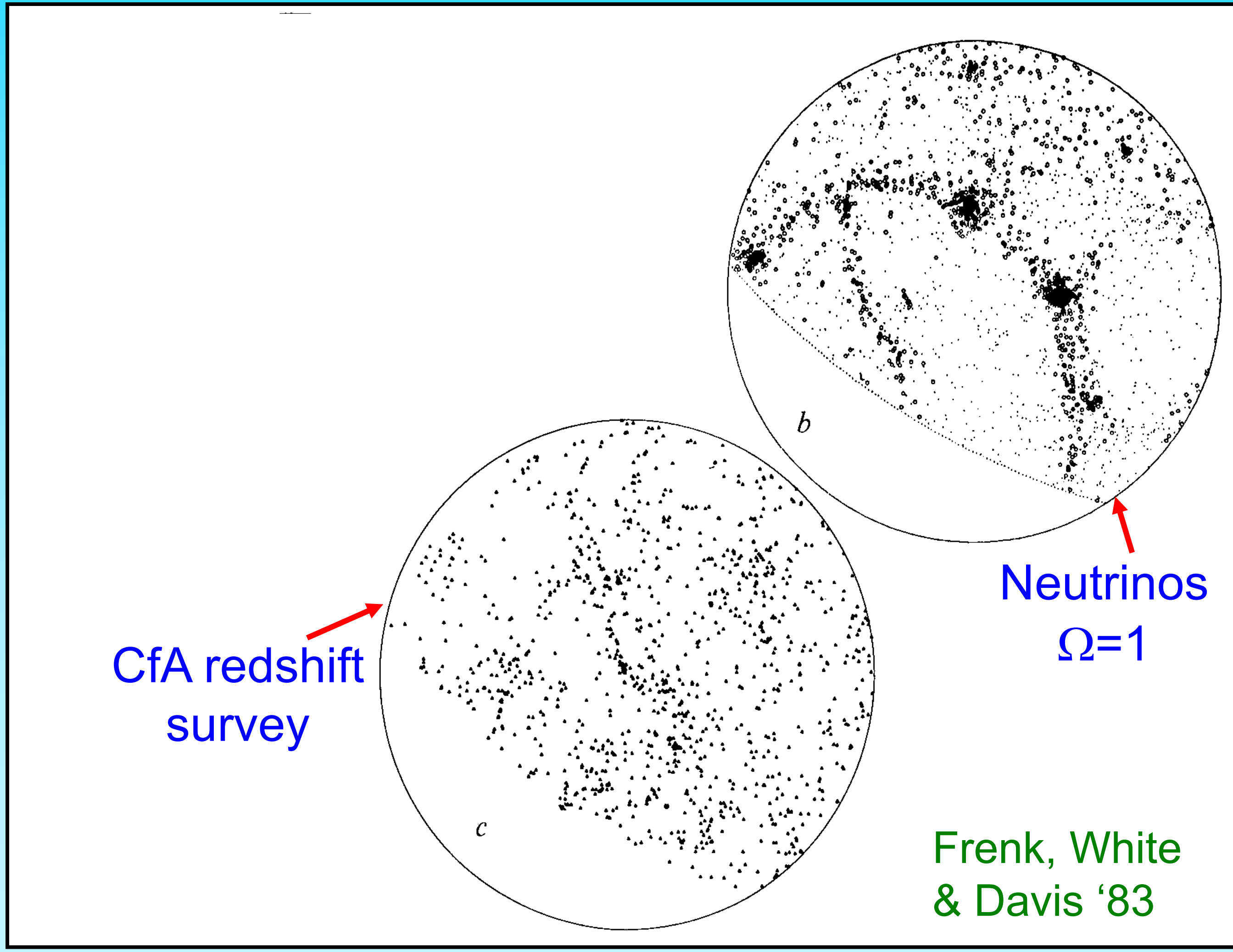
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_{\nu} << 30$ ev



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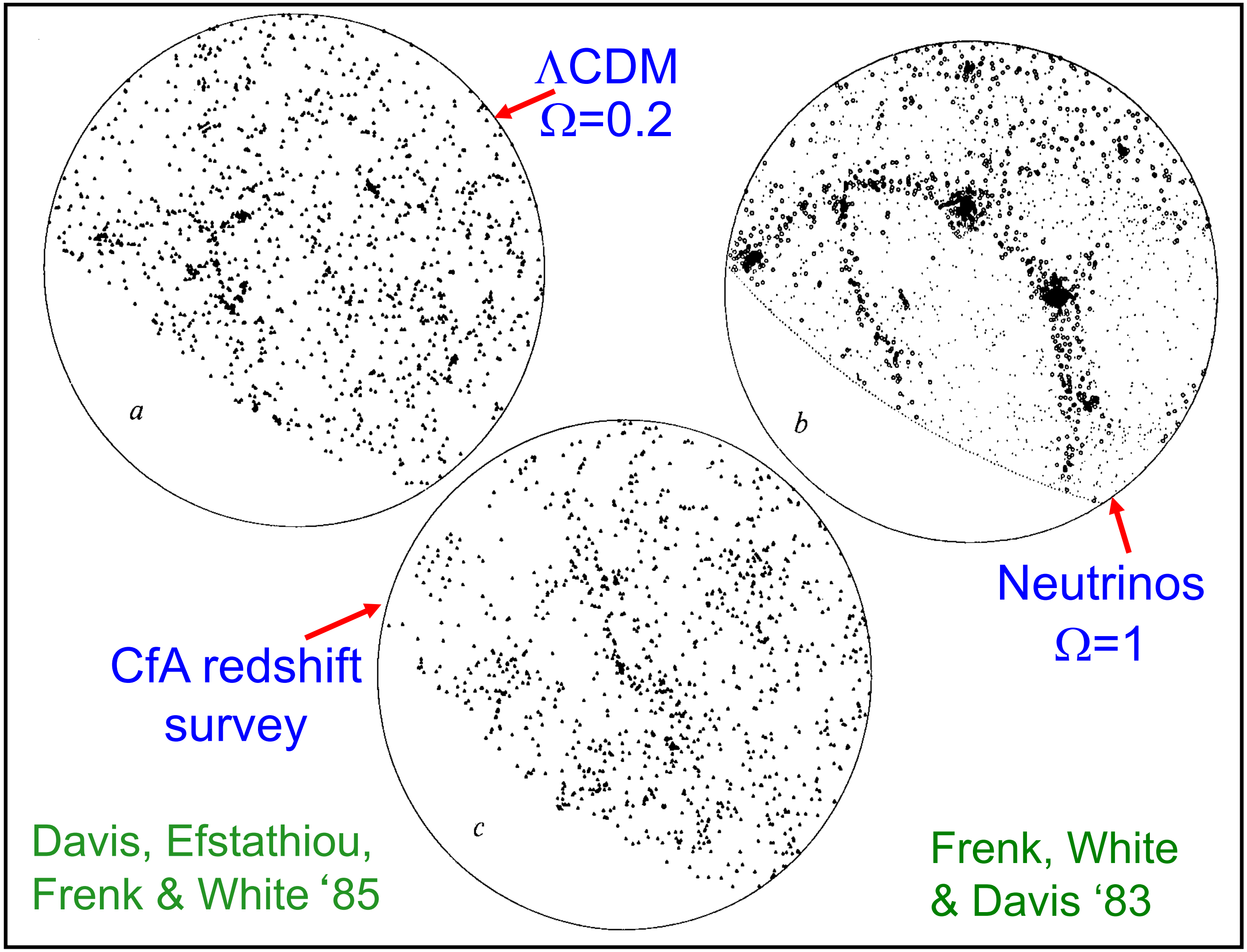
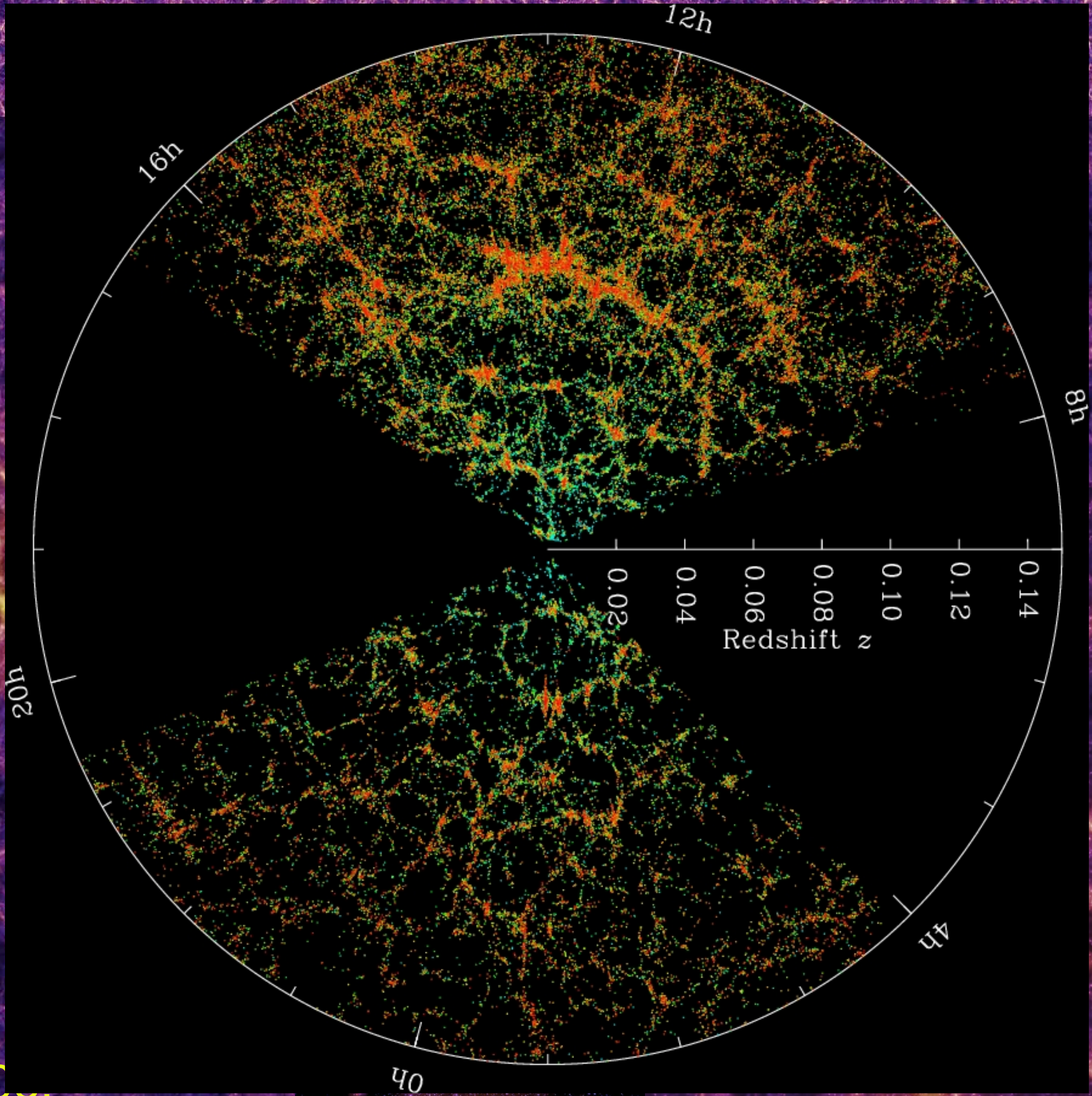


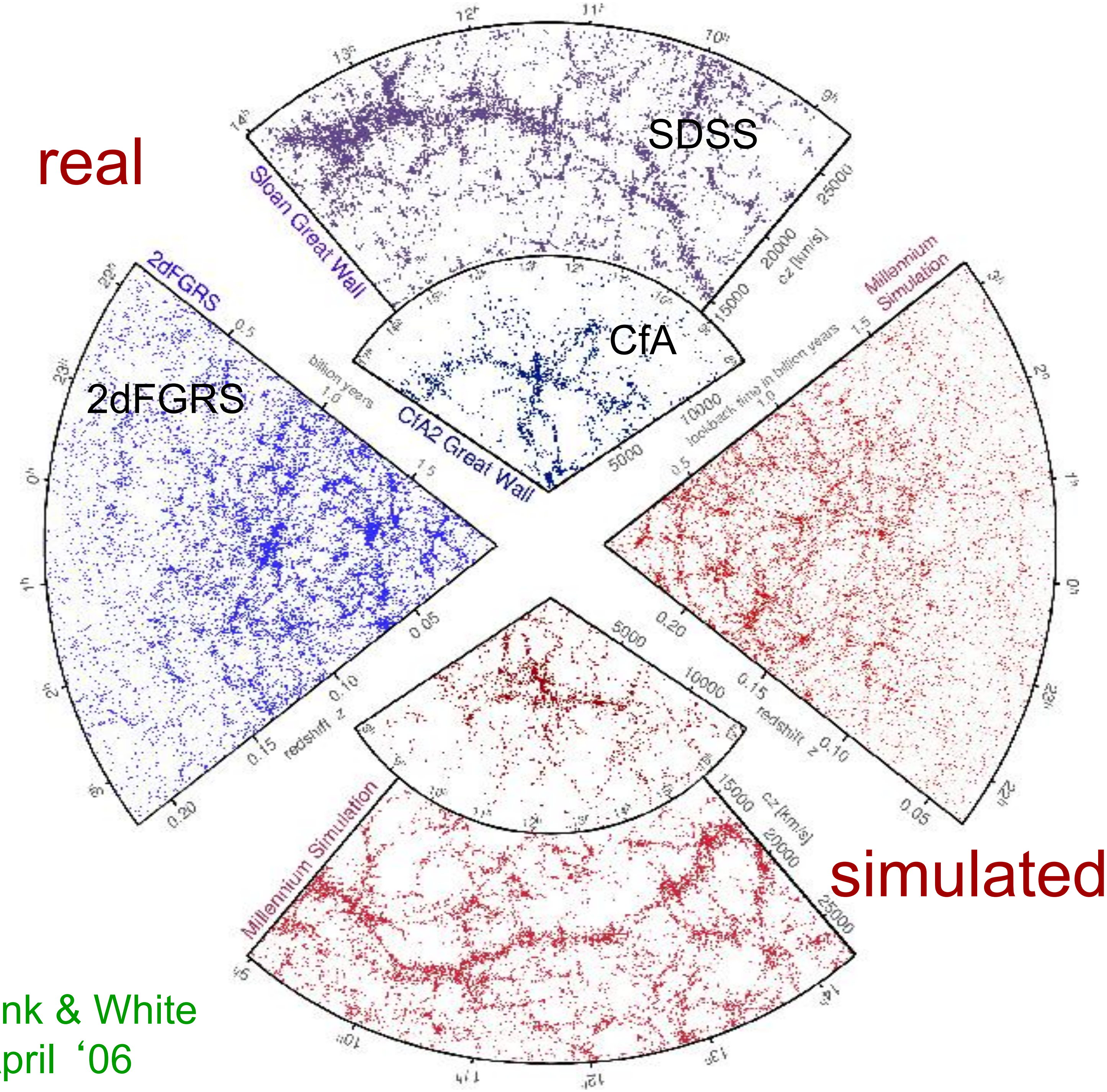
Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

The Millennium/Aquarius/Phoenix simulation series



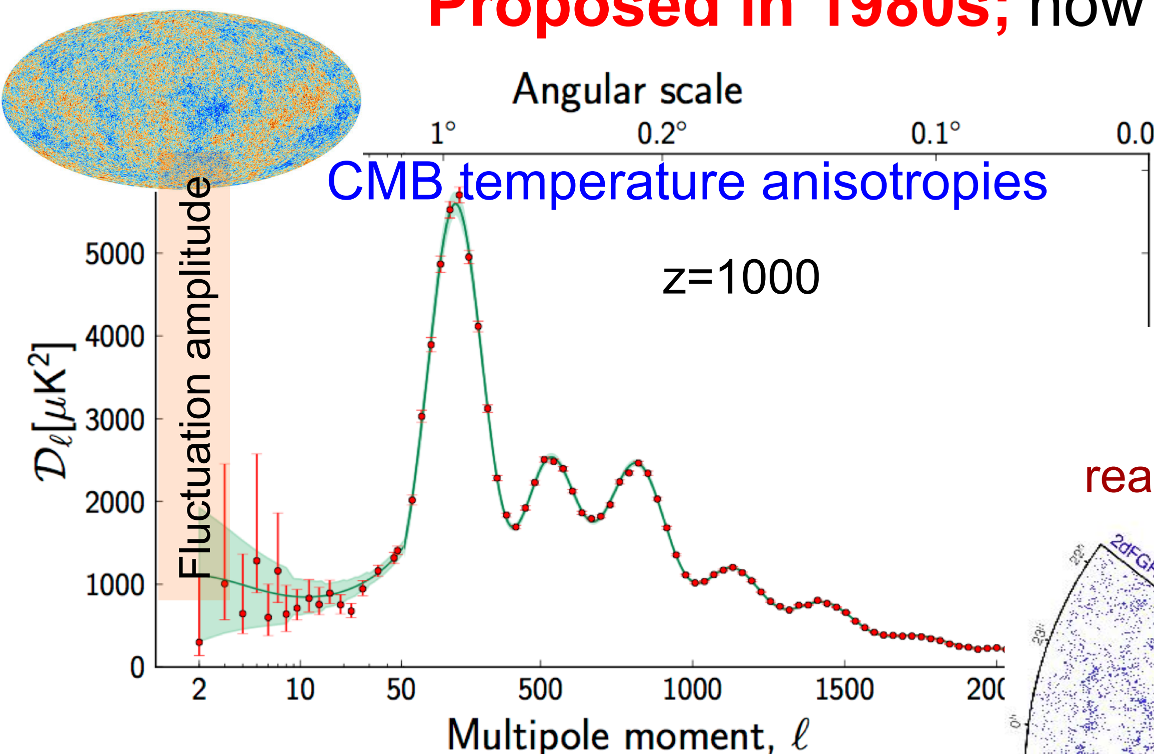
Springel et al '05, '0[illegible]
Gao et al '11



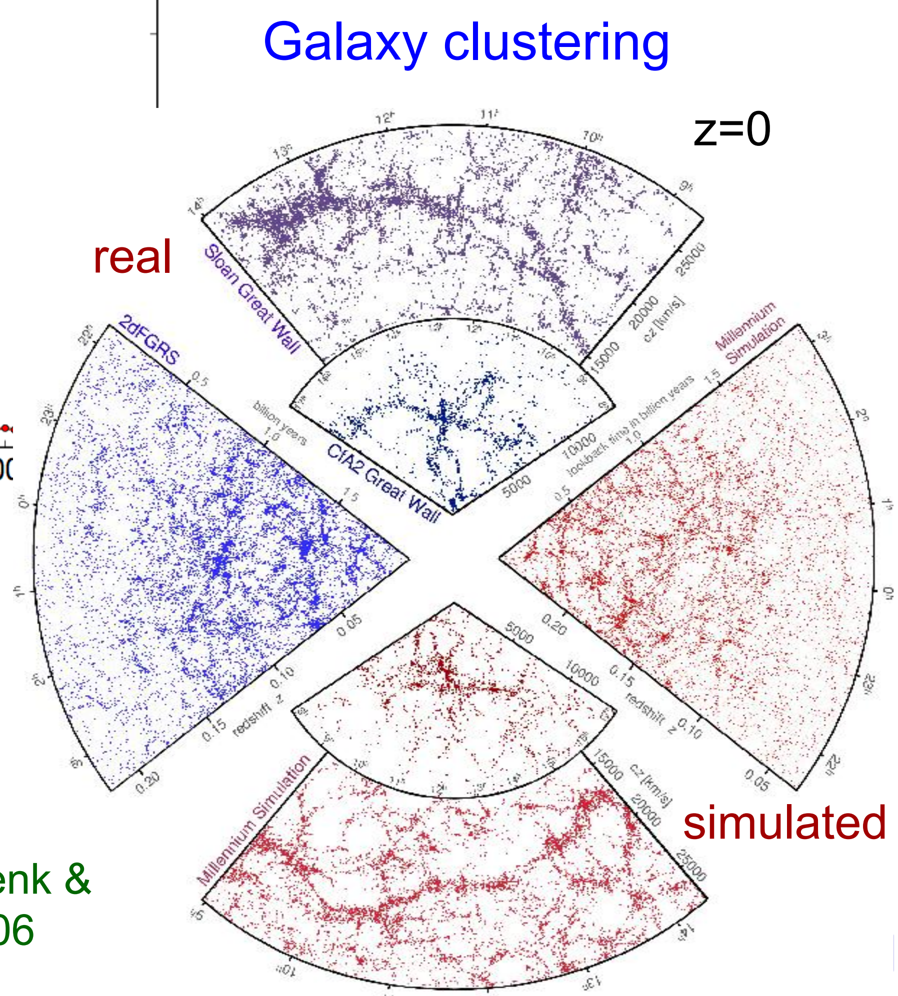
Springel, Frenk & White
Nature, April '06

