The Magneticum Simulations, from Galaxies to Galaxy Clusters

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www.magneticum.org
What we reached so far

Increase of resolution elements in completed cosmological simulations over time.

Cooling + star-formation + SMBH treatment
The Simulations ... 

Physics: 
cooling+sfr+winds 
Springel & Hernquist 2002/2003 
Metals cooling 
Wiersma et al. 2009 
SNIa,SNII,AGB 
Tornatore et al. 2003/2006 
BH+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 

Numerics: 
New Kernels: WC6 
Dehnen et al. 2012 
Low visc. scheme 
mr/hr (time dep. alpha) 
Dolag et al. 2005 
uhr (high order grad.) 
Beck et al. 2015
The Magneticum Simulations

~ 30000 groups with $M > 5 \times 10^{13} \, M_\odot$ @ $z=2$

~ 100 "massive" clusters with $M > 2 \times 10^{14} \, M_\odot$ @ $z=2$

$2 \times 4536^3$
Largest Simulation (Box0/mr)

$z=0$ gas

3800 Mpc

38 Mpc

3.8 Mpc

Stars
Sub-resolution star-formation:

Multi phase model (sub-scale)
Springel & Hernquist 2002

Star formation
\[ \frac{d\rho_x}{dt} = (1 - \beta)\frac{\rho_c}{t_*} \]

supernova mass fraction
star formation timescale

Cloud evaporation
\[ \left. \frac{d\rho_h}{dt} \right|_{evap} = A\beta\frac{\rho_c}{t_*} \]

cloud evaporation parameter

Growth of clouds
\[ \left. \frac{d\rho_c}{dt} \right|_{TI} = - \left. \frac{d\rho_h}{dt} \right|_{TI} = \frac{\Lambda_{net}(\rho_h, u_h)}{u_h - u_c} \]

cooling function

Cold gas
Stars
Hot gas
Chemical enrichment:

Stellar evolution model (sub-scale)

Energy: SNIa, SNII
Metals: SNIa, SNII, AGB winds
H, He, C, Ca, O, N, Ne, Mg, S, Si, Fe, Na, Al, Ar, Ni

![Stars and Hot gas]

**IMF:**
Salpeter, Kroupa, Chabrier, Arimoto & Yoshii

**Life-time:**
Maeder & Meynet 1989
Padovani & Matteucci 1993

**Stellar yields:**
AGB: Groenewegen, Karakas
SNIa: Thielemann
SNII: Woosley & Weaver
Romano, Kobayashi, ...

**Equation:**

\[
R_{\text{SNIa}}(t) = A \int_{M_{\text{B, inf}}}^{M_{\text{B, sup}}} \phi(m_B) \int_{\mu_m}^{\mu_M} f(\mu) \psi(t - \tau_{m_2}) \, d\mu \, dm_B
\]

**SNII and AGB rate:**

\[
R_{\text{SNII|ILMS}}(t) = \phi(m(t)) \times \left(-\frac{dm(t)}{dt}\right)
\]

**Initial mass function (IMF):**

\[
\phi(m) = \frac{dN}{d\log m}
\]

**Life-time of stars**

\[
\tau(m) = \begin{cases} 
10^{[1.34 - \sqrt{1.79 - 0.22(7.76 - \log(m))}/0.11] - 9} & \text{for } m \leq 6.6 \, M_\odot \\
1.2m^{-1.85} + 0.003 & \text{otherwise.}
\end{cases}
\]
Sub-resolution SMBH-formation:

Black Hole model (sub-scale)
Springel & Di Matteo 2006

Seeding
Constant seeding
Seeding on m-sigma

Accretion on BH
$\alpha$-Bondi (Springel & Di Matteo 06)
$\beta$-Bondi (Booth & Schaye 09)
cold/hot (Bachmann et al. 14)

Feedback
Thermal (Springel & Di Matteo 06)
Bubbles (Sijacki et al. 07)
Mass dependent (Bachmann et al. 14)

Merging
Instant merging
Based on velocity

Growth of Black Hole

\[
\dot{M}_B = \alpha \times 4\pi R_B^2 \rho c_s \lesssim \frac{4\pi \alpha G^2 M_\bullet^2 \rho}{(c_s^2 + v^2)^{3/2}}
\]

\[
\dot{M}_\bullet = \min(\dot{M}_B, \dot{M}_{Edd})
\]

Feedback by Black Holes

\[
L_{bol} = 0.1 \times \dot{M}_\bullet c^2
\]

\[
\dot{E}_{feedback} = f \times L_{bol}
\]
What can we do ...

Combining different Simulations

Tiny volume / extreme resolution
Small volume / high resolution
Large volume / normal resolution
Huge volume / poor resolution

Almost 8 orders of magnitudes!

Galaxies

Clusters
What can we do ...

Cluster + SZ
Poster: FM.5.p13

AGN properties
Talk: FM 6.5.04, (M. Hirschmann)

Stellar properties
Poster: S317.p34

Tiny volume / extreme resolution
Small volume / high resolution
Large volume / normal resolution
Huge volume / poor resolution

Almost 8 orders of magnitudes!
Gas mass of halos

$M_{\text{gas}}$ vs. $M_{500c}$

- Lagana 2011
- Kravtsov 2014
- Gonzales 2013
- Lovisari 2014

- Box 1/mr
- Box 2/hr
- Box 4/uhr
Pressure profiles of clusters

Reichard et al. 2011

SPT-CLJ0014-4952

z = 0.752

McDonald et al. 2013
Cluster Cosmology and PLANCK ...

