7th International Conference on

Gravitation and Cosmology

14-19 December 2011, Goa, India

The Natural Science of Cosmology

PJE Peebles

Natural science[a] operates on the hypothesis[b] that nature operates by rules we can discover[c] in successive approximations[d] to a reality thus defined.[e]

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[a] One branch of which is the study of the large-scale nature of our universe.

[b] We have abundant reason to take it as given that the rules exist and may be discovered, but it is not given.

[c] Ideas on occasion play remarkably important roles, but discoveries are established by the weight of empirical evidence.

[d] Every branch of natural science has a standard model and research aimed at improving it that we suppose will prosper and converge toward universal consistency.

[e] Maybe there is a final theory, or maybe it's successive approximations all the way down; it certainly doesn't matter at the present state of the enterprise.

The Relativistic Hot Big Bang ΛCDM Cosmology

1. A homogeneous and isotropic Friedman-Lemaître solution to Einstein's field equation that is

   (a) cosmologically flat,

   (b) expanding and evolving according to standard and conventional physics,

   (c) and with allowance for primeval curvature fluctuations that are close to

      i. adiabatic (homogeneous entropy density),

      ii. Gaussian,

      iii. growing,

      iv. scale-invariant,

      v. and small, $\sim 10^{-5}$.

2. Mass budget:

   (a) dark energy (the new name for Einstein's Λ): 73%;

   (b) nonbaryonic cold dark matter: 23%;

   (c) baryonic matter: 4.6%;

   (d) neutrinos: $< 1.3\%$;

   (e) thermal cosmic microwave radiation: 5×10^{-5};

   (f) starlight: $\sim 5 \times 10^{-7}$;

   (g) and a soupçon of gravitational waves.

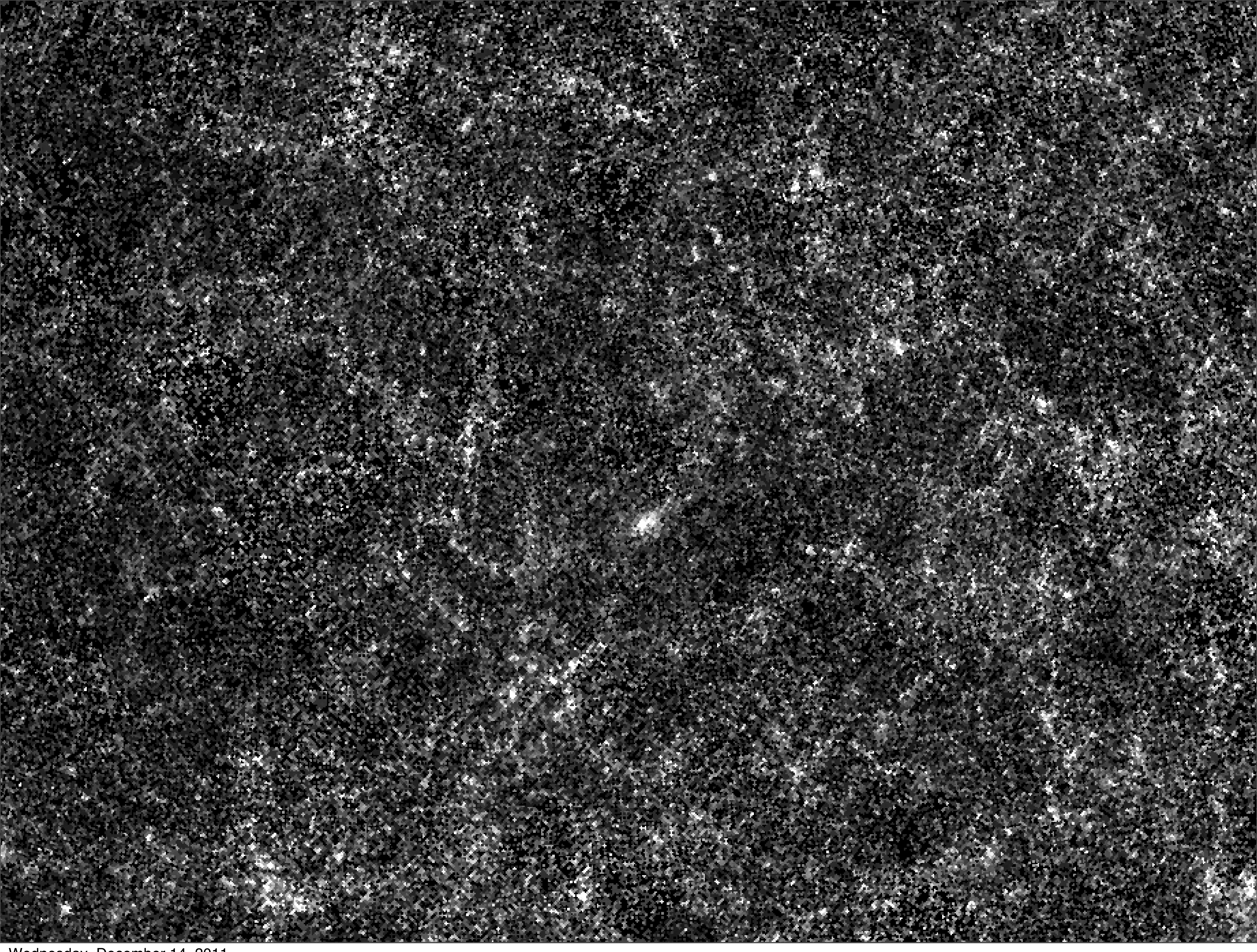
Why does the community generally accept a cosmology in which

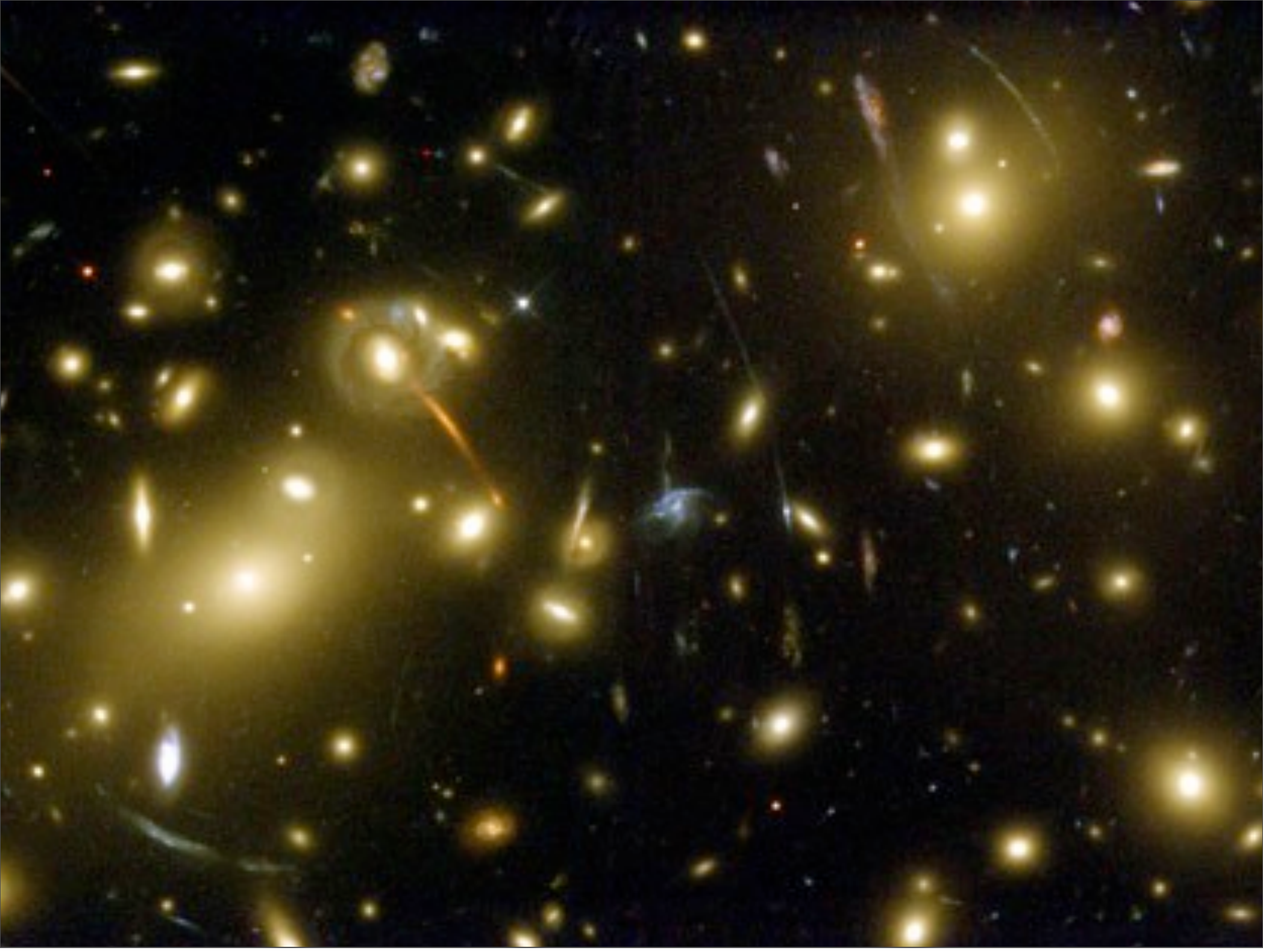
- 95% of the present mass of the universe is in two hypothetical forms, dark matter and dark energy,
- the initial conditions follow from a simple but not unique version of inflation (and why should one trust inflation anyway?),
- and the physical basis, general relativity, is extrapolated to the Hubble length by >14 orders of magnitude from the precision tests on length scales from the Solar System and smaller?

The case is made persuasive by the tight network of measurements.

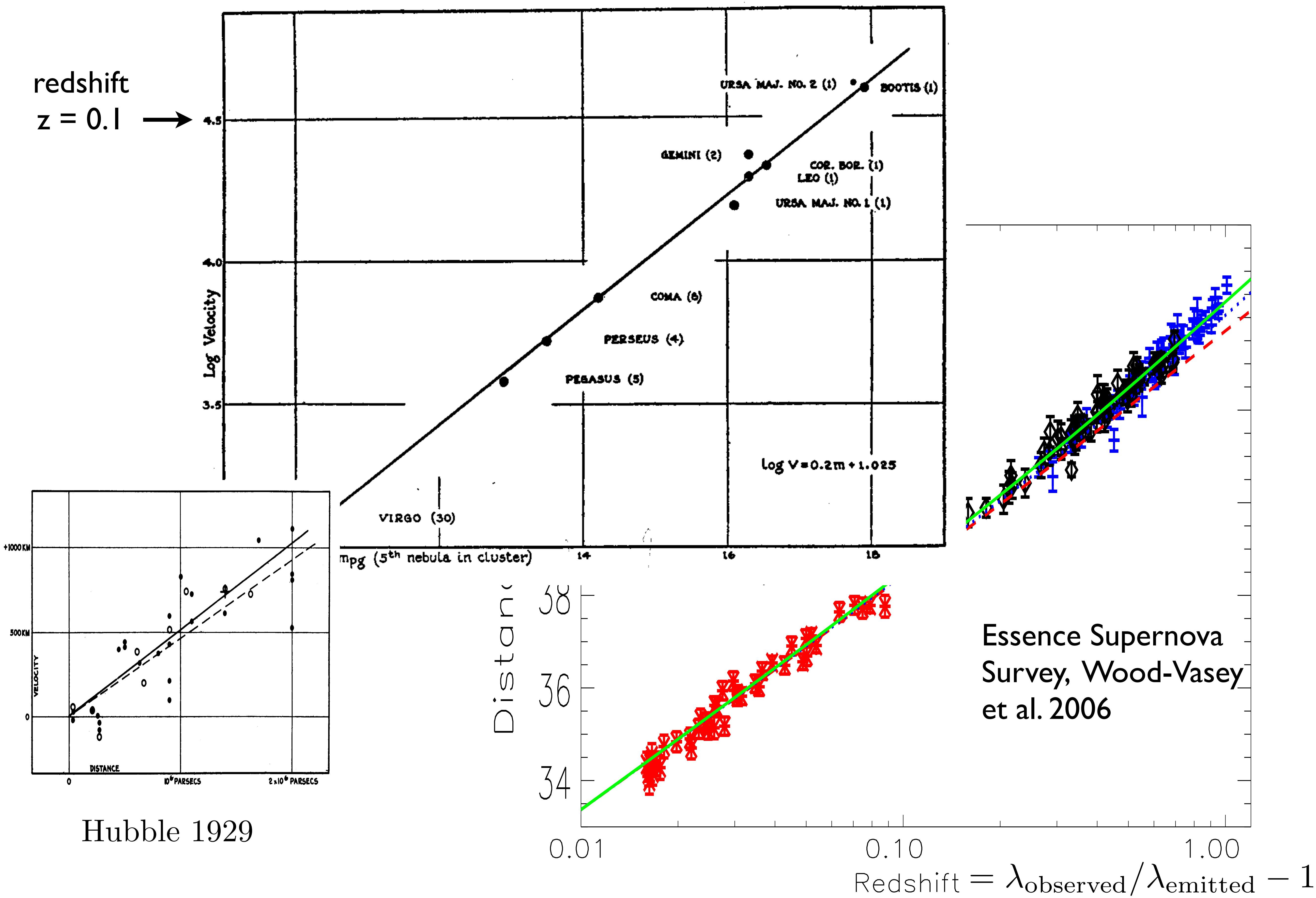
This certainly does not mean we have the final cosmology for what happened after baryogenisis. Natural science is long history of successive approximations.

But we can be sure that if there is a better cosmology it will predict a universe that looks much like ΛCDM, because the tests look at the universe from many sides and find that it looks much like ΛCDM.





