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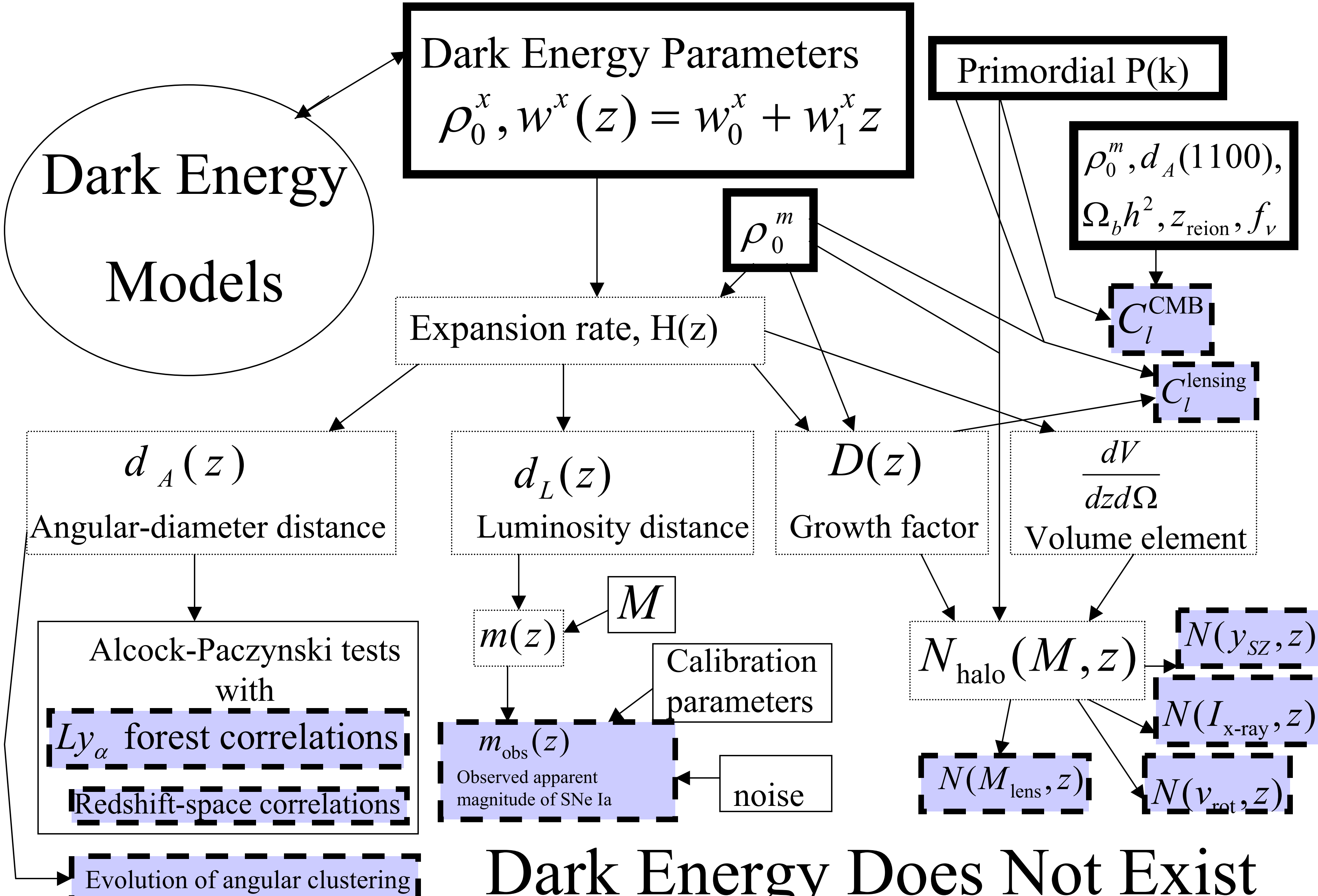
Exploring Dark Energy

