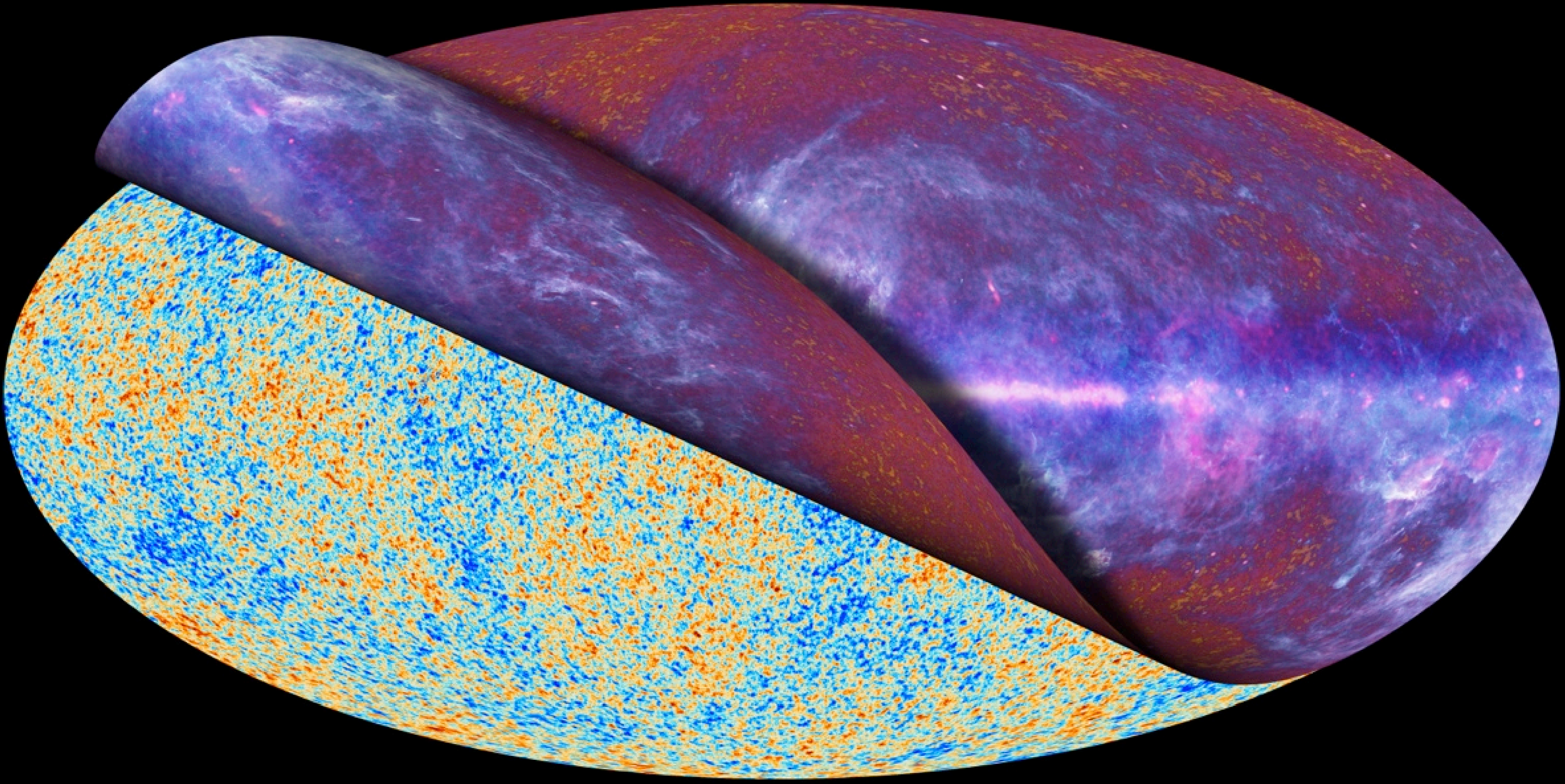

Planck unveils the Cosmic Microwave Background

Planck's constraints on peculiar velocities

(PIP–XIII)

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On behalf of the Planck collaboration

Outline

- The kinetic Sunyaev-Zel'dovich effect (kSZ)
- The Meta X-ray Cluster Sample (MCXC)
- The four filters under use: *AP, uMMF, all sky uMMF* and *Kashlinsky et al.*'s filter
- Constraints on the kSZ monopole in the direction of MCXC clusters. Implications for LTB – inhomogeneous models
- Constraints on clusters' peculiar velocity rms.
- Constraints on bulk flows centered on us.

