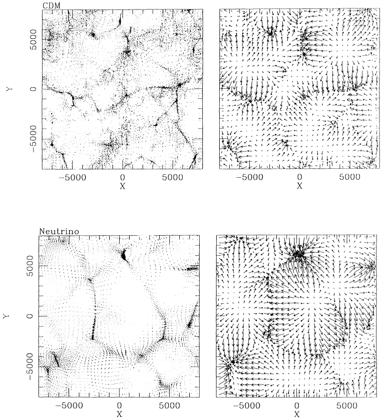
Cosmological Physics through signatures of galaxy motions

Adi Nusser

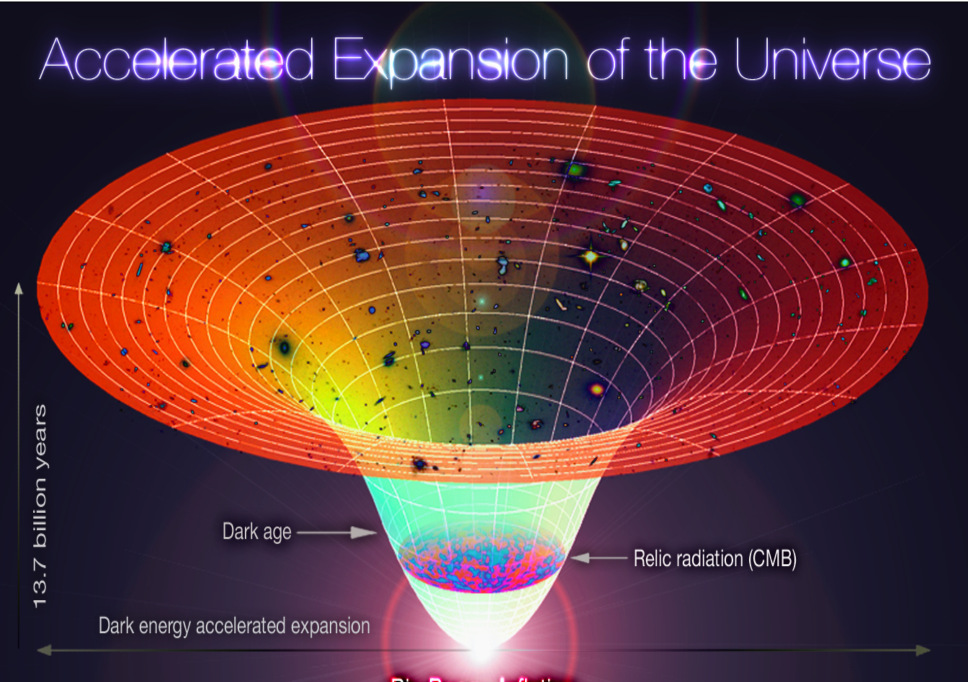


Outline

Collaborators

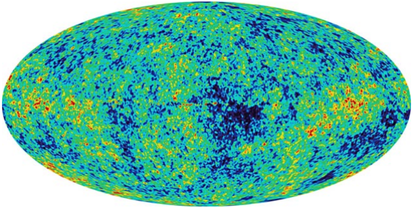
- Marc Davis (UC Berkeley)
- Enzo Branchini (Rome III)
- Martin Feix (Technion)
- Jim Peebles (Princeton)

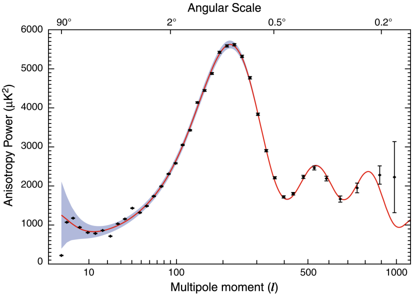
The challenge: structure formation in an accelerating Universe



Cosmic Microwave Background (CMB) radiation

Tiny fluctuations at recombination era — 300,000 years after Big Bang





A lot is known about the Initial Conditions. The shape of C_l is sensitive to some of the cosmological parameters

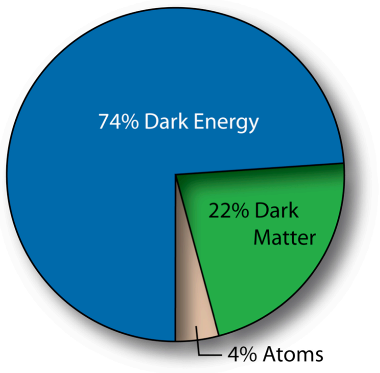
Cosmological parameters inferred from CMB + other data

