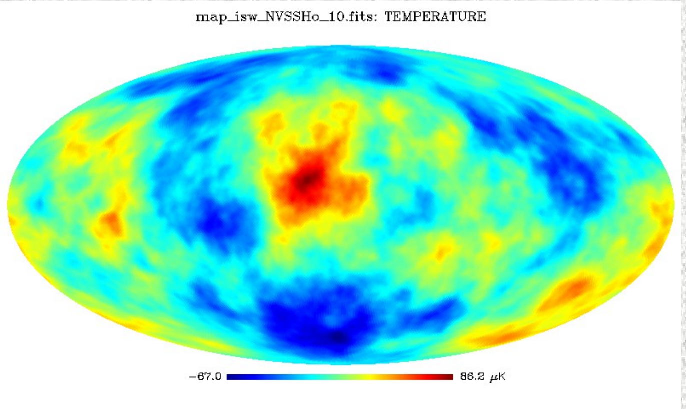
ISW, kSZ

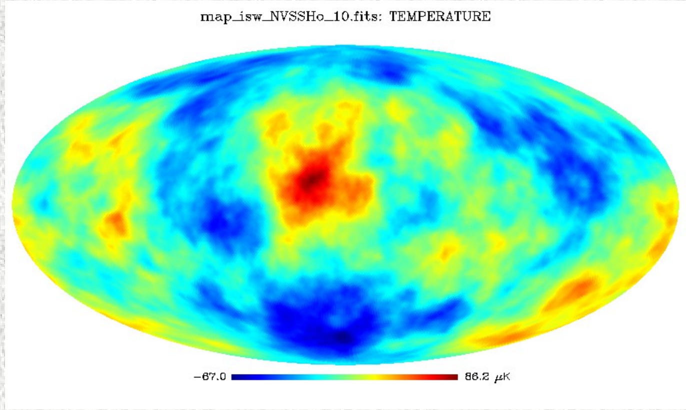


Carlos Hernández-Monteagudo
Centro de **E**studios de **F**ísica del **C**osmos de **A**ragón

[CEFCA]

ISW, kSZ

Integrated Sachs Wolfe, kinetic Sunyaev-Zeldovich effects



Carlos Hernández-Monteagudo

Centro de **E**studios de **F**ísica del **C**osmos de **A**ragón

[CEFCA]

OUTLINE:

ISW
- The Sachs Wolfe effect
- The integrated Sachs Wolfe effect: why is it so relevant for Dark Energy
- Unveiling the Sachs-Wolfe effect in CMB maps. The impact of systematics
- Observational status from cross-correlations, stacking and lensing
- Future prospects (?)

kSZ
- The thermal and the kinetic Sunyaev-Zeldovich effect
- The cosmological implications of the kSZ for Cosmology: missing baryons and homogeneity
- Chasing the kSZ: a tiny signal with an unfortunate frequency dependence
- Recent detections, cosmological implications, and future prospects

Revisiting the CMB temperature (or intensity) anisotropies:

$$B_\nu[T_{CMB}(1+\Delta)] = \frac{2h\nu^3/c^2}{\exp\frac{h\nu}{k_B T_{CMB}(1+\Delta)} - 1}; \quad \Delta \equiv \frac{\delta T_{CMB}}{T_{CMB}}$$

$$\dot{\Delta}_T^{(S)} + ik\mu\,\Delta_T^{(S)} = \dot{\phi} - ik\mu\psi + \dot{\kappa}[-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \tfrac{1}{2}P_2(\mu)\Pi] ,$$

The **linearised** Boltzmann equation for the CMB brightness temperature has this form (at **linear** level of perturbations, all **changes** in the CMB distribution function are **independent** of **frequency**, i.e., the resulting spectrum is **Planckian**, but with a slightly different temperature

For each k or Fourier mode (that evolvse independently of other modes in linear theory), one can write an integral solution:

$$\Delta_{T,P}^{(S)} = \int_0^{\tau_0} d\tau e^{ik\mu(\tau-\tau_0)} S_{T,P}^{(S)}(k,\tau)$$

$$S_T^{(S)}(k,\tau) = g\left(\Delta_{T0} + \psi + \frac{\dot{v}_b}{k} + \frac{\Pi}{4} + \frac{3\ddot{\Pi}}{4k^2}\right) + e^{-\kappa}(\dot{\phi} + \dot{\psi}) + \dot{g}\left(\frac{v_b}{k} + \frac{3\dot{\Pi}}{4k^2}\right) + \frac{3\ddot{g}\Pi}{4k^2} ,$$

Linear theory works extremely well at z ~ *1,100* on observable scales ...

Revisiting the CMB temperature (or intensity) anisotropies:

$$B_\nu[T_{CMB}(1+\Delta)] = \frac{2h\nu^3/c^2}{\exp\frac{h\nu}{k_B T_{CMB}(1+\Delta)} - 1}; \quad \Delta \equiv \frac{\delta T_{CMB}}{T_{CMB}}$$

$$\dot{\Delta}_T^{(S)} + ik\mu\,\Delta_T^{(S)} = \dot{\phi} - ik\mu\psi + \dot{\kappa}\left[-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \tfrac{1}{2}P_2(\mu)\Pi\right],$$

The **linearised** Boltzmann equation for the CMB brightness temperature has this form (at **linear** level of perturbations, all **changes** in the CMB distribution function are **independent** of **frequency**, i.e., the resulting spectrum is **Planckian**, but with a slightly different temperature

For **each *k*** or Fourier mode (that evolvse independently of other modes in linear theory), one can write an **integral** solution:

$$\Delta_{T,P}^{(S)} = \int_0^{\tau_0} d\tau\, e^{ik\mu(\tau-\tau_0)} S_{T,P}^{(S)}(k,\tau)$$

$$S_T^{(S)}(k,\tau) = g\left(\Delta_{T0} + \psi + \frac{\dot{v}_b}{k} + \frac{\Pi}{4} + \frac{3\ddot{\Pi}}{4k^2}\right) + e^{-\kappa}(\dot{\phi} + \dot{\psi}) + \dot{g}\left(\frac{v_b}{k} + \frac{3\dot{\Pi}}{4k^2}\right) + \frac{3\ddot{g}\Pi}{4k^2},$$

Local monopole + gravitational potential: **Sachs Wolfe** effect

Linear theory works extremely well at *z ~ 1,100* on observable scales ...

Revisiting the CMB temperature (or intensity) anisotropies:

$$B_\nu[T_{CMB}(1+\Delta)] = \frac{2h\nu^3/c^2}{\exp\frac{h\nu}{k_B T_{CMB}(1+\Delta)} - 1}\,; \qquad \Delta \equiv \frac{\delta T_{CMB}}{T_{CMB}}$$

$$\dot{\Delta}_T^{(S)} + ik\mu\,\Delta_T^{(S)} = \dot{\phi} - ik\mu\psi + \dot{\kappa}\left[-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \tfrac{1}{2}P_2(\mu)\Pi\right],$$

The **linearised** Boltzmann equation for the CMB brightness temperature has this form (at **linear** level of perturbations, all **changes** in the CMB distribution function are **independent** of **frequency**, i.e., the resulting spectrum is **Planckian**, but with a slightly different temperature

For **each *k*** or Fourier mode (that evolvse independently of other modes in linear theory), one can write an **integral** solution:

$$\Delta_{T,P}^{(S)} = \int_0^{\tau_0} d\tau\, e^{ik\mu(\tau-\tau_0)} S_{T,P}^{(S)}(k,\tau)$$

$$S_T^{(S)}(k,\tau) = g\left(\Delta_{T0} + \psi + \frac{\dot{v}_b}{k} + \frac{\Pi}{4} + \frac{3\ddot{\Pi}}{4k^2}\right) + e^{-\kappa}(\dot{\phi} + \dot{\psi}) + \dot{g}\left(\frac{v_b}{k} + \frac{3\dot{\Pi}}{4k^2}\right) + \frac{3\ddot{g}\Pi}{4k^2},$$

Local monopole + gravitational potential: **Sachs Wolfe** effect

Time varying potentials: **integrated Sachs Wolfe** effect

Linear theory works extremely well at $z \sim 1{,}100$ on observable scales ...

Revisiting the CMB temperature (or intensity) anisotropies:

$$B_\nu[T_{CMB}(1+\Delta)] = \frac{2h\nu^3/c^2}{\exp\frac{h\nu}{k_B T_{CMB}(1+\Delta)} - 1}\,; \qquad \Delta \equiv \frac{\delta T_{CMB}}{T_{CMB}}$$

$$\dot{\Delta}_T^{(S)} + ik\mu\,\Delta_T^{(S)} = \dot{\phi} - ik\mu\psi + \dot{\kappa}\left[-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \tfrac{1}{2}P_2(\mu)\Pi\right],$$

The **linearised** Boltzmann equation for the CMB brightness temperature has this form (at **linear** level of perturbations, all **changes** in the CMB distribution function are **independent** of **frequency**, i.e., the resulting spectrum is **Planckian**, but with a slightly different temperature

For **each *k*** or Fourier mode (that evolvse independently of other modes in linear theory), one can write an **integral** solution:

$$\Delta_{T,P}^{(S)} = \int_0^{\tau_0} d\tau\, e^{ik\mu(\tau-\tau_0)} S_{T,P}^{(S)}(k,\tau)$$

$$S_T^{(S)}(k,\tau) = g\left(\Delta_{T0} + \psi + \frac{\dot{v}_b}{k} + \frac{\Pi}{4} + \frac{3\ddot{\Pi}}{4k^2}\right) + e^{-\kappa}(\dot{\phi} + \dot{\psi}) + \dot{g}\left(\frac{v_b}{k} + \frac{3\dot{\Pi}}{4k^2}\right) + \frac{3\ddot{g}\Pi}{4k^2},$$

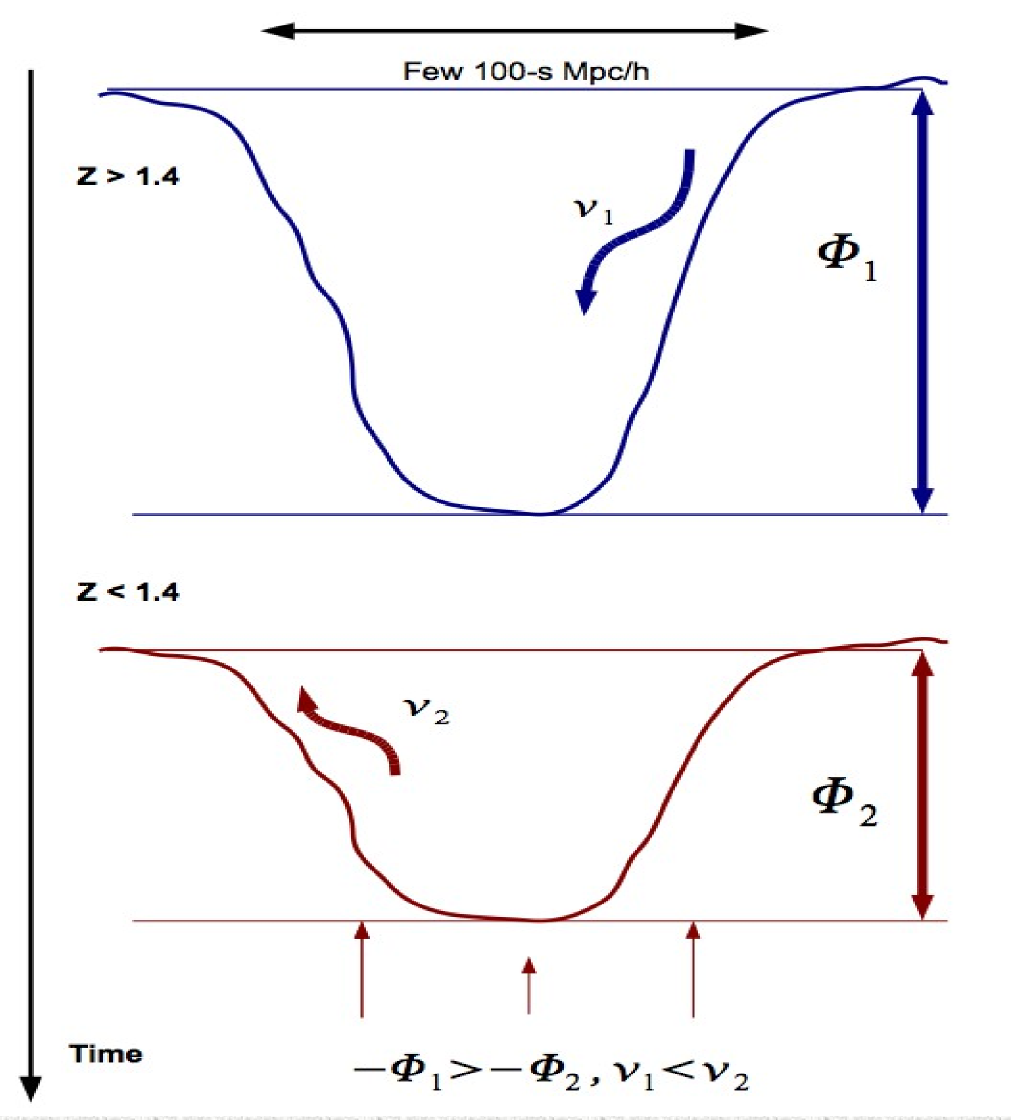
Local monopole + gravitational potential: **Sachs Wolfe** effect

Time varying potentials: **integrated Sachs Wolfe** effect

Doppler or kSZ term

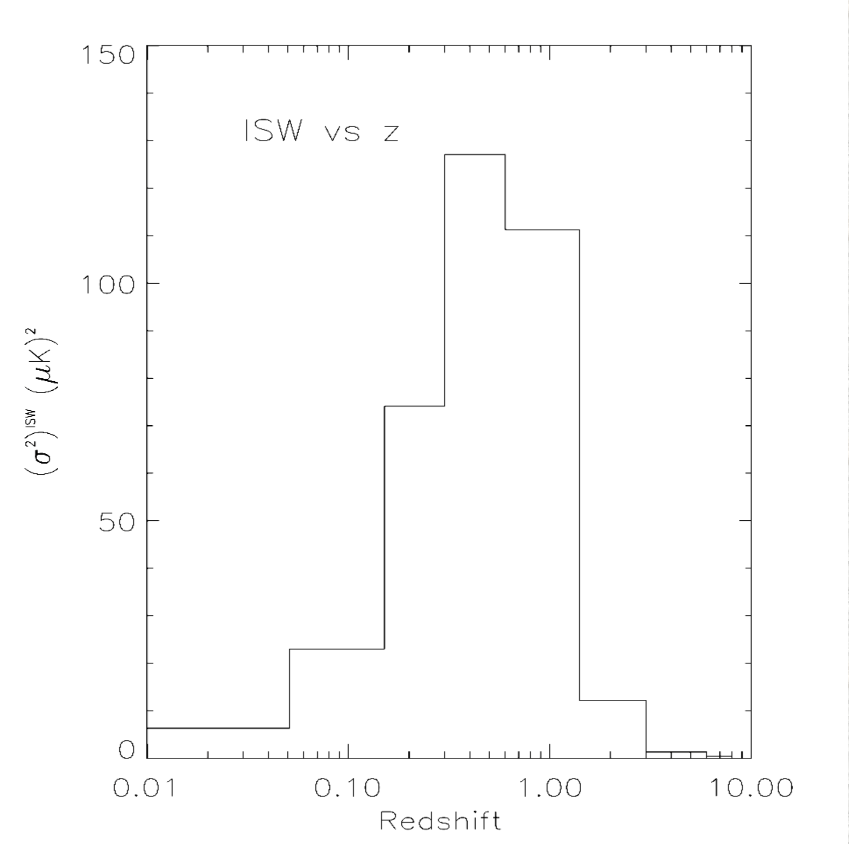
Linear theory works extremely well at *z ~ 1,100* on observable scales ...

The Integrated Sachs Wolfe effect:



$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = -\frac{2}{c^2}\int_0^{r_{\rm LSS}} \mathrm{d}r \; \frac{\partial \phi(r, \hat{\boldsymbol{n}})}{\partial r}$$

LCDM: ISW vs z



The Integrated Sachs Wolfe effect:

$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = -\frac{2}{c^2}\int_0^{r_{\rm LSS}} \mathrm{d}r\ \frac{\partial\phi(r,\hat{\boldsymbol{n}})}{\partial r}$$

- From Poisson's equation: $-k^2\ a^2\ \phi_k = 4\pi G\rho_b(z)\ \delta_k$, with a the scale factor, so

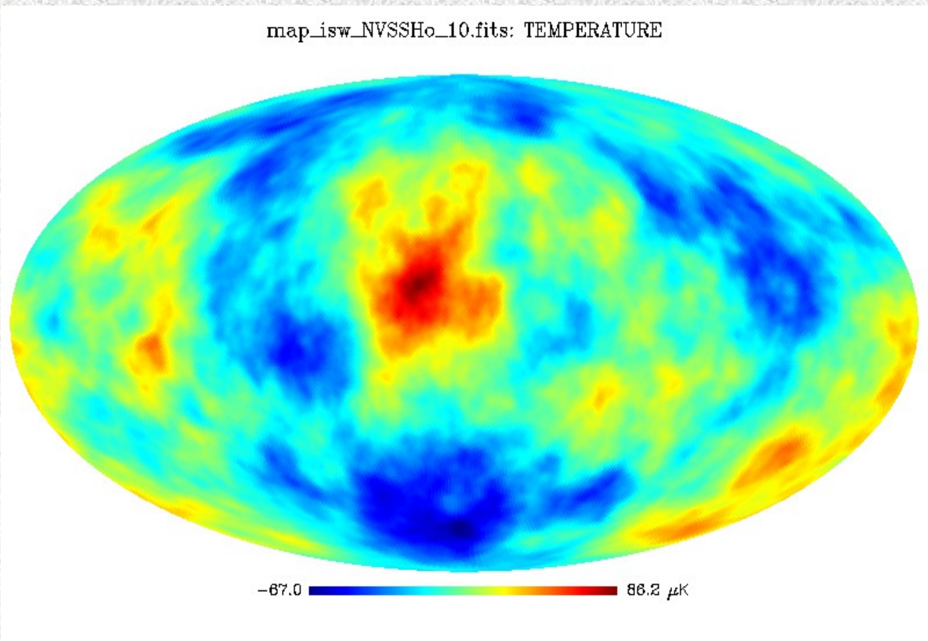
$$\phi_k = -\frac{4\pi G}{k^2}\rho_b(z=0)\ \frac{\delta_k}{a}$$

- In a critical Universe, $\delta_k \propto a$ and $\phi_k = const$
- In a Λ Universe, the growth of potentials is *suppressed* compared to the critical case:

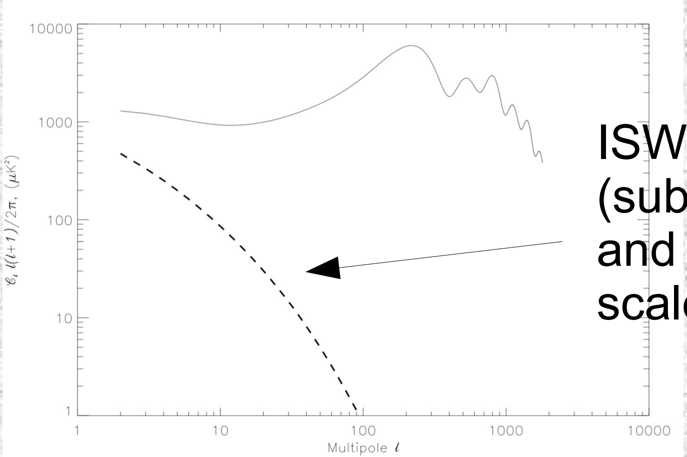
$\Rightarrow$ **positive correlation between ϕ_k and $\delta T/T_0$**

