Turbulent motions and mixing in massive galaxy clusters

- SAMPLE OF MASSIVE GALAXY CLUSTERS AT HIGH RESOLUTIONS
- TURBULENT MOTIONS IN THE INTRA CLUSTER MEDIUM
- MIXING IN THE INTRA CLUSTER MEDIUM

Franco Vazza

Gianfranco Brunetti
Claudio Gheller
Riccardo Brunino

Krakow 18 May 2010

Franco Vazza says:

"I thank the organizers, and I am sorry I could not make to be there with you. I had many problems with the flights from Bologna and I could not reach the conference in time.

I hope that this short presentation of my work (for which Klaus Dolag kindly lent his voice) is useful enough for the topics you are discussing! "

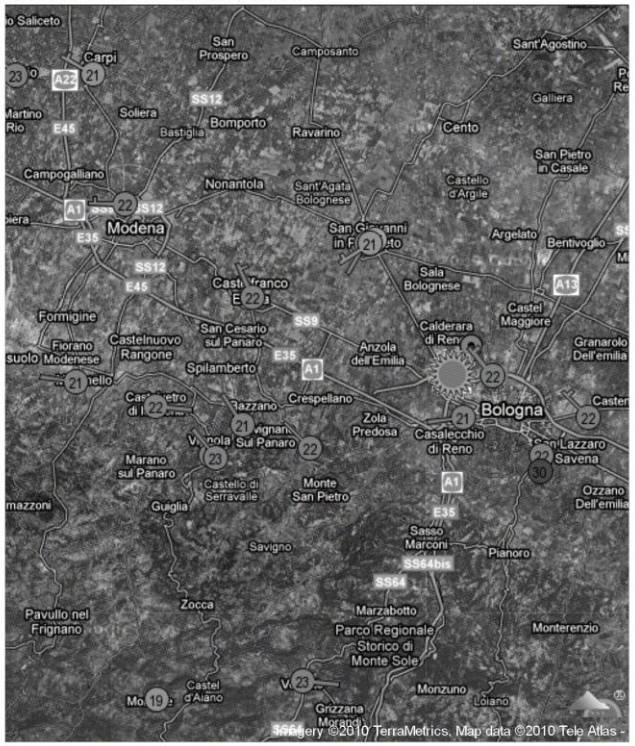
"....and this made me losing a minute already...

so, better to start..."

WunderMap®

Save or send this map to someone as you see it now. Link to current view. – Units are Metric. Change.

Interactive Radar & Weather Stations



Map Controls

- Sponsors
- ☑ NEXRAD Radar (top)
- ☑ Weather Stations
- ☐ Severe Weather
- ☐ Webcams
- ☐ Satellite
- ☐ USGS River
- ☐ Model Data
- ☐ Hurricane
- ☐ Fire
- ☐ Tornado
- ☐ NDFD Forecast
- ☐ Photos
- ☐ Road Trip NEW!

Save this view and settings as default:

Display Options

Opacity: 70%

Animate: 1 Frames — Start

Frame Delay: .25 sec

Radar Options

☐ Storm Tracks

☑ Smoothing

Base Reflectivity: N0R (124 NMI / 0.50°) and/or -- TDWR --

Select a Location:

Search Go

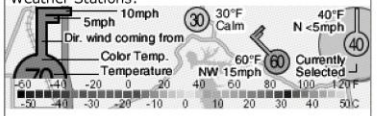
Stations

Place	Station	Temp.
Bologna	IBOLOGNA2	30° C
Bologna	LIPE	22° C
Bologna (Reno - Barca)	IEMILIAR13	21° C
Bologna-San Ruffillo	IEMILIAR43	22° C
Borgo Tossignano	IBOBORGO1	23° C
Carpi (Mo)	IMOCARPI1	21° C
Castelfranco Emilia	ICASTELF1	22° C
Castelvetro Di Modena	IEMILIAR8	22° C
Castenaso	IEMILIAR65	22° C
Correggio	IEMILIAR55	23° C
Dozza	IBOLOGNA18	24° C
Ferrara	IFERRARA4	21° C
Formica Sud	IMODENAS2	23° C
IW4EJK HAMRADIO / APRS	IMODENAS4	22° C
Maranello	IMODENAM3	21° C
Medicina	IBOLOGNA19	21° C
Medicina (BO)	IBOLOGNA10	22° C
Modena	IMODENAM4	22° C
Mulino	IITALIAM2	21° C
Osservatorio Astronomi	IEMILIAR11	22° C
S. Giovanni in Persice	IBOLOGNA4	21° C
S.Giovanni (MADIS)	MAR017	17° C
San Prospero - Imola	IBOIMOLA3	22° C

Map Legends:

NEXRAD Radar:

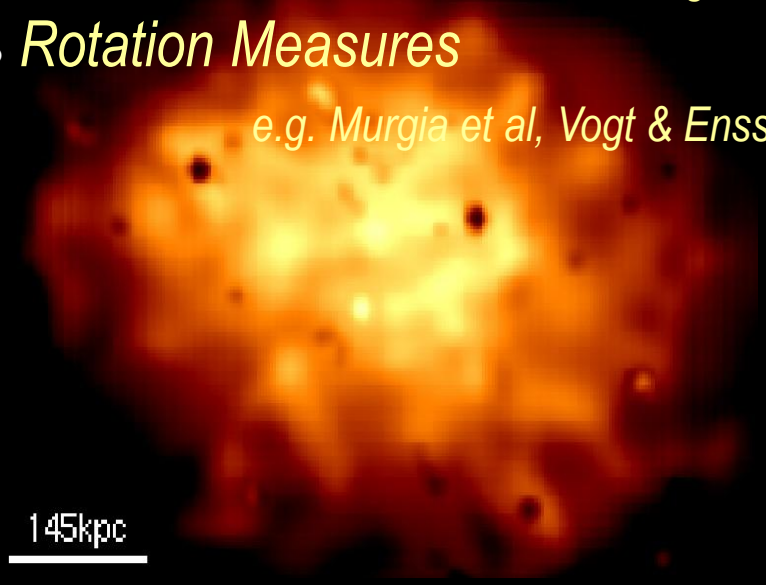
Weather Stations:

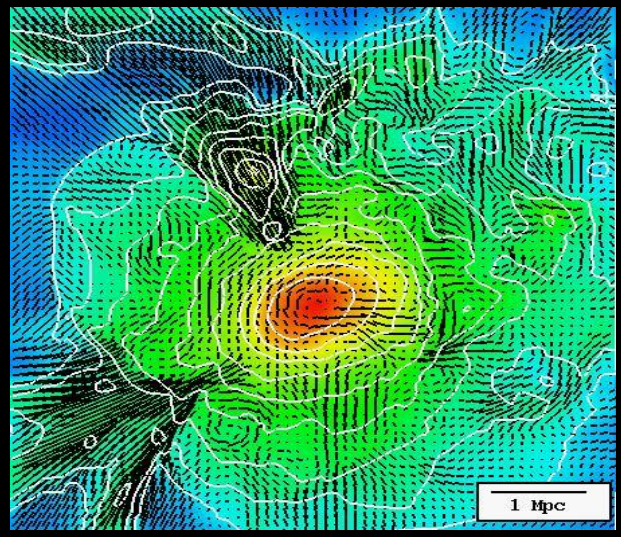


"There are nowadays many (indirect) observational indications for the presence of (subsonic) turbulent motions in galaxy clusters."

OBSERVATIONAL EVIDENCES FOR TURBULENCE

- *Presudo-pressure maps in X-ray*
  Schuecker et al.; Briel & Henri, Ota et al.
- *Lack of resonant scattering*
  e.g. Churazov et al.
- *Metal diffusion* *e.g Rebusco et al.*
- *Non-Thermal Emissions* *e.g. Brunetti et al.*
- *Rotation Measures*
  e.g. Murgia et al, Vogt & Ensslin





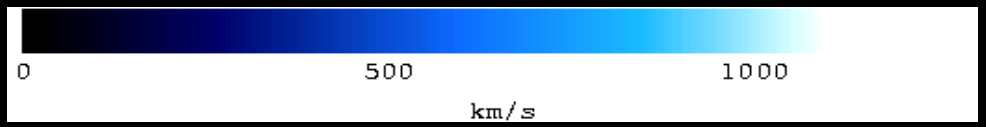
NUMERICAL EVIDENCES FOR TURBULENCE

- *Large Eddies in AMR simulations*
  Norman & Bryan.
- *GADGET with low viscosity*
  Dolag et al..
- *Non thermal pressure support*
  e.g Rasia et al., Lau et al.
- *Sub-grid modeling*
  e.g. Maier et al., Scannapieco & Bruggen

"Also from the numerical view point, many works suggested that the simulated ICM should contain chaotic motions, across a wide range of scales"

Grid simulations of galaxy clusters with ENZO (Bryan et al.1998) & ADAPTIVE MESH REFINEMENT

Velocity field of a cluster simulated with standard mesh refinement (side=4.4Mpc) in ENZO



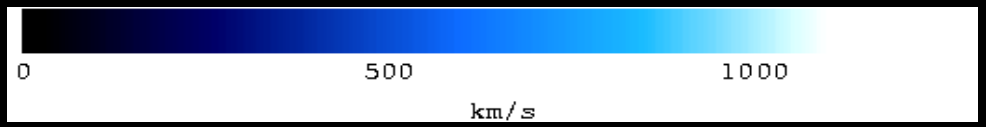
" The study of turbulence, in general, demands a very large dynamical range in simulations, since one would like to have a good scale separation between the forcing scales (e.g. ~Mpc for clusters) to the dissipative scales (e.g. <10kpc).

