The MUSIC of Galaxy Clusters

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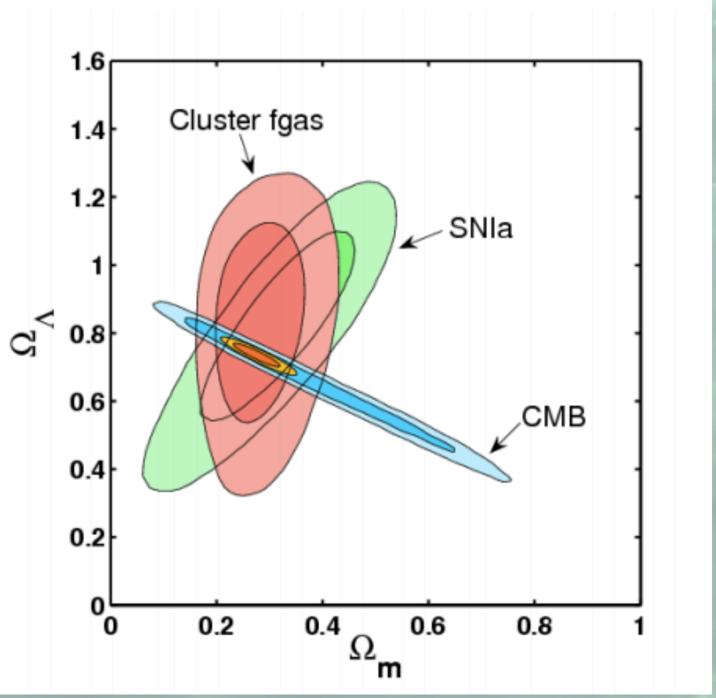
The MUSIC Players

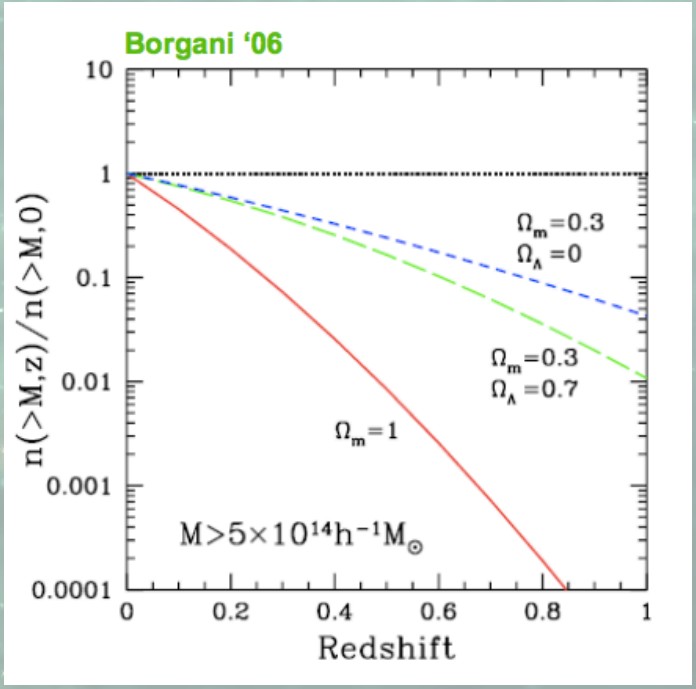
- Federico Sembolini (UAM+Sapienza , PhD thesis. 2014)
- **Jesús Vega (UAM+Obs Paris, PhD Thesis 2015)**
- Marco de Petris (Sapienza)
- Luca Lamagna (Sapienza)
- Anna Siliva Baldi (PhD Roma)
- Giammarco Cialone (Msc. Sapienza)
- Giacomo Durando (Msc. Turin)
- Stefan Gottlöber (AIP)
- Max Meneghetti (Bolonia)
- E. Rasia (Trieste)
- G. Murante (Trieste)
- A. Knebe (UAM)
- Weiguang Cui (UAM)
- G. Yepes (UAM)
  - http://music.ft.uam.es

MUSIC
MUltidark
SImulations
of galaxy
Clusters

COSMOLOGY WITH CLUSTERS OF GALAXIES

- Massive Clusters of galaxies are one of the most powerful cosmological probes. Their abundace with redshift put strong constrains on the total mass and dark energy content of in the Universe. Need large cluster surveys based on X-ray, radio (SZ), or optical to compare with theoretical mass functions from different models n(M,z).
- First step is to *weight* the observed clusters by using tight, well-determined scaling relation between survey observable (e.g. Lx, SZ, Luminosity) and mass, with minimal intrinsic scatter.



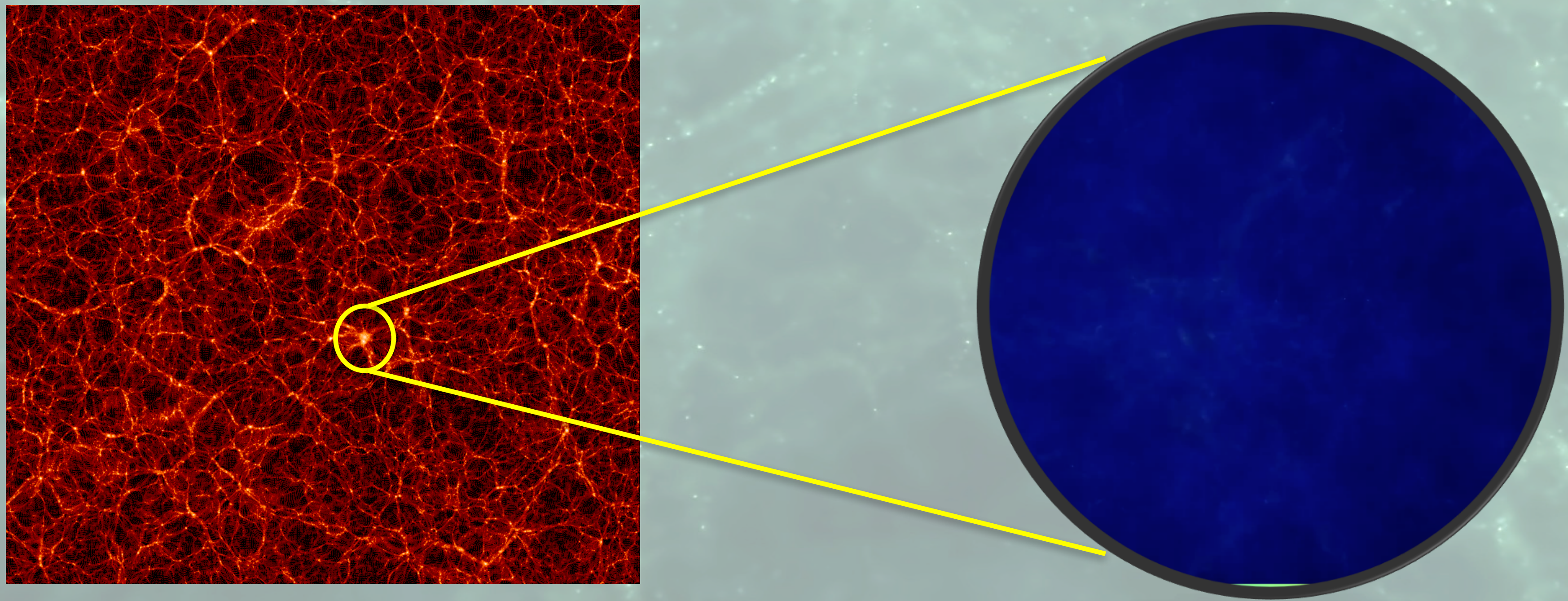


Calibration of scaling relations can only be done by simulating mock galaxy cluster catalogues from large volume simulations.

But clusters physics is complex to simulate..

SIMULATING A CLUSTER CATALOG

- Massive clusters are very rare objects. Need to simulate large boxes (> 1 Gpc). High-resolution hydro-sims + baryonic processes are still very expensive to run in large boxes.
- **Alternative:** objects are selected in big boxes and simulated individually using ZOOMING technique.
- Only baryons are added to the resimulated area.



THE MUSIC PROJECT

Compile an extended sample of high-resolution gasdynamica resimulations of clusters:

Two selection criteria:

- Based on the dynamical state:
  - Bullets vs. Relaxed cluster (from MN simulation, Forero-Romero- 2012)
- A mass selected volume limited sample:
  - Selection of all clusters above a given mass cutoff.
  - Extracted from large N-body volumes: MULTIDARK simulation.
    - an ART dark matter only simulation performed at NAS Ames
    - about 8.6 billion particles (2048^3) in a $(1\ \mathrm{Gpc/h})^3$ volume
    - WMAP7 cosmological parameters

Marenostrum MUltidark SImulations of galaxy Clusters

THE MUSIC DATASET

(Sembolini et al., MNRAS, 2013, 429,323)

Largest dataset of hydrodynamical simulations of galaxy clusters

MARENOSTRUM (MUSIC-1) resimulated clusters
•**164** (82 relaxed clusters – 82 'bullet-like')
Only few objects with $M > 10^{15}\ h^{-1}M_{SUN}$

cooling + SFR resimulations
(Multiphase feedback model: Yepes+ 1997; Springel & Hernquist, 2003)

MULTIDARK (MUSIC-2) resimulated clusters
•**283 lagrangian regions** of 6/h Mpc radius@z=0
•> 500 clusters $M > 10^{14}\ h^{-1}M_{SUN}$
•> 2000 objects $M > 10^{13}\ h^{-1}M_{SUN}$

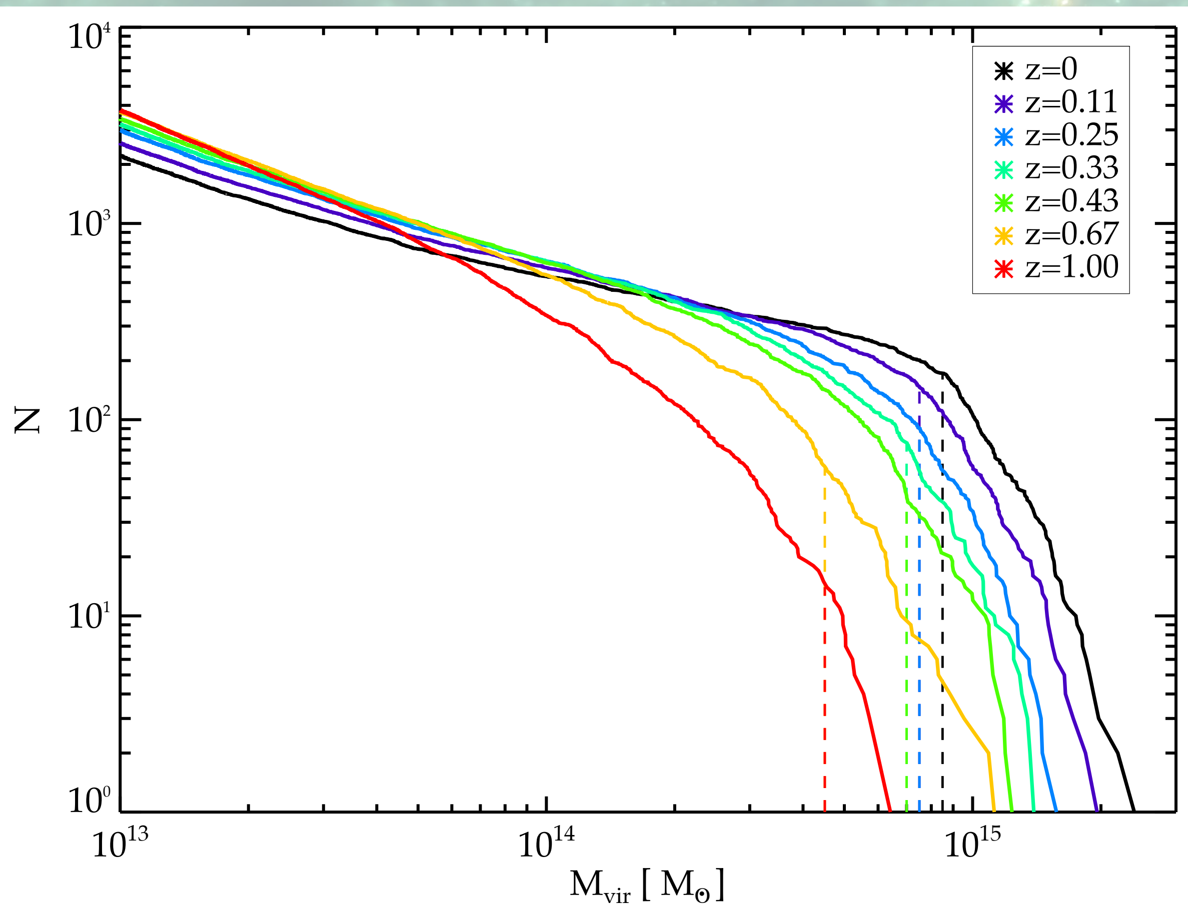
cooling + star formation (CSF) + AGN (Trieste model) resimulations

Many objects with $M > 10^{15} h^{-1}\ M_{SUN}$
$m_{DM}=9.01 \times 10^{8} h^{-1} M_{SUN}$ - $m_{SPH}=1.9\times10^{8} h^{-1} M_{SUN}$
Each cluster described by several millions of particles

700 resimulated clusters with $M > 10^{14}\ h^{-1}M_{SUN}$

Large statistics to study baryonic properties and calibrate scaling relations

MUSIC-2 is a complete mass selected volume limited sample: all objects beyond a (redshift varying) mass limit formed in the $1h^{-1}$Gpc simulation have been resimulated.



z	M_{compl} $[h^{-1}M_\odot]$	N (M_v >M_{compl})
0.00	8.5×10^{14}	172
0.11	7.5×10^{14}	147
0.25	7.5×10^{14}	90
0.33	7×10^{14}	76
0.43	7×10^{14}	41
0.67	4.5×10^{14}	57
1.00	4.5×10^{14}	14

All MUSIC data (X-rays, SZ)will be publicly available through the website **http://music.ft.uam.es**

(initial conditions already available online!)

EXTENSION OF THE MUSIC SAMPLE TOWARDS GROUP-LIKE OBJECTS

- IN ORDER TO ENLARGE THE MUSIC DATABASE TO INCLUDE LOWER MASS CLUSTERS, WE HAVE EXTRACTED A NEW SAMPLE OF OBJECTS FROM THE MULTIDARK SIMULATION:

- WE LOWER THE MINIMUM MASS THRESOLD TO BE COMPLETED IN MASS TO
  - 10^{15} -> 5 X 10^{14} /h Msun
  - A TOTAL OF **154 NEW ZOOMED REGION** CENTRED ON CLUSTERS IN THIS RANGE

- THE NUMBER OF OBJECTS FROM 5E14 TO 5E13 IS TOO LARGE (> 48 K OBJECTS)

- THEREFORE, WE HAVE SELECTED A SUBSAMPLE OF THEM THAT ARE IN ISOLATION

  - WITH NO OTHER OBJECT OF SIMILAR MASS OR HIGHER WITHIN 6 MPC RADIUS AROUND EACH OBJECT.

- THIS SUBSAMPLE WILL BE COMPARED WITH SIMILAR OBJECTS THAT ARE PRESENT IN THE MUSIC DATABASE AS GROUPS CLOSER TO MASSIVE CLUSTERS.

- TOTAL OF 391 ADDITION REGIONS CENTRED ON SELECTED OBJECTS WITH
  - $5\times10^{13} < M < 5\times10^{14}$ Msun.
- THUS THE NEW SAMPLE CONSISTS OF 545 NEW RESIMULATED REGIONS OF 6 MPC.