The kinetic Sunyaev-Zel’dovich effect

- 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)

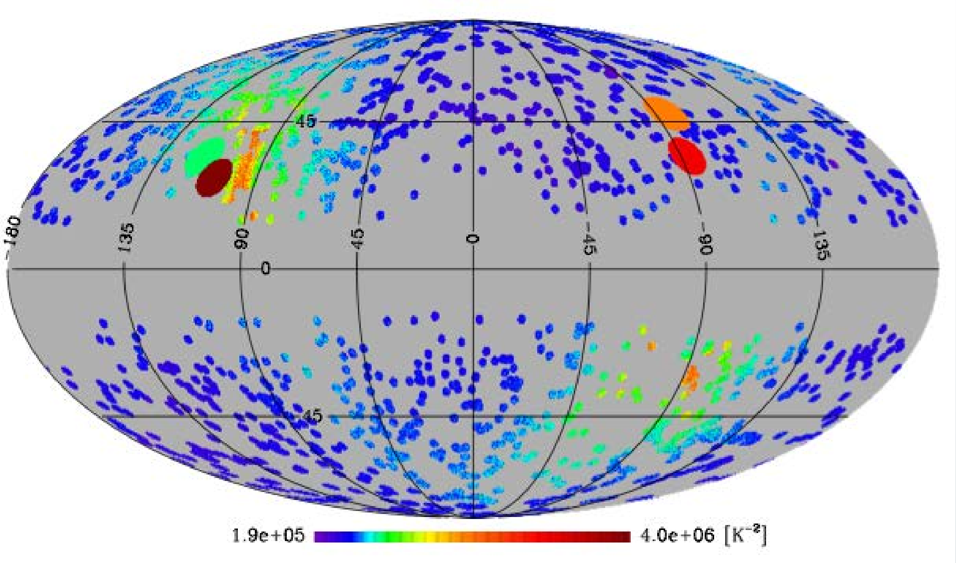
- When looking at the direction of galaxy clusters, it is likely to be contaminated by the (dominant) thermal Sunyaev-Zel’dovich (tSZ) effect, which flips from negative to positive at the cross-over frequency of 217 GHz.

- To avoid the tSZ, we can either look at different frequencies or use **clean** maps (**2D-ILC map**)

HFI nominal frequency [GHz]	HFI effective frequency [GHz]	$y_{\mathrm{SZ}}/\Delta T$ [$\mathrm{K}_{\mathrm{CMB}}^{-1}$]	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 MCXC cluster sample

- X-ray based galaxy and group catalogue (Piffaretti et al. 2011)
- Contains objects in the mass range ~1e13 up to ~1e15 $M_{\odot}$
- Mostly placed at moderately low redshifts (<z> ~ 0.2) some a tail expending up to z~0.8
- After applying two different sky masks, we study two samples of 1,405 and 1,321 objects, respectively



1 μK ➔ 172 km s^{-1}

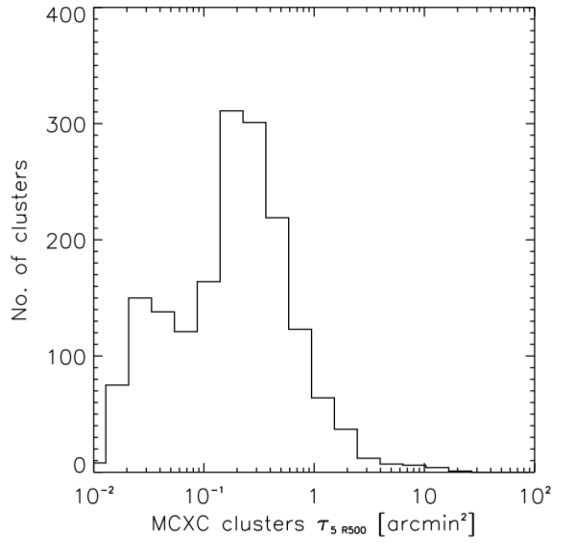
$$\tau_{500} = 1.3530 \times 10^{-5}\, E^{2/3-1/\alpha_{\rm T}}(z) \times$$

$$\left(\frac{D_{\rm A}(z)}{500\, h_{70}^{-1}{\rm Mpc}}\right)^{-2} \left(\frac{511\,{\rm keV}}{k\bar{T}}\right) \left(\frac{M_{500}}{C_{500}}\right)^{\frac{1}{\alpha_{\rm Y}}-\frac{1}{\alpha_{\rm T}}} h_{70}^{-1}\ {\rm arcmin}^2$$

$$\tau_{\rm cyl}(x) = \tau_{500} J(x)$$

(Arnaud et al. 2010)

$$\tau_{\rm sph}(x) = \tau_{500} I(x)$$



Four different filters

- [1] Standard *Aperture Photometry* (**AP**) approach:

  Applied on individual clusters. Average **T** within circle of radius **R** after subtracting average **T** in ring of radii [**R, √2 R**], choice of **R~Θ_{500}**

- [2] *Unbiased Multifrequency Matched Filter* (**uMMF**): (Herranz et al. 2002, Melin et al. 2006)

