Coherent motions of ICM and dark matter in synthetic clusters of galaxies and their impact on kinetic SZ maps

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Outline

Topic

Is it present a coherent matter rotation inside clusters of galaxies?

Testbed

MUSIC-2, a large catalogue of synthetic clusters of galaxies

How to observe

Kinetic Sunyaev-Zel'dovich effect, *among the others ..*

Why clusters rotation?

Do clusters have a non null angular momentum to investigate about their formation?

What about the impact of tidal torques from the surrounding matter, such as in galaxy formation, [Peebles, ApJ 1969] or simply an off-axis merging event [Ricker ApJ1998; Ricker & Sarazin ApJ 2001]?

Does the IntraCluster Medium coherent rotation follow the Dark Matter one?

Testbed

MUltidark SImulations of galaxy Clusters

http://music.ft.uam.es/

MUSIC (Marenostrum-mUltidark SImulations of galaxy Clusters)

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

[Sembolini F. , MDP et al. MNRAS +13]

MUSIC-1 : resimulated clusters from MareNostrum Universe, a non-radiative SPH simulation with 2 billion particles (2×1024^3 gas and dark matter) in a 500 h^{-1}Mpc cubic box [Gottlöber & Yepes ApJ 2007]

164 objects $10^{14} h^{-1} M_{\odot} < M < 2 \cdot 10^{15} h^{-1} M_{\odot}$ (82 relaxed + 82 irregular («Bullet like»)
with radiative physics (cooling + SFR + UV photoionization + SN feedbacks)

WMAP 1($\Omega_M = 0.3$, $\Omega_b = 0.045$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, $n = 1.0$, $h = 0.7$) [Spergel et al. 2003]

MUSIC-2 : resimulated clusters from 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]

>500 clusters $M > 10^{14} h^{-1} M_{\odot}$
>2000 clusters $M > 10^{13} h^{-1} M_{\odot}$
with radiative physics (cooling + SFR + UV photoionization + SN feedbacks),
non radiative (NR) and now also with AGN.

WMAP7+BAO+SNI ($\Omega_M = 0.27$, $\Omega_b = 0.0469$, $\Omega_\Lambda = 0.73$, $\sigma_8 = 0.82$, $n = 0.95$, $h = 0.7$) [Komatsu et al. 2011]

Testbed

MUltidark SImulations of galaxy Clusters

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MUSIC-2

>500 clusters $M>10^{14}h^{-1}M_{\odot}$ + >2000 clusters $M>10^{13}h^{-1}M_{\odot}$

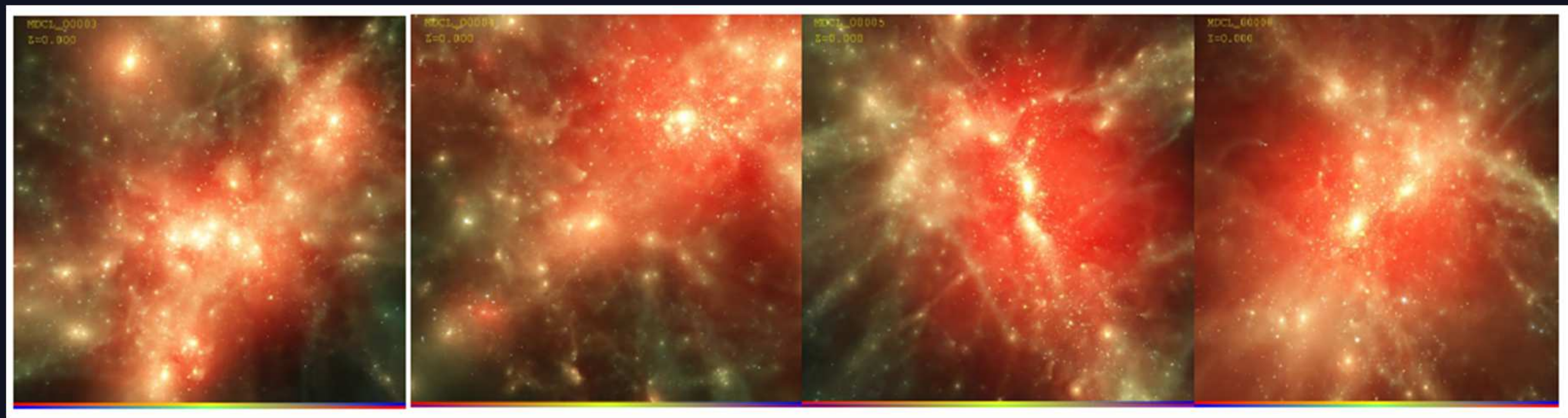
3 flavours

1) non radiative (NR) and

two with radiative physics

2) cooling + SFR + UV photoionization + SN feedbacks (CSF) and

3) feedback from active galactic nuclei (AGN).



