Constraints on the thermal Sunyaev-Zeldovich effect and CMB chemical potential fluctuations and primordial non-Gaussianity from Planck data

Rishi Khatri

$$\bar{y} = 10^{-6} \pm ?$$

$$\bar{y} < 2.2 \times 10^{-6}, \text{ COBE-FIRAS: } < 15 \times 10^{-6}$$

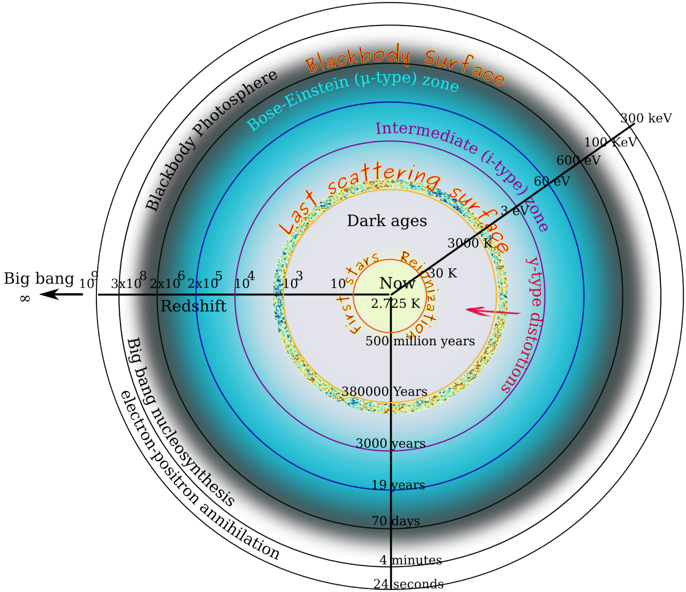
$$\mu_{\rm rms}^{10'} < 6.4 \times 10^{-6}, \text{ COBE-FIRAS: } \bar{\mu} < 90 \times 10^{-6}$$

