Improved Constraints on Dark Energy From Chandra X-ray Observations of the Largest Relaxed Galaxy Clusters

S.W. Allen et al.

(Measuring $\Omega_\Lambda$ and $\Omega_m$ using X-ray Gas Mass Fraction)
Technique

Overview of how $f_{\text{gas}}$ is useful

1) Cluster gas from hot, relaxed clusters, is expected to be a fair tracer of matter content of the universe (Baryonic mass fraction).

2) Measuring Gas Mass Fraction, $f_{\text{gas}}$, and using $\Omega_b$, gives $\Omega_m$. $f_{\text{gas}}$ is also proportional to distances, and so traces expansion.

3) Measure X-ray surface brightness profiles – gives Temperature and mass profiles and thus $f_{\text{gas}}$ profiles.

4) Compare $f_{\text{gas}}$ profiles with expected dependence on cosmology. { $f_{\text{gas}}(z)$, and proportionality to $\Omega_m$ }
Data Sample
And Technical Details

- 42 Clusters
- $0.05 < z < 1.1$
- At Chandra Observatory bet. 1999 – 2005
- Morphologically selected the following:
  - Hot: $kT > 5$ keV ($T \sim 5.8 \times 10^{10}$ K)
    - $f_{\text{gas}}$ does not depend on temperature for hot systems.
  - Dynamically Relaxed
    - Allows hydrostatic equilibrium assumption
- At Right: A galaxy cluster from data set.

MACSJ1423.8+2404

Scale: Image is 2.56 x 1.6 arcmin
(Credit: NAOJ/Subaru/H.Ebeling)
Fgas Measurements

- Don't show measured surface-brightness profiles, or other data.
- But show radial profiles of $f_{\text{gas}}$, obtained from measured surface brightness profiles, and assumed NFW dark matter distribution. (Note convergence at $r_{2500}$)
- Pick value of $f_{\text{gas}}$ at $r_{2500}$ (used in $f_{\text{gas}}(z)$ plots)
- Systematic errors up to 15 %
Variation of $f_{\text{gas}}$ with redshift

\[ f_{\text{gas}}^{\Lambda CDM}(z) = \frac{KA\gamma b(z)}{1 + s(z)} \left( \frac{\Omega_{b}}{\Omega_{m}} \right) \left[ \frac{d_{A}^{\Lambda CDM}(z)}{d_{A}(z)} \right]^{1.5} \]

From Hydrodynamic simulations, expect correct cosmology to give no variation of $f_{\text{gas}}$ with redshift.

$\Lambda$CDM: $\Omega_{m} = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$

SCDM: $\Omega_{m} = 1$, $h = 0.5$
Tested Models of Dark Energy

**LCMD: w = -1**

**Other Constant w:**
(including $w < -1$)

**Evolving w:**

\[ w = \frac{w_{et}z + w_0z_t}{z + z_t} = \frac{w_{et}(1 - a)a_t + w_0(1 - a_t)a}{a(1 - 2a_t) + a_t} \]

$et$ = early time

$o$ = present time

$t$ = at transition
$\Omega_m$ Constraint

$\Omega_m = 0.28 \pm 0.06$ (68% Confidence) for $\Lambda$CDM

Above analysis done with 6 lowest redshift clusters shown at right. Value in good agreement with value obtained from rest of
Constraints on Lambda-CDM

$\Omega_\Lambda = 0.86 \pm 0.21$

Cited as Dark Energy Detection
Constraints on $w$ evolution

Consistent with no evolution in $w$

Davis et al.  

Reiss et al.
Constraints: Summary/Uncertainties

10-15% systematic uncertainty from: x-ray modeling (lots of assumptions), instrument calibration, non-thermal pressure support
Assumptions of spherical symmetry, hydrostatic equilibrium, dark matter profile (NFW), ...
Results comparable with SNIa data according to w0, \( \Omega_m \) ellipses.
Five Year WMAP Observations: Cosmological Interpretation

E. Komatsu et. al.

Constraining Dark Energy Models Via Accurately Measured Distances to Specific Epochs
Distance Priors

2 Distance ratios, associated w/ decoupling epoch, can be measured very precisely by locating peaks and troughs of acoustic oscillations in CMB:

\[ \frac{D_A(z^*)}{r_s(z^*)} \]
\[ \frac{D_A(z^*)}{H(z^*)/c} \]

\( D_A(z^*) \): Proper distance (not comoving) to decoupling epoch

\( r_s(z^*) \): Comoving size of the sound horizon at the decoupling epoch.

