Overview

Infall on cosmic scales (linear)
Infall onto groups and clusters (non-linear)
Large-scale shocks
Infall onto galaxies
Disk formation: Fall's argument
Angular momentum build-up (in brief)
Hot halos ➔ cooling flows
Cold flows, warm flows
Recycling and feedback
Galaxy formation within ΛCDM: score card

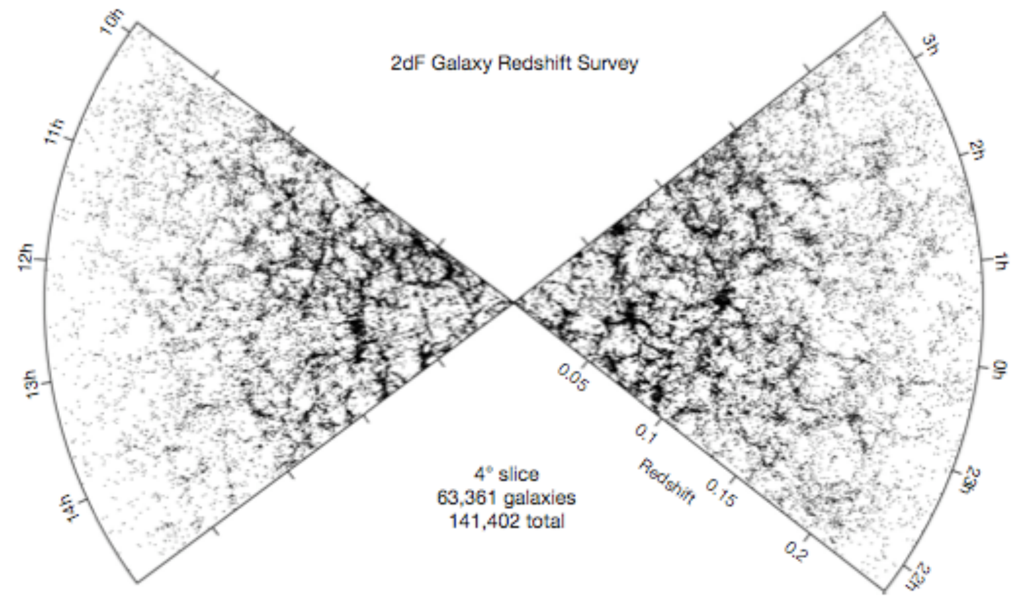
"Nature operates by rules we can discover in successive approximations…"

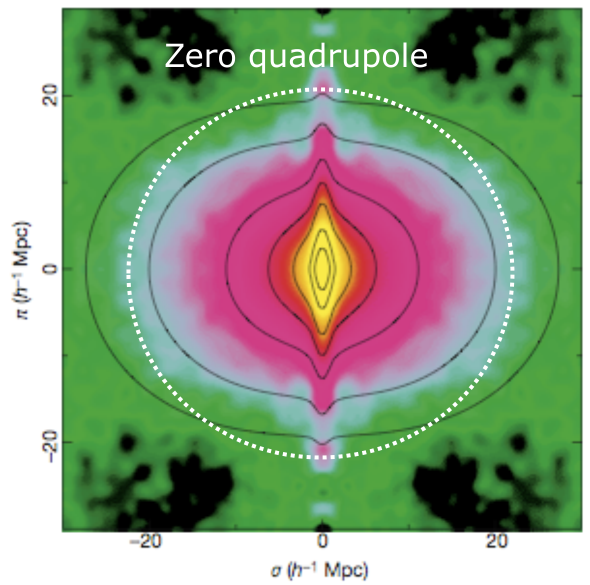
Do we observe Zeldovich-like cosmic infall over huge homogeneous volumes ?

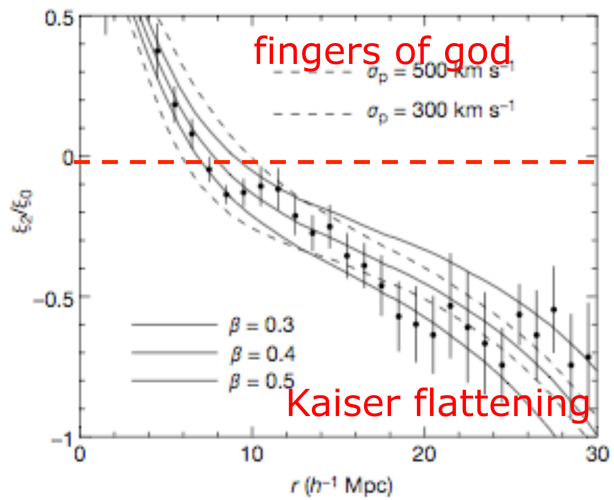
Cosmic infall out to z~0.2

A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey 2001

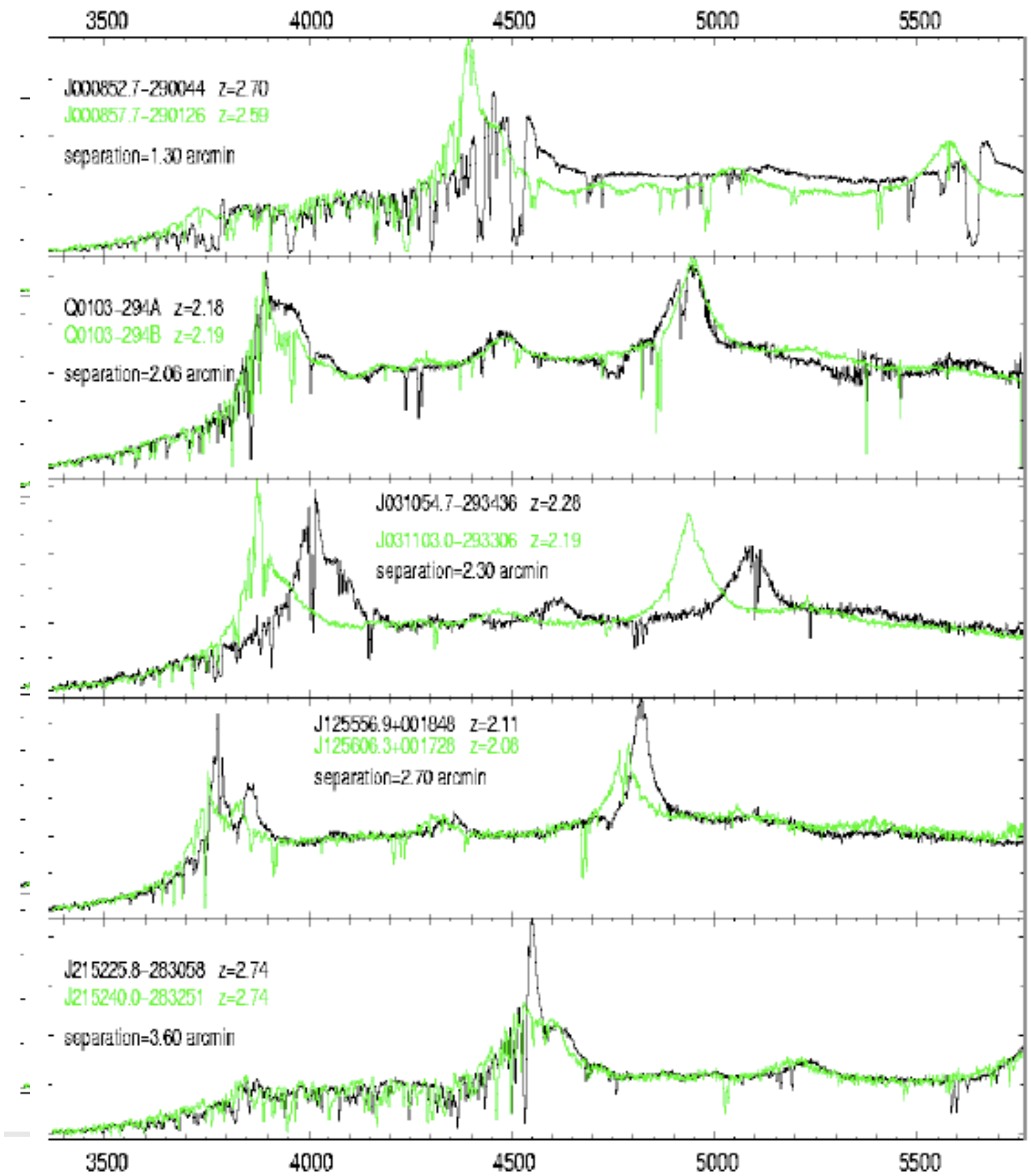
John A. Peacock[1], Shaun Cole[2], Peder Norberg[2], Carlton M. Baugh[2], Joss Bland-Hawthorn[3], Terry Bridges[3], Russell D. Cannon[3], Matthew Colless[4], Chris Collins[5], Warrick Couch[6], Gavin Dalton[7], Kathryn Deeley[6], Roberto De Propris[6], Simon P. Driver[8], George Efstathiou[9], Richard S. Ellis[9,10], Carlos S. Frenk[2], Karl Glazebrook[11], Carole Jackson[4], Ofer Lahav[9], Ian Lewis[3], Stuart Lumsden[12], Steve Maddox[13], Will J. Percival[1], Bruce A. Peterson[4], Ian Price[4], Will Sutherland[1,7] & Keith Taylor[3,10]







Bland-Hawthorn (Bologna 2011)



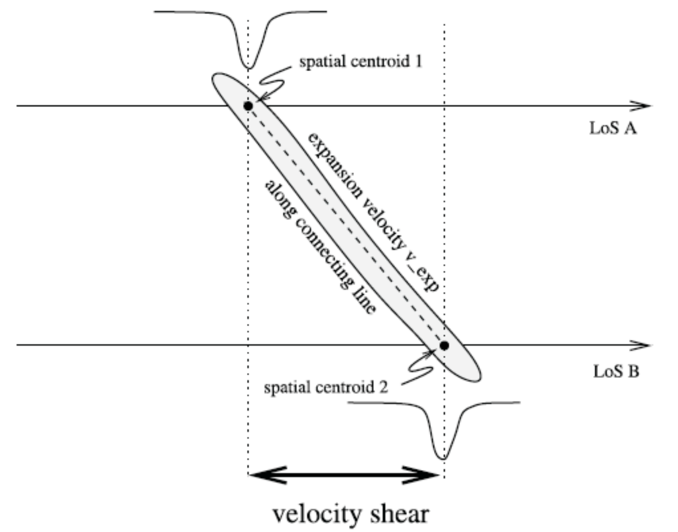
Bland-Hawthorn (Bologna 2011)

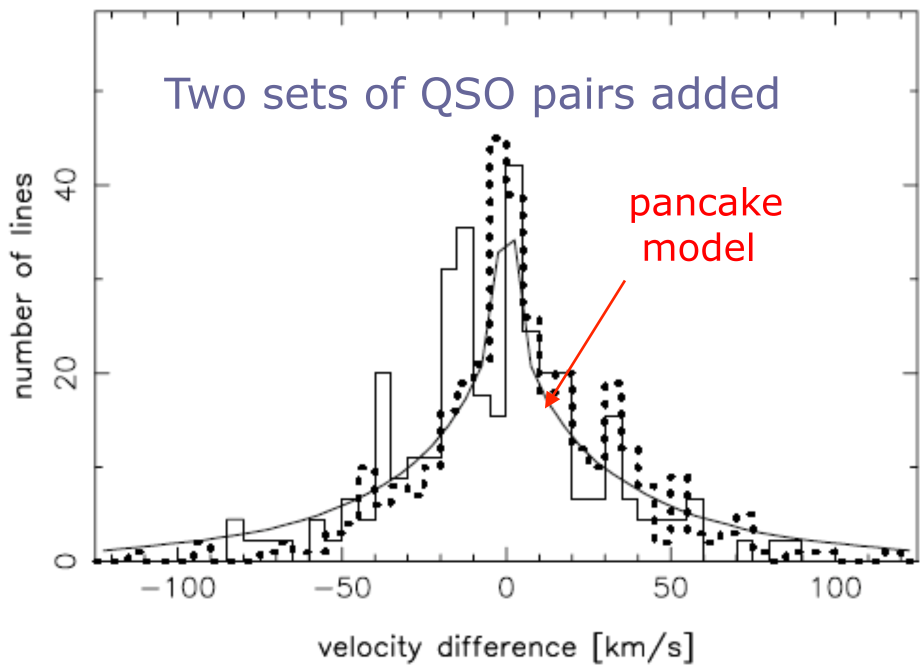
Cosmic infall at z~3.6

EXPANSION AND COLLAPSE IN THE COSMIC WEB[1,2]

Michael Rauch,[3] George D. Becker,[4] Matteo Viel,[5] Wallace L. W. Sargent,[4] Alain Smette,[6,7]
Robert A. Simcoe,[8] Thomas A. Barlow,[4] and Martin G. Haehnelt[5]

Received 2005 April 2; accepted 2005 May 26





Lyα absorbers along paired
QSO sightlines

Weak Kaiser effect seen (z~2.4)

NEUTRAL HYDROGEN OPTICAL DEPTH NEAR STAR-FORMING GALAXIES AT $Z \approx 2.4$ IN THE KECK BARYONIC STRUCTURE SURVEY*

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Submitted to ApJ

ABSTRACT

We study the interface between galaxies and the intergalactic medium by measuring the absorption by neutral hydrogen in the vicinity of star-forming galaxies at $z \approx 2.4$. Our sample consists of 679 rest-frame-UV selected galaxies with spectroscopic redshifts that have impact parameters < 2 (proper) Mpc to the line of sight of one of 15 bright, background QSOs and that fall within the redshift range of its Lyα forest. We present the first 2-D maps of the absorption around galaxies, plotting the median Lyα pixel optical depth as a function of transverse and line of sight separation from galaxies. The Lyα optical depths are measured using an automatic algorithm that takes advantage of all available Lyman series lines. The median optical depth, and hence the median density of atomic hydrogen, drops by more than an order of magnitude around 100 kpc, which is similar to the virial radius of the halos thought to host the galaxies. The median remains enhanced, at the $> 3\sigma$ level, out to at least 2.8 Mpc (i.e. > 9 comoving Mpc), but the scatter at a given distance is large compared with the median excess optical depth, suggesting that the gas is clumpy. We clearly detect two types of redshift space anisotropies. On scales $< 200\ \mathrm{km\,s^{-1}}$, or < 1 Mpc, the absorption is stronger along the line of sight than in the transverse direction. This "finger of God" effect may be partly due to redshift errors, but is probably dominated by gas motions within or very close to the halos. On the other hand, on scales of 1.4 - 2.0 Mpc the absorption is compressed along the line of sight (with $> 3\sigma$ significance), an effect that we attribute to large-scale infall (i.e. the Kaiser effect). Within 100 (200) kpc, and over $\pm 165\ \mathrm{km\,s^{-1}}$, the covering fraction of gas with Lyα optical depth greater than unity is $100^{+0}_{-32}\%$ $(86^{+14}_{-18}\%)$. Absorbers with $\tau_{\mathrm{Ly}\alpha} > 0.1$ are typically closer to galaxies than random. The mean galaxy overdensity around absorbers increases with the optical depth and also as the length scale over which the galaxy overdensity is evaluated is decreased. Absorbers with $\tau_{\mathrm{Ly}\alpha} \sim 1$ reside in regions where the galaxy number density is close to the cosmic mean on scales ≥ 0.25 Mpc.

Subject headings: galaxies: formation — galaxies: halos — galaxies: high-redshift — intergalactic medium — quasars: absorption lines — large-scale structure of Universe

Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma,\pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The function was estimated by counting pairs in boxes of side 0.2 h^{-1} Mpc, and then smoothing with a gaussian of r.m.s. width 0.5 h^{-1} Mpc. To illustrate deviations from circular symmetry, the data from the first quadrant are repeated with reflection in both axes. This plot clearly displays redshift distortions, with finger-of-God elongatio flattening at large radii. The overplotted parameter $\beta = \Omega^{0.6}/b = 0.4$ and a pa are plotted at $\xi = 10, 5, 2, 1, 0.5, 0.2$

The model predictions assume that expressed as a product of the linear Ka $P_s(\mathbf{k}) = P_r(k)(1 + \beta\mu^2)^2(1 + k^2\sigma_p^2\mu^2$ pairwise dispersion of the random comp a very accurate fit to exact nonlinear si $P_r(k)$, we take the estimate obtained by survey[11,39]. This agrees very well with 2dFGRS, as will be discussed elsewher dependence of the quadrupole-to-mon match the full $\xi(\sigma,\pi)$ data very well).

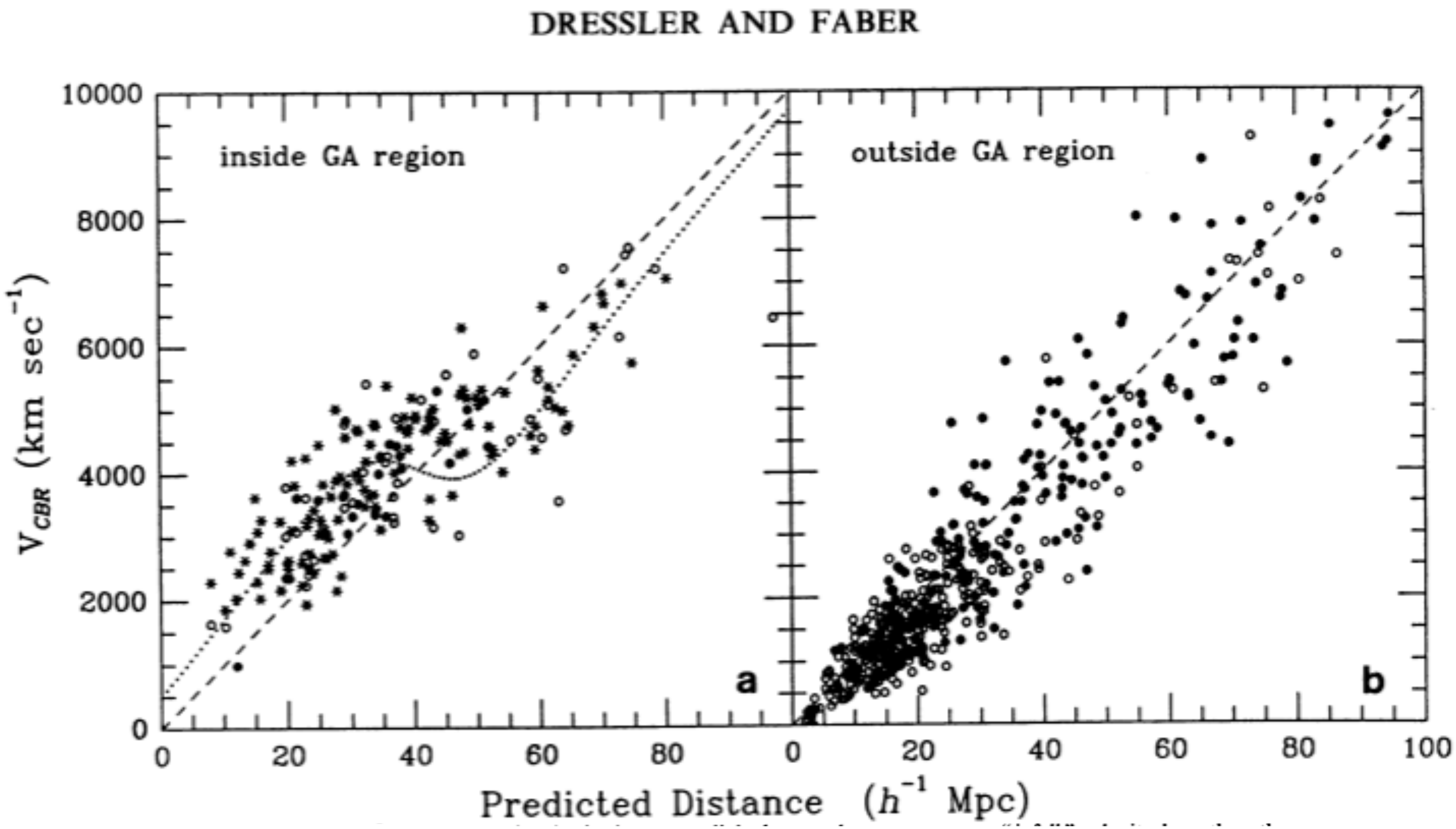
Figure 3 The flattening of the redshift-space correlation function is quantified by the quadrupole-to-monopole ratio, ξ_2/ξ_0. This quantity is positive where fingers-of-God distortion dominates, and is negative where coherent infall dominates. The solid lines show model predictions for $\beta = 0.3$, 0.4 and 0.5, with a pairwise velocity dispersion of $\sigma_p = 400\,\mathrm{km\,s^{-1}}$ (solid lines), plus $\beta = 0.4$ with $\sigma_p = 300$ and $500\,\mathrm{km\,s^{-1}}$ (dashed lines). The ξ_2/ξ_0 ratio becomes more negative as β increases and as σ_p decreases. At large radii, the effects of fingers-of-God become relatively small, and values of $\beta \simeq 0.4$ are clearly appropriate.

The multipole moments of the correlation function are defined as $\xi_\ell(r) = (2\ell + 1)/2\int_{-1}^{1} \xi(\sigma = r\sin\theta, \pi = r\cos\theta)\, P_\ell(\cos\theta)\, d\cos\theta$. In linear theory, the quadrupole-to-monopole ratio is given[40] by $\xi_2/\xi_0 = f(n)(4\beta/3 + 4\beta^2/7)/(1 + 2\beta/3 + \beta^2/5)$. Here $f(n) = (3 + n)/n$, where n is the power-spectrum index of the density fluctuations: $\xi \propto r^{-(3+n)}$. In practice, nonlinear effects mean that this ratio is a function of scale. We model this by using the real-space correlation function estimated from the APM survey[11,39], plus the model for nonlinear finger-of-God smearing given in the caption to Fig. 2.

Kinematic infall around groups & clusters…

This topic, like so many in astronomy, has a chequered history. Easy to detect this, right?

1990: they claimed to see nearside and farside infall



Disputed, at least on the far side...

NO BACK-SIDE INFALL INTO THE GREAT ATTRACTOR

D. S. MATHEWSON, V. L. FORD, AND M. BUCHHORN
Mount Stromlo and Siding Spring Observatories, The Australian National University, ACT 2611, Australia
Received 1991 April 16; accepted 1992 January 30

ABSTRACT

This *Letter* presents the first results of a survey of the peculiar velocities of 1355 spiral galaxies in the southern sky using the Tully-Fisher relation to estimate their distances. The most important result of these measurements is that no back-side infall into the Great Attractor is found, contrary to the findings of Dressler & Faber; rather, evidence is found for a bulk flow of about 600 km s^{-1} on scales greater than 60 h^{-1} Mpc. This, when added to the bulk flow of 450 km s^{-1} recently found by Willick in the opposite part of the sky, suggests that there is bulk flow in the supergalactic plane over very large scales greater than 130 h^{-1} Mpc. The origin of this bulk flow is a puzzle.

