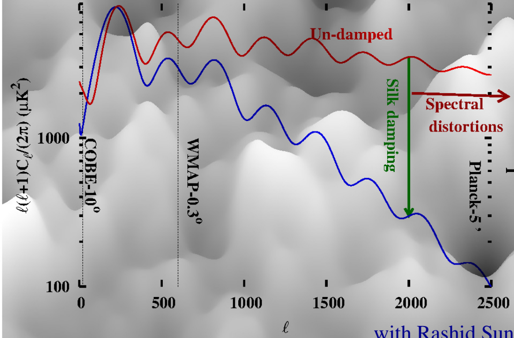
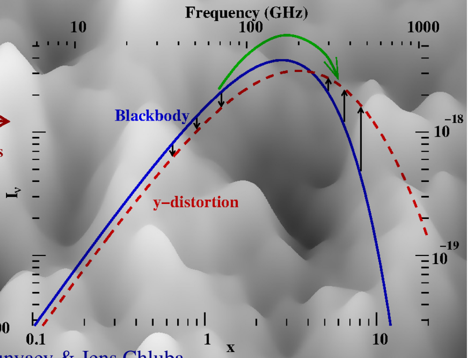
After Planck: The road to observing 17 e-folds of inflation

Rishi Khatri





with Rashid Sunyaev & Jens Chluba

Silk damping: arXiv:1205.2871

Review: arXiv:1302.6553

Forecasts: arXiv:1303.7212

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

Max-Planck-Institut für Astrophysik

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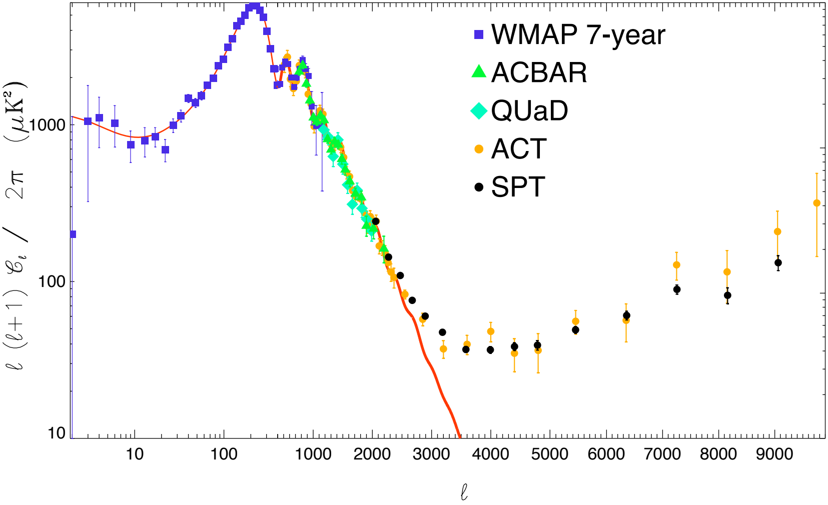
We have reached the resolution limit for CMB anisotropies



Shirokoff et al. (SPT) 2011

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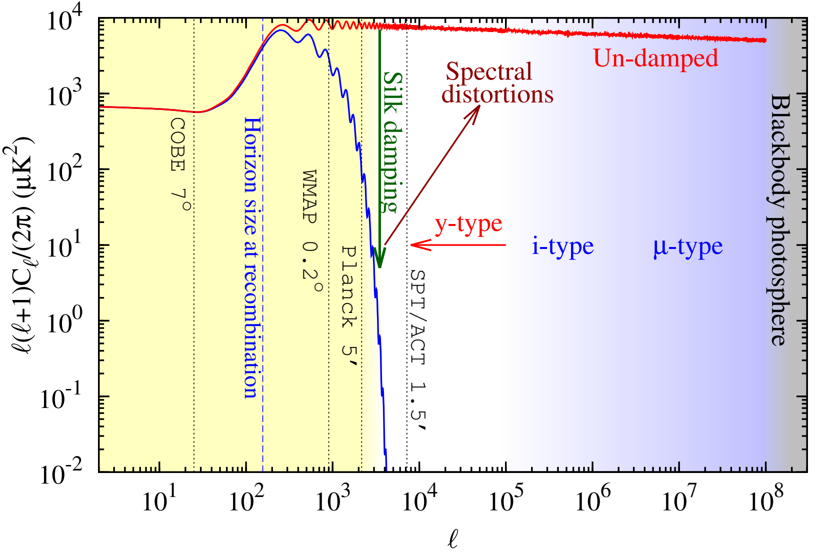
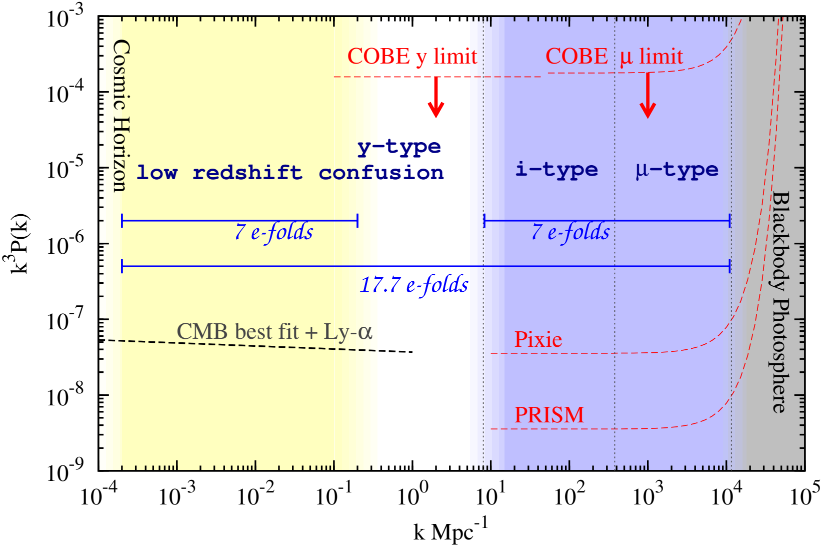


Going from 7 to 17 e-folds of inflation



Planck spectrum

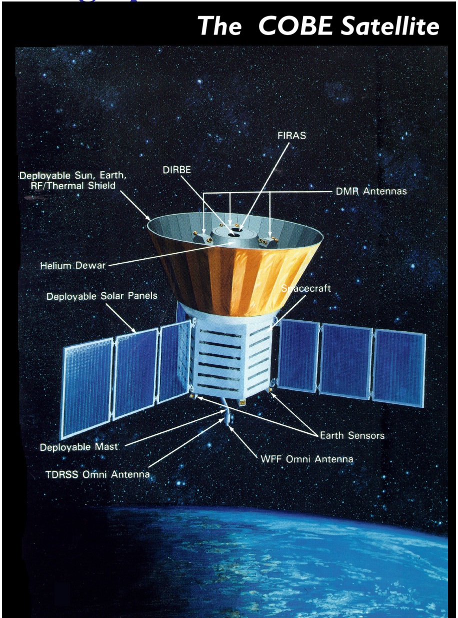
$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(k_\mathrm{B}T)}-1}$$