4 objects with radiative physics (CSF) at z=0

The same object with radiative (CSF) and non radiative (NR) physics at z=0

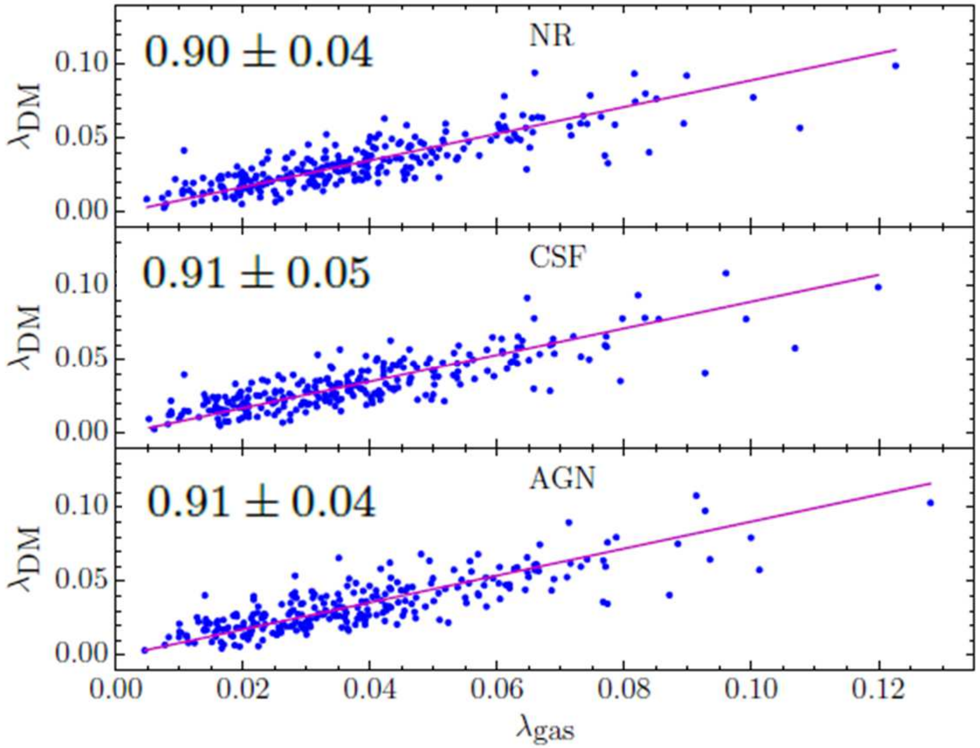
Testbed

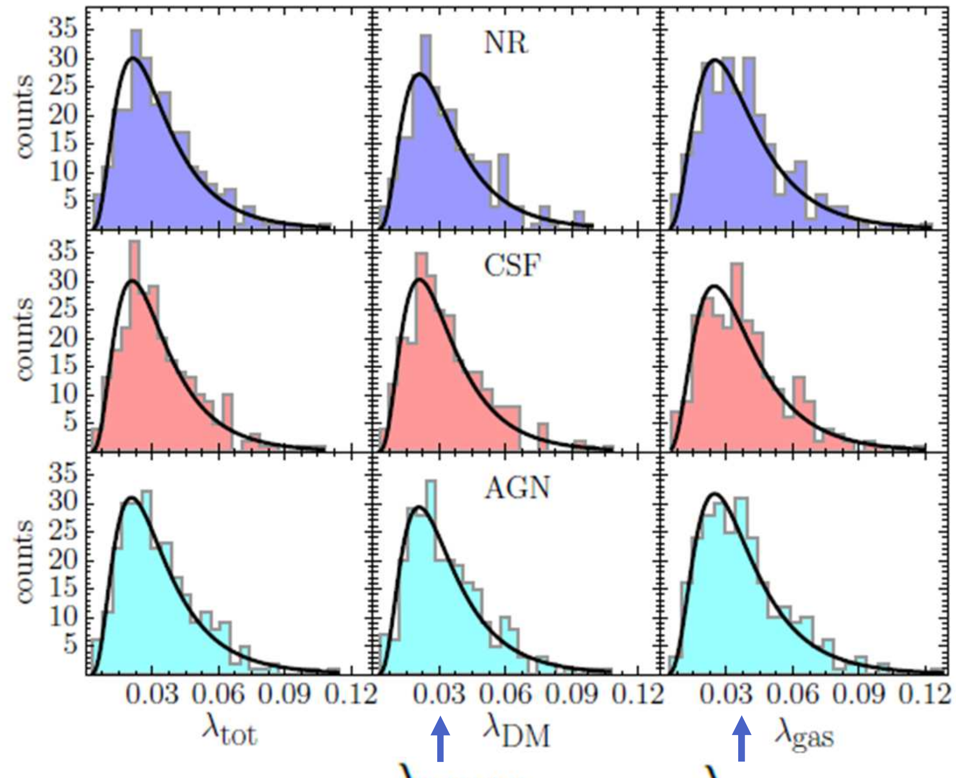
MUSIC-2 Massive clusters (258 objects $M>5\cdot10^{14}M_{\odot}$ @ z=0 NR, CSF and AGN)

Spin parameter to highlight the presence of rotation for the *k* component (gas or DM)

$$\lambda_\kappa = \frac{L_\kappa}{\sqrt{2GM_{\rm vir}R_{\rm vir}}\ M_\kappa}$$

$$P(\lambda)d\lambda = \frac{1}{\lambda\sqrt{2\pi}\sigma}\exp\left(-\frac{\ln^2(\lambda/\lambda_0)}{2\sigma^2}\right)d\lambda$$





$\lambda_{0,\rm DM}$ 0.0289

$\lambda_{0,\rm gas}$ 0.0333

[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

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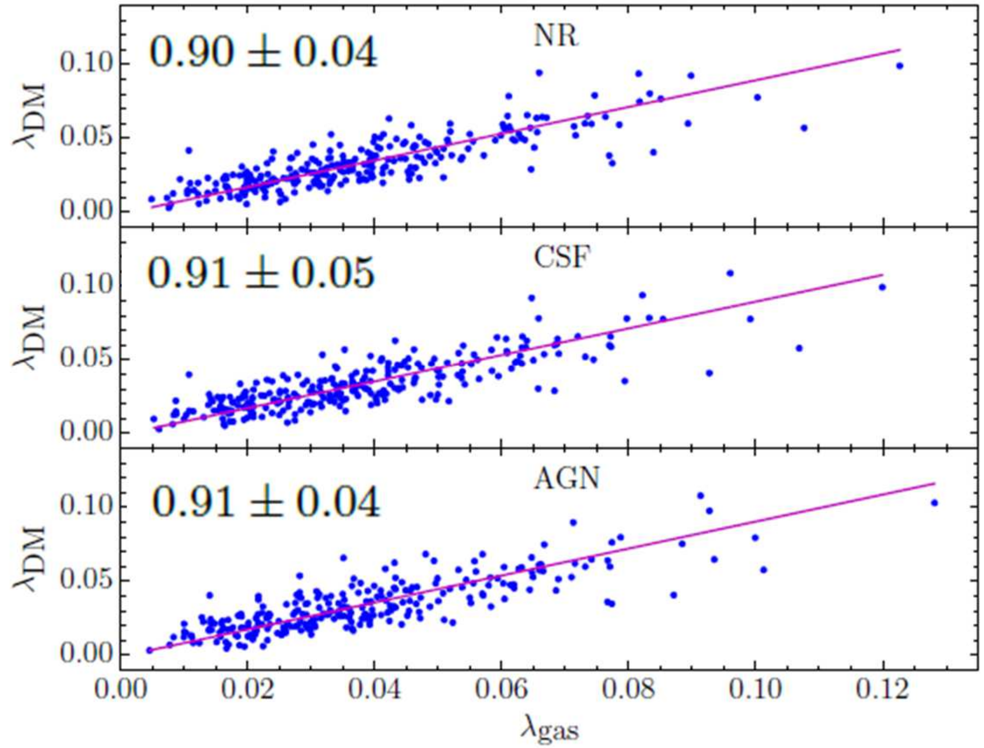


Work	$\lambda_{0,\rm DM}$	$\sigma_{\rm DM}$	$\lambda_{0,\rm gas}$	$\sigma_{\rm gas}$
Bullock et al. (2001)	0.035	0.5	—	—
Van den Bosch et al. (2002)	0.040	0.56	0.039	0.57
Sharma & Steinmetz (2005)	0.0287	0.5329	0.0412	0.430
Gottlöber & Yepes (2007)	0.0351	0.6470	0.0462	0.6086
Macciò et al. (2008)	0.034	0.59	—	—
Bryan et al. (2013)	0.0354	0.62	—	—
this work, NR	0.0289	0.5674	0.0333	0.5470
this work, CSF	0.0288	0.5638	0.0330	0.5489
this work, AGN	0.0289	0.5755	0.0330	0.5416

