Internal dark matter structure of the most massive galaxy clusters since $z=1$

Amandine M. C. Le Brun
PSL Fellow
LUTH, Paris Observatory/PSL University

Collaborators: Monique Arnaud (CEA Saclay), Gabriel Pratt (CEA Saclay), Romain Teyssier (ICS Zürich)

Based on Le Brun et al. 2018,
MNRASL, arXiv:1709.07467

2nd mm Universe @NIKA2, Rome, July 1st 2021
Universality of dark matter profiles


\( n \): proxy for cosmology
- Powerful test of ΛCDM.
- Evolution and shape of c-M are controversial especially at high-redshift and masses
X-ray and SZ observations

Bremsstrahlung
SB dimming with $z$

Inverse Compton scattering
No SB dimming with $z$

$L_x \propto \int n_e^2 \Lambda(T) \, dV$

$Y_{sz} \propto \int (P = n_e T) \, dV$

Complementarity of information
Complementarity of SZ and X-ray surveys

Data: Bleem15 (SPT), Hasselfield13 (ACT), PC VII 2011 (ESZ), PC XXIX 2013 (PSZ1), PC XXVIII 2015 (PSZ2)

SZ selection supposed to be closer to a mass selection
The M2C project (PI M. Arnaud)

- NIR for confirmation and stellar content
- Chandra/XMM follow-up
- Mass profiles from hydrostatic equilibrium
- Systematic comparison with simulations

New representative SZ-selected sample of the most massive clusters up to high $z$

- NIR for confirmation and stellar content
- Chandra/XMM follow-up
- Mass profiles from hydrostatic equilibrium
- Systematic comparison with simulations

Continuation as part of CHEX-MATE
Why high-mass systems?

- Faster convergence to the ‘self-similar’ expectation
- Much less impact of the non-gravitational physics
Pilot study of mass profiles at $z \sim 1$

- Less concentrated than average local cluster?
- Higher dispersion?
- Consistent with theory?

⇒ Need larger sample and new cosmological simulations

Bartalucci, Arnaud, Pratt and Le Brun 2018 (arXiv: 1803.07556)
Why new simulations?

- Cannot directly measure masses and mass profiles
- Need e.g. to assume hydrostatic equilibrium (HSE)
- Need simulations to e.g. constrain HSE bias

Le Brun+17

Figure courtesy of Monique Arnaud

No massive clusters at $z>0.5$ in existing simulations

$M(r) = -\frac{r k T(r)}{G \mu m_p} \left[ \frac{d \ln n}{d \ln r} + \frac{d \ln T}{d \ln r} \right]$
Why new simulations?

No existing hydrodynamical cosmological simulations combines a large enough volume and a high enough resolution to simulate the most massive galaxy clusters as:

- they are rare and appear in large volumes (need to simulate volumes of \( \text{Gpc}^3 \))

- high resolution (\(^\text{kpc}\)) is required to resolve their internal structure.
### Why new simulations?

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<th>Simulation</th>
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<th>( \epsilon )</th>
<th>( \Omega_M )</th>
<th>( \Omega_R )</th>
<th>( \Omega_\Lambda )</th>
<th>( \sigma_8 )</th>
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### Additional Information

- **Large enough size**
- **Too low mass and spatial resolution and sometimes size**

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**Simulations**

- AMR code RAMSES (Teyssier 2002)
- >$15 \times 10^6$ CPU hours (PI Le Brun)
- 3 DMO simulations 1 ($\text{Gpc/h})^3$
- >$470$ few kpc-resolution zooms for selected systems with $M_{500} > 4.49 \times 10^{14} \text{ M}_\odot$:
  - 50 at $z=1$
  - 170 at $z=0.8$
  - 181 at $z=0.6$
  - 75 at $z=0$
- Both DMO and NR runs and tests with more elaborate physics
• **Zoom** ⇒ **gain of a factor > 5 in spatial resolution**

• **Fluctuations are real**
Resolution study

8K and 16K converged over the whole resolved range

Effective resolution of $8192^3$ is minimum required

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Density profiles

- $z \geq 0.6$: nearly no evolution
- $z \leq 0.6$: slightly more evolution in core and outskirts

$\Rightarrow$ Consistent with 'stable clustering'

- Remarkably small scatter with mild increase with $z$

Le Brun et al., 2018

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- Small amounts of evolution and scatter at all $z$.
- Evolution more important in inner and outer regions.
- Nearly no evolution of scatter which is similar in amplitude to that of density profiles.
- No signs of inner slope converging to asymptotic value.
Most relaxed clusters centrally concentrated

Unrelaxed ones span larger variety of profile shapes
Discussion I

• High-mass systems at $z = 1$ had $>1$ major merger during the preceding 4 Gyr. Relaxation time close to about 16 Gyr.

• Naively expect profile has not yet converged to the near-universal form.

• Surprising result that suggests the ‘universal’ profile already in place at $z > 1$ and robust to merging activity.

• Similar to what was obtained for primordial haloes by Angulo et al. 2016 and Ogiya et al. 2016, but at scales that are 21 orders of magnitude larger.
McDonald et al. 2017 found remarkably self-similar evolution in stacked hot gas profile beyond cooling core in massive clusters up to $z \sim 1.9$

Natural consequence of self-similar evolution of underlying dark matter distribution as these systems are dark-matter dominated and gas evolution is dominated by simple gravitational physics.
Conclusions

- Study the 25 most massive clusters at z=0, 0.6, 0.8 and 1. $M_{500} > 5.5 \times 10^{14} \, M_{\odot}$ at $z=1$.

- Scaled DM profiles strikingly similar within $r_{500}$:
  - Low dispersion of 0.15 dex at each $z$ in spite of the variety of dynamical states.
  - Little evolution (never more than ~50%)

- Little evolution of the logarithmic slope and its scatter.

- Have running power law shape typical of NFW-type profiles but show no signs of converging to an asymptotic slope in central regions.

Suggest that this type of profile is already in place at $z>1$ in the highest-mass haloes and remains exceptionally robust to merging activity.

Based on Le Brun et al. 2018, MNRASL, arXiv:1709.07457

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Thank you!
Backup slides
Galaxy clusters and structure formation

- Galaxy clusters: 85% Dark Matter, 12% hot gas, 3% galaxies
- Form and evolve through merger/accretion along filaments
- Test of the physics of hierarchical Dark Matter driven structure formation (Dark Matter and baryons)
- Cosmological parameters via $N(M, z)$ or $f_{\text{gas}}$

Since Big Bang:
- 16.4 Myr
- 3.61 Gyr
- 5.85 Gyr
- Today = 13.8 Gyr

Time since Big Bang:
- 1 Mpc/h
- 36.3 Mpc/h
- 50 Mpc/h
- 100 Mpc/h

$z = 100$, $z = 1.75$, $z = 1$, $z = 0$