AGN Feedback and Scatter in Galaxy Cluster Mass-Observable Relations

Paul Ricker
University of Illinois

Collaborators:
- Hsiang-Yi Karen Yang (Michigan)
- Paul Sutter (IAP)
- Suman Bhattacharya (ANL)

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Outline

- Cluster scaling relations and cosmology
- Effects of cluster dynamics
- Modeling AGN feedback
- Effects of AGN feedback
- Conclusions
Cluster abundance as a function of mass and redshift

\[
\frac{d^2 N}{dM \, dz} = \frac{dV}{dz} n(M, z)
\]

\[
n(M, z) \propto \frac{\rho_b}{\sigma M} \int_{\delta_c}^\infty d\delta \exp\left(-\frac{\delta^2}{2\sigma^2}\right)
\]

Depends on:

- Volume-redshift relation \(dV/dz\)
- Linear growth factor \((\rightarrow \delta(z))\)
- Power spectrum \((\rightarrow \sigma(M, z))\)

Mohr (2005)
Cluster masses must be measured using proxies

\[ P( X | \text{cosmology} ) \approx P( X | M , \eta_1 , \eta_2 , \ldots ) P( M , \eta_1 , \eta_2 , \ldots | \text{cosmology} ) \]

- Mass-observable relation
- Mass function

Scaling relations

N-body

\[ \text{X-ray temperature} \]

Popesso et al. (2005)

\[ \text{Lukić et al. (2007)} \]
Galaxy clusters

Theory view

Observational view

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INPA Seminar at LBL
Reasons we might worry

- Cluster mergers
- Feedback from active galactic nuclei
- Additional sources of pressure support (magnetic fields, cosmic ray pressure, turbulence)
- Clumpy accretion and lack of electron-ion equilibrium
Self-calibration (Levine et al.; Hu; Majumdar & Mohr; Lima & Hu)

- With enough clusters ...  
  - Parametrize cluster physics  
  - Fit it along with cosmology  

Requirements
- Mass function known  
- Assumed mass-observable functional form  
- Well-understood scatter  
- Redshift information (e.g., from optical surveys)

Majumdar & Mohr (2004)
Exploiting multiple observables

\[ \frac{Y_x}{T_x} \approx M_{\text{gas}} \]

Rozo et al. (2010)
Cluster cosmology simulations at Illinois

- Program to parametrize contributions to cluster mass-observable scatter due to different cluster physical processes
- Improve self-calibrated cluster-based estimates of cosmological parameters

Simulations: AMR code FLASH

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FLASH 2.4
- $1024^3$ particles
- $\Delta x = 250$ $h^{-1}$ kpc
- $m_p = 5 \times 10^8$ $h^{-1}$ $M_\odot$
- 600 clusters

FLASH 3.2
- Static DM halo
- $L = 2$ $h^{-1}$ Mpc
- $\Delta x = 1$ $h^{-1}$ kpc
- 1 cluster

FLASH 3.2
- $1024^3$ particles
- $\Delta x = 31$ $h^{-1}$ kpc
- $m_p = 3 \times 10^{10}$ $h^{-1}$ $M_\odot$
- 130 refined clusters
Measuring dynamical state

- **Centroid offset** (Mohr et al. 1995)
- **Multipole power** (Buote & Tsai 1995, 6)
- **Merger history** (Cohn & White 2005)
  - Use particle tags to trace halo progenitors
  - Identify merging events using
    - *Mass jump* – ratio of halo mass to mass of largest progenitor
    - *Mass ratio* – ratio of masses of two largest progenitors
Influence of dynamics on $M-T_X$ and $M-Y$ (Yang et al. 2009, 10)

- Scatter within $R_{500}$ shows strong negative correlation with concentration
- Weak/no sensitivity to mergers and merger-driven distortions

![Scatter plots showing the relationship between $M-T_X$, $M-Y$, and $R_{200}/R_{500}$ for different formation lookback times.](image)
Slope of the concentration dependence

- Sense of correlation disagrees with Shaw et al. 08
- Difference lies in equation of state (Ascasibar et al. 06)
  - Polytropes $P \propto \rho^{\gamma_p}$
  - Extra physics reduces $\gamma_p$ from $5/3 \rightarrow 1$
  - Slope flattens and then changes sign as $\gamma_p$ decreases

\[ T_{X,\Delta} \propto Y_{MT}(\gamma_p, c_\Delta)^{-2/3} M_\Delta^{2/3} \]
Clusters that are outliers in both $M - Y_x$ and $M - Y_{SZ}$ have inconsistent mass estimates.