" Methods in which resolution is increased only depending on overdensity (such as standard mesh refinement strategies in grid codes) may have troubles in describing the evolution of a turbulent eddy in this case."

Vazza, Brunetti, Kritsuk e al.2009 A&A

Grid simulations of galaxy clusters with ENZO (Bryan et al.1998) & ADAPTIVE MESH REFINEMENT

Velocity field of a cluster simulated with new mesh refinement (side=4.4Mpc) in ENZO



" We developed and now routinely use a slightly implemented method, which allows us to refine at the same time on gas/DM overdensity and 1-D velocity "jumps" (possibly associated to shock waves in the ICM)."

" The outcome is that we can usually have the same resolution (e.g. ~25kpc/h) in the cluster center and in the outermost cluster region, and that eddies can be followed all across the cluster volume."

Vazza, Brunetti, Kritsuk e al.2009 A&A

2009 Italian Key Project:

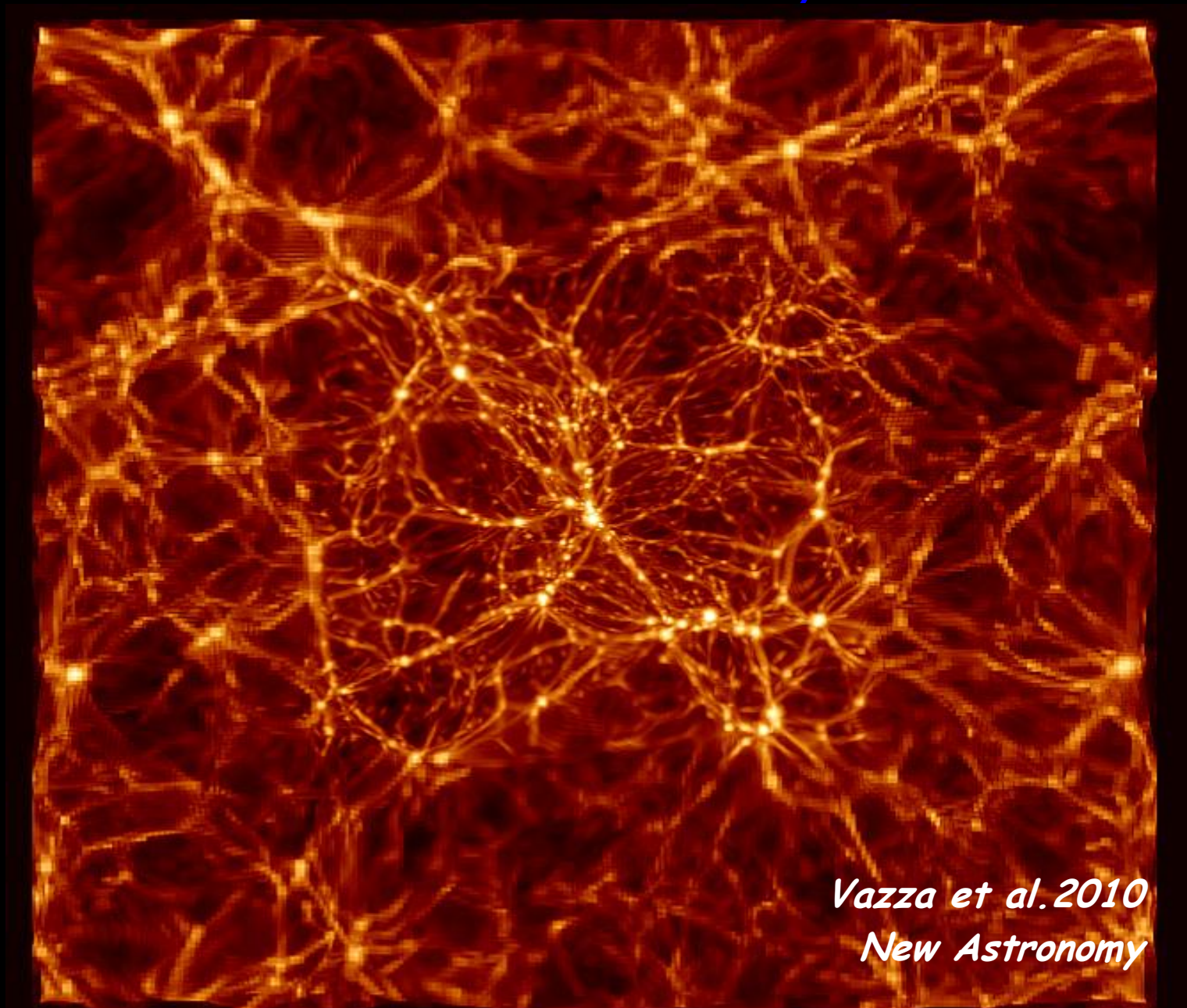
Total volume:
$(480\ \mathrm{Mpc}/h)^3$

DM mass resolution:
$6.7 \times 10^8\ M_o/h$

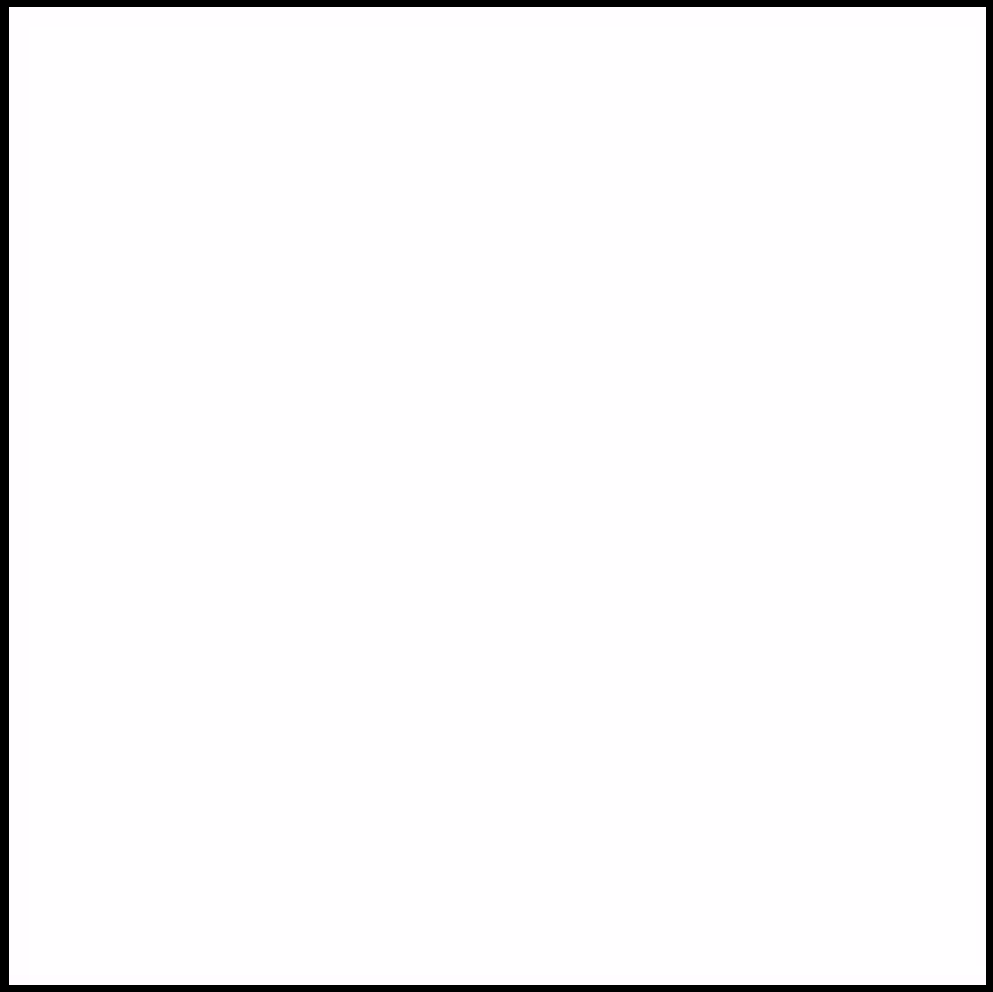
gas resolution:
from 200kpc/h
to 25kpc/h

time resolution (outputs):
$dt_{out}=10^8$ yr

"At the beginning of this year, we burnt a lot of computational resources to produce a statistical sample of Massive ($\sim 10^{15} M_o$) galaxy clusters with this method.
The goal is to study: ICM turbulence, particle acceleration and non-thermal emissions in a statistical way."



