Dark Energy in The Universe
Finally a 2nd Opinion!

“CHANDRA CLUSTER COSMOLOGY PROJECT III: COSMOLOGICAL PARAMETER CONSTRAINTS”
Vikhlinin et al. 2008 (arXiv:0812.2720v1)

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Dark Energy in the news!?  

”Measuring the Mysterious ‘Dark’ Force”  

By Dennis Overbye (December 16, 2008)  

“Dark Energy Stunts Galaxies’ Growth“  

The Economist: “A Shot in the Dark” (Dec 20, 2008)  
What’s on the menu today?

1.) What is our universe made of? What is its density?
2.) What are the different kinds of universes possible?
3.) What is Dark Matter – what is the evidence today?
4.) What is Dark Energy – what was the evidence?
5.) What is Dark Energy – what is the new evidence?
6.) What should you take away from today’s talk?
What is The Universe made of?
Not the same stuff as us, that’s for sure:

$$\Omega = \Omega_{\text{Matter}} + \Omega_{\Lambda} = 0.27 + 0.73 = 1$$
What is The Universe made of?
What is this $\Omega=1$ parameter?

The Theory of Inflation requires us to have a flat universe with $\Omega=1$

WMAP gives very good constraints on $\Omega=1$

$\Omega = \text{average matter density/critical density}$

[Regardless of the type of universe we live in]

- Inflation helps theorists to explain how the large scale structures we see in the universe today evolved from the primeval universe.
- Also explains how the universe is flat (Euclidean), homogeneous and isotropic (on large scales)
- A recent review of inflation can be found here: http://arxiv.org/abs/0901.0549
What **types** of Universe are there?

Each of these slices of the universe is the same size at the present time.
What is Dark Matter?

A form of matter that only interacts with other matter via the gravitational force

Evidence:

- **Galaxy Rotation Curves**
  (Vera Rubin 1975)
  - They do not fall as a function of radius

- **Clusters of Galaxies**
  (Fritz Zwicky 1933)
  - High Mass to light ratio
Galaxy Rotation Curves

A: Predicted based on luminous matter
B: Observed from stellar orbits
Clusters of Galaxies

Virial Theorem: Relates the total KE (over time) of a stable system to the total PE:

\[ 2\langle T \rangle = - \sum_{k=1}^{N} \langle F_k \cdot r_k \rangle \]

Zwicky (1933)
- Estimate 1: total mass of Coma cluster based on motions of galaxies
- Estimate 2: total mass based on number of galaxies and their brightness
- They differed by a factor of about 400
- Later confirmed by X-ray and Gravitational Lensing
Clusters of Galaxies/Grav Lensing

Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys
What is Dark Energy?

A positive cosmological constant which manifests itself as a negative pressure in Einstein’s Field Equations, $\Lambda = 0.73$

$$G_{ab} + \Lambda g_{ab} = kT_{ab}$$

Evidence:

- High Redshift Supernovae
  - Farther away than they should be otherwise
- X-ray Clusters of Galaxies (Vikhlinin 2008)
  - They are evolving too slowly
High-z Supernovae Evidence

Perlmutter, et al. (1998)

Calan/Tololo
(Hamuy et al., A.J. 1996)

Supernova Cosmology Project

More Redshift
(More total expansion of universe since the supernova explosion)
High-z Supernovae Evidence

The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.

Plotting actual supernova data on this graph shows that the data fit the accelerating model best.

If the accelerating model is correct, then the universe must be 14 billion years old.
X-ray Cluster Evidence (2008/12)

- **We Know:** Growth of structure & distance-redshift relation sensitive to DE properties
- **Evidence Based on:** Evolution in number density of massive clusters of galaxies
- **Actually use:** Evolution over time of cluster mass function to trace growth of density perturbation from the early universe
  - Mapping between linear power spectrum & cluster mass fcn relies on model for non-linear gravitational collapse (via n-body simulations)
  - Mass density recently dominated by CDM and Gaussian fluctuations
  - Must use $H_0$ from Hubble Project
X-ray Cluster Evidence (2008/12)

- Two samples used (Universe today~13.6 Gyr)
  - \(43 < z_L > \sim 0.05\) (~0.6 Gyr ago, Universe ~13.001)
  - \(37 < z_H > \sim 0.5\) (~5 Gyr ago, Universe~8.6 Gyr)

- Targets/Samples
  - ROSAT PSPC 400d sample for high-z
  - Chandra deep imaging to get mass

- Mass proxies (checked via simulations)
  - Average X-ray temp (\(T_x\)) in annulus (0.15-1)\(r_{500kpc}\)
    - Avoids radiative cooling effects in central regions
  - Intracluster gas mass (\(M_{\text{gas}}\)) integrated within \(r_{500}\)
  - Combination of the two estimates \(Y_x = T_x \times M_{\text{gas}}\)
Vikhlinin et al. 2008 evidence

Fig. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at \( z = 0 \) adjusted) computed for a cosmology which is close to our best-fit model. The low-\( z \) mass function is reproduced from Fig.[1] which for the high-\( z \) cluster we show only the most distant subsample (\( z > 0.55 \)) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with \( \Omega_A = 0 \). Both the model and the data at high redshifts are changed relative to the \( \Omega_A = 0.75 \) case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to \( \Delta_{\text{crit}} = 500 \) are different. When the overall model normalization is adjusted to the low-\( z \) mass function, the predicted number density of \( z > 0.55 \) clusters is in strong disagreement with the data, and therefore this combination of \( \Omega_M \) and \( \Omega_A \) can be rejected.
Vikhlinin et al. 2008 evidence

Dark Energy constraints in a flat universe from combination of the CMB and cluster data. Adding $\sigma_8$ vs CMB normalization significantly improves things.

Equation of state:

$w_o = \text{equation of state}$

$w_o = \text{dark energy pressure/density}$
What to take away?

We now have two independent lines of evidence for Dark Energy (or a negative pressure pervading The Universe)

1.) High-z Supernovae data are fainter than they would be w/o Dark Energy

2.) The predicted number density of z>0.55 massive X-ray clusters of galaxies is in strong disagreement with a model Universe w/o Dark Energy