# Exploring kinetic Sunyaev-Zel'dovich Effect with MUSIC clusters of galaxies

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# Outline

- Sunyaev-Zel'dovich Effect (SZE) : the Compton scattering of CMB photons by hot gas in a nutshell
- MUSIC: a large catalogue of synthetic clusters to explore *k*-SZE
- Cluster of galaxies rotations: *k*-SZE maps
- Scaling Relation: *k*-SZE vs M

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# The SZ Effect: THE BASIS

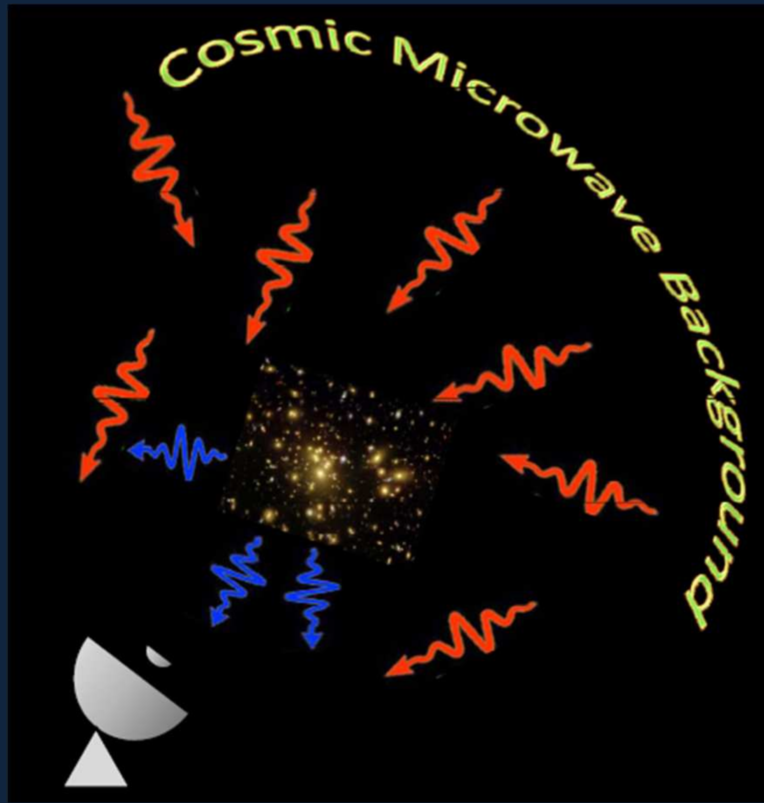
Inverse Compton Scattering of CMB photons with hot electrons (ICM, as an example) results in:

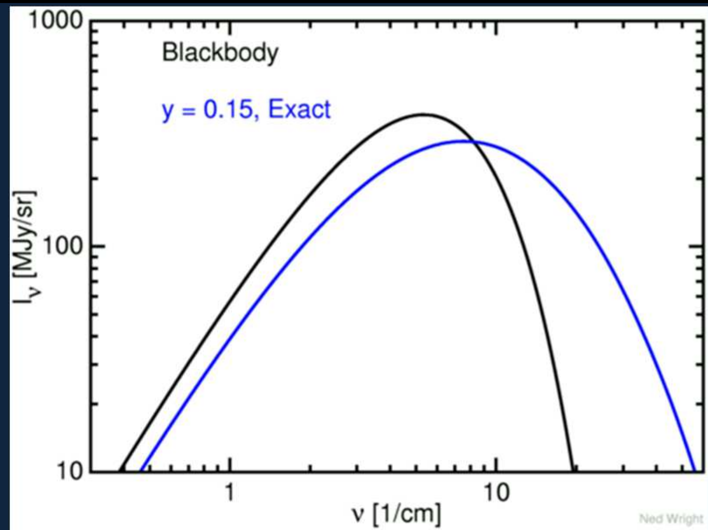
✓ a net energy injection into the CMB photons;

✓ a unique spectral signature;

✓ an effect independent along the redshift;

✓ an effect proportional to the integrated gas pressure along the l.o.s.




courtesy N. Wright

# The SZ Effect: TWO COMPONENTS + ....

*th*-SZE: depends on random motions of the scattering electrons

Intensity or Thermodynamic temperature changes

$$\Delta I_{TSZ} = g(x) I_o y$$

$$\Delta T_{TSZ} = f(x) y T_{CMB}$$

$$x \equiv h\nu / kT$$

$$y = \int \frac{kT_e}{m_e c^2} \sigma_T n_e d\ell = \frac{kT_e}{m_e c^2} \tau$$

*k*-SZE: depends on the systematic motions of the scattering electrons, *i.e.* the scattering medium causing the *th*-SZ effect is moving relative to the CMB monopole (Doppler effect)

$$\Delta I_{KSZ} = -\beta h(x) I_o \tau$$

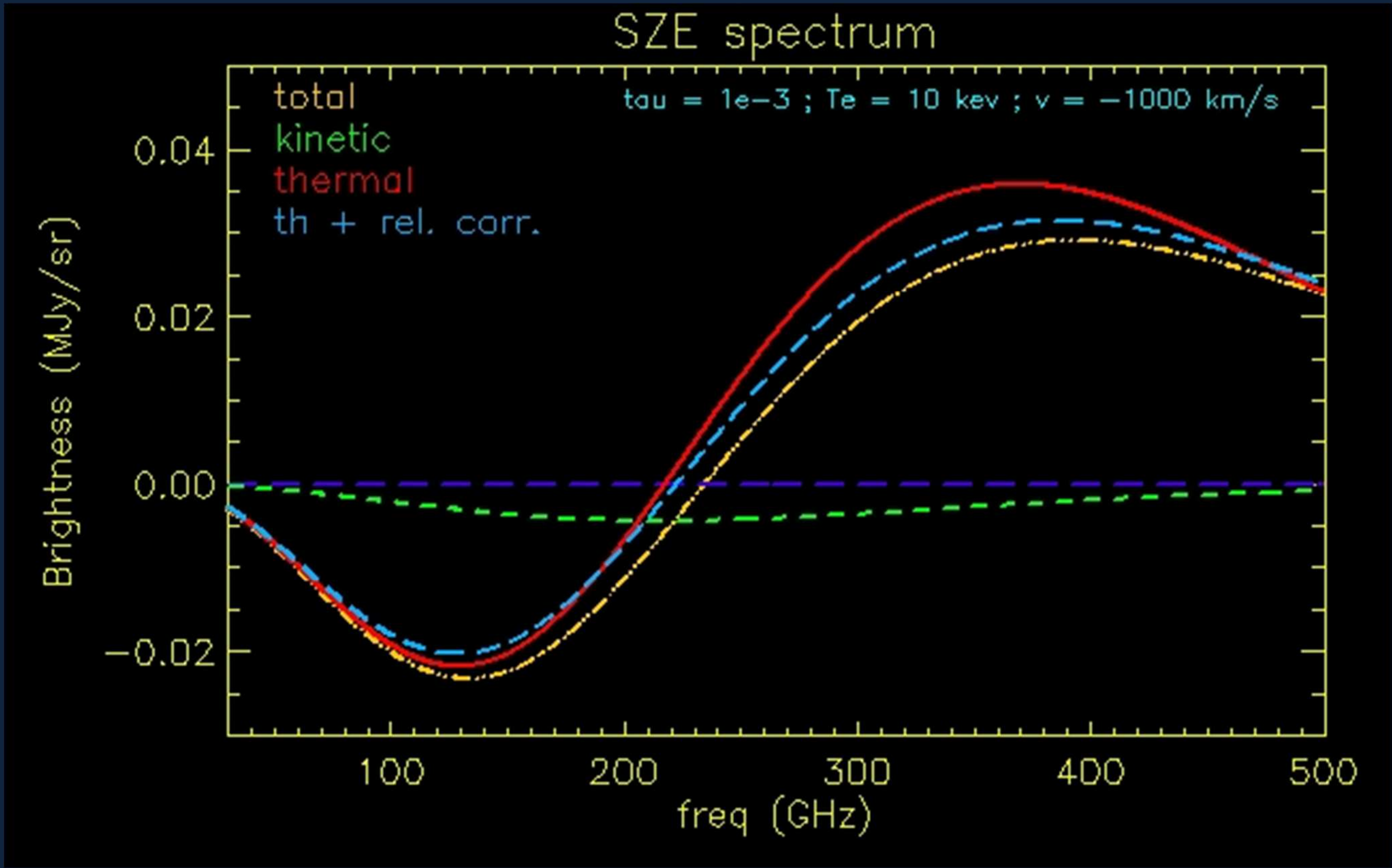
$$\Delta T_{KSZ} = -\beta \tau T_{CMB}$$