$$D_\ell^{\mu T}|_{\ell=2-26} = 2.6 \pm 2.6 \times 10^{-12}\ \text{K}$$

$$f_{\rm NL} < 10^5, k_{\rm S}/k_{\rm L} = 10^6$$

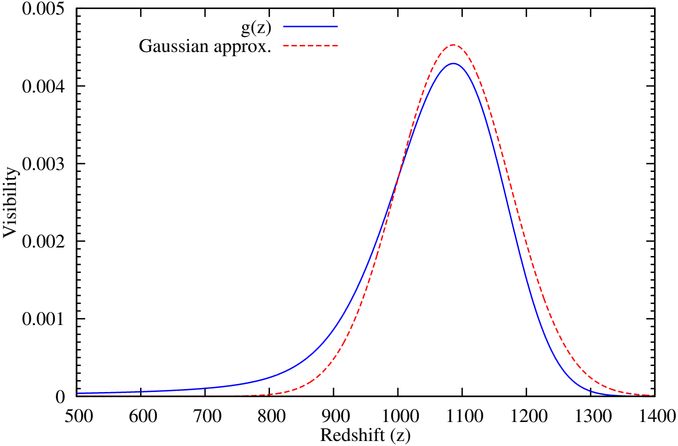
tifr

Important events in the history of the Universe



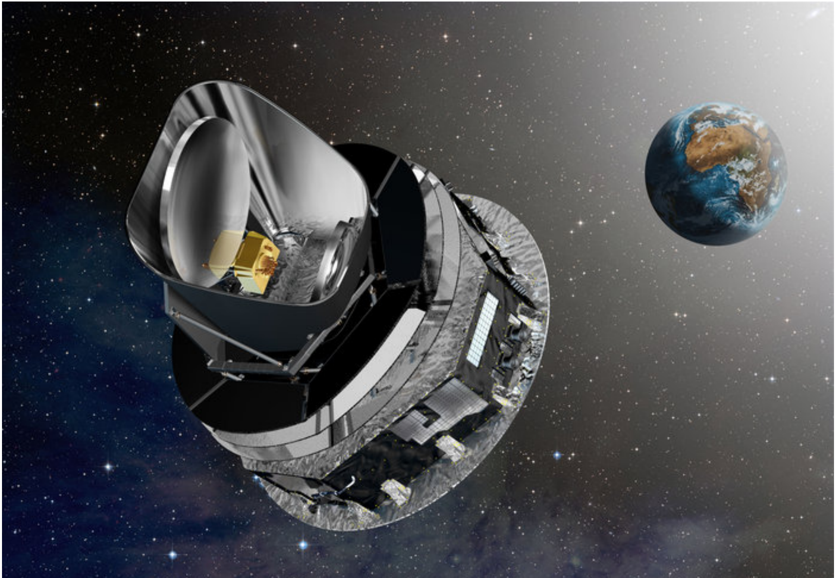
The last scattering surface

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



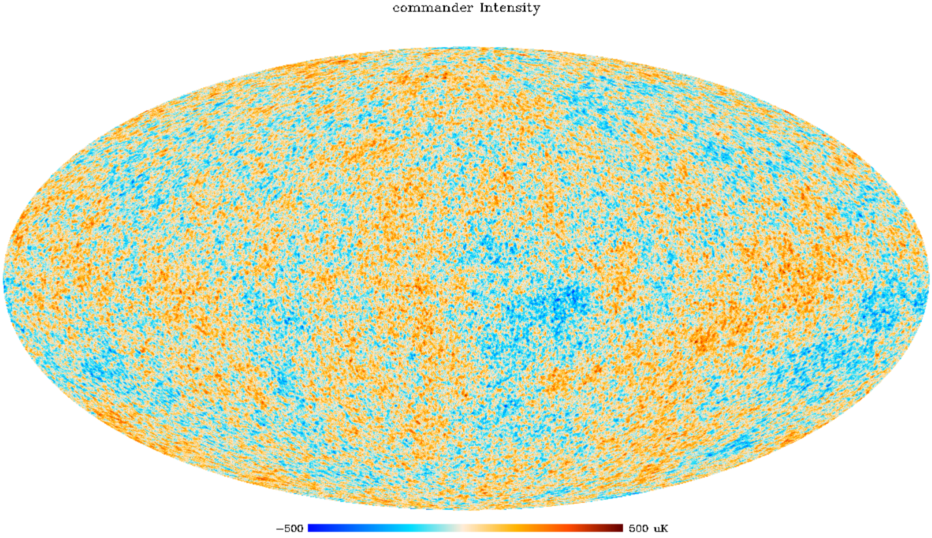
Planck CMB mission May 2009-October 2013

image credit: ESA-D. Ducros

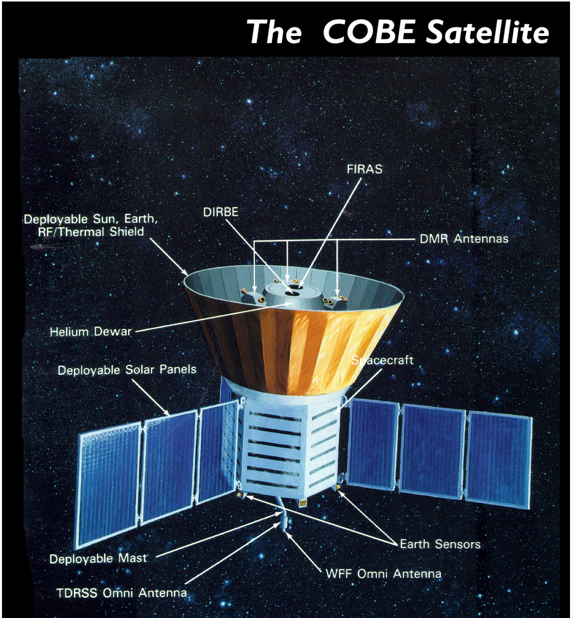


Picture of Universe @ 300000 Years

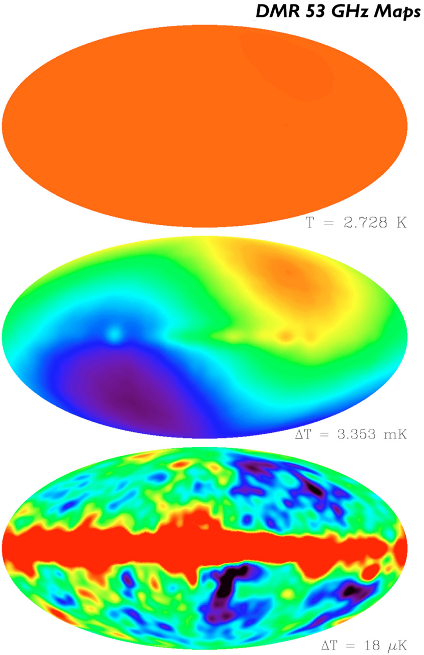
Planck Collaboration 2015



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

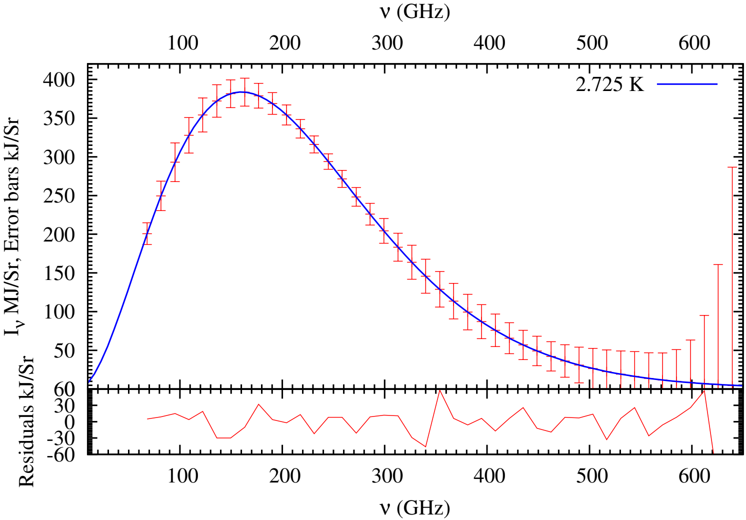


CMB as seen by COBE



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

Fixsen et al. 1996, Fixsen and Mather 2002



Planck spectrum

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$$

Relativistic invariant occupation number/phase space density

$$n(\nu) \equiv \frac{c^2}{2h\nu^3} I_\nu$$

$$n(x) = \frac{1}{e^x - 1} \quad , \quad x = \frac{h\nu}{k_B T}$$

Bose-Einstein spectrum- Chemical potential (μ)