  Applied on patches centred on individual clusters as well, it adjusts to the cluster's size and works in Fourier space and is weighted by the inverse power spectrum in the patch:

$$\Phi = \frac{1}{\Delta}\mathsf{P}^{-1}\left(-\beta\boldsymbol{F} + \alpha\boldsymbol{\tau}\right),$$

where the constants α, β and Δ are given by

$$\begin{aligned} \alpha &= \int dk\, \boldsymbol{F}^{\mathrm{T}}\mathsf{P}^{-1}\boldsymbol{F}, \\ \beta &= \int dk\, \boldsymbol{\tau}^{\mathrm{T}}\mathsf{P}^{-1}\boldsymbol{F}, \\ \Delta &= \alpha\gamma - \beta^2, \\ \text{with } \gamma &= \int dk\, \boldsymbol{\tau}^{\mathrm{T}}\mathsf{P}^{-1}\boldsymbol{\tau}, \end{aligned}$$

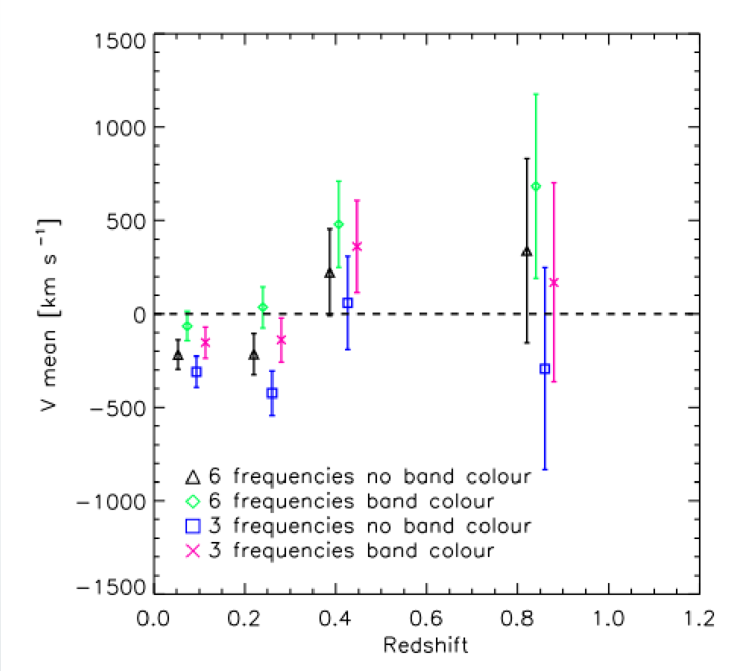
- [3] **All sky** uMMF approach (Mak et al. 2010): all sky uMMF version after adopting an average cluster profile of **Θ_{500} = 8 arcmins.**

- [4] Kashlinsky et al. (2008-2010) approach (**KABKE**):

  Fourier filter of the type $F_l \sim (C_l^{\mathrm{REAL}} - C_l^{\mathrm{LCDM}} B_l^2) / C_l^{\mathrm{REAL}}$

the latter two filters use **REMOVE_DIPOLE on MCXC positions …**

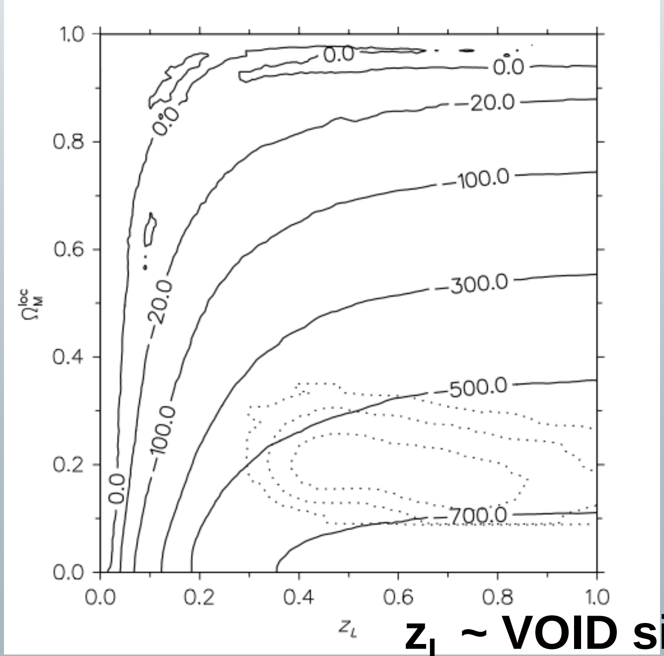
Constraints from **MCXC kSZ monopole**



- NO statistically significant kSZ monopole at any redshift bin ***after correctly accounting for frequency bandpasses*** (72 +/- 60 km s^{-1})

