The cosmic growth rate from an alternative observational test

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Outline

The Universe in a nutshell

The ΛCDM cosmological model

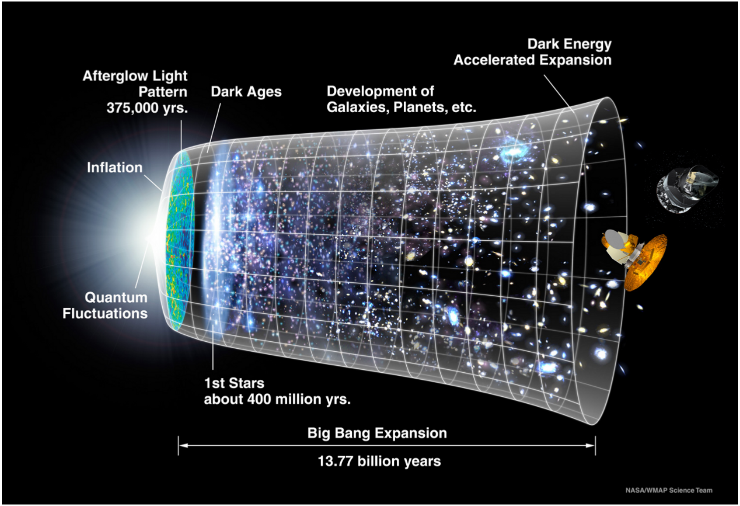

Image credit: NASA / WMAP Science Team

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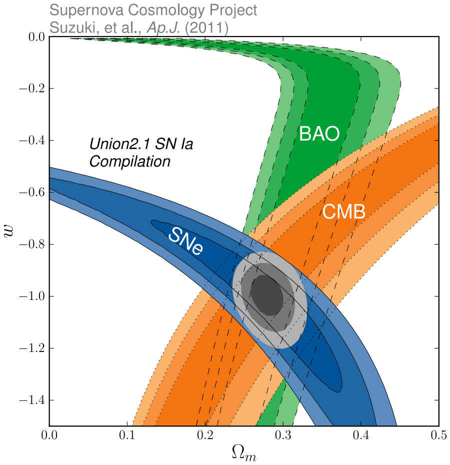