The Integrated Sachs Wolfe effect:

ISW map

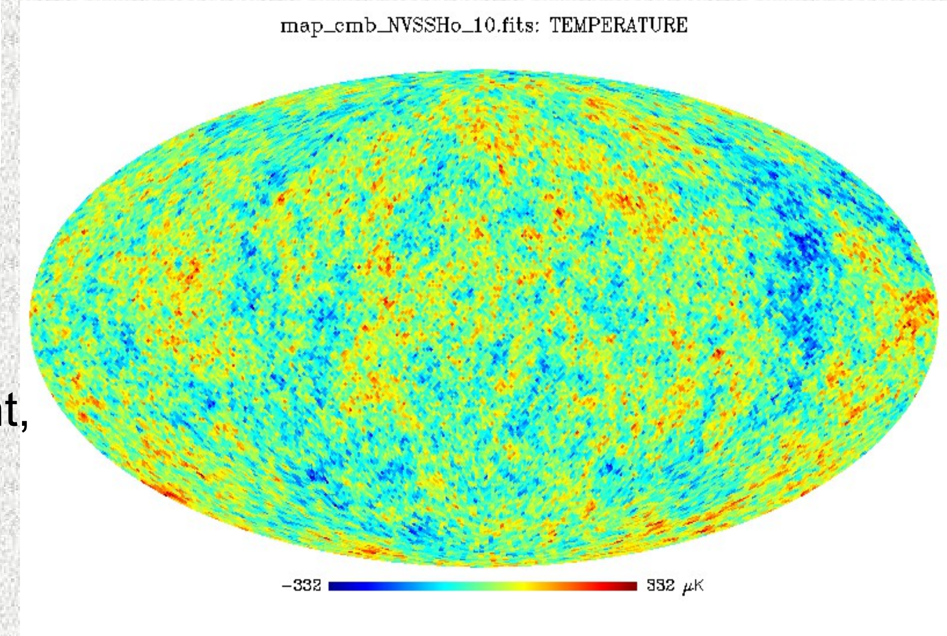


Since it appears on **very large scales,** there are very **few independent** spots on the sky, and one needs to cover **large sky areas** to detect it …



ISW power (subdominant, and on small scales)

Total CMB map (including the ISW map)



The Integrated Sachs Wolfe effect: (unveiling it via cross-correlations)

Crittenden & Turok (96) suggested that, since $\delta\phi \propto \delta$, one could detect the ISW by **X-correlating CMB maps with LSS**

$$\delta T = \sum a_{l,m} Y_{l,m}(\theta, \phi)$$

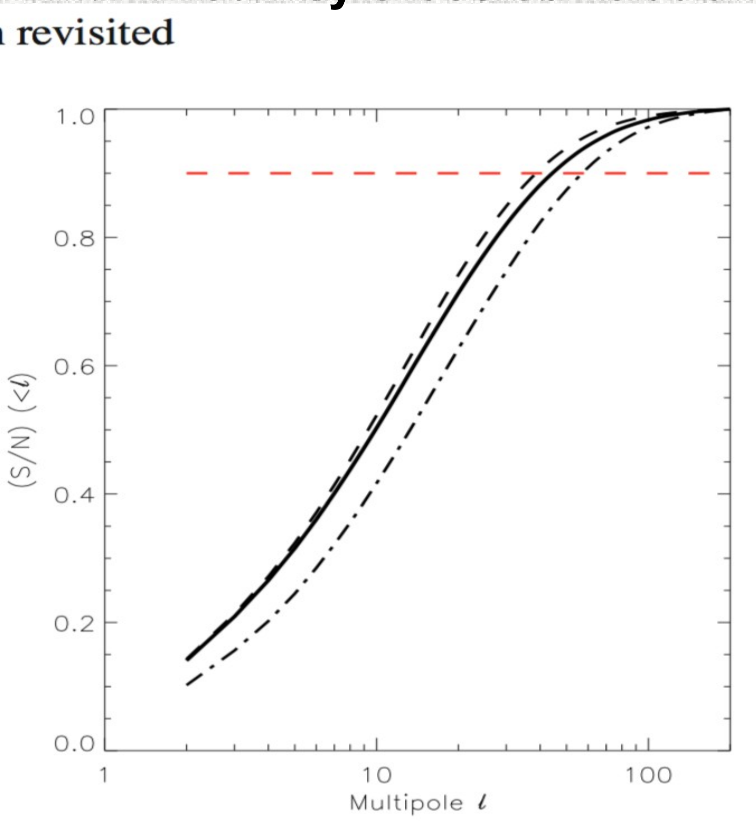
$$\delta N_g = \sum N_{l,m} Y_{l,m}(\theta, \phi)$$

X-correlation function: $\langle \delta T(\mathbf{x}) \delta N_g(\mathbf{x} + \theta) \rangle = \sum \frac{2l+1}{4\pi} C_l^{T,N_g} P_l(\cos\theta)$

$$C_l^{T,N_g} \equiv \langle a_{lm} N_{l,m}^* \rangle$$

The Integrated Sachs Wolfe effect: (unveiling it via cross-correlations)

S/N of the ISW x galaxy survey cross correlation:

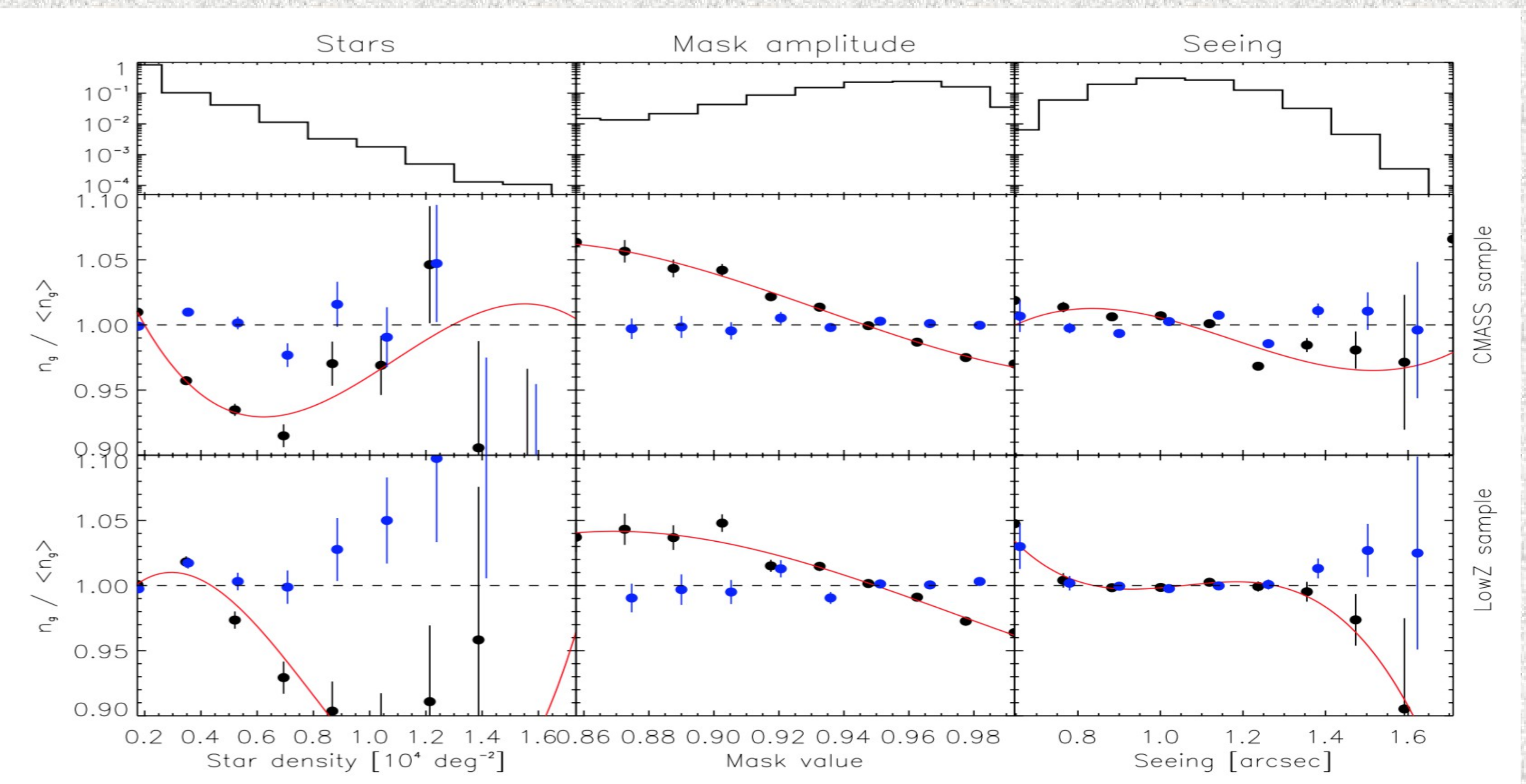


CHM, 2010

Pretty **independently** of the source redshift distribution, the **S/N of this cross-correlation** analysis tends to peak at **low** multipoles / large sky areas (~90% of the S/N should lie below *elle*=50 – 60), where we may have **systematics,** most probably in the galaxy templates

Maximum S/N achievable ~ 7.3

The Integrated Sachs Wolfe effect. Systematics associated to the galaxy survey

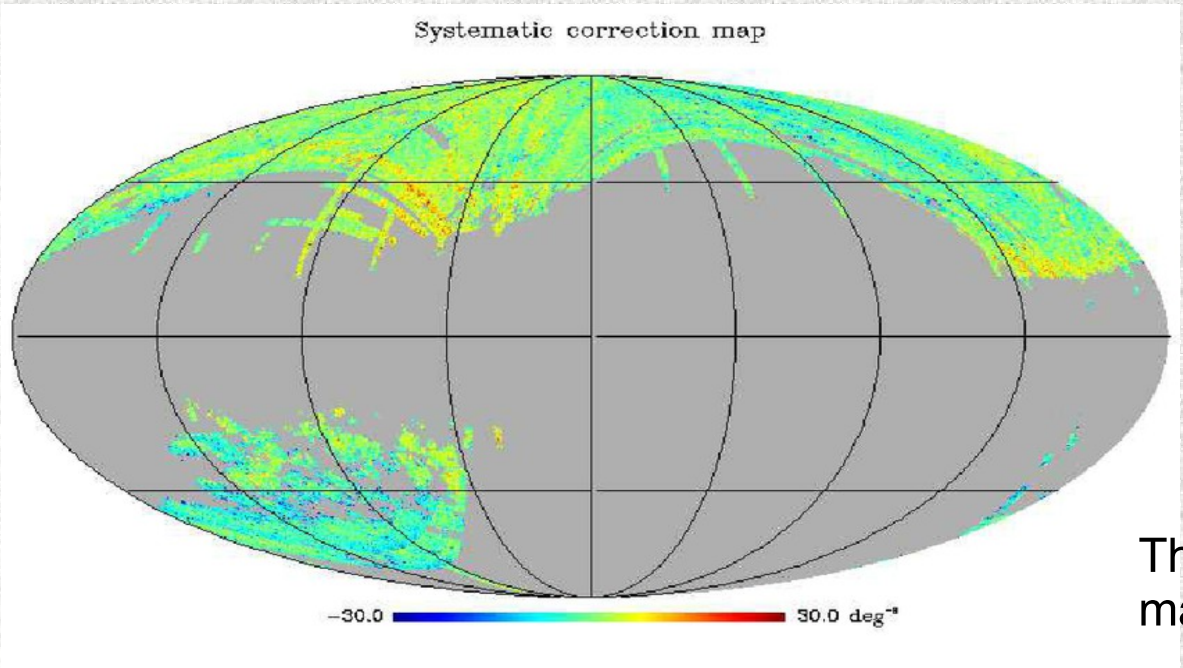


CHM et al., 2014, for the BOSS collab.

Black: before correction
Blue: after correction

On **large scales** our measured galaxy density field maybe **modulated** by artifacts, like **stars**, **seeing**, or **extinction**, and we must correct for this or our clusterting estimates on the large scales will be severely **biased** ...

The Integrated Sachs Wolfe effect. Systematics associated to the galaxy survey

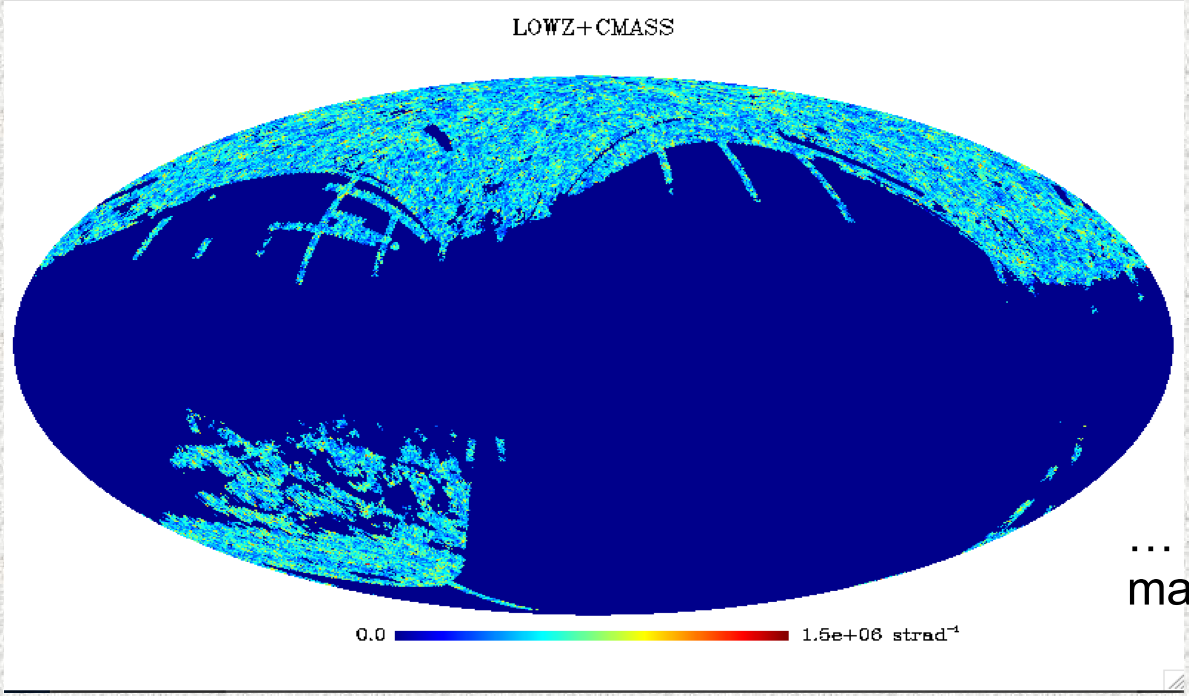


CHM et al., 2014, for the BOSS collab.

This is the correction map ...

On **large scales** our measured galaxy density field maybe **modulated** by artifacts, like **stars**, **seeing**, or **extinction**, and we must correct for this or our clusterting estimates on the large scales will be severely **biased** ...

The Integrated Sachs Wolfe effect. Systematics associated to the galaxy survey



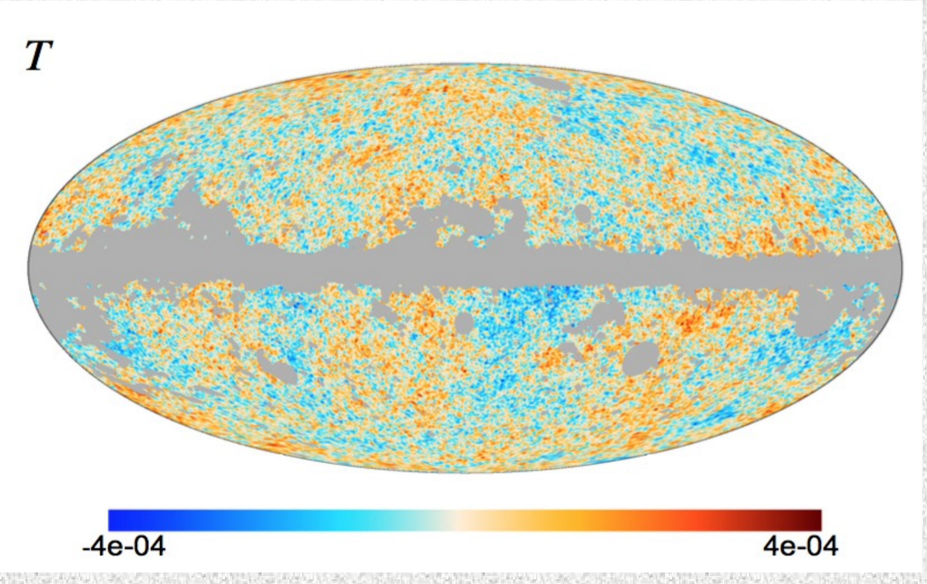
CHM et al., 2014, for the BOSS collab.

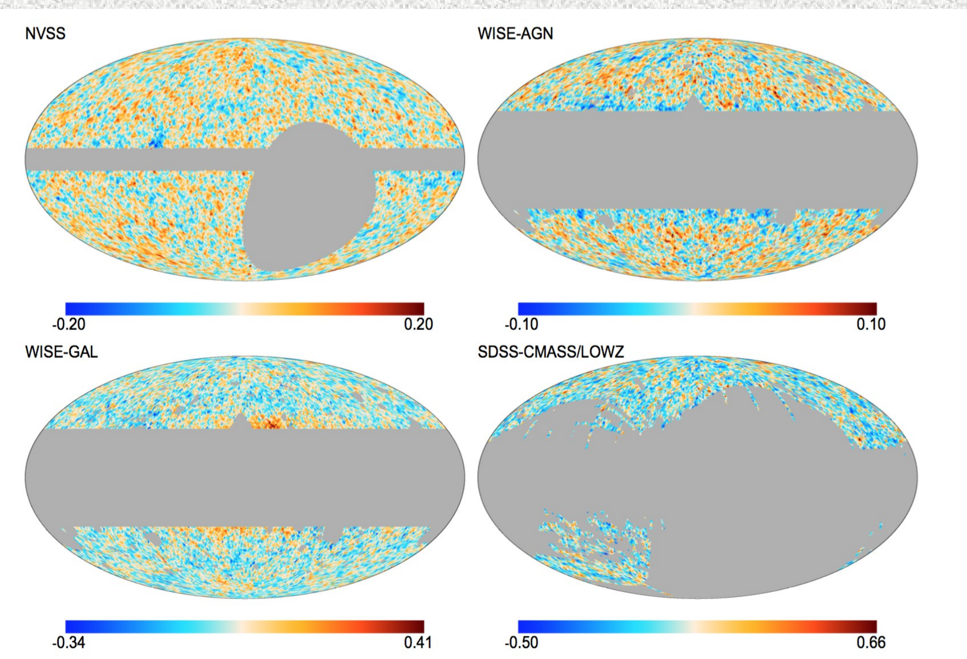
… to be added to this map ...