A little known and very good paper on how to do the statistics right, Malmquist bias, noise, pairwise velocity... **this is hard to do properly!**

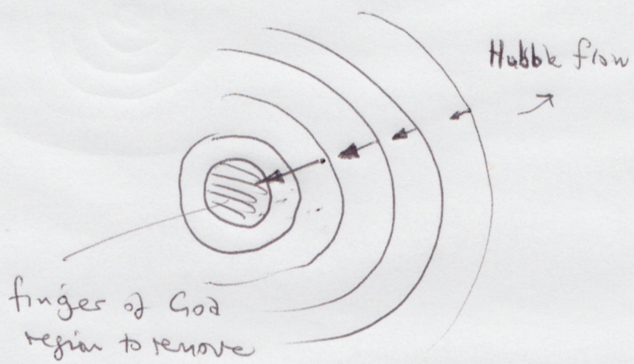
Analysis of the velocity-distance diagrams in the presence of the Great Attractor

T. Ekholm and P. Teerikorpi
Tuorla Observatory, University of Turku, SF-21500 Piikkiö, Finland

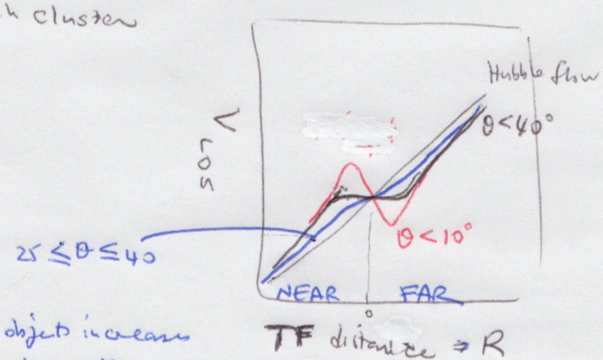
Received 19 August 1993 / Accepted 12 October 1993

Peebles 1980 Virial equation
(see also Peacock 99 p. 545)

Draw for students



$r \simeq 2\text{-}3$ Mpc for a rich cluster



Number of objects increases (weighted) at large R

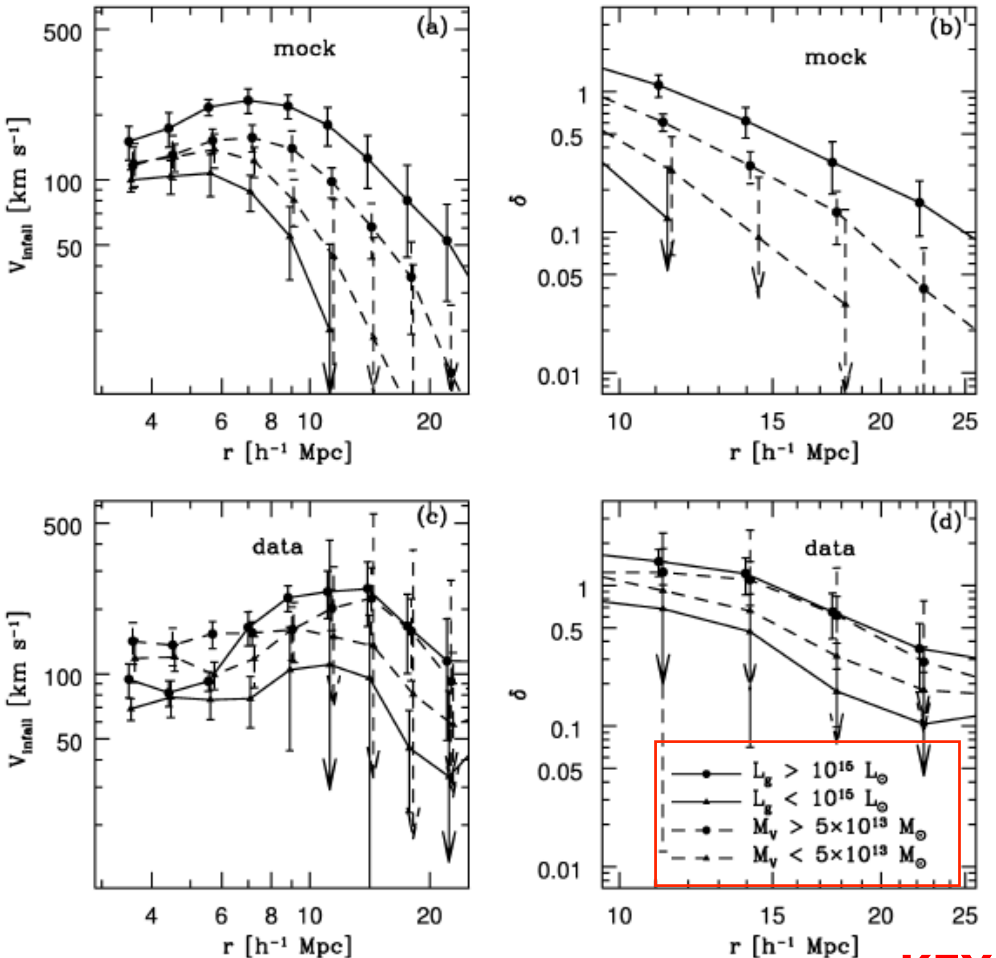
Kinematic infall around groups & clusters…

On scales where linear theory dominates and with assumption of spherical symmetry & radial infall **only** (i.e. no tangential)

$$V_{infall} = -(1/3)\Omega_0^{0.6} H_0 r \delta(r)$$

$$V_r(r,\theta) = V_{infall}(r)\cos(\theta)$$

The match is better on scales larger than 5 Mpc…



KEY

Ceccarelli et al 2005

Accretion shocks on large scales

Formation of Clusters of Galaxies; Protocluster Fragmentation and Intergalactic Gas Heating

R. A. Sunyaev and Ya. B. Zeldovich
Institute of Applied Mathematics, Academy of Sciences, Moscow, USSR

1972

Received February 25, 1972

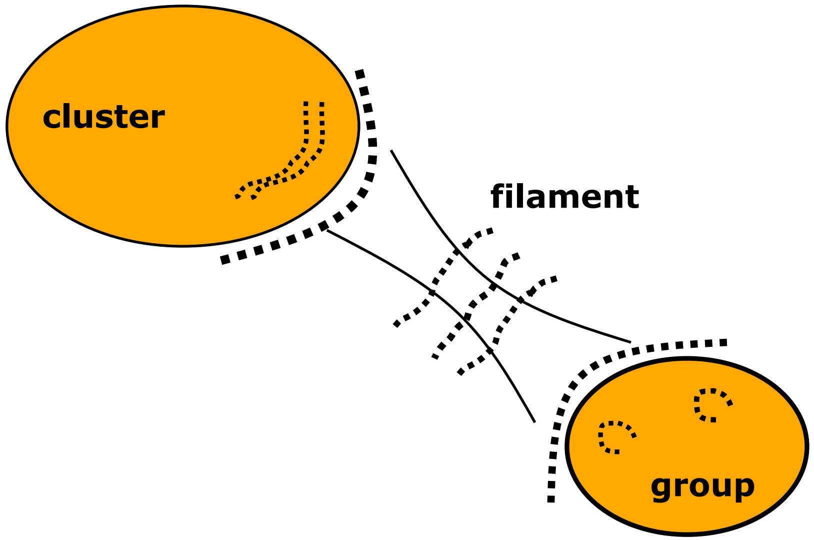
"It is possible that a significant fraction of the intergalactic gas (10-50%) was not subjected to compression in the pancakes but was heated only by the damped shock waves moving away from them…"

In fact, much of the IGM **must stall** in large-scale shocks, **otherwise** the gas compressing into CDM haloes would exceed the x-ray background (Pen 1999, Wu+ 2001), i.e. non-gravitational heating is essential.

Why shocks across the cosmos?

- While the dark matter accretes smoothly onto the "cosmic web," the baryons do not
- Their infall velocities often exceed the local sound speed and a complex network of shocks emerges
- The most well known shocks are the expected **virial shocks** associated with halo collapse, except that simulations reveal shocks also occur even further out (Cen & Ostriker)
- …but there is there clear observed evidence for **Sunyaev-Zel'dovich shocks** associated with filaments and sheets **between** haloes?

- In fact, shocks are likely to occur across the **entire** hierarchy



What is the eventual fate of this gas?

Where are the missing baryons?

How does gas get into galaxies?

This is no longer theoretical:

First image of large-scale CDM shocks on ~Mpc scales

unbelievably overblown abstract!

Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376

Joydeep Bagchi,[1*] Florence Durret,[2] Gastão B. Lima Neto,[3] Surajit Paul[4] 2006

In the current paradigm of cold dark matter cosmology, large-scale structures are assembling through hierarchical clustering of matter. In this process, an important role is played by megaparsec (Mpc)–scale cosmic shock waves, arising in gravity-driven supersonic flows of intergalactic matter onto dark matter–dominated collapsing structures such as pancakes, filaments, and clusters of galaxies. Here, we report Very Large Array telescope observations of giant (~2 Mpc by 1.6 Mpc), ring-shaped nonthermal radio-emitting structures, found at the outskirts of the rich cluster of galaxies Abell 3376. These structures may trace the elusive shock waves of cosmological large-scale matter flows, which are energetic enough to power them. These radio sources may also be the acceleration sites where magnetic shocks are possibly boosting cosmic-ray particles with energies of up to 10^{18} to 10^{19} electron volts.

A B

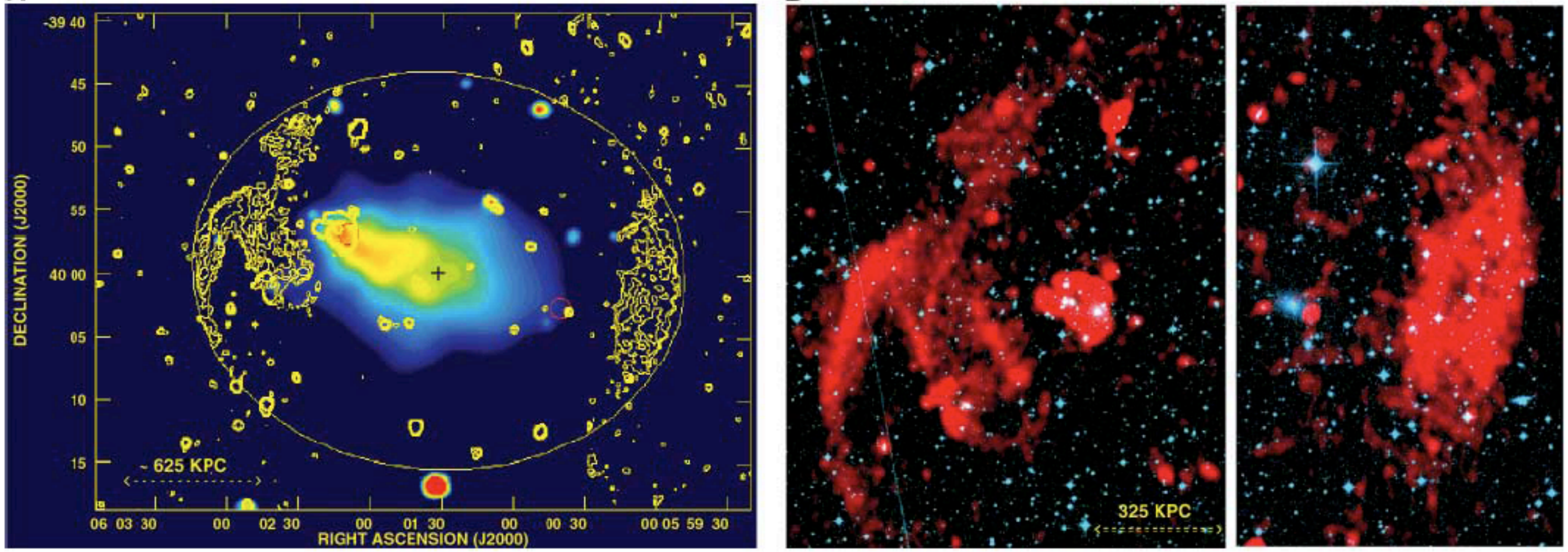


Fig. 1. (**A**) A composite map of radio and x-ray emissions from the galaxy cluster Abell 3376. The radio emission is represented by yellow contours (0.12, 0.24, 0.48, and 1 mJy per beam; beam width: 20 arc sec full width at half maximum Gaussian) obtained from the VLA 1.4-GHz observations (*12*). The yellow ellipse shows an elliptical fit to the peripheral radio structures, and the "+" marks the center of the ellipse. The central color image depicts the thermal bremsstrahlung x-ray emission detected by the Position Sensitive Proportional Counter instrument onboard the Roentgen Satellite (≈12-ks exposure, within 0.14- to 2.0-keV band). The red circles mark the position of the two brightest cluster galaxies—the brightest elliptical galaxy on the lower right and the second brightest elliptical galaxy associated with the bent-jet radio source MRC 0600-399 near the x-ray peak. (**B**) Composite images obtained from superposing the radio and optical images. The VLA 1.4-GHz radio maps (in red) for the eastern (left) and the western (right) radio structures are shown overlayed on the red band Digitized Sky Survey image (in blue).

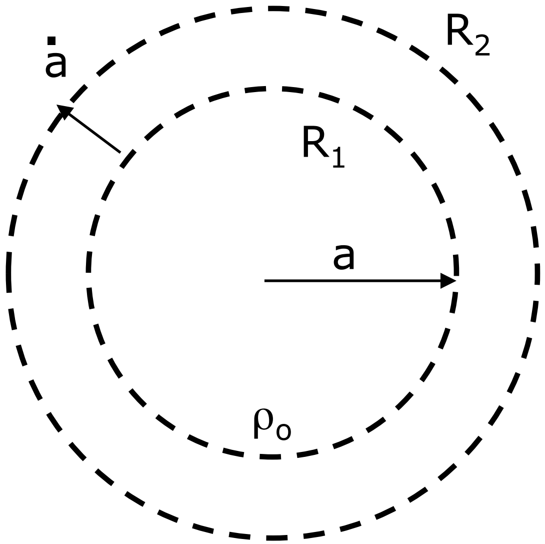
Distribution of shocks in the IGM

- We associate shocks with the collapse of non-linear objects
- The shock velocity v_S ~ lengthscale of perturbation / age of universe

$$v_S = H(z) R_2$$

$$R_2^{\,3} = 3M_S / 4\pi\rho_o$$

- R$_2$ is the physical radius the region would have had if it had expanded with Hubble flow
- Shock temperature $$T_S = \frac{3}{16}\frac{\mu m_P}{k_B} v_S^{\,2}$$
- Note dependence on M_S and redshift



M_s = mass of shocked region

ρ_o = mean IGM density

Simple analytic applications

- R_2 – **when set to natural scales in collapsing hierarchy** – hides a great deal of gas in a Warm Hot Intergalactic Medium (WHIM), >20% in range 10^5-10^7 K

  Cen & Ostriker (1999), Davé et al (2001)

- Improved mass estimates of WHIM gas fraction with **Zel'dovich approximation**

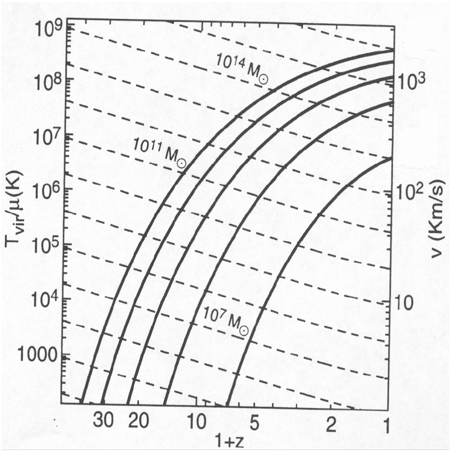
  Nath & Silk (2001)

- Evolution of **virial shocks** with redshift: these may be weak beyond z=2 because IGM temperature is hotter and therefore harder to drive shocks

  Miniati et al (2000, 2004)

- But maybe we can pick up **virial shocks** prior to reionization (z~10) when the IGM was mostly neutral, e.g. **Press-Schechter** models

  Furlanetto & Loeb (2004), Shapiro et al (2006)



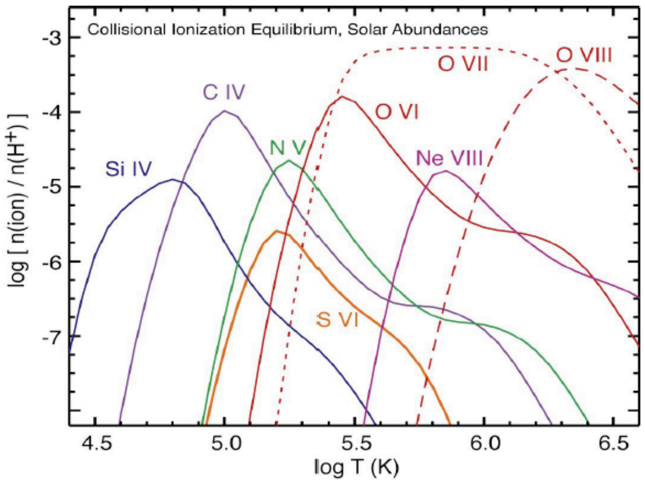
These are all simple semi-analytic estimates that have been checked with numerical simulations. The theory of IGM shocks and redshift evolution is **very** rudimentary.

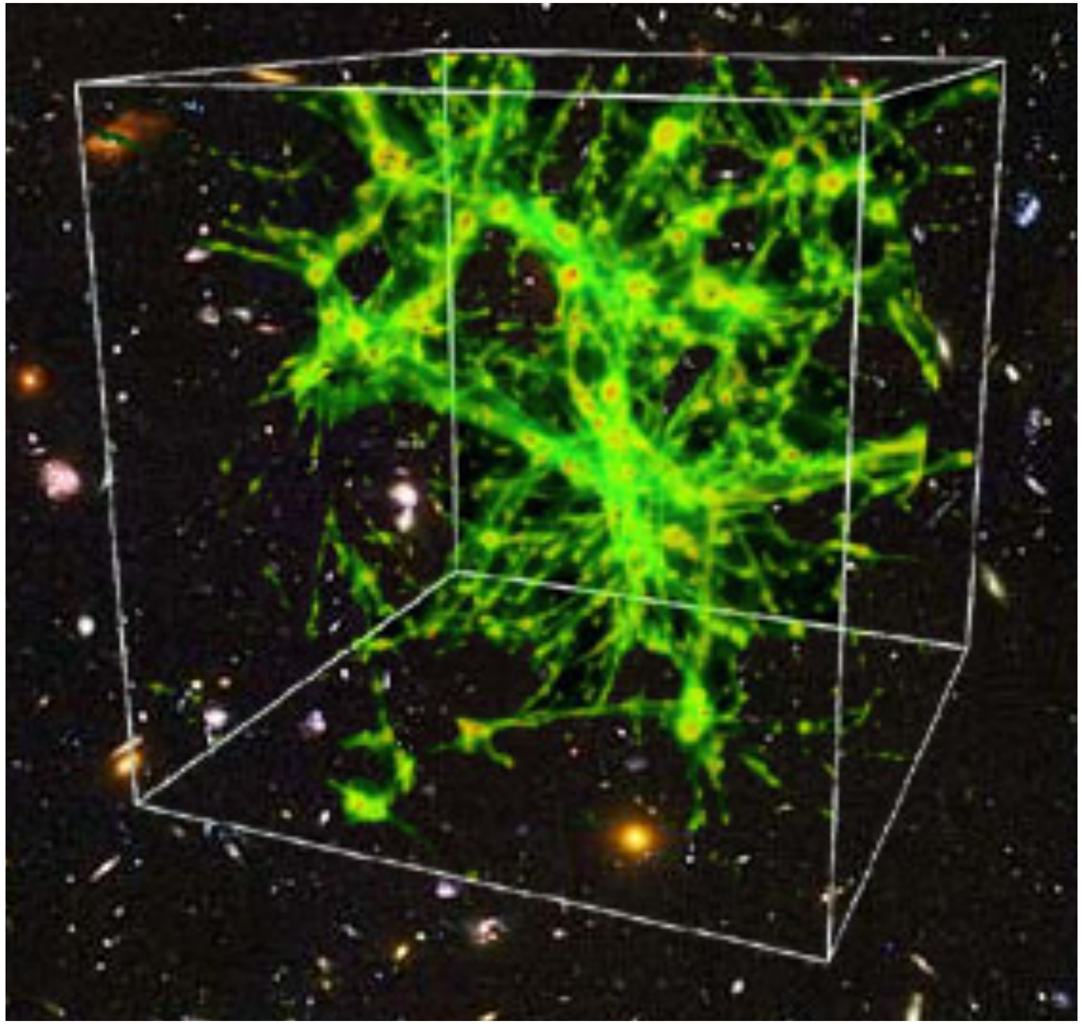
Bland-Hawthorn (Bologna 2011)

WHIM simulations (Cen & Ostriker 1994, 1999, 2001…)

Thermal energy completely dominated by large-scale structure at z~0 where $T_K \sim 10^4$ K in IGM prior to collapse.

But shocks were weaker at high redshift because T_K was higher and v_S was lower.

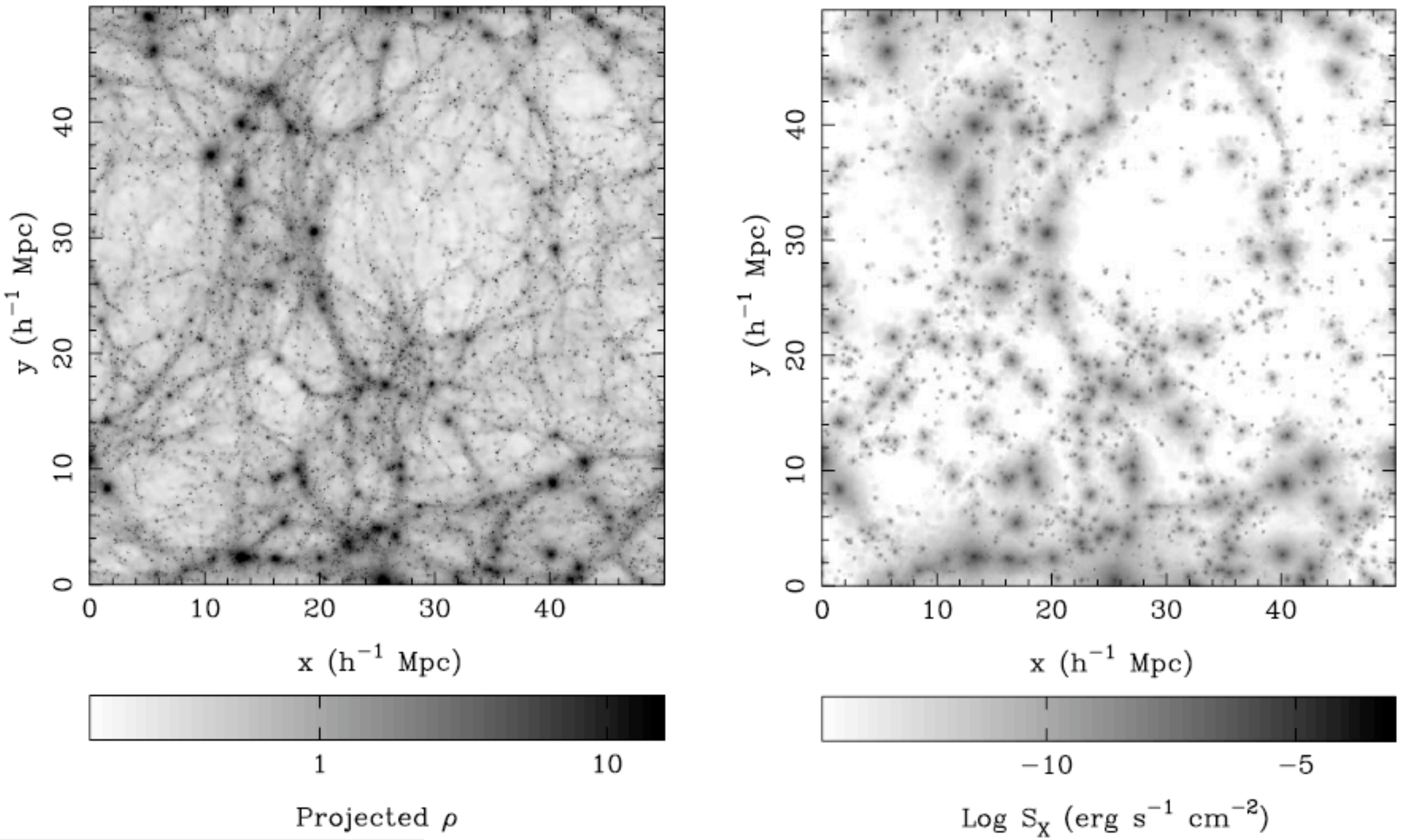




Bland-Hawthorn (Saas Fee 2007)

WHIM simulations

The x-ray background is **strong constraint** on how gas collapses into DM haloes (Kaiser)



Maybe 1/3 of soft x-rays will stay diffuse, only 4% of hard x-rays

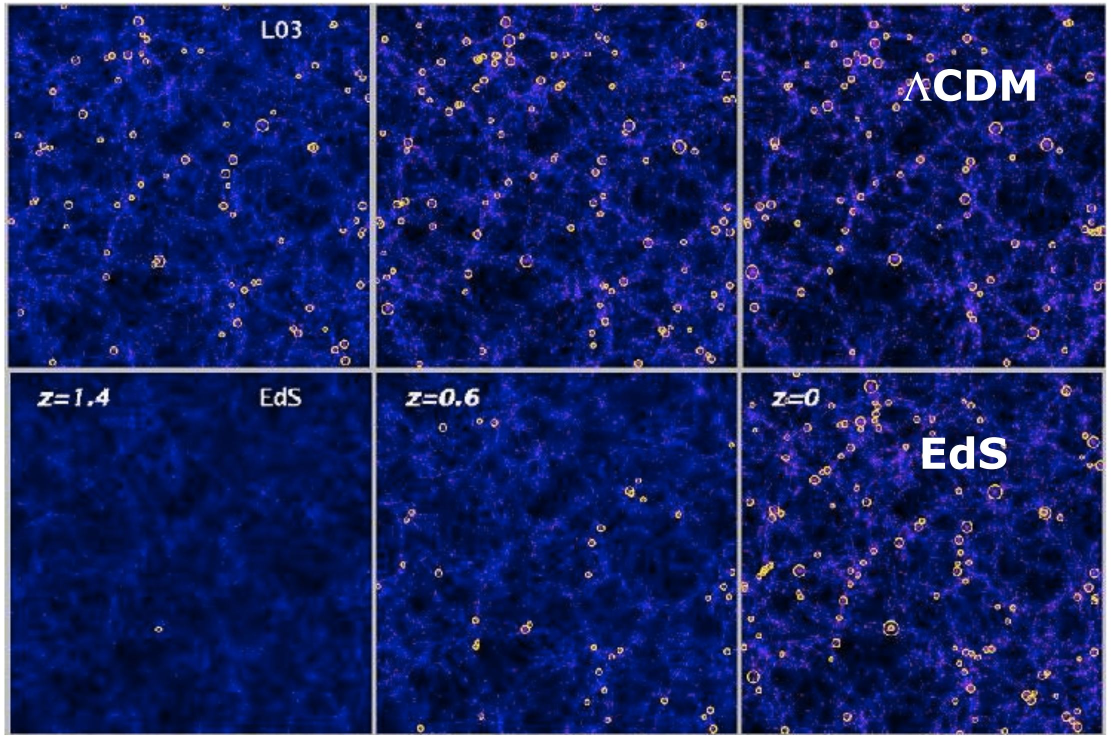
Croft+ 2001

But in x-rays, evidence of missing ingredients…

Comparing clusters to ΛCDM is surprisingly difficult.

