Simulations for Cluster-based Cosmology

Astronomy Colloquium
@LIneA, Webinar Colloquium

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Upshot of talk in <3min

- Dark Energy 73%
- Cold Dark Matter 23%
- Active Galactic Nucleus

Maximize upcoming datasets

Observable

Mass

Astrophysics
Energy budget of our universe (mostly unknown!)
\[ E = mc^2 \]
Galaxy clusters probe cosmology
Number of galaxy clusters probe cosmology

Earlier in time (~5 Billion years ago)
Later in time (300 million years ago)

\( \Omega_M = 0.25, \, \Omega_\Lambda = 0.75, \, h = 0.72 \)

Vikhlinin+09
Number of galaxy clusters probe cosmology

- Earlier in time (~5 Billion years ago)
- Later in time (300 million years ago)

Galaxy Cluster Masses from Chandra X-ray telescope

$\Omega_M = 0.25, \Omega_{\Lambda} = 0.75, h = 0.72$

Vikhlinin+09
Number of galaxy clusters probe cosmology

Galaxy Cluster Mass
Cluster Number Density

Earlier in time (~5 Billion years ago)
Later in time (300 million years ago)

Vikhlinin+09

Masses from Chandra X-ray telescope

ONE DOES NOT SIMPLY
WEIGH A GALAXY CLUSTER

Galaxy Cluster Mass

Vikhlinin+09
Proxy: Gas measurements tell us about the mass

\[ P = f(T, \text{density}) \]

\[ P \propto T \times \text{density} \]
Test the proxy with simulations

\[ P = f(T, \text{density}) \]

\[ P \propto T \times \text{density} \]
Test the proxy with simulations

Mock (synthetic) Chandra X-ray observation

Nagai+07
Test the proxy with simulations

From X-ray "measurements"

From simulation data

20% deviation

mass (solar)
scaled radius

Nagai+07a
Problem: Mass proxies are proxies with assumptions

\[ \text{Mass} \ [M_\odot] \]

\[ 10^{16} \quad 10^{14} \quad 10^{13} \quad 10^{12} \]

\[ r/r_{500} \]

\[ 0.1 \quad 1 \]

\[ \text{mass (solar)} \]

\[ \text{scaled radius} \]

\[ \text{MS0735 (z=0.21); McNamara et al. 2005} \]

\[ 200 \text{ kpc} \]

Nagai+07a
Problem: Mass proxies are proxies with assumptions.
Each observable has different challenges.

- **weak lensing**
  - gal. dynamics
  - good

- **Low accuracy**
  - Low precision

- **High accuracy**
  - High precision

- **SZ effect**
  - Yx
  - Mgas

- **Lx**
  - opt. richness

- **Precision**

Courtesy: Sebastian Bocquet
Galaxy clusters’ dynamical state ties with systematics
Combining observables can improve constraints
Larger datasets from surveys: Galaxy Clusters

... Getting lower masses and further objects

Past Surveys

Current/Future Surveys

Further/Earlier

Further/Earlier

Local leading activities

ACTpol

SPTpol

eRosita

DES

LSST
Larger datasets from surveys: Galaxy Clusters

... Getting lower masses and further objects

Past Surveys

Current/Future Surveys
Larger datasets from surveys: Galaxy Clusters

… Getting more objects for better statistics

Past Surveys

Further/Earlier

Density of clusters found

Clusters per Δz=0.1

0.1 1.0

0 10 10 10 10

0 1 1 1

SDSS RCS-2 Planck REFLEX SPT XXL

Current/Future Surveys

Further/Earlier

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eRosita DES SPTpol

ACTpol LSST
Larger datasets from surveys: Galaxy Clusters

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Density of clusters found

Clusters per $\Delta z=0.1$

Past Surveys

Further/Earlier

Redshift

Current/Future Surveys

Further/Earlier

Redshift
Start to incorporate multiwavelength approaches

Posterior Mass from Hierarchical Bayesian Modeling of multiple observables

LoCuSS Clusters

Farahi+19 Mulroy+19
Each simulation has a (slightly) different approach.

Example: Satellite Statistics to Inform Optically-Selected Cluster Counts

Anbajagane+20

- Describe simulated galaxy cluster population: Mass conditioned estimates of slope, normalization and property covariance.

