Galaxies in the Cosmic Web: where next ?

Joss Bland-Hawthorn
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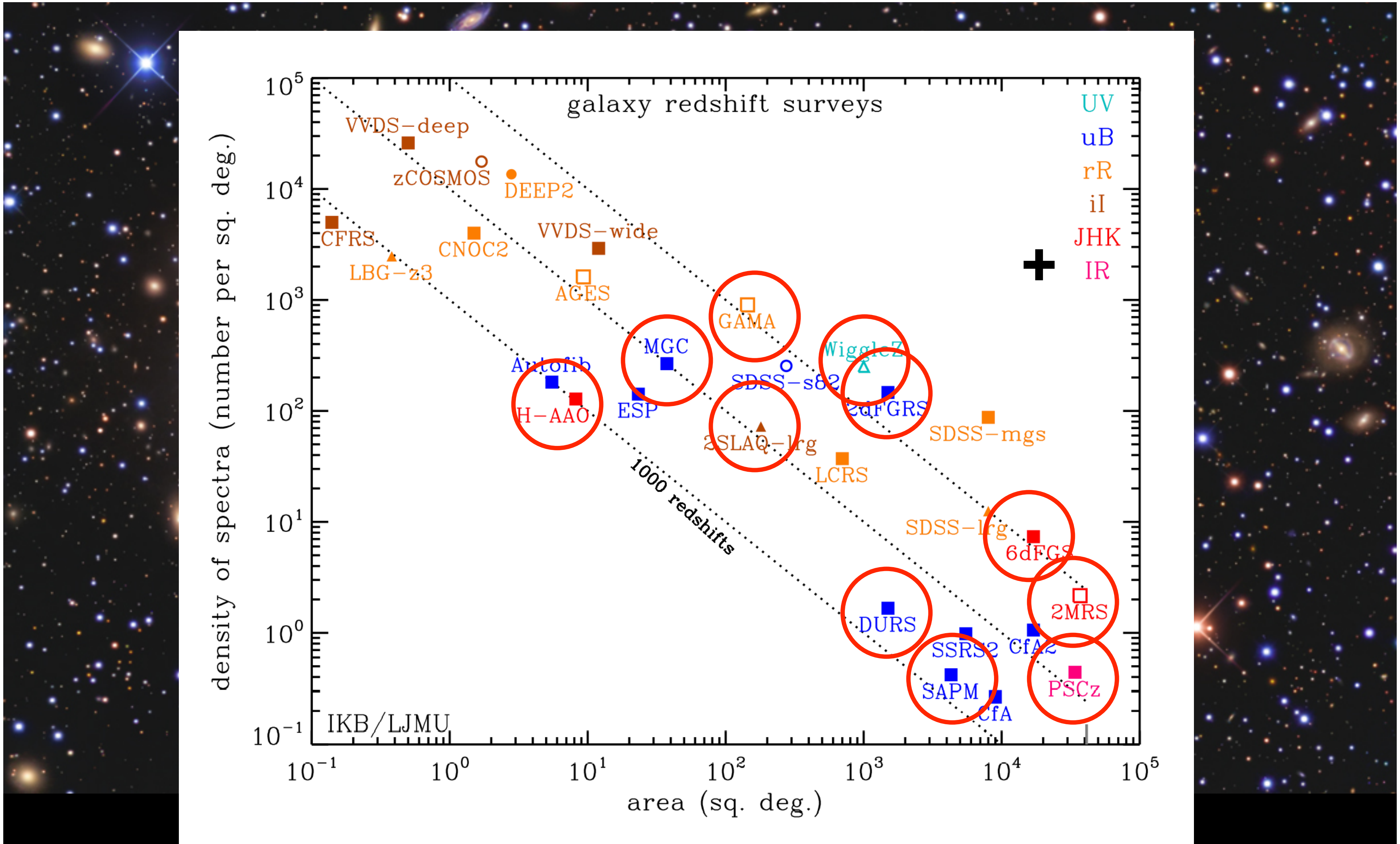
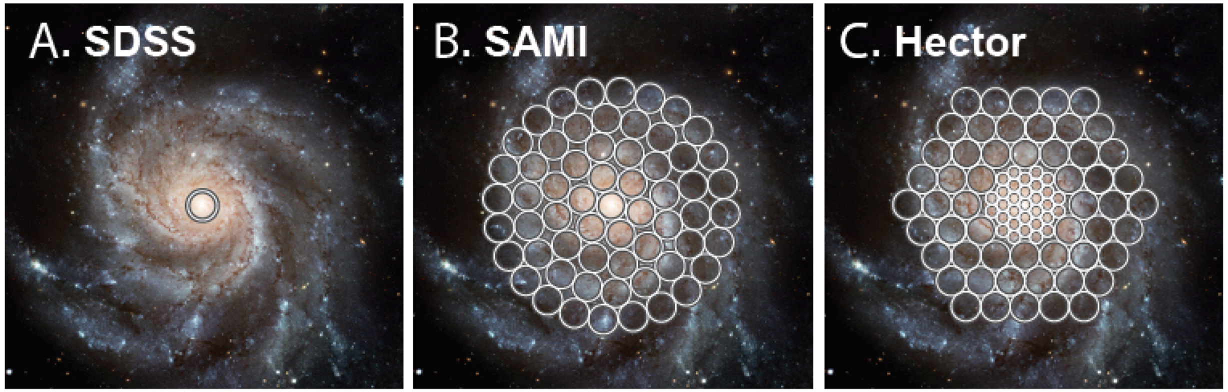


Not everything that <u>counts</u> can be counted, and not everything that can be counted <u>counts</u>. A.E.

Survey information: www.astro.ljmu.ac.uk/~ikb/

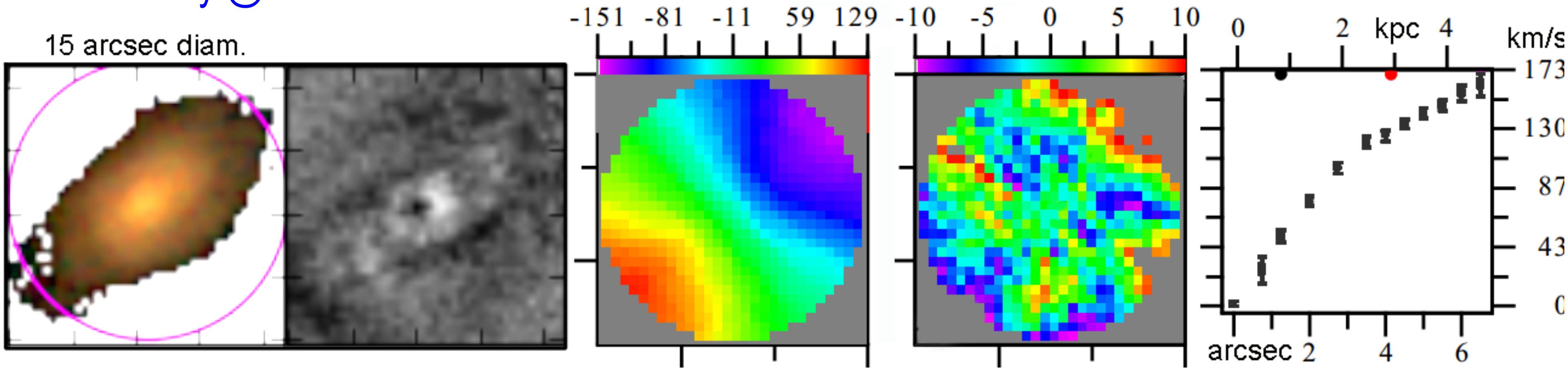
The technological evolution continues…

Before the end of the decade, we will have 100,000+ galaxies with spatially resolved optical, HI kinematics…



cf. Manga

SAMI survey @ AAT



Galaxy studies are an environmental science:

but are there observed environmental dependencies?

Physical Properties and Environments of Nearby Galaxies

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Annu. Rev. Astron. Astrophys. 2009. 47:159–210

They struggle to find a strong environmental dependence beyond cluster vs. field.

Why ?

I will return to this question.

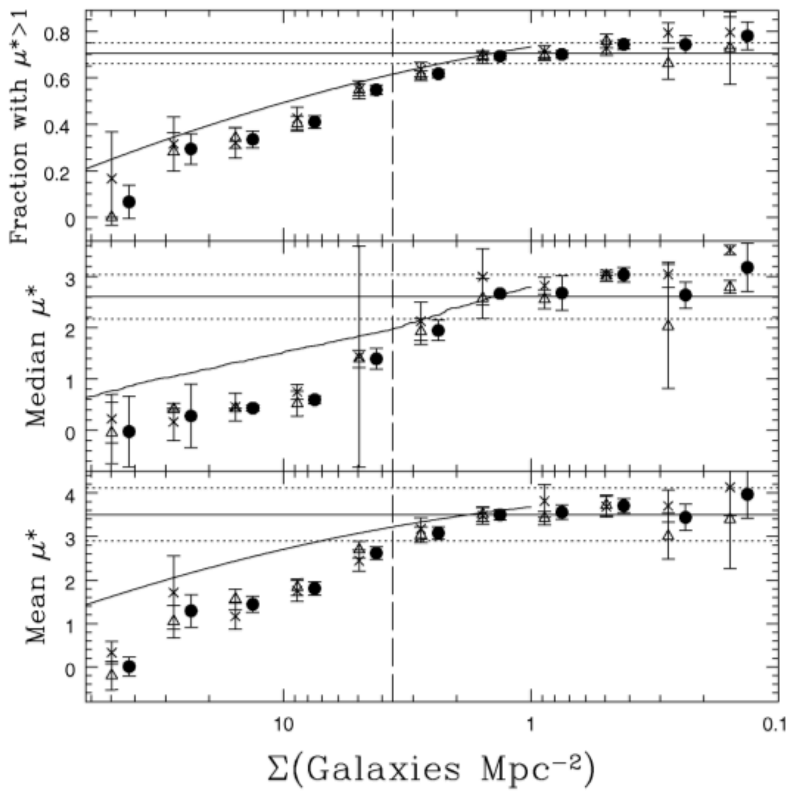
Are there well defined environmental effects over the hierarchy?

Mean star formation rates *appear* to show a trend with environment, but this is mostly a group effect.
Lewis+ 2002; Gomez+ 2003

Scaling relations (e.g. FP) show weak trends with environment.
Blanton & Moustakas 2009

Scatter (e.g. mass-metallicity) may correlate with environment.
Cooper+ 2008

SFR vs. projected local density



Environmental signatures – how do baryons enter or leave a galaxy?

"Galactic engine"

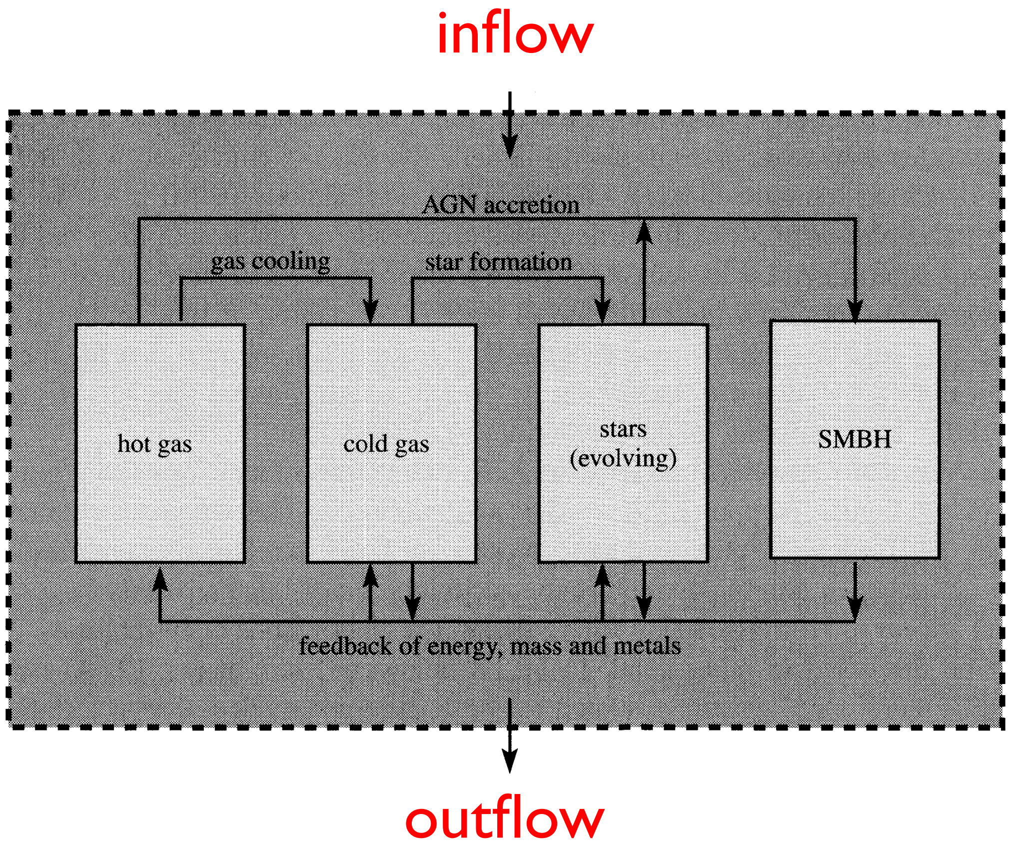
Observables:

structural properties

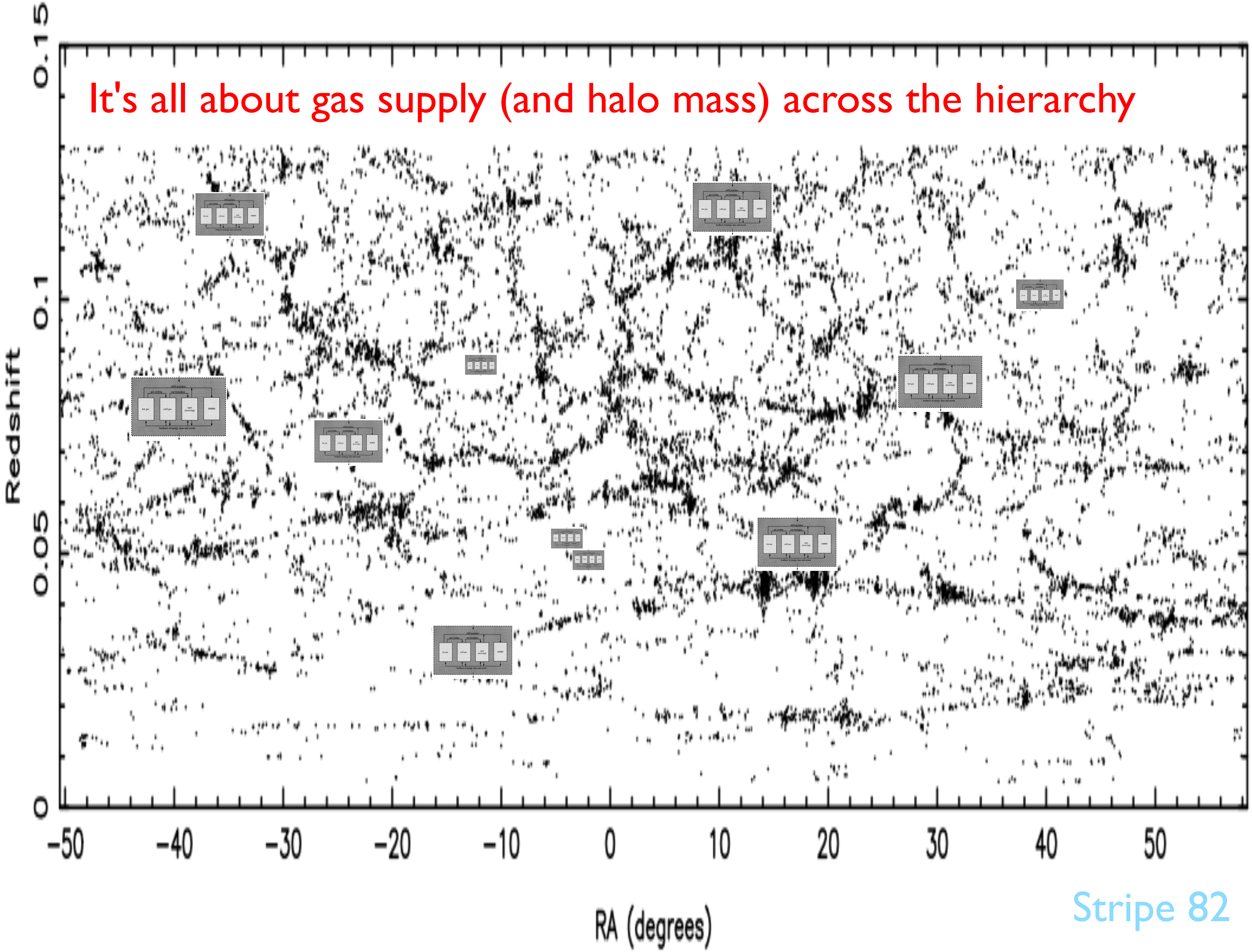
baryon fraction f_b

star formation history

metallicity yield Y_{eff}



Mo, vd Bosch & White 2010


It's all about gas supply (and halo mass) across the hierarchy
Redshift
0
0.05
0.1
0.15
-50
-40
-30
-20
-10
0
10
20
30
40
50
RA (degrees)
Stripe 82

Big questions

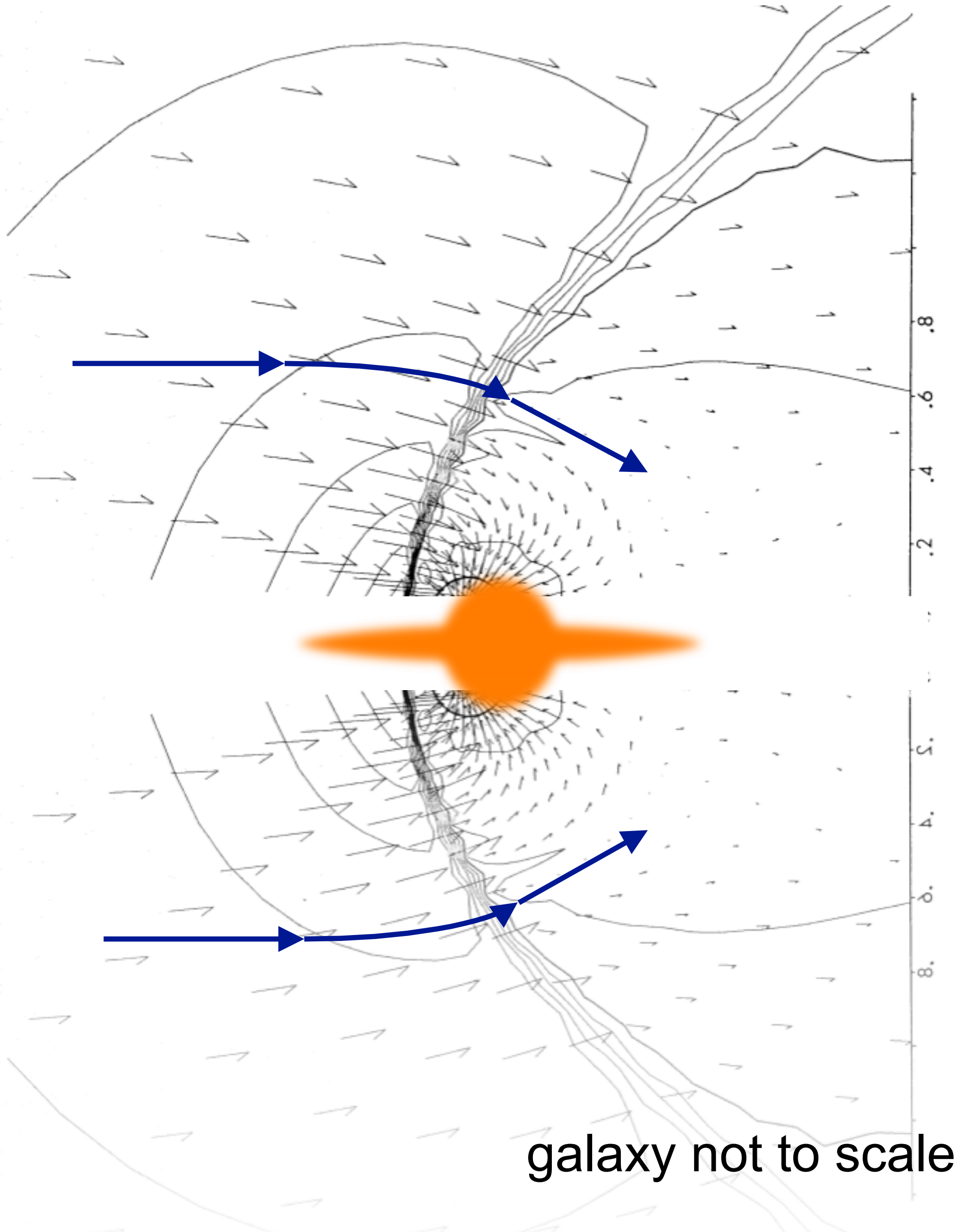
- How does gas get into / out of galaxies ?
- How does baryon fraction vary with environment ?
- How do galaxies get their spin ?

- How are galaxies shaped by their environs at different epochs ?
- How and when was the present Hubble sequence established ?

Gas in…

Galactic, group or cluster accretion (1950-1990)

Spiegel 1966; Larson 1969
Ruderman & Spiegel 1971
Hunt 1971, 1979
Shima+ 1985
Portnoy+ 1993



Accretion in three parts:

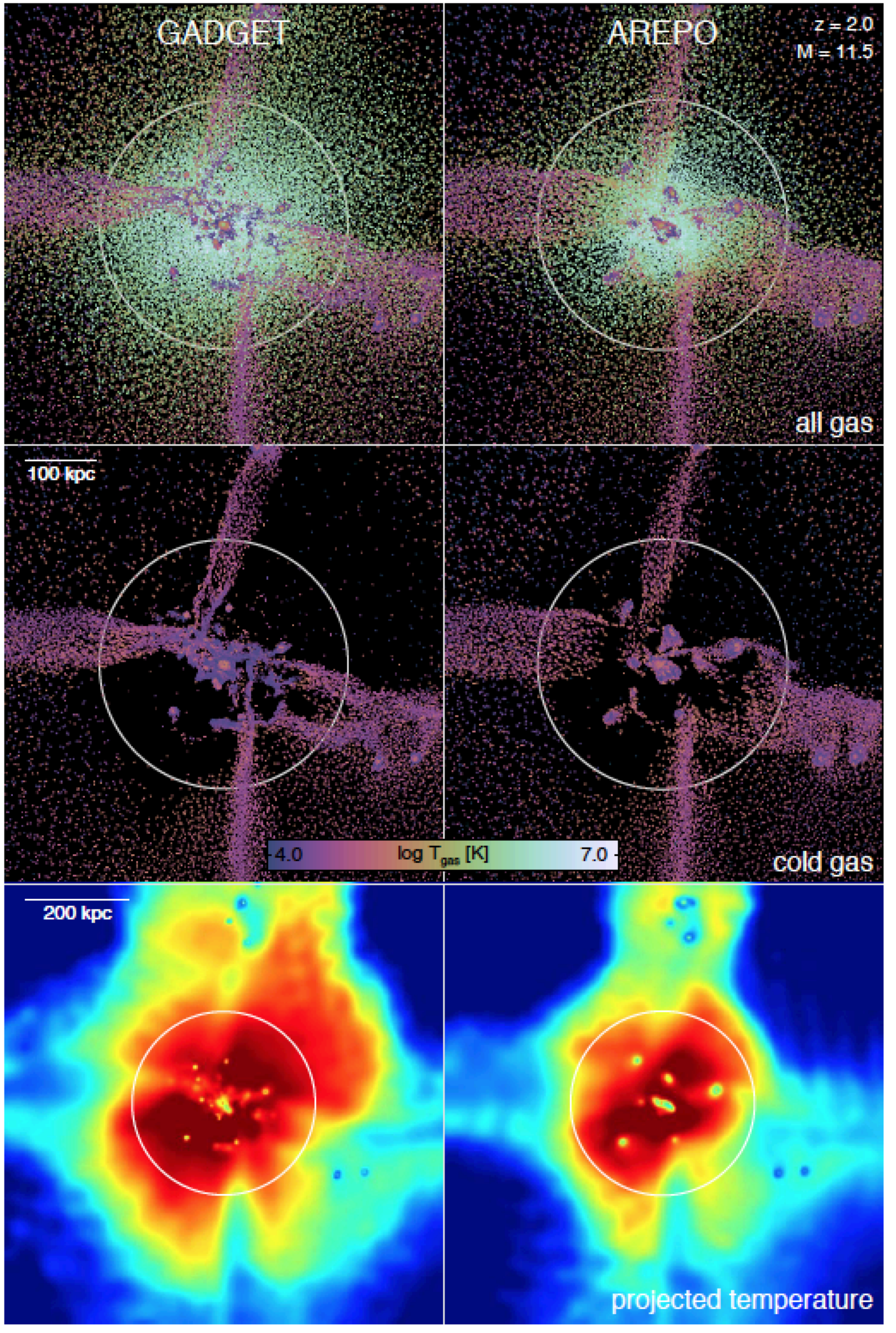
a. cylindrical (sweeping up)
b. spherical (gravitational)
c. Bondi-Hoyle (tail shock)

$$\dot{m} = \frac{4\pi\rho_{gas} G^2 M_{halo}{}^2}{v_{gas}^3}$$

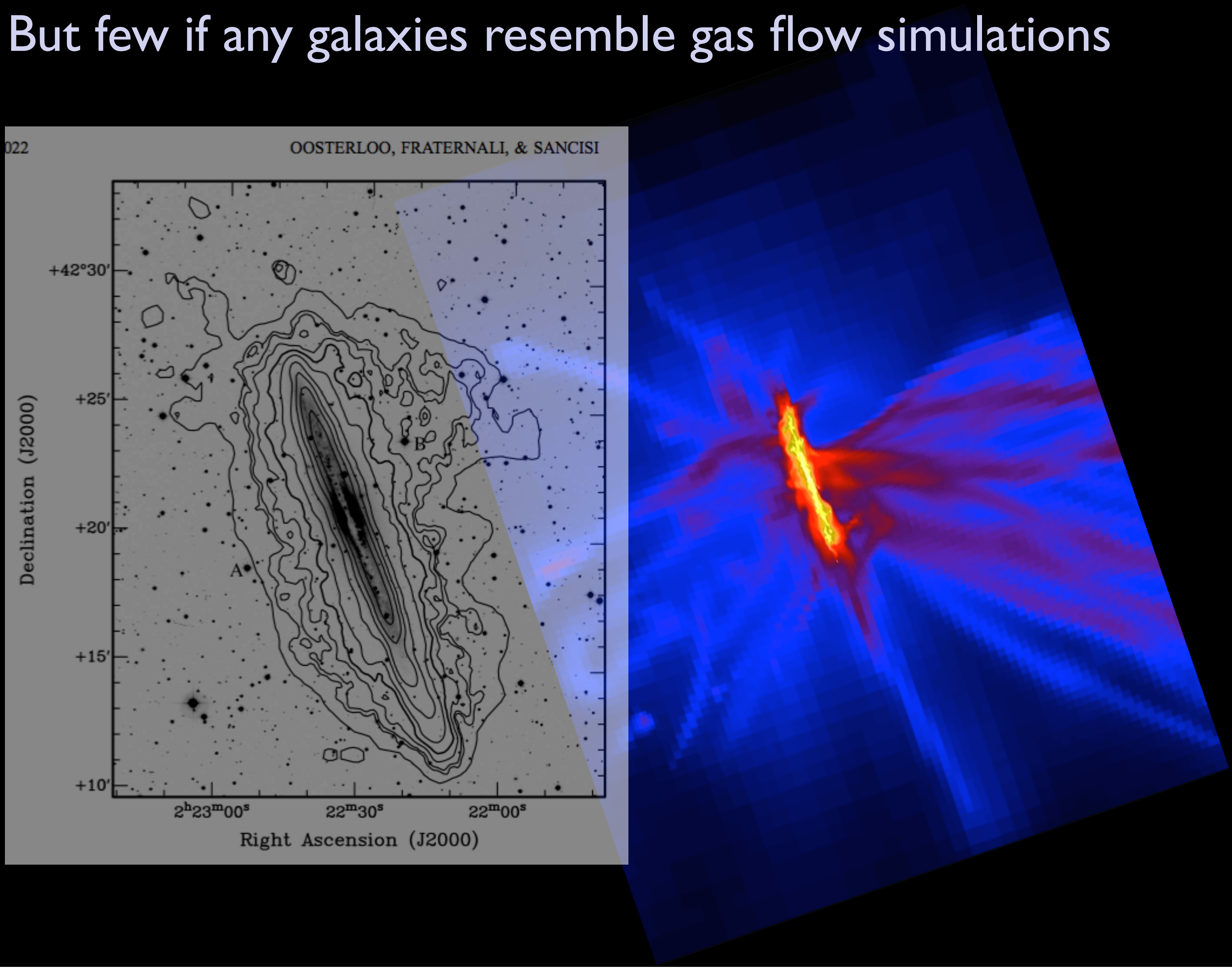
Cold, cool, warm flows
(1990-2015)

Is there a critical halo mass above which hot accretion dominates? (Binney; Silk; Rees)

Not at all clear (Nelson+13)