SCIENCE WITH MUSIC CLUSTERS

We can study scaling relations dependence from cluster:

- **MASS**

  > 100 massive clusters ($M > 10^{15}\ M_{SUN}$) in MULTIDARK (MUSIC-2) simulations

  10^{14}-$10^{15}\ M_{SUN}$ range covered by MARENOSTRUM (MUSIC-1) sim.

- **PHYSICS**

  NR and C.+SFR simulations

- **OVERDENSITY**

  analysis of scaling rel. at Δ = 200,500,1000,1500,2000,2500

- **REDSHIFT**

  analysis of scaling rel. at z = 0, 0.11, 0.25, 0.33, 0.43

- **MORPHOLOGY**

  effect of disturbed morphologies on scaling rel. (MUSIC-2)

MNRAS 2013, 429, 323

The MUSIC of Galaxy Clusters I: Baryon properties and Scaling Relations of the thermal Sunyaev-Zel'dovich Effect

Federico Sembolini[1,2*], Gustavo Yepes[1], Marco De Petris[2], Stefan Gottlöber[3], Luca Lamagna[2], Barbara Comis [2]
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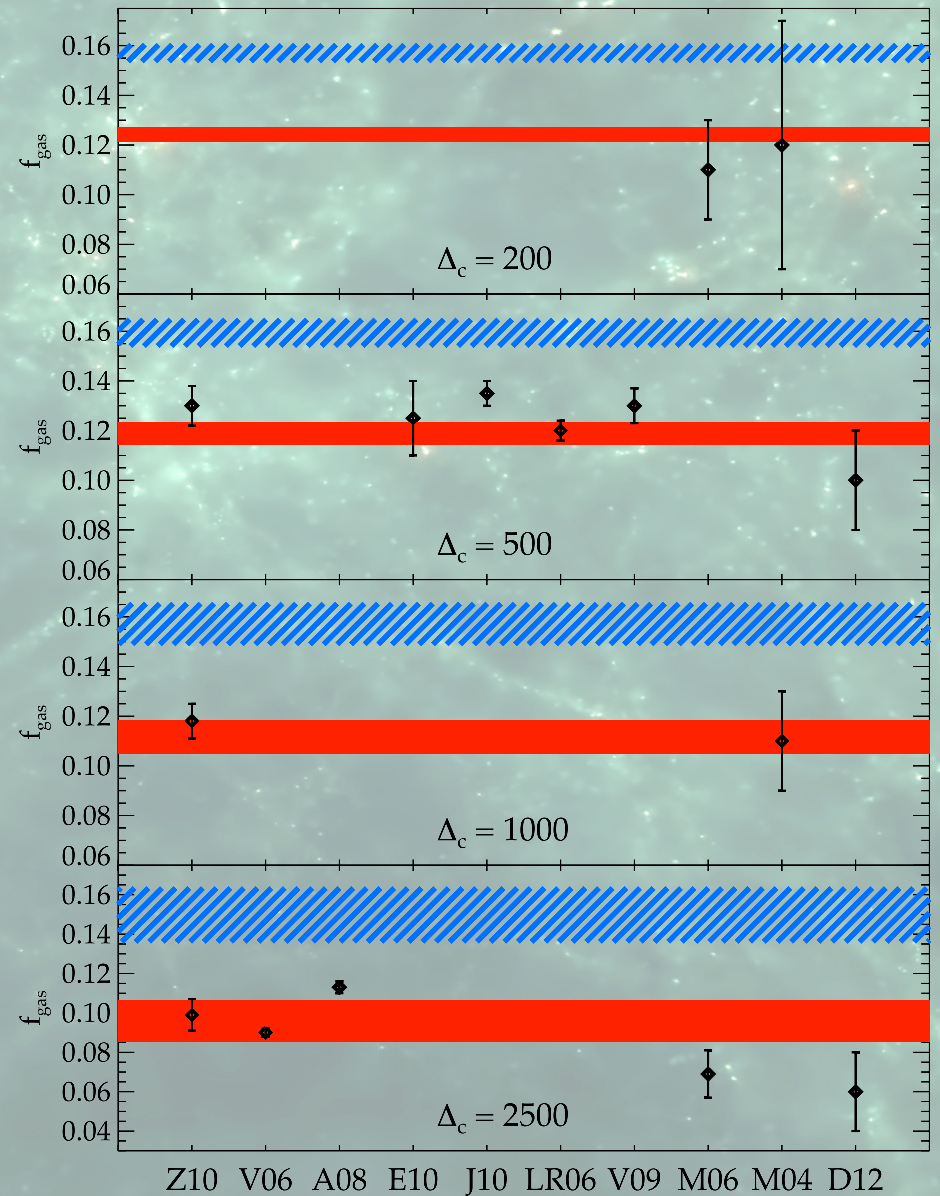
- **Baryon properties**
- **Local Thermal SZ scaling relations**
- **Redshift evolution of the SZ scaling laws**

GAS FRACTION : COMPARISON WITH OBSERVATIONS

CSFR clusters:

- Δ_c=500 $\mathbf{f_{gas}}$ **= (0.118±0.005)**
- f_{gas} **compatible with observations** at overdensities < 2500 (LaRoque 2006 (LR06); Maughan 2006 M(06); Vikhlinin 2006 (V06); Ettori 2010 (E10); Zhang 2010 (Z10))
- f_{star} higher than observational data (0.05 vs 0.01, effect of overcooling?)

NR **CSF**



Sembolini et al. 2013

The Y – M scaling relation

The Y integrated Comptonization parameter is proportional to total thermal energy of electrons in ICM that can be derived from thermal SZ:

$$Y_S = \frac{\sigma_{TH}}{m_e c^2} \frac{\mu}{\mu_e} \left(\Delta G^2 H_0^2\right)^{1/3} E(z)^{2/3} f_{gas} M_{TOT}^{5/3}$$

A = 1.66

in the self similar scenario

B ≈ -28

Where A and B minimize the χ^2 function:

$$\chi^2 = \sum_i \frac{(Log(Y_i) - B - A\log(X_i))^2}{\sigma^2_{\log(Yi)} + (A\sigma_{\log Xi})^2}$$

Y extracted from simulated maps

(ray-tracing)

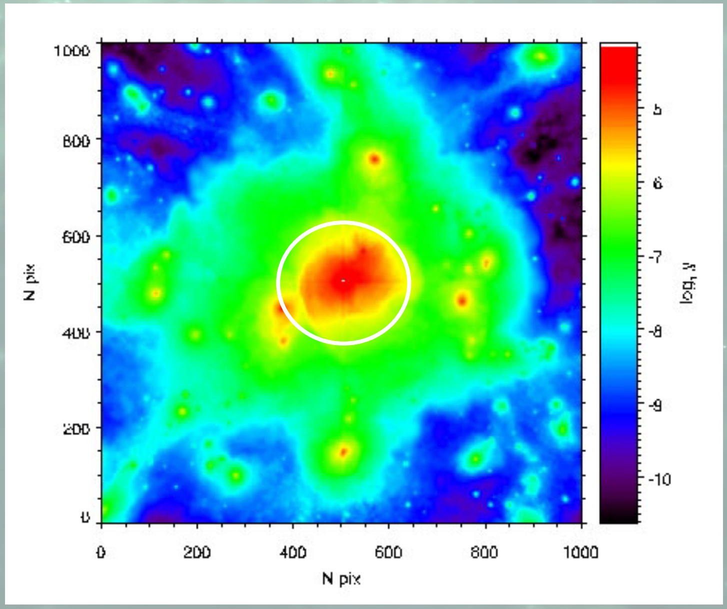
$$y = \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T dl \longrightarrow y_{pix} = \sum_{\alpha} \sum_{i} \frac{k_B \sigma_T}{m_e c^2} T_{e,i} n_{e,i} W(r_i, h_i) d\ell_i$$

resolution

$$Y \equiv \int y \, d\Omega \longrightarrow Y_\Delta D_A^2 = \sum_{i, r<r\Delta} y_i \cdot \pi dl_{pix}^2$$

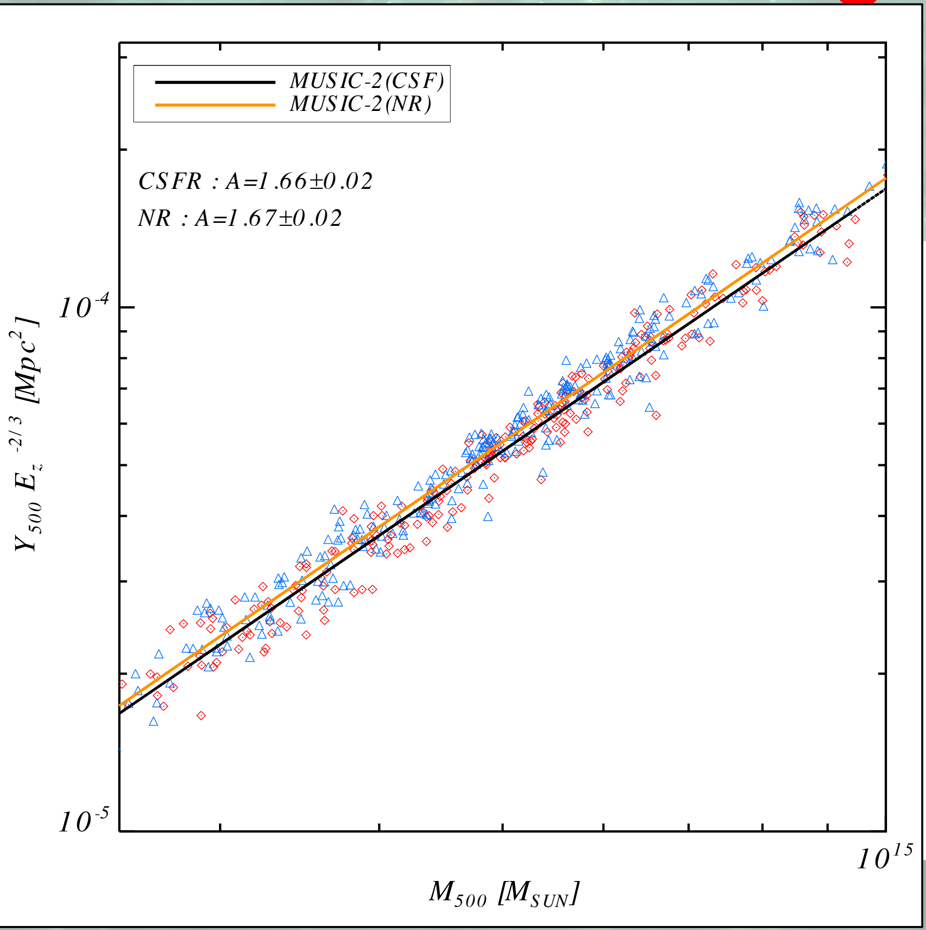
$d\Omega$

$$res \equiv \frac{r_{200}}{20}$$

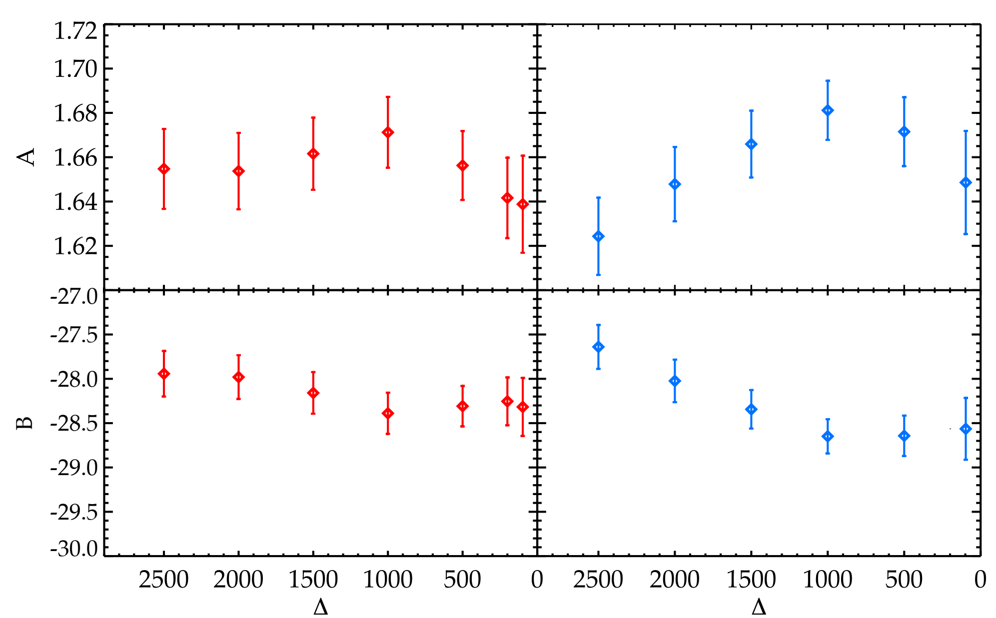


We build the y-map of the cluster and extract the integrated Y
To extract the Y_{SPH} we consider only particles inside r_Δ (spherical integration domain)

Y – M scaling relation : MUSIC



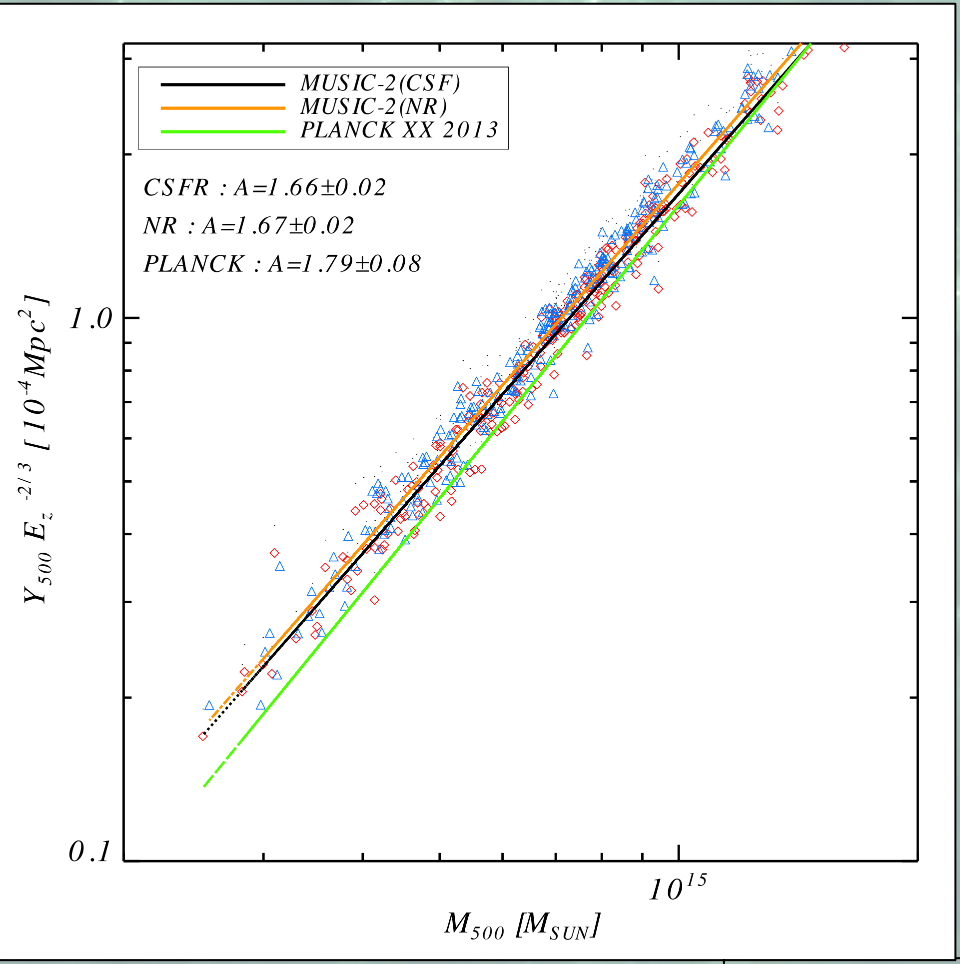
The analysis of MUSIC massive clusters Y-M scaling relation **confirms** the self-similar scenario



