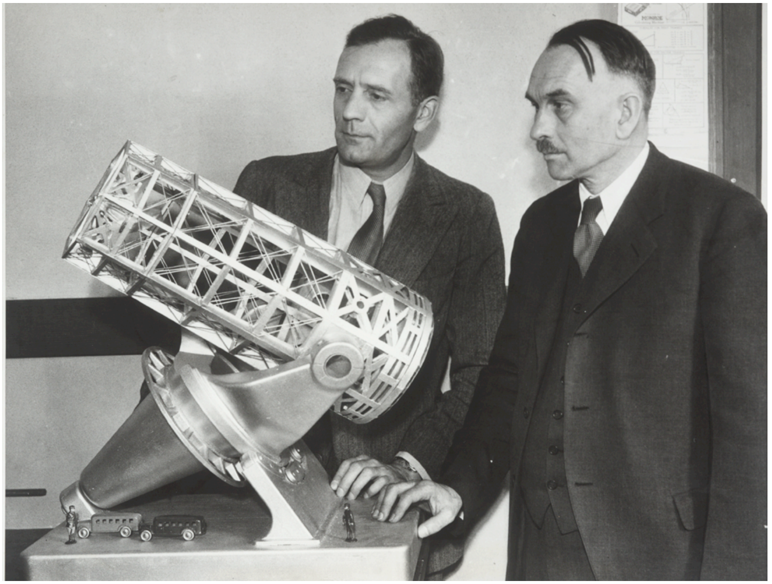
Successes and challenges for the standard cosmology

P. J. E. Peebles

Venice 2007

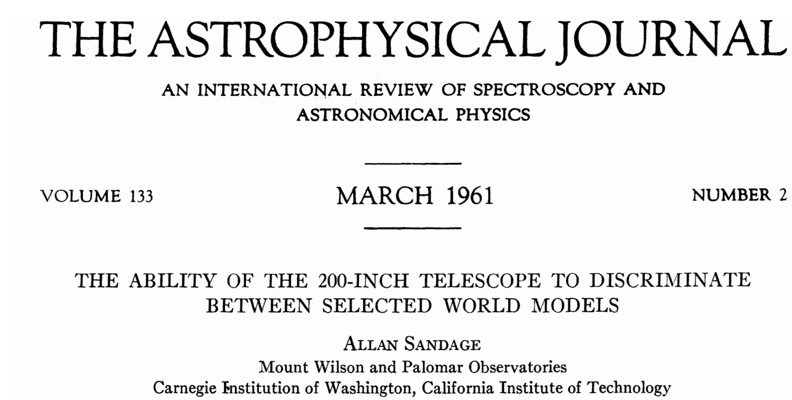


Cosmological Tests

1931: Edwin Hubble and Richard C. Tolman with an early model for the 200-inch Palomar telescope. The key project, in modern jargon, was to test ideas about the expanding universe.

Thirty years later: Allan Sandage's survey indicated that, with the astronomy and technology on hand, the most promising of the cosmological tests is the redshift-magnitude relation.

Forty years after that: the dream was realized.



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THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

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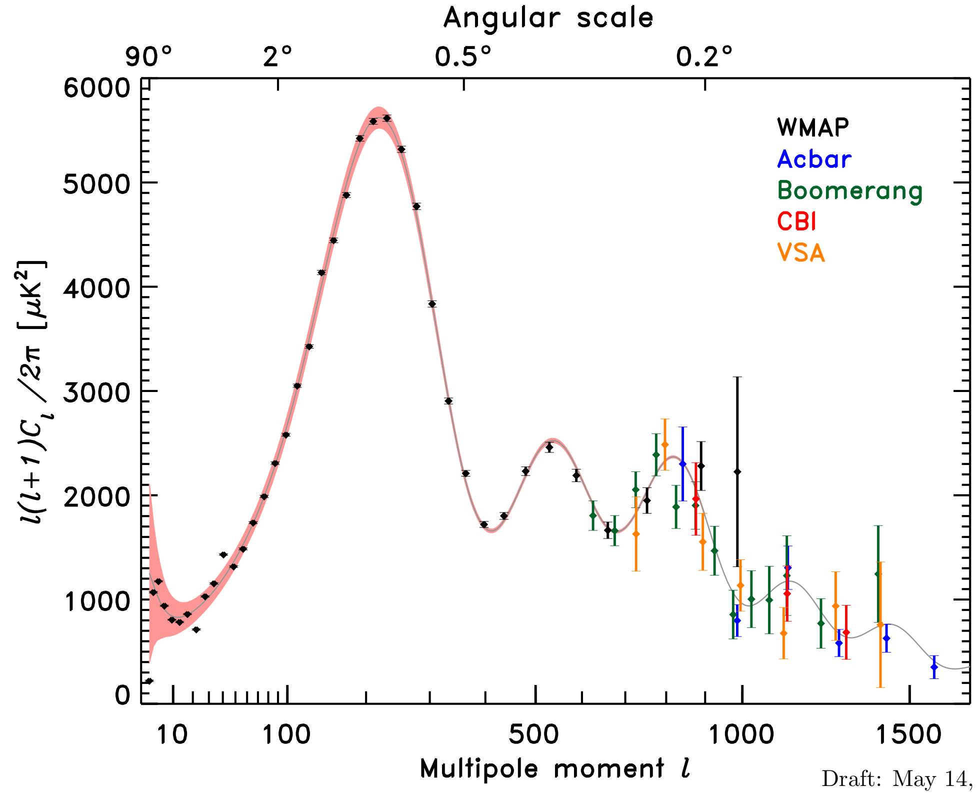
Cosmological Tests: the Present Situation

