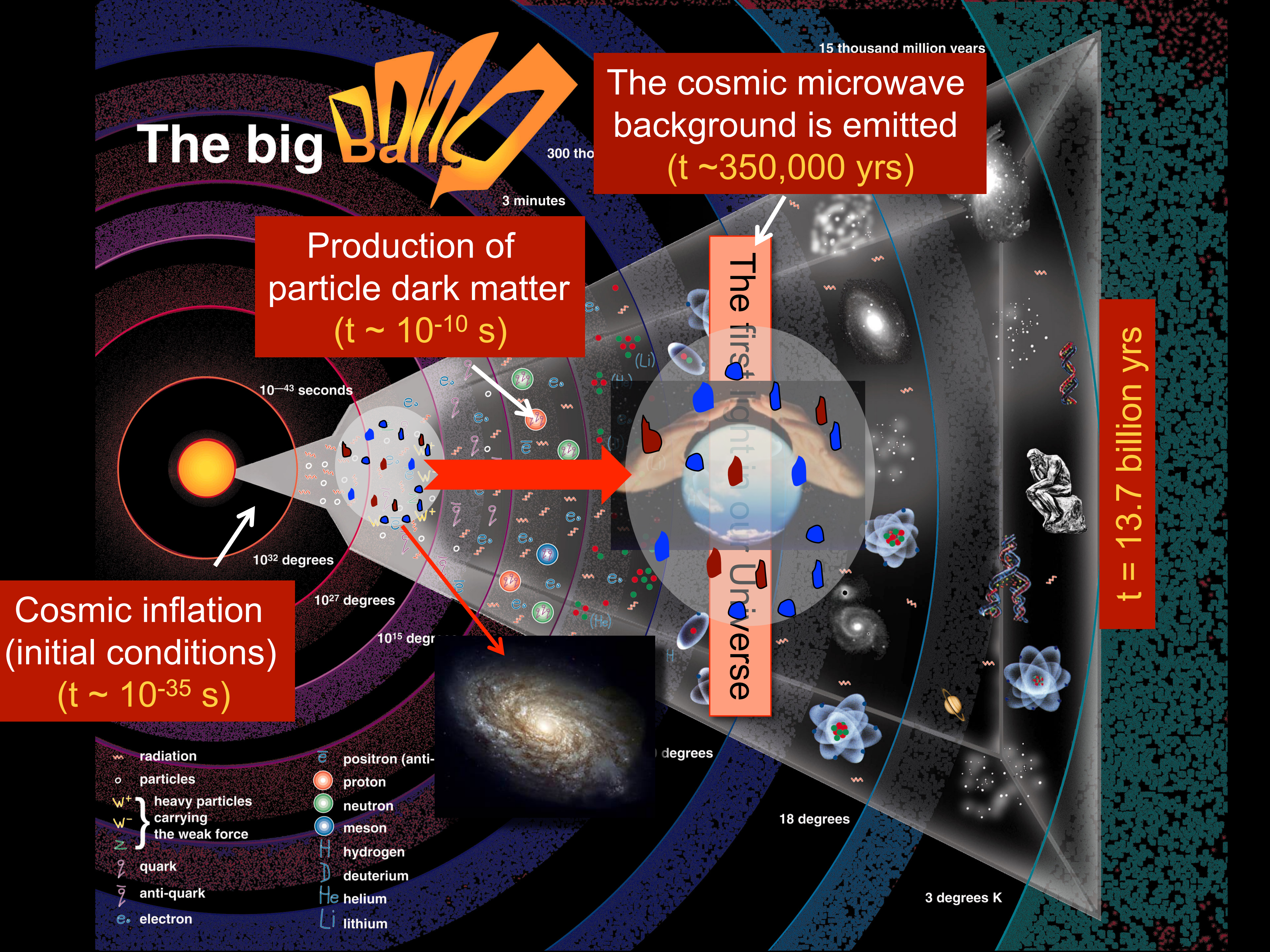
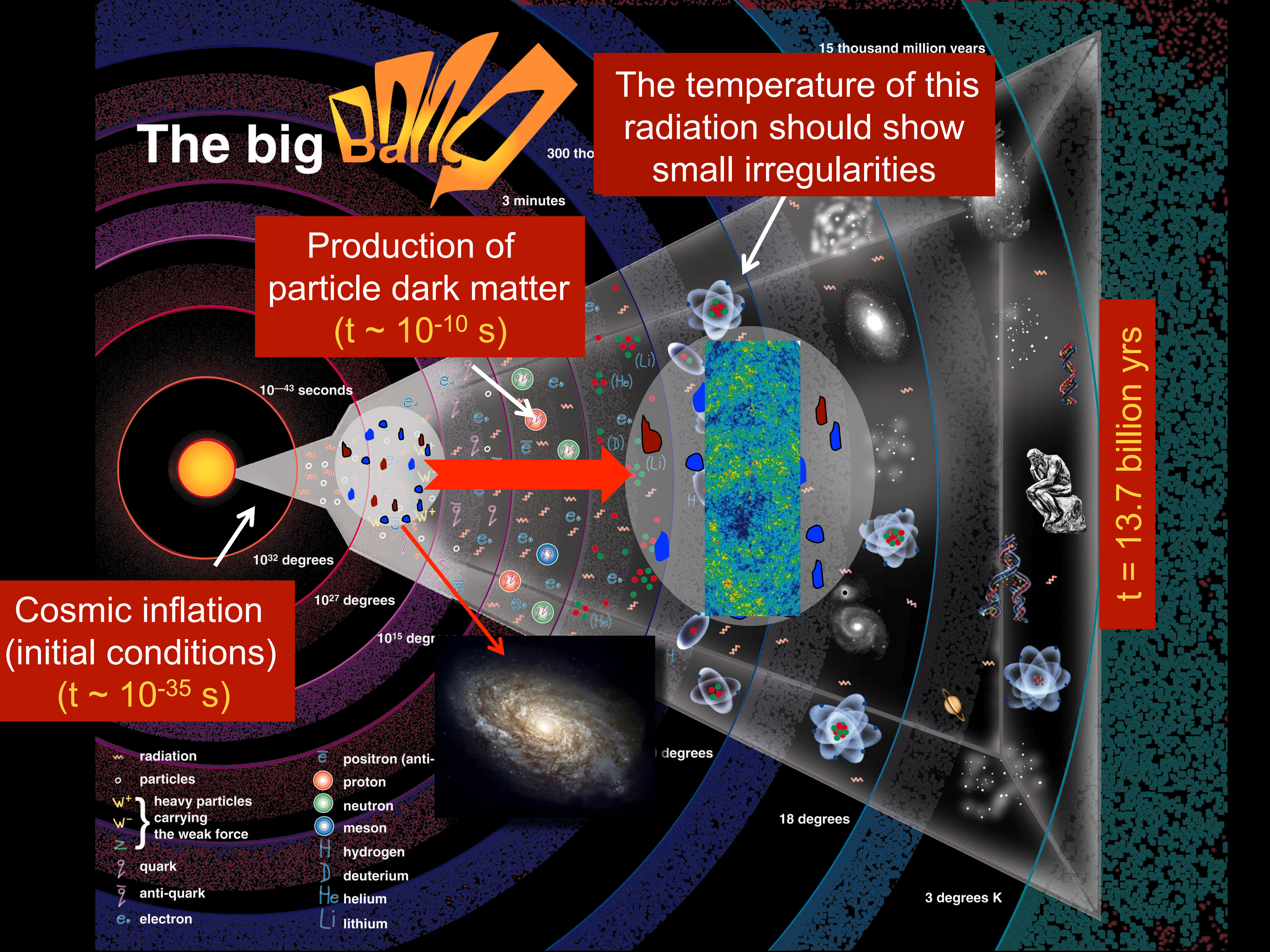
The status of cold dark matter

Carlos S. Frenk
Institute for Computational Cosmology, Durham

... and how to rule it out



The big Bang
15 thousand million years
The cosmic microwave background is emitted
(t ~350,000 yrs)
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
Cosmic inflation (initial conditions)
(t ~ 10^{-35} s)
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
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
300 tho
3 minutes
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degr
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helium
lithium

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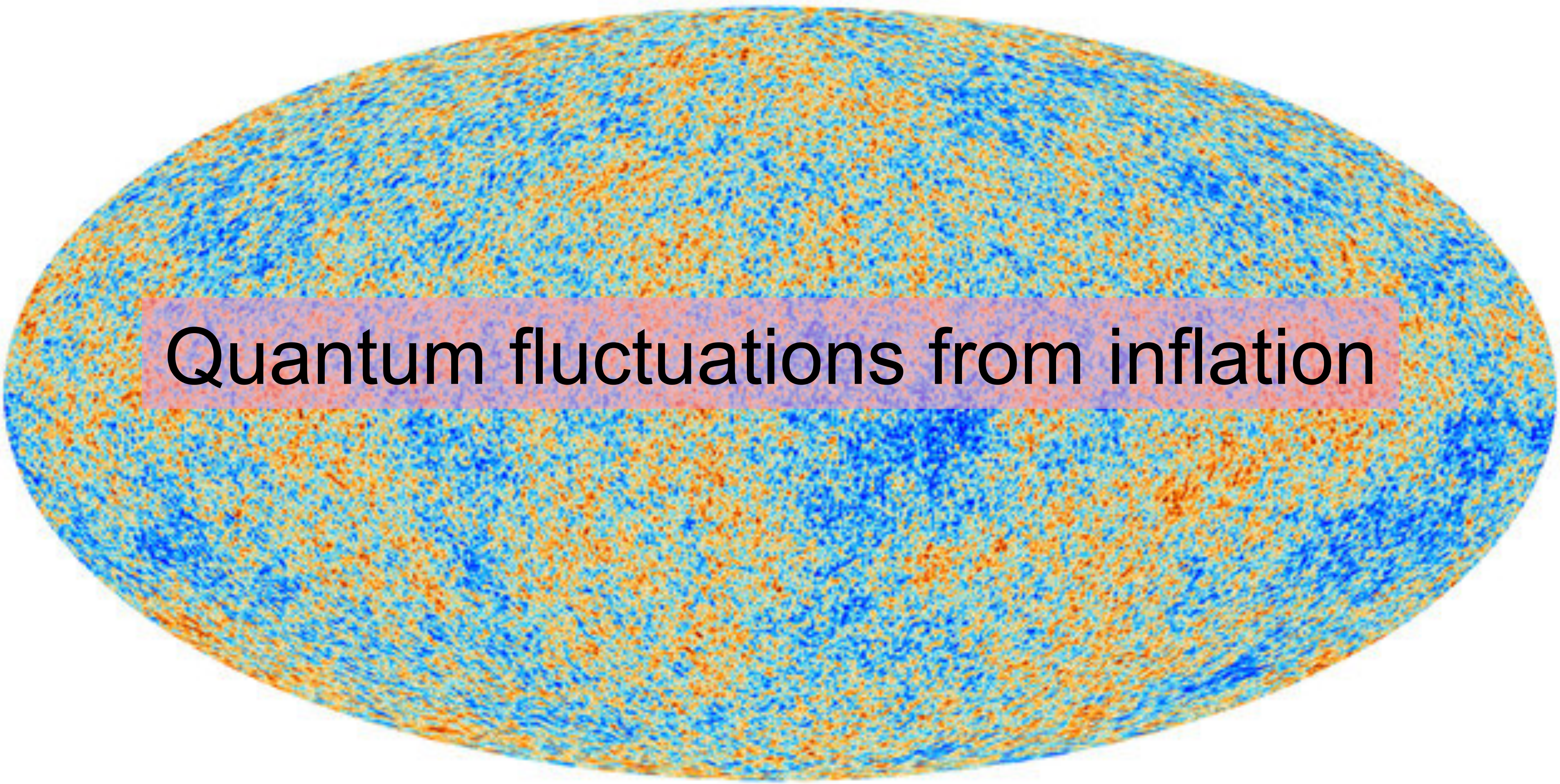
The initial conditions for galaxy formation



Planck collaboration ‘13

Temperature anisotropies in CMB

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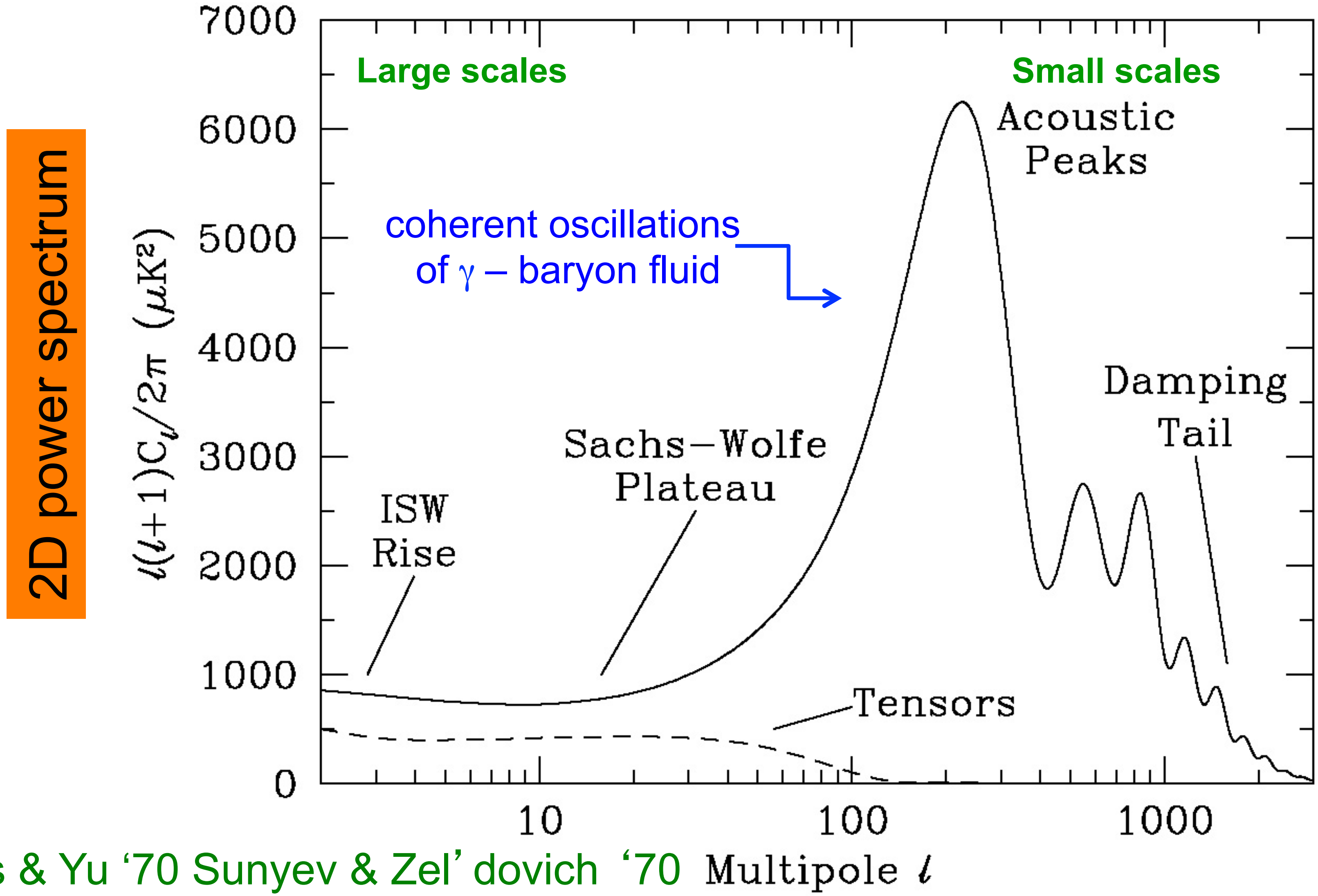

Peebles & Yu '70 Sunyev & Zel'dovich '70

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

Planck: CMB temperature anisotropies

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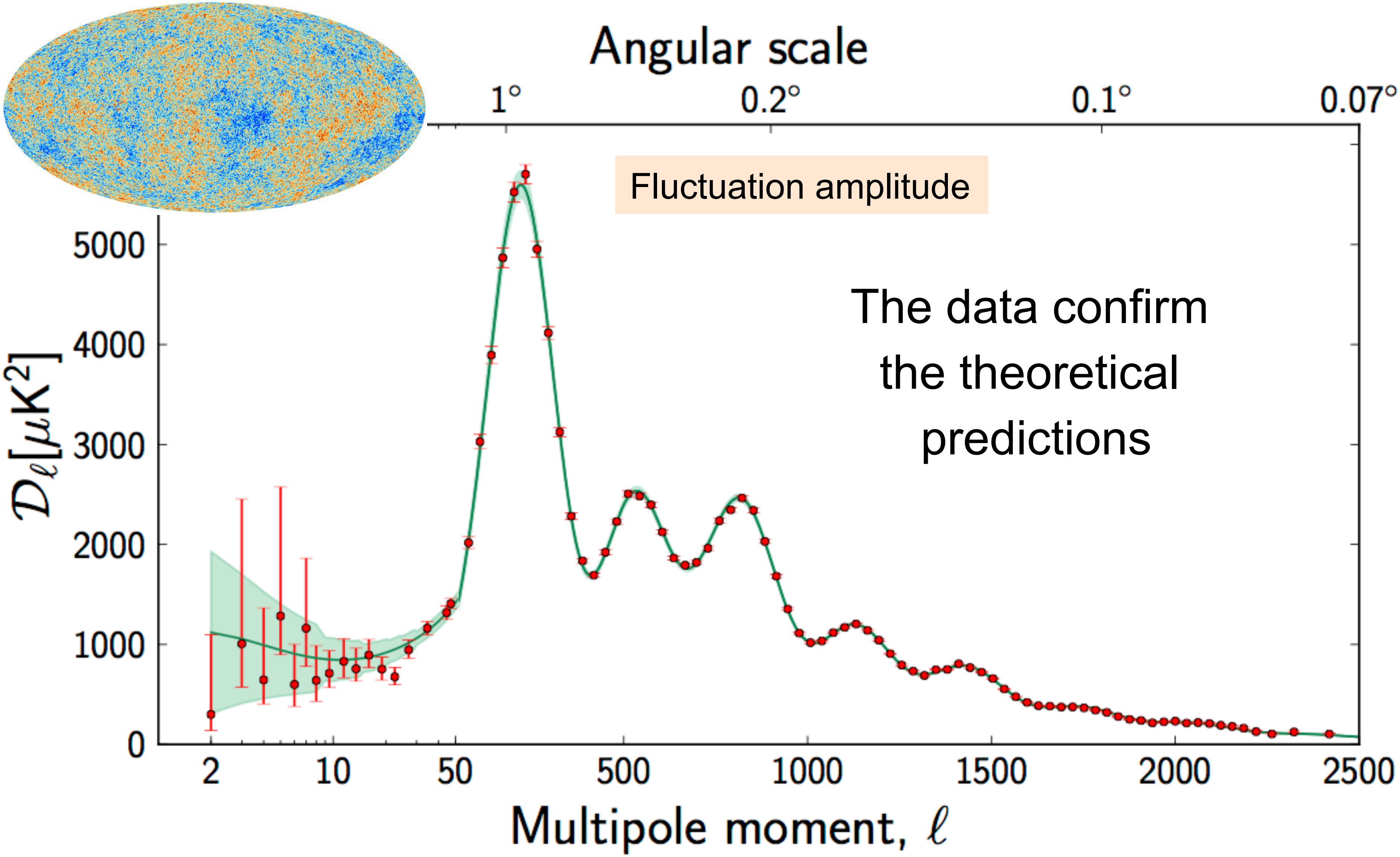

Planck coll. 2015

Institute for Computational Cosmology

The six parameters of minimal ΛCDM model

6 model parameters

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

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

Planck collaboration '13

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Non-baryonic dark matter candidates

From the 1980s:

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

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The dark matter power spectrum

Free streaming →

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

for thermal relic

$m_{CDM} \sim 100GeV$

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

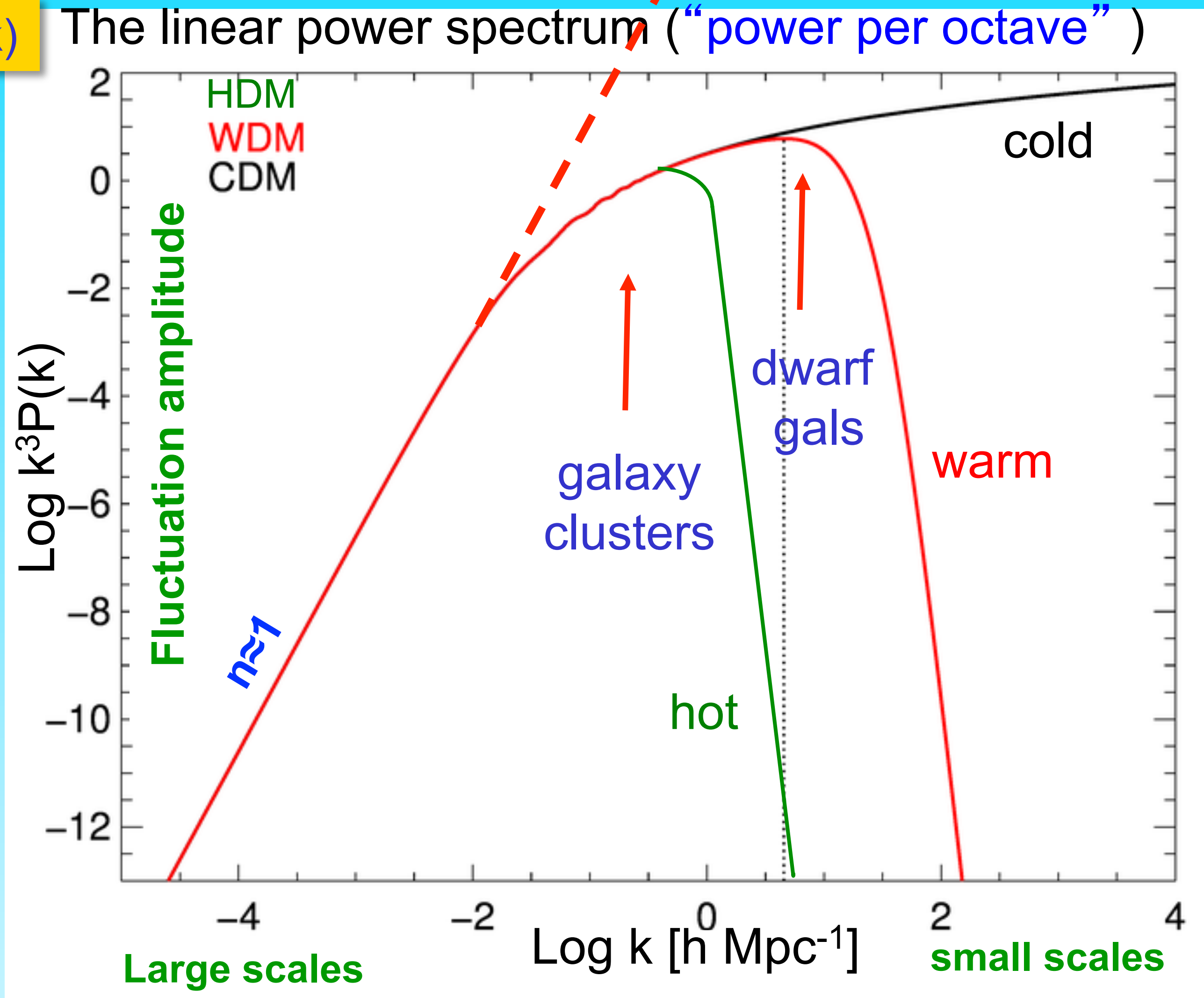
$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$

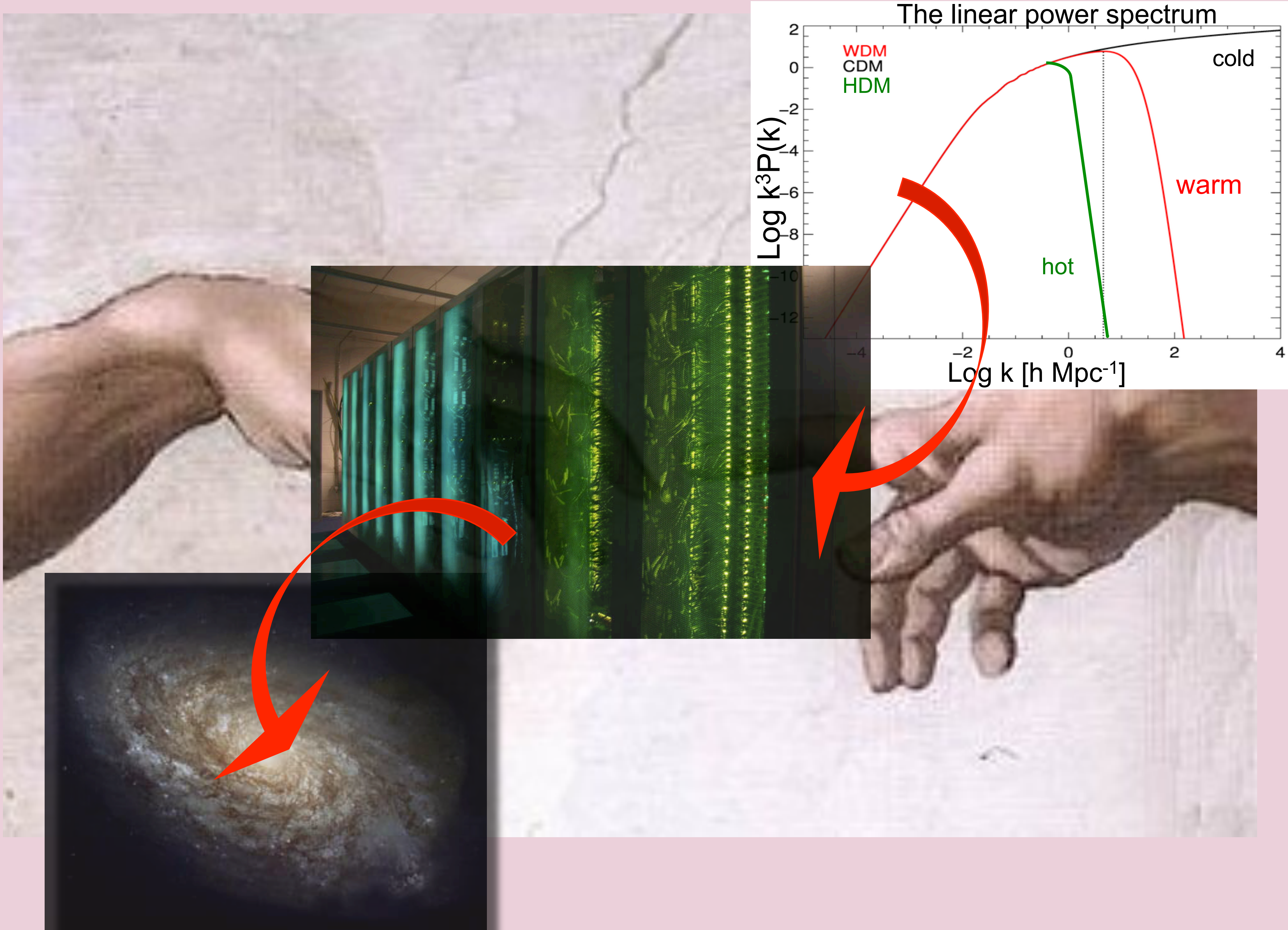
$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15}\ M_o$