As in observational scaling relations, we assume f_{gas} constant

$$Y_{500} = 10^{-28.3\pm0.2}\left(\frac{M_{500}}{h^{-1}\mathrm{M}_\odot}\right)^{1.66\pm0.02} E(z)^{2/3}[h^{-2}Mpc^2]$$

Y – M : MUSIC vs Planck



Planck Results 2013 XX

71 clusters
Cluster masses from X-rays observations (HSE hypothesis, 20% error – mainly due to uncertainty on temperature estimate)

Agreement between MUSIC CSF clusters and Planck scaling relation

$$E^{-2/3}(z)\left|\frac{D_A^2 Y_{500}}{10^{-4}\,Mpc^2}\right| = 10^{-0.19\pm0.02}\left|\frac{(1-b)M_{500}}{6\times10^{14}\,M_{SUN}}\right|^{1.79\pm0.08}$$

HSE bias estimation with MUSIC

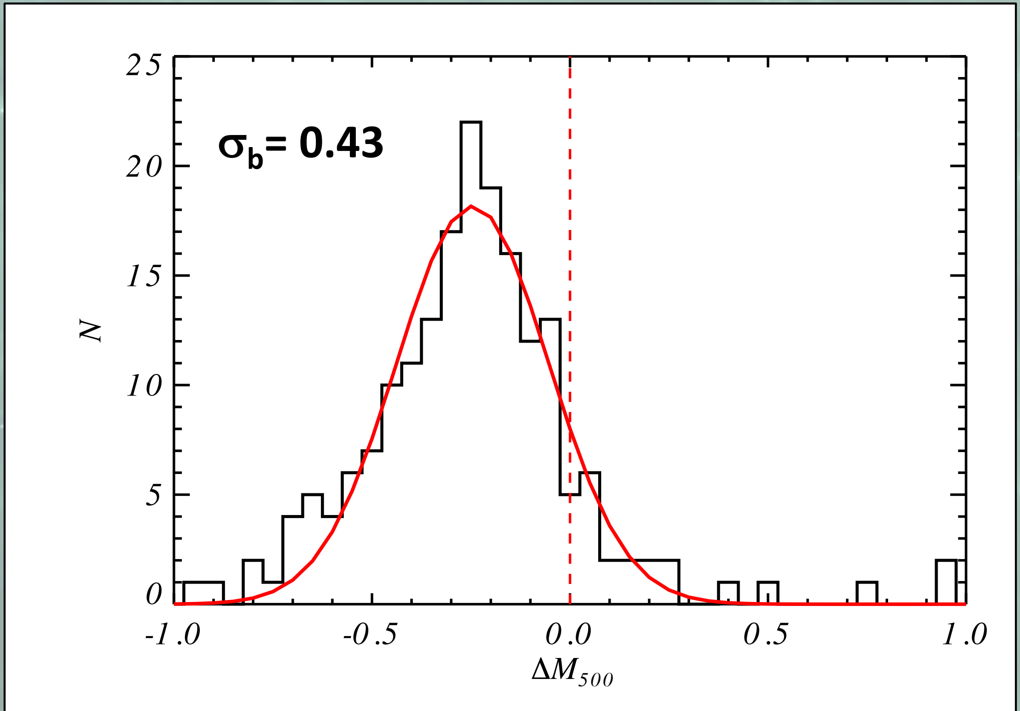
$$\boxed{M_{HSE,\Delta}(<R_\Delta) = -\frac{kTr}{G\mu m_p}\left(\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r}\right)}$$

$$M_{500}^{obs} = (1-b)M_{500}^{true}$$

X-rays observations : bias estimated to be $\mathbf{b \sim 0.2}$

$$\boxed{T_{mw} = \frac{\sum_i T_i m_i}{\sum_i m_i}}$$

MUSIC : temperature profiles using mass-weighted temperature



$\mathbf{b = 0.25}$ for **MUSIC CSF** clusters, in agreement with other simulations (Nagai+ 2007, Lau+ 2009, Kay+ 2012, Rasia+ 2012)

The redshift evolution of the Y-M scaling relation

1. Fitting the evolution of A and B parameters with redshift in the form:

$$\log A(z) = \log A_0 + \alpha_1 \log(1+z)$$

$$\log B(z) = \log B_0 + \alpha_2 \log(1+z)$$

2 .Generating a sample of clusters at different redshifts, looking for a possible dependence from redshift in the form

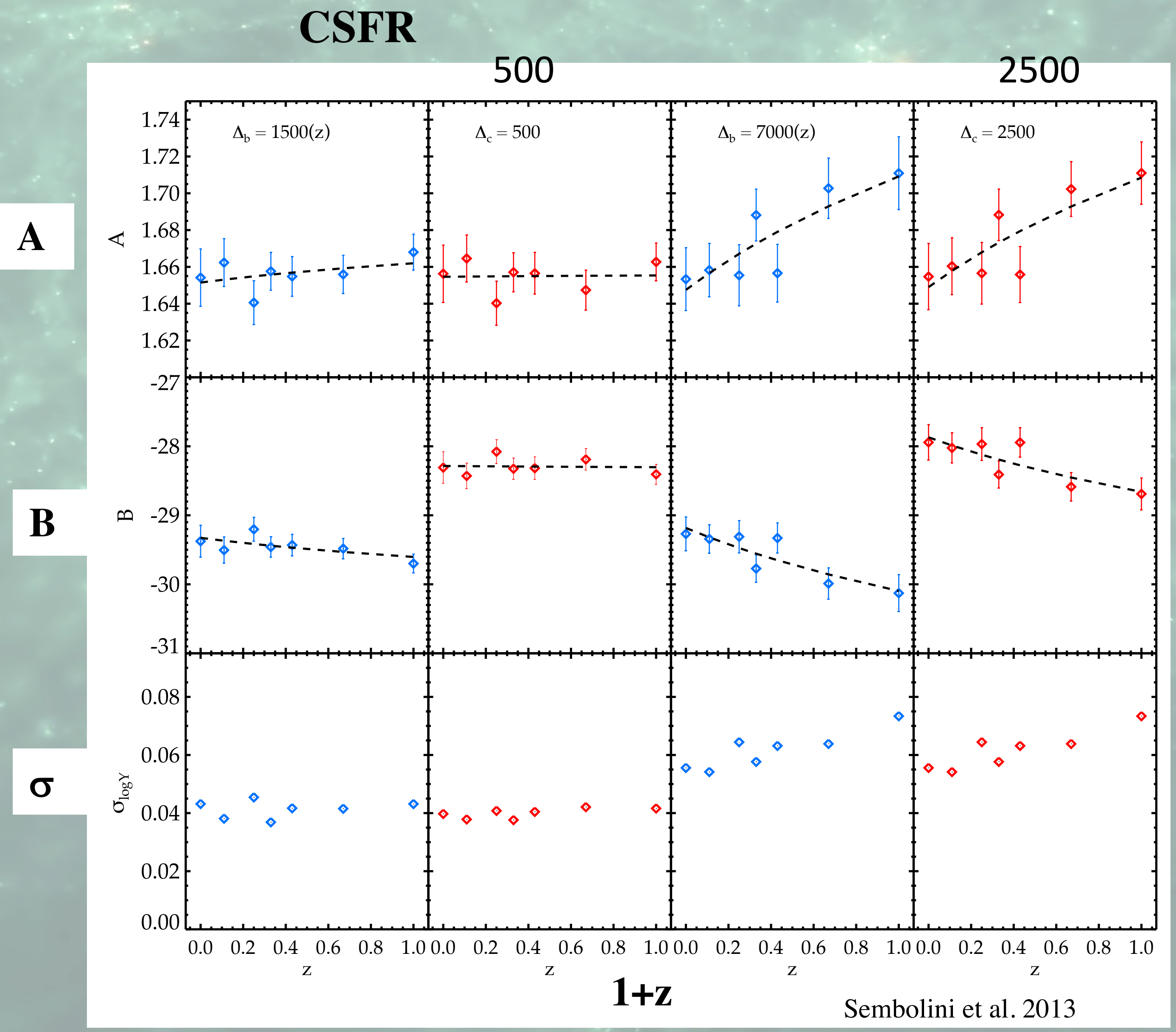
$$Y f_{gas} E^{2/3} \propto M^{A} (1+z)^{\beta}$$

Each cluster appears in the sample only at one redshift and that the subset is populated according to the cluster abundances observed in MUSIC as a function of z. Use MCMC to obtain best fit A and β

z	N(M_v >$5\times10^{14}h^{-1}M_\odot$)
0.00	271
0.11	237
0.25	187
0.33	147
0.43	117
0.67	44
1.00	8

A

Redshift evolution of the Y-M scaling relation



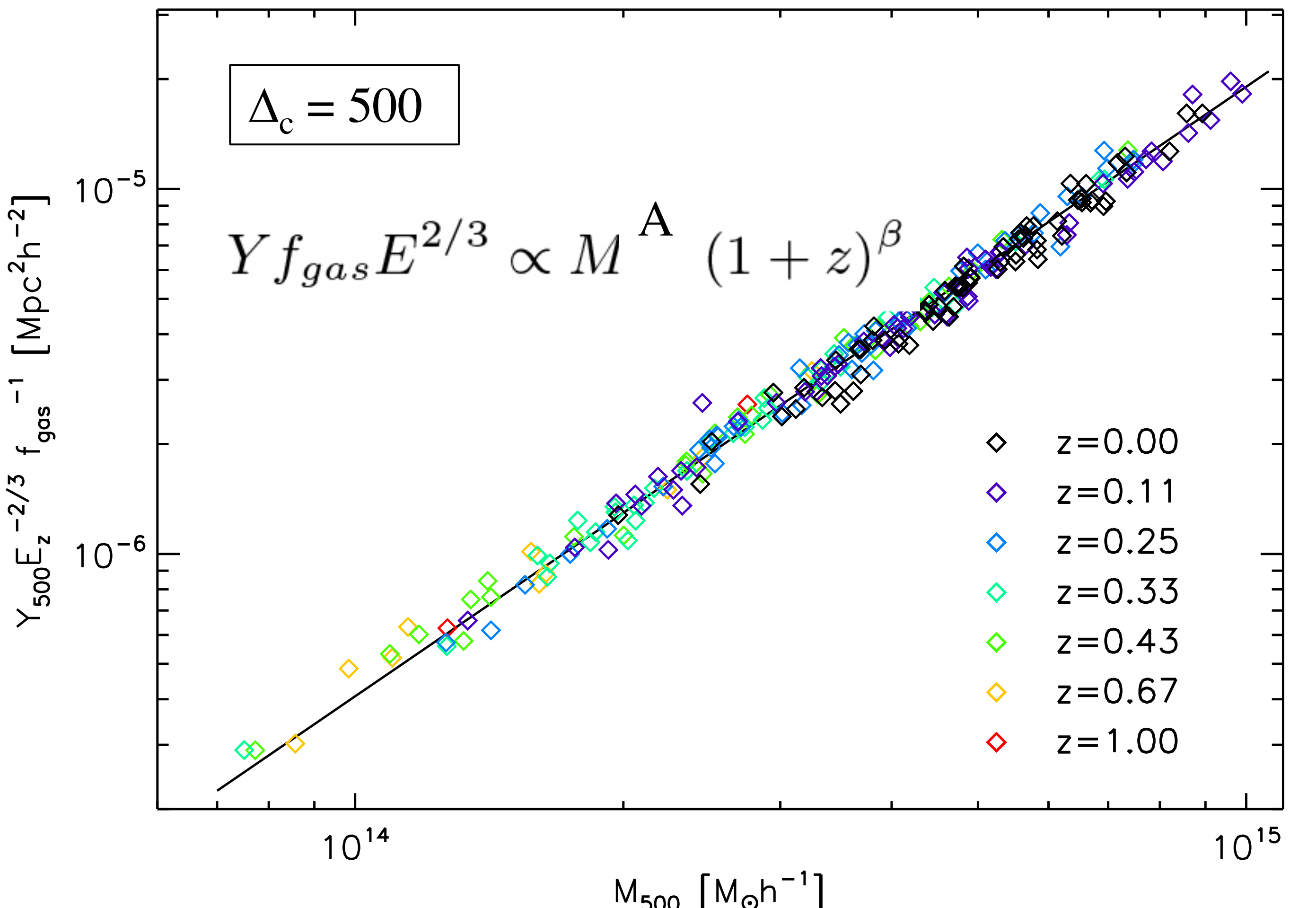
No redshift evolution at low overdensities

Only at high overdensities and at **z > 0.5** a small deviation from self-similarity is present

Redshift evolution of the Y-M scaling relation (2)

[h]

	Δ_c =500	Δ_c =2500	$\Delta_b(z)$ = 1500(z)	$\Delta_b(z)$ = 7000(z)
A	1.672± 0.028	1.627 ± 0.022	1.652± 0.028	1.656 ± 0.023
B	-29.77± 0.42	-28.85± 0.32	-30.65±0.42	-30.61± 0.33
β	0.17 ± 0.10	0.31± 0.14	-0.12± 0.11	0.00± 0.11



The fit results are still fairly consistent with self similarity and **no additional redshift evolution** in the Y-M scaling relation

The MUSIC Work in progress

- Proto-cluster scaling laws (Sembolini+ 2013)
- X-ray vs SZ scaling relations (Biffi+ 2014)

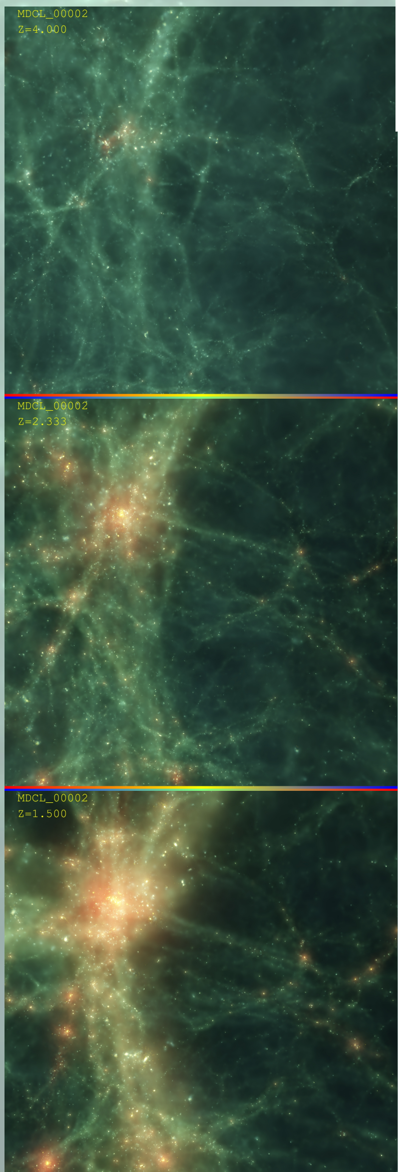
- Kinetic SZ scaling relations (de Petris + 2014)
- Optical scaling relations (Richness vs Mass)
- Strong Lensing statistics (Vega+ 2014)
- Resimulations of all MUSIC clusters with AGN feedback modelling
- (in coll. Murante, Borgani et al). FINISHED

Protoclusters of galaxies in MUSIC simulations

The MUSIC of Galaxy Clusters – III. Properties, evolution and Y–M scaling relation of protoclusters of galaxies