Now we have a considerable network of demanding tests, including

- the CMBR temperature anisotropy power spectrum;
- the CMBR temperature – polarization spectrum;
- the galaxy & Lyα forest power spectrum (with modest bias);
- baryon oscillation signatures;
- $\Omega_{\rm baryon}$ from WMAP & the standard model for the light elements (though we had in reserve the lepton number);
- Ω_m from dynamics, lensing, & the cluster baryon mass fraction;
- the SNeIa z - m relation;
- time scales for expansion & evolution;
- the cluster mass function;
- the ISW effect (at a modest number of standard deviations).



Draft: May 14, 2006

Three-Year Wilkinson Microwave Anisotropy Probe (WMAP[1]) Observations: Temperature Analysis

G. Hinshaw [2], M. R. Nolta [3], C. L. Bennett [4], R. Bean [5], O. Doré [3,11], M. R. Greason [6], M. Halpern [7], R. S. Hill [6], N. Jarosik [8], A. Kogut [2], E. Komatsu [9], M. Limon [6], N. Odegard [6], S. S. Meyer [10], L. Page [8], H. V. Peiris [10,15], D. N. Spergel [11], G. S. Tucker [12], L. Verde [13], J. L. Weiland [6], E. Wollack [2], E. L. Wright [14]

ΛCDM passes tests that probe it in a broad variety of ways: this cosmology proves to be a good approximation to the real world. A substantial paradigm shift, as to MOND, or to a generalization of the Steady State or fractal cosmologies, looks unlikely.

Cosmological Tests: the Future

On the other hand, we have to bear in mind that we are attempting to draw large conclusions from lines of evidence that still are exceedingly limited.

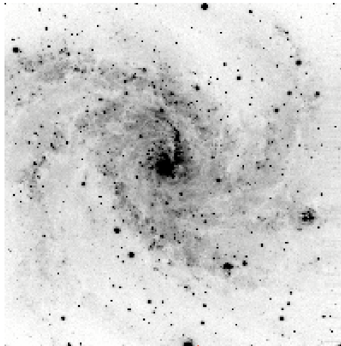
In particular, is the physics of the dark sector really as prescribed in the ΛCDM cosmology, or only the simplest approximation we can get away with at the present level of the evidence?

It is easy to imagine more interesting dark sector physics. For example, the concept of cosmic strings or textures was well motivated a decade ago, and it is still is.

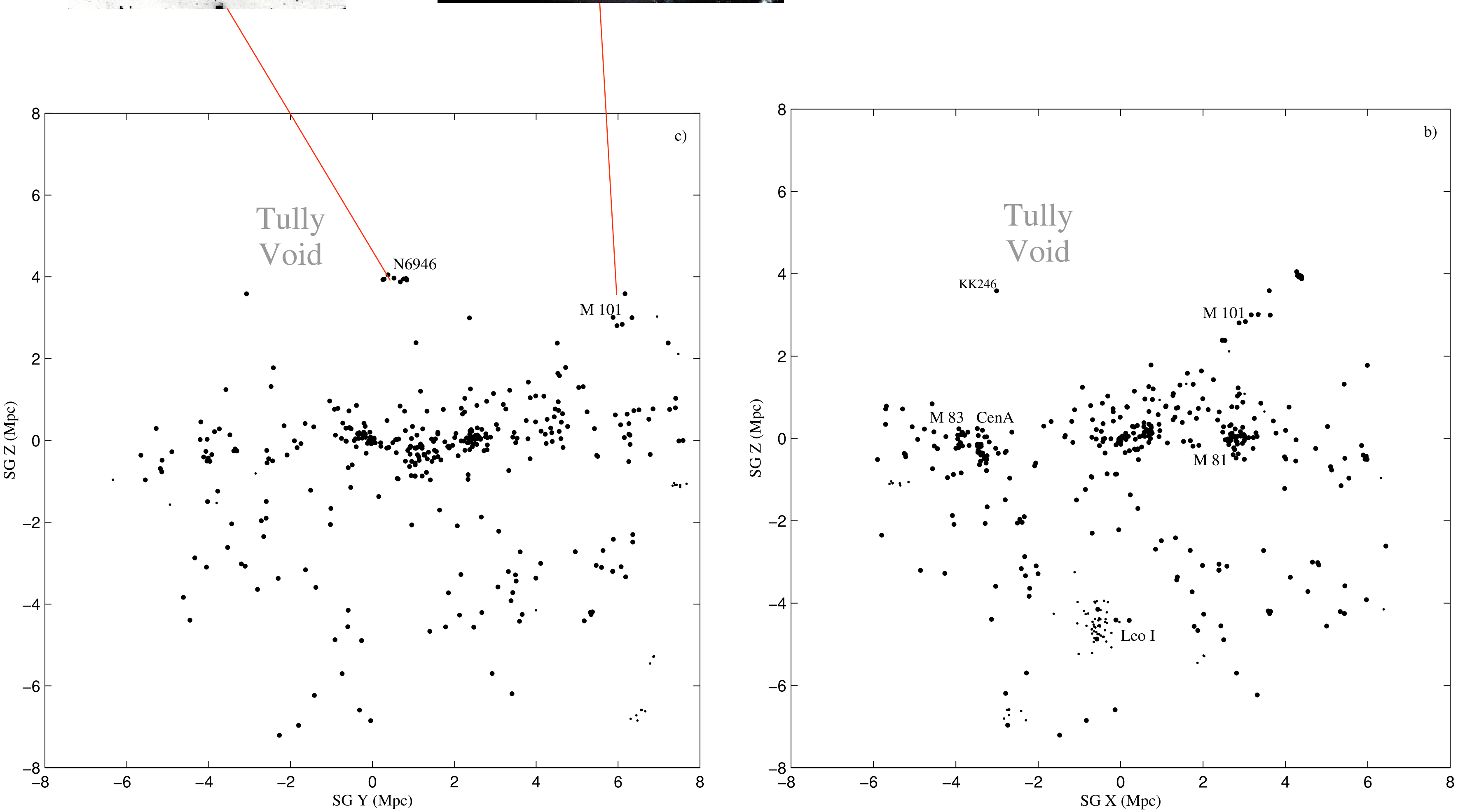
If physics in the dark sector is different enough from ΛCDM to matter it will be manifest in anomalies. And it is worthwhile to look for hints of anomalies.

