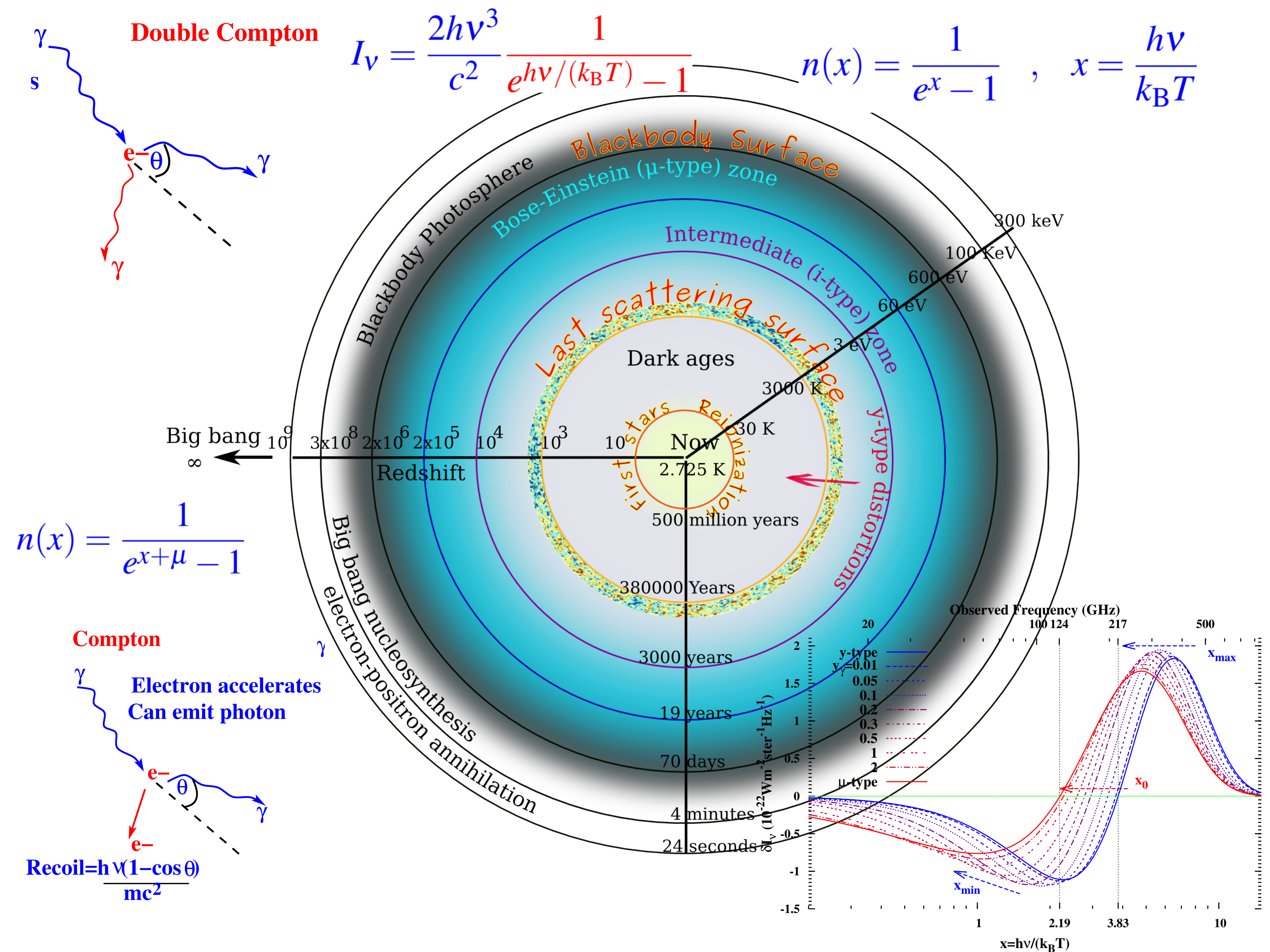
The information hidden in the anisotropies of the CMB spectral distortions

Rishi Khatri

$$\bar{y} = 10^{-6} \pm ?$$
$$\bar{y} < 2.2 \times 10^{-6}, \text{COBE-FIRAS: } < 15 \times 10^{-6}$$
$$\mu_{\rm rms}^{10'} < 6.4 \times 10^{-6}, \text{COBE-FIRAS: } \bar{\mu} < 90 \times 10^{-6}$$
$$D_\ell^{\mu T}|_{\ell=2-26} = 2.6 \pm 2.6 \times 10^{-12}\ \text{K}$$
$$f_{\rm NL} < 10^5, k_{\rm S}/k_{\rm L} = 10^6$$

tifr tata institute of fundamental research



Double Compton
$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$
$n(x) = \frac{1}{e^x - 1}$, $x = \frac{h\nu}{k_B T}$
γ
s
e−
θ
γ
γ
Blackbody Surface
Blackbody Photosphere
Bose-Einstein (μ-type) zone
Intermediate (i-type) zone
y-type distortions
Last scattering surface
Dark ages
First stars
Reionization
Now
2.725 K
30 K
3000 K
3 eV
60 eV
600 eV
100 KeV
300 keV
Big bang
∞
10^9
$3x10^8$
$2x10^6$
$2x10^5$
10^4
10^3
10
Redshift
500 million years
380000 Years
3000 years
19 years
70 days
4 minutes
24 seconds
Big bang nucleosynthesis
electron-positron annihilation
$n(x) = \frac{1}{e^{x+\mu} - 1}$
Compton
γ
Electron accelerates
Can emit photon
γ
e−
θ
γ
e−
Recoil=$\frac{h\nu(1-\cos\theta)}{mc^2}$
Observed Frequency (GHz)
20
100 124
217
500
y-type
y_γ=0.01
0.05
0.1
0.2
0.3
0.5
1
2
μ-type
x_{max}
x_0
x_{min}
δI_ν (10^{-22}Wm^{-2}ster^{-1}Hz^{-1})
2
1.5
1
0.5
0
-0.5
-1
-1.5
1
2.19
3.83
10
$x=h\nu/(k_B T)$

Bose-Einstein spectrum- Chemical potential (μ)

