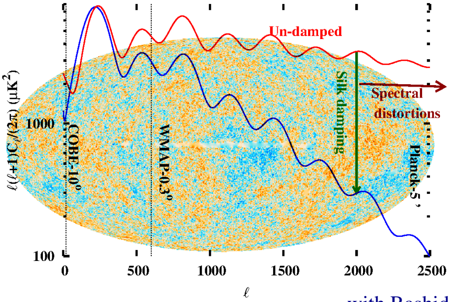
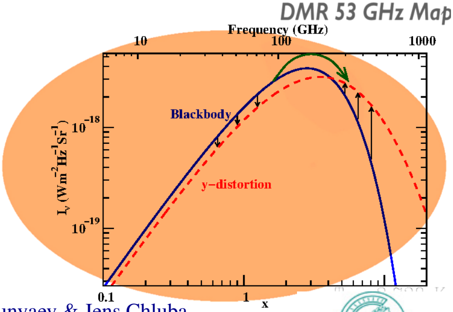
After Planck: The road to observing 17 e-folds of inflation

Rishi Khatri



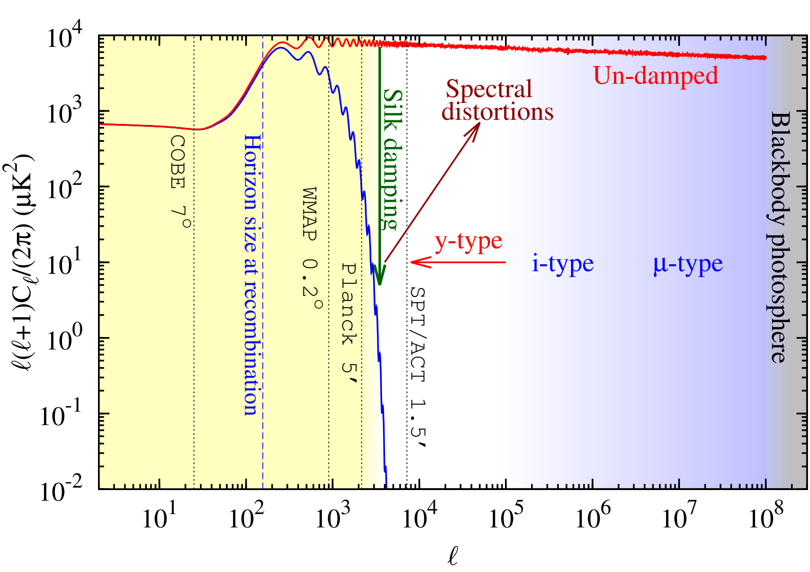


Max-Planck-Institut
für Astrophysik

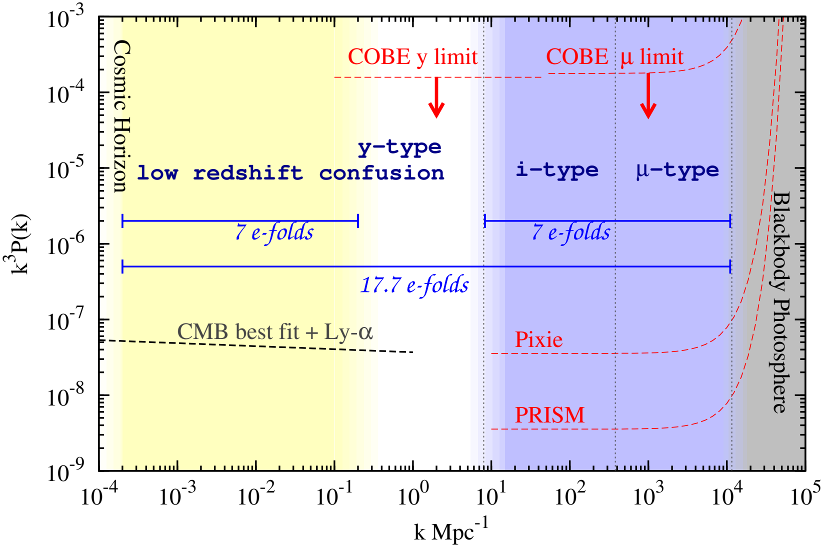
with Rashid Sunyaev & Jens Chluba
Silk damping: arXiv:1205.2871
Review: arXiv:1302.6553
Forecasts: arXiv:1303.7212

MAX-PLANCK-GESELLSCHAFT

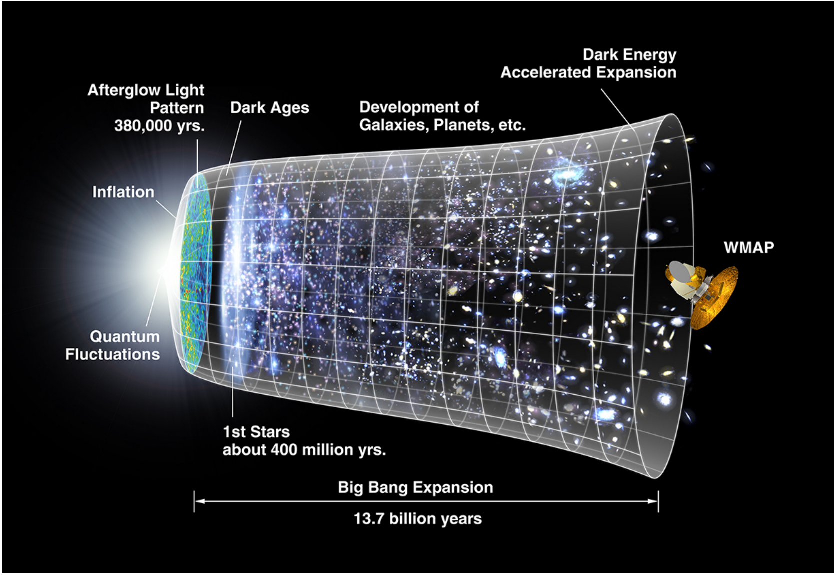
We have reached the resolution limit for CMB anisotropies



