Galaxies in the Cosmic Web: from Voids to Clusters

How does gas get into and out of galaxies

Does the gas reservoir and distribution change with redshift?

The big question is, does galaxy growth depend on its location in the large scale structure?

We know the large scale distribution of galaxies quite well.

Theoretically:

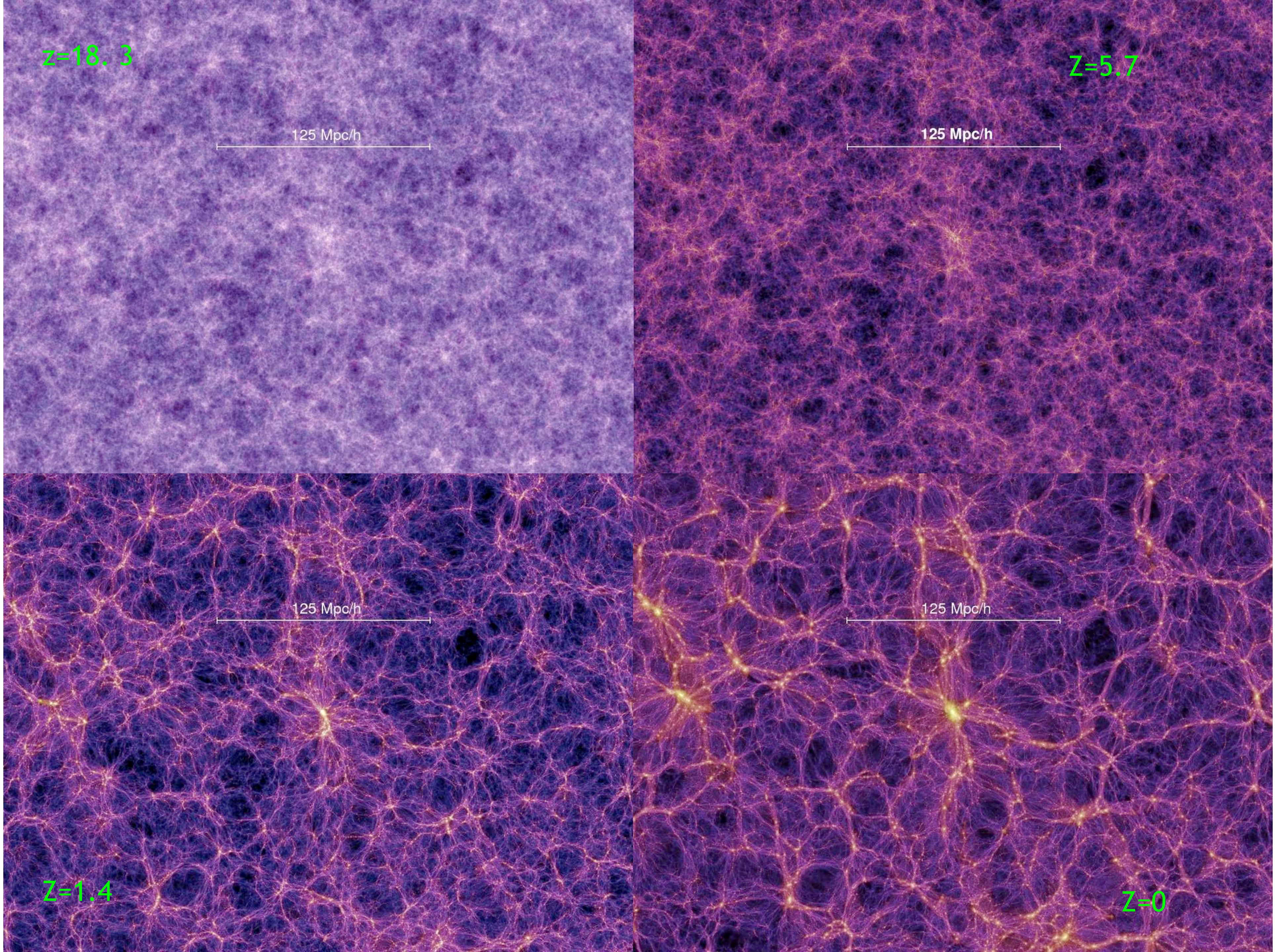
from cosmological simulations such as millennium simulation

Observationally:

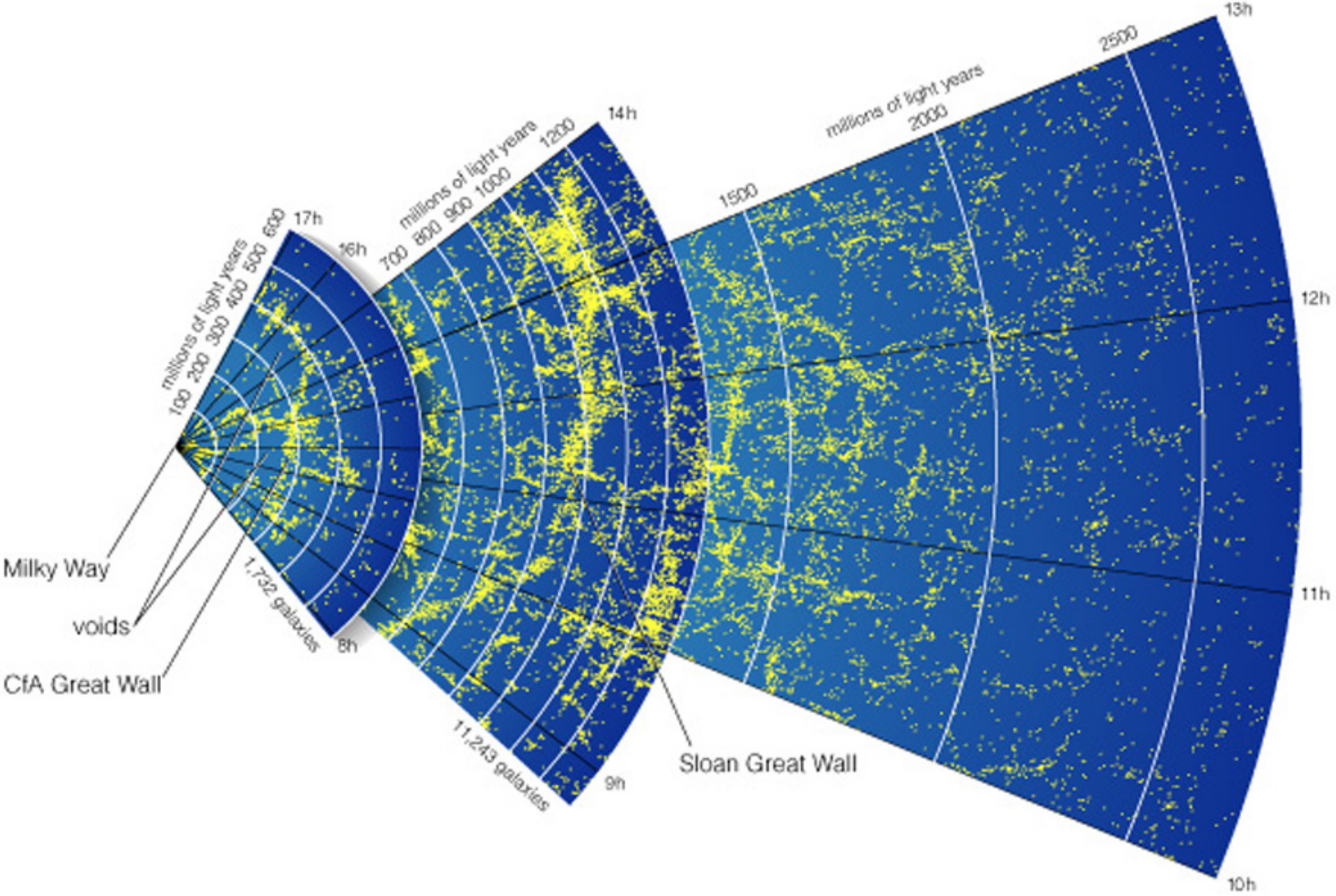
from wide area surveys (e.g. SDSS) and deep surveys (e.g.2DF)

We already know galaxy evolution depends on local density, morphology density relation.

simulations



Observations



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***

We think we understand pretty well how dark matter large scale structure grows .

The physics of galaxy formation is more complicated.

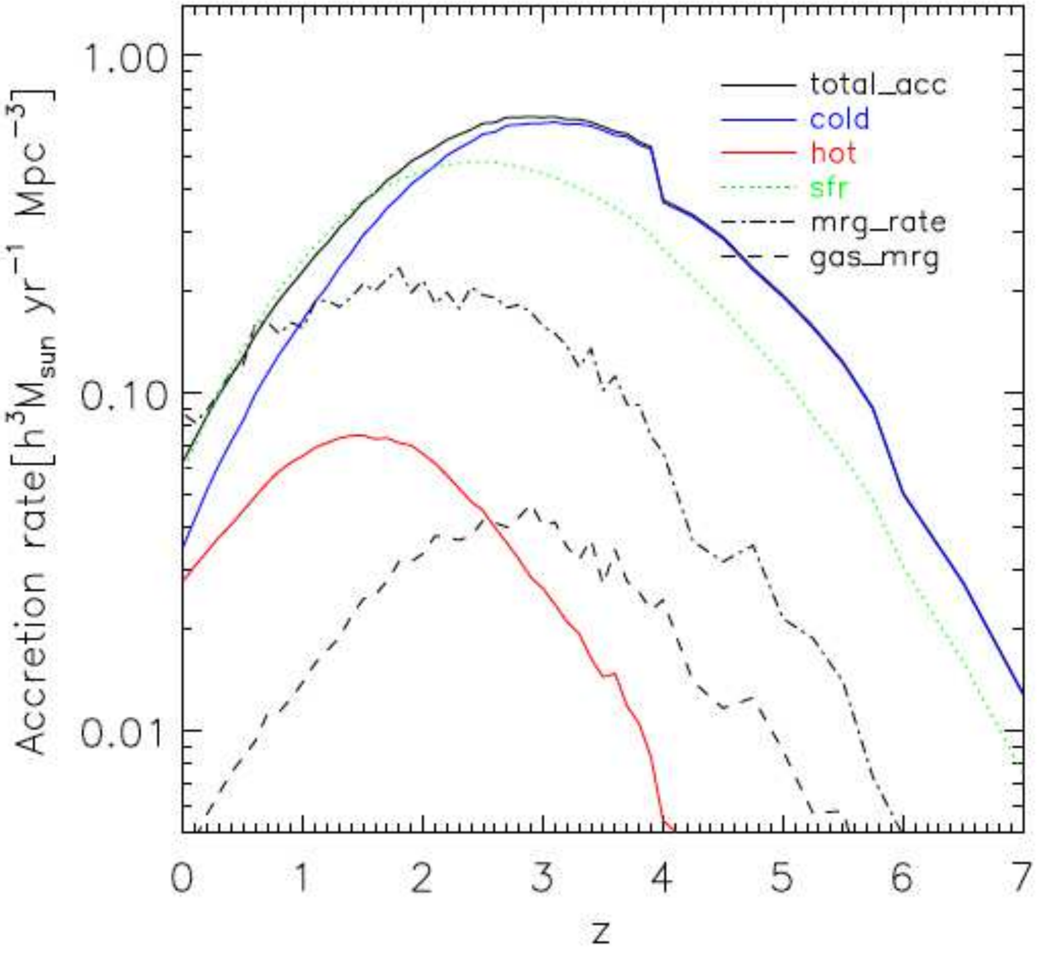
Hierarchical galaxy formation in "standard" LCDM used to make galaxies
grow by merging. The importance of gas accretion was underestimated, and the physics misunderstood.

There are two ways for galaxies to grow

1) Merging with smaller galaxies can add gas and stars

2) Smooth accretion of cool gas dominates galaxy growth at z>1.

Keres et al 2005, Dekel and Birnboim 2006, Binney 1977

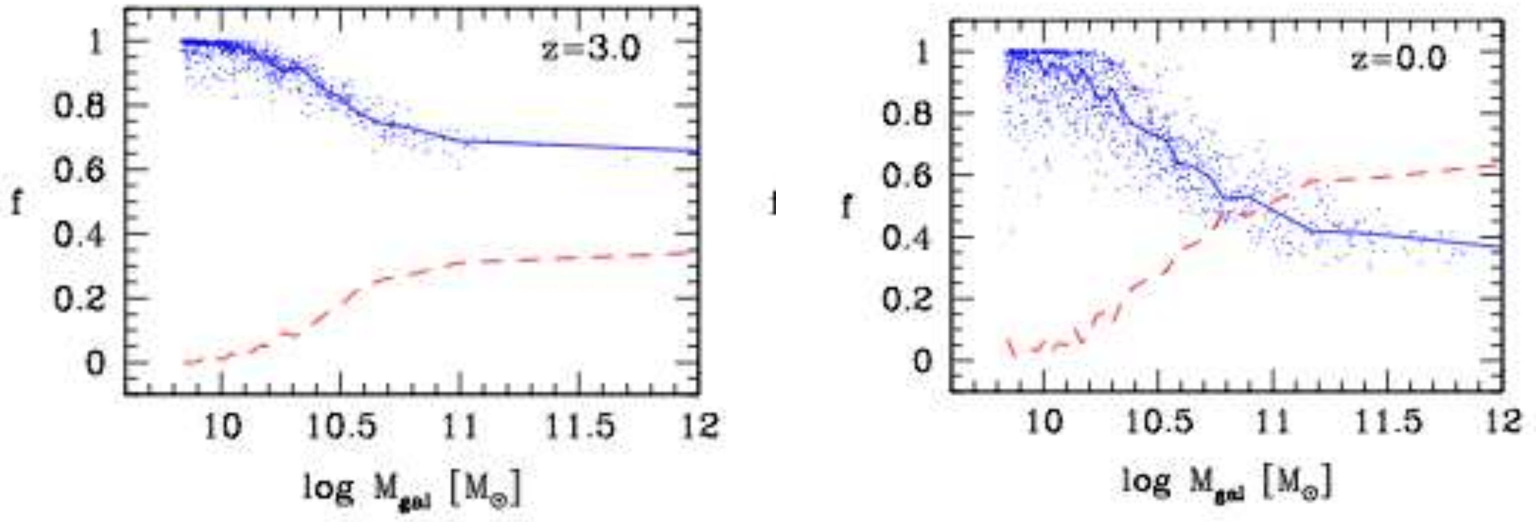


Many recent papers, much debate, new code Arepo (Springel, Hernquist and collaborators)

At high z, gas accretion dominates, even at low z it is important.

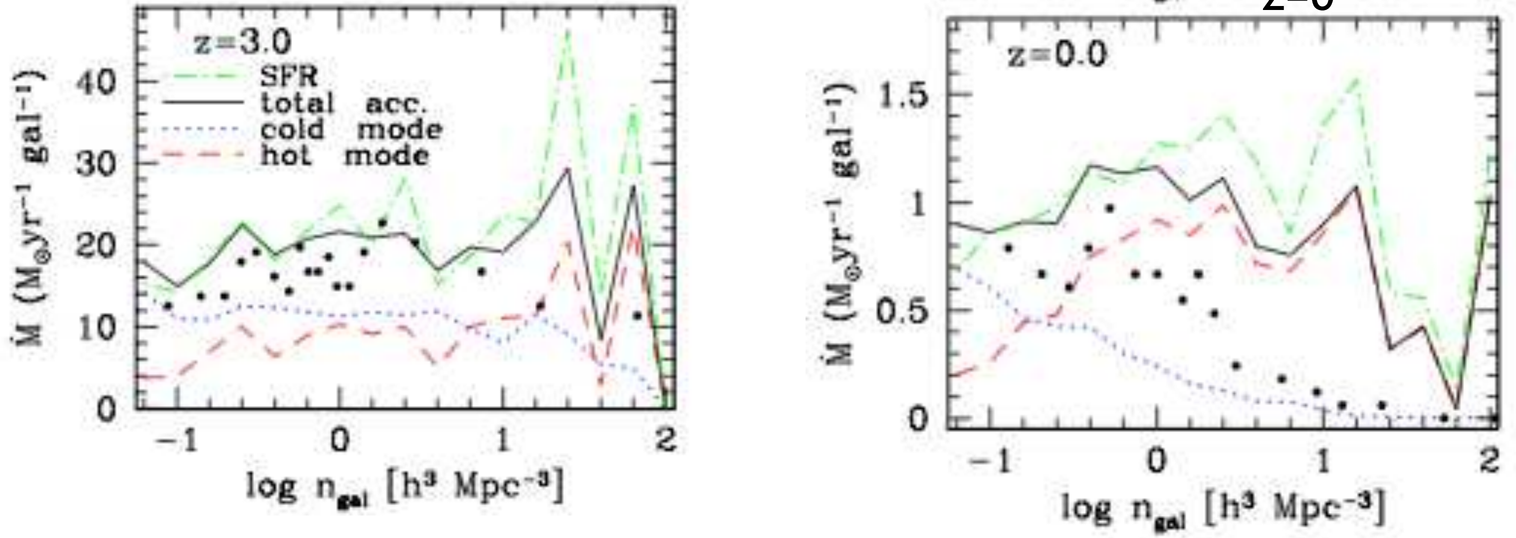
Mode of accretion depends on halo mass

Keres et al 2005



Mode of accretion depends on local galaxy density

In low galaxy density, gas accretion still dominates at z=0



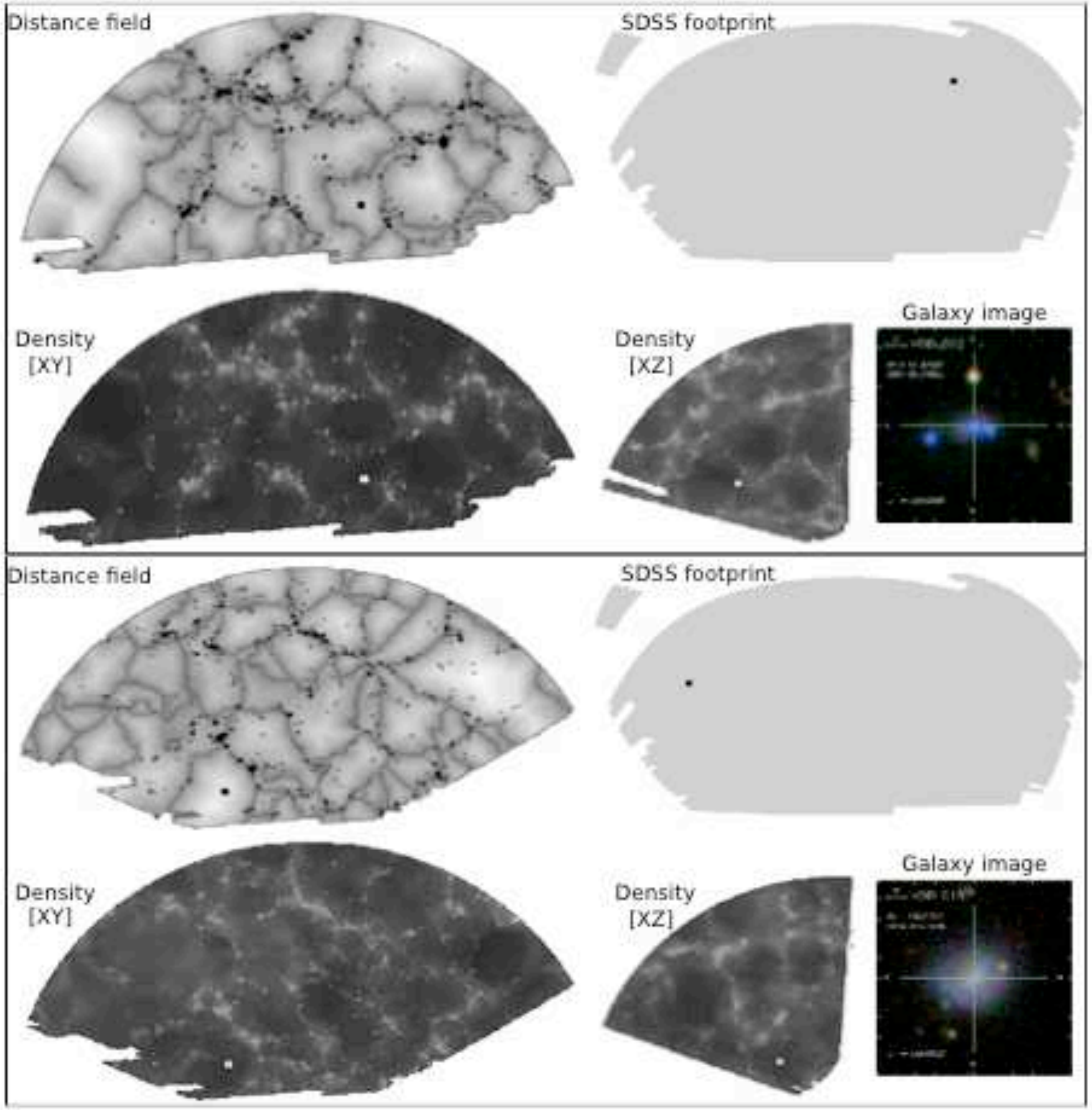
First HI imaging survey of VOID galaxies using SDSS

