What can we do with a machine that is 500xCOSMA-5?

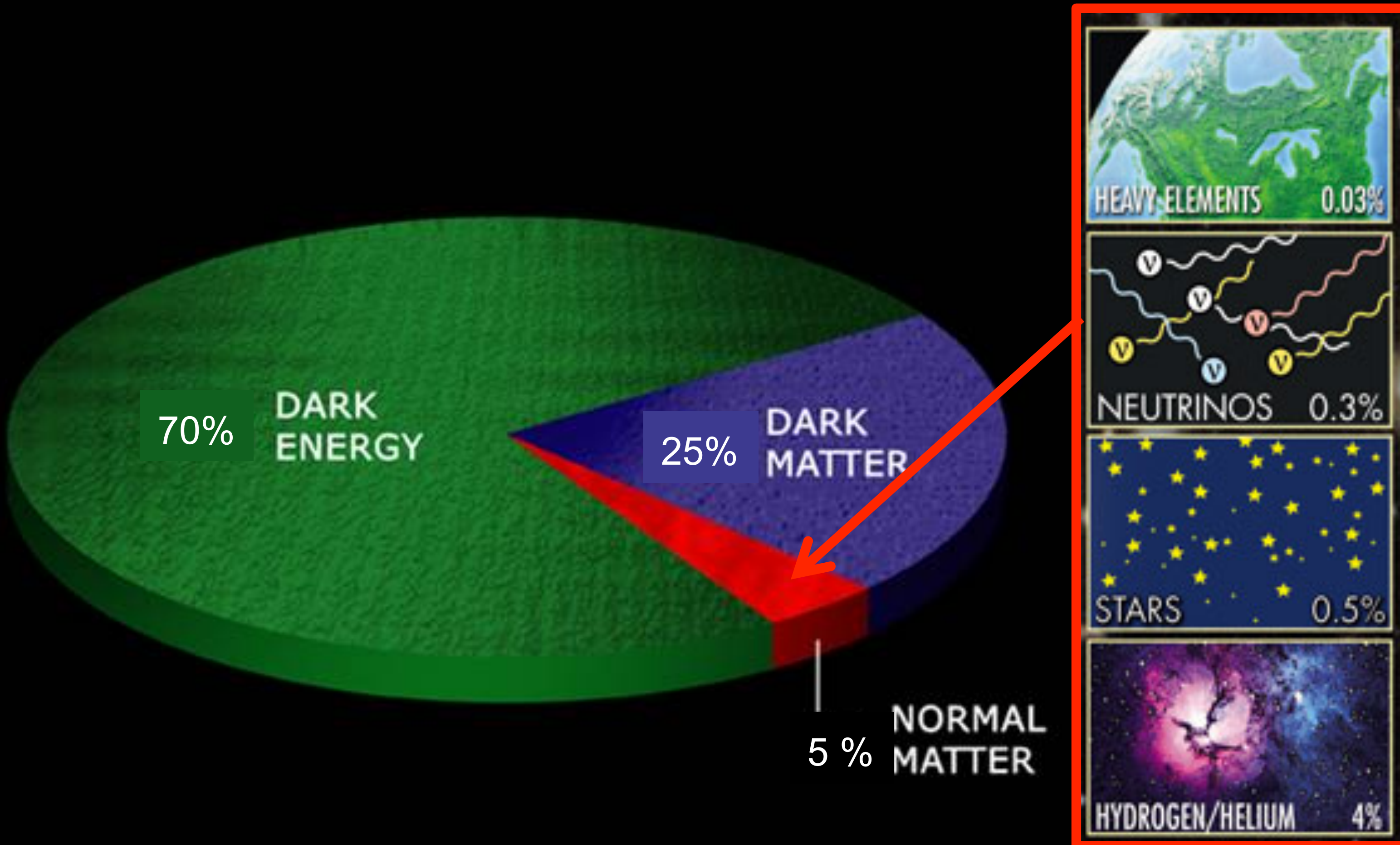
25PB RAM 8 GB/core

Carlos S. Frenk
Institute for Computational Cosmology, Durham

Computational challenges in cosmology

Carlos S. Frenk
Institute for Computational Cosmology, Durham

The content of our universe



University of Durham

Computational challenges in cosmology

Three topics:

- Dark matter discovery
- Dark energy characterization and large-scale structure
- Galaxy formation

The Virgo consortium

Carlos Frenk (PI)

Simon White (PI)

Adrian Jenkins

Scott Kay

Gao Liang

Julio Navarro

Frazer Pearce

Joop Schaye

Volker Springel

Tom Theuns

Peter Thomas

UK, Germany, Netherlands, Canada, China collaboration

Pictures, movies and simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo

+ Raul Angulo, Shaun Cole, Rob Crain
Richard Bower, Ian McCarthy, Jie Wang …

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Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile neutrino majoron; KeVino	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

University of Durham

Non-baryonic dark matter cosmologies

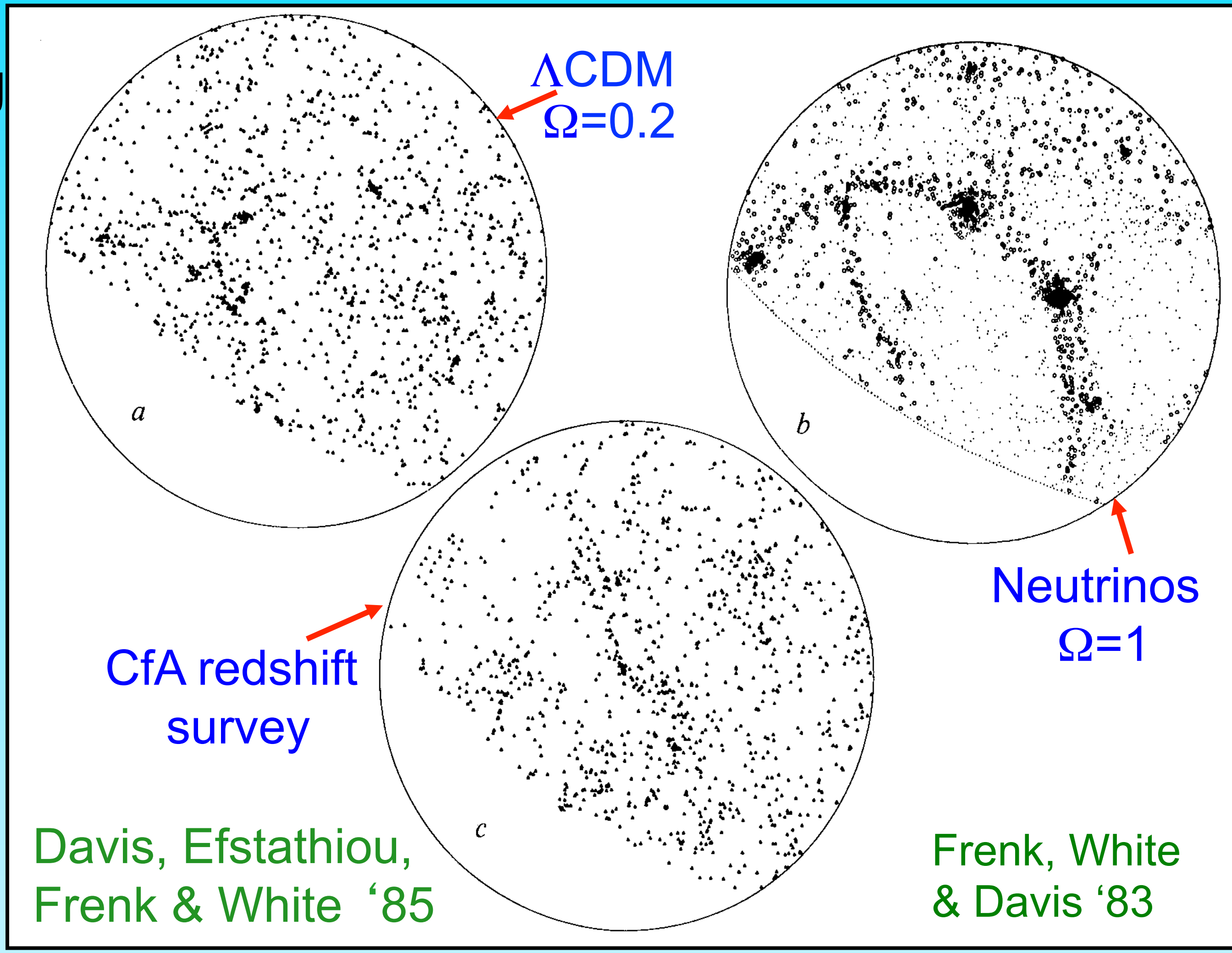
Neutrino DM → unrealistic clust' ing

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 10$ ev

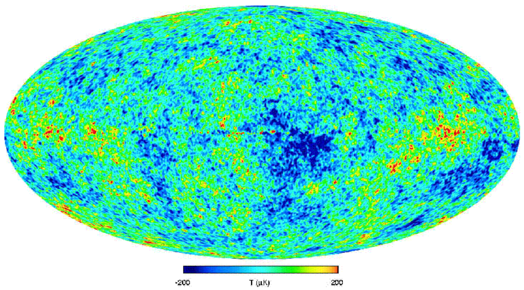
Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

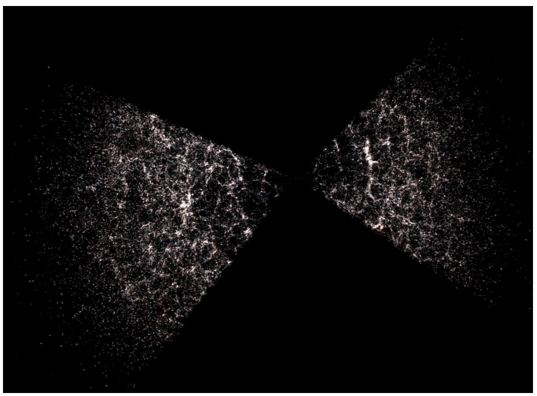


The cosmic power spectrum: from the CMB to the 2dFGRS

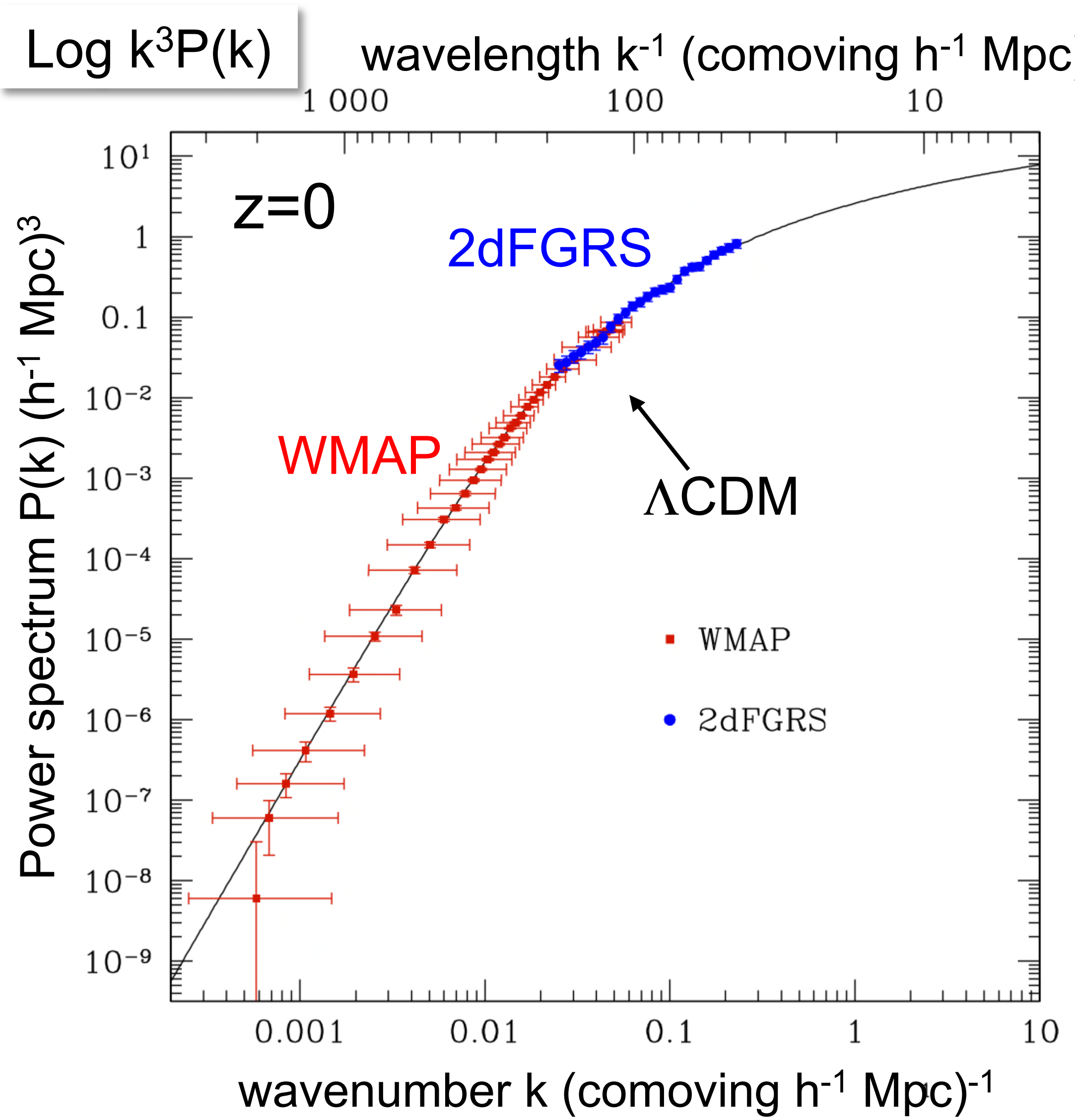
University of Durham



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 →

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

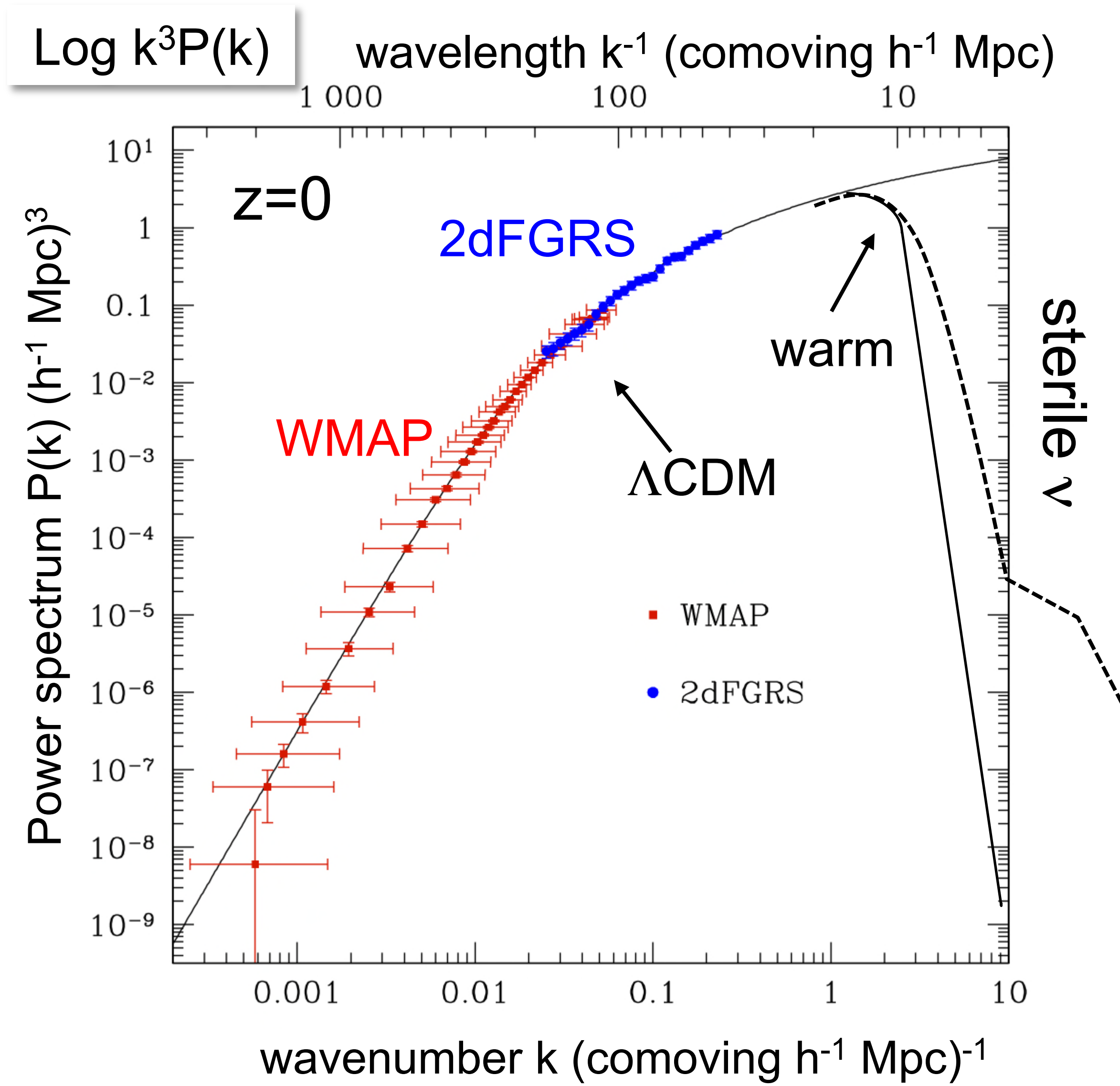
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$

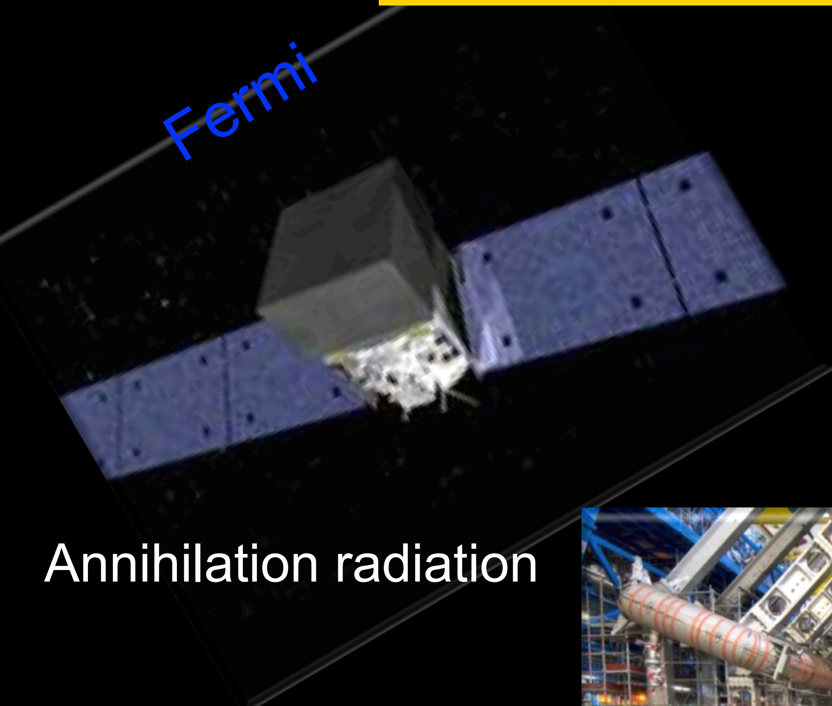


Computer simulations and the identity of the dark matter

Computer simulations →
- Detection strategies
- Interpretation of experimental data
- Astrophysical constraints on DM nature

SUSY cold dark matter

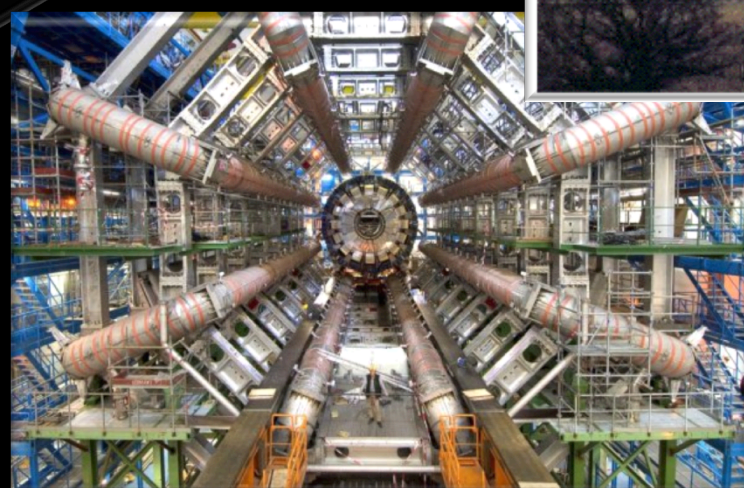
Dark matter discovery possible in several ways



Annihilation radiation

Direct detection

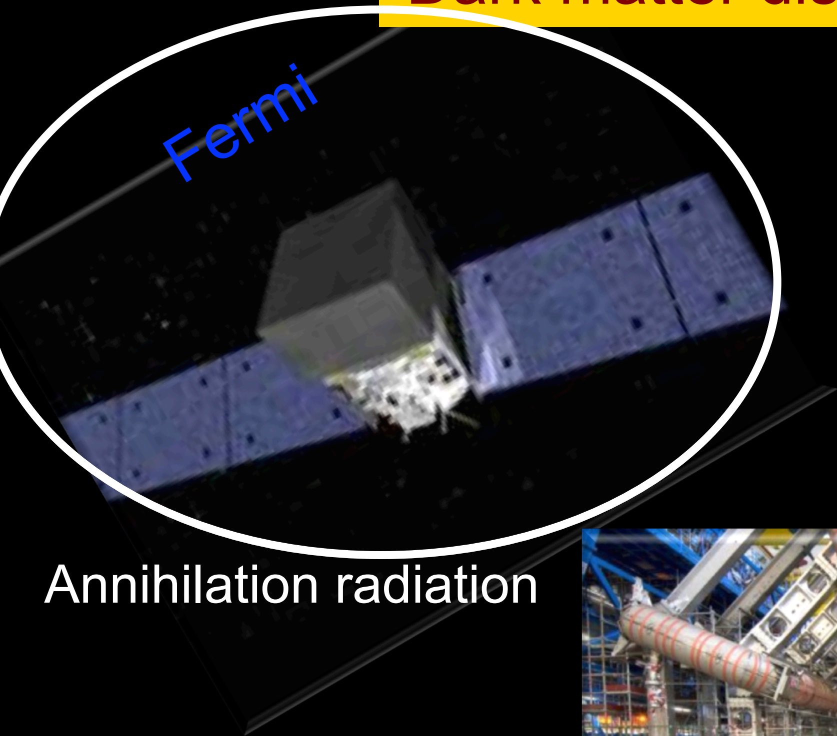
UK DM search
(Boulby mine)



Evidence for SUSY

SUSY cold dark matter

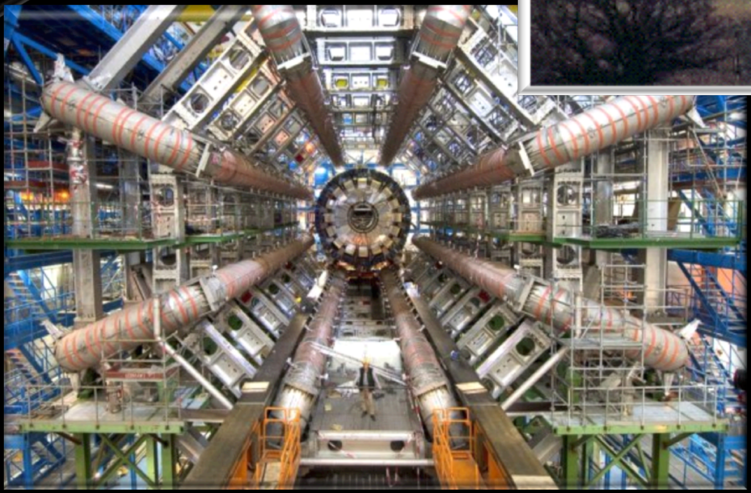
Dark matter discovery possible in several ways



Annihilation radiation

Direct detection

UK DM search
(Boulby mine)

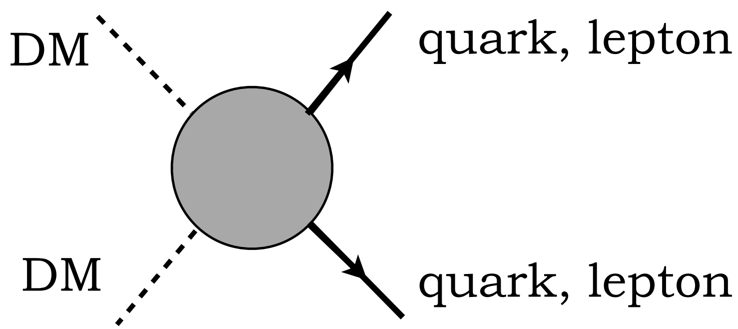


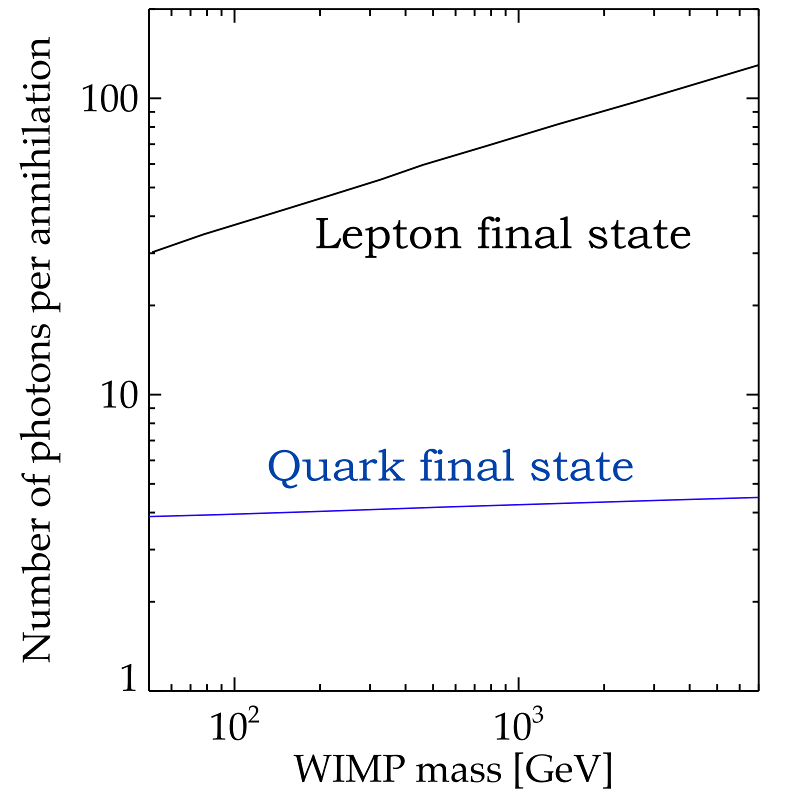
Evidence for SUSY

University of Durham

Indirect dark matter detection

Supersymmetric particles are Majorana particles → annihilate into Standard Model particles (including γ-rays)





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Indirect CDM detection through annihilation radiation

Supersymmetric particles are Majorana particles → annihilate into Standard Model particles (including γ-rays)

Intensity of annihilation radiation at *x* is:

halo density at ***x*** (astrophysics)