Hubble and Humason ~ 1936



Hubble 1929

Essence Supernova Survey, Wood-Vasey et al. 2006

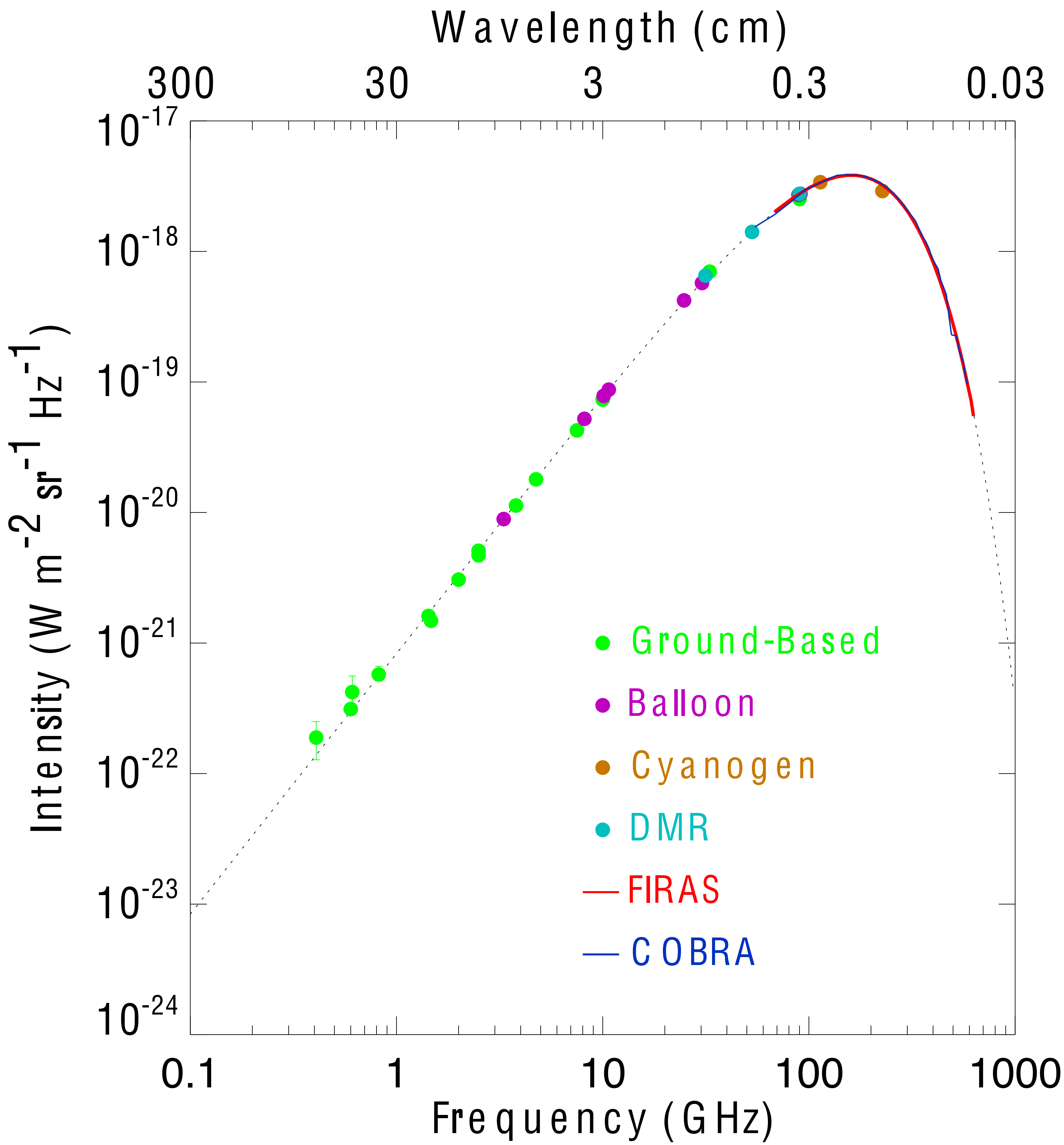
King's College

The linear redshift-distance relation is consistent with an expanding universe, as Lemaître showed in 1927.

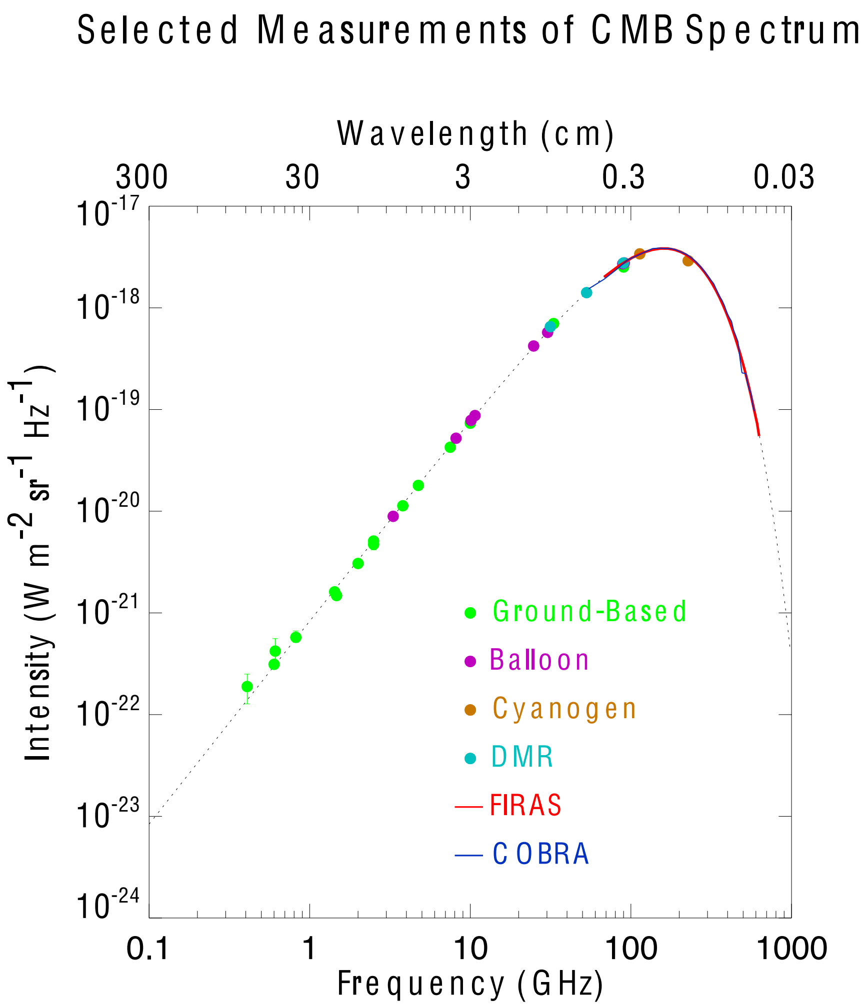
That need not mean the universe is expanding.

And if expanding it need not mean the universe is evolving. A counter example is the classical Hoyle, Bondi and Gold steady state cosmology.

But cosmic evolution is persuasively demonstrated by a fossil from a time when the universe had to have been very different from now, the cosmic microwave background.



compilation by Al Kogut, 2011



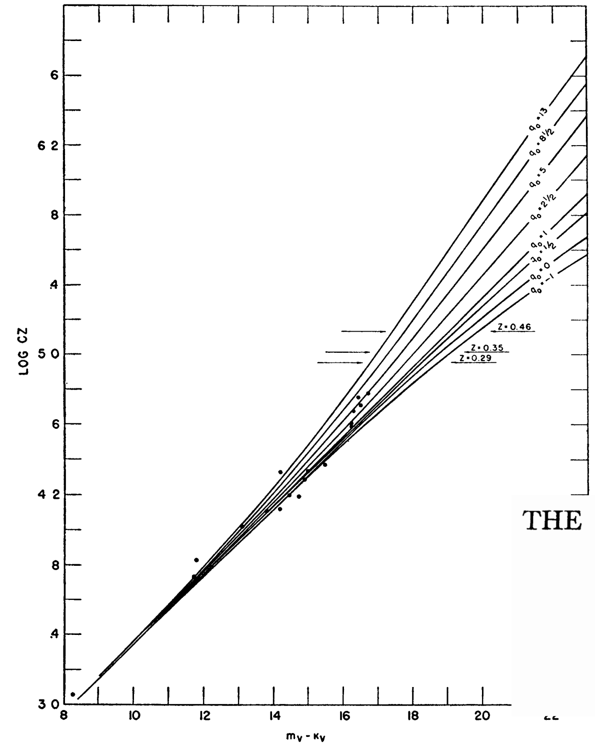
Kogut 2011

The universe is transparent: distant radio sources are observed at CMB wavelengths.

The thermal CMB spectrum thus strongly argues for evolution of the universe from a state hot and dense enough to have been capable of relaxing to thermal equilibrium.

Preserving the thermal spectrum as the universe expanded and cooled requires

- standard electromagnetism,
- quite close to homogeneous expansion, for inhomogeneities produce a mixture of CMB temperatures, contrary to what is measured.



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

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received October 14, 1960; revised November 5, 1960

The case for general relativity, nonbaryonic dark matter, dark energy[a] and all that rests on a network of other tests.

The redshift-magnitude[b] test was worked out in the 1930s; three decades later Sandage showed that it has promise; four decades after that two groups independently completed the test by observations of type Ia supernovae[c].

This rightly celebrated result indicates the rate of expansion of the universe is increasing, a quite distinctive feature of dark energy.

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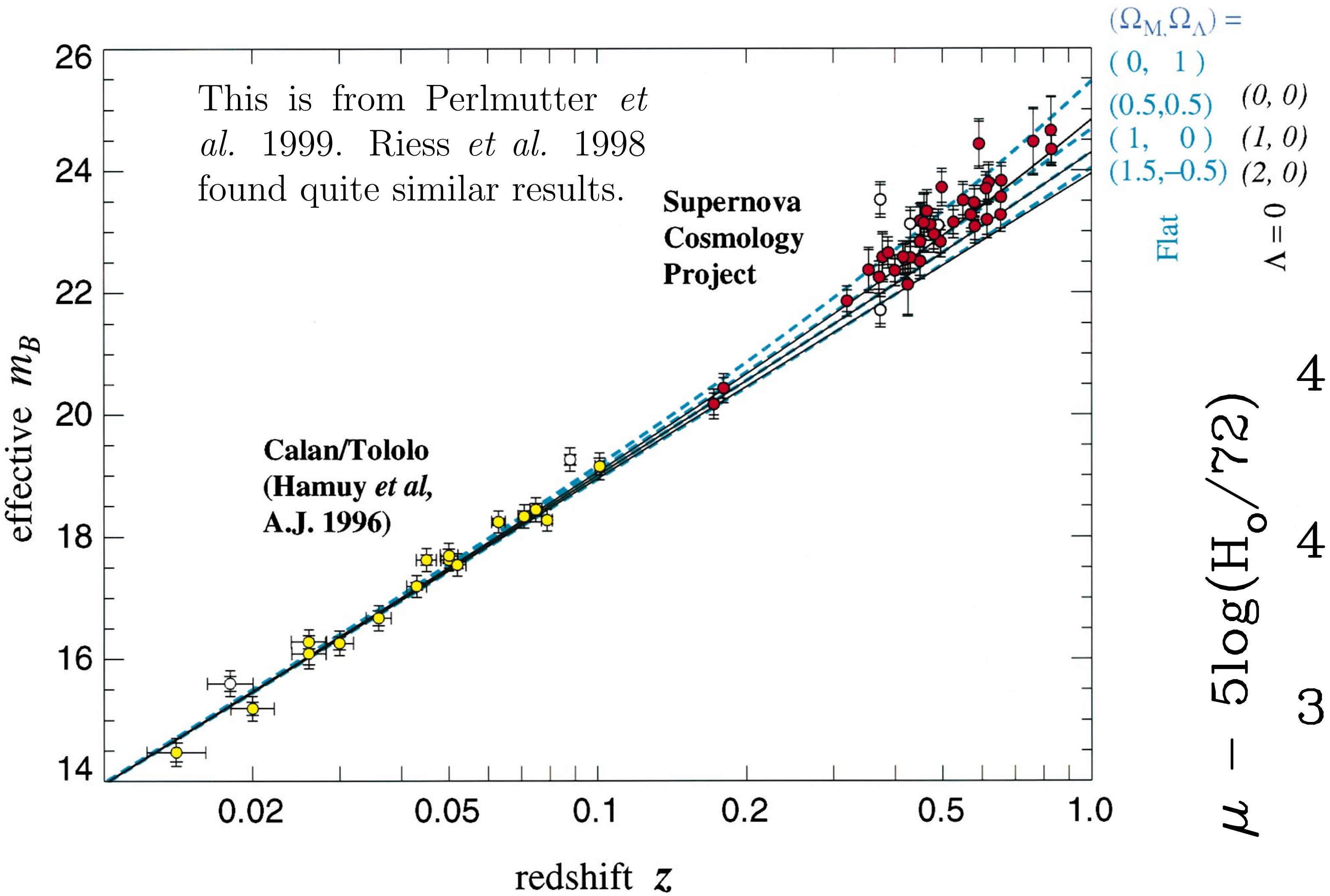
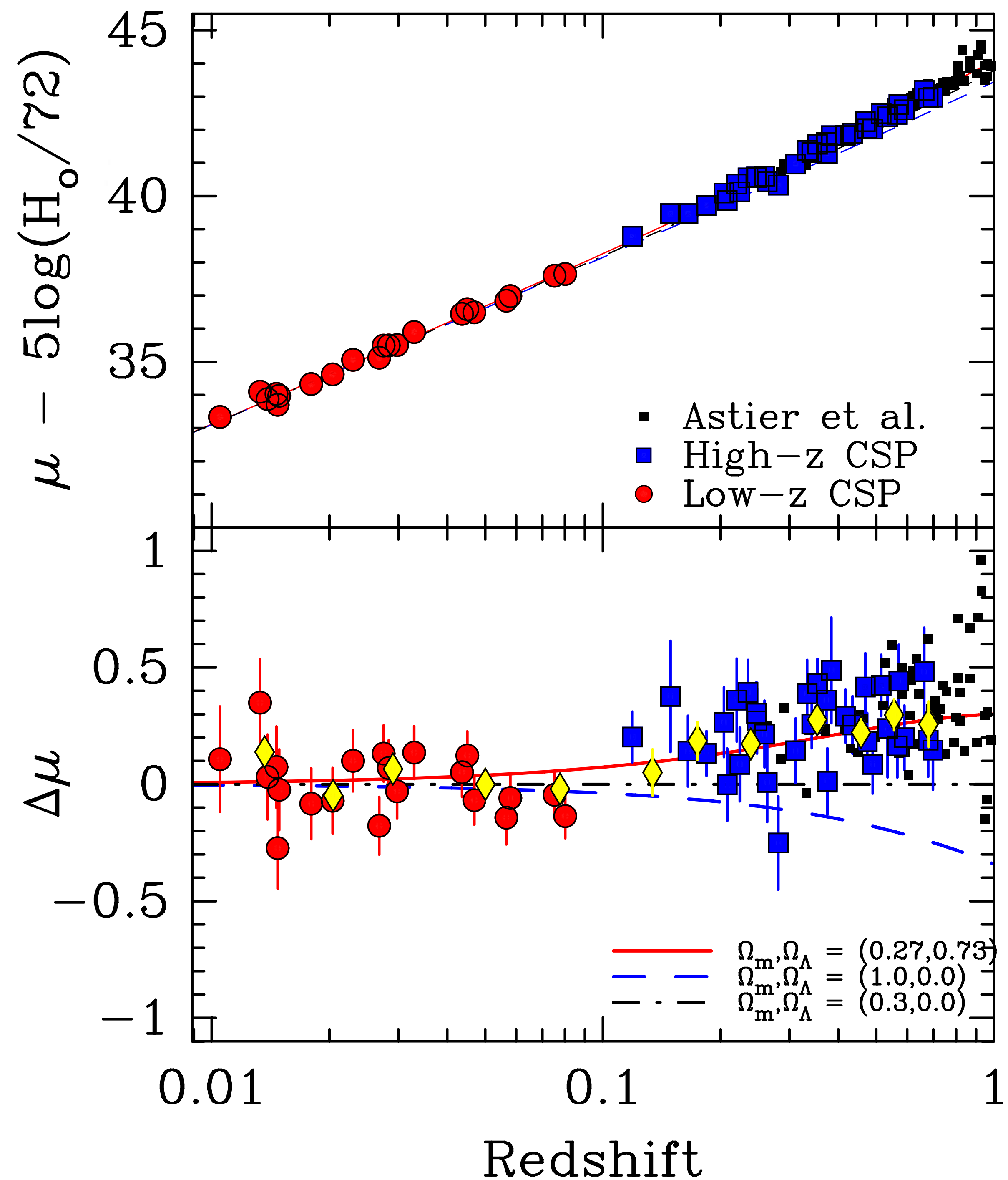
[a]the new name for Einstein's cosmological constant, Λ

