Patchy reionization and the CMB

with

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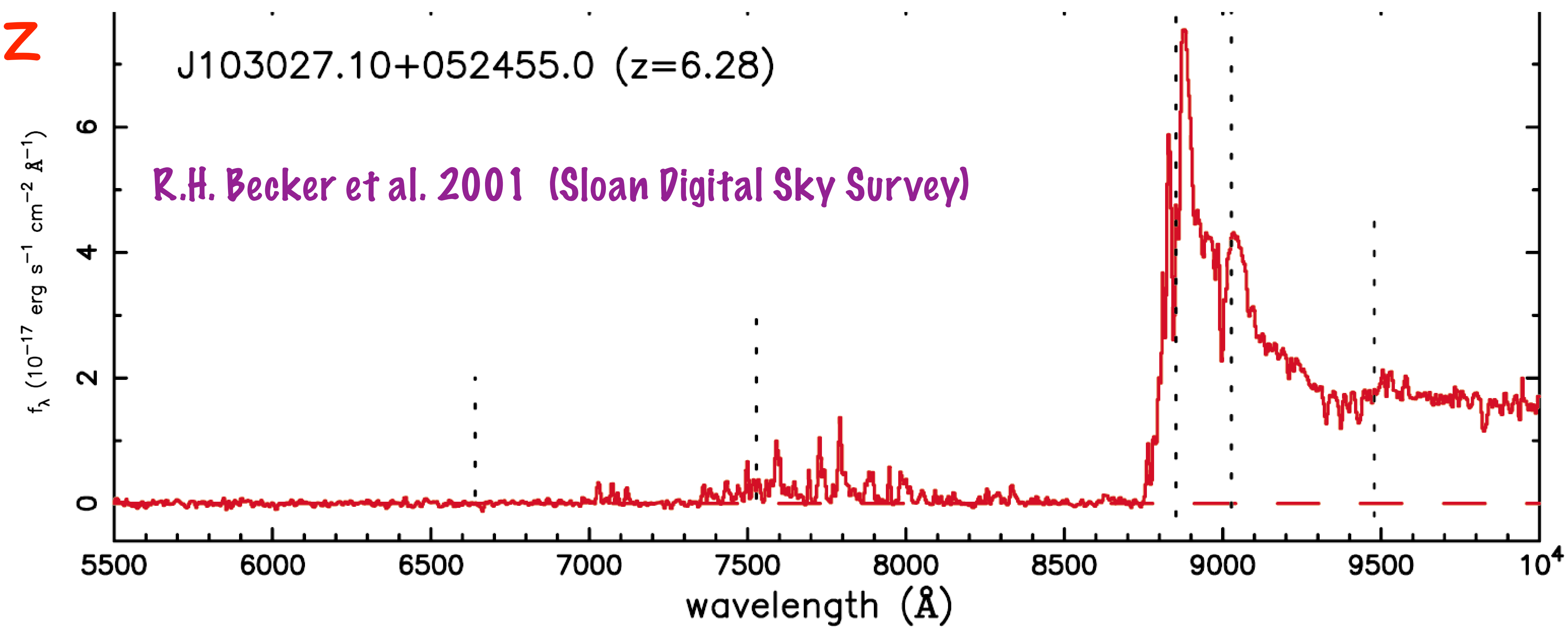
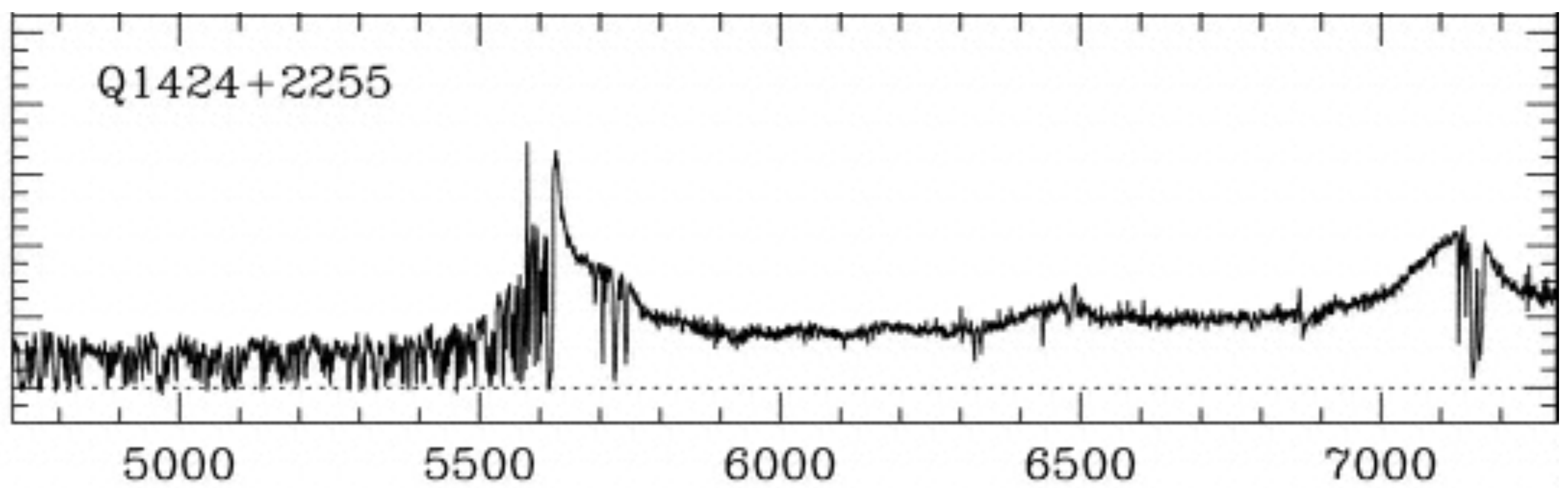
Reionization

High z



Low z



$z \sim 1000 - 1100$:

Photons decouple from electrons.

Electrons combine with protons, CMB formed.

Nearly fully ionized ⟶ Nearly fully neutral.

$z \sim 20 - 30$:

First stars form: very massive, very hot: Many ionizing photons.

$z \sim 10 - 20$:

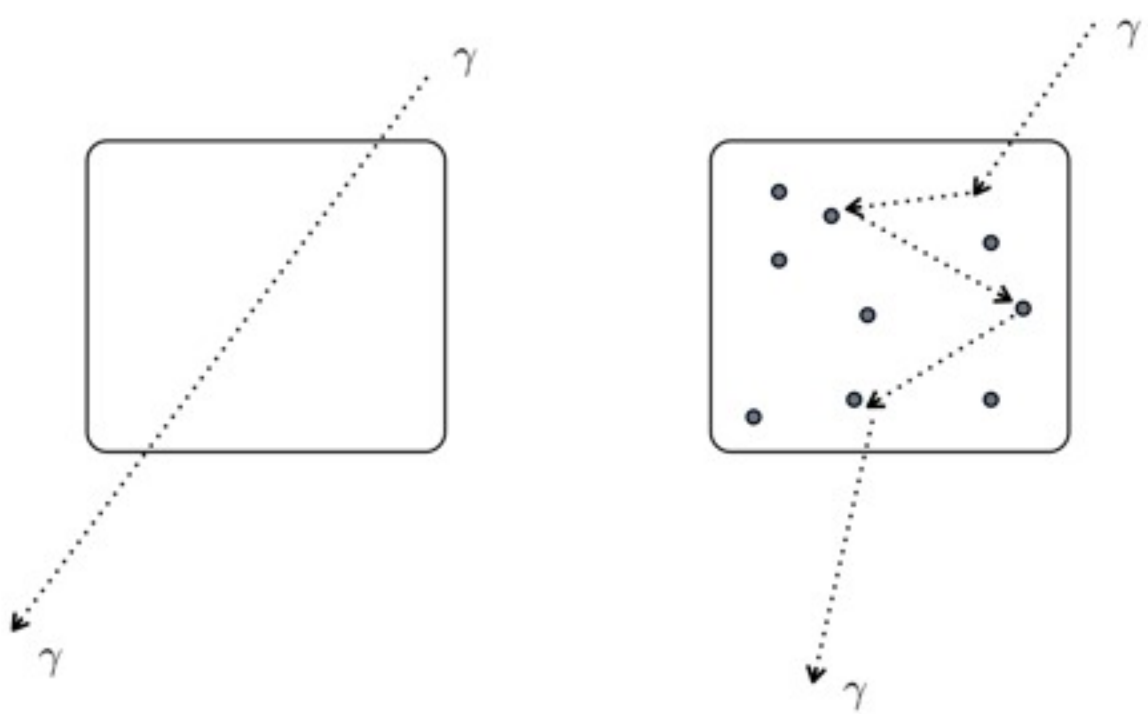
Pop. II stars, early galaxies, AGN. Ionized bubbles are formed.

Universe is partially reionized.