On **large scales** our measured galaxy density field maybe **modulated** by artifacts, like **stars**, **seeing**, or **extinction**, and we must correct for this or our clusterting estimates on the large scales will be severely **biased** ...

The Integrated Sachs Wolfe effect.
(Observational status)

Planck **intensity/temperature** map vs **maps of LSS** from optical/radio/IR





Planck Collaboration, 2016

The Integrated Sachs Wolfe effect.
(Observational status)

Planck **intensity/temperature** map vs **maps of LSS** from optical/radio/IR

Planck Collaboration: *Planck* 2015 results. XXI.

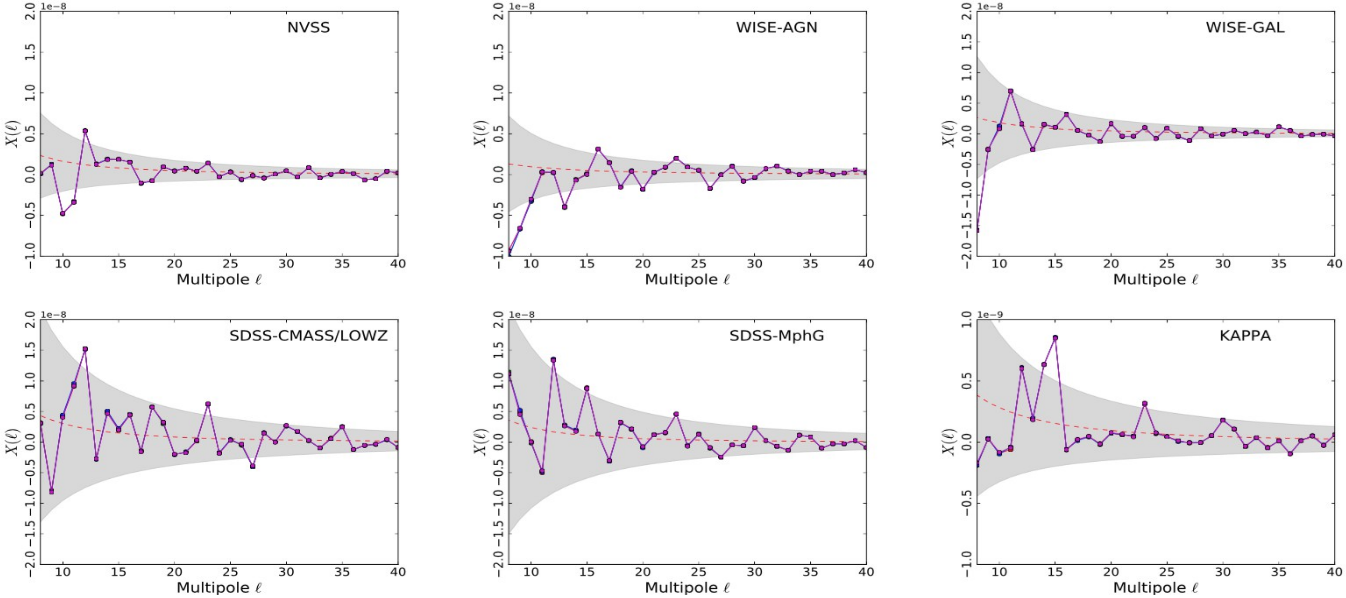


Fig. 6. Measured ISW-LSS cross-spectra (CAPS). *From left to right*, snd top to bottom, the panels show the cross-correlation of the four CMB maps with NVSS, WISE-AGN, WISE-GAL, SDSS-CMASS/LOWZ, SDSS-MphG, and Kappa. Grey areas represent $\pm 1\sigma$ uncertainities derived from simulations. Spectra derived from the *Planck* CMB maps are virtually the same.

Planck Collaboration, 2016

The Integrated Sachs Wolfe effect. (Observational status)

Planck **intensity/temperature** map vs **maps of LSS** from optical/radio/IR

Planck Collaboration, 2016

A&A 594, A21 (2016)

Table 2. ISW amplitudes A, errors σ_A, and significance levels $S/N = A/\sigma_A$ of the CMB-LSS cross-correlation (survey-by-survey and for different combinations).

LSS data	COMMANDER		NILC		SEVEM		SMICA		Expected
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.61	0.94 ± 0.36	2.59	0.95 ± 0.36	2.62	0.95 ± 0.36	2.61	2.78
WISE-AGN ($\ell_{\min} \geq 9$)	0.95 ± 0.60	1.58	0.96 ± 0.60	1.59	0.95 ± 0.60	1.58	1.00 ± 0.60	1.66	1.67
WISE-GAL ($\ell_{\min} \geq 9$)	0.73 ± 0.53	1.37	0.72 ± 0.53	1.35	0.74 ± 0.53	1.38	0.77 ± 0.53	1.44	1.89
SDSS-CMASS/LOWZ	1.37 ± 0.56	2.42	1.36 ± 0.56	2.40	1.37 ± 0.56	2.43	1.37 ± 0.56	2.44	1.79
SDSS-MphG	1.60 ± 0.68	2.34	1.59 ± 0.68	2.34	1.61 ± 0.68	2.36	1.62 ± 0.68	2.38	1.47
Kappa ($\ell_{\min} \geq 8$)	1.04 ± 0.33	3.15	1.04 ± 0.33	3.16	1.05 ± 0.33	3.17	1.06 ± 0.33	3.20	3.03
NVSS and Kappa	1.04 ± 0.28	3.79	1.04 ± 0.28	3.78	1.05 ± 0.28	3.81	1.05 ± 0.28	3.81	3.57
WISE	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.88 ± 0.45	1.97	2.22
SDSS	1.49 ± 0.55	2.73	1.48 ± 0.55	2.70	1.50 ± 0.55	2.74	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.90 ± 0.31	2.90	3.22
All	1.00 ± 0.25	4.00	0.99 ± 0.25	3.96	1.00 ± 0.25	4.00	1.00 ± 0.25	4.00	4.00

Notes. These values are reported for the four *Planck* CMB maps: COMMANDER; NILC; SEVEM; and SMICA. The last column gives the expected S/N within the fiducial ΛCDM model.

Below **S/N=3** for external galaxy surveys, combining with the **internal lensing** map of the CMB yields **S/N ~ 4**

The Integrated Sachs Wolfe effect.
(Observational status)

Planck **intensity/temperature** map vs **maps of LSS** from optical/radio/IR

Planck Collaboration, 2016

A&A 594, A21 (2016)

Table 2. ISW amplitudes A, errors σ_A, and significance levels $S/N = A/\sigma_A$ of the CMB-LSS cross-correlation (survey-by-survey and for different combinations).

LSS data	COMMANDER		NILC		SEVEM		SMICA		Expected
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.61	0.94 ± 0.36	[illegible]	[illegible]	2.62	0.95 ± 0.36	2.61	2.78
WISE-AGN ($\ell_{min} \geq 9$)	0.95 ± 0.60	1.58	[illegible]	1.59	[illegible]	1.58	1.00 ± 0.60	1.66	1.67
WISE-GAL ($\ell_{min} \geq 9$)	0.73 ± 0.53	1.37	[illegible]	[illegible]	0.74 ± 0.53	1.38	0.77 ± 0.53	1.44	1.89
SDSS-CMASS/LOWZ	[illegible]	2.42	[illegible]	2.40	1.37 ± 0.56	2.43	1.37 ± 0.56	2.44	1.79
SDSS-MphG	[illegible]	[illegible]	1.59 ± 0.68	2.34	1.61 ± 0.68	2.36	1.62 ± 0.68	2.38	1.47
Kappa ($\ell_{min} \geq 8$)	[illegible]	[illegible]	1.04 ± 0.33	3.16	1.05 ± 0.33	3.17	1.06 ± 0.33	3.20	3.03
NVSS and Kappa	[illegible]	[illegible]	1.04 ± 0.28	3.78	1.05 ± 0.28	3.81	1.05 ± 0.28	3.81	3.57
WISE	[illegible]	1.88	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.88 ± 0.45	1.97	2.22
SDSS	[illegible]	2.73	1.48 ± 0.55	2.70	1.50 ± 0.55	2.74	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.90 ± 0.31	2.90	3.22
All	1.00 ± 0.25	4.00	0.99 ± 0.25	3.96	1.00 ± 0.25	4.00	1.00 ± 0.25	4.00	4.00

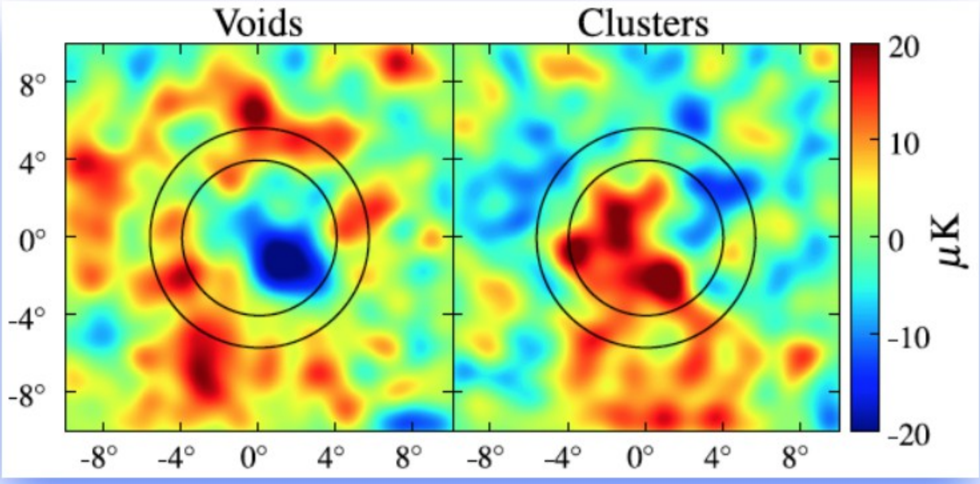
Notes. These values are reported for the four *Planck* CMB maps: COMMANDER; NILC; SEVEM; and SMICA. The last column gives the expected S/N within the fiducial ΛCDM model.

This will not change significantly until new LSS surveys, covering larger areas of the sky while getting into greater depth, are compared to CMB maps (DESI, SKA, Euclid?)

Below **S/N=3** for external galaxy surveys, combining with the **internal lensing** map of the CMB yields **S/N ~ 4**

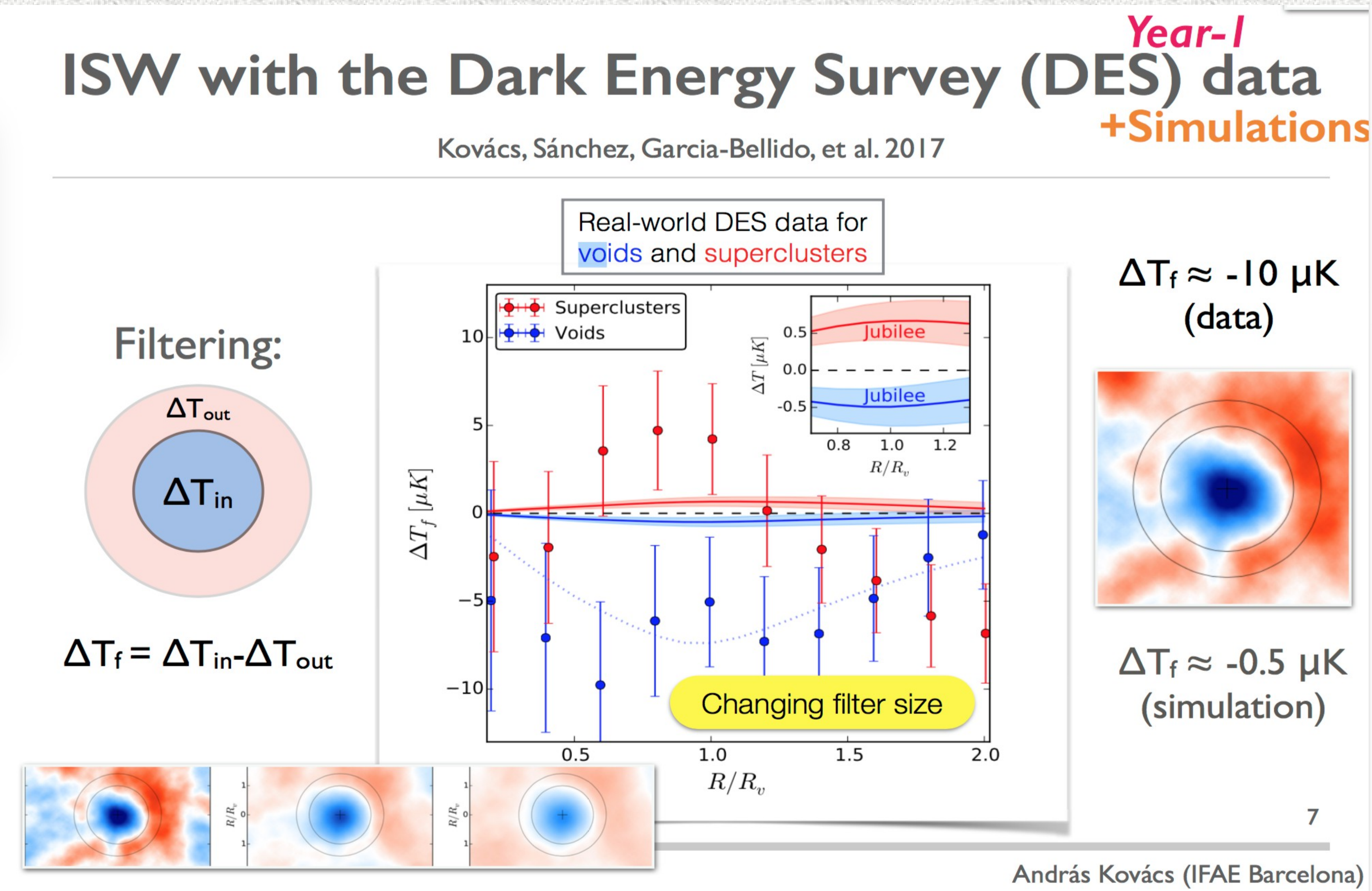
The Integrated Sachs Wolfe effect. (Observational status: stacking on voids and superclusters)

There is more **controversy** about several results found after **stacking** CMB data on the position of **voids** identified in spectroscopic and photometric surveys:

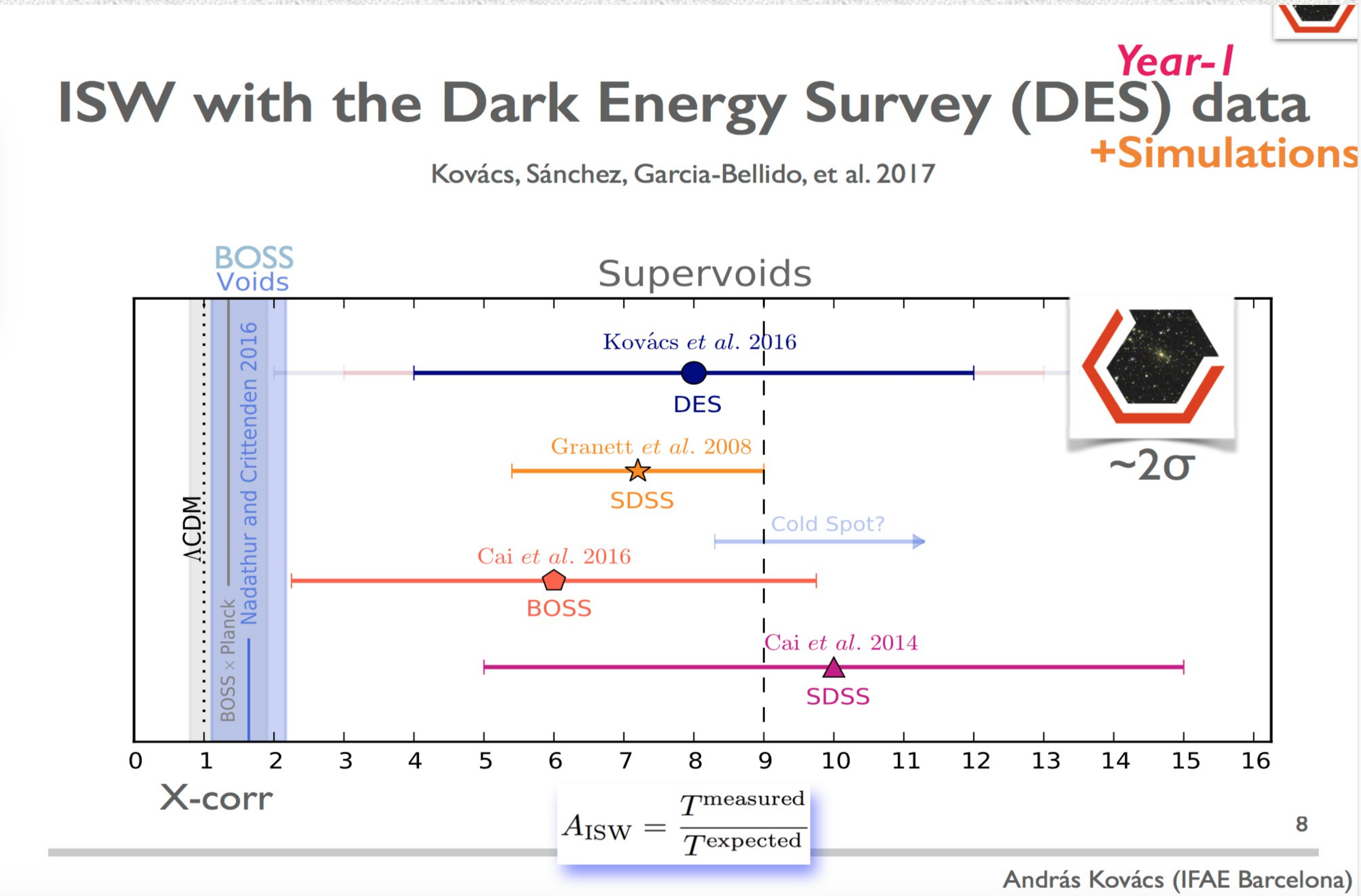


Granett, Neyrinck, Szapudi 2008

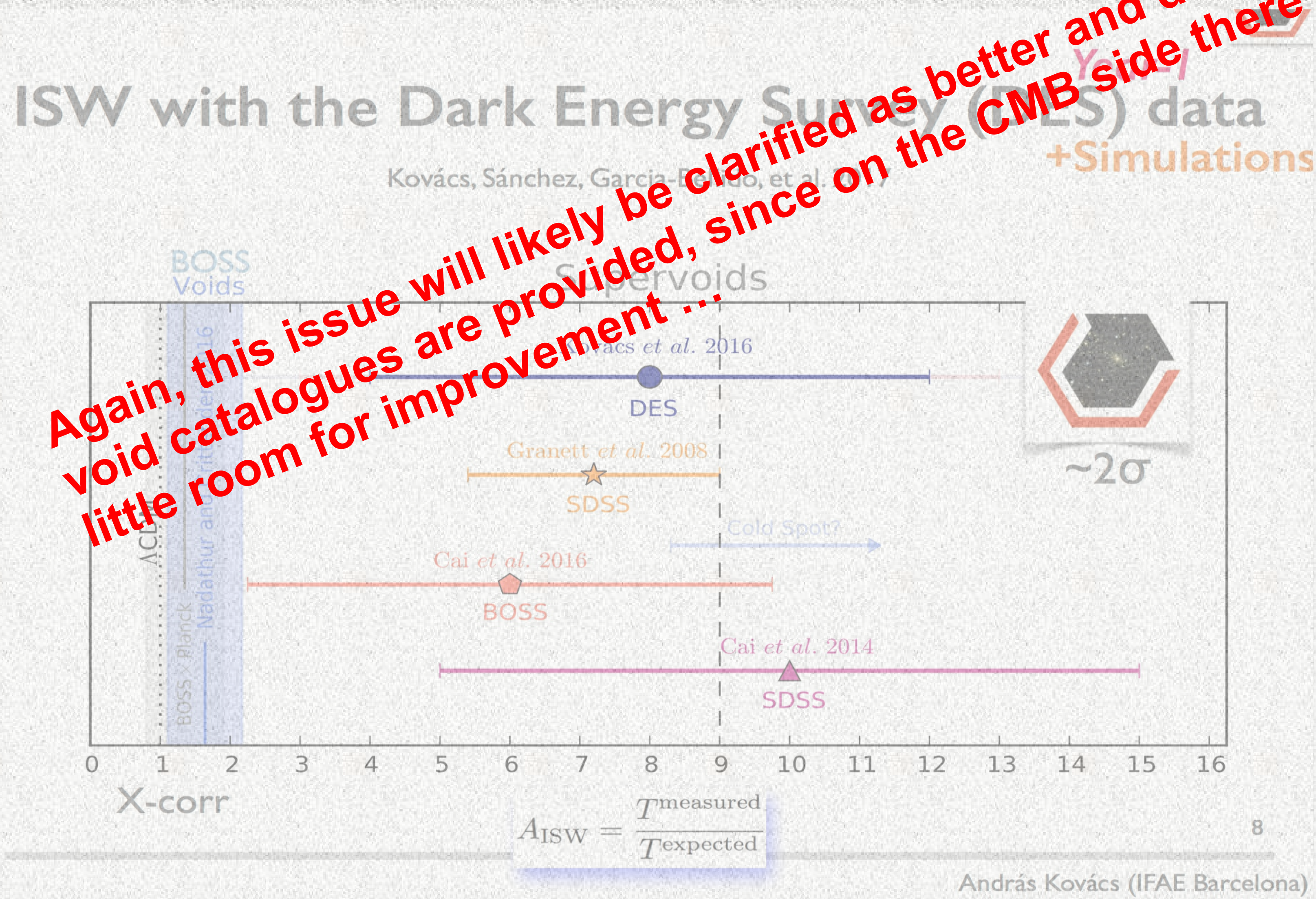
The Integrated Sachs Wolfe effect.
(Observational status: stacking on voids and superclusters)



