The bright side of galaxy clusters

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+ cosmo-numerical group @OATS (S. Borgani, G. Murante, S. Planelles, W. Cui et al.)

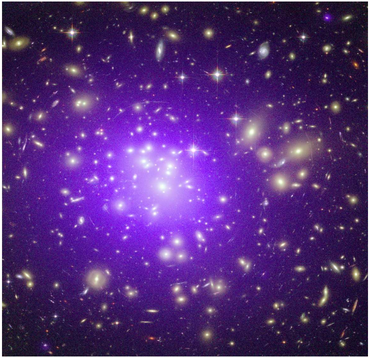
Overview

1. Motivation: study of galaxy clusters
2. Synthetic X-ray observations
   - PHOX: photon X-ray simulator
3. Results & applications
   - Reconstruction of ICM thermal structure
   - The ICM velocity structure
   - Scaling laws among global properties
4. Summary
5. Further applications: AGN emission with PHOX

Why galaxy clusters?

- Largest gravitationally-bound structures in the Universe
- Masses of $\sim 10^{14}$–$10^{15}\ h^{-1}\ M_{\odot}$, sizes of $\sim$ few Mpc
- Potential well dominated by dark matter (**DM**)
- Comprise thousends of **galaxies**
- Most of the baryonic matter is in the form of **hot, diffuse gas (ICM)** with $T \sim 10^7$–10^8 K:

  GCs are very **bright, extended sources in the X-rays** (bremsstrahlung + metal emission lines)



Abell 1689, composite image. X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI.

→ Use ICM observable properties (optical; radio; X-rays; lensing; SZ-effect) to trace the invisible ones

→ reconstruct cluster structure and employ clusters for cosmology & astrophysics!

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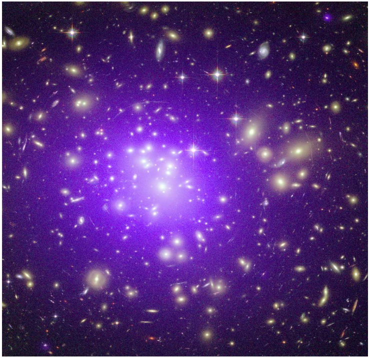

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X-rays allow to investigate several issues, e.g. can be used to **weight clusters**. Simplest assumption:

- gas traces DM potential well
- gas is in hydrostatic equilibrium

$$\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM}{r^2}$$

- + spherical symmetry
- + only thermal pressure support

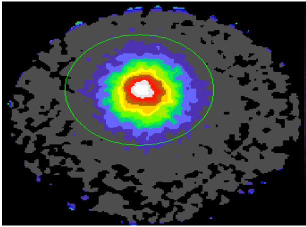
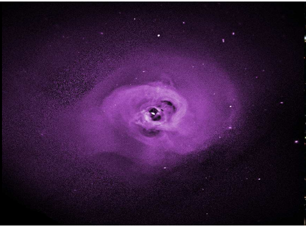
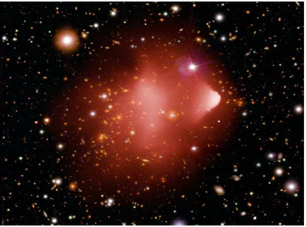
... then:

Hydrostatic mass

$$M(< r) = -\frac{k_B T_{gas}}{G \mu m_p}\left(\frac{\mathrm{d}\ln \rho_{gas}}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T_{gas}}{\mathrm{d}\ln r}\right)$$

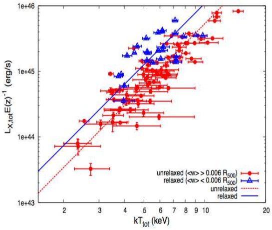
Nature is more complex

Not all clusters are simple to model...

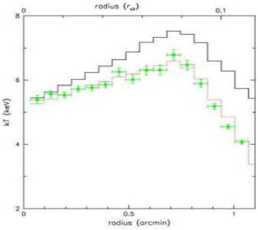




Abell 2589; Perseus cluster; Bullet cluster.

