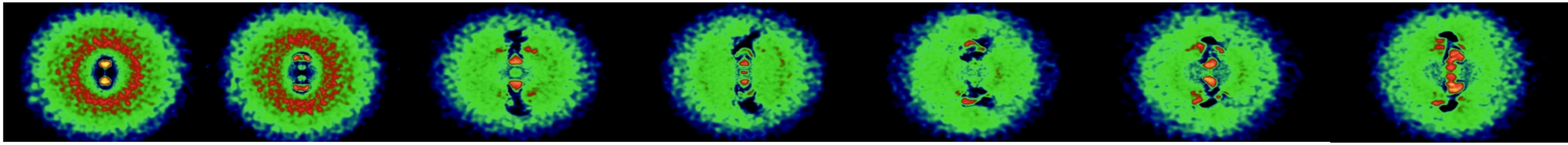


Cosmological Simulations of AGN Feedback in Groups and Clusters: Implementation, Results and Uncertainties

Debora Sijacki
Hubble Fellow
CfA, Harvard

Structure in Clusters and Groups of Galaxies in the Chandra Era
July 12-14 2011

Introduction

To solve the overcooling flow problem in cosmological simulations:

- SNe heating only (e.g. Borgani, 2004) X (energetically disfavoured)
- **CRs from SNe and structure formation shocks** X (energetically disfavoured)
- thermal conduction (Jubelgas et al. 2006) ? (only for Braginskii, no B fields!)
- physical viscosity (Sijacki et al. 2007) ? (only for Braginskii, no B fields!)
- AGN-driven bubbles and winds ✓ (enough E, but how?)

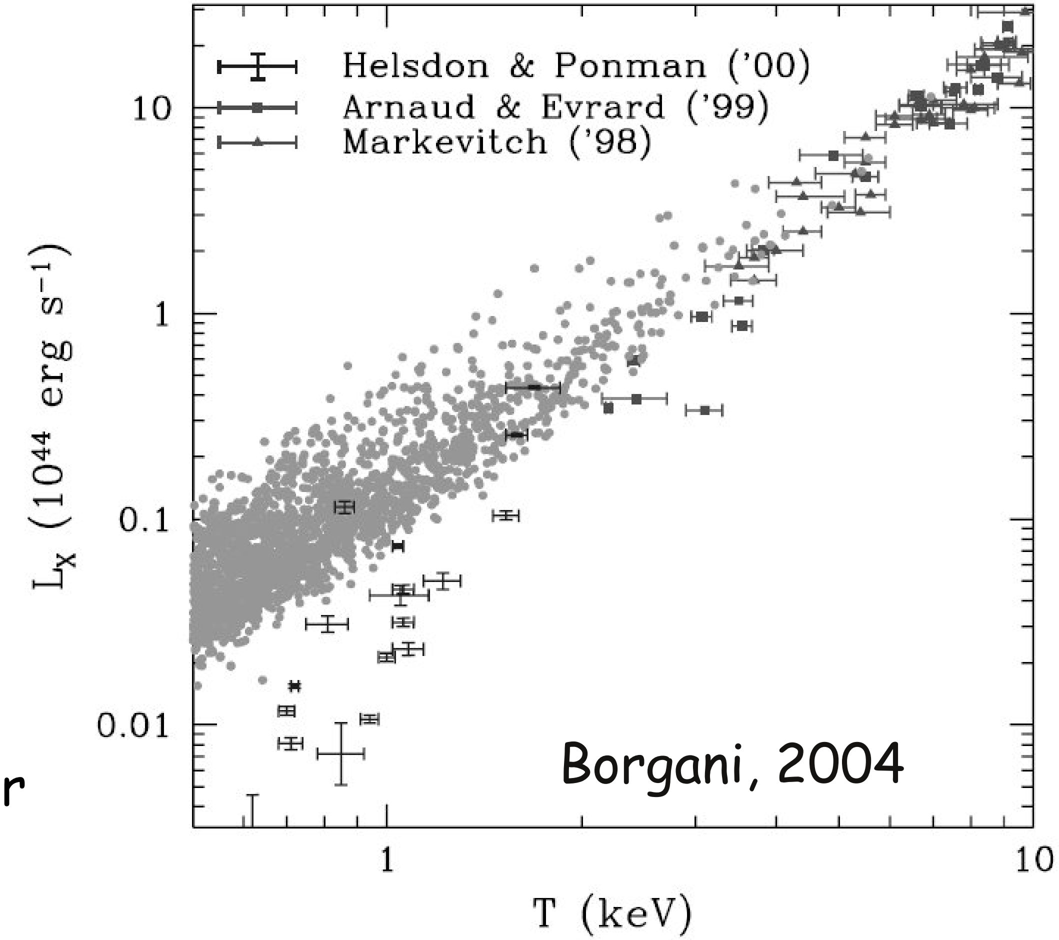
Other (related) problems:

1. Scaling relations that deviate from self-similarity

2. Gas radial profiles e.g. temperature, density

3. Metallicity gradients

4. Ages and masses of central cluster galaxies,...



Borgani, 2004

Implementation

Phenomenological BH growth and feedback models in cosmological simulations of galaxy clusters:

I MPA group:

Springel 2005; Sijacki 2006, 2007, 2008, 2009

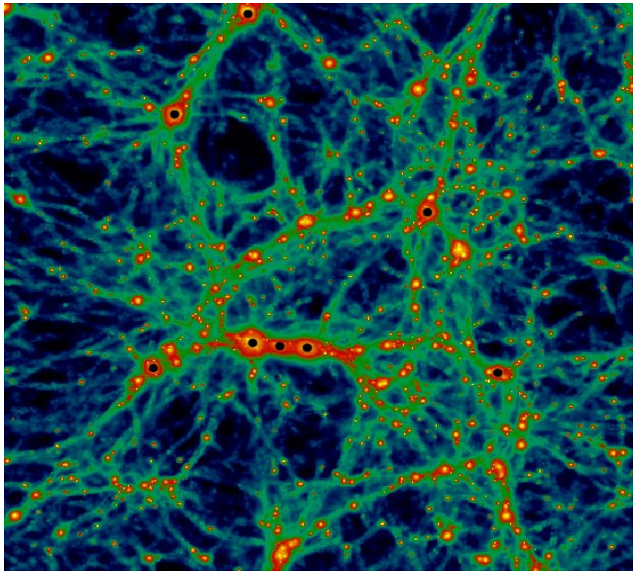
II Leiden group:

Booth & Schaye 2009;

III French-Swiss group:

Teyssier 2011; Dubois 2010

Implementation



MPA group Tree-SPH code GADGET

- BHs: collisionless sink particles
- Black hole seeding with FOF finder on the fly:
  every halo with M > Mthresh acquires a central BH of mass Mseed
  typical choices Mthresh = $10^{10}M_\odot$ Mseed = $10^5M_\odot$
- BH growth:

via mergers with other BHs (within smoothing length & Vrel < Cs)
or via gas accretion (Bondi-like) limited to the Eddington rate

$$\dot{M}_{\rm BH} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{\left(c_{\rm s}^2 + v^2\right)^{3/2}} \qquad \dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r}\,\sigma_{\rm T}\,c}$$

with α = 100 volume average of Bondi rates for cold and hot ISM

Implementation

MPA group Tree-SPH code GADGET:

- BH feedback is in two modes (analogous to X-ray binaries):

1. Quasar feedback if BHAR > 0.01 x Eddington rate
   small fraction of bolometric luminosity couples THERMALLY to the surrounding gas

$$\dot{E}_{\rm feed} = \epsilon_{\rm f} L_{\rm r} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{M}_{\rm BH}c^2$$

with $\varepsilon_r = 0.1$ and $\varepsilon_f=0.05$

- BHs are in quasar mode at high redshifts (until z ~ 1-2), inhabiting protogroups/clusters and acquire most of their mass (i.e. Soltan's argument)

Implementation

EXTENSIONS:

1. viscous bubbles
2. CR bubbles
3. BH spins
4. BH recoils

MPA group Tree-SPH code GADGET:

1. Radio feedback if BHAR < 0.01 x Eddington rate

THERMAL bubbles (determined by the BH)

$$E_{\rm bub} = \epsilon_{\rm m}\epsilon_{\rm r}c^2\delta M_{\rm BH}$$

with $\varepsilon_r = 0.1$, $\varepsilon_m = 0.2$, $\delta_{BH} = 0.01$.

$$R_{\rm bub} = R_{\rm bub,0}\left(\frac{E_{\rm bub}/E_{\rm bub,0}}{\rho_{\rm ICM}/\rho_{\rm ICM,0}}\right)^{1/5}$$

with $R_{bub,0} = 30$kpc, $E_{bub,0} = 10^{55}$erg, $rho_{ICM,0} = 10^4$Msun/kpc^3, and Rbub scaling derived from solutions for radio cocoon expansion.

- BHs are in radio mode at low redshifts in massive groups and clusters - "maintenance mode" regulating central gas cooling rate

Implementation

Leiden group (Joop Schaye):

Similarities:
1. Based on the same code GADGET
2. Based on the same model for BH growth and feedback

Differences:
1. Due to different EOS Bondi-like prescription has 2 parameters, with α depending on local gas density to some power β (no difference in cosmological simulations)

2. Only quasar feedback prescription (no radio mode)

3. Energy in quasar mode not injected continuously but stored until temperature of the surrounding particles can be increased by 10^8K

Implementation

French-Swiss group (Roman Teyssier):

Similarities:

1. Based on the same model for BH growth and feedback

Differences:

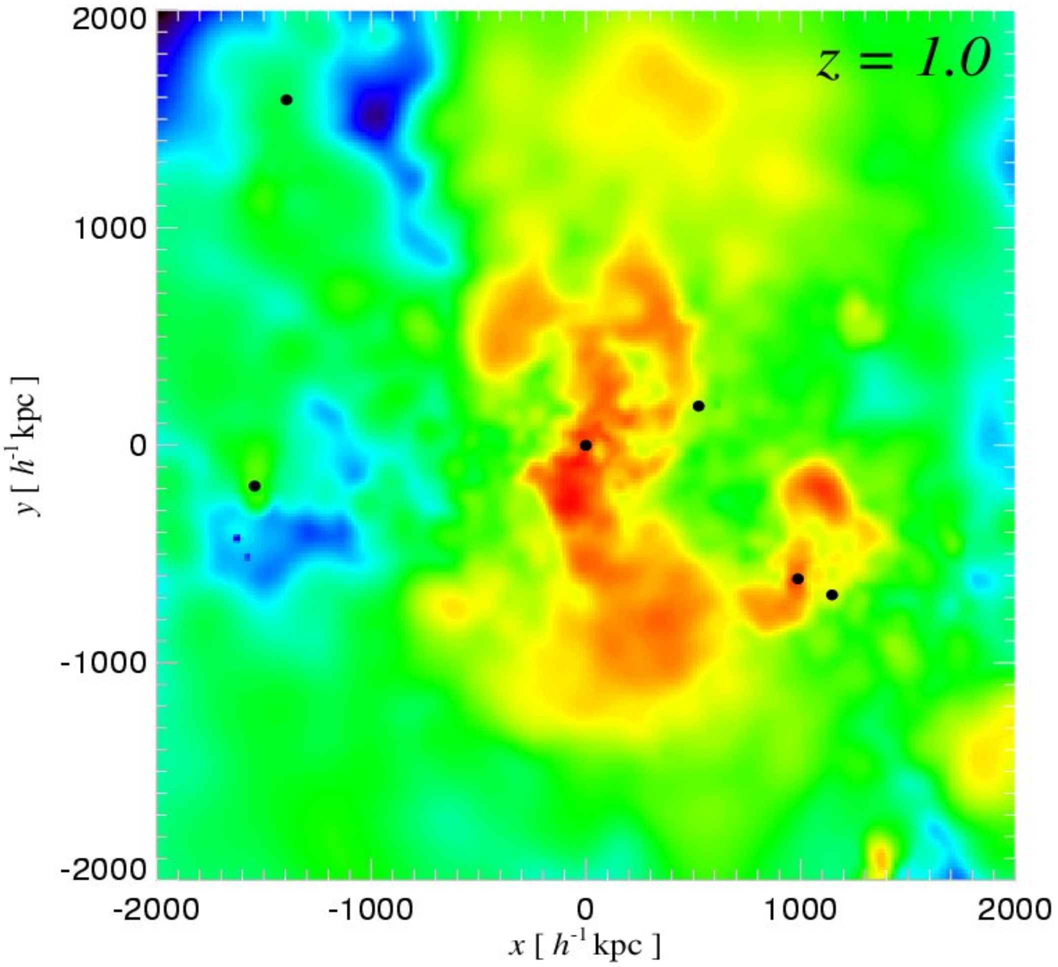
1. Implemented in grid-based code RAMSES

