Exploring Dark Energy

With Galaxy Cluster Peculiar Velocities
Exploring D.E. with cluster $\nu_{pec}$

- Philosophy
- Advertisement
- Cluster velocity—velocity correlation functions as probes of dark energy
- POTENT on 100 Mpc scales
Dark Energy Parameters
\[ \rho_0^x, w^x(z) = w_0^x + w_1^x z \]

Expansion rate, \( H(z) \)

Angular-diameter distance, \( d_A(z) \)

Luminosity distance, \( d_L(z) \)

Growth factor, \( D(z) \)

Volume element, \( \frac{dV}{dzd\Omega} \)

Calibration parameters

Observed apparent magnitude of SNe Ia, \( m_{\text{obs}}(z) \)

Evolution of angular clustering

Alcock-Paczynski tests with \( L_{\alpha} \) forest correlations

Redshift-space correlations

Dark Energy Does Not Exist In A Vacuum
**DASH (The Davis Anisotropy Shortcut)**

Dash is a combination of numerical computation with analytic and semi-analytic approximations which achieve fast and accurate $C_l$ computation.

How fast? About 30 times faster than CMBfast

How accurate?

Applications:

- parameter estimation (Knox, Christensen & Skordis 2001, note: age and mcmc)
- error forecasting
On to peculiar velocities…

\[ \dot{\delta} = i k \nu \quad \delta(x, \eta) = D(\eta)\delta(x, \eta_0) \]

\[ \rightarrow \nu \propto \dot{D} \]

For \( z < 0.5 \), \( \dot{D} \) is much less dependent on the nature of the dark energy than is the case for \( D(z) \) or \( r(z) \).

\( \rightarrow \) Peculiar velocities may be helpful in breaking \( \Omega_m, w \) degeneracies.
Growth factor vs. \( z \)
(normalized to standard CDM)

Time derivative of growth factor vs. \( z \)

Dotted lines are for \( w = -0.7 \).
Solid lines are for \( w = -1 \)
Measuring $v_{\text{pec}}$ with the SZ effect

Spectral distortion characterized by Compton $y$ parameter

\[
y = \frac{k \sigma_T}{m_e c^2} \int dl T_e(l)n_e(l) \tau \frac{k T_e}{m_e c^2}
\]

\[
\frac{\Delta I_{\nu}}{I_{\nu}} = y f(x) \quad ; \quad x = \frac{h \nu}{k T_{\text{CMB}}}
\]

As $x \to 0$, $f(x) \to -2$

Kinetic

\[
\frac{\Delta I_{\nu}}{I_{\nu}} = -\frac{\nu}{c} \tau x \frac{e^x}{e^x - 1} \quad \to \quad \left( \frac{\delta T}{T} \right)_{\text{SZ}} = -\frac{\nu}{c} \tau
\]

Combine to get velocity:

\[
\frac{v}{c} = -\frac{k T_e}{m_e c^2} \left( \frac{\delta T}{T} \right)_{\text{SZ}} \frac{y}{y}
\]

Sunyaev & Zeldovich 1980
Thermal SZ

Kinetic SZ

Holzapfel et al. (1997)
A possible survey strategy

• Survey large area with large detector array at 30 GHz to find clusters.
• Follow up with a smaller array of detectors at 150 GHz and 220 GHz targeting the clusters. (Or maybe even FTS to get $T_e$)
• Follow up with optical photometric or spectroscopic redshifts
How well can $v_{\text{pec}}$ be measured?

Holzapfel et al. (1997):

Abell 2163: $v_r = +490^{+1370}_{-880} \text{ km/s}$

Abell 1689: $v_r = +170^{+815}_{-630} \text{ km/s}$

Aghanim et al. (2001): Planck will result in cluster peculiar velocities with errors of 500 to 1,000 km/s.

These large errors are due to Planck’s big 5’ beam and noisy maps.

