
CENTRO DE ESTUDIOS DE FÍSICA DEL COSMOS
DE ARAGÓN
(CEFCA)

Finding the missing baryons by their motion imprint on the Cosmic Microwave Background.

PIP XVIII, PRL (submitted)

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FUNDACIÓN AGENCIA ARAGONESA
PARA LA INVESTIGACIÓN Y EL DESARROLLO

Outline

- The kinetic Sunyaev-Zel'dovich effect (kSZ)
- The Central Galaxy Catalogue (CGC)
- Measuring the kSZ pairwise momentum
- Correlating with a reconstruction of the peculiar velocity field

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- Correlating with a reconstruction of the peculiar velocity field
- **Constraints on the missing baryons**
- **Constraints on the Copernican Principle**

The kinetic Sunyaev-Zel'dovich effect (kSZ)

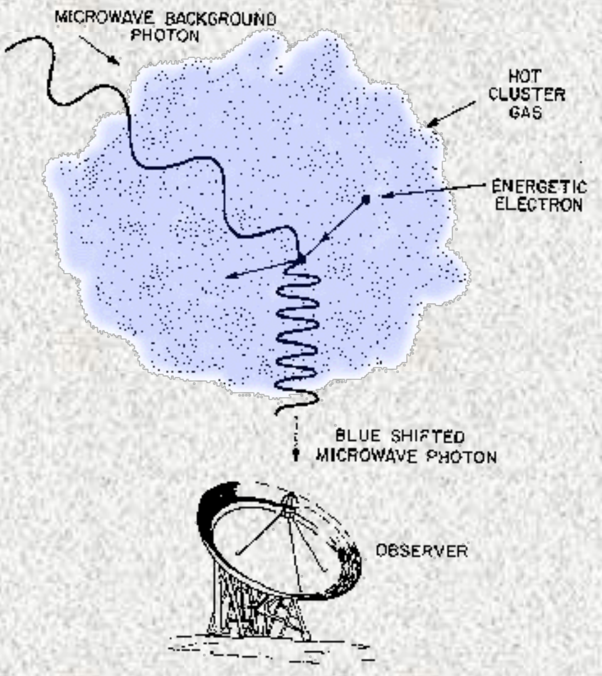
- The kSZ effect expresses the Doppler kick experienced by CMB photons when scattering off rapidly moving electrons

$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = -\int dl\,\sigma_{\mathrm{T}}\, n_{\mathrm{e}} \frac{\boldsymbol{v}_{\mathrm{e}}\cdot\hat{\boldsymbol{n}}}{c}$$

- The kSZ temperature anisotropies is independent of frequency (just like primary CMB anisotropies)

- When looking at the direction of hot gas clouds, it is likely to be contaminated by the (dominant) thermal Sunyaev-Zel'dovich (tSZ) effect, which flips from negative to positive at the cross-over frequency of 217 GHz.

- To avoid the tSZ and other contamination, we use **different channels** and **foreground-cleaned** maps, like **SEVEM, SMICA, COMMANDER** and **NILC.**



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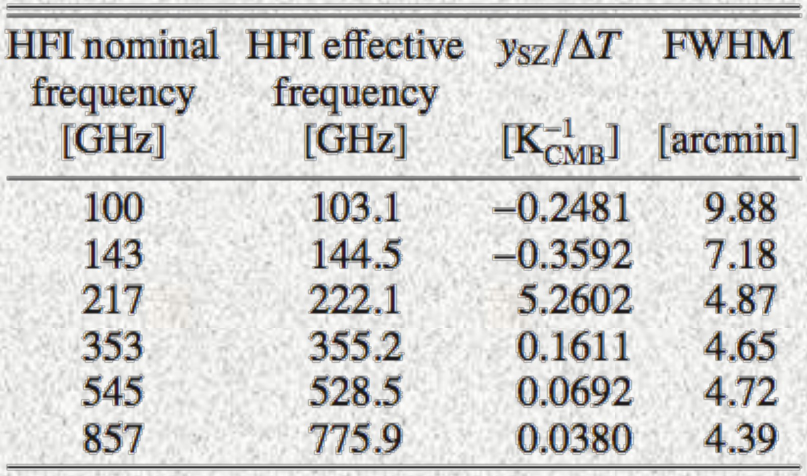


HFI nominal frequency [GHz]	HFI effective frequency [GHz]	$y_{SZ}/\Delta T$ [K_{CMB}^{-1}]	FWHM [arcmin]
100	103.1	−0.2481	9.88
143	144.5	−0.3592	7.18
217	222.1	5.2602	4.87
353	355.2	0.1611	4.65
545	528.5	0.0692	4.72
857	775.9	0.0380	4.39

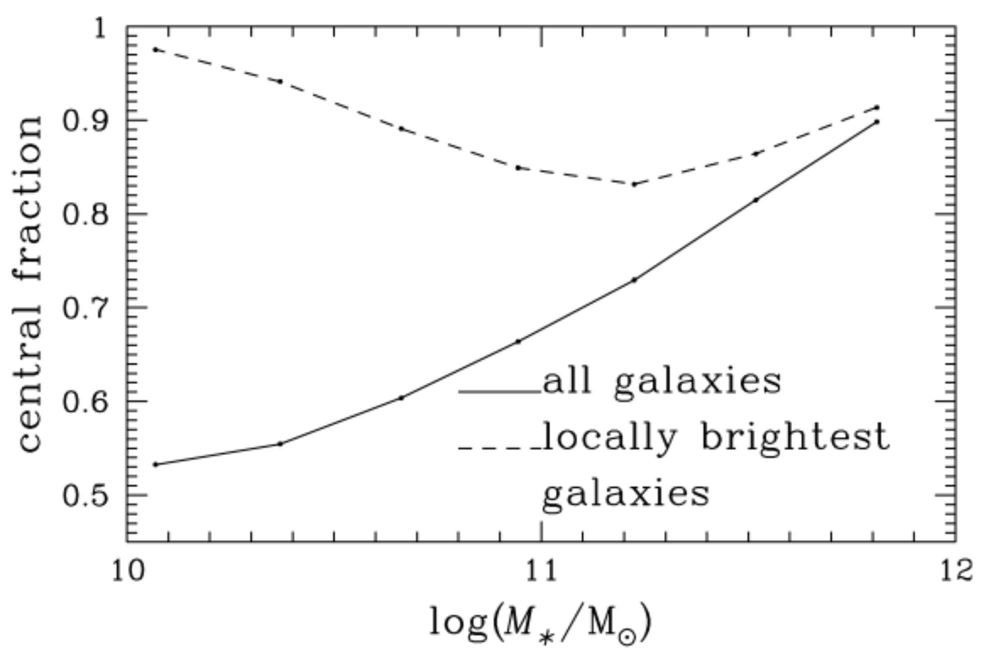
The Central Galaxy Catalogue (CGC)

- Based upon SDSS DR7 NYUAV galaxy catalogue after ***isolating*** brightest galaxies in 1 Mpc (transversal direction) and 1000 km/s (LOS)

- It consists of 262 673 galaxies placed at **z~0.12**, of which ~83% should be true central galaxies.

- Using the Millennium simulation, from M_* we may estimate M_{halo}

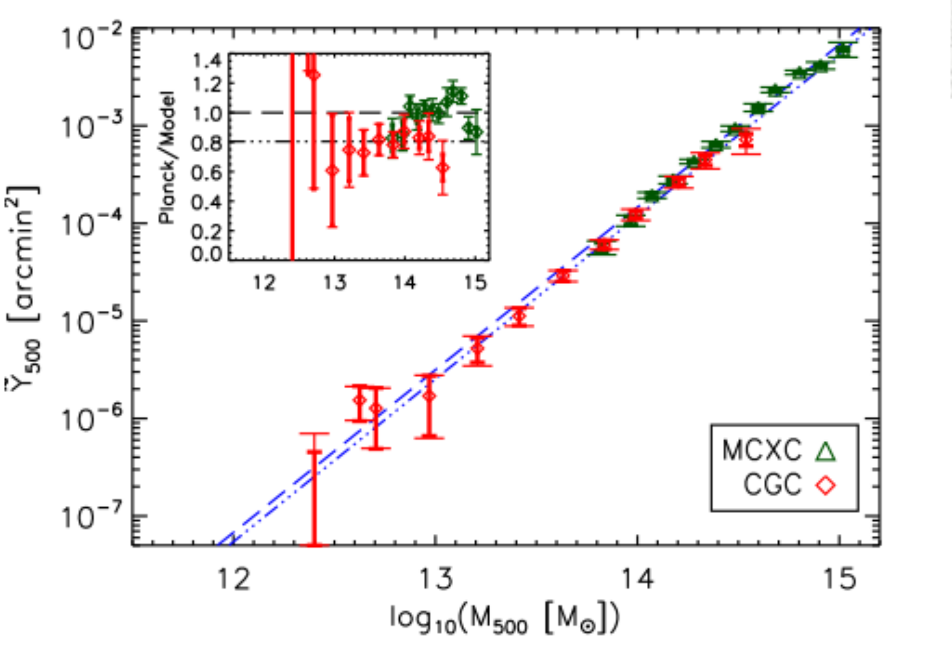
- When placing them in a grid, we retain only the 150,000 most nearby ones



