The RomulusC Simulation
Exploring Galaxy Evolution in Clusters with High Resolution

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The Rich Physics of Clusters
AGN Feedback and Galaxy Evolution

Energy dissipation via shocks, sound waves in Perseus (Fabian+ 2003)

Quenched, green valley, and blue cloud galaxies in Virgo (Boselli + Gavazzi 2014)

“Jellyfish” galaxies experiencing ram pressure stripping that also host AGN (Poggianti+ 2017)
The Rich Physics of Clusters
AGN Feedback and Galaxy Evolution

RomulusC

Gas Density
Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

Zoom-In Simulation

$M_{200}(z=0) = 1.5 \times 10^{14} \, M_{\text{sun}}$

Resolution:

250 pc, 2e5 $M_{\text{sun}}$

Tremmel+, in prep

Tremmel+ 2017

Menon+ 2015
Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

<table>
<thead>
<tr>
<th>Name</th>
<th>Spatial Res. $^a$ (kpc)</th>
<th>$M_{DM}$ $^b$ ($M_\odot$)</th>
<th>$M_{gas}$ $^b$ ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RomulusC</td>
<td>0.25</td>
<td>$3.39 \times 10^5$</td>
<td>$2.12 \times 10^5$</td>
</tr>
<tr>
<td>TNG300$^b$</td>
<td>1.5</td>
<td>$7.88 \times 10^7$</td>
<td>$7.44 \times 10^6$</td>
</tr>
<tr>
<td>TNG100$^b$</td>
<td>0.75</td>
<td>$5.06 \times 10^6$</td>
<td>$9.44 \times 10^5$</td>
</tr>
<tr>
<td>TNG50 (in progress$^c$)</td>
<td>0.3</td>
<td>$4.43 \times 10^5$</td>
<td>$8.48 \times 10^4$</td>
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<tr>
<td>Horizon-AGN$^d$</td>
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<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>
</tr>
<tr>
<td>Magneticum$^e$ high res</td>
<td>3.75</td>
<td>$6.9 \times 10^8$</td>
<td>$1.4 \times 10^8$</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>EAGLE$^e$ (50, 100 Mpc)</td>
<td>0.7</td>
<td>$9.6 \times 10^6$</td>
<td>$1.8 \times 10^6$</td>
</tr>
<tr>
<td>Omega500$^h$</td>
<td>5.4</td>
<td>$1.56 \times 10^9$</td>
<td>$2.7 \times 10^8$</td>
</tr>
</tbody>
</table>

**Zoom-In Simulation**

$M_{200}(z=0) = 1.5e14 \ M_\odot$

**Resolution:**

250 pc, 2e5 $M_\odot$

Marinacci+ 17, Dubois+ 14, Bocquet+ 16, Armitage+ 18, Schaye+ 14, Shirasaki+ 18
Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

Romulus25

Resolution:
250 pc, 2e5 M_{\odot}

Tremmel+ 2017
Menon+ 2015
Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

- Accurate SMBH dynamics (Tremmel+ 2015, 2018)
- Early SMBH seeding (Tremmel+ 2017)
- Angular momentum limited accretion (Tremmel+ 2017, Pontzen, MT+ 2017)
- Thermal AGN feedback (Tremmel+ 2017)

Zoom-In Simulation
$M_{200}(z=0) = 1.5 \times 10^{14} \, M_\odot$

Resolution:
250 pc, 2e5 M$_\odot$
Accretion and Feedback in Romulus
Thermally driven outflows with angular momentum limited accretion

Modify the effective Bondi radius according to effective potential from resolved gas kinematics

\[ \dot{M}_{\text{bondi}} \sim \pi R_{\text{acc}}^2 \rho v \]

\[ U_{\text{eff}} = U_g + E_{\text{rot}} \sim E_{\text{gas,th}} \]

Tremmel+ 2017

Pontzen, MT+ 2017
Accretion and Feedback in Romulus

**Thermally driven** outflows with angular momentum limited accretion

0.2% mass-energy transferred **thermally** to surrounding gas

Overcooling is avoided due to

- **spatial** (250 pc) and time \((10^3-10^4 \text{ yrs})\) resolution for SMBH and gas

- Brief **cooling shutoff** (\(10^3-10^4 \text{ yrs}\))

- **Large-scale outflows** launched from 100 pc scales

Sub-Grid models **not optimized** for halos more massive than \(1e12 \text{ M}_{\odot}\)

RomulusC  \(z = 0.5\)

Snowcluster March 22, 2018
Accretion and Feedback in Romulus

AGN-driven winds ubiquitous throughout simulation
Results from RomulusC: The ICM
Results from RomulusC: The ICM
RomulusC lies on observed Mass-Temp-Entropy relations

\[ M_{500} - T_{500} \]

\[ S(R_{500,2500}) - T_{500} \]

