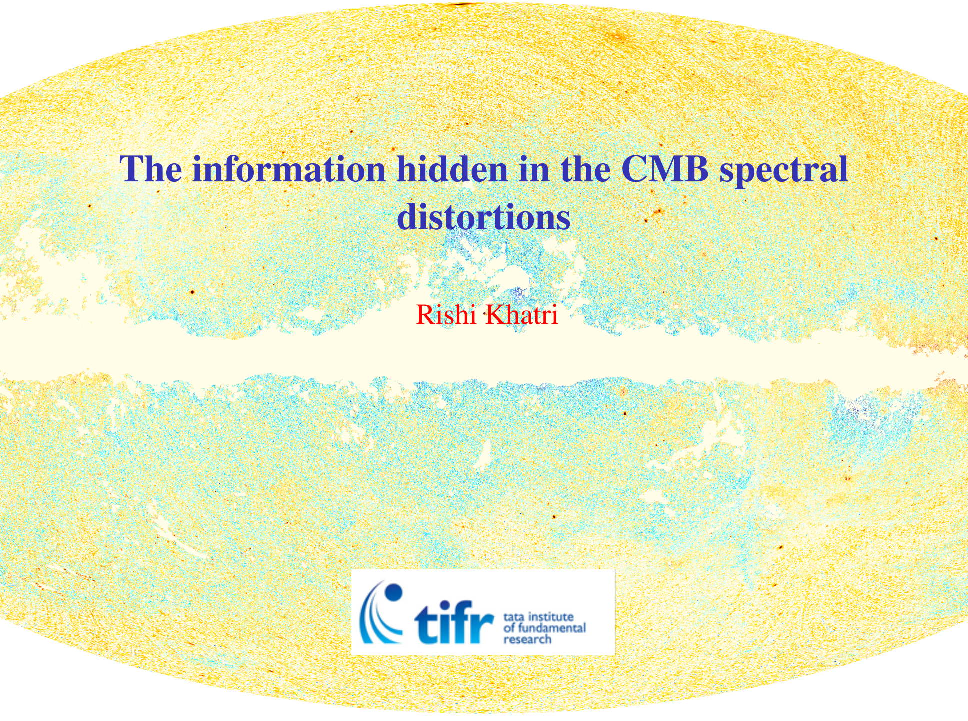
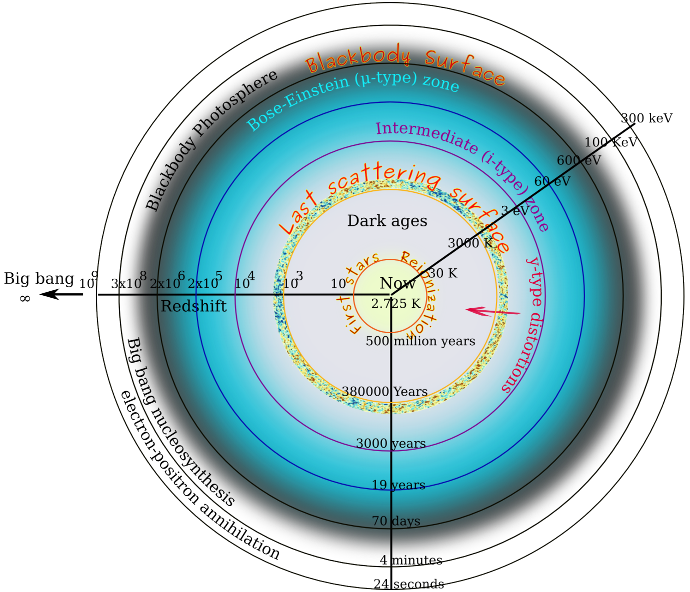


The information hidden in the CMB spectral distortions

Rishi Khatri

tifr tata institute of fundamental research

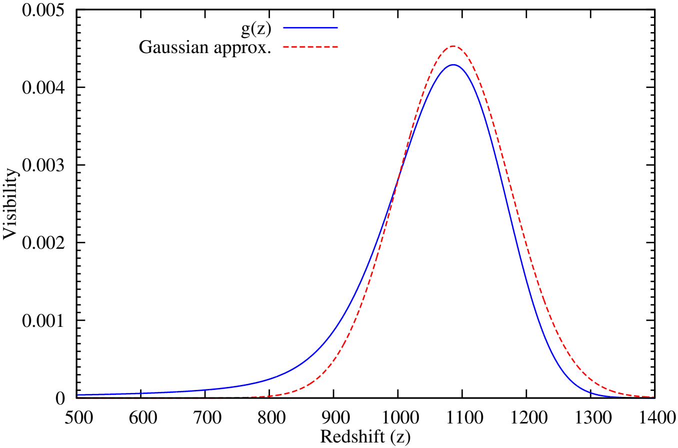
Important events in the history of the Universe



The last scattering surface

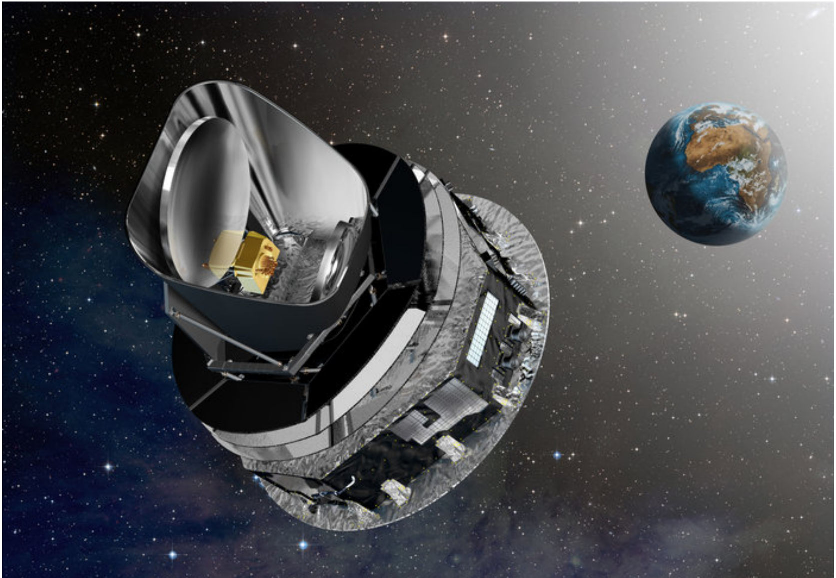
Sunyaev & Zeldovich 1970

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



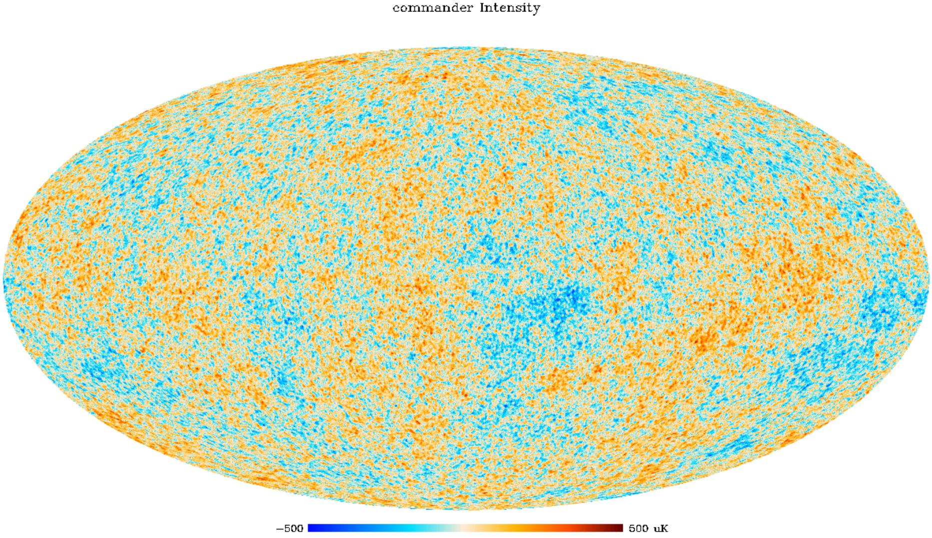
Planck CMB mission May 2009-October 2013

