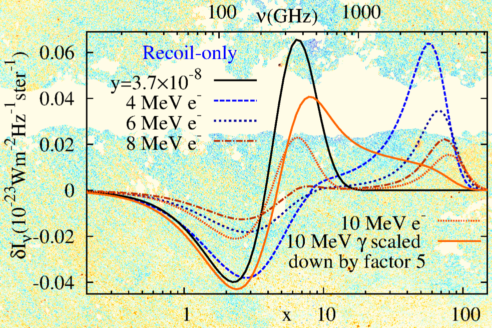
The information hidden in the shape of the CMB spectral distortions

Rishi Khatri



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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

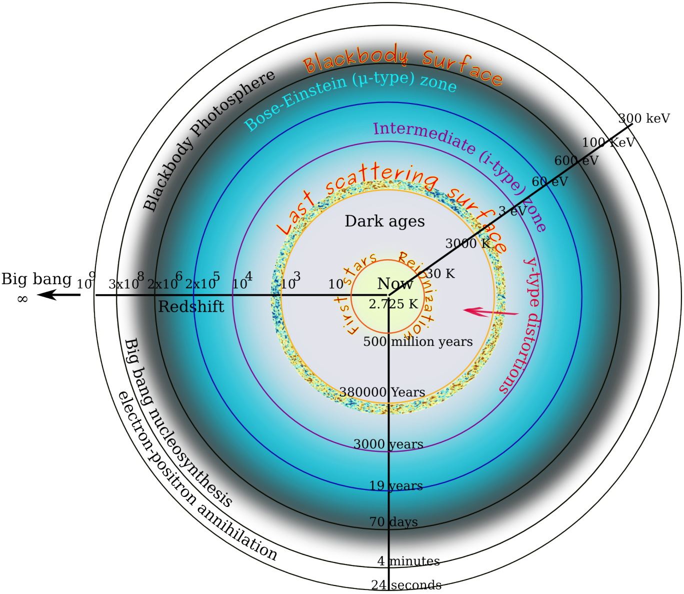
1990: COBE measures spectrum (blackbody) and anisotropies almost simultaneous measurement of blackbody spectrum by Canadian rocket experiment COBRA

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

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

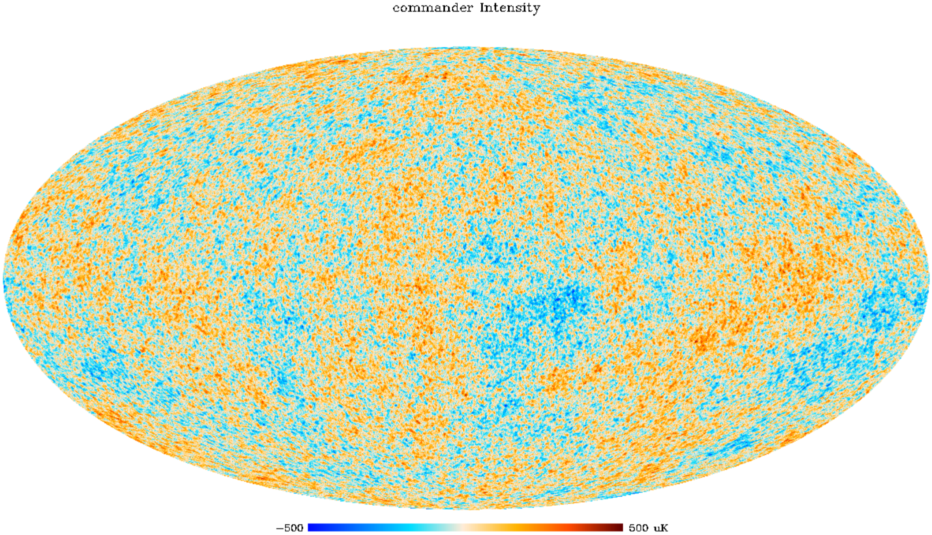
2030:Primordial B-modes ? CMB spectrum ?

