MOVING DARK ENERGY AND THE CMB DIPOLE

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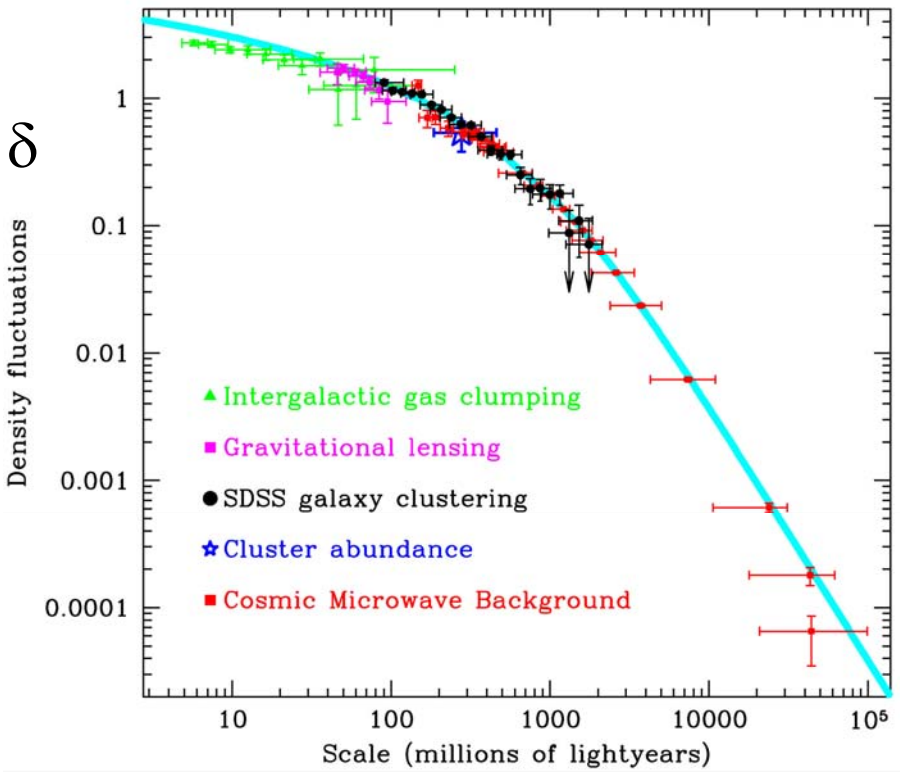
Standard Cosmology

