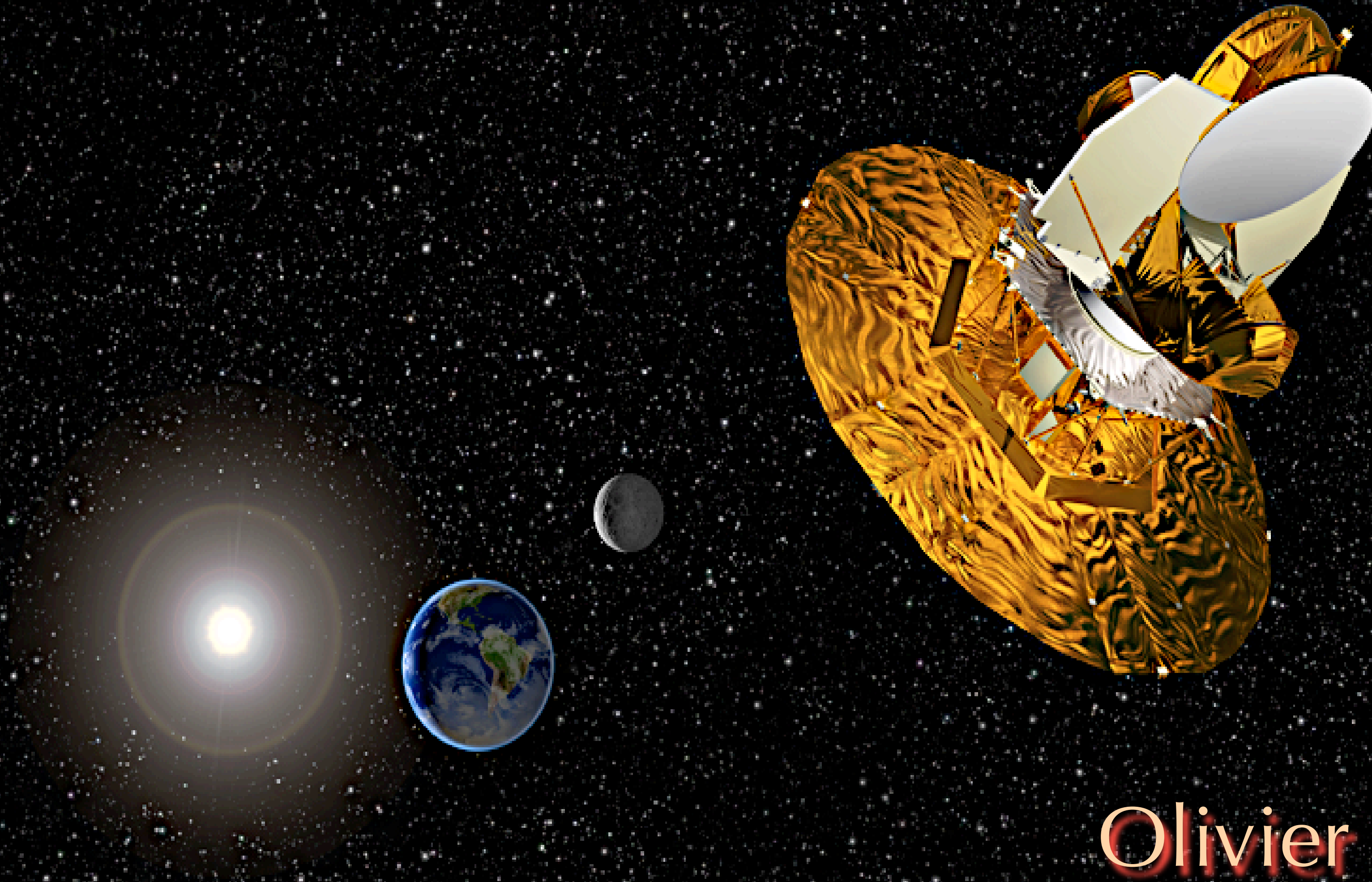
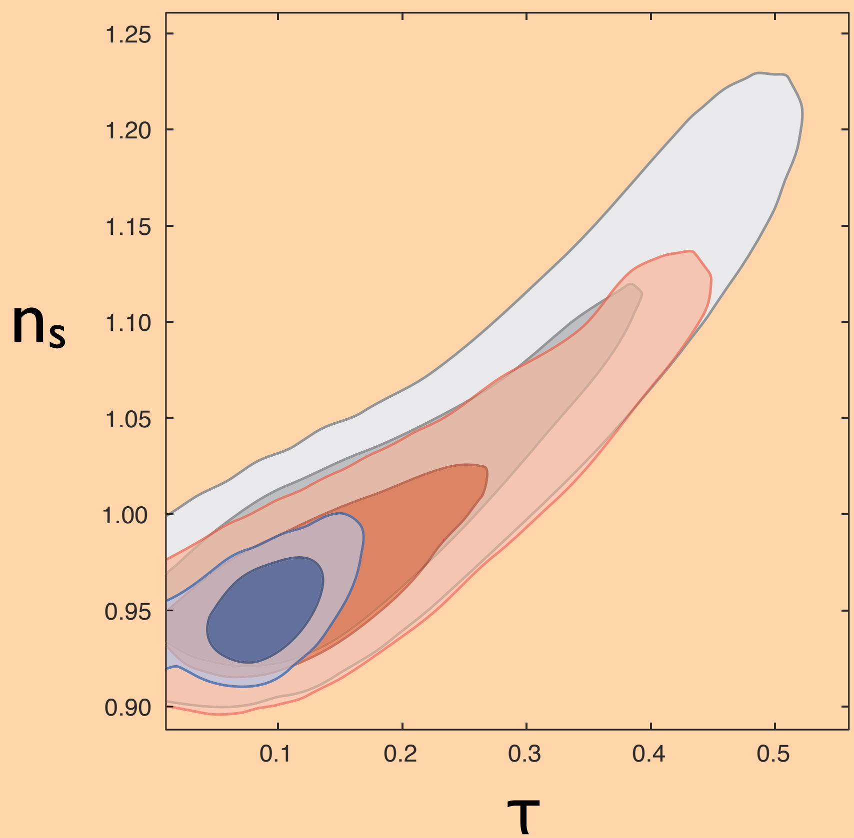
Probing reionization history through CMB external correlations



Olivier Doré
CITA

Strong Inflation - reionization connection for CMB interpretation

Measuring τ via CMB polarization allows to break the most severe CMB TT degeneracy and impacts on other key parameters



