Synergy with Planck on EoR: Cross correlating the Cosmological 21cm Signal with CMB

Collaboration LOFAR-Planck

Nabila Aghanim

M. Douspis, V. Jellic, L. Koopmans, M. Langer, G. Mellema, H. Tashiro, R. Thomas, S. Zaroubi

Reionisation :

When did reionisation start?
How did reionisation proceed (sources, duration)?

Two observational constraints

Gunn-Peterson effect :

absorption of the $\mathrm{Ly}-\alpha$ from the high redshift quasars

Neutral hydrogen fraction $\bar{x}_H = 1 - 4\%$ at $z = 6$ (Fan et al, 2006)

CMB anisotropies :

Thomson scattering of CMB photons by electrons during reionisation

Optical depth $\tau = 0.087 \pm 0.017 \longrightarrow z_{\rm re} \sim 11$ (WMAP 5)

New constraints

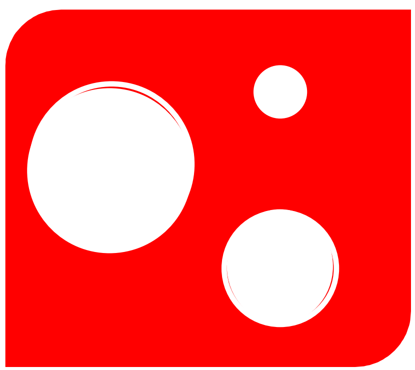
Redshifted 21 cm line fluctuations (~150-350 MHz)

Introduction: The basic idea

CMB photons scatter off ionised bubbles produced during the EoR

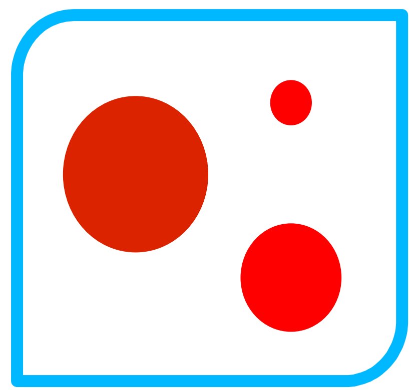
⇒ secondary CMB anisotropies thermal SZ effect, **kinetic SZ effect** & imprint on polarisation