*Total*-SZE *th*-SZE *k*-SZE *Rel. Corr.*

$$\Delta I = \frac{2k^3T^3}{h^2c^2} \frac{x^4 e^x}{(e^x - 1)^2} \int d\tau \left[ \theta f_1(x) - \beta + R(x, \theta, \beta) \right]$$

$$\theta = kT_e / mc^2$$

# The SZ Effect: TWO COMPONENTS + ....



# SZE: a multimeter in Cosmology

A useful *multimeter* in Cosmology:

- Thermometer: $T_{CMB}$ (z) from clusters distorted spectra
  [Luzzi G., MDP et al. JCAP +15 and SIF Communication]

- Baryometer: M from *th*-SZE brightness, already studied with MUSIC clusters and protoclusters
  [Sembolini F., MDP et al. MNRAS +12, Sembolini F., MDP et al. MNRAS +14]

- Speedometer: v *(radial)* from *k*-SZE;

- ….

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MUltidark SImulations of galaxy Clusters

# Dataset

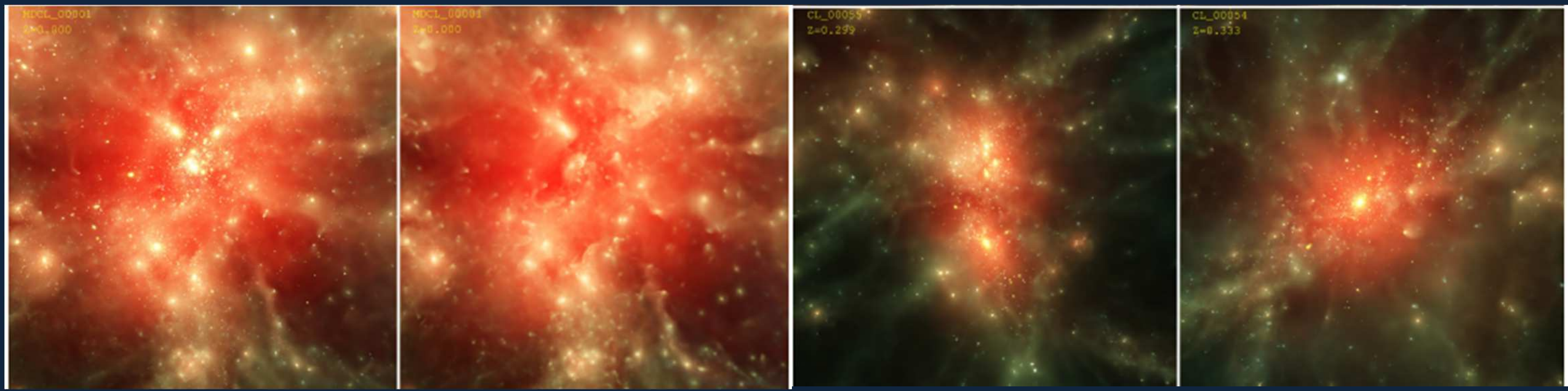
MUSIC (Marenostrum-MultiDark SImulations of galaxy Clusters)

A catalogue of synthetic clusters *(also)* to study SZ science extracted from 2 large volume hydrodynamic simulations:

[Sembolini F. , MDP et al. MNRAS +12]

1. The MareNostrum Universe, a non-radiative SPH simulation with 2 billion particles ($2\times1024^3$ gas and dark matter ) in a 500 $h^{-1}$ Mpc cubic box [Gottlöber & Yepes ApJ 2007]
2. The MultiDark Simulation, a Dark-Matter only N-body simulation with 9 billion particles ($2048^3$ dark matter) in a 1 $h^{-1}$ Gpc cubic box [Prada et al. 2011].

radiative (CSF) and no-radiative (NR) physics at z=0 a Bullet-like cluster and a relaxed cluster at z=0.3



# Speedometer

*Obs Probs*

✓ *k*-SZE has the same spectrum of CMB: *i.e.* challenging to discriminate
✓ *k*-SZE is fainter than *th*-SZE : *i.e.* challenging to detect

a) several on-source attempts: mainly upper limits, low S/N or tension with other obs [see P.D. Mauskopf et al. MNRAS 2012, Sayer J. et al. arXiv:1509.02950v1]

b) the first *(statistical)* attempt: measure large scale bulk flow via the galaxy cluster *k*-SZ signal in WMAP map using galaxy clusters info from X-ray surveys (A. Kashlinsky et al. ApJ 2008, 2011)

c) the first *(statistical)* detection: measurements of the mean pairwise momentum of clusters in ACT map using BOSS to identify 5000 objects (N. Hand et al. PRL 2012).

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# Clusters rotation

- Check if clusters have a non null angular momentum to infer about their formation; see as an example the tidal torques from the surrounding matter such as in galaxy formation.

- Does an "universal" spin profile, consistent with solid-body rotation or not, exist?

or

- Are IntraCluster Motions (turbolence) dominant?