Tremmel+, in prep
Results from RomulusC: The ICM
Baryon Fractions

Total Baryons

Hot Gas

Stars

Tremmel+, in prep

Snowcluster March 22, 2018
Results from RomulusC: The ICM

The structure of the ICM

Temperature

RomulusC, $z = 0.2$

Entropy

Tremmel+, in prep
Results from RomulusC: The Brightest Cluster Galaxy (BCG) and AGN Feedback

BCG, z = 0

Tremmel+, in prep
Results from RomulusC: The BCG and AGN Feedback

AGN Winds and Quenching the BCG

Tremmel+, in prep

1000 $kms^{-1}$

$t = 8.4$ Gyr

$0.1 R_{200}$
Results from RomulusC: The BCG and AGN Feedback

AGN feedback limits gas cooling

Tremmel+, in prep
Results from RomulusC: The BCG and AGN Feedback

Powerful AGN winds quench star formation without destroying cool core

Tremmel+, in prep
Results from RomulusC: AGN and Quenching in Satellite Galaxies
Results from RomulusC: Quenching in Satellites

Low mass galaxies are nearly all quenched

Tremmel+, in prep
Results from RomulusC: Quenching in Satellites

Low mass galaxies are nearly all quenched

Observed relationship between quenching and galaxy mass, cluster position do not apply to dwarf galaxies

Tremmel+, in prep
Results from RomulusC: Quenching in Satellites

More Massive galaxies quench after closer approaches to cluster center

Pre-Processed?
More easily stripped by ram pressure?

High Mass \((M_{\text{star}} > 5\, \text{e}9)\)

Low Mass \((M_{\text{star}} < 5\, \text{e}9)\)

Stronger ram pressure

Hard to see this effect from observations
Results from RomulusC: AGN in Satellites
SMBH activity depends on radial position within the cluster

$M_\star > 10^{9.7}$, $< L_{\text{bol}} >_{10 \text{Myr}} > 1 \times 10^{43} \text{ ergs/s}$

$M_{\star} > 5 \times 10^9 \text{ M}_{\odot}$

10% rad. eff.

Ram pressure-driven AGN?
Ricarte+, in prep

Tremmel+ in prep

Marshall+ 2018
Summary

RomulusC: galaxy evolution and AGN in clusters with unprecedented detail

- Realistic ICM structure, overall properties
- Large scale AGN winds lead to quenching in BCG without disruption of cool core structure
- **Predicts** large quenched fraction for low mass galaxies regardless of mass, distance from cluster center
- **Predicts** peak of AGN activity around 0.8 x R$_{200}$
Future Work
RomulusC: galaxy evolution and AGN in clusters with unprecedented detail

• Examine effects of Ram Pressure on star formation and SMBH activity (Ricarte+ in prep)

• Study the nature of SMBH growth in dense environments (Ricarte+ in prep)

• Follow the evolution of AGN-driven outflows and their effect on the ICM (Chadayammuri+ in prep)

• Study the evolution of dwarf galaxies in clusters vs the field (Munshi+ in prep, Tremmel+ in prep, Wright+ in prep)

• Metallicity and density structure of the ICM (Butsky+ in prep)

More simulations in the works! 2e14-1e15 M\textsubscript{sun} halos
Summary

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Results from RomulusC: The ICM

The structure of the ICM

![Graph showing the structure of the ICM with data from Arnaud 2010 and McDonald 2014.](image)
Sub-grid Model Optimization

Extensive parameter search limited to low mass halos ($1e12$ $M_{\odot}$ and lower)

Tremmel+ 2017
Results from RomulusC: AGN in Satellites

low-level SMBH activity is suppressed in cluster environments

Active Fraction

RomulusC, $L_{\text{bol,10Myr}} > 1e42$ ergs/s
$L_{\text{bol,10Myr}} > 1e43$ ergs/s
Romulus25, $L_{\text{bol,10Myr}} > 1e42$ ergs/s
$L_{\text{bol,10Myr}} > 1e43$ ergs/s

$z = 0$  rad. eff. = 0.1
BH-Mstar

$M_{BH}$ vs $M_*$

- Schramm+Silverman 13
- Romulus25

$M_{star}$-$M_{halo}$

- Romulus25
- Moster+ 13
- Kravtsov+ 14

Romulus25; Tremmel+ 2017
BH Acc history

SF History

Romulus25; Tremmel+ 2017
\[ \sigma(\dot{M}_{\text{BH}})/<\dot{M}_{\text{BH}}>_{50\text{Myr}} \]

- Red: Advect
- Green: Bondi
- Blue: Romulus8

Time (Gyr)

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \]

Tremmel+ 2017
Ram pressure example