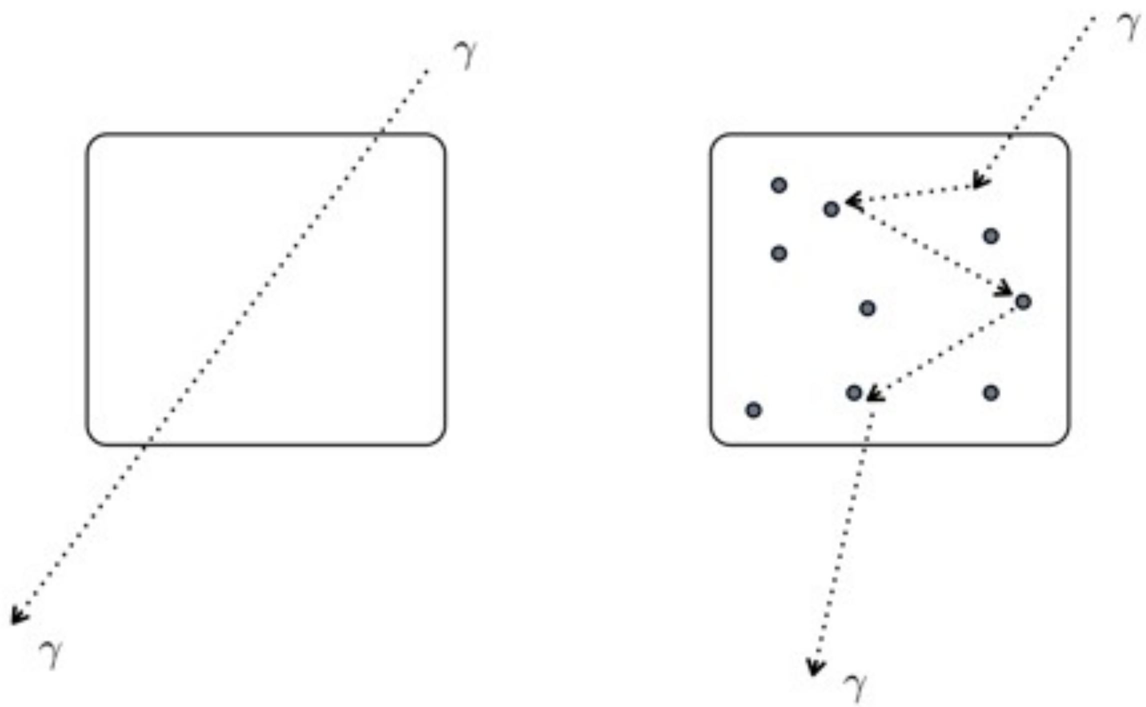
$z \sim 6 - 10$:

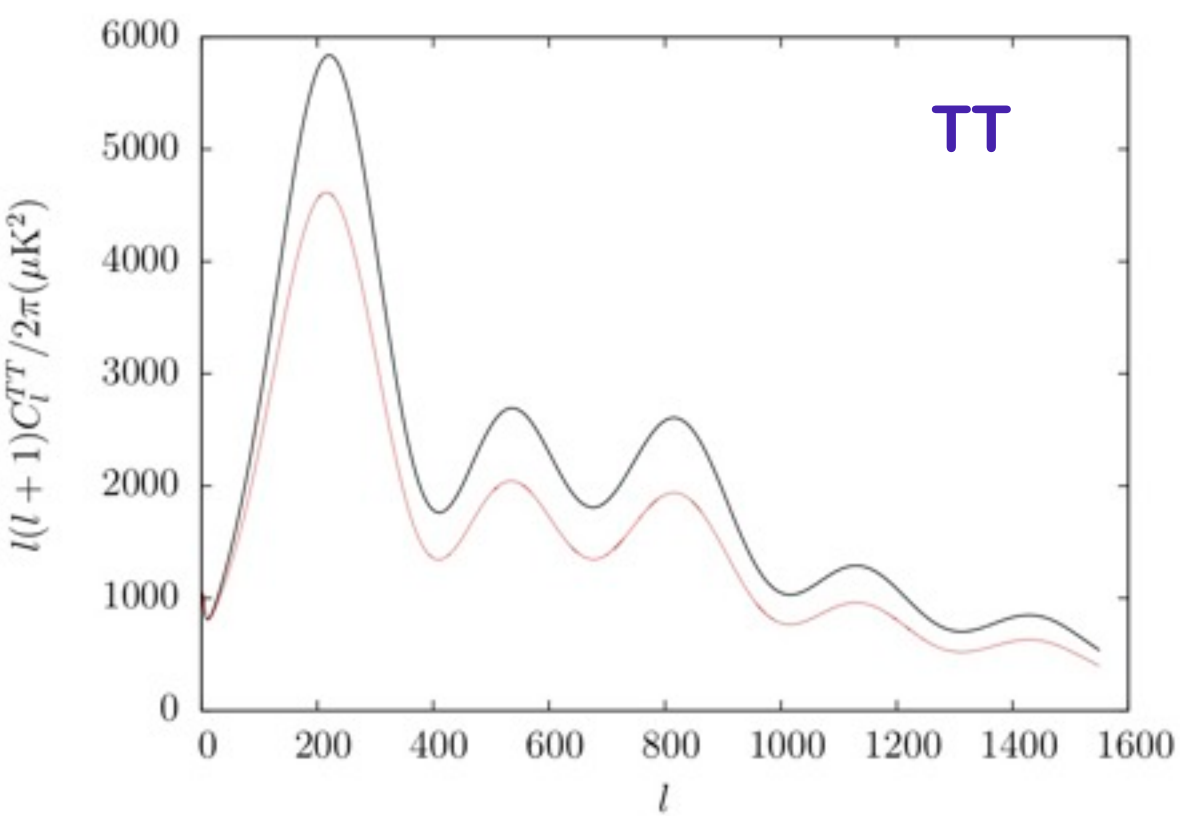
Ionized bubbles coalesce. Universe is nearly fully ionized.