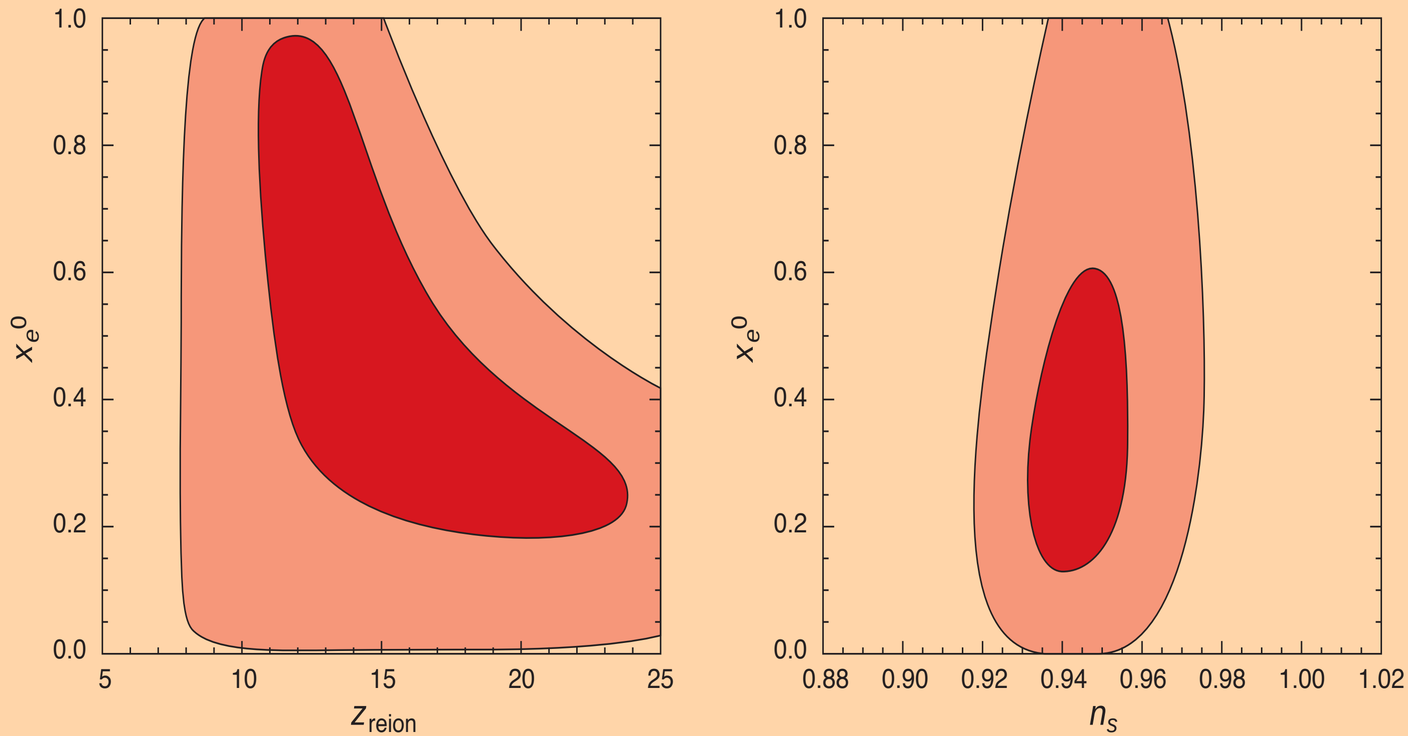
Driven by low l EE

Spergel et al. 06

(and see Rachel Bean's talk this afternoon)

- However reionization is a complicated process whose physics is known but hard to compute
- Can we learn about the detailed reionization history?
- Can our ignorance bias the cosmological interpretation?

Is WMAP-3 sensitive to the details of reionization?

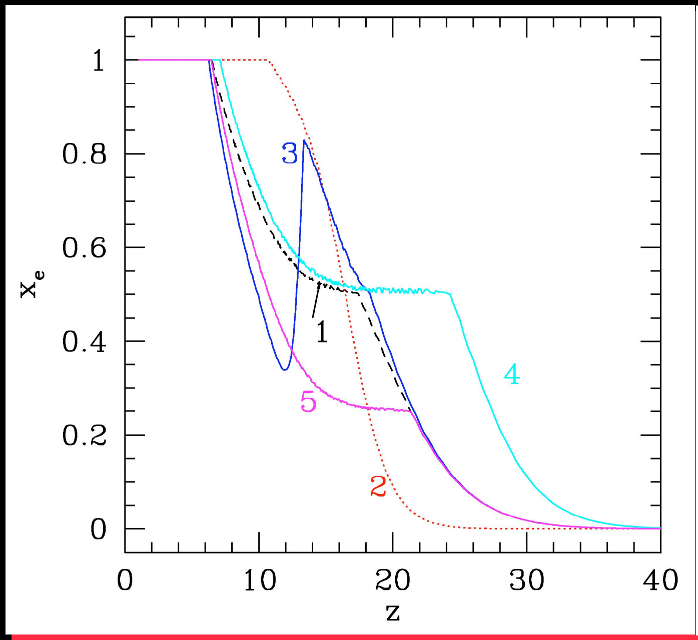


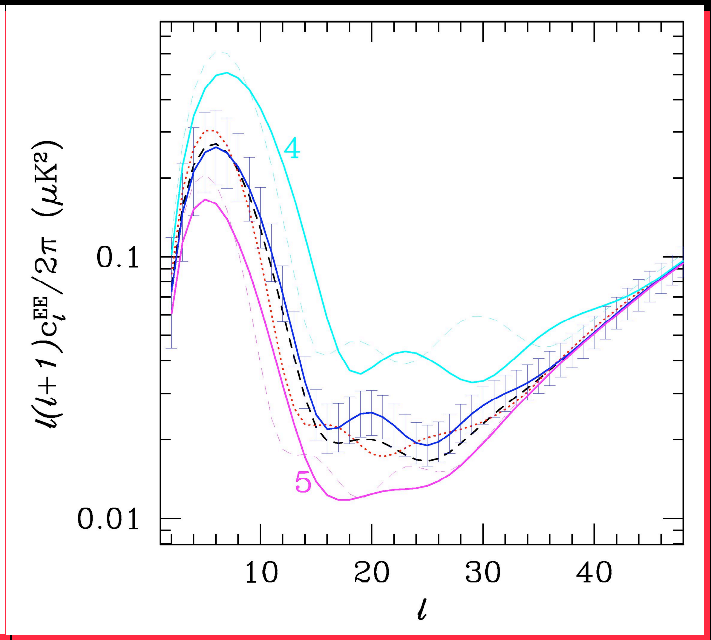
WMAP-3 in τ (mean) = 0.093 ±0.029 / peak = 0.092

Universe partially reionized at z_{reion} with a reionization fraction x_e^o fully reionized at $z=7$ as suggested by high z quasars (Fan et al. 05) and GRBs (Totani et al. 05)

WMAP-3 conclusions are not sensitive to the details of reionization history

What about WMAP-8 and Planck?