image credit: ESA-D. Ducros

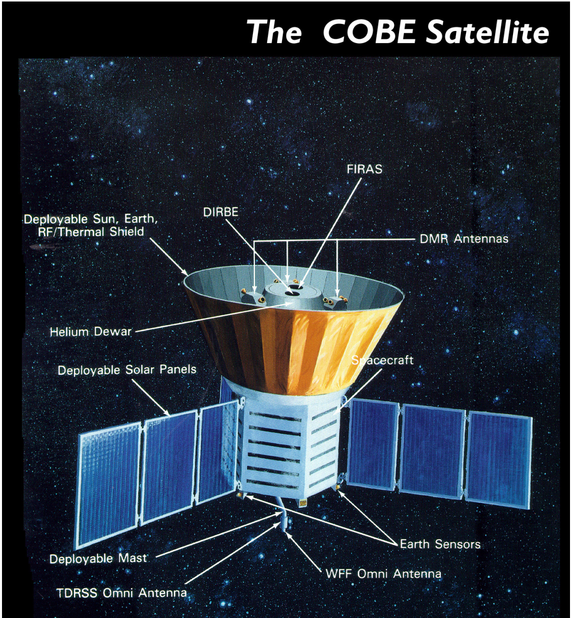


Picture of Universe @ 300000 Years

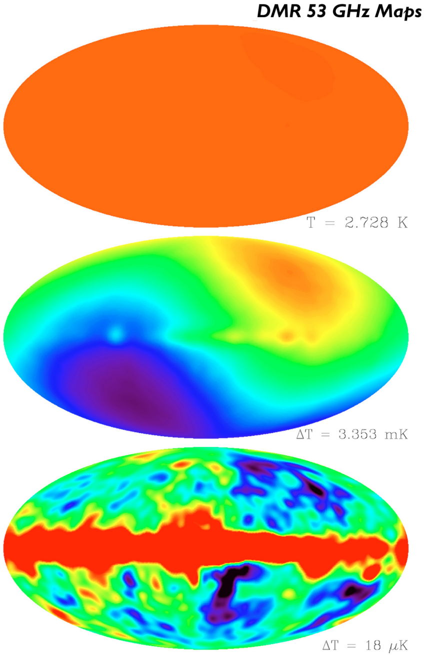
Planck Collaboration 2015



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

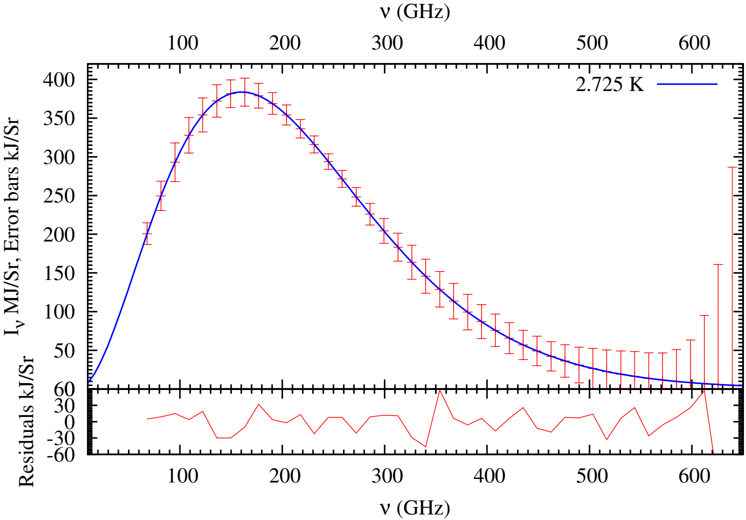


CMB as seen by COBE



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

Fixsen et al. 1996, Fixsen and Mather 2002



Planck spectrum

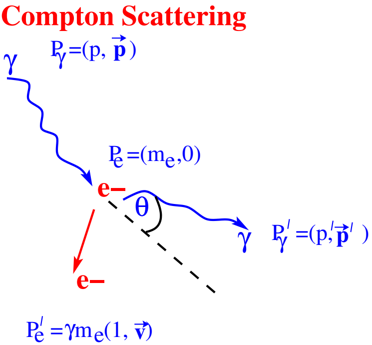
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_\mathrm{B}T)} - 1}$$

Relativistic invariant occupation number/phase space density

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

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

Compton scattering



$$\Delta p/p \approx -p/m_{\mathrm{e}}(1-\cos\theta)$$

Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} T_\gamma}{m_{\mathrm{e}} c^2}, \qquad T_\gamma = 2.725(1+z)$$

Doppler effect:

$$y_e = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} c^2}$$

In early Universe $y_\gamma \approx y_{\mathrm{e}}$

y: Amplitude of distortion

$$y = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} \left(T_{\mathrm{e}} - T_\gamma\right)}{m_{\mathrm{e}} c^2}$$

Efficiency of energy exchange between electrons and photons

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No. of scatterings

Doppler effect:

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No. of scatterings   Energy transfer per scattering

Doppler effect:

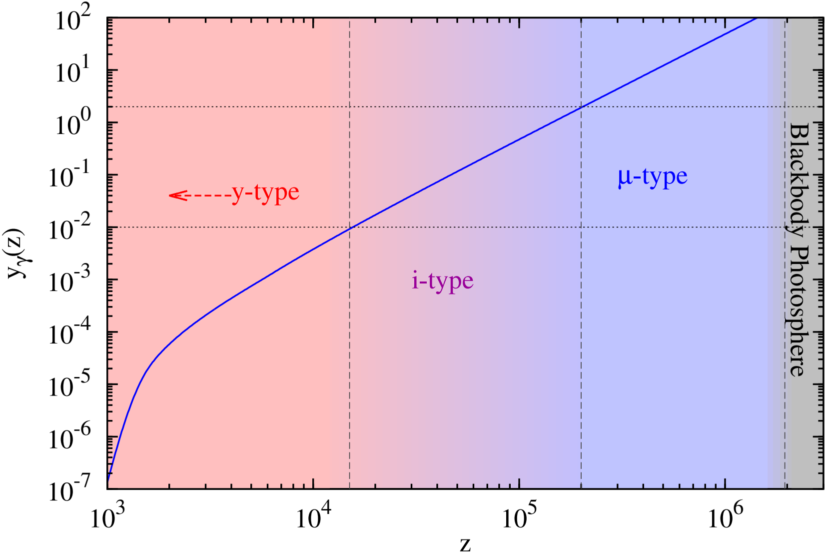
$$y_e = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\mathrm{e}}{m_\mathrm{e} c^2}$$

In early Universe $y_\gamma \approx y_\mathrm{e}$

y: Amplitude of distortion

$$y = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} \left(T_\mathrm{e} - T_\gamma\right)}{m_\mathrm{e} c^2}$$

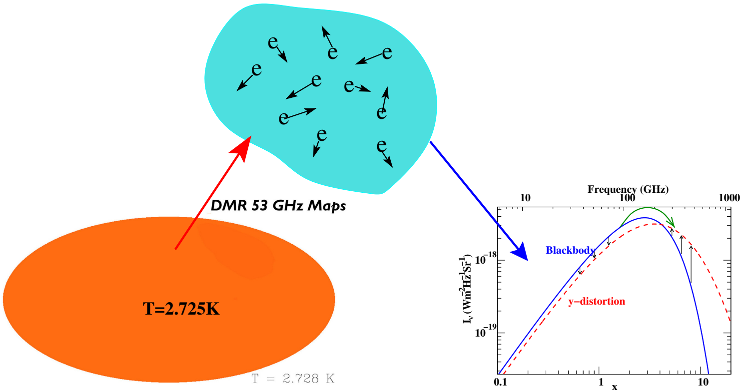
Efficiency of energy transfer between electrons and photons



y-type (Sunyaev-Zeldovich effect) from clusters/reionization

$$y_\gamma \ll 1\ ,\ T_{\rm e} \sim 10^4$$

$$y = (\tau_{\rm reionization})\frac{k_{\rm B}T_{\rm e}}{m_{\rm e}c^2} \sim (0.06)(1.6\times 10^{-6}) \sim 10^{-7}$$



y-type (Sunyaev-Zeldovich effect) from clusters/reionization

$$n_{SZ} = y \;\; T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\mathrm{Pl}}}{\partial T}$$

$$= \mathbf{y} \;\; \frac{\mathbf{x e^x}}{(\mathbf{e^x - 1})^2} \left(\mathbf{x} \frac{\mathbf{e^x + 1}}{\mathbf{e^x - 1}} - \mathbf{4} \right)$$