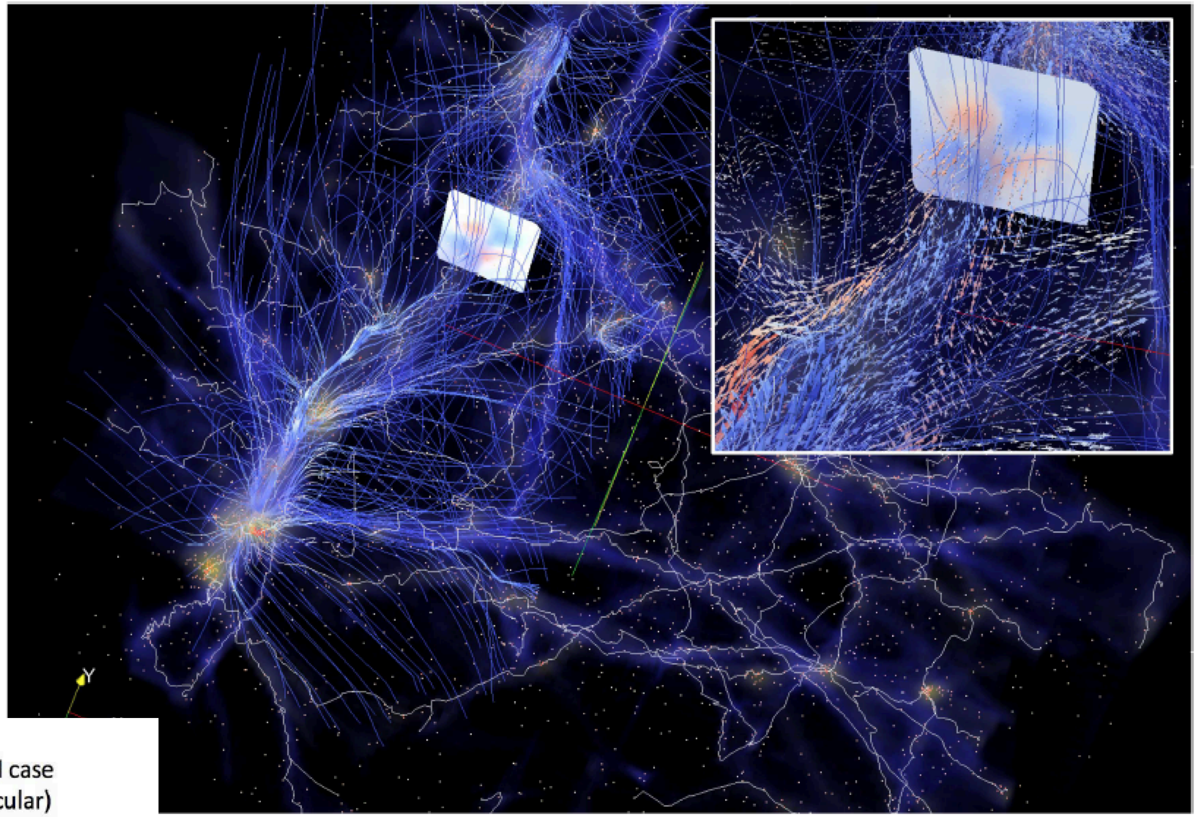


But few if any galaxies resemble gas flow simulations

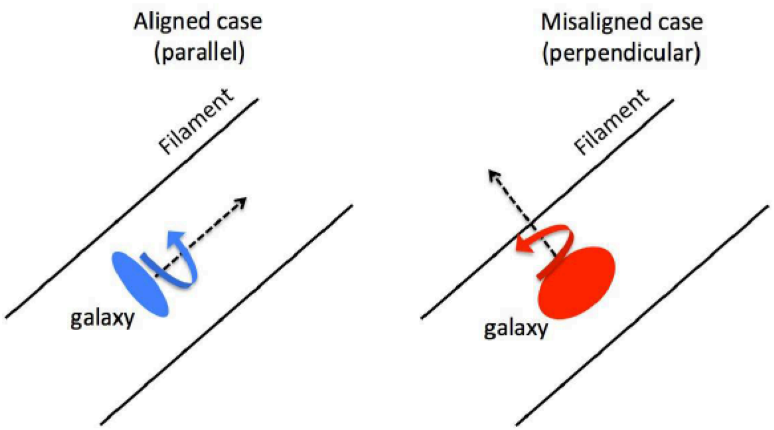


Galactic accretion with vorticity & helicity (2011-2015)

Swirling filaments: are large-scale structure vortices spinning up dark halos? 11



Spinning up haloes
Spin-aligned galaxies



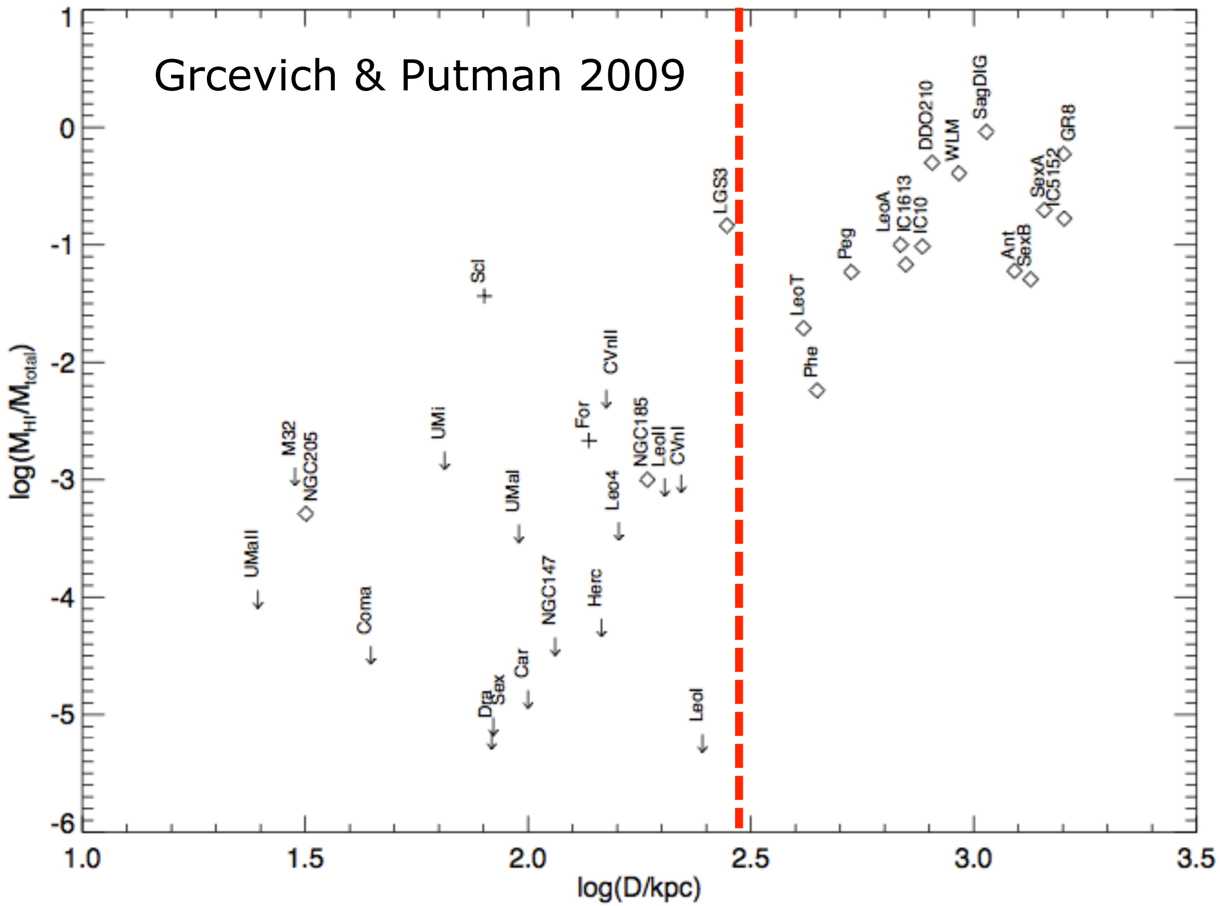
<u>Paris/Oxford group:</u>
Pichon; Codis; Laigle; Dubois; Slyz;
Welker; Sousbie; Powell; Tilsson; Kimm

Gas out…

(observed winds are **not** evidence for escape!)

Gas depletion profiles are evidence for gas loss across an entire population…

HI content of Local Group (MW+M31 combined)



All groups with good data (e.g. M81) show much the same

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GAS DEPLETION IN LOCAL GROUP DWARFS ON ~250 kpc SCALES: RAM PRESSURE STRIPPING ASSISTED BY INTERNAL HEATING AT EARLY TIMES

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Received 2010 December 2; accepted 2011 February 22; published 2011 April 8

THE EPOCH OF ASSEMBLY OF TWO GALAXY GROUPS: A COMPARATIVE STUDY

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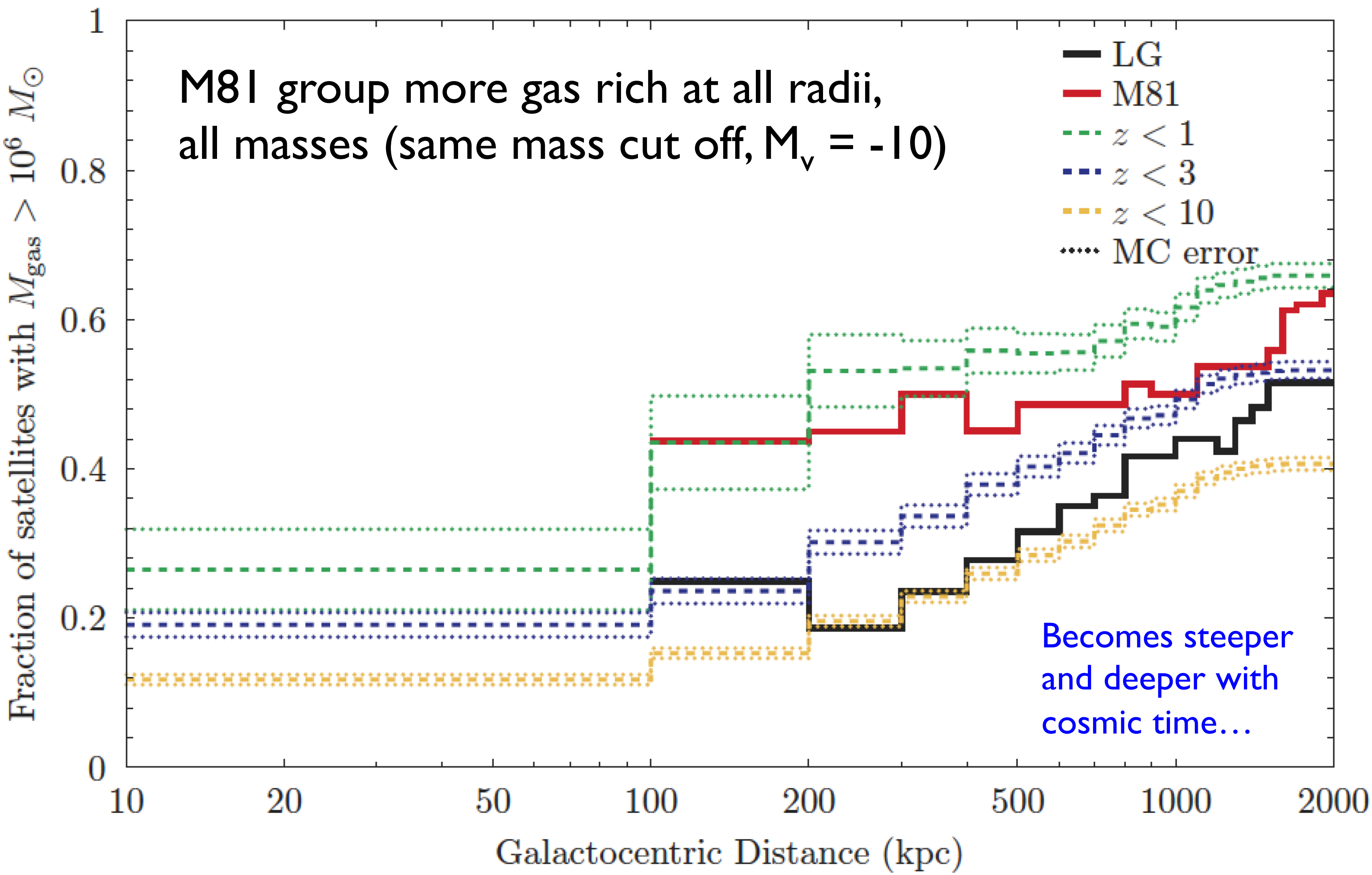
Draft version July 29, 2013

ABSTRACT

Nearby galaxy groups of comparable mass to the Local Group show global variations that reflect differences in their evolutionary history. Satellite galaxies in groups have higher levels of gas deficiency as the distance to their host decreases. The well established gas deficiency profile of the Local Group reflects an epoch of assembly starting at $z \lesssim 10$. We investigate whether this gas deficiency profile can be used to determine the epoch of assembly for other nearby groups. We choose the M81 group as this has the most complete inventory, both in terms of membership and multi wavelength observations. We expand our earlier evolutionary model of satellite dwarf galaxies to not only confirm this result for the Local Group but show that the more gas-rich M81 group is likely to have assembled at a later time ($z \lesssim 1-3$).

