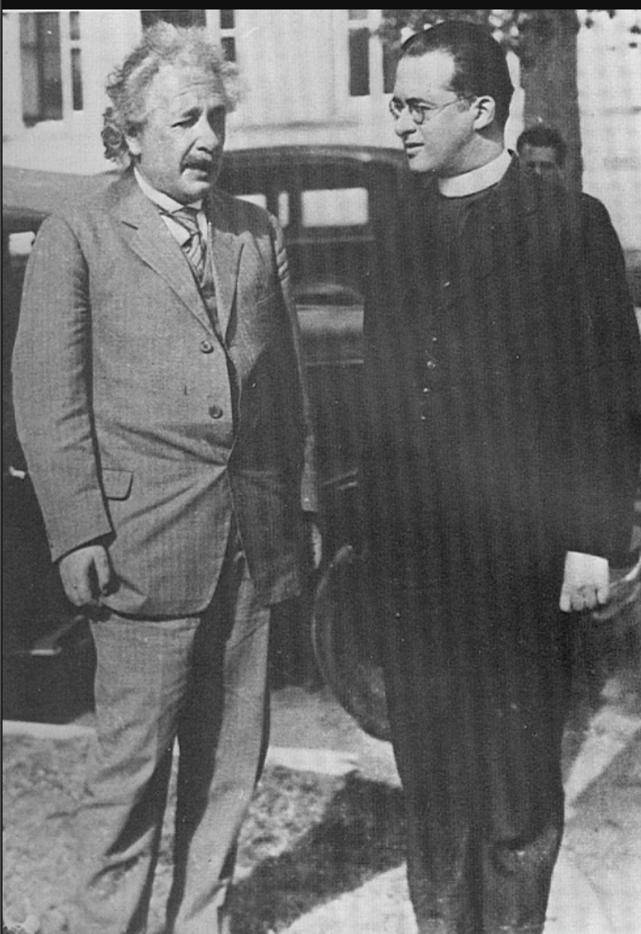
University of California-Berkeley

Astronomy Department

The Dark Sector of Cosmology: Successes and Challenges

Jim Peebles, 12 October 2006

Courtesy of
les archives
Lemaître,
Louvain-la-Neuve



Bruxelles, july 30, 1947

Dear Professor Einstein

I have been asked to contribute to the volume which will be dedicated to you in the LIBRARY OF LIVING PHILOSOPHERS.I have choisen for subject " The cosmological Constant" a subject that I have had sometimes the advantage to discuss in conversation with you. I remember that the last time I met you at Princeton some of my reasons impressed you some what. That is the reason why I make some effort to modify your present attitude against what I always have considered as one of your greatest contribution to Science.

The main points of my paper are I) that gravitational mass, which has a definit effect, could not have been identified with energy, which is defined but for an additive constant, if theory would not provide some mean of adjustement ne when the zero level of energy is changed at will.

2) that the cosmical constant is necessary to get a time-scale of evolution which would definitely clear out from the dangerous limit imposed by the known duration of geologic ages.

3) that the instability of equilibrium between gravitational attraction and cosmical repulsion , is the only mean to understant an evolution on the stellar scale during

Courtesy of les archives Lemaître

THE INSTITUTE FOR ADVANCED STUDY
Founded by Mr. Louis Bamberger and Mrs. Felix Fuld
PRINCETON, NEW JERSEY

September 26,1947

Professor G.Lemaitre
9 rue Henry de Braekeleer
Brussels,Belgium

Dear Professor Lemaitre:

I thank you very much for your kind letter of July 30th. In the meantime I received from Professor Schillpp your interesting paper for his book. I doubt that anybody has so carefully studied the cosmological ~~xxxxxxx~~ implications of the theory of relativity as you have. I can also understand that in the shortness of T_0 there exists a reason to try bold extrapolations and hypotheses to avoid contradiction with facts. It is true that the introduction of the λ term offers a possibility, it may even be that it is the right one.

Since I have introduced this term I had always a bad conscience. But at that time I could see no other possibility to deal with the fact of the existence of a finite mean density of matter. I found it very ugly indeed that the field law of

Courtesy of les archives Lemaître, Louvain-la-Neuve

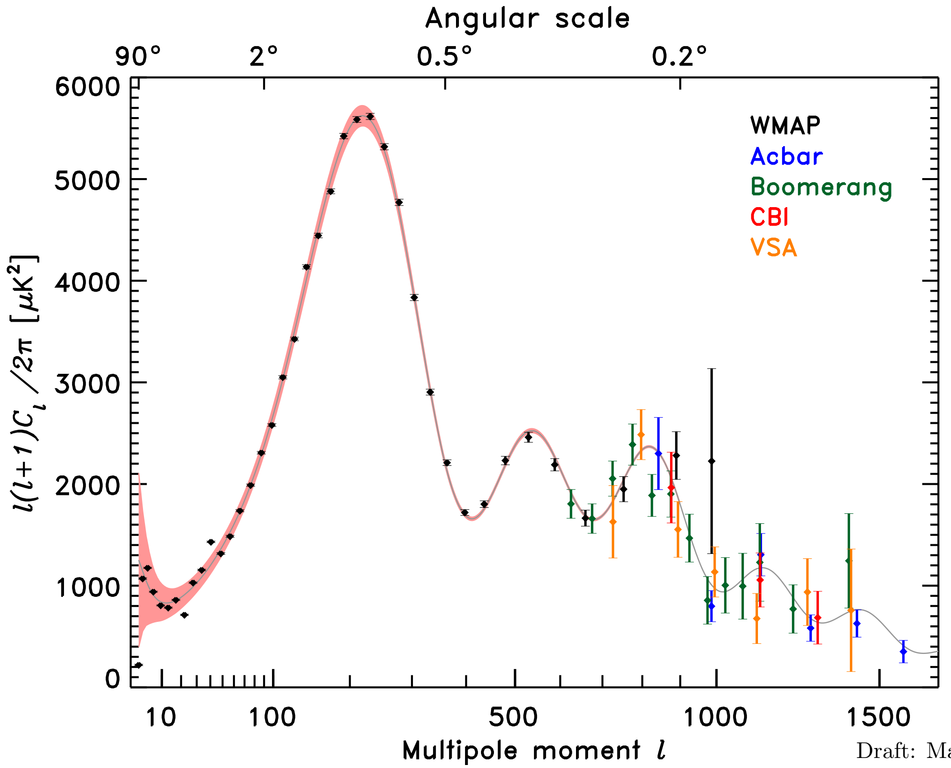
THE INSTITUTE FOR ADVANCED STUDY
Founded by Mr. Louis Bamberger and Mrs. Felix Fuld
PRINCETON, NEW JERSEY

Your argument 1) for the λ term I do not find convincing. Since it is known that energy is equal to the inert mass there is no more room for an additive constant of energy.

There is one fundamental point in the theory of relativity which is problematic and may have to do with the problem of the explosion time T_0. The elementary length $d\tau = \sqrt{g_{ik}dx_i dx_k}$ is supposed to be an invariant. This is the basis for the whole mathematical theory of gravitation. Besides this it is also assumed that there are uniquely determined physical objects (rods and clocks) which can be used to measure this invariant.

The situation is much better now: ΛCDM passes demanding tests from

- the CMBR temperature anisotropy power spectrum;
- the CMBR temperature – polarization spectrum;
- the galaxy and Lyα forest power spectrum (with modest bias);
- the baryon oscillation signature;
- $\Omega_{\rm baryon}$ from 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;
- the cluster mass function; and
- 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]

We are drawing large conclusions from exceedingly limited evidence, and we have to bear in mind that Nature may well have more surprises for us.

But the ΛCDM cosmology passes an impressive network of demanding tests. Surprises may well drive perturbative adjustments to the cosmology, but I conclude that a revolutionary adjustment — as replacement of dark matter with some generalization of MOND — is unlikely.

The standard relativistic hot Big Bang ΛCDM cosmology very likely gives us a useful approximation to what actually happened as the universe expanded and cooled from redshift $z \sim 10^{10}$.

Is it equally likely that this cosmology includes all the physics relevant to observational extragalactic astronomy? Or might it be the simplest approximation we can get away with at the current level of evidence?

You don't have to decide: it's good science to operate on the assumption that the ΛCDM cosmology has all the relevant physics unless or until the observations force us to improve the model.

But it also is good science to pay attention to apparent anomalies, consider tests that might help determine which if any are real, and explore what the anomalies, if real, might teach us.

I shall discuss some apparent anomalies in the dark sector, a possible remedy — a fifth force in the dark sector — and the test from the tidal disruption of satellite galaxies.

What is in the voids defined by the galaxies?

THE ORIGIN OF DWARF GALAXIES, COLD DARK MATTER, AND BIASED GALAXY FORMATION

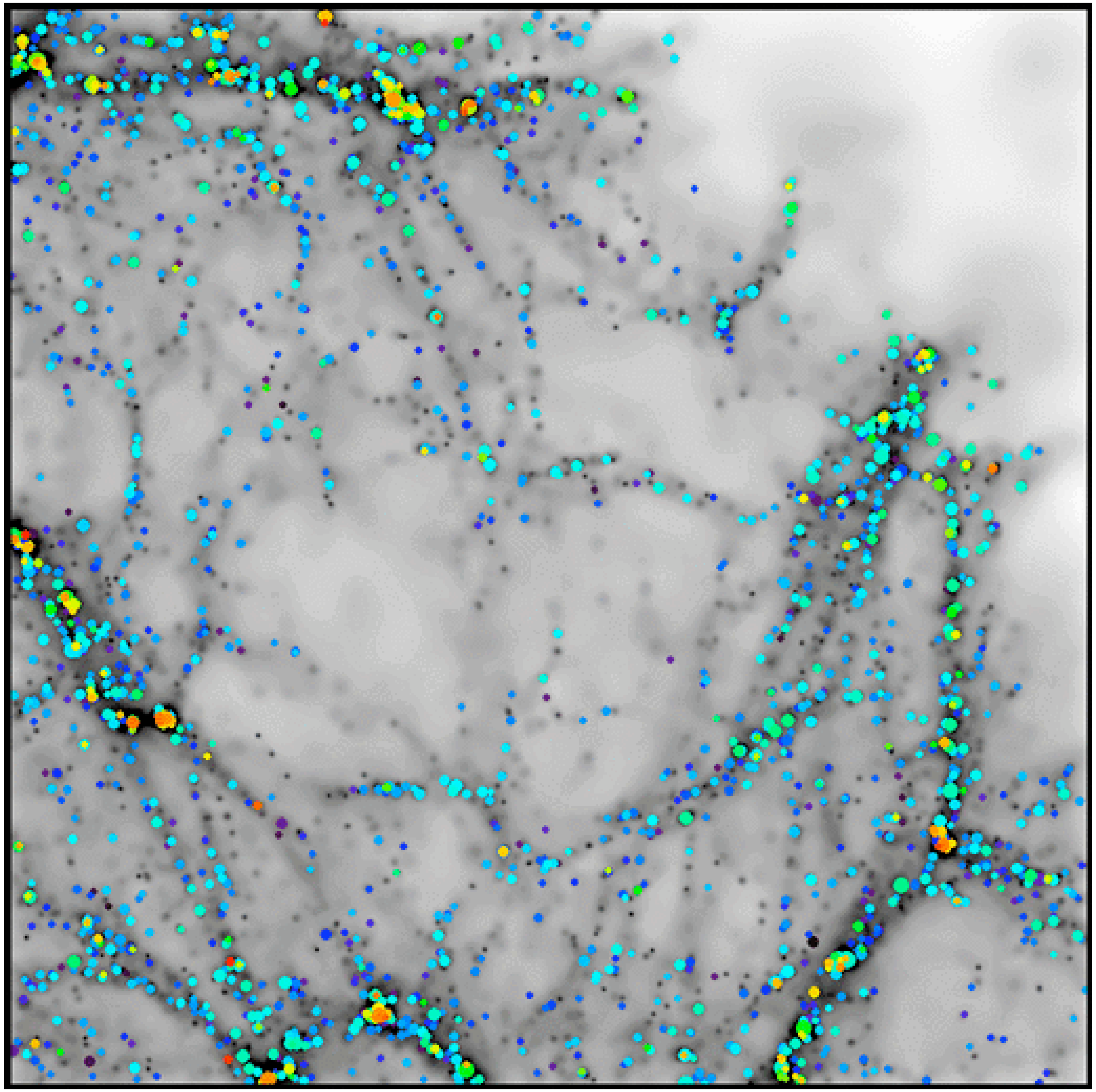
AVISHAI DEKEL
Department of Astronomy, Yale University; and Department of Physics, Weizmann Institute of Science

AND

JOSEPH SILK
Astronomy Department, University of California, Berkeley
Received 1985 April 25; accepted 1985 August 14

6. The dwarfs should be present also in the regions void of bright galaxies, and, in general, the galaxy luminosity function is expected to vary with the background density; the ratio of faint to bright galaxies should be larger in regions of lower density.