Planck's cosmic recipe

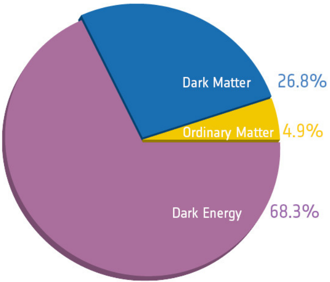

Image credit: ESA and the Planck Collaboration

Growth rate of density perturbations

Probing the nature of cosmic acceleration

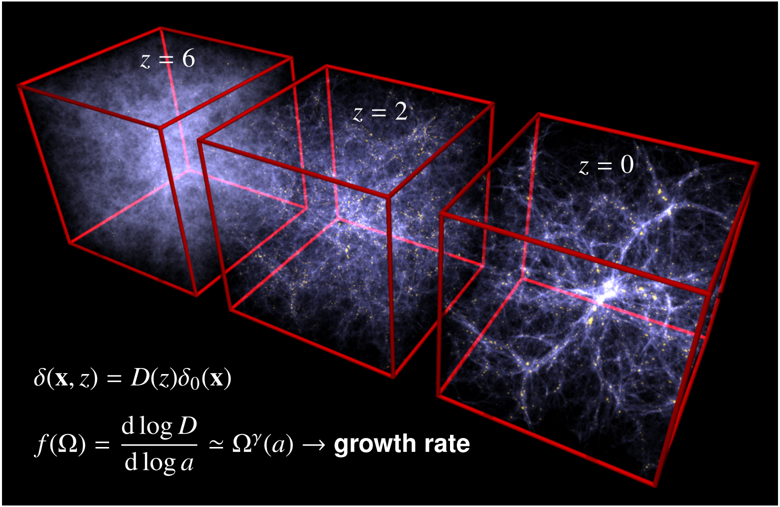

Image credit: V. Springel / MPIA Garching

Growth rate of density perturbations

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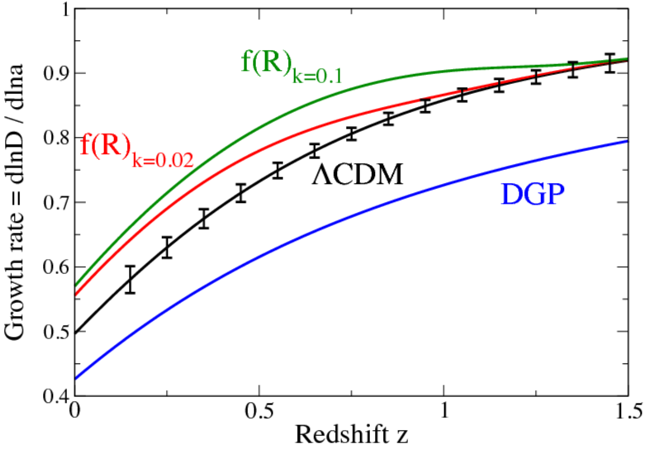
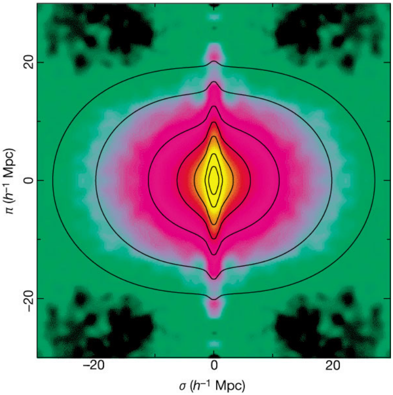


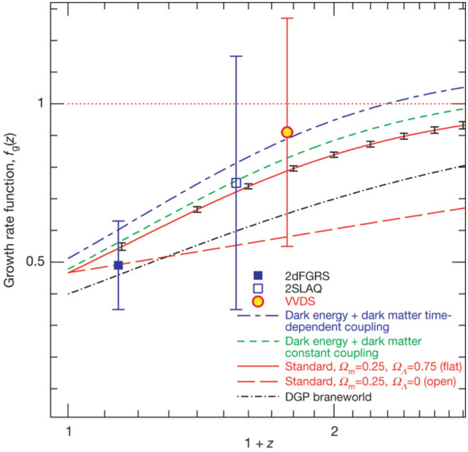
Huterer et al., Astropart.Phys. 63 (2015)

Growth rate of density perturbations

Measuring the growth rate with redshift-space distortions



Peacock et al., Nature 410 (2001)



Guzzo et al., Nature 451 (2008)

Outline

Peculiar velocities from LF variations

Basic concepts

- Peculiar motion introduces systematic variations in the observed luminosity distribution of galaxies (Nusser et al. 2011; Tammann et al. 1979)

$$M = M_{\rm obs} + 5\log_{10}\frac{D_L(z_{\rm obs})}{D_L(z)}$$

- Linear theory ($c = 1$):

$$\frac{z_{\rm obs} - z}{1 + z_{\rm obs}} = V(t, r) - \Phi(t, r) - {\rm ISW} \approx V(t, r)$$

- Maximize probability of observing galaxies given their magnitudes and redshifts:

$$\log P_{\rm tot} = \sum_i \log P_i(M_i|z_i, V_i) = \frac{\phi(M_i)}{\int_{a_i}^{b_i}\phi(M)dM}$$

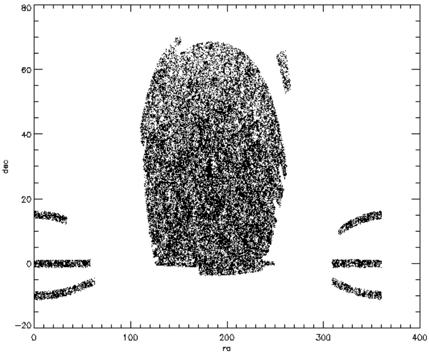
- Velocity models:

$$V(t, \mathbf{r}) \rightarrow V(\{x_i\}), \quad V(t, \mathbf{r}) \rightarrow V(\beta) \text{ (linear reconstruction; } \beta = f/b)$$

- Method **independent** of galaxy bias and traditional distance indicators

SDSS Data Release 7

NYU Value-Added Galaxy Catalog (Blanton et al. 2005)



- Use r-band magnitudes (Petrosian)
- $14.5 < m_r < 17.6$
- $-22.5 < M_{\rm obs} < -17.0$
- $0.02 < z < 0.22$
- $N \sim 5 \times 10^5$
- Adopt pre-Planck cosmological parameters (Calabrese et al. 2013)

- Realistic mocks for testing

  → SDSS footprint
  → photometric offsets between stripes
  → overall tilt over the sky

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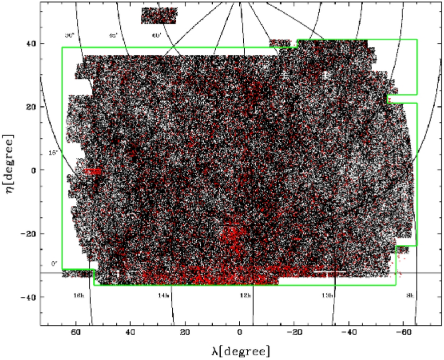