Vazza et al. 2010
New Astronomy



Gas density

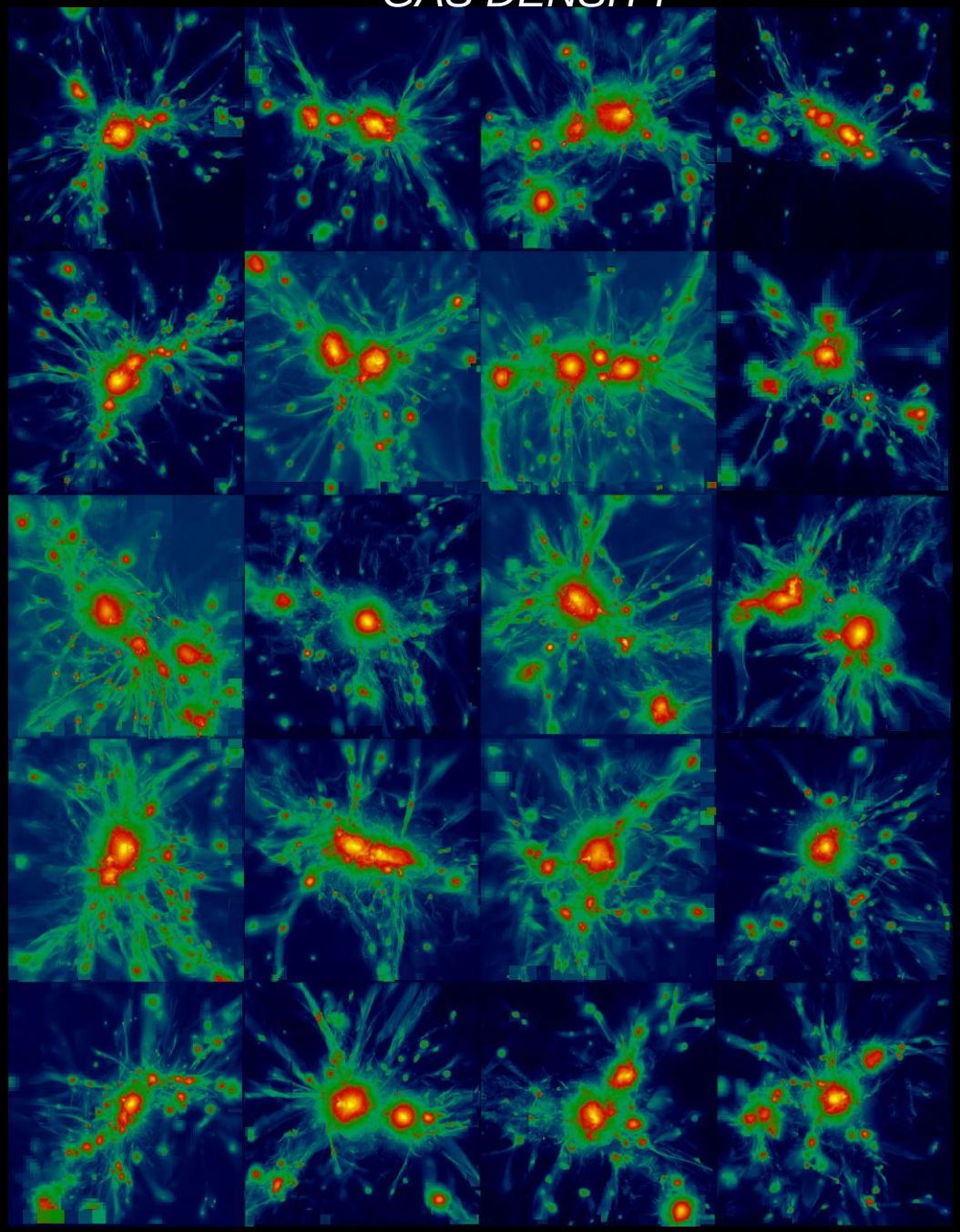
Gas temperature

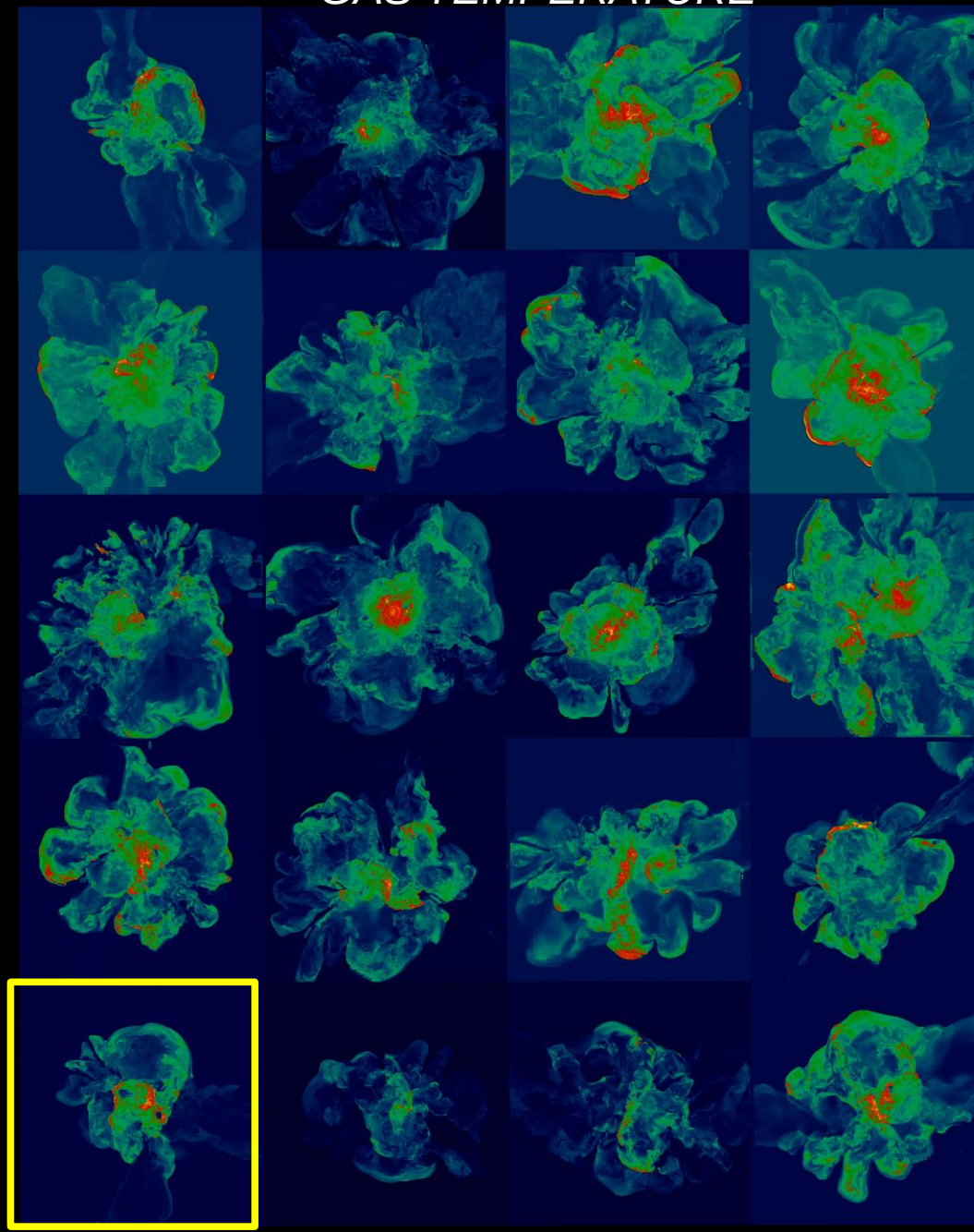
"These are movies showing the evolution within the region of adaptive mesh refinement in our typical runs. The code for the rendering is SPLOTCH (Dolag et al.2008)"