The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Planck coll. 2015



Springel, Frenk & White 2006

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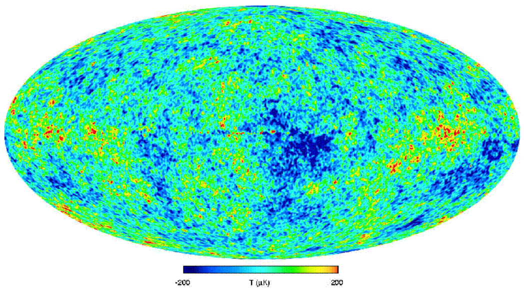
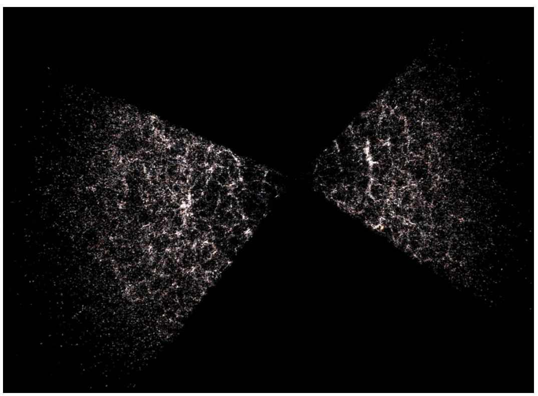
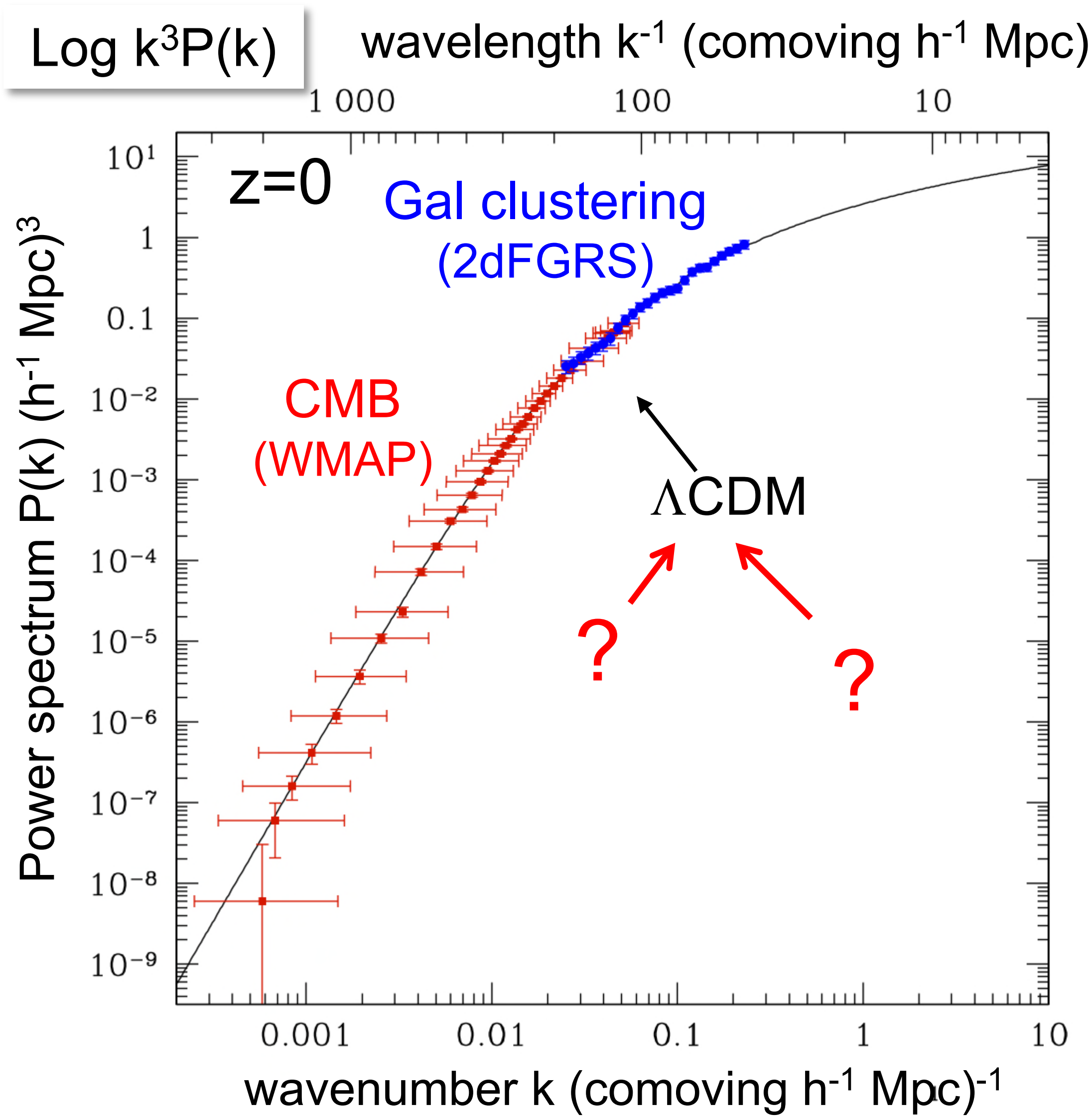
The cosmic power spectrum: from the CMB to the 2dFGRS



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 →

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

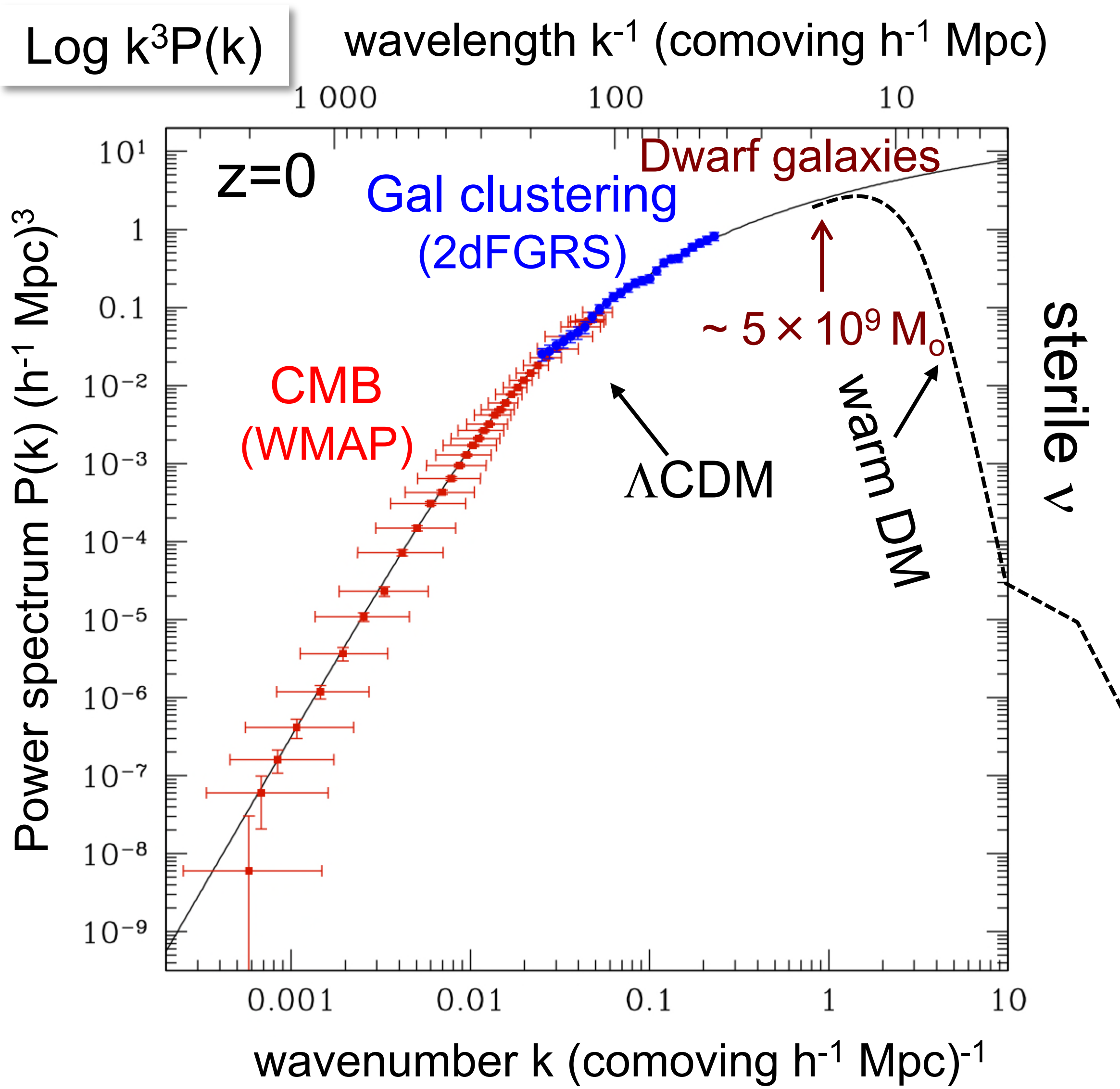
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



Sterile neutrinos

Explain:

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

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

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

Both CDM & WDM compatible with CMB & galaxy clustering

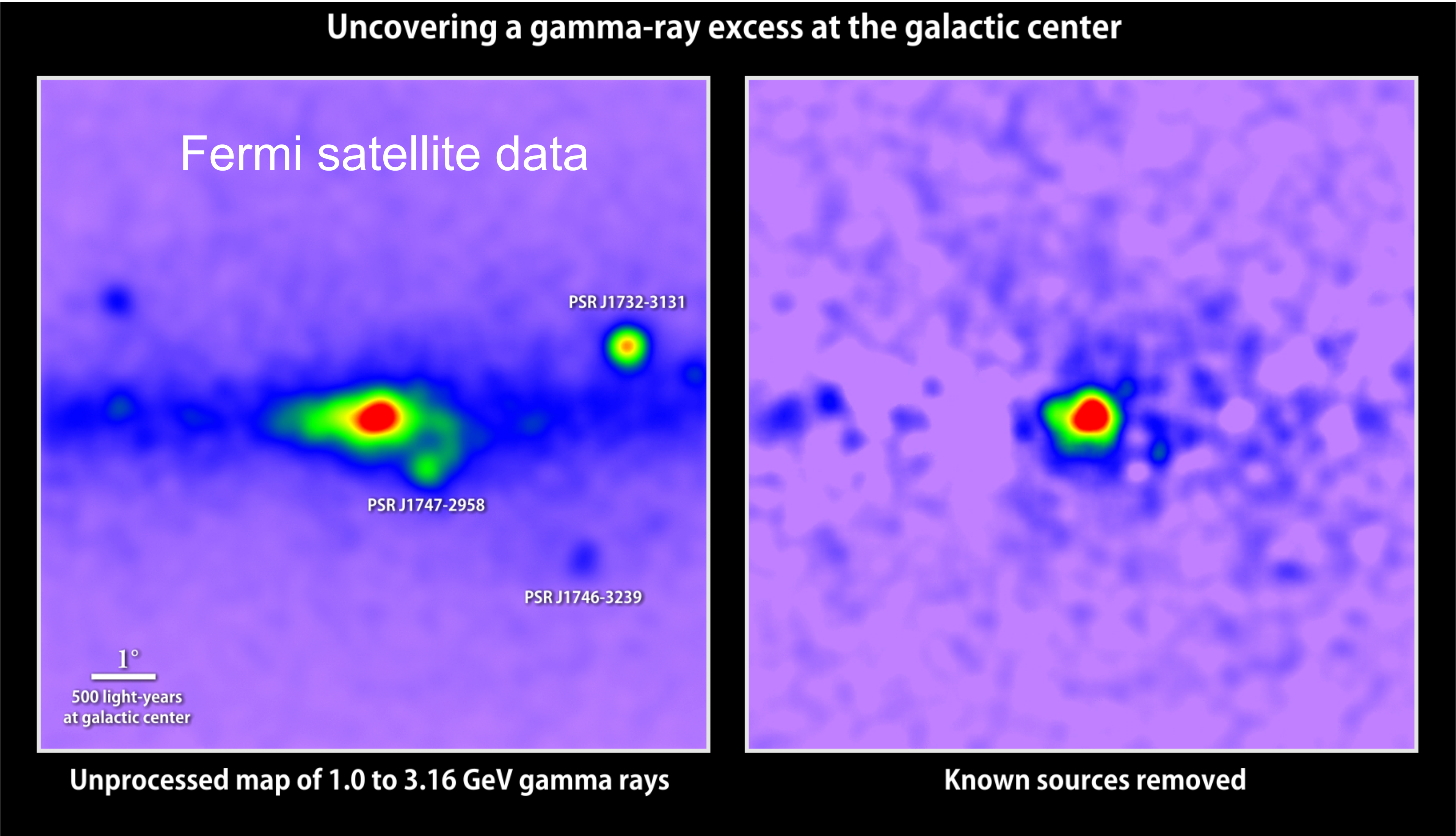
Claims that both types of DM have been discovered:

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

Cold dark matter

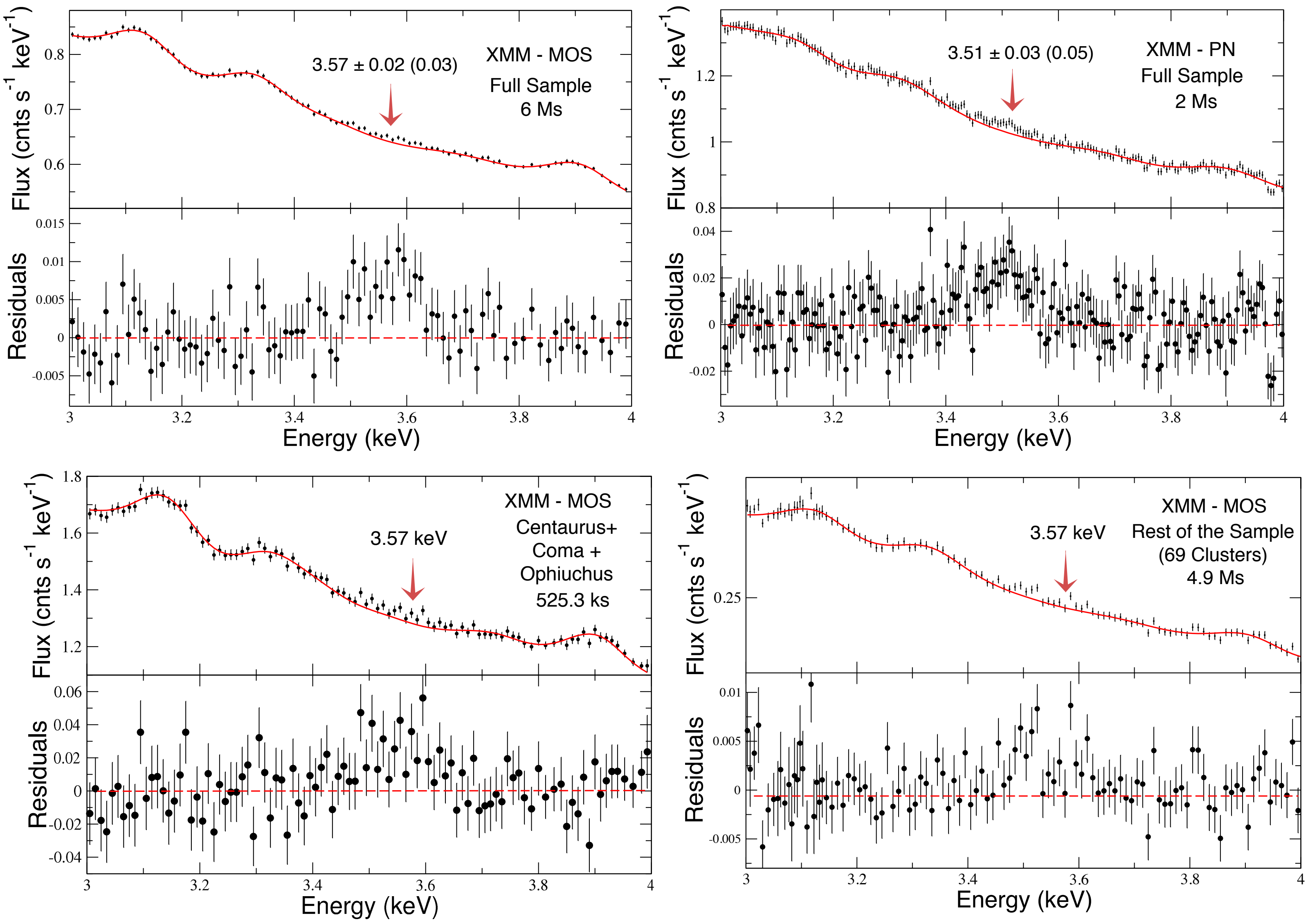
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

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



Warm dark matter
WDM decay line in 69 stacked clusters?

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



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)

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Three problems of CDM on small scales

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

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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

Institute for Computational Cosmology

cold dark matter warm dark matter

How can we distinguish between these?