WMAP Cosmological Parameters

Model: lcdm+sz+lens

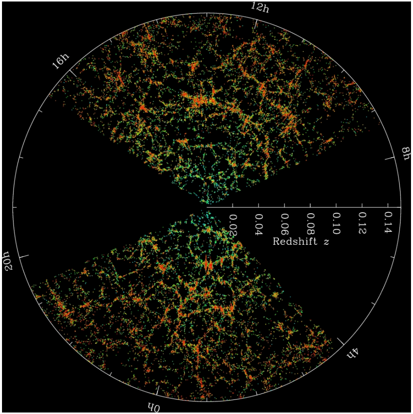
Data: wmap7

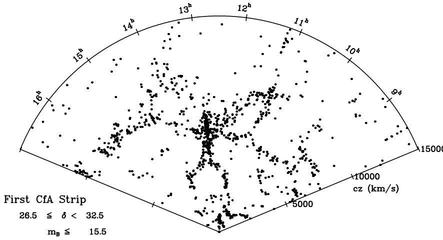
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1-n_s$	0.037 ± 0.014
$1-n_s$	$0.0079 < 1-n_s < 0.0642$ (95% CL)	$A_{\mathrm{BAO}}(z=0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\mathrm{eq}})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
k_{eq}	$0.00974^{+0.00041}_{-0.00040}$	ℓ_{eq}	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\mathrm{hor}}(z_{\mathrm{dec}})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z=0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z=0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
A_{SZ}	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	$0.5952 \pm 0.0016\ ^\circ$	t_*	379164^{+5187}_{-5243} yr
z_{dec}	1088.2 ± 1.2	z_d	1020.3 ± 1.4
z_{eq}	3196^{+134}_{-133}	z_{reion}	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		



The distribution of galaxies in space: redshift surveys

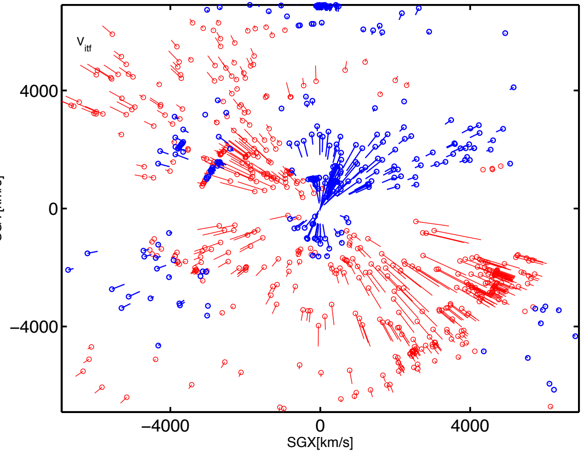
SDSS, from M. Blanton





$$cz = Hr + V_{\text{pec}}$$

Radial peculiar motions of galaxies in space



From Davis et al based on SFI++ data of Springob et al

- based on TF relation $L \propto V_c^4$.
- only radial component
- $< 10^4$ galaxies
- very noisy data
- a lot of biases
- restricted to $< 300\mathrm{Mpc}$ $(30,000\mathrm{km\,s^{-1}})$.

The equations for structure formation (without gas)

Euler

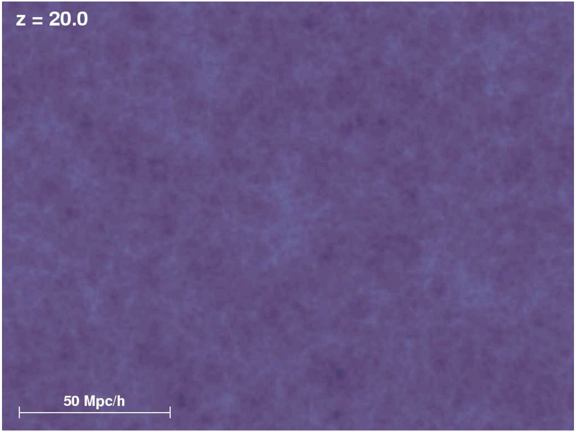
$$\frac{d\mathbf{V}}{dt} + H\mathbf{V} = -\frac{\boldsymbol{\nabla}\Phi}{a}$$

Poisson

$$\frac{\boldsymbol{\nabla}^2\Phi}{a^2} = 4\pi G\bar{\rho}_m\delta(\mathbf{x}, t)$$

Structure formation is driven by the gravity of the DM density contrast $\delta(\mathbf{x}, t)$, but the rate is dictated by $H(t)$ and $\Omega_m = \bar{\rho}_m/\rho_{crit}$.