- Use r-band magnitudes (Petrosian)
- $14.5 < m_r < 17.6$
- $-22.5 < M_{\mathrm{obs}} < -17.0$
- $0.02 < z < 0.22 \rightarrow 0.06 < z < 0.12$
- $N \sim 5 \times 10^5 \rightarrow 2 \times 10^5$
- Adopt pre-Planck cosmological parameters (Calabrese et al. 2013)

- Realistic mocks for testing

  → SDSS footprint

  → photometric offsets between stripes

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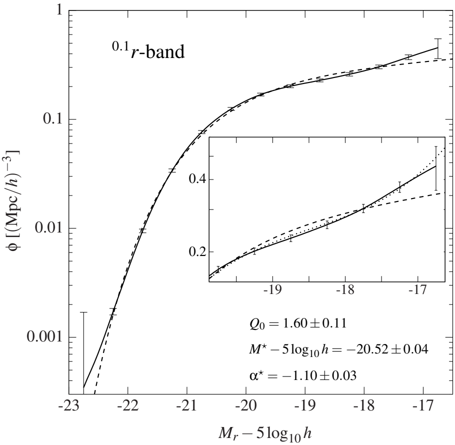
LF estimators

"Non-parametric" spline-estimator of $\phi(M)$



Feix et al., JCAP 09 (2014) — arXiv:1405.6710

- Normalization unimportant for our analysis
- Two-parameter Schechter function does quite well
- To reduce errors, adopt more flexible form for $\phi(M)$
- Model $\phi(M)$ as a spline with sampling points $\{\phi_j(M)\}$ for $M_j < M < M_{j+1}$
- Advantage: smoothness, nice analytic properties for integrals / derivatives)
- Parameterize luminosity evolution:

$$e(z) = Q_0(z - z_0) + O\left(z^2\right)$$

An example

Redshift-binned velocity model

- Expand binned velocity field in SHs:

$$V(t, \mathbf{r}) \rightarrow \tilde{V}(\hat{\mathbf{r}}) \quad \tilde{V}(\hat{\mathbf{r}}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{\mathbf{r}})$$

- For $N \gg 1$, $P_{\rm tot}$ is well approximated by a Gaussian (simplifies computation):

$$\log P_{\rm tot}(\mathbf{d}|\mathbf{x}) \approx -\frac{1}{2}(\mathbf{x}-\mathbf{x}_0)^T \Sigma^{-1}(\mathbf{x}-\mathbf{x}_0) + \mathrm{const}, \quad \text{where } \mathbf{x}^T = \left(\{q_j\}, \{a_{lm}\}\right)$$

- Marginalize over LF parameters $\{q_j\}$ and construct posterior for $C_l = \left\langle |a_{lm}|^2 \right\rangle$ by applying Bayes' theorem:

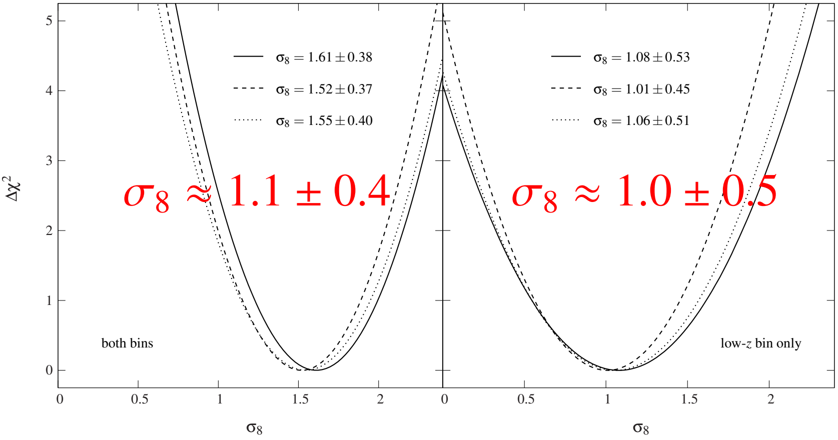
$$P\left(\{C_l\}\right) \propto \int P\left(\mathbf{d}|\{a_{lm}\}\right) P\left(\{a_{lm}\}|\{C_l\}\right) da_{lm}$$

- Assume $\{a_{lm}\}$ as normally distributed
- For a ΛCDM model prior, $C_l = C_l\left(\{c_k\}\right)$:

$$C_l = \frac{2}{\pi} \int dk k^2 P_\Phi(k) \left| \int dr W(r) \left(\frac{l j_l}{r} - k j_{l+1} \right) \right|^2$$

