The information hidden in the shape of the CMB spectrum

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Important events in the history of CMB

1948: Prediction of 5K thermal radiation by Alpher and Herman following up on the idea of Gamow

1965: Discovery of CMB

1960s-1990s: Numerous ground based and rocket based attempts to measure CMB spectrum and anisotropies

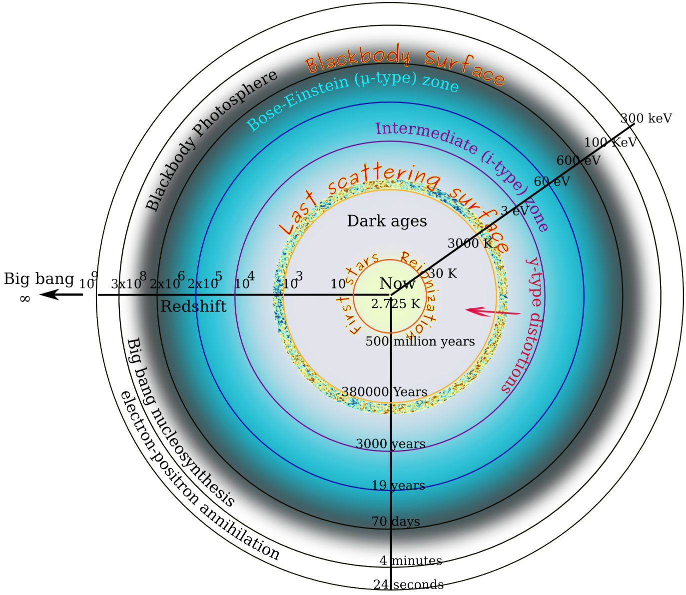
1990: COBE measures spectrum (blackbody) and anisotropies almost simultaneous measurement of blackbody spectrum by Canadian rocket experiment COBRA

2000-2015: WMAP,Planck,SPT,ACT,Boomerang... etc - tremendous increase in precision

Bicep2,SPT,ACT - First measurements of (lensing) B-mode polarization

2030:Primordial B-modes ? CMB spectrum ?

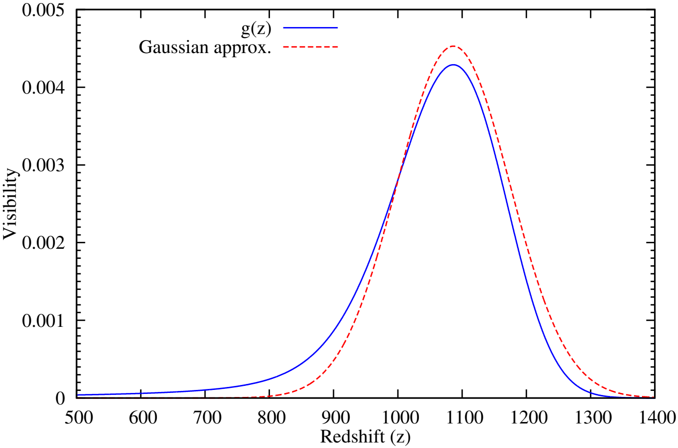
Important events in the history of the Universe



The last scattering surface

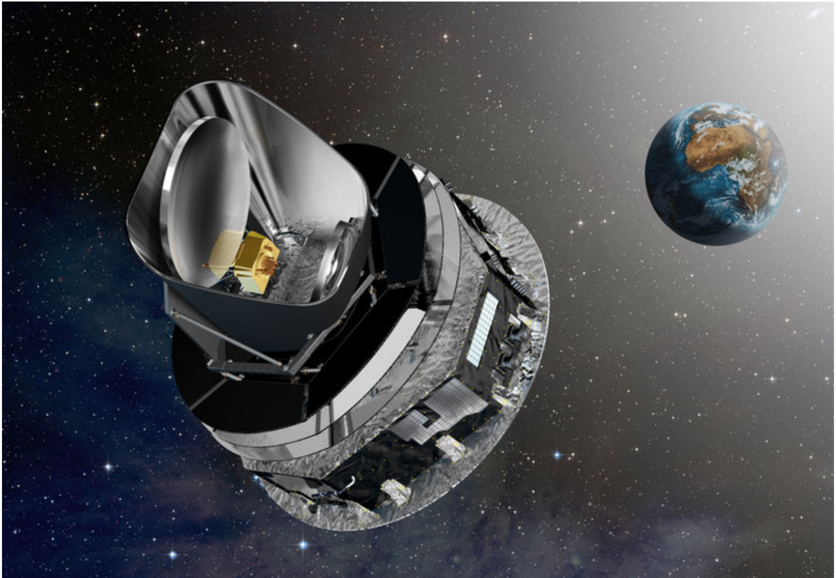
Sunyaev & Zeldovich 1970

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



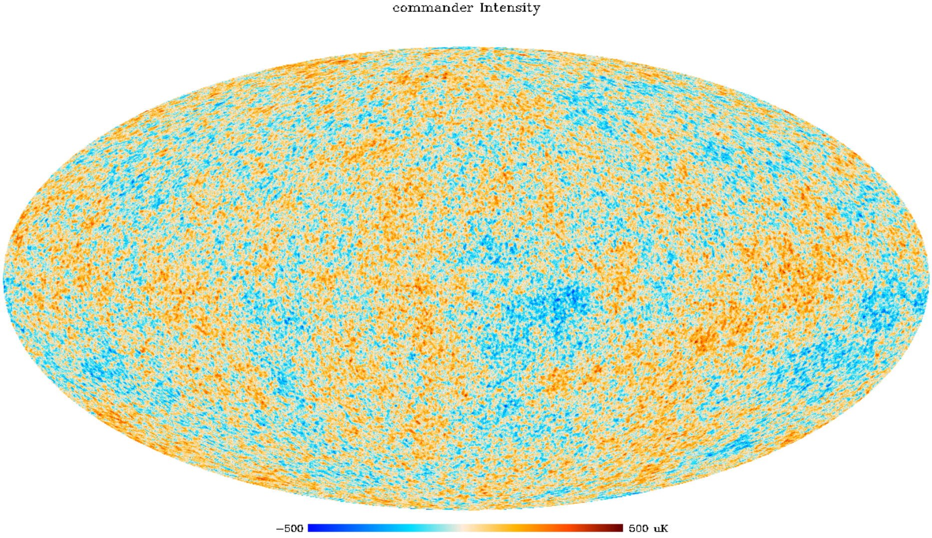
Planck CMB mission May 2009-October 2013