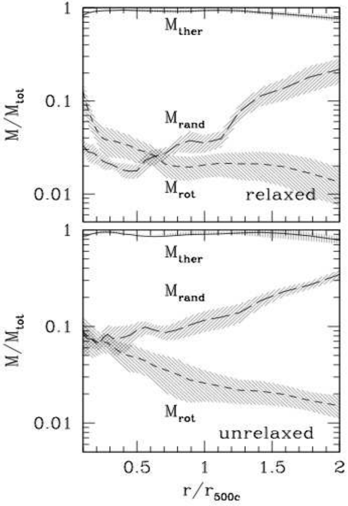
Maughan+ (2011)



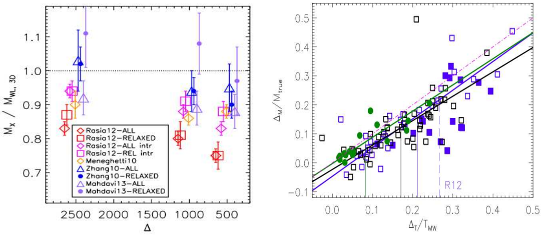
Mazzotta+ (2004)



Lau+ (2009)



Rasia+ (2012;2014)



What is the origin of these features?

Are the assumptions reliable?

What about...

- ... the complexity of the ICM thermal structure?
- ... the effects of non-thermal motions in the ICM?
- ... the effects of the cluster dynamical state?
- ... the deviation from the spherical symmetry?
- ... the intrinsic effects due to the observational method (e.g. for X-rays)?
- ... the differences in numerical/observational results?

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Bridging numerical simulations to X-ray observations

Simulations

* Cosmological hydrodynamical simulations of large-scale structures from which cluster catalogs are extracted, or zoomed re-simulations of single clusters
* Eulerian/Lagrangian approach — simulations performed with the SPH code Gadget-2/3
* Gravity (to describe DM) + hydro (for baryonic matter):
  adiabatic runs, or including additional physics (gas cooling, star formation, metal enrichment, feedback processes from SNe winds and *AGNs*)
* **ADVANTAGE:** *direct access to 3D intrinsic properties as well as to evolution in time*

X-ray simulators

EXAMPLES: X-MAS (Gardini+ 2004;Rasia+ 2008); XIM (Heinz+ 2009); etc.

GOAL: obtain observable-like quantities out of simulations that resemble as faithfully as possible those extracted from real X-ray observations.

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PHOX: X-ray emission from hydro-numerical simulations

Unit 1

Generate an ideal cube of photons, sampling the model X-ray emission spectrum calculated for every emitting (gas) element.

Unit 2

Project along the l.o.s. and add Doppler-shift to photon energy due to l.o.s. motion (of the emitting element);
select a sub-region of the 3-D photon cube.

Unit 3

Convolution with the instrumental response: choose an instrument (account for FoV, quantum efficiency, effective area and energy resolution) and assume a realistic exposure time.

V. Biffi et al. (2012)
Observing simulated galaxy clusters with PHOX: a novel X-ray photon simulator
MNRAS 420 (2012) 3545.