2. Different seeding prescription (based on gas & stellar density and stellar velocity dispersion)

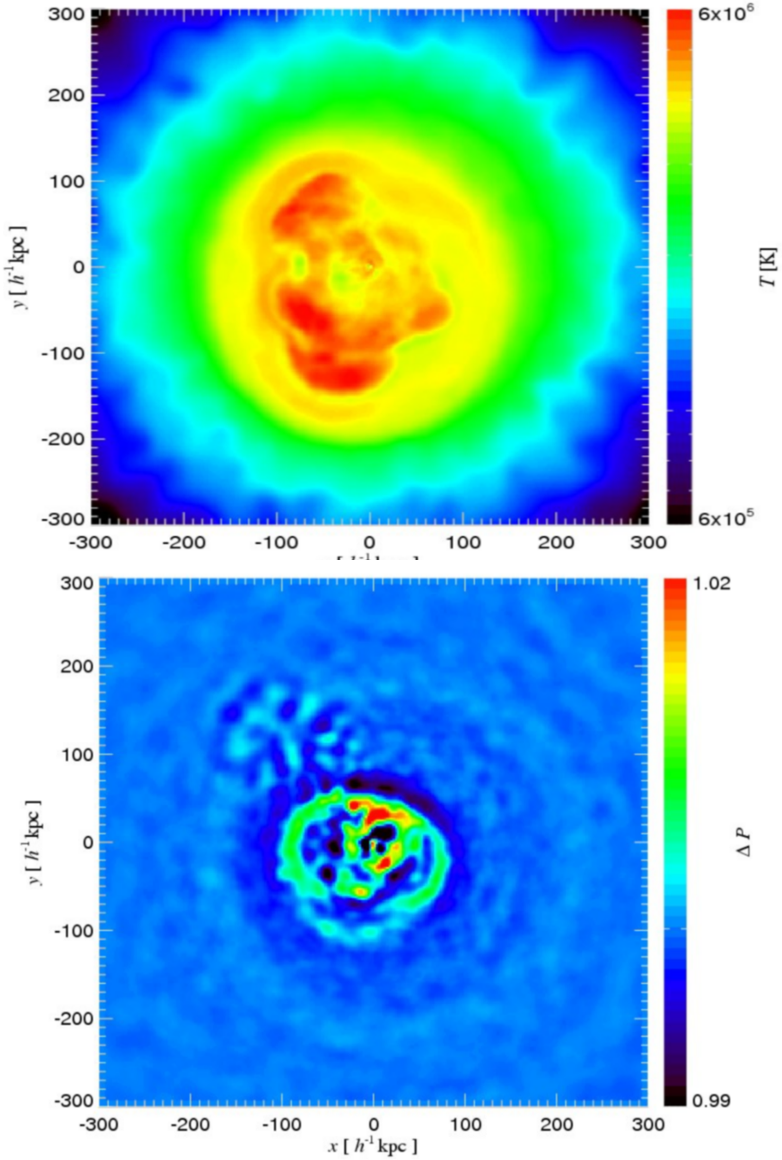
3. Only quasar feedback prescription (no radio mode) as Schaye

Dubois 2010: AGN feedback is sub-relativistic bipolar outflow - mass, momentum and energy deposition in a small cylinder

Results



MAP OF A GALAXY CLUSTER AT Z = 1
WITH OVERPLOTTED BHs



Results:

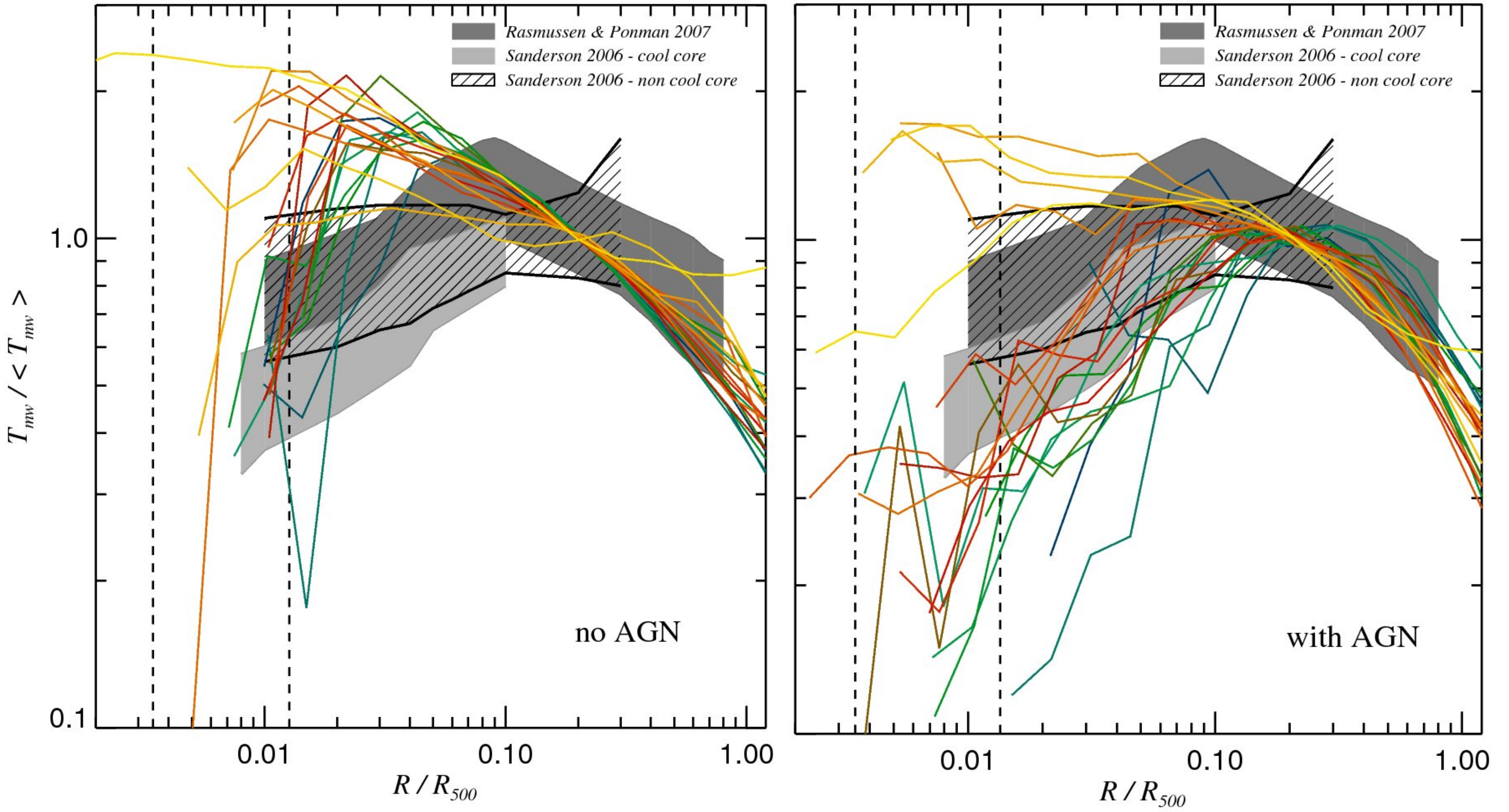
Statistical properties

Puchwein, Sijacki & Springel, 2008, ApJ
Sijacki et al.

Resimulation at very high resolution of 21 Millennium clusters with gas & BH physics – mass resolution increased by up to 64 times

range of halo masses: 8×10^{12} – 1.5×10^{15} Msun/h

TEMPERATURE PROFILES

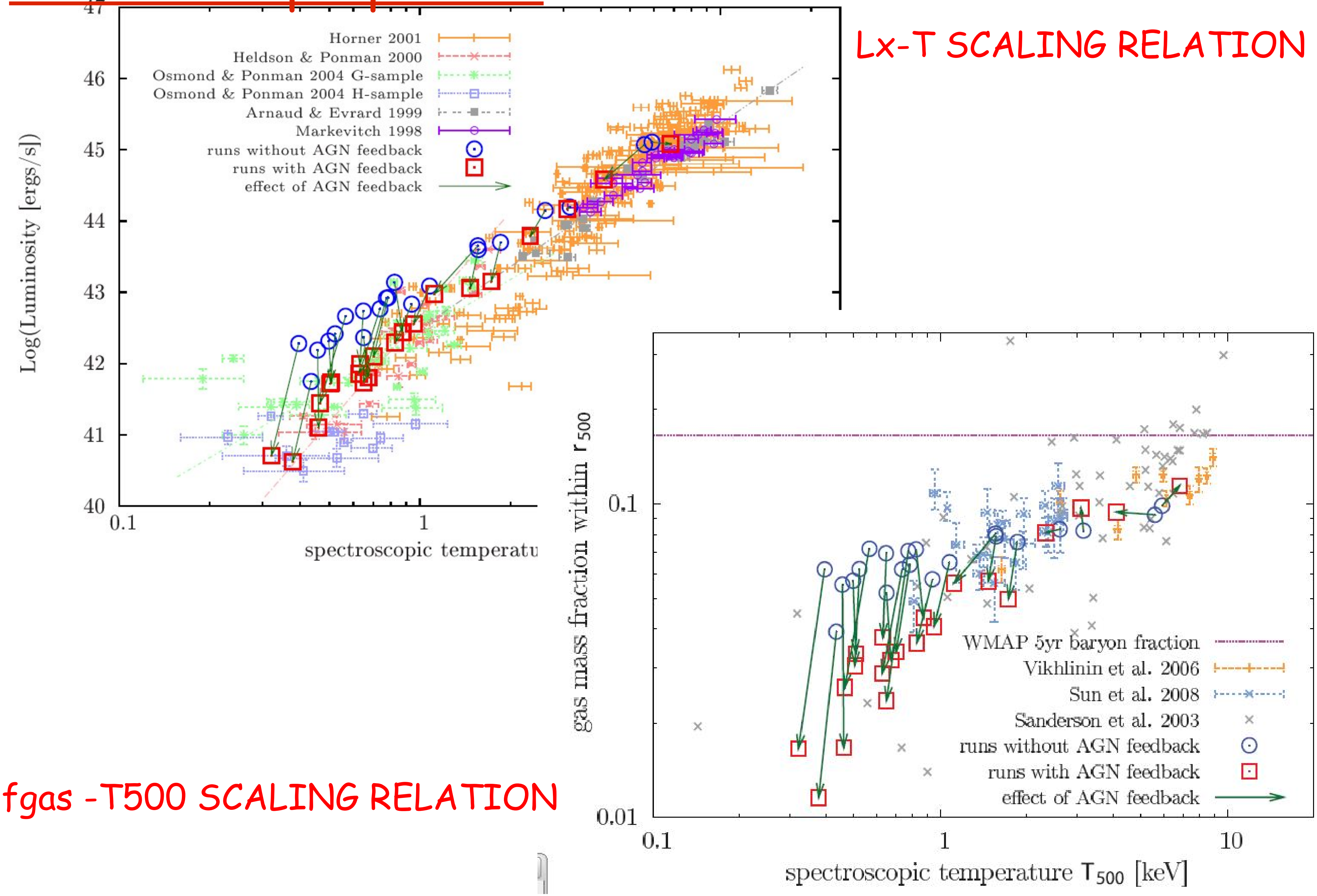


Results:

