Probing the epoch of pre-reionization by cross-correlating cosmic microwave and infrared background anisotropies.

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Atrio-Barandela & Kashlinsky (2014)  
CIB fluctuations.

Figure 1: Top: Spitzer field at 3.6µm. Bottom: residual large scale background fluctuations (in false color) after masking all resolved sources (Kashlinsky et al 2012).
What is the origin of the CIB fluctuations?.

The Cosmic Infrared Background traces variations in the total production of photons over cosmic history.

**Two hypothesis:**

♦ Primordial galaxies and black holes at the epoch of reionization at $z \sim 10 - 15$ (Kashlinsky et al 2015 and references to earlier work).

♦ Extragalactic background light from a faint, extended components missed in galaxy point-source surveys like a Intrahalo light from stars tidally stripped from their parent galaxies at low redshift (Zemcov et al 2014).
Testing the High-z Origin: Data.

Figure 2: Field-averaged CIB fluctuations at 3.6 $\mu$m (left), 4.5 $\mu$m (middle) and cross power (right); black line: Contribution from remaining known galaxies (Sullivan et al 2007); shaded area: CIB fluctuations from the remaining known populations (Helgason et al. 2012); dashed line: shot-noise contribution; blue line: high-z $\Lambda$CDM contribution; red line: sum of Shot-Noise, known galaxies and high-z galaxy population from $\Lambda$CDM. (Figure from Kashlinsky et al 2012).
If \((\delta F_{CIB,5'})\) is the amplitude at \(q_5 = 2\pi/5'\), the power on scales 100"-1000" is

\[
P(q) = P_{SN} + \frac{2\pi}{q_5^2} (\delta F_{CIB,5'})^2 \frac{P_{\Lambda CDM}(q/d_A)}{P_{\Lambda CDM}(q_5/d_A)}
\]

with

At 3.6\(\mu\)m \(P_{SN} = 4.8 \times 10^{-11} [(nW)^2/(m^4 sr)]\) \((\delta F_{CIB,5'}) = 0.07 [nW/m^2 sr]\)

At 4.5\(\mu\)m \(P_{SN} = 2.2 \times 10^{-11} [(nW)^2/(m^4 sr)]\) \((\delta F_{CIB,5'}) = 0.05 [nW/m^2 sr]\)

A template of POP-III stars reionizing the medium instantaneously requires

\[
\Delta(5') \equiv \frac{\delta F_{CIB,5'}}{F_{CIB}} = 0.1
\]
Can we test the High-z CIB origin with CIB-CMB Cross-Correlation?

Figure 3: Top: Reconstructed CIB fluctuations from Spitzer. Bottom: simulated Planck data of an area 25 times larger than the CIB field.
When does reionization takes place?

- Latest results:

<table>
<thead>
<tr>
<th>DATA</th>
<th>$\tau$</th>
<th>$z_{reion}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMAP 9yr</td>
<td>0.089 ± 0.014</td>
<td>10.6 ± 1.1</td>
</tr>
<tr>
<td>PLANCK+WP+highL+BAO (2013)</td>
<td>0.092 ± 0.013</td>
<td>11.3 ± 1.1</td>
</tr>
<tr>
<td>PLANCK TT+lowP (2015)</td>
<td>0.078 ± 0.019</td>
<td>9.9 (+1.8) (−1.6)</td>
</tr>
<tr>
<td>PLANCK TT+lowP+lensing+BAO (2015)</td>
<td>0.066 ± 0.013</td>
<td>8.8 (+1.3) (−1.2)</td>
</tr>
</tbody>
</table>

WMAP: Reinization starts at $z \approx 13$. Planck: Reioniation proceeds quickly from $z \approx 10.6$ ($x_{HI} = 0.9$) to $z \approx 5.8$ ($x_{HI} = 0.02$) (Mitra et al 2015).
What is the thermal history of the IGM?

Thermal history of the low-density neutral IGM due to heating by accreting stellar black holes in high mass X-ray binaries (BH-HMXBs) for three values of the model parameter $f_X = 0.1, 1, 10$ (green, blue, black).

Expected: $f_X > 1$ and $T_{IGM} \approx 10^4K$
Reionization by POP III stars.