Kathryn Kreckel (Stanonik), Erwin Platen, Burcu Beygu, Miguel Aragon-Calvo, JvG, van de Weygaert, van der Hulst, Peebles, Kovacs, Yip

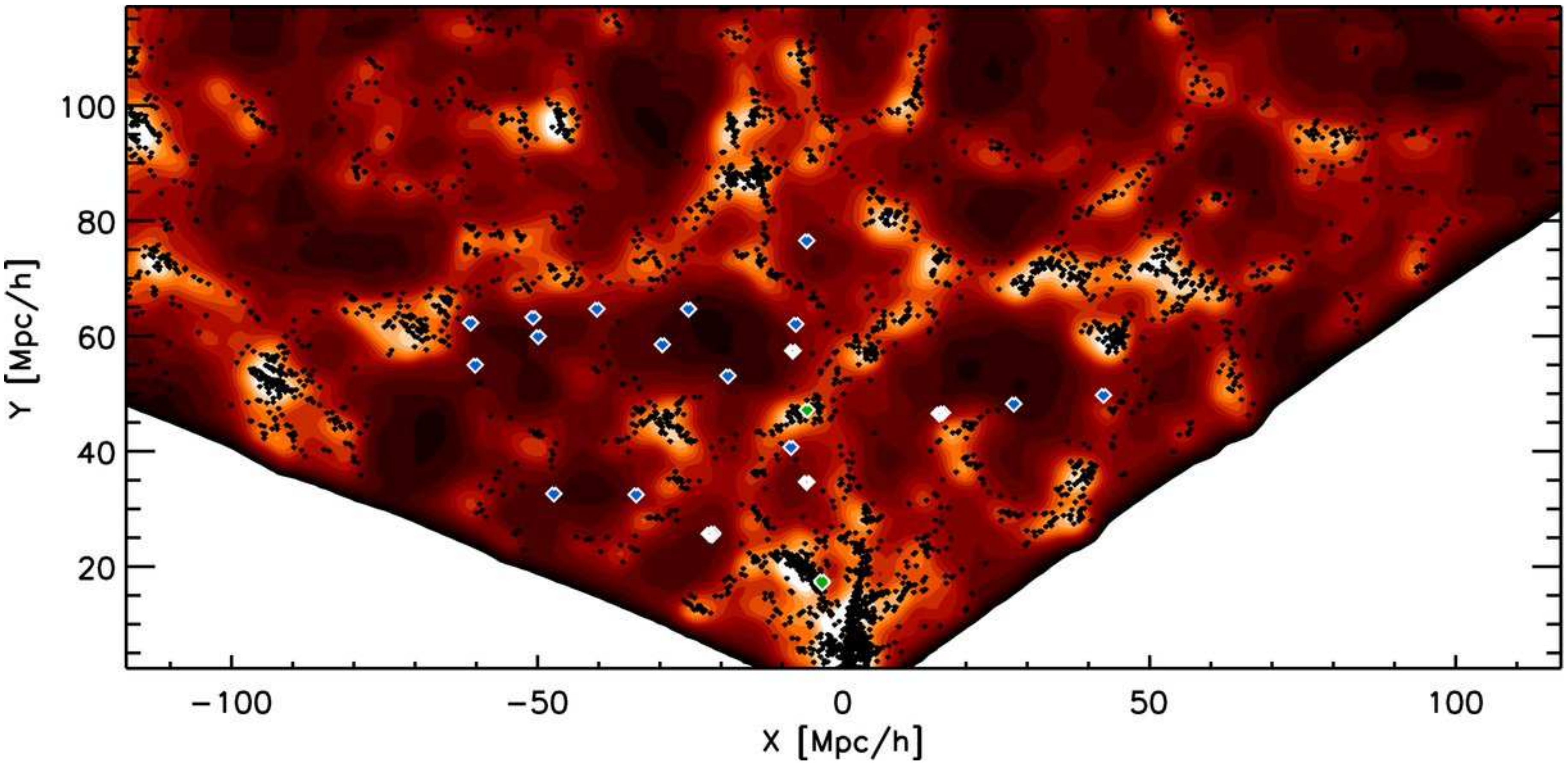
Select galaxies in the deepest under densities of SDSS selected voids

Use a geometric method (Voronoi tesselation) to describe large scale density field in SDSS, without making assumptions about the shapes of voids. Use the watershed void finder to find deepest underdensities.

Use WSRT backend that probes large instantaneous velocity range to make HI observations.


Distance field
SDSS footprint
Density [XY]
Density [XZ]
Galaxy image
Distance field
SDSS footprint
Density [XY]
Density [XZ]
Galaxy image

Using a Voronoi tessellation to define density field and the watershed void finder to find the deepest under densities, we find a sample of 60 galaxies in the voids.



Reconstructed density field, black SDSS, diamond void galaxies, green control sample

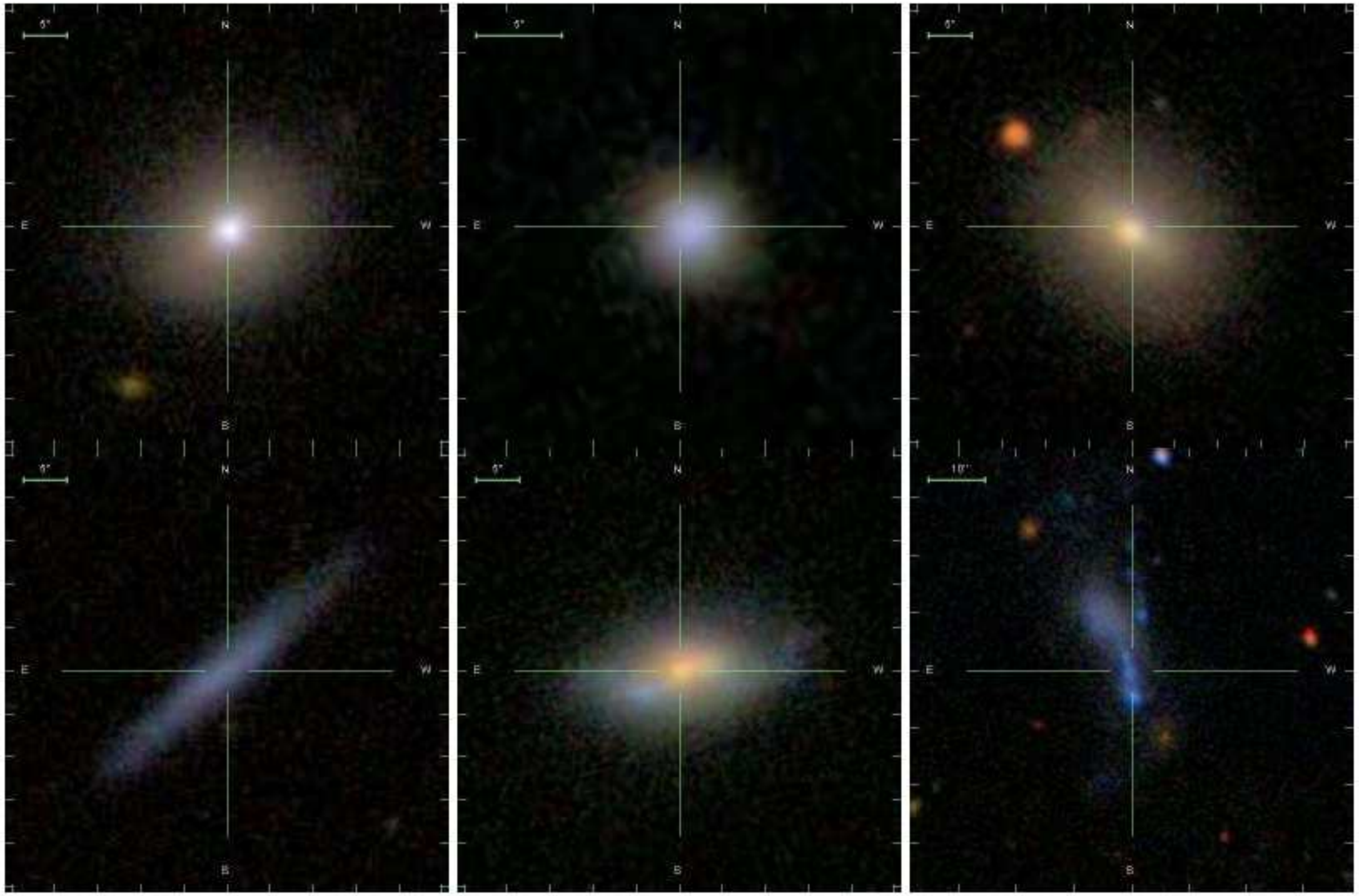
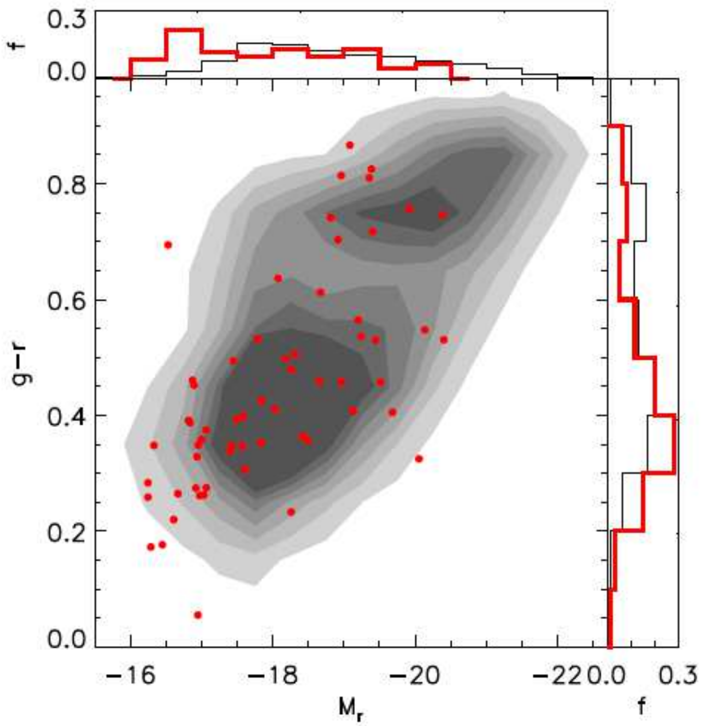


Fig. 4.—: The VGS includes a range of stellar morphologies, with elliptical (VGS_24, top left; VGS_41, top center), lenticular (VGS_05, top right), bulge free (VGS_10, bottom left), bulge dominated (VGS_34, bottom center), and irregular (VGS_17, bottom right) galaxies.

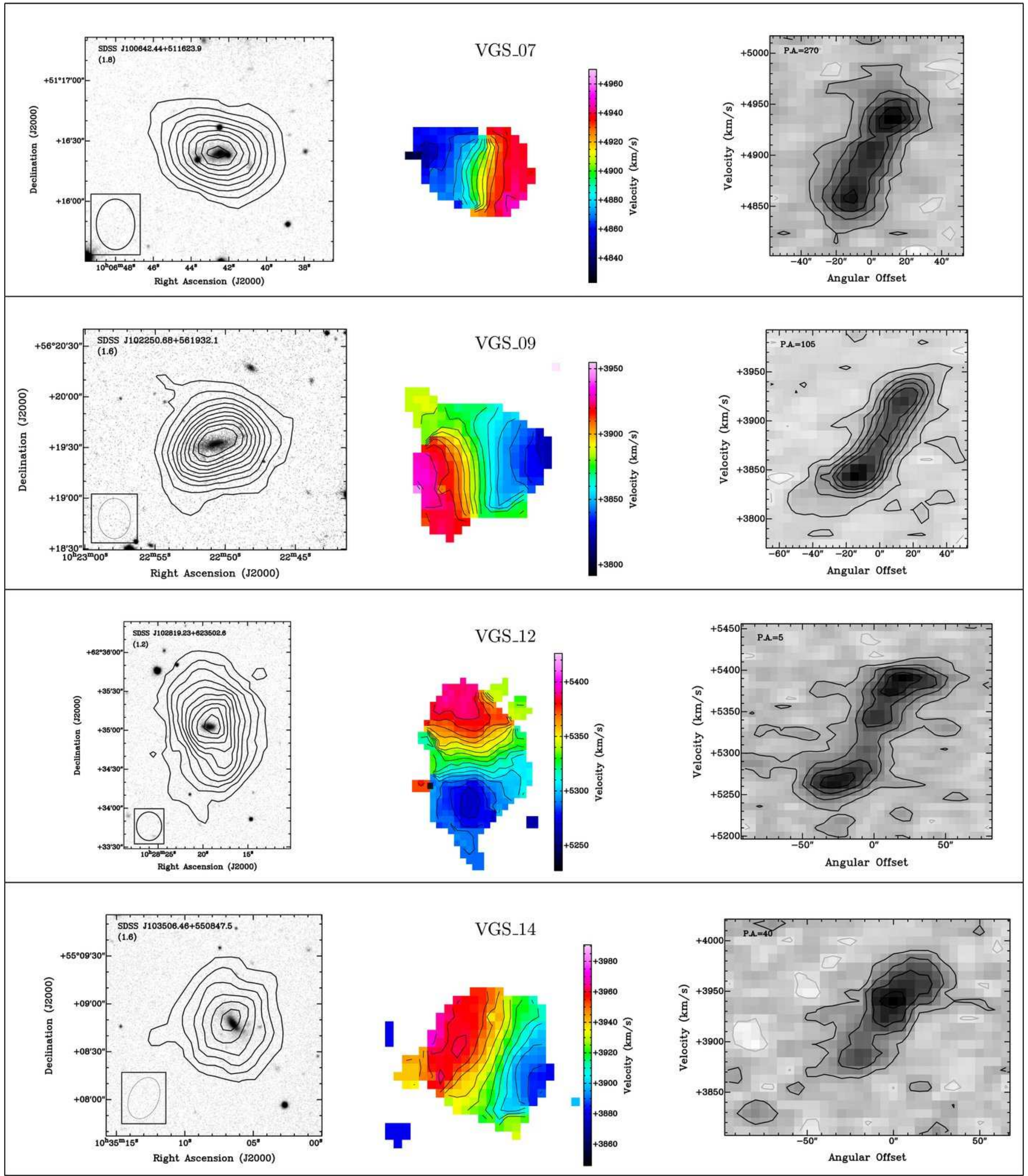


Red: void galaxies
Grey: a magnitude-limited sample of galaxies selected from SDSS in similar redshift range 0.01 <z <0.03.

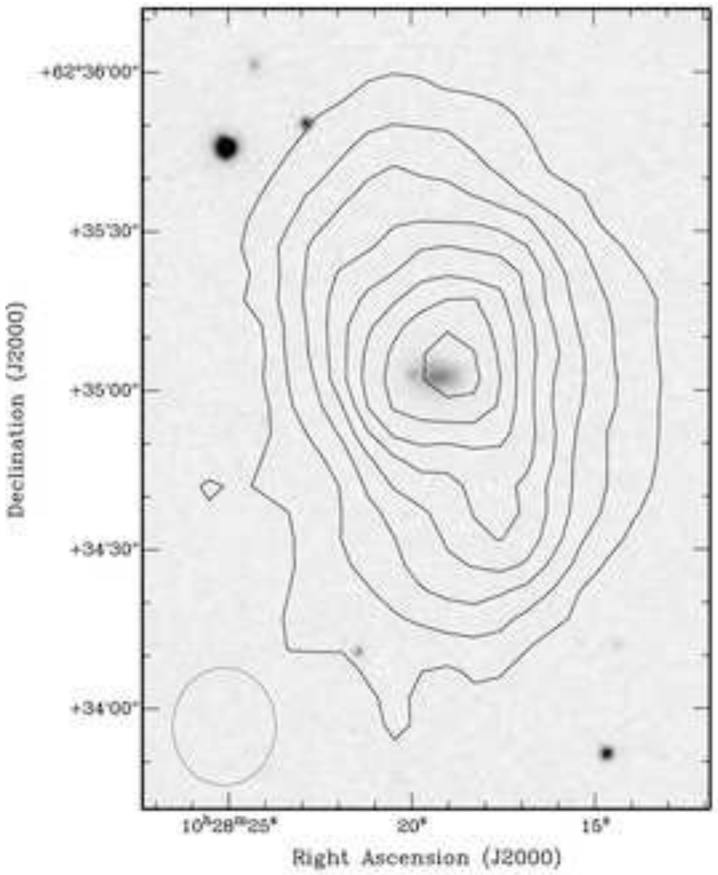
Void galaxies are typically faint and blue, but do span whole color range.
There are no void galaxies with stellar mass greater than $3x10^{10}$ M_{sun}.

