# The 2011 Gruber Cosmology Prize

Marc Davis
George Efstathiou
Carlos Frenk
Simon White

# Chapter 1 – Surveying the Universe

Marc Davis

Berkeley 1981

# Redshift Surveys

## key to understanding structure in the Universe

- Original CfA1 Survey:
  - *1.5m telescope, Mt Hopkins ~200 nights over ~2 years*
  - *Survey measured ~2000 redshifts at rate ~25/clear night*
  - *I came to Berkeley so Simon & I could work together on its interpretation*

- CfA1 results:
  - told us about filamentary structure of the galaxy distribution.
  - was a big surprise to the Astrophysics community and motivated numerical simulations of LSS

- Simon & I hired Carlos Frenk as a new postdoc, and we got the best code and code master, George Efstathiou, to work with us

- Thus the ‘Gang of 4’ was born!

# DEFW

# How to understand what redshift surveys are telling us?

o. 2, 1982 GALAXY REDSHIFTS

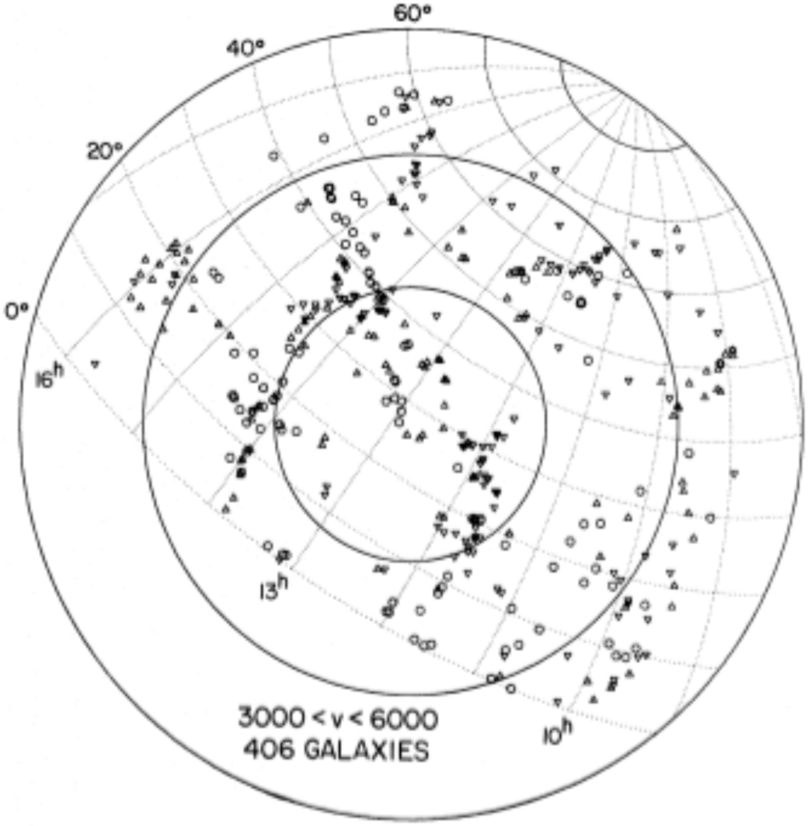


FIG. 2$b$.—Same as Fig. 2$a$ for galaxies in the range $3000 < v < 6000$ km s$^{-1}$, again selecting only objects with $M < -18.5$

CfA1 survey (1982) over Northern hemisphere. The 1st redshift survey

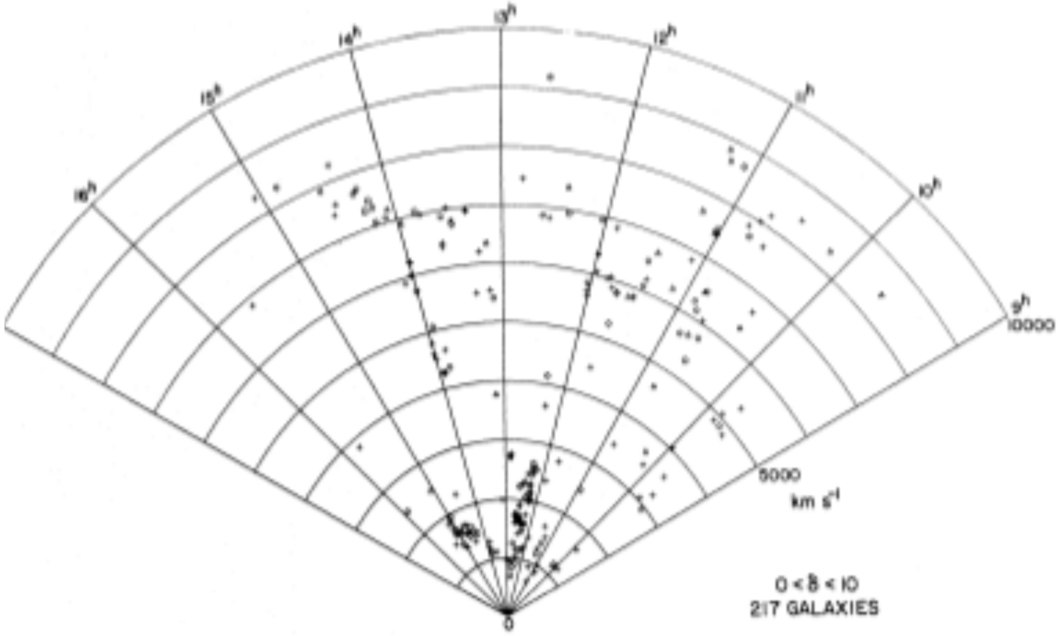


FIG. 4$a$.—A transverse map of the northern cap survey with observed velocity plotted versus right ascension for different wedges of declination. Compare to Fig. 2 for orientation. All galaxies shown are selected to have $M < -18.5$ and are in the velocity range $0 < v < 10{,}000$ km s$^{-1}$. The different symbols denote morphological type generally as listed by Nilson (1973). Circles are ellipticals, diamonds denote SOs, pluses are spirals, and triangles are irregulars. This figure shows the declination wedge $0 < \delta < 10°$.

# Early N-body simulation

982 GALAXY REDSHIFTS

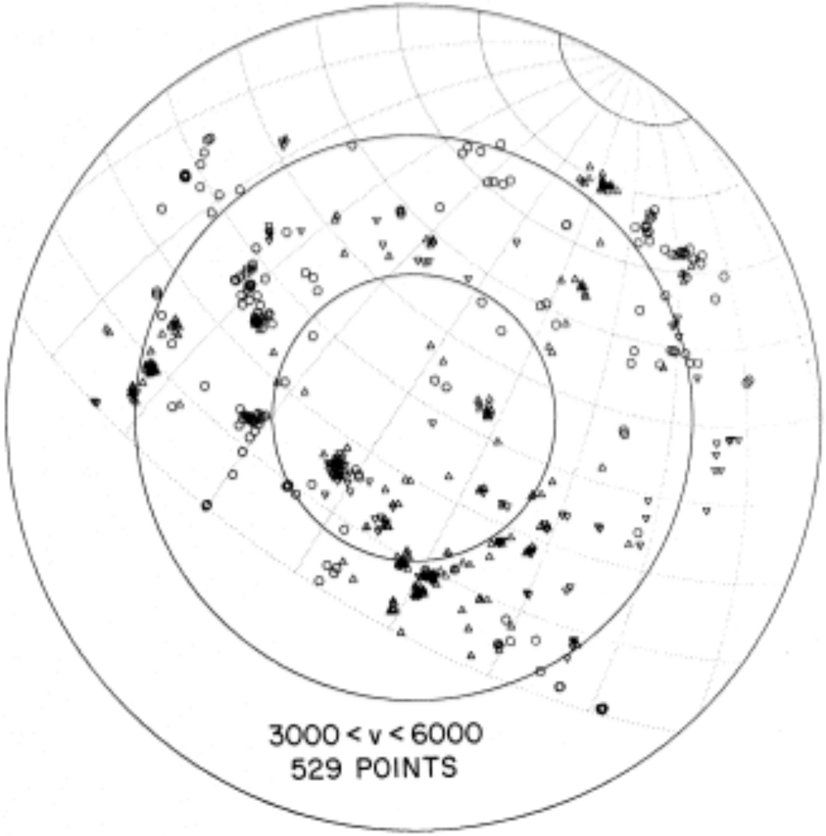
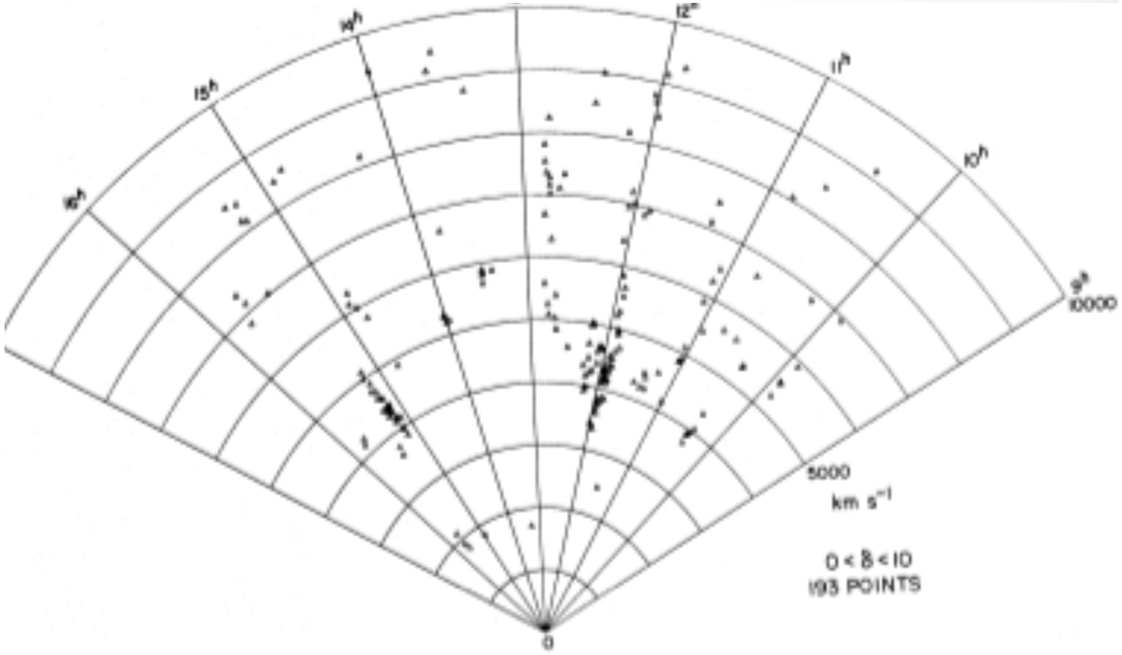


FIG. 6c.—Same as Fig. 6a for points in the range 3000 < v < 6000 km s$^{-1}$

20,000 particle, n=-1 power law simulation, (Efstathiou & Eastwood, 1981)

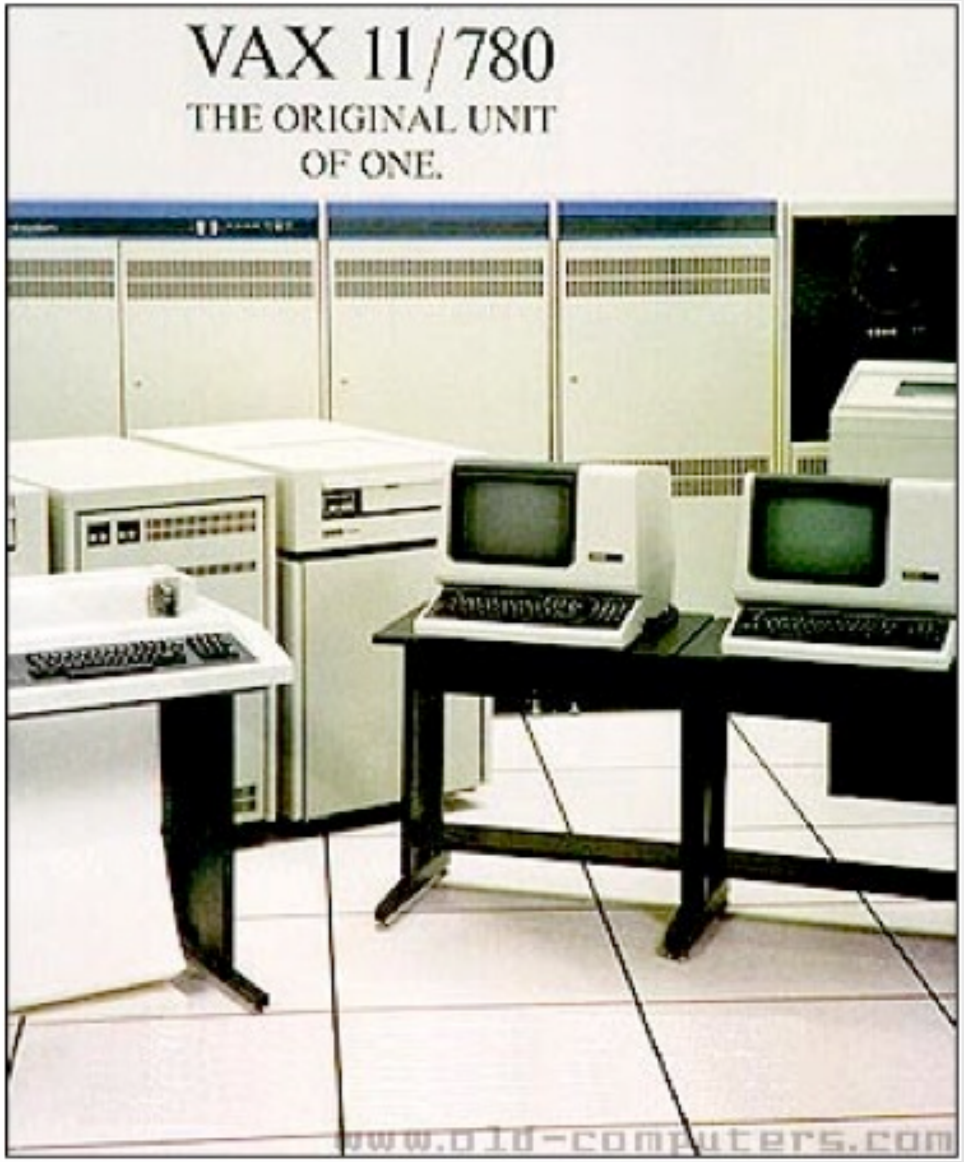
Prior to the invention of inflationary cosmology by Linde & Guth, this was about as good initial conditions as could be devised



# Computer of 1980's

- 4 Mbytes RAM, ~2 Mb useable
- 1 processor ~1 Mhz
- required a cooled room to house lots of racks of memory and hard disks
- weight ?? several thousand kilos.

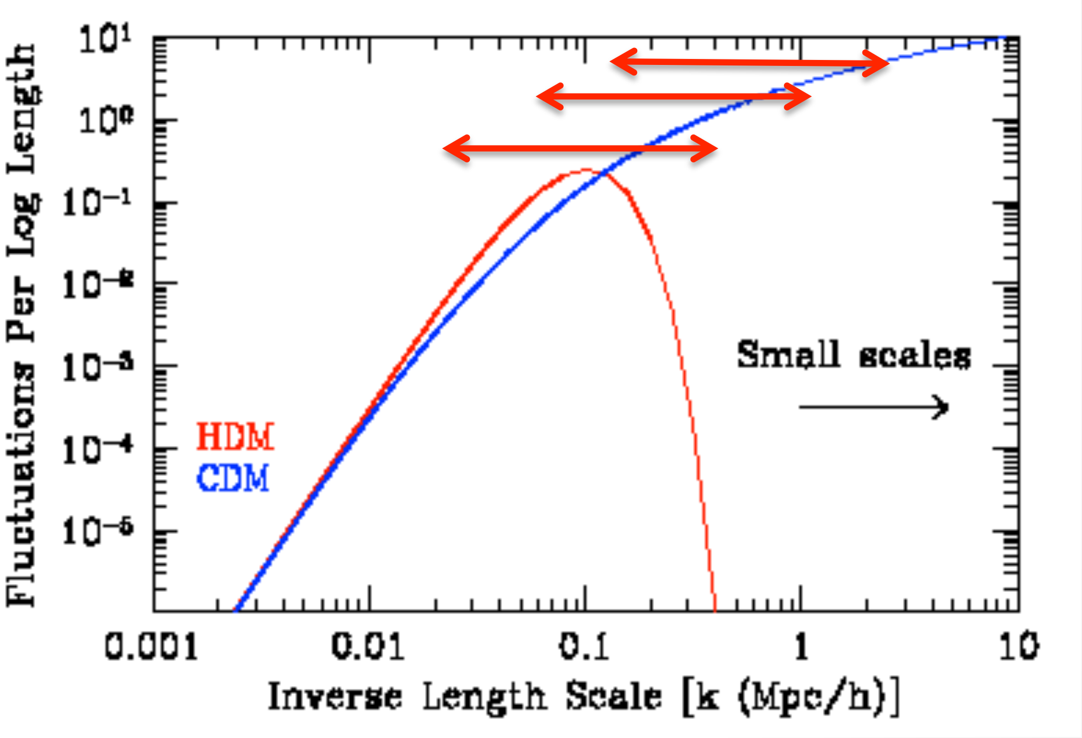
- This was the ONLY computer in the department, and we wanted >50% of computation time for >6 months
- Devise backups every day in case system crashed



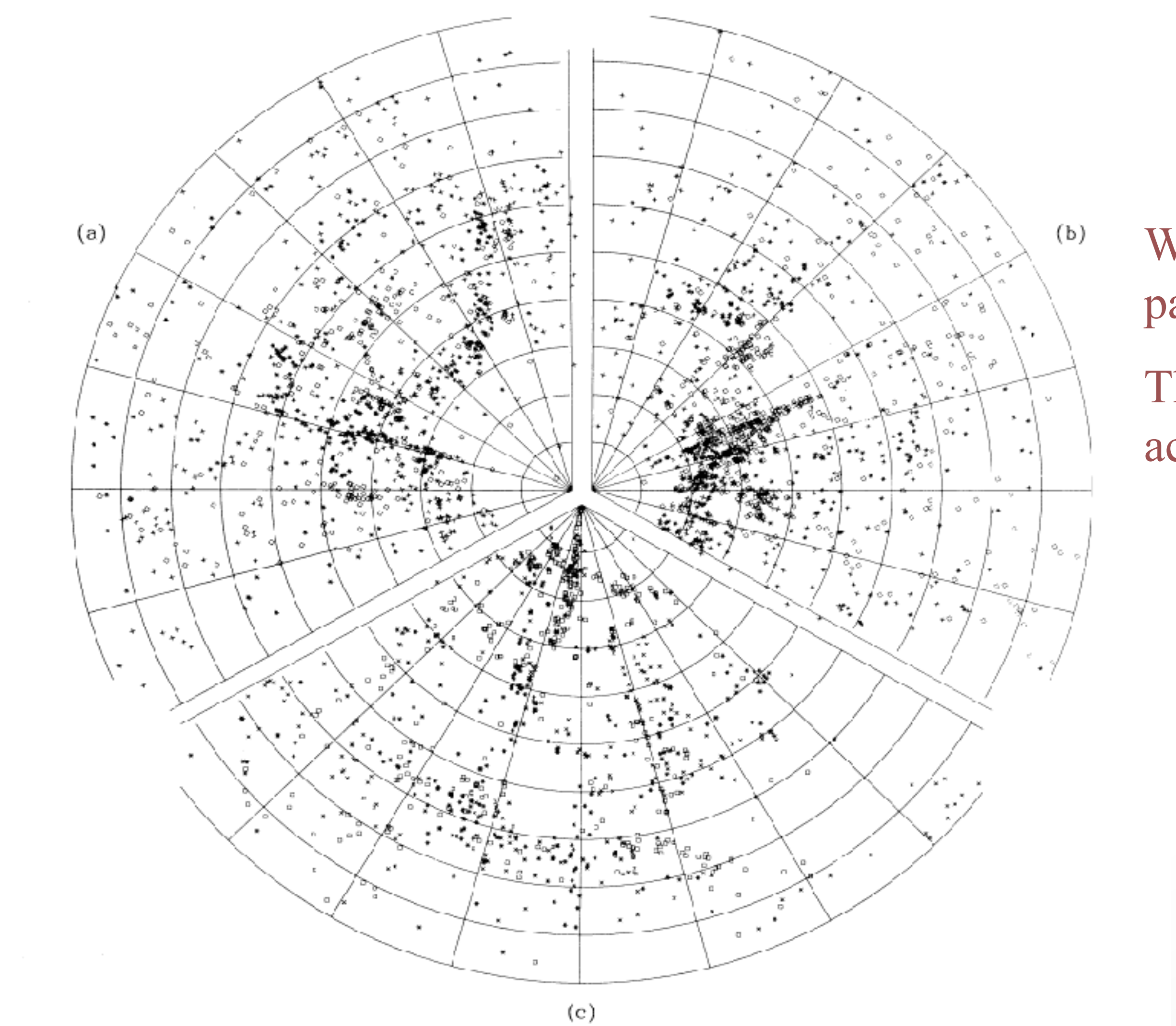
# Getting ready for large simulations

## How to specify initial conditions?

- $32^3$ particles allowed specification of 16 waves in each direction.
- Needed to understand how to use Zel'dovich method for specification of $\delta_k$ and $v_k$. This was critical, and we were unaware of anyone using this method. Method published in 1983.
- The VAX was going to take ~3 months per run, so we had to be careful. (mistake in a Fortran common statement!)



# CfA1 survey results & simulations by DEFW

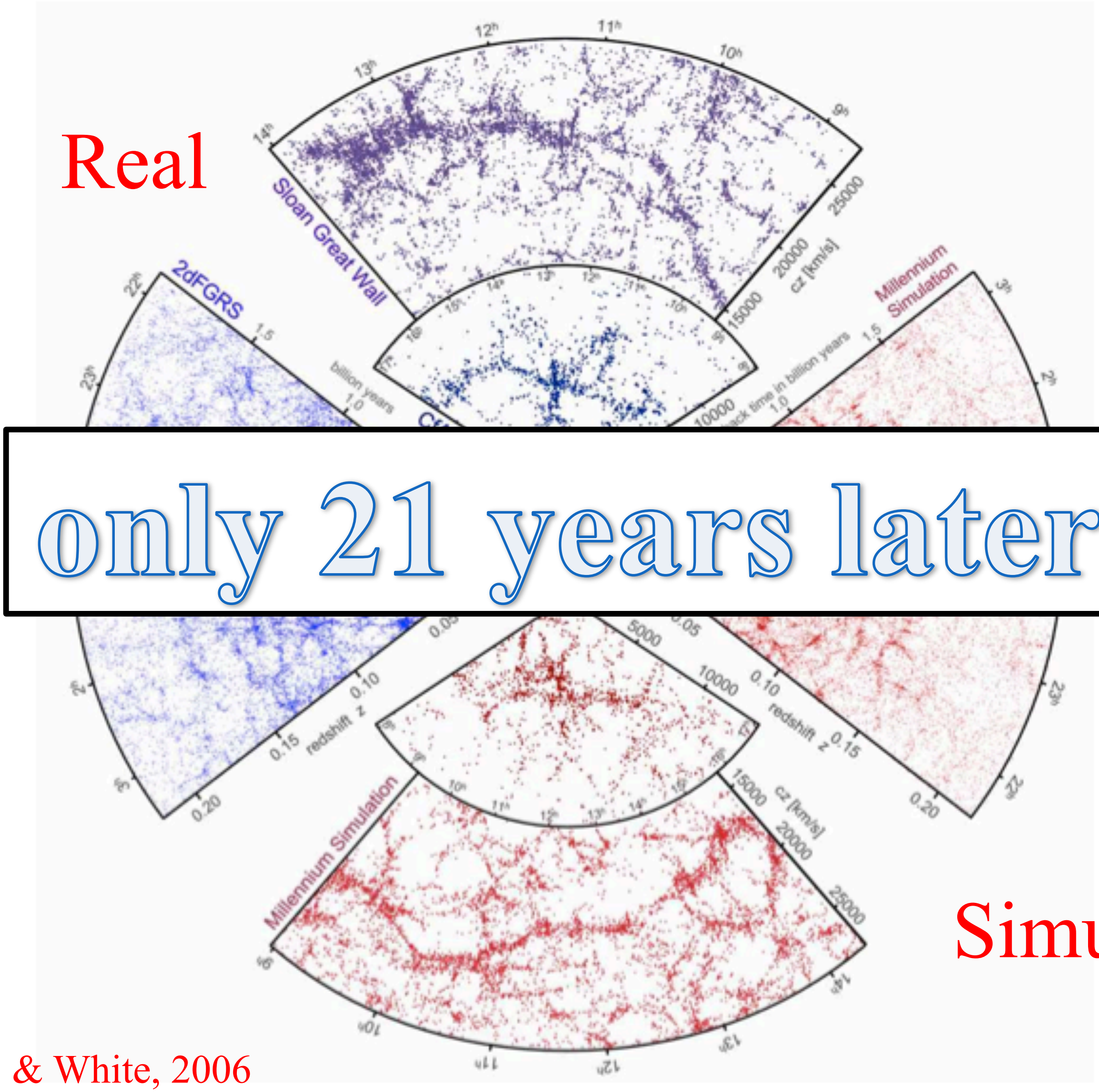


Which is the real sky ($32^3$ particles) ??

The birth of CDM, but was actually ΛCDM (1985).

# Simulations Compared to Data, 2006

Real



only 21 years later

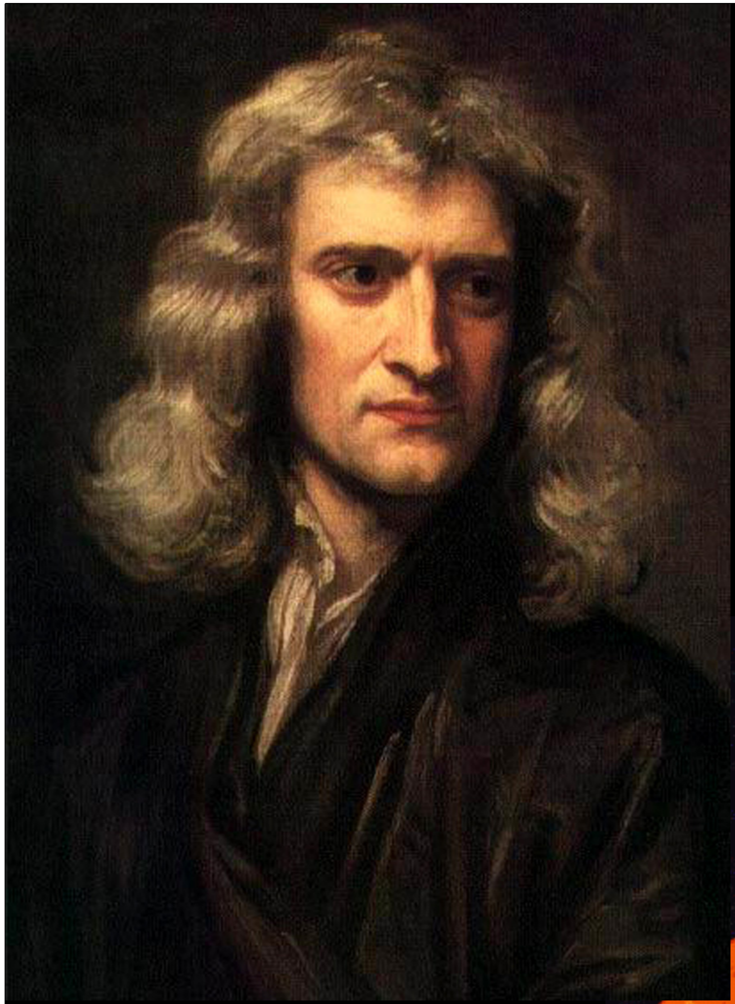
Simulation

Springel, Frenk, & White, 2006

# Chapter 2 – N-body simulations

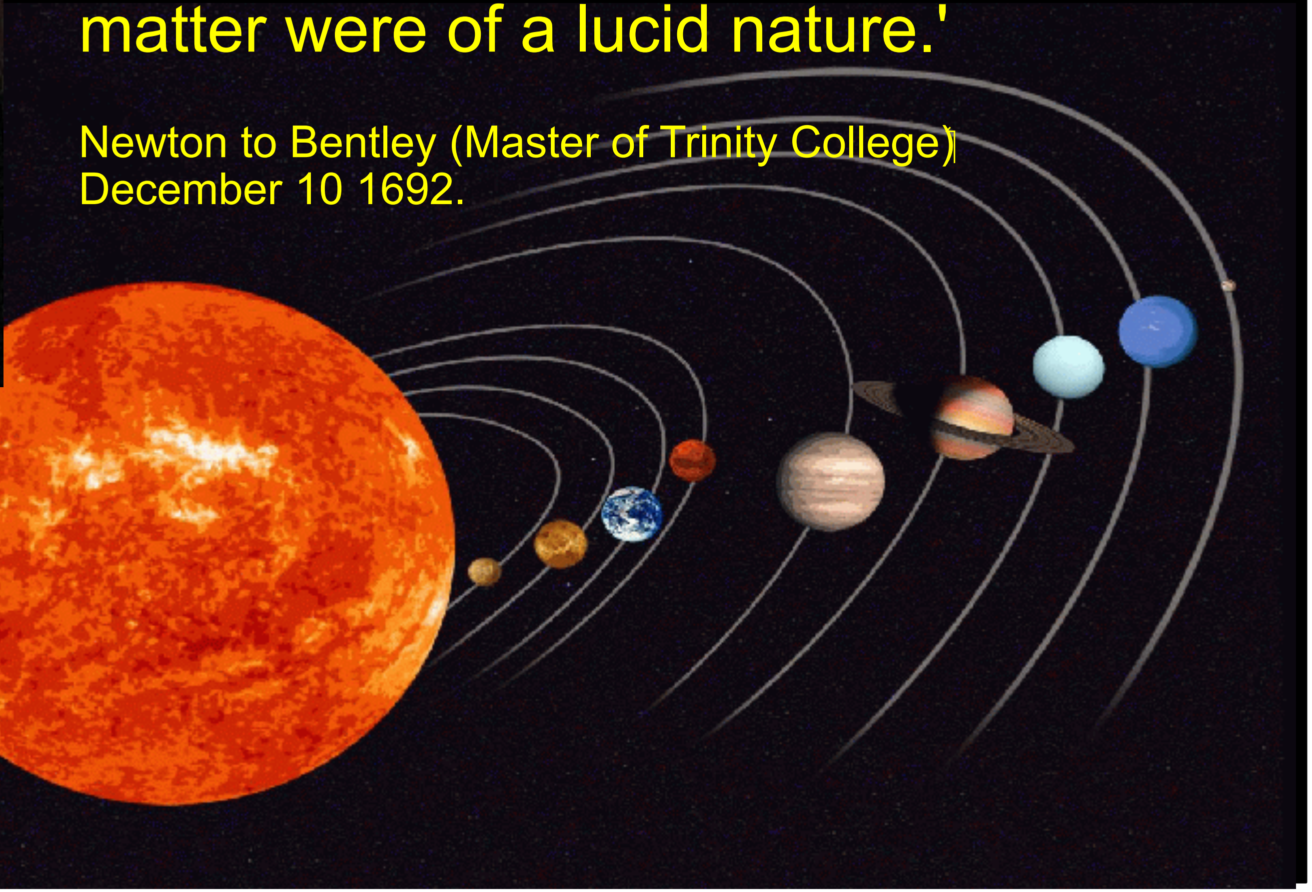
George Efstathiou

Berkeley 1981

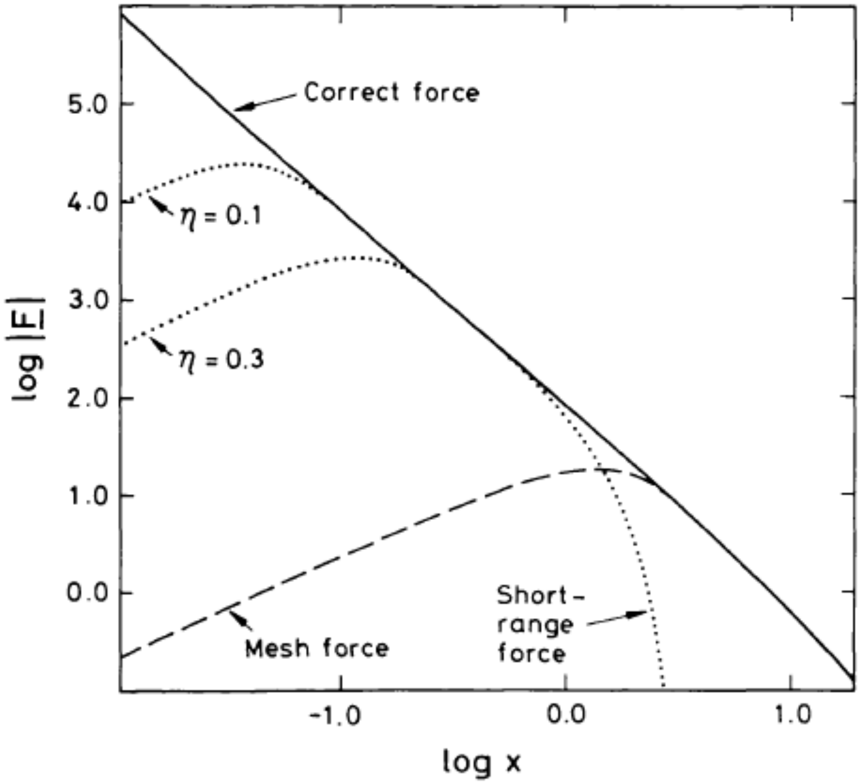


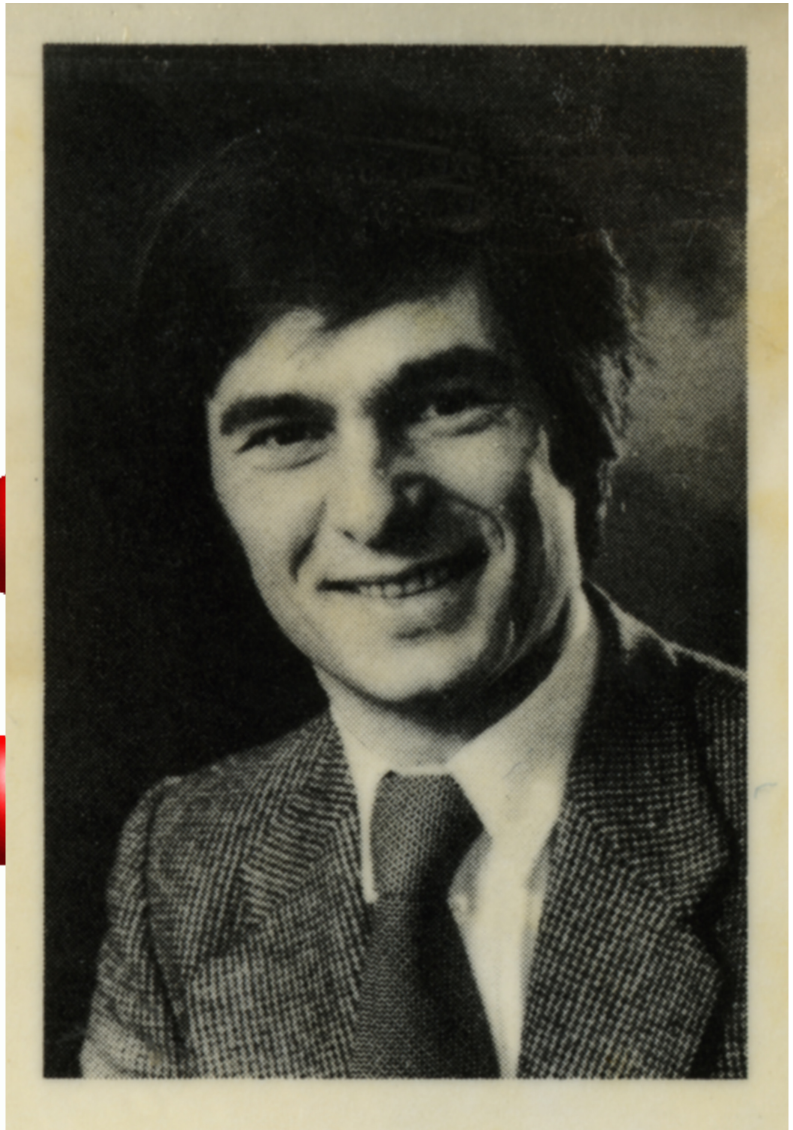
`But if the matter were evenly disposed thoughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another ....... And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.'