The Void Problem

In ΛCDM simulations the voids defined by natural homes for $L \sim L_*$ galaxies contain halos that look like suitable homes for dwarf galaxies.

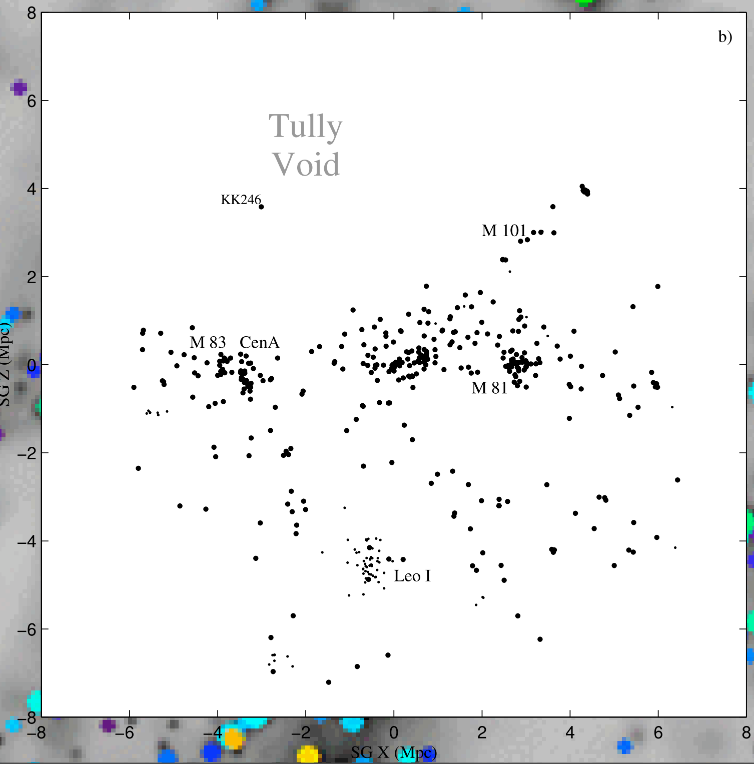


The Local Tully Void



Catalog of Neighboring Galaxies Karachentsev *et al.* 2004

The simulation shows tendrils — streams — of dwarf CDM halos running into low density regions. Should we have expected to see this phenomenon more clearly in the Tully Void?



Here the scales of depth and width are about the same.

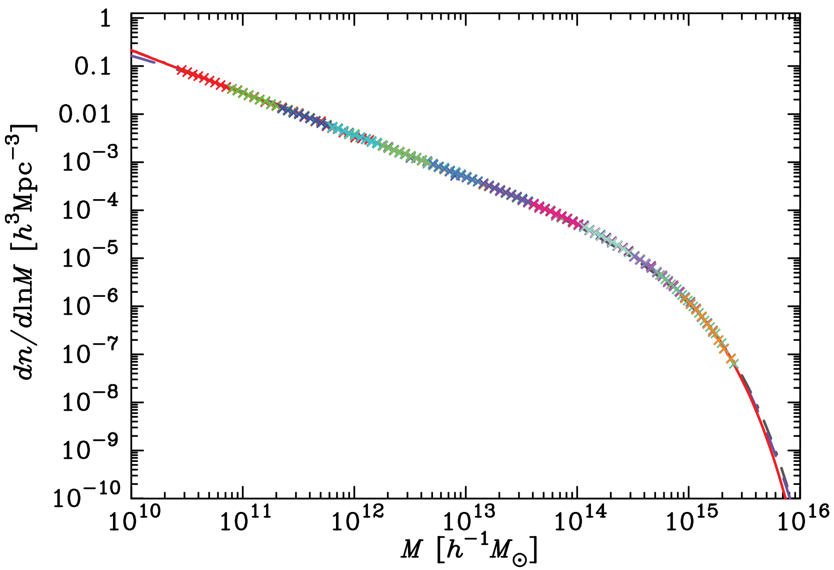
Dwarf halos and galaxies in voids:
1. Dwarf halo mass functions in voids and in the cosmic mean