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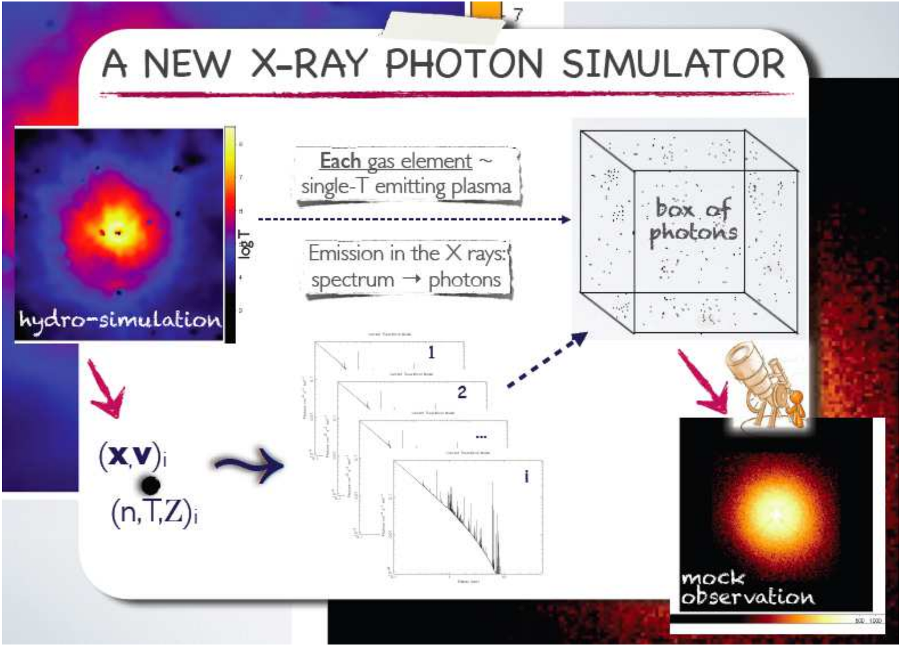
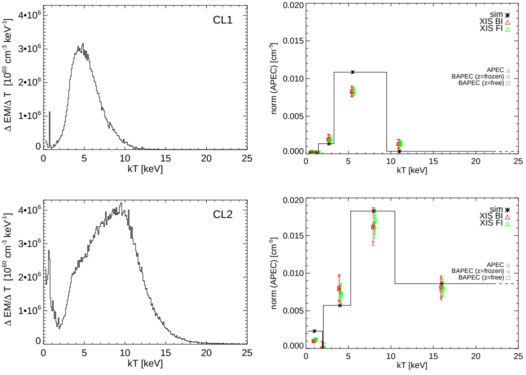

A NEW X-RAY PHOTON SIMULATOR
hydro-simulation
log T
Each gas element ~
single-T emitting plasma
Emission in the X rays:
spectrum → photons
box of
photons
(x,v)i
(n,T,Z)i
1
2
...
i
mock
observation

ICM thermal structure

ICM often has a multi-phase structure: multi-temperature fitting can help to constrain its thermal components: $\mathrm{K}_{APEC} \propto E.M. = \int n_H n_e \mathrm{d}V$

- 2 simulated clusters with different thermal structures
- Synthetic X-ray observations with Suzaku: spectra
- Multi-T spectral modelling (5 *fixed*-T APEC components): reconstruct ICM temperature distribution



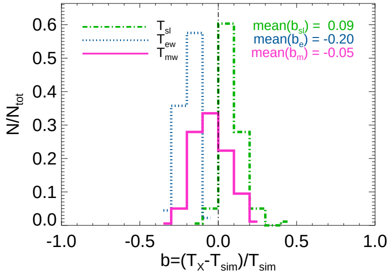
Biffi et al. (2012); simulations by K. Dolag.

X-ray obs: Peterson+ (2003); Kaastra+ (2004); recent study by Frenk+ 2013.

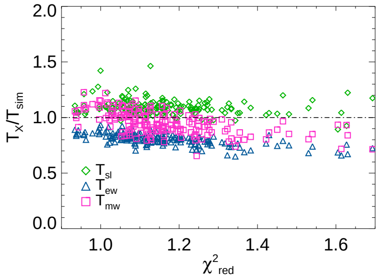
Estimating the ICM temperature: bias(es)

Theoretically, e.g. from simulations, one can define different ICM "temperature" values: there is a bias between the X-ray temperature and the "true", dynamical one ($\mathbf{T_X < T_{mw}}$)

$$T_{sim} = T_w = \frac{\sum_i w_i T_i}{\sum_i w_i}$$



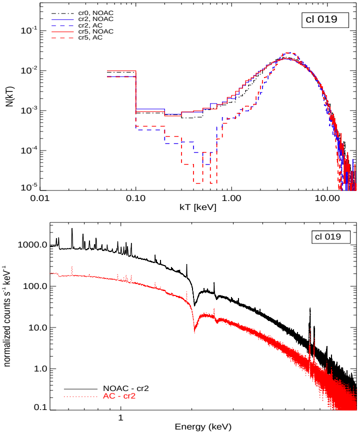
Biffi, Sembolini et al. (2014); subsample of MUSIC-2 clusters simulated with the SPH code Gadget.