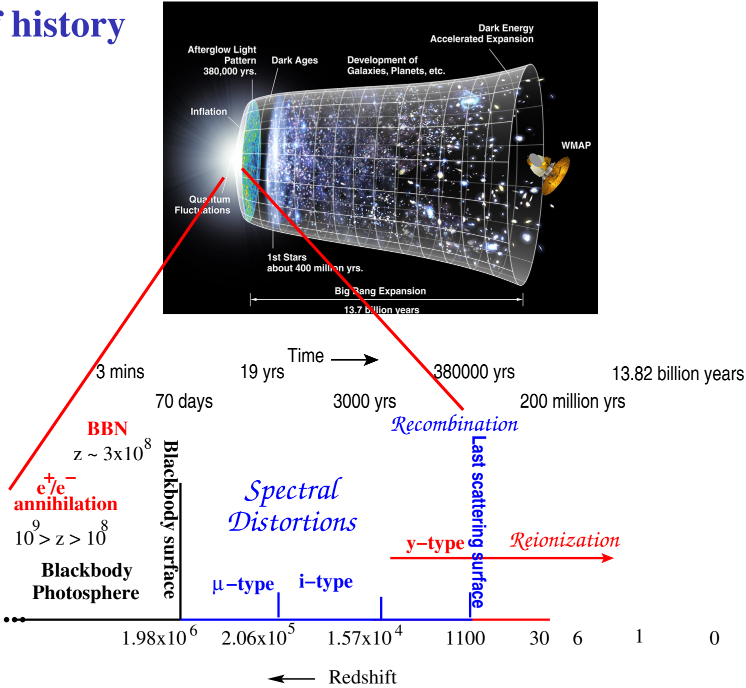
Going from 7 to 17 e-folds of inflation



Brief history of the Universe



Brief history



Planck spectrum

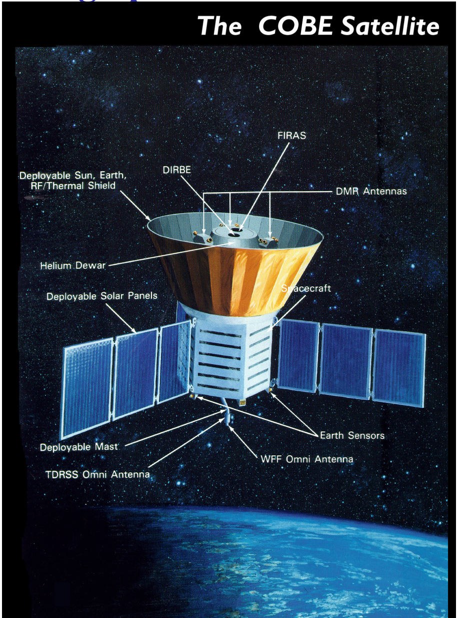
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_\mathrm{B}T)} - 1}$$

Relativistic invariant occupation number/phase space density

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

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

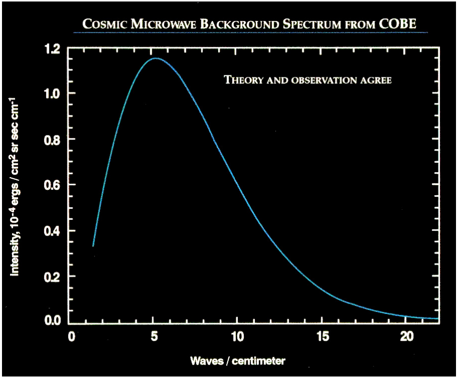
COBE-FIRAS confirmed blackbody spectrum of CMB at high precision



Nobel prize for Planck 1918

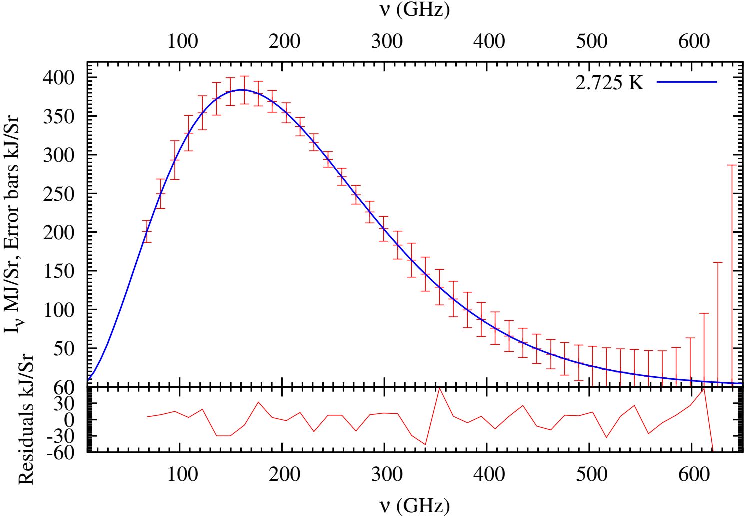
Nobel Prize for Mather 2006

Fixsen et al. 1996

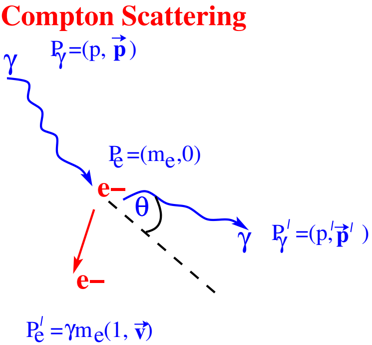


The CMB spectrum from COBE agrees with the Planck spectrum

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

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

Efficiency of energy exchange between electrons and photons

Recoil:

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

No. of scatterings

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

Recoil:

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

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 $y_\gamma \approx y_{\mathrm{e}}$

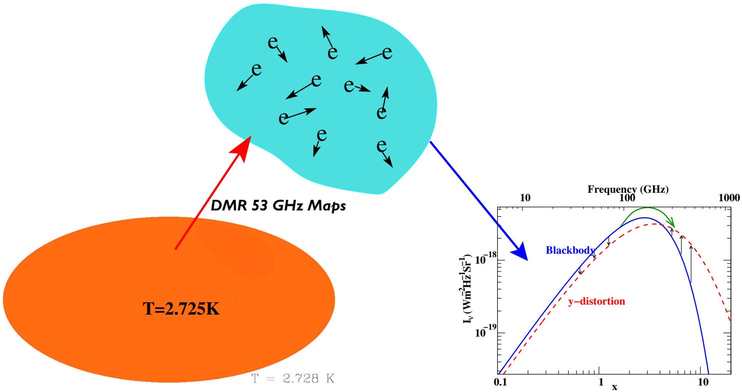
y: Amplitude of distortion

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

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

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

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



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

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

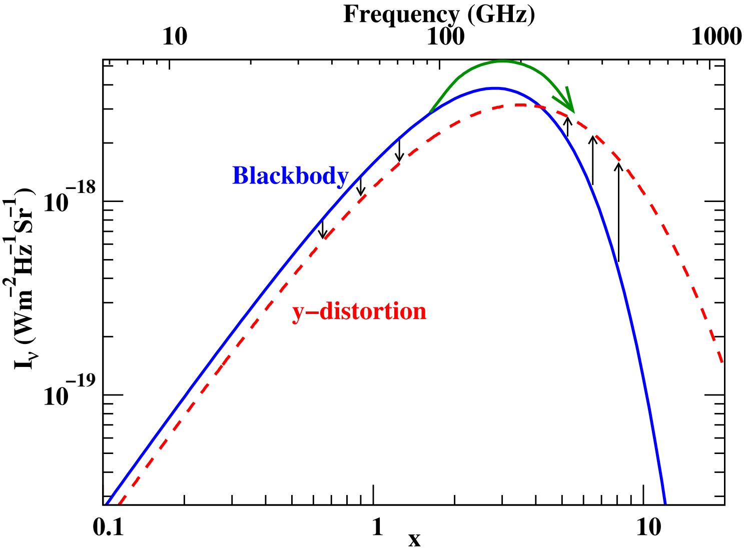
$$= \mathbf{y} \; \frac{\mathbf{x e^x}}{(\mathbf{e^x - 1})^2} \left(\mathbf{x} \frac{\mathbf{e^x + 1}}{\mathbf{e^x - 1}} - \mathbf{4} \right)$$