image credit: ESA-D. Ducros

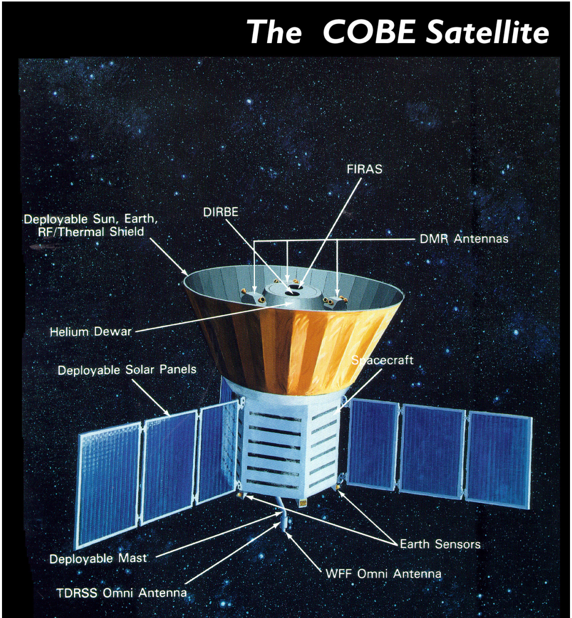


Picture of Universe @ 300000 Years

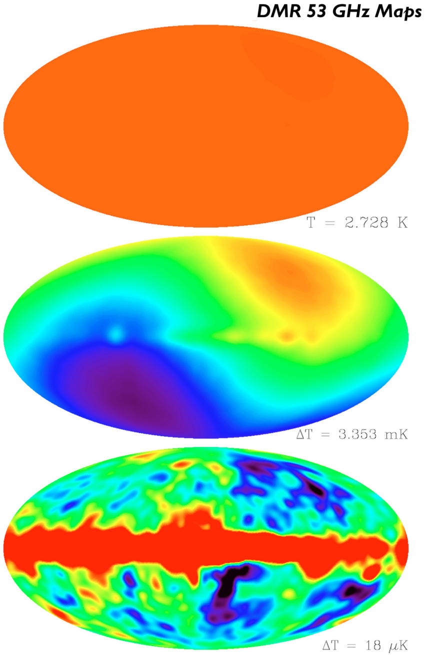
Planck Collaboration 2015



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

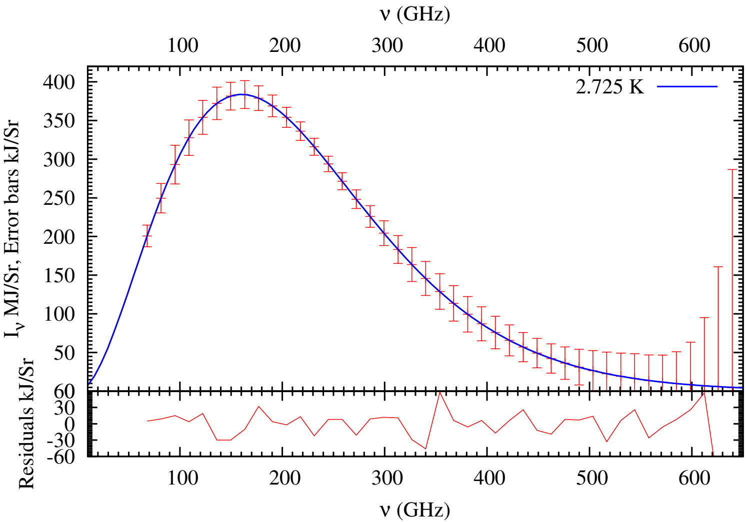


CMB as seen by COBE



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

Fixsen et al. 1996, Fixsen and Mather 2002



Planck spectrum

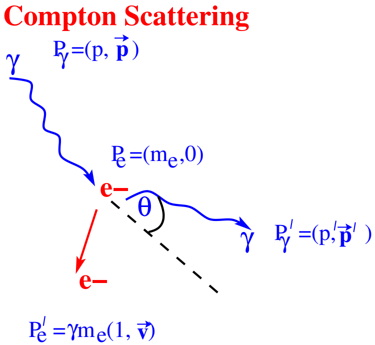
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$$

Relativistic invariant occupation number/phase space density

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

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

Compton scattering



$$\Delta p/p \approx -p/m_e(1-\cos\theta)$$

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:

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

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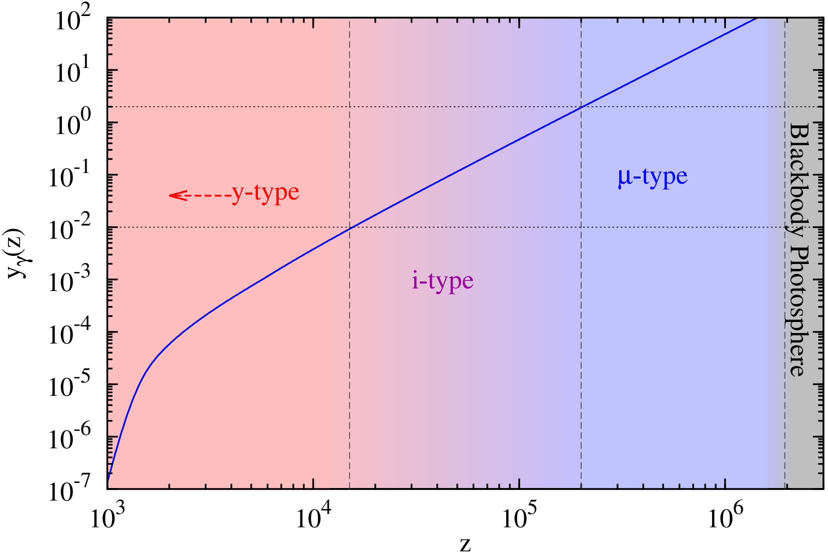
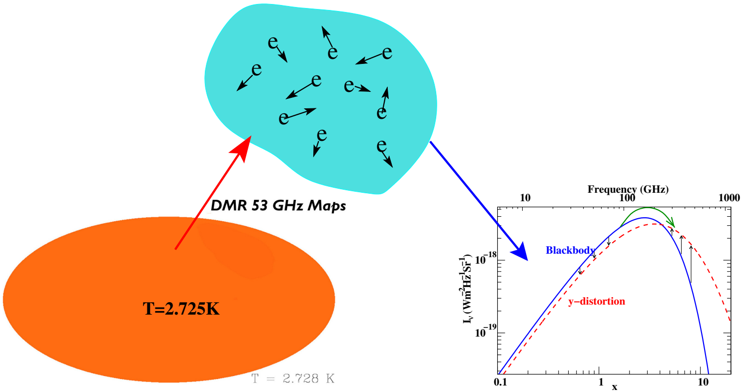
Efficiency of energy transfer between electrons and photons



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

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

$$y = (\tau_\mathrm{reionization})\frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2} \sim (0.06)(1.6\times10^{-6}) \sim 10^{-7}$$



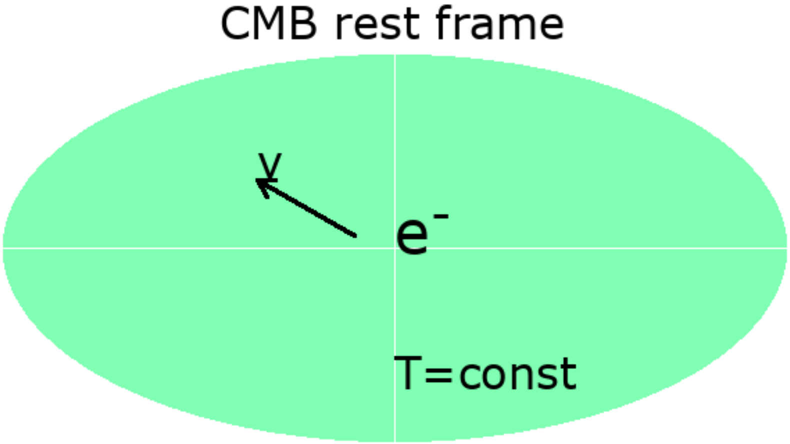
y-type (Sunyaev-Zeldovich effect) from clusters/reionization

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

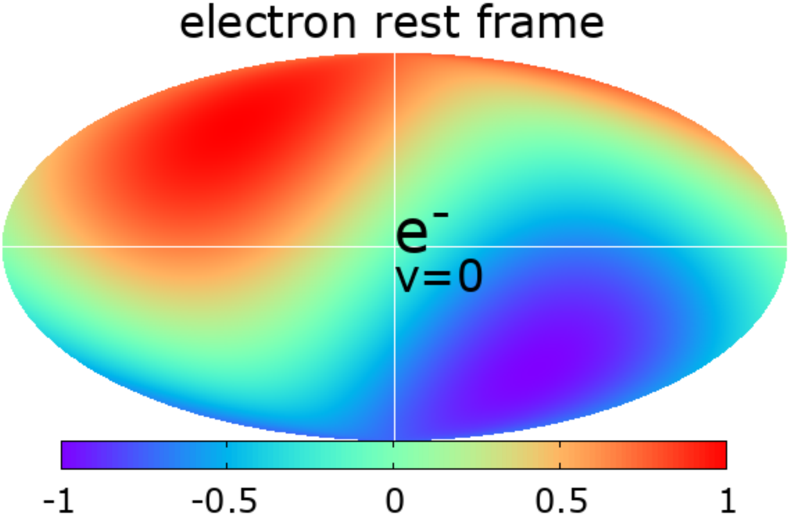
$$= \mathbf{y} \;\; \frac{\mathbf{x e^x}}{(\mathbf{e^x - 1})^2} \left(\mathbf{x} \frac{\mathbf{e^x + 1}}{\mathbf{e^x - 1}} - \mathbf{4} \right)$$

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

SZ effect in CMB rest frame: Doppler boost



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



Proof that final spectrum is blackbody+Y(SZ)

We are averaging intensity or equivalently occupation number $n(T)$. Expand Planck spectrum $n_{\rm Planck}(T+\delta T)$ about T in Taylor series and average, $(\langle \delta T \rangle \equiv 0)$.