$\lambda_{\rm tot}$ ↑ $\lambda_{\rm DM}$ ↑ $\lambda_{\rm gas}$

$\lambda_{0,\rm DM}$ 0.0289 $\lambda_{0,\rm gas}$ 0.0333

[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

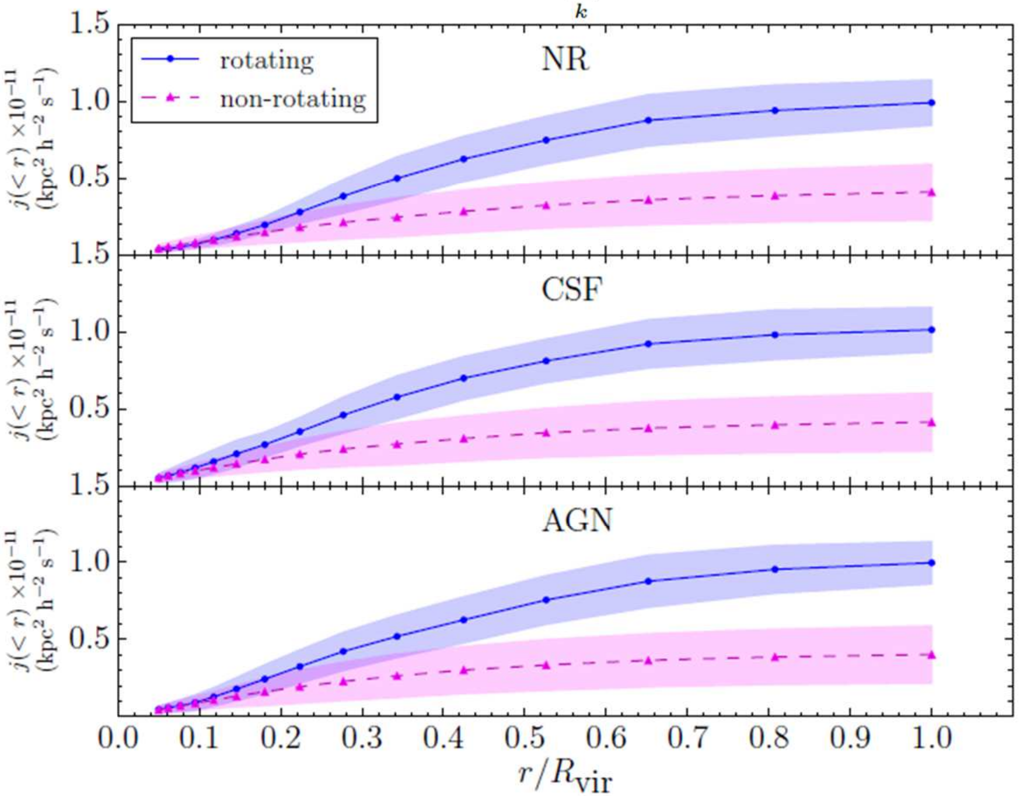
MUSIC-2 Relaxed clusters (146 objects (56%))
MUSIC-2 Rotating clusters (7 objects (3%))

$$\Delta r = 0.10 \ \cup \ M_{\rm sub}/M_{\rm vir} = 0.10$$
$$\lambda_{\rm gas} > \lambda_{\rm gas,crit} = 0.07$$

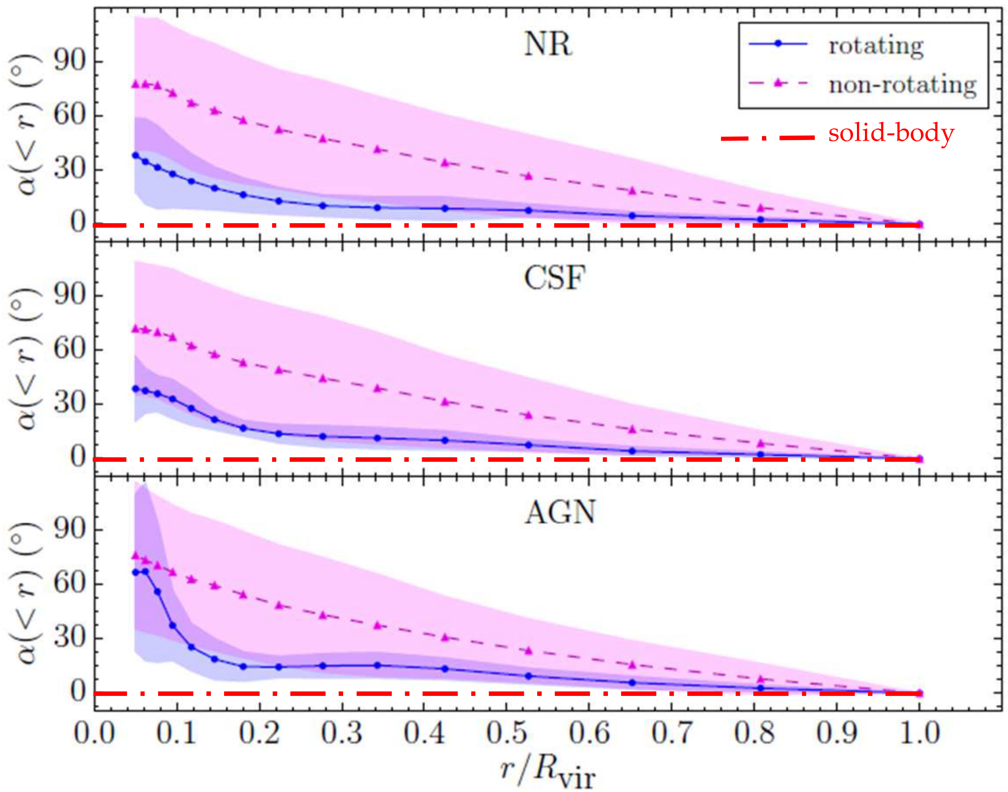
Specific angular momentum for ICM: amplitude and direction

$$j(<r_i) = \frac{\left|\sum_k^{N_i} \boldsymbol{r}_k \times m_k \boldsymbol{v}_k\right|}{\sum_k^{N_i} m_k}$$

$$\alpha(<r_i) = \arccos\left[\hat{j}(<r_i) \cdot \hat{j}(<R_{\rm vir})\right]$$



(b) modulus



(a) direction

DM profiles show similar behaviours [Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