Statistical properties

Puchwein, Sijacki & Springel, 2008, ApJ

Lx-T SCALING RELATION

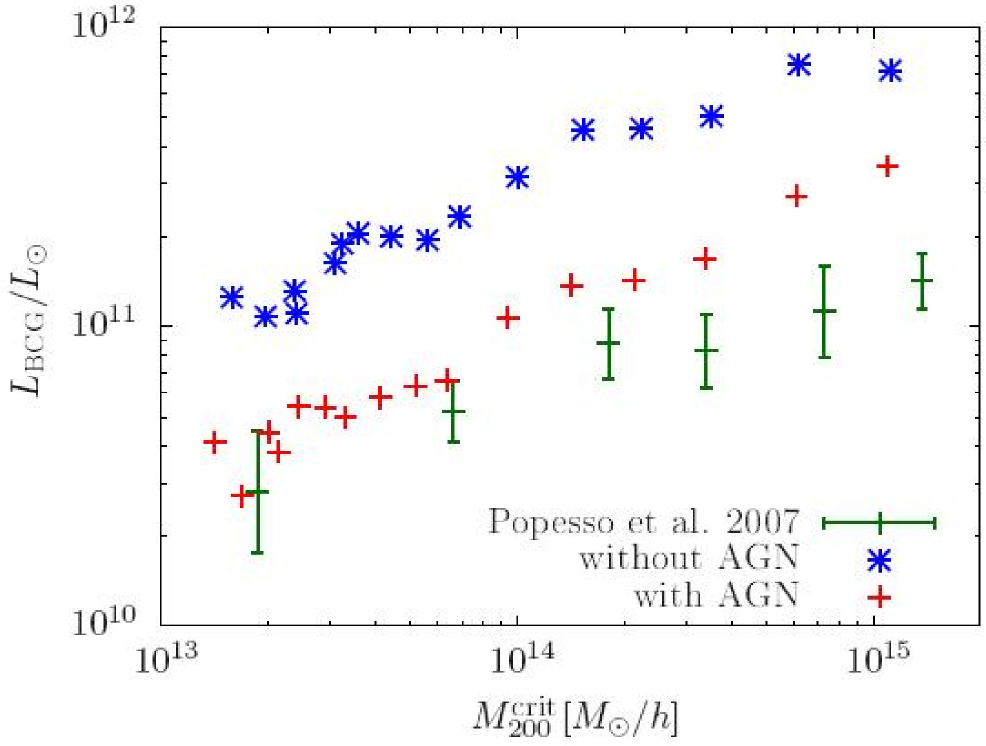


fgas -T500 SCALING RELATION

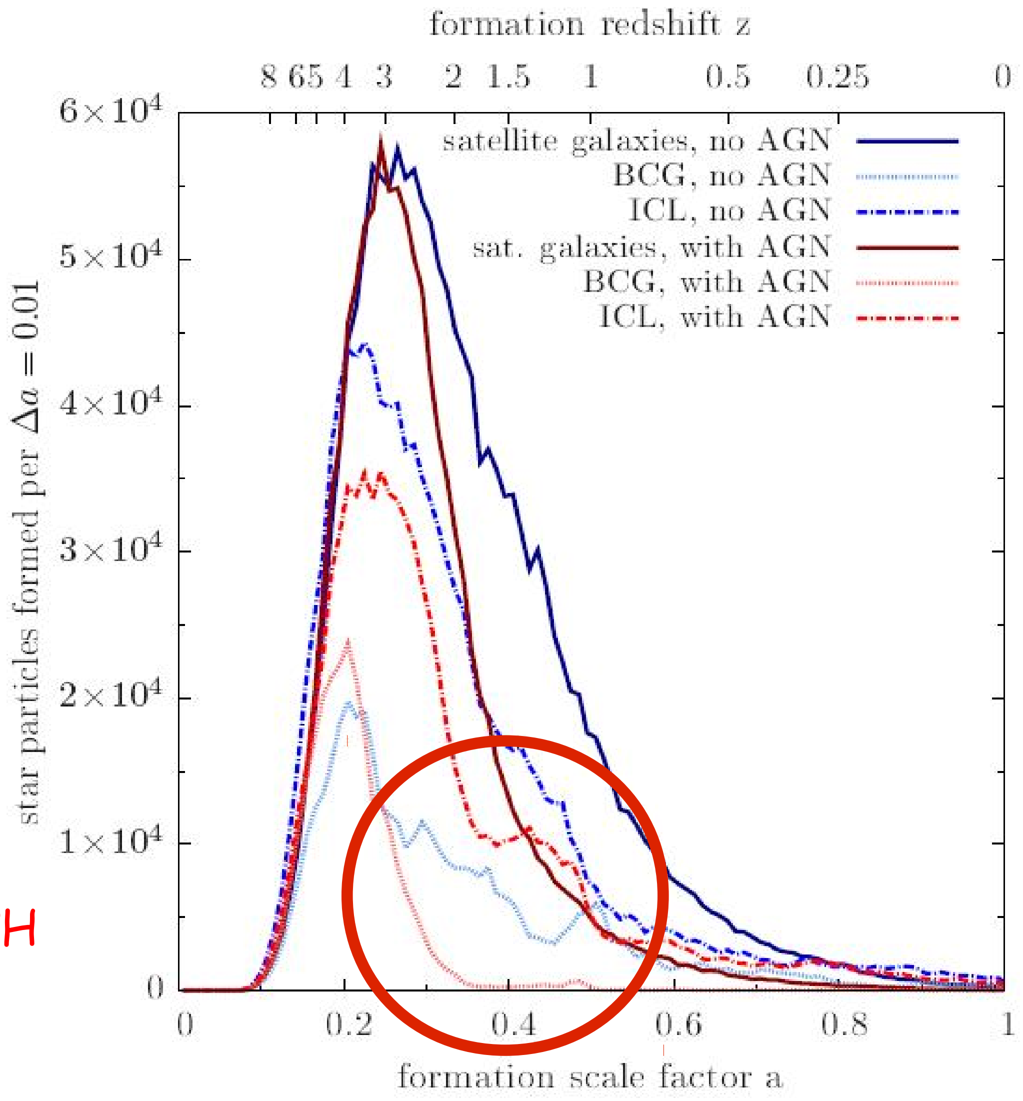
Results:

BCG, satellites and ICL

Puchwein, Springel, Sijacki & Dolag 2010, MNRAS



BCG LUMINOSITIES

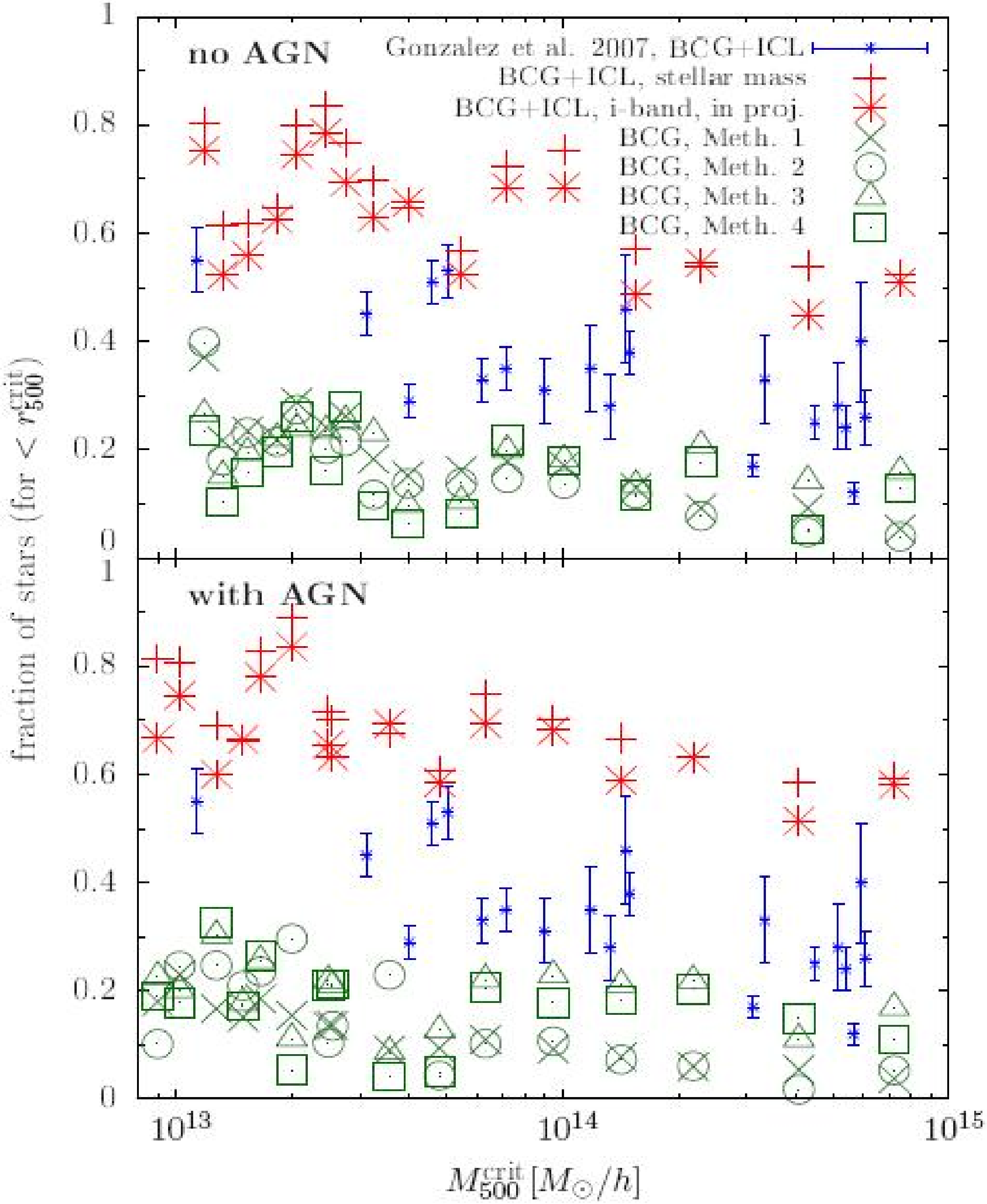


BCG STAR FORMATION EPOCH
DOWN-SIZING

Results:

BCG, satellites and ICL

Puchwein, Springel, Sijacki & Dolag 2010, MNRAS



FRACTION OF IC STARS

TOO MUCH IC STARS:

- AGN feedback not efficient enough in small mass galaxies?

- intracluster star formation within “cold blobs” which are stripped from infalling galaxies?

Results

The cosmological results of all three groups qualitatively agree:

Similarities:

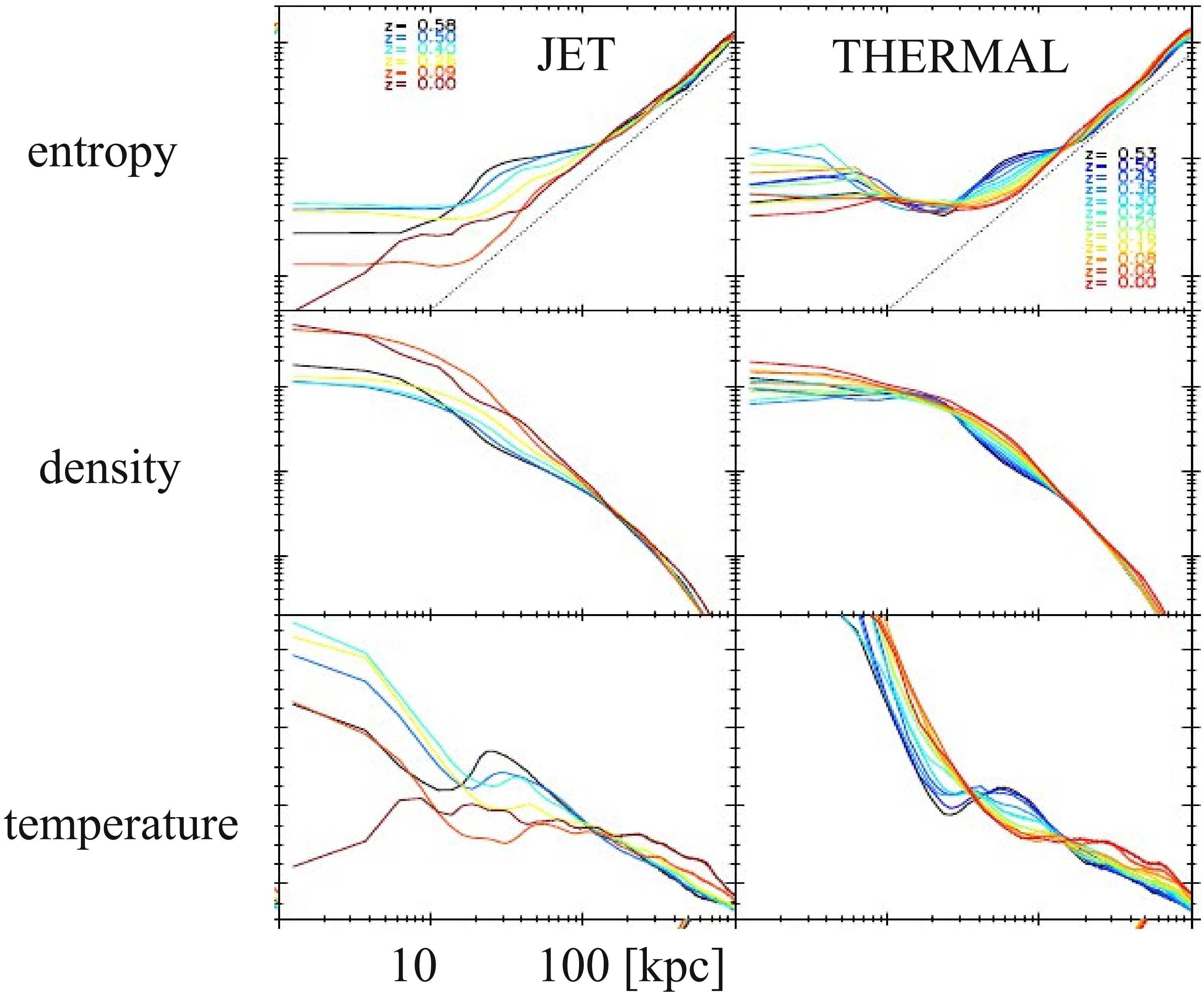
1. AGN feedback is energetic enough to offset overcooling
2. Central gas density is decreased
3. Lower SFR in massive galaxies
4. Stellar mass of the BCG significantly reduced
5. Lower baryon fraction within Rvir

Differences:

1. No significant differences between MPA and Leiden group (not too surprising)
2. Hard to quantify detailed differences between Teyssier's group and others: they have only one high resolution object!
3. But, ...