PRECISION DETERMINATION OF THE MASS FUNCTION OF DARK MATTER HALOS

Michael S. Warren,[1] Kevork Abazajian,[1] Daniel E. Holz,[1] and Luís Teodoro[1,2]

Received 2005 June 16; accepted 2006 April 6

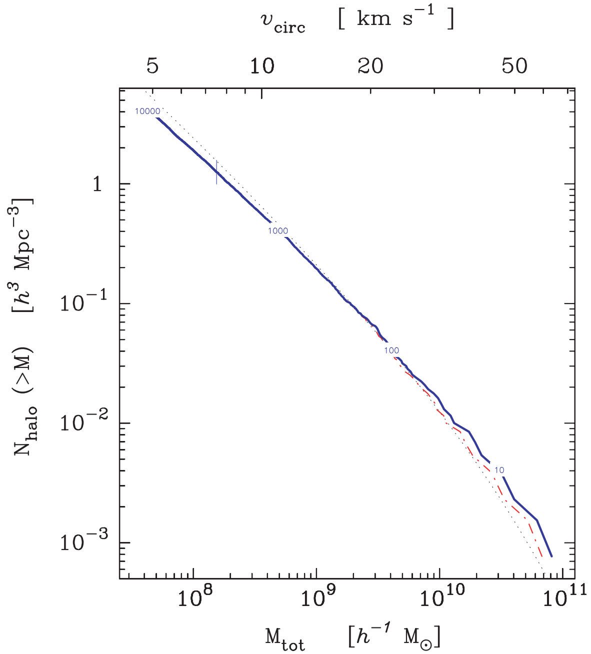
The Astrophysical Journal, 646:881–885, 2006 August 1



$$n(>m) = 2.1\,h^3 \left(\frac{10^9 h^{-1}\ \mathrm{Mpc}}{m}\right)^{0.9}\ \mathrm{Mpc}^{-3}$$

Dwarf galaxies in voids: Suppressing star formation with photo-heating

Matthias Hoeft, Gustavo Yepes, Stefan Gottlöber, Volker Springel, MNRAS 2006



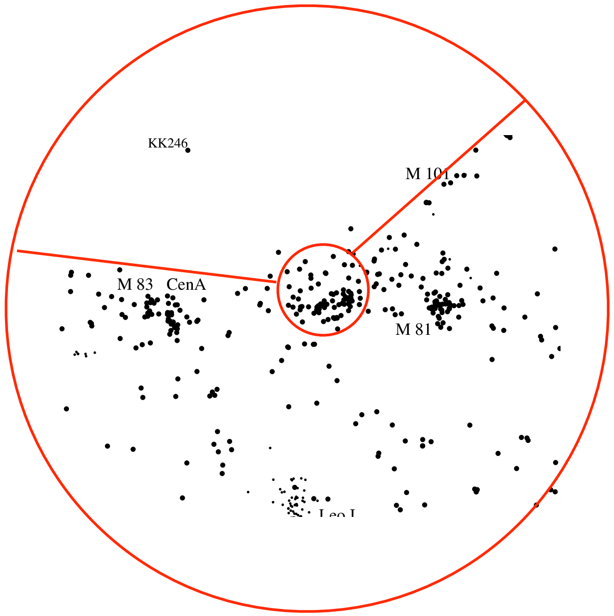
$$n(>m) = 0.2\,h^3 \left(\frac{10^9 h^{-1}\ \mathrm{Mpc}}{m}\right)^{1.1}\ \mathrm{Mpc}^{-3}$$

These are from pure CDM numerical simulations, not the Halo Occupation paradigm.

Warren *et al.* compute down to $m_{\mathrm{total}} = 3 \times 10^{10} m_\odot$, but the close approximation to a power law invites the extrapolation to extreme dwarf halos.

The ratio of number densities, roughly 1 to 10 at halo mass $10^9 m_\odot \lesssim m_{\mathrm{total}} \lesssim 10^{11} m_\odot$, seems reasonable: it is comparable to estimates of the galaxy and mass void density contrasts.

Dwarf halos and galaxies in voids:
2. Dwarf galaxy density contrast
in the Local Void



A CATALOG OF NEIGHBORING GALAXIES

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Received 2003 November 3; accepted 2004 January 13

The volume of the Local Void within 7 Mpc distance is about one third of the total volume within 7 Mpc.

The Warren *et al.* and Hoeft *et al.* simulations predict the number density of dwarf CDM halos is about one tenth of the mean.

So we might expect that 1 in 30 of the galaxies are in voids.

There are 29 galaxies brighter than $M_B = -18$ at distances $1 < D < 7$ Mpc. So we expect about one of them in the Local Void. None is observed, which is fine.

There are 250 galaxies at $-18 < M_B < -10$ and $1 < D < 7$ Mpc. We expect about one in 30 of them is in the void, which would be about 10 void dwarfs. So where are they?

