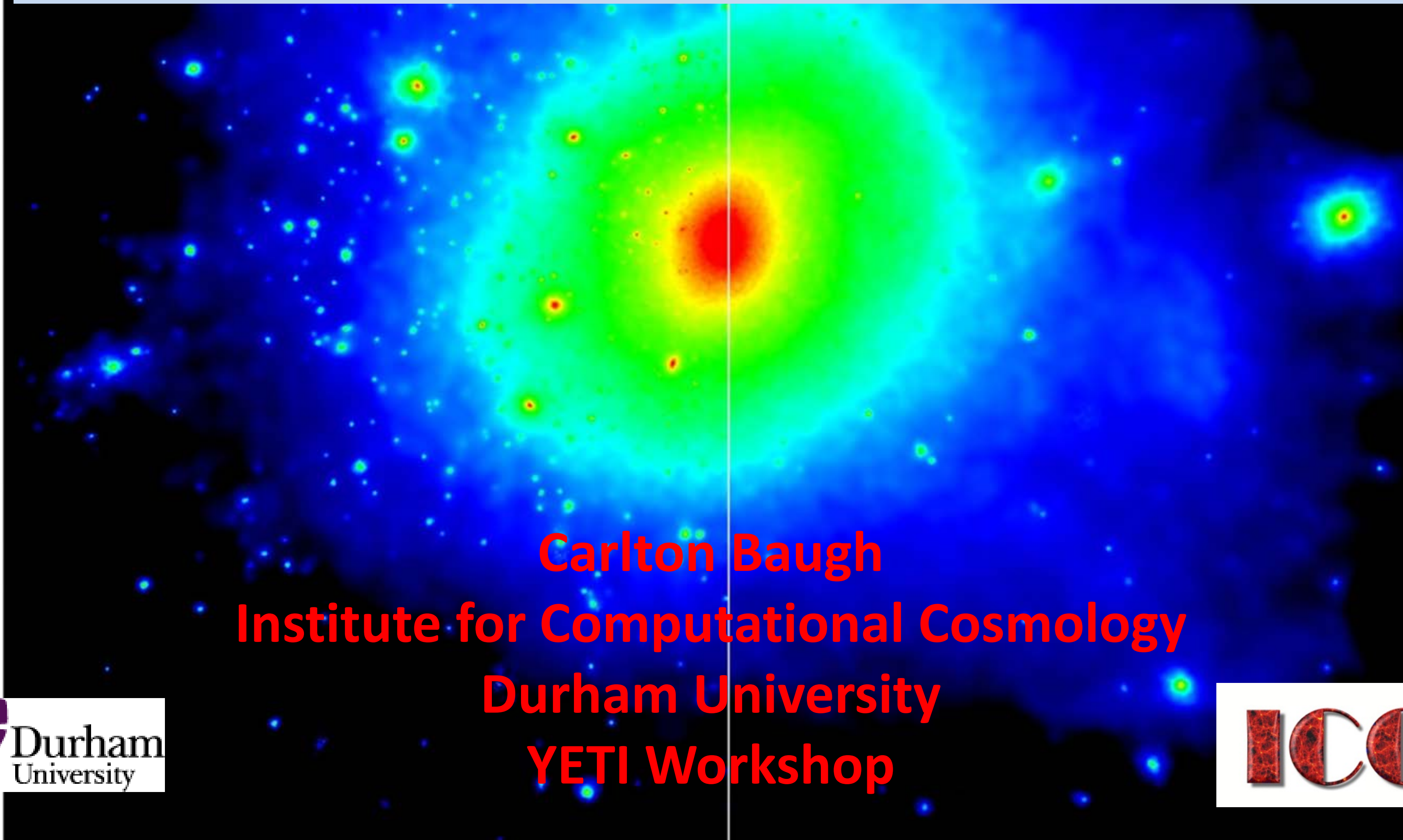
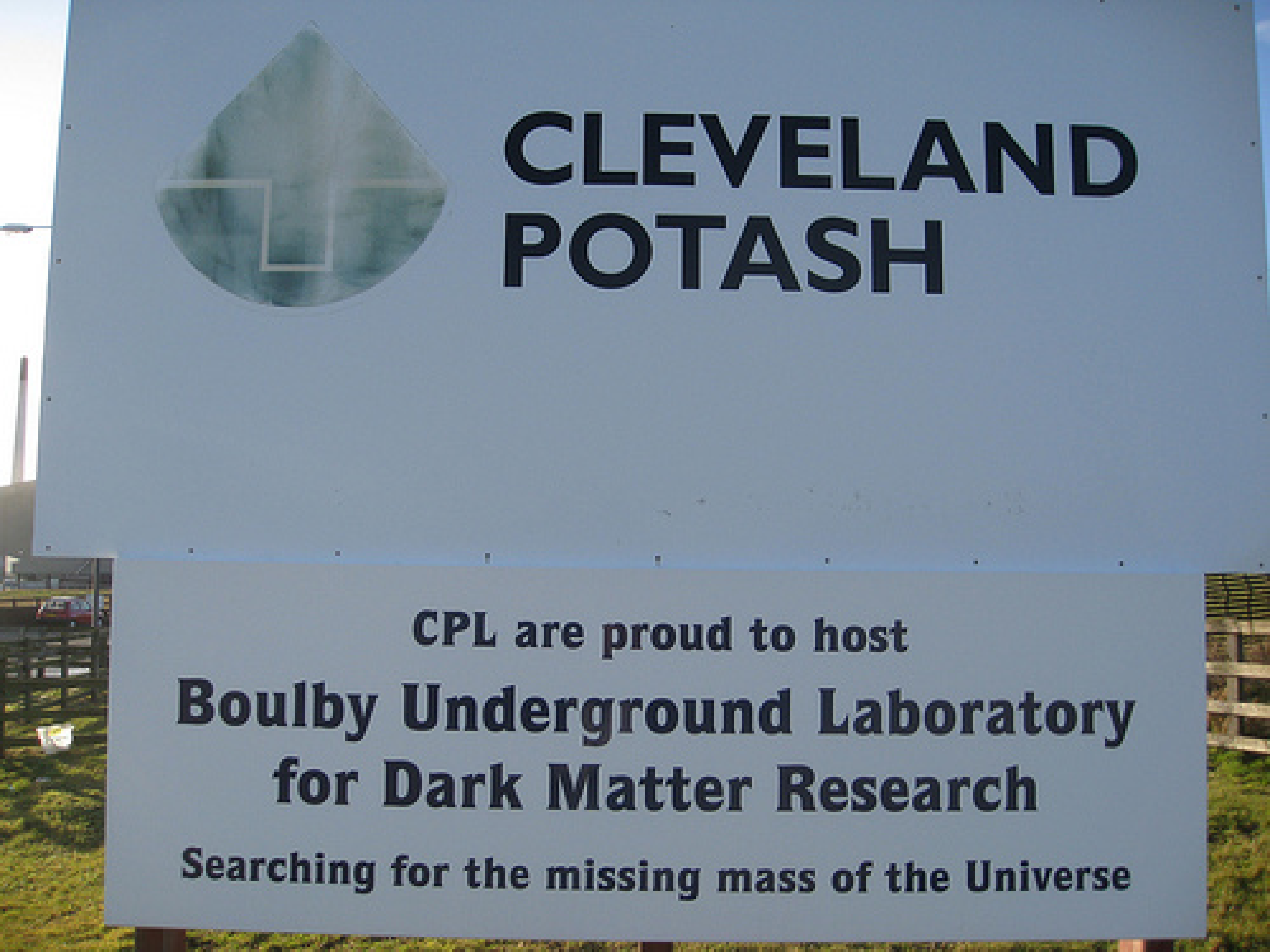
Cosmological Structure Formation: probing the nature of dark matter and dark energy with computers



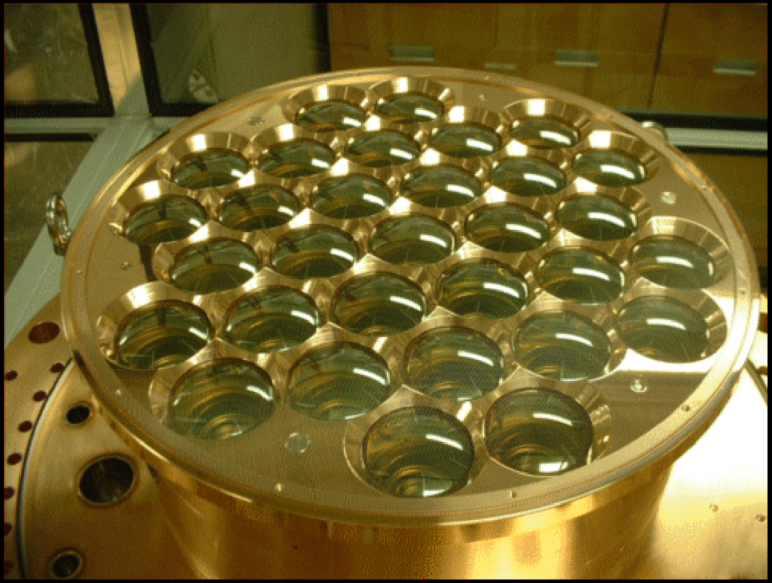
Carlton Baugh
Institute for Computational Cosmology
Durham University
YETI Workshop

Durham University

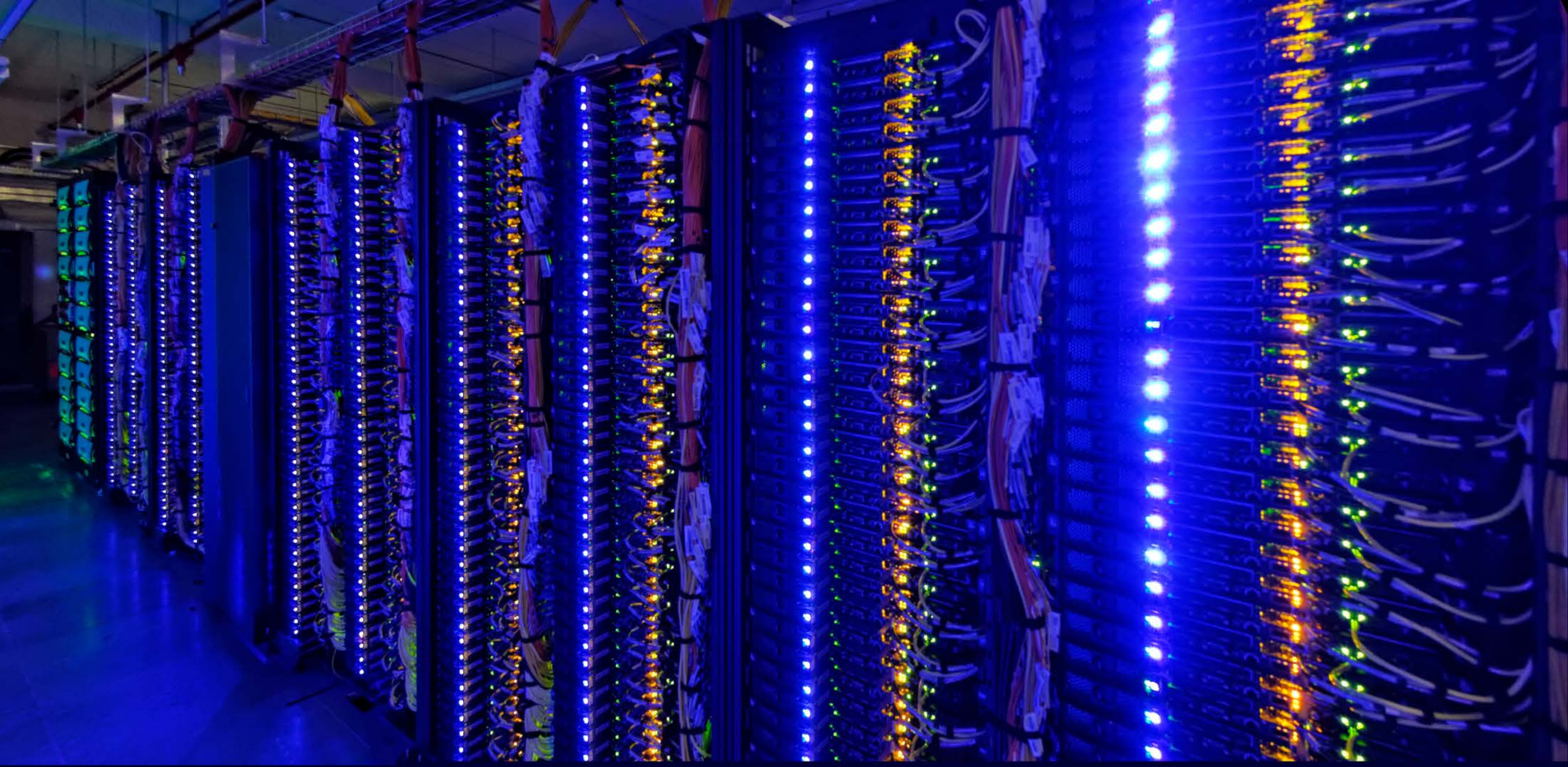
ICC


CLEVELAND
POTASH
CPL are proud to host
Boulby Underground Laboratory
for Dark Matter Research
Searching for the missing mass of the Universe

The Hunt for Dark Matter



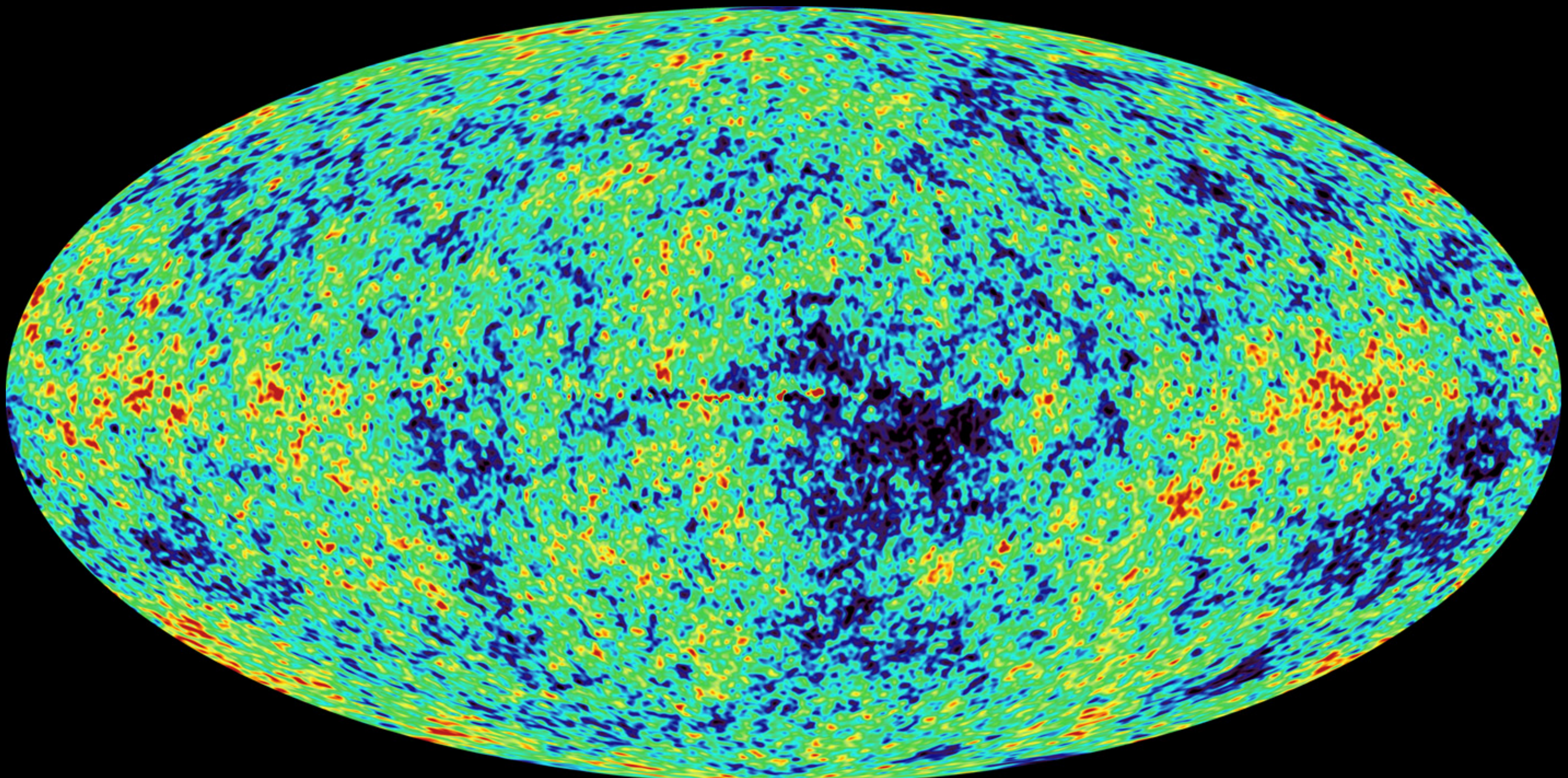
ZEPLIN-III WIMP Detector



How can computers help us to understand dark matter?

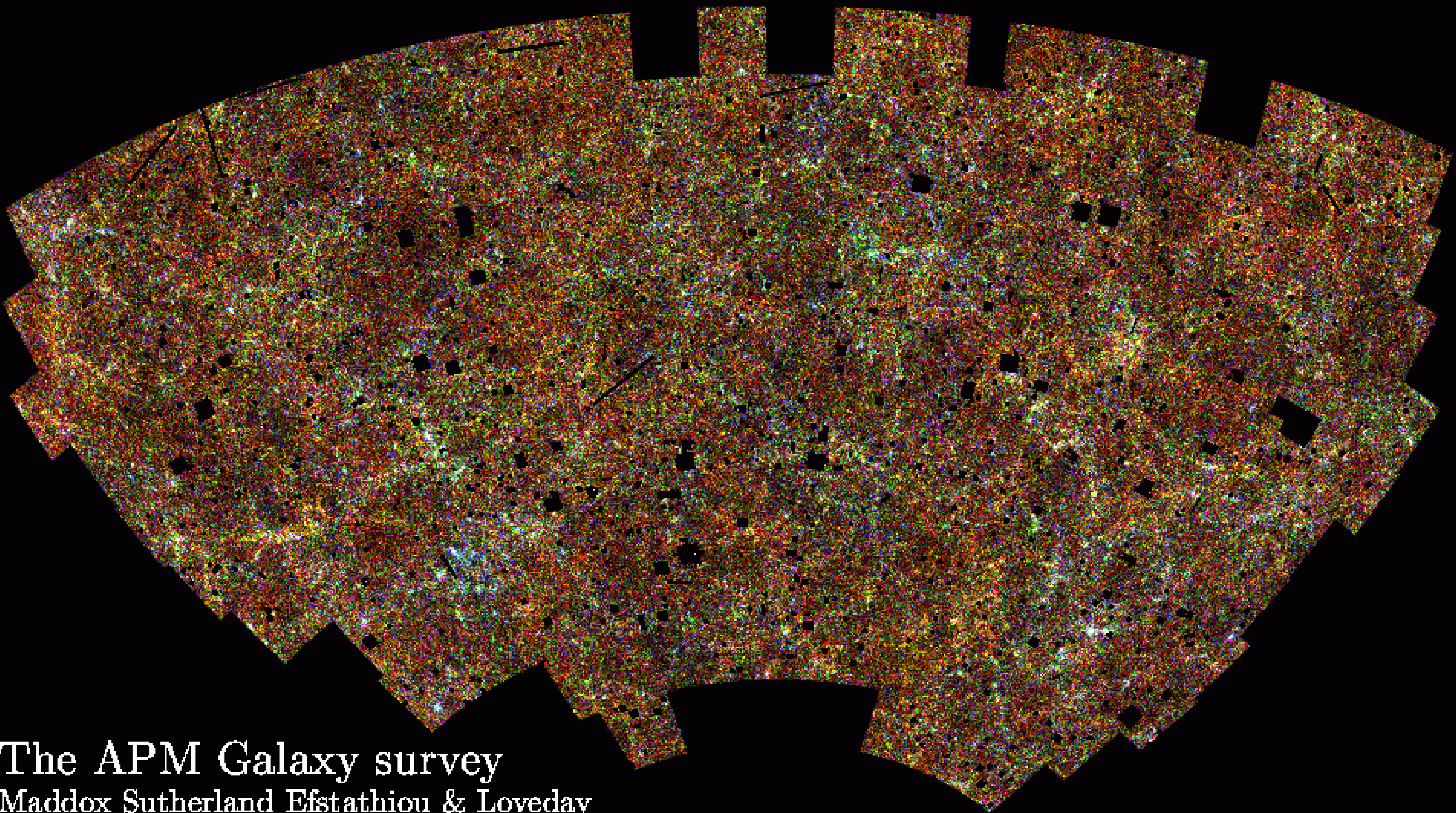
What do we know about the Universe?