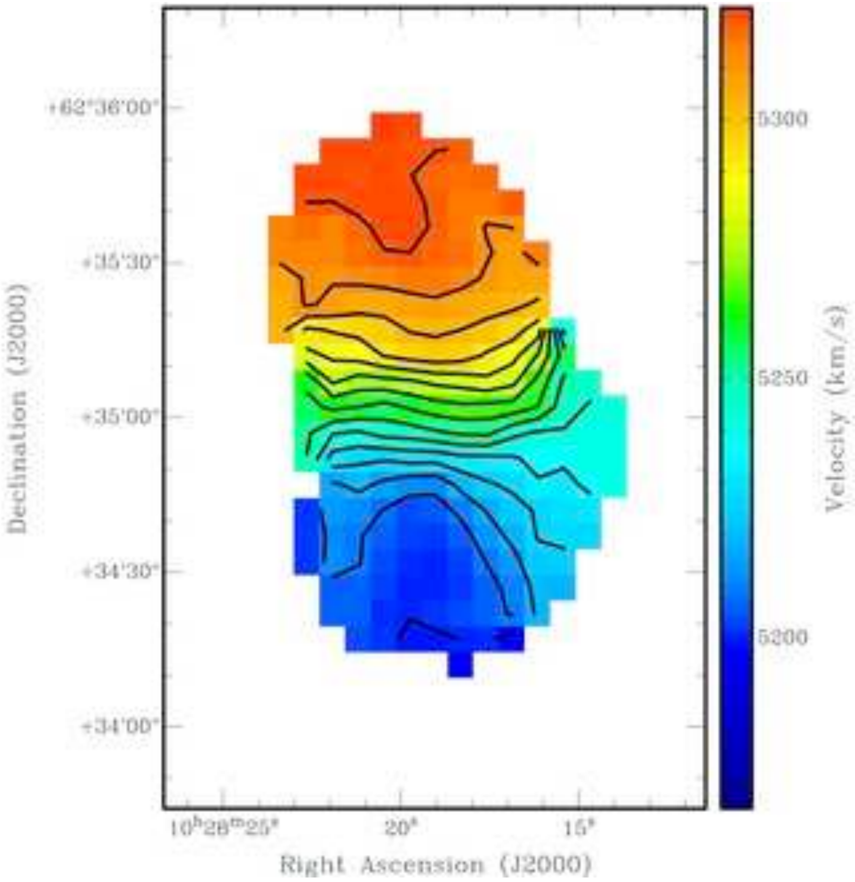
Contours HI
Greyscale optical

Void galaxies have large HI envelopes.



The void galaxy survey

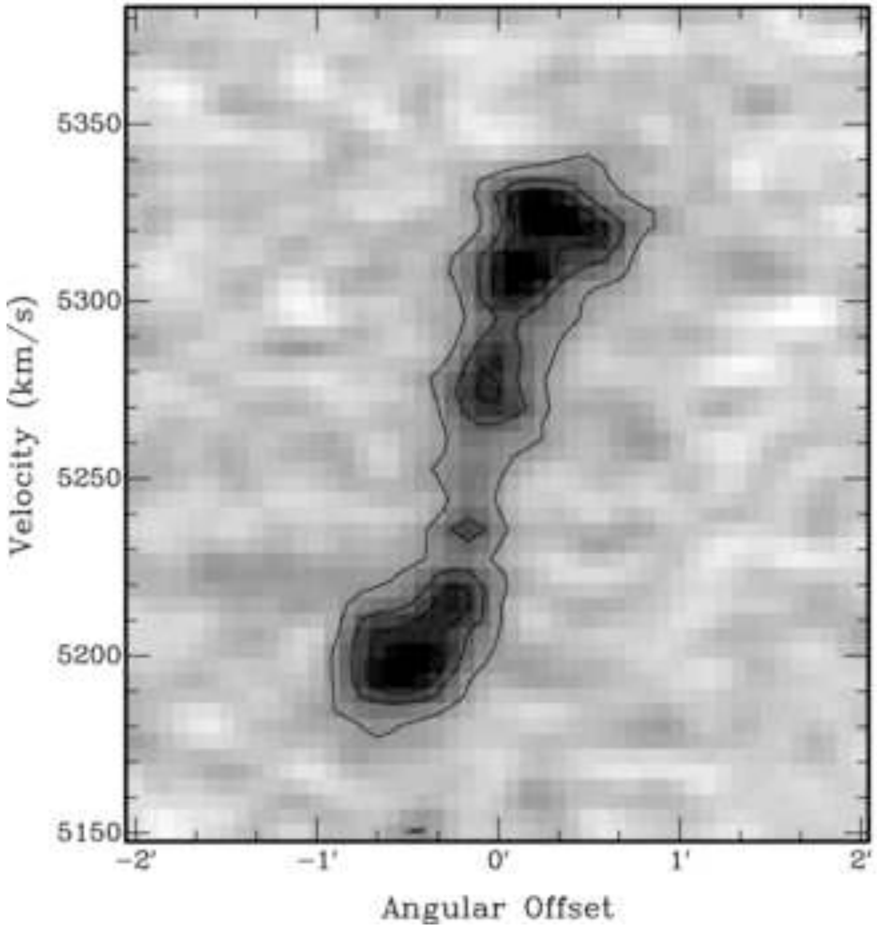


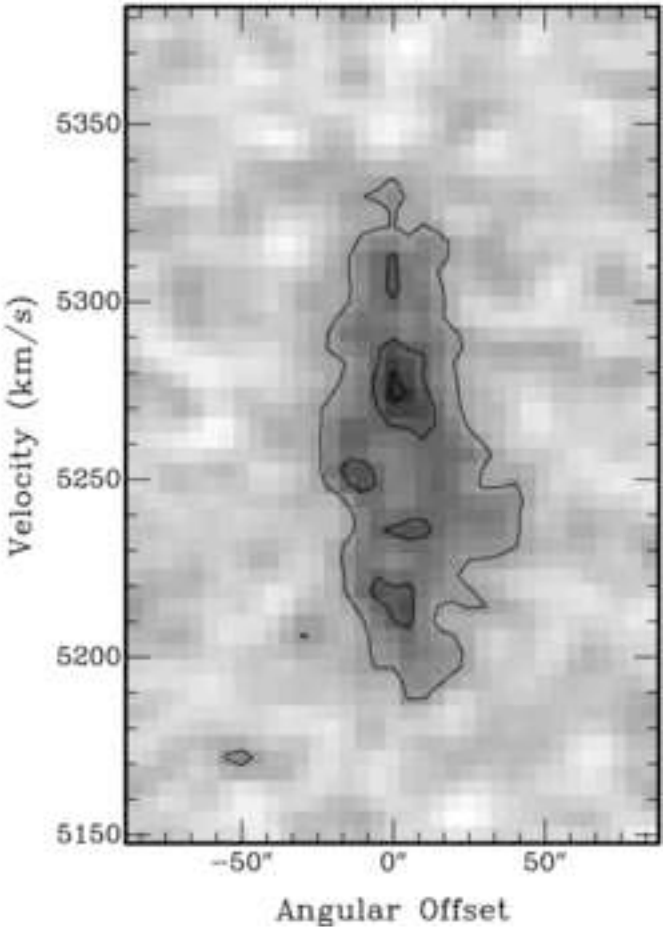


A polar disk

Stanonik et al 2009

Kreckel et al 2012

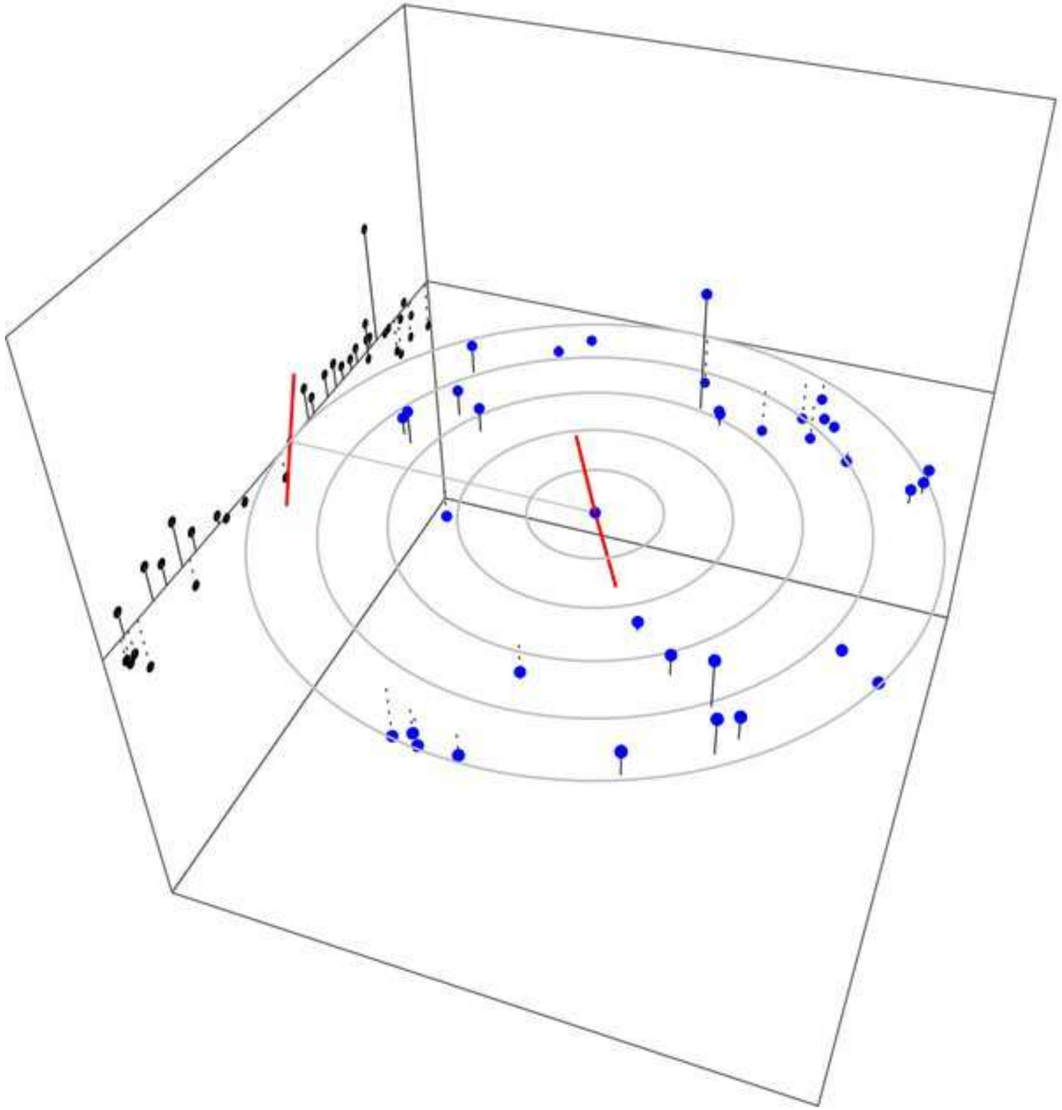




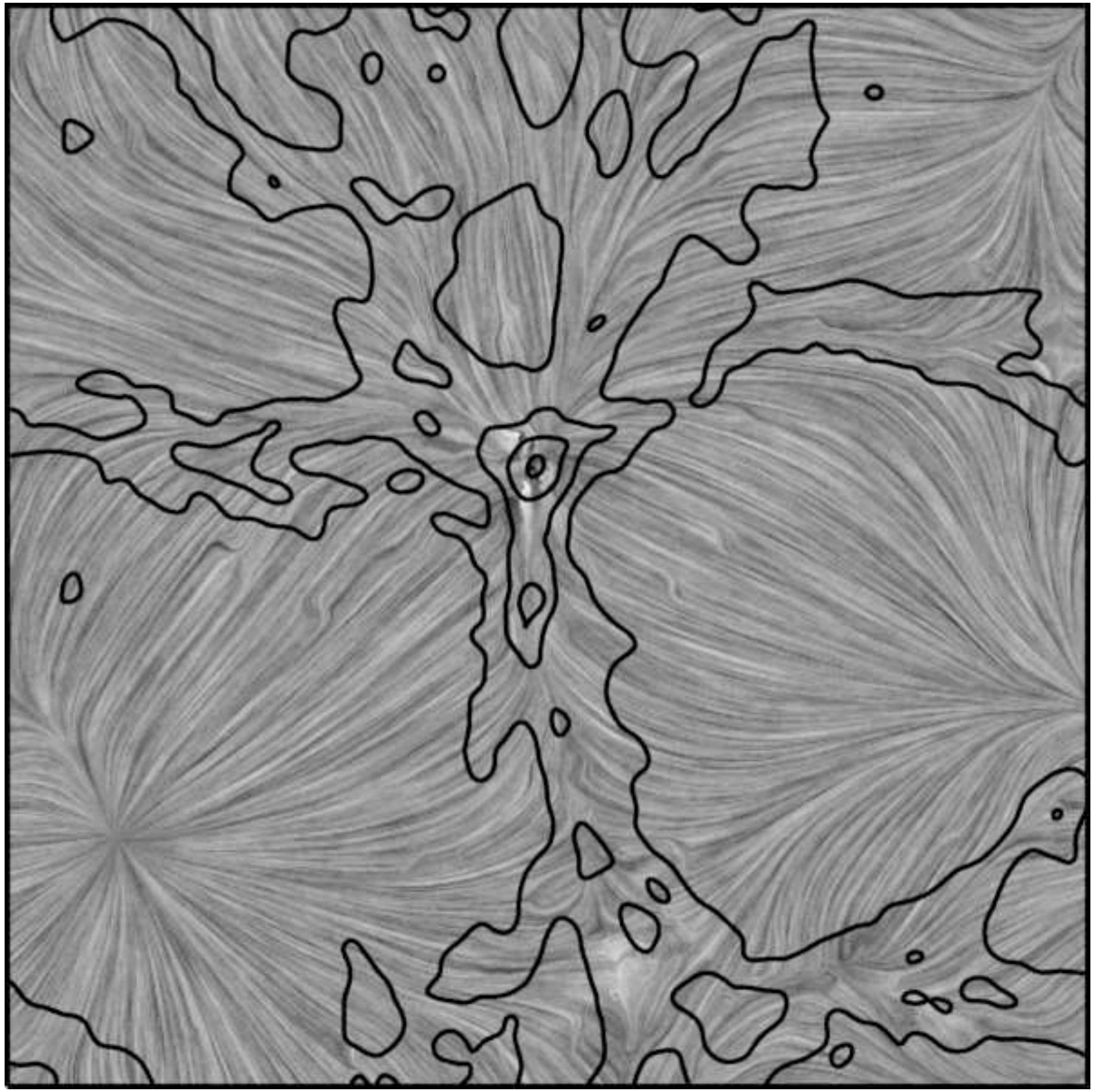
Polar ring. Mass in HI ($3x10^9$ Msun) > Mass in stars ($1x10^9$ Msun)

HI much more extended than stellar disk. No optical or UV counterpart to polar ring. Tidal interaction would destroy rotation in disk.

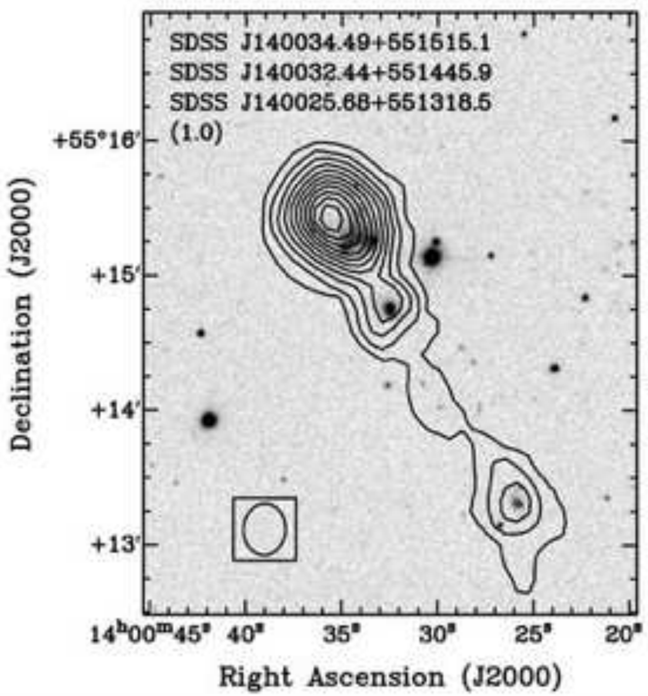
Possible example of cold mode accretion.