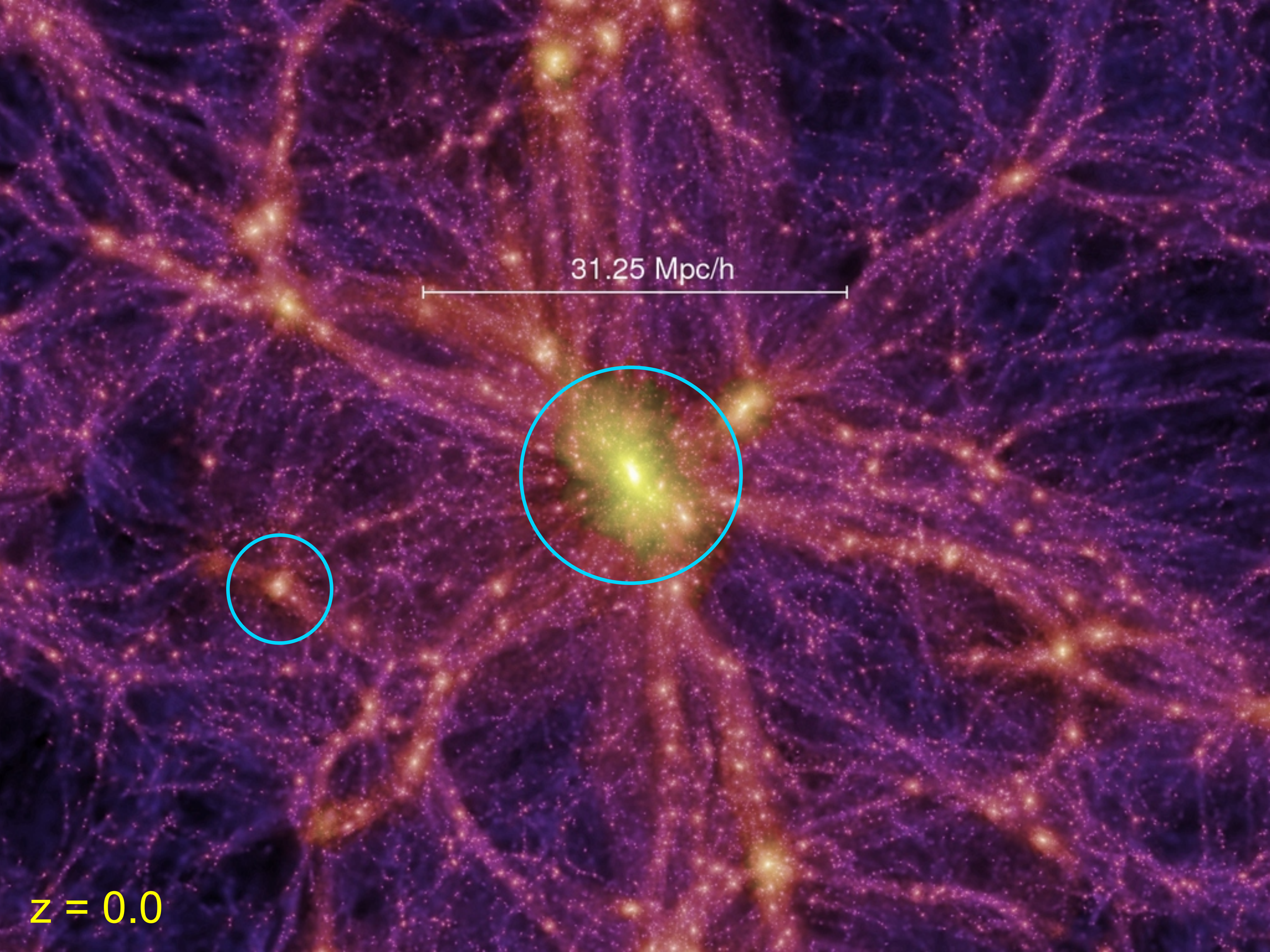
$$I(x) = \frac{1}{8\pi}\sum_f \frac{dN_f}{dE}\langle\sigma_f v\rangle \int_{los}\left(\frac{\rho_\chi}{M_\chi}\right)^2 l dl$$

cross-section (particle physics)

$\langle\sigma v\rangle = 3\times10^{-26} cm^3 s^{-1}$ → relic abundance in simple SUSY models

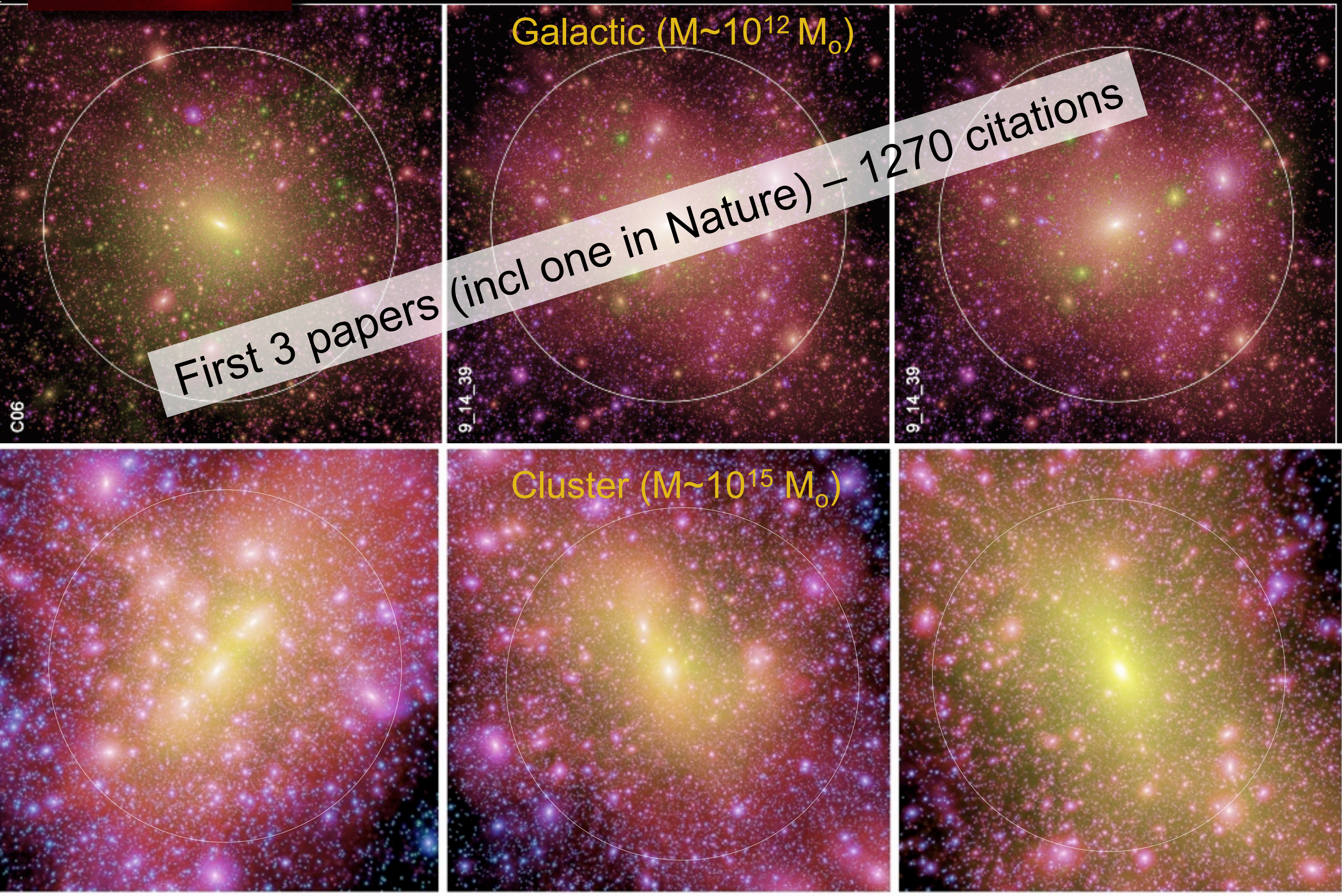
⟹ Theoretical expectation requires knowing ρ(***x***)

⟹ Accurate high resolution N-body simulations of halo formation from CDM initial conditions

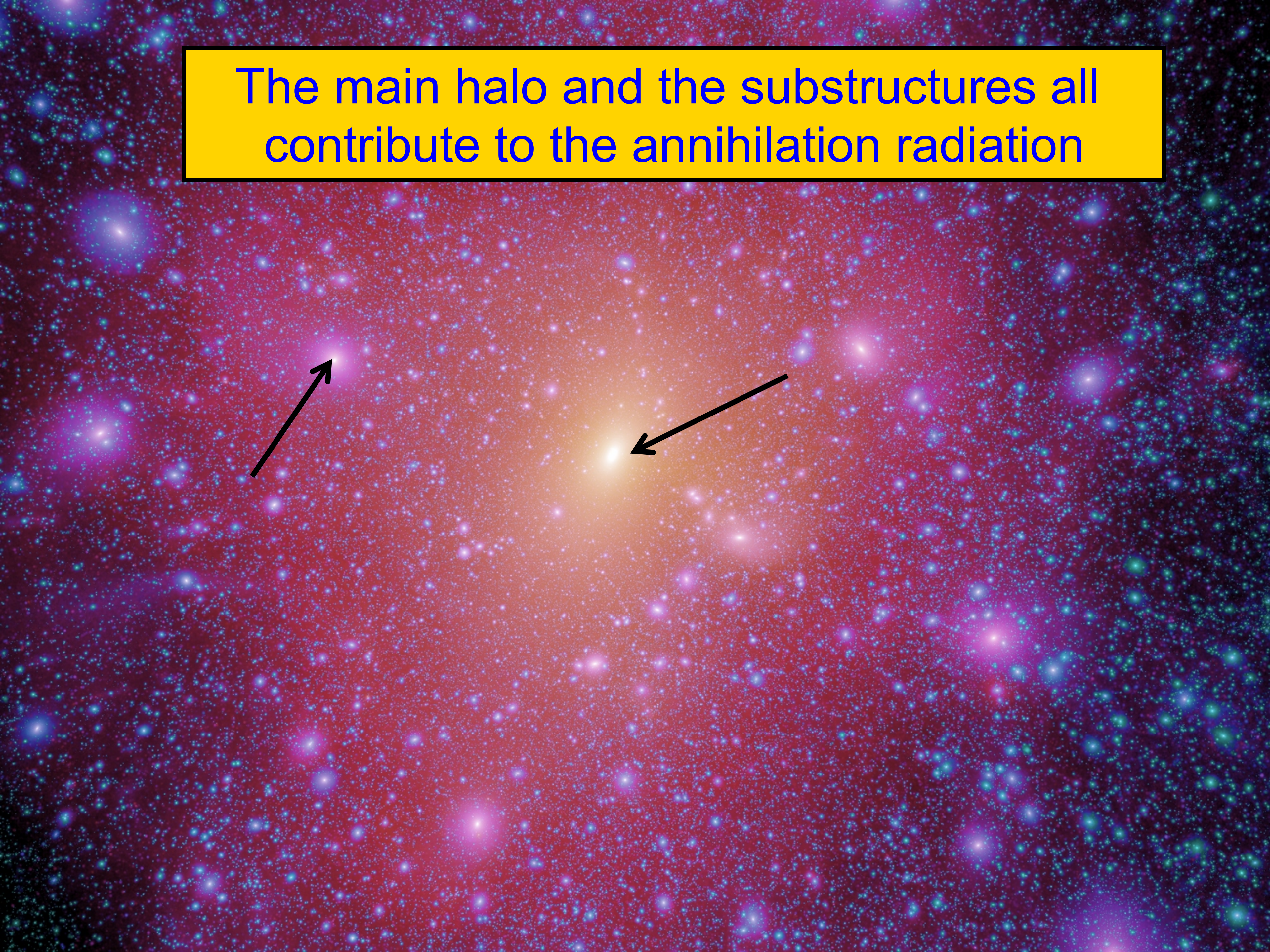

31.25 Mpc/h
z = 0.0

VIRGO

Aquarius (galactic) & Phoenix (cluster)halos



The main halo and the substructures all contribute to the annihilation radiation



Halo density profiles

University of Durham

NFW:

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

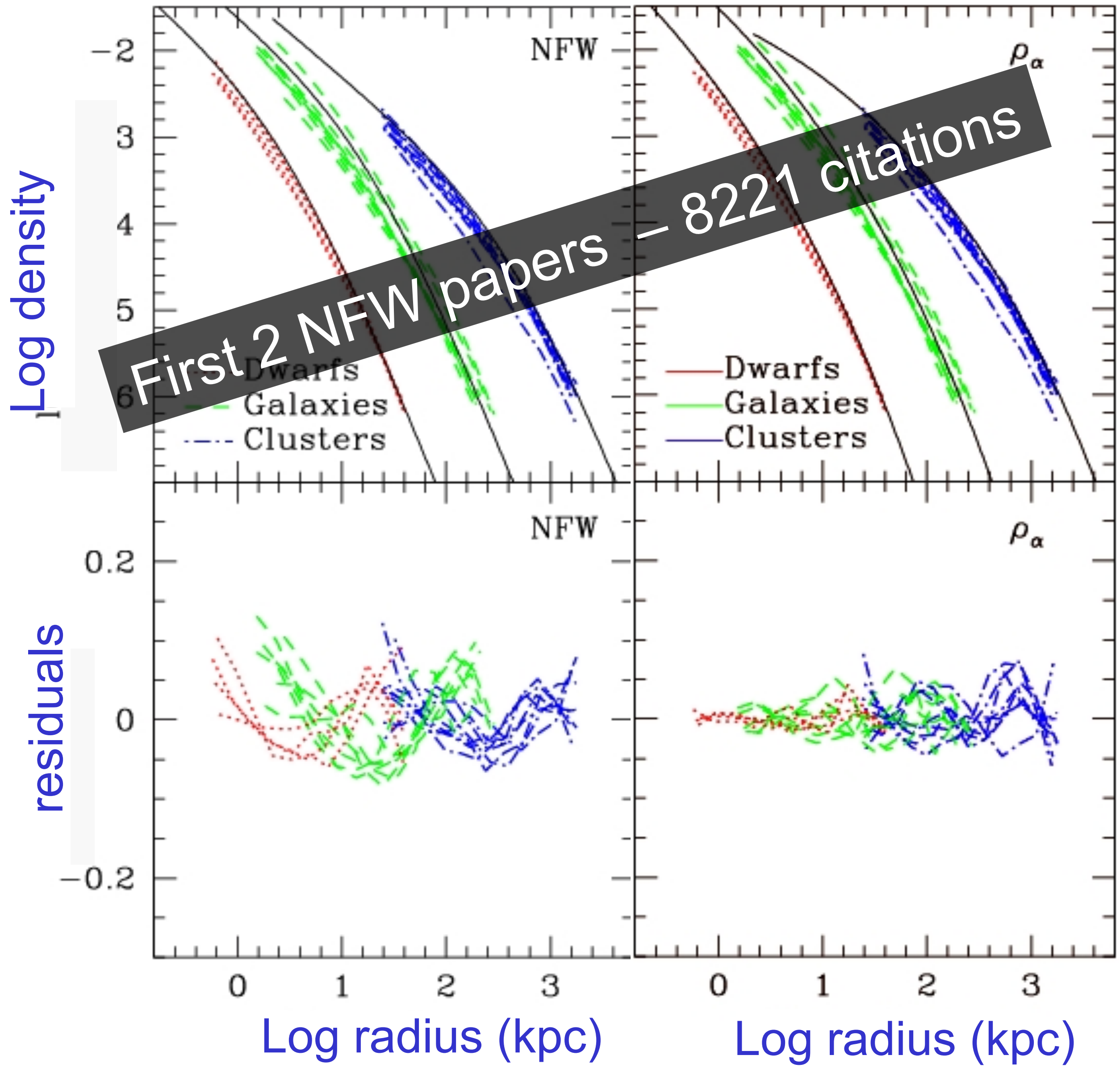
Einasto:

$$\frac{d\log\rho_\alpha}{d\log r} = -2\left(\frac{r}{r_{-2}}\right)^\alpha$$

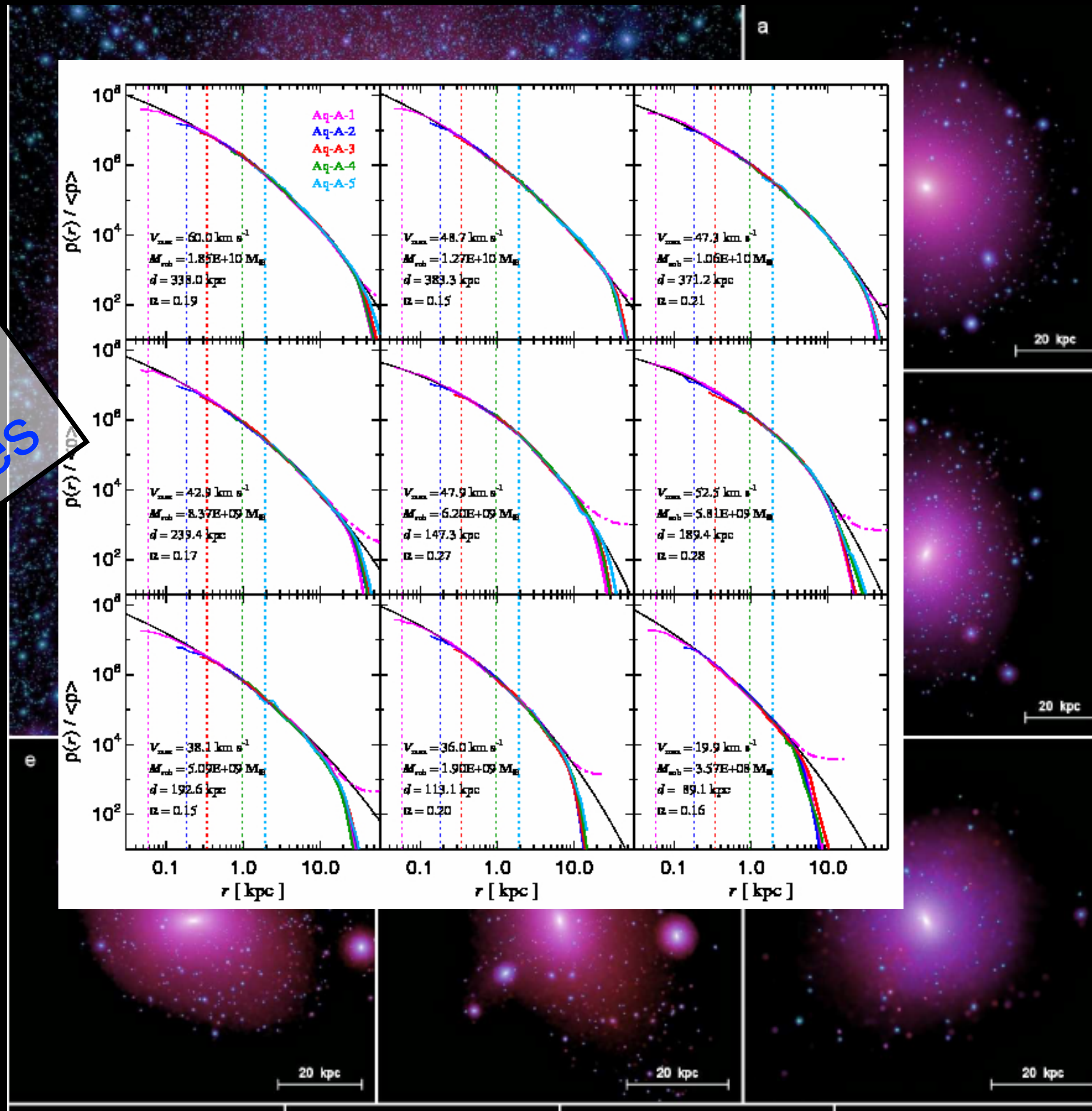
Has extra param: α

(similar to stellar distribution in ellipticals - Einasto)

Navarro et al 04



CDM subhalos also have cuspy profiles



Aquarius

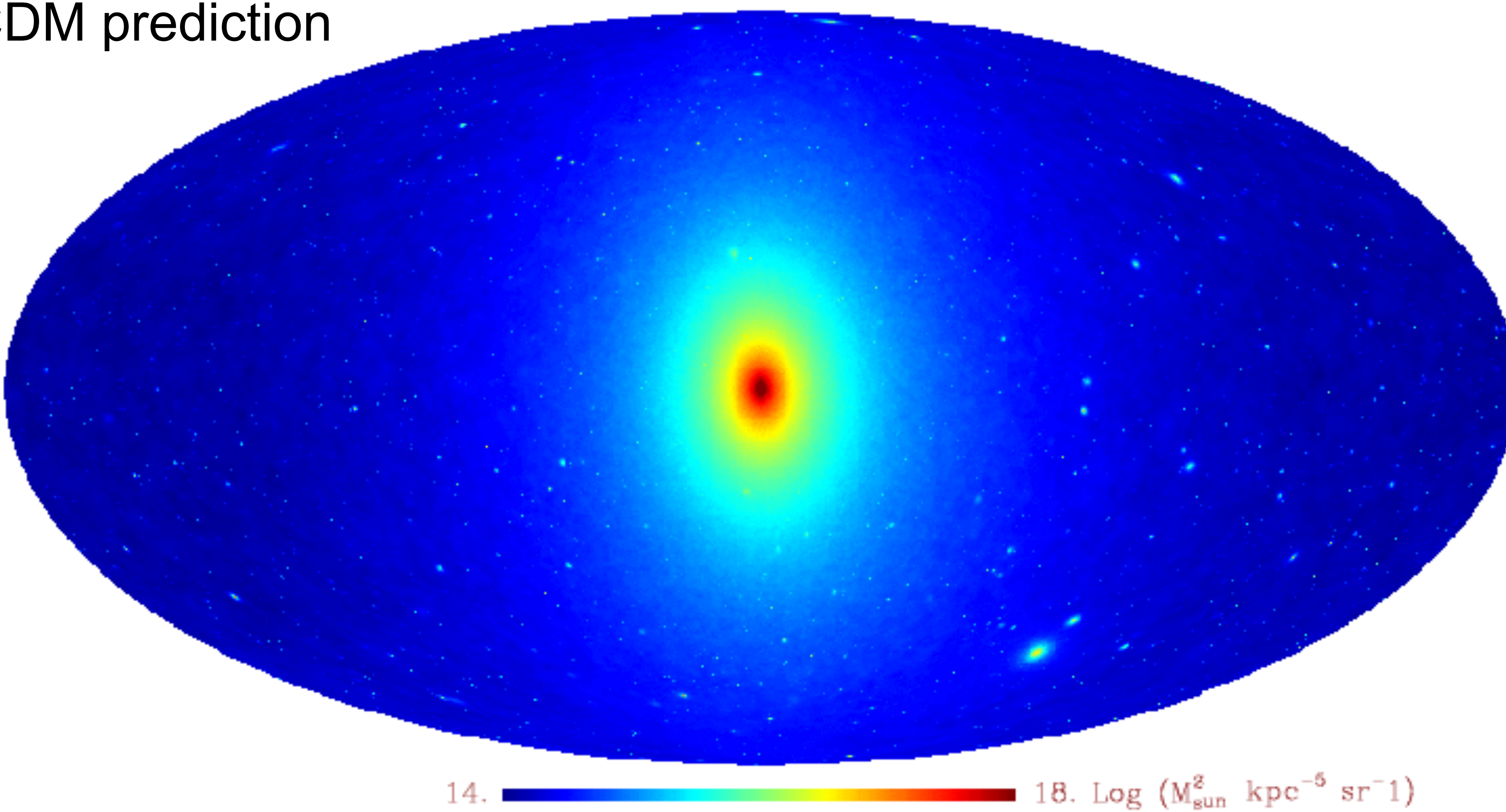
Springel et al '08

The Milky Way seen in annihilation radiation

University of Durham

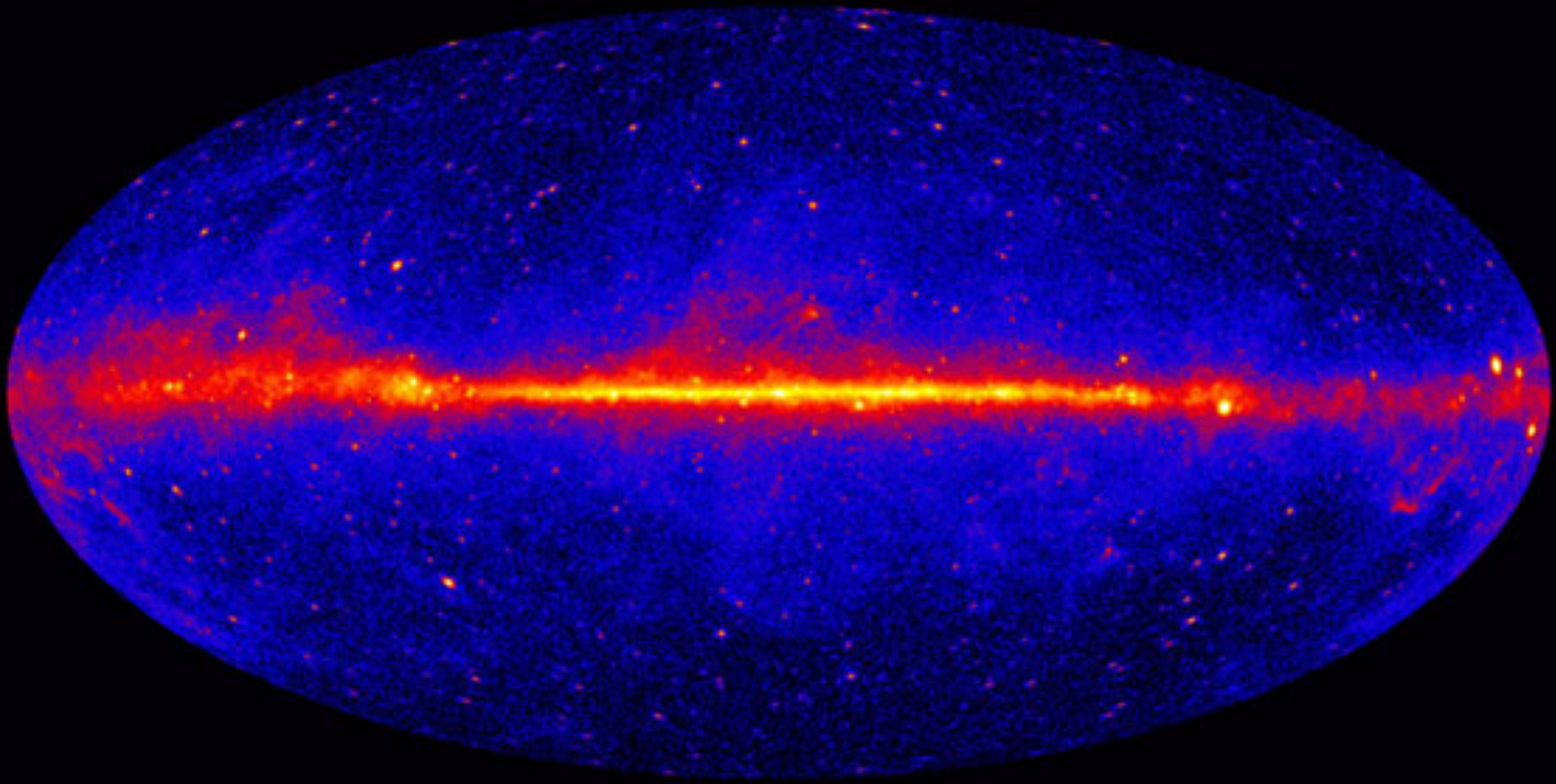
Aquarius simulation: $N_{200} = 1.1 \times 10^9$

CDM prediction

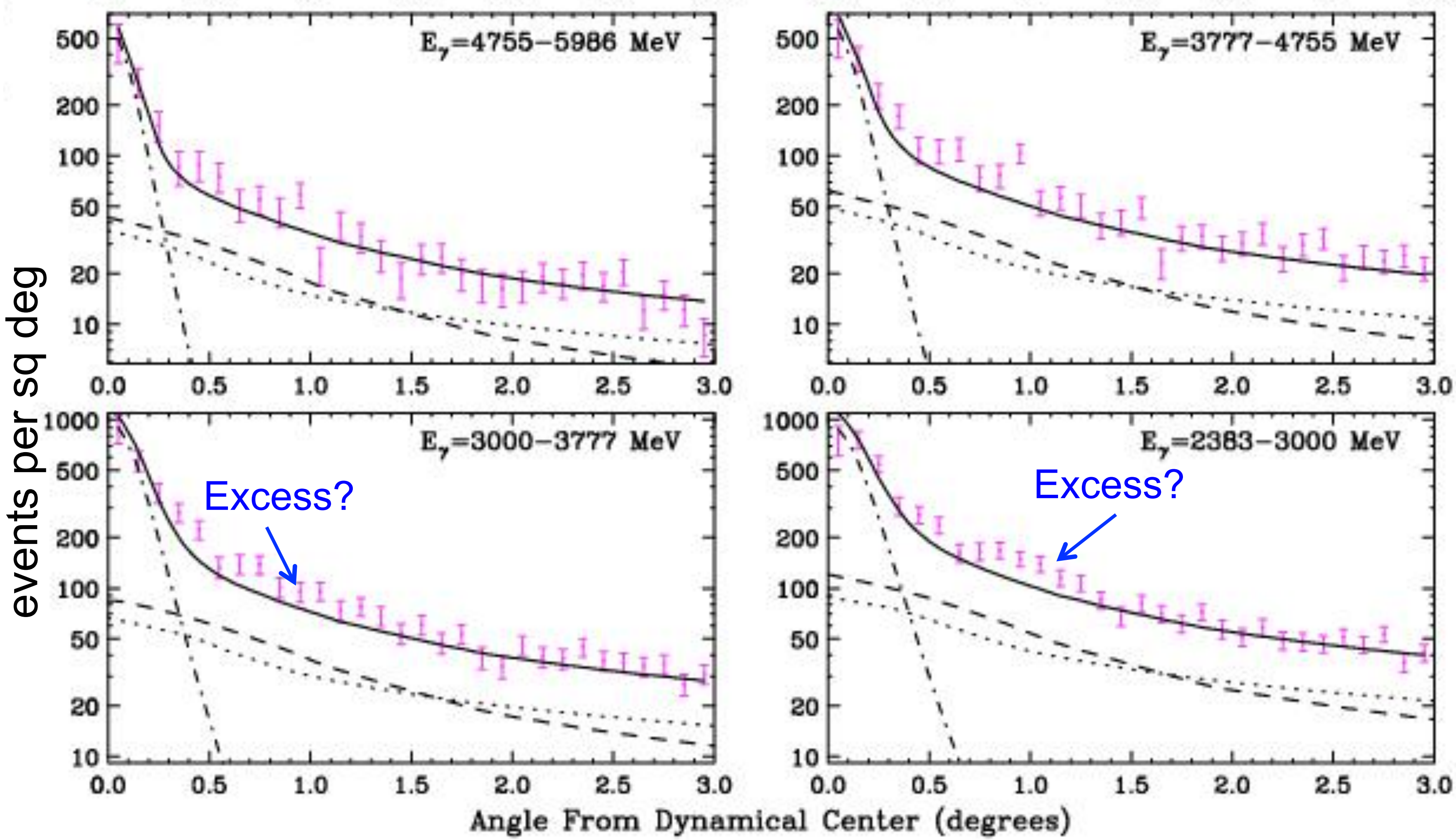


Springel et al. ’08 (Nature)

Fermi 3-year all sky map



Annihilation radiation from the Galactic Centre?