This is a pure DM LambdaCDM simulation.
Notice the Dekel-Silk (1985) effect.

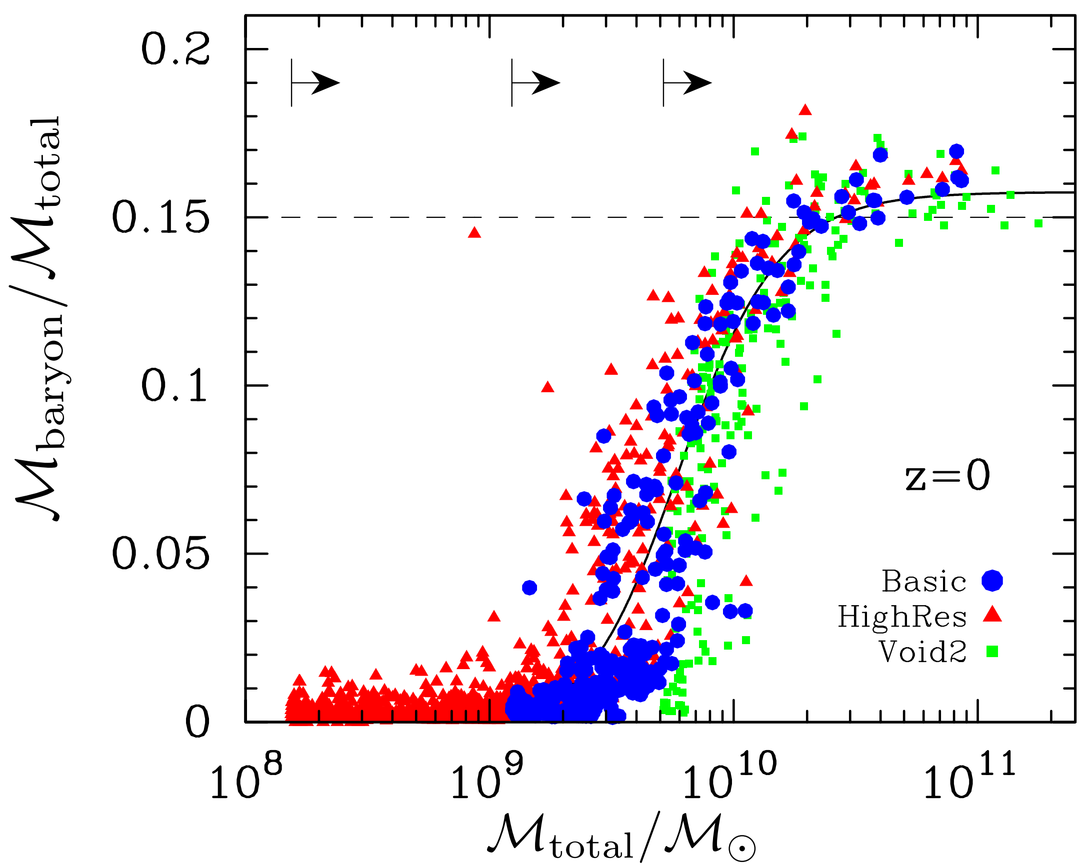


$50 \times 50 \times 15h^{-1}$ Mpc

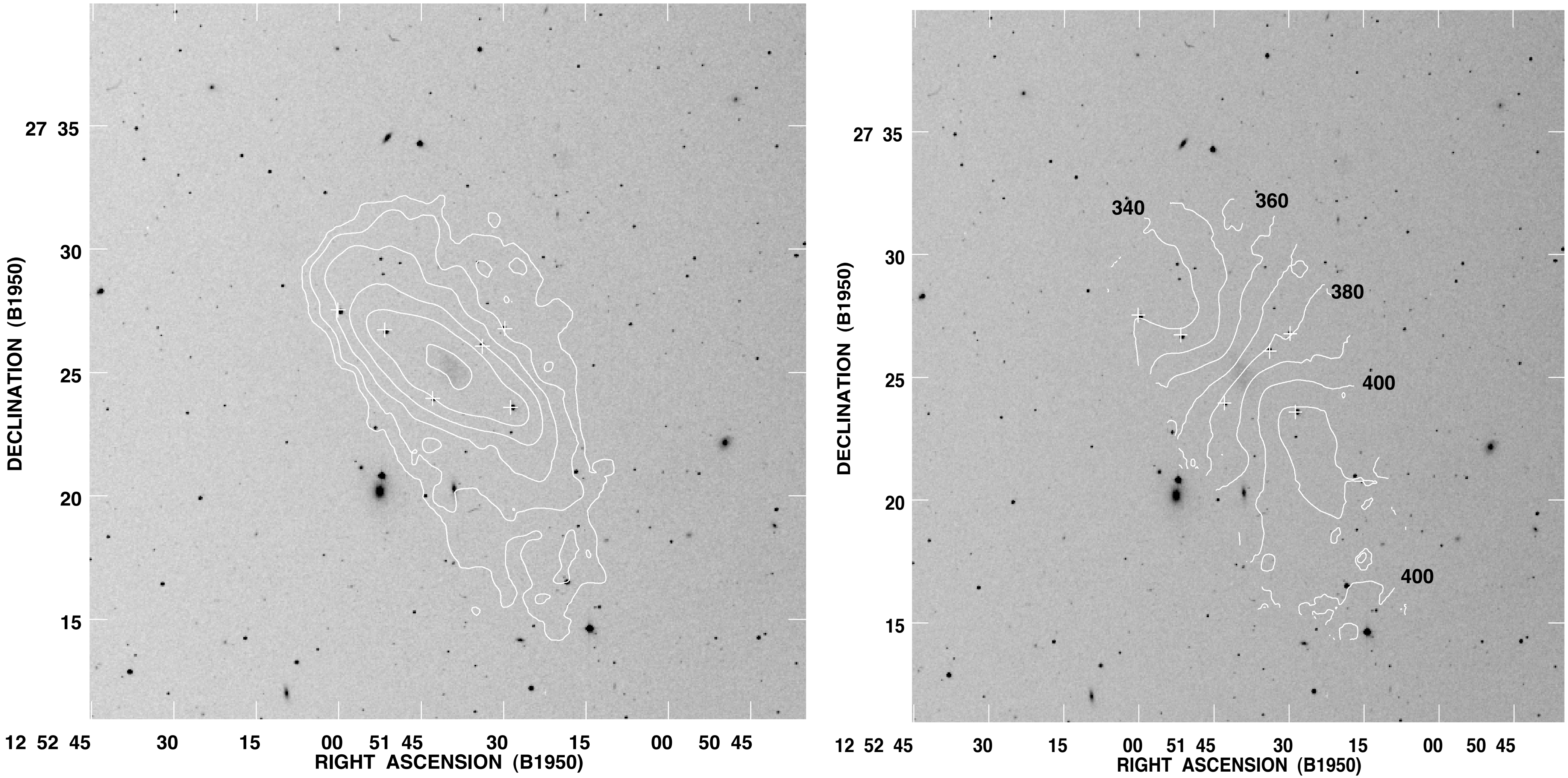
H. Mathis & S. D. M. White, MN 337, 1193, 2002

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

Matthias Hoeft[1], Gustavo Yepes[2], Stefan Gottlöber[3], and Volker Springel[4]

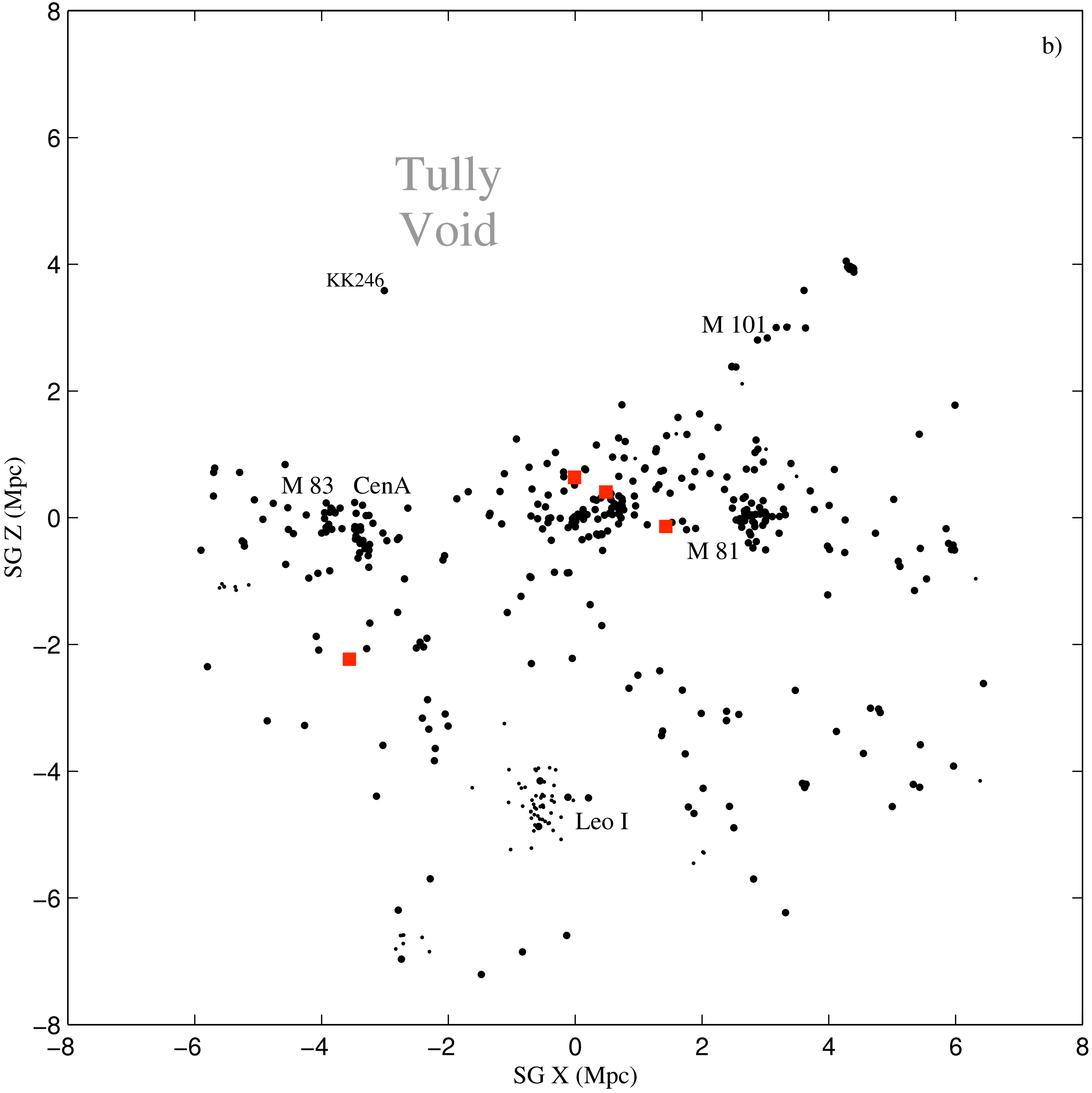


Gottlöber et al. (2003) predicted that a typical 20 h^{-1} Mpc diameter void should contain up to 1000 halos with mass $\sim 10^9\ h^{-1}\,\mathrm{M}_\odot$ and still about 50 halos with mass $\sim 10^{10}\ h^{-1}\,\mathrm{M}_\odot$. Assuming a magnitude of $M_B = -16.5$ for the galaxy hosted by a halo of mass $3.6 \times 10^{10} h^{-1}\mathrm{M}_\odot$ (Mathis & White 2002), they predict that about five such galaxies should be found in the inner regions of a typical void of diameter 20 h^{-1} Mpc.



The Carignan and Purton 21-cm surface density and velocity maps of DDO 154

Stellar mass: $3 \times 10^7 M_\odot$
HI plus He mass: $2 \times 10^8 M_\odot$
total mass within 6 kpc: $3 \times 10^9 M_\odot$



Why does this map look so different from what Dekel & Silk (1985) point out might reasonably be expected in the LambdaCDM cosmology?

The Karachentsev *et al.* (2004) Catalog of Neighboring Galaxies. The larger circles show the galaxies at $v_{\rm LG} < 550$ km s^{-1}. The smaller circles show galaxies at somewhat greater distance.

The red squares are, left to right, the gas dwarfs
ESO 215-G?009
DDO 154
UGCA292
NGC3741

The local sheet at SGZ = 0 is part of the Local Supercluster. The Tully Void is really empty.