With Galaxy Cluster Peculiar Velocities

Exploring D.E. with cluster v_{pec}

- Philosophy
- Advertisement
- Cluster velocity—velocity correlation functions as probes of dark energy
- POTENT on 100 Mpc scales



Dark Energy Does Not Exist In A Vacuum

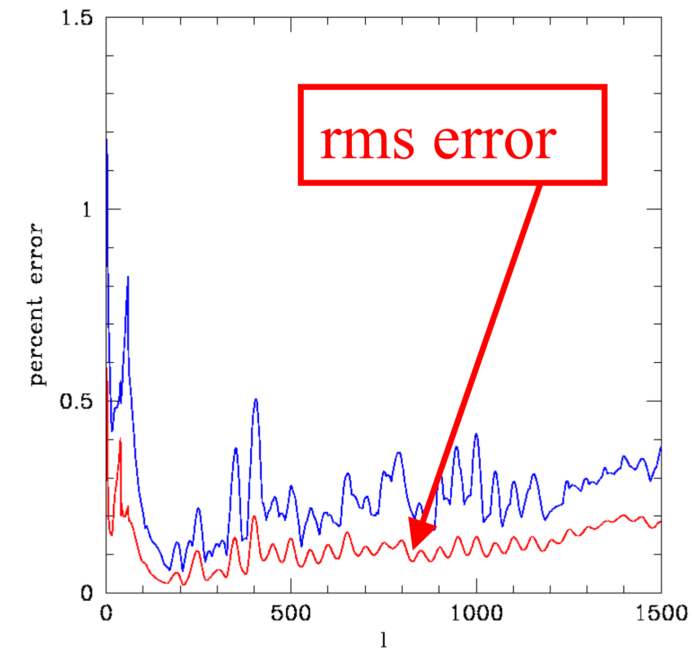
Kaplinghat, Knox and Skordis (2002)