ICM evolution should be driven by adiabatic compression in CDM collapse leading to accretion shocks (Kaiser 1986)

Since no preferred scale, clusters should be self similar, but they are not, **e.g. complex L_x-T relation**



Rosati, Borgani & Norman 2002, ARAA

Even on the ~Mpc scales of clusters, simple accretion formalisms **cannot** explain the x-ray properties….

We need extra ingredients!

Early success: Lyα forest

An alternative model for the Lyα absorption forest

H.G. Bi[1], G. Börner[1], and Y. Chu[2] 1992

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Str. 1, W-8046 Garching, Federal Re
[2] Center for Astrophysics, University of Science and Technology of China, Hefei, People's Repul

Received April 15, accepted August 5, 1992

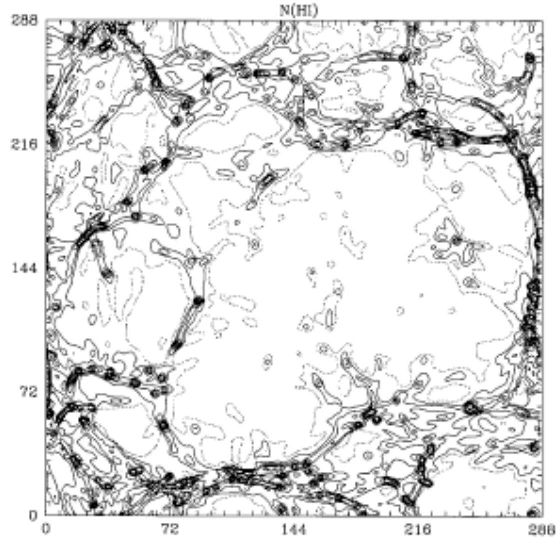
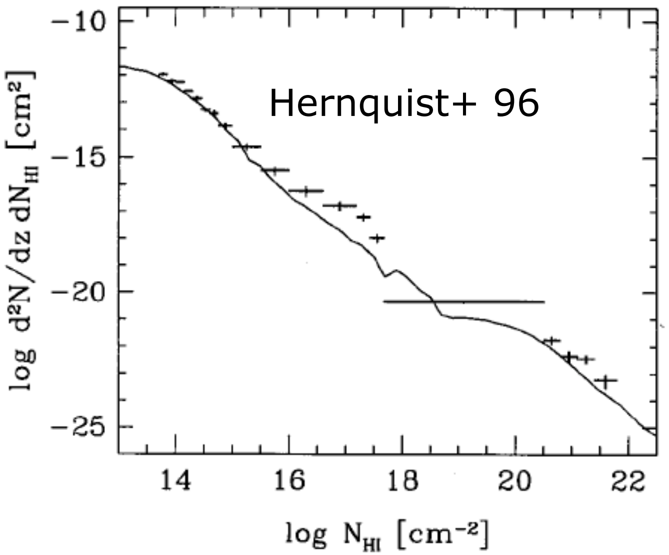


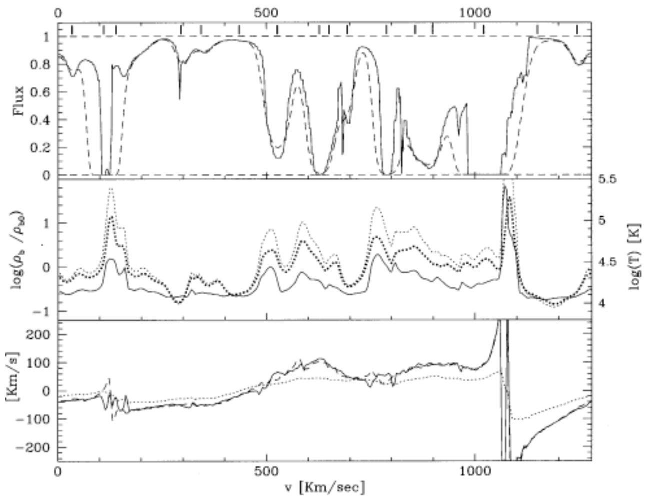
FIG. 2c

Bi+ 1992 simulated clumpy IGM irradiated by cosmic background UV

Miralda-Escude+ 1996

Then followed Cen+ 1994 and many others…





Bland-Hawthorn (Saas Fee 2007)

What can we say about cool gas on large scales?

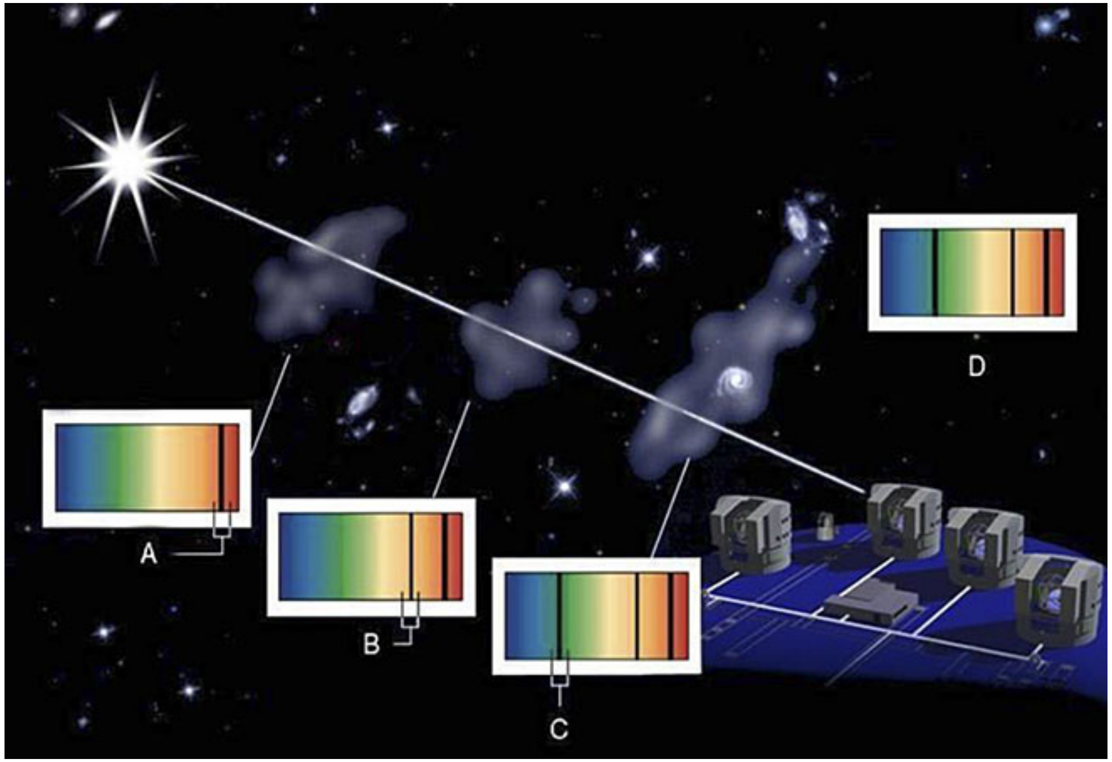
As you have seen from Drs. Nicastro and Viel, we know a lot about the **high-z universe** (from QSO absorption lines) and find that **a lot of gas is locked up in Lyα clouds**.

We see evidence of **rare Lyα clouds in the local universe** from observations towards 3C 273 (Morris; Bahcall; Shull; Fox).

It's hard to understand how gas gets into galaxies for two reasons:

(1) much of the activity happened long ago;

(2) we cannot easily see or locate cold, warm, hot gas in the local universe, especially if it is diffuse.



Shocks on galactic scales?

Is this how galaxies get their gas?

Shocked into hot haloes followed by a "cooling flow"?

Hot accretion via cooling in haloes — central tenet of GF

- **History:** Hoyle 1953, Binney 1977, Rees & Ostriker 1977, Silk 1977, White & Rees 1978, White & Frenk 1991…

Cooling, dynamics and fragmentation of massive gas clouds: clues to the masses and radii of galaxies and clusters

M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

J. P. Ostriker *Department of Astronomy, Princeton University, Princeton, New Jersey 08540, USA*

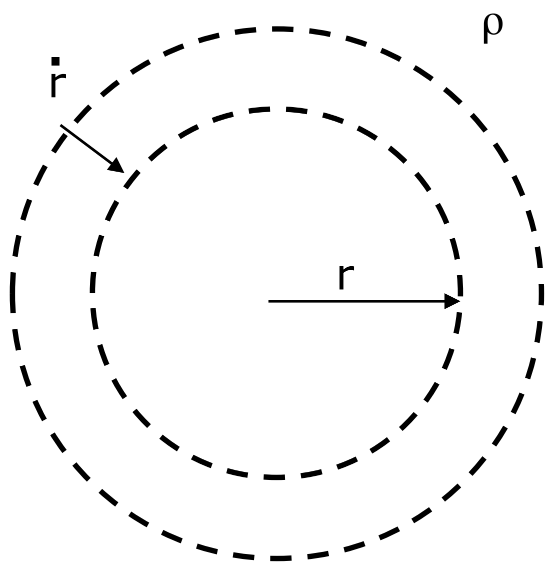
Summary. We investigate the extent to which the characteristic masses and sizes of galaxies (and clusters) are determined by processes occurring at the epoch when the pregalactic material has stopped expanding with the background Universe but has not yet fragmented into stars. Unless pregalactic clouds collapse in an exceedingly homogeneous fashion, their kinetic energy of infall will be thermalized via shocks before the contraction has proceeded by more than a factor ~ 2. What happens next depends on the relative value of the cooling and collapse timescales. Masses in the range 10^{10}–$10^{12} M_\odot$ cool so efficiently that they always collapse at the free-fall rate, and probably quickly fragment into stars. Larger masses, however, may experience a quasi-

Cooling within the dark halo:

$$\dot{M}_{cool} = -4\pi r_{cool}^{2}\ \rho(r_{cool}) \times \dot{r}_{cool}$$

$$L_X = \dot{M}_{cool} \frac{\partial \phi}{\partial r}$$

$$= \dot{M}_{cool}(r_{cool}) \int_{r_o}^{r_{cool}} \frac{v_c^2(r)}{r}\, dr$$



COOLING FLOWS IN CLUSTERS OF GALAXIES

A. C. Fabian

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, United Kingdom

1994

KEY WORDS: clustering, galaxy formation, radio sources, X rays

Table 1 Cooling flow properties of the 55 X-ray brightest clusters[a]

Cluster	Redshift	O	R	Flux[b]	L_X[c]	Central Cooling Time (10^9 yr)	Bin Size (kpc)	Mass Flow Rate ($M_\odot$ yr^{-1})
A426	0.0183	√	√	75.0	110	0.48 ± 0.02	31 I	183
Ophiuchus	0.028	—	—	44.5	152	3.1 ± 7.4	29 L	75
Coma	0.0232	×	0	32.0	75	95 ± 239	47 I	0*
Virgo	18 Mpc	√	√	30.0	1	0.03 ± 0.01	3 L	10
A2319	0.0564	×	×	12.1	170	13.1 ± 2.2	73 I	66
A3571	0.0391	—	—	11.5	77	7.8 ± 12.9	35 L	79
Centaurus	0.0109	√	√	11.2	6	0.49 ± 0.10	10 L	18
Tri. Aust.	0.051	—	—	11.0	126	65 ± 254	160 L	0
3C129	0.022	—	√	9.59	20	5.1 ± 4.5	44 L	61
AWM7	0.0172	×	—	9.14	12	3.9 ± 1.2	65 I	42
A754	0.0542	×	×	8.53	105	9.5 ± 12.5	48 L	24
A2029	0.0767	×	√	7.52	197	3.8 ± 0.7	99 I	402
A2142	0.0899	×	—	7.50	272	3.0 ± 0.8	48 H	188
A2199	0.0300	√	√	7.12	30	2.4 ± 1.8	42 L	150
A3667	0.0530	×	—	6.68	83	165 ± 236	112 I	0*
			√	6.63	241	2.3 ± 0.5	70 L	570
			√	6.37	75	3.8 ± 0.6	69 I	236
			—	5.90	92	21.5 ± 17.3	70 H	10
			×	5.88	147	20.1 ± 5.9	92 I	12
			√	5.87	280	2.1 ± 0.5	32 L	702
			√	5.67	25	2.1 ± 0.3	43 I	112
			√	5.30	89	2.5 ± 0.4	81 I	478
			0	5.20	83	175 ± 38	153 I	0*
			√	4.78	69	4.2 ± 0.5	92 I	187
			√	4.67	25	0.90 ± 0.11	35 L	142
			×	4.36	2	2.2 ± 3.3	16 L	9
			—	4.21	42	—	—	50
			×	4.15	92	8.7 ± 1.1	146 I	326
			—	3.67	112	—	—	—
			—	3.52	39	4.5 ± 4.8	25 L	45
			0	3.45	7	21.5 ± 3.7	92 I	0
			×	3.41	78	25.4 ± 5.0	139 I	0
			√	3.28	18	15.2 ± 24.5	83 L	54
			—	3.03	26	14.6 ± 9.3	86 L	23
			—	2.99	46	23.2 ± 3.8	197 I	0
			√	2.90	35	1.8 ± 0.7	50 L	315
			√	2.66	14	1.1 ± 0.2	40 L	90
			√	2.64	13	4.1 ± 1.0	68 I	45
			—	2.60	24	13.5 ± 4.6	59 I	19

COOLING FLOWS AND GALAXY FORMATION

We have seen that the most massive galaxies observed at $z > 0.5$ have many properties that can be interpreted as due to a surrounding cooling hot medium. Often $t_{\rm cool} \sim t_{\rm grav}$ and $\dot{M}$ is maximized (hence maximal cooling flow). Where $\dot{M}$ is a few thousand $M_\odot\,{\rm yr}^{-1}$ a very large galaxy can then form in a few billion years:

$$M = 10^{12} \left(\frac{\dot{M}}{1000\,M_\odot\,{\rm yr}^{-1}}\right)\left(\frac{t_{\rm a}}{10^9\,{\rm yr}}\right) M_\odot. \tag{8}$$

Cooling flows therefore must play some part in the formation of the most massive galaxies, i.e. the central cluster galaxies. Indeed, any theory of galaxy formation in which gas falls into potential wells, is heated to the virial temperature, and then cools with the possibility that $t_{\rm cool} \gtrsim t_{\rm grav}$ (e.g. Rees & Ostriker 1977, Silk 1977, White & Rees 1978, White & Frenk 1991) requires cooling flows.

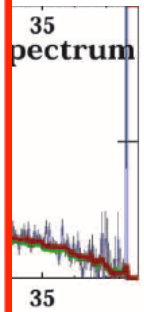
Do cooling flows exist?

- **Not** according to XMM/Newton spectra of 14 top-ranked "cooling flow" clusters.

03

Something ap
keep the gas

...black hole
provide an
source of fe



Roughly three-quarters of rich clusters of galaxies host **cooling-flow** X-ray sources in which $t_{\rm cool} \lesssim 300\,$Myr at $r \simeq 10\,$kpc. These systems must be several Gyr old, so this **cooling time** is at least an order of magnitude shorter than the lifetime, and even shorter cooling times must occur at smaller radii. Consequently, in the absence of heating these systems would develop infinite central densities within the next $\lesssim 100\,$Myr. The X-ray morphologies of the systems are remarkably similar to one another (Donahue et al. 2006), which suggests that they are in approximate steady states, presumably because the central black hole is acting like a thermostatically controlled central-heating system. The cooling-flow phenomenon[10] occurs in individual galaxies as well as in rich clusters of galaxies, but such cooling flows have been less thoroughly studied because they are much harder to observe.

The cooling-flow phenomenon has a major impact on galaxy formation by effectively quenching star formation in halos more massive than $M_{\rm trap}$.

[10] The name "cooling flow" is a misnomer derived from a defunct model: in these systems gas radiates but in a time-averaged sense neither cools nor flows inwards.

Ha:

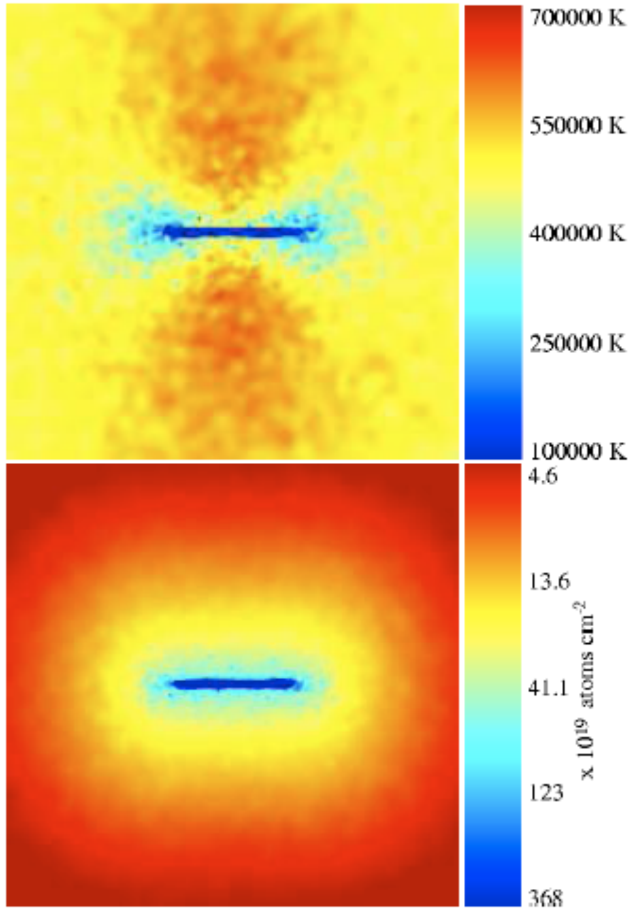
Disks through cooling flows?

Multi-Phase Galaxy Formation: High Velocity Clouds and the Missing Baryon Problem 2004

Ariyeh H. Maller[1], James S. Bullock[2,3,*]

Cooling flows within galactic haloes: the kinematics and properties of infalling multi-phase gas 2006

Tobias Kaufmann [1 *], Lucio Mayer [1], James Wadsley [2], Joachim Stadel [1] and Ben Moore [1]



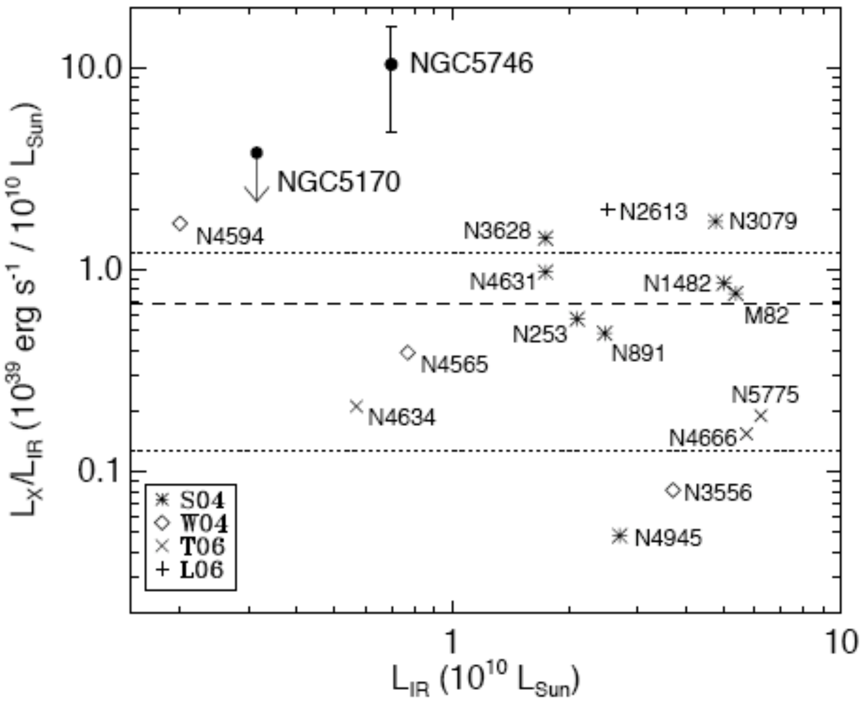
They ignore the long literature on thermal instability in cooling flows.

Linear thermal instability is almost **completely suppressed** (because an overdense blob convects back to its equilibrium location faster than an instability can grow); Binney, Nipoti, Fraternali 09.

Non-linear thermal instability possible but tends to produce tiny fragmentary clouds. SPH is **not** the way to do this.

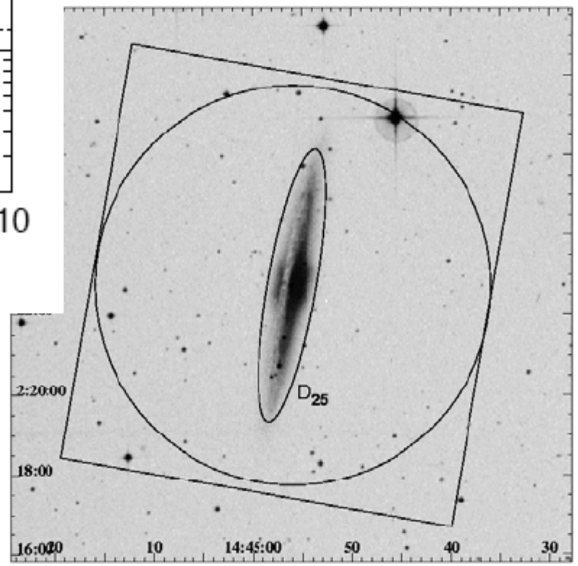
Discovery of a very extended X-ray halo around a quiescent spiral galaxy – the "missing link" of galaxy formation

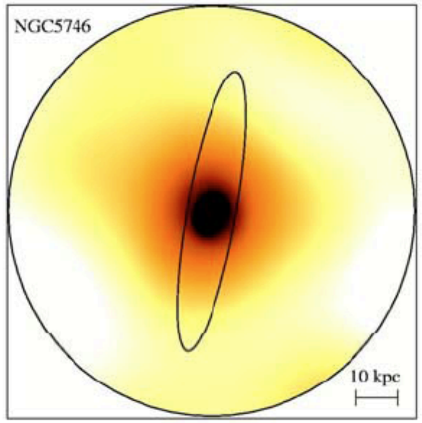
Pedersen+ 06; Rasmussen+ 06



Don't believe papers that make these claims. Extraordinary claims require extraordinary evidence.