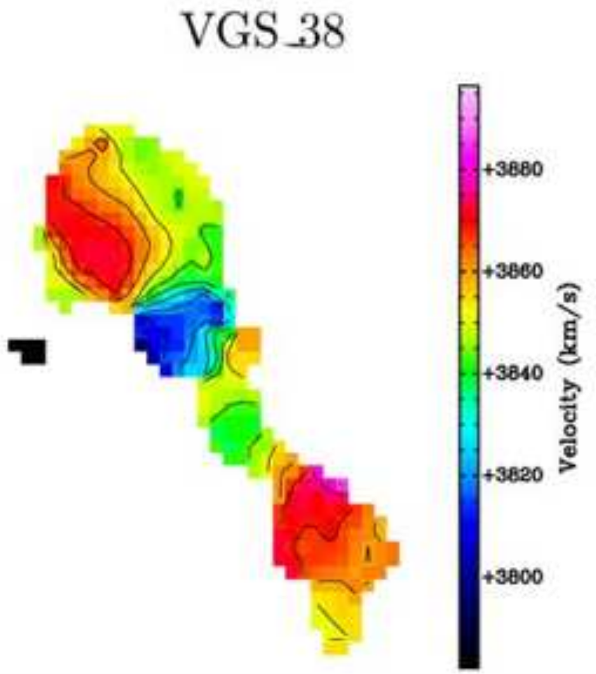


Location and orientation of the polar disk within the wall, between the two voids. The full volume of the sphere with galaxies brighter than $m_g = 17.76$ *out to 10 Mpc has been plotted, with concentric circles every 2 Mpc in the plane of the wall. This demonstrates the loneliness of our galaxy and the emptiness of the bounding voids. An edge-on view is projected on the left, showing the thinness of the wall. The red line indicates the position and orientation of the projected major axis of the H i disk.*



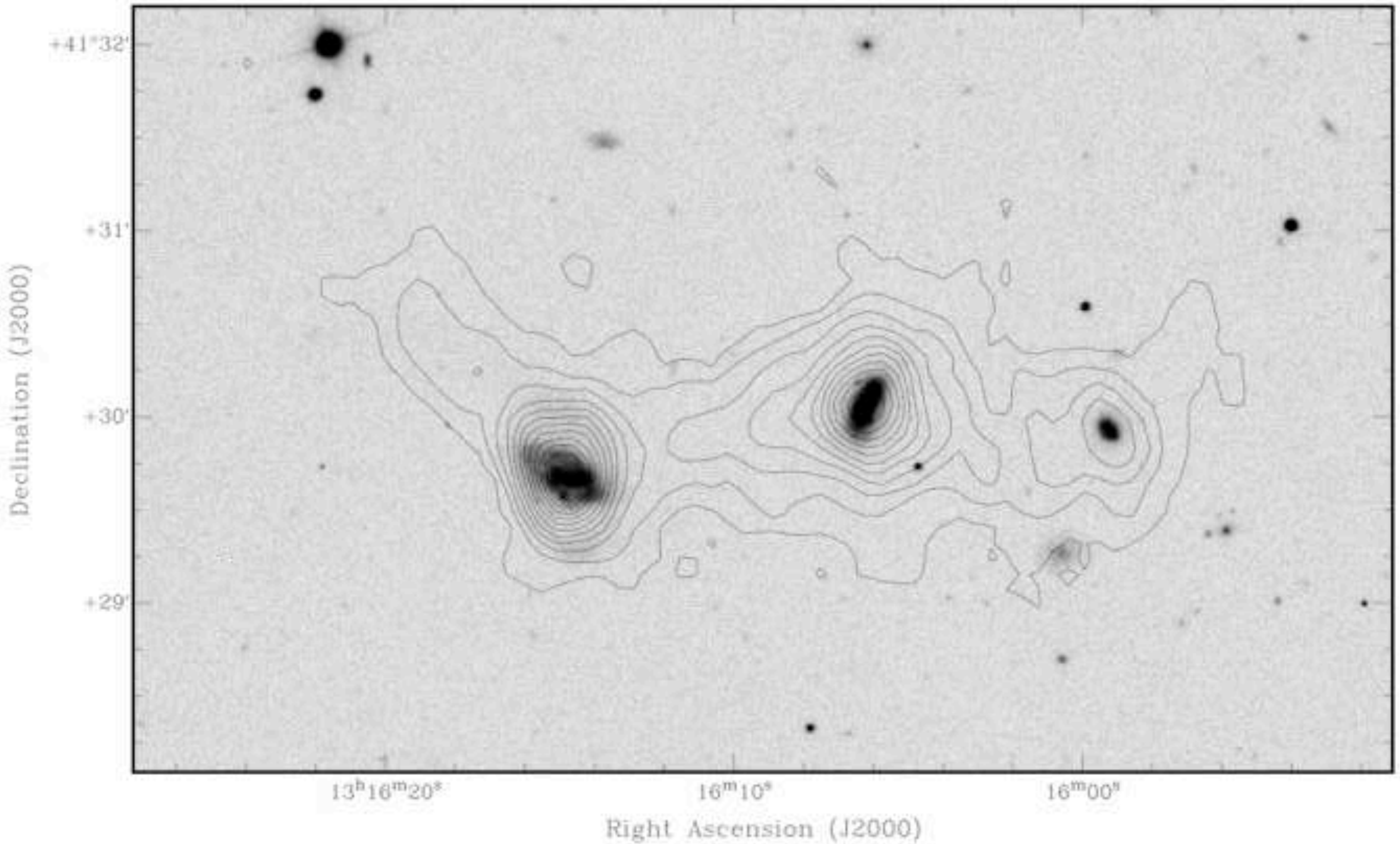
Gas flows out of the void





A filament in a void?

Beygu et al 2013



More polar rings (and filaments?) in voids

CONCLUSIONS Void Galaxy Survey

Kreckel et al 2011, 2012,2014, Beygu et al 2013, 2014, 2016

By looking in voids you select an interesting sample of small galaxies (no stellar masses > $3x10^{10}M_{sun}$).

Most of these galaxies are gas rich. Many show kinematic signs of disturbances and possibly ongoing accretion.

Some evidence that these galaxies are metal poor.

Several other studies of void galaxies:

Rojas et al 2005, 2006 based on SDSS
Pustilnik et al Lynx –Cancer void

There are other amazing hints that galaxies in voids maybe growing through smooth accretion.

NGC 6946
M101
M51

Peebles noted that massive galaxies are not in high density regions

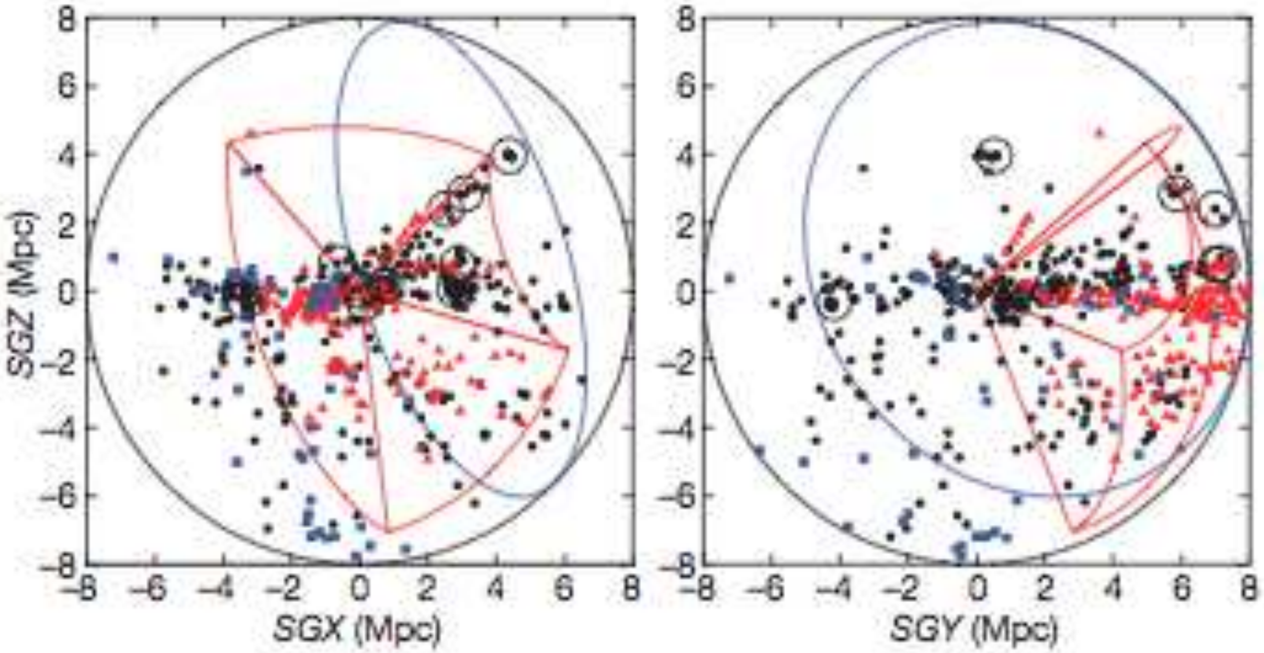


Figure 1 | Galaxies at radial distances 1 < *D* < 8 Mpc from the centre of the Local Group of galaxies. The Local Sheet is the concentration along the centre plane, and the Local Void is the region on the upper left in the left-hand projection. The ten most luminous galaxies (including M31 and the Milky Way at *D* < 1 Mpc) are indicated by the open circles. The orthogonal projections are plotted in supergalactic coordinates[63]. Black filled circles: 337 galaxies largely discovered on photographic plates and with well-measured distances[64]. Red triangles: 172 galaxies added by the Sloan Digital Sky Survey[65] (SDSS), with redshift errors of less than 50 km s^{-1}. Blue squares: 53 galaxies discovered by the H I Parkes All Sky Survey (HIPASS) from 21-cm emission by atomic hydrogen[30]. SDSS and HIPASS have less secure redshift distances and cover only the parts of the sky roughly indicated by the red and blue curves, respectively. There are many more dwarf galaxies to be discovered at this distance.

Kormendy noted that these giant galaxies are bulgeless

BULGELESS GIANT GALAXIES CHALLENGE OUR PICTURE OF GALAXY FORMATION BY HIERARCHICAL CLUSTERING*,†

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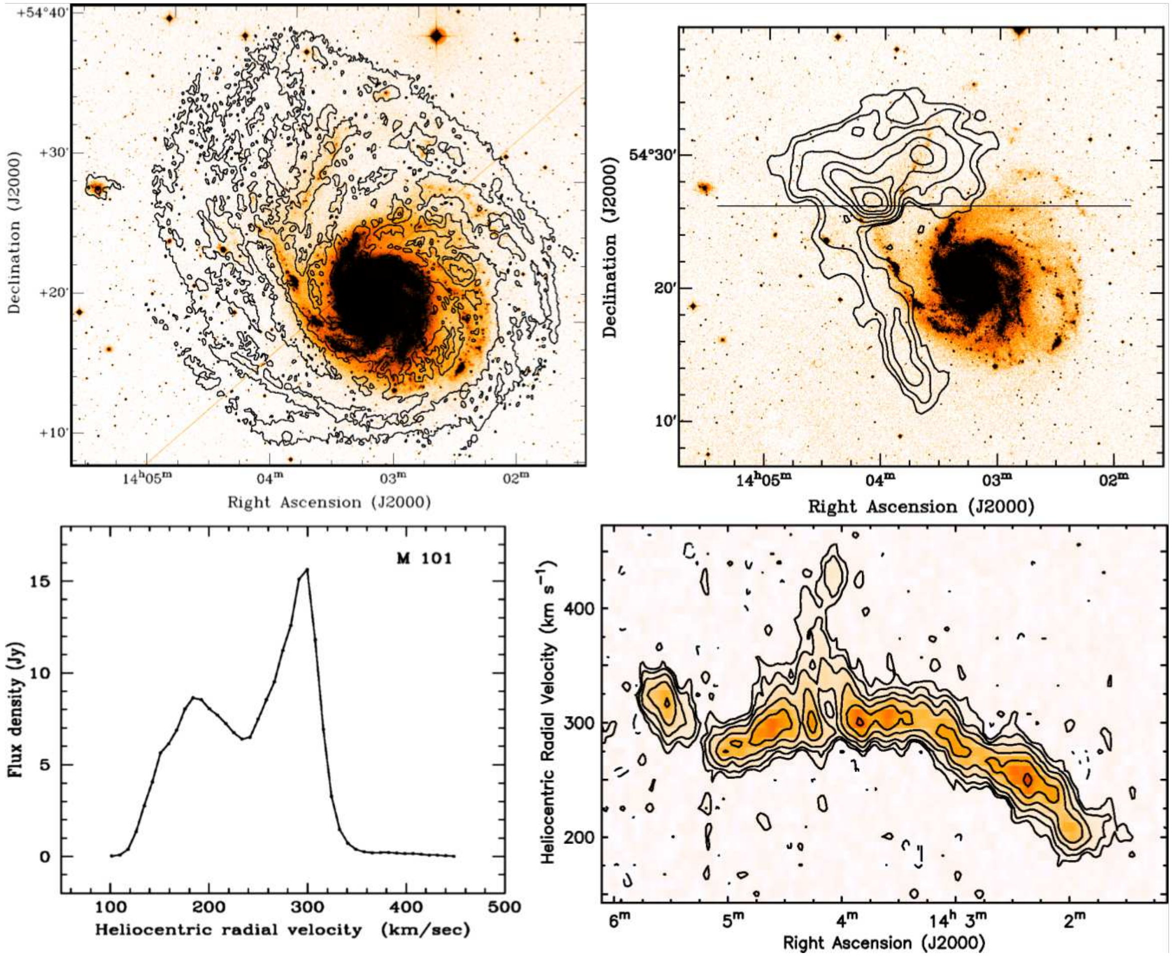
ABSTRACT

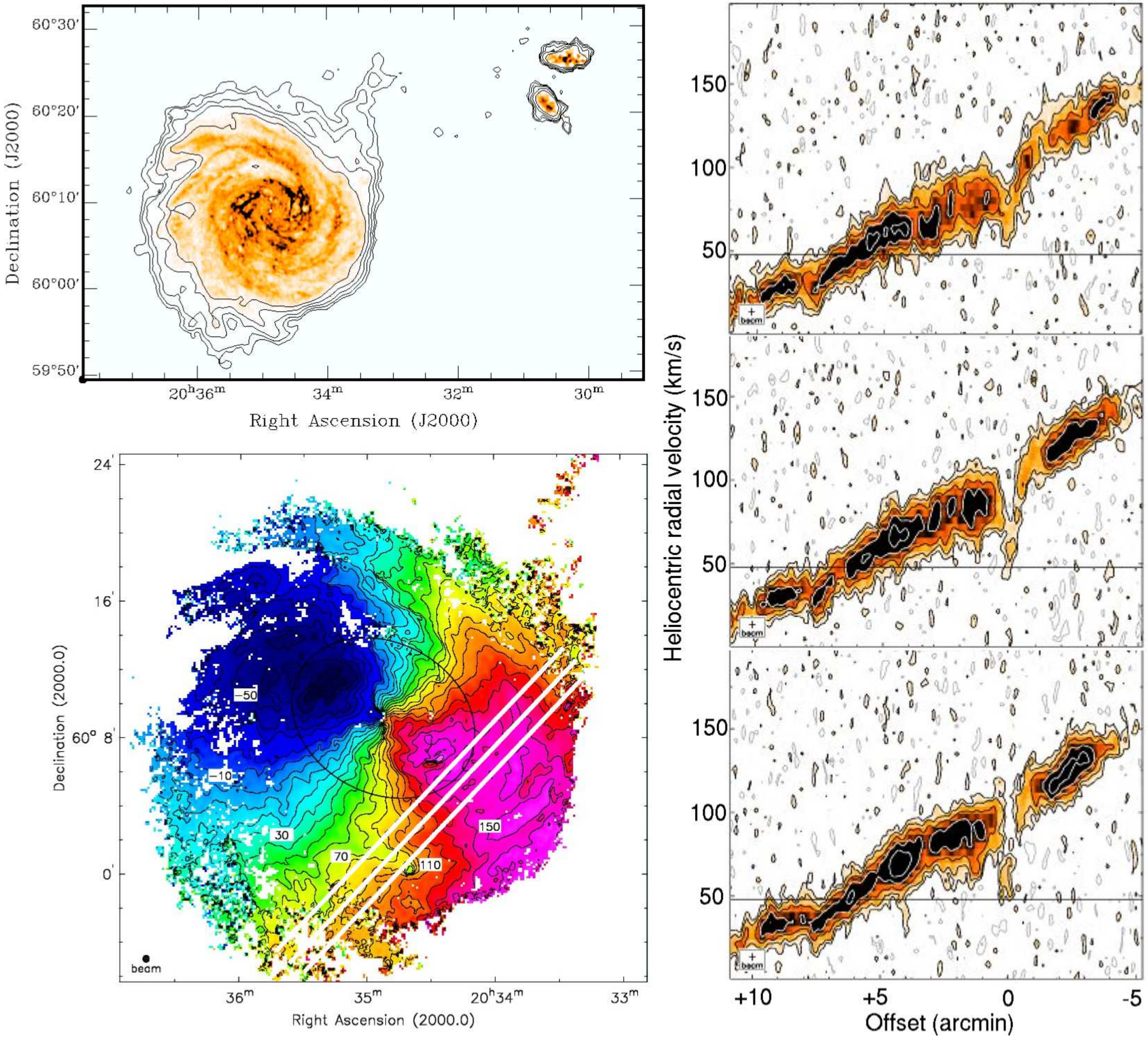
To better understand the prevalence of bulgeless galaxies in the nearby field, we dissect giant Sc-Scd galaxies with *Hubble Space Telescope* (*HST*) photometry and Hobby-Eberly Telescope (HET) spectroscopy. We use the HET High Resolution Spectrograph (resolution $R \equiv \lambda/\mathrm{FWHM} \simeq 15,000$) to measure stellar velocity dispersions in the nuclear star clusters and (pseudo)bulges of the pure-disk galaxies M 33, M 101, NGC 3338, NGC 3810, NGC 6503, and NGC 6946. The dispersions range from 20 ± 1 km s^{-1} in the nucleus of M 33 to 78 ± 2 km s^{-1} in the pseudobulge of NGC 3338. We use *HST* archive images to measure the brightness profiles of the nuclei and (pseudo)bulges in M 101, NGC 6503, and NGC 6946 and hence to estimate their masses. The results imply small mass-to-light ratios consistent with young stellar populations. These observations lead to two conclusions. (1) Upper limits on the masses of any supermassive black holes are $M_\bullet \lesssim (2.6 \pm 0.5) \times 10^6\ M_\odot$ in M 101 and $M_\bullet \lesssim (2.0 \pm 0.6) \times 10^6\ M_\odot$ in NGC 6503. (2) We show that the above galaxies contain only tiny pseudobulges that make up $\lesssim$3% of the stellar mass. This provides the strongest constraints to date on the lack of classical bulges in the biggest pure-disk galaxies. We inventory the galaxies in a sphere of radius 8 Mpc centered on our Galaxy to see whether giant, pure-disk galaxies are common or rare. We find that at least 11 of 19 galaxies with $V_{circ} > 150$ km s^{-1}, including M 101, NGC 6946, IC 342, and our Galaxy, show no evidence for a classical bulge. Four may contain small classical bulges that contribute 5%-12% of the light of the galaxy. Only four of the 19 giant galaxies are ellipticals or have classical bulges that contribute ~1/3 of the galaxy light. We conclude that pure-disk galaxies are far from rare. It is hard to understand how bulgeless galaxies could form as the quiescent tail of a distribution of merger histories. Recognition of pseudobulges makes the biggest problem with cold dark matter galaxy formation more acute: How can hierarchical clustering make so many giant, pure-disk galaxies with no evidence for merger-built bulges? Finally, we emphasize that this problem is a strong function of environment: the Virgo cluster is not a puzzle, because more than 2/3 of its stellar mass is in merger remnants.