It has been brought to my attention that the void dwarf problem may be reduced to the previously unsolved problem of excess numbers of dwarf DM halos in the ΛCDM cosmology.

I don't consider this promising because many of the known extreme dwarfs are fragile, and surely more likely to survive in the less busy environment of the voids.

What is the effect of merging and accretion on giant elliptical galaxies at $z < 1$?

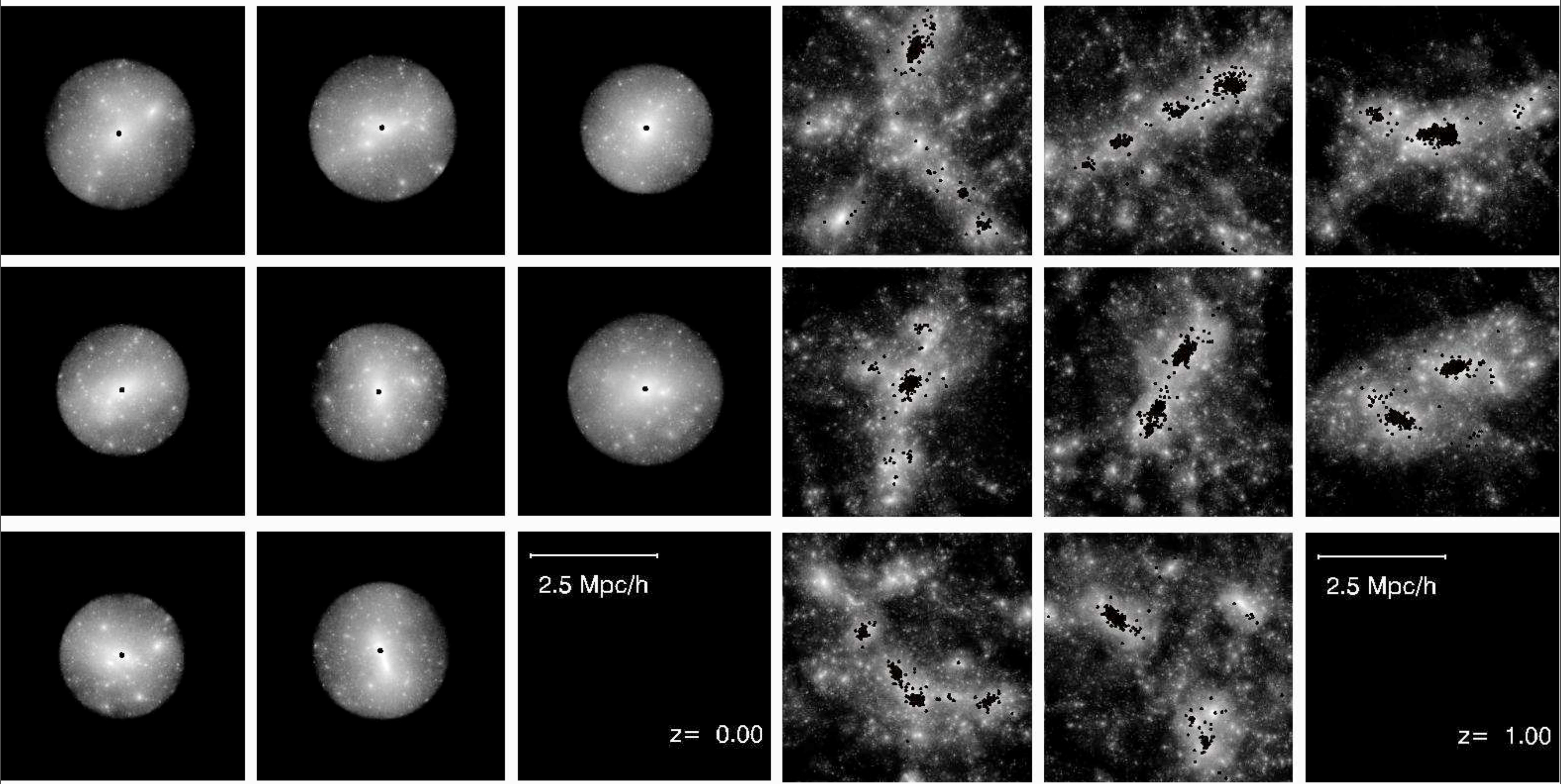


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each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

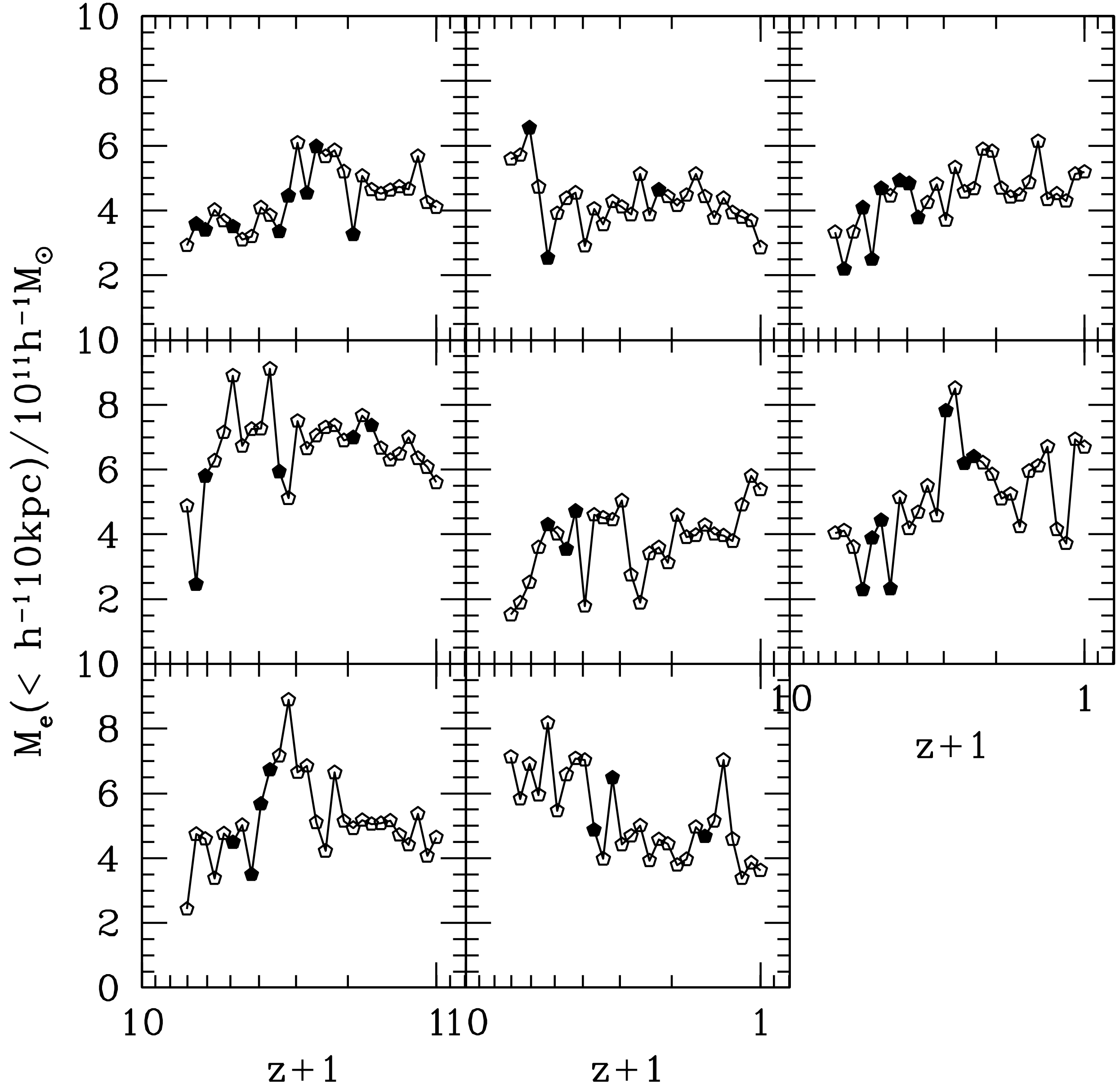
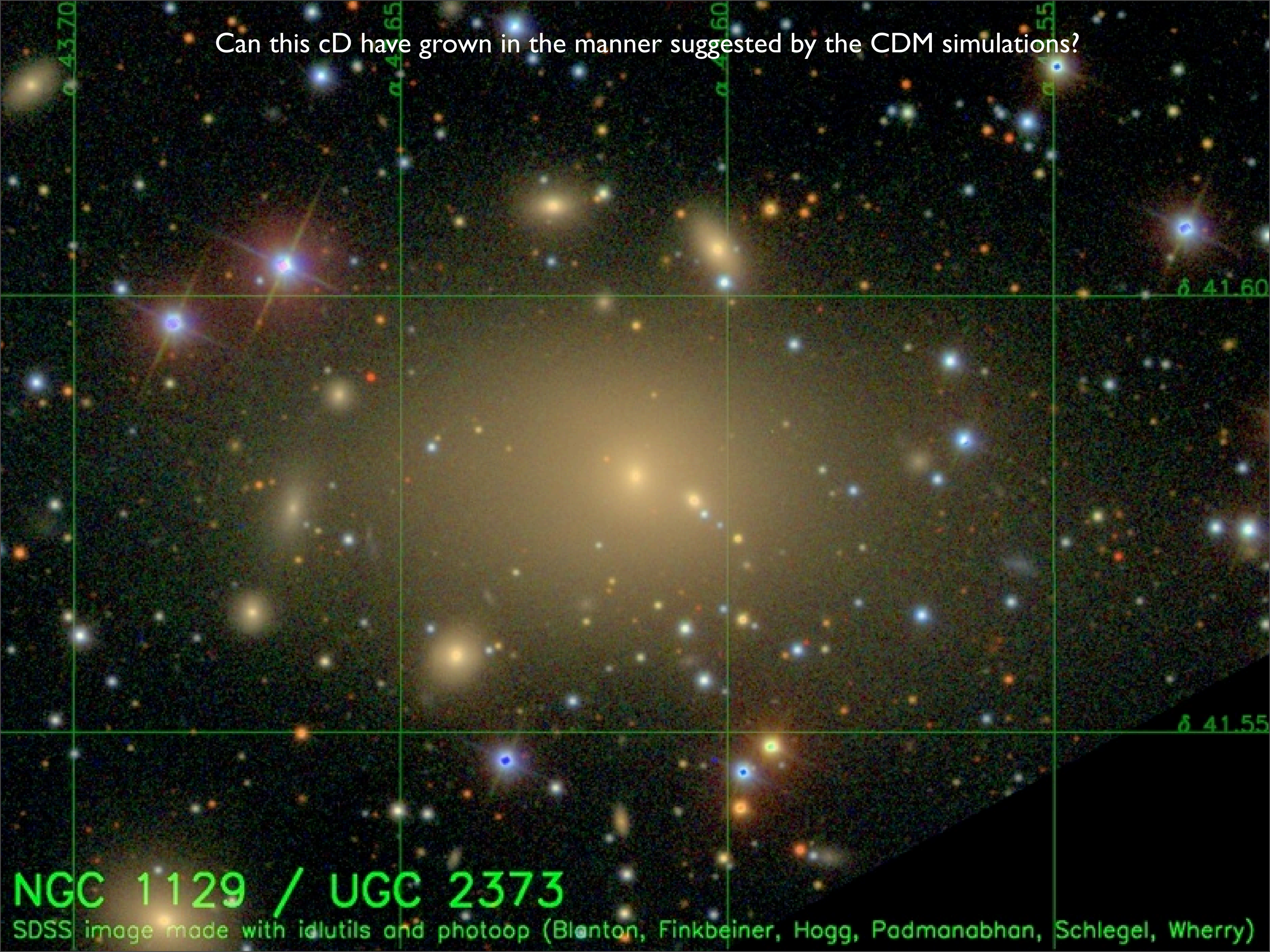


Fig. 3.— The total mass within physical distance $10h^{-1}$ kpc of the center of the most massive progenitor of the final halo at each time plotted and for each of our 8 simulations. Symbols switch between filled and open each time the identity of the most massive progenitor changes.

Gao, Loeb, Peebles, White, Jenkins, ApJ 2004

Can this cD have grown in the manner suggested by the CDM simulations?

