Unified Modeling of Galaxy Populations in Clusters

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Outline

• Scientific background (Why it matters)
• The Galaxy Clustering Problem (Why Blue Waters)
• Charm++ and ChaNGa (Key Challenges)
• Recent results (Accomplishments)
Clusters: the science

- Largest bound objects in the Universe
- Visible across the entire Universe
- Baryonic content is observable
- “Closed box” for galactic evolution
Clusters: the challenge

- Good models of stellar feedback
- Good models of AGN (black hole) feedback
- Hydrodynamic instabilities require good algorithms
- Resolution: $10^5$ Msun particles in $10^{15}$ Msun object
- Highly “clustered” computation
Clustered/Multistepping Challenges

• Computation is concentrated in a small fraction of the domain

• Load/particle imbalance

• Communication imbalance

• Fixed costs:
  – Domain Decomposition
  – Load balancing
  – Tree build
Load distribution
Gravity
Gas
Communication
SMP load sharing

Time Profile

29.4 seconds

Percentage Utilization

Time (34ms resolution)
LB by Compute time

Time Profile

Star Formation

Percentage Utilization

Time (34ms resolution)

15.8 seconds
Charm Nbody GrAvity solver

- Massively parallel SPH
- SNe feedback creating realistic outflows
- SF linked to shielded gas
- SMBHs
- Optimized SF parameters

Menon+ 2014, Governato+ 2014
Charm++

• C++-based parallel runtime system
  – Composed of a set of globally-visible parallel objects that interact
  – The objects interact by asynchronously invoking methods on each other

• Charm++ runtime
  – Manages the parallel objects and (re)maps them to processes
  – Provides scheduling, load balancing, and a host of other features, requiring little user intervention
Scaling to .5M cores

![Graph showing time per step and parallel efficiency scaling to 0.5M cores with 12G and 24G systems.](image-url)
**The ROMULUS Simulations**

Certified organic, free-range, locally grown supermassive black holes

- Early Seeding in low mass halos
- Self-consistent and physically motivated dynamics, growth, and feedback
- Naturally produces large-scale outflows
- No unnecessary additives or assumptions

**ROMULUSC**

$10^{14} \, M_{\odot}$ Galaxy Cluster
Tremmel+ 2019
(stars, uvj colors)

**ROMULUS25**

25 Mpc Volume
Tremmel+ 2017 (gas temp)

Resolution:
250 pc (grav)
50 pc (hydro)
~$1e5 \, M_{\odot}$
Galaxy Cluster Observables

Butsky et al, submitted
Galaxy populations
Outflows and Quenching

Chadayamumuri, in prep
AGN feedback and Non/Cool Cores

Chadayammuri, in prep
Exploring the physics of groups & clusters in a holistic manner

- Diffuse gas properties
  - Baryon fraction, entropy profile
  - CC/NCC dichotomy & mergers

- Evolution of Cluster galaxies
  - Quenching & morphology changes

- AGN/BH evolution & dynamics
  - Merger rates & LISA
  - Feedback mode & duty cycles

- Cosmology: LSS/CMB tension
  - Stellar, gas, dark matter dynamics
  - Hydrostatic bias
Take Aways

• Galaxy Clusters are hard:
  – Scale is set by galactic (i.e. star formation) physics
  – Orders of magnitude larger than galaxies
  – Computational effort is spatially concentrated.
  – (Probably should include MHD/cosmic rays)

• But now clusters are doable
  – Capability machines
  – Advanced load balancing techniques
  – First “holistic” simulations of galaxy clusters
Acknowledgments

- NSF ITR
- NSF Astronomy
- NSF SSI
- NSF XSEDE program for computing
- BlueWaters Petascale Computing
- Blue Waters PAID Program
- NASA HST
- NASA Advanced Supercomputing
Modeling Star Formation: it's hard

- Gravitational Instabilities
- Magnetic Fields
- Radiative Transfer
- Molecular/Dust Chemistry
- Driven at large scales: differential rotation
- Driven at small scales: Supernovae and Stellar Winds
- Scales unresolvable in cosmological simulations
Resolution and Subgrid Models

• Maximize Simulation Resolution
  – Capture tidal torques/accretion history (20+ Mpc)
  – Adapt resolution to galaxy (sub-Kpc, $10^5$ Msun)

• Capture Star Formation in a sub-grid model
  – Stars form in high density environments
  – Supernova/stellar winds/radiation regulate star formation
  – Mitigate issues with poor resolution (overcooling)
  – Tune to match present day stellar populations
Previous PRAC: good morphologies
Good morphologies across a population

$z = 3 \quad z = 2 \quad z = 1.2 \quad z = 0.75 \quad z = 0.5$
Black hole/AGN feedback

- Supernova feedback doesn't suppress star formation in massive galaxies
  - Modeling of more energetic feedback required