Hooper & Goodenough '11

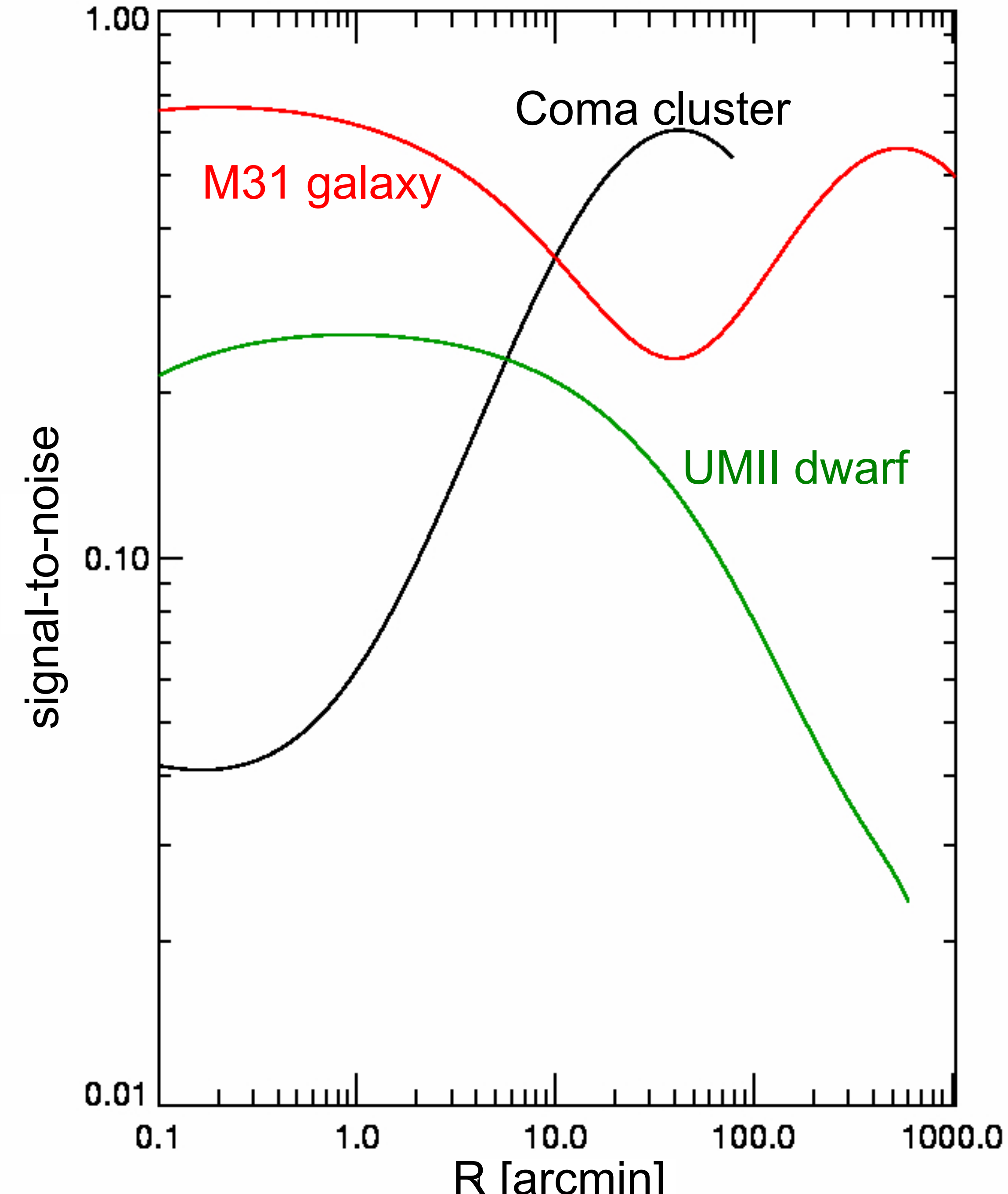
University of Durham

Annihilation radiation

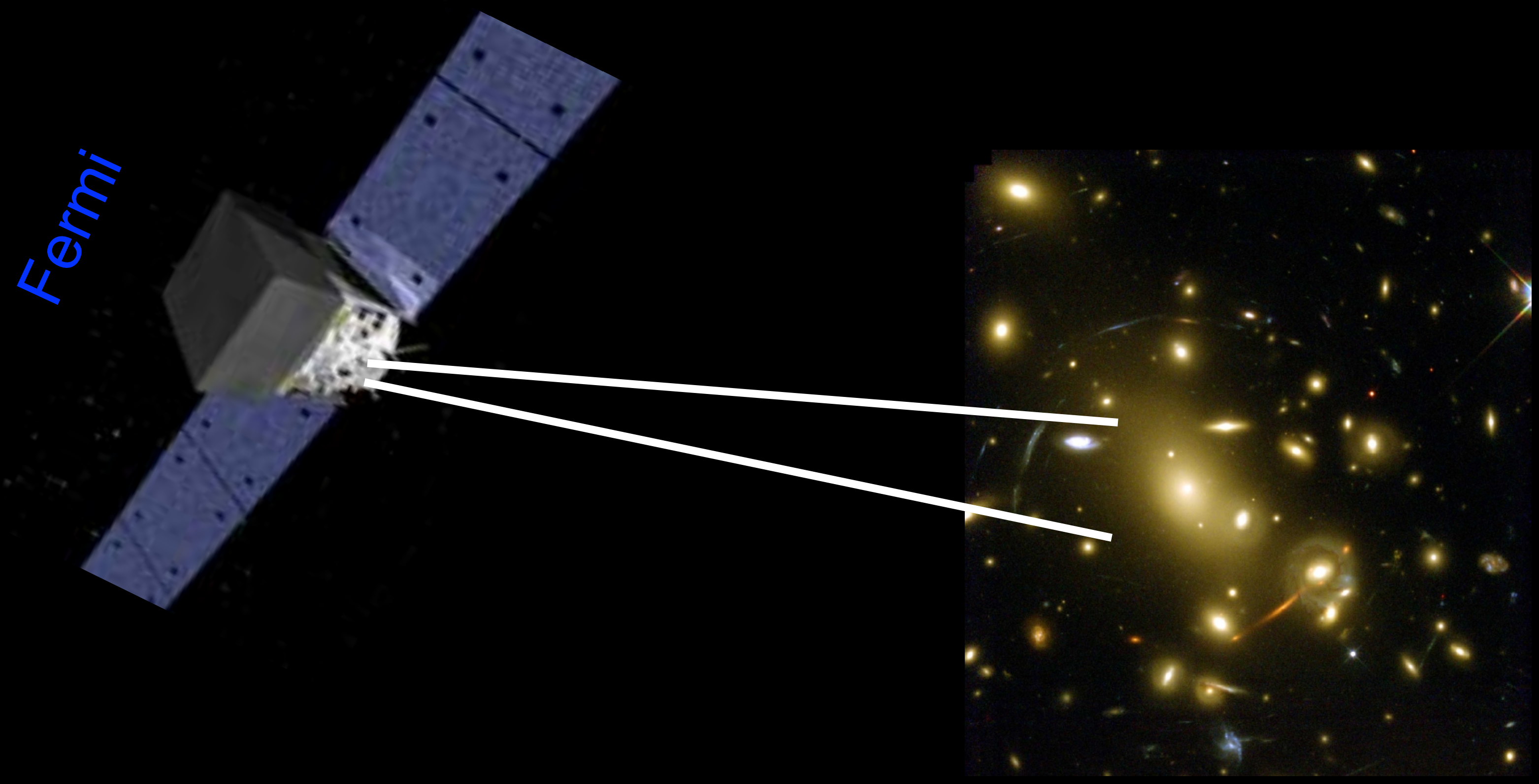
Signal-to-noise

larger S/N in clusters than in MW dwarfs

Gao, Frenk, Jenkins, Springel & White '11



Galaxy clusters in Fermi

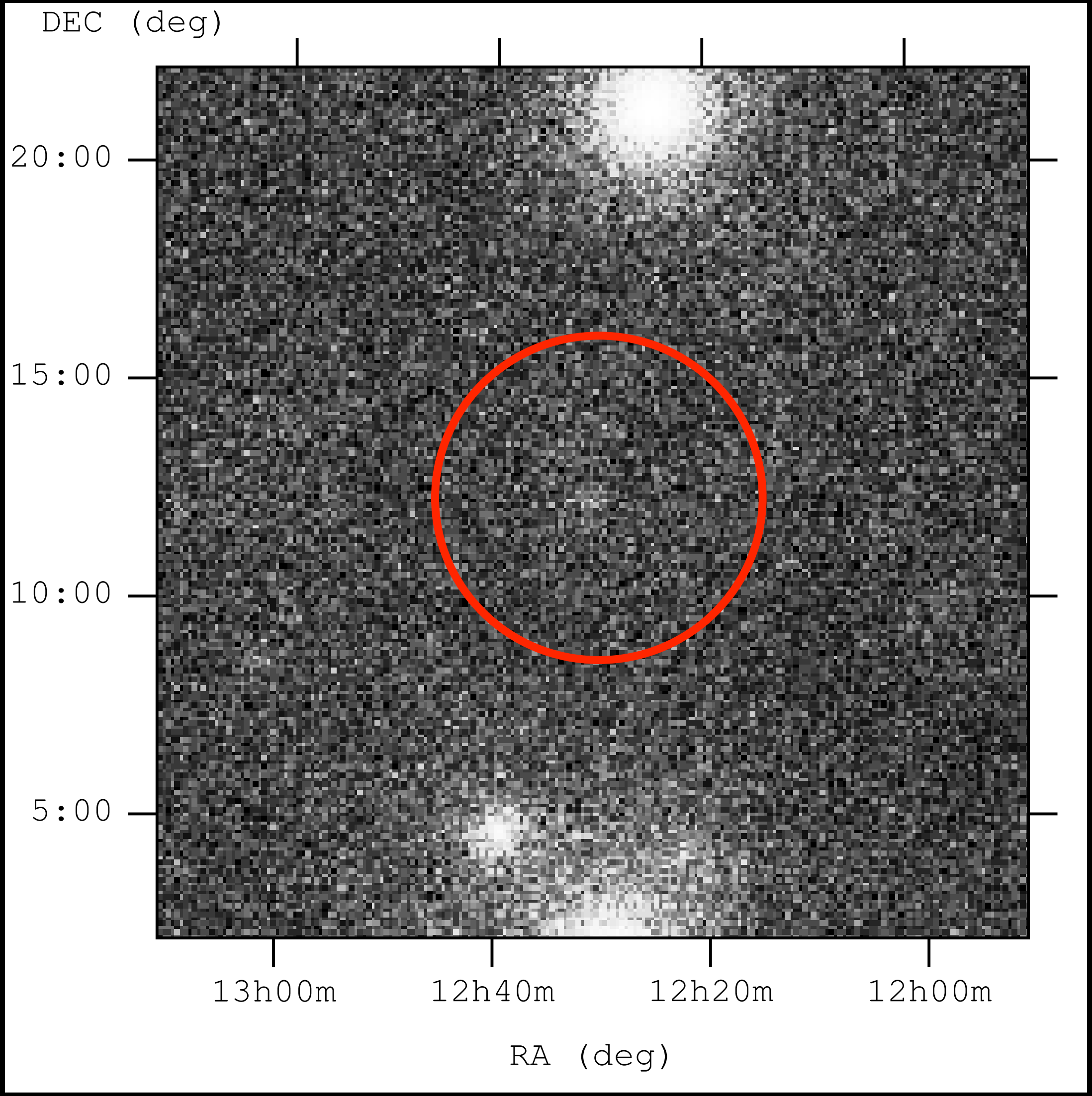


The Virgo cluster in Fermi

Fermi-LAT image

100MeV – 100 GeV

3-year data



Han, Frenk, Eke, Gao, White ‘12

Upper limits on x-section

University of Durham

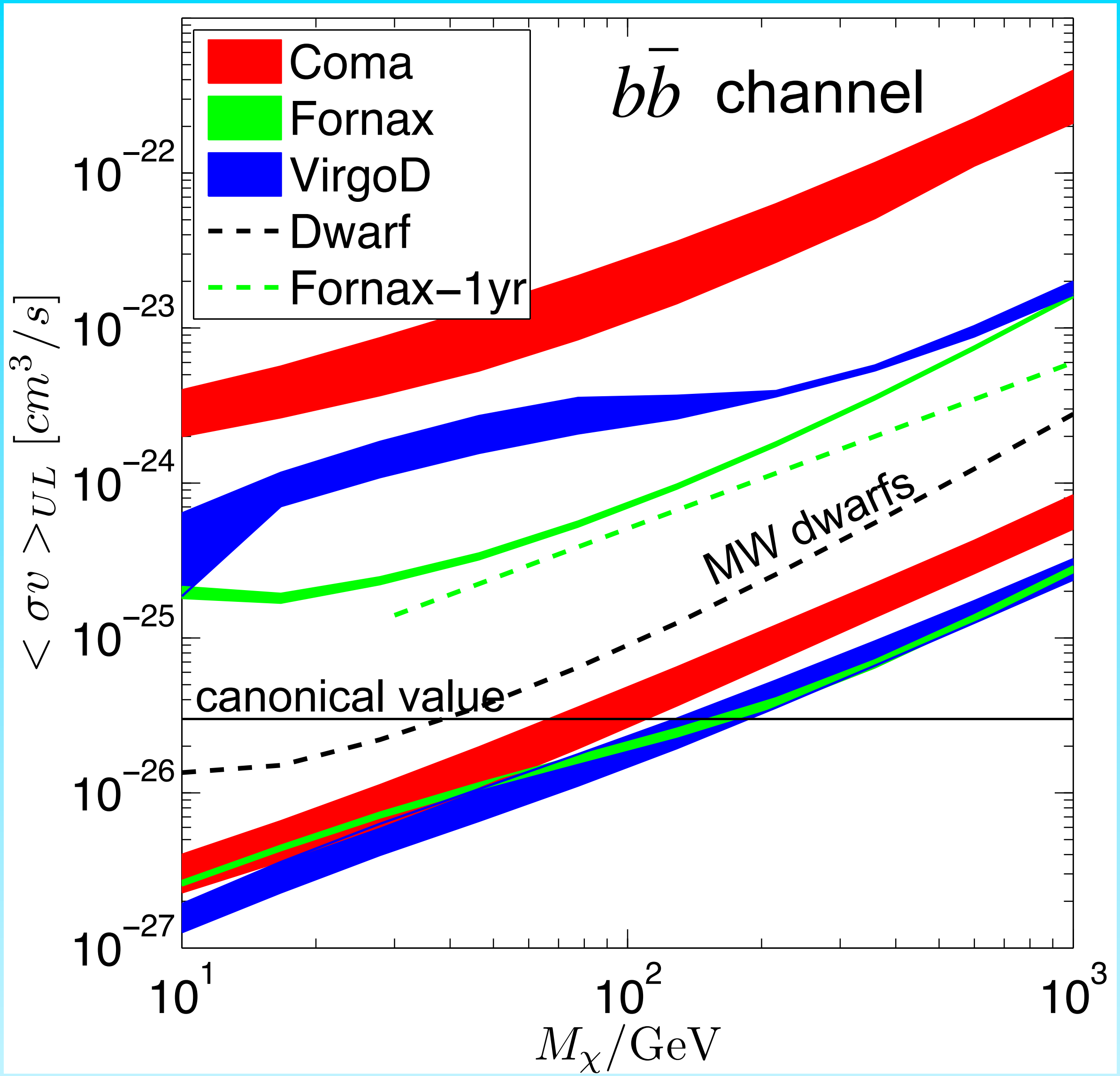
Bands = uncertainty in CR

Canonical x-section:

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$$

excluded for M<100 GeV

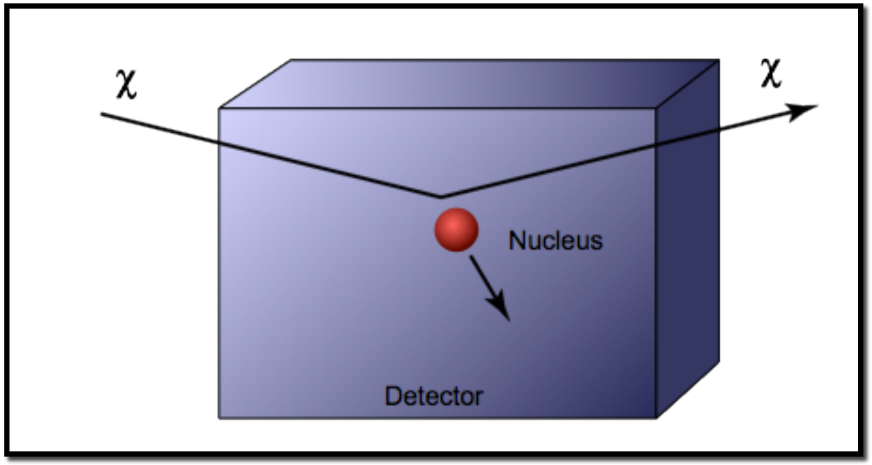
(for $M_{cut} = 10^{-6} M_o$)



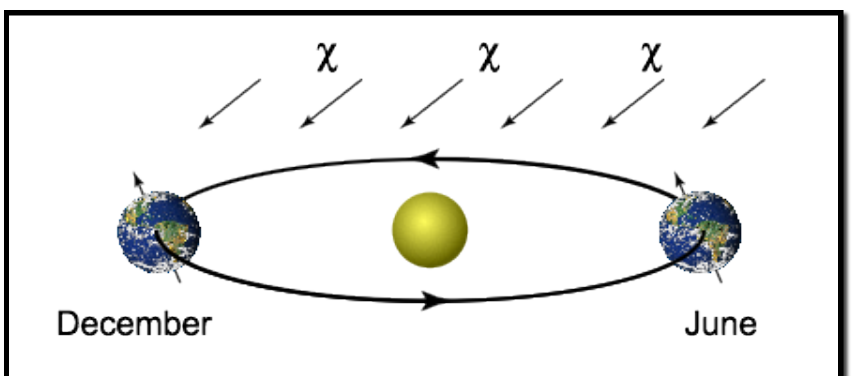
Han, Frenk, Eke, Gao, White '12

Institute for Computational Cosmology

Direct detection of WIMPS



- WIMP + nucleus → WIMP + nucleus
- Measure recoil energy (~10KeV)
- Suppress background enough to be sensitive to a signal, or...



- Search for an annual modulation due to the Earth's motion in the halo

Adapted from Joachim Edsjo

Cold dark matter searches

University of Durham

Astrophysical input *normally assumed* for direct searches:

Standard Halo Model (SHM):

- Smooth mass distribution
- Smooth velocity distribution
- "Featureless" phase-space

Density: ~0.3 GeV / c^2 / cm^3

Velocity: Maxwellian

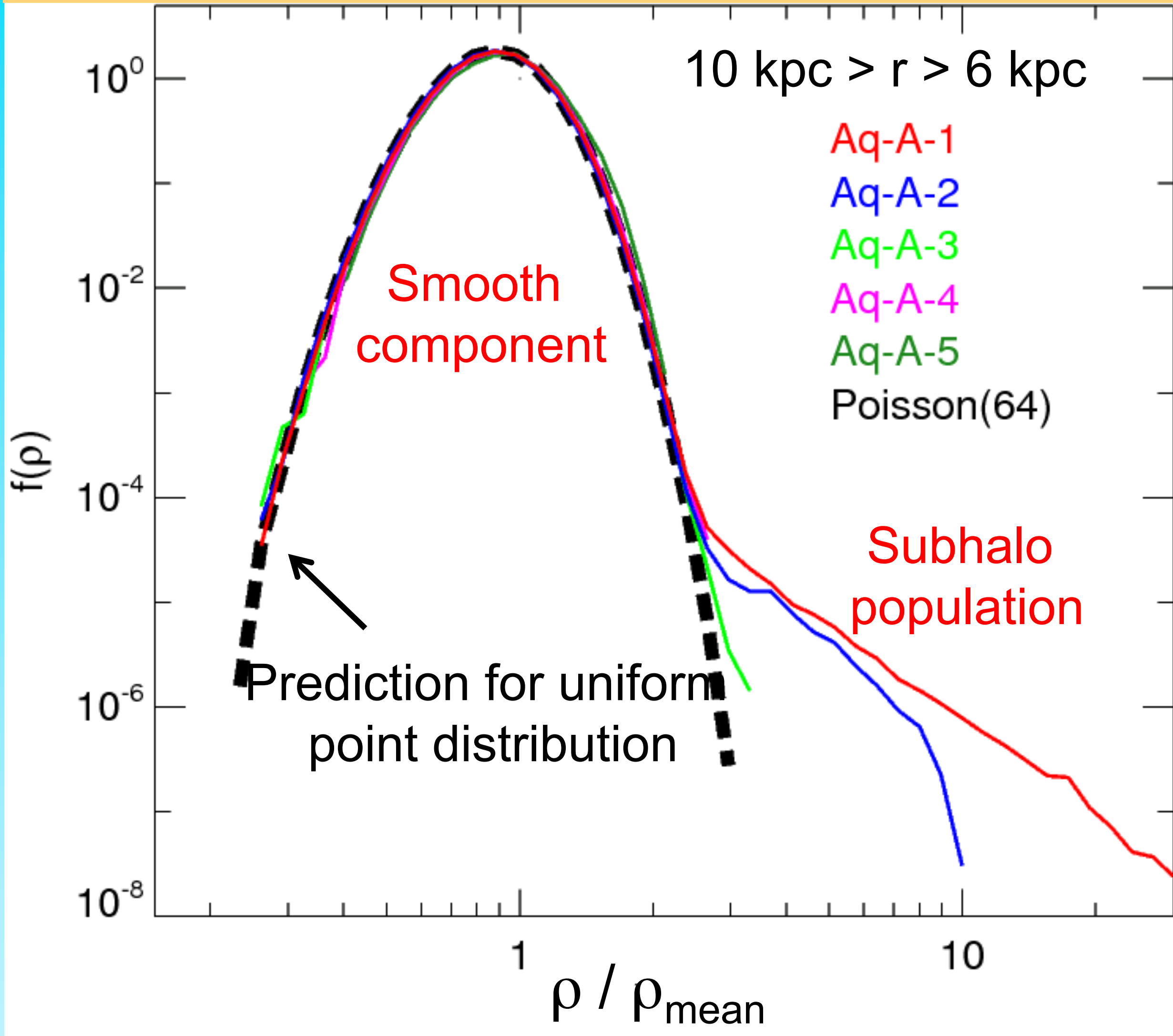
WIMP searches: nuclear recoil events

Axion searches: axion-photon conversion

CDM distribution around the Sun

University of Durham

Density prob distribution fn around solar circle



- Estimate ρ at a point by adaptive smoothing w. 64 nearest particles
- Fit to smooth ρ profile stratified on ellipsoids

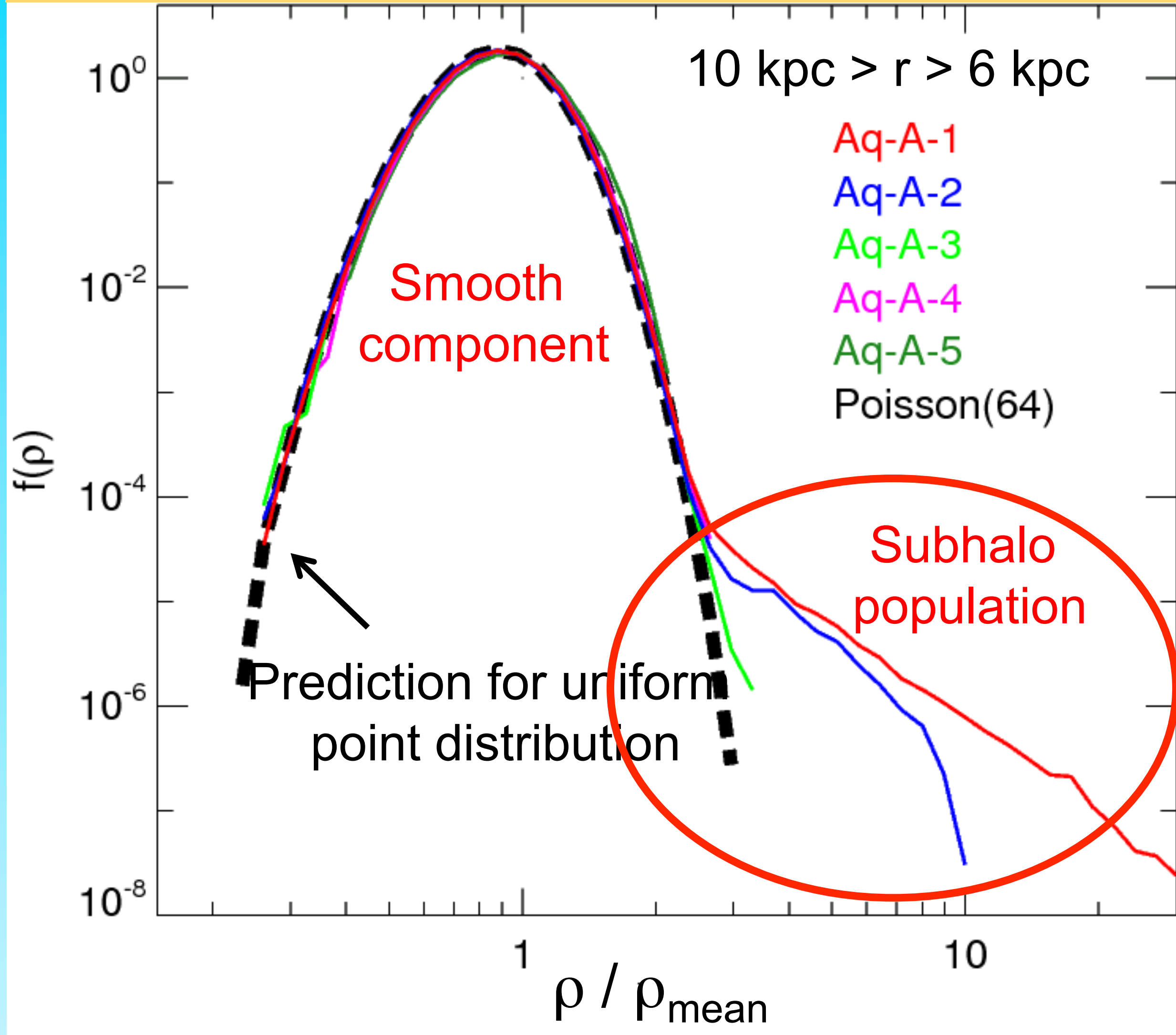
Vogelsberger et al '09

CDM distribution around the Sun

University of Durham

- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about smooth model for the remaining points is ~4%
- With >99.9% confidence, the DM density near the Sun differs from smooth mean value by < 15%