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

Average y-distortion (Sunyaev-Zeldovich effect) limits

(Zeldovich and Sunyaev 1969)

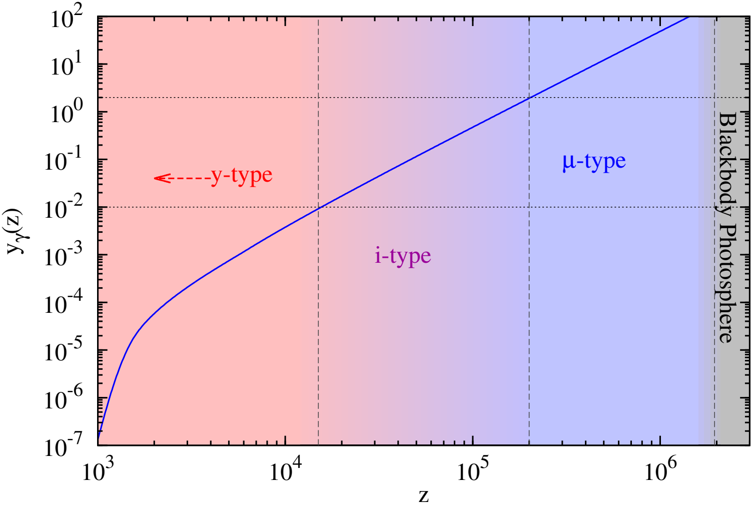
COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*



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)

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

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

Bose-Einstein spectrum- Chemical potential (μ)

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

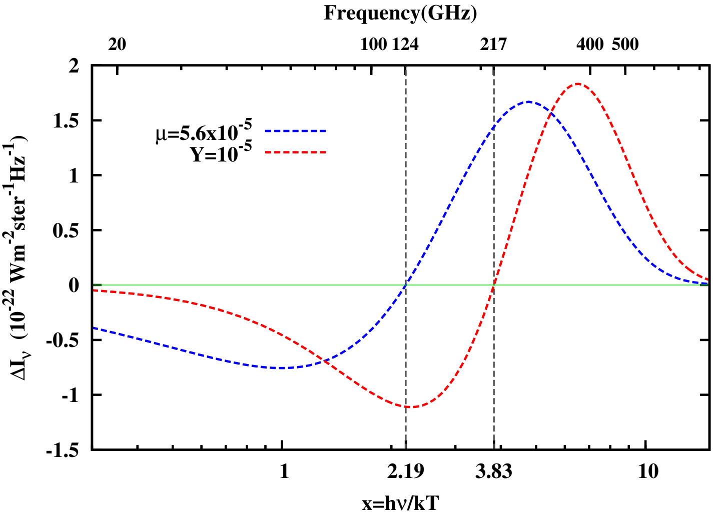
Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

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)

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

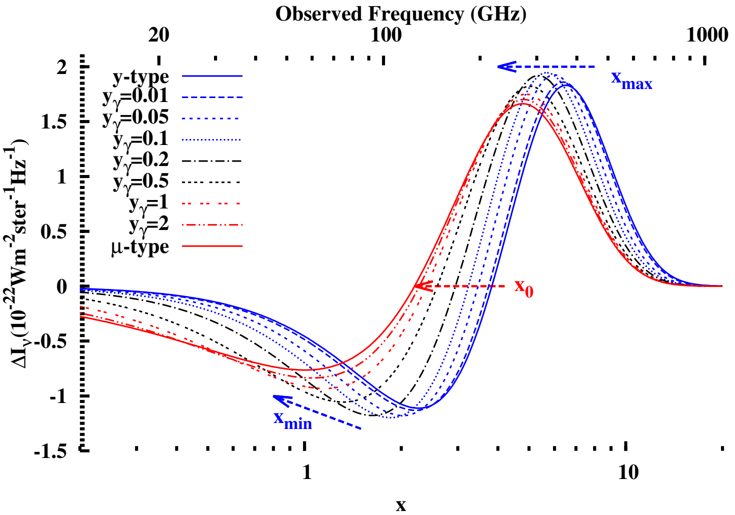
COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ *(Fixsen et al. 1996)*



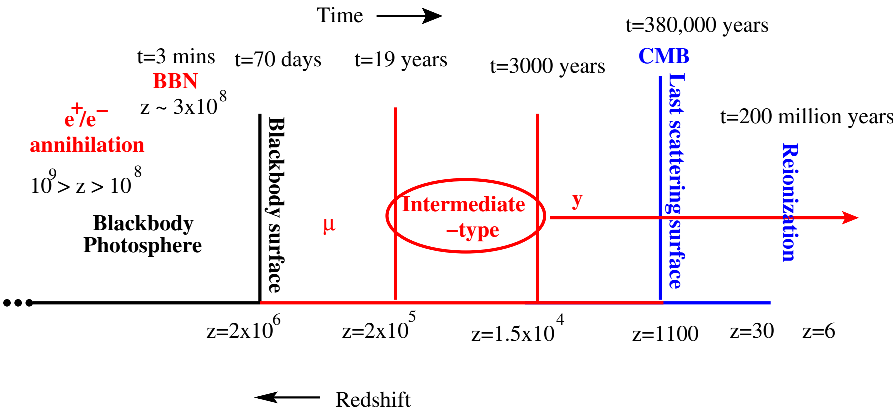
Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

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

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

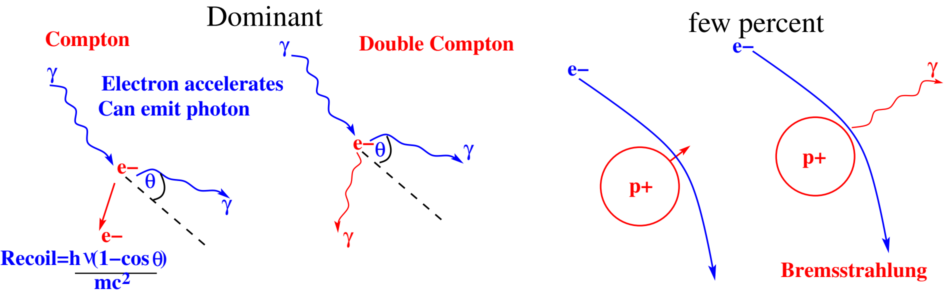


Intermediate-type distortions



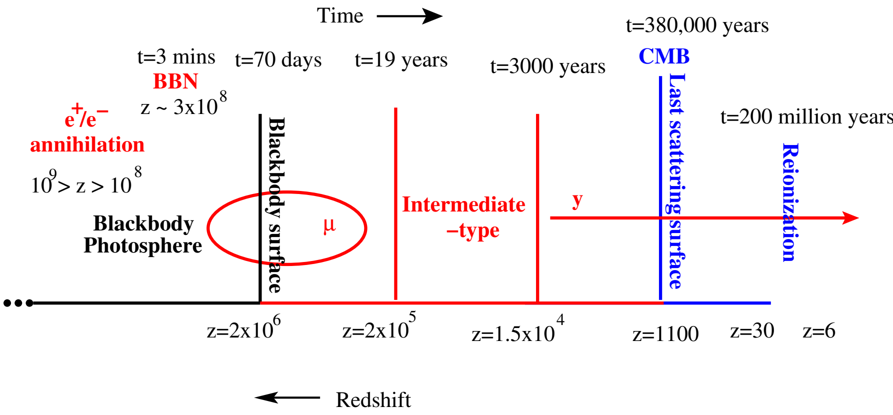
intermediate-type distortions: Numerically solve Kompaneets equation