Growth of structure in a simulation



Linear theory and dependence on cosmological background

The Fundamental Relation for this talk

$$\delta = -\frac{1}{\boxed{f(\Omega)}} \nabla \cdot \mathbf{v}$$

- obtained from the full EOM in the limit of $\delta \ll 1$
- $f(\Omega) \approx \Omega^{\gamma}_{matter}$
- $0.5 < \gamma < 0.6$ is the *growth index*, it is dictated by the underlying theory of gravity and dark energy

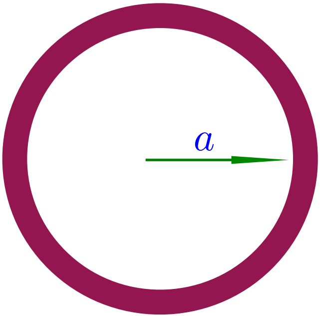
Goals

Constrain Ω, γ... Test underlying gravitational theory... Test basic paradigm on large scales...

Methodology

Application of the Fundamental Relation (or variants of it) to peculiar velocity catalogues and redshift surveys

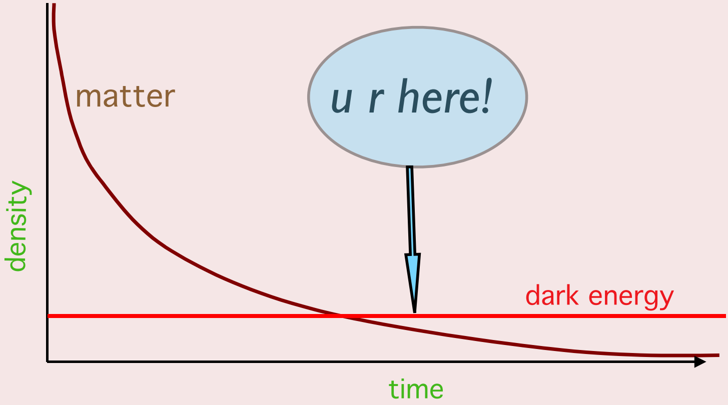
Dynamics of the Background



General relativity: $$E = \frac{\dot{a}^2}{2} - \frac{GM}{a} - \frac{4\pi G}{3}\rho_v a^2$$

For DE described by a Cosmological Constant

$$\rho_v = const \ \& \ P_v = -\rho_v c^2$$



Dark Energy

The usual candidates

- quintessence: a scalar field
- $\tilde{f}(R)$ gravity: $S = \frac{1}{16\pi G}\int d^4x \tilde{f}(R)\sqrt{-g} + S^{matter}$
- DGP (Dvali, Gabadadze & Porrati) gravity

Since

In GR $\ddot{a} = -4\pi G(\rho + 3P)a/3$

hence

Dark Energy should mimic GR with an EOS $P = w\rho c^2$ with $w \to -1$ at late times

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Strategies for inferring cosmological information from data

A. **statistical properties of observed velocities:**
   - P_δ^{CMB} versus P_v yields constraints on $f(\Omega)$
   - moments of velocities, e.g. bulk flow

B. **velocity-velocity comparison:**
   - get δ_{gal} from observed galaxy distribution
   - use the Fundamental Relation to get V_{gal} from δ_{gal}
   - the comparison V_{gal} versus V_{obs} constrains f and $g(\delta_{gal})$, i.e. galaxy biasing

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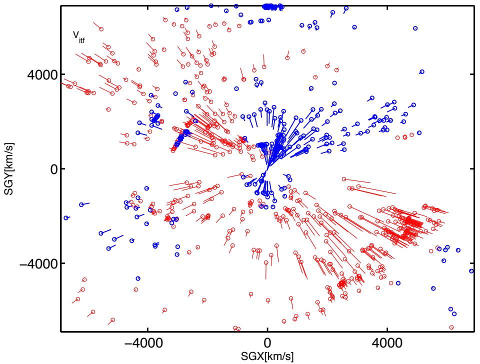
Definition

$$\mathbf{B}(r) = \frac{3}{4\pi r^3} \int_{x<r} \mathbf{V}(\mathbf{x}) d^3x$$

V(x) is the 3D velocity field

But....

