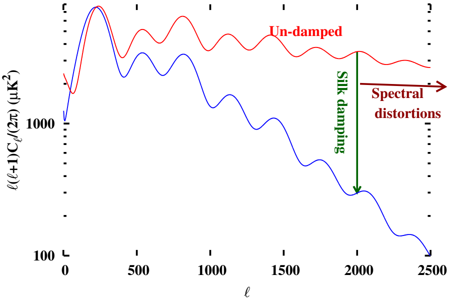
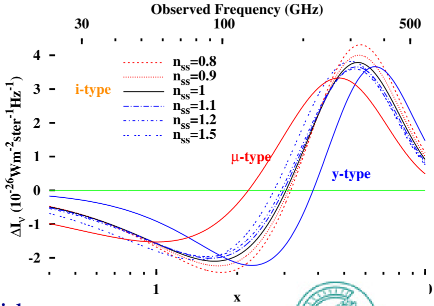
After Planck: The Road to Observing 17 e-Folds of Inflation

Rishi Khatri



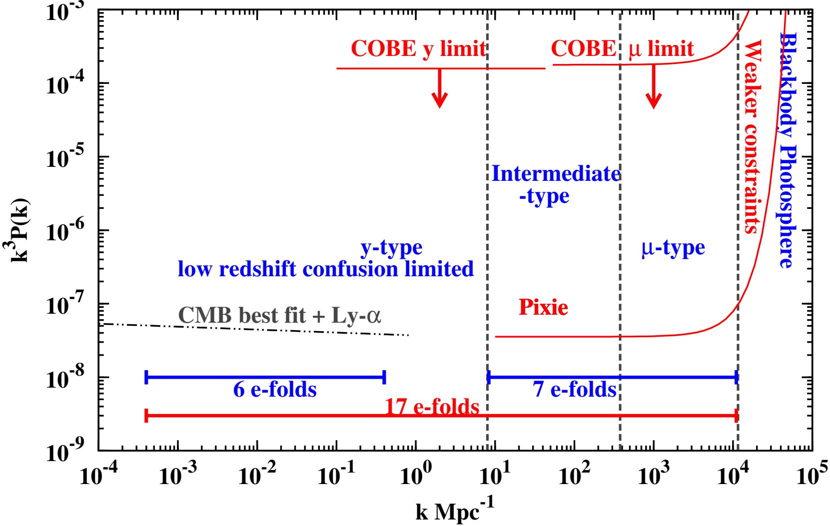


Max-Planck-Institut
für Astrophysik

with
Jens Chluba (JHU)
Rashid Sunyaev(MPA)

MAX-PLANCK-GESELLSCHAFT

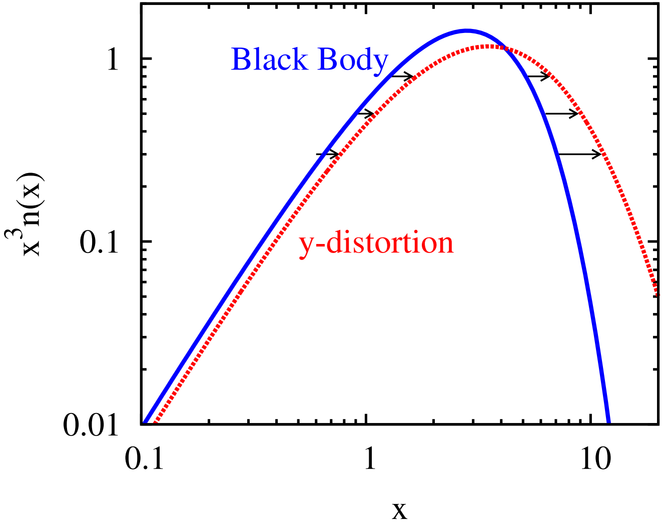
Going from 6-folds at present to 17 e-folds - almost 1/3 of inflation ?



y-distortion (Sunyaev-Zeldovich effect)

(Zeldovich and Sunyaev 1969)