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

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

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

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

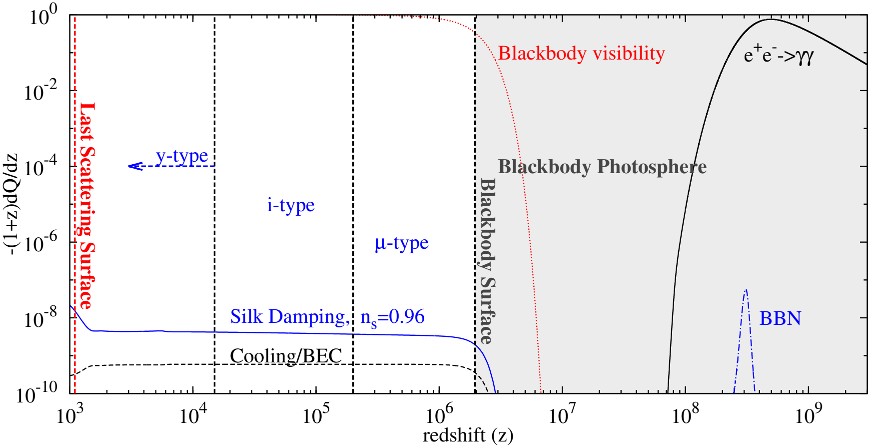
Numerical studies: Illarionov and Sunyaev 1975, Burigana, Danese, de Zotti 1991, Hu and Silk 1993, Chluba and Sunyaev 2012

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

$$\mathscr{T}(z) \approx 1.007\left[\left(\frac{1+z}{1+z_{\mathrm{dC}}}\right)^5 + \left(\frac{1+z}{1+z_{\mathrm{br}}}\right)^{5/2}\right]^{1/2} + 1.007\varepsilon \ln\left[\left(\frac{1+z}{1+z_\varepsilon}\right)^{5/4} + \sqrt{1+\left(\frac{1+z}{1+z_\varepsilon}\right)^{5/2}}\right]$$

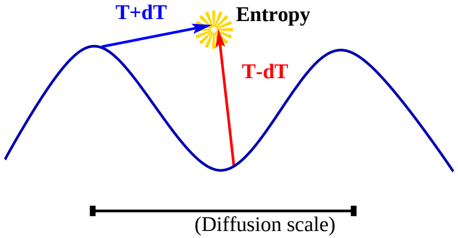
$$+ \left[\left(\frac{1+z}{1+z_{\mathrm{dC}}{}'}\right)^3 + \left(\frac{1+z}{1+z_{\mathrm{br}}{}'}\right)^{1/2}\right],$$

The general picture



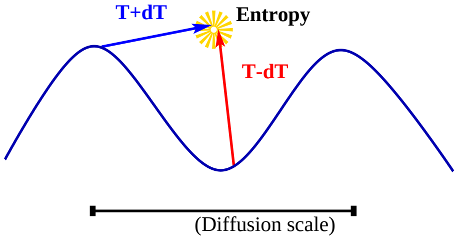
Silk damping

Photon diffusion ⟶ mixing of blackbodies



Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies

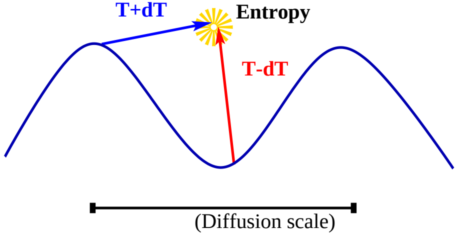


Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



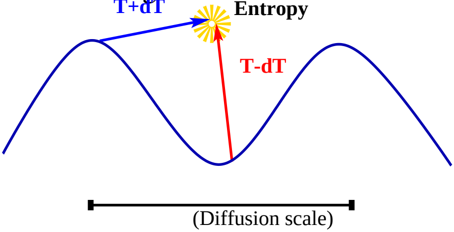
Mixing of blackbodies gives *y*-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

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

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



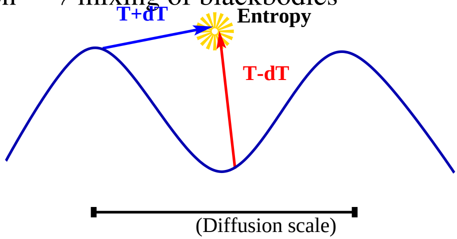
Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

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

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

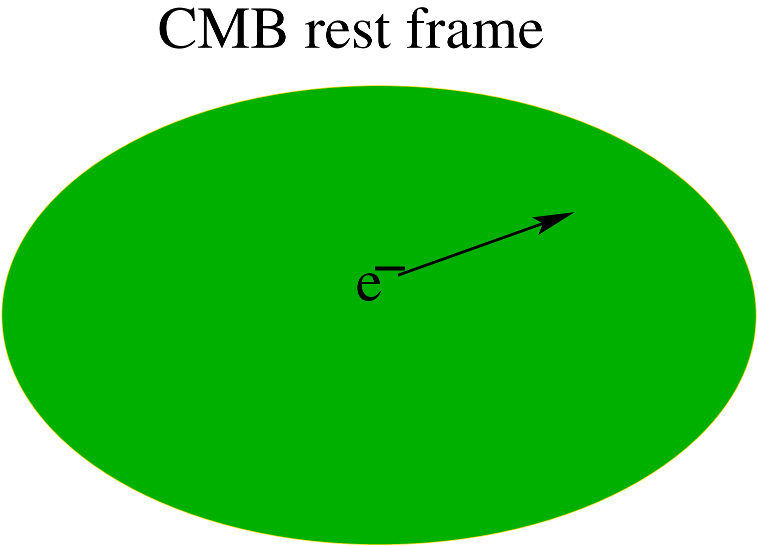
$$< n_{\rm Planck} > = \frac{1}{e^{\frac{h\nu}{kT}}-1} + \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T \frac{\partial n_{\rm Pl}}{\partial T} + \frac{1}{2} \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\rm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