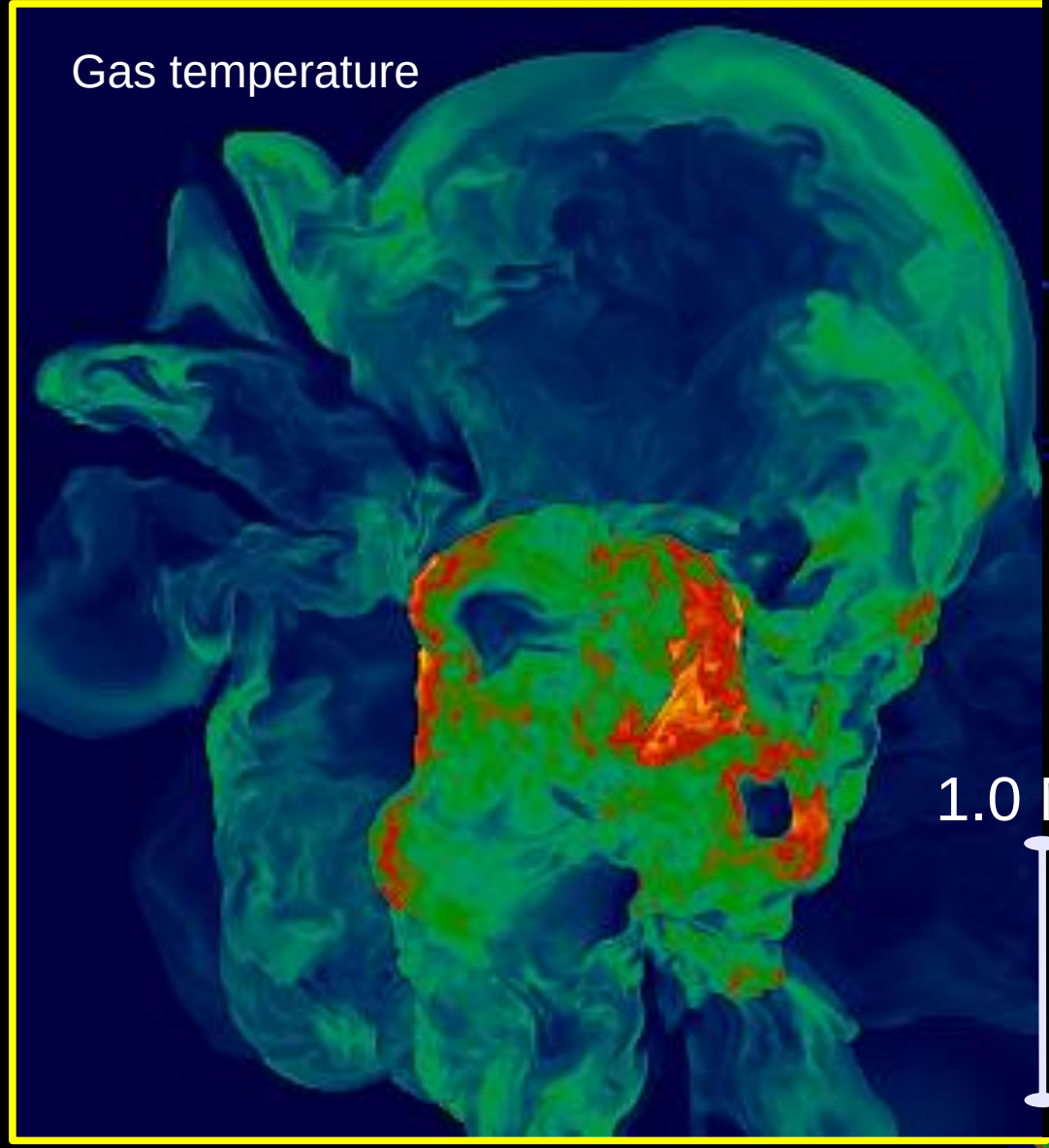
"This is a quick loot at the sample at z=0. The data for all clusters are beeing publicly relased to whoever might be interested, via web portal at http://data.cineca.it "

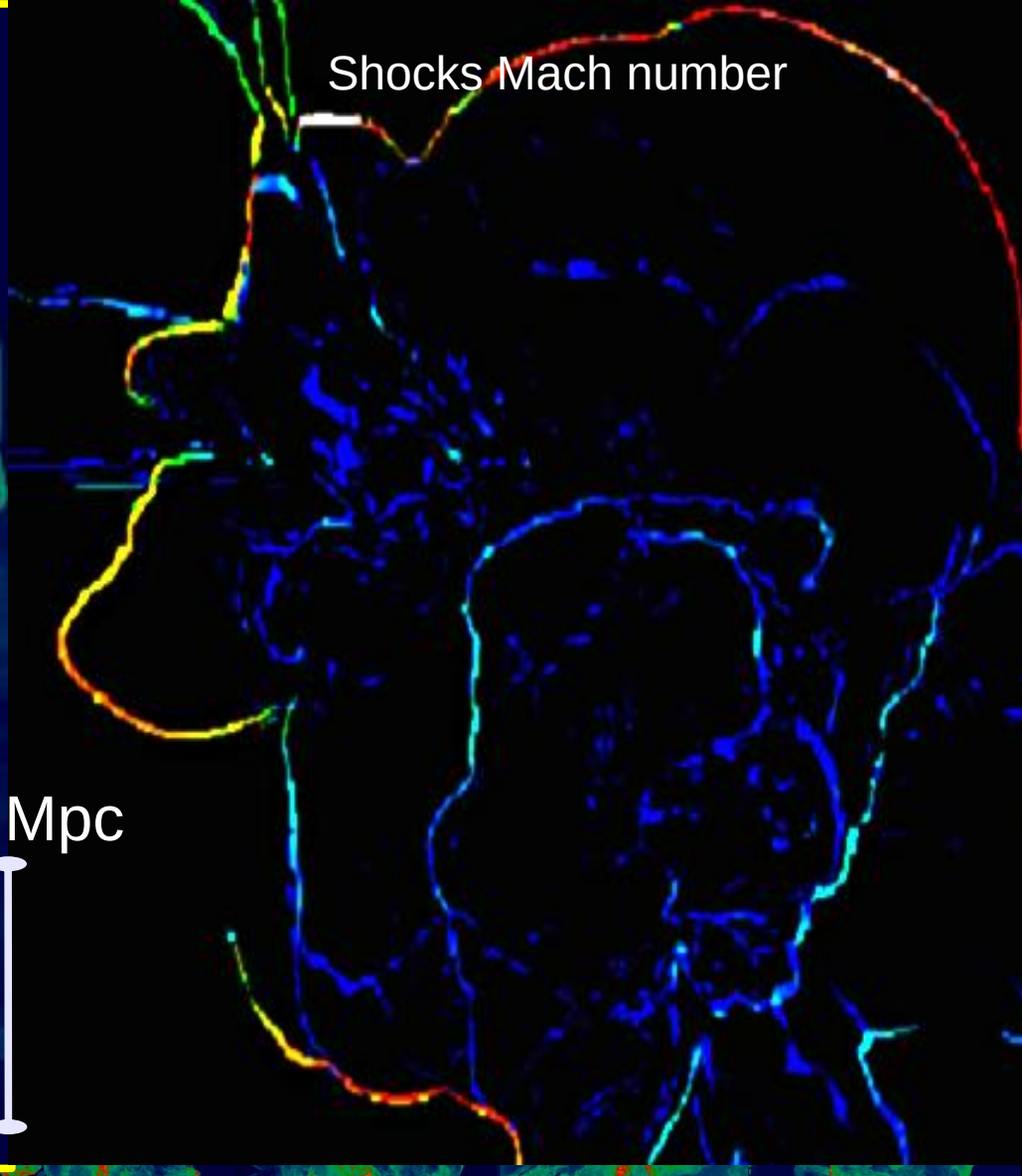
GAS DENSITY

GAS TEMPERATURE





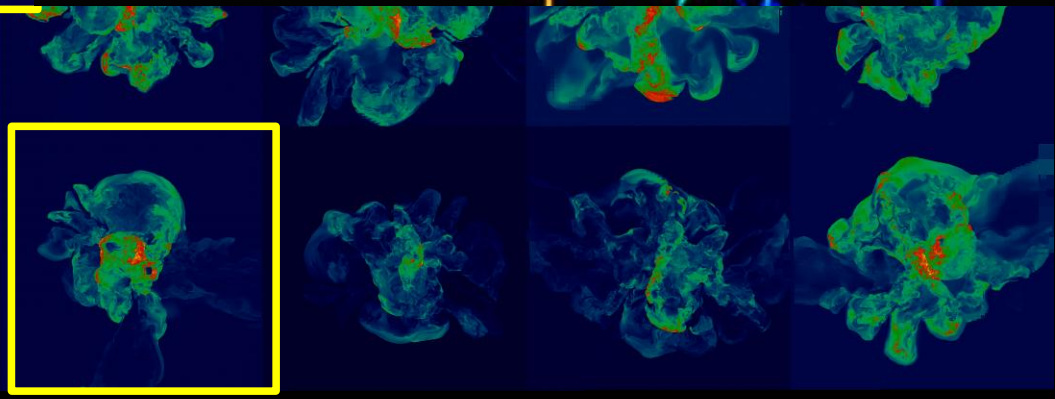




1.0 Mpc

"This is the typical amount of details contained in every data.