$$\Delta I_{sz} = I_{sz} - I_{planck} = \frac{2h\nu^3}{c^2} n_{sz}$$

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

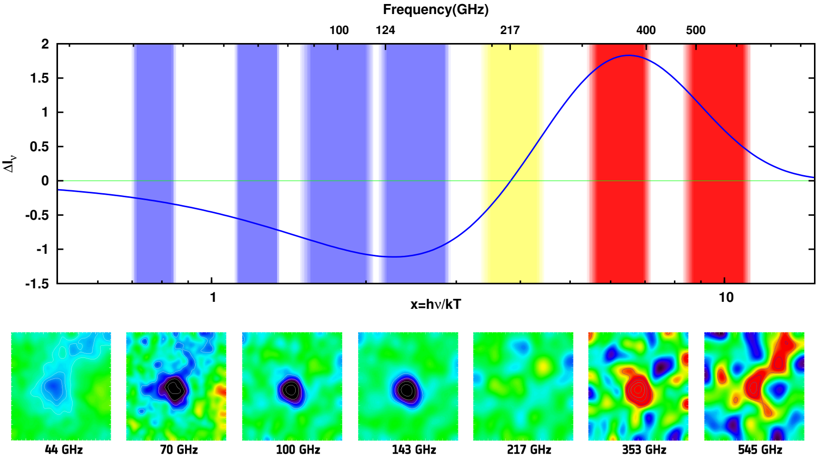
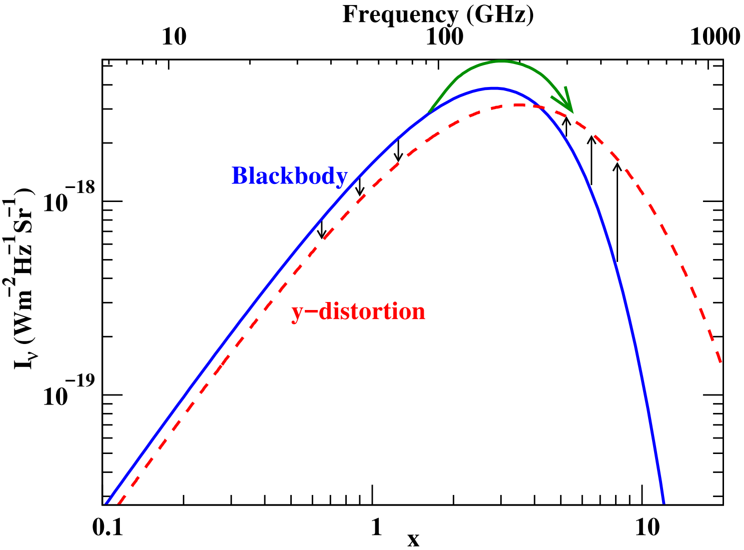


Image credit: ESA / HFI & LFI Consortia

Average y-distortion (Sunyaev-Zeldovich effect) limits

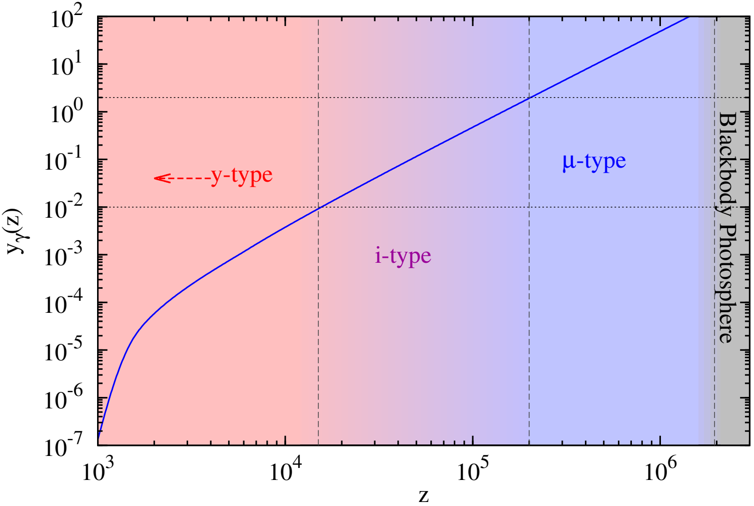
(Zeldovich and Sunyaev 1969)

COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*



For $y_\gamma \gg 1$ equilibrium is established.

- T_e and T_γ converge to common value
- The photon spectrum relaxes to equilibrium Bose-Einstein distribution



Bose-Einstein spectrum- Chemical potential (μ)

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

Bose-Einstein spectrum- Chemical potential (μ)

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

Bose-Einstein spectrum- Chemical potential (μ)

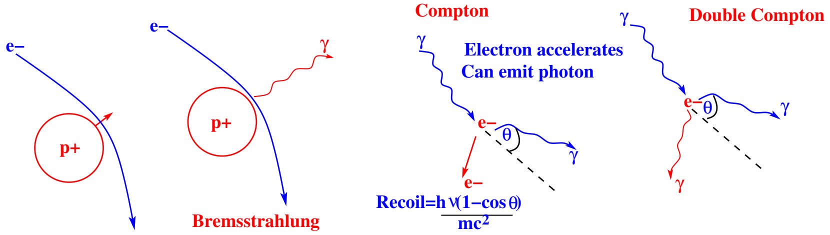
$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

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

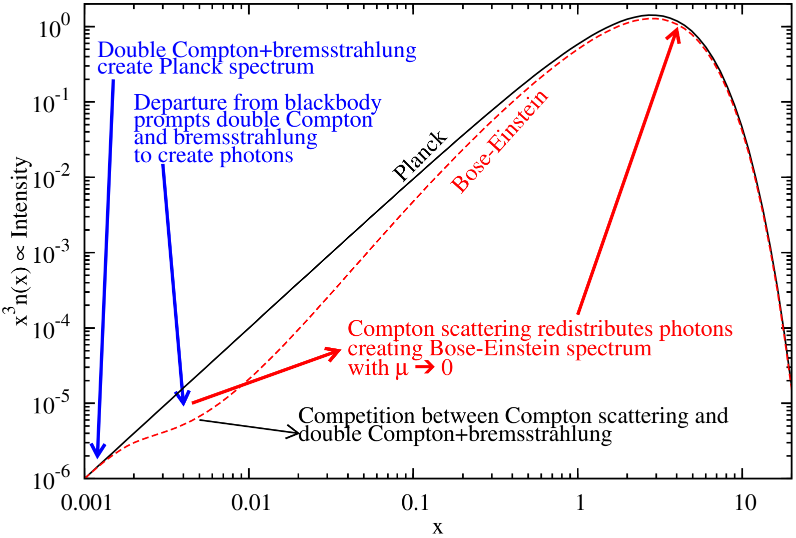
Idea behind analytic solutions:

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

Important physical processes for CMB spectrum



Creation of CMB Planck spectrum



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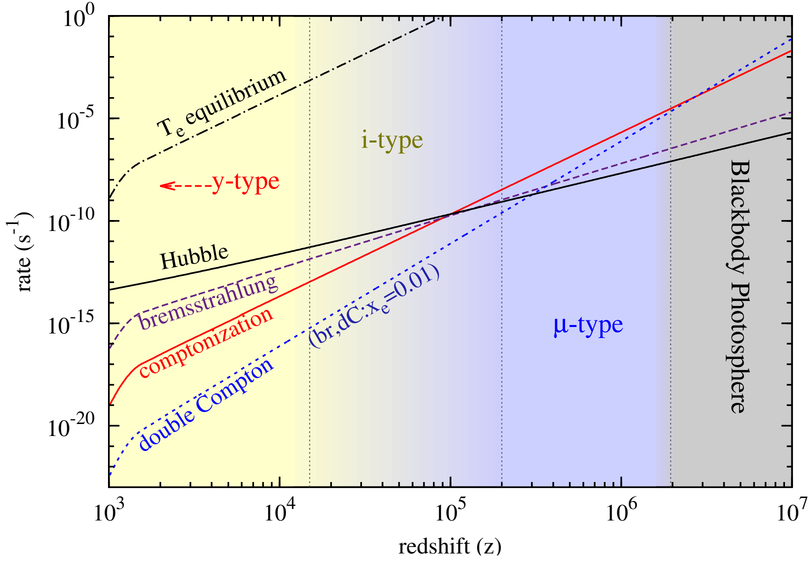
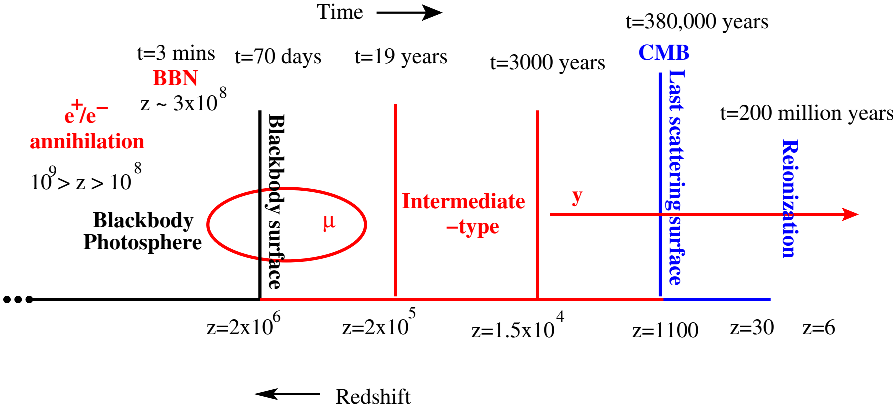