- 5 different physically motivated models
- Models 1-3 have the same
- A single step reionization history is enough for WMAP but not for Planck
- Assuming a double step reionization scenario avoid any significant bias in measuring
- Uncertainties in reionization history limits τ measurement to σ(τ)=0.01

Holder *et al.*, astro-ph/0302404

Outline

How external measurements can help us
to control reionization effects?

- Reionization effects in the CMB temperature
- Probing kinetic Sunyaev-Zeldovich effect with gravitational weak lensing
- Probing details of reionization cross-correlating 21cm temperature fluctuations with CMB temperature at degree scale

Reionization effects on the CMB

- Damping: blending of photons from different line of sight

$$\bar{T} + \Delta T \rightarrow (\bar{T} + \Delta T) - (\bar{T} + \Delta T)(1 - e^{-\tau}) + \bar{T}(1 - e^{-\tau})$$
$$\rightarrow \bar{T} + \Delta T e^{-\tau}$$

$$C_\ell = C_\ell e^{-2\tau}$$

(Ignore scale dependence here)

Current numbers tell us we have a suppression by ~30% for *l* greater than 40
Makes it hard to measure absolute initial conditions normalization

- Doppler effects

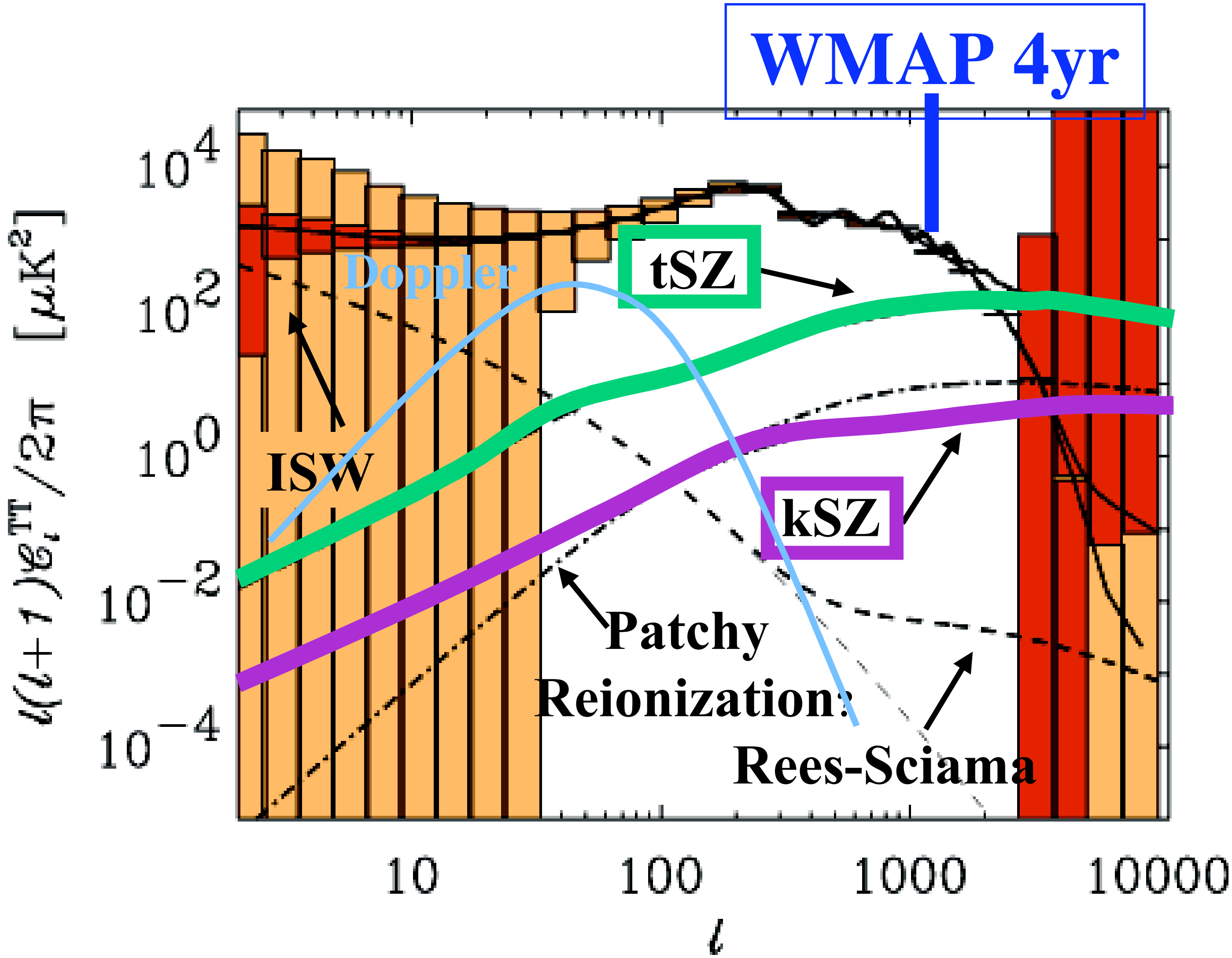
$$\frac{\Delta T}{T}(\hat{n}) = \sigma_T \int_{\eta_{ion}}^{\eta_0} d\eta \, x_e(\hat{x}) n_p(\hat{x}) \hat{n} \cdot v_e(\hat{x})$$

Cancellation along the line of sight due to variation in v_e

- Except larger scales: *l~100*
- Reduced if modulations in n_p: *Ostriker-Vishniac effect, kinetic Sunyaev-Zeldovich*
- Reduced if modulations in x_e : *Patchy reionization*