Density prob distribution fn around solar circle

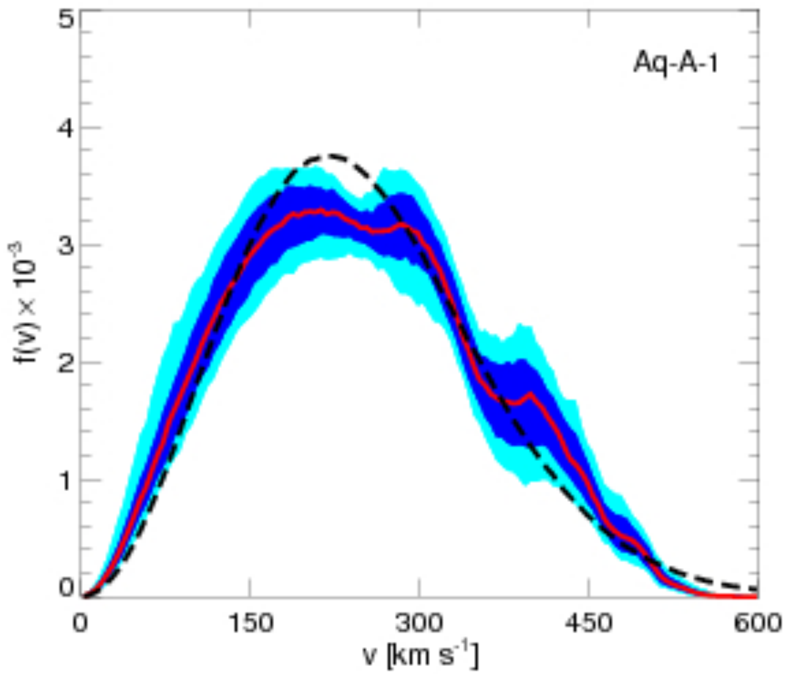


Vogelsberger et al '09

Direct detection: halo velocity distribution

Aquarius simulation

Vogelsberger et al ‘09



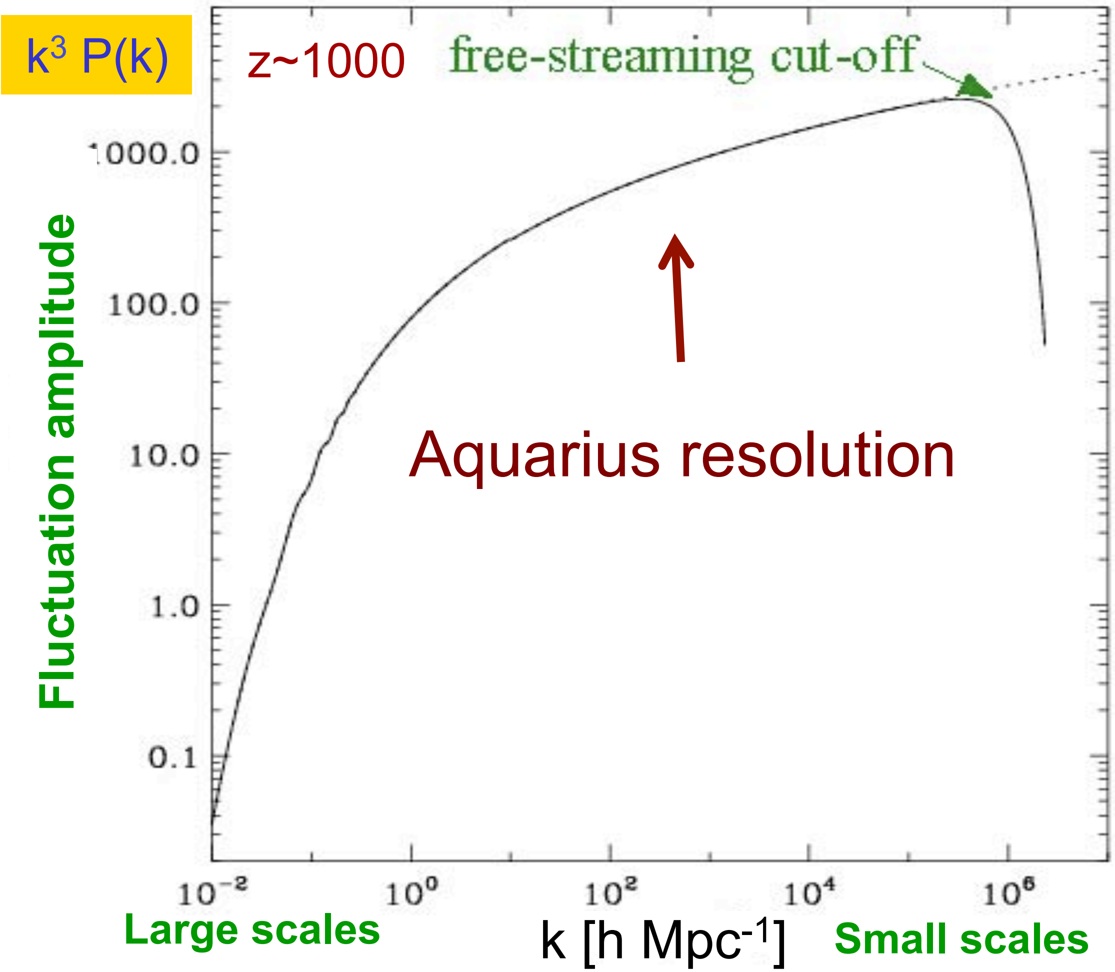
Experiments assume “standard halo modeL” → Gaussian vel distr

Simulations → fewer particles in tail of distribution;
smooth fall off to escape vel.

The cold dark matter power spectrum

The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



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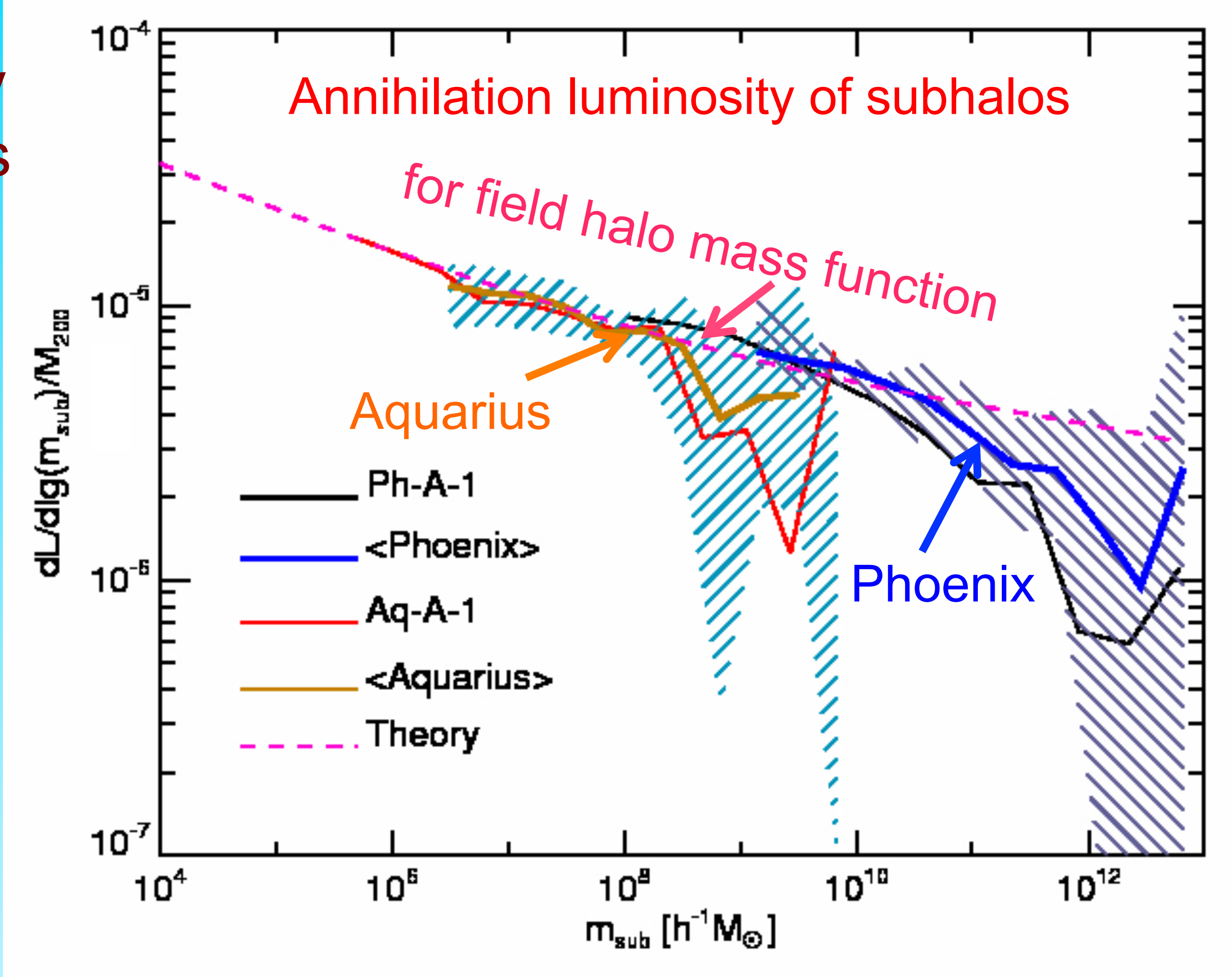
Extrapolation to Earth mass

University of Durham

Annihilation luminosity of subs. per unit mass

Subhalo L (per halo mass) similar to L of field halo mass fn.

Extrapolate using halo mass function (x1.5) + mass-concentration reln



Gao, Frenk, Jenkins, Springel & White '11

Institute for Computational Cosmology

University of Durham

Dark matter detection: computational challenge

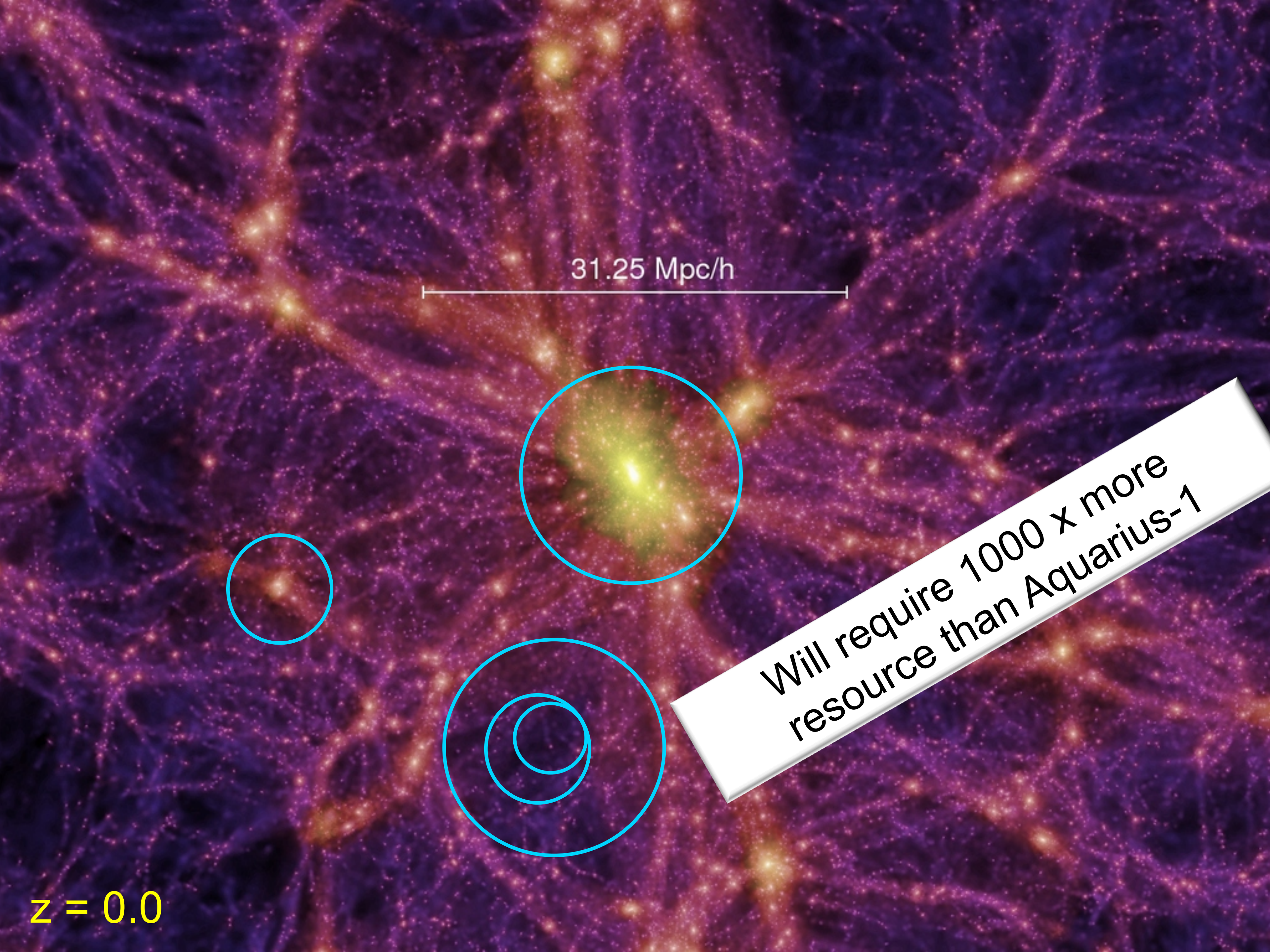
High resolution simulations of dark matter halos are essential to predict the expected signatures of DM and interpret any eventual signal

Aquarius level -1 (2008)

- → m_X=1000 M_o
- → 1 M cpu hrs
- → Still largest sim of this kind!

Further progress will require:

- → Better resolution
- → Clever techniques


31.25 Mpc/h
Will require 1000 x more
resource than Aquarius-1
z = 0.0

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

University of Durham

Free streaming →

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

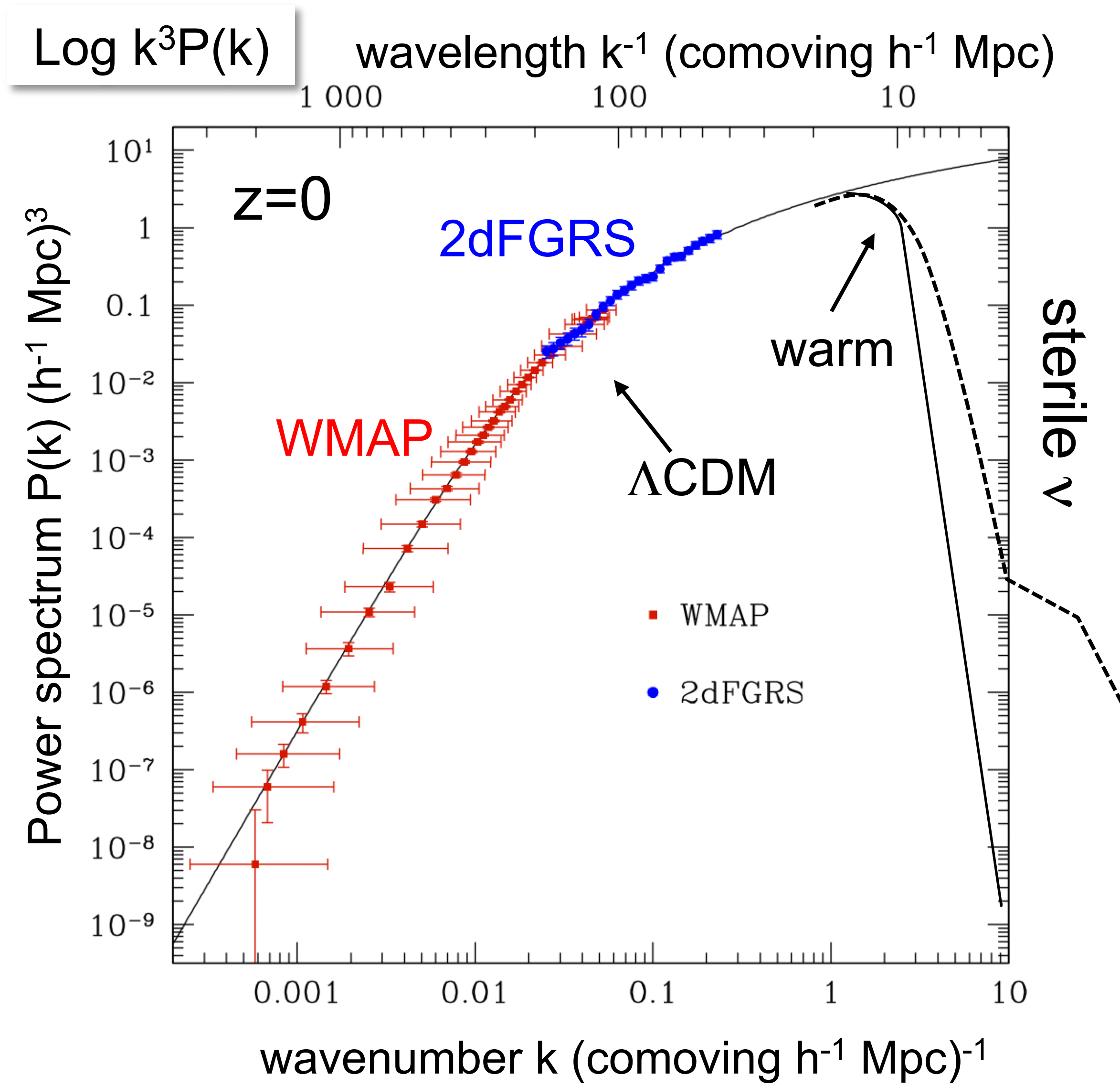
for thermal relic

$m_{CDM} \sim 100GeV$

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

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



University of Durham

SUBMITTED TO APJ, 2014 F
Preprint typeset using LATEX

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine

[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

DETECTION OF AN U

ESRA BULBUL[1,2], M

[1] Har

We detect a wea
spectrum of 73 g
independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based

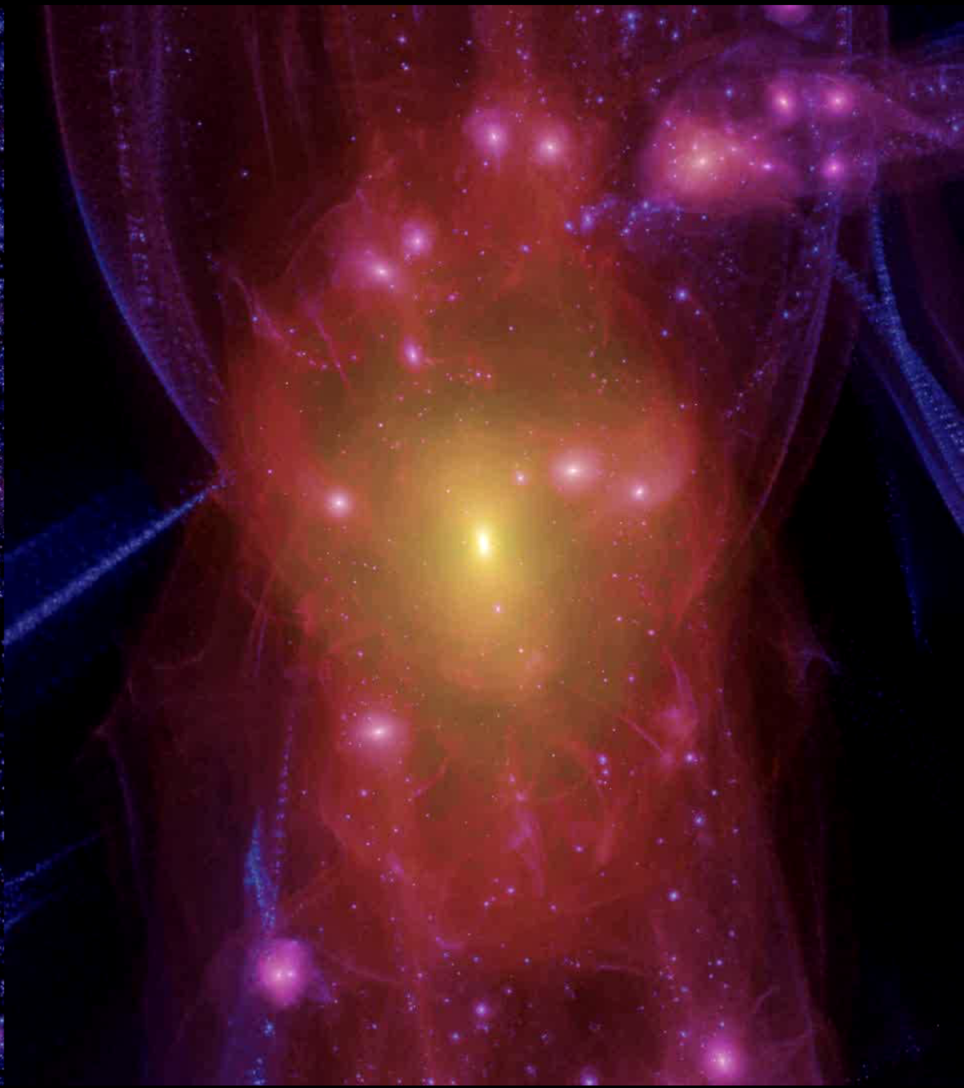
Cold Dark Matter Warm Dark Matter

13.4 billion years ago

Institute for Computational Cosmology

cold dark matter

warm dark matter



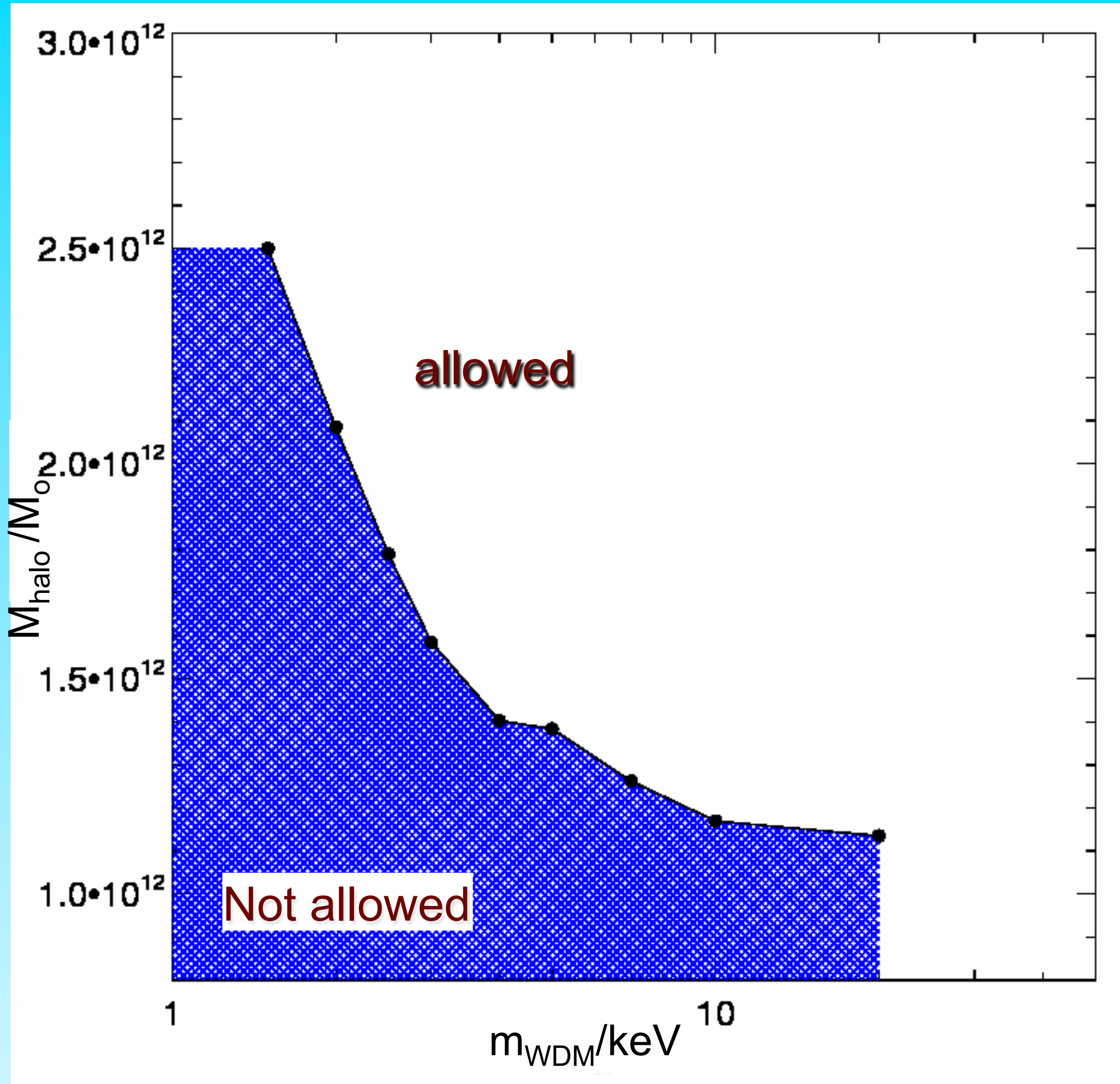
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘14

Limits on WDM particle mass

University of Durham

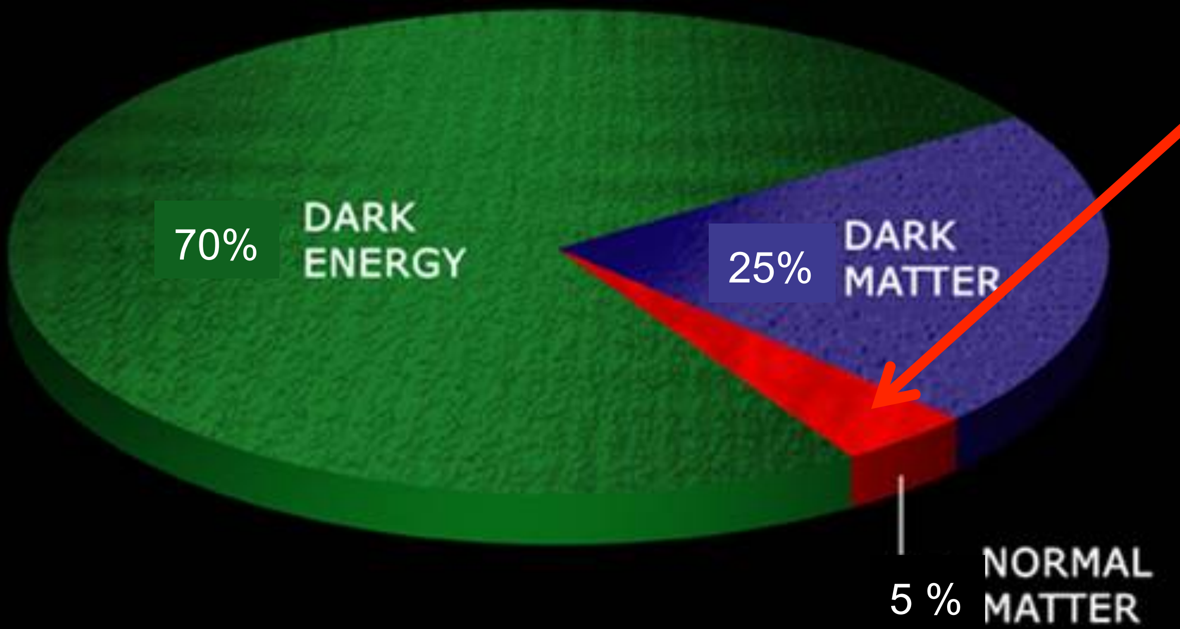
Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

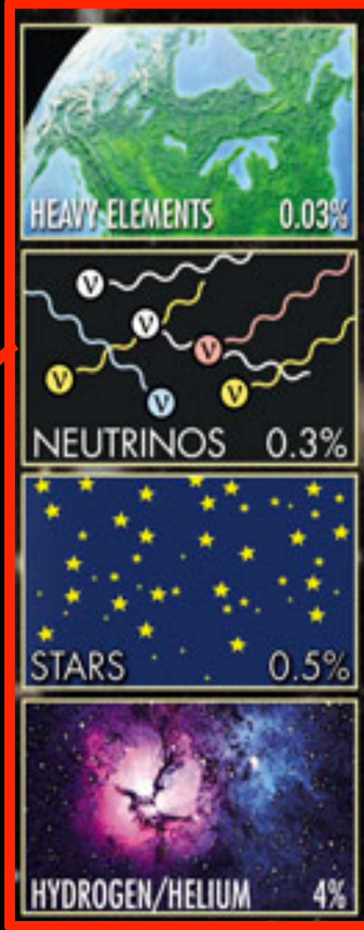
For standard galaxy formation model, WDM ruled out if $M_{halo} < 1.1 \times 10^{12}\ M_o$