Homogeneity and isotropy on very large scales

Cosmological Principle ⇒ $V_{Matter} = V_{CMB}$

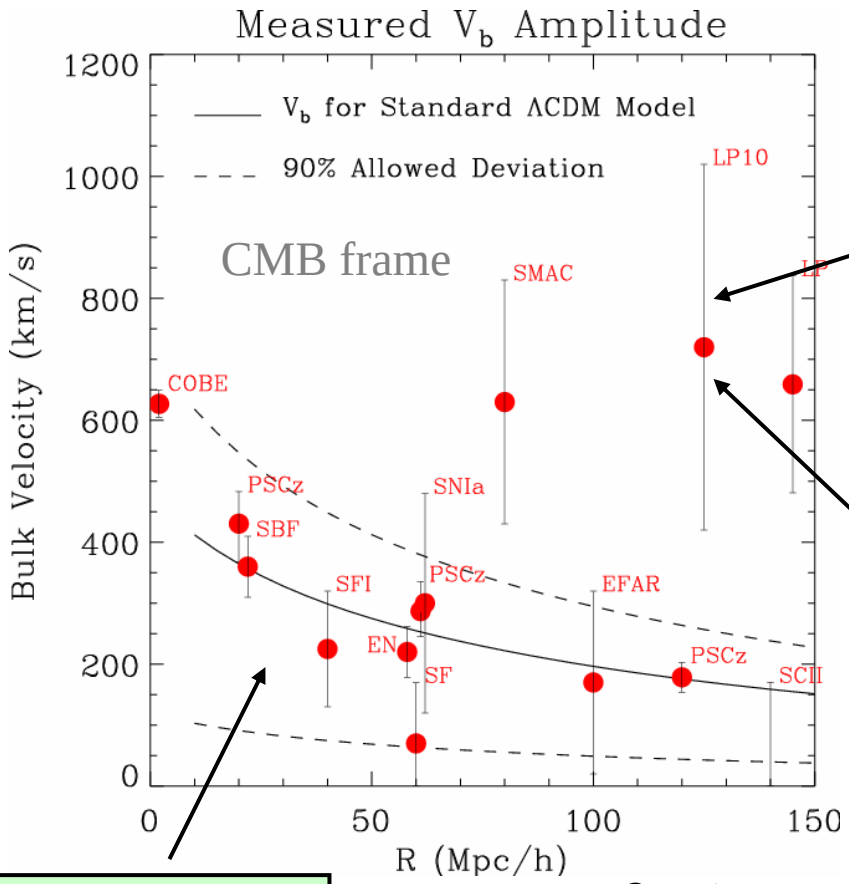


Density fluctuations

$$\nabla \cdot v = -H_0 \Omega_M^{0.6} \delta(x)$$

Peculiar velocities

Peculiar velocity surveys



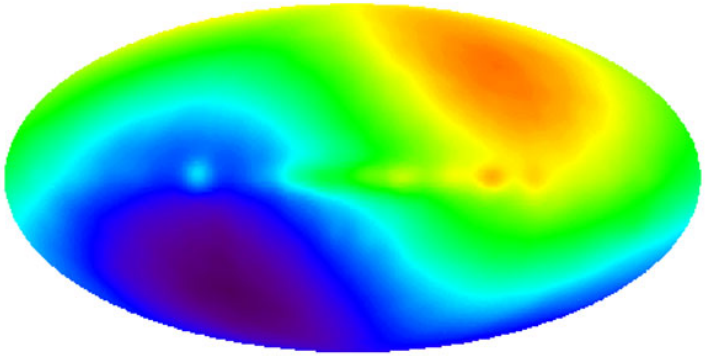
Courteau, Dekel, (2001)

R > 100h^{-1} Mpc convergence ?

Systematics in distance indicators? Cosmological Principle violation?

R < 60h^{-1} Mpc convergence

Bulk flows and the CMB dipole



$$\left.\frac{\delta T}{T}\right|_{dipole} = \vec{n}\cdot(\vec{v}_{dec} - \vec{v}_0)$$

Bulk flow $V_b \equiv$ velocity of a matter volume with respect to an observer who measures a vanishing CMB dipole

What if the dipole is not kinematic? Paczynski, Piran, Turner ('90)

Does dark energy affect the CMB dipole?

A.L.M., JCAP 05 (2006) 015

Dark energy

Accelerated expansion (SN Ia) p<0

Equation of state w_{DE}< -0.78 (WMAP1)

Nature:

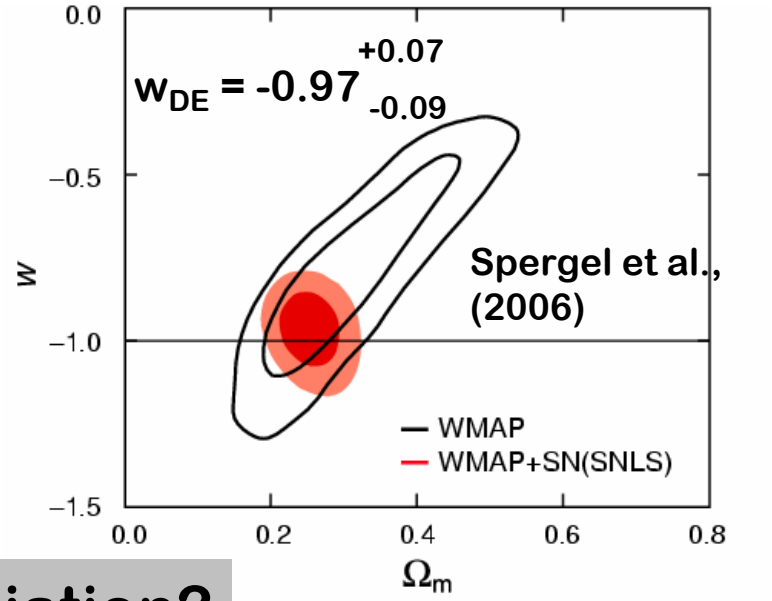
Λ, quintessence, k-essence, … ?

w_{DE}: constant, scaling,…?

Clustering properties?

Decoupled from matter and radiation?

Are there dark energy bulk motions?