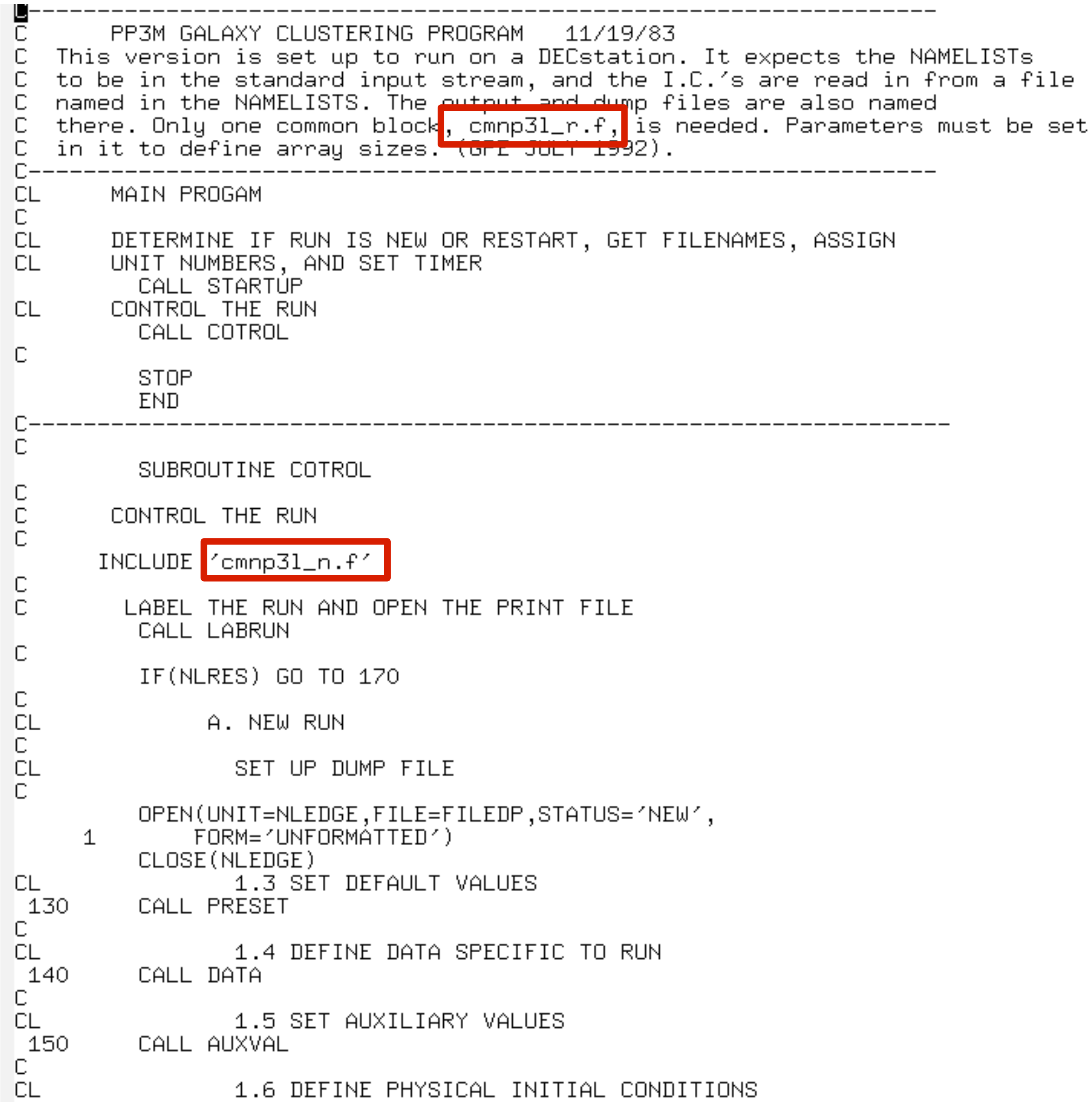
Newton to Bentley (Master of Trinity College)
December 10 1692.



$$\underline{\mathbf{F}}_{ij} = -\frac{G m_i m_j (\underline{\mathbf{x}}_i - \underline{\mathbf{x}}_j)}{|\underline{\mathbf{x}}_i - \underline{\mathbf{x}}_j|^3}$$

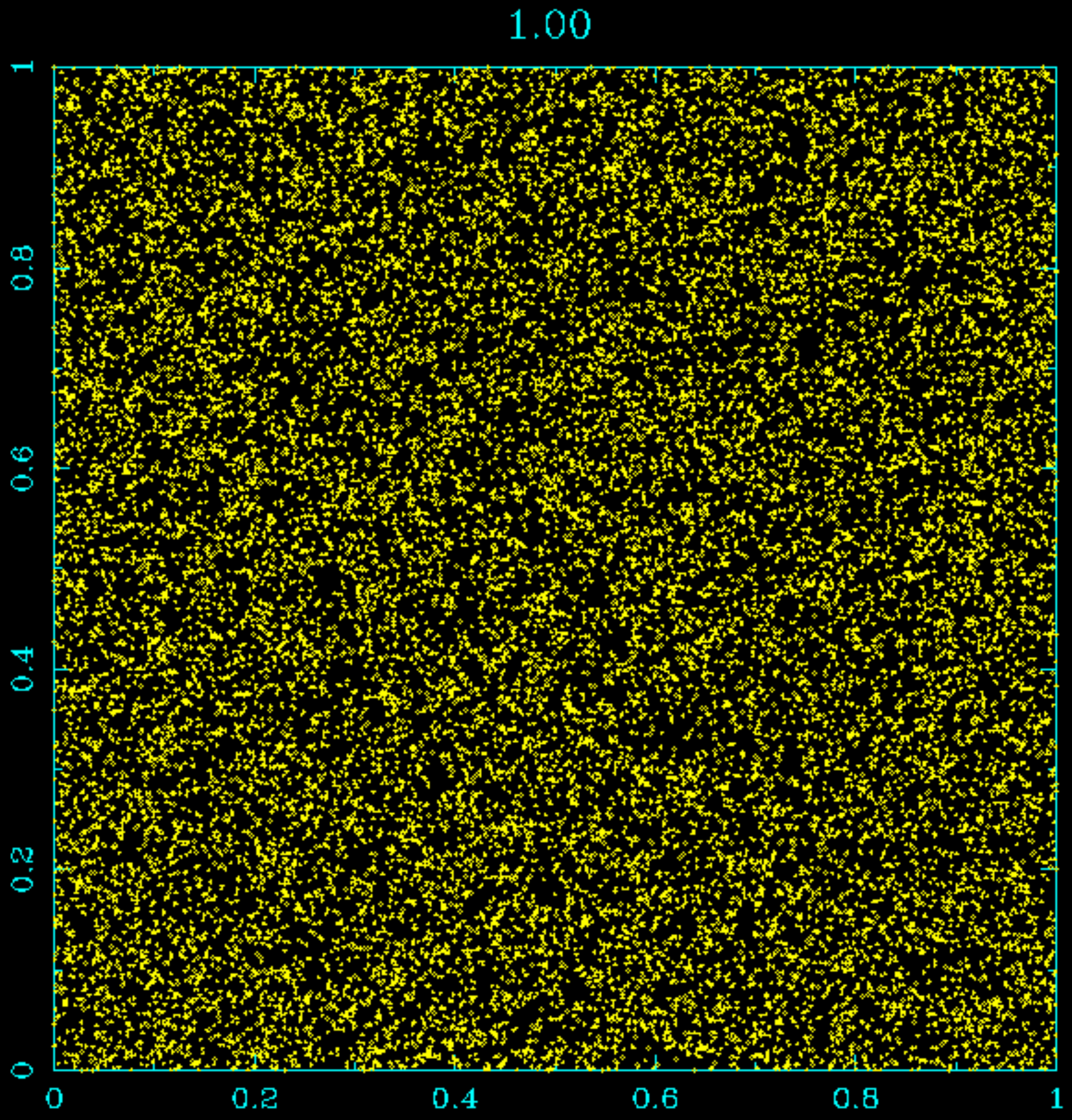






```
C------------------------------------------------------------------
C       PP3M GALAXY CLUSTERING PROGRAM   11/19/83
C   This version is set up to run on a DECstation. It expects the NAMELISTs
C   to be in the standard input stream, and the I.C.'s are read in from a file
C   named in the NAMELISTS. The output and dump files are also named
C   there. Only one common block, cmnp3l_r.f, is needed. Parameters must be set
C   in it to define array sizes. (GPE JULY 1992).
C------------------------------------------------------------------
CL      MAIN PROGAM
C
CL      DETERMINE IF RUN IS NEW OR RESTART, GET FILENAMES, ASSIGN
CL      UNIT NUMBERS, AND SET TIMER
          CALL STARTUP
CL      CONTROL THE RUN
          CALL COTROL
C
          STOP
          END
C-------------------------------------------------------------------
C
          SUBROUTINE COTROL
C
C       CONTROL THE RUN
C
       INCLUDE 'cmnp3l_n.f'
C
C        LABEL THE RUN AND OPEN THE PRINT FILE
          CALL LABRUN
C
          IF(NLRES) GO TO 170
C
CL              A. NEW RUN
C
CL                SET UP DUMP FILE
C
          OPEN(UNIT=NLEDGE,FILE=FILEDP,STATUS='NEW',
     1        FORM='UNFORMATTED')
          CLOSE(NLEDGE)
CL                1.3 SET DEFAULT VALUES
 130      CALL PRESET
C
CL                1.4 DEFINE DATA SPECIFIC TO RUN
 140      CALL DATA
C
CL                1.5 SET AUXILIARY VALUES
 150      CALL AUXVAL
C
CL                1.6 DEFINE PHYSICAL INITIAL CONDITIONS
```


NO SMOKING
ICL



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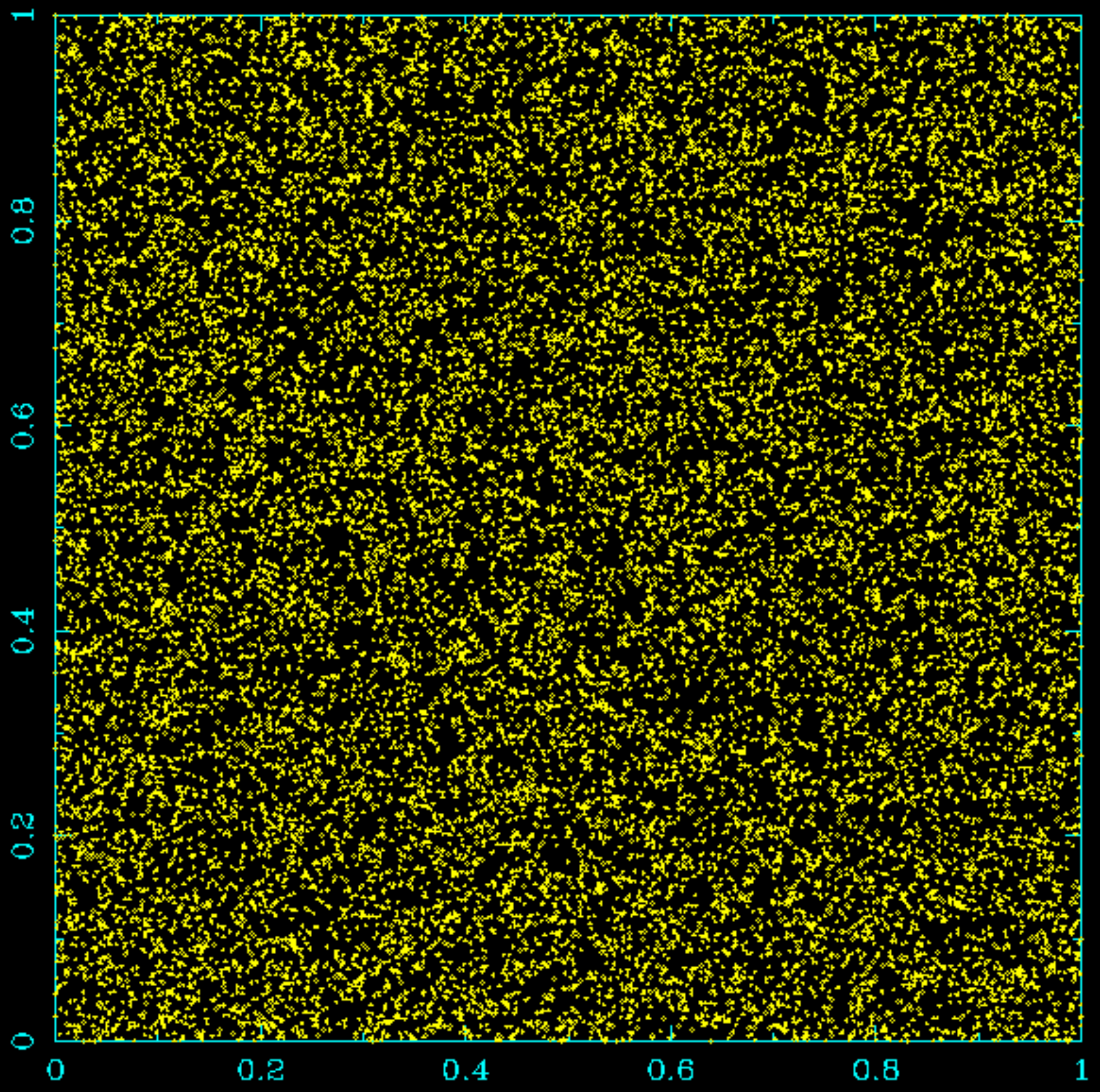

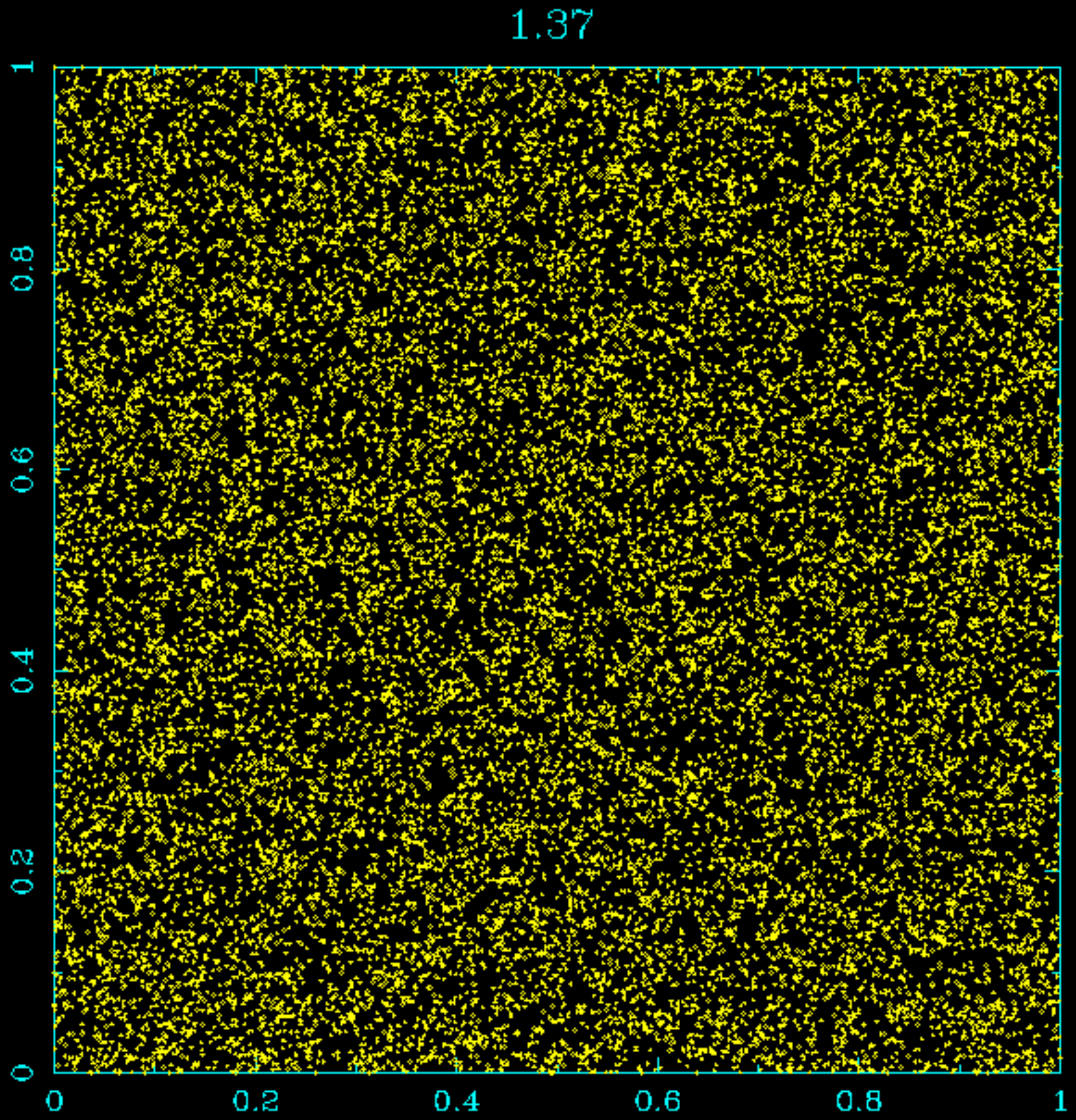
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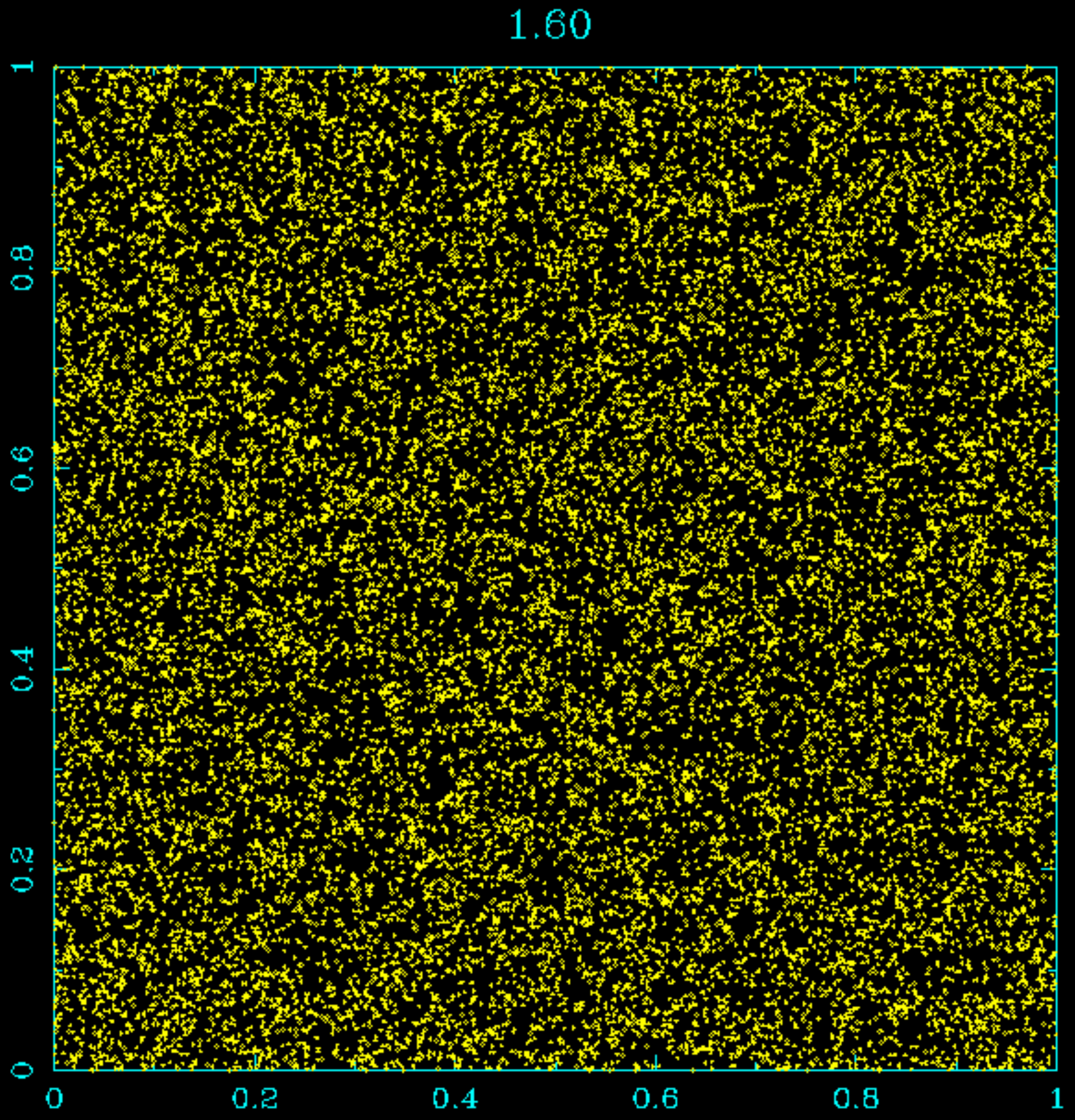
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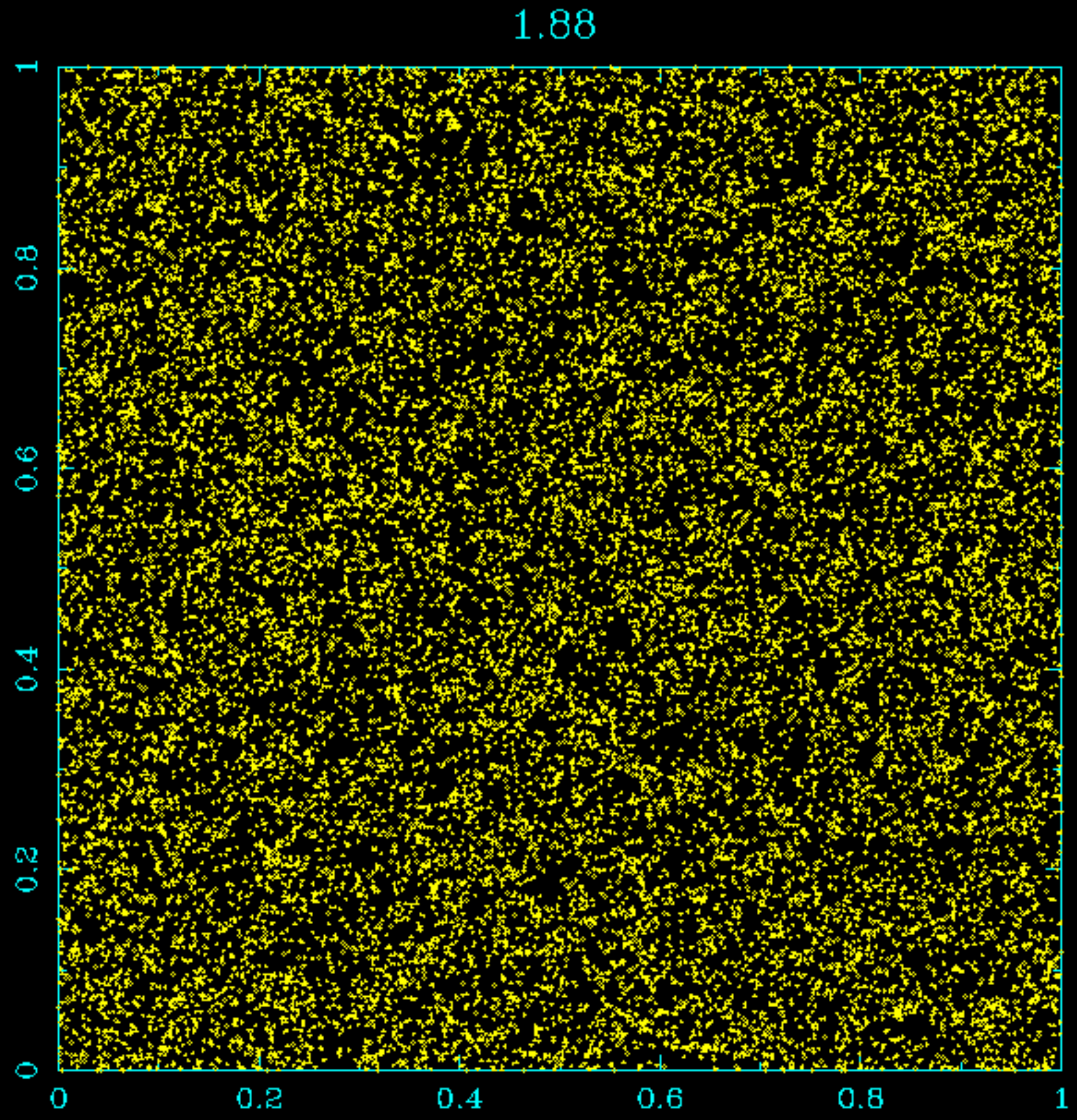
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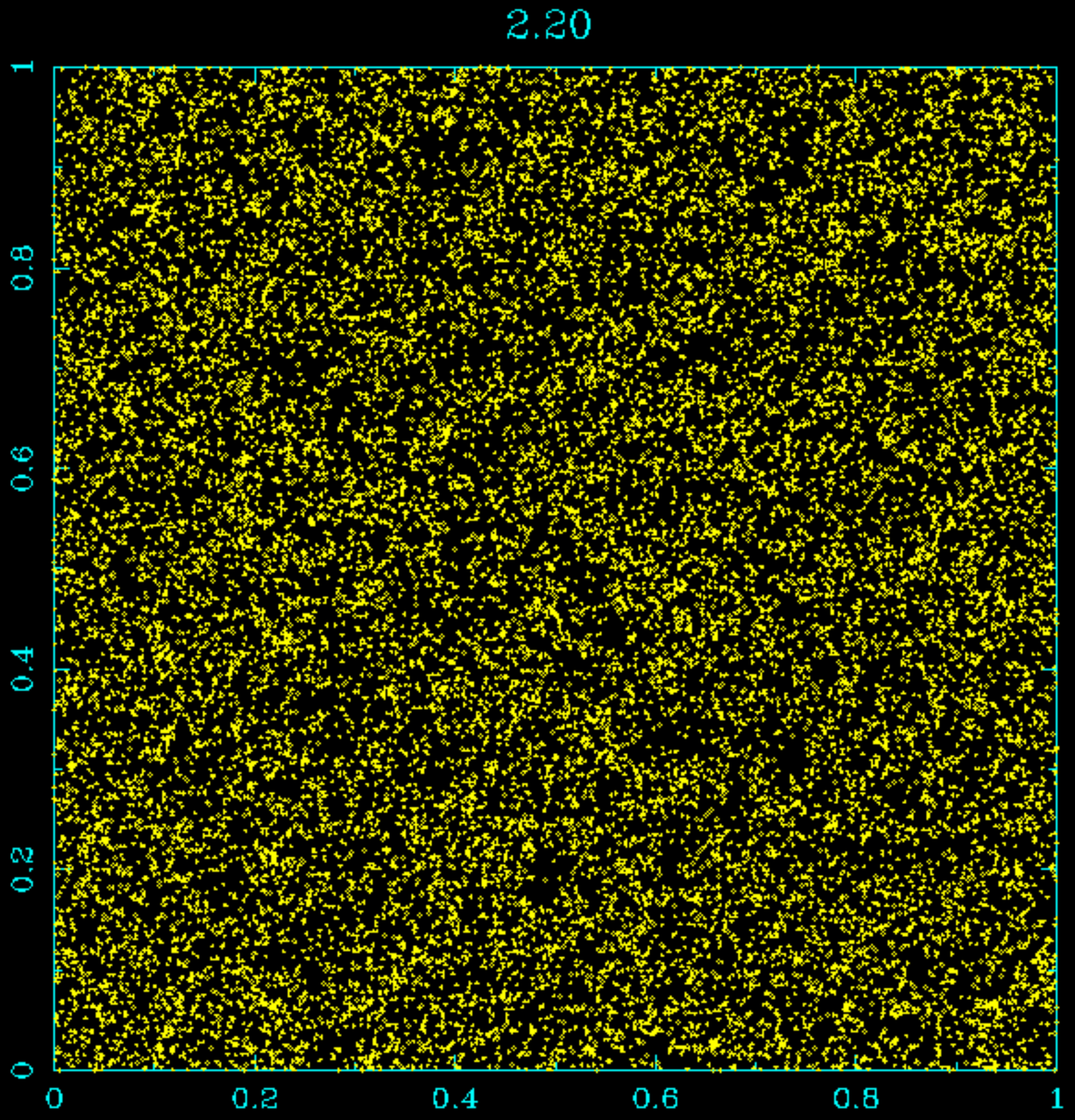
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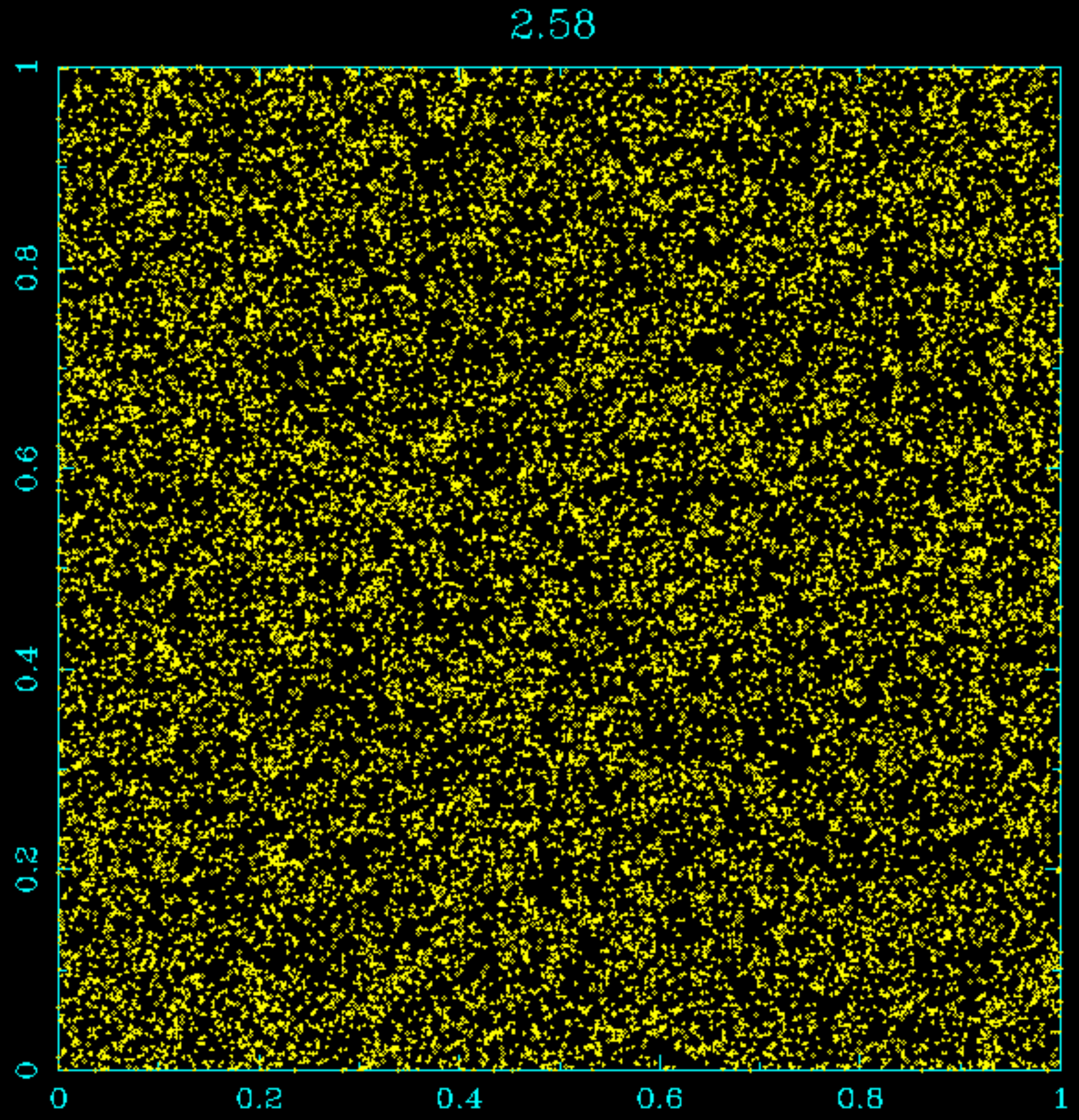
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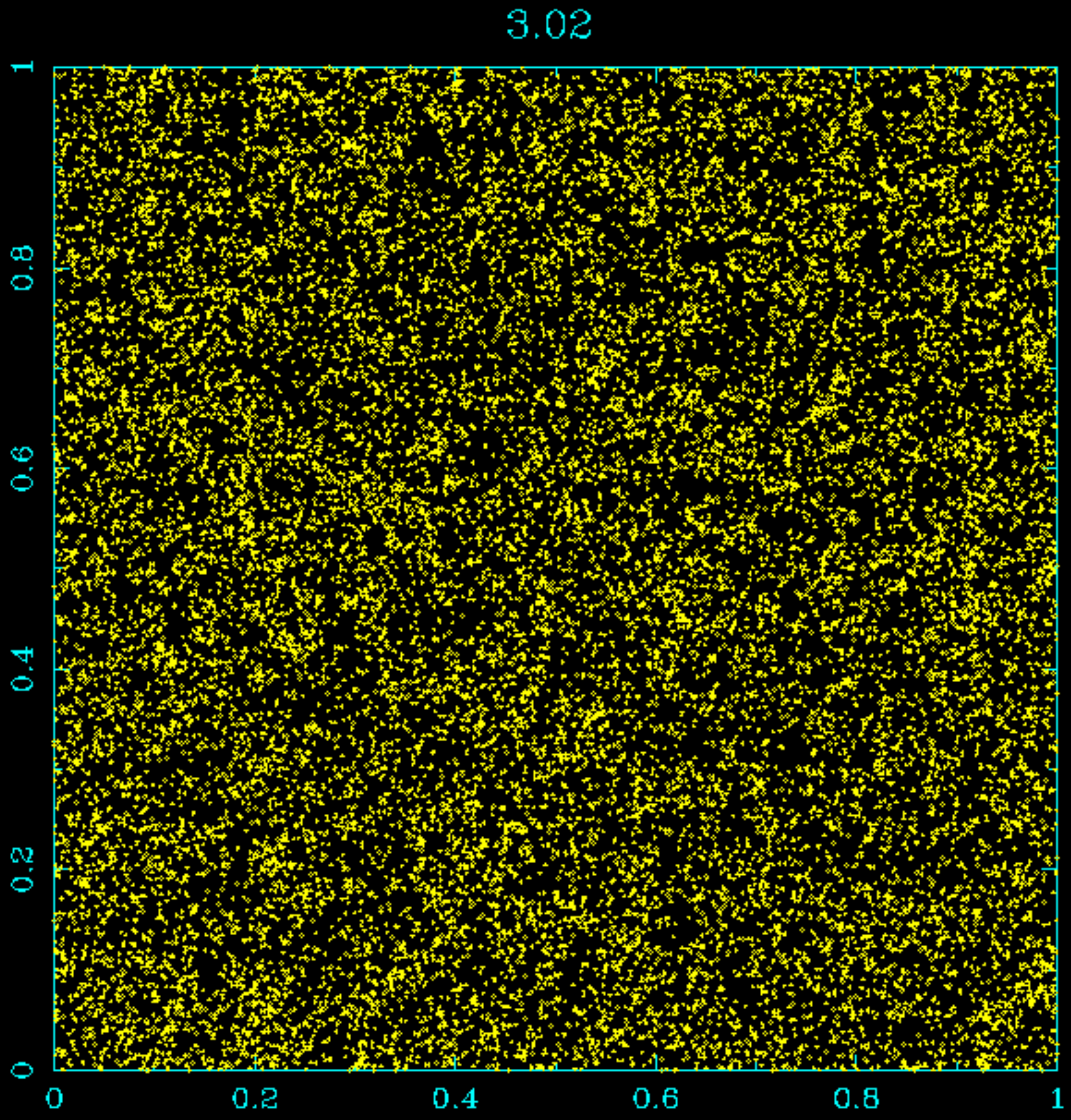
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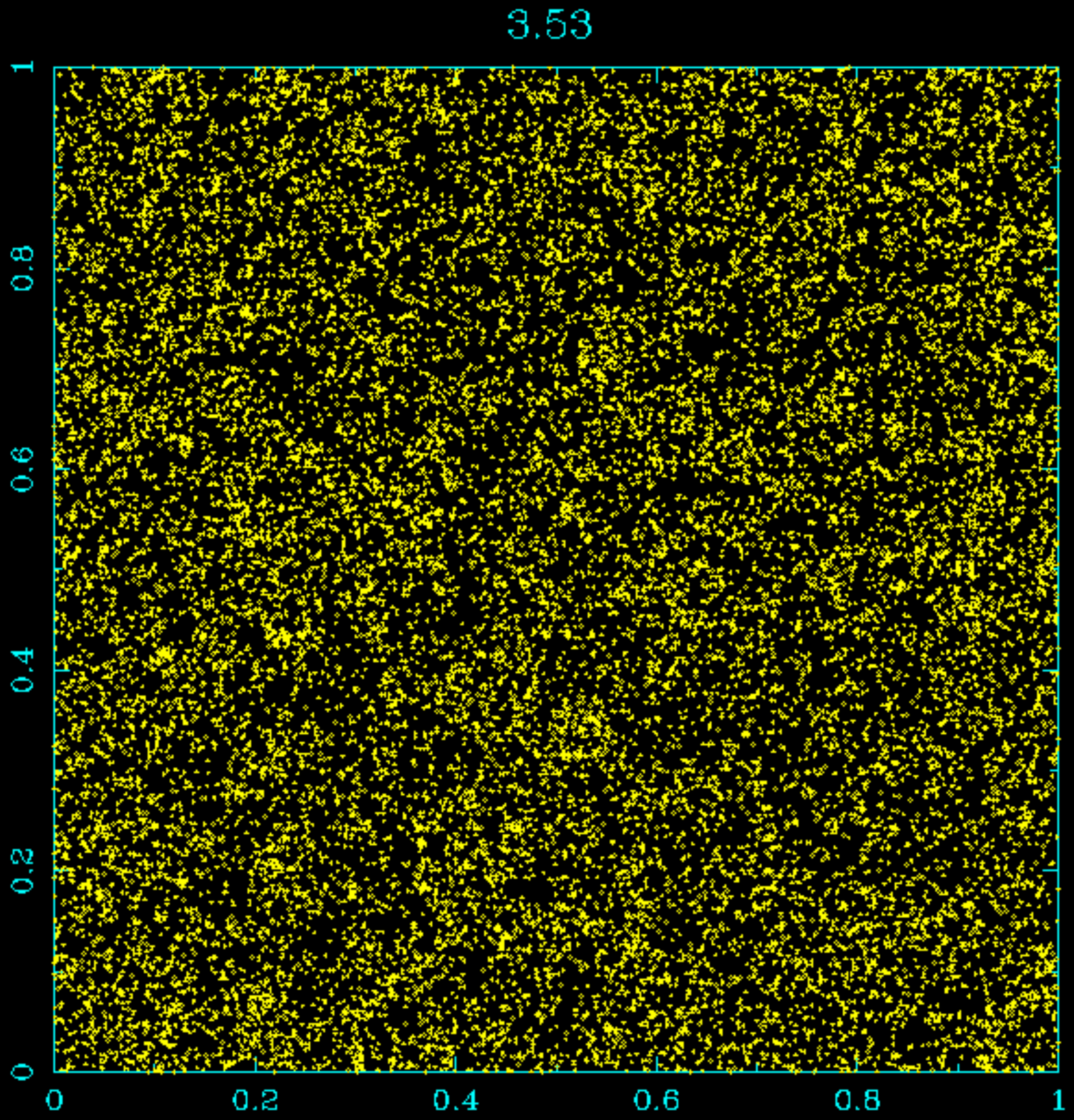
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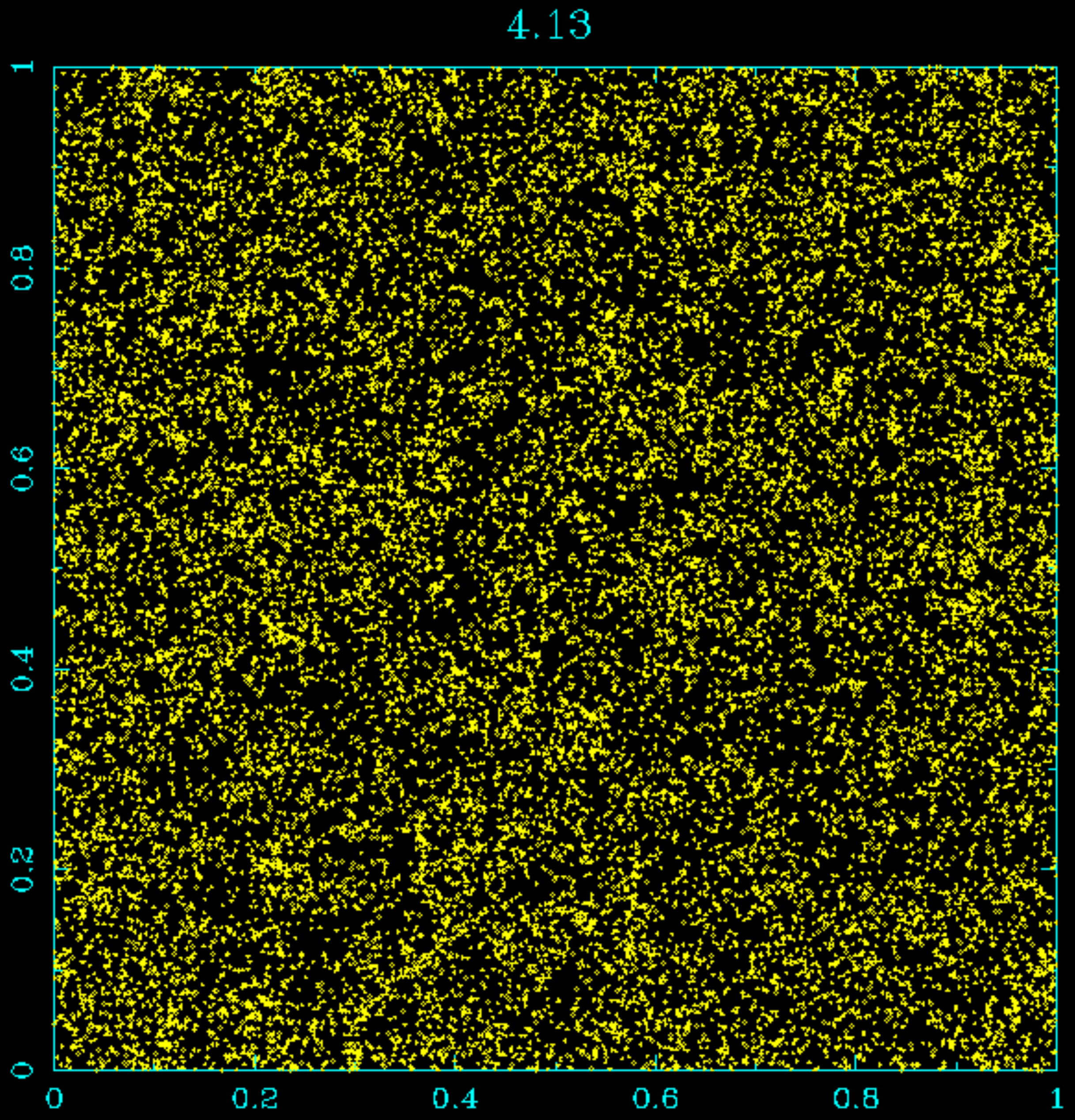
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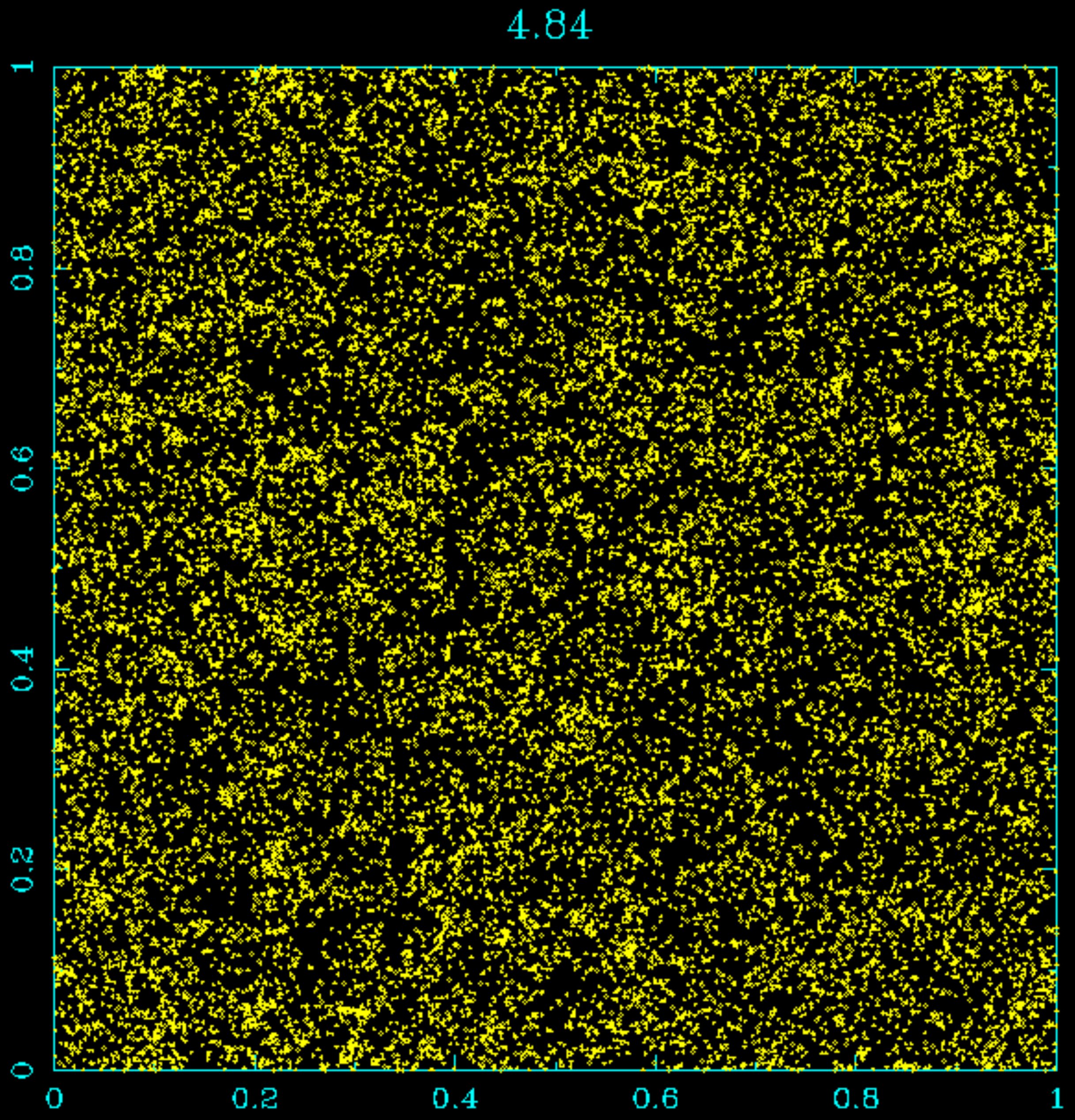