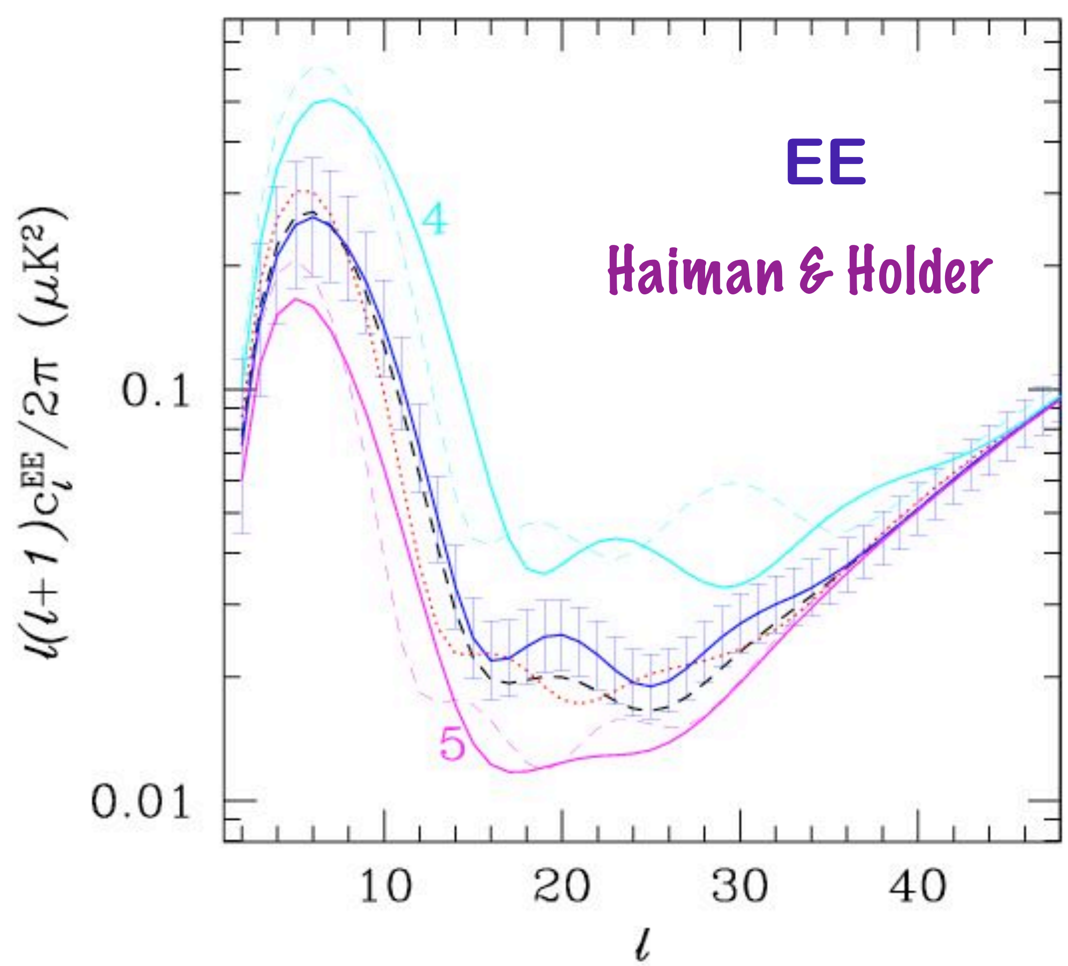
Effect on the CMB



Effect on the CMB







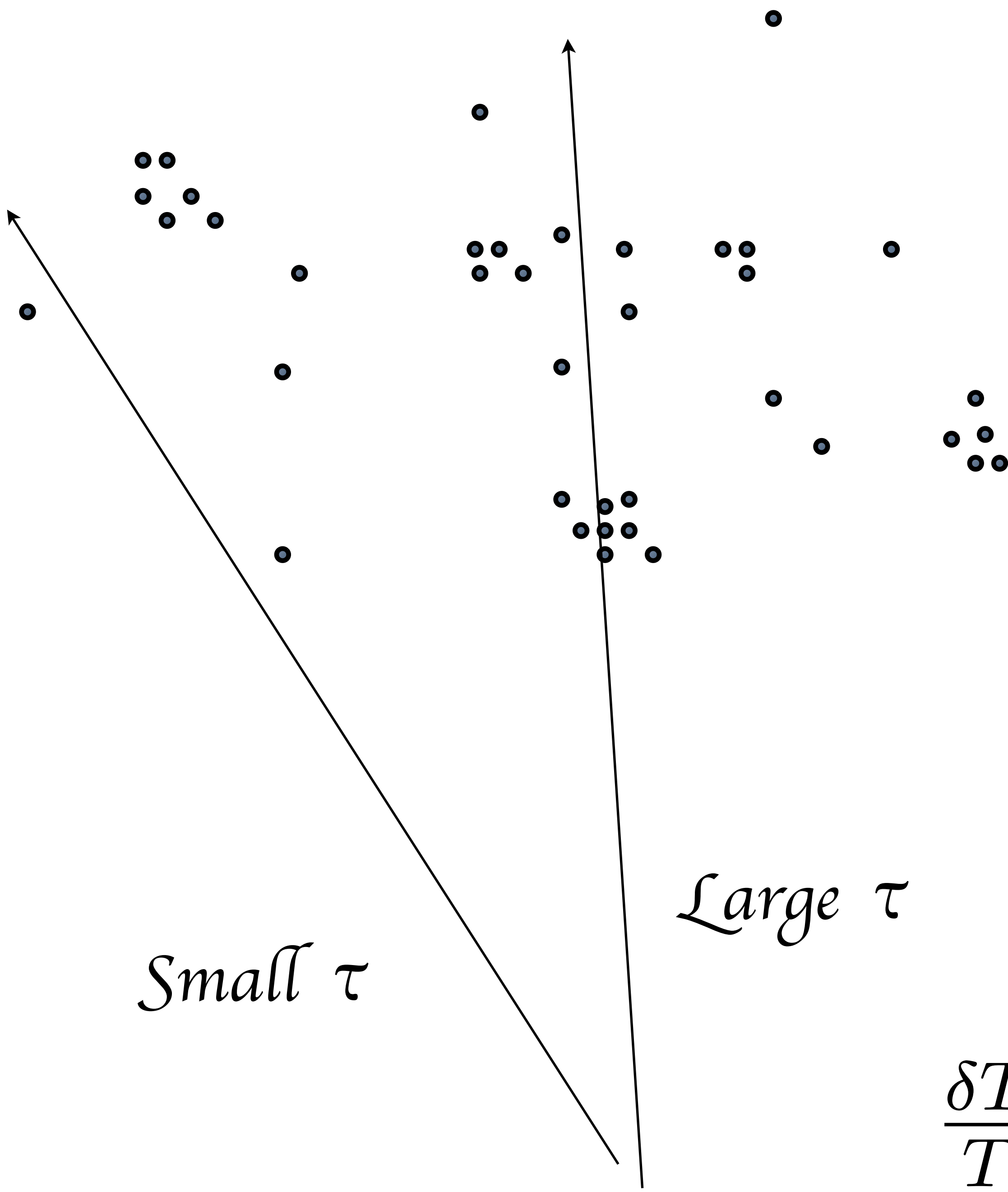
Optical depth:

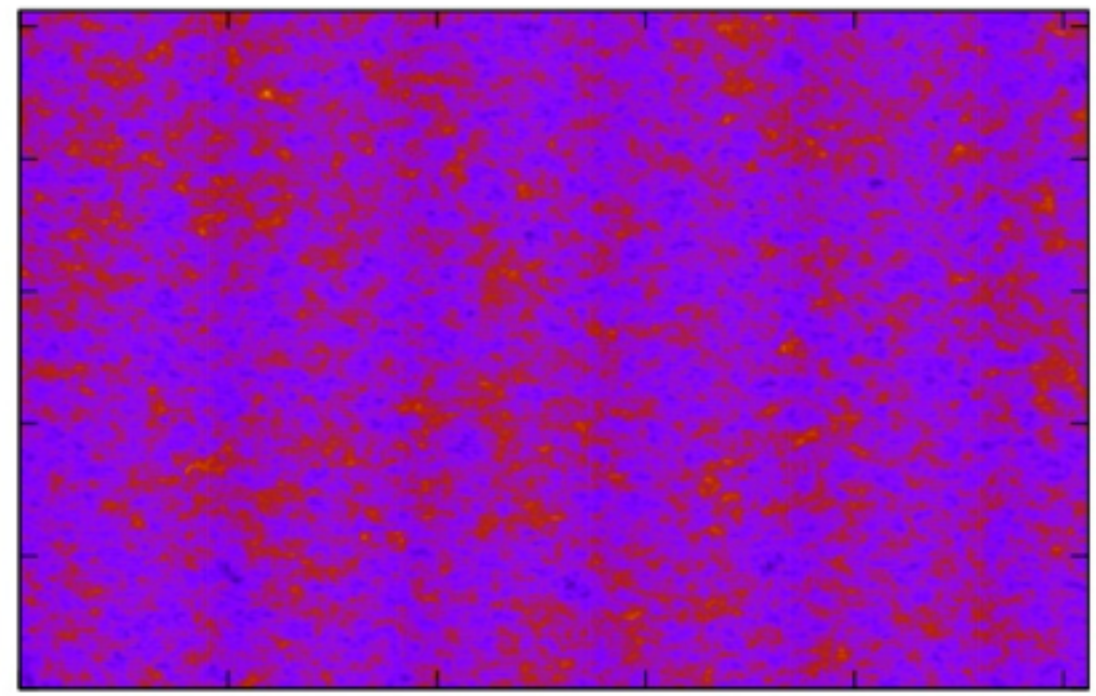
$$\tau = \int dl \; n_{\mathrm{e}}(l) \; \sigma_{\mathrm{T}}$$

$$\frac{\delta T}{T} \; (\mathrm{obs}) = \frac{\delta \mathrm{T}}{\mathrm{T}} (\mathrm{em}) \; \mathrm{e}^{-\tau} \qquad C_l^{TT} \propto A \; e^{-2\tau}$$

CMB TT spectrum damped by exp (-2τ)

What if reionization was patchy ?





$$\frac{\delta T}{T}(\hat{n}) \propto \exp -\tau(\hat{n})$$

Patchy τ is scale dependent.

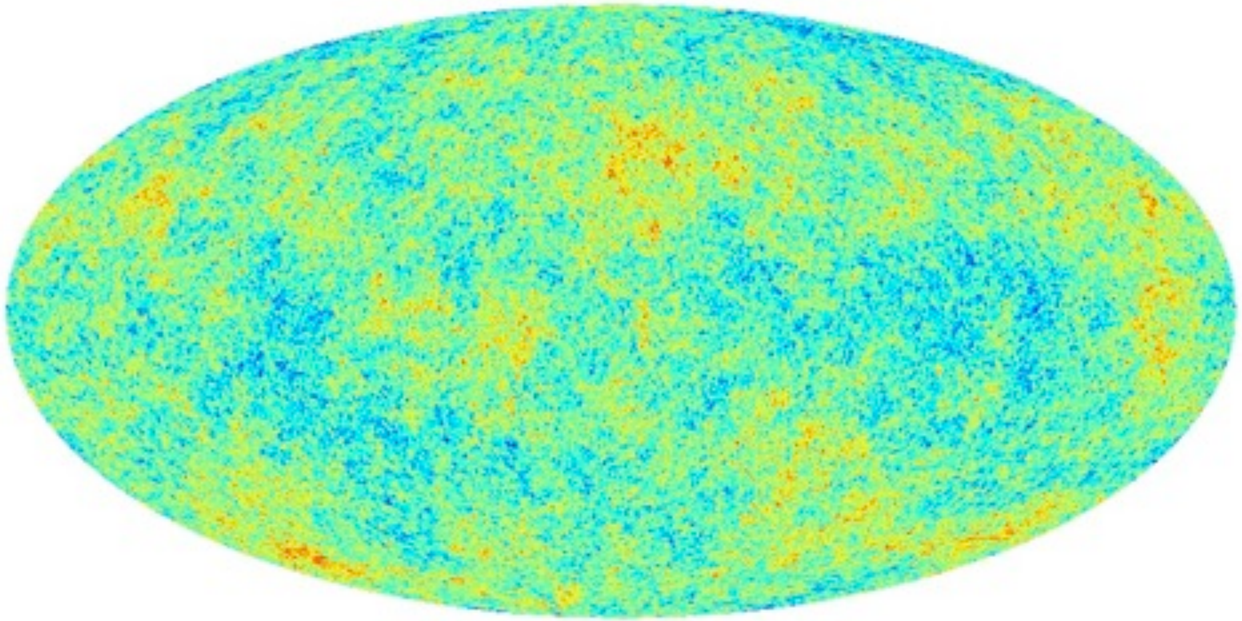
What if reionization was patchy ?