Constraints on σ_8

Results from SDSS data analysis ($l_{max} = 5$ in two redshift bins)



Feix et al., JCAP 09 (2014) — arXiv:1405.6710

Outline

1. Motivation
2. Methodology and data
3. Application to SDSS
   - Linear velocity reconstruction
   - Growth constraints at $z \sim 0.1$
4. Conclusions

Building the velocity field of SDSS galaxies

Linear velocity reconstruction (Nusser & Davis 1994; Nusser et al. 2012)

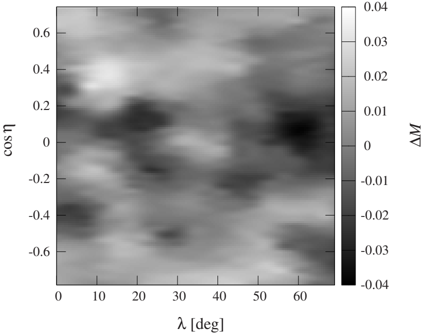
- Reconstruct the large-scale velocity field as a function of $\beta = f/b$
- Assume $\beta = \mathrm{const}$ over sample range
- Smooth redshift-space density field on a scale $R_s \sim 10h^{-1}$ Mpc
- Problem in “harmonic” space:

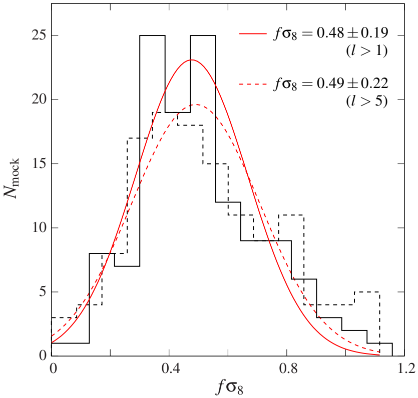
$$\frac{1}{s^2}\frac{\mathrm{d}}{\mathrm{d}s}\left(s^2\frac{\mathrm{d}\Phi_{lm}}{\mathrm{d}s}\right) - \frac{1}{1+\beta}\frac{l(l+1)\Phi_{lm}}{s^2} = \frac{\beta}{1+\beta}\left(\delta^g_{lm} - \frac{\mathrm{d}\log S}{\mathrm{d}s}\frac{\mathrm{d}\Phi_{lm}}{\mathrm{d}s}\right)$$

- Boundary conditions: set $\delta = 0$ outside data volume (zero-padding)
- Must exclude monopole and dipole terms
- Models robust w.r.t. small-scale issues, e.g. details of galaxy bias
- Assign galaxy velocities for discrete β-values $\rightarrow$ likelihood analysis

Constraints on $f\sigma_8$ at $z \sim 0.1$

Results for SDSS mock catalogs ($l_{\max} = 150$)





Feix et al., PRL 115, 011301 (2015) — arXiv:1503.05945

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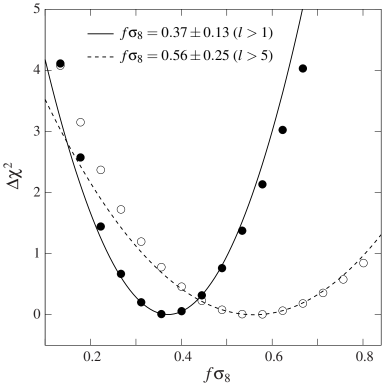

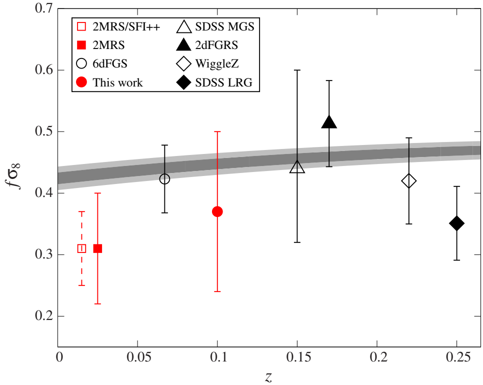

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Conclusions

- ML estimators extracting the large-scale velocity field through spatial modulations in the observed LF of galaxies offer a powerful and complementary alternative to currently used methods
- New growth measurements are in agreement with the results from Planck
- Luminosity-based constraints on the growth rate at $z \sim 0.1$ are both **compatible** and **consistent** with those coming from RSD analyses of similar datasets
- Consistency is striking in view of the different possible systematic biases associated with the different methods
- Luminosity-based techniques are less sensitive to nonlinear corrections than the two-point statistics which enter the analysis of RSDs