MAGNETICUM

From Galaxies to Galaxy Clusters

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Abstract

The *Magneticum* simulations (www.mageticum.org) follow the formation of cosmological structures in a hitherto unaccomplished level of detail, performing a set of large scale and high resolution simulations. We model in detail the complex, non-gravitational, physical processes known to be crucial for galaxy and galaxy cluster formation. This allows detailed comparisons to a variety of multi-wavelength observational data and the formation processes of structures across a large range of physical scales.

Physics included in the simulations:

- cooling, star formation, winds (Springel & Hernquist 2003)
- metals, detailed stellar evolution and chemical enrichment through SN-Ia, SN-II and AGB, detailed metal depending cooling (Tornatore et al. 2003/2006), Wiersma et al. 2009
- improved model for black hole sink particles and AGN feedback (Springel & Di Matteo 2006, Fabjan et al. 2010, Hirschmann et al. 2014, Steinborn et al. 2015)
- thermal conduction (1/20th Spitzer) (Dolag et al. 2004)
- low viscosity scheme to track turbulence and higher order SPH kernels (Dolag et al. 2005, Dehnen & Aly 2012, Beck et al. 2016)

Name	Size	Medium [mr]	High [hr]	Ultra high [uhr]	Extremely high
Box 0	$[2688\ \mathrm{Mpc/h}]^3$	2×4536^3			
Box 1	$[896\ \mathrm{Mpc/h}]^3$	2×1536^3			
Box 2b	$[640\ \mathrm{Mpc/h}]^3$		2×2880^3		
Box 2	$[352\ \mathrm{Mpc/h}]^3$	2×594^3	2×1584^3		
Box 3	$[128\ \mathrm{Mpc/h}]^3$	2×576^3	2×576^3	2×1536^3	
Box 4	$[48\ \mathrm{Mpc/h}]^3$	2×81^3	2×576^3	2×576^3	
Box 5	$[18\ \mathrm{Mpc/h}]^3$		2×81^3	2×216^3	2×576^3

Tab. 1: Overall *Magneticum* simulation set listed by box size (volume) and resolution (number of particles).