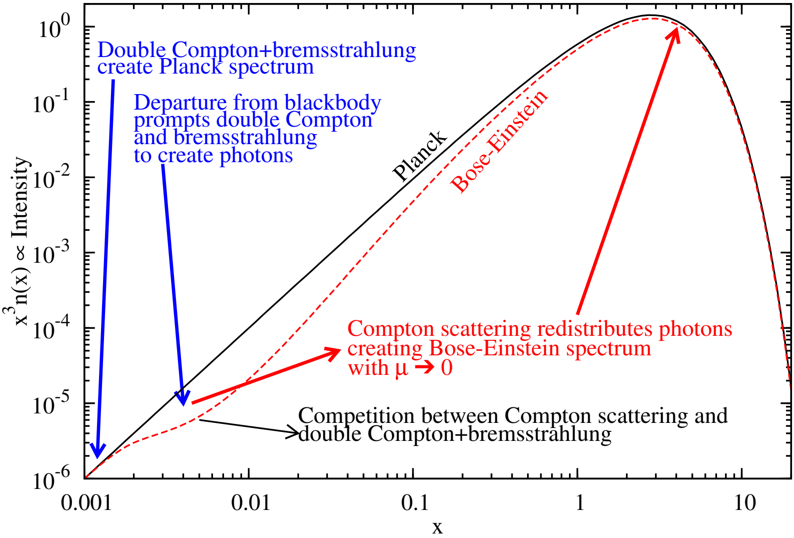
$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

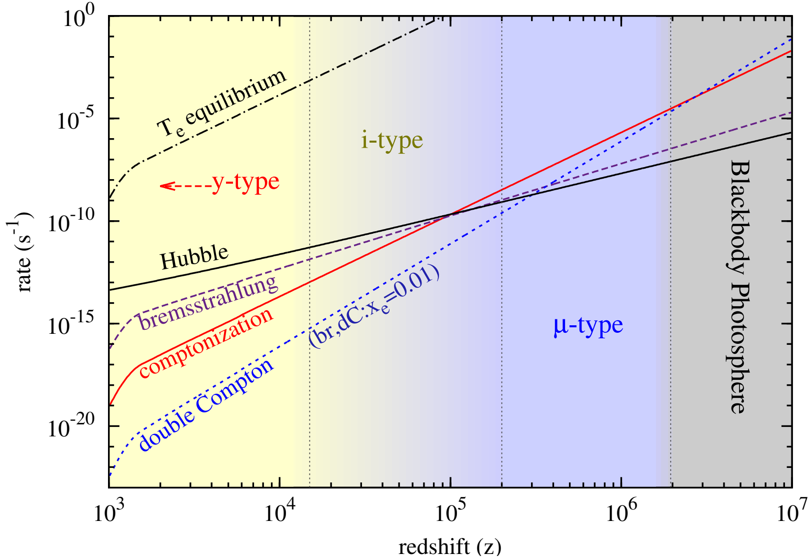
Idea behind analytic solutions:

If we know rate of production of photons and energy injection rate, we can calculate the evolution/production of μ (and T)

Creation of CMB Planck spectrum

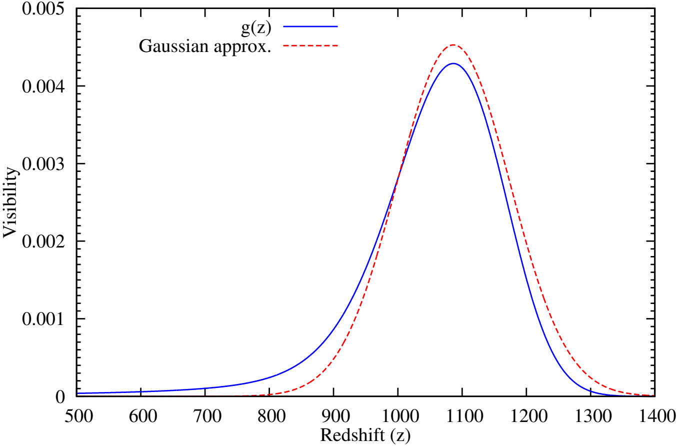


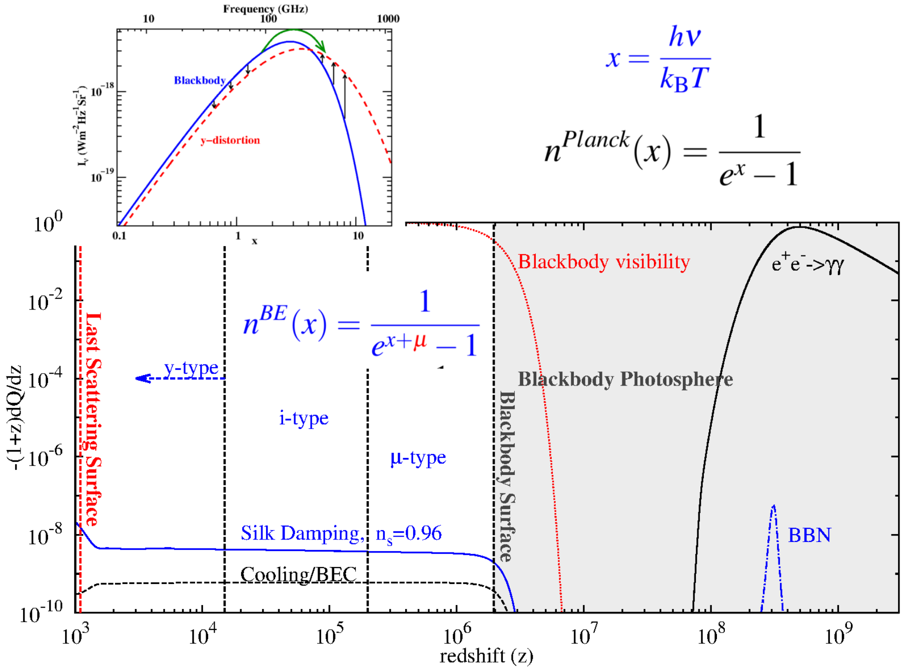
Creation of CMB Planck spectrum



The last scattering surface

Define by Thomson scattering $\dot{\tau} = n_e \sigma_T c, g(z) = \dot{\tau} e^{-\tau}$