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

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

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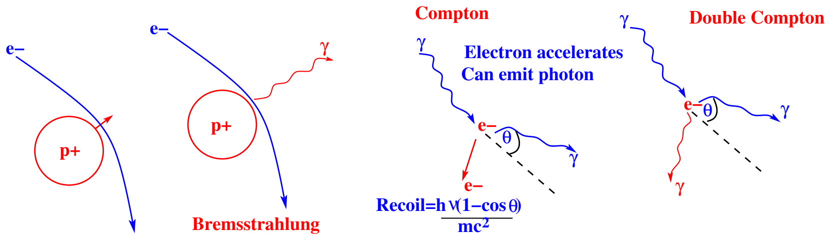
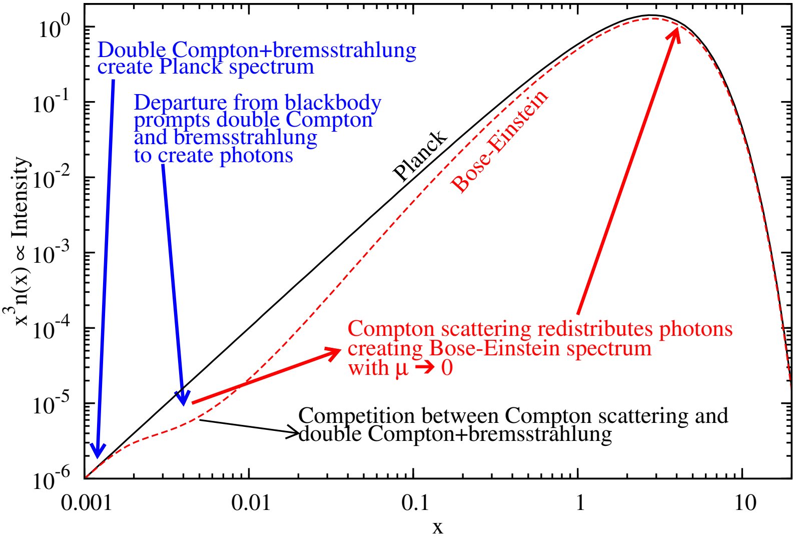
Idea behind analytic solutions:

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

Important physical processes for CMB spectrum



Creation of CMB Planck spectrum



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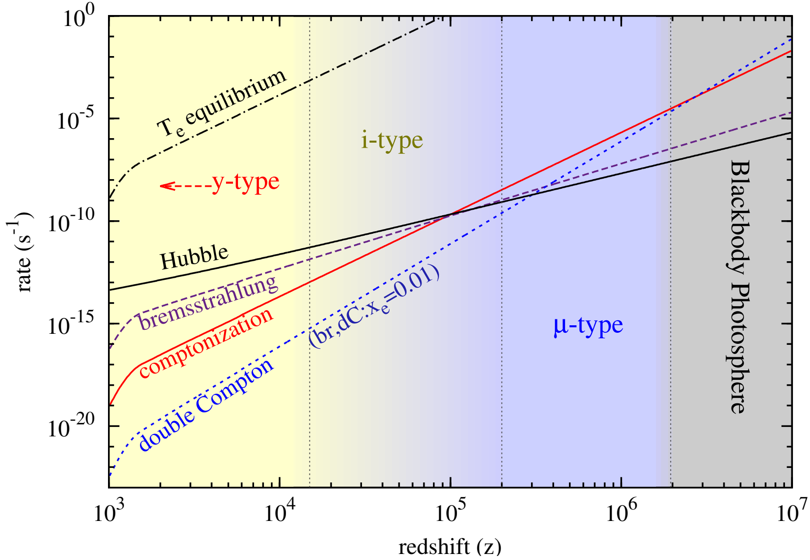
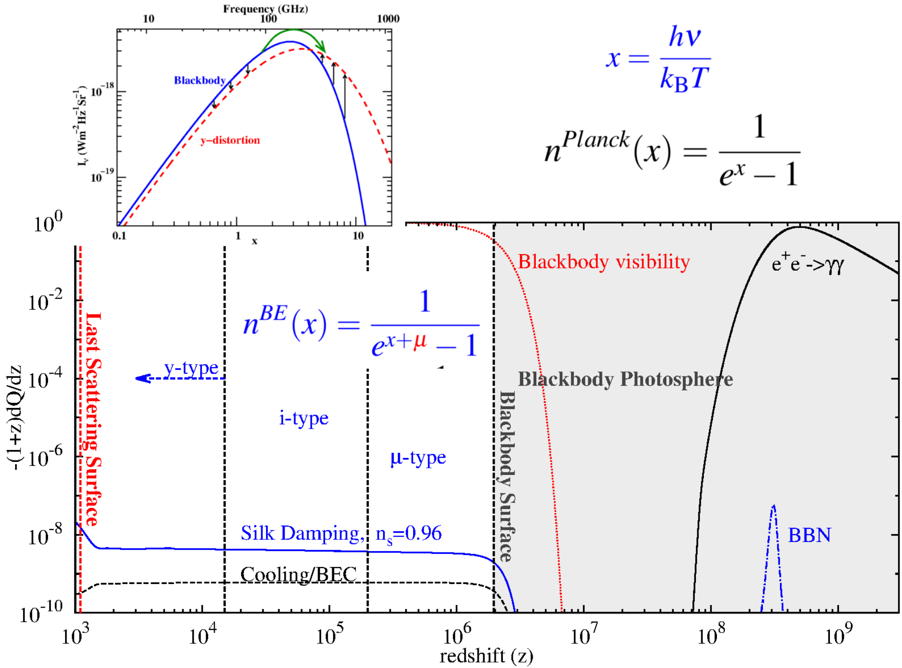