The *Magneticum* Simulations

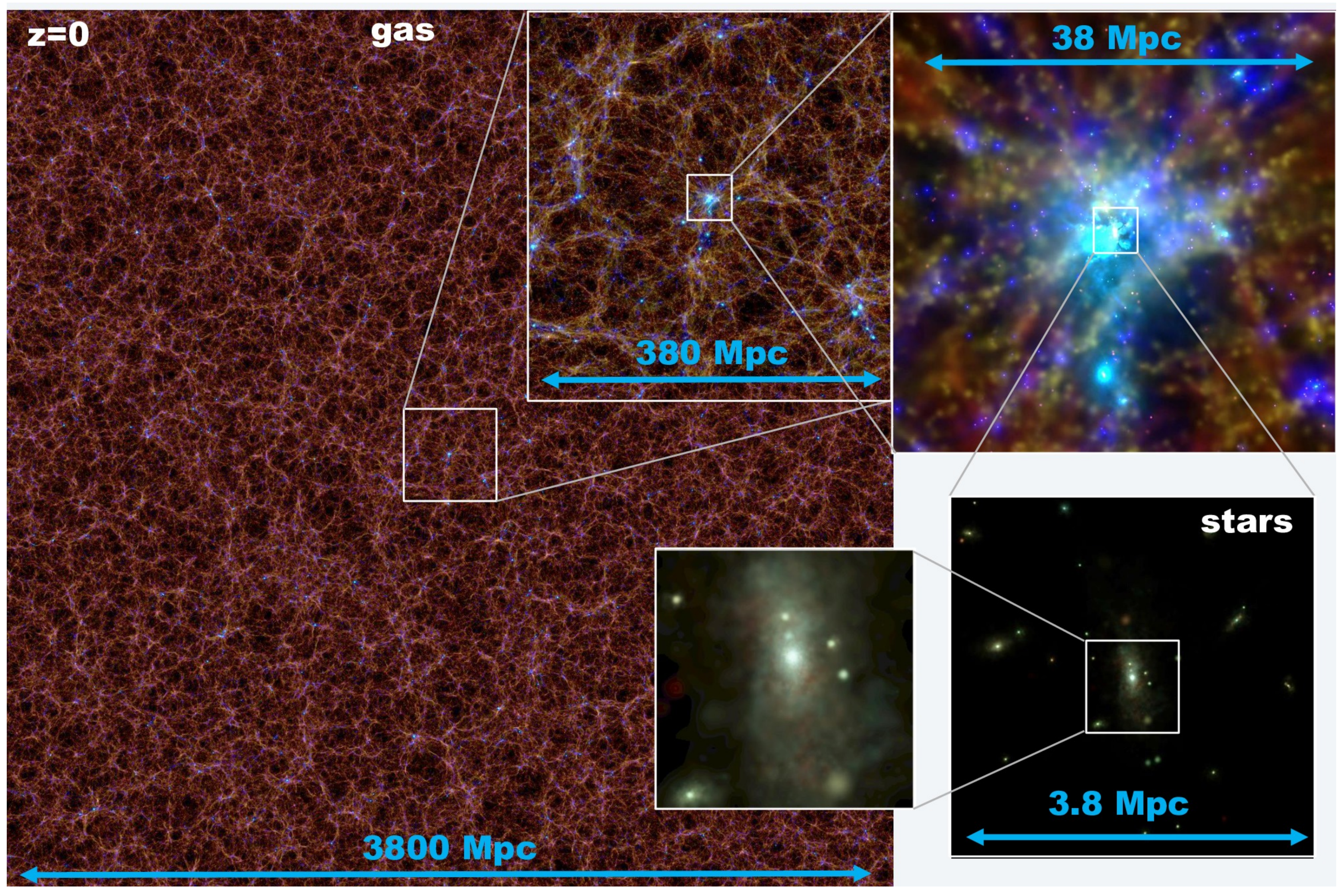

Fig. 1: Visualization of the large scale distribution of the gas and stellar component at GPc size within **Box0/mr**, zooming onto the most massive galaxy cluster, where individual galaxies become visible.