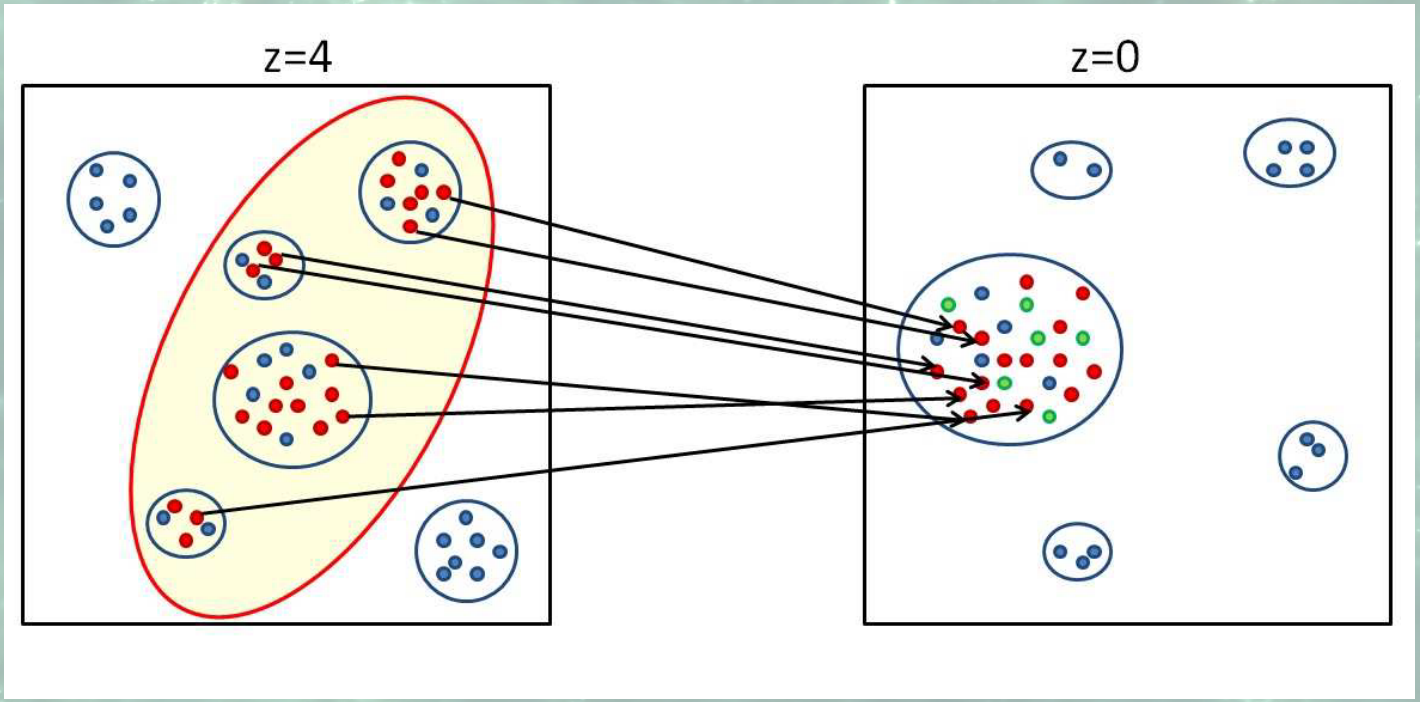
Federico Sembolini ✉; Marco De Petris; Gustavo Yepes; Emma Foschi; Luca Lamagna; Stefan Gottlöber

Mon Not R Astron Soc (2014) 440 (4): 3520-3531. **DOI:** https://doi.org/10.1093/mnras/stu554



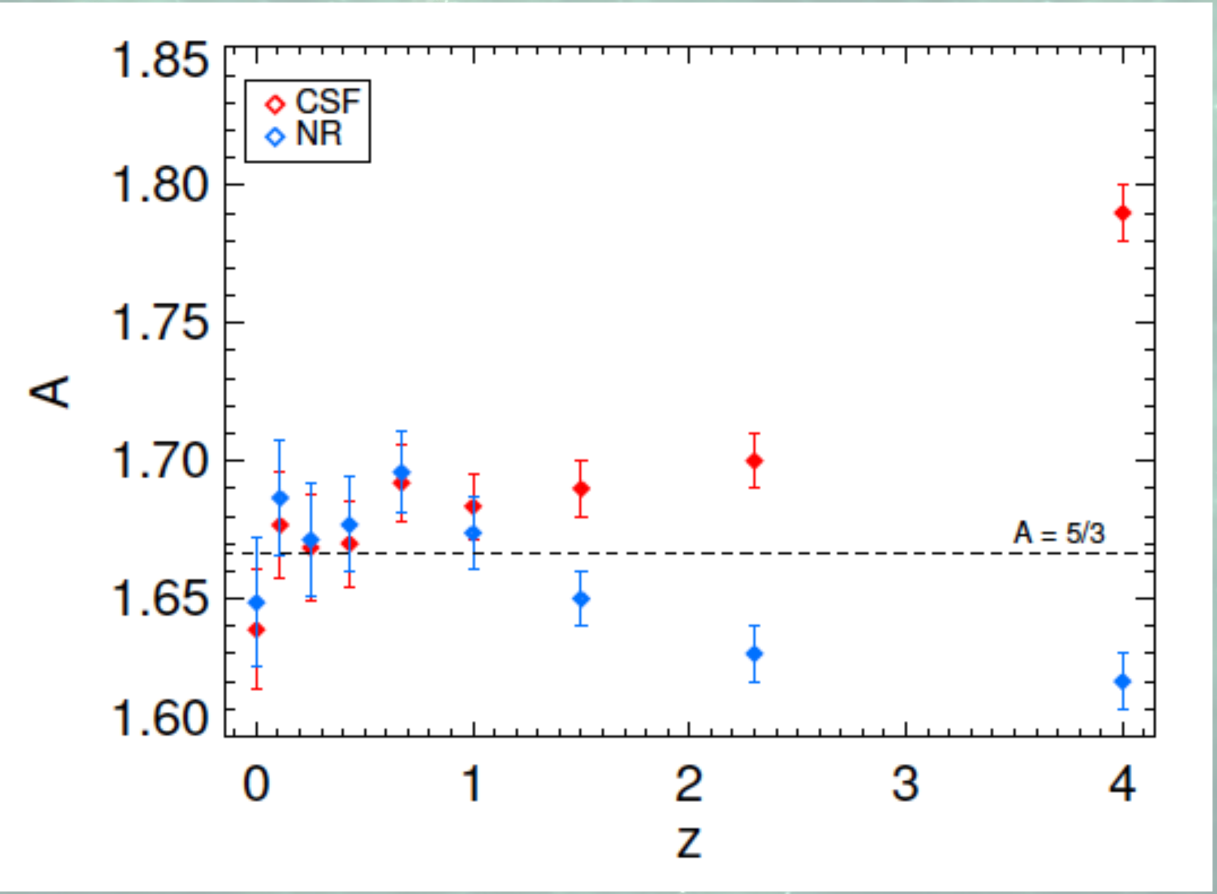
- Only radiative clusters analysed
- Analysis of protoclusters evolving in the most massive clusters of galaxies - $M_v > 5\times10^{14}\ h^{-1}M_{SUN}$ at z=0 (282 clusters):
  - 282 main progenitors (most massive protocluster for each object)
  - 5 most massive protoclusters for each clust (1410 protoclusters)
- 3 different redshifts analysed:
  - z = 1.5, 2.3, 4.0
- Properties of protoclusters studied at virial radius
- At z = 4 ~ 70% of most massive objects correspond to the most massive objects at z = 0 (>80% at z = 1.5)

Defining a protocluster in a numerical simulation



- Using merger-tree, we trace all the objects at high redshift(s) which will end up into a cluster at $z = 0$
- We define as protocluster the most massive high-redshift object among all the cluster's progenitors

Evolution of the Y-M relation in PROTOCLUSTERS



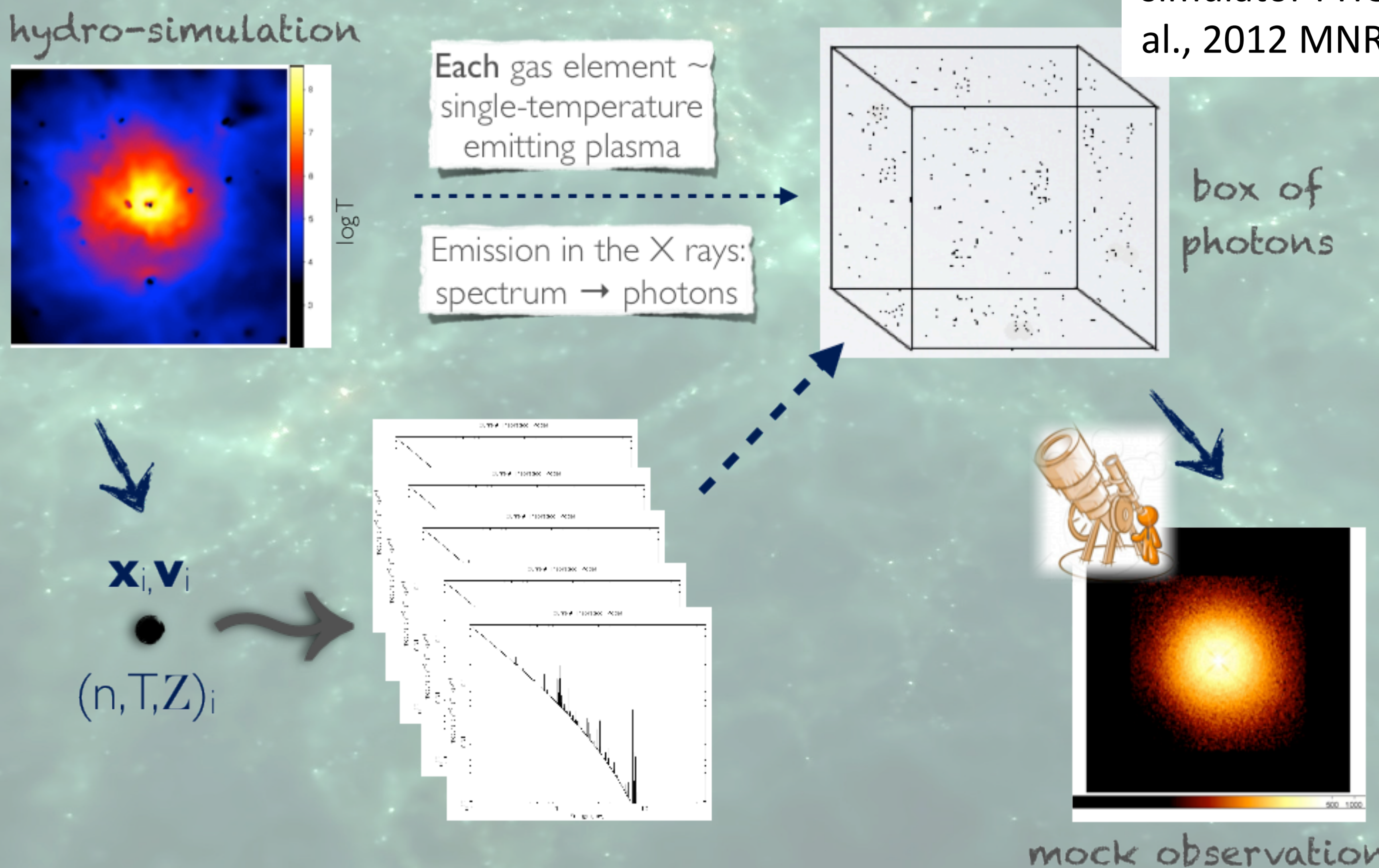
- Y-M scaling relation starts to deviate from self-similarity at z > 0.5 (Sembolini et al. 2013)
- Deviation from self-similarity becomes stronger at **z >2**
- Effect of resolution of physical effect?

MNRAS 439, 588, 2014

The MUSIC of galaxy clusters – II. X-ray global properties and scaling relations

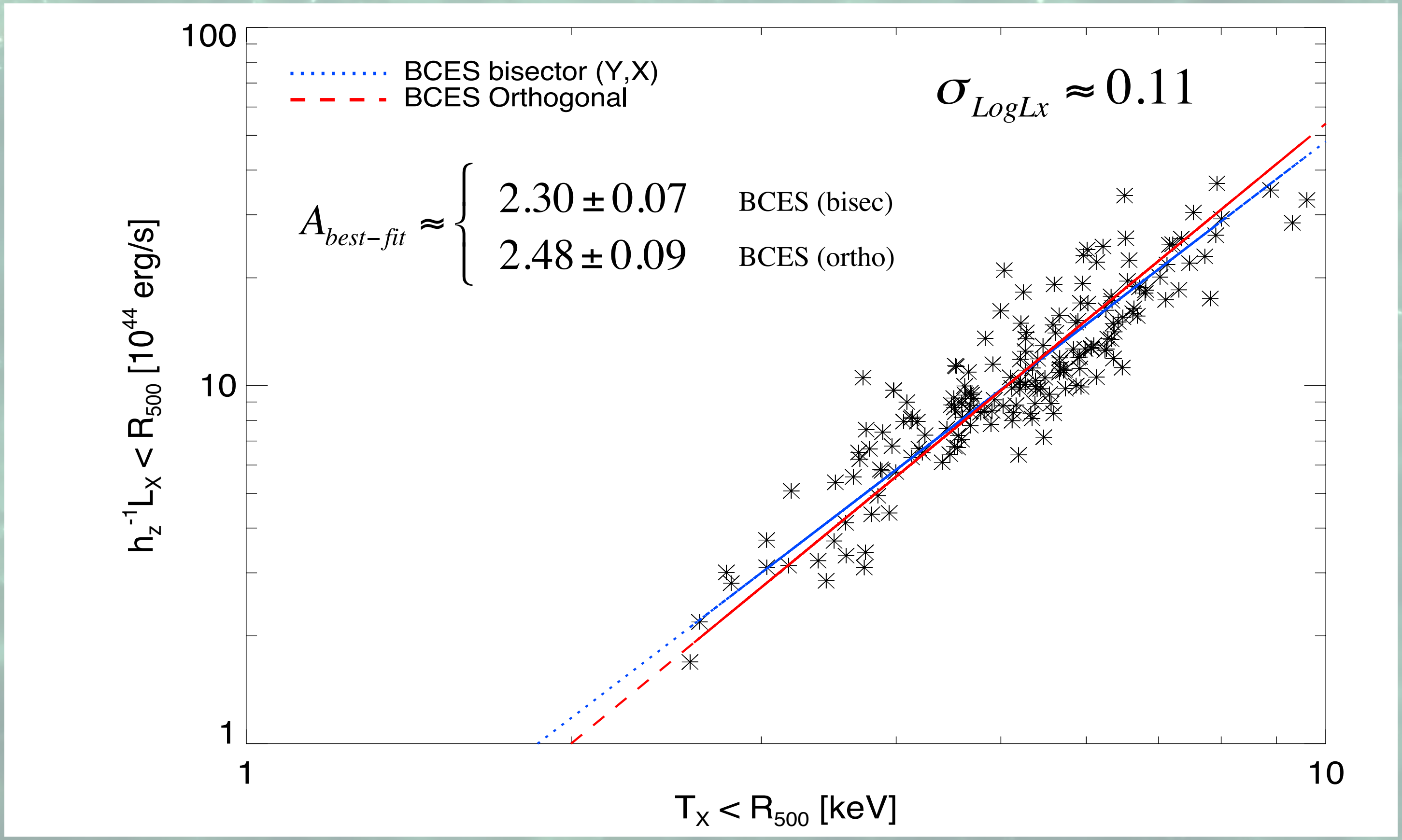
V. Biffi,[1,2★] F. Sembolini,[1,3] M. De Petris,[3] R. Valdarnini,[2,4] G. Yepes[1] and S. Gottlöber[5]