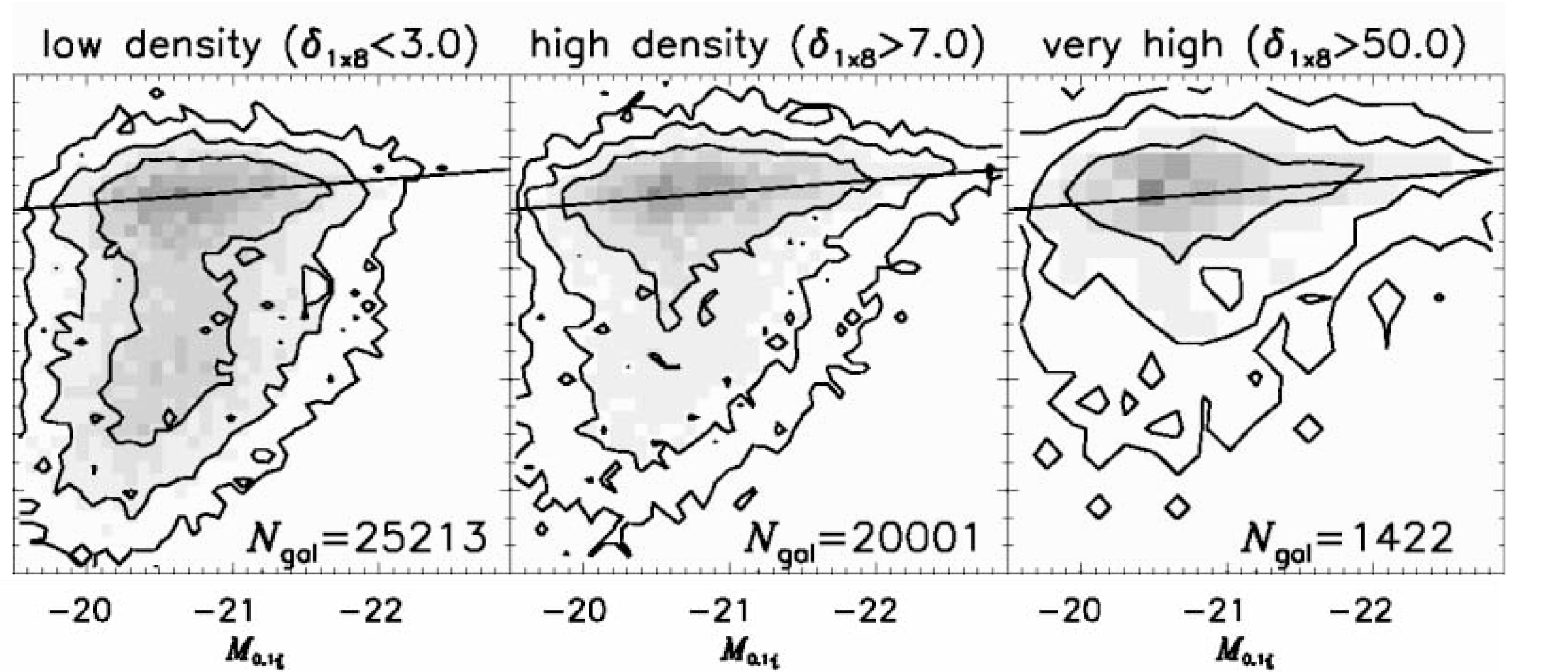


THE DEPENDENCE ON ENVIRONMENT OF THE COLOR-MAGNITUDE RELATION OF GALAXIES

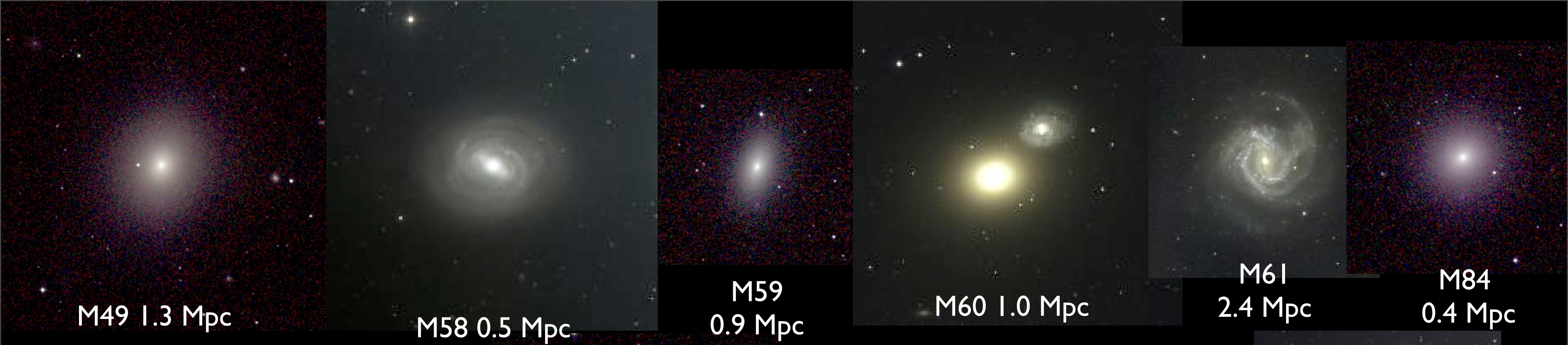
David W. Hogg,[1] Michael R. Blanton,[1] Jarle Brinchmann,[2] Daniel J. Eisenstein,[3] David J. Schlegel,[4]
James E. Gunn,[4] Timothy A. McKay,[5] Hans-Walter Rix,[6] Neta A. Bahcall,[4]
J. Brinkmann,[7] and Avery Meiksin[8]

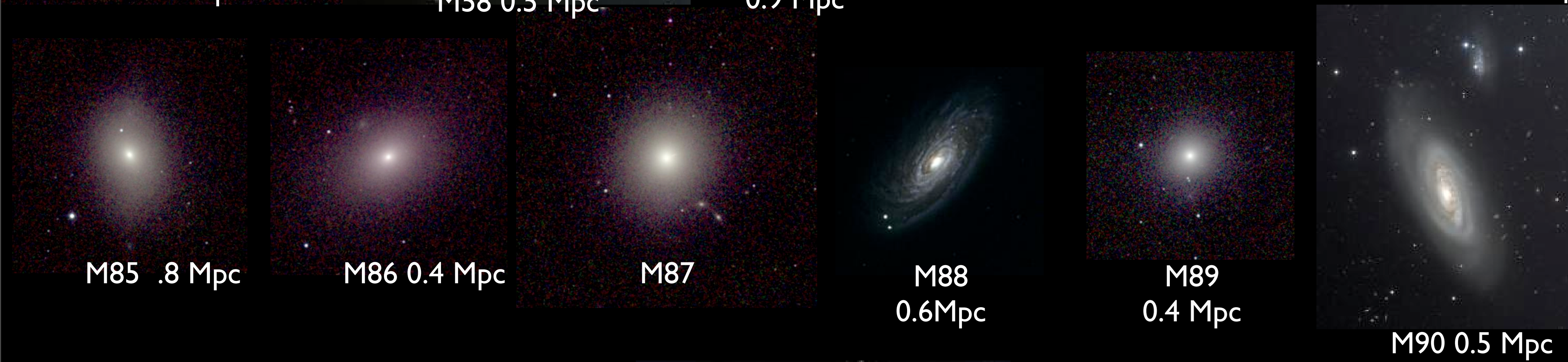
Received 2003 July 11; accepted 2003 December 2; published 2004 January 16

(bowdlerized)



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





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

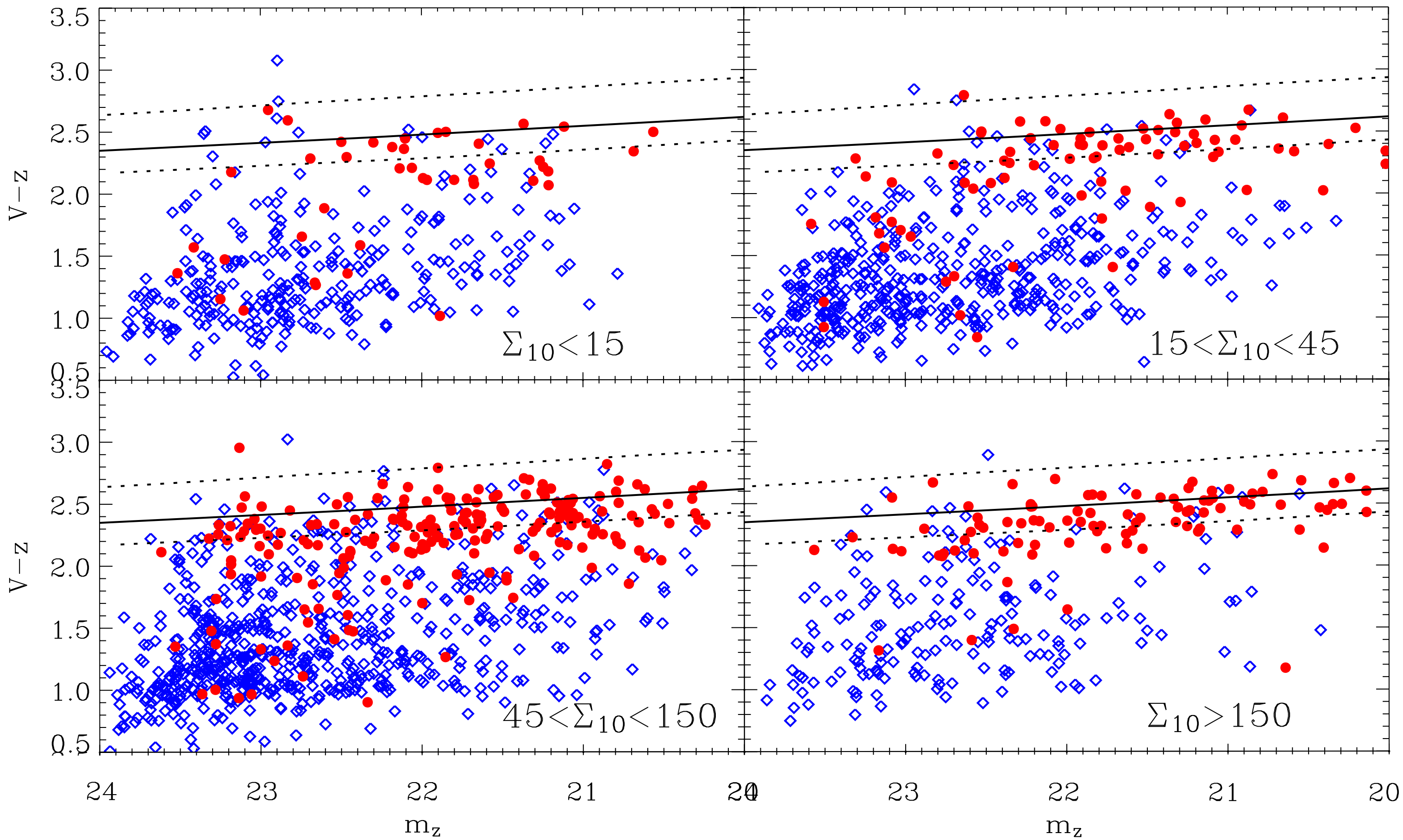
This shows Nigel Sharp's list of Messier galaxies in the Virgo cluster, with projected distances from M 87. The images, from NOAO and 2MASS, have a roughly common angular scale, but contrasts can differ.

Or with the remarkable stability of the color-magnitude relation at redshift z = 0.7?

Submitted to ApJS

The Cosmic Evolution Survey (COSMOS): The morphological content and enviromental dependence of the galaxy color-magnitude relation at $z \sim 0.7$

P. Cassata[1,2], L. Guzzo[3], A. Franceschini[2], N. Scoville[4,5], P. Capak[4], R. S. Ellis[4], A. Koekemoer[6], H. J. McCracken[7], B. Mobasher[6], A. Renzini[8], E. Ricciardelli[2], M. Scodeggio[1] Y. Taniguchi[9], D. Thompson[10,4]



With thanks to Paolo Cassata and Gigi Guzzo for permission to show their pre-publication result.

It has been brought to my attention that the color of a galaxy naturally relaxes to the red sequence after suppression of star formation. (There is some ongoing star formation in ellipticals, to be sure, but I gather the young stars are metal-rich, as if formed out of gas shed by stars in the island universe.)