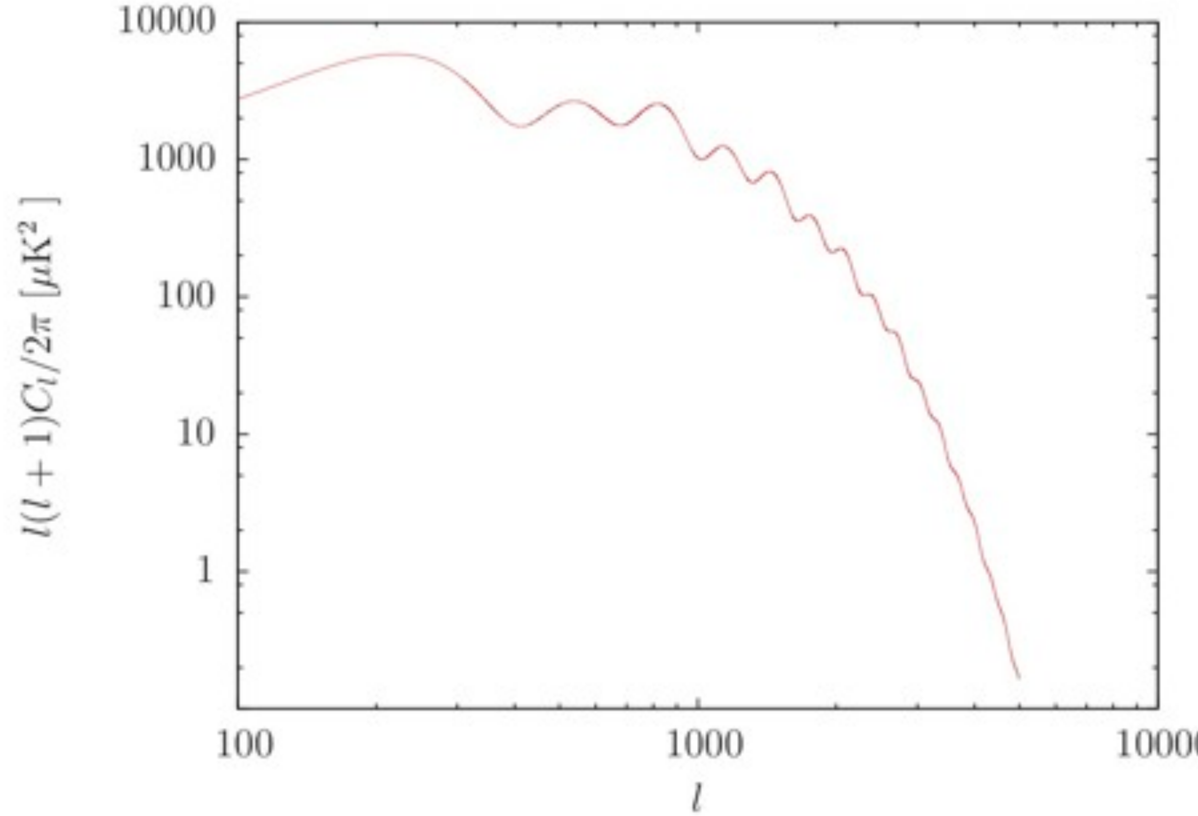
Bubble size at $z = 6 \sim$ *8 Mpc.*

Comoving distance to $z = 6 \sim$ *8000 Mpc.*

$$\theta_{1/2} \sim 1/1000$$

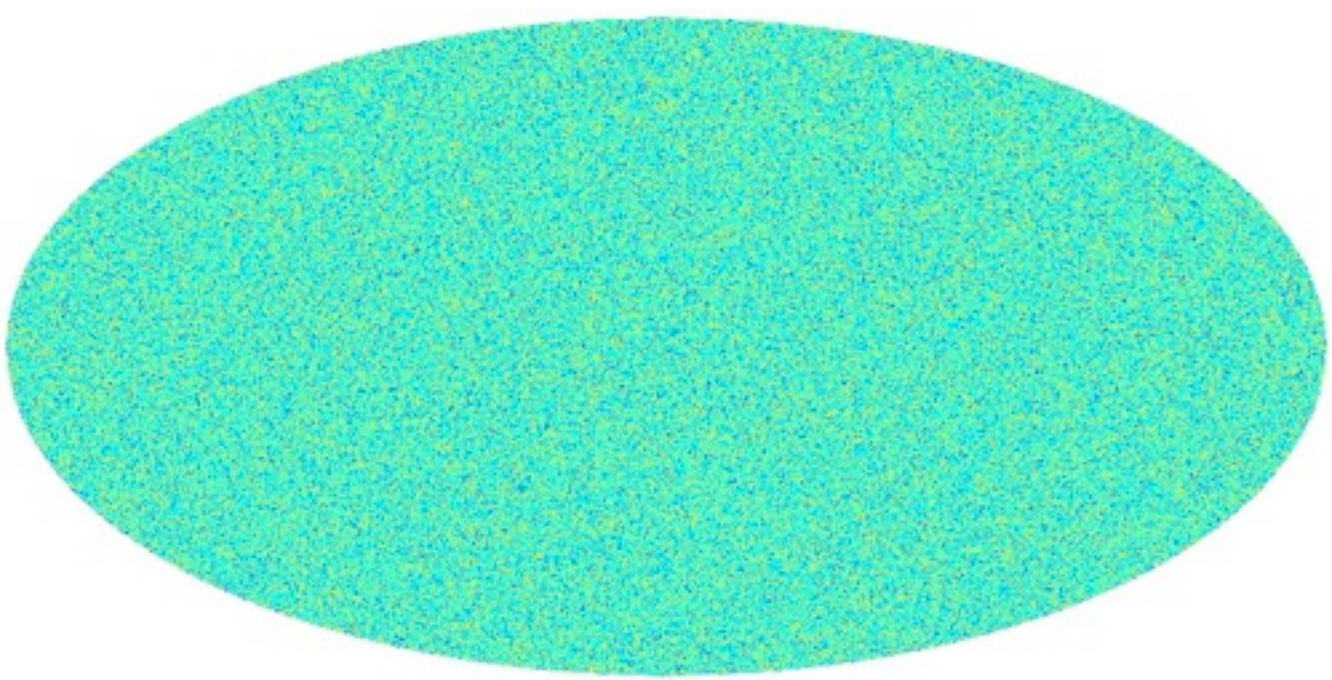
$$l \sim 3000$$

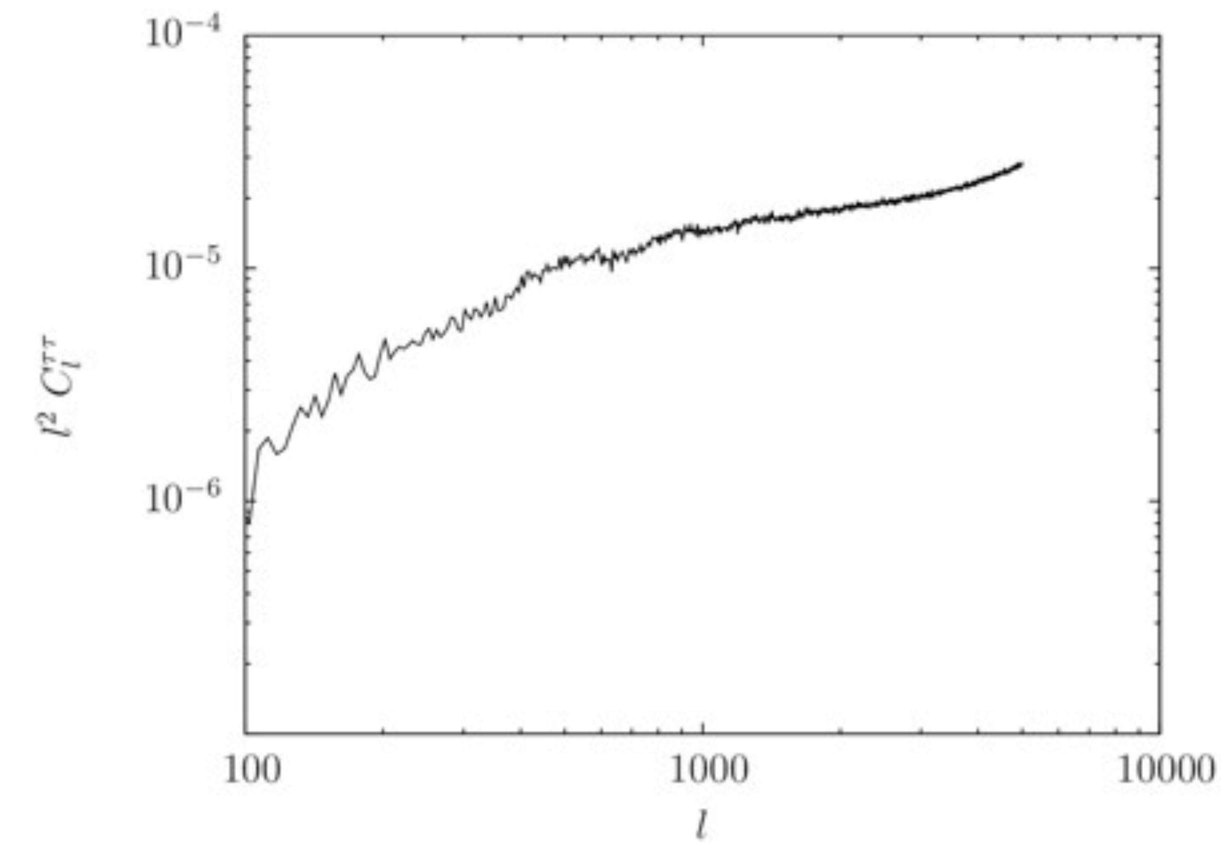




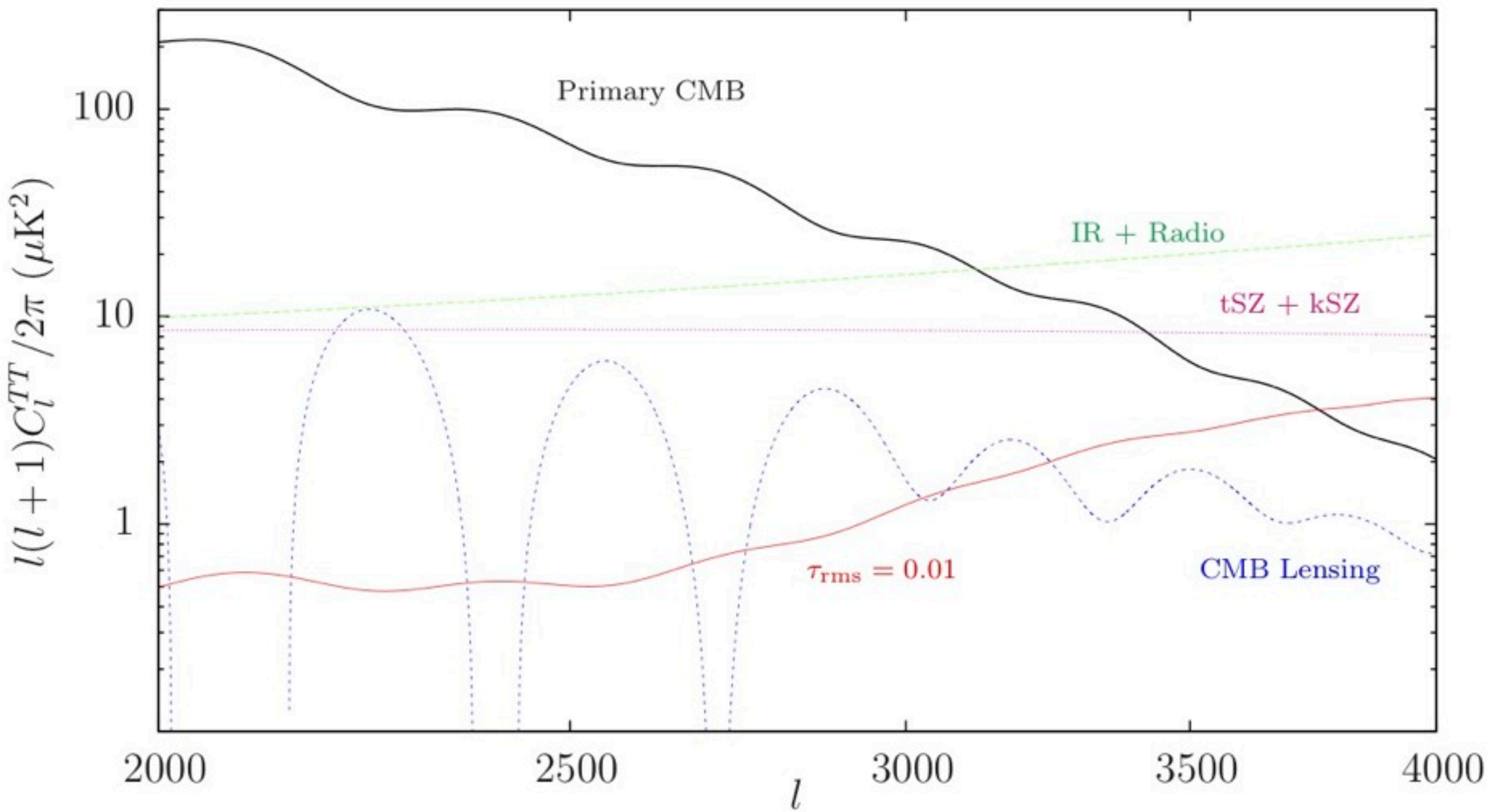