The Universe was smoother in the past



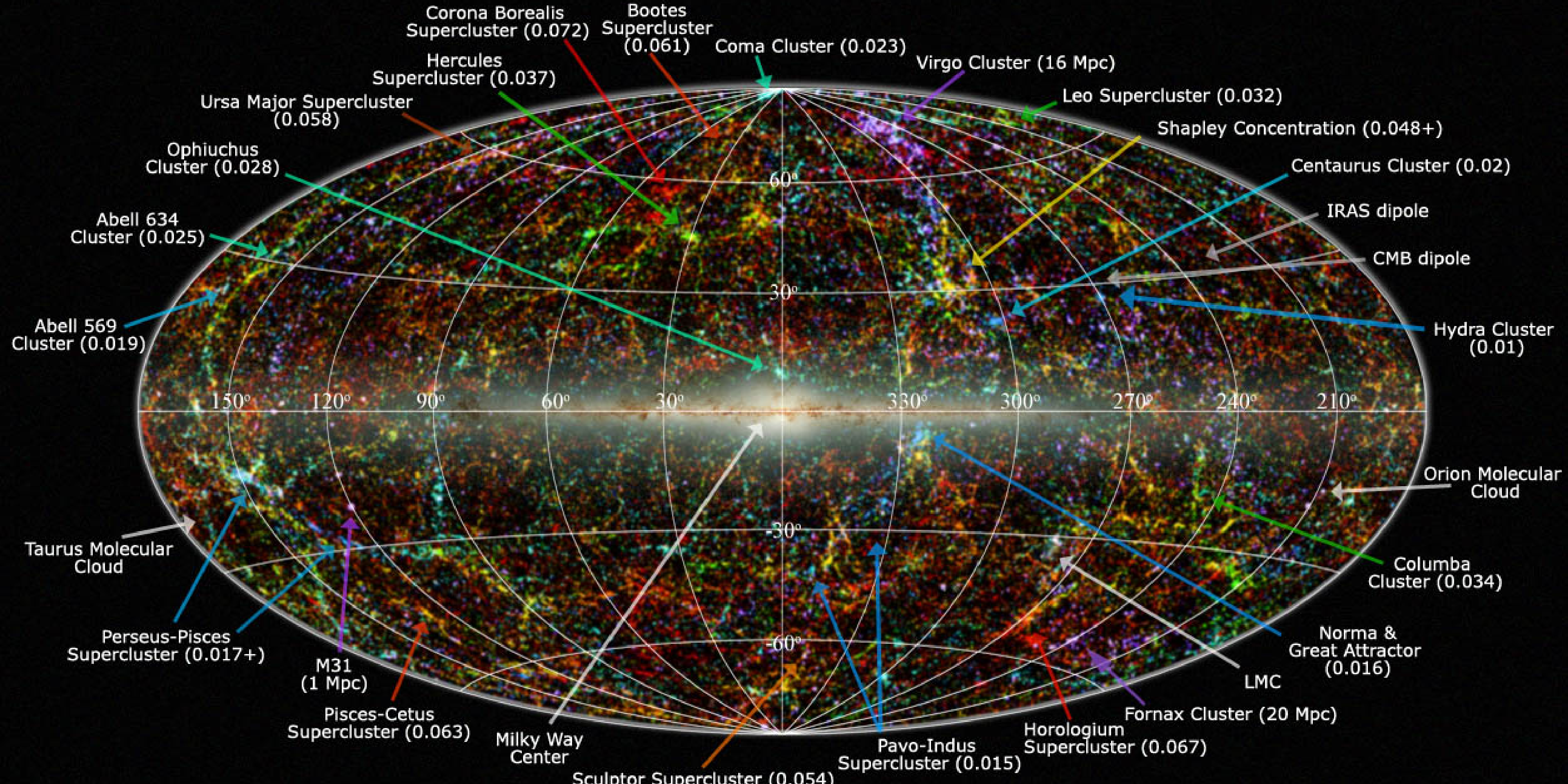
The Universe – 380,000 years after the Big Bang

The Universe is much lumpier today: Galaxies are clustered



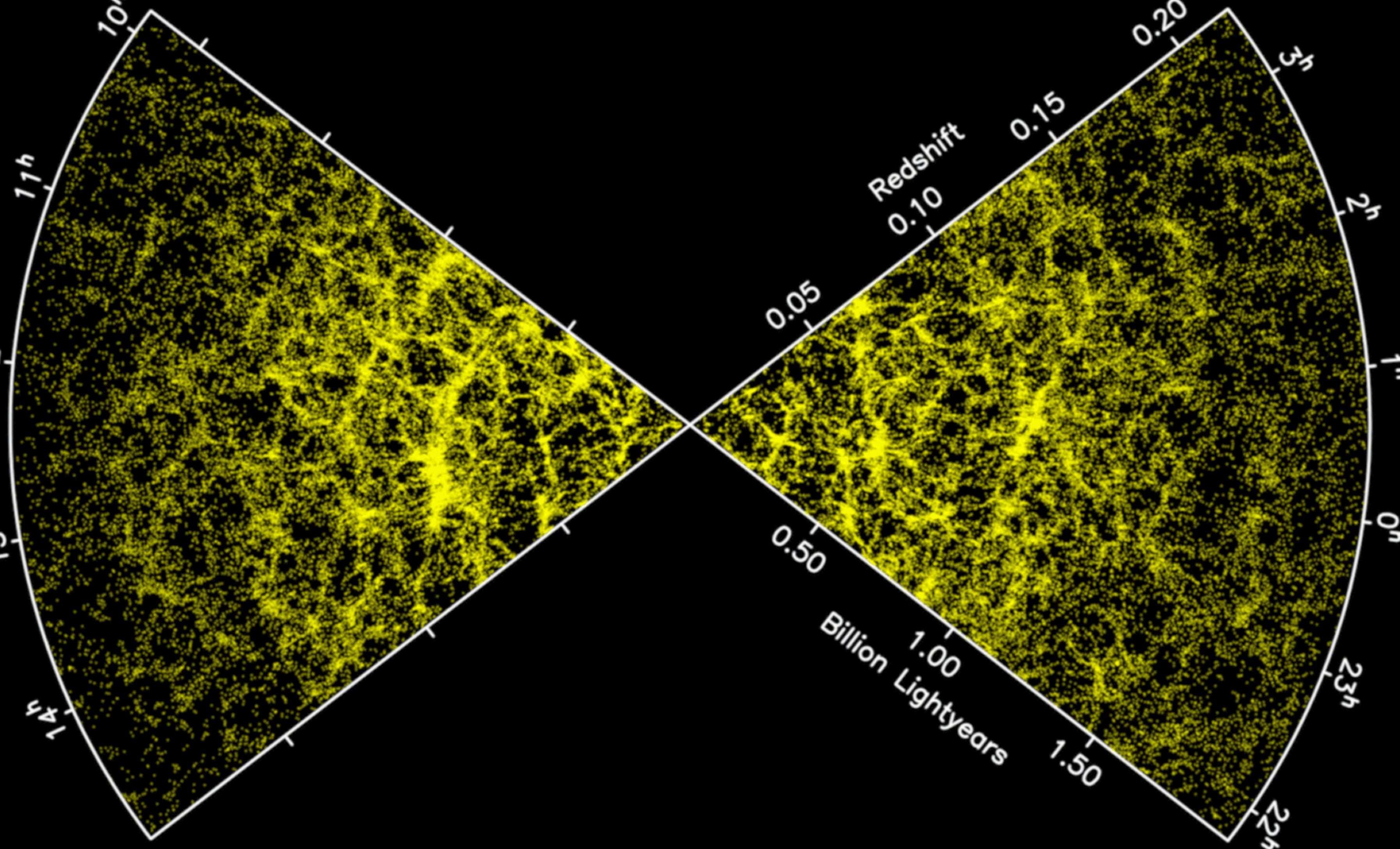
The APM Galaxy survey
Maddox Sutherland Efstathiou & Loveday

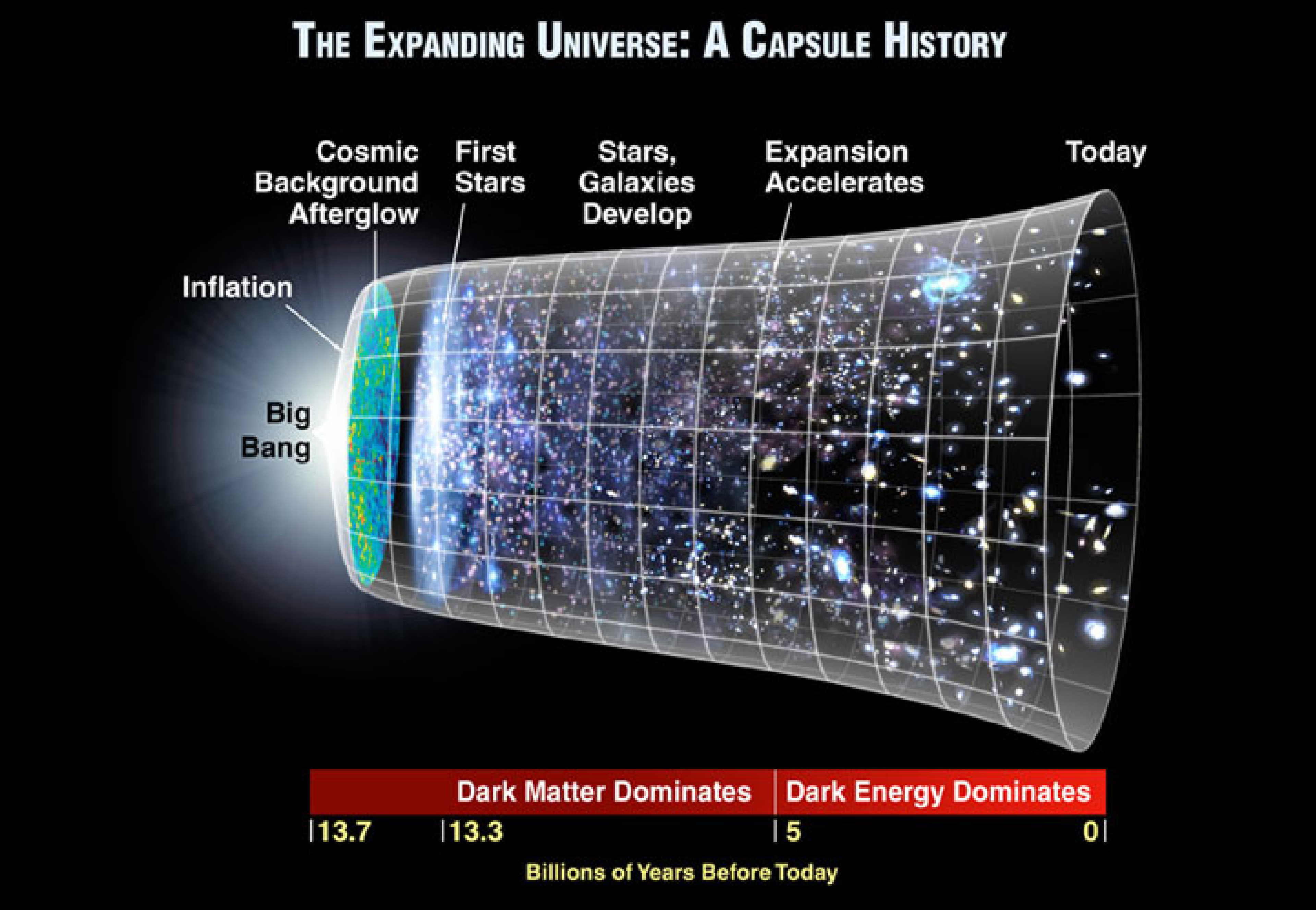
Large Scale Structure in the Local Universe



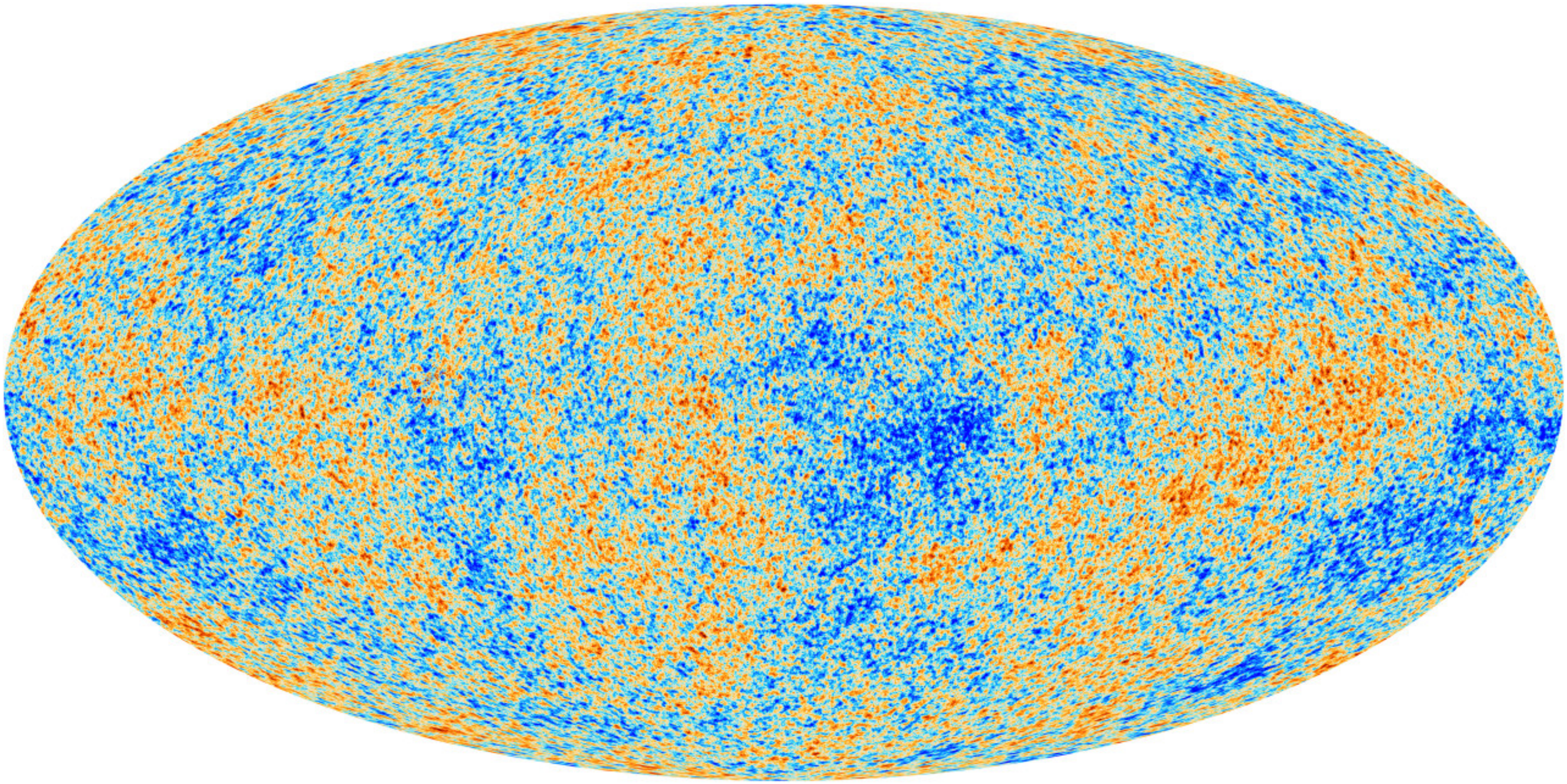
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)

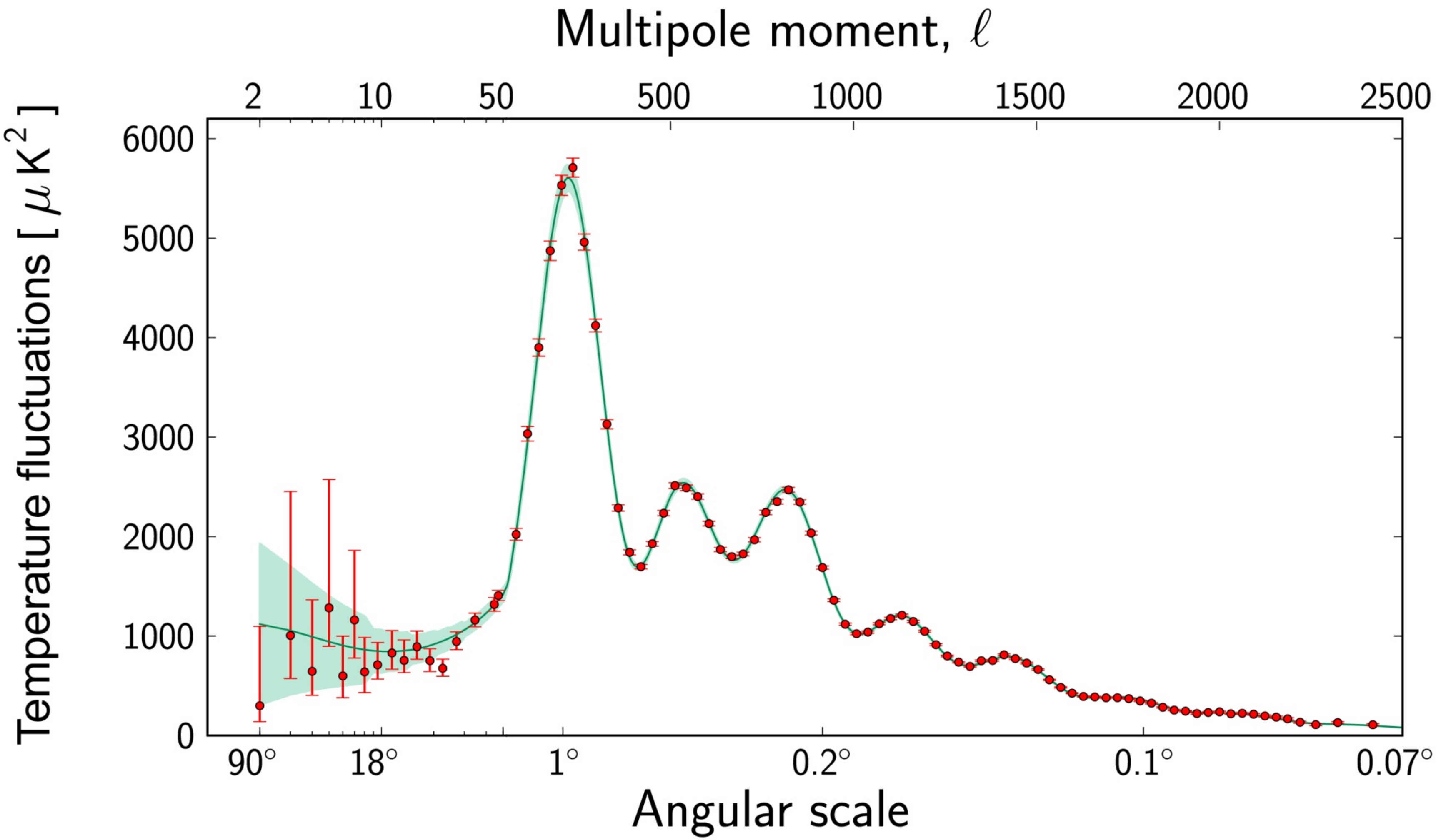
Two degree field galaxy redshift survey



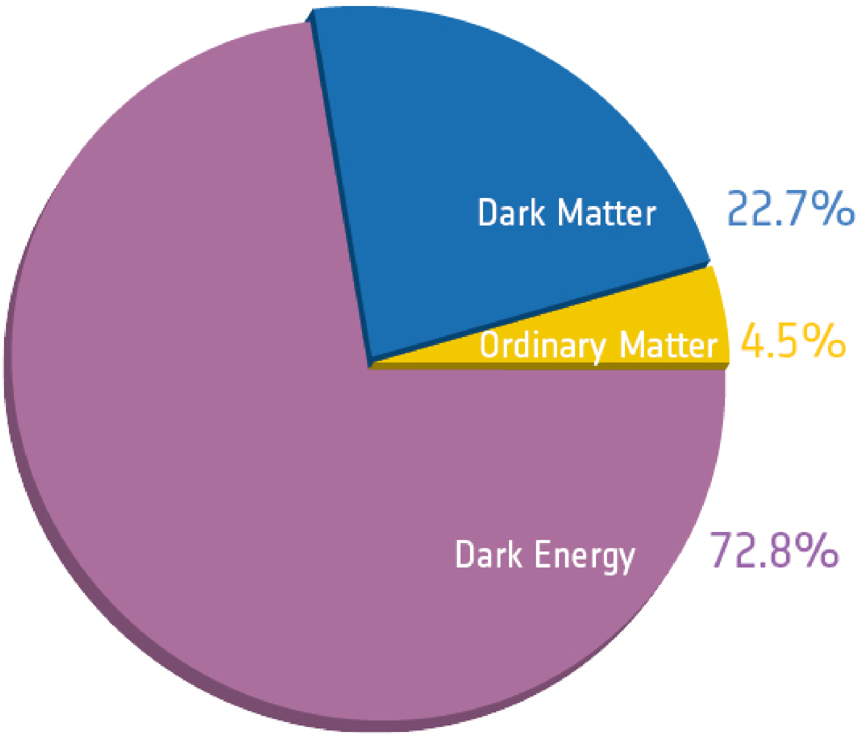

THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

The Universe – the Planck view

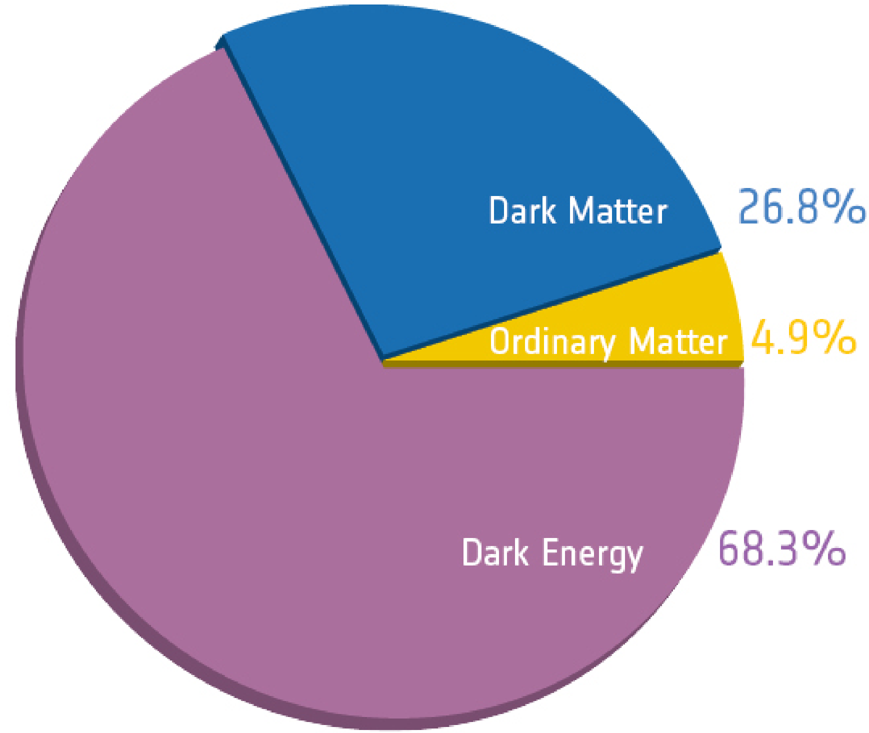




Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale



Before Planck

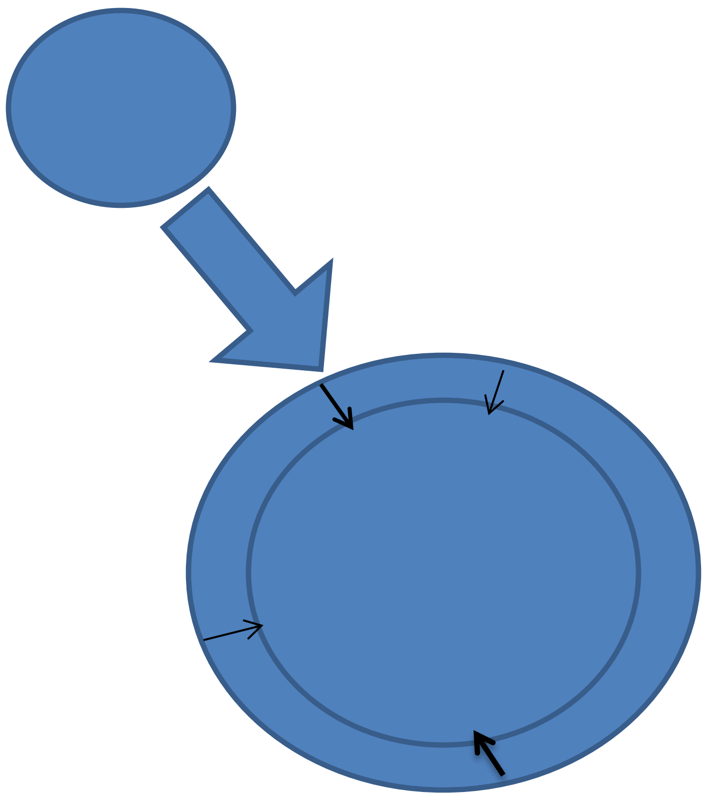


After Planck

Key ideas: cosmic structure

- Gravity is the primary cosmic architect
- Small primordial density ripples from Inflation
- Dark matter dominates over normal matter: collisionless, non-baryonic, gravitational force