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



Bose-Einstein spectrum

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

$$x = \frac{h\nu}{k_{\mathrm{B}}T}$$

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

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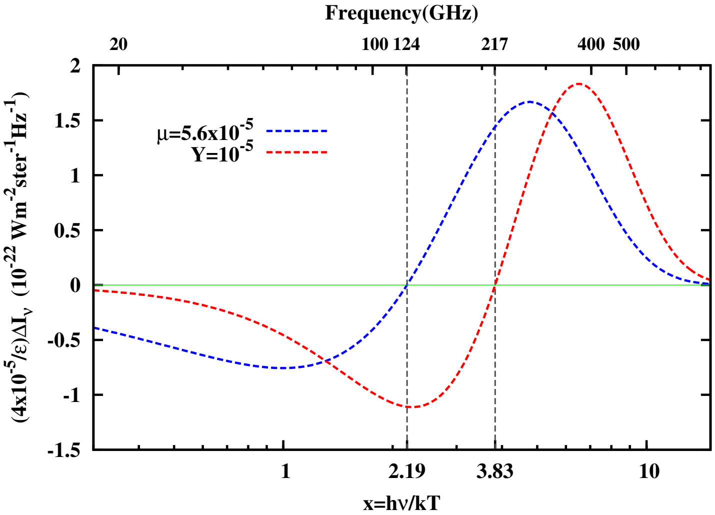
To get analytic solution, just need to determine rate of production of photons (when energy production rate is given)

μ-distortion: Bose-Einstein spectrum

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



y parameters

Sunyaev-Zeldovich effect:

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

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Recoil:

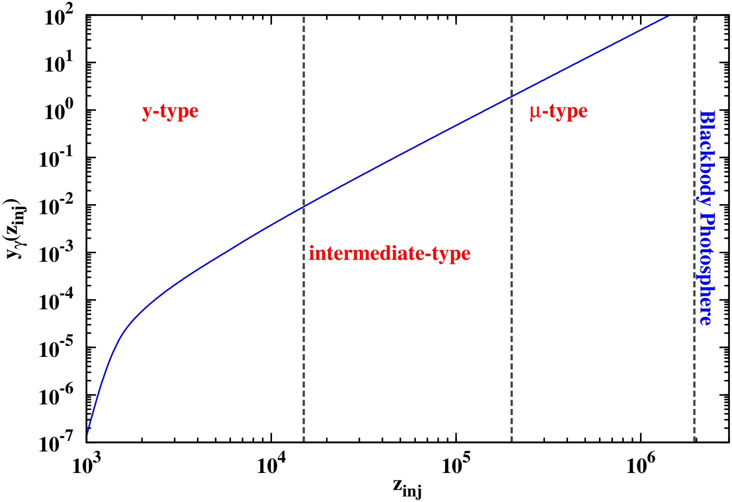
$$y_\gamma = \int \mathrm{d}t \, \frac{k_\mathrm{B} \sigma_\mathrm{T} n_\mathrm{e}}{m_\mathrm{e} c} T_\gamma, \quad T_\gamma = 2.725(1+z)$$

Doppler effect:

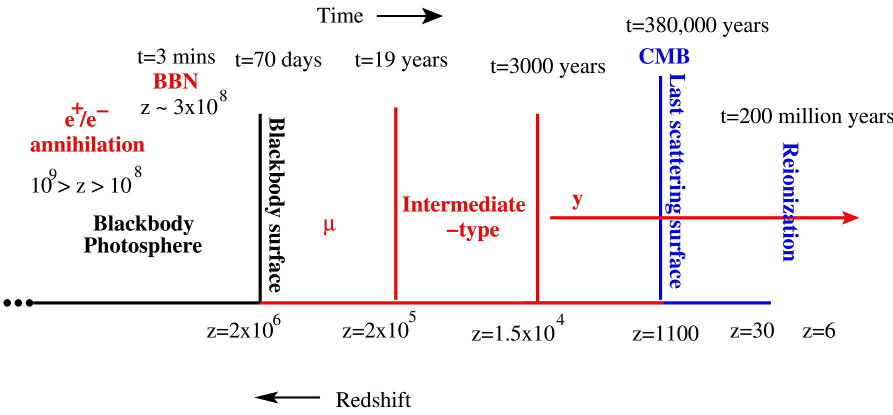
$$y_e = \int \mathrm{d}t \, \frac{k_\mathrm{B} \sigma_\mathrm{T} n_\mathrm{e}}{m_\mathrm{e} c} T_\mathrm{e}$$