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…

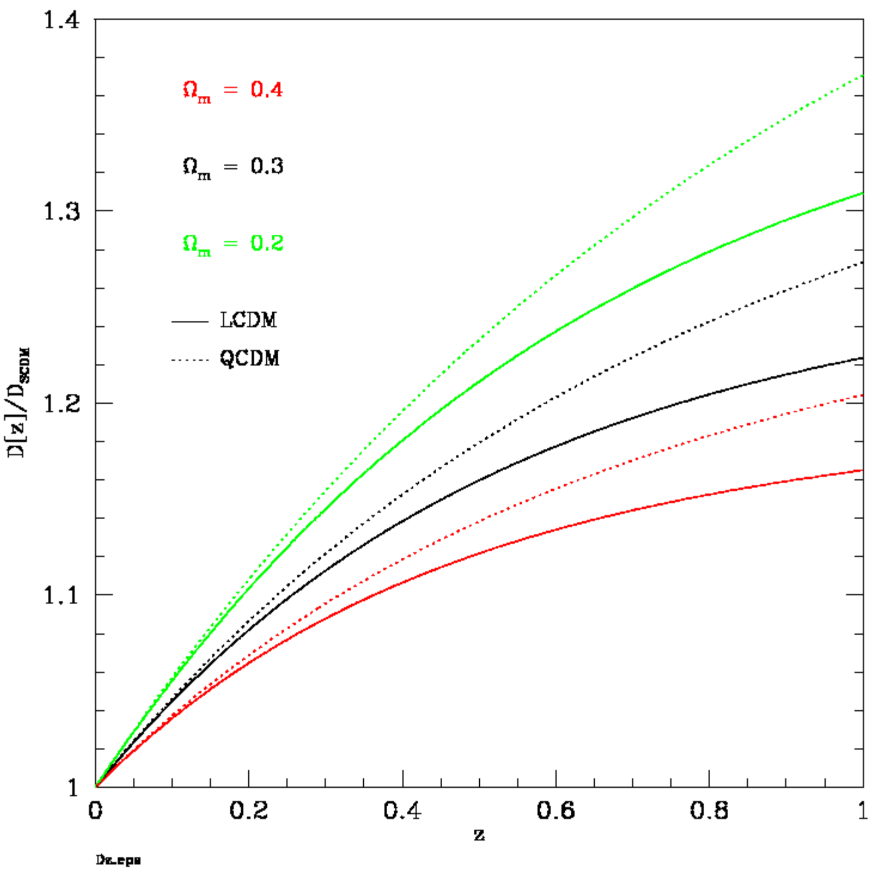
continuity equation

$$\dot{\delta} = ikv \qquad \delta(x,\eta) = D(\eta)\delta(x,\eta_0)$$

$$\rightarrow v \propto \dot{D}$$

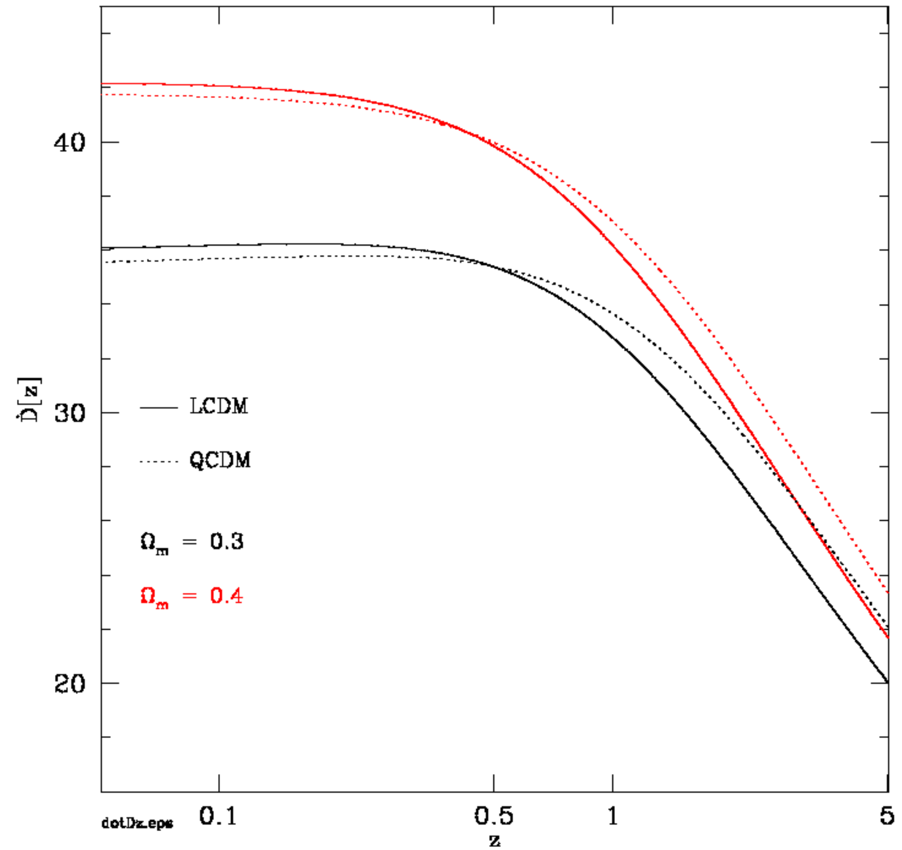
For $z < 0.5$, $\dot{D}$ is much less dependent on the nature of the dark energy than is the case for $D(z)$ or r(z).