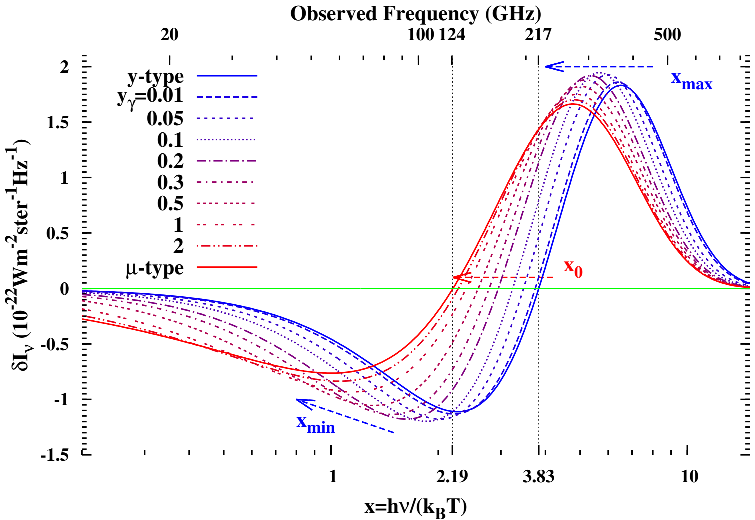


Frequency (GHz)
10
100
1000
Blackbody
y–distortion
I_ν (Wm^{-2}Hz^{-1}Sr^{-1})
10^{-18}
10^{-19}
0.1
1
x
10
$x = \frac{h\nu}{k_B T}$
$n^{Planck}(x) = \frac{1}{e^x - 1}$
$n^{BE}(x) = \frac{1}{e^{x+\mu} - 1}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
-(1+z)dQ/dz
Last Scattering Surface
y-type
i-type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

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



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

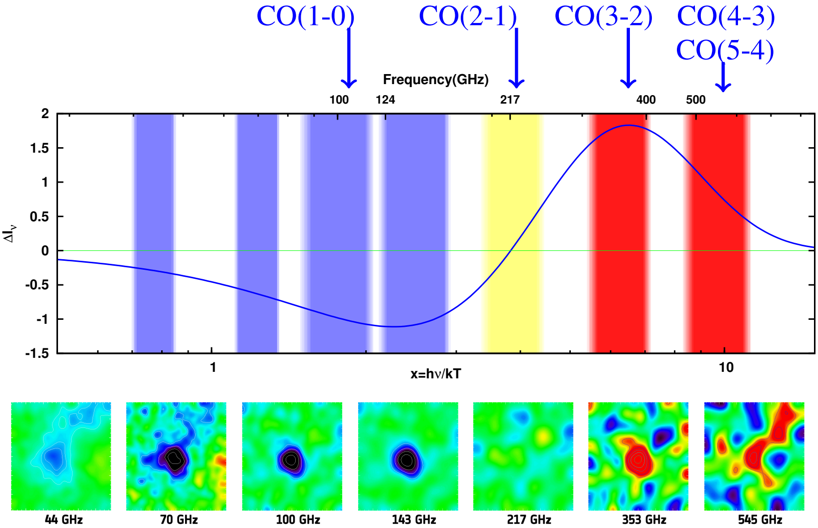
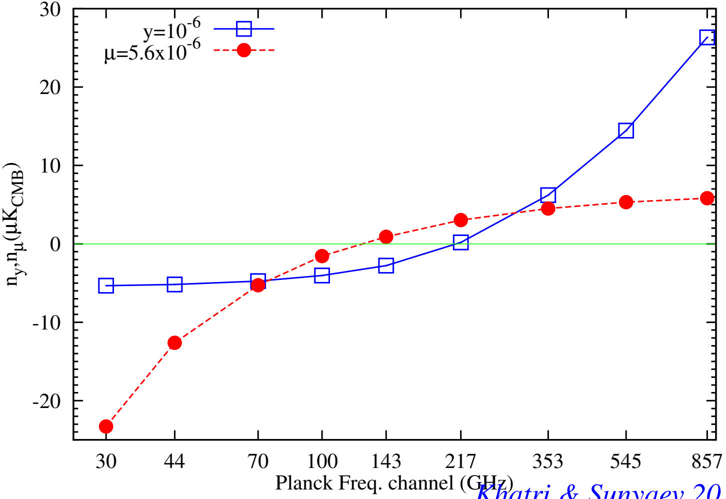