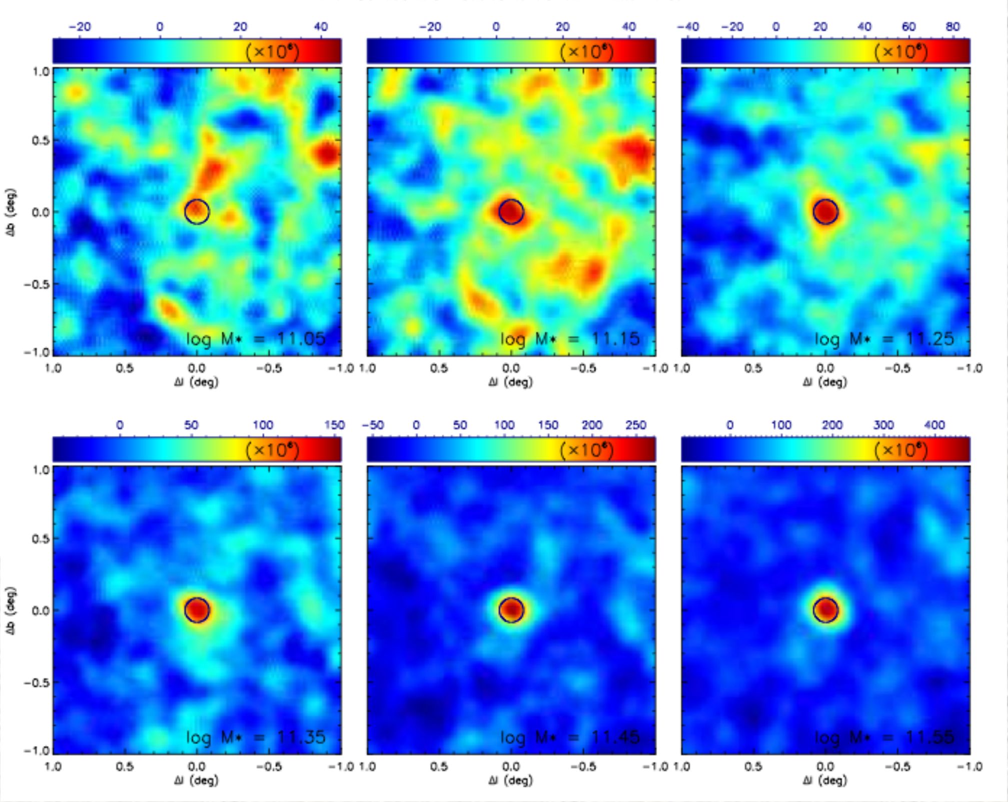
Fraction of brightest galaxies that are actually central galaxies in the Millenium simulation (Guo et al. 2011, *Planck* PIP-XI)

The Central Galaxy Catalogue (CGC)

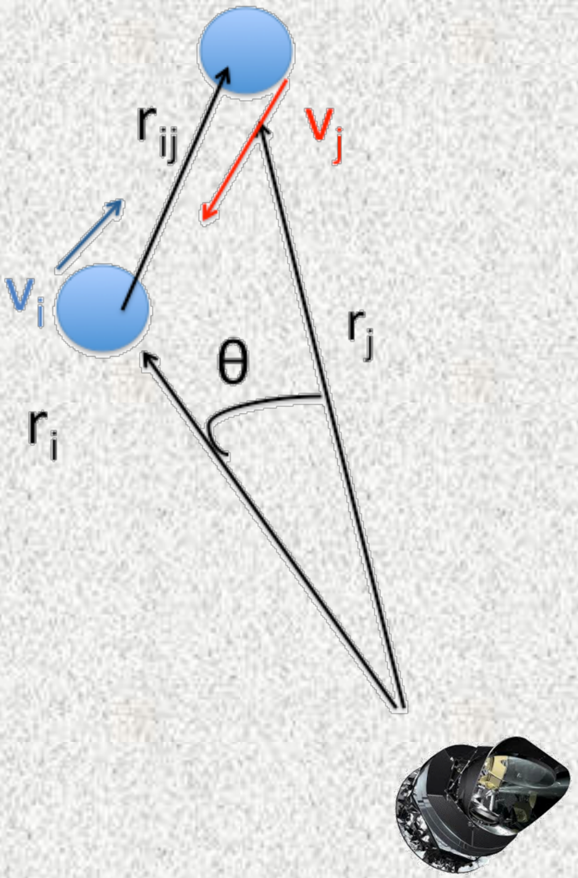
Stacked Y maps in the direction of CGs for different stellar mass bins(Guo et al. 2011, *Planck* PIP-XI)



Y vs M relation obtained from CGs (*Planck* PIP-XI)



Measuring the kSZ pairwise momentum



$$\hat{p}_{\rm kSZ}(r) = -\frac{\sum_{i<j}(\delta T_i - \delta T_j)\, c_{i,j}}{\sum_{i<j} c_{i,j}^2},$$

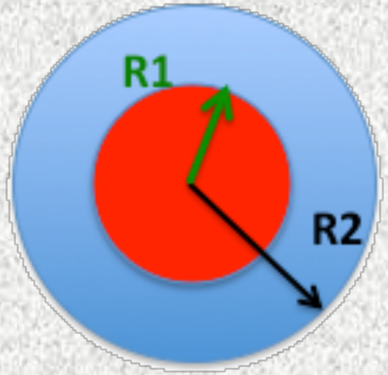
$$c_{i,j} = \hat{\boldsymbol{r}}_{i,j}\cdot\frac{\hat{\boldsymbol{r}}_i+\hat{\boldsymbol{r}}_j}{2} = \frac{(r_i - r_j)(1+\cos\theta)}{2\sqrt{r_i^2+r_j^2-2r_ir_j\cos\theta}}.$$

Pairwise momentum expresses the mutual infall of two objects due to gravitational interaction

Groth et al. 1981, Juszkiewicz et al. 1998, Ferreira et al. 1999, Hand et al. 2012

Measuring the kSZ pairwise momentum

APERTURE PHOTOMETRY



We do not assume any gas profile around CGs, but try different apertures

$$T_{AP} = <T(r<R1)> - <T(R1<r<R2>)$$

$$\delta T_i = T_{\rm AP}(\hat{\boldsymbol{n}}_i) - \bar{T}_{\rm AP}(z_i, \sigma_z)$$

$$\bar{T}_{\rm AP}(z_i, \sigma_z) = \frac{\sum_j T_{\rm AP}(\hat{\boldsymbol{n}}_j)\exp\left(-\frac{(z_i-z_j)^2}{2\sigma_z}\right)}{\sum_j \exp\left(-\frac{(z_i-z_j)^2}{2\sigma_z}\right)}.$$

- We use R2=SQRT(2) R1 and vary R1
- We set all galaxies within a redshift shell at the same zero level

Measuring the kSZ pairwise momentum

$$\hat{p}_{\mathrm{kSZ}}(r) = -\frac{\sum_{i<j}(\delta T_i - \delta T_j)\,c_{i,j}}{\sum_{i<j} c_{i,j}^2},$$

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$$\delta T_i = T_{\mathrm{AP}}(\hat{\boldsymbol{n}}_i) - \bar{T}_{\mathrm{AP}}(z_i, \sigma_z)$$

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- The pecculiar kSZ parwise momentum (**pkSZ)** is built upon quantities evaluated along the line of sight,
- It expresses the gravitational infall/collapse of structure

- The estimates of the kSZ temperature anisotropies are obtained after applying **aperture photometry (AP, T_{AP})** on the CGs, with varying aperture

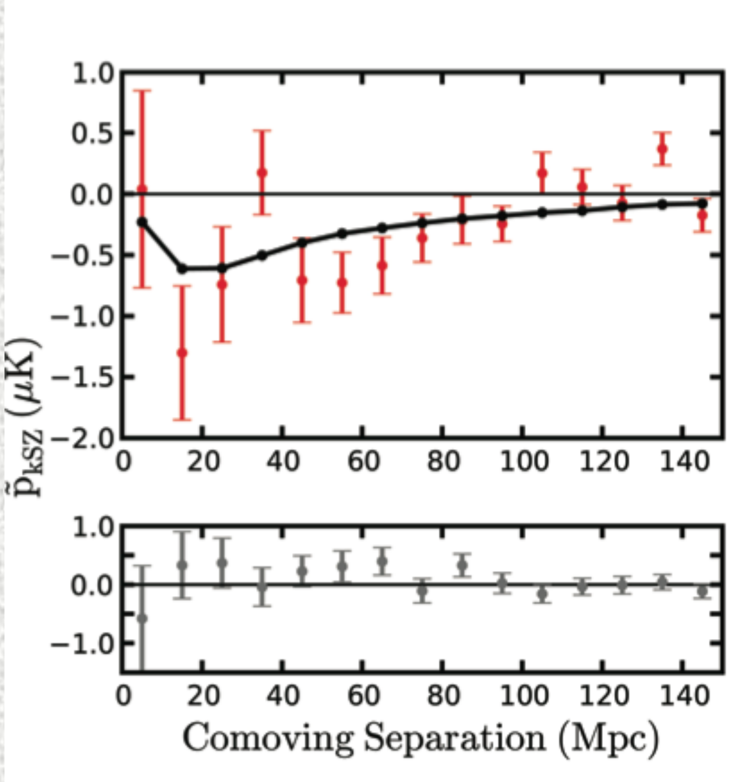
- We subtract the average T_{AP} within a thin redshift shell of width σ_z ~0.01 (as in Hand et al. 2012, although results do not depend critically on this choice)

Groth et al. 1981, Juszkiewicz et al. 1998, Ferreira et al. 1999, Hand et al. 2012