A possible observational approach:

the *rotational k*-SZE induced by ICM rotation

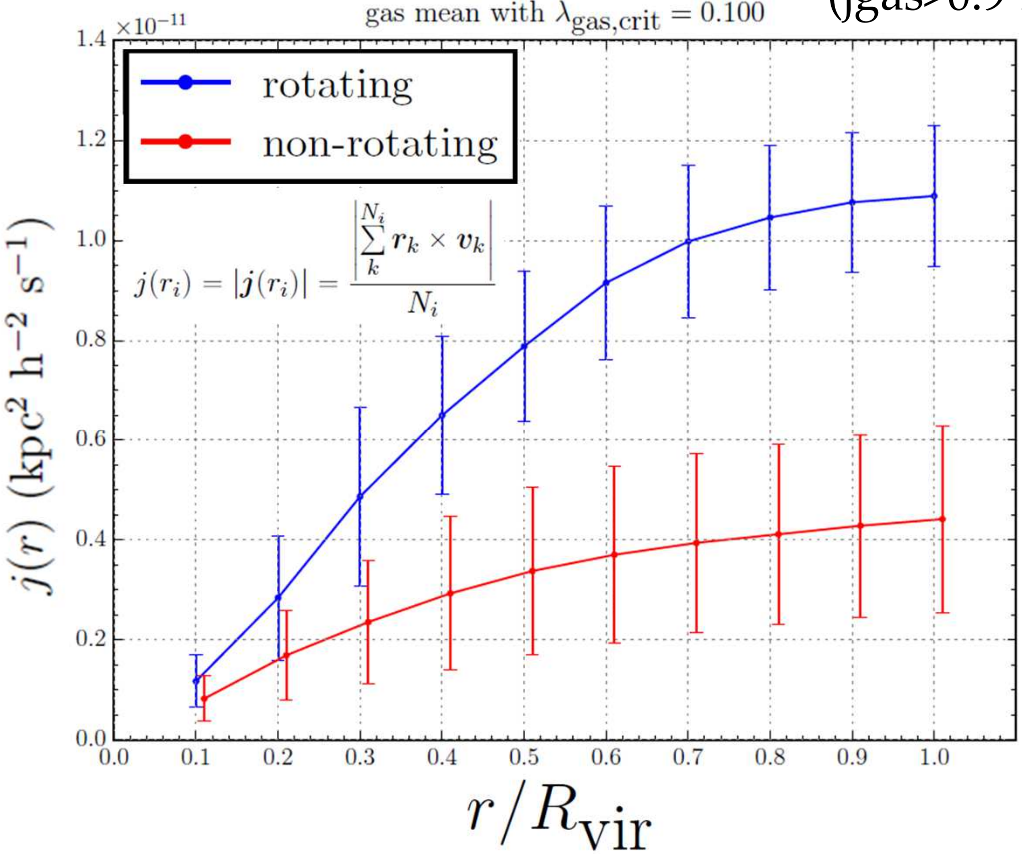
[Chluba J. & Mannheim K. A&A 2002, Cooray A. & Chen X. ApJ 2002]

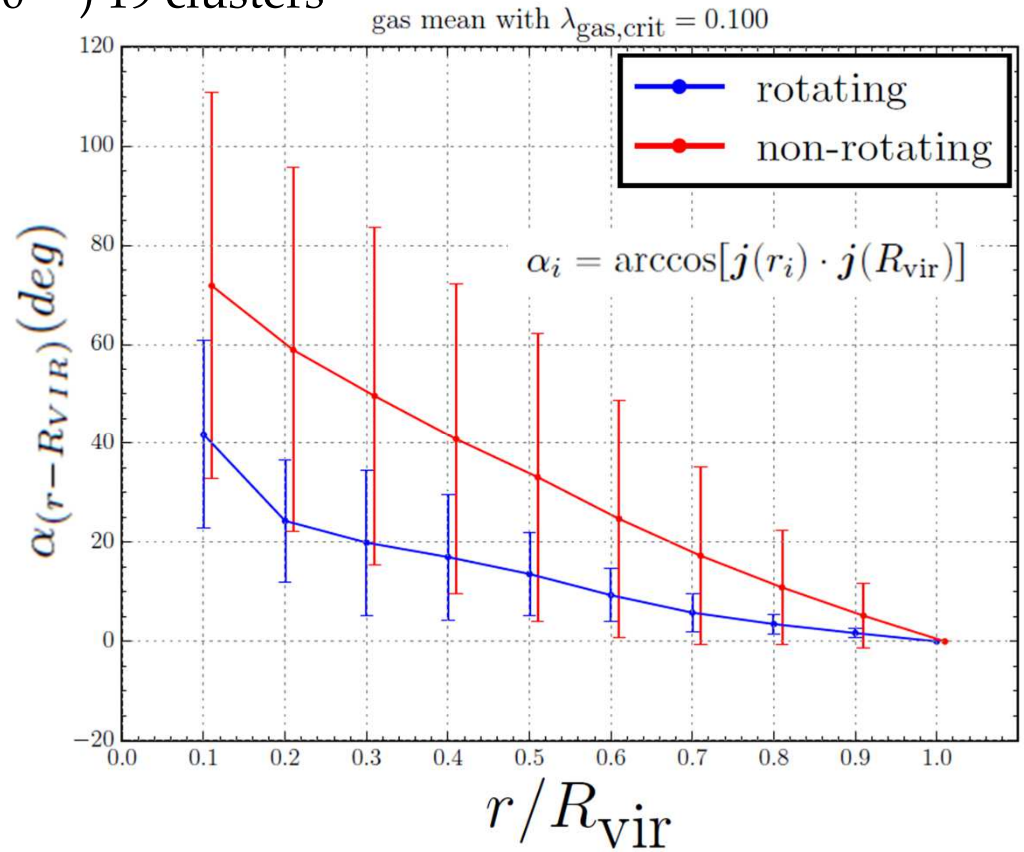
Solid-body assumption due to the limited information about gas motions since high-resolution simulations of clusters at the time were limited to DM only.

# Clusters rotation

Dataset: MUSIC-2 clusters (258 objects with $M>5\ 10^{14} M_{\odot}$ @ z=0 with gas but NR)
Specific angular momentum for gas: amplitude and direction
Possible segregation between Rotating and Non-Rotating objects?