Results

...There are differences between Teyssier and Dubois AGN feedback implementation (Dubois2011)

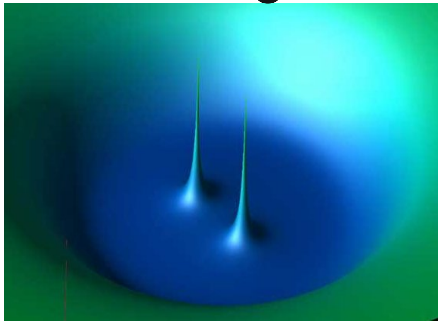


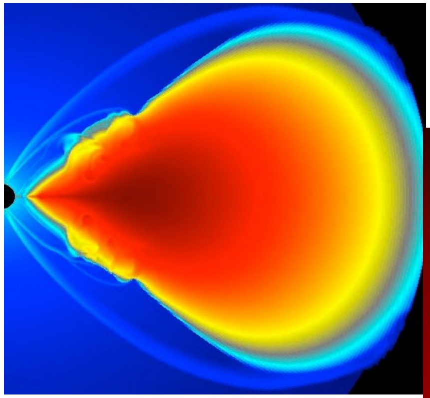
Uncertainties in...

...Physical mechanisms that should occur on widely different scales: how to incorporate them faithfully in fully cosmological simulations?

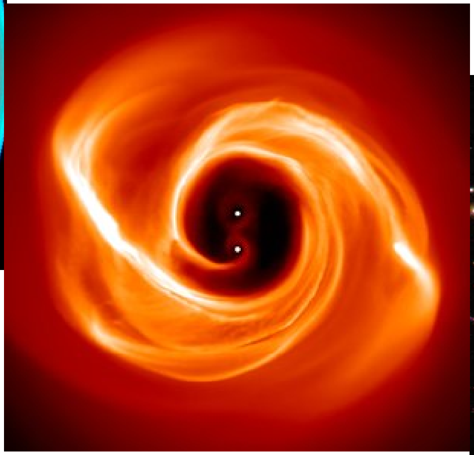
- Sub-grid models need higher level of sophistication
- Much more powerful computing could breach the gap between (some of) these length-scales

BH mergers

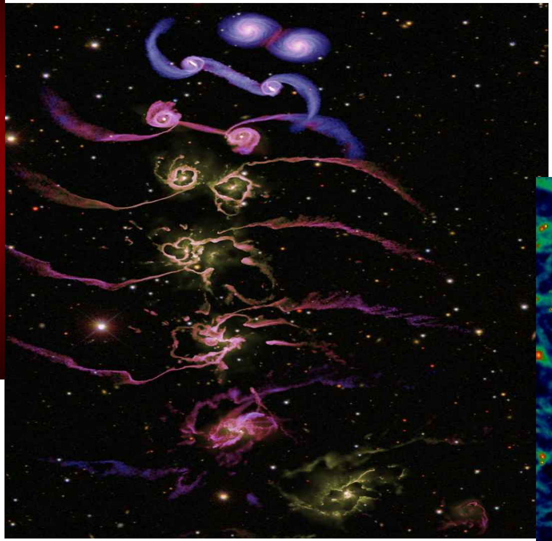




BH accretion disk

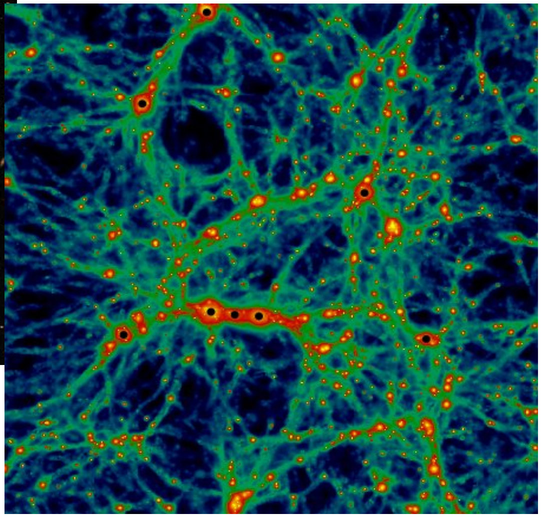


circumbinary disk



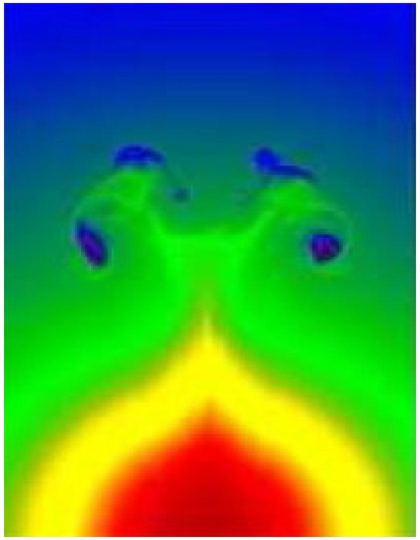
galaxy merging

cosmological structure formation



Uncertainties in...

...Physical mechanisms that do probably occur but we don't know their magnitude/parametrization

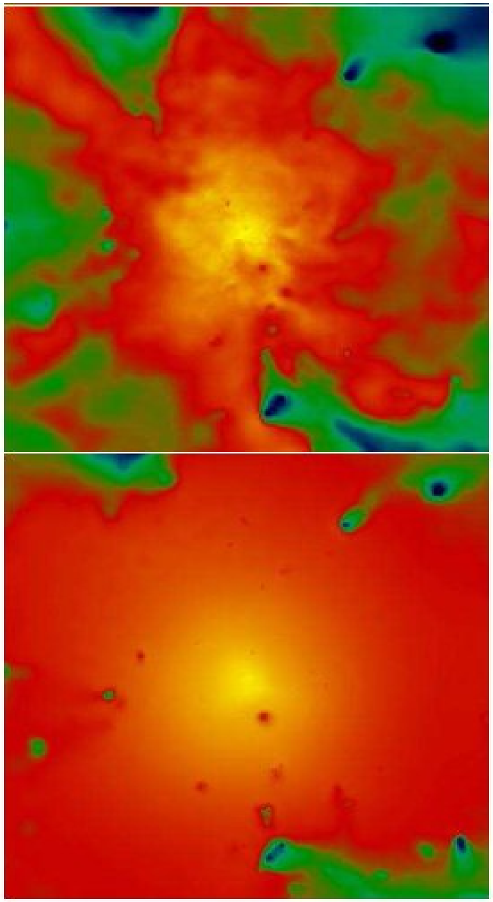


Observational multiwavelength input is essential!

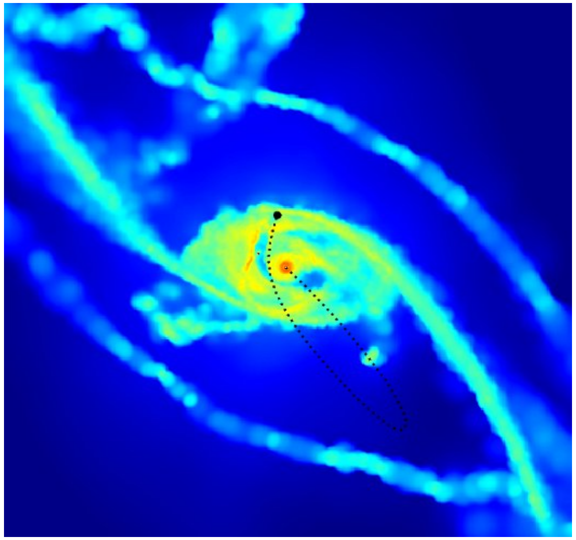
- Detailed comparisons with well studied cases
- Statistical comparisons over a range of redshifts

VISCOSITY
Reynolds et al.,
Ruszkowski et al.
Sijacki et al.
Dong et al.

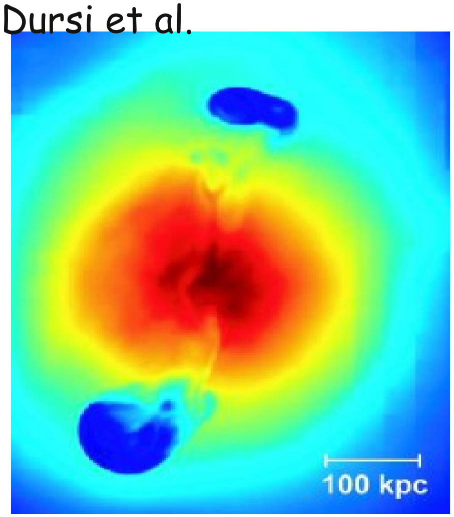
THERMAL CONDUCTION
Balbus et al. Jubelgas et al.
Parrish et al. Bogdanovic et al.

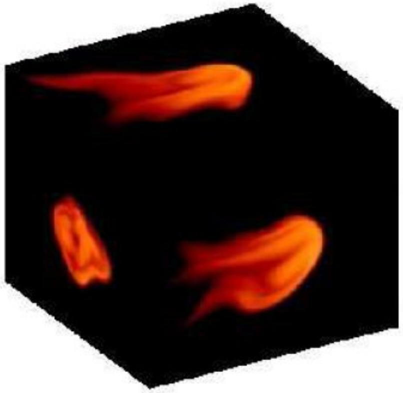


BH MERGING - RECOILS
Escala et al., Cuadra et al.
Merritt et al., Sijacki et al.



MHD JETS and BUBBLES
Xu et al.,Ruszkowski et al.
O'Neill et al. Robinson et al.
Dursi et al.



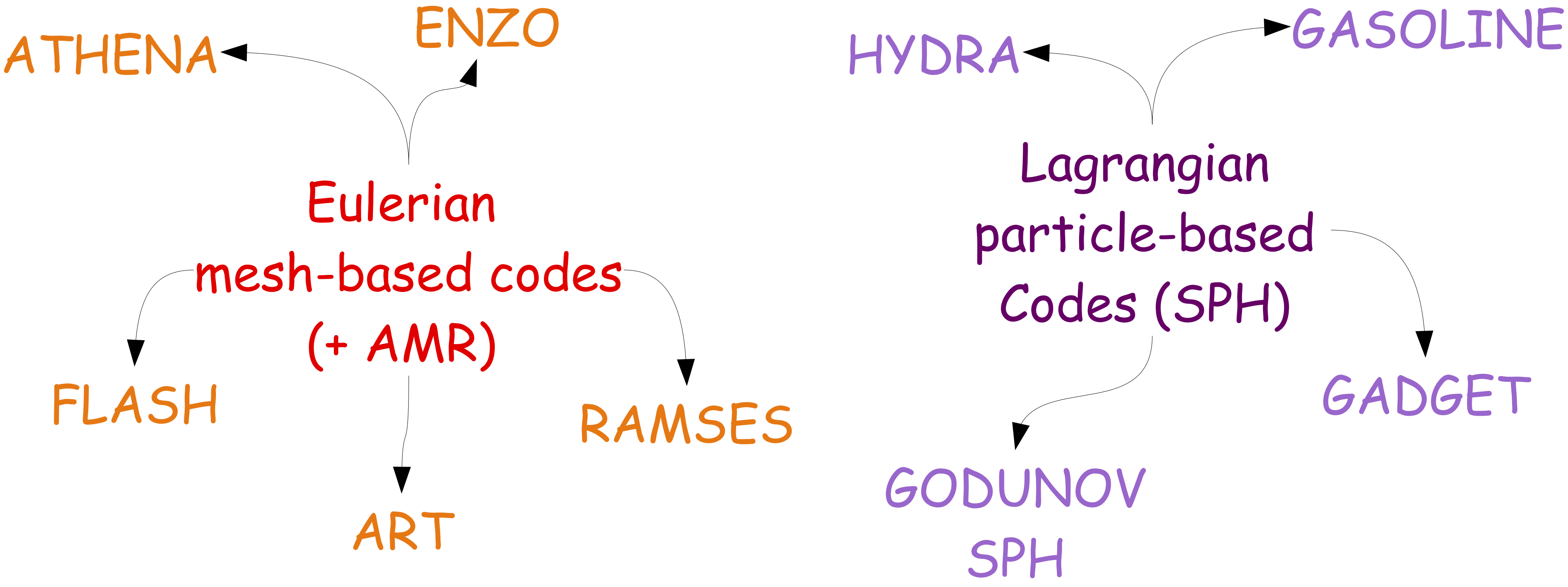


COSMIC RAY BUBBLES
Guo et al., Sijacki et al.,
Ruszkowski et al.

Uncertainties in...