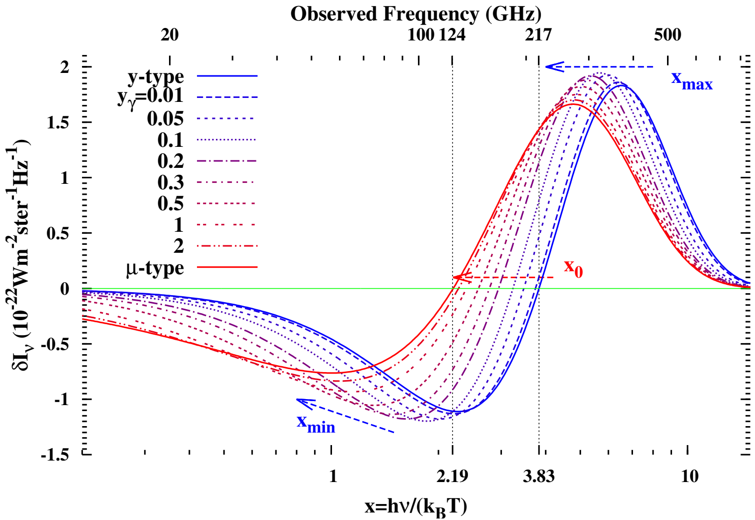


Frequency (GHz)
10
100
1000
Blackbody
y–distortion
I_ν ($Wm^{-2}Hz^{-1}Sr^{-1}$)
10^{-18}
10^{-19}
0.1
1
x
10
$x = \frac{h\nu}{k_B T}$
$n^{Planck}(x) = \frac{1}{e^x - 1}$
$n^{BE}(x) = \frac{1}{e^{x+\mu} - 1}$
Blackbody visibility
$e^+e^- \to \gamma\gamma$
Last Scattering Surface
y-type
i-type
μ-type
Blackbody Photosphere
Blackbody Surface
BBN
Silk Damping, n_s=0.96
Cooling/BEC
-(1+z)dQ/dz
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8
10^9
redshift (z)

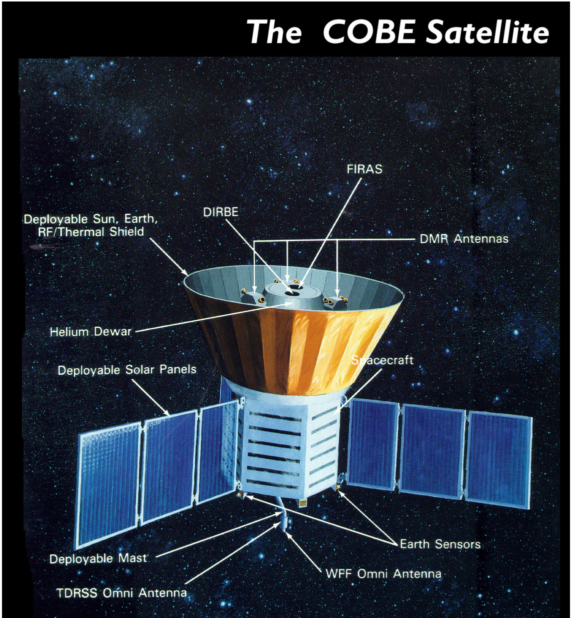
Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

Solve Kompaneets equation with initial condition of $y-$type solution.

$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n+n^2+\frac{T_e}{T}\frac{\partial n}{\partial x}\right), \quad \frac{T_e}{T} = \frac{\int (n+n^2)x^4 dx}{4\int nx^3 dx}$$

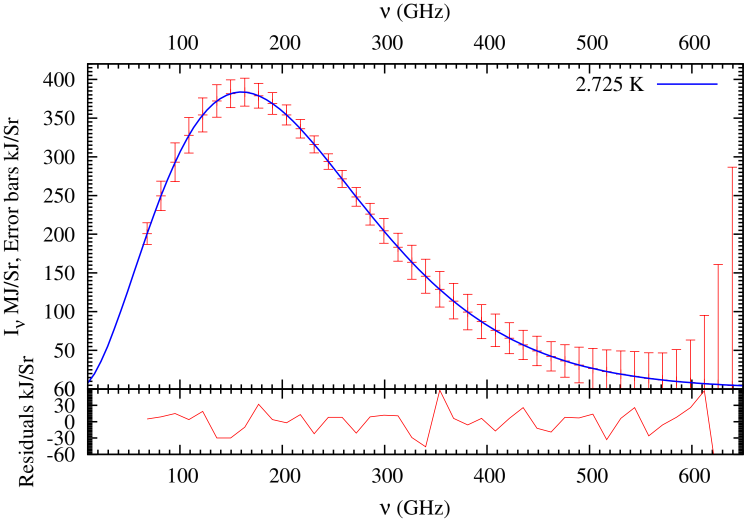


25 years ago: Cosmic Background Explorer (COBE) 1989-1993



No deviations from a Planck spectrum at $\sim 10^{-4}$

Fixsen et al. 1996, Fixsen and Mather 2002



y-type (Sunyaev-Zeldovich effect) from cluster Abell 2319 seen by Planck

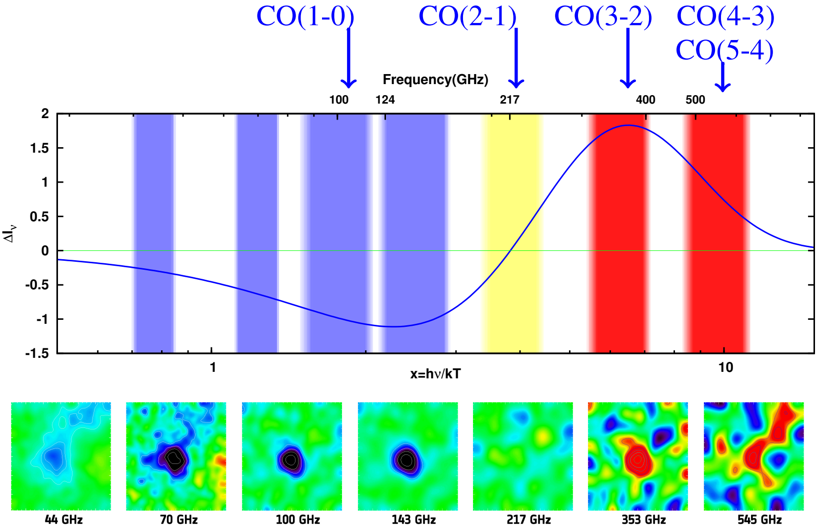
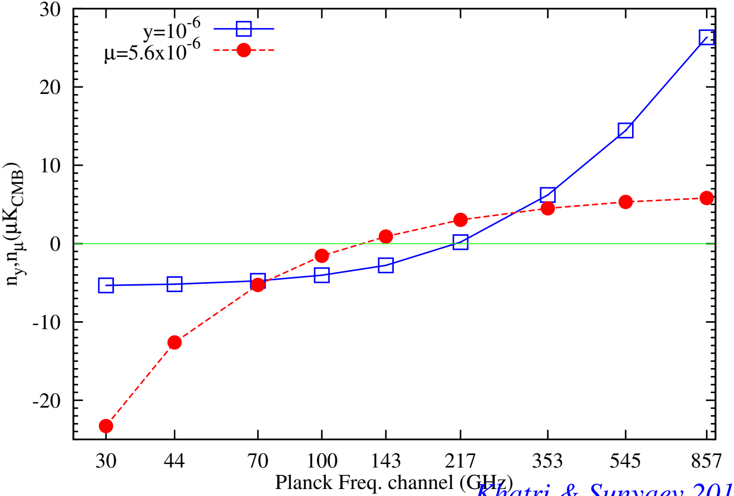