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

2/3 — Black body

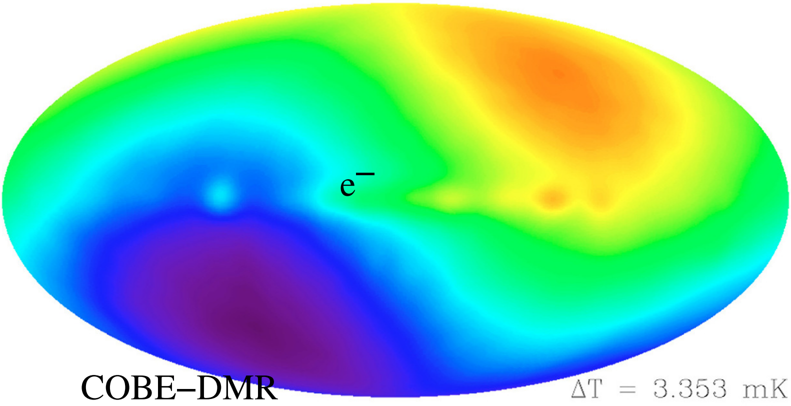
1/3 — Kompaneets operator/SZ

SZ effect in CMB rest frame: Doppler boost



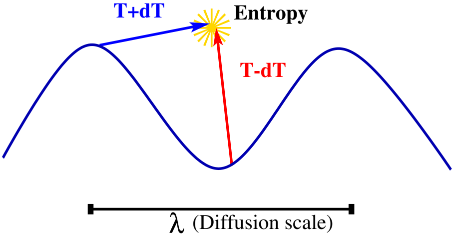
SZ effect in electron rest frame: Mixing of blackbodies in the dipole seen by the electron

Electron rest frame



Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

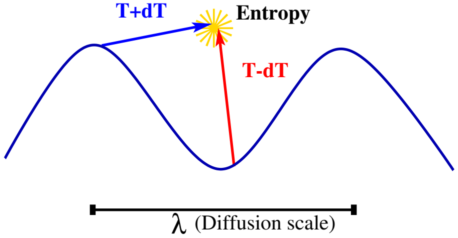
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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

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

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

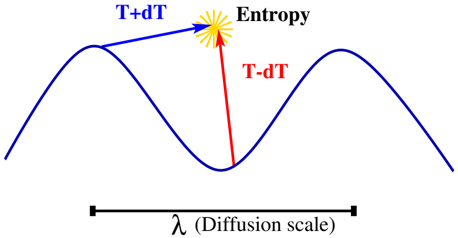
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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

$$1.5\times10^4 \lesssim z \lesssim 2\times10^6 \implies 8 \lesssim k_D \lesssim 10^4\ \mathrm{Mpc}^{-1}$$

Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



Apply mixing of blackbodies result to CMB

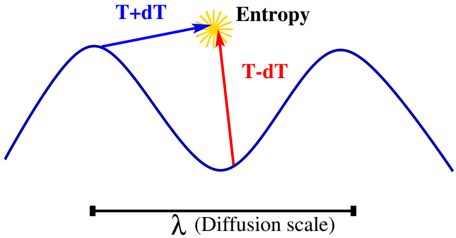
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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

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

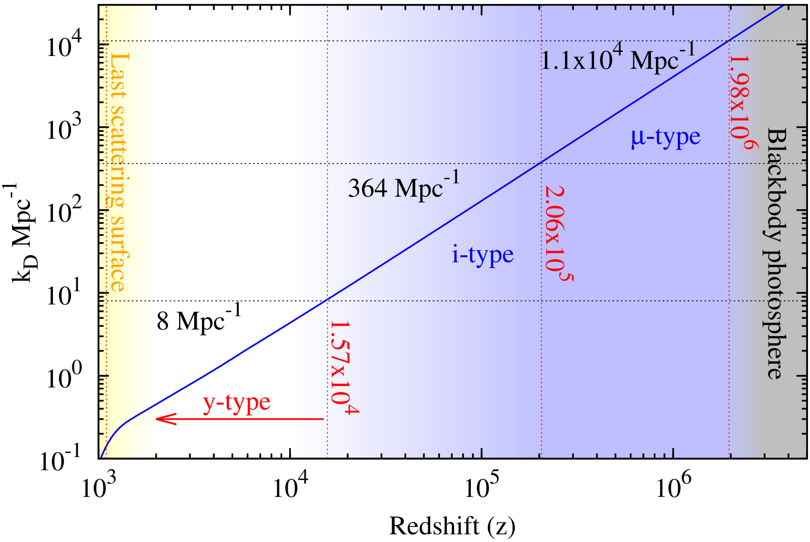
Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012

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

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

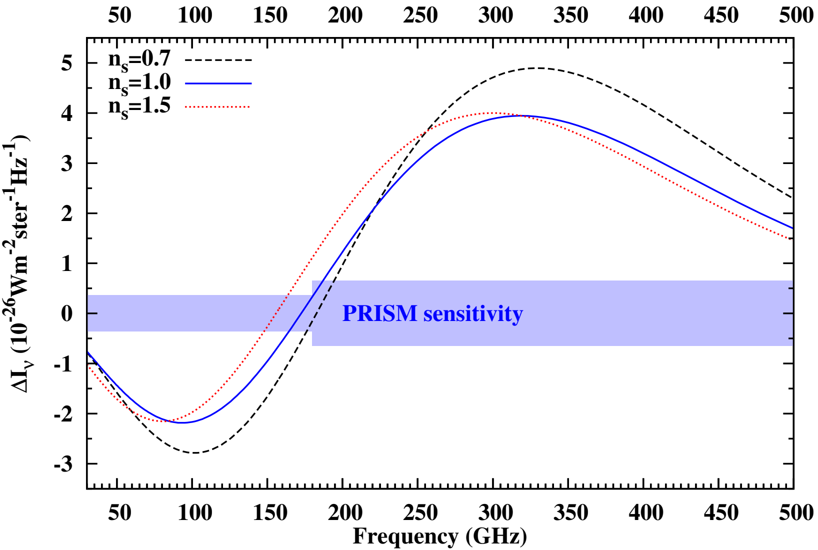
Total energy in the standing wave is independent of time

The Silk damping scale



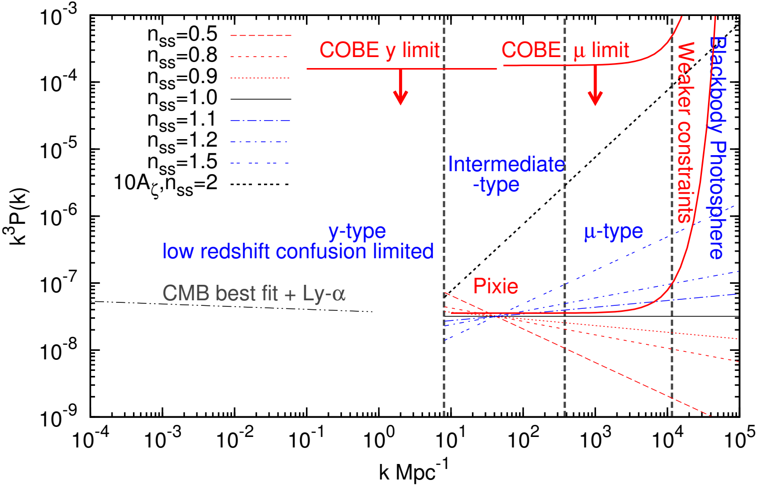
Silk damping *(Khatri and Sunyaev 2012b)*