Almost any disk with a hot halo is a galactic wind or the data have not been reduced properly.





Detection of a Hot Gaseous Halo Around the Giant Spiral Galaxy NGC 1961

Michael E. Anderson[1], Joel N. Bregman[1]

NEXT TIME:
This appears to be first reliable detection after the Galaxy

ABSTRACT

Hot gaseous halos are pred
important for our understandin
detected at distances beyond
Chandra ACIS-I instrument to
candidate galaxy: the isolated
rants around the galaxy for 3
point source emission, and fou
50 kpc. We fit β-models to the
kpc of $5 \times 10^9 M_\odot$. When this p
virial radius), the implied hot h
assume a gas metallicity of $Z =$
of gas, but falls significantly b
searches, and suggests that NC
the cosmic mean, which would
baryon Tully-Fisher relationshi
gas is no more than 0.4 $M_\odot$/y
gas consumption rate through s
halo for galaxy formation mod

Subject headings: galaxies: ha
galaxies

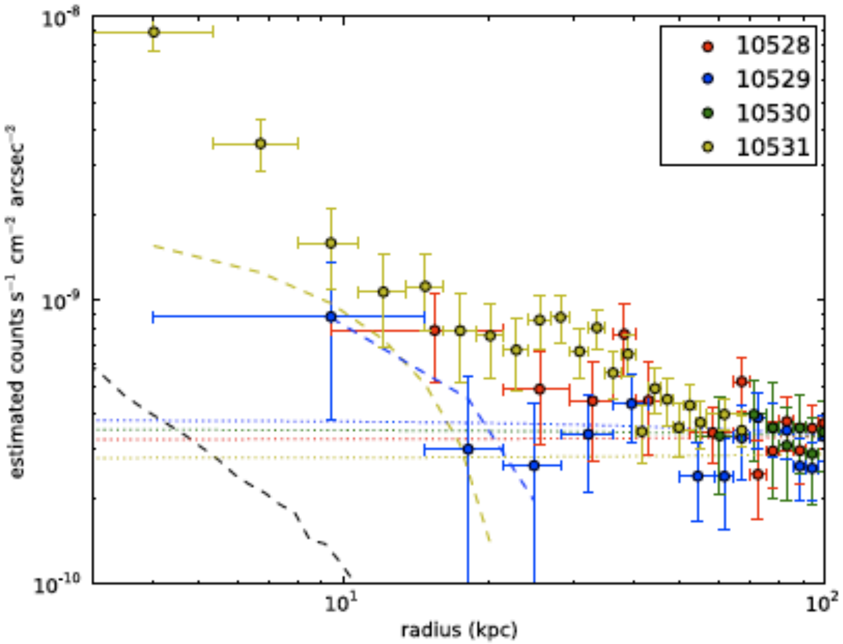
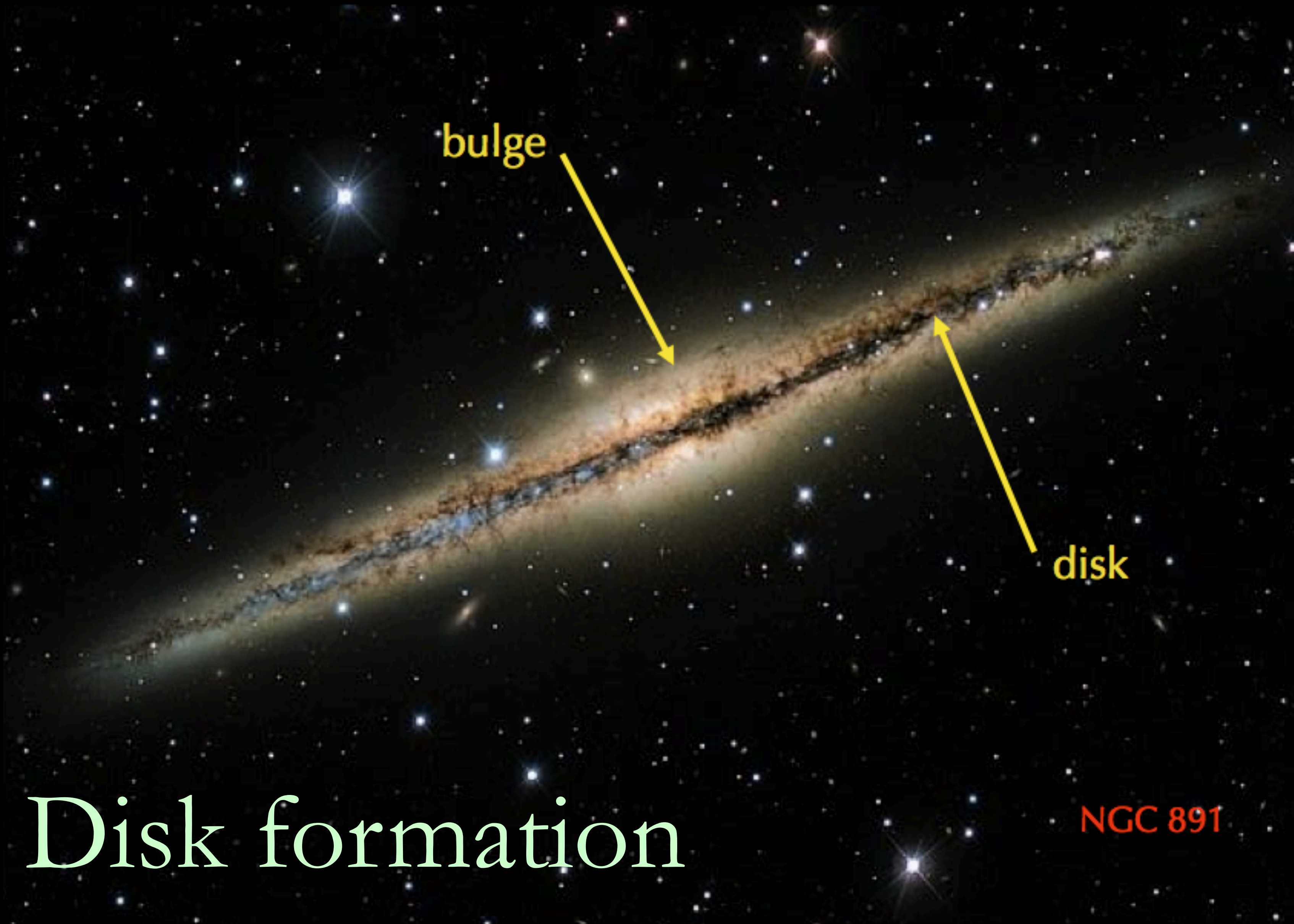


Fig. 5.— Log-log plot of radial surface brightness profiles for all four observations. The black dashed line is the estimated contribution of stars, and the colored dashed lines are the estimated contributions of X-ray binaries. The colored data points are the surface brightness profile with resolved and unresolved point sources subtracted. Unlike Figures 3 and 4, we have not subtracted the sky X-ray background from the surface brightness profile. The smoothed sky X-ray background is indicated by the four dotted colored lines. We detect emission above the background out to 40-50 kpc which is more spatially extended than the other galactic components.

A Milky Way-like external galaxy seen edge on



Disk formation

Spin: the disk must have collapsed down from an initially large volume

GALAXY FORMATION: SOME COMPARISONS BETWEEN THEORY AND OBSERVATION

S. Michael Fall
Institute of Astronomy, Cambridge, England.

1983

In terms of the dimensionless spin parameter

$$\lambda \equiv J|E|^{1/2}G^{-1}M^{-5/2}$$

N-body simulations reveal that the distribution of halo spins is log normal, i.e.

$$p(\lambda)d\lambda \propto \exp\left\{-\frac{1}{2}\left[\frac{\ln(\lambda/\bar{\lambda})}{\sigma(\ln\lambda)}\right]^2\right\}d\ln\lambda,$$

$$\bar{\lambda} \approx 0.05 \quad \text{and} \quad \sigma(\ln\lambda) \approx 0.5.$$

Most haloes have low spin, little dependence on cosmology parameters

λ parameter measures degree of rotational support

acceleration $\quad a = \frac{v^2}{r}$

gravity $\quad g \sim \frac{GM}{r^2}$

ang. mom. $\quad J \sim m r v$

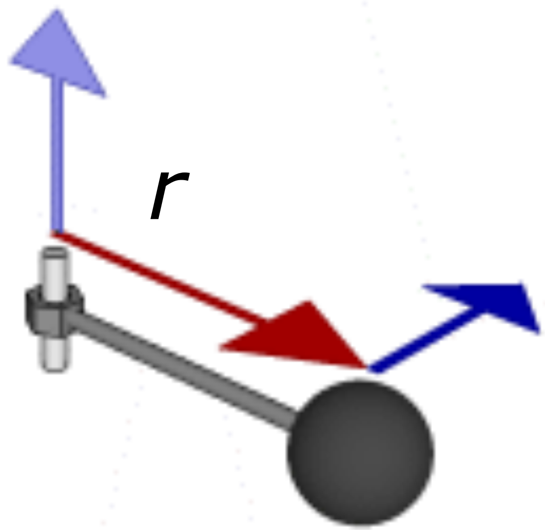
grav. binding energy $\quad E \sim \frac{GM^2}{r}$

$$\left.\begin{array}{l} a = \frac{v^2}{r} \\ g \sim \frac{GM}{r^2} \\ J \sim m r v \\ E \sim \frac{GM^2}{r} \end{array}\right\} \text{remove } v, r$$

$$\frac{a}{g} \sim \frac{v^2 r}{GM} \sim \frac{J^2 E}{G^2 M^5} = \lambda^2$$

$\lambda \sim 0.05$ dark matter halos

$\lambda \sim 1$ disks



Sadly, we won't have time to chat about tidal torque theory $\boldsymbol{T} = \boldsymbol{r} \times \boldsymbol{F}$.

This is a beautiful topic – next time!

consider a spherical halo with a constant circular velocity v_c out to some truncation radius r_t. Without having to specify the rotation curve of the dark material, its angular momentum and mass can be expressed as

$$J_H = \sqrt{2}\,\lambda_H\, v_c^3\, r_t^2/G, \qquad M_H = v_c^2\, r_t/G, \qquad \text{(H for halo)} \tag{3}$$

when terms of order λ_H^2 are neglected in the energy $E_H = -v_c^4\, r_t/2G$. Now suppose the gas that collapses in such a halo arranges itself into an exponential disc with a scale - radius α^{-1} determined by the circular velocity v_c and the specific angular momentum $J_D/M_D = 2v_c/\alpha$. Since the disc material would have experienced the same tidal torques as the halo material before dissipating any energy it seems reasonable to set $J_D/M_D = J_H/M_H$; this implies

$$R_H/R_D = 0.30(\alpha r_t) = 0.42/\lambda_H \approx 6. \qquad \text{(D for disc)} \tag{4}$$

The first equality follows from the expressions $R_H = \frac{1}{2} r_t$ and $R_D = 1.67\,\alpha^{-1}$ for the median radii of the halo and disc and the last equality is appropriate for $\lambda_H \approx 0.07$. These results agree nicely with the more exact calculations of Fall & Efstathiou (1980), which include the effects of a bulge and the gravity of the disc.

Fall's argument

We can relate factor by which baryons collapse in radial direction before they reach centrifugal balance in a disk to the initial rotation of a protogalaxy, i.e.

Consider a luminous disk D and halo H. The baryons destined to become the disk receive the same external torques as the dark matter, say, prior to dissipation.

During and after collapse, the specific angular momenta are conserved such that there is no angular momentum transfer.

It can be shown

$$J_D/M_D = J_H/M_H.$$

which leads to

$$J_D/M_D = 2v_c\alpha^{-1},$$

$$J_H/M_H = \sqrt{2}\lambda v_c r_t.$$

$$\alpha r_t = \sqrt{2}/\lambda.$$

α = exponential disk scale length
v_c= isothermal halo circular velocity
r_T = halo truncation radius

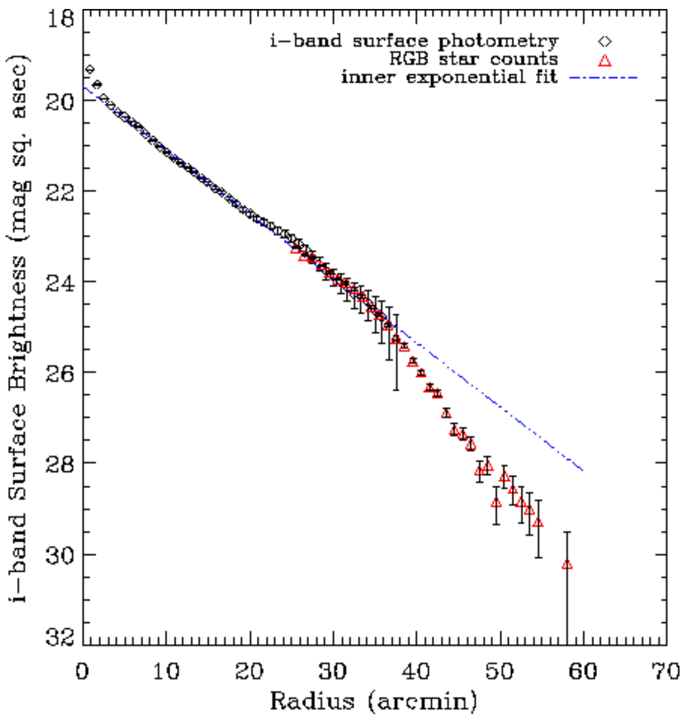
For α^{-1} = 3 kpc,

r_T = 100 kpc

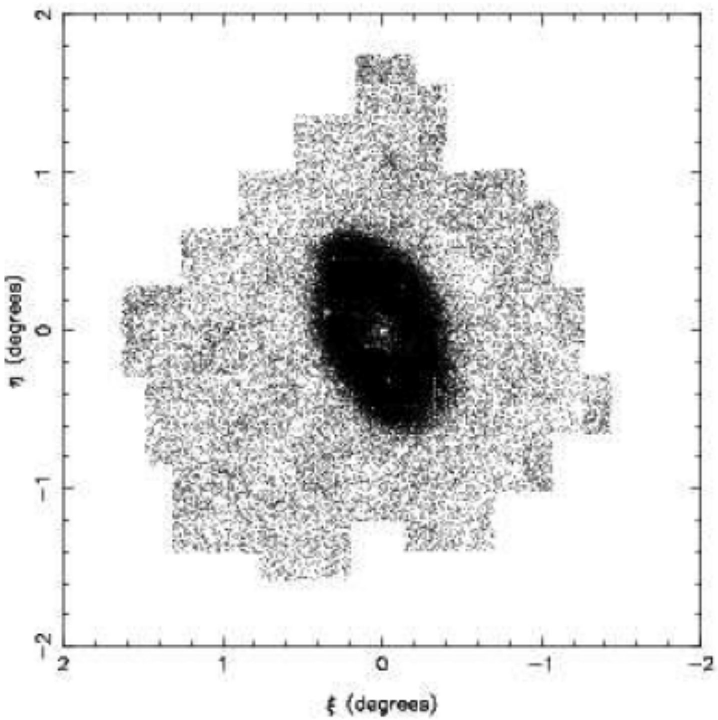
Does either the HI or stellar disk edge relate to the protocloud?

But where is the edge?

First “break radius” confirmed with star counts



M33: Ferguson+ 2006



Remarkably clean edge with **no** sign of tidal structure

What does truncation mean ?

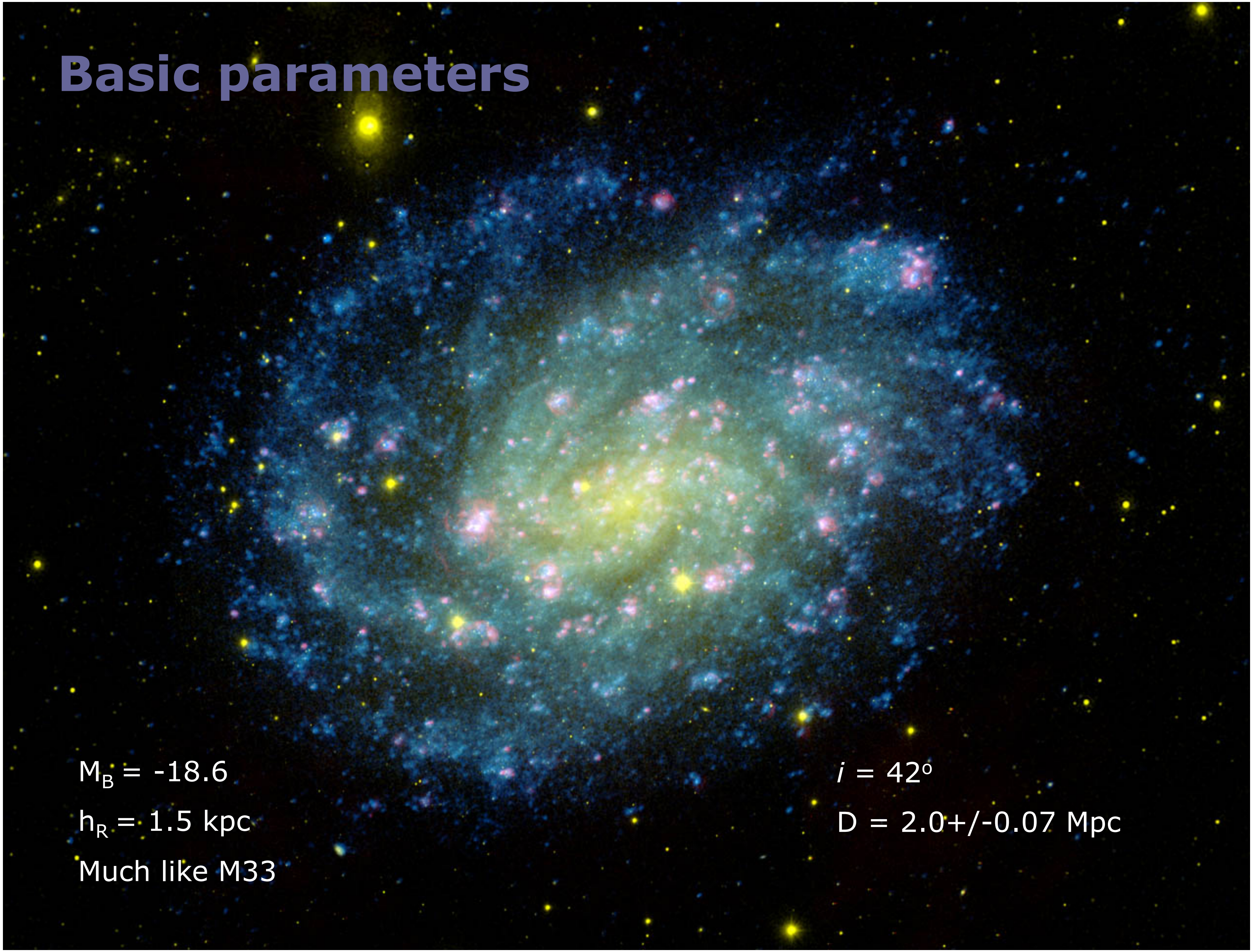
Matter moves in ~ circular orbits, and angular momentum increases outwards, so the surface brightness cut-off represents material moving with the highest specific angular momentum ***j***.

This **may** reflect the maximum value of ***j*** for baryonic material in the original protocloud.

That *would* be interesting.

e.g. van der Kruit 1980

Basic parameters



$M_B = -18.6$

$h_R = 1.5$ kpc

Much like M33

$i = 42^o$

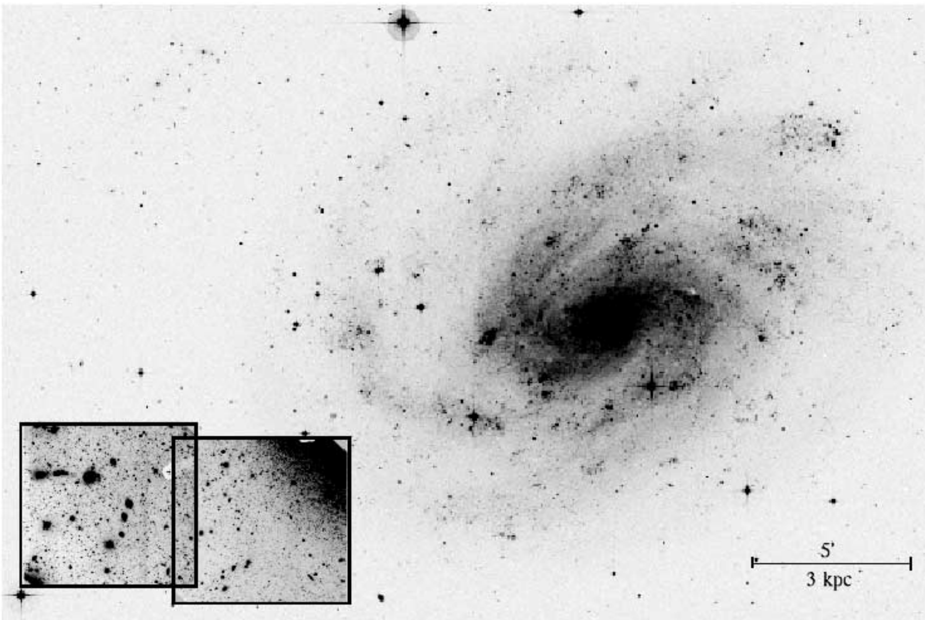
D = 2.0+/-0.07 Mpc

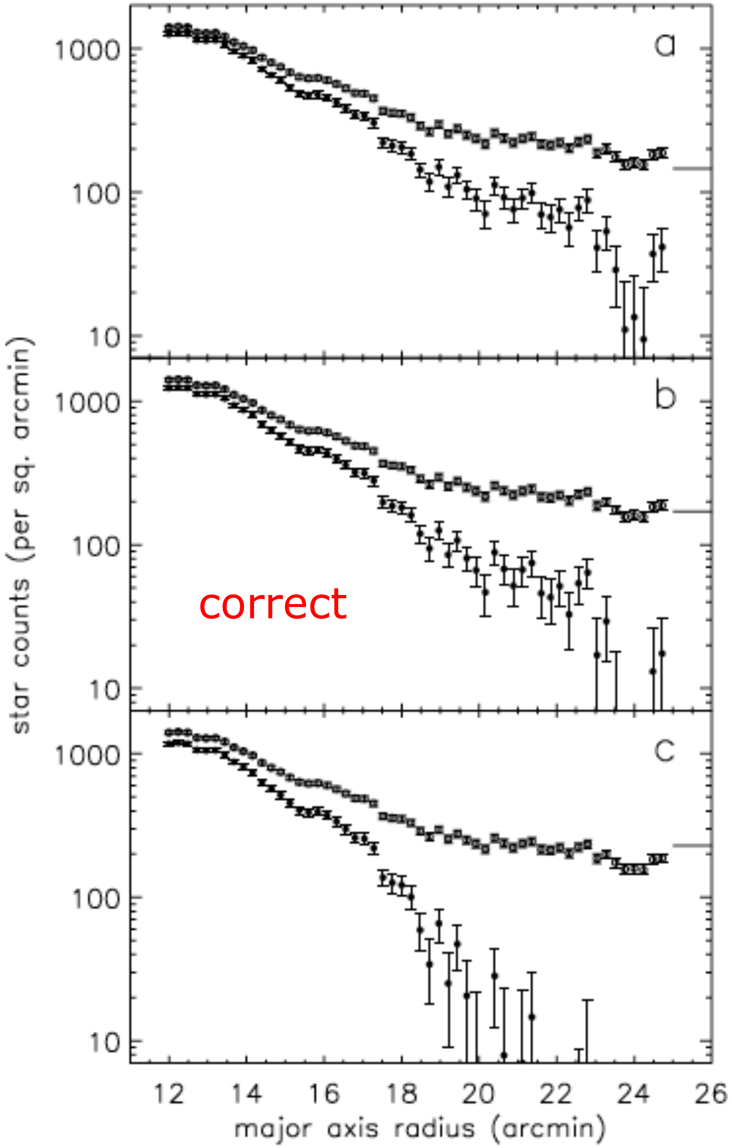
First "continuously exponential disk"

i.e. no sign of truncation or break

NGC 300: Bland-Hawthorn+ 2005

NGC 7793: Vlajic+ 2009, 2011





Bland-Hawthorn (Bologna 2011)