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

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

Black body

Kompaneets operator/SZ

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

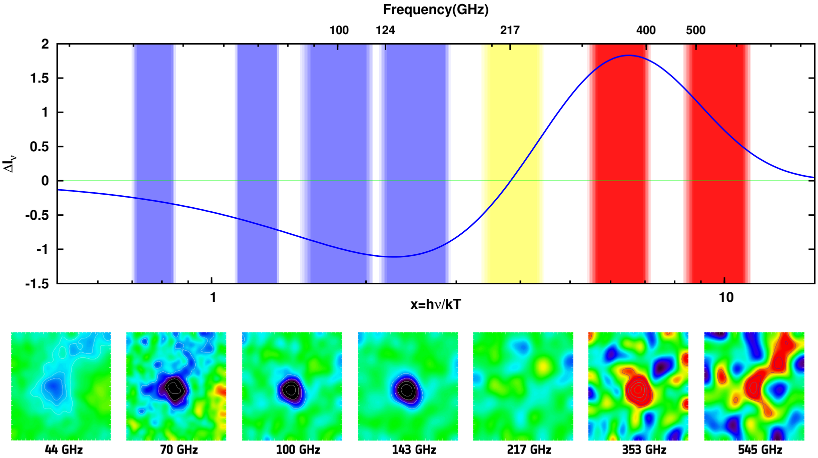
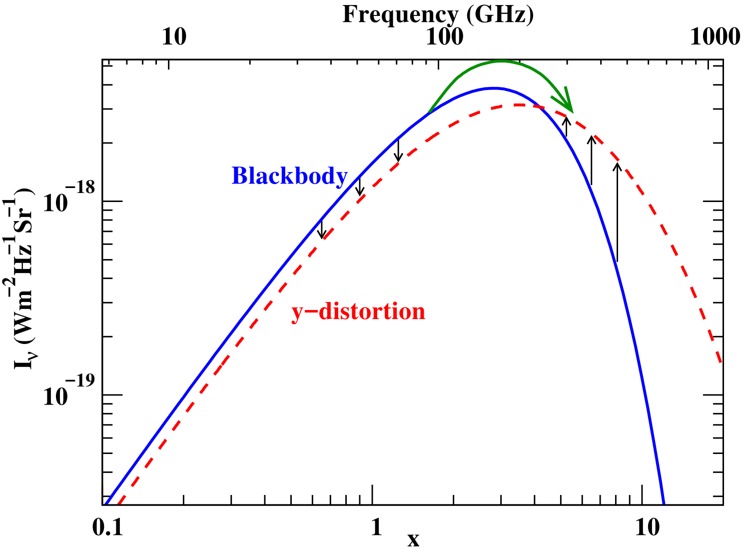


Image credit: ESA / HFI & LFI Consortia

Average y-distortion (Sunyaev-Zeldovich effect) limits

(Zeldovich and Sunyaev 1969)

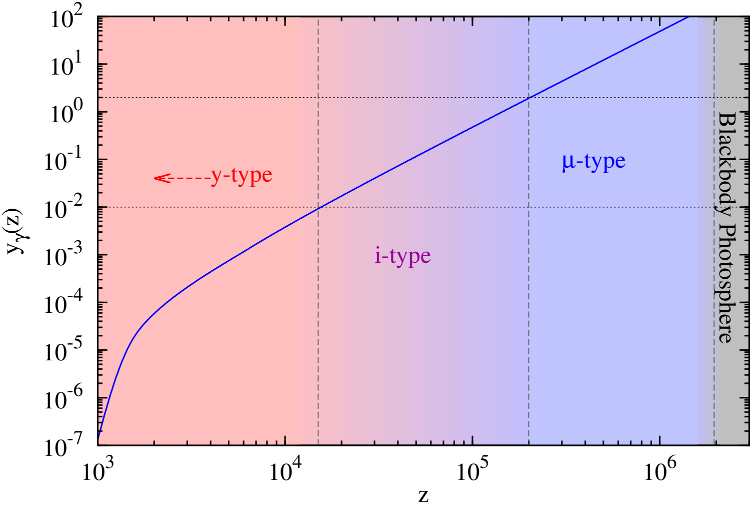
COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*



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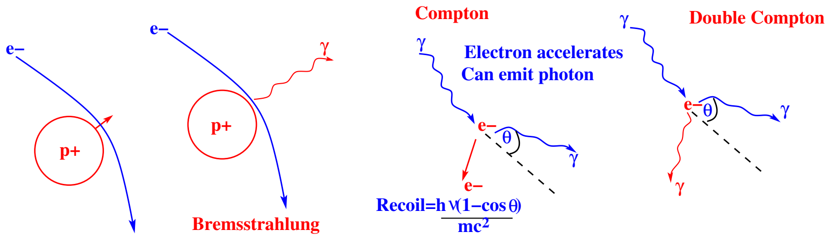
Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

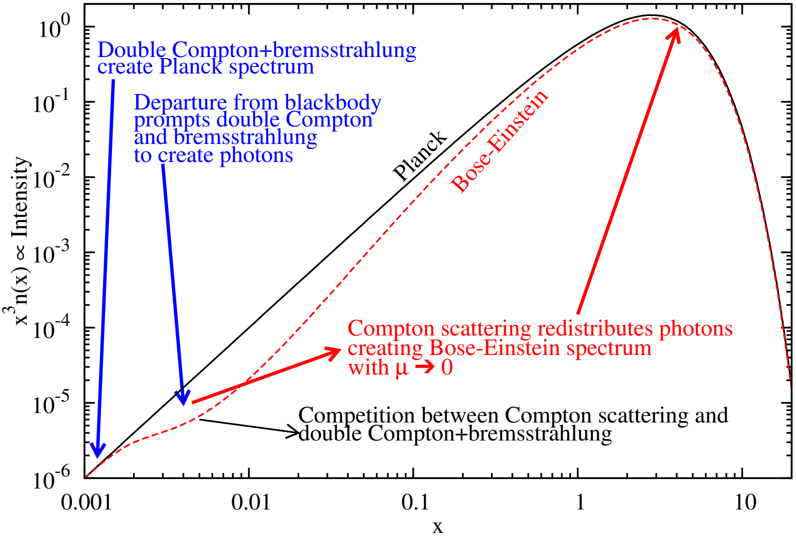
Idea behind analytic solutions:

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

Important physical processes for CMB spectrum



Creation of CMB Planck spectrum



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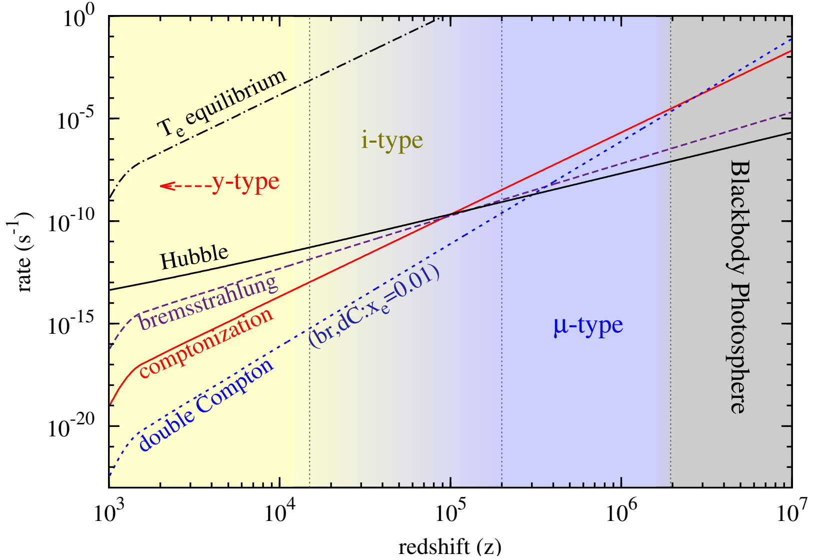
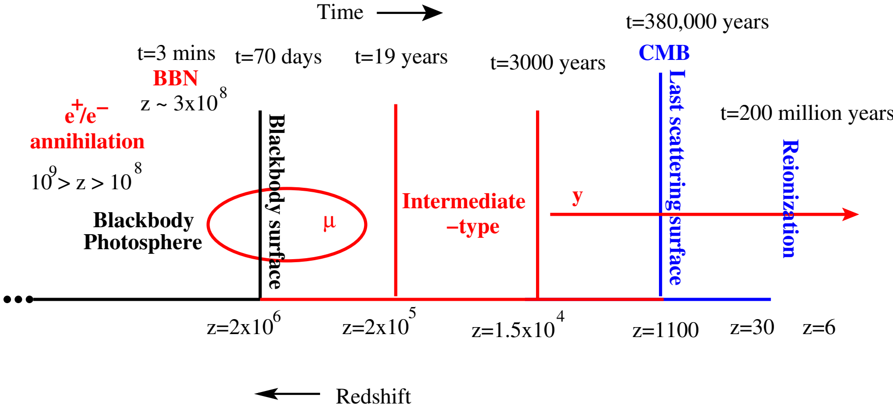


μ-type distortions



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 $\sim 10\%$, $z_{\rm dC} \approx 1.96\times 10^{6}$

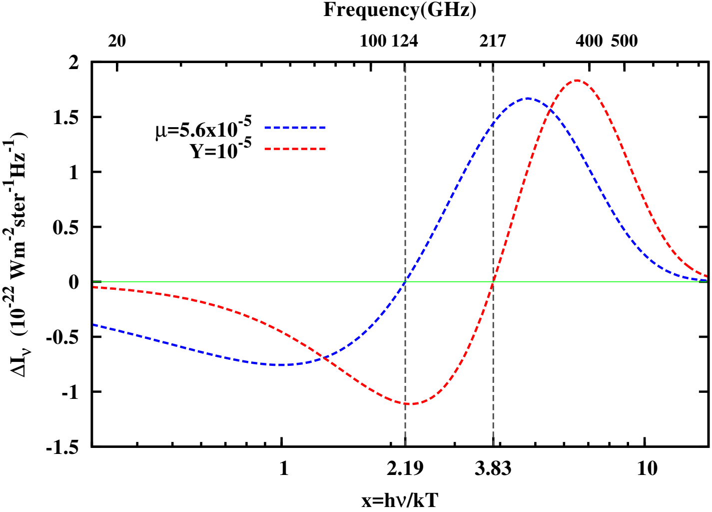
Numerical studies: Illarionov and Sunyaev 1975, Burigana, Danese, de Zotti 1991, Hu and Silk 1993, Chluba and Sunyaev 2012