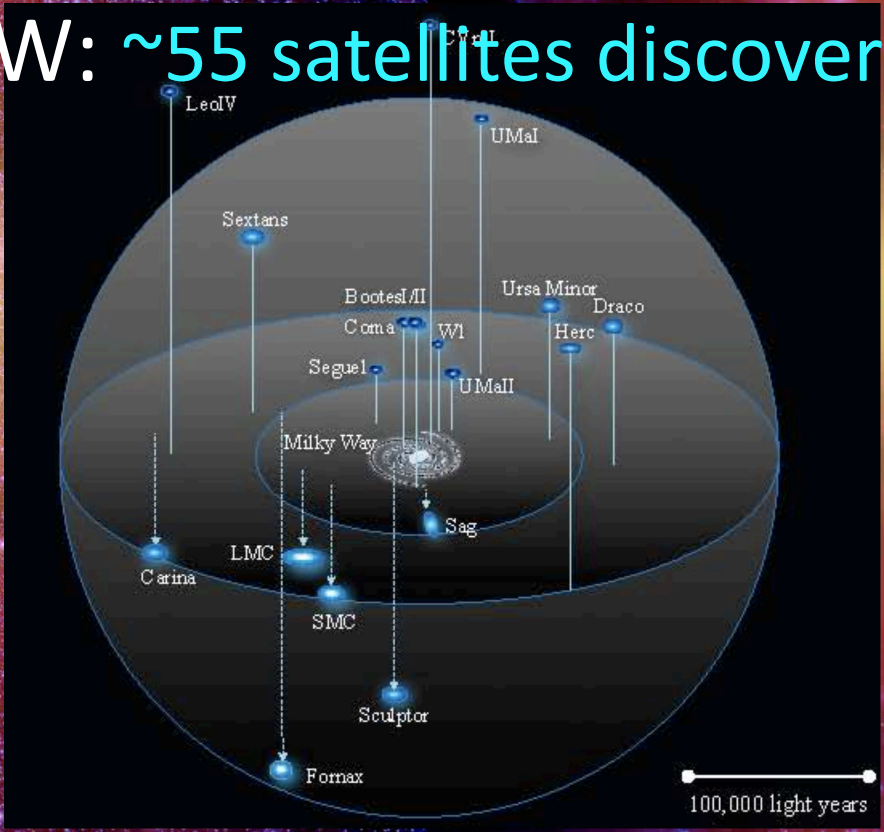
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12 cold dark matter | warm dark matter

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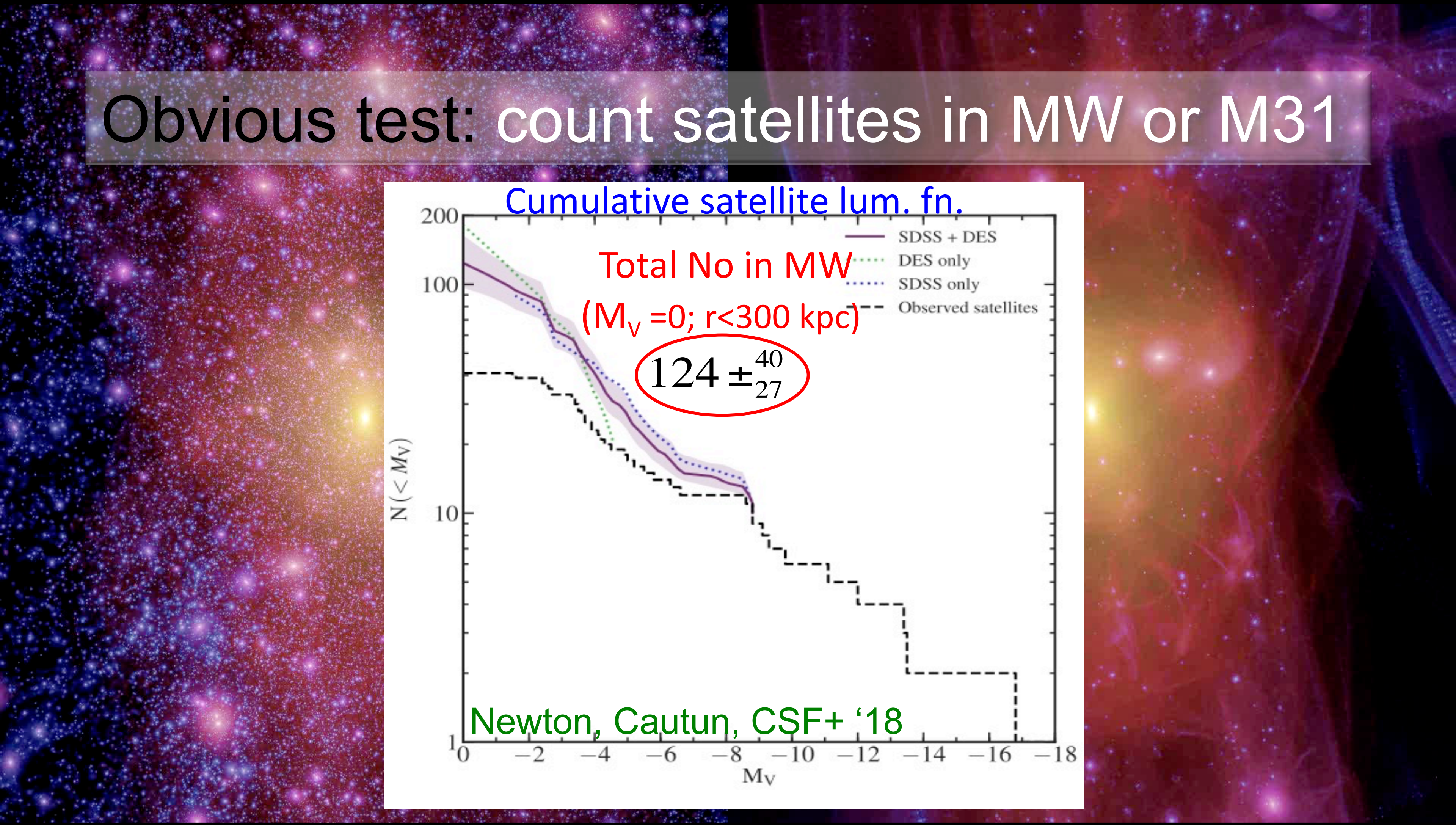

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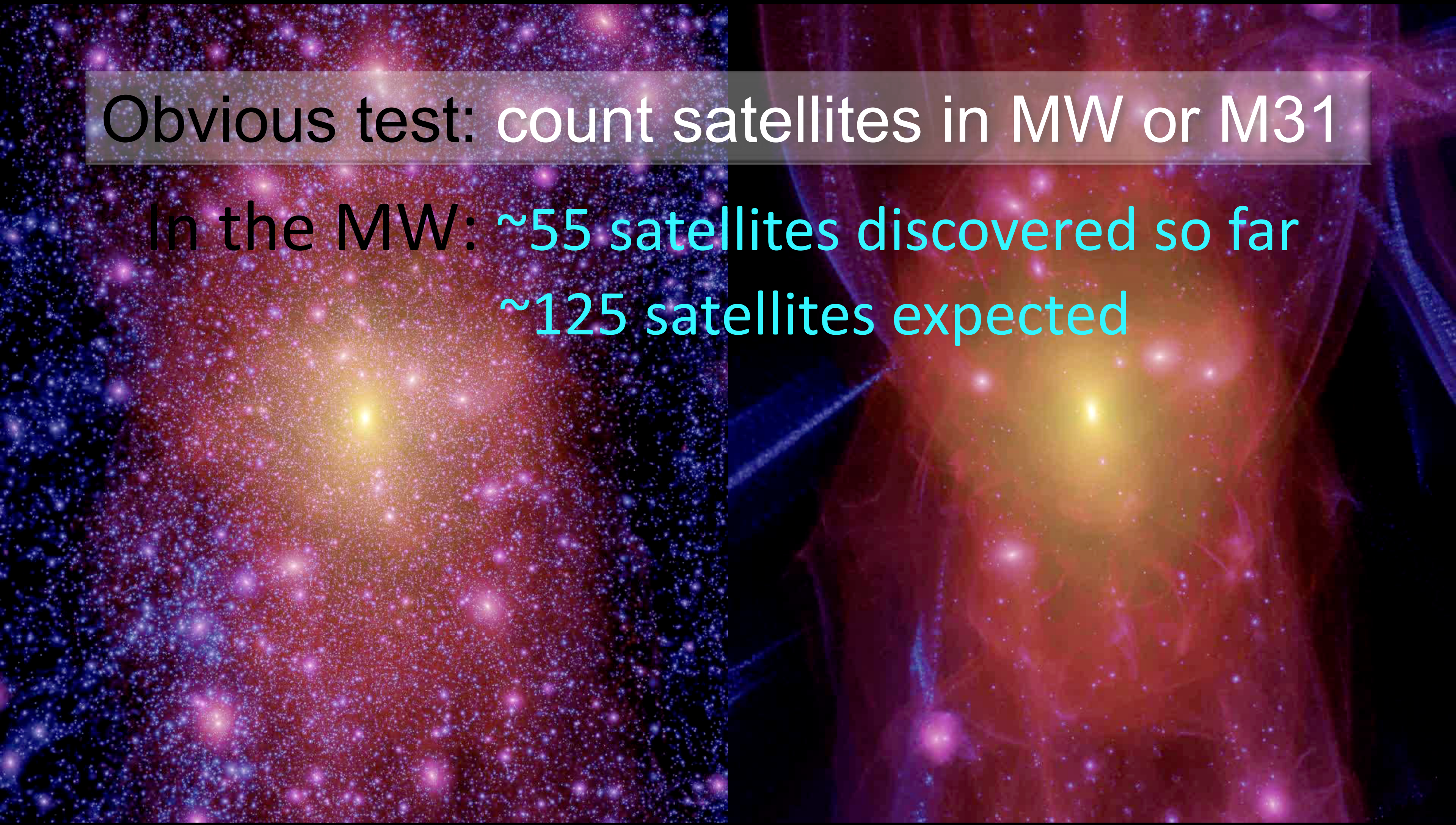
cold dark matter | warm dark matter



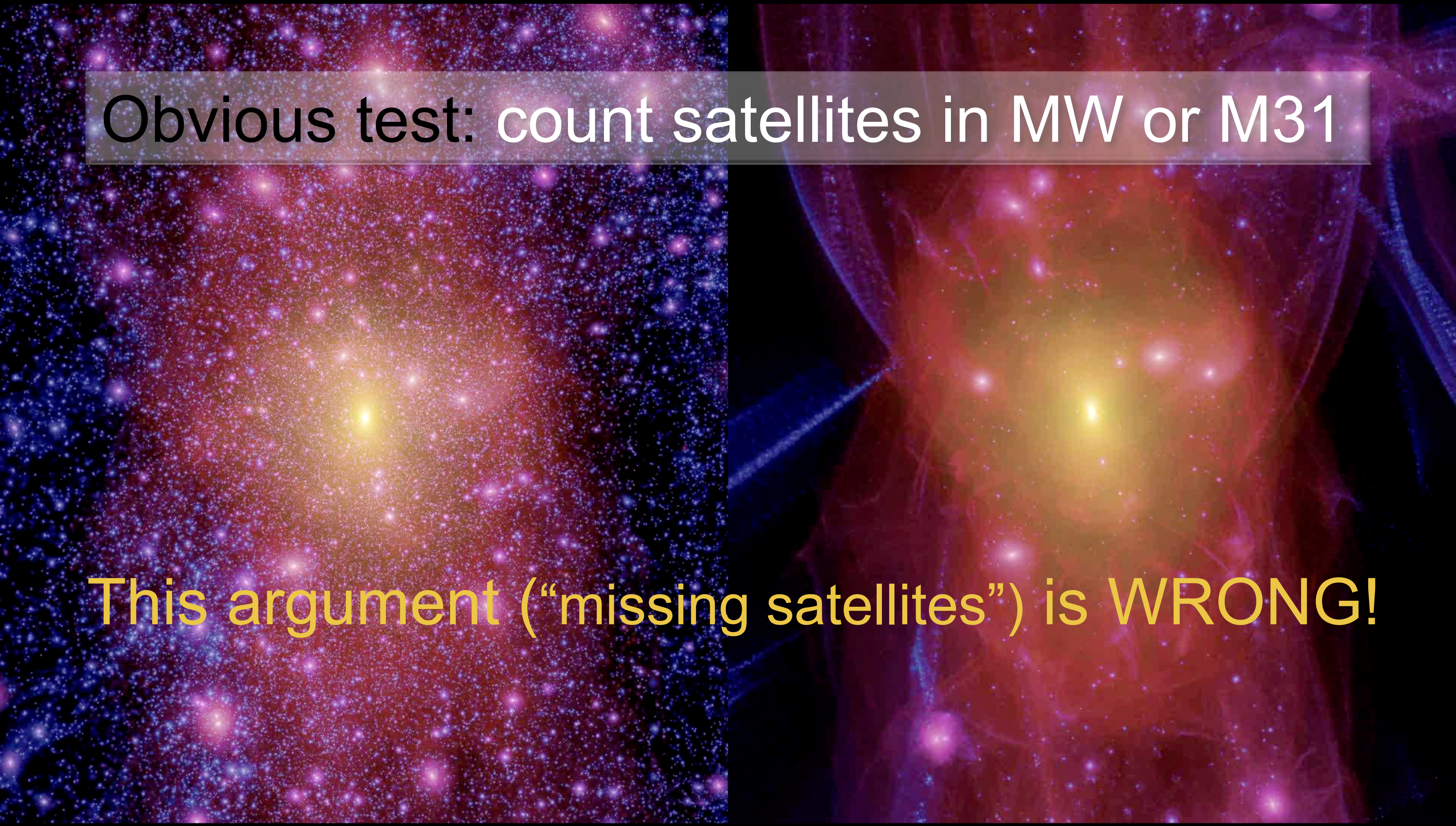
Obvious test: count satellites in MW or M31

In the MW: ~55 satellites discovered so far

~125 satellites expected

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

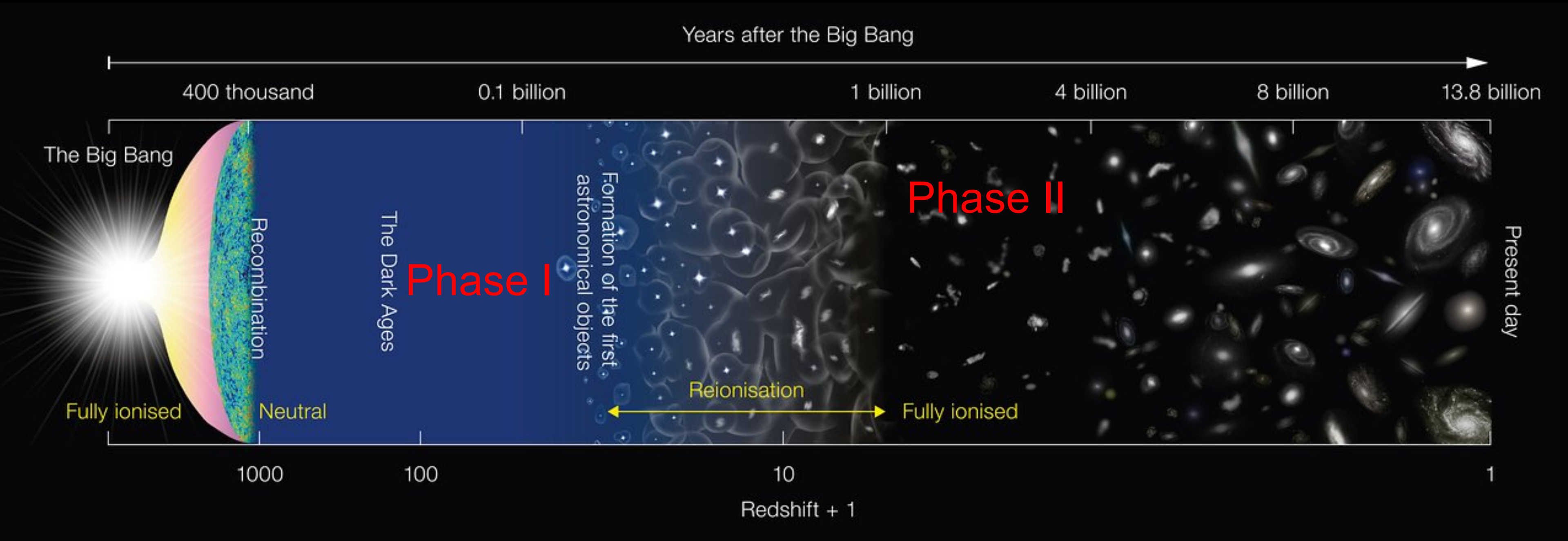
cold dark matter warm dark matter



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


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}" < 10^4K – galaxy formation is interrupted

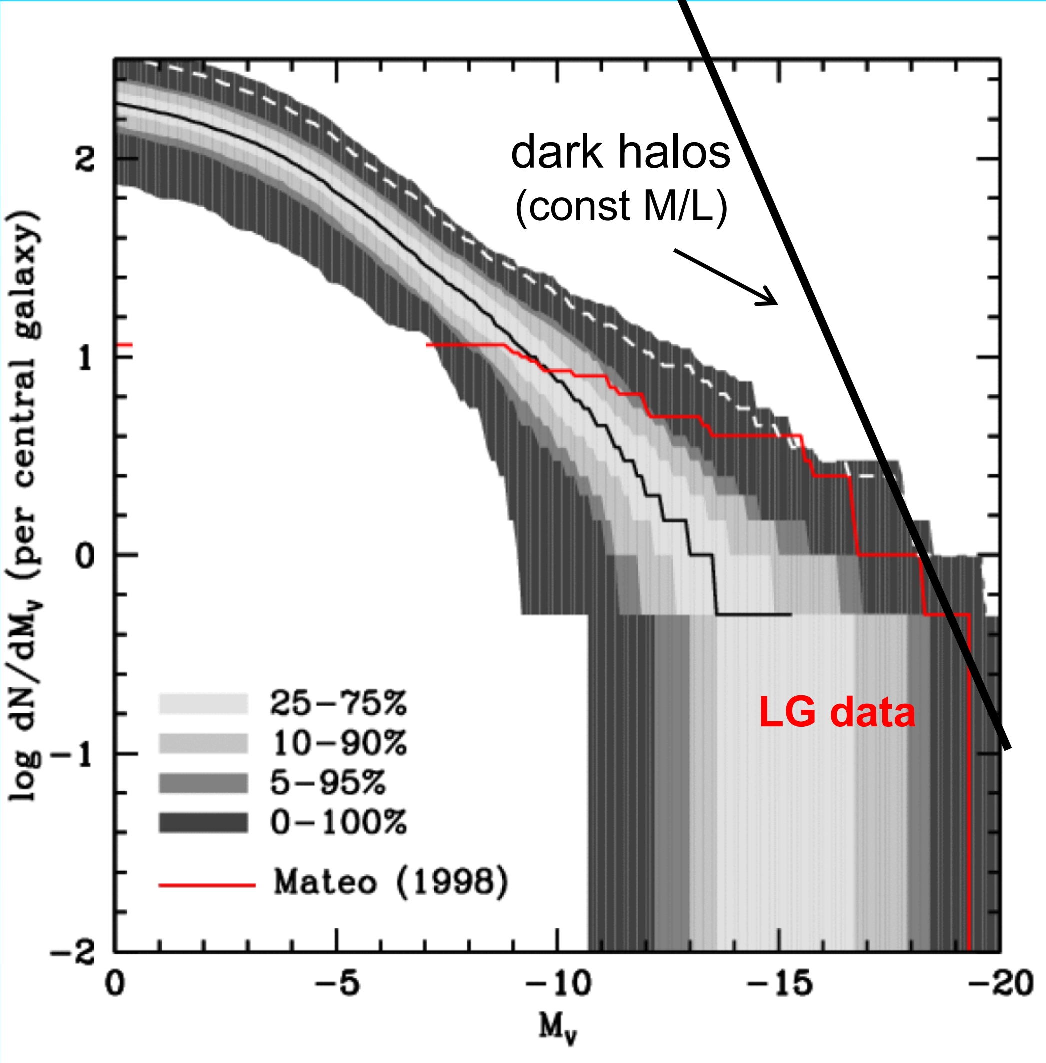
Phase II: Halos with "T_{vir}" > 10^4K form → galaxy formation resumes

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 (~10% of cases)