Cosmology with moving dark energy

Four homogeneous fluids (decoupled from recombination):

Radiation: (ρ_R, p_R, v_R) $w_R=1/3$

Baryons: (ρ_B, p_B, v_B) $w_B=0$

Dark Matter: $(\rho_{DM}, p_{DM}, v_{DM})$ $w_{DM}=0$

Dark energy: $(\rho_{DE}, p_{DE}, v_{DE})$ $w_{DE}=w_{DE}(z)$

$$(T^{\mu}_{\ \nu})_\alpha = (\rho_\alpha + p_\alpha) u^\mu_\alpha u_{\nu\alpha} - p_\alpha \delta^\mu_{\ \nu}$$

Linear regime:

$$\vec{v}_\alpha^{\,2} \ll 1$$

$$\begin{aligned} \rho_\alpha &= \rho_\alpha(\eta), \\ p_\alpha &= p_\alpha(\eta), \\ u^\mu_\alpha &= \frac{1}{a}(1, v^i_\alpha(\eta)) \end{aligned}$$

$\alpha = R, B, DM, DE$

zero-modes

Cosmology with moving dark energy

Perturbed metric (linear regime)

$$ds^2 = a^2(\tau)\left(dt^2 + 2S_i(t)\,dt\,dx^i - \delta_{ij}\,dx^i\,dx^j\right)$$

Total energy-momentum tensor

$$\begin{aligned}
T^0{}_0 &= \sum_\alpha \rho_\alpha \\
T^0{}_i &= \sum_\alpha (\rho_\alpha + p_\alpha)(S_i - v_{i\alpha}) \\
T^i{}_0 &= \sum_\alpha (\rho_\alpha + p_\alpha) v^i_\alpha \\
T^i{}_j &= -\sum_\alpha p_\alpha \delta^i{}_j
\end{aligned}$$

Cosmology with moving dark energy

Einstein equations

$$\vec{S} = \frac{\sum_\alpha (\rho_\alpha + p_\alpha)\vec{v}_\alpha}{\sum_\alpha (\rho_\alpha + p_\alpha)}$$

"cosmic center of mass velocity"

"inertial mass density"

Momentum conservation

$$|\vec{S} - \vec{v}_\alpha| \propto a^{3w_\alpha - 1}$$

Effects on the CMB dipole

Perturbed photon energy

$$\mathcal{E} \simeq \frac{E}{a}\left(1 + \frac{d\delta x^0}{d\eta} + \vec{n}\cdot(\vec{S} - \vec{v})\right)$$

CMB dipole

$$\left.\frac{\delta T}{T}\right|_{dipole} = \frac{\hat{\mathcal{E}}_0 - \hat{\mathcal{E}}_{dec}}{\hat{\mathcal{E}}_{dec}} \simeq \vec{n}\cdot(\vec{S} - \vec{v})\Big|^0_{dec}$$

"center of mass motion"

Doppler

Effects on the CMB dipole

Today only matter and dark energy contribute to S_0

$$\vec{S}_0 - \vec{v}_0 \simeq \frac{\Omega_M(\vec{v}_M^0 - \vec{v}_0) + (1 + w_{DE}^0)\Omega_{DE}(\vec{v}_{DE}^0 - \vec{v}_0)}{1 + w_{DE}^0\Omega_{DE}}$$

At decoupling only matter and radiation contribute to S_{dec}

$$\vec{S}_{dec} - \vec{v}_{dec} \simeq \frac{\Omega_{DM}}{\Omega_M}(\vec{v}_{DM}^{dec} - \vec{v}_B^{dec})$$

emitter

Matter bulk flows and moving dark energy

In the absence of dark energy ($\Omega_{DE} = 0$) or for a pure cosmological constant ($w_{DE} = -1$).

$$\left.\frac{\delta T}{T}\right|_{dipole} \simeq \vec{n} \cdot (\vec{v}_M^0 - \vec{v}_0)$$

Vanishing dipole in the matter rest frame, i.e. very large scale bulk flows are not possible