Inside the virial region of every cluster, the number of cells at the highest resolutions is N ~ 10^8



"The combination between our "old" cluster simulations at intermediate mass, and these "new" at large mass provide an interesting spectral & morphological representation of chaotic motions in clusters.

I will shortly present results about:
- the 3rd order structure function of the velocity field;
- 3D power spectra
- the pair dispersion statistics of advected passive tracers "

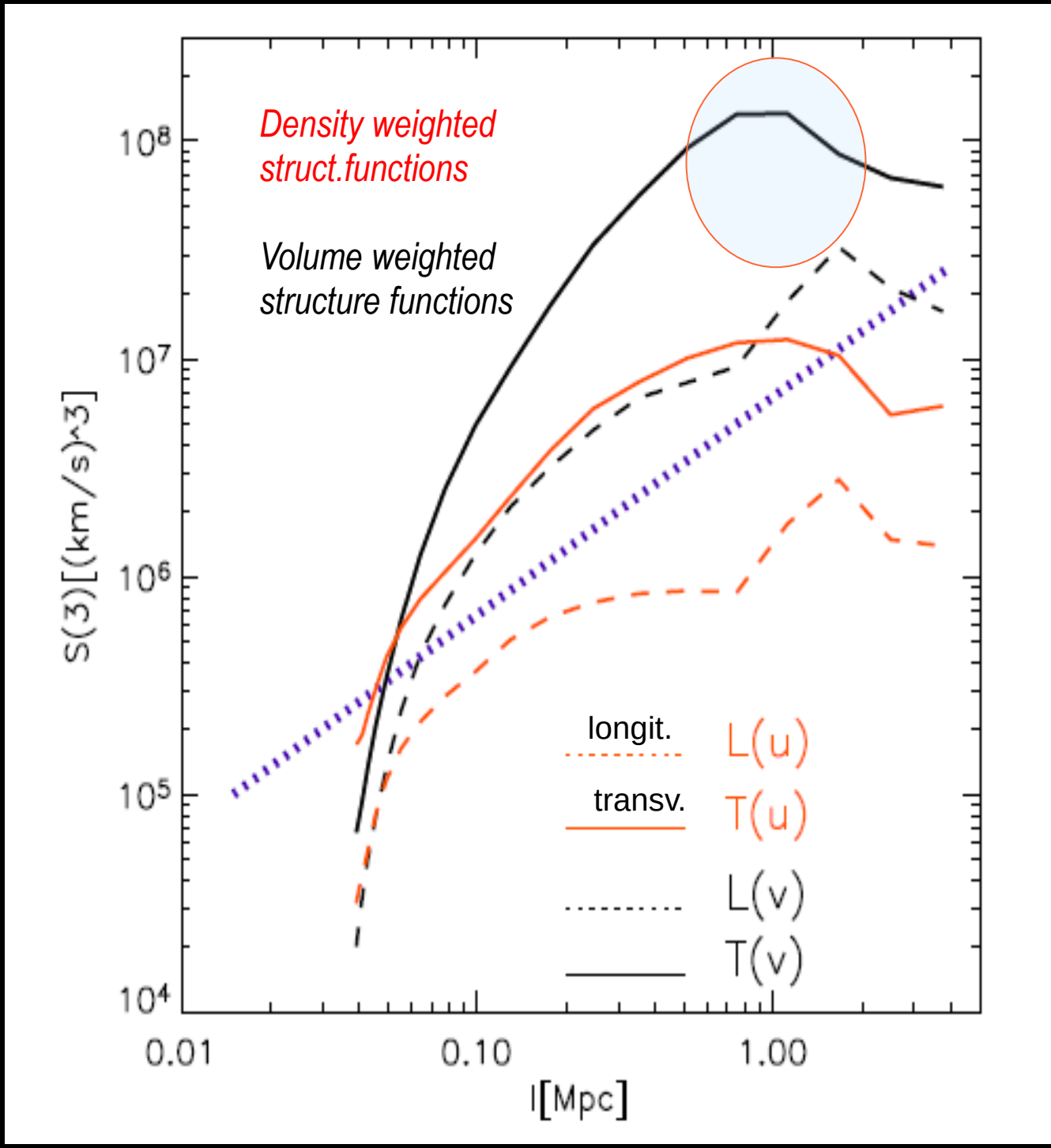
3rd order structure functions

$$S_p(l) = < |\mathbf{v}(\mathbf{r}+\mathbf{l}) - \mathbf{v}(\mathbf{r})|^3 >$$

"A representative result for a cluster.

- an "outer injection " scale of ~ 1-1.5 R_{vir}

- a power law distribution of energy, for ~2 decades in k "