Important events in the history of the Universe

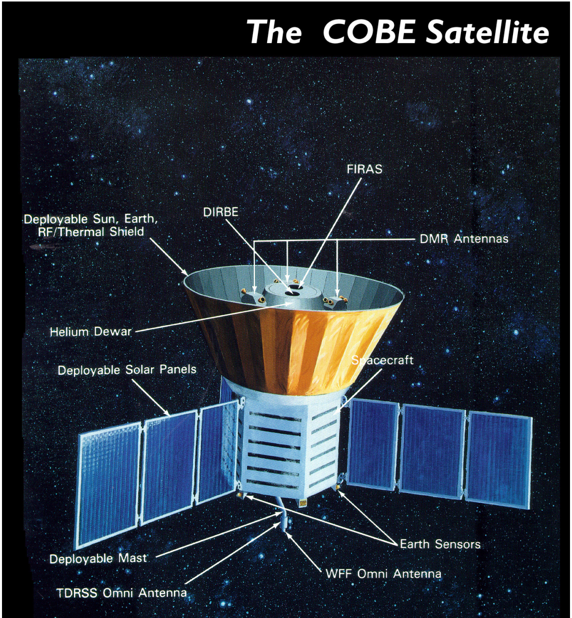


Picture of Universe @ 300000 Years

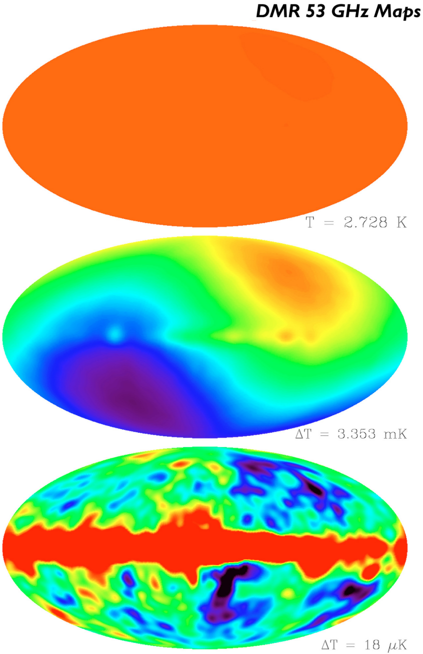
Planck Collaboration 2015



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

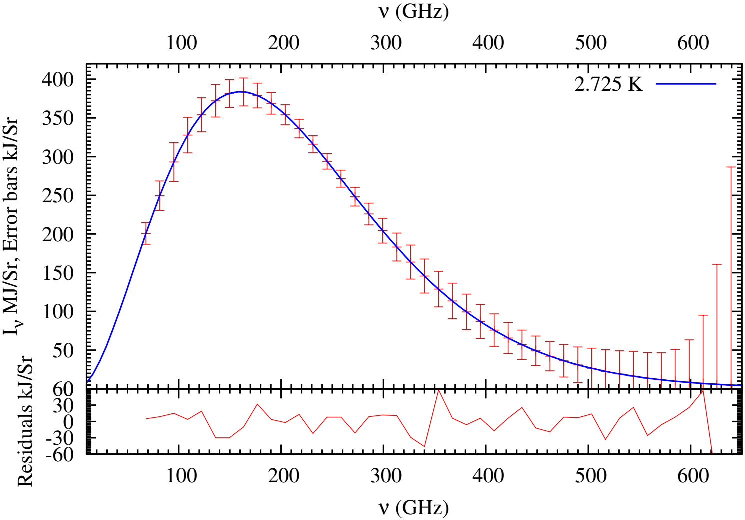


CMB as seen by COBE



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

Fixsen et al. 1996, Fixsen and Mather 2002



Planck spectrum

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

Relativistic invariant occupation number/phase space density

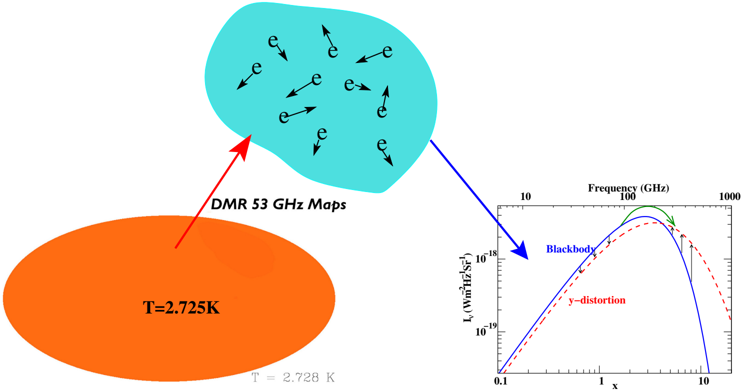
$$n(\nu) \equiv \frac{c^2}{2h\nu^3} I_\nu$$