$k^3\ P(k)$



Non-linear evolution



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Non-linear evolution: simulations

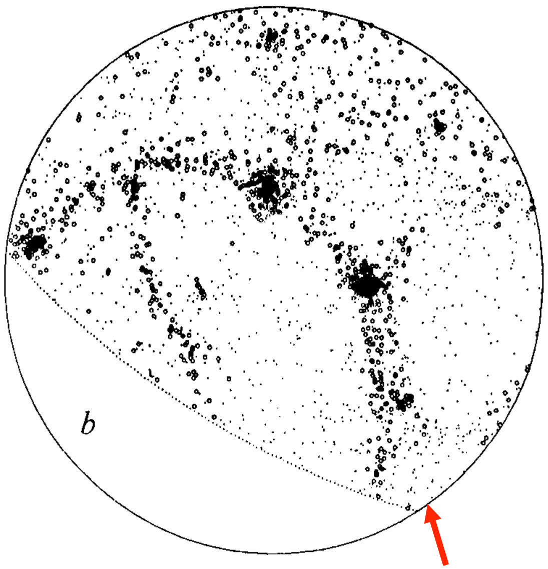
Initial conditions + assumption about content of Universe

Relevant equations:

Collisionless Boltzmann,
Poisson, Friedmann eqn,
Radiative hydrodynamics
Astrophysics (subgrid)

How to make a virtual universe

Non-baryonic dark matter cosmologies



Frenk, White & Davis '83

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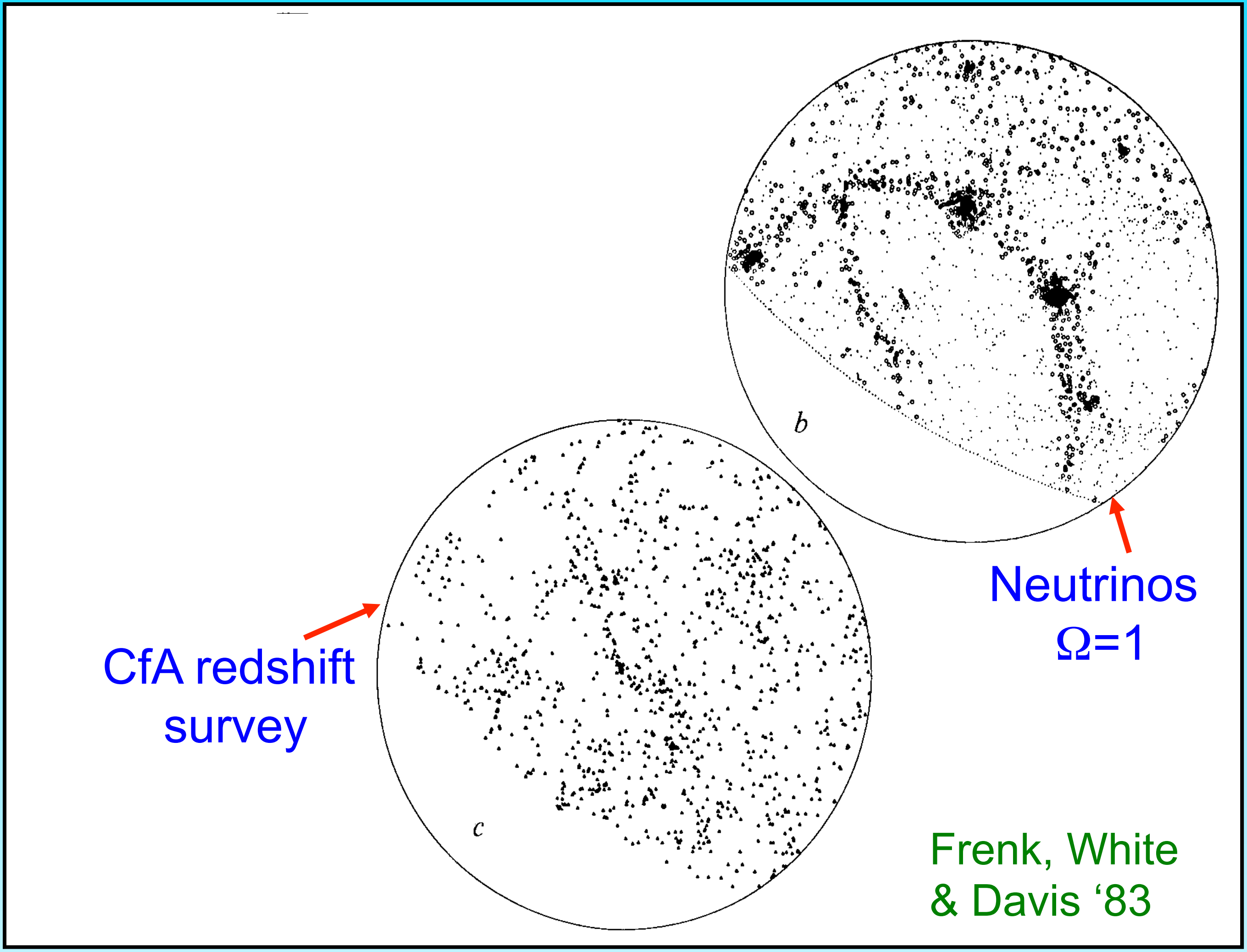
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_ν << 30 ev



Non-baryonic dark matter cosmologies

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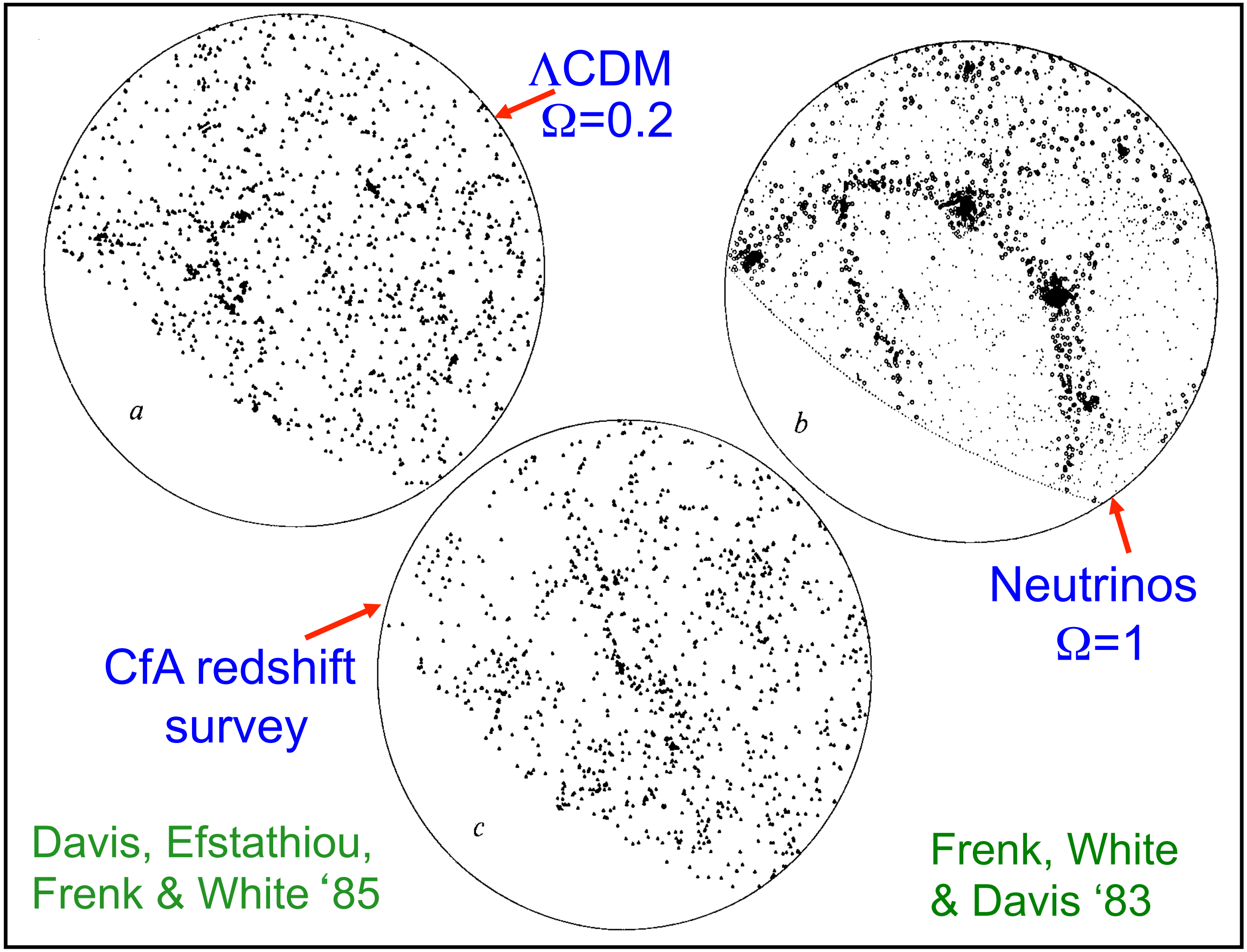
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_{ν}<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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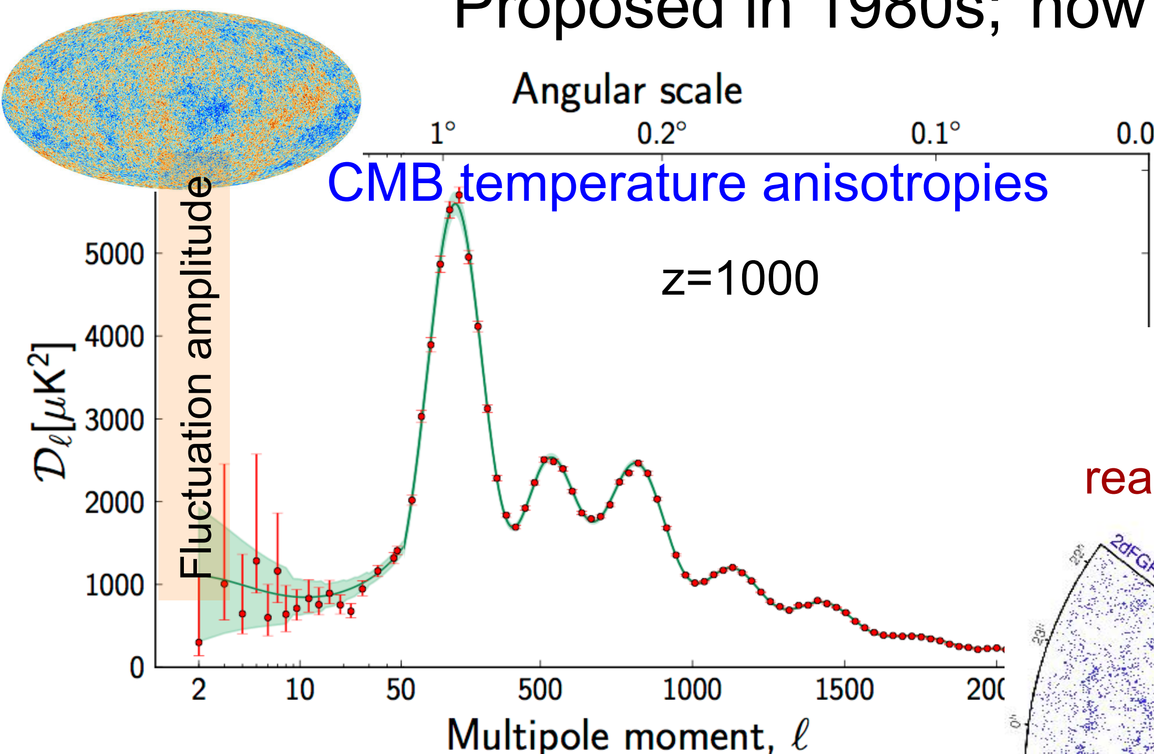
The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:

CMB temperature anisotropies

z=1000



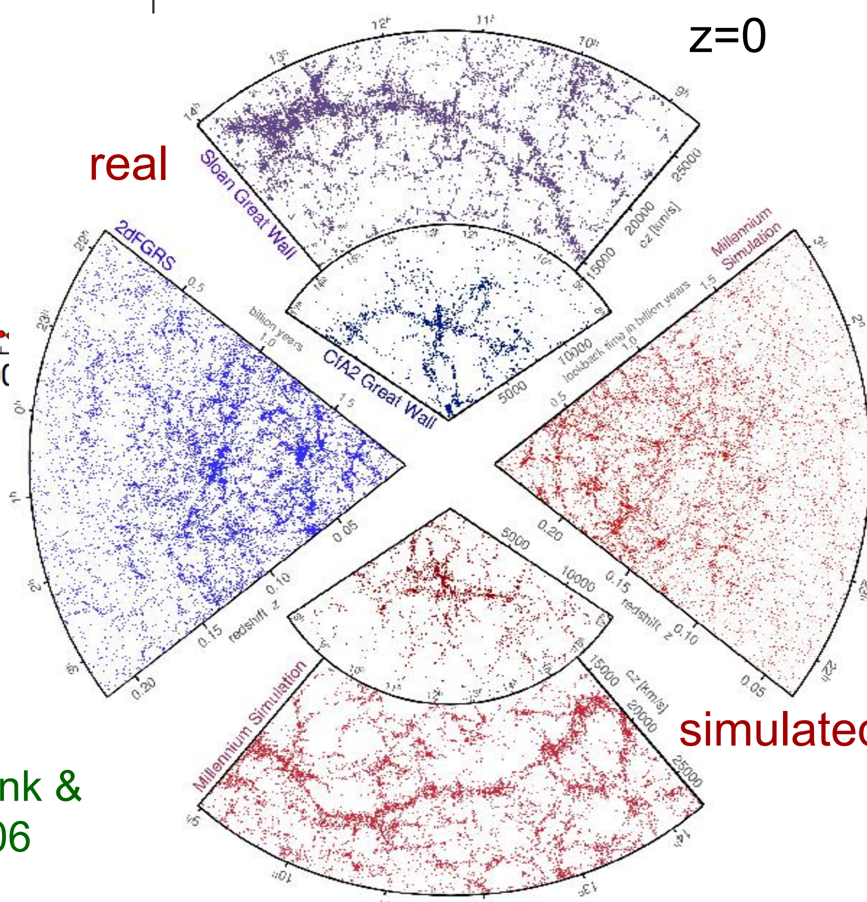
Planck coll. 2015

Galaxy clustering

z=0

real

simulated



Springel, Frenk & White 2006

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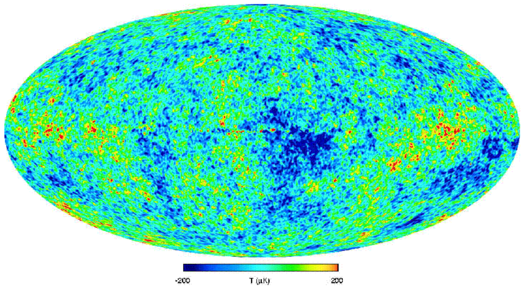
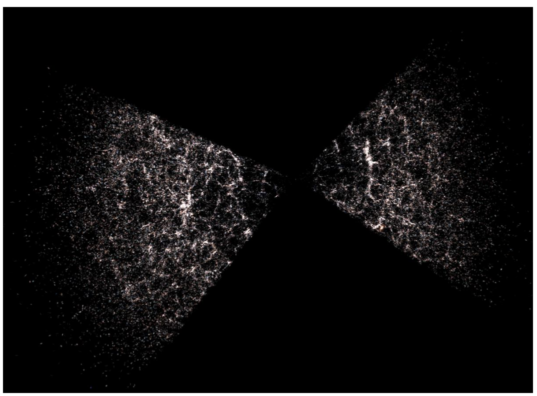
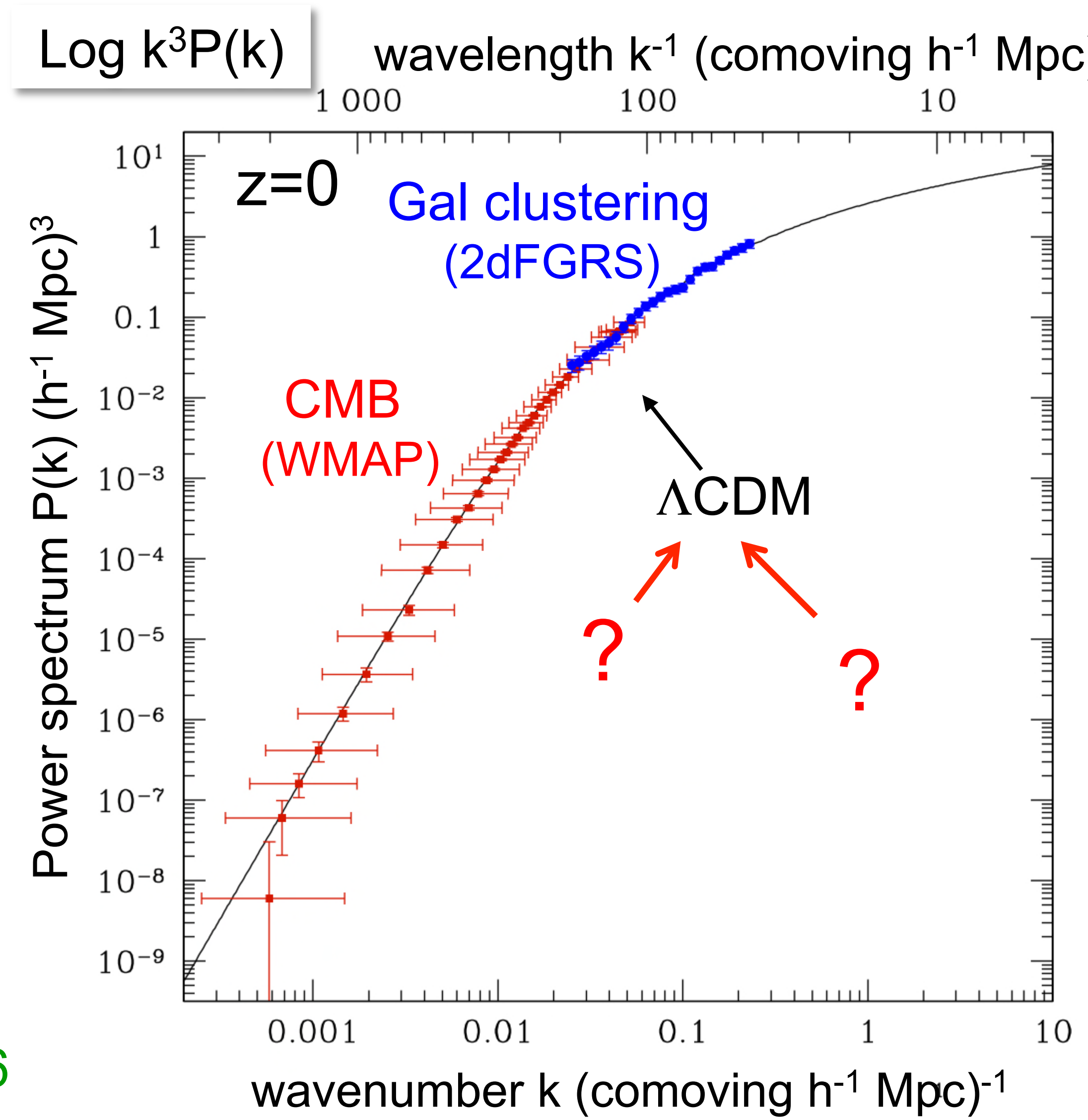
The cosmic power spectrum: from the CMB to the 2dFGRS



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 →

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

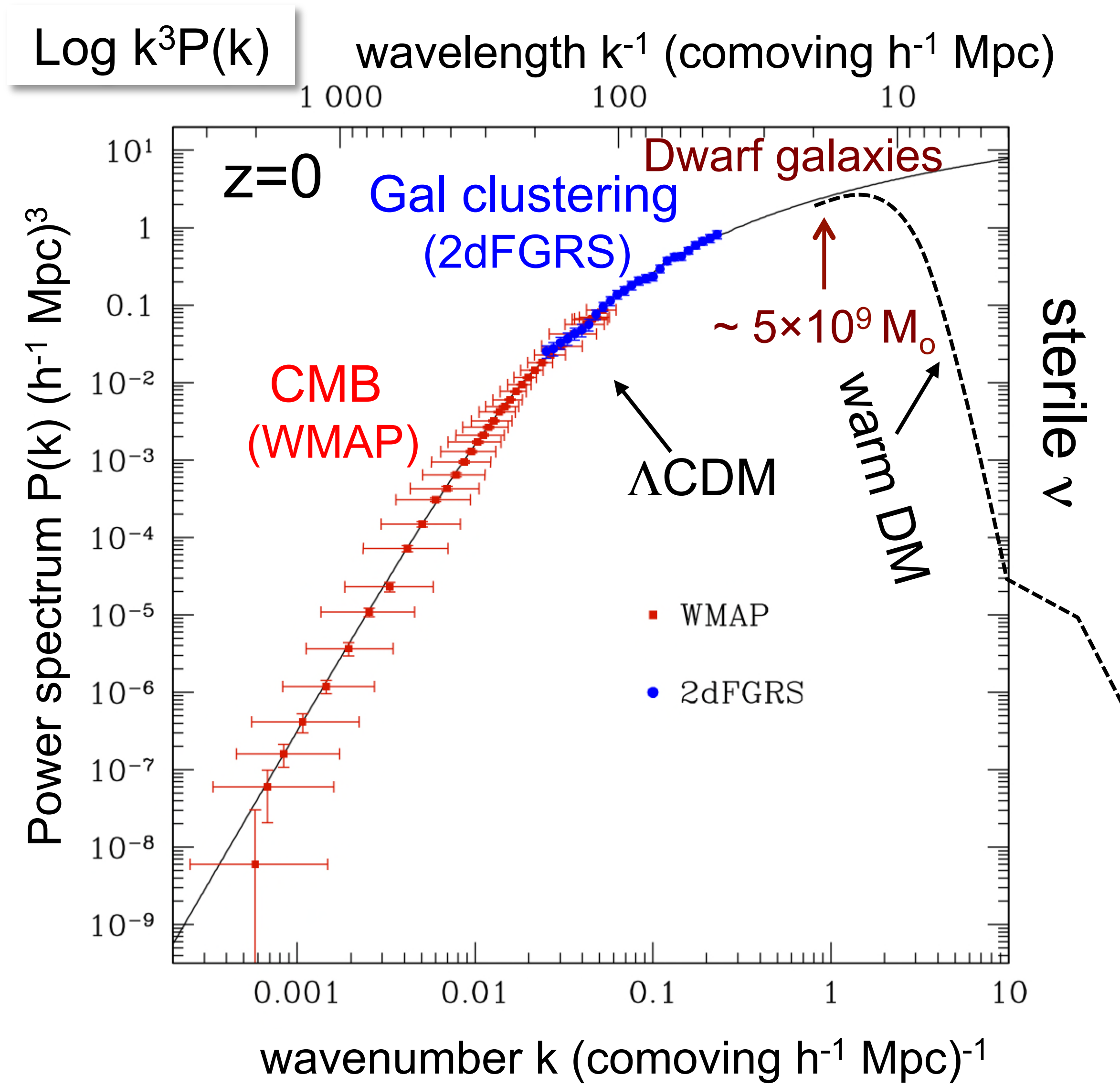
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$



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Four problems on small scales

Traditionally ascribed to CDM:

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

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Sterile neutrinos

Explain:

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

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

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

Very unlikely that both are right!