The complex multi-temperature structure of the ICM can also bias T_X when a single-T fit is performed

Estimating the ICM temperature: bias(es)

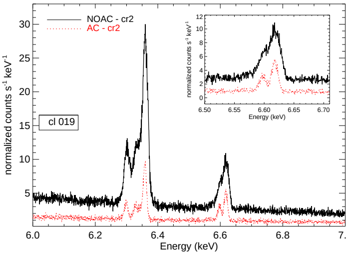
The presence of different thermal components (especially cold clumps) in the ICM might also depend on numerics...



Biffi & Valdarnini (2015).

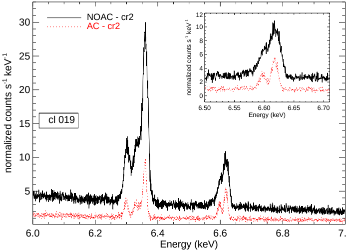
- problems for standard SPH technique to treat gas mixing
- addition of *artificial conductivity* term (Valdarnini 2012)
- improved gas mixing, suppression of cold gas component
- study on a set of 8 simulated clusters with different dynamical states

The numerical approach itself can have an impact in shaping the ICM thermal (and dynamical) structure
→ effects mirrored by mock X-ray properties.



Biffi & Valdarnini (2015).

- improved SPH (artificial viscosity & conductivity) also impact gas velocity field
- sims: gas velocity field measurable *directly*
- X-ray obs: derivable from broadening of heavy-ion (e.g. Fe) emission lines — *BUT* high spectral resolution required...



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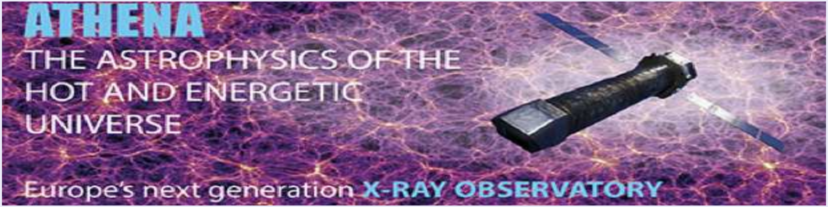


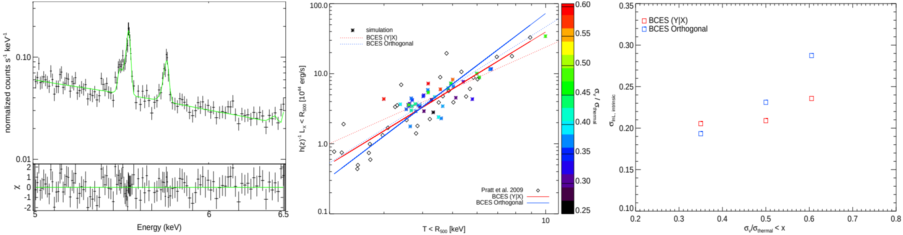
energy range: 0.3–12 keV
spectral resolution: 2.5 eV @ 6 keV (X-IFU)

http://www.the-athena-x-ray-observatory.eu/

ICM velocity diagnostics & scaling relations

Deviations from self-similar appearance of clusters can be due to the presence of non-thermal motions in the ICM!

Biffi et al. (2013); subsample of simulated clusters from the Magneticum simulation (K. Dolag).