[b]apparent magnitude is a measure of observed energy flux density; redshift is $z = \frac{\lambda_{\rm observed}}{\lambda_{\rm emitted}} - 1$

[c]no hydrogen in the spectrum — likely explosive nuclear burning of a CO white dwarf — and with luminosities astronomers showed can be brought to a near standard value



Near Infrared Hubble Diagram
Freedman *et al.* 2009



It takes nothing from the importance of the SNe measurements to ask what community opinion would have been if the only demanding cosmological tests were

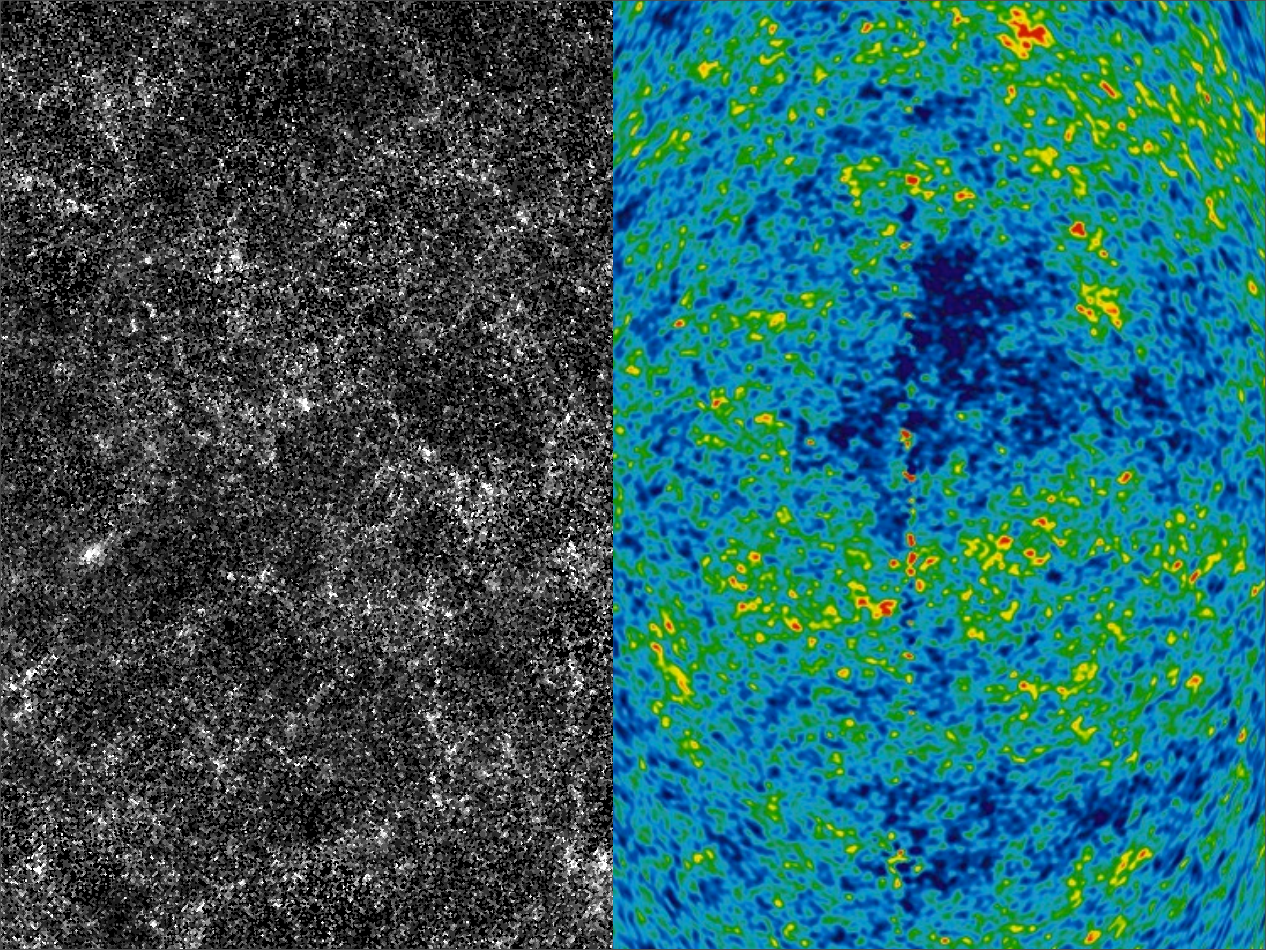
- the thermal CMB spectrum, which argues for near homogeneous expansion from a hot early universe, but not for GR, and
- the galaxy redshift-distance and SNe Ia redshift-magnitude measurements.

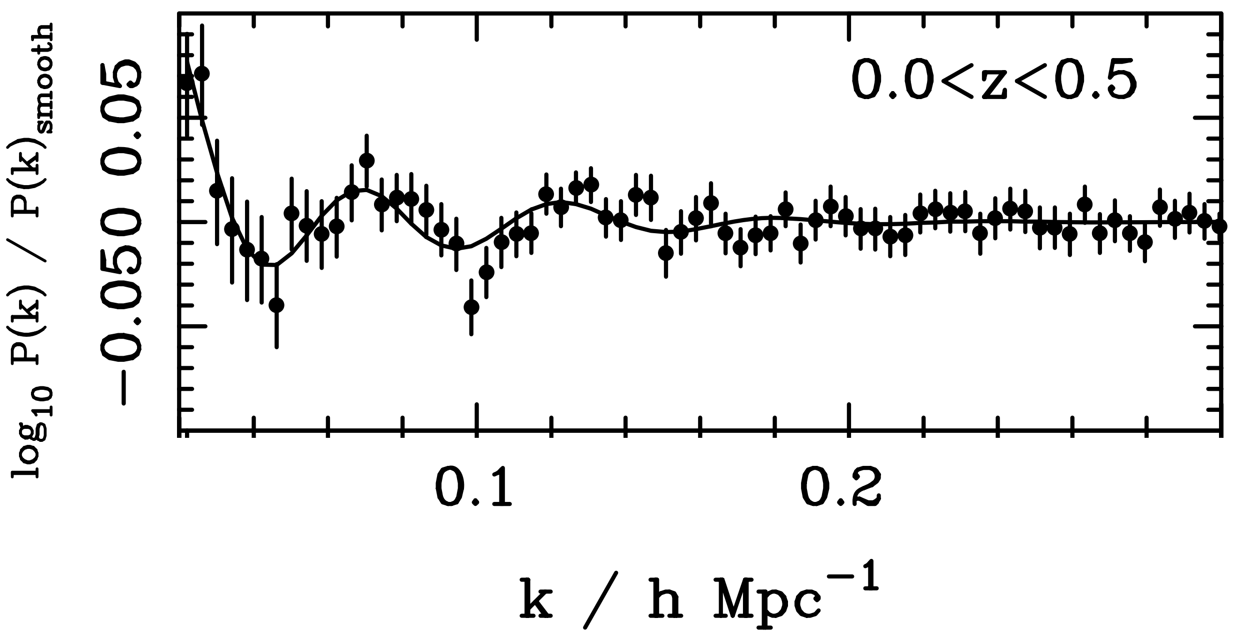
I expect many would have taken the conservative position to be that there has to be some subtle undetected error in the supernovae measurements, because

- if Λ is not zero, the only other "natural" value suggested by quantum physics is many tens of orders of magnitude too large;
- the value of Λ indicated by the SNe measurements requires that we flourish at a special epoch, just as the universe is making the transition from expansion dominated by matter to expansion dominated by Λ.

One also would have been quite justified to ask instead why we should trust the enormous extrapolation of general relativity theory to the scales of cosmology.

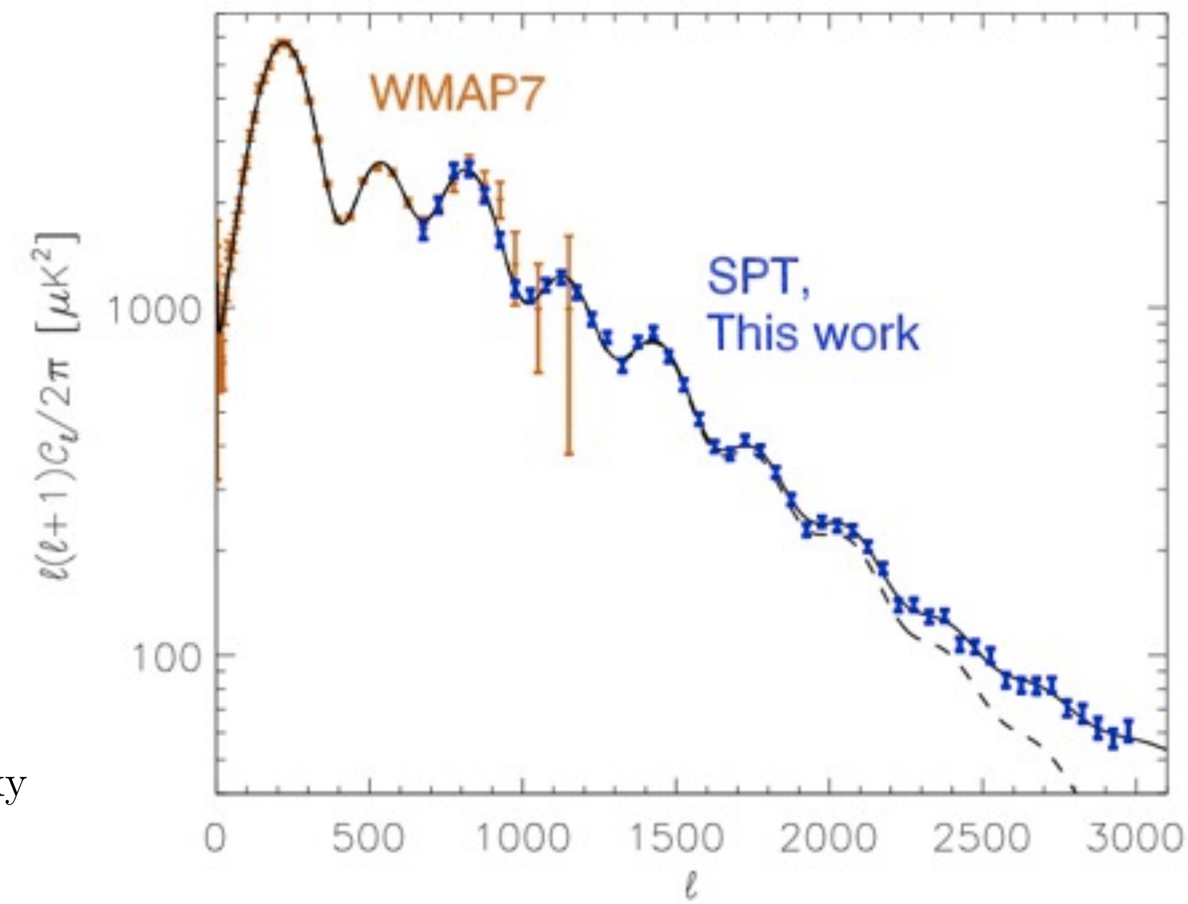
That is, it is essential that we have other independent evidence of GR and Λ.