The Integrated Sachs Wolfe effect. (Observational status: stacking on voids and superclusters)



The Integrated Sachs Wolfe effect. (Observational status: stacking on voids and superclusters)



Again, this issue will likely be clarified as better and deeper void catalogues are provided, since on the CMB side there is little room for improvement …

The Integrated Sachs Wolfe effect. (Summary)

- ISW are generated **below *z=1*** on the **large** angular scales by the **decay** of the large scales gravitational **potentials** during the onset of the **accelerated** expansion

- It can be picked by **cross-correlating CMB** maps with **gravitational potential** spatial **tracers**, such as galaxy surveys or projected potential/kappa maps from CMB lensing.

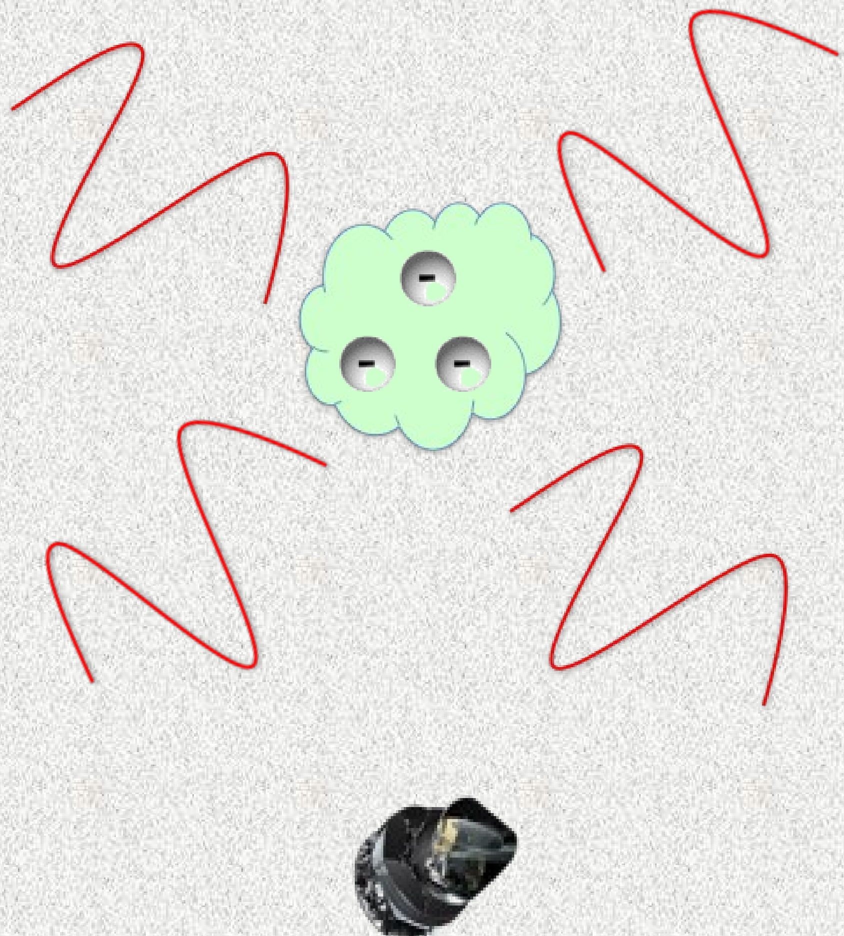
- While the expected maximum S/N for ISW detection is close to **7 (~ 7.3)**, so far we are at the **S/N~3 leve**l if we rely on LSS surveys, and **S/N~4** after including *Planck* kappa/lensing map

- There is little hope for improvement on the CMB side, and only with **deeper and wider LSS surveys** we may be in the position to improve ISW measurements. **Large angle systematics** must be kept under severe control

- There is some signal associated to **super-voids** (and super-clusters) whose ampiltude is ~10x larger than what LCDM predicts. This is all still preliminary and under study.

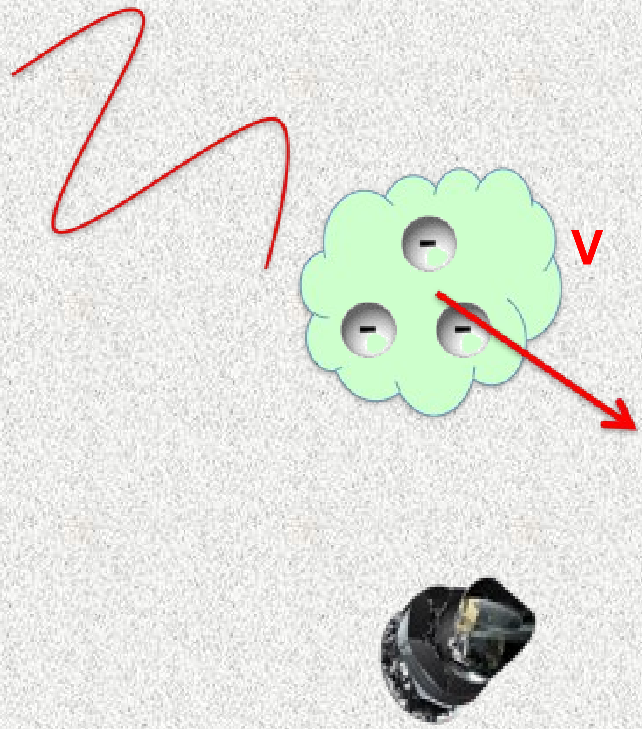
Changing gears …

The kinetic Sunyaev-Zeldovich effect.



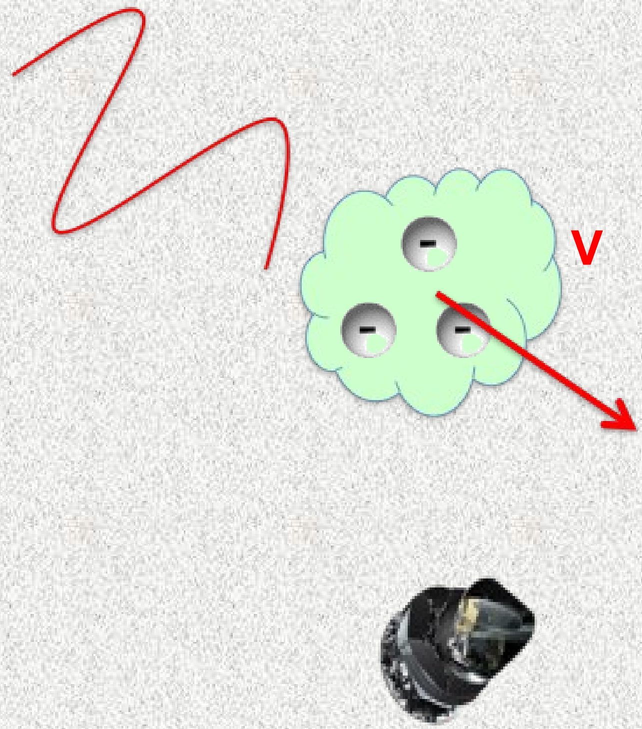
Zeldovich to Sunyaev: ***how could one see an electron cloud in space?***

The kinetic Sunyaev-Zeldovich effect.



But what if the electron cloud **moves with respect to the photon bath**?

The kinetic Sunyaev-Zeldovich effect.



In electron's rest frame:

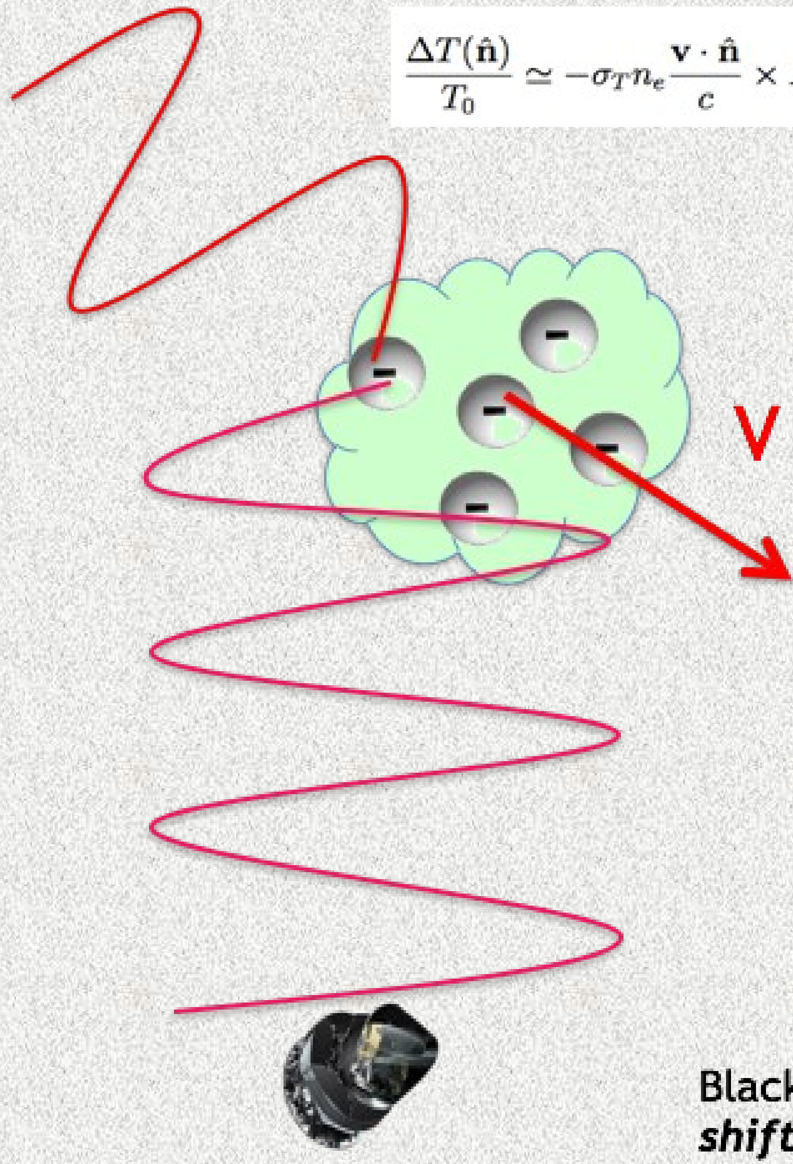
$T(\mathbf{n}) = T_0 (1 + \mathbf{v}.\mathbf{n}/c)$

And the electrons **must mirror** (scatter) what they see!

But what if the electron cloud **moves with respect to the photon bath**?

The kinetic Sunyaev-Zeldovich effect.

$$\frac{\Delta T(\hat{\mathbf{n}})}{T_0} \simeq -\sigma_T n_e \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{\rm cloud} = -\dot{\tau}_T \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{\rm cloud} = -\tau_T \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c}$$



If electrons are **not** too hot, its **Thomson** scattering and there's **NO energy exchange** at the electron's frame …

Black body CMB spectrum is ***shifted but preserved!***

The kinetic Sunyaev-Zeldovich effect.
(The physics behind the effect)

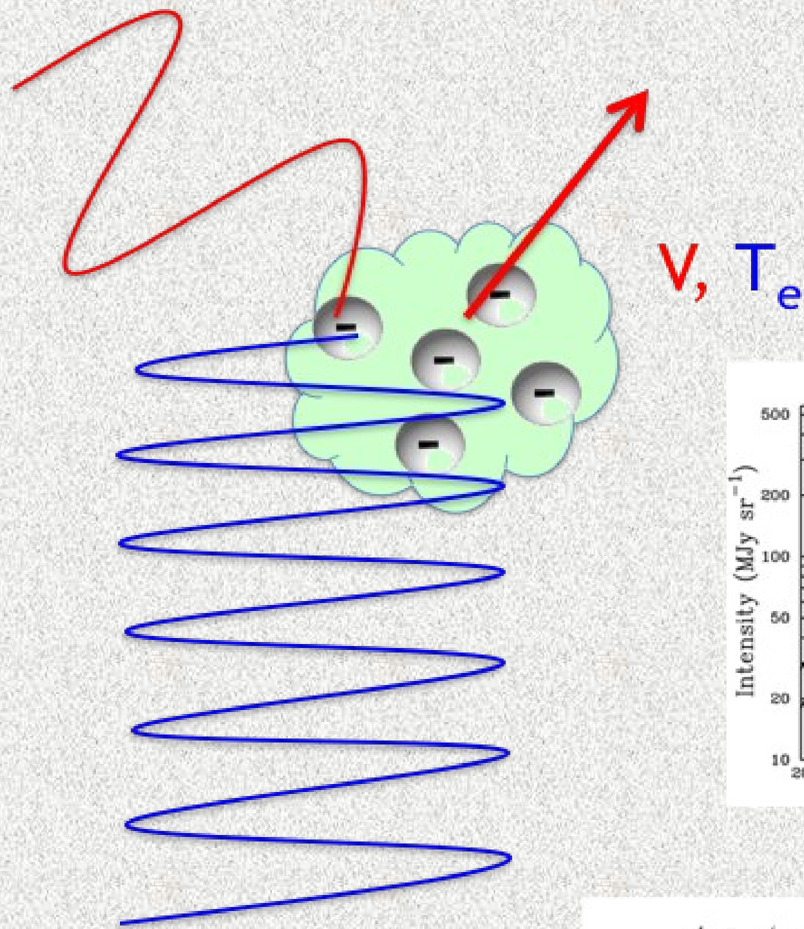
- In a thermalized photon-baryon bath, in the electron's frame, Thomson scattering does not transfer energy but simply changes the direction of CMB photons...
- If the electron cloud is moving with respect to the CMB photon bath, there is however a net flux of momentum that *affects **all** photons in the same way* -> *there is **no** distortion of the (frequency independent) brightness temperature.*

$$\frac{\Delta T(\hat{\mathbf{n}})}{T_0} \simeq -\sigma_T n_e \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{cloud} = -\dot{\tau}_T \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{cloud} = -\tau_T \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c}$$

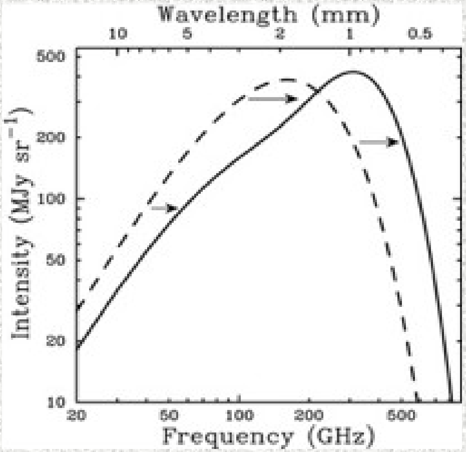
- However, due to its anisotropic nature, ***if*** there is a local **quadrupole** in the CMB intensity distribution, it will generate *linear polarization*

$$\begin{pmatrix} I_{\parallel} \\ I_{\perp} \end{pmatrix} d\Omega(\hat{\mathbf{n}}) = \tau_T \, \frac{3}{8\pi} \begin{pmatrix} \cos^2\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I'_{\parallel} \\ I'_{\perp} \end{pmatrix} d\Omega(\hat{\mathbf{n}}')$$

But if there is a energy gain/loss for the photon, if photon frequencies actually change in the scattering, then we meet the tSZ ...



$\Delta T_{tSZ} \sim k_B T_e / (m_e c^2)$



$$g(x) = \frac{x^4 e^x}{(e^x - 1)^2}\left(x \frac{e^x + 1}{e^x - 1} - 4\right) \approx -2\,x^2 \text{ for } x \ll 1,$$

Summary of the interaction of CMB photons with ionised gas clouds ...

$$\frac{\Delta T_{kSZ}(\hat{\mathbf{n}})}{T_0} \sim n_e \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{cloud}$$

$$\frac{\Delta T_{tSZ}(\hat{\mathbf{n}})}{T_0} \sim n_e T_e \times L_{cloud} \sim p_e \times L_{cloud}$$

$$E(\hat{\mathbf{n}}) \sim n_e Q_2^{CMB}$$

Frequency dependent in $T_{thermodyn}$ units!