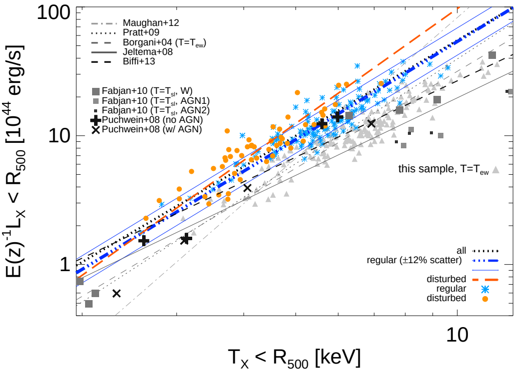


$\sigma_v/\sigma_{thermal}$ = amount of non-thermal motions relative to thermal ones

- Mimick expected performance of up-coming X-ray high-resolution spectrometer: e.g. **Athena** ↔ resolve non-thermal broadening of Fe emission line (e.g. @6.7 keV)
- Possibility to check against simulation the inferred gas velocities
- Relate cluster position in the L_X-T_X plane to amount of non-thermal ICM motions

L_X-T_X relation

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 simulated clusters.

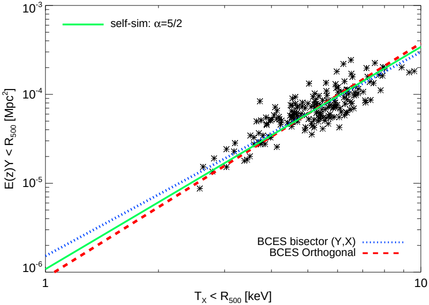


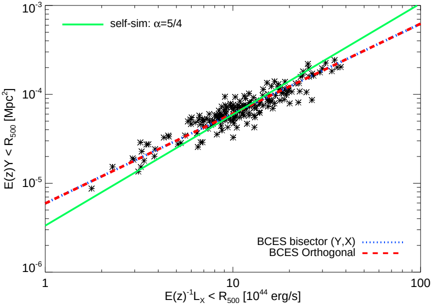
- Large cluster sample: better constraints on scatter
- Quantities derived with observable-like approach: more faithful comparison to obs.
- Sims: shallower slope and higher normalization (temperature bias + lack of AGN feedback treatment in these sims)
- Differences depending on cluster dynamical state

Physical processes treated in the simulation & estimation of observables from simulated clusters are both important in comparing against observations.

SZ/X-ray scaling relations (I)

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 simulated clusters.

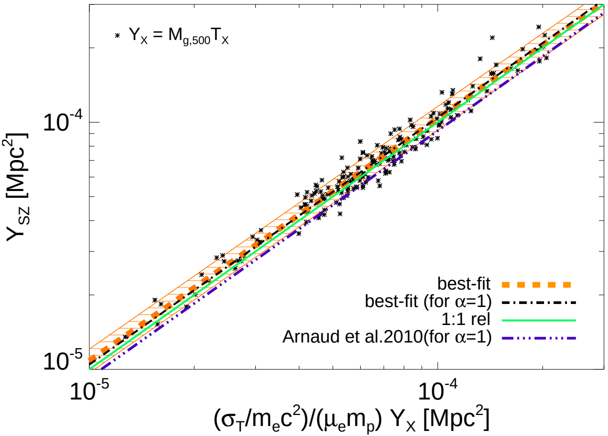




- observational approach introduces additional scatter in the relations
- L_X is particularly sensitive to the thermo-dynamical structure of the ICM
- observed deviation from self-similarity

SZ/X-ray scaling relations (II)

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 simulated clusters.



SZ-effect and X-ray emission are sensitive to ICM temperature in a different way: they can be combined to minimize the relation scatter — deviations from 1:1 depend on thermal structure.

Summary

- Study the ICM in clusters to constrain (i) statistical properties and (ii) deviations from theoretical expectations;
- Use cosmological simulations to study *directly* intrinsic 3D properties (thermal structure, gas velocity field, metallicity), dynamical state, redshift evolution;
- Generate mock X-ray properties from simulations to
  - (i) compare against observed clusters in a more proper way,
  - (ii) constrain the numerical modeling,
  - (iii) help the interpretation of the underlying physics, and
  - (iv) possibly predict the observational achievements of up-coming X-ray instruments.