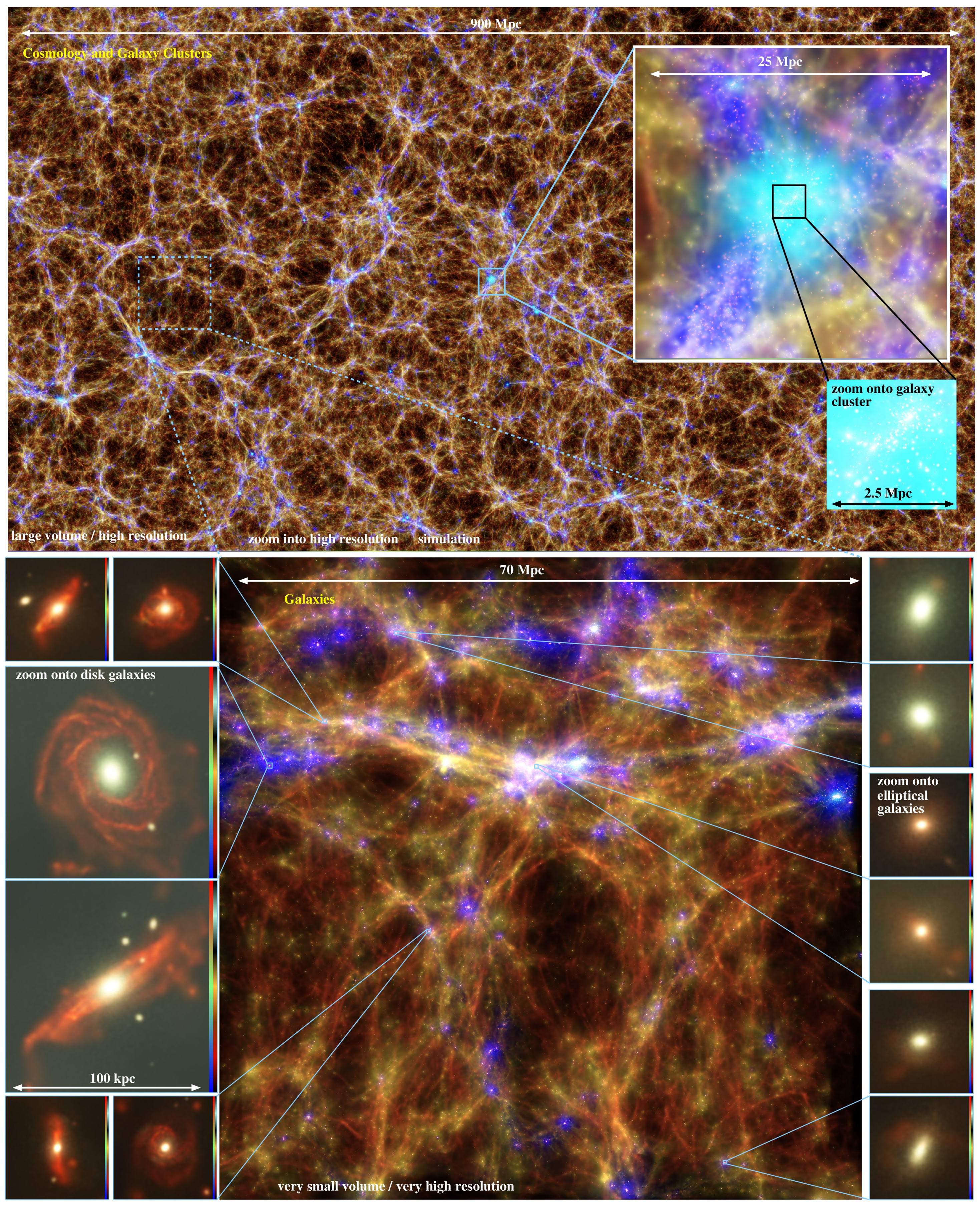

Fig. 2: The shown region of **Box2b/hr** (upper part) spans a total size of ≈ 900 Mpc. Shown is the gas which fills the space between the galaxies (color coded according to its temperature from cold/brown to hot/light blue) together with the galaxies and stars forming in the simulation (colored in white). The zoom onto the galaxy cluster reveals the ability of this simulation to resolve up to thousands of individual member galaxies within massive clusters, each resolved with hundreds up to even ten thousands of stellar particles, where many of them are resolved enough to host BH sink particles (see poster by L. Steinborn). In the smaller simulation volumes, as the example of **Box4/uhr** shows, the resolution finally is sufficient enough to resolve the morphology of galaxies within the simulations, reproducing the two observed fundamental galaxy types in our universe, elliptical and spiral galaxies (see talk by A. Teklu and talk by R.-S. Remus).

The Web Interface

The outcome of the *Magneticum* simulations is now available within a first test operation of the cosmological simulation web portal (c2papcosmosim1.srv.lrz.de, see Ragagnin et al., in prep). Users are able to access data products extracted from the simulations via a user-friendly web interface. Here the user browse through visualizations of cosmological structures while guided by meta data queries which help to select galaxy clusters and galaxy groups of interest. At the moment, Phox is the first enabled service on this platform and allows one to perform virtual X-ray observations where FITS files with photon lists are returned in the so-called SIMPUT format, taking the specifications of various existing and future X-ray telescopes into account.

