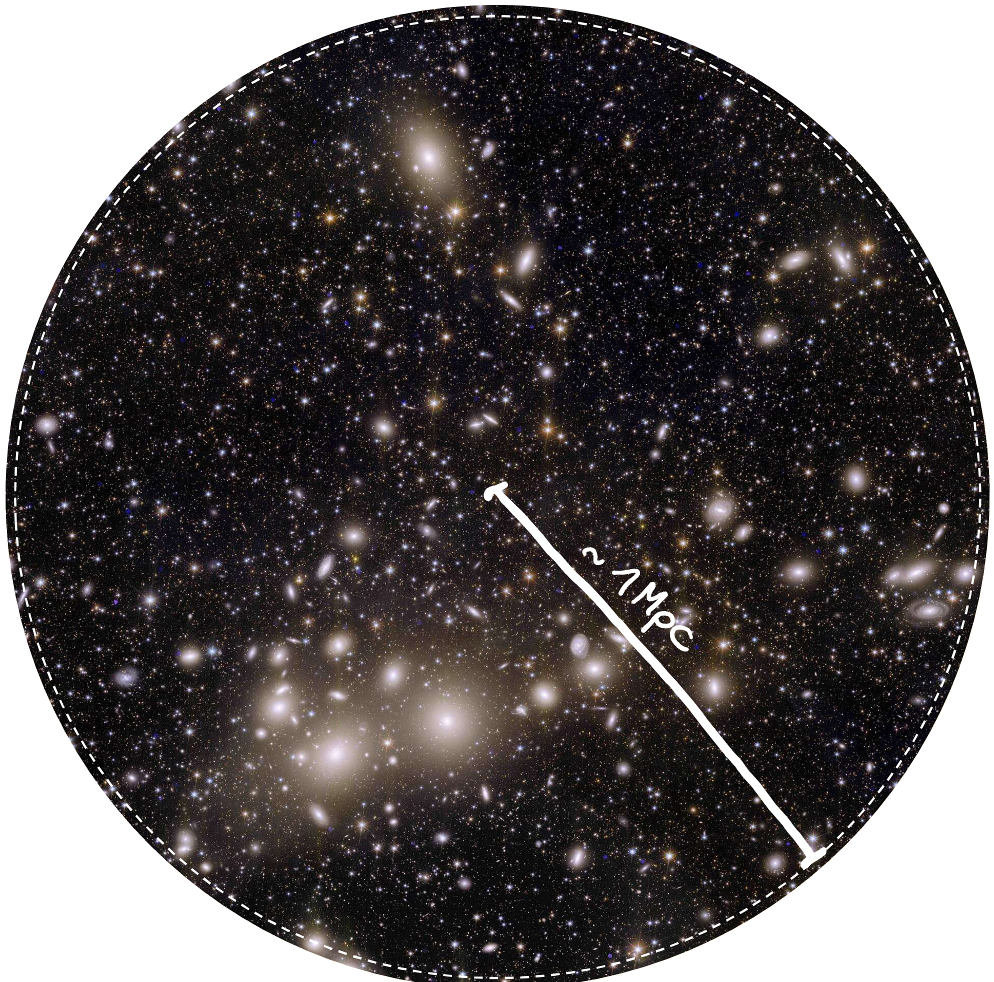
Cool-Core Demographics Unveiled: Insights From TNG-Cluster

Katrin Lehle
Institute for Theoretical Astrophysics,
Heidelberg University

Galaxy clusters are the most massive structures in the universe



The Perseus cluster – a nearby galaxy cluster

ESA/Euclid/Euclid Consortium/NASA image processing by J.-C. Cuillandre+G. Anselmi

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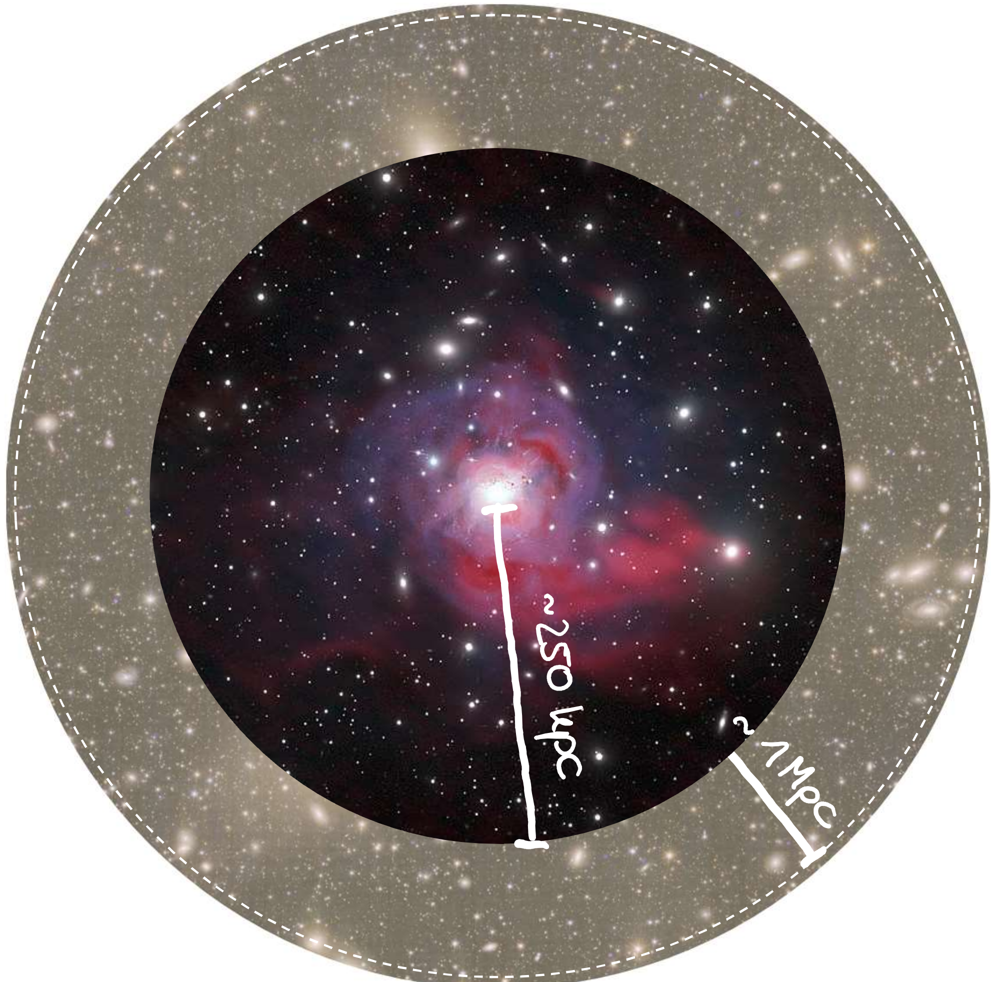

The Perseus cluster – a nearby galaxy cluster

sketch not to scale

ESA/Euclid/Euclid Consortium/NASA image processing by J.-C. Cuillandre+G. Anselmi

M. Gendron-Marsolais,
J. Hlavacek-Larrondo,
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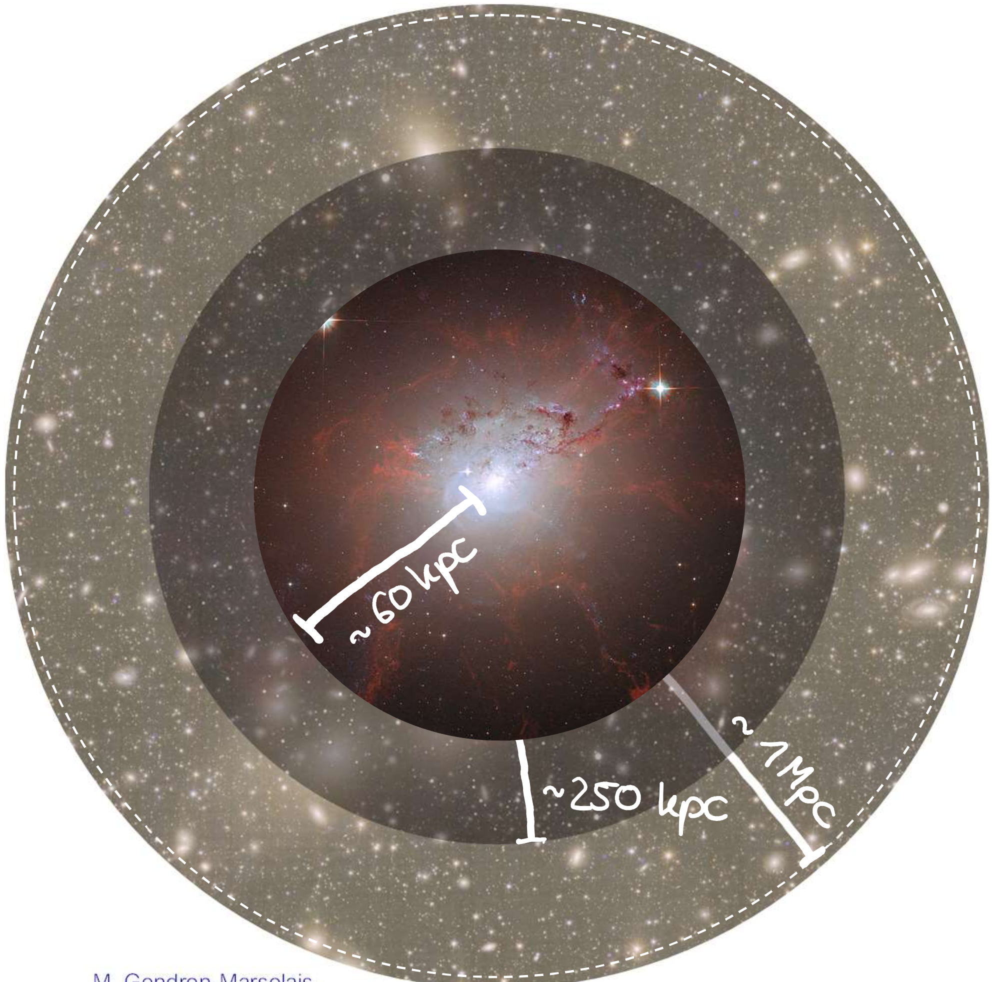

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NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration

Simulating massive galaxy clusters is a computational challenge

For simulating realistic galaxy clusters, it is required to

- simulate large volumes (r_{halo} ~ Mpc)
- cover a large range of time scales
- simulate a large box volume to get a reasonable cluster count