Synthetic X-ray observations of MUSIC galaxy clusters in the have been performed by means of the X-ray photon simulator PHOX (Biffi et al., 2012 MNRAS)



Synthetic Chandra spectra → X-ray luminosity Lx, temperature Tx inside R_{500}

L_X-T_X scaling relation for MUSIC clusters

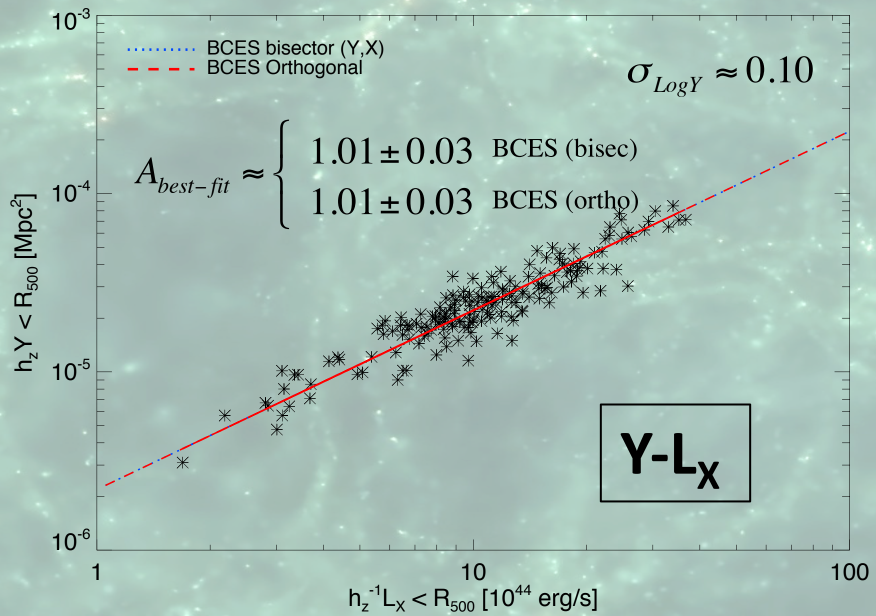


$$\boxed{L_X \propto T_X^A \rightarrow A \approx 2}$$

- Steeper than self-similar predictions
- Still shallower than (some) observations

Biffi, etal 2014

X-SZ scaling relation for MUSIC clusters



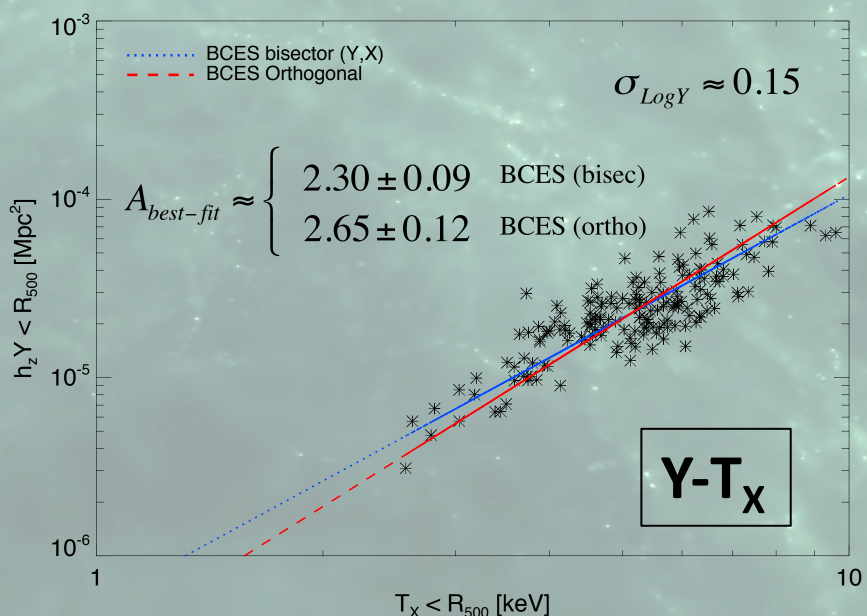
Mixed SZ/X-ray scaling relations:

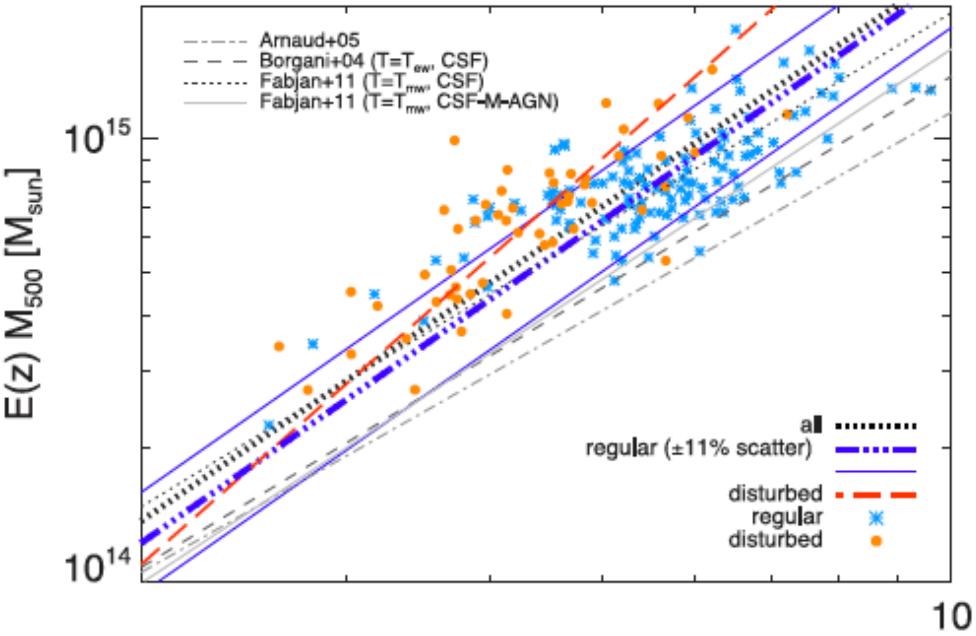
- ***Y-L$_X$*** $A_{self-similar} \approx 1.25$
- ***Y-T$_X$*** $A_{self-similar} \approx 2.5$

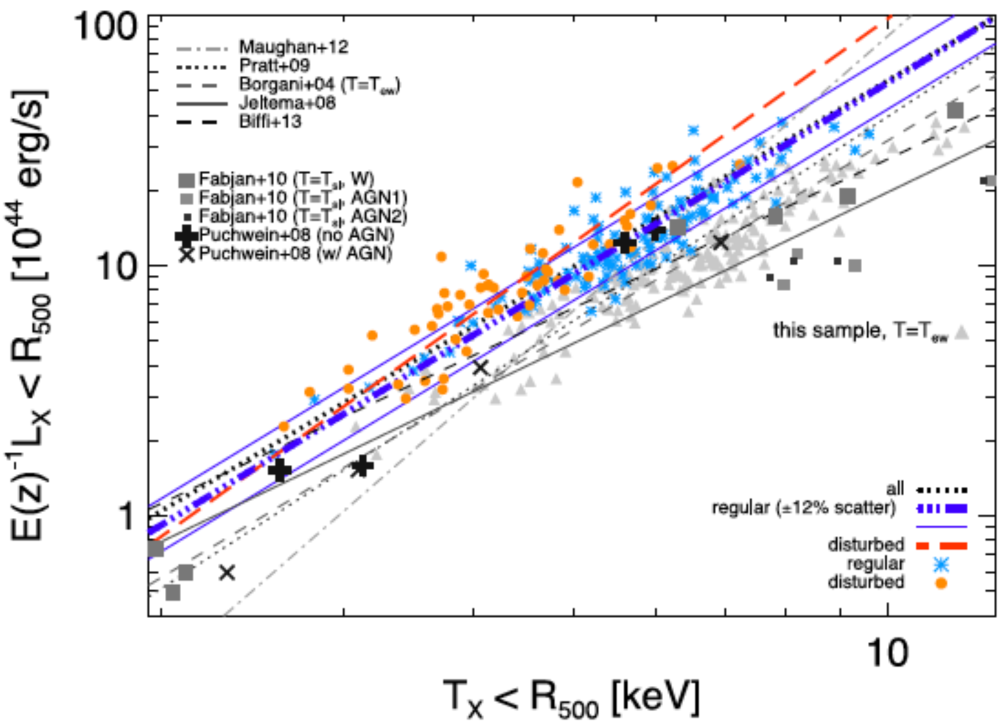
Best-fit relations mirror self-similarity, but:

- Y-L_X is shallower
- Y-T_X closer to self-similar pred.

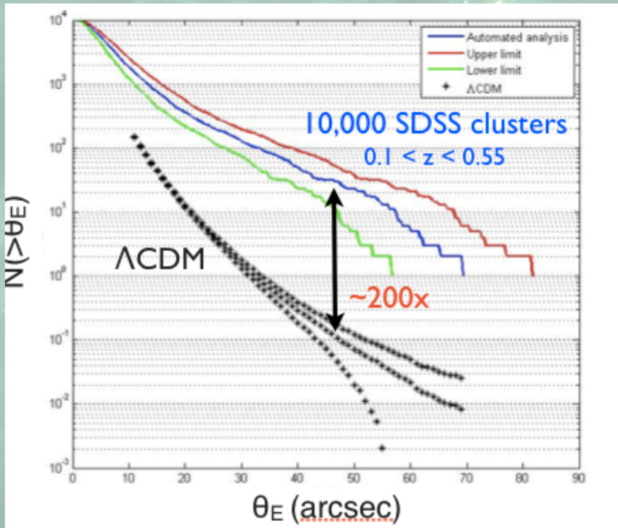
Scatter is present, most likely introduced by X-ray measures (consistent w/ literature, e.g. Morandi et al.07)

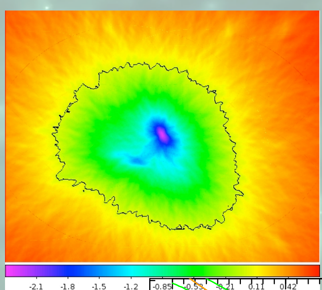


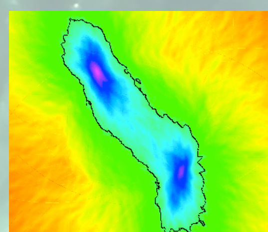


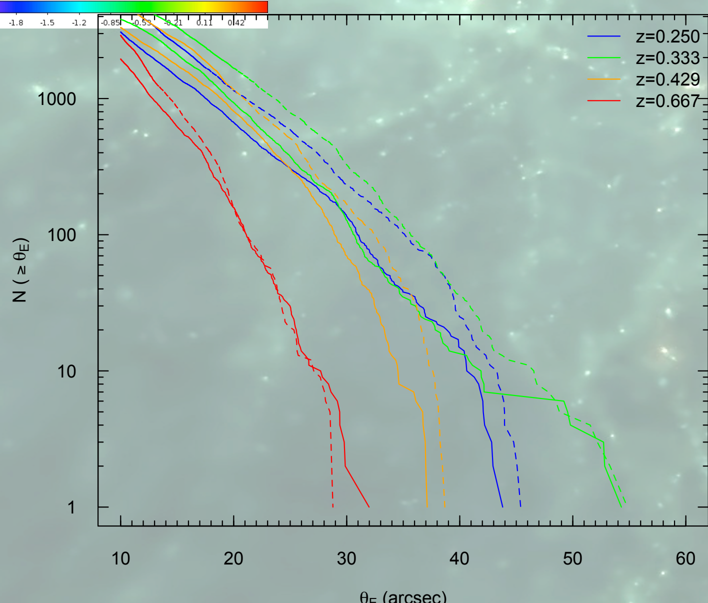


Comparison of MUSIC X-ray scaling relations with observations and other simulation works.









STRONG LENSING STATISTICS

(J. Vega & D.Valls-Gabaud)

Tension with ΛCMD?

The observed distribution of Einstein radii is much larger than the one predicted by analytical models within the ΛCDM model.

MUSIC dataset: triaxiality, sub-structures, unrelaxed/merging clusters

- taking **100 random orientations** of each MUSIC cluster to explore explicitly the effects of triaxiality, sub-structures and relaxation
- Using detailed **ray-tracing** (*Skylens*, Meneghetti et al. 2008) in each projection to compute 2D convergence maps and critical lines

Projected M_{2D} and c_{2D} bear no relation with the actual 3D values

- Critical lines: sizes and ellipticities.
- Correct NFW model from these effects
- Largest θ_E = 55'', unrelaxed cluster @ z=0.333 (MACS0717)
- Full cosmological distribution of θ_E combining halo abundance + Monte-Carlo samples.

Make predictions on the distribution of θ_E for SDSS and all-sky surveys, comparison with CLASH clusters,...

The Astrophysical Journal, 797:34 (21pp), 2014 December 10
doi:10.1088/0004-637X/797/1/34

THE MUSIC OF CLASH: PREDICTIONS ON THE CONCENTRATION–MASS RELATION

M. Meneghetti[1,2,3], E. Rasia[4], J. Vega[5,6], J. Merten[2,7], M. Postman[8], G. Yepes[5], F. Sembolini[5], M. Donahue[9], S. Ettori[2,3], K. Umetsu[10], I. Balestra[11,12], M. Bartelmann[13], N. Benítez[14], A. Biviano[12], R. Bouwens[15], L. Bradley[16], T. Broadhurst[17,18], D. Coe[8], N. Czakon[10], M. De Petris[19], H. Ford[16], C. Giocoli[20], S. Gottlöber[21], C. Grillo[22], L. Infante[23], S. Jouvel[24,25], D. Kelson[26], A. Koekemoer[7], O. Lahav[25], D. Lemze[16], E. Medezinski[16], P. Melchior[27], A. Mercurio[11], A. Molino[14], L. Moscardini[20], A. Monna[28,29], J. Moustakas[30], L. A. Moustakas[2], M. Nonino[12], J. Rhodes[1,7], P. Rosati[31], J. Sayers[7], S. Seitz[28], W. Zheng[8], and A. Zitrin[7,33]

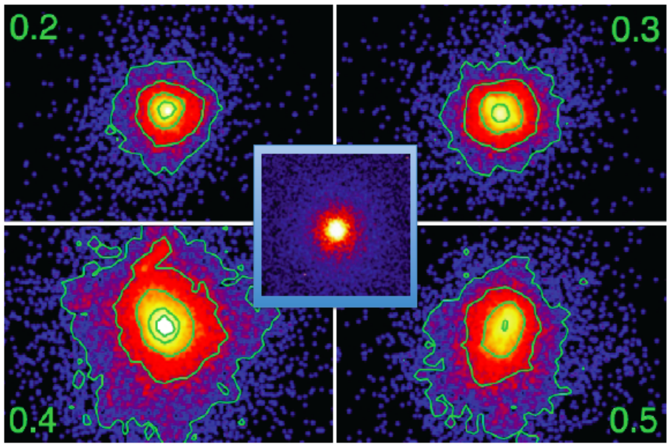
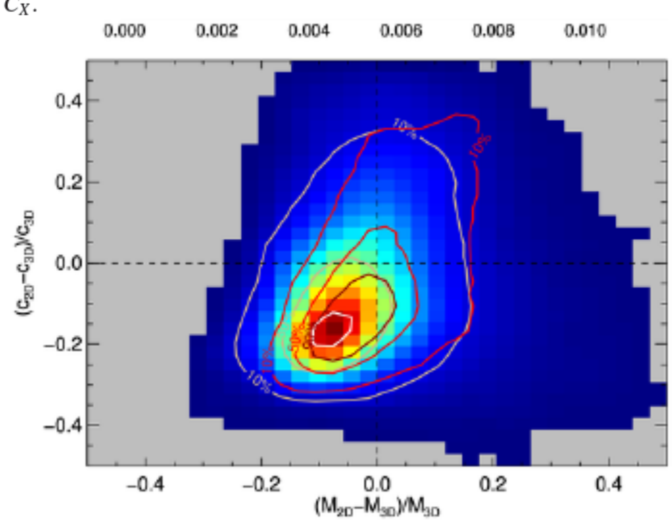
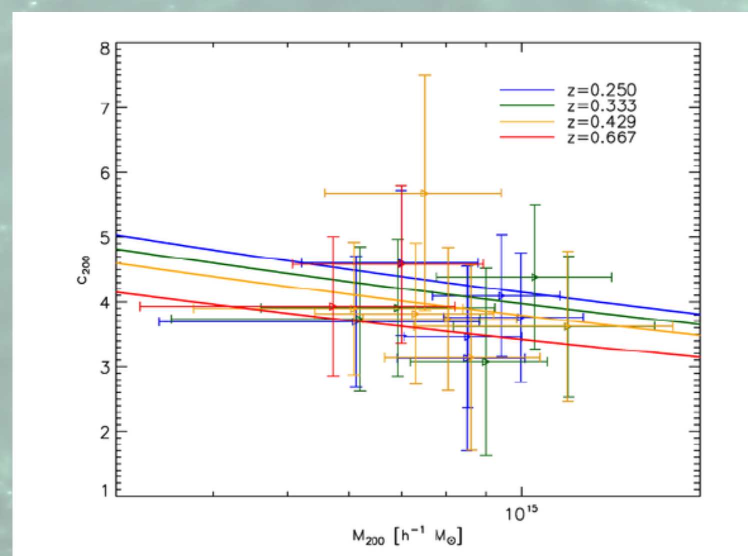


Fig. 1. Examples of simulated clusters which match the CLASH cluster Abell 383 (shown in the small inset) with four increasing values of C_X.