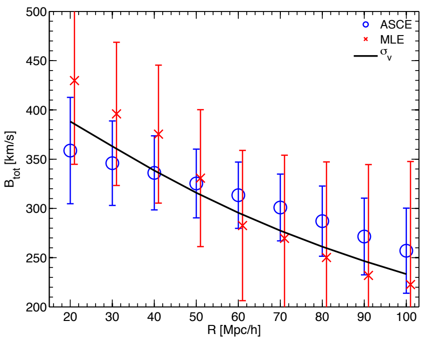
Data: noisy and sparse radial velocities!

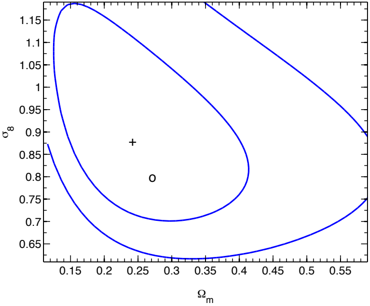


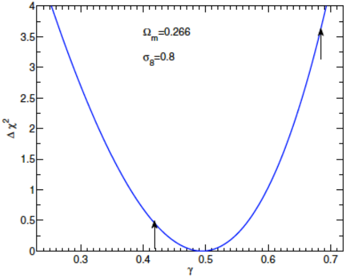
BF from the sparse SFI++ catalogue of peculiar velocities

Methods for inferring BF from observed velocities:

1. **MLE:** simply assume $\mathbf{V}(\mathbf{x}) = \mathbf{B} = \textit{constant}$ *(Kaiser 84)*
2. **ASCE:** interpolate using physically motivated basis for the velocity field *(AN & Davis 11)*. This is similar to constrained realisations *(Courtois, Hoffman, Tully & Gottlöber 12)*



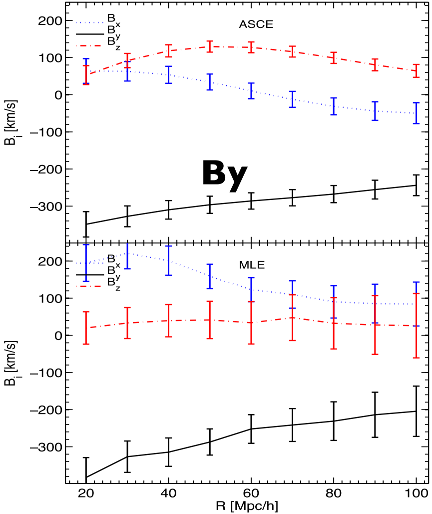


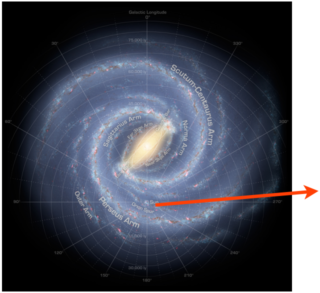


σ_8 = the clustering amplitude

Ω_m^γ fixes velocity amplitude

The 3 components (Galactic coordinates)





B is at 40 deg to the SGP
B is pretty featureless

Constant direction and slowly decaying

Some BF values

$R[\mathrm{Mpc}]$	$B(R)[\mathrm{km\ s}^{-1}]$	l	b
~ 2 (CMB dip.)	627 ± 22	276 ± 3	30 ± 3
60	333 ± 38	276 ± 2	14 ± 2
150	257 ± 44	279 ± 4	10 ± 4

Note: external fluctuations give $\mathbf{B} = const$.

Is there a "dark flow" (or Kashlinsky flow)?

Dark flow = large bulk flow ($\sim 1000\,\mathrm{km\ s^{-1}}$) over a very large scale. Such a flow will introduce detectable systematic differences in the observed galaxy magnitudes, $M_0 = m - 5\log(cz)$.