(jgas>0.9 10 -11) 19 clusters



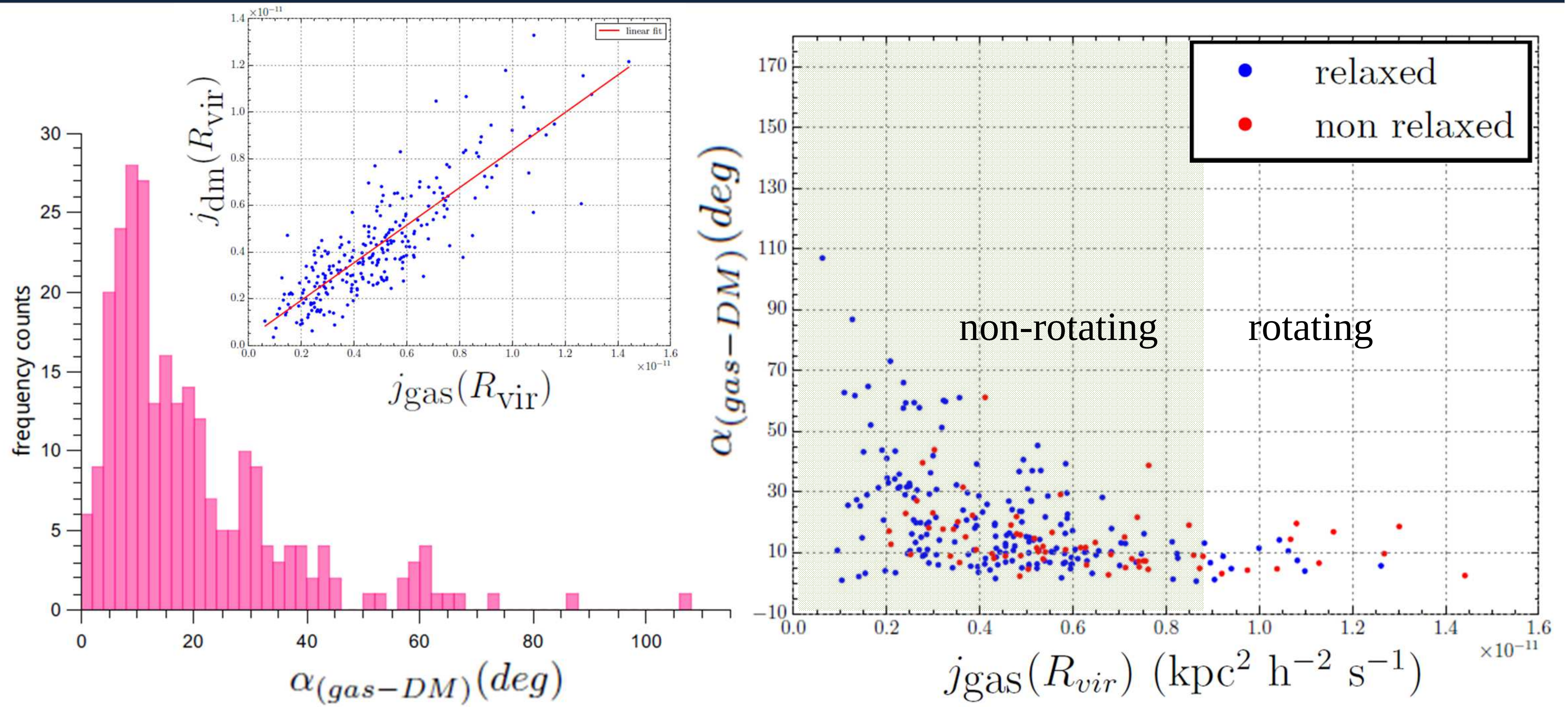




courtesy A.S.Baldi 2015

# Clusters rotation

Alignment of gas and DM specific angular momenta at virial radius for Rotating clusters:

around 10 deg and almost independent on cluster relaxation




courtesy A.S.Baldi 2015

# Clusters rotation

Relaxation indicators for cluster dynamical state:

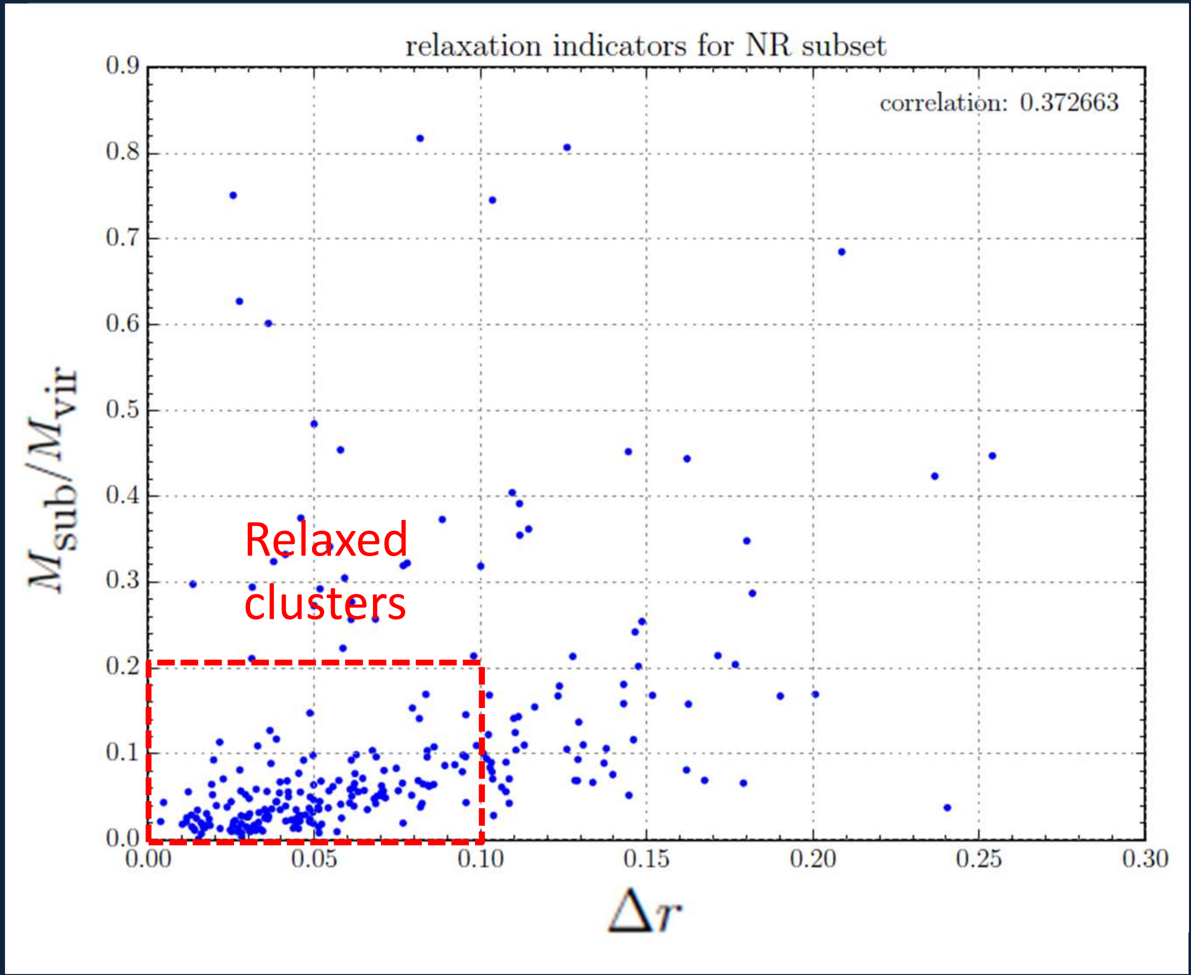
- ✓ Virial ratio

$$\eta = \frac{2T}{|U|}$$

- ✓ Major mergers : presence of substructures within the cluster virial radius

- ✓ Center-of-Mass offset

$$\Delta r = \frac{|r_\delta - r_{\rm CM}|}{R_{\rm vir}}$$



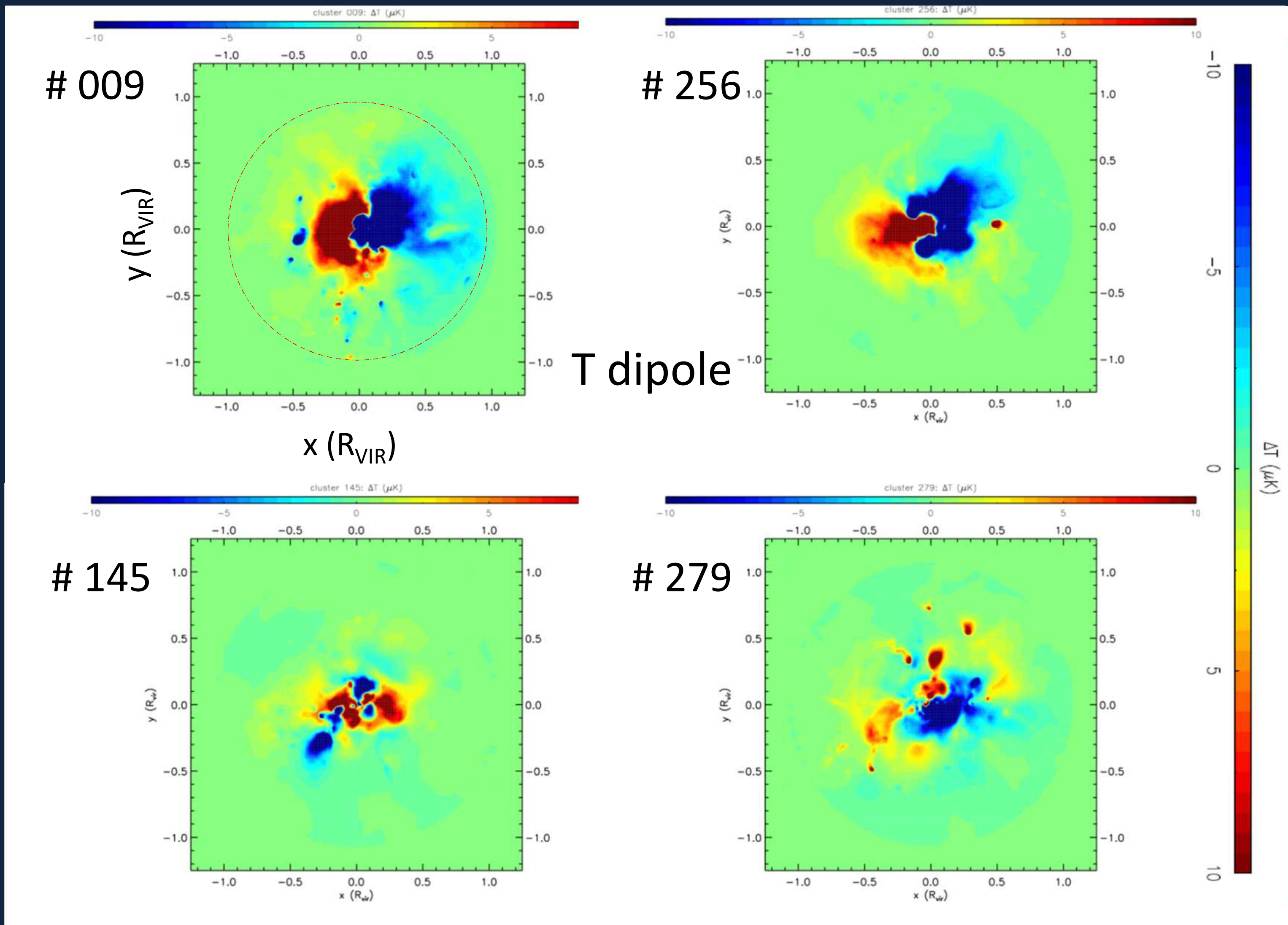
# Clusters rotation

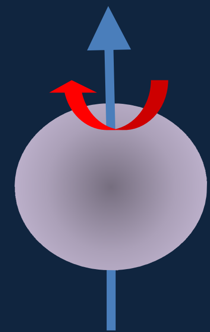
$$\Delta T(\theta,\phi) = T_{CMB}\sum_{i=0}^{n}\beta_i\sigma_T n_{ei} d\rho dl^2$$

*k*-SZE maps of clusters inside $R_{vir}$ orthogonal to $L_{gas}$ vector

ICM coherent rotation

ICM turbolenece



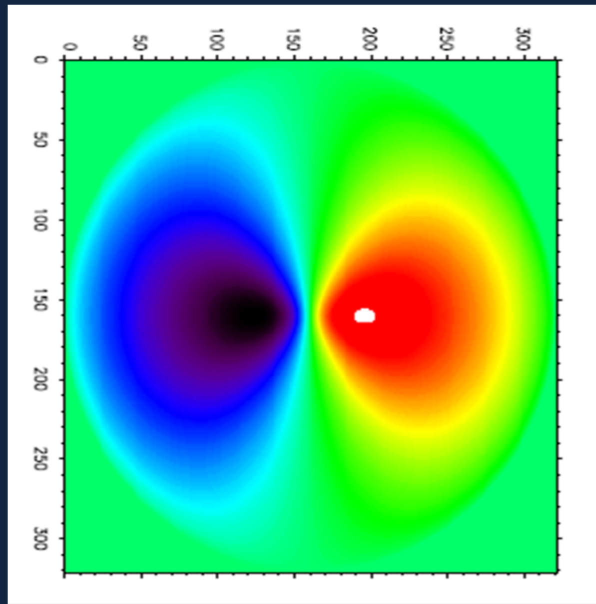



courtesy F. Sembolini 2015

# Clusters rotation

Toy Model:

Map of CMB temperature fluctuations (dipole) assuming a solid-body approach [Cooray A. & Chen X. ApJ 2002] :



$$\frac{\Delta T}{T}(\theta,\ \phi) = \sigma_T e^{-\tau}\eta(\theta)\cos\phi\sin i$$

electron density weighted by the rotational velocity component

$$\eta(\theta) = \int_{d_c\theta}^{R_{\rm vir}} \frac{2r\,dr}{\sqrt{r^2 - d_c^2\theta^2}} n_e(r)\omega d_c\theta$$