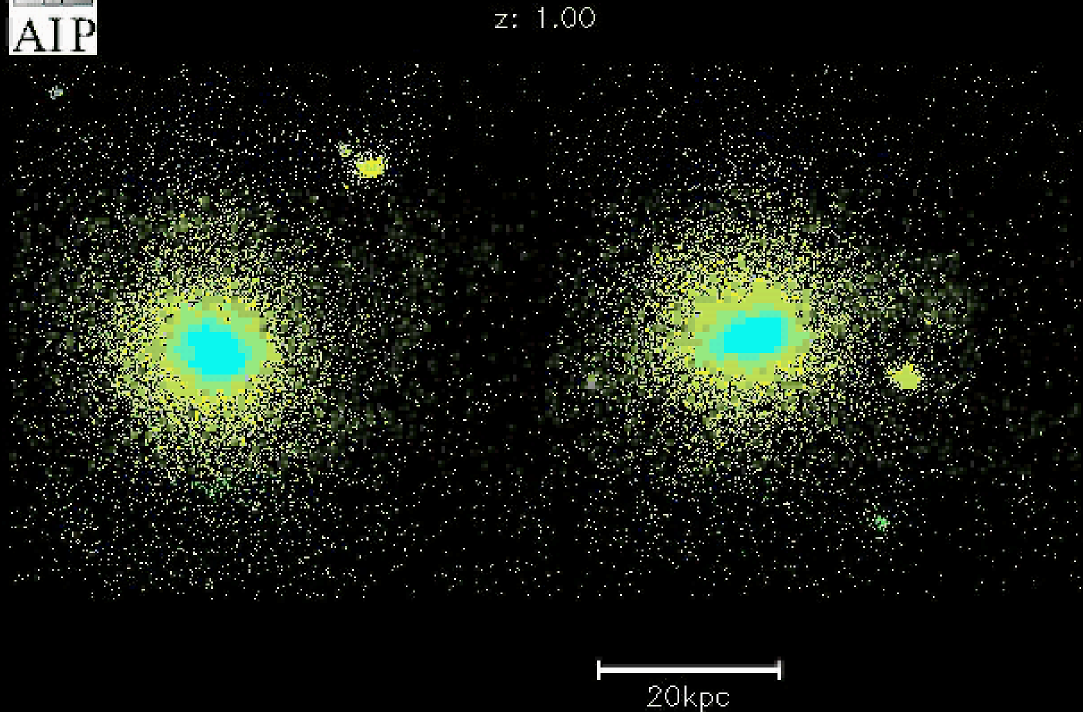
But the tilt of the red sequence requires that the luminosity of the galaxy correlates with some combination of stellar age, heavy element abundance, and chemistry.

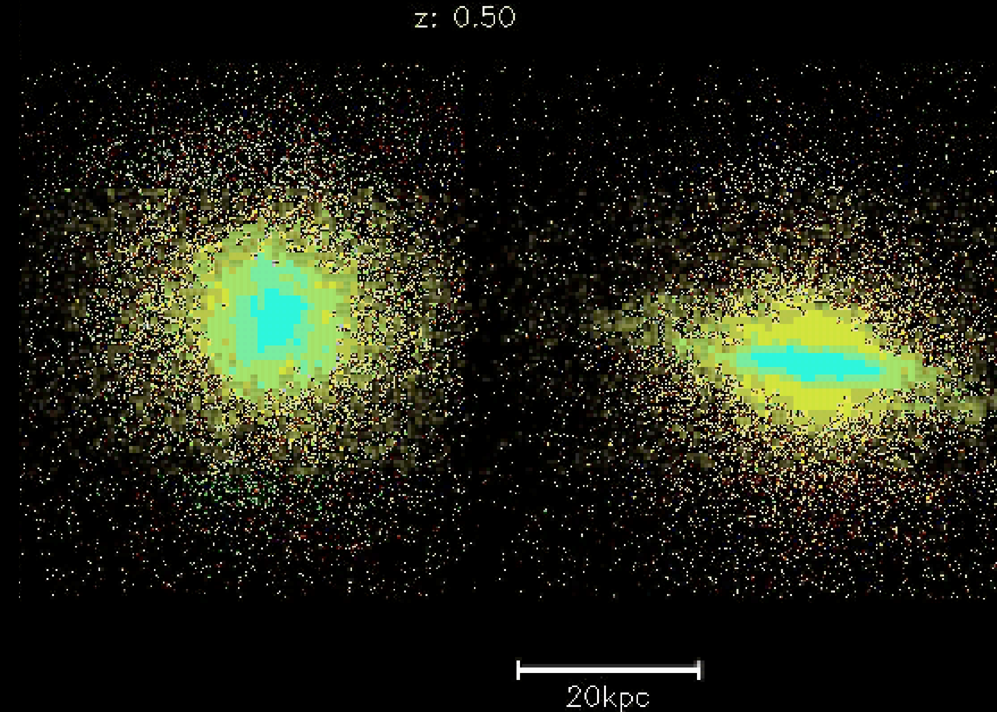
The mix of stellar age, heavy element abundance, and chemistry in the neighborhood of a giant elliptical is correlated with the ambient density, while the color-magnitude relation seems to be insensitive to ambient density.

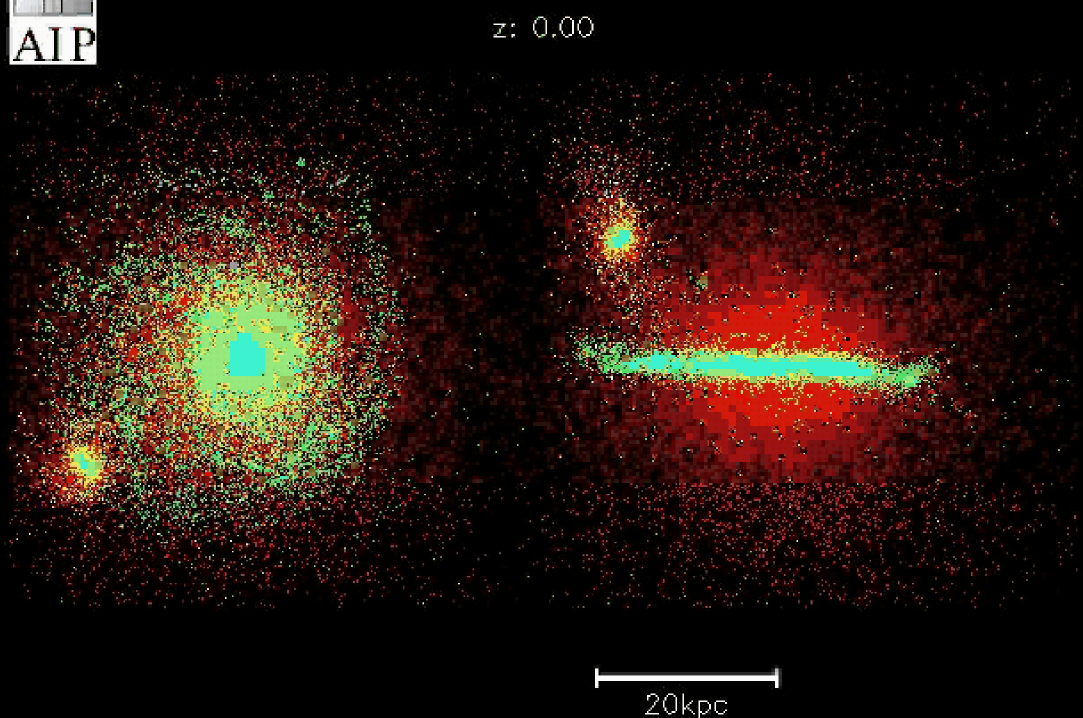
This situation brings to my mind the picture of galaxies as island universes.

This situation does not lead me to think of the substantial flushing of matter through the effective radii of giant galaxies at modest redshifts that is predicted by the ΛCDM cosmology.

What is the effect of merging and accretion on spiral galaxies at $z < 1$?







Matthias Steinmetz,
Astrophysical Institute
Potsdam

Formation of a disk Galaxy in
the LambdaCDM cosmology

ASTROPHYSICAL JOURNAL, 574:L39–L42, 2002 July 20

DECIPHERING THE LAST MAJOR INVASION OF THE MILKY WAY

GERARD GILMORE
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, UK; gil@ast.cam.ac.uk
ROSEMARY F. G. WYSE[1,2]
Johns Hopkins University, Department of Physics and Astronomy, 3400 North Charles Street, Baltimore, MD 21218; wyse@pha.jhu.edu
AND
JOHN E. NORRIS
Research School of Astronomy and Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Weston Creek, Canberra, ACT 2611, Australia; jen@mso.anu.edu.au
Received 2002 May 10; accepted 2002 June 14; published 2002 June 25

ABSTRACT

We present first results from a spectroscopic survey of ~2000 F/G stars 0.5–5 kpc from the Galactic plane, obtained with the Two Degree Field facility on the Anglo-Australian Telescope. These data show the mean rotation velocity of the thick disk about the Galactic center a few kiloparsecs from the plane is very different than expected, being ~100 km s^{-1} rather than the predicted ~180 km s^{-1}. We propose that our sample is dominated by stars from a disrupted satellite that merged with the disk of the Milky Way some 10–12 Gyr ago. We do not find evidence for the many substantial mergers expected in hierarchical clustering theories. We find yet more evidence that the stellar halo retains kinematic substructure, indicative of minor mergers.

The consensus I think I see developing is that within the LambdaCDM cosmology the Milky Way must be atypical.


Is the small bulge of this galaxy also atypical within LambdaCDM?
NGC 4565 HST

THE ASTROPHYSICAL JOURNAL, 514:818–843, 1999 April 1

HIGH-VELOCITY CLOUDS: BUILDING BLOCKS OF THE LOCAL GROUP

LEO BLITZ
University of California, Berkeley, CA 94720; blitz@gmc.berkeley.edu; and University of Maryland, College Park, MD 20742
DAVID N. SPERGEL
Princeton University Observatory, Princeton, NJ 08544; dns@astro.princeton.edu; and University of Maryland, College Park, MD 20742
PETER J. TEUBEN
University of Maryland, College Park, MD 20742; teuben@astro.umd.edu
DAP HARTMANN
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; dap@abitibi.harvard.edu
AND
W. BUTLER BURTON
Leiden University Observatory, Leiden, Netherlands; burton@strw.leidenuniv.nl
Received 1998 February 20; accepted 1998 November 9

ABSTRACT

We suggest that the high-velocity clouds (HVCs) are large clouds, with typical diameters of 25 kpc, containing 3×10^7 $M_\odot$ of neutral gas and 3×10^8 $M_\odot$ of dark matter, falling onto the Local Group; altogether the HVCs contain 10^{10} $M_\odot$ of neutral gas. Our reexamination of the Local Group hypothesis for the HVCs connects their properties to the hierarchical structure formation scenario and to the gas seen in absorption toward quasars. We show that at least one HVC complex (besides the Magellanic

6. LOCAL GROUP DYNAMICS

6.1. *Cosmological Background*

The continuing accretion of gas and dark matter onto galaxies and groups is a prediction of all hierarchical models of the formation of structure in the universe.

The issue: are some high velocity clouds primordial, falling into the Milky Way for the first time, which would be from distances of about 1 Mpc?

A&A 382, 43–52 (2002)
DOI: 10.1051/0004-6361:20011553

Astronomy & Astrophysics

An H I survey of the Centaurus and Sculptor groups

Constraints on the space density of low mass galaxies

W. J. G. de Blok[1], M. A. Zwaan[2], M. Dijkstra[3], F. H. Briggs[3], and K. C. Freeman[4]

[1] Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia
[2] School of Physics, Univ. of Melbourne, Parkville, VIC 3052, Australia
[3] Kapteyn Astronomical Institute, PO Box 800, 9700 AV Groningen, The Netherlands
[4] Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Australia

Cold dark matter theories of galaxy formation predict the existence of a large number low mass dark matter sub-halos that might appear as tiny satellites in galaxy groups. Our results support and extend similar conclusions derived from previous H I surveys that a H I rich population of these satellites does not exist.

The evidence I read is that the HI clouds observed around other galaxies are within 100 kpc of the galaxy, and more likely to be bound to the galaxy rather than falling in for the first time.

These look to me like pretty serious discrepancies between what the theory seems to predict and the observations seem to suggest.

Am I fooling myself?

In case I'm not let us consider a possible remedy, a scalar interaction that produces a long-range fifth force in the dark sector.

A Long-Range Scalar Interaction in the Dark Sector

The starting idea is that the nonbaryonic dark matter interacts with a scalar field by an action of the form

$$\mathcal{A} = -\int |\phi| ds\,, \qquad \text{or} \tag{1}$$

$$\mathcal{A} = \int \sqrt{-g}\, d^4x\, (i\bar{\psi}\gamma\partial\psi - \phi\bar{\psi}\psi)\,. \tag{2}$$

The idea has a long history: Nordström (1912) introduced the classical form (1), which is equivalent to Yukawa's (1935) form (2) when the de Broglie wavelength is small.

Within quantum field theory there is good reason to question whether any scalar field can avoid acquiring a mass $\gg H_o$ that is unacceptable for this purpose, but some superstring theorists find the low mass quite conceivable.

In the 1950s through 1970s Pascual Jordan and Bob Dicke led explorations of scalar-tensor gravity physics, with this action for particles in the Einstein frame.

Damour, Gibbons & Gundlach (1990) noted that the tight empirical constraints we now have on a long-range scalar interaction in the visible sector allow a substantial scalar interaction in the dark sector.