Baryon acoustic oscillation power spectrum (Percival *et al.* 2010).

This is the square of the fourier transform of the large-scale galaxy distribution.



CMB Anisotropy Spectrum (WMAP7 & SPT, Keisler *et al.* 2011).

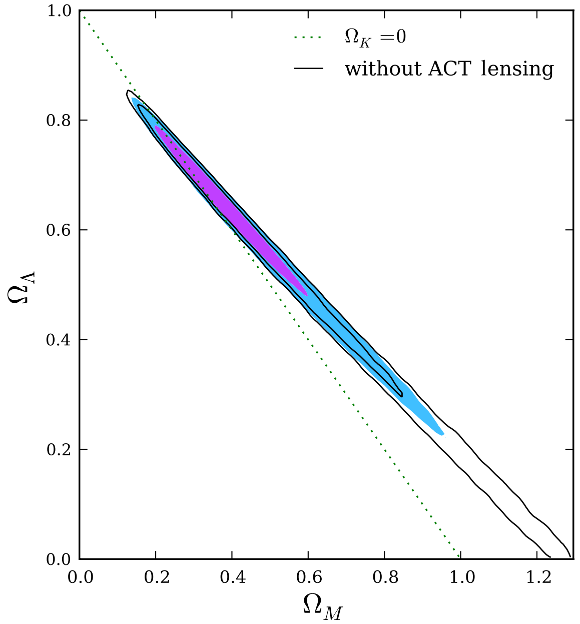
This is the square of the spherical harmonic transform of the CMB temperature across the sky, normalized to variance of the CMB temperature per logarithmic interval of angular scale $\theta \sim \pi/l$.

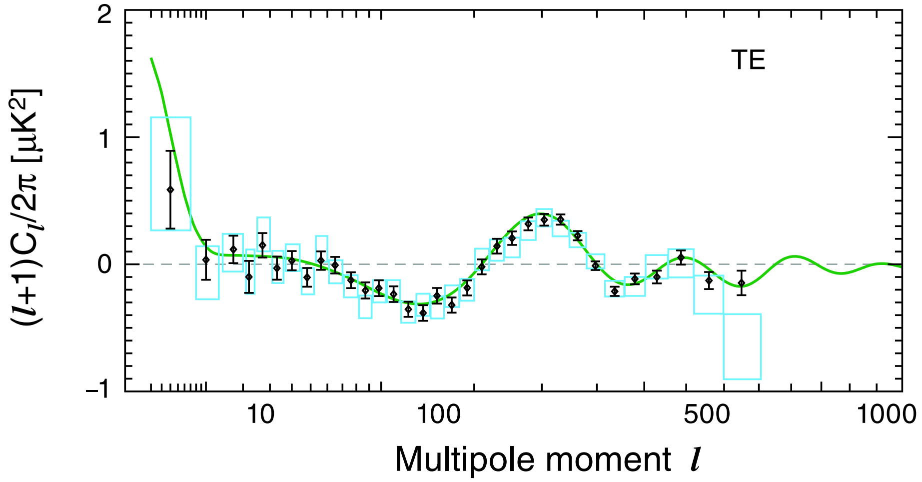
The ringing of primeval adiabatic pressure waves in the coupled plasma and radiation left patterns in the distributions of baryons and the CMB. The former, known as BAO, are detected in the distribution of luminous galaxies.

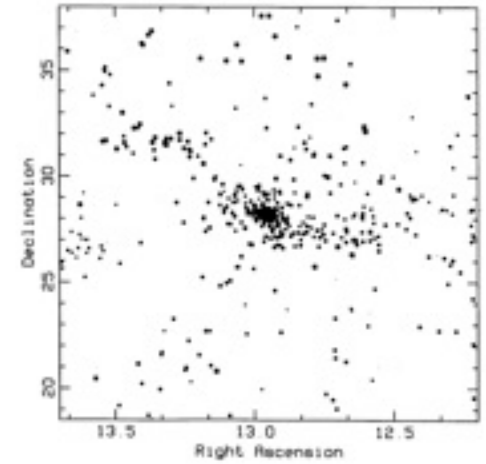
Nonbaryonic dark matter is essential for this beautiful model fit to the CMB anisotropy measurements.

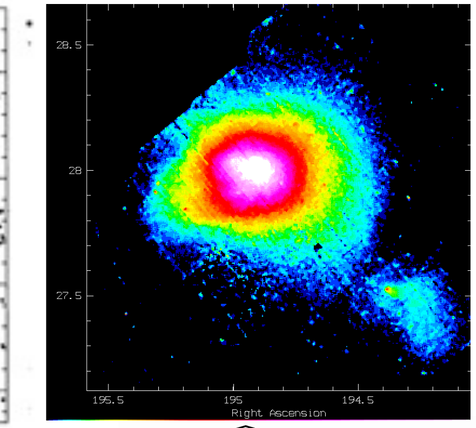
The BAO measurement is less precise but very important. It fixes a linear scale, which agrees with the astronomers' distance scale. That with the CMB anisotropy requires $\Lambda > 0$ with near flat space sections.

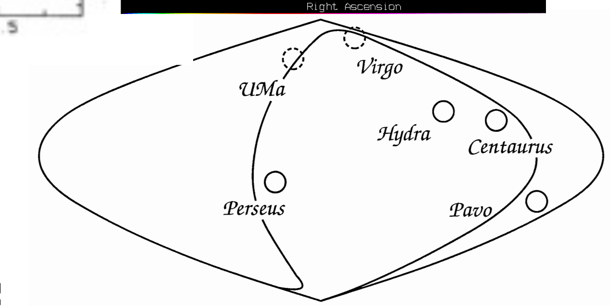
This is independent evidence for dark matter and dark energy, consistent with and checking the SNe measurements, in a relativistic cosmology that is looking good.