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

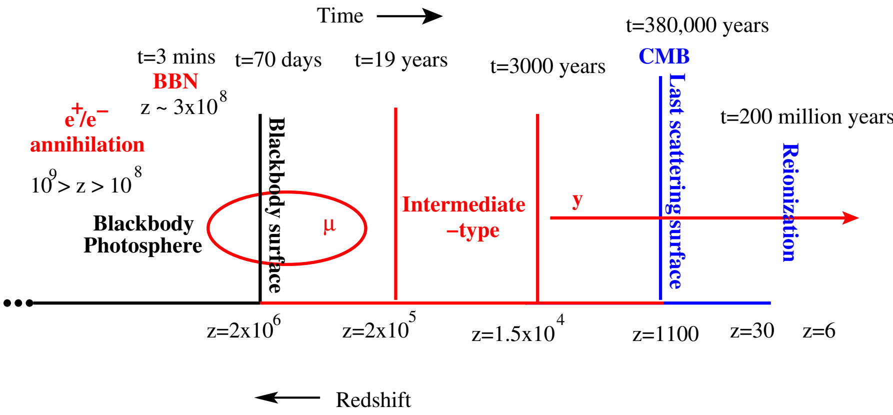
$$y_\gamma = \int_{z_{\rm inj}}^{0} {\rm d}t \, \frac{k_{\rm B}\sigma_{\rm T} n_{\rm e}}{m_{\rm e} c} T_\gamma$$



Cosmic Photosphere



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

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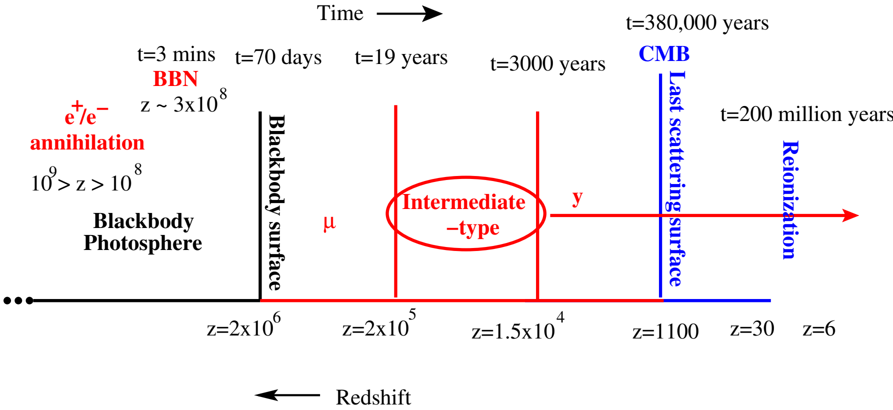
New solution, accuracy $\sim 1\%$
(*Khatri and Sunyaev 2012a*)

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

Intermediate-type distortions



intermediate-type distortions: Numerically solve Kompaneets equation

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

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

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

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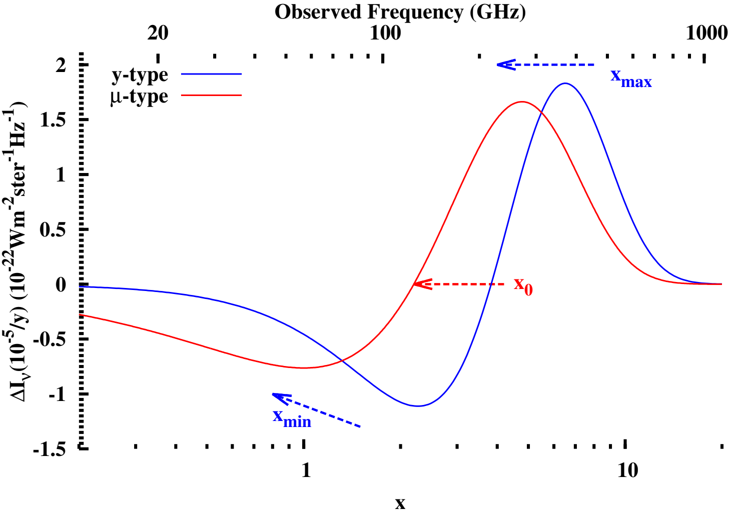