$$\rho_{gas} = \rho_0\left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

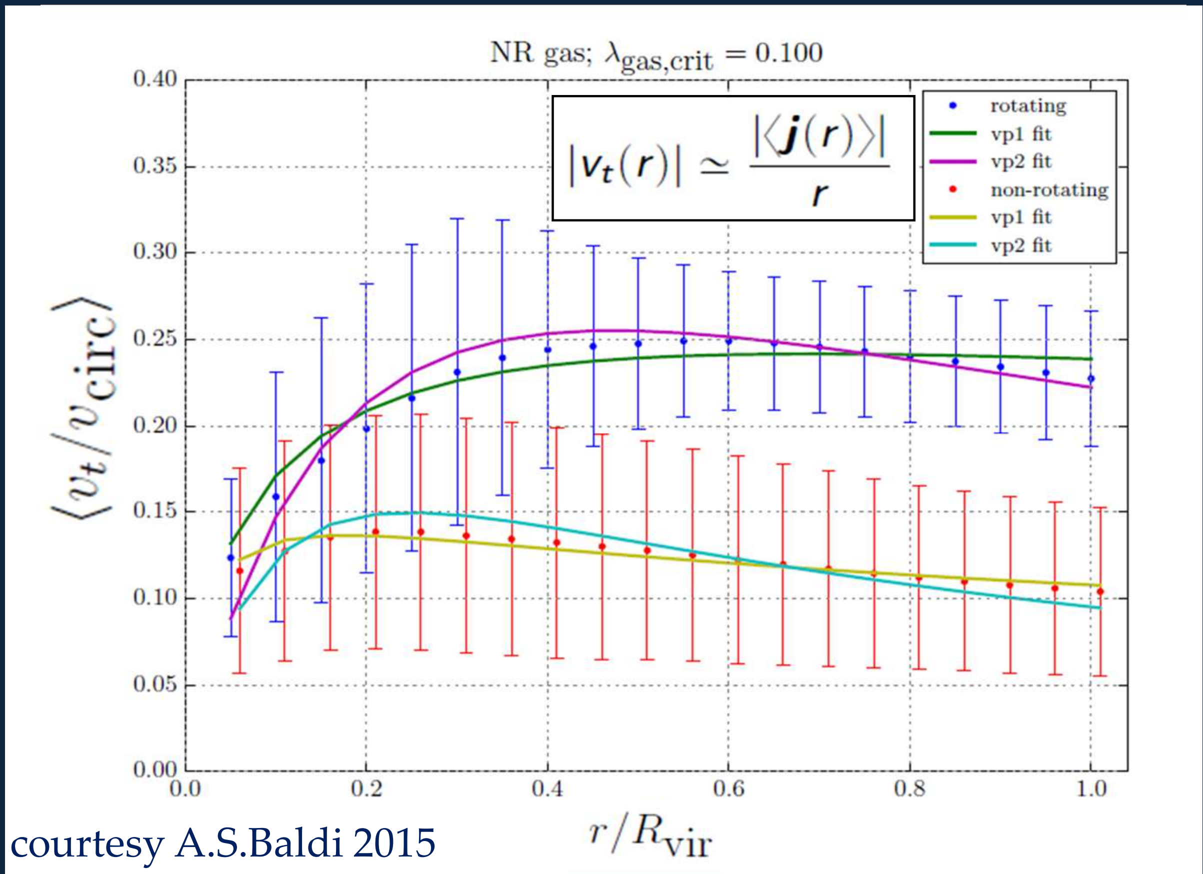
Gas radial profile (*King, …*)

$$\omega = \frac{3\lambda V_c c^2 f^2(c)}{R_{vir} h(c)\sqrt{cg(c)}}$$

Angular velox (NFW DM profile, *c*)

# Clusters rotation

- MUSIC clusters gas tangential velocity radial profile as inferred from the mean specific angular momentum, for Rotating and Non Rotating halos



courtesy A.S.Baldi 2015

Fits with Bianconi's models:
[Bianconi M. et al. MNRAS +13]

$$\text{vp1}: \quad u_\varphi^2 = u_0^2 \left[ \frac{\ln(1+S)}{S} - \frac{1}{S+1} \right]$$

$$\text{vp2}: \quad u_\varphi^2 = u_0^2 \frac{S^2}{(1+S)^4},$$

- MUSIC clusters gas density radial profile:

Semplified Vikhlinin profile [Vikhlinin et al. ApJ +06]

# Clusters rotation

From a *k*-SZE map

$$\frac{\Delta T_{rk-SZE}}{T_{CMB}}(\theta, \phi) = \omega n_{e0}\sigma_T e^{-\tau}\eta(\theta)cos\phi sini/v_L$$

*if, if, if, ...(X-info, angle i unkown)*

$$\omega = \frac{\Delta T_{rk-SZE}}{T_{CMB}} \frac{v_L}{n_{e0}e^{-\tau}\sigma_T\eta(\theta_d)}$$

work in progress

$$J = I\omega$$

$$\lambda = \frac{J}{\sqrt{2}VMR}$$

DM and gas rotation axis *almost* coincident results that by *k*-SZE we can also infer on the DM angular momentum

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# Scaling Relation

Scaling laws based on a Self Similarity assumption [Kaiser MNRAS 1986]

observables *vs* cluster parameter

Y – M, Lx – M and Lr - M

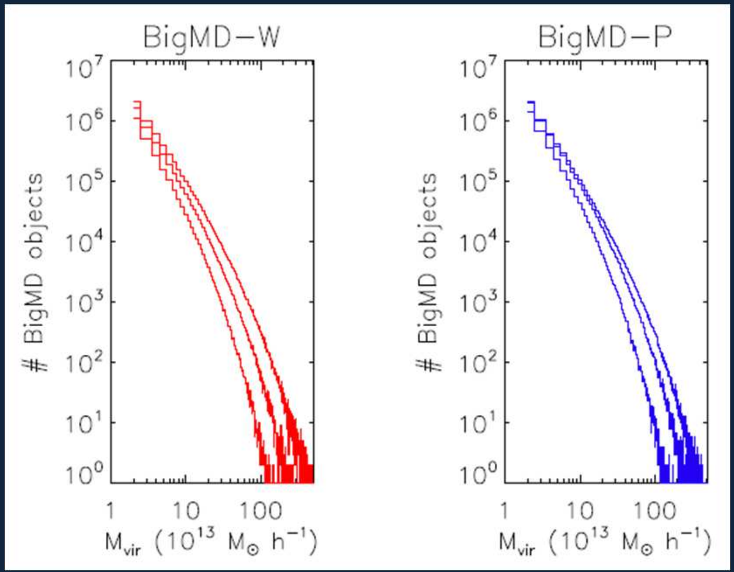
A possible new scaling law B - M

absolute value of the integrated *k*-SZE *vs* cluster mass

$$B(\hat{n})_\Delta D_A^2 = \int_{A_\Delta} b(\hat{n}) dA = -\frac{\sigma_T}{\mu_e m_p} \beta_{los} f_{gas} M_\Delta,$$