M81 group: **Higher** gas fraction and **shallower** depletion profile



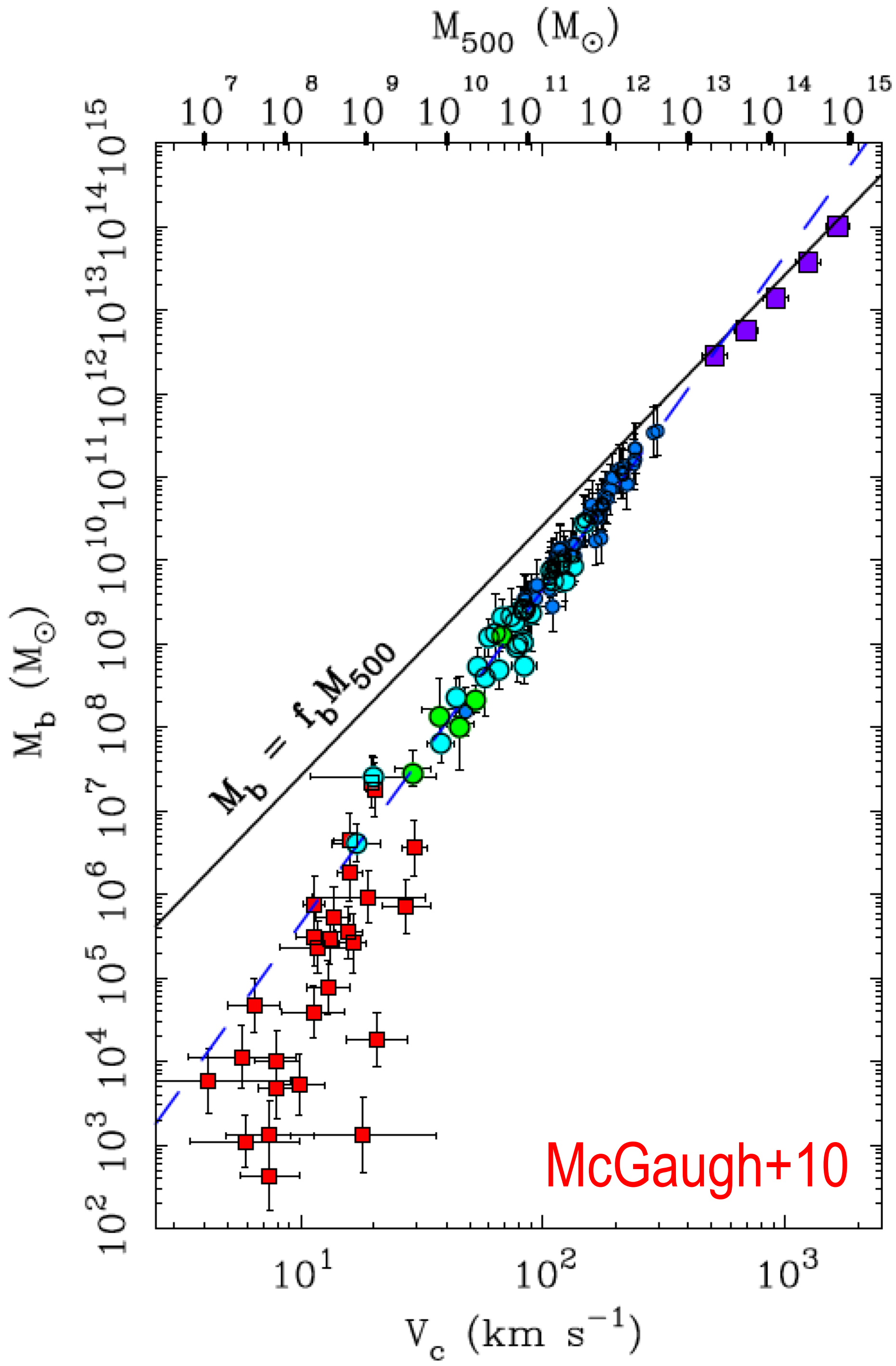
There are clear differences in HI mass between comparable mass groups, but this may reflect different stages of evolution (not f_b)

Big questions

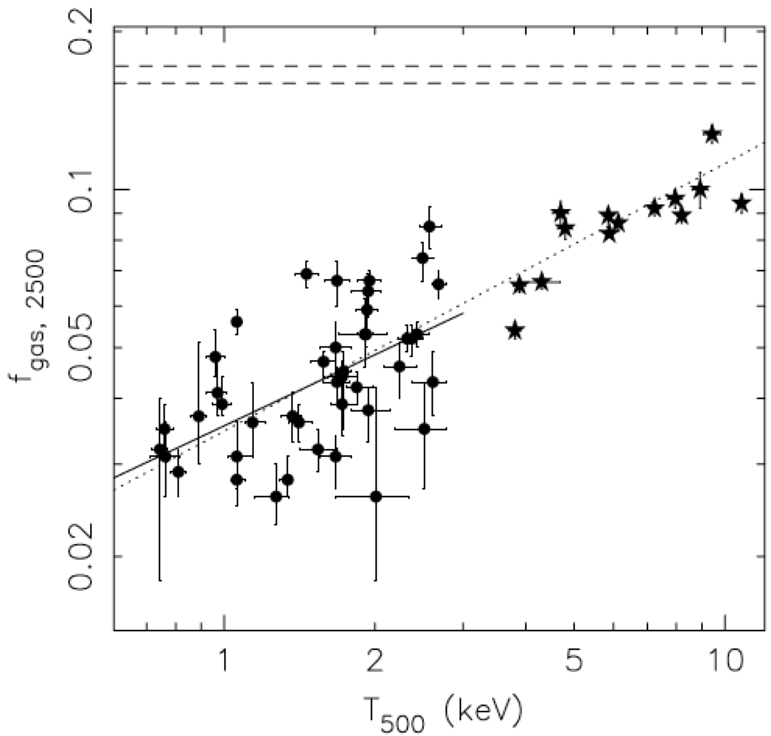
- How does gas get into galaxies ?
- How does baryon fraction vary with environment ?
- How do galaxies get their spin ?

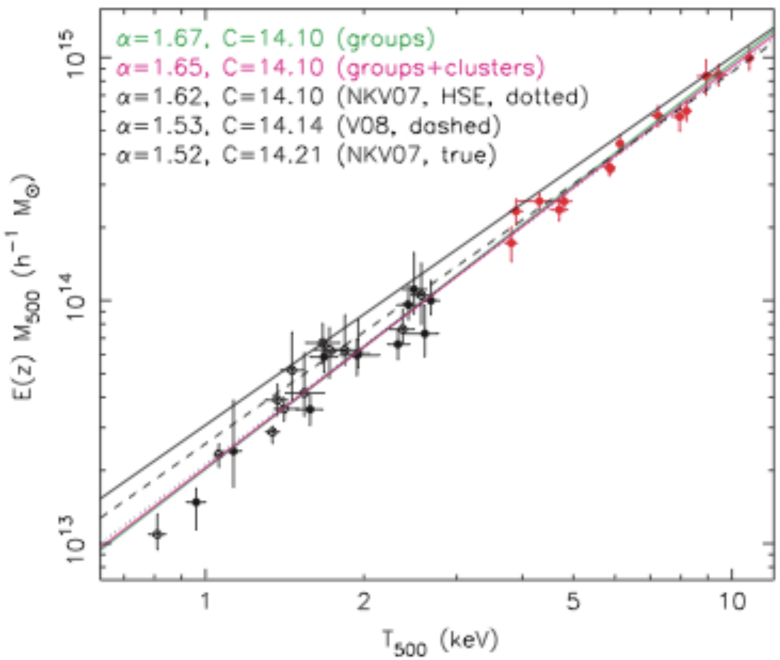
- How are galaxies shaped by their environs at different epochs ?
- How and when was the present Hubble sequence established ?

Well established baryon fraction variations with **total mass**.



The scatter is worse than shown here.





Galaxy clusters

Hard to interpret but big scatter in lower mass clusters, clear variations even in higher mass clusters.

The scatter is more extreme in groups but even harder to interpret.

Sun+ 09

Variations in baryon fraction across large-scale structure ?

Variations in f_b ~ 5% leads to only σ_8 ~ 1% variation in matter power spectrum.

Cosmological – intrinsic

- inhomogeneous BBNS (review: Malaney & Mathews 1993)
- baryon-CDM isocurvature (review: Gordon & Lewis 03)

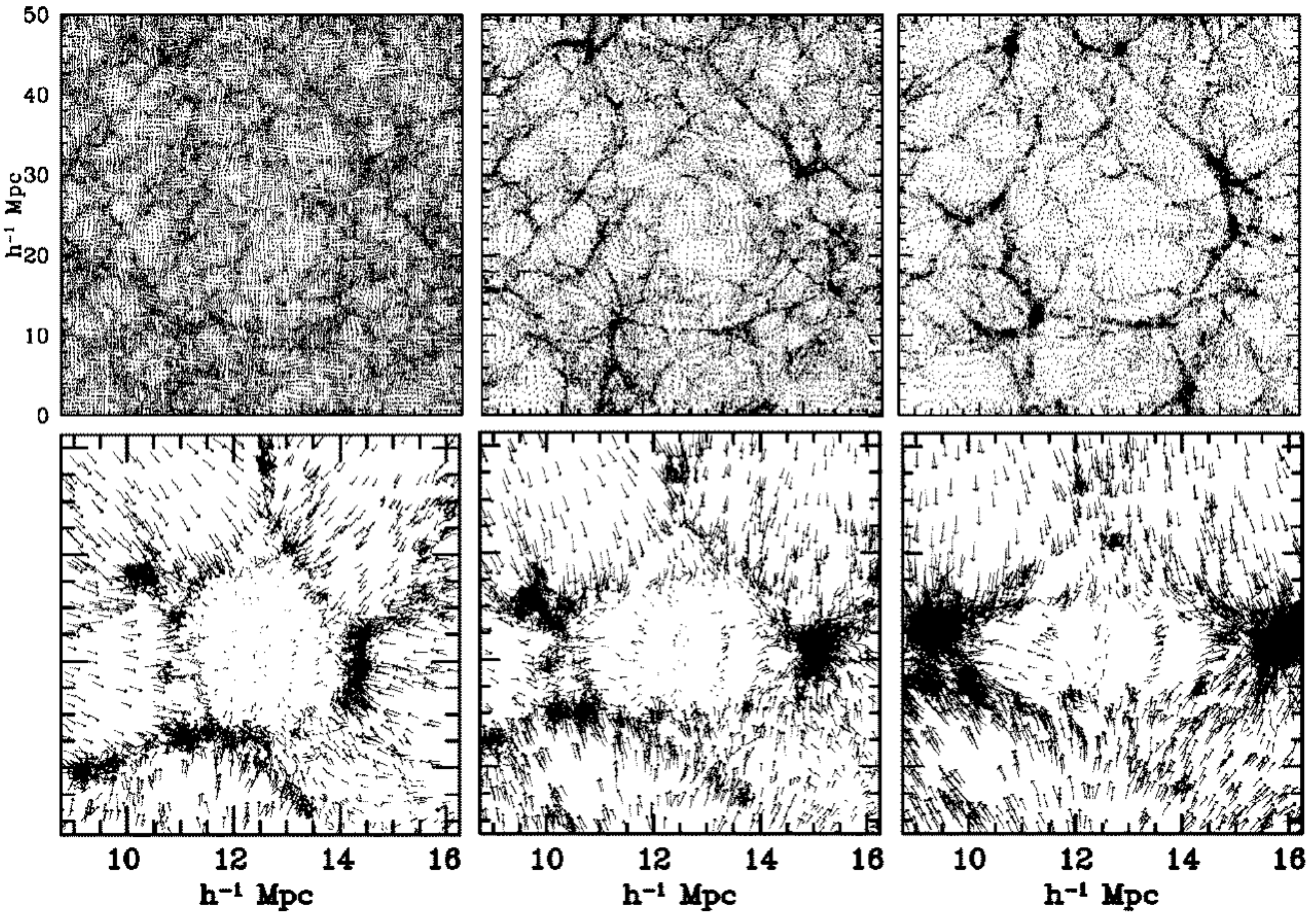
Cosmological – dynamical

- asymmetric collapse (Pichon+11; Kimm+12)
- time delay (McBride+09; Boylan-Kolchin+10)
- large-scale vorticity (Zhu+10)

But are such variations observed?

Only in special cases due to interaction.

Can we separate dark matter + baryons through asymmetric collapse? Pichon+11; Kimm+11; Codis+12; Tilsson+13

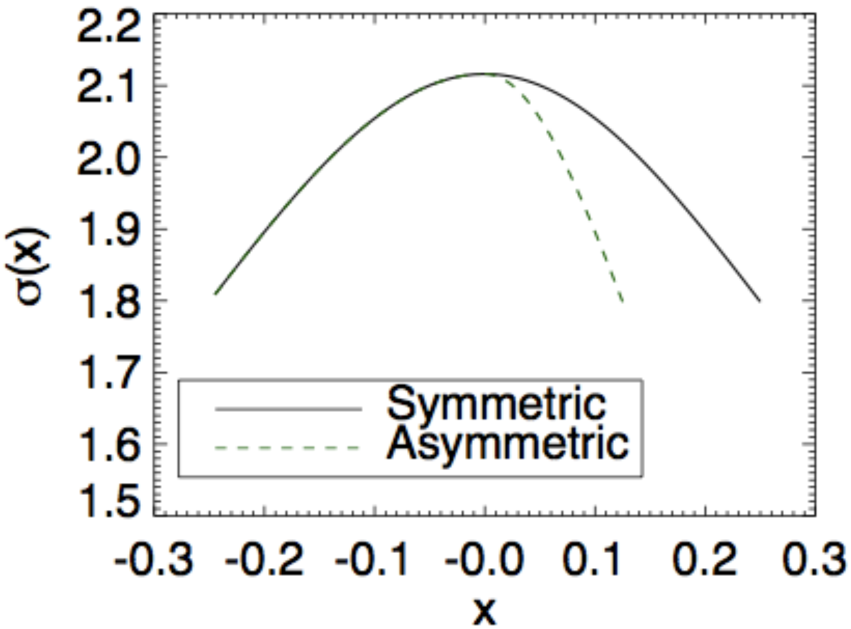


Sheth & vdW 2004

1D toy model

$$\ddot{x} \;=\; 2\pi G \int_{-\infty}^{\infty} \mathrm{Sgn}(x'-x)\sigma(x')dx'$$

Rule: when gas sheets cross, they stick while conserving momentum & mass.