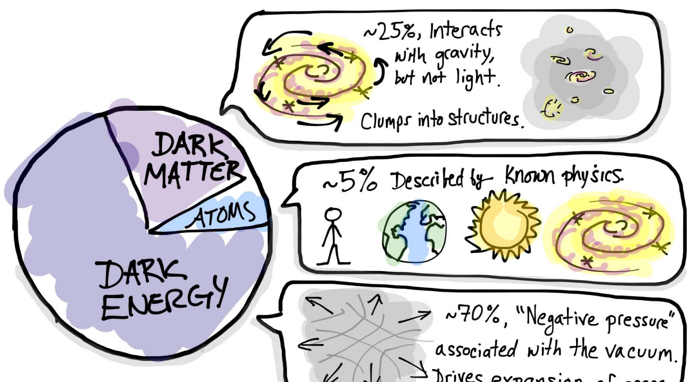
computationally expensive

- incorporate a sophisticated physics model
- resolve the small-scale constituents of a cluster

high resolution required

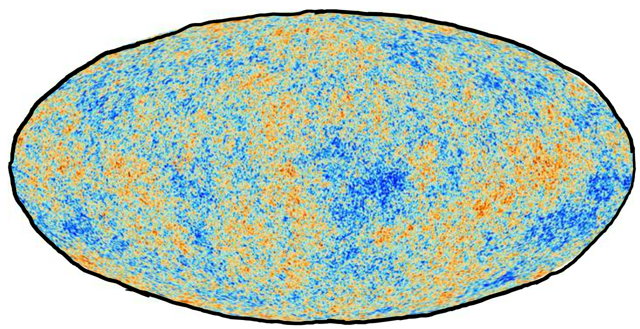
Ingredients for a cosmological simulation:

A cosmological model



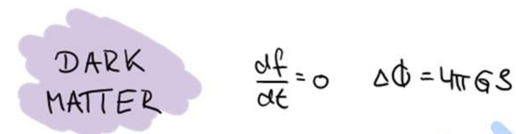
Credit: Jessie Muir

Initial conditions

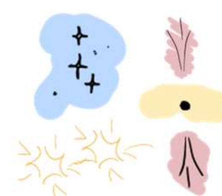


Equations

(describing matter content and evolution)



(Magneto)HydroDynamics



Galaxy formation model

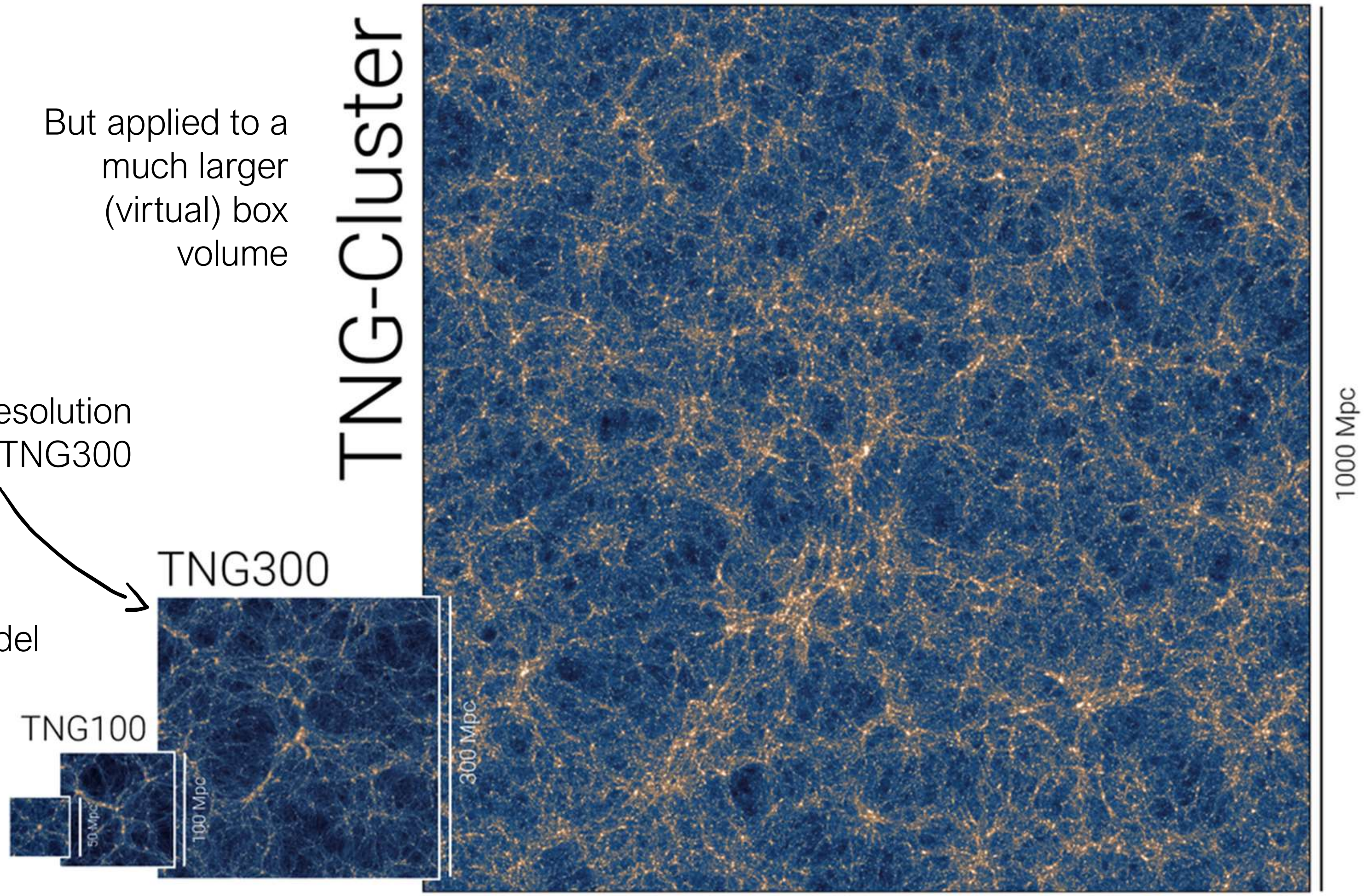
TNG-Cluster – A spin-off from the IllustrisTNG simulation

Cosmological hydrodynamical simulation solving gravity and ideal MHD in an expanding spacetime.

But applied to a much larger (virtual) box volume

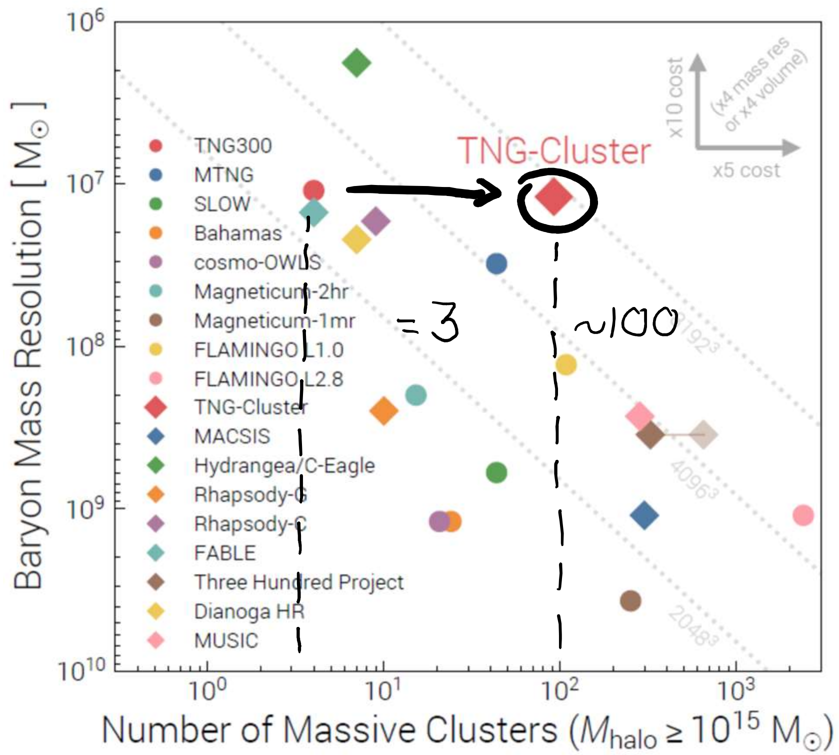
Keeping the same resolution as in TNG300

TNG-Cluster adopts the well-validated galaxy formation model from IllustrisTNG.



The IllustrisTNG Collaboration

TNG-Cluster offers a unique combination of high-mass galaxy clusters and high resolution



D. Nelson et al 2024 (+KL)

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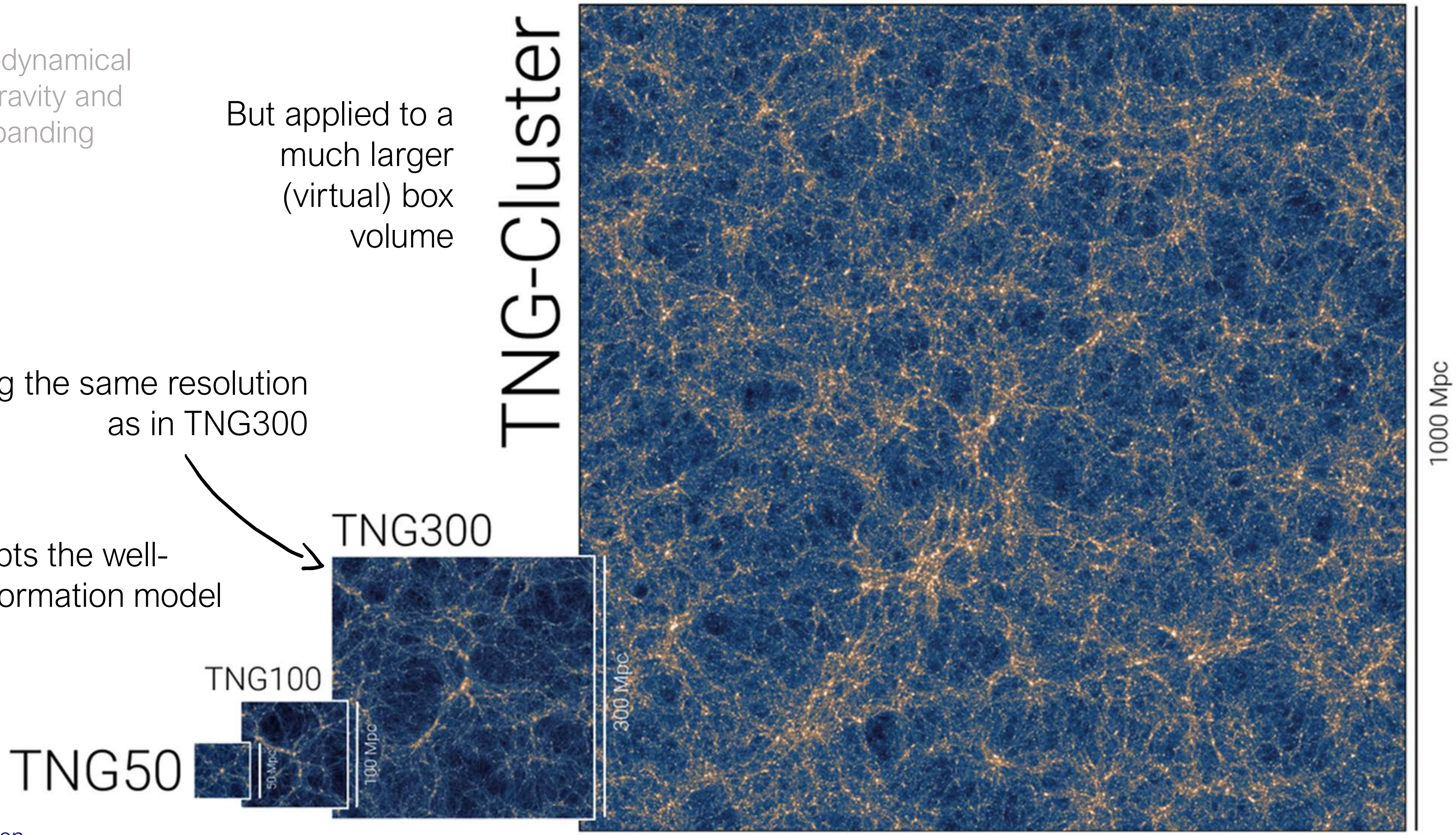