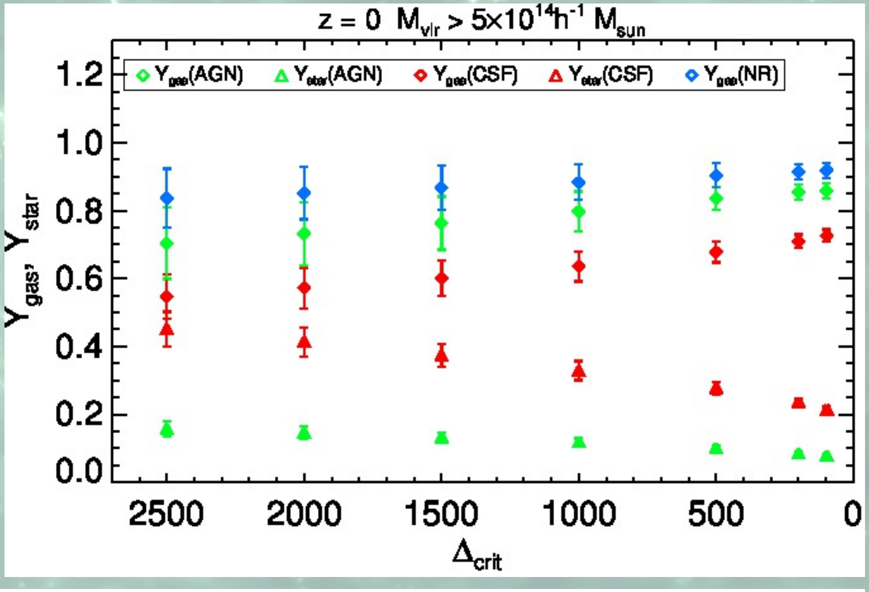
- Selection of MUSIC clusters that mimic the X-ray emission of selected CLASH clusters (X-MAS code by E- Rasia).
- Use the MUSIC equivalent clusters to derive properties of the concentration-Mass relation, shapes, projection effect etc.

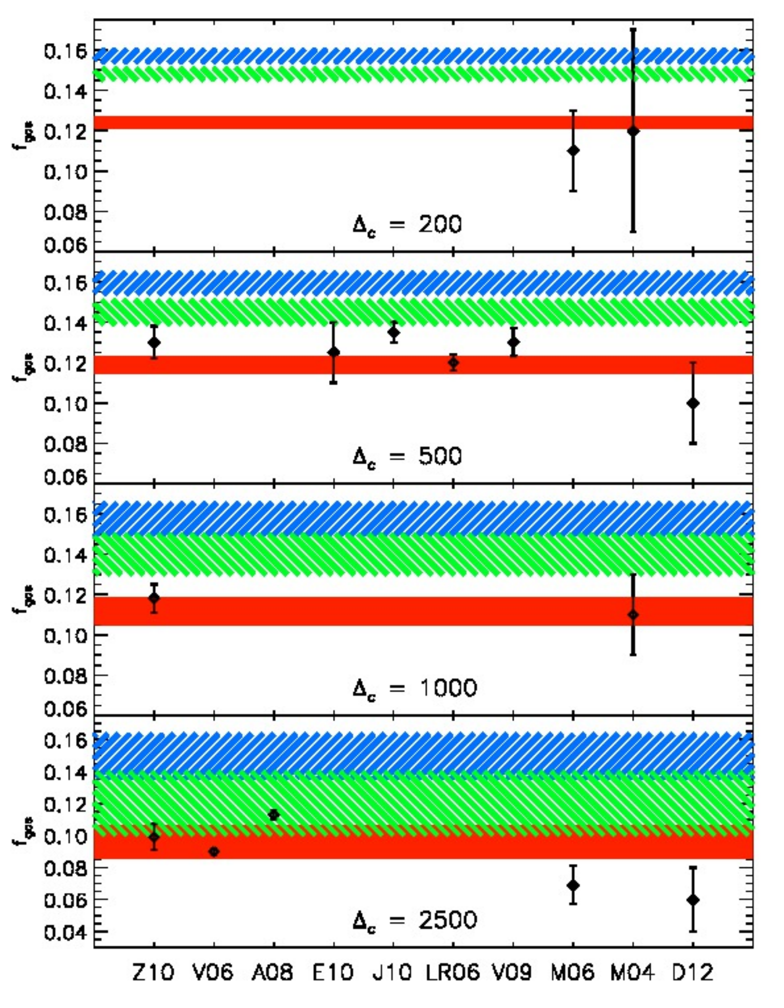


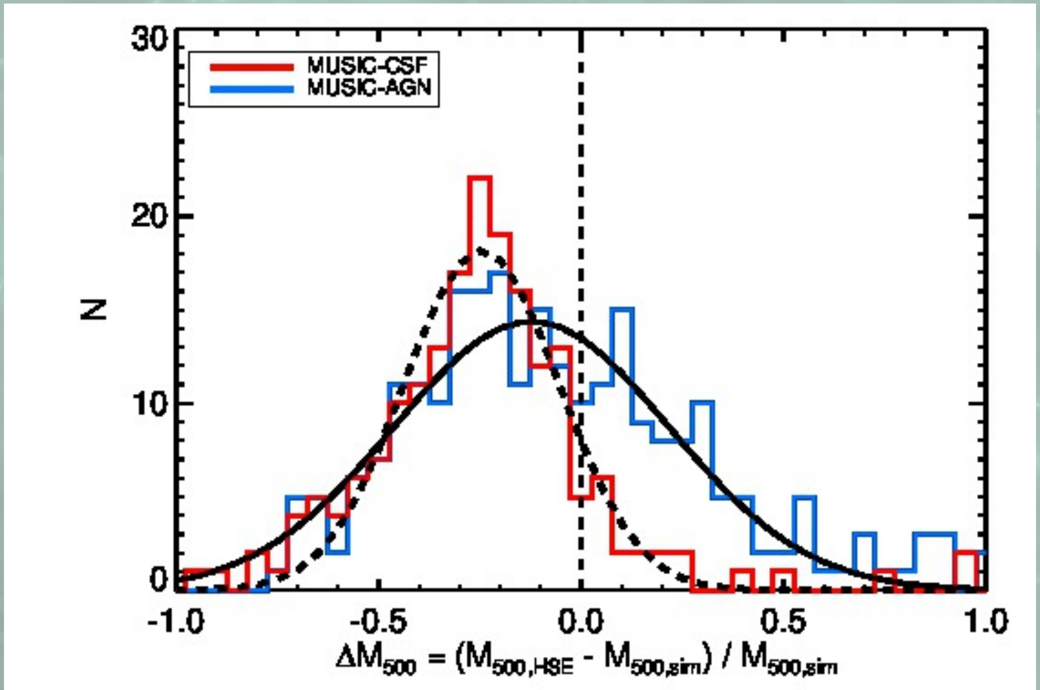


MUSIC with AGN FEEDBACK

Same code as in Trieste's first Dianoga simulations (Planelles et al 2014)





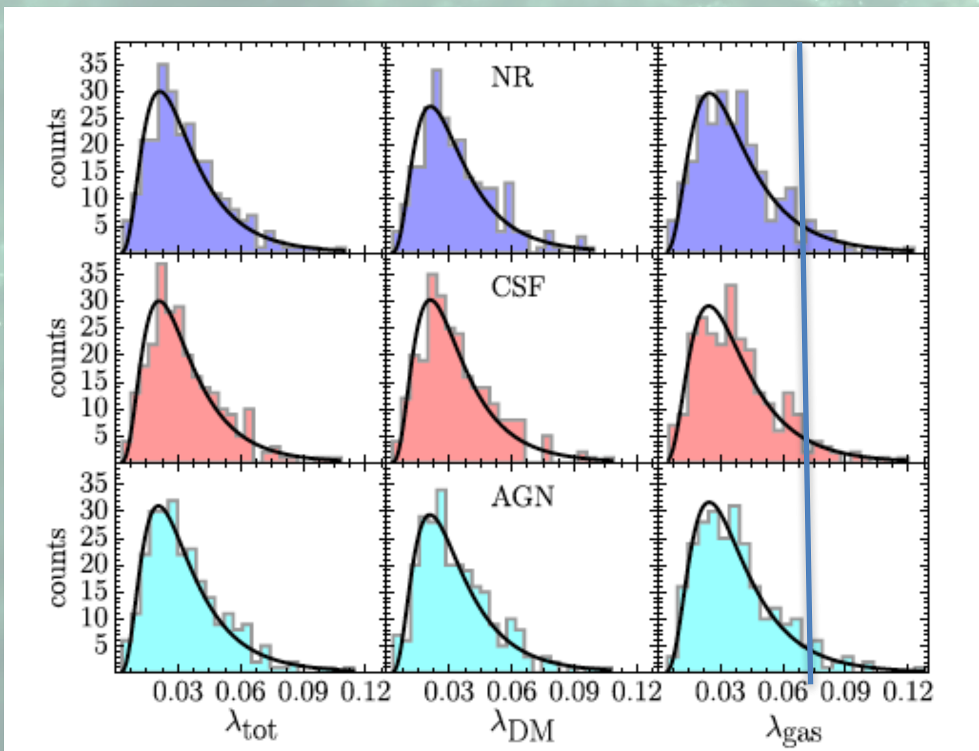


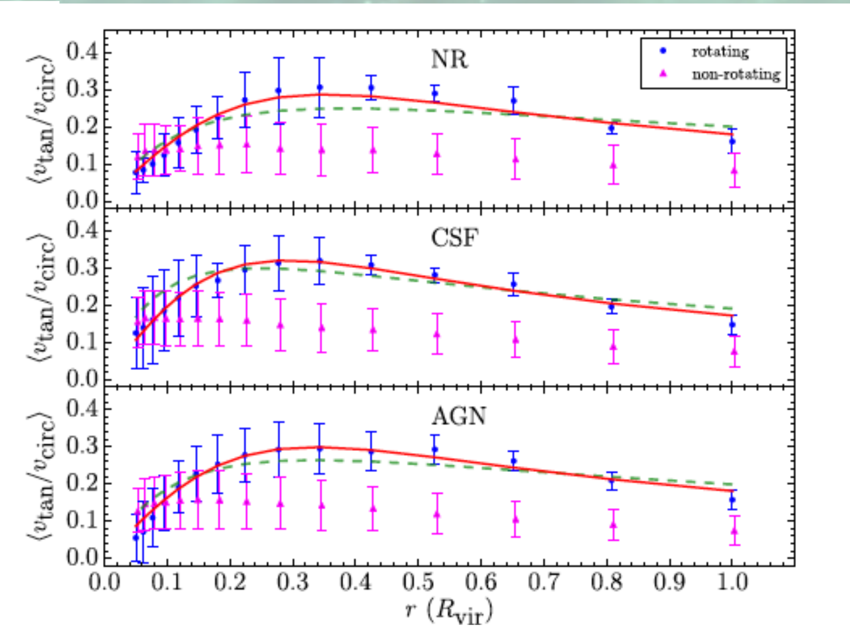
CLUSTER GAS ROTATIONS

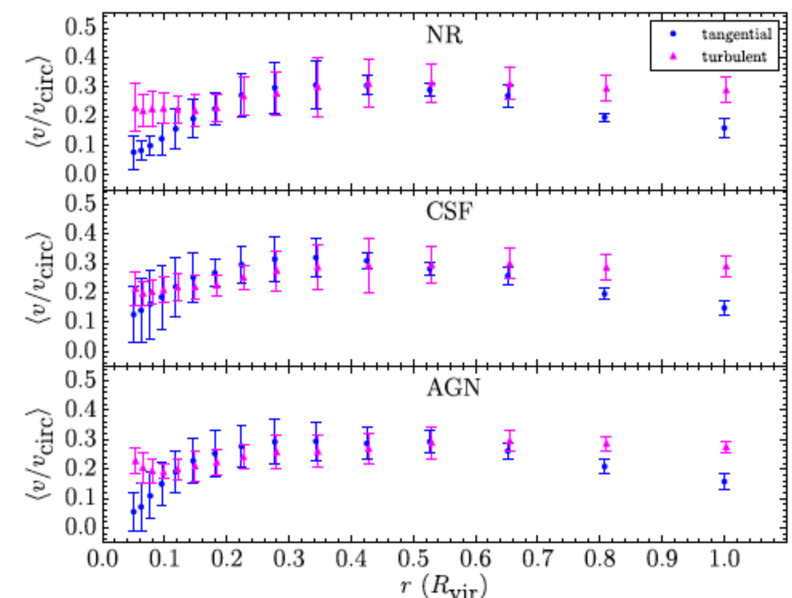
On the coherent rotation of diffuse matter in numerical simulations of clusters of galaxies

MNRAS 465, 2584–2594 (2017)

Anna Silvia Baldi,[1★] Marco De Petris,[1] Federico Sembolini,[1,2,3] Gustavo Yepes,[2,3] Luca Lamagna[1] and Elena Rasia[4,5]







Rotating clusters : $\lambda_{gas} > \lambda_{gas\_crit} = 0.07$
4% of clusters are classified as rotating clusters.
Rotational support is marginal (16% at Rvir) but non negligible.
40 % of rotating clusters exhibit co-rotation of gas and dark matter.
Rotation of gas can be used to derive dark matter motions from k-SZ or X-ray spectroscopy.