$G = 1 \quad a = 0.3$

$x \propto \xi \quad b = 0.3$

2.2. Setting up the initial conditions

Let $\sigma(\xi)$ $(-1 < \xi < 1)$ be the initial density distribution at $t = 0$, the Big Bang. If no shell crossing has happened since Big Bang the acceleration is constant and is given by

$$a(\xi) = -2\pi G \Sigma_{\rm tot} \xi$$

Let $v(\xi) = v_{\rm tot}\xi$ be the initial velocity field. which makes all the sheets collapse at the same time. This collapse time is given by

$$t_{\rm collapse} = -\frac{2v(\xi)}{a(\xi)} = \frac{2v_{\rm tot}}{2\pi G \Sigma_{\rm tot}\xi}$$

The position and velocity at a later time τ is given by

$$x(\tau) = v_{\rm tot}\xi\tau + \frac{a(\xi)\tau^2}{2}$$
$$v(\tau) = v_{\rm tot}\xi + a(\xi)\tau$$

We set $v_{\rm tot} = 0.75$, which at $\tau = 1$ gives max(v)=max(x)=0.25.

$$\sigma(\xi) = \frac{k}{1 - a\cos(b\pi\xi)} \;, -1 < \xi < 1. \qquad (2)$$

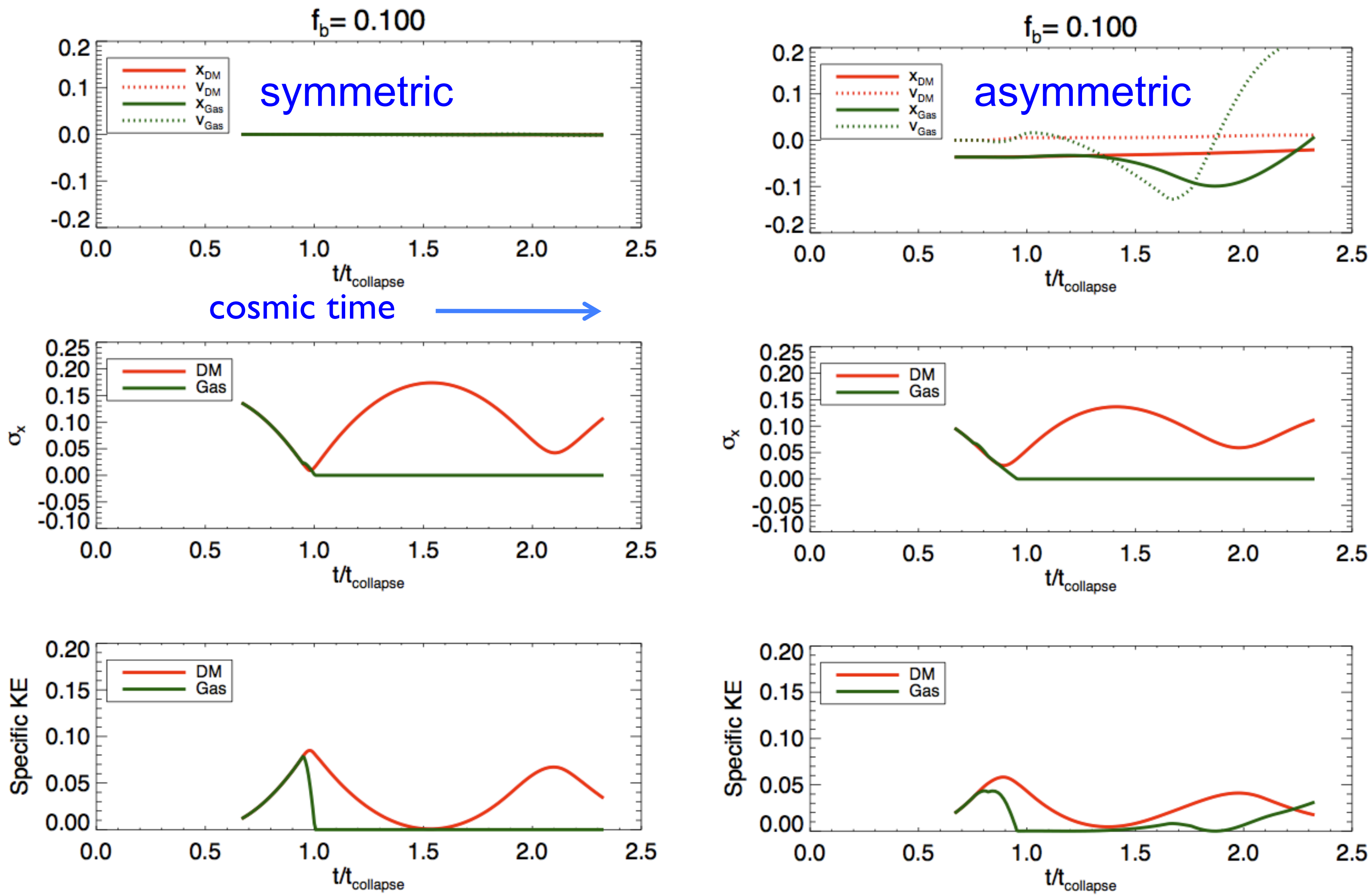
Using $\int_{-1}^{1} \sigma(\xi)d\xi = 1$, the normalization constant is given by

$$k = \frac{\pi b\sqrt{1-a^2}}{4\tan^{-1}((1+a)\tan(b\pi/2)/\sqrt{1-a^2})}$$

To sample such a distribution we use the method of inverse transform sampling. Let $F(>\xi)$ be the cumulative distribution, then for u uniformly sampled between 0 and 1, the ξ is given by

$$\xi \;=\; F^{-1}(u)$$
$$\;=\; \frac{2}{b\pi}\tan^{-1}\left(\tan\left(\frac{(b\pi\sqrt{1-a^2})}{2k}(u-0.5)\right)\frac{\sqrt{1-a^2}}{1+a}\right)$$

Environmental signatures – how baryons enter a sheet, filament, group or cluster?



x_{gas} & v_{gas} depend weakly on f_b

The effects of asymmetry are weaker in 3D

symmetric

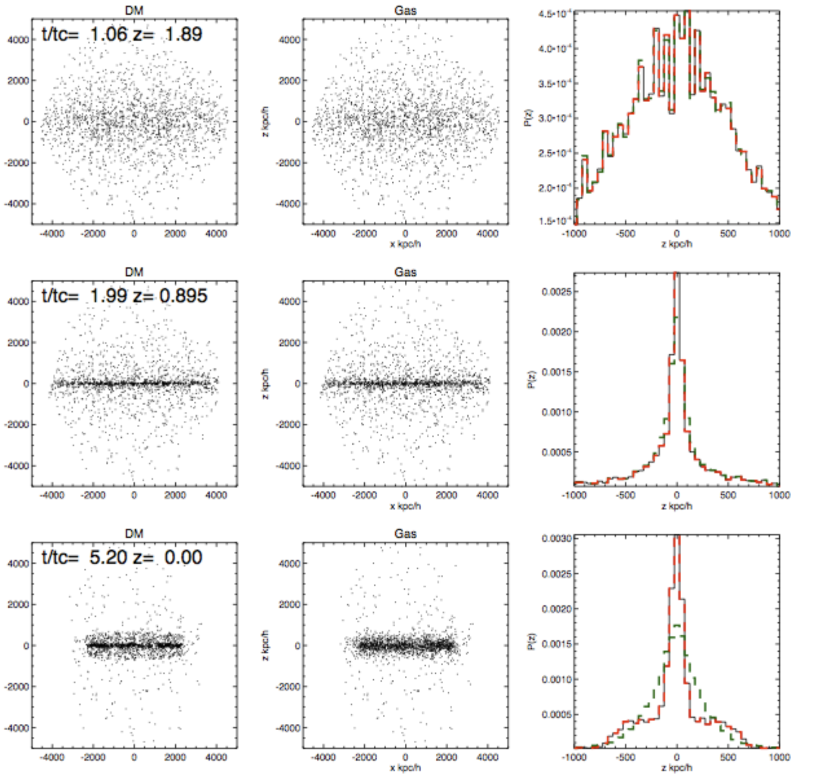


Fig. 9.— The distribution of particles in x-z space as a function of time for a 10 Mpc simulation with symmetric cosi
perturbation along z direction.

asymmetric

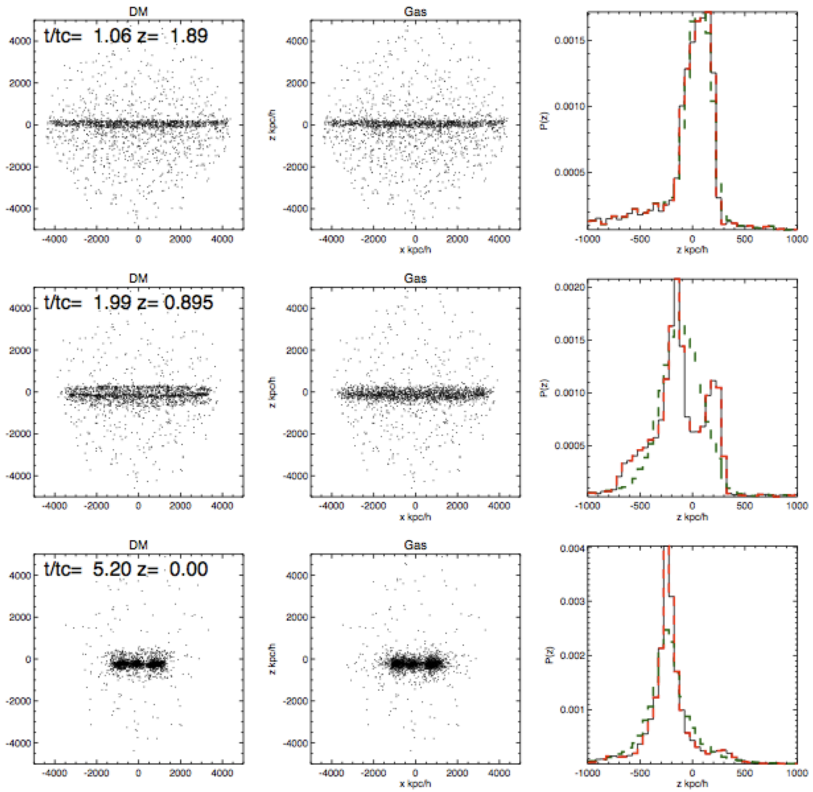
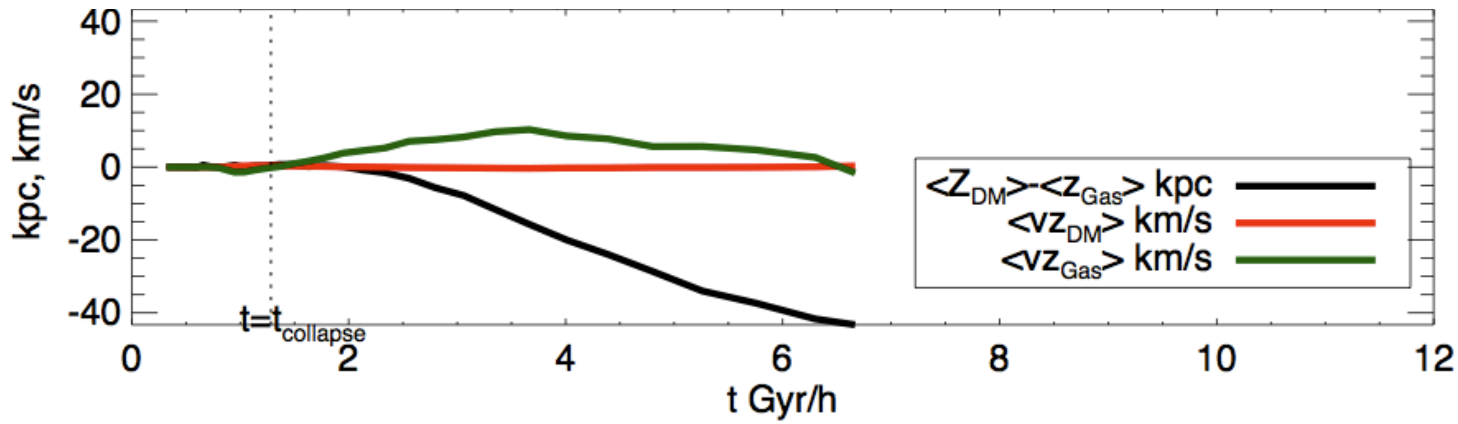


Fig. 10.— The distribution of particles in x-z space as a function of time for a 10 Mpc simulation with asymmetric perturbation along z direction.

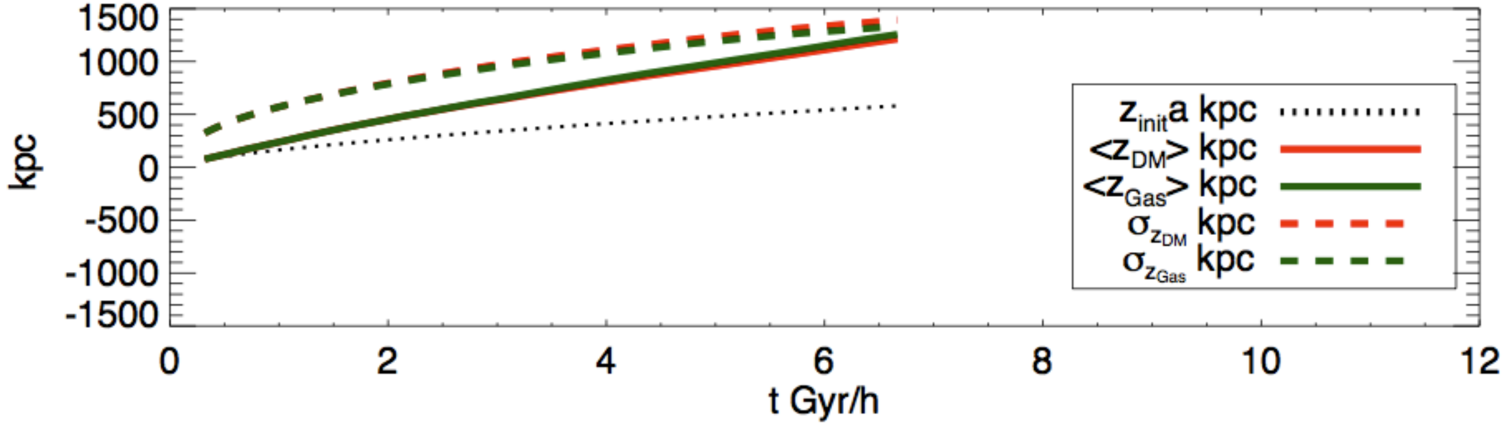
GADGET+SPH

Two effects are evident:

1. Gas and DM separation is much weaker in 3D shown here



2. Gas+DM exhibits strong systemic (barycentric) drift



GADGET+SPH

Conclude:

I cannot motivate a major new survey based on large-scale baryon/DM separation (except for well-established depletion profiles in groups, clusters)

To detect subtle variations with local environment will inevitably require a large survey sample, and new physical parameters.

Are there observed environmental dependencies?

Physical Properties and Environments of Nearby Galaxies

Michael R. Blanton and John Moustakas

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Annu. Rev. Astron. Astrophys. 2009. 47:159–210

They struggle to find a strong environmental dependence beyond cluster vs. field.

Why ?

This may reflect (i) difficulty of defining environment; (ii) inadequacy of existing data.

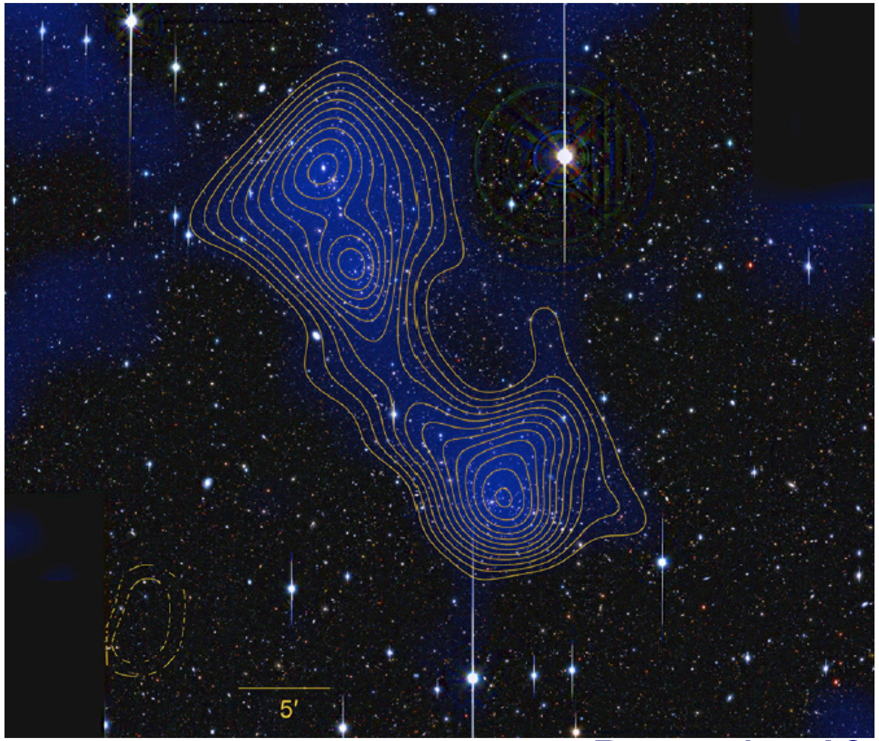
What is environment?