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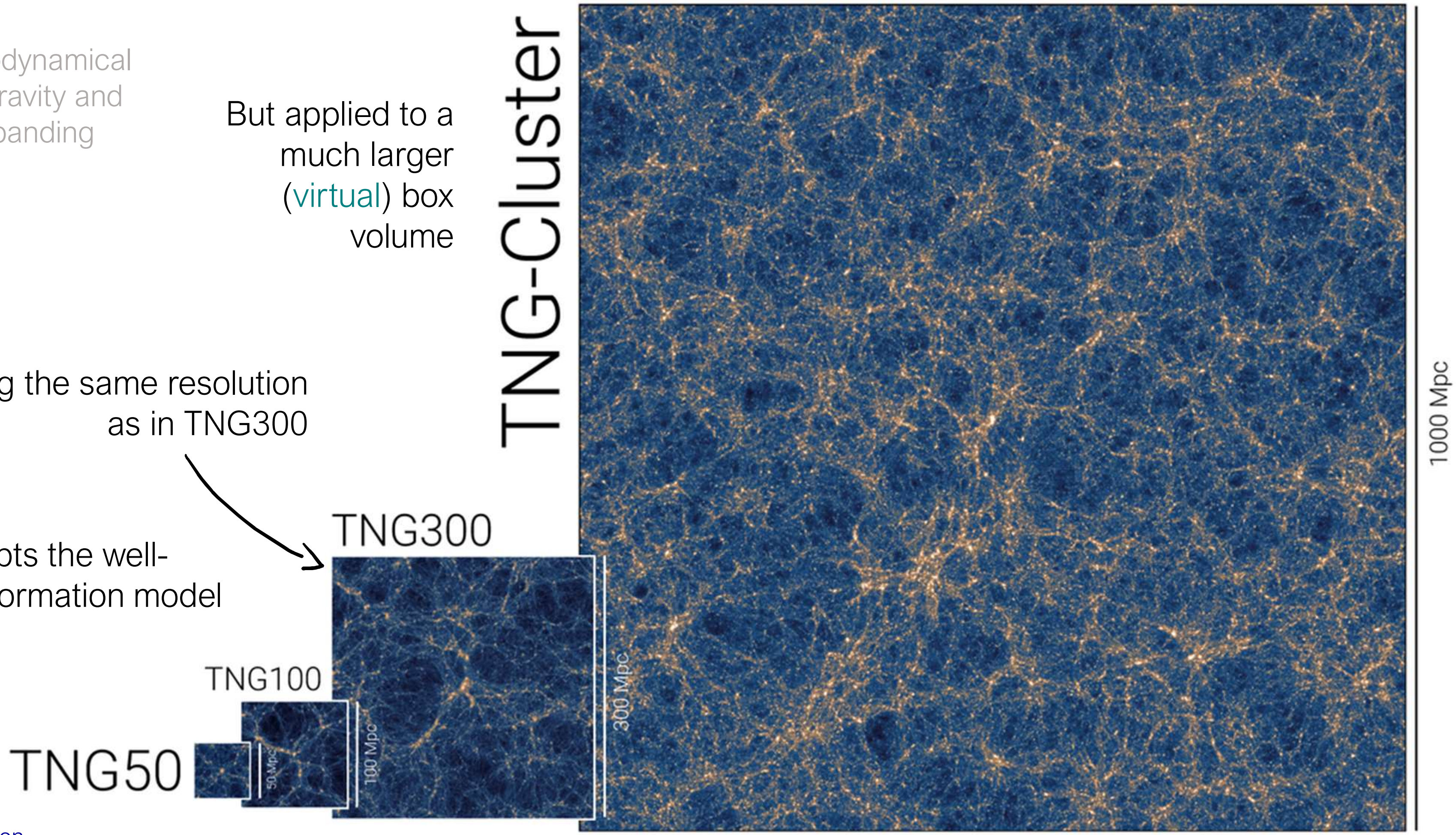
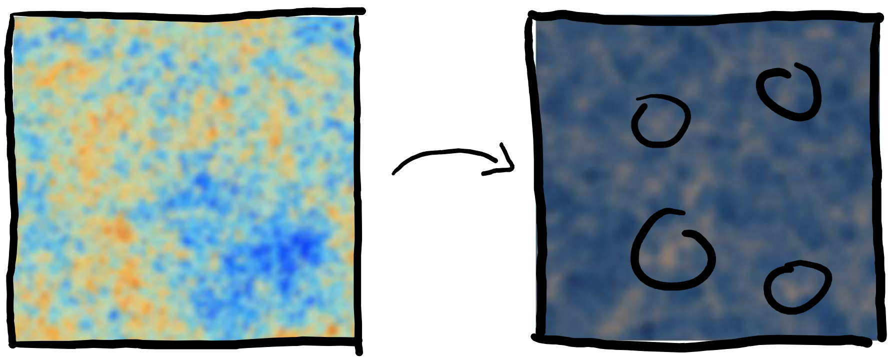


The IllustrisTNG Collaboration

TNG-Cluster is a patchwork of ~350 zoom simulations



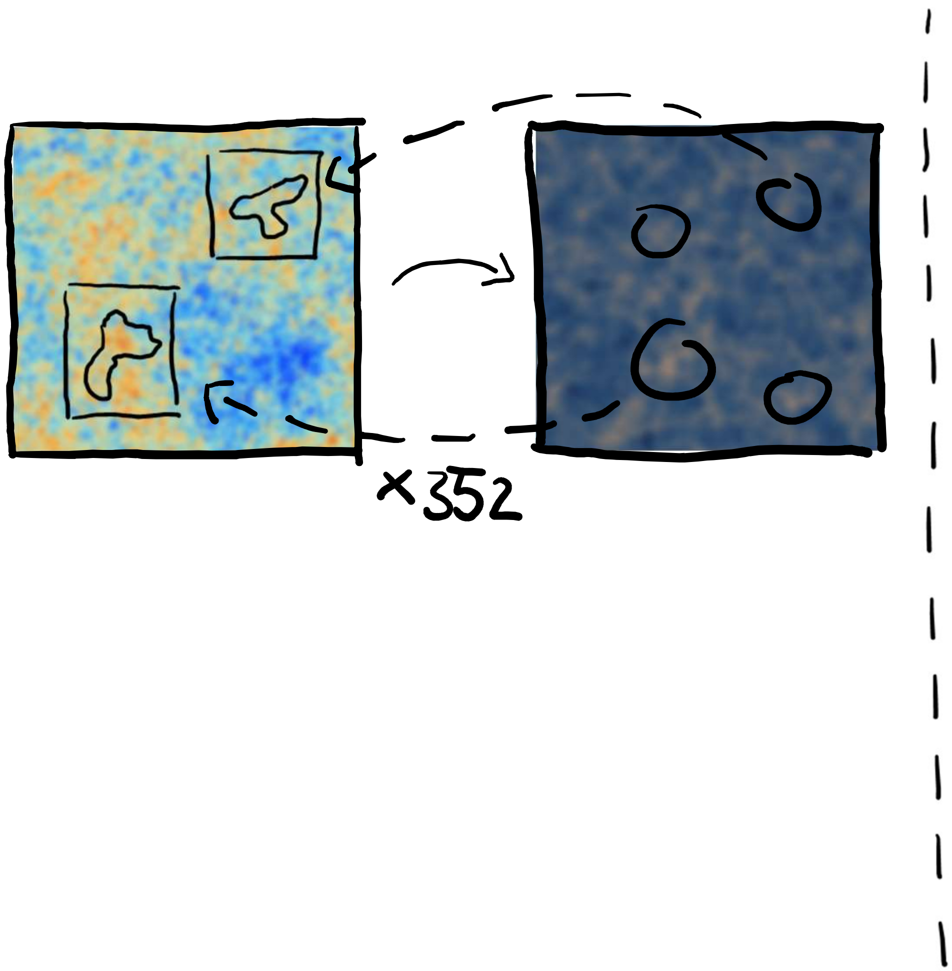
Halos are selected solely based on mass at z=0.

Halo selection criteria:

(i) include all halos with $\log(M_{200}) > 15.0\ M_{\odot}$

(ii) compensate the drop-off of statistics in TNG300 for lower mass halos

TNG-Cluster is a patchwork of ~350 zoom simulations



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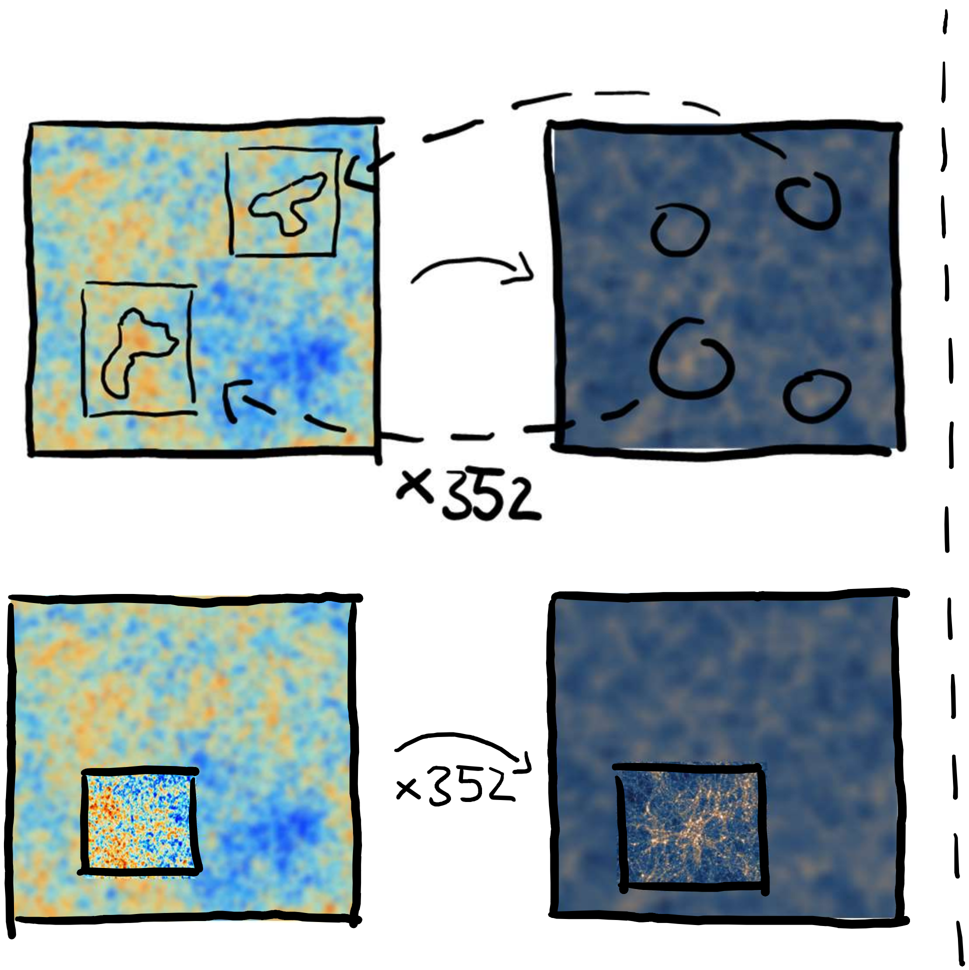