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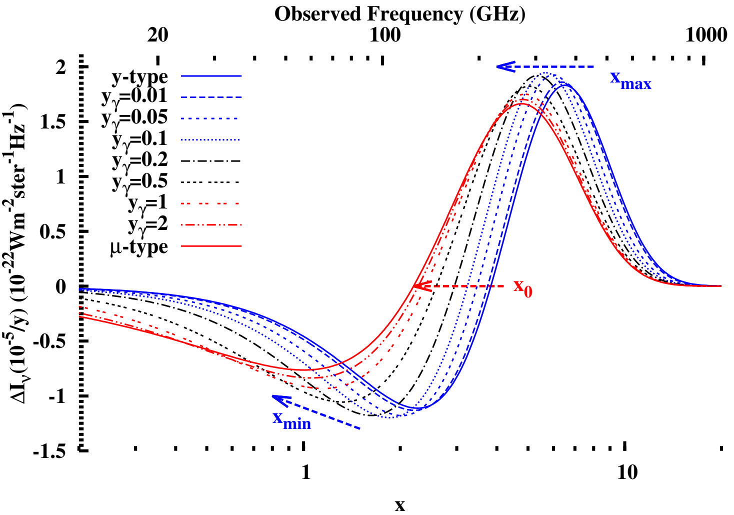

Algorithm for fast solution, $\sim 1\%$ level accuracy

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

- Calculate μ type distortion using the analytic solution, integrating upto 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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- Calculate intermediate type distortions by adding up pre-calculated numerical solutions in δy_γ bins.

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

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

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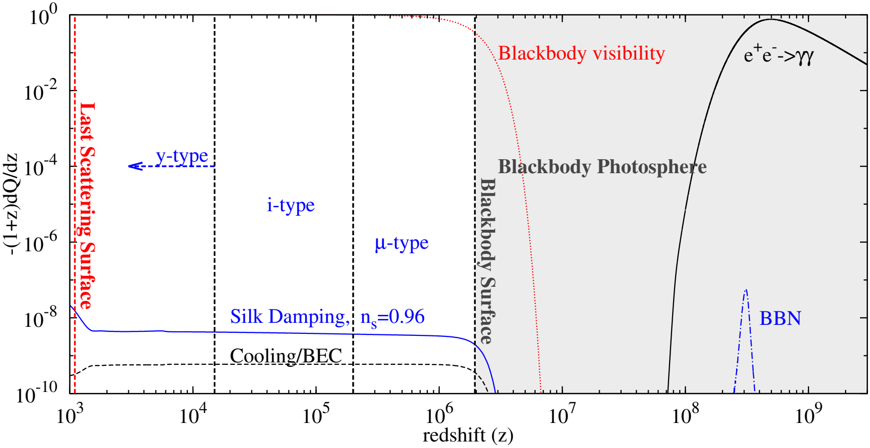
- Add rest of the energy to y-type distortions.