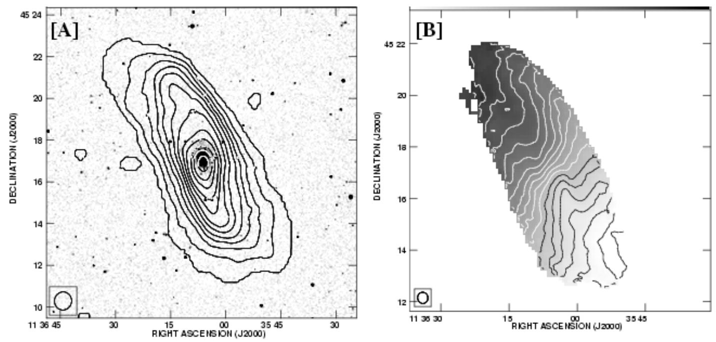
Dwarf halos and galaxies in voids: 3. Issues

In the Local Void one expects

a. one galaxy brighter than the LMC, $M_B \sim -18$, which is fine, but

b. some ten galaxies at about the luminosity $M_B = -13$ of NGC3741.

Why are galaxies like this not seen in the Local Void?



NGC 3742
Distance 3 Mpc
Begum, Chengalur
and Karachentsev 2005

Issues

1. The faint end of the halo mass function is much steeper than the galaxy luminosity function.

2. There are many fewer satellites of the Milky Way than low mass halo satellites of a halo that looks like a suitable home for the Milky Way.

3. The Local Void is empty, but the model says there are significant numbers of dwarf halos in voids relative to the total.

The commonly discussed remedy for (1) and (2), baryon loss, does not naturally apply to (3). One might have expected rather that a dwarf halo has a better chance of becoming observable in starlight or HI in the more tranquil environment of a void.

Dwarf halos and galaxies in voids: 4. Answers?

(a) Maybe conditions for survival of detectable extreme dwarf galaxies are less favorable in voids? Maybe a dwarf halo in a void typically has lower escape velocity than a halo with the same mass in a denser region? To be discussed.

(b) Why am I fussing about the absence of some ten void dwarfs? Maybe the Local Void and surroundings are atypical?

Since dwarfs a few hundred kiloparsecs away from a normal galaxy tend to be gas-rich the Arecibo ALFALFA survey will be an invaluable test of the theory applied to more voids, and to larger ones.

(c) Maybe we're missing some physics, perhaps in the dark sector?

Late Merging Puzzles

Late Merging. 1. Simulations predict that at $z < 1$ the most massive galaxies exchange considerable amounts of matter with the surroundings to distances of several megaparsecs.