see eg Knox & Haiman astro-ph/9902311 for a review

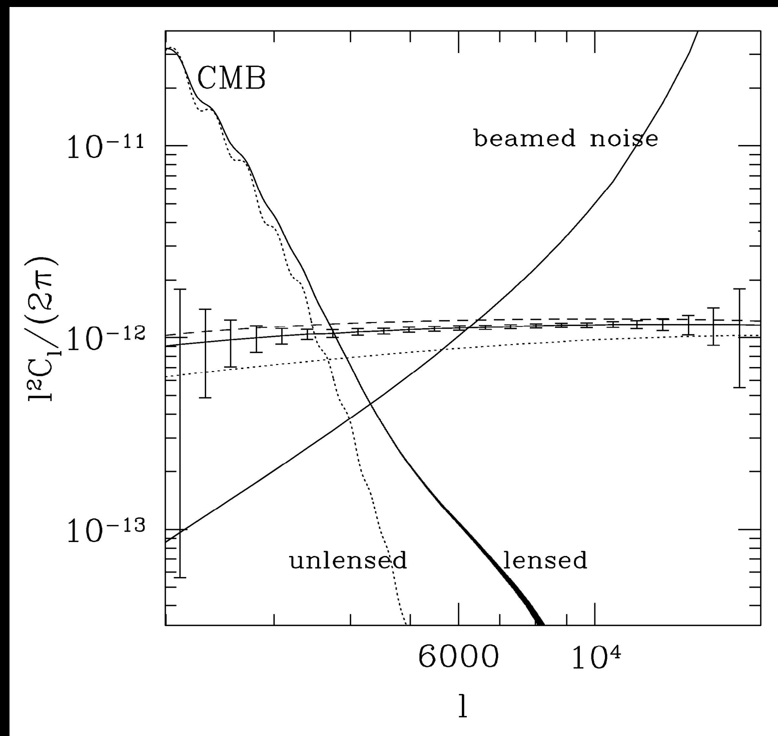
Reionization effects on the CMB



Doré, Hennawi & Spergel *et al.* 04

Probing tau with kSZ

ACT error bars



- $z_r = 7$
- $z_r = 16.5$
- $z_r = 21$ & 7

Zhang *et al*. astro-ph/0304534

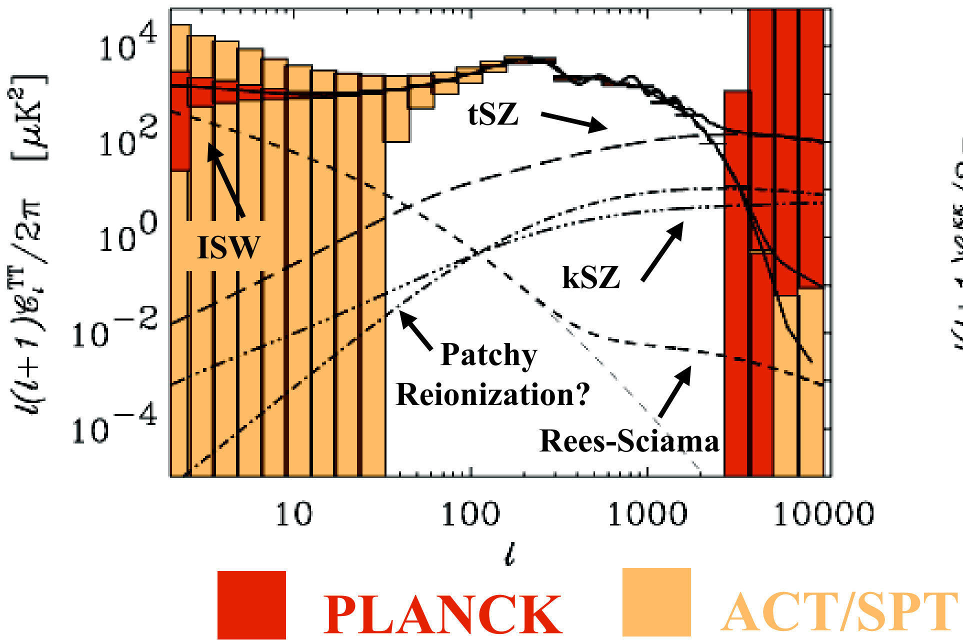
- In principle 1% measurement of kSZ allows a 3% determination of z_r if all the other parameters are known
- But degeneracy with σ_8 that goes as $z_r \sim (\Omega_b h)^6 \, \sigma_8^{15}$

- But extra-uncertainties in extracting the kSZ (lensing, patchy reionization (same spectra), point sources) (SZ has a distinct spectra)...

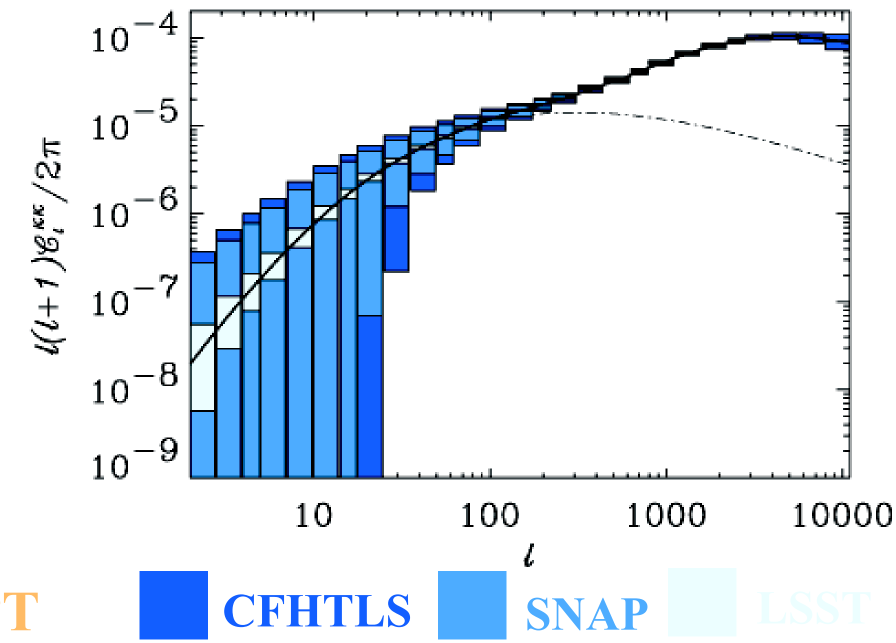
(See also Albert's talk)

Can gravitational lensing help?