kSZ – EoR map "should" anti-correlate



EoR map

$\delta T_{EoR} \sim n_H$



KSZ map

$(\delta T/T)_{kSZ} \sim n_e$

$n_e \cong 1 - n_H$

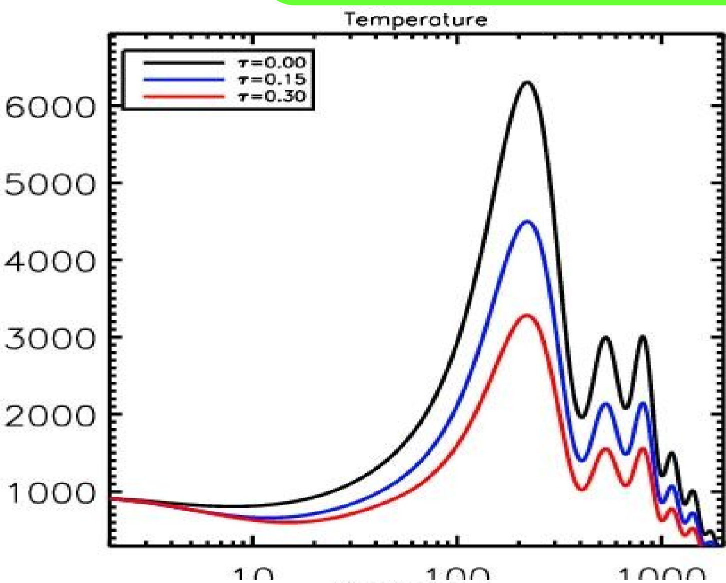
anti-correlation

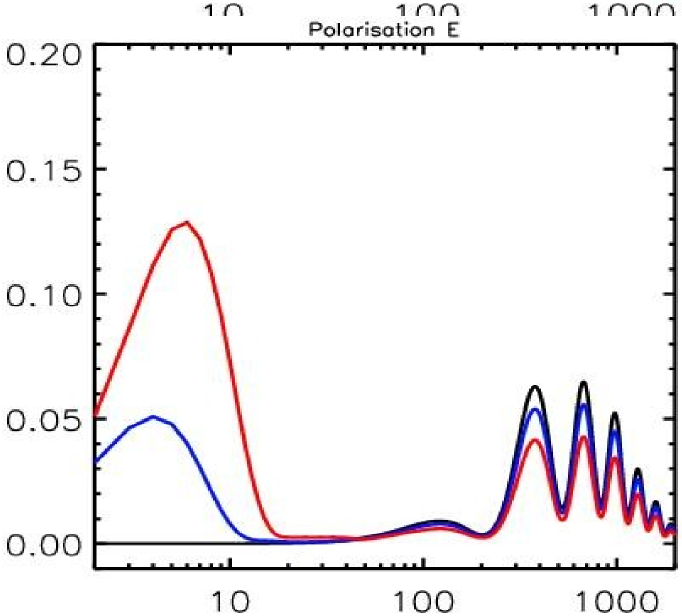
CMB-EoR X-correlation should suffer less from the foregrounds and systematics as in the case of autocorrelation studies

21-cm experiments (e.g. 21CMA, LOFAR, MWA & SKA) and CMB (Planck)

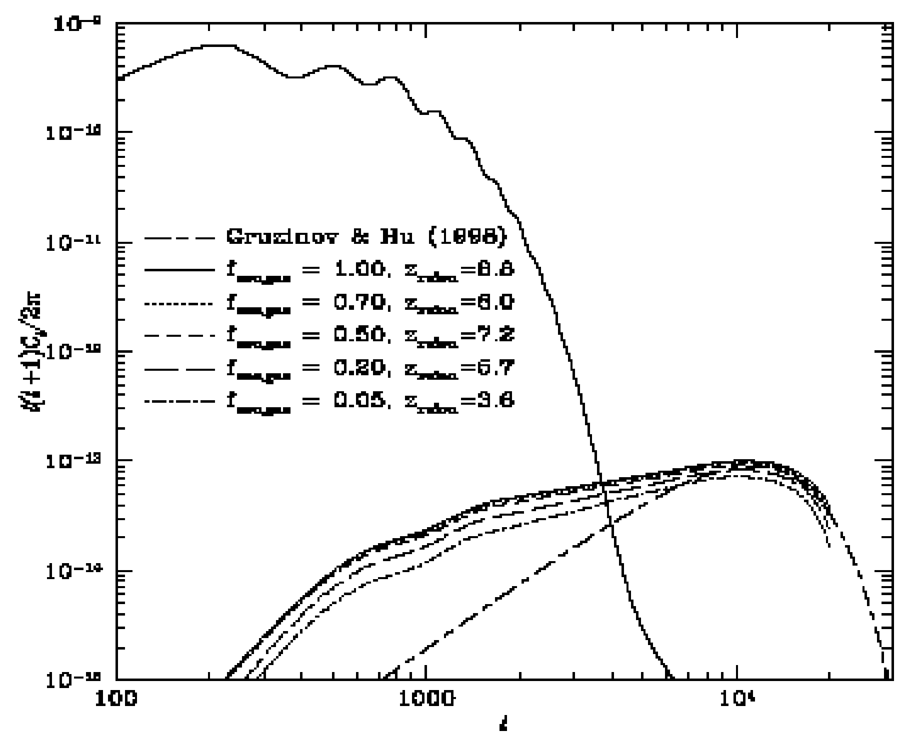
Reionisation effects on CMB

$$\left(\frac{\delta T}{T}\right)_{\mathrm{kSZ}} = -\sigma_{\mathrm{T}} \bar{n}_{\mathrm{H}(0)} \int \frac{(1+z)^2}{H} e^{-\tau} \bar{\chi}_e \cdot (1 + \delta + \delta_{\chi_e} + \delta\delta_{\chi_e}) v_r \mathrm{d}z$$





Secondary anisotropies from KSZ



21 cm transitions of HI { Absorb 21 cm line from CMB $T_{cmb} > T_g$

Emit 21 cm line to CMB $T_g > T_{cmb}$

Produce fluctuations of CMB brightness temperature

$$T_{21}(\hat{\boldsymbol{n}};\nu) = [1 - \bar{x}_e(1+\delta_x)](1+\delta_b)T_0$$

$$T_0 = 23\left(\frac{\Omega_b h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z_{obs}}{10}\right)\right]^{1/2} \mathrm{mK}.$$