Image credit: ESA / HFI & LFI Consortia

Each Planck frequency channel contains contribution from many components

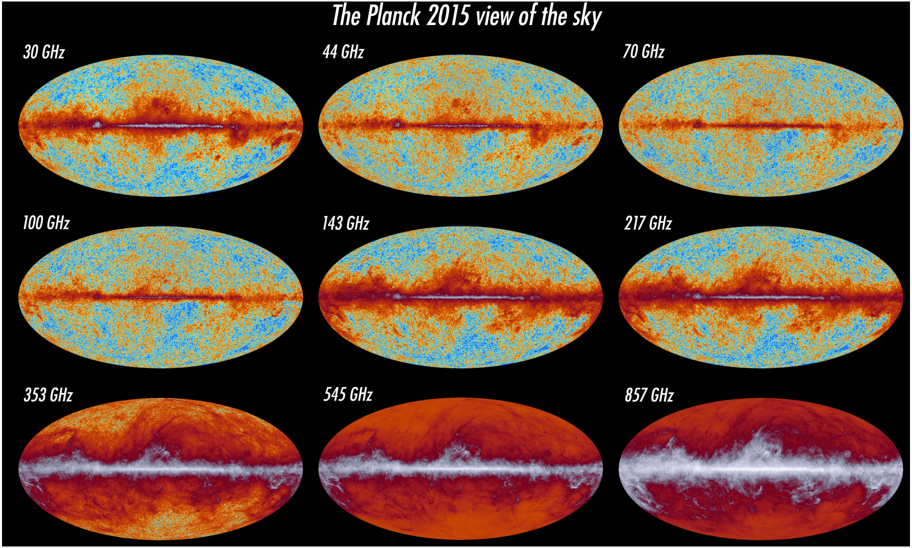
Sunyaev-Zeldovich or *y*-distortion signal is a weak signal $\lesssim 100\ \mu$K except in the central part of strong nearby clusters



Khatri & Sunyaev 2015

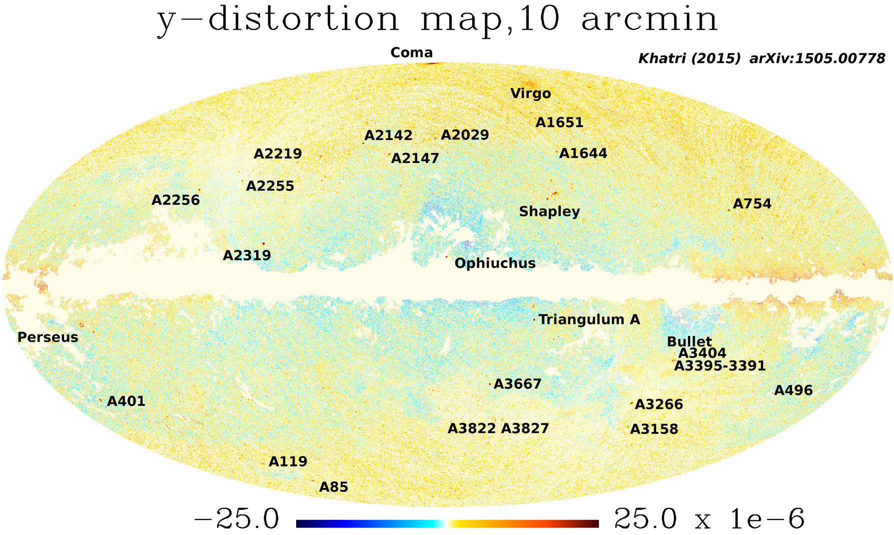
Combine Planck frequency maps to filter out the desired signal