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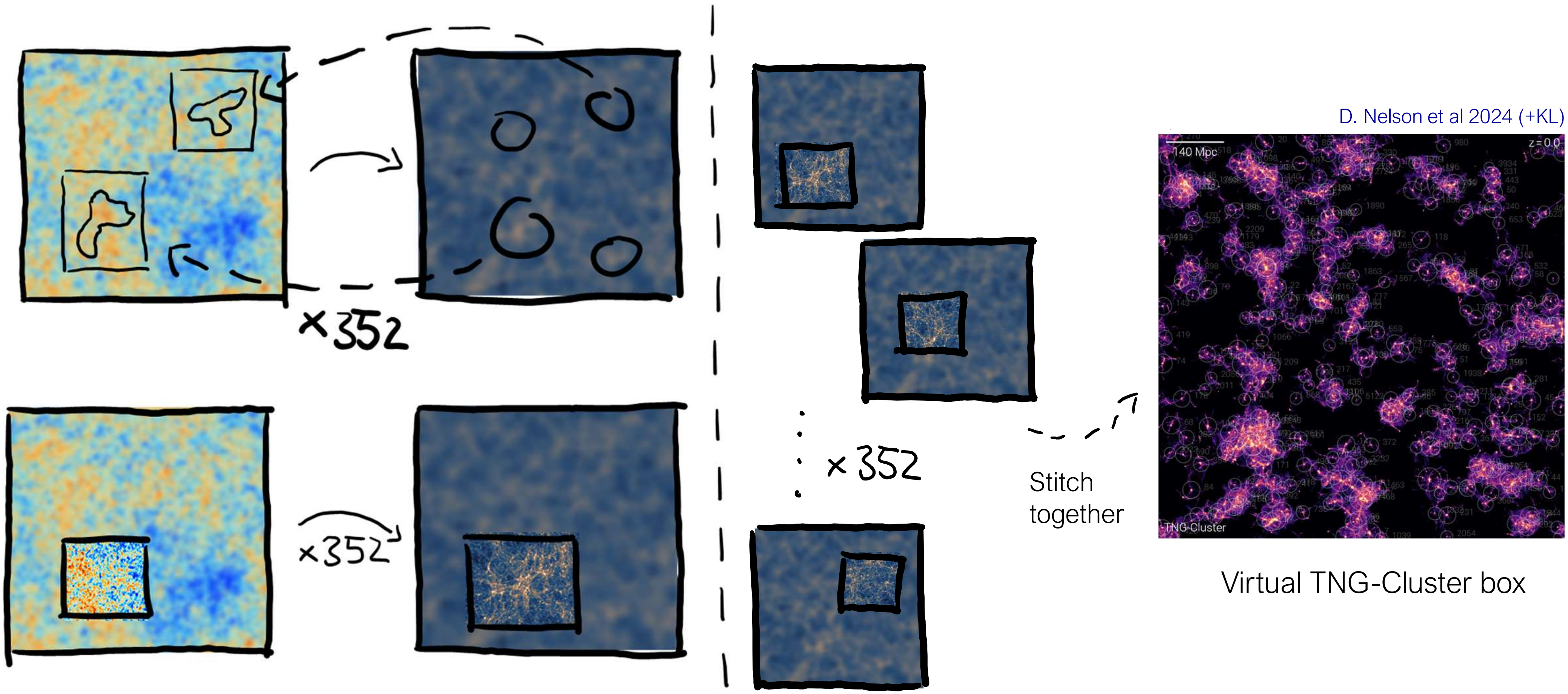
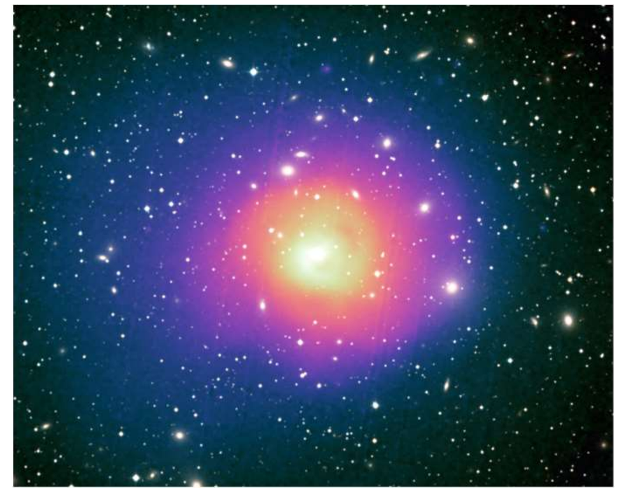


Virtual TNG-Cluster box

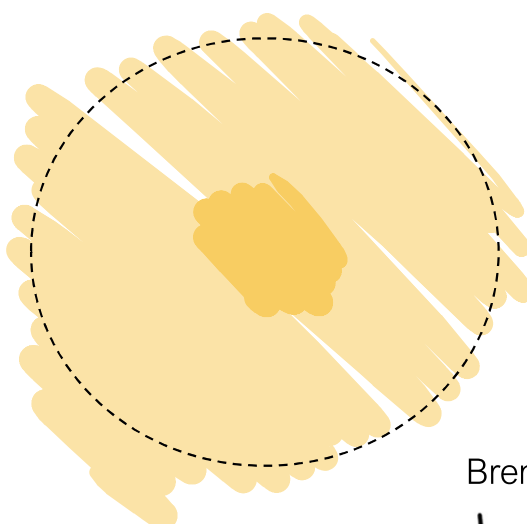
We study the gas in the core of galaxy clusters

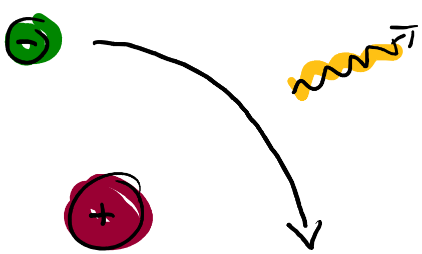
Understanding the physics shaping the cores of galaxy clusters is necessary to explain the formation and evolution of galaxies and clusters.



ESA/XMM-Newton/DSS-II/J. Sanders et al. 2019

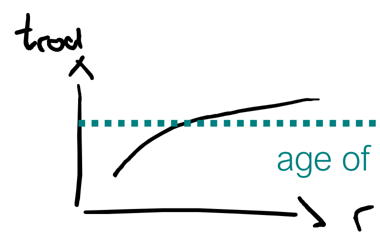
The hot atmosphere of the galaxy cluster can cool via Bremsstrahlung.





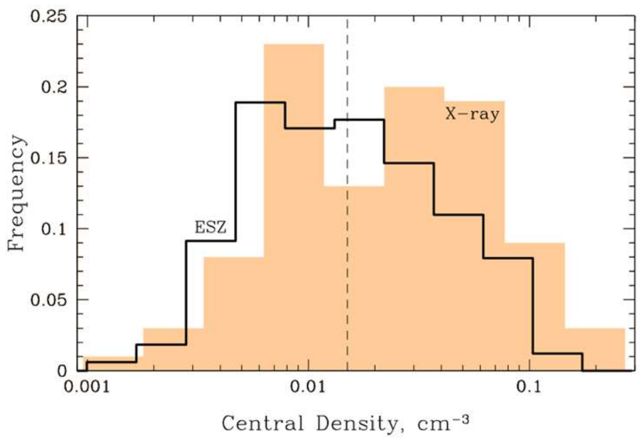
Bremsstrahlung ↓

$$t_{cool} \propto T^{1/2} n^{-1}$$

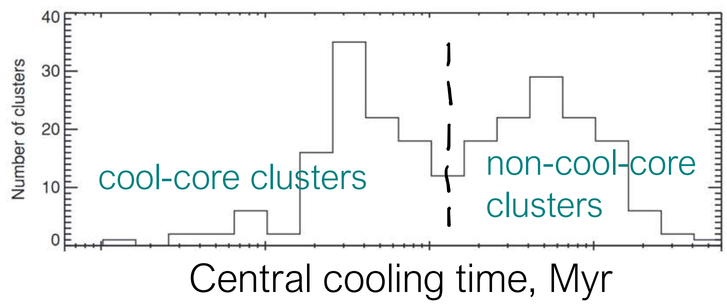


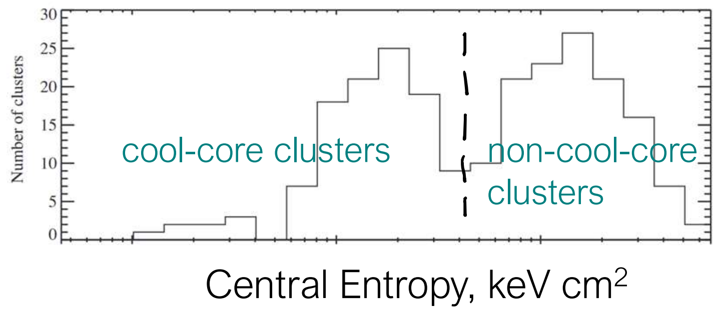
The cores of (some) galaxy clusters can cool efficiently.

The interplay between cooling and heating processes produce a variety of core properties



Andrade-Santos et al. 2017





Cavagnolo et al. 2009

Questions arise:

Are the distributions of core properties bimodal?

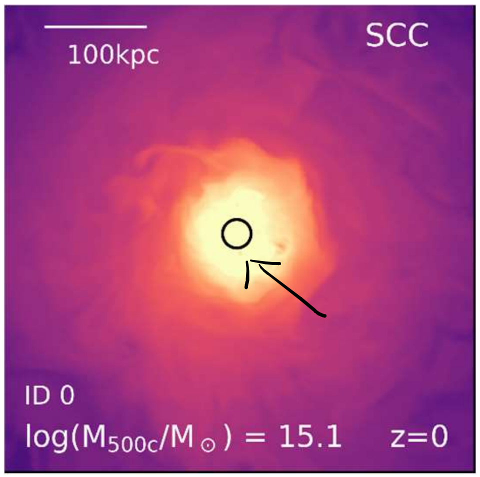
How to distinguish between CCs and NCCs?

What are the properties of CCs and NCCs?

Can clusters evolve from CC to NCC? And back?