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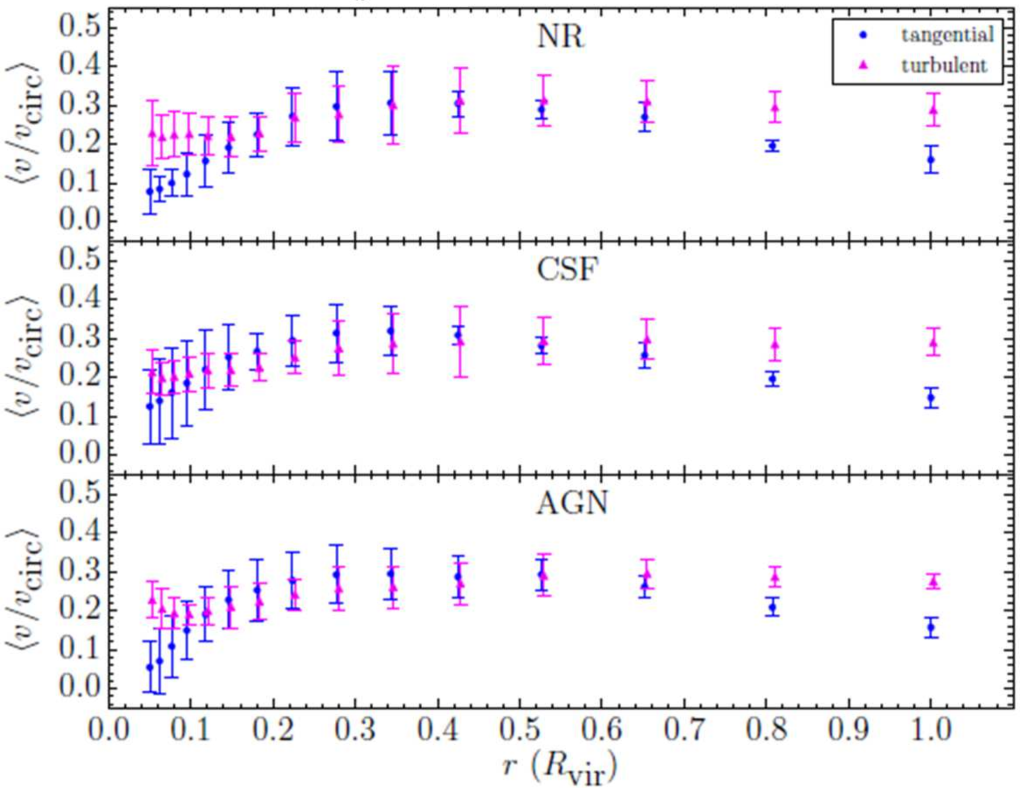
$$\Delta r = 0.10 \ \cup \ M_{\rm sub}/M_{\rm vir} = 0.10$$

$$\lambda_{\rm gas} > \lambda_{\rm gas,crit} = 0.07$$

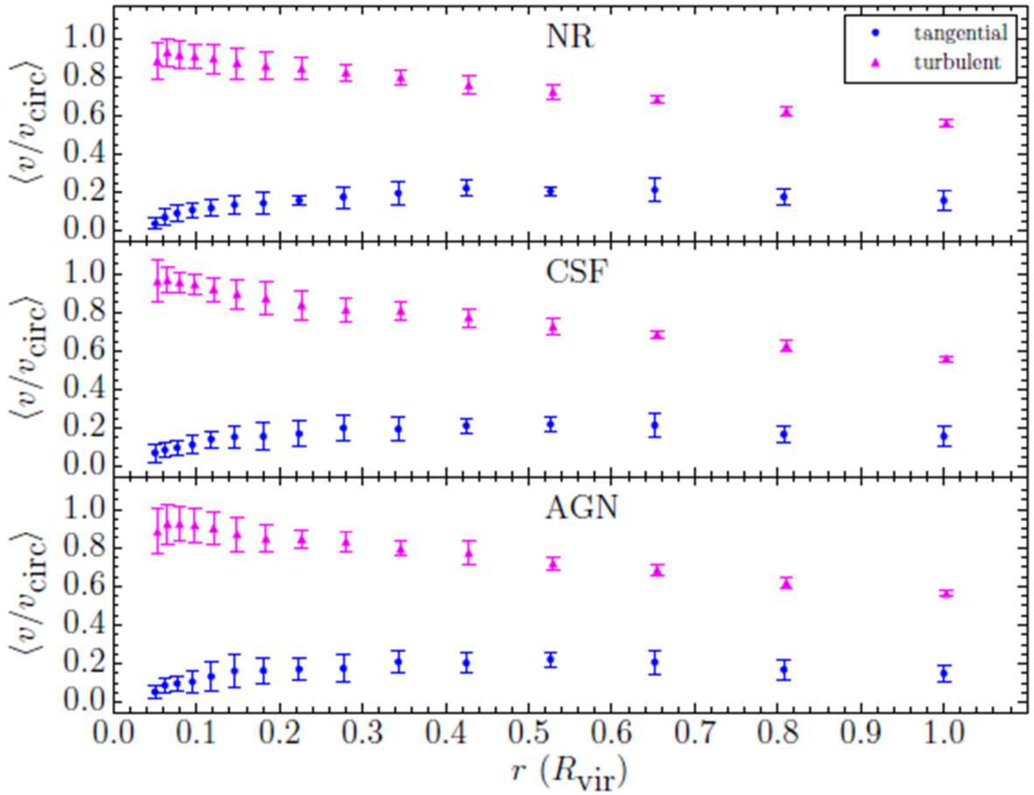
Tangential and turbulent velocity r-profiles for ICM and DM (rotating clusters)

$$v_{\rm tan}(r_i) = \frac{\left|\sum_k^{N_i} \frac{r_k \times m_k v_k}{|r_k|}\right|}{\sum_k^{N_i} m_k} \qquad v_{\rm tan}(r_i) \sim \langle j(r_i) \rangle / r_i$$

$$v_{\rm turb}(r_i) = \left[\sum_k^{N_i} m_k \left(\frac{|r_k \times v_k|}{|r_k|} - v_{\rm tan}(r_i) \right)^2 / \sum_k^{N_i} m_k \right]^{\frac{1}{2}}$$



ICM



DM

[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

MUSIC-2 Relaxed clusters (146 objects (56%))
MUSIC-2 Rotating clusters (7 objects (3%))

$\Delta r = 0.10 \cup M_{\rm sub}/M_{\rm vir} = 0.10$

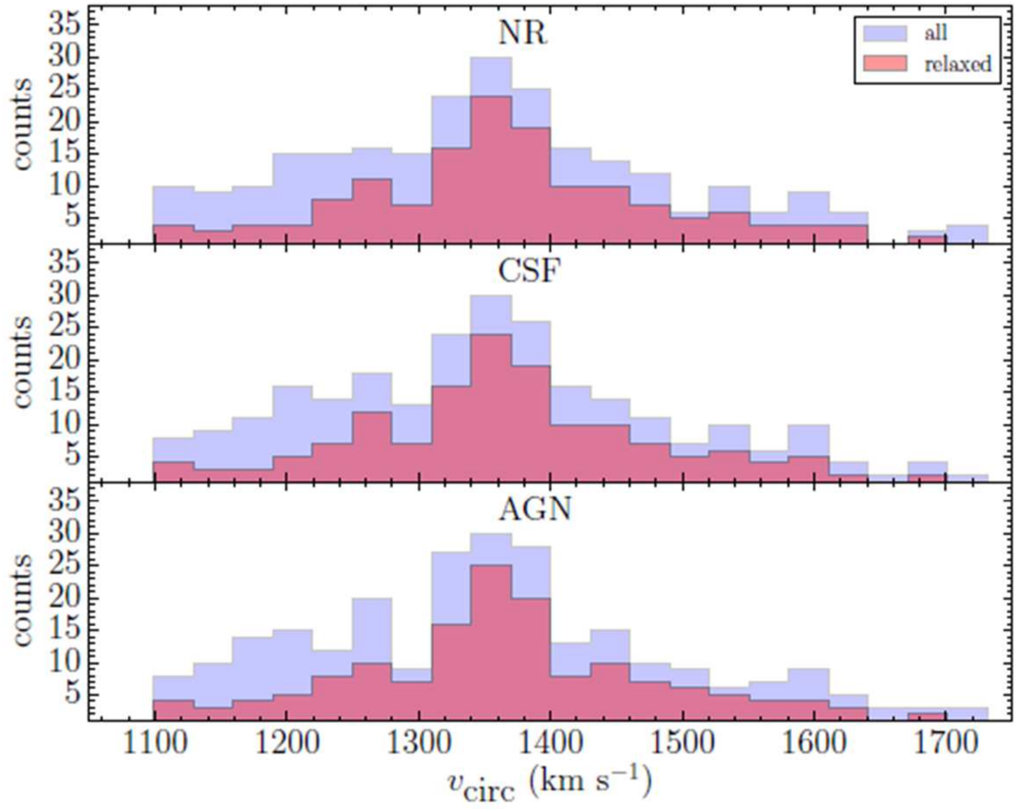
$\lambda_{\rm gas} > \lambda_{\rm gas,crit} = 0.07$