First kSZ detection from ACT

Hand et al. 2012

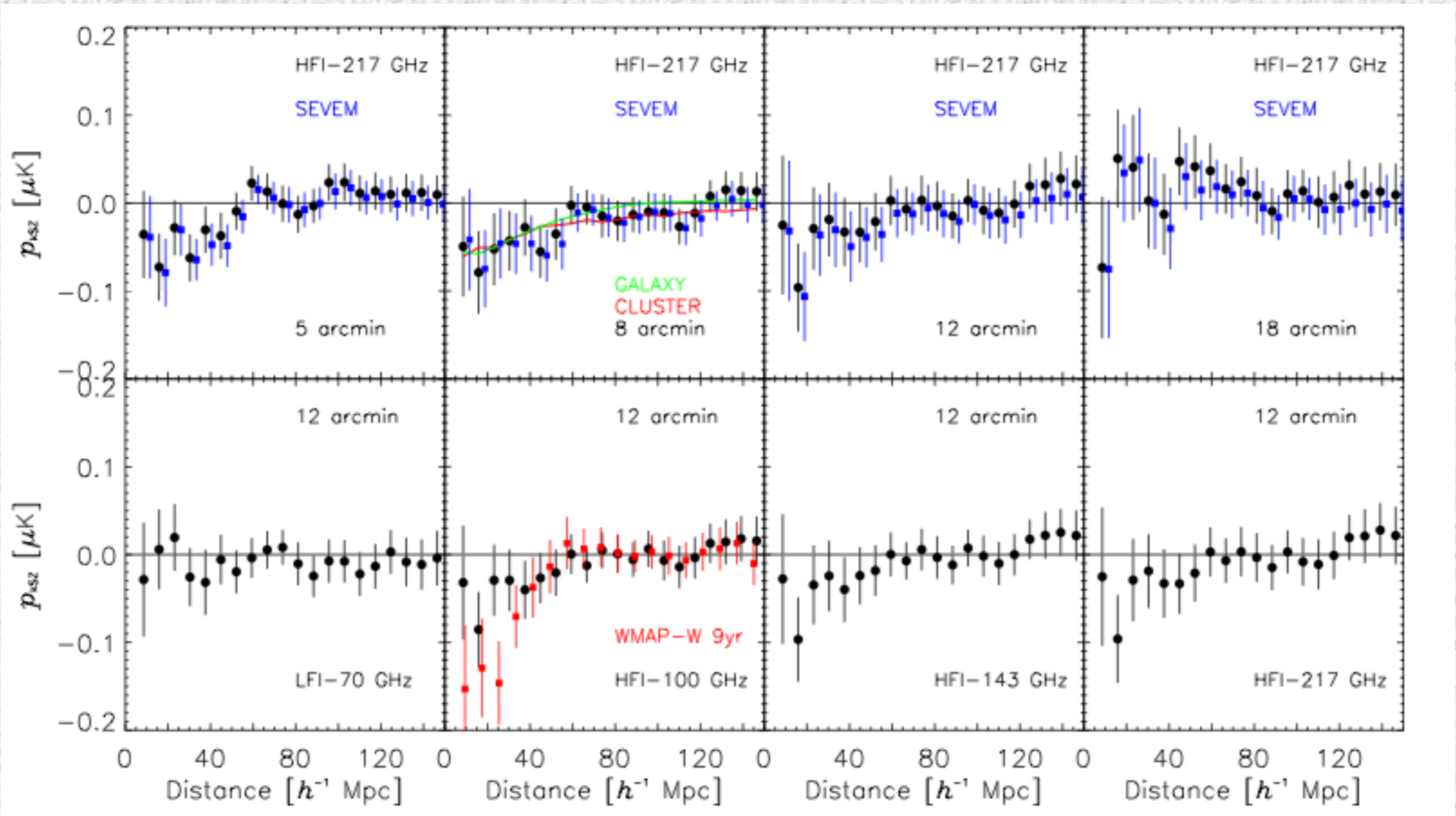
$$\hat{p}_{\rm kSZ}(r) = -\frac{\sum_{i<j}(\delta T_i - \delta T_j)\,c_{i,j}}{\sum_{i<j} c_{i,j}^2},$$



The *Atacama Cosmology Telescope* collaboration provided the first detection of the kSZ by stacking estimates of *filtered* maps at 145 GHz on the positions of LRGs identified by BOSS. ACT **has FWHM~1.3** arcmin, where *Planck's* best angular resolution is close to **FHWM=5 arcmin.**

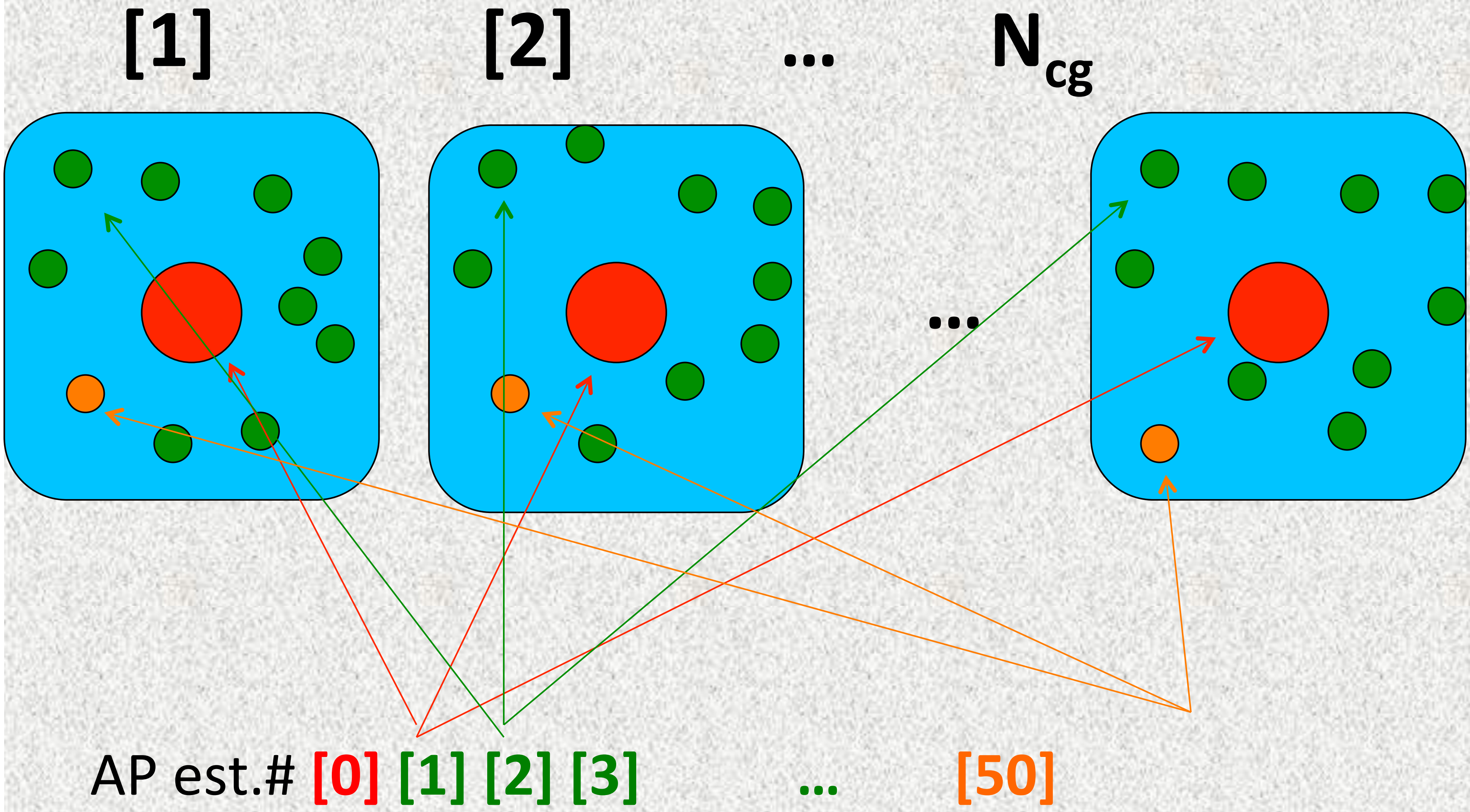
Measuring the kSZ pairwise momentum

$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = -\int dl\, \sigma_{\mathrm{T}}\, n_{\mathrm{e}} \frac{\boldsymbol{v}_{\mathrm{e}} \cdot \hat{\boldsymbol{n}}}{c}$$



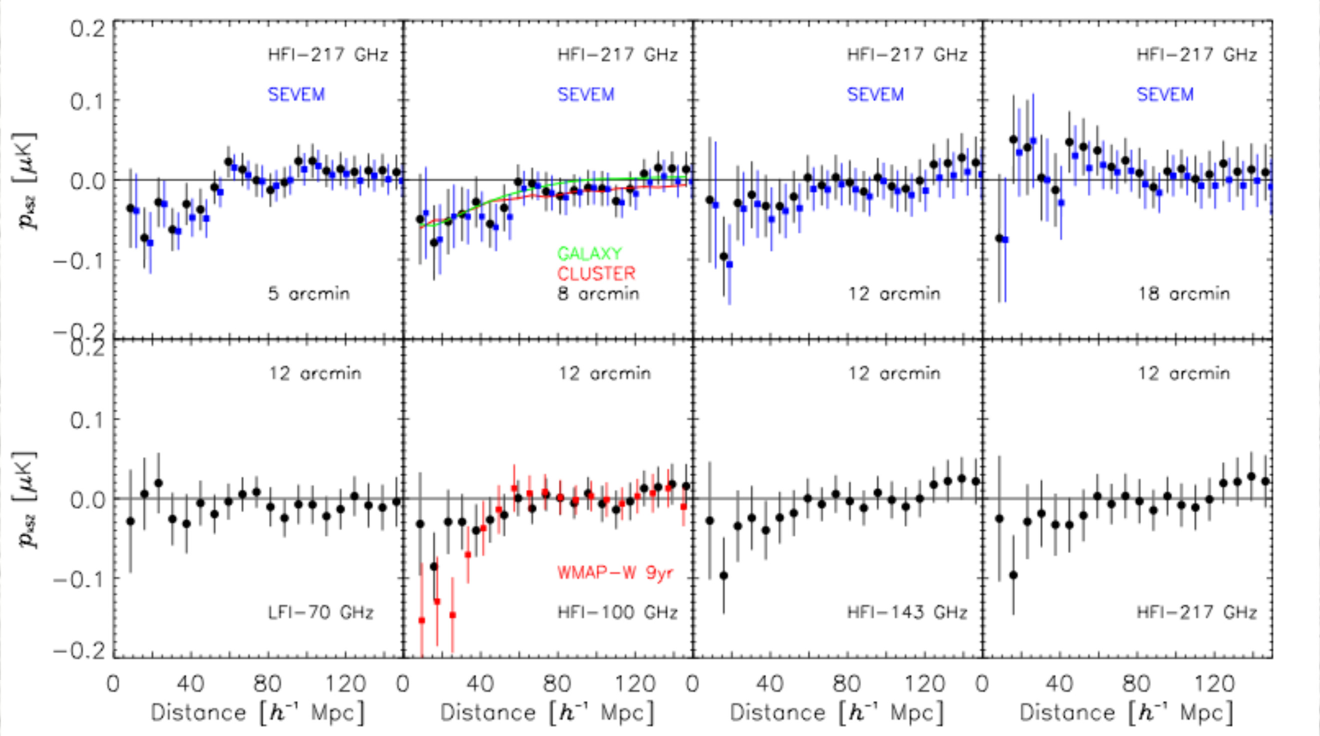
We found a colour-free decrement (up to **2.5 σ**) for the cleaned SEVEM map and for apertures of 8 – 12 arcmin. For SEVEM @ 8 arcmin, a fit to the output of numerical simulations yields **S/N ~ 2.2**