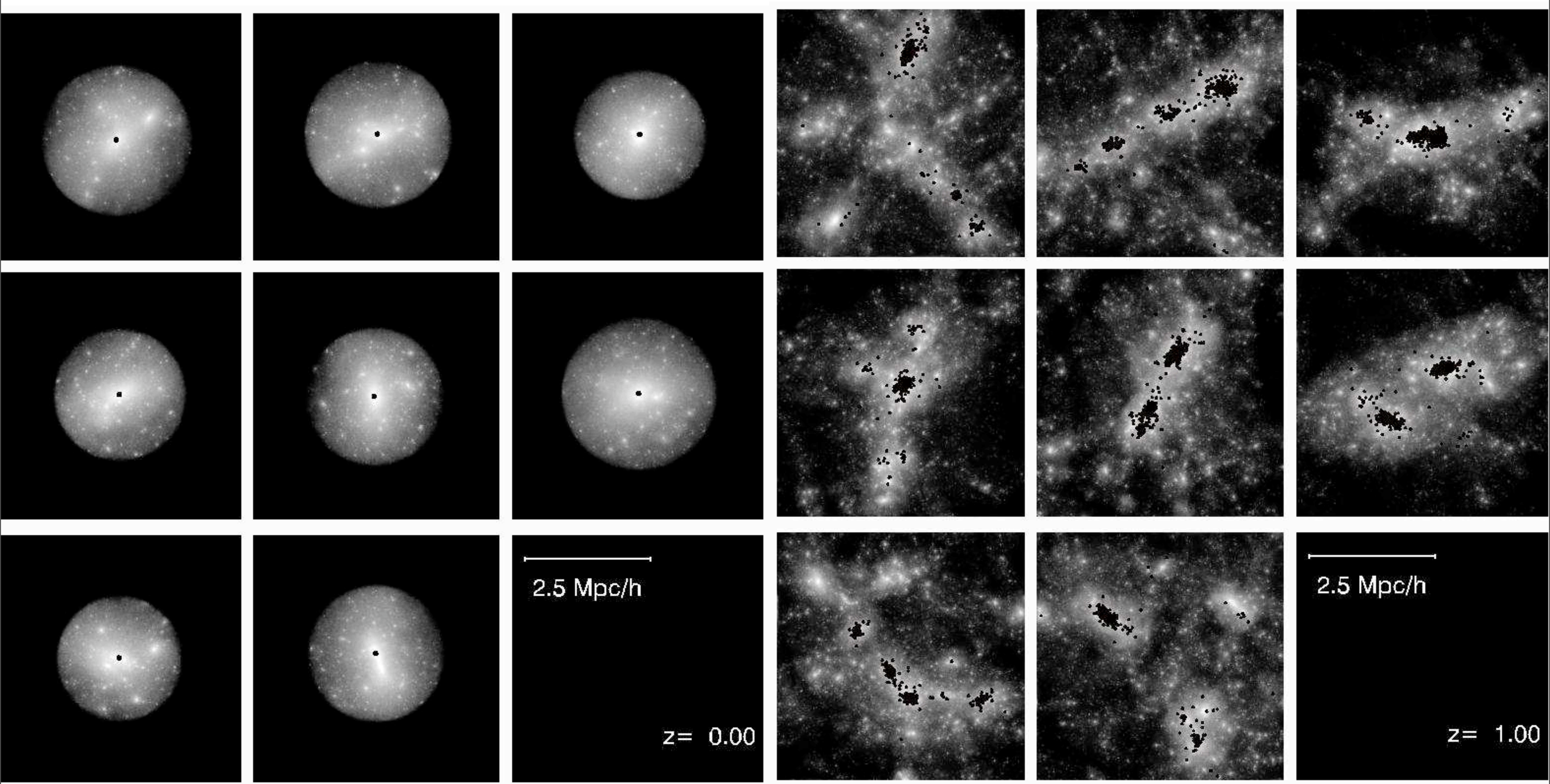


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each image is $5h^{-1}$Mpc on a side in physical (not comoving) units.

Early Formation and Late Merging of the Giant Galaxies

Liang Gao[1] Abraham Loeb[2] P. J. E. Peebles[3] Simon D. M. White[1] and Adrian Jenkins[4]

Late Merging. 2. The structures of the most massive galaxies are little correlated with environment. That does not suggest late exchange of matter with the surroundings.

THE DEPENDENCE ON ENVIRONMENT OF THE COLOR-MAGNITUDE RELATION OF GALAXIES

David W. Hogg,[1] Michael R. Blanton,[1] Jarle Brinchmann,[2] Daniel J. Eisenstein,[3] David J. Schlegel,[4]
James E. Gunn,[4] Timothy A. McKay,[5] Hans-Walter Rix,[6] Neta A. Bahcall,[4]
J. Brinkmann,[7] and Avery Meiksin[8]