Planck collaboration/ESA 2015



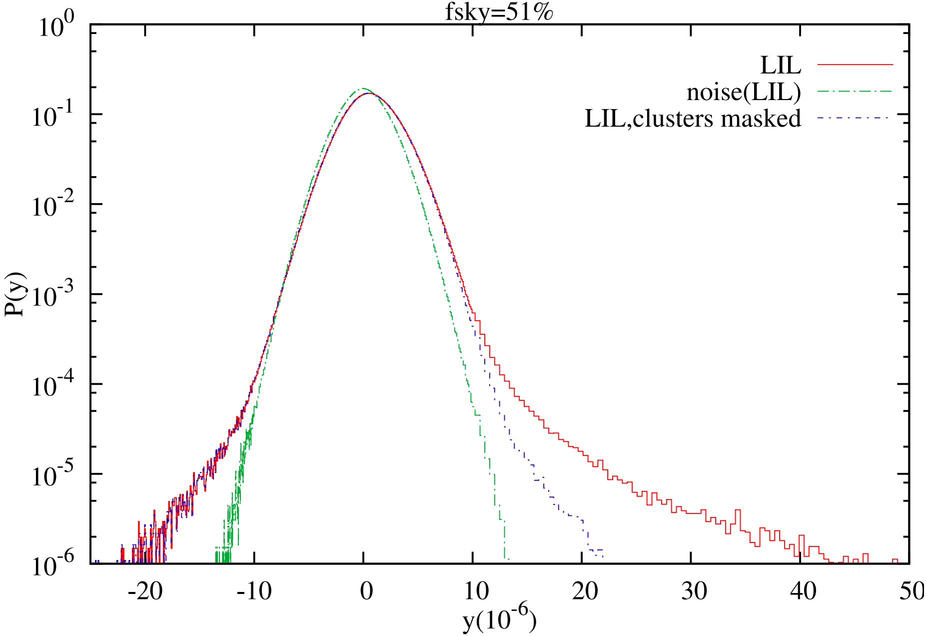
SZ/y-distortion

y-distortion map



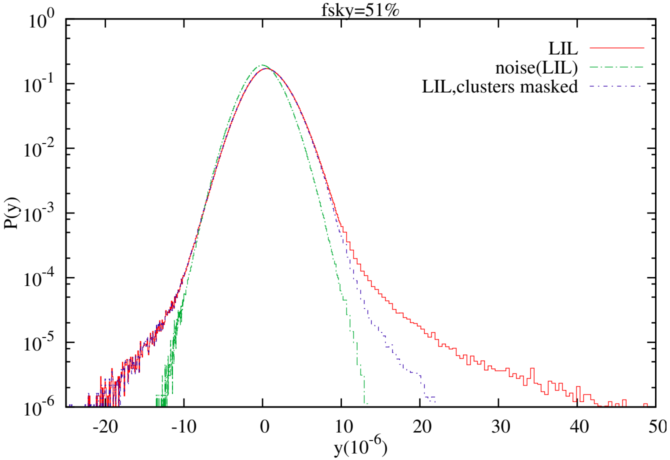
Map pdfs (*Khatri & Sunyaev 2015*)

skewness even at small *y* as predicted (*Rubino-Martin & Sunyaev 2003*)



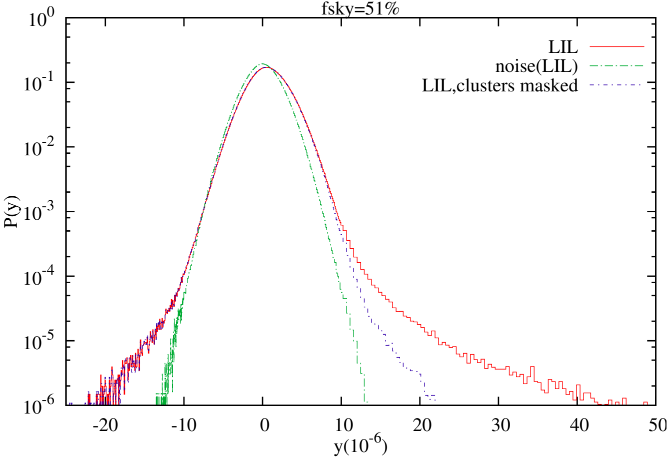
New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

(Khatri & Sunyaev 2015)



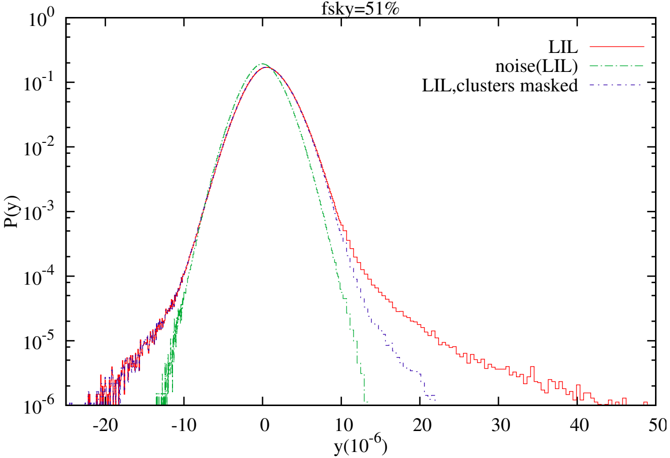
New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

average the full pdf: $\langle y \rangle \approx 1.0 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*



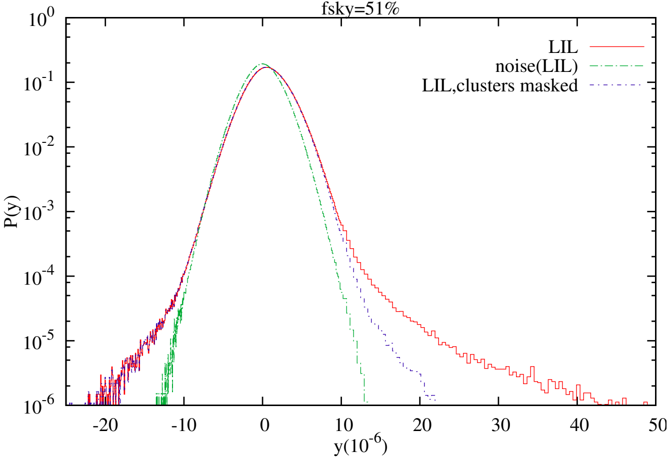
New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

average the positive tail: $\langle y \rangle < 2.2 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*



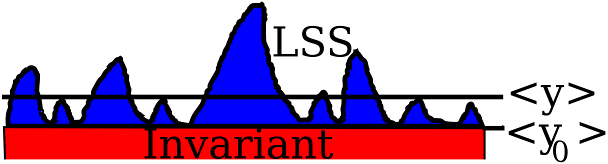
New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

average the positive tail: $\langle y \rangle < 2.2 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*



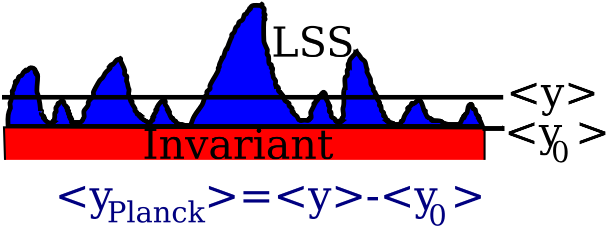
6.8 times stronger compared to the COBE-FIRAS upper limit:
$\langle y \rangle < 15 \times 10^{-6}$ *(Fixsen et al. 1996)*