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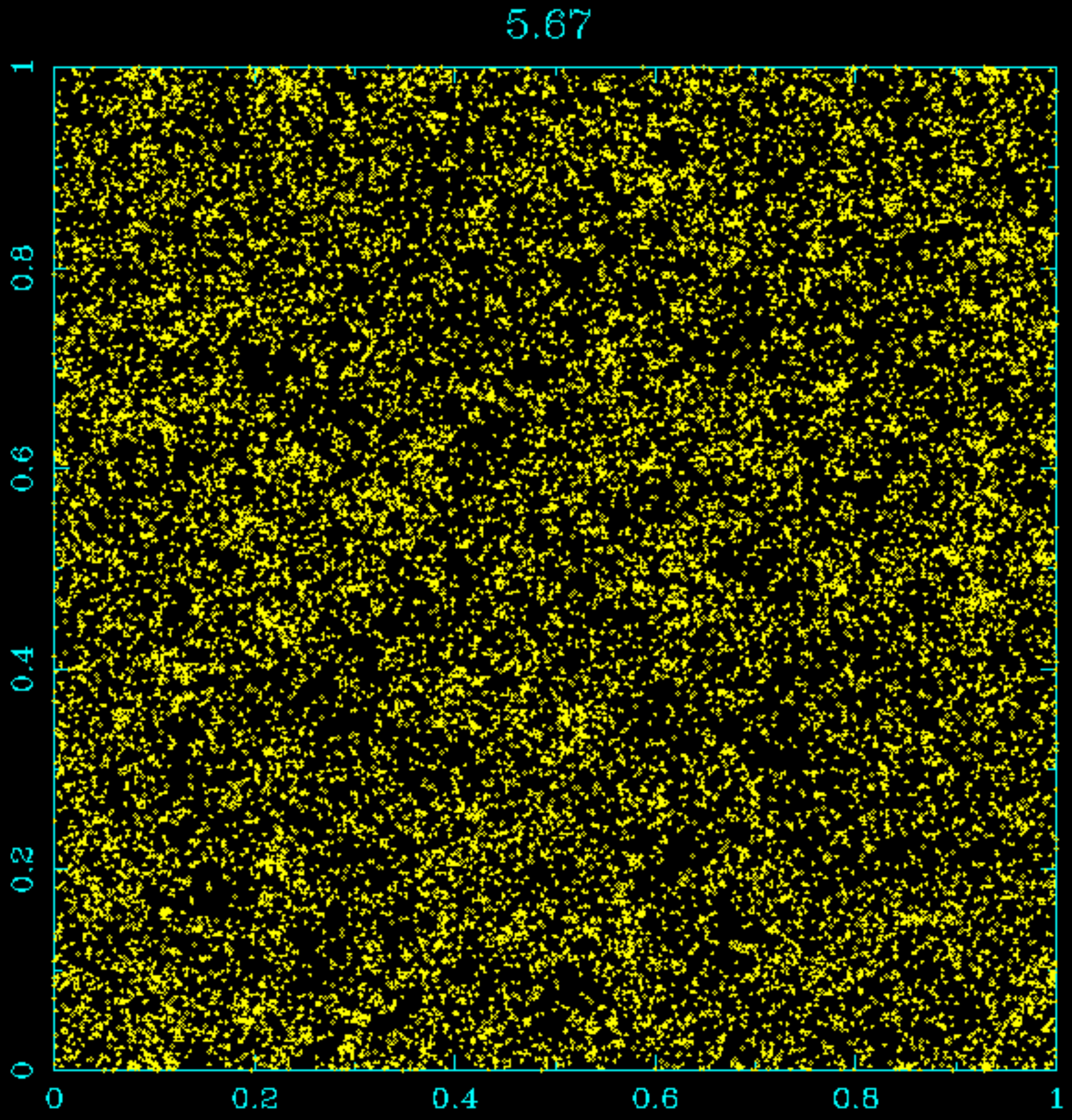
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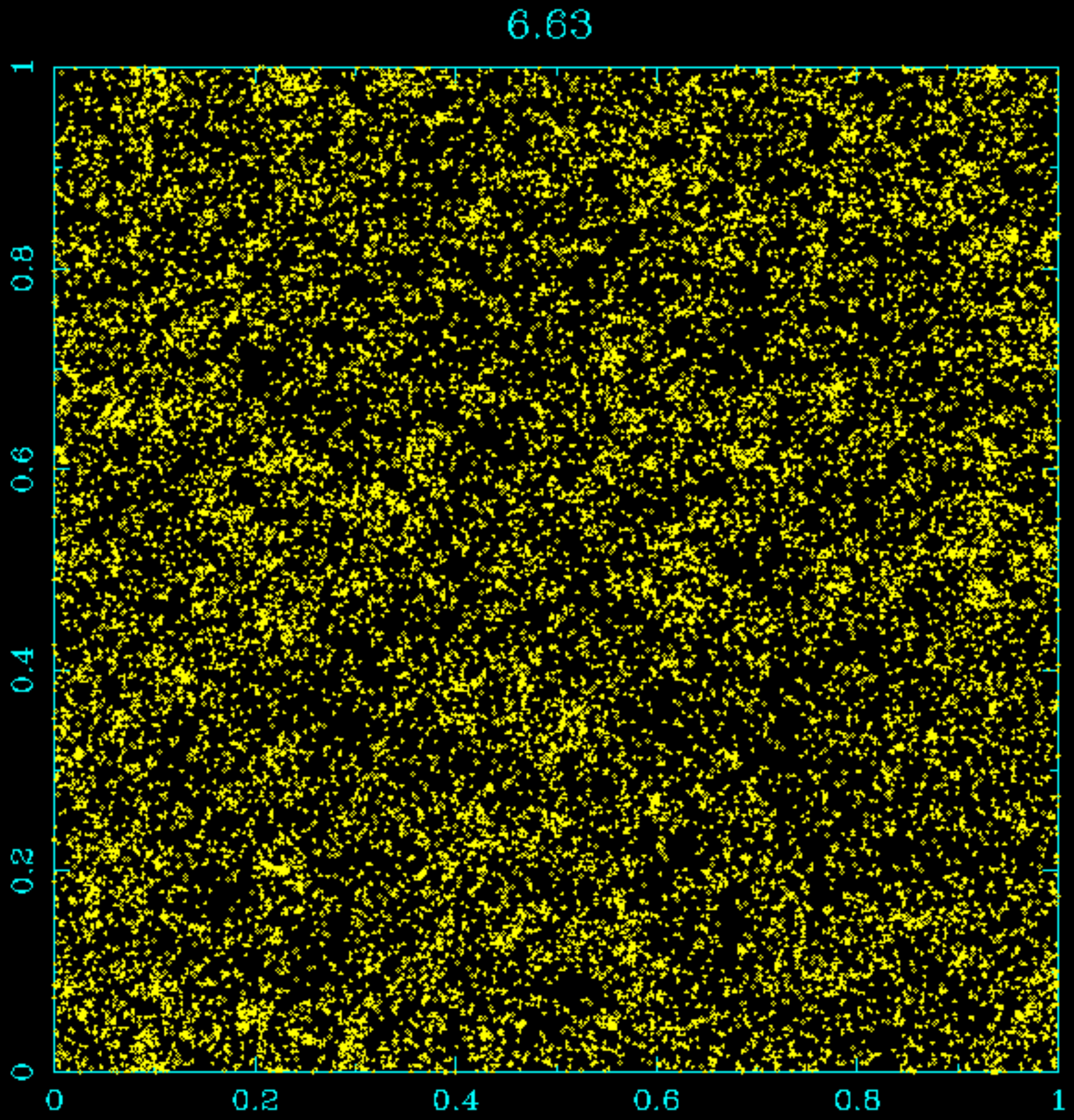
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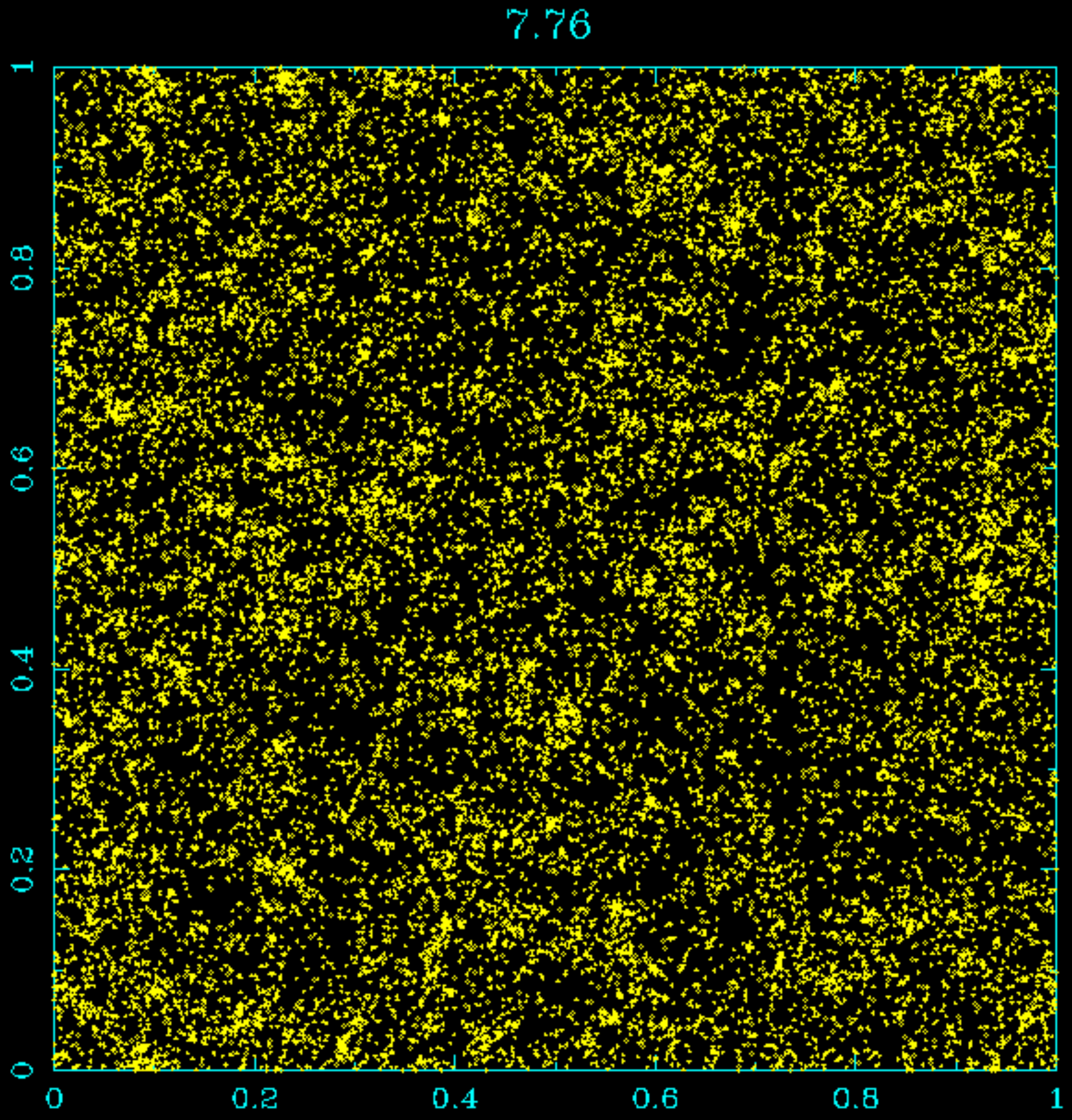
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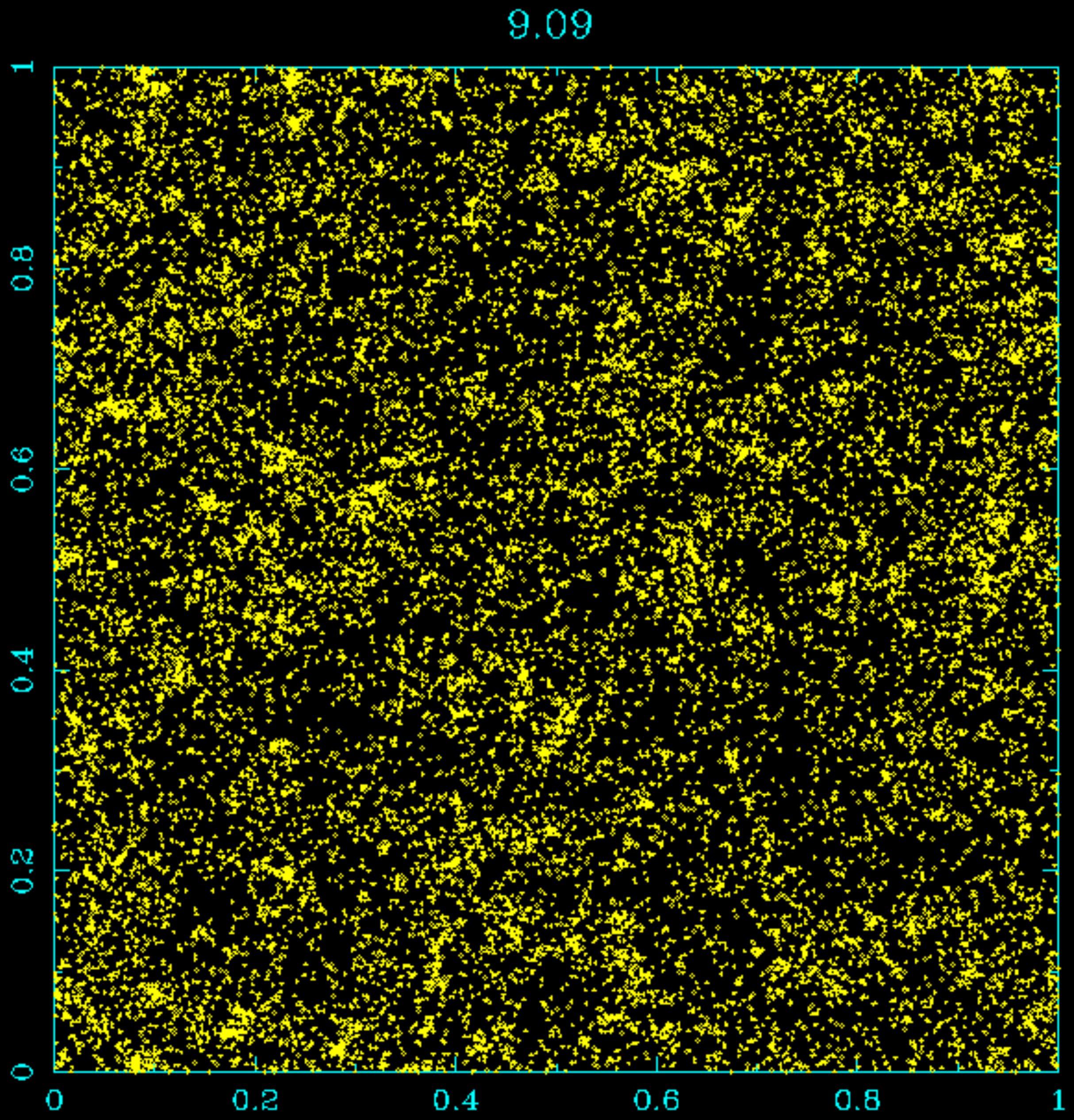
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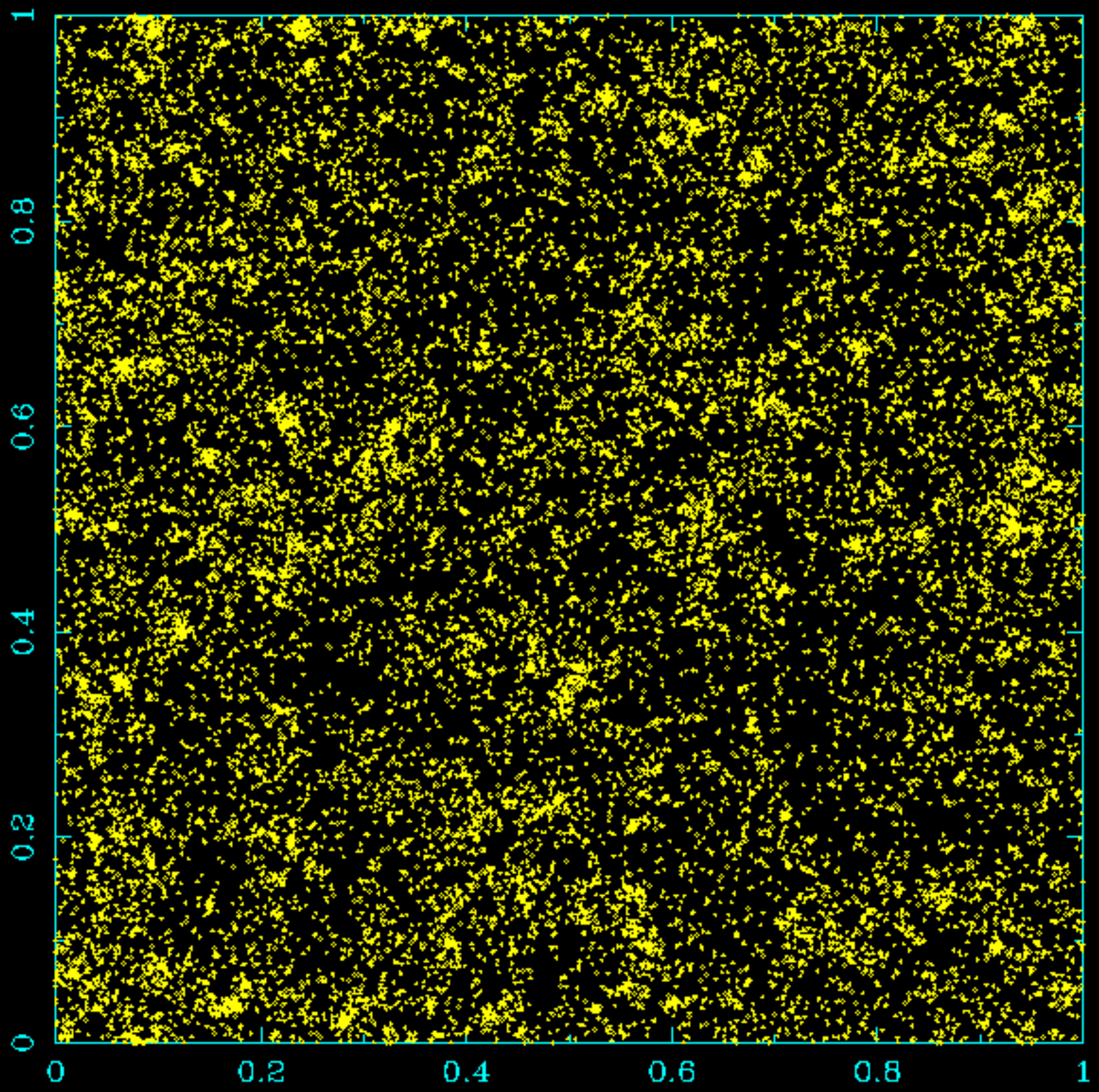