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

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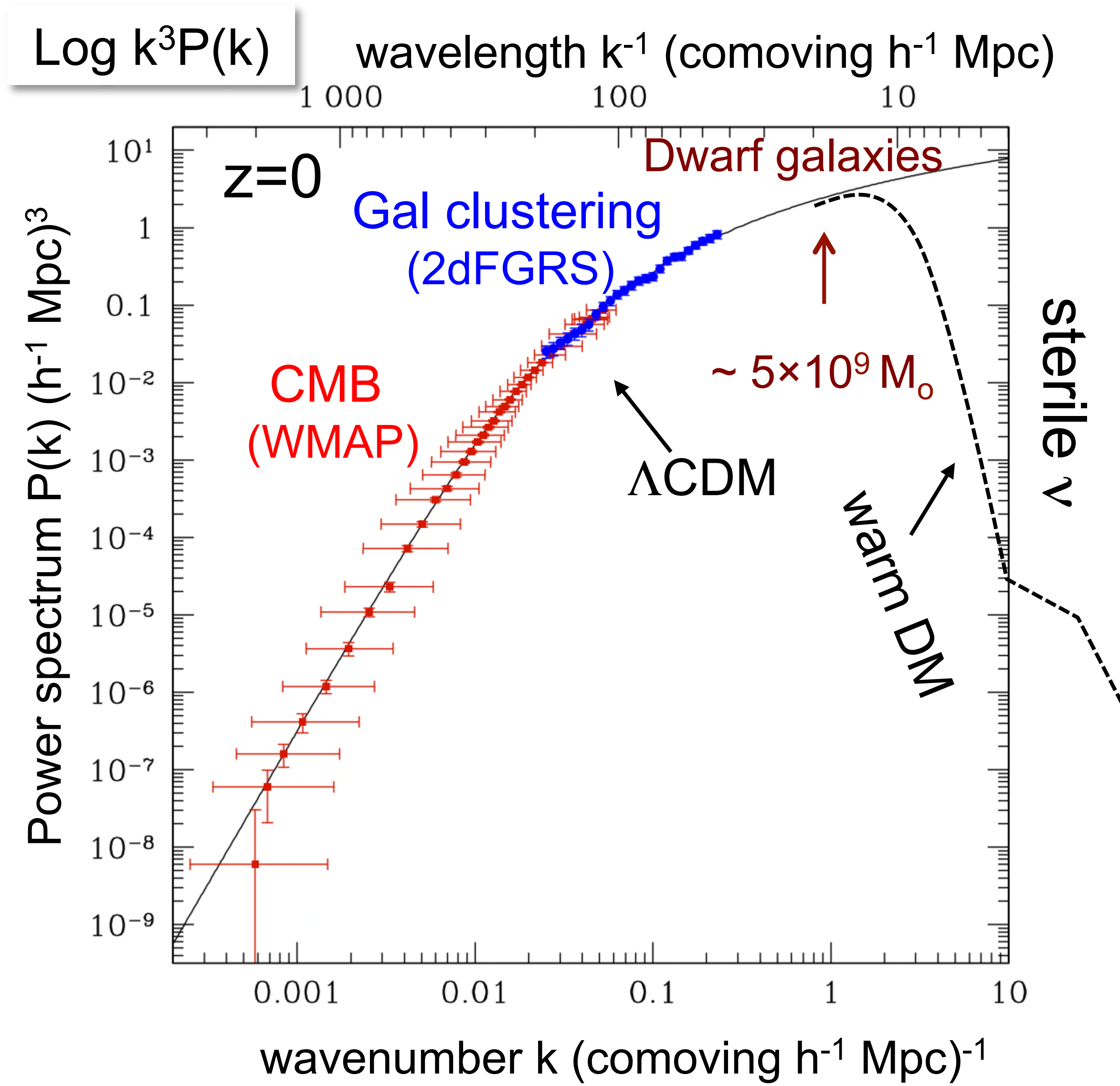

The identity of the dark matter is encoded in dwarf galaxies and in the halo of the MW

(strongly non-linear regime)

Cold Dark Matter Warm Dark Matter

13.4 billion years ago

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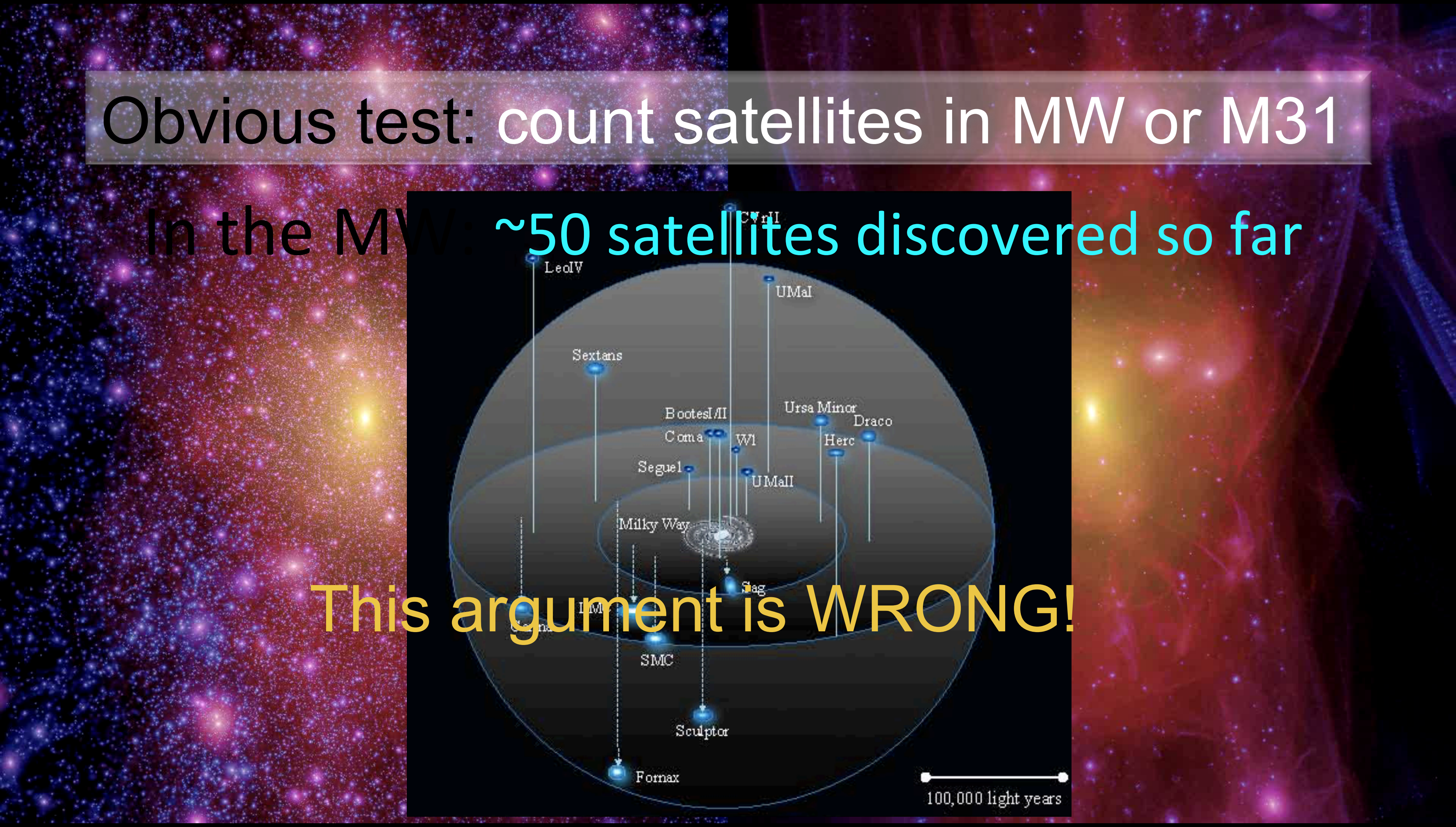
cold dark matter warm dark matter

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: ~50 satellites discovered so far

This argument is WRONG!

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

Most subhalos never make a galaxy!

Because:

- Reionization heats gas to 10^4K, preventing it from cooling and forming stars in small halos ($T_{vir} < 10^4$K)
- Supernovae feedback expels residual gas in slightly larger halos

Luminosity Function of Local Group Satellites

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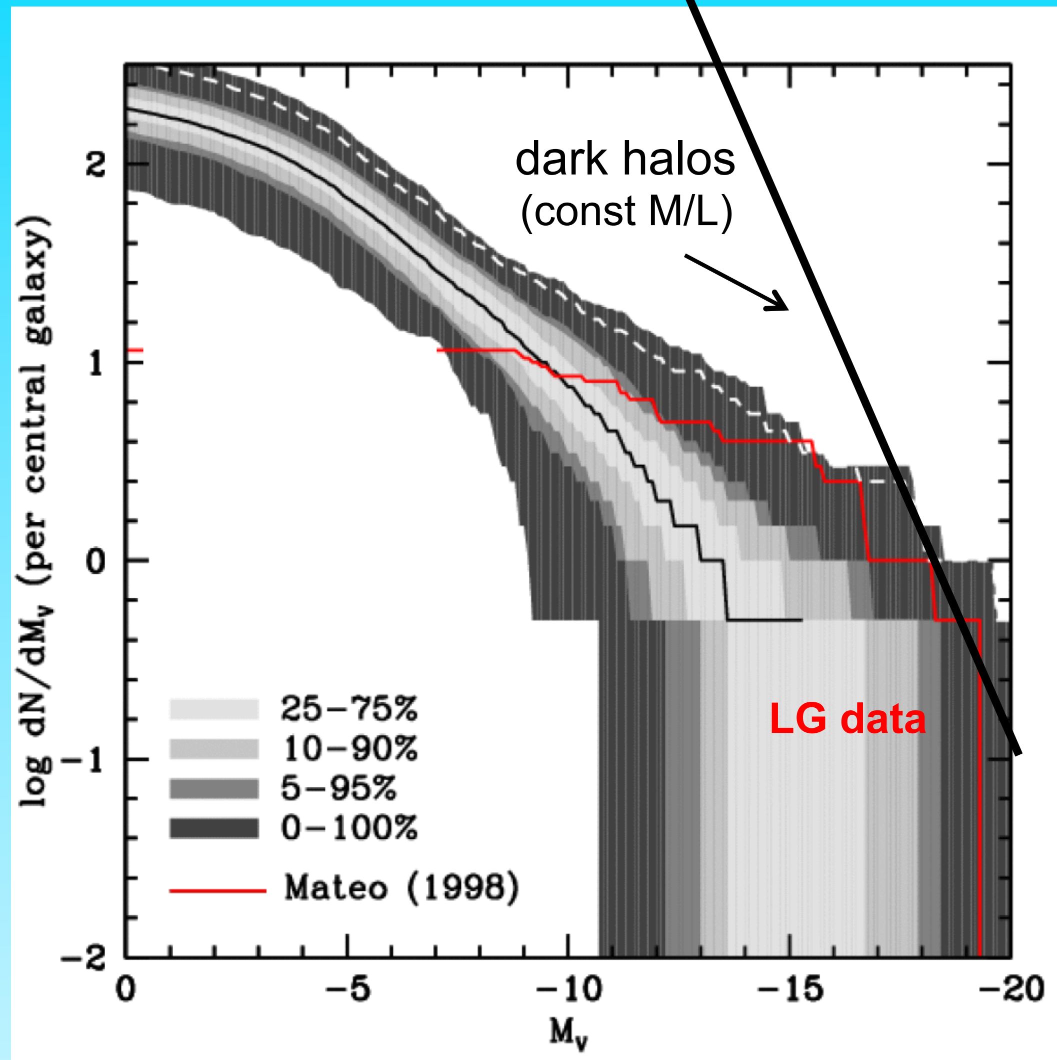
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~10% of cases)



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

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Luminosity Function of Local Group Satellites

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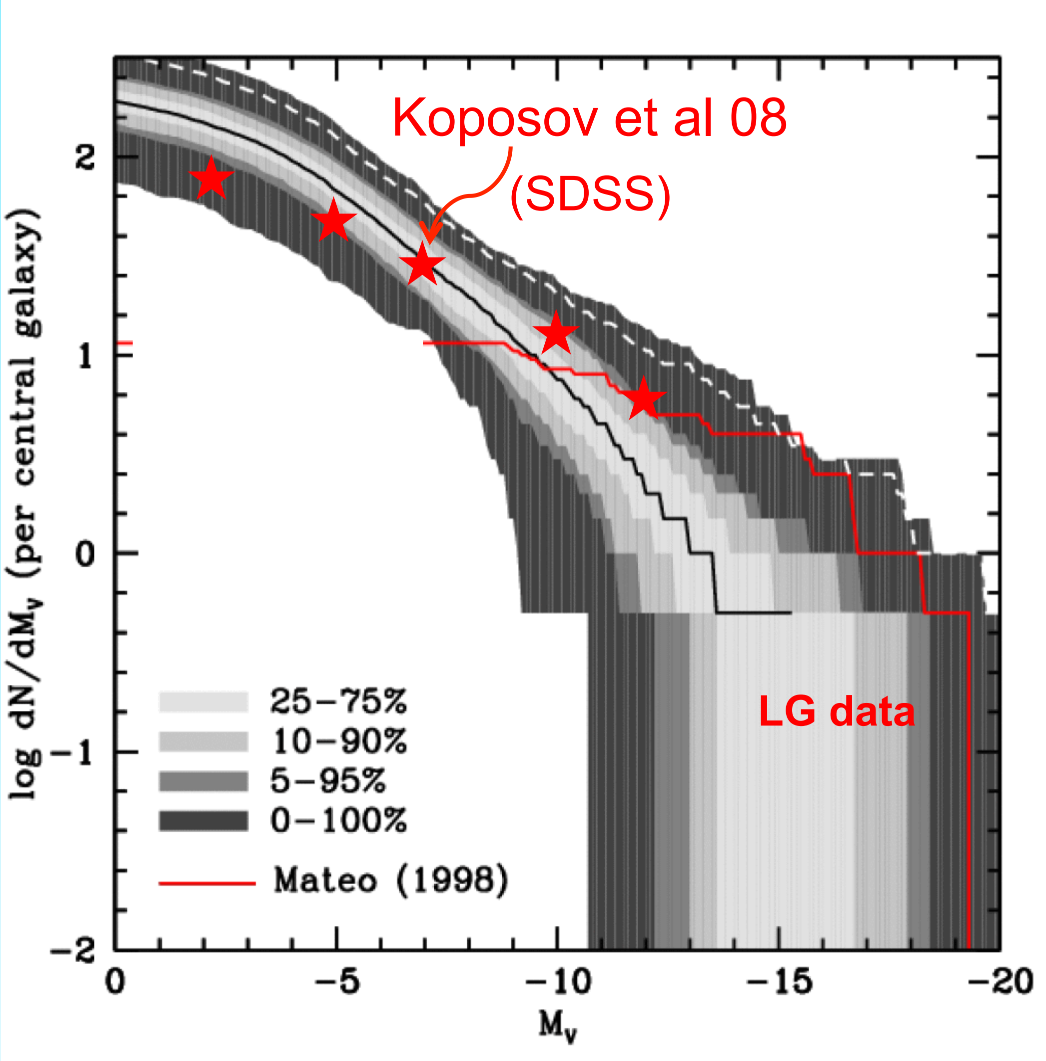


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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…