Planck is sensitive to only the fluctuations in *y*



$$\langle y_{Planck} \rangle = \langle y \rangle - \langle y_0 \rangle$$

Planck is sensitive to only the fluctuations in y



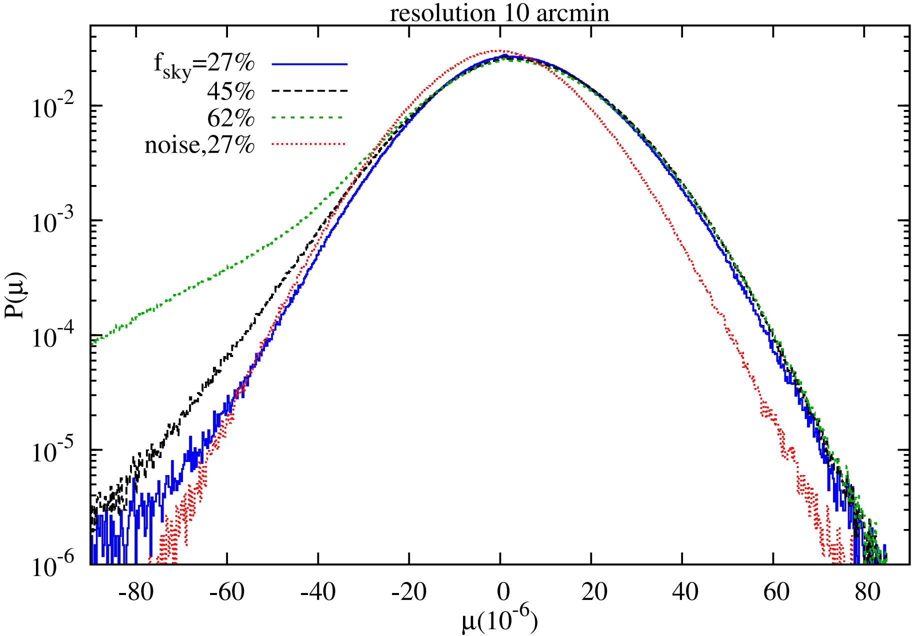
- In the standard model of cosmology the invariant component is smaller, $\langle y_0 \rangle \ll \langle y \rangle$
- This upper limits rules out models involving preheating of the IGM

  Springel et al. 2001,Munshi et al. 2012
- Most simulations predict $\langle y \rangle \ll\sim 10^{-6} - 3 \times 10^{-6}$

  Refregier et al. 2000, Nath & Silk 2001, White et al. 2002,Schaefer et al. 2006
- Indications from our analysis of Planck that true value may be closer to $\approx 10^{-6}$ (*Khatri & Sunyaev 2015*).

μ-distortion

(Khatri & Sunyaev 2015)



Upper limit on the μ-distortion fluctuations

- Variance: $\sigma^2_{\rm map} = \mu^2_{\rm rms} + \sigma^2_{\rm noise}$
- Remove the noise contribution from map variance using half-ring half difference maps from Planck
- Remove mean $\langle\mu\rangle$ to get the central variance, $\mu^{\rm central}_{\rm rms} \equiv (\mu^2_{\rm rms} - \langle\mu\rangle^2)^{1/2}$

Upper limit on the μ-distortion fluctuations

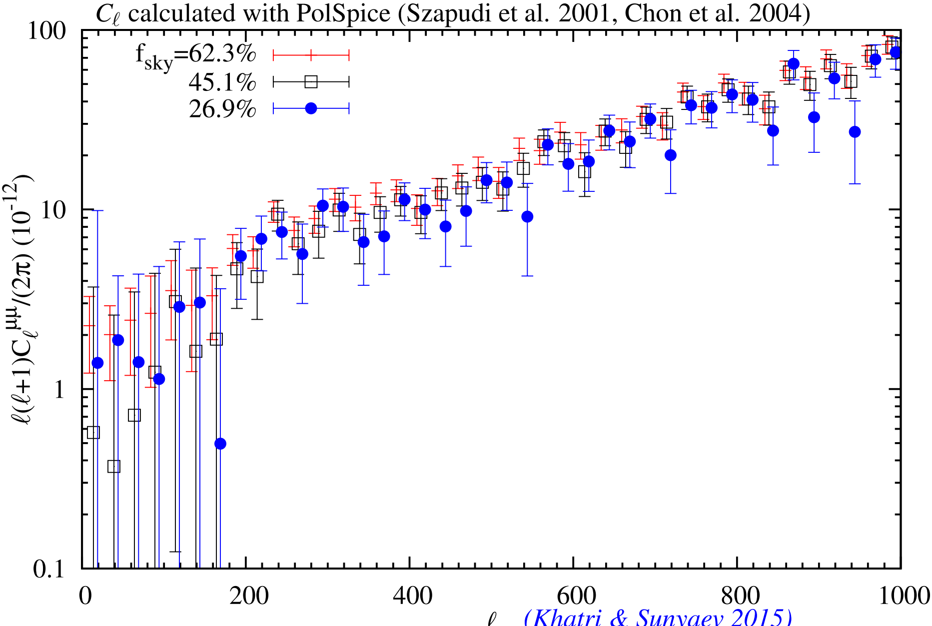
- Variance: $\sigma^2_{\rm map} = \mu^2_{\rm rms} + \sigma^2_{\rm noise}$
- Remove the noise contribution from map variance using half-ring half difference maps from Planck
- Remove mean $\langle\mu\rangle$ to get the central variance, $\mu^{\rm central}_{\rm rms} \equiv (\mu^2_{\rm rms} - \langle\mu\rangle^2)^{1/2}$

- Limit from Planck data *(Khatri & Sunyaev 2015)*: $\mu^{\rm central}_{\rm rms} < 6.4 \times 10^{-6}$ at 10' resolution (2×10^{-6} at 30') assuming all signal is due to contamination from y-distortion and foregrounds