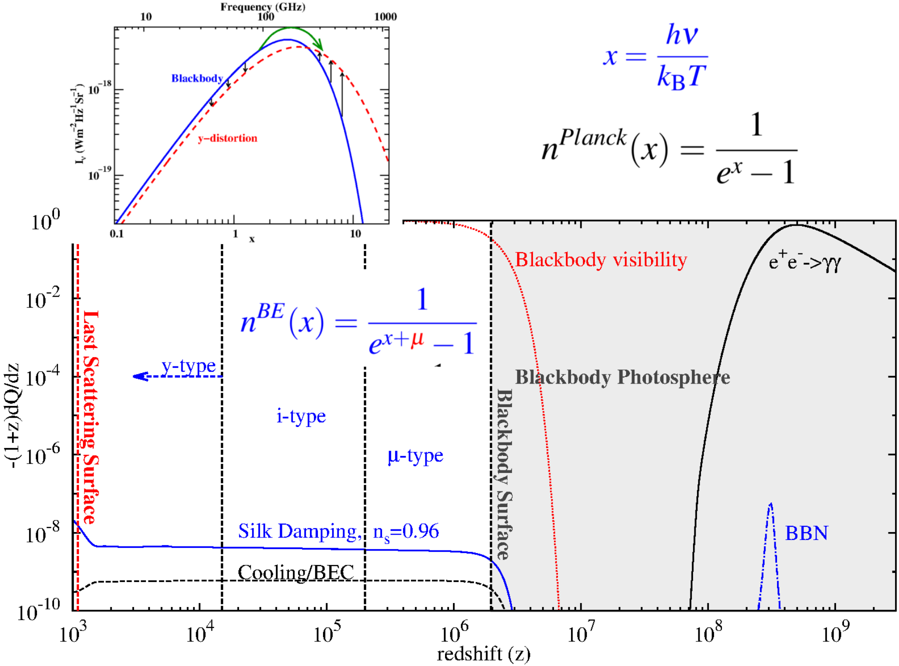
New solution, accuracy $\sim 1\%$
(*Khatri and Sunyaev 2012a*)

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

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

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



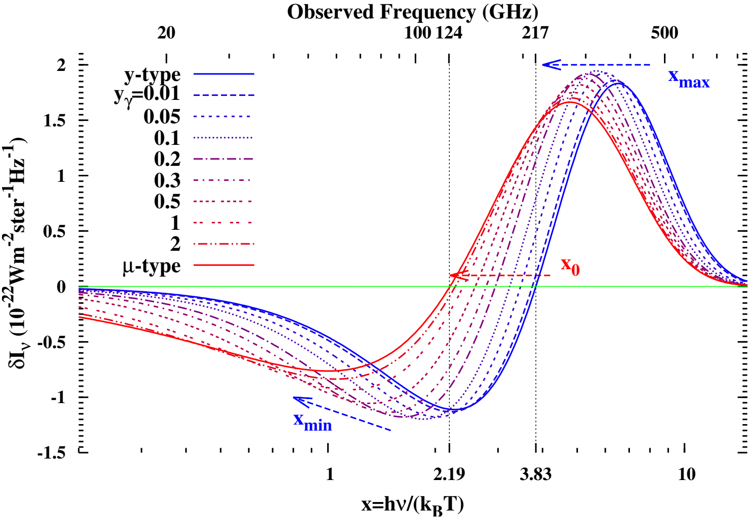


Frequency (GHz)
Blackbody
y–distortion
x
$x = \frac{h\nu}{k_B T}$
$n^{Planck}(x) = \frac{1}{e^x - 1}$
$n^{BE}(x) = \frac{1}{e^{x+\mu} - 1}$
Blackbody visibility
$e^+e^- \rightarrow \gamma\gamma$
Last Scattering Surface
y-type
i-type
μ-type
Blackbody Photosphere
Blackbody Surface
Silk Damping, n_s=0.96
Cooling/BEC
BBN
-(1+z)dQ/dz
redshift (z)

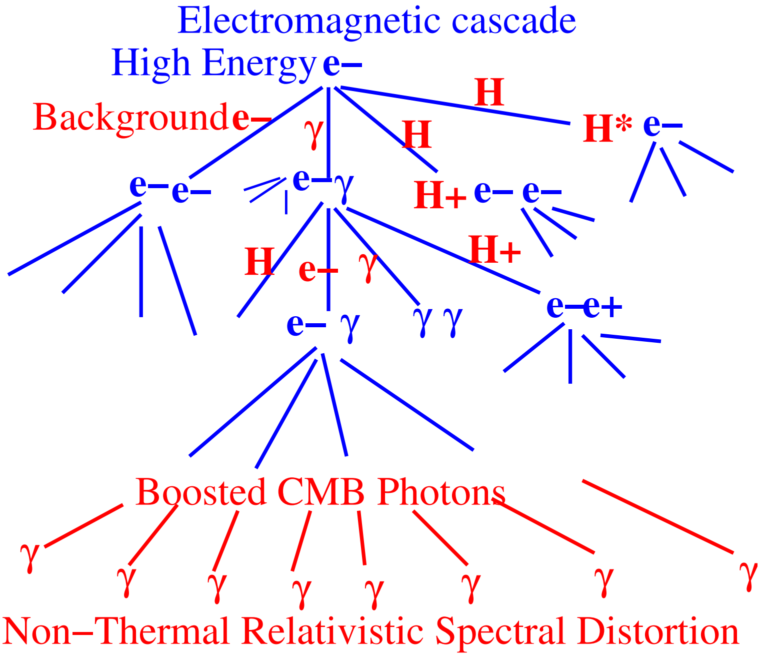
Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

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

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

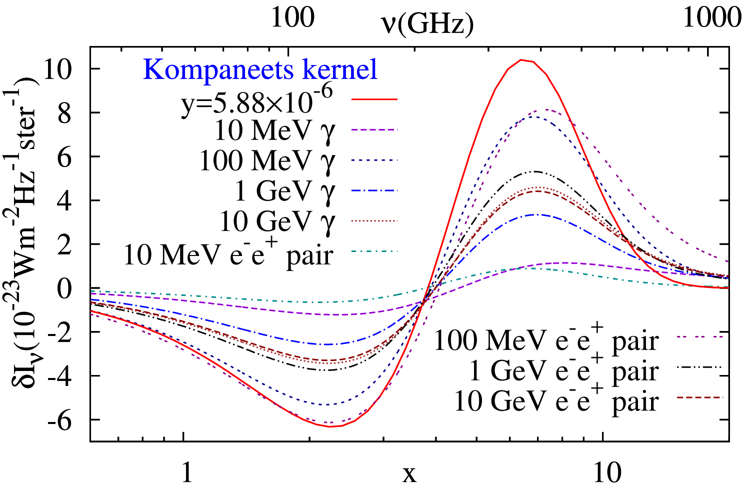


Non-Thermal Relativistic Distortions


Electromagnetic cascade
High Energy e−
Background e−
γ
H
H
H* e−
e− e−
e− γ
H+ e− e−
H
e−
γ
H+
e− γ
γ γ
e− e+
Boosted CMB Photons
γ
γ
γ
γ
γ
γ
γ
γ
Non−Thermal Relativistic Spectral Distortion

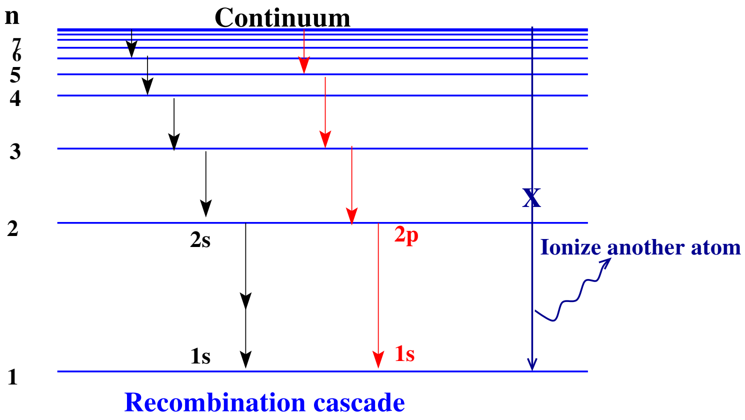
At $z \lesssim 10^5$ the shape of the CMB distortion depends on the spectrum of injected particles