- This rules out giant void models as alternative explanations to LCDM

VOID density parameter



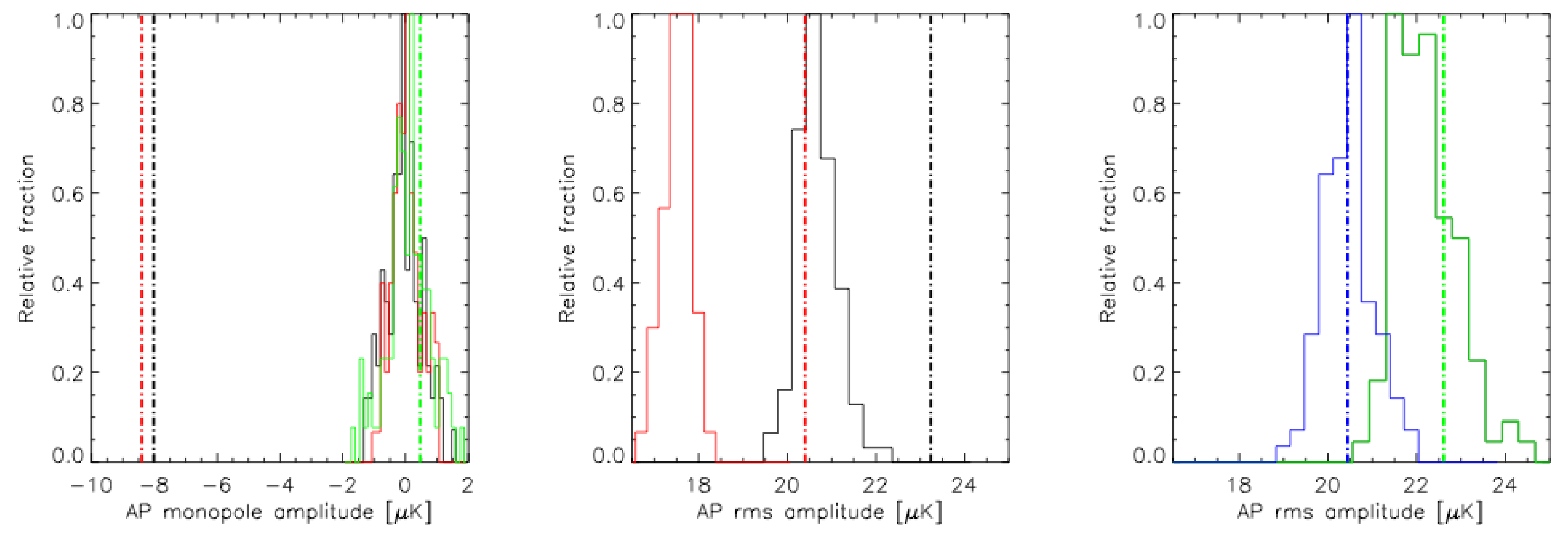
z_L ~ VOID size

$$\delta(r) = \begin{cases} \delta_0 \left[1 - 3\left(\frac{r}{L}\right)^2 + 2\left(\frac{r}{L}\right)^3\right] & r \leq L, \\ 0 & r > L, \end{cases}$$

Constraints from **MCXC kSZ monopole**

Clusters at an average redshift of <z> ~ 0.18, at a speed of ~ c<z> wrt a local observer, remain mostly at rest (72 +/- 60 km s^{-1}) wrt the CMB!