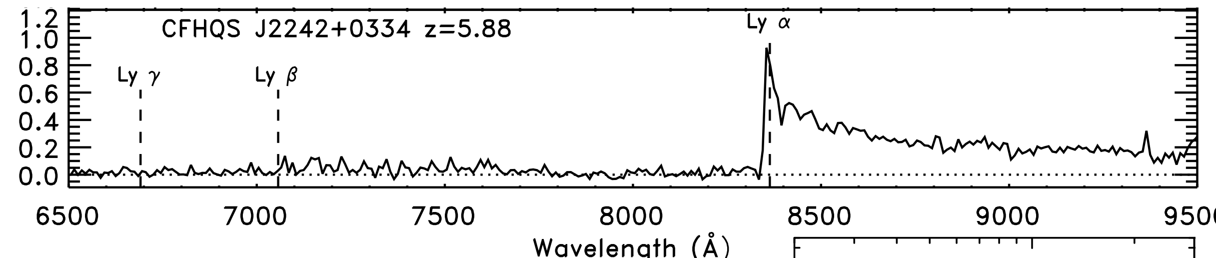


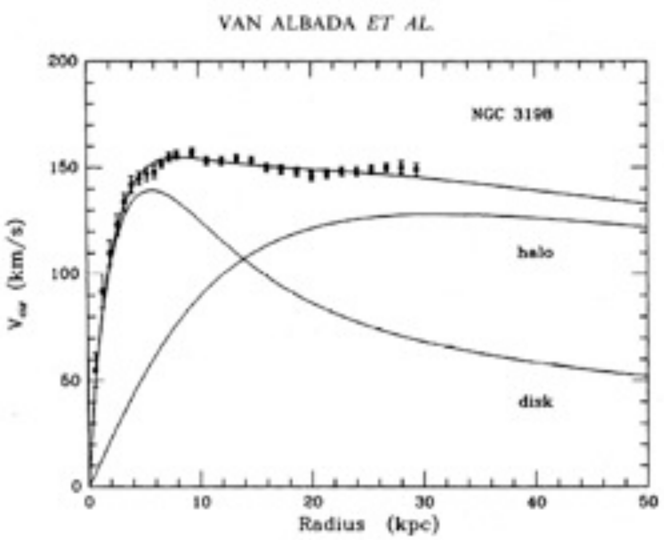


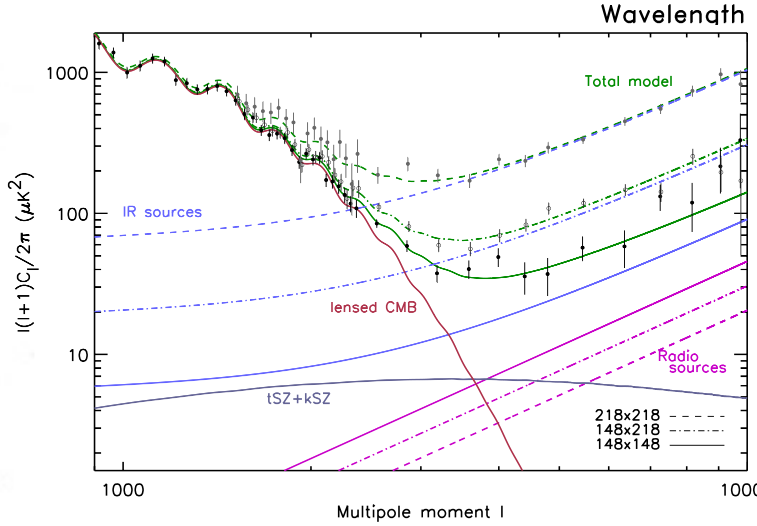


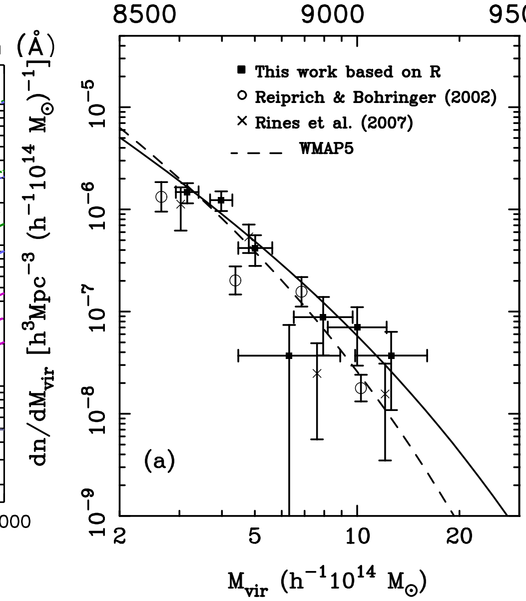


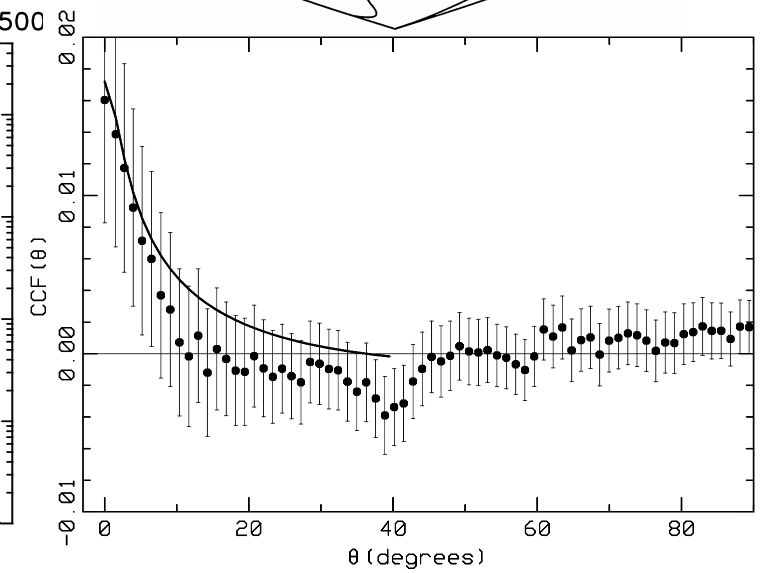


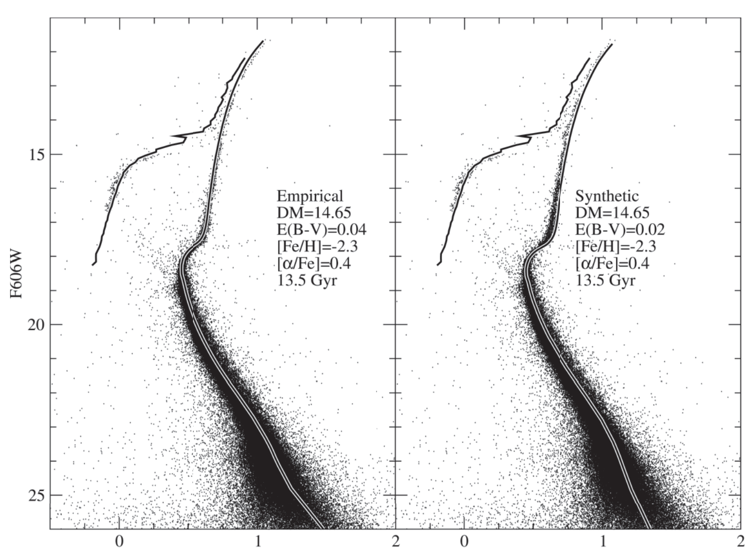


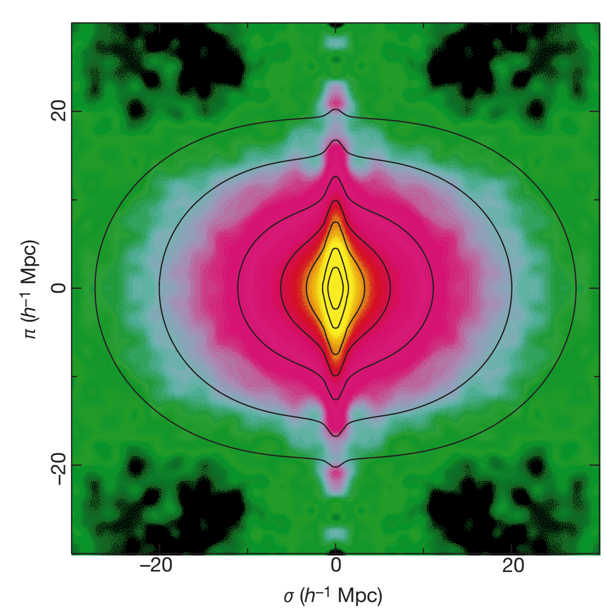


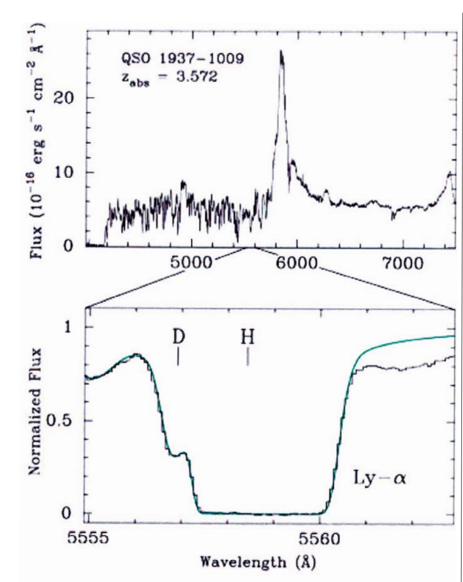


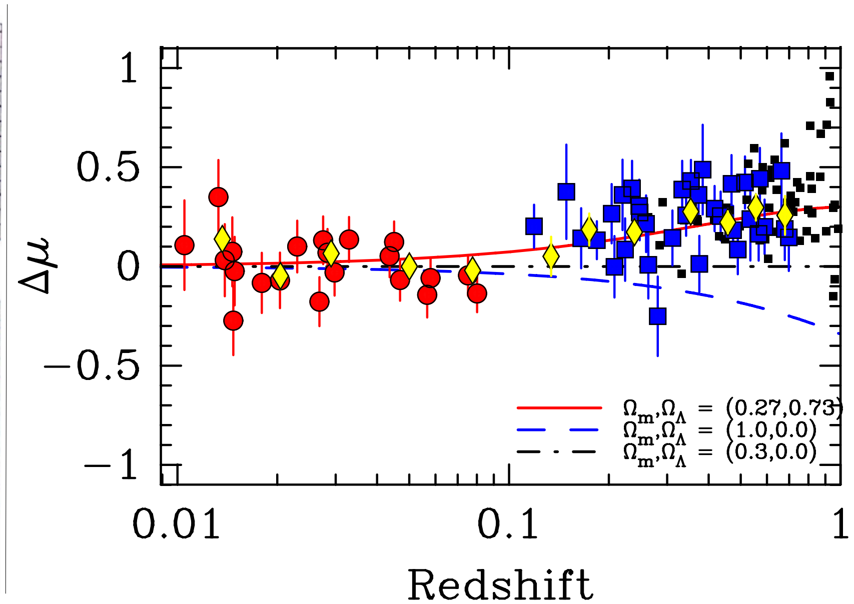












Wednesday, December 14, 2011

I conclude that the network of cosmological tests is cross-checked well enough to make a persuasive case that ΛCDM is a good approximation.

But the history of natural science is one of ever better models, along three paths.

1. Stay with the accepted model until forced from it.

   This is a long and productive tradition: community opinion often proves to be right. But we can think of examples where it was wrong.

2. Follow interesting ideas.

   Ideas stimulate research, as did the classical steady state cosmology, and may lead to great advances, as did Einstein's GR.

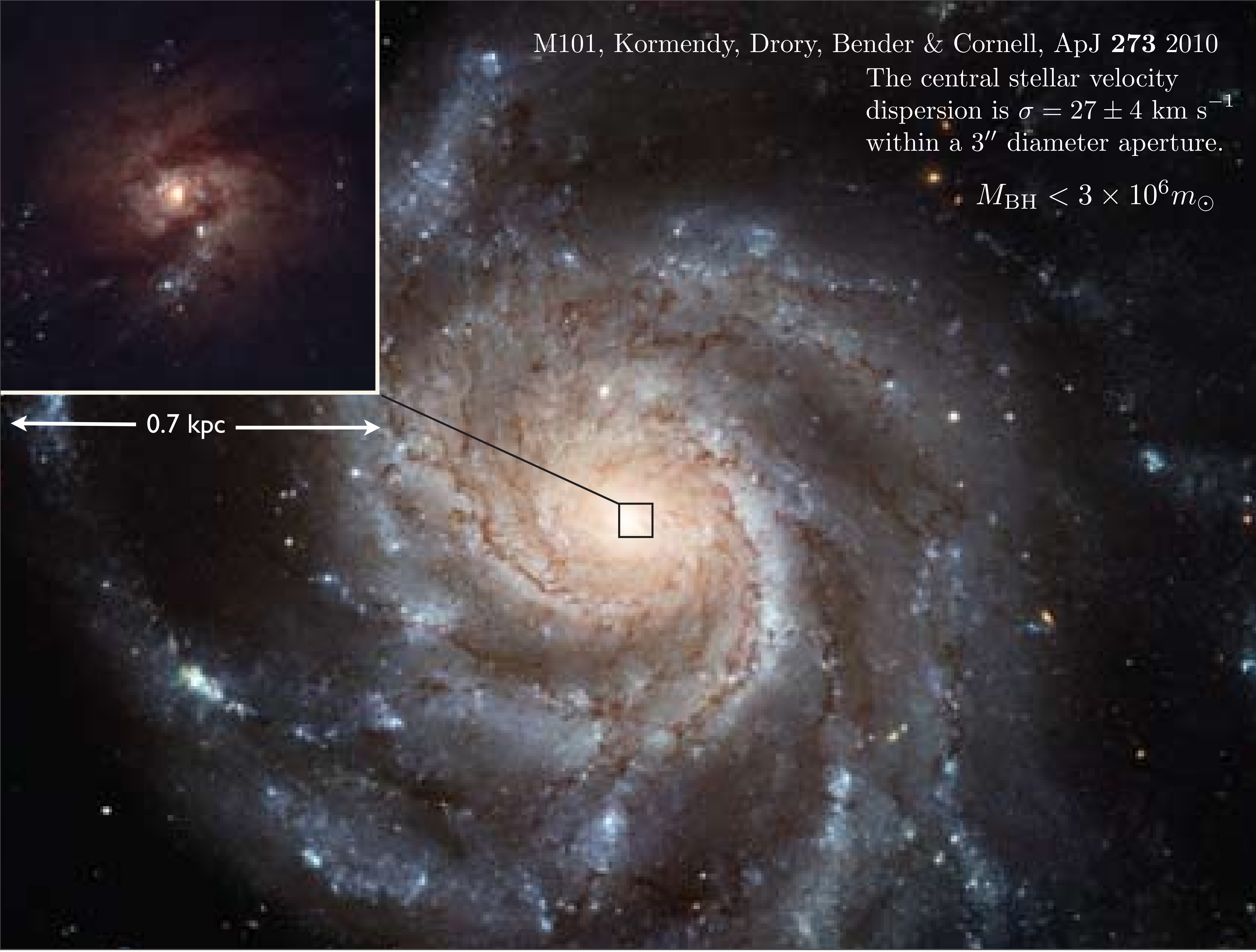
   Inflation and modified gravity certainly are stimulating research; whether more productive than that remains to be seen.

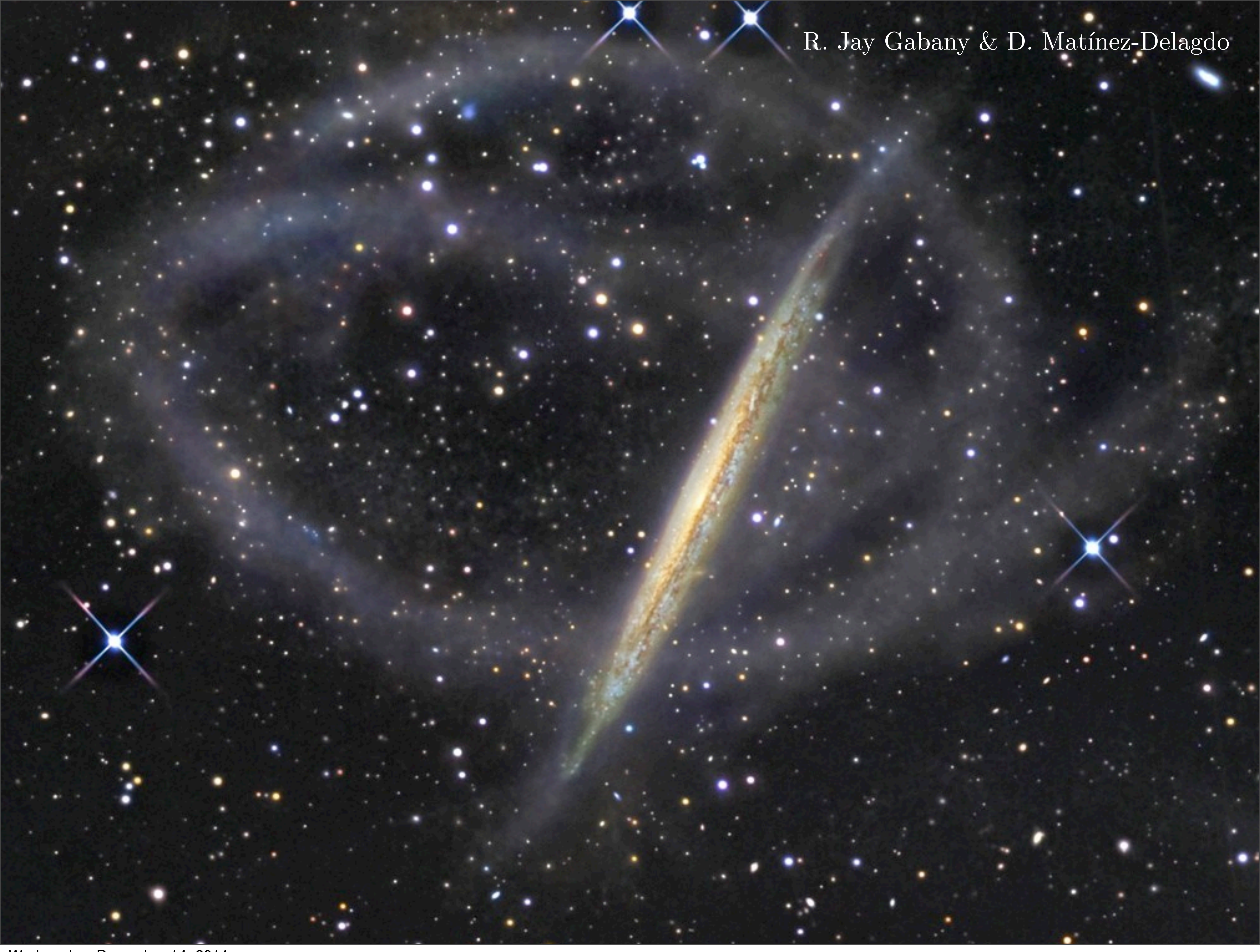
3. Seek anomalies.