CLUSTER GAS ROTATIONS

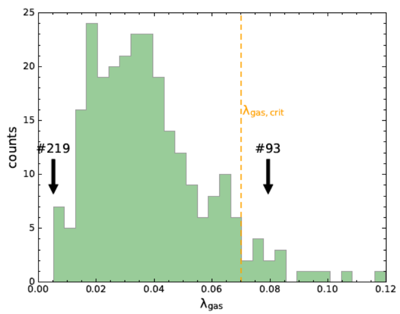
On the coherent rotation of diffuse matter in numerical simulations of clusters of galaxies

MNRAS 465, 2584–2594 (2017)

Anna Silvia Baldi,[1★] Marco De Petris,[1] Federico Sembolini,[1,2,3] Gustavo Yepes,[2,3]
Luca Lamagna[1] and Elena Rasia[4,5]

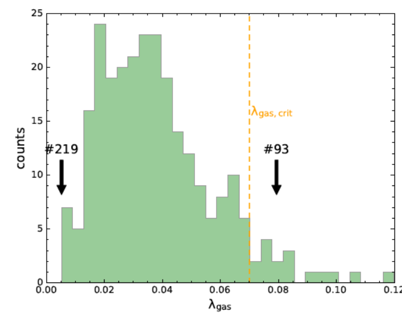
Cluster #93

- $M_{\rm vir} = 1.33 \times 10^{15} h^{-1}$ $M_\odot = 1.90 \times 10^{15}$ $M_\odot$
- $R_{\rm vir} = 2.268$ h^{-1} Mpc $= 3.240$ Mpc
- $\lambda_{\rm gas} = 0.0769$ ➜ the **most rotating** cluster in the sample



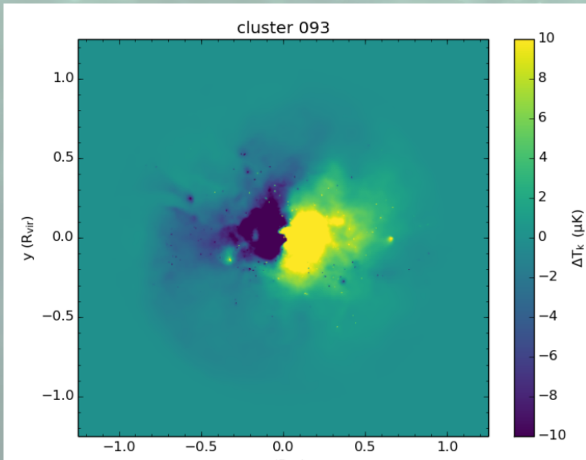
Cluster #219

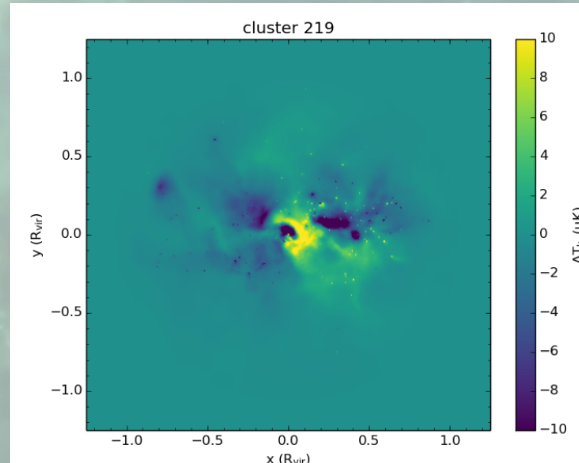
- $M_{\rm vir} = 8.56 \times 10^{14} h^{-1}$ $M_\odot = 1.22 \times 10^{15}$ $M_\odot$
- $R_{\rm vir} = 1.960$ h^{-1} Mpc $= 2.800$ Mpc
- $\lambda_{\rm gas} = 0.0052$ ➜ the **least rotating** cluster in the sample



Two extreme cases of clusters:

The **most** rotationally supported gas and the least one in relaxed MUSIC cluster sample.





Rotation of gas as seen by high resolution KSZ maps from NIKKA2 camera.

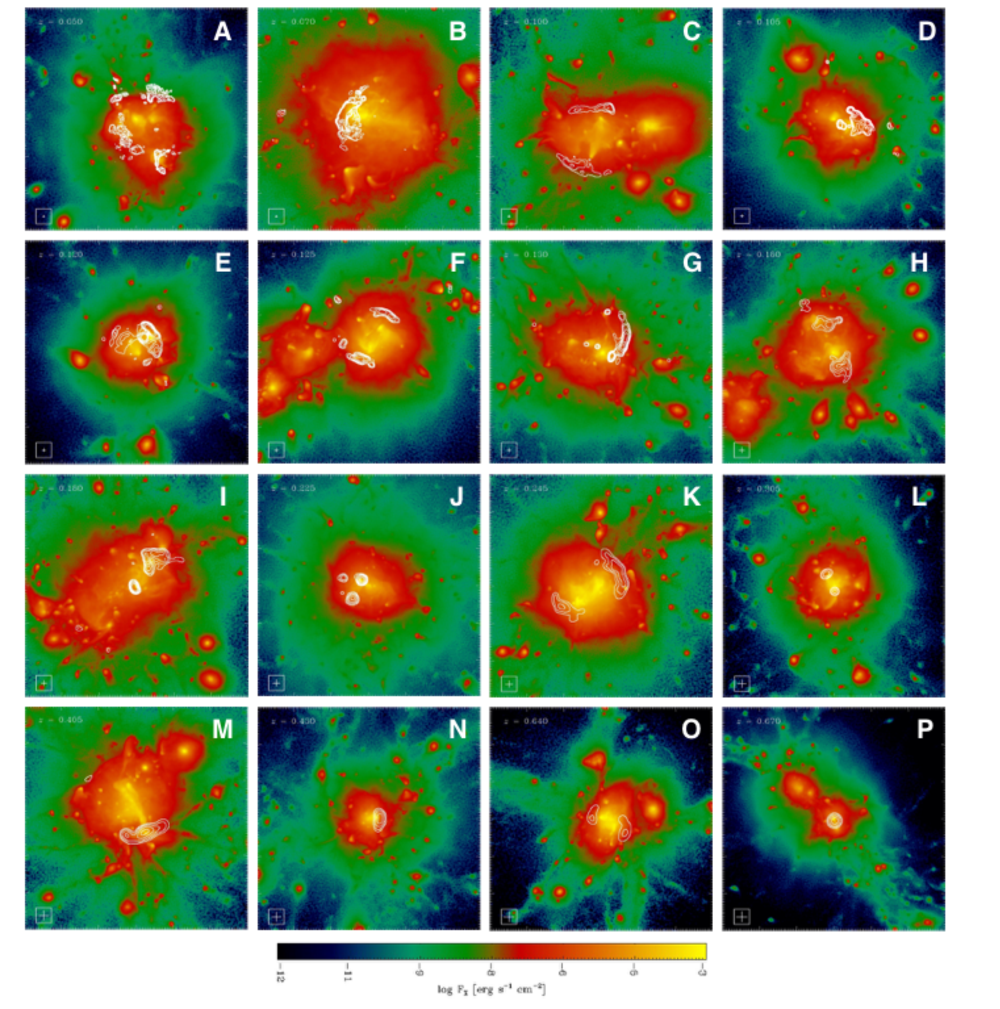
Rotating gas shown as a clear dipole in the maps.

Radio - MUSIC

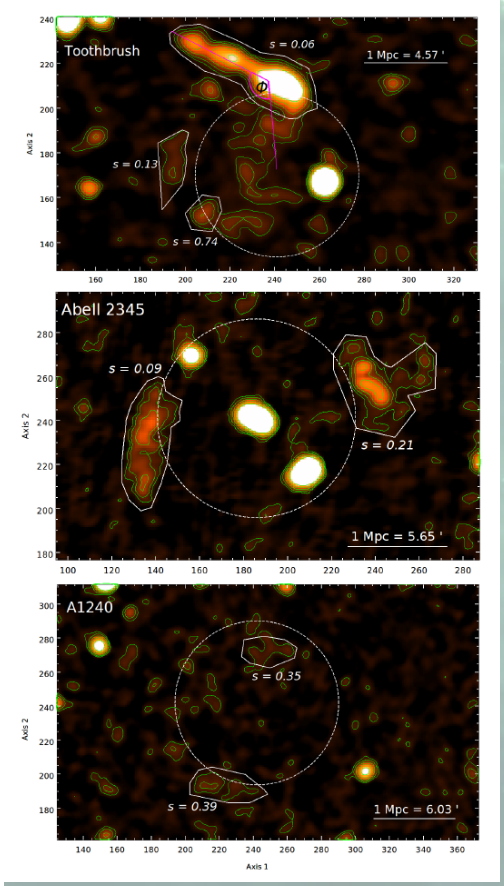
Can cluster merger shocks reproduce the luminosity and shape distribution of radio relics? MNRAS, in press

Sebastián E. Nuza[1*], Jakob Gelszinnis[2], Matthias Hoeft[2], and Gustavo Yepes[3]

Radio Relics in MUSIC CLUSTERS



NRAO VLA Sky Survey



More info about this work to Sebastian

nIFTy CLUSTER COMPARISON PROJECT

nIFTy galaxy cluster simulations – I. Dark matter and non-radiative models

MNRAS 457, 4063–4080 (2016)

Federico Sembolini,[1,2,3★] Gustavo Yepes,[1,2] Frazer R. Pearce,[4] Alexander Knebe,[1,2] Scott T. Kay,[5] Chris Power,[6] Weiguang Cui,[6] Alexander M. Beck,[7,8,9] Stefano Borgani,[10,11,12] Claudio Dalla Vecchia,[13,14] Romeel Davé,[15,16,17] Pascal Jahan Elahi,[18] Sean February,[19] Shuiyao Huang,[20] Alex Hobbs,[21] Neal Katz,[20] Erwin Lau,[22,23] Ian G. McCarthy,[24] Guiseppe Murante,[10] Daisuke Nagai,[22,23,25] Kaylea Nelson,[23,25] Richard D. A. Newton,[5,6] Valentin Perret,[26] Ewald Puchwein,[27] Justin I. Read,[28] Alexandro Saro,[7,29] Joop Schaye,[30] Romain Teyssier[26] and Robert J. Thacker[31]

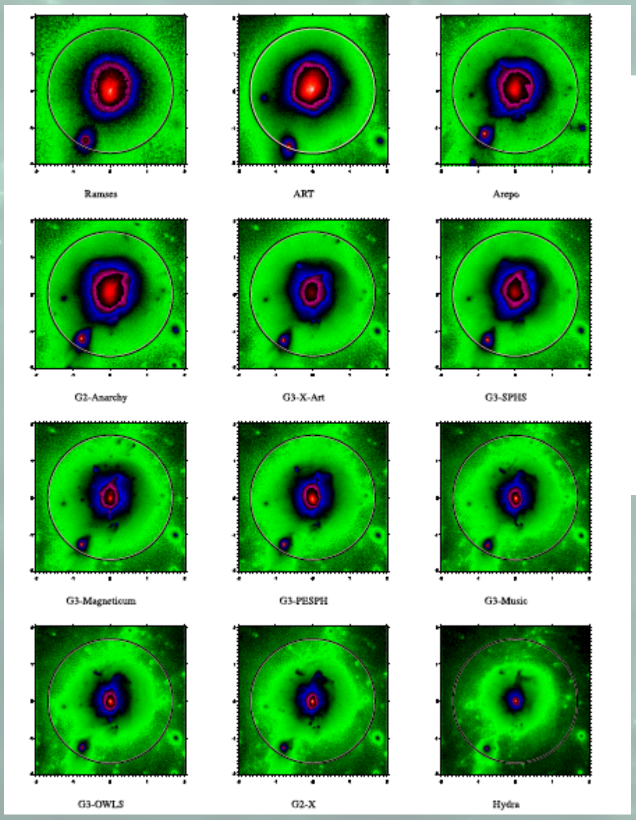
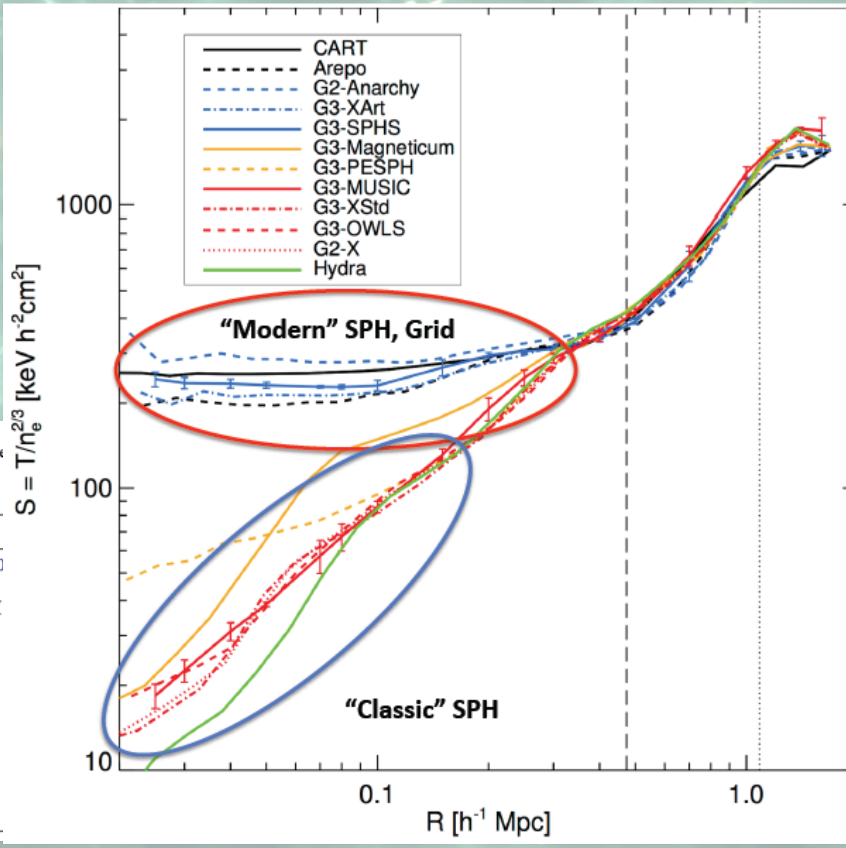


Table 1. List of all the simulation codes participating in the comparison project.