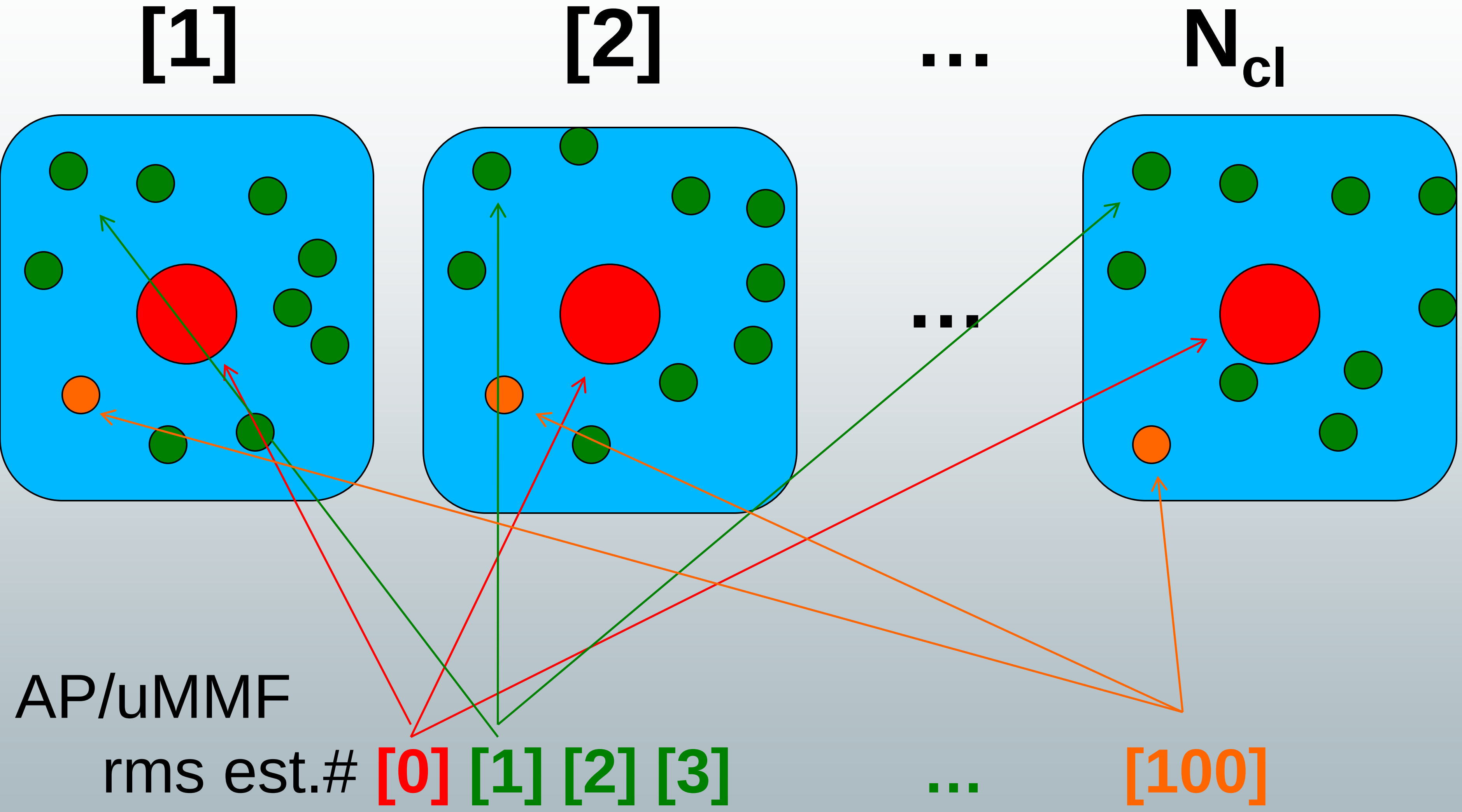
Constraints from **MCXC kSZ AP rms**



AP output histograms in 100 GHz, 143 GHz and 217 GHz (raw) and 2D-ILC (tSZ-free) maps. We use AP estimates from the MCXC cluster positions (vertical dot-dashed lines), and from **100 neighboring positions** for each MCXC cluster.

We clearly see the AP tSZ-induced monopoles at 100 and 143 GHz, tSZ-induced excess rms-s at 100 and 143 GHz, but no evidence of kSZ-induced excess rms in the 217 GHz (raw) and 2D-ILC maps

Using 100 neighbor positions …



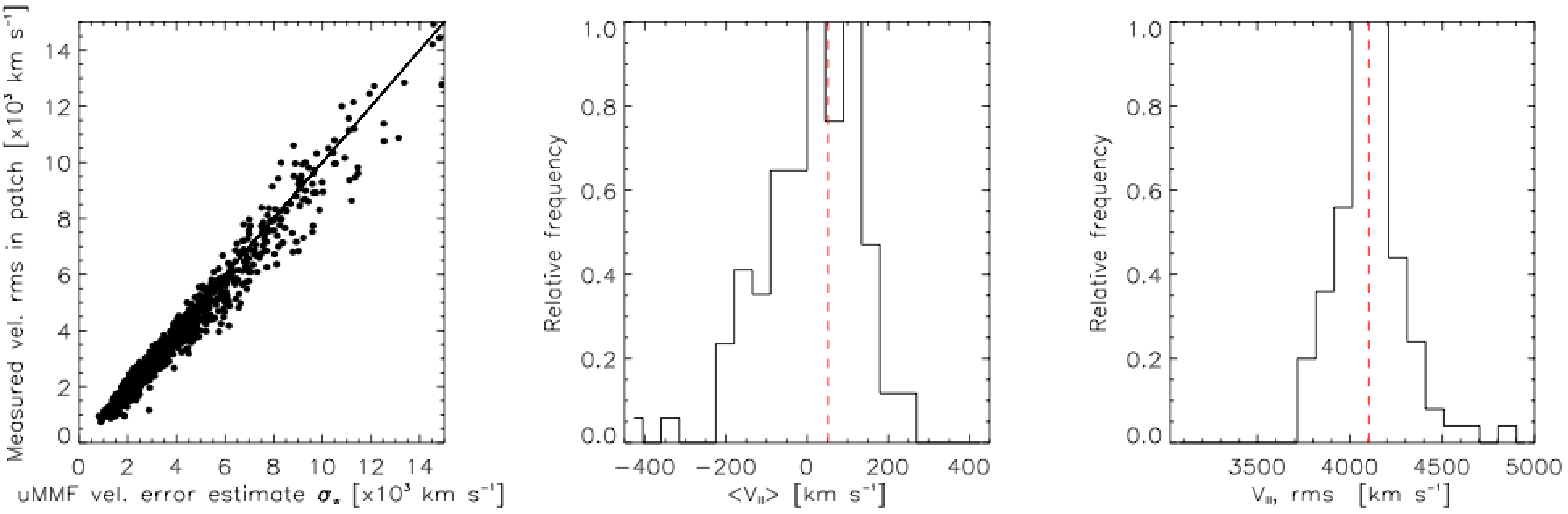
[1] [2] … N_{cl}

…

AP/uMMF

rms est.# [0] [1] [2] [3] … [100]