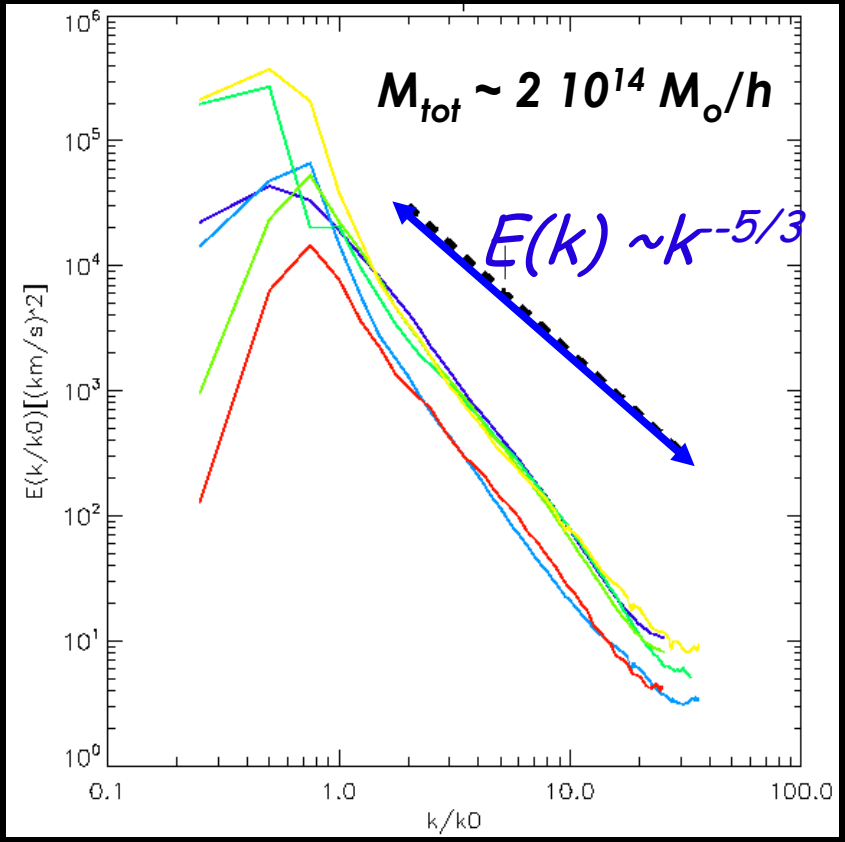


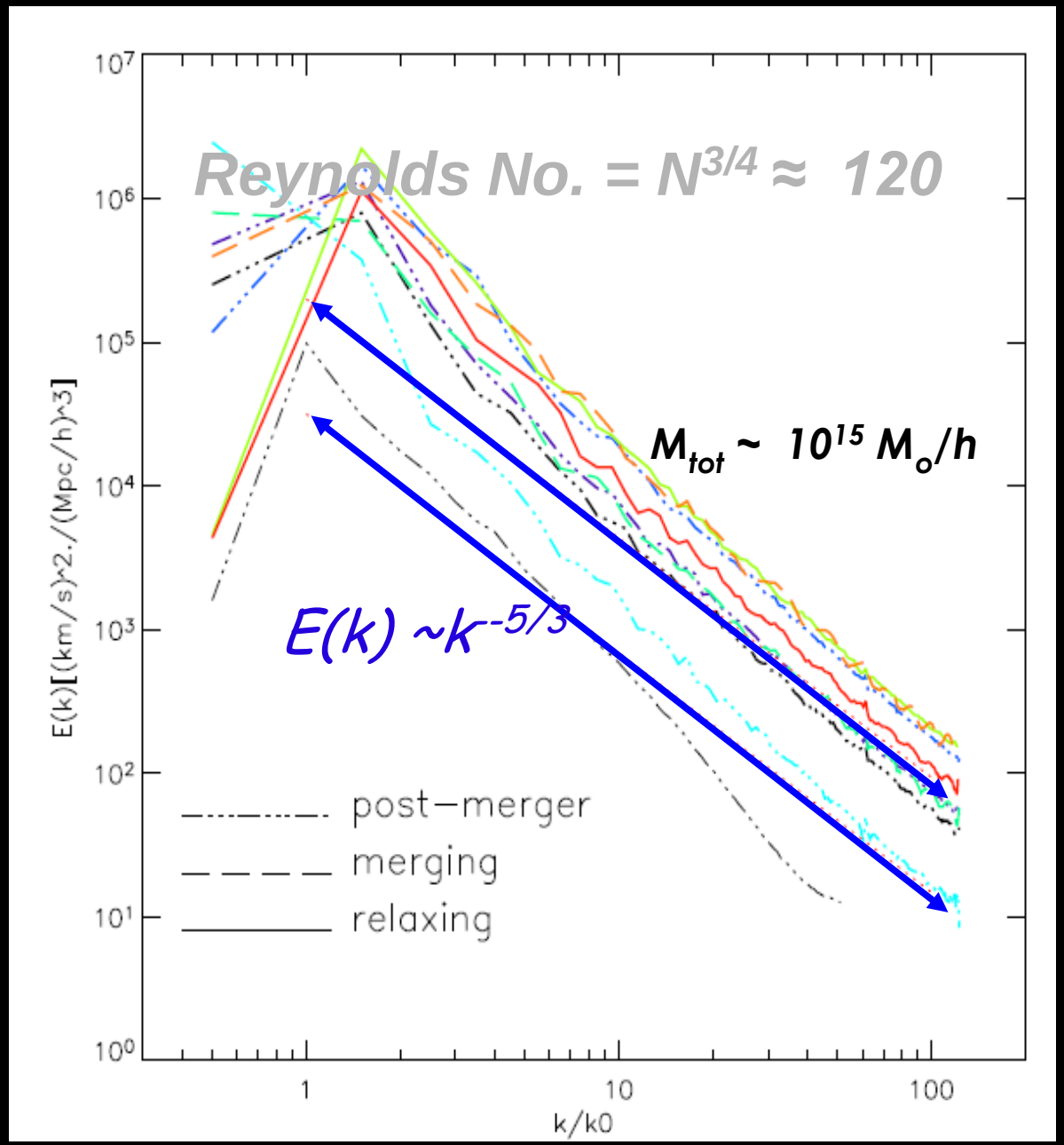
3D power spectra

$$E(\mathbf{k}) = \frac{1}{2}|\tilde{\mathbf{v}}(\mathbf{k})|^2,$$

$$\tilde{\mathbf{v}}(\mathbf{k}) = \frac{1}{(2\pi)^3}\int_V \mathbf{v}(\mathbf{x})e^{-2\pi i\,\mathbf{k}\cdot\mathbf{x}}d^3x$$

Reynolds No. = $N^{3/4}$ ≈ 70





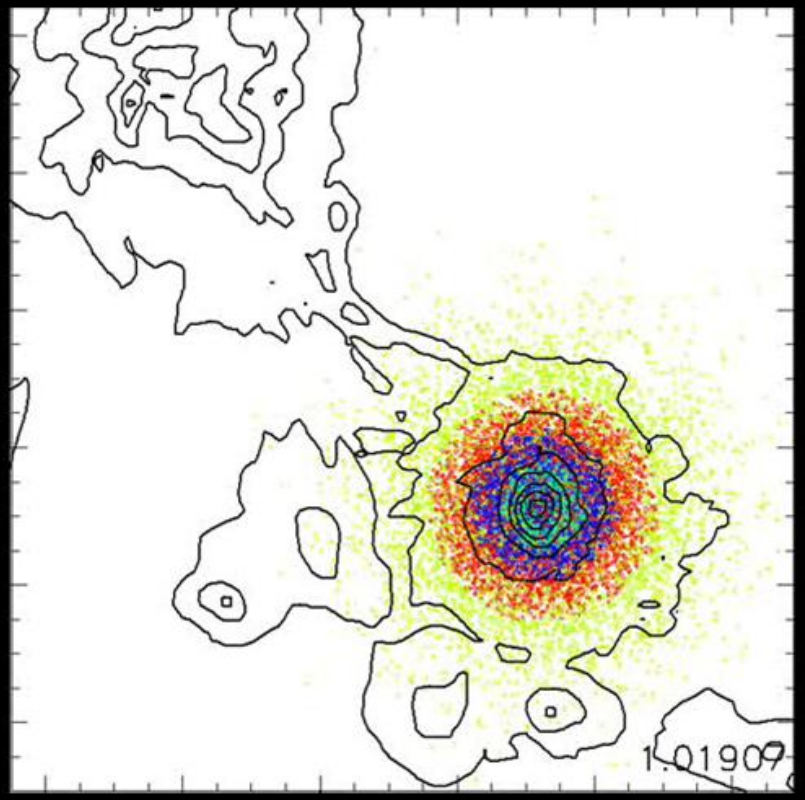
"Results for moderate mass clusters and for the most massive ones k0 is normalized to be the frequency at Rvir for every cluster"

"We developed the possiblity of injecting an following passive lagrangian tracers in the evolving ICM of our simulations."

"many"
N~10^5-10^6
passive tracers
advected by the
evolving ICM

~

"lagrangian" &
"eulerian" view
together



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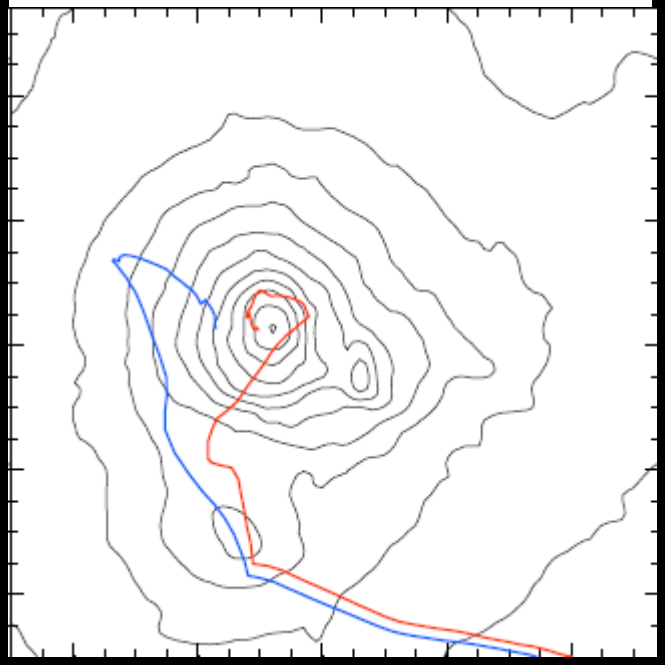
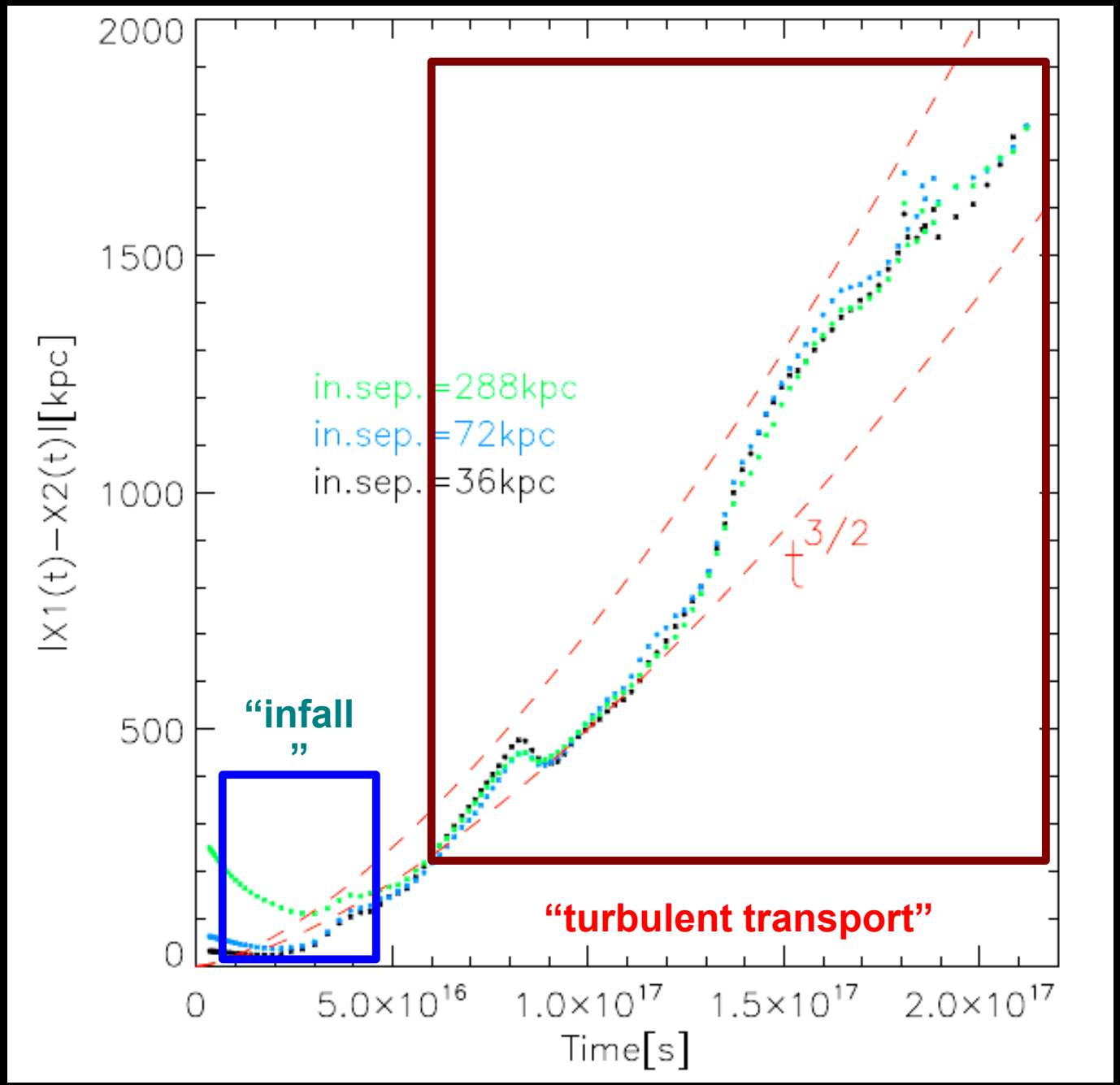
PAIR DISPERSION STATISTICS