Relativistic invariant occupation number/phase space density

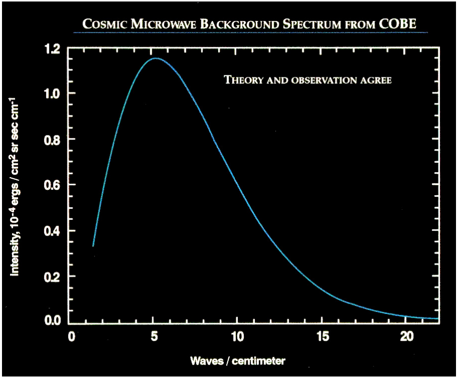
$$n(\nu) \equiv \frac{c^2}{2h\nu^3} I_\nu$$

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

COBE-FIRAS confirmed blackbody spectrum of CMB at high precision

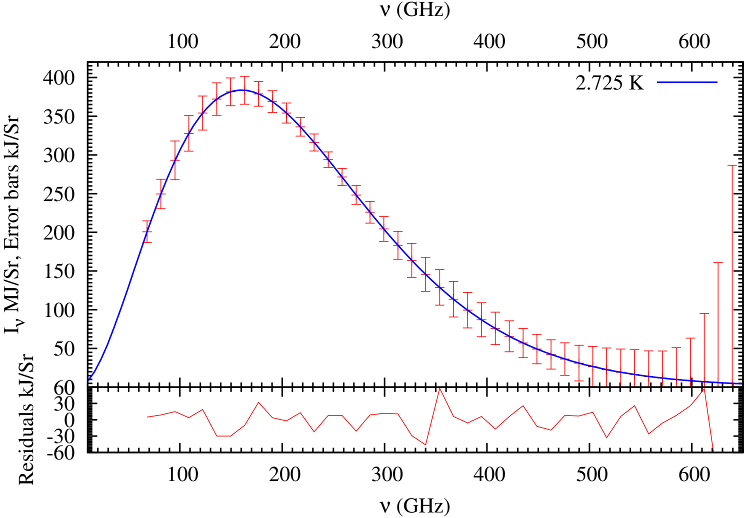


Nobel prize for Planck 1918
Nobel Prize for Mather 2006 (+ Smoot for anisotropies)
Fixsen et al. 1996

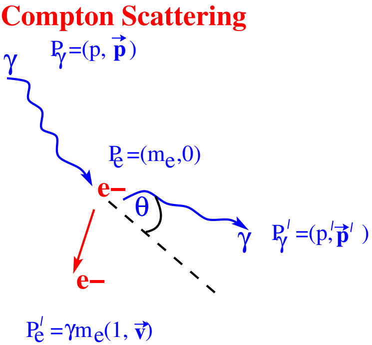


The CMB spectrum from COBE agrees with the Planck spectrum

Fixsen et al. 1996, Fixsen & Mather 2002



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

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

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No. of scatterings

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No. of scatterings Energy transfer per scattering

Doppler effect:

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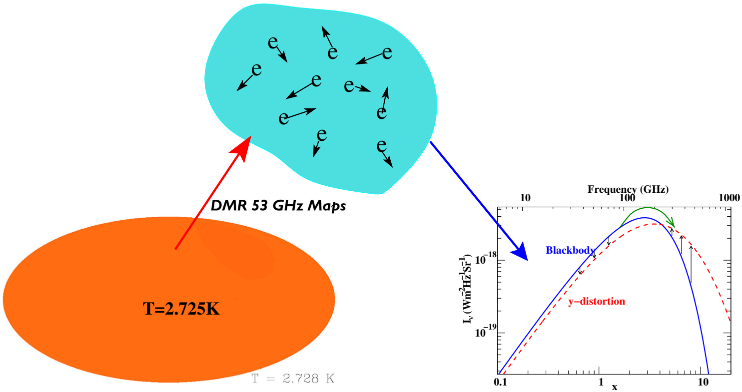
y-type (Sunyaev-Zeldovich effect) from clusters/reionization

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

$$y = (\tau_{\rm reionization})\frac{k_{\rm B}T_{\rm e}}{m_{\rm e}c^2} \sim (0.1)(1.6\times 10^{-6}) \sim 10^{-7}$$



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

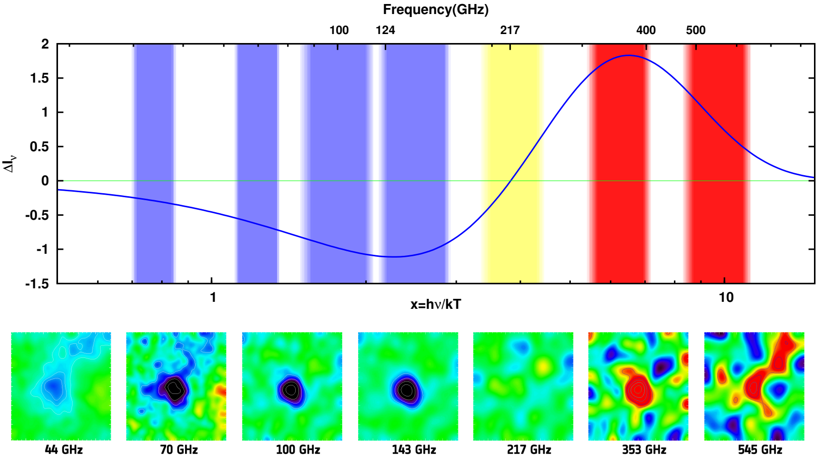
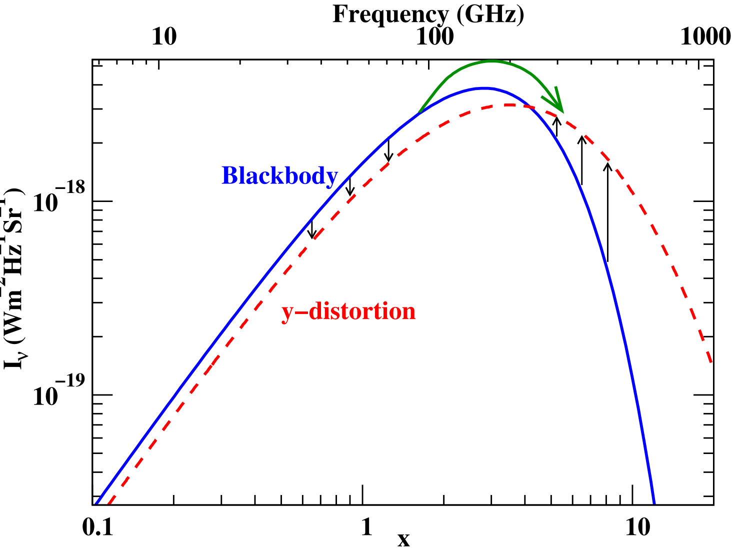