μ-type distortions



Compton + double Compton + bremsstrahlung

Analytic solution: $\mu = 1.4 \int \frac{dQ}{dz} e^{-\mathscr{T}(z)} dz$

(Sunyaev and Zeldovich 1970)

Solutions for $\mathscr{T}(Z)$

Old solutions

(*Sunyaev and Zeldovich 1970, Danese and de Zotti 1982*)
Extension of old solutions to include both double Compton and bremsstrahlung

$$\mathscr{T}(z) \approx \left[\left(\frac{1+z}{1+z_{\rm dC}}\right)^{5} + \left(\frac{1+z}{1+z_{\rm br}}\right)^{5/2}\right]^{1/2} + \varepsilon \ln\left[\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/4} + \sqrt{1+\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/2}}\right]$$

This solution has accuracy of $\sim 10\%$, $z_{\rm dC} \approx 1.96 \times 10^{6}$

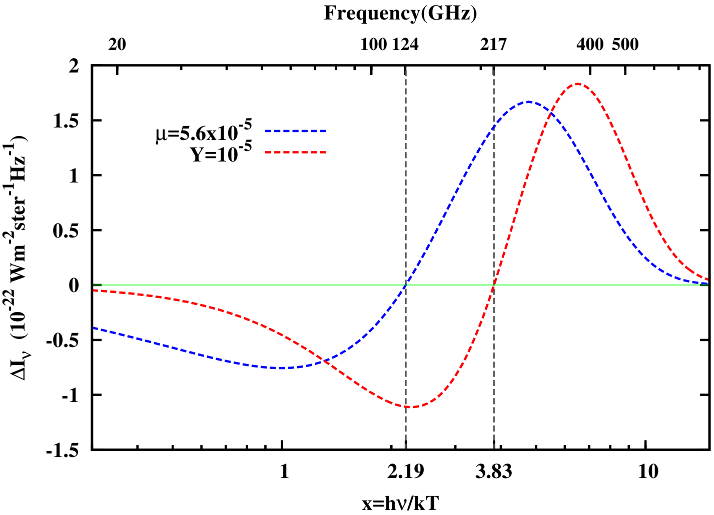
Numerical studies: Illarionov and Sunyaev 1975, Burigana, Danese, de Zotti 1991, Hu and Silk 1993, Chluba and Sunyaev 2012

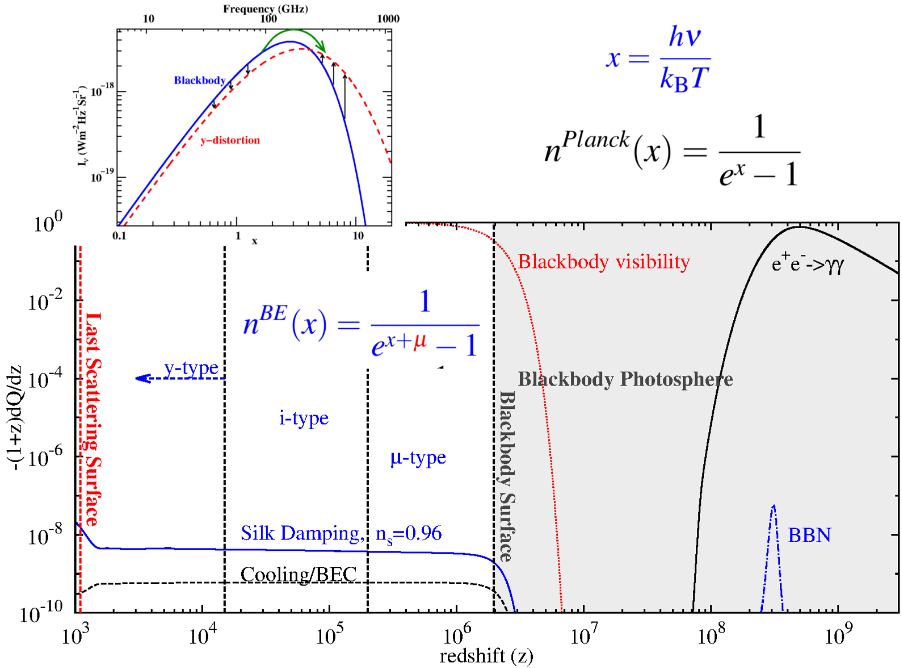
New solution, accuracy $\sim 1\%$
(*Khatri and Sunyaev 2012a*)

$$\mathscr{T}(z) \approx 1.007\left[\left(\frac{1+z}{1+z_{\rm dC}}\right)^{5} + \left(\frac{1+z}{1+z_{\rm br}}\right)^{5/2}\right]^{1/2} + 1.007\varepsilon \ln\left[\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/4} + \sqrt{1+\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/2}}\right]$$
$$+\left[\left(\frac{1+z}{1+z_{\rm dC}'}\right)^{3} + \left(\frac{1+z}{1+z_{\rm br}'}\right)^{1/2}\right],$$

μ-distortion: Bose-Einstein spectrum, $y_\gamma \gg 1$

COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ *(Fixsen et al. 1996)*



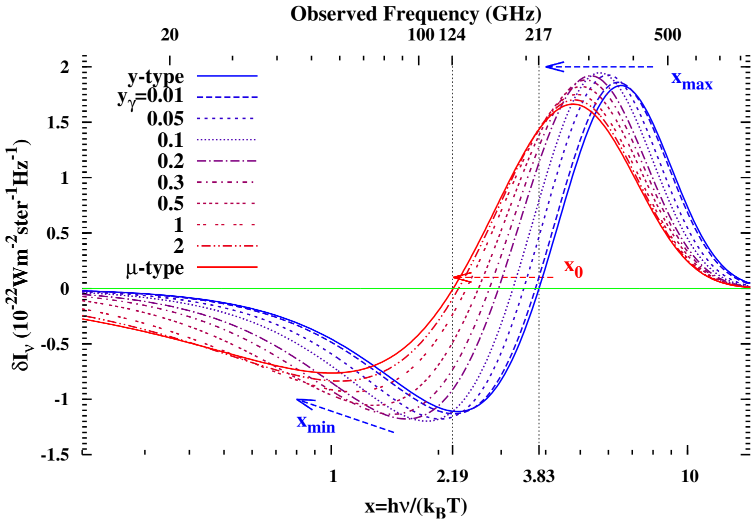


Frequency (GHz)
10
100
1000
Blackbody
y–distortion
I_ν ($Wm^{-2}Hz^{-1}Sr^{-1}$)
10^{-18}
10^{-19}
0.1
1
10
x
$x = \frac{h\nu}{k_B T}$
$n^{Planck}(x) = \frac{1}{e^x - 1}$
$n^{BE}(x) = \frac{1}{e^{x+\mu} - 1}$
Blackbody visibility
$e^+e^- \to \gamma\gamma$
Last Scattering Surface
y-type
i-type
μ-type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

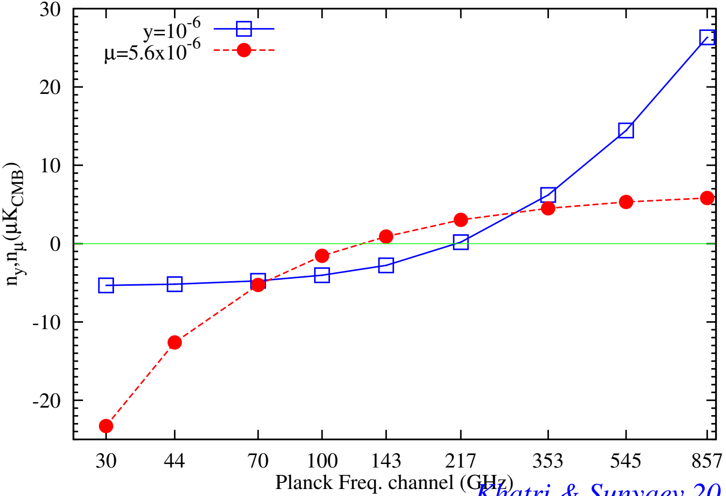
Solve Kompaneets equation with initial condition of $y-$type solution.