M101, NGC 6946 -- the same galaxies that Peebles points out

In this paper we report the discovery of neutral hydrogen moving at high speed perpendicular to the disk of the nearby spiral galaxy M101. This material is found in two locations where the spiral structure itself seems particularly disturbed. The mass involved is 10^7–10^8 $\mathcal{M}_\odot$. The velocities appear redshifted by up to about 150 km/s with respect to the "local" H I disk of M101, and yet they seem to connect smoothly to other features seen in that disk. The origin of these high-velocity H I structures is not clear. It is unlikely that they were caused by supernova explosions or even by any spiral dynamics, but they may have resulted from fairly recent collisions of large, extragalactic gas clouds with the disk of M101.



Kamphuis, 1993; van der Hulst and Sancisi, 1988



NGC 4696 (Boomsma , Oosterloo, Fraternali, van der Hulst, Sancisi, 2008)

HI holes and velocity wiggles. Evidence for infall?

Really interesting paper:

The effect of filaments and tendrils on HI content of galaxies

Odekon, Hallenbeck, Haynes, Koopmann, Phi and Wolfe ApJ in press

They use 10,000 galaxies from ALFALFA with HI detections and 5,000 with upper limits.

They find:

1. At fixed local density and stellar mass, the HI deficiency decreases with distance from the filament spine.

2. There are still smaller filamentary structures in voids, called tendrils.

Galaxies in tendrils are more gas rich, bigger, and not redder--suggesting a more advanced stage of evolution.

3. At fixed stellar mass and color, galaxies closer to the spine or in high density environments are more HI deficient. As galaxies enter dense regions, they first lose HI gas, then redden.

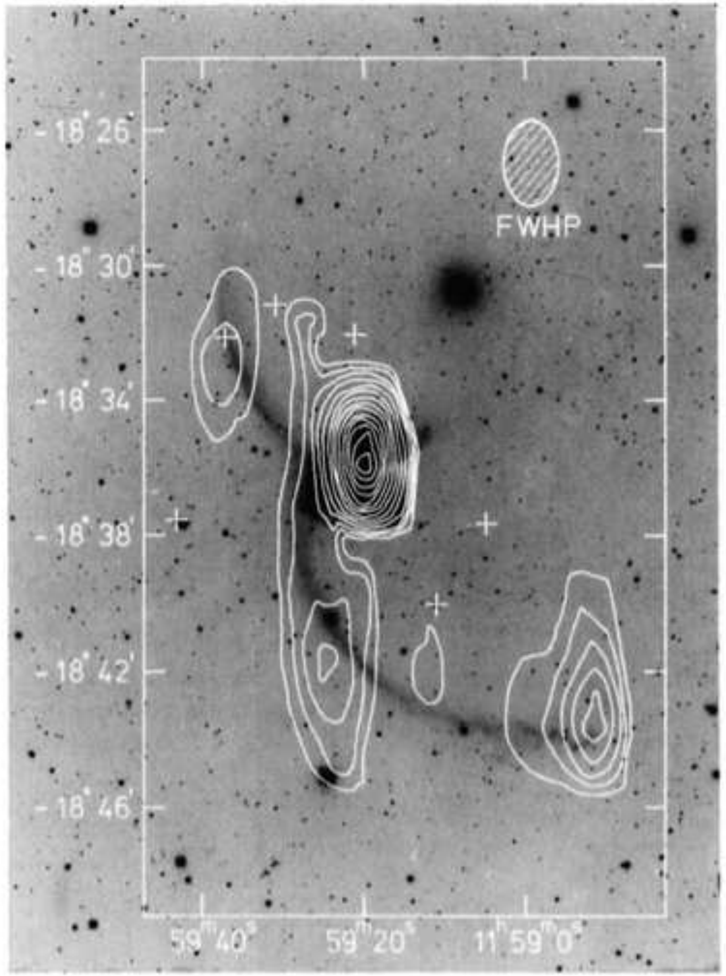
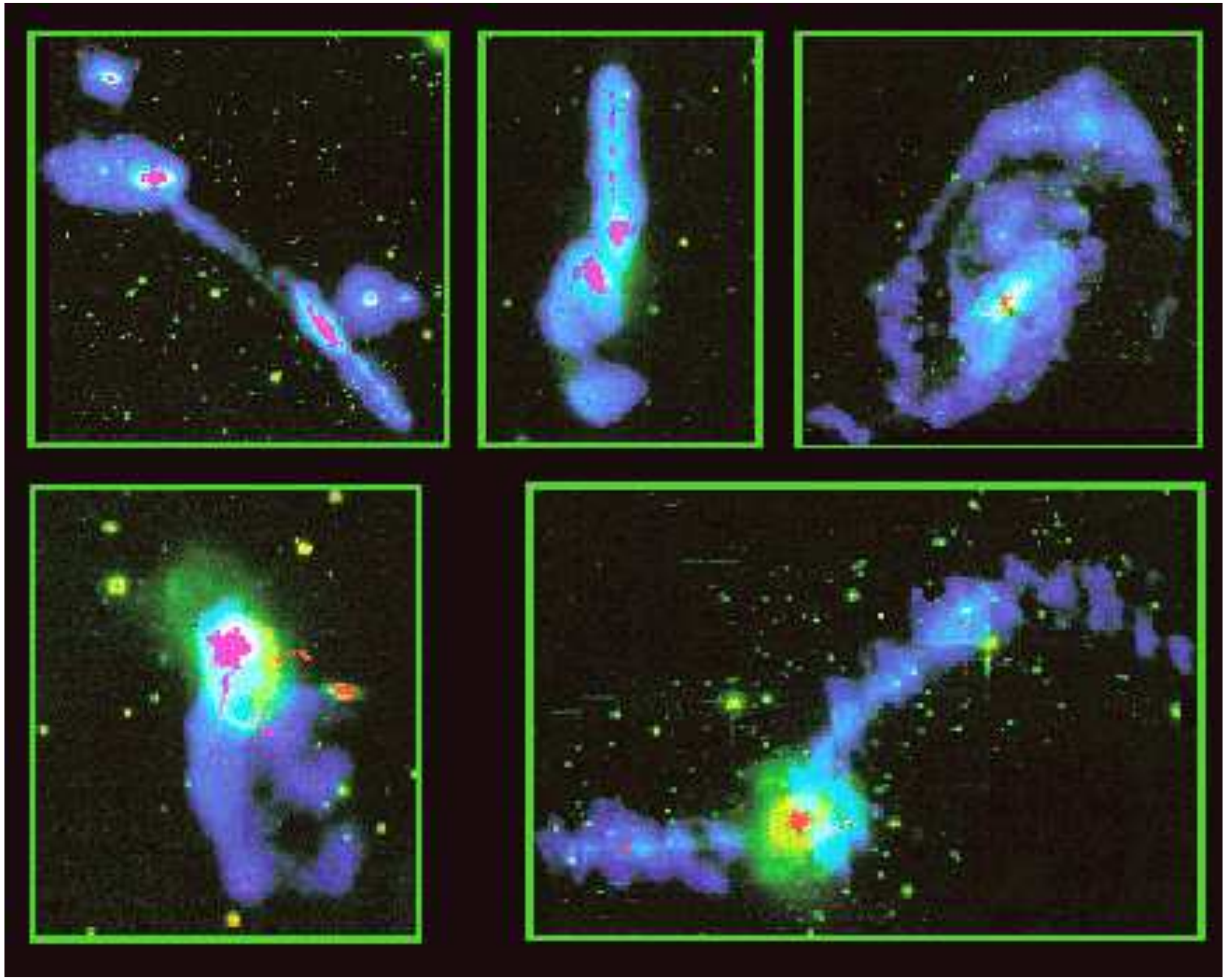


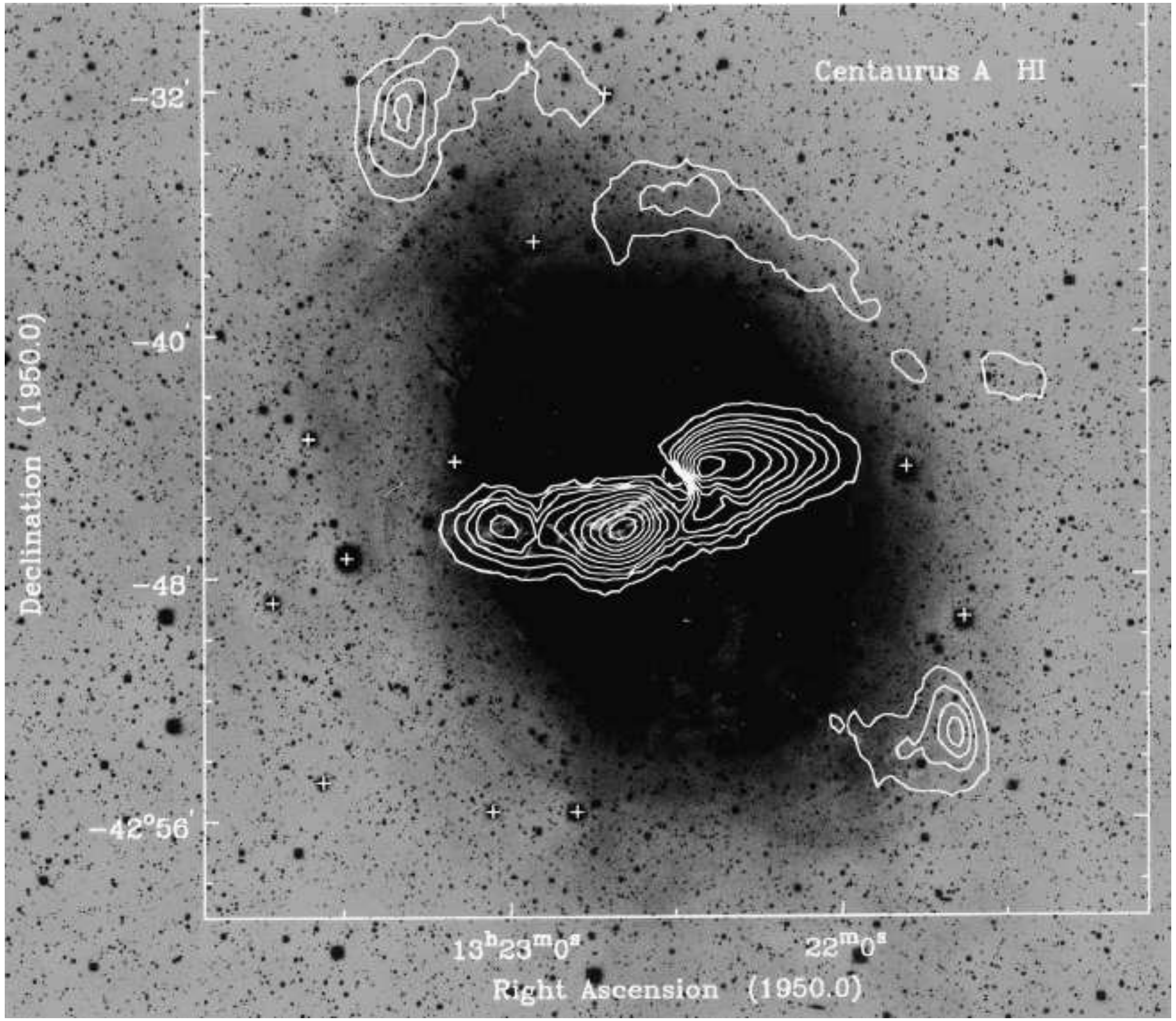
Fig. 5. H I column density distribution in NGC 4038/39 superposed on a 4 m CTIO photograph. (courtesy Schweizer) The contour interval is 4.5 10^{19} atoms cm^{-2}. The hatched ellipse in the upper right corner represents the CLEAN halfpower beam. The crosses are fiducial marks indicating star positions

Van der Hulst 1978

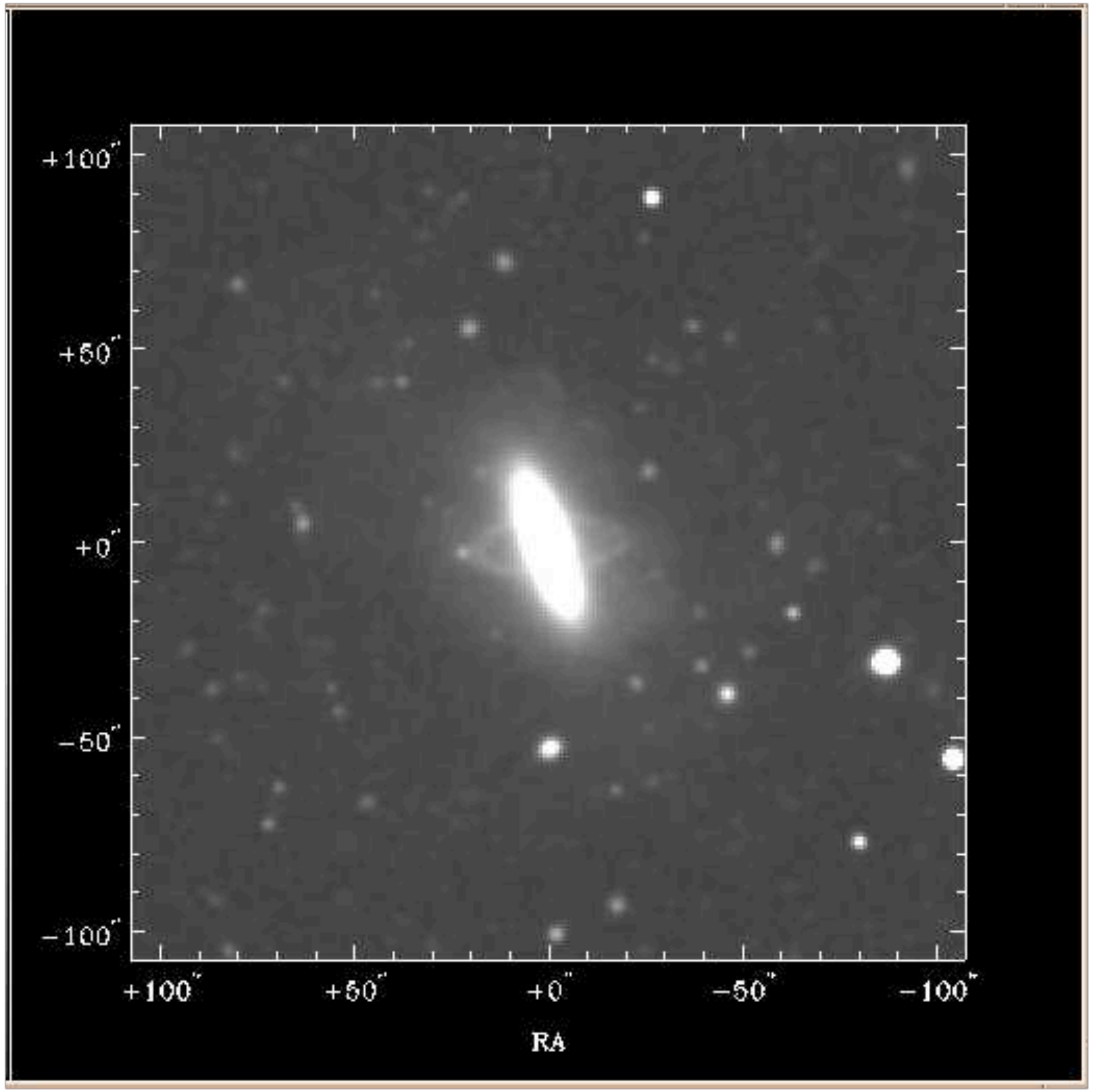


The Fate of Gas in a Merging Sequence (Hibbard 1995)
Blue HI, red H alpha, yellow-green stars (R band)Fall back of HI .. Too much HI in some for sum of two

Do mergers bring in extra gas?



Schiminovich , van Gorkom van der Hulst and Kasow 1996


+100"
+50"
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+0"
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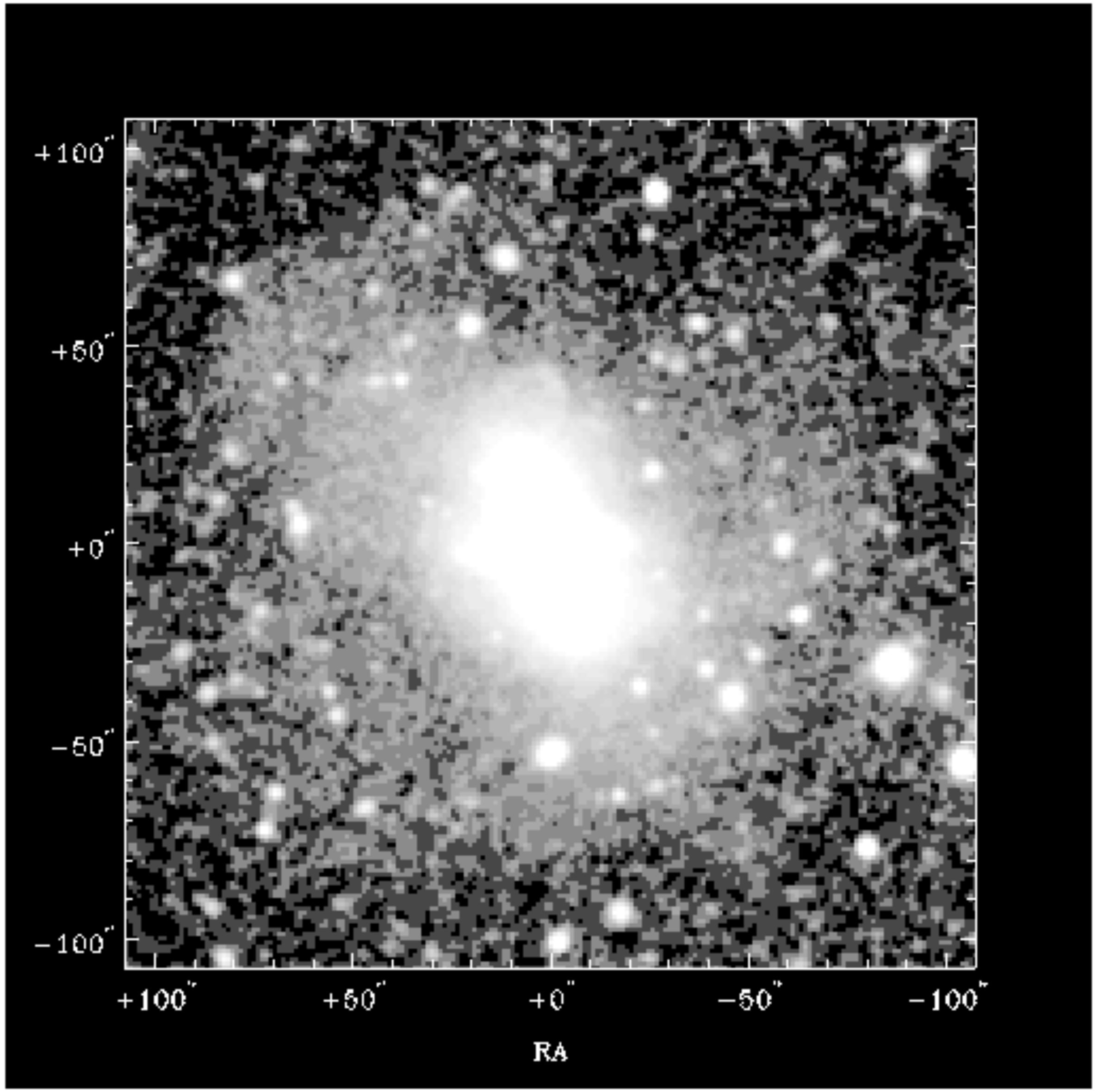
RA