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

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

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

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



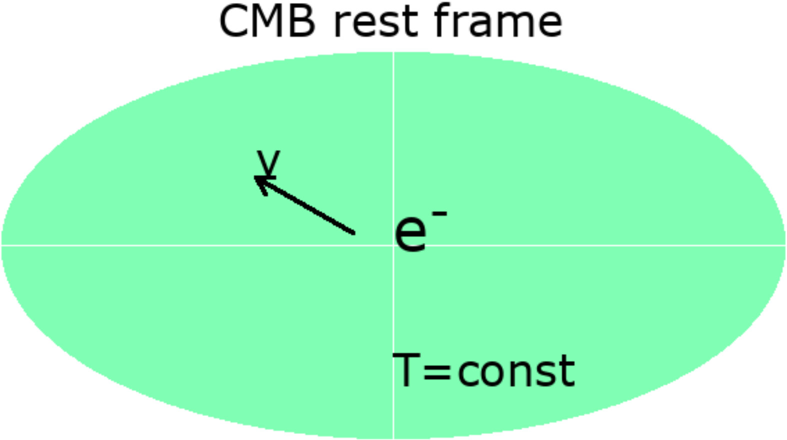
y-type (Sunyaev-Zeldovich effect) from clusters/reionization

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

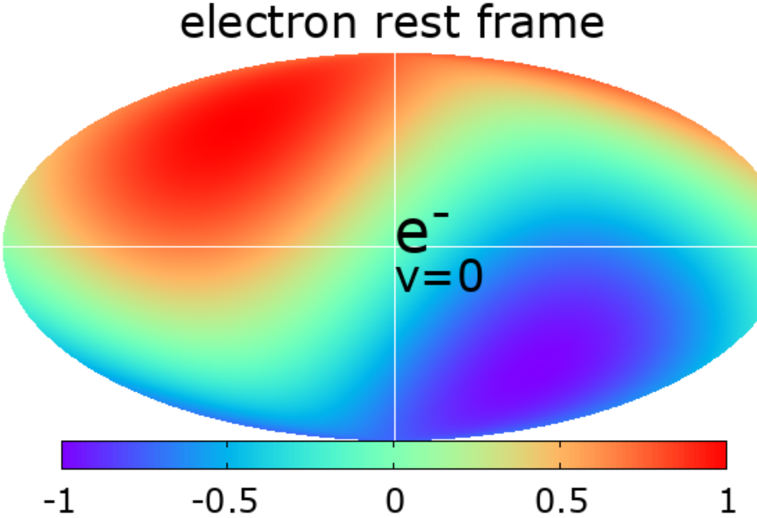
$$= \mathbf{y} \;\; \frac{\mathbf{x e^x}}{(\mathbf{e^x - 1})^2} \left(\mathbf{x} \frac{\mathbf{e^x + 1}}{\mathbf{e^x - 1}} - \mathbf{4} \right)$$

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

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 $n_{\mathrm{Planck}}(T+\delta T)$ about T in Taylor series and average, $(\langle \delta T \rangle \equiv 0)$.

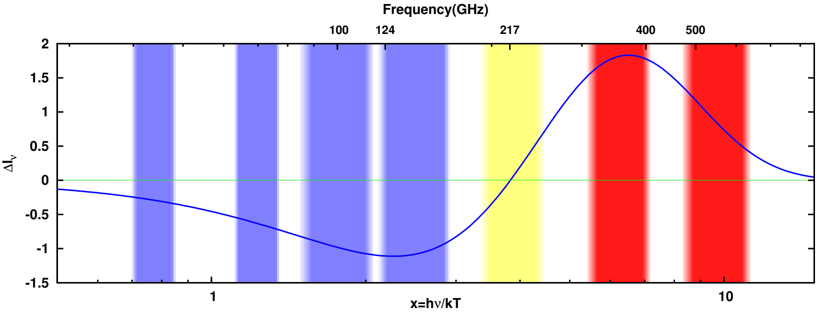
$$< n_{\mathrm{Planck}} > = \frac{1}{e^{\frac{h\nu}{kT}}-1} + \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T \frac{\partial n_{\mathrm{Pl}}}{\partial T} + \frac{1}{2} \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial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