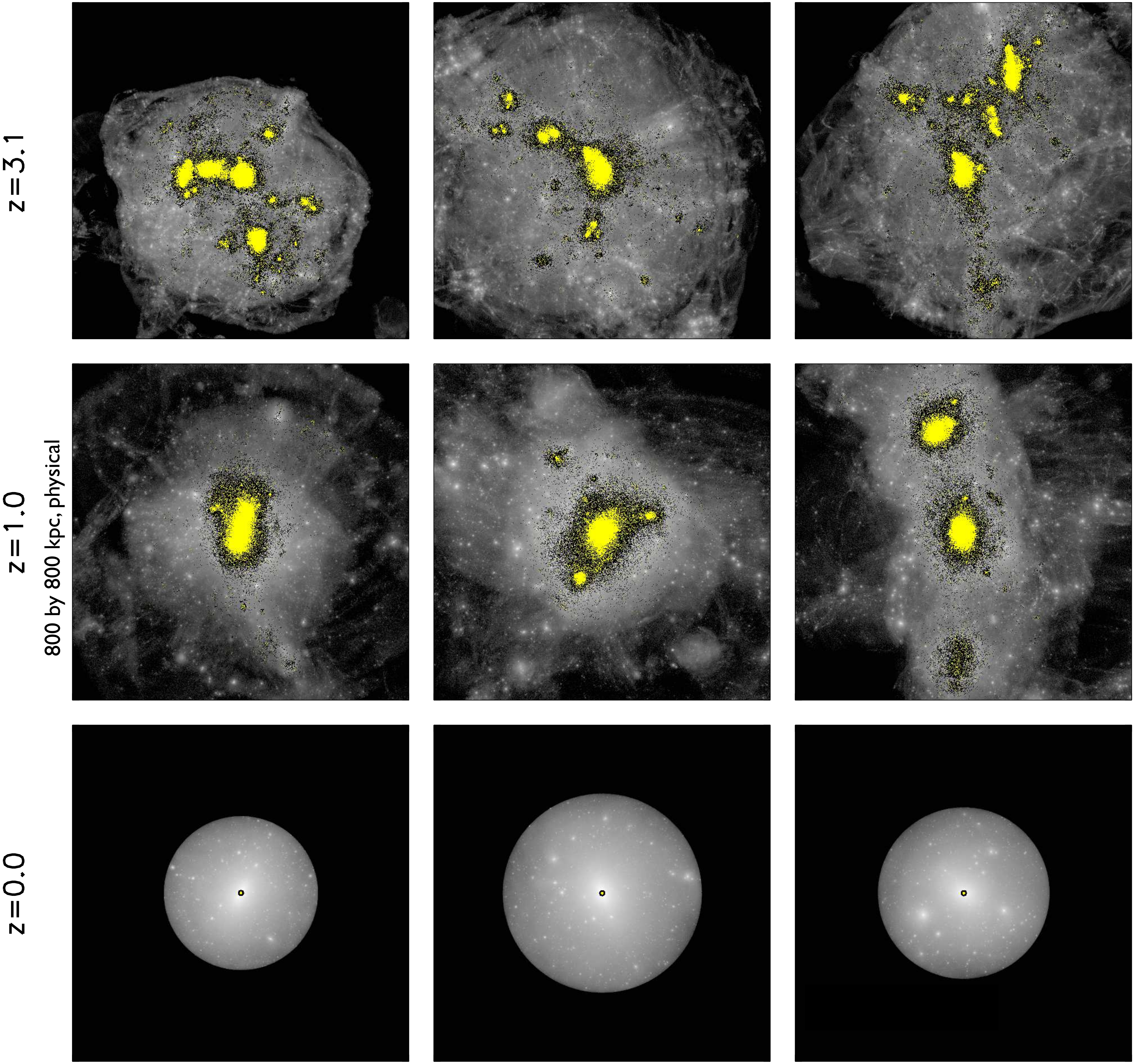
   Closer study may show an anomaly is only apparent, thus improving understanding of the standard model, or that the anomaly is real, thus pointing to a better model.

   Structure on the scales of galaxies offers rich hunting grounds, from highly redshifted 21-cm radiation to gravitational waves to the evidence found in nearby galaxies.

   I offer an example of the last: nearby galaxies give the impression of having evolved in near isolation, not what would be naïvely expected from ΛCDM.


M101, Kormendy, Drory, Bender & Cornell, ApJ **273** 2010
The central stellar velocity dispersion is $\sigma = 27 \pm 4$ km s^{-1} within a $3''$ diameter aperture.
$M_{\rm BH} < 3 \times 10^6 m_\odot$
0.7 kpc


R. Jay Gabany & D. Matínez-Delagdo



AQUARIUS pure DM halos of L* galaxies (Springel et al. 2008)

Images by Jie Wang, Durham, in colaboration with Adi Nusser, Technion

The grey scale shows particles at r200 > r > 7 kpc at z = 0.

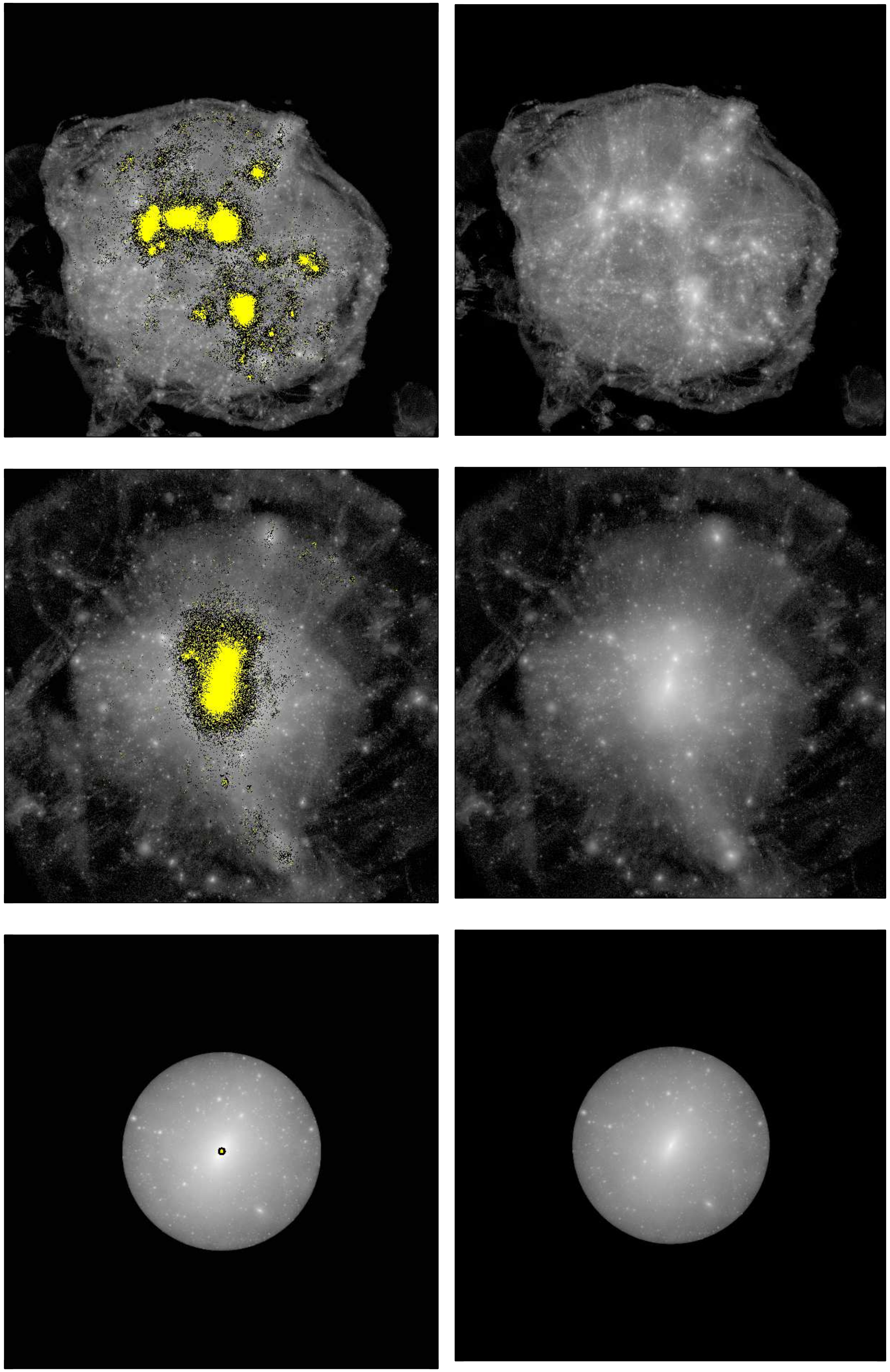
Overplotted in black are particles at 3 < r < 7 kpc at z = 0.

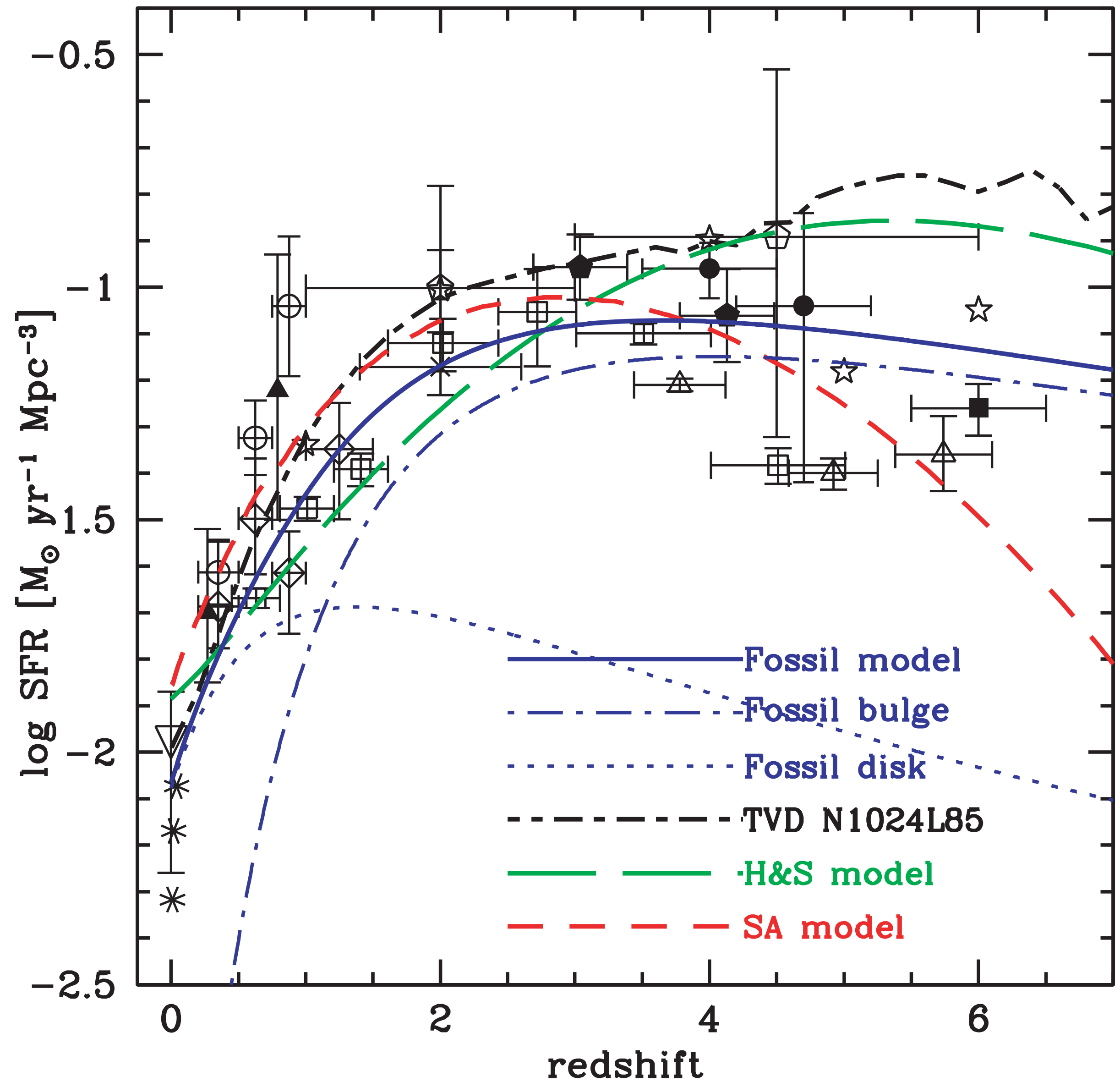
Overplotted in yellow are particles at r < 3 kpc at z = 0.

z=3.1

z=1.0

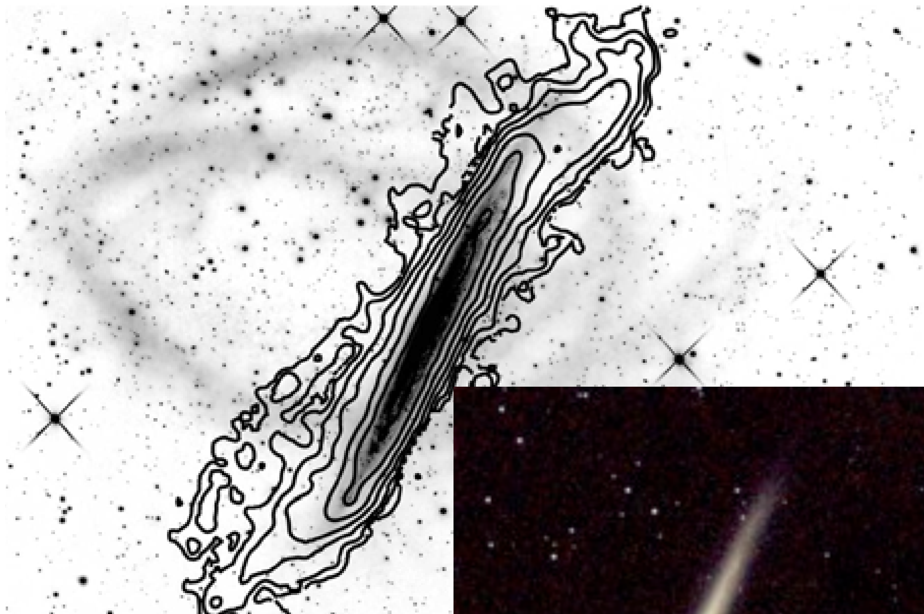
z=0.0




log SFR [M$_\odot$ yr^{-1} Mpc^{-3}]
redshift
−0.5
−1
1.5
−2
−2.5
0
2
4
6
Fossil model
Fossil bulge
Fossil disk
TVD N1024L85
H&S model
SA model

