

A conclusive test of cold dark matter

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Durham

... and how to rule it out
within ~ 5 years

The new 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
- Has made a number of **predictions** that were subsequently **verified** empirically (e.g. CMB, LSS, galaxy formation)

The big Bang



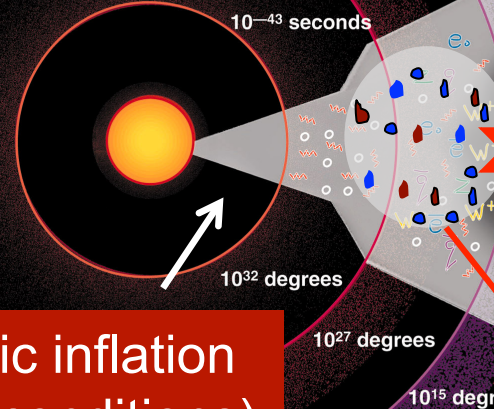
The cosmic microwave background is emitted
($t \sim 350,000$ yrs)

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



degrees

18 degrees

3 degrees K

15 thousand million years

300 tho

3 minutes

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

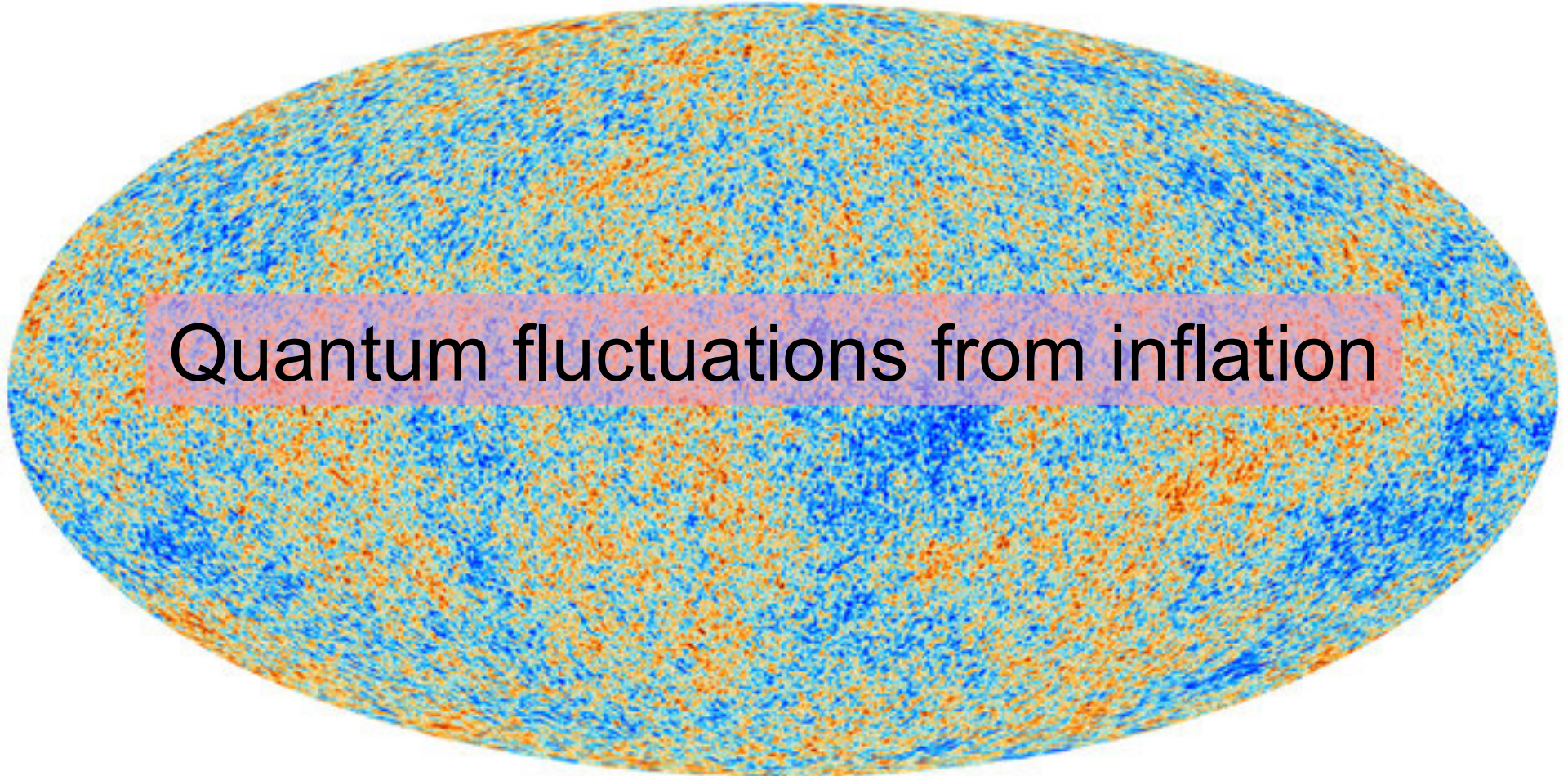
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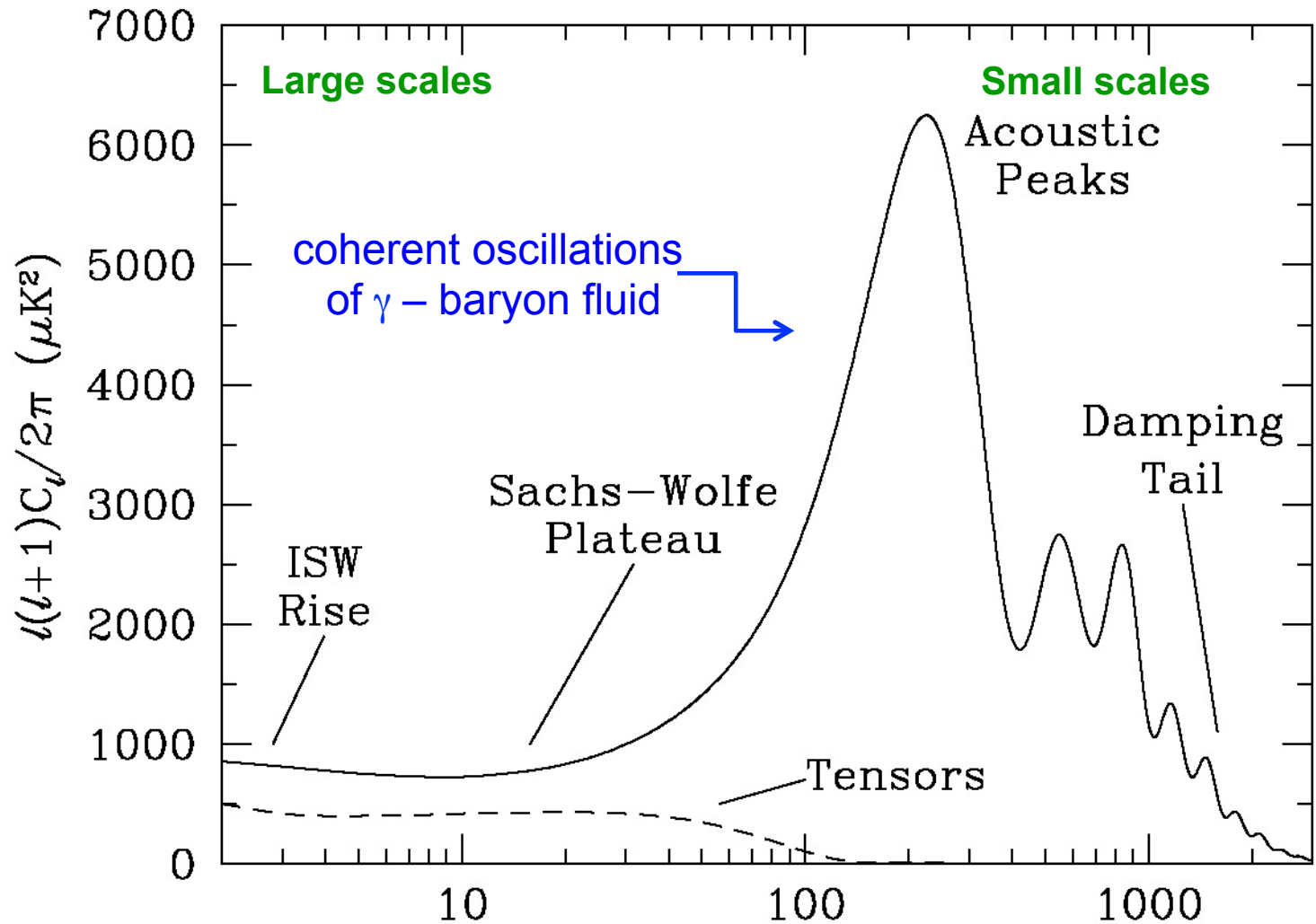
The initial conditions for galaxy formation



Quantum fluctuations from inflation

Temperature anisotropies in CMB

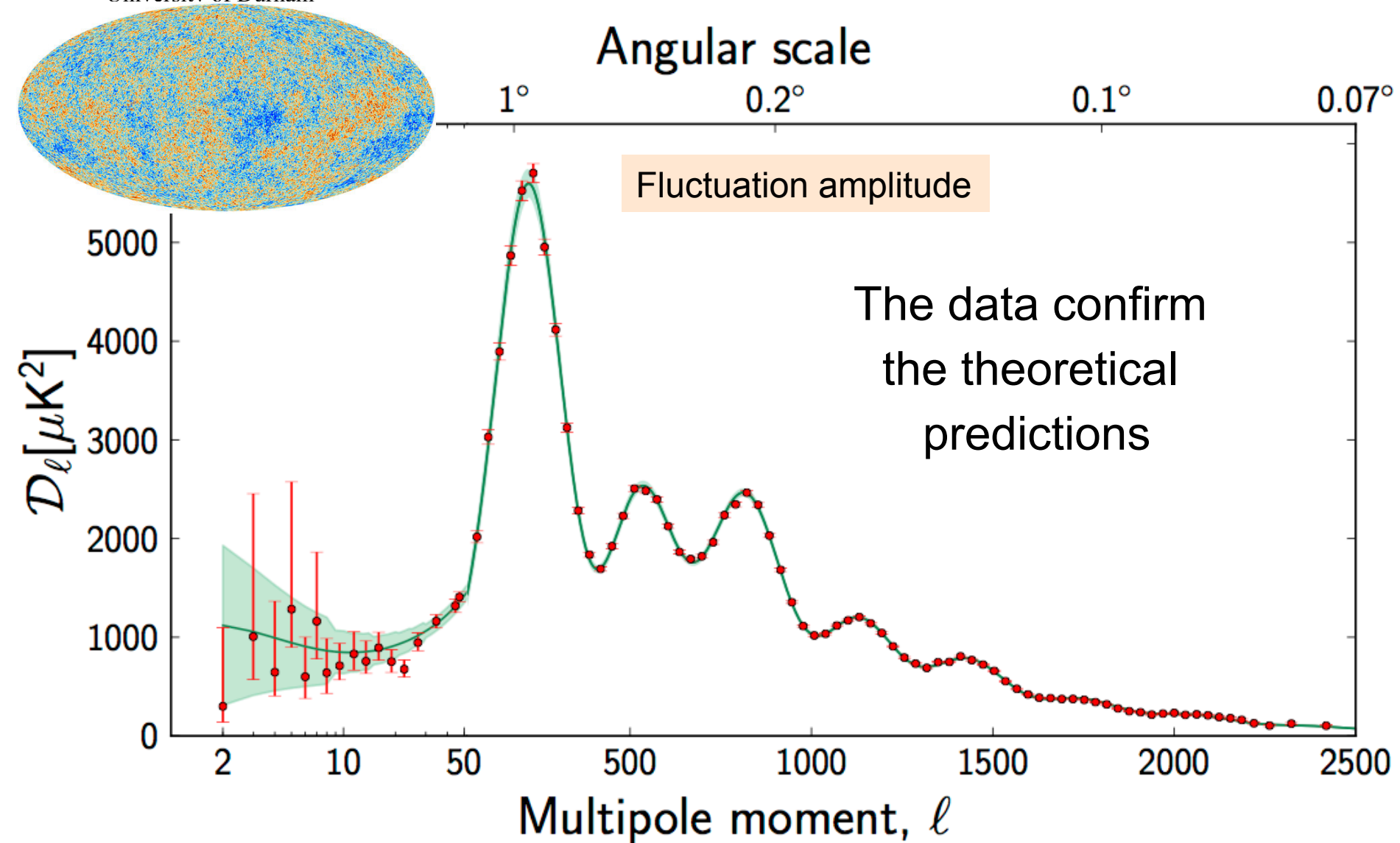
2D power spectrum



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	$\Omega_b h^2$	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!

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

These possibilities can be tested with astrophysics

The dark matter power spectrum

$k^3 P(k)$

The linear power spectrum (“power per octave”)

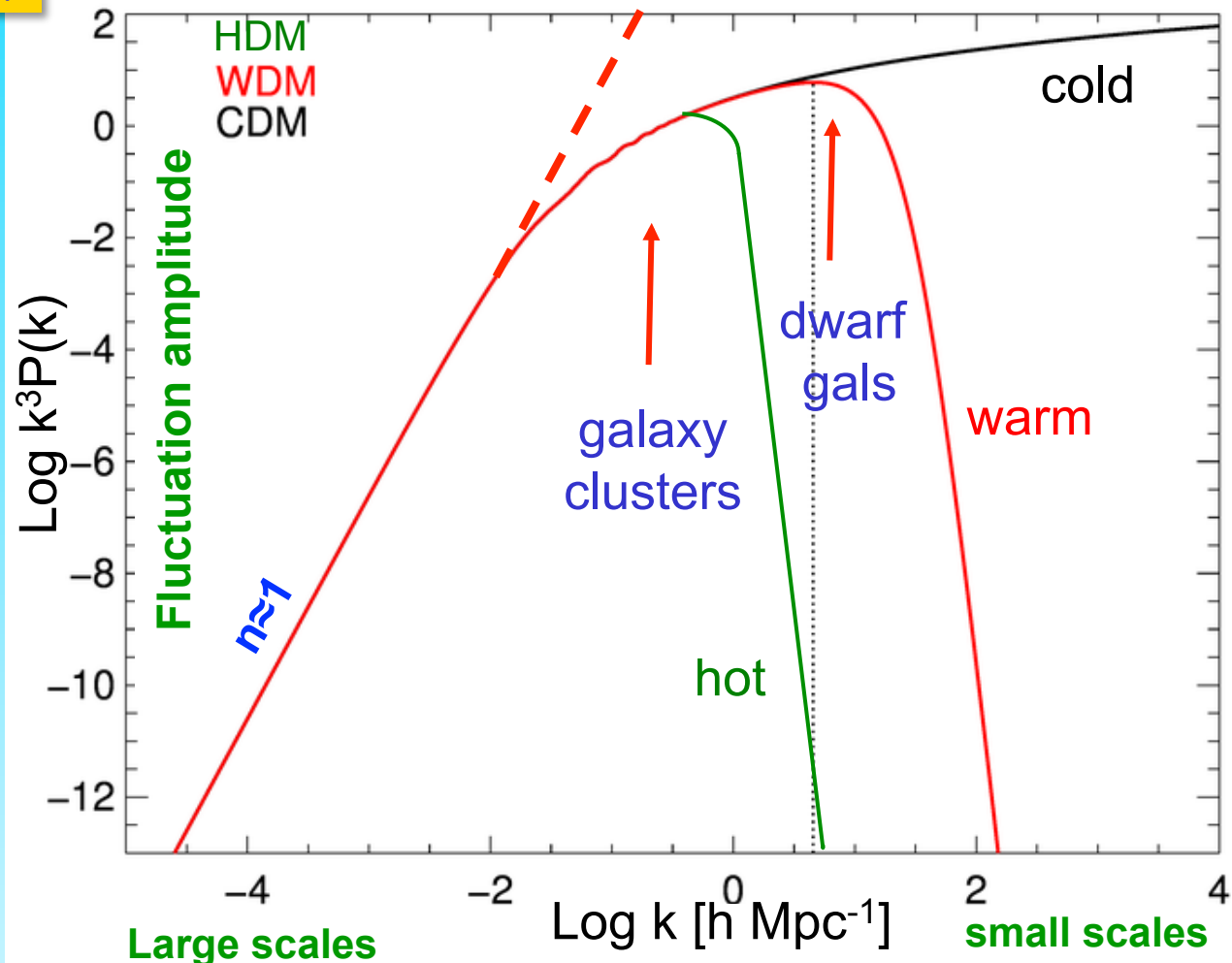
Free streaming $\rightarrow$

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

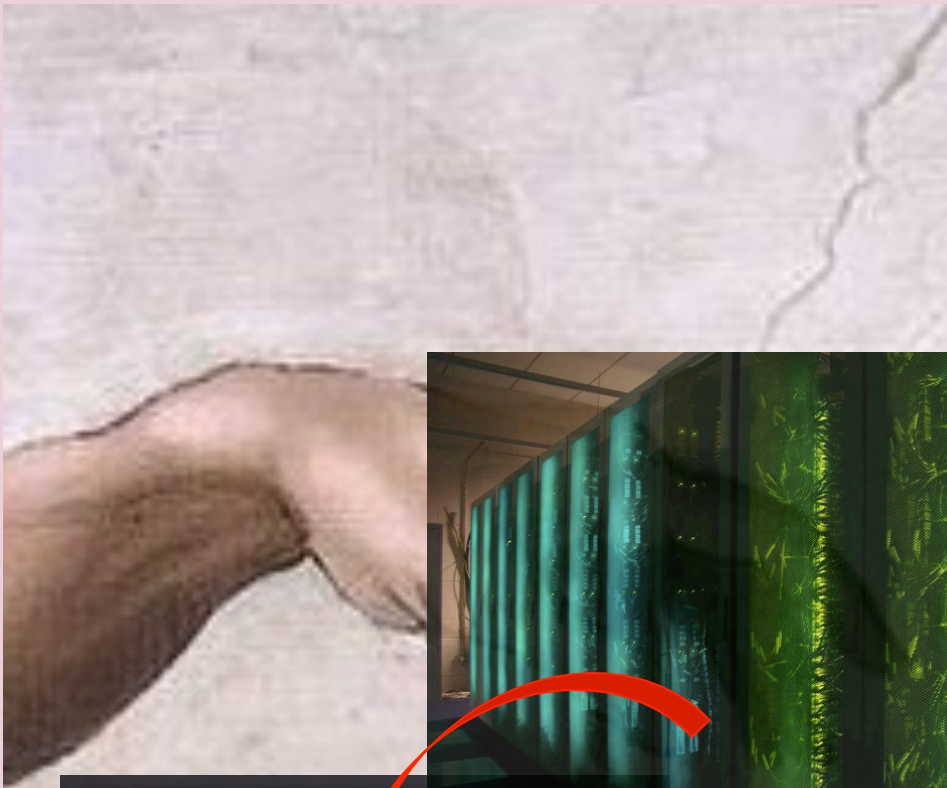
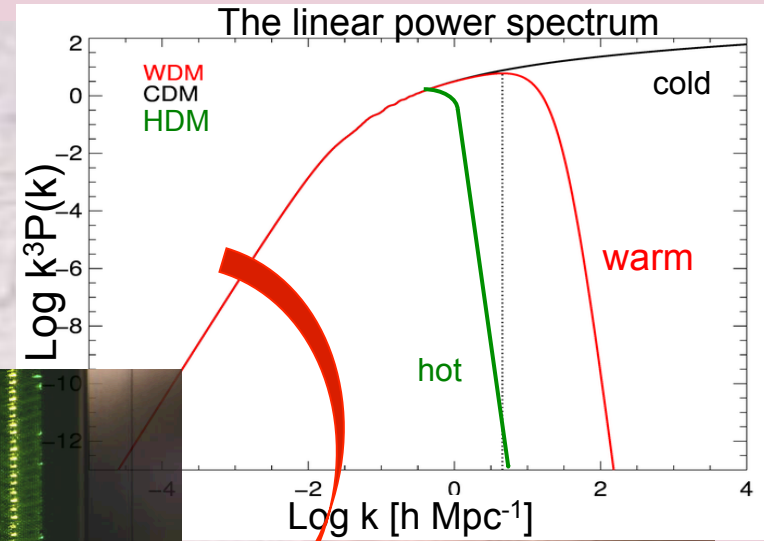
$m_{\text{CDM}} \sim 100 \text{ GeV}$
susy; $M_{\text{cut}} \sim 10^{-6} M_{\odot}$