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

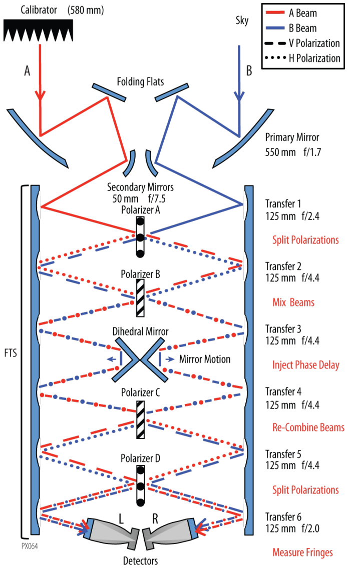


Pivot point $k_0 = 42\ \mathrm{Mpc}^{-1}$

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

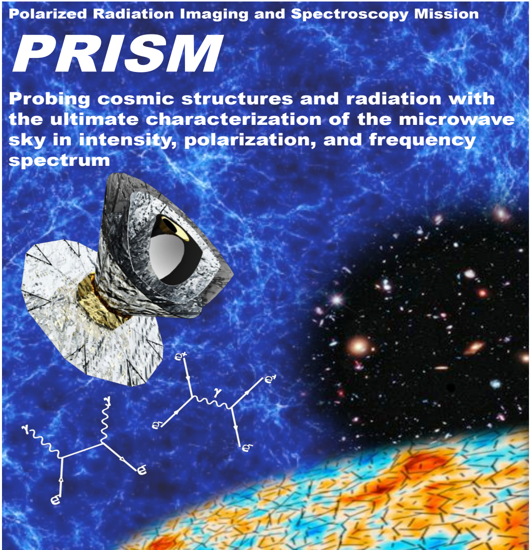


Spectrum: Pixie will improve over the COBE precision by at least 3 orders of magnitude *(Kogut et al. 2011)*



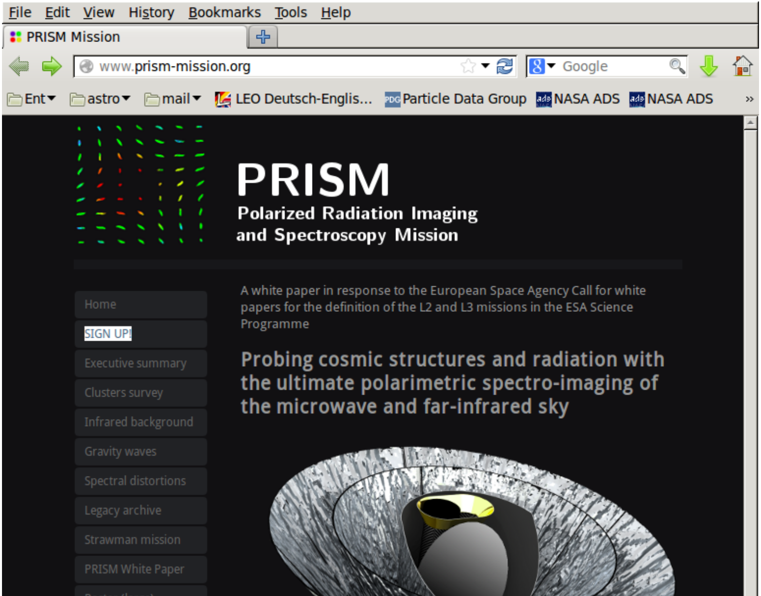
New proposal to ESA for L class mission

10 times more sensitive than Pixie



Please Sign Up to show your support for PRISM

http://www.prism-mission.org/



Fisher matrix forecasts

Model:

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

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

I_ν^{damping} contains i-type and μ-type distortions

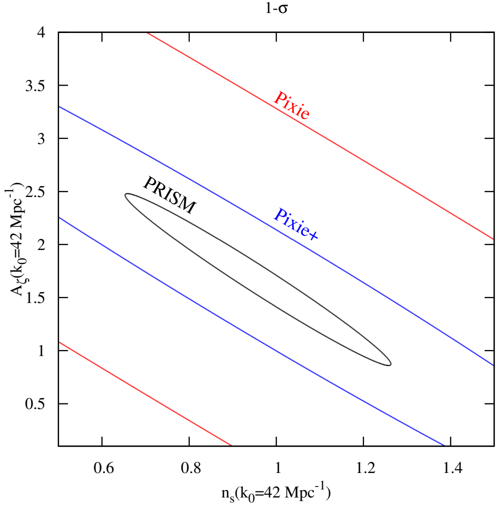
Fisher matrix forecasts

(Khatri and Sunyaev 2013)

Pixie-like experiments:

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

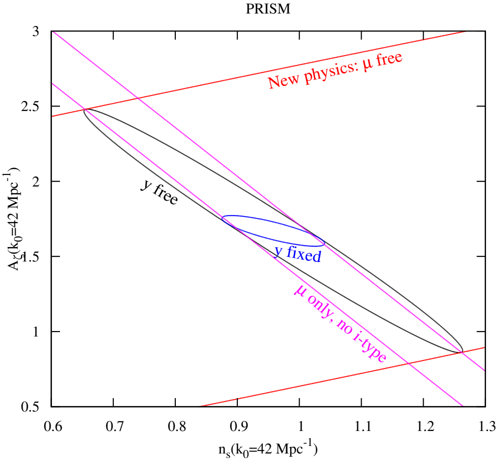
Pixie=(15,5)



Importance of *i*-type distortions,degeneracies

(Khatri and Sunyaev 2013)

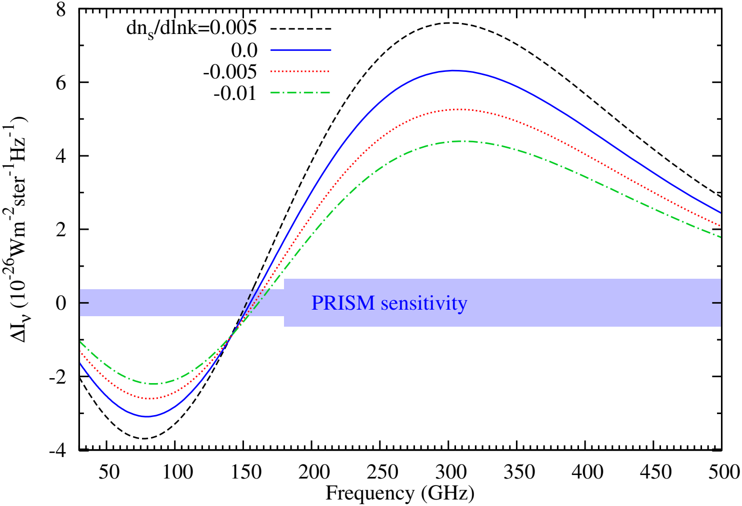
Information in the shape of *i*-type distortions breaks the $A_\zeta - n_s$ degeneracy



Running spectral index

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

Long lever arm: Main effect in the amplitude of distortion



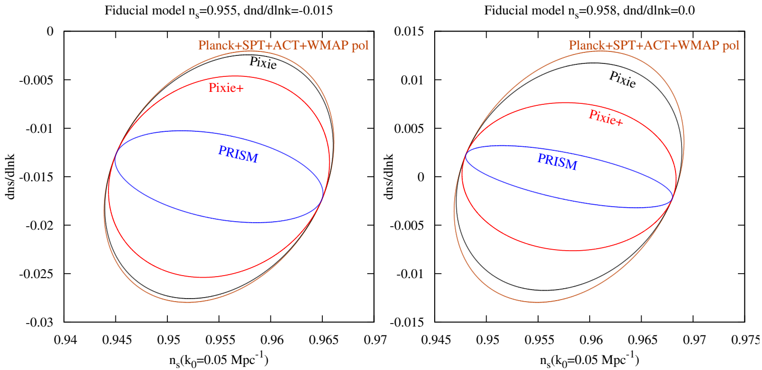
Fisher matrix forecasts with Planck+SPT+ACT+WMAP-pol