Cross-correlation with CMB (polarisation and temperature):
theoretical approach (power spectra) + **simulations**

$$C_\ell^{E-21}(z_{obs}) = \langle\, a_{\ell m}^{E} \;\; a_{\ell m}^{21}(z_{obs})\,\rangle$$

$$C_l^{21-D}(z) = \langle a_{lm}^{21}(z) a_{lm}^{D*} \rangle$$

Formalism of X-correlation with CMB

Tashiro et al. 2008 et 2009

$$C_\ell^{E-21}(z_{\rm obs}) = -\frac{3}{\pi}T_0\sqrt{\frac{(\ell+2)!}{(\ell-2)!}}\int dk \int d\eta k^2 \dot{\tau} e^{-\tau} D_E(k,\eta)$$
$$\times \left[\frac{4}{3}(1-\bar{x}_e)P_{\Phi\delta_b} - \bar{x}_e P_{\Phi\delta_x}\right] \frac{j_\ell(k(\eta_0-\eta_{\rm obs}))j_\ell(k(\eta_0-\eta))}{(k(\eta_0-\eta))^2}$$

$$l^2 C_l^{21-D}(z) \approx -T_{\rm cmb}T_0(z)D(z)\left[\frac{4}{3}\overline{x}_H(z)P_{\Phi\delta_b}\left(\frac{l}{r(z)}\right) - \overline{x}_e(z)P_{\Phi\delta_x}\left(\frac{l}{r(z)}\right)\right]\frac{\partial}{\partial\eta}(\dot{D}\dot{\tau}e^{-\tau})$$

$P_{\Phi\delta_b}$: cosmological model ($h, \Omega_M, \Omega_B, \ldots$)

$P_{\Phi\delta_x}$: reionisation model

Toy model of reionisation:

$$\bar{x}_{\rm H}(z) = \frac{1}{1+\exp[-(z-z_{\rm re})/\Delta z]}$$

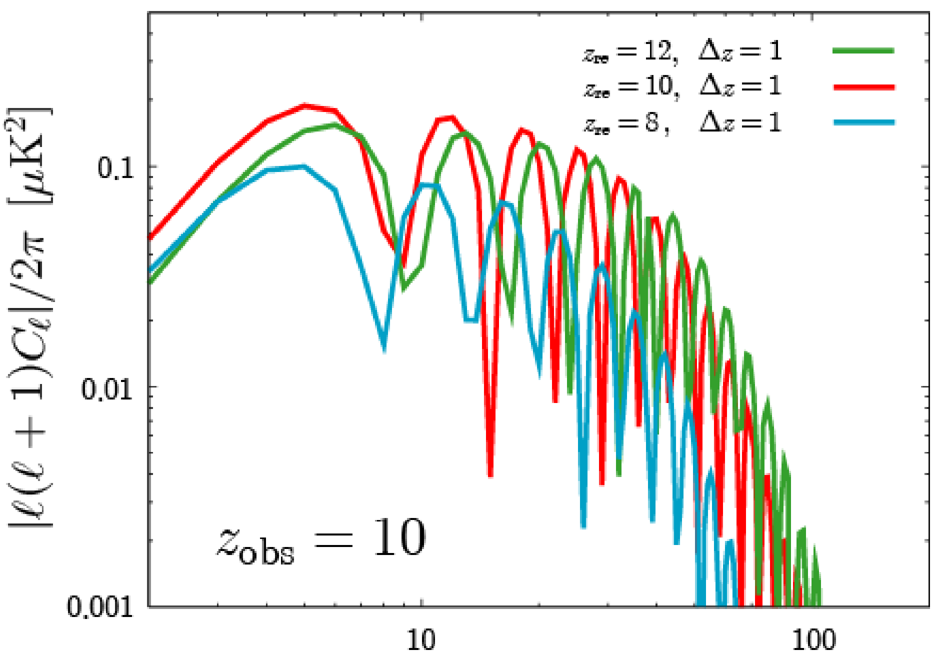
z_{re} : Reionisation epoch

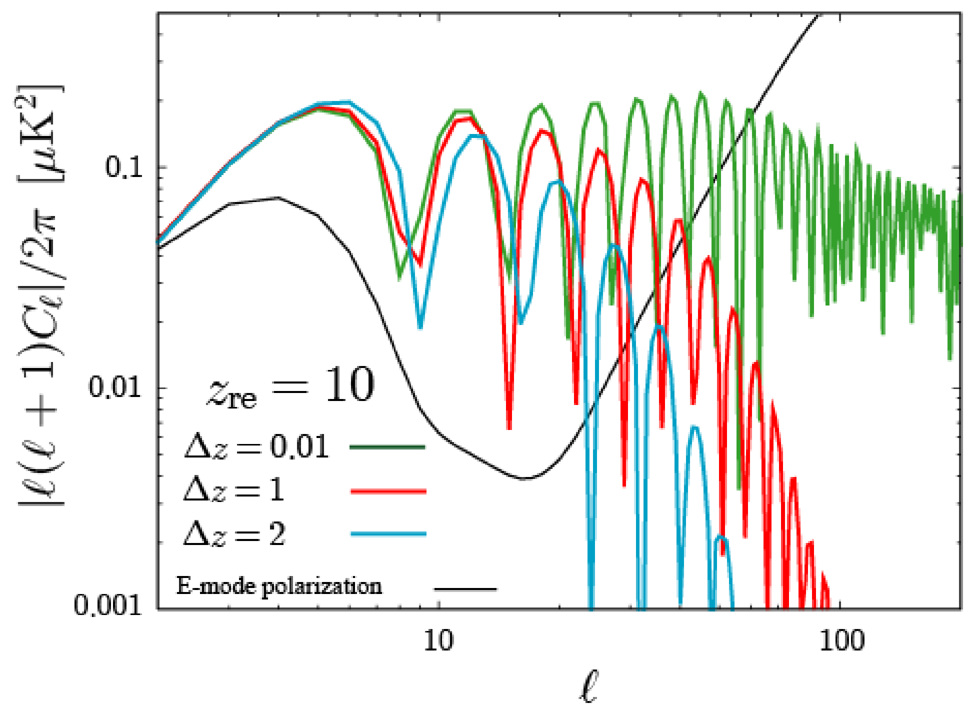
Δz : Reionisation duration

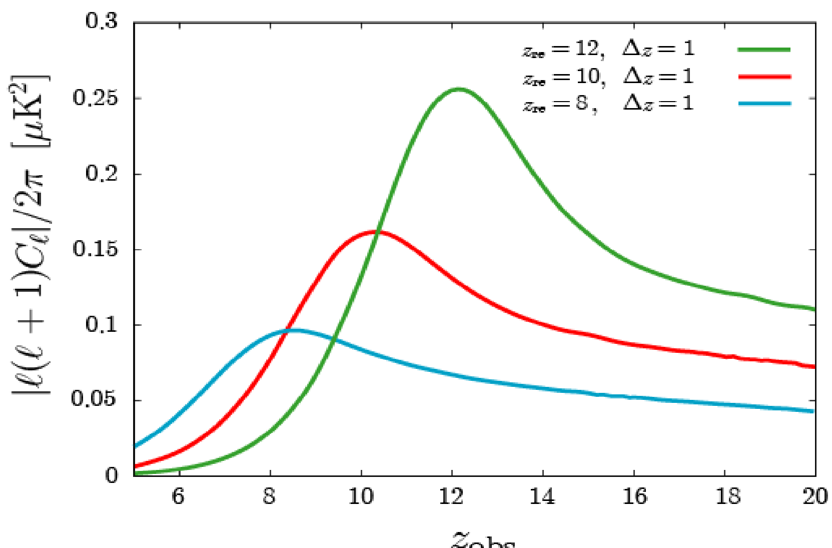
21cm-CMB polarisation

First peak position relates to the angular scale of the CMB quadrupole, Amplitude relates to duration or reionisation