Kennedy, Cole & Frenk '14

The content of our universe

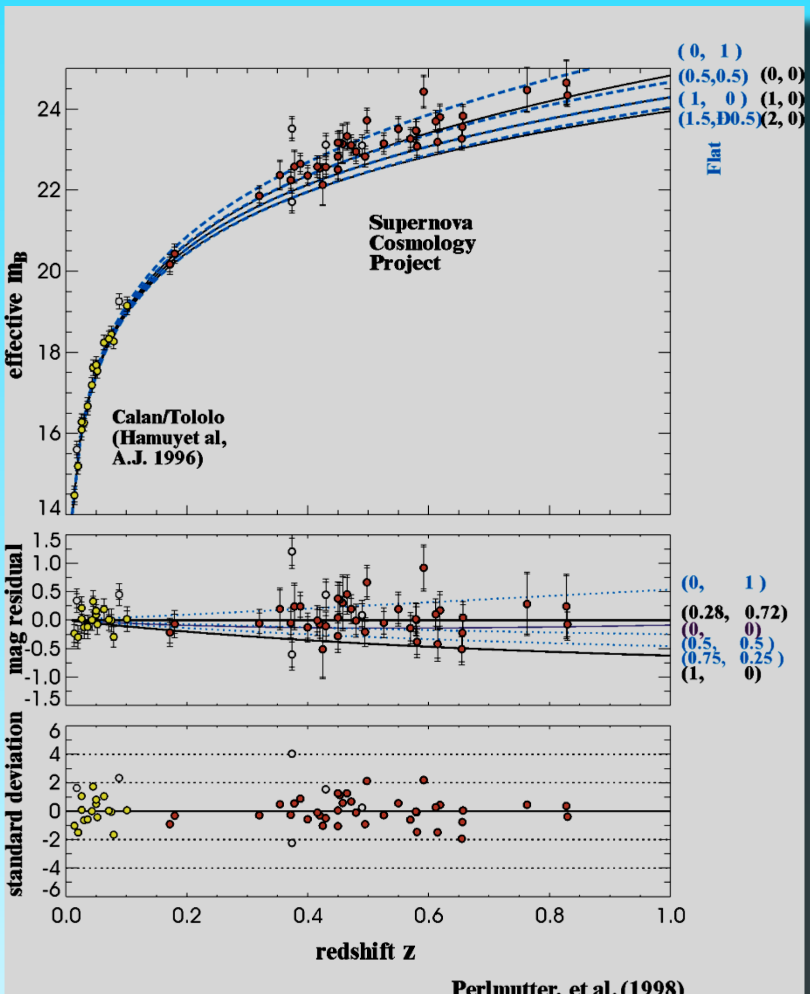


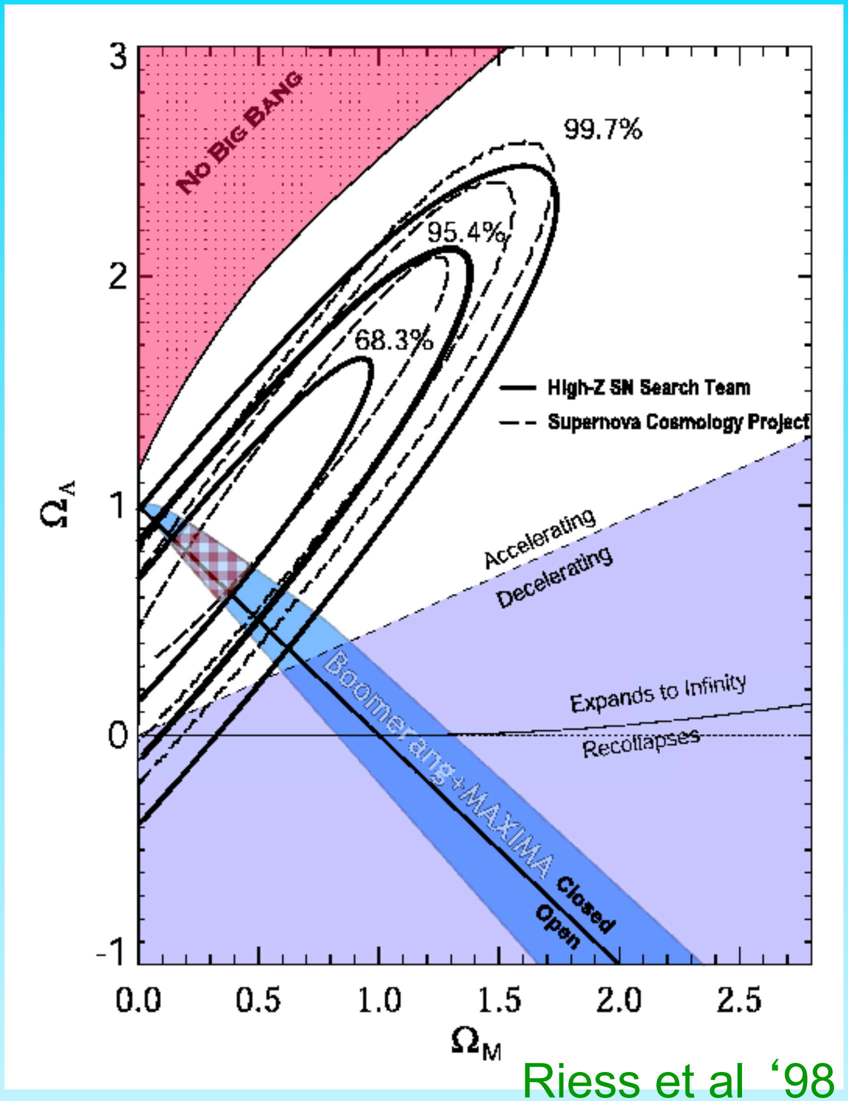


University of Durham

Evidence for Λ from high-z supernovae

Distant SN are fainter than expected if expansion were decelerating





Riess et al '98

Institute for Computational Cosmology

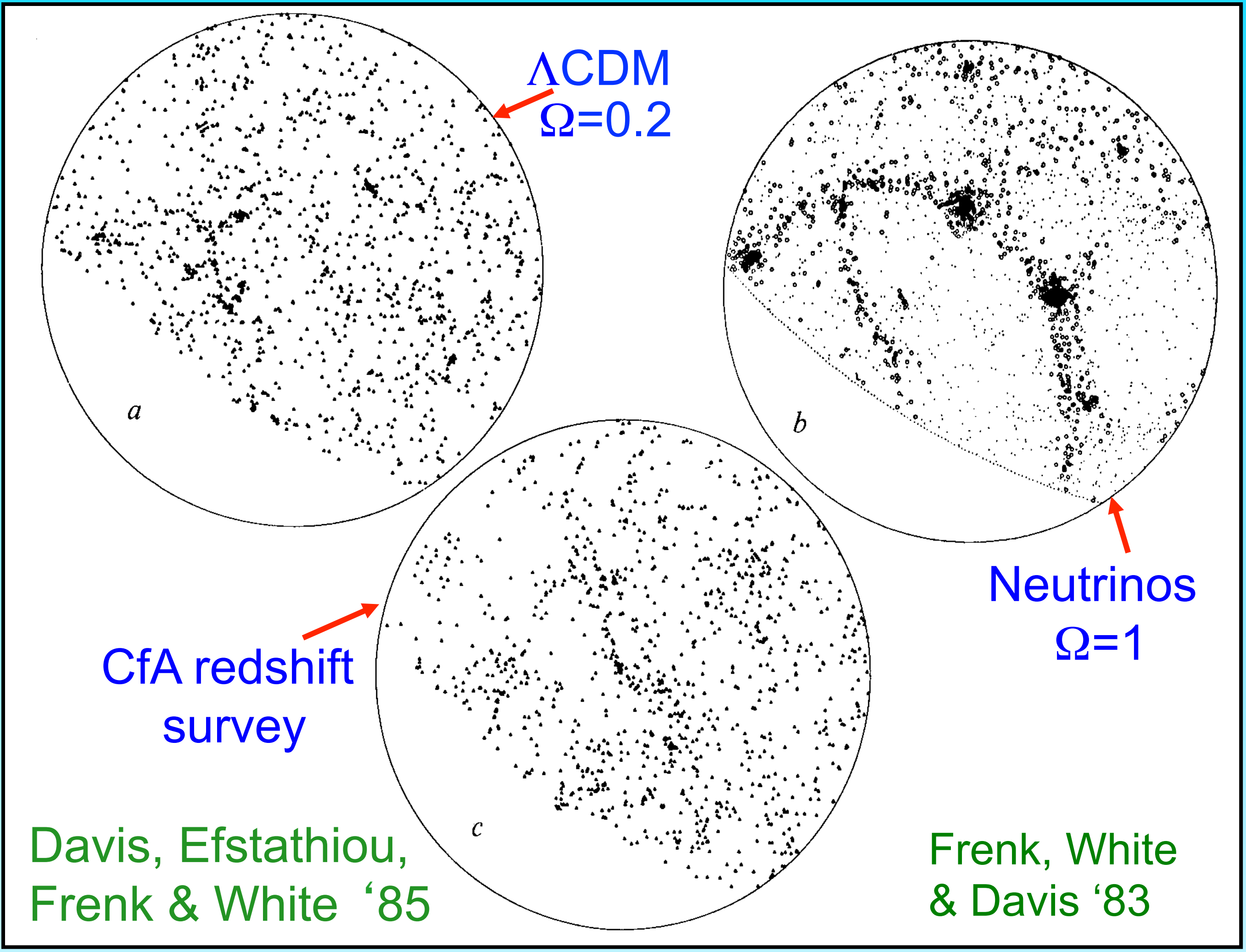
Non-baryonic dark matter cosmologies

Neutrino DM → unrealistic clust'ing

Neutrinos cannot make appreciable contribution to Ω → m_ν << 10 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



University of Durham

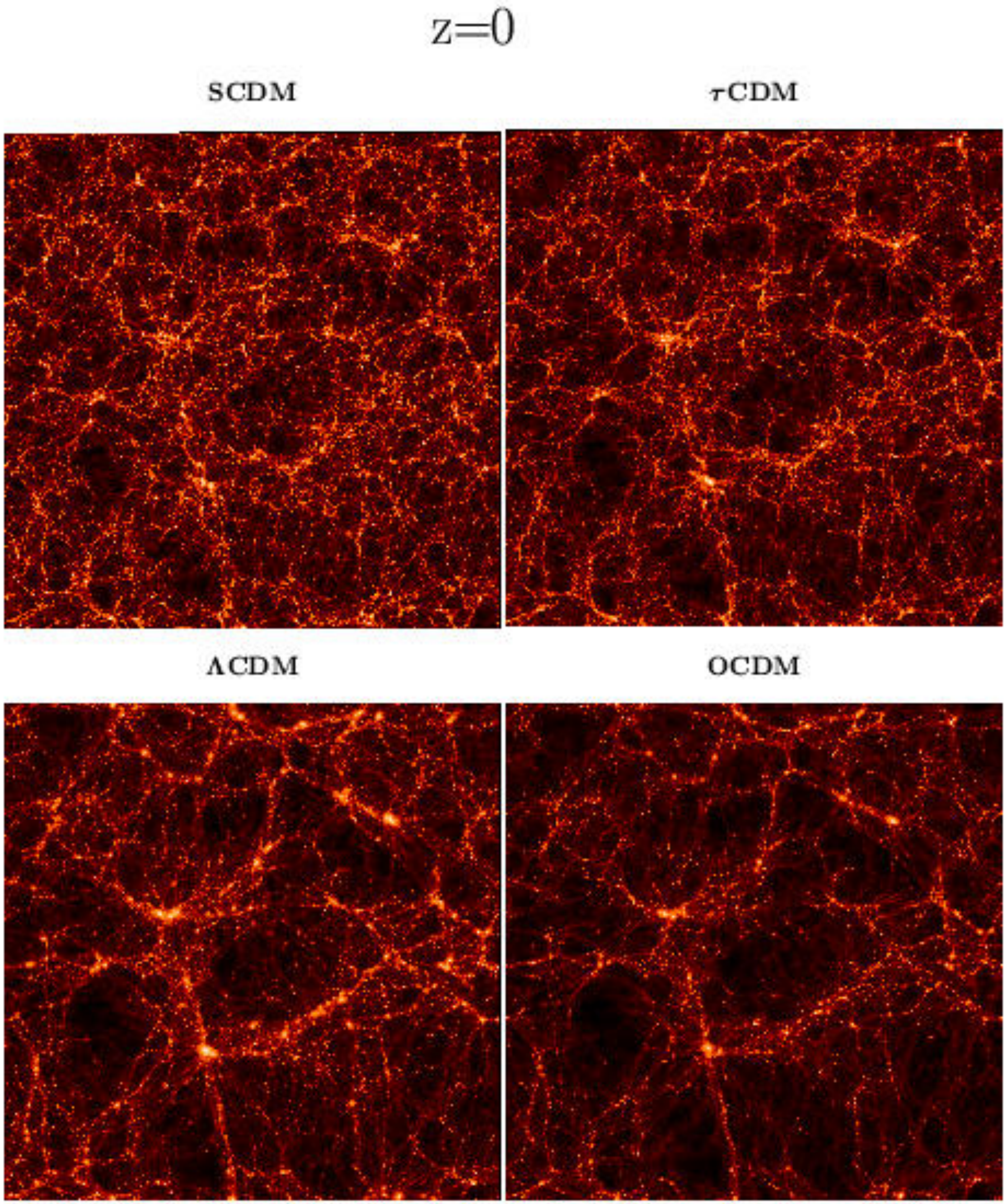
The Virgo consortium

Jenkins et al 1998

(436 citations)

Jenkins et al 2001

(1091 citations)



The VIRGO Collaboration 1996

ICC

University of Durham

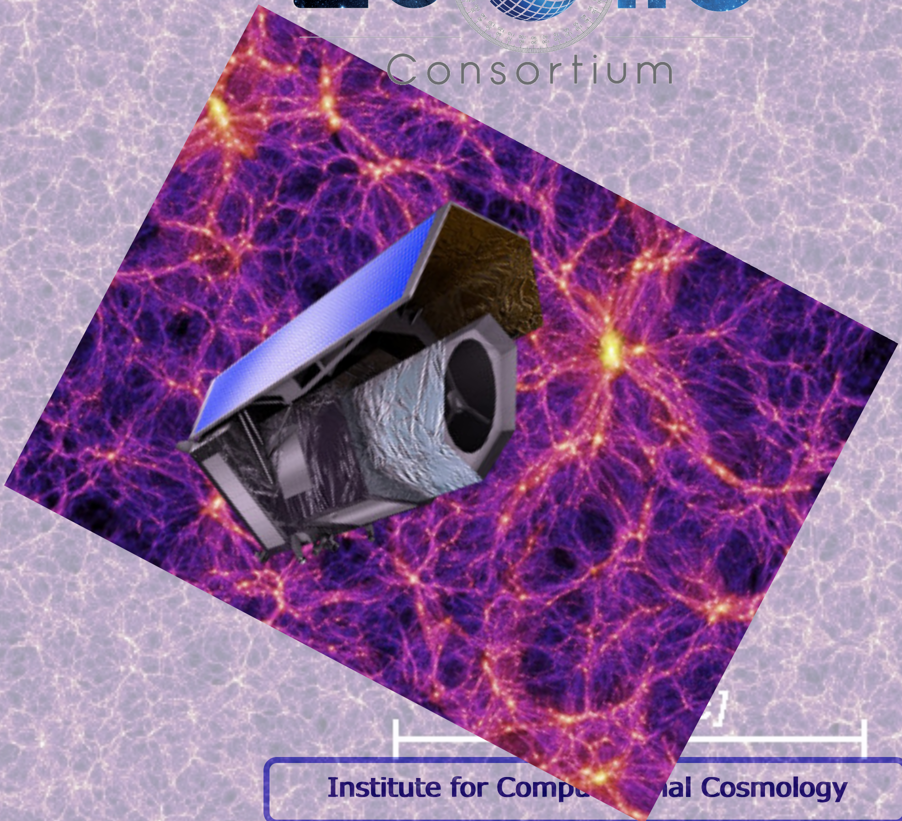
LSST

Large Synoptic Survey Telescope

MS-DESI

Euclid

Consortium



DES

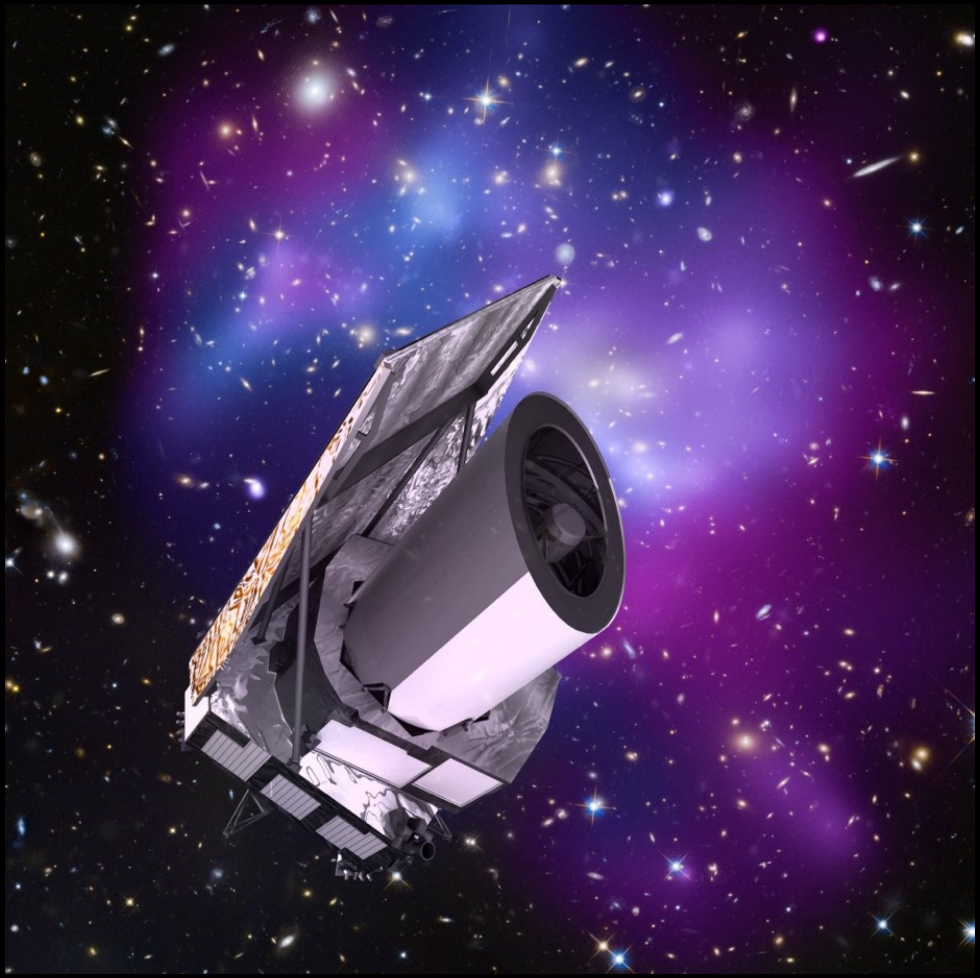
Institute for Compu al Cosmology

The large-scale structure of the Universe

University of Durham

Euclid mission

- Launch 2020 - 6 yr mission
- Will probe expansion history and growth of structure over much of the visible universe
- Aims to measure BAO scale, z-space distortions and gravitational lensing at a subpercent level of precision



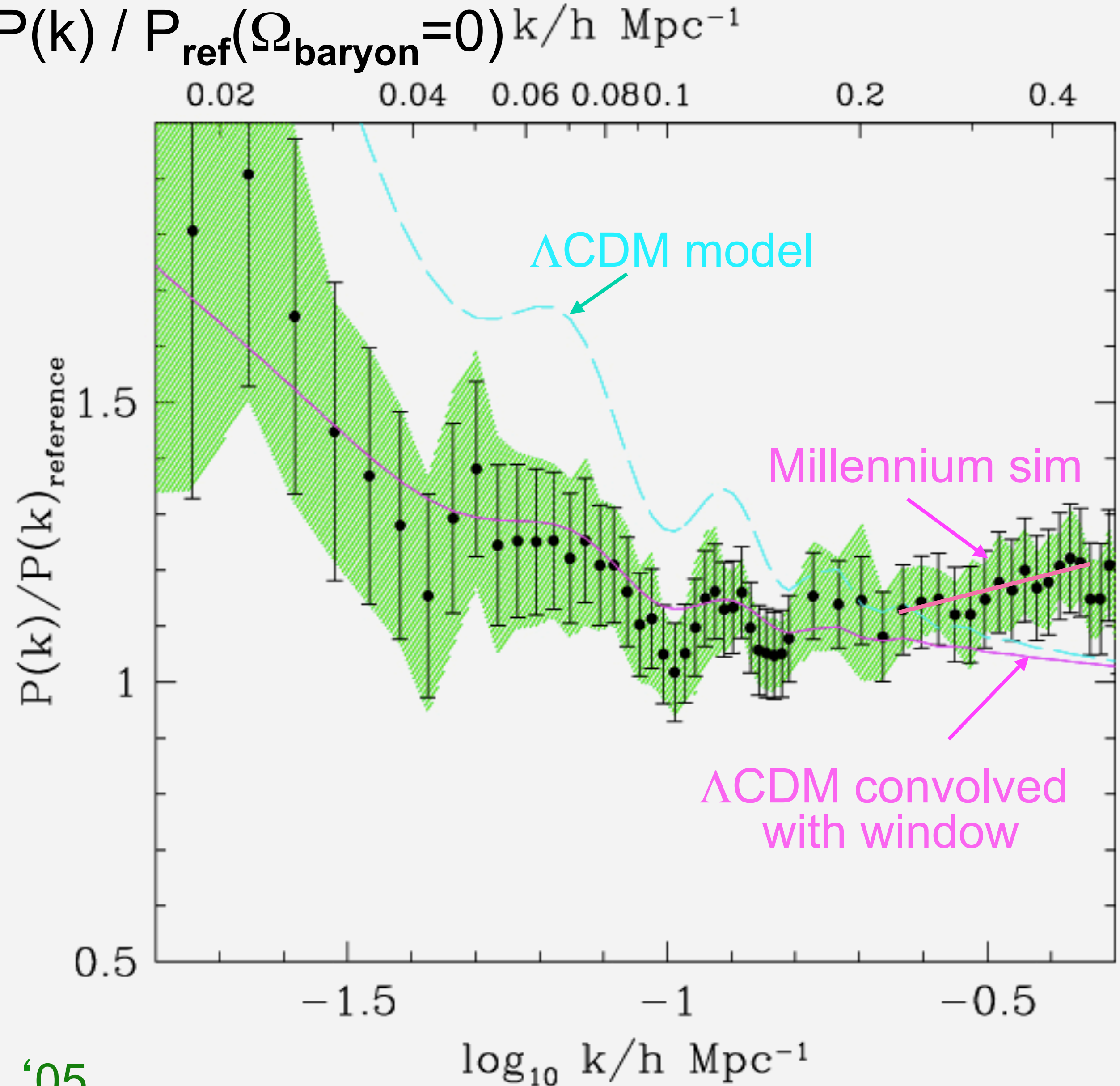
Baryon acoustic oscillations in 2dFGRS

University of Durham

220,000 redshifts

Baryon oscillations conclusively detected in 2dFGRS!!!

Consistent with structure growth by gravitational instability in a ΛCDM universe



Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

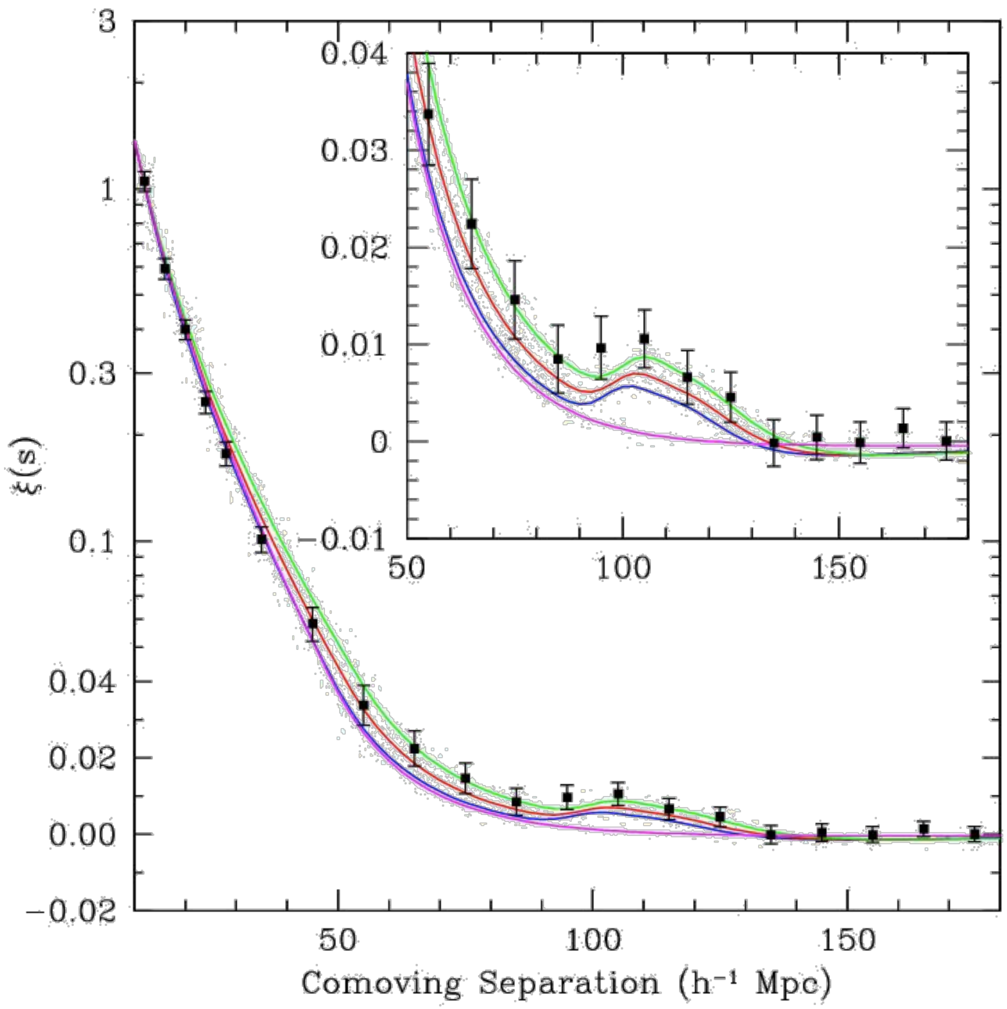
Baryon acoustic oscillations in SDSS

- 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



Eisenstein et al '05

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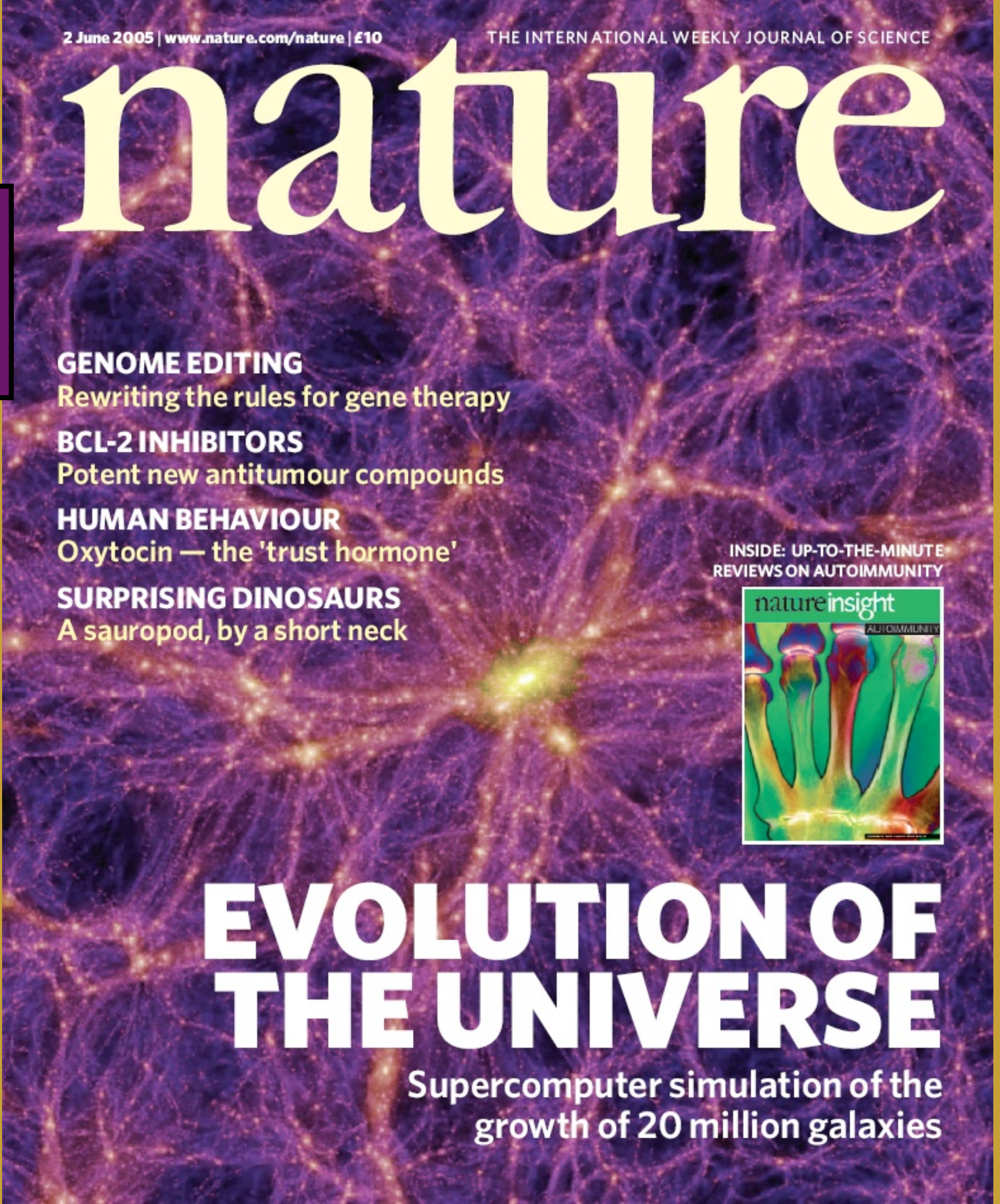
The Millennium Simulation