Image credit: ESA / HFI & LFI Consortia

Average y-distortion (Sunyaev-Zeldovich effect) limits

(Zeldovich and Sunyaev 1969)

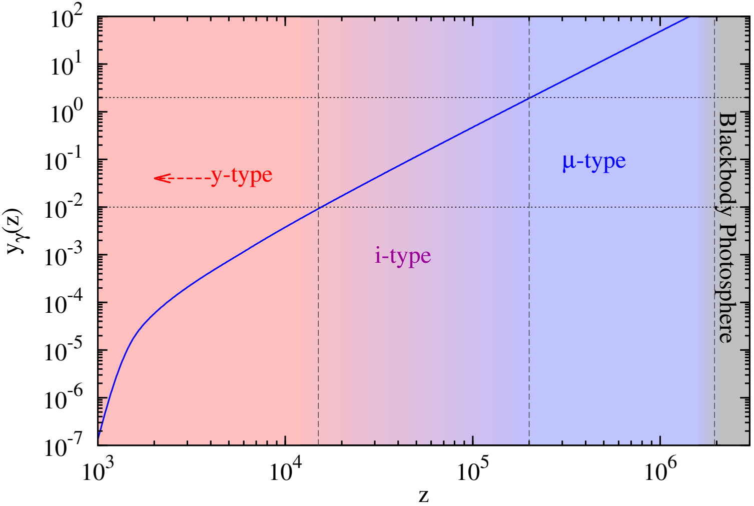
COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*



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)

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

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

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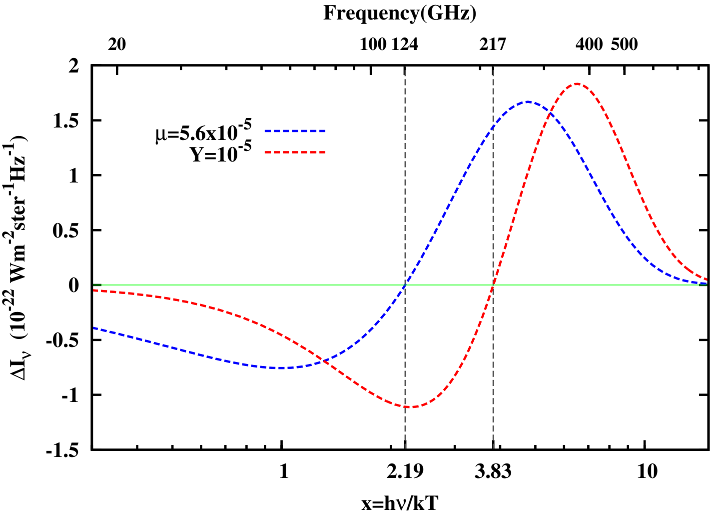
Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

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)

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

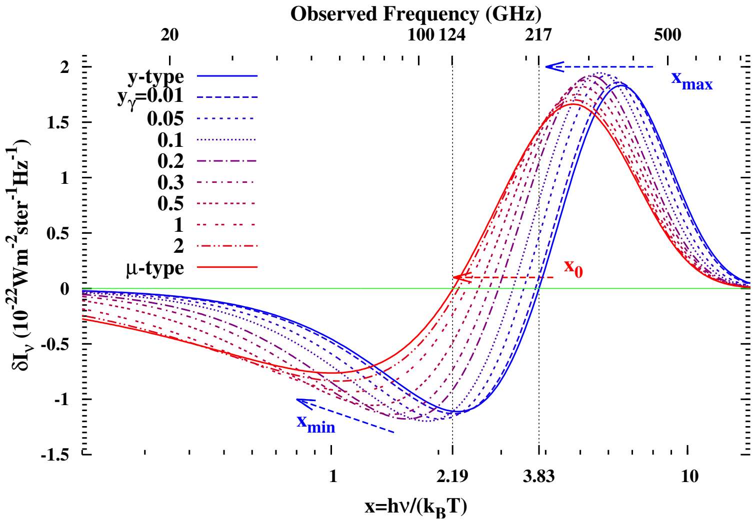
COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ *(Fixsen et al. 1996)*



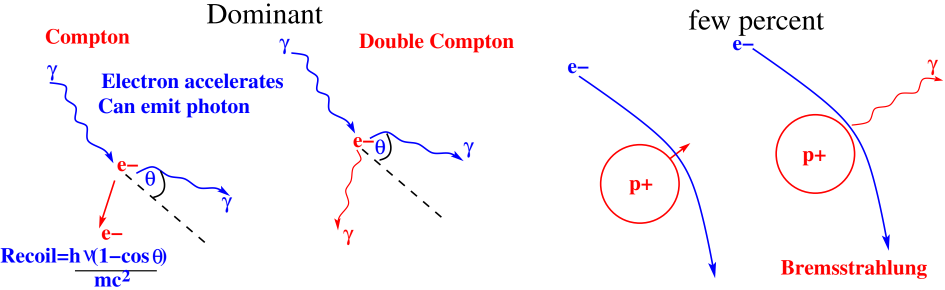
Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