Acharya and Khatri 2018



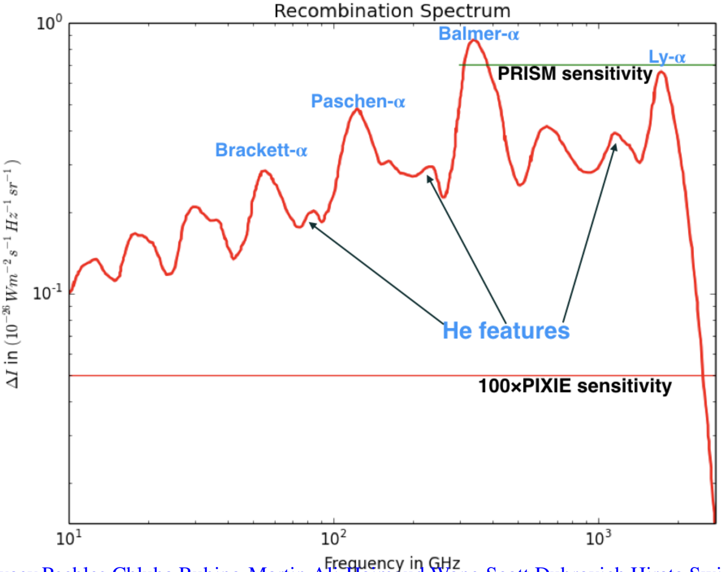
Cosmological recombination cascade

Several photons are emitted as electrons cascades down to the ground state



Cosmological recombination spectrum

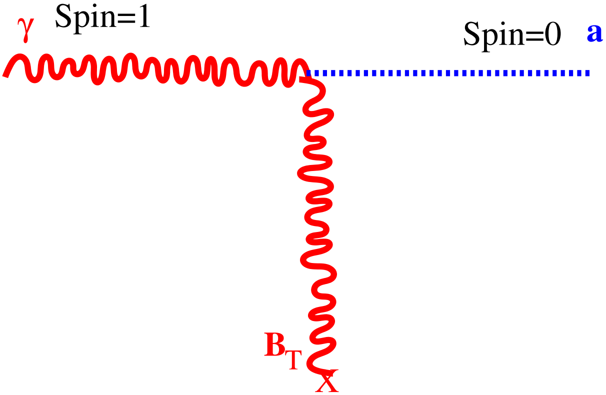
Calculation by Debajyoti Sarkar



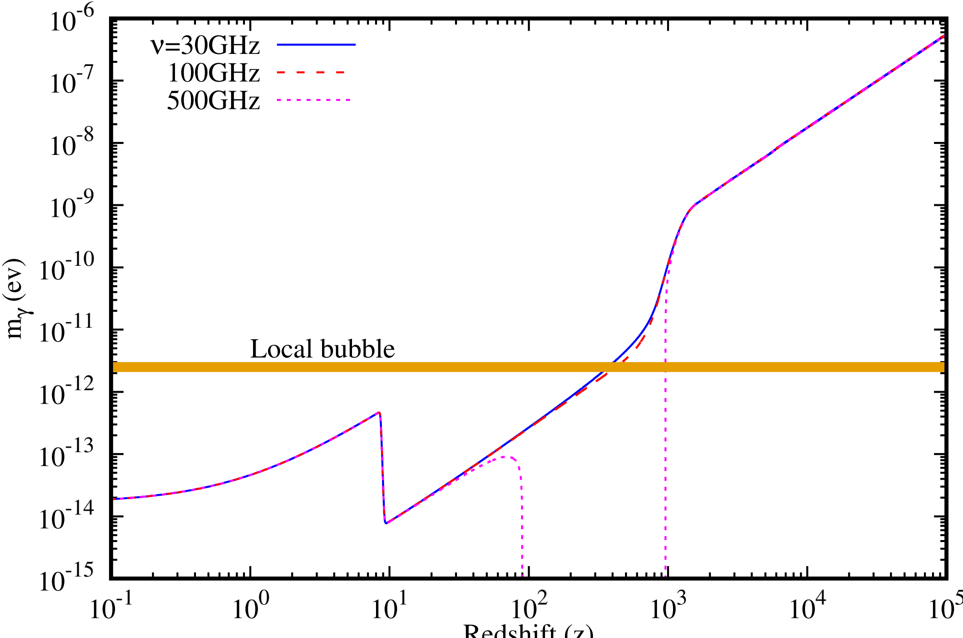
Sunyaev,Peebles,Chluba,Rubino-Martin,Ali-Haimoud,Wong,Scott,Dubrovich,Hirata,Switzer..

Photon-axion conversion

Axion: pseudo-scalar particle with low mass and two photon coupling to photons

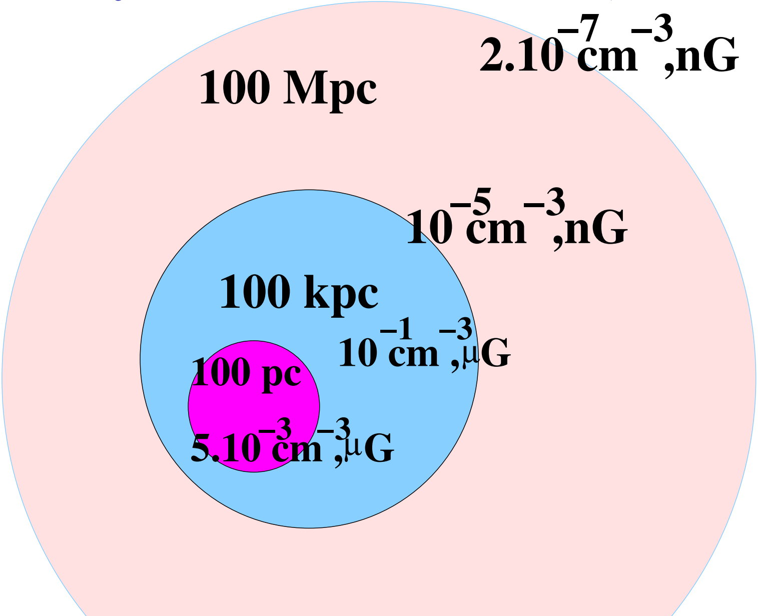


Evolution of the effective mass of the photon



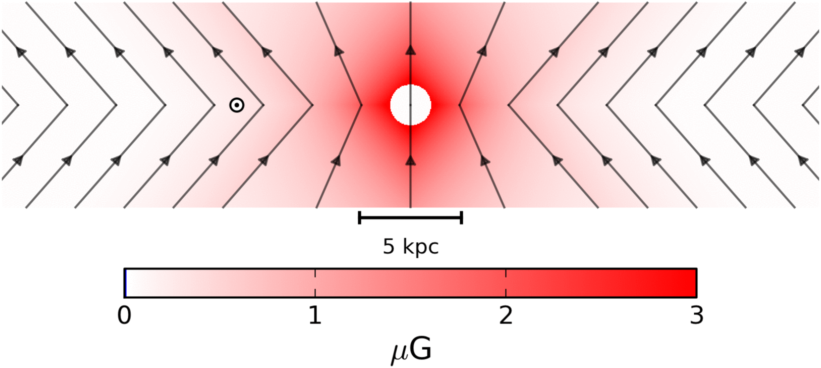
Photon-axion conversion in MilkyWay magnetic field

Mukherjee, Khatri & Wandelt 2017 (n_e, B)