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



Each Planck frequency channel contains contribution from many components

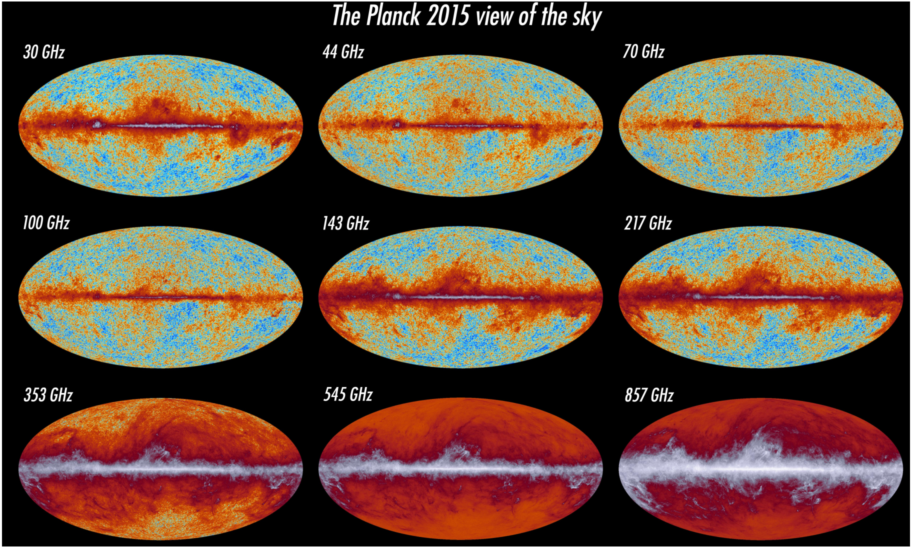
Sunyaev-Zeldovich or y-distortion signal is a weak signal $\lesssim 100\ \mu$K except in the central part of strong nearby clusters



Khatri & Sunyaev 2015

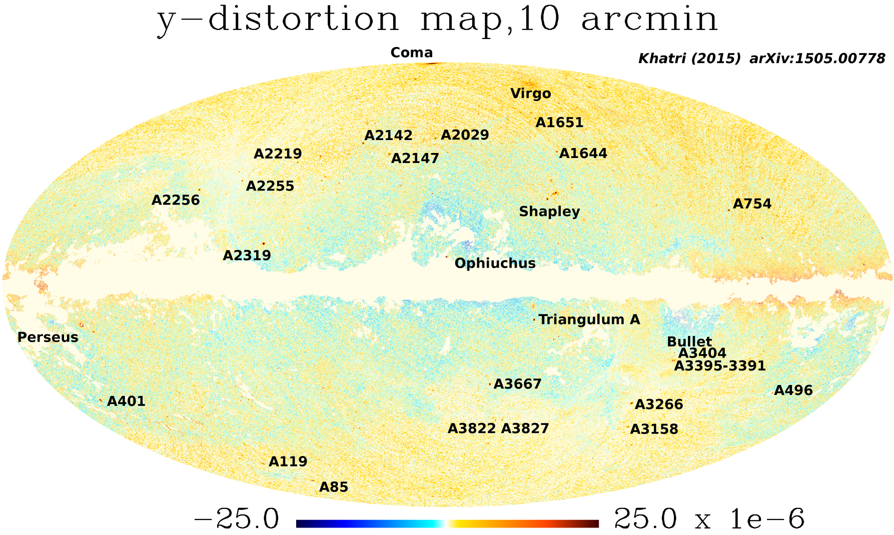
Combine Planck frequency maps to filter out the desired signal

Planck collaboration/ESA 2015



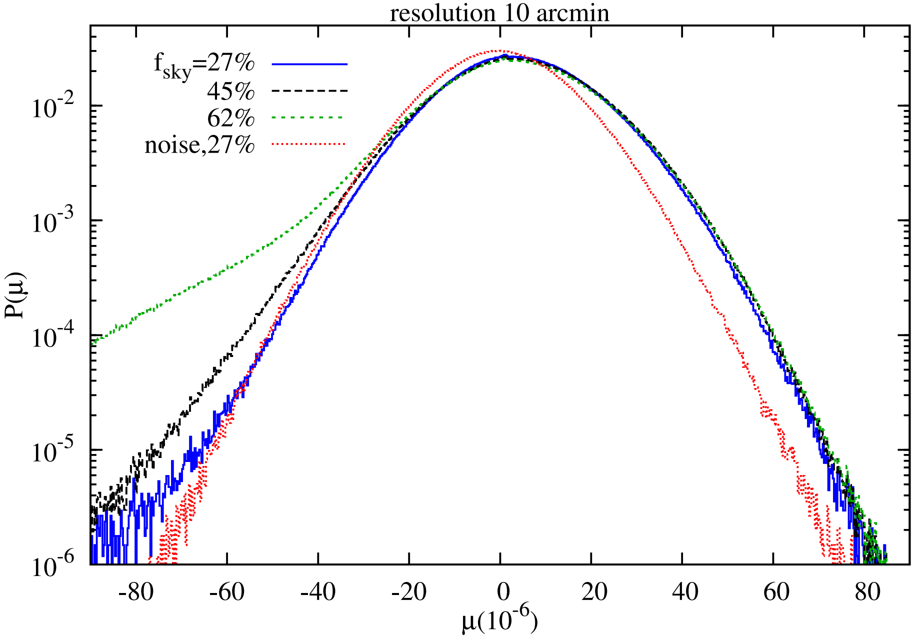
SZ/y-distortion

y-distortion map



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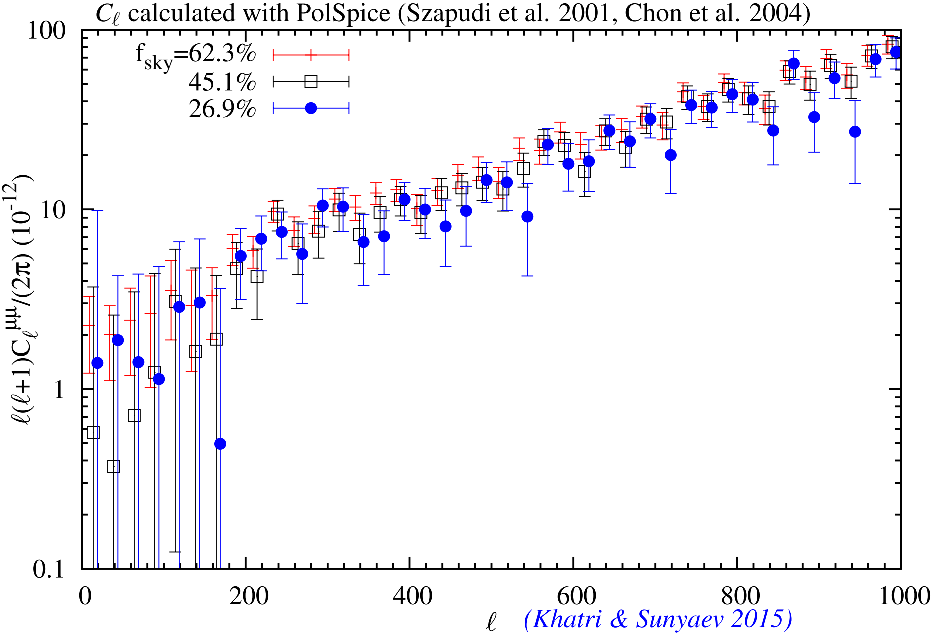
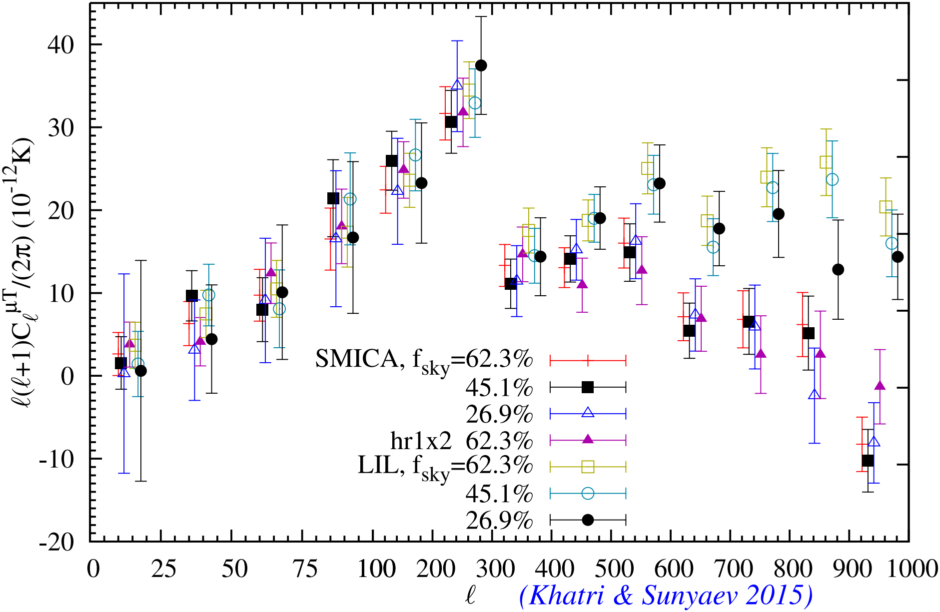
- COBE limit: $\langle\mu\rangle < 90 \times 10^{-6}$ *(Fixsen et al. 1996)*