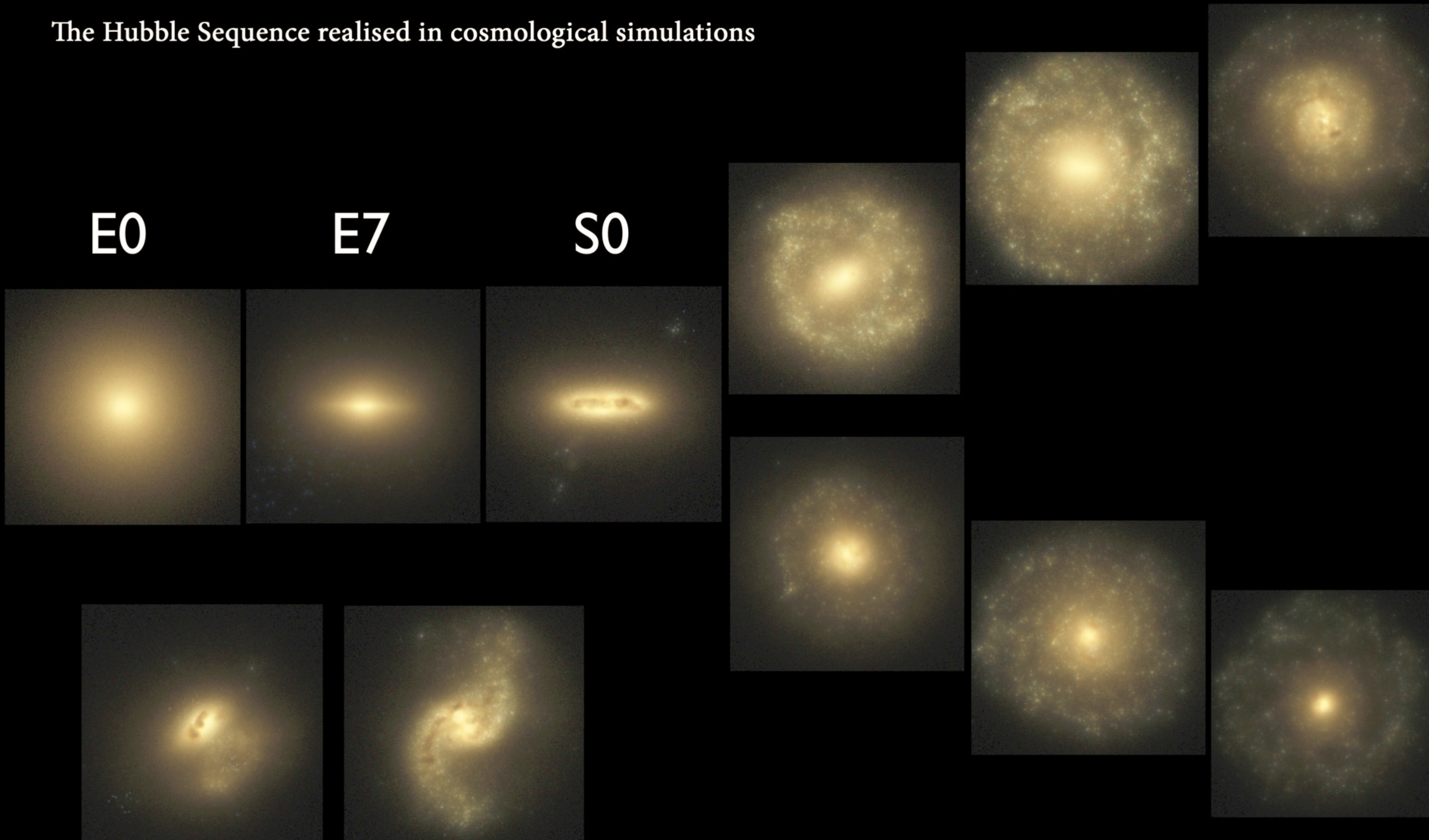
Durham University VIRGO ICC DiRAC PRACE

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

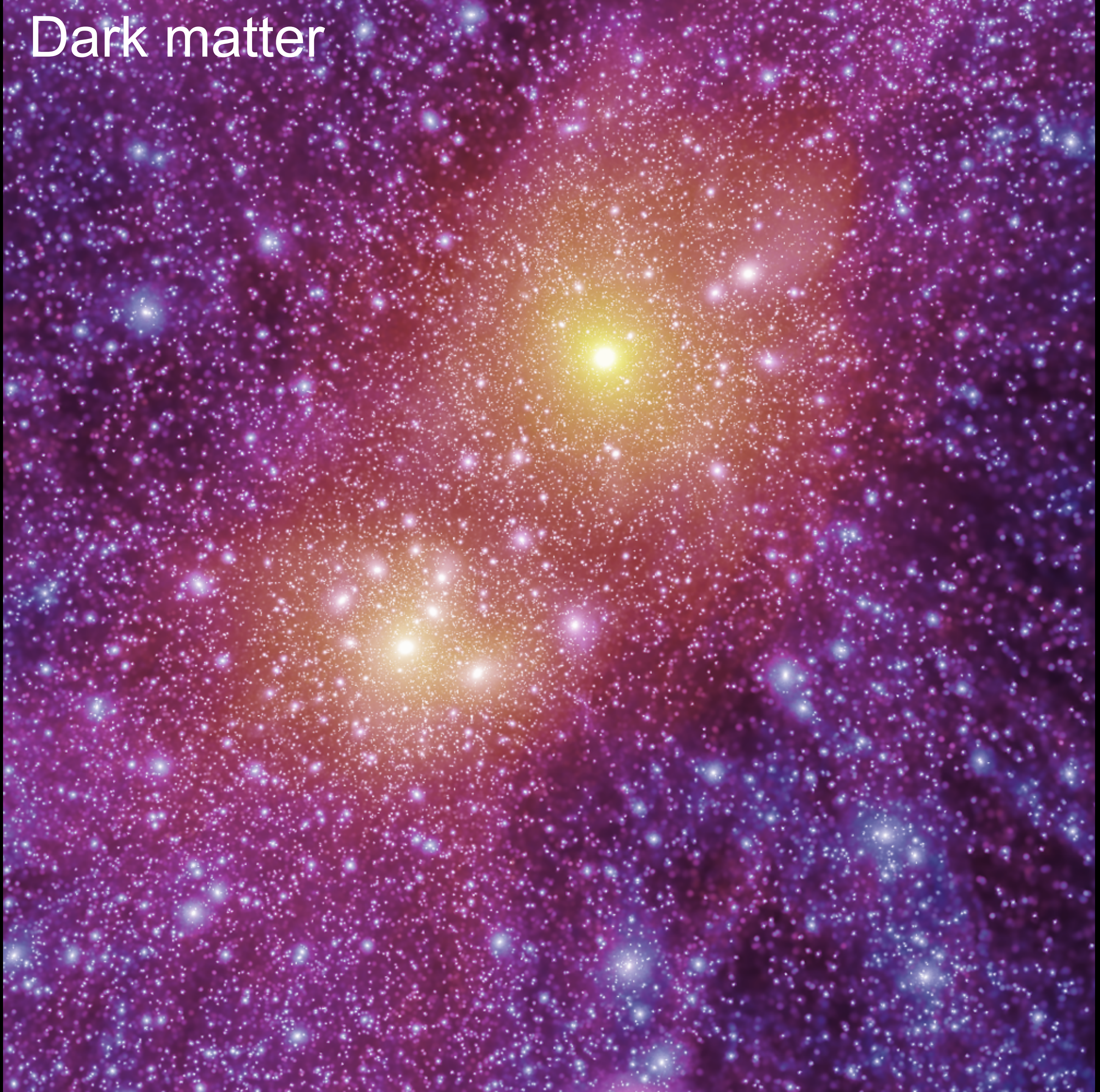


Trayford et al '15

APOSTLE EAGLE full hydro simulations

Local Group

CDM



Sawala et al '16

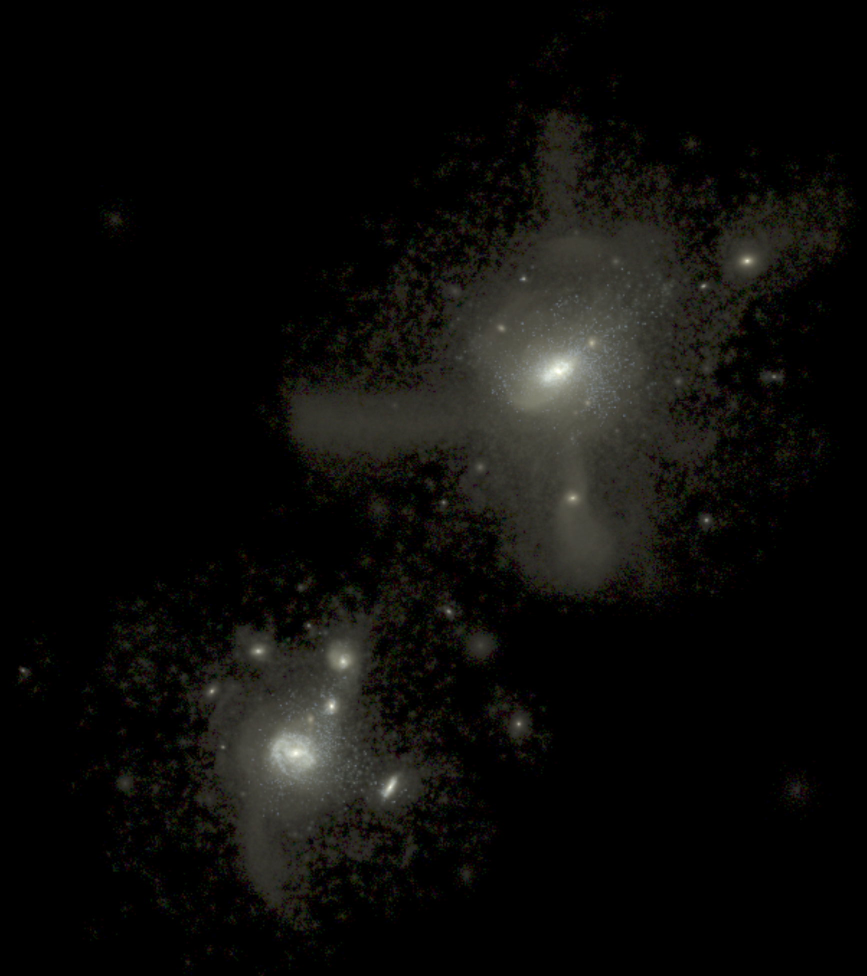
VIRGO

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

Stars



Far fewer satellite galaxies than CDM halos

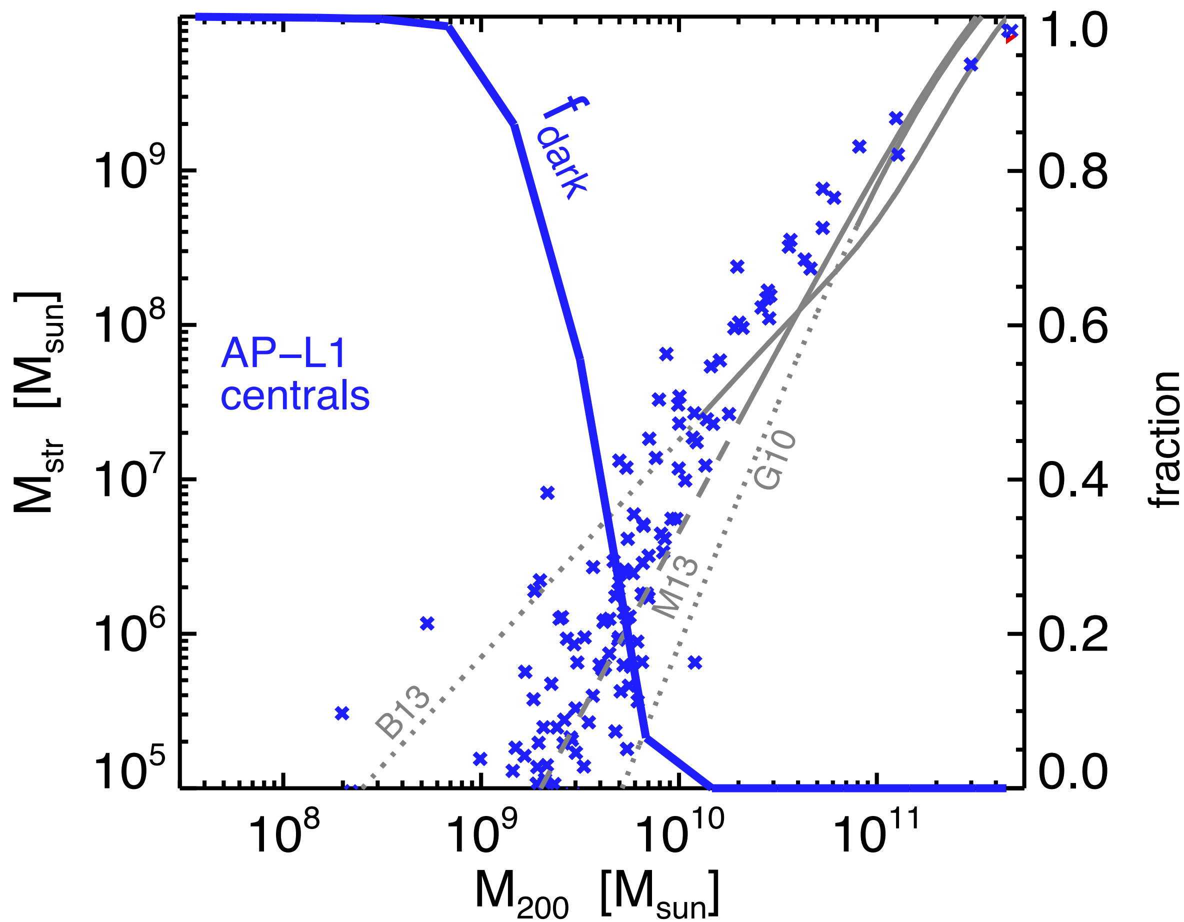
Sawala et al ‘16

University of Durham

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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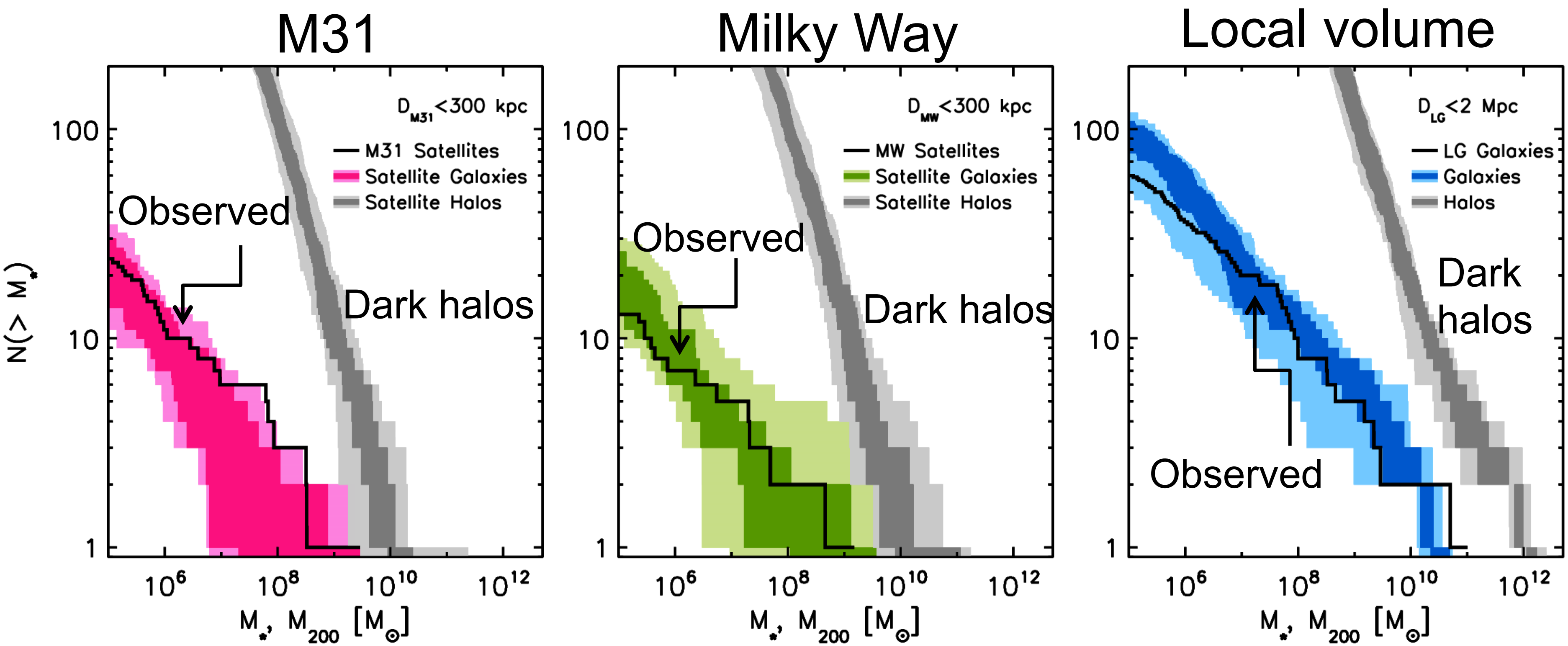
EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

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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!

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Four problems on small scales

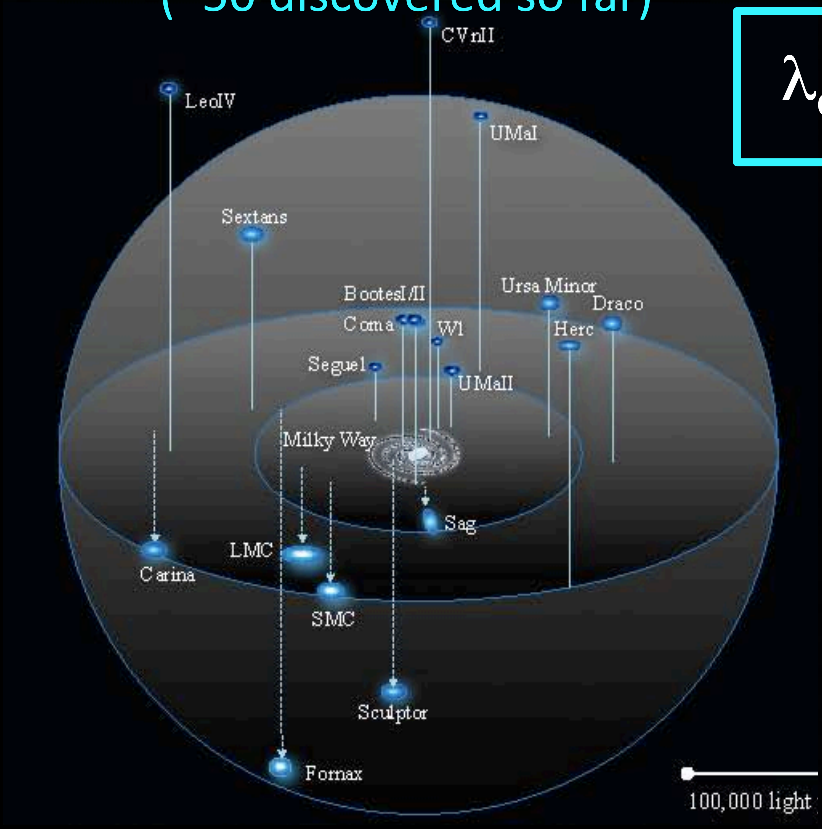
Traditionally ascribed to CDM:

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

How about in WDM?

The satellites of the MW

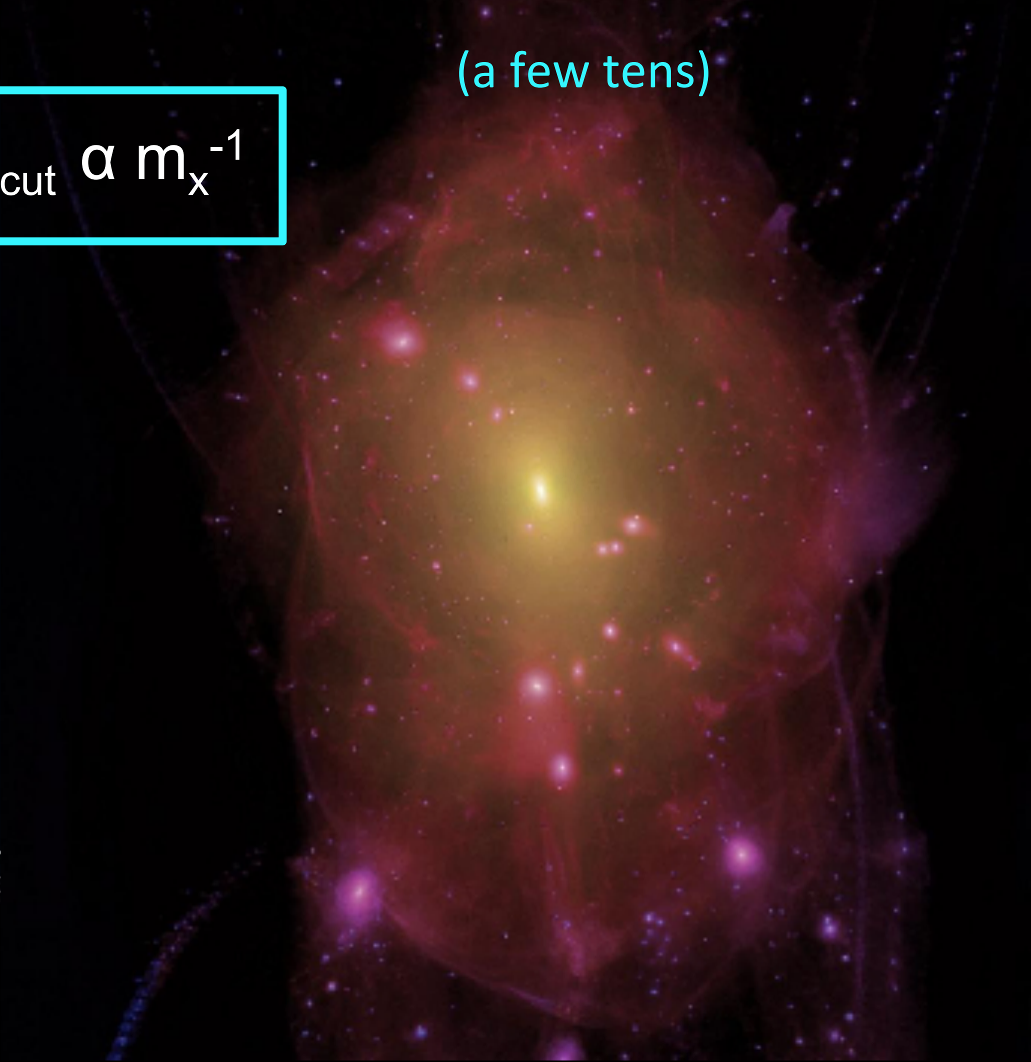
(~50 discovered so far)



λ_{cut} α m_x^{-1}

Dark matter subhalos in WDM

(a few tens)



Warm DM: different ν mass

z=3

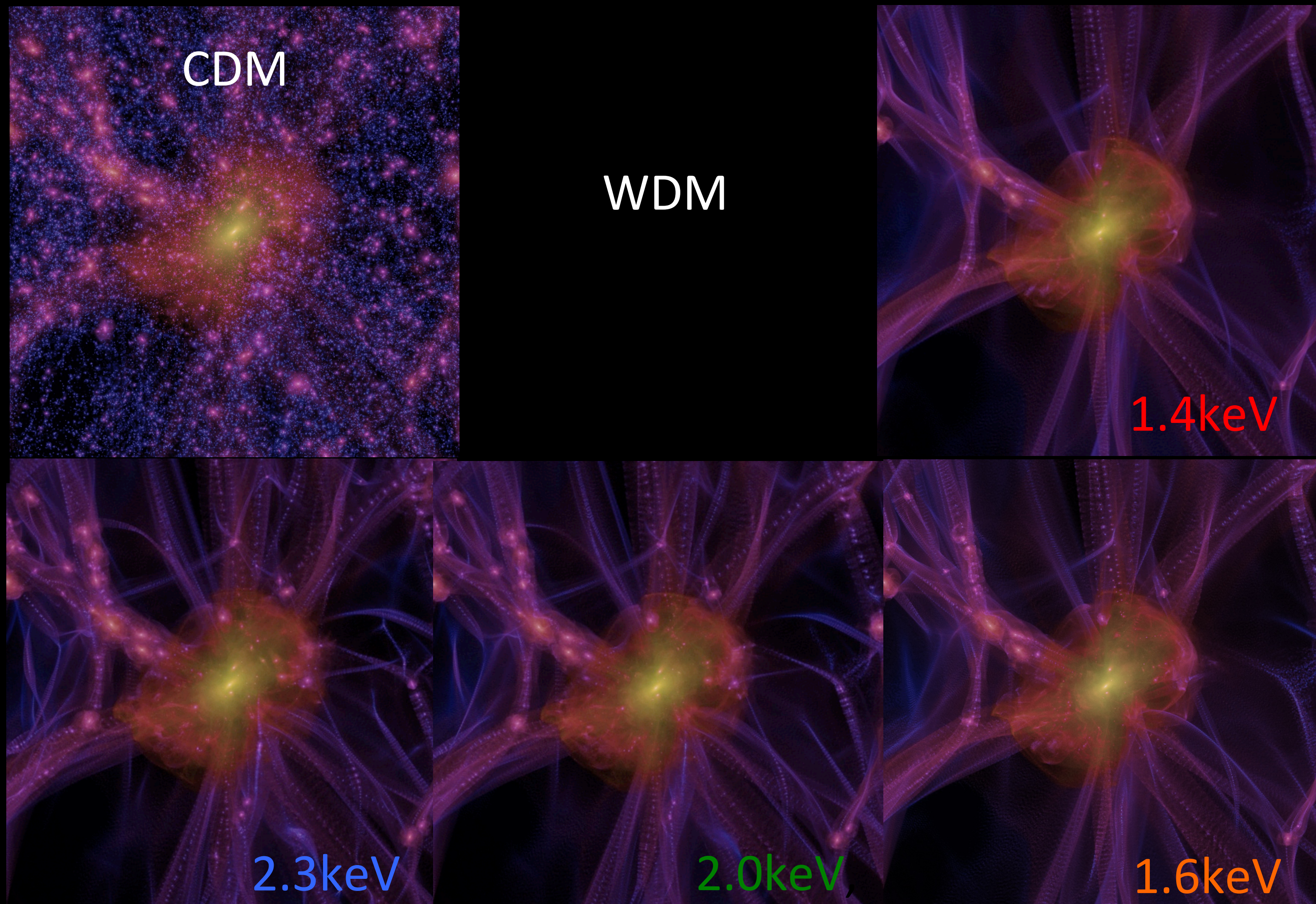
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



Luminosity Function of Local Group Satellites in WDM

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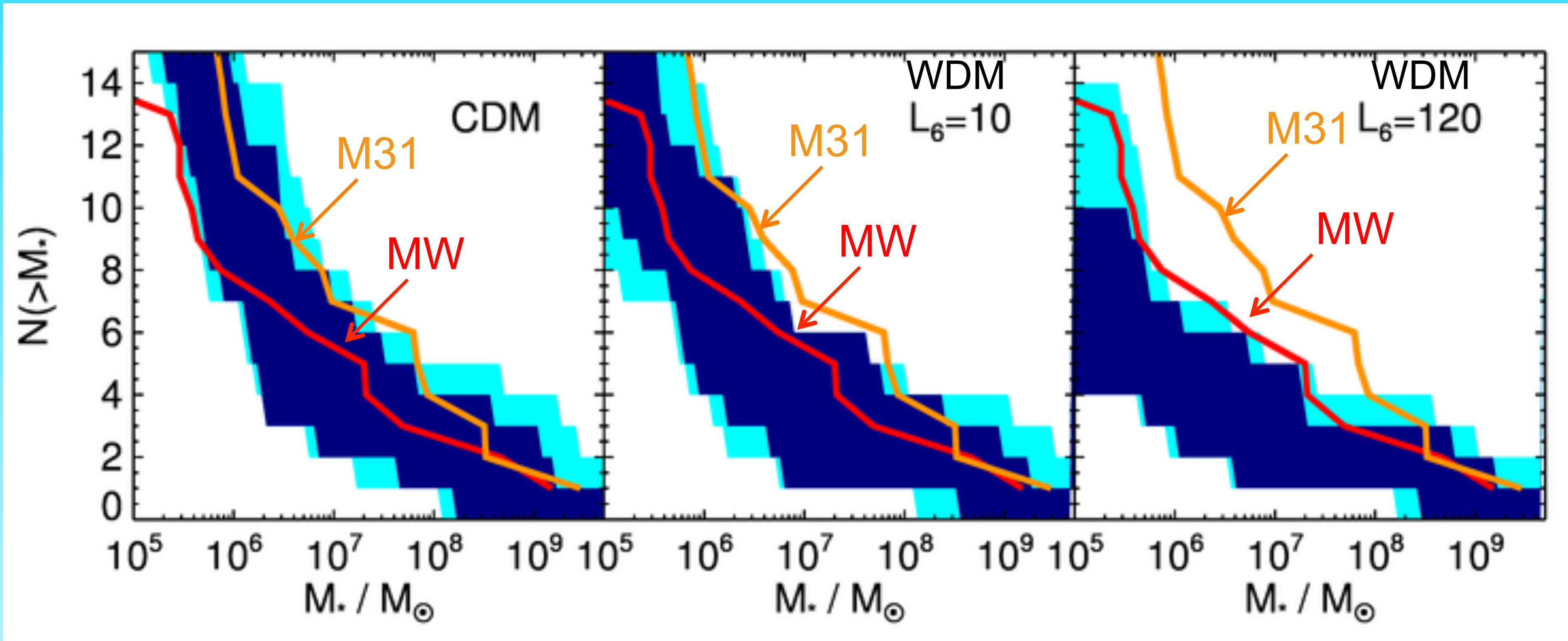
From "Warm Apostle:" 7keV sterile ν $M_h \sim 10^{12} M_o$



→ Can rule out parts of sterile ν parameter space

Lovell et al. '16

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When "baryon effects" are taken into account

→

Observed abundance of satellites is compatible with CDM but rules out some WDM models

→

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

University of Durham

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

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

"Too-big-to-fail" problem in CDM:

N-body CDM sims produce too many massive subhalos (e.g. >10 with V_{max}>30 km/s)

BUT: Milky Way has only 3 sats with V_{max}>30 km/s

Why did the big subhalos not make a galaxy?

When “baryon effects” are taken into account

→

No too-big-to-fail problem in CDM
similar result for WDM

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The peculiar alignment of the Milky Way satellites

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The satellites of the Milky Way

The 11 bright satellites within 250 kpc of the Milky Way lie roughly on a great circle on the sky (Lynden-Bell ‘67, Kroupa, etal ‘05)

The Great Pancake (Libeskind ‘05)

Sculptor, Draco, Sextans

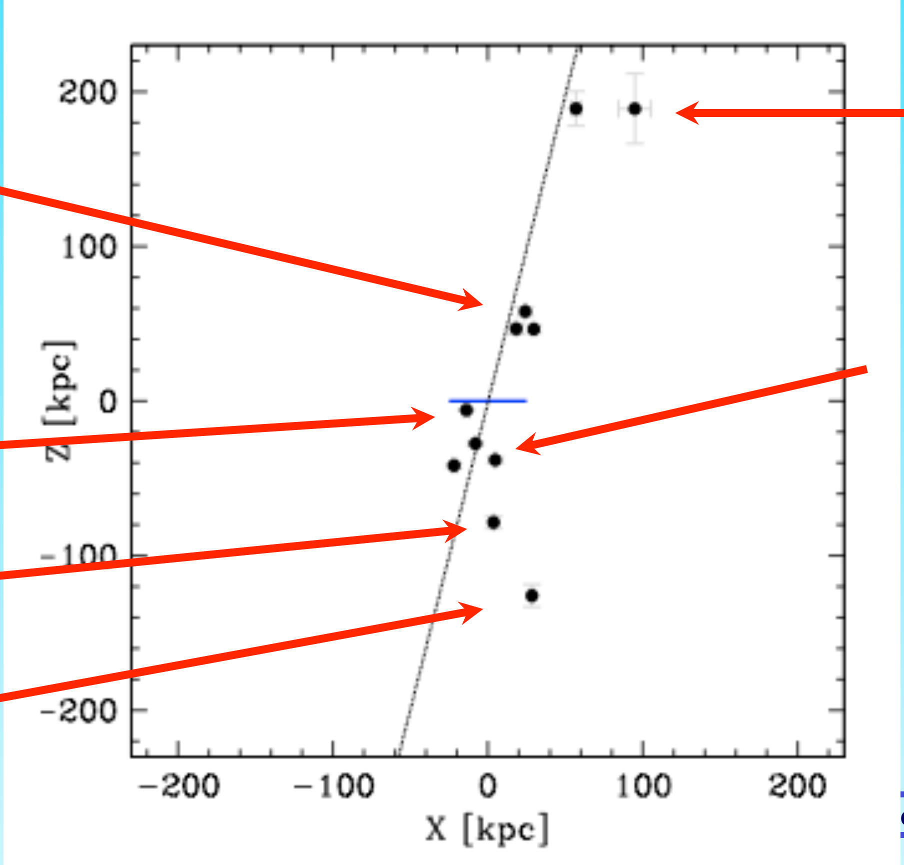
Leo I & II

LMC, SMC, Ursa Minor

Sagittarius Dw

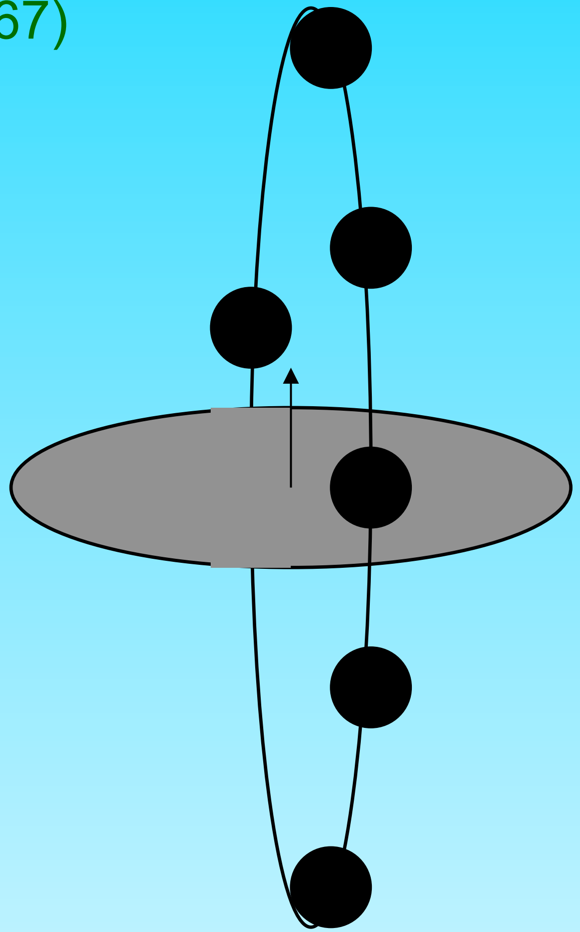
Carina

Fornax



The satellites of the Milky Way

The 11 bright satellites within 250 kpc of the Milky Way lie on a great circle on the sky (Lynden-Bell '67)



… and ~7 of them seem to be rotating coherently (Kroupa+ -05)

Andromeda (Ibata+'15) ; also seems to have a plane of satellites and now Cen A (Pawlowsky+'18) also seems to have one