Image credit: ESA / HFI & LFI Consortia

Each Planck frequency channel contains contribution from many components

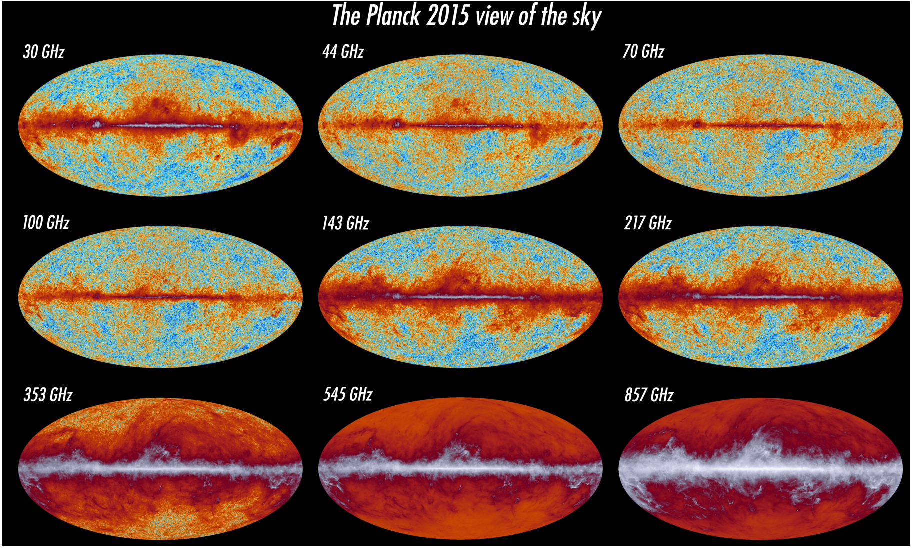
Sunyaev-Zeldovich or y-distortion signal is a weak signal $\lesssim 100\ \mu$K except in the central part of strong nearby clusters



Khatri & Sunyaev 2015

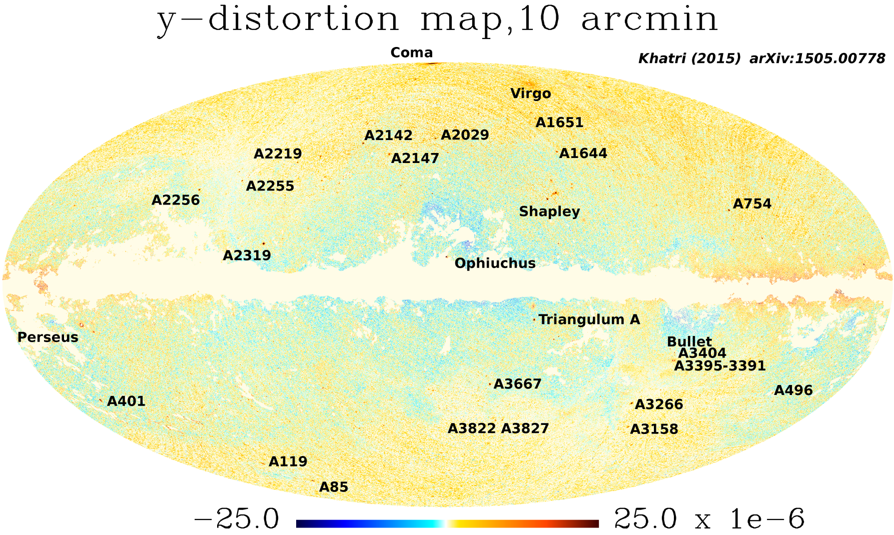
Combine Planck frequency maps to filter out the desired signal

Planck collaboration/ESA 2015



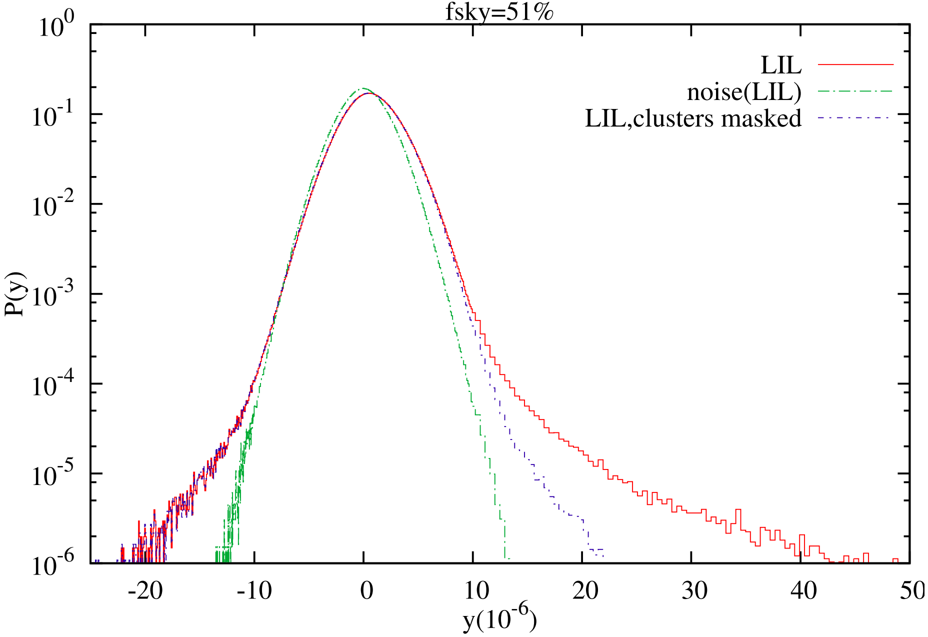
SZ/y-distortion

y-distortion map



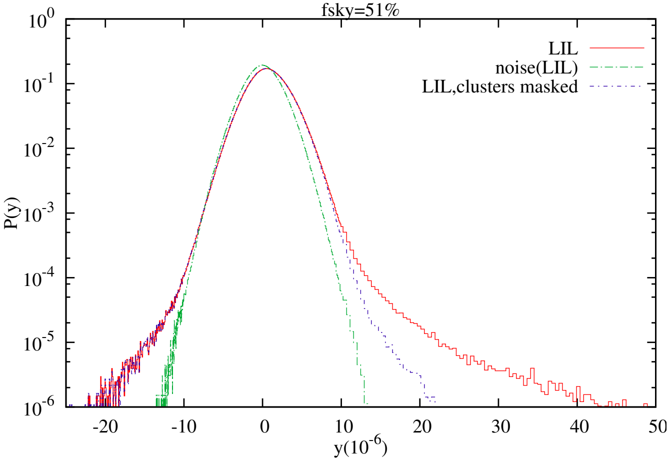
Map pdfs (*Khatri & Sunyaev 2015*)