Constraints from **MCXC kSZ uMMF rms**



Measured vel.rms vs expected value

Histogram of measured uMMF velocities

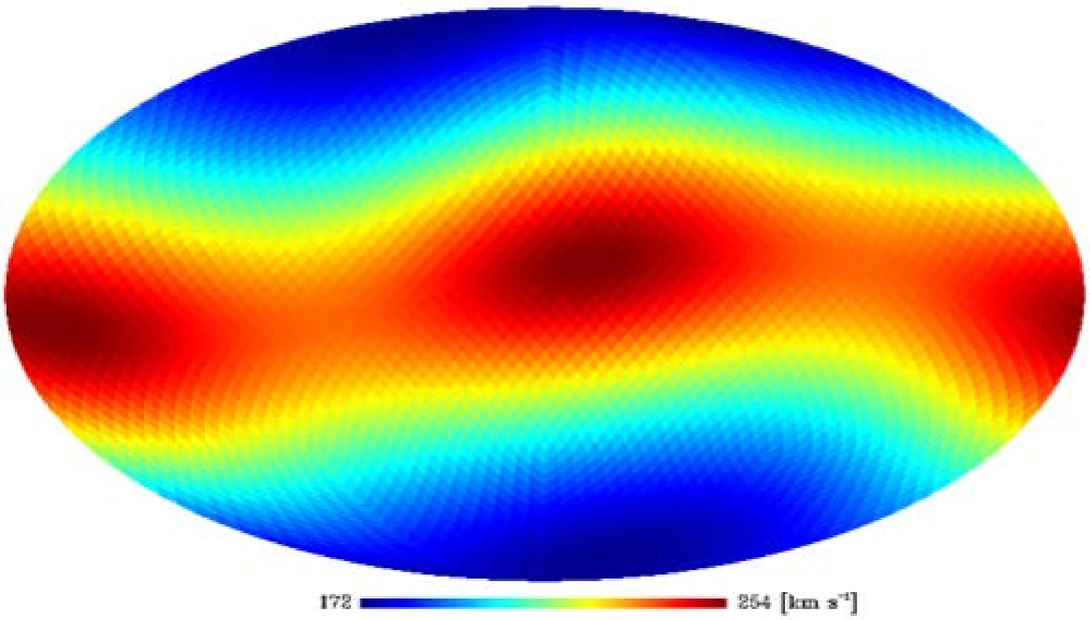
Histogram of uMMF velocity rms

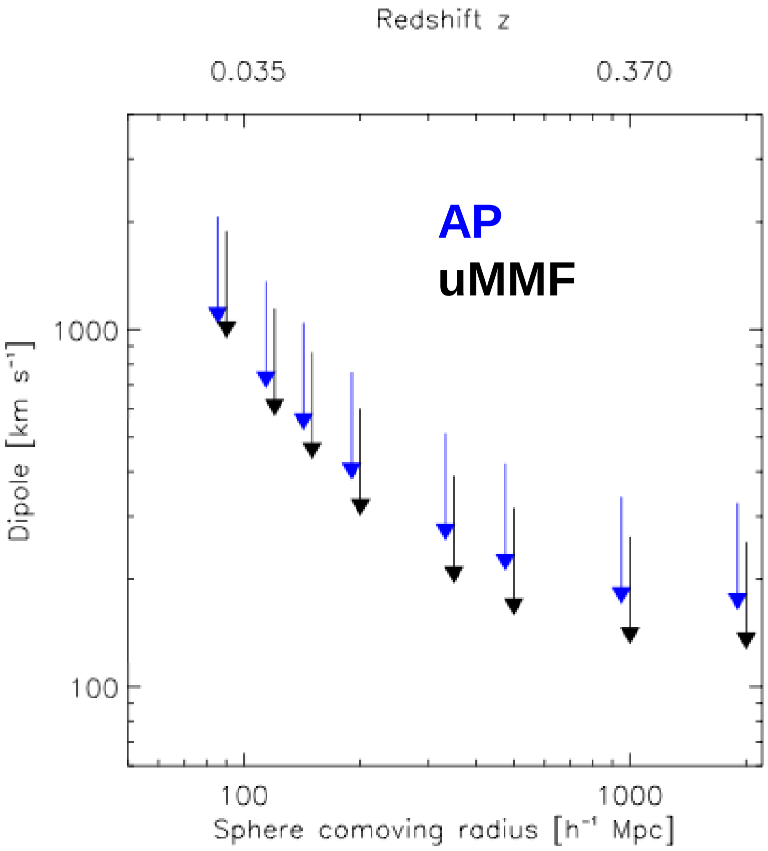
From the histogram of rms-values, ***we set 95% C.L. upper limits for the MCXC clusters' radial peculiar velocity to be at the level of 800 km s^{-1}*** for a subset of the ~1,000 most massive MCXC galaxy clusters. The LCDM prediction is ~230 km s^{-1}