➔ Peculiar velocities may be helpful in breaking Ω_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_{pec} with the SZ effect

Thermal

Spectral distortion characterized by Compton y parameter

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

$$\frac{\Delta I_\nu}{I_\nu} = y f(x) \quad ; \quad x = \frac{h\nu}{kT_{\mathrm{CMB}}}$$

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

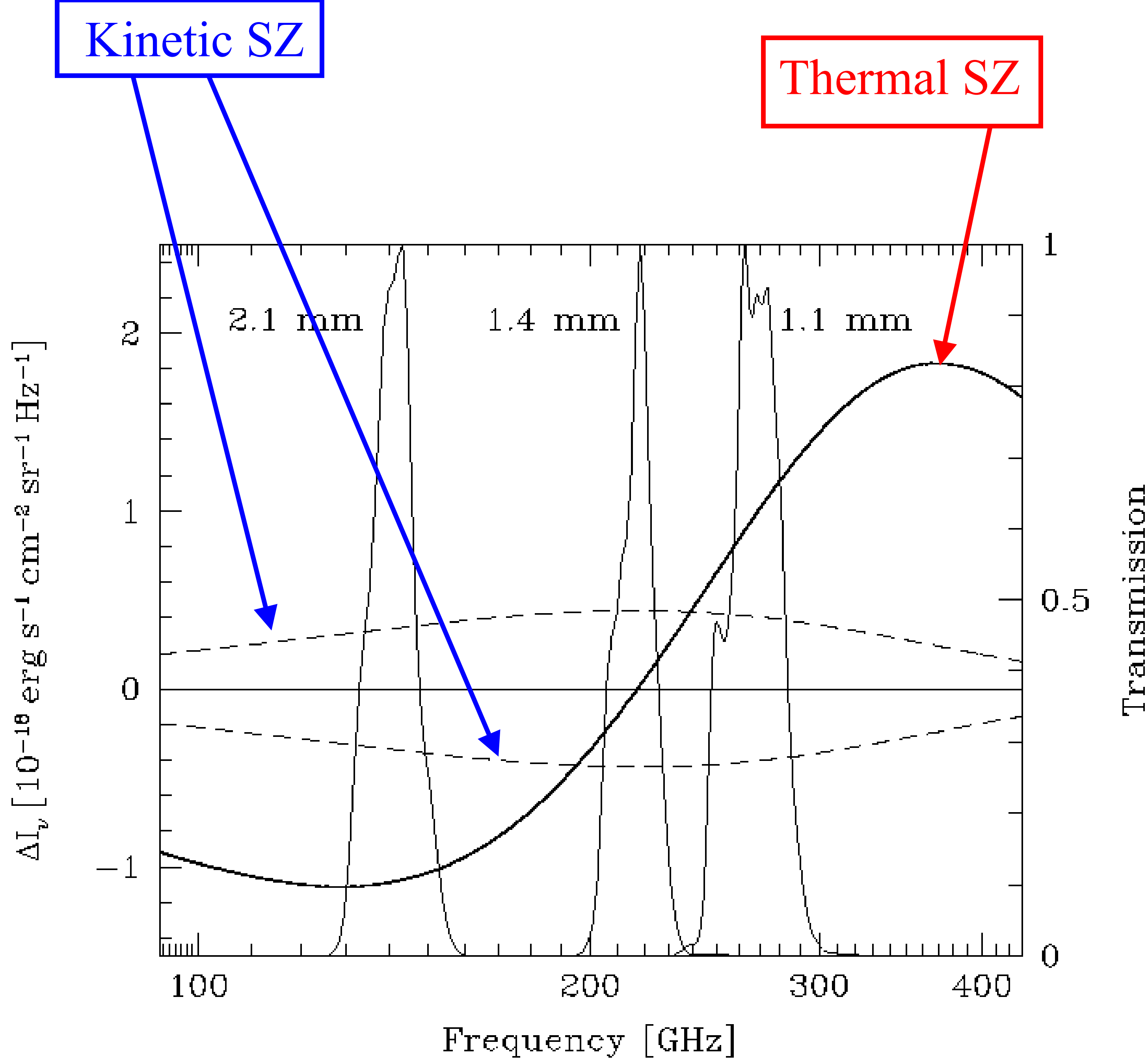
Kinetic

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

Combine to get velocity:

$$v / c = -\frac{kT_e}{m_e c^2}\frac{(\delta T / T)_{SZ}}{y}$$

Sunyaev & Zeldovich 1980



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_{pec} be measured?