...Hydro and gravity solvers of different codes used to simulate galaxy clusters

- Much more careful code comparisons are needed!
- Improvements in basic code solvers



Eulerian mesh-based codes (+ AMR)

ATHENA

ENZO

FLASH

ART

RAMSES

Lagrangian particle-based Codes (SPH)

HYDRA

GASOLINE

GADGET

GODUNOV SPH

The Santa Barbara Cluster Comparison Project

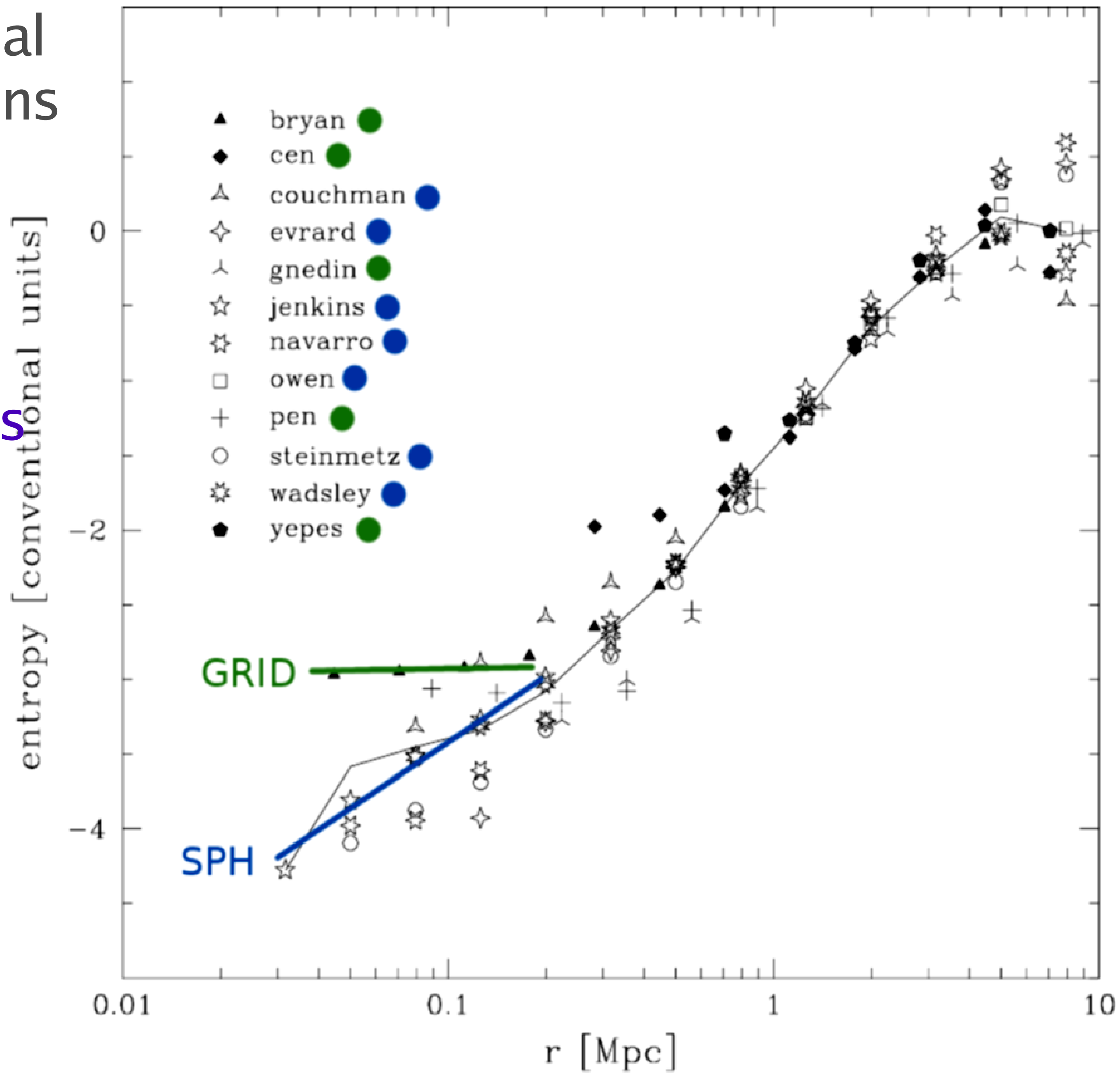
Frenk et al. 1999

Non-radiative cosmological hydrodynamical simulations

12 codes

SPH simulations:
power-law entropy profiles

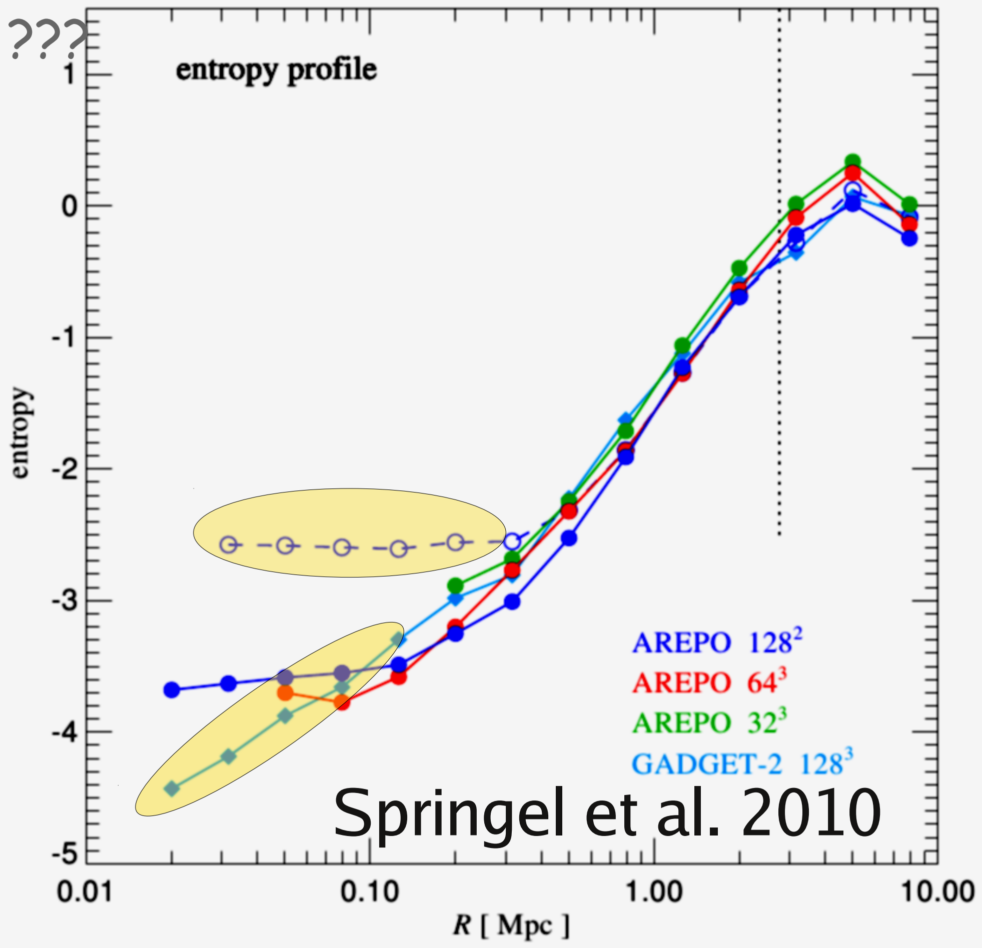
GRID-based simulations:
cored entropy profiles



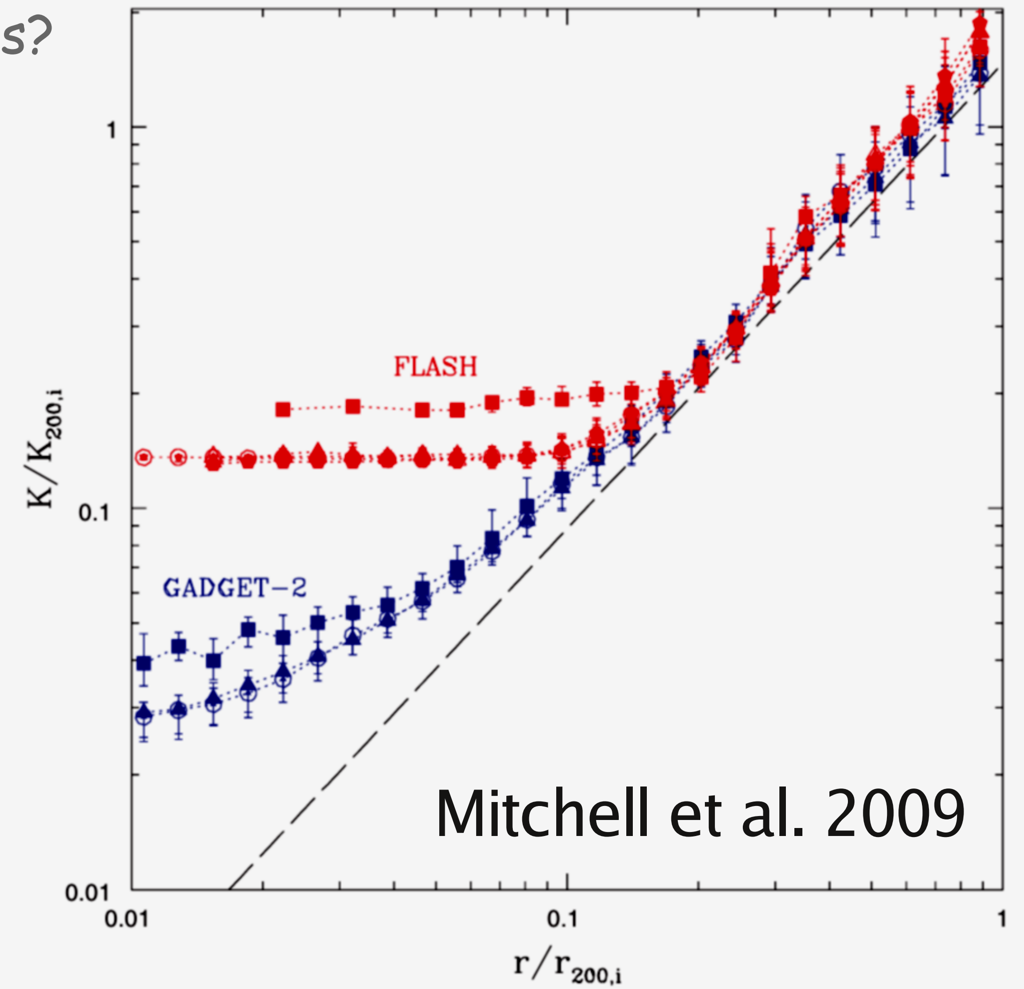
Discrepancy between SPH and grid entropy profiles

What causes this discrepancy???

- lower effective resolution of grid codes?
- different gravity solvers?
- Galilean non-invariance of grid codes?
- artificial viscosity of SPH codes?
- treatment of fluid instabilities?
- gravitational N-body noise?
- ???



Springel et al. 2010

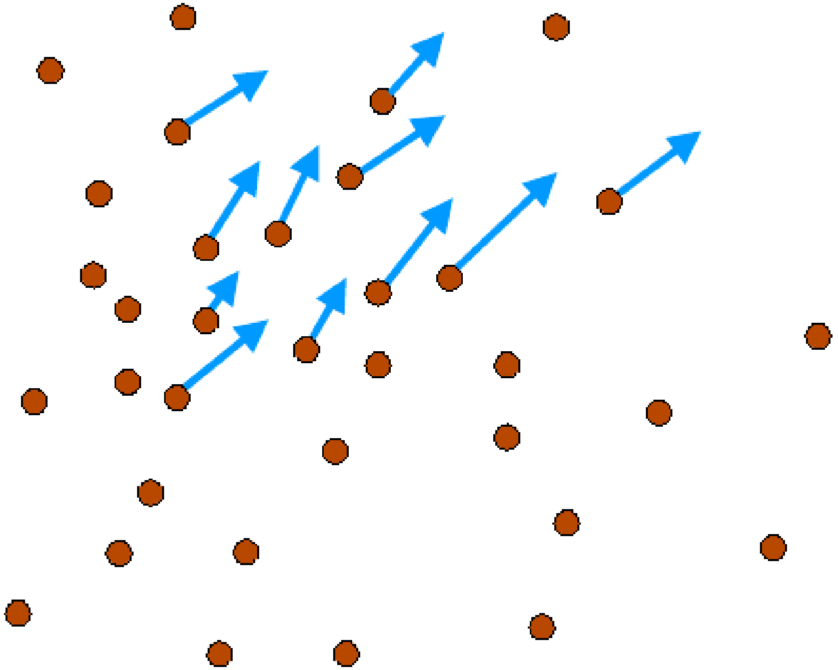


Mitchell et al. 2009

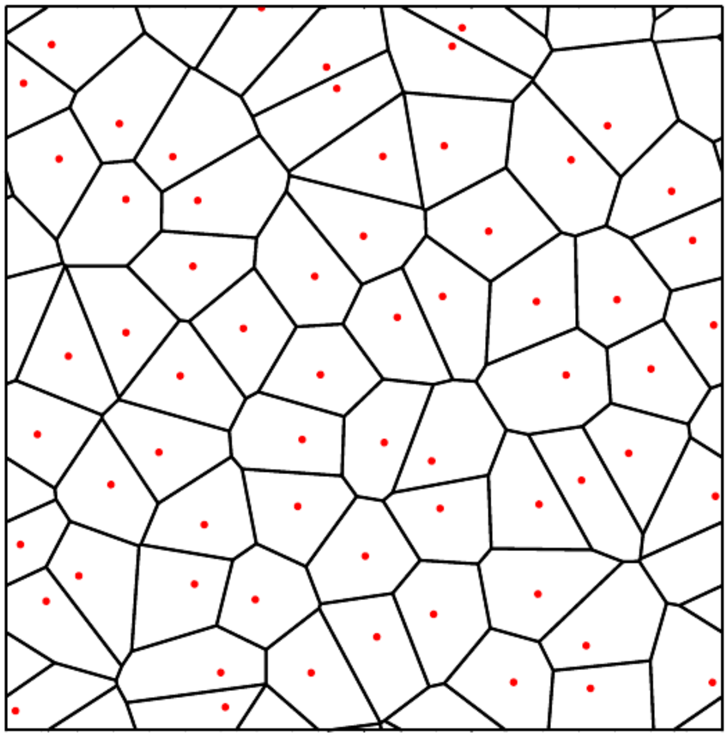
FUNDAMENTAL IMPLICATIONS FOR:
- UNDERSTANDING ASTROPHYSICS OF GALAXY CLUSTERS
- USING GALAXY CLUSTERS AS HIGH-PRECISION COSMOLOGICAL PROBES