BF from SDSS, $14.5 < m_{\mathrm{r}} < 17.6$

$R[\mathrm{Mpc}]$	$B(R)[\mathrm{km\ s^{-1}}]$	l_{fixed}	b_{fixed}
$100 - 300$	-150 ± 150	266	33
$300 - 500$	300 ± 150	266	33

No evidence for dark flow in SDSS

Velocities

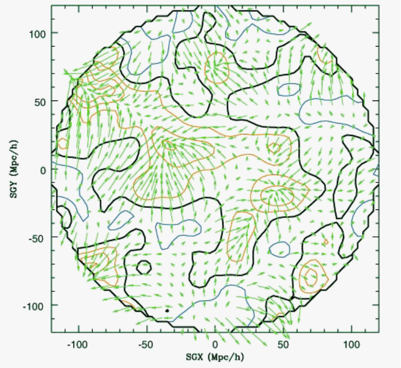
from the Fundamental Relation applied to a galaxy redshift survey. Requires an assumed $f(\Omega)$ and a *biasing relation* between galaxies and mass.

versus

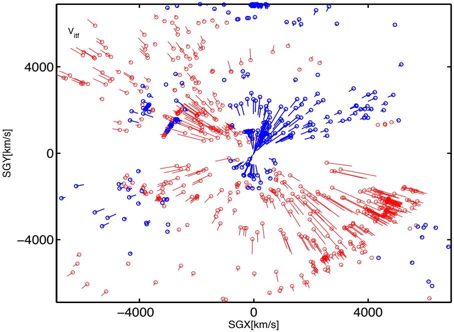
Velocities

directly from the Tully-Fisher relation. Requires careful removal of observational biases.

flow from PCSZ (by E.Branchini)

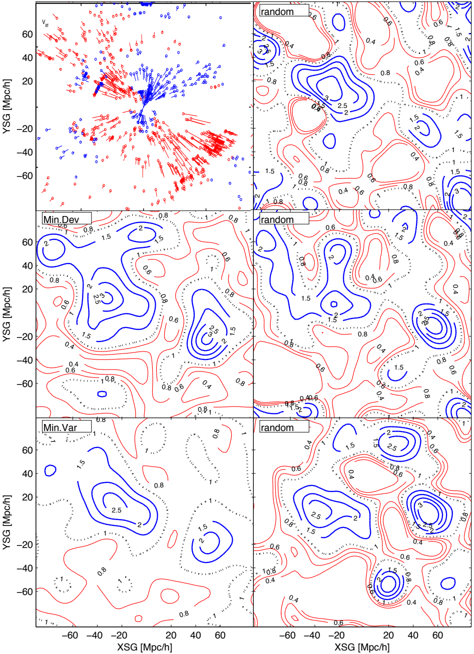


Tully-Fisher velocities



A Caution

2MRS



Two basic "obstacles" (related to V_{gal} from δ_{gal})

Galaxy Biasing

What is $\delta_{gal}(\delta_{DM})$?

Redshift Distortions in redshift surveys

We observe galaxies at $cz = Hr + V^{radial}$ rather than Hr.

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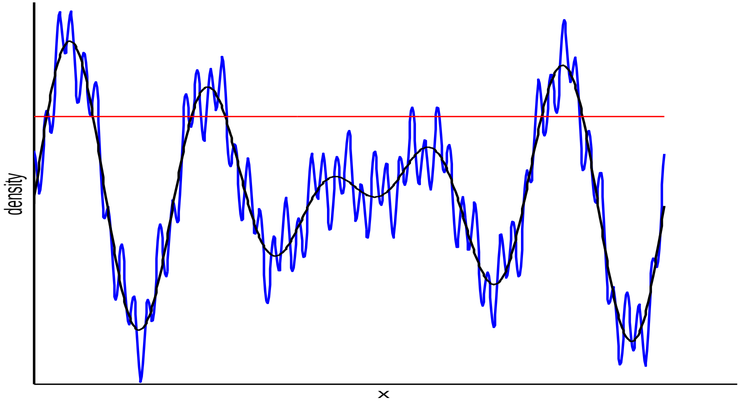
Galaxy Biasing

Galaxies preferentially form at peaks of δ_{DM}



Galaxy Biasing

Linear Galaxy Biasing

On large scales (Kaiser 87)

$$\delta_{gal} = \boxed{b}\,\delta_{DM}$$

b is the linear bias factor.