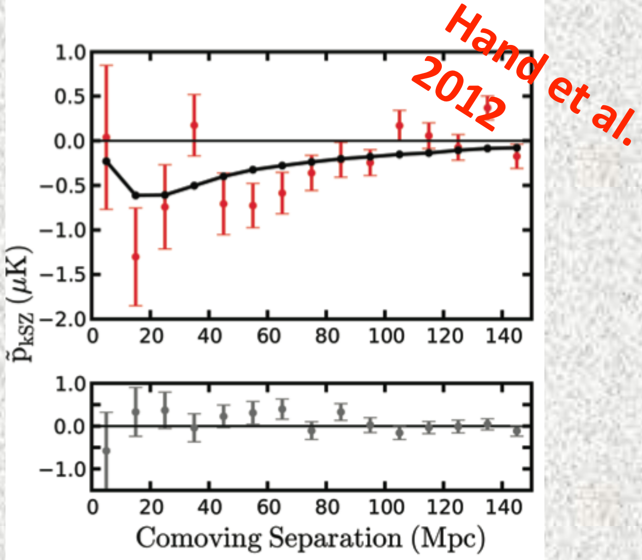
Error computation



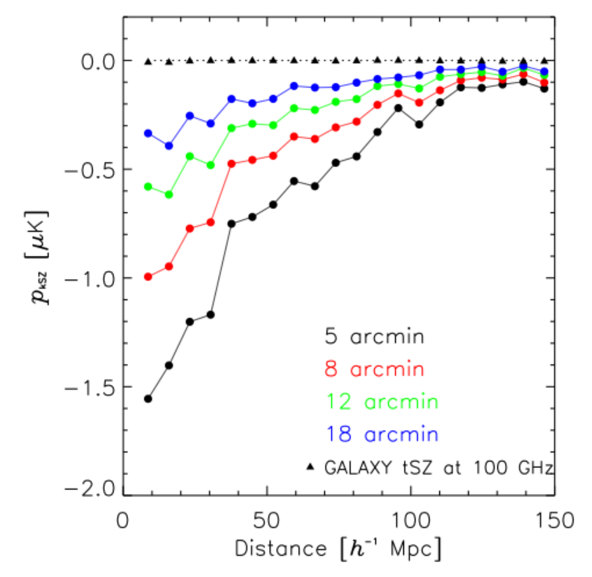
We rotate/displace the entire CGC over the CMB maps with no known sources

Measuring the kSZ pairwise momentum





Hand et al. 2012



Simulated clusters of Dolag & Sunyaev. 2013

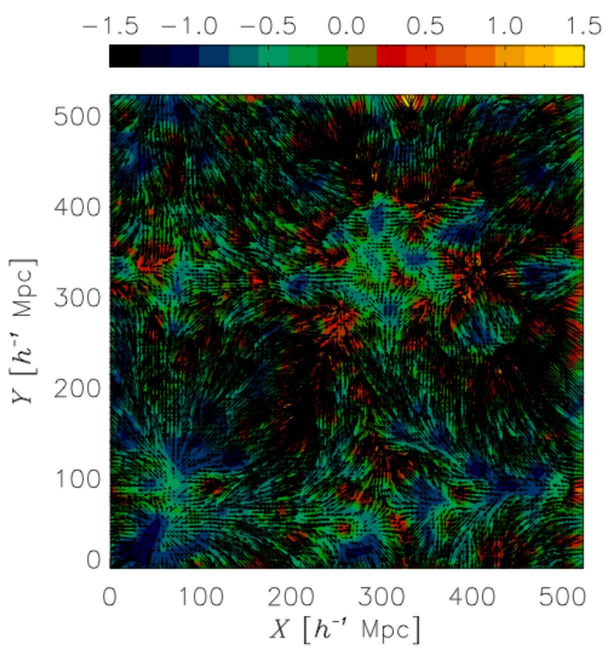
- The behaviour of the kSZ signal wrt aperture is different to what is found in simulated clusters.
- The impact of tSZ seems to be ***negligible***

Method II: Inverting galaxy density into velocity

Dedeo et al.2005, Ho et al.2010

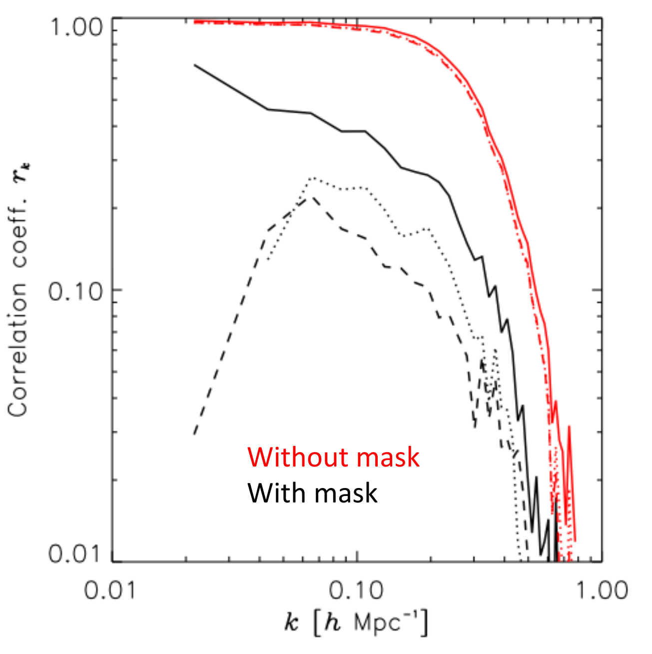
$$\frac{\partial \delta(\mathbf{x})}{\partial t} + \nabla \mathbf{v}(\mathbf{x}) = 0$$

We invert the *linear continuity* equation to estimate the peculiar velocity field from the CG density field



Correlation coefficient: ORIG. VEL x RECOV.VEL

$$r_k = \frac{P^{\text{orig, rec}}(k)}{\sqrt{P^{\text{orig, orig}}(k)\, P^{\text{rec, rec}}(k)}}$$

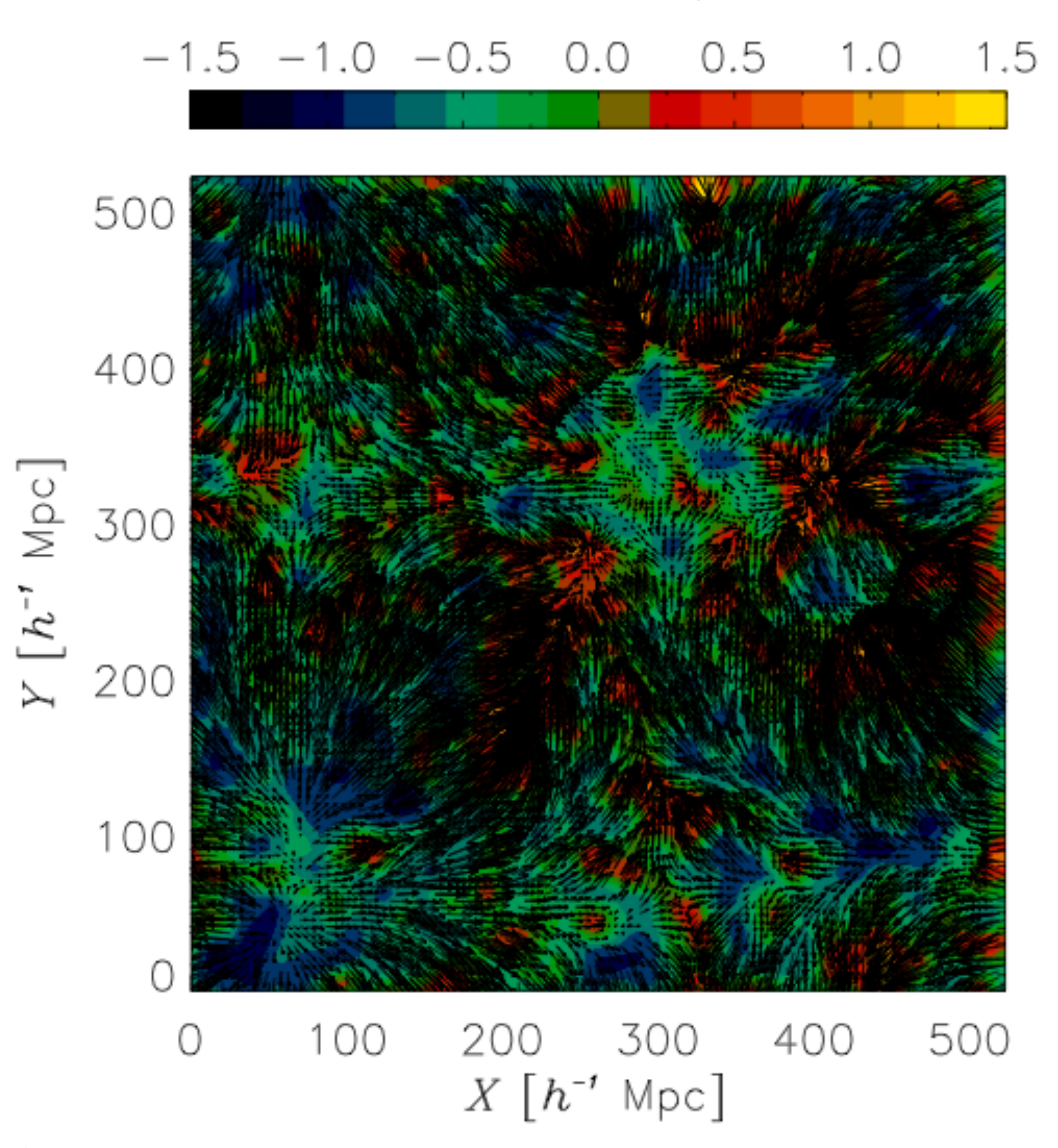


- Three approaches: **LINEAR, LOG-LINEAR, LOG-2LPT**
- Impact of mask: LINEAR method most promising after all