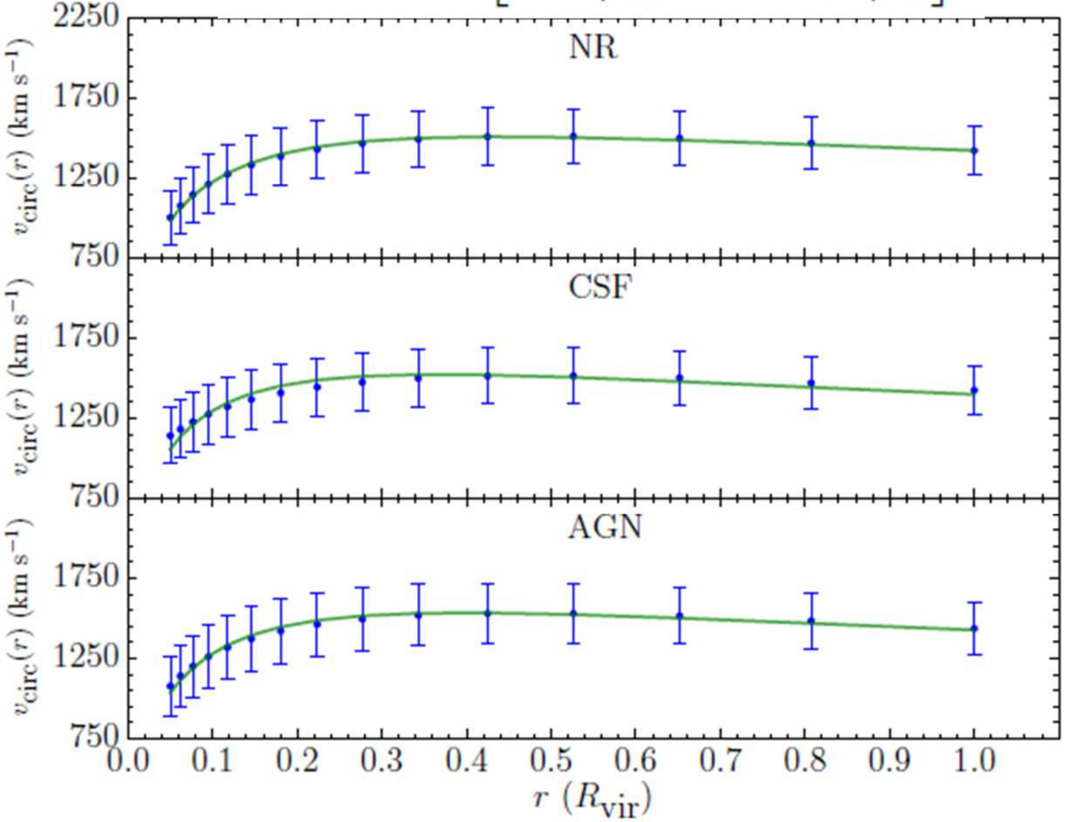
Circular velocities distribution and radial profiles

$\langle v_{\rm circ} \rangle = (1365 \pm 145)\,{\rm km\,s^{-1}}$

$v_{\rm circ}(r) = \sqrt{GM(r)/r}$

$v_{\rm circ}(r) = v_{c0} \left[\frac{\ln(1+r/r_0)}{r/r_0} - \frac{1}{1+r/r_0} \right]^{\frac{1}{2}}$



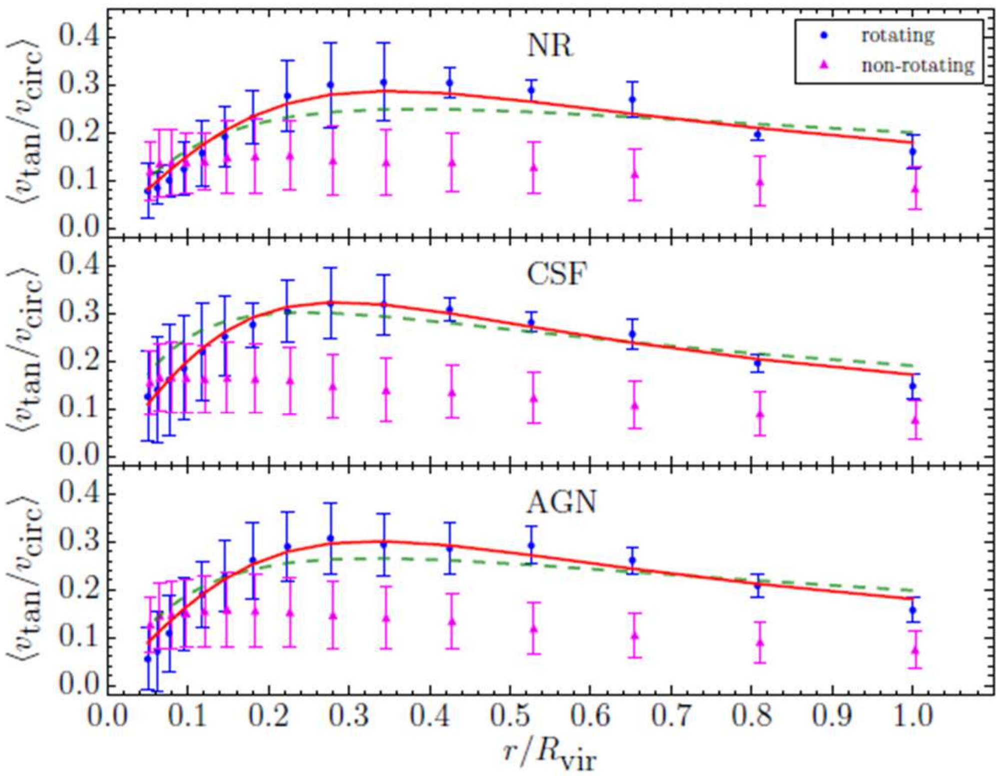


[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

MUSIC-2 Relaxed clusters (146 objects (56%))
MUSIC-2 Rotating clusters (7 objects (3%))
ICM tangential velocity radial profiles

$$\Delta r = 0.10 \;\cup\; M_{\rm sub}/M_{\rm vir} = 0.10$$
$$\lambda_{\rm gas} > \lambda_{\rm gas,crit} = 0.07$$