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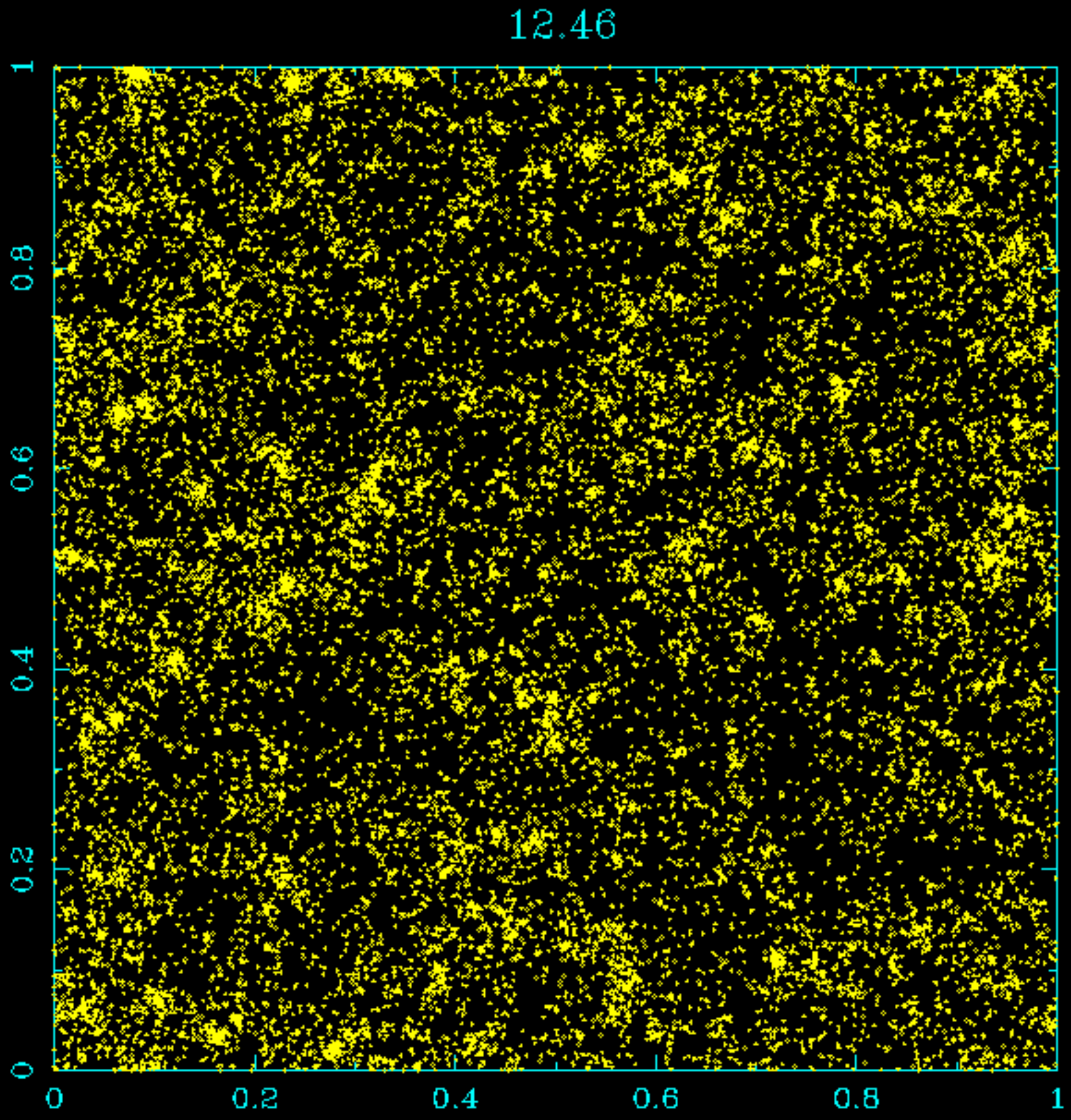
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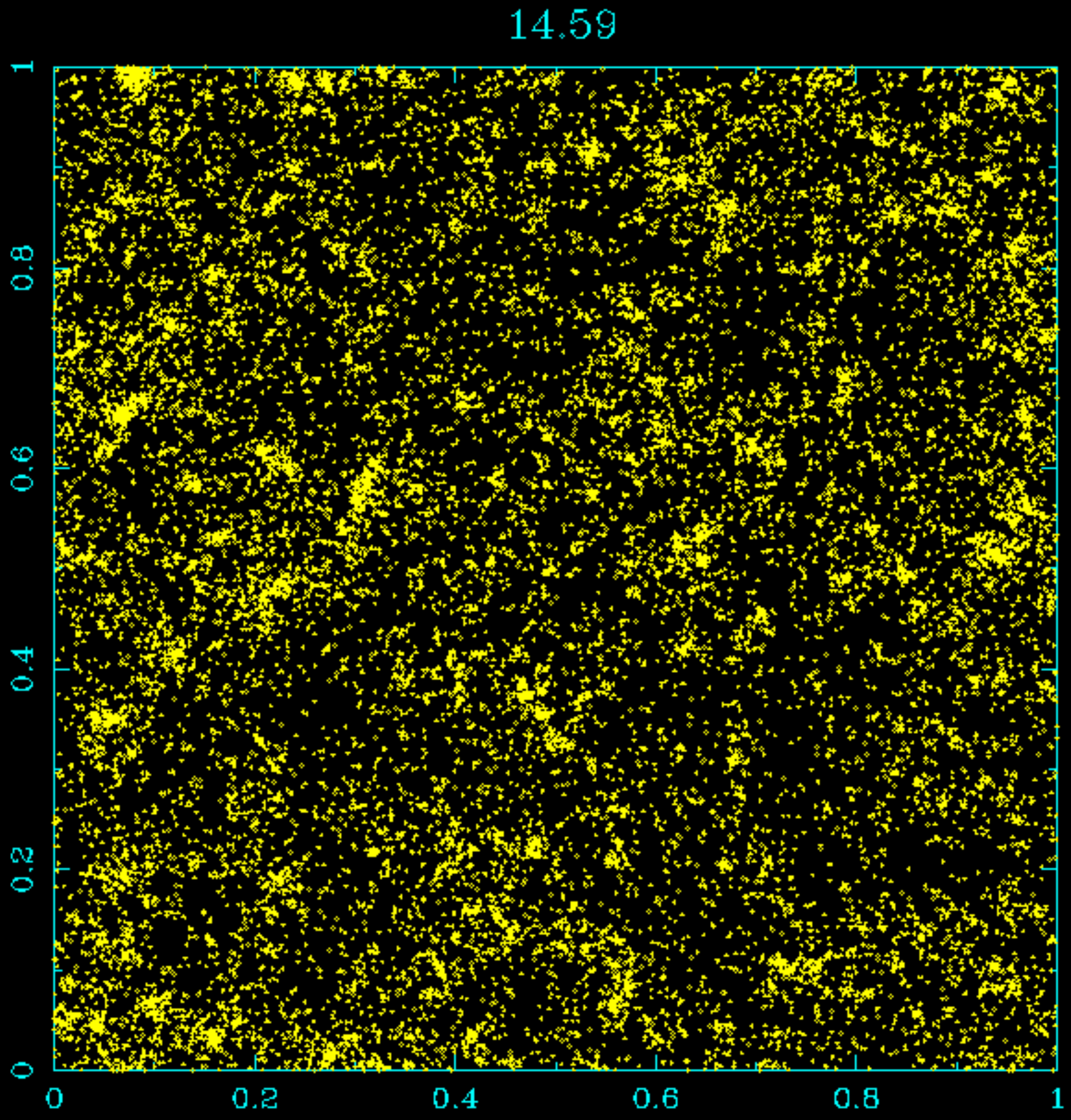
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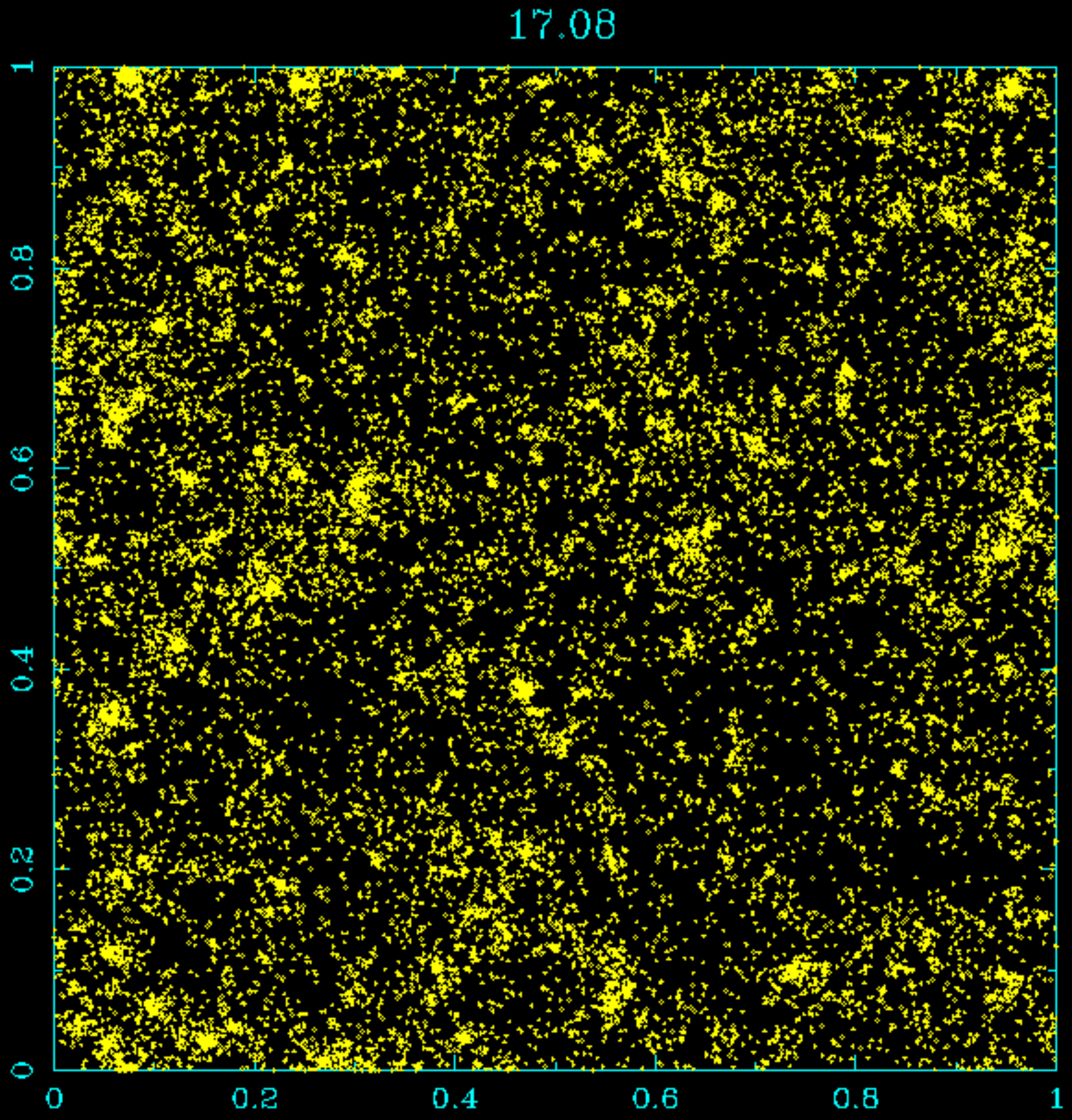
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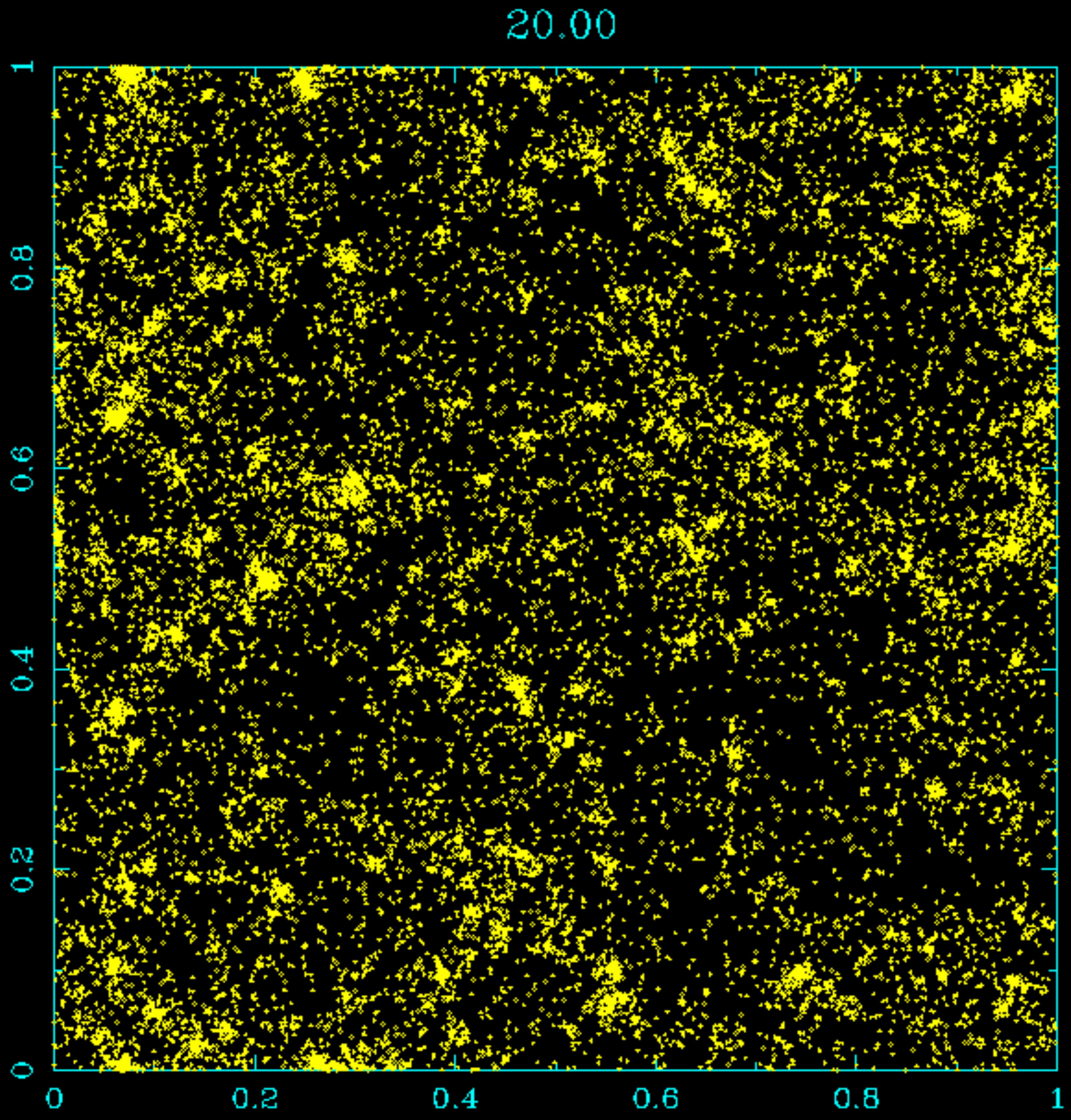


20.00


B-100

31/12/83

## Cold particle N-body simulations.

(a) Power-spectrum.

The power-spectrum used is the one that Dick & I calculated including 3-types of neutrinos (massless) & $\Omega_T = 1$. For constant curvature fluctuations, the resultant power-spectrum is fairly well fit by

$$P(k) = \frac{A k}{\{1 + 1.7k + 9k^{3/2} + k^2\}^2} \qquad (1)$$

where k has units of $h^2$ Mpc.

(b) Simulations with $L = 25 h^{-2}$ Mpc.

The first set of simulations was done with equation (1) and a box length of $25 h^{-2}$ Mpc. The models are –

| | run at | Rmax | |
|---|---|---|---|
| PMGN1. DAT | RGO | 4·5 | These used the old version of the code with $r^2$ force interpolation |
| PMGN2. DAT | RGO | 4·5 | |
| PMGN3. DAT | RGO | 4·0 | |
| PMGN4I. DAT | Camb. | 3·0 | These used the new version with linear interpolation. |
| PMGN4RI DAT | Camb | 4·0 | |
| PMGN5I. DAT | RGO | 3·0 | |
| PMGN5RI. DAT | Camb | 4·0 | |

The model parameters were

$M = 64$

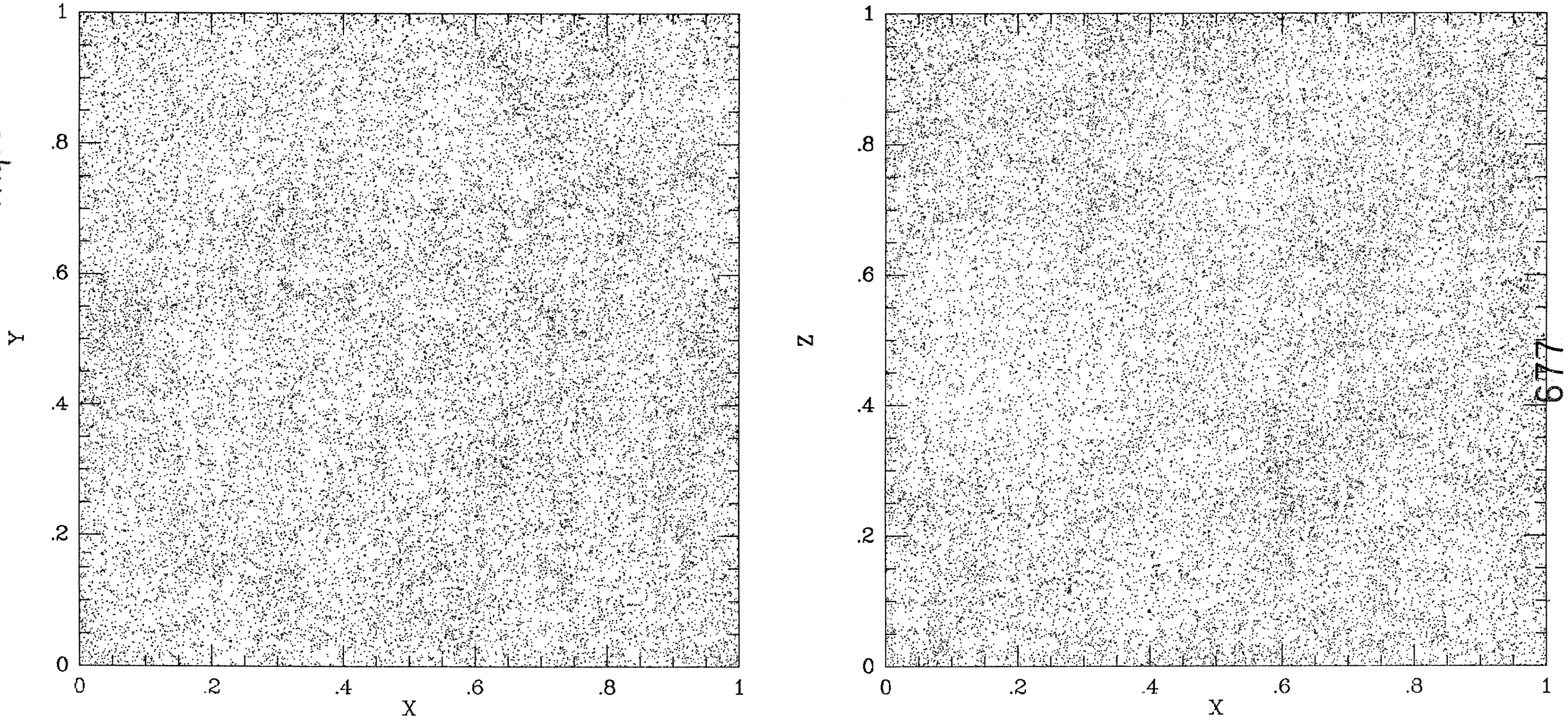
$\eta = 0.3$

$dp = 0.02$

$\alpha = 1.0 \qquad (p = a^{\alpha})$

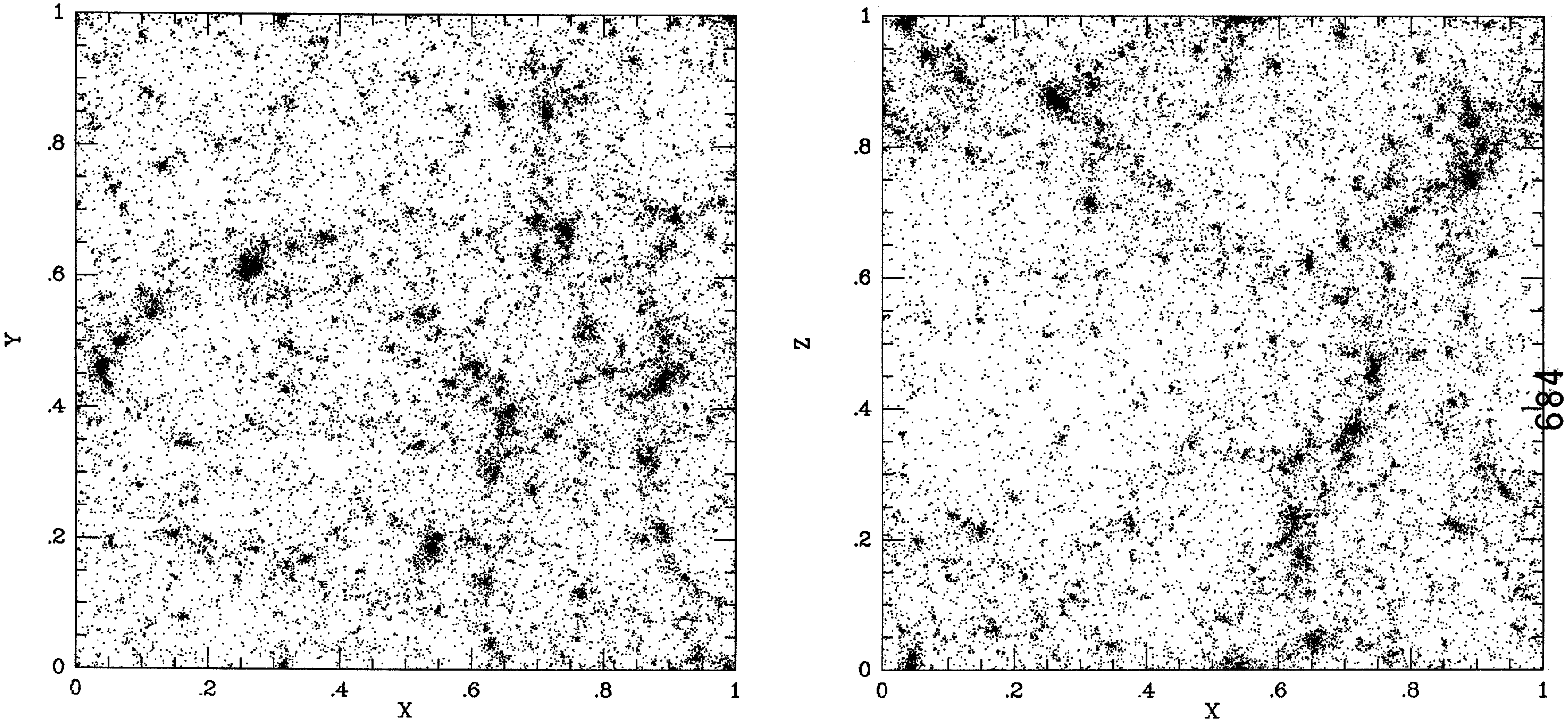
3.

PMGNSI.DAT



R = 1.0

10.



R = 4.0

THE ASTROPHYSICAL JOURNAL, **292**:371–394, 1985 May 15

13.

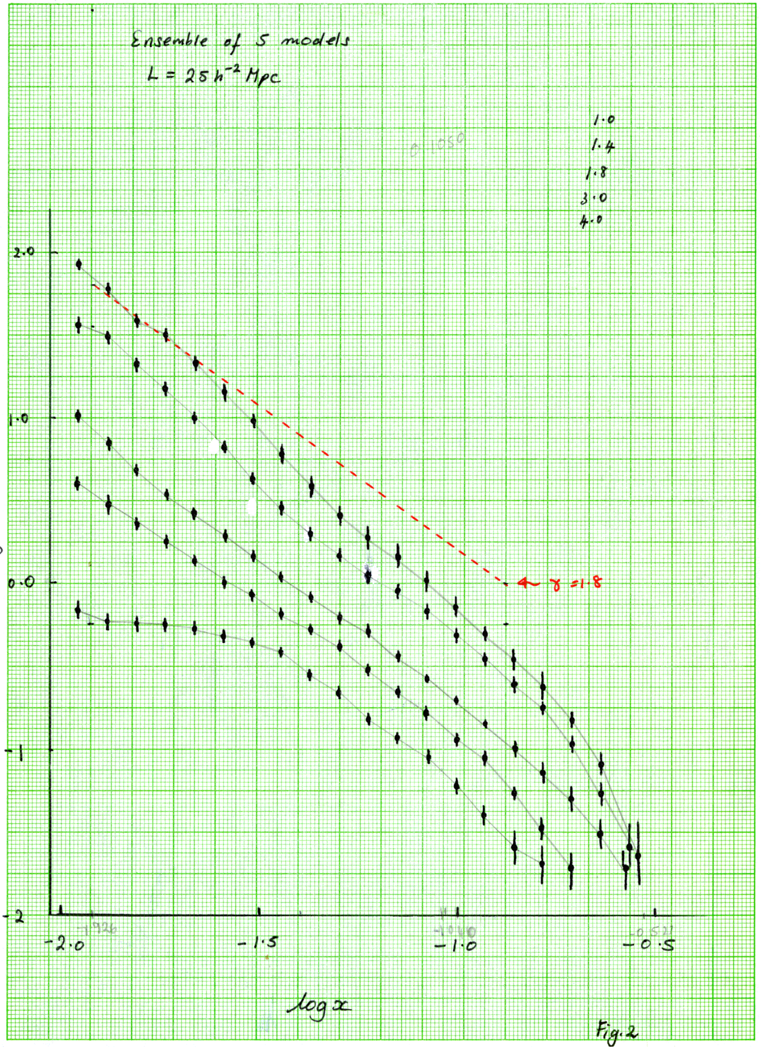
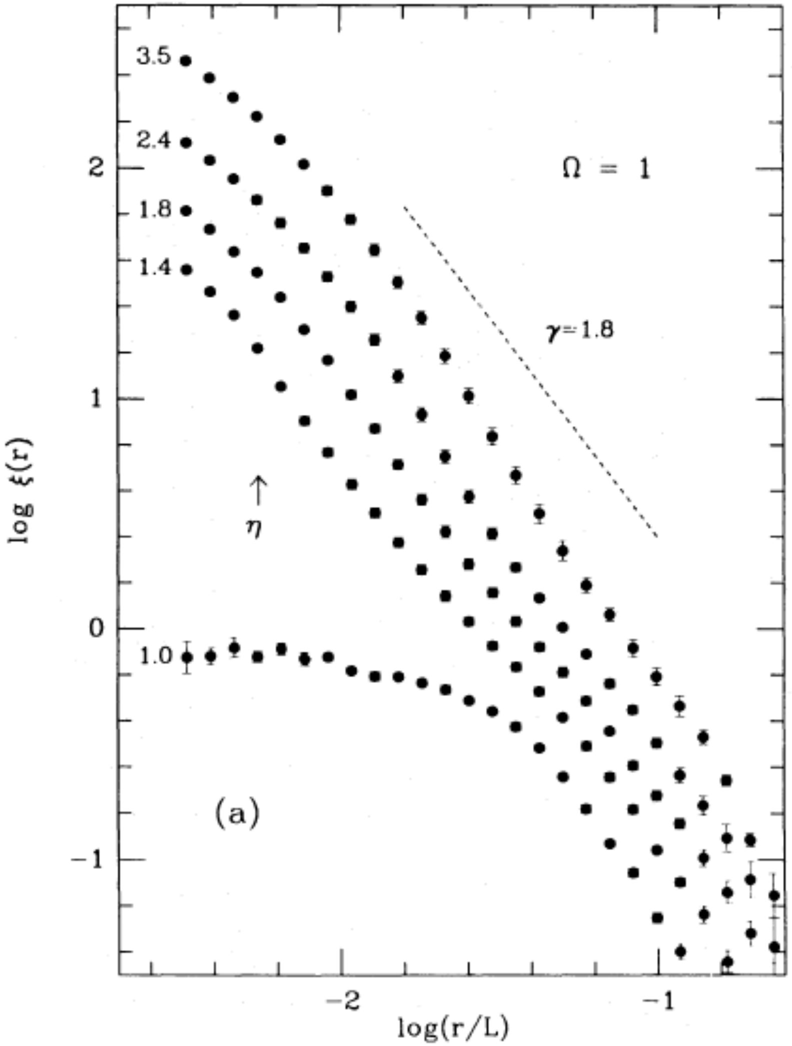


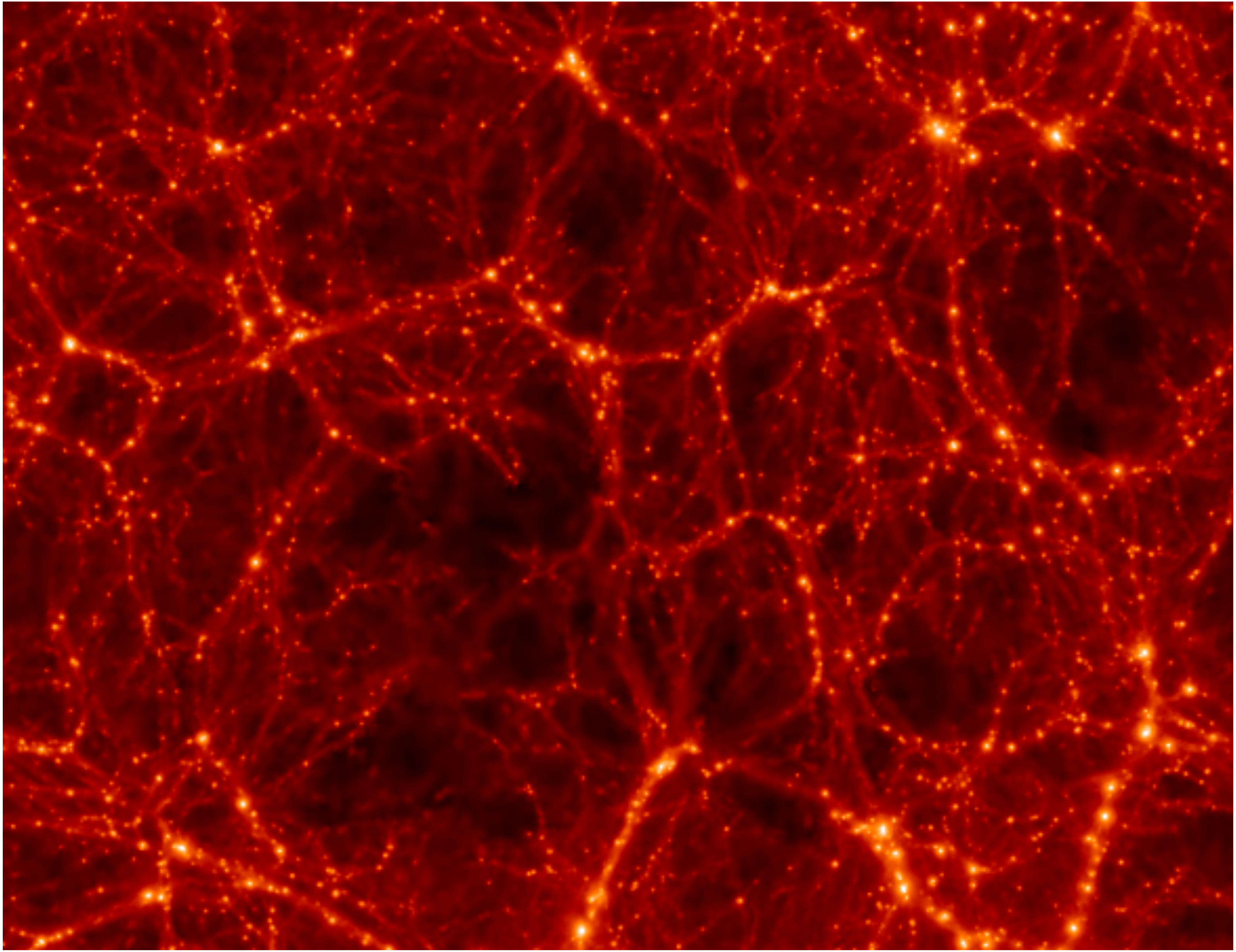
Fig. 2



observation even in a universe with $\Omega = 1$. If this
sible to reconcile a flat universe with most aspects

of the observed galaxy distribution.

*Subject headings:* galaxies: clustering — galaxies: formation — numerical methods

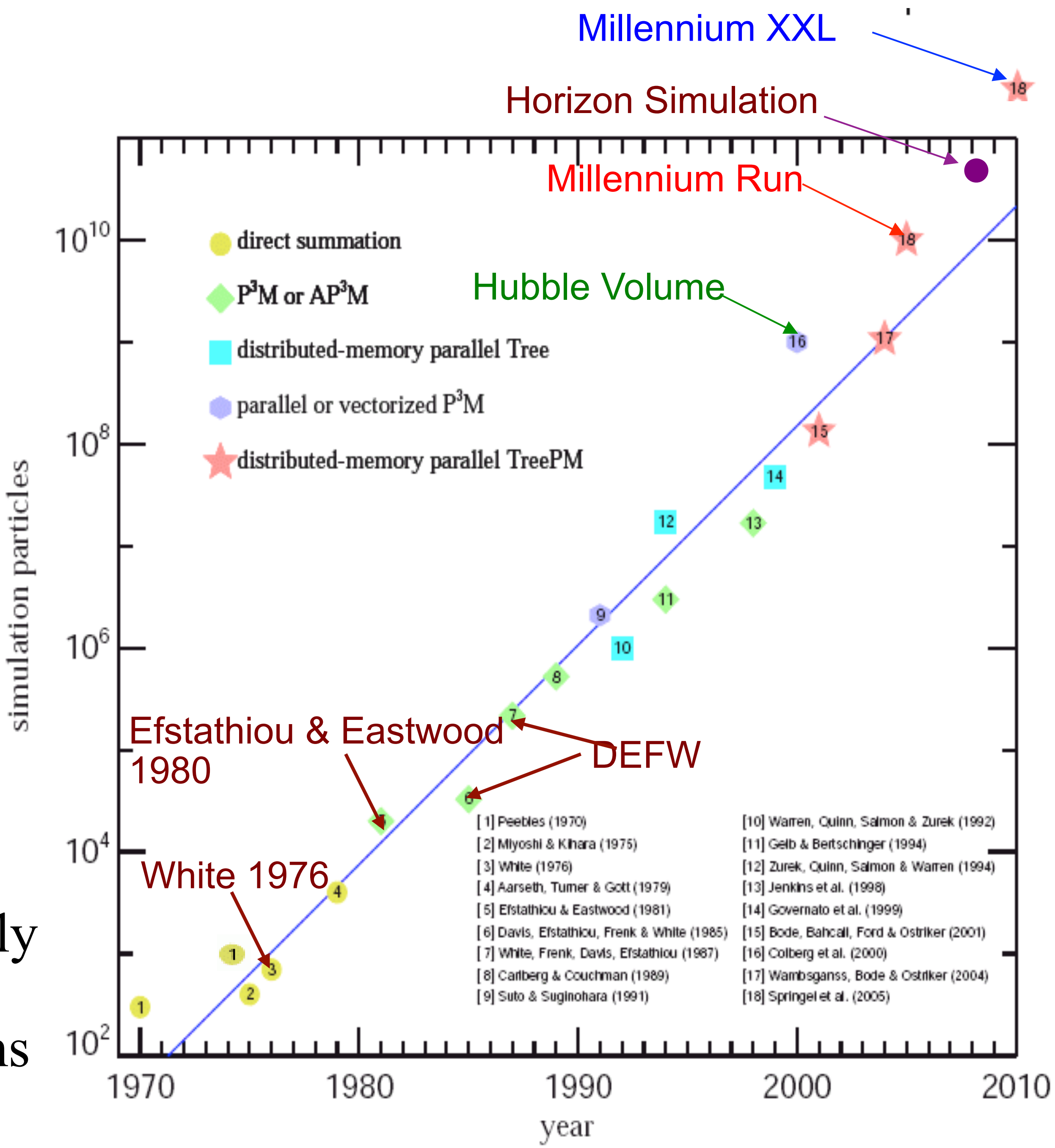


- Computers double their speed every 18 months

- A naive N-body force calculation needs $N^2$ op's

- Simulations double their size every 16.5 months

- Progress has been roughly equally due to hardware and to improved algorithms

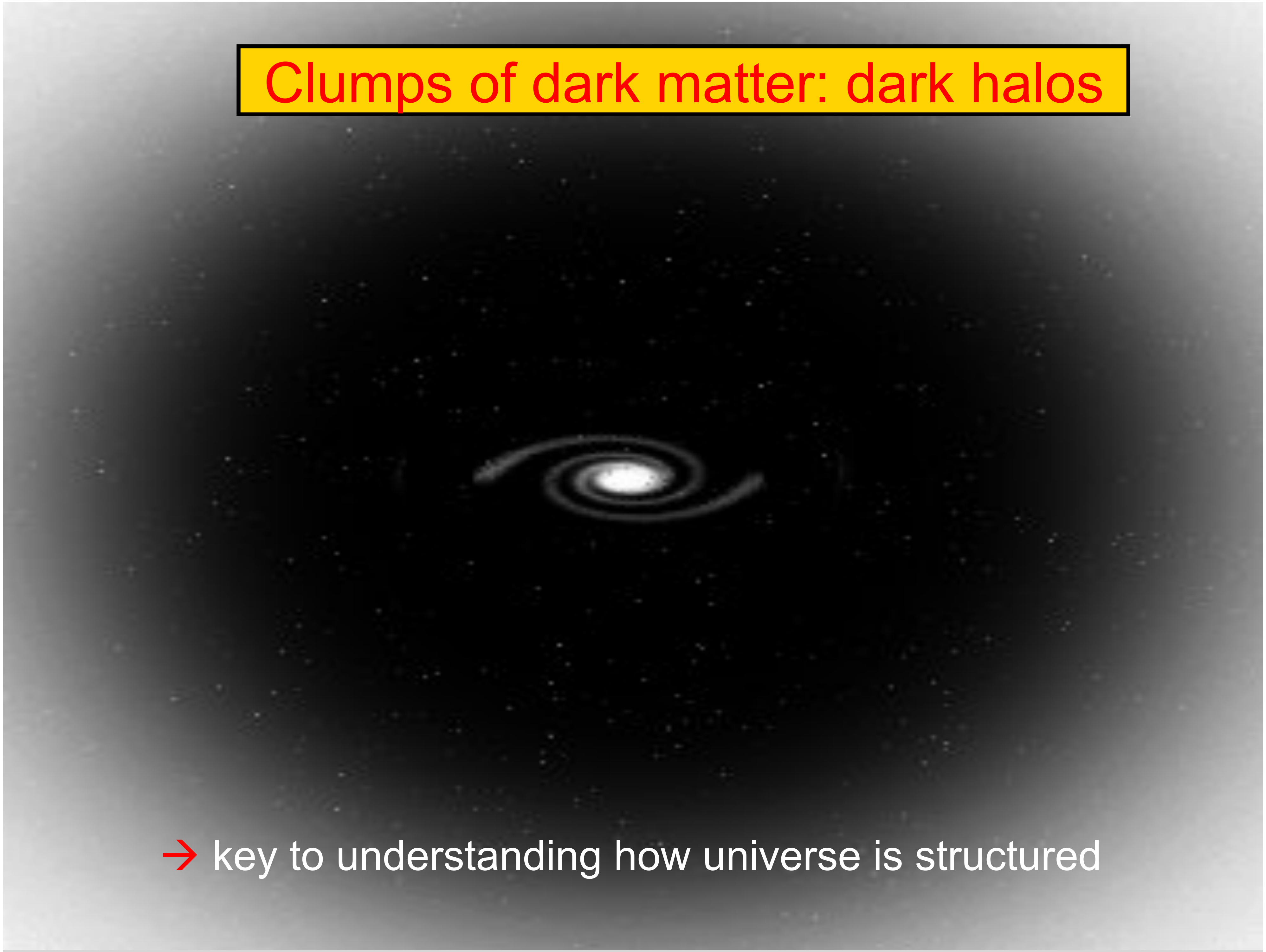


# Chapter 3 – Where galaxies form

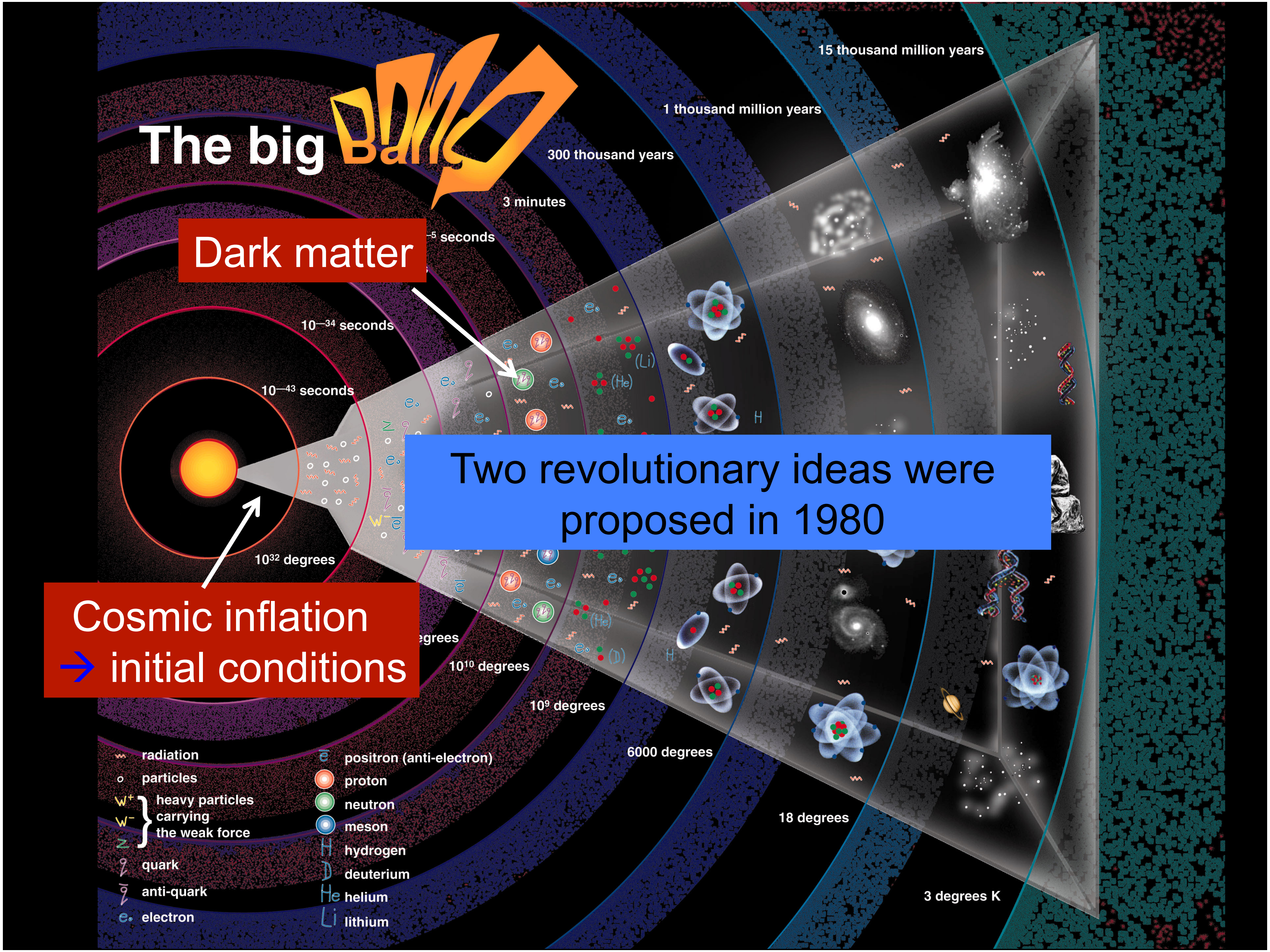
Carlos Frenk

Berkeley 1981

# Clumps of dark matter: dark halos



→ key to understanding how universe is structured



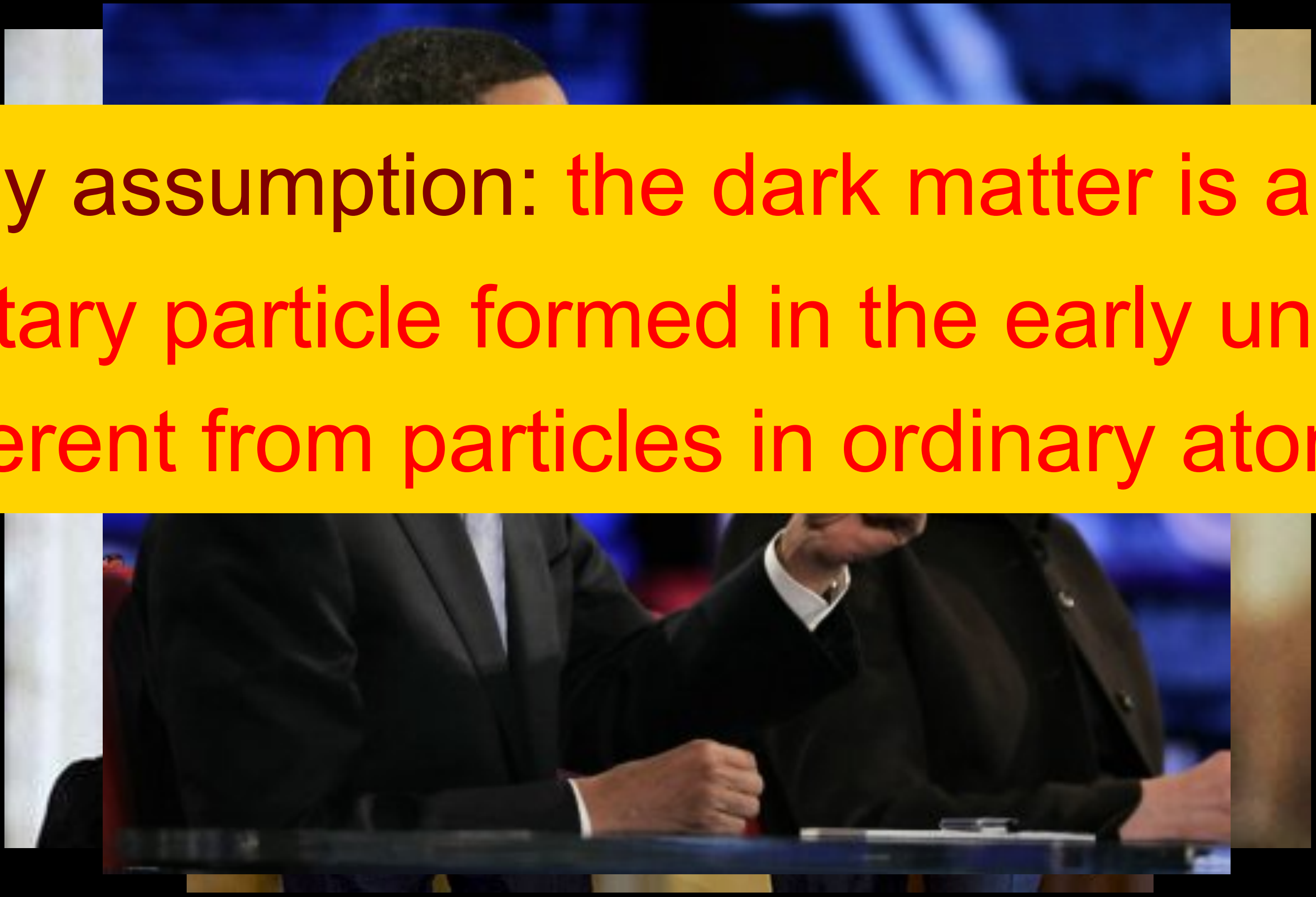
Two revolutionary ideas were proposed in 1980