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

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



Non-linear evolution

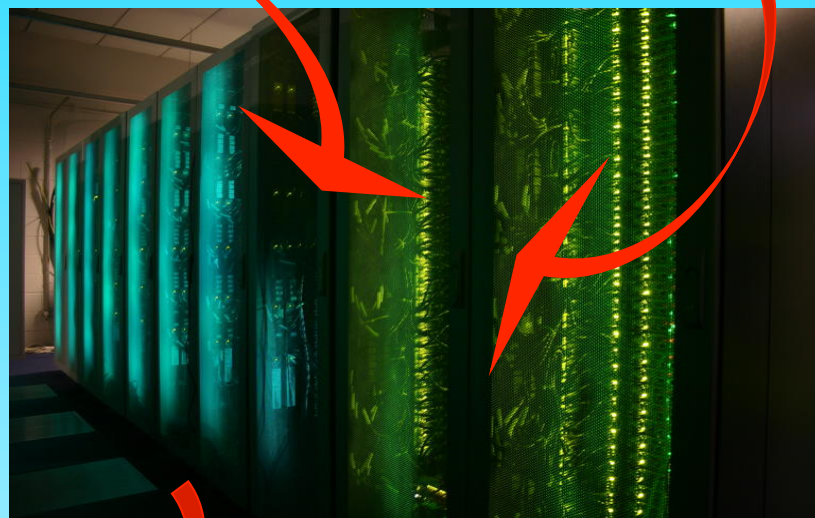


Non-linear evolution: simulations

Initial conditions + assumption about content of Universe

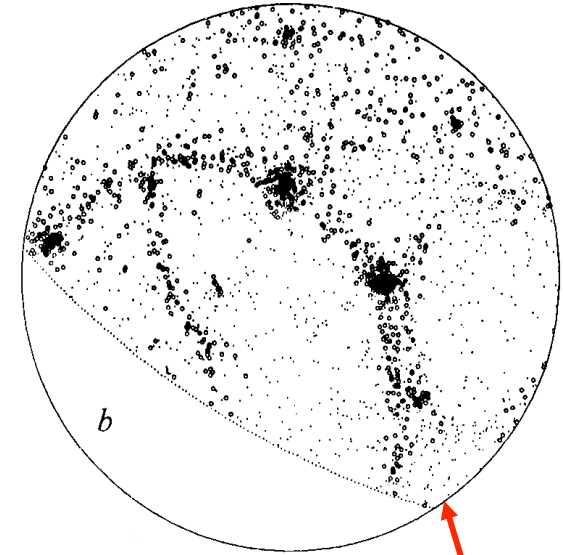
Relevant equations:

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



How to make a virtual universe

Non-baryonic dark matter cosmologies



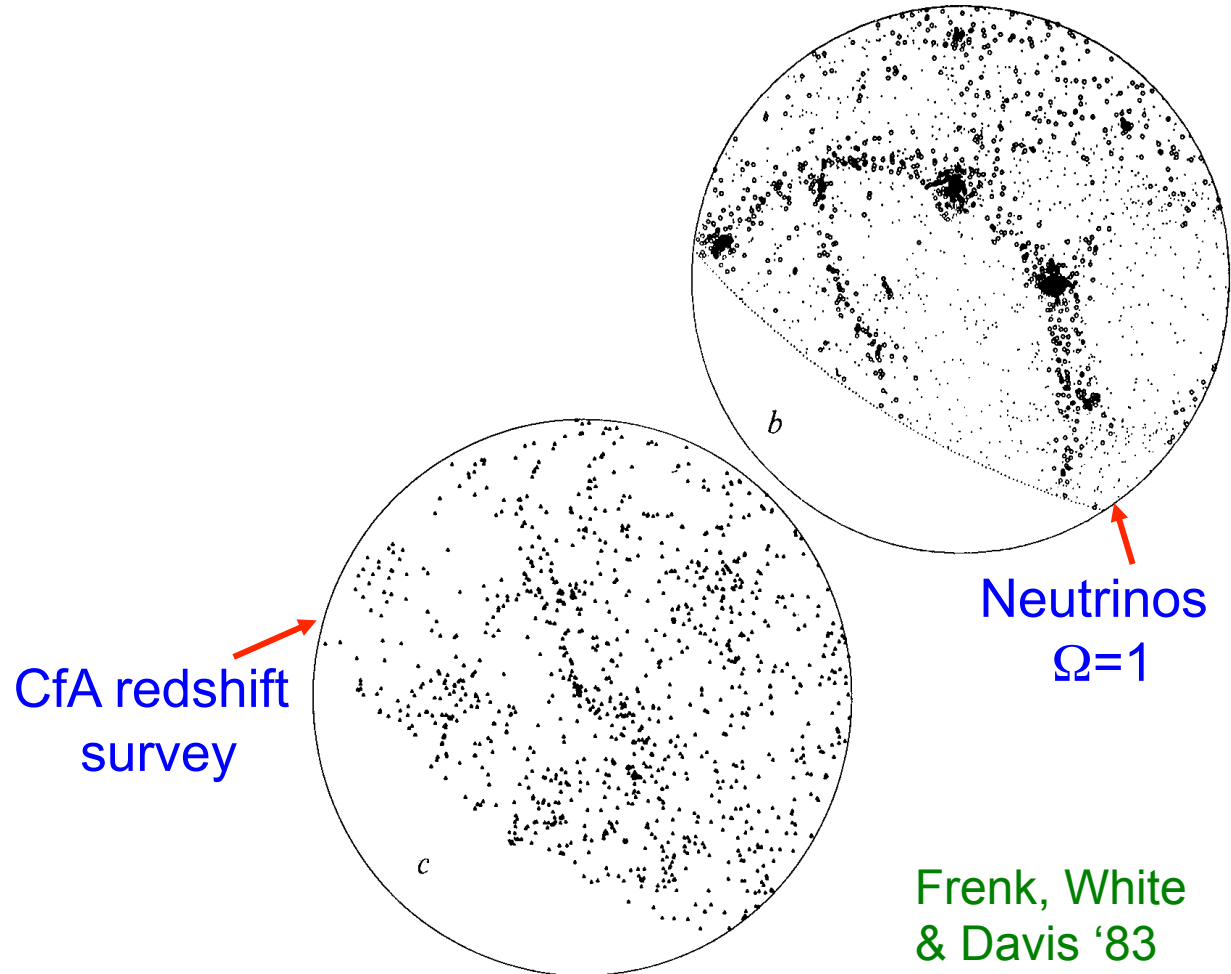
Neutrinos
 $\Omega=1$

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



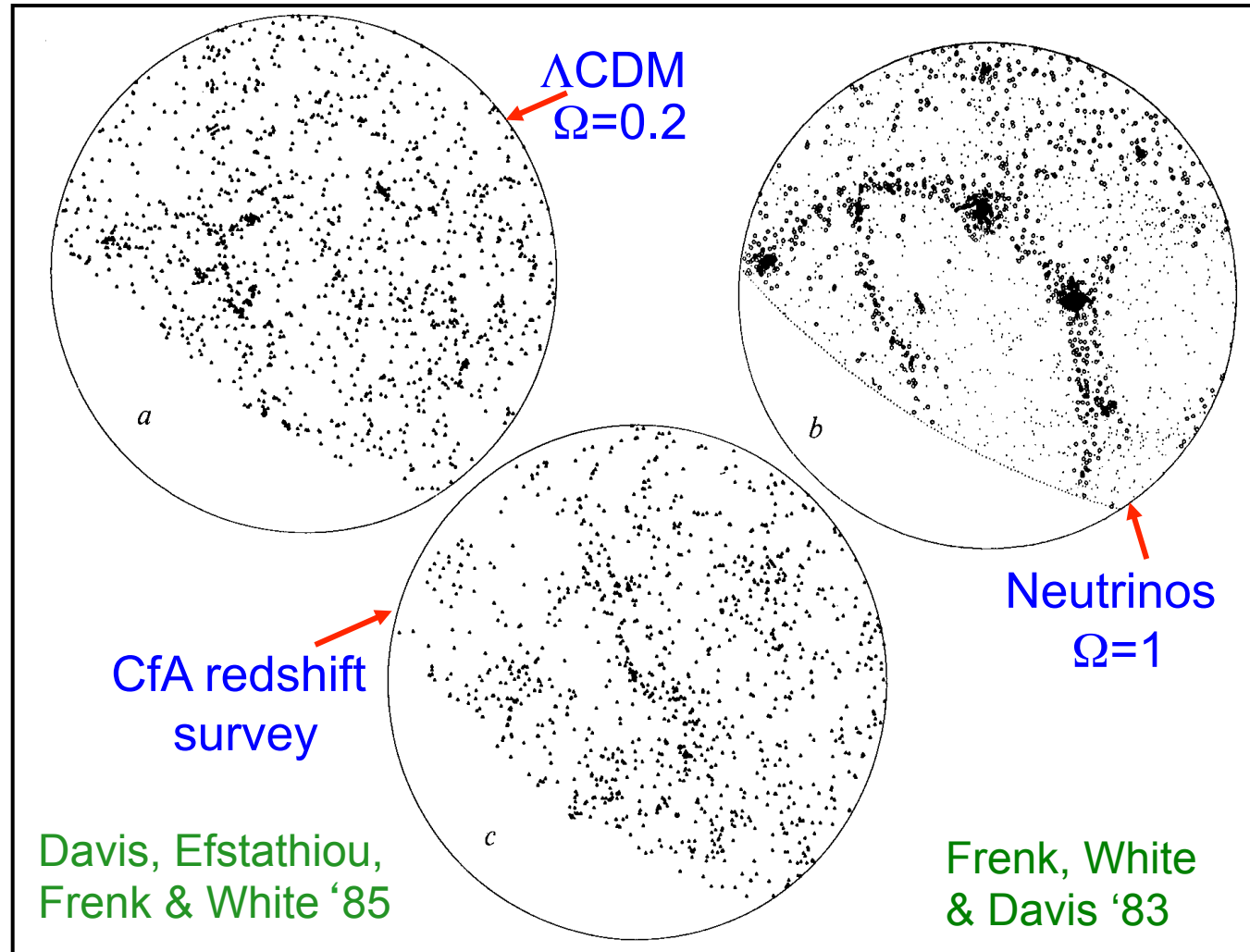
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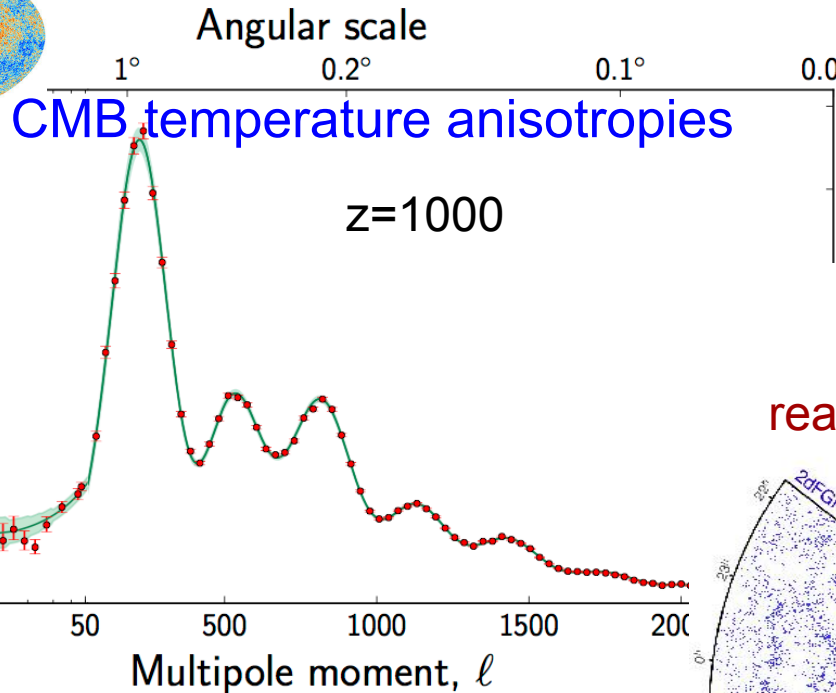
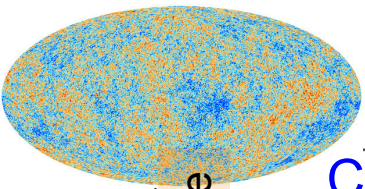
Early CDM N-body
simulations gave
promising results

In CDM structure
forms hierarchically



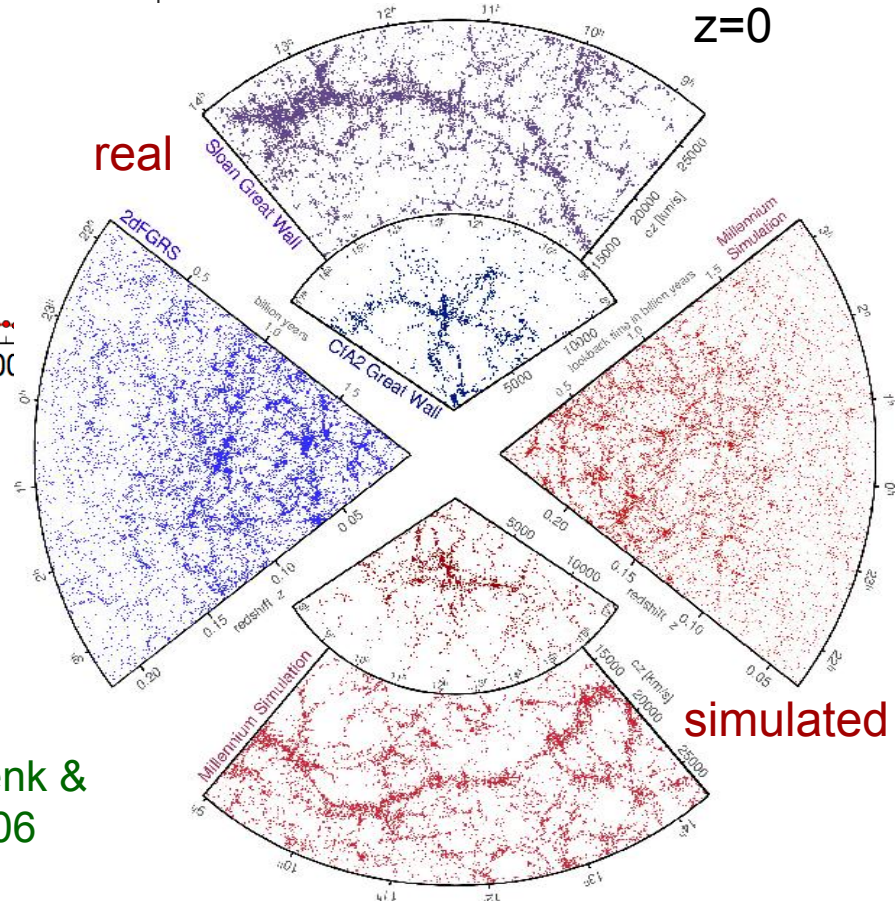
The Λ CDM model of cosmogony

Proposed in 1980s; now empirically supported by:



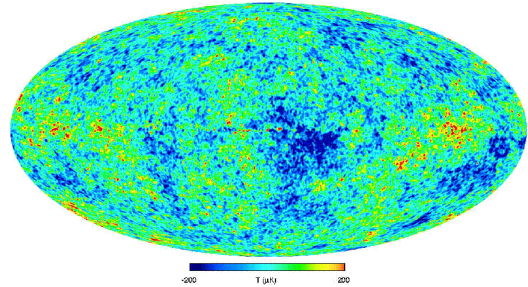
Planck coll. 2015

Galaxy clustering



Springel, Frenk &
White 2006

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

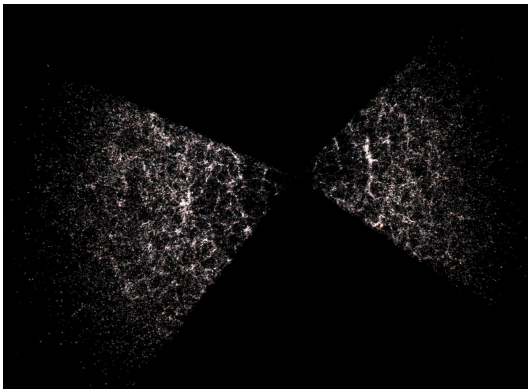


$z \sim 1000$

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

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

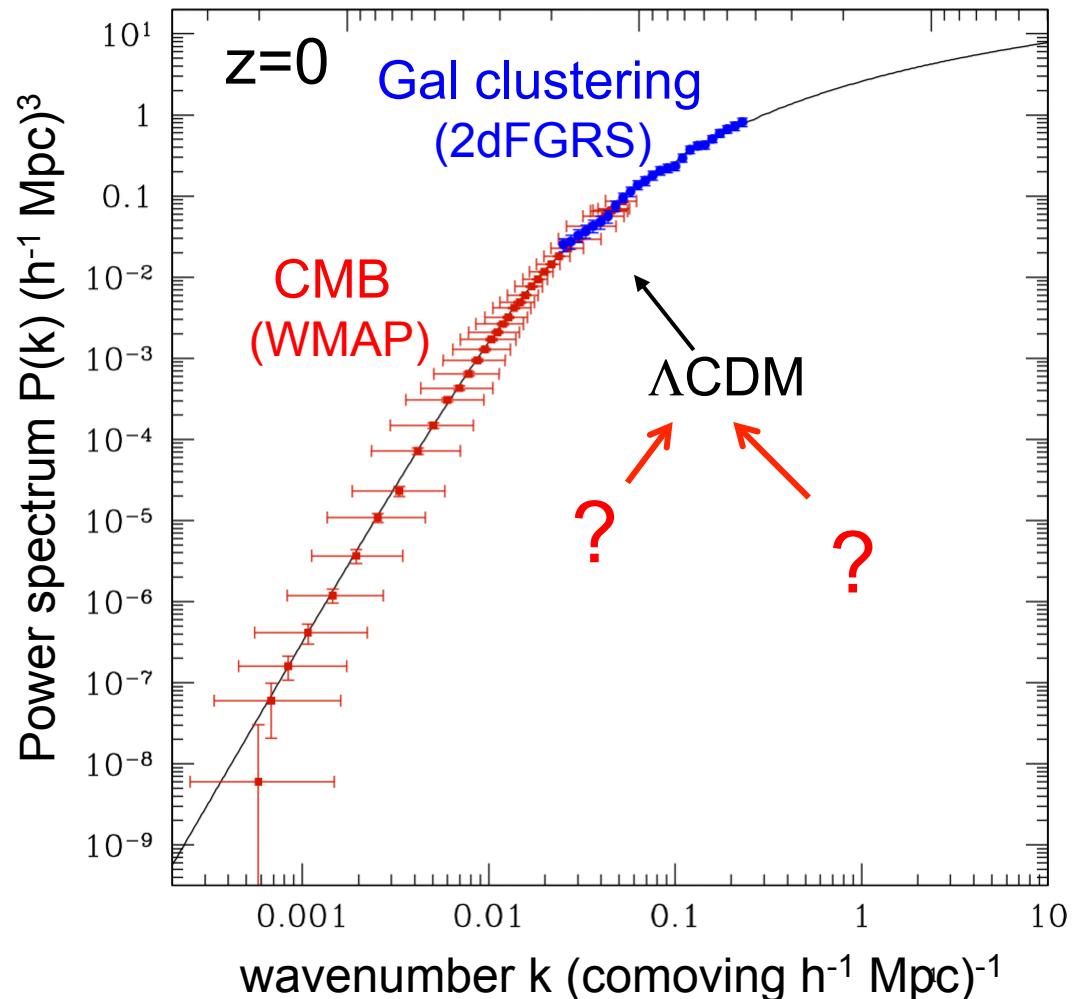
1 000 100 10



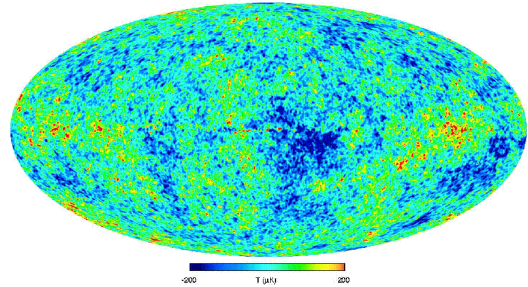
$z \sim 0$

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

Sanchez et al 06



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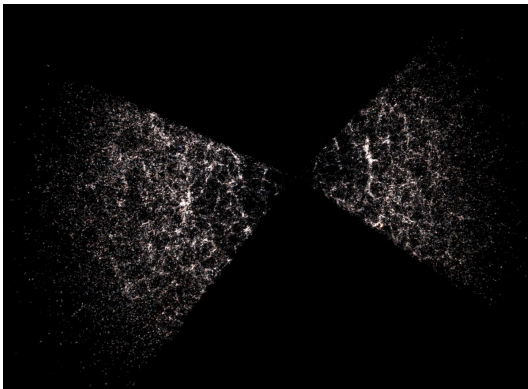