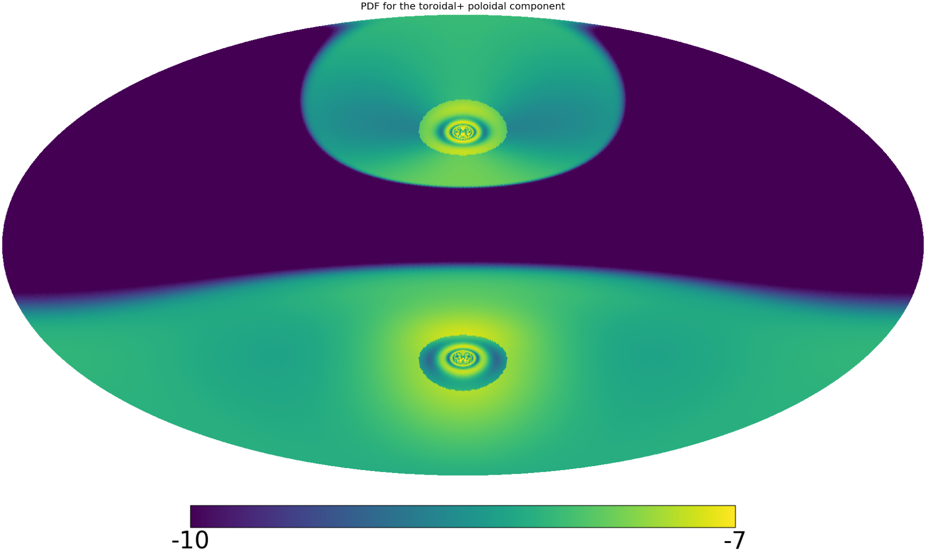
Galactic magnetic field: Poloidal field

Jansson& Farrar 2012



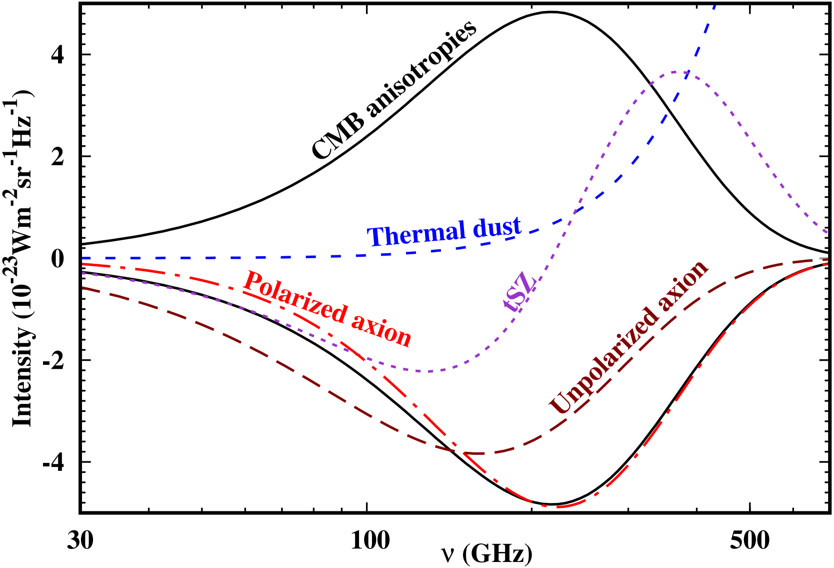
Axion distortions: Polarized & Anisotropic

(Mukherjee, Khatri & Wandelt 2017) - Perfect target for next generation of CMB missions



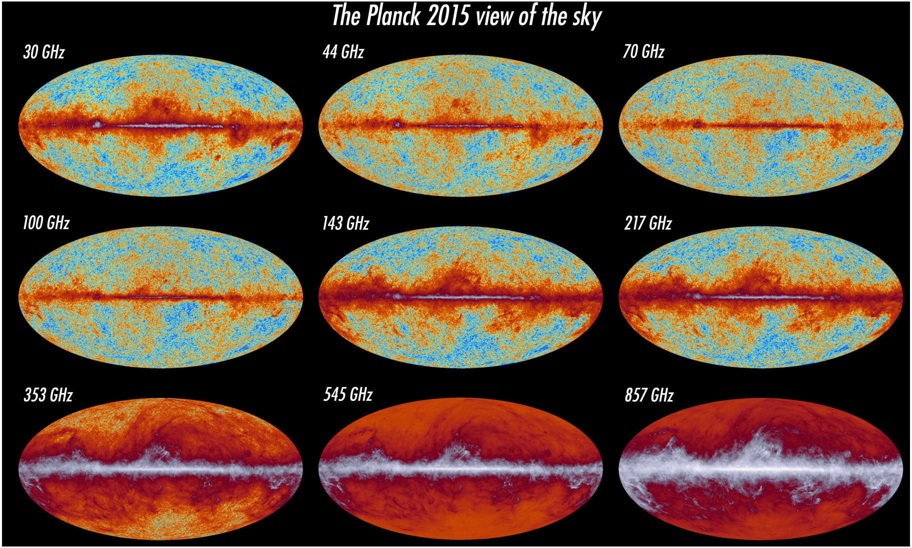
Axion distortions: Polarized & Anisotropic

Mukherjee, Khatri & Wandelt 2017



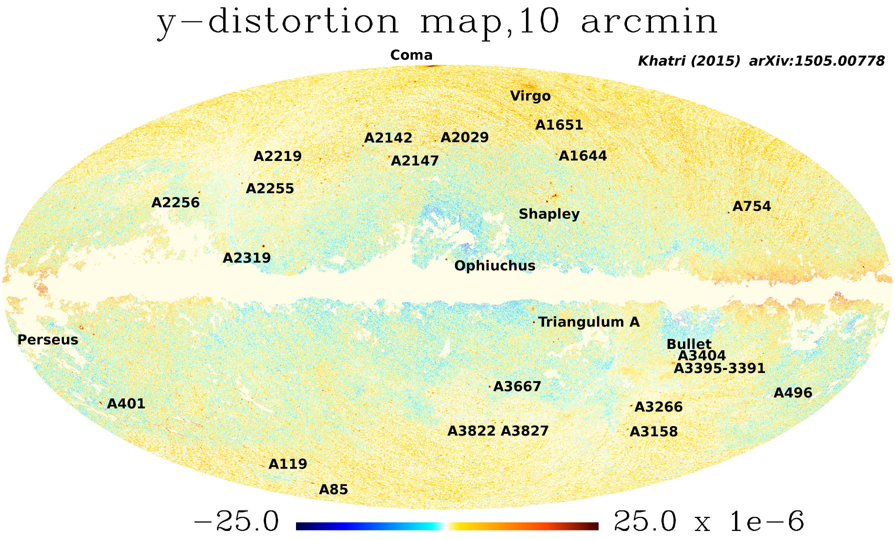
Combine Planck frequency maps to filter out the desired signal

Planck collaboration/ESA 2015



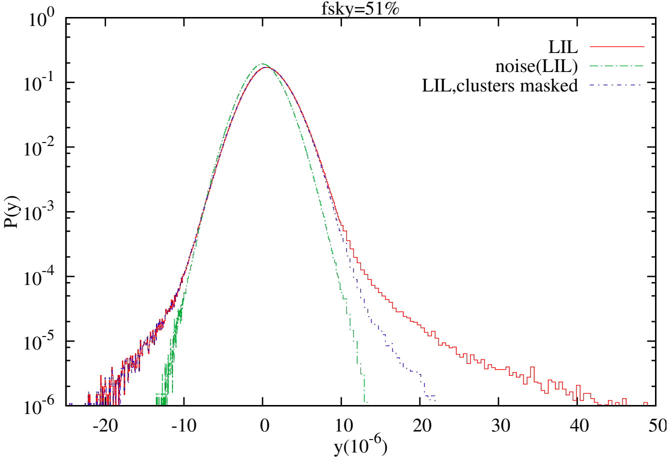
SZ/y-distortion

y-distortion map



New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

average the positive tail: $\langle y \rangle < 2.2 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*



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

Lower limit on $\langle y \rangle$ from Planck and SPT detected clusters

Observed clusters $\Rightarrow$ Minimum average y-distortion in the CMB

$\langle y \rangle > 5.4 \times 10^{-8}$ (*Khatri & Sunyaev 2015*)