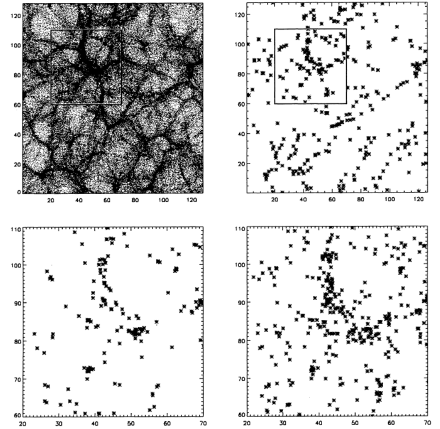
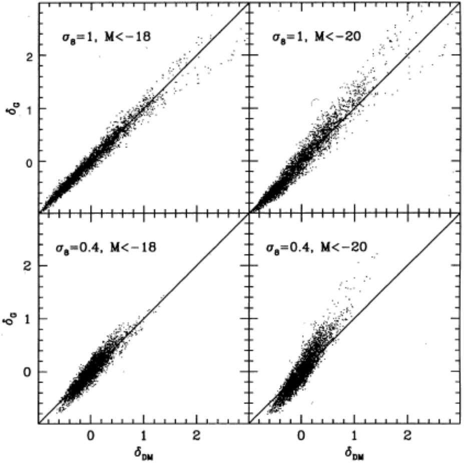
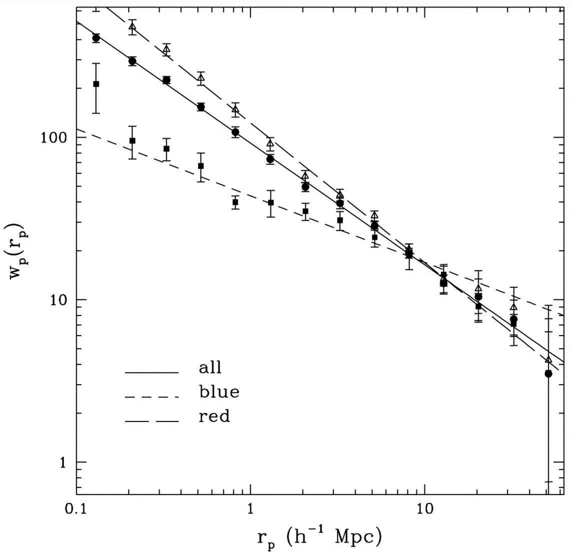


Figure 8. A 15-Mpc slice through the simulation volume. The top left panel shows all the dark matter particles. The top right panel show all the galaxies brighter than $M(B) = -18$. The lower left panel shows all the early-type galaxies in a subvolume of the simulation (outline by a box in the panels above). The lower right panel shows all the late-type galaxies in this subvolume.



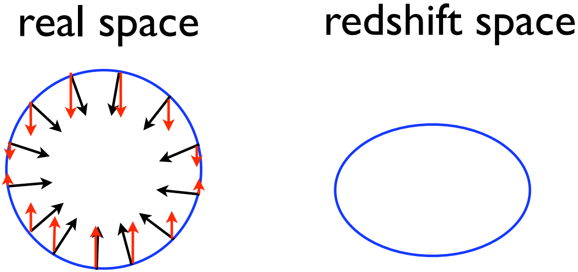
Kauffmann, AN, Steinmetz 97

Biasing in observations (SDSS)



Zehavi et al 2002 97

Redshift distortions



$$cz = Hd + V_{pec}$$

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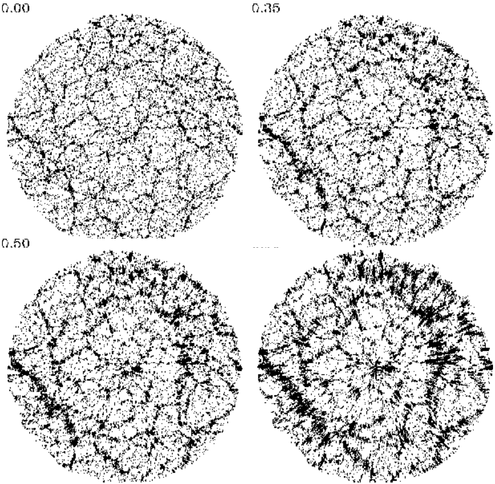

by Hume Feldman

Definition

$$s \equiv Hr + V^{\mathrm{radial}}$$

Hence

$$\begin{aligned}\delta^{\mathrm{s}} &= \delta^{\mathrm{r}} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V^{\mathrm{radial}}\right) \\ &= -\frac{1}{f}\nabla\cdot\mathbf{V} - [\nabla\cdot\mathbf{V}]_{\mathrm{radial}}\end{aligned}$$

δ^{r} is isotropic but δ^{s} is not!