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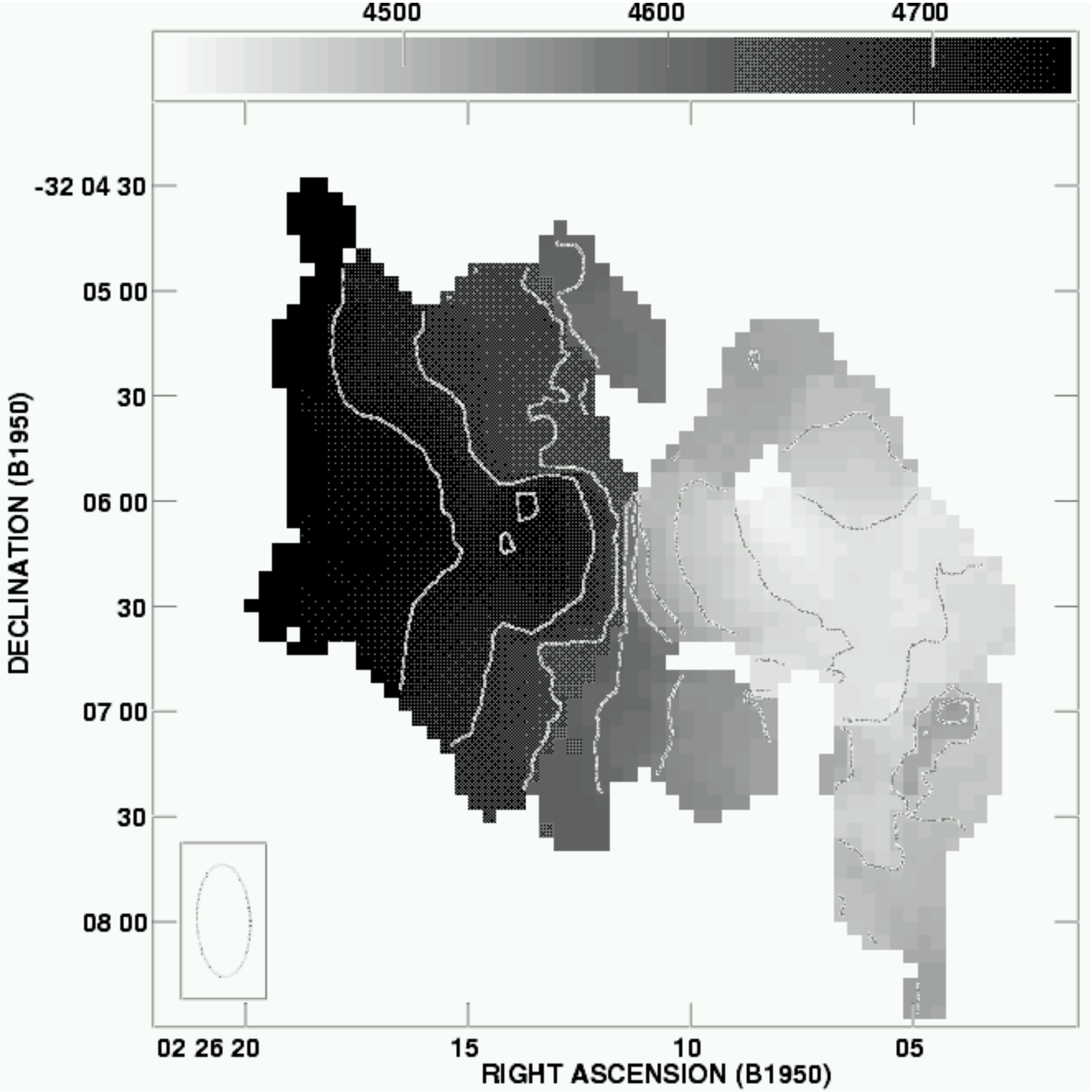
Disk in formation



HI in MCG -5-7-1 note the regular velocity field

Schiminovich, van Gorkom and van der Hulst 2012

Finally in 2018

Enhanced atomic gas fractions in recently merged galaxies: quenching is not a result of post-merger exhaustion

Ellison, Catinella, Cortese 2018 sample of 100 post merger candidates

Could be net cooling of ionized/hot ISM/halo gas

The origin of faint tidal features around galaxies in the RESOLVE survey

Hood, Kannappan, Stark et al 2018

Tidal features in gas rich galaxies may arise from accretion of cosmic gas and/or gas-rich satellites

VIVA

VLA Imaging of Virgo Galaxies in Atomic Gas

Aeree Chung, Hugh Crowl,

Kenney, van Gorkom, Vollmer, Schiminovich

Select galaxies over wide range of local densities.

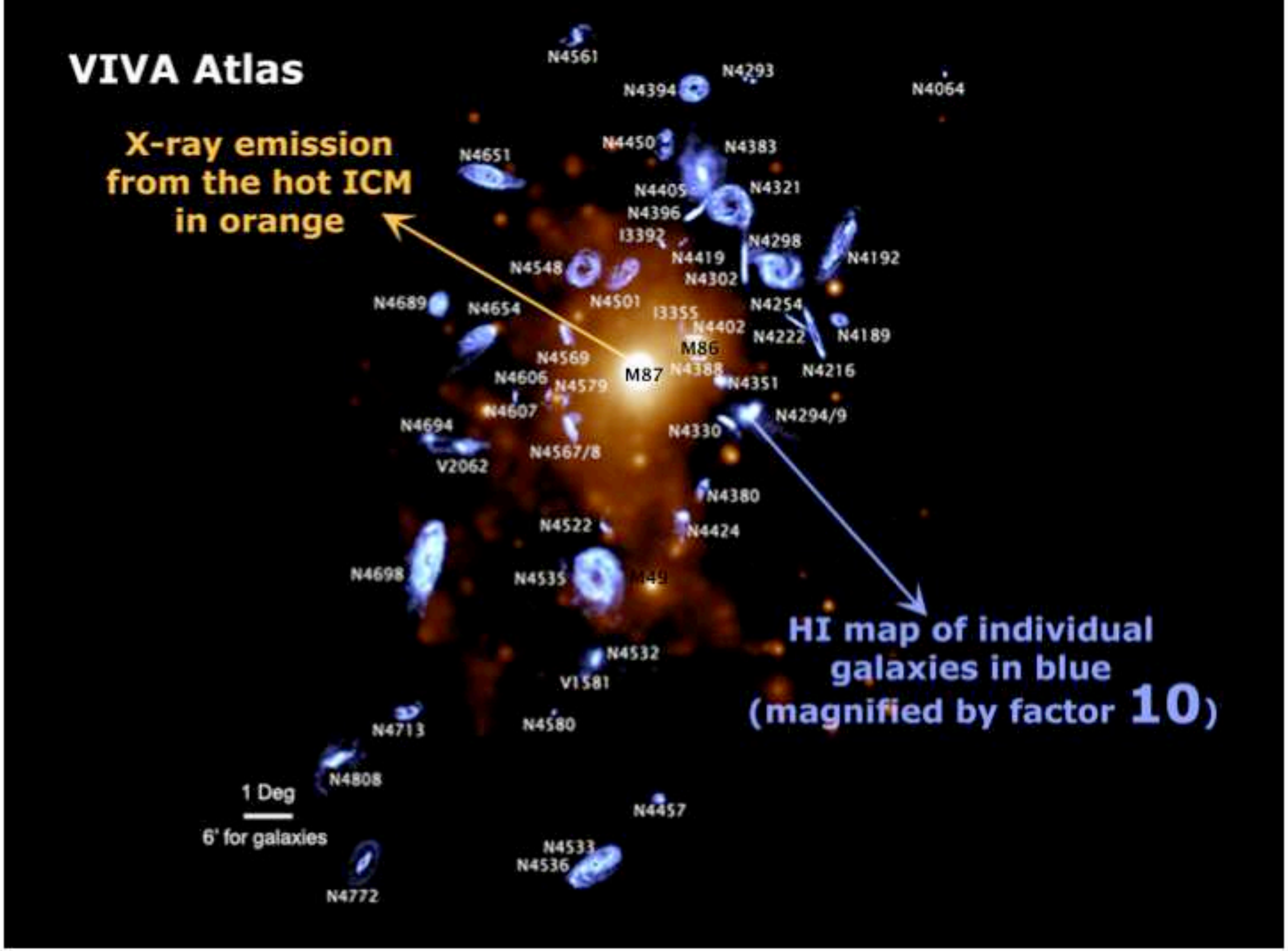
Select galaxies with wide range of star formation properties.

Identify galaxies undergoing trauma.

Make sophisticated guess as to what is happening.

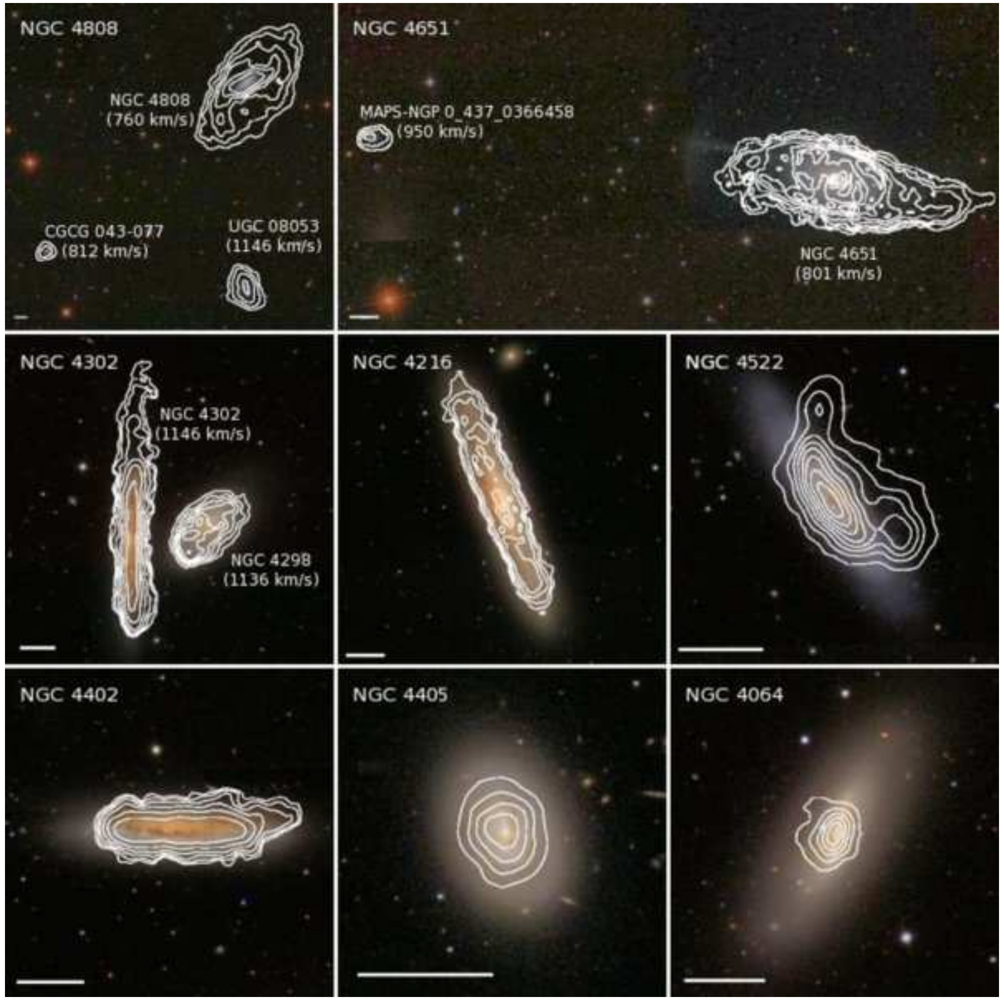
Use simulation to make a more sophisticated guess.

Compare timescales from stellar population synthesis with timescales from simulation.



VIVA Atlas
X-ray emission from the hot ICM in orange
HI map of individual galaxies in blue (magnified by factor 10)
N4561
N4293
N4394
N4064
N4450
N4383
N4651
N4405
N4321
N4396
I3392
N4298
N4192
N4419
N4548
N4302
N4501
N4689
N4254
N4654
I3355
N4402
N4222
N4189
M86
N4569
N4216
M87
N4388
N4606
N4579
N4351
N4607
N4294/9
N4694
N4330
N4567/8
V2062
N4380
N4522
N4424
N4698
N4535
M49
N4532
V1581
N4713
N4580
N4808
1 Deg
6' for galaxies
N4457
N4533
N4536
N4772

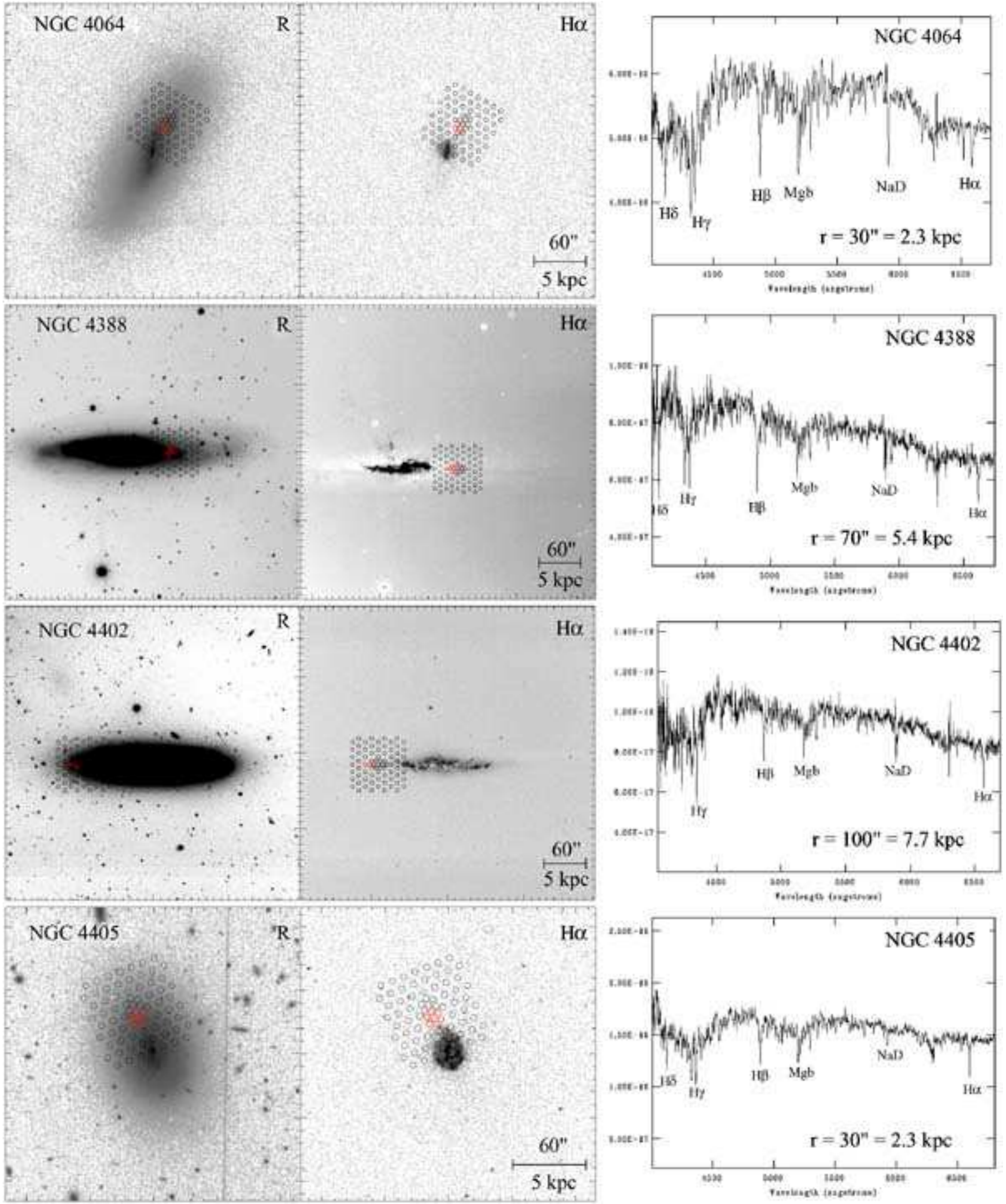
Galaxies in around the Virgo cluster -- VIVA



Chung et al, 2009

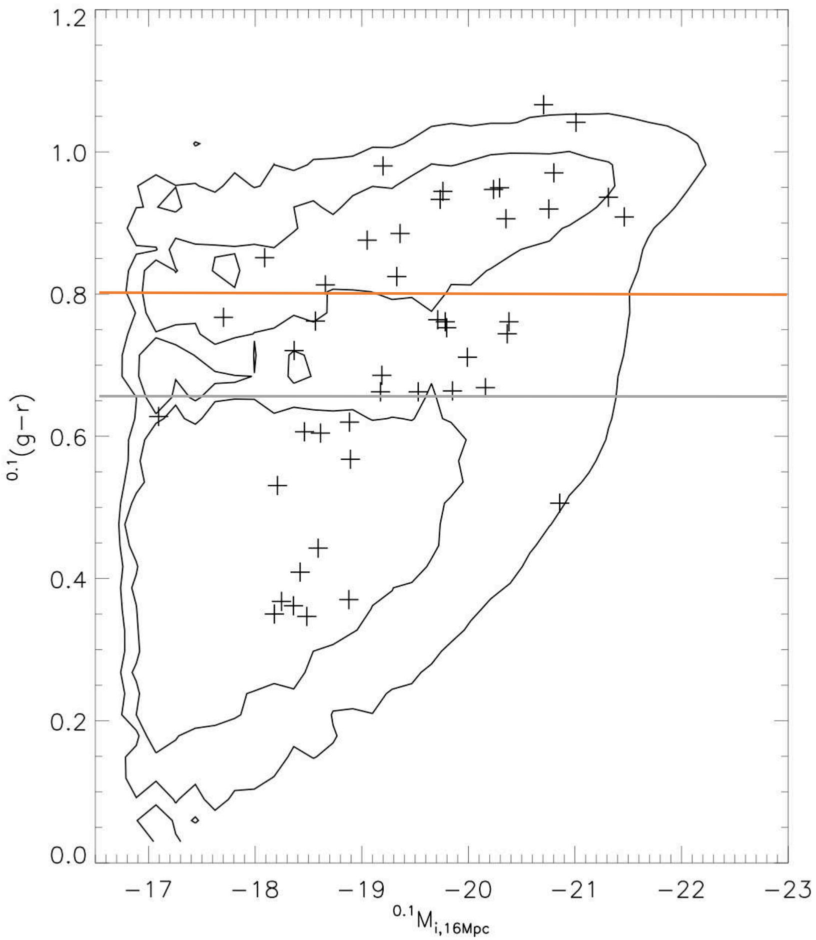
Different H! morphologies indicate different stages of stripping.