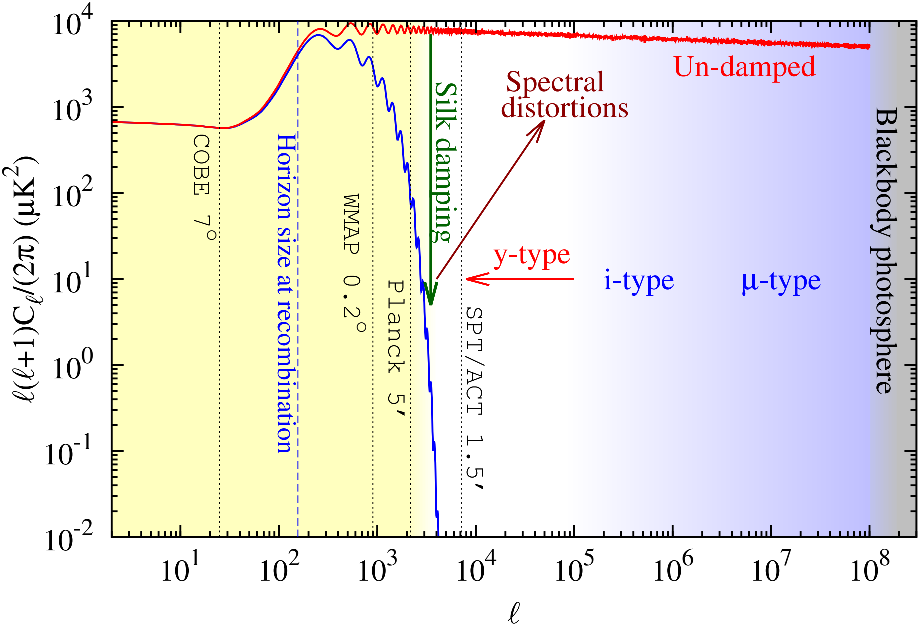
Power spectrum: $C_\ell^{\mu\mu}|_{\ell=2-26} = (2.3 \pm 1.0) \times 10^{-12}$



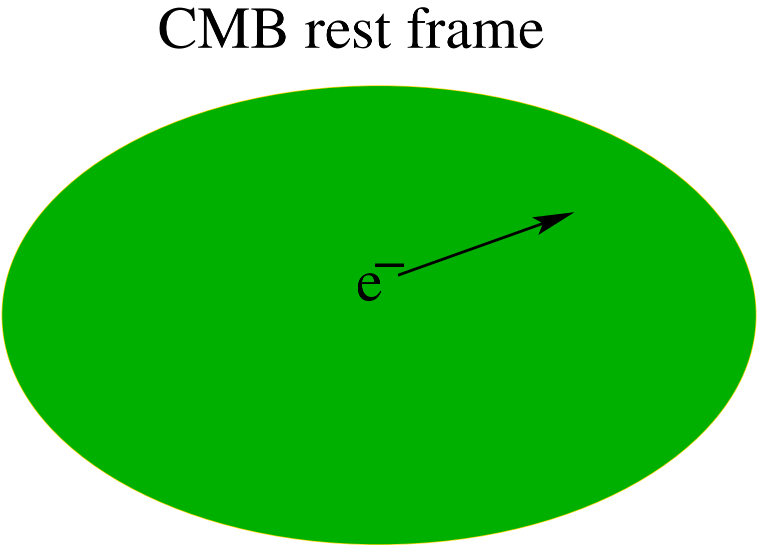
Power spectrum: $C_\ell^{\mu T}|_{\ell=2-26} = (2.6 \pm 2.6) \times 10^{-12}$ K



Silk damping: 17 e-folds of inflation!

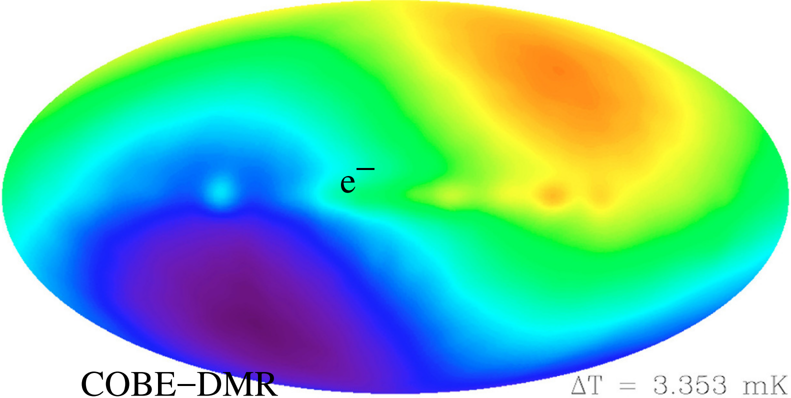


SZ effect in CMB rest frame: Doppler boost



SZ effect in electron rest frame: Mixing of blackbodies in the dipole seen by the electron

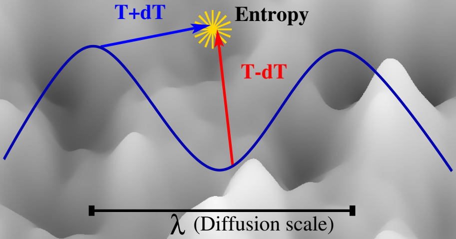
Electron rest frame



COBE−DMR

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

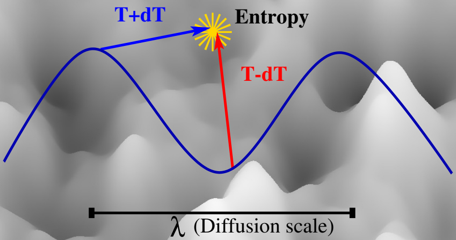
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\Delta E}{E_\gamma}\bigg|_{\mathrm{distortion}} \approx -\frac{\mathrm{d}}{\mathrm{d}t}2\int\frac{k^2\mathrm{d}k}{2\pi^2}P_i(k)\left[\Theta_0^2+3\Theta_1^2+(\ell>1\ \mathrm{terms})\right]$$

$\frac{\Delta T}{T}=\sum_\ell(-i)^\ell(2\ell+1)P_\ell\Theta_\ell$

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



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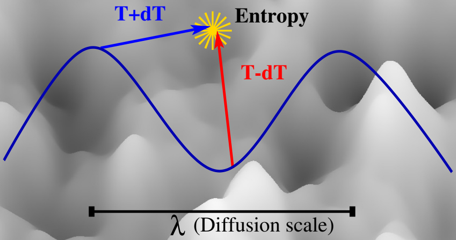
$$1.5\times 10^4 \lesssim z \lesssim 2\times 10^6 \implies 8 \lesssim k_D \lesssim 10^4\ \mathrm{Mpc}^{-1}$$

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



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Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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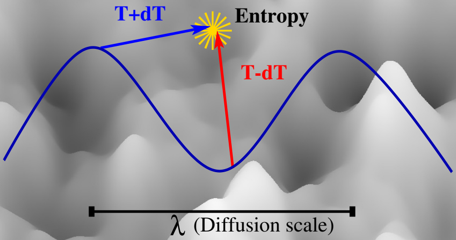
density $\Theta_0 \propto \cos(kr_s)e^{-k^2/k_D^2}$, velocity $\Theta_1 \propto \sin(kr_s)e^{-k^2/k_D^2}$