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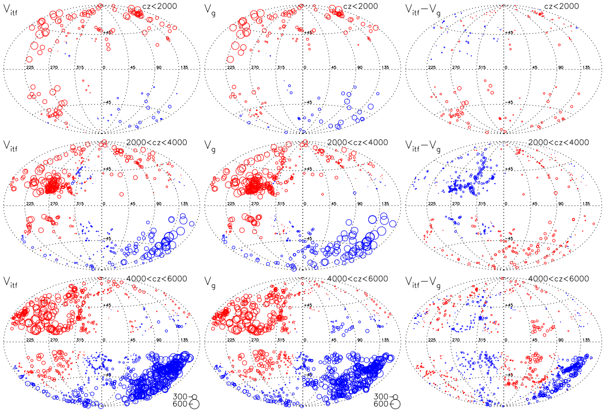

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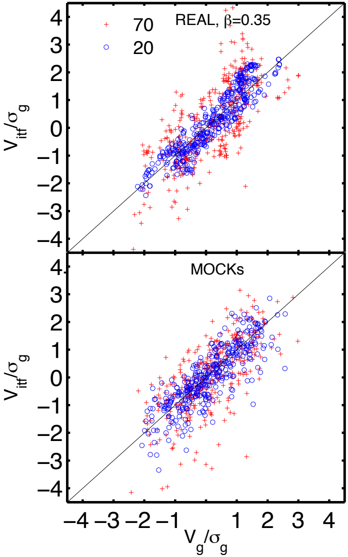

$$\beta = f(\Omega)/b$$

Is the Universe close to homogeneity on a few Gpc scale?

The Cosmological Principle

Increasing degree of homogeneity as the Universe is viewed on larger and large scales

Probing scales larger than $L_{\rm data}$

- Let δ^s be the redshift space density contrast derived from the galaxy distribution in an observed volume.
- Let $\mathbf{V}_{\rm ext}$ be the component of the velocity field due to mass distribution external to the survey volume
- Note that
- Hence signatures of external fluctuations must be present in δ^s inside the survey volume.

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- Hence signatures of external fluctuations must be present in $\delta^{\rm s}$ inside the survey volume.

Probing scales larger than $L_{\rm data}$

- Let $\delta^{\rm s}$ be the redshift space density contrast derived from the galaxy distribution in an observed volume.
- Let $\mathbf{V}_{\rm ext}$ be the component of the velocity field due to mass distribution external to the survey volume
- Note that
  - $\delta^{\rm s} = -f^{-1}\boldsymbol{\nabla}\cdot\mathbf{V} - [\boldsymbol{\nabla}\cdot\mathbf{V}]_{\rm radial}$
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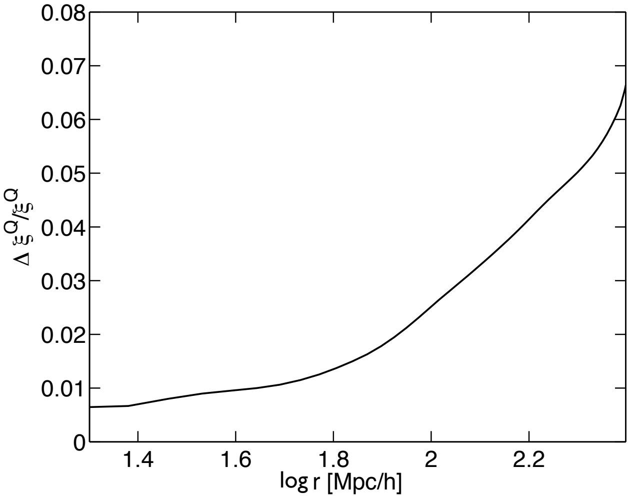
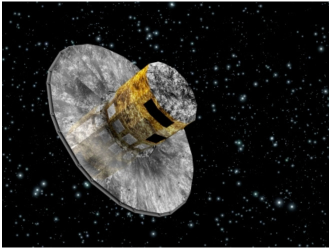
Ratio of redshift distortions for two different $\mathbf{V}_{\rm ext}$. Survey volume $\sim 1\mathrm{Gpc/h}$.