Tashiro et al. 2008







Long duration of reionisation damps the oscillations on small scales

→ **VERY DIFFICULT!**

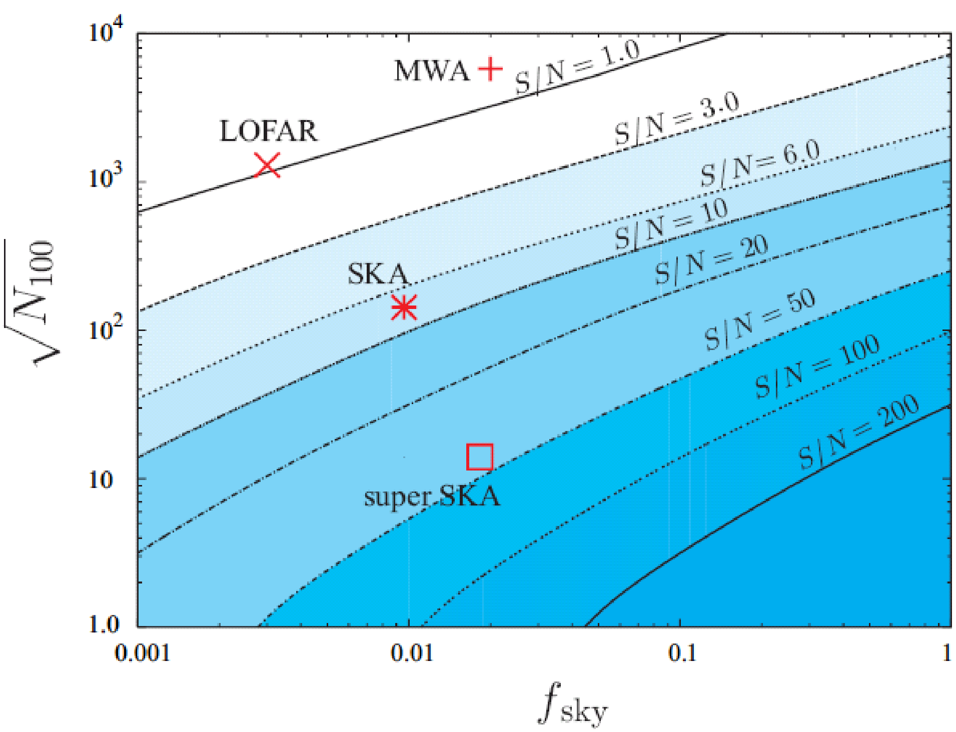
Observability of 21cm-CMB temperature cross-correlation

Signal to Noise ratio analysis *(Tashiro et al. 2009)*

$$\left(\frac{S}{N}\right)^2 = f_{\rm sky} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} (2\ell+1) \frac{|C_\ell^{21-\alpha}|^2}{|C_\ell^{21-\alpha}|^2 + (C_\ell^{21} + N_\ell^{21})(C_\ell^{\alpha} + N_\ell^{\alpha})} \qquad \alpha = D \;\text{or}\; E$$