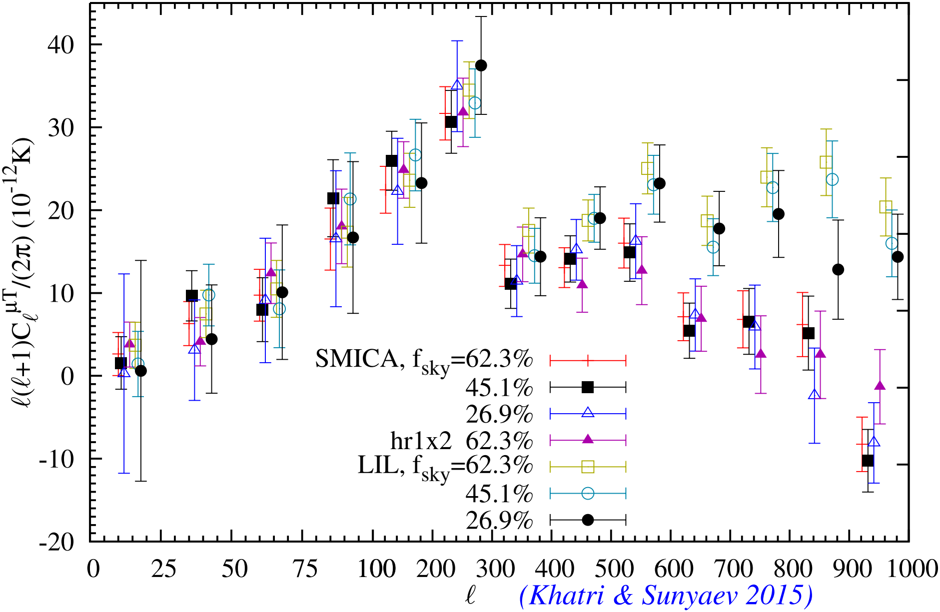
Upper limit on the μ-distortion fluctuations

- Variance: $\sigma_{\rm map}^2 = \mu_{\rm rms}^2 + \sigma_{\rm noise}^2$
- Remove the noise contribution from map variance using half-ring half difference maps from Planck
- Remove mean $\langle\mu\rangle$ to get the central variance, $\mu_{\rm rms}^{\rm central} \equiv (\mu_{\rm rms}^2 - \langle\mu\rangle^2)^{1/2}$
- Limit from Planck data *(Khatri & Sunyaev 2015)*: $\mu_{\rm rms}^{\rm central} < 6.4 \times 10^{-6}$ at 10' resolution (2×10^{-6} at 30') assuming all signal is due to contamination from y-distortion and foregrounds
- COBE limit: $\langle\mu\rangle < 90 \times 10^{-6}$ *(Fixsen et al. 1996)*

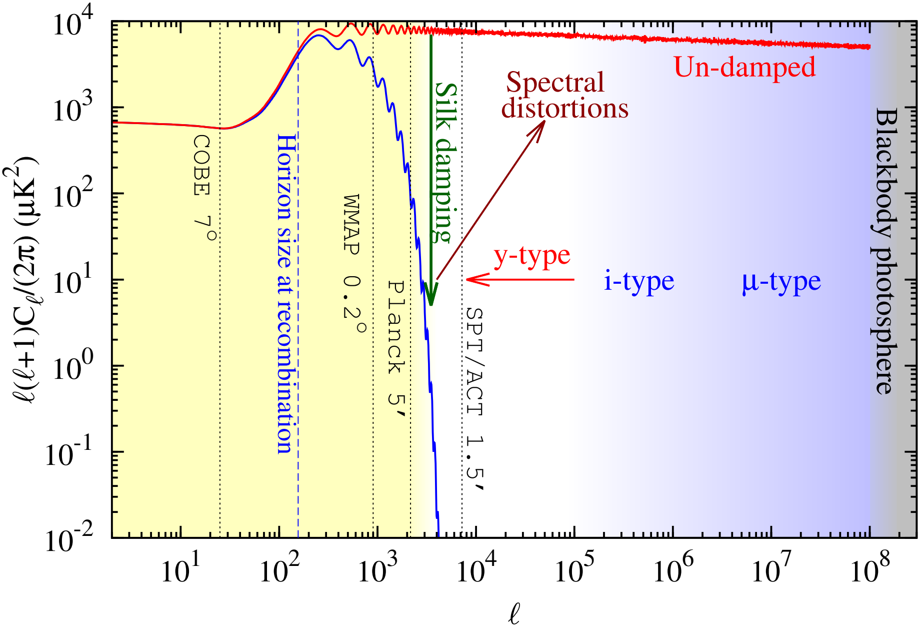
Power spectrum: $C_\ell^{\mu\mu}|_{\ell=2-26} = (2.3 \pm 1.0) \times 10^{-12}$



Power spectrum: $C_\ell^{\mu T}|_{\ell=2-26} = (2.6 \pm 2.6) \times 10^{-12}$ K

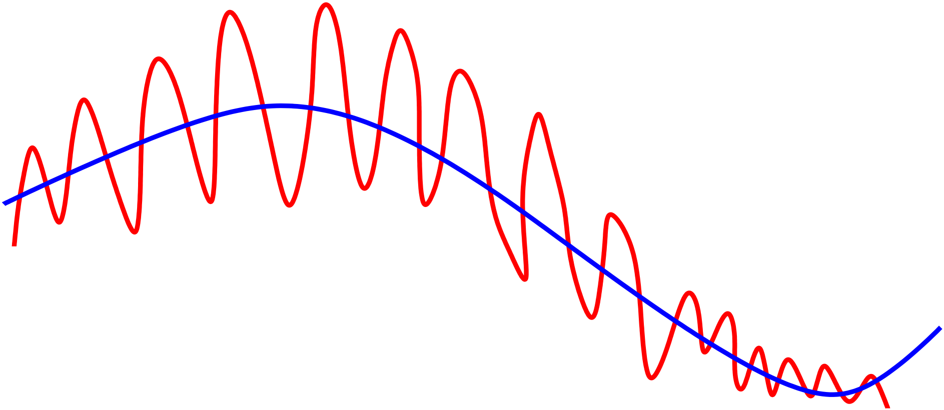


Silk damping: 17 e-folds of inflation!