(Khatri and Sunyaev 2013)

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

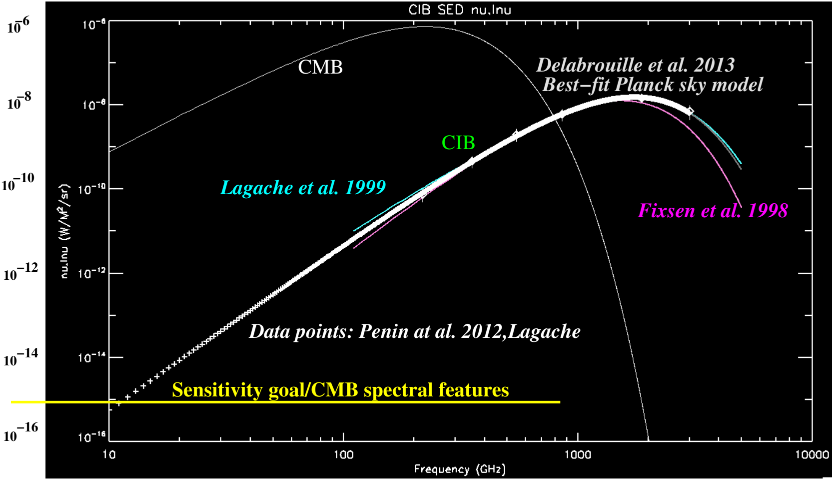
(x,y) $\equiv$ (Resolution GHz , $\delta I(\nu) = 10^{-26}\mathrm{Wm}^{-2}\mathrm{Sr}^{-1}\mathrm{Hz}^{-1}$)

Pixie=(15,5)



Foregrounds

Figure courtesy Jacques Delabrouille



Summary

- The shape of the μ and intermediate type distortions is rich in information

Summary

- The shape of the μ and intermediate type distortions is rich in information
- With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds

Summary

- The shape of the μ and intermediate type distortions is rich in information
- With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds
- Spectral distortions take us a little nearer to the end of inflation

Summary

- The shape of the μ and intermediate type distortions is rich in information
- With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds
- Spectral distortions take us a little nearer to the end of inflation
- μ-type and intermediate type distortions can be calculated very fast using analytic and pre-calculated cosmology-independent high precision numerical solutions (Green's functions). This allows us to explore the rich multidimensional parameter space

Summary

- The shape of the μ and intermediate type distortions is rich in information
- With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds
- Spectral distortions take us a little nearer to the end of inflation
- μ-type and intermediate type distortions can be calculated very fast using analytic and pre-calculated cosmology-independent high precision numerical solutions (Green's functions). This allows us to explore the rich multidimensional parameter space
- 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

Summary continued

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

There is more....

- Cosmological recombination spectrum gives measurement of primordial helium

  Kurt,Zeldovich,Sunyaev,Peebles,Dubrovich,Chluba,Rubino-Martin

Summary continued

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

There is more....

- Cosmological recombination spectrum gives measurement of primordial helium

  Kurt,Zeldovich,Sunyaev,Peebles,Dubrovich,Chluba,Rubino-Martin

- Resonant scattering on C,N,O and other ions during and after reionization makes the optical depth to the last scattering surface frequency dependent

  Basu, Hernandez-Monteagudo, and Sunyaev 2004

Summary continued

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

There is more....

- Cosmological recombination spectrum gives measurement of primordial helium

  Kurt,Zeldovich,Sunyaev,Peebles,Dubrovich,Chluba,Rubino-Martin

- Resonant scattering on C,N,O and other ions during and after reionization makes the optical depth to the last scattering surface frequency dependent

  Basu, Hernandez-Monteagudo, and Sunyaev 2004

- Sunyaev-Zeldovich effect from hot electrons during reionization/WHIM can give a measurement of average electron temperature, find missing baryons

  Zeldovich & Sunyaev 1969, Hu, Scott, Silk 1994, Cen and Ostriker 1999,2006,

Summary continued

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

There is more....

- Cosmological recombination spectrum gives measurement of primordial helium

  Kurt,Zeldovich,Sunyaev,Peebles,Dubrovich,Chluba,Rubino-Martin

- Resonant scattering on C,N,O and other ions during and after reionization makes the optical depth to the last scattering surface frequency dependent

  Basu, Hernandez-Monteagudo, and Sunyaev 2004

- Sunyaev-Zeldovich effect from hot electrons during reionization/WHIM can give a measurement of average electron temperature, find missing baryons

  Zeldovich & Sunyaev 1969, Hu, Scott, Silk 1994, Cen and Ostriker 1999,2006,

- Primordial non-gaussianity on extremely small scales
  Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_{\rm s}-5)/2}$

  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$

  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)

- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$

  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_\mathrm{s}-5)/2}$

  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)

- Adiabatic cooling: Opposite sign to Silk damping with $n_\mathrm{s} = 1$

  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)

- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_\mathrm{decay}}{1+z}\right)^2}}{(1+z)^4}$

  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)
- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)
- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)
- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)
- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Primordial magnetic fields : $\propto (1+z)^{(3n+7)/2}$, n is the spectral index of magnetic field power spectrum *(Jedamzik, Katalinic, and Olinto 2000)*

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)
- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)
- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Primordial magnetic fields : $\propto (1+z)^{(3n+7)/2}$, n is the spectral index of magnetic field power spectrum *(Jedamzik, Katalinic, and Olinto 2000)*
- Black holes: Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)
- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)
- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Primordial magnetic fields : $\propto (1+z)^{(3n+7)/2}$, n is the spectral index of magnetic field power spectrum *(Jedamzik, Katalinic, and Olinto 2000)*
- Black holes: Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010
- Quantum wave function collapse: $\frac{dQ}{dz} \propto (1+z)^{-4}$
  Lochan, Das and Bassi 2012

There is still a long road ahead for CMB cosmology

CMB spectrum is very rich in information about the early Universe, late time Universe and fundamental physics

There is still a long road ahead for CMB cosmology

CMB spectrum is very rich in information about the early Universe, late time Universe and fundamental physics

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 $y_\gamma = 2$.

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

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 $y_\gamma = 2$.

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

- Calculate intermediate type distortions by adding up pre-calculated numerical solutions (Green's functions) in δy_γ bins.

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

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

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 $y_\gamma = 2$.

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

- Calculate intermediate type distortions by adding up pre-calculated numerical solutions (Green's functions) in δy_γ bins.