Holzapfel et al. (1997):

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

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

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.

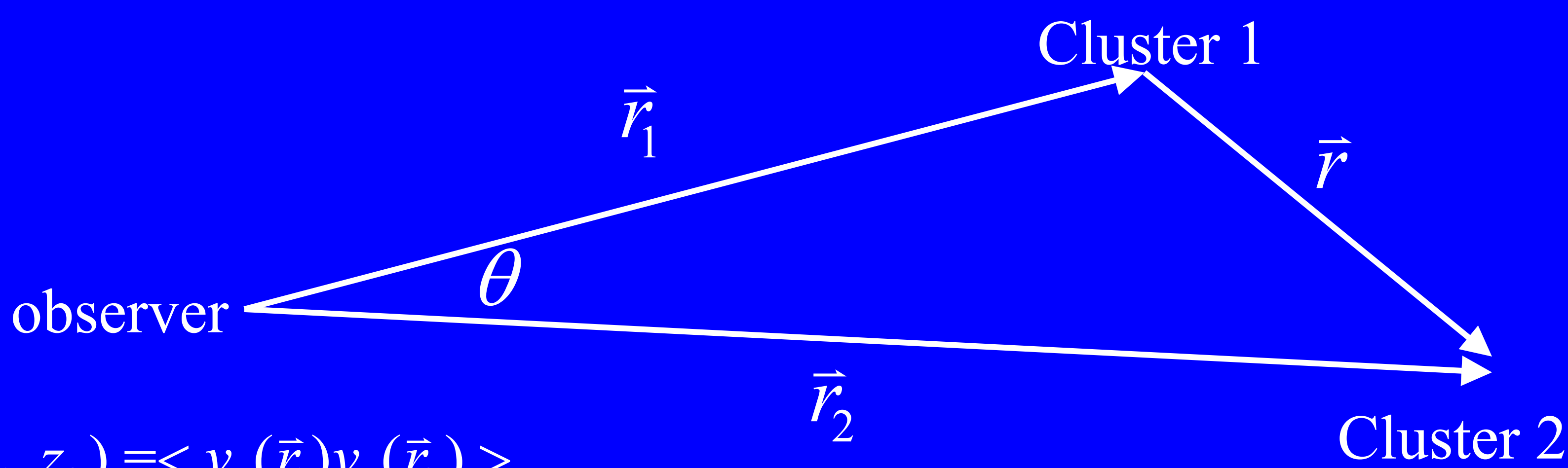
With a smaller beam a cluster stands out better against the confusing background of CMB anisotropy and other clusters.

$$\sigma_v \approx 25\ \mathrm{km/sec}\ (.01/\tau)\left(\frac{\sqrt{(\Delta T_{\mathrm{CMB}})^2 + (\Delta T_{\mathrm{noise}})^2}}{2\mu\mathrm{K}}\right)$$

Haehnelt & Tegmark (1996)

Becker et al. (2001) → 2μK

What Are The Expected Signals?