Dark matter

Cosmic inflation

→ initial conditions

# What is the dark matter?

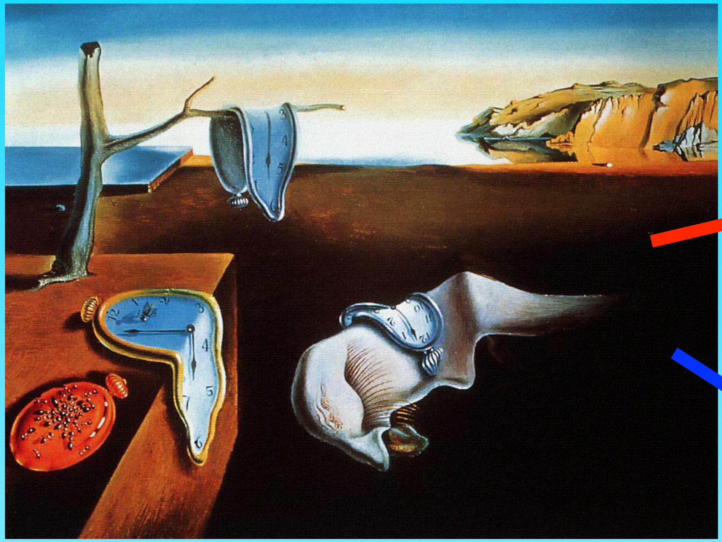


Key assumption: the dark matter is an elementary particle formed in the early universe, different from particles in ordinary atoms

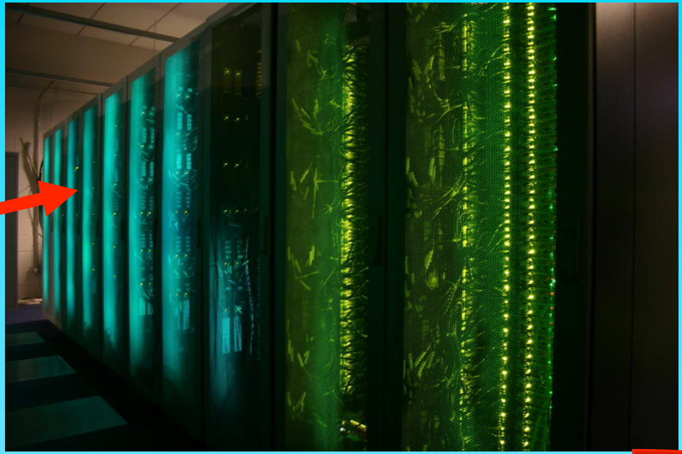
University of Durham

# The formation of cosmic structure

$t=10^{-35}$ seconds



"Cosmology machine"



Simulations

t=13.8 billion yrs

Supercomputer simulations use the laws of physics to calculate how small primordial seeds grow into galaxies today

# The `Gang of Four' - 1983

# What is the dark matter?

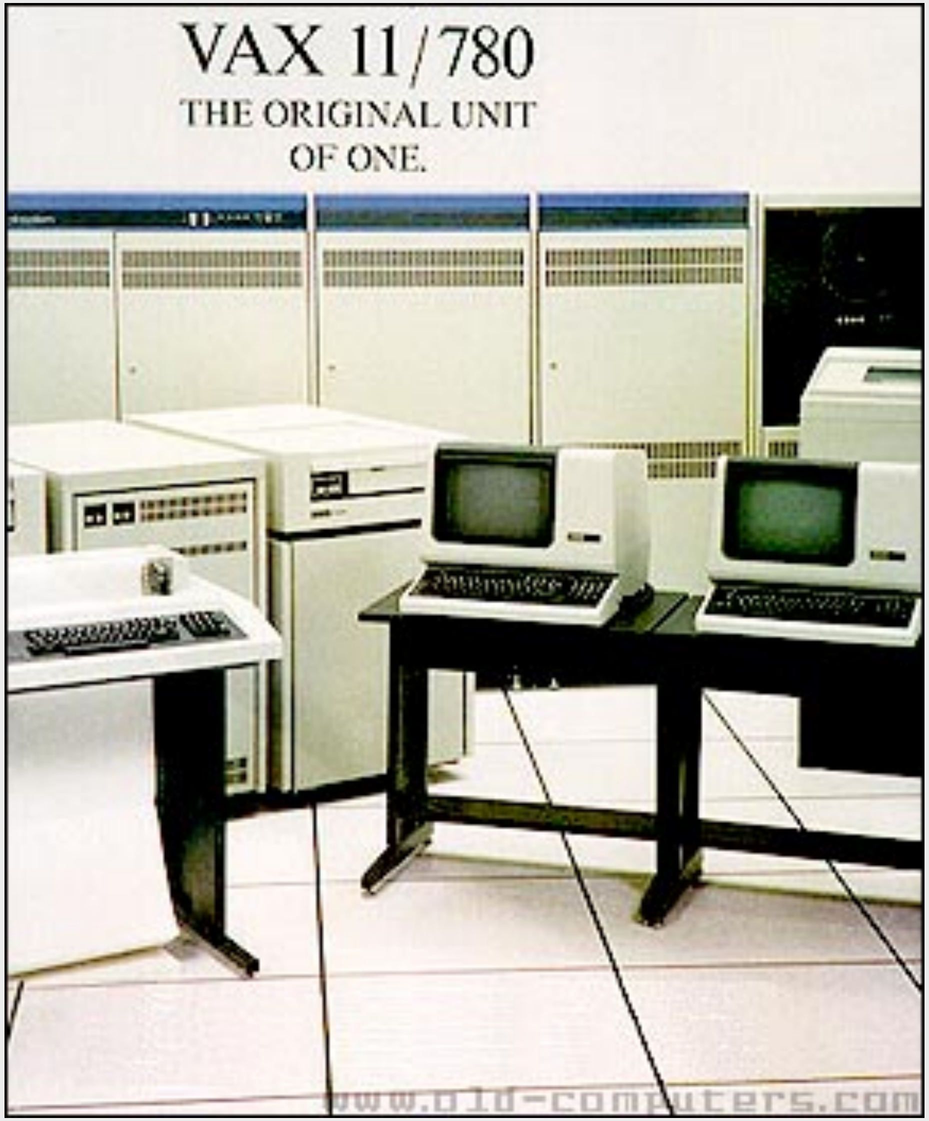
# Particle dark matter candidates

| Type | example | mass |
|---|---|---|
| ~~hot~~ | ~~neutrino~~ | ~~a few eV~~ |
| warm | sterile $\nu$<br>majoron | keV-MeV |
| cold | axion<br>neutralino | $10^{-5}$eV-<br>>100 GeV |


z = 48.4
T = 0.05 Gyr
500 kpc

ICC
University of Durham

# The universe in a computer


VAX 11/780
THE ORIGINAL UNIT OF ONE.

December 1981

Speed = 500,000 FLOPS
RAM = 4 Mbytes

# The Aquarius simulations

2008

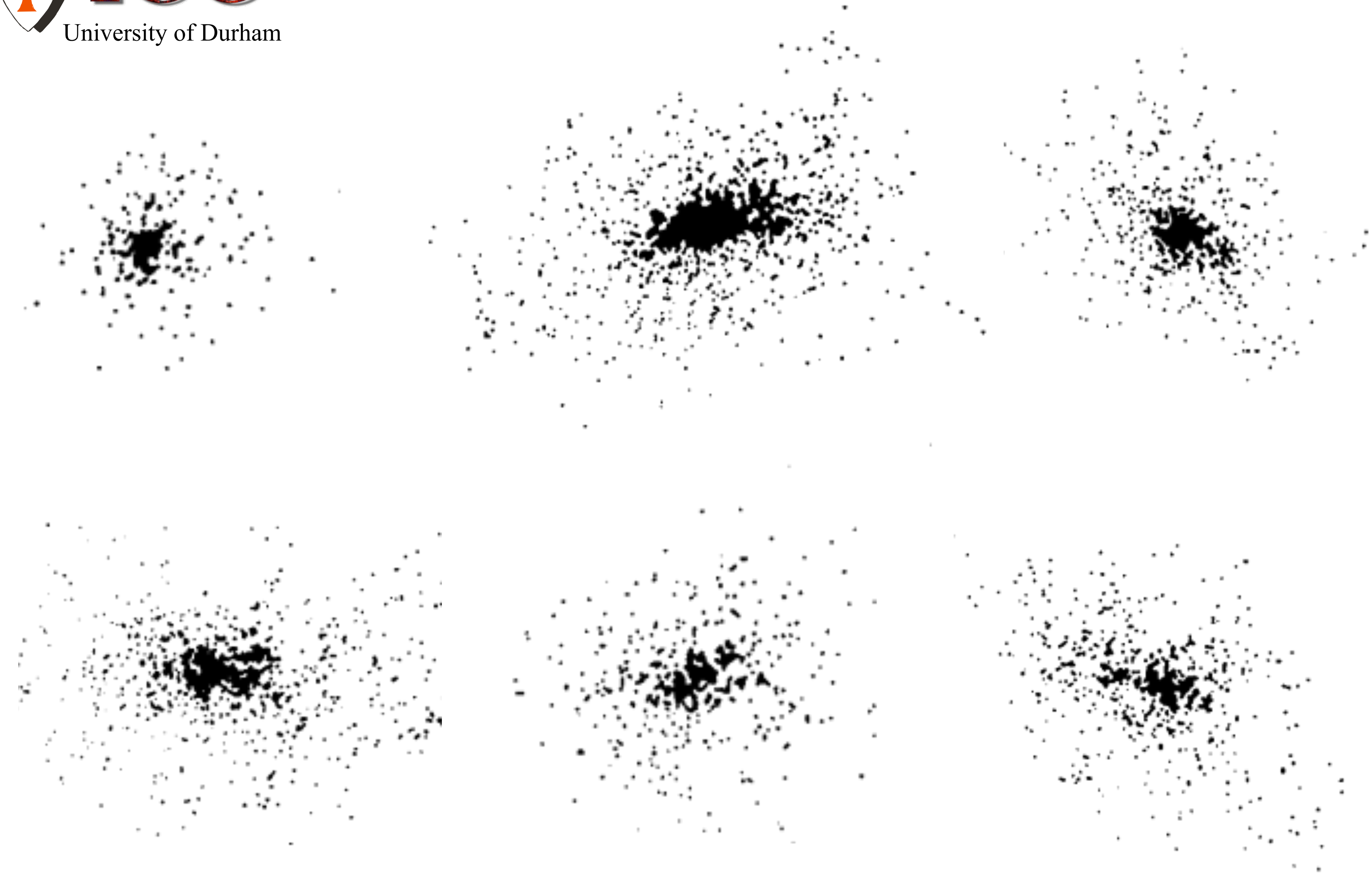
Julich BlueGene

800 Teraflops
144 Terabytes RAM

a Tera = a trillion ($10^{12}$)

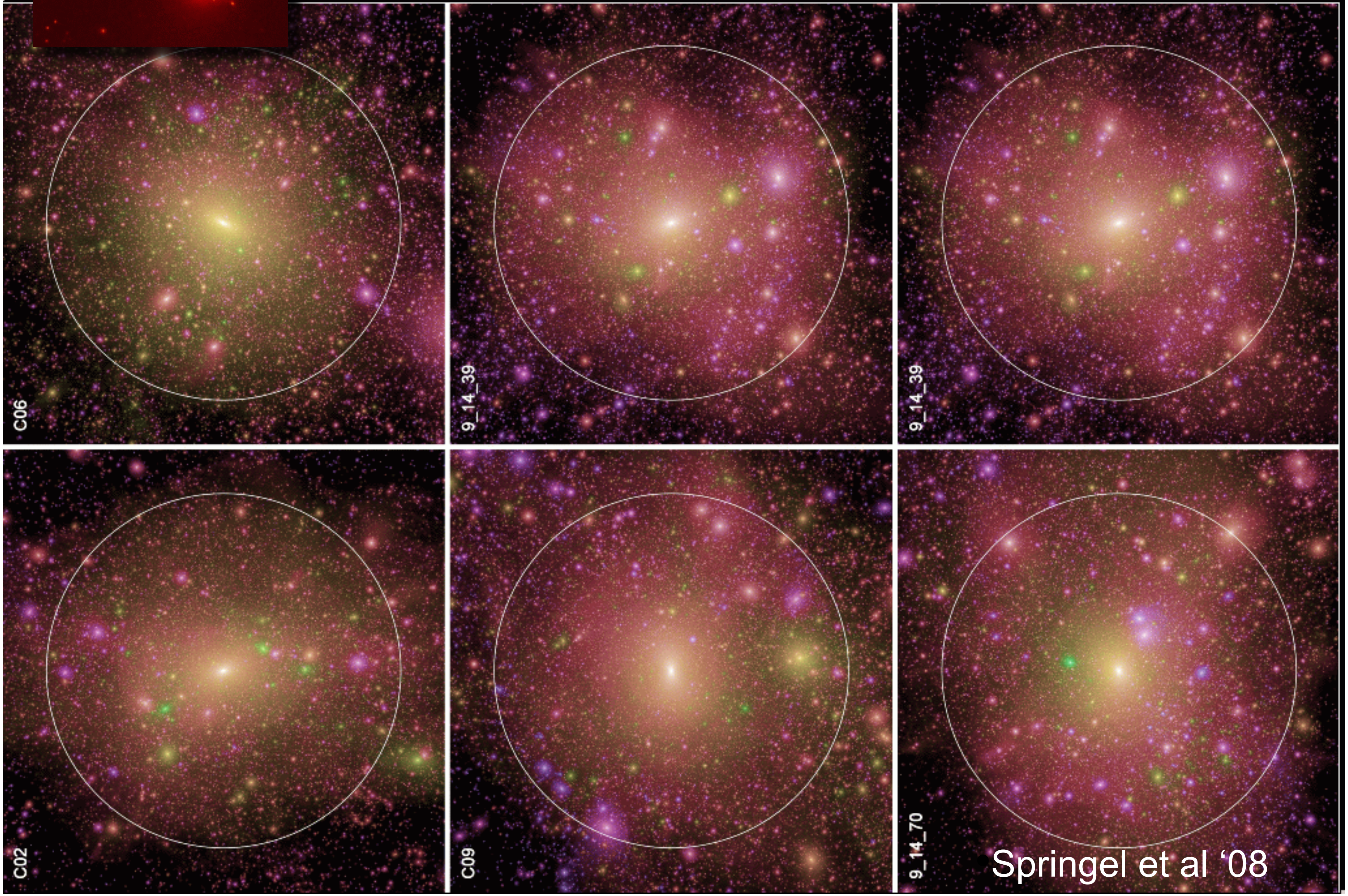
→ over a billion times faster than VAX 780

# 6 CDM halos with ~1000 particles (1988)



Frenk, White, Davis, Efstathiou ‘88

# 6 CDM halos with 200 million particles (2008)

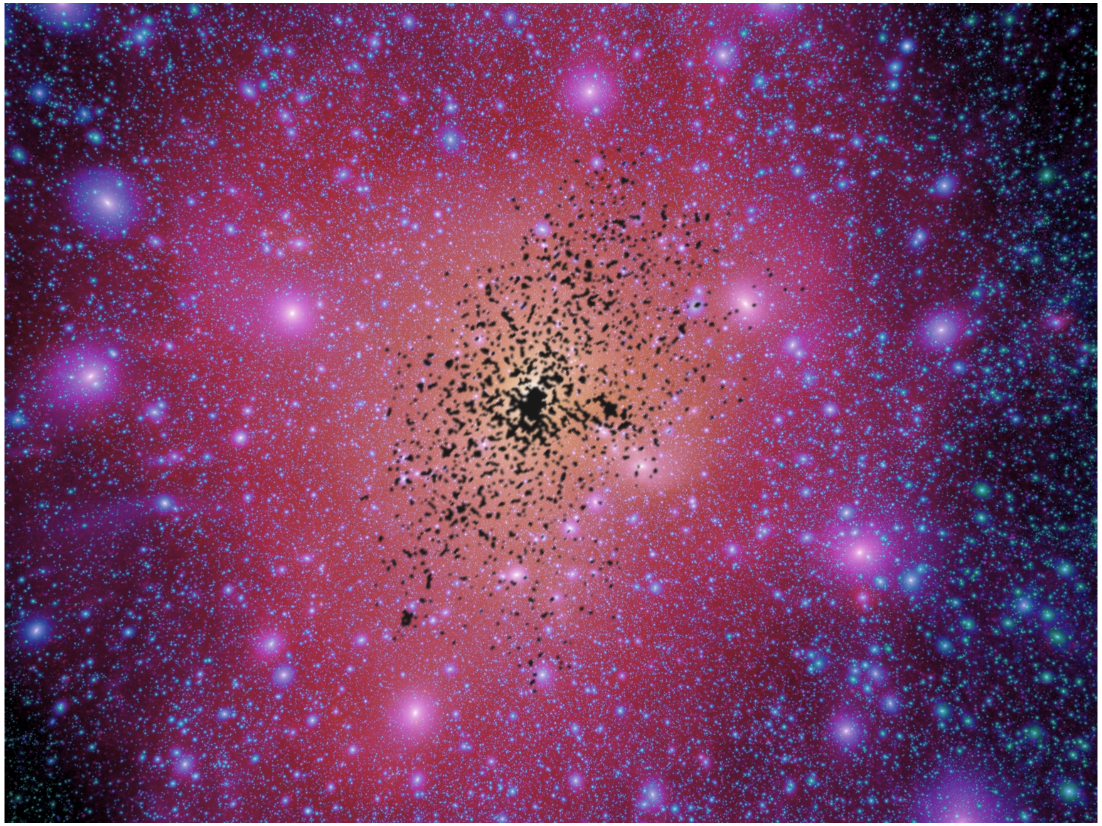


Springel et al '08

1 billion particles (2008)

4000 particles (1988)

# 1 billion particles (2008)



University of Durham

# The properties of CDM halos

Frenk, White, Davis, Efstathiou 1988

rotation curves

516 FRENK *ET AL.* Vol. 327

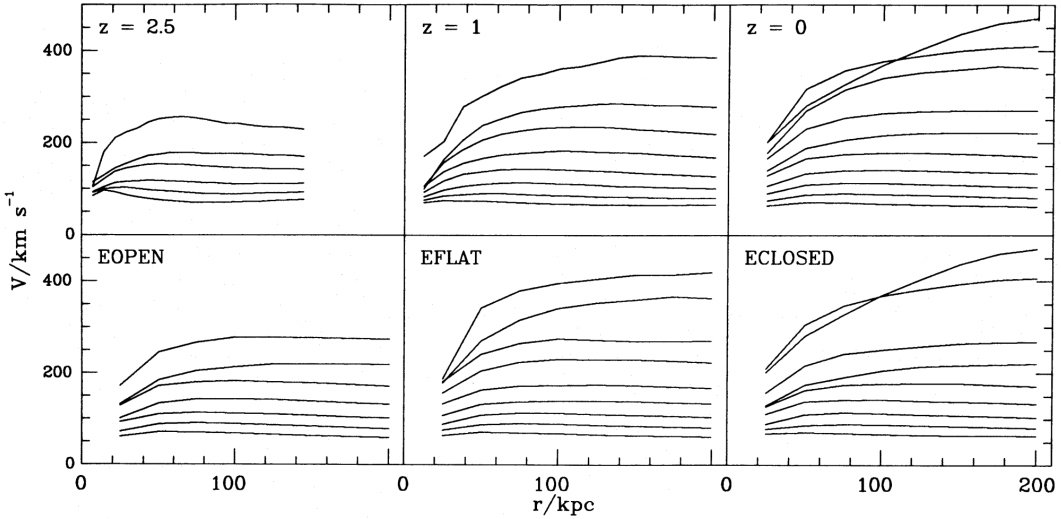


FIG. 6.—Circular velocity curves, $V(r) = [GM(r)/r]^{1/2}$, for halos in the simulations. Each curve plotted is an average for all halos with characteristic velocity log ($V_c$) in a bin of width 0.1. The top row includes halos in all nine simulations at the three epochs shown whereas the bottom row refers to halos in each ensemble separately and at $z = 0$ only.

angular momentum

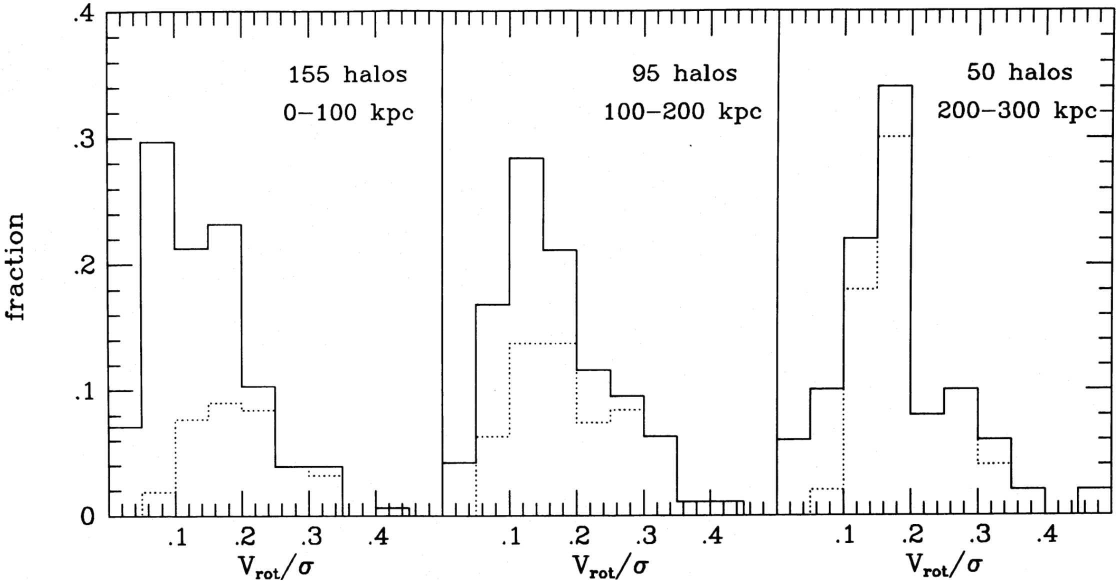
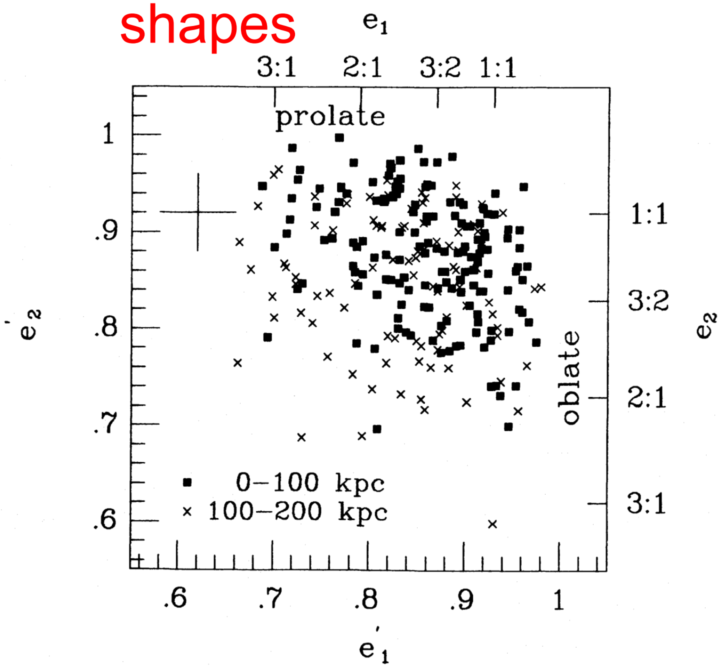


FIG. 7.—Histograms of the ratio of mean rotation speed $V_{rot}$ to three-dimensional velocity dispersion $\sigma$ of particles in successive 100 kpc shells. Halos with $V_c > 127$ km s$^{-1}$ in all nine simulations are considered. The solid lines refer to all such halos with a symmetric mass distribution and the dashed lines to the subset with a well-defined angular momentum (see text).

shapes



University of Durham

# The properties of CDM halos

Frenk, White, Davis, Efstathiou 1988

halo mass function

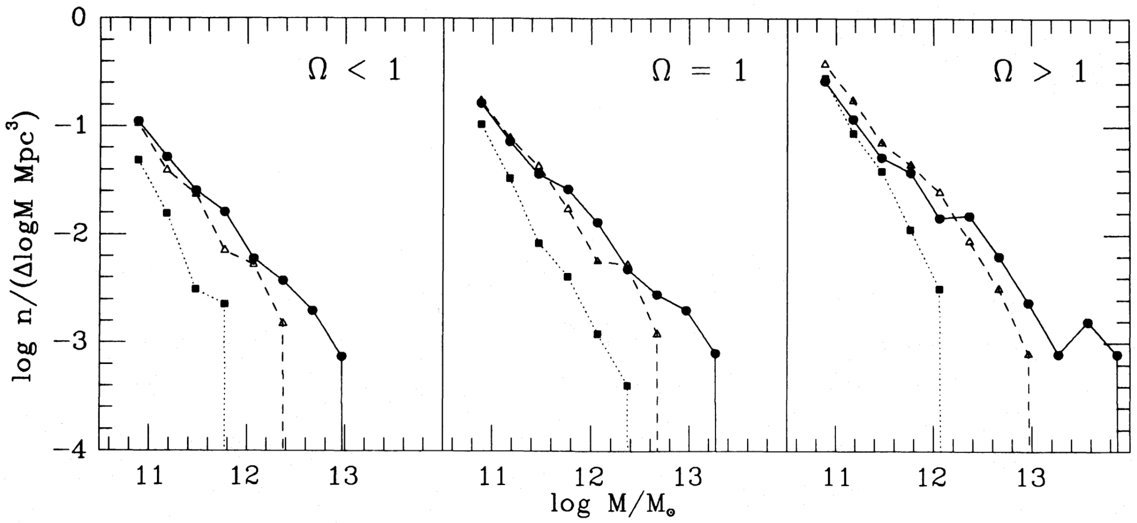


FIG. 10.—Number of halos per unit volume and per unit logarithmic mass interval in each of the three ensembles. Three epochs are shown: $z = 2.5$ (*dotted lines*), $z = 1$ (*dashed lines*), and $z = 0$ (*solid lines*).

Tully-Fisher

Mass-to-light ratio

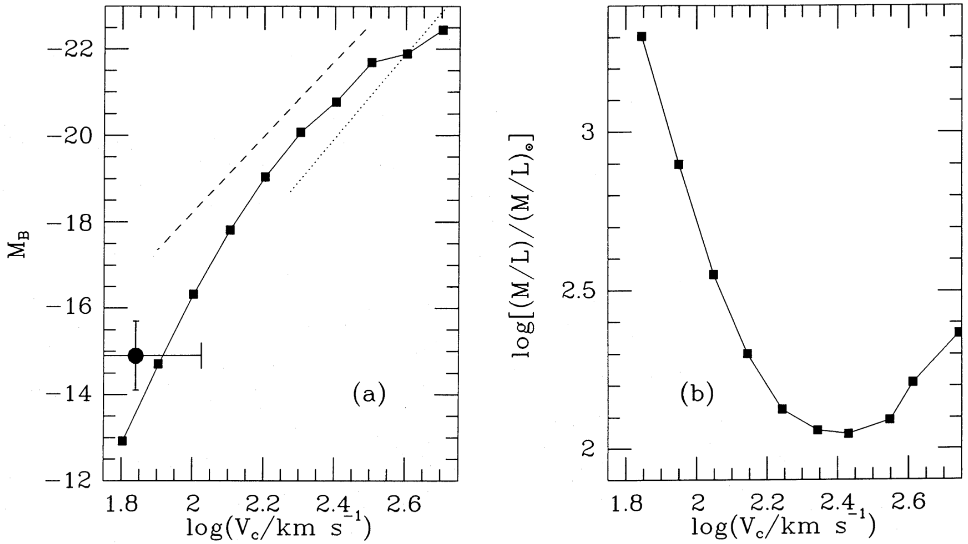


FIG. 12.—(*a*) The inferred luminosity-circular velocity relation for halos in the simulations. The "$B_T$ magnitude" of the "galaxy" associated with each halo is plotted against characteristic velocity. The dashed and dotted lines give the observed relations for spirals and ellipticals, respectively. The point with error bars refers to dwarf irregulars in the Virgo cluster. (See text for details.) (*b*) Predicted mass-to-light ratios in solar units for the "galaxies" associated with the halos in our simulations.