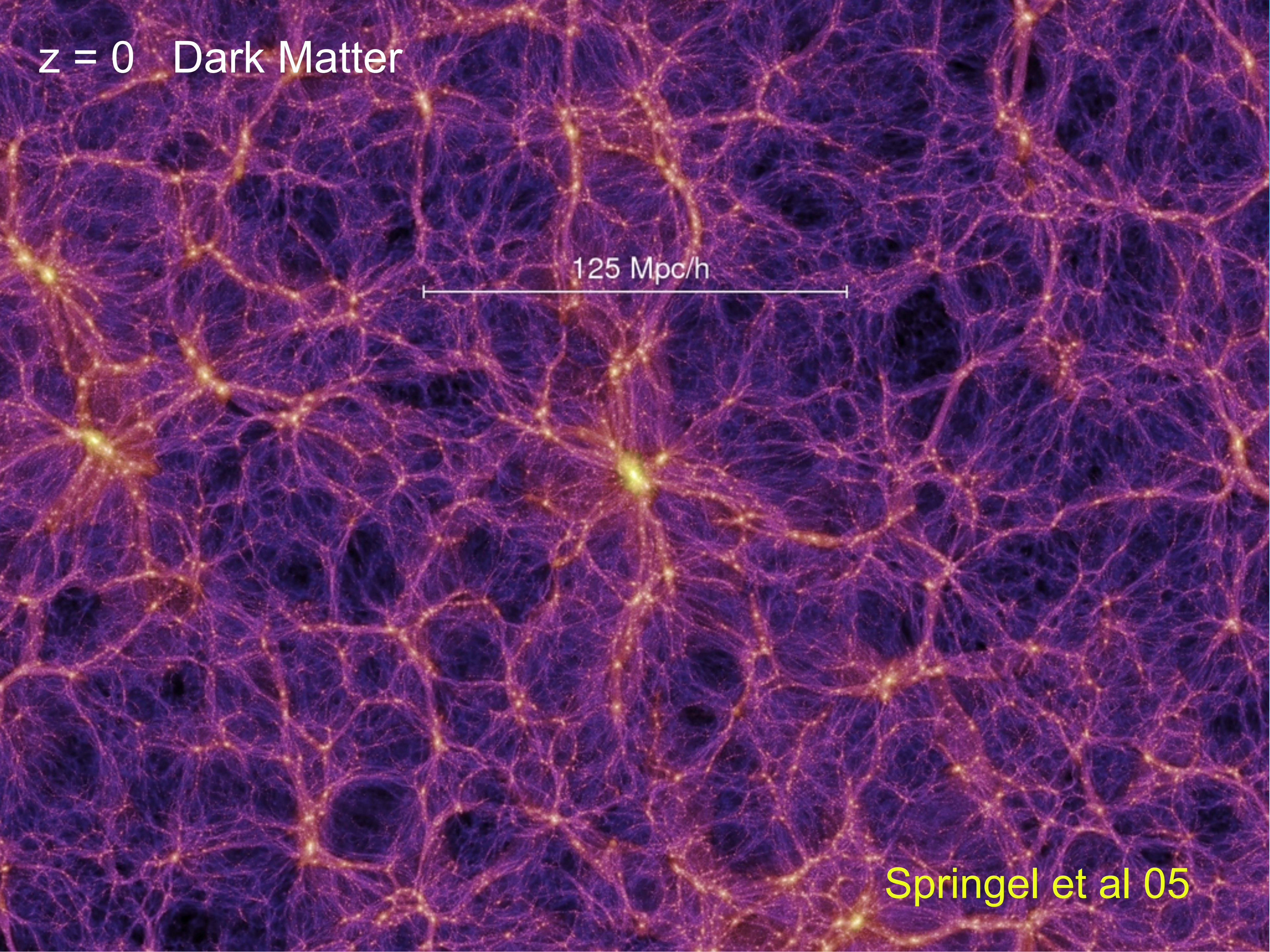
Springel et al 05

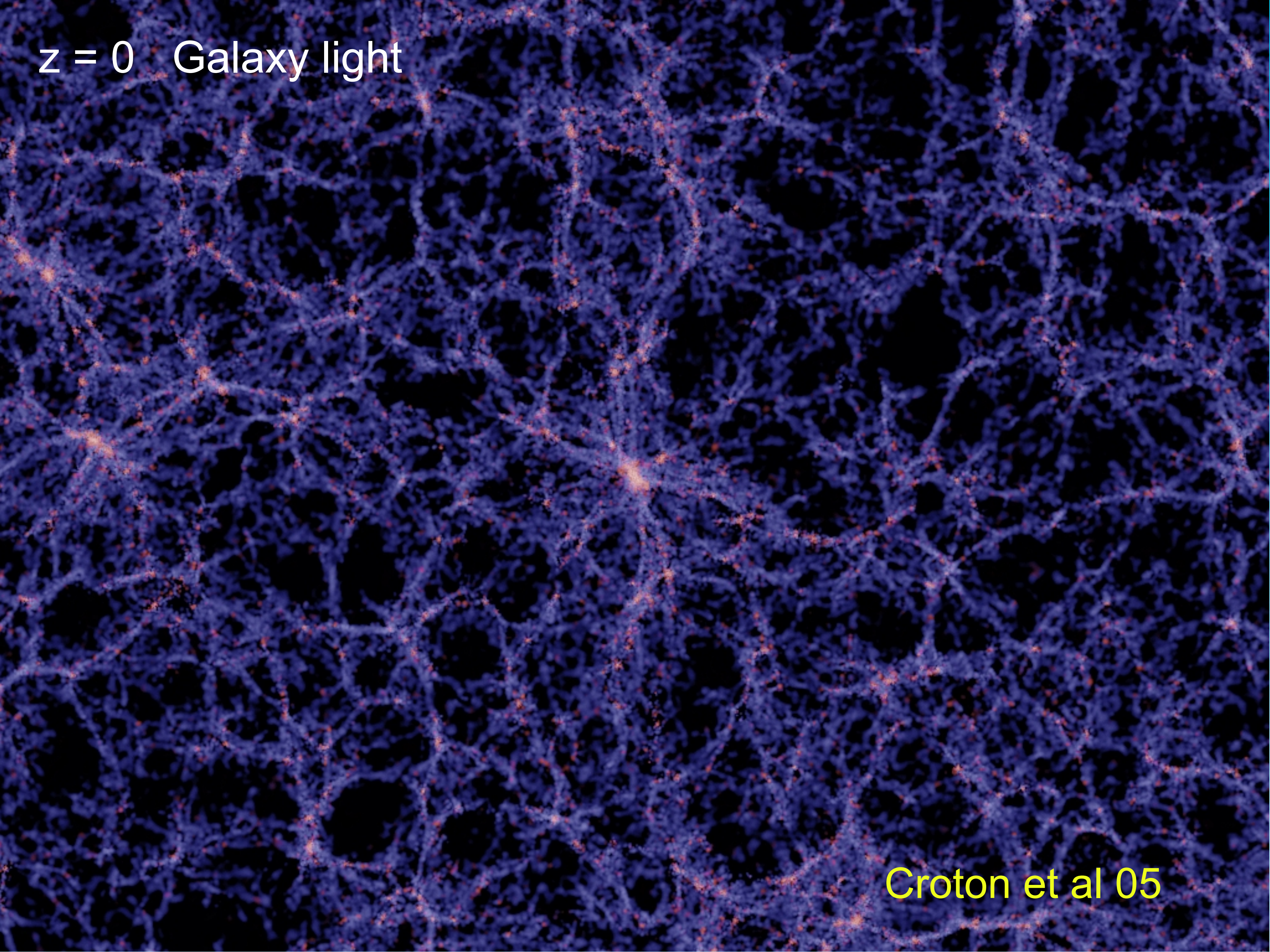
www.durham.ac.uk/virgo

www.mpa-garching.mpg.de/Virgo

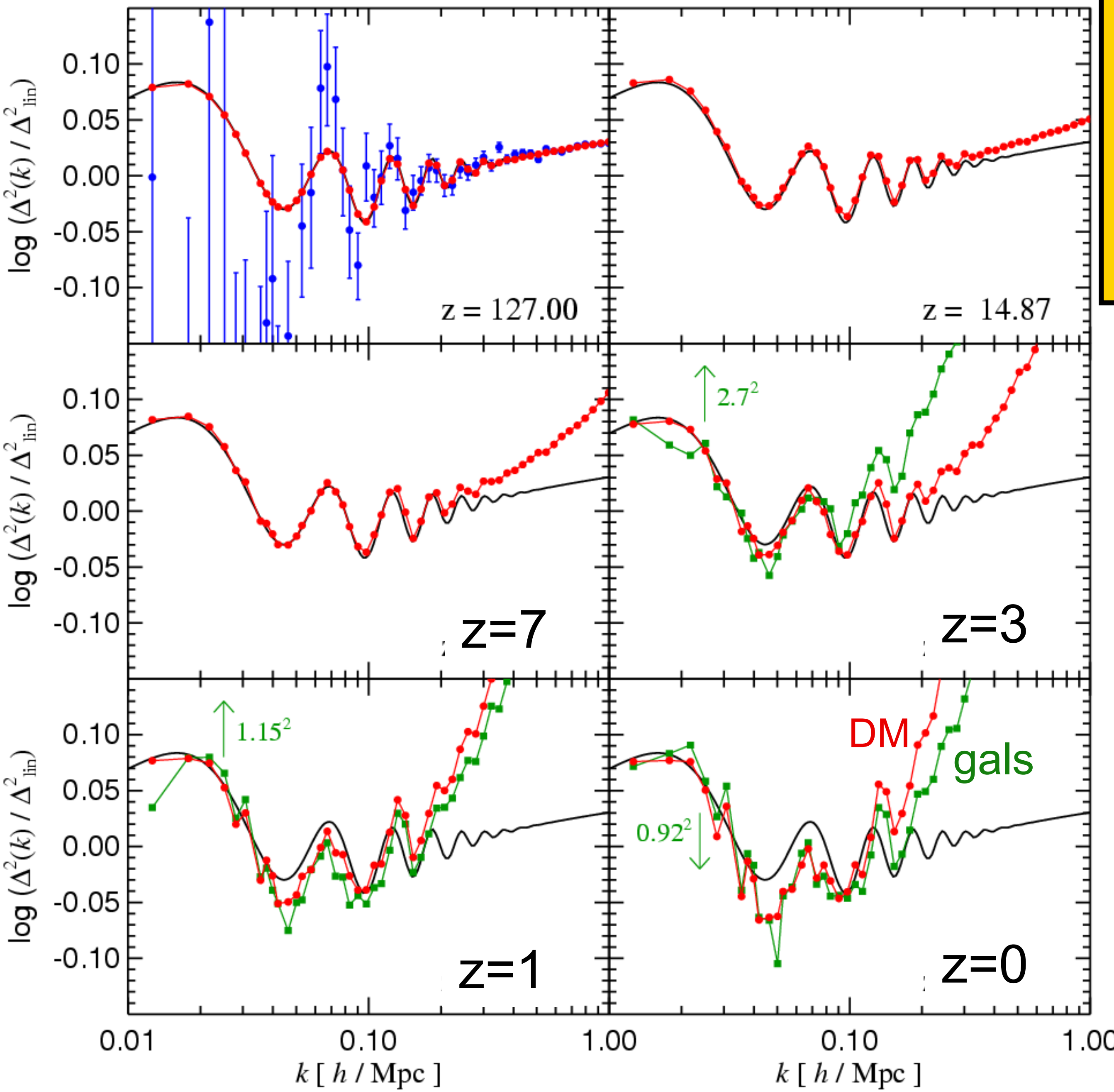
June 2/05




z = 0 Dark Matter
125 Mpc/h
Springel et al 05


z = 0 Galaxy light
Croton et al 05

Millennium simulation



Baryon wiggles in the galaxy distribution

Power spectrum from MS divided by a baryon-free ΛCDM spectrum

Galaxy samples matched to plausible large observational surveys at given z

Springel et al 2005

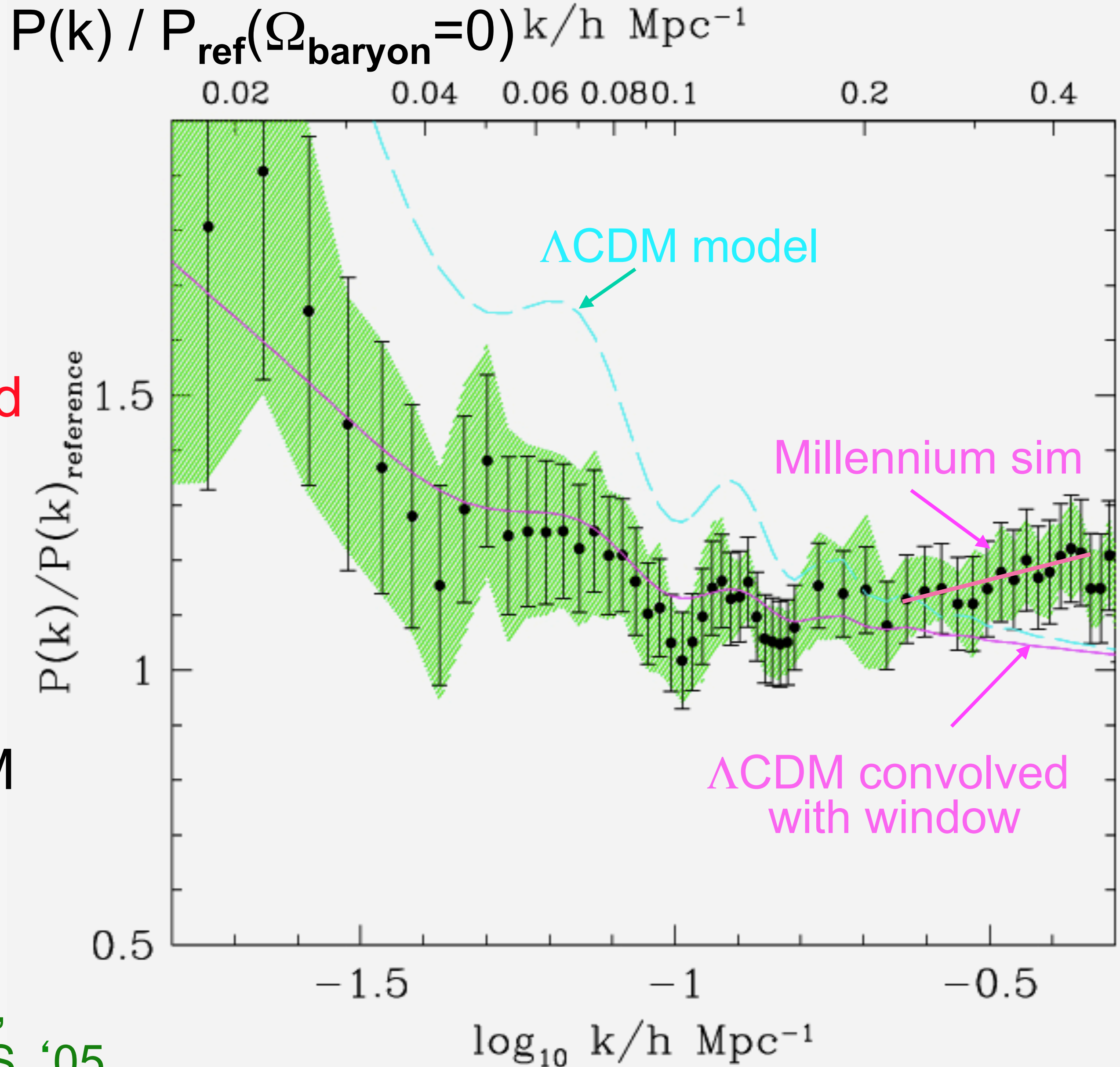
Baryon acoustic oscillations in 2dFGRS

University of Durham

220,000 redshifts

Baryon oscillations conclusively detected in 2dFGRS!!!

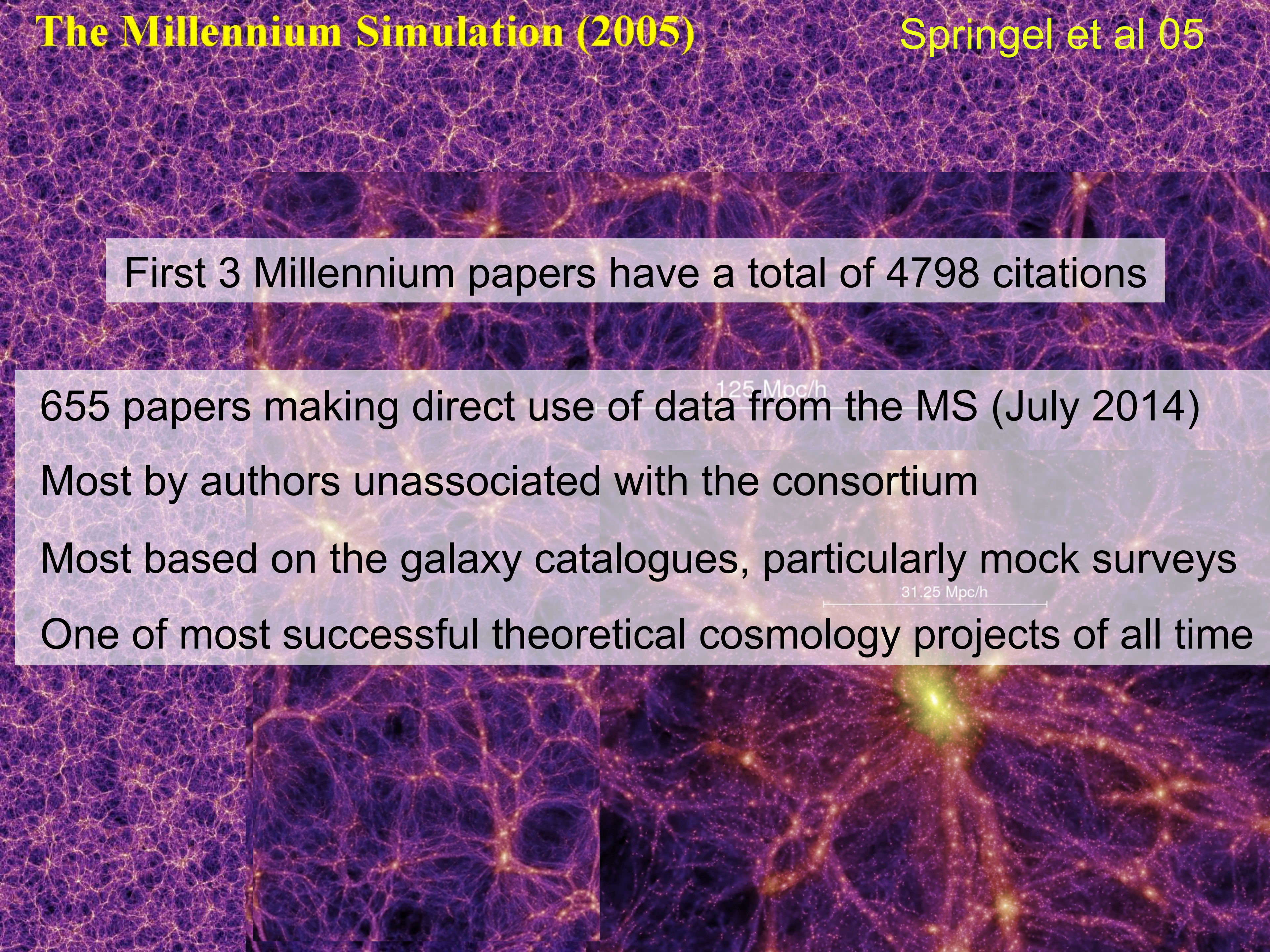
Consistent with structure growth by gravitational instability in a ΛCDM universe



Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

The Millennium Simulation (2005)

Springel et al 05



First 3 Millennium papers have a total of 4798 citations

655 papers making direct use of data from the MS (July 2014)

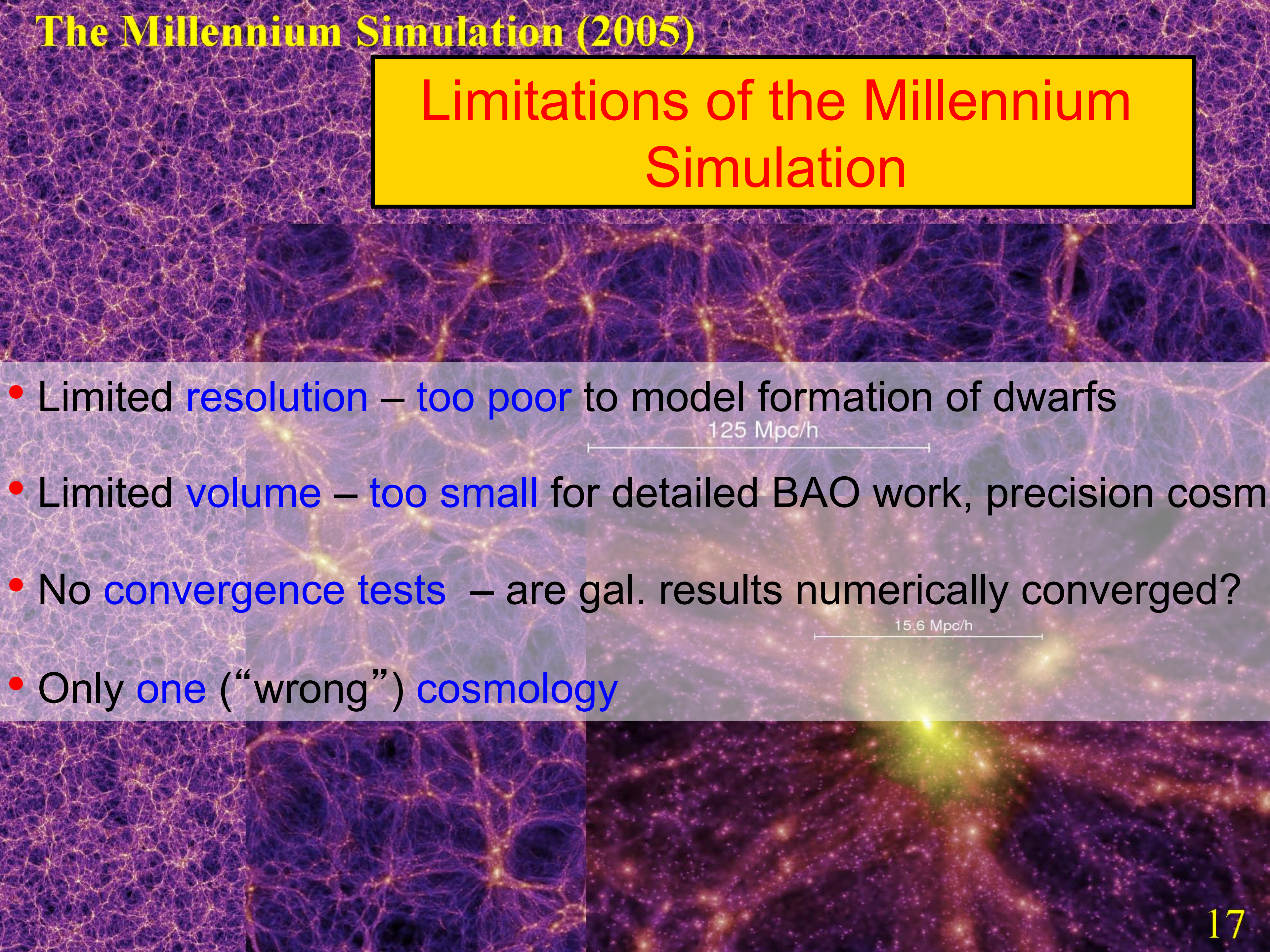
Most by authors unassociated with the consortium

Most based on the galaxy catalogues, particularly mock surveys

One of most successful theoretical cosmology projects of all time

The Millennium Simulation (2005)

Limitations of the Millennium Simulation



- Limited resolution – too poor to model formation of dwarfs
- Limited volume – too small for detailed BAO work, precision cosm
- No convergence tests – are gal. results numerically converged?
- Only one (“wrong”) cosmology

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Millennium-II (2008)