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

Luminosity Function of Local Group Satellites

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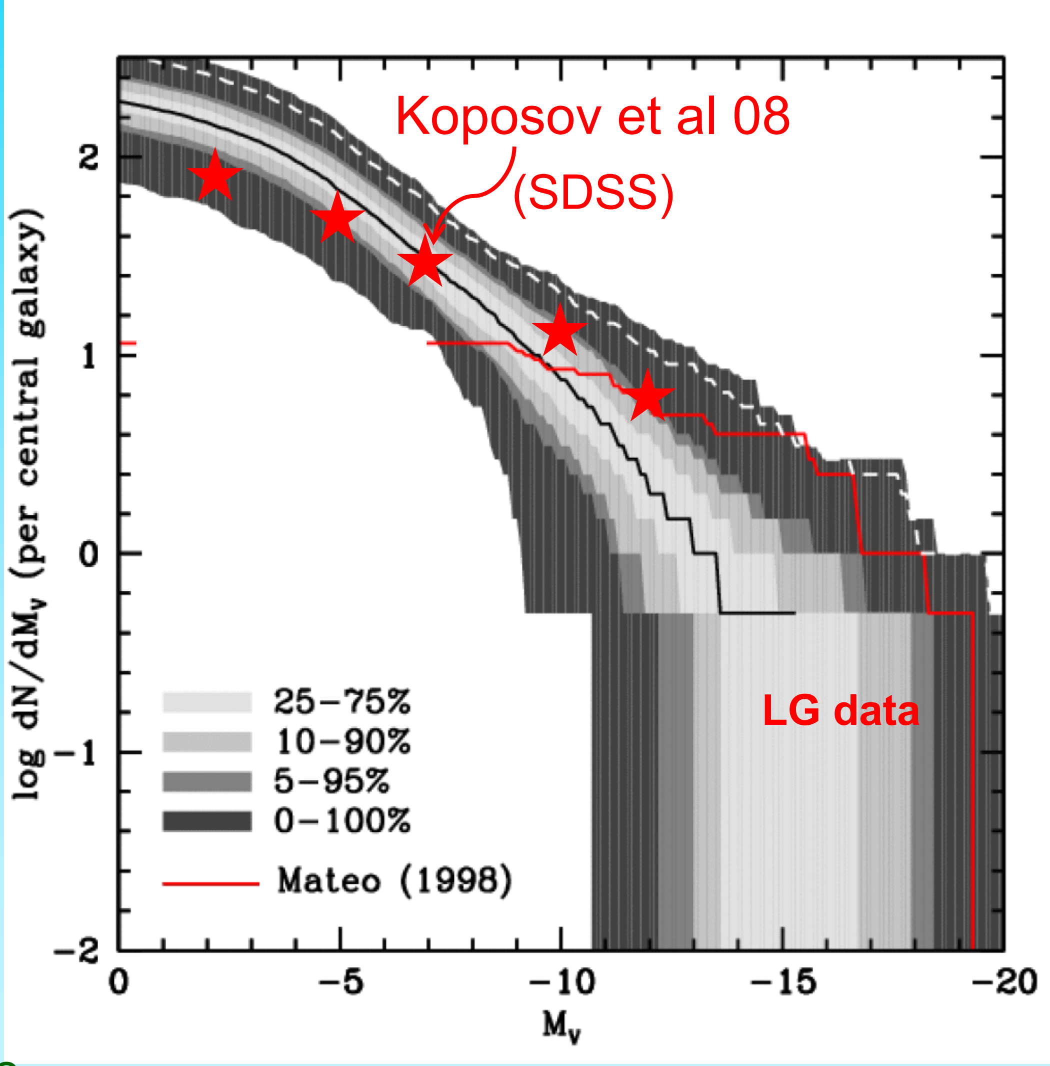

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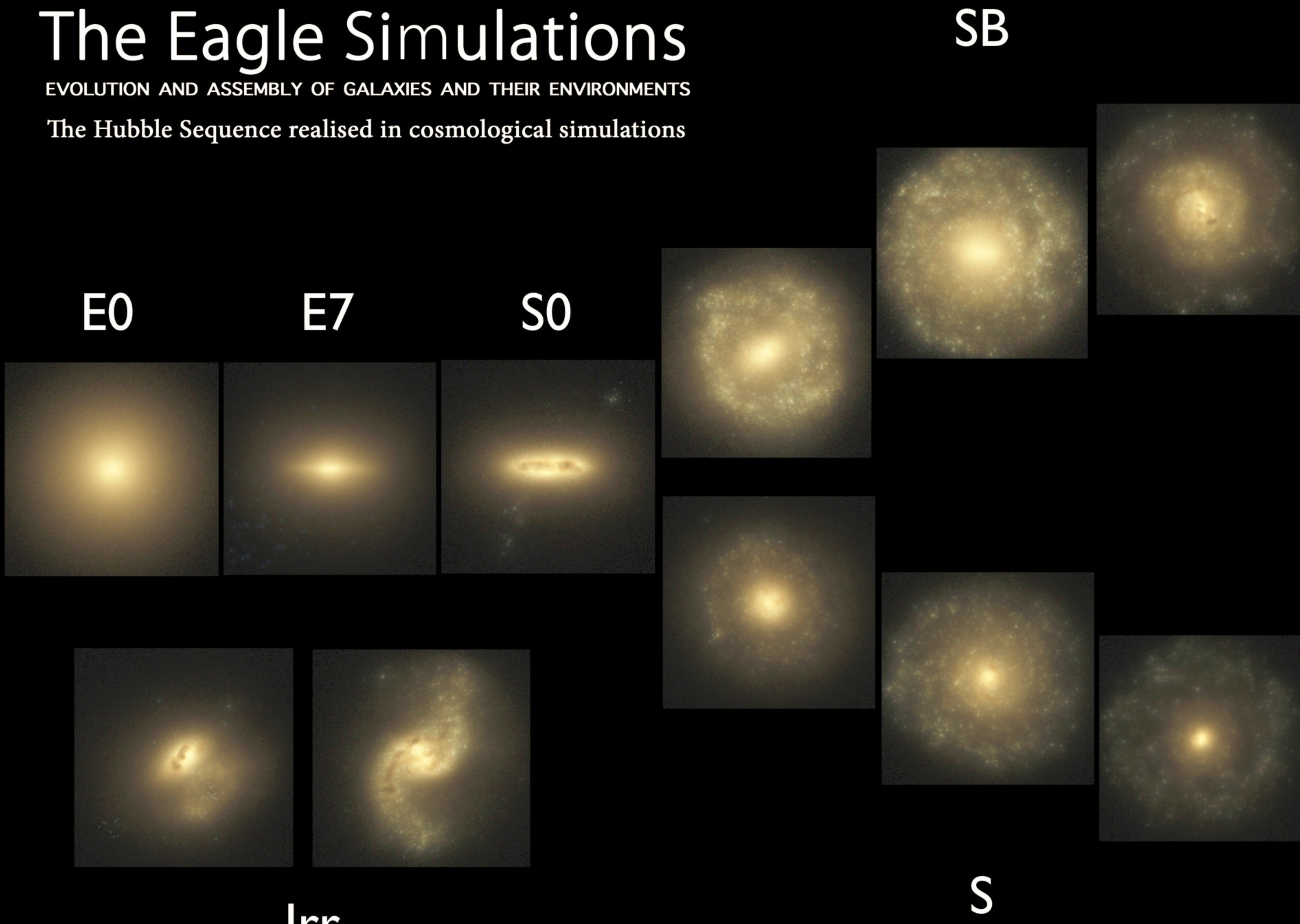
VIRGO
icc.dur.ac.uk/Eagle
"Evolution and assembly of galaxies and their environment"
THE EAGLE PROJECT
Virgo Consortium
Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.
Leiden: Rob Crain, Joop Schaye.
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…
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



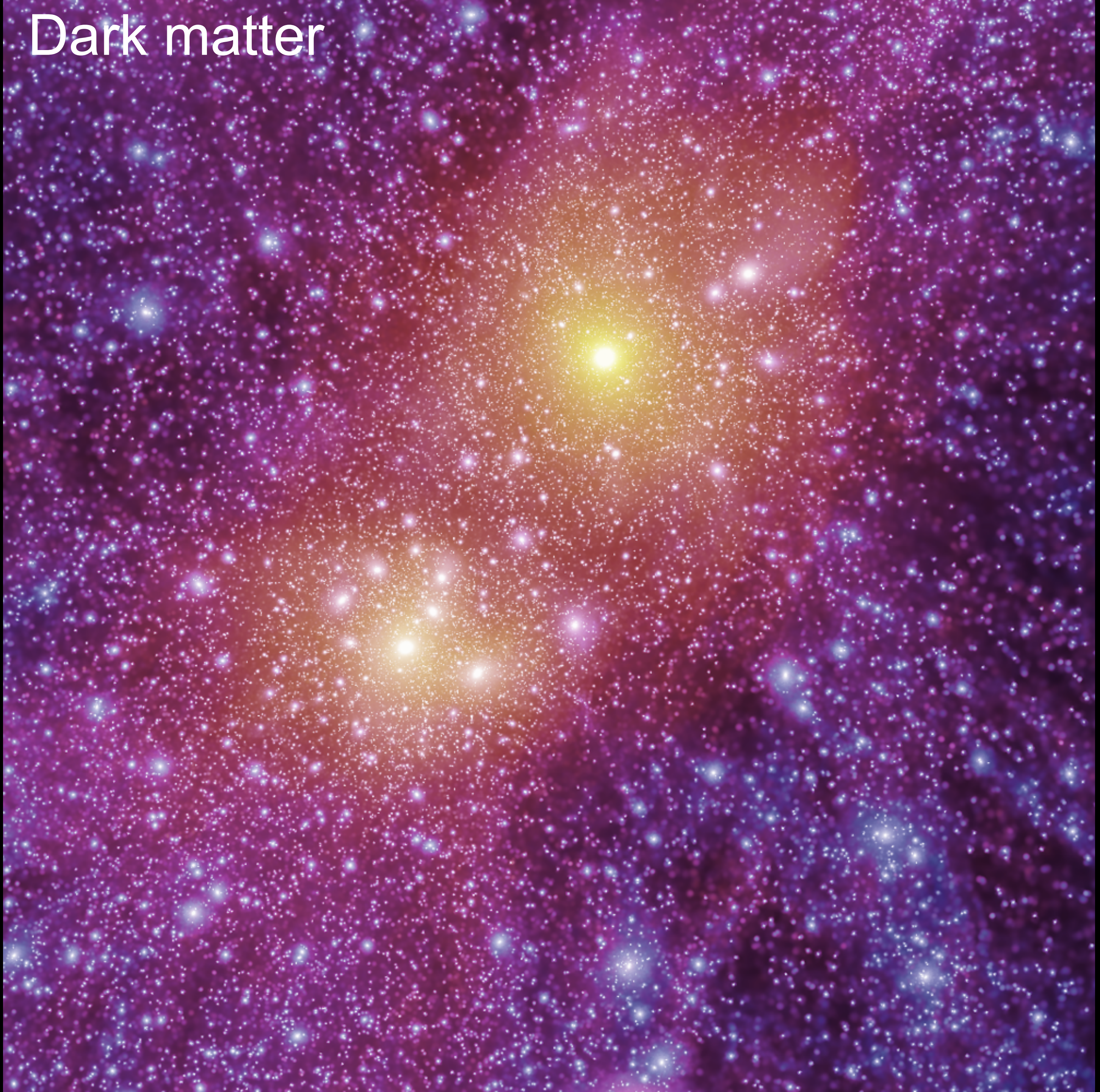
Trayford et al '15

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala et al ‘16

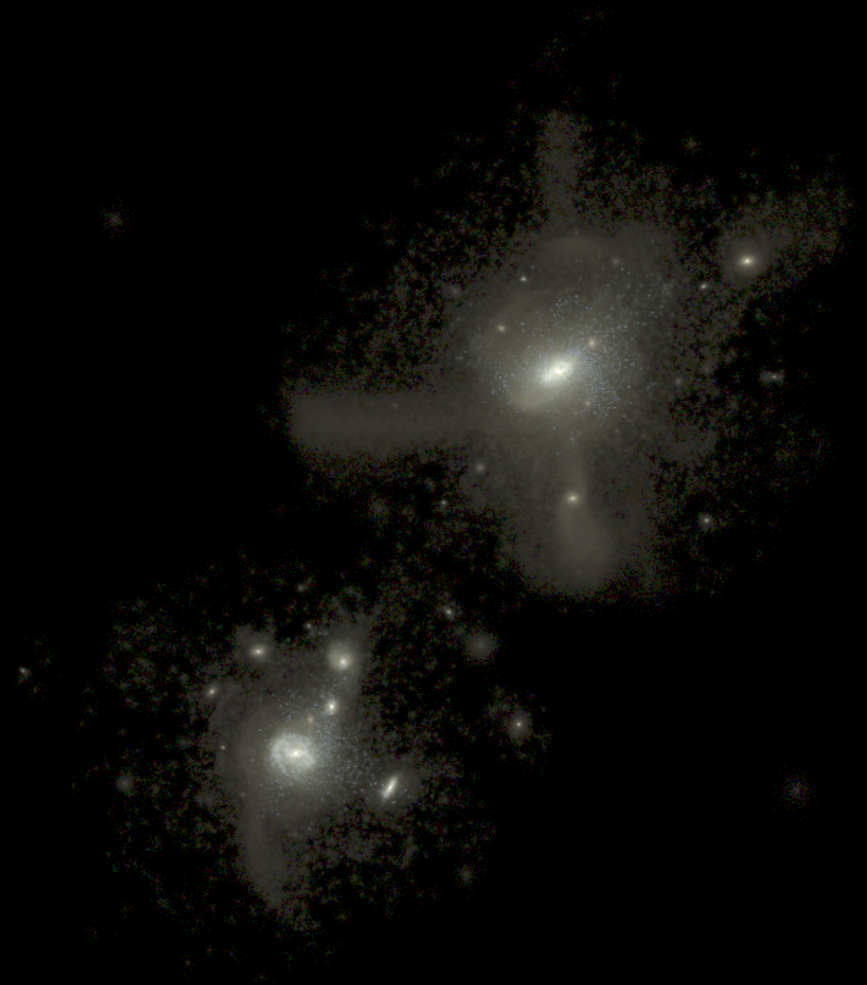


Stars

APOSTLE EAGLE full hydro simulations

Local Group

Stars

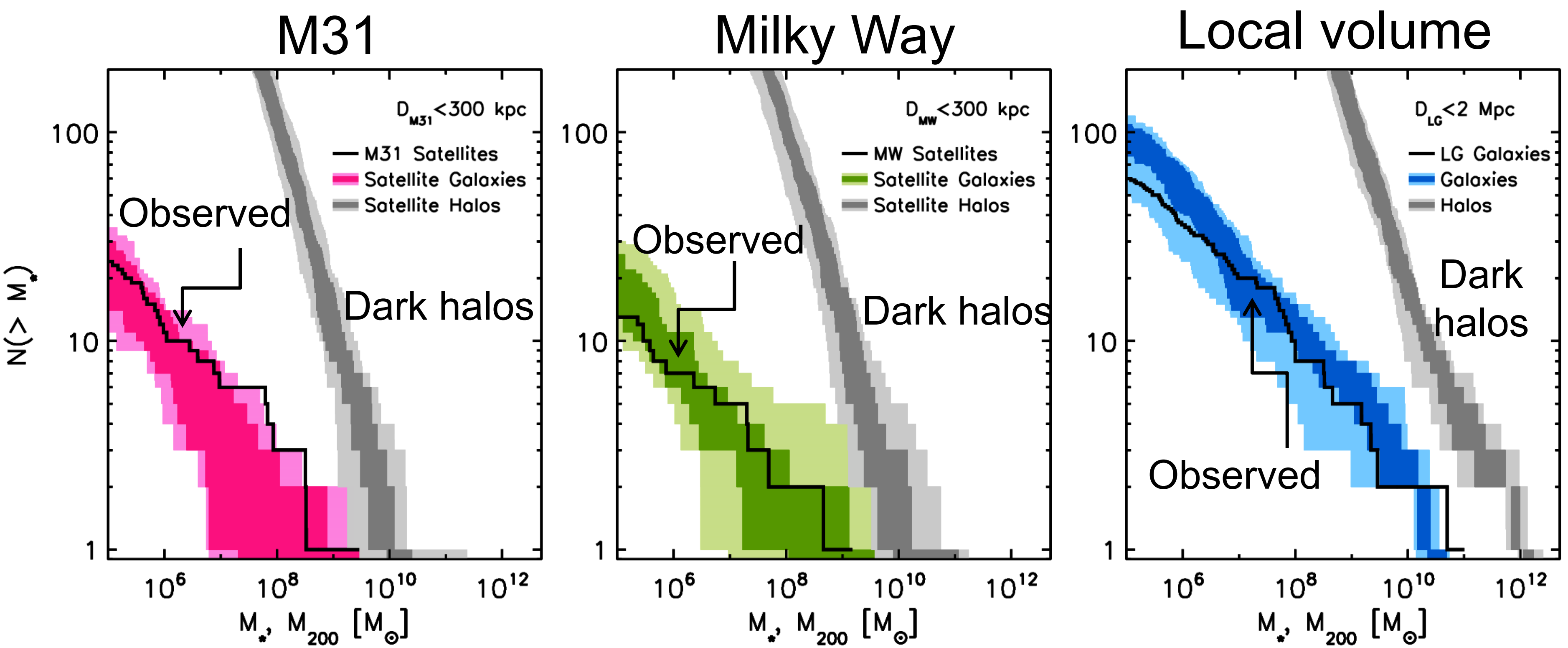


Far fewer satellite galaxies than CDM halos

Sawala et al ‘16

EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

When "baryon effects" are taken into account

→

Observed abundance of satellites is compatible with CDM

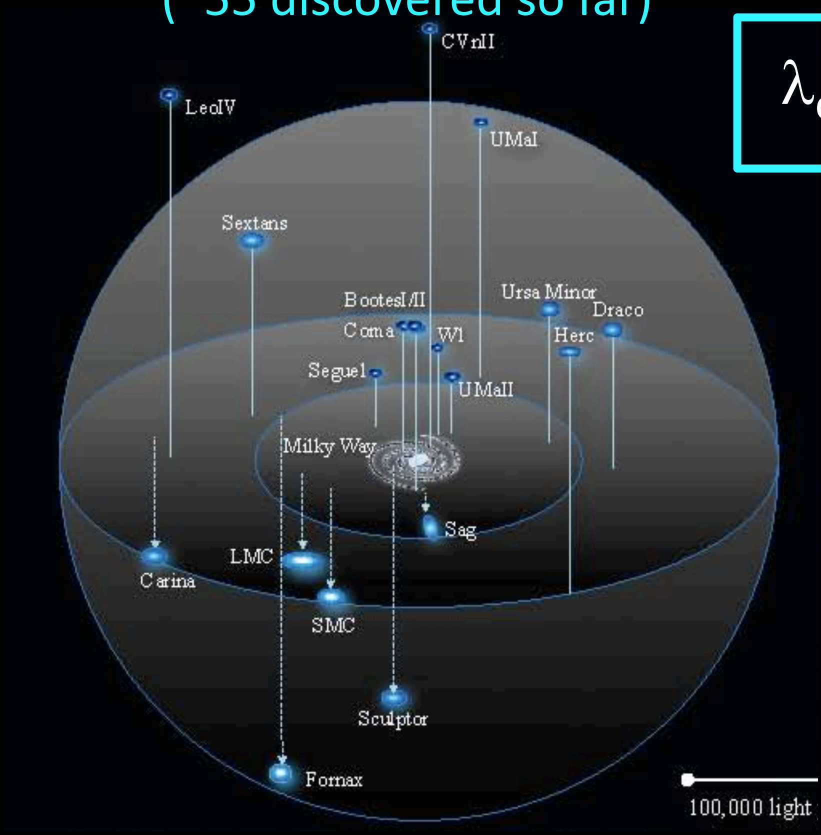
→

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

How about in WDM?