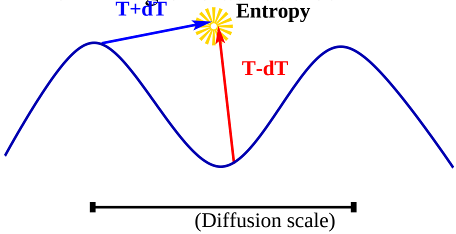
$$n_{y-type} = 0.25 n_y \int_{z(y_\gamma=0.01)}^{z=0} \frac{dQ}{dz} \tag{3}$$

The general picture



Silk damping

Photon diffusion $\longrightarrow$ mixing of blackbodies



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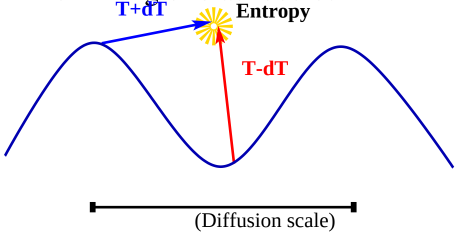

Mixing of blackbodies gives y-type distortion

Zeldovich, Illarionov & Sunyaev 1972, Chluba & Sunyaev 2004

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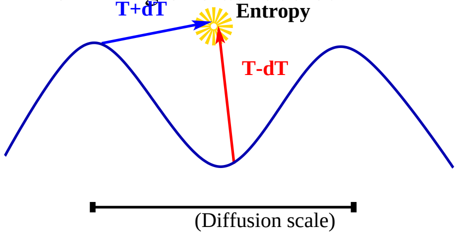

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$$< n_{\rm Planck} > = \frac{1}{e^{\frac{h\nu}{kT}}-1} + \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T \frac{\partial n_{\rm Pl}}{\partial T} + \frac{1}{2} \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T^4 \frac{\partial}{\partial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

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

2/3 — Black body

1/3 — Kompaneets operator/SZ

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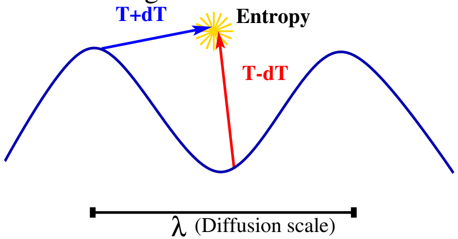

Apply mixing of blackbodies result to CMB

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

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

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

Tight coupling: density $\Theta_0 \propto \sin(kr_s)$, velocity $\Theta_1 \propto \cos(kr_s)$

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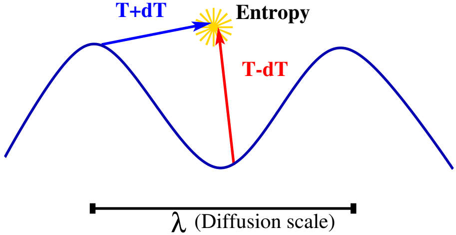

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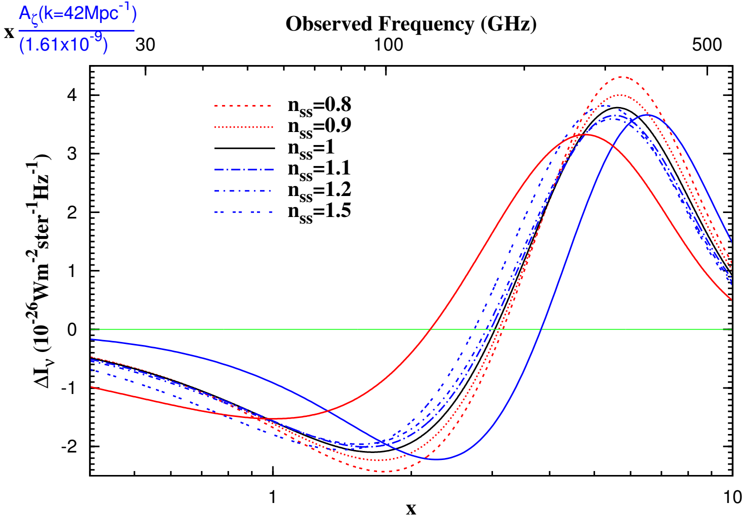
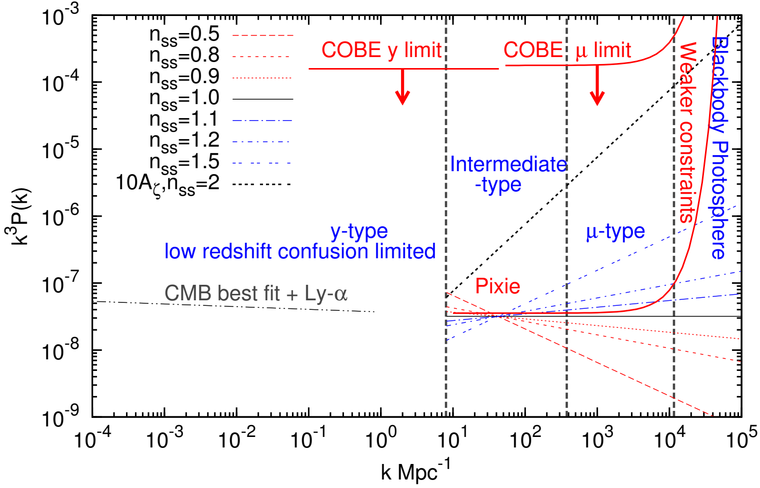
Total energy in the standing wave is independent of time