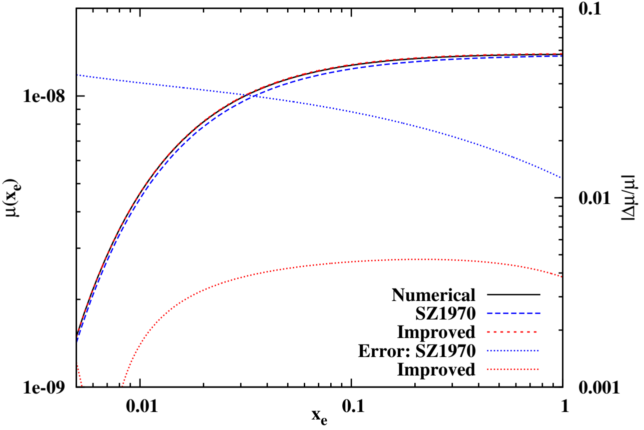
$$n_{i-type} = \frac{1}{Q_{num}} \sum_i \frac{dQ}{dy_\gamma}({y_\gamma}^i) \delta {y_\gamma}^i n({y_\gamma}^i) \tag{2}$$

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

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

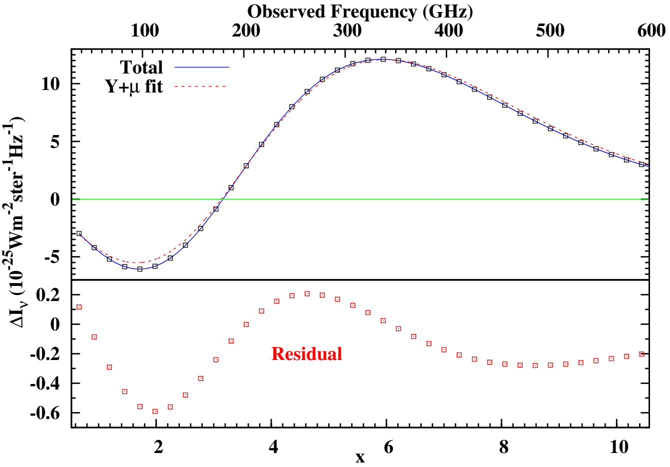
$$n_{y-type} = 0.25 n_y \int_{z(y_\gamma=0.01)}^{z=0} \frac{dQ}{dz} \tag{3}$$

Accuracy of new solutions is better than 1%

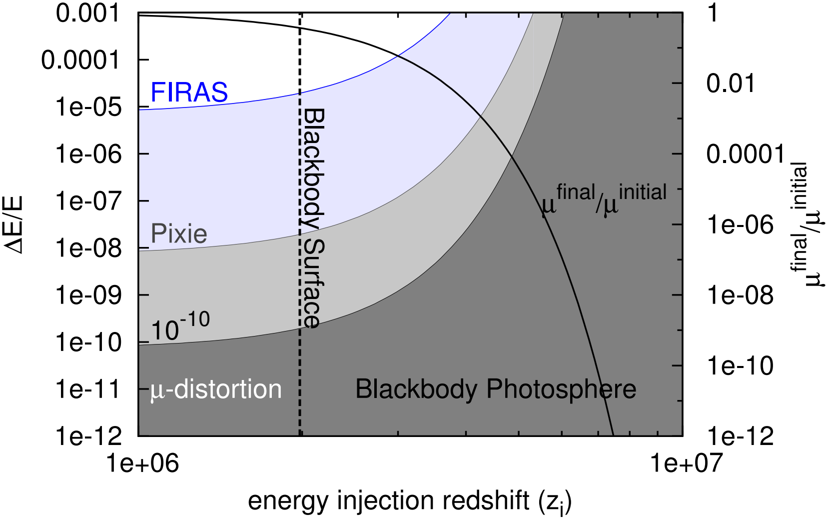


y+μ cannot fully mimic i-type distortion

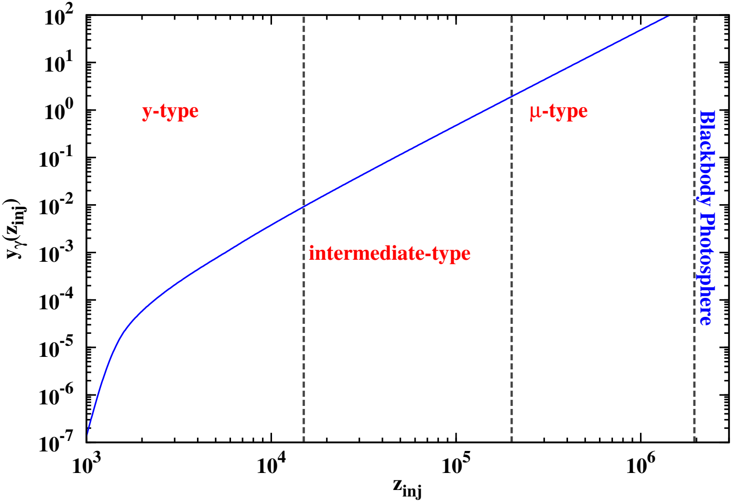
μ type and intermediate-type distortions are not independent. For Silk damping, intermediate-type distortions must contain about the same amount of energy as μ-type distortions.



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)*

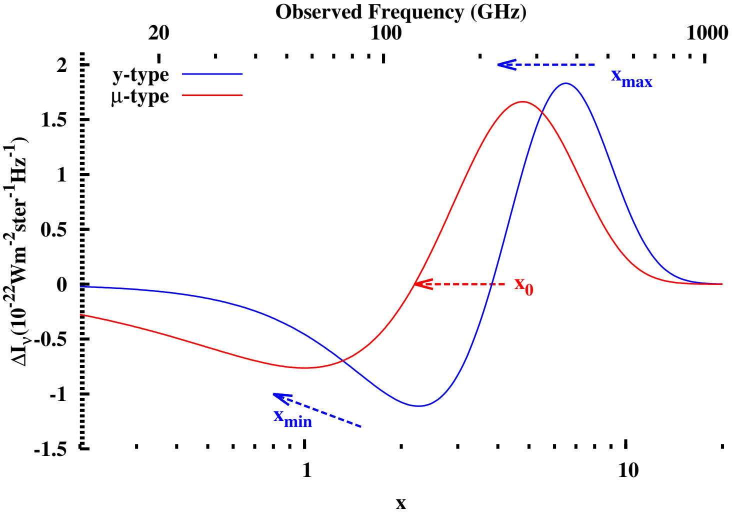
Solve Kompaneets equation with initial condition of $y-$type solution.

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

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

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

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



Sensitivity of Pixie−like Experiment, resolution 15 GHz

$W\ m^{-2}\ Hz^{-1}\ Sr^{-1}$

Signal		Physics/parameters
y−distortion from reionization/WHIM	5×10^{-26}	Find missing baryons reionization temperature
Amplitude of i+ μ−type distortion from Silk damping	1×10^{-26}	Amplitude of primordial power spectrum on 100 pc−100kpc scales
H recombination spectrum Shape of i−type distortion	3×10^{-27}	Baryon density Shape of primordial power spectrum
Detect helium feature in recombination spectrum	1×10^{-27}	Detect primordial helium
Precise measurement of He features	1×10^{-28}	Measure primordial helium baryon density etc. with some precision (10−20% ?)

Richness

Amplitude of Signal