Testbed: BigMultiDark clusters

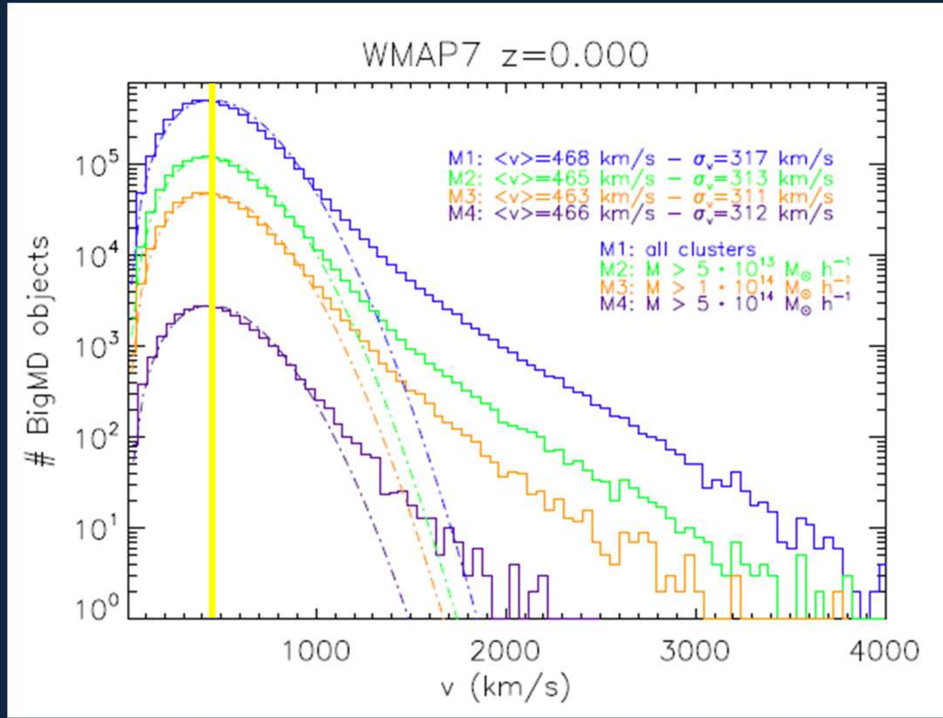
Dark Matter (DM) only N-body simulation performed with the adaptive refinement tree (ART) code [Kravtsov et al. 1997], resolved with $2048^3$ particles in a $(1\ h^{-1}\ \mathrm{Gpc})^3$ cube [Kravtsov et al. 1997; Prada et al. 2012]

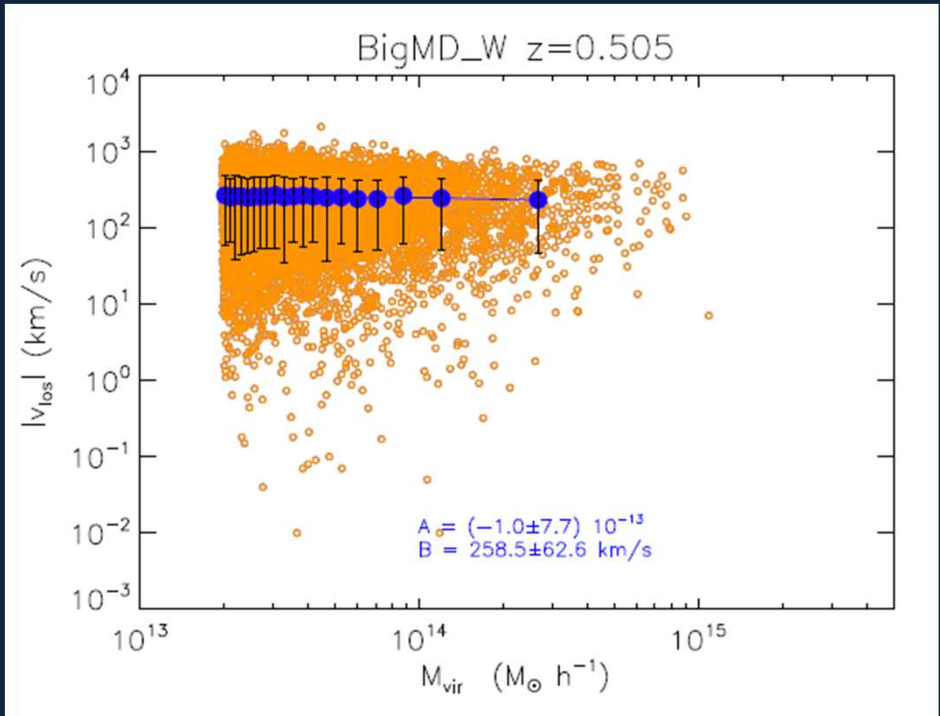



z = 0, 0.5 and 1

# Scaling Relation

Clusters peculiar velocities almost independent on their mass: Maxwell distribution with <v>~460 km/s
[Bahcall et al. ApJ (1994), Dolag & Sunyaev MNRAS (2013)]