(a) gas

Spin parameter threshold to select rotating clusters

$$\lambda_{\rm gas,crit} = 0.07$$

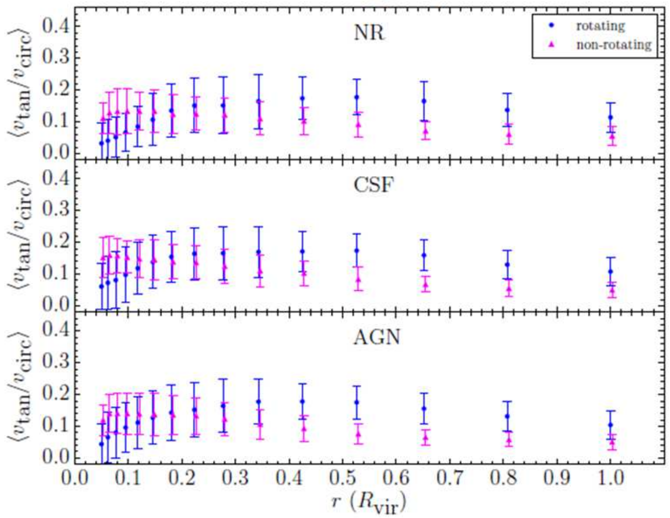
Fit with Bianconi's model
[Bianconi M. et al. MNRAS +13]

$$v_{\tan}(r) = v_{t0}\,\frac{r/r_0}{(1+r/r_0)^2}$$

Fit with a new modified model

$$v_{\tan}(r) = v_{t0}\,\frac{r/r_0}{1+(r/r_0)^2}$$

$$\lambda_{\rm gas,crit} = 0.03$$



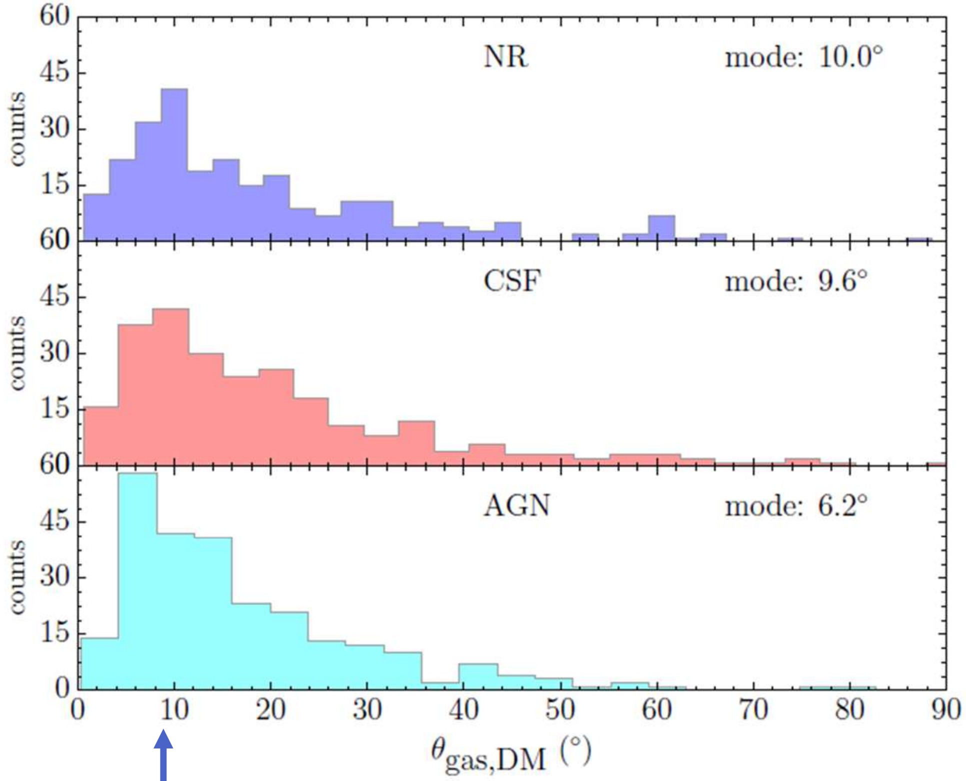
[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

Testbed

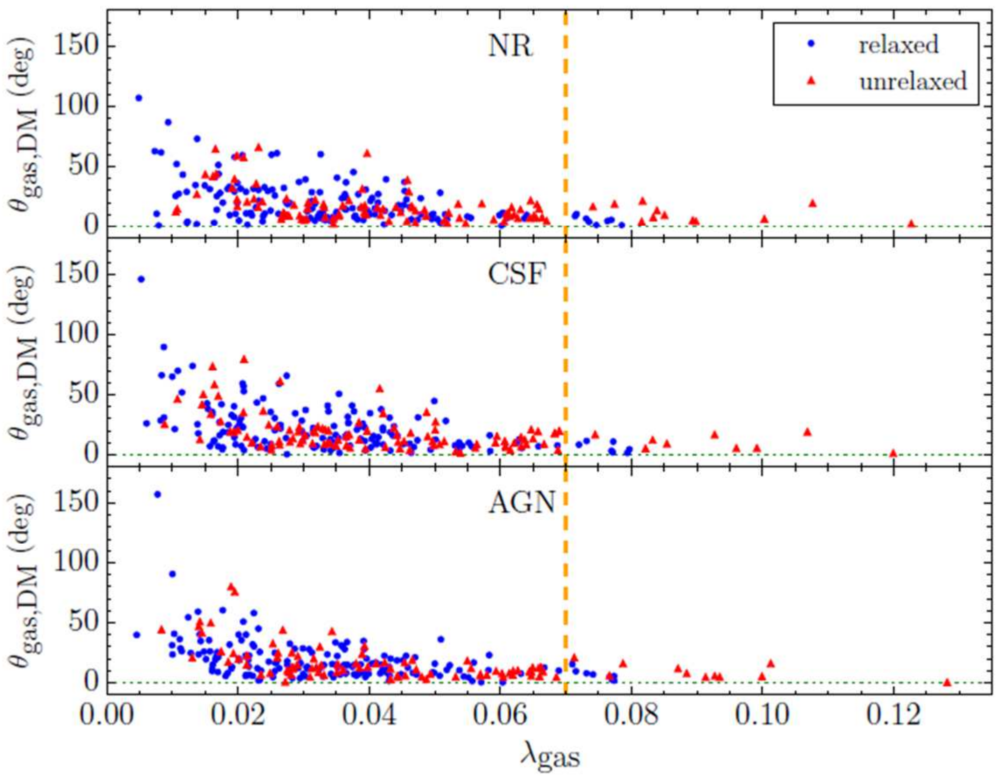
MUSIC-2 Massive clusters (258 objects $M>5\cdot10^{14}M_\odot$ @ z=0 NR, CSF and AGN)