The satellites of the MW

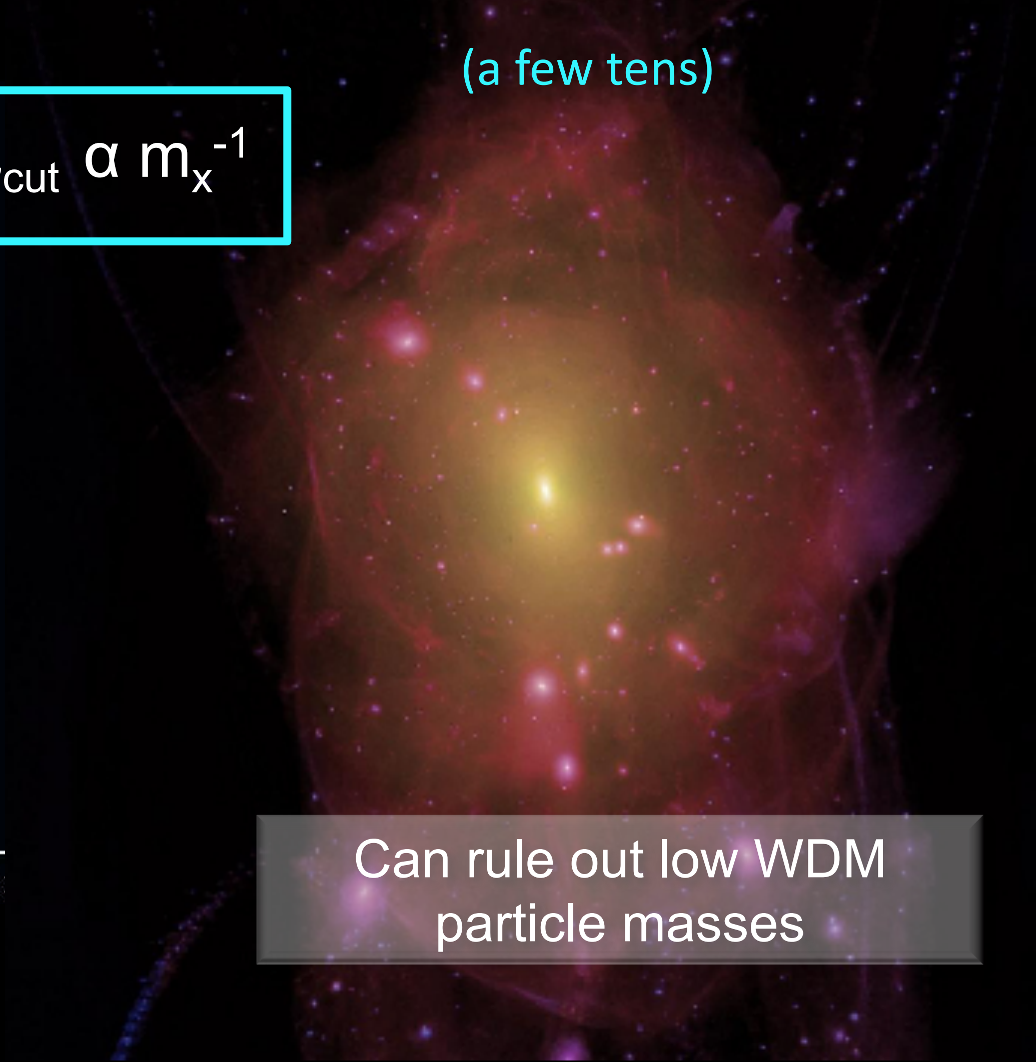
(~55 discovered so far)



λ_{cut} α m_x^{-1}

Dark matter subhalos in WDM

(a few tens)

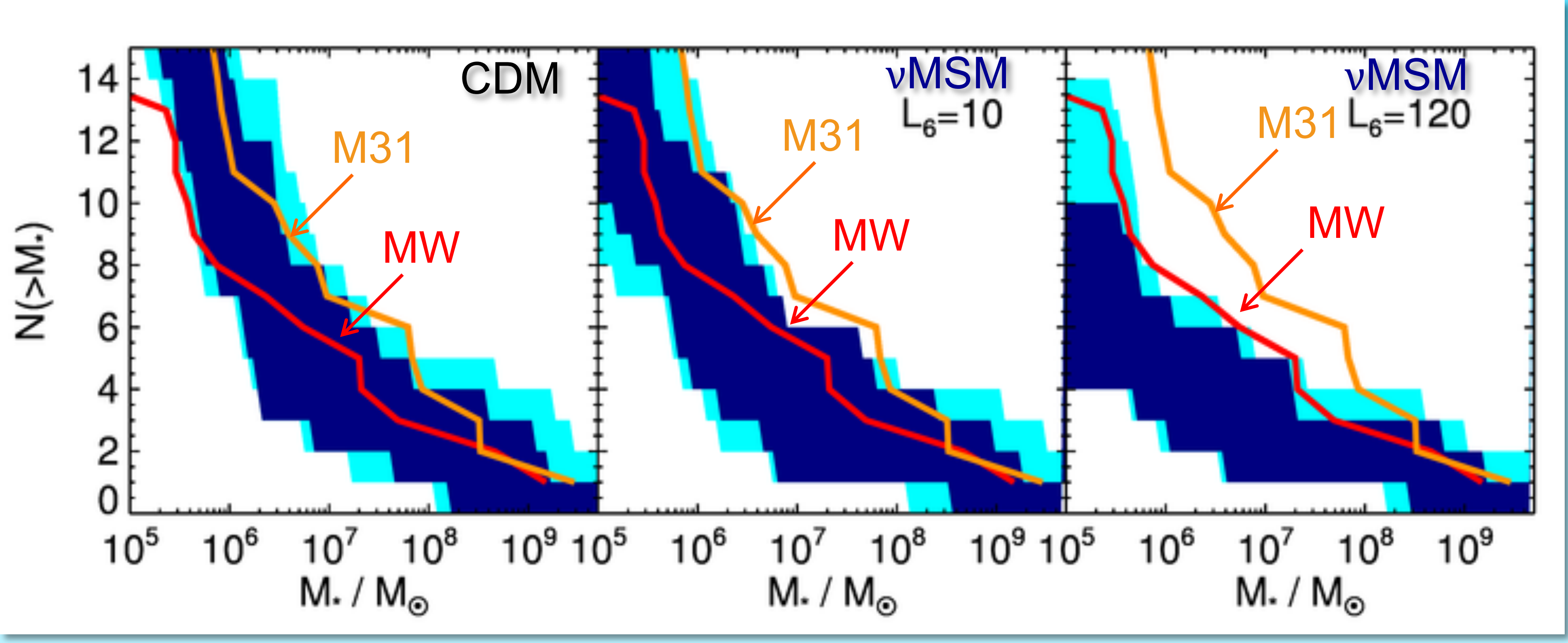


Can rule out low WDM particle masses

Luminosity Function of Local Group Satellites in WDM

University of Durham

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



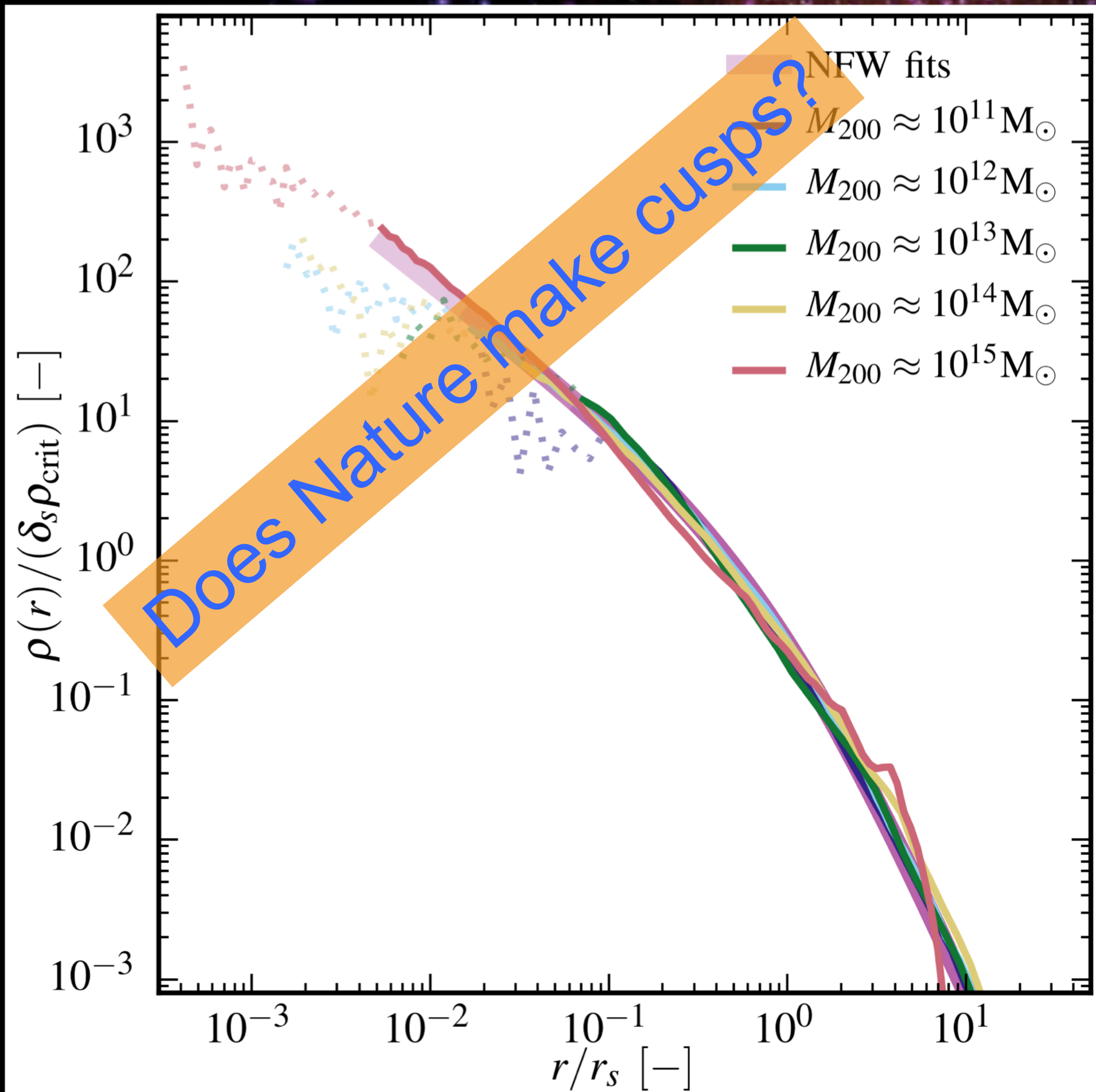
Lovell et al. '16

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:

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

(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 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)

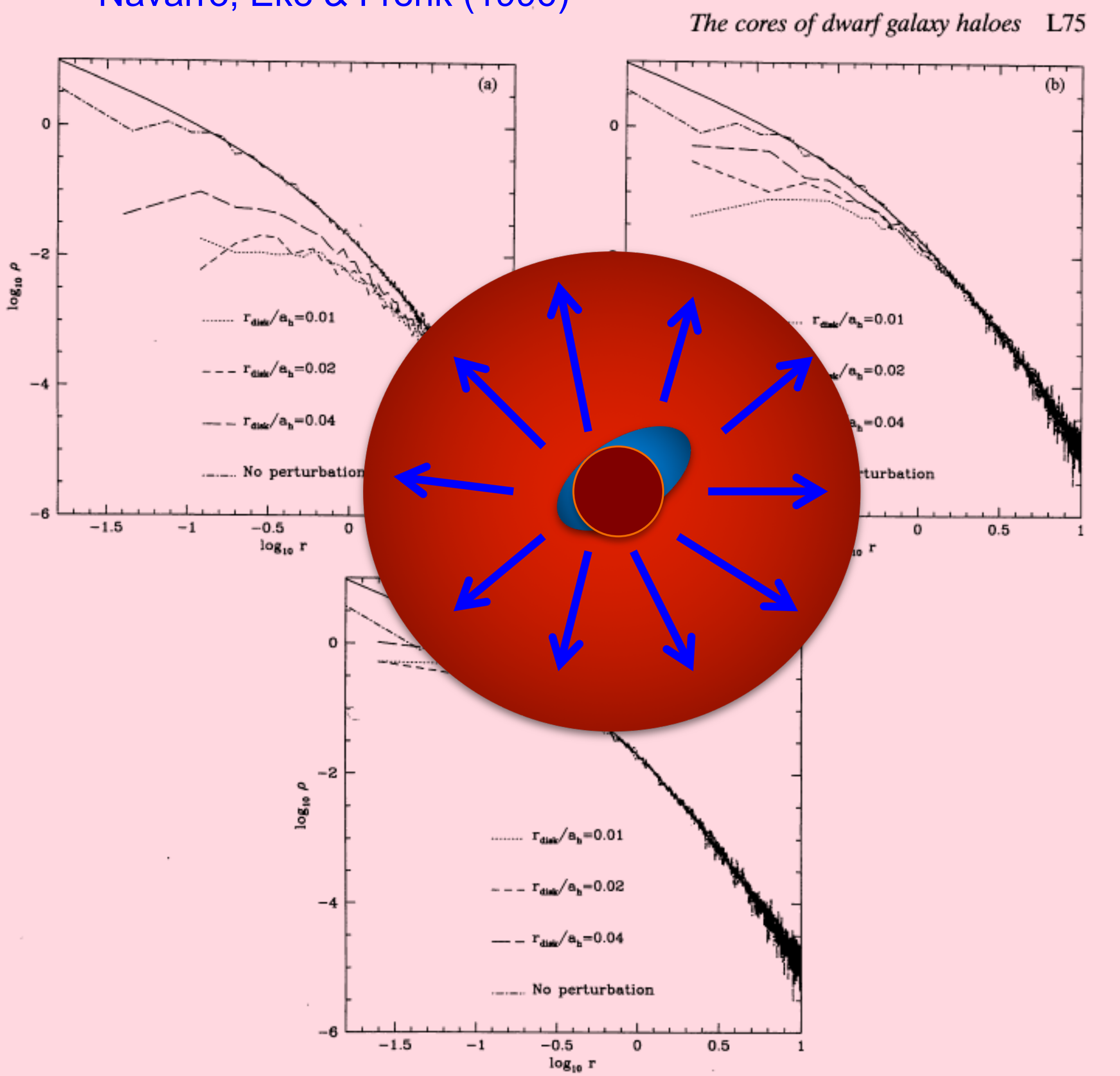


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

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Core formation

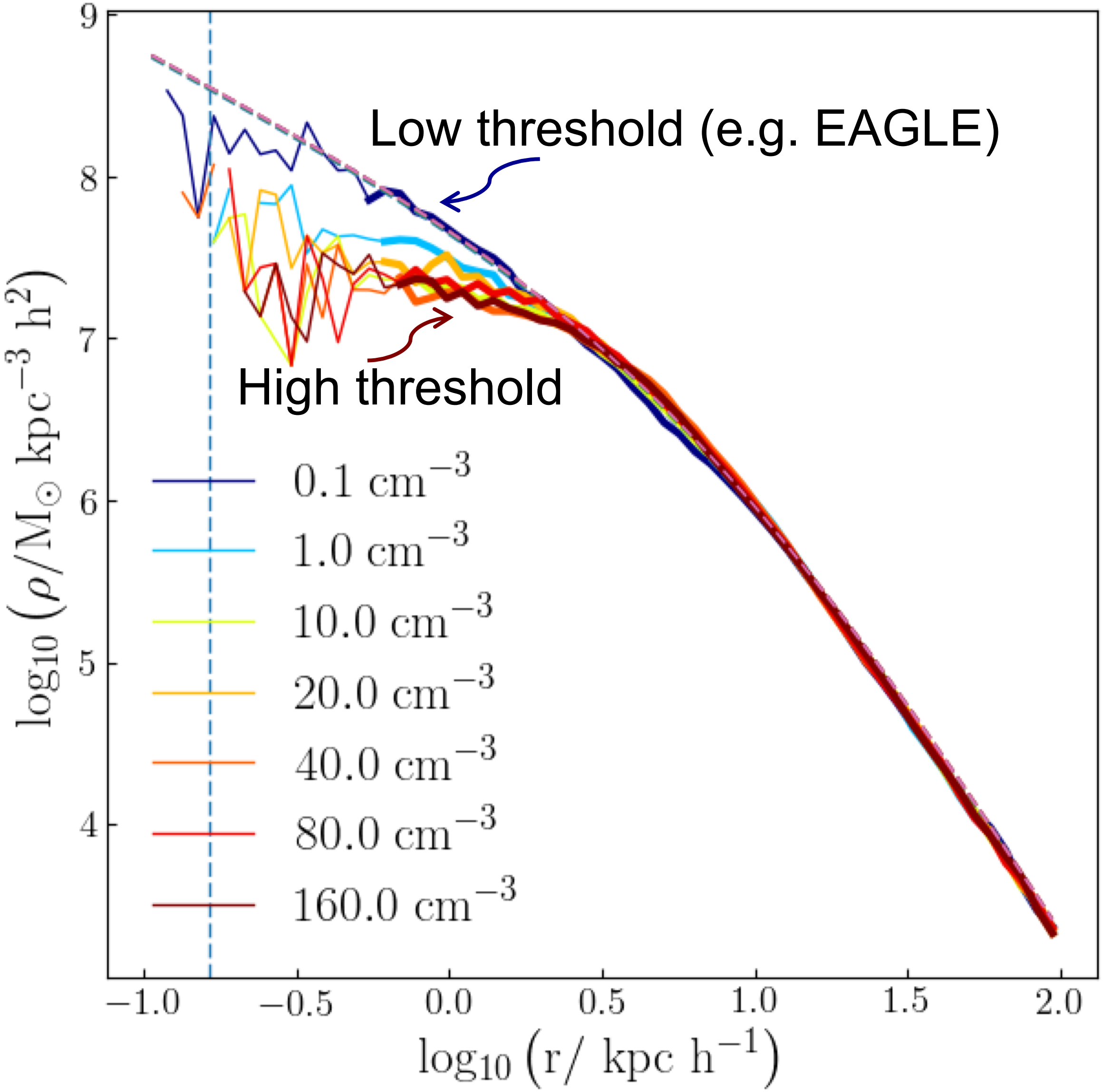
In the absence of a treatment of the (multi-phase) interstellar medium, need a “subgrid” model for star formation

Key parameter: gas density threshold for star formation

Physically meaningless

Cores or cusps in simulations?