Recent discussions along this and similar similar lines of thought include Gradwohl & Frieman (1992); Casas, Garcia-Bellido & Quiros (1992); Damour & Polyakov (1994); Wetterich (1995); Anderson & Carroll (1997); Bean (2001); Amendola (2000); Amendola & Tocchini-Valentini (2002); França & Rosenfeld (2002); Damour, Piazza & Veneziano (2002); Comelli, Pietroni & Riotto (2003); Amendola, Gasperini & Piazza (2004).

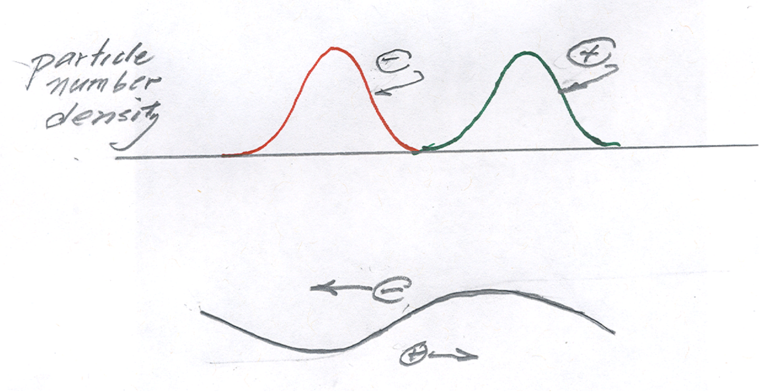
The variant to be considered here is developed with Glennys Farrar (NYU), Neal Dalal (IAS), Steve Gubser (Princeton), Adi Nusser (Technion) and Renyue Cen (Princeton) in astro-ph/0307316, hep-th/0402225, hep-th/0407097, astro-ph/0412586, & work in progress.

If there are two dark matter species with action

$$A = \int \sqrt{-g}\, d^4x\, \phi_{,i}\phi^{,i}/2 \;-\; \sum_{\text{particles}} \int [m_+(\phi) ds_+ + m_-(\phi) ds_-],$$

$$\frac{dm_+}{d\phi} < 0, \qquad \frac{dm_-}{d\phi} > 0, \qquad \frac{d^2 m_\pm}{d\phi^2} \geq 0.$$

Then ϕ can relax to quasistatic equilibrium with larger values where there are more (+) particles, smaller values where there are more (−) particles.



A (+) particle is pushed toward larger ϕ, to reduce its energy $m_+(\phi)$, and a (−) particle is pushed in the opposite direction to reduce its energy. The result is that like particles are attracted, unlike repelled.

Suppose there are two species in the dark sector, with

$$m_{\rm DM} = m - y\phi, \qquad m_s = y_s\phi, \qquad y\bar{n} < y_s\bar{n}_s,$$

and ϕ has relaxed to quasistatic equilibrium, where $m_s \sim 0$. Then these relativistic particles produce the potential

$$V_s = \sum_{\rm particles} \int y_s\phi\, ds \simeq \int d^4r\, y_s\phi\, n_s\langle\sqrt{1-v^2}\rangle$$

$$\frac{\delta V_s}{\delta\phi} = y_s n_s\langle\sqrt{1-v^2}\rangle \simeq \frac{y_s^2\bar{n}_s}{\epsilon_s}\phi,$$

where $\epsilon_s = y_s\phi/\sqrt{1-v^2}$ is a mean particle energy. Then the field equation is

$$\nabla^2\phi = \phi/r_s^2 - y\, n(\mathbf{r},t)\,, \quad r_s = \sqrt{\epsilon_s/y_s^2\bar{n}_s}\,.$$

Since $\epsilon_s \propto a(t)^{-1}$ and $n_s \propto a(t)^{-3}$ the Yukawa cutoff length scales with the expansion of the universe as $r_s \propto a(t)$, which may be a Good Thing.

Constraints

The screening matter is excluded from regions where $y\phi \gtrsim \epsilon$ or, more approximately, $\delta\rho/\rho \gtrsim y_s\bar{n}_s/y\bar{n}$, which can't be too close to unity.

The ratio of mass densities in screening and nonrelativistic DM is

$$\frac{\rho_s}{\rho} = \frac{3}{2}\beta\Omega_m(Hr_s)^2S^2, \qquad S = \frac{y_s\bar{n}_s}{y\bar{n}}.$$

Light element production requires $\rho_s \lesssim 0.5aT_o^4$, which implies

$$\beta S^2 r_s^2 \lesssim 3000,$$

where r_s is measured in megaparsecs. This is viable, but tight.

The present screening particle energy is

$$\frac{\epsilon_s}{M_{\rm Pl}} = \frac{3}{2}y_s\beta^{1/2}S\Omega(Hr_s)^2 \simeq 5\times 10^{-8}y_s\beta^{1/2}Sr_s^2$$

which maybe makes ϵ_s uncomfortably close to the Planck mass.

Simulations

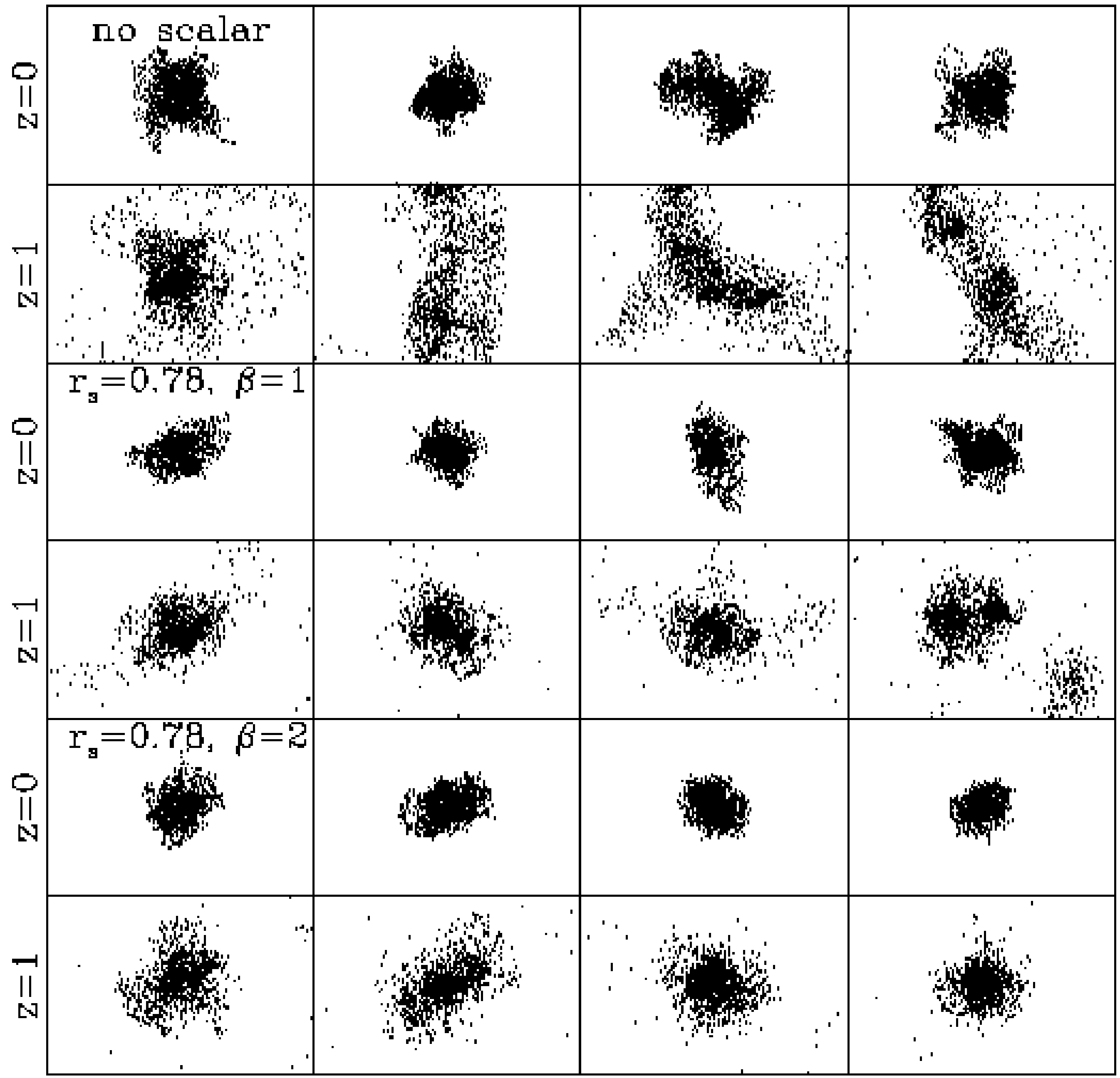
But it is easy to adapt a standard numerical N-body Fourier transform computation of the gravitational force to the Yukawa scalar force law.

Our preliminary explorations — on Adi Nusser's laptop — assume standard adiabatic scale-invariant initial conditions, take the parameters in the scalar model to be in the range

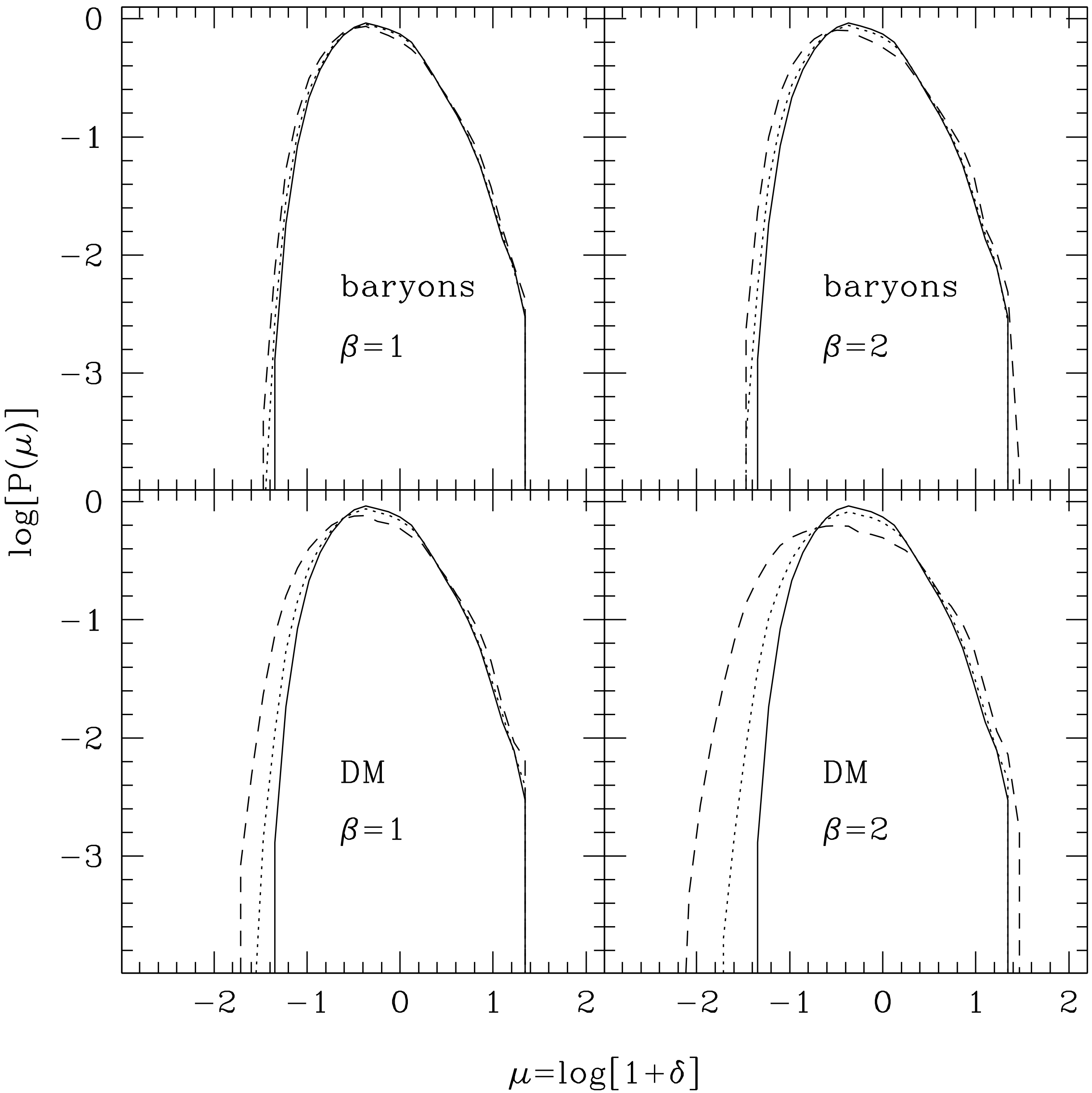
$$\beta \sim 1, \qquad r_s \sim 1 \text{ Mpc},$$

and, since the scalar force would have negligible effect on most cosmological tests, use conventional cosmological parameters,

$$\Omega_m = 0.3, \qquad \Omega_\Lambda = 0.7, \qquad h = 0.7.$$



The panels are $2 \times 3h^{-1}$ Mpc.