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

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

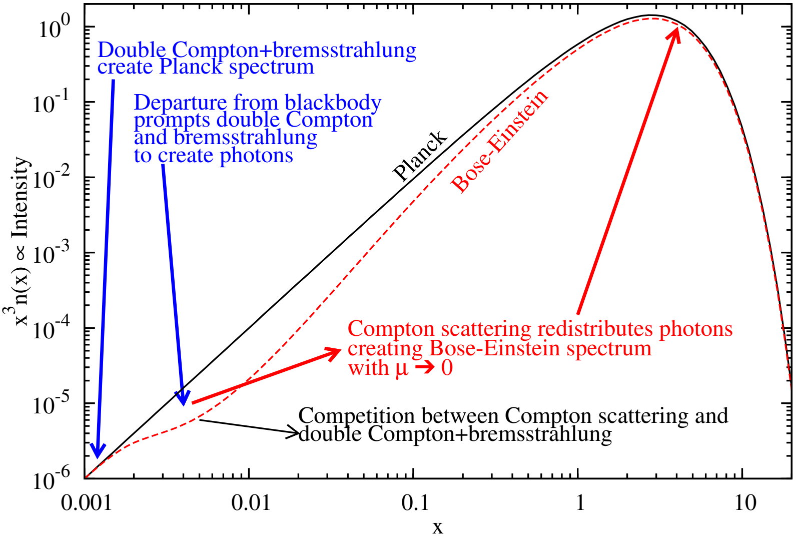


Processes responsible for creation of CMB spectrum

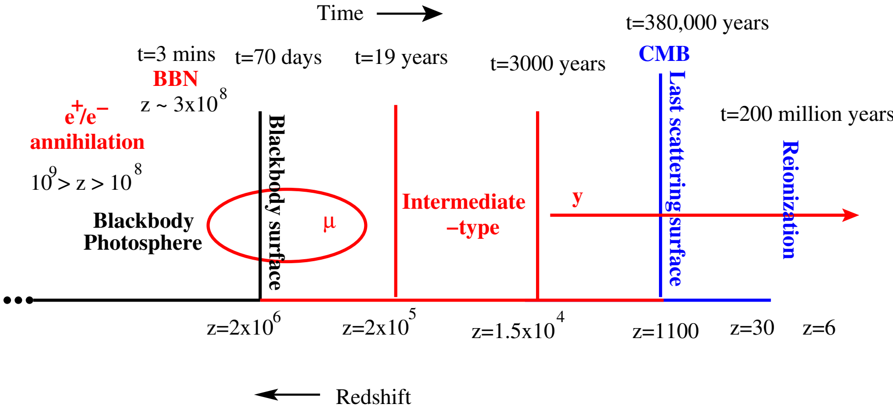


- Double Compton and bremsstrahlung create/absorb photons ($\propto 1/x^2$)
- Compton scattering distributes them over the whole spectrum

Creation of CMB Planck spectrum



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

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

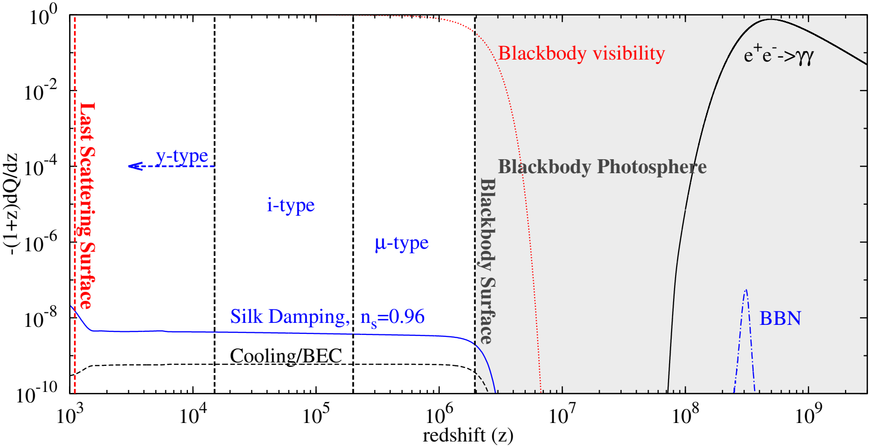
This solution has accuracy of $\sim 10\%$, $z_{\rm dC} \approx 1.96 \times 10^{6}$

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*)

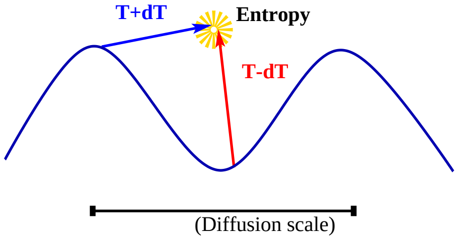
$$\mathscr{T}(z) \approx 1.007\left[\left(\frac{1+z}{1+z_{\rm dC}}\right)^{5} + \left(\frac{1+z}{1+z_{\rm br}}\right)^{5/2}\right]^{1/2} + 1.007\varepsilon \ln\left[\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/4} + \sqrt{1+\left(\frac{1+z}{1+z_{\varepsilon}}\right)^{5/2}}\right]$$
$$+\left[\left(\frac{1+z}{1+z_{\rm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

The general picture



Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



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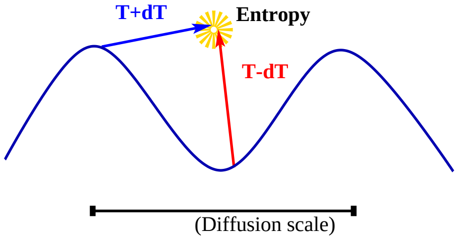

Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

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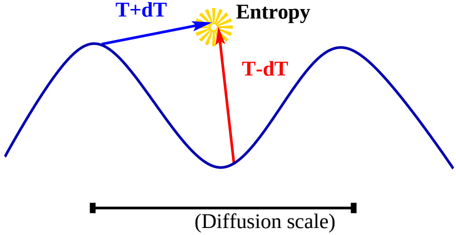

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$$< n_{\rm Planck}\left(T + \frac{\delta T}{T}\right) > = < \frac{1}{e^{\frac{h\nu}{k(T+\delta T/T)}} - 1} >$$

Silk damping

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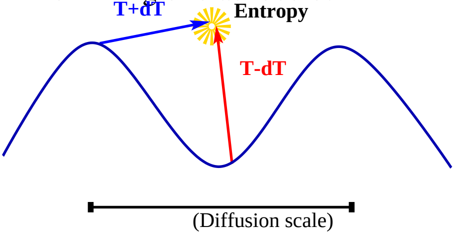

Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

$$< n_{\rm Planck} > = \frac{1}{e^{\frac{h\nu}{kT}} - 1} + \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T \frac{\partial n_{\rm Pl}}{\partial T} + \frac{1}{2} \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\rm Pl}}{\partial T}$$

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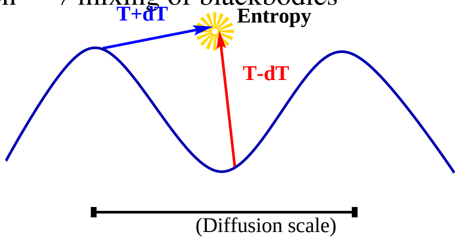

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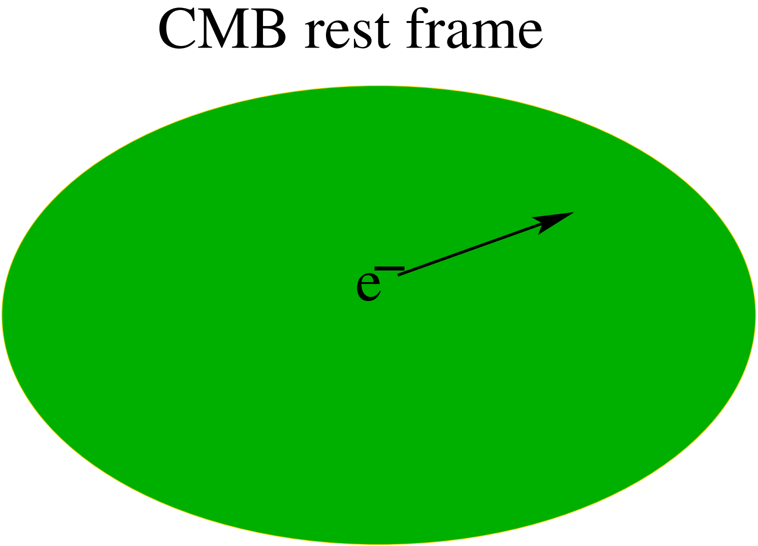
$$= n_{\rm Planck}\left(T + \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle \right) + \frac{1}{2} \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle n_{SZ}$$