$$P(t) \equiv < |X_1(t) - X_2(t)| >$$



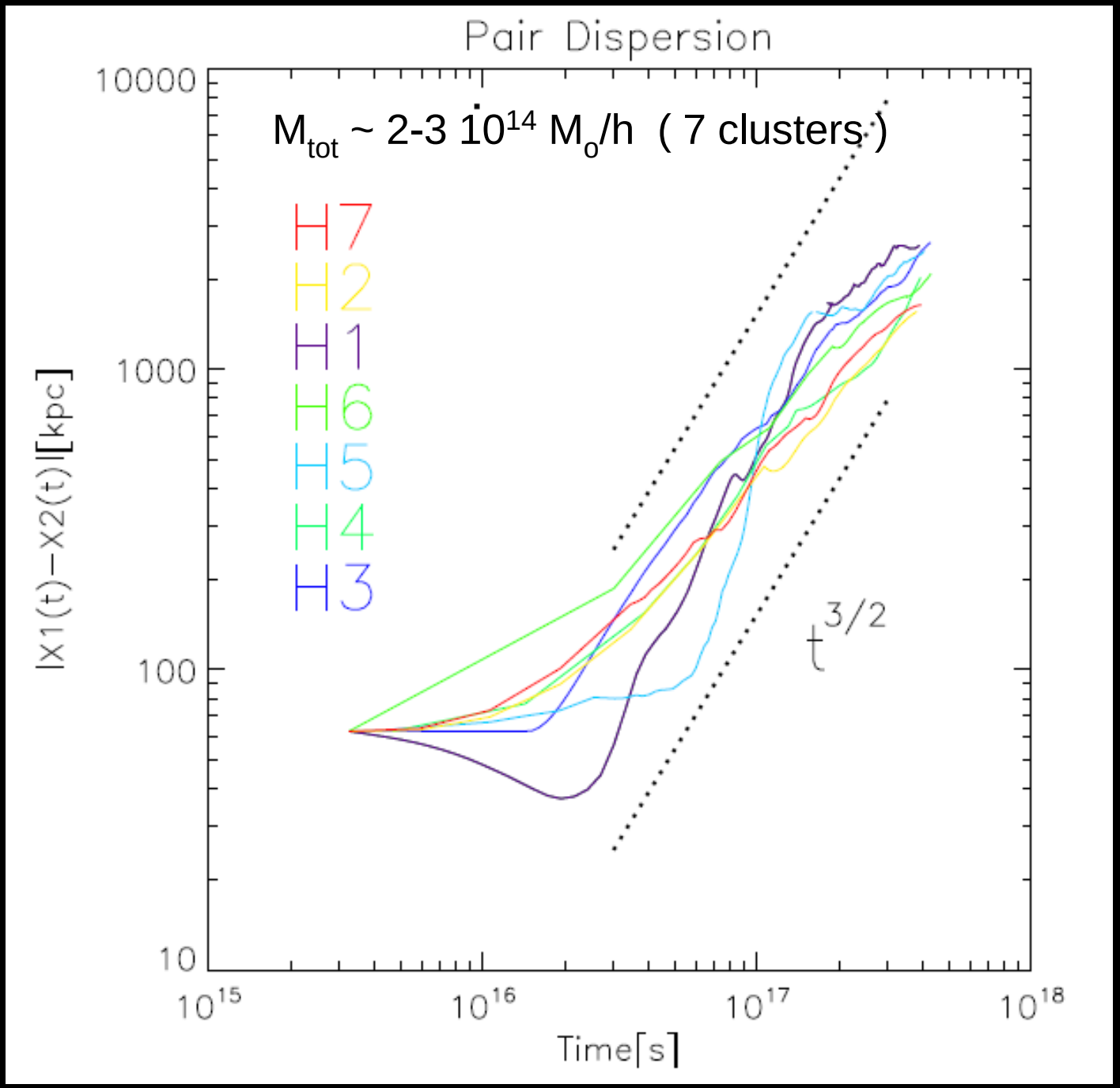
" The mean separtion of pairs of tracers shows the trend of an increase with time as in the "classic" turbulent transport ~$t^{3/2}$.

After the initial 'infall' epoch, the long-time trend is independent of the initial separation, as in 'classic' turbulent scenario. "



" The trend is similar for many different clusters, with different dynamical histories.

The implied transport velocities of gas particles in the evolving ICM is of the order of v ~100-200 km/s "