CMB noise power spectrum — Primordial CMB + Noise power spectrum of Planck

21 cm noise power spectrum — Experimental noise



$$\frac{\ell^2 N_\ell^{21}}{2\pi} = \left(\frac{\ell}{100}\right)^2 \frac{1}{t_{\rm obs}\Delta\nu} \left(\frac{100\ell_{\rm max}}{2\pi} \frac{\lambda^2}{A/T}\right)^2$$

A/T is the sensitivity

$t_{\rm obs}$ is the total integration time

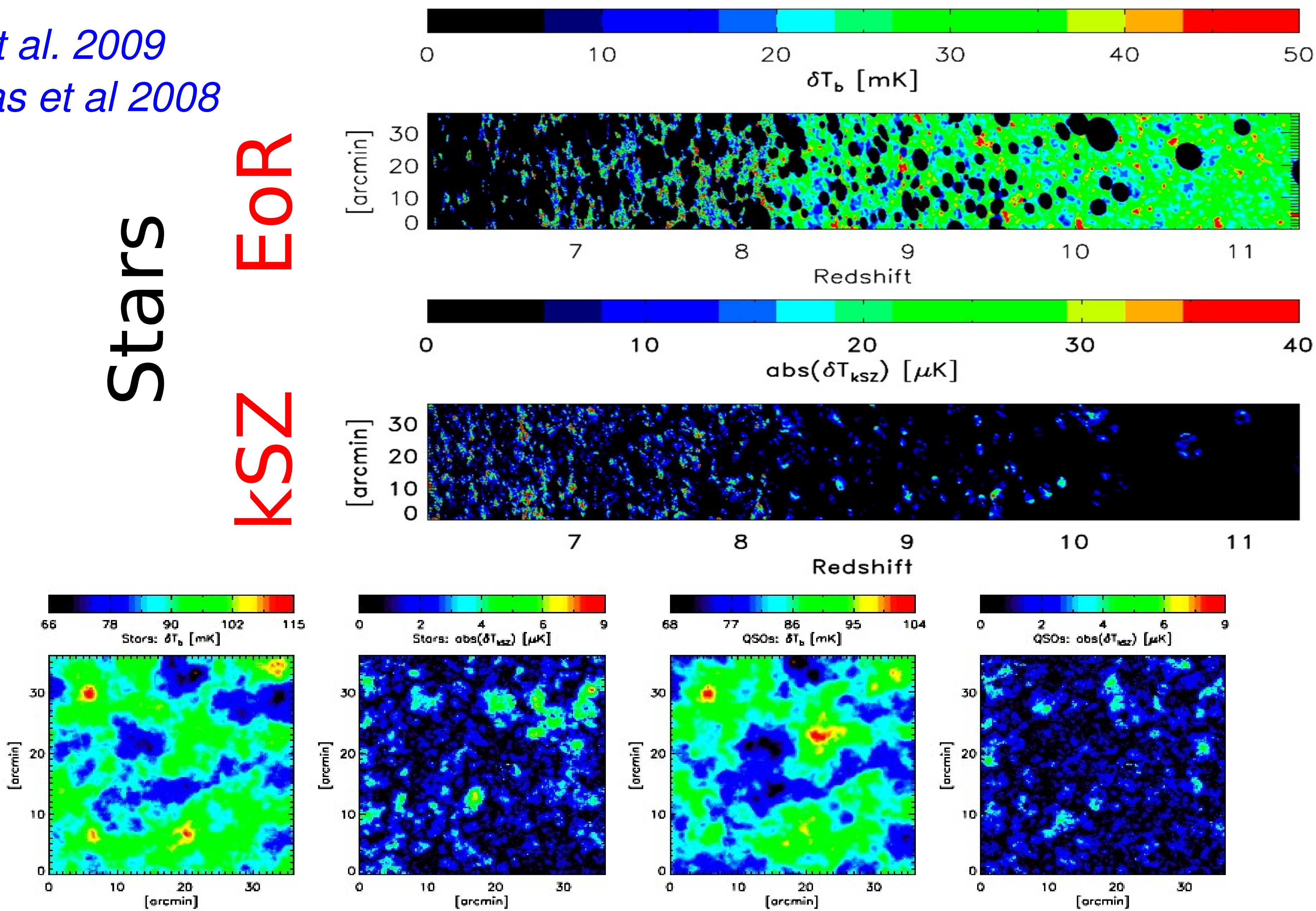
$\ell_{\rm max}$ is the maximum multipole $\quad \ell_{\rm max} = 2\pi \frac{D}{\lambda}$