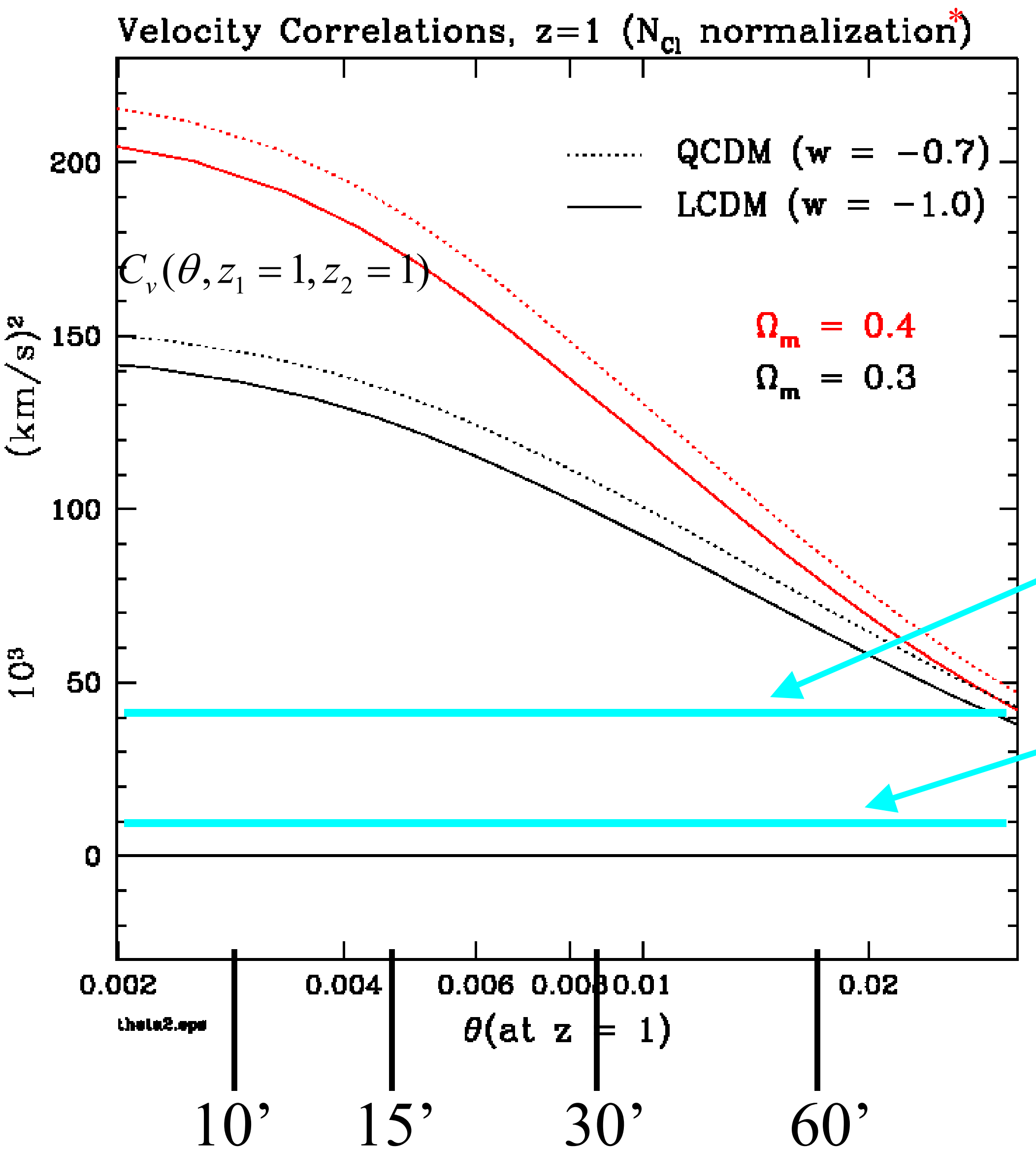
$$C_v(\theta, z_1, z_2) \equiv < v_r(\vec{r}_1) v_r(\vec{r}_2) >$$

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

$$\Psi_{perp}(r) = \frac{\dot{D}_1 \dot{D}_2}{2\pi^2} \int dk P_0(k) \frac{j_1(kr)}{kr}$$

$$\Psi_{para}(r) = \frac{\dot{D}_1 \dot{D}_2}{2\pi^2} \int dk P_0(k) [j_0(kr) - 2\frac{j_1(kr)}{kr}]$$