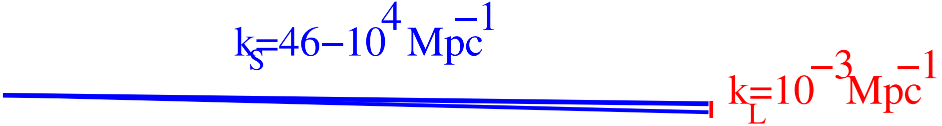


Non-Gaussianity: short wavelength modes correlated with long wavelength fluctuations

$$\phi(\mathbf{x}) = \phi_G(\mathbf{x}) + f_{\rm NL}\phi_G(\mathbf{x})^2$$



Fluctuations in μ if non-Gaussianity (Pajer & Zaldarriaga 2012)



Khatri& Sunyaev 2015

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{\mu T} \approx 2.4\times10^{-17} f_{\rm NL}\ {\rm K}$$

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{\mu\mu} \approx 1.7\times10^{-23} \tau_{\rm NL}$$

$$\tau_{\rm NL} = \frac{9}{25} f_{\rm NL}^2$$

Fluctuations in μ if non-Gaussianity (Pajer & Zaldarriaga 2012)

$k_S = 46 - 10^4\ \mathrm{Mpc}^{-1}$

$k_L = 10^{-3}\ \mathrm{Mpc}^{-1}$

Khatri & Sunyaev 2015

$$f_{\rm NL} < 10^5$$

$$\tau_{\rm NL} < 10^{11}$$

$$5 \times 10^4 \lesssim \frac{k_S}{k_L} \lesssim 10^7$$

Only other comparable constraints from primordial black holes
Byrnes, Copeland, & Green 2012

Resonant scattering on metals during reionization

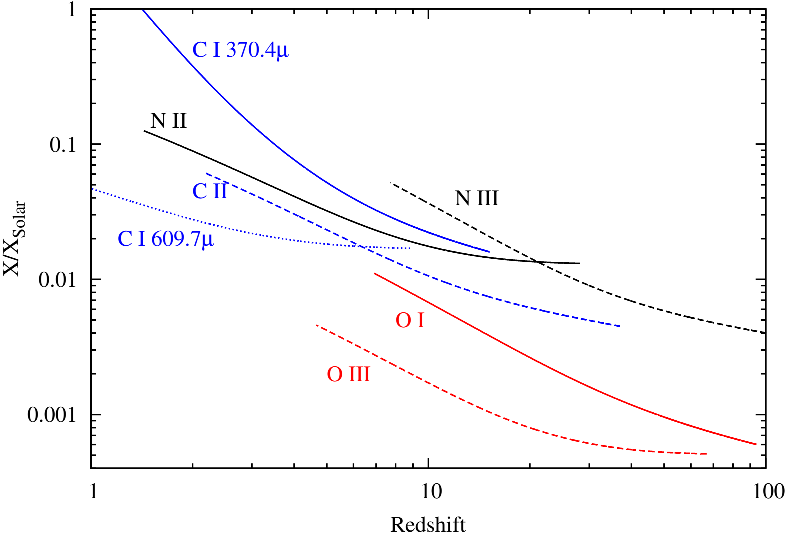
$\tau_{\rm LSS}(\nu) = \tau_e + \sum_X \tau_X(\nu)$

Basu, Hernandez-Monteagudo & Sunyaev 2004

Atom/ Ion	Wavelength (in μ)	Oscillator strength	HFI freq. (GHz)	Scattering redshift	$\mathcal{B}$ factor	Opt. depth for 10^{-2} solar abundance	$[X]_{\rm min}$ for $l = 10$	$\langle [X]_{\rm min} \rangle$ in $l = 10$–20
C I	609.70	1.33×10^{-9}	143	2.4	0.76	6.4×10^{-6}	5.3×10^{-3}	2.6×10^{-3}
			217	1.3	0.92	3.9×10^{-6}	1.4×10^{-2}	6.8×10^{-3}
			353	0.4	0.99	1.6×10^{-6}	2.1×10^{-1}	1.2×10^{-1}
	370.37	9.08×10^{-10}	143	4.7	0.15	1.2×10^{-6}	2.8×10^{-2}	1.3×10^{-2}
			217	2.8	0.09	3.7×10^{-7}	1.6×10^{-1}	8.1×10^{-2}
C II	157.74	1.71×10^{-9}	143	12.3	0.79	1.8×10^{-5}	2.7×10^{-2}	6.2×10^{-3}
			217	7.9	0.94	1.1×10^{-5}	7.7×10^{-3}	3.0×10^{-3}
			353	4.4	0.99	5.6×10^{-6}	7.7×10^{-2}	3.6×10^{-2}
N II	205.30	3.92×10^{-9}	143	9.2	0.76	1.1×10^{-5}	7.6×10^{-3}	2.6×10^{-3}
			217	5.8	0.92	6.8×10^{-6}	8.6×10^{-3}	3.8×10^{-3}
			353	3.1	0.99	3.5×10^{-6}	1.3×10^{-1}	6.8×10^{-2}
	121.80	2.74×10^{-9}	143	16.2	0.16	2.1×10^{-6}	1.3×10^{-1}	3.8×10^{-2}
			217	10.5	0.09	6.4×10^{-7}	3.4×10^{-1}	1.1×10^{-1}
N III	57.32	4.72×10^{-9}	143	35.6	0.79	2.5×10^{-5}	2.3×10^{-3}	7.4×10^{-4}
			217	23.4	0.94	1.5×10^{-5}	6.1×10^{-3}	2.0×10^{-3}
O I	63.18	3.20×10^{-9}	143	32.2	0.88	1.0×10^{-4}	5.3×10^{-4}	1.7×10^{-4}
			217	21.2	0.96	6.3×10^{-5}	2.0×10^{-3}	6.4×10^{-4}
			353	12.5	1.00	3.1×10^{-5}	2.2×10^{-1}	4.9×10^{-2}

Constraints on metal production from the first stars

Assuming relative calibration between channels of 10^{-5}



ν = 50-600 GHz

LiteBIRD

What is needed to detect the CMB spectrak distortion anisotropies:

- No CO contamination, enough channels to separate foregrounds
- Precise interchannel calibration (better than 10^{-5}?)
- Precise calibration of zero level (limits average y distortion measurement in Planck)
- High sensitivity
- Polarization
  (resonant scattering on lines also generates polarization *(Hernandez-Monteagudo,Rubino-Martin & Sunyaev 2007)*, second order (transverse) kinetic Sunyaev-Zeldovich effect from clusters ($\propto \upsilon_t^2 \tau$) gives polarized y-type distortion *(Sunyaev & Zeldovich 1980)*)

High angular resolution not necessary!

CO mask, annotations to second Planck cluster catalog, μ-map and masks publicly available

http://www.mpa-garching.mpg.de/~khatri/szresults/

http://www.mpa-garching.mpg.de/~khatri/muresults/