\( H(z^*)/c \): Hubble horizon size at the decoupling epoch

\( z^* \): Defines decoupling epoch

\[ l_A \equiv (1 + z_*) \frac{\pi D_A(z_*)}{r_s(z_*)} \]
\[ R(z_*) \equiv \sqrt{\Omega_m H_0^2 (1 + z_*) D_A(z_*)} \]

\[ z_* = 1048 \left[ 1 + 0.00124 (\Omega_b h^2)^{-0.738} \right] \left[ 1 + g_1 (\Omega_m h^2)^{g_2} \right] \]

\[ g_1 = \frac{0.0783 (\Omega_b h^2)^{-0.238}}{1 + 39.5 (\Omega_b h^2)^{0.763}} \]

\[ g_2 = \frac{0.560}{1 + 21.1 (\Omega_b h^2)^{1.81}} \]
Priors alone provide decent results

Major Caveat: Full WMAP Analysis
Requires assumption of cosmology!

Just distance priors
How to use priors to constrain cosmology

Chi Square!

\[ \chi^2_{WMAP} \equiv -2 \ln L = (x_i - d_i)(C^{-1})_{ij}(x_j - d_j) \]

\[ x_i = (l_A, R, z_*) \] Computed using favorite cosmology (\( \Omega_m, \Omega_b, H_0 \), etc.)

Minimize Chi Square with respect to \( H_0, \Omega_b, \Omega_m \), which leaves you with a distribution of \( w(a)\) and \( \Omega_k \)

**TABLE 10**

<table>
<thead>
<tr>
<th>( l_A(z_*) )</th>
<th>5-year ML(^a)</th>
<th>5-year Mean(^b)</th>
<th>Error, ( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R(z_*) )</td>
<td>1.710</td>
<td>1.721</td>
<td>0.019</td>
</tr>
<tr>
<td>( z_* )</td>
<td>1090.04</td>
<td>1091.13</td>
<td>0.93</td>
</tr>
</tbody>
</table>

\(^a\) Maximum likelihood values (recommended)
\(^b\) Mean of the likelihood

**TABLE 11**

Inverse covariance matrix for the WMAP distance priors

<table>
<thead>
<tr>
<th>( l_A(z_*) )</th>
<th>( R(z_*) )</th>
<th>( z_* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_A(z_*) )</td>
<td>1.800</td>
<td>1.103</td>
</tr>
<tr>
<td>( R(z_*) )</td>
<td>5667.577</td>
<td>-92.263</td>
</tr>
<tr>
<td>( z_* )</td>
<td>2.923</td>
<td></td>
</tr>
</tbody>
</table>
Measured w Evolution

\[
w(a) = \frac{a \tilde{w}(a)}{a + a_{\text{trans}}} - \frac{a_{\text{trans}}}{a + a_{\text{trans}}}
\]

\[
\tilde{w}(a) = \tilde{w}_0 + (1 - a) \tilde{w}_a.
\]
EXTRA SLIDES ....

Dark Energy equation of state

\[ w_{\text{early}} = -1 \text{ and } w_{\text{late}} = w_0 + (1 - a)w_a \]

\[ w(a) = \tilde{w}(a) f(a/a_{\text{trans}}) + (-1) [1 - f(a/a_{\text{trans}})] \]

\[ f(x) \text{ goes to zero for } x \ll 1, \text{ and to unity for } x \gg 1 \]

\[ w(a) = \frac{a\tilde{w}(a)}{a + a_{\text{trans}}} - \frac{a_{\text{trans}}}{a + a_{\text{trans}}} \]

\[ \tilde{w}(a) = \tilde{w}_0 + (1 - a)\tilde{w}_a. \]
Dark Energy Models

Komatsu et al.

Graphs showing the behavior of dark energy models as a function of redshift. The graphs depict the evolution of 
$rac{\rho_{de}(z)}{\rho_m(z)} \times 10^6$ and 
$w_{\text{eff}}(z) = P_{de}(z)/\rho_{de}(z)$, with different values of $z_{\text{trans}}$ and $w_0$, along with their derivatives.

- $w_0 = -1.1$
- $w' = 1$

Parameters: $z_{\text{trans}} = 0.5$, $z_{\text{trans}} = 2.0$, $z_{\text{trans}} = 10$.