Summary of the interaction of CMB photons with ionised gas clouds ...

$$\frac{\Delta T_{kSZ}(\hat{\mathbf{n}})}{T_0} \sim n_e \frac{\mathbf{v}\cdot\hat{\mathbf{n}}}{c} \times L_{cloud}$$

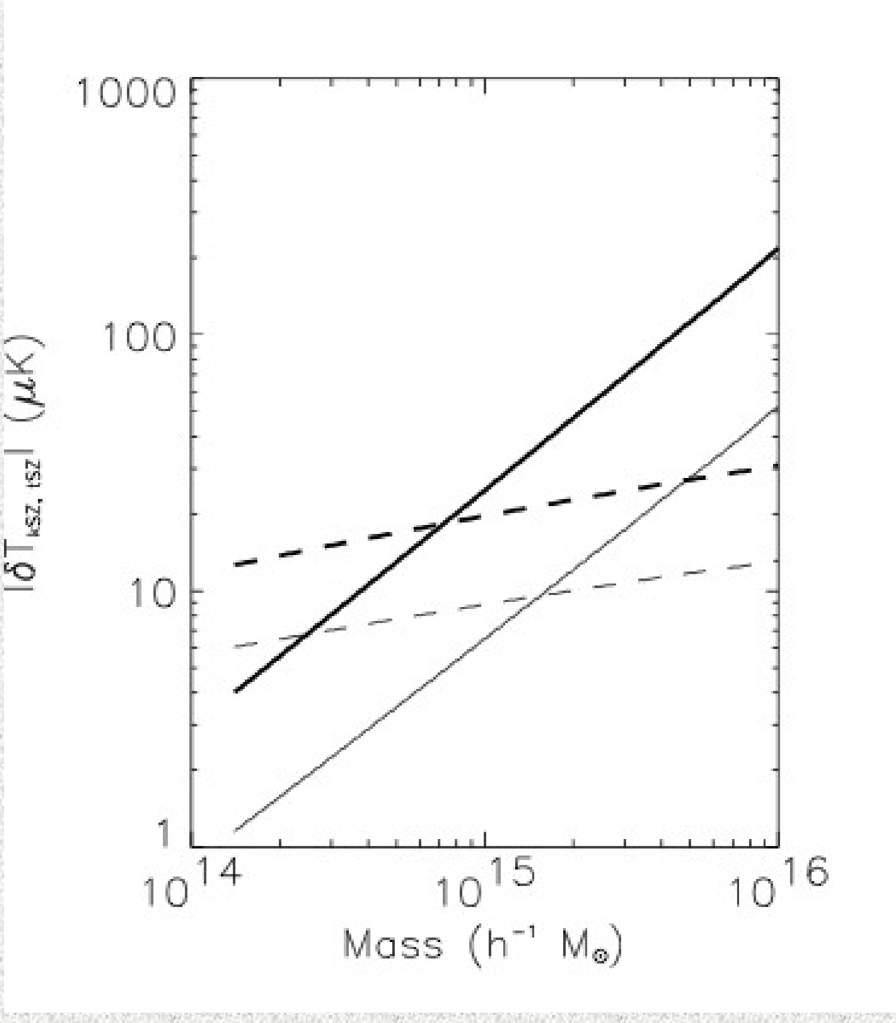
$$\frac{\Delta T_{tSZ}(\hat{\mathbf{n}})}{T_0} \sim n_e T_e \times L_{cloud} \sim p_e \times L_{cloud}$$

$$E(\hat{\mathbf{n}}) \sim n_e Q_2^{CMB}$$

Frequency dependent in $T_{thermodyn}$ units!

The **tSZ** will more easily detectable in **collapsed** structures, whereas the **kSZ** will be detected in **comoving** gas, **regardless** it is collapsed or not.

The tSZ vs the kSZ in halos:



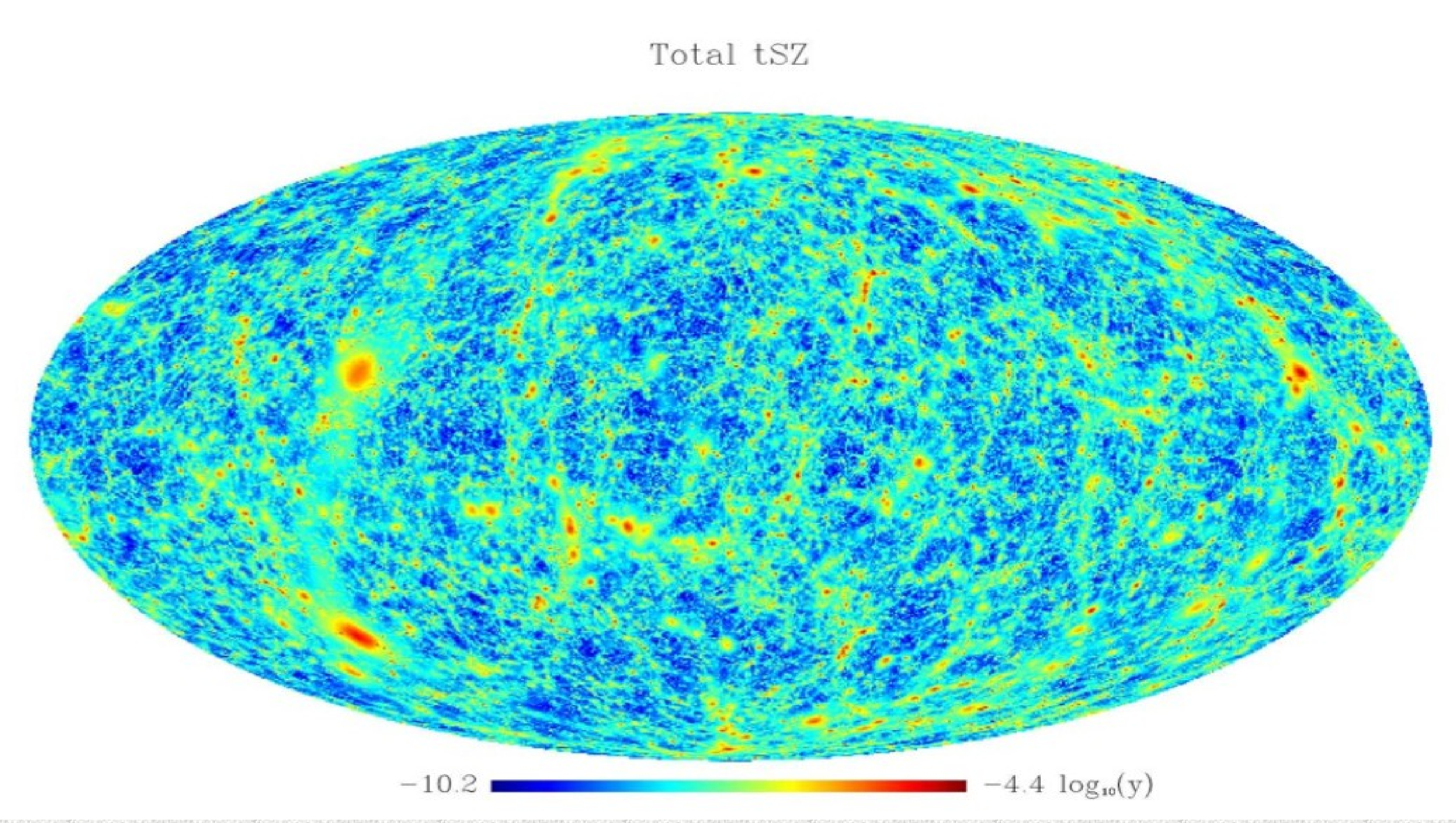
Dashed lines: kSZ
Solid lines: tSZ @ 222 GHz
(two different redshifts shown: z=0,1)

CHM et al, ApJ, 2006

At **low** masses, the **kSZ/tSZ ratio drops**, with the kSZ eventually **dominating** ...

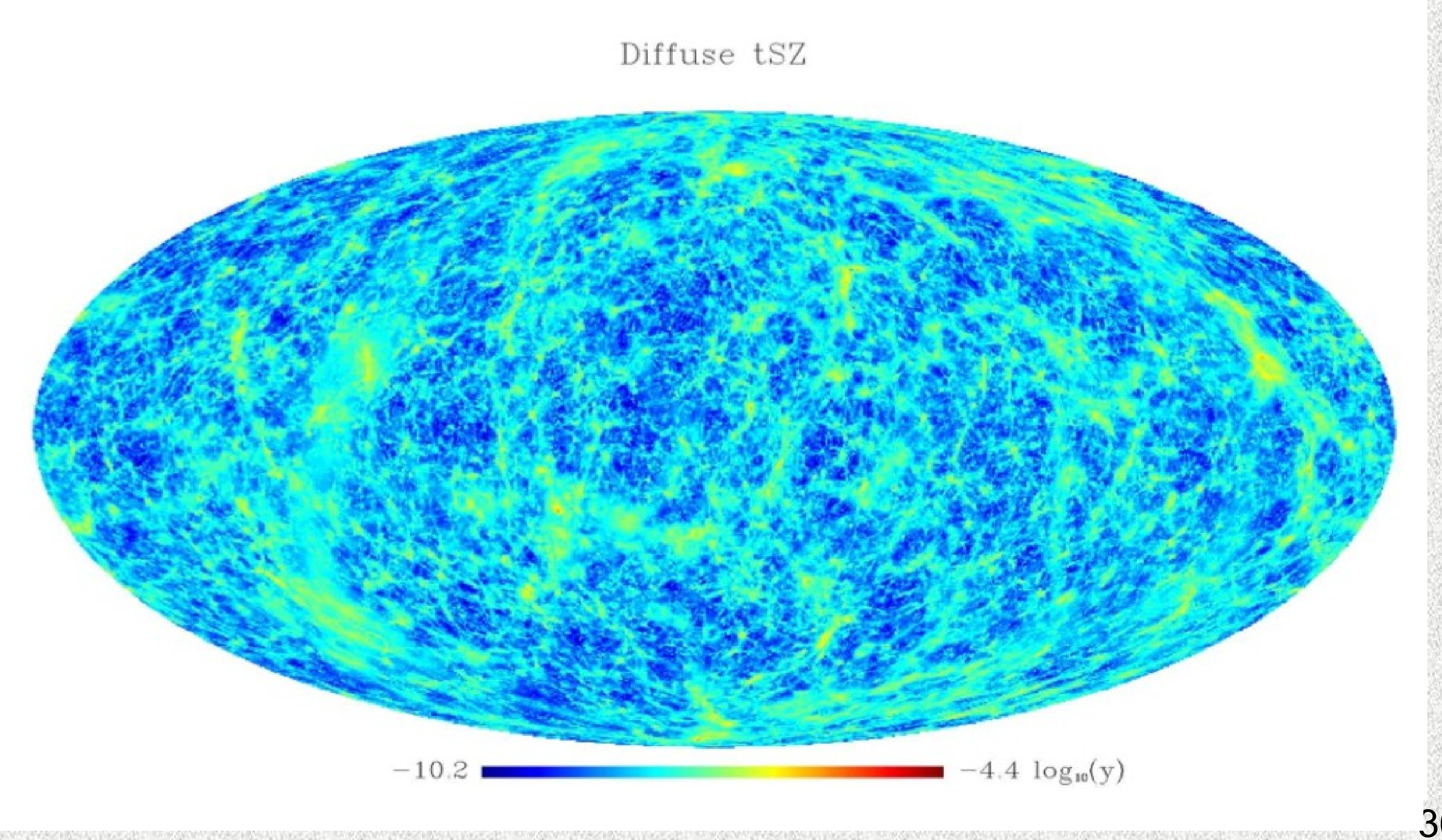
Addressing the *missing baryon* problem with the thermal el Sunyaev-Zeldovich (**tSZ**) and kinetic Sunyaev-Zeldovich (**kSZ**) effects

CHM et al, ApJLetters 2006



Addressing the *missing baryon* problem with the thermal el Sunyaev-Zeldovich (**tSZ**) and kinetic Sunyaev-Zeldovich (**kSZ**) effects

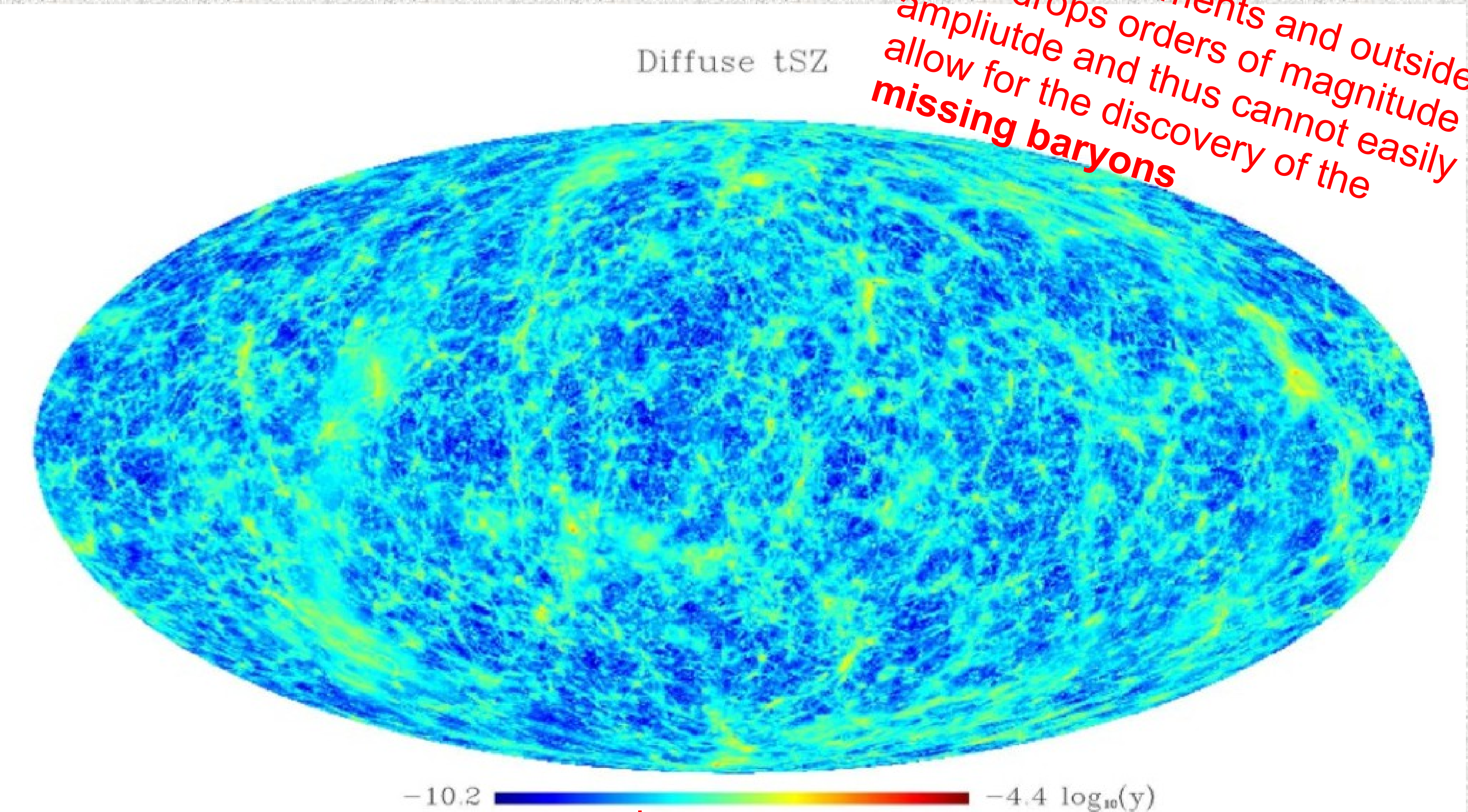
CHM et al, ApJLetters 2006



Addressing the *missing baryon* problem with the thermal el Sunyaev-Zeldovich (**tSZ**) and kinetic Sunyaev-Zeldovich (**kSZ**) effects

CHM et al, ApJLetters 2006

The **tSZ** in filaments and outside halos drops orders of magnitude in ampliutde and thus cannot easily allow for the discovery of the **missing baryons**

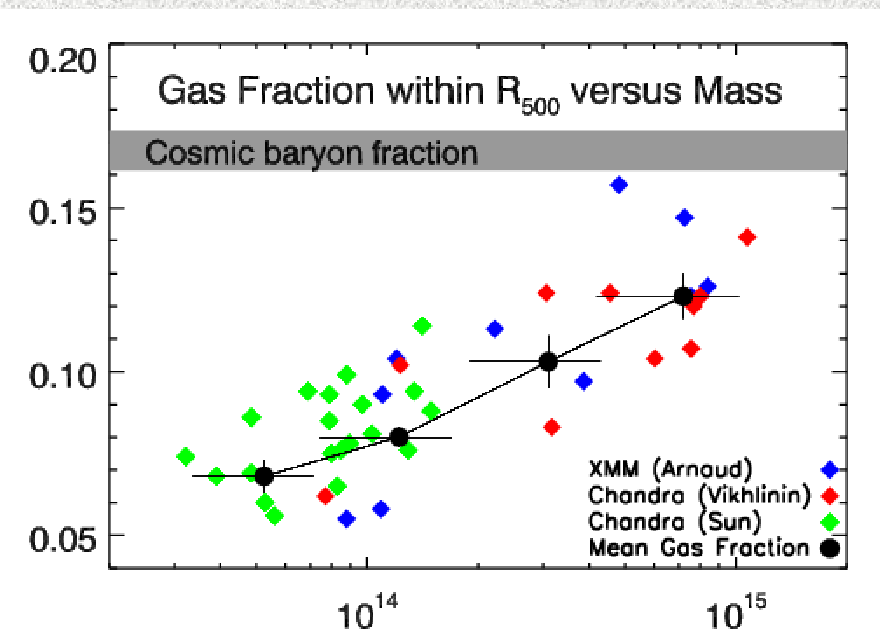


The **kSZ** should be more **effective** in finding those baryons

The problem of the *missing baryons*

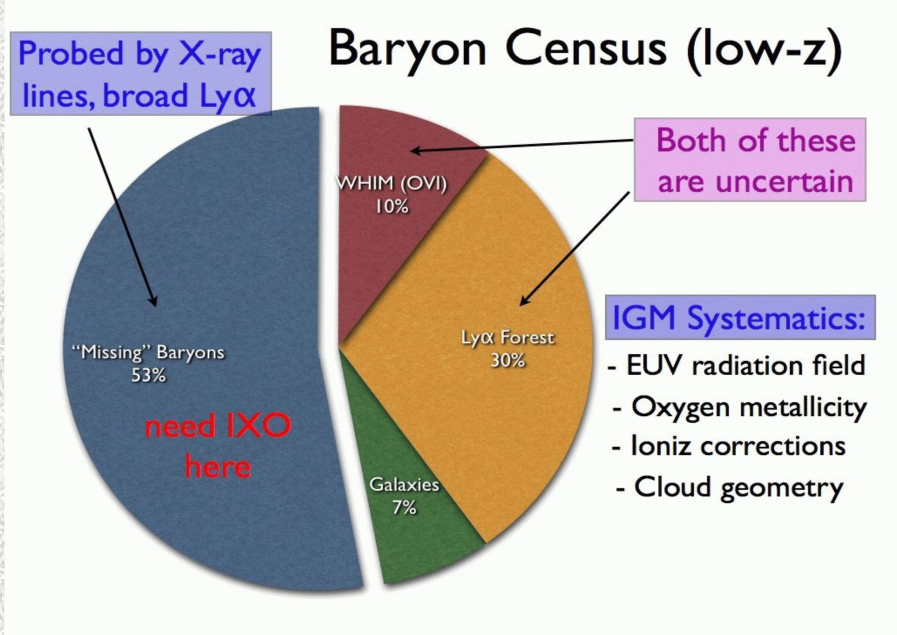
X rays

Rasheed, Bahcall & Bode (2010)