NGC 5907

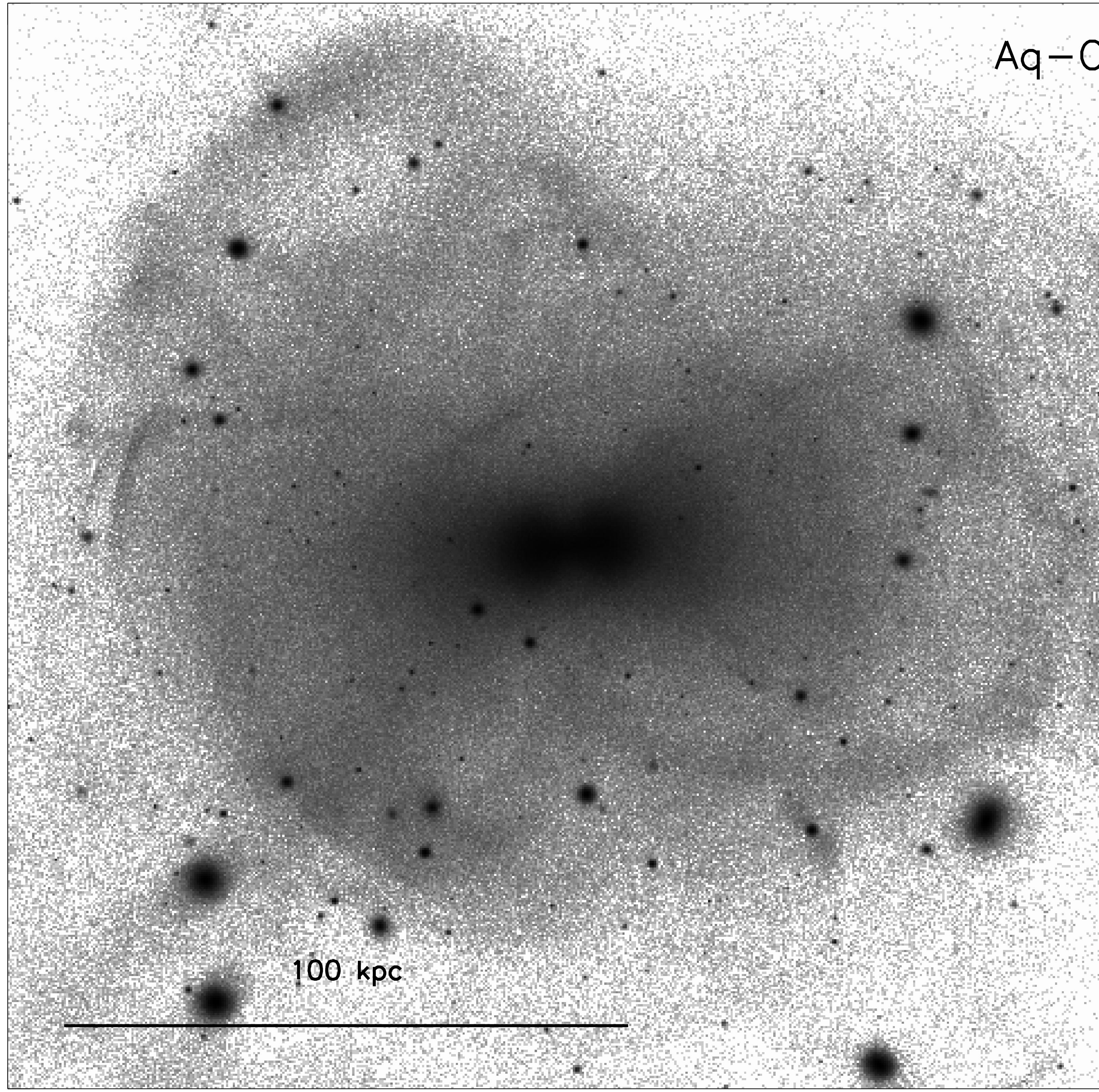
Martínez-Delgado *et al.* 2008 optical image, van der Hulst 21-cm contours



2MASS

There is starlight above the planes of some thin disk galaxies, in streams and smoother components, but it amounts to a few percent of the total.

So where are the remnants of the stars that were forming in abundance at redshift $z \sim 3$, when ΛCDM seems to predict an L_* galaxy typically was in scattered pieces?



Springel *et al.* Aquarius dark matter halos, Wang, Peebles and Nusser halo star formation model.

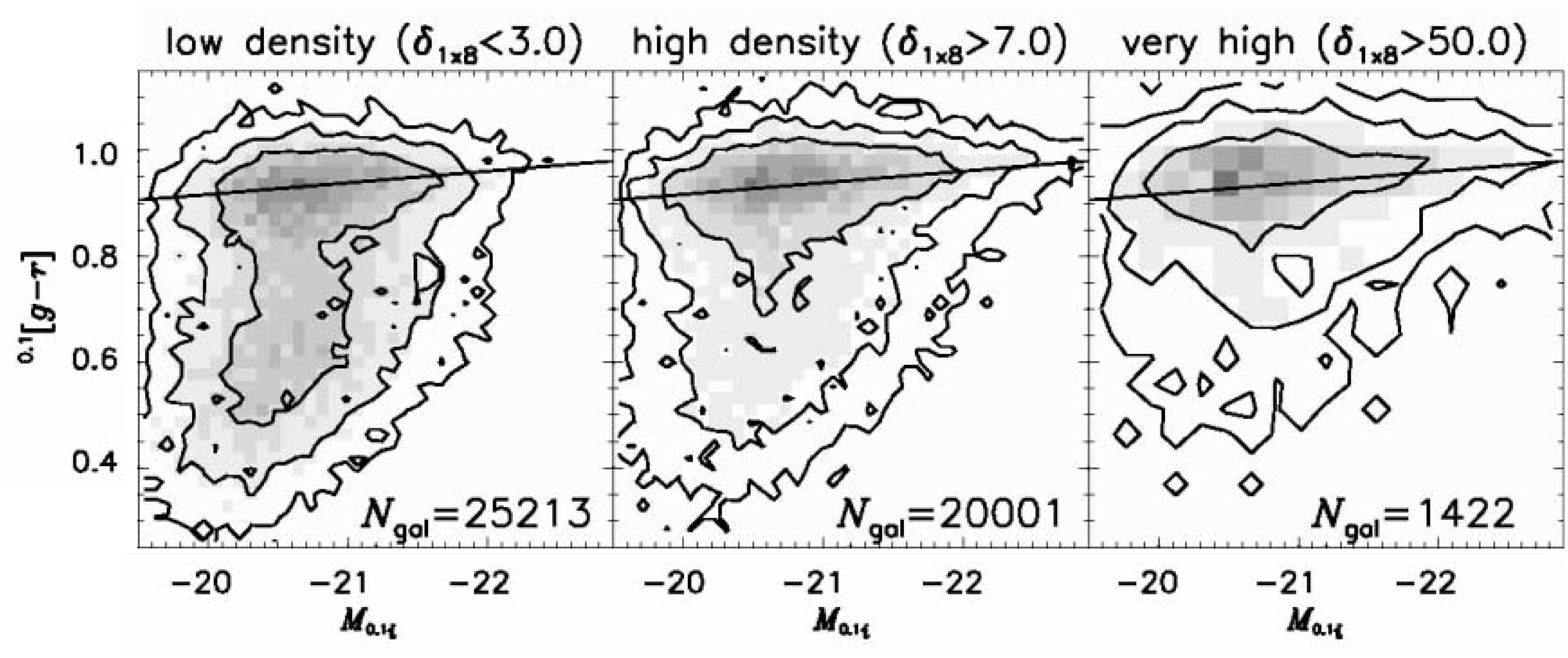
More on Island Universes

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]

Received 2003 July 11; accepted 2003 December 2; published 2004 January 16

(bowdlerized)



The local number density contrast is the average within a cylinder of radius $1h^{-1}$ Mpc and half-length $8h^{-1}$ Mpc in redshift space.

The SDSS magnitudes and colors are measured at $\sim 80\%$ of the nominal Petrosian magnitude, that is, well outside the half-light radius.

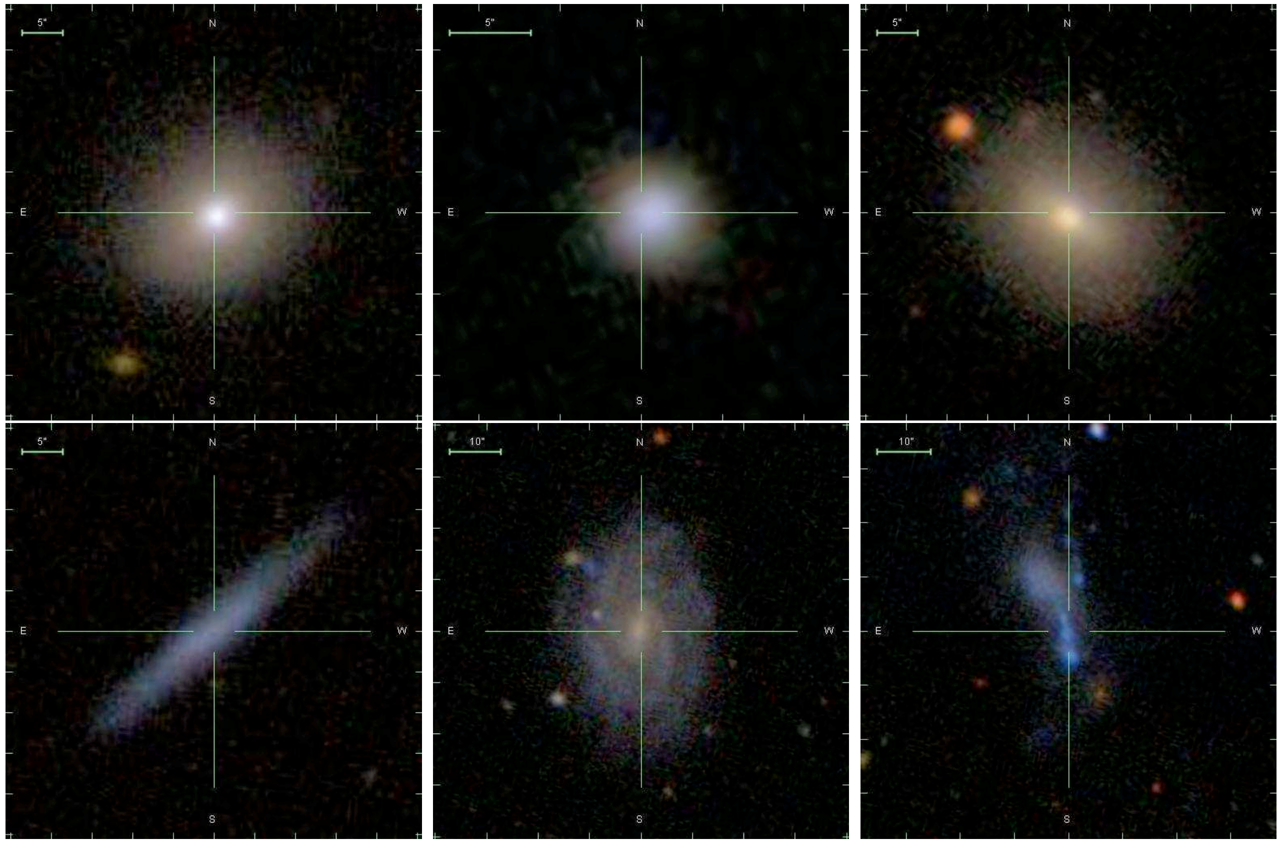


Figure 5.4: The VGS includes a range of stellar morphologies, with elliptical (VGS_24, top left; VGS_41, top center), lenticular (VGS_05, top right), bulge free (VGS_10, bottom left), spiral (VGS_15, bottom center), and irregular (VGS_17, bottom right) galaxies.

Kathryn Kreckel's thesis on the Void Galaxy Survey: galaxies in really low density regions

The following text will be submitted to the Astronomical Journal. The full reference for this work is Kreckel, K., Platen, E., Aragón-Calvo, M. A. , van Gorkom, J. H., van de Weygaert, R., van der Hulst, J. M., Beygu, B. 2011, in prep.