(Haas+ 2011; Muldrew+ 2012; Blanton & Moustakas 2009)

Statistical environment –
a measure of "crowding"

Parameter	Distance-related parameter value	Minimum mass/luminosity	References
From observations			
(Projected) galaxy number density	Average of nearest 10 galaxies	$m_V < 16.5$	1, 2, 3
		$M_V < -20.4$	3
	Group average	$M_B < -17.5$	4
Cluster-/group-centric radius	–	$M_r < -20.5$	5, 6
	–	$M_V < -20.4$	3
	–	$m_V < 16.5$	2
	Scaled to the virial radius	$r < 17.77$	7
Projected galaxy number density out to the Nth nearest neighbour with a maximum radial velocity difference Δv	$N = 3$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$R < 24.1$	8, 9, 10
	$N = 4,5$	$M_R < -20$	11 - 16
	$N = 4,5$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_r < -20$	13, 14
	$N = 4,5$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_r < -20.6$	16
	$N = 5$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_r < -20.6$	11
	$N = 5$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_r < -20$	12
	$N = 5, 10, 20$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$I_{AB} < 25$	17
	$N = 10$	$M_V < -20$	18
	$N = 10$	$I < -24$	15
	$N = 10$, in clusters	$M_b < -19$	19
Galaxy number density in sphere of proper radius r	$r \simeq 1\,h^{-1}\,\mathrm{Mpc}$	$r < 17.77$	20
	$r = 8\,h^{-1}\,\mathrm{Mpc}$, $\Delta v \leq 800\,\mathrm{km\,s^{-1}}$	$r < 17.77$	21, 22, 23
Number of neighbours in cylinders with projected radius r	$r = 0.1$–$10\,h^{-1}\,\mathrm{Mpc}$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_{0.1r} - 5\mathrm{Log}_{10}\,h < -19$	24, 25
	$r = 0.5, 1, 2\,h^{-1}\,\mathrm{Mpc}$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$M_r < -20$	26
	$r = 1\,h^{-1}\,\mathrm{Mpc}$, Δv corresponding to 8 Mpc	$r < 17.77$	27
	$r = 1$ - $10\,h^{-1}\,\mathrm{Mpc}$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$I_{AB} < 25$	17
	$r = 2\,h^{-1}\,\mathrm{Mpc}$, $\Delta v = 1000\,\mathrm{km\,s^{-1}}$	$r < 17.77$	28
Mass density due to nearest neighbour ($\rho = 3M_{\mathrm{ngb}}/4\pi r^3_{\mathrm{ngb}}$)	$N = 1$ or N for which ρ is maximal $\Delta v = 400, 600\,\mathrm{km\,s^{-1}}$	$M_{r,\mathrm{ngb}} \gtrsim M_{r,\mathrm{gal}} + 0.5$	29
Projected galaxy number density in annuli	$\{0.5,1,2\} < R/(h^{-1}\,\mathrm{Mpc}) < \{1,2,3\}$	$M_r < -20$	26
	$1 < R/(h^{-1}\,\mathrm{Mpc}) < 3$	$r < 17.77$	28
From simulations			
Halo mass	-	$M > 2.35 \times 10^{10}\,h^{-1}\,\mathrm{M_\odot}$	30
Number of neighbours in spheres of radius R	$R = 2\,h^{-1}\,\mathrm{Mpc}$	$V_{\max} > 120\,\mathrm{km\,s^{-1}}$	31
Mass or density in spheres of radius R	$R = 1, 2, 4, 8\,h^{-1}\,\mathrm{Mpc}$	–	32, 33
	$R = 5\,h^{-1}\,\mathrm{Mpc}$	–	34, 35
	$R = 5, 8\,h^{-1}\,\mathrm{Mpc}$	–	36
	$R = 7\,h^{-1}\,\mathrm{Mpc}$	–	30
	$R = 18, 25\,h^{-1}\,\mathrm{Mpc}$	–	37
Matter density in spherical shells	$2 < R/(h^{-1}\,\mathrm{Mpc}) < 5$	–	38, 39, 40
	$2 < R/(h^{-1}\,\mathrm{Mpc}) < 7$	–	30
	$R_{\mathrm{FOF}} < R < 2\,h^{-1}\,\mathrm{Mpc}$	–	30
	$R_{\mathrm{vir}} < R < 3R_{\mathrm{vir}}$	–	41
Average mass density of surrounding haloes	$N = 7$	$200 < V_{\max}/\mathrm{km\,s^{-1}} < 300$	42

Physical environment – I



Dietrich+ 12

How do we define physical structures?

Ideally these would be defined in terms of EUV/x-ray emissivity, CMB SZ or weak lensing signal.

But while useful for dense groups & cluster mass scales, these are much less sensitive to large-scale structure and low densities.

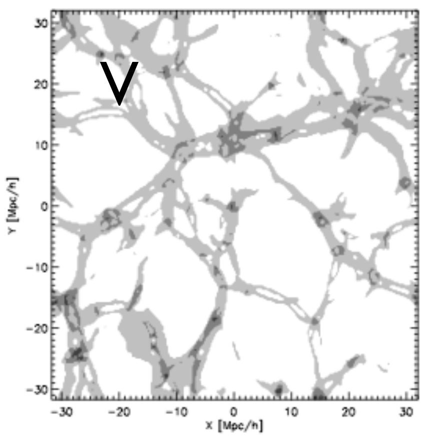
For the foreseeable future, we are limited to **galaxy redshift surveys**.

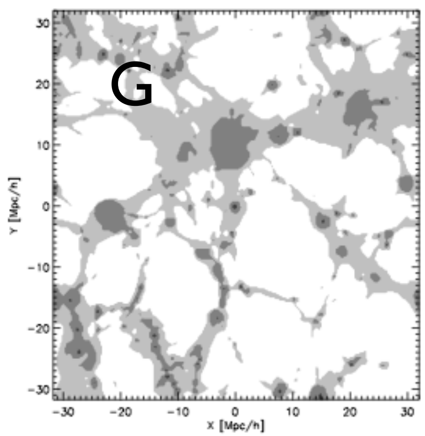
Physical environment – II

"A collection of connected points having the same environmental attributes."

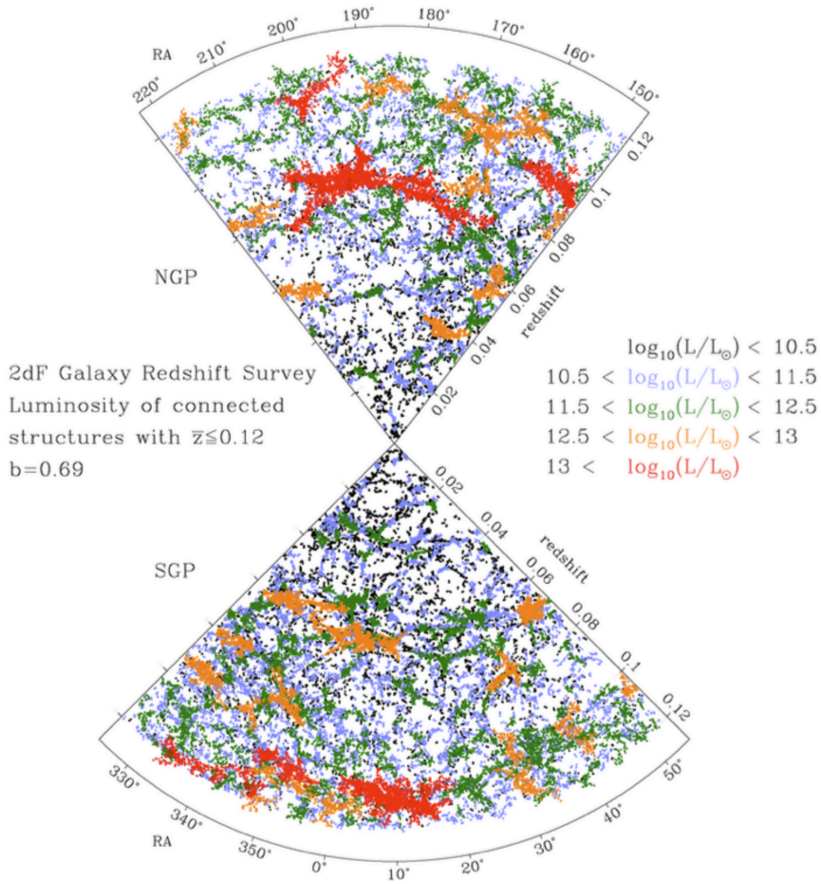
1. **Double pass friends of friends** (Murphy+ 2011)
2. **Multiscale mapping** (Barrow+ 1985; Aragon-Calvo+ 2007; Smith+ 2012)
3. **Geometric classifiers** (Lemson & Kauffman 1999; Sousbie+ 2008)
4. **Dynamic classifiers** (Hahn+ 2007; Hoffman+ 2012)

Dynamic classifiers – **G**ravitational tidal tensor, **V**elocity shear tensor – are the most physical but have not been demonstrated on data yet.





$$\Sigma_{\alpha\beta} = -\frac{1}{2}\left(\frac{\partial v_\alpha}{\partial r_\beta} + \frac{\partial v_\beta}{\partial r_\alpha}\right)/H_0 \qquad T_{\alpha\beta} = \frac{\partial^2 \phi}{\partial r_\alpha \partial r_\beta}$$



Future innovative surveys:

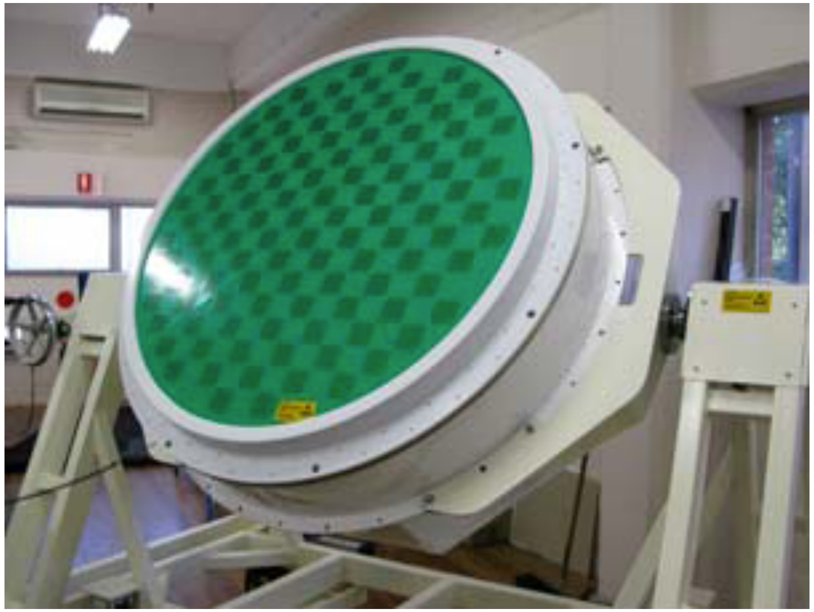
radio, optical ($10^{5\text{-}6}$ galaxies; $z < 0.2$)

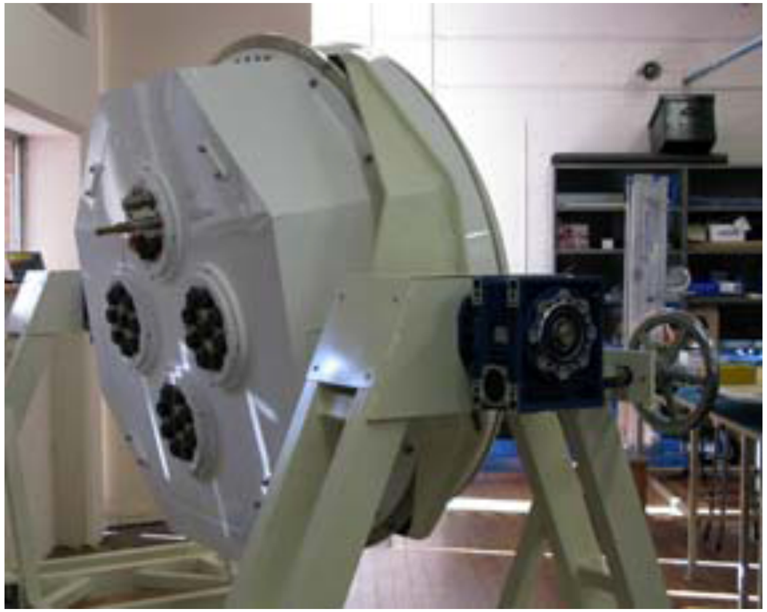
Motivation:

Distribution and kinematics of cool gas

Distribution and kinematics of stars, warm gas

The ASKAP PAF – a new radio camera





April 2011: Front view & rear view of the ASKAP PAF

- *PAF = Phased Array Feeds (checkerboard array: 188 elements)*
- *Beamformer: creates up to 36 beams, each 1.2 deg FWHM*
- *resulting field of view is 30 square degrees (5.5 deg × 5.5 deg)*