Photometric quality

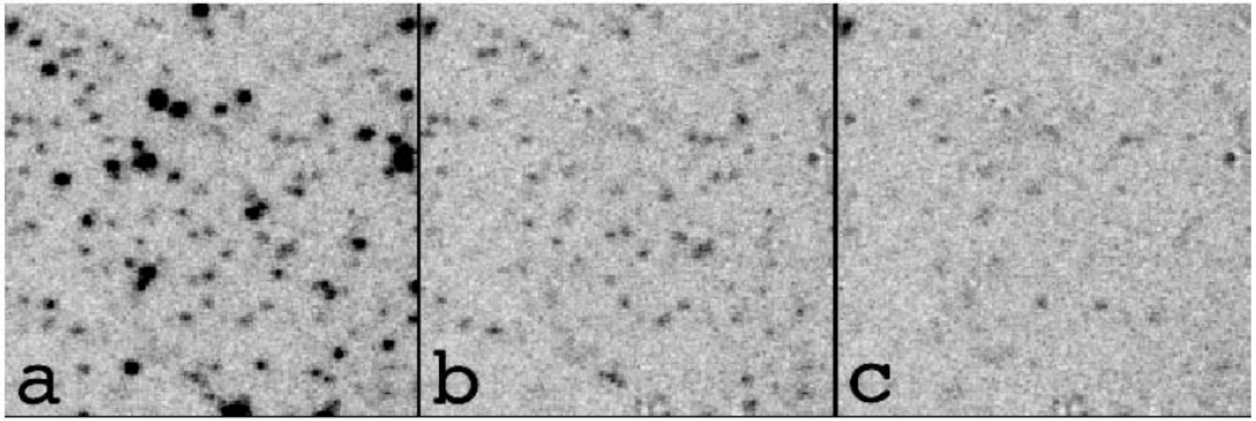
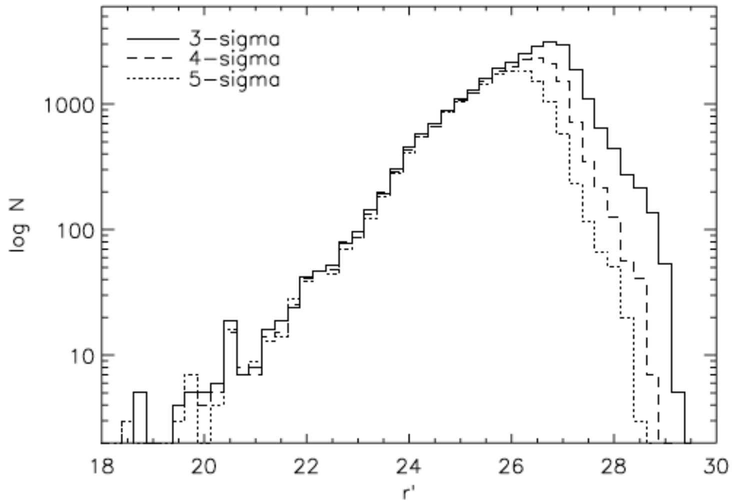


FIG. 3.—A 25″ × 25″ subset from the center of field 1 to demonstrate the quality of the DAOPHOT photometric analysis. The images show (*a*) before source subtraction, (*b*) with 5 σ sources subtracted, and (*c*) with 3 σ sources subtracted. The PSF is mildly elliptic (10%–15%) and 0″.60 along the long axis.

Slightly elliptic psf: 0.56″x0.60″

Top 2% photometric

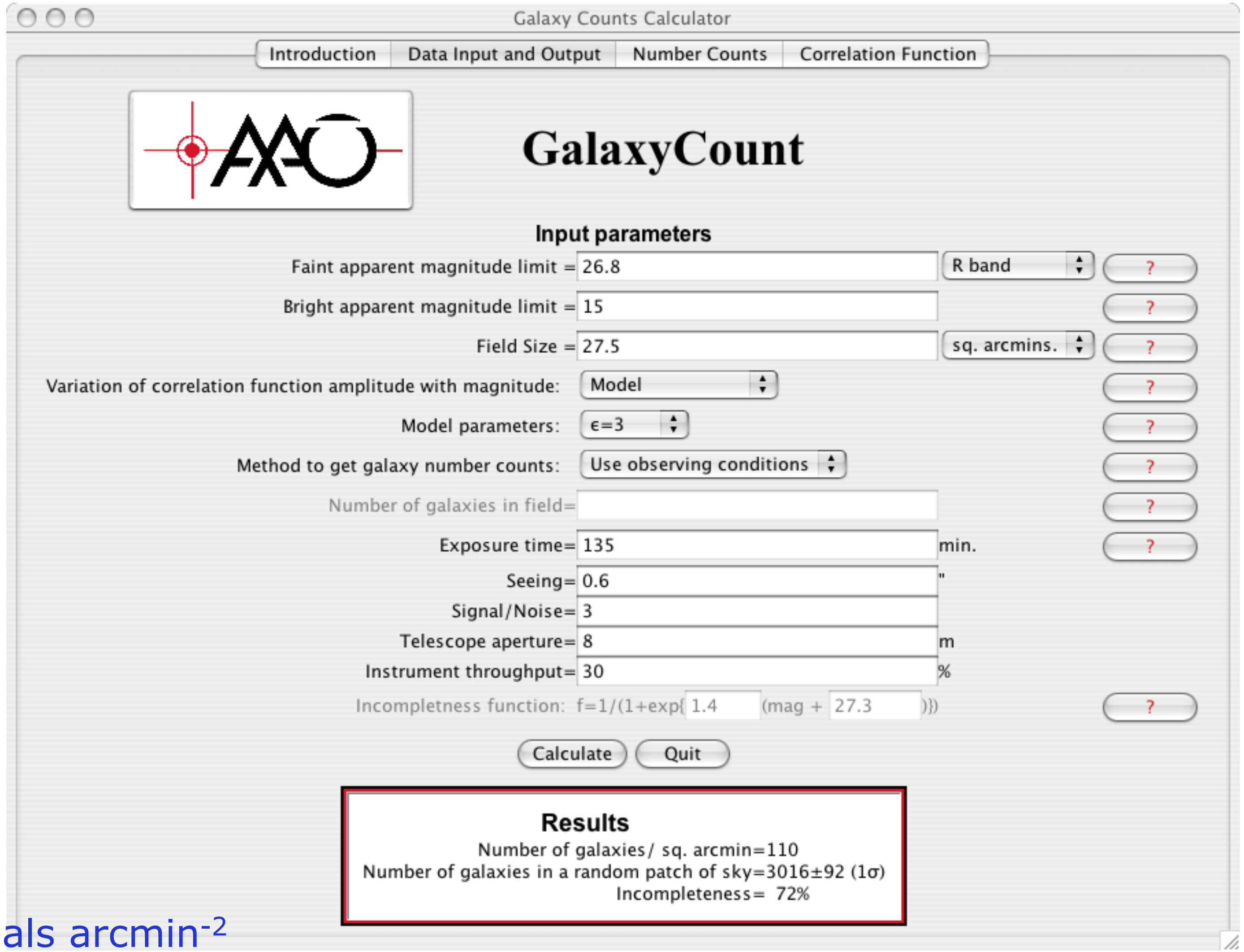
r′=27.0 (3σ) 70% complete



There are very few disks mapped in this way. You need a big telescope and exceptional seeing.

r′-R=0.2

GalaxyCount (www.aao.gov.au/astro/GalaxyCount)



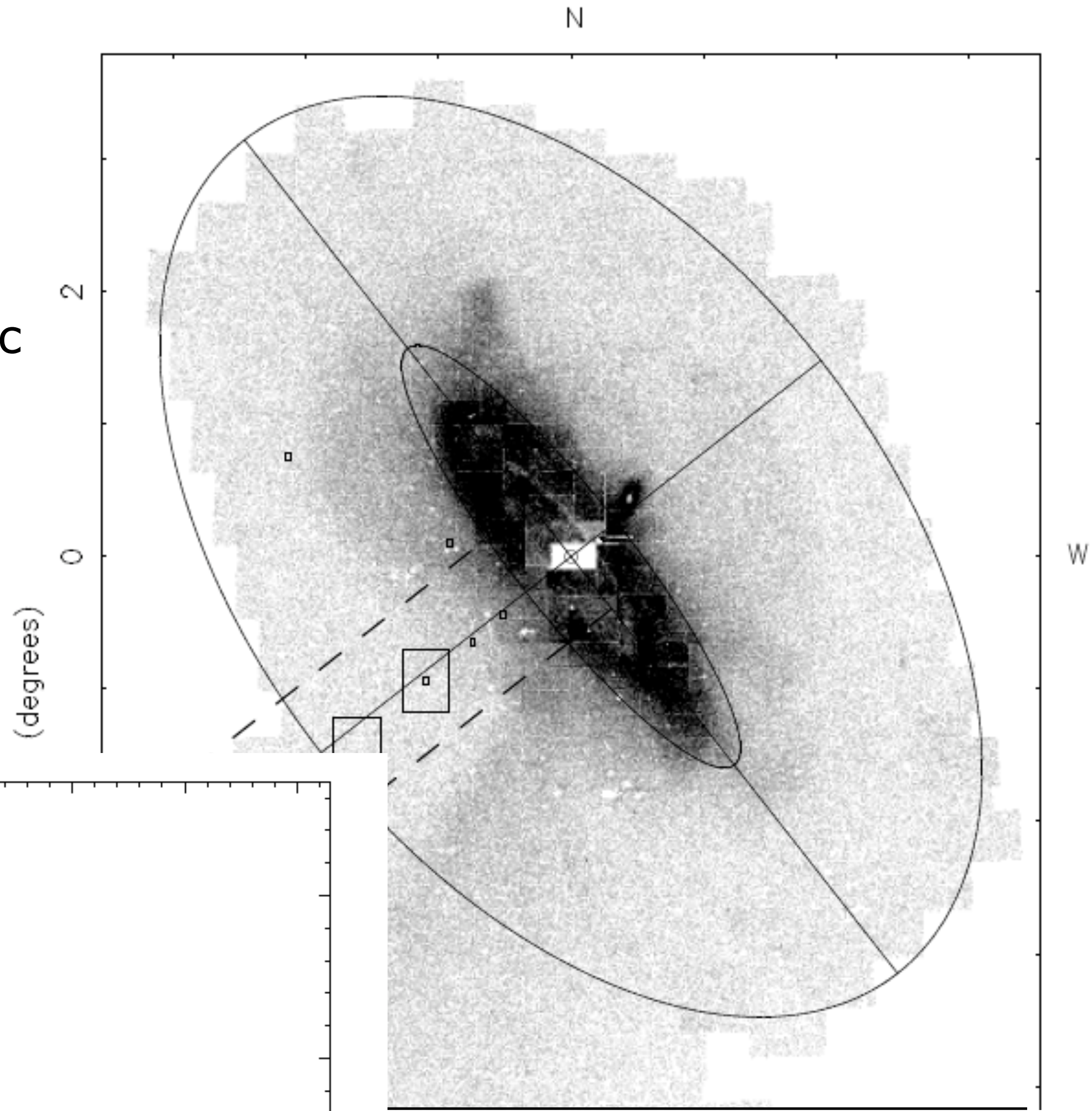
b = 110 +/- 20 gals arcmin^{-2}

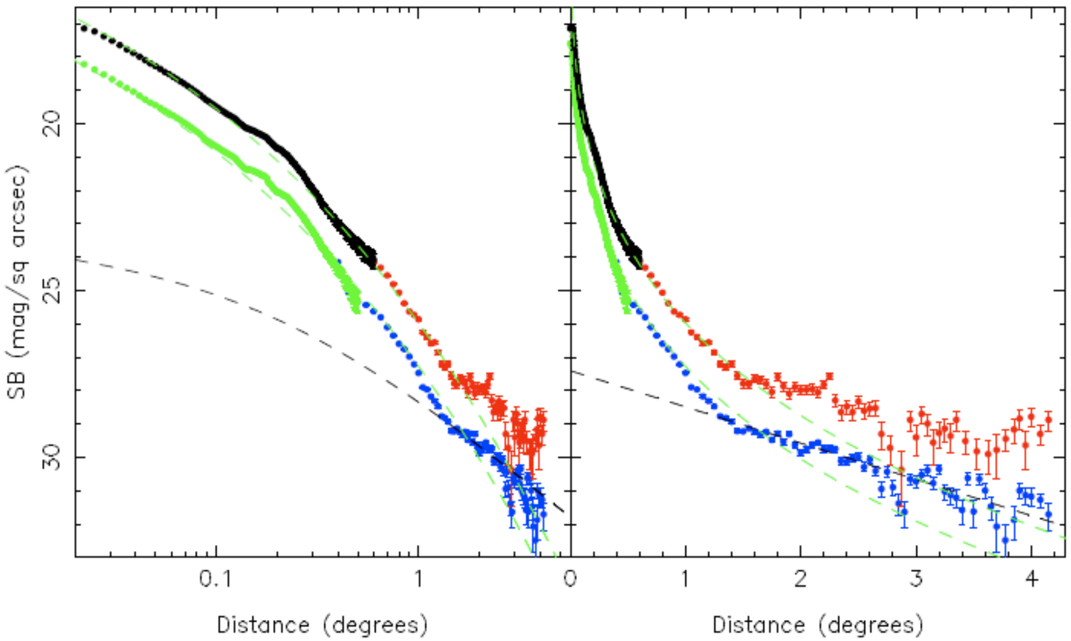
Ellis & JBH (2007), MNRAS, in press

Minor axis of M31

Exponential disk to > 50 kpc

(Irwin+ 2005)

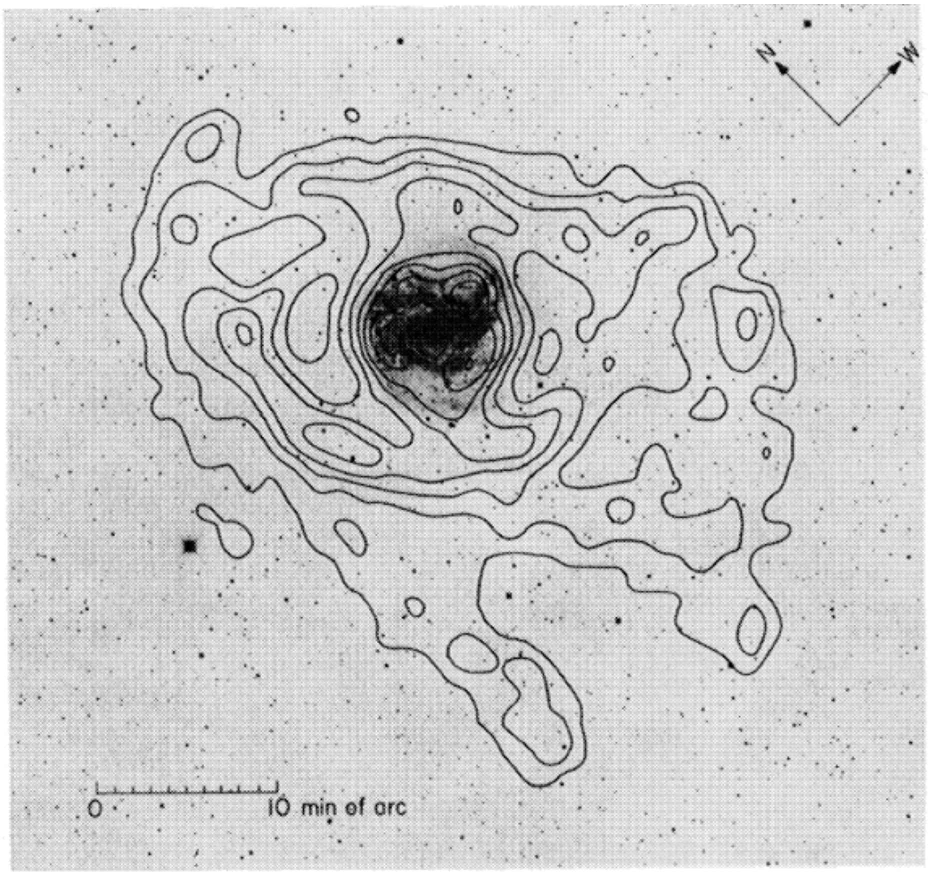


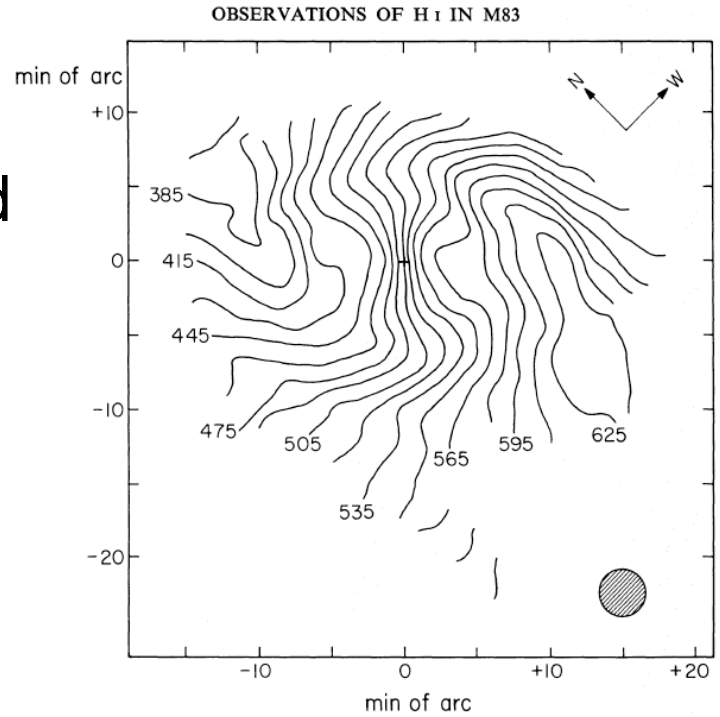


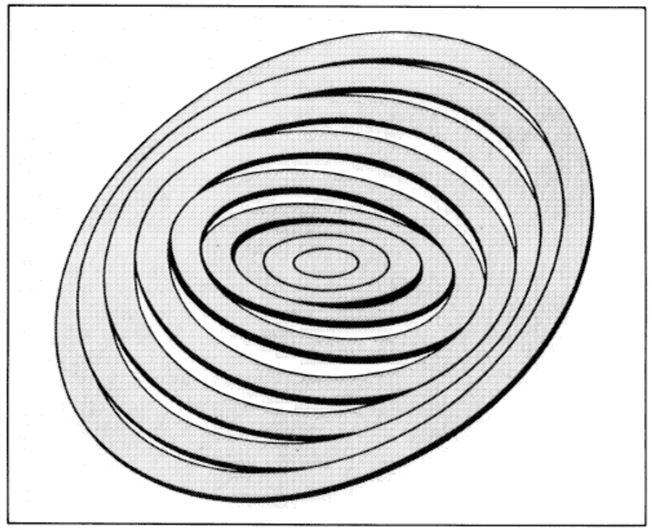
Does the gas have a well defined edge?

Hard to say:

Most outer HI disks are warped and
 get messy further out





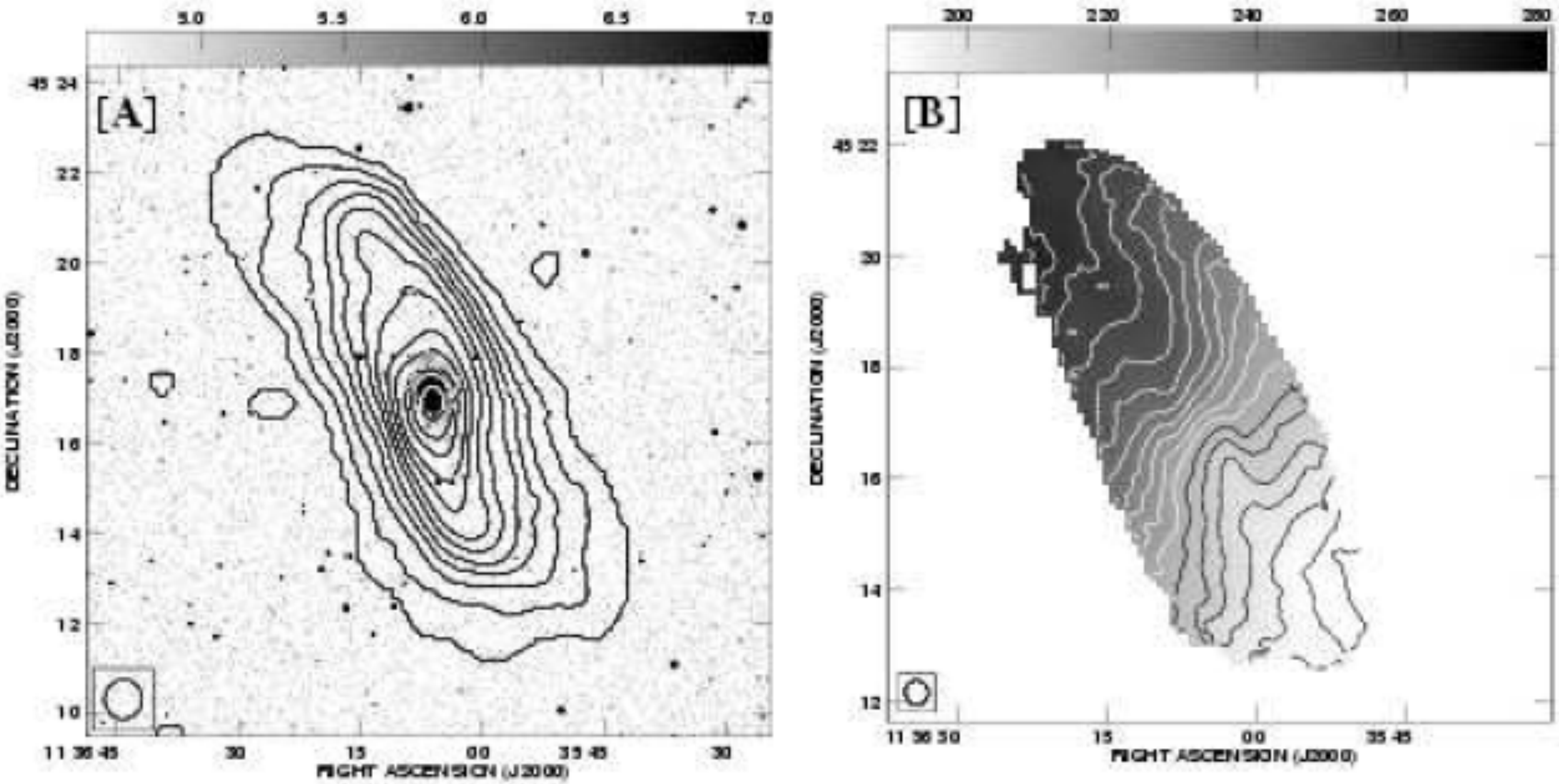


M83: Rogstad+ 1974

HI envelopes can be huge…

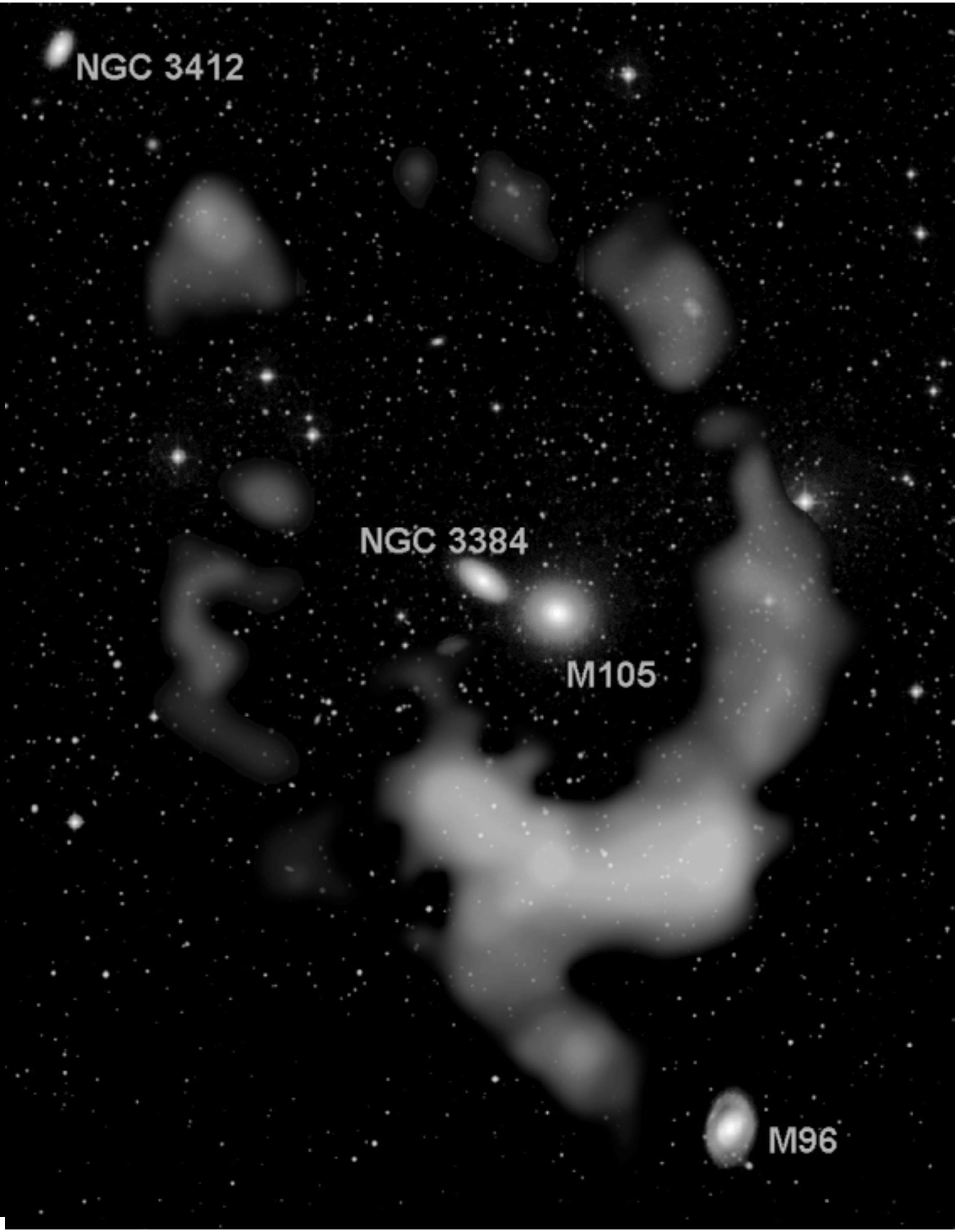
New record holder: NGC 3741

HI seen to 38 optical scale lengths



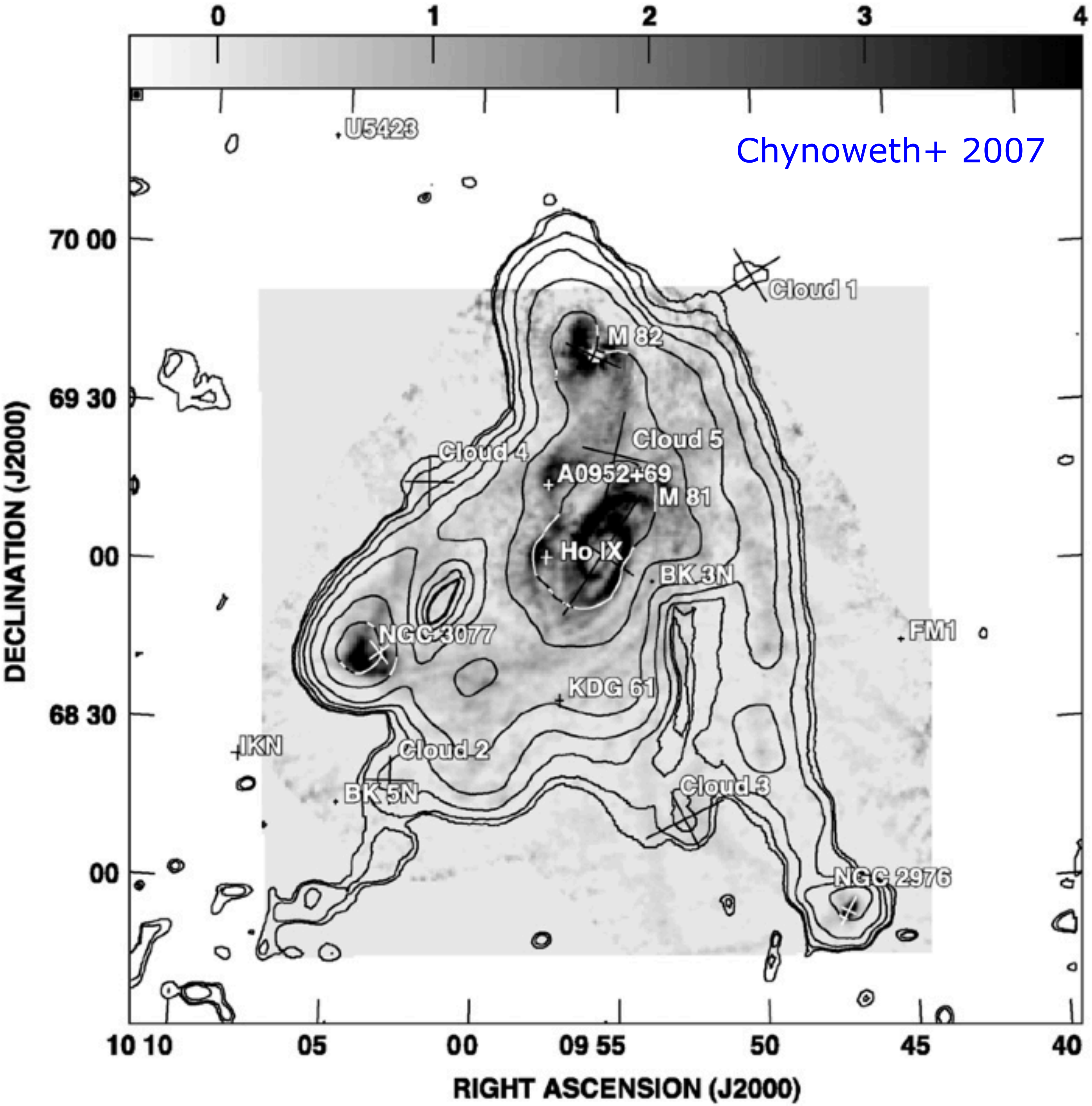
Begum+ 2005

Gas is messy outside optical disk



Leo Ring

(Schneider+1981)

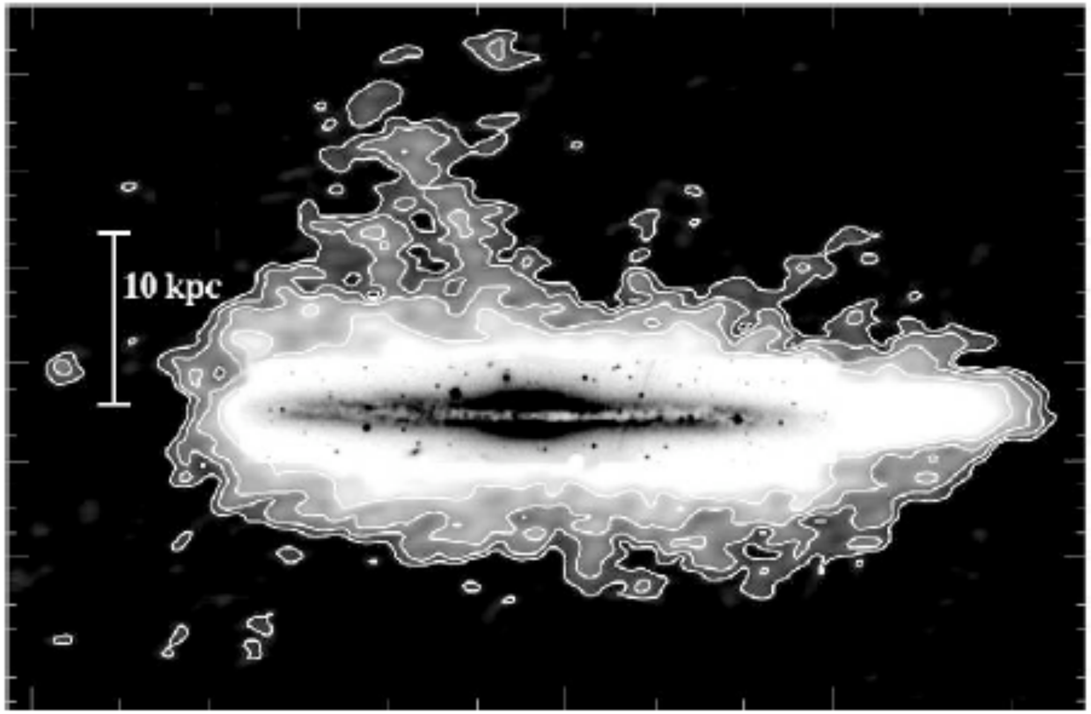


Chynoweth+ 2007
0
1
2
3
4
U5423
Cloud 1
M 82
Cloud 5
Cloud 4
A0952+69
M 81
Ho IX
BK 3N
FM1
NGC 3077
KDG 61
IKN
Cloud 2
BK 5N
Cloud 3
NGC 2976
70 00
69 30
00
68 30
00
DECLINATION (J2000)
10 10
05
00
09 55
50
45
40
RIGHT ASCENSION (J2000)

NGC 891: external view of the Galaxy

Slowly rotating HI halo

Possible slow accretion
 onto plane?



HI: <0.3 M_o yr^{-1} (Fraternali+ 2007)

X-rays: <0.1 M_o yr^{-1} (Bregman+ 1997)

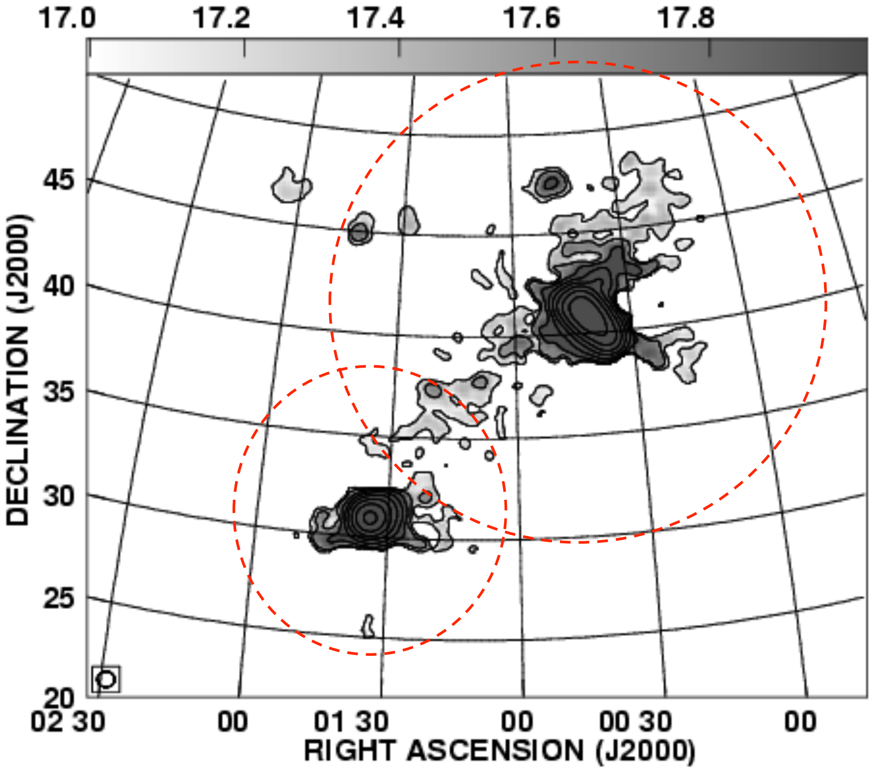
EUV: <0.1 M_o yr^{-1} (Miller+ 2000)

Model: Mapelli, Moore & JBH 2009

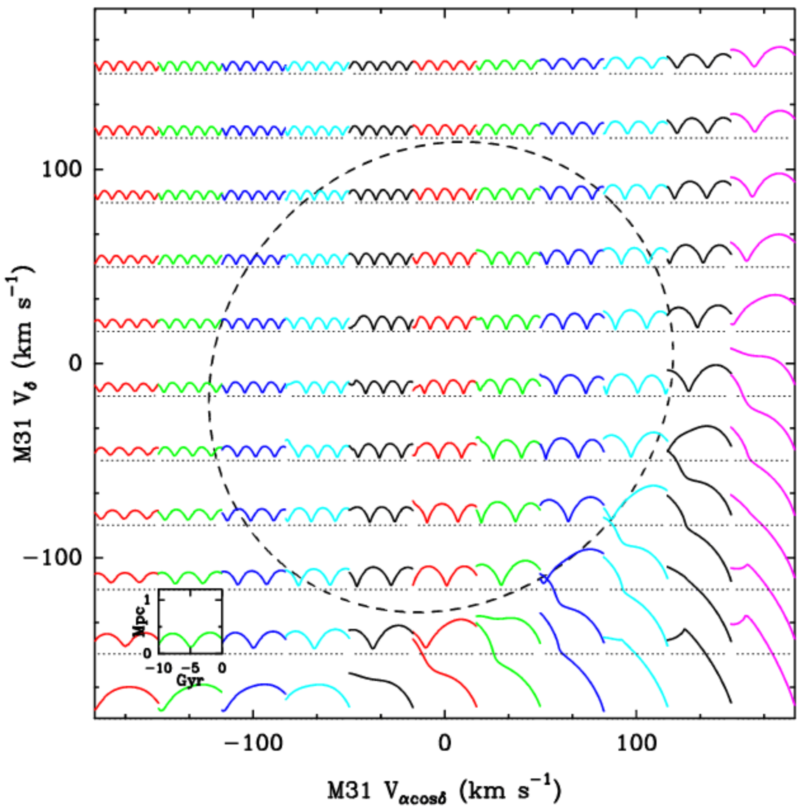
M31 – M33 filament

These galaxies may have
undergone several orbits…

Braun 2004



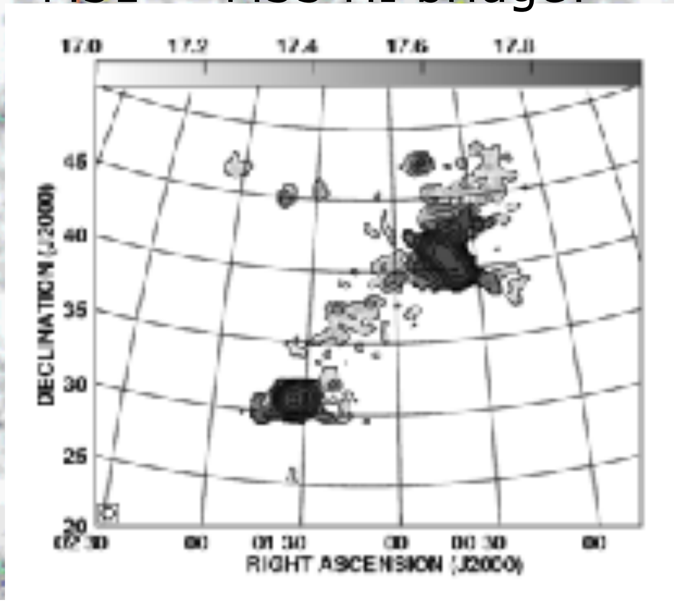
Loeb 2004

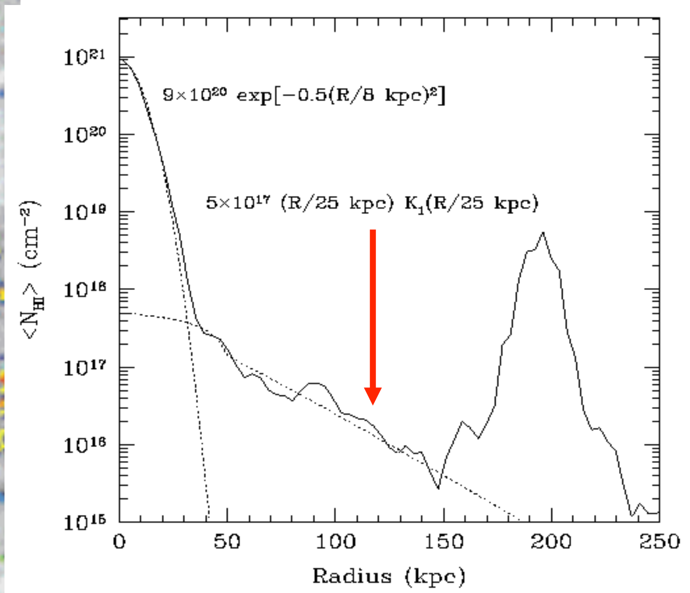


…and gas may have been dislodged
in earlier passage, rather than
"primordial"

Reaching down to the HI cosmic web?

M31 — M33 HI bridge?

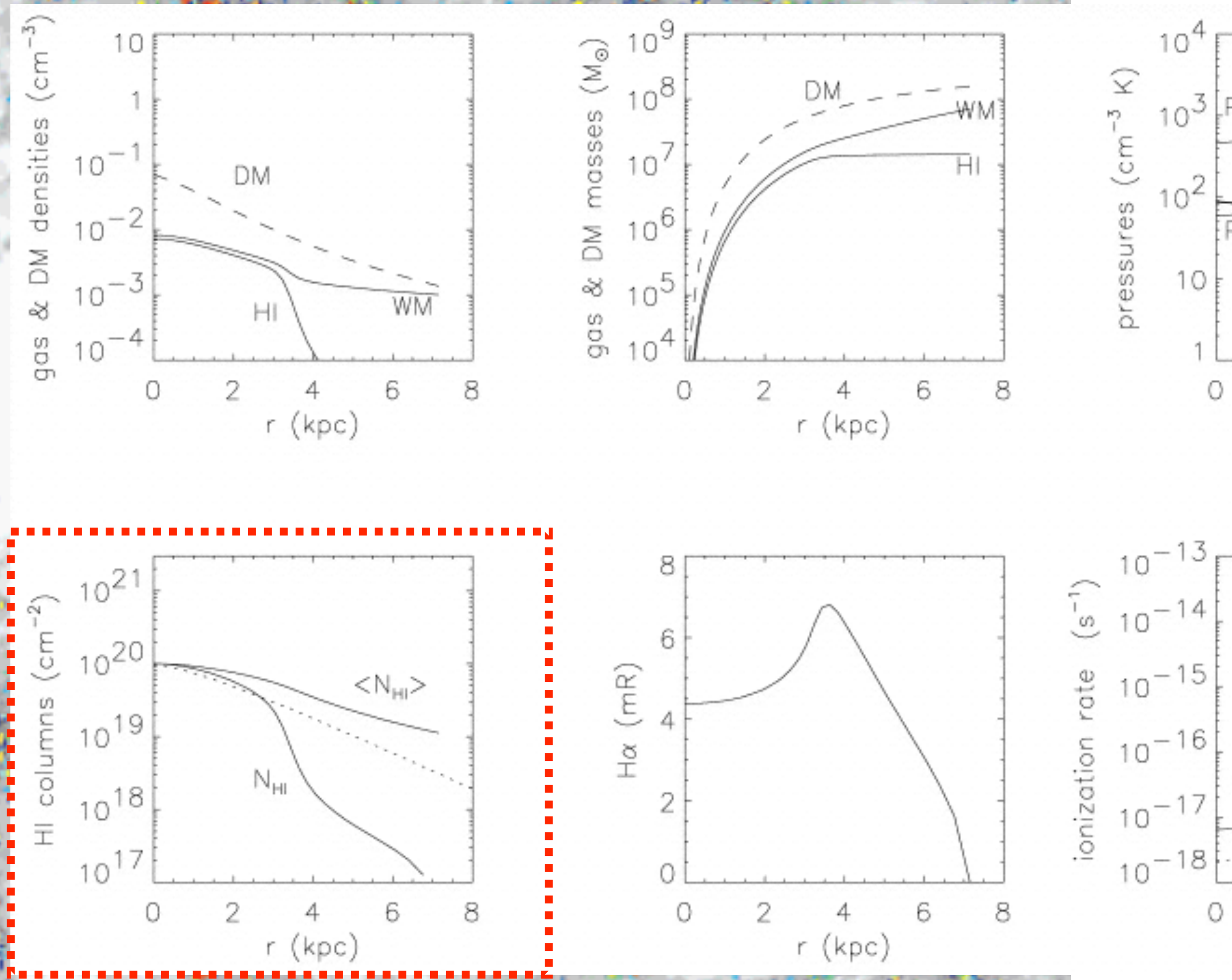


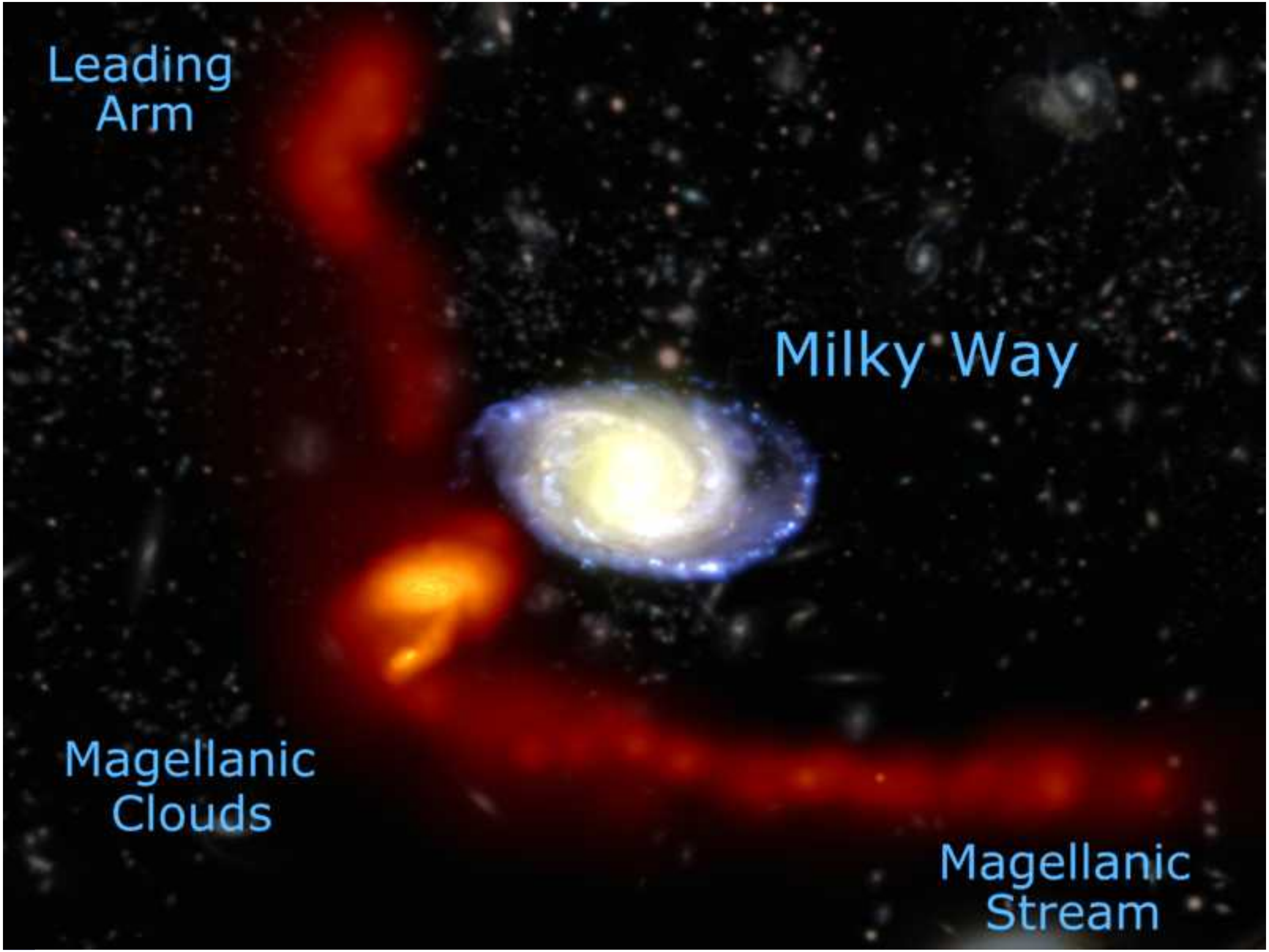


Two major problems:

(i) HI gas well within R_{vir}

(ii) $<10^{18}$ cm^{-2} does not survive ~ T_H




Leading
Arm
Milky Way
Magellanic
Clouds
Magellanic
Stream


Bland-Hawthorn (Bologna 2011)

But is any of this infalling gas "primordial" or simply dislodged from earlier passages?