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)



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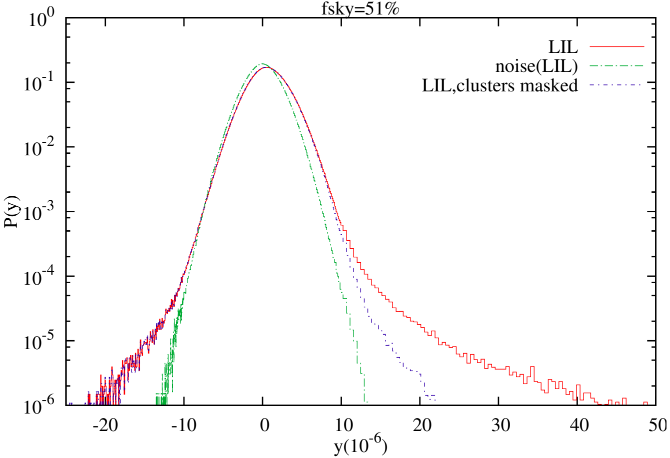
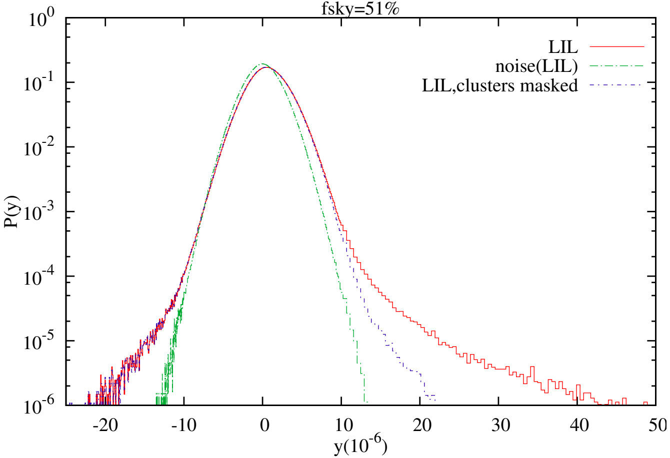
average the full pdf: $\langle y \rangle \approx 1.0 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*



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)*



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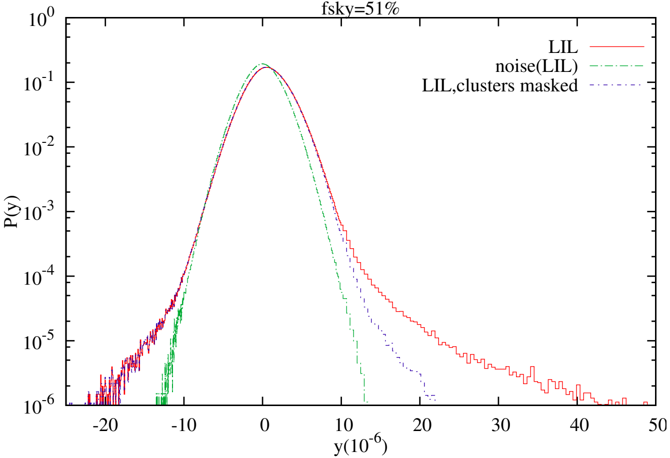
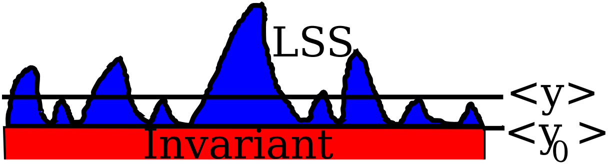


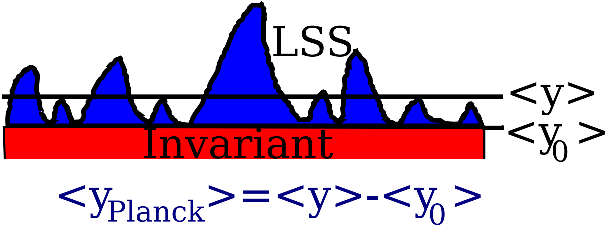
6.8 times stronger compared to the COBE-FIRAS upper limit:
$\langle y \rangle < 15 \times 10^{-6}$ *(Fixsen et al. 1996)*