CMB



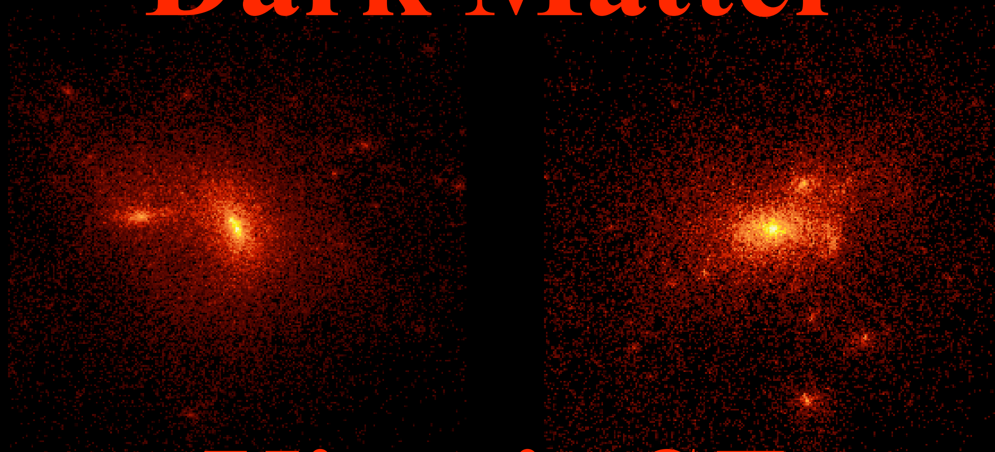
Weak-lensing



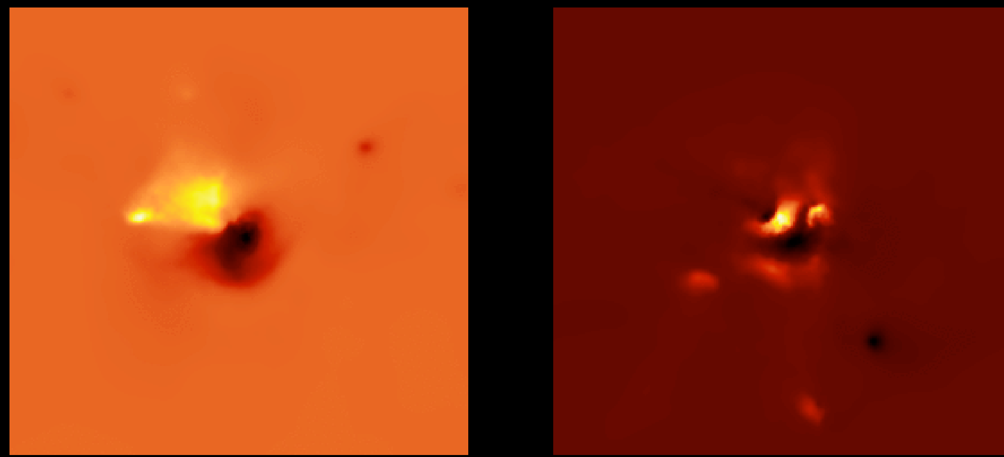
Soon to come CMB and WL survey will both achieve high signal to noise ratio on arcminute scale

Can Weak-Lensing help probing the kSZ?

Dark Matter



Kinetic SZ



Martin White simulations

Nature of the kSZ-WL correlation

- Isotropy of the velocity field implies that the two point vanishes

$$\langle \frac{\Delta T}{T}\kappa \rangle \sim 0$$

- Lowest order non-vanishing correlation: 3 points function - 1point WL, 2 points kSZ

$$\langle \frac{\Delta T}{T}(\ell_1)\frac{\Delta T}{T}(\ell_2)\kappa(\ell_3)\rangle$$

- Simplest 3 points function: collapsed statistic - condense 3 point function into easily measurable C_l

$$C_l^{\mathrm{kSZ}^2-\kappa} = \langle \left(\frac{\Delta T}{T}\right)^2 (\ell_1)\kappa(\ell_2)\rangle$$

- Filter temperature field before squaring in order to avoid spurious mode coupling

$$\Theta^{\mathrm{kSZ}} = f(\ell)\frac{\Delta T}{T}(\ell)$$

WL-kSZ technicalities

- Cross power spectrum between kSZ² and weak lensing is a 'Limber' projection of the hybrid

$$C_\ell^{\mathrm{kSZ}^2-\kappa} \sim \int dD(\text{window functions}) \times \int d^2\mathbf{k}(\text{filter functions}) B_{\delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}}}$$

- Need to evaluate correlation between 5 fields at 3 points in *k*-space in the fully non-linear regime

$$B_{\delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}}} = \langle \delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} \rangle$$

- Proceed by analogy with the kSZ auto-power spectrum (Ma & Fry 02)

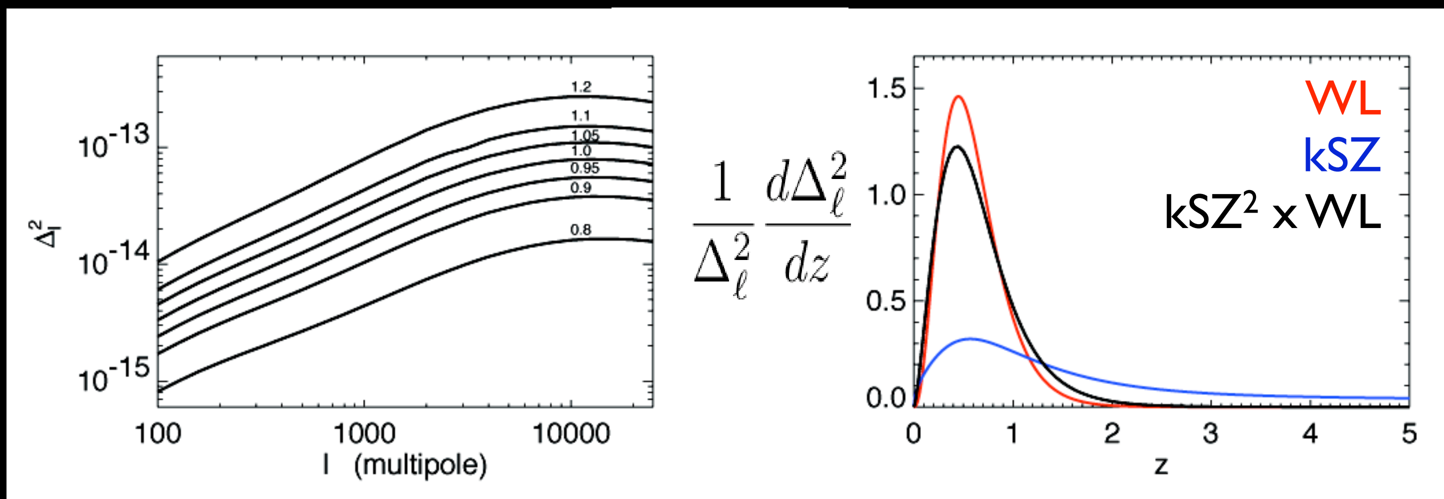
$$P_{p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}}} \approx \frac{v_{\mathrm{rms}}^2}{3} P_{\delta\delta}^{\mathrm{NL}} \quad \longrightarrow \quad B_{\delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}}} \approx \frac{v_{\mathrm{rms}}^2}{3} B_{\delta\delta\delta}^{\mathrm{NL}}$$

- Presume hybrid bispectrum is generated by bulk flows coupling to non-linear three point density correlations

(see also Hume Feldman and Simon Dedeo talk)