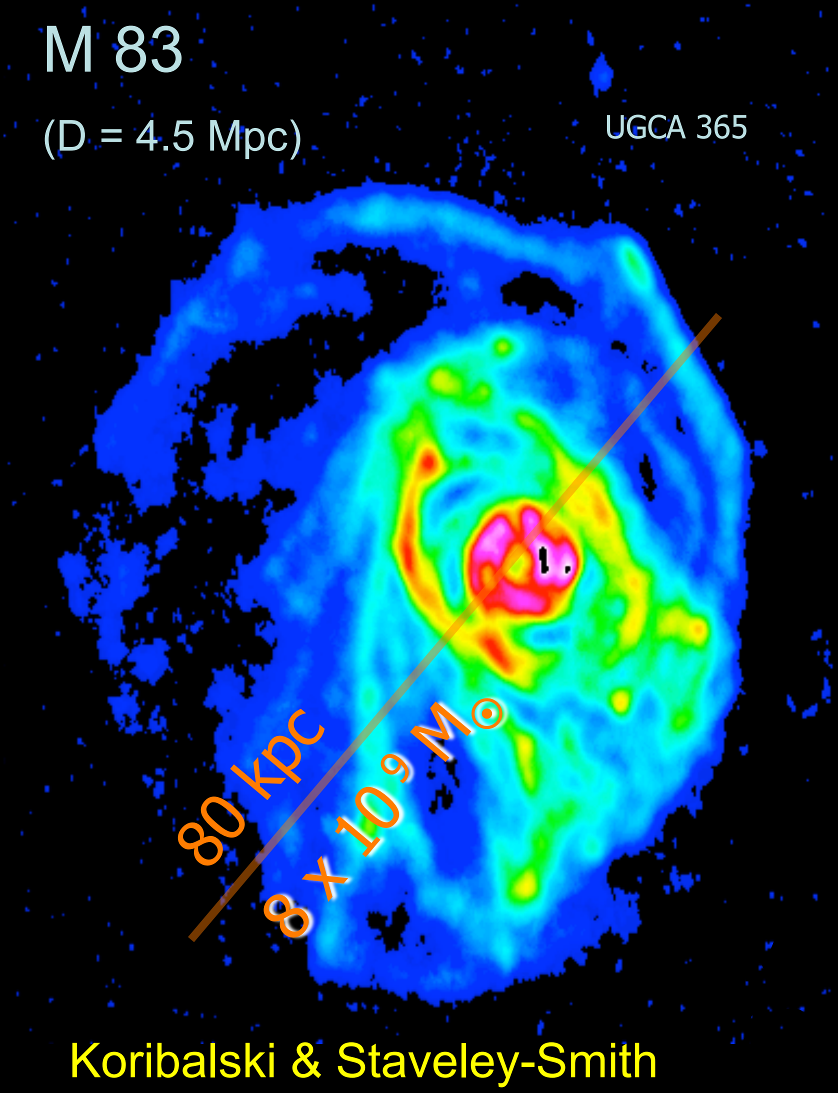
WALLABY – sensitivity & scales

600,000 HI sources to z ~ 0.2

- e.g., 8h integration time
  ➡ 5σ M_{HI} limit
  = 5 x 10^6 $M_\odot$ (D = 10 Mpc)
  = 5 x 10^8 $M_\odot$ (D = 100 Mpc)
  = 3 x 10^{10} $M_\odot$ (D = 800 Mpc)

- 10” beam
  = 0.5 kpc (D = 10 Mpc)
  = 5 kpc (D = 100 Mpc)
  = 39 kpc (D = 800 Mpc)

- 30” beam
  = 1.5 kpc (D = 10 Mpc)
  = 15 kpc (D = 100 Mpc)
  = 116 kpc (D = 800 Mpc)



GAMA: we expect 3×10^4 groups down to LG mass with complete HI follow-up (2015-18)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Galaxy and Mass Assembly (GAMA): the GAMA galaxy group catalogue (G^{3}Cv1)

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Sydney-AAO Multibundle Instrument – **SAMI**

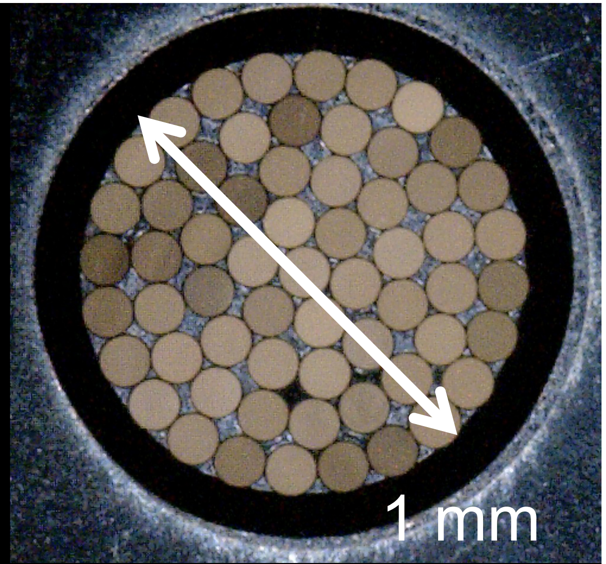
$R \sim 5000$ (370-550 nm, 620-740 nm)

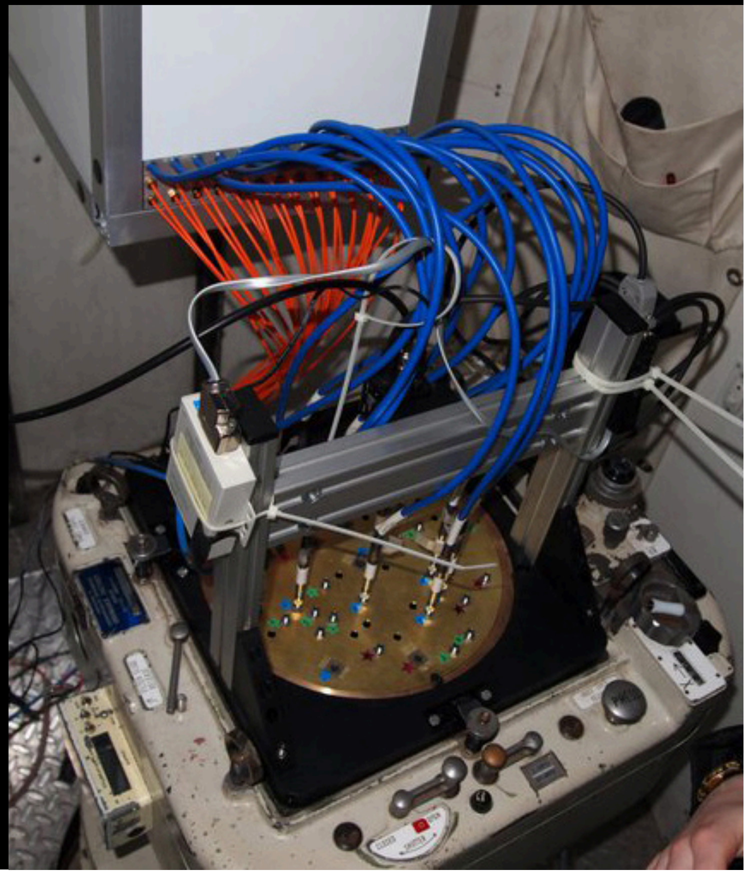
3400 galaxies with integral field spectroscopy

Target GAMA fields to $b_J \sim 16.5$; mass selected

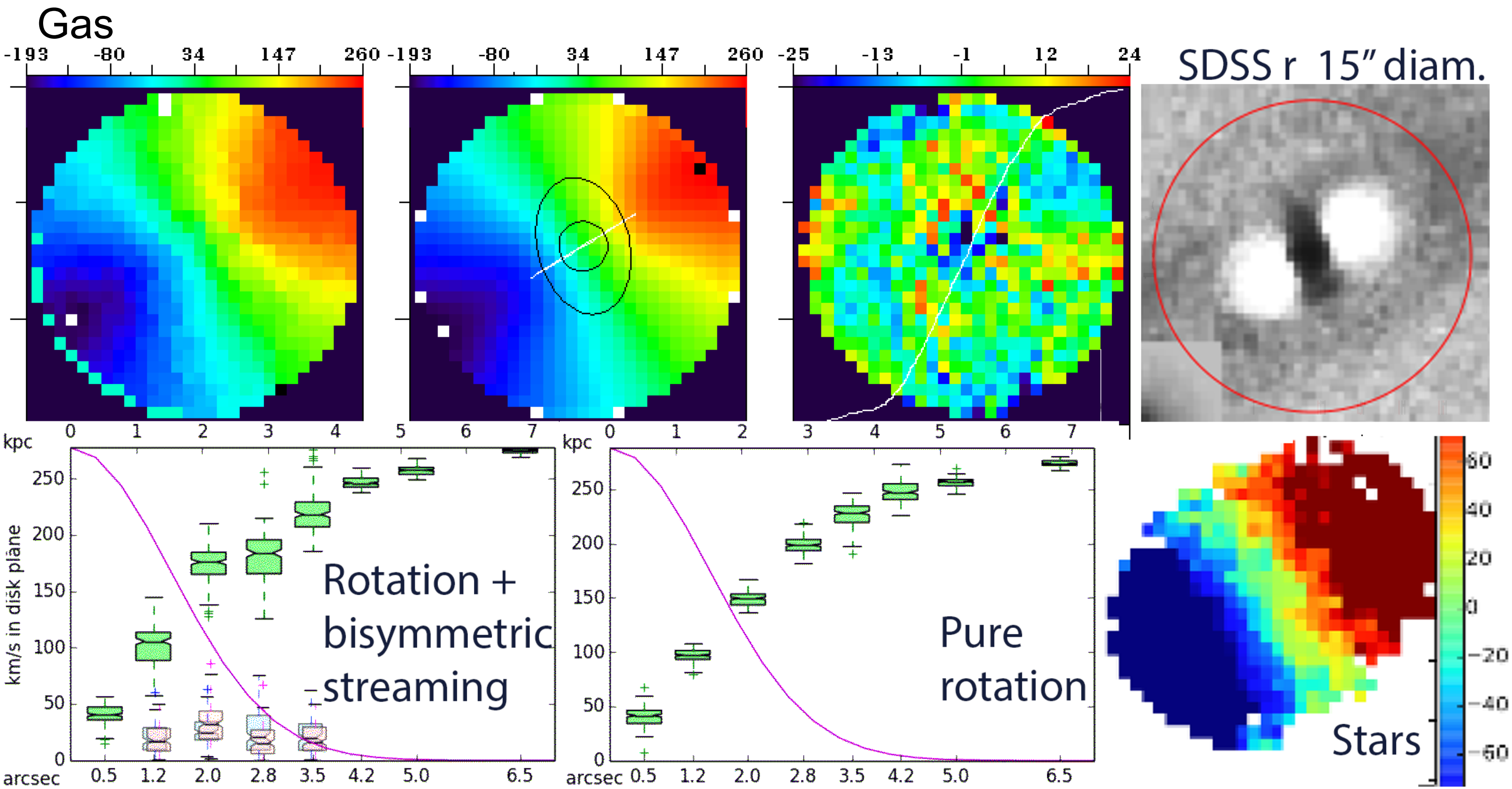
First release in July 2014

Croom+ 2012





SAMI: We now have 1000+ data sheets like this…



G. Cecil

The SAMI Pilot Survey: The Kinematic Morphology-Density Relation in Abell 85, Abell 168 and Abell 2399

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D. Heath Jones[6], James T. Allen[1], Julia J. Bryant[1,2], Michael Goodwin[3],
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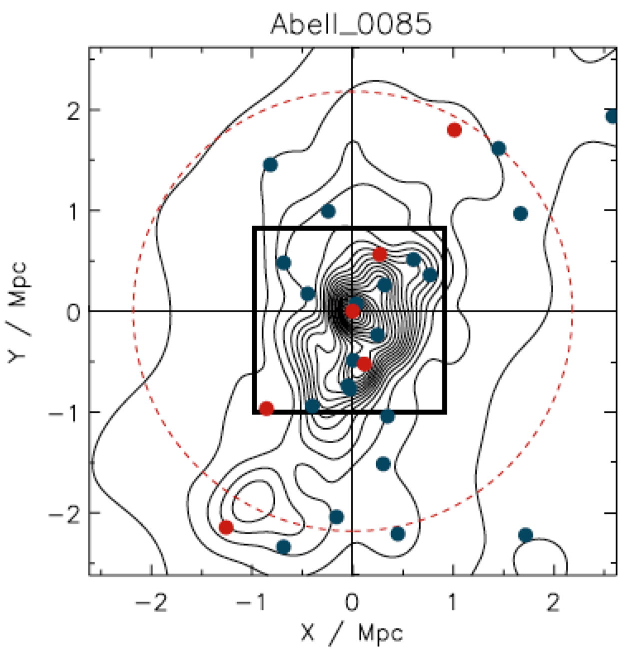
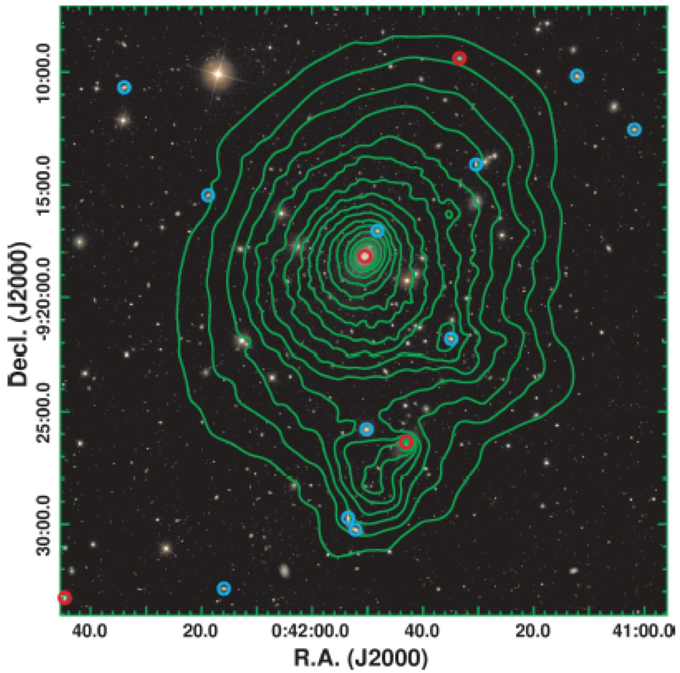
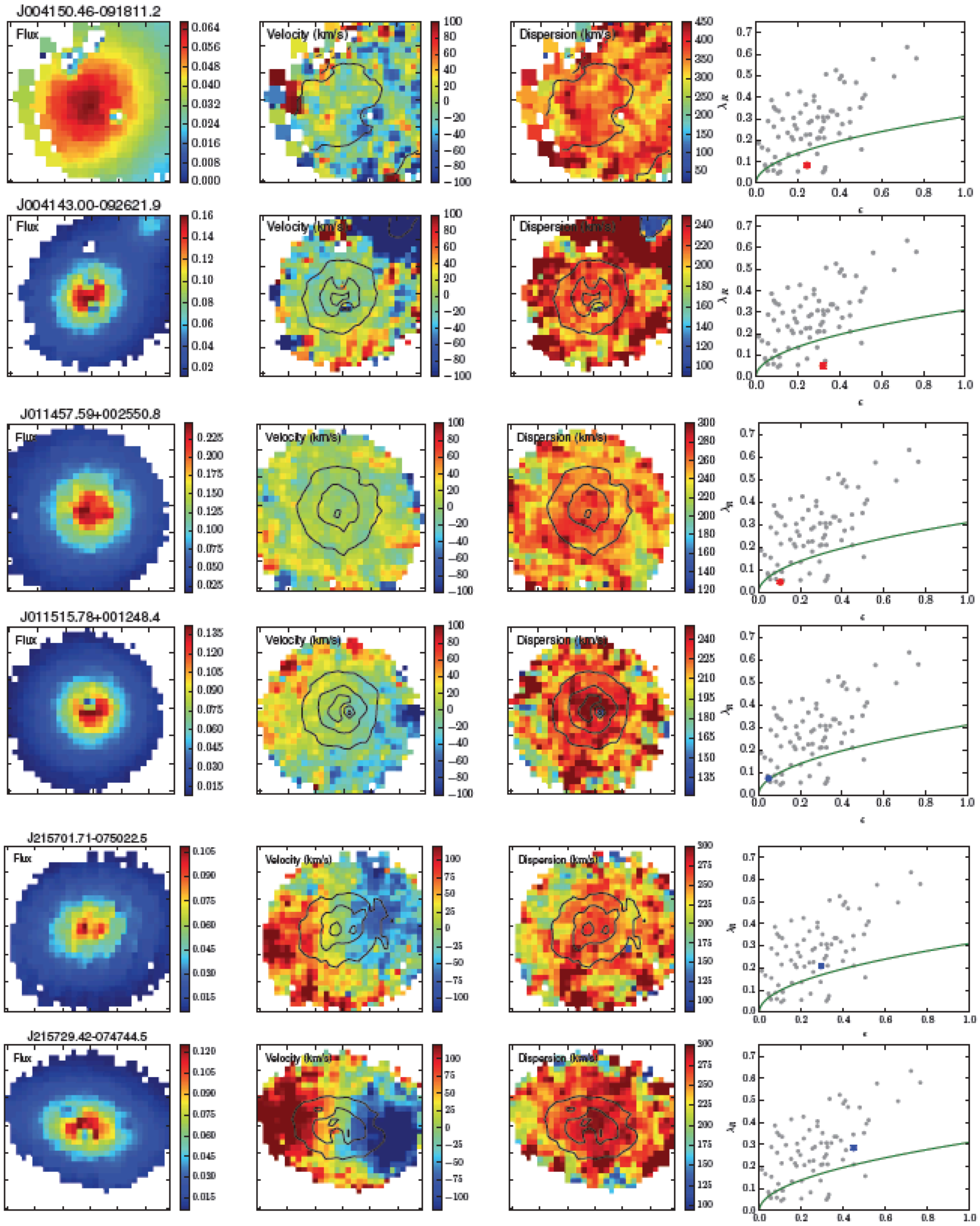
Clear variations in slow/fast rotator fraction with environment.