HIGH-VELOCITY CLOUDS: BUILDING BLOCKS OF THE LOCAL GROUP

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Received 1998 February 20; accepted 1998 November 9

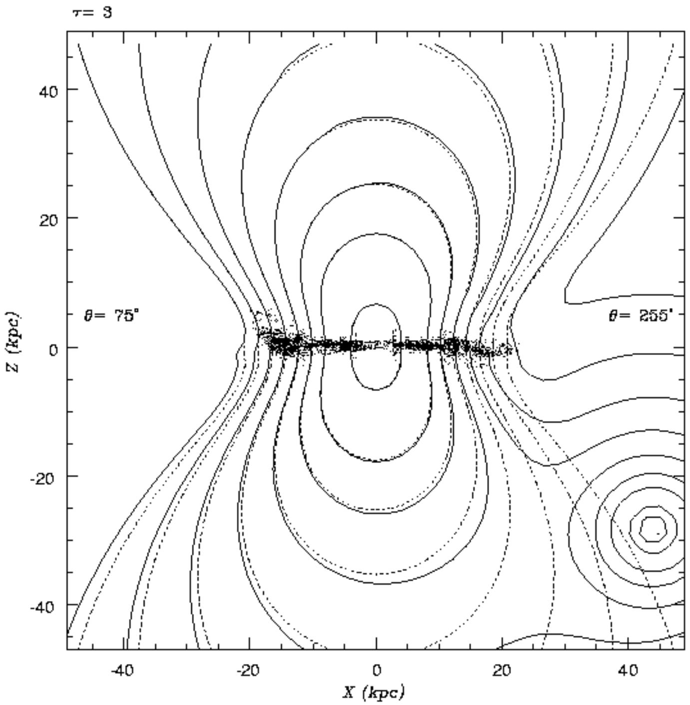
Adopting an old idea of Oort, they proposed that the HVCs were self-gravitating and therefore mostly ~1 Mpc from the Galaxy, and thus very massive.

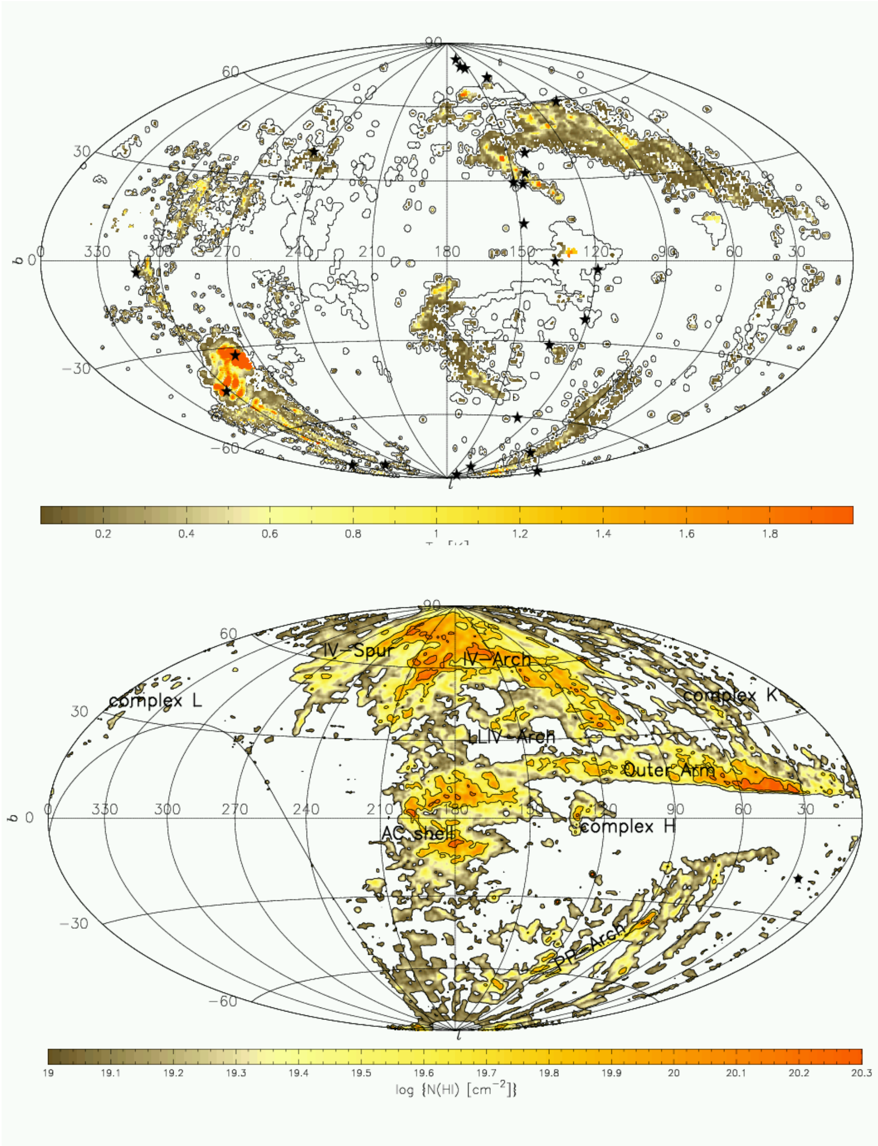
They thought the HVC population represented huge levels of HI accretion onto the Local Group, i.e. that we are surrounded by a huge **Oort cloud**, a very appealing notion.

“Anomalous” Galactic H I

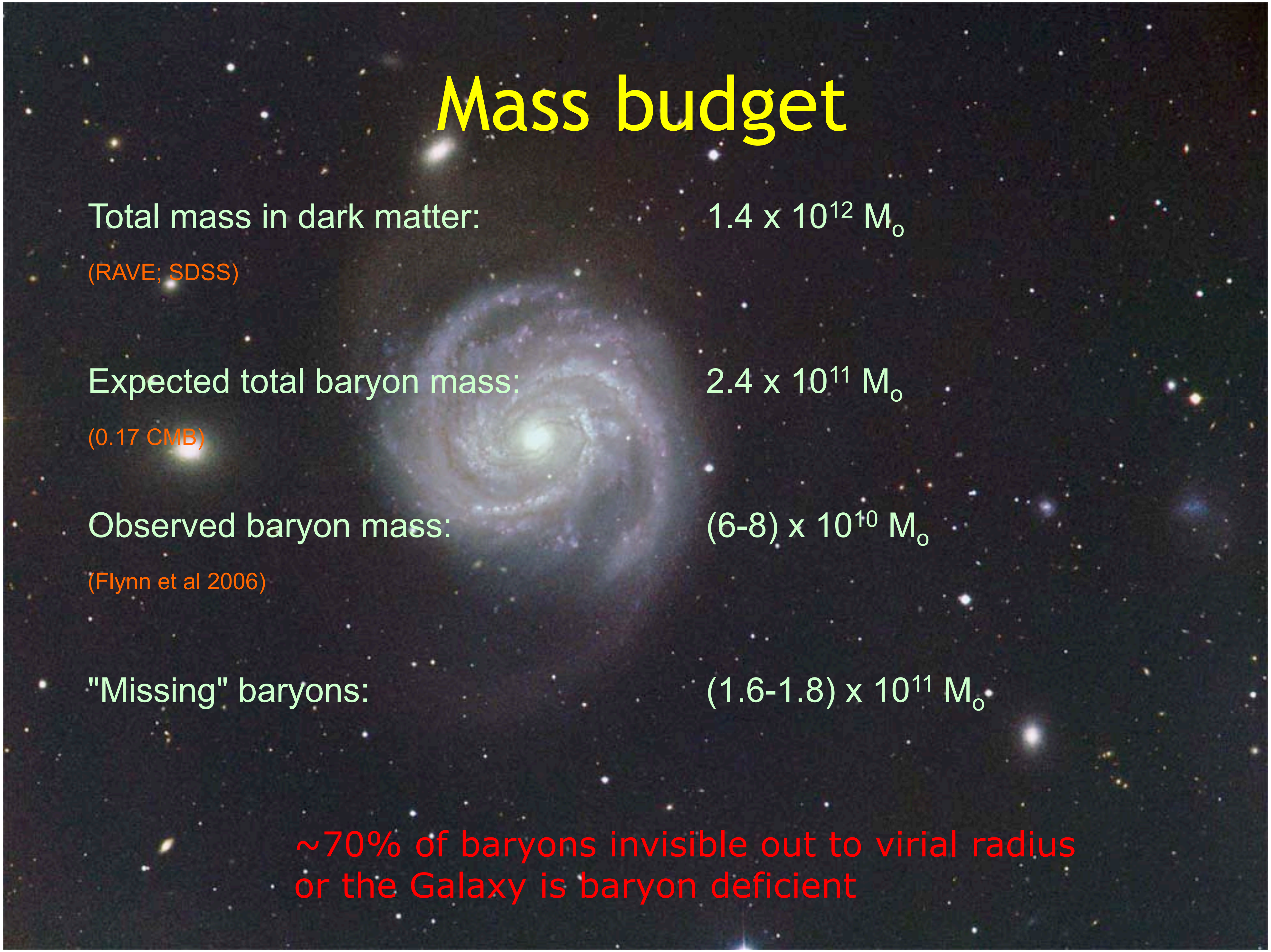
Blitz+ 1999 idea was attractive but…

Hα distances (JBH+ 1998-2002) and stellar absorption line distances show that most HVCs are within 50 kpc





HVC (> 90 km s^{-1}) & IVC (< 90 km s^{-1}) – Wakker et al. 2004



Mass budget

Total mass in dark matter: 1.4×10^{12} M_o

(RAVE; SDSS)

Expected total baryon mass: 2.4×10^{11} M_o

(0.17 CMB)

Observed baryon mass: $(6\text{-}8) \times 10^{10}$ M_o

(Flynn et al 2006)

"Missing" baryons: $(1.6\text{-}1.8) \times 10^{11}$ M_o

~70% of baryons invisible out to virial radius
or the Galaxy is baryon deficient

What evidence do we have that cool gas is broken down? **(JBH+ 2007: "a warm rain")**

1. It's easier to hide warm than cold gas (ionized HVCs)
2. Gas depletion in dwarfs (~250 kpc)
3. Magellanic Stream (~50 kpc)
4. Smith Stream (~20 kpc)
5. Accretion activity is concealed in the disk-halo interaction
6. **The story is incomplete** but GF, like most astro. processes, is inefficient

1. EUVX halo accreted via disk-halo interaction

WARM GAS AND IONIZING PHOTONS IN THE LOCAL GROUP

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Received 1999 January 14; accepted 1999 July 13; published 1999 August 16

1999

ABSTRACT

Several lines of argument suggest that a large fraction of the baryons in the universe may be in the form of warm ($T \sim 10^5$–10^7 K) gas. In particular, loose groups of galaxies may contain substantial reservoirs of such gas. Observations of the cosmic microwave background by *COBE* place only weak constraints on such an intragroup medium within the Local Group. The idea of a Local Group corona dates back at least 40 years (Kahn & Woltjer). Here we show that gas at $T \sim (2–3) \times 10^6$ K (the approximate virial temperature of the Local Group)—extremely difficult to observe directly—can in principle radiate a large enough flux of ionizing photons to produce detectable Hα emission from embedded neutral clouds. However, additional constraints on the corona—the most stringent being pulsar dispersion measures toward the Magellanic Clouds, and the timing mass—rule out an intragroup medium whose ionizing flux dominates over the cosmic background or the major Local Group galaxies. A cosmologically significant coronal gas mass could remain invisible to Hα observations. More massive galaxy groups could contain extensive coronae which are important for the baryon mass and produce a strong, local ionizing flux.

Subject headings: cosmic microwave background — diffuse radiation — intergalactic medium — Local Group

$$M(r) \approx 7 \times 10^{11} \left(\frac{r_0}{100\ \mathrm{kpc}}\right)^2 \left(\frac{r}{r_0}\right) \left(\frac{n_0 r_0 T_{\mathrm{keV}}}{10^{20}\ \mathrm{cm}^{-2}}\right) \left(\frac{T_{\mathrm{keV}}}{0.2}\right)^{-1} M_\odot$$

Limit set by COBE Compton y -parameter and quadrupole moment

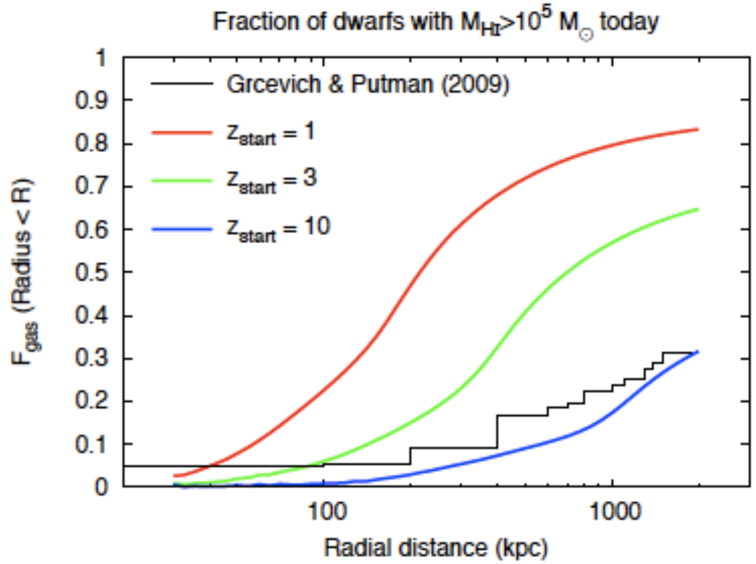
An EUVX halo is expected in the context of virial shock heating, is consistent with the timing mass, and the baryon inventory.

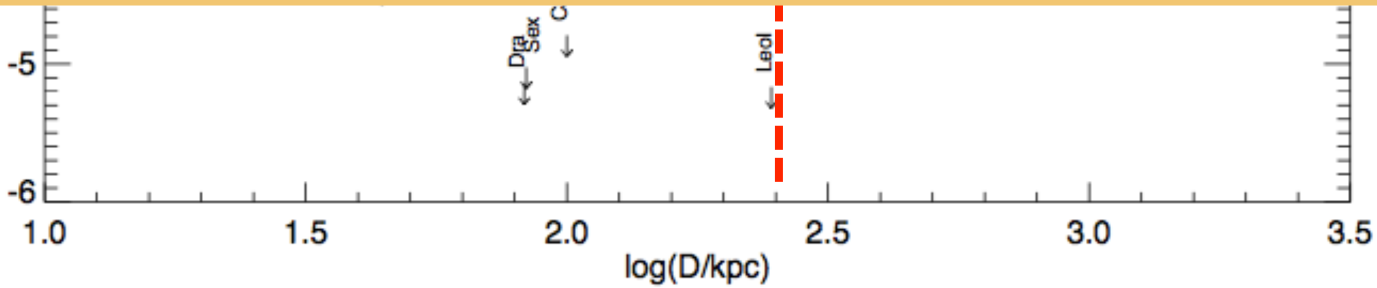
2. Local Group Dwarfs (excl. Magellanic System)

Gas Depletion in Local Group Dwarfs on ~250 kpc Scales

Nichols, M. & Bland-Hawthorn, J. 2011, ApJ, 732, 17

- A recent survey of the Galaxy and M31 reveals that more than 90% of dwarfs within 270 kpc are deficient in HI gas.
- *At such an extreme radius, the density of coronal halo gas is an order of magnitude too low to remove HI gas through ram pressure stripping.*
- Early star formation that is present in all dwarfs allows this gas to be heated, and more easily stripped even by this low density coronal gas as the dwarfs fall into the halo.
- Early infall and star formation times ($z = 3$–10) are required to reconcile the distribution of gas deficient galaxies and expected orbits from N-body simulations.





3. The Magellanic Stream

THE SOURCE OF IONIZATION ALONG THE MAGELLANIC STREAM

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To be submitted to ApJL

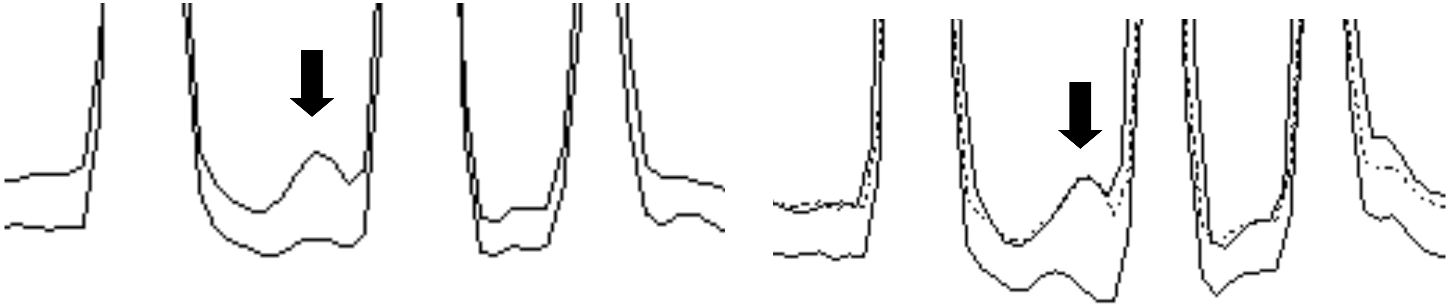
ApJ, 2007

ABSTRACT

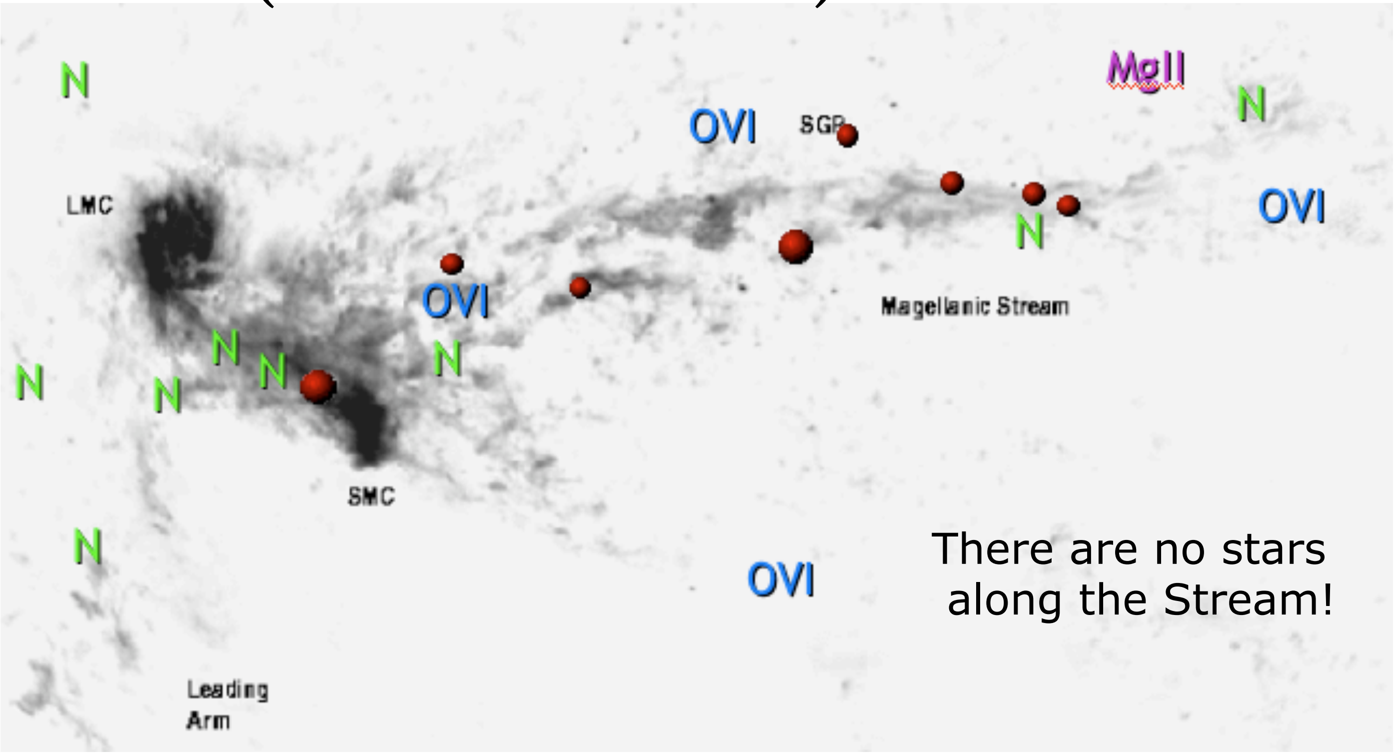
Since its discovery in 1996, the source of the bright Hα emission (up to 750 mR[1]) along the Magellanic Stream has remained a mystery. There is no evidence of ionising stars within the HI stream, and the extended hot halo is far too tenuous to drive strong shocks into the clouds. We now present a hydrodynamical model that explains the known properties of the Hα emission and provides new insights on the lifetime of the Stream clouds. The upstream clouds are gradually disrupted due to their interaction with the hot halo gas. The clouds that follow plough into gas ablated from the upstream clouds, leading to shock ionisation at the leading edges of the downstream clouds. Since the following clouds also experience ablation, and weaker Hα (100−200 mR) is quite extensive, a disruptive cascade must be operating along much of the Stream. In our model, the clouds are evolving on timescales of 100−200 Myr, such that the Stream must be replenished by the Magellanic Clouds at a fairly constant rate. The ablated material falls onto the Galaxy as a warm drizzle which suggests that diffuse ionized gas at 10^4K may be an important constituent of galactic accretion. The observed Hα emission provides a new constraint on the rate of disruption of the Stream and, consequently, the infall rate of metal-poor gas onto the Galaxy. When the ionized component of the Stream is fully accounted for, the rate of gas accretion is 0.4 $M_\odot$ yr^{-1}, roughly twice the rate deduced from HI observations alone.