Our approach

GADGET (Springel et al. 2001, 2005)
Lagrangian method (SPH)
particles act as fluid elements



AREPO (Springel et al. 2010)
finite volume method on a
moving mesh (Lagrangian nature)



ADVANTAGES:

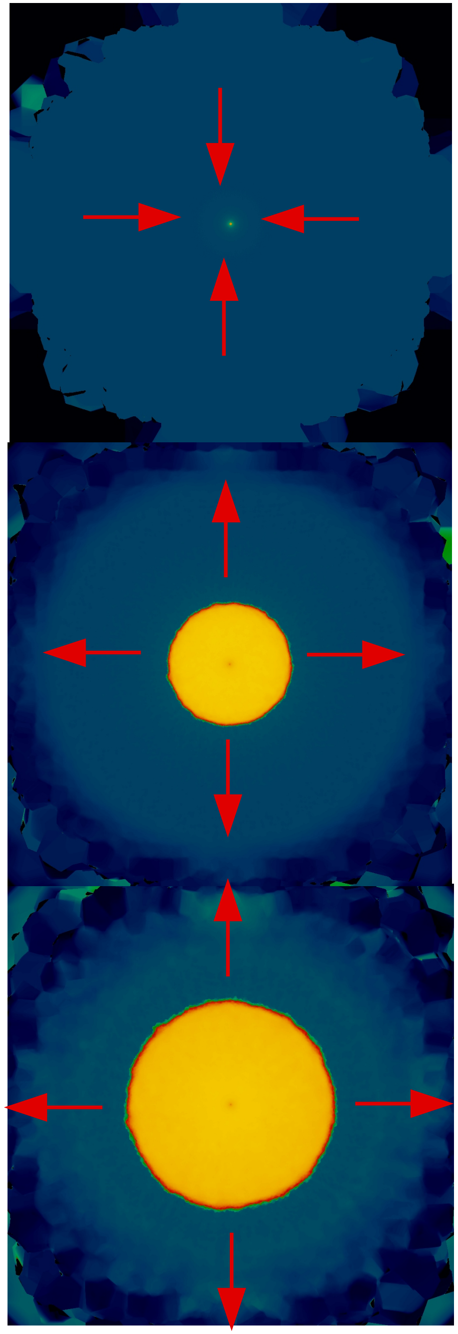
- identical initial conditions
- identical gravity solver

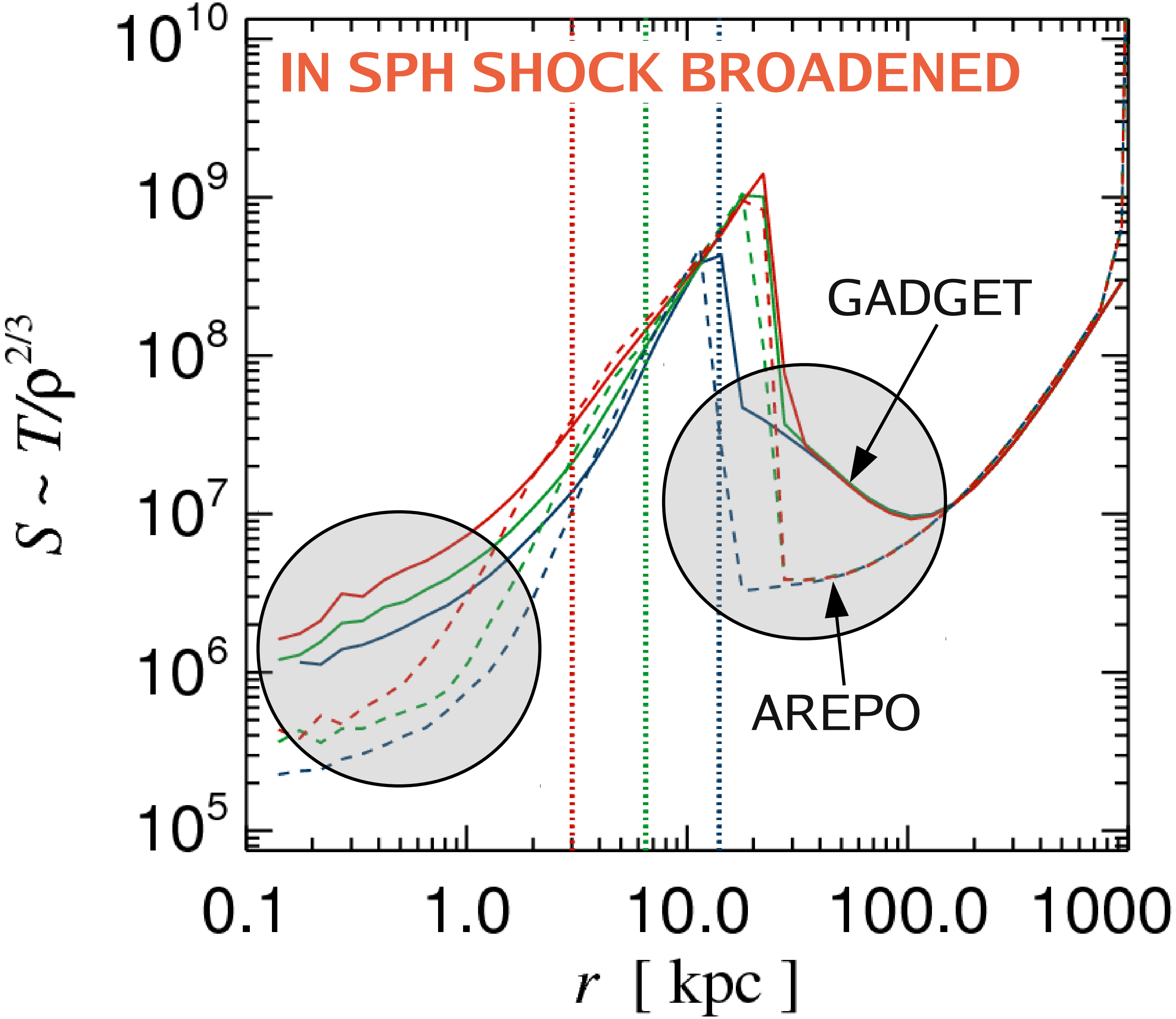
PHILOSOPHY:

devise as simple as possible numerical tests to isolate different physical/numerical effects and gauge their importance

Inflow of cold gas into a static potential: Strong shock

- NO GAS SELF-GRAVITY, NO COOLING
- STATIC HERNQUIST DM POTENTIAL
- RADIAL INFALL OF COLD GAS

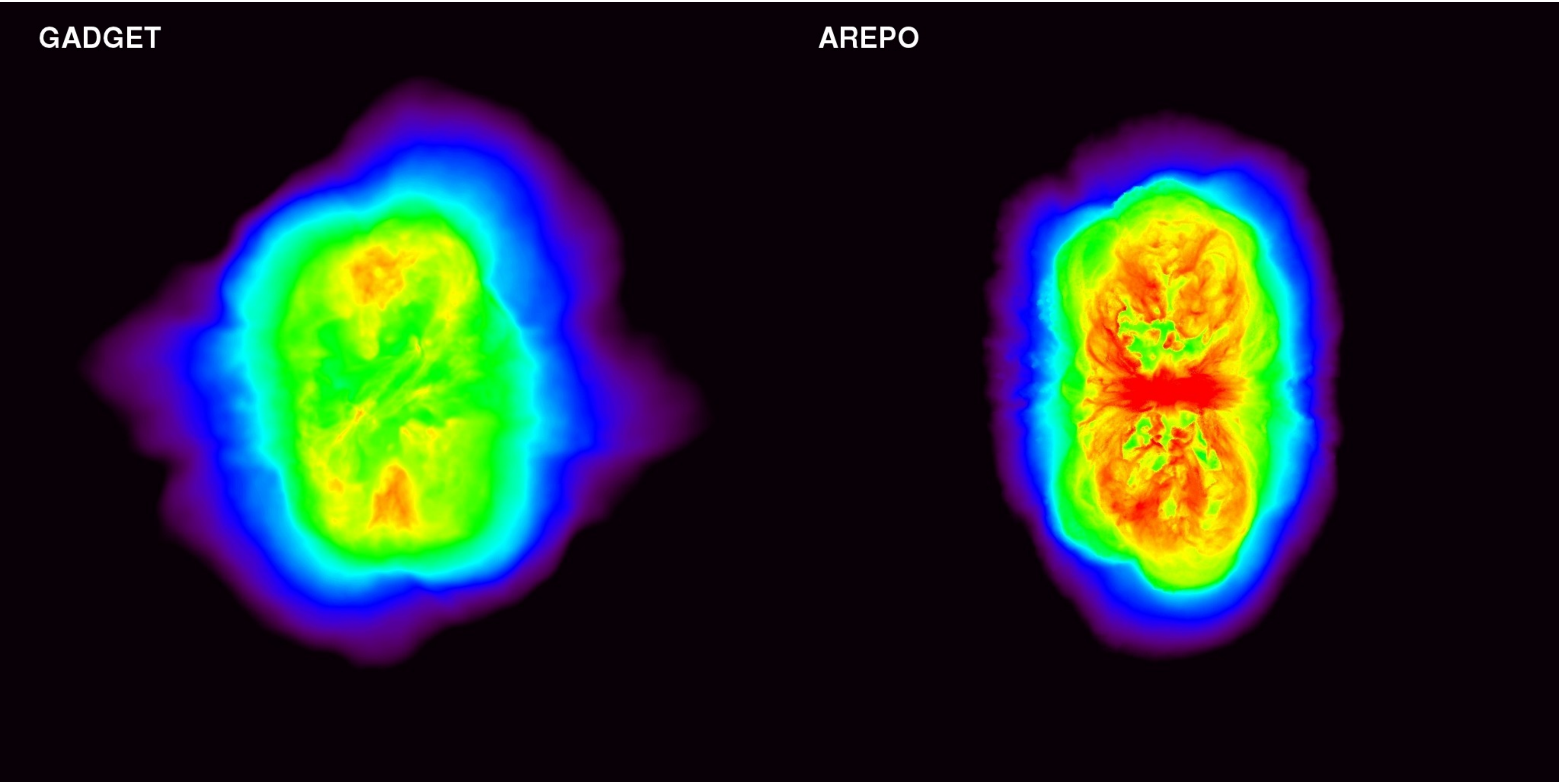




IN SPH SHOCK BROADENED

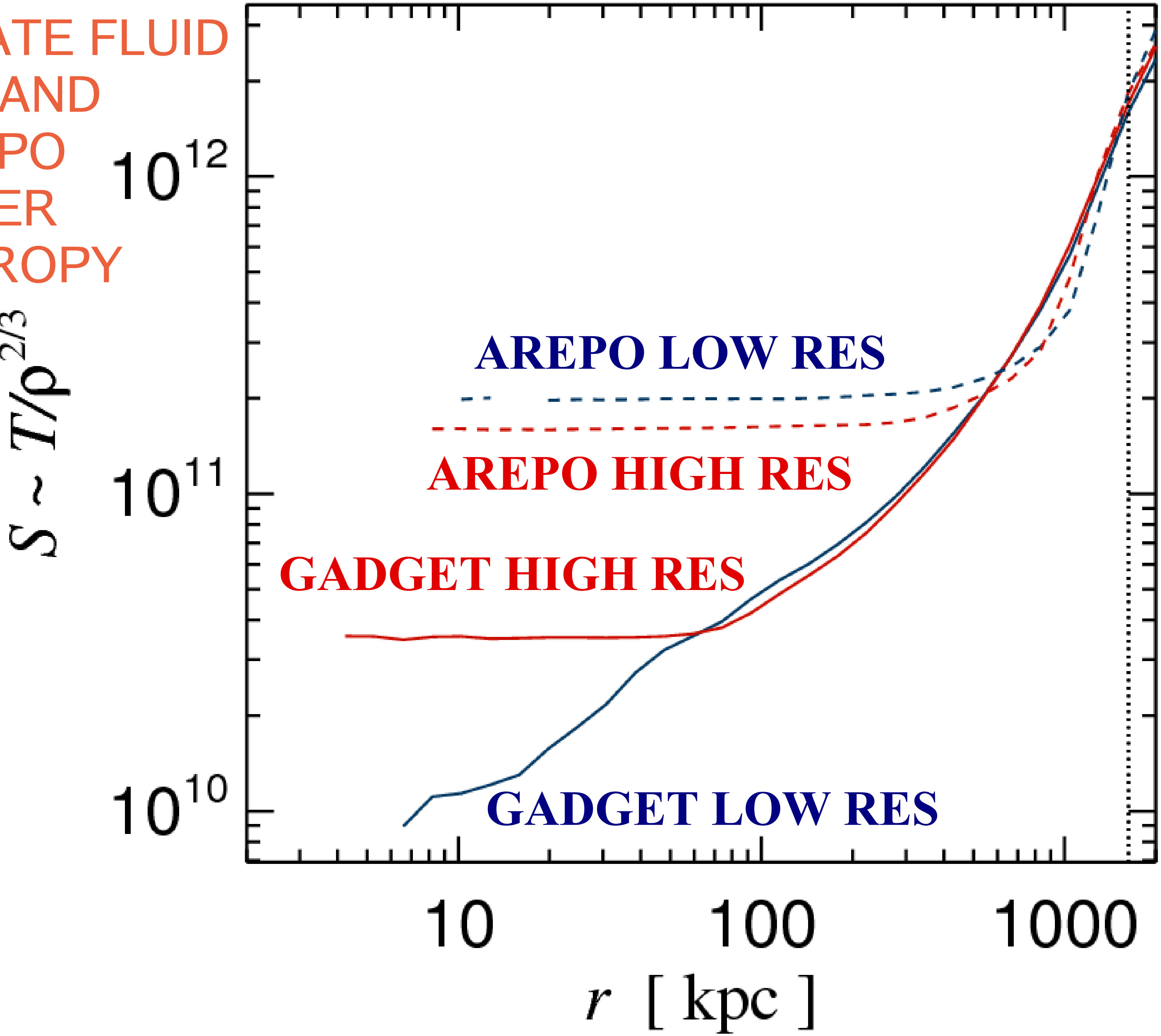
Infall of two cold gas spheres into a static potential:
interacting shocks and fluid mixing