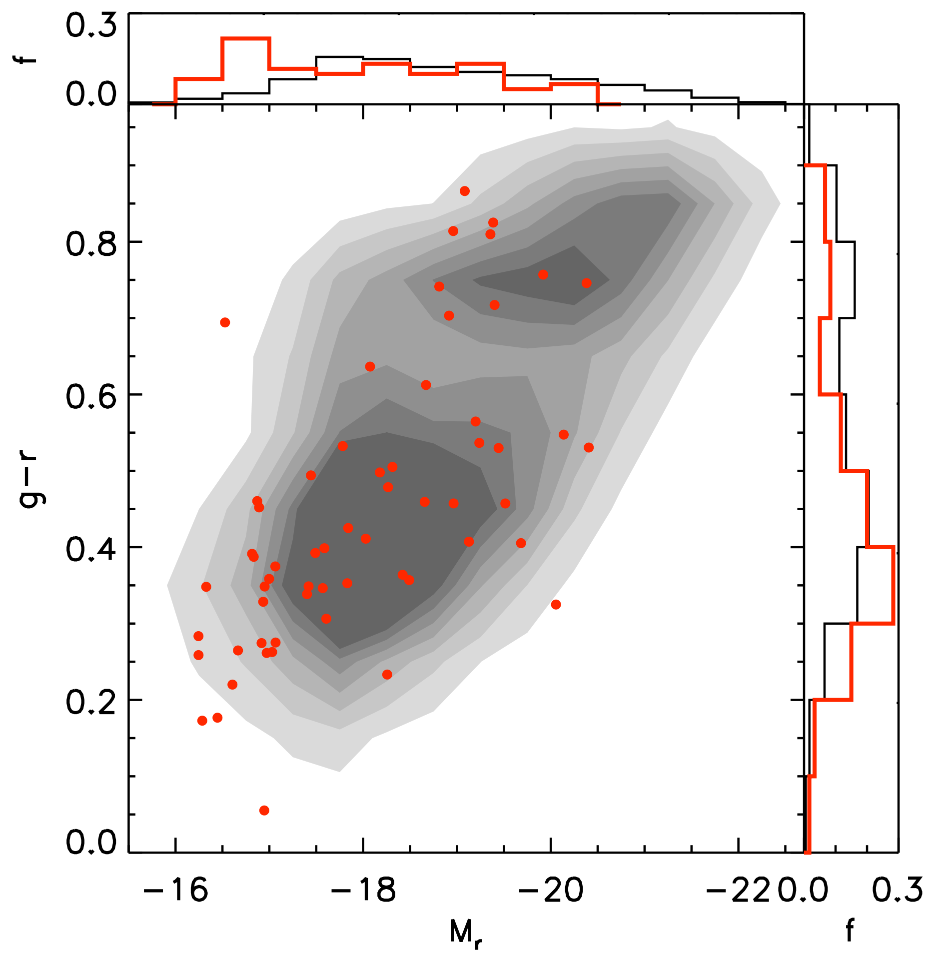
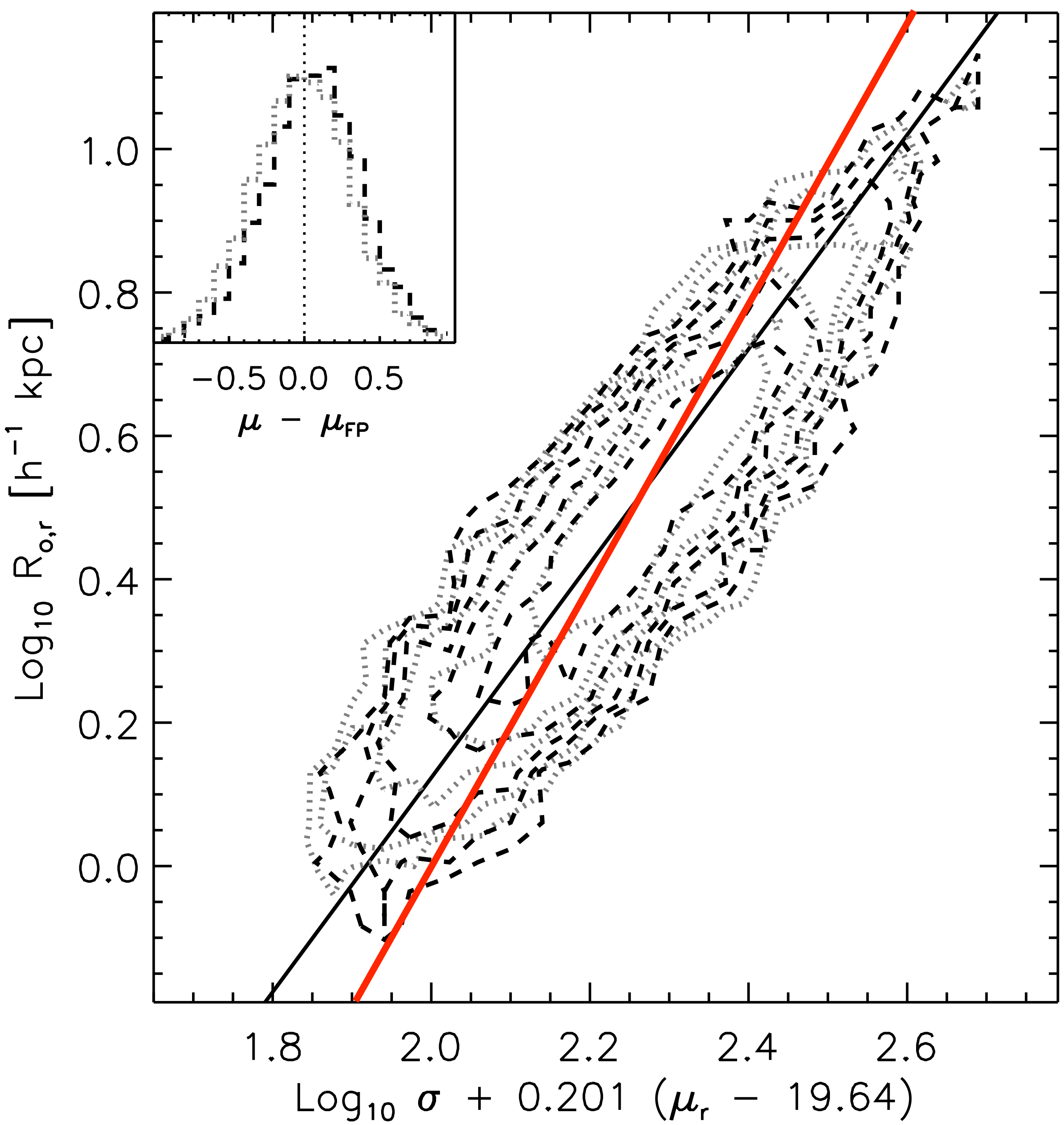


Figure 5.3: Color magnitude diagram of the VGS (red) compared with a magnitude limited sample of galaxies from SDSS selected in a similar redshift range $0.01 < z < 0.03$. Our void galaxies are typically blue and faint, but do span a range of colors and luminosities.



M. Bernardi *et al.* (2006) study of the effect of environment on the fundamental plane for SDSS early-type galaxies. Dashed contours: galaxies at higher ambient density; dotted, lower density.

The red line is the relation

$$\log \sigma + 0.2\mu = 0.5 \log R + \text{ constant}$$

that follows from the virial theorem if M/L is constant. The scaling indicated by the tilt of the contours relative to the red line,

$$M/L \propto R^{0.3}$$

shows exceedingly little environmental effect.

Many nearby galaxies appear to have evolved as island universes. This curious behavior will teach us something of value.

The conservative idea is that it will lead to a better understanding of ΛCDM.

The speculative idea is that ΛCDM has to be adjusted. It would seem helpful to hasten growth of mass concentrations that become galaxies so that

- variations of environment at assembly are less pronounced,
- merging of star-bearing subhalos after stellar disk formation is less frequent,
- while ensuring that evolution on the larger scales probed by the network of cosmological tests is not seriously affected.

I offer an example, the effect of adding to ΛCDM a new dark matter component, a gas of evanescent particles that interact only with gravity and a massless scalar field.

This is a scenario: I have only a schematic example of possible implications.

Evanescent Dark Matter

Imagine adding to ΛCDM a new dark matter component that interacts only with gravity and a scalar field with classical action

$$S = \int d^4x\, a(t)^3\, (\partial\Phi)^2/2 - \sum_i \int |\Phi(\vec{x}_i(t), t)|\, ds_i, \tag{1}$$

In the nonrelativistic limit with gravitational potential $\psi(\vec{x}, t)$,

$$\Phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t), \tag{2}$$

$$\ddot{\phi}(t) + 3\frac{\dot{a}}{a}\dot{\phi} = -\bar{n}(t), \tag{3}$$

$$\ddot{\delta}\phi(t) + 3\frac{\dot{a}}{a}\dot{\delta}\phi - \frac{\nabla^2\delta\phi}{a^2} = -(n(\vec{x}, t) - \bar{n}(t)), \tag{4}$$

$$\frac{\nabla^2\psi}{a^2} = 4\pi G[\rho_{\rm dm}(\vec{x}, t) - \bar{\rho}_{\rm dm} + \phi(t)(n(\vec{x}, t) - \bar{n}(t))], \tag{5}$$

$$\frac{d}{dt}\phi(t)a(t)^2\frac{d\vec{x}}{dt} = -\nabla\delta\phi - \phi(t)\nabla\psi. \tag{6}$$

On small scales the fifth force $-\nabla\delta\phi/a$ between evanescent particles is $(4\pi G\phi^2)^{-1} = (m_{\rm pl}/\phi)^2$ times gravity, which can be big, and hasten formation of a dense core in a young galaxy.

On larger scales equation (4) says the fifth force is suppressed by $\sim (tk/a)^2$, which can hide it from the classical cosmological tests.

The interaction with the particles drives the field to zero, making the evanescent particles relativistic and eliminating them from galaxies at low redshift, when they're not wanted.

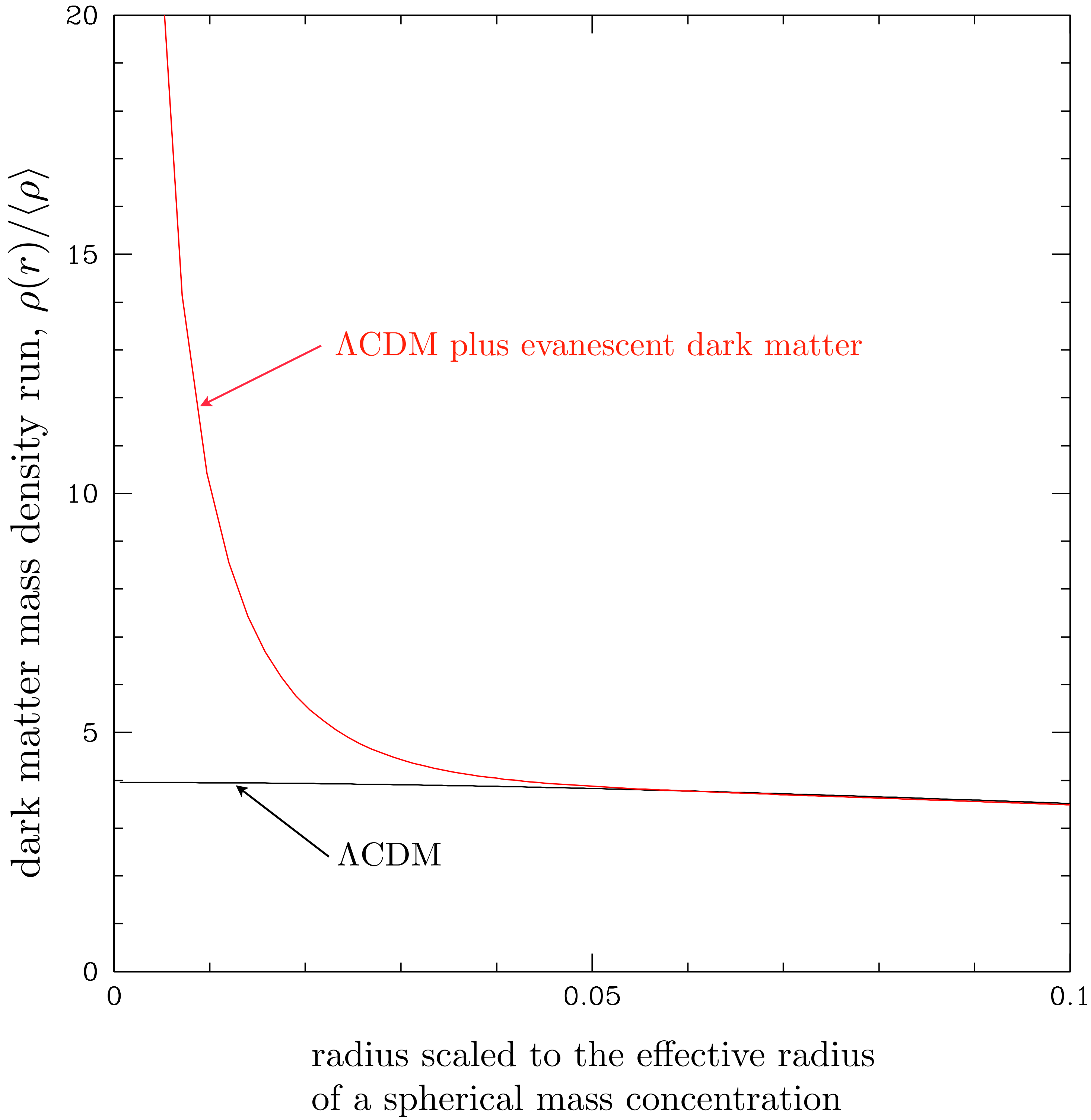


Illustration of the Effect of Evanescent Dark Matter

The field value and ratio of evanescent to ordinary dark matter mass densities at very high redshift are

$$4\pi G\phi^2 = 1.8 \times 10^{-3},$$

$$\phi\bar{n}/\rho_{\rm dm} = 2 \times 10^{-4}.$$

The mass density as a function of radius in this spherically symmetric halo is plotted at redshift

$$z = 20,$$

when $\phi \to 0$ and the evanescent matter leaves the dark matter halo.

The central concentration of dark matter induced by the evanescent dark matter could have interesting effects: early formation of massive black holes, which promote formation of stellar halos around massive black holes, ... and dream on.

1. General relativity theory with standard physics passes a demanding test.
   (a) Ideas in natural science have great power, on occasion.
   (b) This case is persuasive because it is cross-checked by many independent measurements.
   (c) But there are viable alternatives, and good science demands their close study.

2. The case for dark matter and dark energy is persuasive.
   (a) So is dark matter annihilating and/or interacting, warm, hot, evanescent and/or something completely different?
   (b) An alternative, MOND, is seriously problematic, but I have to admire its galaxy physics.
   (c) The search for evolution of Einstein's Λ is good science but not to be compared to the LHC search for a Higgs sector. Let us continue to explore a broader range of ideas.
   (d) The curious value of Λ supports interest in multiverses. Are we approaching the time when "data-free science" will no longer be an oxymoron?

3. The case for inflation is promising.
   (a) It is readily adjusted to fit statistical homogeneity, a hot big bang, and near scale-invariant Gaussian initial conditions.
   (b) A more specific feature, tilt from scale-invariance, is detected at 2 to 3σ, unless reionization has a complicated history. The case for tilt is promising but not yet persuasive.
   (c) If detected primeval gravitational waves or non-gaussianity may add to the case for inflation.
   (d) Did inflation really happen? A persuasive case awaits closer tests of inflation and alternatives.

4. Research on cosmic structure, from superclusters to supermassive black holes, is opening new paths to tests of gravity physics and cosmology,
   (a) rich in data,
   (b) and producing some fascinating challenges to accepted ideas.