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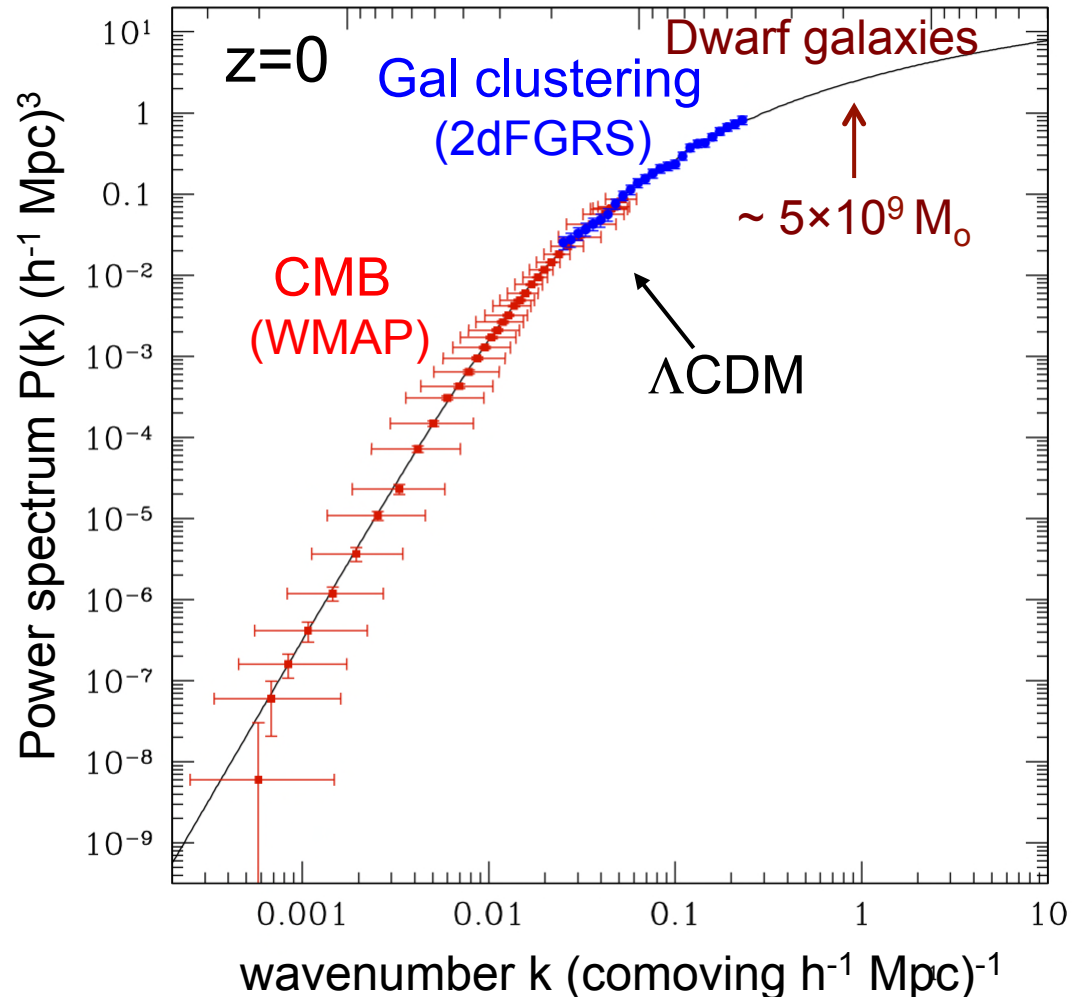
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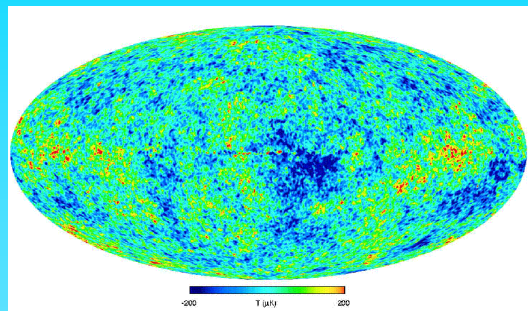
Small-scale “crisis” in CDM

Four problems of CDM:

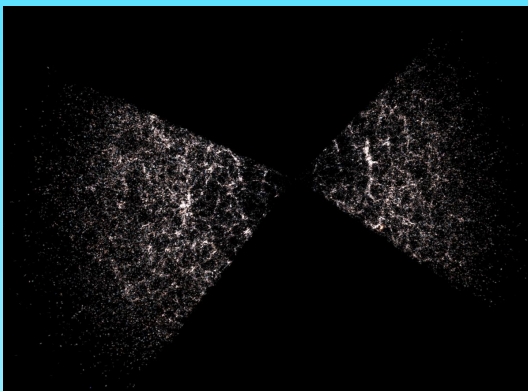
1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “plane of satellites” problem
4. The “core-cusp” problem

See Sawala, CSF + 16 (arXiv:1511.01098)

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



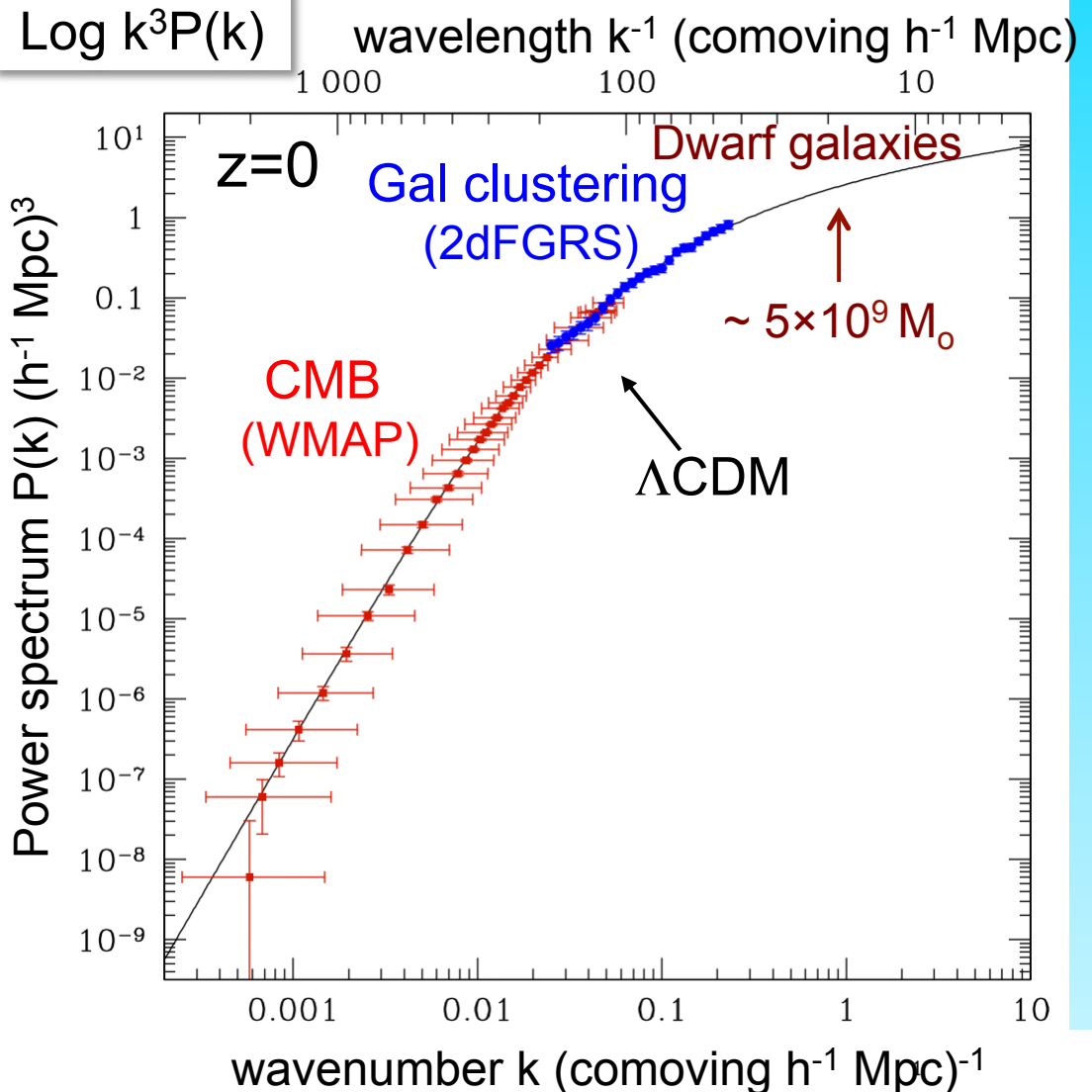
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Sanchez et al 06



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

Free streaming →

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

for thermal relic

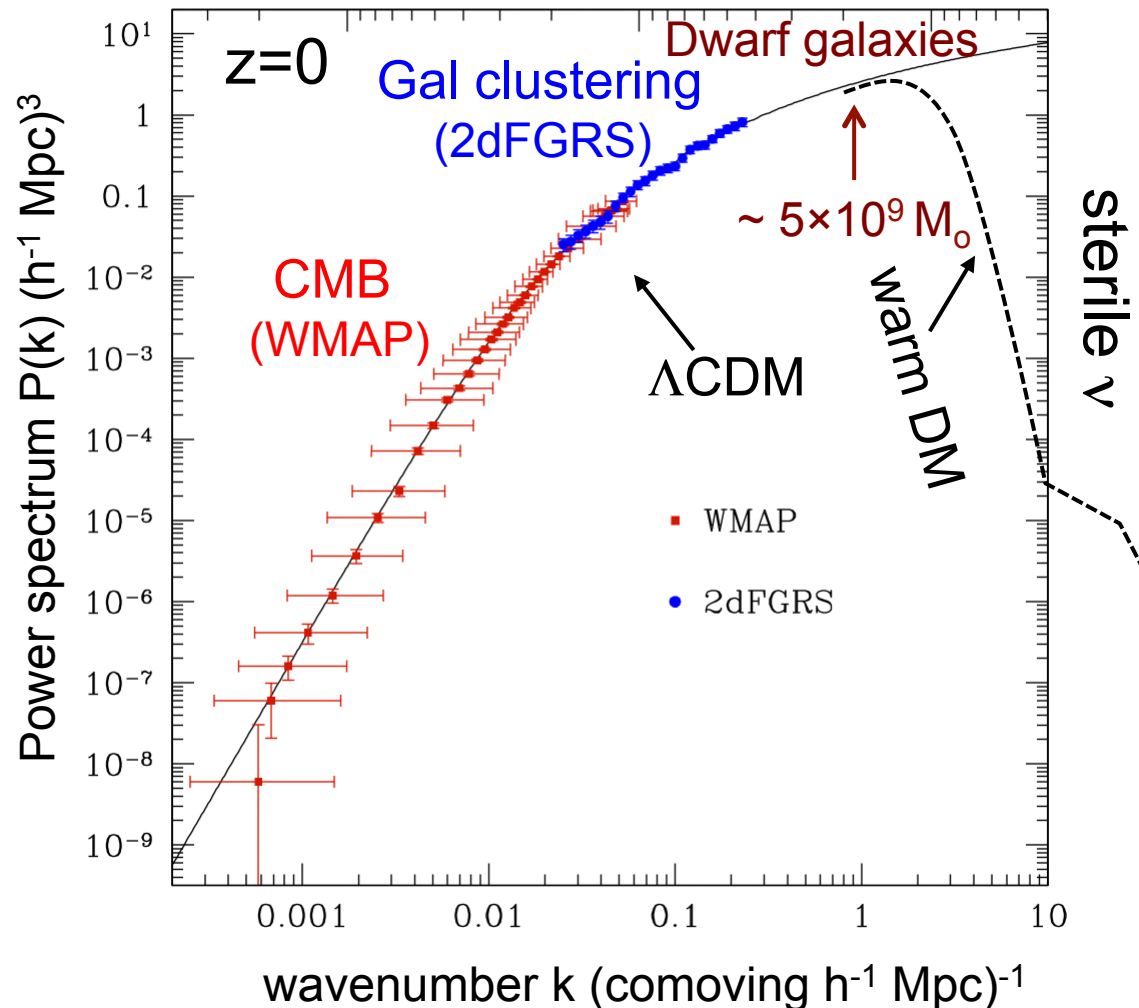
$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

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

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

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

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

Very unlikely that both are right!

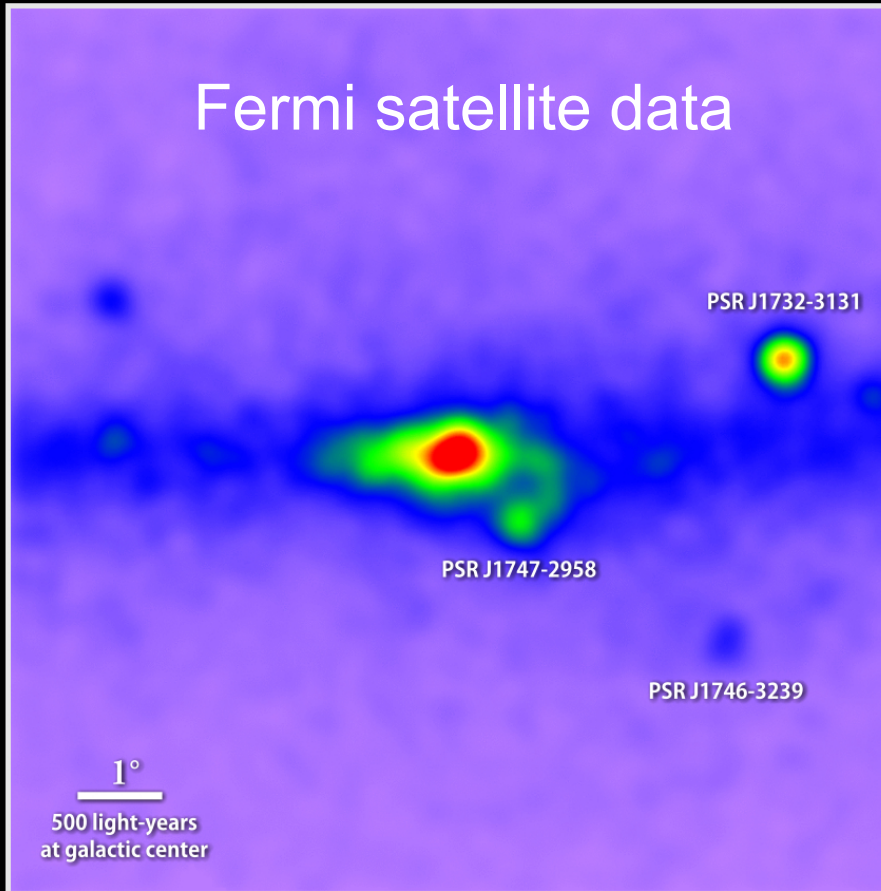
Cold dark matter

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

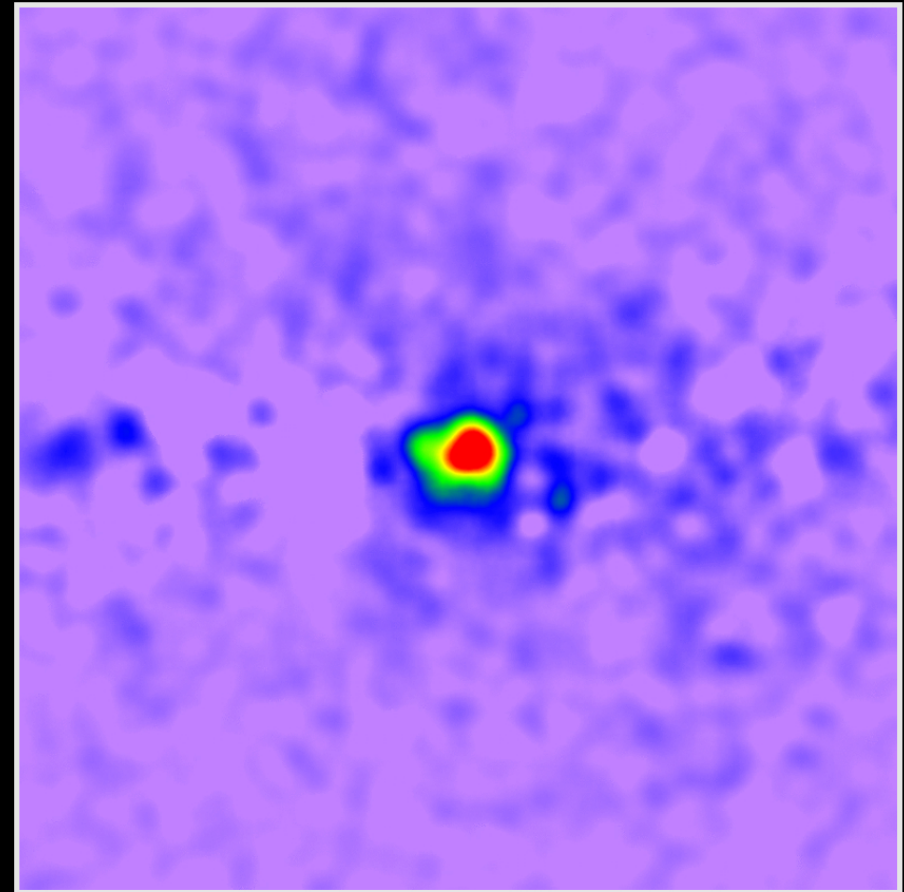
Tansu Daylan,¹ Douglas P. Finkbeiner,^{1,2} Dan Hooper,^{3,4} Tim Linden,⁵
Stephen K. N. Portillo,² Nicholas L. Rodd,⁶ and Tracy R. Slatyer^{6,7}

Uncovering a gamma-ray excess at the galactic center

Fermi satellite data



Unprocessed map of 1.0 to 3.16 GeV gamma rays

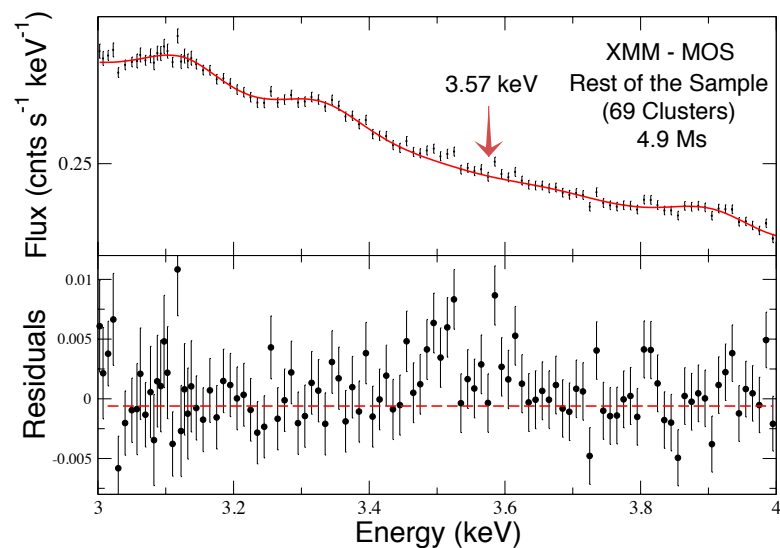
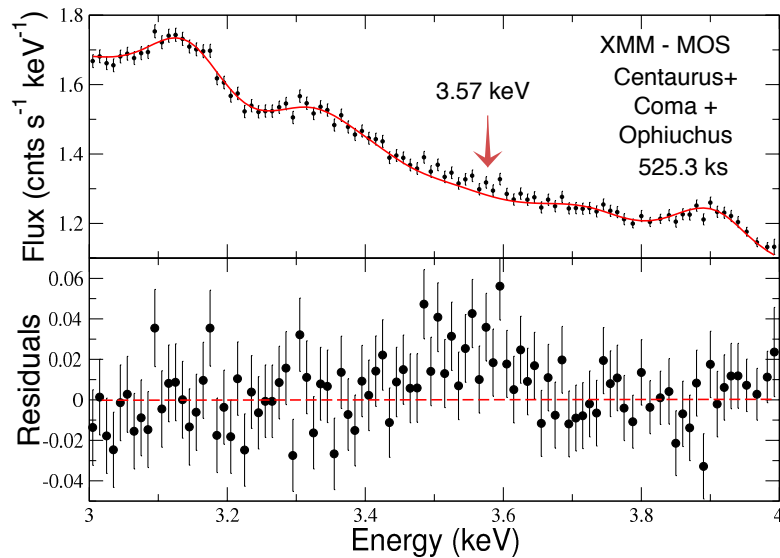
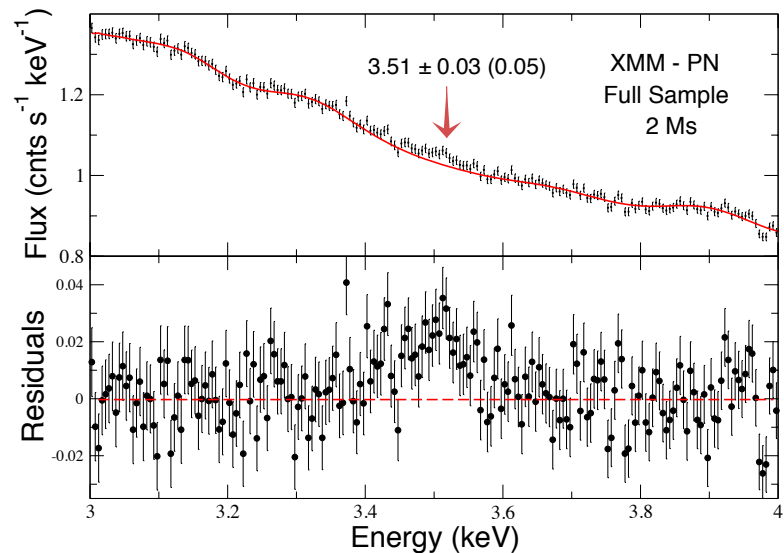
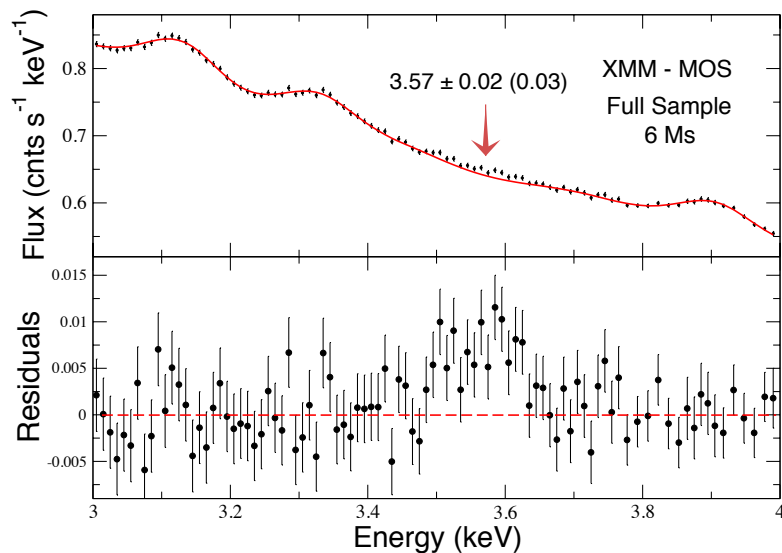


Known sources removed

Warm dark matter WDM decay line in 69 stacked clusters?