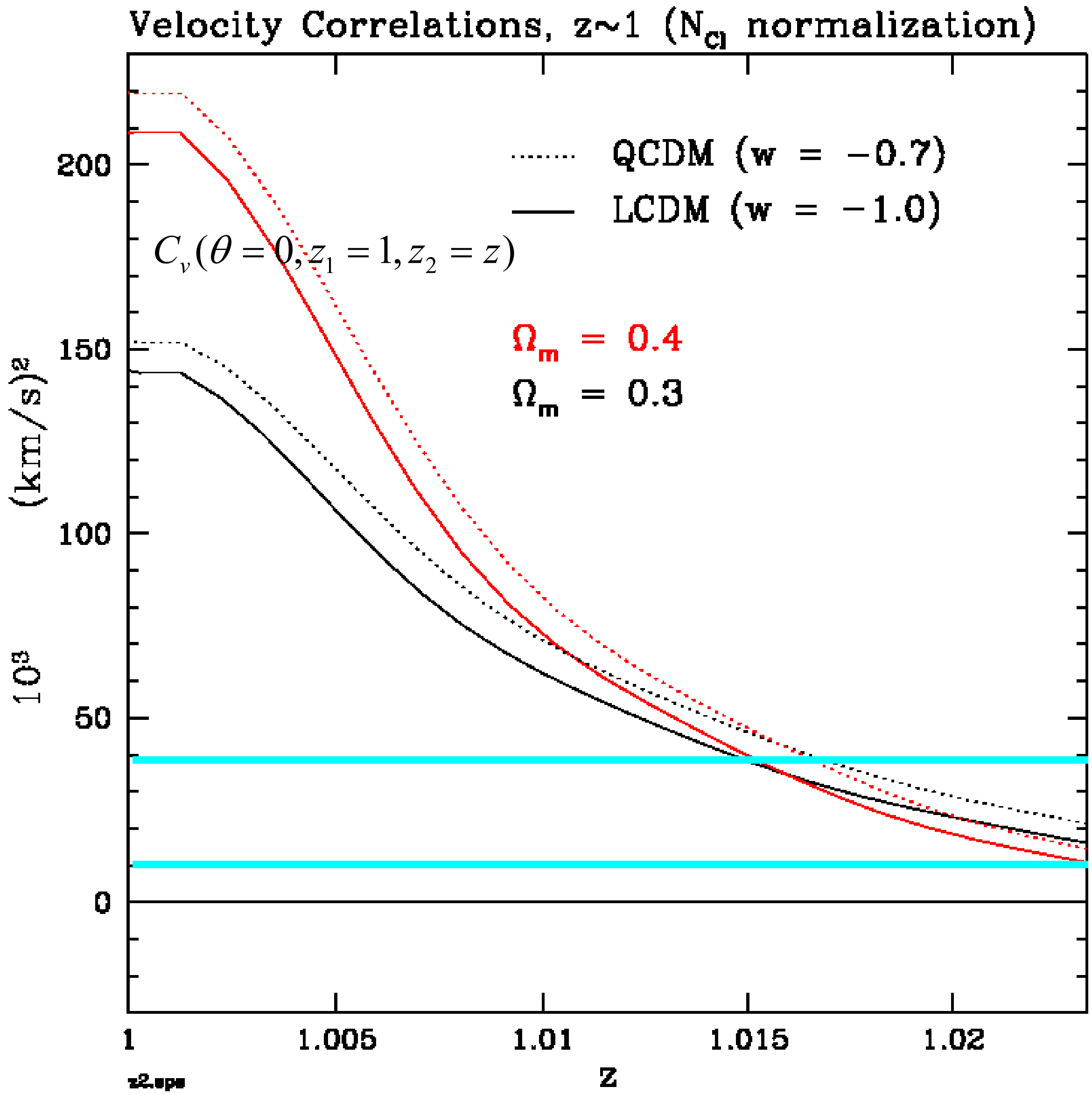
Expected correlation of radial component of velocities for clusters with the same redshift but in different directions