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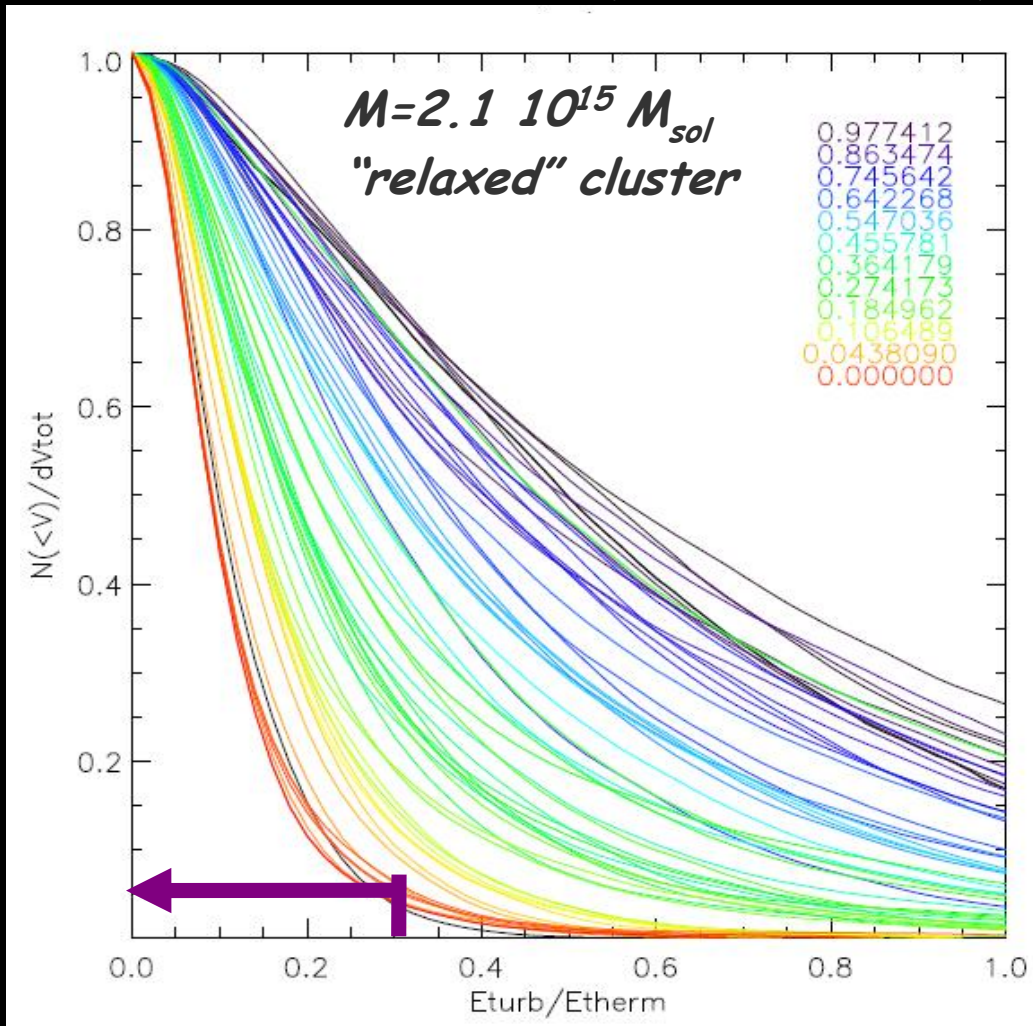
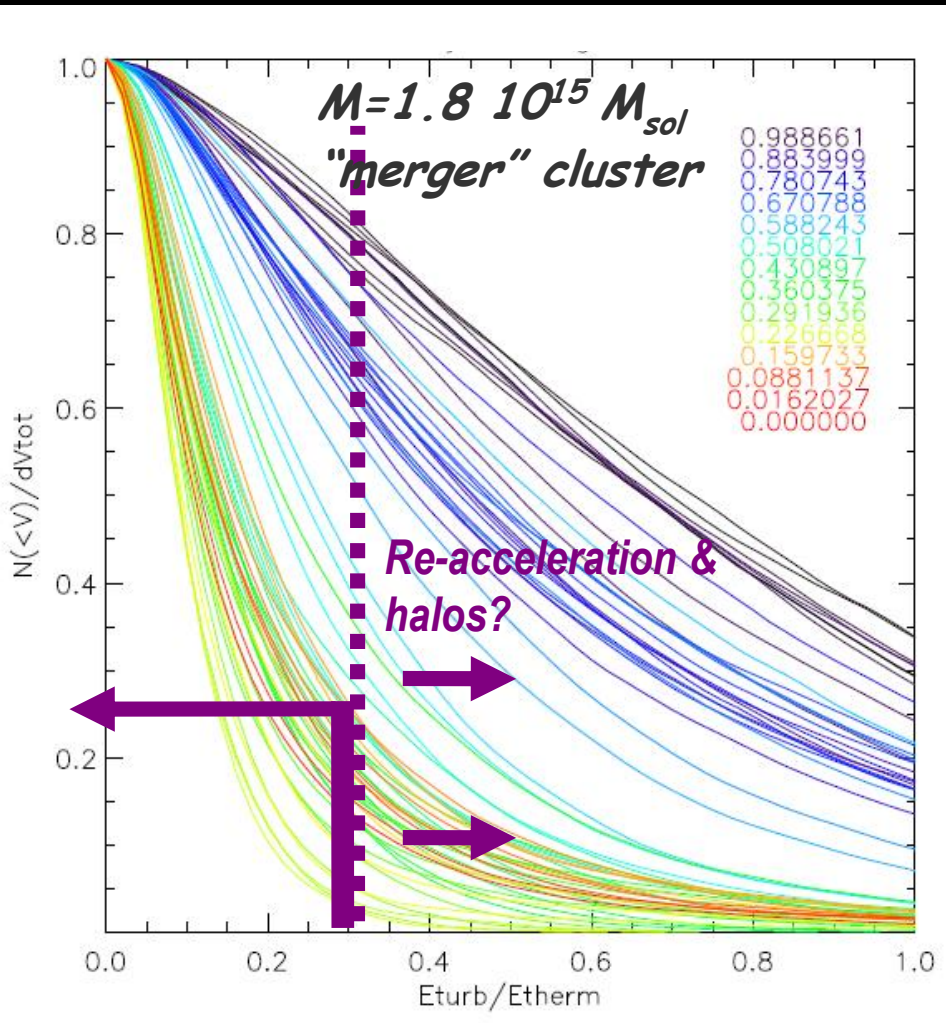
transport velocities of v~100-200km/s

How much is the kinetic (turbulent) energy compared to the thermal energy?
(B field amplification, particle re-acceleration...)





"Less than < 5% of the volume inside Rvir/4 has Eturb/Eth > 30% for quiet clusters at z=0"

"About ~ 30% of the volume inside Rvir/4 has Eturb/Eth > 30% for merger clusters"

"What? Time is already left?
Gosh!
Ok, I skip to the conclusions...

~

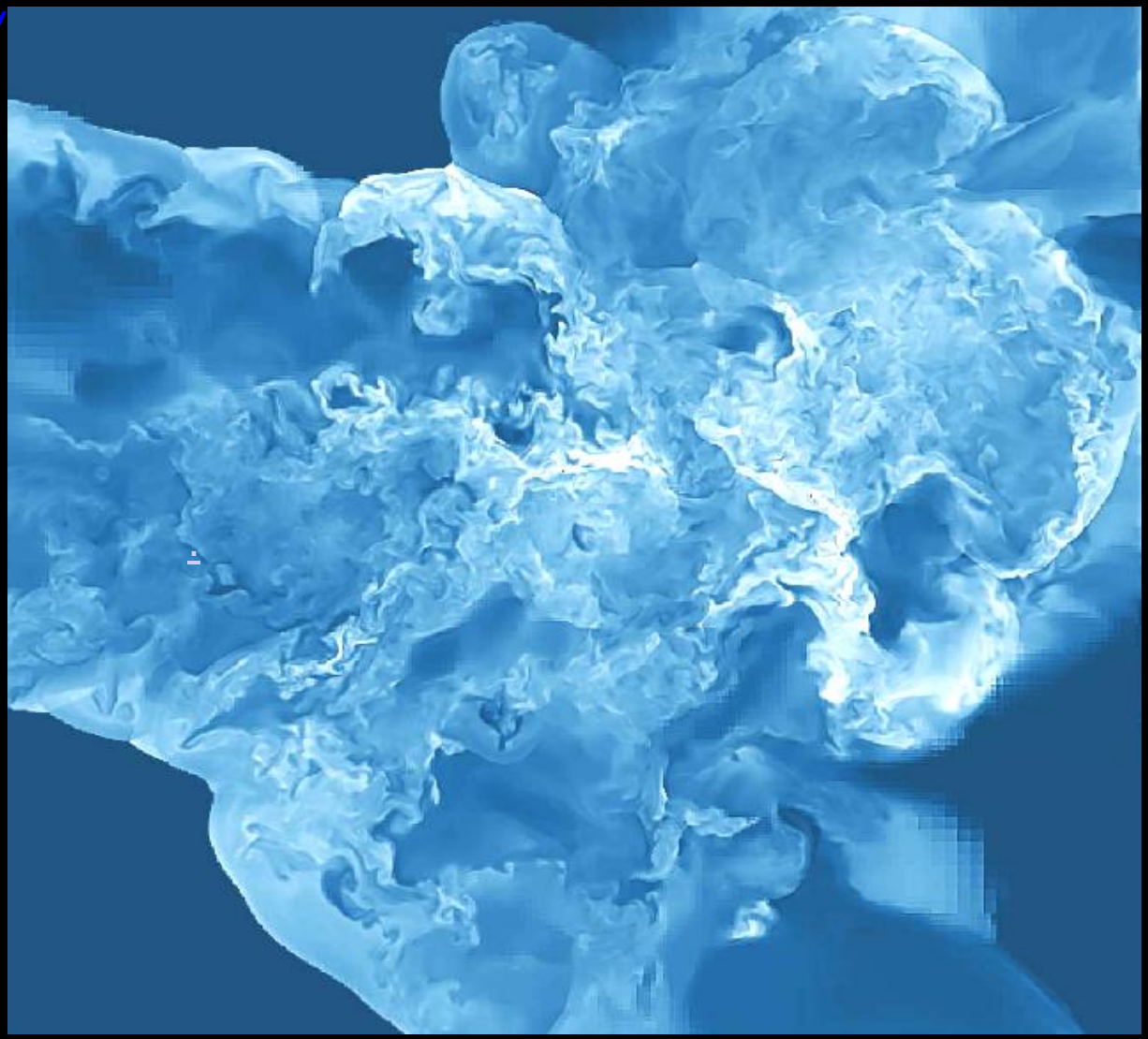
Maybe the best picture we obtained so far of one of our simulated cluster, with 4 levels of refinement (dynamical range N ~ 600), may convince you that the simulated ICM necessarily contain (subsonic) turbulent motions... "

conclusions

- Cosmological grid simulations with AMR provide robust indication that galaxy clusters host subsonic turbulent motions

- Turbulent motions are characterized by outer ("injection") scales of ~Mpc with a power-law energy distribution for several (2-3) orders of magnitude in k's.

- Epsiodic phases with >30% energy in chaotic motions (compared to thermal energy) are found for dynamically active clusters at z~0



Thanks and have a good conference!

Franco Vazza