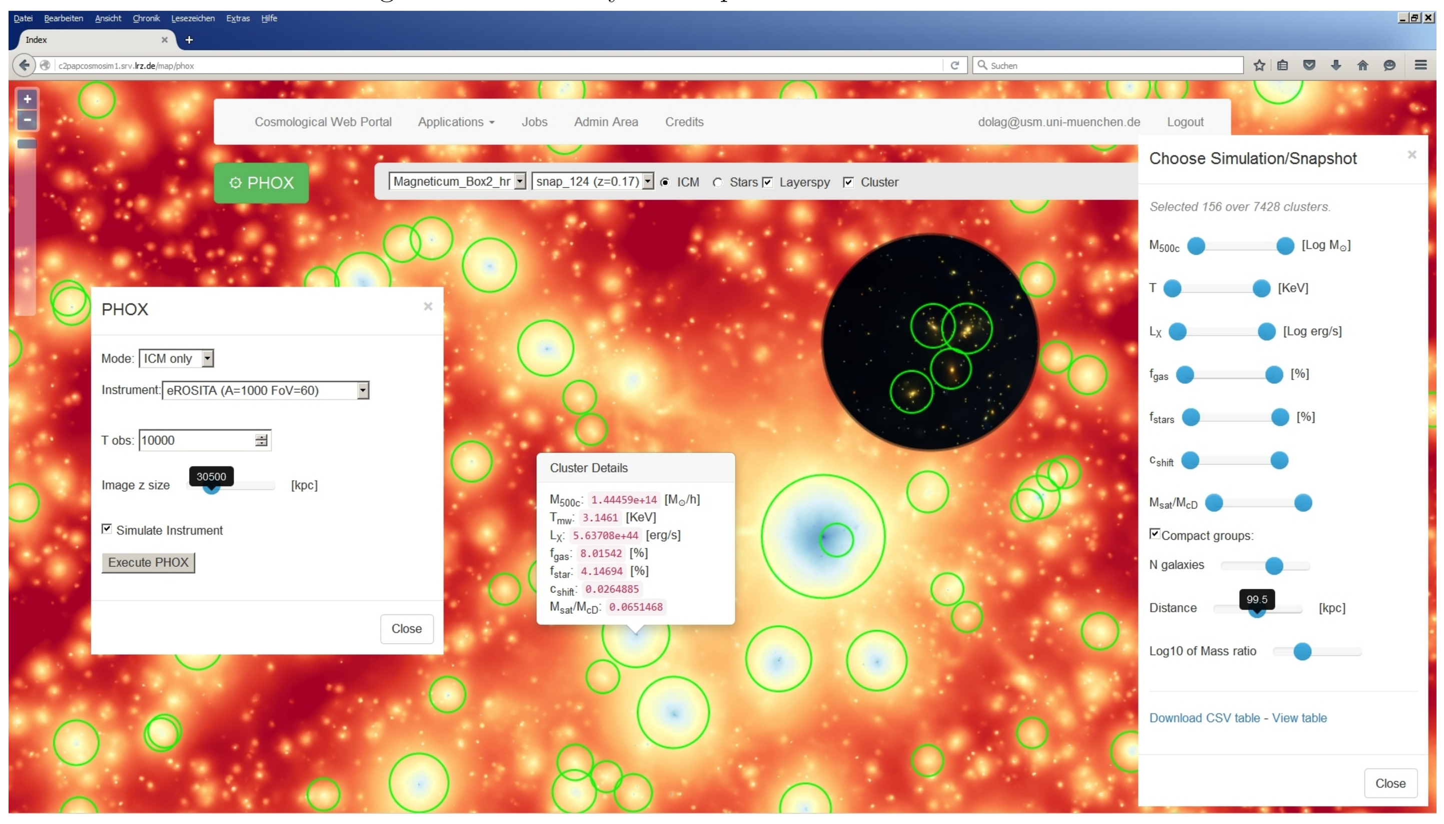

Fig. 3: The graphical interface of the web portal, selecting **Box2/hr** at z=0.17, visualizing the diffuse media with the layerspy option for the stellar component activated (top right circle) and massive halos overlaid as green circles. The popup shows the properties of the currently chosen cluster. On the right, the cluster restriction interface, which also allows one to download all meta data of the actually selected halos as CSV table, is visible. The left window shows the Phox service interface.

Galaxy Properties

The galaxies from the ***Magneticum*** simulations reproduce in detail the observed relation between stellar mass and size (see talk by R.-S. Remus) as well as the relation between specific angular momentum and stellar mass (see talk by A. Teklu) for the different morphological types. The simulations also show that disk galaxies preferentially populate dark matter halos where the angular momentum vector of the dark matter component in the central region is better aligned with that of the outer part.