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



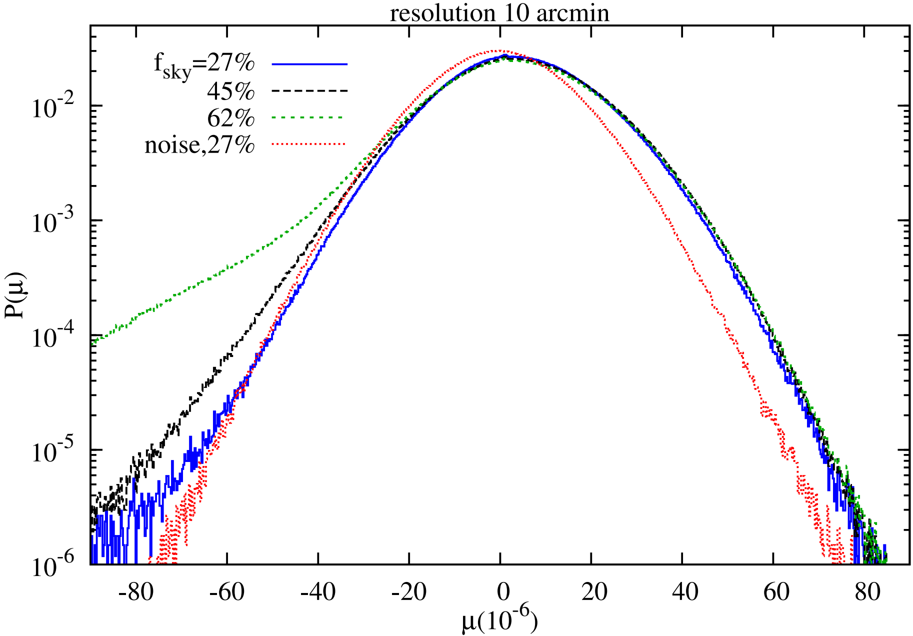
- In the standard model of cosmology the invariant component is smaller, $\langle y_0 \rangle \ll \langle y \rangle$
- This upper limits rules out models involving preheating of the IGM

  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, $\mu^{\rm central}_{\rm rms} \equiv (\mu^2_{\rm rms} - \langle \mu \rangle^2)^{1/2}$

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- 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

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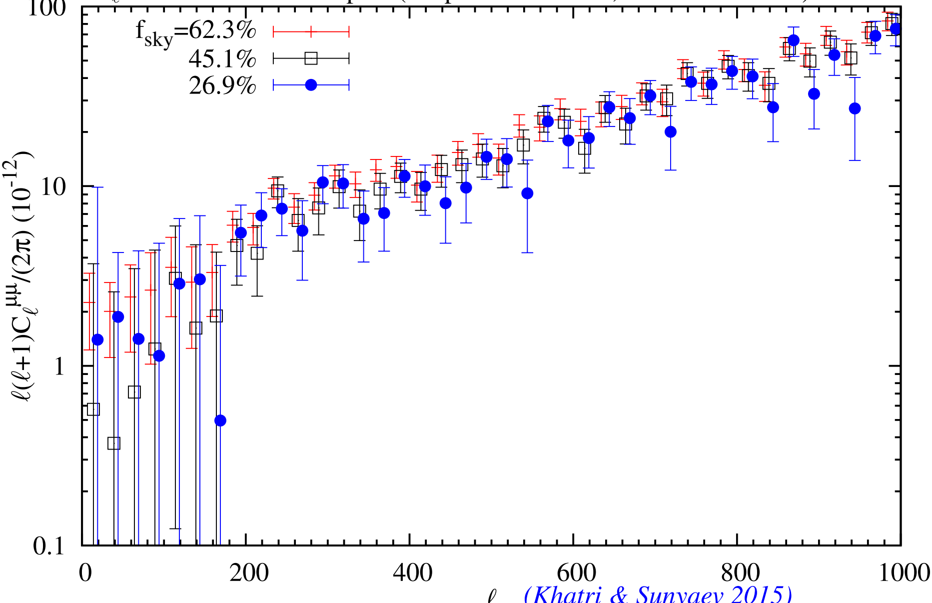
- COBE limit: $\langle \mu \rangle < 90 \times 10^{-6}$ *(Fixsen et al. 1996)*

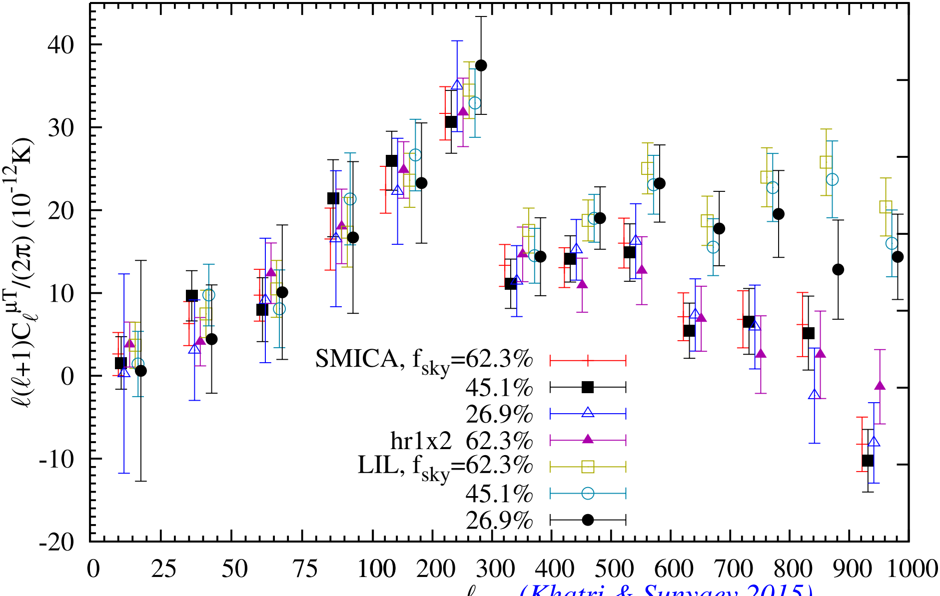
Power spectrum: $C_\ell^{\mu\mu}|_{\ell=2-26} = (2.3 \pm 1.0) \times 10^{-12}$

C_ℓ calculated with PolSpice (Szapudi et al. 2001, Chon et al. 2004)