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

Black body

Kompaneets operator/SZ

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



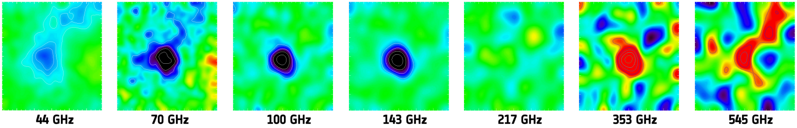
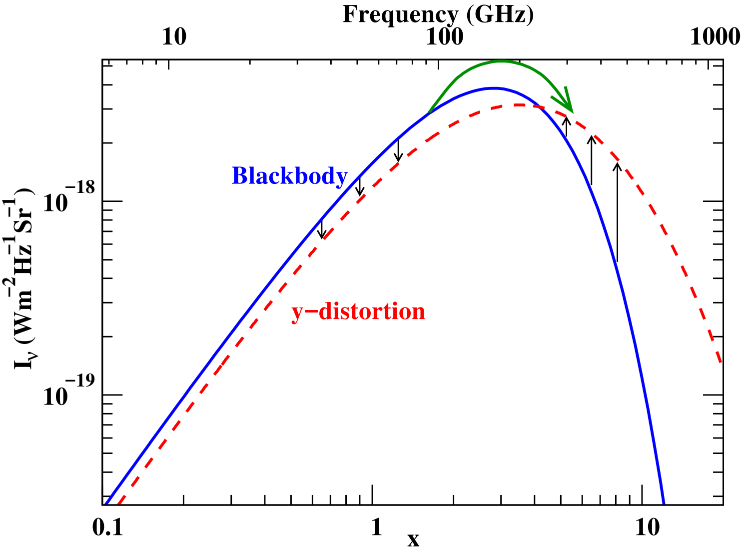


Image credit: ESA / HFI & LFI Consortia

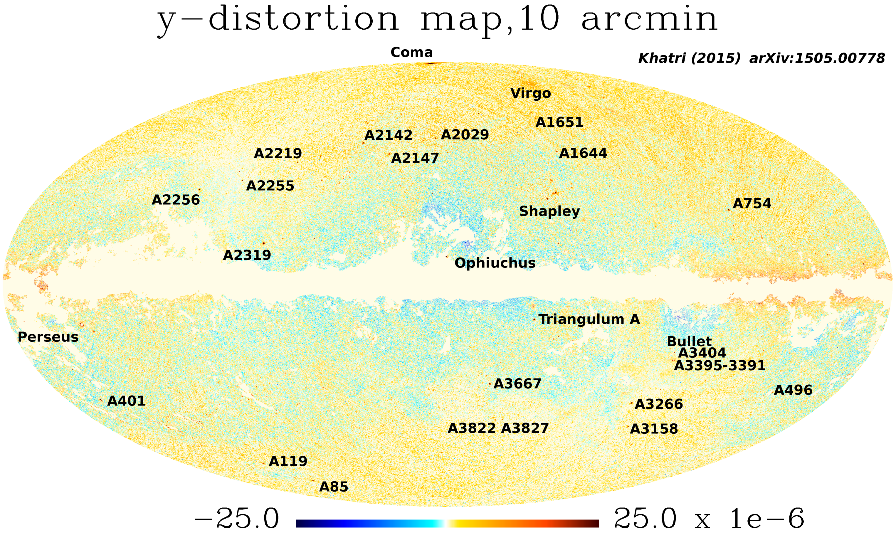
Average y-distortion (Sunyaev-Zeldovich effect) limits

(Zeldovich and Sunyaev 1969)

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

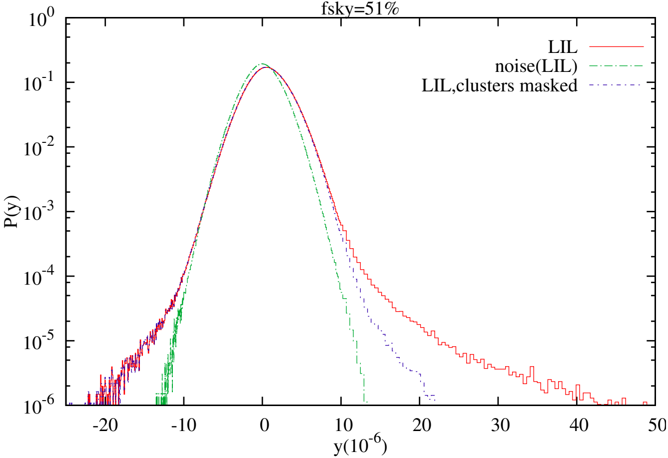


y-distortion map



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 ⇒ Minimum average *y*-distortion in the CMB