Constraints on local bulk flows

After computing the dipole amplitudes of the kSZ AP/uMMF estimates according to the MCXC cluster positions in the sky, we ***set upper these upper limits (@ 95% C.L.) to the kSZ dipole on spheres centred on us:***

95% C.L. kSZ dipole upper limit on the sky:





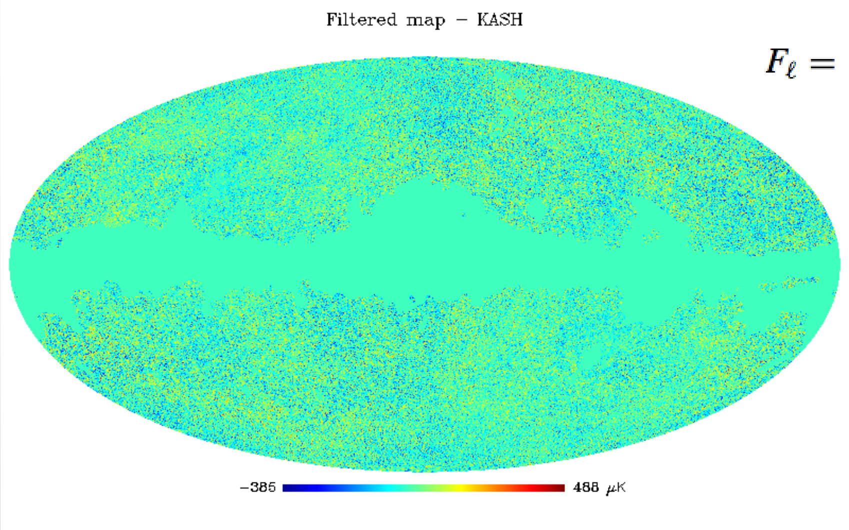
Two very different methods yield very similar constraints!

KABKE results

… in apparent contradiction with the Kashlinsky et al. 2008-2012 results, where a claim of a~1,000 km s^{-1} kSZ dipole is presented ….

Constraints on local bulk flows (II)

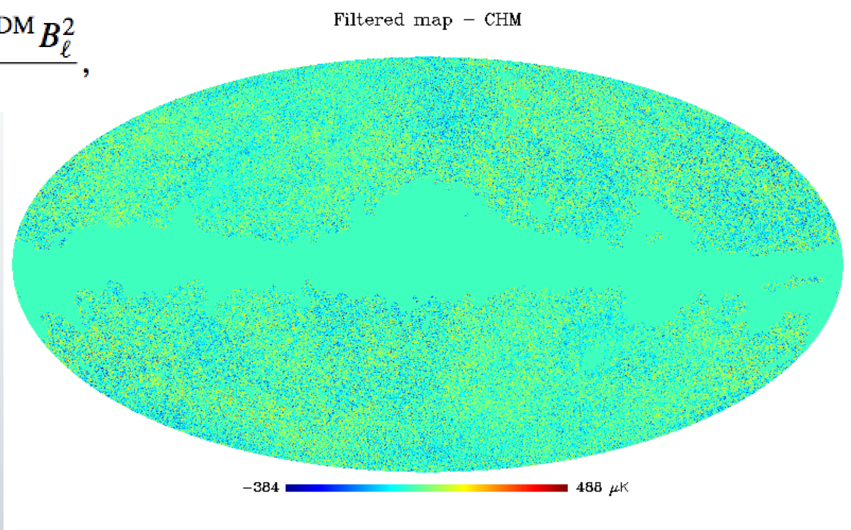
KABKE

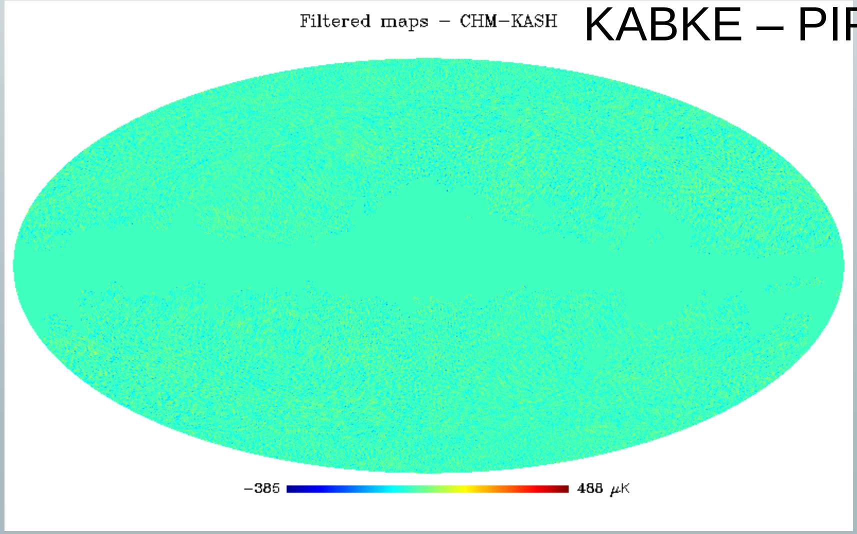


KABKE filter:

$$F_\ell = \frac{C_\ell(\mathrm{sky}) - C_\ell^{\Lambda\mathrm{CDM}} B_\ell^2}{C_\ell(\mathrm{sky})},$$