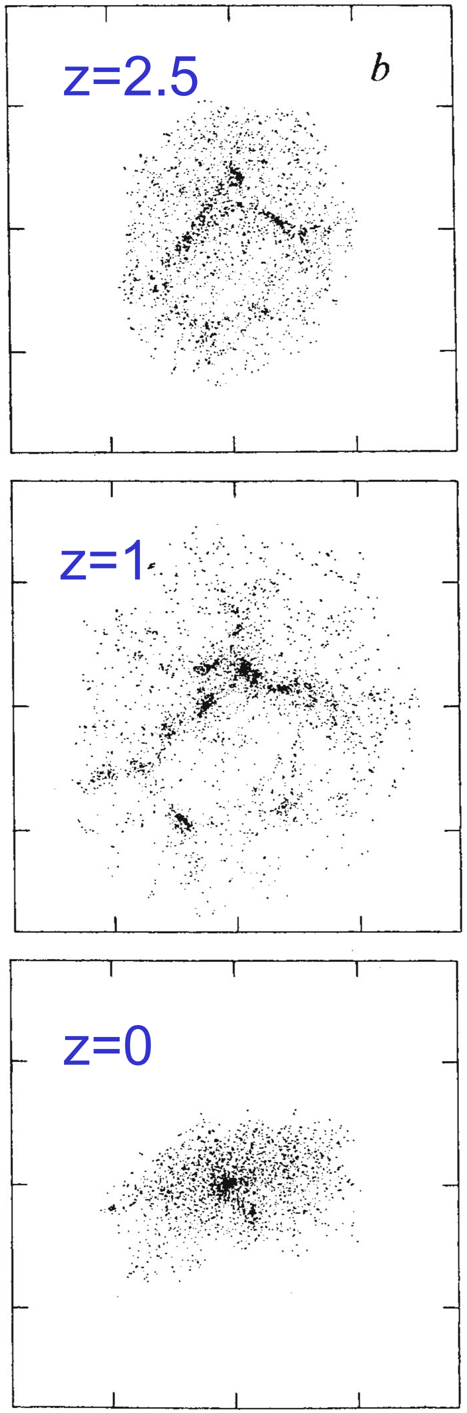
These results have not changed with larger simulations

NATURE VOL. 317 17 OCTOBER 1985
LETTERS TO NATURE

# Cold dark matter, the structure of galactic haloes and the origin of the Hubble sequence

**Carlos S. Frenk*, Simon D. M. White†,**
**George Efstathiou‡ & Marc Davis§**

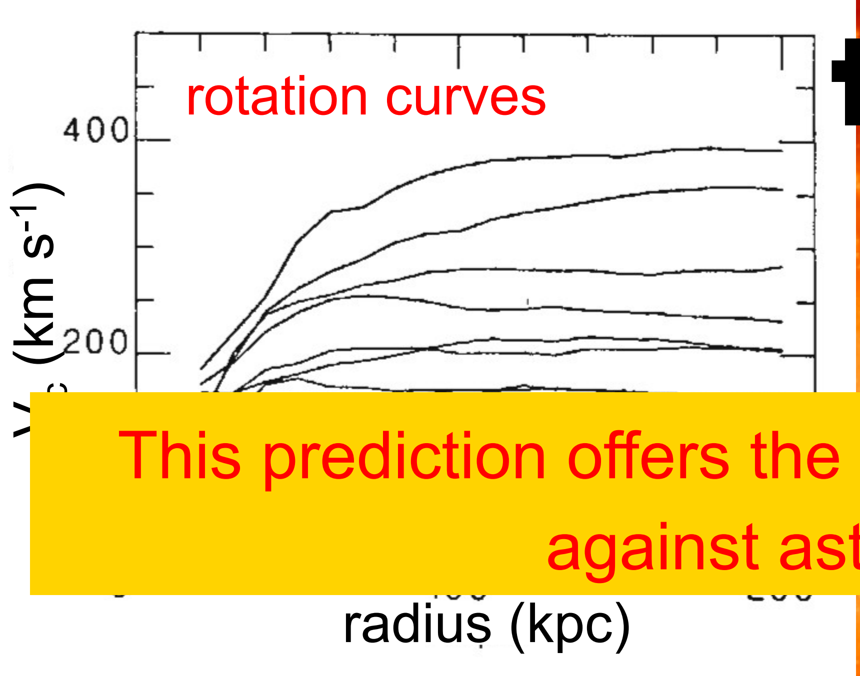
**A popular theory for galaxy formation holds that the Universe is dominated by exotic particles such as axions, photinos or gravitinos (collectively known as cold dark matter, CDM)[1–3]. This hypothesis can reconcile the aesthetically pleasing idea of a flat universe with the standard theory of primordial nucleosynthesis and with upper limits on anisotropies in the cosmic microwave background[4–6]. The resulting model is consistent with the observed dynamics of galaxy clustering only if galaxy formation is biased towards high-density regions[7,8]. We have shown that such a biased model successfully matches the distribution of galaxies on megaparsec (Mpc) scales[9]. If it is to be viable, it must also account for the structure of individual galaxies and their haloes. Here we describe a simulation of a flat CDM universe which can resolve structures of comparable scale to the luminous parts of galaxies. We find that such a universe produces objects with the abundance and characteristic properties inferred for galaxy haloes. Our results imply that merging plays an important part in galaxy formation and suggest a possible explanation for the Hubble sequence.**



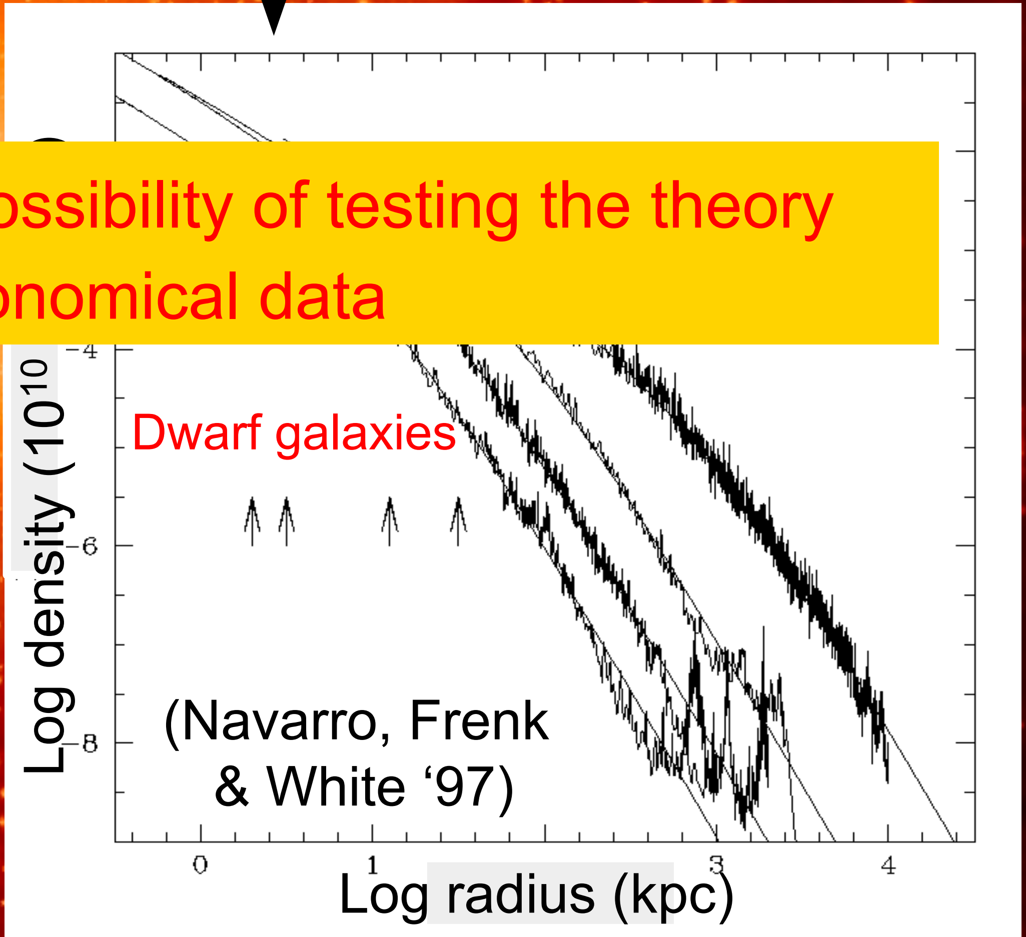
# CDM rules

1987

# The Density Profile of Cold Dark Matter Halos



20 years later



(Navarro, Frenk & White '97)

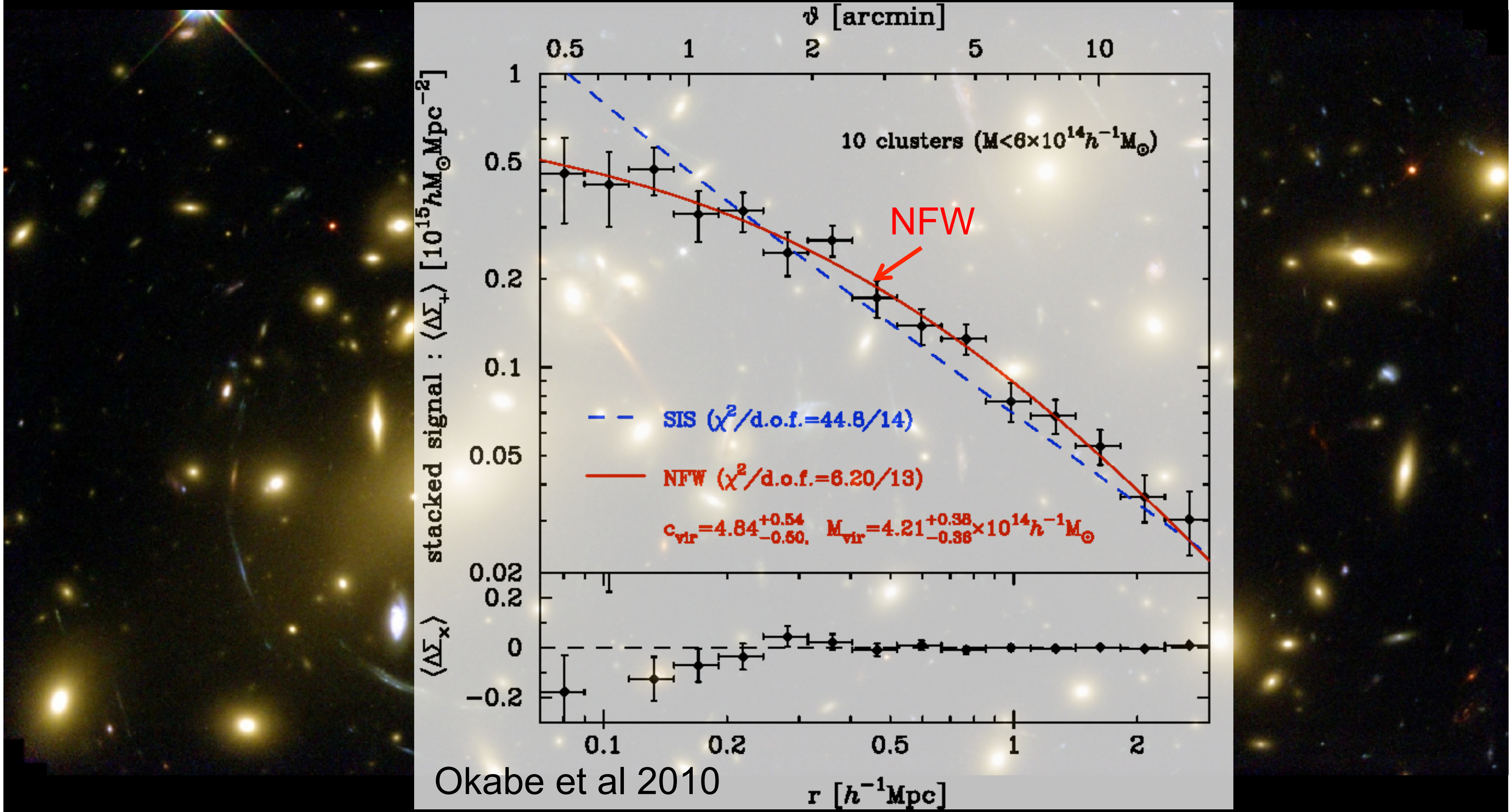
This prediction offers the possibility of testing the theory against astronomical data

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

# Is it really cold dark matter?

Peering deeper into the dark

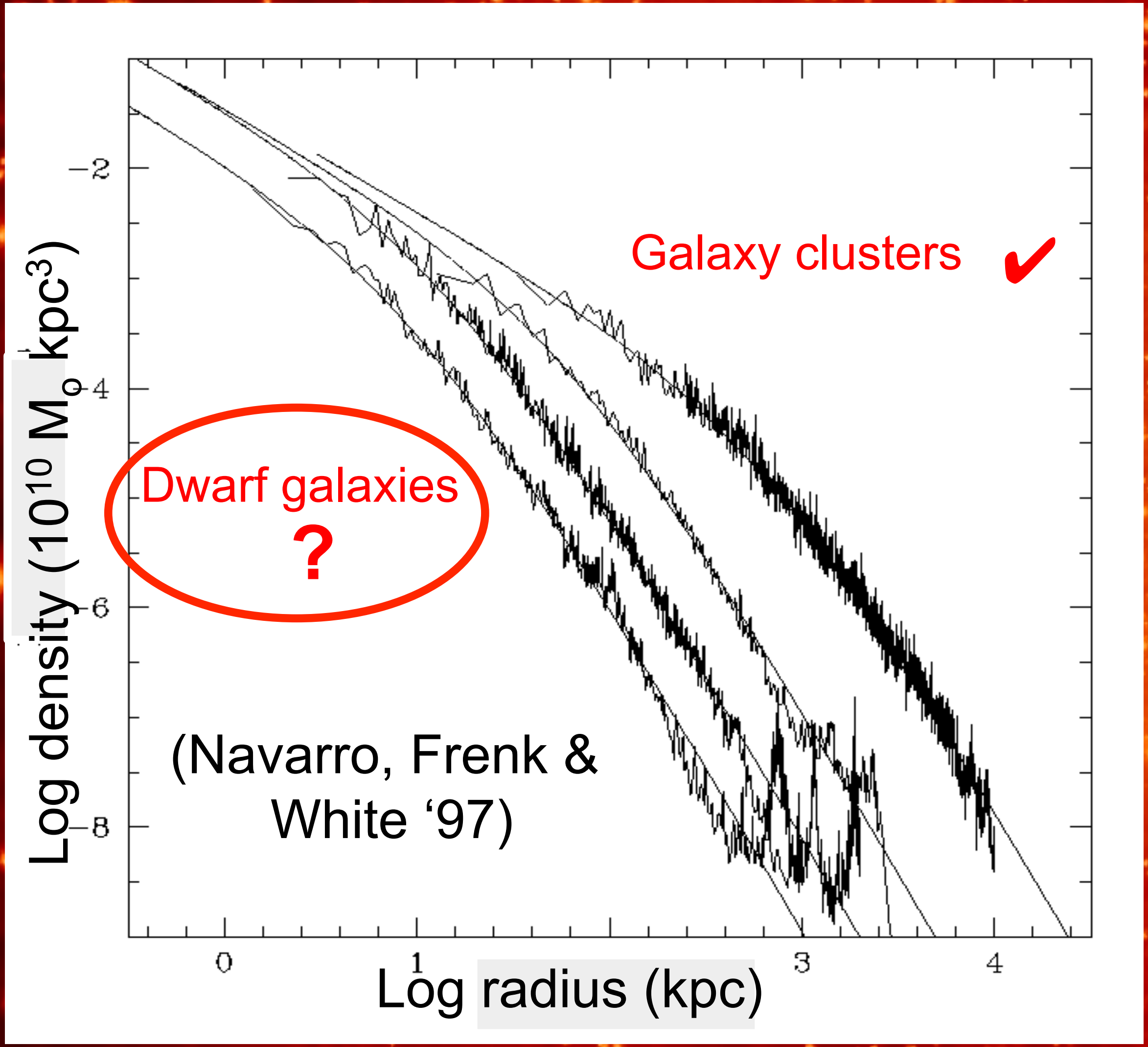
# Gravitational lensing



Okabe et al 2010

Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs

# The Density Profile of Cold Dark Matter Halos

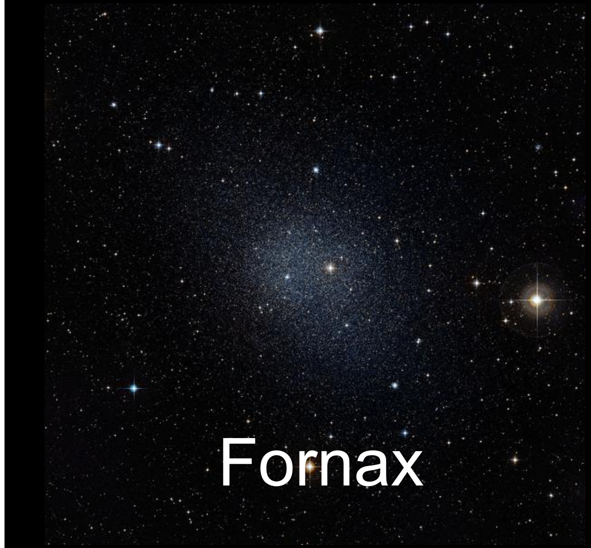


(Navarro, Frenk & White '97)

✓

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

# Dwarf galaxies around the Milky Way



Fornax

Sculptor

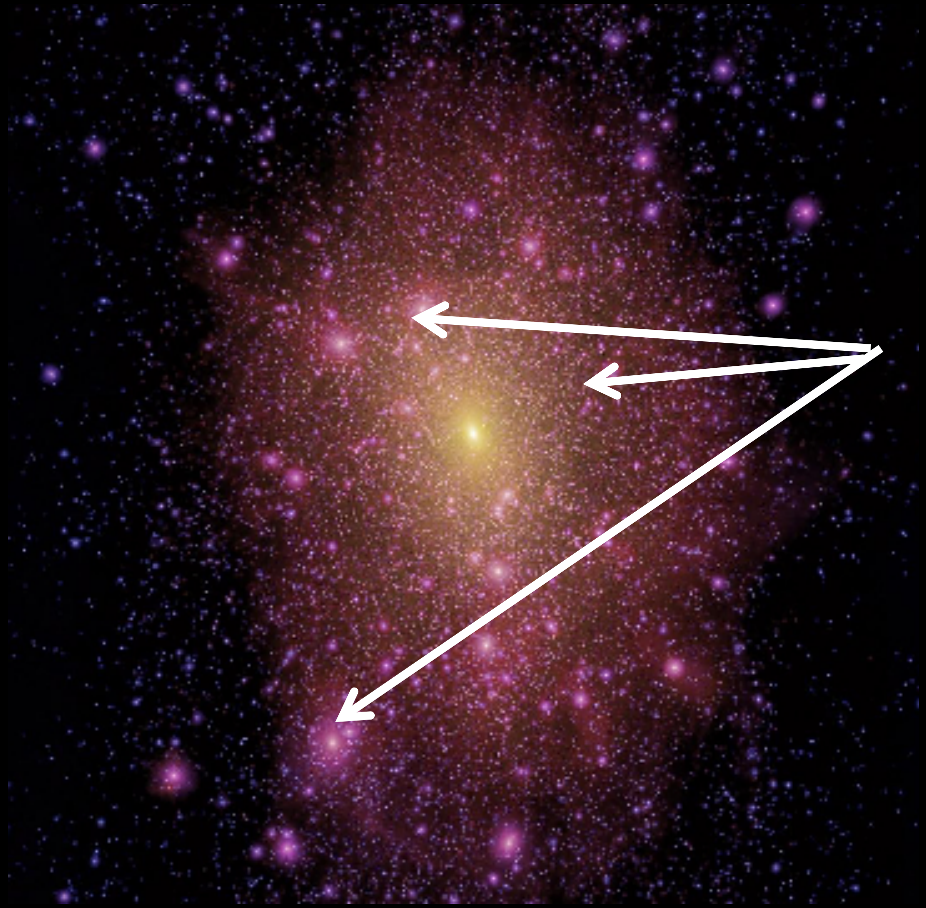
Leo I

Sextans

Carina

Sagittarius

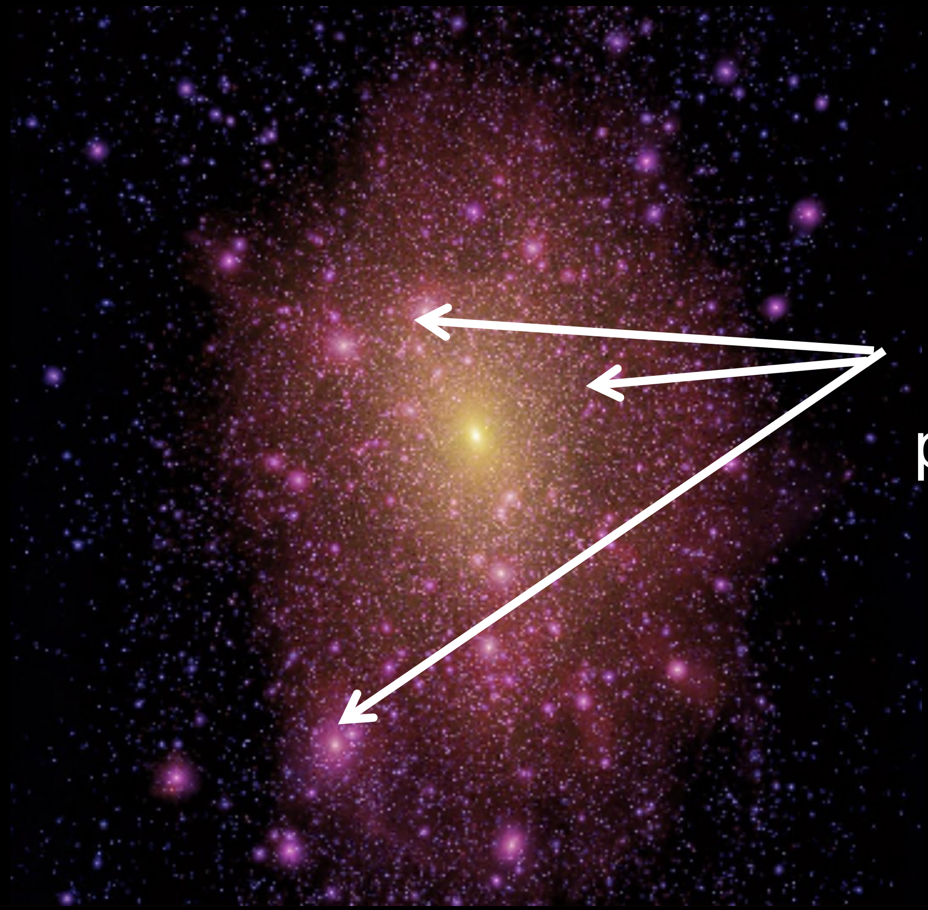
# cold dark matter



The Milky Way satellites would form in subhalos

Lovell, Eke, Frenk, Gao, Jenkins, White, Theuns et al 2011

# cold dark matter



Recent data suggest that CDM halos do not have the right properties to host the satellites

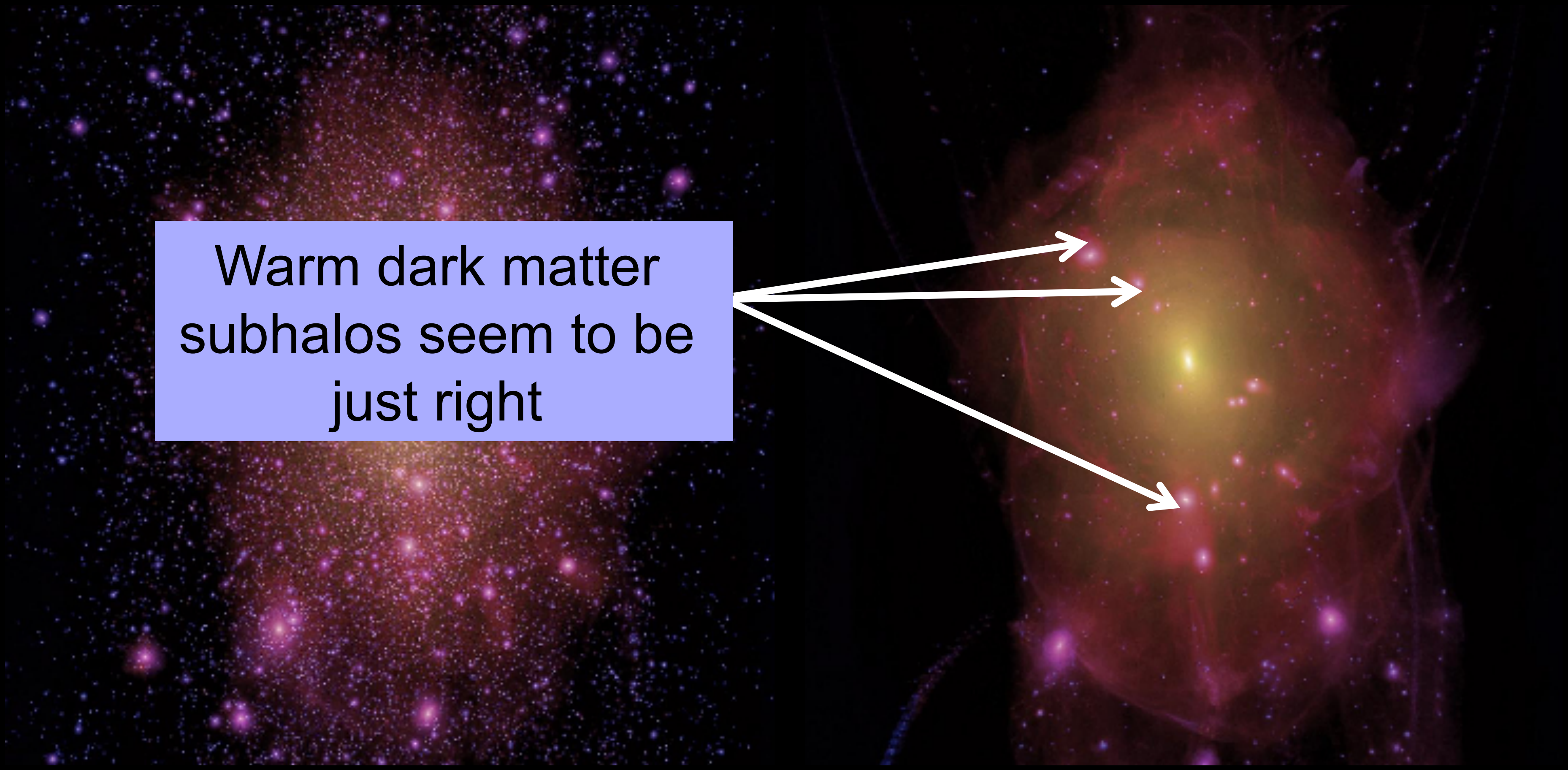
Lovell, Eke, Frenk, Gao, Jenkins, White, Theuns et al 2011

# Particle dark matter candidates

| Type | example | mass |
|---|---|---|
| ~~hot~~ | ~~neutrino~~ | ~~a few eV~~ |
| warm | sterile $\nu$<br>majoron | keV-MeV |
| cold | axion<br>neutralino | $10^{-5}$eV->100 GeV |

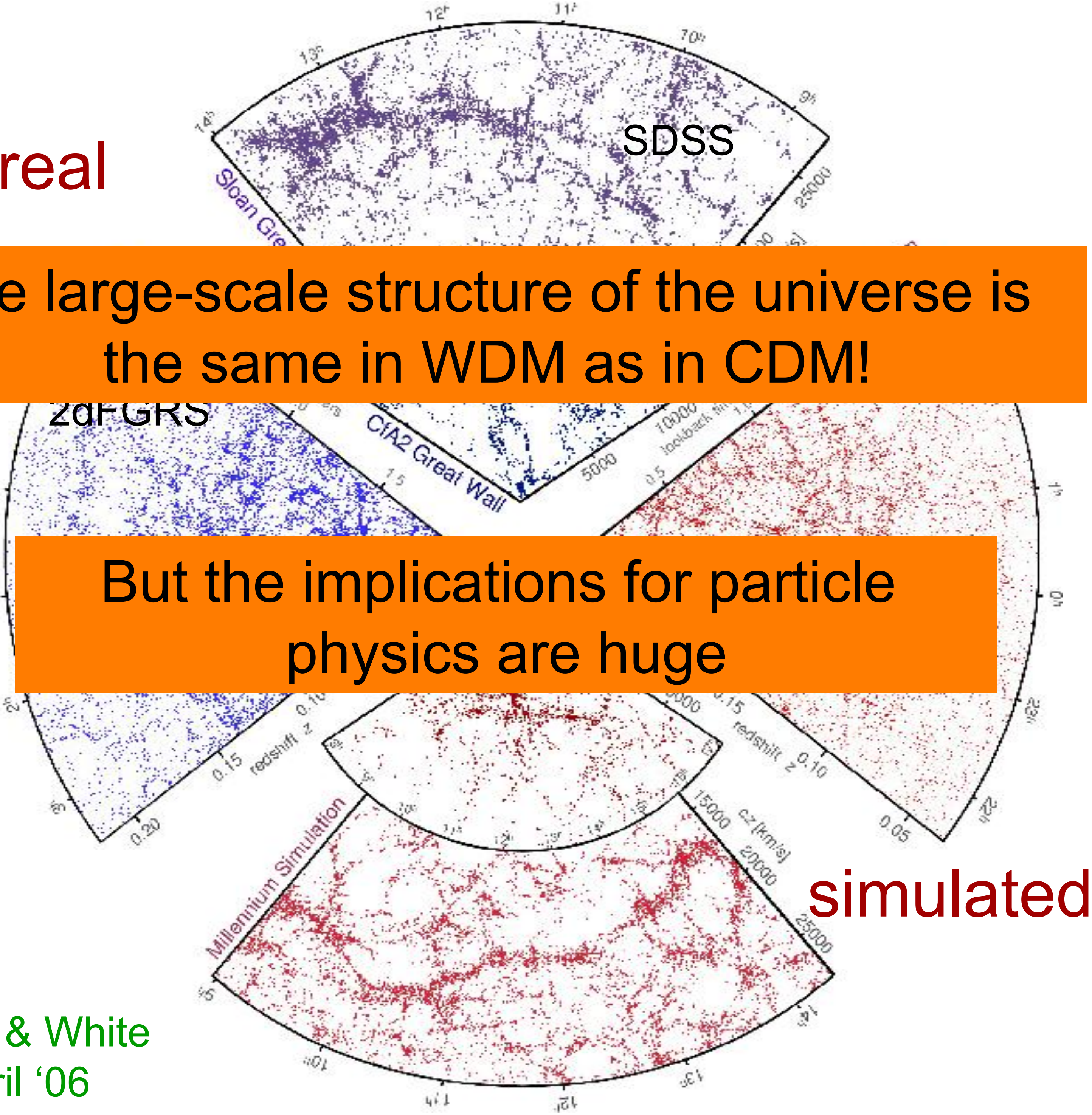
cold dark matter

warm dark matter



Warm dark matter subhalos seem to be just right

Lovell, Eke, Frenk, Gao, Jenkins, White, Theuns et al 2011



real

The large-scale structure of the universe is the same in WDM as in CDM!

But the implications for particle physics are huge

simulated

Springel, Frenk & White
Nature, April ‘06

# Searching for the dark matter ?

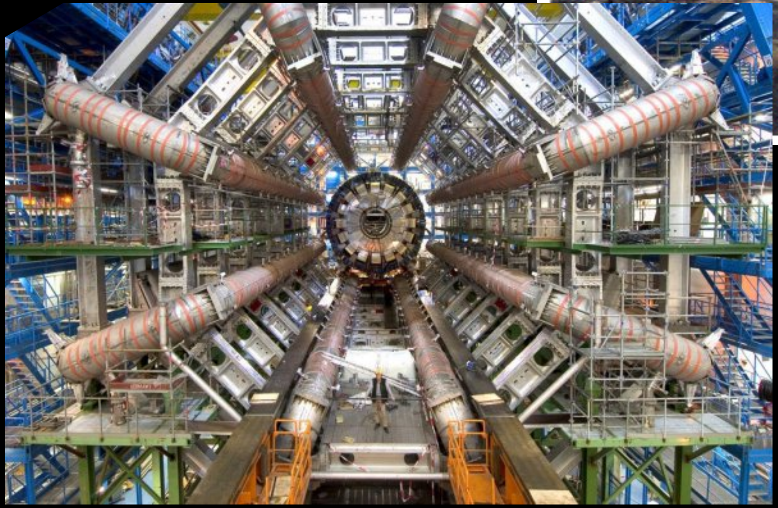
# Cold dark matter ?

## Dark matter discovery possible in several ways

Annihilation radiation

Direct detection

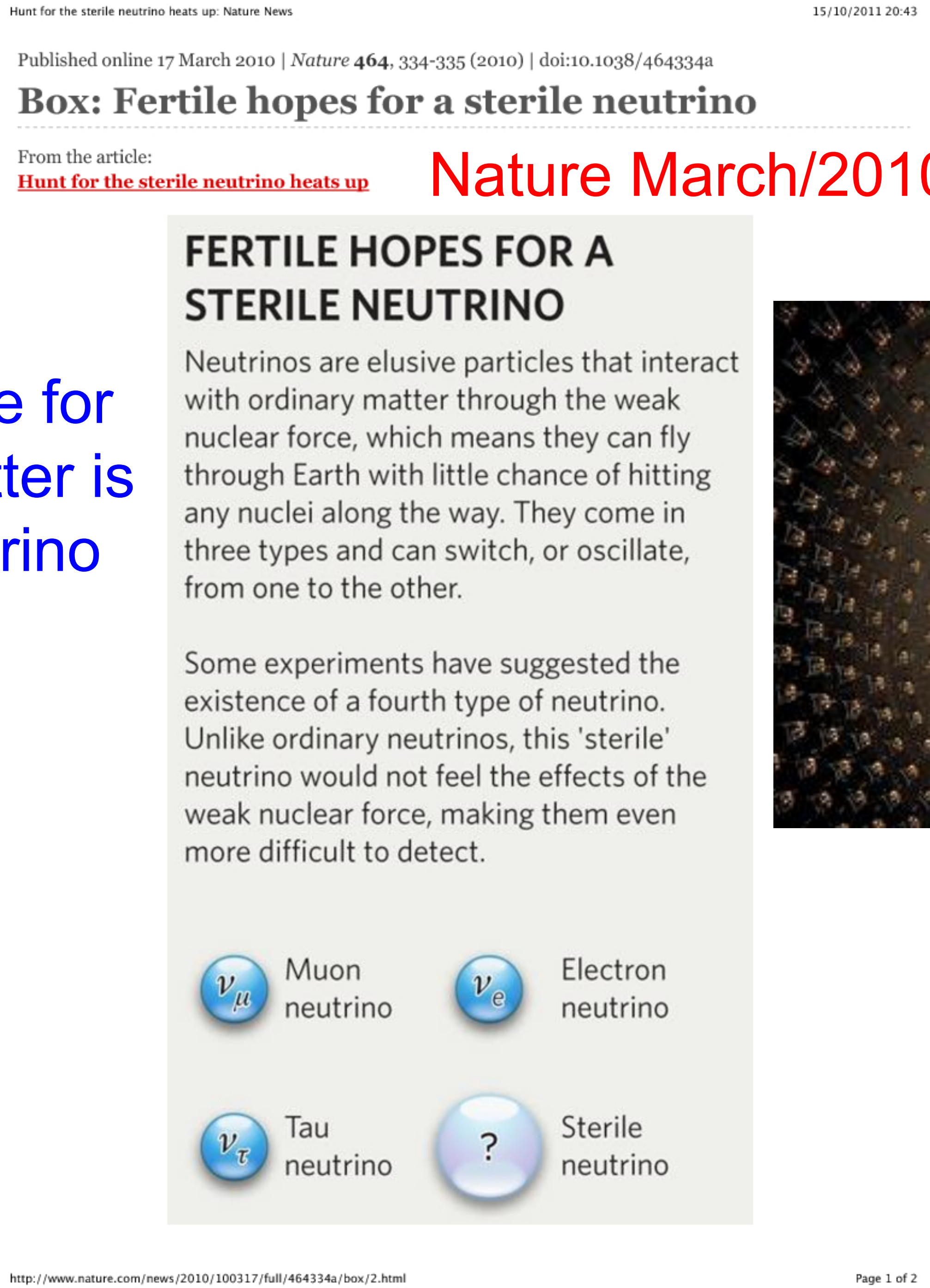
UK DM search
(Boulby mine)



Evidence for SUSY

Best candidate for warm dark matter is a sterile neutrino

Nature March/2010



Hunt for the sterile neutrino heats up: Nature News 15/10/2011 20:43

Published online 17 March 2010 | *Nature* **464**, 334-335 (2010) | doi:10.1038/464334a

## Box: Fertile hopes for a sterile neutrino

From the article:
**Hunt for the sterile neutrino heats up**

### FERTILE HOPES FOR A STERILE NEUTRINO

Neutrinos are elusive particles that interact with ordinary matter through the weak nuclear force, which means they can fly through Earth with little chance of hitting any nuclei along the way. They come in three types and can switch, or oscillate, from one to the other.

Some experiments have suggested the existence of a fourth type of neutrino. Unlike ordinary neutrinos, this 'sterile' neutrino would not feel the effects of the weak nuclear force, making them even more difficult to detect.