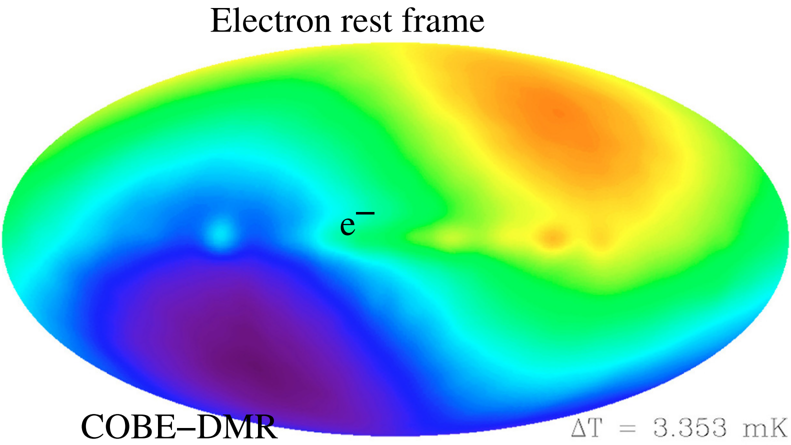
2/3 — Black body

1/3 — Kompaneets operator/SZ

SZ effect in CMB rest frame: Doppler boost

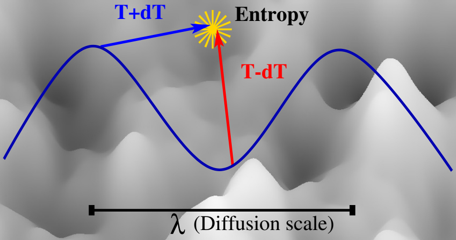


SZ effect in electron rest frame: Mixing of blackbodies in the dipole seen by the electron



Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

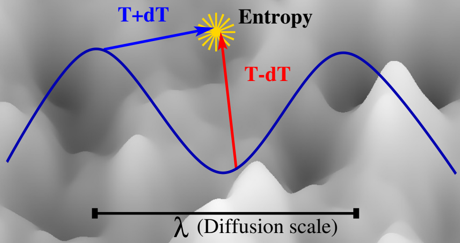
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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

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

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

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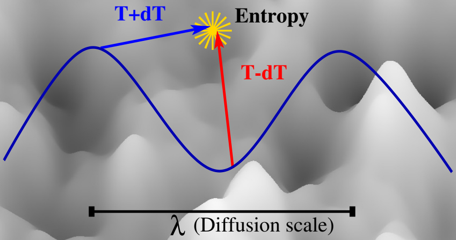

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density $\Theta_0 \propto \cos(kr_s)e^{-k^2/k_D^2}$, velocity $\Theta_1 \propto \sin(kr_s)e^{-k^2/k_D^2}$

Silk damping

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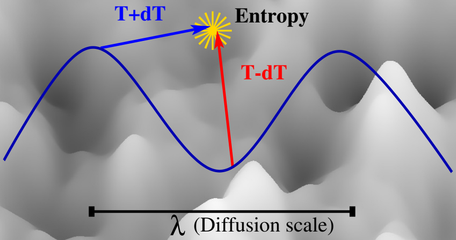

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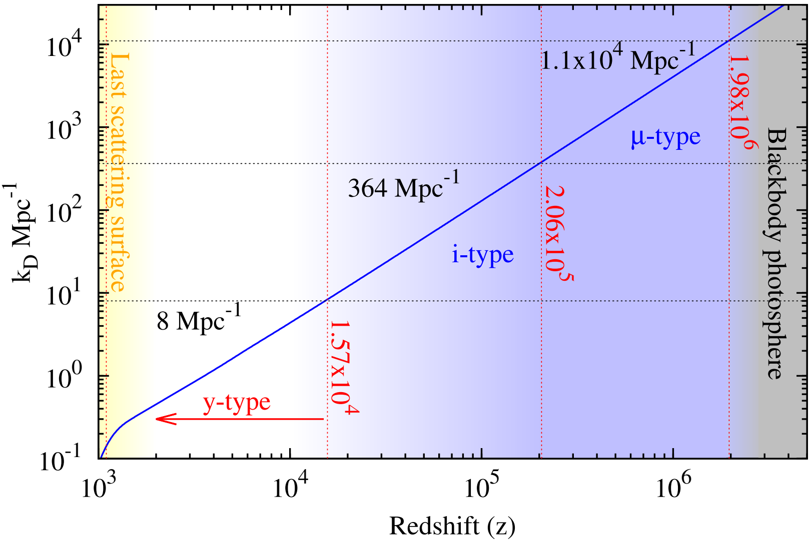
density $\Theta_0 \propto \cos(kr_s)e^{-k^2/k_D^2}$, velocity $\Theta_1 \propto \sin(kr_s)e^{-k^2/k_D^2}$

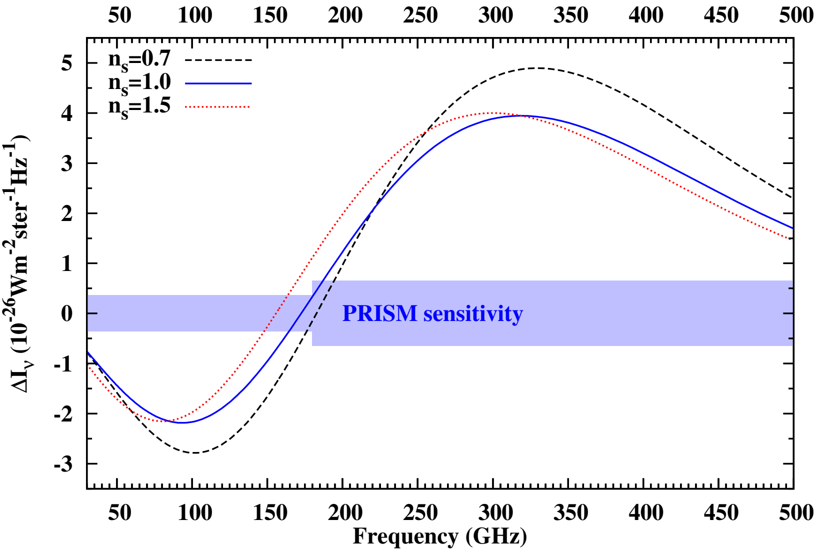
Total energy in the standing wave is independent of time