E=3.57 keV

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





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

cold dark matter

warm dark matter

How can we distinguish between these?

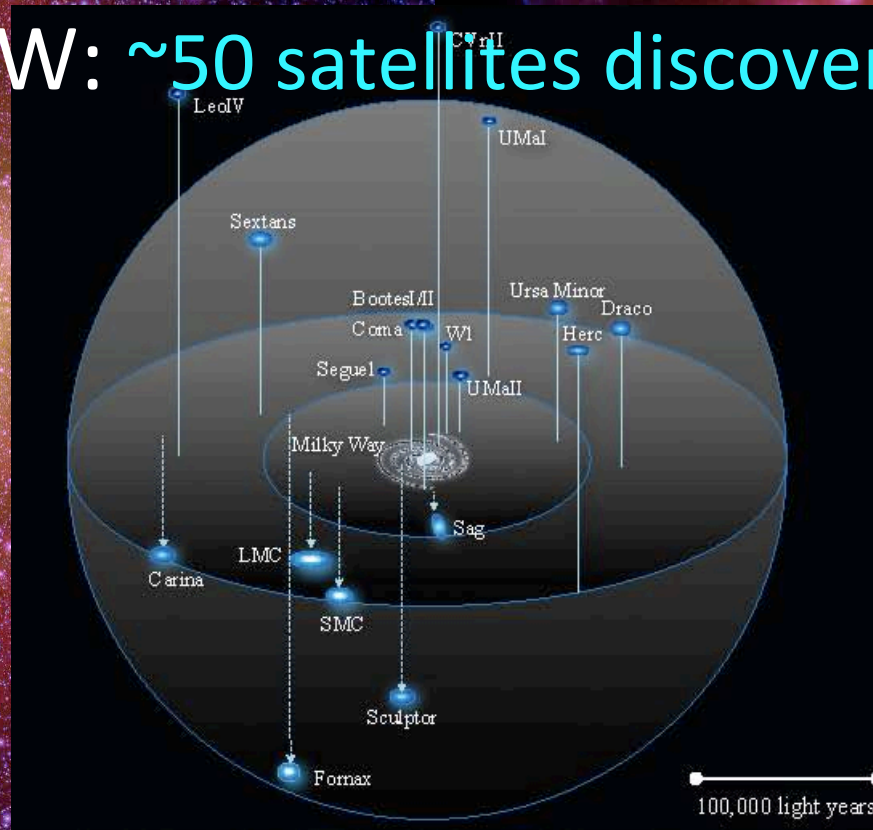
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

cold dark matter

warm dark matter

Obvious test: count satellites in MW or M31

In the MW: ~50 satellites discovered so far

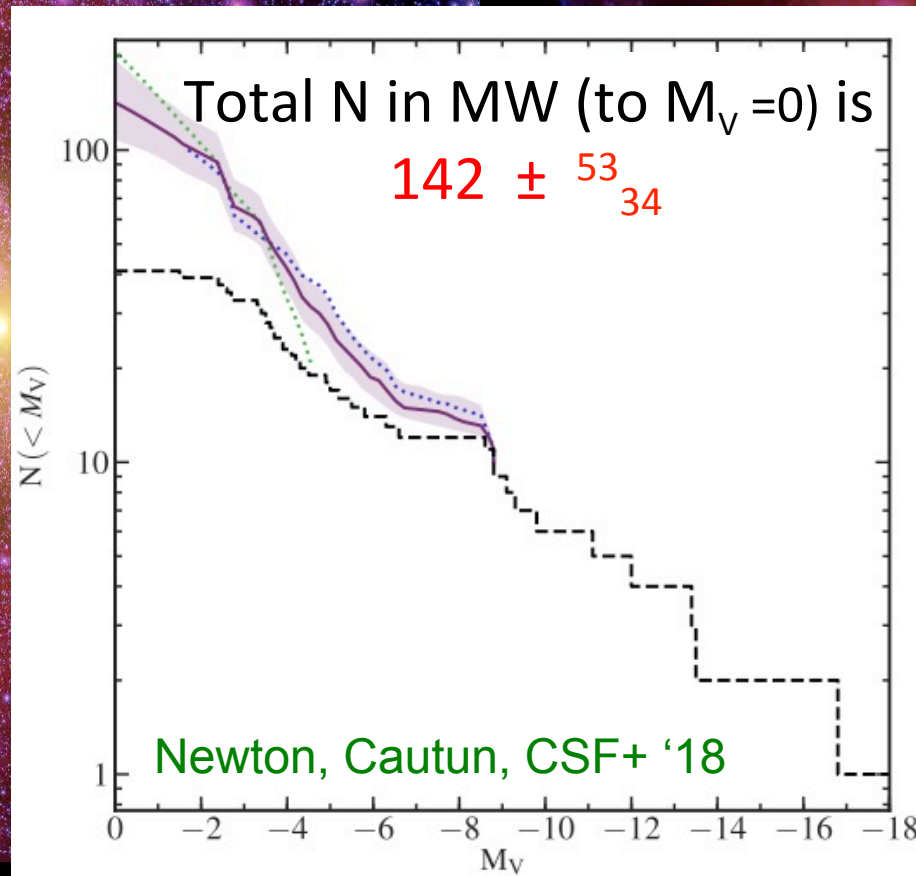


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

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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

This argument is WRONG!

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

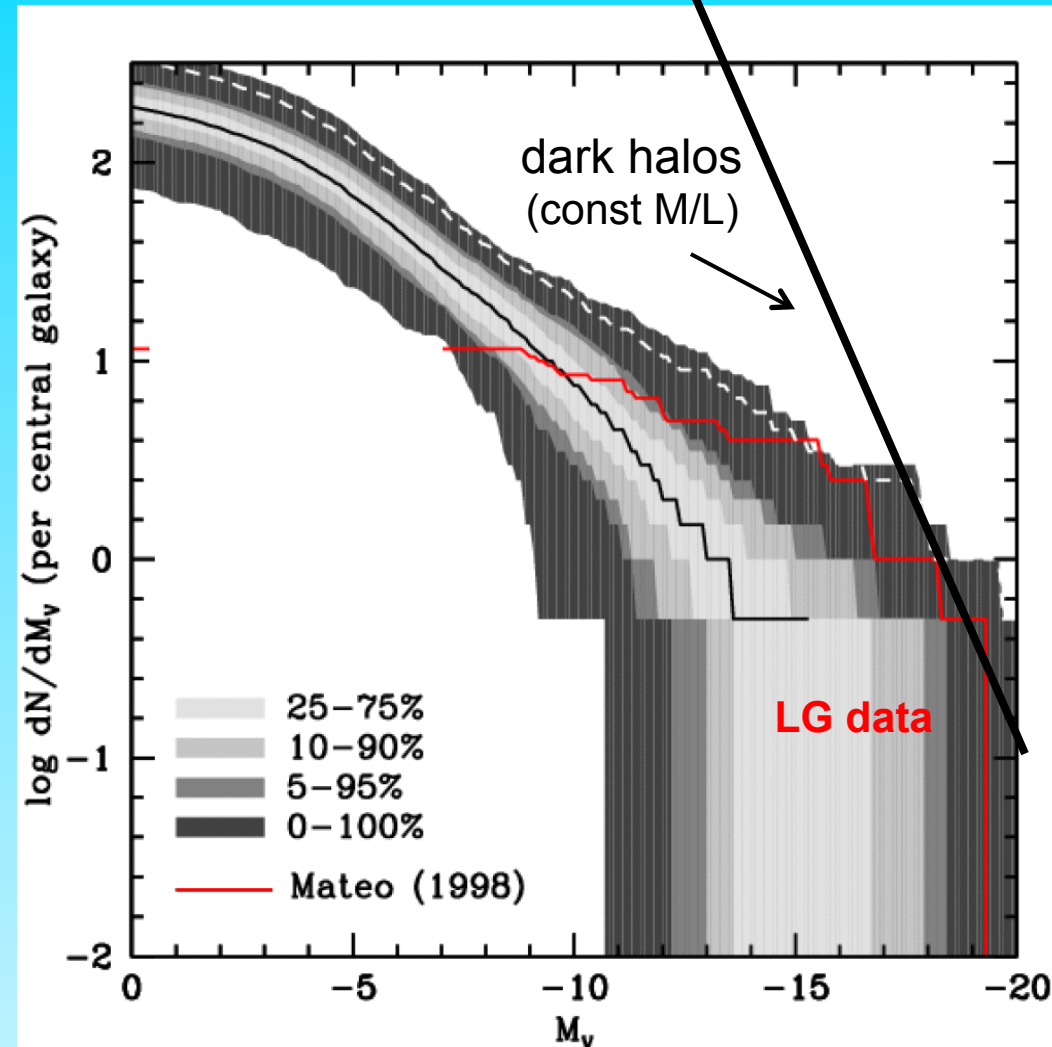
Most subhalos never make a galaxy!

Because:

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

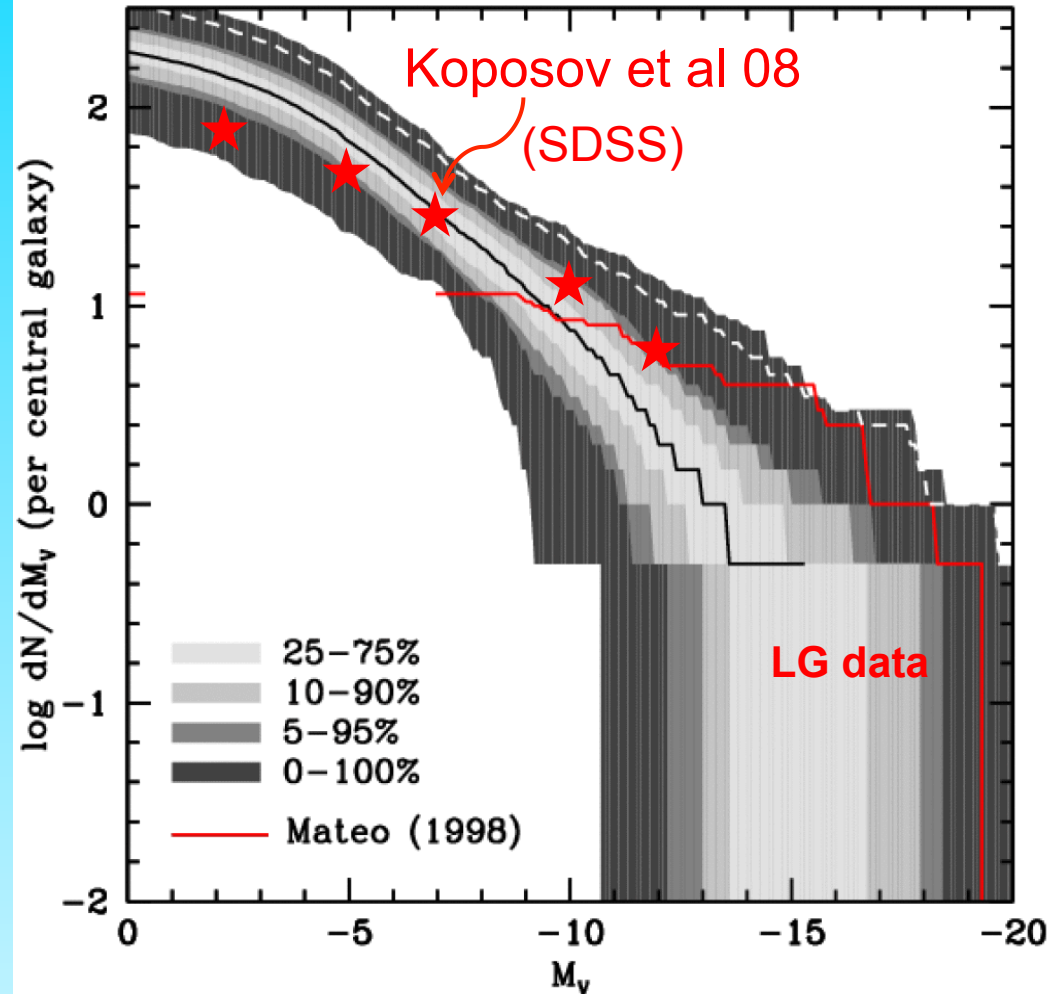
Luminosity Function of Local Group Satellites

- 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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VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and
their environment”

THE EAGLE PROJECT

Virgo Consortium

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

Leiden: Rob Crain, Joop Schaye.

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

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

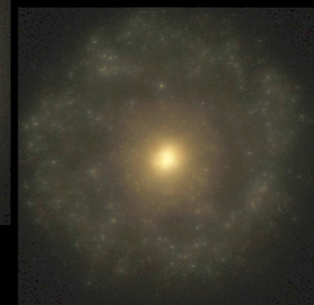
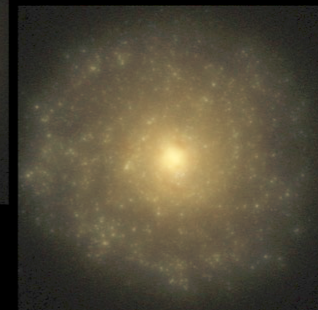
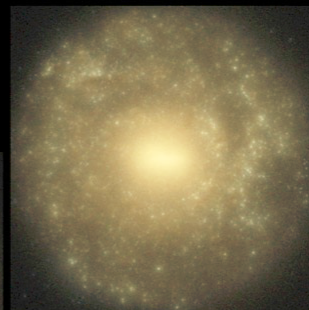
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



S

Irr

Trayford et al '15



VIRG

Dark matter

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala et al '16



Stars

VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

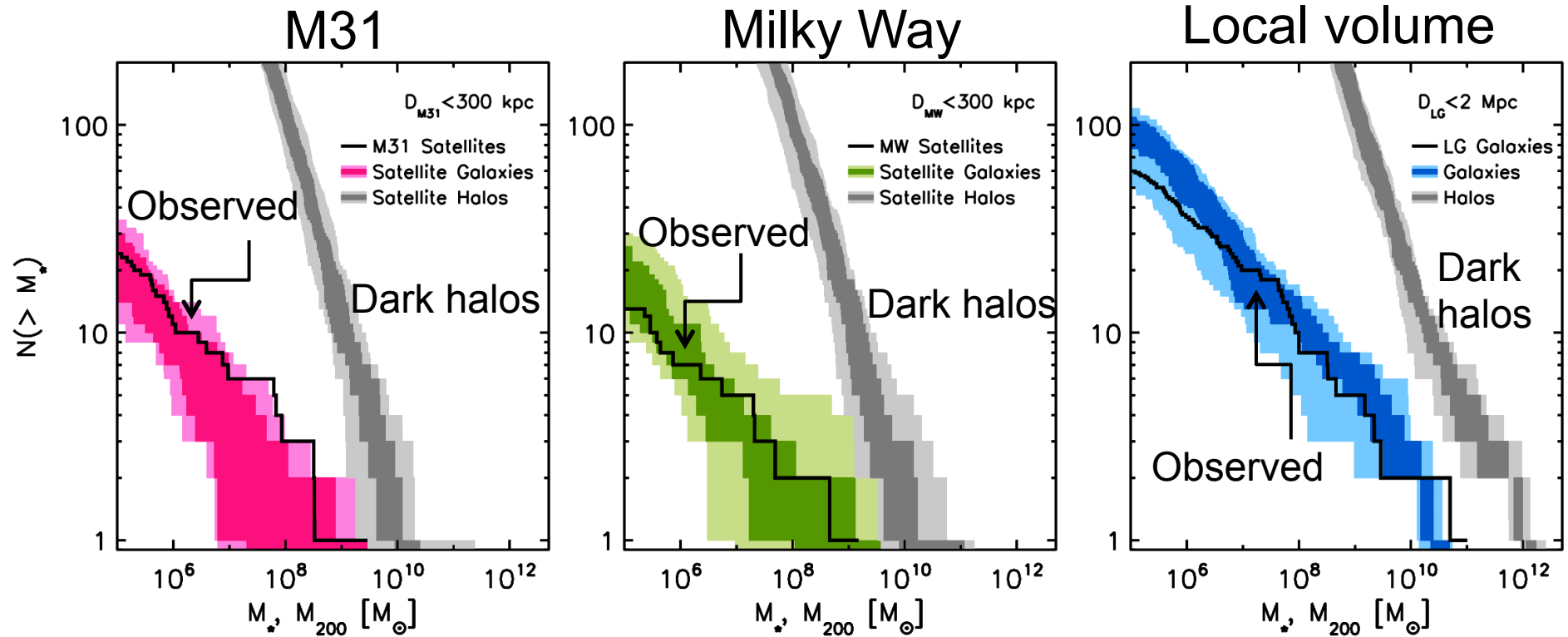
Stars

Far fewer satellite galaxies than CDM halos

Sawala et al '16



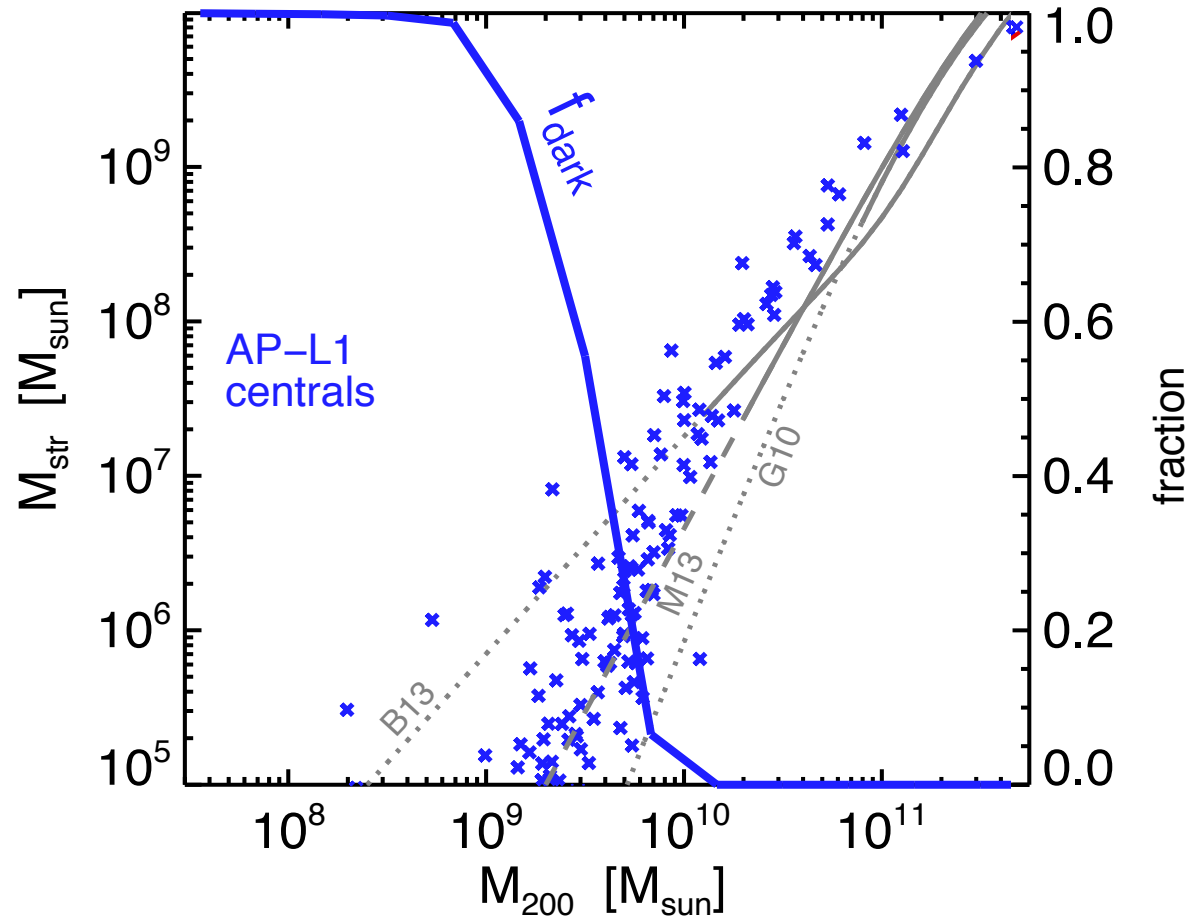
EAGLE Local Group simulation



Fraction of dark subhalos

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

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

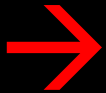


All halos of mass $< 5 \times 10^8 M_{\odot}$ or $V_{\max} < 7 \text{ km/s}$ are dark ($m_* < 10^4 M_{\odot}$)

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!