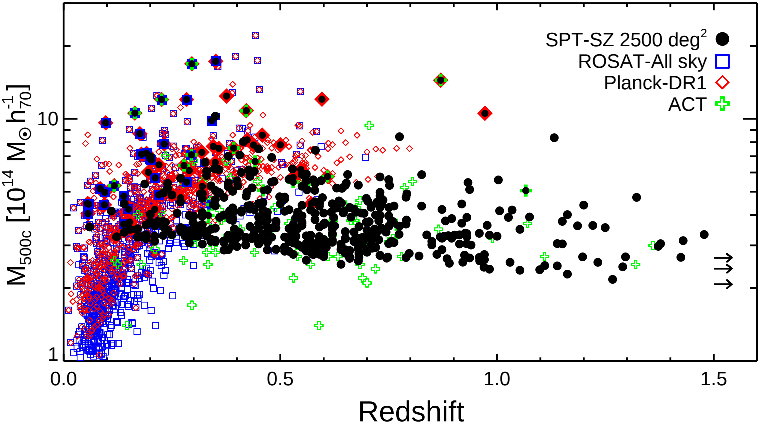


Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

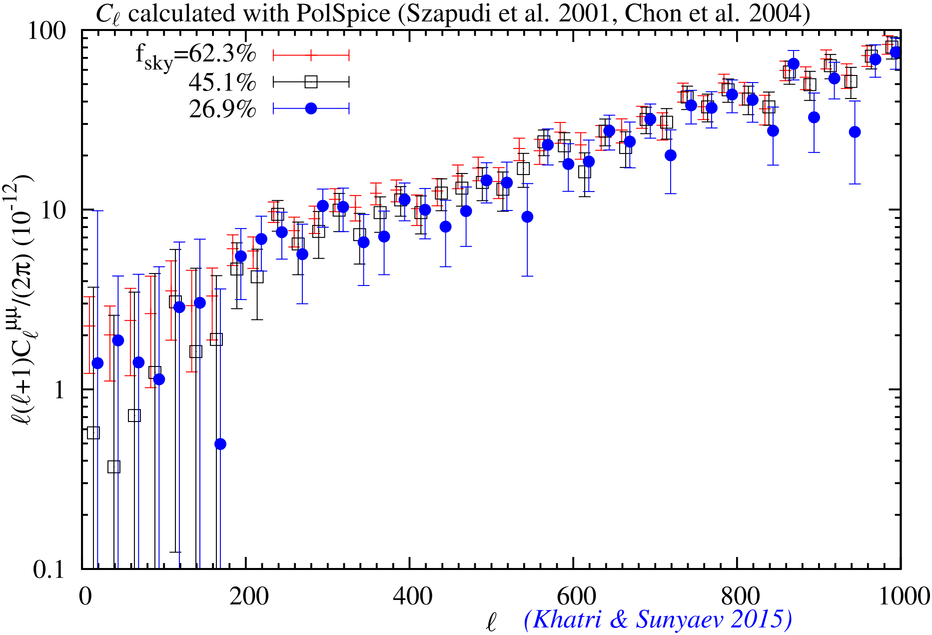
μ-distortion

Upper limit on the μ-distortion fluctuations

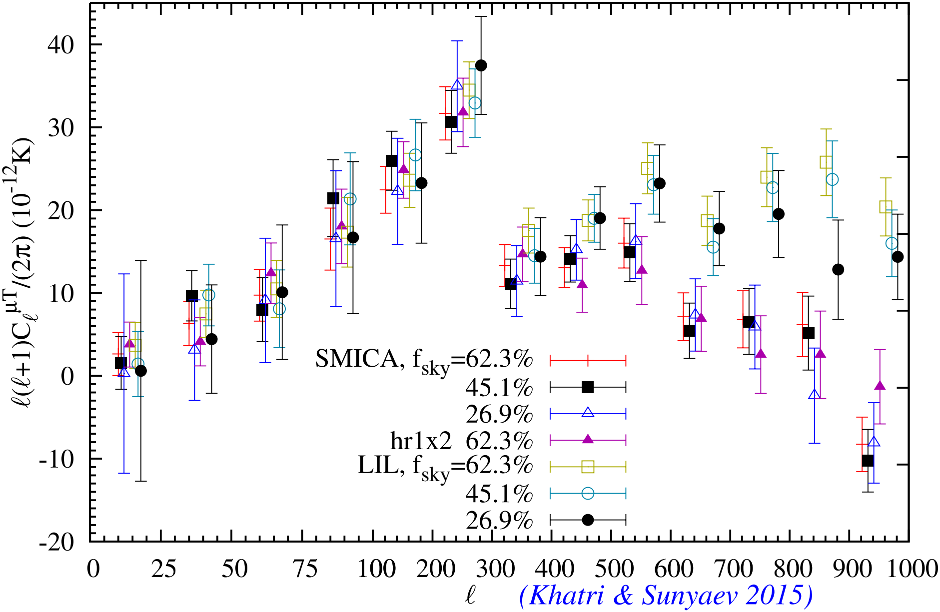
- Variance: $\sigma^2_{\rm map} = \mu^2_{\rm rms} + \sigma^2_{\rm noise}$
- Remove the noise contribution from map variance using half-ring half difference maps from Planck
- Remove mean $\langle\mu\rangle$ to get the central variance, $\mu^{\rm central}_{\rm rms} \equiv (\mu^2_{\rm rms} - \langle\mu\rangle^2)^{1/2}$

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

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

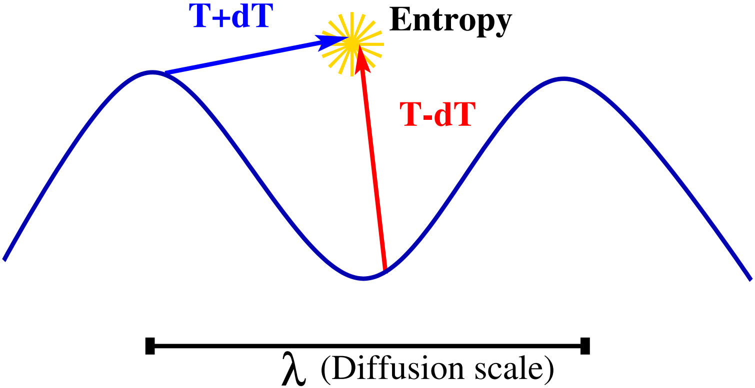


Power spectrum: $C_\ell^{\mu T}|_{\ell=2-26} = (2.6 \pm 2.6) \times 10^{-12}$ K



Example: Sound wave dissipation before recombination

Blackbody photons from the different parts of the sound wave mix:
Silk damping



Photons scatter on electrons and do random walk through plasma.
Diffusion Length=distance traversed by photons since big bang.

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

$k_S = 46 - 10^4\ \mathrm{Mpc}^{-1}$

$k_L = 10^{-3}\ \mathrm{Mpc}^{-1}$

Khatri & Sunyaev 2015

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

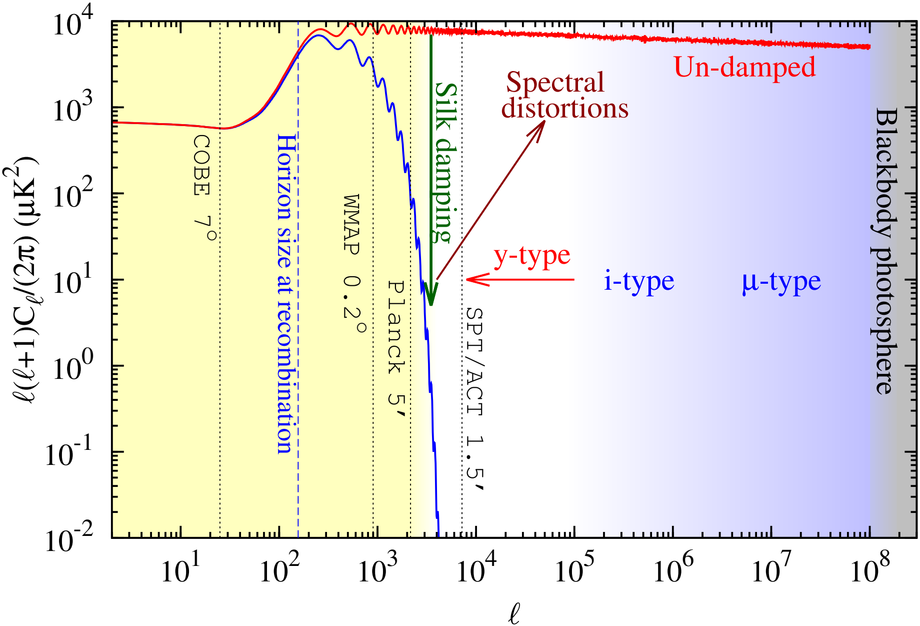
$$\tau_{\mathrm{NL}} < 10^{11}$$

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

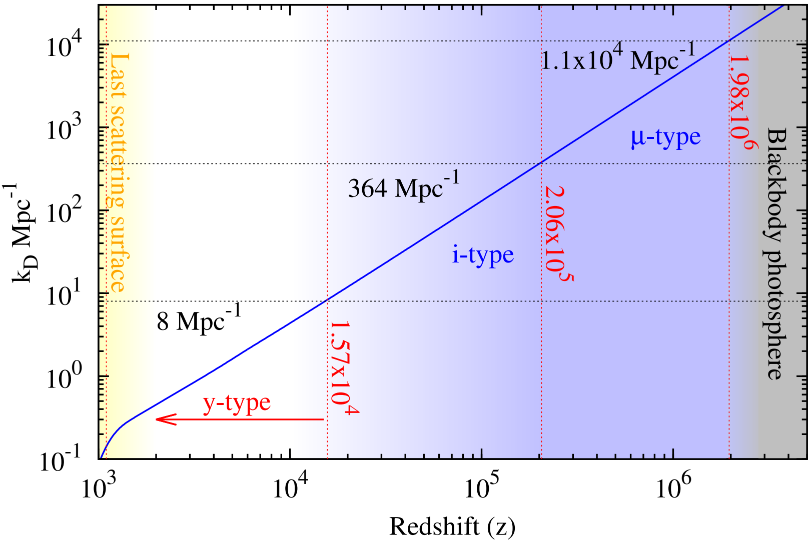
Only other comparable constraints from primordial black holes

Byrnes, Copeland, & Green 2012

Silk damping: 17 e-folds of inflation!