The Silk damping scale



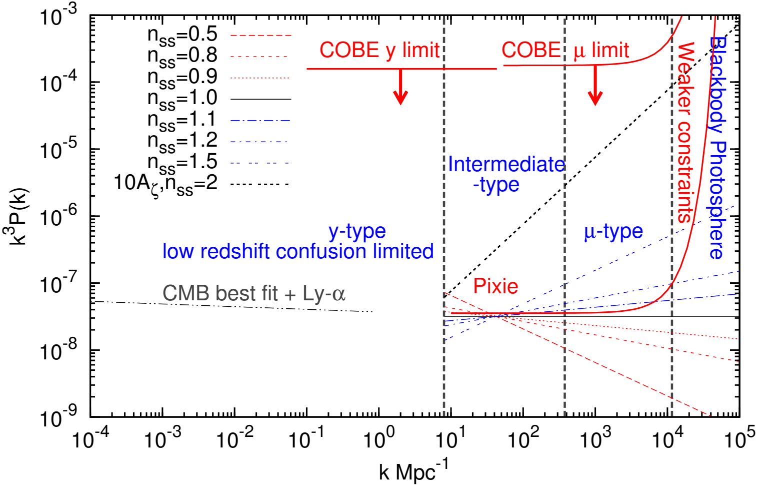
Silk damping *(Khatri and Sunyaev 2012b)*

Add spectra for different $k_D(y_\gamma)$ with weights $\propto P_i(k_D)$

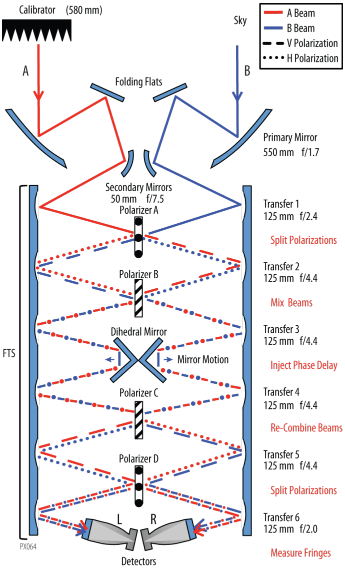


Pivot point $k_0 = 42\ \mathrm{Mpc}^{-1}$

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



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

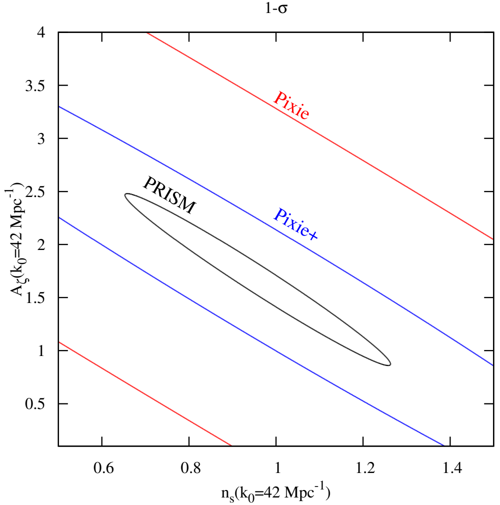
Fisher matrix forecasts

(Khatri and Sunyaev 2013)

Pixie-like experiments:

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

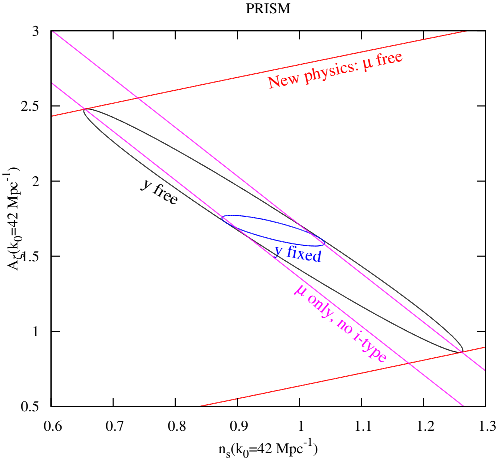
Pixie=(15,5)



Importance of *i*-type distortions,degeneracies

(Khatri and Sunyaev 2013)

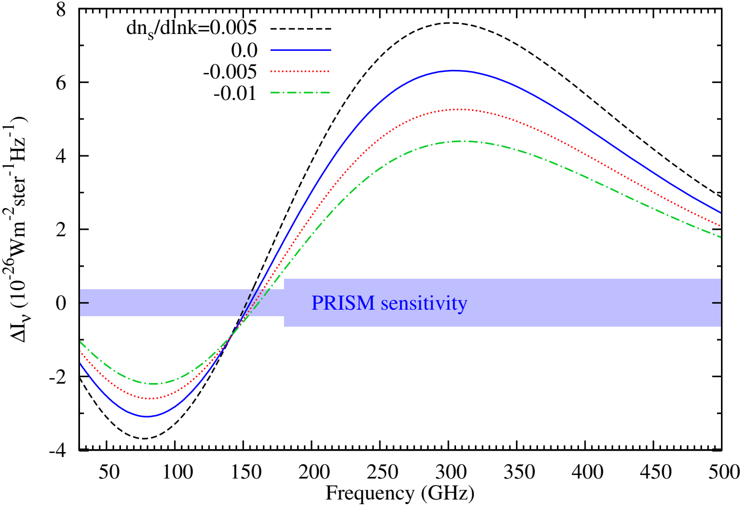
Information in the shape of *i*-type distortions breaks the $A_\zeta - n_s$ degeneracy



Running spectral index

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

Long lever arm: Main effect in the amplitude of distortion



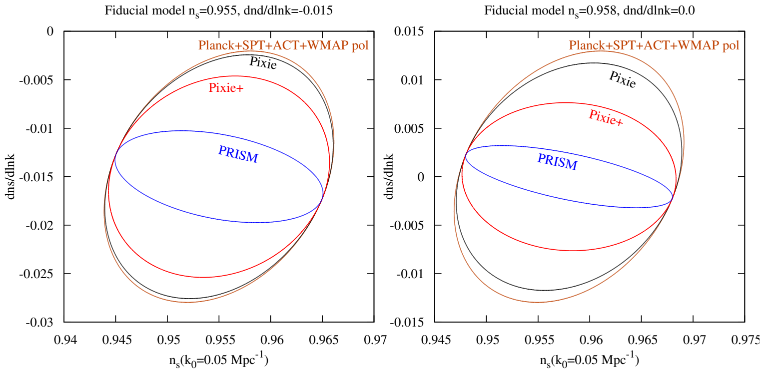
Fisher matrix forecasts with Planck+SPT+ACT+WMAP-pol

(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)