University of Durham



Benitez-Llambay, CSF et al ‘17

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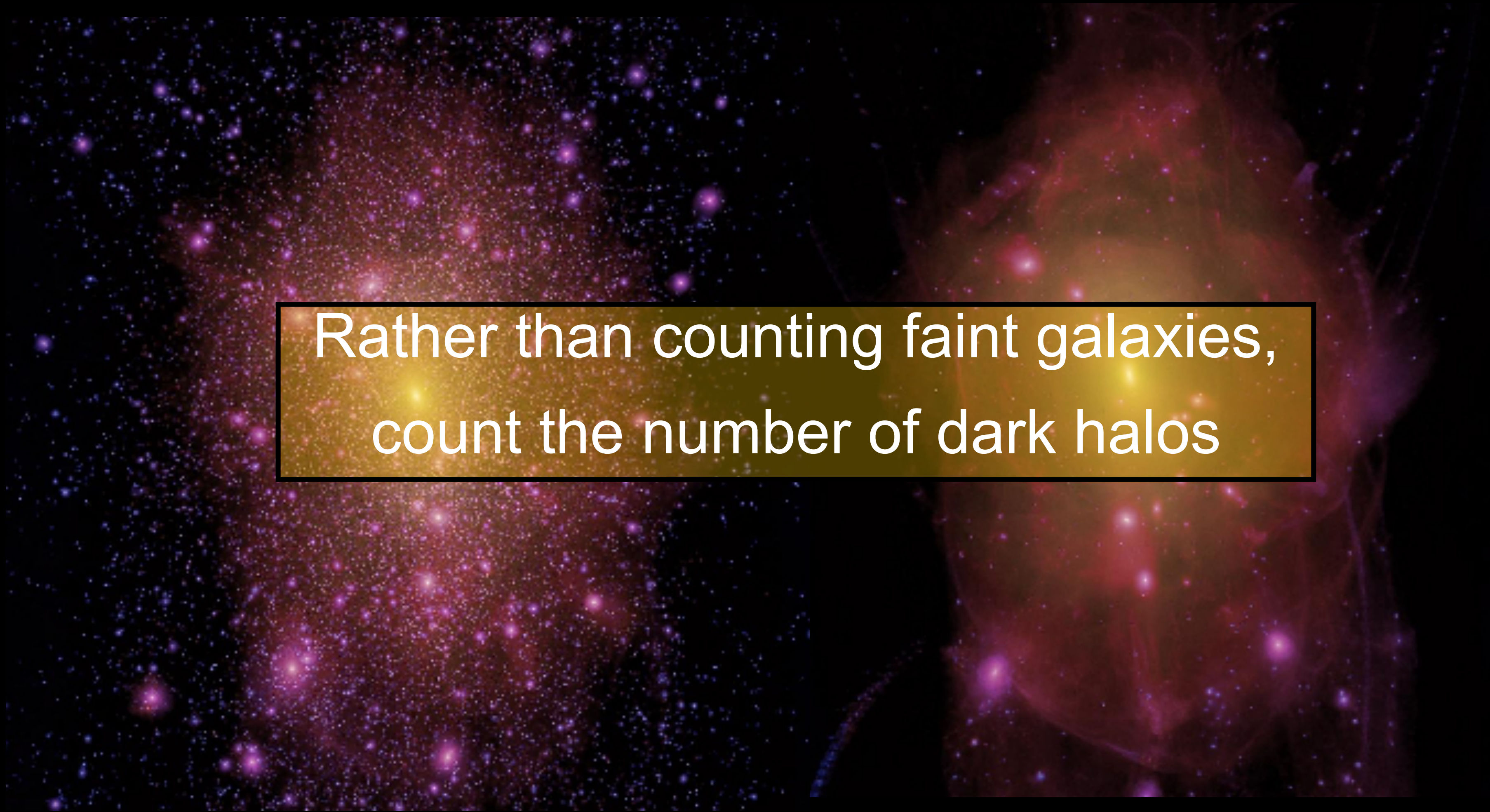
Cores in halos can be generated by “baryon effects”

Is there any way can distinguish CDM from WDM?

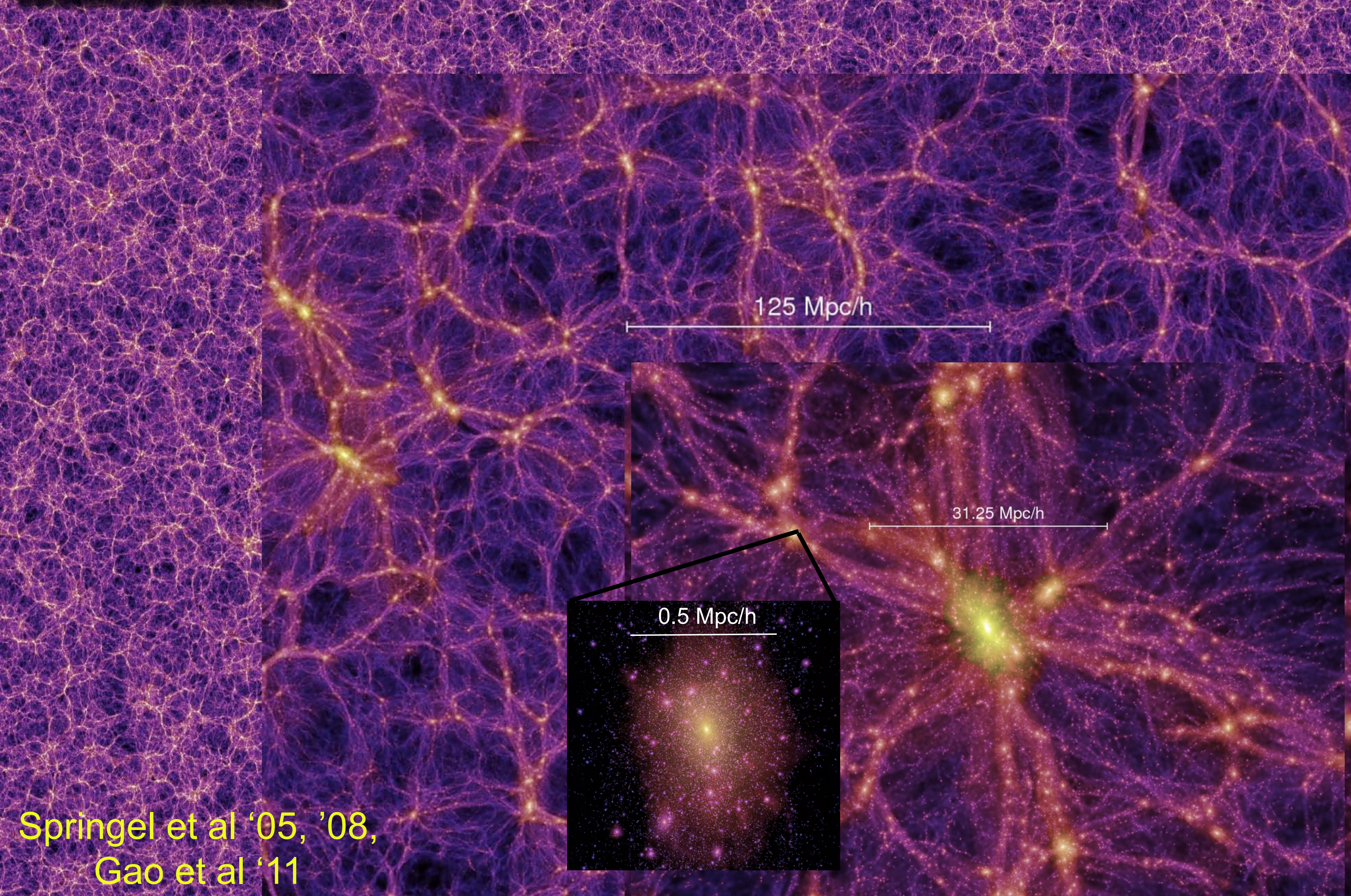
There is no need for despair: there is a way to distinguish them

Can we distinguish CDM/WDM?

cold dark matter　　　　warm dark matter



The Millennium/Aquarius/Phoenix simulation series

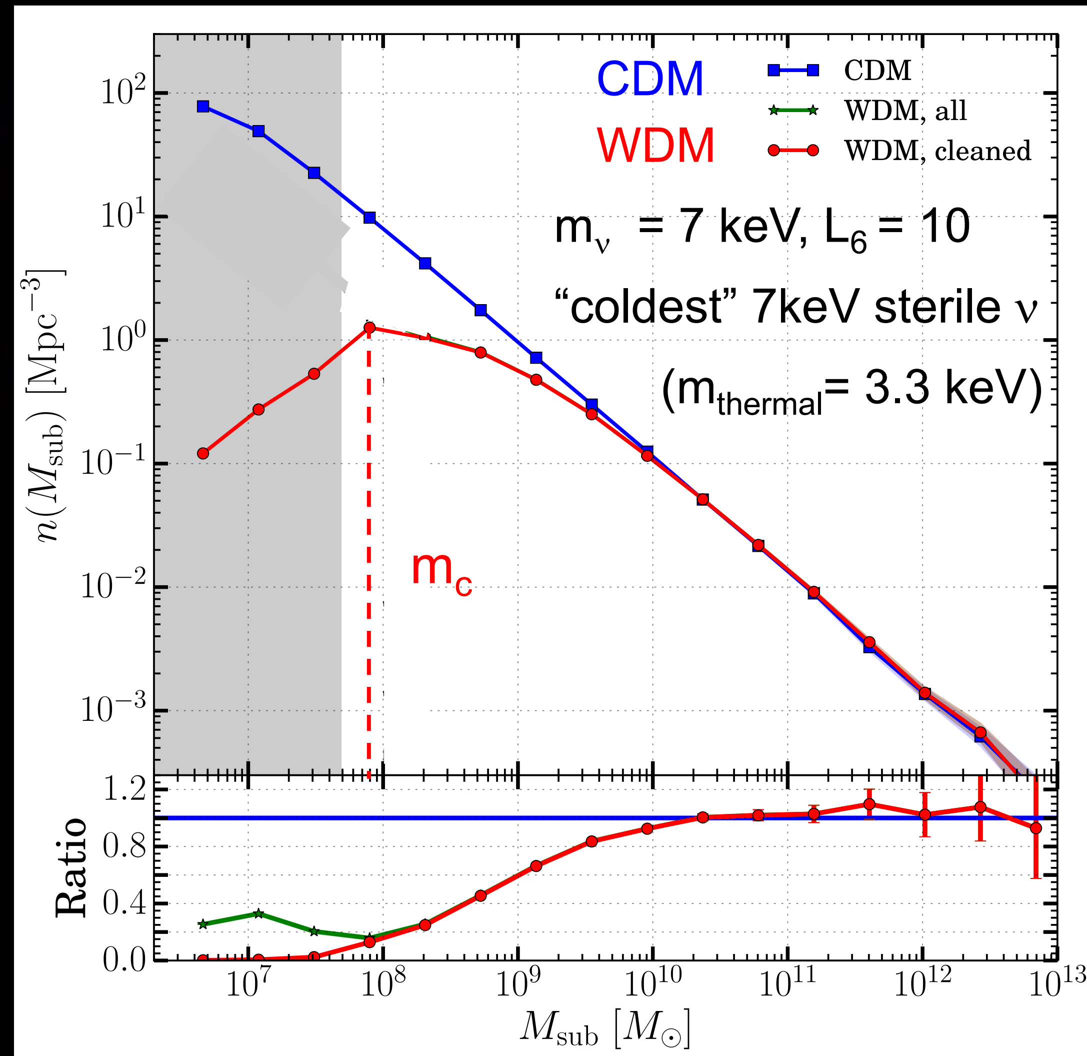


Springel et al ‘05, ’08,
Gao et al ‘11

The subhalo mass function

CDM

WDM



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

10 x fewer at 10^8 M_o

Bose, CSF et al '16

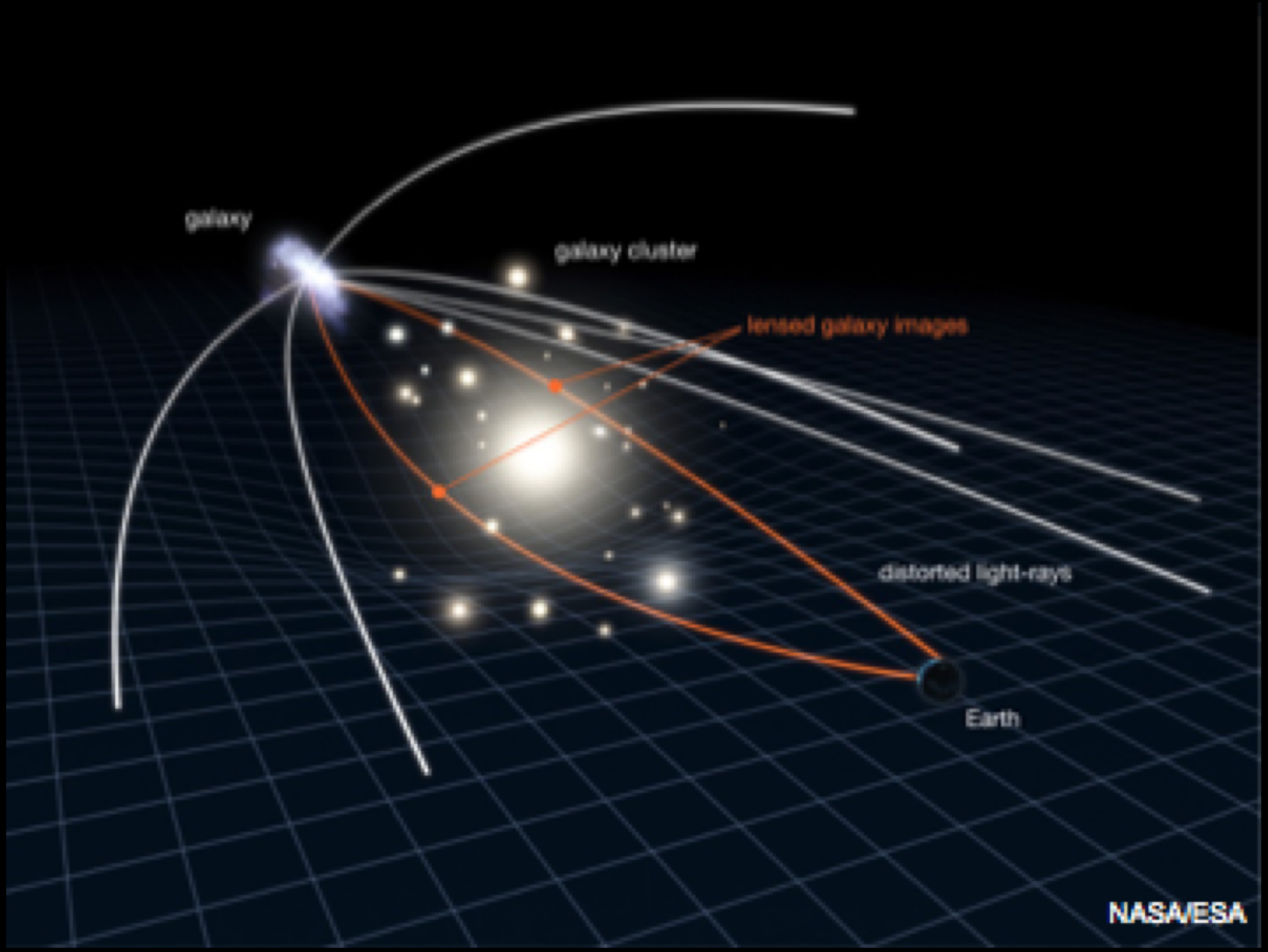
Can we distinguish CDM/WDM?