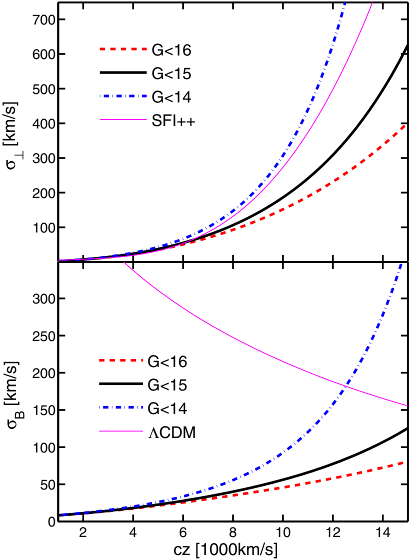
Astrometry of galaxies with Gaia (2013-2018)



$$v_{\parallel} = -\sum_{lm} \frac{d\Phi_{lm}}{ds} Y_{lm}$$

$$\boldsymbol{v}_{\perp} = -\sum_{lm} \frac{\Phi_{lm}}{s} \boldsymbol{\Psi}_{lm}$$

Pros: free of biases, allows tests of potential flow ansatz



Galaxies as standard candles

For a Schechter luminosity function ($\alpha = -1$):

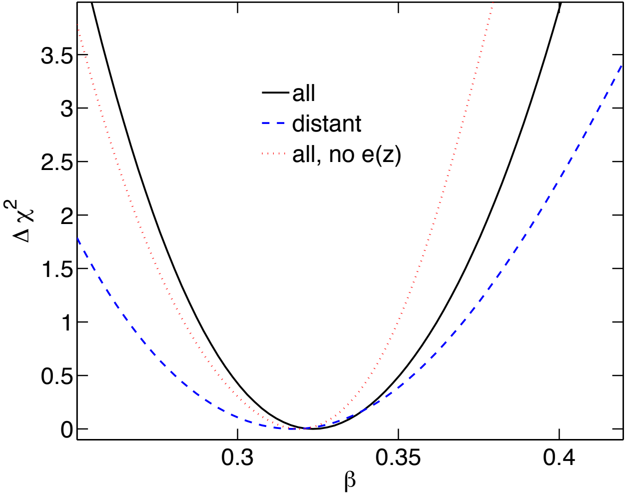
- $< L >_{L>2L_*} = 2.77L_*$, $\sigma_{L>2L_*} = 0.81L_*$
- $< L >_{L>4L_*} = 4.85L_*$, $\sigma_{L>4L_*} = 0.74L_*$

How do we use this? (*Tamman, Yahil & Sandage 79*)

- take a very large redshift survey
- as estimate of magnitudes, compute $M_0 = m - 5log(cz) = m - 5log(Hr + V)$
- true magnitudes are $M_t = m - 5log(Hr)$
- constrain a model for V by maximising $P(M_0)$, assuming $P(M_t)$ does not depend on velocity.

Application to 2MRS

As a velocity model, take $V(\beta = f/b)$ from the 2MRS galaxy distribution. Tune β such as $P(M_0)$ is maximum (or by minimising the scatter in $M_est = m - 5log(cz - V(\beta)$ with respect to β.



This is remarkably consistent with Davis et al using direct distance indicators!

Concluding remarks

- ΛCDM is a good approximation on scales $10s - 100s$ Mpc/h.
- The scales $100s$ Mpc to CMB, remain to be assessed.
- Almost surely, ΛCDM needs tweaking on small scales smaller that a few Mpc
- Bulk flow is reasonable. But,
  - it is hard to pin-point specific structures causing it
  - it could simply be an accumulated effect over scales of a few 100s Mpc (see Bilicki et al 2011)
- Direct distance indicators such as Tully-Fisher are limited and are difficult to analyze. We have to explore other possibilities.

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