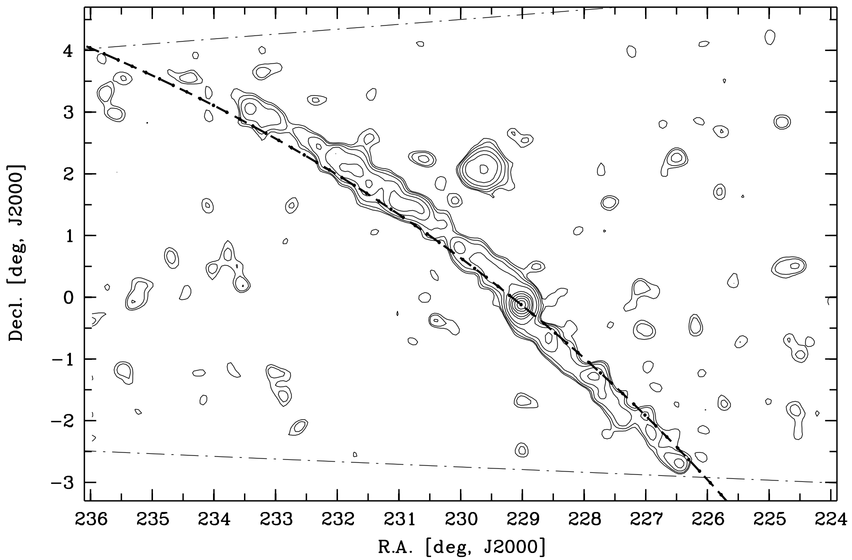


The distributions of the density contrasts in dark matter and baryons smoothed with a top-hat spherical window of radius $5h^{-1}$ Mpc at the present epoch. The standard model is the solid curve, the dotted curve shows the effect of the scalar force with $r_s = 0.78h^{-1}$ Mpc, and the dashed curve, $r_s = 1.56h^{-1}$ Mpc. The simulation box width is $50h^{-1}$ Mpc.

An important test: tidal tails of satellite galaxies.

Galilean Equivalence for Galactic Dark Matter

Michael Kesden[1] and Marc Kamionkowski[2]
[1] *Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada*
[2] *California Institute of Technology, Mail Code 130-33, Pasadena, CA 91125*



Palomar 5: Odenkirchen et al. 2003: classical tidal tails

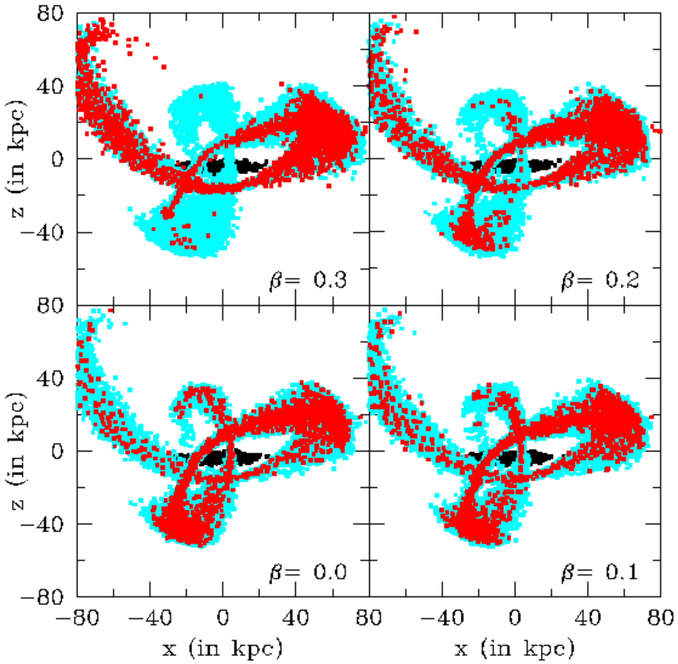
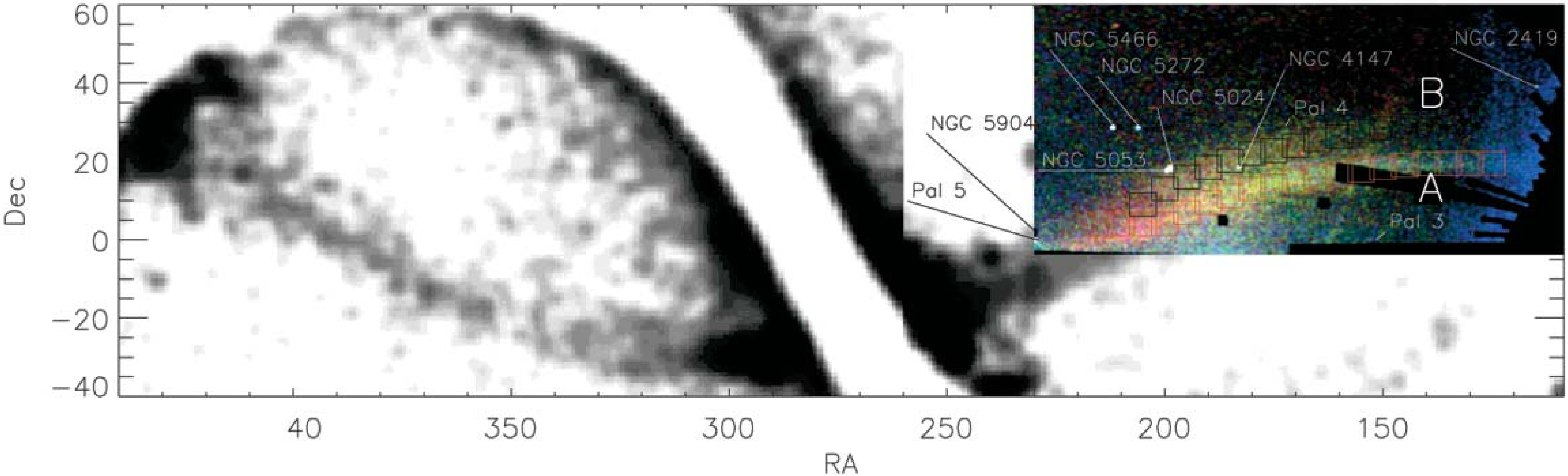


FIG. 1: Simulations of the tidal disruption of a satellite galaxy in the presence of a dark-matter force. The charge-to-mass ratio β increases from 0.0 in increments of 0.1 going counterclockwise from the bottom left. The Galactic disk is in black. Sgr stars are shown in red (dark grey) while the Sgr dark matter is blue (light grey). The tidal streams are projected onto the orbital plane. Orbits are counterclockwise; the upper left figure shows that for $\beta = 0.3$ (a dark-matter force 9% the strength of gravity) stars are almost absent from the leading stream (at 12 o'clock with respect to the Galactic center).

Belokurov et al. 2006: the Field of Streams



the Majewski et al. 2003: 2MASS M giants

the Belokurov et al. 2006: SDSS color cut of stars

A Simple Model for Tidal Stripping of a Dwarf Spheroidal

A dwarf spheroidal satellite of the Milky Way would be disturbed by a fifth DM force (an effect Frieman & Gradwohl 1991 first considered).

Suppose the dwarf DM distribution is spherical with the inner NFW profile $\rho \propto r^{-1}$, the star mass is negligible, the los star velocity dispersion is σ, and the star distribution is isothermal.

Then the gravitational potential and spatial distribution of stars in an isolated dwarf are

$$\phi = \sigma^2 r/r_*, \qquad n_* \propto e^{-\phi/\sigma^2} = e^{-r/r*}.$$

If the DM fifth force is β times gravity then the accelerations of baryons and DM caused by the Milky Way DM halo at galactocentric distance R are

$$g_b = \frac{v_c^2}{R}, \qquad g_d = (1+\beta)\frac{v_c^2}{R}.$$

The difference is represented by a effective potential on the baryons, $\phi_5 = \beta(v_c^2/R) r \cos\theta$. Thus in the rest frame of the dwarf DM halo the stars see the potential

$$\phi_t = \frac{\sigma^2 r}{r_*}\left[1 + \beta\left(\frac{v_c}{\sigma}\right)^2 \frac{r_*}{R}\cos\theta\right].$$

In the isothermal model the star density surfaces are ellipses — or a parabola at escape.

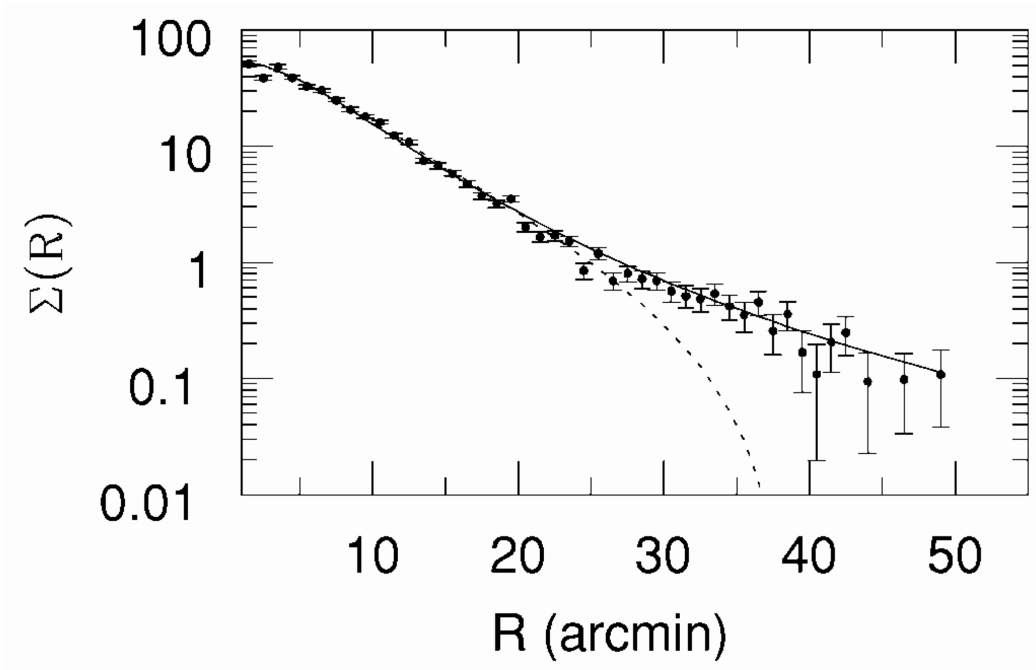
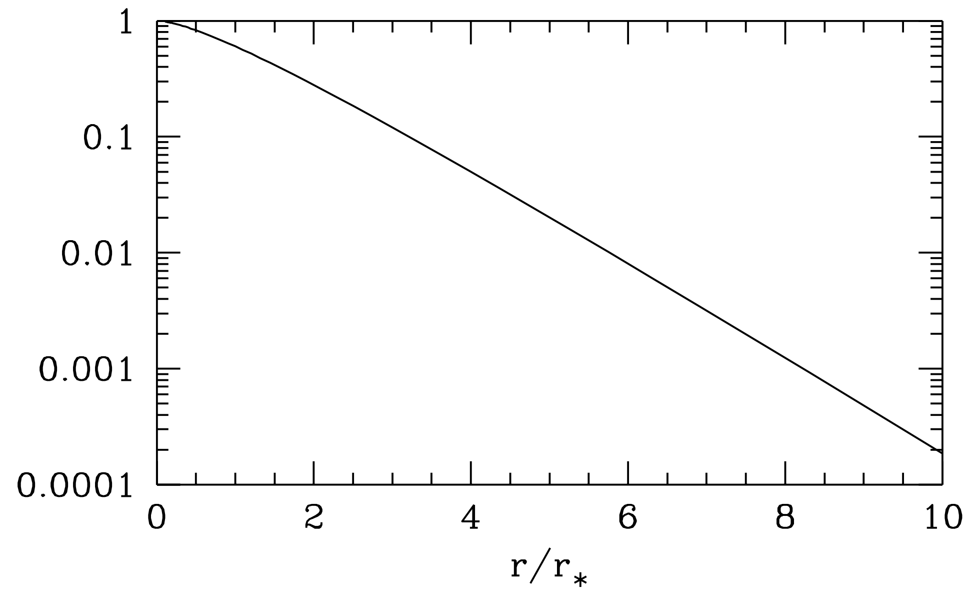


FIG. 2.—Azimuthally averaged surface brightness proȚle of Draco. The solid and dashed curves show, respectively, the best-Țtting Plummer proȚle and a King (1962) proȚle Țt to the data within 25′.