Silk damping *(Khatri and Sunayev 2012b)*



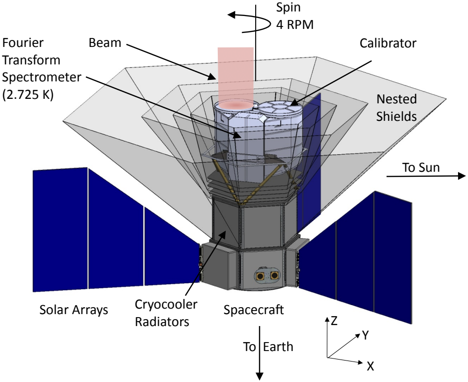
Pivot point $k_0 = 42\ \mathrm{Mpc}^{-1}$

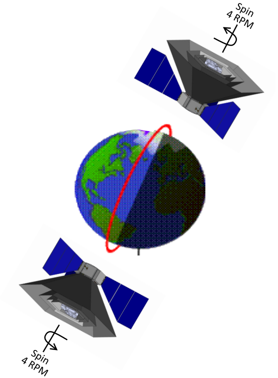
$$P_\zeta = (A_\zeta 2\pi^2/k^3)(k/k_0)^{n_\mathrm{s}-1+\frac{1}{2}\mathrm{d}n_\mathrm{s}/\mathrm{d}\ln k(\ln k/k_0)}$$



Spectrum: Pixie will improve over the COBE precision by at least 3 orders of magnitude