We use 6 metrics to define the (non-)cool-core state of a cluster

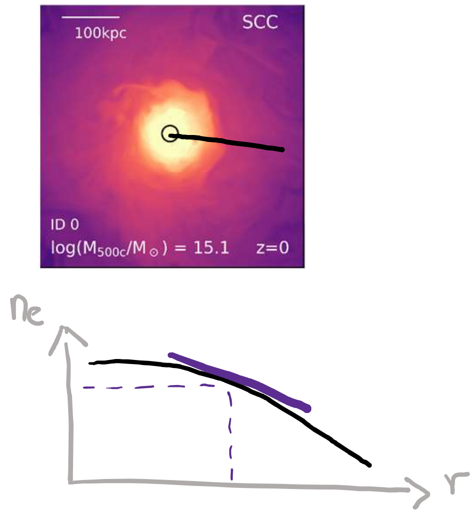
3D



Mass-weighted mean of cooling time, entropy or electron number density within aperture of $r = 0.012\ r_{500}$

$t_{cool,0}$ K_0 $n_{e,0}$

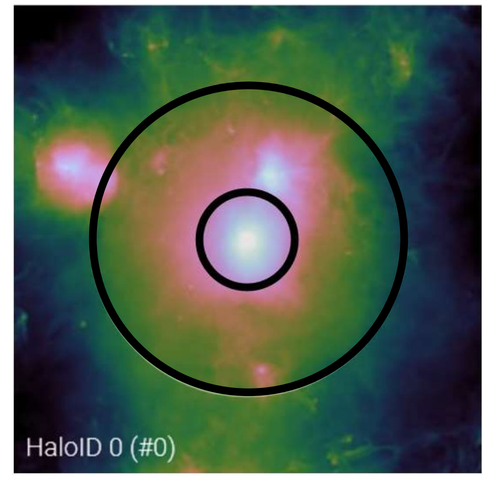
3D



Slope of the electron number density profile at $r = 0.04\ r_{500}$

α

2D

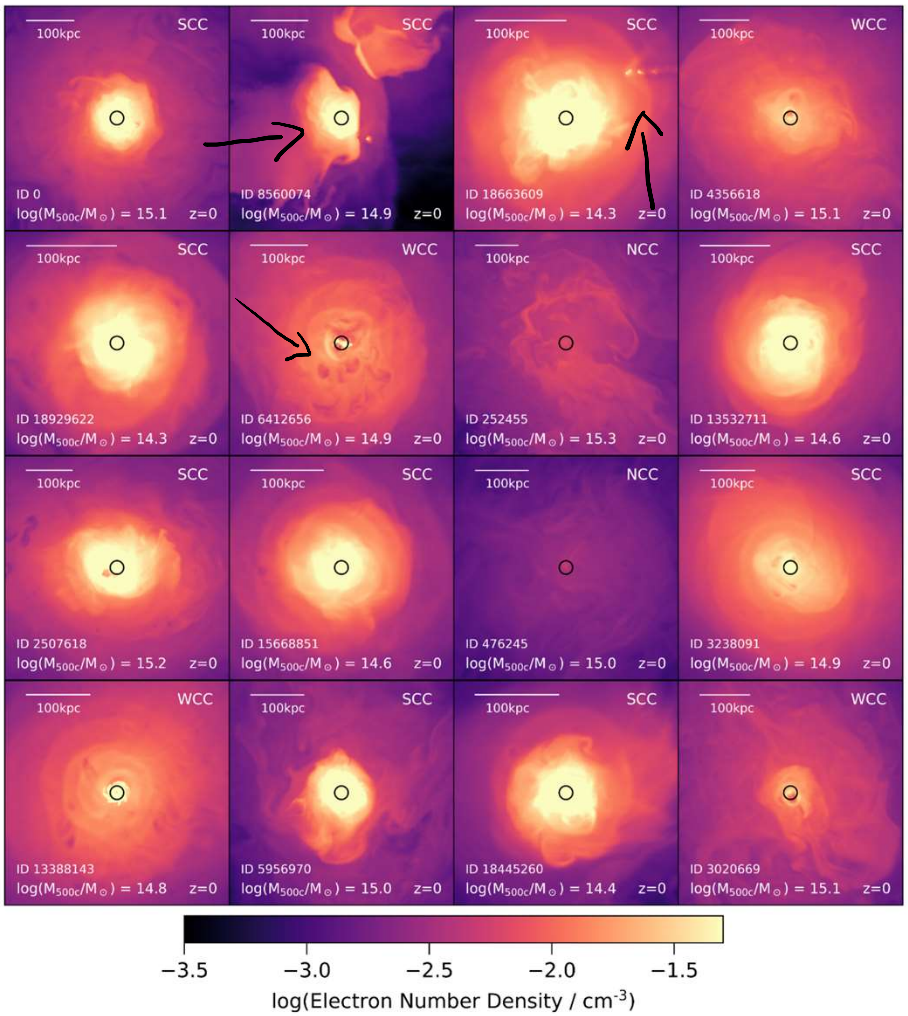


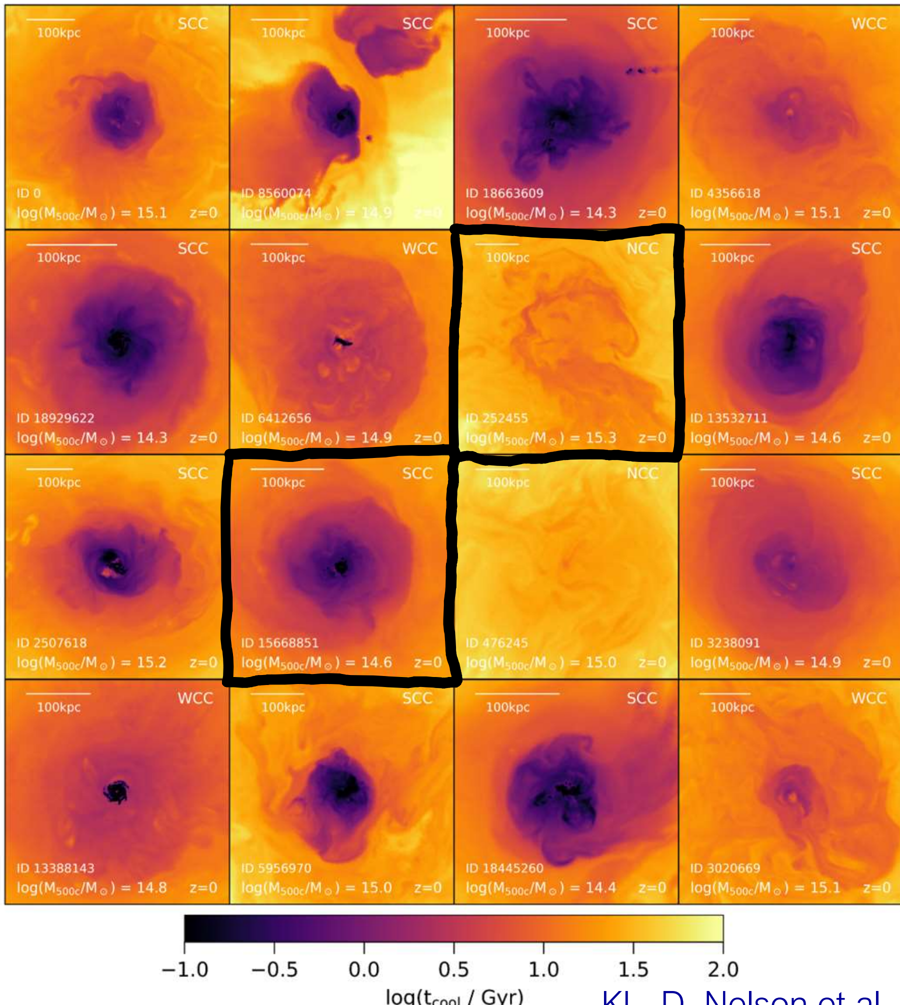
Concentration of X-ray luminosity within two apertures

C_{phys} C_{scaled}

1. TNG-Cluster produces a variety of cores.

Simulated cluster cores resemble structures from known halos

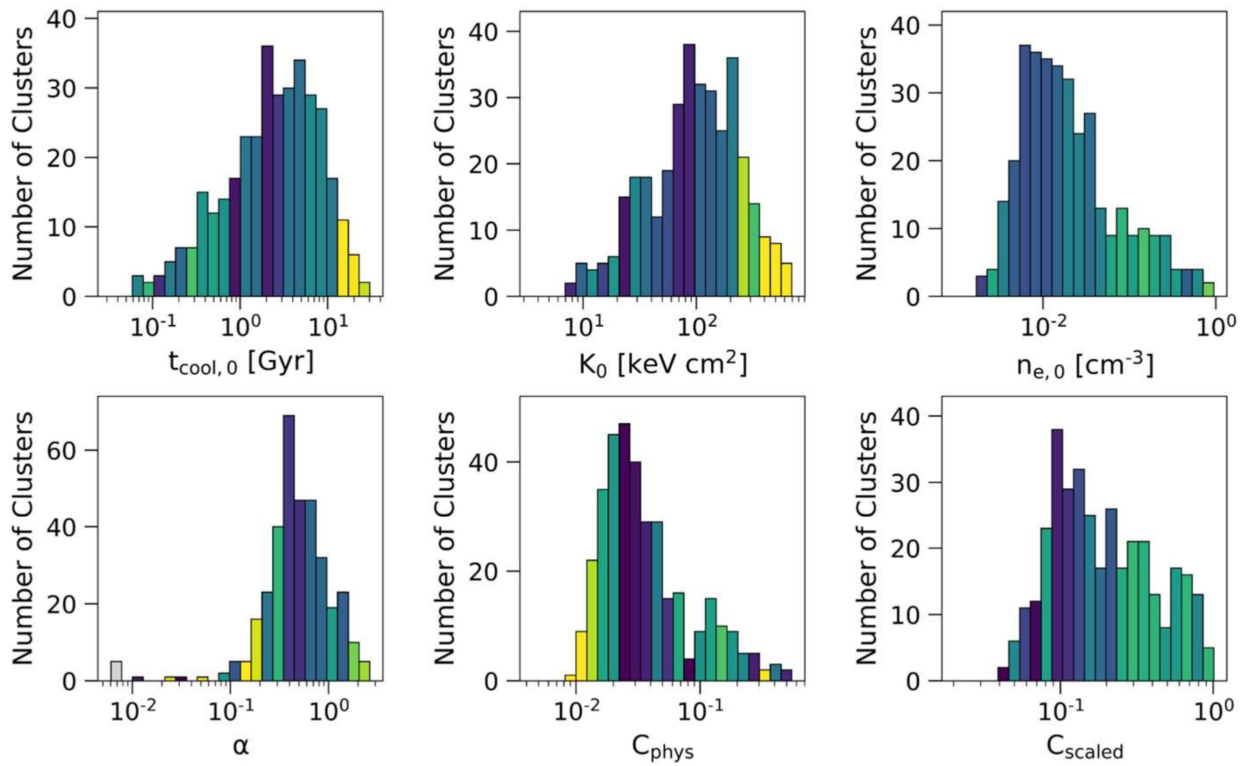




KL, D. Nelson et al. 2023

II. core properties are unimodally distributed.

With no a-priori cluster selection, the distributions of core properties are unimodal