- POP-III stars radiate at Eddington luminosities at temperatures $T \sim 10^5$K. During their life-time $[t_{POP-III} \sim 3 \times 10^6$yr] (Schaerer 2002)

- Total number of ionizing photons, $N_\gamma = 10^{62} \frac{M_{POP-III}}{M_\odot}$.

- Mass of the ionized bubbles, $M_{ion} = \frac{10^5}{\kappa} M_{POP-III}$, where $\kappa$ is the number of photons required to ionized an atom.

- $\kappa$ will be normalized to the mean optical depth $\tau = \sigma_T \int n_e dl$
Projected number density of CIB sources.

- A **lower limit** on the projected number density of sources/bubbles can be set from the measured **upper limit** on the CIB shot-noise power $P_{SN}$ and the amplitude of the clustering component of the CIB fluctuations (Kashlinsky et al. 2007).

\[
\delta F_{CIB,5'} \simeq 10^{-10} \left[ \frac{(nW)^2}{(m^2\text{sr})^2} \right] \\
\Delta(5') \equiv \left( \frac{\delta F_{CIB,5'}}{F_{CIB}} \right) \simeq 0.1 \\
P_{SN} \sim \frac{F_{CIB}^2}{n_{sources}} \leq 10^{-11} \left[ \frac{(nW)^2}{(m^2\text{sr})^2} \right] \\
\Rightarrow n_{sources} \geq 10^{11} \left( \frac{P_{SN}}{10^{-11}(nW)^2m^{-4}\text{sr}^{-2}} \right) \text{sr}^{-1}
\]
The TSZ effect from the ionized bubbles.

- Single Bubble of angular size $\omega_B$:

$$
\delta T_{TSZ,pix} = G(\nu) \left[ \frac{4}{3} \sigma_T \left( \frac{k_B T_e}{m_e c^2} \right) n_e R_{ion} \right] \frac{\omega_B}{\omega_{pix}}
$$

- From the ionized bubble population:

$$
\Delta T_{TSZ} \simeq \frac{4}{\pi} G(\nu) \left( \frac{k_B T_e}{m_e c^2} \right) \left( \frac{\sigma_T}{d_A^2} \right) \left( \frac{M_{ion}}{\mu m_H} \right) n_{sources} T_{CMB}
$$

$$
\simeq 200 G(\nu) \left( \frac{0.5 \text{Gpc}}{d_A} \right)^2 \left( \frac{M_{POP-III}}{10^2 \mu M_\odot} \right) \left( \frac{T_e}{10^4 K} \right) \left( \frac{n}{10^{11} \text{sr}^{-1}} \right) \text{nK}
$$

$\mu \equiv$ mean gas molecular weight and \( \tau = 0.044 \).
S/N of the CIB-TSZ cross-power.

- Coherence of the CIB and TSZ sources:

\[ C = \frac{P_{\text{CIB} \times \text{TSZ}}}{P_{\text{CIB}} P_{\text{TSZ}}} \quad \Rightarrow \quad P_{\text{CIB} \times \text{TSZ}} \simeq \sqrt{C} \sqrt{P_{\text{CIB}}} \sqrt{P_{\text{TSZ}}} \]

- Since the Coherence \( C \leq 1 \) then

\[
\text{S/N} \sim 7 \frac{T_{\text{TSZ}}}{200nK} \frac{\Delta (5^\prime)}{0.1} \frac{5 \mu K}{\sigma_{\text{noise}}} \left( \frac{N_{\text{pix}, 5^\prime}}{3 \times 10^6} \right)^{\frac{1}{2}},
\]
CIB-TSZ Cross-Correlation.