PIP-XIII



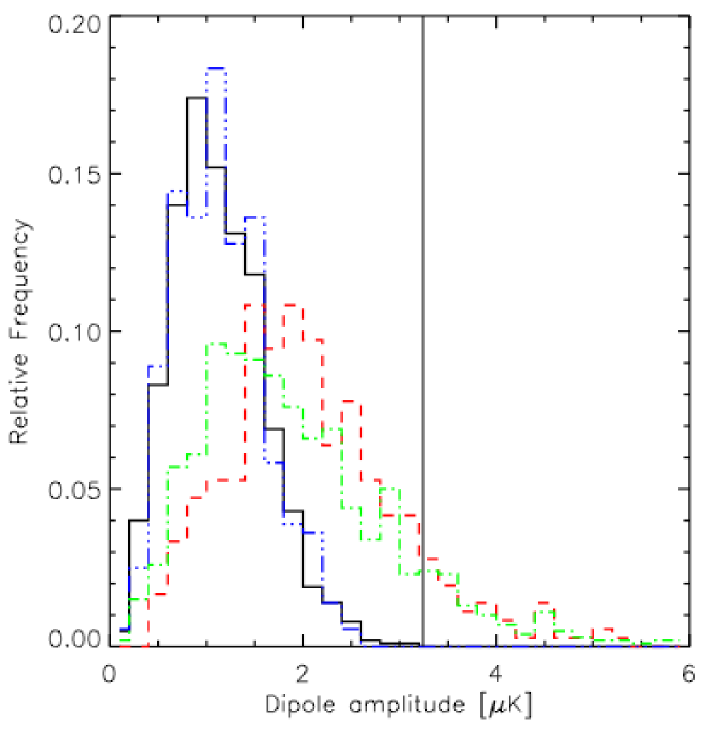


KABKE – PIP-XIII

We reproduce practically identical filtered maps in WMAP data, and very similar ones in Planck data

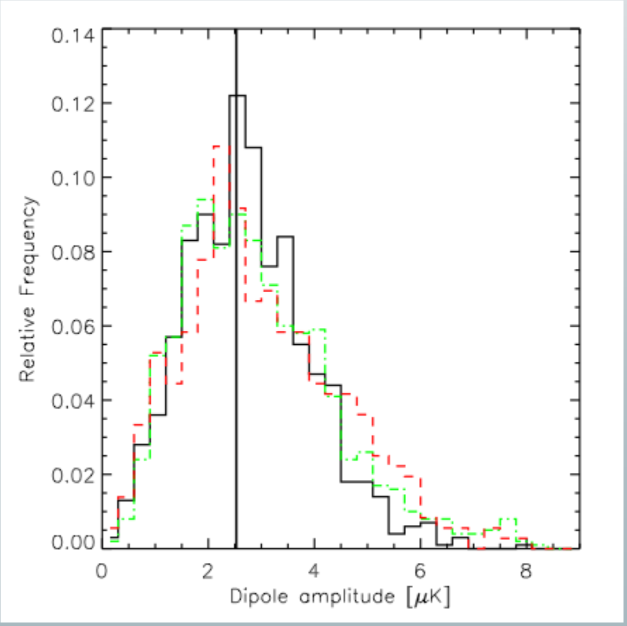
Constraints on local bulk flows (III)

After implementing the Kashlinsky et al. (08-10) filter, we ***reproduce their measured values of the dipole, but find that they are consistent with CMB residuals after running CMB Monte Carlo and rotating the MCXC sample in galactic longitude***



Entire MCXC sample

We find that the assumption that clusters are randomly placed on the sky (***no clustering***) is only valid for restricted (most massive) samples, but not for the entire one.



200 most massive MCXC clusters

Conclusions

- After implementing **four** different filters extracting kSZ signal at the position of MCXC galaxy clusters, we find **no significant evidence for a non-zero kSZ monopole. This rules out a large family of giant voids / LTB inhomogeneous models (in agreement with Zhang & Stebbins 2011)**

- Upper limits of MCXC cluster peculiar radial velocities lie ***at the level of 800 – 1,000 km s^{-1} at 95% C.L***., a factor of 2—3 above theoretical LCDM predictions

- *Planck* finds ***no evidence for any bulk flow on spheres centred on the obse***rver, up to radii of ~ 1 Gpc (~ 300 km s^{-1} at 95% C.L.), pointing to a largely homogeneous universe on supra Gpc scales.

- *Planck*’s constraints on peculiar velocities are ***consistent*** with the LCDM scenario

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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