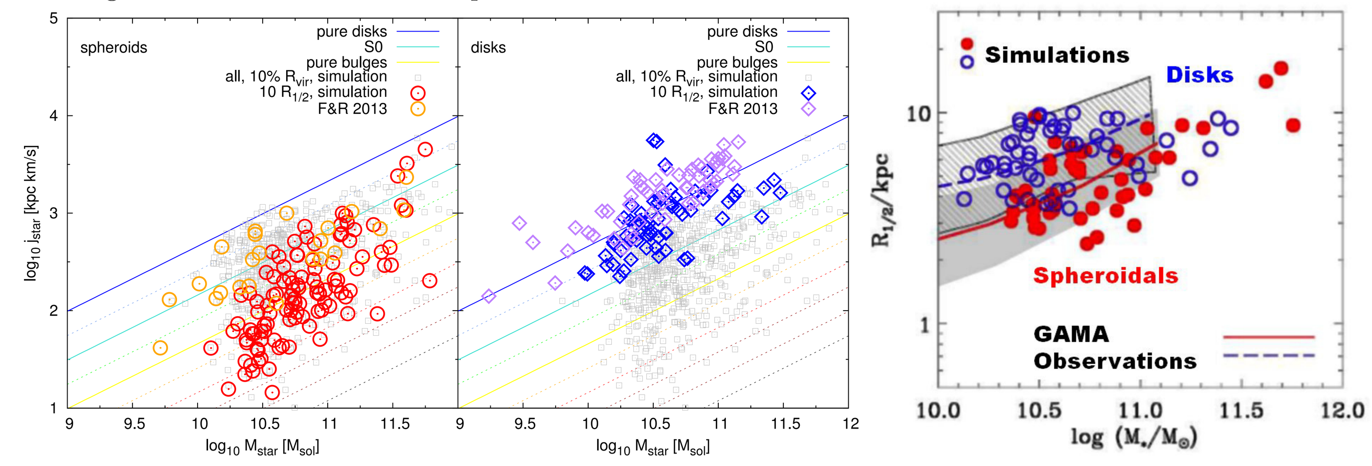

Fig. 4: Stellar mass–specific-angular-momentum (left and middle panels) and mass–size (right panel) relations at $z = 0.1$ for galaxies selected from the ***Magneticum*** simulations. *Left panel:* Simulated galaxies classified as spheroids (red circles) in comparison to observed ellipticals (orange circles) from Fall & Romanowsky 2013. *Middle panel:* Same as left panel but for disk galaxies from simulations (blue diamonds) and observations (purple diamonds). See also Teklu et al. 2015. *Right panel:* Stellar mass–size relation for simulated spheroids (red circles) and disks (blue circles) in comparison to the observed relations for elliptical (red line, gray area) and spiral (blue line, hatched area) galaxies from the GAMA survey (Baldry et al. 2012).

The Outer Halos of Galaxies and Clusters

Our simulations show that not only the dark matter radial density profile but also the outer stellar radial density profiles can be well described by a universal profile. This profile, $\rho(r) = \rho_{-2}\ \exp\left\{-\frac{2}{\alpha_{Ein}}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha_{Ein}} - 1\right]\right\}$ (where α_{Ein} controls the curvature, ρ_{-2} is the density and r_{-2} the radius at which $\rho(r) \propto r^{-2}$), is also known as Einasto profile. We find that the fitting parameters of those Einasto profiles are not independent but closely correlated for fixed total mass. The amount of curvature of the outer stellar halo density profile is therefore a diagnostic for the merging history of galaxies. This can also well explain the observed differences between the stellar outer halo density profiles of the Milky Way and Andromeda (see Remus et al, in prep).