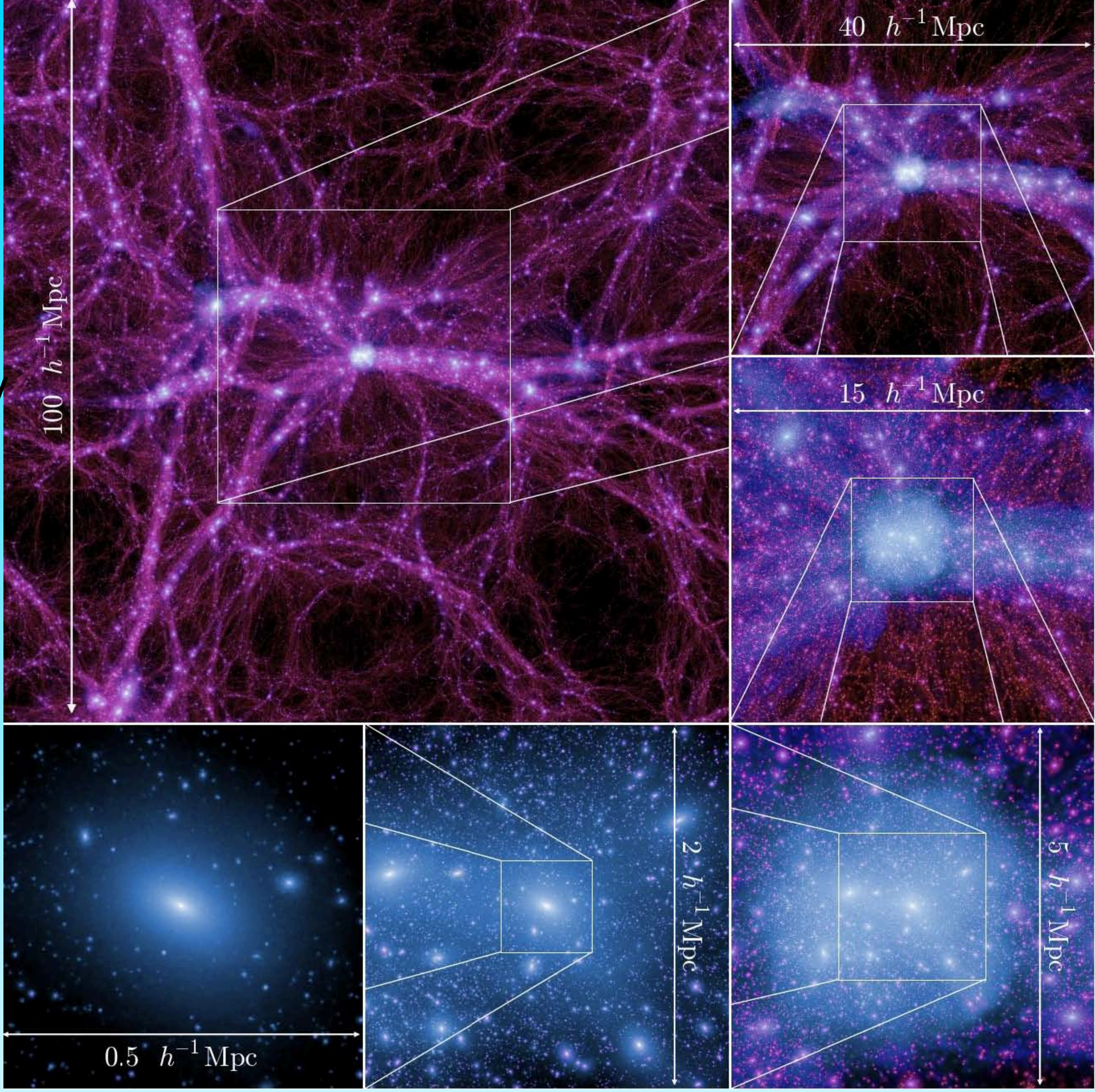
Same cosmology

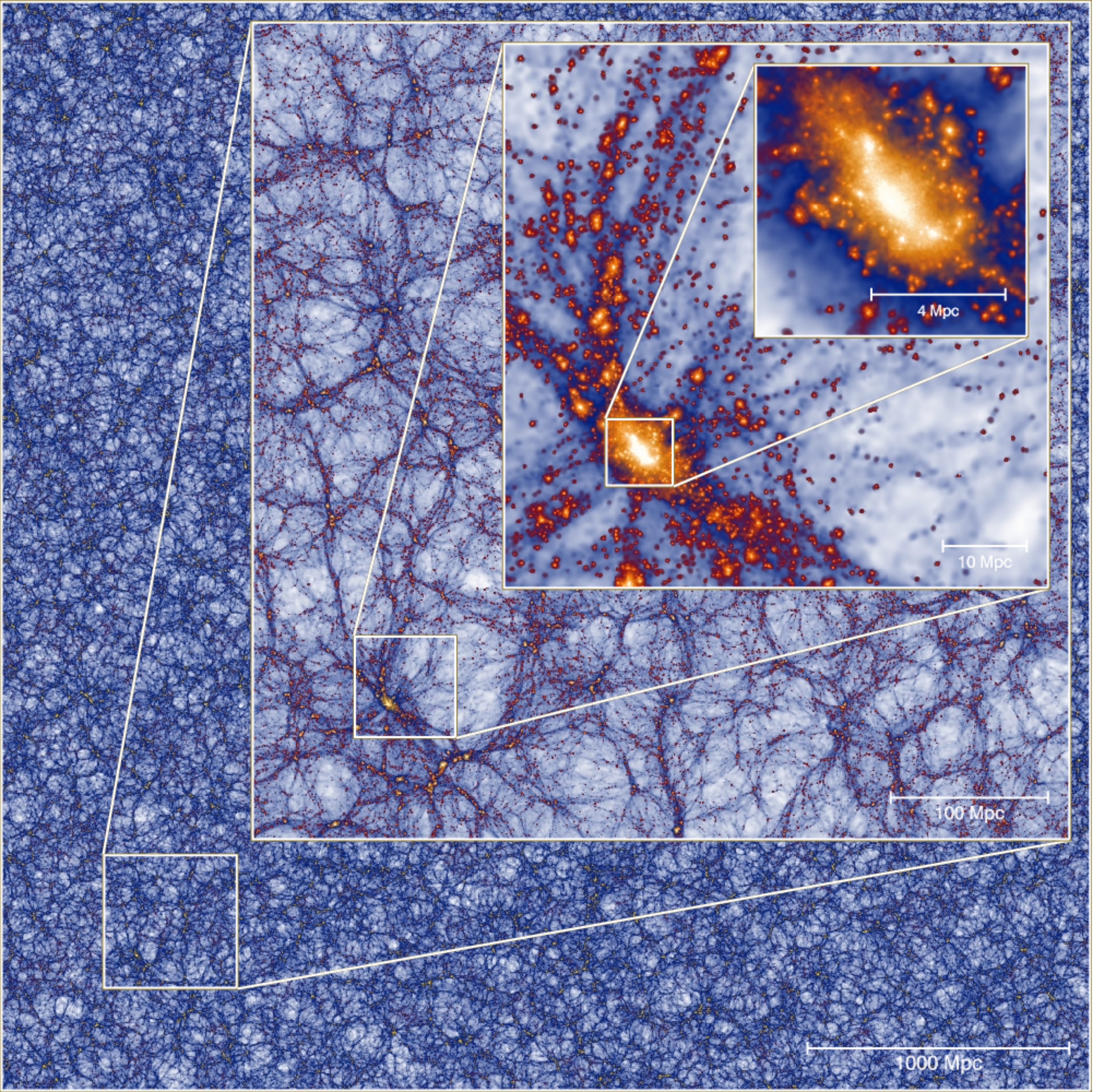
Same N

1/5 linear size

Resolution tests of MS results and extension to smaller scales

Boylan-Kolchin et al '10





The MXXL

Angulo, Springel et al. '12

Bigger than the Millennium run by factors of

30 in $N_{particle}$

200 in volume

6 in $m_{particle}$

3×10^8 galaxies $M_* > 10^{10} M_\odot$

3×10^5 clusters $M_* > 10^{14} M_\odot$

Millennium-XXL was successfully executed on JUROPA in 2010

PARAMETERS OF FINAL RUN

6720^3 ~ 303 billion particles

3000 Mpc/h box, Millennium cosmology

12288 cores: 3072 MPI-task / 4 threads (70% of Juropa)

9216^3 FFT mesh

86 trillion force calculations

Cost: 2.7 million CPU hours (~300 years), corresponding to 9.3 days wallclock time (including FOF+SUBFIND)

Peak memory usage: 29 TB
(105 bytes/particle)

700 million halos at z=0 (44% of particles)

About 25 billion (sub)halos in merger trees

Largest cluster has 9×10^{15} $M_\odot$

Size of a full snapshot: ~10 TB

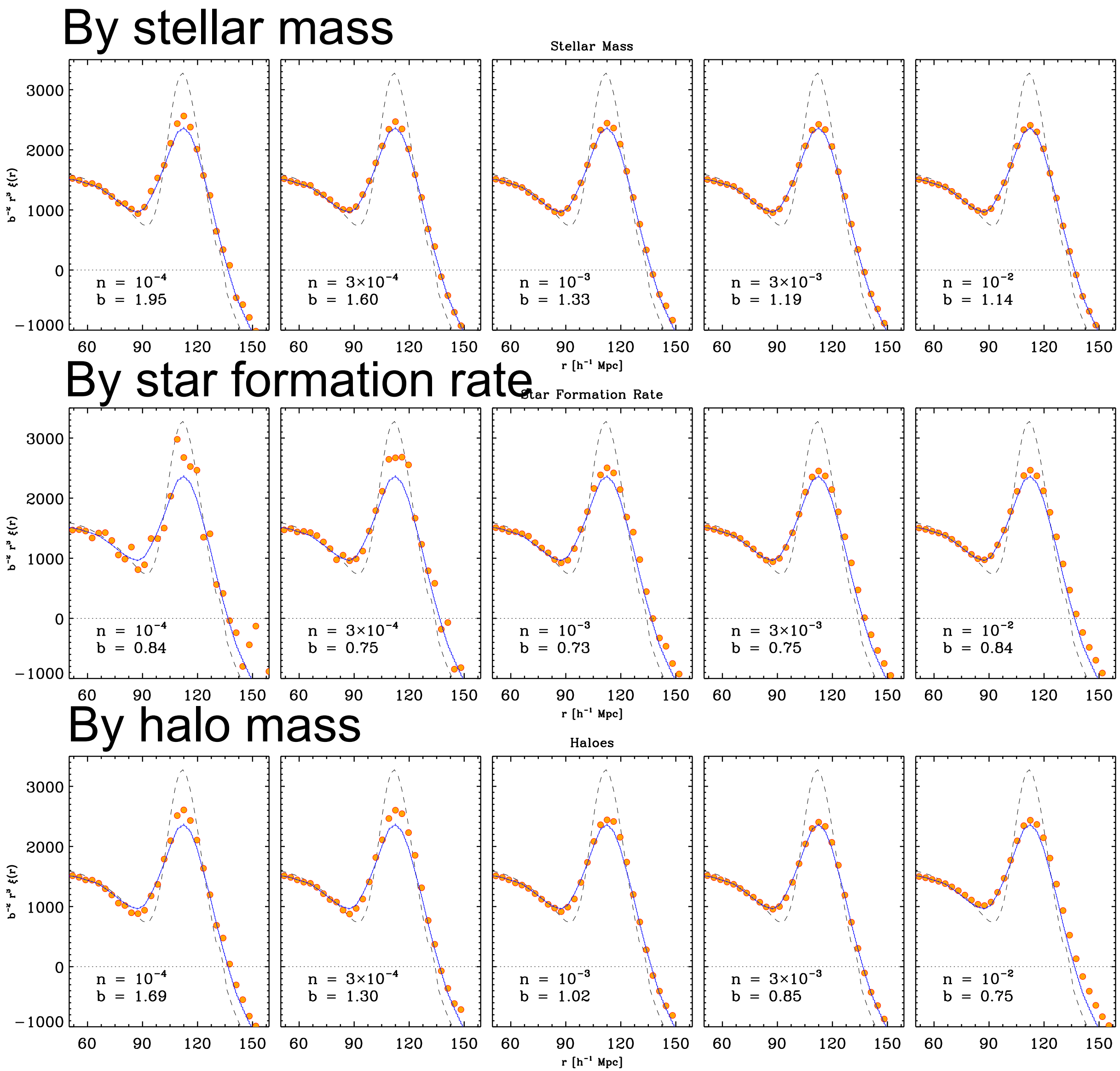
More than 120 TB stored for science

JUROPA
Jülich
Forschungszentrum

Carried out by Raul Angulo and Volker Springel within the Virgo Consortium

Different galaxy catalogues in the MXXL simulation trace the BAO features with a mass- and scale-dependent bias

CORRELATION FUNCTION OF THE GALAXY DISTRIBUTION AT Z=0 FOR DIFFERENT SELECTION



Galaxy formation effects distort shape of BAO by up to 5%

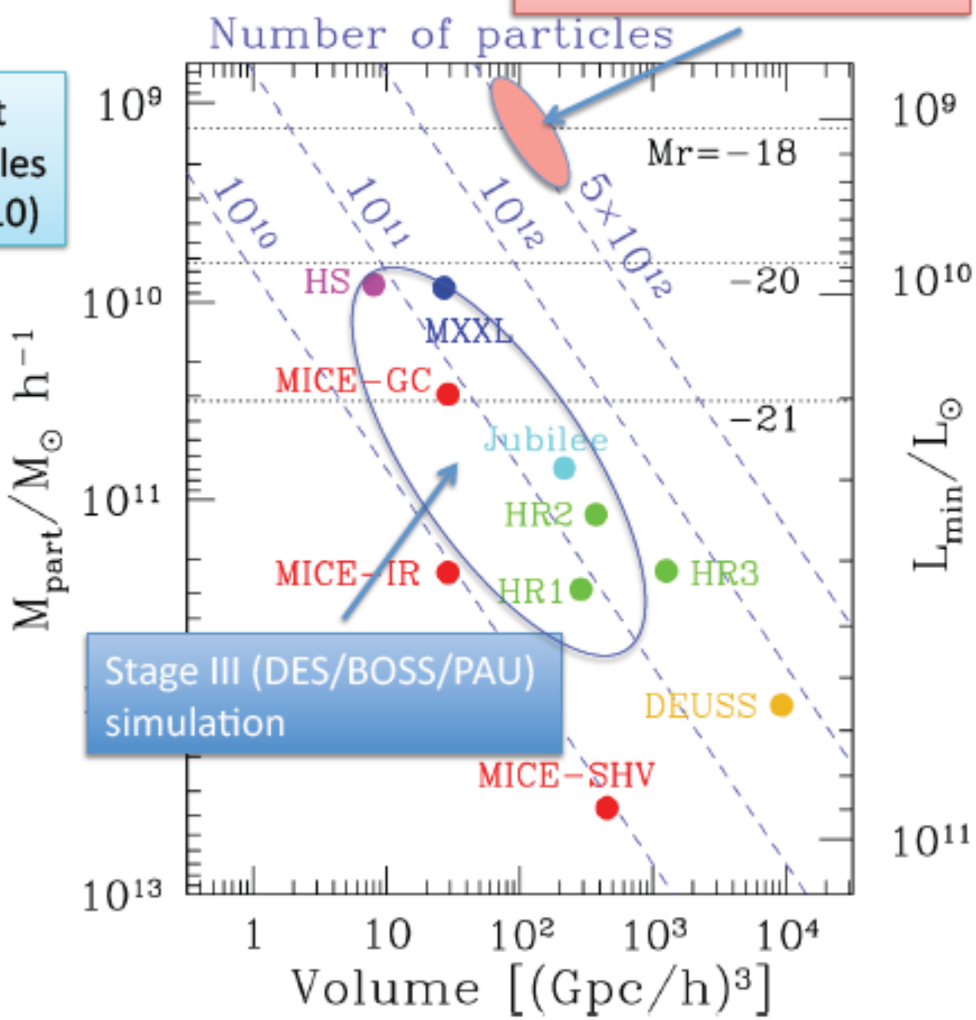
Angulo et al ‘14

State of the art in Nbody simulations

Stage-IV (Euclid/LSST) Simulations

Need to push current limits by at least one order of magnitude in num.particles (larger volumes, fainter galaxies $L_\star$ /10)

MXXL: Angulo et al.
Horizon Sim: Teyssier et al.
MICE: Fosalba et al.
HR1,2,3: Kim et al.
DEUSS: Alimi et al.
Jubilee: Watson et al.



Fundamental Cosmology,
Fuerteventura June 5, 2014

Simulations of Non-standard models

Status: 2012

[source: Marco Baldi]

1. Quintessence and Early DE
2. Inhomogeneous large-voids (LTB)
3. WDM
4. NG initial conditions
5. Massive neutrinos
6. Self-interacting DM
7. Linear spatial DE fluctuations
8. Non-linear spatial DE fluctuations (MG)

complexity

- Nbody codes already developed (green)
- Partially developed (orange)
- Mostly TB developed (red)

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Estimating the PS covariance

Measurements of matter power spectrum → constraints on cosmological parameters

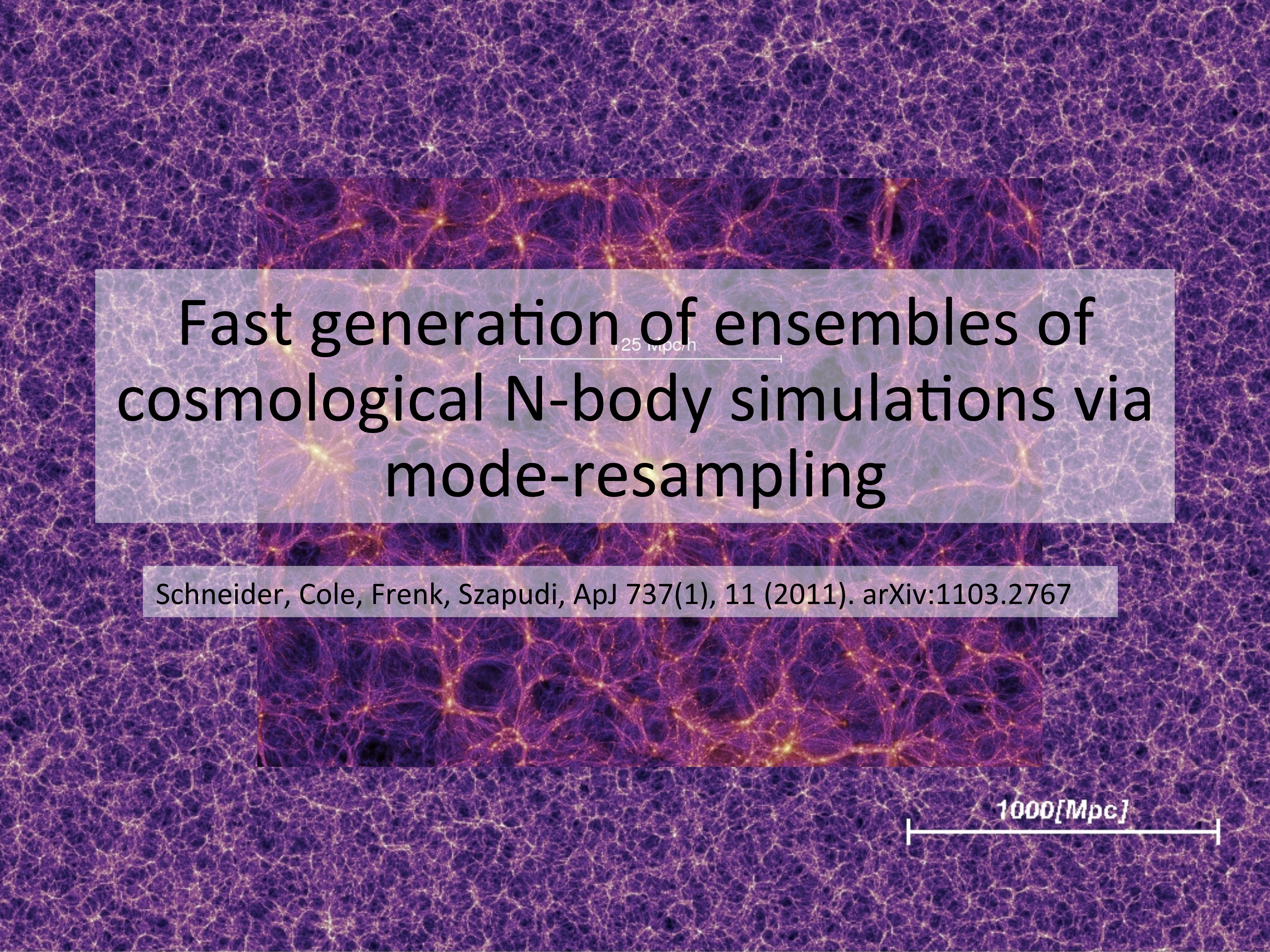
Only if mean power spectrum predicted by the cosmological model and its error distribution are known

→ Need accurate estimates of the PS covariance matrix

Takahashi et al '09 show that for a given cosmology, this can be achieved with… 5000 large N-body simulations!!!

Fast generation of ensembles of cosmological N-body simulations via mode-resampling

Schneider, Cole, Frenk, Szapudi, ApJ 737(1), 11 (2011). arXiv:1103.2767



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Large structure and dark energy

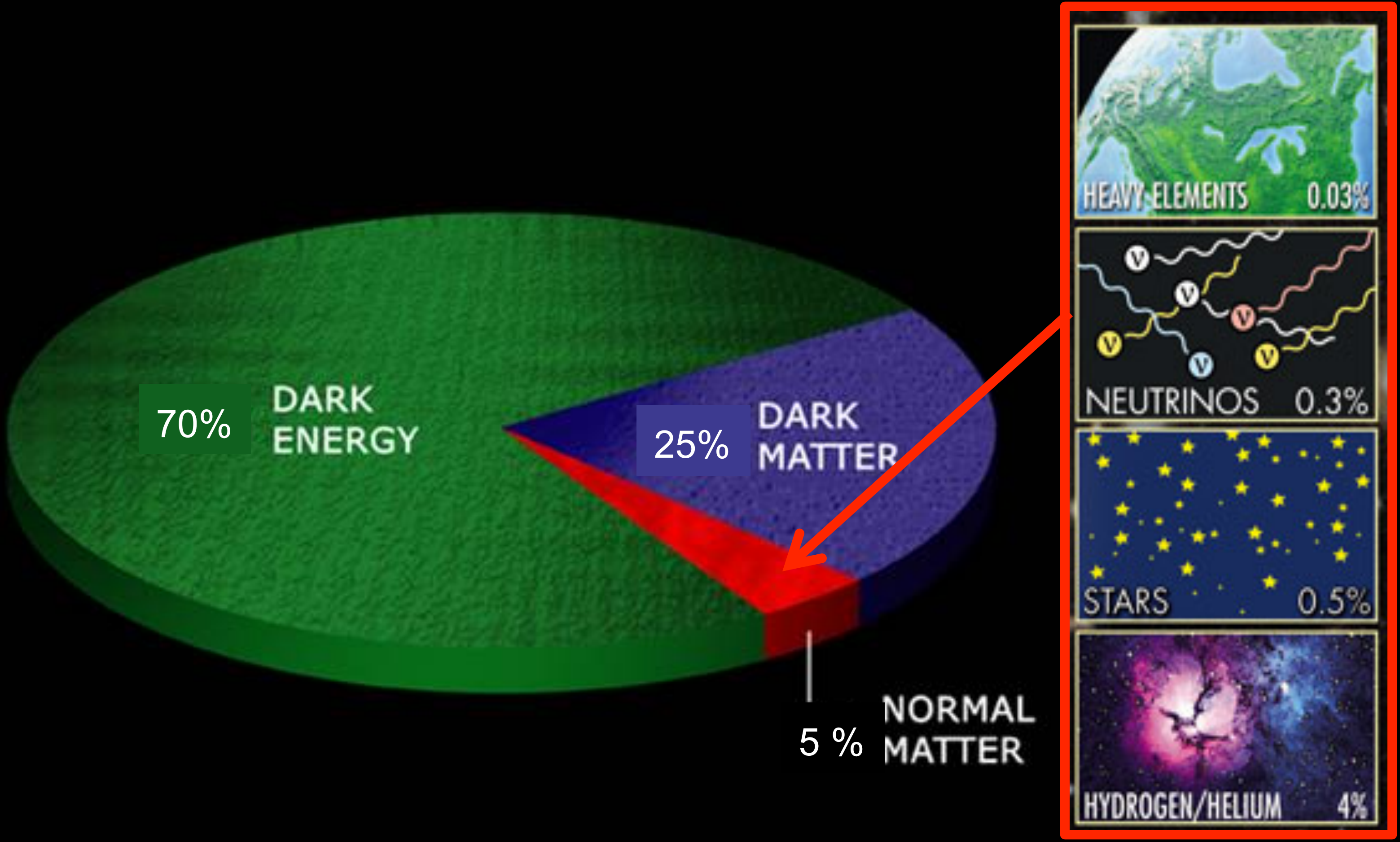
Euclid (and other projects) will measure something (BAOs, RSD, lensing, halo mass fn)

However, these measurements will be meaningless without a proper theoretical basis

Linear theory/perturbation theory completely inadequate

→ This requires a concerted programme of large-scale simulations

The content of our universe



VIRGO

The "Evolution and assembly of galaxies and their environment" (EAGLE) simulation project

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…

+ Virgo Consortium

NAM 2014

DiRAC

ICC Institute for Computational Cosmology

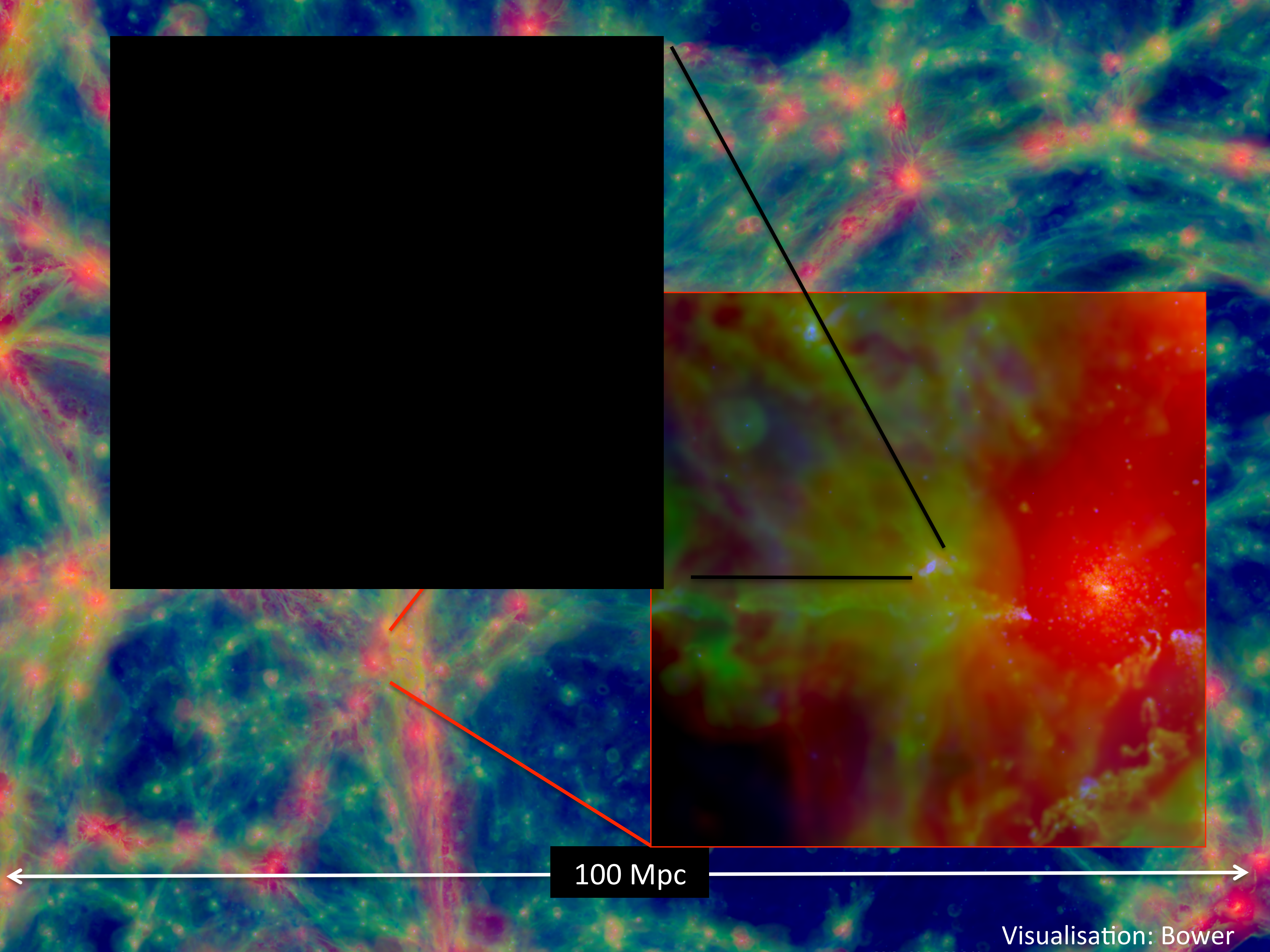
PRACE

EAGLE: Evolution and Assembly of GaLaxies and their Environments

- Anarchy-SPH (Gadget-3) + Planck Cosmology
- Resolution 10^6 solar masses
- 25, 50 and 100 Mpc boxes
- Subgrid physics
  - Star formation
  - Cooling
  - Chemical evolution
  - Stellar feedback -> thermal
  - AGN feedback -> ang. mom.
- Evolution to z= 0