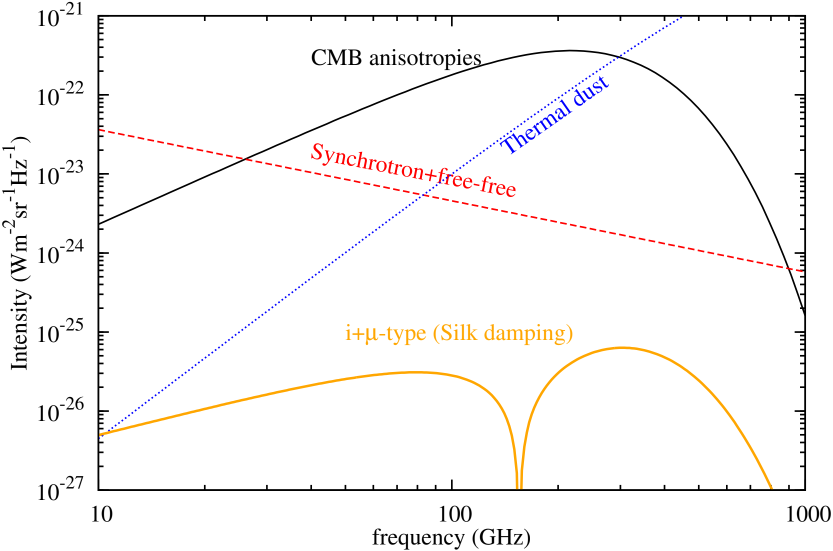


Detectability of primordial perturbations

Assuming $n_\mathrm{s} = 0.96$

$$\begin{aligned} &\text{Pixie} && : A_\zeta(42\,\mathrm{Mpc}^{-1}) = 1.1 \times 10^{-9} \\ &\text{PRISM} && : A_\zeta(42\,\mathrm{Mpc}^{-1}) = 9.9 \times 10^{-11} \end{aligned}$$

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

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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, PRISM

Public code/pre-calculated numerical solutions

Example Mathematica code + high precision pre-calculated numerical solutions for i-type distortions available at
http://www.mpa-garching.mpg.de/~khatri/idistort.html
Fortran version soon.

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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$$n_{i-type} = \frac{1}{Q_{num}} \sum_i \frac{dQ}{dy_\gamma}({y_\gamma}^i)\,\delta {y_\gamma}^i\, n({y_\gamma}^i) \tag{2}$$

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

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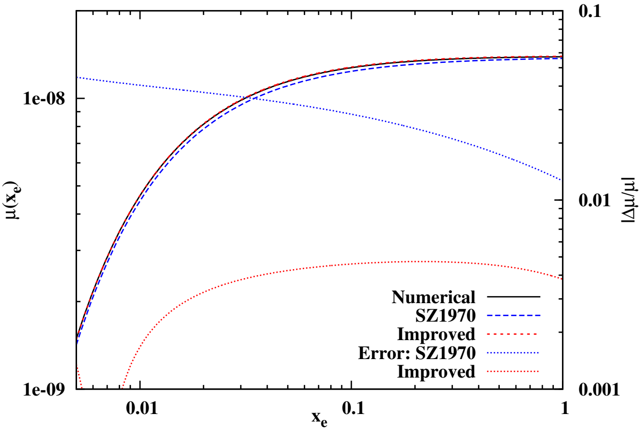
- Add rest of the energy to y-type distortions.

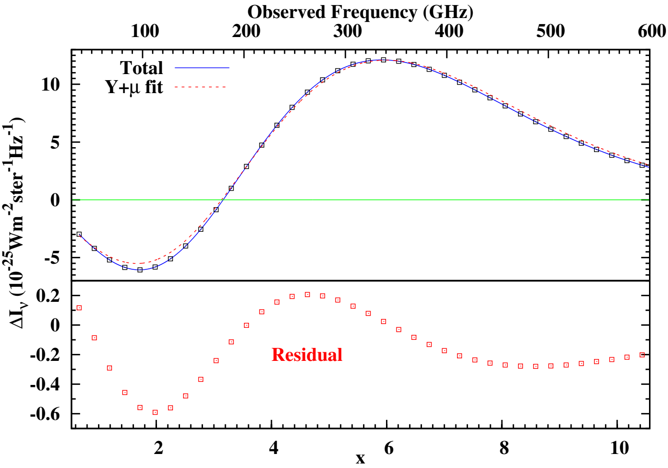
$$n_{y-type} = 0.25 n_y \int_{z(y_\gamma=0.01)}^{z=0} \frac{dQ}{dz} \quad (3)$$

Accuracy of new solutions is better than 1%

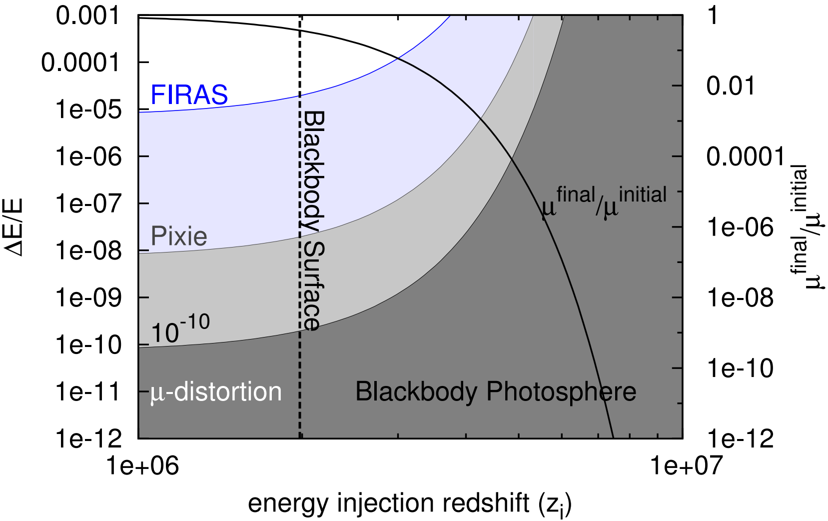


$y+\mu$ cannot fully mimic i-type distortion

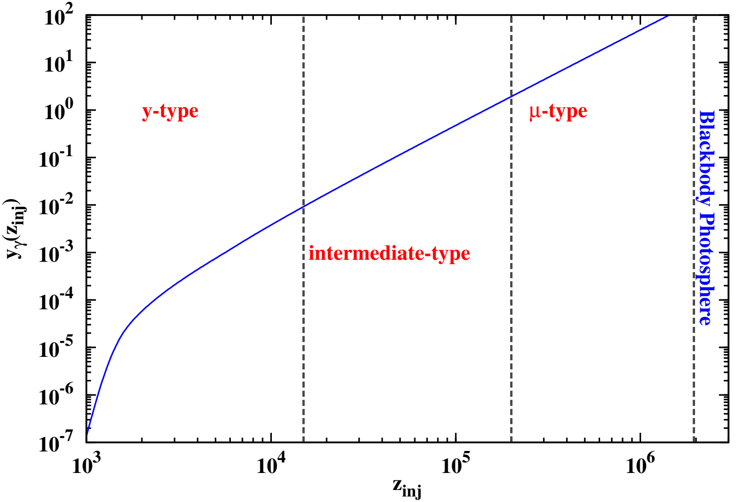
μ type and intermediate-type distortions are not independent. For Silk damping, intermediate-type distortions must contain about the same amount of energy as μ-type distortions.