multiply

convolve





CMB spectra -



Primary CMB
IR + Radio
tSZ + kSZ
$\tau_{\rm rms} = 0.01$
CMB Lensing
100
10
1
2000
2500
3000
3500
4000
l
$l(l+1)C_l^{TT}/2\pi\ (\mu K^2)$

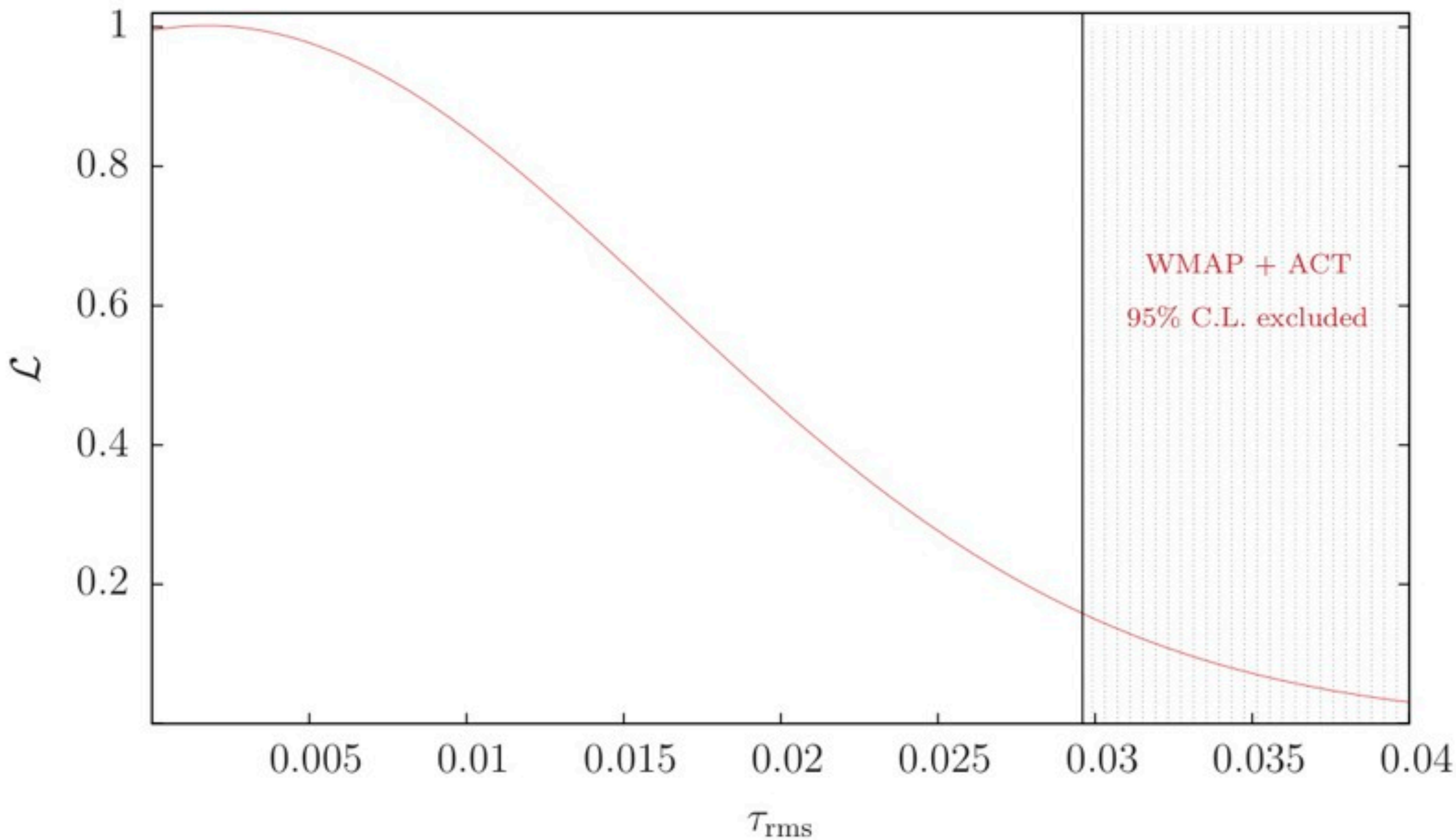
Maximum likelihood analysis with WMAP + ACT