CMB powerspectrum allows to measure cosmology with extreme high precision!
Cluster Cosmology and PLANCK ...

SZ imprint of Cosmological Structures onto CMB

$D_\ell [\mu K^2]$
Cluster Cosmology and PLANCK ...

\[ D_e [\mu K^2] \]

\[ CMB \]

\[ CMB + BAO \]

\[ SZa + BAO \text{ (proj)} \]

\[ \Omega_m \]

\[ 0.28 \ 0.30 \ 0.32 \ 0.34 \ 0.36 \ 0.38 \ 0.40 \]

\[ 0.70 \ 0.75 \ 0.80 \ 0.85 \ 0.90 \]

SZ imprint of Cosmological Structures onto CMB

Counting Galaxy Clusters

Planck

SPT und ACT
Cluster Cosmology and PLANCK...

SZ imprint of Cosmological Structures onto CMB

Counting Galaxy Clusters

Planck

SPT und ACT

SZ Powerspectrum
Cluster Cosmology and PLANCK ... 

SZ imprint of Cosmological Structures onto CMB

Counting Galaxy Clusters

SZ Powerspectrum
Using Magneticum Pathfinder

Bocquet et al. 2015
Using Magneticum Pathfinder

Bocquet et al. 2015
Verifying with Magneticum

Magneticum Pathfinder

\[ N(>M^{\text{tot}})/\text{Mpc}^3 \]

\[ M^{\text{tot}} [M_{\odot}/h] \]

Graph showing the relationship between the number density of massive objects and their total mass. The graph includes multiple curves, each labeled with different parameters: xhr, uhr, hr, and mr.
Verifying with Magneticum

Magneticum Pathfinder

![Graph showing the distribution of mass in a cosmological simulation.](image)

- $N(>M^{\text{tot}})/\text{Mpc}^3$
- $M^{\text{tot}} [M_{\odot}/h]$

Lines with labels:
- $\text{xhr}$
- $\text{uhr}$
- $\text{hr}$
- $\text{mr}$

Legend:
- $\text{Box0}$
Magneticum Pathfinder SZ Maps

8.8 x 8.8 degree lightcone up to z=5

Predicted (y) from map: $1.2 \times 10^{-6}$

Reconstructed (y) from public PLANCK data: $5.4 \times 10^{-8} < (y) < 2.2 \times 10^{-6}$ (Khatri & Sumyaev 2015)
Magneticum Pathfinder SZ Maps

8.8 x 8.8 degree lightcone up to z=5

Localized Universe (z=0-0.02) + FullSky map (z=0.02-0.17) + deep Lightcones (z=0.17-5.2)

Predicted y map from Local Universe simulation
Local Universe simulations give important contribution!
Intra cluster light

cD Galaxy

member Galaxies

ICL

4.5 Mpc
Intra cluster light

Einasto profile

\[ \rho_{-2} \exp \left\{ -\frac{2}{\alpha_{Ein}} \left[ \left( \frac{r}{r_{-2}} \right)^{\alpha_{Ein}} - 1 \right] \right\} \]

Simulations: Dolag et al. 2010
Obs (A119): Bender et al 2015
From ICL to outer halos of galaxies

Remus et al., in prep

Well covers the differences between outer halo density profiles observed in Milky Way and Andromeda.
Dynamics of galaxies

Stellar Angular Momentum

\[
\log_{10} I_{\text{star}10} \, [\text{kpc km/s}] \quad \log_{10} M_{\text{star}10} \, [M_{\odot}] \quad \text{Stellar mass}
\]

pure disks
S0
pure bulges
simulation

Teklu et al. 2015
Dynamics of galaxies

Circularity

$\epsilon = \frac{jz}{j_{circ}}$

Teklu et al. 2015
Dynamics of galaxies

Halo Spin

Holds even for the DM only simulation!

Teklu et al. 2015
Simulations vs. observations

Spheroidals

Simulations

Observations

Disks

Simulations

Observations

Stellar mass

Stellar mass

Teklu et al. 2015

pure disks
SO
pure bulges
all, 10% $R_{vir}$, simulation
10 $R_{1/2}$, simulation
F&R 2013
Simulations vs. observations

Simulations

Disks

Spheroidals

GAMA Observations

Remus et al. 2015
Comparison to observations holds also for higher redshifts!

Simulations vs. observations

Remus et al., in prep

de Sande et al. (2013)
van Dokkum et al. (2009)
Onodera et al. (2012)
Toft et al. (2012).

Newman et al. 2010
Black Hole properties

Steinborn et al. 2015
AGN properties (optical + X-ray)

Bolometric LF

Soft X-ray LF

Hard X-ray LF

Hirschmann et al. 2014
AGN distribution

Same AGN luminosity cut then observers.

Steinborn, In prep.
Conclusions (general)

1) ICM: Clusters well reproduced
   pressure profiles, SZ powerspectrum, Cluster counts, no tension with CMB cosmology!

2) Galaxies: Dynamics well reproduced
   spin, morphologies, colors, mass-size relation

3) Black holes: Observations well reproduced
   mass functions, luminosity functions, correlation functions, AGN-host connections

4) Universality in outer halos
   from galaxies to clusters, not directly related to morphology, reflecting recent dynamical activity

More into details (future)

1) Large volumes for Planck/eROSITA
   for the first time, hydro-dynamical simulations cover large volumes and „enough“ physical processes

2) ICM/AGN constarain sub-grid models
   combination of observables from ICM, AGNs (and galaxies) start to constrain our sub-grid models