Angular momenta direction for ICM and DM and *vs* ICM spin parameter

$$\theta_{\rm gas,DM} = \arccos\left[\hat{L}_{\rm gas}(R_{\rm vir}) \cdot \hat{L}_{\rm DM}(R_{\rm vir})\right]$$



larger cluster rotation ⇨ ICM & DM co-rotation



<10 deg for 40% of all clusters and almost independent on cluster relaxation

NEW gas angular momentum fraction $\ell_{\rm gas} = L_{\rm gas}/L_{\rm DM} \sim 0.17$

[Baldi A.S., MDP et al. submitted MNRAS 2016, arxiv:1606.02148]

How to observe

How to infer the presence of possible cluster rotation by observations?

multi-λ and multi-*obs approaches*

- ✓ Optical obs of velocity of member galaxies

  [Tovmassian, Ap 2015 and Manolopoulou M. & Plionis M., 2016, submitted & **see POSTER ⇨**]

- ✓ Doppler shift on ICM X-ray emission lines

  [Dupke & Bregman, ApJ 2001, & **see Ettori's TALK**]

  or

  X-ray surface brightness maps ellipticity

  [Fang et al., ApJ 2009 and Bianconi et al. MNRAS 2013]

- ✓ kinetic-Sunyaev-Zel'dovich effect due to ICM motions

  [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

How to observe

How to infer the presence of possible cluster rotation by observations?

multi-λ and multi-*obs approaches*

Discrete sampling

✓ Optical obs of velocity of member galaxies

[Tovmassian, Ap 2015 and Manolopoulou M. & Plionis M., 2016, submitted & **see POSTER ⇨**]

Diffuse sampling

✓ Doppler shift on ICM X-ray emission lines

[Dupke & Bregman, ApJ 2001, & **see Ettori's TALK**]

or

X-ray surface brightness maps ellipticity

[Fang et al., ApJ 2009 and Bianconi et al. MNRAS 2013]

✓ kinetic-Sunyaev-Zel'dovich effect due to ICM motions

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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

kinetic Sunyaev-Zel'dovich Effect observations

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

$$\Delta I_k = -i_0 h(x) \frac{V_r}{c} \tau \qquad \Delta T_k = -T_{\mathrm{CMB}} \frac{V_r}{c} \tau$$

Toy Model [Cooray A. & Chen X. ApJ 2002]

Map of CMB temperature fluctuations assuming a solid-body approach = dipole

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

electron density weighted by the rotational velocity component

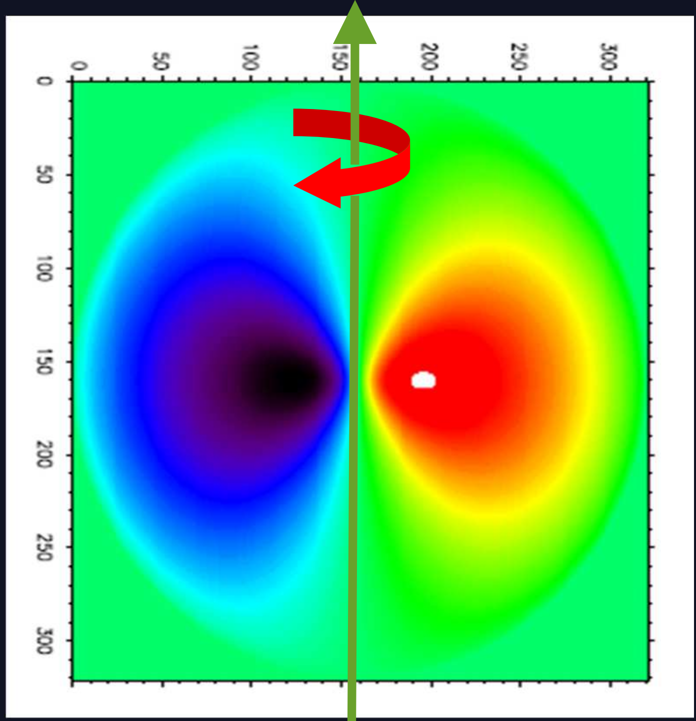
$$\eta(\theta) = \int_{d_c\theta}^{R_{\mathrm{vir}}} \frac{2r\,dr}{\sqrt{r^2 - d_c^2\theta^2}} n_e(r) \omega d_c \theta$$

Gas radial profile (*King, …*)

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

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

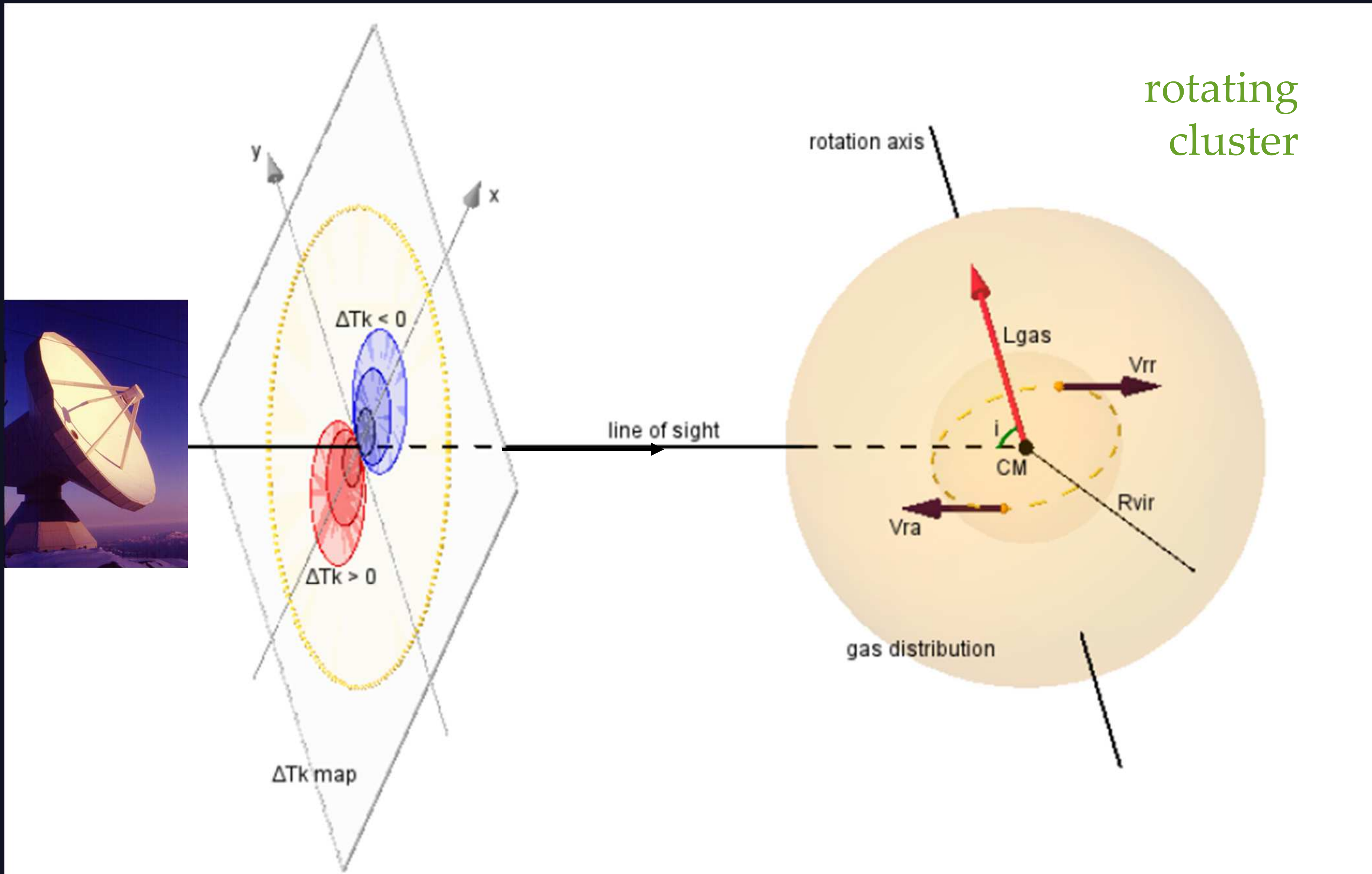
Angular velocity (NFW DM profile, *c*)