Quantify differences/robustness of models predictions with Local Linear Regression (Evrard14)

Example: Satellite Statistics to Inform Optically-Selected Cluster Counts
Early vs. Late forming halos split in the PDF

Teaser slide for 8/20

Anbajagane+20
Shapes sensitive to accretion and cosmology, impacting mass-observable relations

- **Cosmology Sensitivity**
  - (e.g. Kasun+Evrard 05, Allgood+06)

- **Environmental Dependence**
  - (e.g. White, Cohn, Smit 10)

**Diagram:**
- **Shape** vs **Mass**
- **Sigma8**
- **w/ DE**
- **w/out DE**
Shape/morphology as a key relaxedness criterion

Bulk asymmetry measures → unrelaxed
(e.g. Mohr+1993, Jeltema+05)

Peakedness/Cool-core → relaxed
(e.g. Vikhlinin+07, Bohringer+10)

Combination of visual measures in X-ray (e.g. Rasia+13, Mantz+15)
Varied shapes in mass-limited Omega500 sample

Nelson+14
Varied shapes in mass-limited Omega500 sample

Adaptive Refinement Tree
62 clusters w/ M500 > 3e14
Box size: 500 Mpc/h
Non Radiative, Cooling and Star Formation, Active Galactic Nuclei

Nelson+14
Varied morphology in mass-limited Omega500 sample

Team work that went into the simulations (DN PI and computing at Yale, DR on code, KN on running the NR, AW on CSF, CA on initial AGN implementation, EL on running AGN, MC on new AGN)

Team work needed for large scale simulations
Varied morphology in mass-limited Omega500 sample

Developed hydrocode, halo finder

PI: Enabled science and resources for simulations

Ran the first NR box, Developed merger tree+db

Ran CSF, Developed tracer particle capability

Ran later CSF, AGN boxes, database

Developed initial AGN module

Developing state-of-art AGN module
Recent accretion drives ICM shape

“Slow accretor”

Ellipticity of Isophotes

Shift of centroid

“Fast accretor”

**Over plotted X-ray relaxation criteria from the SPA code (Mantz+15)**
Shape and accretion study of Omega500 clusters

Shape: Axis ratio

Accretion Rate (modified Diemer+Kravtsov14)

\[ \Gamma_{200m}(a_i) = \frac{\log(M_{200m_i}) - \log(M_{200m_0})}{\log(a_i) - \log(a_0)} \]

Max Merger Ratio

3 1
Accretion rate *and* accretion mode matter

Chen, CA, Kravtsov+

arxiv:1903.08662
Accretion rate and accretion mode matter.

Max Merger Ratio
- $<1:6$
- $1:6 - 1:3$
- $>1:3$

Chen, CA, Kravtsov+
arxiv:1903.08662
Accretion rate and accretion mode matter

Max Merger Ratio

- <1:6
- 1:6 - 1:3
- >1:3

Chen, CA, Kravtsov+
arxiv:1903.08662

Fast accreting

More Elliptical
A characteristic timescale for shape relaxation

Increasing negative correlation

~4.5 Gyr (consistent with gas motions timescale from Nelson+12))

Larger radii

Chen, CA, Kravtsov+ arxiv:1903.08662
A characteristic timescale for shape relaxation increasing negative correlation.

~4.5 Gyr (consistent with gas motions timescale from Nelson+12)

(Larger radii)

Chen, CA, Kravtsov+ arxiv:1903.08662
Connecting accretion and shape to scatter in MOR

![Graph showing the relationship between Mass and Observable with a residual arrow pointing to the scatter.](image-url)
Residual varies monotonically with accretion rate.
Rounder clusters are hotter with higher residuals

Chen, CA, Kravtsov+
arxiv:1903.08662
Groundwork for “baryon pasting” prescriptions

Halo property: Mass, accretion rate, shape, etc.