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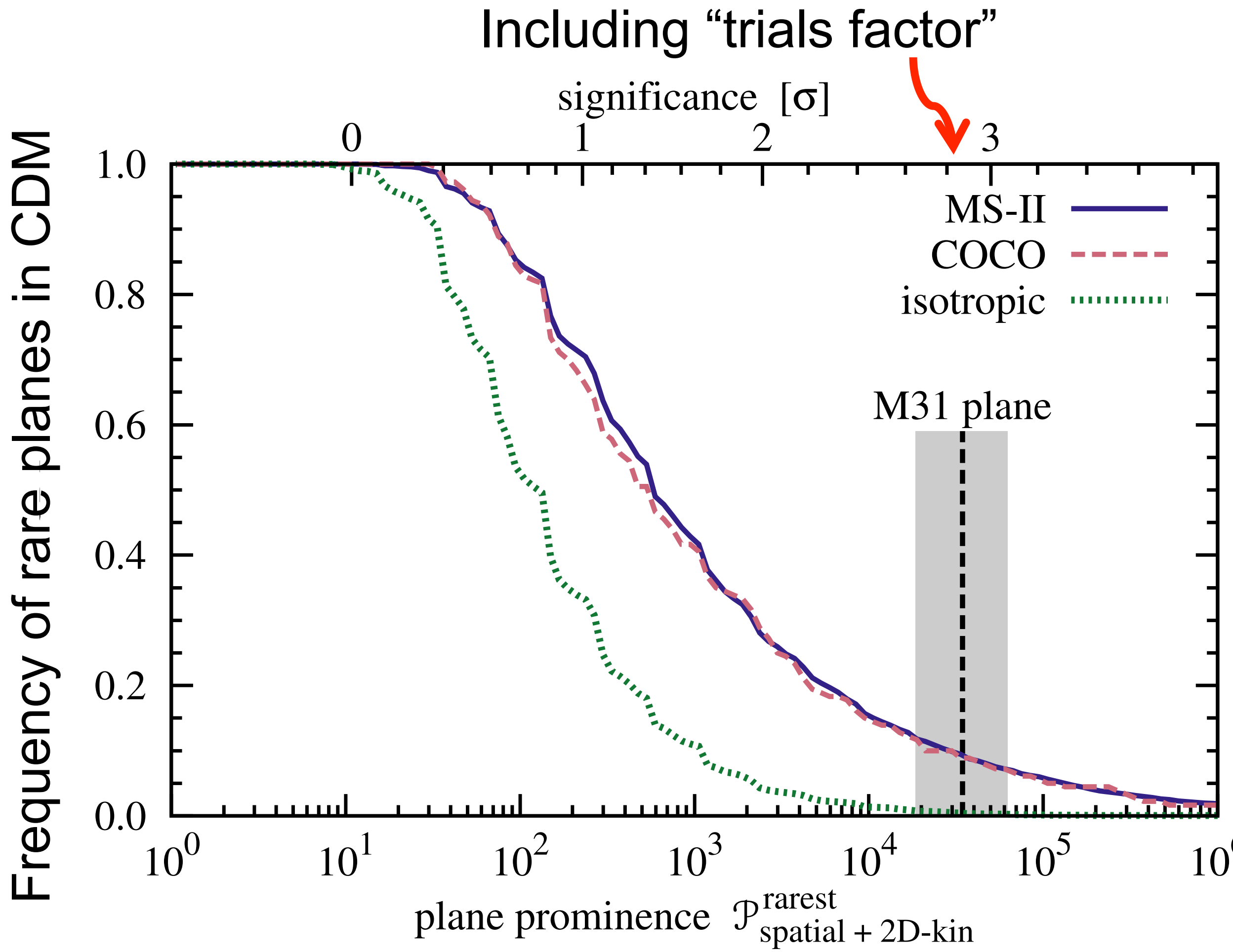
The significance of Ibata's plane

- Significance of Ibata's plane in M31 is reduced by x100 when trials factor is included
- 8.8% of halos in ΛCDM simulation have even more prominent disks than Ibata's



In random distribution, 1 in 30,000 chance of finding a plane of 15 sats (out of 27) as thin found by Ibata et al., with at least 13 having same sense of rotation

Cautun, CSF, et al '15

Shao, Cautun, CSF ‘18

Four problems on small scales

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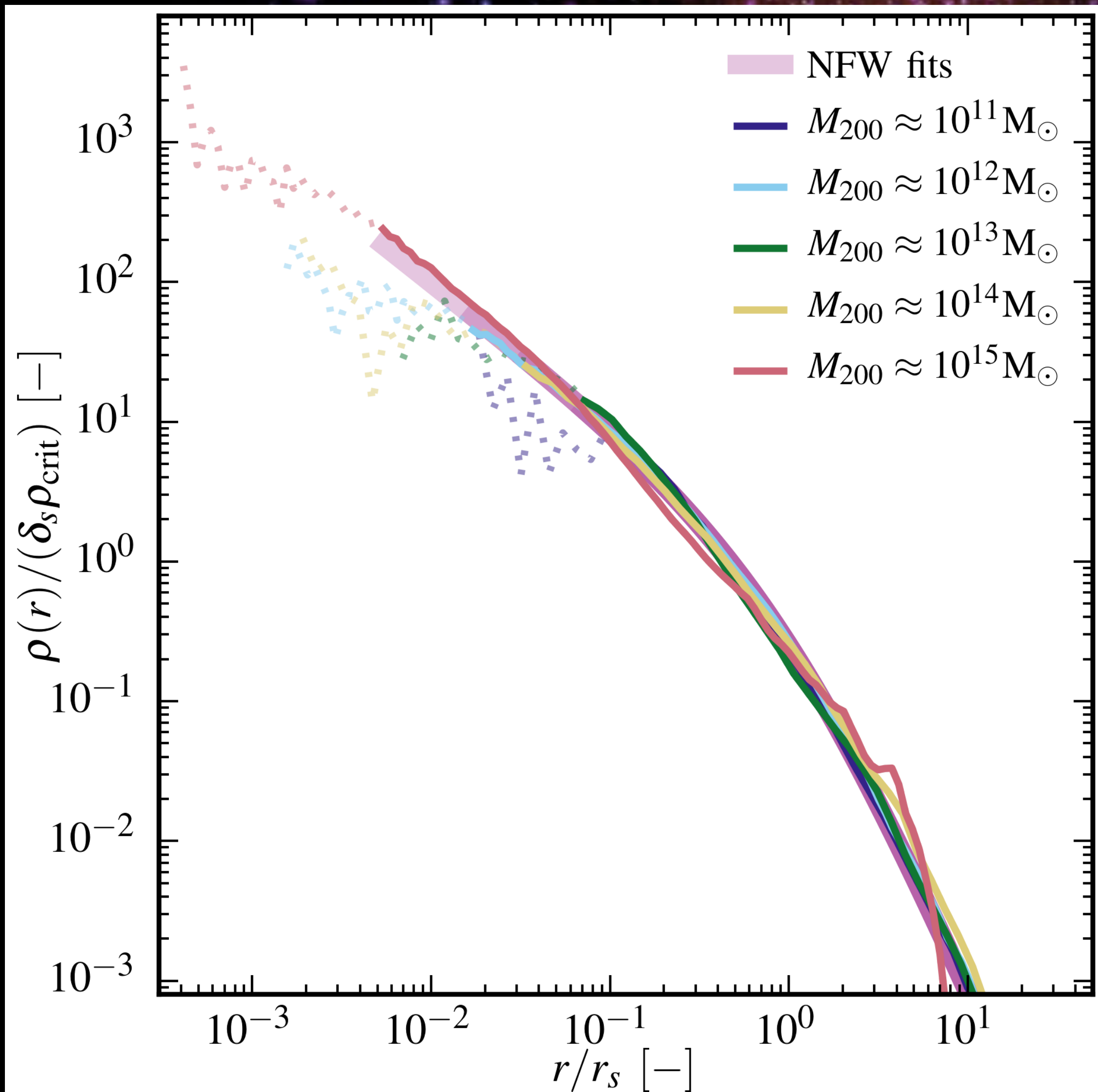
The Density Profile of Cold Dark Matter Halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

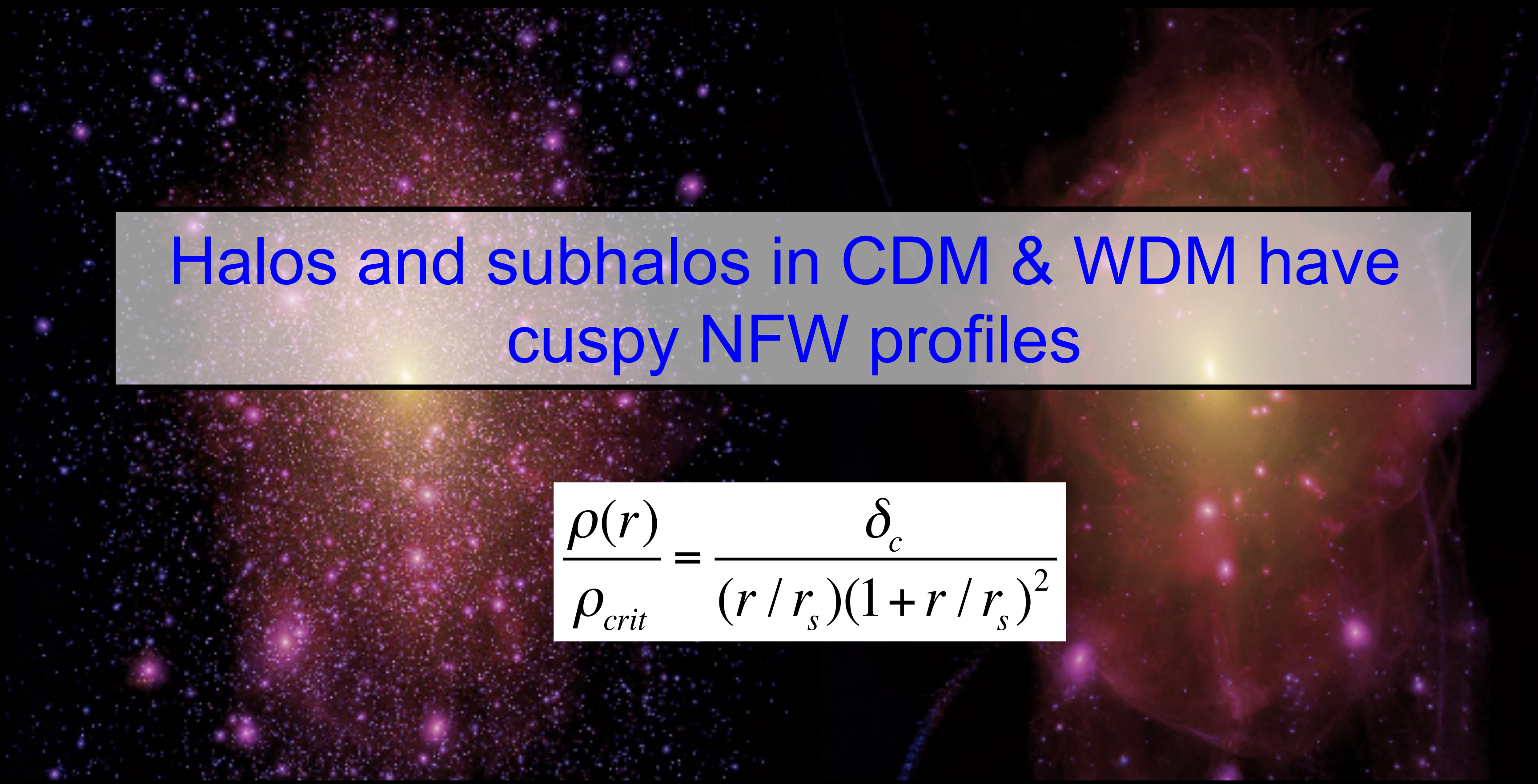
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

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

The core-cusp problem

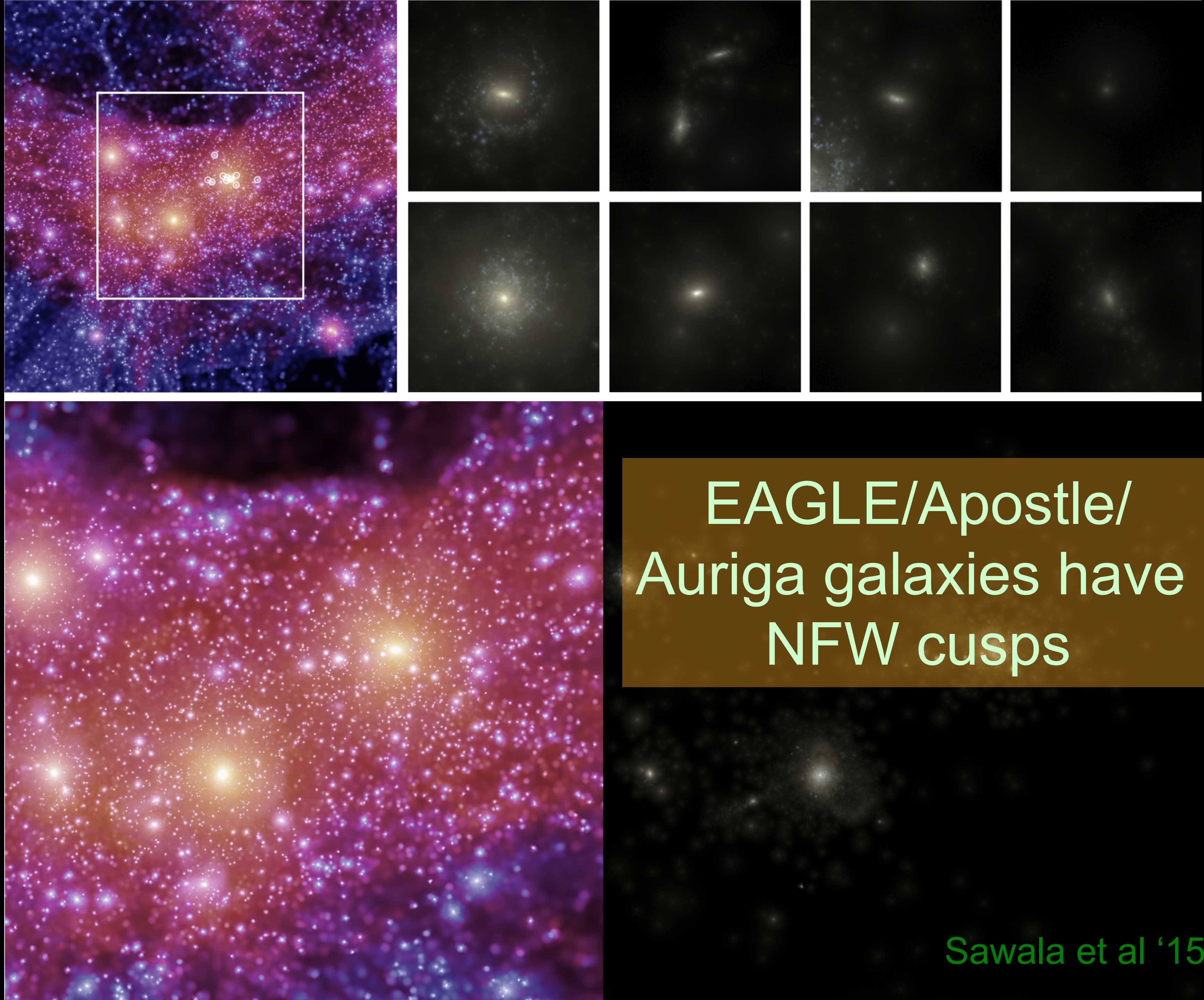
cold dark matter   warm dark matter



Halos and subhalos in CDM & WDM have cuspy NFW profiles

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

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



EAGLE/Apostle/ Auriga galaxies have NFW cusps

Sawala et al ‘15


Does Nature have them?
Sawala et al '15

Many nearby galaxies now have hi-res 2D HI velocity fields → ideal for infering potential

Assume: gas is in centrifugal equilibrium on approximately circular orbits

The diversity of rotation curves

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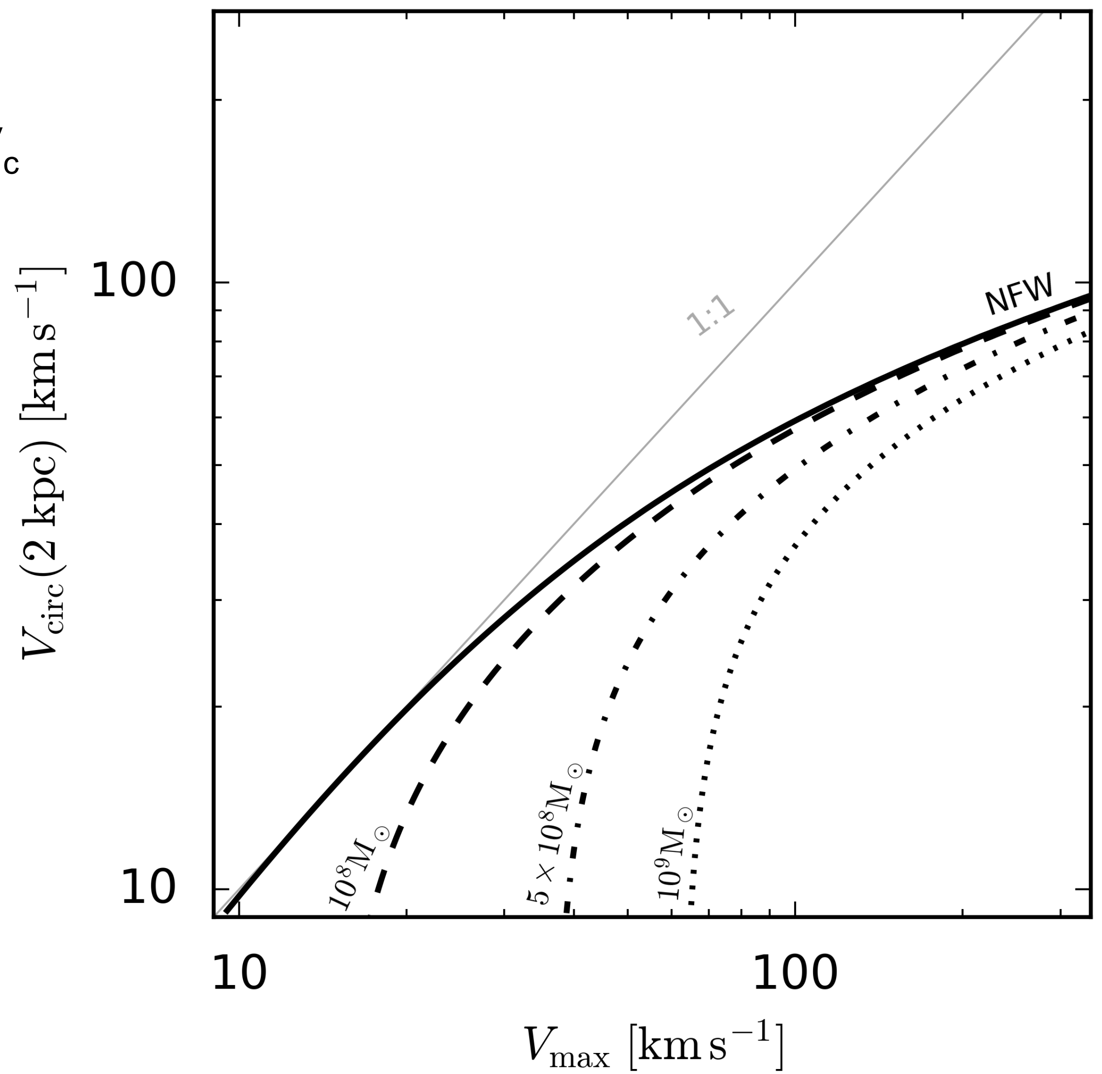
$$V_c = \sqrt{\frac{GM}{r}}$$

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



Oman+ '17

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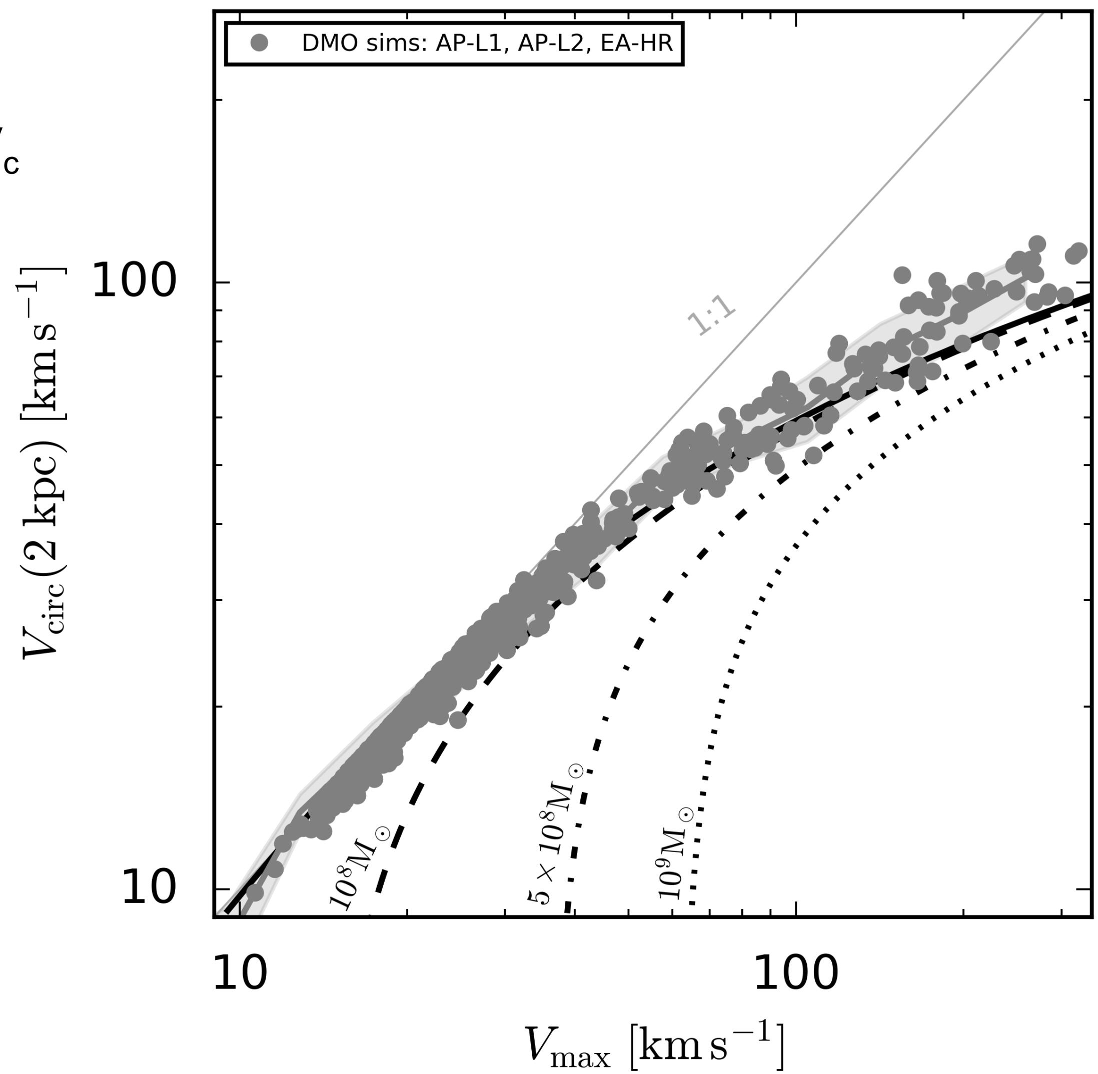
The diversity of rotation curves

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

V_{max} = max V_c



Oman+ '17

Institute for Computational Cosmology

The diversity of rotation curves

University of Durham

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

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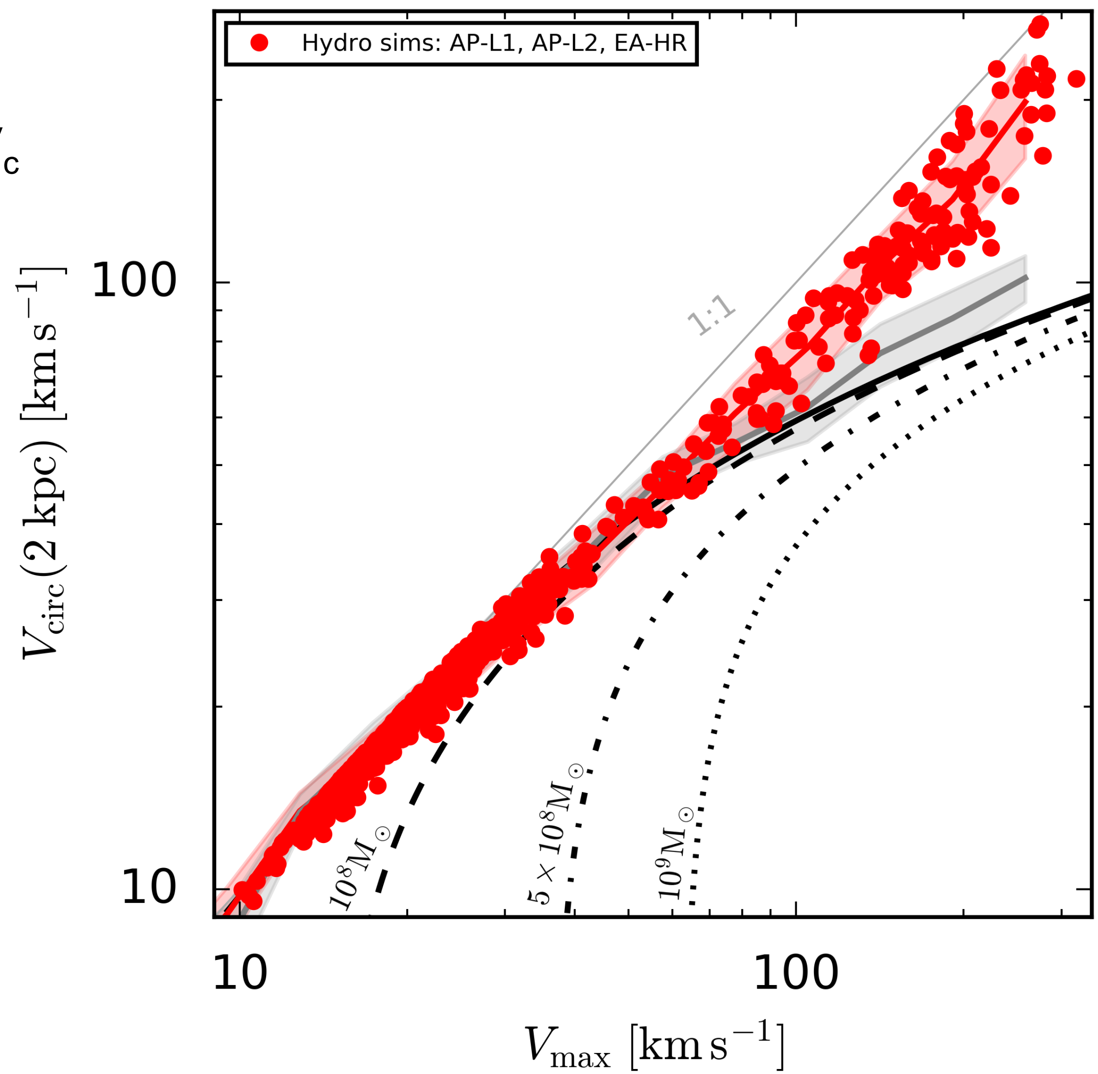