With a smaller beam a cluster stands out better against the confusing background of CMB anisotropy and other clusters.

$$\sigma_v \approx 25 \text{ km/sec } (0.01/\tau) \left( \frac{\sqrt{(\Delta T_{\text{CMB}})^2 + (\Delta T_{\text{noise}})^2}}{2 \mu \text{K}} \right)$$

Haehnelt & Tegmark (1996)
What Are The Expected Signals?

\[ C_v(\theta, z_1, z_2) \equiv \langle v_r(\vec{r}_1)v_r(\vec{r}_2) \rangle \]

\[ = \Psi_{\text{perp}}(r) \cos(\theta) + (\Psi_{\text{para}}(r) - \Psi_{\text{perp}}(r)) \frac{(\vec{r}_1 \cdot \vec{r})(\vec{r}_2 \cdot \vec{r})}{r^2 r_1 r_2} \]

\[ \Psi_{\text{perp}}(r) = \frac{D_1 D_2}{2\pi^2} \int dk P_0(k) \frac{j_1(kr)}{kr} \]

\[ \Psi_{\text{para}}(r) = \frac{D_1 D_2}{2\pi^2} \int dk P_0(k) [j_0(kr) - 2 \frac{j_1(kr)}{kr}] \]
Expected correlation of radial component of velocities for clusters with the same redshift but in different directions.

\[ \Omega_m = 0.4 \]
\[ \Omega_m = 0.3 \]

200 km/sec errors (16 micro-K for $\tau=0.01$)

100 km/sec errors (8 micro-K for $\tau=0.01$)

*Pierpaoli, Scott & White (2001)*
Expected correlation of radial component of velocities for clusters in the same direction but with different redshifts

Note: redshifts may need to be determined to better than .01!
Velocity Bias

- Our calculations were for randomly selected locations in the Universe, but measurements will be made where clusters are bias.
- Velocity bias not calculated yet (unpublished work by Sheth).
- Easily calculable.
POTENT on 100 Mpc scales

We can reconstruct the gravitational potential from cluster peculiar velocities, as has been done with galaxy peculiar velocities, but with much cleaner velocity measurements.

Why?

• Use as input for better modeling of cluster and galaxy formation.

• Combine with other surveys to directly measure large-scale bias.

* Bertschinger & Dekel 1989
Gravitational Potential
Reconstruction

\[ \Phi(r, \theta, \phi) = \sum_{l,m} \int dk k^2 \Phi_{lm}(k) j_l(kr) Y_{lm}(\theta, \phi) \]

Reconstruction weight:

\[ W_{\phi}(lmk, l'm'k') = \frac{\Delta k}{H_0} \frac{\Delta k'}{H_0} \delta_{ll'} \delta_{mm'} k^3 k'^3 \times \int dr r^2 X^2(r) w(r) j_l(kr) j_l(k'r) \]

\[ X(r) \equiv -\frac{2}{3} \frac{dD}{da} \sqrt{\frac{\Omega_m / a + \Omega_\Lambda a^2}{\Omega_m}} \]
Gravitational Potential Reconstruction

\[ w_v(r) = \frac{dN}{dr} \frac{1}{\sigma_v^2} \frac{1}{r^2} \]

From G. Holder

350 km/s

\[ k^4 P_\Phi(k) \]

\[ l = 20, 50, 75, 125, 225 \]

Ignore these
Conclusions

• CMB is important for breaking degeneracies between dark energy parameters and other parameters
• DASH will be available soon.
• Peculiar velocities are sensitive to $\dot{D}(z)$ instead of $D(z)$
• At $z < 0.5$, $\dot{D}(z)$ is much more dependent on $\Omega_m$ than $w$.
• Cluster peculiar velocities can be measured very well (in principle) for $z > 0.2$, well enough to measure the velocity correlations and reconstruct the large—scale gravitational potential.
• Theory/observable relationship is even more straightforward than other uses of clusters such as $dN/dz$.

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