- The TSZ-CIB cross-power on angular scale $\theta = 2\pi/q$ is given by the Limber equation

$$P_{CIB \times TSZ}(q) = \int dr(z) \left( \frac{dF_{CIB}}{dr} \right) \left( G_\nu \frac{dY_C}{dr} \right) P_3 \left( \frac{q/r}{z} \right) \frac{r^2}{r^2},$$

$$P_{CIB}(q) = \int dr(z) \left( \frac{dF_{CIB}}{dr} \right)^2 P_3 \left( \frac{q/r}{z} \right) \frac{r^2}{r^2},$$

$$P_{TSZ}(q) = \int dr(z) \left( G_\nu \frac{dY_C}{dr} \right)^2 P_3 \left( \frac{q/r}{z} \right) \frac{r^2}{r^2},$$

where

$$\frac{dY_c}{dr} = \frac{k_B T_e}{m_e c^2} \frac{d\tau}{dr}, \quad \frac{d\tau}{dr} = \frac{\rho_B(0)}{\mu m_p} \sigma_T x_e(z)(1 + z)^2.$$

We choose the ionization fraction $x_e(z) = f_I f_*(z)$, $f_*(z)$ is the fraction that is locked into stars and $f_I$ the number of ionized atoms per baryon in CIB sources.
Parameters and Normalization.

- CIB fluctuation are normalized to the amplitude of Kashlinsky et al. (2012).

- The mean optical depth at the end of recombination is $\Delta \tau = 0.05$.

- The temperature of the IGM is fixed at $T_{IGM} = 10^4 K$. 
Ionization Fraction as a function of baryons locked into CIB sources:

\[ \frac{df_\star}{dz} = F_\star \exp\{[(z - z_{\text{min}})/\Delta z]^{2}\} \]

The final fraction of baryons in CIB sources is \( \sim 1\% \), determined by \( \tau \).
Coherence:

\[ C = \frac{P_{\text{CIB}} \times P_{\text{TSZ}}}{P_{\text{CIB}} P_{\text{TSZ}}} \]

\( C \) is larger if reionization is "instantaneous" and occurs at higher redshifts.
Sky covered by the Euclid mission at completion (6 year) in ecliptic coordinates (wide survey $\sim 15,000\,\text{deg}^2$. [From Euclid Consortium/ESA/Science Survey Working Group]
• The Euclid NISP (Near Infrared Spectrograph and Photometer) instrument will observe in three filters: Y(0.92-1.146 $\mu$m), J(1.146-1.372 $\mu$m) and H(1.372-2.0 $\mu$m)

• Reionization photons would fall in different Euclid NIR bands, depending on the moment of emission.

<table>
<thead>
<tr>
<th>Photon energy</th>
<th>1+z</th>
<th>$\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ly-continuum (13.6eV)</td>
<td>10</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.4</td>
</tr>
<tr>
<td>Ly-$\alpha$ (10.2eV)</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.8</td>
</tr>
</tbody>
</table>

CIB-TSZ tomography: Cross-correlation with the CIB at different frequencies will probe the redshift of reionization.
The 217GHz channel is needed to subtract the intrinsic CMB contribution.
• PLANCK noise in CMB difference maps $\nu - 217\text{GHz}$ is $\sigma_{\text{noise}}^{\nu-217\text{GHz}} = (9.6, 10.3, 32.0)\mu\text{K}$ for $\nu = (100, 143, 353)\text{GHz}$ on pixels corresponding to the FWHM at each frequency. Combining the three channels $\sigma_{\text{noise}}^{\text{Planck}} = 7.8\mu\text{K}$ on pixels of $5'$ after 2 yrs.

• SPT: 2,540 deg$^2$ at $(95, 150, 220)\text{GHz}$, with resolution $(1.7, 1.2, 1.0)\arcmin$. The noise in the Comptonization parameter scaled to $5'$ pixels is $\sigma_{\text{noise}}^{\text{SPT}} = 4.74\mu\text{K}$, over $1/6$ the area of EUCLID.
Results.

\[ \sigma_{\text{noise}} = 5 \mu K \]

\[ \theta_{\text{2\pi/q}} \] (arcmin)

Signal/Noise

- PLANCK+SPT
- PLANCK

The Near Infrared Background II: From Reionization to the Present Epoch

Garching, June 1-3, 2015.
Conclusions.

• The cross-correlation of the CIB and its TSZ contribution can be measured at:

\[ \frac{S}{N} = 6 \left( \frac{7 \mu K}{\sigma_{\text{noise}}} \right) \left( \frac{\Omega_{\text{sky}}}{15,000 \text{deg}^2} \right)^{\frac{1}{2}} \left( \frac{\tau}{0.05} \right) \left( \frac{T_e}{10^4 K} \right) \left( \text{Coherence} \right)^{1/2}. \]