The surface projection of the model

$$n_* \propto e^{-r/r_*}.$$

The model is significantly different from the measurements, but it may give a useful approximation to the situation.

The fit of model to data indicates $\theta_* \simeq 5$ arc min, which at $D = 75$ kpc is

$$r_* = 100 \text{ pc}.$$

For Milky Way circular velocity $v_c = 220$ km s^{-1}, galactocentric distance 80 kpc, $r_* = 100$ pc, and $\sigma = 12$ km s^{-1} the stars in the model spheroid see the potential

$$\phi_t = \frac{\sigma^2 r}{r_*}\left(1 + 0.4\beta\cos\theta\right).$$

At $\beta = 1$ the dwarf spheroidal in this model is stable at $R = 80$ kpc; the baryons slip out of the DM potential when the dwarf falls to $R \simeq 40$ kpc.

What is the nature of the disruption? As R decreases

the potential well the dwarf stars see tilts,

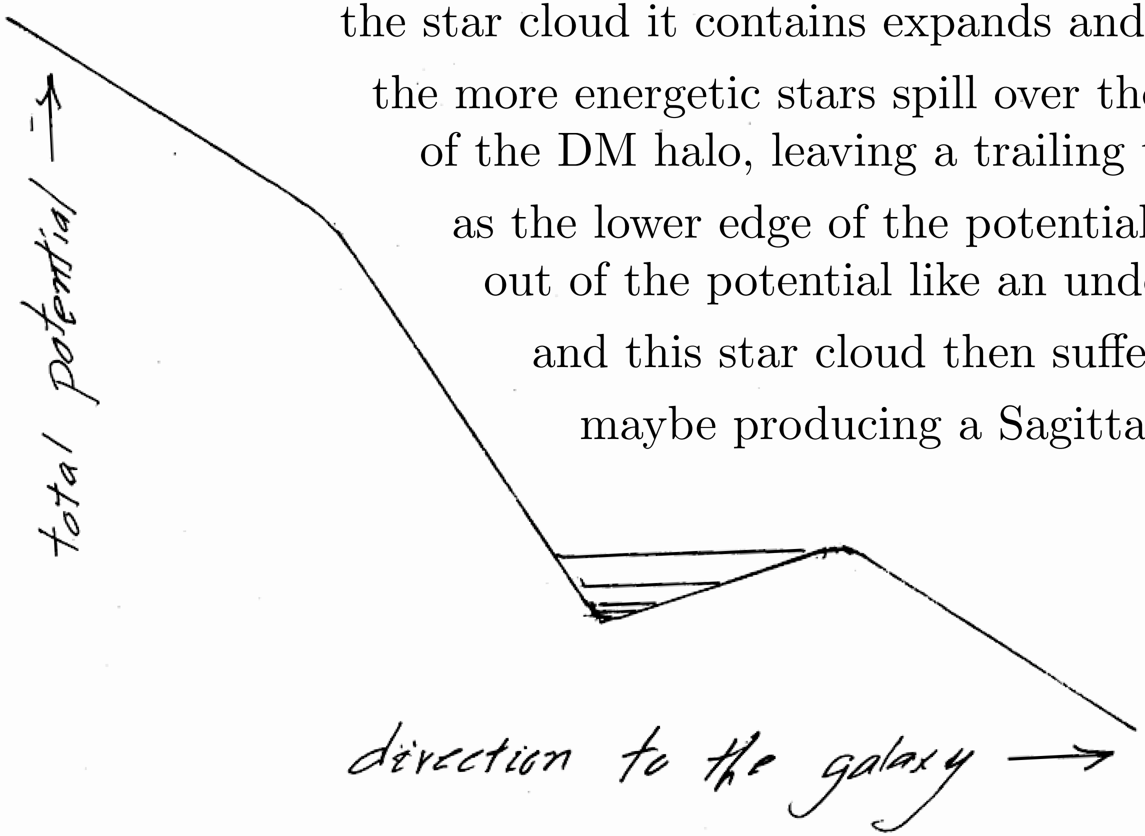
the star cloud it contains expands and cools,

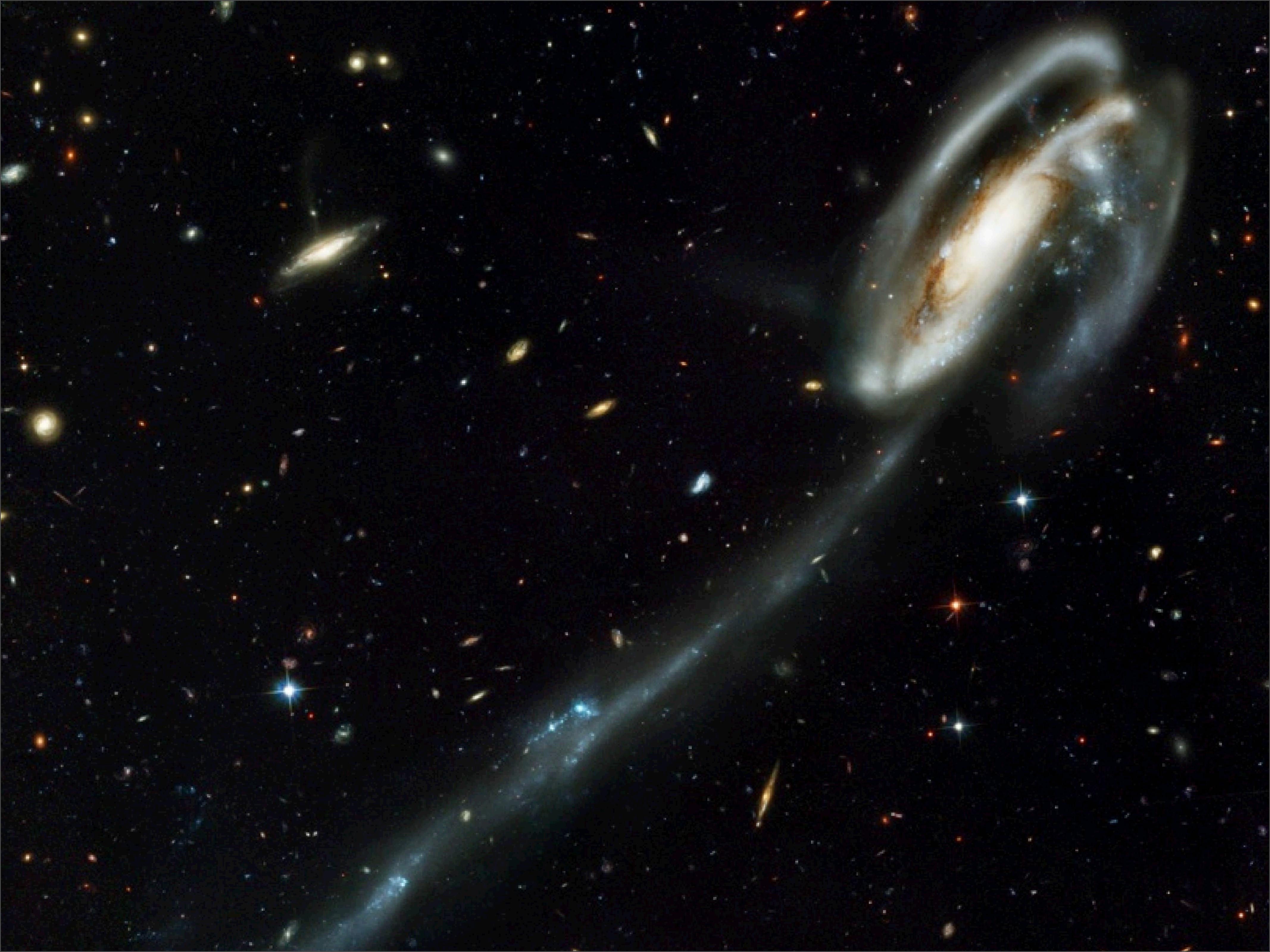
the more energetic stars spill over the edge of the $\rho \propto r^{-1}$ part of the DM halo, leaving a trailing tail,

as the lower edge of the potential grows level the rest of the stars slip out of the potential like an underdone fried egg slips off a spatual,

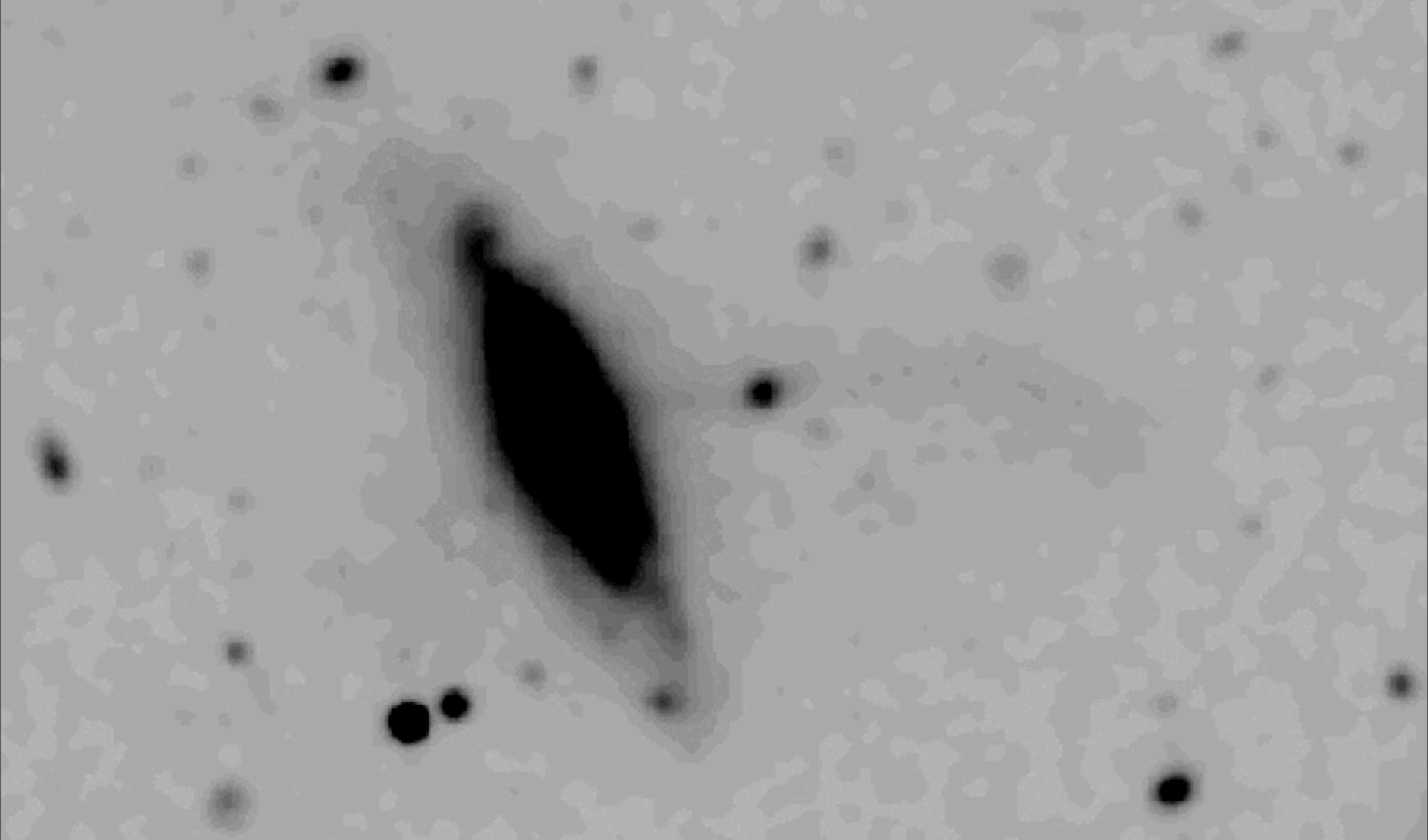
and this star cloud then suffers classical tidal disruption,

maybe producing a Sagittarius-like stream?





Forbes, Beasley, Bekki, Brodie and Strader 2003



The elegant N-body simulation on Duncan Forbes' web site shows that the truncated left-hand tail is not inconsistent with standard physics: Newtonian dynamics can be subtle. Bearing in mind that the dwarf is (in projection) in the baryon-dominated part of the giant I think it's reasonable to wonder what a simulation of the DM fifth force model would show.

The physical science of cosmology is enormously richer than when Einstein and Lemaître were debating the merits of the cosmological constant.

Among the many things we have learned, in my opinion, is that we still have a lot to learn.