Crowl and Kenney 2008



- SparsePak positions on *R-band image (left) and Ha image (center). The composite spectrum from several summed fibers (indicated by the red circles on the images) is also shown (right). The radius given for each composite spectrum is the distance from the galaxy center to the center of the composite spectrum region. Shown here are images and spectra for NGC 4064, NGC 4388, NGC 4402, and NGC 4405.*

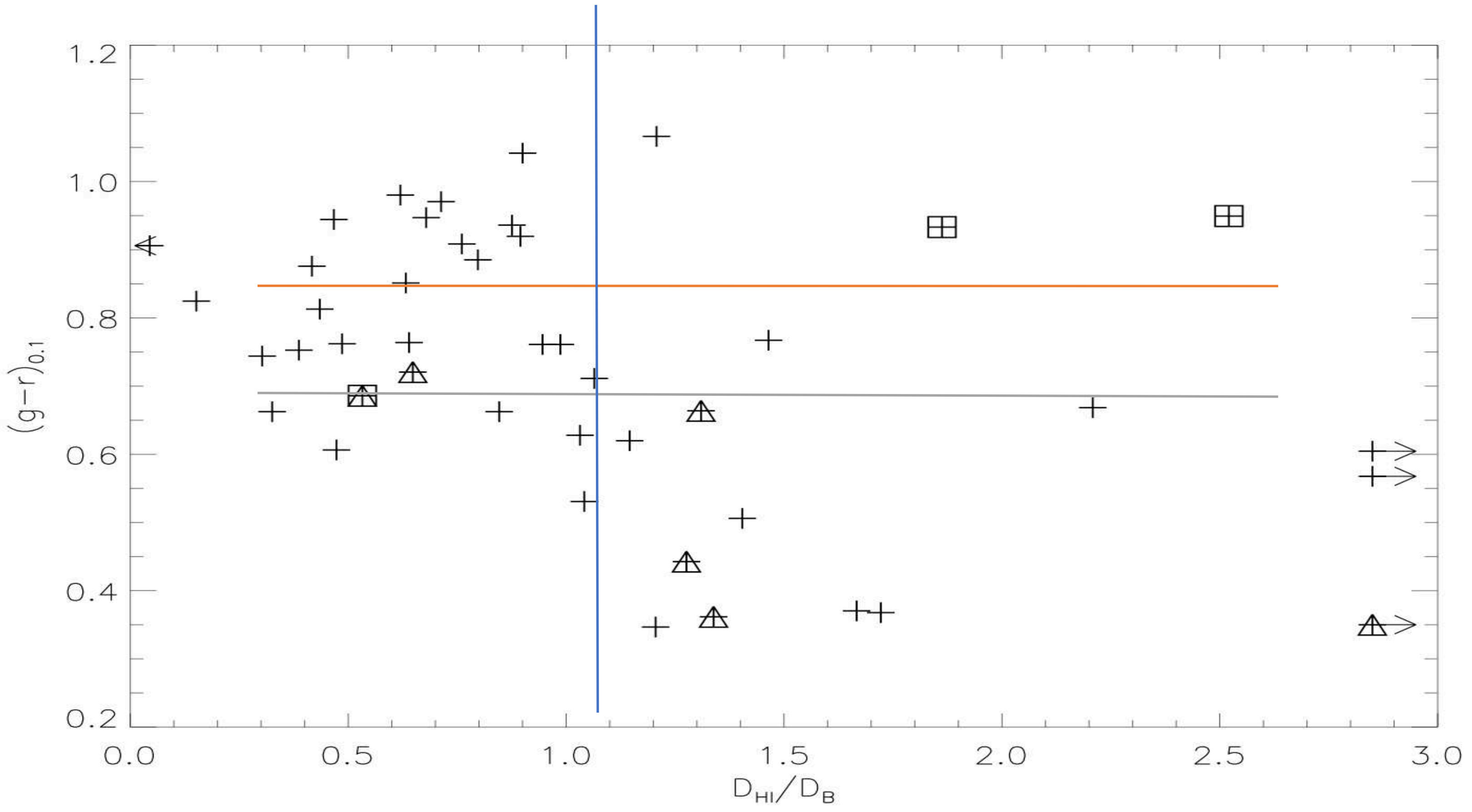
Global colors of VIVA galaxies on SDSS C-M diagram



Crosses -- VIVA galaxies; contours -- SDSS

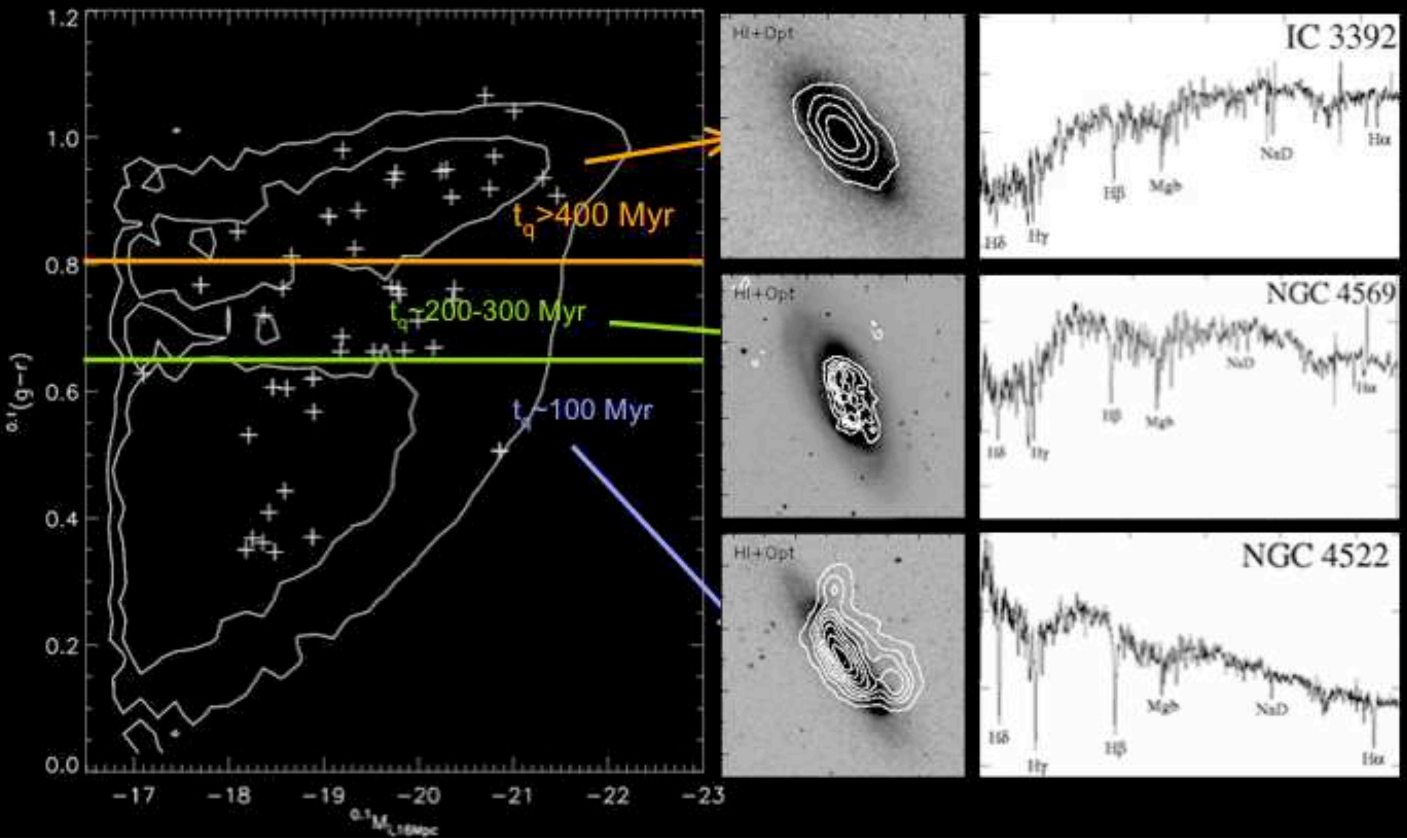
Crowl, Chung et al in prep

Galaxies in blue cloud have $D(HI)/D_{opt} > 1$
Galaxies on red sequence have mostly $D(HI)/D_{opt} < 1$



Triangles -- HI tails at about the virial radius of Virgo; squares -- merger remnants

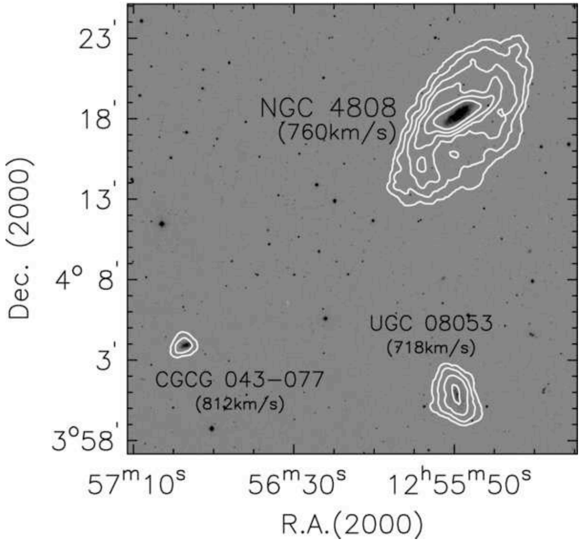
Color-Magnitude Diagram of VIVA Sample

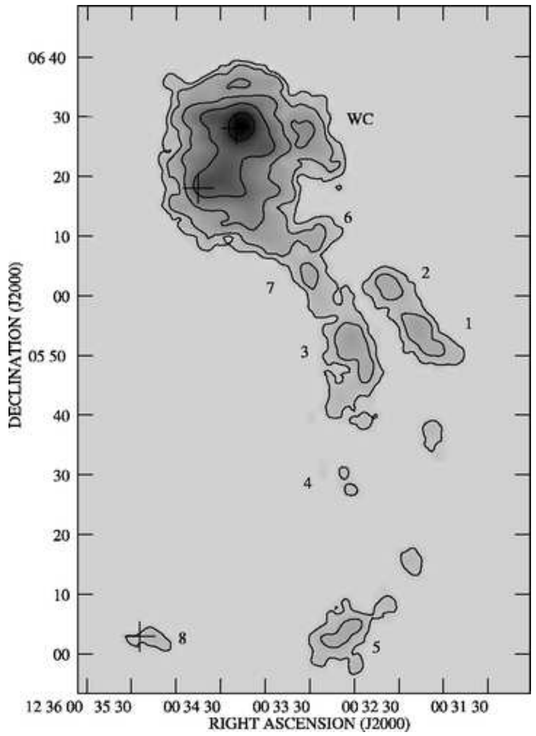


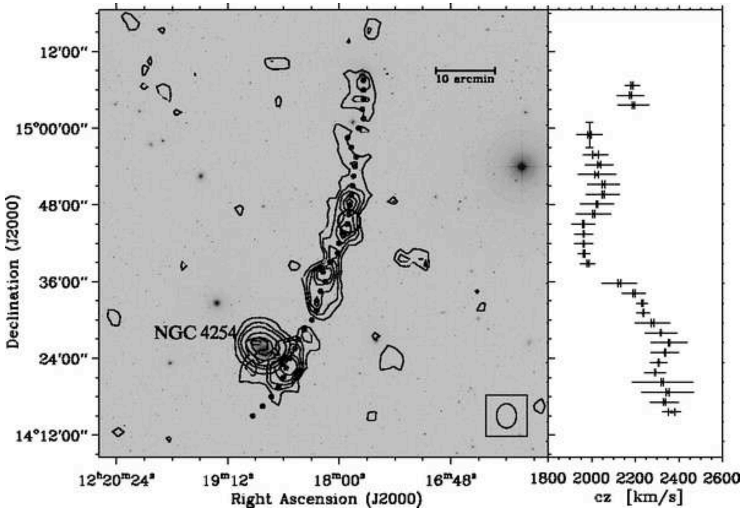
Contours -- 140000 SDSS galaxies (Blanton et al 2003); crosses -- VIVA galaxies (Crowl et al, in prep.)

Virgo

Very gas rich galaxies and long HI tails far out







In the very outskirts of Virgo there may be an excess of gas.

Also for clusters, people are now looking at dynamics and large scale environment.

Use of phase space diagrams, taking into account projected distance from center and relative velocities.

For example Jaffe et al 2015, 2016

A963

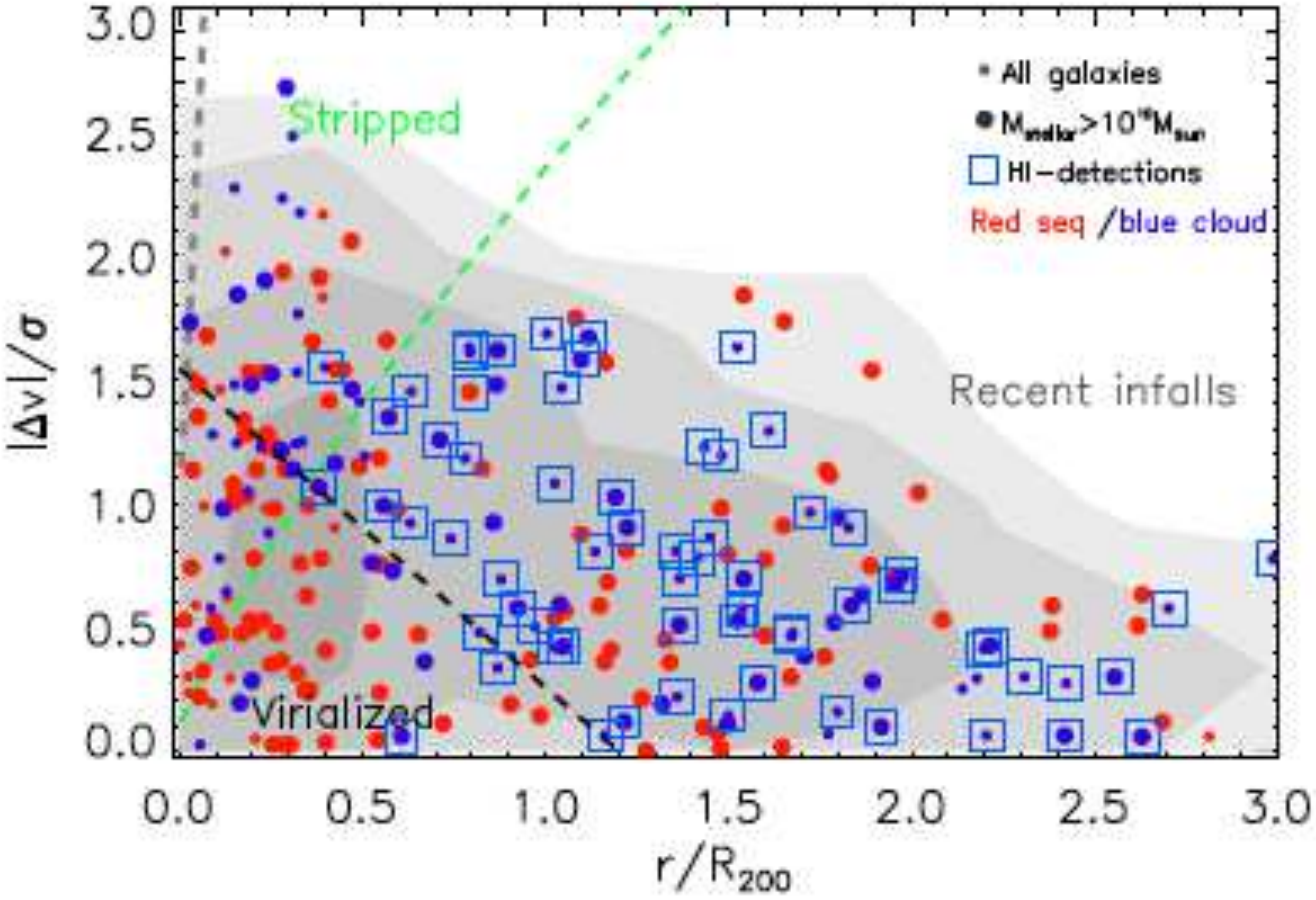


Figure 7. The same PPS as in Figure [7] is shown, but with added information: As before, massive galaxies ($M_* > 10^{10} M_\odot$) are represented with larger filled circles, HI-detected galaxies are enclosed by a blue open circle, and grey countours follow the number density of the galaxies. In addition, galaxies are divided into red-sequence and blue cloud, as defined in the top panels of Figure [2]. The dashed grey line delimits the area in PPS (left of the line) where a MW galaxy is expected to be completely stripped as it falls into the cluster. The solid green line (and shaded area) delimits the area where the model galaxies are stripped enough to fall out of the detection limit of our survey (see Section [5]). The additional dashed black line indicates the region in PPS where galaxies are most likely to have been in the cluster for more than a pericentric passage (i.e. the "virialized" region). The region to the right of all dashed lines thus contains galaxies that have most likely recently joined the cluster.