$$\{\tau_{\rm rms}, A_{\rm s}, n_{\rm s}, h, \Omega_{\rm m}h^2, \Omega_{\rm b}h^2\}$$

J. Lesgourgues 2011

CMB Boltzmann code CLASS

Maximum likelihood analysis with WMAP + ACT



$\tau_{rms} < 0.029$ *at 95% C.L.*

Can we do better with Planck (2013) ?

Lamarre et al 2011

$f_{sky} \sim$ 65 - 70 %

For the 143 GHz channel:

12 bolometers

Noise = 62 $\mu K\, s^{1/2}$ per bolometer (for Stokes I)

= 5.2 $\mu K\, s^{1/2}$ per array.

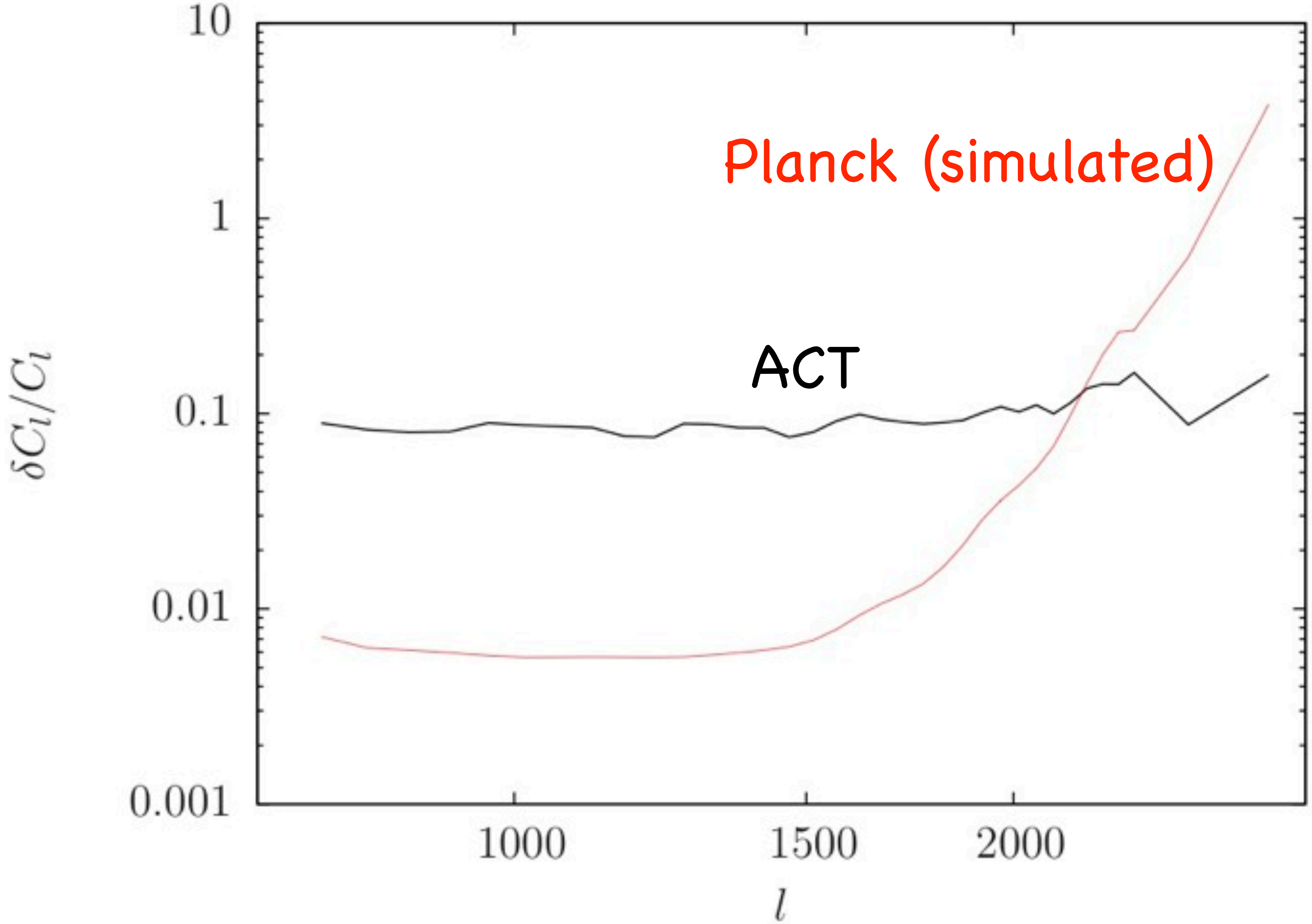
Great, but:

Beam FWHM = 7 arc minutes.

Beam effects important for $l > \frac{\sqrt{8\ \ln 2}}{7'}$ $\quad l > 1200$

Can we do better with Planck (2013) ?

unfortunately not.



Can ACTPol (2014) do better ?

Niemack et al 2010

$f_{sky} \sim 10\ \%$

For the 150 GHz channel:

Noise = 6 μK $s^{1/2}$ per array.