CDM in “crisis”

Four problems of CDM:

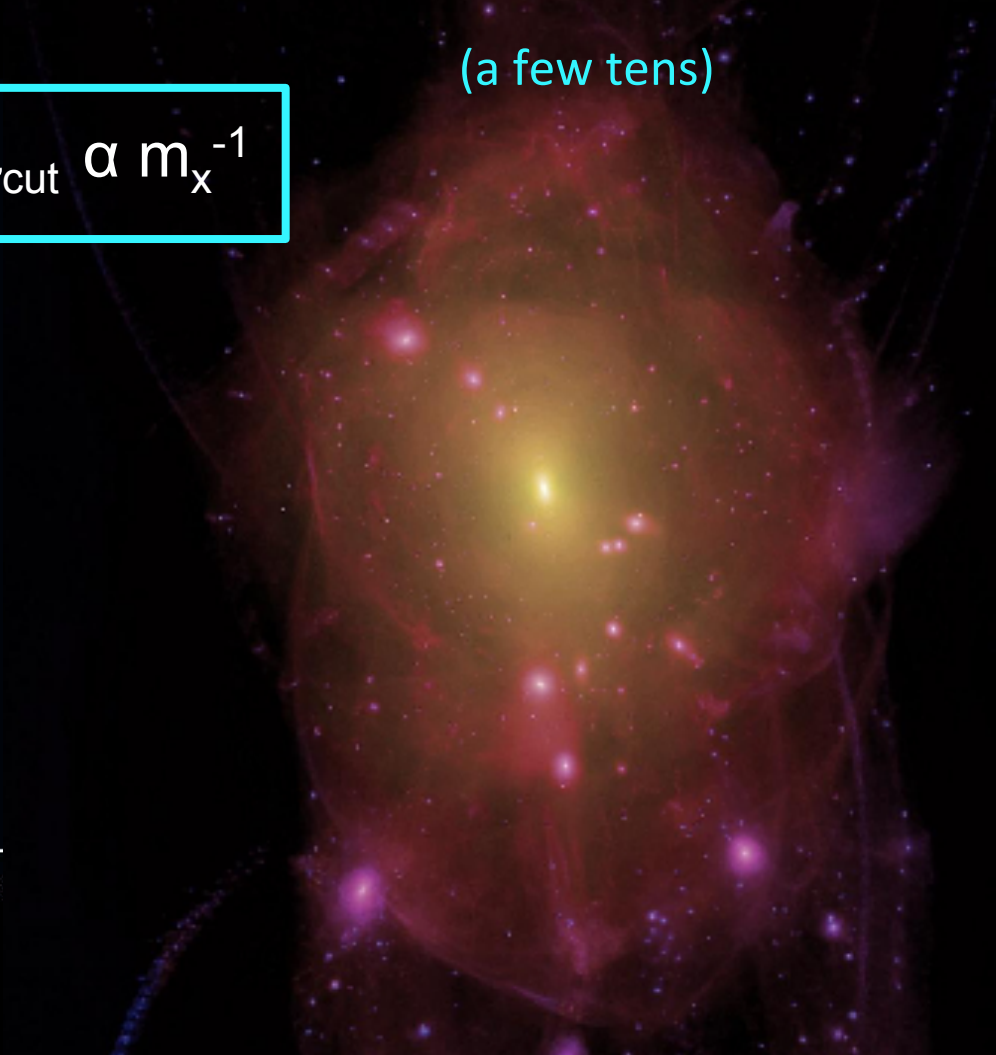
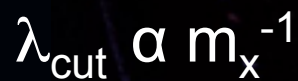
- ~~1. The “missing satellites” problem~~
2. The “too-big-to-fail” problem
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4. The “core-cusp” problem

See Sawala, CSF + 16 (arXiv:1511.01098)



Dark matter subhalos in WDM

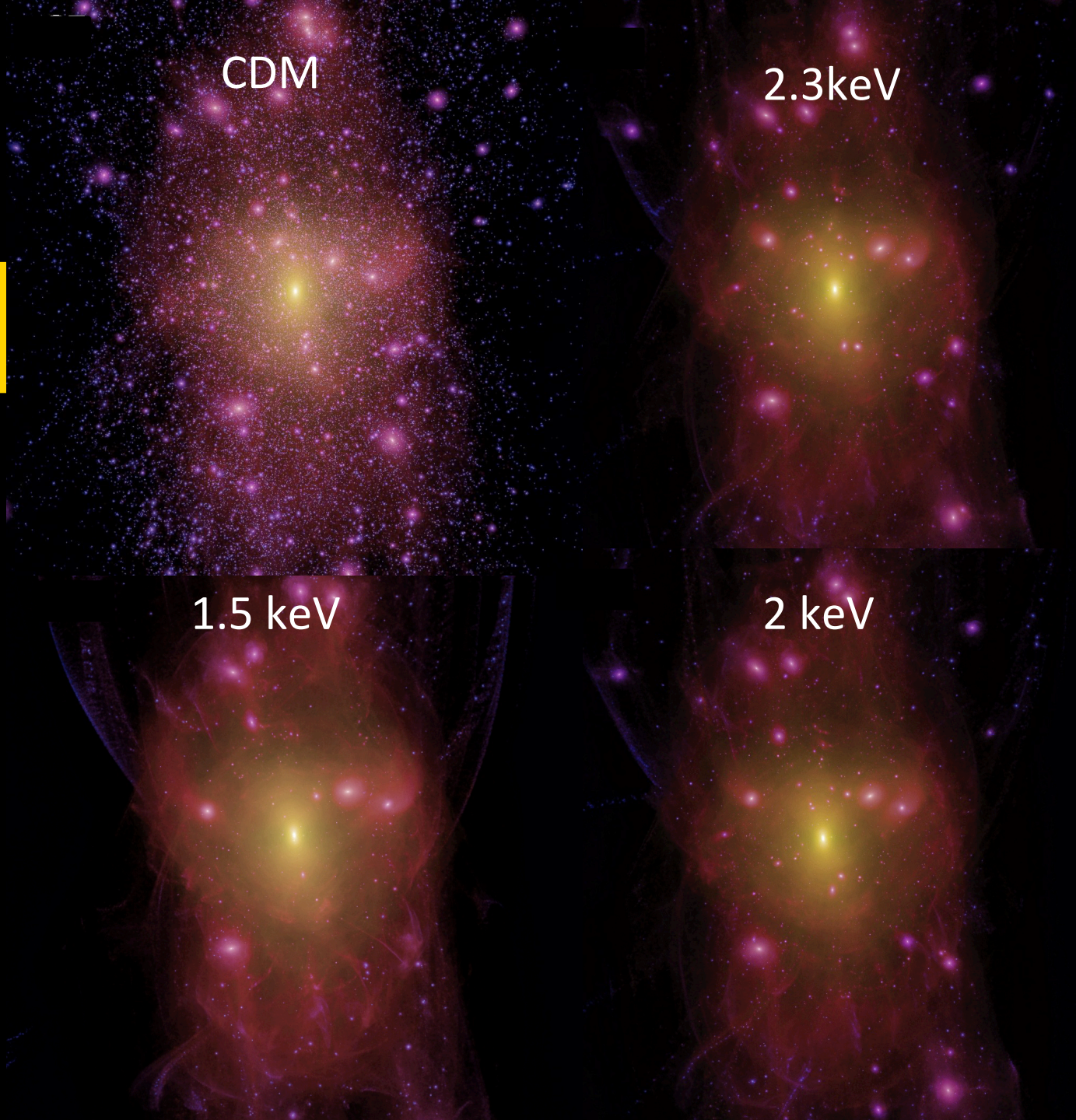
(a few tens)





Warm DM:
different ν mass

- WDM
- 2.3 keV
- 2.0 keV
- 1.5 keV

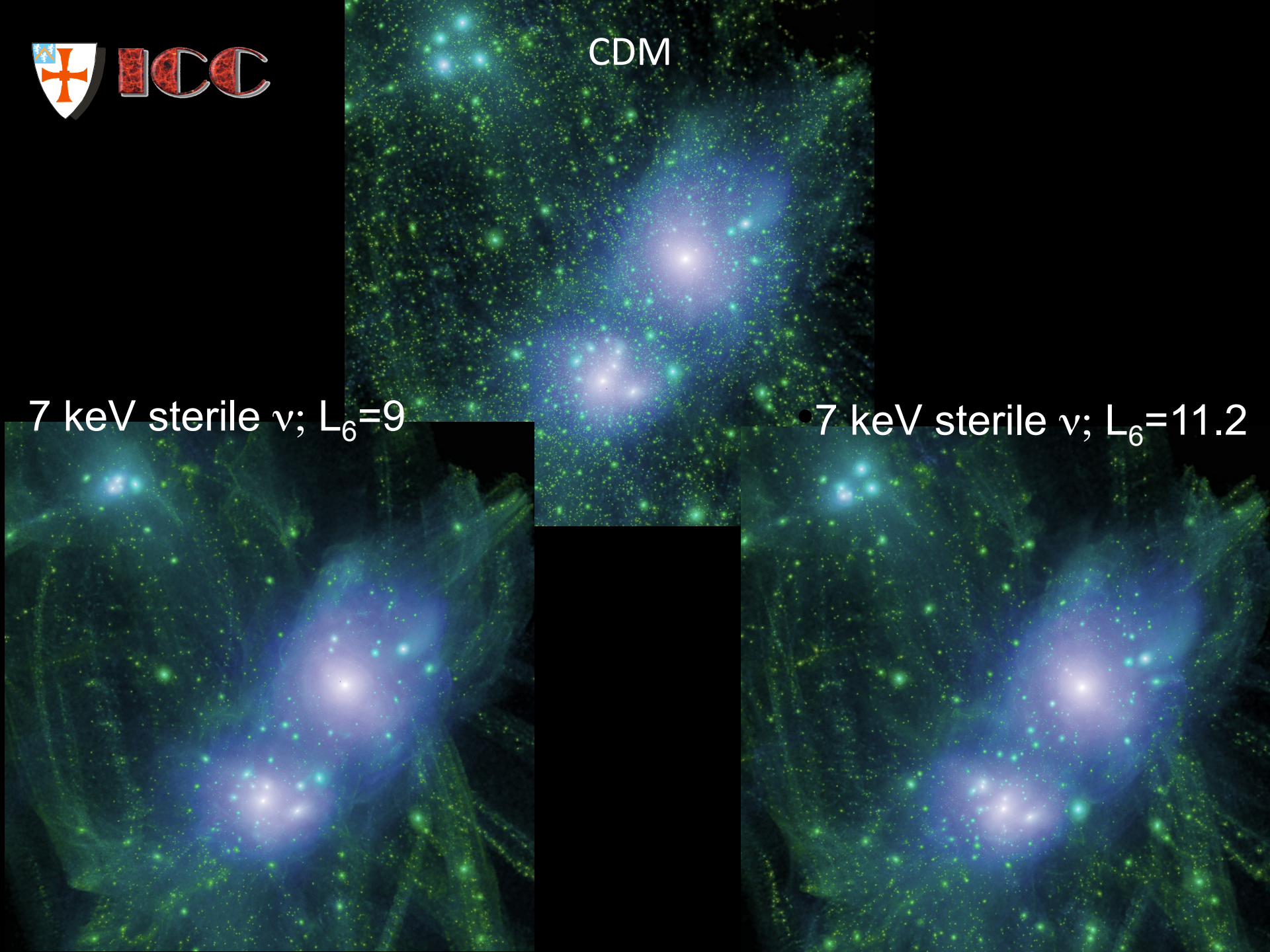




CDM

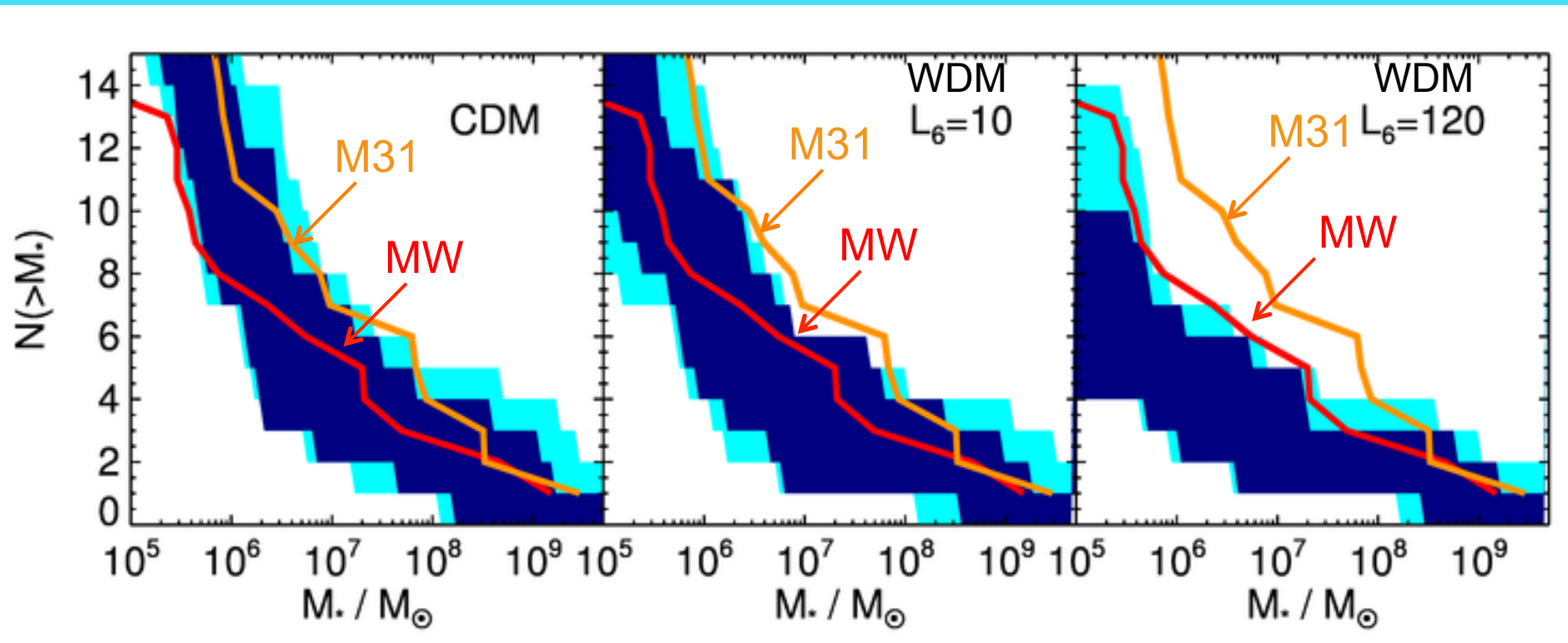
7 keV sterile ν ; $L_6=9$

• 7 keV sterile ν ; $L_6=11.2$



Luminosity Function of Local Group Satellites in WDM

From “Warm Apostle:” 7keV sterile ν $M_h \sim 10^{12} M_\odot$



→ Can rule out parts of sterile ν parameter space

CDM in “crisis”

Four problems of CDM:

- ~~1. The “missing satellites” problem~~
2. The “too-big-to-fail” problem
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See Sawala, CSF + 16 (arXiv:1511.01098)

CDM in “crisis”

Four problems of CDM:

~~1. The “missing satellites” problem~~

~~2. The “too-big-to-fail” problem~~

→ Solved by (subtle) **baryon** effects

CDM in “crisis”

Four problems of CDM:

~~1. The “missing satellites” problem~~

~~2. The “too-big-to fail” problem~~

~~3. The “plane of satellites” problem~~

→ Solved by doing the statistics properly
(Cautun, CSF+ '17)

CDM in “crisis”

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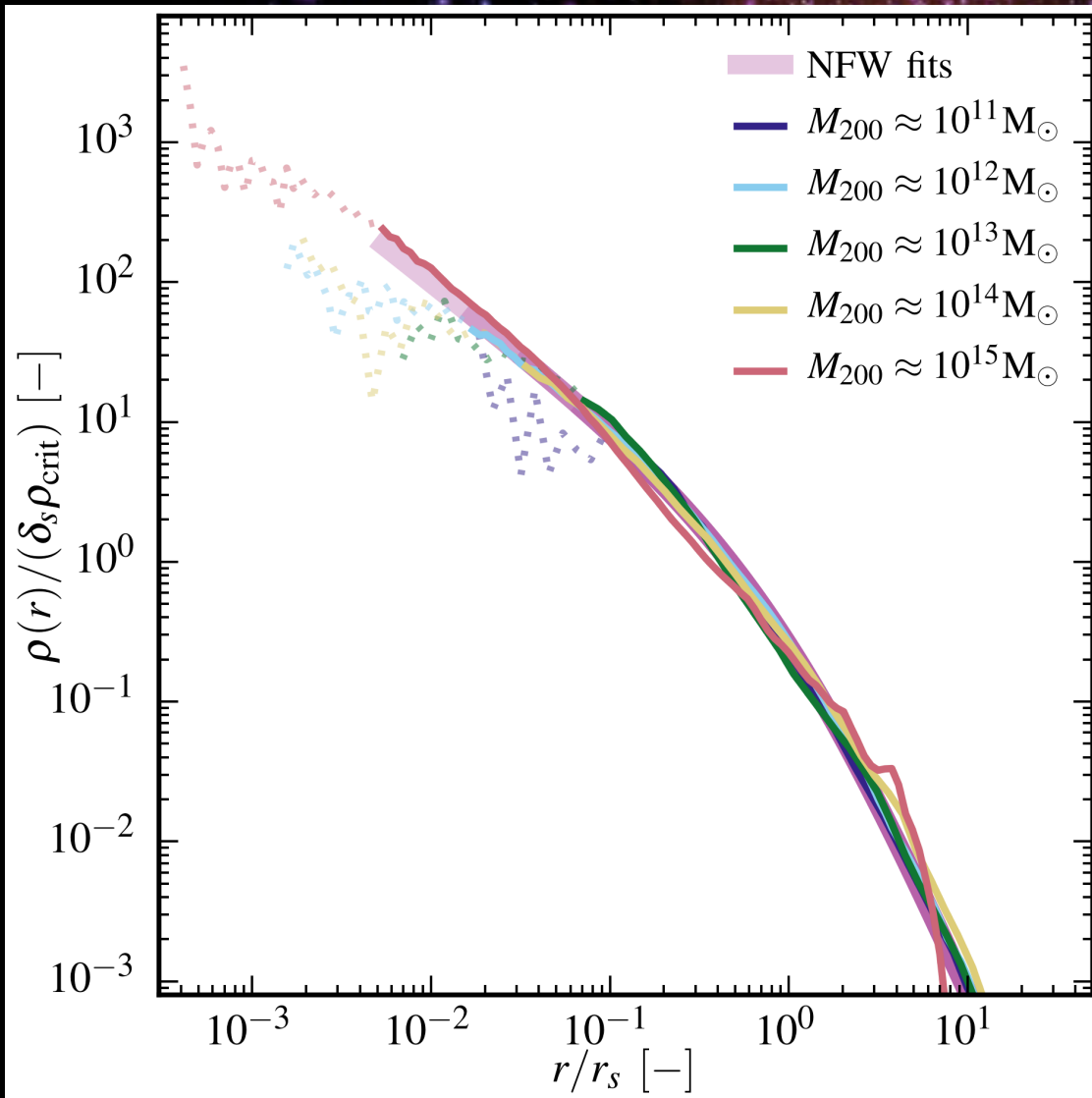
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4. The “core-cusp” problem

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)