- Components of AGN modeling:
  - Seed (1e6 Msun) BH form in dense, low metallicity gas
  - BH grow from accreting gas, and release energy into the surrounding gas (Active Galactic Nuclei)
  - BH in merging galaxies sink to the center and merge (LIGO, eLISA)
Results: A cluster at unprecedented resolution

- Structure of the brightest cluster galaxy
- Other galaxies in the cluster environment
- The state of the intracluster medium
Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

Zoom-In Simulation

\[ M_{200}(z=0) = 1.5 \times 10^{14} \text{ } M_{\odot} \]

Resolution:

250 pc, 2e5 \text{ } M_{\odot}

<table>
<thead>
<tr>
<th>Name</th>
<th>Spatial Res.</th>
<th>( M_{DM} )</th>
<th>( M_{gas} )</th>
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<tr>
<td>RomulusC</td>
<td>0.25 kpc</td>
<td>3.39 \times 10^5</td>
<td>2.12 \times 10^5</td>
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<tr>
<td>TNG300(^b)</td>
<td>1.5</td>
<td>7.88 \times 10^7</td>
<td>7.44 \times 10^6</td>
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<tr>
<td>TNG100(^b)</td>
<td>0.75</td>
<td>5.06 \times 10^6</td>
<td>9.44 \times 10^5</td>
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<tr>
<td>TNG50 (in progress(^c))</td>
<td>0.3</td>
<td>4.43 \times 10^5</td>
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<td>Horizon-AGN(^d)</td>
<td>1</td>
<td>8.0 \times 10^7</td>
<td>1.0 \times 10^7</td>
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<tr>
<td>Magneticum(^e)</td>
<td>10</td>
<td>1.3 \times 10^{10}</td>
<td>2.9 \times 10^9</td>
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<tr>
<td>Magneticum(^e) high res</td>
<td>3.75</td>
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<td>1.4 \times 10^8</td>
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<tr>
<td>Magneticum(^e) ultra high res</td>
<td>1.4</td>
<td>3.6 \times 10^7</td>
<td>7.3 \times 10^6</td>
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<tr>
<td>C-EAGLE(^f,g)</td>
<td>0.7</td>
<td>9.6 \times 10^6</td>
<td>1.8 \times 10^6</td>
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<td>EAGLE(^g) (50, 100 Mpc)</td>
<td>0.7</td>
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<td>1.8 \times 10^6</td>
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<td>Omega500(^h)</td>
<td>5.4</td>
<td>1.56 \times 10^9</td>
<td>2.7 \times 10^8</td>
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Marinacci+ 17, Dubois+ 14, Bocquet+ 16, Armitage+ 18, Schaye+ 14, Shirasaki+ 18
Outflows in the BCG
Winds are ubiquitous through time
Stellar Mass

![Graph showing the relationship between $M_{*_{BCG}}(<50\, \text{kpc})$ and $M_{500}$](image)

- **Abundance Matching**
- **RomulusC**
- **Kravtsov+ 18**
- **De Maio+ 18**
Morphology of BCG
Quenching in the cluster

![Graph showing quenched fraction vs. log M_\star [M_\odot] at different redshifts.](image)
Quenching with radius

CDF vs $D_{\text{min}}/R_{200}$

CDF vs $D_{\text{quench}}/R_{200}$

CDF vs $D_{z=0}/R_{200}$

CDF vs $Z_{\text{quench}}$

- Black: All
- Blue: $M_* > 5.0 \times 10^9 M_\odot$
- Red: $M_* \leq 5.0 \times 10^9 M_\odot$
IntraCluster Medium

\[
\log S(R_{2500}) \text{ [keV cm}^2\text{]} \quad \log T_{500} \text{ [keV]}
\]

- RomulusC, \( z=0.3 \)
- RomulusC, \( z=0 \)
- Sun+ 09
Zoomed Cluster simulation
Luminosity Function

PAID: ChaNGa GPU Scaling

- ChaNGa has a preliminary GPU implementation
- Goals of PAID:
  - Tesla → Kepler optimization
  - SMP optimization
  - Multistep Optimization
  - Load balancing
- Personnel:
  - Simon Garcia de Gonzalo, NCSA
  - Michael Robson, Harshitha Menon, PPL UIUC
  - Peng Wang, Tom Gibbs (NVIDIA)
PAID GPU Progress

• 2X speed up of main gravity kernel; 1.4X speedup of 2\textsuperscript{nd} gravity kernel
  – Interwarp communication
  – Caching of multipole data
  – Higher GPU occupancy
  – Overall speedup of 60%

• SMP queuing of GPU requests
  – Reduced memory use, allowing more host threads
  – GPU memory management still an issue
Broader Impacts: Pre-Majors and Supercomputing

- UW Pre-Major in Astronomy Program:
  - Engage underrepresented populations in research early
  - Establish a cohort
  - Plug major leak in the STEM education pipeline

- Simulation data analysis is ideal for this research
  - Science and images are compelling
  - Similarity to Astronomical data reduction