Observable: Integrated property, profile, etc.
Baryon Pasters

H. Miyatake (Nagoya)
K. Osato (Tokyo)
M. Shirasaki (NAOJ)
D. Nagai (Yale)
H. Aung (Yale)
S. Green (Yale)
E. Lau (Miami)
C. Avestruz (Michigan)
A. Hearin (ANL)
B. Nord (FNAL)
G. Evrard (Michigan)
A. Farahi (Michigan)
H. I. Huang (UofA)
R. Makiya (Kavli IPMU)
Baryon Pasters

- Still under development, but we already have a prototype pipeline.
  - C++ with Python wrapper
  - MPI capability
- Modular code design
  - Interface to inputs/outputs
  - Different SAMs for pasting baryonic profiles
  - Instrumental-specific noise properties

Diagram:

1. Halo catalog/DM particles
2. Compute SAMs based on halo properties
3. Paste baryons at halo positions/DM particles
4. Project to X-ray/SZ
5. Add noise
6. Fits images
Baryon Pasters: Some Science Goals

- Accurate modeling of selection functions
- Seek for (physically) reasonable (multi-variate) mass-observable relations
- Modification to cosmic shear, cluster/galaxy lensing, galaxy clustering
- [Your area of interest here?]
Baryon Pasters: Planned Efforts

- Mass accretion rate and shape dependence (Machado, CA+)
- Calibrate SAM of gas down to CGM (Osato+)
- Modification of DM profile due to baryonic effects (Shirasaki, Huang+)
- Paint gas (and galaxies) onto filaments (Aung, Green+)
- Unified models of stars and gas (Hearin, Makiya+)
- Gaseous substructure (TBD)
Baryon pasting example: SZ effect

Shaw+10 model (Pressure profile model calibrated from simulations)

Will be used in upcoming HSCxPlanck analysis
Baryon pasting example: SZ effect (backlight)

K. Osato
(U of Tokyo)

Shaw+10 model
(Pressure profile model calibrated from simulations)

Will be used in upcoming HSCxPlanck analysis
Baryon pasting example

Input: Lightcone simulation

E. Lau
(Miami)
First X-ray and SZ maps from LSST Simulations

Courtesy: Hironao Miyatake, Andrew Hearin, Erwin Lau - Baryon Pasting efforts
“Baryon pasting” application

Halo property:
Mass, accretion rate, DM density

Observable:
Tx, Ysz

Compare with Shaw model
Weak lensing mass estimate has model dependence

Example: Testing bias of z=1 MXXL halos with different concentration assumptions
Weak lensing mass calibration

- Stacked mass fitting vs. individual fit in hierarchical framework
- Test observational effects, e.g. miscentering, selection…
- Model profile dependence, e.g. radial range, c-M assumptions…
- Profile independent measures, e.g. aperture mass
Larger datasets from surveys: Galaxy Clusters

... Getting more objects for better statistics

Current/Future Surveys

Further/Earlier

Density of clusters found

Clusters per $\Delta z=0.1$

- eRosita
- DES
- ACTpol
- SPTpol

Redshift

0.1
1.0
Larger datasets from surveys: Galaxy Clusters

… Getting more objects for better statistics

Eclipse
Last fall!

LSST
Gemini
South

Courtesy of LSST facebook group

Density of clusters found
Clusters per Δz=0.1

Further/Earlier

Current/Future Surveys
```
import numpy as np
reshape_size=int(np.i

gamma_inf = loaded

gamma_inf = loaded

kappa_inf = loaded

def f, axes = plt.subplots
  axes[0].pcolormesh(k)
axes[0].set_title('c0')
axes[1].pcolormesh(e)
axes[1].set_title('c1')
```

- Configuration is given in `sampleconfig.py`. In particular, this specified which `sireadex` to use to read the simulation data.
# Training in data and computation

## Syllabus

### The Unix Shell
- Files and Directories
- History and Tab Completion
- Pipes and Redirection
- Looping Over Files
- Creating and Running Shell Scripts
- Finding Things
- Reference...

### Programming in Python
- Using Libraries
- Working with Arrays
- Reading and Plotting Data
- Creating and Using Functions
- Loops and Conditionals
- Defensive Programming
- Using Python from the Command Line
- Reference...

### Version Control with Git
- Creating a Repository
- Recording Changes to Files: `add`, `commit`, ...
- Viewing Changes: `status`, `diff`, ...
- Ignoring Files
- Working on the Web: `clone`, `pull`, `push`, ...
- Resolving Conflicts
- Open Licenses
- Where to Host Work, and Why
- Reference...

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**At your department**

**At professional meetings (AAS, SACNAS, ...)**
Summary

- We’ll need a confluence of N-body, hydro and semi-analytic modeling to fully leverage the next generation of cosmology experiments.

- A galaxy cluster’s mass accretion history is a critical component in developing models that paint baryons onto DM only simulations.

- Community code development will likely play a key role in the era of LSST.