Logarithmic linearisation

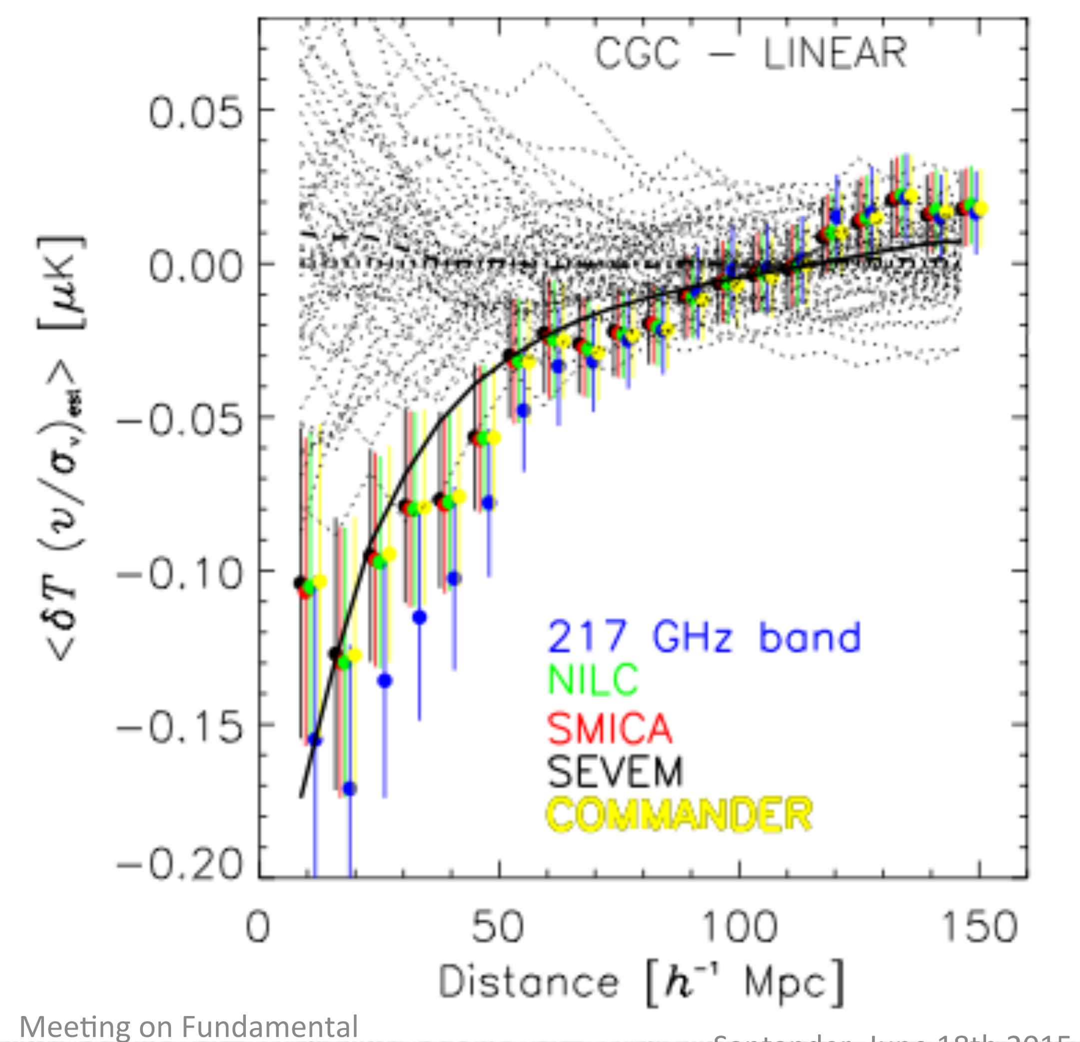
$$\delta^{\mathrm{LOG}}(\mathbf{x}) = \ln\left(1 + \delta^{g}(\mathbf{x})\right) - \langle \ln\left(1 + \delta^{g}\right).\rangle_{\mathrm{spatial}}$$

Inverting galaxy density into velocity



Velocity field recovered for a slice of the CGC

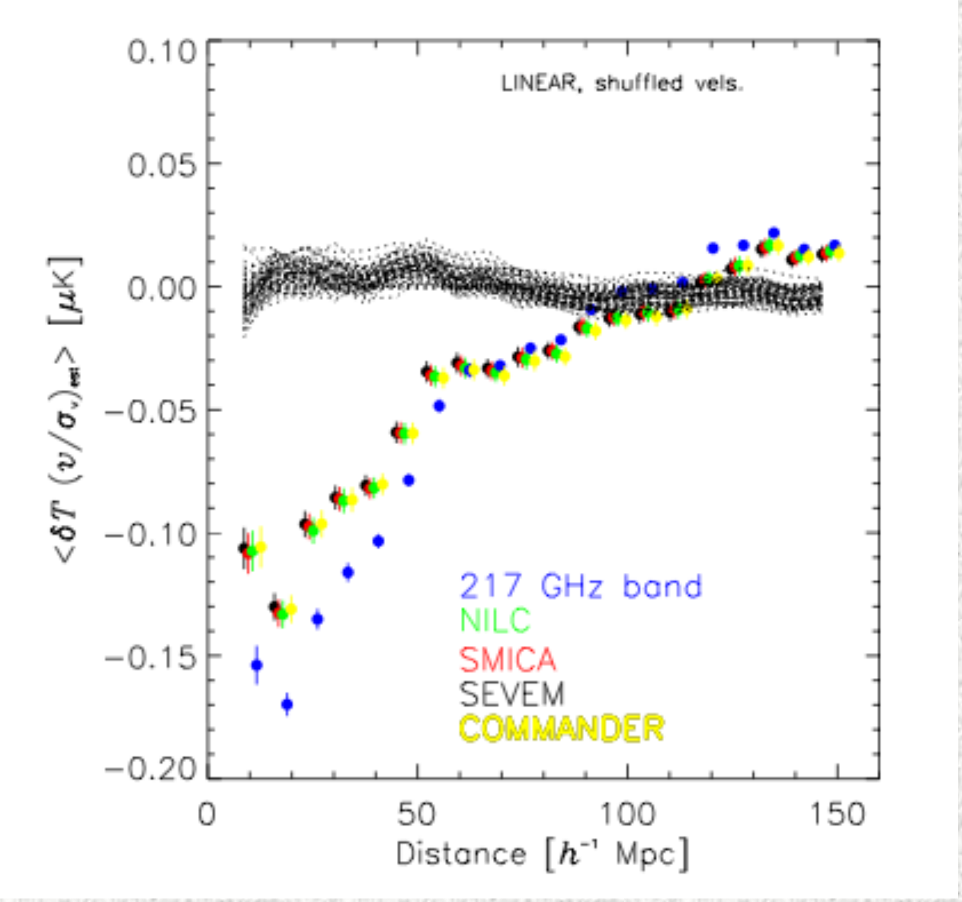
The $\delta T_{kSZ} - v_{los}$ correlation



$<T_{kSZ} . v/\sigma_v>$: correlation between kSZ temperature anisotropies and recovered velocities (with RMS=1)

S/N up to 3.8

Consistency tests

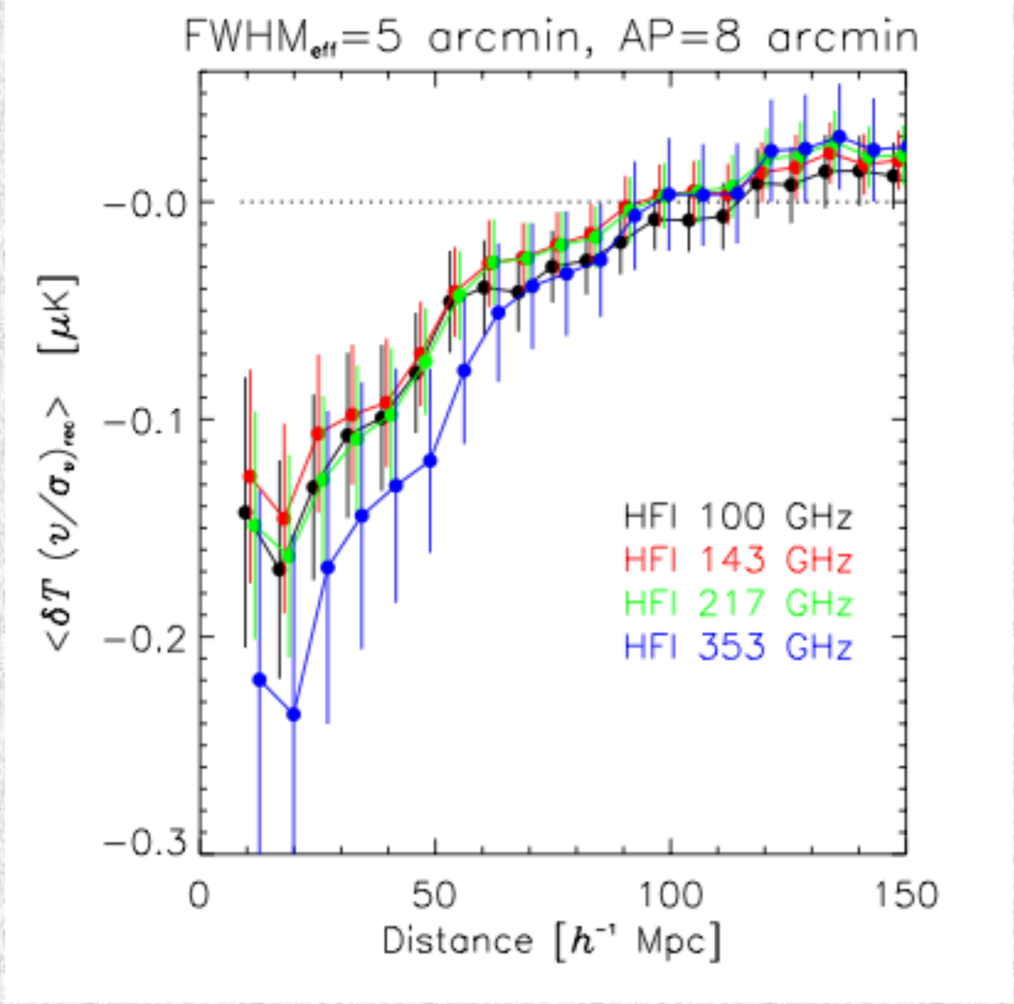


- We compute correlation after ***shuffling*** the recovered velocities among the CGs: the correlation is only recovered for the correct configuration

- The coupling of intrinsic **CMB large modes** with **large spatial modes of the recovered velocities** constitutes the largest contribution to the variance: the low-*k* modes of the recovered velocities are suppressed after shuffling these