The core-cusp problem

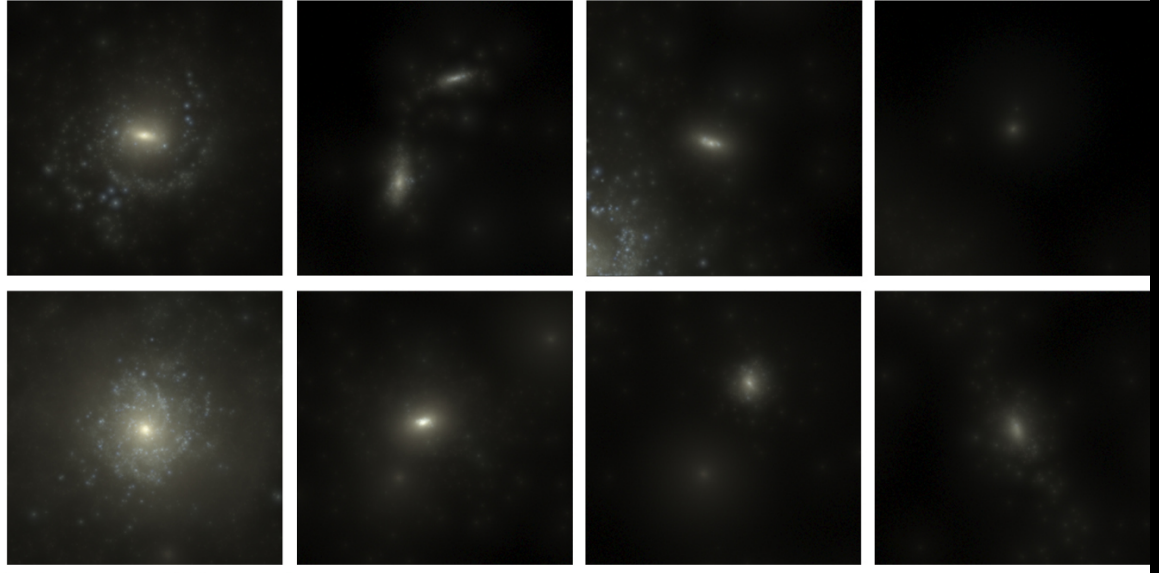
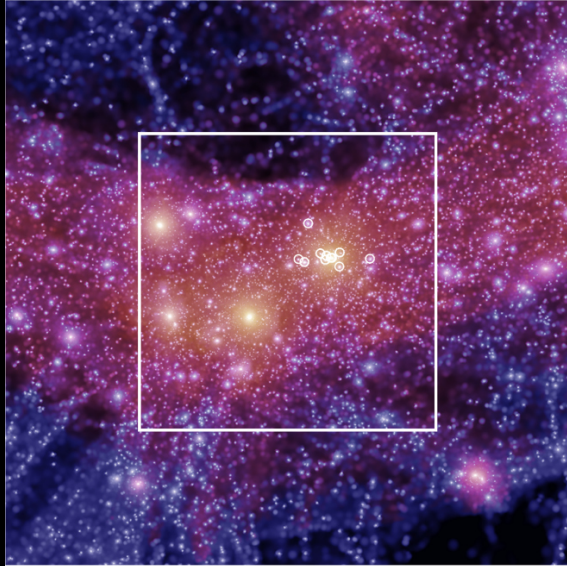
cold dark matter

warm dark matter

Halos and subhalos in CDM & WDM have
cuspy NFW profiles

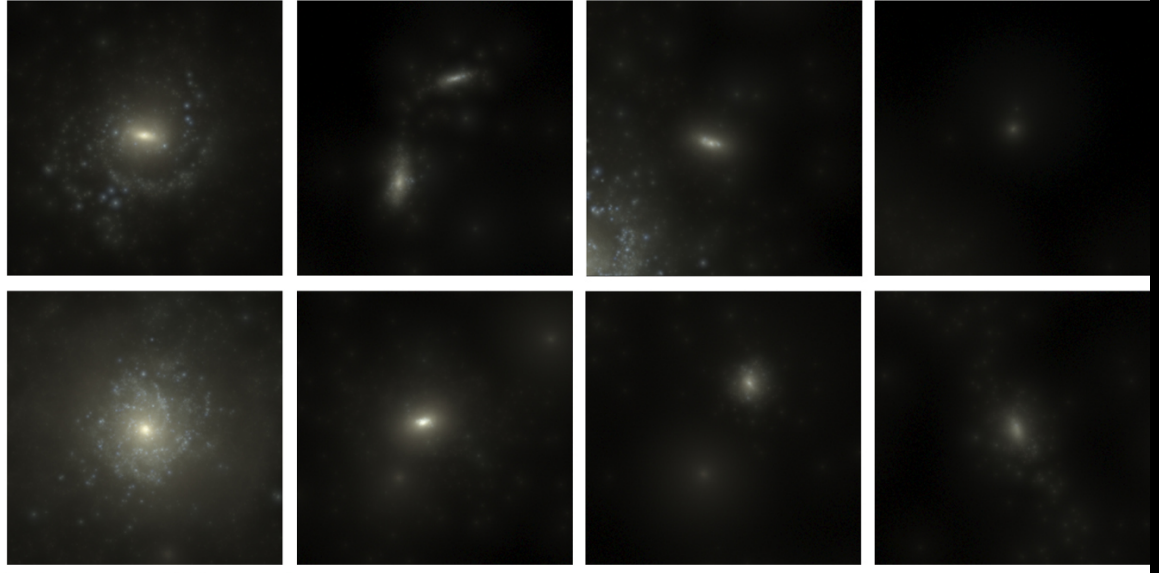
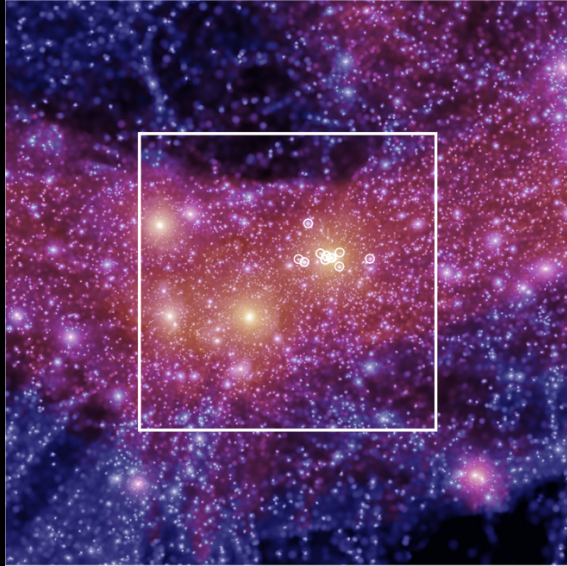
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Lovell, Eke, Frenk, Gao, Jenkins, Theuns '12



EAGLE/Apostle/
Auriga galaxies have
NFW cusps

Sawala et al '15

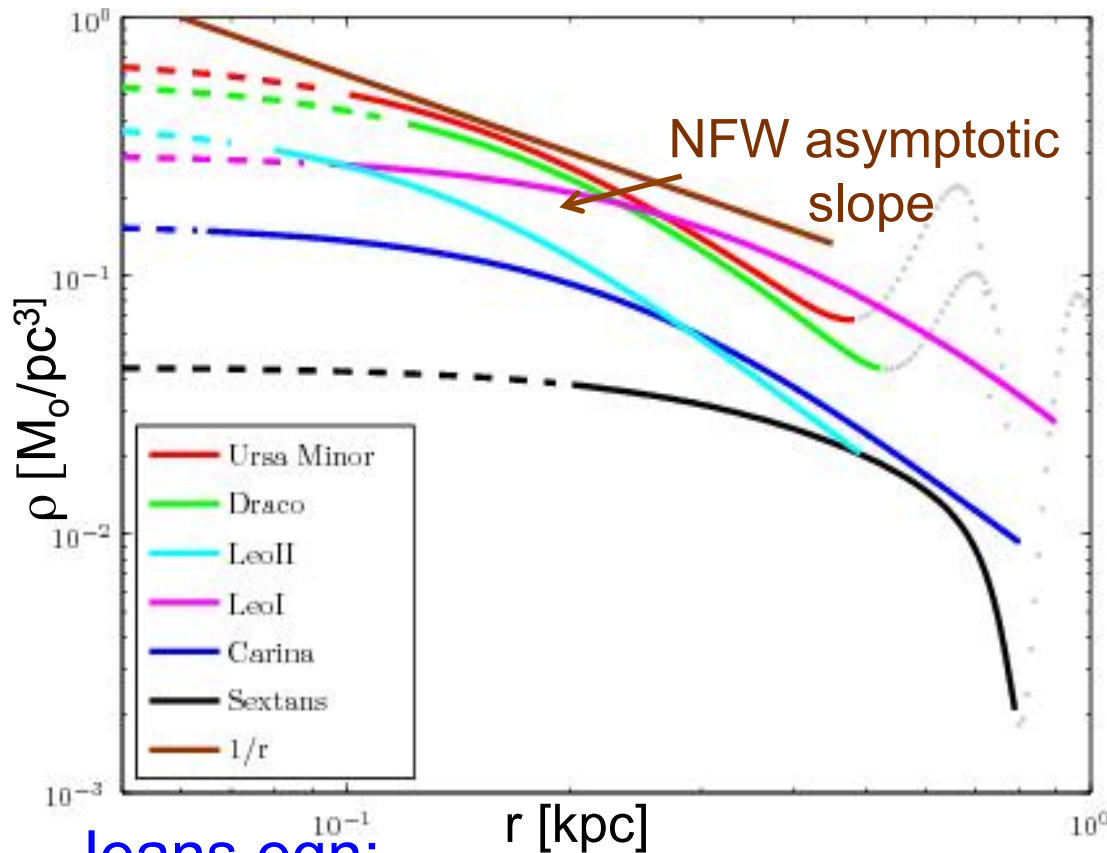


Does Nature have them?



Sawala et al '15

The DM halos of dwarf spheroidals



Gilmore et al '07

Inferred density profiles for 6 dwarf spheroidals

“...dark matter forms **cored** mass distributions, with a core scale length of greater than about 100pc...”

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

vel. anisotropy 

Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim

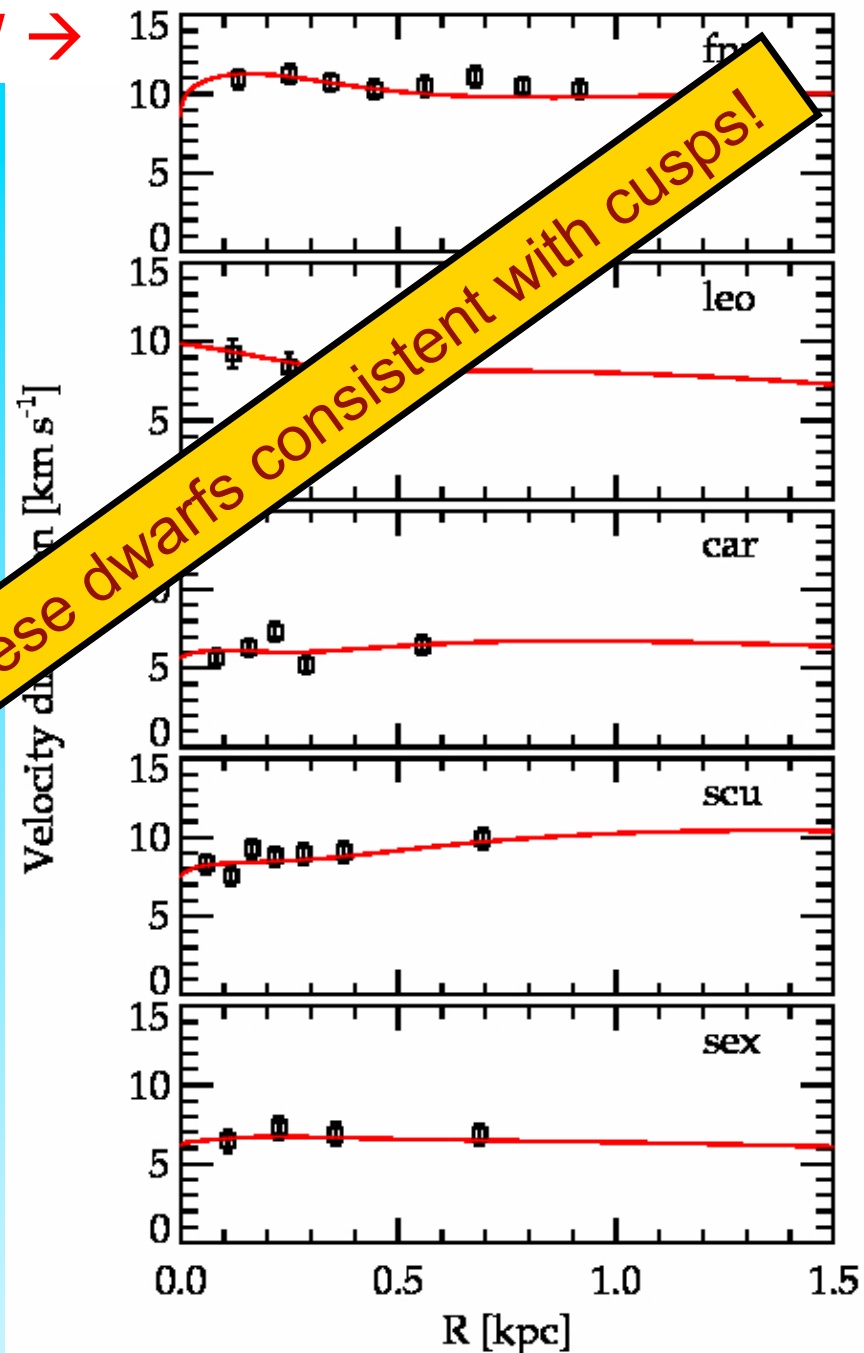
Cuspy!

vel. an...

- Assume isotropic
- Solve for σ_r
- Compare with observed $\sigma_r(r)$
- "best fit" subhalo

Photometric and kinematical data for these dwarfs consistent with cusps!

Strigari, Frenk & White '10





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

Assume: gas is in centrifugal equilibrium on approximately circular orbits

Analysis of 2D velocity fields

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

$\downarrow$

$\bullet$ 3D BAROLO fit $\leftarrow$ Tilted-ring model corrected for asymmetric drift

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

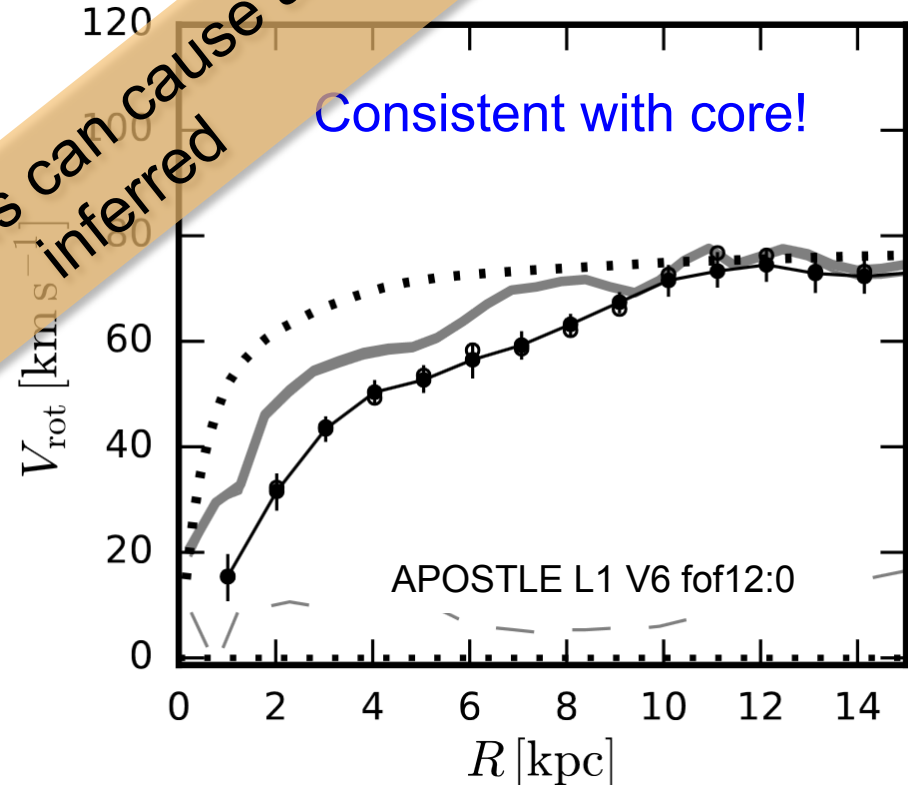
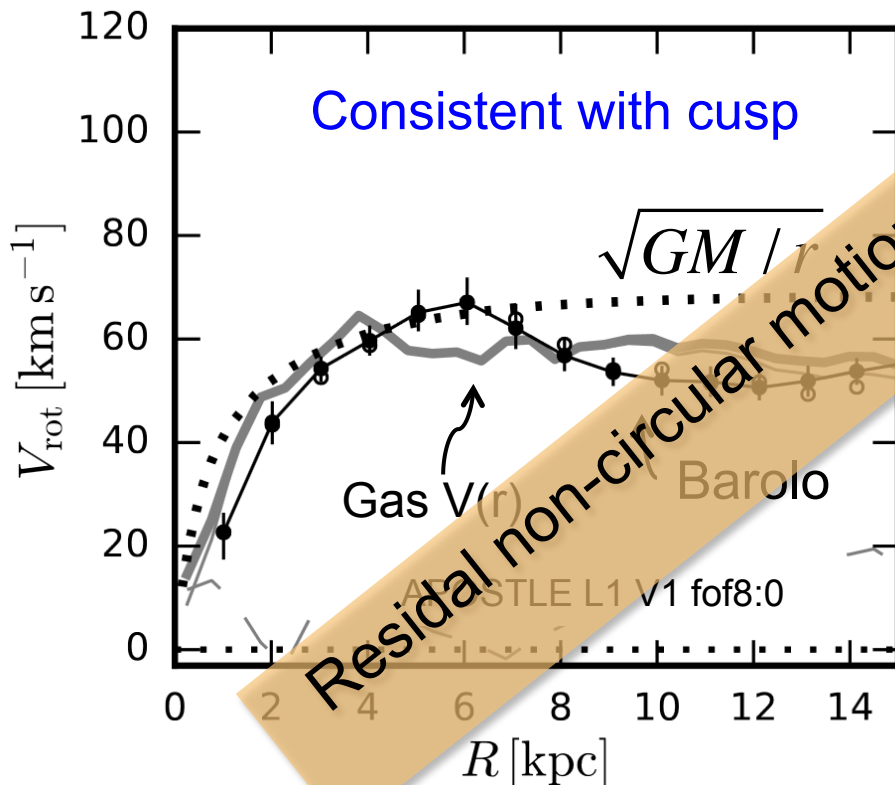
Rotation curves of 2 APOSTLE dwarfs

APOSTLE galaxies all have NFW cusps

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

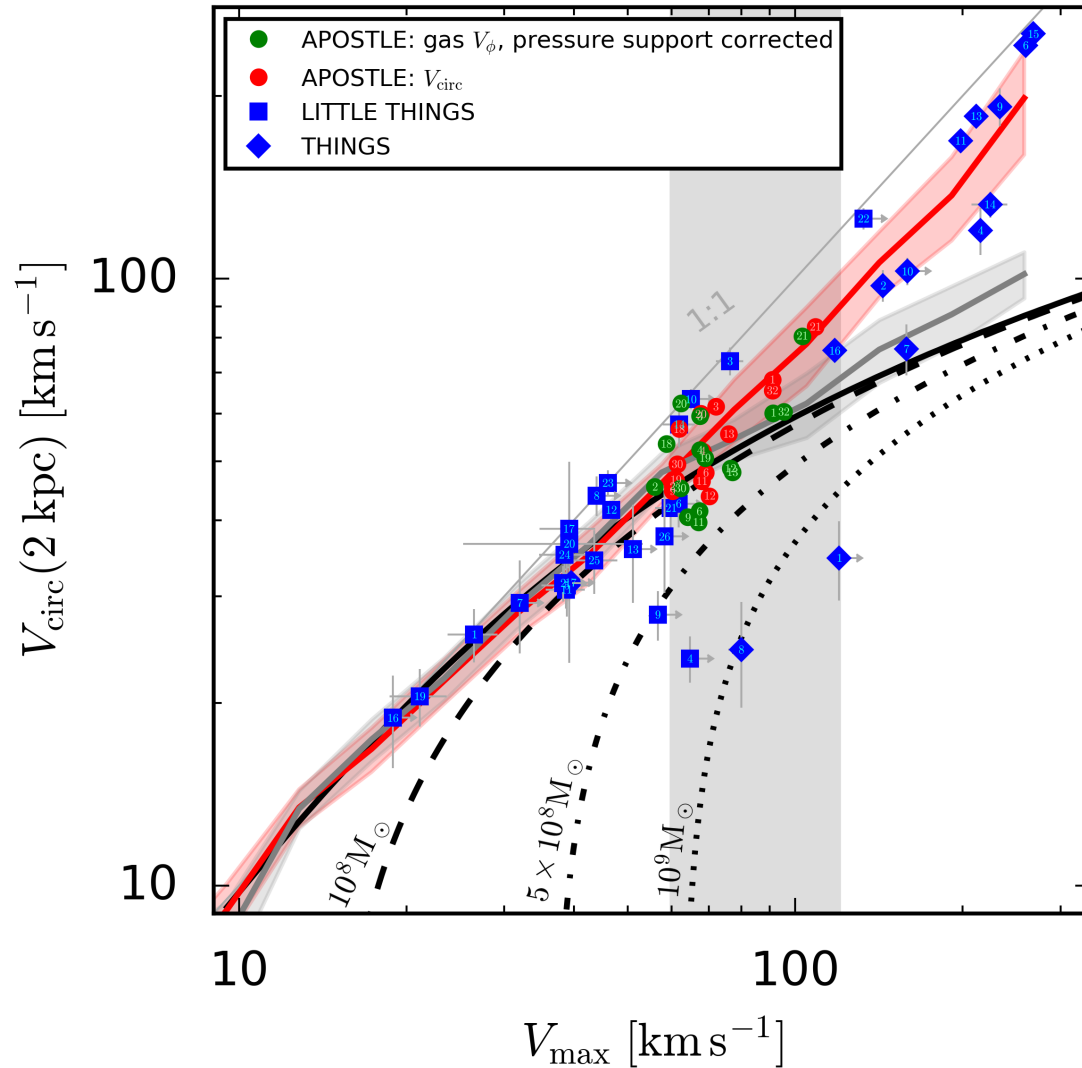
3D BAROLO fit

Tilted-ring model corrected for asymmetric drift

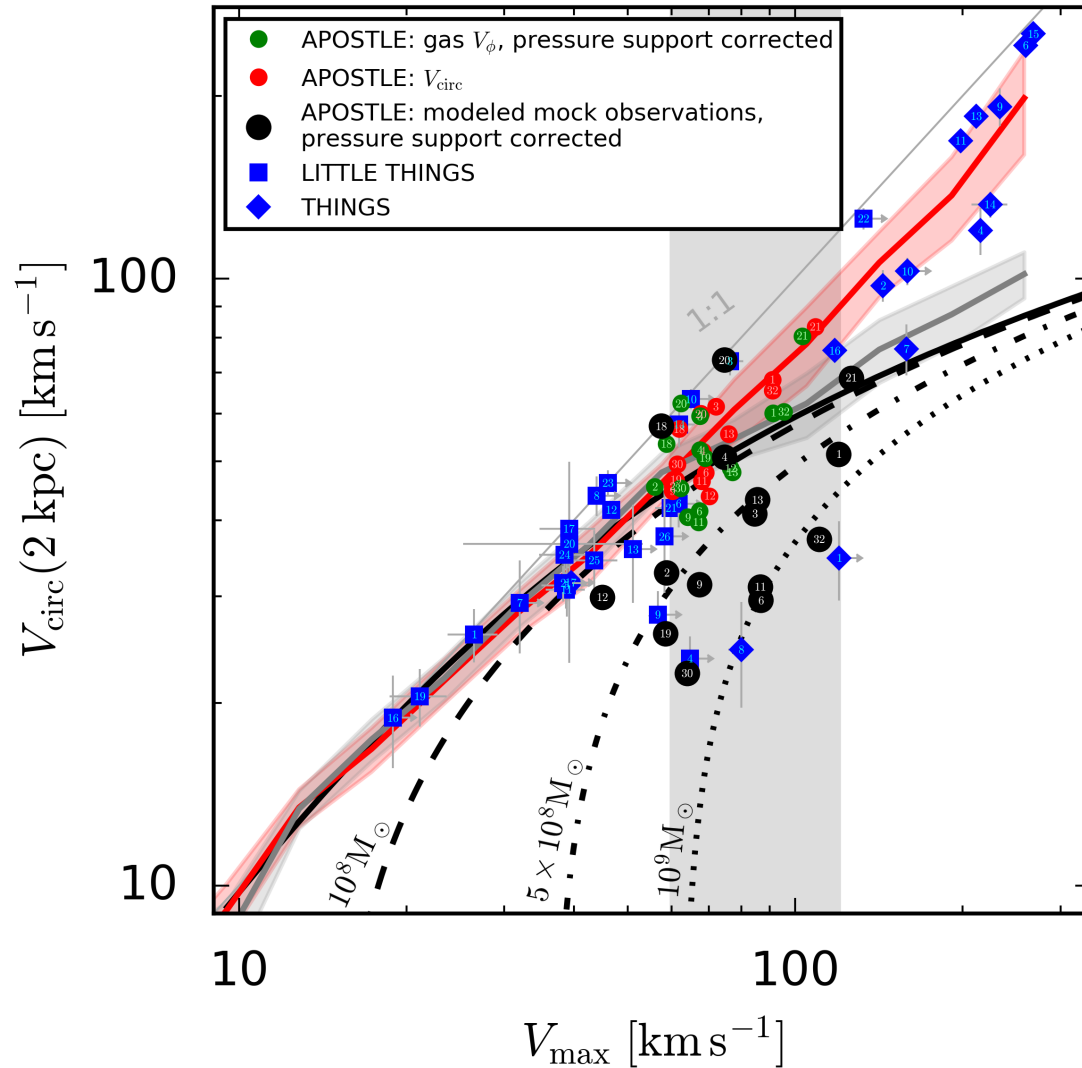


Oman et al '18; Marasco et al '18

The diversity of rotation curves



The diversity of rotation curves





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) (Read &
Gilmore '05; Pontzen &
Governato '12,'14; Bullock &
Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