cold & hot spots

kinetic Sunyaev-Zel'dovich Effect observations

The dipole in a nutshel



[courtesy A.S. Baldi]

kinetic Sunyaev-Zel'dovich Effect observations

MUSIC-2 Rotating clusters

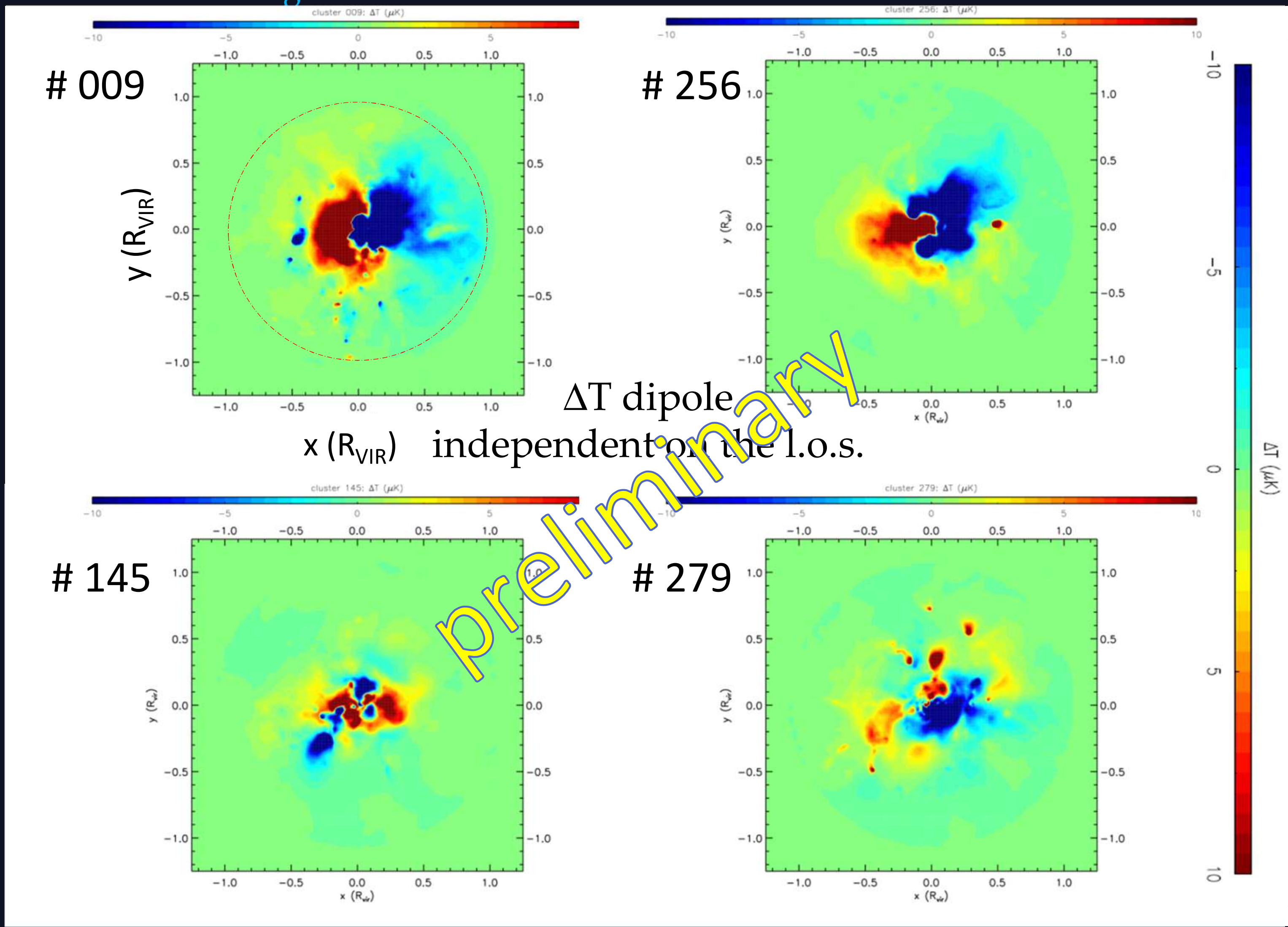
k-SZE maps of clusters inside R_{vir}

l.o.s orthogonal to L_{gas} vector

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

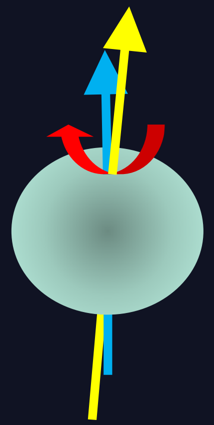
ICM coherent rotation

ICM turbolence



kinetic Sunyaev-Zel'dovich Effect observations

MUSIC-2 Rotating clusters



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

High angular resolution instruments to map kinematic SZ effect towards clusters at a frequency around 200 GHz are necessary such as an example NIKA2 camera at the 30-m IRAM telescope [Monfardini et al. 2014])

+

X-ray band obs with future satellites such as Athena [Barcons et al. 2015]

+

Comparison with rotating Abell/ACO clusters with SDSS DR10 spectroscopy [Manolopoulou M. & Plionis M., 2016, submitted]

Conclusions

- A small fraction of relaxed massive MUSIC-2 clusters show a coherent rotation of ICM and DM with fixed orientation along the radius;
- This result is almost independent on the physical models to describe ICM properties;
- A simple model to describe the tangential velocity radial profile is derived;
- Among several observational approaches, kSZE observations could detect clusters ICM rotation.

thank you for your attention