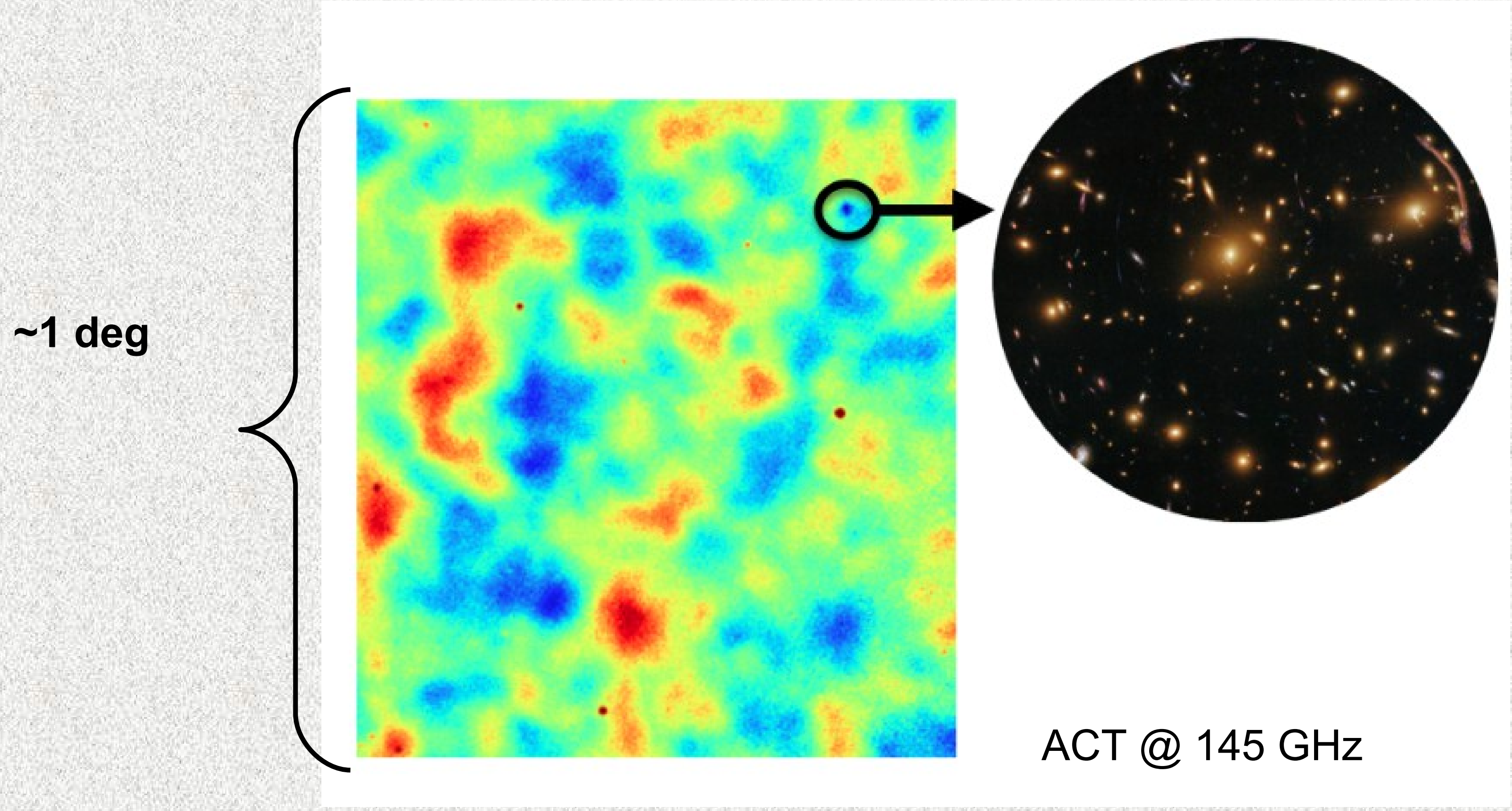
UV spectroscopy

M. Shull (2015)



The kinetic Sunyaev-Zeldovich effect: Observational challenge

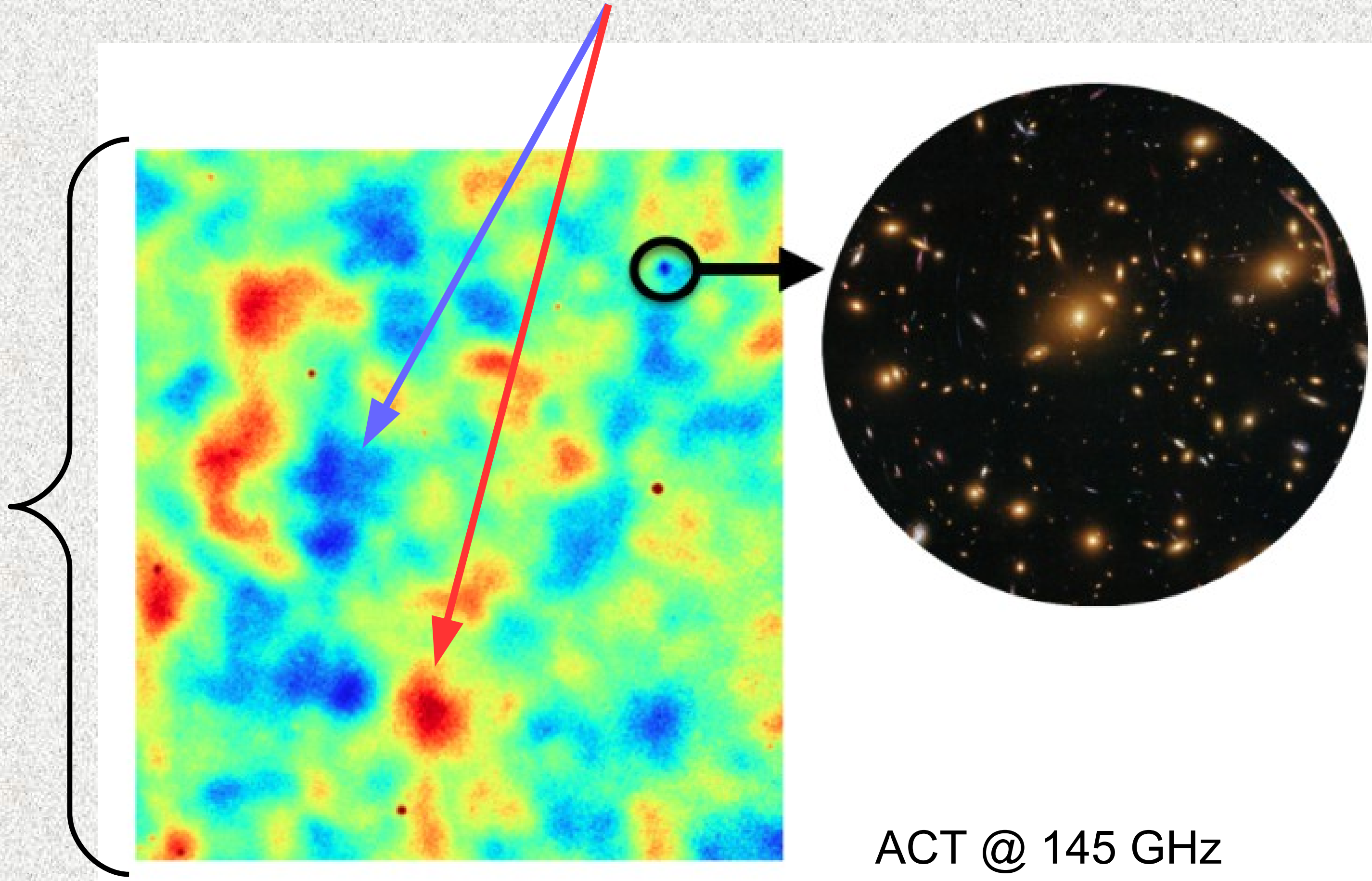
One image is more worth than one thousand words …



The kinetic Sunyaev-Zeldovich effect: Observational challenge

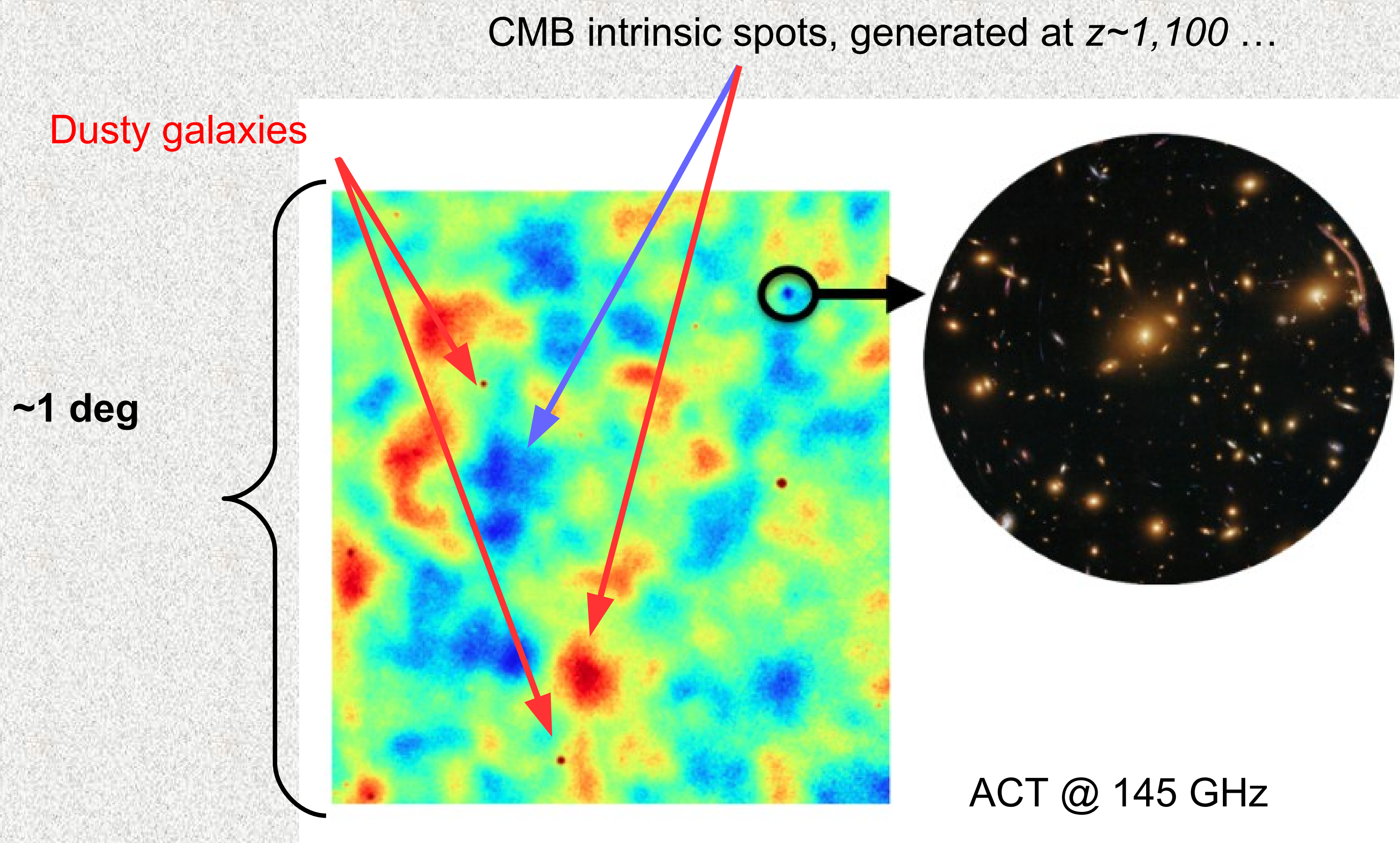
CMB intrinsic spots, generated at *z~1,100* …

~1 deg

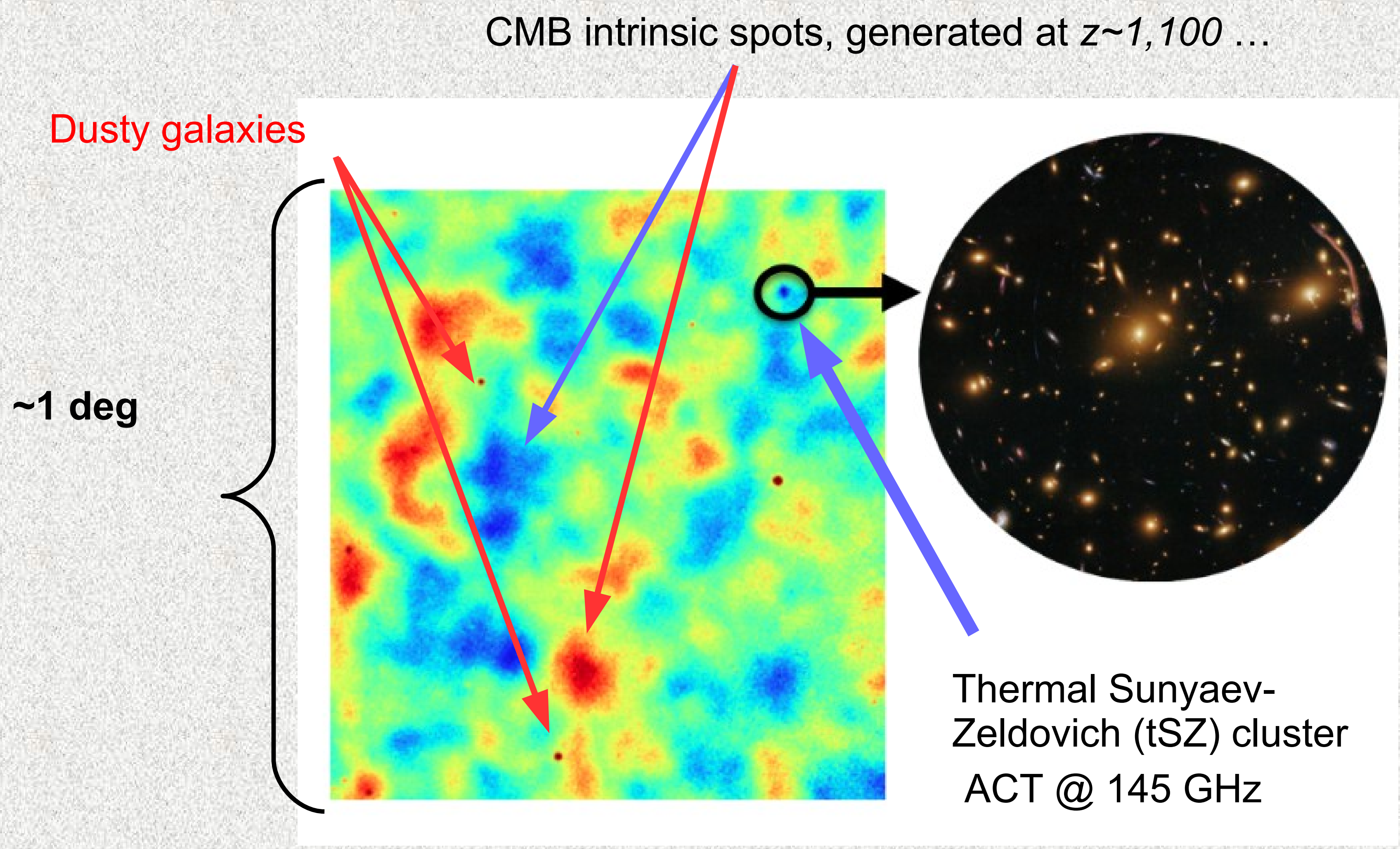


ACT @ 145 GHz

The kinetic Sunyaev-Zeldovich effect: Observational challenge



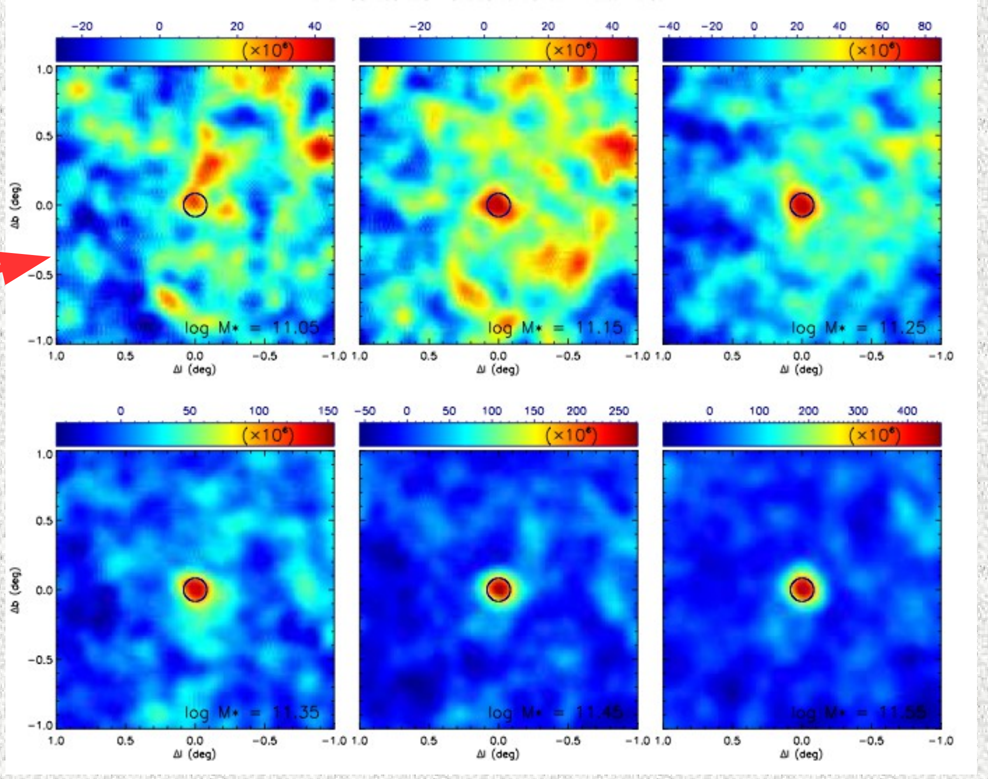
The kinetic Sunyaev-Zeldovich effect: Observational challenge



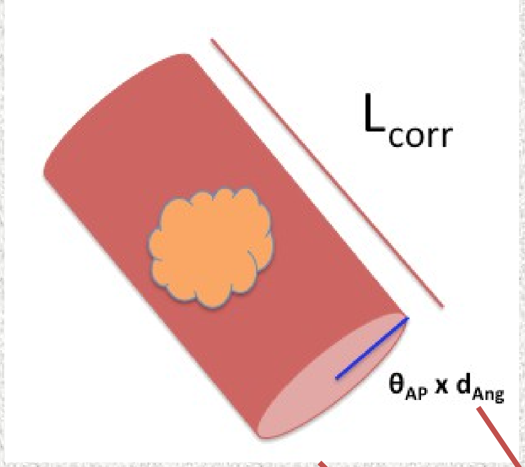
The need to look at the direction of galaxy clusters and groups knowing to host ionized gas …

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

- Luminous Red Galaxies selected from Sloan / BOSS
- Brightest Central Galaxies selected from Sloan
- Galaxy clusters and groups from DES
- LSS probed by WISE galaxies



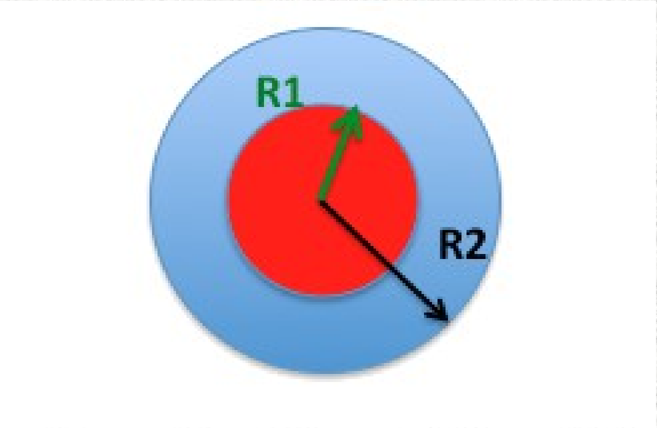
Let's try to count electrons by searching for the kSZ …



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

τ_T = $\int dl\, n_e\, \sigma_T$ ~ number of electrons

We are effectively observing through **cylinders** of depth L_{corr} accounting for the typical **correlation length** of peculiar velocities



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

Simple **Aperture Photometry** (AP) approach

The kinetic Sunyaev-Zeldovich effect.
(implications for homogeneity)

Constraints from kSZ ***non detections!***

kSZ statistics @ 0th order. Mean or average of kSZ temperature (compatible with zero)

Using *Planck* data combined with the Meta Catalogue of X-ray detected Clusters of galaxies (MCXC), we address the study of peculiar motions by searching for evidence of the kinetic Sunyaev-Zeldovich effect (kSZ). By implementing various filters designed to extract the kSZ generated at the positions of the clusters, we obtain consistent constraints on the radial peculiar velocity average, root mean square (rms), and local bulk flow amplitude at different depths. For the whole cluster sample of average redshift 0.18, the measured average radial peculiar velocity with respect to the cosmic microwave background (CMB) radiation at that redshift, i.e., the kSZ monopole, amounts to 72 ± 60 km s^{-1}. This constitutes less than 1 % of the relative Hubble velocity of the cluster sample with respect to our local CMB frame. While the linear ΛCDM prediction for the typical cluster radial velocity rms at $z = 0.15$ is close to 230 km s^{-1}, the upper limit imposed by *Planck* data on the cluster subsample corresponds to 800 km s^{-1} at 95 % confidence level, i.e., about three times higher. *Planck* data also set strong constraints on the local bulk flow in volumes centred on the Local Group. There is no detection of bulk flow as measured in any comoving sphere extending to the maximum redshift covered by the cluster sample. A blind search for bulk flows in this sample has an upper limit of 254 km s^{-1} (95 % confidence level) dominated by CMB confusion and instrumental noise, indicating that the Universe is largely homogeneous on Gpc scales. In this context, in conjunction with supernova observations, *Planck* is able to rule out a large class of inhomogeneous void models as alternatives to dark energy or modified gravity. The *Planck* constraints on peculiar velocities and bulk flows are thus consistent with the ΛCDM scenario.