The cores of dwarf galaxy haloes L75

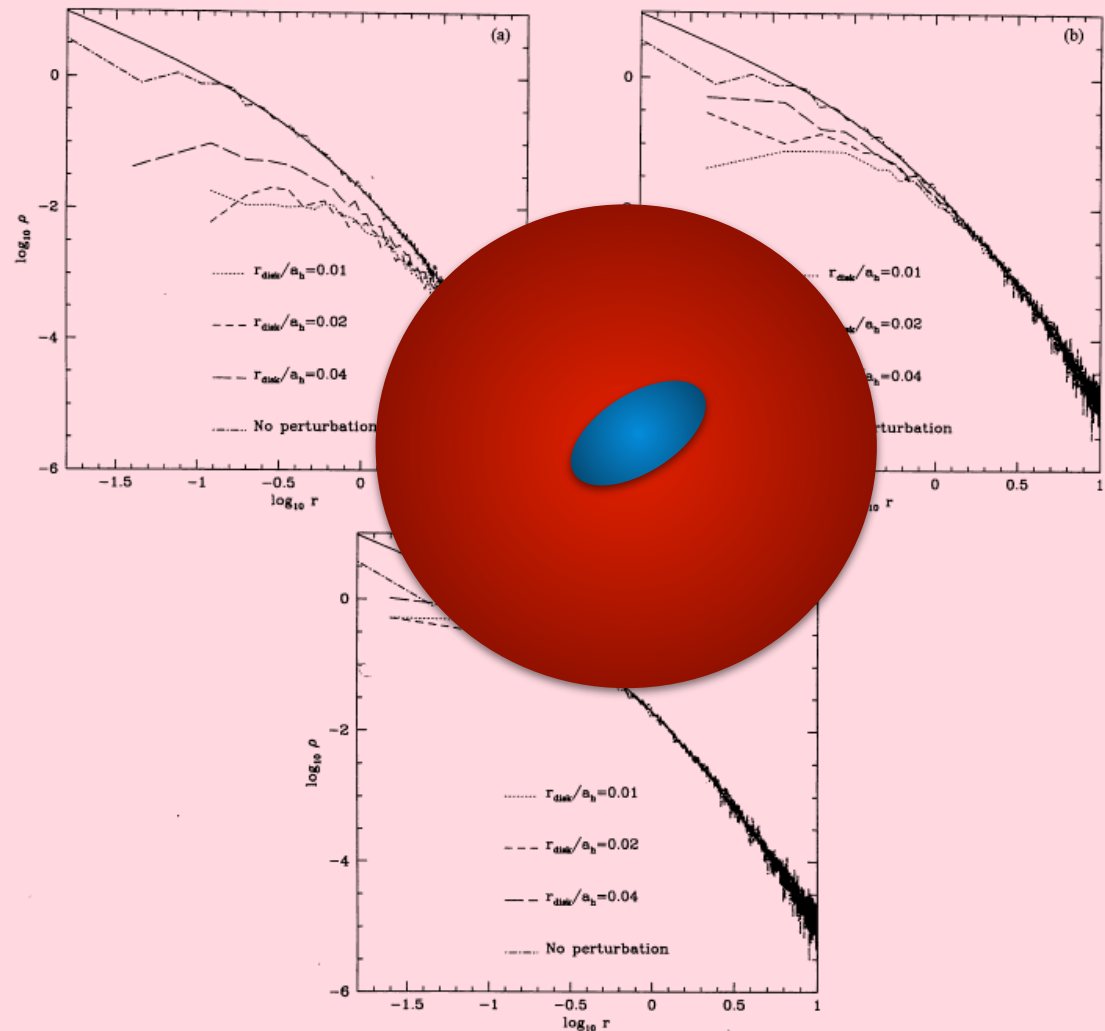


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{\text{disc}}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

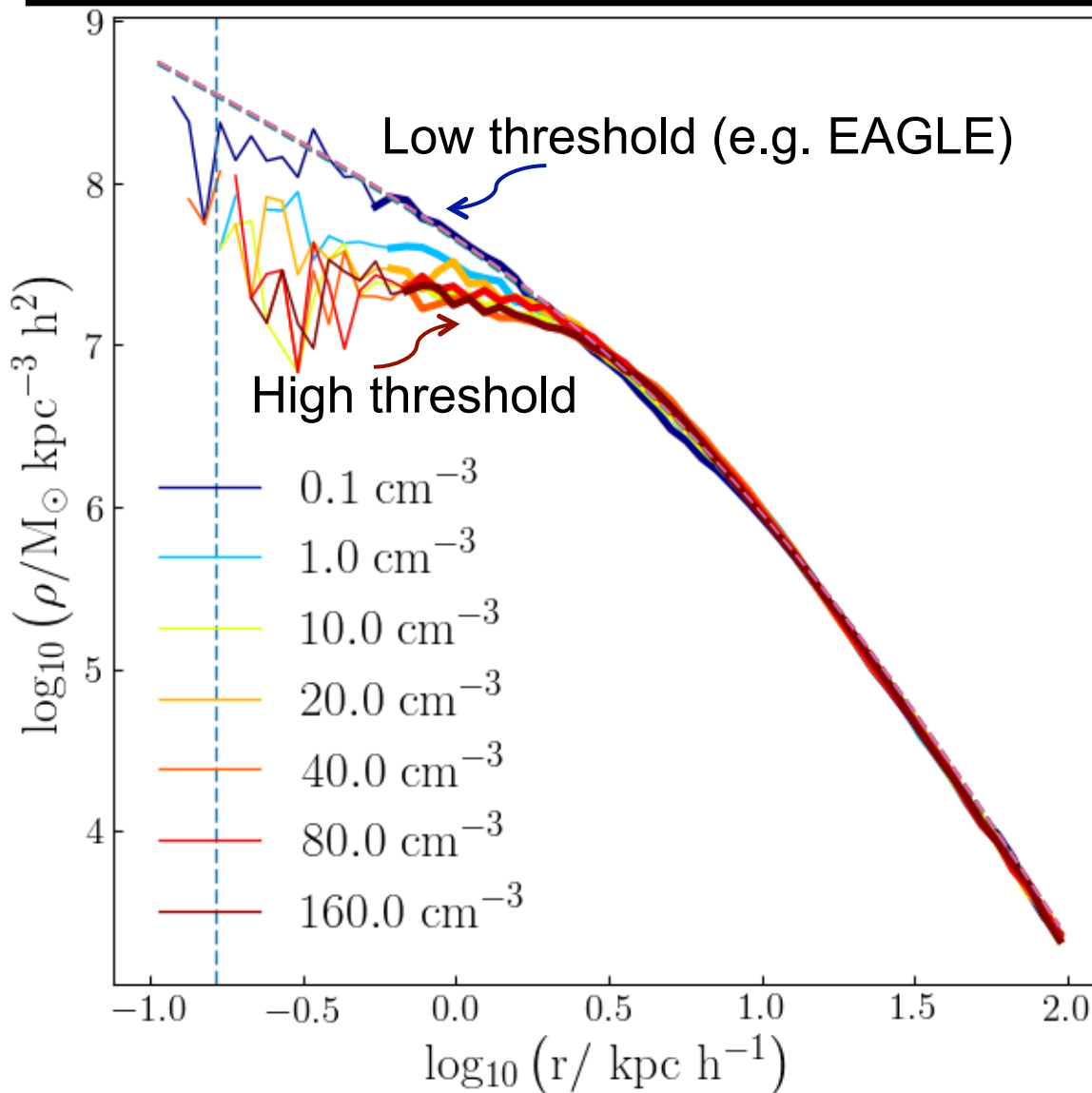
Cores or cusps in simulations?

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?



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~~



Conclusions so far

The CDM small-scale “CRISIS” (a time of intense difficulty or danger)

What crisis?

1. The **interpretation** of astronomical observations is **hard**
→ be **skeptical!**
2. Consider new particle dark matter candidates that are
motivated by physics, not by trying to solve **non-existent**
astronomical **problems**



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 background of the slide is a deep space image showing a dense field of galaxies and galaxy clusters, with a prominent bright yellow and orange cluster in the center. A semi-transparent yellow rectangular box with a black border is centered over the image, containing the text.

The subhalo mass function

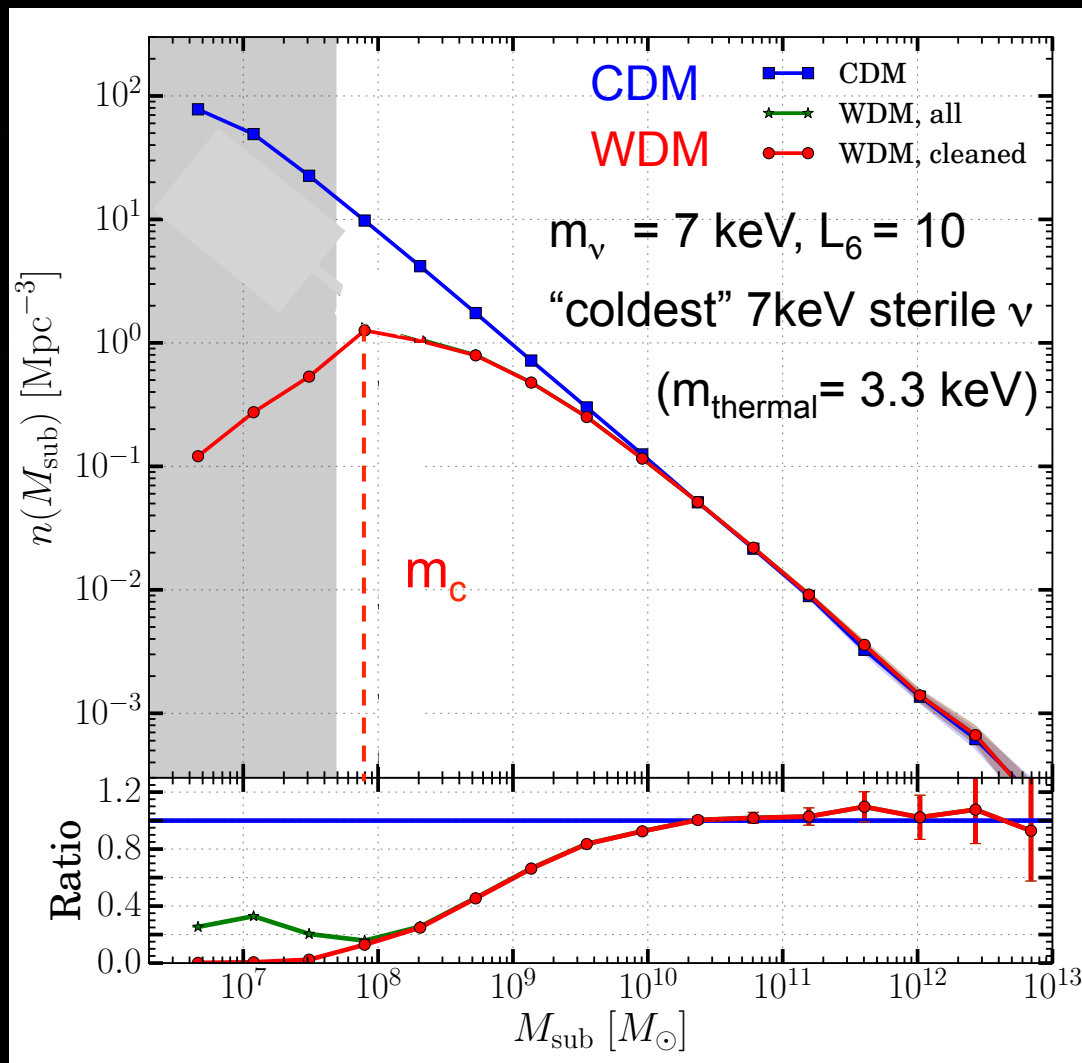


CDM

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

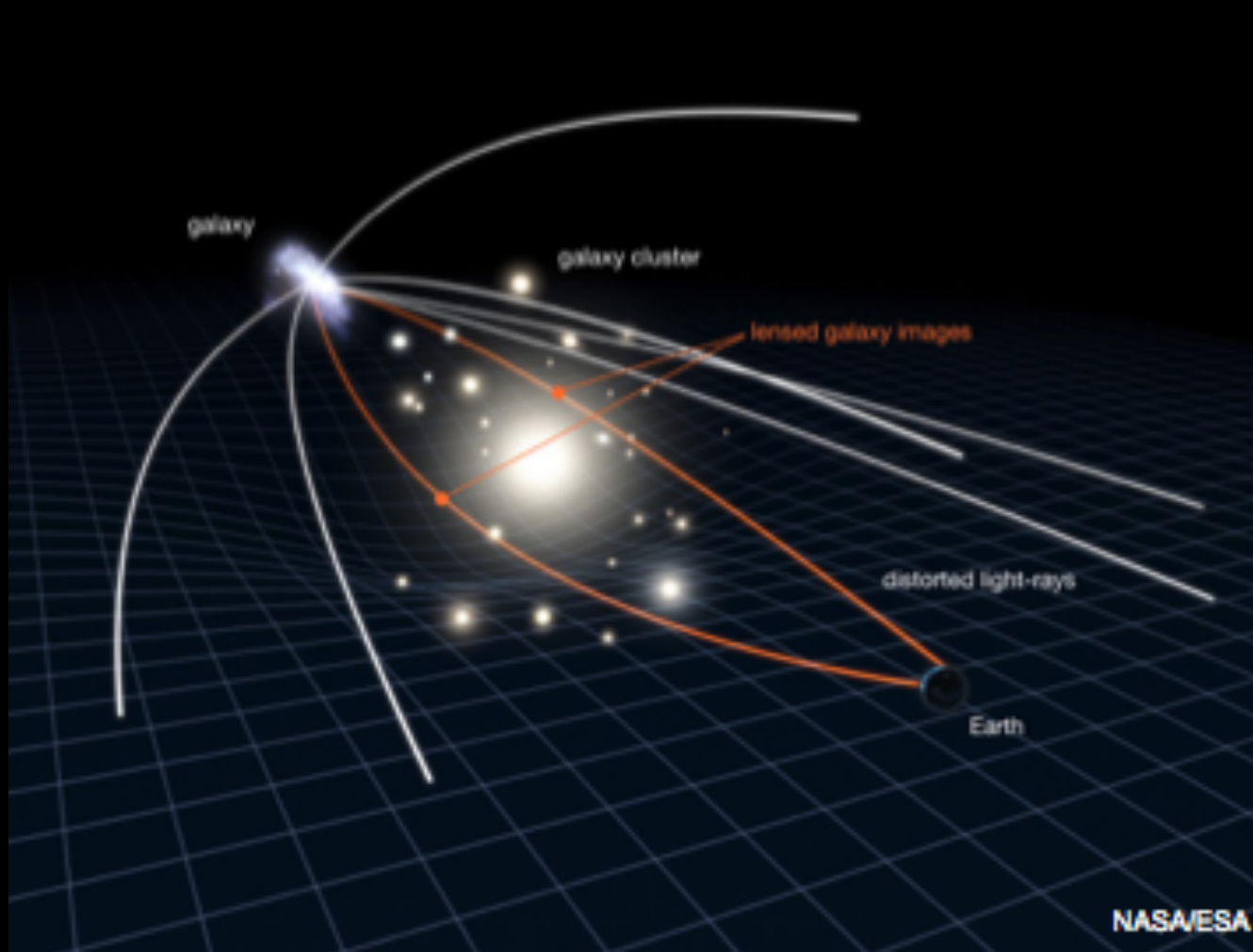
Dark halos can be detected through
gravitational lensing



Gravitational lensing: Einstein rings

How to rule out CDM

Gravitational lensing: Einstein rings



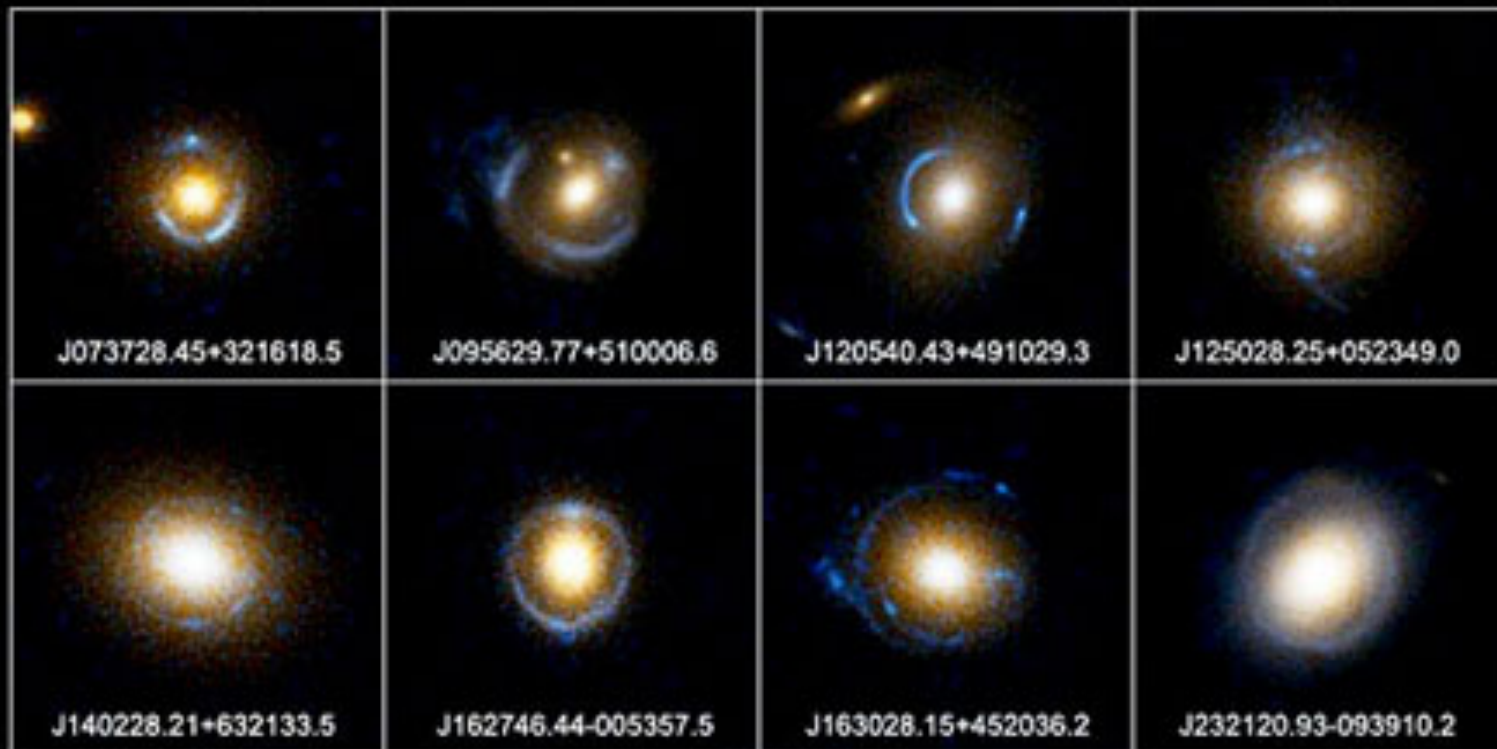
When the source and the lens are well aligned → strong arc or an Einstein ring