Next paper will have 10x sources







Random selection of SAMI stellar kinematics.

You can almost do this by eye!

Angular momentum variations will be targetted in the next generation of surveys

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THE COSMIC HISTORY OF THE SPIN OF DARK MATTER HALOS WITHIN THE LARGE-SCALE STRUCTURE*

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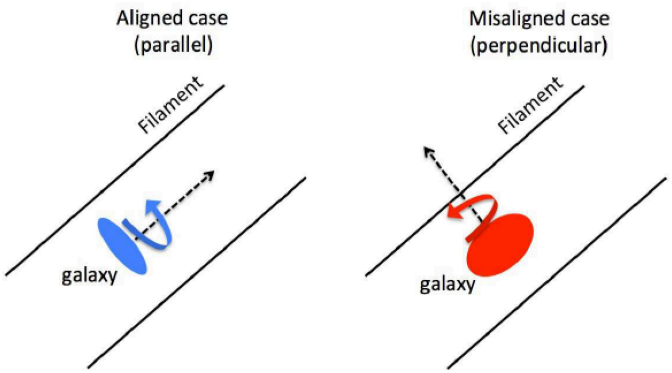
ABSTRACT

We use *N*-body simulations to investigate the evolution of the orientation and magnitude of dark matter halo angular momentum within the large-scale structure since $z = 3$. We look at the evolution of the alignment of halo spins with filaments and with each other, as well as the spin parameter, which is a measure of the magnitude of angular momentum. It was found that the angular momentum vectors of dark matter halos at high redshift have a weak tendency to be orthogonal to filaments and high-mass halos have a stronger orthogonal alignment than low-mass halos. Since $z = 1$, the spins of low-mass halos have become weakly aligned parallel to filaments, whereas high-mass halos kept their orthogonal alignment. This recent parallel alignment of low-mass halos casts doubt on tidal torque theory as the sole mechanism for the buildup of angular momentum. We see evidence for bulk flows and the broadening of filaments over time in the alignments of halo spin and velocities. We find a significant alignment of the spin of neighboring dark matter halos only at very small separations, $r < 0.3\,\mathrm{Mpc}\,h^{-1}$, which is driven by substructure. A correlation of the spin parameter with halo mass is confirmed at high redshift.

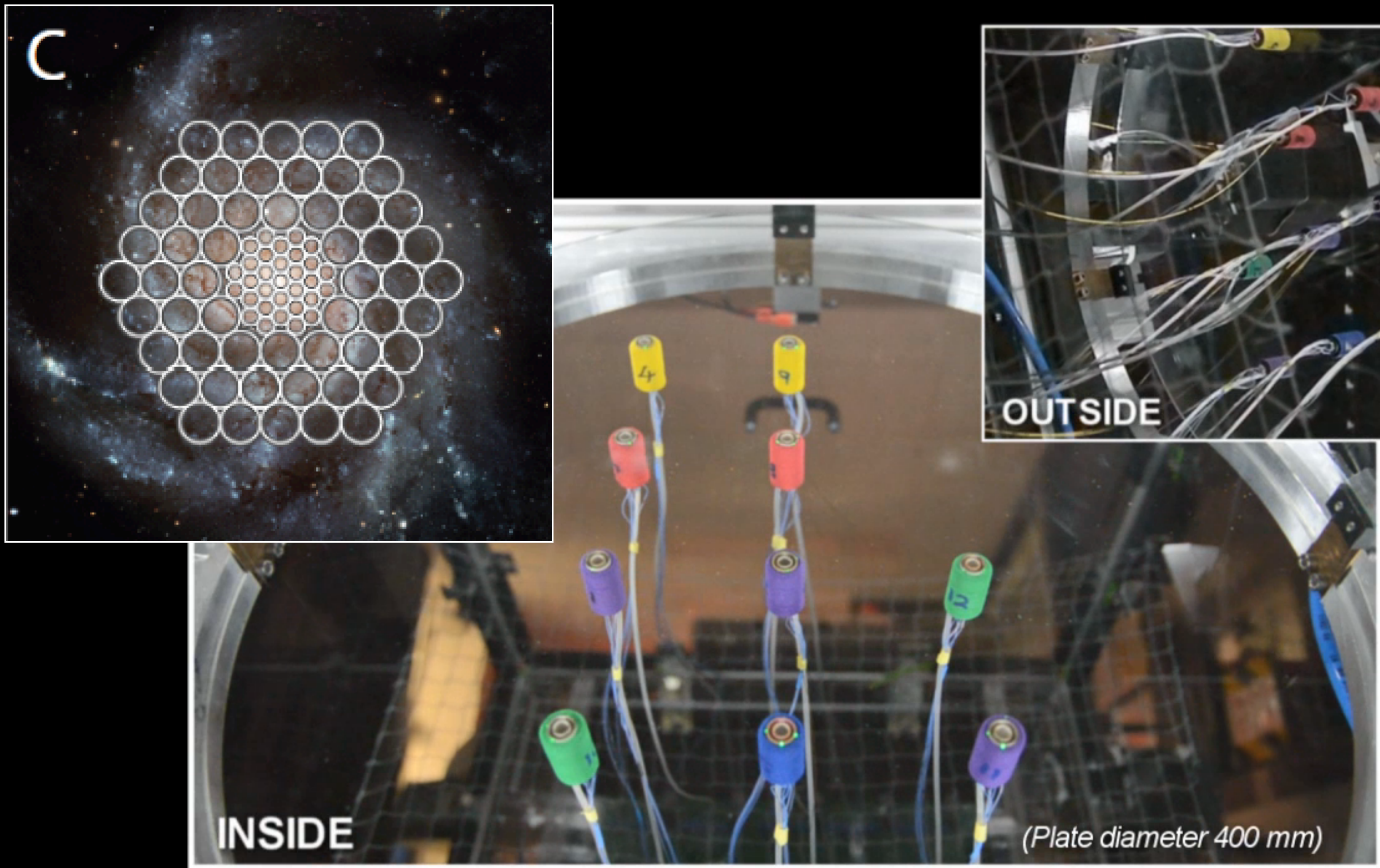
Key words: cosmology: theory – large-scale structure of universe



N ~ 60,000 galaxies to detect spin alignment with LSS

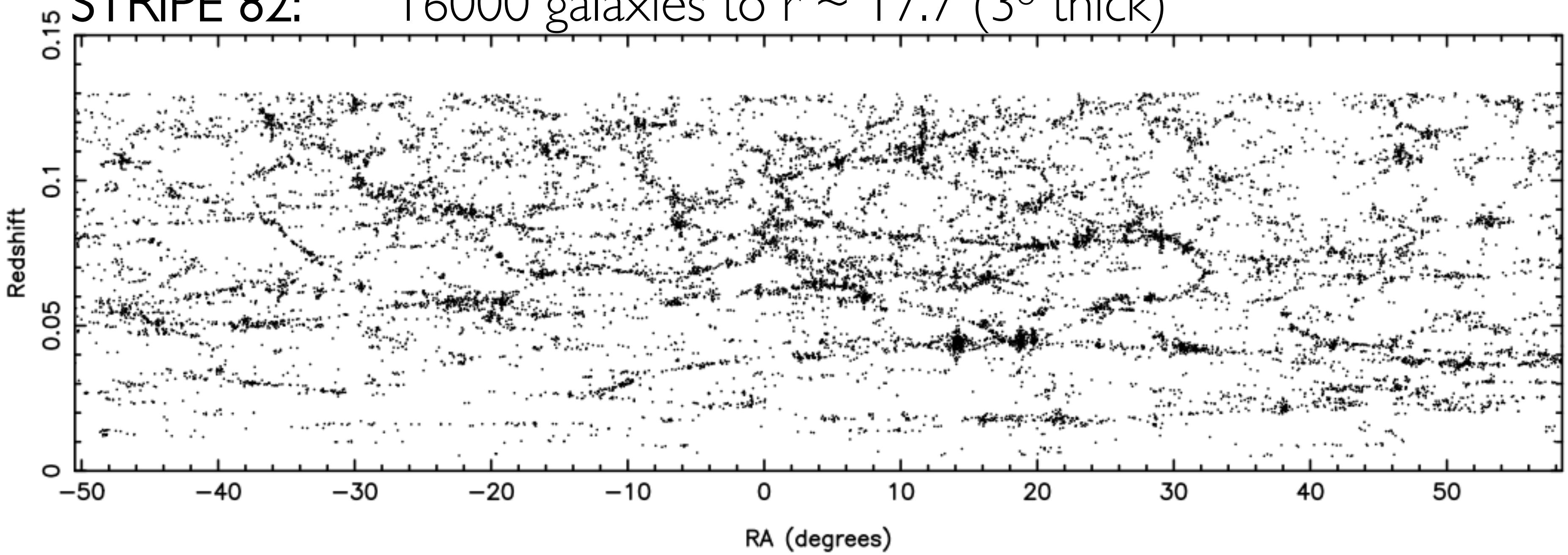
N ~ 150,000 galaxies (Dubois+14)

Hector - starbug positioning of 100 bundles



Hector survey fields – need sample density to be at least as good as this…

STRIPE 82: 16000 galaxies to r ~ 17.7 (3° thick)



Mass selection range specified by GAMA ***g-i*** or VISTA ***J***

Hector to provide kinematics, radial properties (e.g. SFR), asymmetries (complemented by HI)

Goal: to understand how angular momentum is distributed across the hierarchy, and its relation to local and global properties.

Hector survey size N

We propose to carry out a densely sampled, volume limited survey.

Local density δ_L = 3 x 5 bins
Galaxy mass M = 10 bins
Galaxy inclination i = 5 bins
Redshift interval Δz = 3 bins
Galaxies per bin $\rho \sim 30$

N ~ 3 x 5 x 10 x 5 x 3 x 30 ~ 100,000 galaxies

Note 1 Local density δ_L covers 5 classes at three different densities: voids V_i, sheets S_i, filaments F_i, groups G_i and clusters C_i

Note 2 ρ is large because every SAMI galaxy is complex (kinematic anomalies, disk-halo interaction, variable gas & dust, bars & warps)

How do we assess environmental impact?

Step I – carry out densely sampled, volume limited survey

Step II – classify galaxies into **filaments** F_i defined with respect to <u>local</u> mean density δ_L, **sheets** S_i with respect to δ_L ...

Step III – compare **filaments** F_i at a fixed δ_L, **sheets** S_i at a fixed δ_L ...

Step IV – stack **filaments** F_i at a fixed δ_L, **sheets** S_i at a fixed δ_L ...

Step V – compare $F = \Sigma F_i$ across all δ_L, $S = \Sigma S_i$ across all δ_L ...

It is <u>not</u> clear whether we should do any of this in a fixed mass range.

Summary

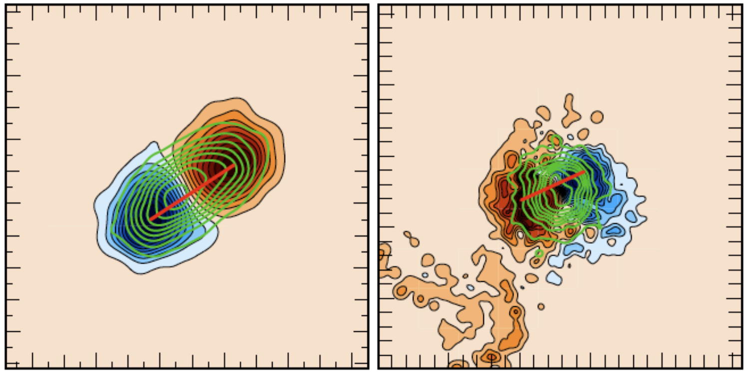
A case is proposed for **physical environment** over **statistical environment**. We must distinguish between filaments in voids (**∇.v > 0)** and filaments in dense regions (**∇.v < 0)**…

We need to reach down to substantial numbers of (dwarf) **void galaxies** while retaining enough filaments, groups and clusters for intercomparisons. **A full treatment takes us to a survey of ~100,000 galaxies.**

2-4m class telescopes, supported by all-sky HI and photometric surveys, are needed **into the next decade** to tackle these issues.

Simulations will need to extract "integral field observations" matched to SAMI of ~10^5 galaxies and **measure key parameters**.

Dubois+ 14



COSMOLOGY

2014 Gruber Cosmology Prize

By establishing a connection between observations of the nearby universe with the universe on the whole, Jaan Einasto, Kenneth Freeman, R. Brent Tully, and Sidney van den Bergh pioneered Near Field Cosmology—an area of study that helped establish both that the distribution of galaxies is not random but has a definite structure, and that dark matter played a key role in the evolution of that structure.

Jaan Einasto ➔ anag. Estonia

Kenneth Freeman

R. Brent Tully

Sidney van den Bergh