Key words. cosmology: observations – cosmic microwave background – large-scale structure of the Universe – galaxies: clusters: general

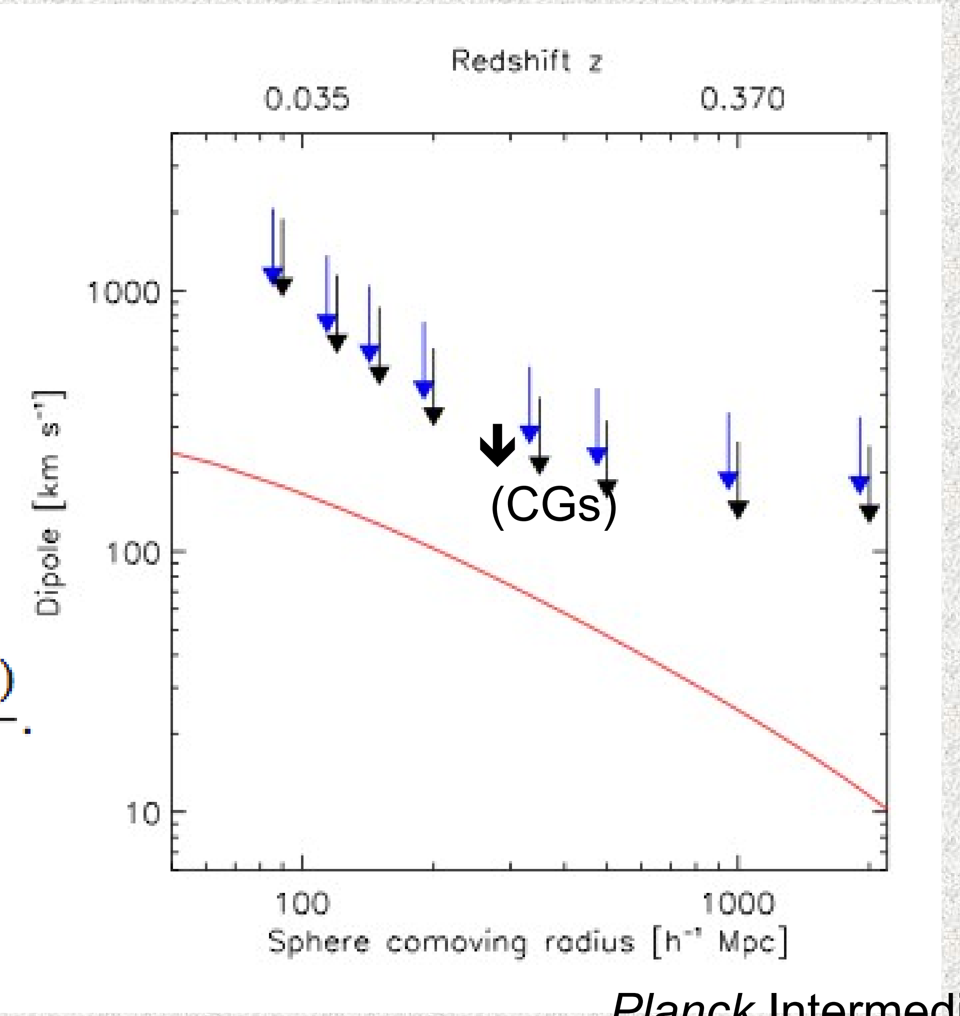
Planck Intermediate Results. XIII

Rashid Sunyaev to Sarah Church:
“*Sarah, look yourself, you have clusters at z~1 and yet they are at rest with the CMB!!*”

kSZ statistics @ 1st order. Dipole of kSZ temperature field (compatible with zero)

Planck Intermediate Results. XIII. Looking at the direction of ~1,500 X-ray galaxy clusters.

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

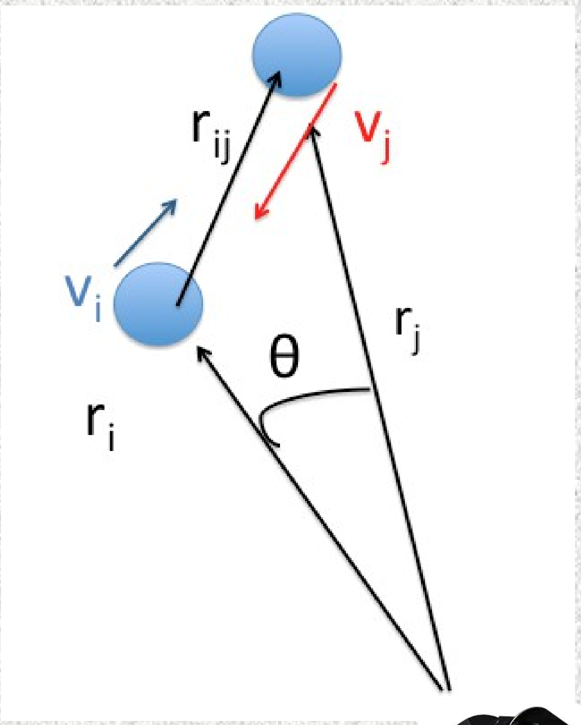


Strongest evidence for the Copernican Principle!

Planck Intermediate Results. XIII

The kinetic Sunyaev-Zeldovich effect.
(observational approaches)

1st statistical approach: the kSZ **pairwise momentum**



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

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

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

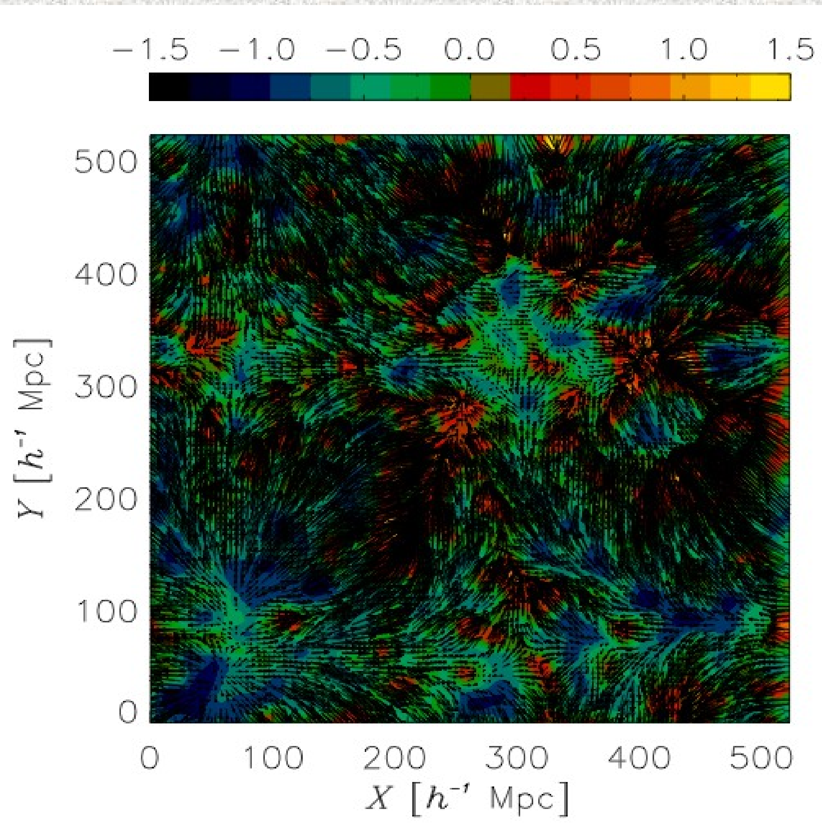
Groth et al. 1981, Juszkiewicz et al. 1998, Ferreira et al. 1999, Hand et al. 2012

The kinetic Sunyaev-Zeldovich effect. (observational approaches)

2nd statistical approach: the kSZ x **velocity reconstruction**

Dedeo et al.2005, Ho et al.2010

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



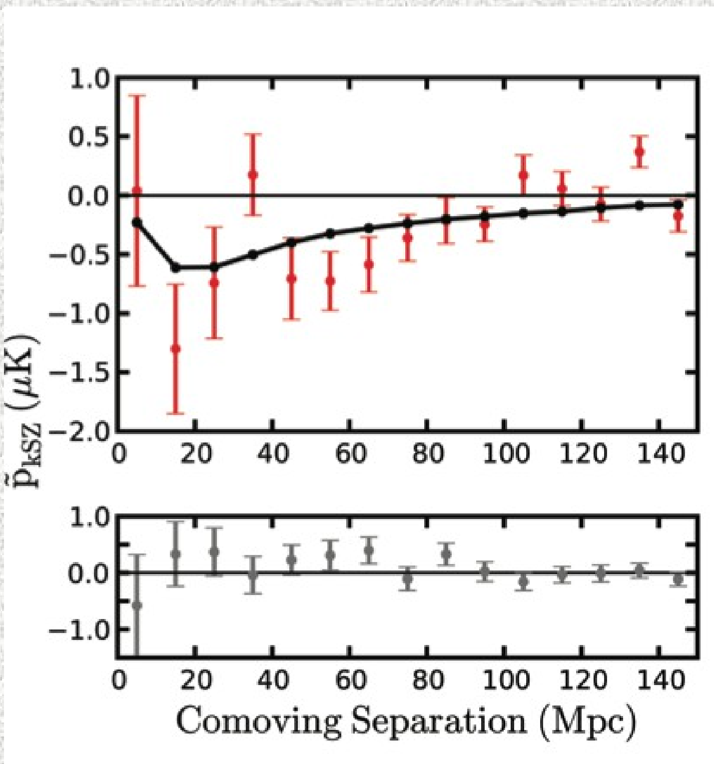
We invert the density field into the peculiar field on large scales (via the continuity equation above), and cross correlate kSZ temperature estimates with the "expected" peculiar radial velocity:

$$\langle \delta T_{kSZ,\, i} \;.\; (\mathbf{v}_j . \mathbf{n}_j)/\sigma \rangle \; [r]$$

Planck Intermediate Results XXXVII (2015)

The kinetic Sunyaev-Zeldovich effect: Observational status

ACT's first detection of the kSZ pairwise momentum:



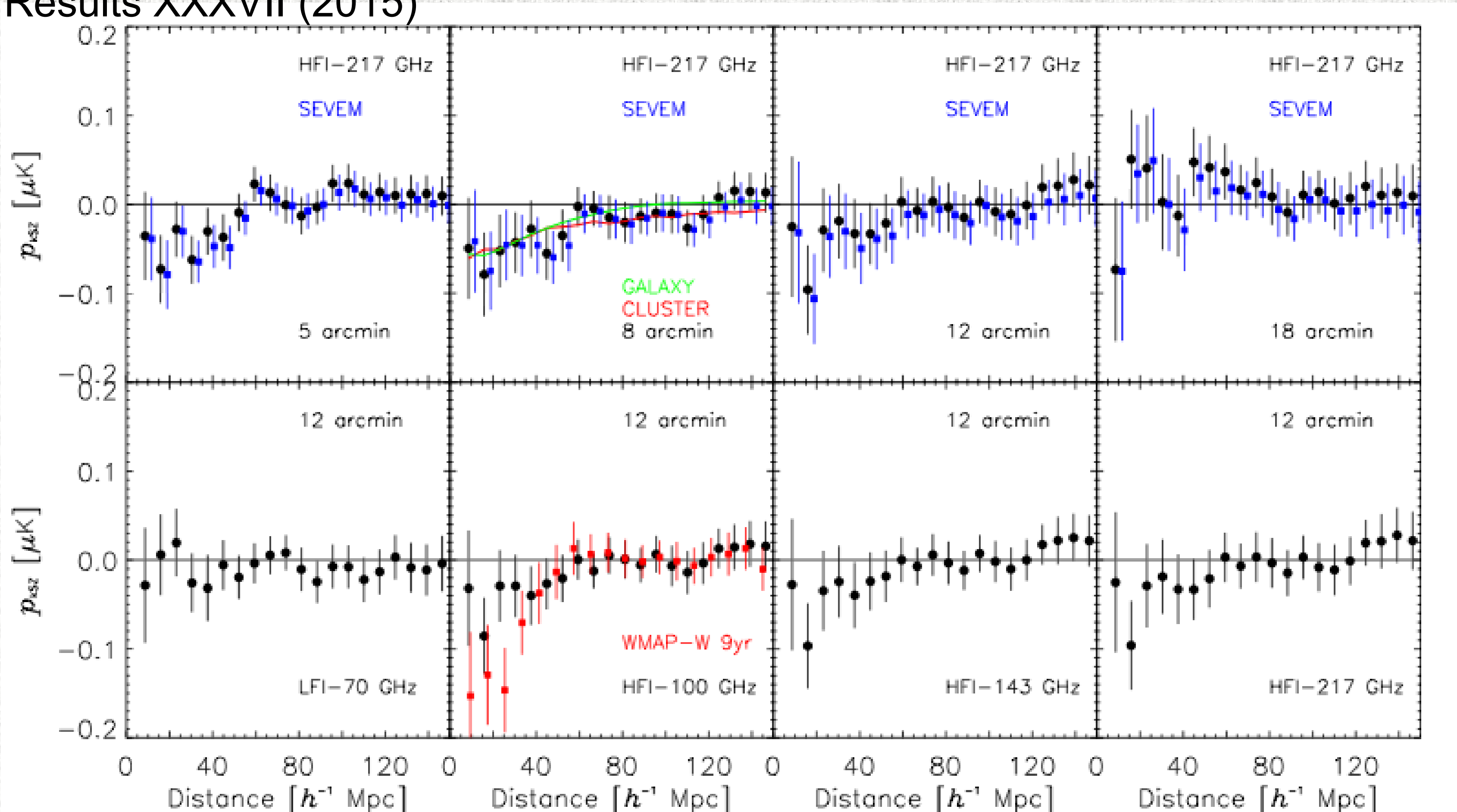
Hand et al. 2012

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

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 ~5e13 M_sun LRGs identified by BOSS, of typical mass . ACT **has FWHM~1.3** arcmin, where *Planck's* best angular resolution is close to **FHWM=5 arcmin.**

The kinetic Sunyaev-Zeldovich effect: Observational status

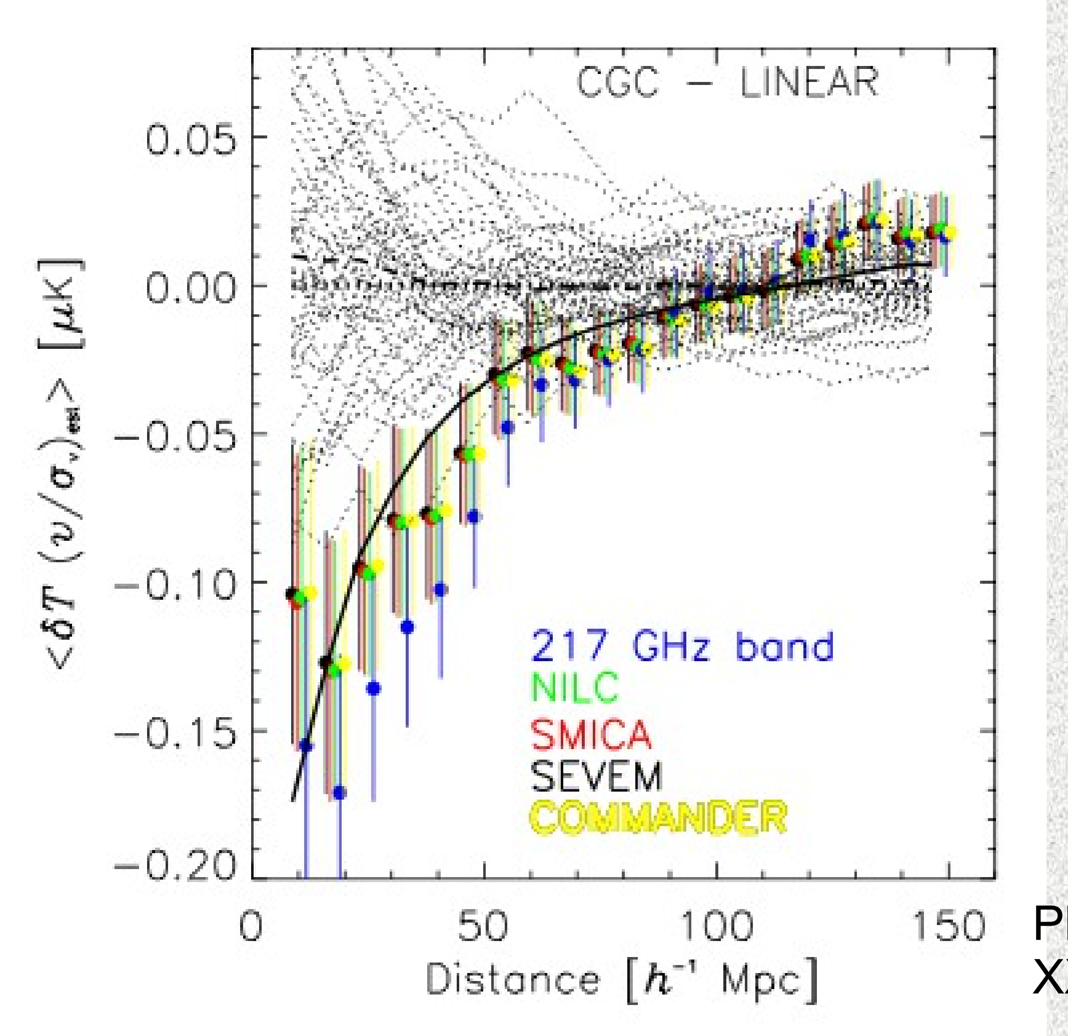
This was followed by *Planck* on Sloan local BCG sample in Planck Intermediate Results XXXVII (2015)