Subject headings: Galaxies: interaction, evolution, Magellanic Clouds – shock waves – instabilities – hydrodynamics

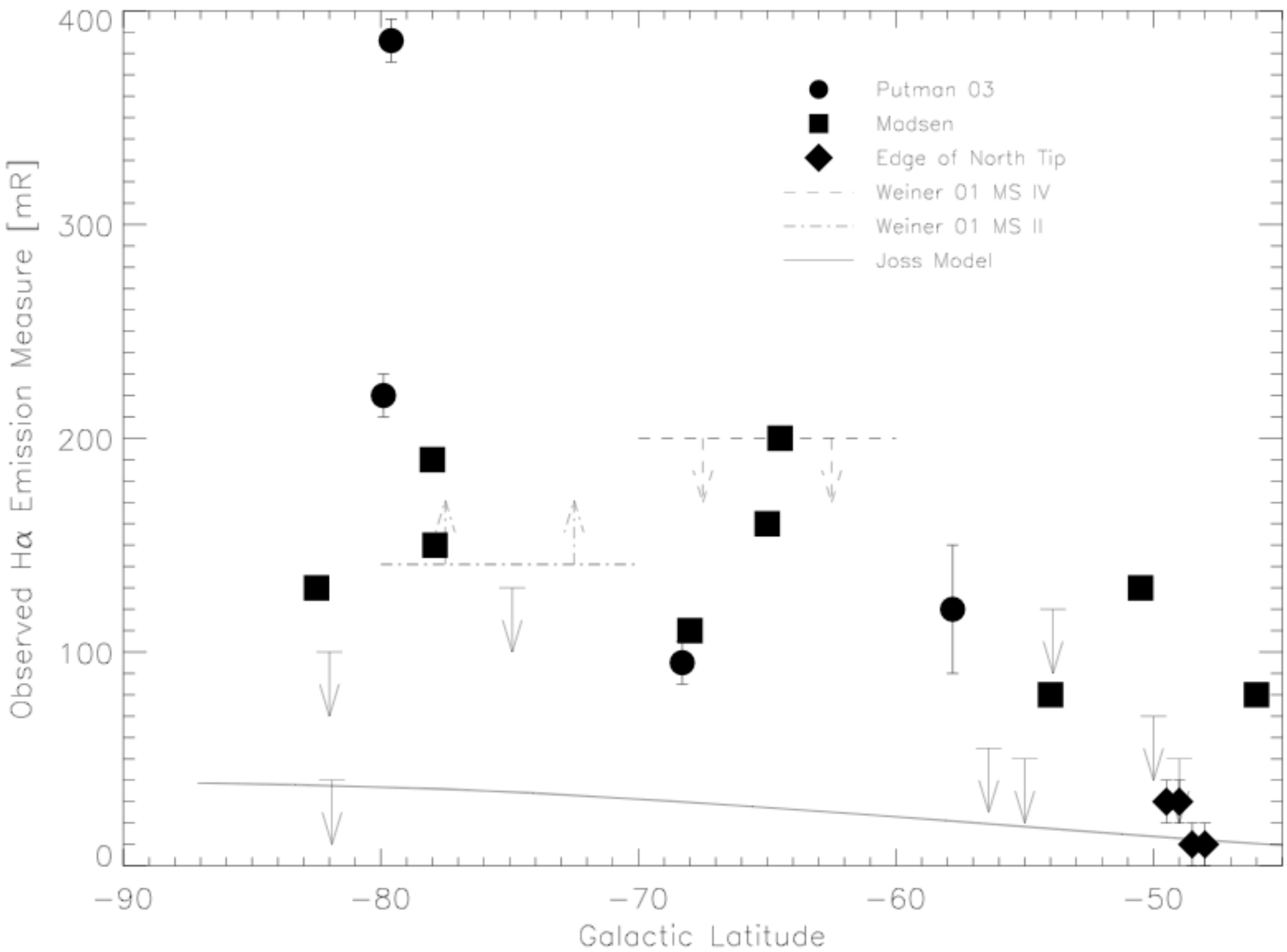
Hα detections along the Magellanic Stream



Narrow line emission (25-45 km s^{-1} FWHM)

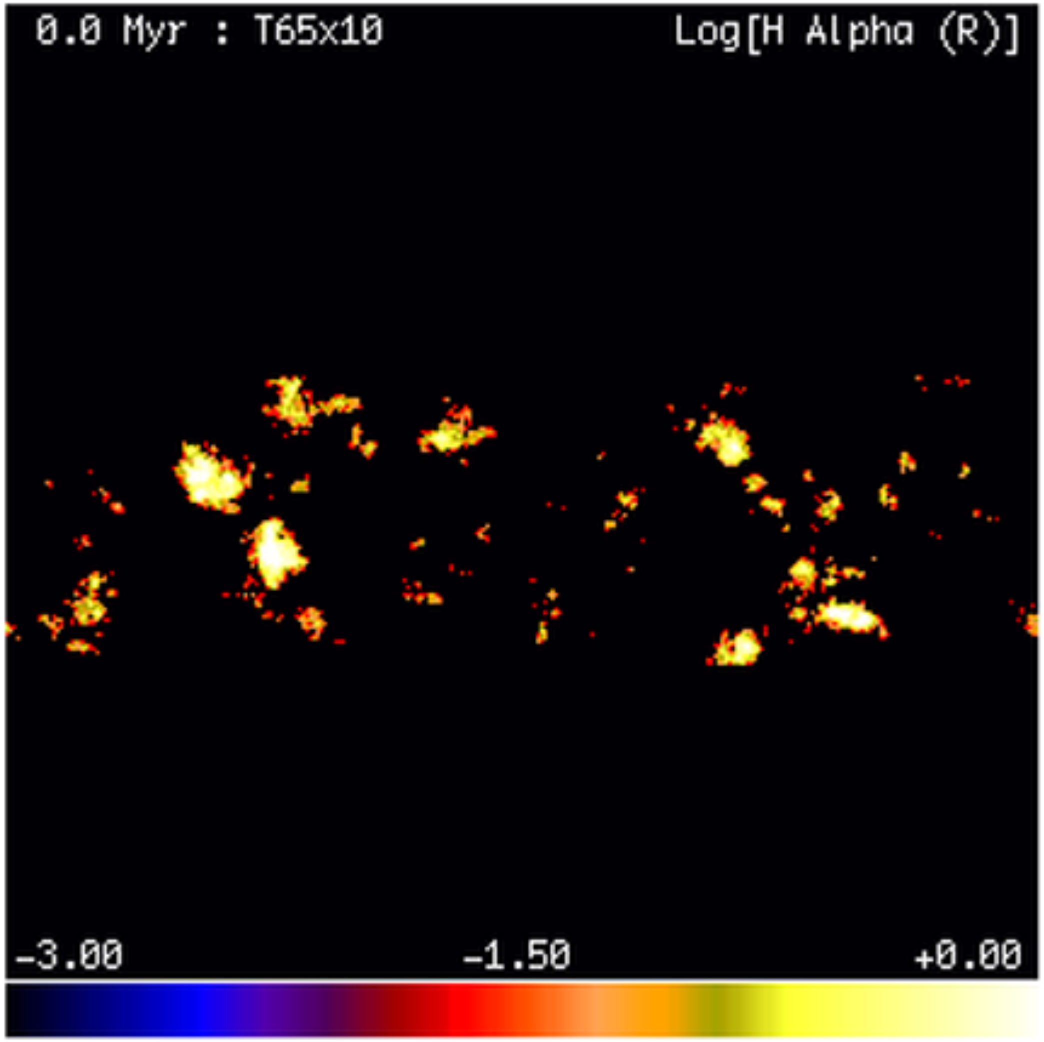


G. Madsen compilation



Bland-Hawthorn (Bologna 2011)

Fractal clouds disrupted by KH



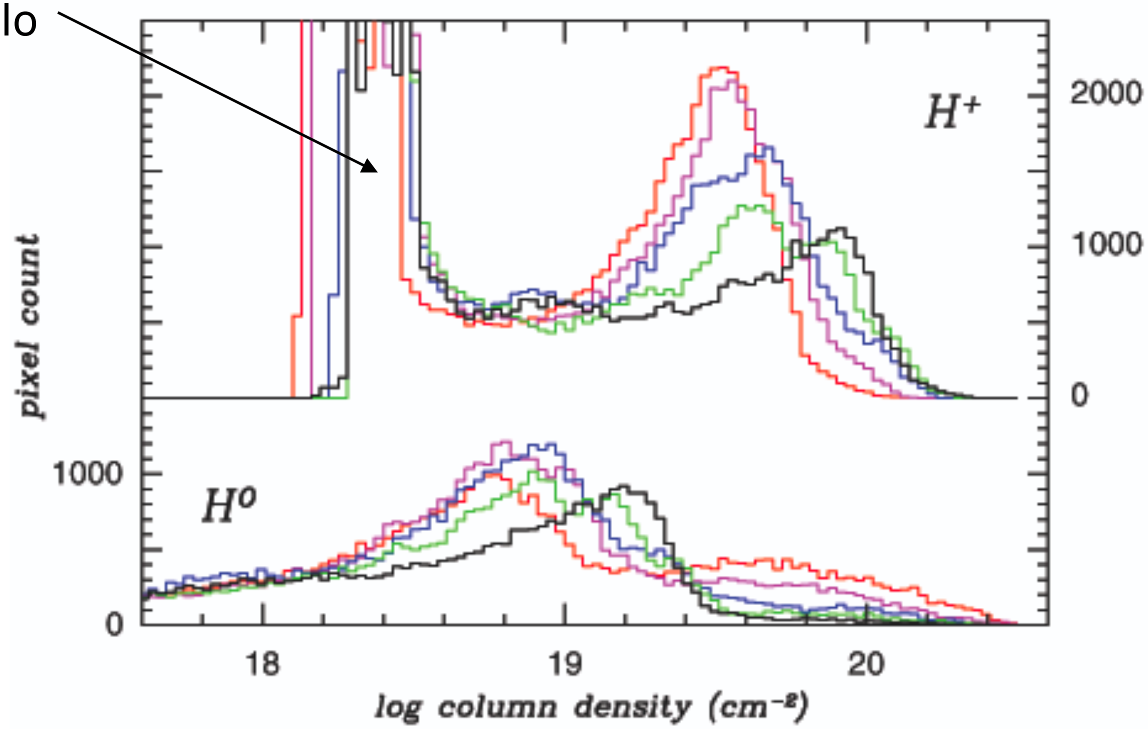
JBH et al (2007), ApJ

Conversion of HI to H^+

Shock induced ionization rate = 1.5 x 10^{47} phot/s/kpc

or about 0.5 M_o/yr along the entire Stream

X-ray halo



Time since onset of cascade:

70 Myr

120 Myr

170 Myr

220 Myr

270 Myr

Marseille 2007

4. Smith Stream

L22 LOCKMAN ET AL. Vol. 679

1644 NICHOLS & BLAND-HAWTHORN Vol. 707

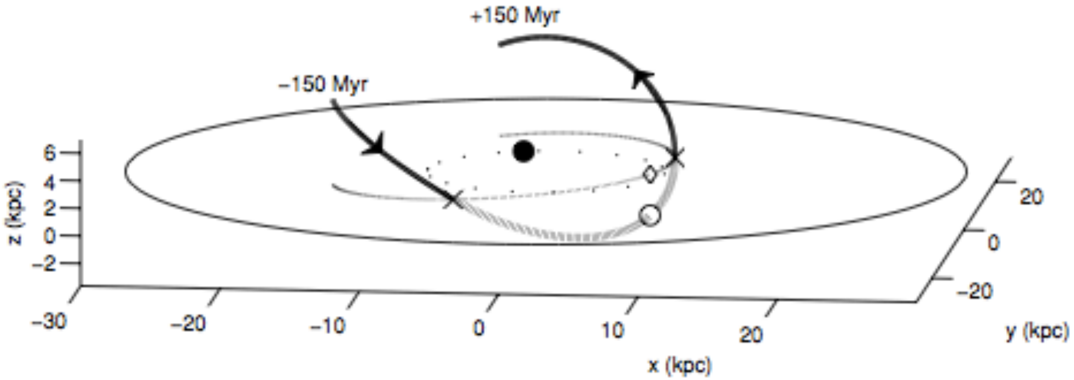


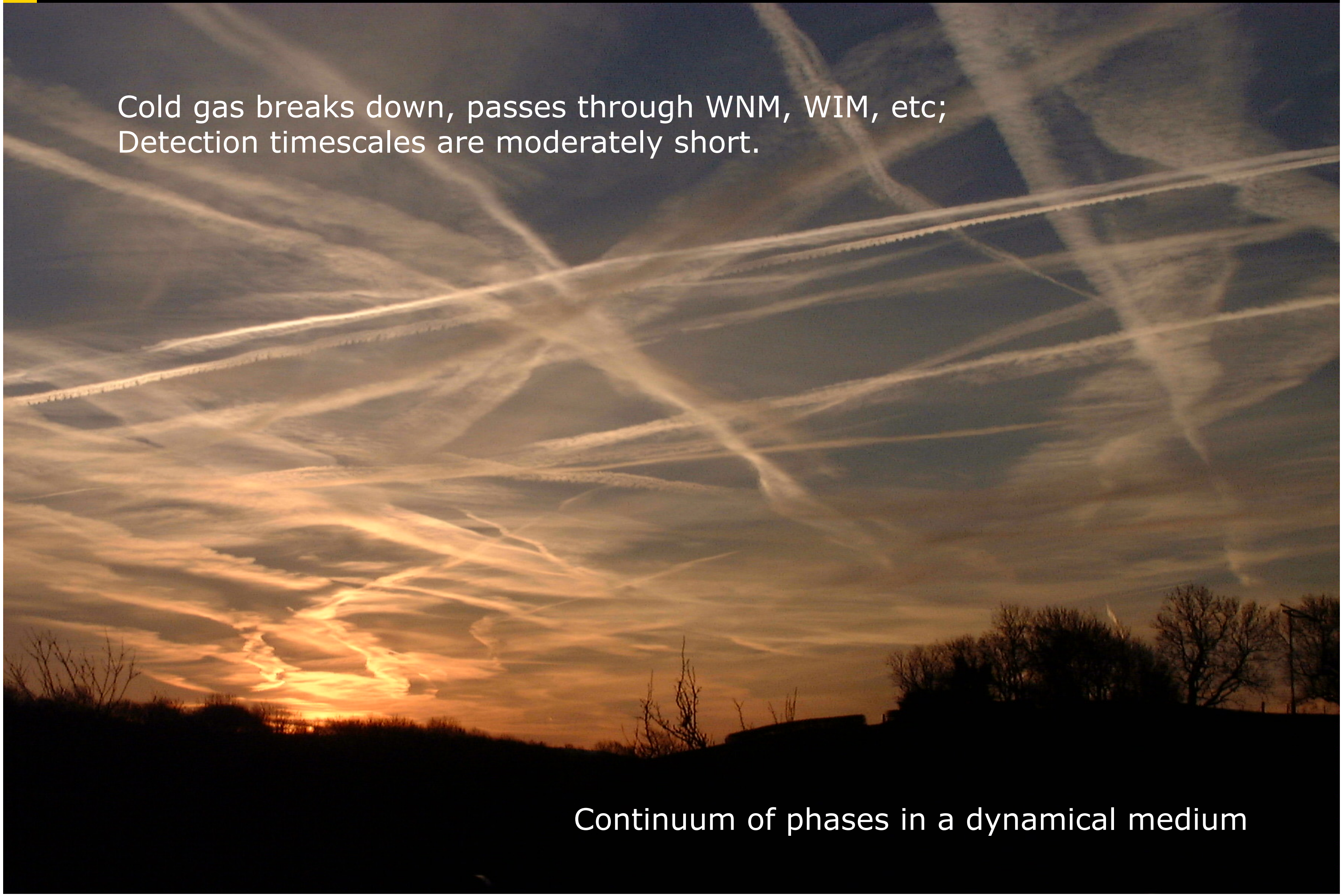
Figure 3. Orbit of the Smith Cloud, calculated using the potential from Wolfire et al. (1995). The current position is represented by an unfilled circle and the Smith Cloud is travelling in the direction of the arrows, with heights below the disk represented by a dotted line. The Sun's position is shown as a filled circle on the Solar Circle. The thin dotted line represents the projection of the Smith Cloud onto the disk. The disk is represented by a solid line at 30 kpc.

longitude and toward the plane and that it is interacting with the Galactic ISM. Arrows mark the tracks of the velocity-position slices of Figs. 2 and 3.

FIG. 3.—GBT H I velocity-position slice through the major axis of the Cloud at the location of the arrows in Fig. 1. Marks on the vertical axis are every

$$t_{evap} \approx 60\ (n_c / 1\,cm^{-3})(r_c / 30\,pc)^2 (T_m / 2\times10^6 K)^{-2.5} (\ln C/30)\ \ Myr$$

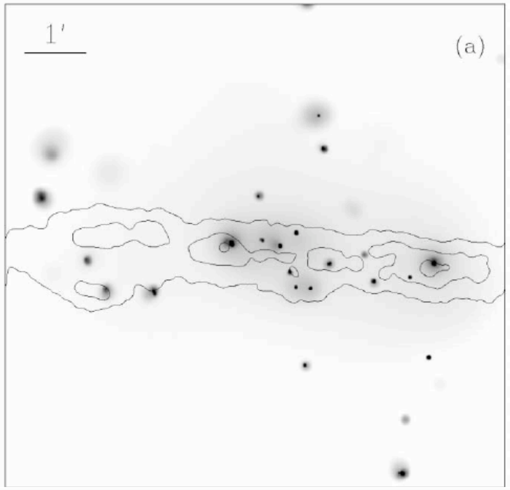
What is the extended halo?

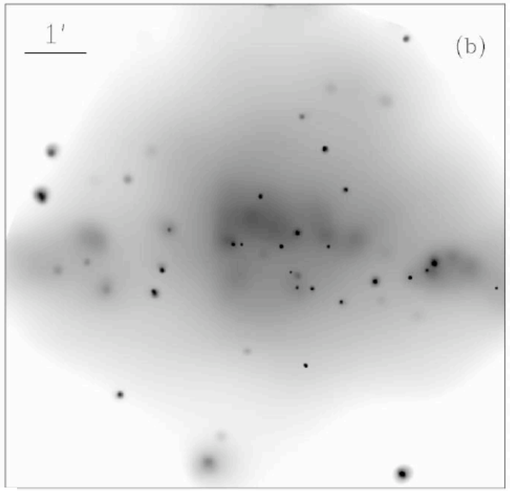


Cold gas breaks down, passes through WNM, WIM, etc;
Detection timescales are moderately short.

Continuum of phases in a dynamical medium

Disk-halo interactions are strong



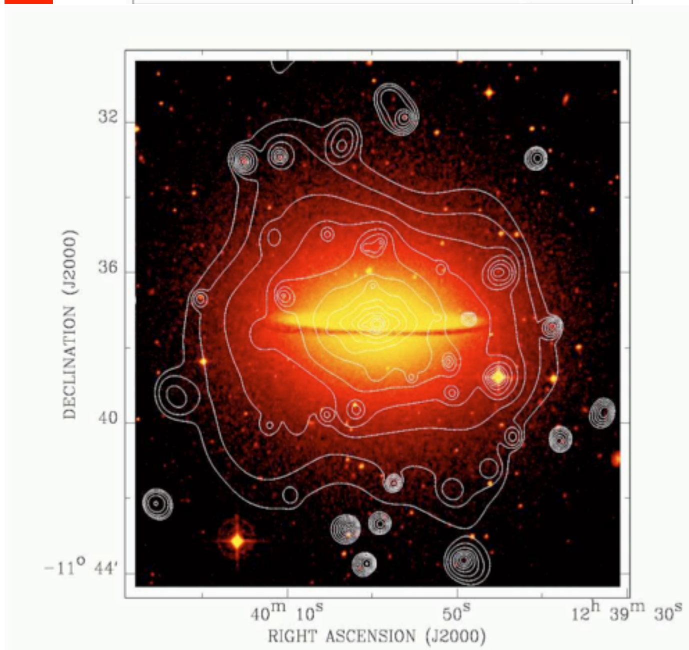


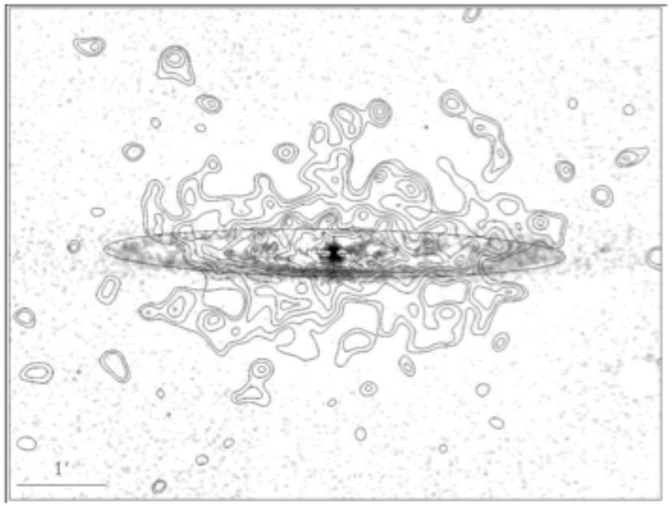
NGC 4631

$L_x \sim 10^{39.5}$ erg/s

Chandra/ACIS3

Wang+ 2001





NGC 4594

$L_x \sim 10^{39}$ erg/s

Chandra/ACIS3

Just in case there are doubts…

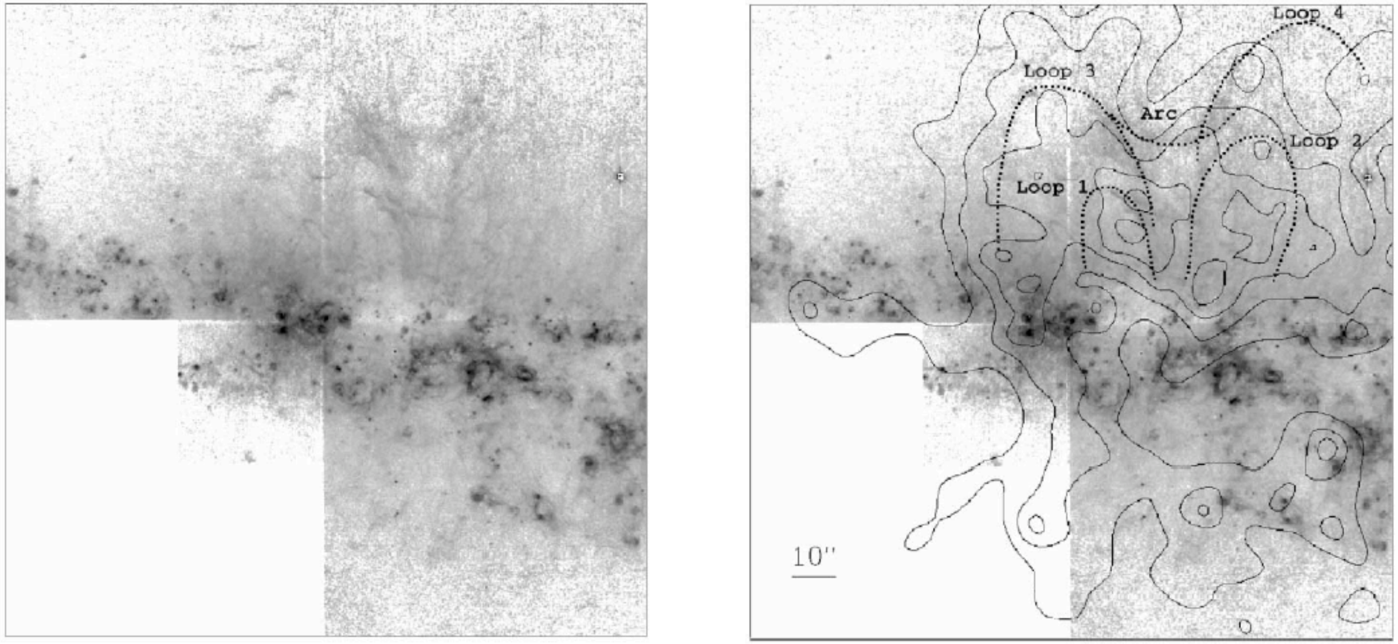


FIG. 5.—*HST* WFPC2 Hα image of the central 5.5 × 5.5 kpc region of NGC 4631 (Fig. 2*b*). The high-level X-ray contours in Fig. 2 are plotted, and a few tentatively identified Hα-emitting loops are outlined in the right-hand panel.

NOTE: Disk-halo interaction ~ 5 M_o yr^{-1} is a problem for detecting gas accretion directly across the optical disk **unless** we select disks in the quiescent phase… otherwise accretion is mixed up with recycling (e.g. Bologna work; JBH 2009).

Summary and Speculation

Galaxy formation is a very inefficient process

- 10% collapsed form (galaxies/clusters)
- 90% still in the IGM (various phases)

Most of the accretion and feedback happened early on.

ΛCDM

While successful on the largest scales, ΛCDM struggles in regions of high density and high density contrast:

Overcooling: predicted cosmic fraction of cooled baryons is larger than observed; too many low mass gals predicted

Disk angular momentum: angular momentum loss is too high, disk scale lengths are too small

Halo density profiles: too centrally concentrated

Dark satellites: too many satellites predicted in Local Group

The fact that Λ**CDM** demands feedback is no bad thing.

The real universe is rife with feedback processes across the hierarchy.