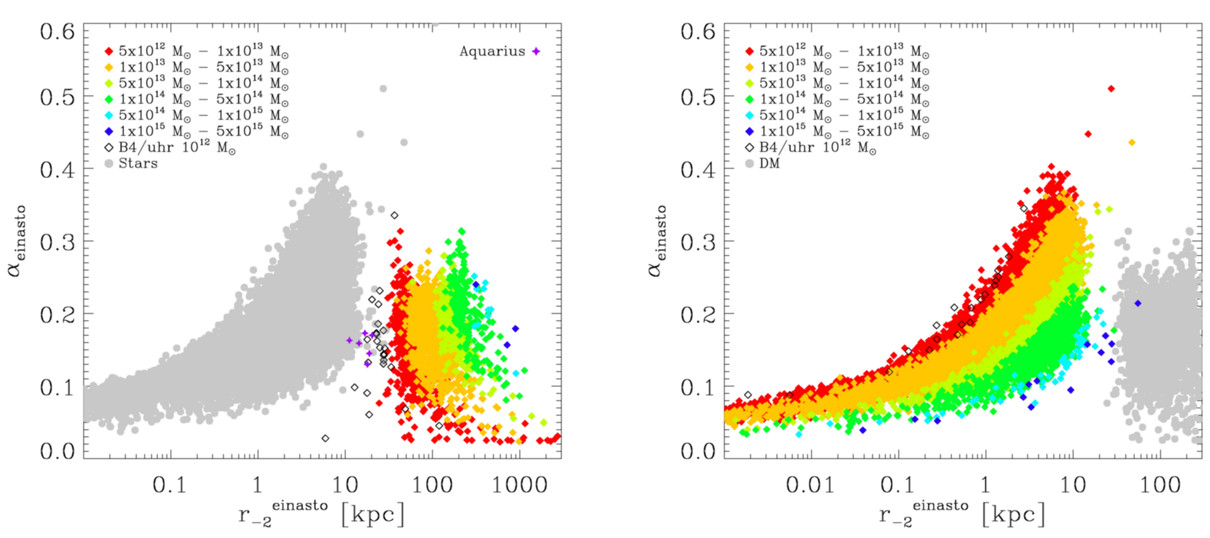

Fig. 5: Best-fit parameters for Einasto profile fits to the outer halos of galaxies, ranging from halo masses of $5 \times 10^{12} M_\odot$ up to massive clusters with several times $10^{15} M_\odot$ (color coded). *Left panel:* Fits to the dark matter components. *Right panel:* Fits to the stellar outer halos. See Remus et al., in prep.

Relevant *Magneticum* Papers

Beck et al. 2016: *An improved SPH scheme for cosmological simulations*, MNRAS, 455, 2110
Biffi et al. 2013: *Investigating the velocity structure and X-ray observable properties of simulated galaxy clusters with PHOX*. MNRAS, 428, 1395
Bocquet et al. 2016 *Halo mass function: baryon impact, fitting formulae, and implications for cluster cosmology*, MNRAS, 456, 2361
Dolag et al. 2015: *Constraints on the distribution and energetics of fast radio bursts using cosmological hydrodynamic simulations*, MNRAS, 451, 4277
Dolag et al. 2016: *SZ effects in the Magneticum Pathfinder Simulation: Comparison with the Planck, SPT, and ACT results.* MNRAS submitted
Hirschmann et al. 2014: *Cosmological simulations of black hole growth: AGN luminosities and downsizing*, MNRAS, 442, 2304
Ragagnin et al. 2016: *A web interface for hydrodynamical, cosmological simulations*, in prep
Remus et al. 2013: *The Dark Halo-Spheroid Conspiracy and the Origin of Elliptical Galaxies*, ApJ, 766, 71
Remus et al. 2016: *The Co-Evolution of Total Density Profiles and Central Dark Matter Fractions in Simulated Early-Type Galaxies*, MNRAS submitted
Remus et al. 2016: *A Universal Density Profile for the Outer Stellar Halos of Galaxies*, in prep
Steinborn et al. 2015, *A refined sub-grid model for black hole accretion and AGN feedback in large cosmological simulations*, MNRAS, 448, 1504
Steinborn et al. 2016, *Origin and properties of dual and offset AGN in a cosmological simulation at z=2*, MNRAS, 458, 1013
Teklu et al. 2015, *Connecting Angular Momentum and Galactic Dynamics: The Complex Interplay between Spin, Mass, and Morphology*, ApJ, 812, 29