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

$$\Phi(r,\theta,\phi) = \sum_{l,m} \int dk k^2 \tilde{\Phi}_{lm}(k) j_l(kr) Y_{lm}(\theta,\phi)$$

Reconstruction weight:

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

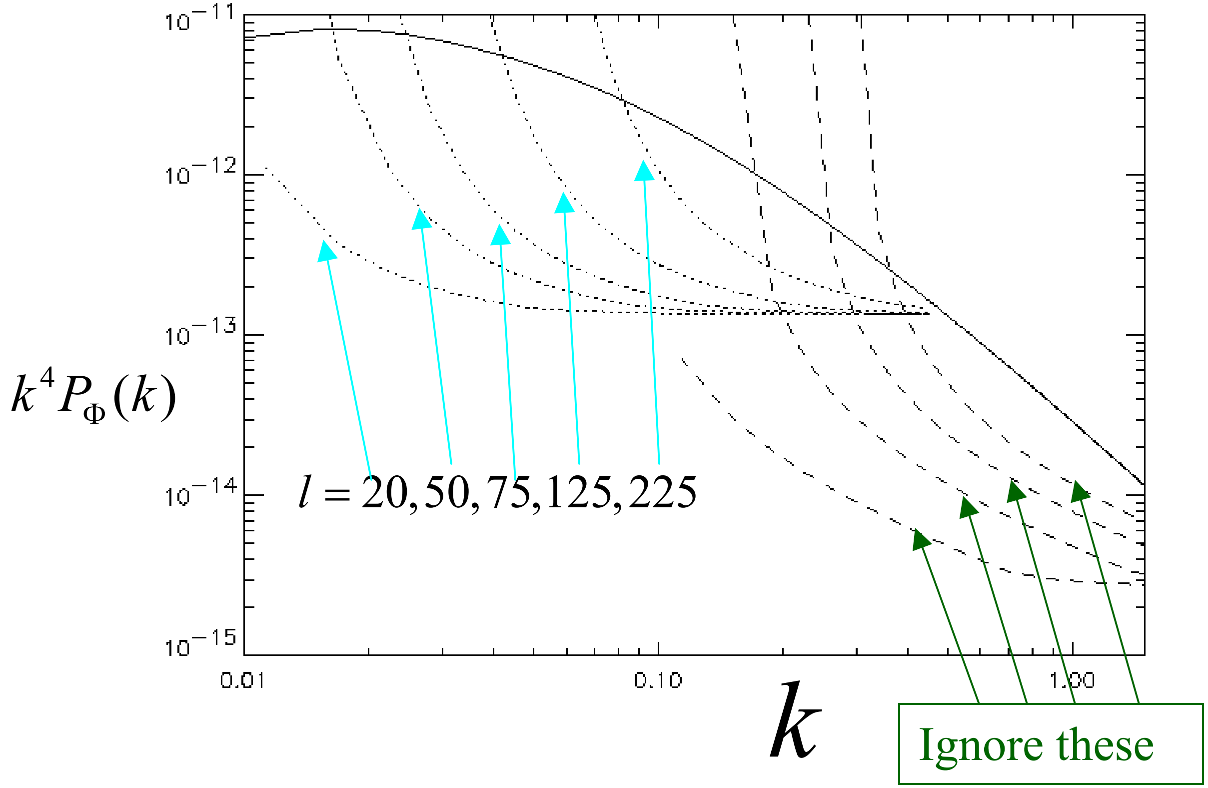
$$X(r) \equiv -\frac{2}{3} \frac{dD}{da} \frac{\sqrt{\Omega_m / a + \Omega_\Lambda a^2}}{\Omega_m}$$

Gravitational Potential Reconstruction

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

From G. Holder

350 km/s



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 Ω_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.

Thanks to G. Holder and S. Meyer for useful conversations