← 20 Mpc →

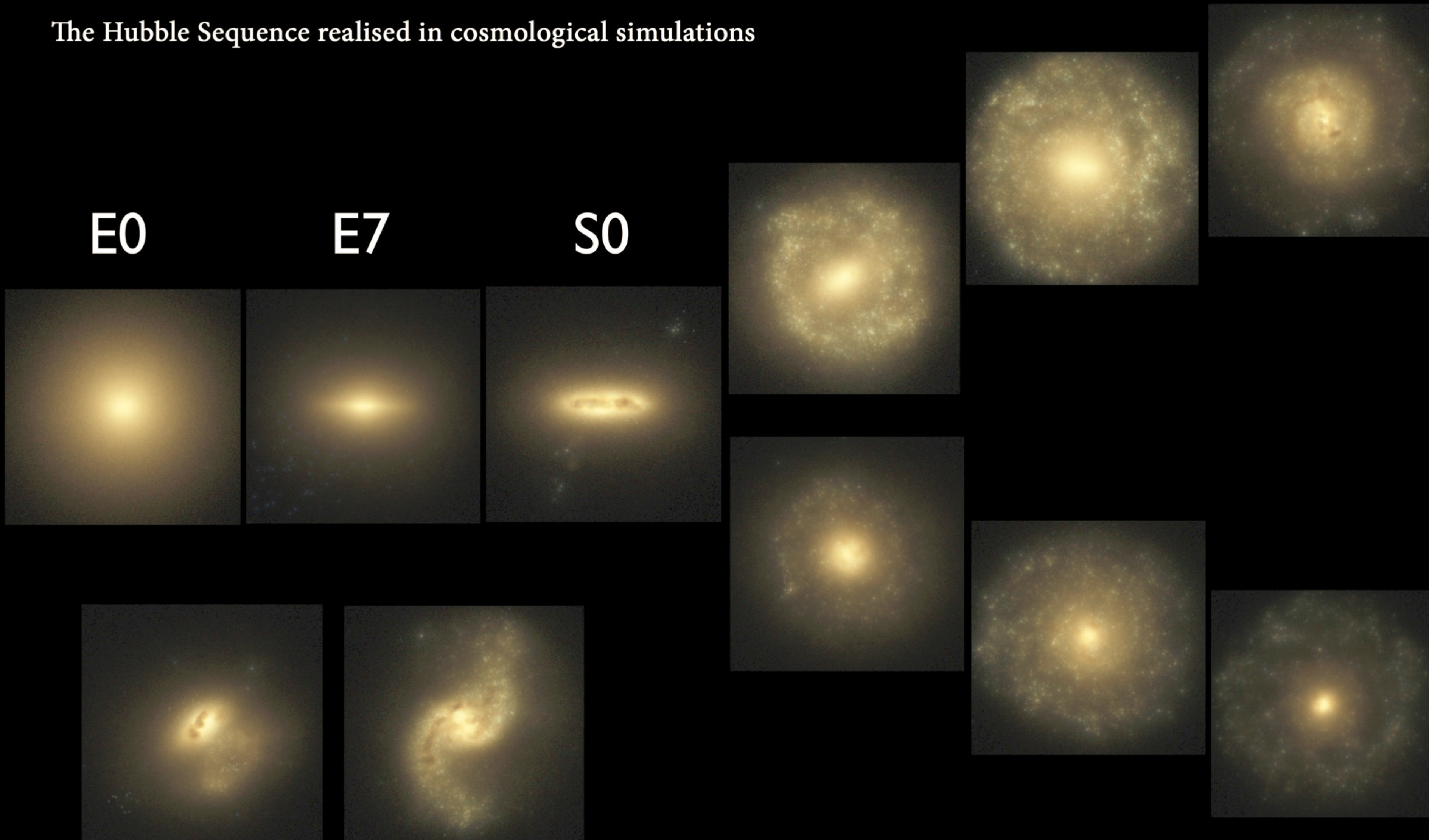
This is is only 1/8000 of the total volume


100 Mpc
Visualisation: Bower

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

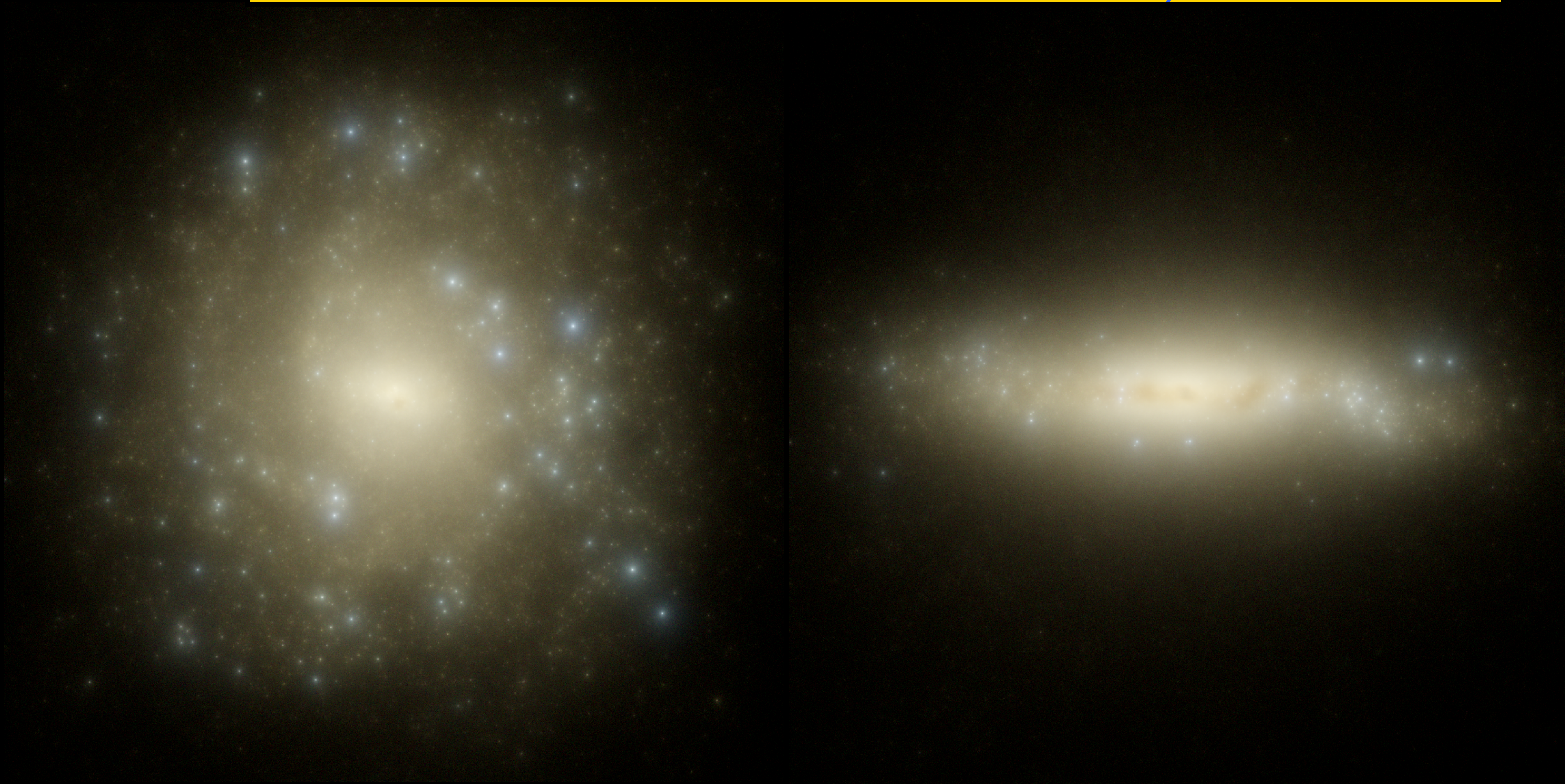
The Hubble Sequence realised in cosmological simulations



Trayford/Baes

Hydrodynamic simulations

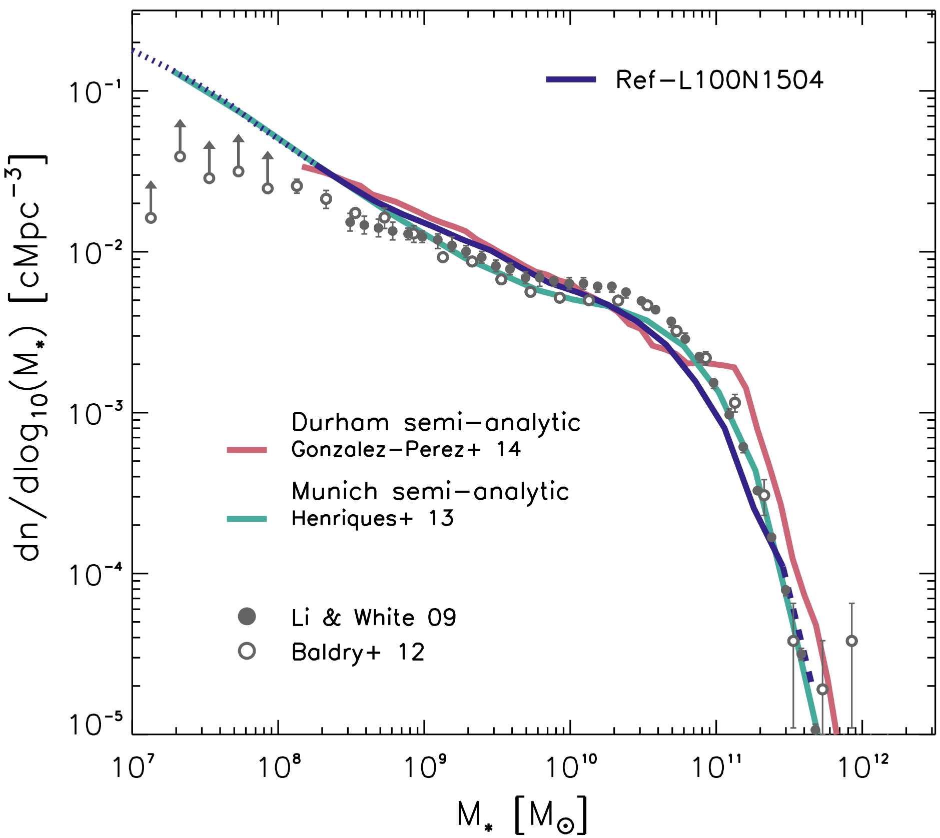
Eagle (Evolution and Assembly of galaxies and their environment)

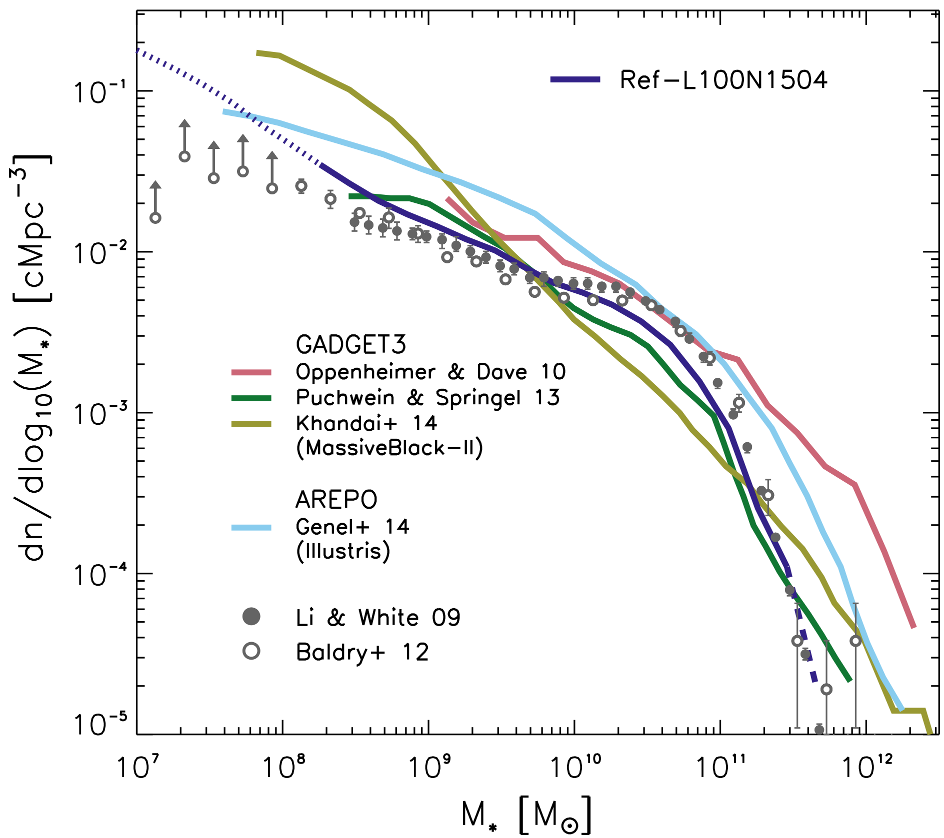


Virgo consortium – Schaye et al ’14; Sawala et al ‘14

Institute for Computational Cosmology

EAGLE compared to other models

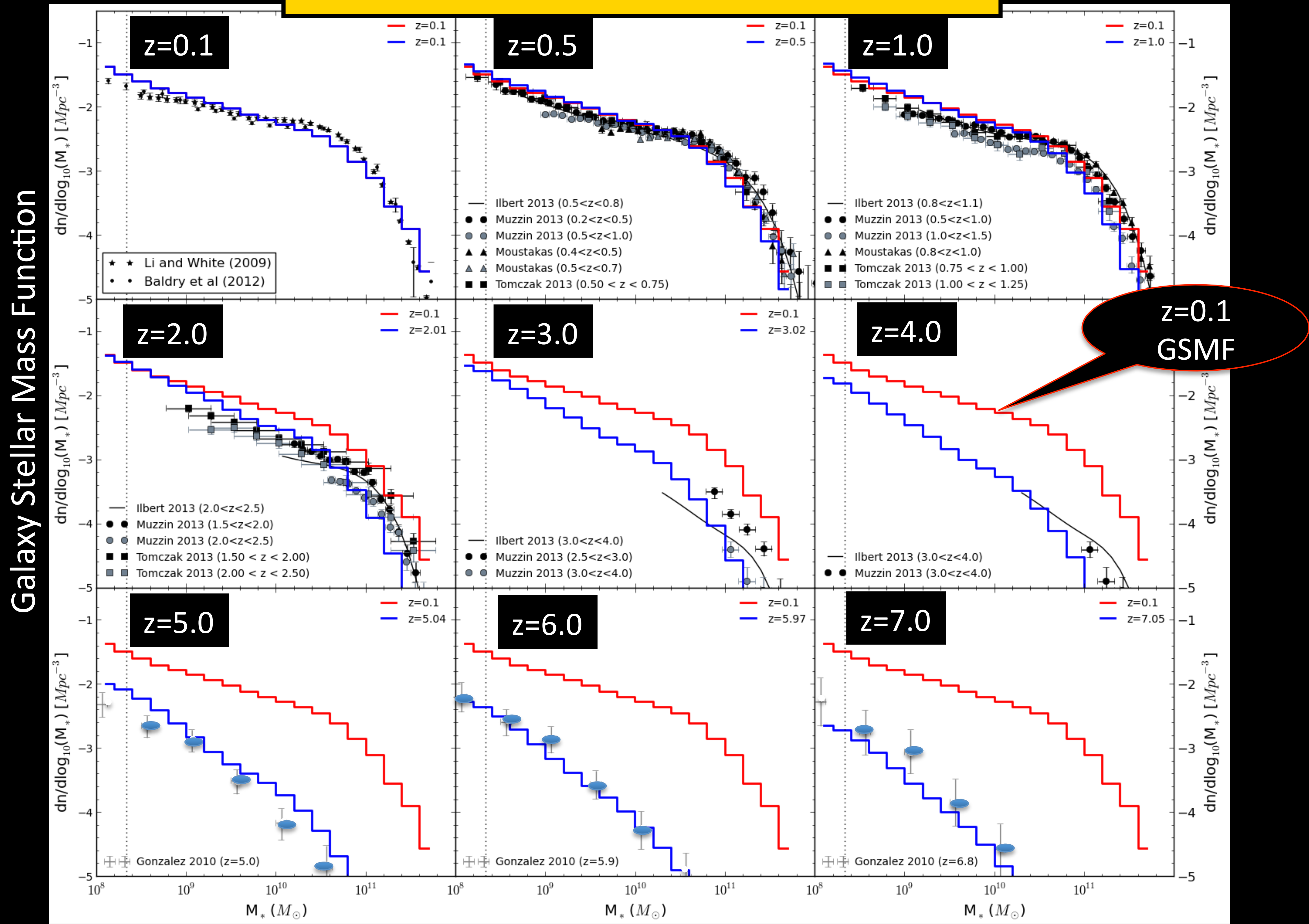




Semi-analytic models

Hydrodynamic simulations

Evolution of the mass function



EAGLE full hydro simulations

Local Group

Sawala et al ‘14

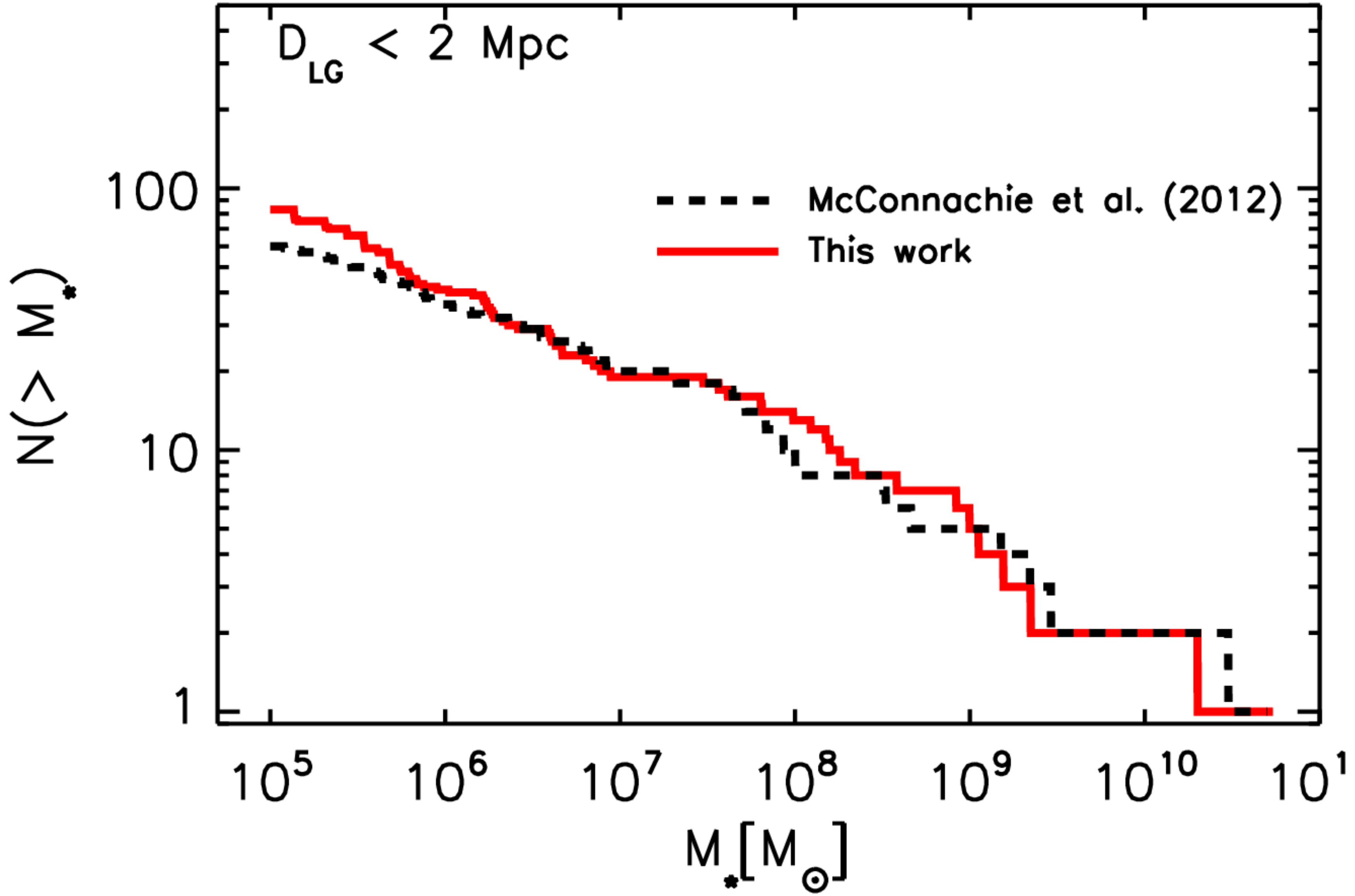
The ‘’satellite problem’’ in CDM is a myth!

EAGLE full hydro simulations

Local Group

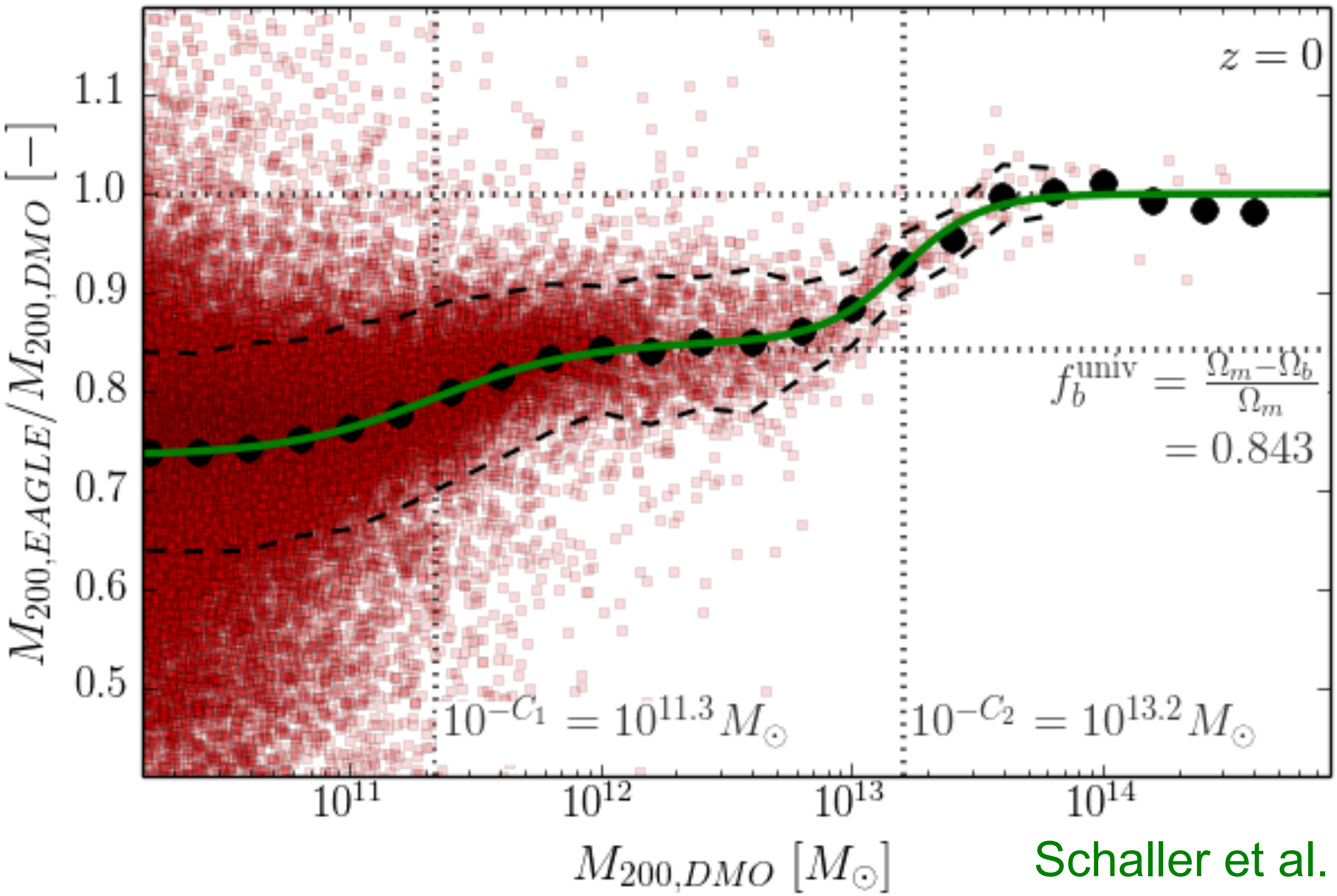
Sawala et al ‘14

The stellar mass fn in the Local Group



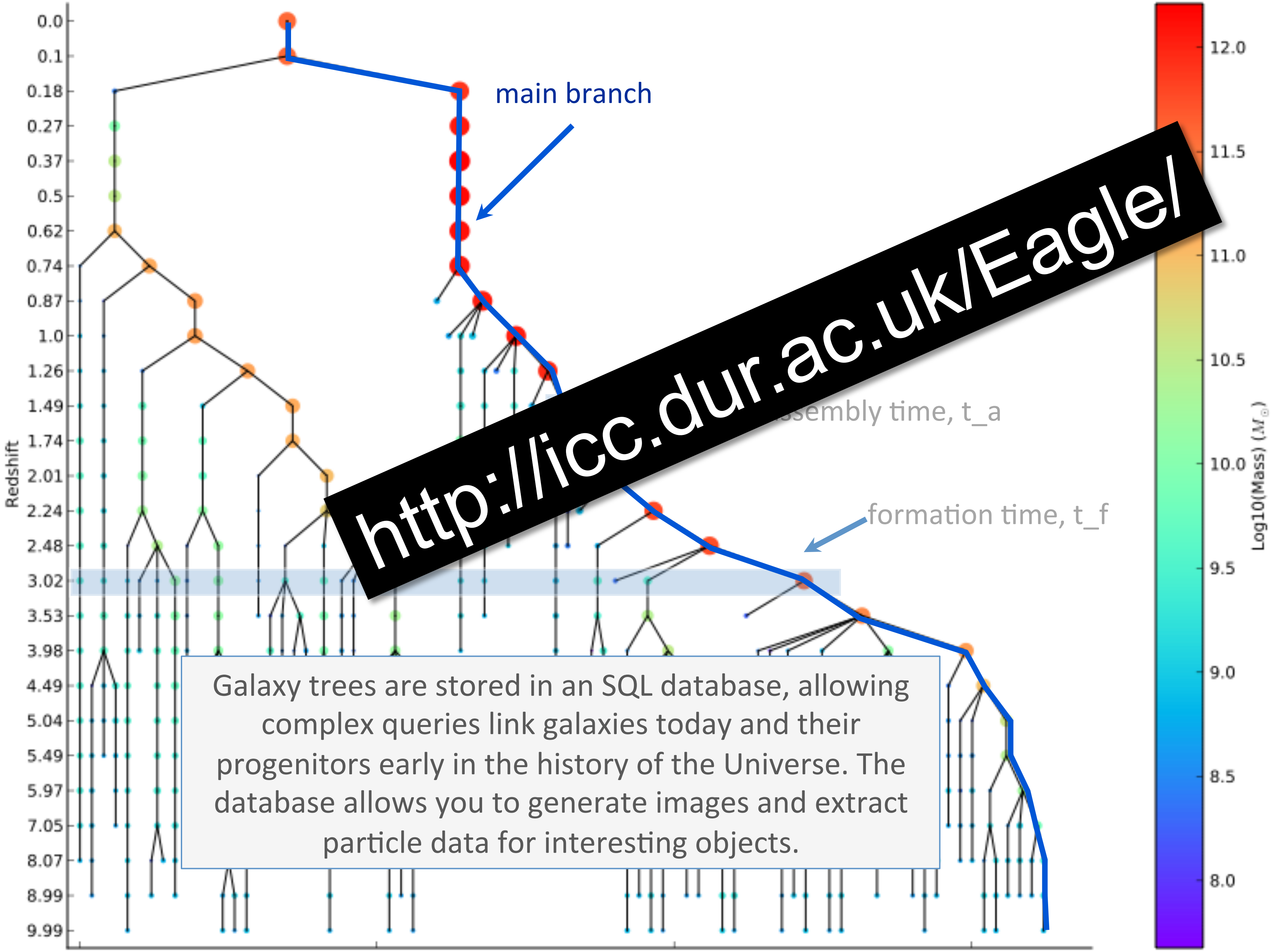
Baryon effects: halo masses

Average modification of halo masses as a function of mass



Schaller et al. '14

See also Sawala et al. '12, '14



http://icc.dur.ac.uk/Eagle/

Galaxy trees are stored in an SQL database, allowing complex queries link galaxies today and their progenitors early in the history of the Universe. The database allows you to generate images and extract particle data for interesting objects.

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Conclusions: computational challenges in cosmology

The need for exoscale computing

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Conclusions: computational challenges in cosmology

What can we do with a machine that is 500xCOSMA-5?

25PB RAM w 8 GB/core; 3.5M core

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Conclusions: computational challenges in cosmology

What can we do with a machine that is 500xCOSMA-5?

25PB RAM w 8 GB/core; 3.5M core

1. DARK MATTER DISCOVERY

Resolve Earth mass in CDM simulations (in special regions

> Accurate predictions for annihilation/decay radiation

> Accurate predictions for direct detection (new halo model)

> Predictions for alternative models: WDM, SIDM, etc

➔ Essential to guide searches and interpret any signal

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Conclusions: computational challenges in cosmology

What can we do with a machine that is 500xCOSMA-5?

25PB RAM w 8 GB/core; 3.5M core

2. DARK ENERGY AND LARGE-SCALE STRUCTURE

MXXL with 10x Millennium resolution: to be populated with semi-analytic galaxies or HoD (6PB RAM; 1EB data)

- Accurate predictions for new generation of surveys (Euclid, etc): BAO, RSD, lensing, halo mass fn …
- Explore different DE models
- Compute covariance matrix with sufficient accuracy

➔ Essential to interpret data from Euclid and other surveys

Conclusions: computational challenges in cosmology

University of Durham

What can we do with a machine that is 500xCOSMA-5?

25PB RAM w 8 GB/core; 3.5M core

3. GALAXY FORMATION

EAGLE in 750 Mpc cube (25PB RAM); Local Group :m_{gas}= 10 M_o

> Accurate characterization of gal pop at all epochs: CDM, WDM

> Interpret data from ALMA, JWST, SKA, etc

> Effects of baryons on halo structure and large-scale structure

➔ Essentiall for DM searches, DE and galaxy surveys