tobs underestimated (400 vs ~1000h)
CMB signal underestimated small scale anisotropies not accounted for

$\Delta z = 0.01 \quad z_{re} = 10; \quad z_{obs} = 10$

Simulations for LOFAR: patchy RH

Jelic et al. 2009
Thomas et al 2008



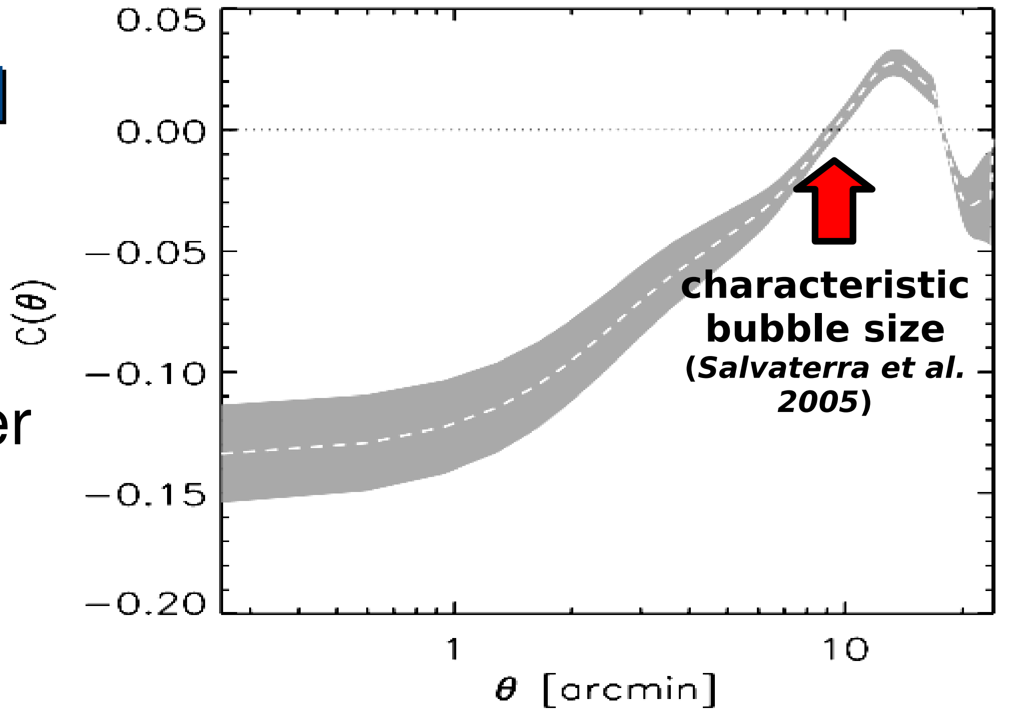
EoR [mK] **|kSZ| [μ K]**

Stars C_0=-0.16±0.02

EoR [mK] **|kSZ| [μ K]**

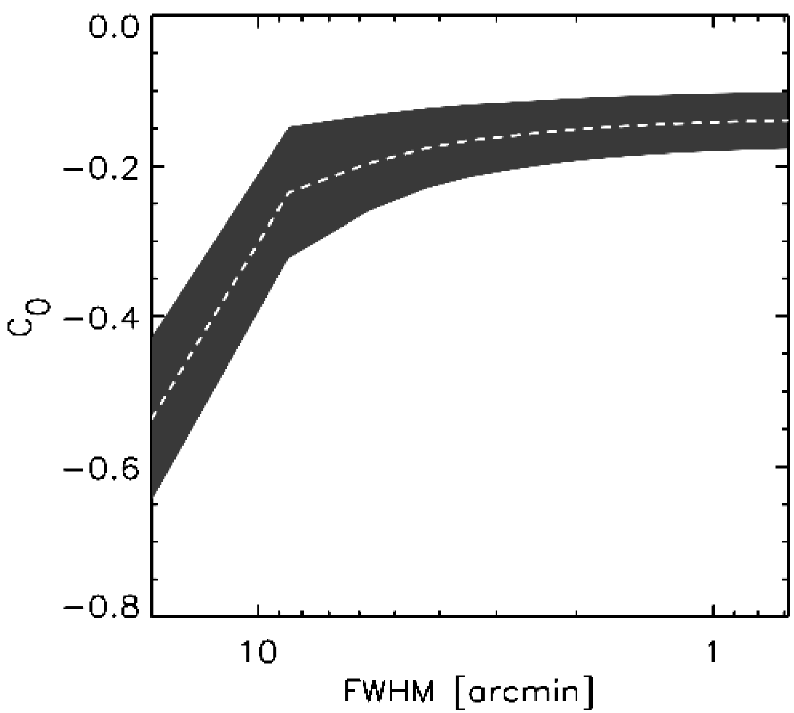
QSOs C_0=-0.05±0.02

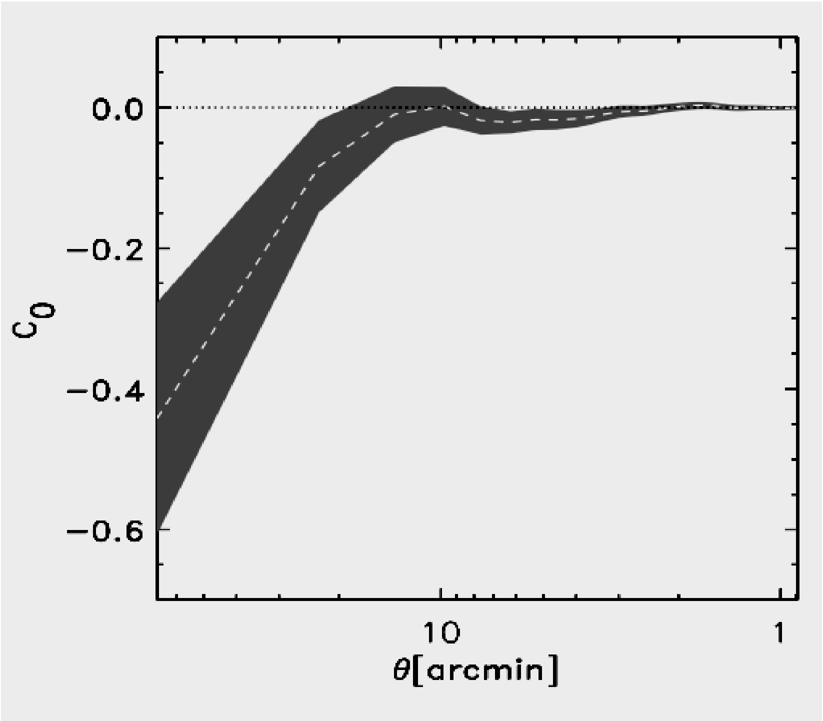
X-correlation: patchy RH



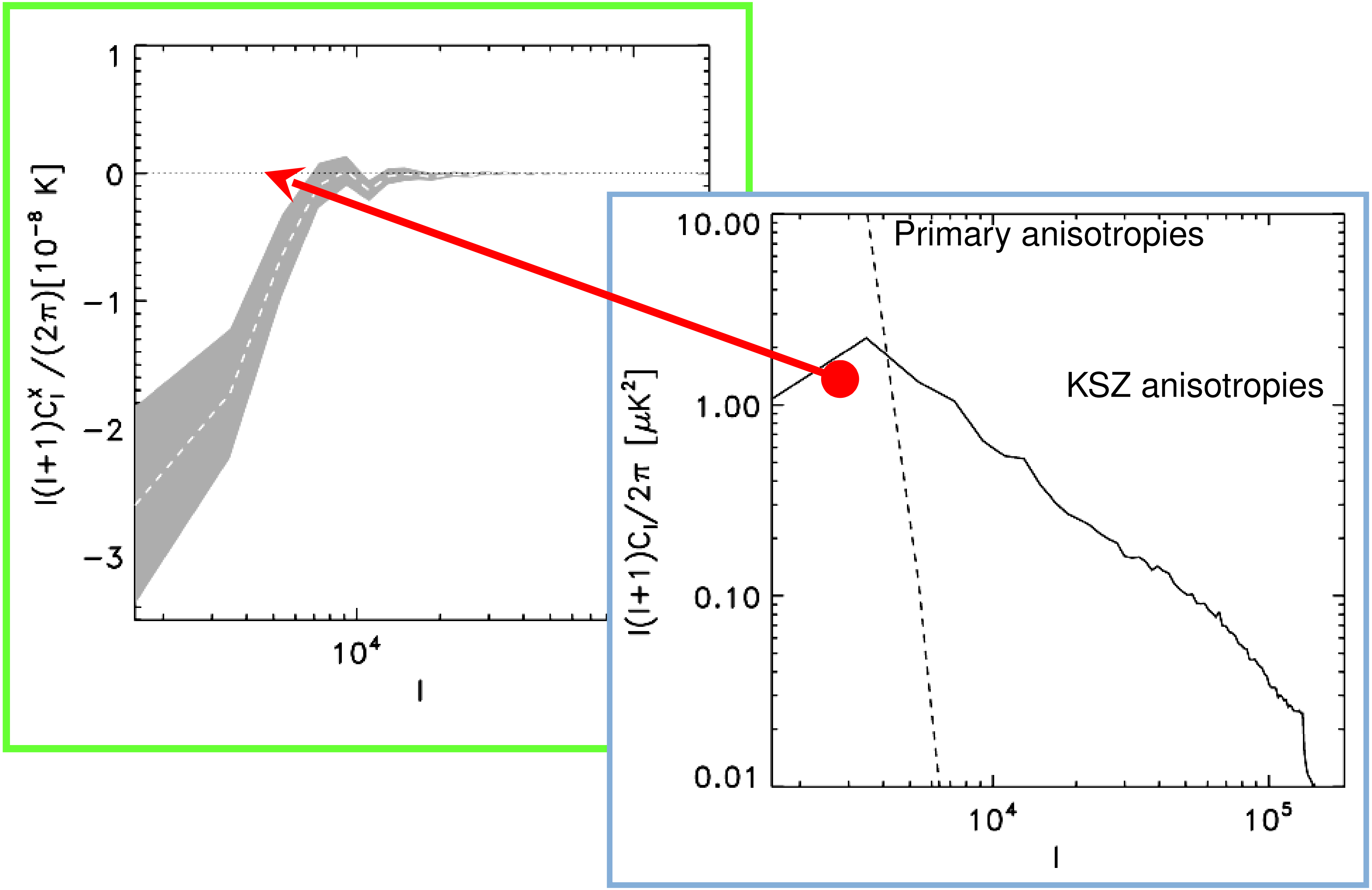
Adding the primary CMB : no significant cross-correlation even after filtering to focus on small scales

Theoretical computations on going





Cross-correlation: adding primary CMB



Conclusions

Mesuring the reionisation signals (including X-correlation) is challenging but feasible (need low frequencies ~150-350 MHz)

Planck data products

- Early Release Compact Source Catalogue (~End 2010)
- Cluster catalogue (1000-3000), IR and radio galaxy catalogues
- All-sky maps in 9 bands (30 to 857GHz) for intensity and 7 for polarisation
  - Cosmic Microwave Background
  - Galactic emission maps (synchrotron, free-free, dust)
  - SZ maps

Possible/obvious synergies: ISM and galactic B, clusters (SZ, X, radio), galaxies, cosmology (reionisation, cosmological parameters) Some already under discussion with LOFAR