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**

The kinetic Sunyaev-Zeldovich effect: Observational status

First detection of the kSZ – velocity cross-correlation with Sloan BCG sample :



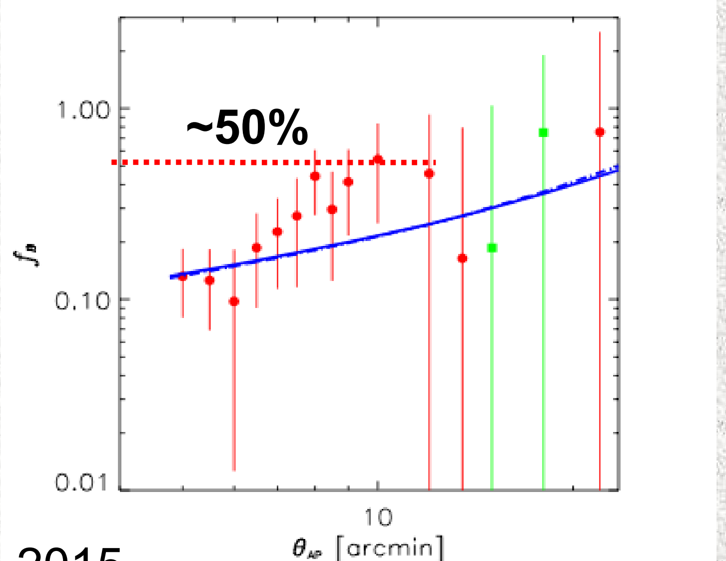
$<\delta T_{kSZ, i} \; . \; (\mathbf{v}_j . \mathbf{n}_j)/\sigma>$ [r]: correlation between kSZ temperature anisotropies and recovered velocities (with RMS=1)

S/N up to 3.8

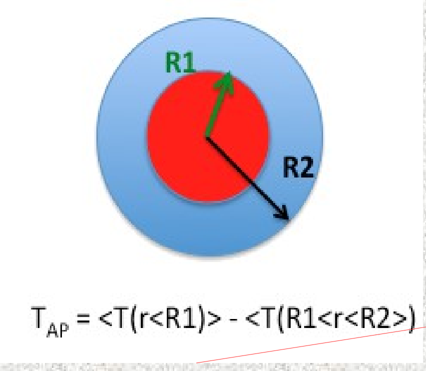
Planck Intermediate Results XXXVII (2015)

The kinetic Sunyaev-Zeldovich effect:

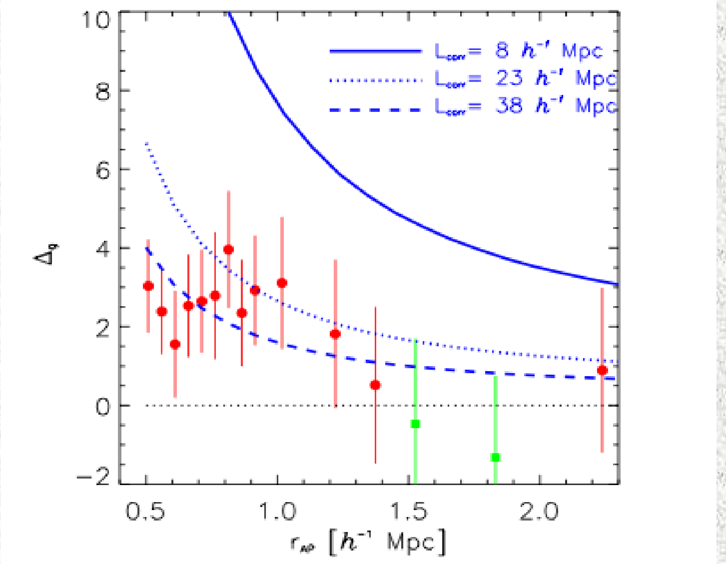
Finding the missing baryons



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



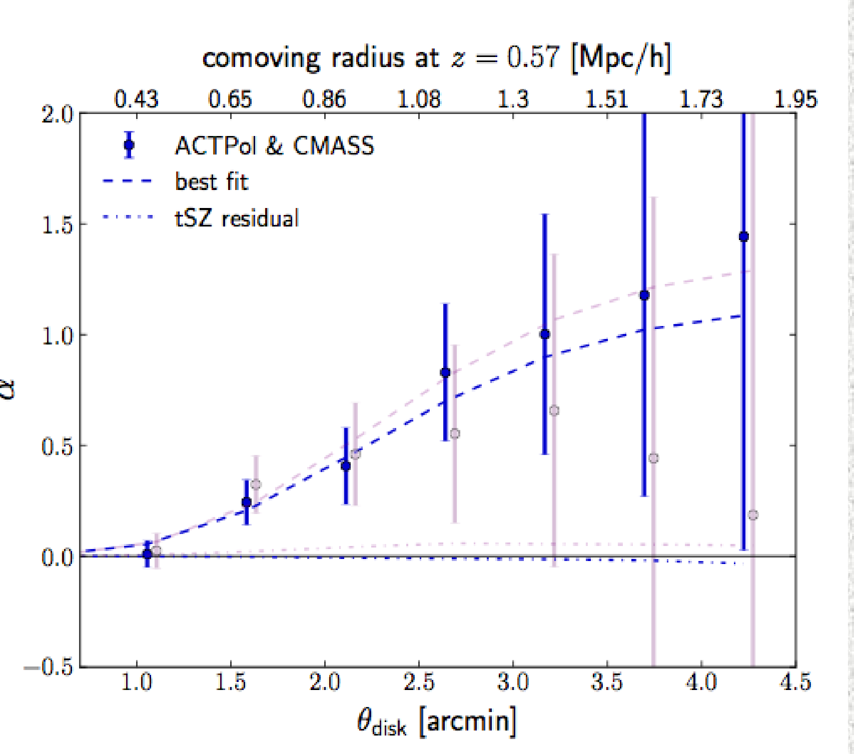
CHM et al, PRL, 2015



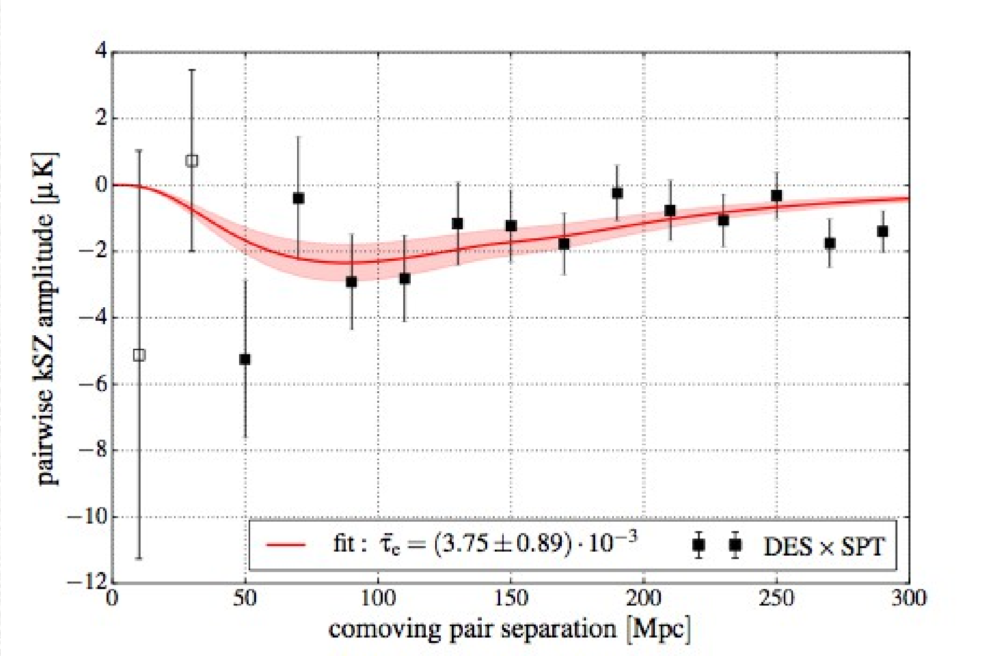
Average gas overdensity within cylinder of a given depth Lcorr :

The kinetic Sunyaev-Zeldovich effect:

Latest results from high-resolution experiments like the *South Pole Telescope (SPT)* and the *Atacama Cosmology Telescope Pol (ACTPol)*



Schaan et al. 2016, for the ACTPol collab: α = <δTobs / δTmodel >

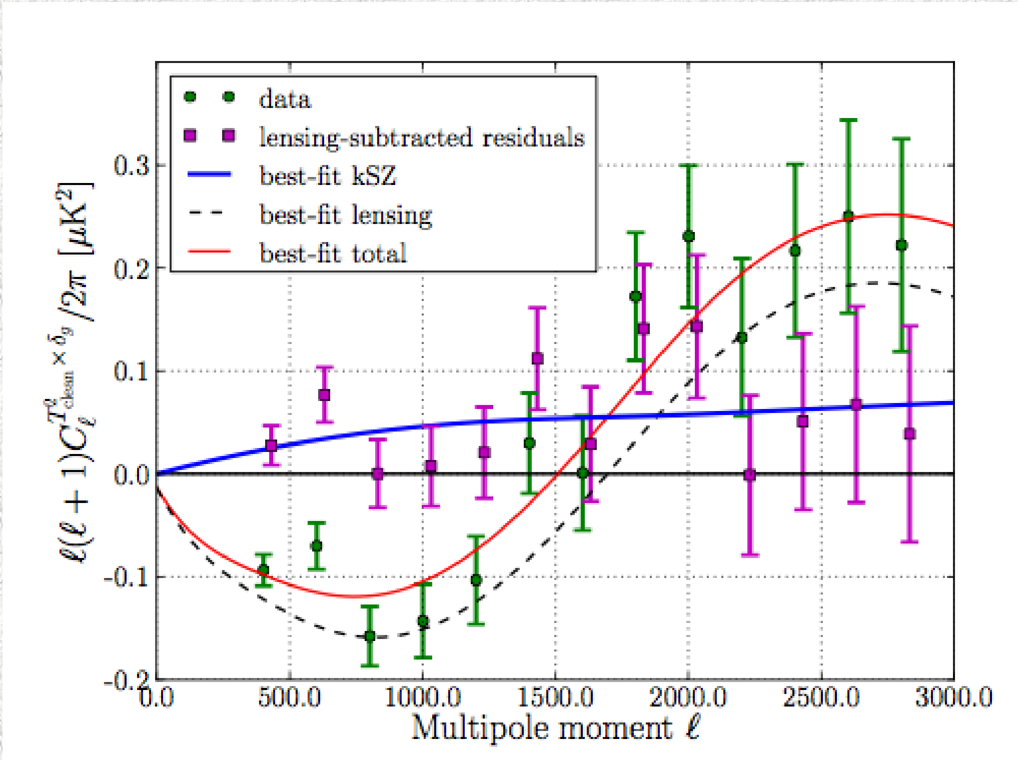


Soergel et al., 2016, for the SPT collab.

Highest S/N achieved so far (~ 4 – 5)

The kinetic Sunyaev-Zeldovich effect.
(Further developments)

Hill et al. 2016



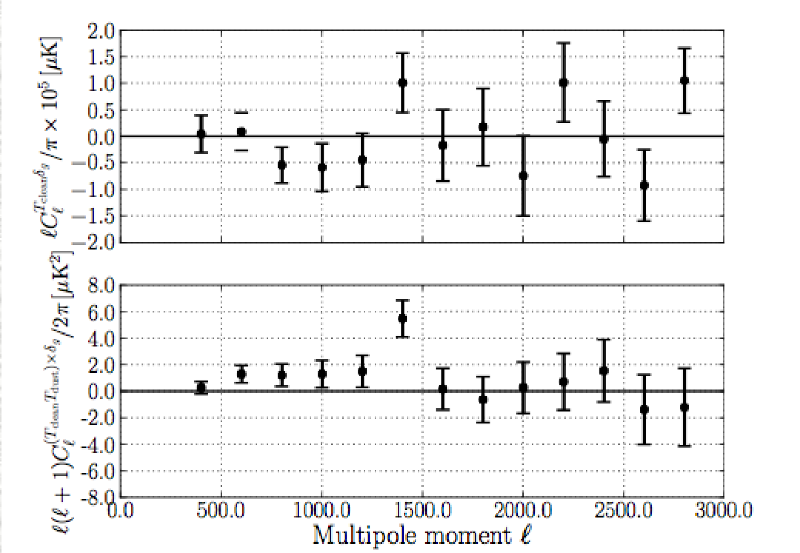
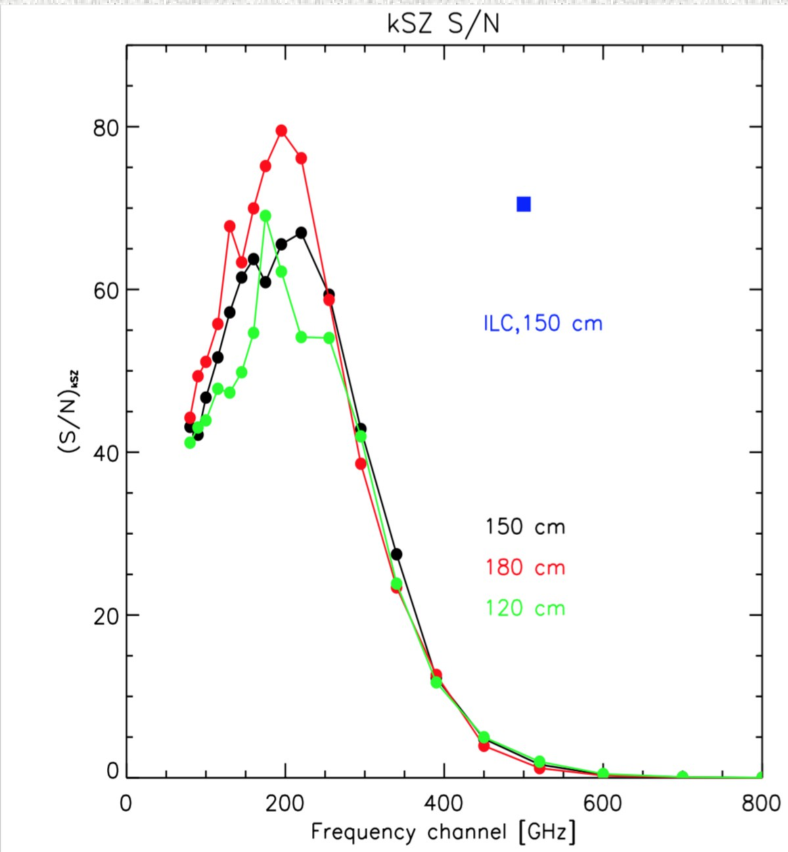


FIG. 2: Dust null tests. *Top*: Cross-correlation of $T_{\rm clean}$ with *WISE* galaxies. This verifies that any mean emission (e.g., dust or tSZ) of the galaxies is removed in $T_{\rm clean}$. *Bottom*: Cross-correlation of $(T_{\rm clean}T_{\rm dust})$ with *WISE* galaxies. This verifies that any *WISE*-galaxy-correlated dust emission (including fluctuations) in $T_{\rm clean}$ is sufficiently removed. Rescaling $T_{\rm dust}$ from 545 GHz to 100–217 GHz (a factor of $\approx$ 400–500) yields a dust contribution to the data points in Fig. 1 of $\lesssim 0.003\,\mu{\rm K}^2$, well below the statistical errors.

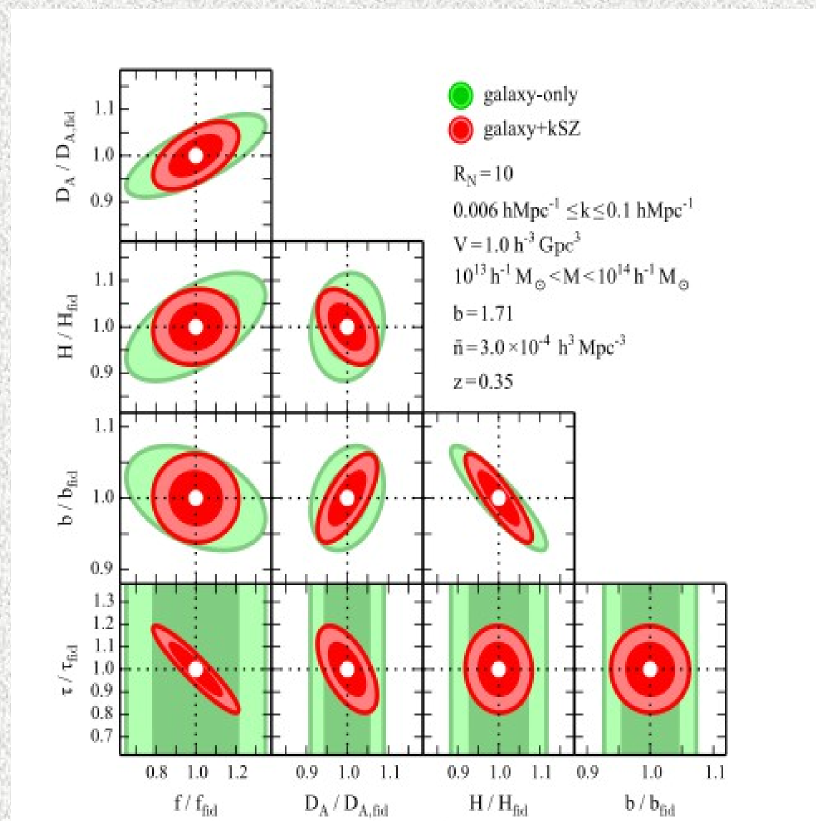
$<(\delta T_{kSZ})^2\ \delta_{gal}>$: it computes the correlation of the ***squared*** CMB temperature field with the galaxy density contrast. It is however contaminated by CMB ***lensing …. They claim to have detected ALL baryons with this approach!***

The kinetic Sunyaev-Zeldovich effect. (Future forecasts)

KSZ forecasts for the CORE mission:



Sugiyama et al. 2016



Astro.ph/170310456

The kinetic Sunyaev-Zeldovich effect. Summary.

- The kSZ is caused by the peculiar motion of free electrons wrt the CMB, and is thus sensitive to the **projected peculiar momentum**

- It can also be used to probe l**arge scale peculiar velocity fields**, and this can set constraints on **gravity** on those scales. This provides the **strongest constraints on the homogeneity in the universe**

- It can be used to **probe baryons** at any redshift of the universe. It has provided very significant progress (if not solved completely) the problem of the **missing baryons**

- It will be highly **complementary** to upcoming LSS surveys, considerably **reducing** the uncertainty in **cosmological parameter**s like the Thomson optical depth towards the last scattering surface, or the growth function f(z)=dln(D)/dln(a), and even the Hubble function and D_{Ang}