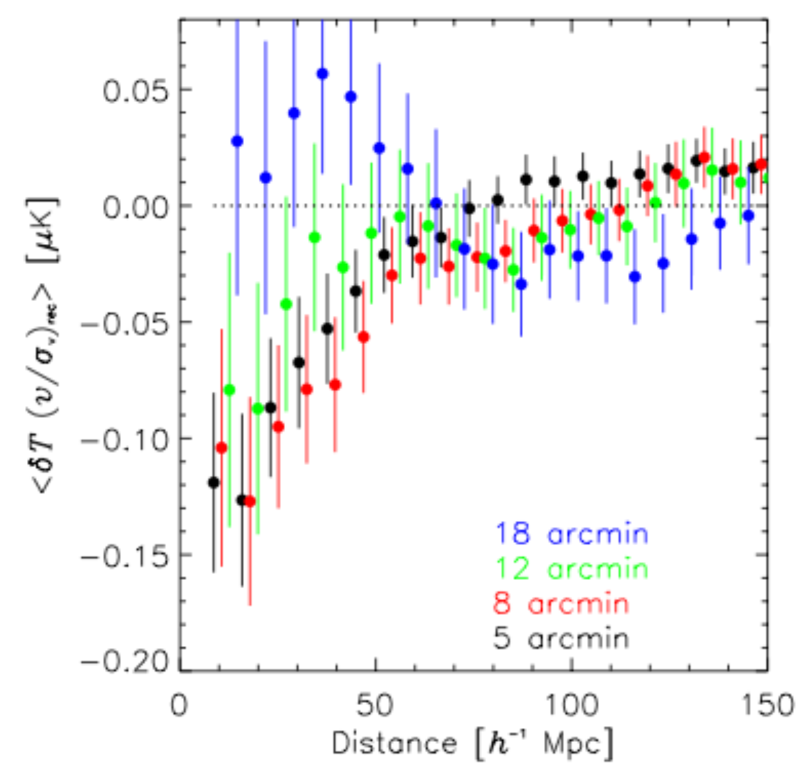
Consistency tests

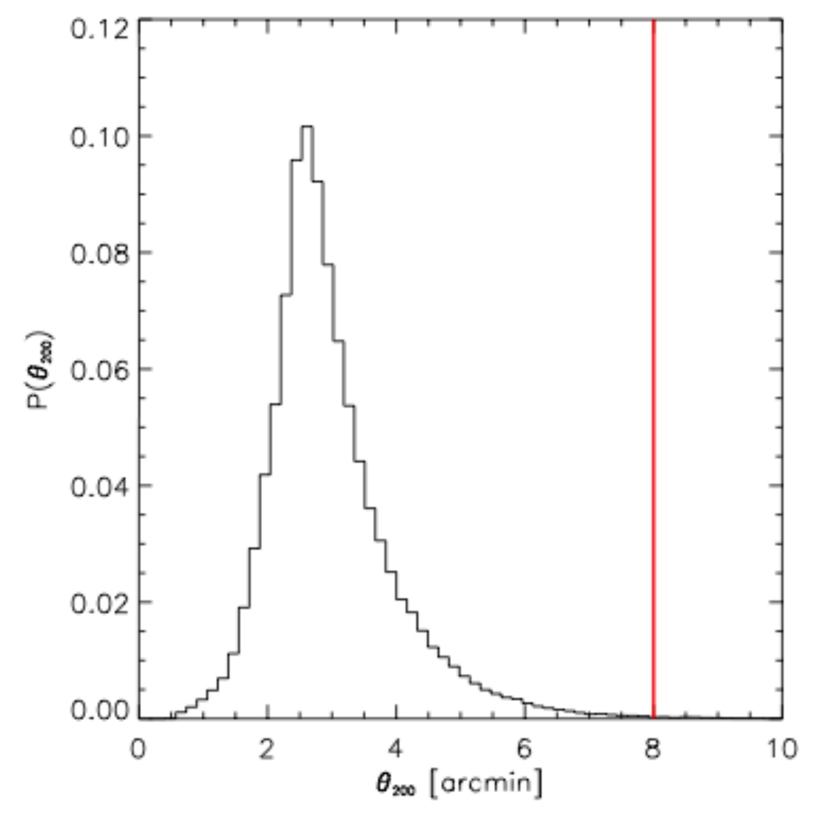
We expect **NO** frequency dependence in the kSZ signal:



After de-convolving and convolving all HFI raw channels to the same FWHM=5 arcmin, we only find some signatures of **dust** at 353 GHz

Hints for unbound gas ??

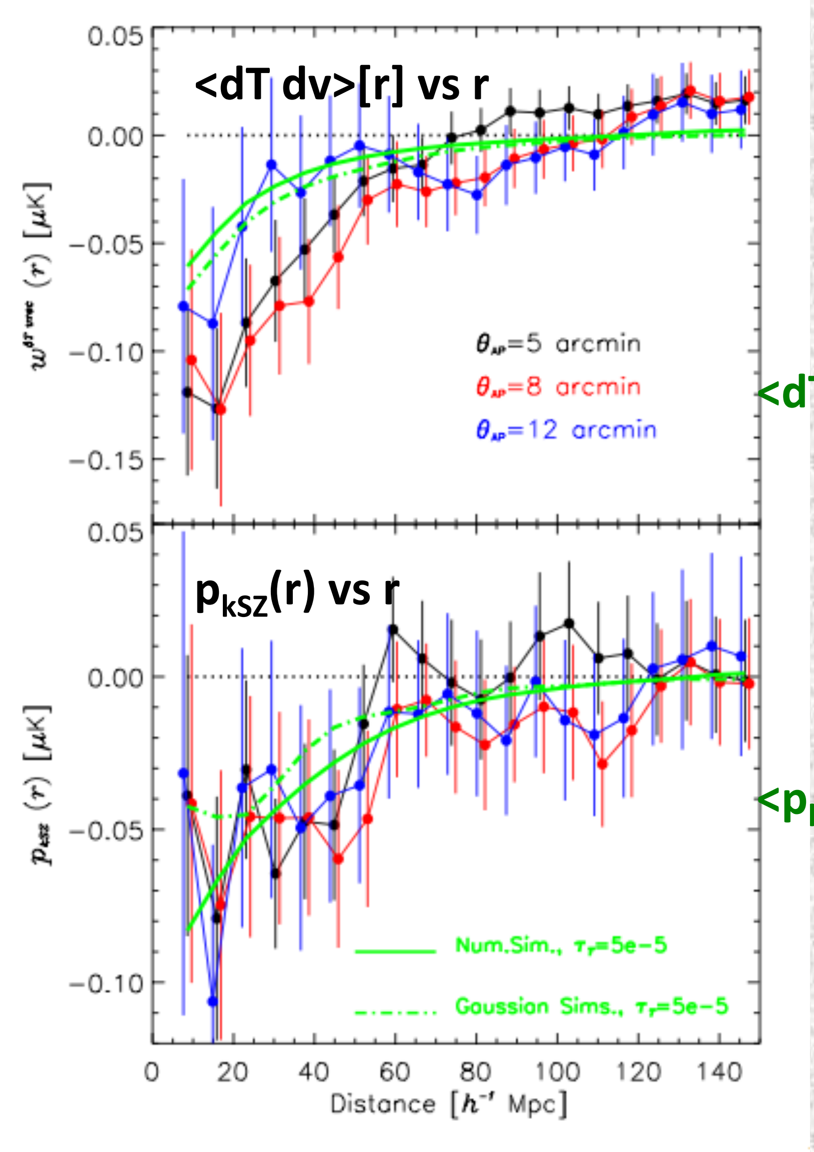




As for the peculiar kSZ pairwise momentum, we find more kSZ signal at apertures close to 8 arcmin (~0.8 Mpc at z~0.12) than at 5 arcmin, and it extends up to ~12 arcmin.

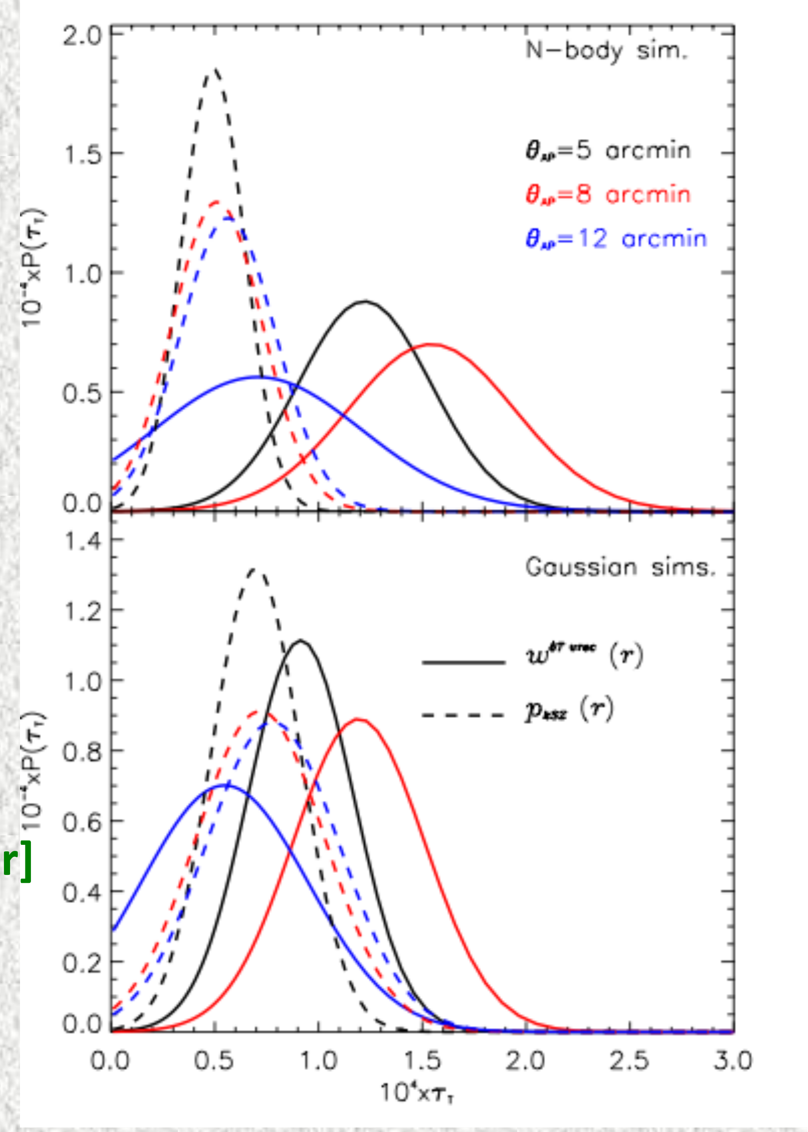
The typical CG virial radius is below 400 Kpc, or typically 5—6 arcmins.