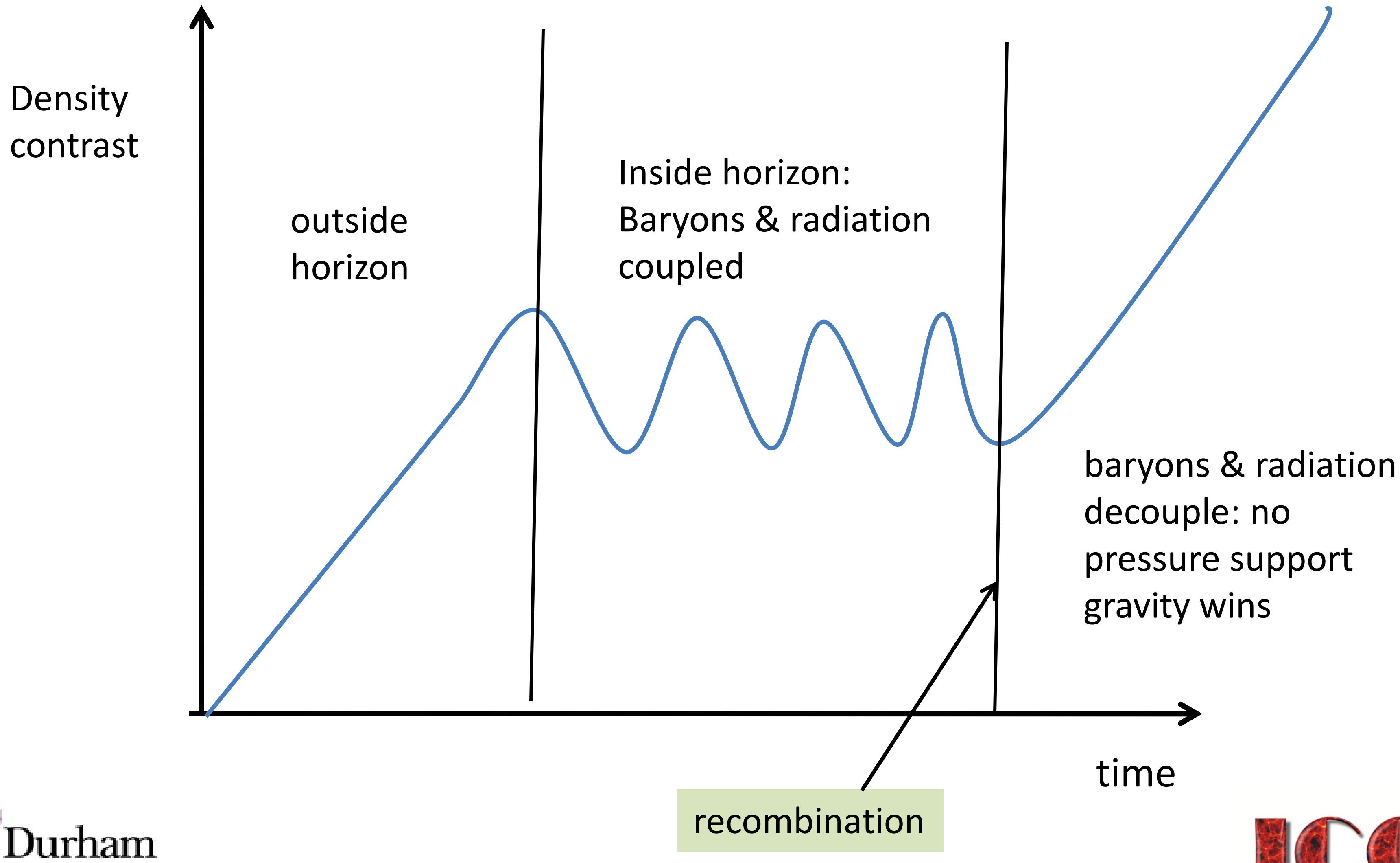
Density ripples in an expanding Universe



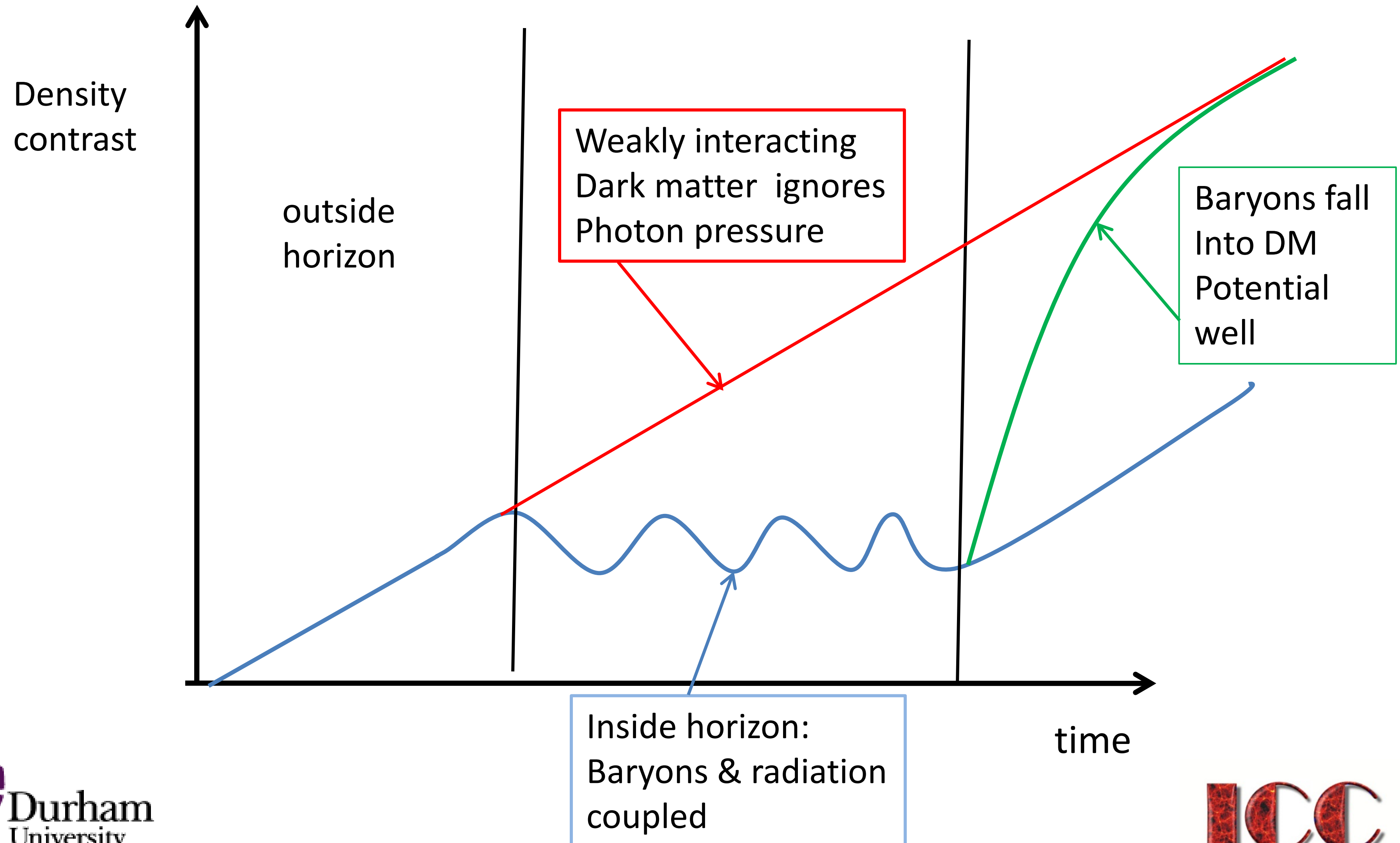
- Overdense sphere
- Initially expands with Universe
- Behaves like a mini-universe with a different density parameter
- Eventually reaches a maximum radius and collapses under gravity
- Increase expansion rate: harder to collapse

Durham University

The growth of a baryonic perturbation



The growth of a dark matter perturbation



Why do we need simulations?

- Perturbation theory breaks down

  - write down fluid equations in linear form

  - perturbation theory works when fluctuations are small

- Can follow perturbation growth in special cases

  - spherical top-hat: parametric solutions

Simulations: the basic idea

- Follow gravitational instability over cosmic history
- Need to take into account expansion of Universe
- Represent matter using particles: these are not cold dark matter particles!
- Choose box size and particle number to suit problem (and resources!)
- Simulation box has periodic boundary conditions

The N-body method uses a finite set of particles to sample the underlying distribution function

"MONTE-CARLO" APPROACH TO COLLISIONLESS DYNAMICS

We discretize in terms of N particles, which approximately move along characteristics of the underlying system.

$$\ddot{\mathbf{x}}_i = -\nabla_i \, \Phi(\mathbf{x}_i)$$

$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2]}$$

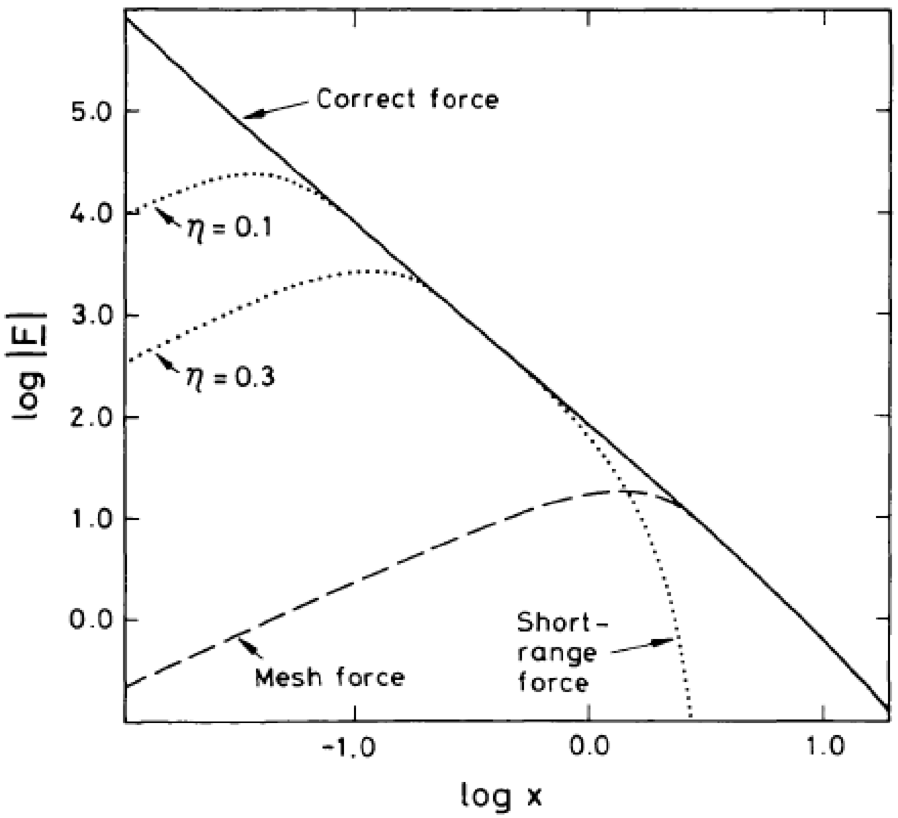
The need for **gravitational softening**:

- Prevent large-angle particle scatterings and the formation of bound particle pairs.
- Ensure that the two-body relaxation time is sufficiently large.
- Allows the system to be integrated with low-order intergations schemes.

} Needed for faithful collisionless behaviour

(from Volker Springel)

Gravitational force law



Efstathiou et al 1985

- Need efficient algorithm to compute gravitational force
- Small scales: direct pair count: scales as N^2
- Large scales: mesh and Fourier transfrom: NlogN
- Periodic boundary conditions
- Softening: avoid two body effects and relaxation

Two conflicting requirements complicate the study of **hierarchical** structure formation

DYNAMIC RANGE PROBLEM FACED BY COSMOLOGICAL SIMULATIONS

Want **small particle mass** to resolve internal structure of halos

Want **large volume** to obtain respresentative sample of universe

need large **N**

where N is the particle number

Problems due to a small box size:

- Fundamental mode goes non-linear soon after the first halos form. ⇨ Simulation cannot be meaningfully continued beyond this point.
- No rare objects (the first halo, **rich** galaxy clusters, etc.)

Problems due to a large particle mass:

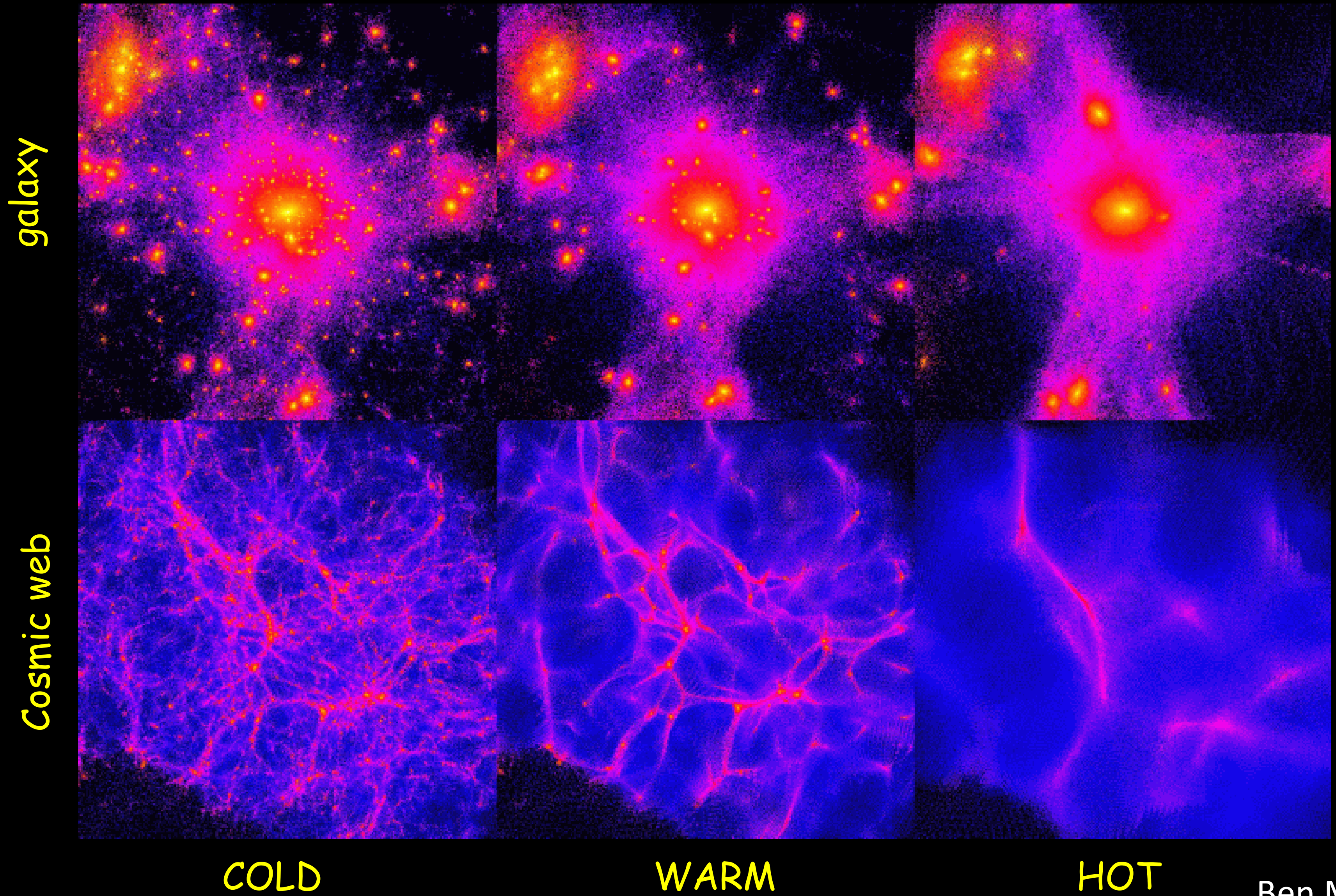
- Physics cannot be resolved.
- Small galaxies are missed.

At any given time, halos exist on a large range of mass-scales !

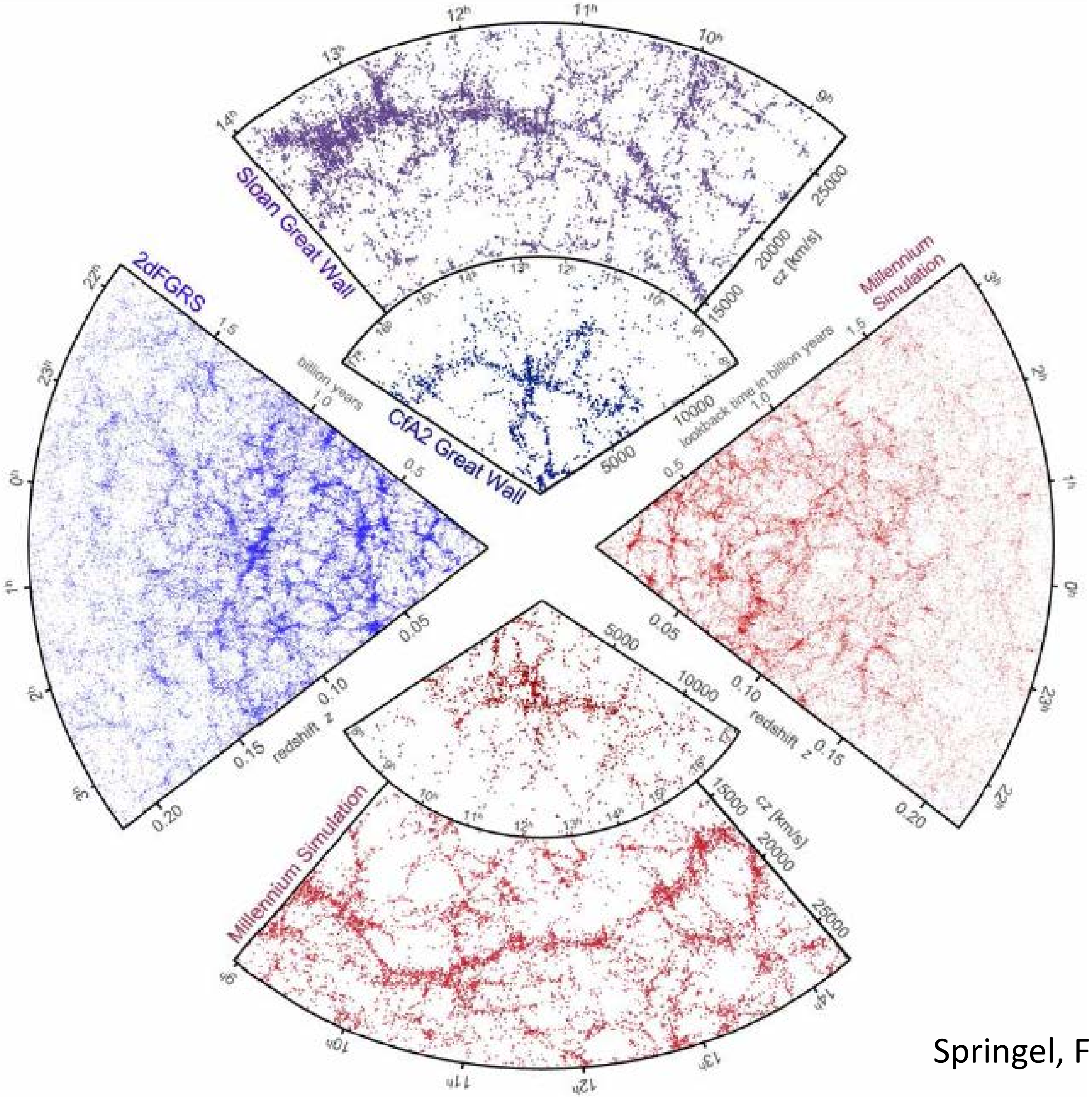
(from Volker Springel)

