Thermal component subtracted, $\Delta T = 3.353$ mK
Dipole component subtracted, $\Delta T = 18 \mu$K
Fluctuations are $\Delta T/T \sim 10^{-5}$. Universe had inhomogeneities at $z \sim 1000$. All components removed but background fluctuations
First Recombination - Then Reionization

After recombination, the IGM was mostly neutral (ionization fraction $< \sim 10^{-4}$). Had it stayed this way, we would not see any photons with wavelengths shorter than Lyman $\alpha$ (1216 Å) in the rest-frame of the source. H I optical depth for Ly$\alpha$ is given by (assumes $\Lambda=0$, but not relevant here).

$$\tau = 4.14 \times 10^{10} h^{-1} \frac{n_{\text{HI}}(z)/\text{cm}^{-3}}{(1+z)\sqrt{1+\Omega_m z}}$$

where $n_{\text{HI}}(z)$ is the neutral hydrogen density at redshift $z$.

Because we do see photons with $\lambda/(1+z) < 1216$ Å in QSO spectra, most (nearly all) gas must be ionized in the cosmos.

Present day neutral fraction, $x = n_{\text{HI}} / n_{\text{H}} \approx 10^{-5}$ at $z=0$. 
Where QSO light passes through ionized regions (HII regions) the UV radiation will get through.
Gunn & Peterson (1965) Effect

Gunn & Peterson proposed using Ly$\alpha$ absorption in QSO spectra as a probe of the neutral hydrogen density. For QSO at redshifts $\sim z_{\text{reionize}}$ the neutral fraction of the IGM creates a complete “GP” absorption trough.

GP optical depth to Ly$\alpha$ photons is, $f$ is the oscillator strength of Ly$\alpha$

$$\tau_{\text{GP}} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z)n_{\text{HI}},$$

(Same formula as before, but written in terms of fundamental constants gives:)

$$\tau_{\text{GP}}(z) = 4.9 \times 10^5 \left( \frac{\Omega_m b^2}{0.13} \right)^{-1/2} \left( \frac{\Omega_b b^2}{0.02} \right) \left( \frac{1+z}{7} \right)^{3/2} \left( \frac{n_{\text{HI}}}{n_H} \right)$$

where even a tiny neutral fraction, $x \sim 10^{-4}$, gives rise to complete GP absorption. This test is only sensitive to the end of reionization when the IGM is already mostly ionized (saturates for higher neutral fraction at earlier stages).
Fan et al. 2006 (from Fan, Carilli, & Keating review article).
Fan et al. 2006 (from Fan, Carilli, & Keating review article).

Analysis of these data play upper limits of $\tau \sim 0.1$ and 0.4 based on lack of complete troughs.
Best fit is $\tau_{GP} \sim (1+z)^{4.3}$

Fan et al. 2006 (from Fan, Carilli, & Keating 2006 review article).
from Fan, Carilli, & Keating 2006 review article

SDSS J1030+0524

complete GP absorption

SDSS J1148+5251

does not show clear transmission

z=6.28

z=6.42
First Recombination - Then Reionization

Stages of Reionization

Tuesday, November 27, 12
Sources of Reionization

Regardless of the details, something must reionize the Universe by $z \sim 6$. This requires that the emissivity of UV ionizing photon per comoving volume element keep up with the density of neutral hydrogen. Miralda-Escudé, Haehnelt & Rees (2000) derived:

$$\dot{N}_{ion}(z) = 10^{51.2} s^{-1} Mpc^{-3} \left( \frac{C}{30} \right) \times \left( \frac{1+z}{6} \right)^3 \left( \frac{\Omega_b h^2}{0.02} \right)^2$$

where $C = \langle n_H^2 \rangle / \langle n_H \rangle^2$ is the “clumping” factor of the IGM. Old simulations took this to be $\sim 10-100$ (Gnedin & Osteriker 1997). Latest ones are more like $C \sim 3-6$ (Pawlik et al. 2009, Finlator et al. 2009).
Sources of Reionization

**Option 1: Quasars and AGN.** Fan et al. 2001 showed that quasars could not maintain IGM ionization at $z \sim 6$. The density of bright quasars drops rapidly at $z > 2-3$ (recall previous discussion). Similar conclusions from Miralda-Escudé (2003), Yan & Windhorst (2004), and Meiksin (2005).

**Option 2: Galaxies.** Rewrite the equation for reionization in terms of SFR density (Madau et al. 1999; Bunker et al. 2004; Bouwens et al. 2005; Finkelstein, Papovich et al. 2010):

$$\dot{\rho}_* \approx (0.026 \, M_\odot \text{yr}^{-1}\text{Mpc}^{-3}) \left( \frac{1}{f_{\text{esc,rel}}} \right) \frac{C}{30} \left( \frac{1+z}{7} \right)^3$$

or in terms of the UV luminosity density:

$$\rho_{\text{UV}} = 1.25 \times 10^{25} \epsilon_{53}^{-1} \left( \frac{1+z}{8} \right)^3 \left( \frac{\Omega_b h_{70}^2}{0.0463} \right)^2 \frac{C}{f_{\text{esc}}},$$
Sources of Reionization

**Option 2: Galaxies.** Rewrite the equation for reionization in terms of SFR density (Madau et al. 1999; Bunker et al. 2004; Bouwens et al. 2005; Finkelstein, Papovich et al. 2010):
Simulating Reionization

Reionization appears not to occur instantaneously, but rather depends on local density (see Finlator et al. 2009). First things to reionize are overdense regions, then voids, then moderate-density structures.
Reionization appears not to occur instantaneously, but rather depends on local density (see Finlator et al. 2009). First things to reionize are overdense regions, then voids, then moderate-density structures.
Summary of Reionization Constraints

from Fan et al. review article