Physical property		Aperture	SCC threshold	WCC threshold	NCC threshold
Central cooling time	$t_{cool,0}$	$0.012\,r_{500c}$	< 1 Gyr	$1\,\mathrm{Gyr} \le t_{cool,0} < 7.7\,\mathrm{Gyr}$	≥ 7.7 Gyr
Central entropy	K_0	$0.012\,r_{500c}$	$\le 22\,\mathrm{keV\,cm^2}$	$22 < K_0/(\mathrm{keV\,cm^2}) \le 150$	$> 150\,\mathrm{keV\,cm^2}$
Central electron density	$n_{e,0}$	$0.012\,r_{500c}$	$> 1.5 \cdot 10^{-2}\,\mathrm{cm^{-3}}$	$0.015 \ge n_{e,0}/\mathrm{cm^{-3}} > 0.005$	$\le 0.5 \cdot 10^{-2}\,\mathrm{cm^{-3}}$
Cuspiness	α	$0.04\,r_{500c}$	> 0.75	$0.75 \ge \alpha > 0.5$	≤ 0.5
Physical concentration	C_{phys}	40 kpc, 400 kpc	> 0.155	$0.155 \ge C_{phys} > 0.075$	≤ 0.075
Scaled concentration	C_{scaled}	$0.15\,r_{500c}, r_{500c}$	> 0.5	$0.5 \ge C_{scaled} > 0.2$	≤ 0.2

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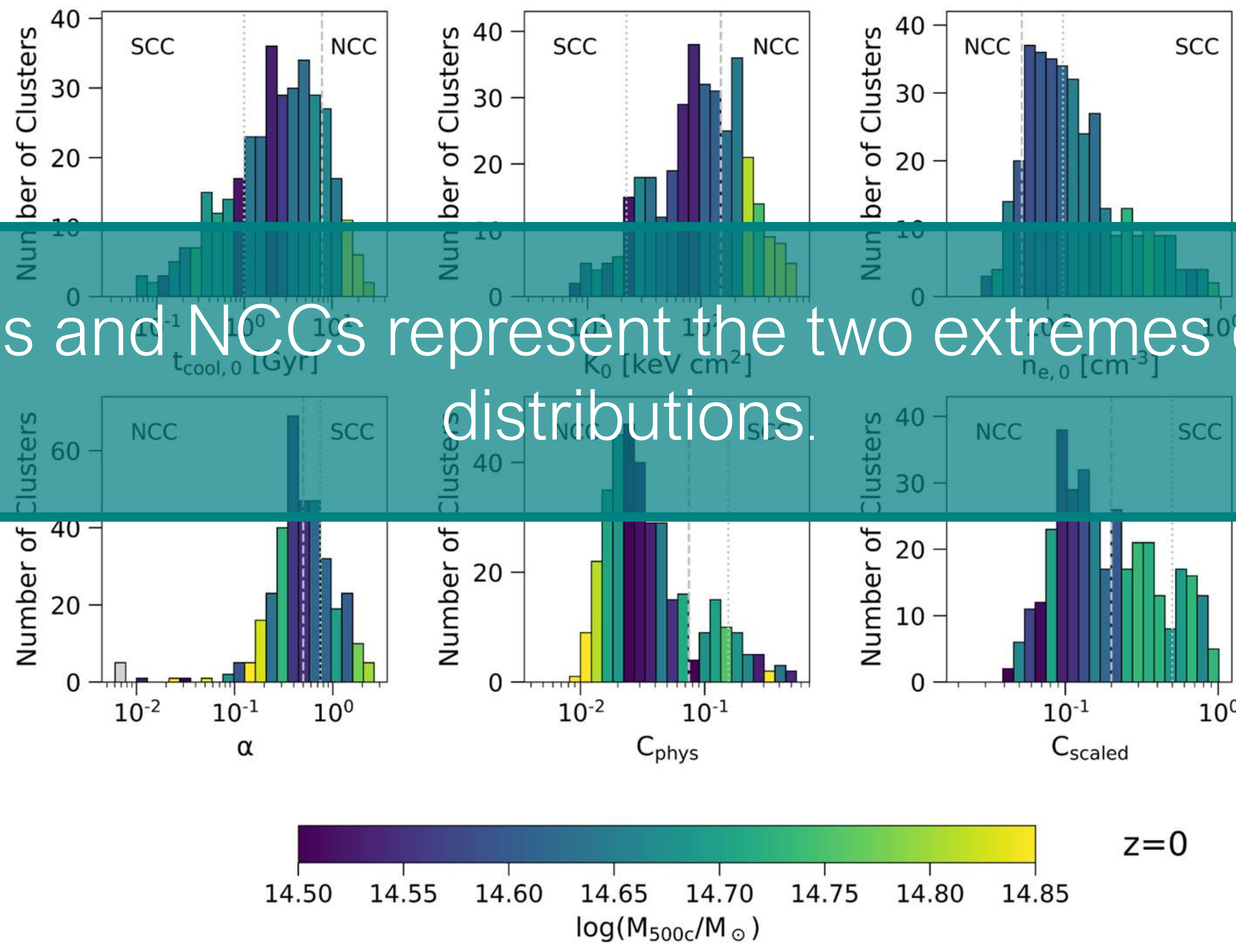
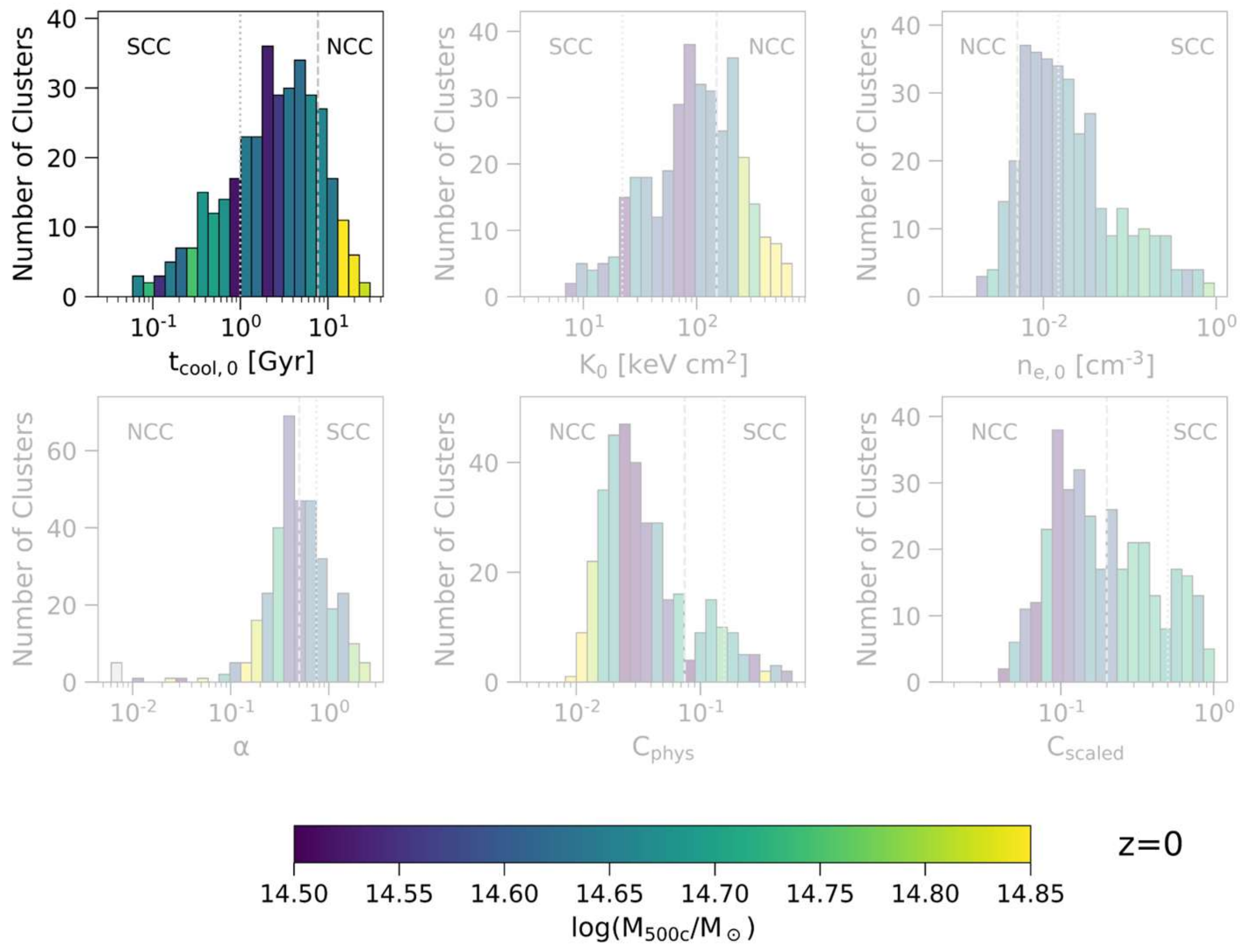


SCCs and NCCs represent the two extremes of the distributions.

KL, D. Nelson et al. 2023

Throughout the talk we use the central cooling time as our fiducial criterion



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III. a quarter of all clusters are strong cool-cores.

TNG-Clusters produces realistic cool-core fractions

The fraction of CCs, using central cooling time as criterion, is

$f_{SCC} = 24 \pm 2\ \%$ $t_{cool,0} < 1 Gyr$

$f_{WCC} = 60 \pm 3\ \%$

$f_{NCC} = 16 \pm 2\ \%$ $t_{cool,0} > 7.7 Gyr$

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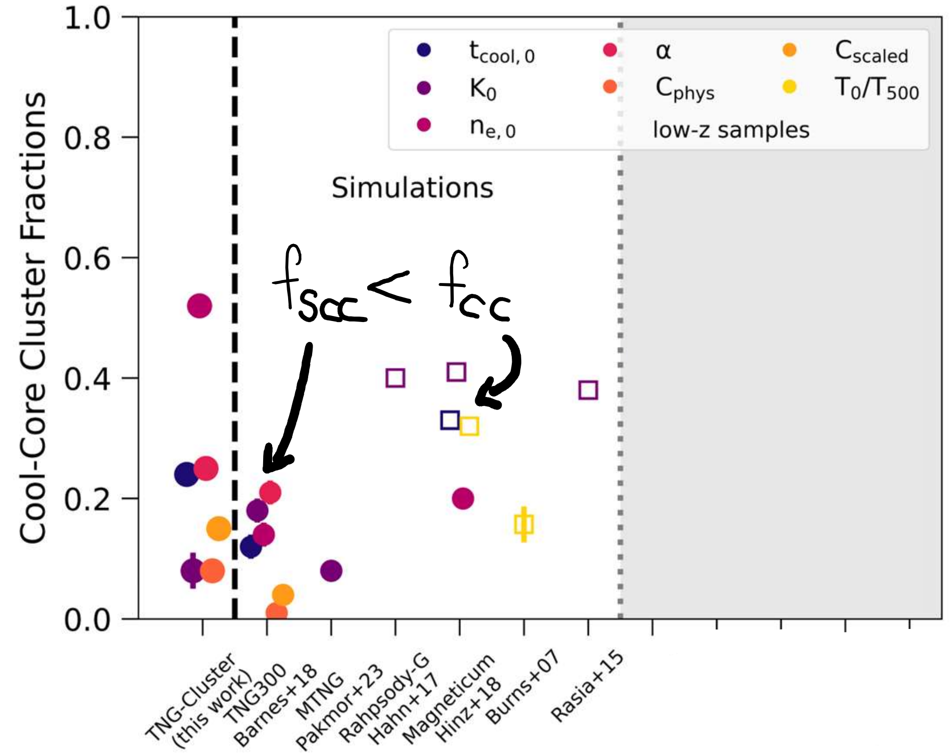