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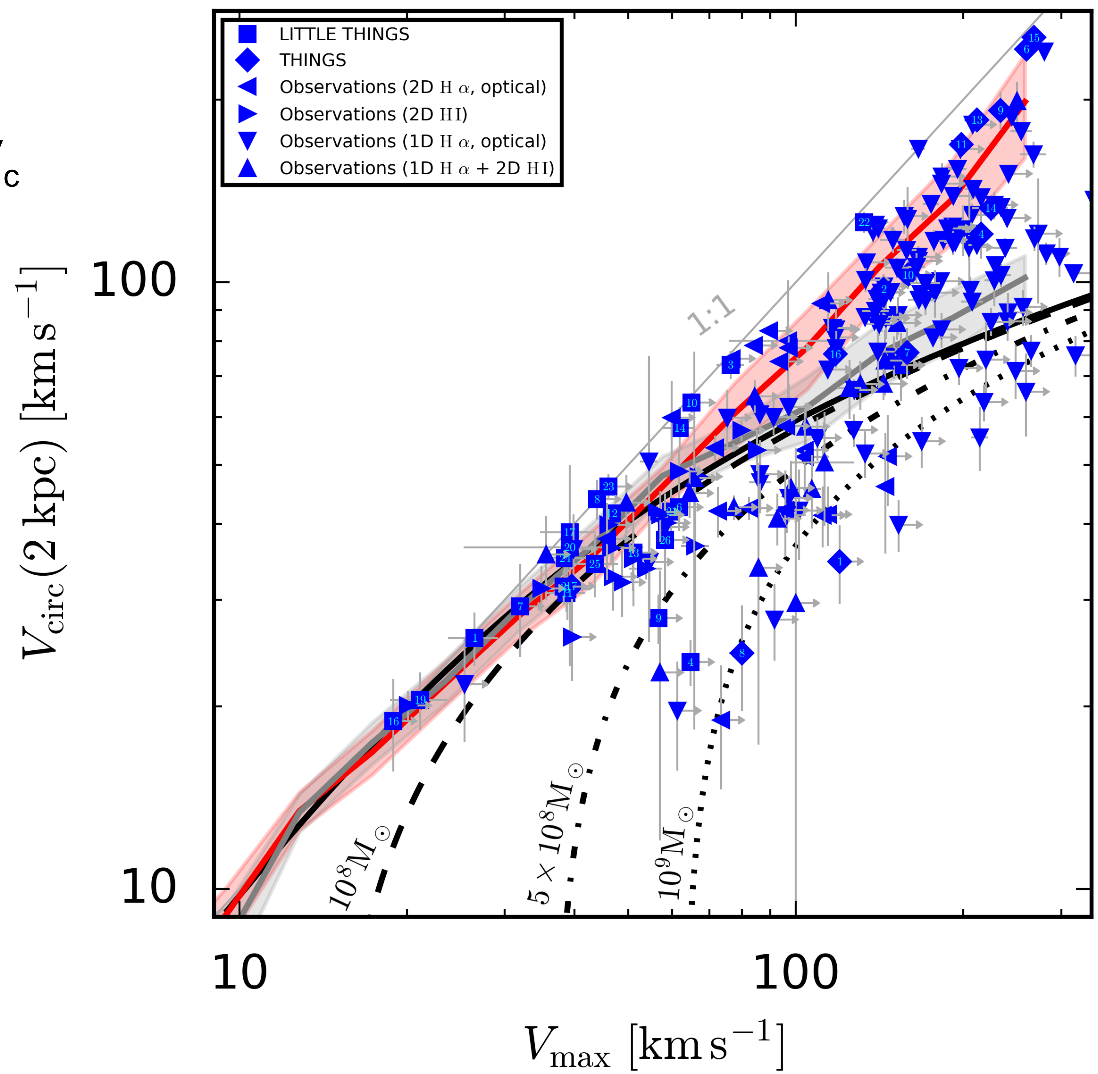

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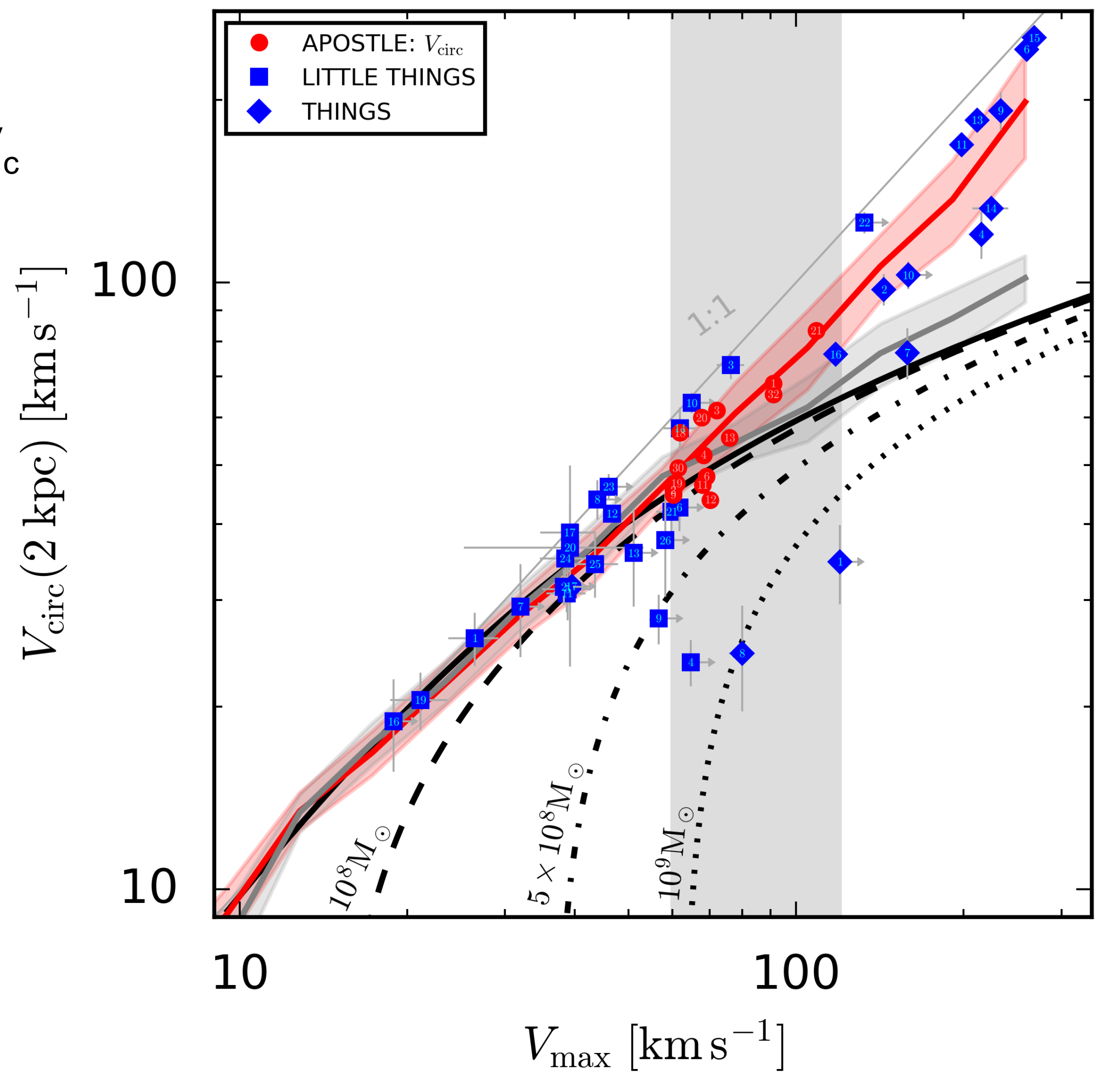

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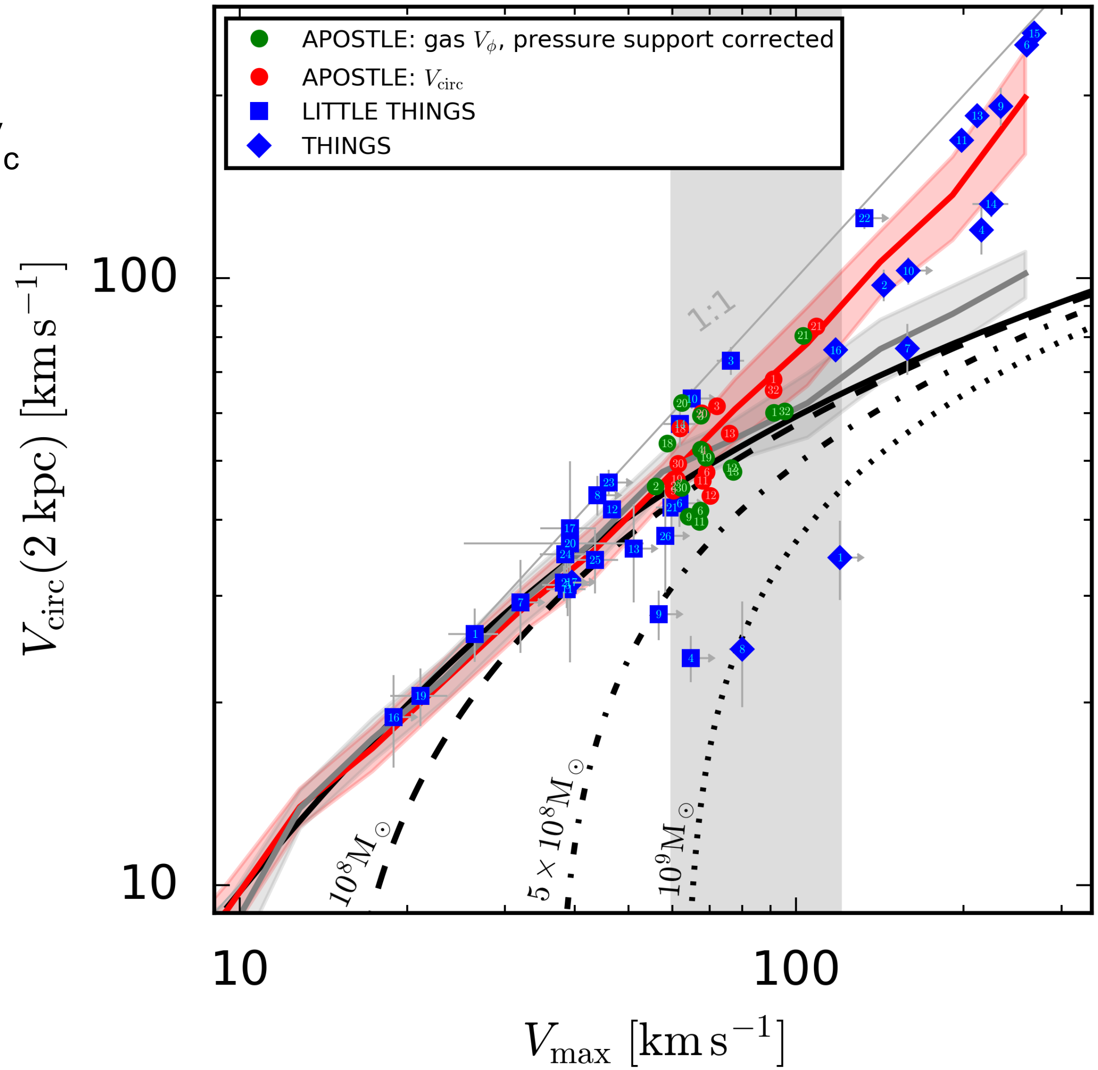

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Analysis of 2D velocity fields

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{v}}$

Tilted-ring model corrected for asymmetric drift

^{3D}BAROLO fit

Let's apply this to APOSTLE galaxies by making a mock 2D velocity field data cube and analysing it just as the real data

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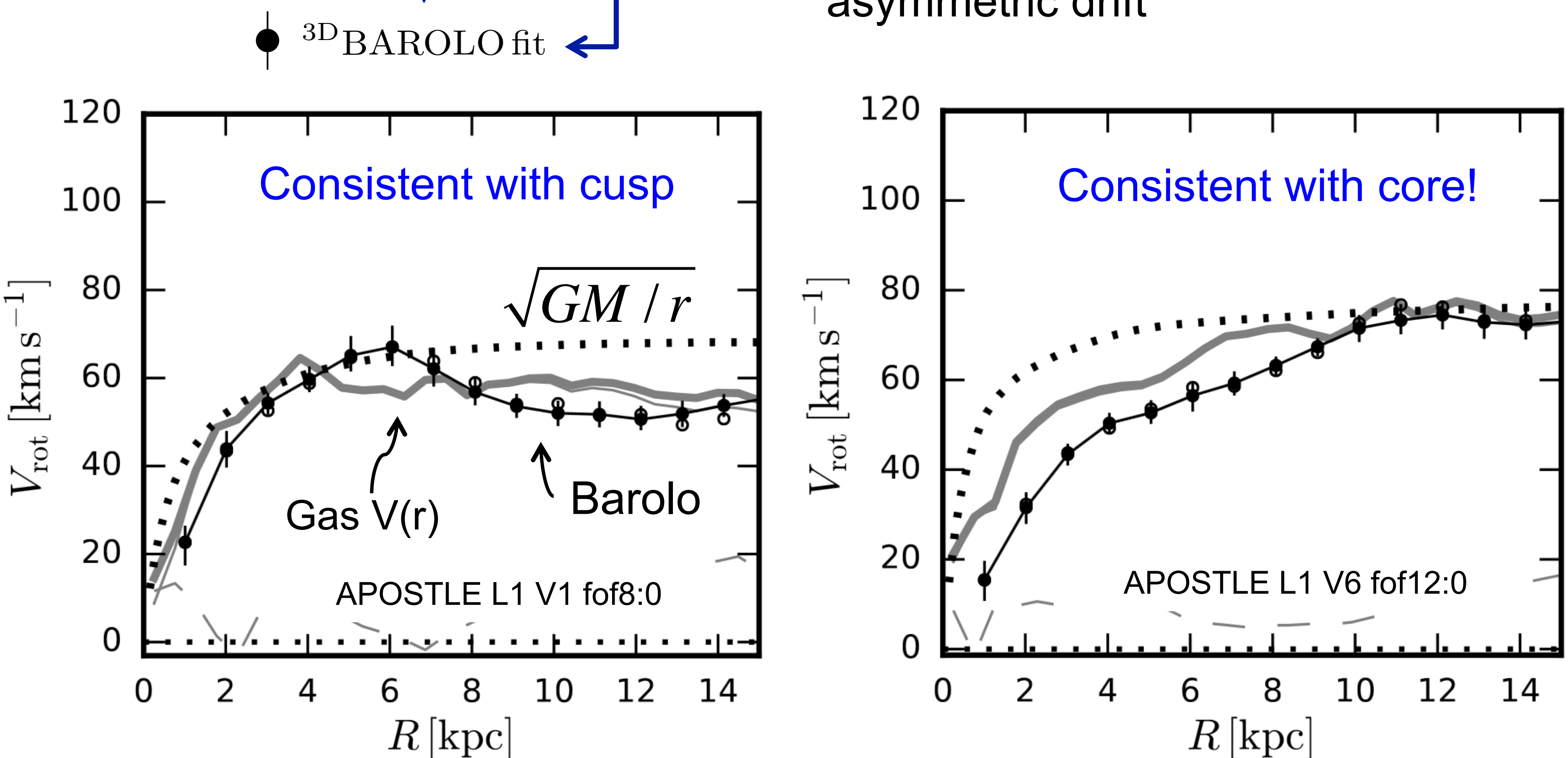
Rotation curves of 2 APOSTLE dwarfs

APOSTLE galaxies all have NFW cusps

2D velocity field → V_c (r) (rotn curve); in dynamical equilibrium: $V_c = \sqrt{\frac{GM(<r)}{v}}$

Tilted-ring model corrected for asymmetric drift



Oman et al '18; Marasco et al '18

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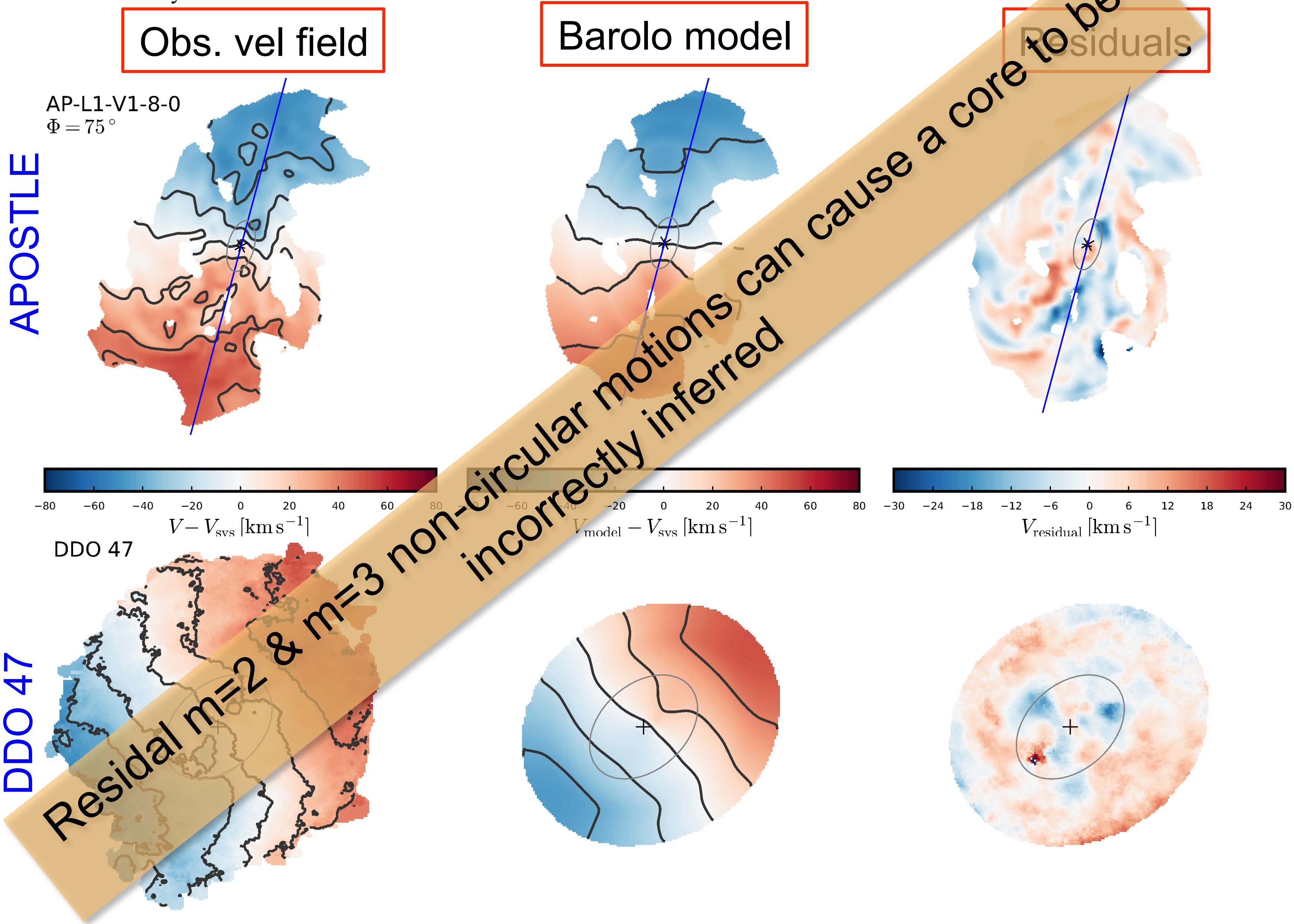
Non-circular motions



Residal m=2 & m=3 non-circular motions can cause a core to be incorrectly inferred

The diversity of rotation curves

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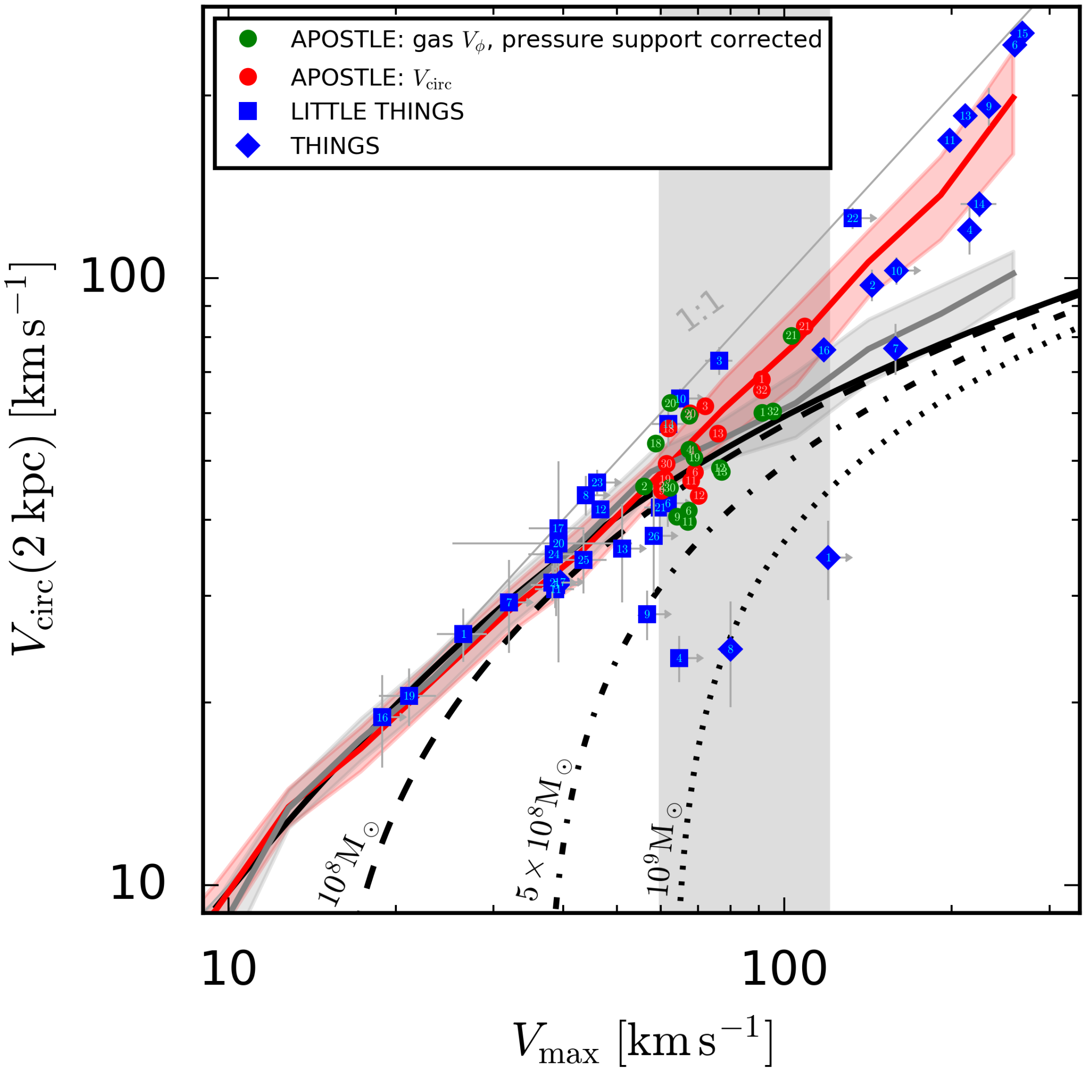

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The diversity of rotation curves

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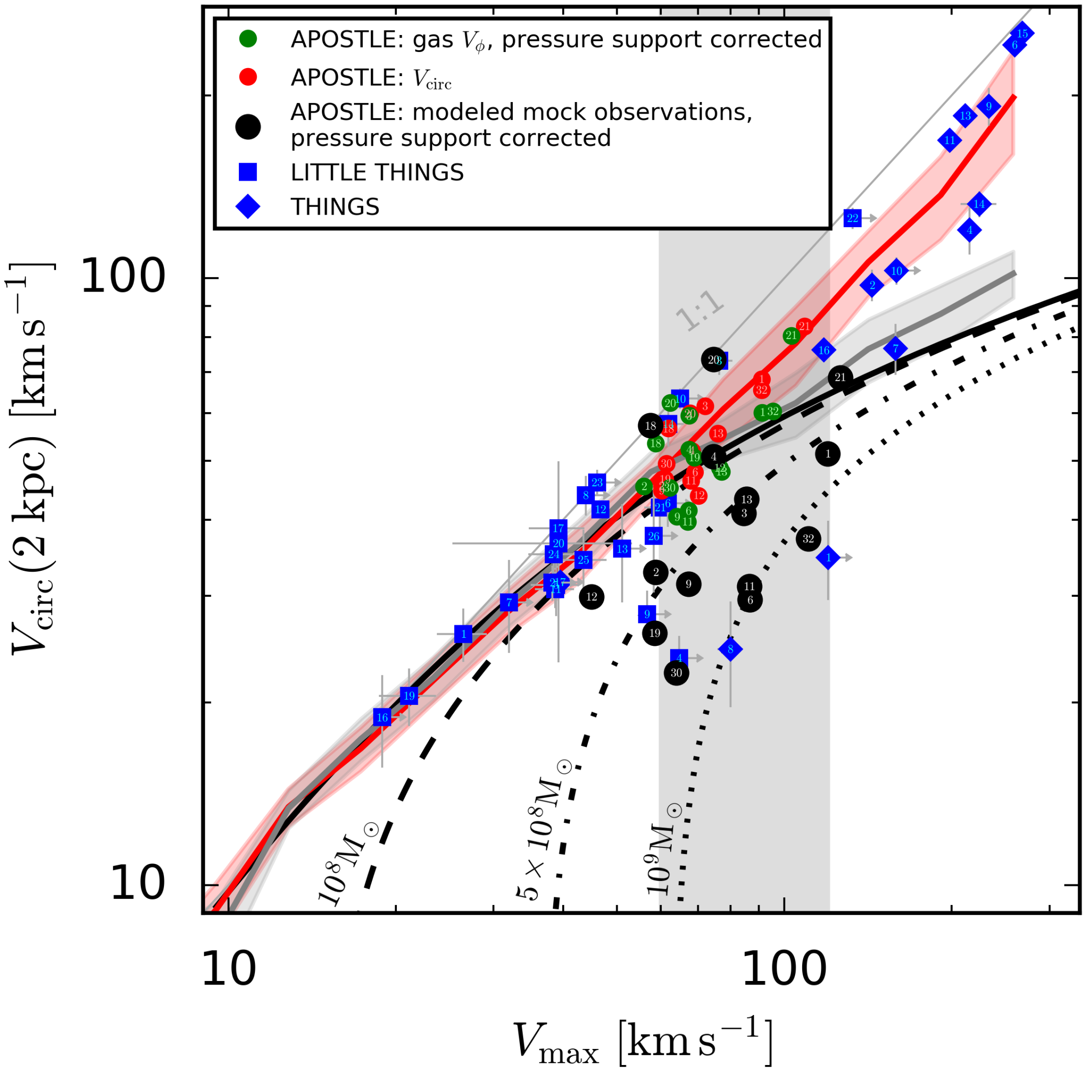

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Cores or cusps in nature?