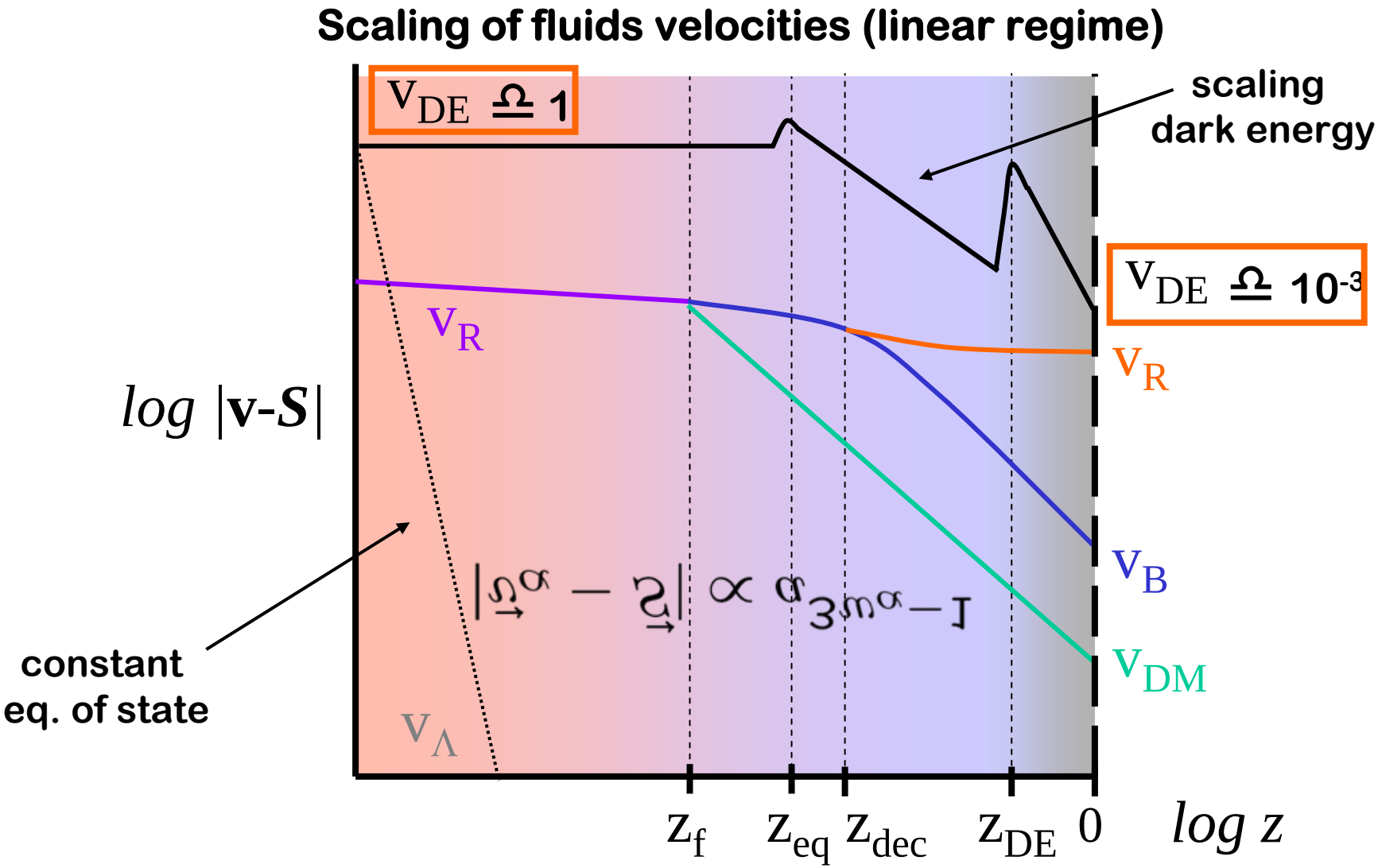
Matter bulk flows and moving dark energy

Matter bulk flows on the largest scales require moving dark energy
(Ω_{DE} 🕒 0, w_{DE} 🕒 -1 and v_{DE} 🕒 v_M)

$$\vec{V}_b \simeq \frac{(1+w^0_{DE})\Omega_{DE}}{1+w^0_{DE}\Omega_{DE}}(\vec{v}^0_M - \vec{v}^0_{DE}) + \frac{\Omega_{DM}}{\Omega_M}(\vec{v}^{dec}_{DM} - \vec{v}^{dec}_B)$$

non-vanishing for moving dark energy

A primordial dark energy flow?



Conclusions

The usual interpretation of CMB dipole is not appropriate when moving dark energy is present

CMB dipole due to the motion of observer (emitter) w.r.t the *cosmic center of mass*

Matter bulk flows on the largest scales require moving dark energy

A primordial dark energy flow could have survived until present in scaling models

Further evidence of DE *bulk* motion required
(work in progress with J. Beltrán)