kSZ²-WL correlation

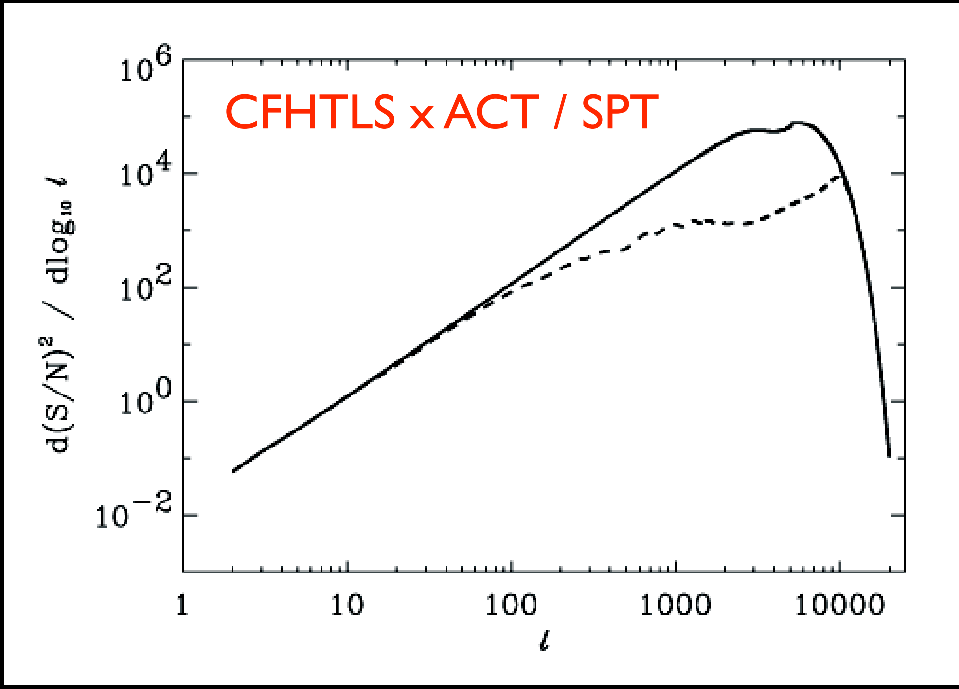
Angular Power Spectra   Redshift dependance



- Correlation coefficient reaches ~ 0.8 at arcminute scales (l > 3000)
- Probes dominant low-z contribution to the kSZ signal
- Like thermal SZ, signal is a strong probe of σ_8 with scaling $C_l \propto \sigma_8^7$

Doré, Hennawi & Spergel *et al.* 04

kSZ^{2}xWL signal to noise ratio



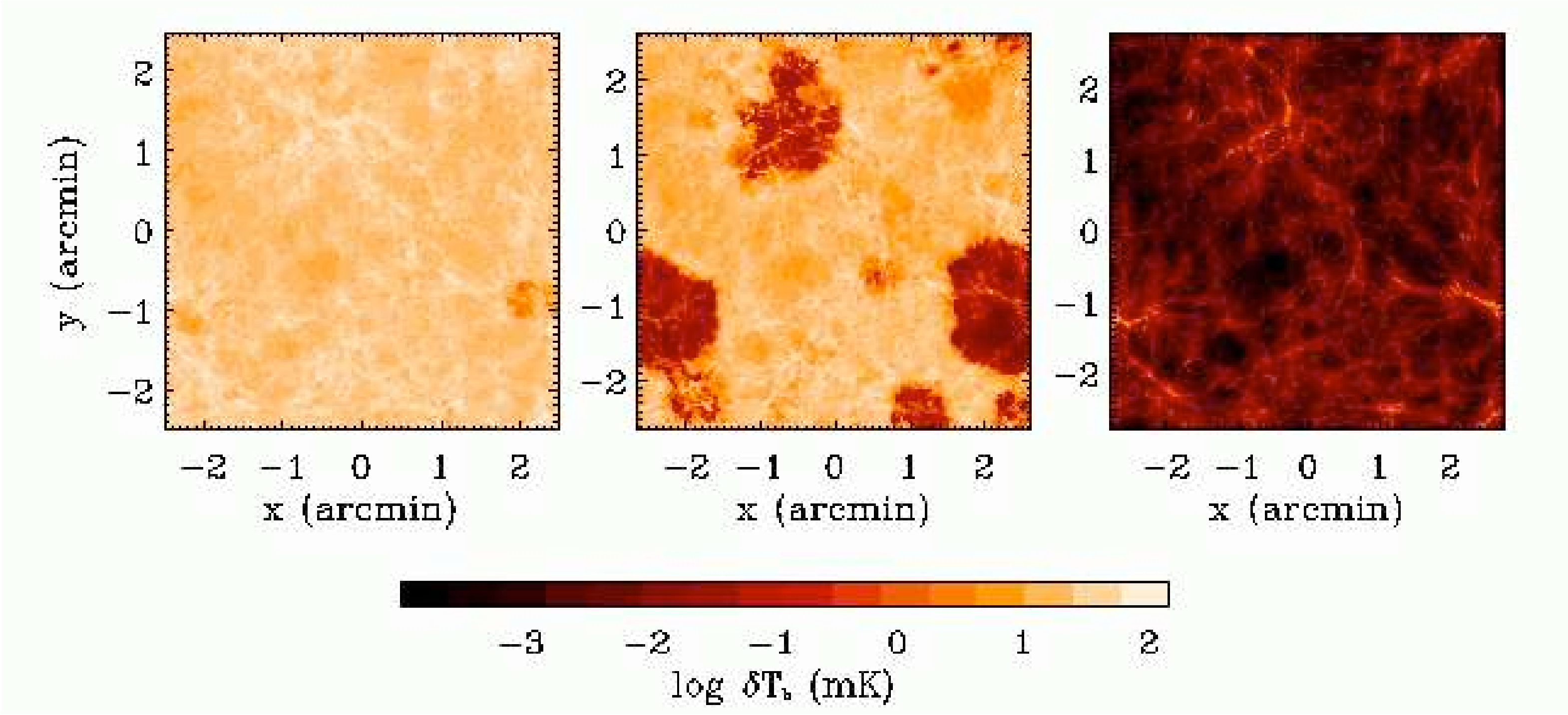
- Total signal to noise ratio > 220 CFHTLS x ACT/SPT
- Multiply by √40 for the entire SPT area
- S/N reaches 1.8 per multipole around l ~ 5000
- Even with maximal patchy reionization (Santos et al. 2003) total S/N~50
- Spurious correlation with tSZ residuals limits PLANCK x LSST. Total S/N would be ~ 1000

Doré, Hennawi & Spergel *et al.* 04

Why is kSZ^2-WL interesting?

- Probe Hybrid Bispectrum: $B_{\delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}}} = \langle \delta p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} \rangle$
- 3-point coupling between dark matter and *baryon momentum*\
  - Sensitive to energy injection?
  - Bias of gas in densest regions
  - Study mode coupling of gastrophysical processes
- Strong probes of σ_8
- Isolates kSZ: WL won't correlate with patchy reionization
  - Important since PR is uncertain by orders of magnitude and has same shape as kSZ
  - Test any other components
- Specific Signature: Two point correlation vanishes $\langle \frac{\Delta T}{T} \kappa \rangle \sim 0$ but three point does not $C_\ell^{\mathrm{kSZ}^2-\kappa} = \langle \left(\frac{\Delta T}{T} \right)^2 \kappa \rangle$

21cm emission at reionization



- At the moment of reionization, 21cm hyperfine in HI transition will appear in emission ($T_s > T_{CMB}$) or in absorbtion ($T_s < T_{CMB}$) when viewed against the CMB
- Line transition thus well localized in *z* space
- Fluctuations in temperature originate from variation in HII due to large scale fluctuations and details of radiation transfer