Let’s compare both measurements:



$\langle dT\, dv\rangle[r]$ vs r

$p_{kSZ}(r)$ vs r



$P(\tau_T)$ vs τ_T

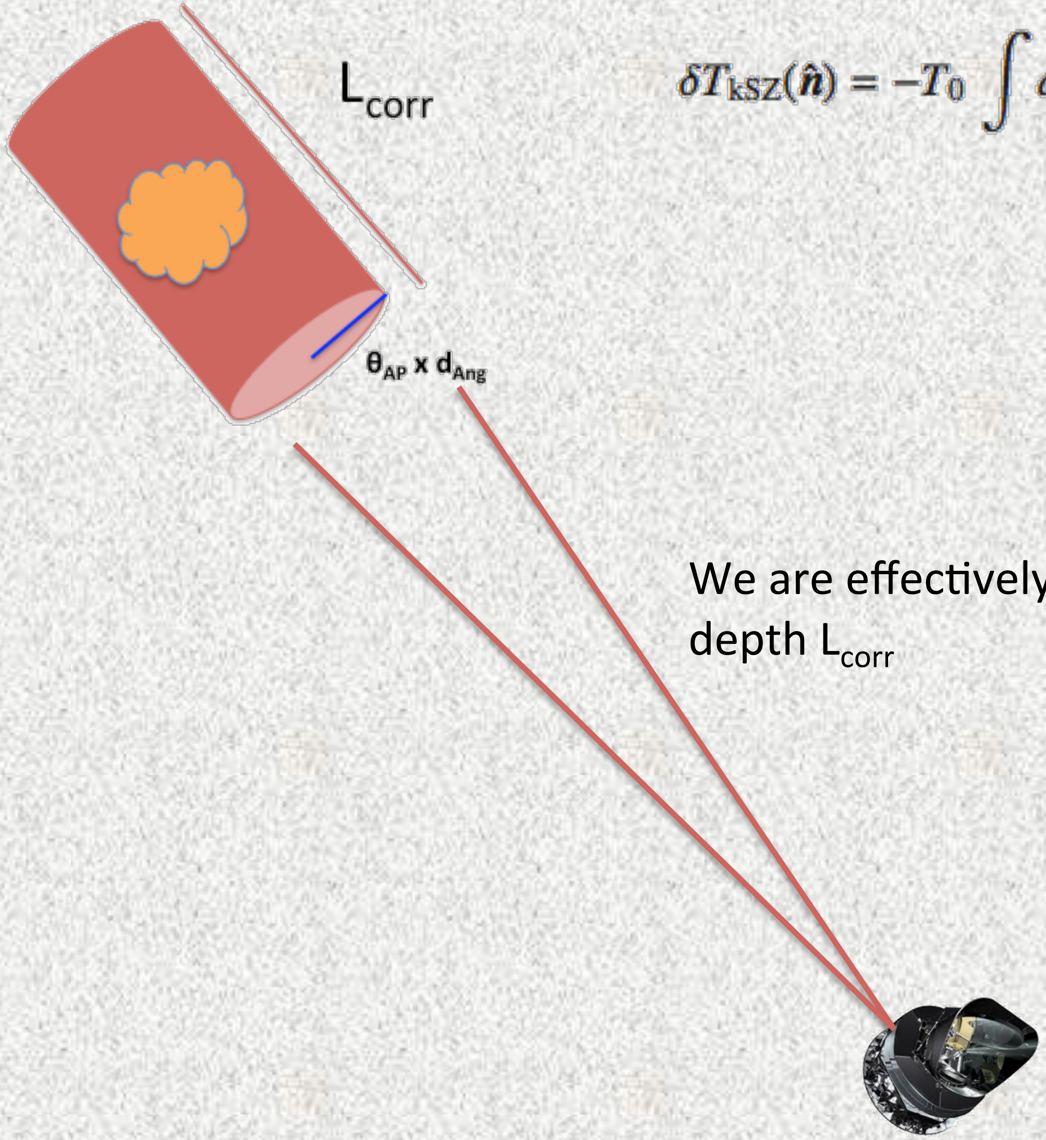
$\langle dT\, dv\rangle_{sim}[r] = \tau_T \langle v_i\, v^{est}_j\rangle_{sim}[r]$

$\langle p_{kSZ}\rangle_{sim}[r] = \tau_T \langle (v_{i\,-}\, v_j)\, c_{ij}\rangle_{sim}[r]$

$$\delta T_{\rm kSZ}(\hat{n}) = -T_0 \int dl\, \sigma_{\rm T} n_e \left(\frac{v}{c}\cdot\hat{n}\right) \simeq -T_0\, \tau_T \left(\frac{v}{c}\cdot\hat{n}\right).$$

τ_T ~ number of electrons

Let’s count the electrons we have detected …



$$\delta T_{\mathrm{kSZ}}(\hat{\boldsymbol{n}}) = -T_0 \int dl\, \sigma_{\mathrm{T}} n_{\mathrm{e}} \left(\frac{\boldsymbol{v}}{c} \cdot \hat{\boldsymbol{n}}\right) \simeq -T_0\, \tau_T \left(\frac{\boldsymbol{v}}{c} \cdot \hat{\boldsymbol{n}}\right).$$

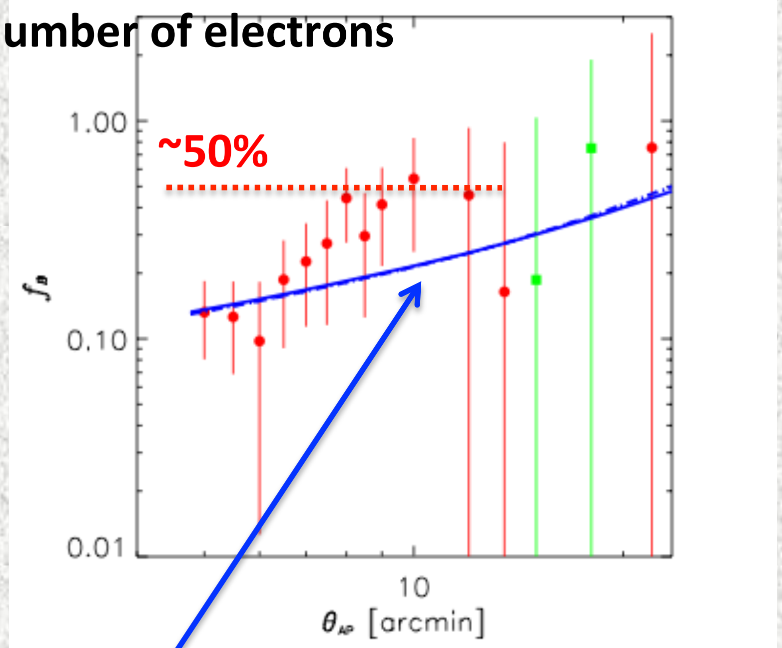
τ_T = \int dl n_e σ_T ~ number of electrons

We are effectively observing through **cylinders** of depth L_{corr}

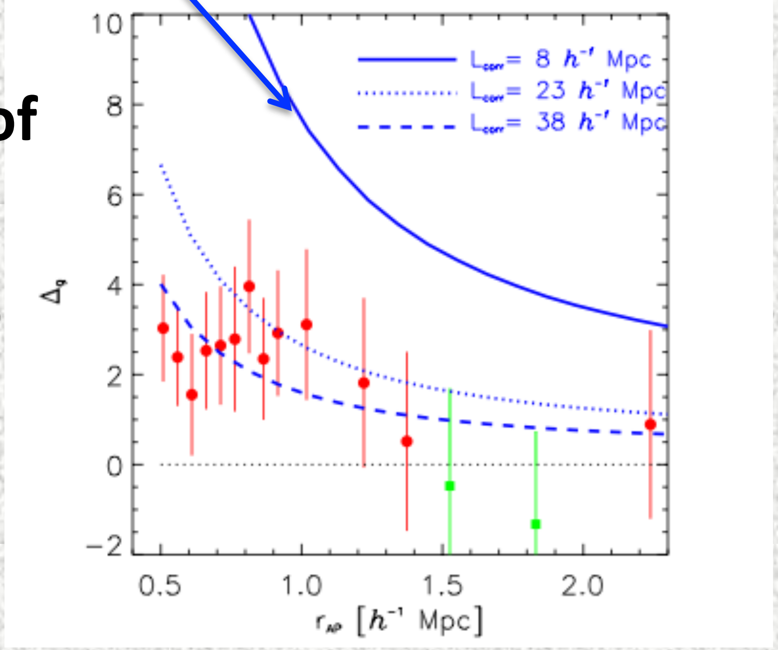
Fraction of electrons/baryons detected around CGs wrt *all* electrons/baryons existing at that *z:*

τ_{T} = \int dl n_e σ_T ~ number of electrons

$$\langle f_{\rm b}\rangle_z(\theta_{\rm AP}) = \langle \frac{\tau_{\rm T}(\theta_{\rm AP},z)/(\sigma_T \bar{n}_{\rm e}(z) L_{\rm corr}/(1+z))}{1/f_{\rm vol}(z)} \rangle_z \approx \pi \frac{\langle \tau_{\rm T}(\theta_{\rm AP},z)\rangle_z}{\sigma_{\rm T}\bar{n}_{\rm e,0}}\,\theta_{\rm AP}^2\,\langle n_{\rm CG}(z)\,d^2_{\rm Ang}(z)\rangle_z,$$



DM predictions from N-body Millennium sim.