ICC

Why temperature of dark matter is important



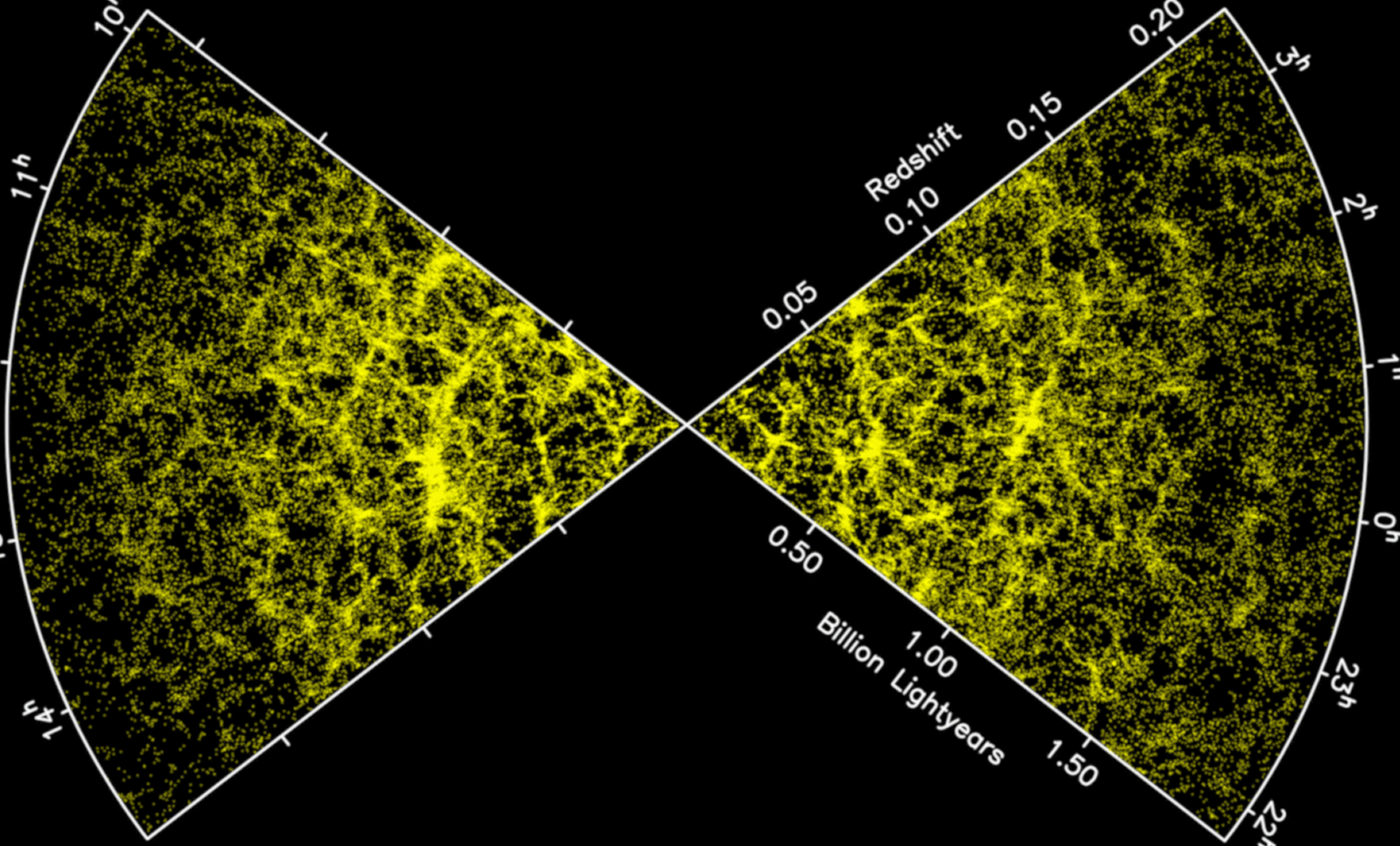
Ben Moore



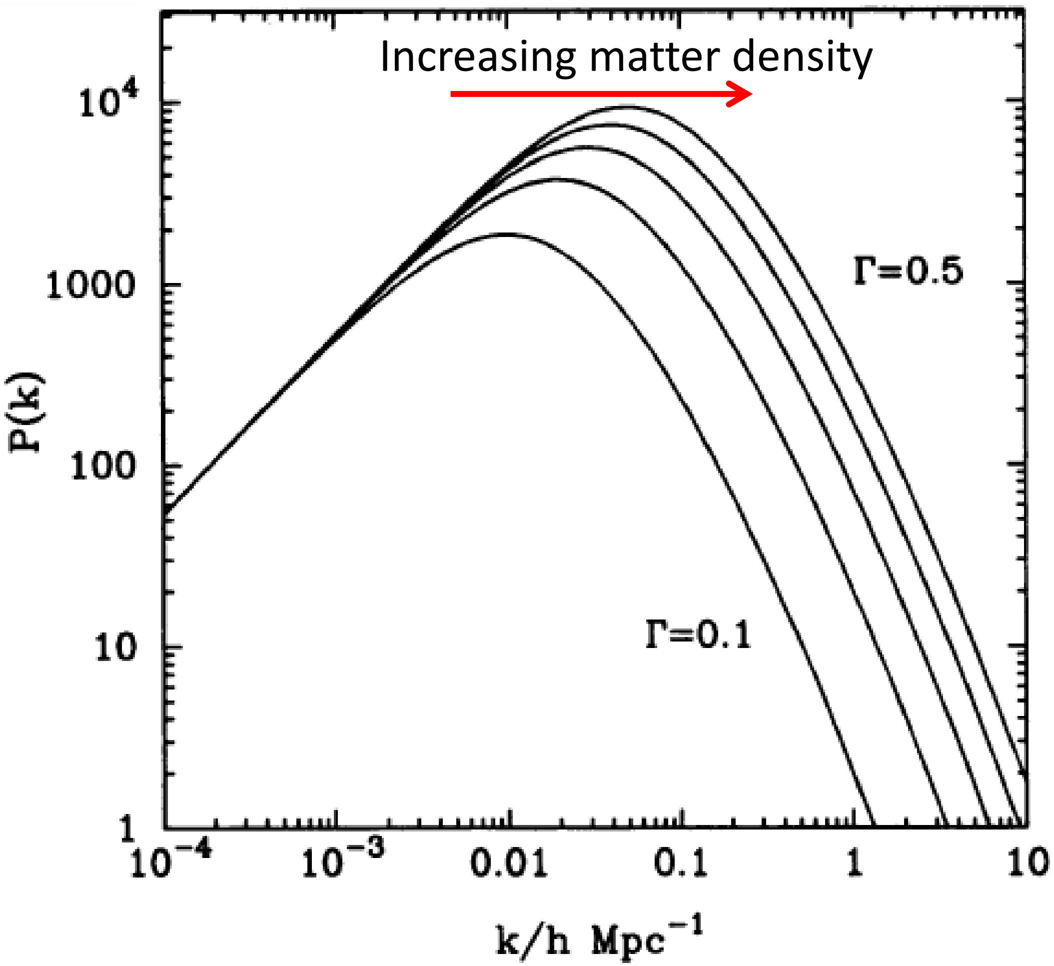
Springel, Frenk & White 2006

What have we learnt from the large-scale structure of the Universe?

Clumpiness of galaxy distribution: gravitational instability



Quantifying clustering: two point statistics

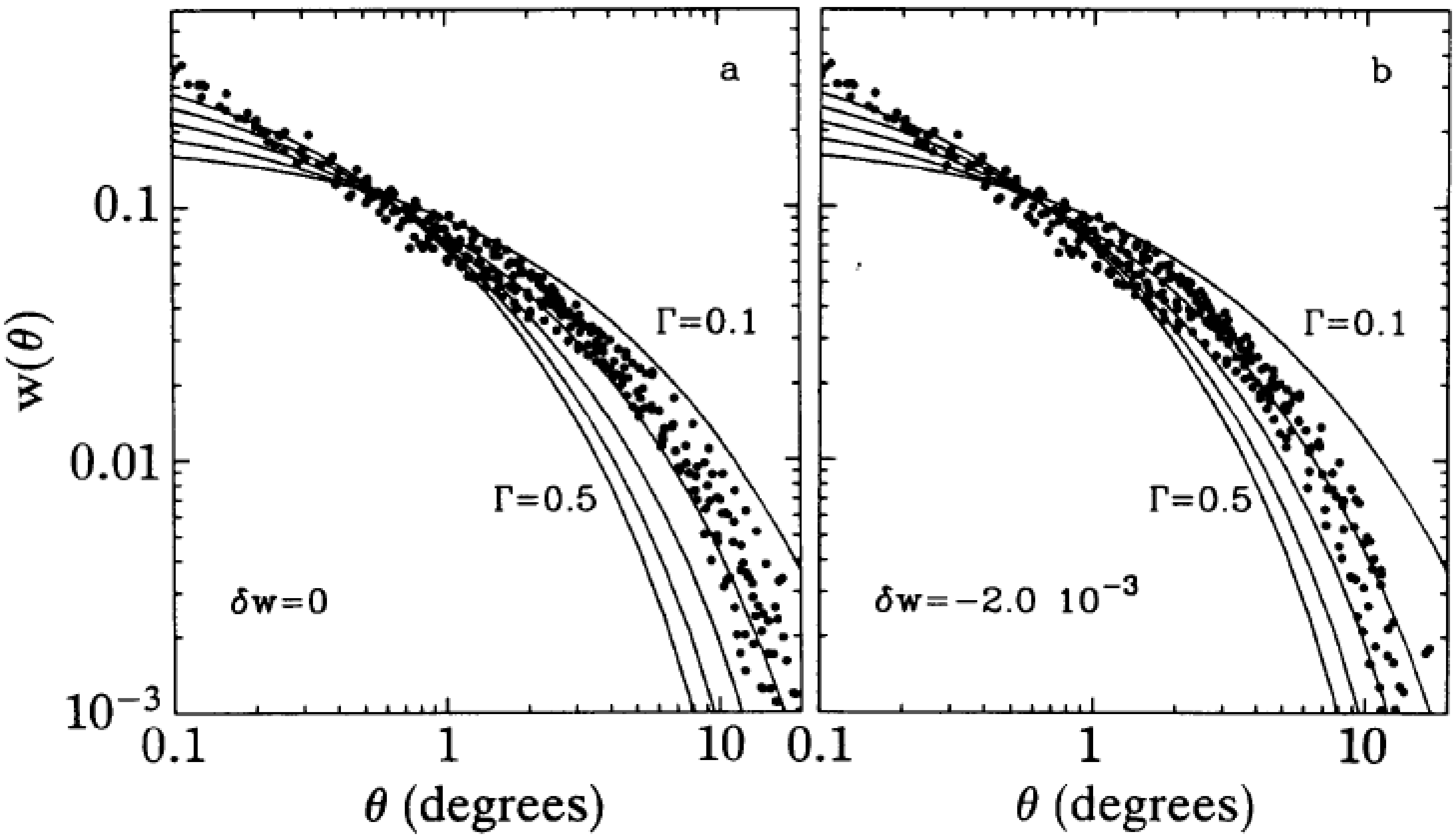


Power spectrum P(k,z):

$$\frac{k^3}{2\pi^2} P(k,z) = \delta_H^2 \left(\frac{ck}{H_0}\right)^{3+n} \frac{T^2(k,z) D_1^2(z)}{D_1^2(0)}$$

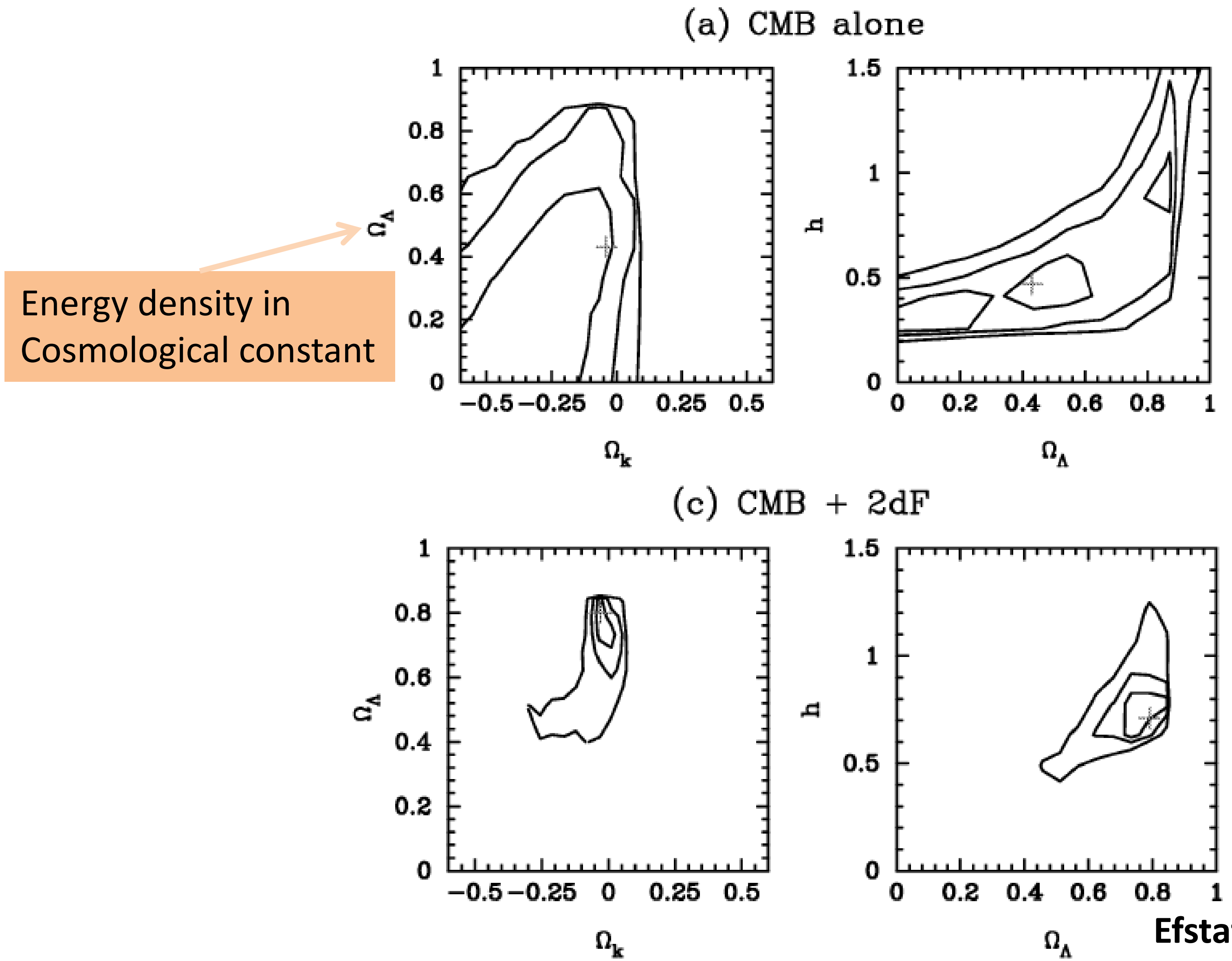
Two-point correlation function is the Fourier transform of P(k)

Early 1990s: more clustering than expected



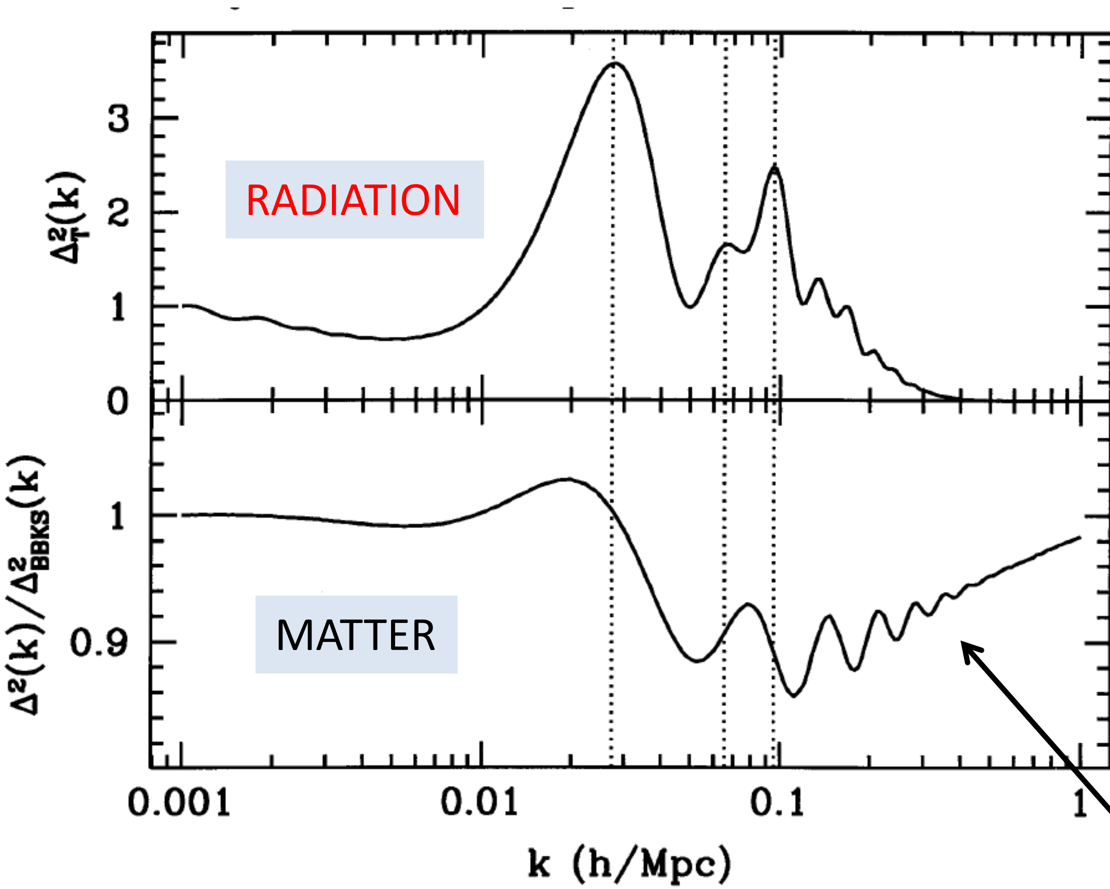
IRAS Survey: Saunders et al. 1991; APM Survey: Maddox et al. 1990

2002: CMB + LSS Dark energy



Efstathiou et al. 2002

Baryonic acoustic oscillations

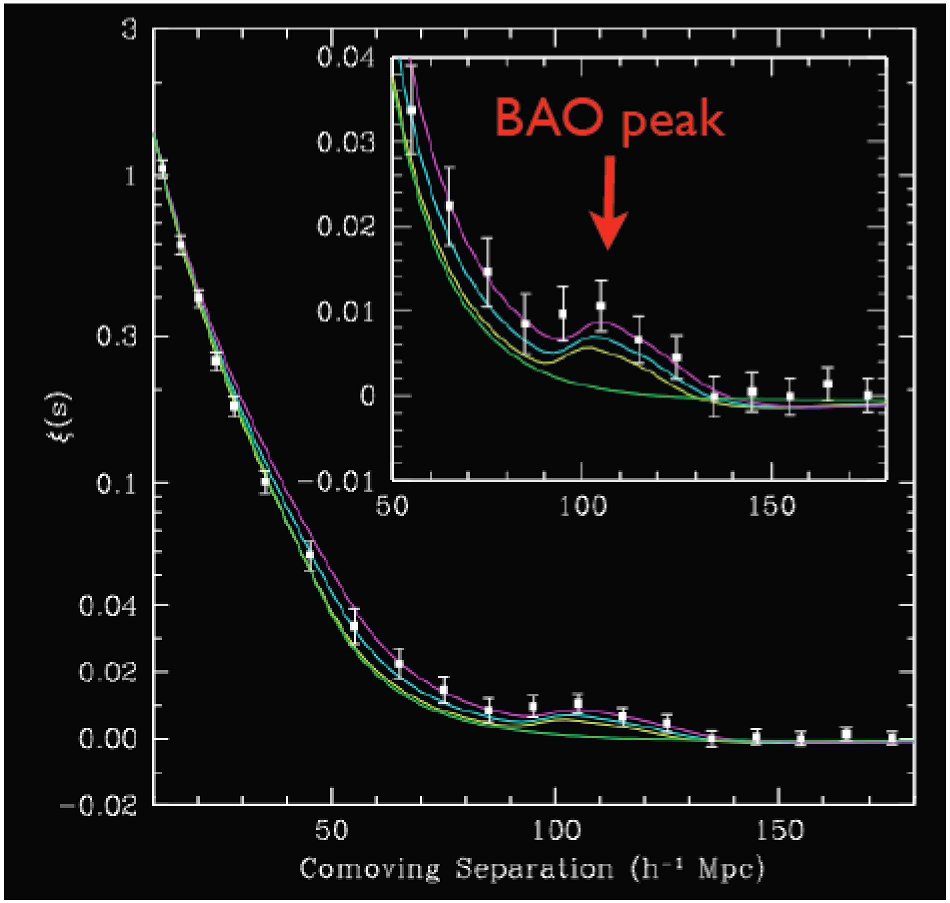


Meiksin, White & Peacock 1999

- First predicted by Peebles & Yu 1970, Zeldovich 1970
- Clear peaks in radiation spectrum
- Peaks out of phase between Cl and P(k)
- Reduced amplitude in matter P(k)
- BAO scale related to sound horizon at recombination
- Considered as a standard ruler

Divide matter spectrum by Featureless reference to Emphasize BAO signal

Detection of BAO



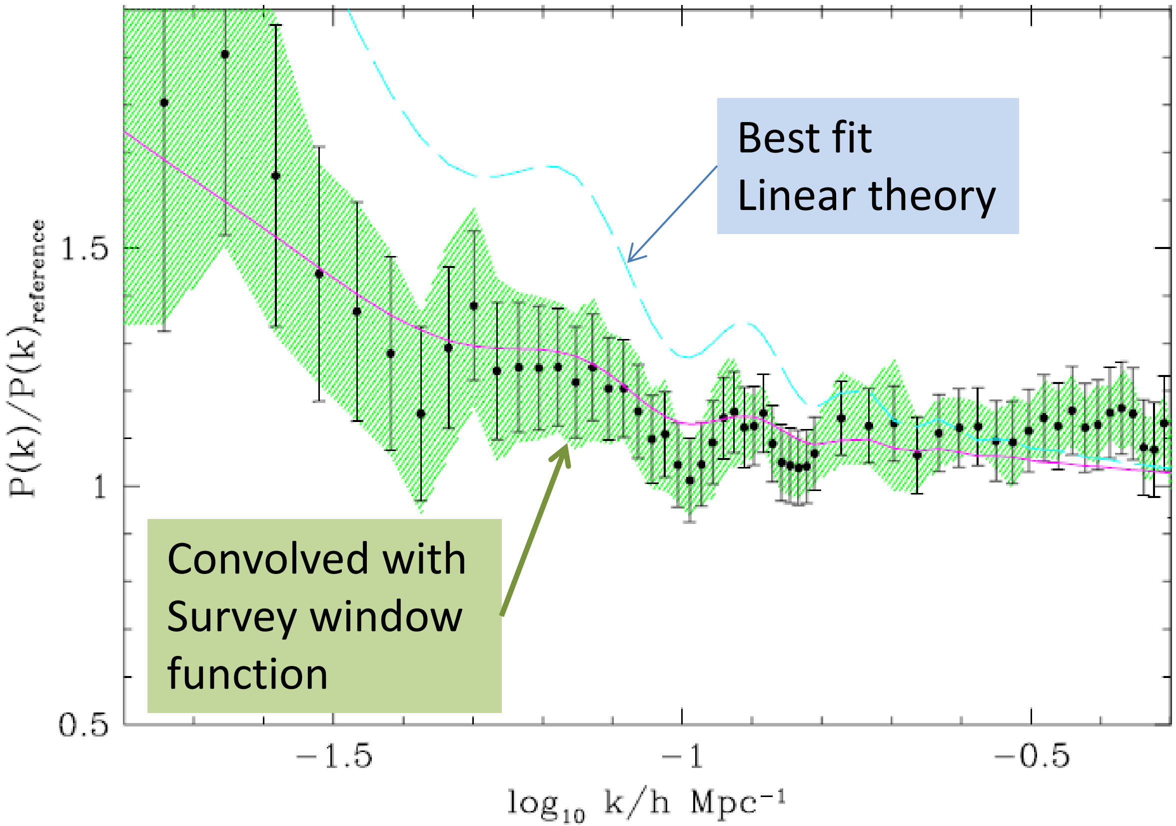
- Eisenstein et al 2005
- 47,000 SDSS LRGs
- 0.72 cubic Gpc
- Constraint on spherically averaged BAO scale
- Constrain distance parameter:

$$D_V(z) = \left[D_M(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

Angular diameter distance

Hubble parameter

Detection of BAO



Cole et al. 2005 2dFGRS main galaxy sample

Durham University

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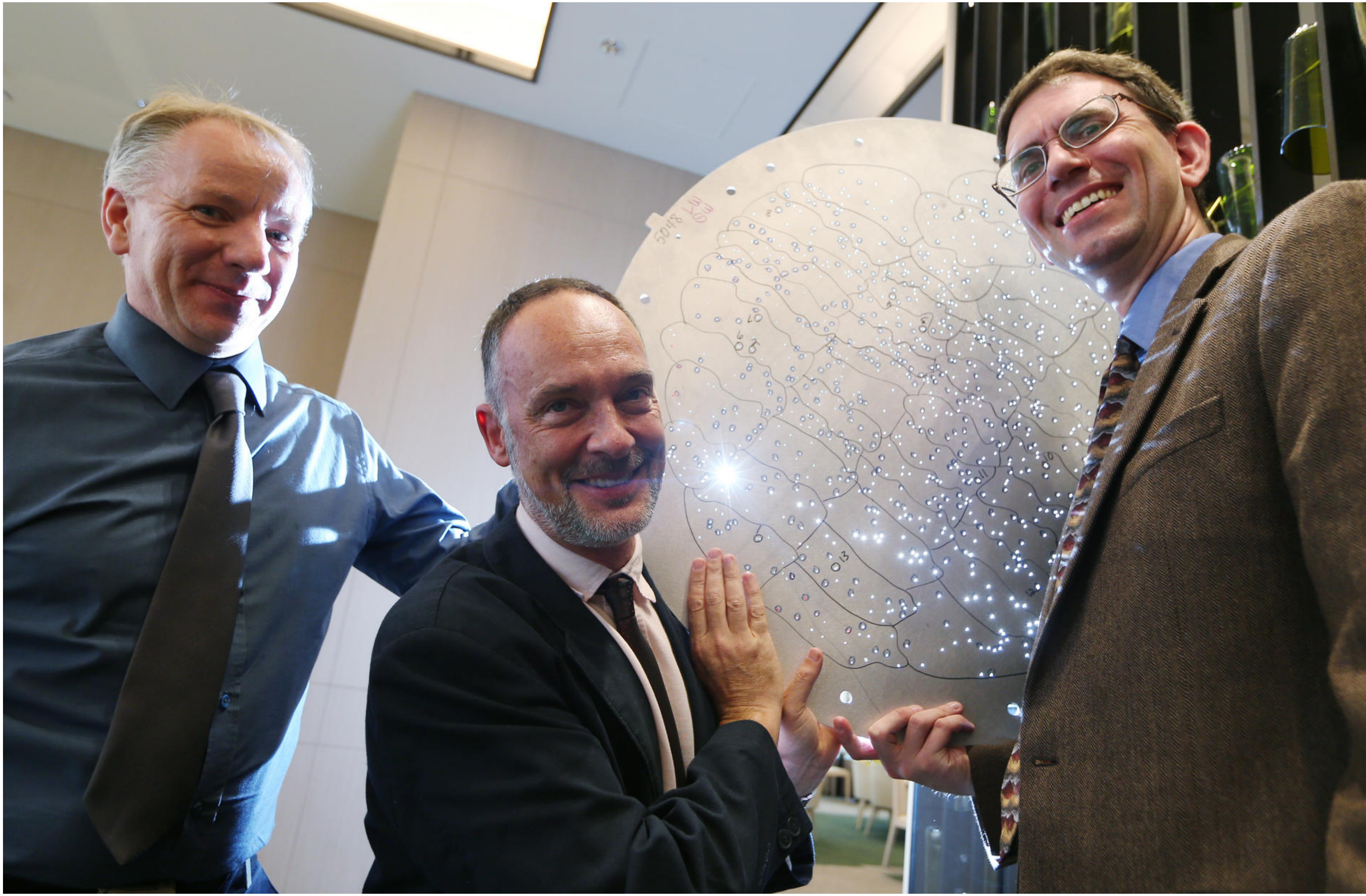