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

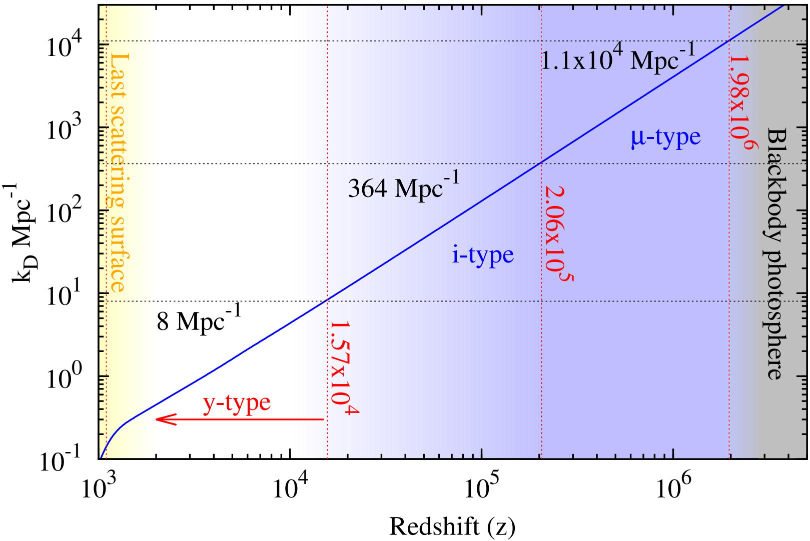
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\Delta E}{E_\gamma}\bigg|_{\mathrm{distortion}} \approx -\frac{\mathrm{d}}{\mathrm{d}t} 2\int \frac{k^2\mathrm{d}k}{2\pi^2} P_i(k)\left[\Theta_0^2 + 3\Theta_1^2 + (\ell > 1 \text{ terms})\right]$$

density $\Theta_0 \propto \cos(kr_s)e^{-k^2/k_D^2}$, velocity $\Theta_1 \propto \sin(kr_s)e^{-k^2/k_D^2}$

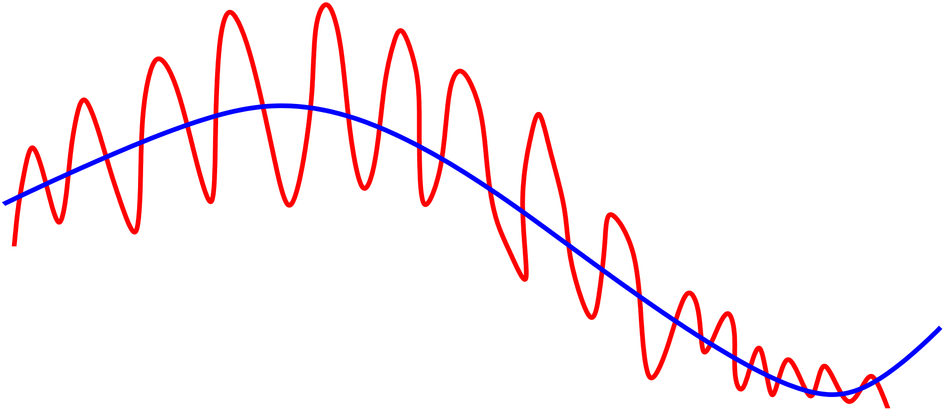
Total energy in the standing wave is independent of time

The Silk damping scale

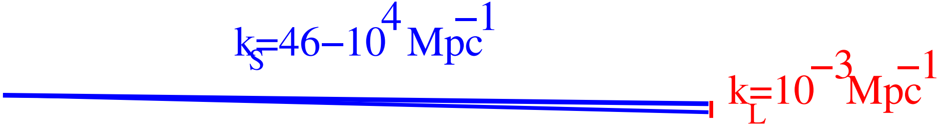


Non-Gaussianity: short wavelength modes correlated with long wavelength fluctuations

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



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 Mpc^{-1}

k_L=10^{-3} 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

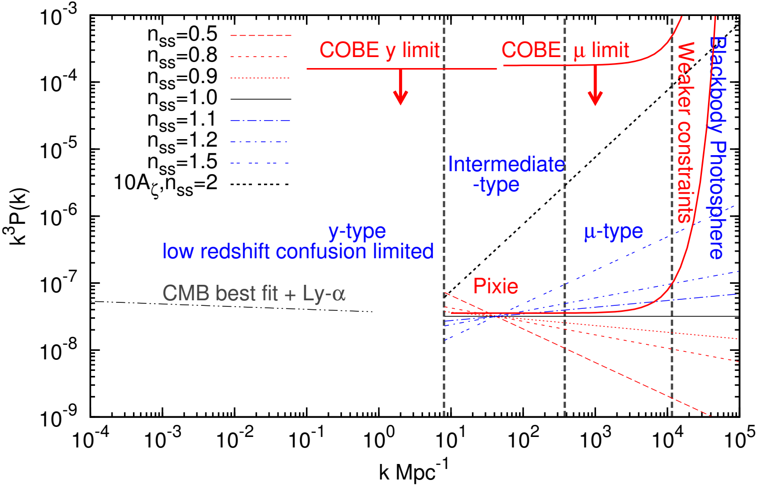
Byrnes, Copeland, & Green 2012

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

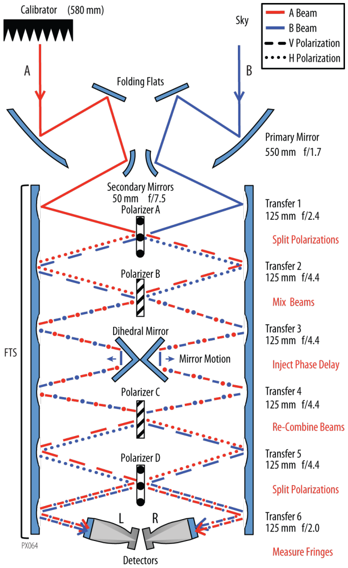
Future: Many orders of magnitude improvement in next decade
PIXIE (NASA), LiteBIRD (JAXA)

Pivot point $k_0 = 42\ \mathrm{Mpc}^{-1}$

$$P_\zeta = (A_\zeta 2\pi^2/k^3)(k/k_0)^{n_s - 1 + \frac{1}{2} dn_s/d\ln k (\ln k/k_0)}$$



Spectrum: Pixie will improve over the COBE precision by at least 3 orders of magnitude *(Kogut et al. 2011)*



Fisher matrix forecasts

Model:

$$\Delta I_\nu = t I_\nu^t + y I_\nu^y + I_\nu^{\rm damping}(n_{\rm s}, A_\zeta, {\rm d}n_{\rm s}/{\rm d}\ln k).$$

Marginalize over temperature (t) and SZ effect (y)

$I_\nu^{\rm damping}$ contains i-type and μ-type distortions

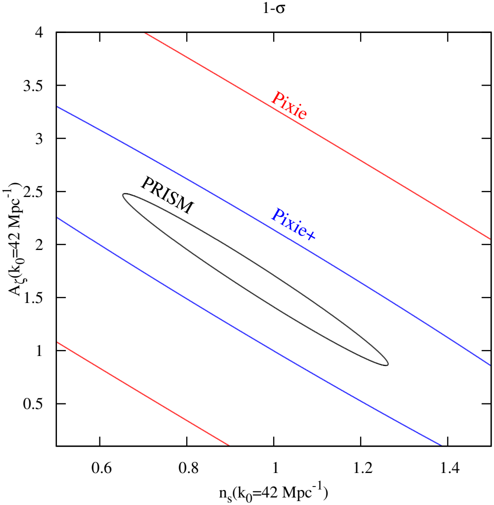
Fisher matrix forecasts

(Khatri and Sunyaev 2013)

Pixie-like experiments:

(x,y) ≡ (Resolution GHz , $\delta I(\nu) = 10^{-26}\mathrm{Wm}^{-2}\mathrm{Sr}^{-1}\mathrm{Hz}^{-1}$)

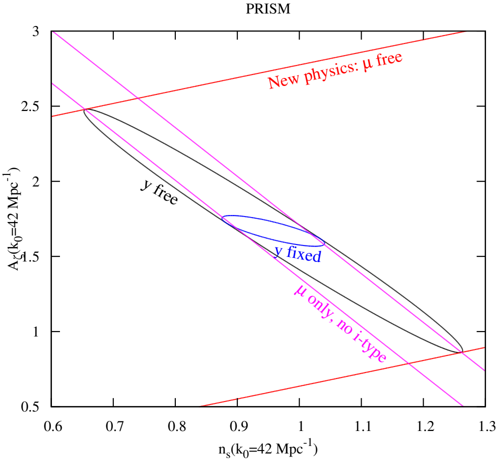
Pixie=(15,5)