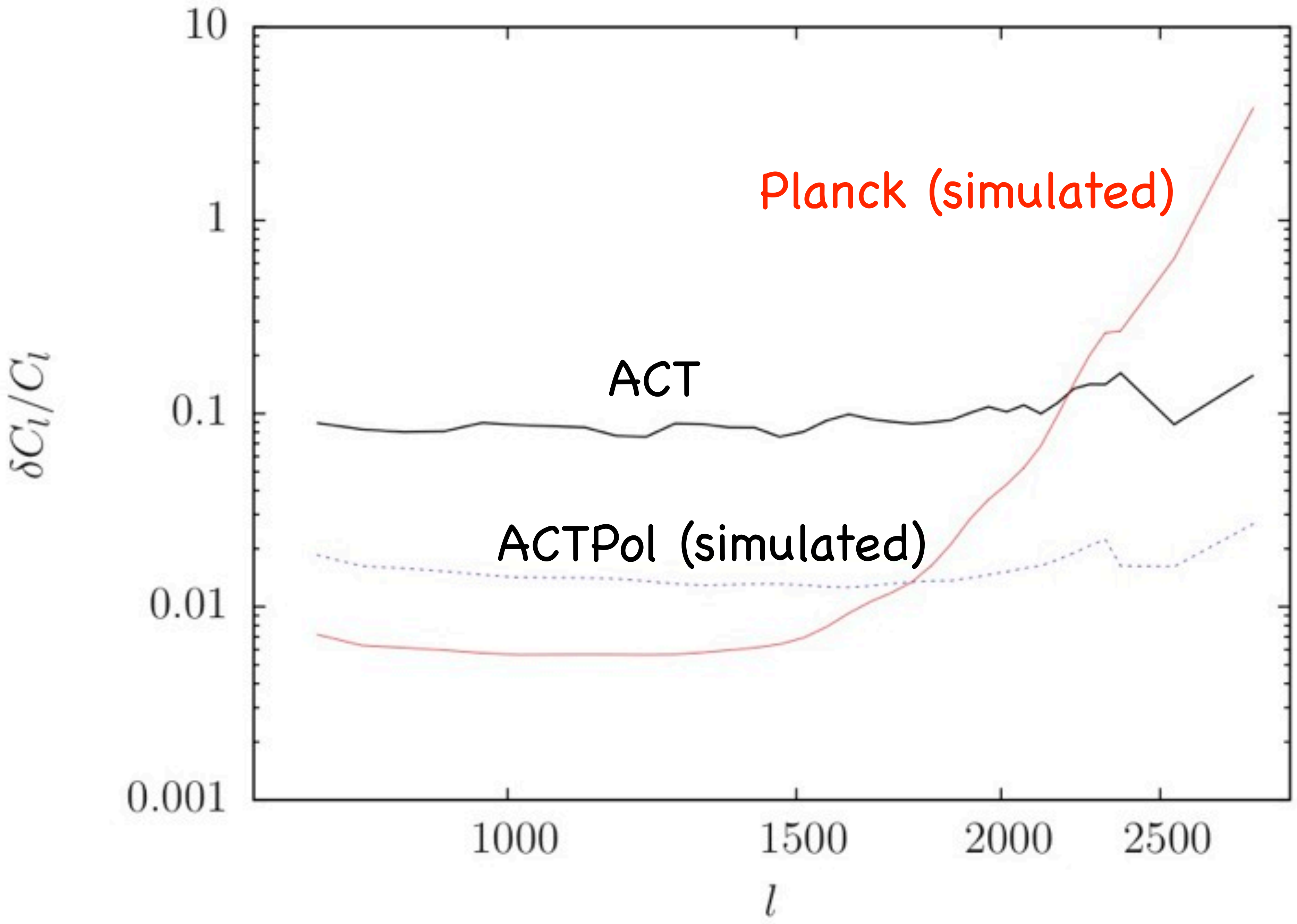
most importantly,

Beam FWHM = 1.4 arc minutes !

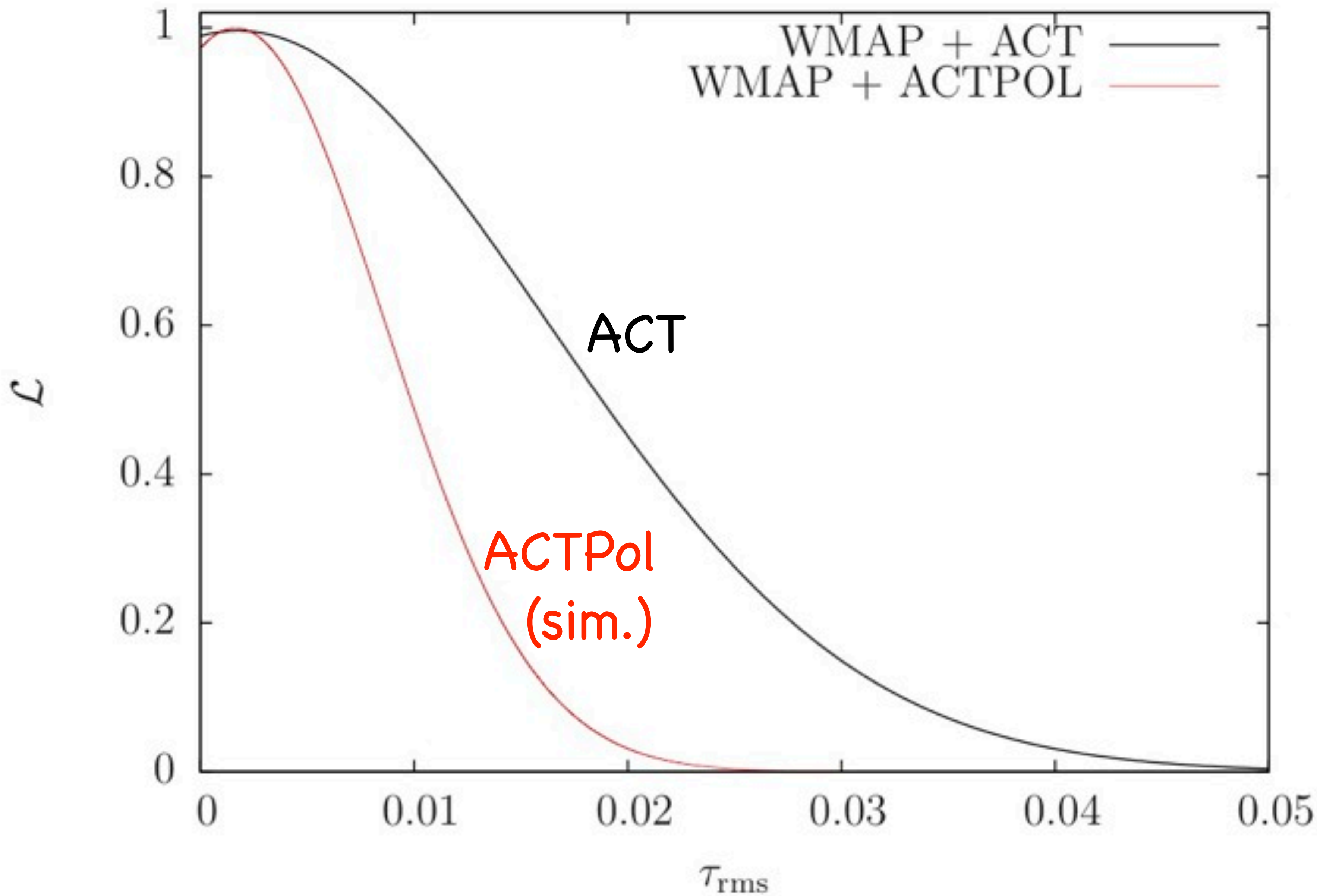
Beam effects important for $l > \frac{\sqrt{8\ \ln 2}}{7'}$ $\quad l > 5800$

Can ACTPol (2014) do better ?

Yes !



Maximum likelihood analysis with WMAP + ACTPol (simulated)



$\tau_{rms} < 0.015$ at 95% C.L. with WMAP + ACTPol

$\tau_{rms} < 0.029$ at 95% C.L. with WMAP + ACT

Can we constrain patchy τ_{rms} < 0.005 ?

Yes, with the 1-point function.

The patchy tau map has power on very small scales l > 2000.

In contrast, the primary CMB has power on large scales l < 500.

The observed map is $\frac{\delta T}{T}(\hat{n}) \times e^{-\tau(\hat{n})}$

Band pass filter the CMB map into 2 regions: Small scale map
Large scale map

Can we constrain patchy $\tau_{rms} < 0.005$?