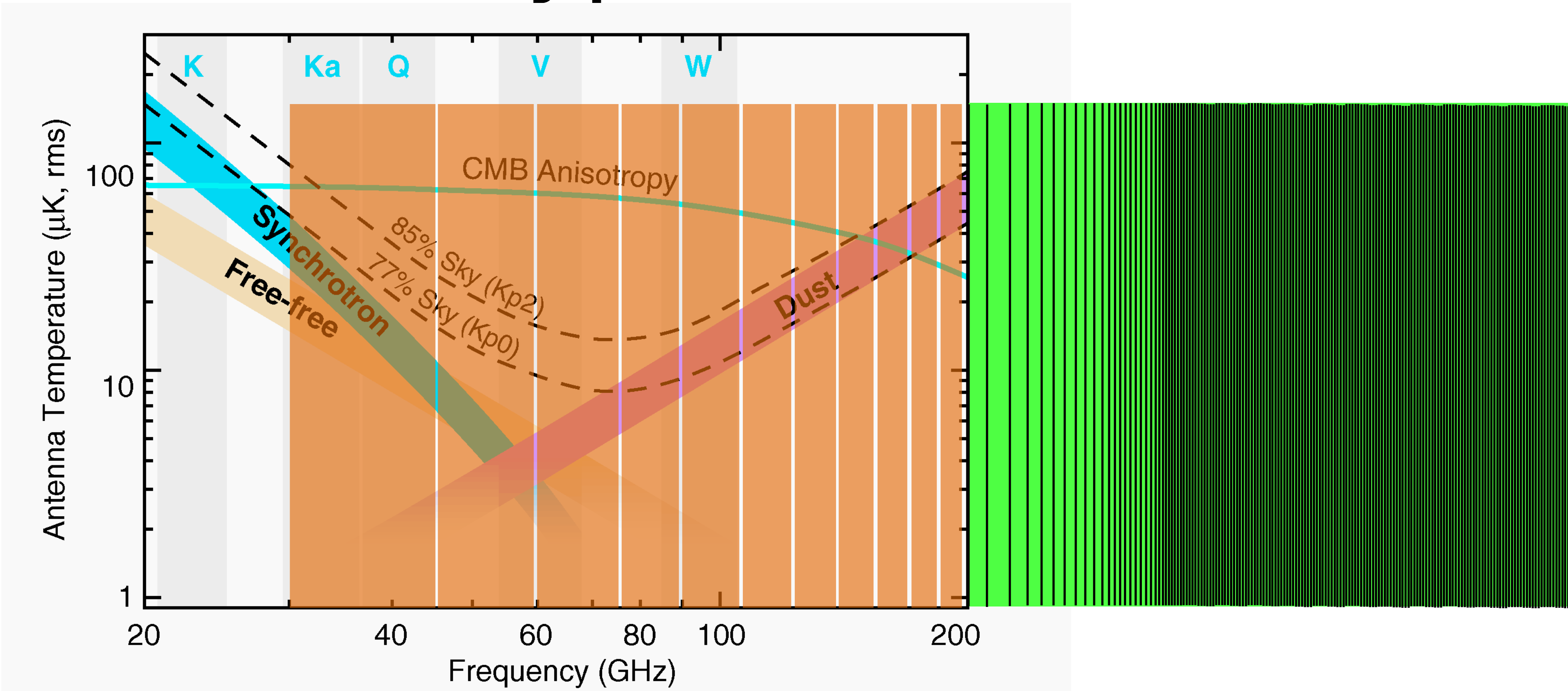
Kogut et al. 2011





PIXIE vs Typ Pol

Courtesy: Dale Fixsen



10 bands 30 GHz through 200 GHz …

PLUS 390 more bands to 6 THz

FTS gets extra bands for free: why not use them?

Fisher matrix forecasts

Model:

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

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

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

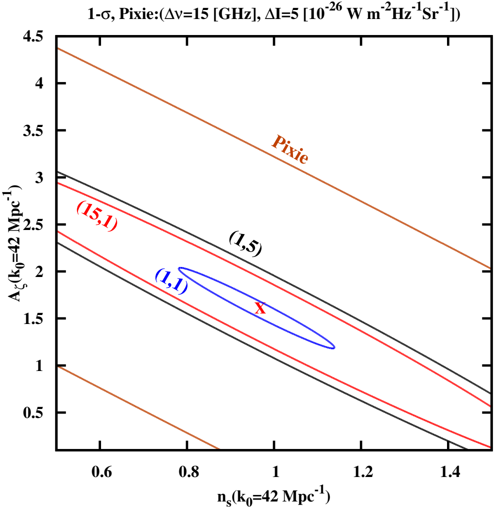
Fisher matrix forecasts

(Khatri and Sunyaev 2013)

Pixie-like experiments:

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

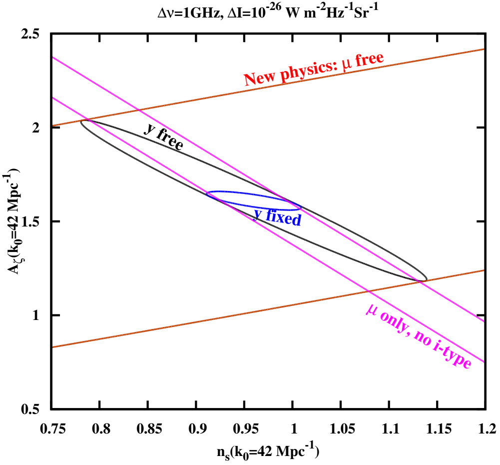
Pixie=(15,5)