Zaldarriaga, Furlanetto & Hernquist 06

21cm x CMB fluctuation

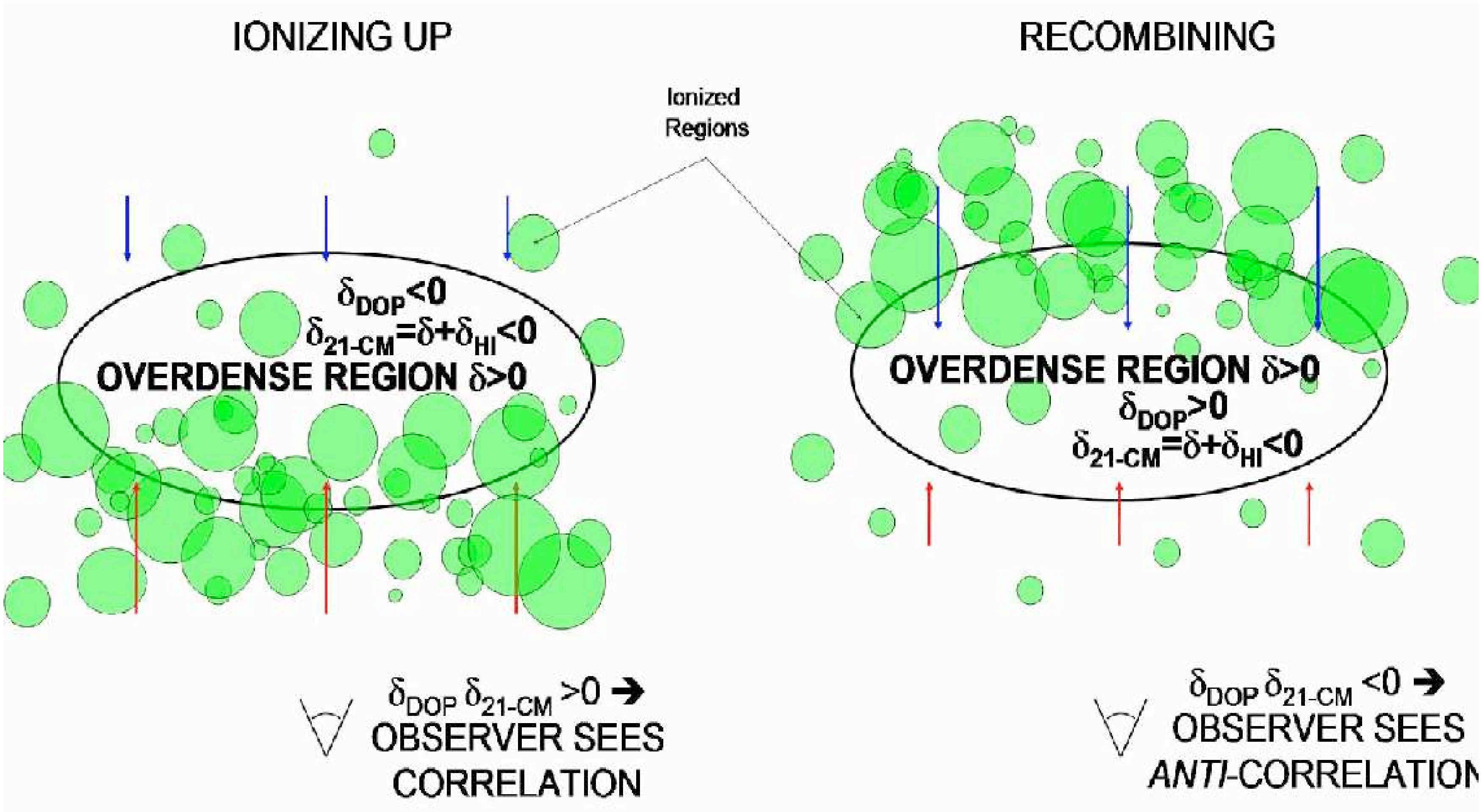
- Naively expect anti-correlation since Doppler effect of the CMB caused by free electron
- Well localization of the hyperfine emission in z space should prevent cancellation along the line of sight

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

- Cross-correlation vanishes if $\dot{D}\dot{\tau}e^{-\tau}$ is constant, *i.e.* we probe how quick or fast the structure growth and reionization proceeds
- Sign depends on direction of reionization, *i.e.* reionization and recombination
- $P_{\delta\delta}(k)$ peaks at matter-radiation equality $k_{eq} \approx 0.011 \mathrm{Mpc}^{-1}(\Omega_m h^2/0.15)$ that translates into a peak at $l \sim 100$