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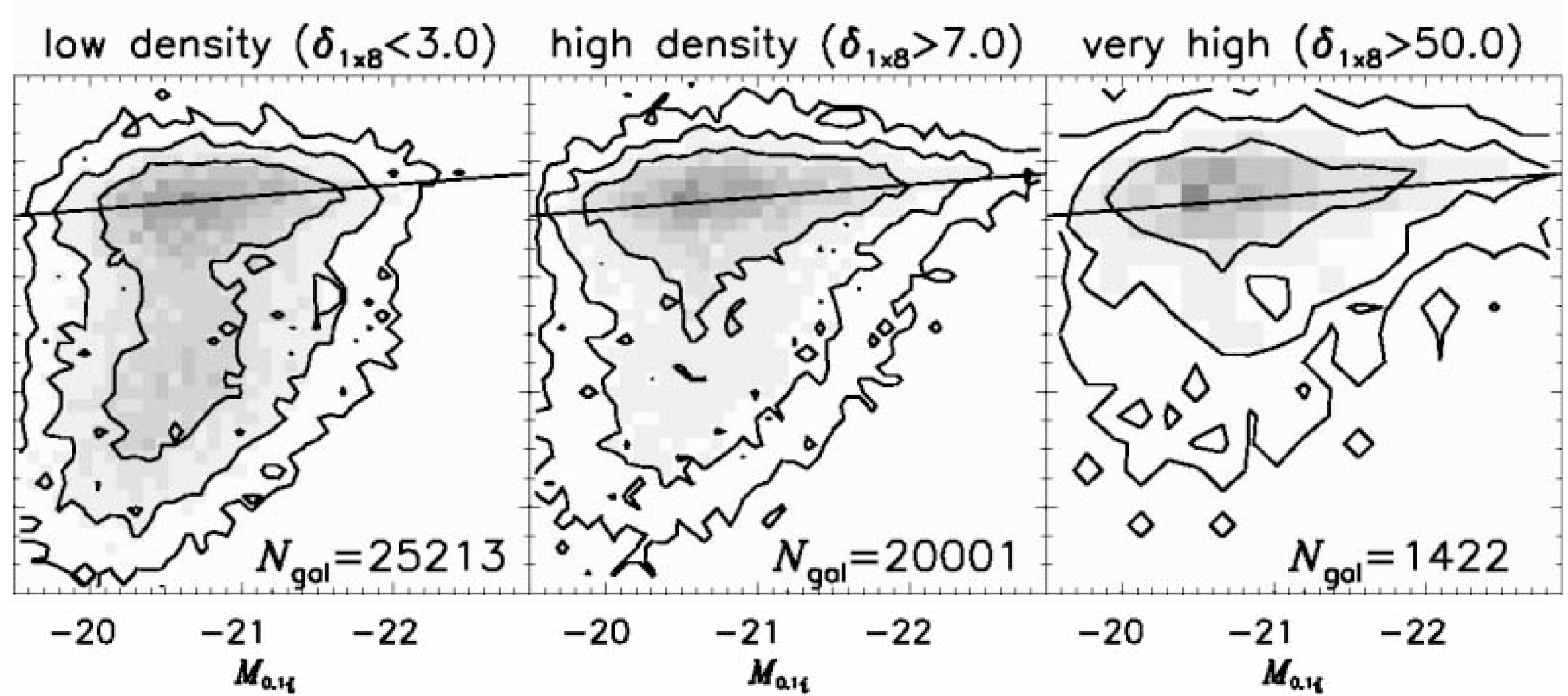
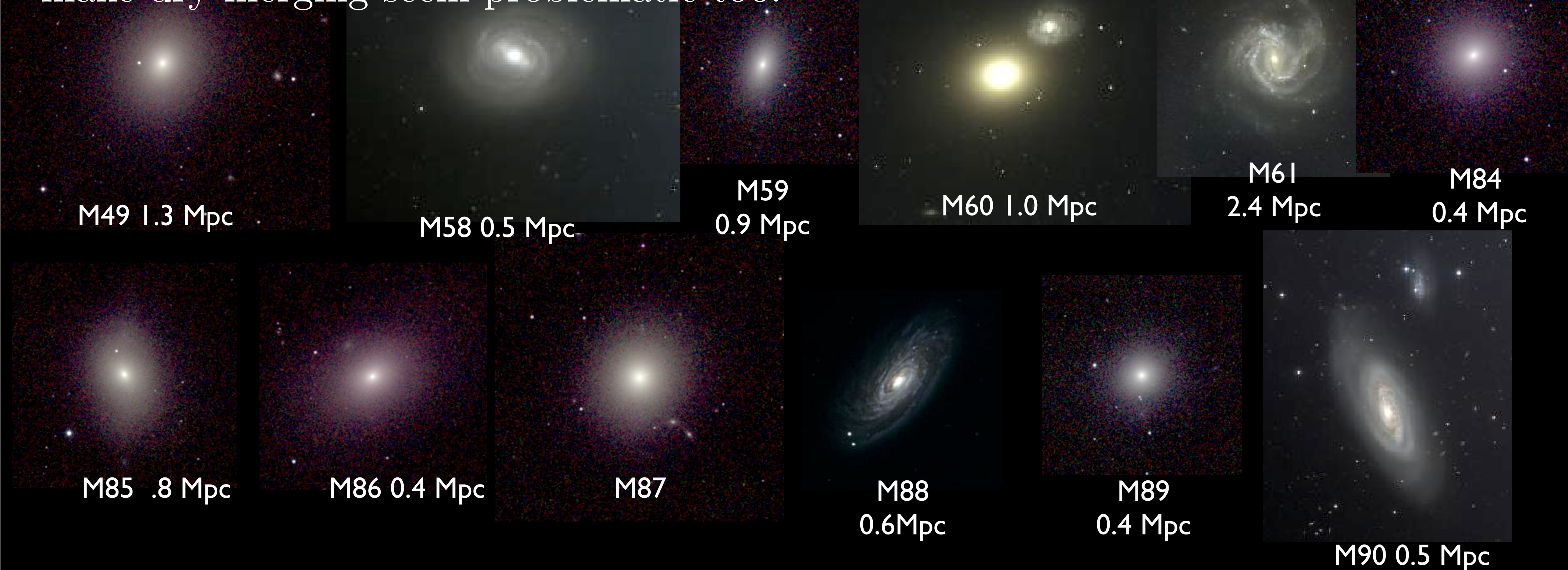
(bowdlerized)



These SDSS colors are measured at about 80% of the nominal Petrosian magnitude, that is, well outside the half-light radius

Late Merging. 3. The predicted distances over which matter is exchanged make dry merging seem problematic too.



future mergers by M87 won't be all that dry, and I suppose mergers since z = 1 have been wetter.

This shows Nigel Sharp's list of Messier galaxies in the Virgo cluster, with projected distances from M 87.
The images, from NOAO and 2MASS, have a roughly common angular scale, but contrasts can differ.

HST image of M87

Late Merging. 4. When galaxies like this merge what happens to their AGNs?

Is the undisturbed appearance of M87 misleading? Should we expect to see examples of large galaxies with displaced or lost massive central compact objects?

Again, advances in observation and theory will be followed with interest: they are going to teach us something of value.

ΛCDM seems to predict that most of the matter now within the effective radii of the most massive galaxies was at redshift $z = 2$ distributed over physical distances ~ 3 Mpc.

That is contrary to the indications that the giants have evolved as a good approximation to island universes.

Late Merging. 5.

Predicted merging and accretion at $z < 1$ is less vigorous at $L \sim L_*$ than in giants. But are merging and accretion modest enough to allow formation of galaxies with small bulges and thin disks that formed at $z > 1$? Or is the Milky Way exceptional?

These are still more of the ample supply of assignments for theory and observation.