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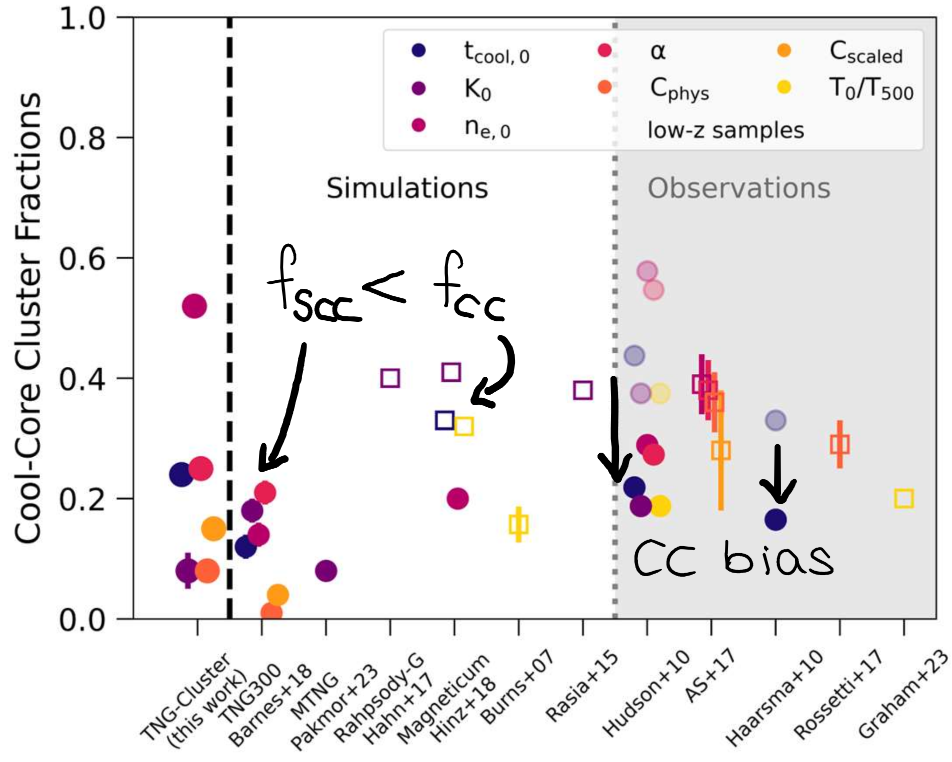

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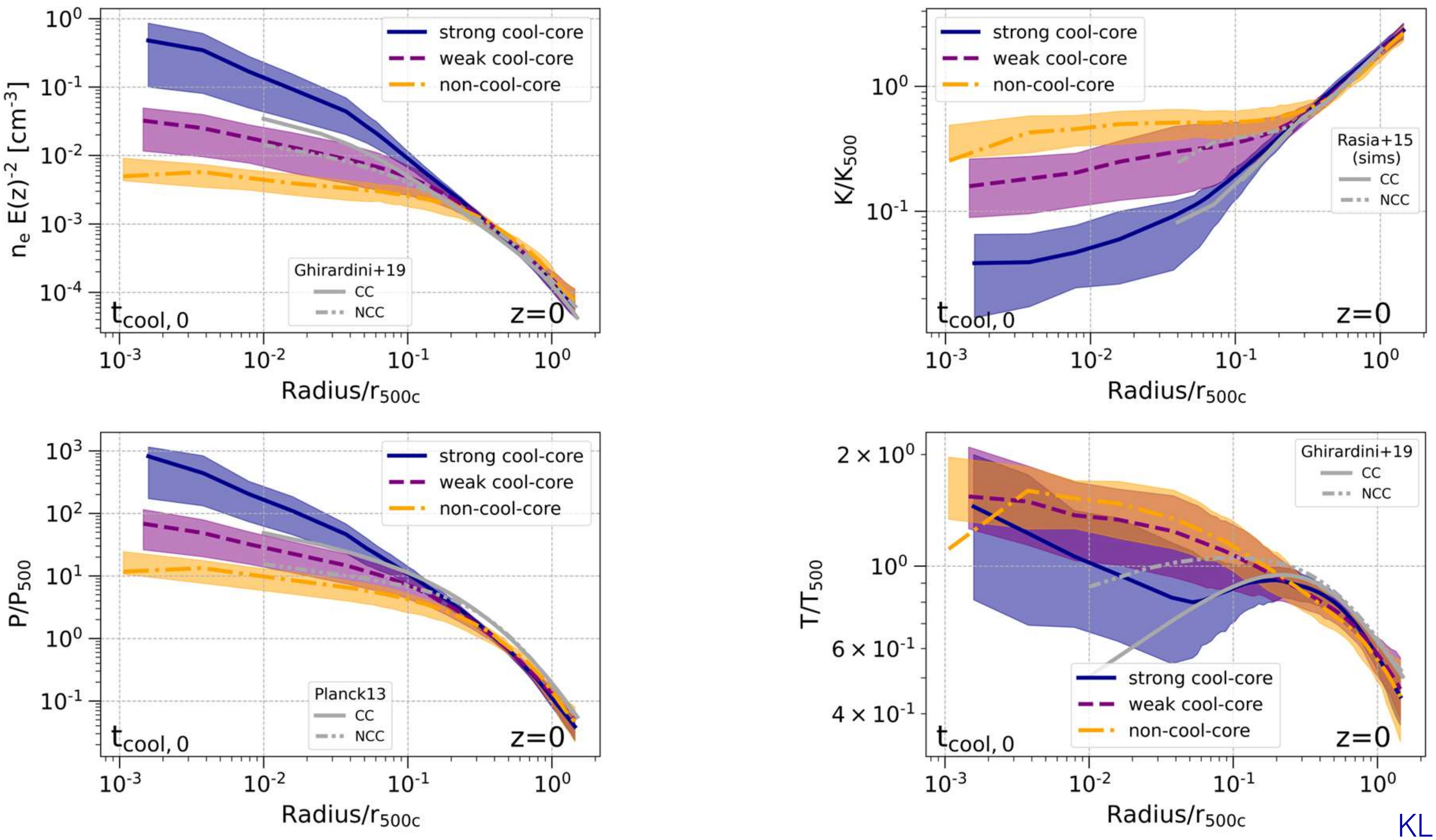
IV. the thermodynamic radial structures of CCs and NCCs differ.

The thermodynamic profiles for SCCs and NCCs are clearly separated in the core



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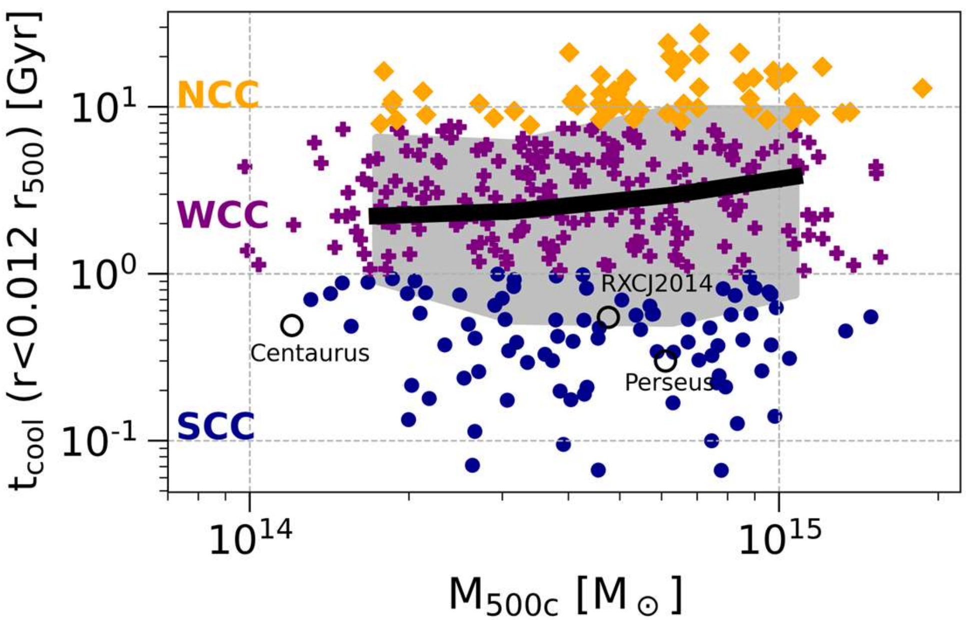
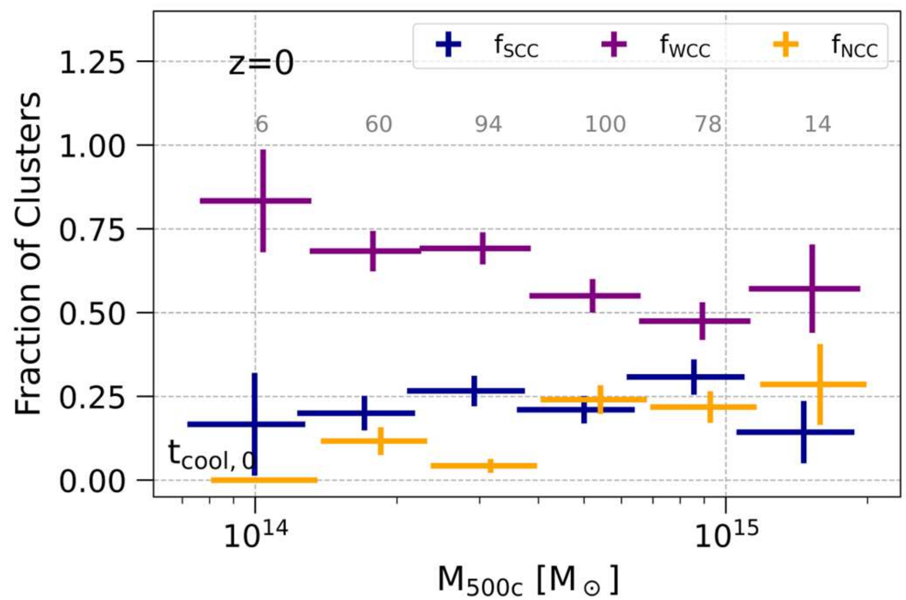
V. does the number of CCs depend on mass?