Jaffe et al 2015

Phase space diagrams have now also been successfully used for VIRGO (Hyein Yoon, Chung, Smith and Jaffe 2017)

A History of HI Stripping in Virgo: A Phase-space View of VIVA galaxies

Successfully puts different HI morphological classes in a phase space diagram and distinguishes:

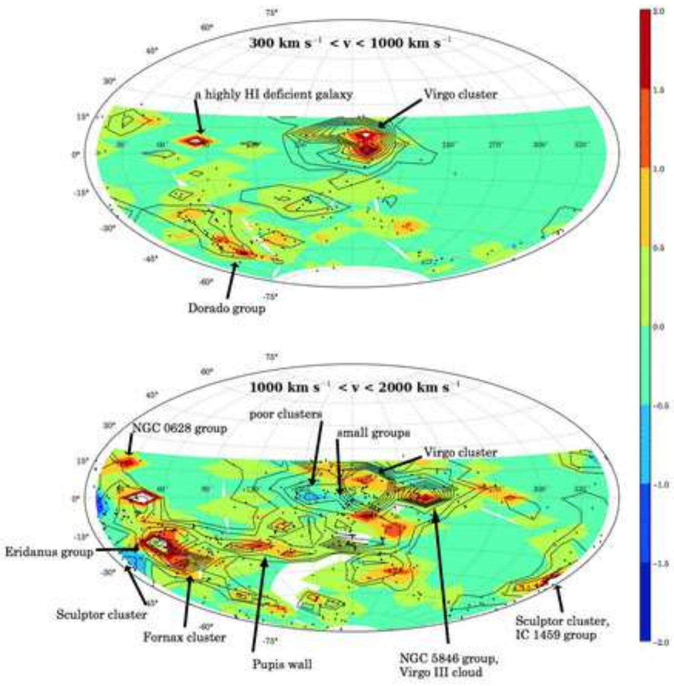
Asymmetric HI distribution… undergoing active stripping during first infall
Symmetric strongly stripped HI.. . either deep inside cluster or backsplash galaxies

Jellyfish galaxies Jaffe et al 2018

GASP IX. Jellyfish galaxies in phase-space: an orbital study of intense ram-pressure stripping in clusters

Phase space diagram analysis of more than 100 Jellyfish galaxies suggests longest tails are galaxies seen during first infall on radial orbits.

Are we close to making a neutral hydrogen image of the universe?



Red is very gas poor, blue is gas rich
Contours galaxy density

May explain galaxy conformity?

Figure 7.
Sky distribution of the H I deficiency parameter in two-dimensional bins overlaid with HyperLEDA density contours. The colours represent average H I deficiencies of different areas. Red and orange regions have on average more H I-deficient galaxies and dark blue regions have on average more H I-rich galaxies than the green and light blue regions. Density contours are 10, 30, 50, 70, 90, 110 galaxies. Black dots represent the individual galaxies of our HOPCAT and NOIRCAT samples.

HI deficiency maps.. Denes, Kilborne and Koribalski, 2014

The future

CHILES

CHILES, the COSMOS HI Large Extragalactic Survey

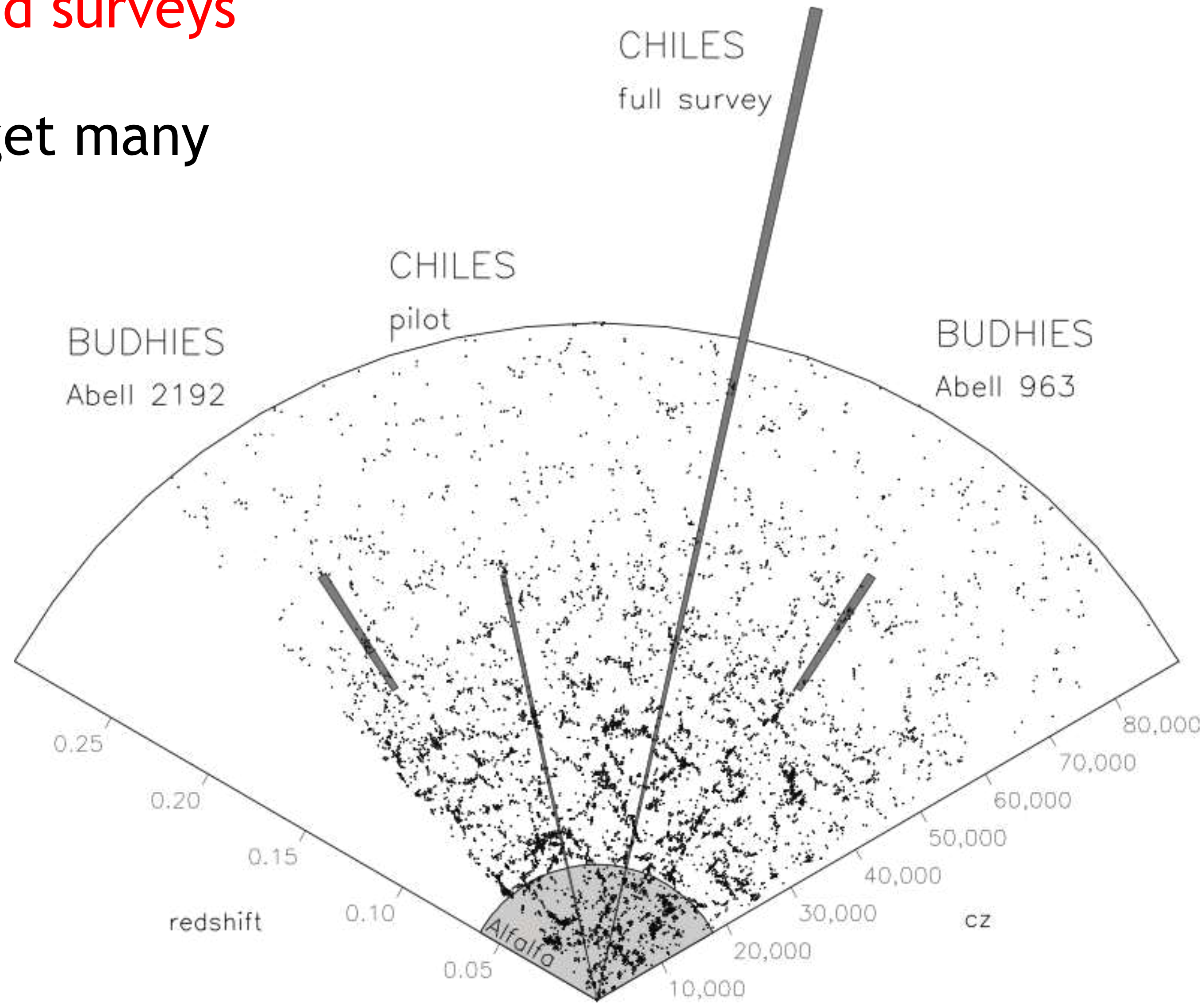
1002 hours JVLA B array

Chiles people…..van der Hulst …
et al

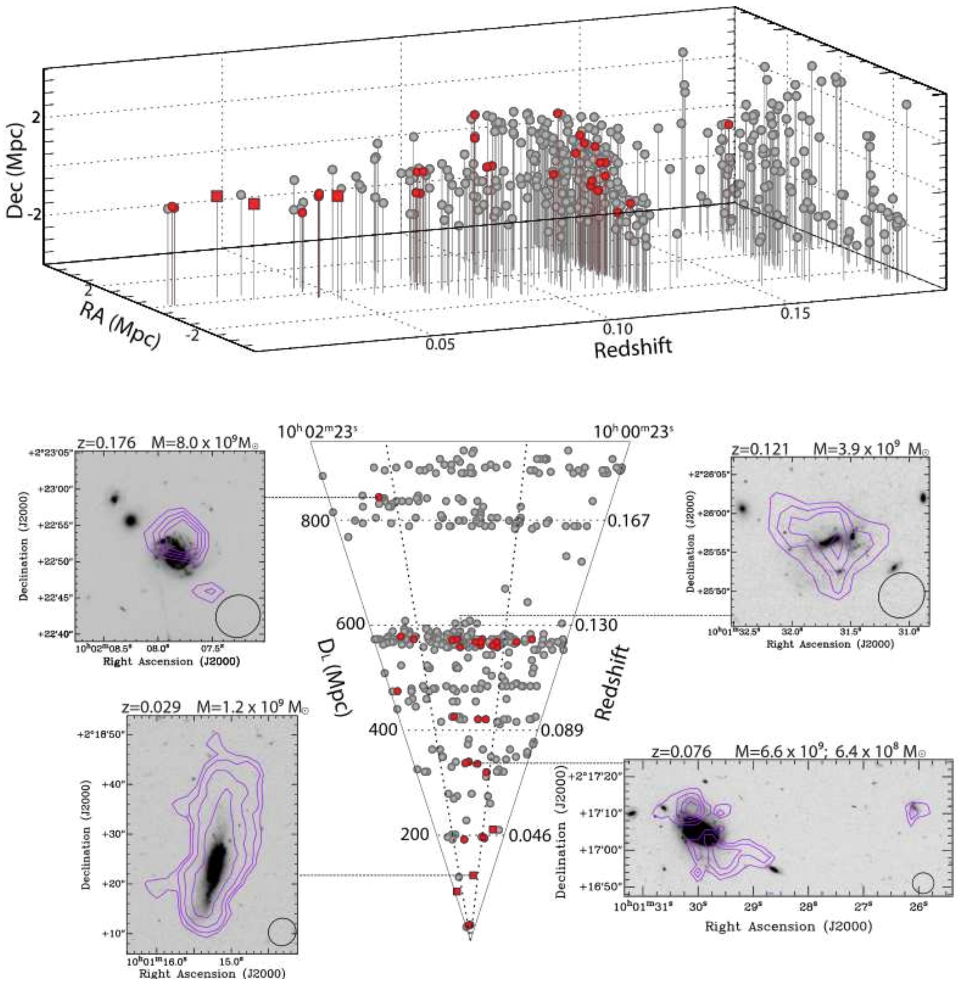
SKA Science and a path finder for the path finders

HI blind surveys

We are about to get many more



First imaging survey that probes cosmic web on larger scale



Results of the pilot FERNANDEZ et al 2013

60 hours B array 0<z<0.2

Recently lots of different methods have been tested to define the large scale structure in the cosmic web. Serious work has started to derive the properties of galaxies as a function of location in the cosmic web.

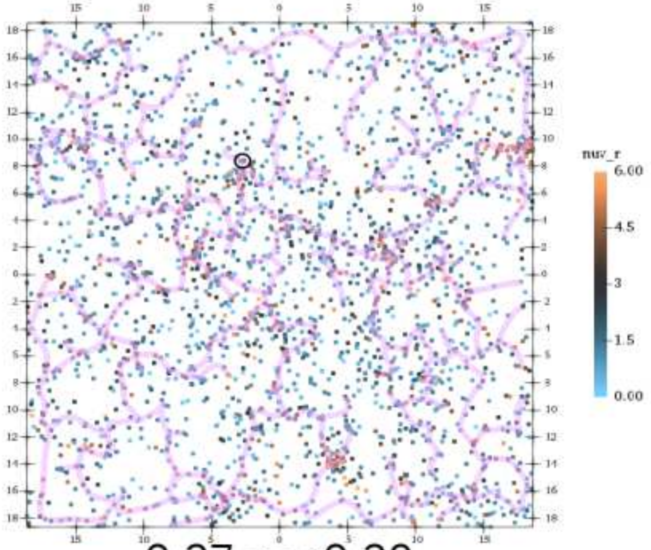
A popular algorithm, DisPerSE (Sousbie 2011), the Discrete Persistent Structure Extractor code, is being used by several groups now.

Kraljic, Arnouts, Pichon, Laigle, de la Torre et al 2017
Galaxy Evolution in the metric of the CosmicWeb

Chen, Ho, Mandelbaum, Bahcall, Brownstein et al 2016
Detecting effects of filaments on galaxy properties in SDSS III

Laigle, Pichon, Arnouts, McCracken, Dubois et al 2017
COSMOS2015 photometric redshifts probe the impact of filaments on galaxy properties

Ancillary Data: Identifying the Cosmic Web



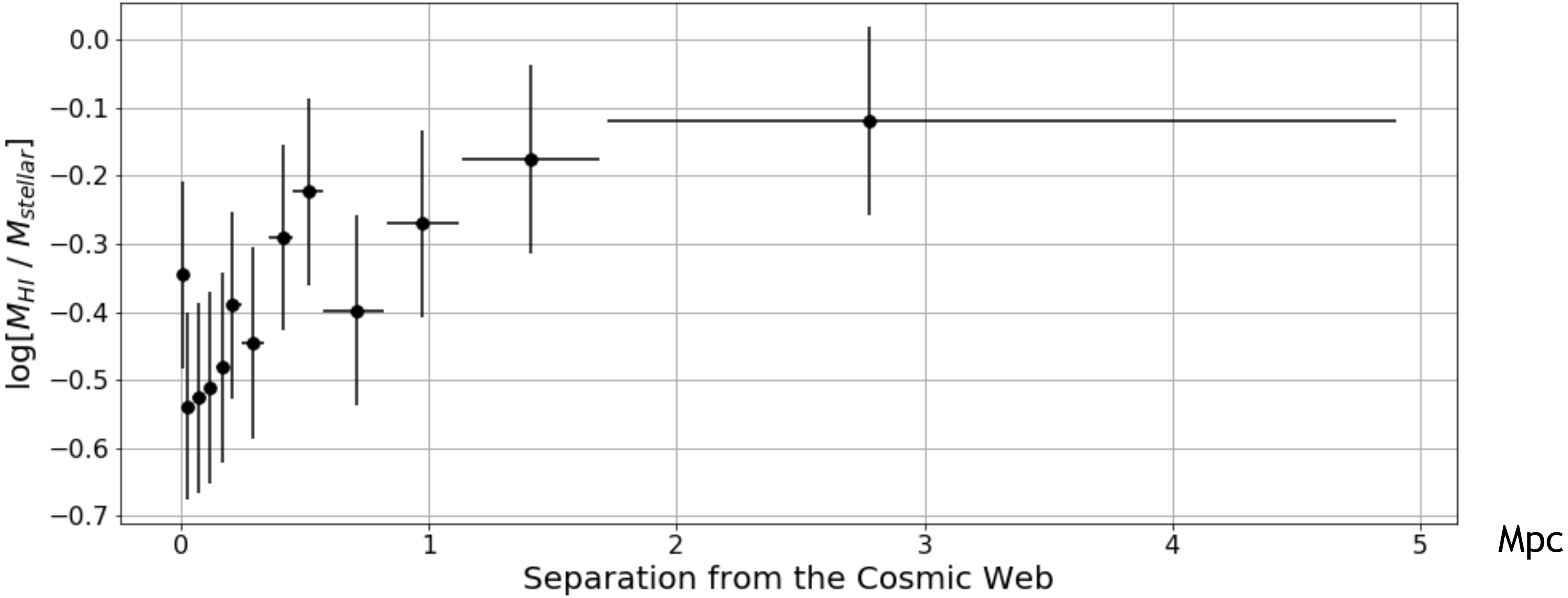
0.37<z<0.38

DisPerSE - a scale free, topological structure finding algorithm

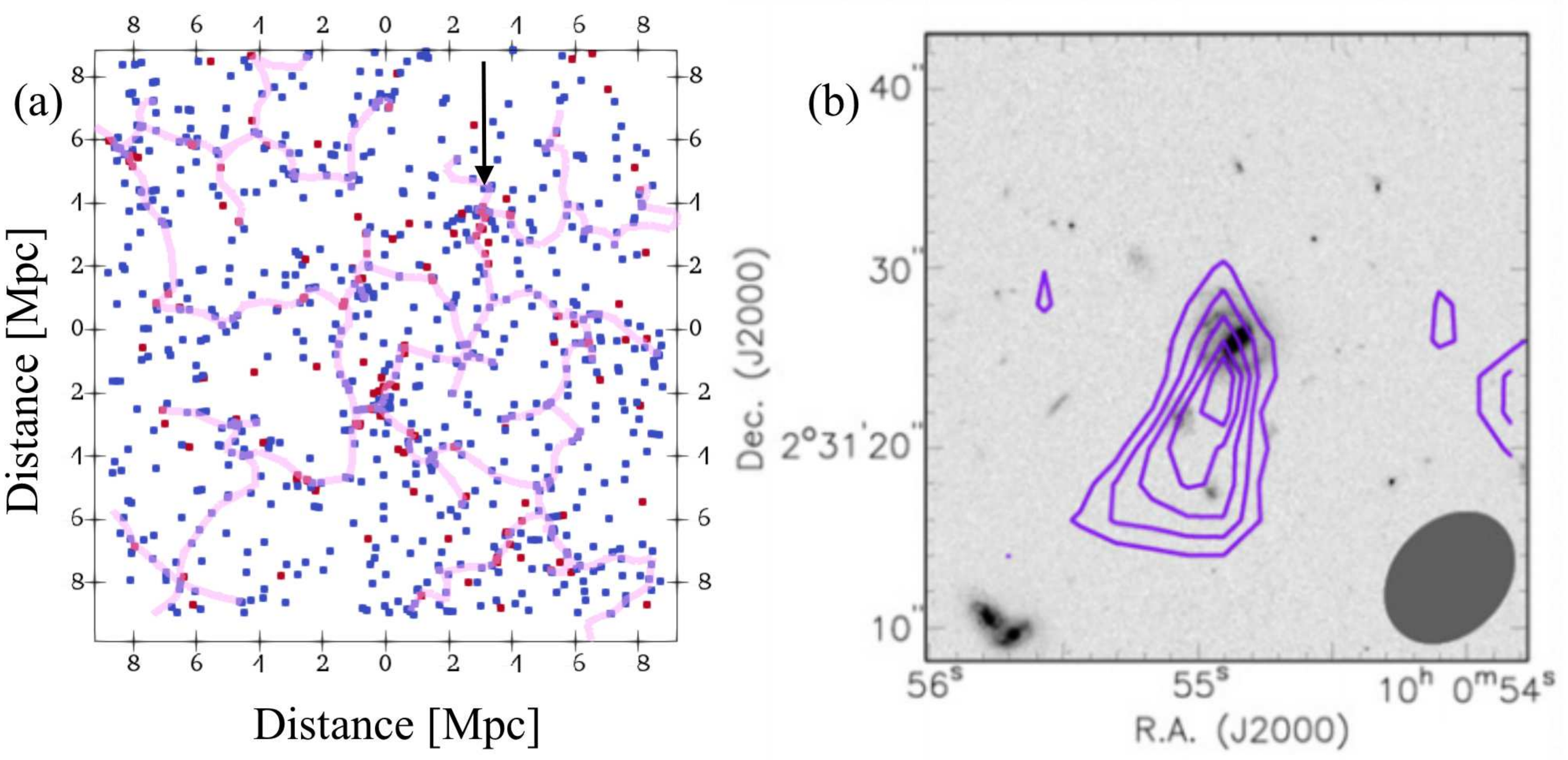
Cosmic web identified by DisPerSE

N. Luber+ in prep

Predicted HI gas fraction for CHILES detections as function of location in Cosmic We



Luber et al , in prep 2018



Galaxy at z=0.376 is extended in HI in the direction of a filament

HI at z=0.12 and z=0.17

Hess, Luber..van der Hulst…et al, submitted