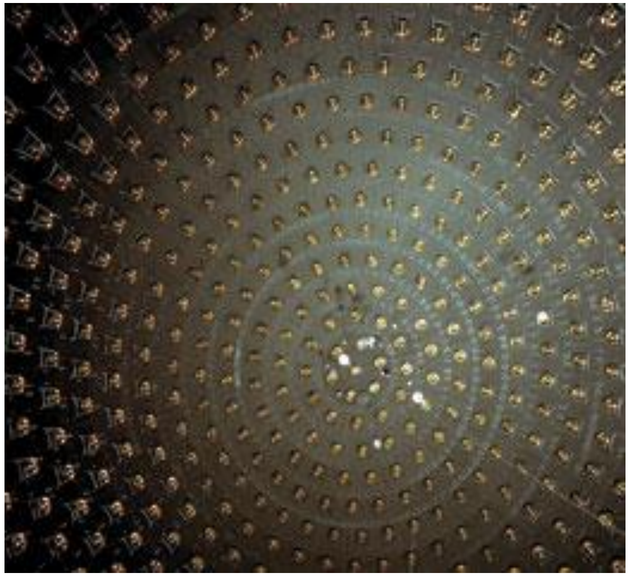
$\nu_\mu$ Muon neutrino

$\nu_e$ Electron neutrino

$\nu_\tau$ Tau neutrino

? Sterile neutrino

http://www.nature.com/news/2010/100317/full/464334a/box/2.html Page 1 of 2



MiniBoone (Fermilab)

There has been great progress in cosmology in the past 30 years

… and there is still a lot more to come

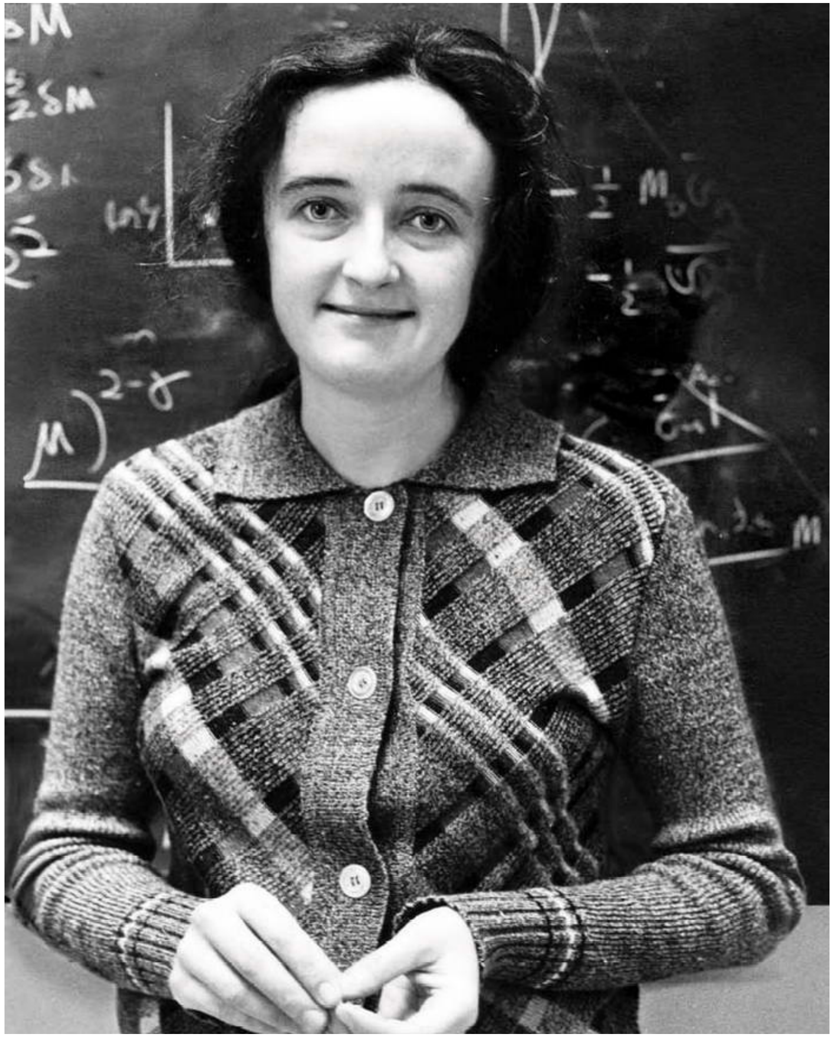
# Chapter 4 – The large-scale structure

Simon White

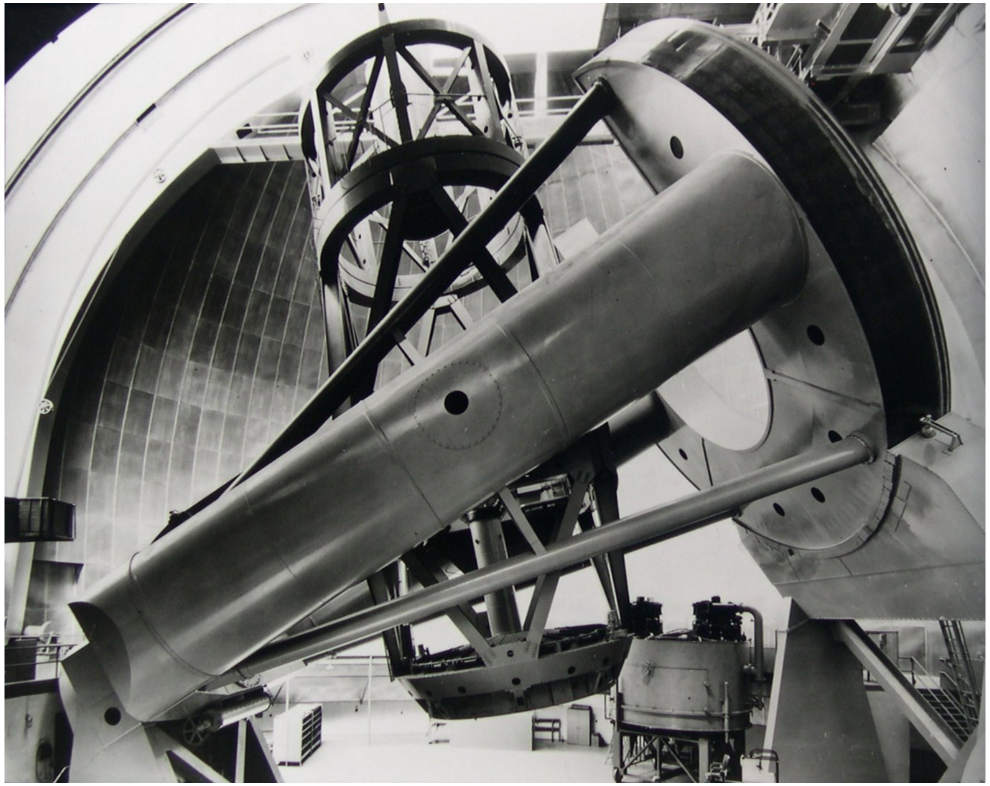
Berkeley 1981

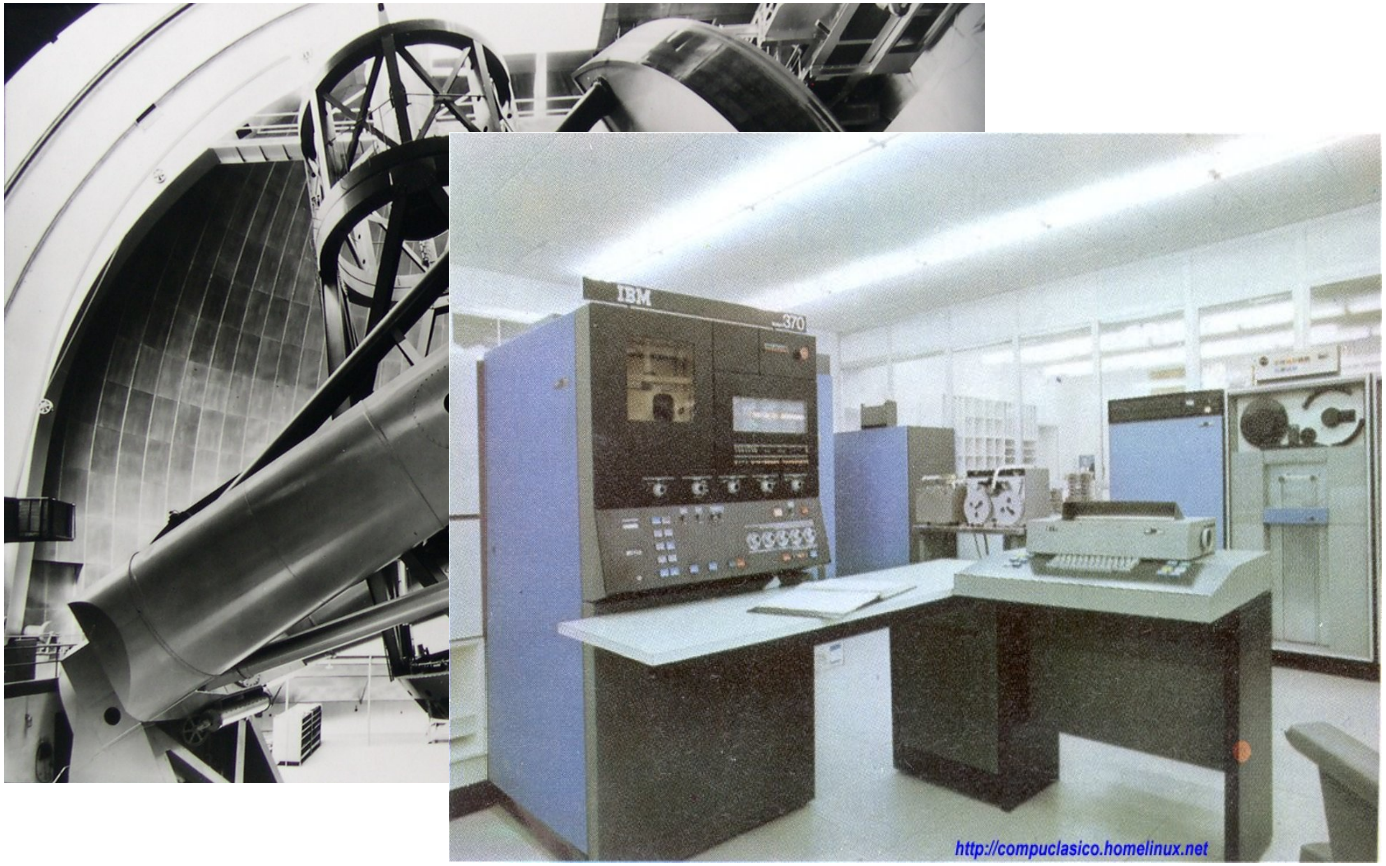
Fritz Zwicky
Unseen ("dark") matter (1933)

Fritz Zwicky
Unseen (“dark”) matter (1933)



Beatrice Tinsley
Galaxy evolution (1970's)





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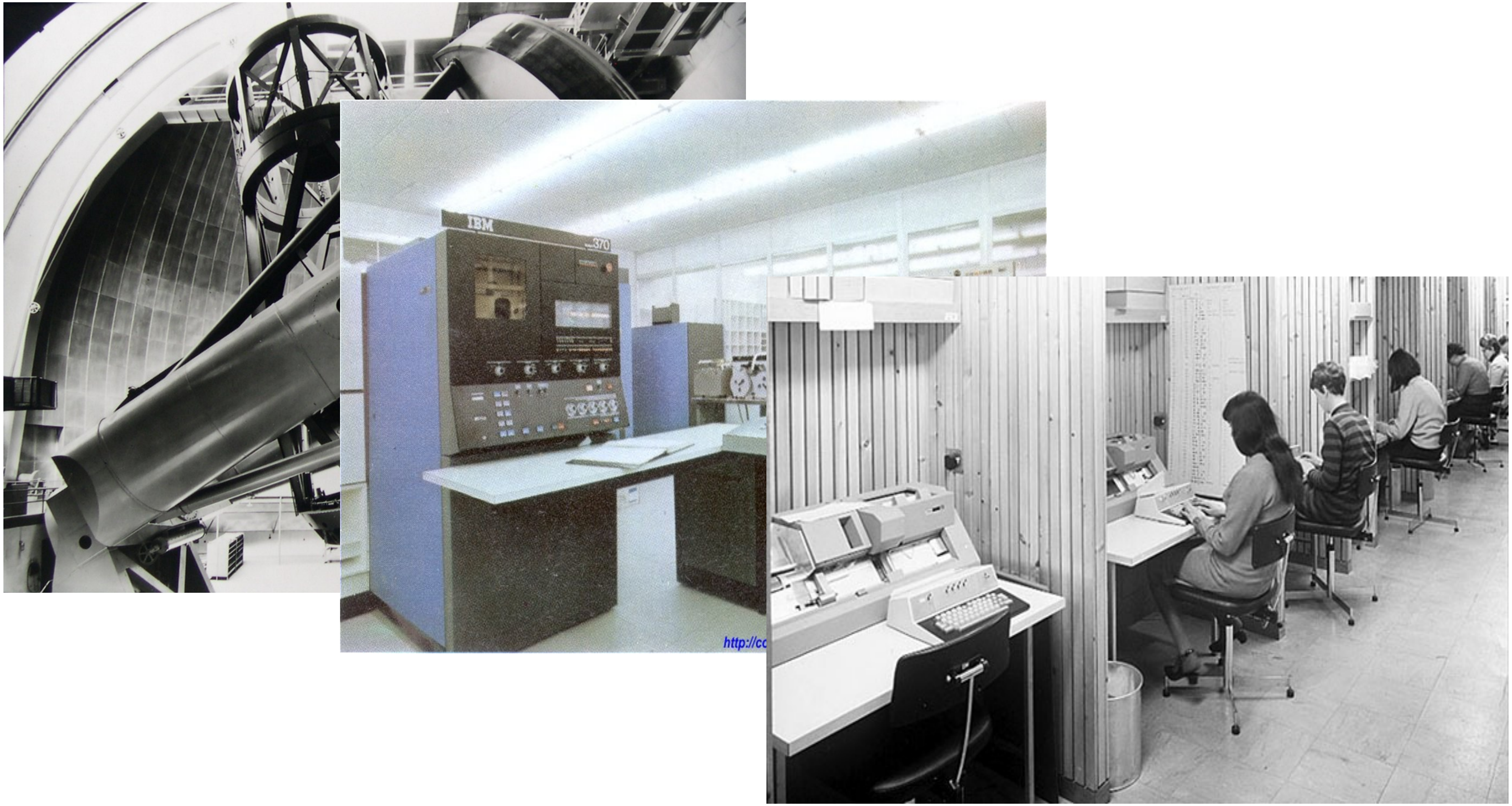
IBM
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HYDROSTATICS (METRIC)
INPUT CREDIBILITY (METRIC)
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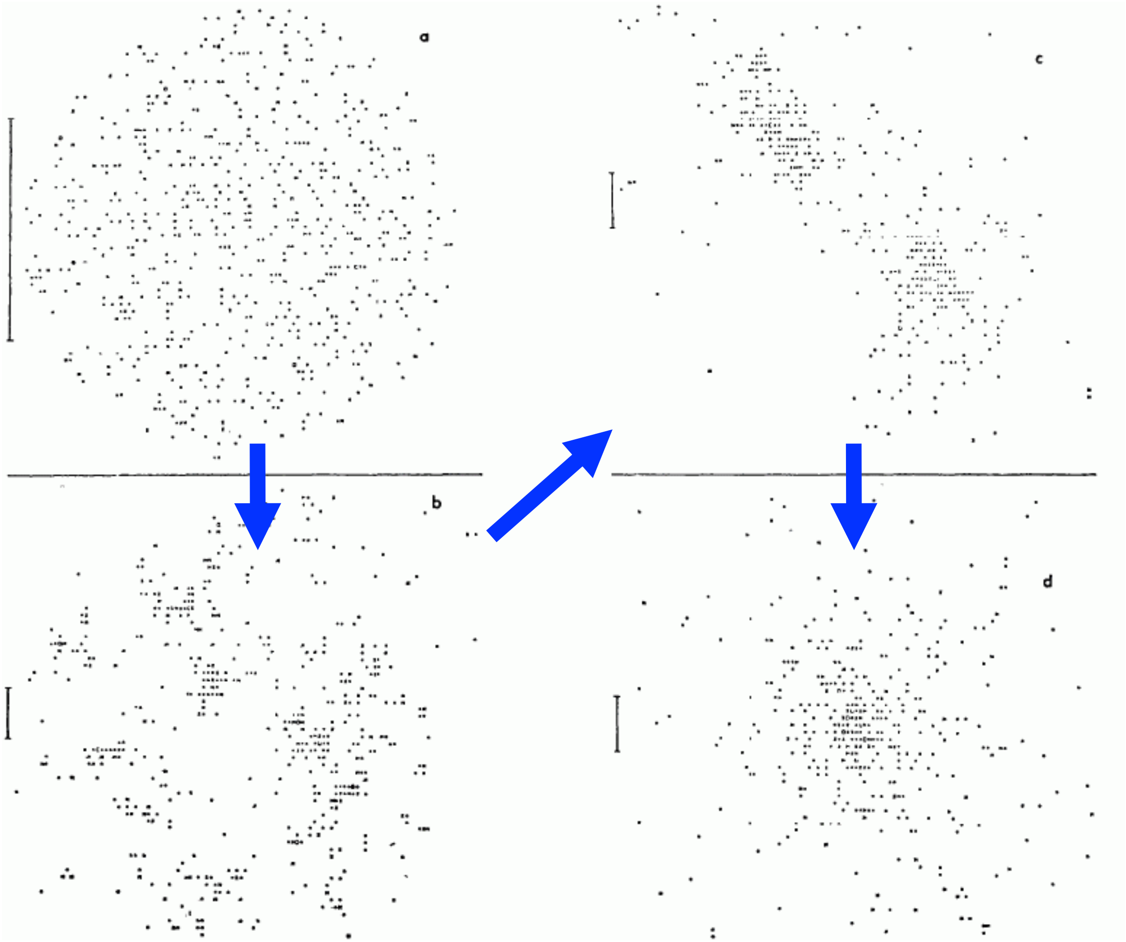
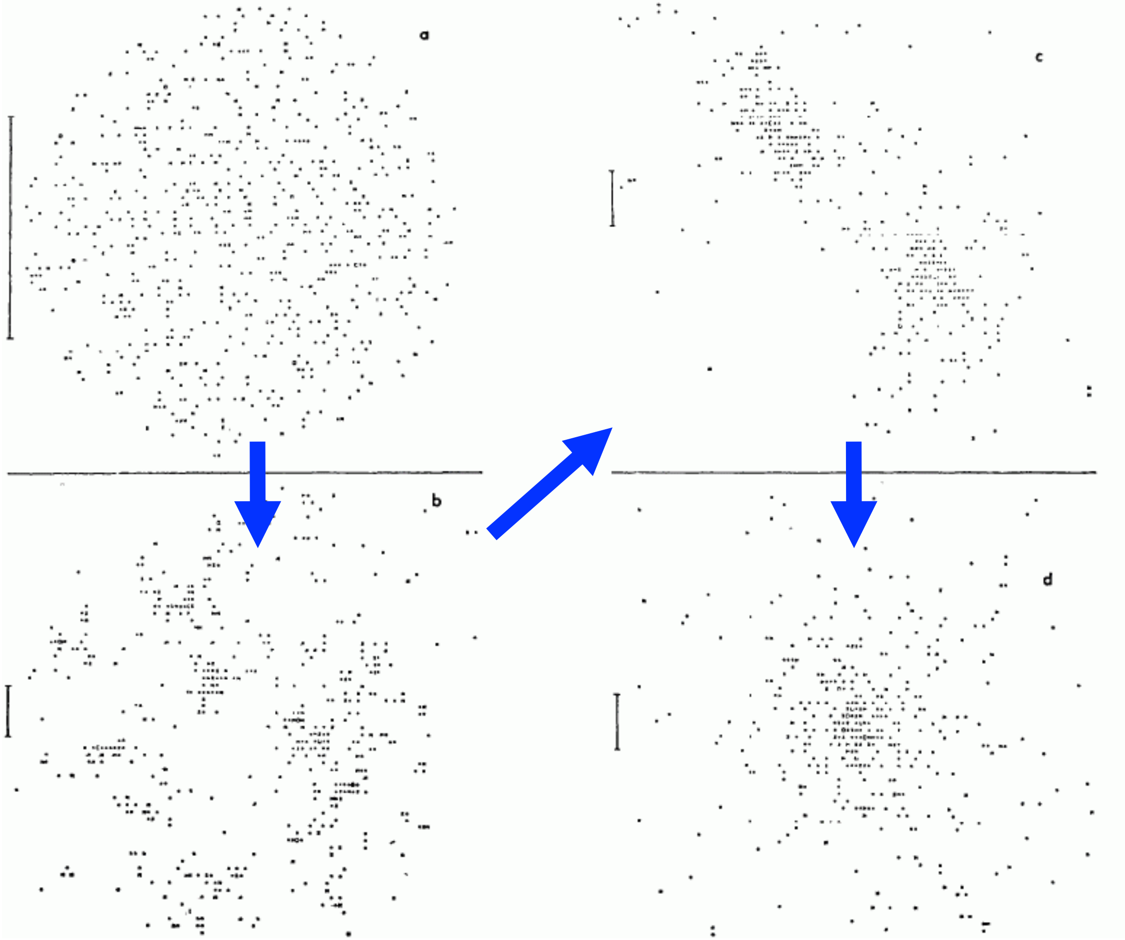
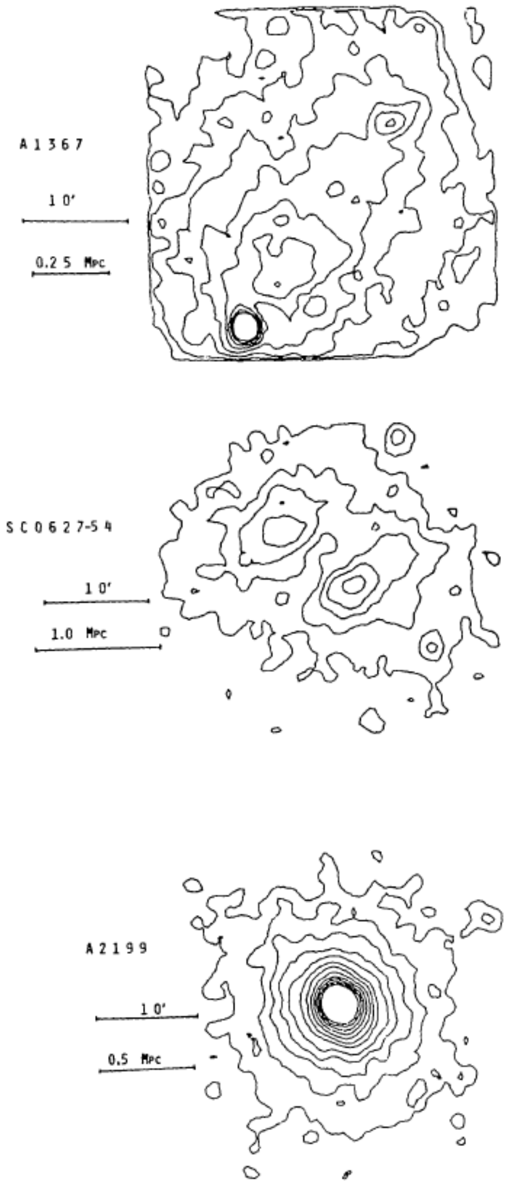
STATICAL (METRIC) STABILITY
CENT



cluster simulation 1977

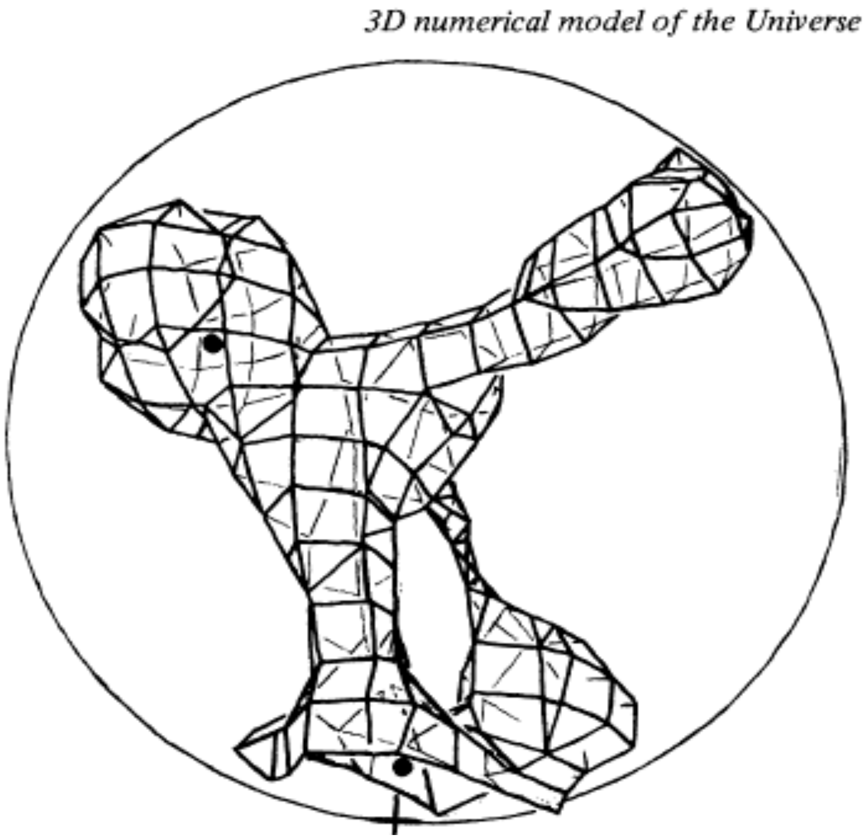


cluster simulation 1977

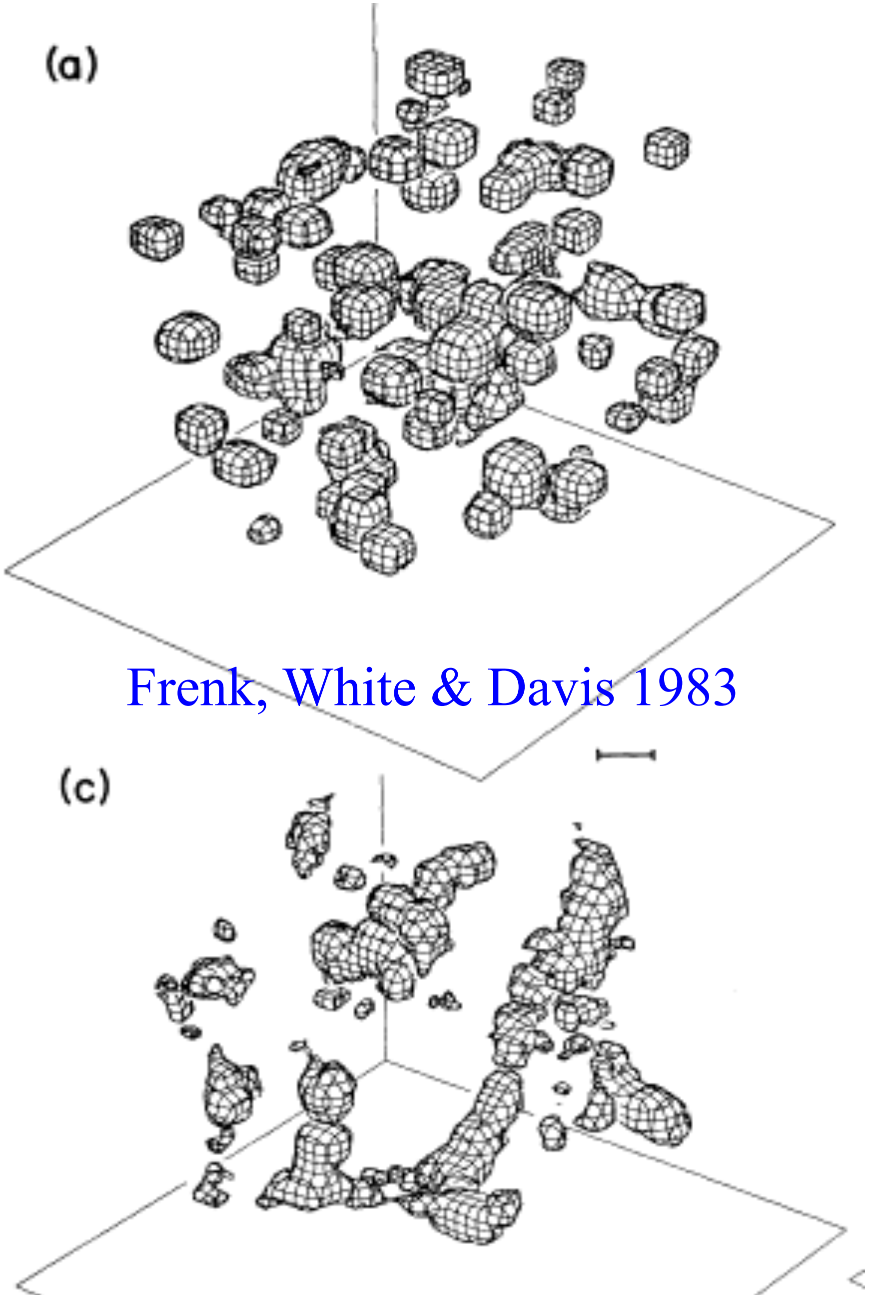


cluster images 1980

# Chickens and blobs (1981-1982)



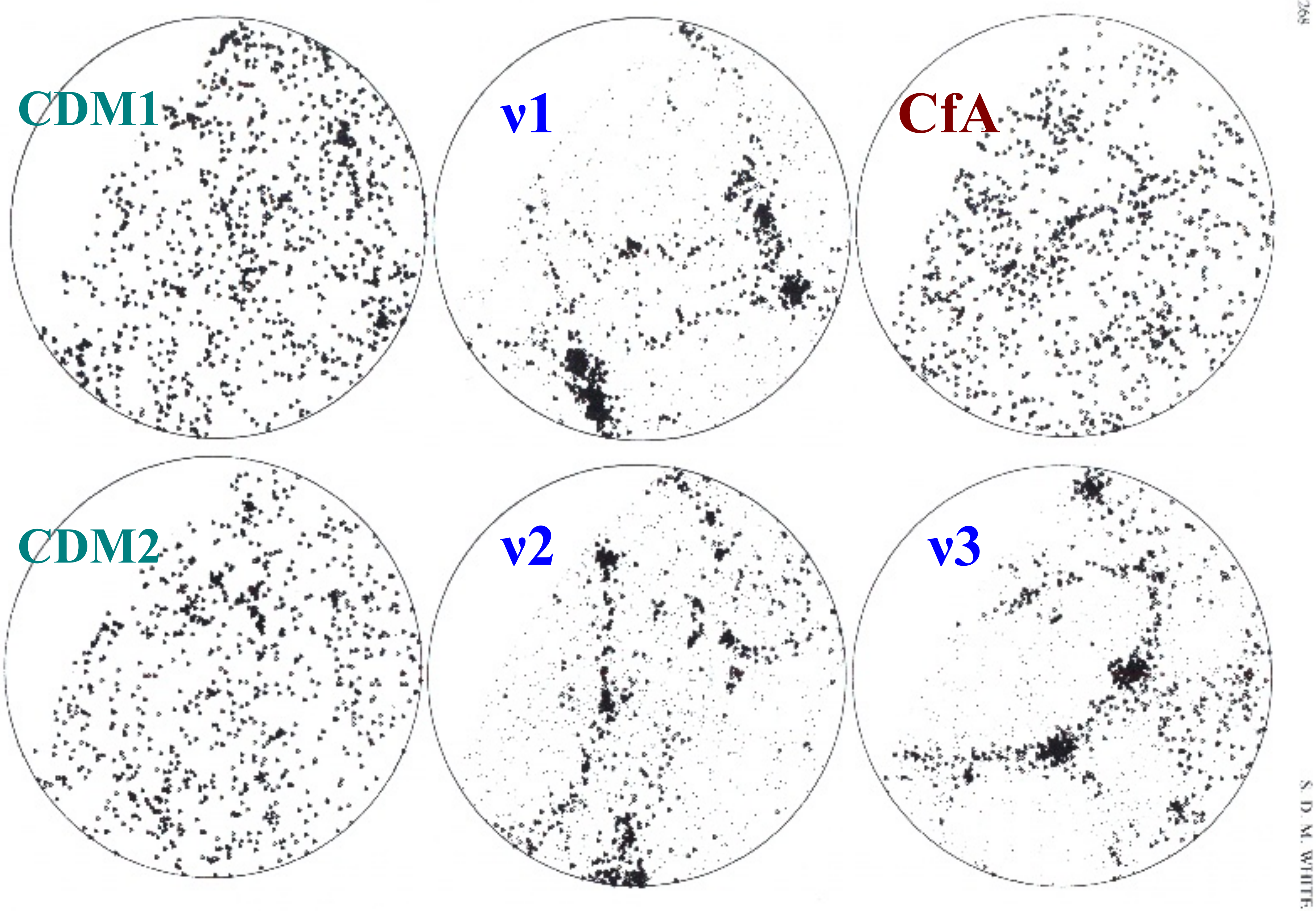
Klypin & Shandarin 1983



Frenk, White & Davis 1983

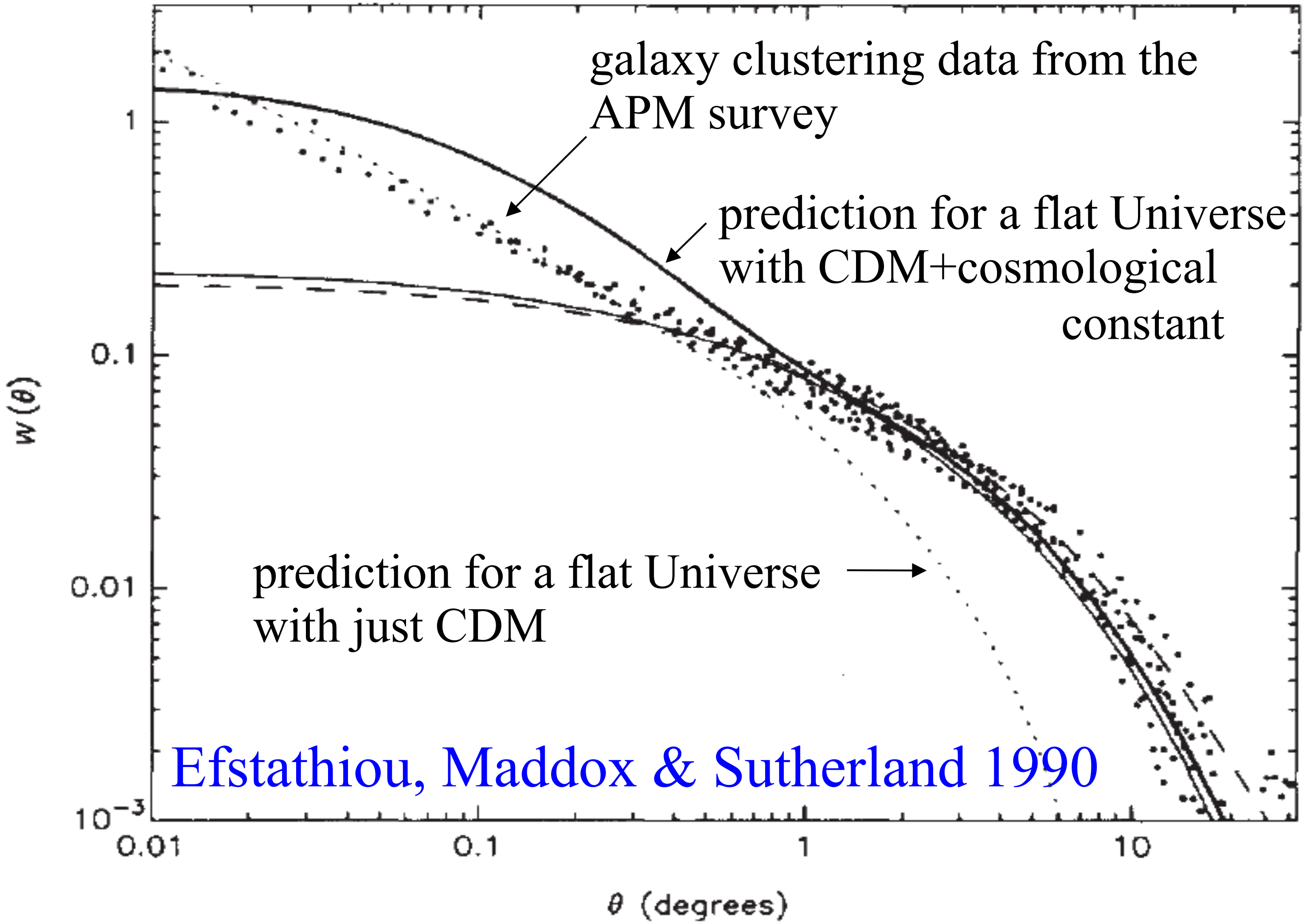
# Excluding massive neutrinos as the Dark Matter

White, Frenk & Davis 1983 -- confirmed by the Fermilab MINOS experiment in 2006



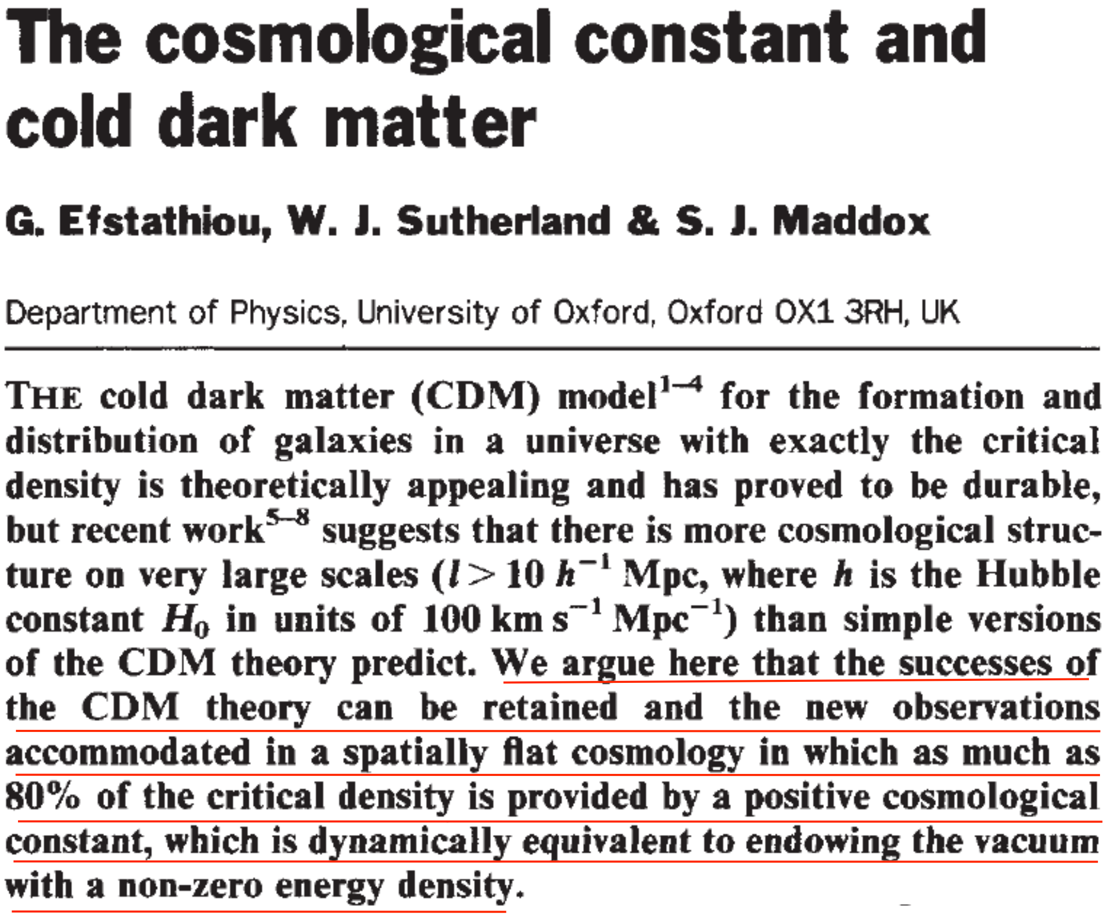
# But standard CDM needed something else...