cold dark matter　　　　　　　　warm dark matter

Dark halos can be detected through gravitational lensing

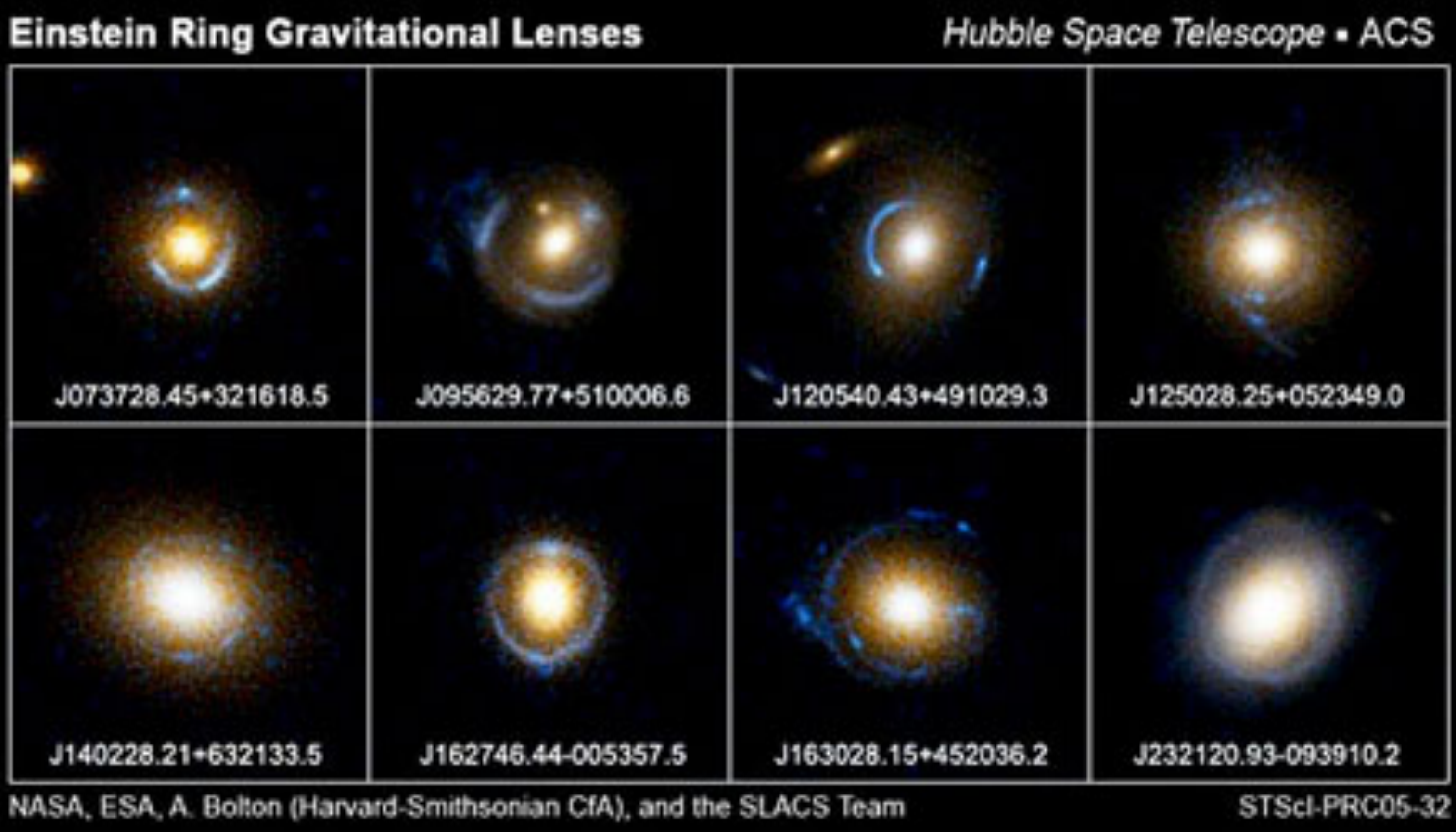
How to rule out CDM

Gravitational lensing: Einstein rings

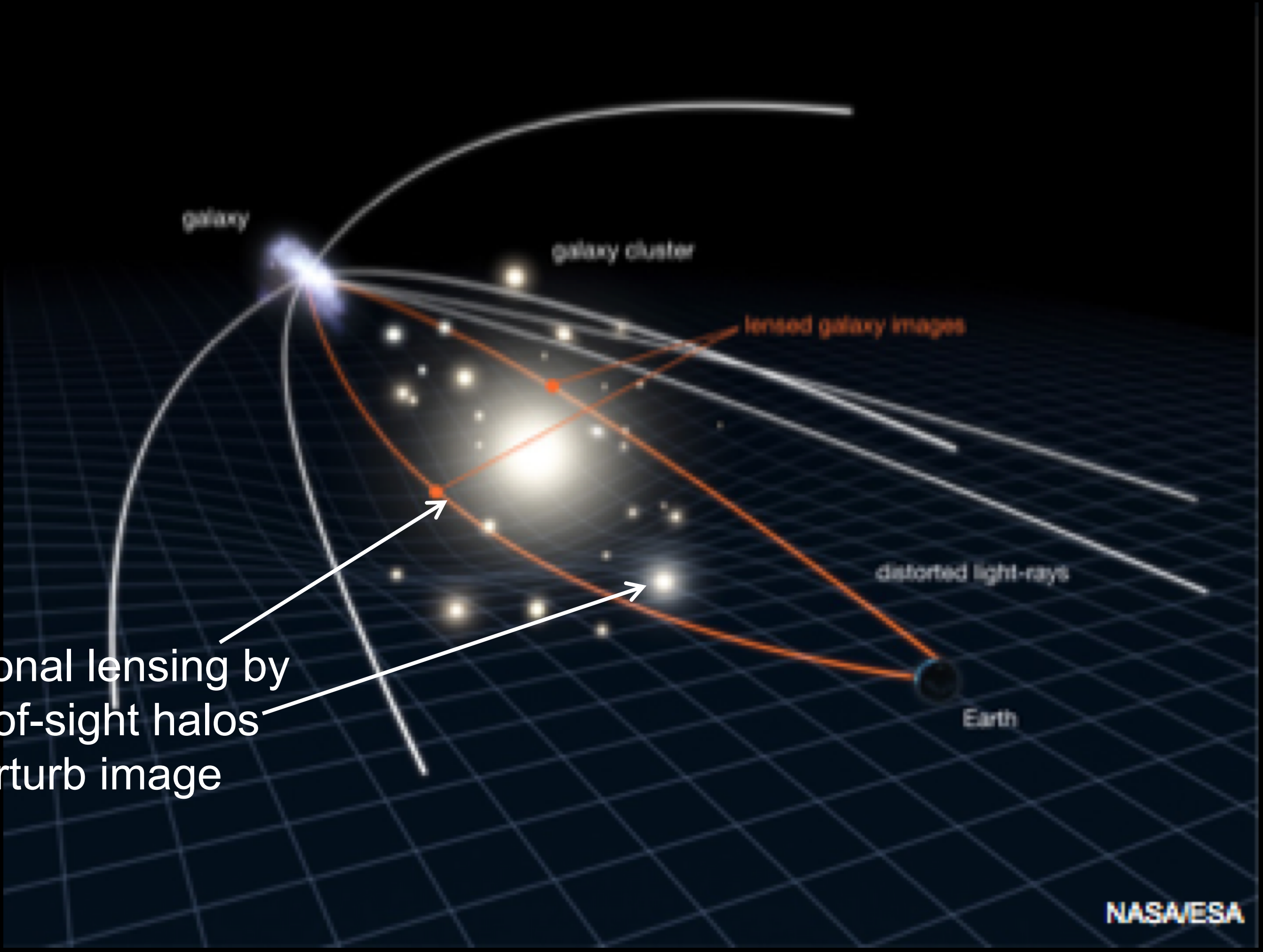


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



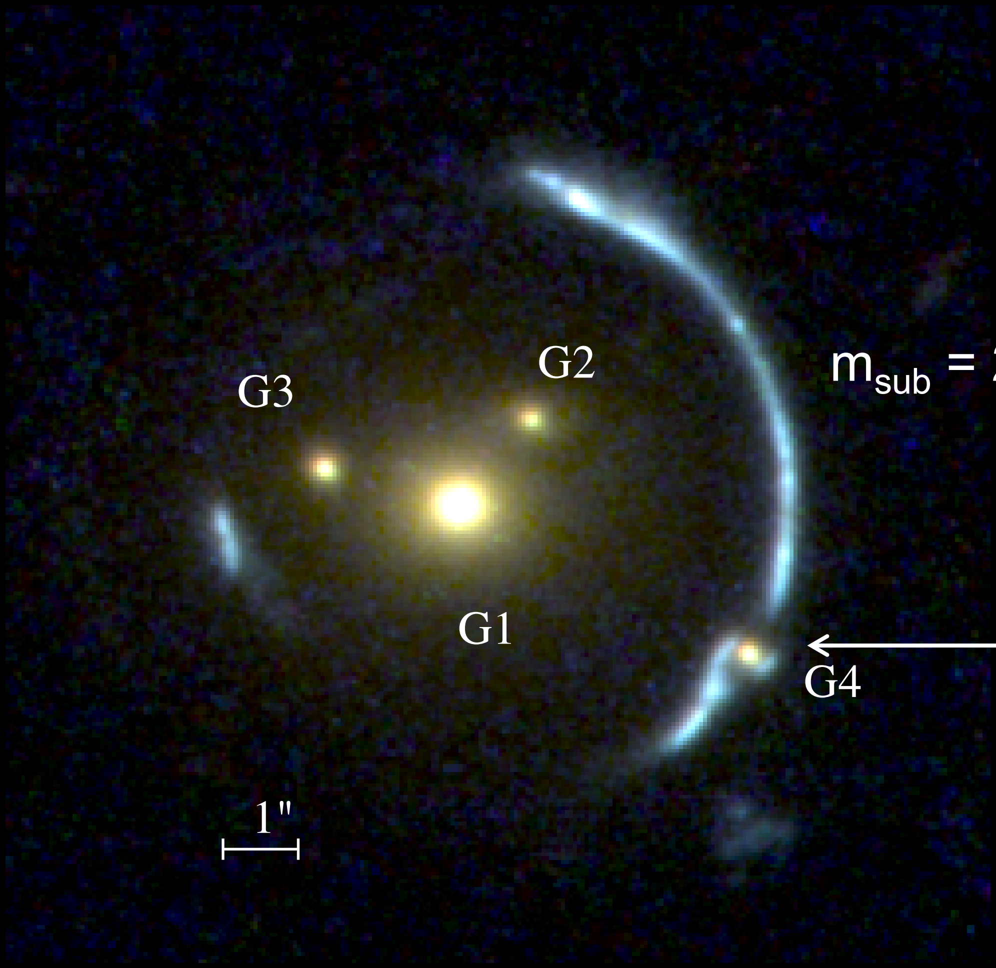
Gravitational lensing: Einstein rings



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

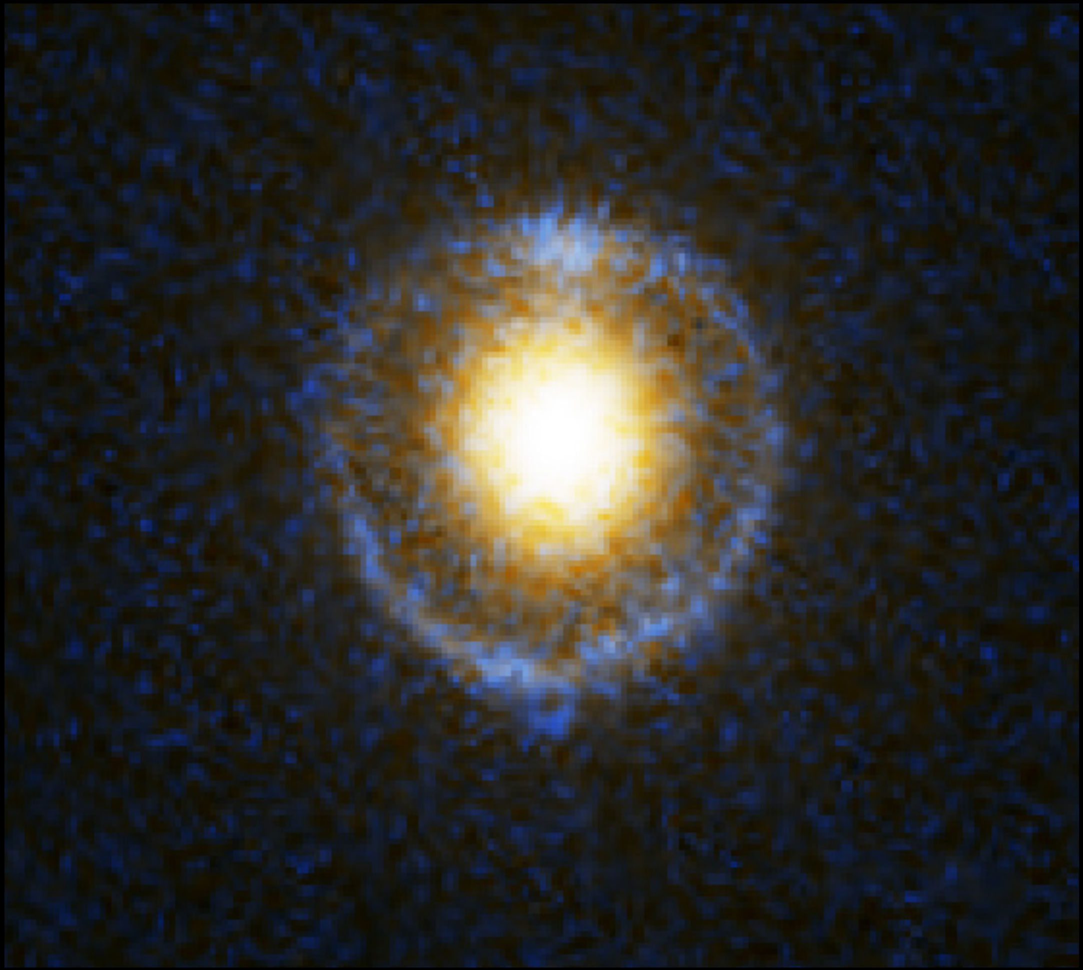


$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



Vegetti & Koopmans '09

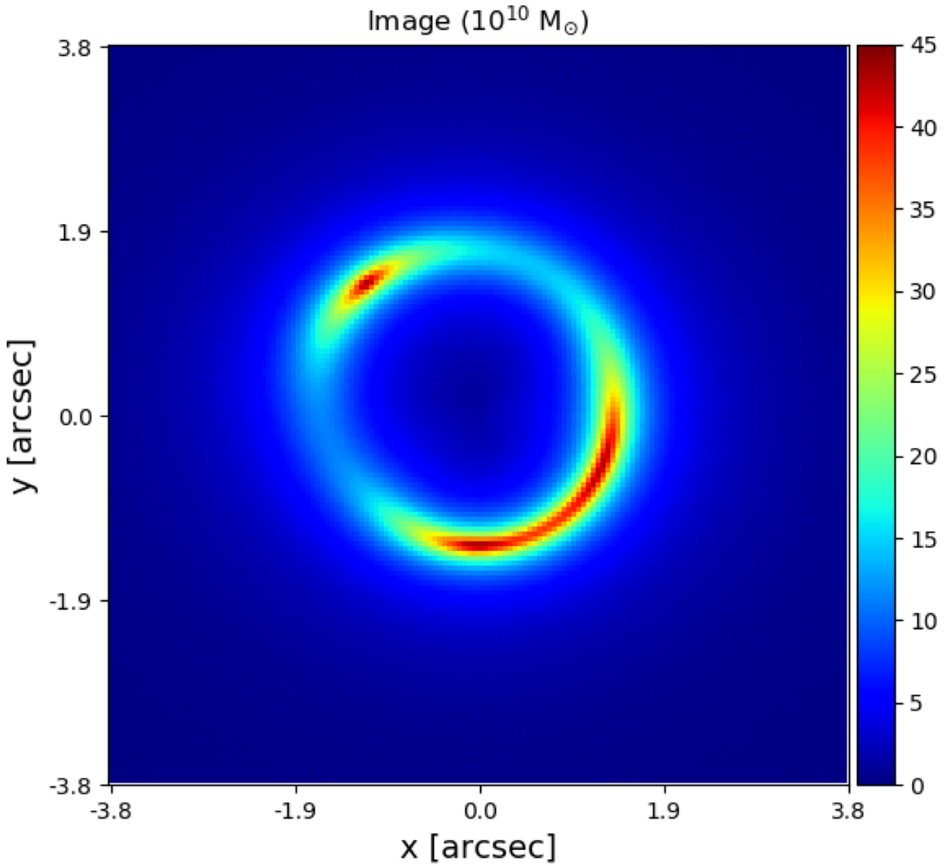
Gravitational lensing: Einstein rings

University of Durham

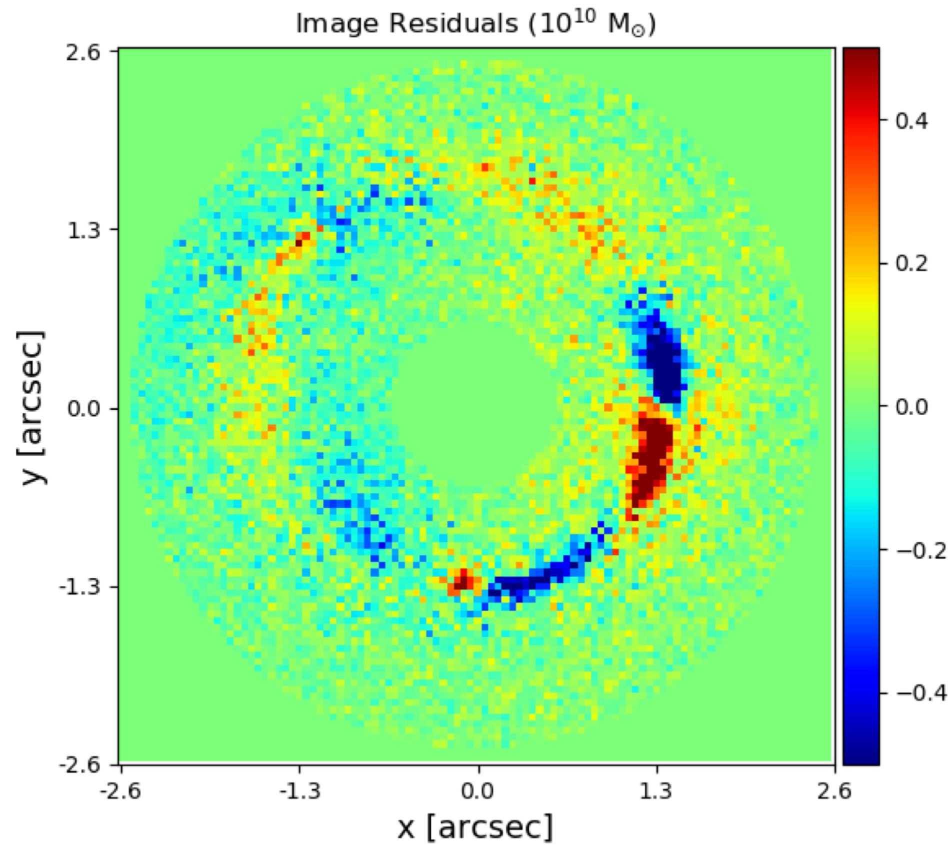
HST "data": $z_{source}=1$; $z_{lens}=0.2$

$10^{10}M_o$ halo – easy to spot

Image



Residuals



He, Li, CSF et al '19

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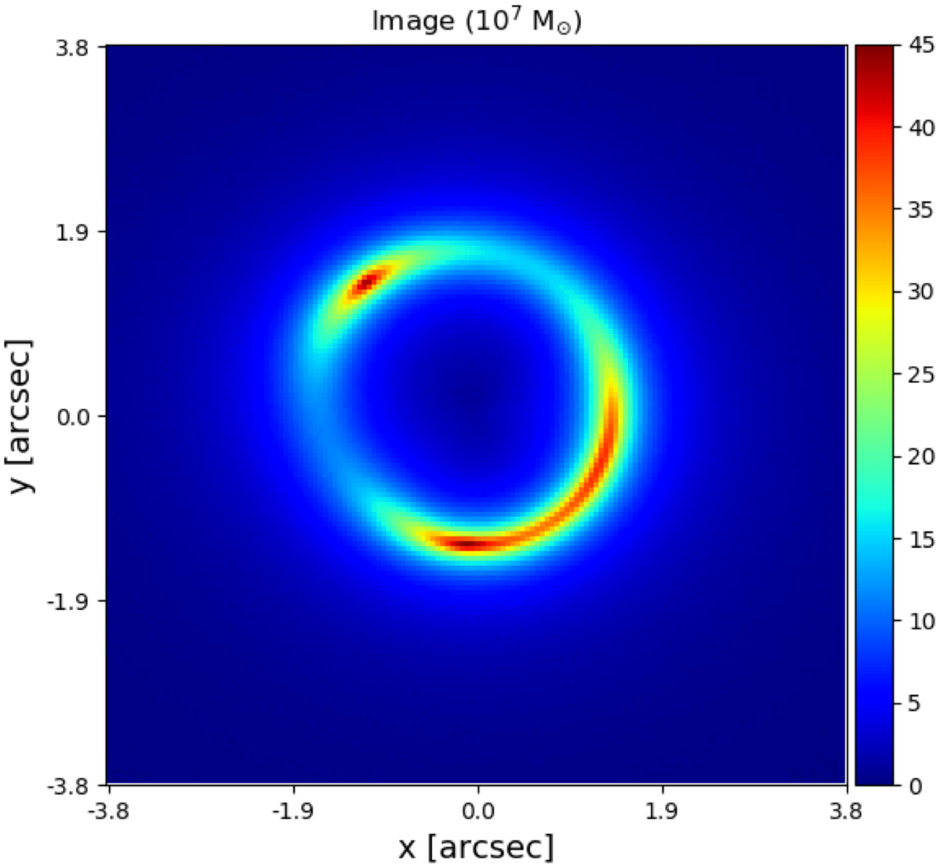
Gravitational lensing: Einstein rings