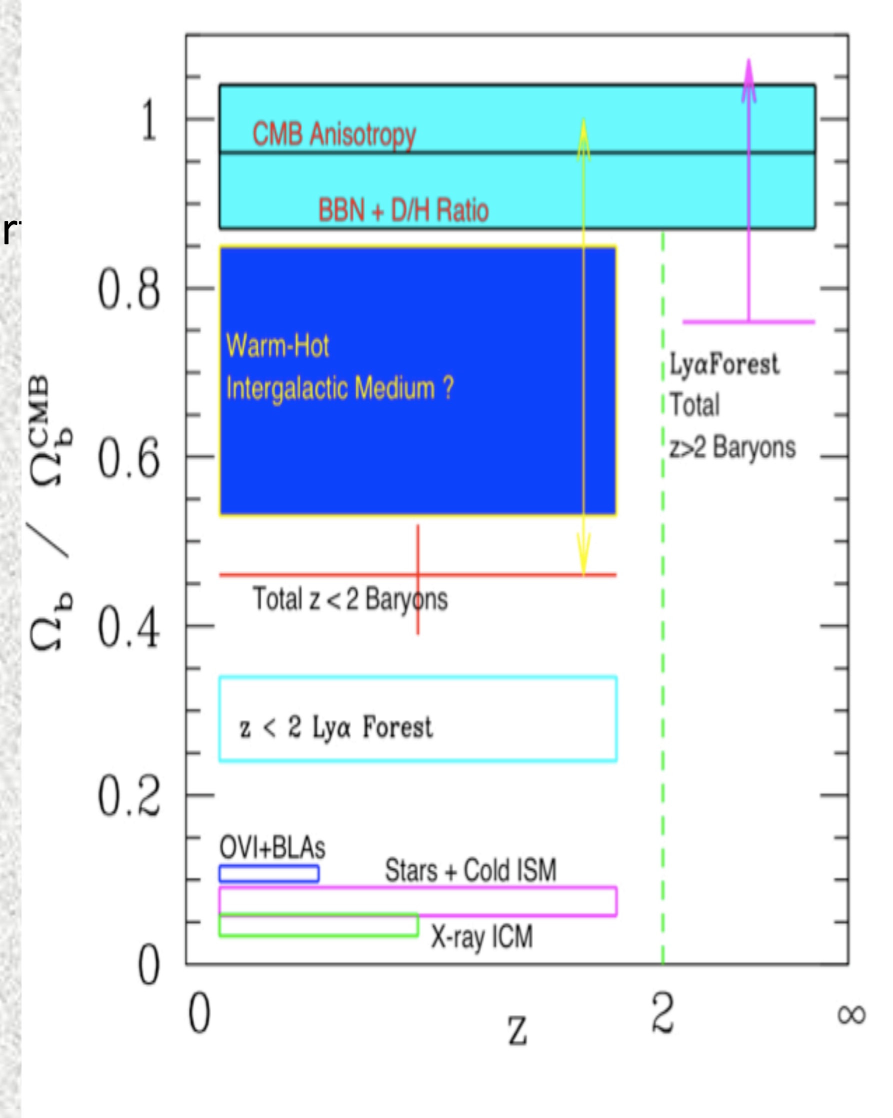
Average gas overdensity within cylinder of a given depth L_{corr} :

$$\Delta_{\rm g}(r_{\rm AP}) = \langle \frac{\tau_{\rm T}(\theta_{\rm AP},z)}{\sigma_{\rm T}\bar{n}_{\rm e}(z)L_{\rm corr}/(1+z)} \rangle_z \approx \frac{\langle \tau_{\rm T}(\theta_{\rm AP},z)\rangle_z}{\langle \sigma_{\rm T}\bar{n}_{\rm e}(z)L_{\rm corr}/(1+z)\rangle_z}$$

$$\delta T_{\rm kSZ}(\hat{\boldsymbol{n}}) = -T_0 \int dl\,\sigma_{\rm T} n_{\rm e}\left(\frac{\boldsymbol{v}}{c}\cdot\hat{\boldsymbol{n}}\right) \simeq -T_0\,\tau_T\left(\frac{\boldsymbol{v}}{c}\cdot\hat{\boldsymbol{n}}\right).$$

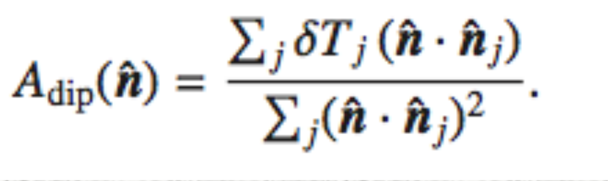
THE MISSING BARYON PROBLEM

- Counting the amount of baryons in the local universe yields a result that falls a factor of 2-4 shor when compared to observations at redshifts *z~5-6 (Ly-alpha absorbers)* and z~1,050 *(CMB observations)*
- The Universe has grown *bigger* and ***transparent*** since then...
- The hidden baryons should be found in a diffuse low density warm hot phase (WHIM) at T \in [1e5,1e7] K
- Observations of diffuse X-ray emission around clusters (Zappacosta et al. 02) or absorption lines along bright high-z QSOs (Nicastro et al. 05) have yielded some evidence of diffuse baryons at low redshift.

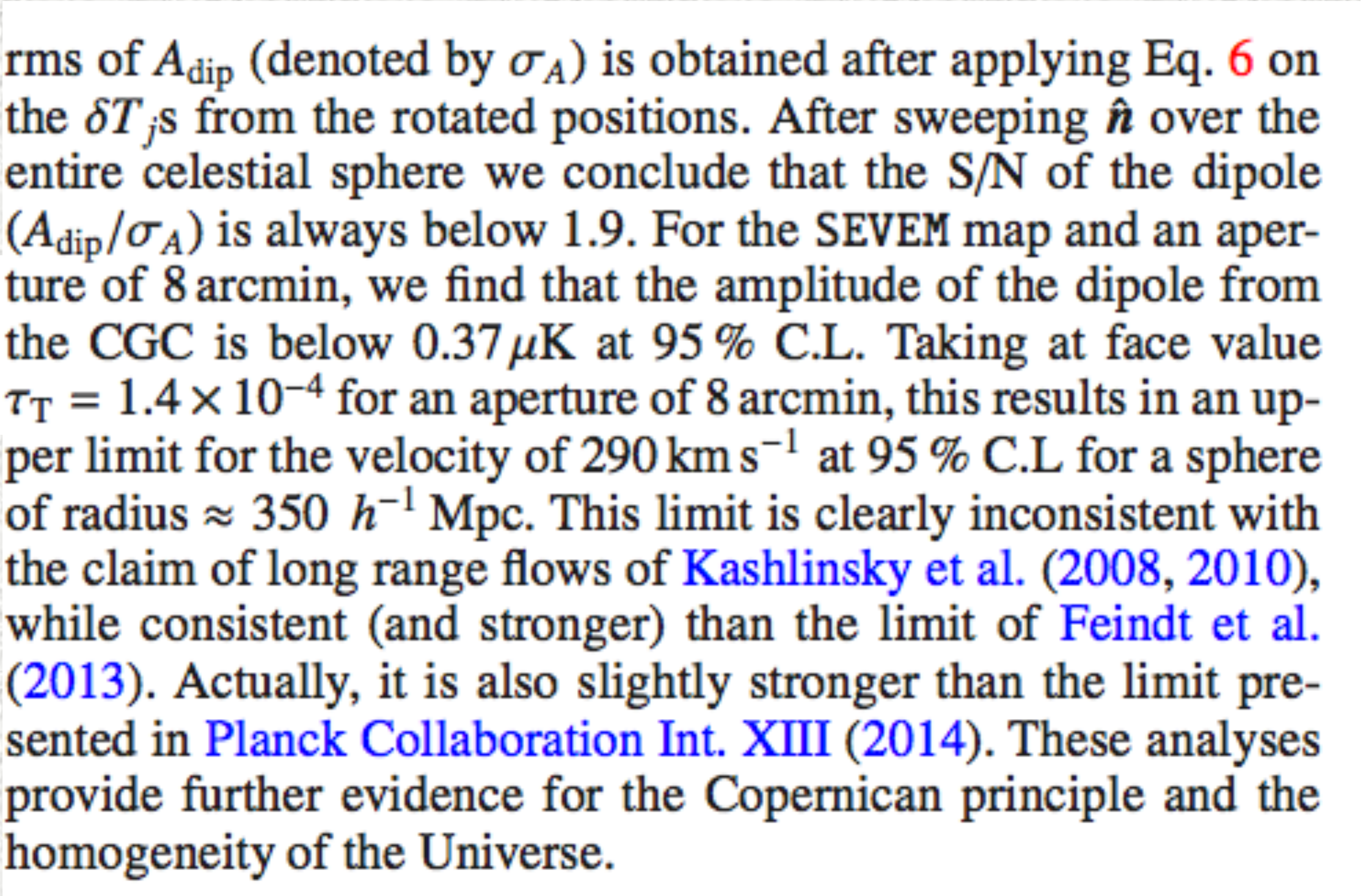


Nicastro et al. (05)

Testing the Copernican principle …



$$A_{\rm dip}(\hat{\boldsymbol{n}}) = \frac{\sum_j \delta T_j\,(\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{n}}_j)}{\sum_j (\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{n}}_j)^2}.$$



rms of $A_{\rm dip}$ (denoted by σ_A) is obtained after applying Eq. 6 on the δT_js from the rotated positions. After sweeping $\hat{\boldsymbol{n}}$ over the entire celestial sphere we conclude that the S/N of the dipole ($A_{\rm dip}/\sigma_A$) is always below 1.9. For the `SEVEM` map and an aperture of 8 arcmin, we find that the amplitude of the dipole from the CGC is below 0.37 μK at 95 % C.L. Taking at face value $\tau_{\rm T} = 1.4\times10^{-4}$ for an aperture of 8 arcmin, this results in an upper limit for the velocity of 290 km s^{-1} at 95 % C.L for a sphere of radius ≈ 350 h^{-1} Mpc. This limit is clearly inconsistent with the claim of long range flows of Kashlinsky et al. (2008, 2010), while consistent (and stronger) than the limit of Feindt et al. (2013). Actually, it is also slightly stronger than the limit presented in Planck Collaboration Int. XIII (2014). These analyses provide further evidence for the Copernican principle and the homogeneity of the Universe.

Summary:

- We have detected the kSZ around Central Galaxies at *z~0.12* via two different estimators, namely the **pairwise momentum** and the **cross-correlation function of estimated LOS velocities with kSZ anisotropies.** Both estimators yield comparable and consistent results

- We have found that the kSZ is **not** compatible with a 1-halo term only, and requires the presence **of unbound gas** around the CG halos.

- We have estimated that the gas overdensity surrounding the CGs has a similar shape and amplitude as predictions for Dark Matter around halos of similar mass to the CG hosts. This means that, while **finding roughly 50% of the total amount of baryons behind the SDSS footprint at *z~0.12*, we are also finding by first time *all* the missing baryons around the CGs.**

- Furthermore, the absence of any measurable kSZ dipole in those galaxies **provides further evidence of the Copernican principle of isotropy and homogeneity, setting the strongest constraints on bulk flows on a sphere of ~ 350 Mpc/h radius centred upon us.**