Cores

Cusps

No convincing evidence for cores in observed galaxies

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

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) (Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

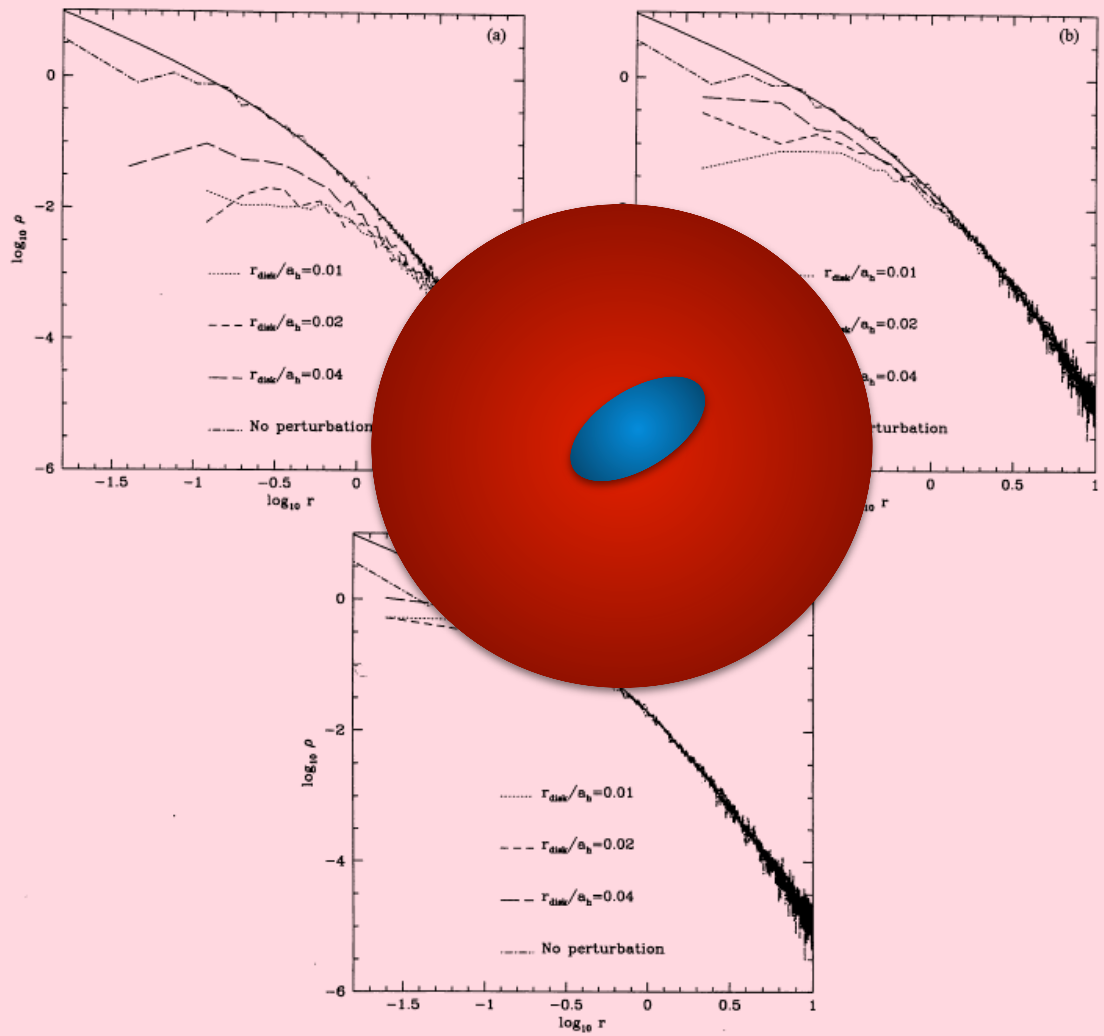

Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

Cores or cusps in simulations?

Key parameter: gas density threshold for star formation

High density → NEF mechanism

Low density → not enough central gas density to perturb DM

Cores or cusps in simulations?

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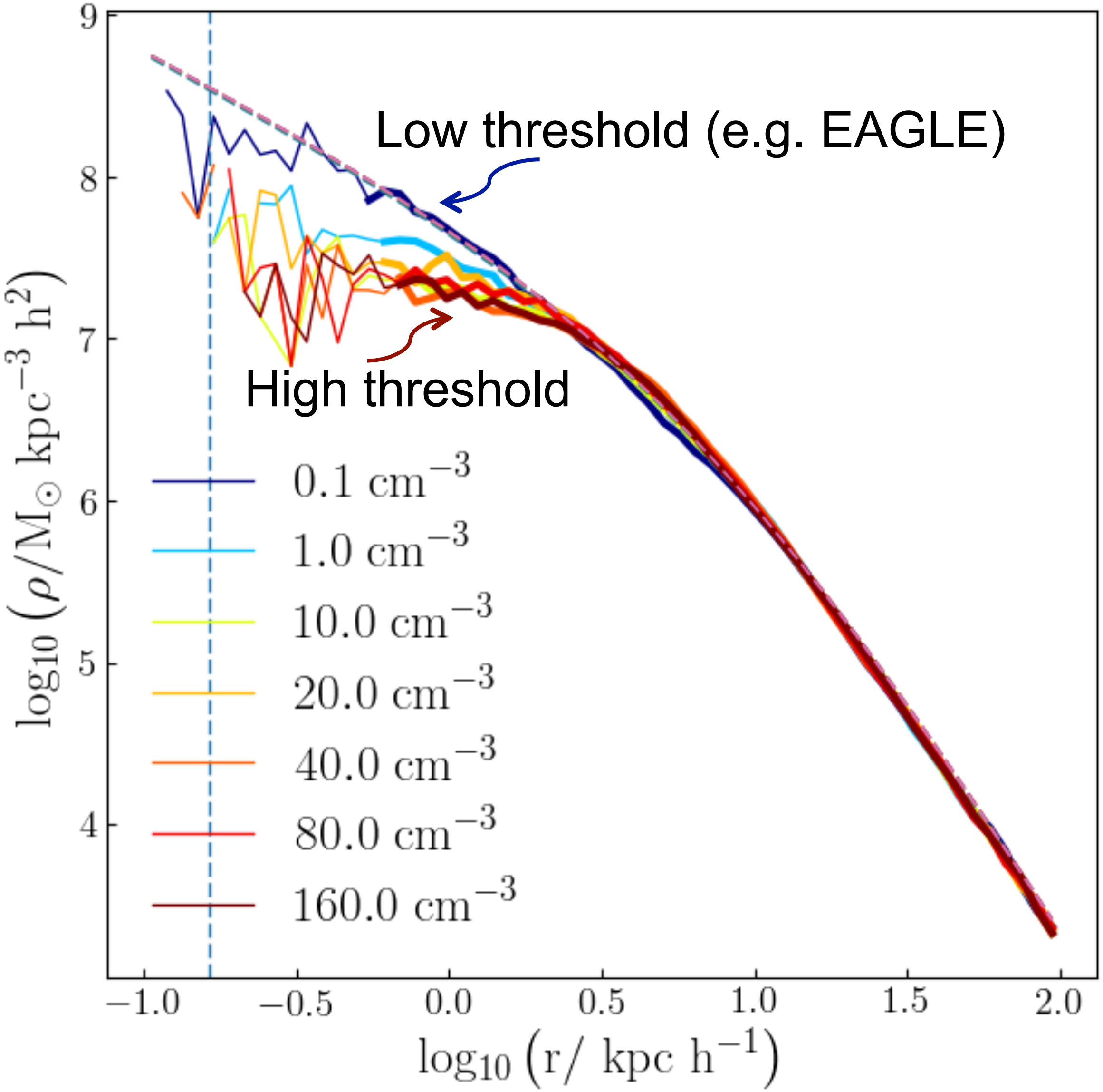

Benitez-Llambay, CSF et al '17

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Four problems on small scales

Traditionally ascribed to CDM:

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

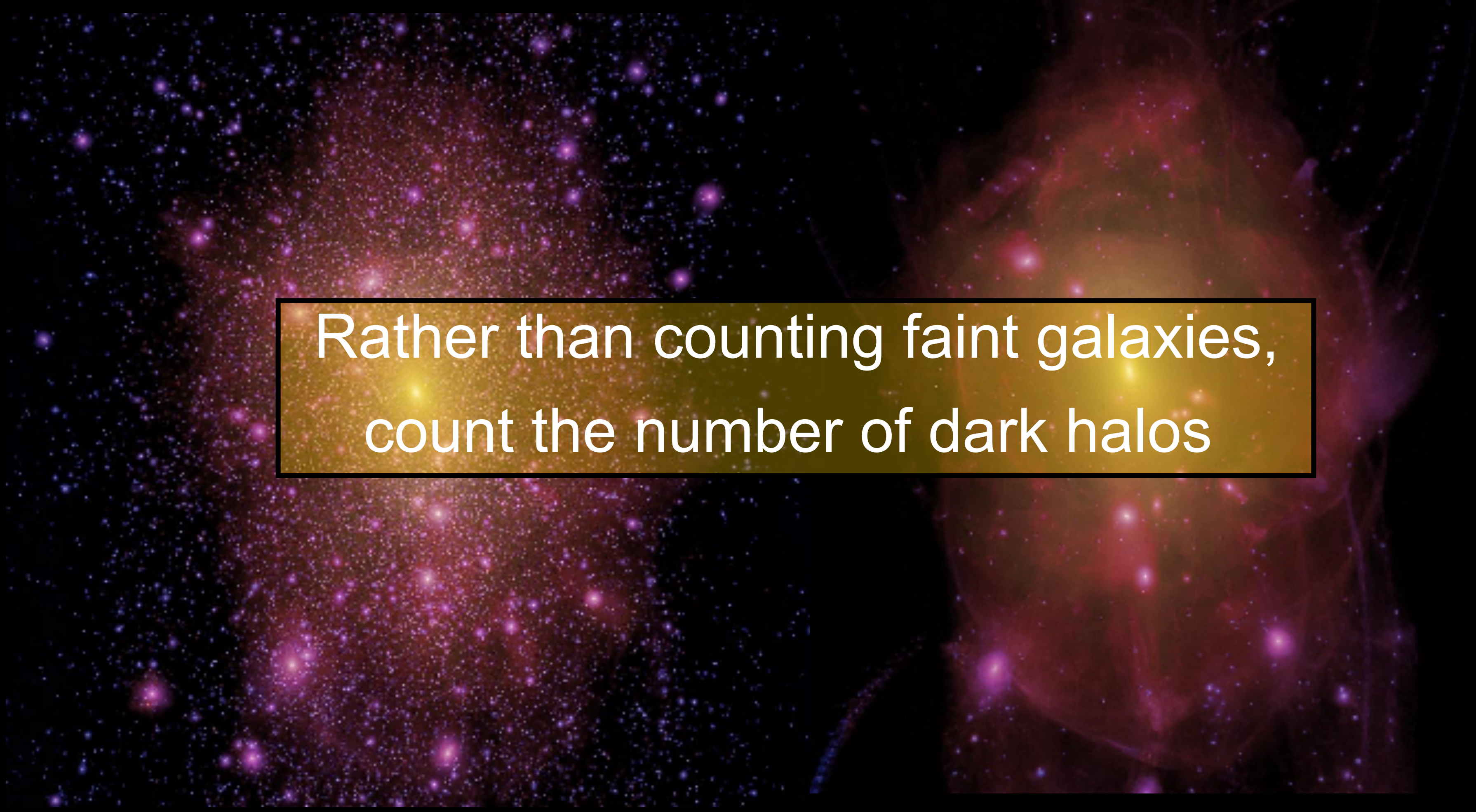
Is there any way can distinguish CDM from WDM?

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

Can we distinguish CDM/WDM?

cold dark matter

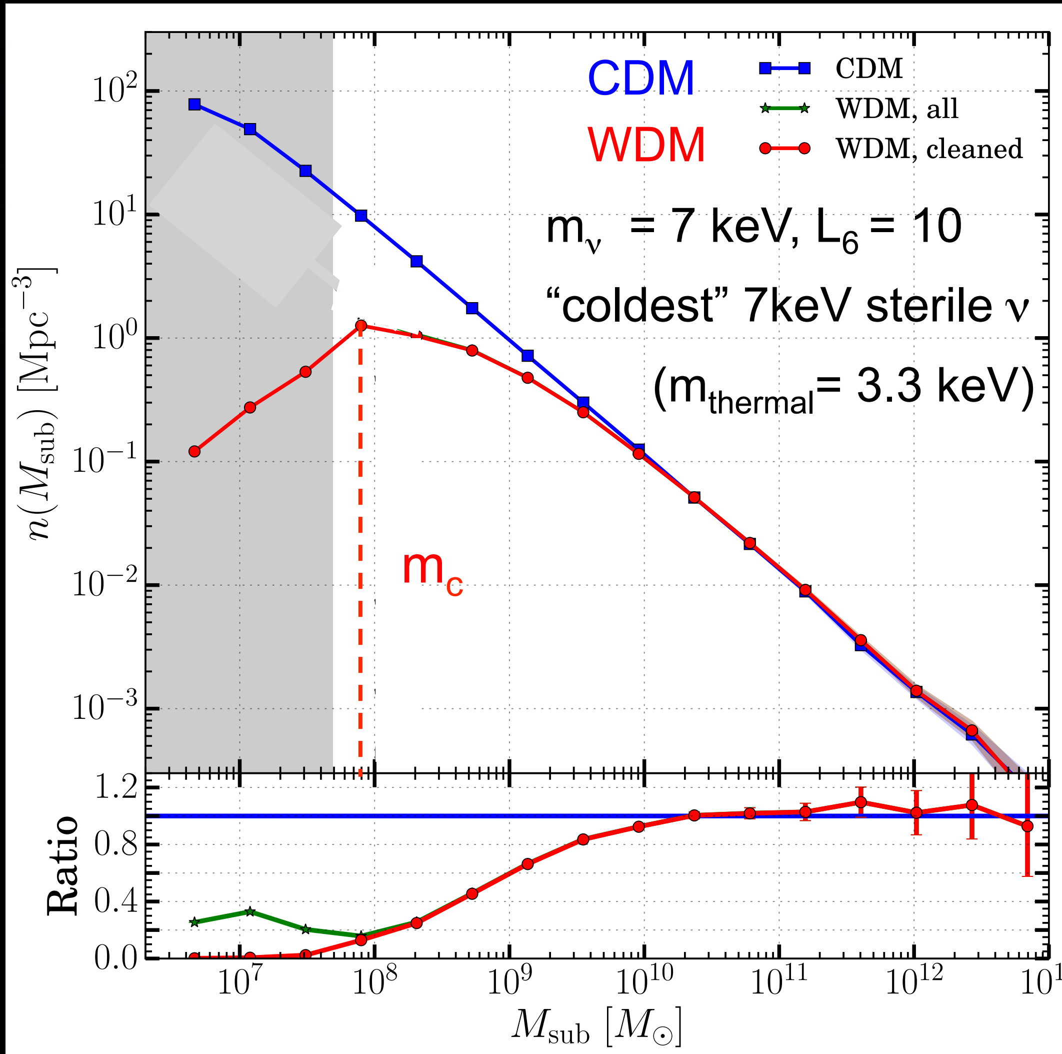
warm dark matter



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

The subhalo mass function

CDM　　　　WDM

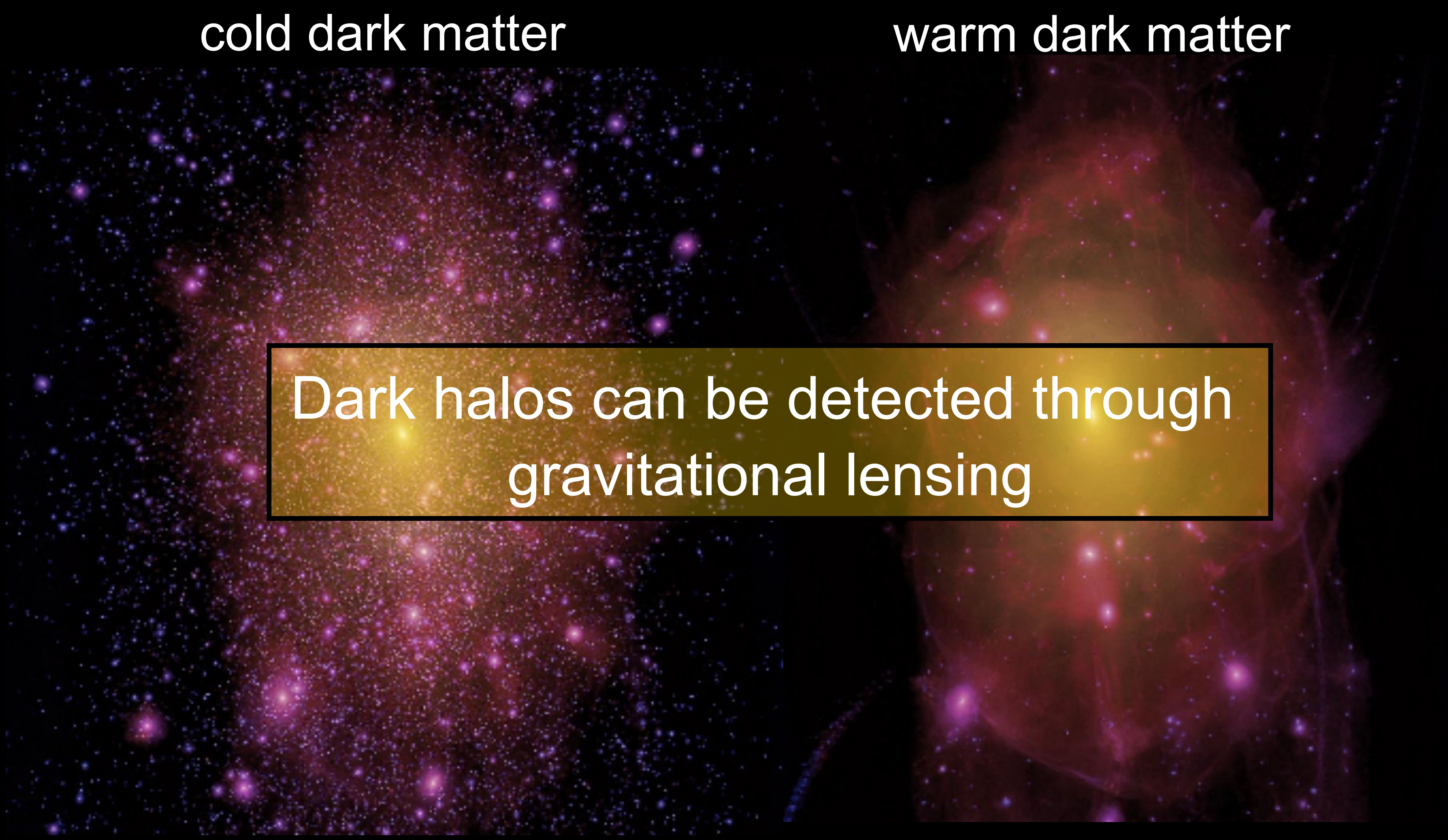


3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

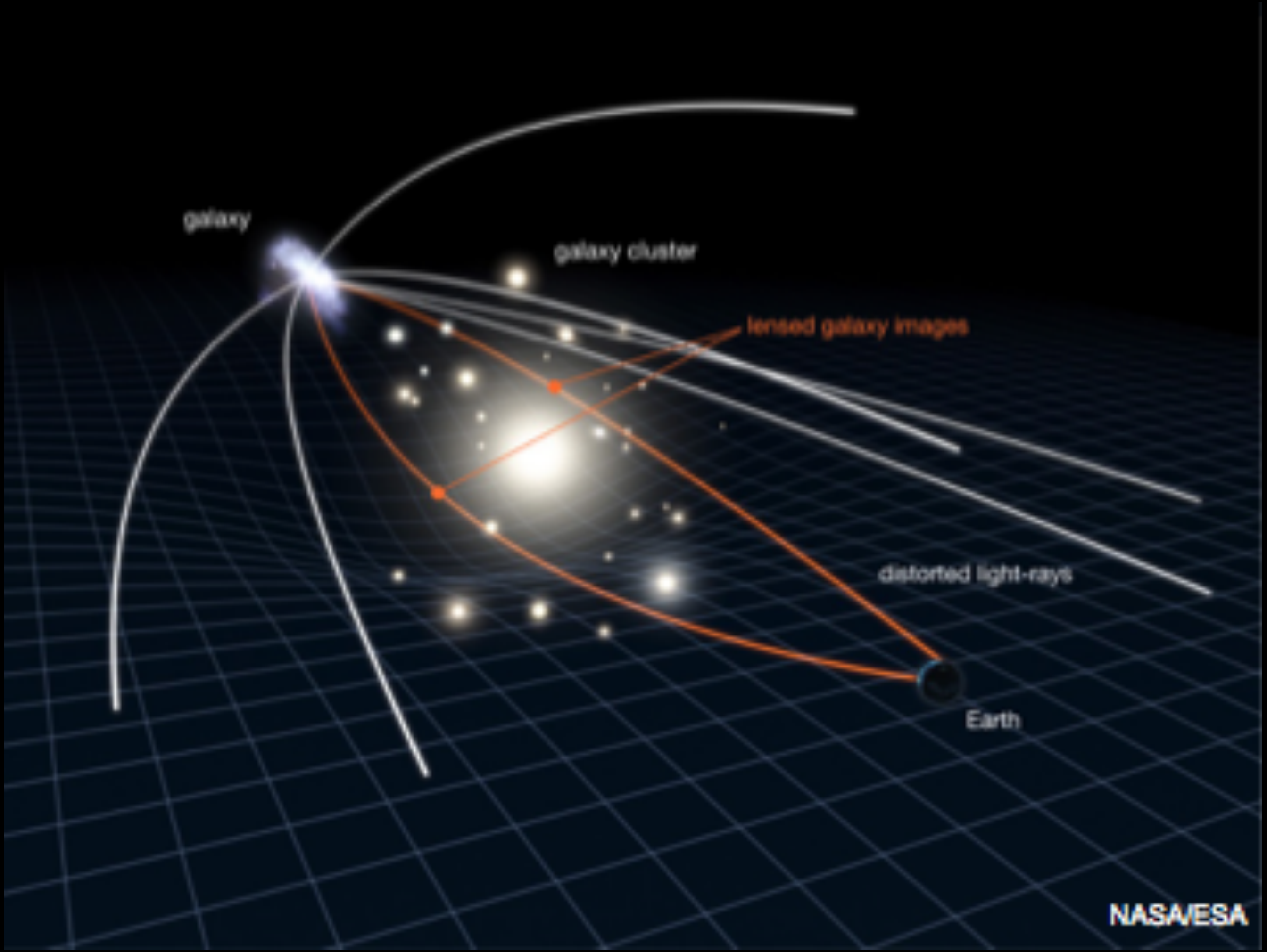
Bose, CSF et al '16

Can we distinguish CDM/WDM?



