Cosmology with the Chandra cluster data

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The Goal: constrain dark energy

- dark energy affects expansion of the Universe

- $H(z)$ can be “observed” through
  
  - distances: $D(z) \propto \int \frac{dz}{H(z)}$
  
  - growth of structure: $\ddot{\delta} + 2H\dot{\delta} - 4\pi G \rho_M \delta = 0$

  ($\delta = \rho_M / \langle \rho_M \rangle - 1$)

- Given $\langle \delta^2(M) \rangle$, theory predicts $N_{\text{clusters}}(M)$
The Plan

1. Find many high-$z$ clusters

2. Measure their $M$ as accurately as possible
The Survey

- Over 400 deg$^2$ of ROSAT pointed observations
- 100% optically identified, 95% clean
- 37 high-flux clusters at $z > 0.4$
- Volume = $3 \times V(z < 0.1)$
- All distant clusters followed up with Chandra (nearly complete)
  \[ \Delta T/T \approx 10\% - 15\% \]
ROSAT data

ROSAT model

Chandra
Comparison of ROSAT and Chandra fluxes
The Challenge

For structure-cosmology connection, see Richstone, Loeb, Turner 1992; Jeltema et al. 2005
The approach

- Develop structure-insensitive mass proxies
- Calibrate using realistic numerical simulations and *Chandra* observations of low-$z$ clusters
- Use these proxies for high-$z$ clusters
Temperature profiles from Chandra

Vikhlinin etal astro-ph/0507092
Total and gas density profiles

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• Relations are nearly self-similar \((M \propto T^\alpha, \alpha = 1.6 \pm 0.1)\)

• Evolution is also self-similar, \(M/T^{3/2} \propto h^{-1}(z)\)  
  
(Kotov & Vikhlinin '05)
11 individual galaxy clusters simulated with and without cooling
virial masses from $8 \times 10^{13}$ to $10^{15} h^{-1}$ Msun

**Cosmological N-body+gasdynamics ART code**
(Kravtsov 1999, 2003; Kravtsov et al. 2002)

$m_{\text{dm}} = 3 \times 10^8 h^{-1}$ Msun, $m_* \sim 10^6 h^{-1}$ Msun

peak resolution $\sim 2 h^{-1}$ kpc

2-4 $\times 10^7$ mesh cells per cluster

**Gasdynamics**: Eulerian AMR (2$^{\text{nd}}$ order Godunov)

**N-body dynamics** of DM and stellar particles

**Radiative cooling and heating of gas**: metallicity dependent taking into account atomic and molecular processes

**Star formation** using the Kennicutt (1998) recipe

**Thermal stellar** feedback

**Metal enrichment** by SNII/Ia + Advection of metals
Testing Chandra measurement biases

work by D. Nagai, A. Kravtsov, A.V.

- generate “Chandra data” for clusters from cosmological simulations
- reduce with the real data analysis pipeline
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Are simulations realistic?
Current results: 160d

$z = 0.05$

$z = 0.55$

$\Omega_M = 0.27$

$\Omega_\Lambda = 0$
Current results: 160d: $w$

For $\Omega_M = 0.3$, \[ w < -0.9 \ (68\%), \]
\[ < -0.7 \ (90\%), \]
\[ < -0.6 \ (95\%) \]