...an open Universe?
...more relativistic neutrinos?
...a cosmological constant?



Efstathiou, Maddox & Sutherland 1990

Nature 1990



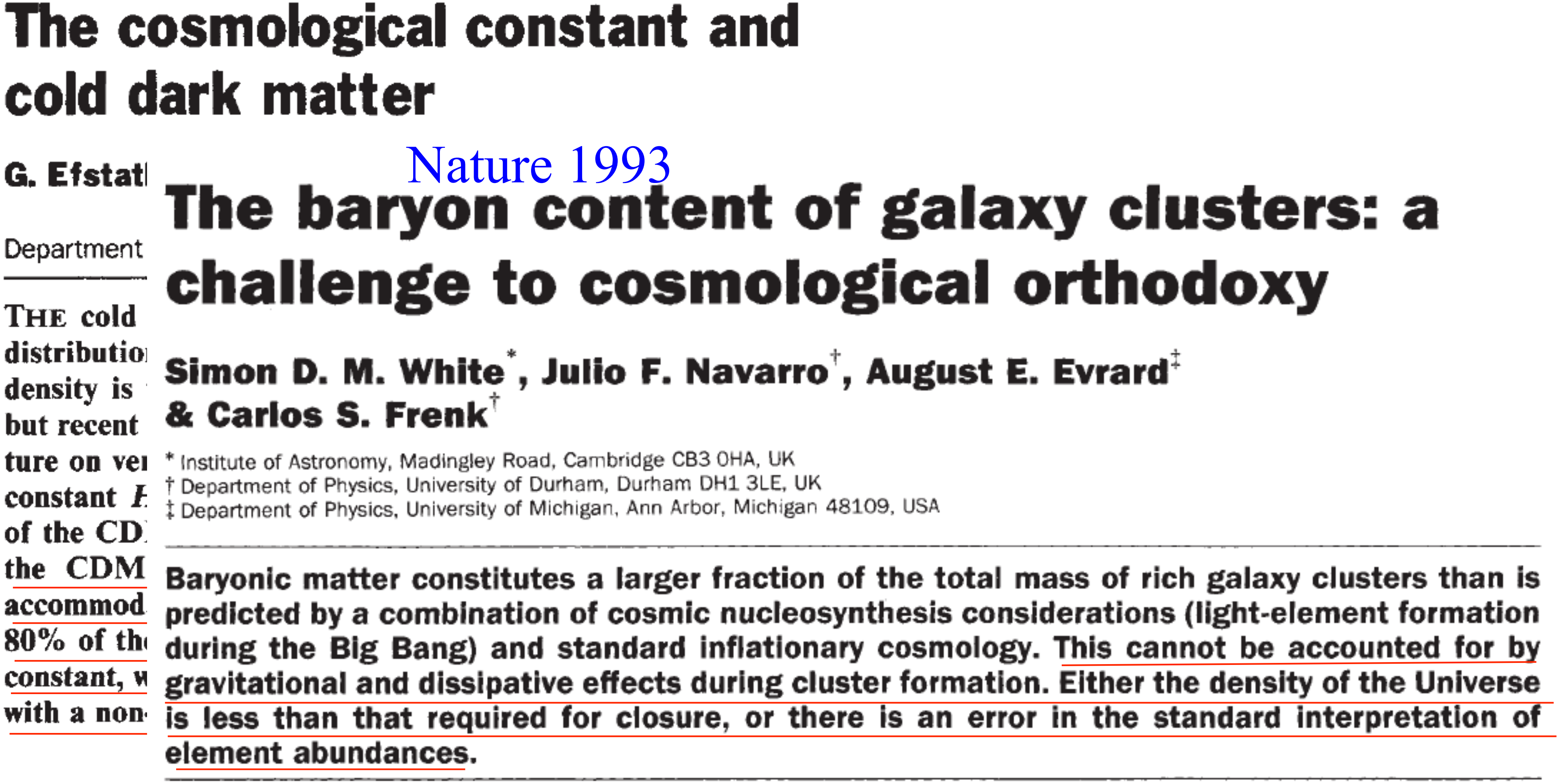
# The cosmological constant and cold dark matter

**G. Efstathiou, W. J. Sutherland & S. J. Maddox**

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ Mpc, where $h$ is the Hubble constant $H_0$ in units of 100 km $s^{-1}$ $Mpc^{-1}$) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density.

Nature 1990



# The cosmological constant and cold dark matter

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constant, w
with a non

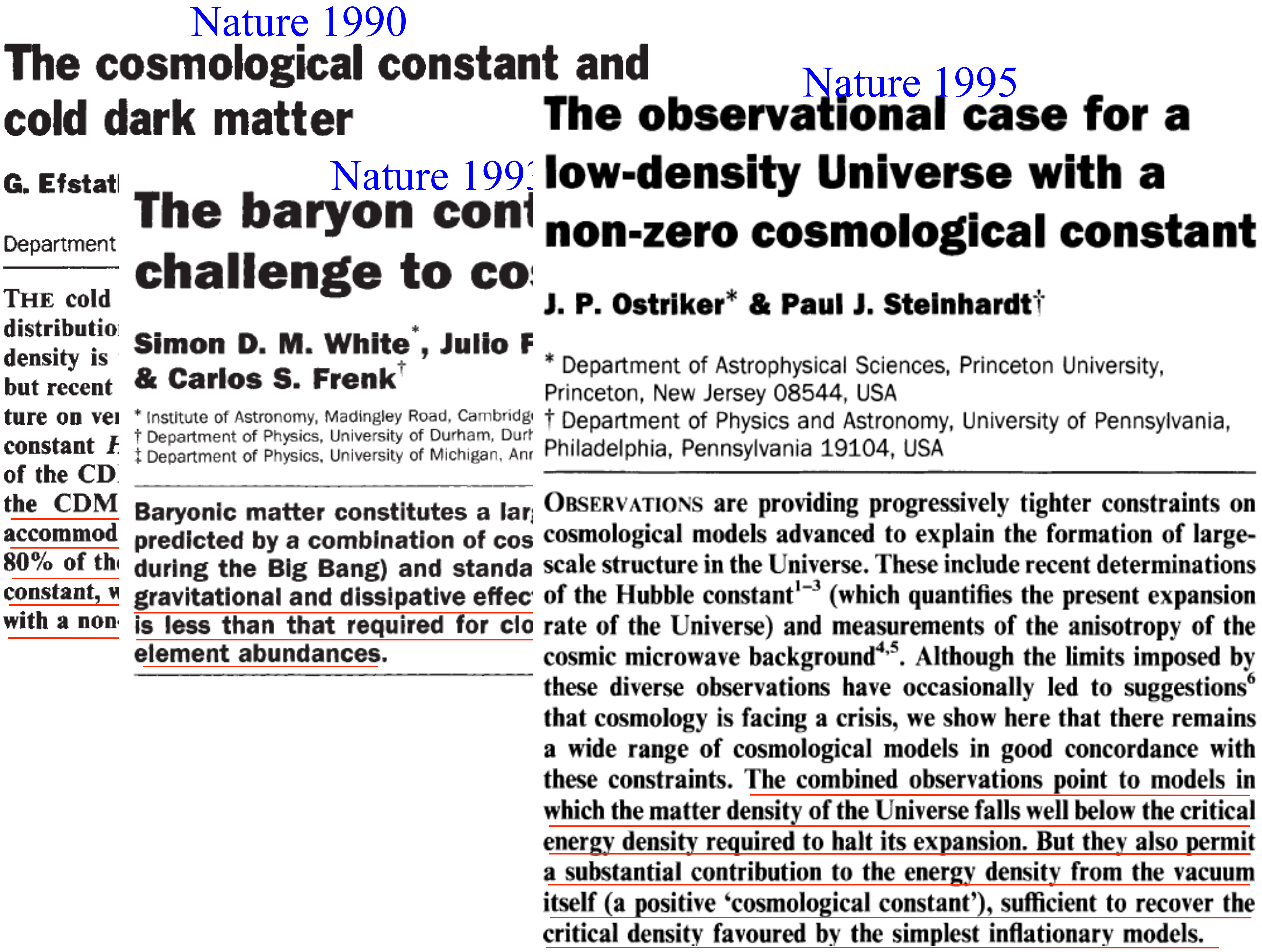
Nature 1993

# The baryon content of galaxy clusters: a challenge to cosmological orthodoxy

**Simon D. M. White**[*], **Julio F. Navarro**[†], **August E. Evrard**[‡] **& Carlos S. Frenk**[†]

[*] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
[†] Department of Physics, University of Durham, Durham DH1 3LE, UK
[‡] Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

**Baryonic matter constitutes a larger fraction of the total mass of rich galaxy clusters than is predicted by a combination of cosmic nucleosynthesis considerations (light-element formation during the Big Bang) and standard inflationary cosmology. This cannot be accounted for by gravitational and dissipative effects during cluster formation. Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.**



Nature 1990

# The cosmological constant and cold dark matter

G. Efstat

Department

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Nature 199

# The baryon cont challenge to co

**Simon D. M. White***, **Julio F**
**& Carlos S. Frenk**†

* Institute of Astronomy, Madingley Road, Cambridg
† Department of Physics, University of Durham, Dur
‡ Department of Physics, University of Michigan, Ann

**Baryonic matter constitutes a lar**
**predicted by a combination of cos**
**during the Big Bang) and standa**
**gravitational and dissipative effec**
**is less than that required for clo**
**element abundances.**

---

Nature 1995

# The observational case for a low-density Universe with a non-zero cosmological constant

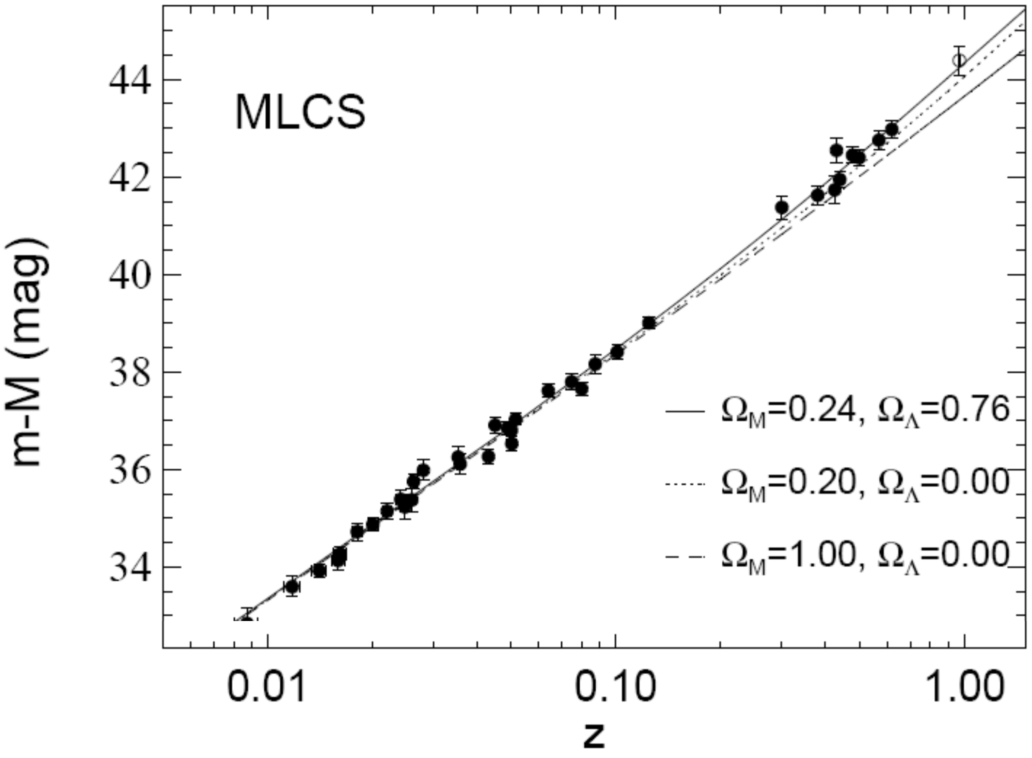
**J. P. Ostriker* & Paul J. Steinhardt**†

* Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA
† Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determinations of the Hubble constant[1–3] (which quantifies the present expansion rate of the Universe) and measurements of the anisotropy of the cosmic microwave background[4,5]. Although the limits imposed by these diverse observations have occasionally led to suggestions[6] that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. The combined observations point to models in which the matter density of the Universe falls well below the critical energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive 'cosmological constant'), sufficient to recover the critical density favoured by the simplest inflationary models.

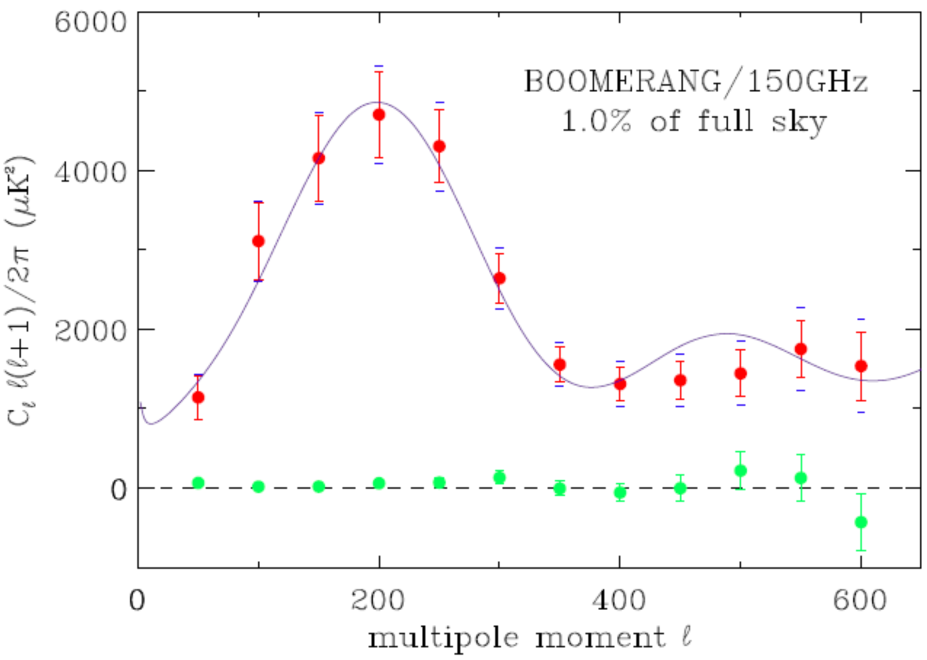
# Prevailing theoretical prejudice is sometimes right...

...the Universe is accelerating..



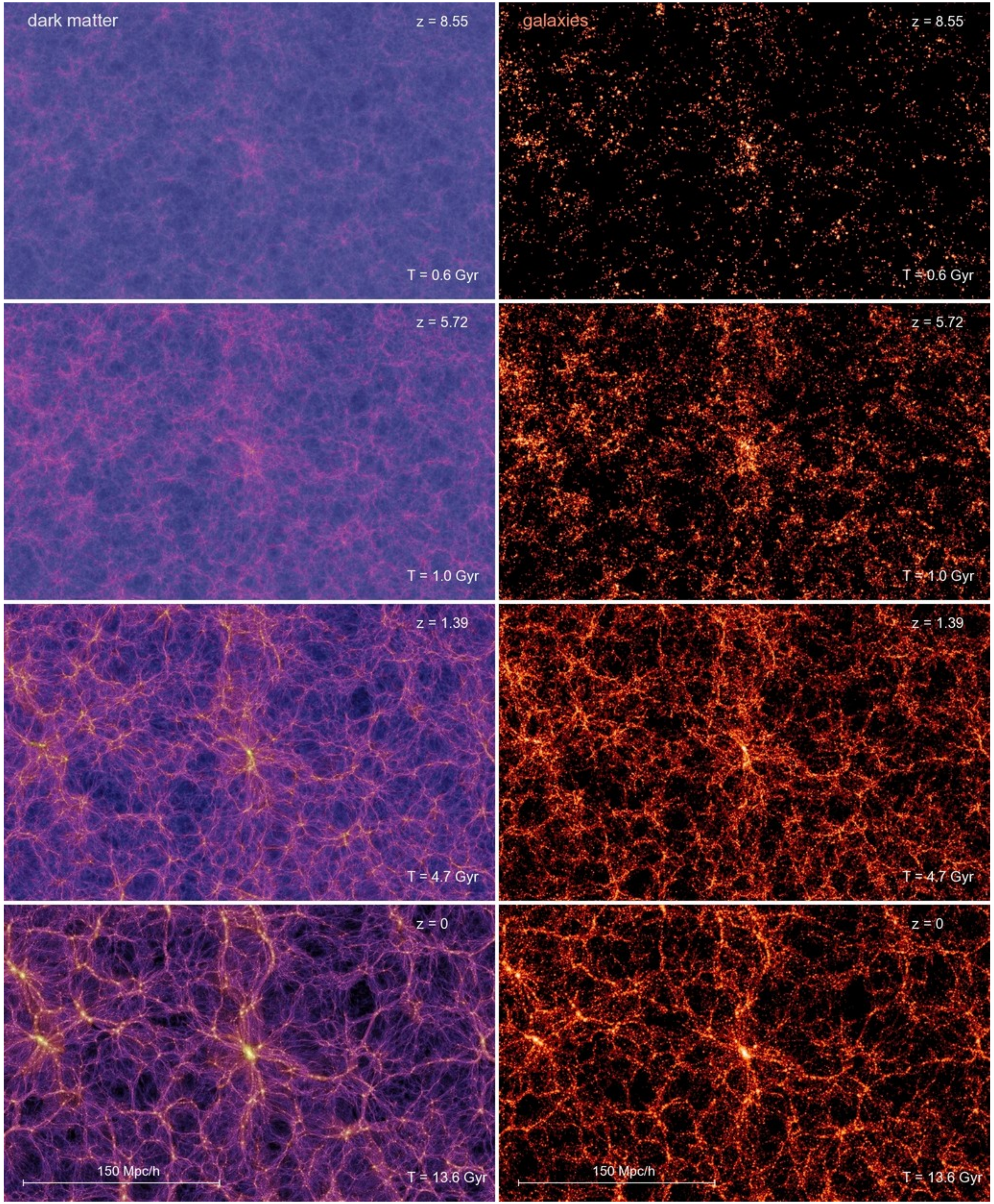
Riess et al 1998

..and it is flat!



de Bernardis et al 2000

# Large-scale structure at high redshift

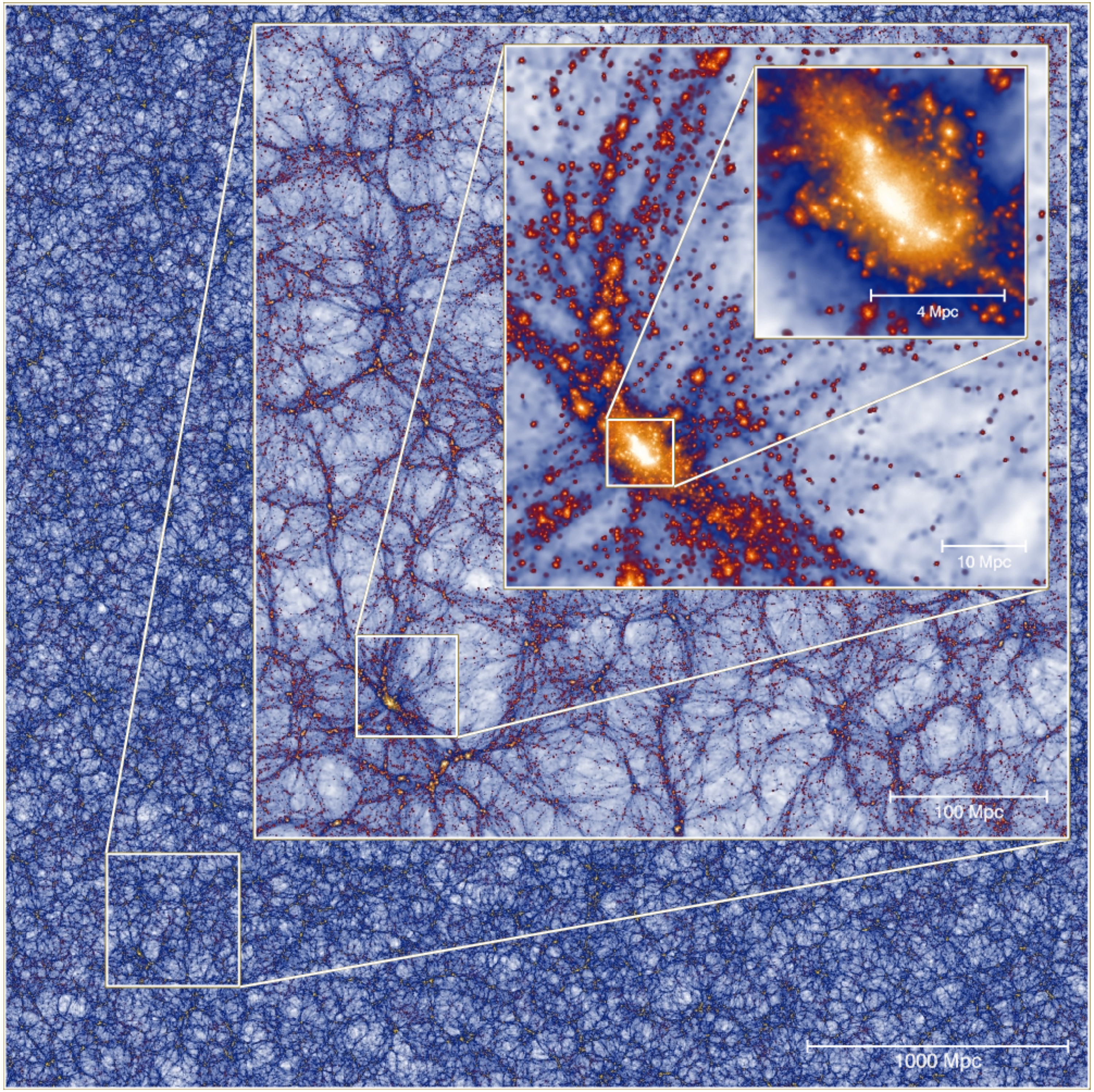


Springel, Frenk & White 2006

Large-scale structure in the **mass** distribution is weaker at high redshift

Large-scale structure in the **galaxy** distribution varies little with redshift and is as strong at z=8.5 as at z=0

→ Galaxies are strongly biased (and Ω~1) at z=2



# The MXXL

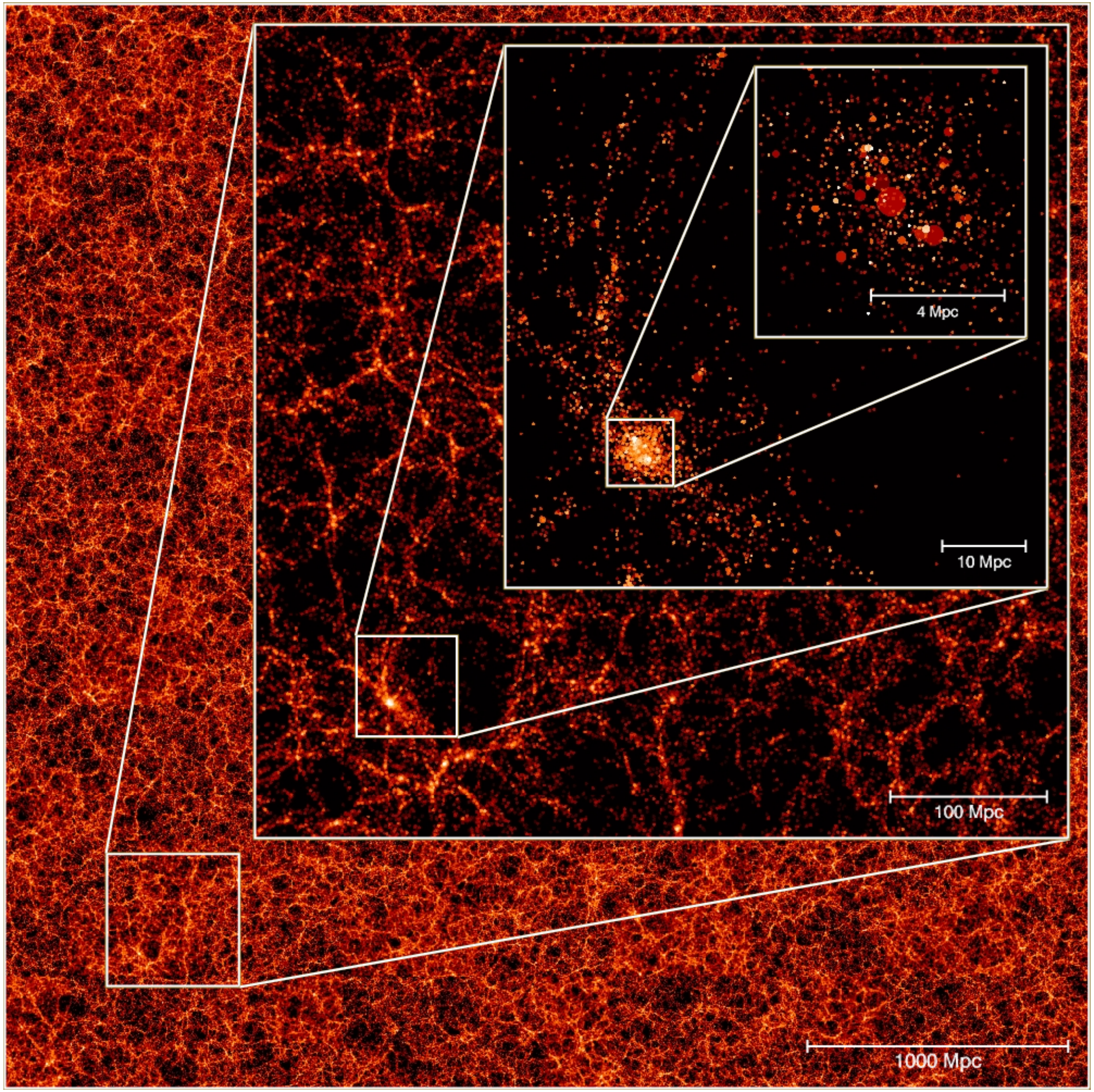
Angulo, Springel
et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{\text{particle}}$

200 in Volume

6 in $m_{\text{particle}}$



# The MXXL

Angulo, Springel et al 2011

Bigger than the Millennium Run by factors of

30 in $N_{particle}$

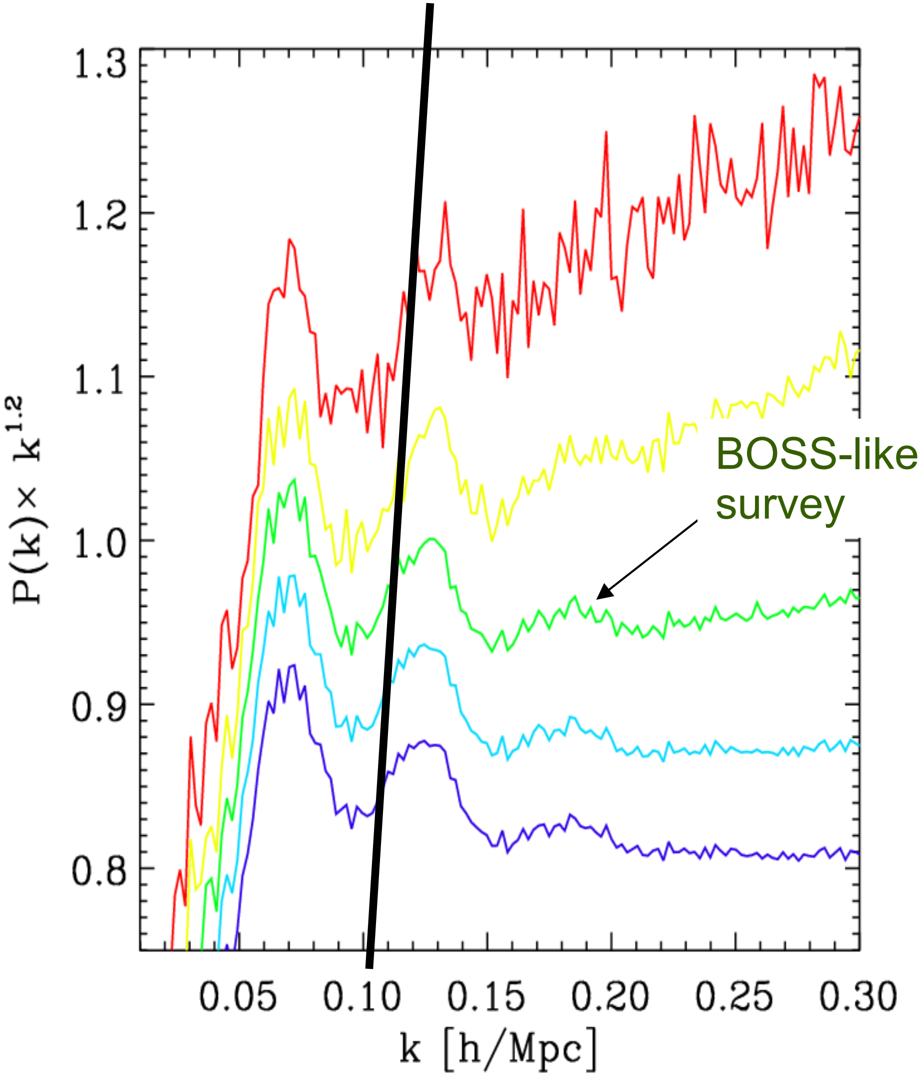
200 in Volume

6 in $m_{particle}$

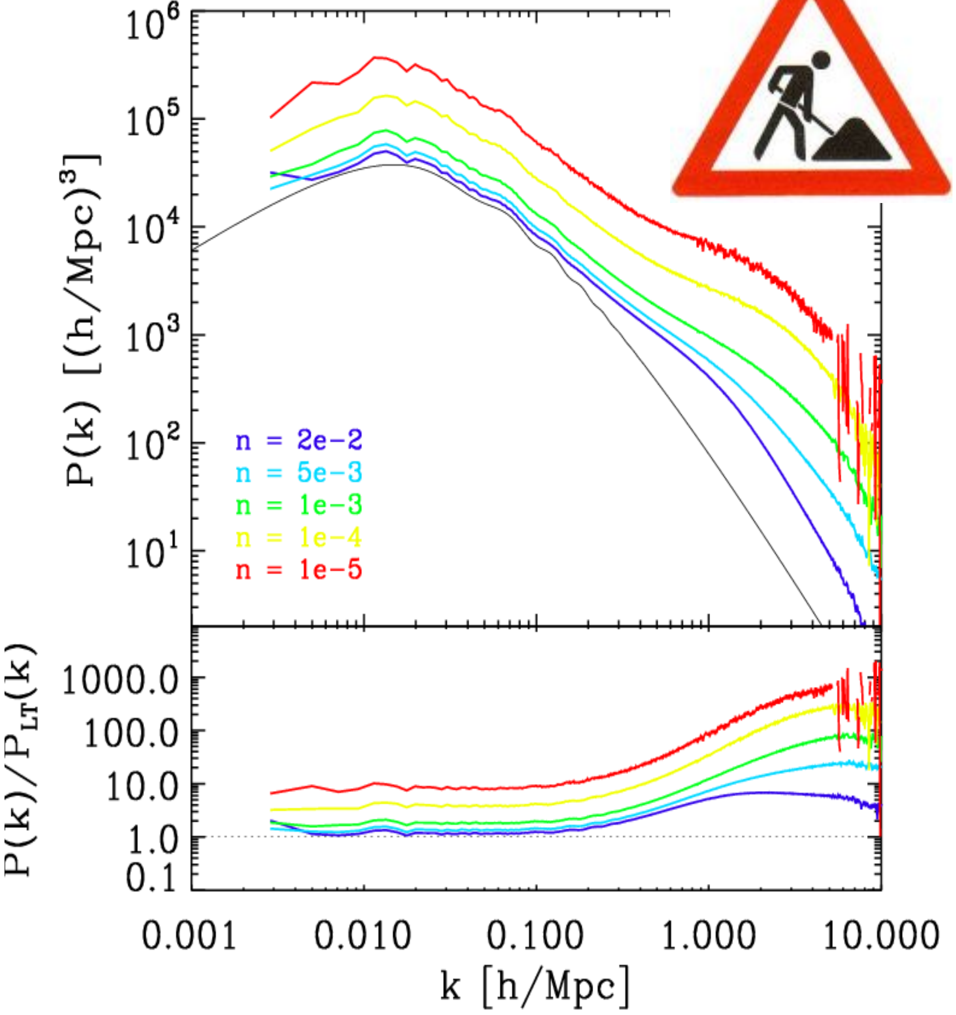
$3.3\times10^{8}$ galaxies at $z = 0$ with $\log M_*/M_\odot > 10$

# Different galaxy catalogues in the z=0 MXXL simulation trace the Baryon Acoustic Oscillation features with a scale-dependent bias

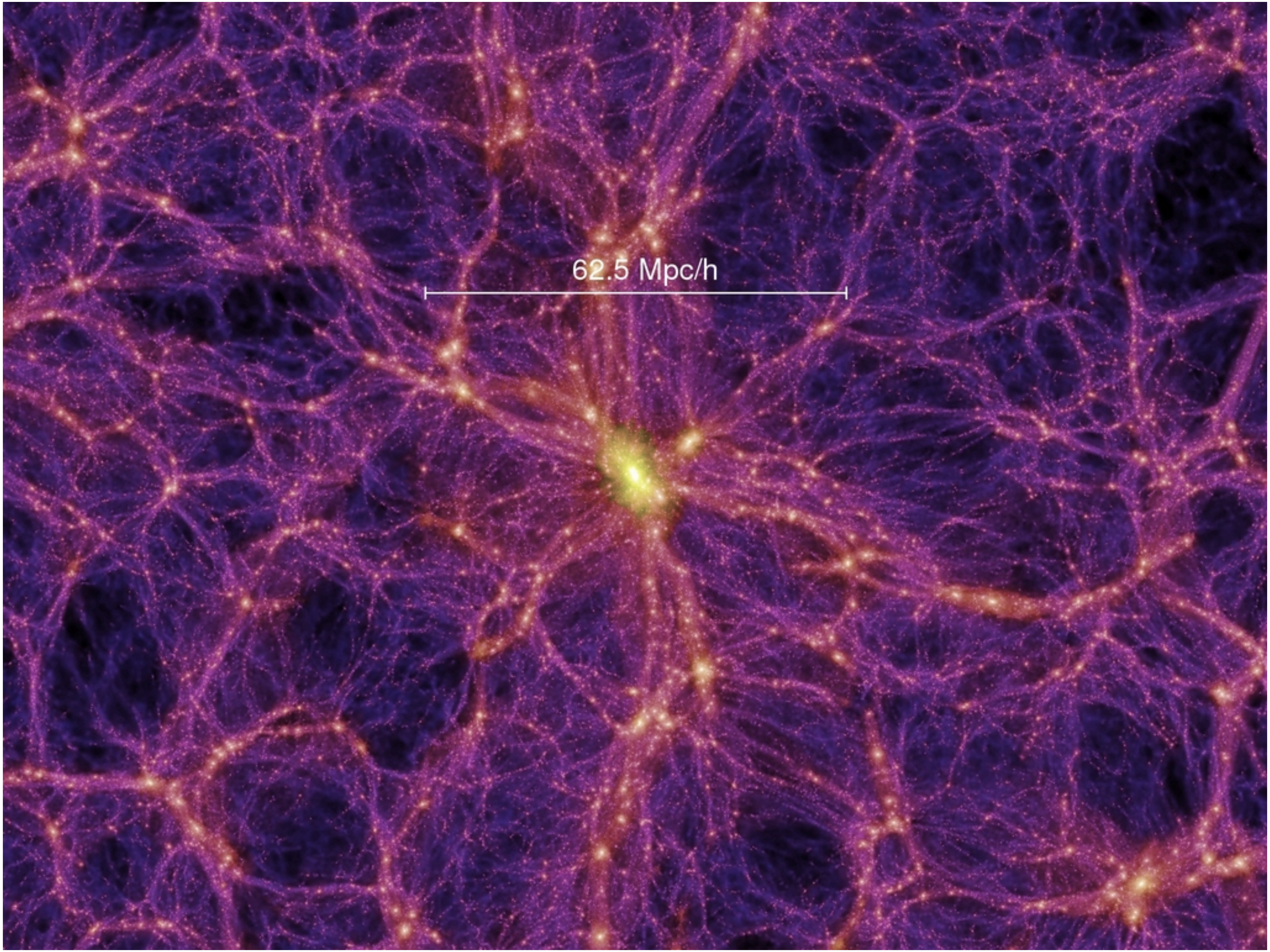
**Makes it difficult to use the BAOs to measure the precise expansion history and so constrain Dark Energy**



BOSS-like survey



**Angulo et al. (2011)**


62.5 Mpc/h