By excluding such cases we can reduce systematic errors in mass calibration by as much as a third.
Updated dynamics results (1024 $h^{-1}$ Mpc volume)

- Sense of concentration correlation is maintained with much better resolution
Updated dynamics results (1024 $h^{-1}$ Mpc volume)

- Sense of correlation flips when we consider quantities within $R_{200}$
- Scatter dependence on power ratios starts to become important within $R_{200}$
AGN feedback in clusters
AGN modeling in simulations

Seeding and merging of AGN within cosmological context

Accretion onto AGN

Feedback onto surroundings

Constant seed mass
Seeding on M-σ relation

Instant merging
Merging based on proximity
Merging based on velocity

Frequency of tests

α-Bondi (Sijacki et al. 07)
β-Bondi (Booth & Schaye 09)
Stochastic (Pope 07)

Bubble (Sijacki et al. 07)
Jet (Cattaneo & Teyssier 07)
**AGN modeling (Yang, Sutter, & Ricker 2012)**

- **Accretion model**

  \[ \dot{M}_{bh} = \min \left[ \alpha \dot{M}_{\text{Bondi}} \left( M_{bh}, \rho_{\text{grid}}, c_{s,\text{grid}} \right), \dot{M}_{\text{Edd}} (M_{bh}) \right] \]

- **Feedback model**

  - **Jets (Cattaneo & Teyssier 07)**

    \[ \dot{M}_{\text{gas}} = \eta \dot{M}_{bh} |\Psi (x)| \]
    \[ \dot{P}_{\text{gas}} = \sqrt{2} \epsilon_f \dot{M}_{bh} c \Psi (x) \]
    \[ \dot{E}_{\text{gas}} = \epsilon_f \dot{M}_{bh} c^2 (1 - \eta) |\Psi (x)| \]

  - **Bubbles (Sijacki et al. 07)**

    \[ \dot{E}_{\text{gas}} = \epsilon_m \epsilon_f \Delta M_{bh} c^2 \]
    \[ R_{\text{bub}} = R_0 \left( \frac{\dot{E} \Delta t \rho_0}{E_0 \rho} \right)^{1/5} \]
AGN model parameter sensitivity

Vary:

- Resolution ($\Delta x$)
- Accretion strength ($\alpha$)
- Mechanical heating efficiency ($\epsilon_f \epsilon_m$)
- Bubble injection frequency ($\delta_{bh}$)
- Size and offset of injection region ($R_0, R_{dis}, r_{ej}, h_{ej}$)
- Thermal-to-kinetic ratio ($\epsilon_m / (1-\epsilon_m)$)

Most important
AGN in a single cluster

- With dynamical AGN it is possible to achieve feedback cycles that look like observations
- Significant variation in results due to variation in AGN modeling and parameter choices

Fiducial run

- Bubbles
- $\alpha = 1$
- $R_0 = 30 \, h^{-1} \, \text{kpc}$
- $R_{\text{dis}} = R_{\text{bub}}$
- $\epsilon_f = 0.1$
- $\epsilon_m = 0.2$
- $\delta_{bh} = 0.01\%$
Varying bubble accretion strength ($\alpha$)
Different parameter choices lead to different histories.
Max influence of parameter uncertainty on observable properties

- $Y_{SZ}$ and $T_x$ model uncertainty within $R_{500}$ is ~ 10%
Trajectories of scaling relations

- AGN feedback contributes significantly to $L-T$ and $M-T$ scatter regardless of model; $Y_{sz}-Y_{x}$ continues to be tight
Conclusions

- **Dynamics**
  - When considering effects of dynamics only, observable scatter of $M-T$ and $M-Y$ within $R_{500}$ is insensitive to merger effects
  - Correlation with halo concentration can be used to reduce scatter
  - Outliers are outliers in multiple observables ⇒ can improve scatter by throwing out clusters with inconsistent mass estimates

- **AGN + cooling**
  - AGN effects are likely to be dominant driver of scatter in cluster mass-observable relations
  - Nevertheless AGN may still be manageable for $M-T$ and $M-Y$

- **Future/ongoing**
  - AGN in cosmological runs