Code name	Reference
CART	Rudd, Zentner & Kravtsov (200
AREPO	Springel (2010)
HYDRA	Couchman, Thomas & Pearce (
GADGET:	Springel (2005)
G2-Anarchy	Dalla Vecchia et al. in prep.
G3-X	Beck et al. (2015)
G3-SPHS	Read & Hayfield (2012a)
G3-Magneticum	Hirschmann et al. (2014)
G3-PESPH	Huang et al. in prep.
G3-MUSIC	Sembolini et al. (2013)
G3-OWLS	Schaye et al. (2010)
G2-X	Pike et al. (2014)



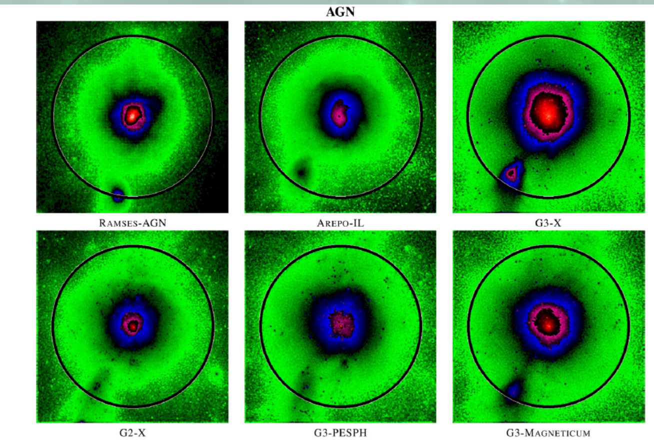
Largest comparison project of galaxy clusters since **Santa Barbara 98**
One of the MUSIC clusters resimulated with 13 different codes.
Classical and New SPH versions performs similar to AMR
Next: introducing radiative effects

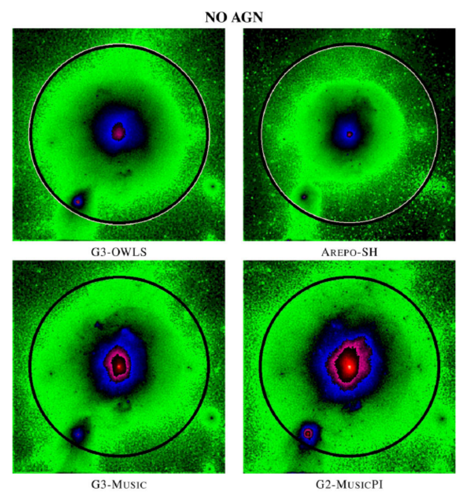
nIFTy CLUSTER COMPARISON PROJECT

nIFTy galaxy cluster simulations – II. Radiative models

MNRAS **459**, 2973–2991 (2016)

Federico Sembolini,[1,2★] Pascal Jahan Elahi,[3] Frazer R. Pearce,[4] Chris Power,[5,6] Alexander Knebe,[1,2] Scott T. Kay,[7] Weiguang Cui,[5,6] Gustavo Yepes,[1,2] Alexander M. Beck,[8] Stefano Borgani,[9,10,11] Daniel Cunnama,[12] Romeel Davé,[13,14,15] Sean February,[16] Shuiyao Huang,[17] Neal Katz,[17] Ian G. McCarthy,[18] Giuseppe Murante,[9] Richard D. A. Newton,[7] Valentin Perret,[19] Ewald Puchwein,[20] Alexandro Saro,[7,21] Joop Schaye[22] and Romain Teyssier[19]

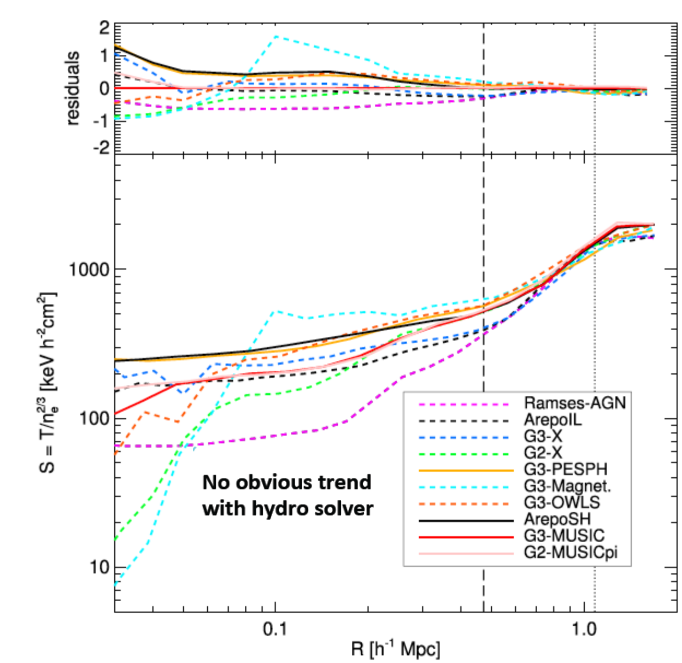


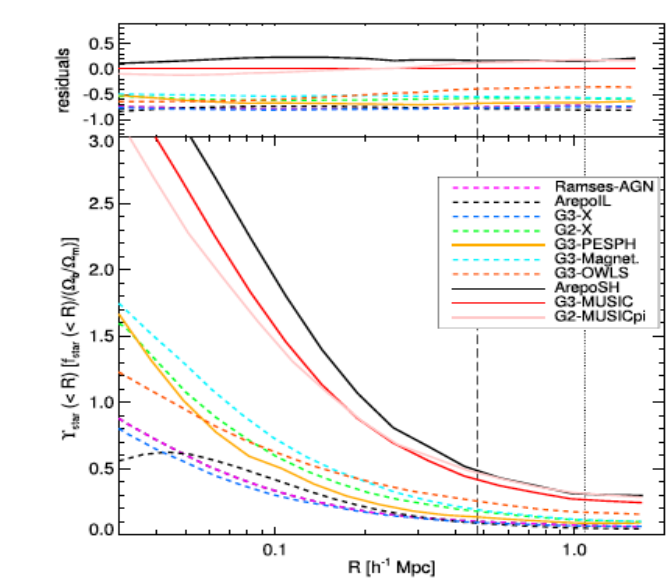


DIFFERENT HYDRO CODES + RADIATIVE PROCESSES:

- COOLING
- SF
- SN FEEDBACK
- AGN FEEDBACK

Type	Code name	CSF	AGN	Versions	Reference
Grid-based	RAMSES	Y	Y	RAMSES-AGN	Teyssier et al. (2011)
Moving mesh	AREPO	Y	Y	AREPO-IL	Vogelsberger et al. (2013, 2014)
		Y	N	AREPO-SH	
Modern SPH	G3-X	Y	Y		
	G3-PESPH	Y	N		Huang et al. (in prep.)
	G3-MAGNETICUM	Y	Y		Hirschmann et al. (2014)
Classic SPH	G3-MUSIC	Y	N	G3-MUSIC	Sembolini et al. (2013)
				G2-MUSICPI	Piontek & Steinmetz (2011)
	G3-OWLS	Y	Y		Schaye et al. (2010)
	G2-X	Y	Y		Pike et al. (2014)





nIFTy CLUSTER COMPARISON PROJECT

nIFTY galaxy cluster simulations – III. The similarity and diversity of galaxies and subhaloes

MNRAS 458, 1096–1116 (2016)

Pascal J. Elahi,[1★] Alexander Knebe,[2,3] Frazer R. Pearce,[4] Chris Power,[5,6] Gustavo Yepes,[2] Weiguang Cui,[5,6] Daniel Cunnama,[7] Scott T. Kay,[8] Federico Sembolini,[2,9] Alexander M. Beck,[10] Romeel Davé,[11,12,13,14] Sean February,[15] Shuiyao Huang,[16] Neal Katz,[16] Ian G. McCarthy,[17] Giuseppe Murante,[18] Valentin Perret,[19] Ewald Puchwein,[20] Alexandro Saro[21] and Romain Teyssier[22]

ABSTRACT

We examine subhaloes and galaxies residing in a simulated Λ cold dark matter galaxy cluster ($M^{\rm crit}_{200} = 1.1 \times 10^{15}\,h^{-1}\,{\rm M}_{\odot}$) produced by hydrodynamical codes ranging from classic smooth particle hydrodynamics (SPH), newer SPH codes, adaptive and moving mesh codes. These codes use subgrid models to capture galaxy formation physics. We compare how well these codes reproduce the same subhaloes/galaxies in gravity-only, non-radiative hydrodynamics and *full feedback physics* runs by looking at the overall subhalo/galaxy distribution and on an individual object basis. We find that the subhalo population is reproduced to within $\lesssim$10 per cent for both dark matter only and non-radiative runs, with individual objects showing code-to-code scatter of $\lesssim$0.1 dex, although the gas in non-radiative simulations shows significant scatter. Including feedback physics significantly increases the diversity. Subhalo mass and $V_{\rm max}$ distributions vary by ≈20 per cent. The galaxy populations also show striking code-to-code variations. Although the Tully–Fisher relation is similar in almost all codes, the number of galaxies with $10^9\,h^{-1}\,{\rm M}_{\odot} \lesssim M_* \lesssim 10^{12}\,h^{-1}\,{\rm M}_{\odot}$ can differ by a factor of 4. Individual galaxies show code-to-code scatter of ∼0.5 dex in stellar mass. Moreover, systematic differences exist, with some codes producing galaxies 70 per cent smaller than others. The diversity partially arises from the inclusion/absence of active galactic nucleus feedback. Our results combined with our companion papers demonstrate that subgrid physics is not just subject to fine-tuning, but the complexity of building galaxies *in all environments* remains a challenge. We argue that even basic galaxy properties, such as stellar mass to halo mass, should be treated with errors bars of ∼0.2–0.4 dex.

nIFTy galaxy cluster simulations – IV. Quantifying the influence of baryons on halo properties

MNRAS 458, 4052–4073 (2016)

Weiguang Cui,[1,2★] Chris Power,[1,2] Alexander Knebe,[3,4] Scott T. Kay,[5] Federico Sembolini,[3,4] Pascal J. Elahi,[6] Gustavo Yepes,[3,4] Frazer Pearce,[7] Daniel Cunnama,[8] Alexander M. Beck,[9] Claudio Dalla Vecchia,[10,11] Romeel Davé,[12,13,14] Sean February,[15] Shuiyao Huang,[16] Alex Hobbs,[17] Neal Katz,[16] Ian G. McCarthy,[18] Giuseppe Murante,[19] Valentin Perret,[20] Ewald Puchwein,[21] Justin I. Read,[22] Alexandro Saro,[9,23] Romain Teyssier[23] and Robert J. Thacker[24]

ABSTRACT

Building on the initial results of the nIFTy simulated galaxy cluster comparison, we compare and contrast the impact of baryonic physics with a single massive galaxy cluster, run with 11 state-of-the-art codes, spanning adaptive mesh, moving mesh, classic and modern smoothed particle hydrodynamics (SPH) approaches. For each code represented we have a dark-matter-only (DM) and non-radiative (NR) version of the cluster, as well as a full physics (FP) version for a subset of the codes. We compare both radial mass and kinematic profiles, as well as global measures of the cluster (e.g. concentration, spin, shape), in the NR and FP runs with that in the DM runs. Our analysis reveals good consistency ($\lessapprox$20 per cent) between global properties of the cluster predicted by different codes when integrated quantities are measured within the virial radius R_{200}. However, we see larger differences for quantities within R_{2500}, especially in the FP runs. The radial profiles reveal a diversity, especially in the cluster centre, between the NR runs, which can be understood straightforwardly from the division of codes into classic SPH and non-classic SPH (including the modern SPH, adaptive and moving mesh codes); and between the FP runs, which can also be understood broadly from the division of codes into those that include active galactic nucleus feedback and those that do not. The variation with respect to the median is much larger in the FP runs with different baryonic physics prescriptions than in the NR runs with different hydrodynamics solvers.

nIFTy galaxy cluster simulations – V. Investigation of the cluster infall region

MNRAS 464, 2027–2038 (2017)

Jake Arthur,[1★] Frazer R. Pearce,[1] Meghan E. Gray,[1] Pascal J. Elahi,[2,3] Alexander Knebe,[4,5] Alexander M. Beck,[6] Weiguang Cui,[3,7] Daniel Cunnama,[8,9] Romeel Davé,[8,9,10] Sean February,[11] Shuiyao Huang,[12] Neal Katz,[12] Scott T. Kay,[13] Ian G. McCarthy,[14] Giuseppe Murante,[15] Valentin Perret,[16] Chris Power,[3,7] Ewald Puchwein,[17] Alexandro Saro,[18] Federico Sembolini,[4,5] Romain Teyssier[19] and Gustavo Yepes[4,5]

ABSTRACT

We examine the properties of the galaxies and dark matter haloes residing in the cluster infall region surrounding the simulated Λ cold dark matter galaxy cluster studied by Elahi et al. at $z = 0$. The $1.1 \times 10^{15}\,h^{-1}\,{\rm M}_{\odot}$ galaxy cluster has been simulated with eight different hydrodynamical codes containing a variety of hydrodynamic solvers and sub-grid schemes. All models completed a dark-matter-only, non-radiative and full-physics run from the same initial conditions. The simulations contain dark matter and gas with mass resolution $m_{\rm DM} = 9.01 \times 10^8\,h^{-1}\,{\rm M}_{\odot}$ and $m_{\rm gas} = 1.9 \times 10^8\,h^{-1}\,{\rm M}_{\odot}$, respectively. We find that the synthetic cluster is surrounded by clear filamentary structures that contain ∼60 per cent of haloes in the infall region with mass $\sim10^{12.5}$–$10^{14}\,h^{-1}\,{\rm M}_{\odot}$, including 2–3 group-sized haloes ($>10^{13}\,h^{-1}\,{\rm M}_{\odot}$). However, we find that only ∼10 per cent of objects in the infall region are sub-haloes residing in haloes, which may suggest that there is not much ongoing pre-processing occurring in the infall region at $z = 0$. By examining the baryonic content contained within the haloes, we also show that the code-to-code scatter in stellar fraction across all halo masses is typically ∼2 orders of magnitude between the two most extreme cases, and this is predominantly due to the differences in sub-grid schemes and calibration procedures that each model uses. Models that do not include active galactic nucleus feedback typically produce too high stellar fractions compared to observations by at least ∼1 order of magnitude.

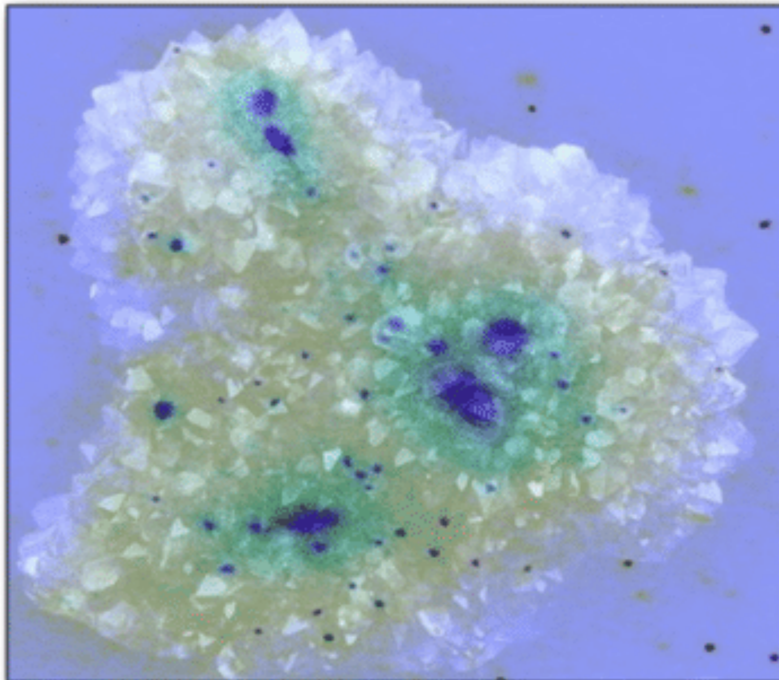
The 300 Comparison Project

- **300+ Clusters** selected from a **new** Mutidark Planck 1Gpc volume done in **Planck** cosmology.
- Larger resimulated areas (15 Mpc radius) .
- Several SPH, AMR and Moving Mesh codes + different subgrid physics implementations.
- Synthetic maps of X-ray, SZ, Optical and Lensing will be provided to user participants.
- **+ BONUS**
- The Multidark-Planck N-body simulation at full resolution (3840^3 particles) has been used for yet another comparison project on ***Semi-Analytical Galaxy Modelling***. (Galacticus, SAGE, SAG)
- Now, we can do the cross-correlations between SAM and hydro galaxies in clusters and in the field (several field regions devoid of clusters are being simulated) .

CRYSTAL CLEAR CLUSTERS:

where hydrodynamical simulations meet semi-analytical models

SOC:
Alexander Knebe
Frazer Pearce
Chris Power
Gustavo Yepes
Daniel Cunnama



hands-on workshop on galaxy clusters as found in full physics hydro-simulations and semi-analytical models

June 25-30, 2017 @ “La Cristalera” in Miraflores de la Sierra, Madrid, Spain

http://popia.ft.uam.es/CrystalClearClusters

CONCLUSIONS

- **MUSIC** is currently one of the **largest dataset** of a **mass selected volume limited sample** of hydrodynamical simulated galaxy clusters.

- Constitutes a powerful test suite to study the effects of different physical modeling in shaping the scaling laws of galaxy clusters in different wavebands, ranging from X-ray, optical and radio.

- Every body is very welcome to play with the **MUSIC of galaxy clusters.**

ICS AVAILABLE ONLINE AT

http://music.ft.uam.es

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Z=49.000

THANK YOU

MUSIC

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of galaxy

Clusters

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