Simulating the Cosmic Melting Pot in the Virialization Regions of Galaxy Clusters

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Accurate Determination of Mass Function and Clustering of Dark Matter halos with N–body simulations

- **Einstein–de Sitter (flat matter only)**
- **No Dark Energy**
  - Fast growth of structure

- **ΛCDM**
- **With Dark Energy**
  - Slow growth of structure
Hydrodynamical Simulations of Galaxy Clusters

N-body+Gasdynamics with Adaptive Refinement Tree (ART) code

Box size ~ 100 Mpc
Spatial resolution ~ a few kpc

Modern cosmological hydro simulations include the effects of baryons (i.e., gas cooling, star formation, heating by SNe/AGN, metal enrichment and transport)

But, also remember the limitations - e.g., a single fluid approximation!

$R_{500}$ is a spherical region within which the mean enclosed density is 500 times the critical density of the Universe
Modern hydrodynamical cluster simulations reproduce observed ICM profiles outside cluster cores ($r>0.15 \times r_{500}$).
Recent Advances at the Crossroads of Cluster Astrophysics & Cosmology

Dark Energy Task Force (2006)

The CL technique has the statistical potential to exceed the BAO and SN techniques but at present has the largest systematic errors. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to non-linear astrophysical processes.

Before

Uncertain by 100%

Hydro. sim. without “galaxies”
Evrard et al. 1996

ASCA X-ray observations
Finoguenov et al. 2001

Now

Accurate to 10%

Hydro. sim. with “galaxies”
Kravtsov et al. 2006
Nagai et al. 2007

Chandra X-ray obs.
Vikhlinin et al. 2006
Local \( z < 0.1 \) sample of 49 clusters + 37 high-\( z \) clusters from the 400d X-ray selected cluster sample

\[
\sigma_8 = 0.813 \left( \frac{\Omega_M}{0.25} \right)^{-0.47} \pm 0.013
\]

\[
w_0 = -0.99 \pm 0.045
\]

\[
\Omega_{\text{DE}} = 0.740 \pm 0.012
\]
Testing non-GR theories of the Cosmic Acceleration with Next Generation X-ray surveys

eROSITA (scheduled launch in 2013)

All-sky survey for 4yrs + targeted obs.
Science Goals: Study the LSS and Dark Energy
~100,000 clusters up to z~1.3
A_{eff}~1500 cm² @ 1.5keV; Θ_{eff}~25-40 arcsec

\[ G(z) \times (1+z) \]

Dashed line: DGP gravity
Solid line: Einstein’s gravity

“Simulated data” for 2000 X-ray+weak lensing clusters
Vikhlinin et al. 2009
Normalizations of the model and observed $Y_x$-$M$ relations are shifted by ~10%.

Weak lensing mass is larger than X-ray mass by about 10%, on average.

X-ray “pressure” = $Y_x$ = gas mass x temperature measured excluding cluster core regions

The Physics of Cluster Outskirts is the key!!
Gas (bulk+turbulent) motions are predicted to be ubiquitous in the ICM.

Drivers of gas motions:
- Accretion/Mergers (on large scales)
- Energy injection from SNe/AGN (in cluster cores)

Implications:
- Hydrostatic mass modeling
- X-ray/SZE observable-mass relations
- ICM temperature and entropy profiles
- SZ power spectrum
- Metal distribution (e.g., by mixing)
- Particle acceleration

Observationally, we know very little about the nature of gas motions in clusters!!
Non-thermal Pressure in Cluster Outskirts

Gas motions due to incomplete virialization are ubiquitous in ΛCDM clusters.

- **Major Merger**
  - $M \sim 1-3$ (transonic)
  - $2h^{-1}\text{Mpc}$

- **Minor Merger**
  - $M \sim 0.3$ (subsonic)
  - $0.82h^{-1}\text{Mpc}$

**Cluster-centric radius in units of $r_{500c}$**

Bias in the Hydrostatic Mass

\[ M_{\text{tot}}(< r) = \frac{-r}{G\rho_{\text{gas}}} \left( \frac{dP_{\text{therm}}}{dr} + \frac{dP_{\text{rand}}}{dr} \right) \]

Non-thermal pressure due to gas motions is the dominant uncertainty for interpreting the recent SZ power spectrum measurements by ACT, Planck, and SPT.  

\[ \Delta T_{\text{cmb}} \equiv f_\nu(x) y = \left( \frac{k_B \sigma_T}{m_e c^2} \right) \int n_e(l) T_c(l) dl \]

Missing Cluster Astrophysics #2
Cluster outskirts are very clumpy

Mock Chandra X-ray simulation of a $\Lambda$CDM cluster

Hydrodynamical cluster simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}$) arise from infalling groups from the filaments

Suzaku X-ray measurements of cluster outskirts
The observed entropy profile is inconsistent with the prediction of hydrodynamical cluster simulations.
Evidence for Gas Clumping in Cluster Outskirts

A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$

Suzaku observation of Perseus

Chandra observation of A133

A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$
Electron temperature is lower than gas (or ion) temperature in the outskirt of dynamically active clusters.

Rudd & Nagai, 2009
Chuzhoy & Loeb 2004, Akahori & Yoshikawa 2010, Wong et al. 2010, also talk by Helen Russell
New Frontier: Exploration of the Virialization Regions of Galaxy Clusters

Cluster outskirts is a new territory for studying the physics of cluster formation
- Important for understanding thermodynamic and chemical evolution of clusters
  - Cluster outskirts are turbulent and clumpy filled with non-equilibrium electrons
- Critical for cluster-based cosmological tests
  - Calibration of observable-mass relations
  - Interpretation of SZ power spectrum

Chandra observation of gas clumps in the outskirt of A133