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X-ray emission from the ~~ICM~~ AGNs

PHOX for ICM emission:

- use (hot) **gas** particles in the simulation belonging to ICM;
- consider temperature, density and metallicity (average or with specified chemical abundances);
- X-ray model spectrum for *hot diffuse plasma*: **APEC** (from XSPEC package).

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PHOX for **AGN** emission

⟶ Partially modify PHOX-Unit 1:

- Sims w/ AGN feedback: construct ideal X-ray spectrum ∀ **BH-particle**;
- particular spectrum shape: power-law
  - ∗ luminosity from BHAR, following Churazov+2005
  - ∗ assumption for: $L_{rad} \rightarrow L_{SHR}$ and L_{HXR}
  - ∗ L_{SHR} and L_{HXR} + power-law spectrum → constraints on spectral parameters

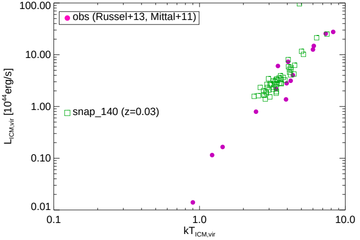
+ standard PHOX procedure:

- sample spectrum with discrete number of photons;
- collect all photons from all BH-particles in a 3-D box associated to sim. output;
- similarly to ICM photon cube: select spatial sub-region, project along l.o.s. and convolve with a real instrument characteristics.

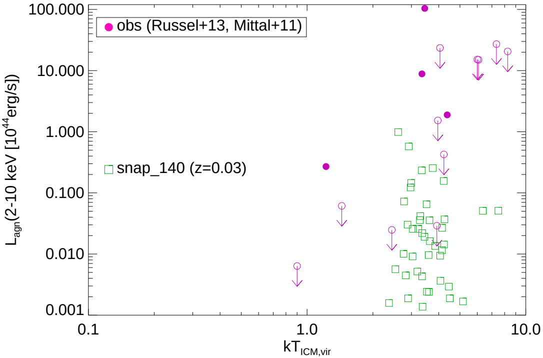
Preliminary

→ Study the contribution from the central AGN to the global ICM luminosity

L_{ICM}-T_{ICM}



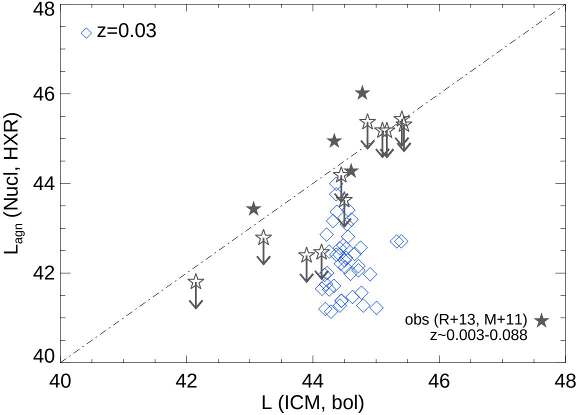
L_{AGN}-T_{ICM}



H.R. Russel et al. (2013)
MNRAS 432 (2013) 530.

R. Mittal et al. (2011)
A&A 532 (2011) A133.

Preliminary



∗ tested for a few clusters and central AGNs with PHOX, to be done for the sample
— e.g. investigate performance of Athena at high-redshift

Thanks!

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Fig. 1 from Churazov et al. (2005)

$$\frac{L_{rad}}{L_{Edd}} = \begin{cases} \varepsilon_r \left(10\frac{\dot{M}}{\dot{M}_{Edd}}\right), & \text{if } BHAR > 0.1 \\ \varepsilon_r \left(10\frac{\dot{M}}{\dot{M}_{Edd}}\right)^2, & \text{if } BHAR < 0.1 \end{cases}$$