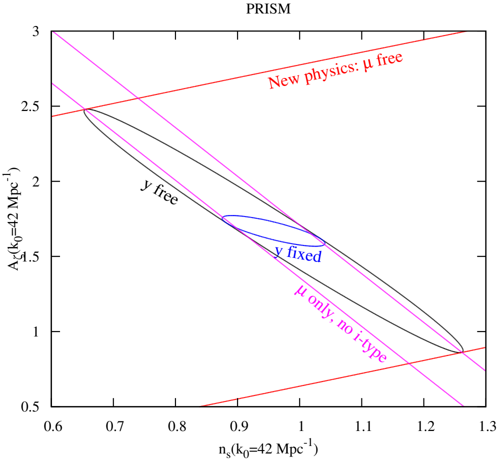
The Silk damping scale



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

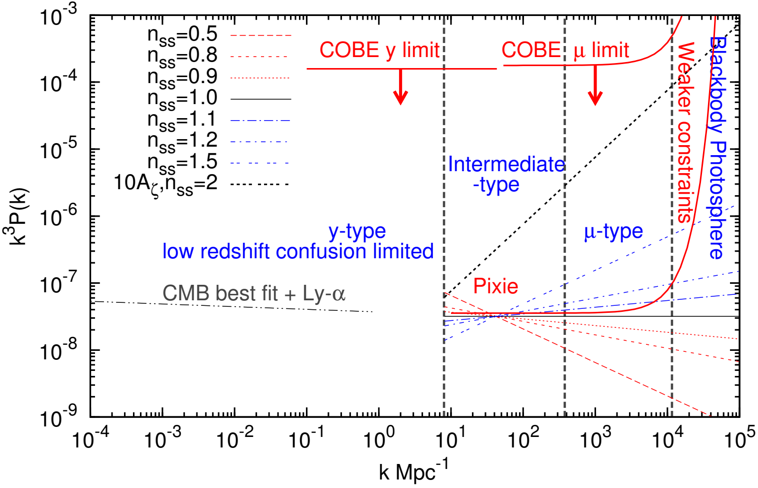


We have (re-)entered the era of CMB spectrum cosmology

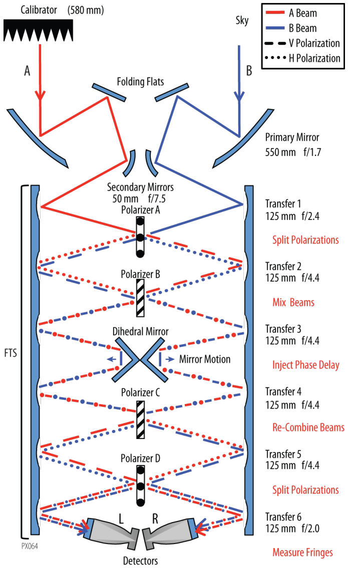
Future: Many orders of magnitude improvement in next decade
PIXIE (NASA), LiteBIRD (JAXA)

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

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



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



Fisher matrix forecasts

Model:

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

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

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

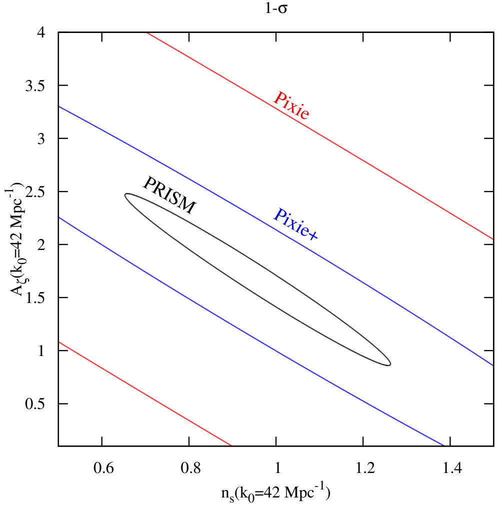
Fisher matrix forecasts

(Khatri and Sunyaev 2013)

Pixie-like experiments:

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

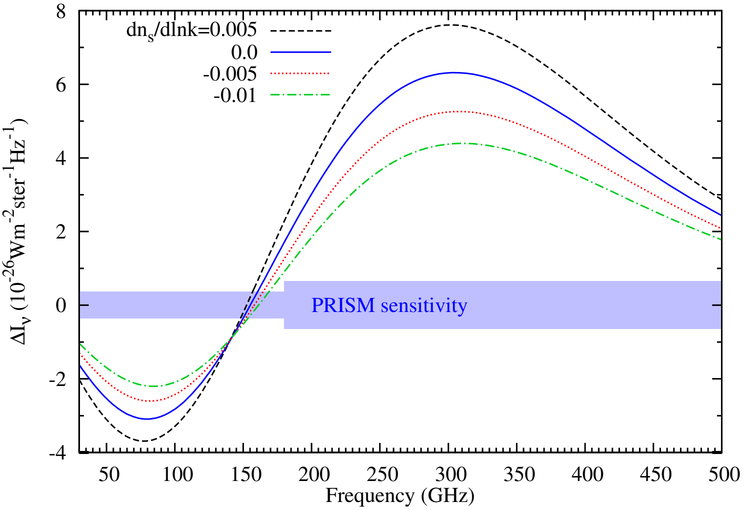
Pixie=(15,5)



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 $k_0 = 0.05$

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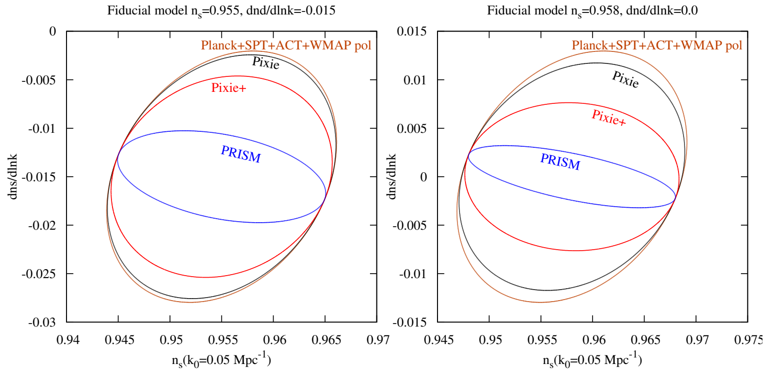
Pixie=(15,5)



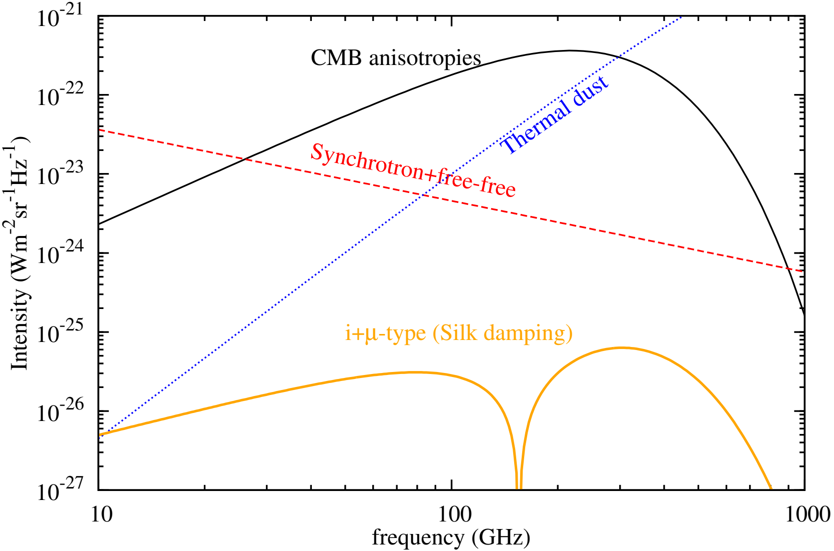
Detectability of primordial perturbations

Assuming $n_{\rm s} = 0.96$

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

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

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

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  Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012

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

There is still some way to go for CMB cosmology

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This information is accessible and within reach of experiments in (hopefully) not too far future: LiteBIRD,PIXIE,CORE

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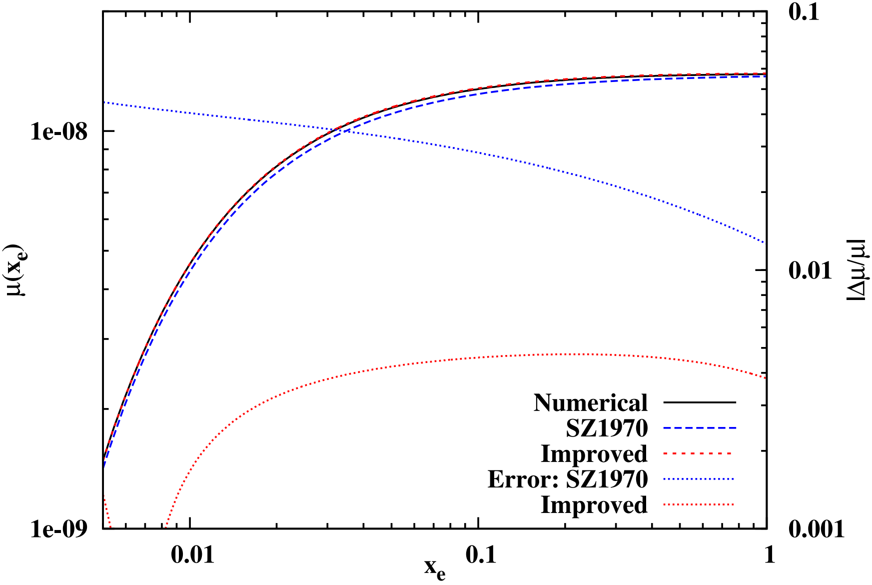
- Add rest of the energy to y-type distortions.

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

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.