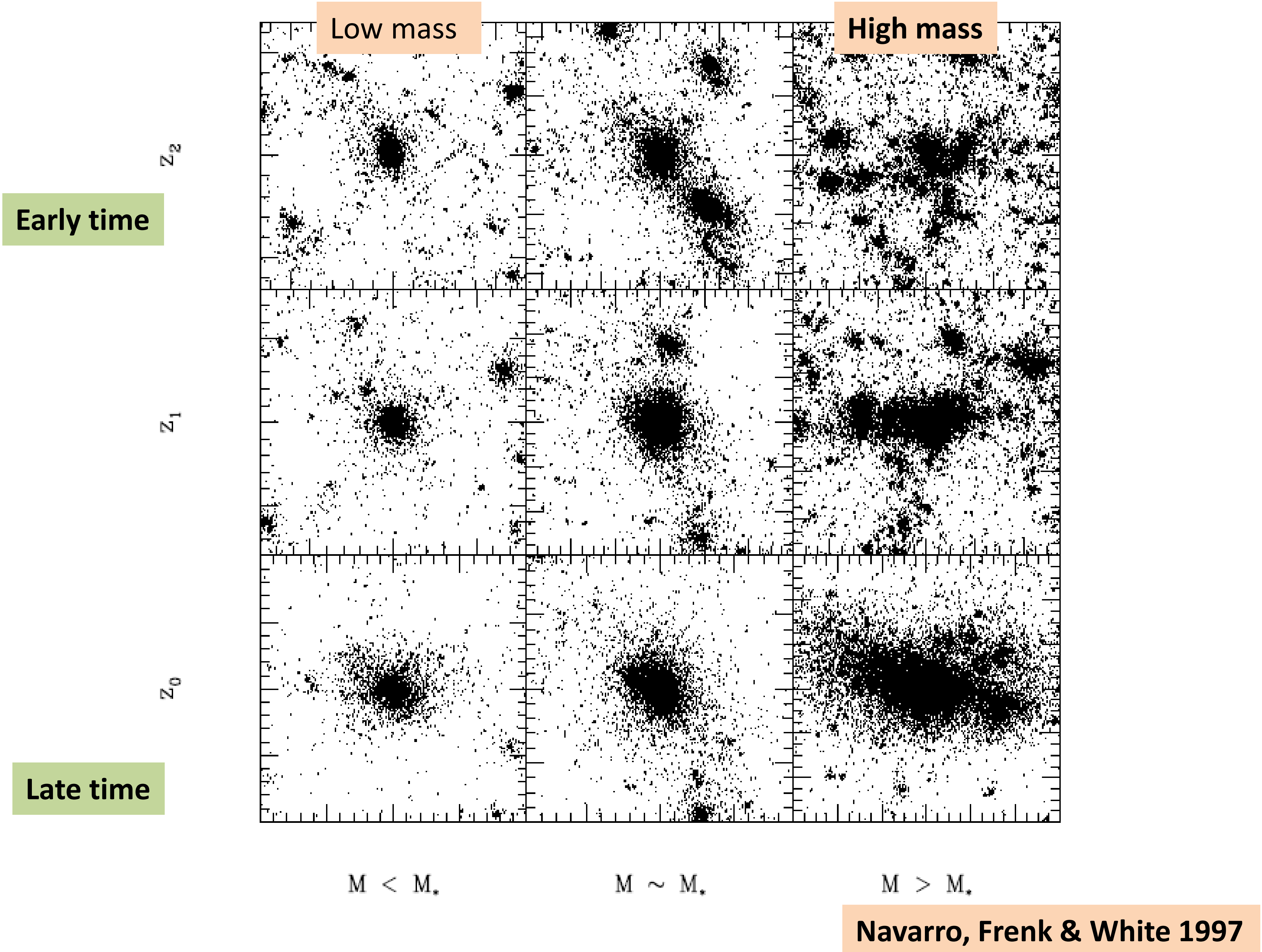
2014 Shaw Prize in Astrophysics: Shaun Cole, John Peacock, Daniel Eisenstein


z = 48.4
T = 0.05 Gyr
500 kpc

Is Lambda-CDM the right answer?

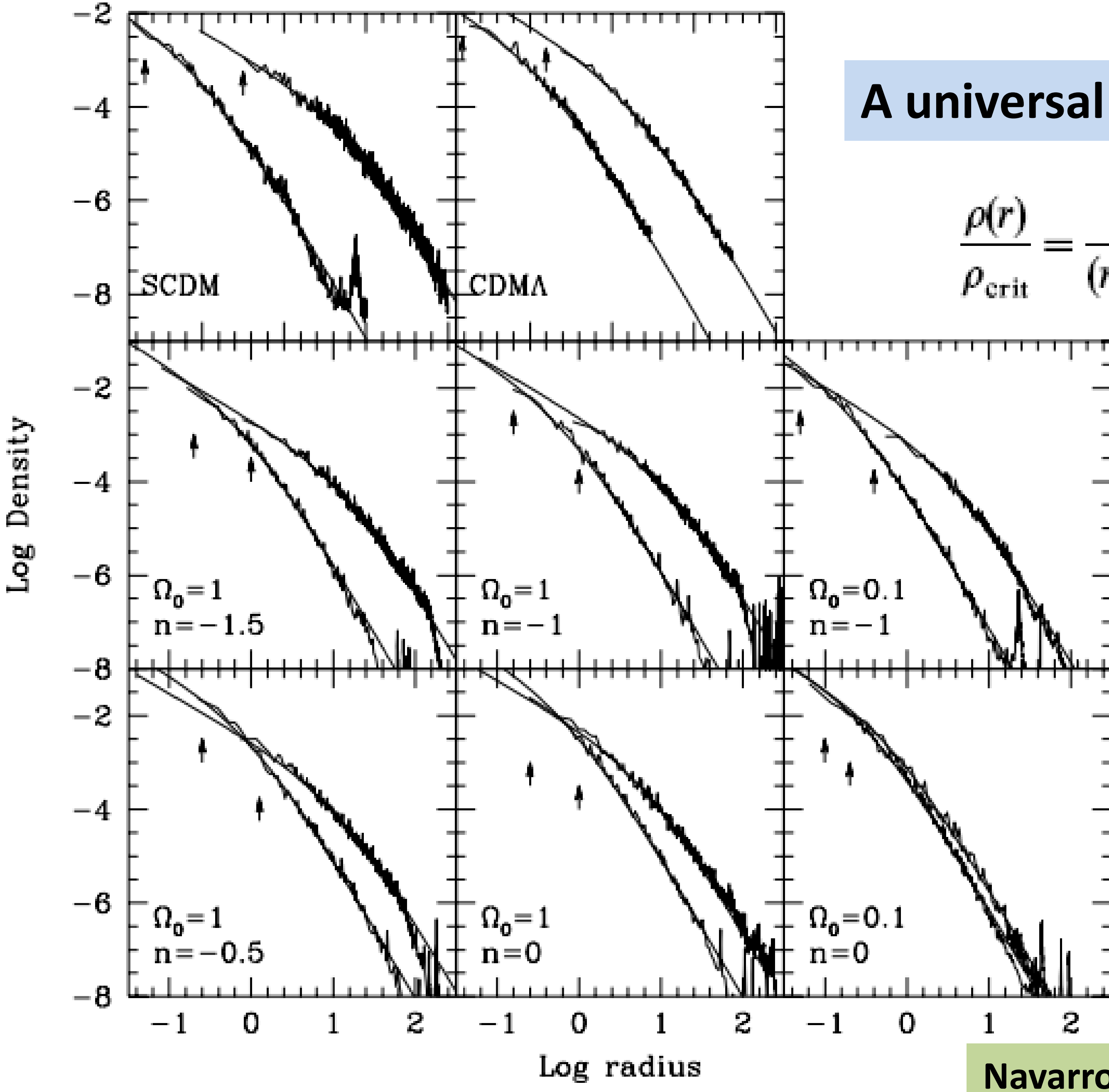
- Seen it works well on large scales
- But, what is the cosmological constant?
- Does it work on small scales?

The nature of dark matter halos


Low mass
High mass
Early time
Late time
z_2
z_1
z_0
$M < M_*$
$M \sim M_*$
$M > M_*$
Navarro, Frenk & White 1997

A universal density profile

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



Navarro, Frenk & White 1997

The structure of DM haloes

- Rotation curves of galaxies
- Dark matter annihilation signal
- Density and angular momentum of gas

The fitting formulae we have used to describe the mass profile of our simulated haloes are the following: (i) The NFW profile, given by

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1 + r/r_{\rm s})^2}; \tag{2}$$

(ii) the modification to the NFW profile proposed by M99,

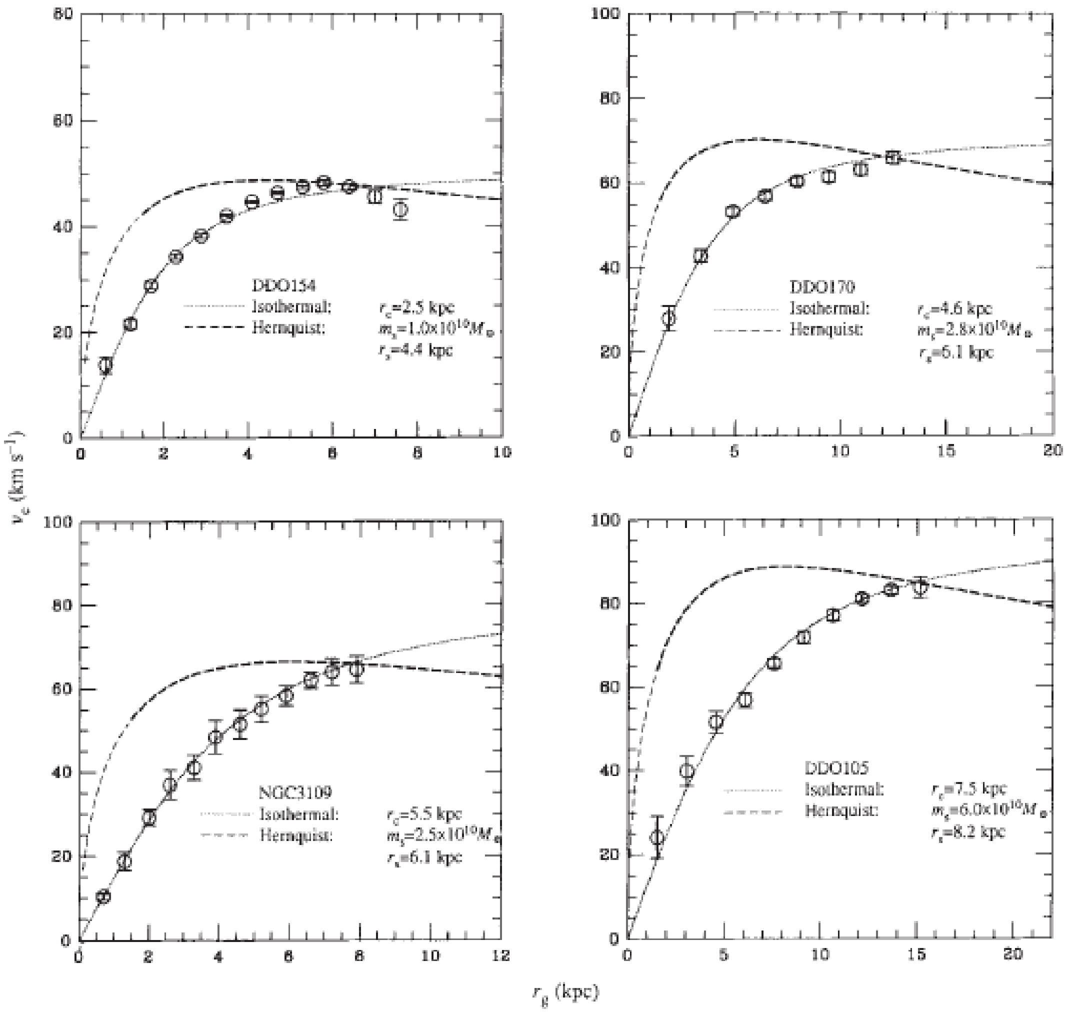
$$\rho(r) = \frac{\rho_{\rm M}}{(r/r_{\rm M})^{1.5}[1 + (r/r_{\rm M})^{1.5}]}, \tag{3}$$

and (iii) the Einasto profile,

$$\ln[\rho(r)/\rho_{-2}] = (-2/\alpha)[(r/r_{-2})^{\alpha} - 1]. \tag{4}$$

Do galaxies really live in CDM halos?

Rotation speed



radius

CDM halos have cuspy cores:

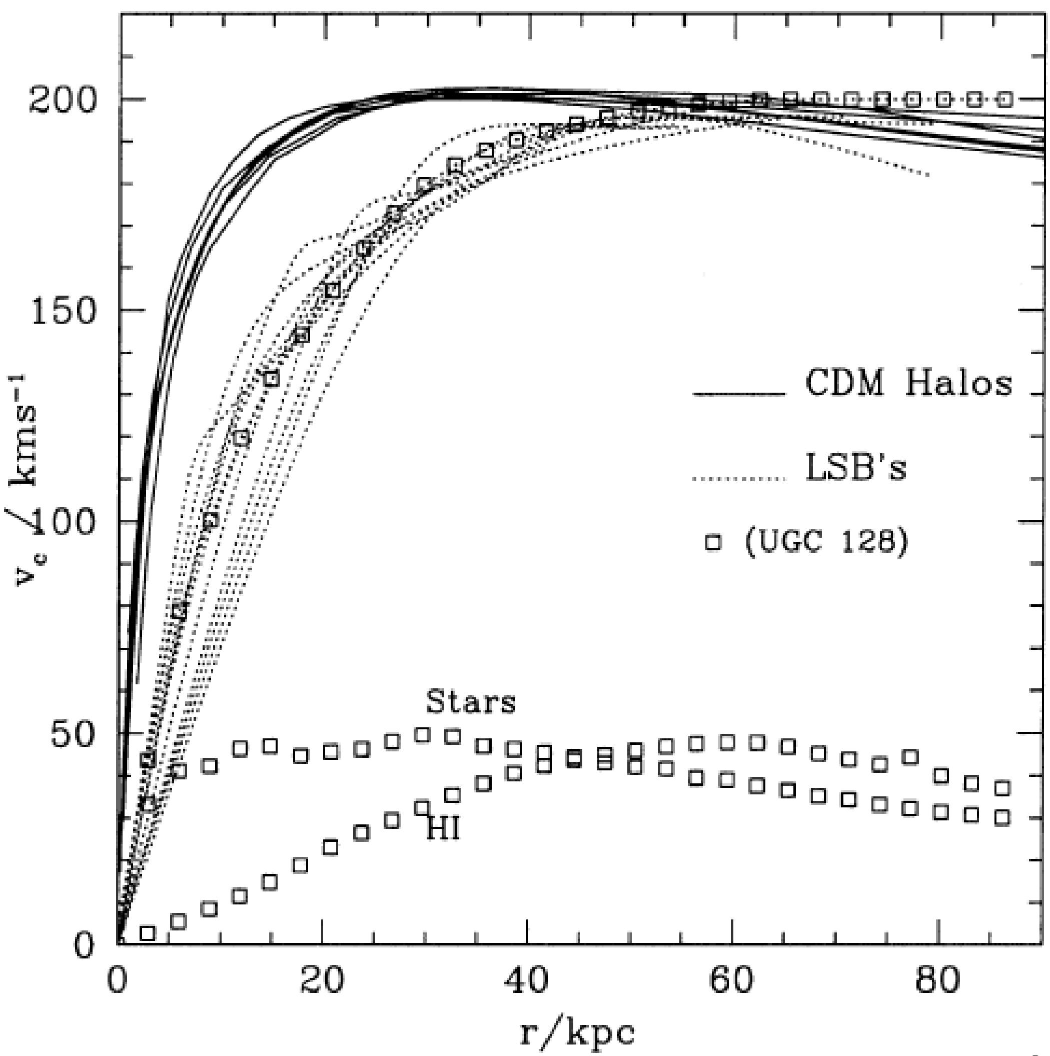
Imply more dark matter in centre

Than suggested by measured Rotation curves:

Dwarf galaxies – dominated by Dark matter – favour isothermal -- constant density cores