SLAC sample of strong lenses

Einstein Ring Gravitational Lenses

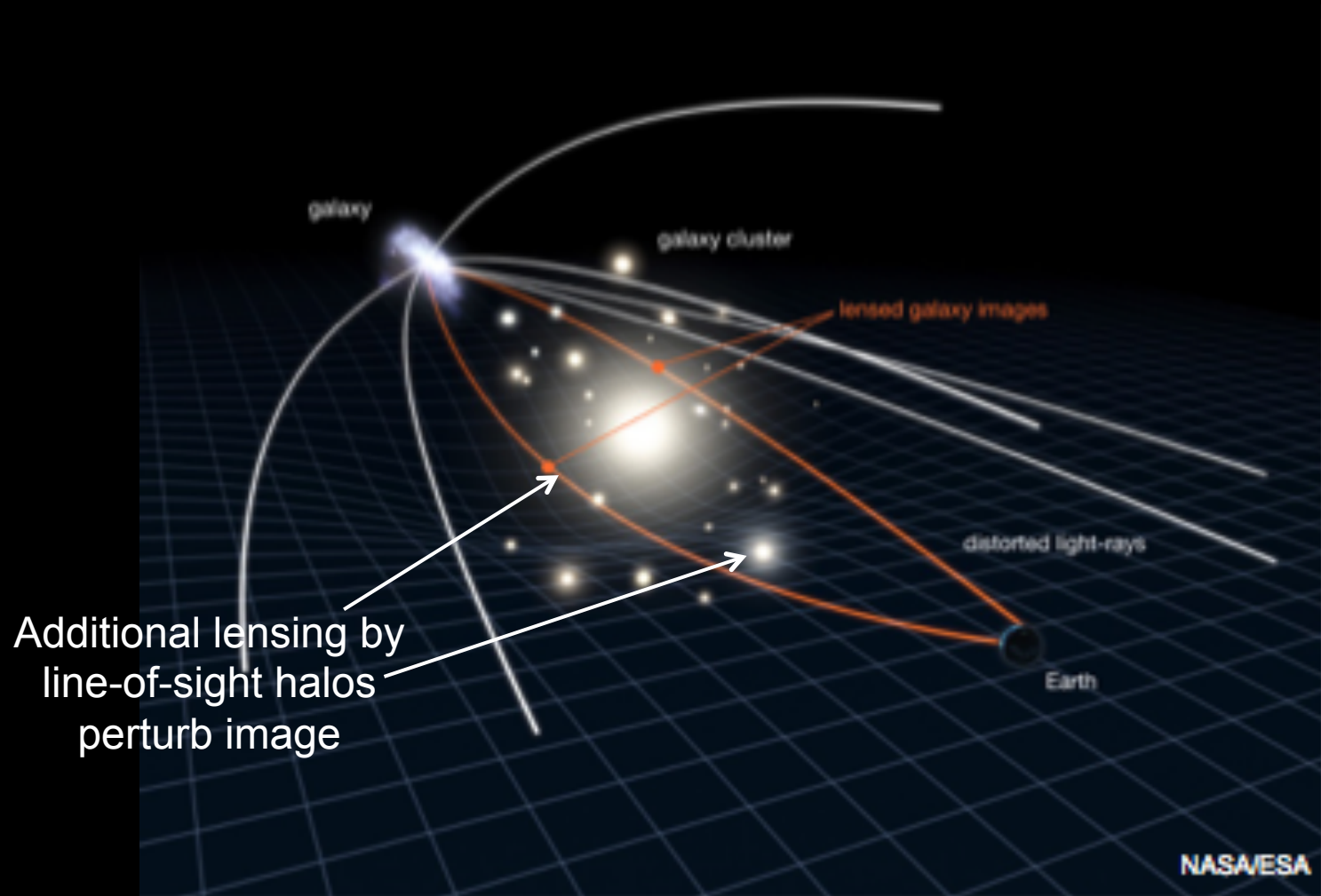
Hubble Space Telescope • ACS



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

STScI-PRC05-32

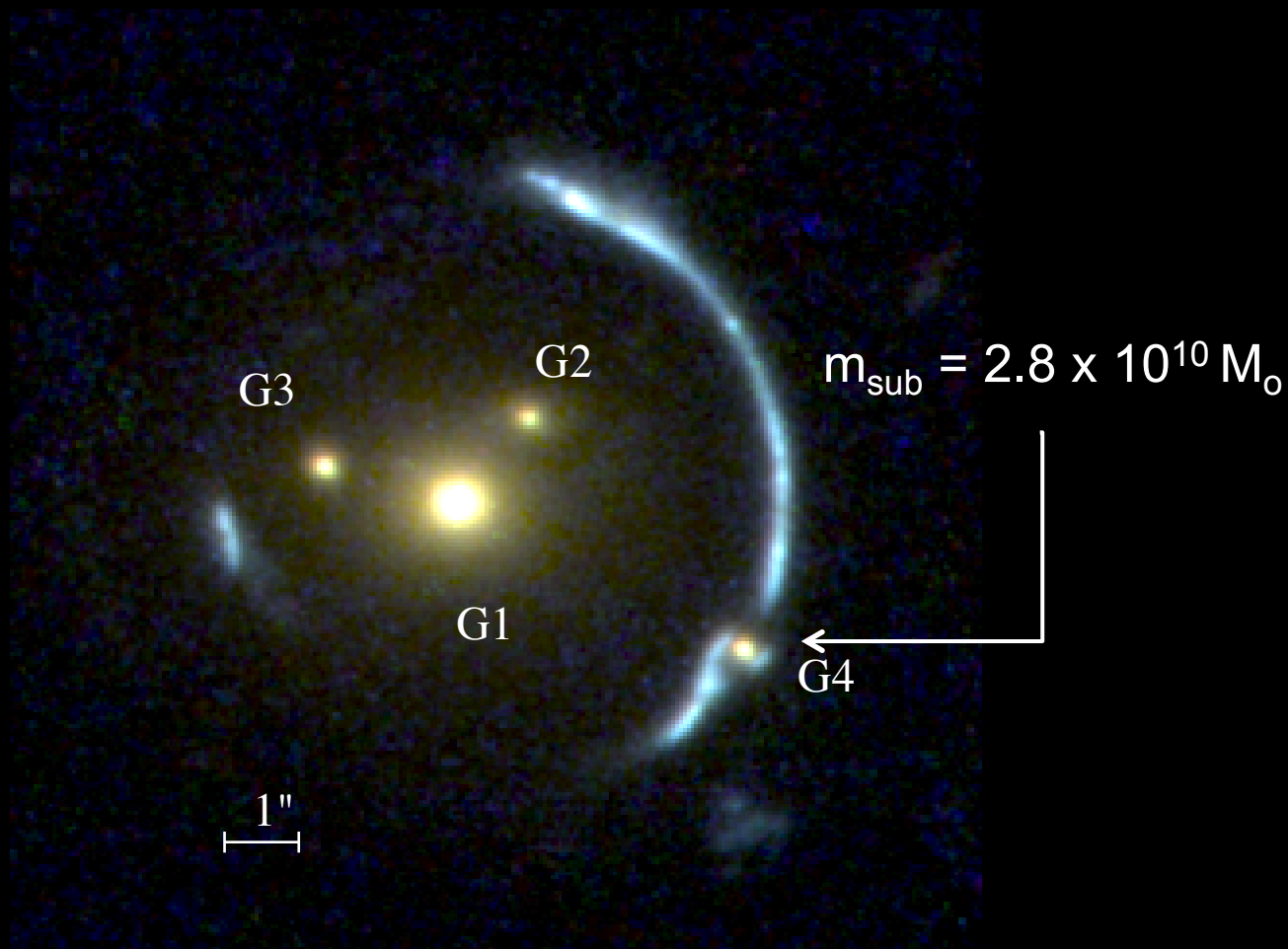
Gravitational lensing: Einstein rings



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





Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



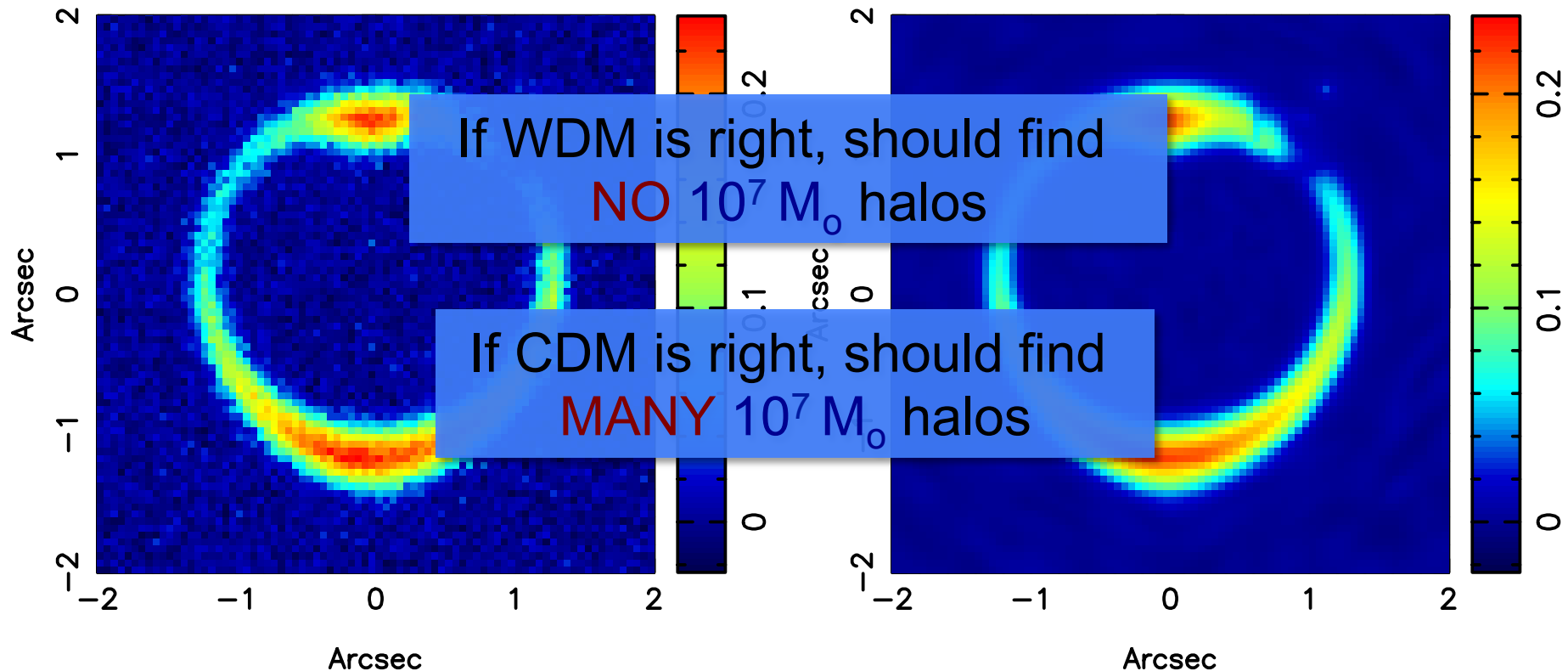
Vegetti & Koopmans '09

Detecting substructures with strong lensing

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

Data

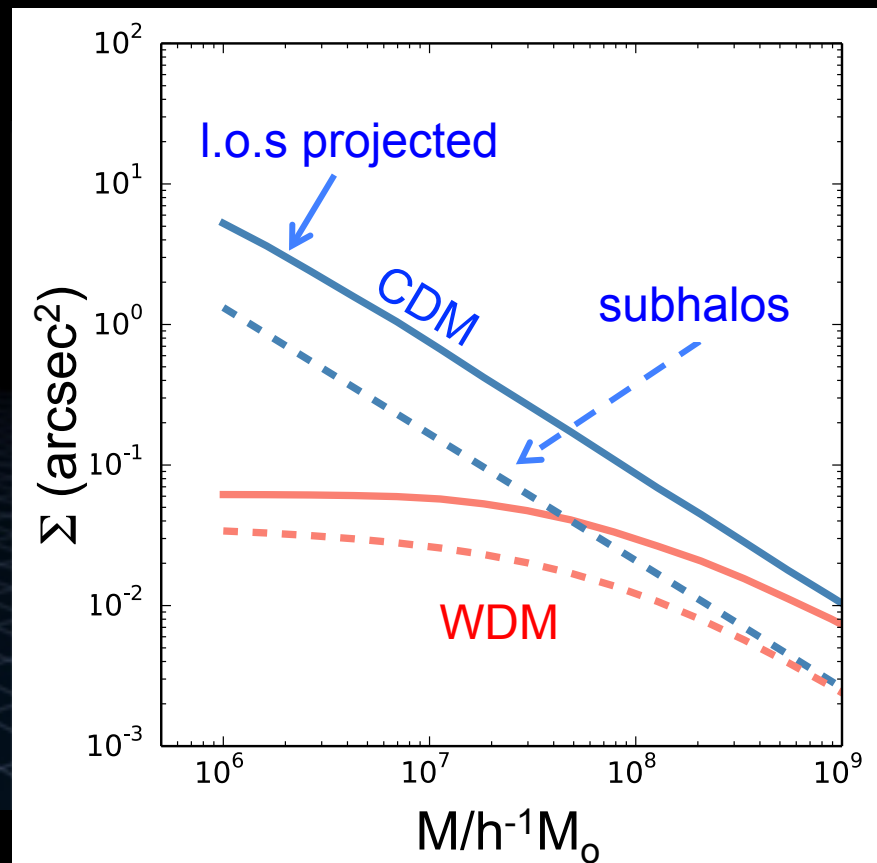
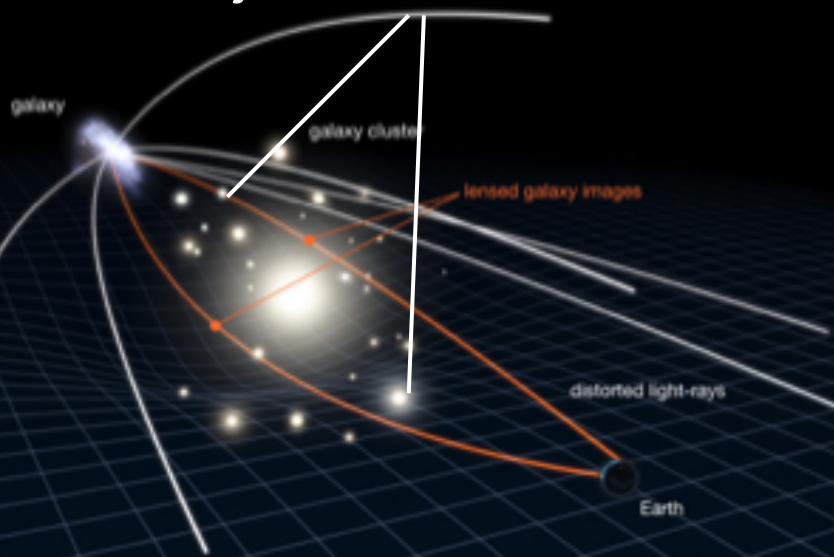
Model



Substructures vs interlopers

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

Projected l.o.s halos

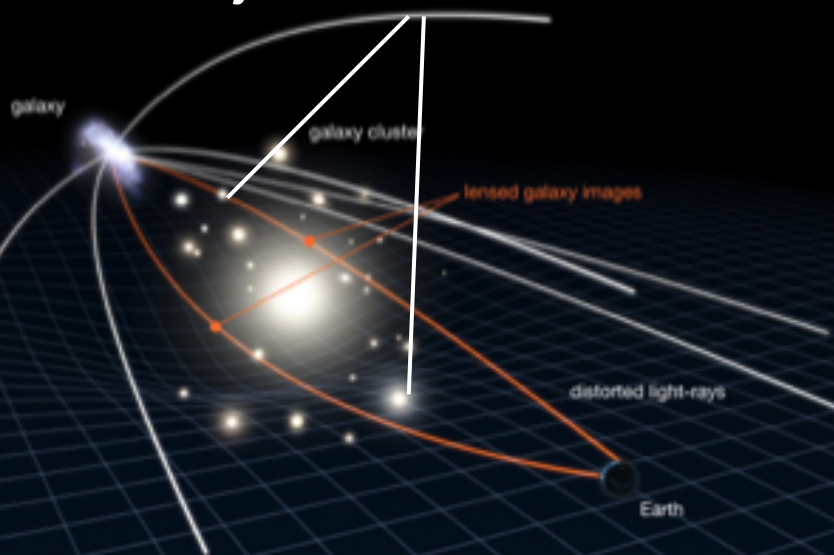


The number of line-of-sight haloes is larger than that of subhaloes

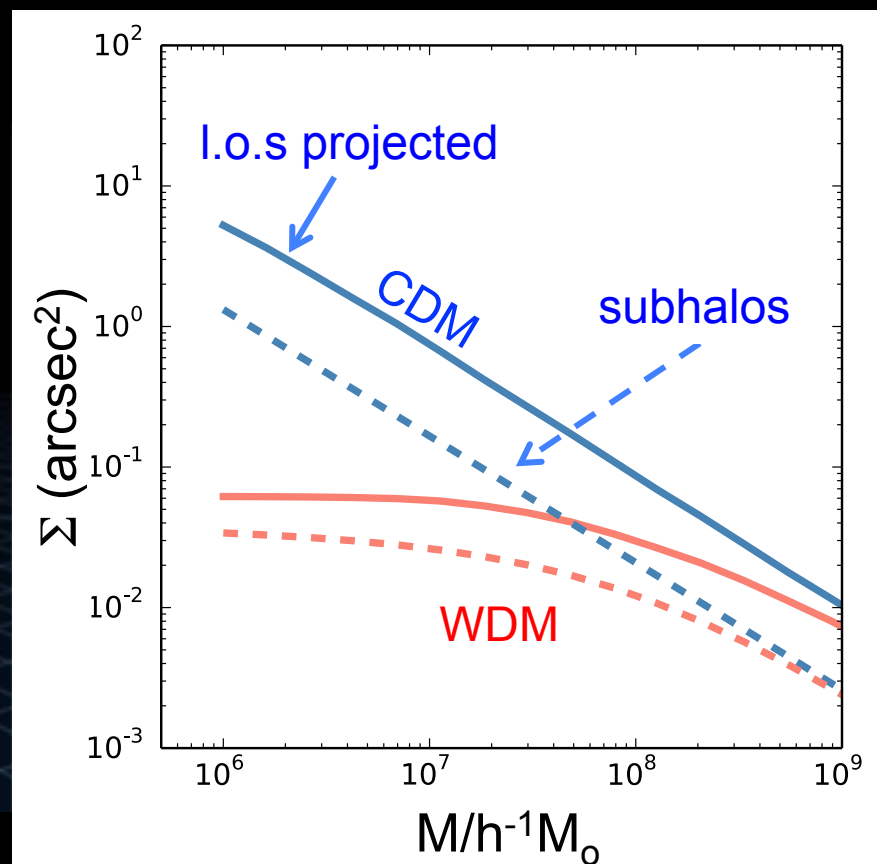
Substructures vs interlopers

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**

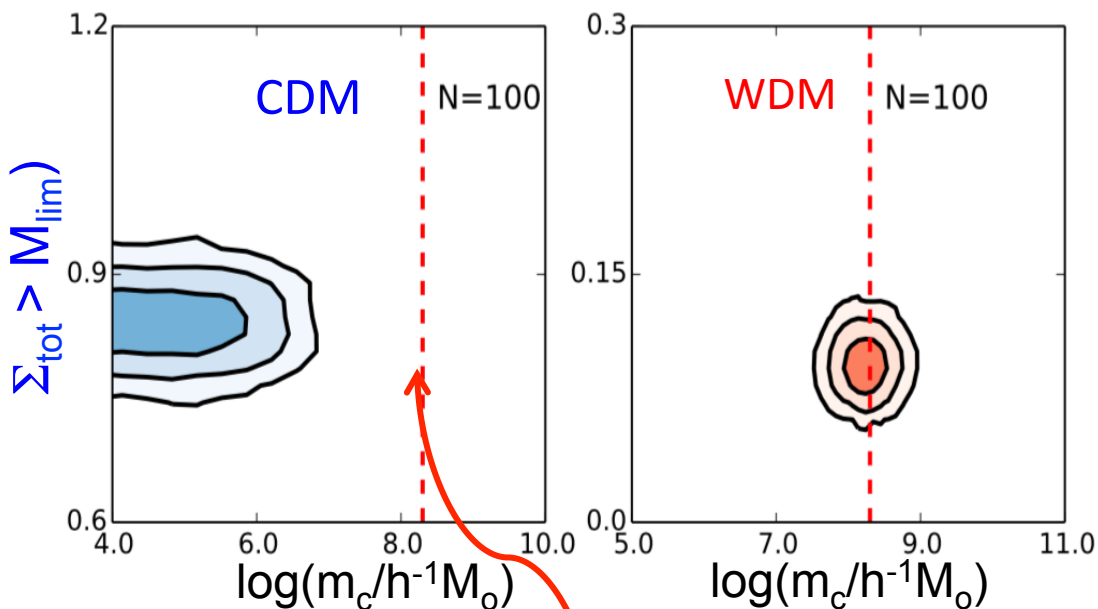
Detecting substructures with strong lensing

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. Halos $< \sim 5 \cdot 10^8 M_\odot$ are dark; halos $> 10^{10} M_\odot$ are bright
 2. No evidence for cores; baryon effects can make them
 3. When **baryons** taken into account $\rightarrow$ **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 $\rightarrow$ and can potentially **rule out CDM!**