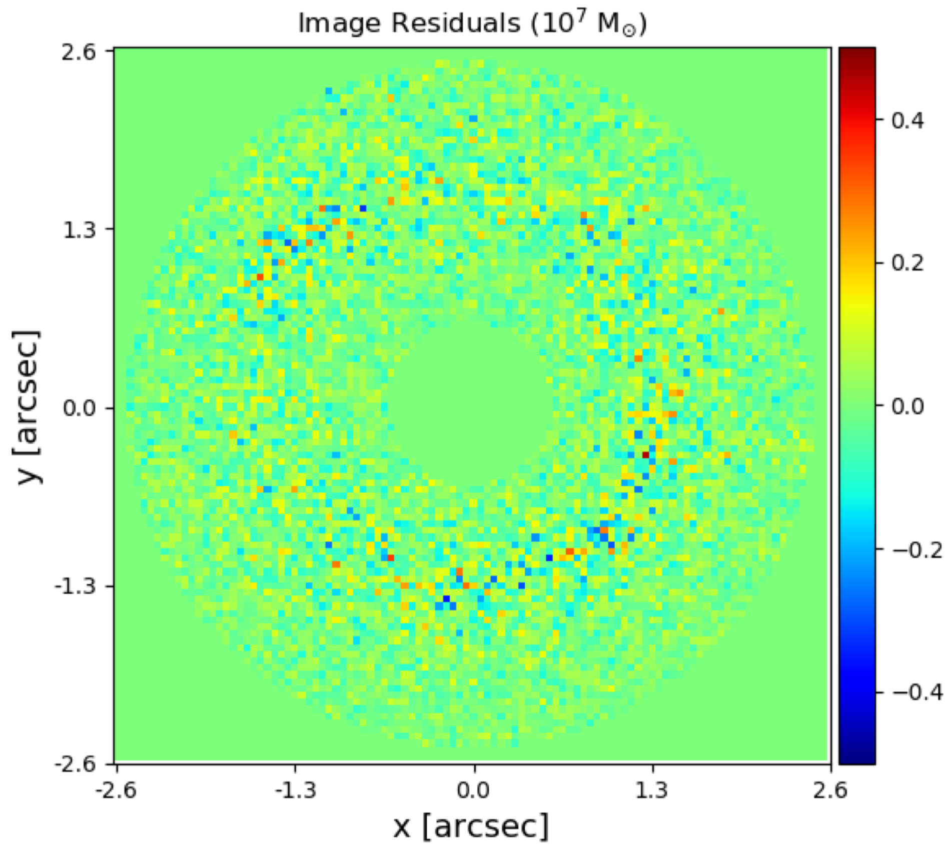
University of Durham

HST "data": z_{source}=1; z_{lens}=0.2 10^7 M_o halo – NOT so easy to spot

Image



Residuals



He, Li, CSF et al '19

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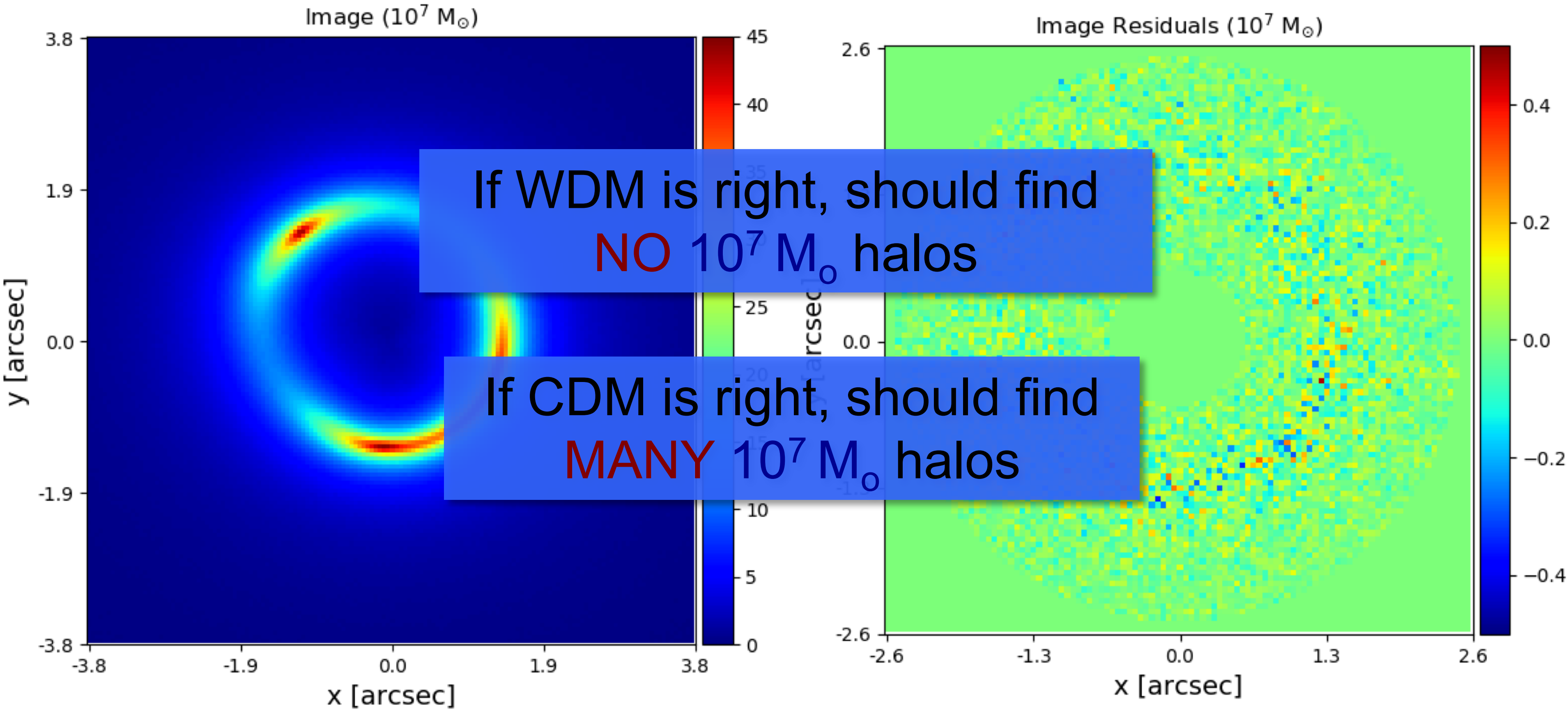
Detecting substructures with strong lensing

Can detect subhalos as small as $10^7 - 10^8 M_o$



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

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

He, Li, CSF et al '19

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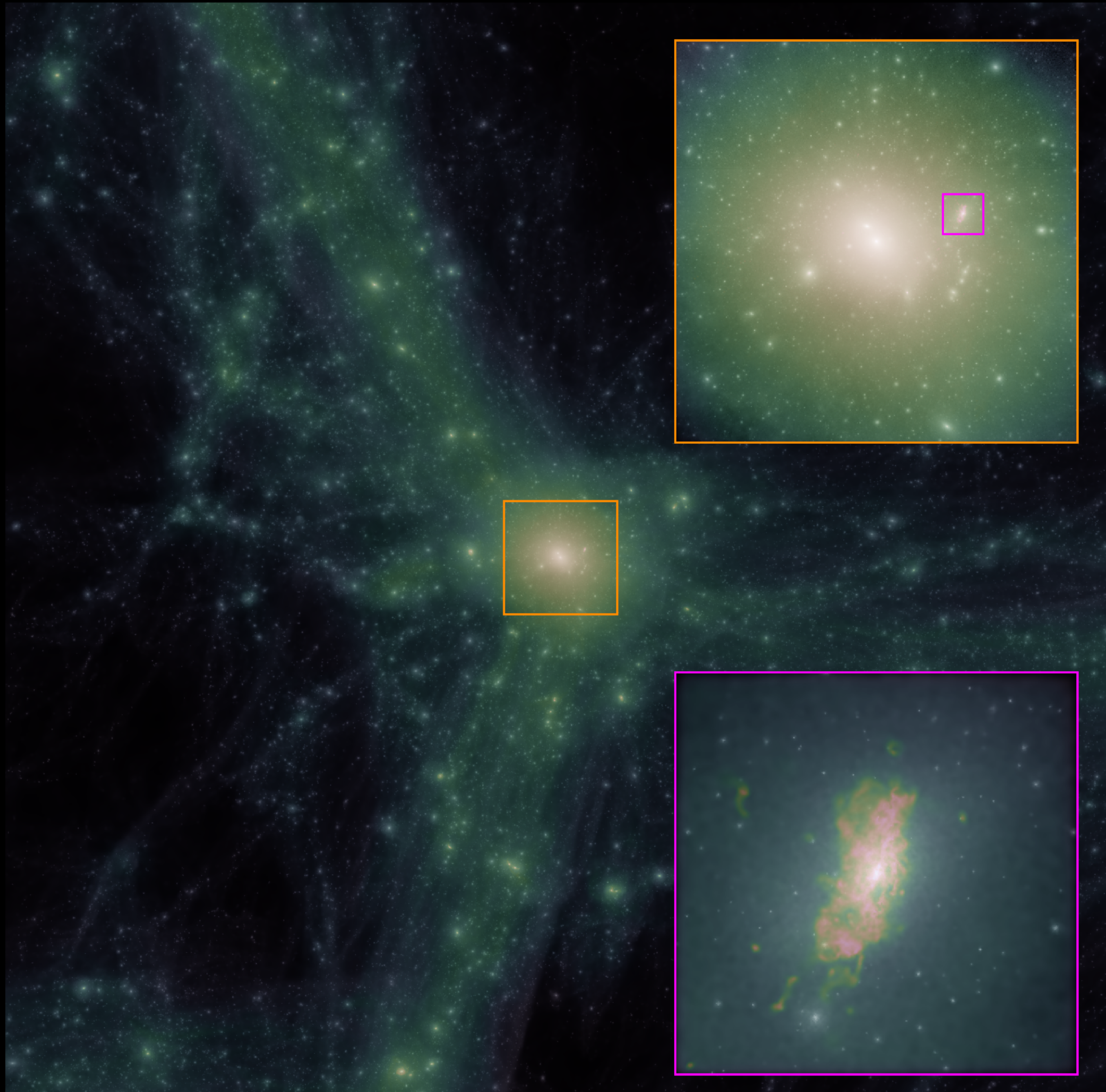
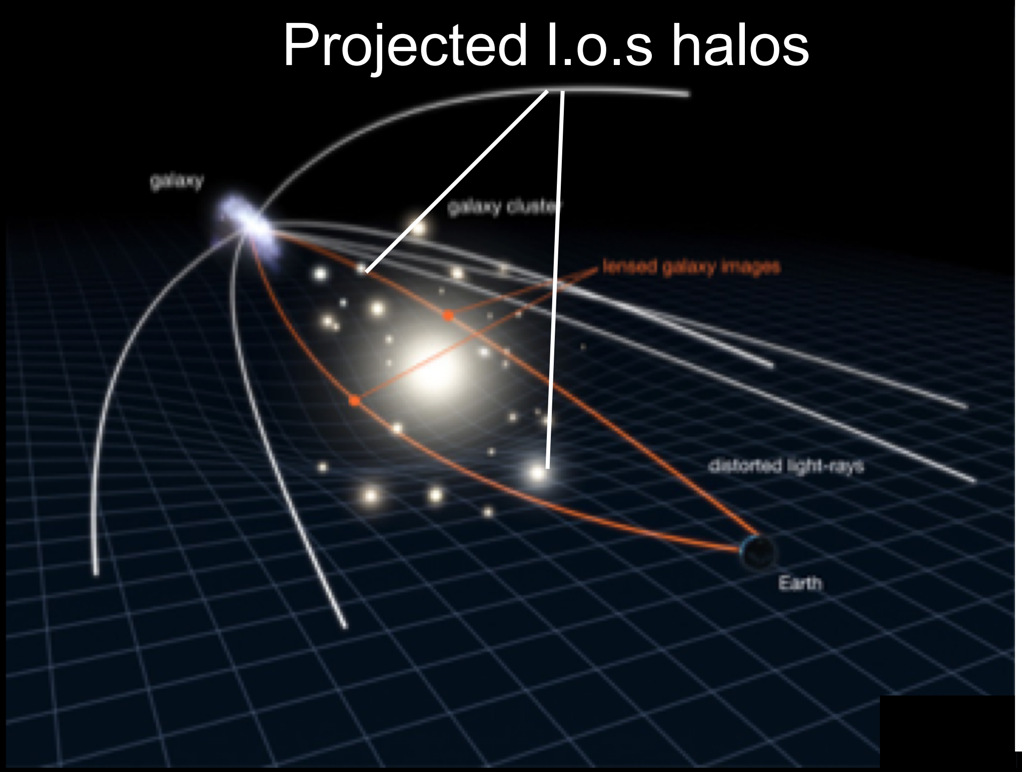
A high res. simulation of a CDM galaxy cluster

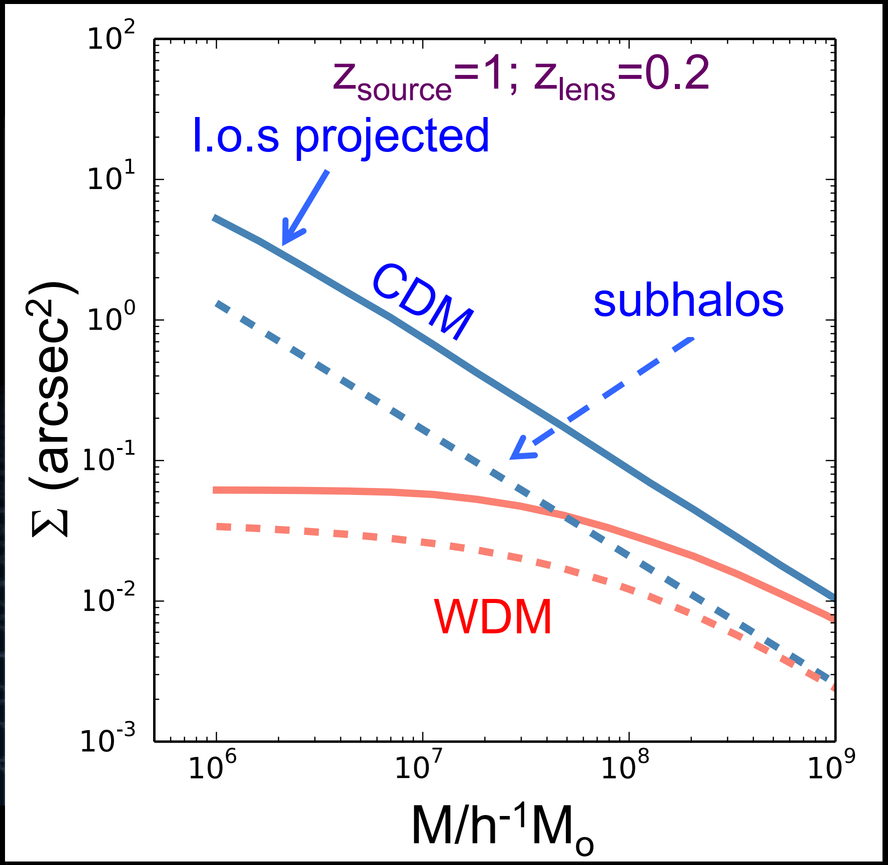


Richings, CSF + ‘19

Substructures vs interlopers

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



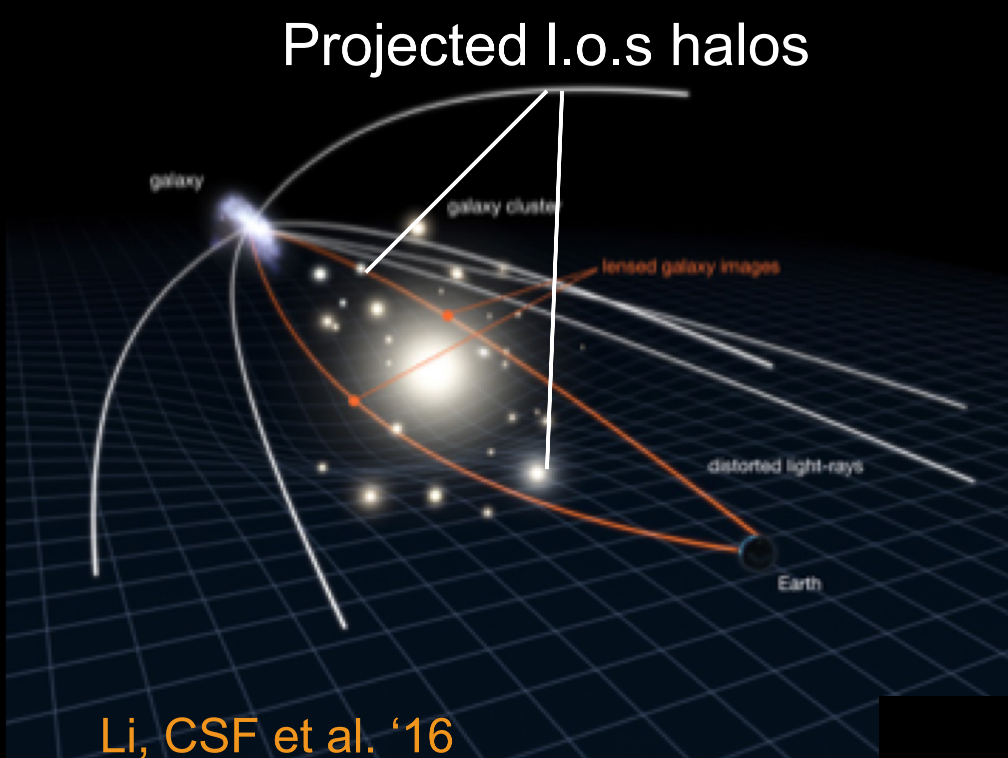


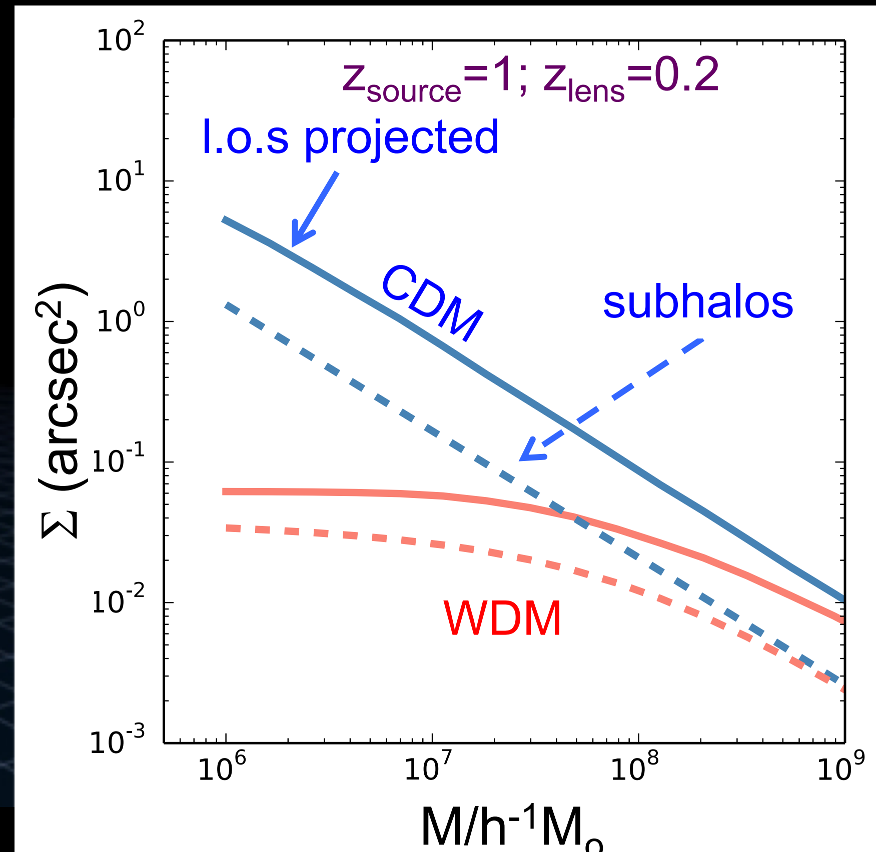
The number of line-of-sight haloes is larger than that of subhaloes

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

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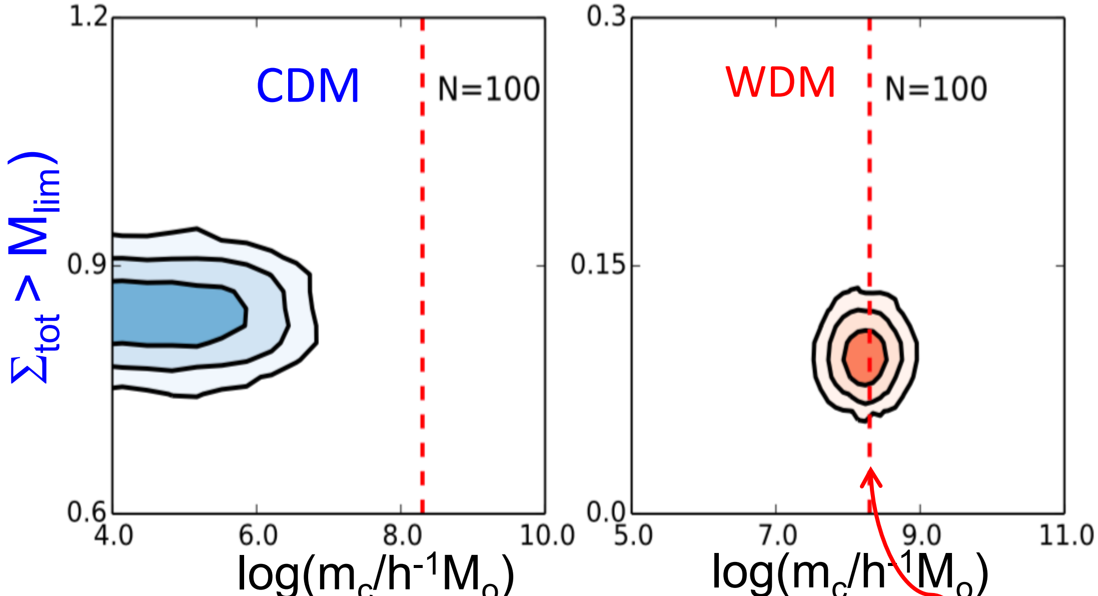
Detecting substructures with strong lensing

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

m_c= halo cutoff mass

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

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

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Conclusions

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

1. 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!