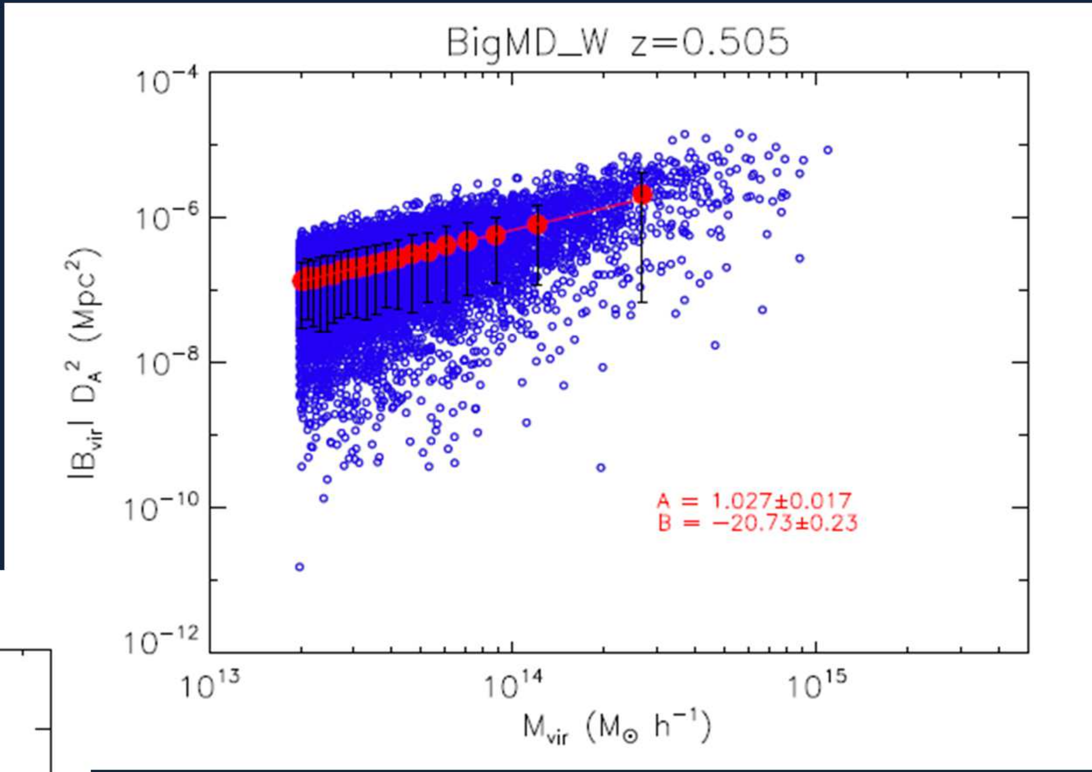



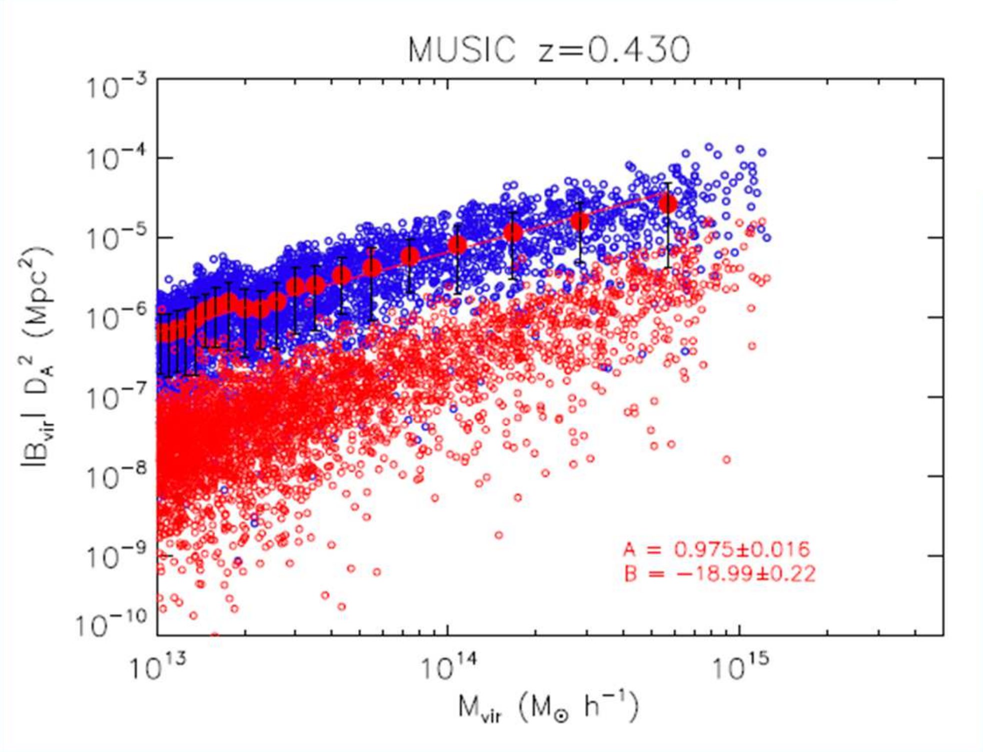

Absolute value of *los* velocities $<|v_{los}|>$~250 km/s almost independent on mass and redshift

| | BigMD-W | | |
|---|---|---|---|
| z | 0.000 | 0.505 | 1.000 |
| $\sigma_{v_{los}}$ (km/s) | 327 | 323 | 302 |
| $\|v_{los}\|$ (km/s) | 255±59 | 252±62 | 237±66 |

# Scaling Relation

Absolute value of the *k*-SZE integrated up to the virial radius versus cluster virial mass: linear dependence in a log-log space.




The impact of ICM motions studying MUSIC clusters.
The blue circles are referring to k-SZE of peculiar motions + ICM turbolence while the red circles only of ICM motions.

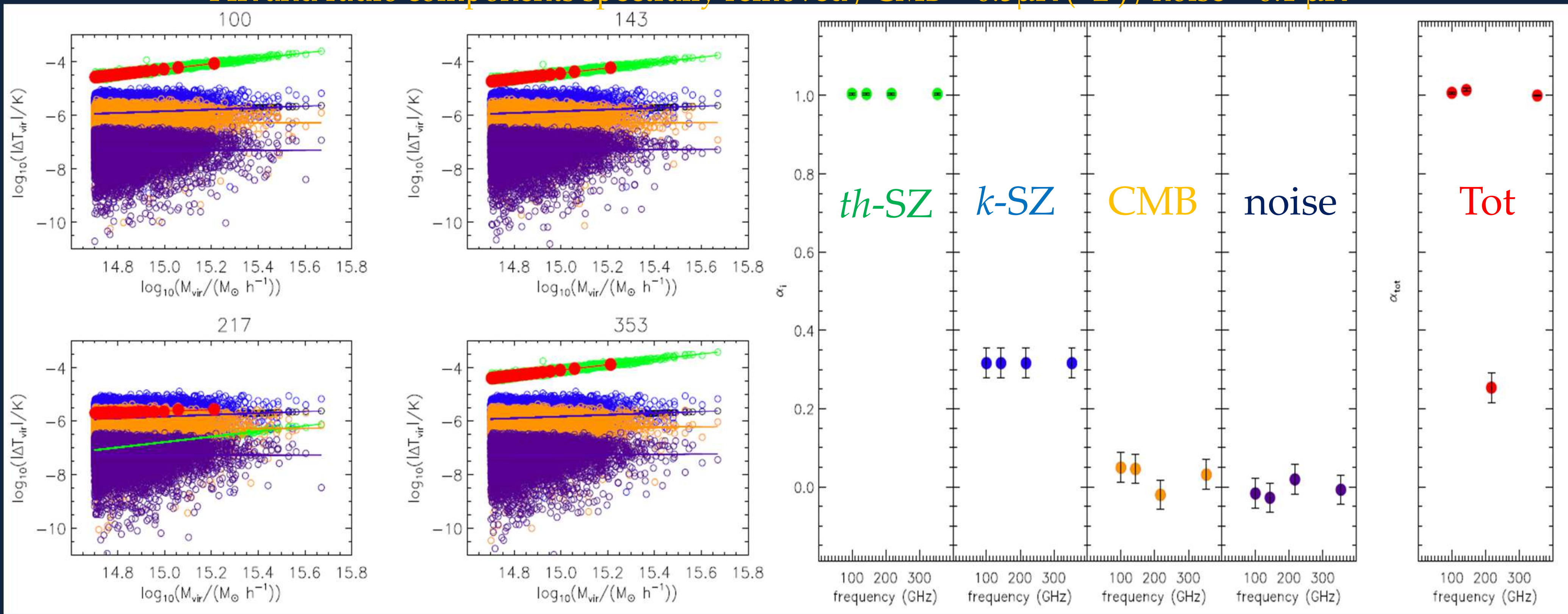
# Scaling Relation

## A statistical detection of *k*-SZE by recovering the slope of |ΔT| *vs* M

$$|\Delta T_\Delta| \propto |c_{th}M^{\alpha_{th}} + c_k M^{\alpha_k} + c_{cmb}M^{\alpha_{cmb}} + c_g M^{\alpha_g} + c_n M^{\alpha_n}|$$

a *synthetic* sky at 4 bands (100, 143, 217 and 353 GHz)

FIR and radio components spectrally removed / CMB ~ 0.5μK (~2′) / noise ~ 0.1 μK




15107 clusters with M > 5 $10^{14}$ $M_\odot$ $h^{-1}$ @ z=0.505 — components slopes — total slope

# Conclusions

- Analysis of gas and DM angular momenta in MUSIC clusters to highlitgh the presence of ICM coherent rotations
- Maps of *k*-SZE of possible rotating candidates: a challenging observational goal! High Sensitivity + High Angular resolution
- A new scaling relation, B – M, for a statistical detection of *k*-SZE
- On-going analysis:
  - Infer gas and DM (?) angular momenta from *k*-SZE maps
  - Comparison with results derived from X-ray maps (by PHOX or X-mas) of the same MUSIC clusters.

Thank you for your attention