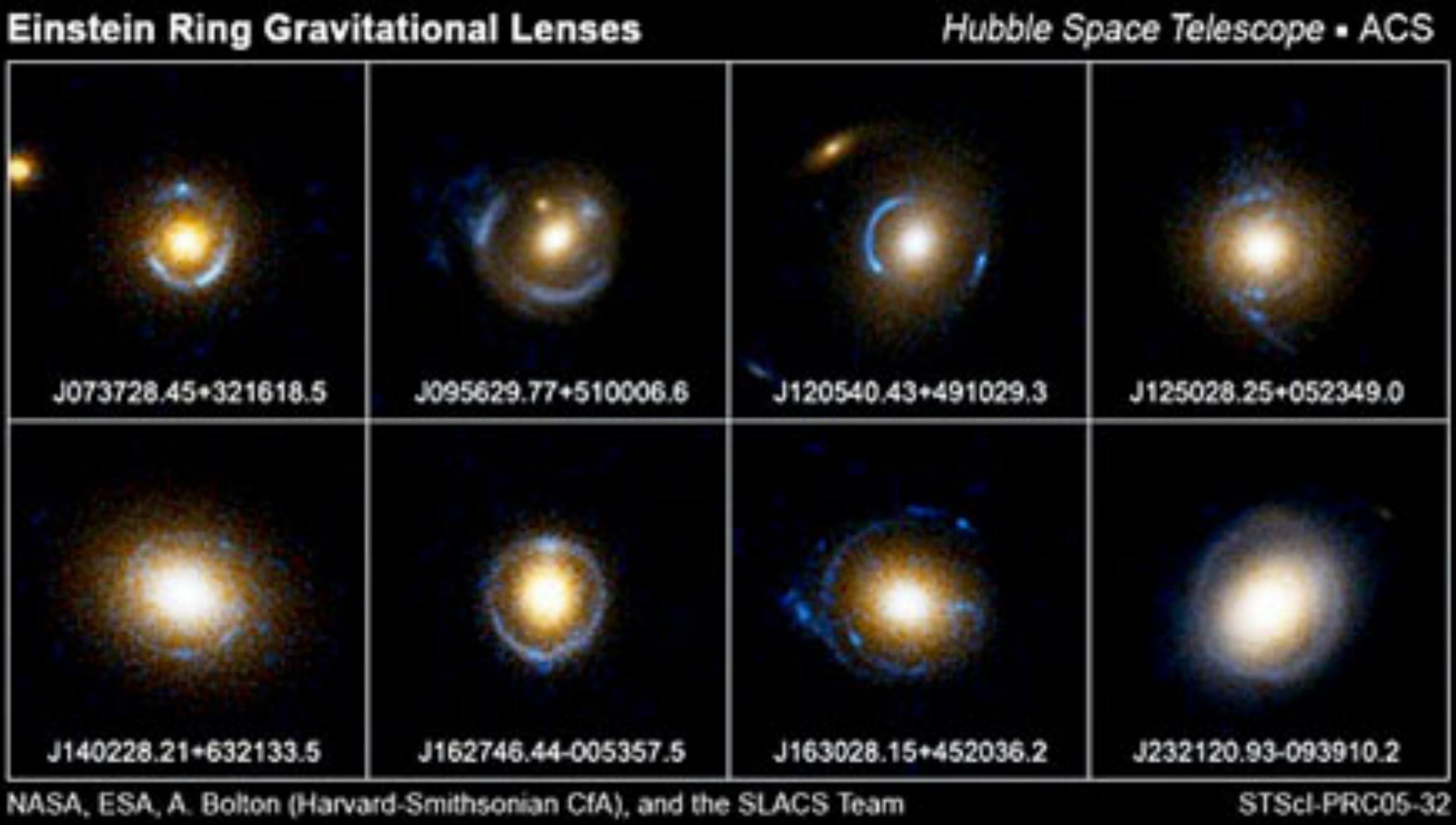
How to rule out CDM

Gravitational lensing: Einstein rings

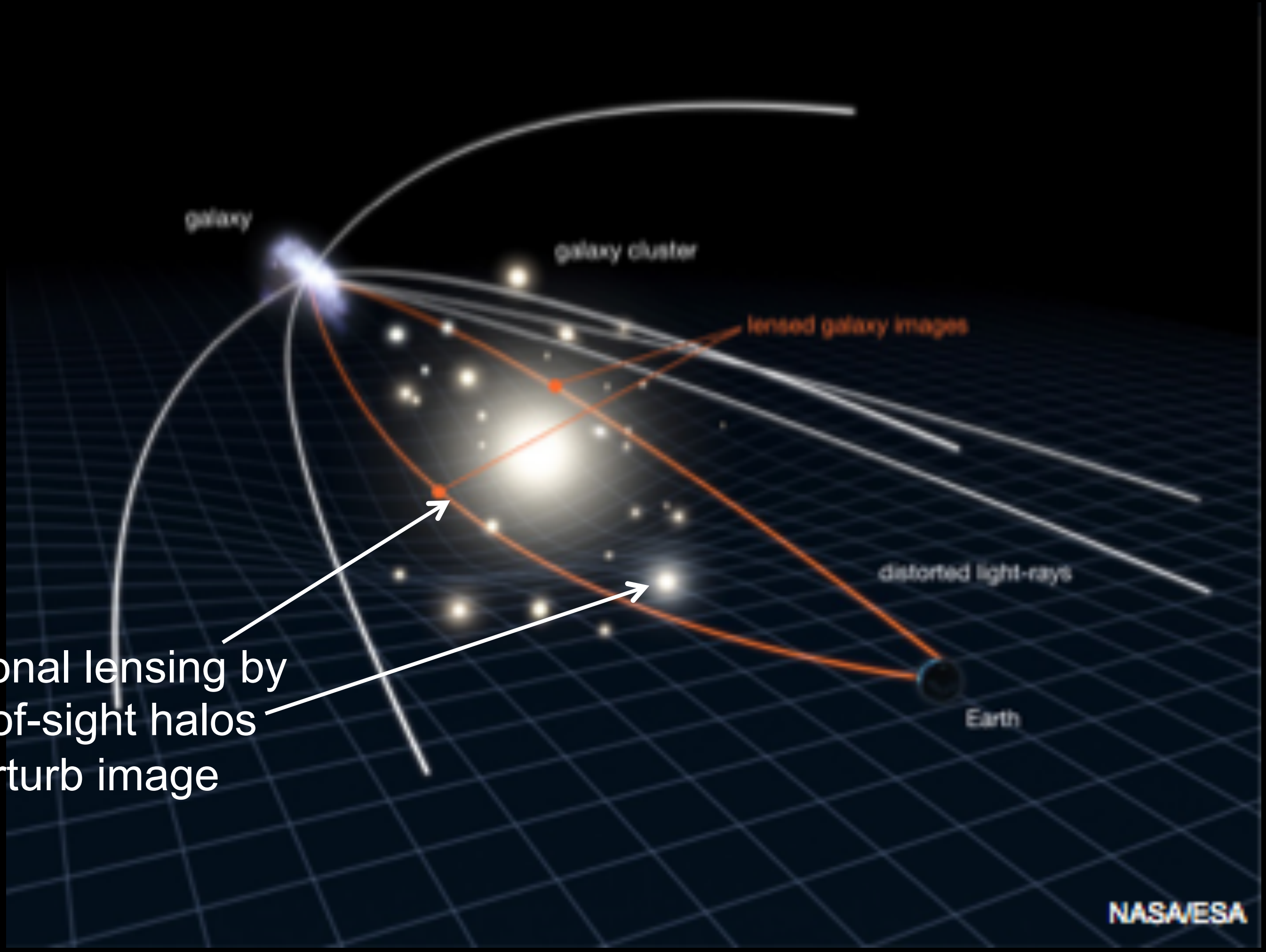


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



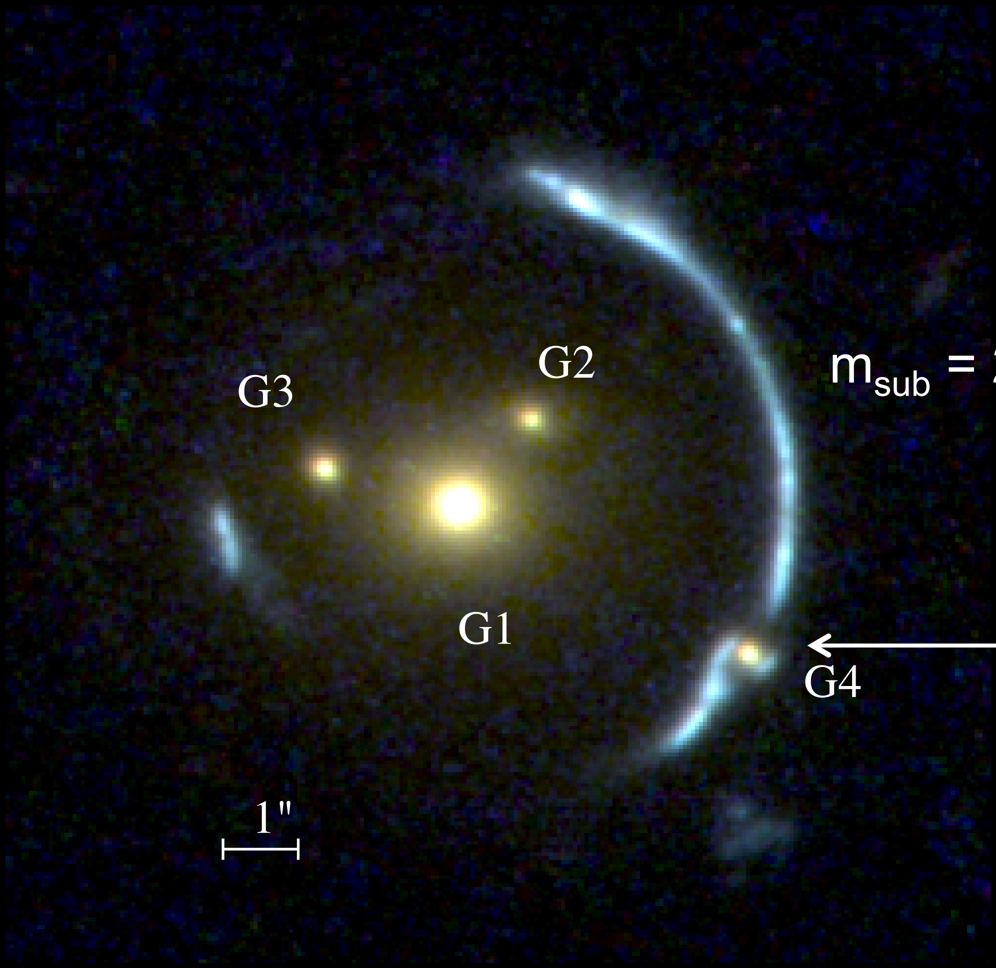
Gravitational lensing: Einstein rings



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



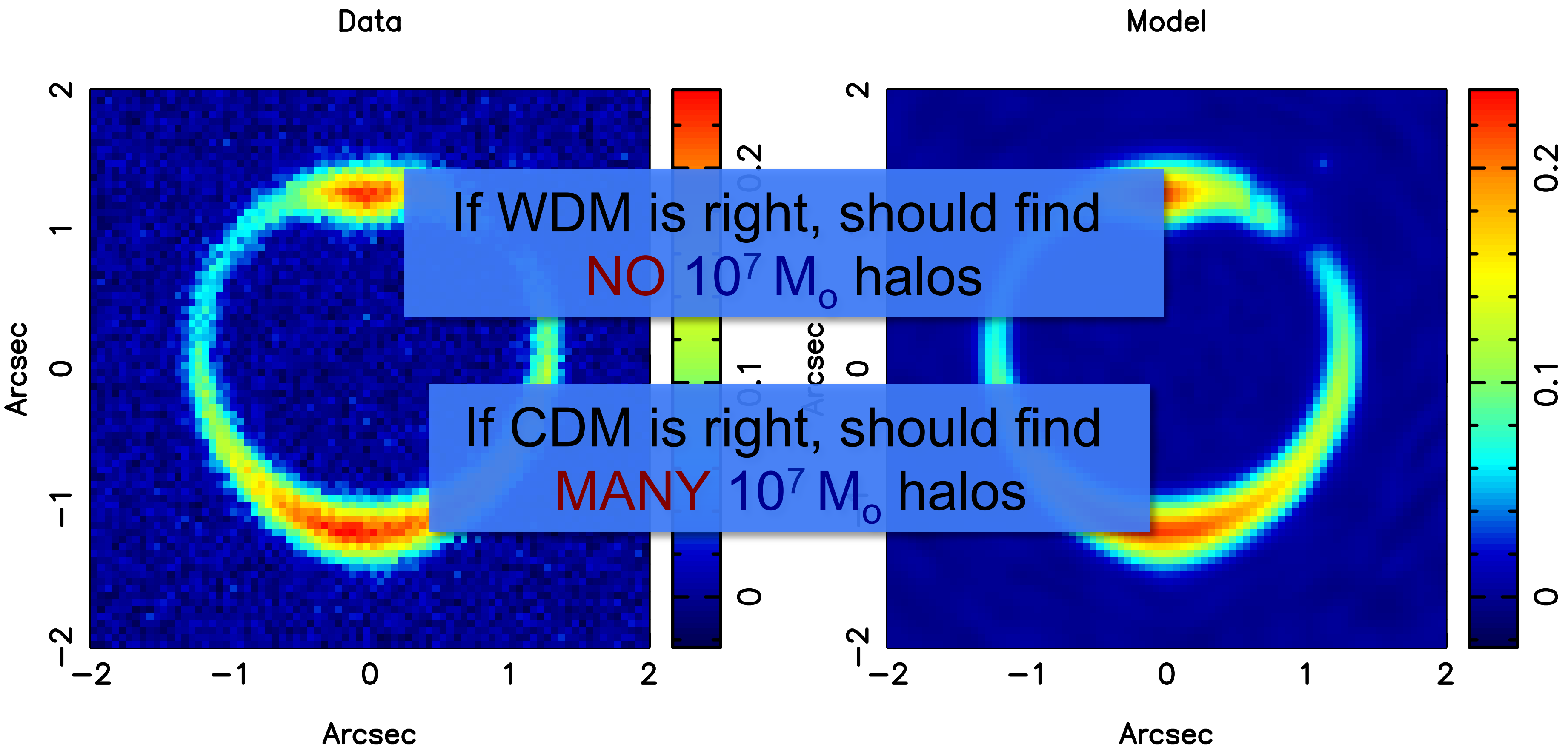
$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

Detecting substructures with strong lensing

University of Durham

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



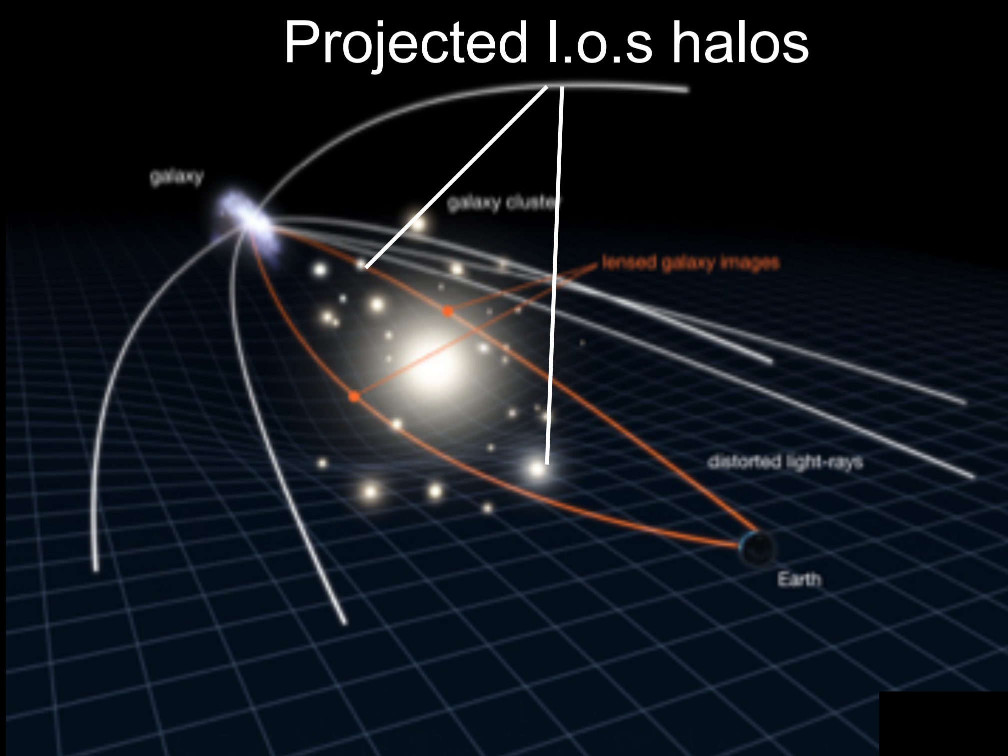
If WDM is right, should find NO 10^7 M_o halos

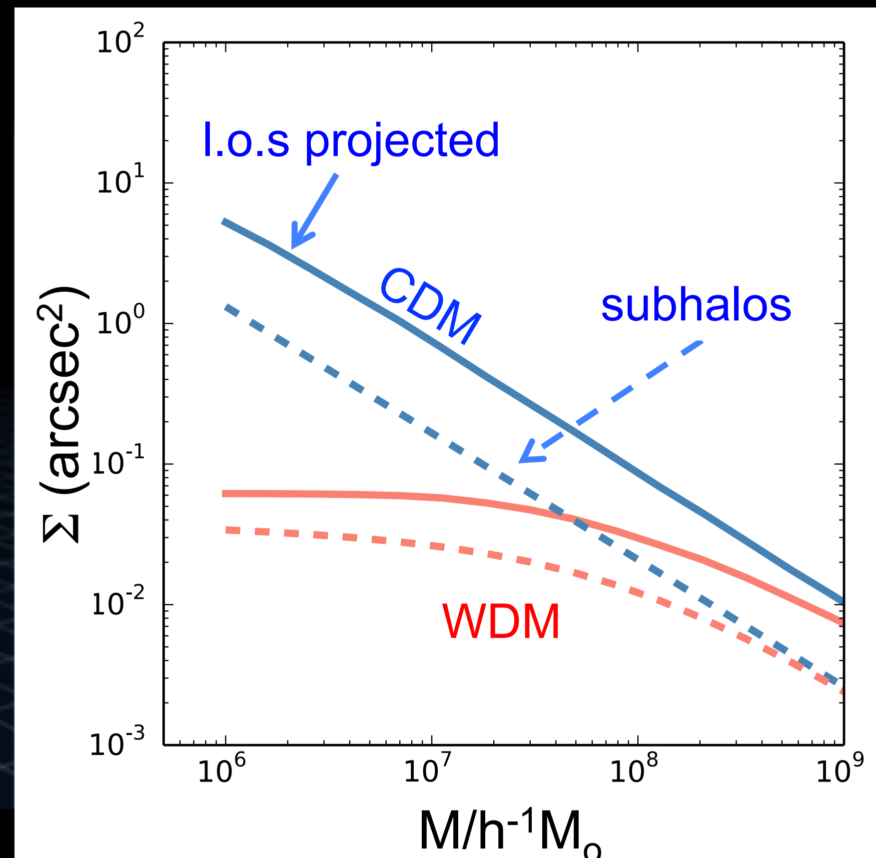
If CDM is right, should find MANY 10^7 M_o halos

Vegetti & Koopmans ‘09

Substructures vs interlopers

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



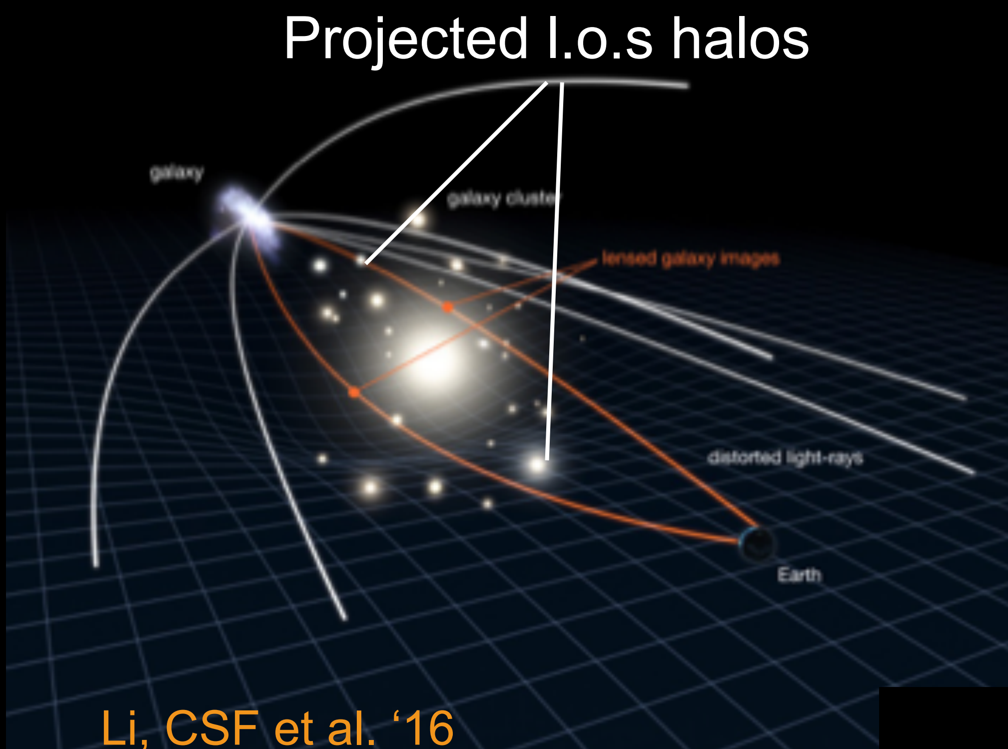


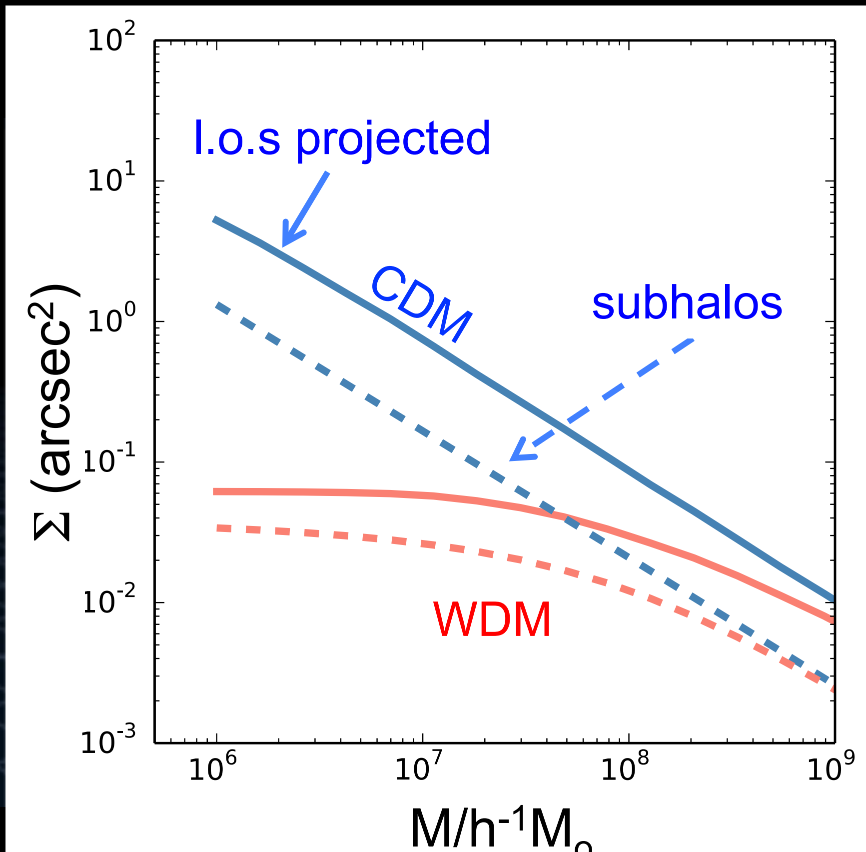
The number of line-of-sight haloes is larger than that of subhaloes

Li, CSF et al. '16

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

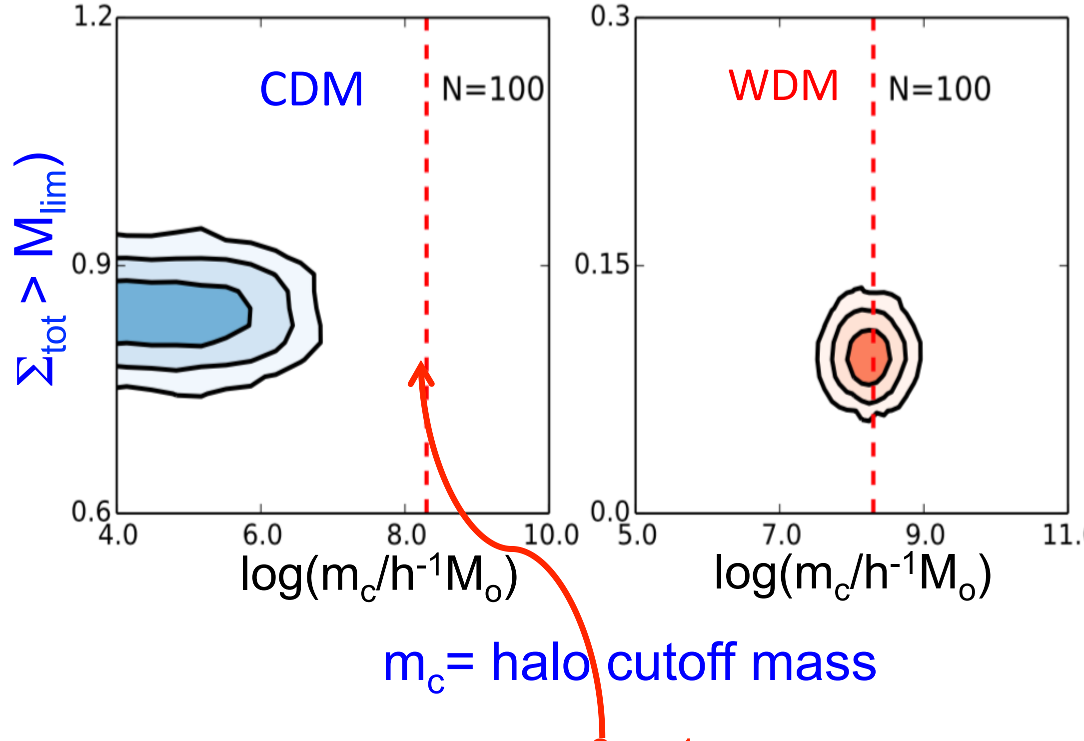
University of Durham

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

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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. Halos < ~5.10^{8}M$_0$ are dark; halos >10^{10}M$_0$ are bright
2. No evidence for cores; baryon effects can make them
3. When baryons taken into account → No satellite, too-big-to-fail, plane of sats, core/cusp problems in CDM
4. Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!