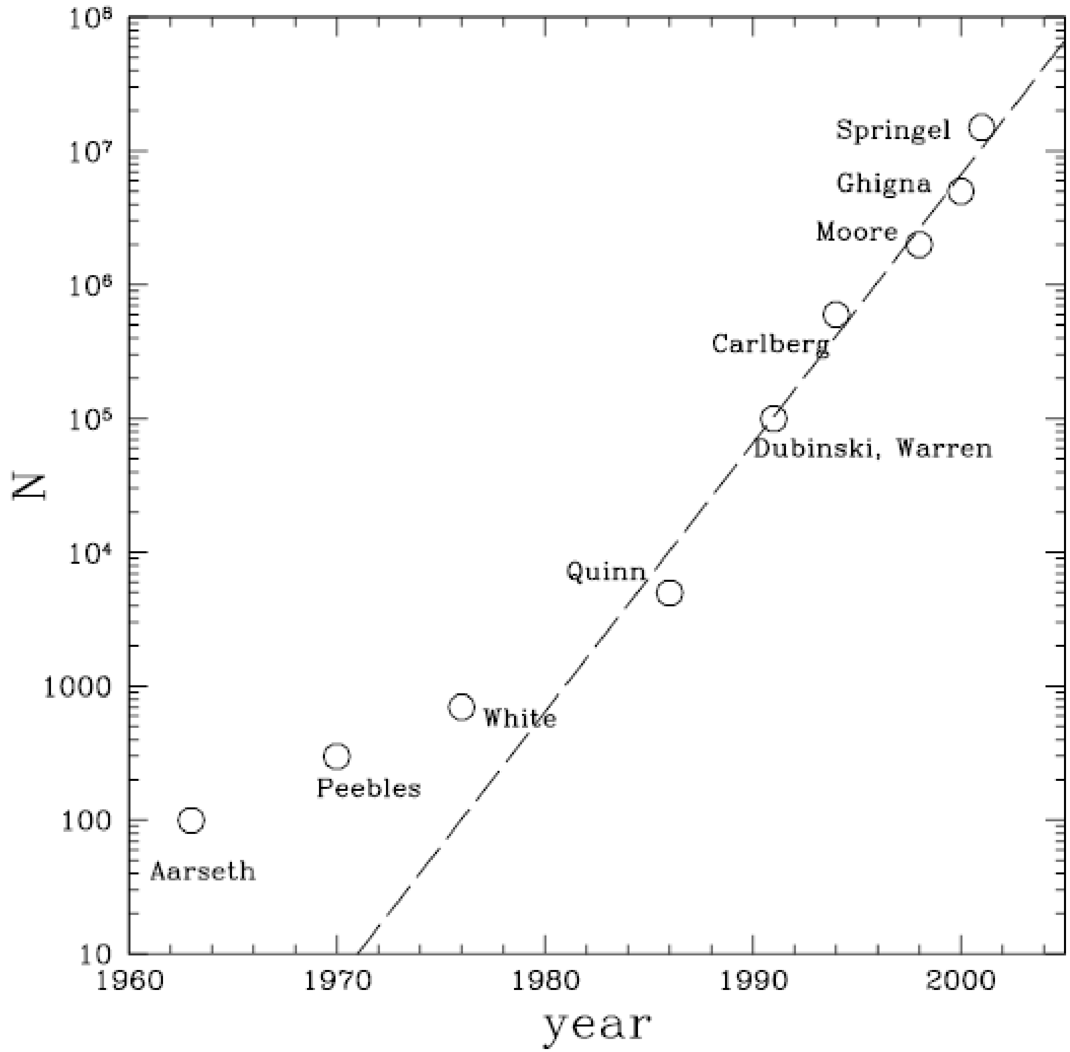
Moore 1994

Cusps vs cores

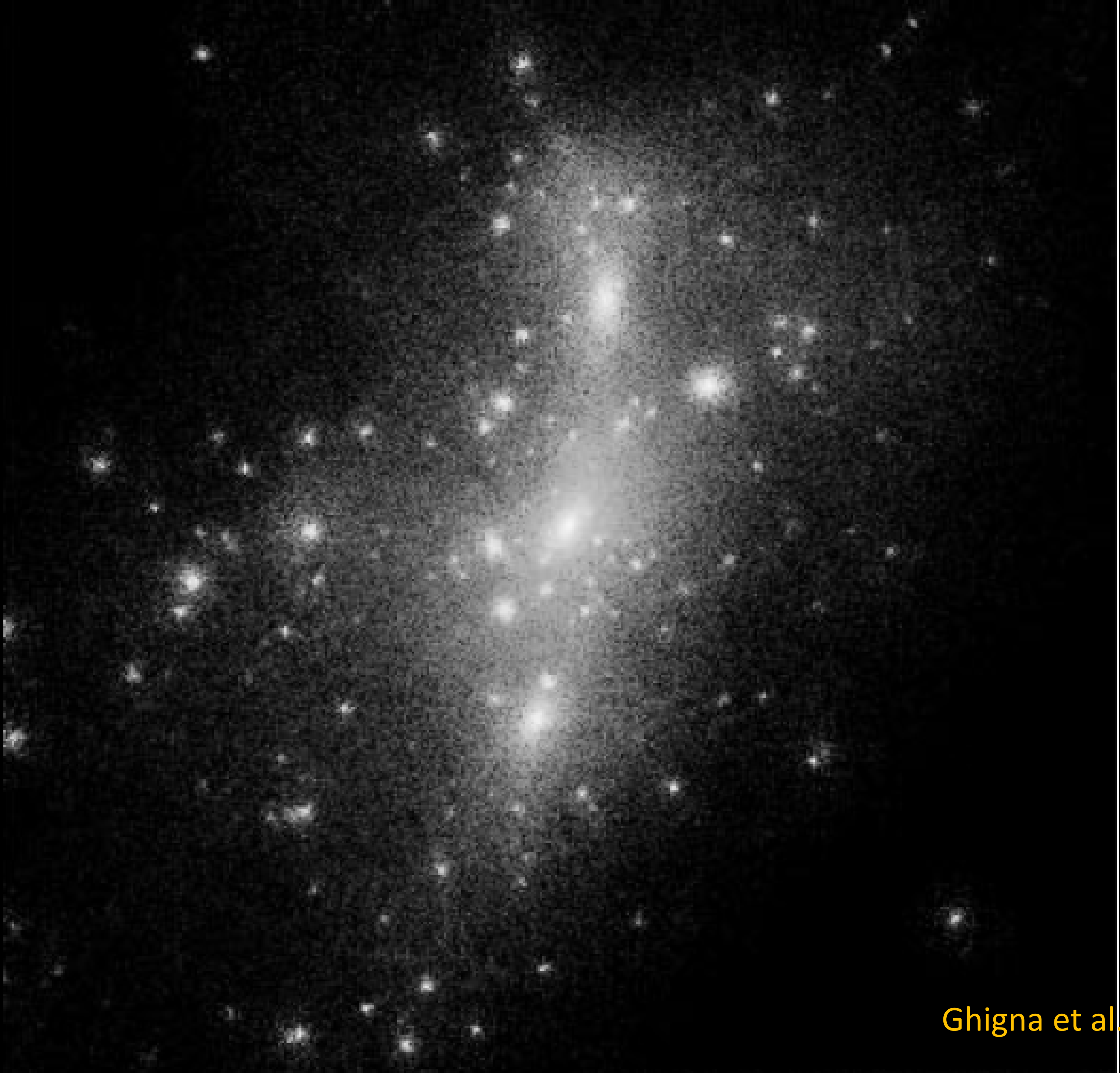


Moore et al 1999

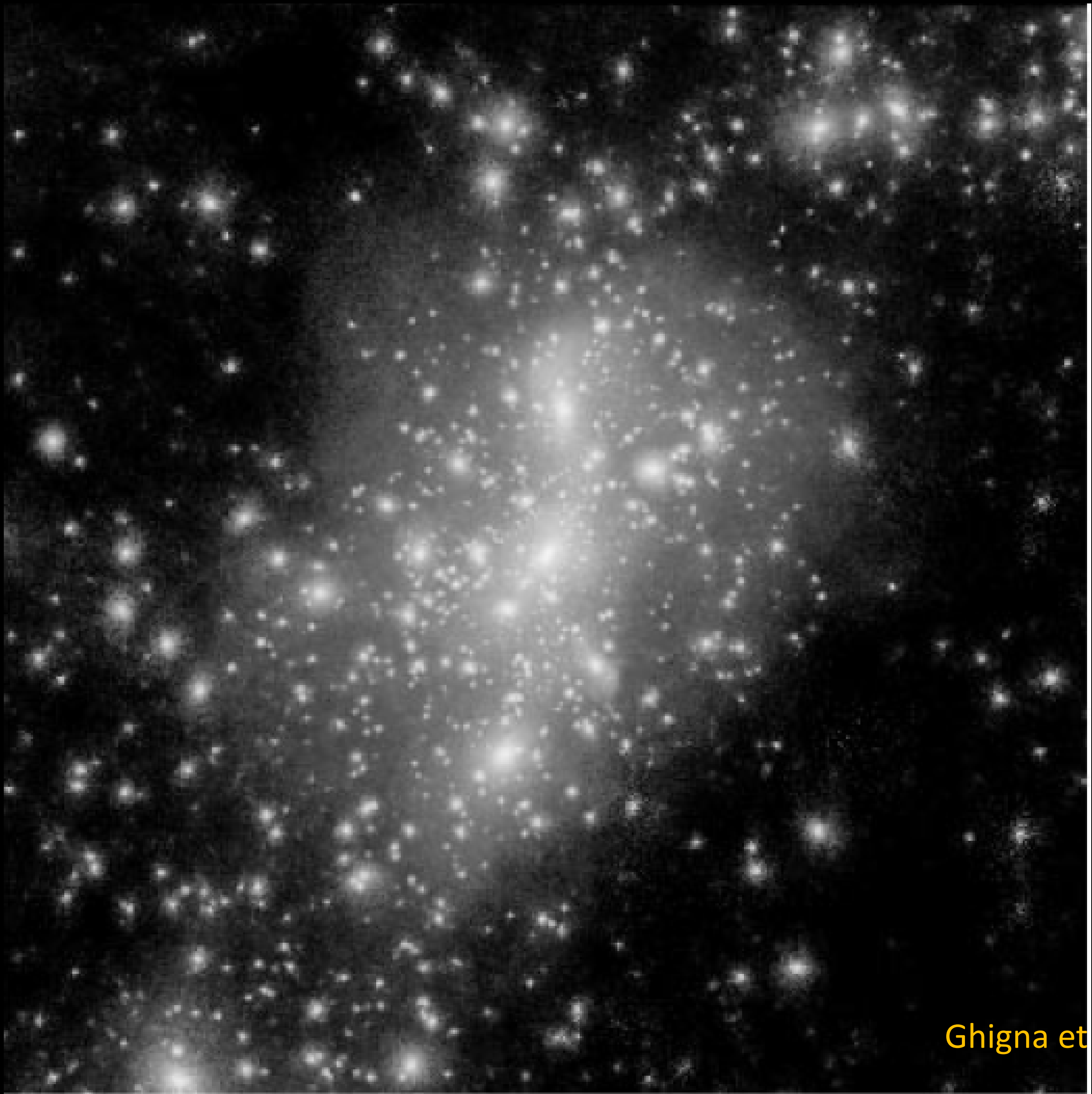
N-body simulations of clusters: more particles, same answers?



Moore 2000

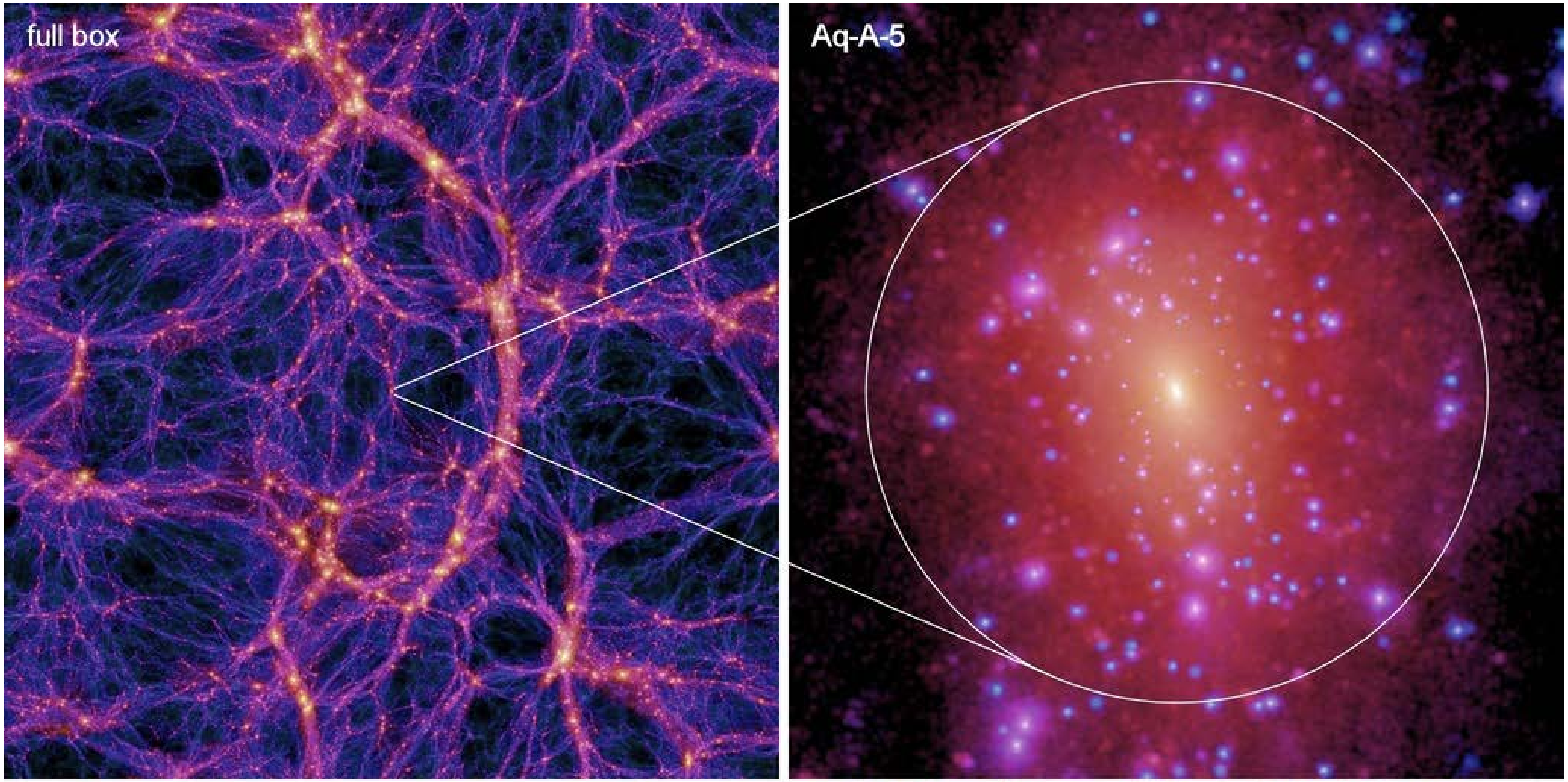


Ghigna et al. 2000



Ghigna et al. 2000

Formation of a Milky Way like DM halo



Durham University

Aquarius halo: Volker Springel et al. 2008

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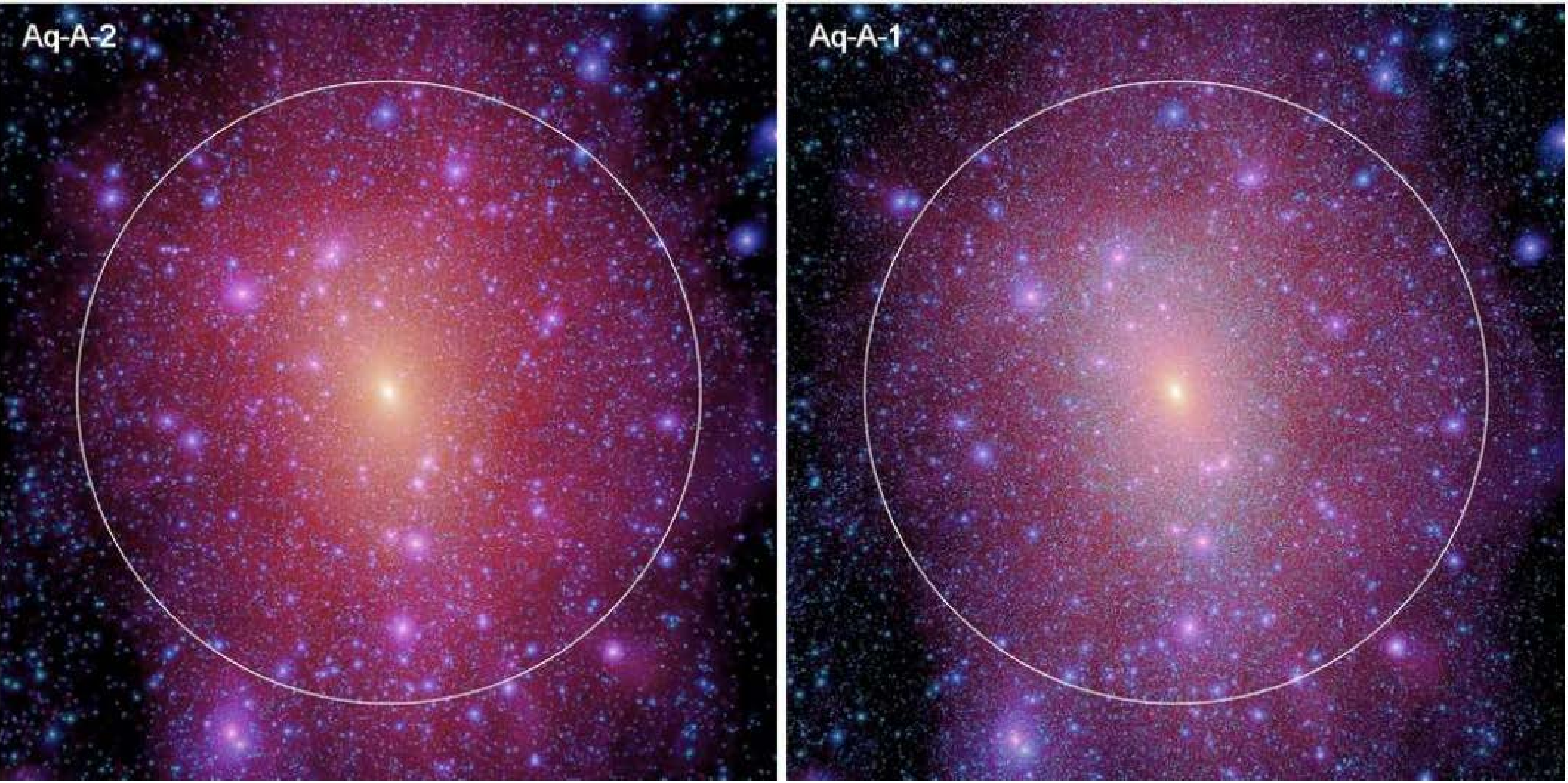
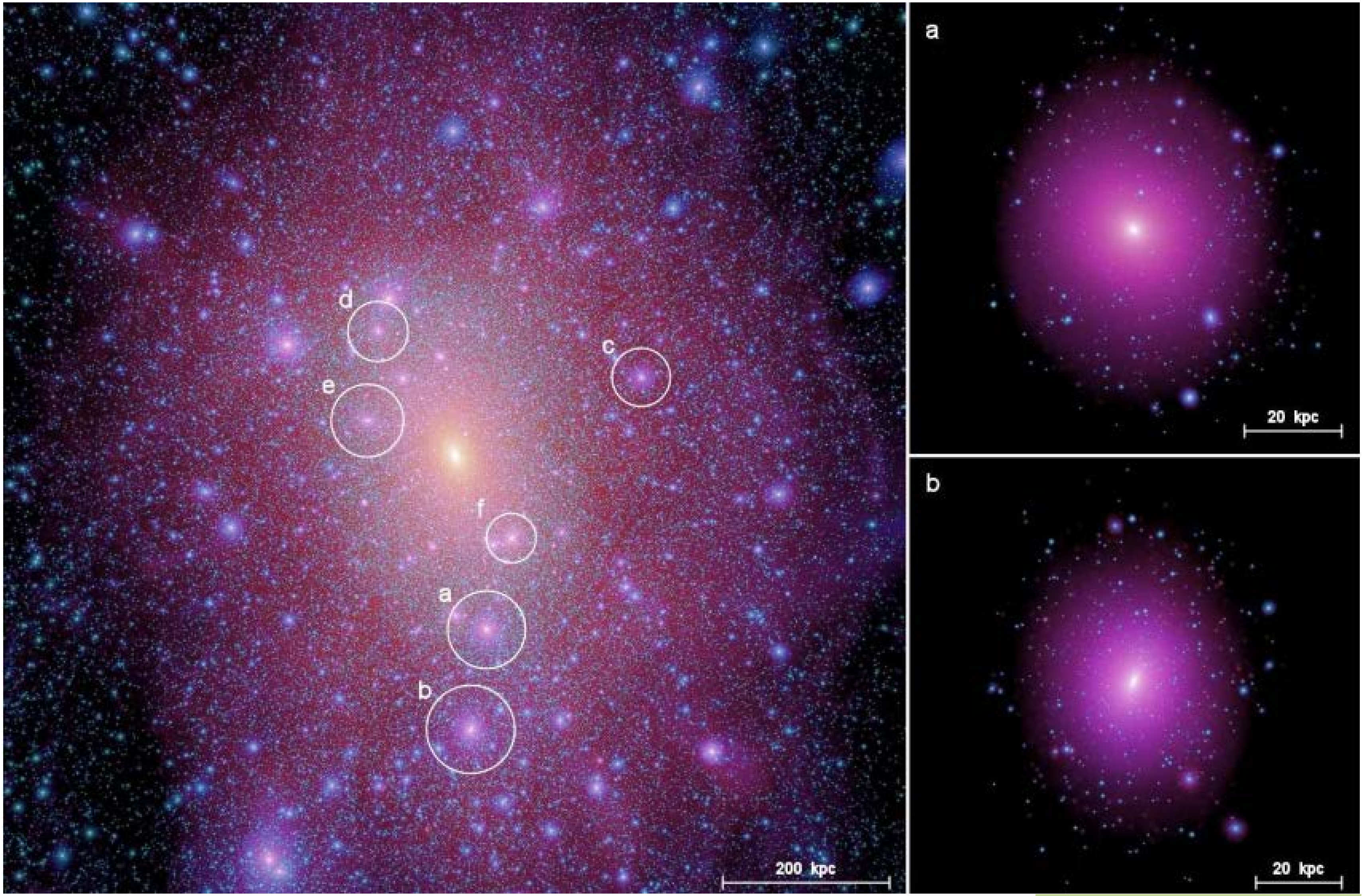
Dark Matter Substructures



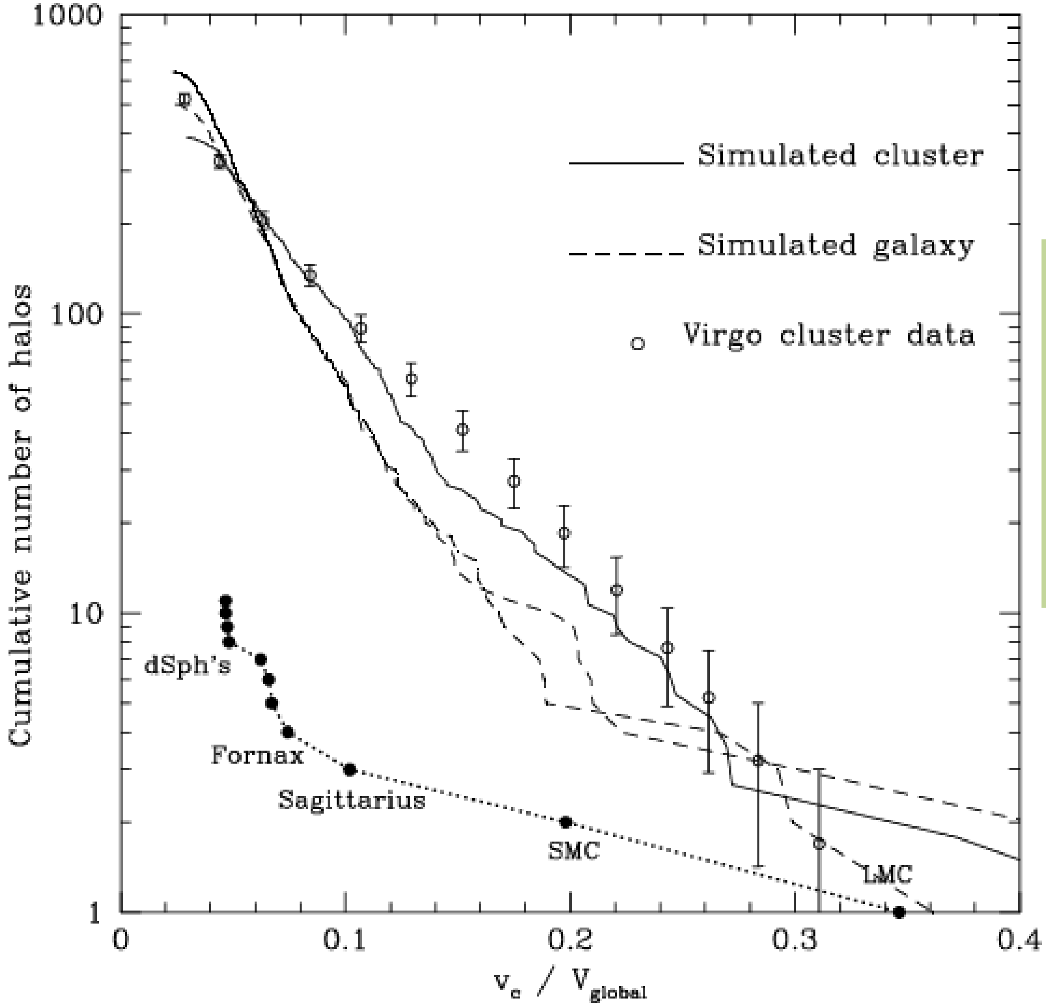
Springel et al 2008

Hierarchies of substructure



Springel et al 2008

Is substructure a problem for CDM?