Importance of *i*-type distortions,degenracies

(Khatri and Sunyaev 2013)

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



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

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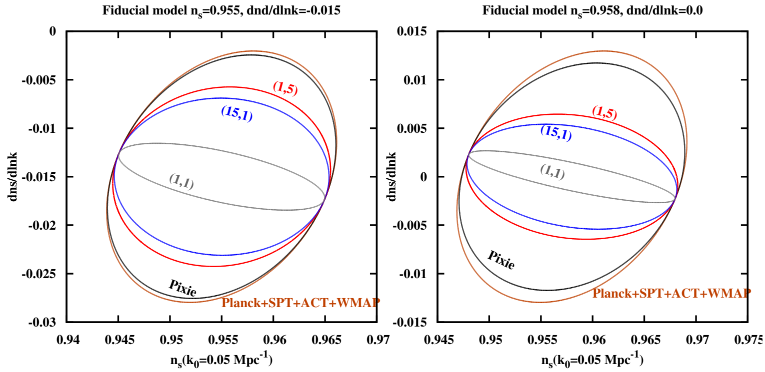

Summary

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- μ-type and intermediate type distortions can be calculated very fast using analytic and pre-calculated cosmology-independent high precision numerical solutions. 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

The future is bright

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

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This information is accesible and within reach of experiments in near future like Pixie

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.

Numerical Kompaneets+double Compton+bremsstrahlung solver:
CosmoTherm code by Jens Chluba
`www.chluba.de/CosmoTherm`

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)

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  Tashiro, Sabancilar, Vachaspati 2012

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- Primordial magnetic fields : $\propto (1+z)^{(3n+7)/2}$, n is the spectral index of magnetic field power spectrum *(Jedamzik, Katalinic, and Olinto 2000)*

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- 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)
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- Quantum wave function collapse: $\frac{dQ}{dz} \propto (1+z)^{-4}$
  Lochan, Das and Bassi 2012

Summary continued

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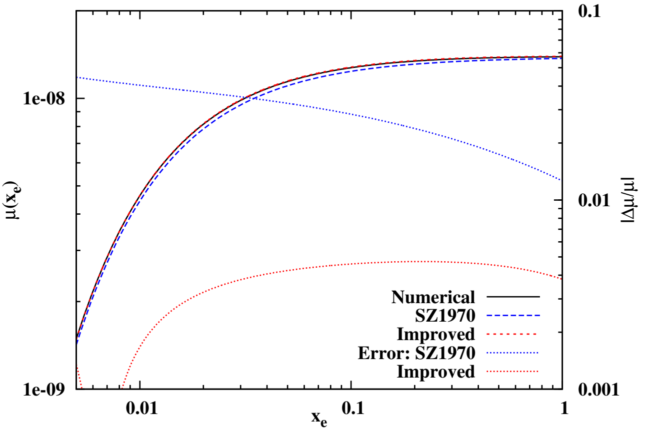
- Primordial non-gaussianity on extremely small scales

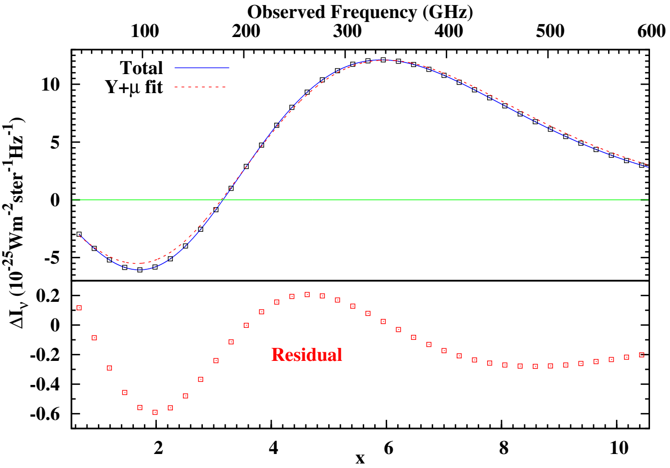
  Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012

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