Alvarez, Komatsu, Dore, Shapiro astro-ph/0512010

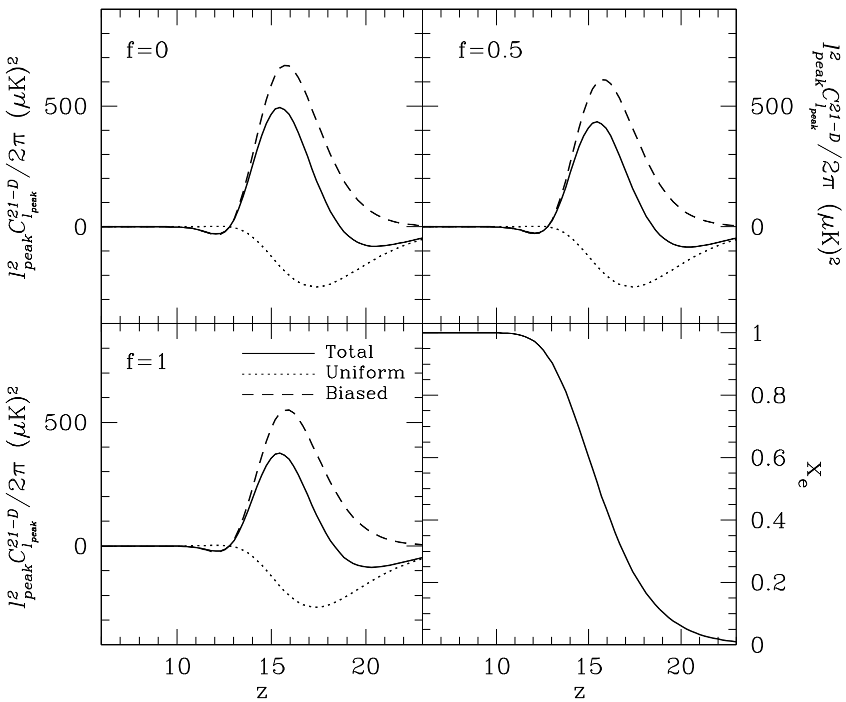
Correlation principles



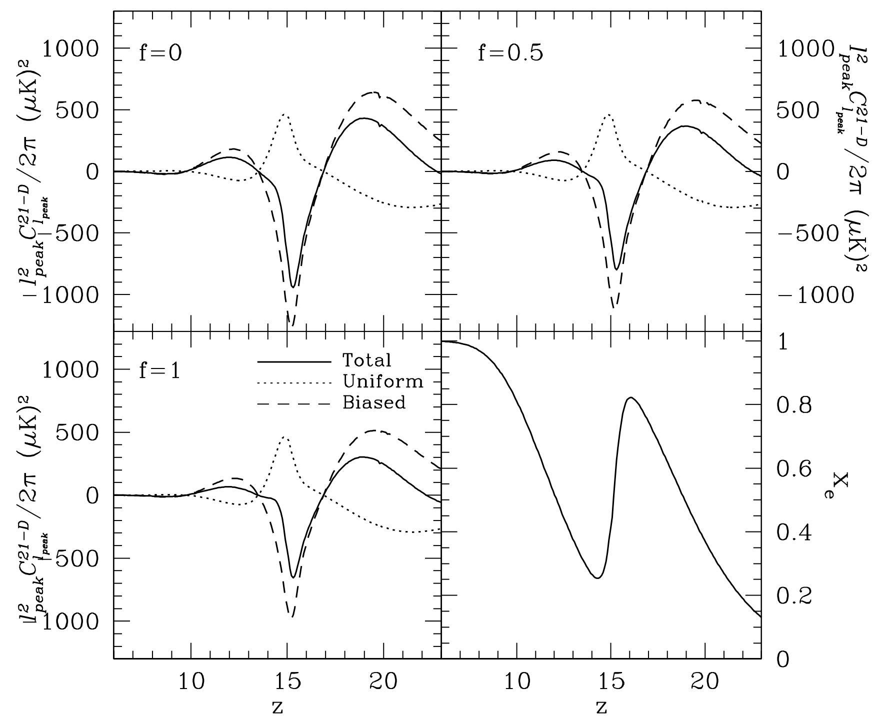
Ionized gas falling in from the near side

Ionized gas falling in from the far side

Various models of reionization



"Standard" reionization



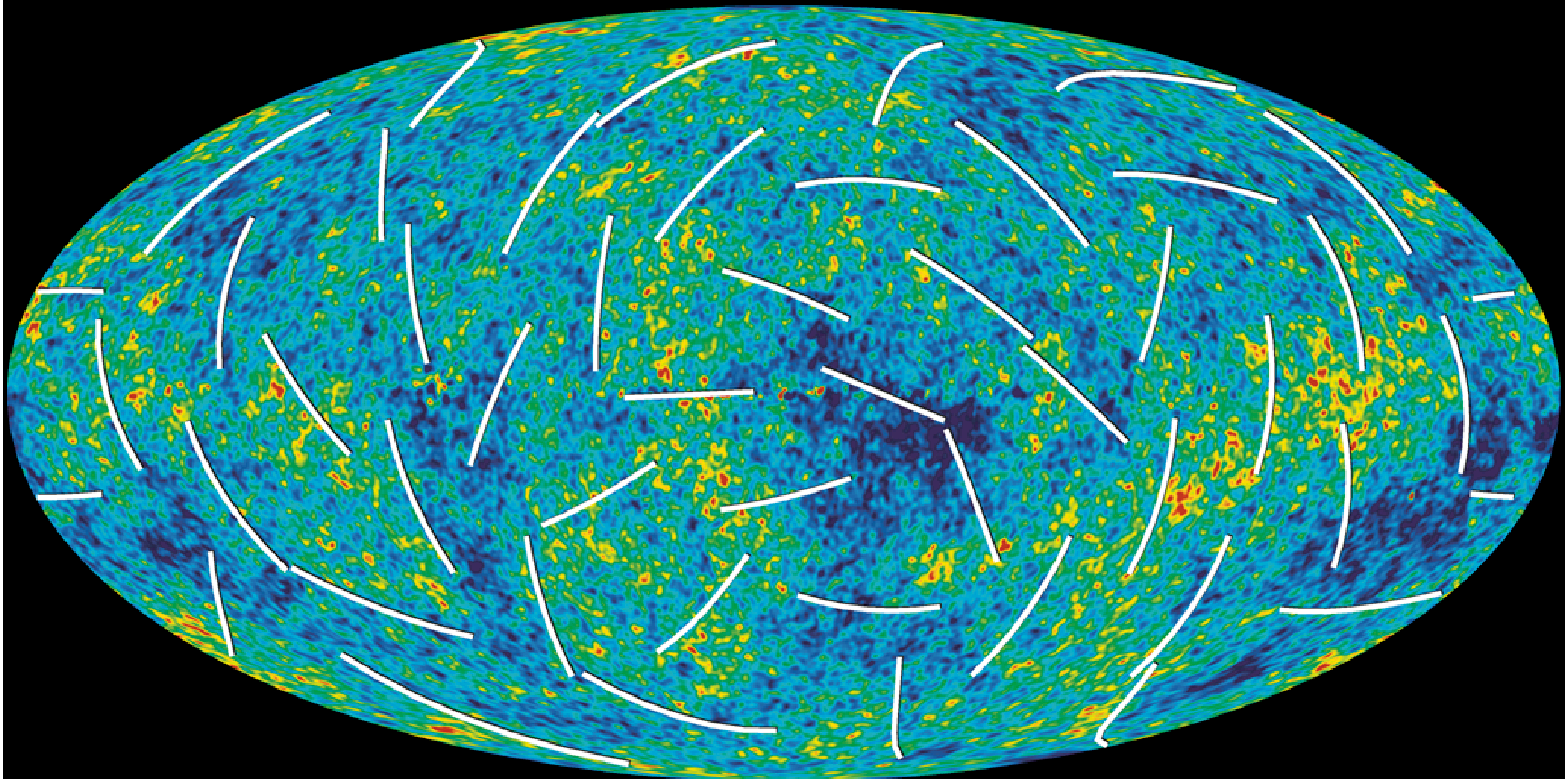
Double reionization (Cen 03)

Remarks on the 21cm-CMB correlation

- A (anti-)correlation between CMB and 21cm emission is expected
- Sharp *z* localization prevents usual line of sight cancellation
- It peaks at degree scale so that WMAP current maps are all you need
- Linear theory appropriate here
- Cross-correlation signal so in principle less sensitive to systematics
- It allows unique features of reionization to be detected
- SNR varies between 3 and 6 sigma for SKA (1yr) x WMAP

Conclusions

- Precise control of reionization history is required/desired to extract the most of future CMB measurements
- Correlation with external data-sets will allow this and provide valuable self-consistency checks
- In particular, amongst others, we can expect
  - a strong detection of the kSZ-WL correlation in the coming 5-10 years
  - a detection of the 21cm-CMB correlation in 10 years with some specific z signals



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