- NO GAS SELF-GRAVITY, NO COOLING
- STATIC HERNQUIST DM POTENTIAL
- ~~RADIAL INFALL OF COLD GAS~~



Infall of two cold gas spheres into a static potential: interacting shocks and fluid mixing

MORE ACCURATE FLUID INSTABILITIES AND MIXING IN AREPO LEAD TO HIGHER CENTRAL ENTROPY



Bow shock in 3D

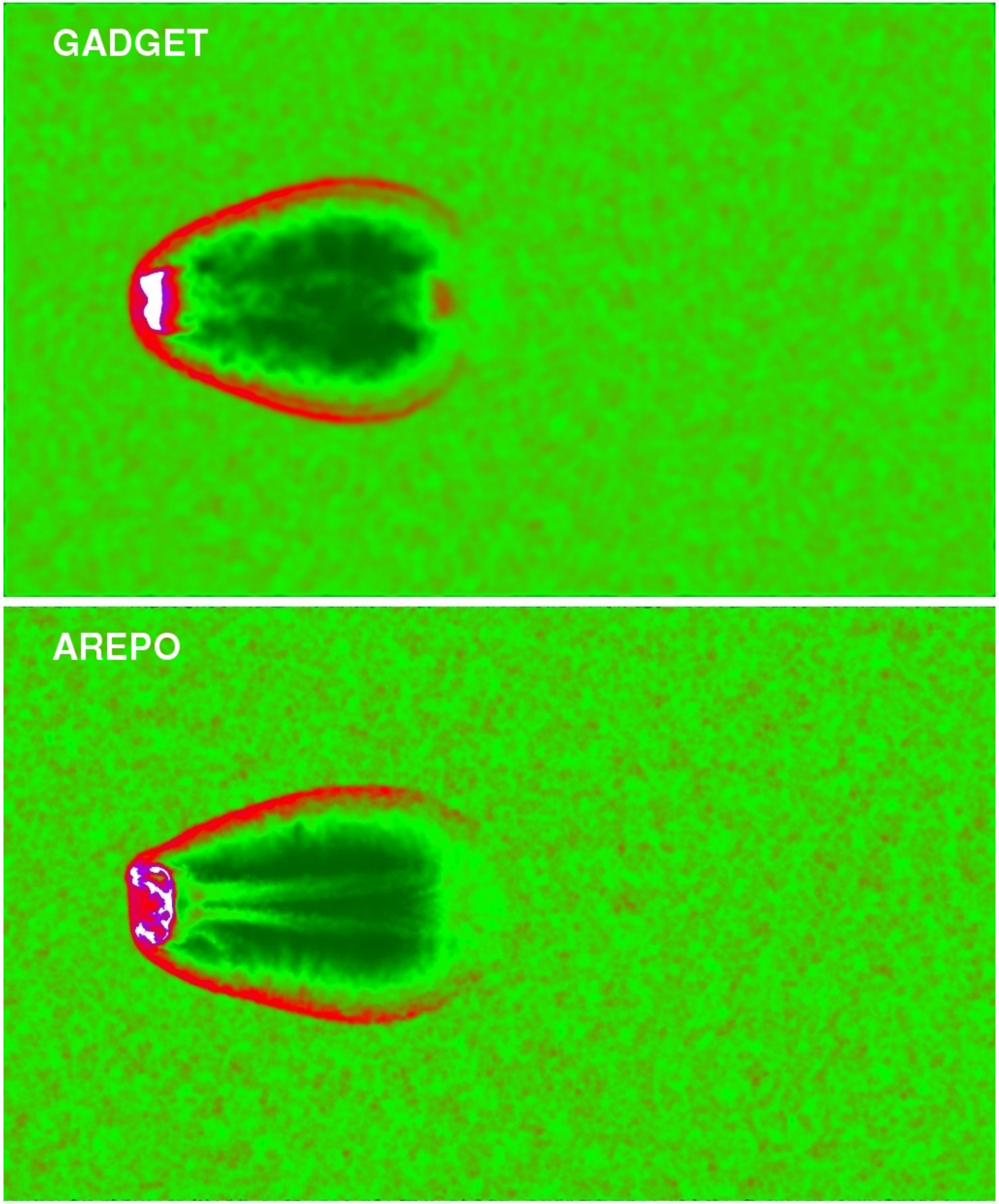
"BLOB" experiment (Agertz et al. 2007):

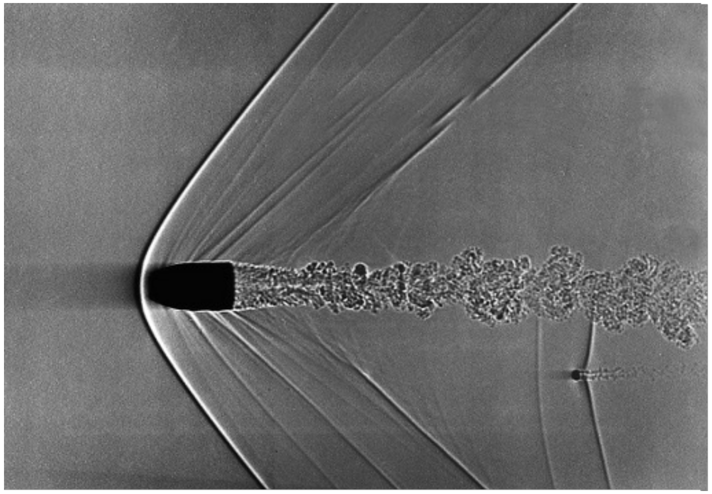
- high density blob in pressure equilibrium with surrounding hot medium

- external medium velocity = 1000km/s

tests:
 - development of dynamical instabilities, such as RT and KH

implications for:
- survival of satellites in clusters
- mixing of multi-phase medium
- level of turbulence



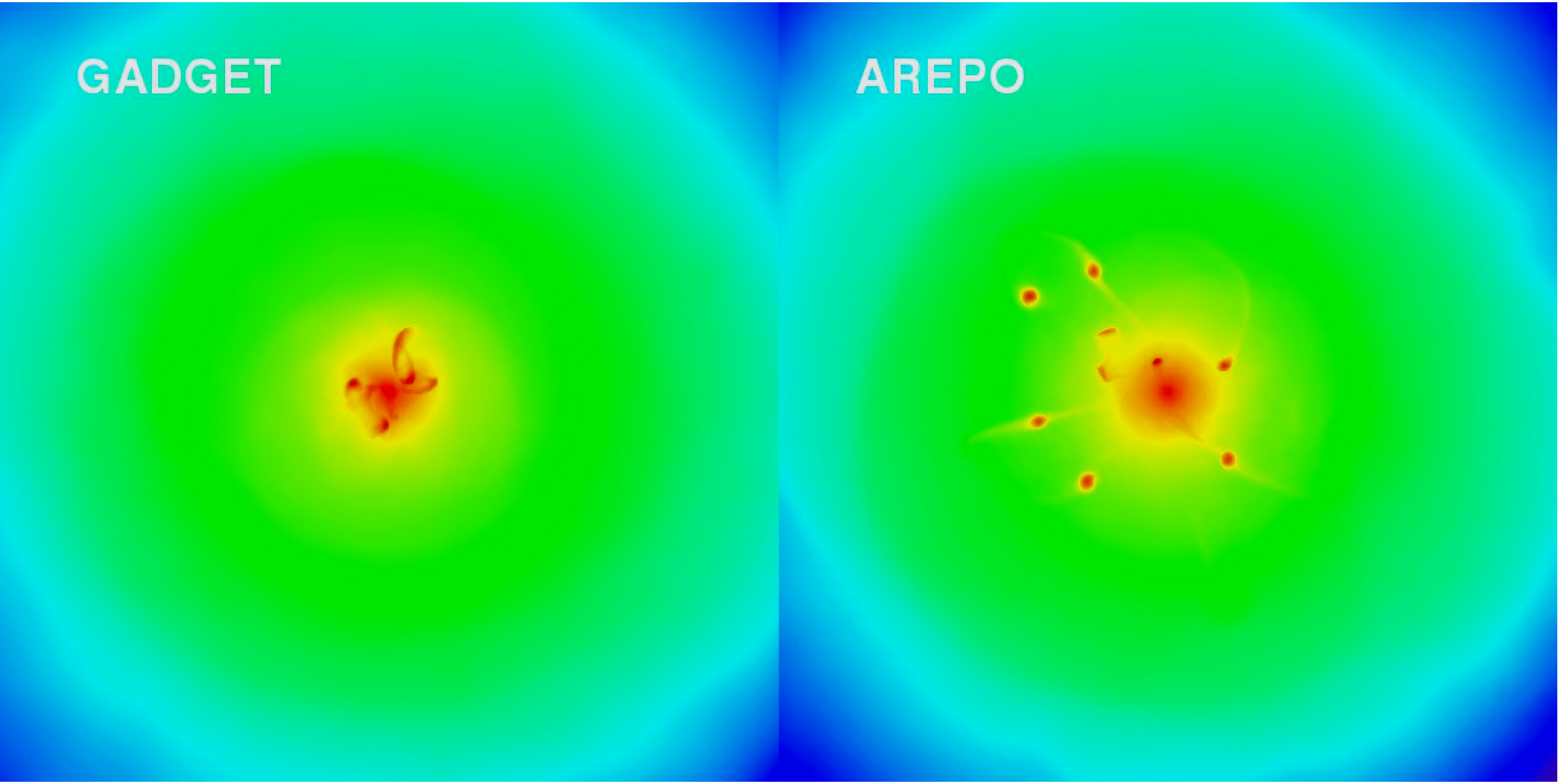


“Generalized Blob” Test

- ten dense blobs moving through the hot halo atmosphere:

NO COOLING $P_{BLOB} \sim 0.01 \times \max(P_{ICM})$

NO ROTATION

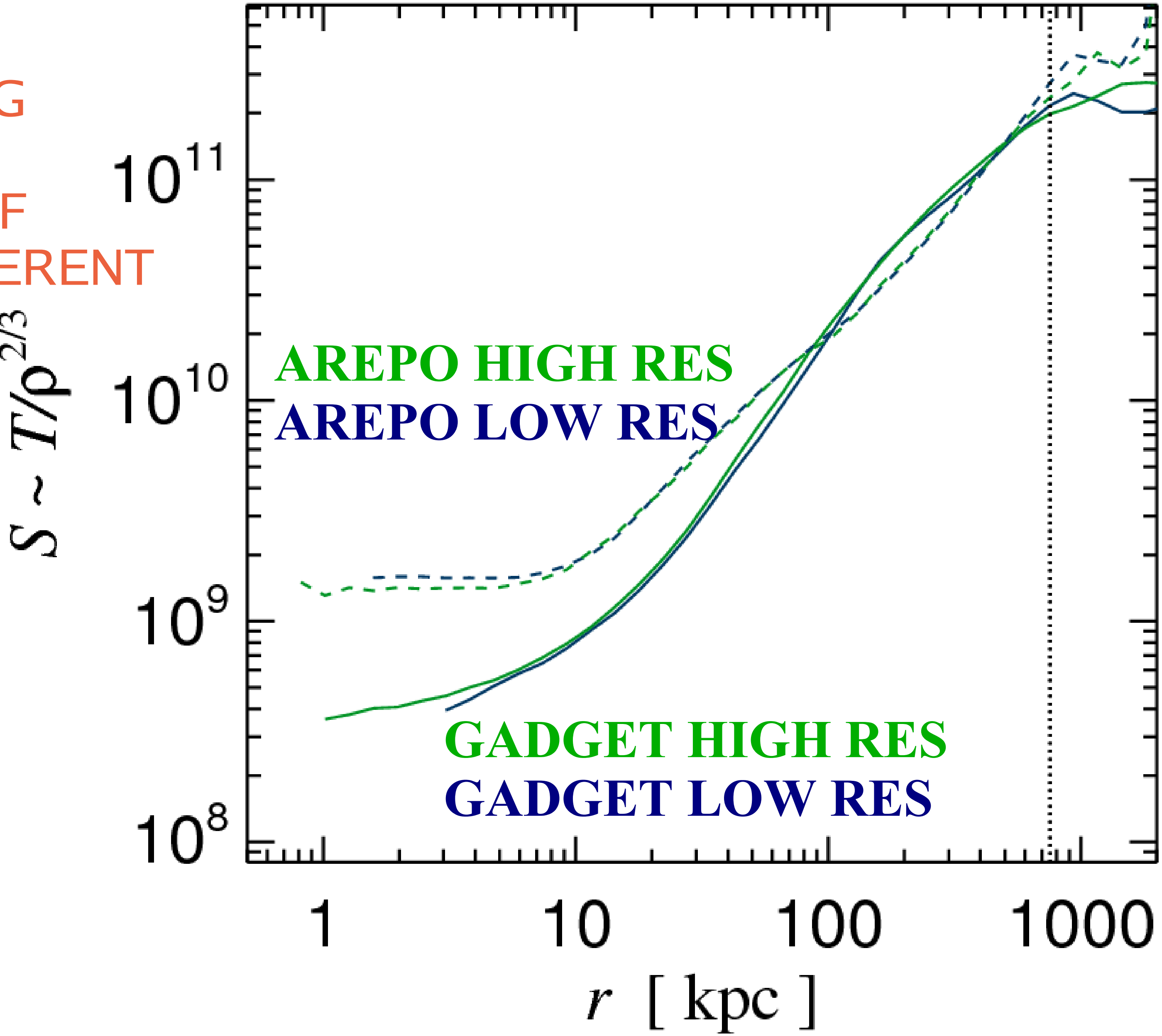


“Generalized Blob” Test

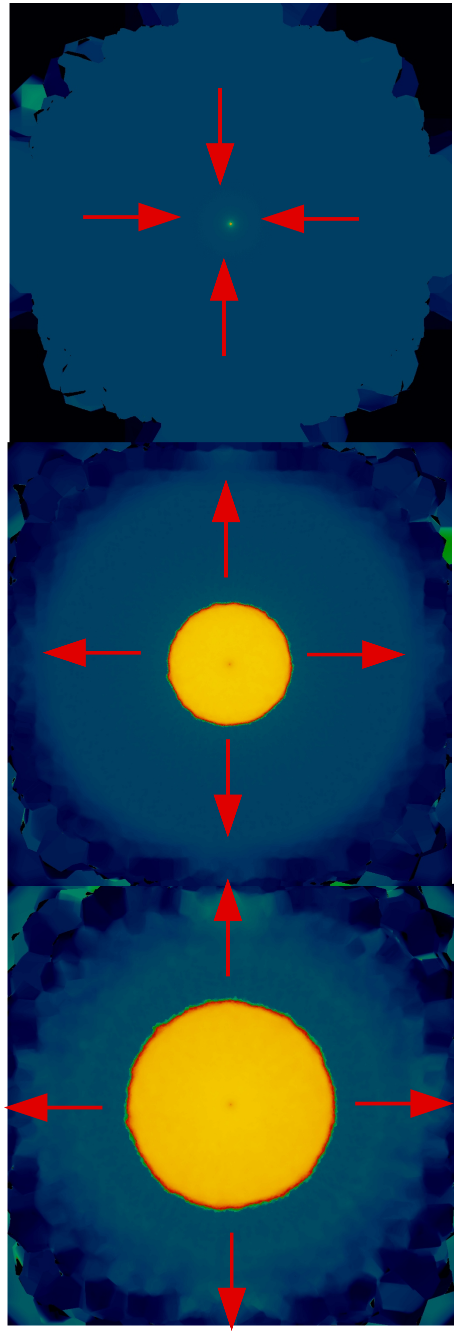
- ten dense blobs moving through the hot halo atmosphere:

NO COOLING
NO ROTATION

DIFFERENT STRIPPING IN AREPO LEADS TO DIFFERENT ORBITS OF THE BLOBS AND DIFFERENT DISIPATION DUE TO STIRRING MOTIONS

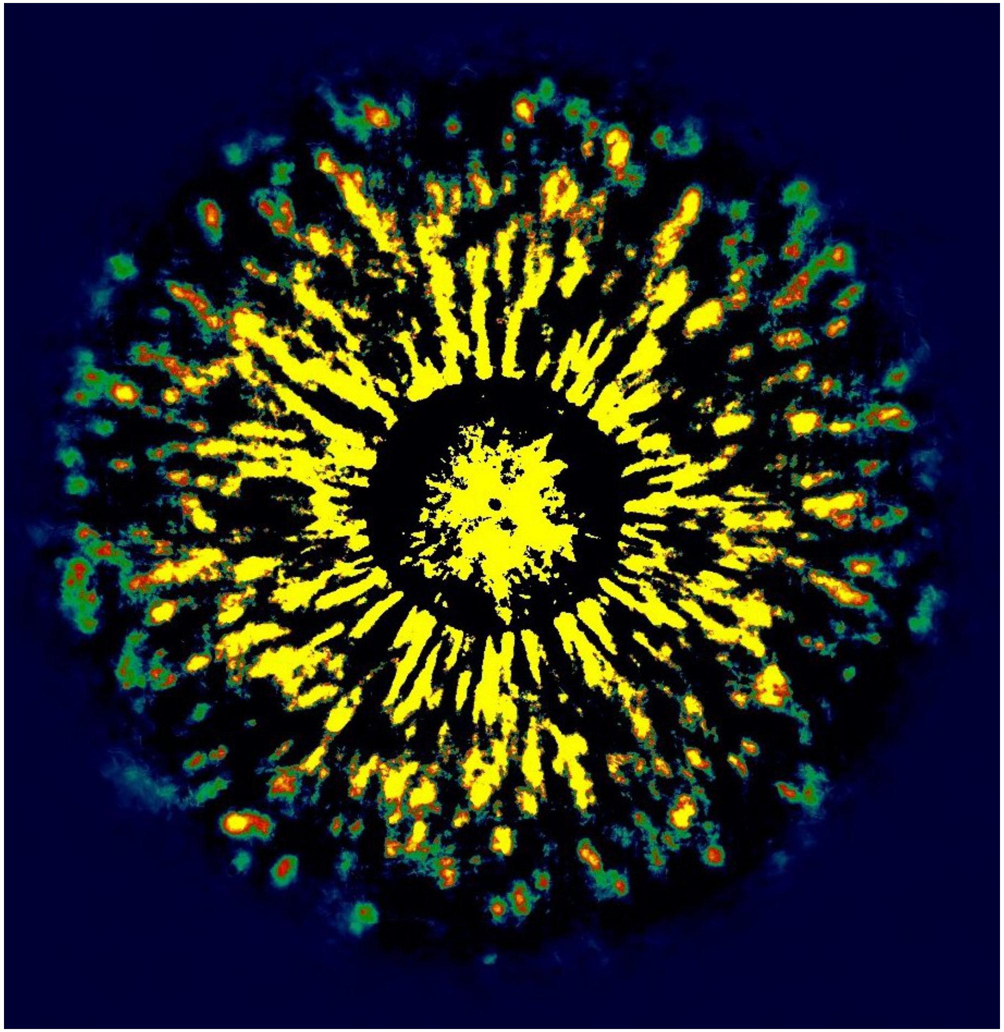


Inflow of cold gas into a static potential: Strong shock



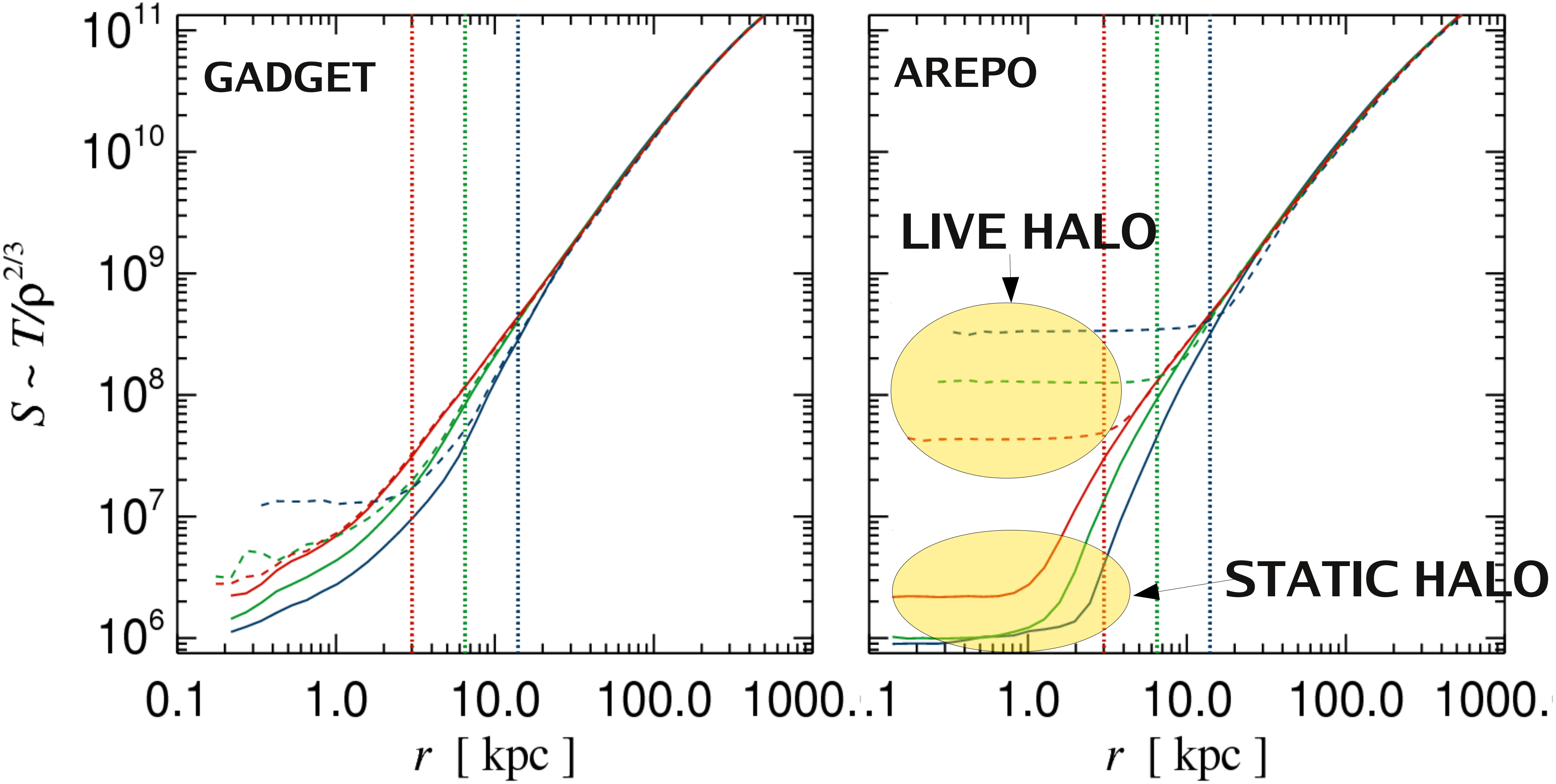
- NO GAS SELF-GRAVITY, NO COOLING
- ~~STATIC HERNQUIST DM POTENTIAL~~ → LIVE HALO
- RADIAL INFALL OF COLD GAS

GAS DENSITY DIFFERENCE MAP:
LIVE HALO – STATIC HALO



Inflow of cold gas into a static potential: Strong shock

AREPO MUCH MORE AFFECTED BY GRAVITATIONAL N-BODY NOISE, WHICH LEADS TO OVERPRODUCTION OF ENTROPY



Conclusions

AGN are a key ingredient in cosmological structure formation

- Great progress in the last couple of years in incorporating BH growth and feedback processes in fully cosmological simulations

- Not only galaxy cluster properties with AGN are much more realistic, but also the same models reproduce BH-galaxy scaling laws, BH mass density at $z = 0$, and even brightest quasars at $z = 6$!

- Results of three independent groups in good qualitative agreement:
=> coherent picture, but detailed understanding still lacking

- For a new breakthrough in the field improved numerical modelling is needed:
more sophisticated codes, detailed code comparisons, ambitious simulation programs (exascale!), and careful comparison with observational data