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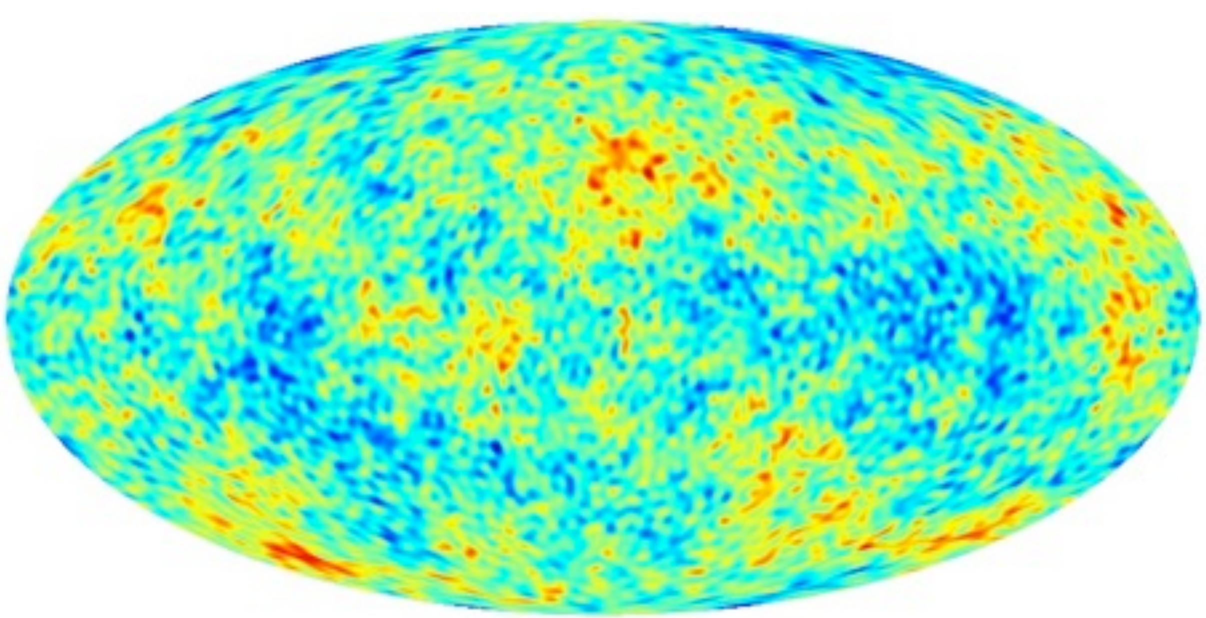
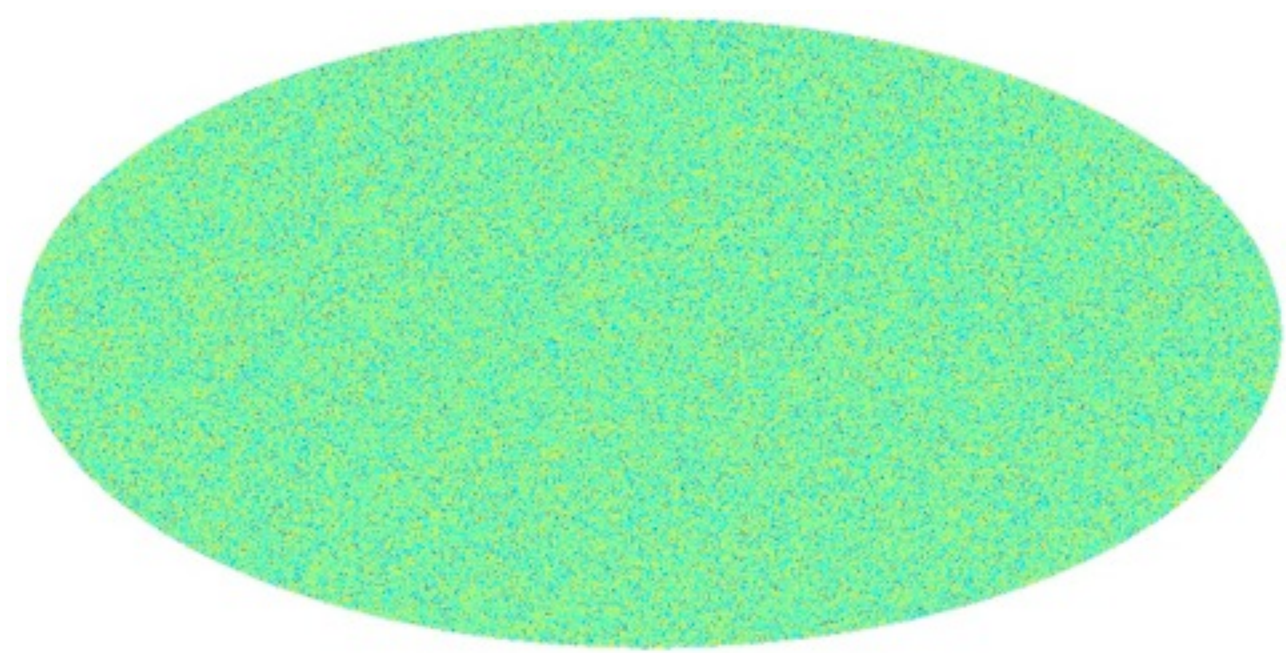
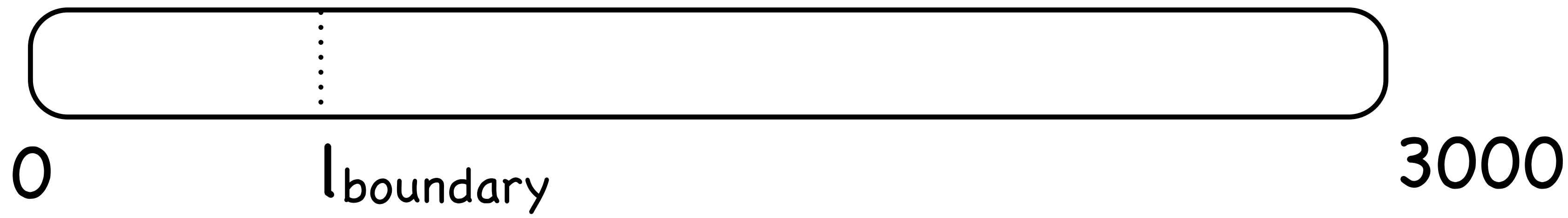




1. Choose a scale $l_{boundary}$.



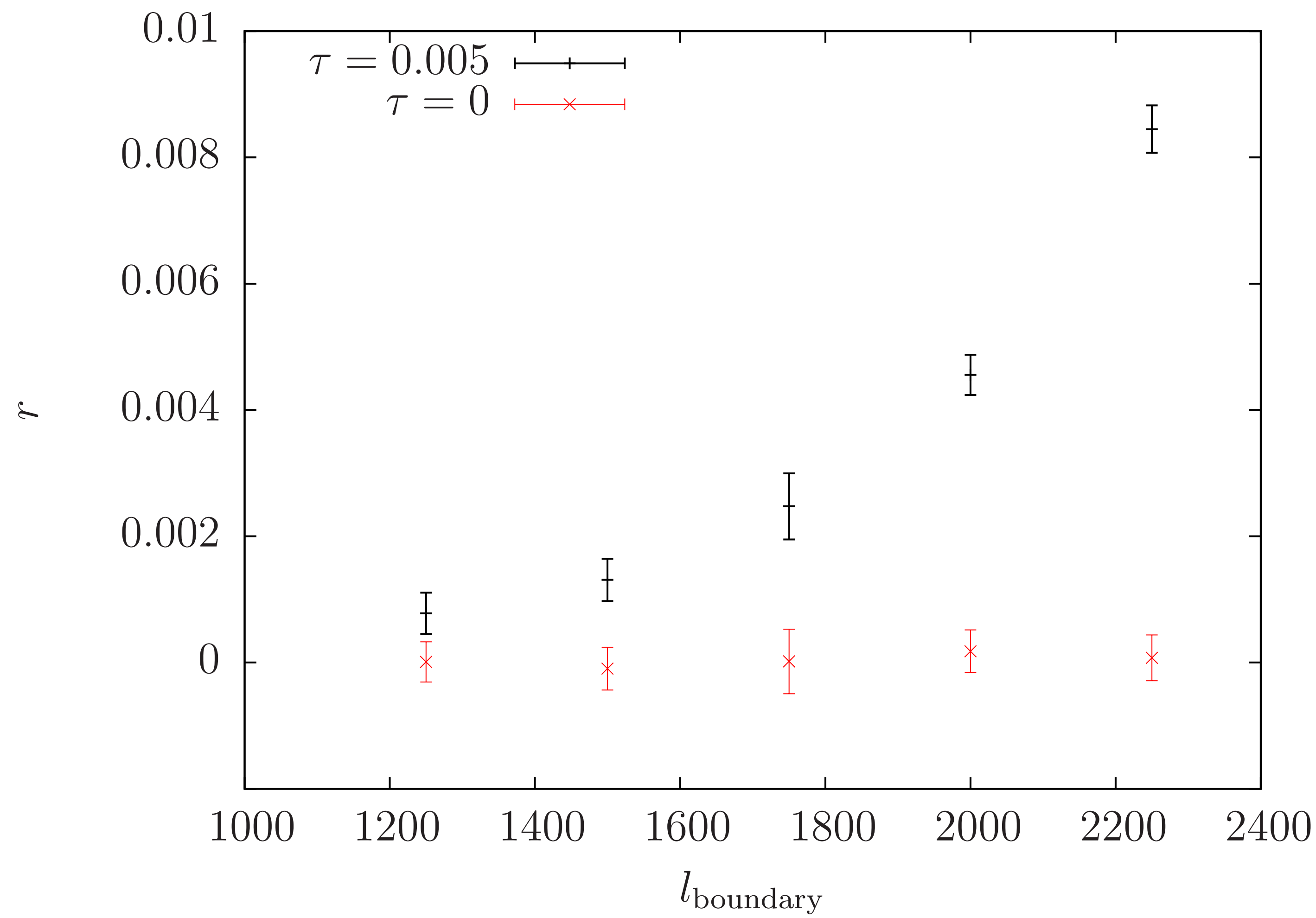
2. Use Healpix (Gorski et al.) to prepare CMB maps with scales $l < l_{boundary}$ and $l > l_{boundary}$.

3. Square the maps: $$f = T^2 - \langle T^2 \rangle$$

4. Compute the cross correlation: $$r = \frac{\langle f_{\rm low} f_{\rm high} \rangle}{\langle f_{\rm low}^2 \rangle^{1/2} \langle f_{\rm high}^2 \rangle^{1/2}}$$

5. Expect r = 0 for the primary CMB.
   $r \neq 0$ when patchy τ is present.

Cross correlation for τ_{rms} = 0.005



Simulated CMB maps using Healpix

Possible contaminants:

CMB Lensing.

Sunyaev-Zeldovich terms (t and k).

Infrared and radio background.

Conclusions:

1. The Universe is reionized between $6 < z < 20$. Ionized bubbles form around luminous sources, resulting in patchy reionization.

2. CMB photons are Thomson scattered by free electrons. The optical depth is different along different lines of sight. This introduces anisotropies on the scale of the ionized bubbles.

3. Current data excludes very patchy scenarios $\tau_{rms} > 0.03$.

4. With future data sets (ACTPol, SPTPol), and better modeling of the secondaries, one can detect small patchiness $\tau_{rms} < 0.005$.