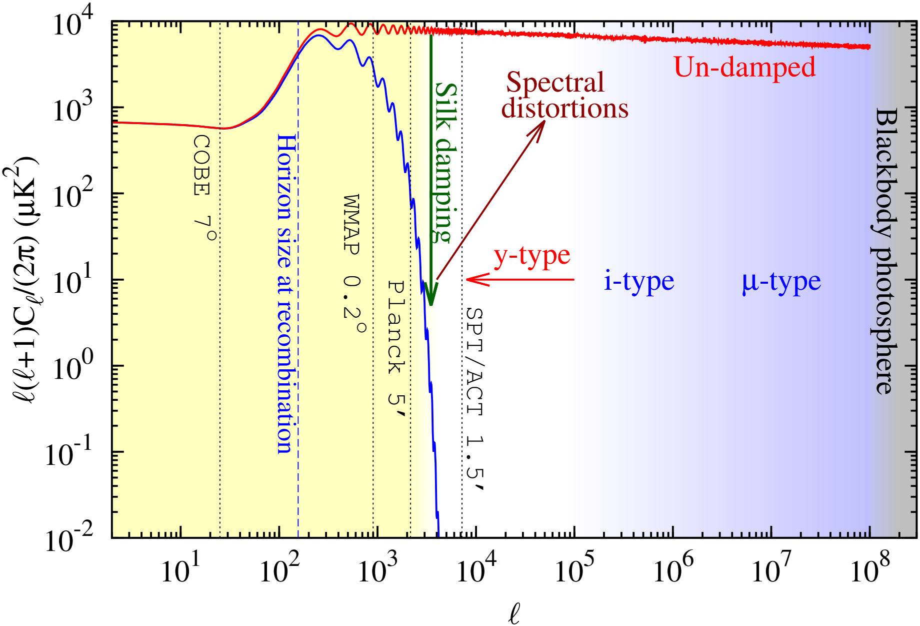
(Khatri & Sunyaev 2015)

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



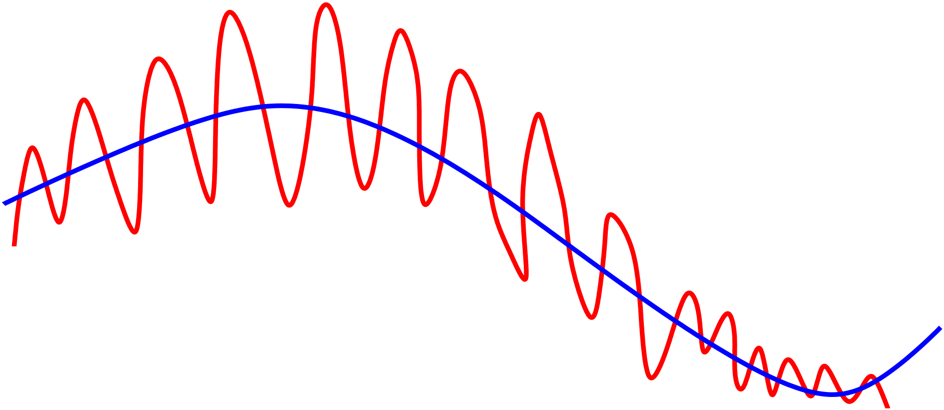
(Khatri & Sunyaev 2015)

Silk damping: 17 e-folds of inflation!

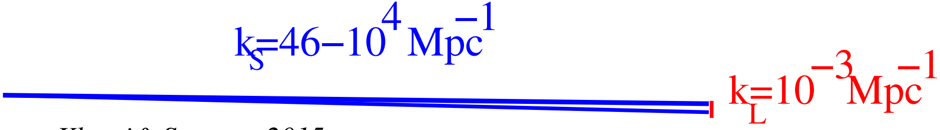


Non-Gaussianity: short wavelength modes correlated with long wavelength fluctuations

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



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



Khatri& Sunyaev 2015

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{\mu T} \approx 2.4\times 10^{-17} f_{\rm NL}\ {\rm K}$$

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{\mu\mu} \approx 1.7\times 10^{-23} \tau_{\rm NL}$$

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

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

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

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

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

Only other comparable constraints from primordial black holes

Byrnes, Copeland, & Green 2012

We have (re-)entered the era of CMB spectrum cosmology

Future: Many orders of magnitude improvement in next decade
PIXIE (NASA), LiteBIRD (JAXA)

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Opportunity for an Indian CMB experiment?

Component separation methods: Internal linear combination

y map = linear combination of channel maps

$$y(p) = \sum_i w_i T_i(p)$$

Weights are given by minimizing the variance of y preserving the y signal.

In principle can be done in any space:
pixel, harmonic, needlet, ...

Alternative: parameter fitting (LIL)

- Fit a (non-linear) parametric model
- CMB + y + dust or CMB + CO + dust or CMB + μ + dust
- dust: grey body with spectral index as free parameter, temperature fixed to 18 K : 2 parameters
- CO: fixed line ratios : 1 parameter

Advantages: Can use χ^2 for CO vs y to decide which is the dominant component in a given part of the sky $\Rightarrow$ CO mask, alternative validation of Planck cluster catalog *(see arXiv:1505.00778 for details)*
Map, validation annotation to second Planck cluster catalog publicly available
`http://www.mpa-garching.mpg.de/~khatri/szresults/`

Disdvantage: Have to assume a model

Map pdfs (*Khatri & Sunyaev 2015*)