Importance of i-type distortions,degeneracies

(Khatri and Sunyaev 2013)

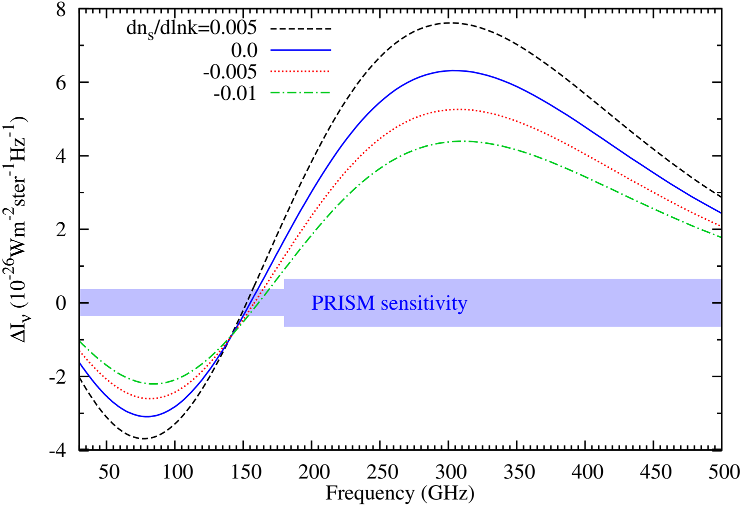
Information in the shape of i-type distortions breaks the $A_\zeta - n_s$ degeneracy



Running spectral index

Fix the pivot point at $k = 0.05\ \mathrm{Mpc}^{-1}$

Long lever arm: Main effect in the amplitude of distortion



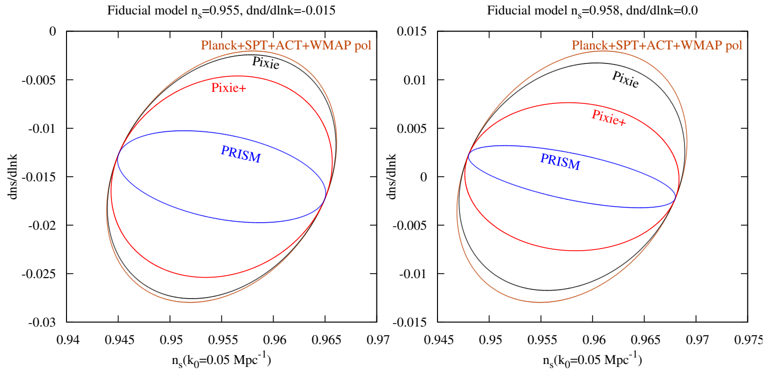
Fisher matrix forecasts with Planck+SPT+ACT+WMAP-pol

(Khatri and Sunyaev 2013)

Planck parameters, running spectrum, Pivot point $k_0 = 0.05$

(x,y) $\equiv$ (Resolution GHz , $\delta I(\nu) = 10^{-26}\mathrm{Wm}^{-2}\mathrm{Sr}^{-1}\mathrm{Hz}^{-1}$)

Pixie=(15,5)



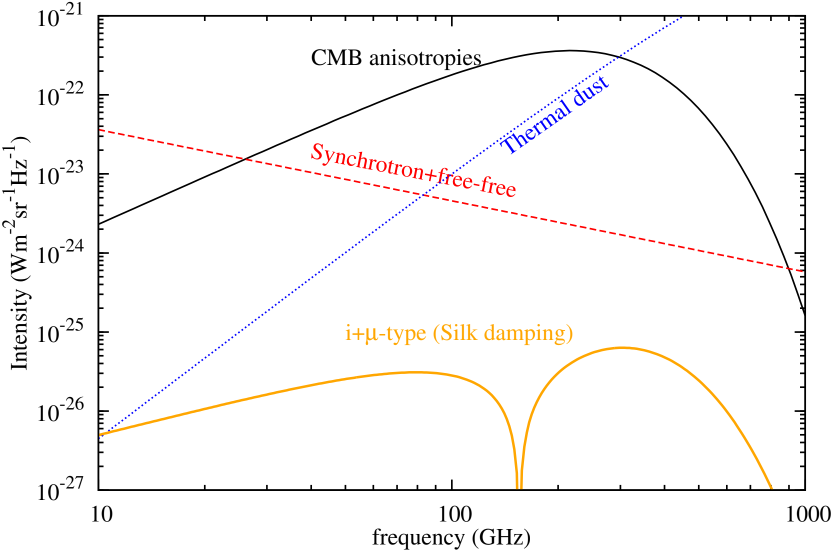
Detectability of primordial perturbations

Assuming $n_{\rm s} = 0.96$

$$\text{Pixie} \quad : A_\zeta(42\ \text{Mpc}^{-1}) = 1.1 \times 10^{-9}$$

$$\text{PRISM} \quad : A_\zeta(42\ \text{Mpc}^{-1}) = 9.9 \times 10^{-11}$$

Foregrounds



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- i-type distortions are quite powerful in removing degeneracies between power spectrum parameters. The extra information comes from the shape of the i-type distortion

Summary continued

With intermediate-type distortions we can distinguish between different mechanisms of energy injection which have different redshift dependence

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There is more....

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  Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012

Summary continued

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  Lochan, Das and Bassi 2012

There is still a long road ahead for CMB cosmology

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This information is accessible and within reach of experiments in not too far future: Pixie

Public code/pre-calculated numerical solutions

Example Mathematica code + high precision pre-calculated numerical solutions for i-type distortions available at
`http://theory.tifr.res.in/~khatri/idistort.html`
Planck Results/Maps
`http://theory.tifr.res.in/~khatri/muresults/`
`http://theory.tifr.res.in/~khatri/szresults/`

Algorithm for fast solution, $\sim 1\%$ level accuracy

(*Khatri and Sunyaev 2012b, arXiv:1207.6654*)

- Calculate μ type distortion using the analytic solution, integrating up to the redshift when $y_\gamma = 2$.

$$n_{\mu-type} = 1.4 n_\mu \int_\infty^{z(y_\gamma=2)} \frac{dQ}{dz} e^{-\mathscr{T}} \tag{1}$$

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http://www.mpa-garching.mpg.de/ khatri/idistort.html

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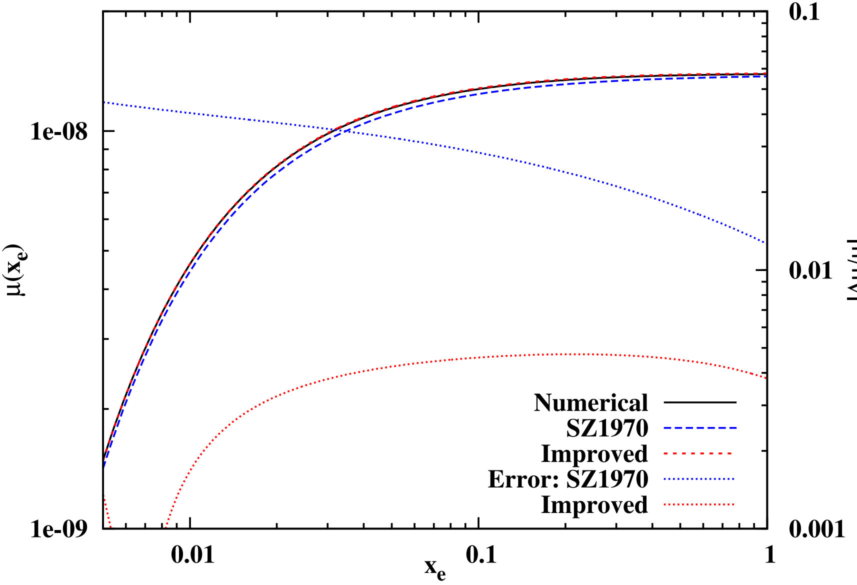
- Add rest of the energy to y-type distortions.

$$n_{y-type} = 0.25 n_y \int_{z(y_\gamma=0.01)}^{z=0} \frac{dQ}{dz} \tag{3}$$

Accuracy of new solutions is better than 1%



y+μ cannot fully mimic i-type distortion

(*Khatri and Sunyaev 2012b, arXiv:1207.6654*)

μ type and intermediate-type distortions are not independent. For Silk damping, intermediate-type distortions must contain about the same amount of energy as μ-type distortions.