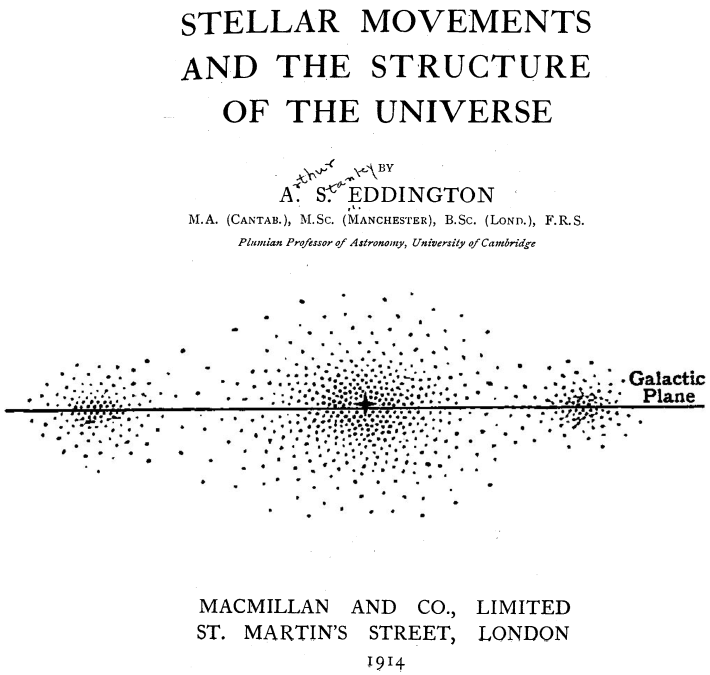
NGC 4565 HST image

What is the lesson?

My impression is that the cosmic evolution of structure is more advanced than expected in the standard ΛCDM model. The evidence suggests to me that

1. voids have grown more nearly empty than predicted,
2. giant galaxies have evolved to become closer approximations to island universes than predicted,
3. and, though the situation is more uncertain, present-day field $L \sim L_*$ galaxies had gathered more of the material they are going to collect by $z \sim 1$, allowing the formation of field spiral galaxies with smaller bulges and older thin disks than seems to be the expectation from ΛCDM.

One can think of ways to adjust ΛCDM to remedy these apparent challenges without violating the tests this cosmology passes, but that is another lecture.



STELLAR MOVEMENTS AND THE STRUCTURE OF THE UNIVERSE

BY

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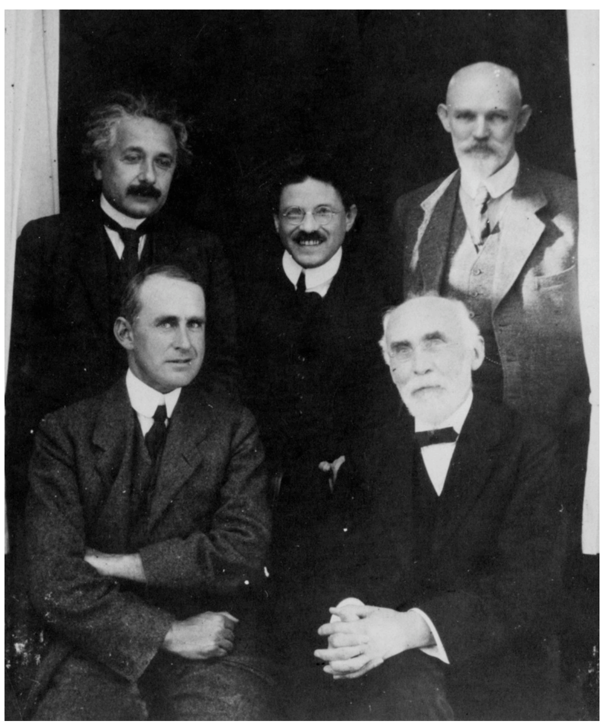
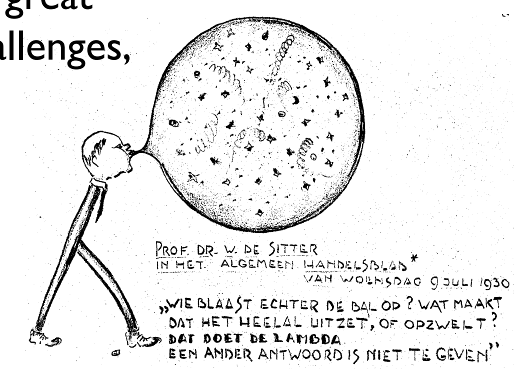
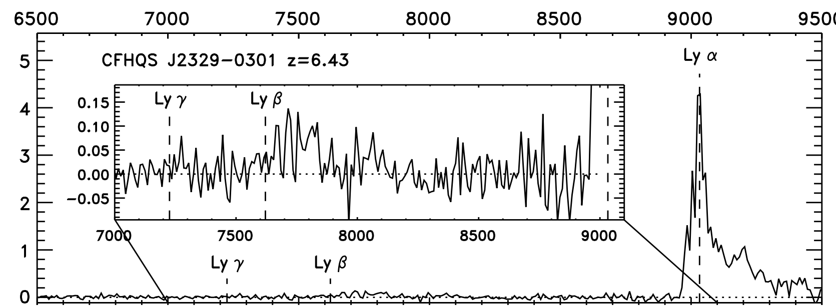
1914



A Century of Cosmology led to great discoveries that present new challenges,



from the enigmas of dark matter and dark energy,



Canada French High-z Quasar Survey, z = 6.43

to the many enigmas of the cosmic evolution of structure.