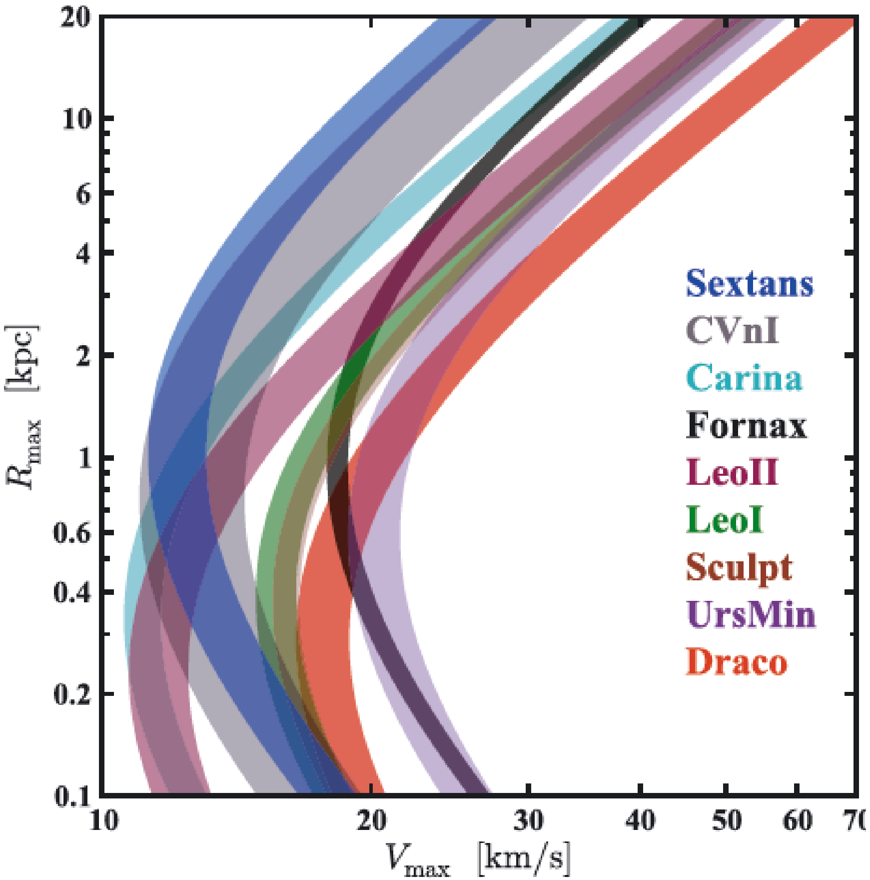
Milky Way Satellite Problem:

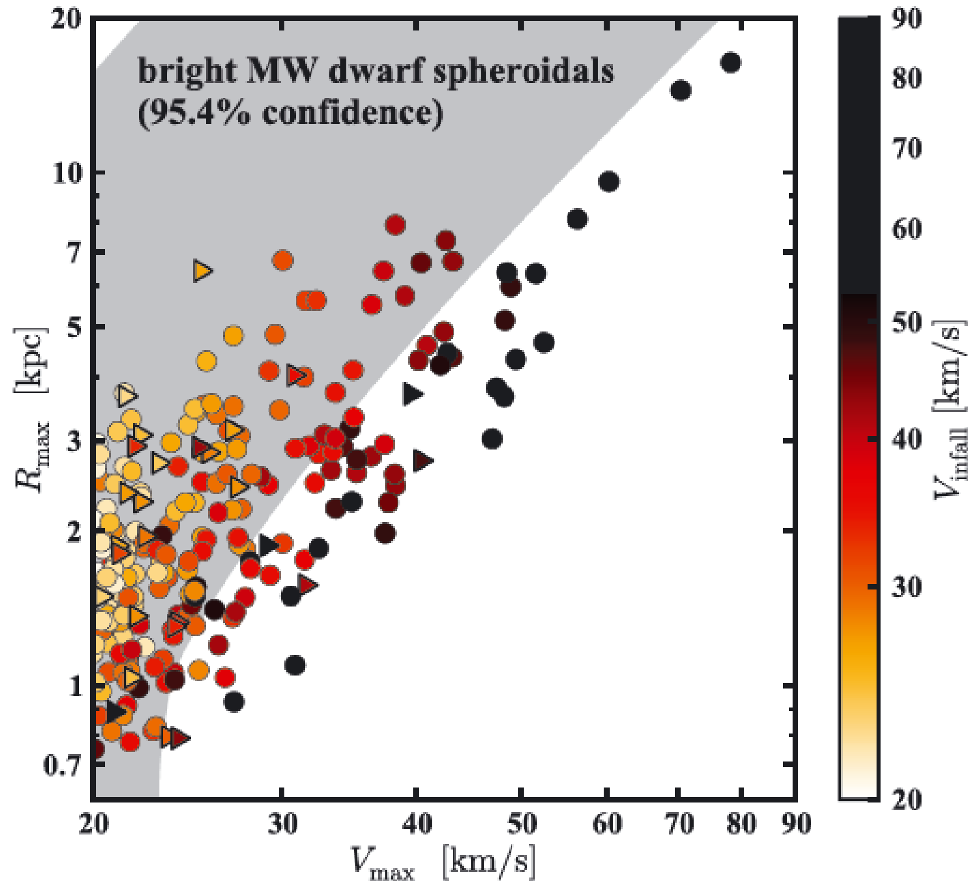
Identifying dark matter subhalos with galaxies, CDM predicts more satellite galaxies than we observe around the Milky Way

Moore et al 1999

Too big to fail?

More massive CDM subhalos appear too dense compared to observed satellites





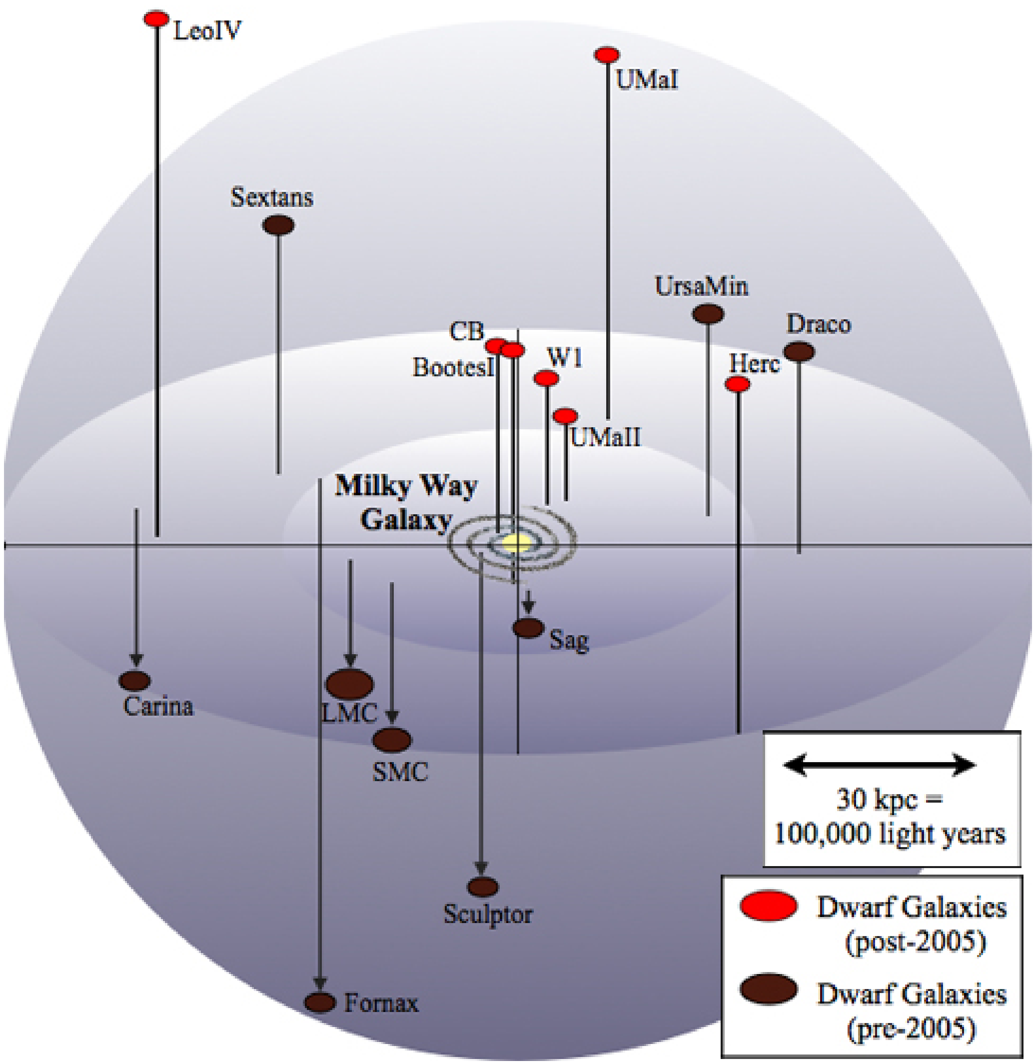
Boylan-Kolchin et al. 2011

Small scale problems of CDM

- **CDM haloes too cuspy**
  - galaxies rotate too quickly in centre
  - observations favour constant density core
- **CDM haloes have too much substructure**
  - matching subhalos to galaxies gives too many Milky Way satellites
- **CDM subhaloes too dense**
  - massive subhaloes too dense

Solutions?

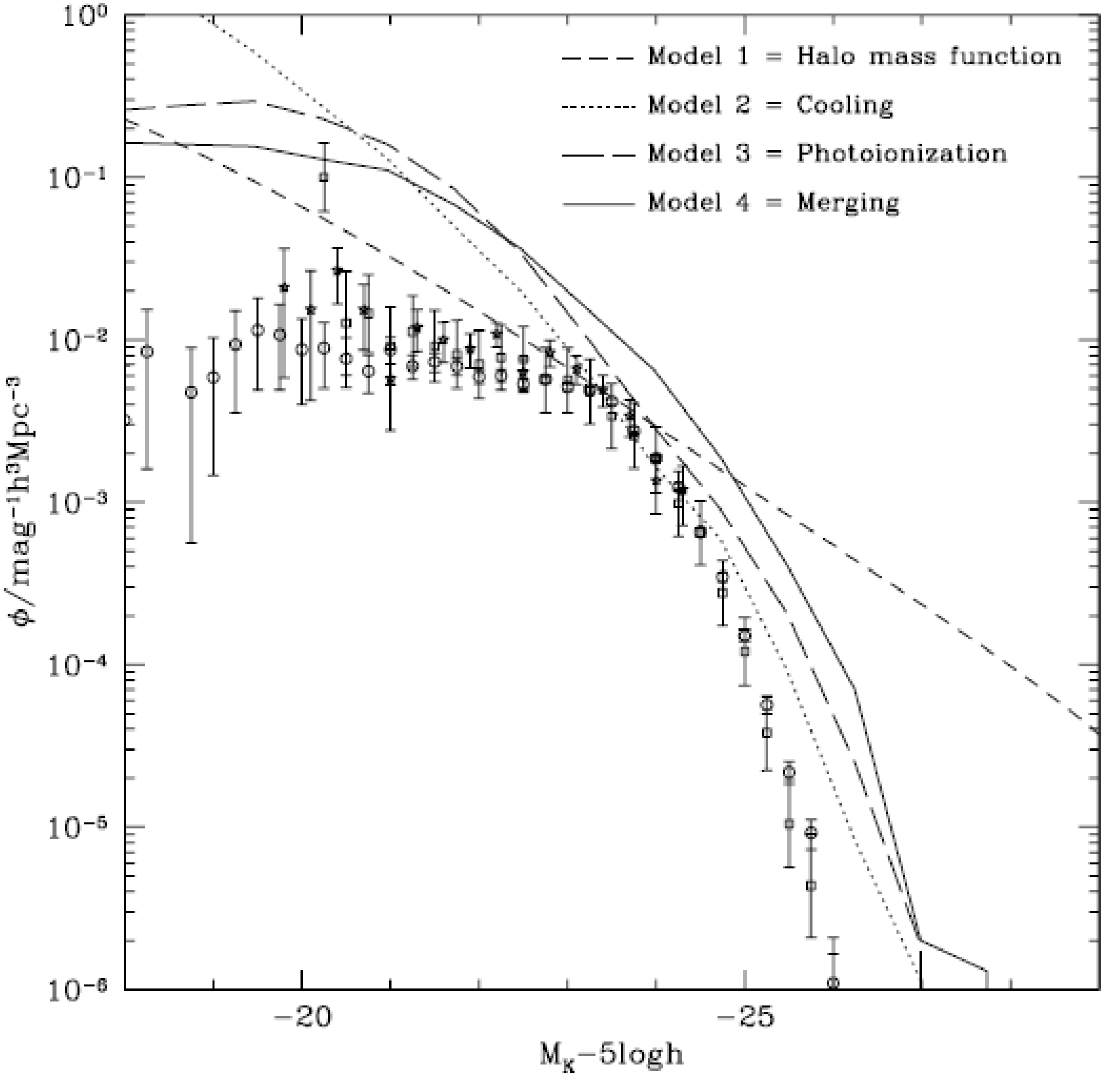
More satellites observed



Willman et al. 2005
Belokurov et al. 2007
Tollerund et al. 2008

Image by M Geha

Need to worry about baryons



Galaxy formation efficiency varies with dark matter halo mass

Supernova heating

Photoionisation heating

Benson et al. 2003

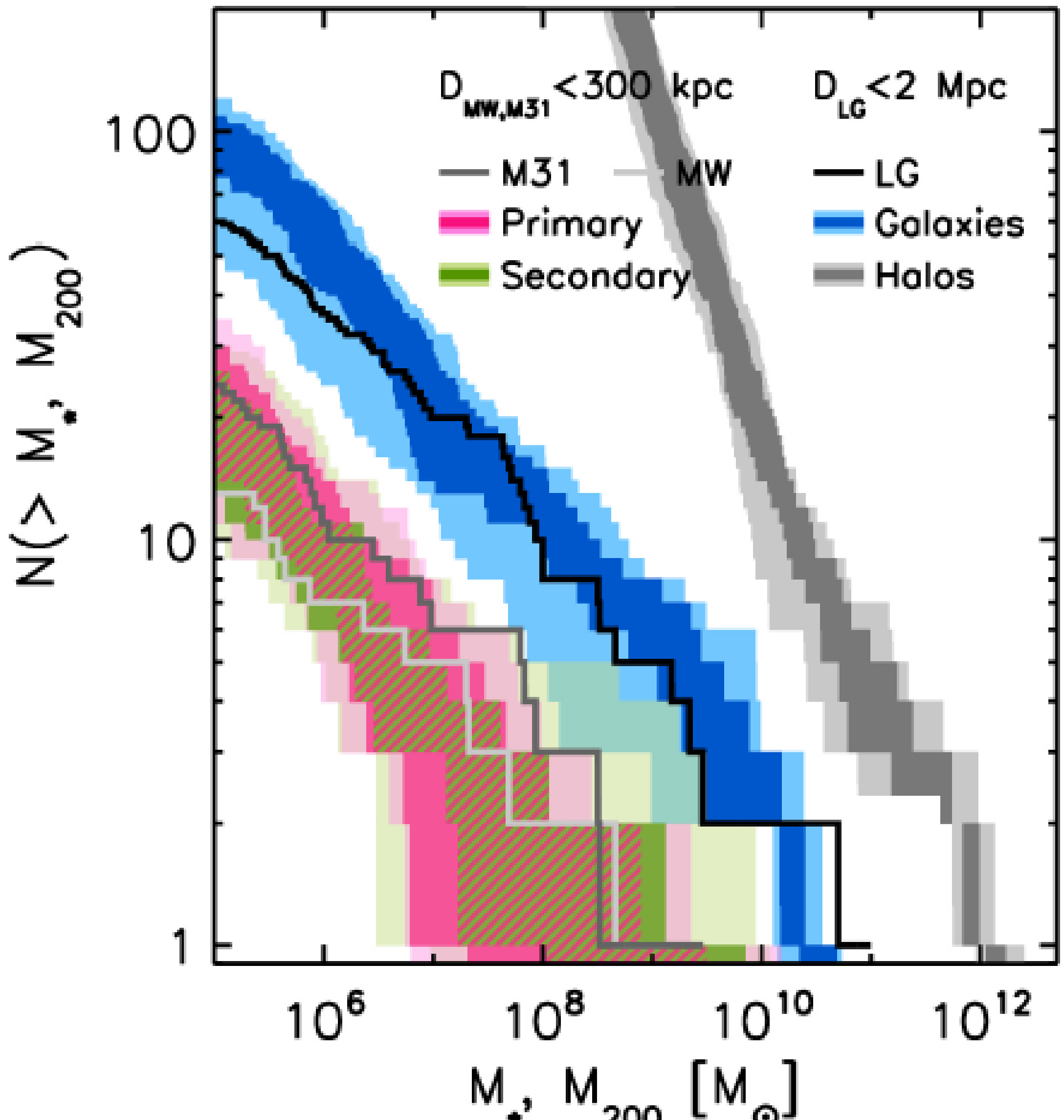
Impact of baryonic physics

Dark matter

stars

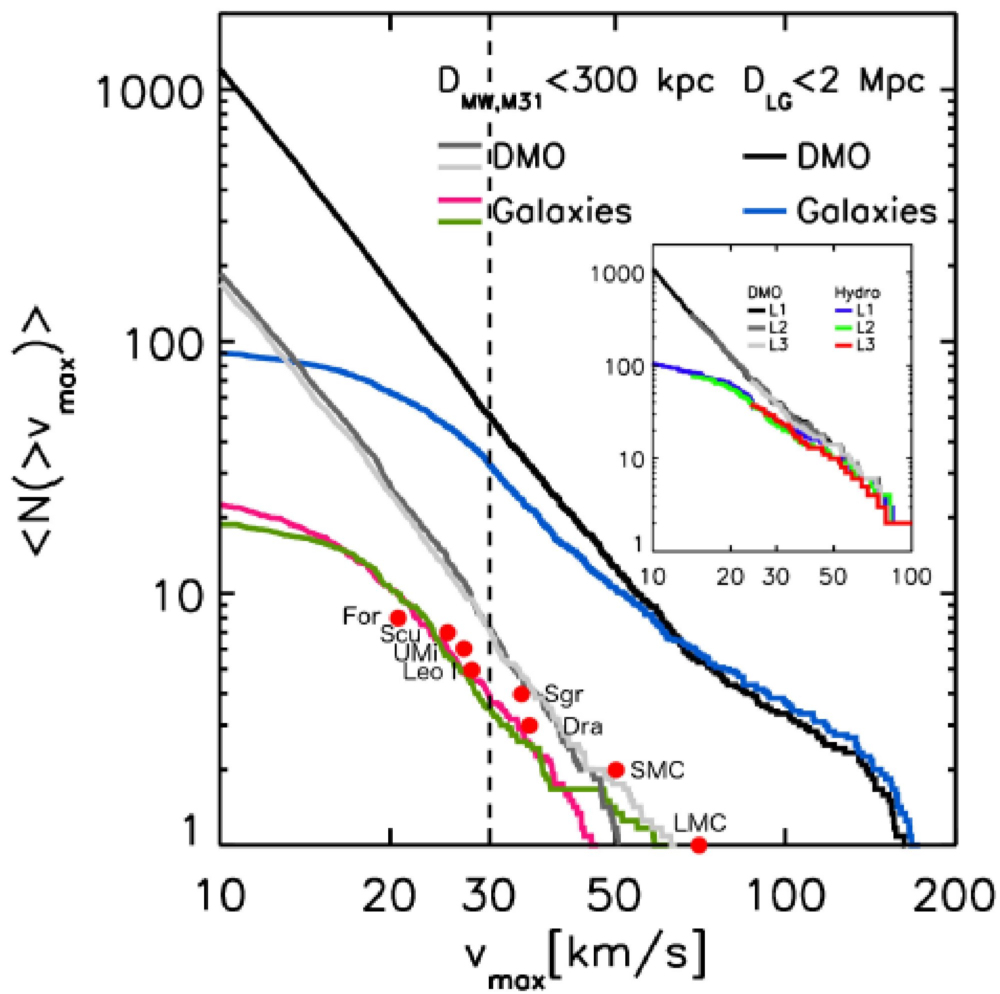
Sawala et al 2014

Impact of baryonic physics



Sawala et al 2014

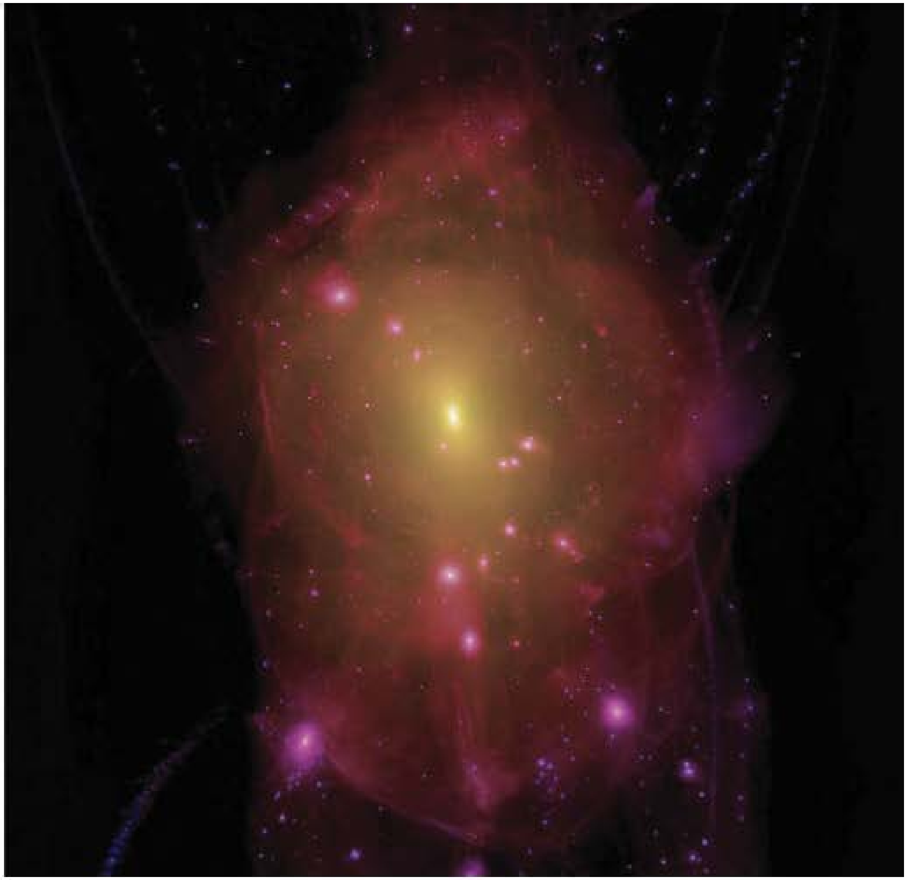
Impact of baryonic physics



Sawala et al 2014

Changing the dark matter particle

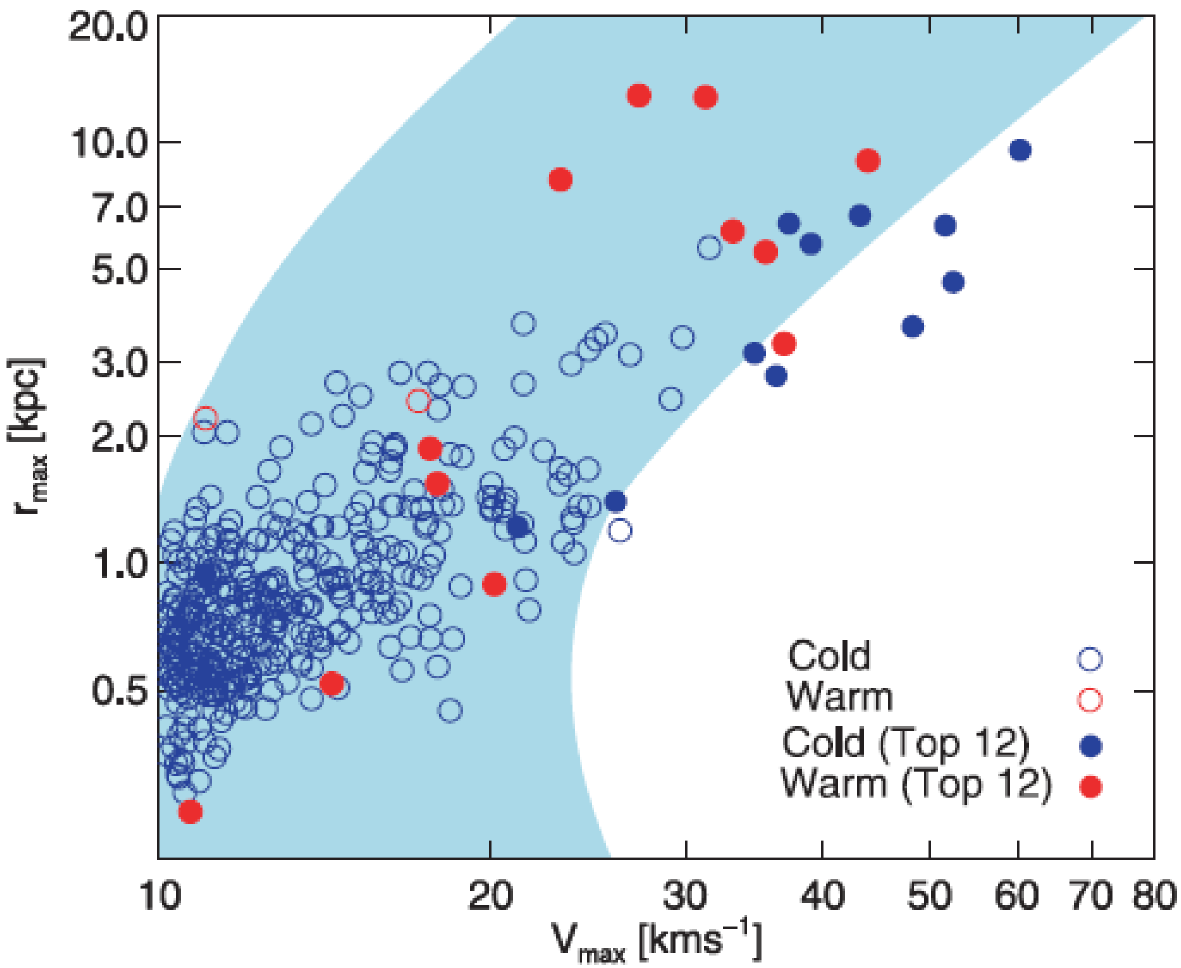
Cold dark matter



Warm dark matter:
Resonantly produced 2KeV sterile neutrino

Lovell et al 2012.