The number of NCCs increases with halo mass





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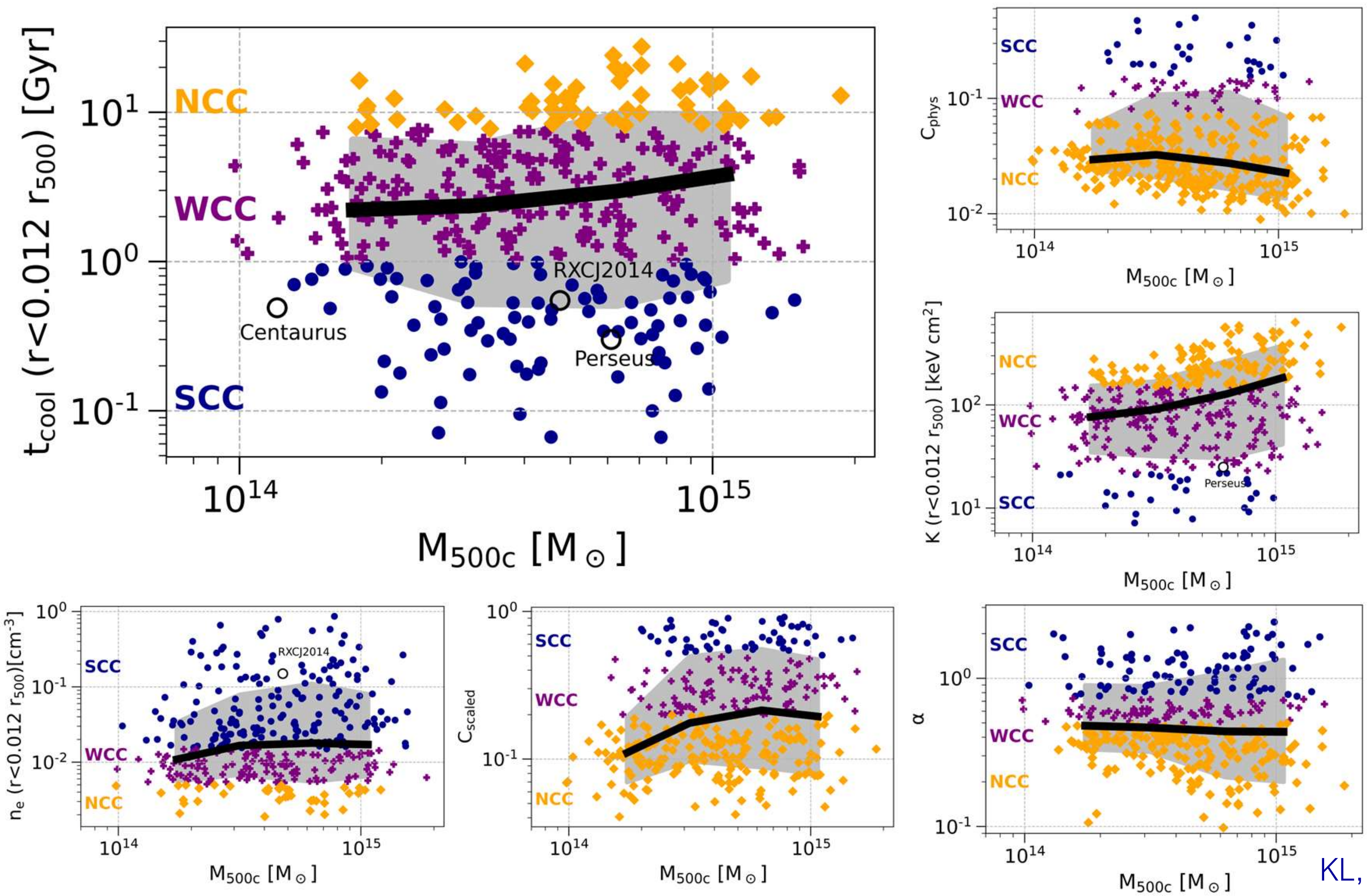
Core properties show different trends with halo mass



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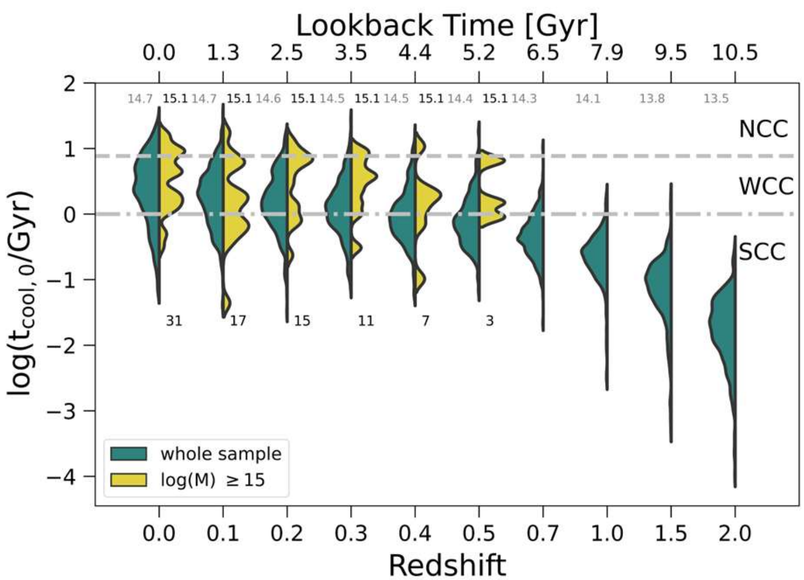
So far: census of CCs and NCCs in TNG-Cluster

Next:

I. Understand evolution of core properties:



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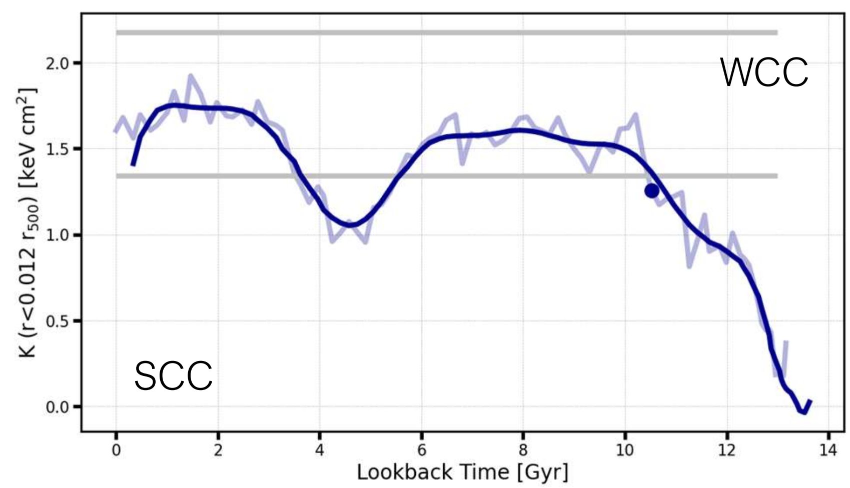
II. Study transformation mechanisms:

Most prominent candidates: AGN feedback and mergers

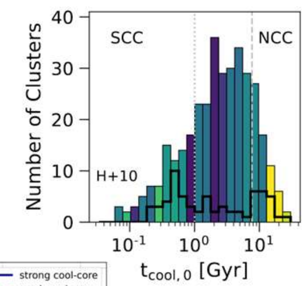


Take-home message

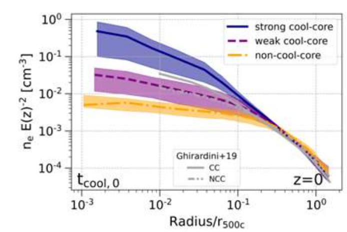
KL, D. Nelson et al. 2023
arXiv:2311.06333

Using the TNG-Cluster simulation and employing six criteria to define CCs, we find:

I. TNG-Cluster produces a variety of cores.

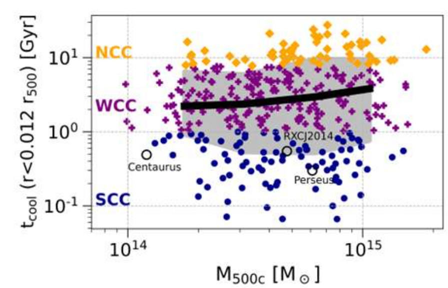


II. the distributions of core properties are unimodal and SCCs and NCCs represent the extremes of these distributions.

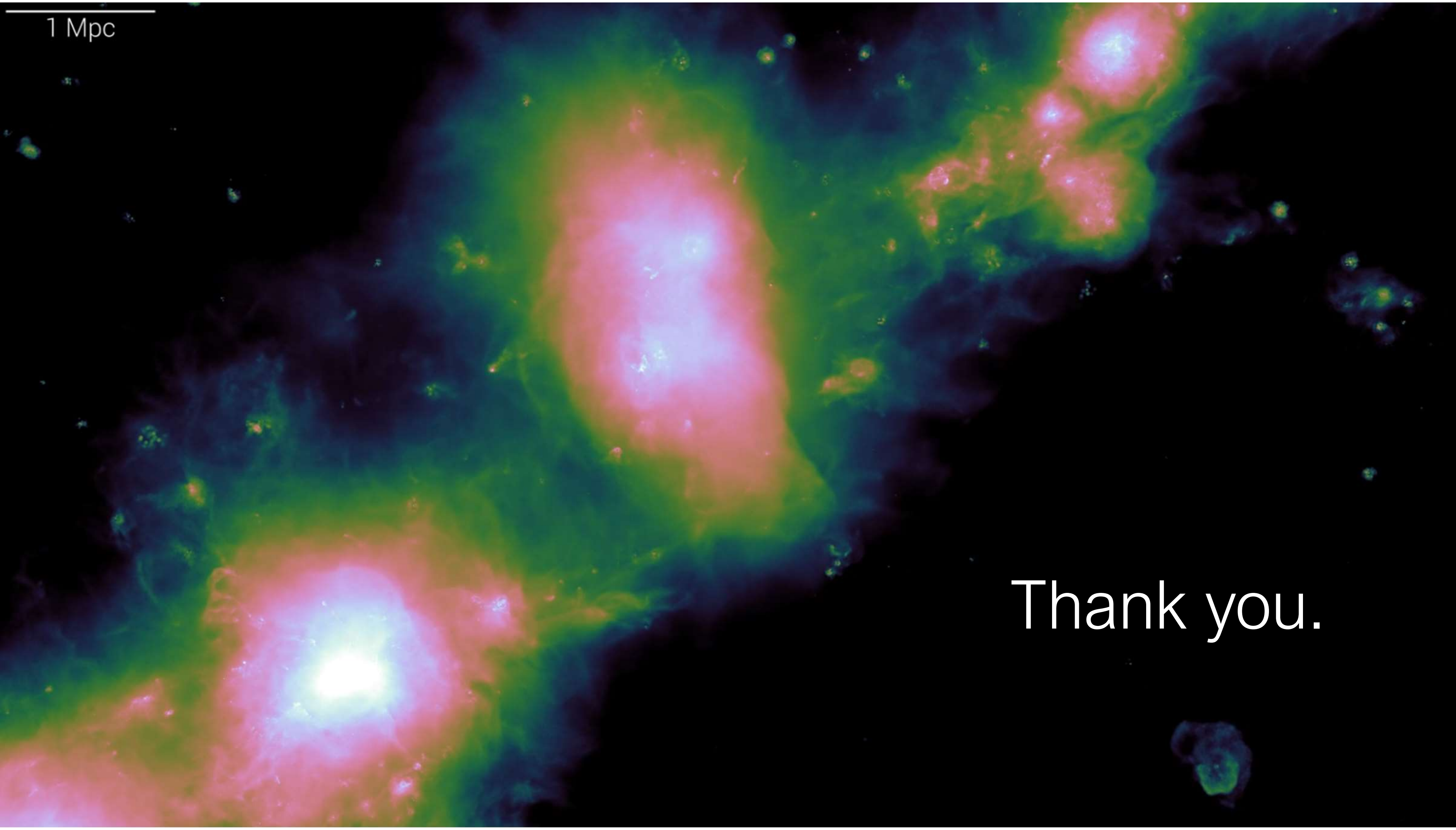


III. TNG-Cluster produces realistic CC fractions.

IV. the radial structure for CCs and NCCs is clearly separated in the center.



V. depending on criterion the CC fraction shows different trends with mass and redshift.


1 Mpc
Thank you.