Blackbody photosphere



$$y_\gamma = \int_{z_{\rm inj}}^{0} {\rm d}t \, \frac{k_{\rm B}\sigma_{\rm T} n_{\rm e}}{m_{\rm e} c} T_\gamma \quad \Big| \; y_\gamma \gg 1 \implies \mu \, , \; y_\gamma \ll 1 \implies y$$



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

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

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

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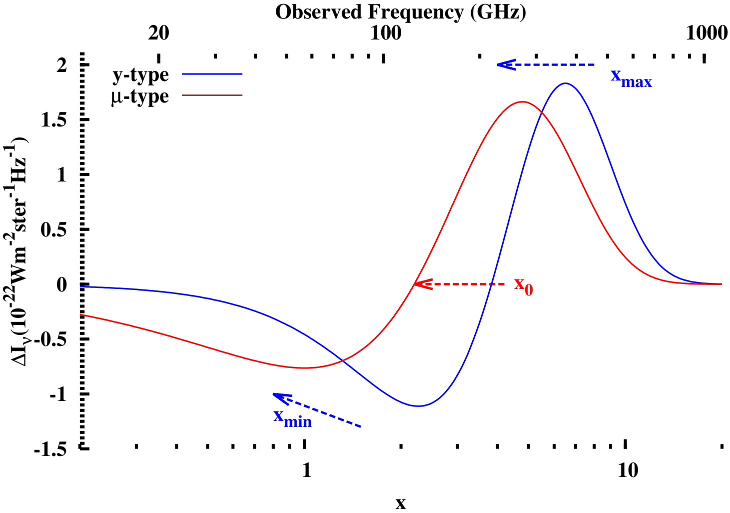
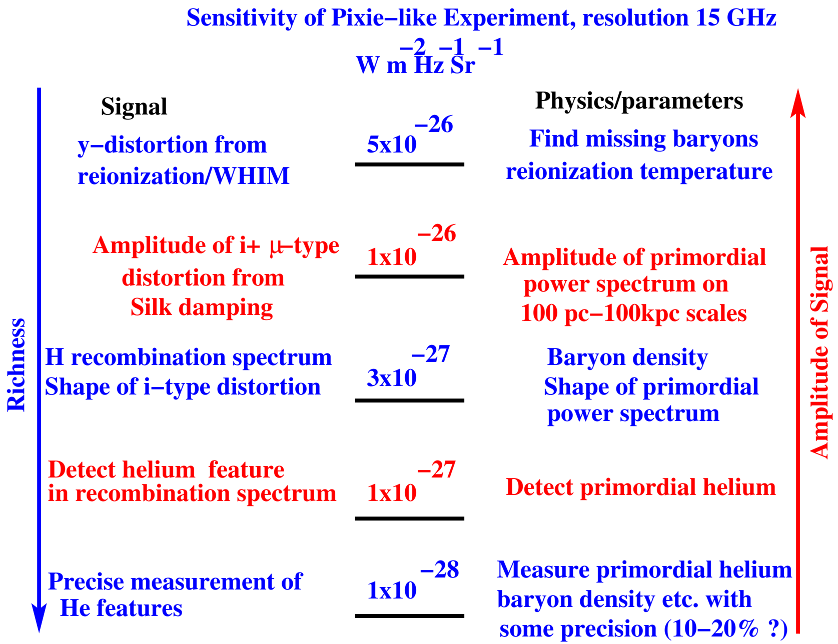
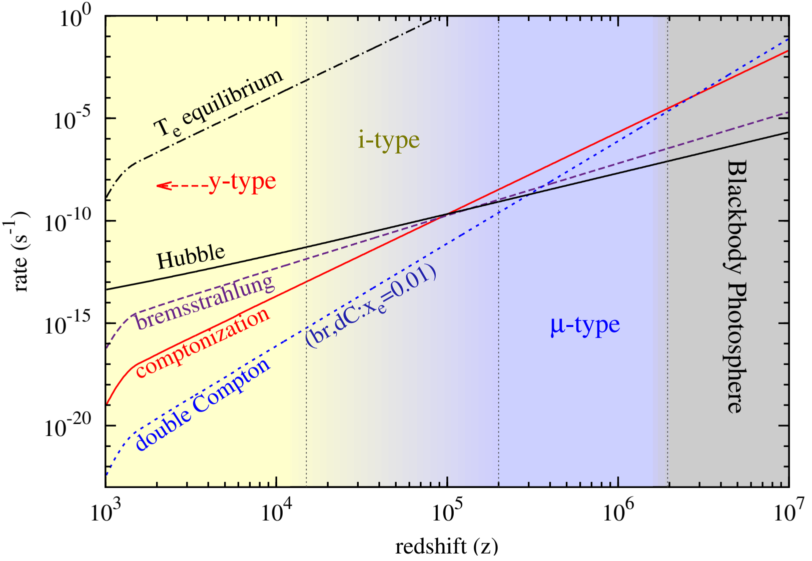



Sensitivity of Pixie−like Experiment, resolution 15 GHz
W m−2 Hz−1 Sr−1
Signal
Physics/parameters
y−distortion from reionization/WHIM
5x10−26
Find missing baryons reionization temperature
Amplitude of i+ μ−type distortion from Silk damping
1x10−26
Amplitude of primordial power spectrum on 100 pc−100kpc scales
H recombination spectrum
Shape of i−type distortion
3x10−27
Baryon density
Shape of primordial power spectrum
Detect helium feature in recombination spectrum
1x10−27
Detect primordial helium
Precise measurement of He features
1x10−28
Measure primordial helium baryon density etc. with some precision (10−20% ?)
Richness
Amplitude of Signal

Rates of different processes



Bose-Einstein spectrum

$$
\begin{aligned}
n_{\mathrm{BE}} &= \frac{1}{e^{\frac{h\nu}{k_{\mathrm{B}}T_{\mathrm{BE}}}+\mu} - 1} \\
&= \frac{1}{e^{x-0.456\mu x+\mu} - 1} \\
&\approx n_{\mathrm{pl}}(x) + \frac{\mu e^{x}}{(e^{x}-1)^{2}}\left(\frac{x}{2.19} - 1\right),
\end{aligned}
$$