WDM: solves too big to fail



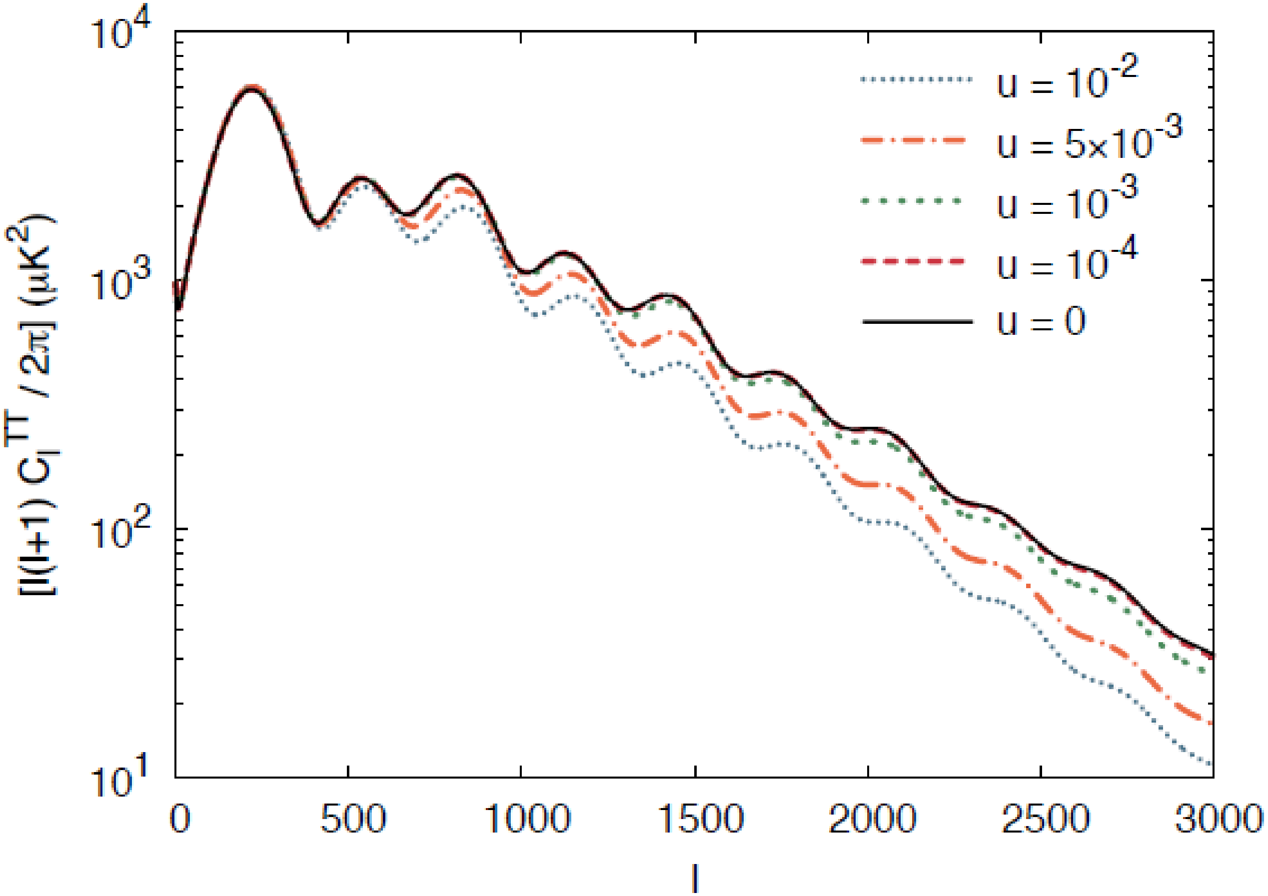
Many fewer subhalos with WDM ~ 2 keV

Massive subhaloes less dense in WDM, due to later formation time

Lovell et al 2012

Do we really need to abandon CDM?

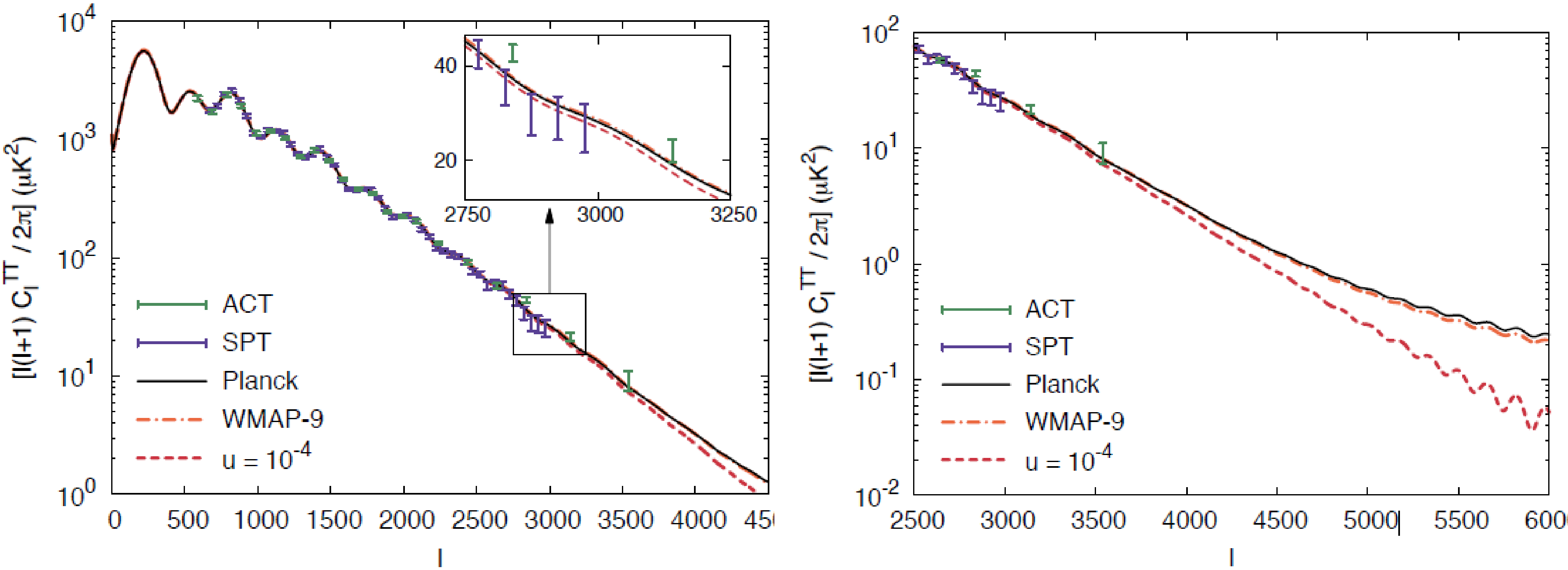
Dark matter – photon interactions



Increasing Interaction strength

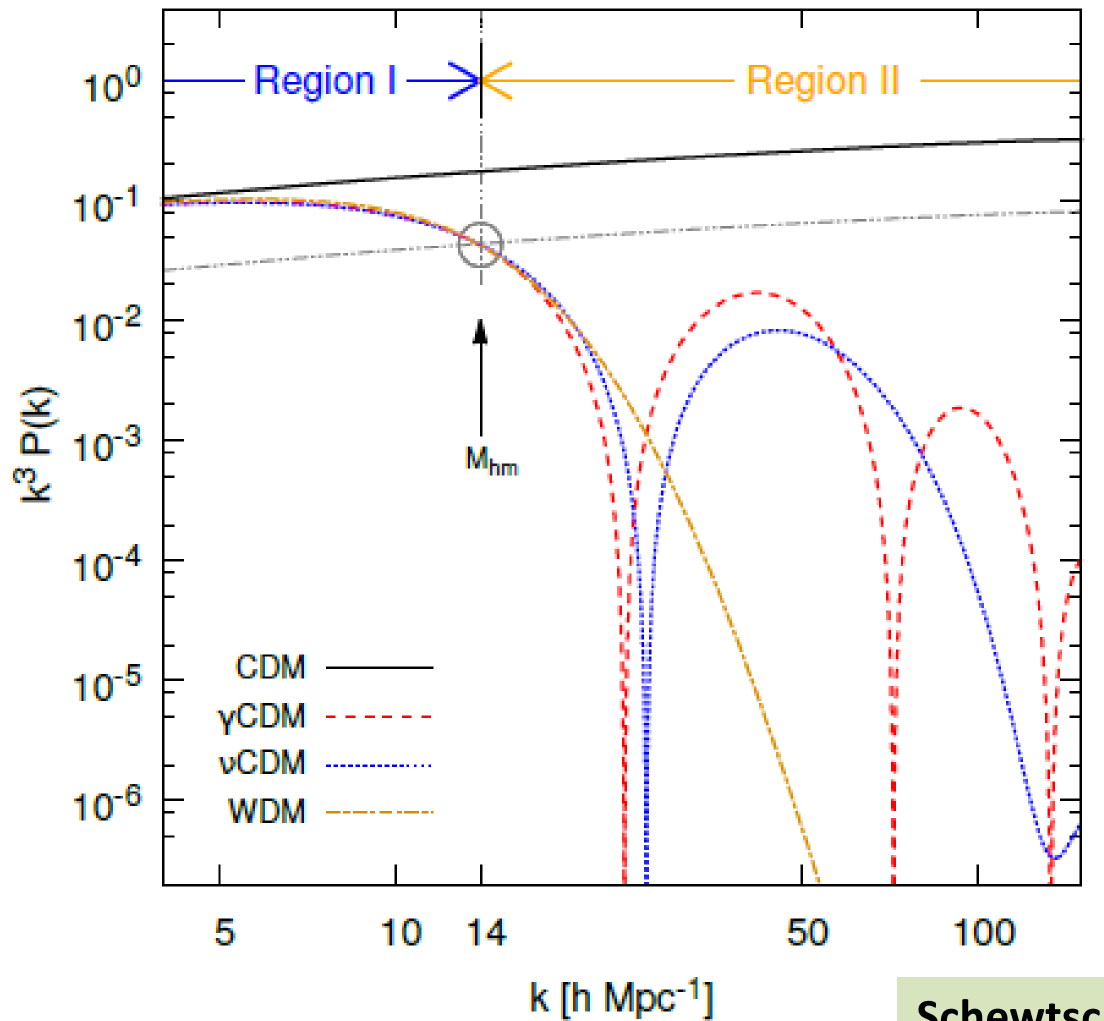
Wilkinson et al. 2014

Constraints on interaction strength

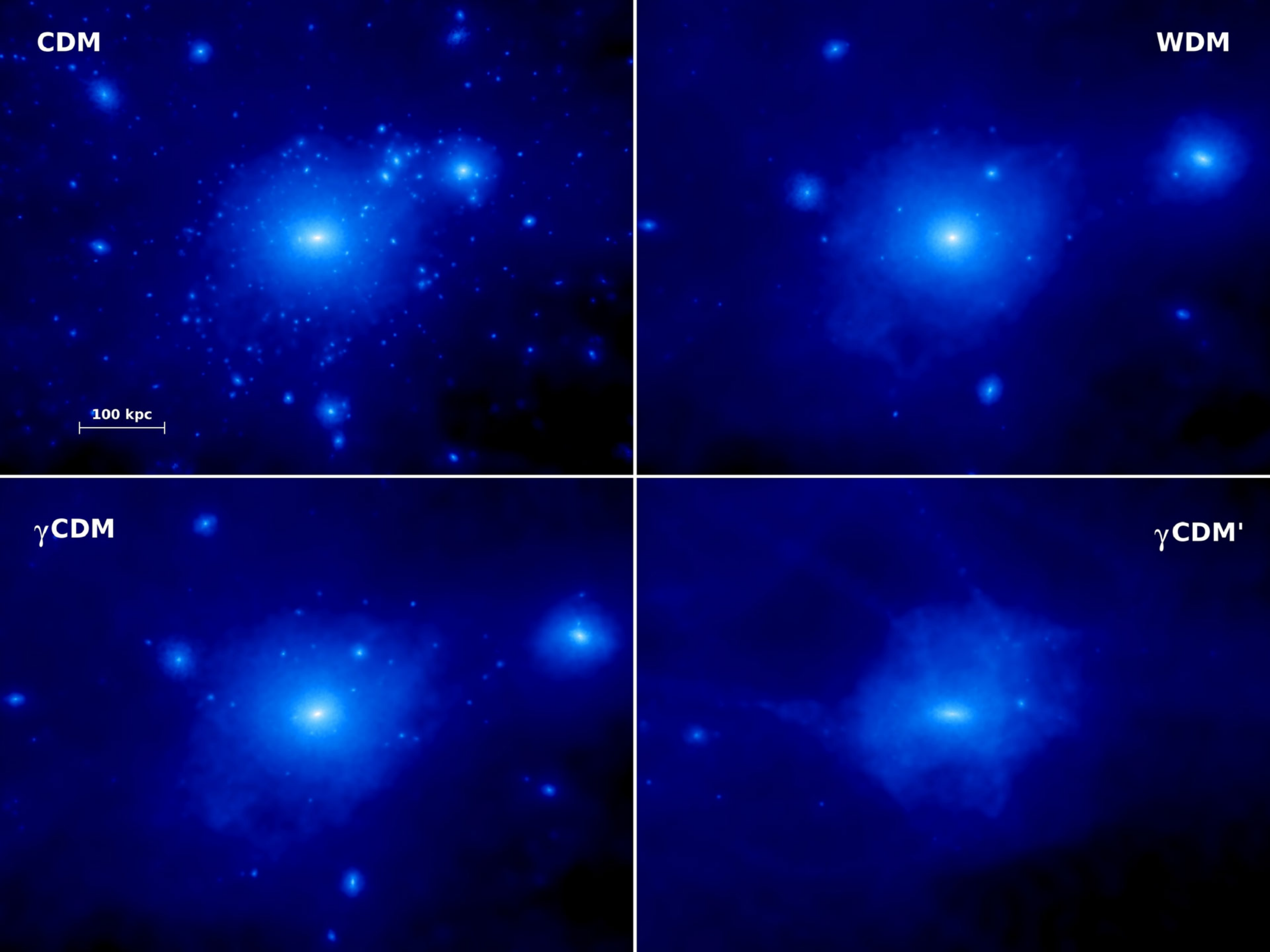


Wilkinson et al. 2014

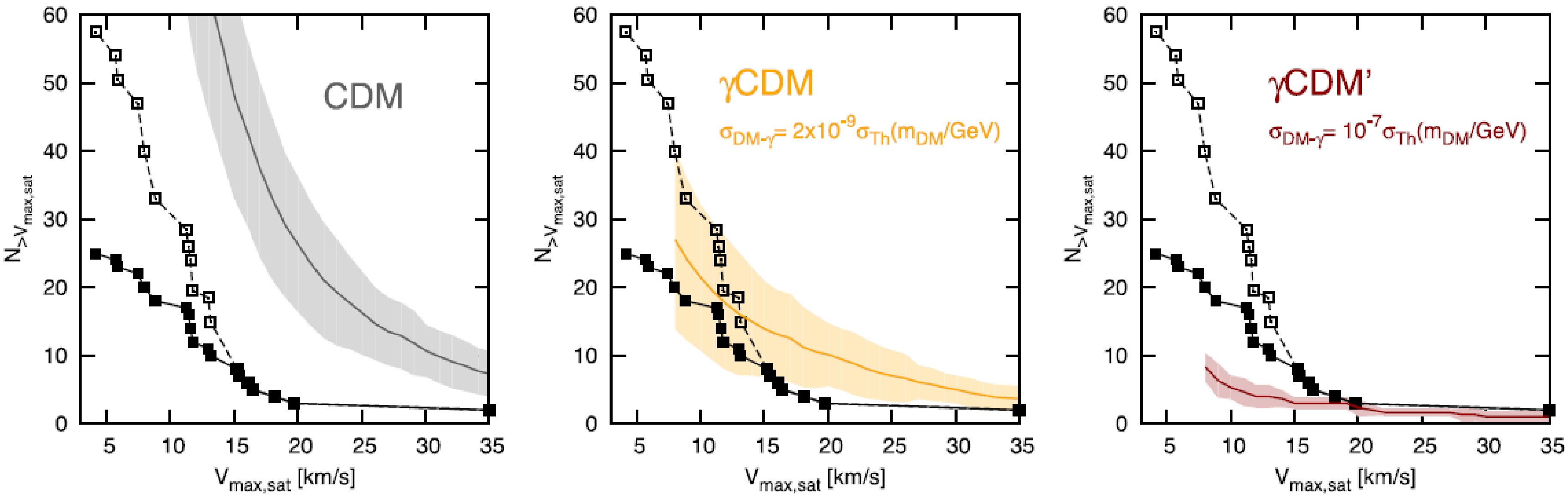
Impact on matter power spectrum



Schewtschenko et al. 2014


CDM
WDM
100 kpc
γCDM
γCDM'

DM-photon interactions and Milky Way Satellites

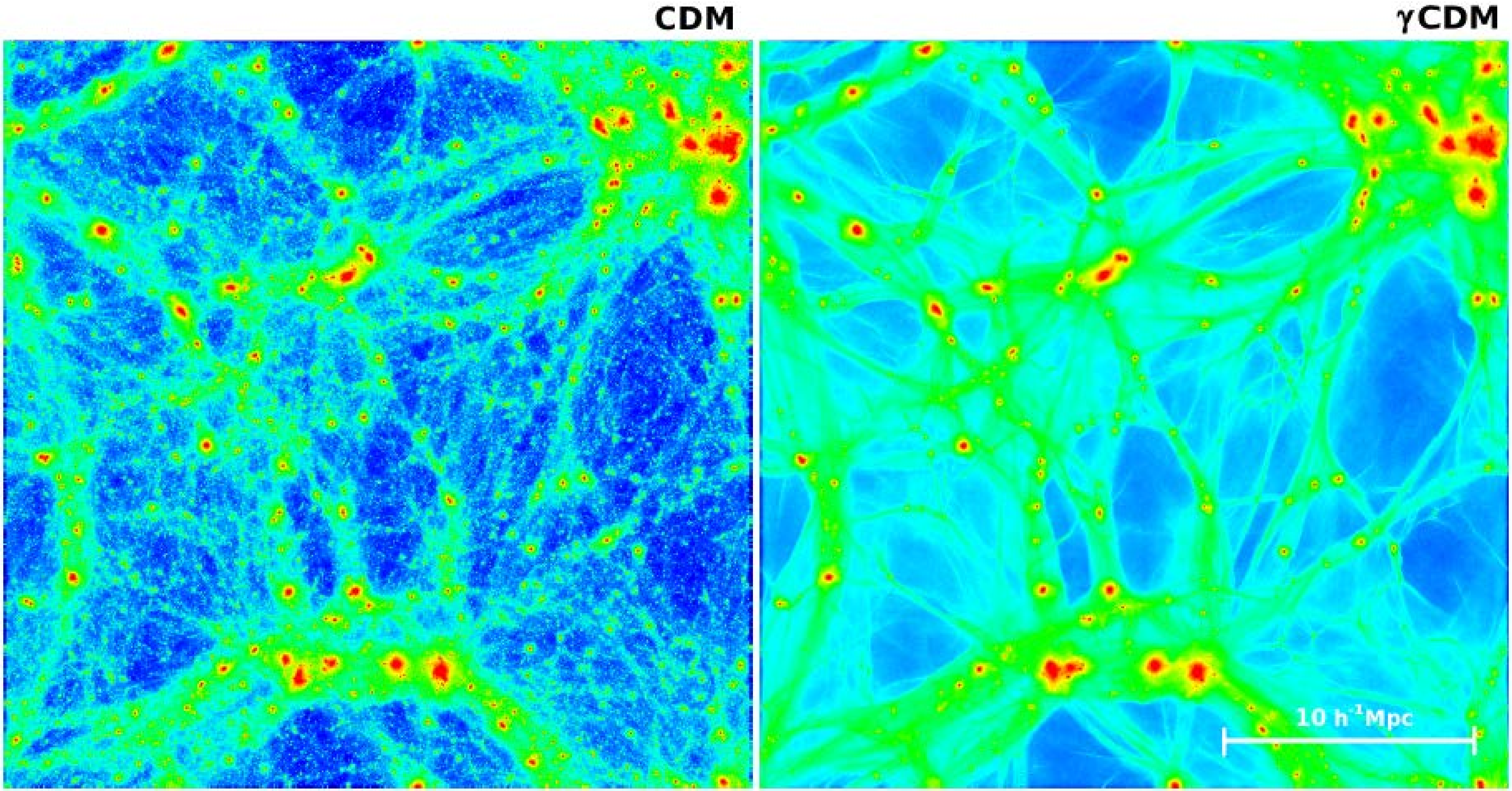


Changing interaction strength changes number of subhaos

Much tighter constraint on cross-section than from CMB

Boehm et al. 2014

Impact on matter distribution



Schewtschenko et al. 2014

Further reading

- Large scale structure

  Springel, Frenk & White 2006
- Dark matter and cosmic structure

  Frenk & White 2012
- Cold dark matter controversies on small scales
  Weinberg et al. arXiv:1306.0913
- Local group galaxies emerge from the dark
  Sawala et al. arXiv:1412.2748