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

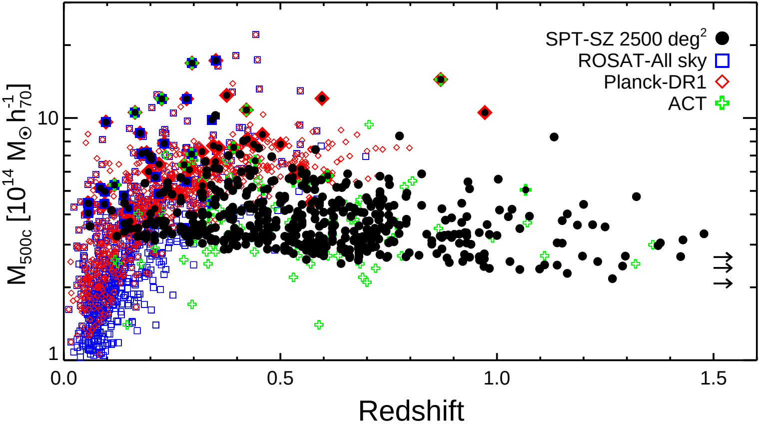
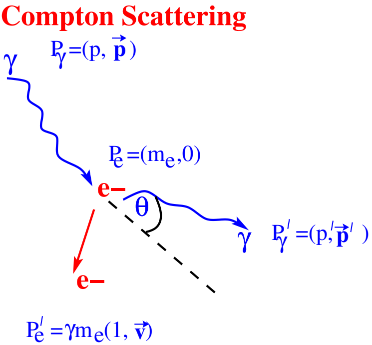


Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

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:

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

No. of scatterings

Doppler effect:

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Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int \underbrace{\mathrm{d}t\, c\sigma_\mathrm{T} n_\mathrm{e}}_{\text{No. of scatterings}} \underbrace{\frac{k_\mathrm{B} T_\gamma}{m_\mathrm{e} c^2}}_{\text{Energy transfer per scattering}}, \qquad T_\gamma = 2.725(1+z)$$

Doppler effect:

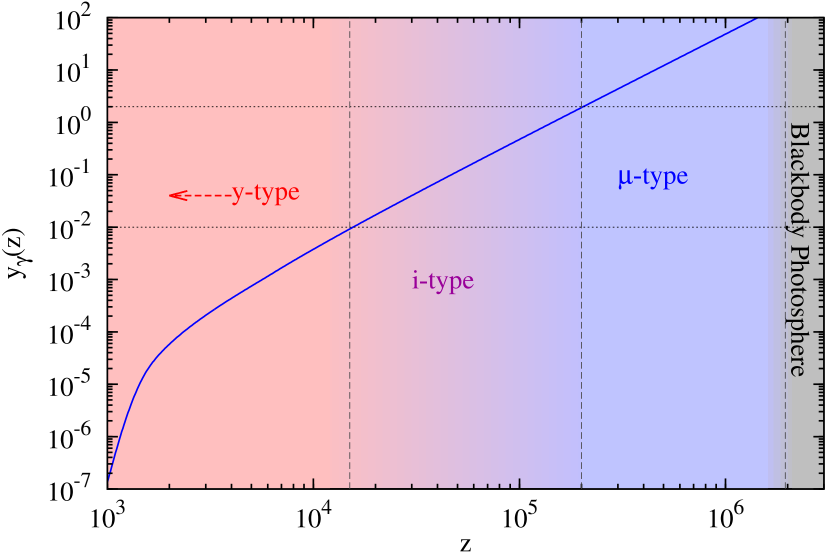
$$y_e = \int \mathrm{d}t\, c\sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\mathrm{e}}{m_\mathrm{e} c^2}$$

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

y: Amplitude of distortion

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

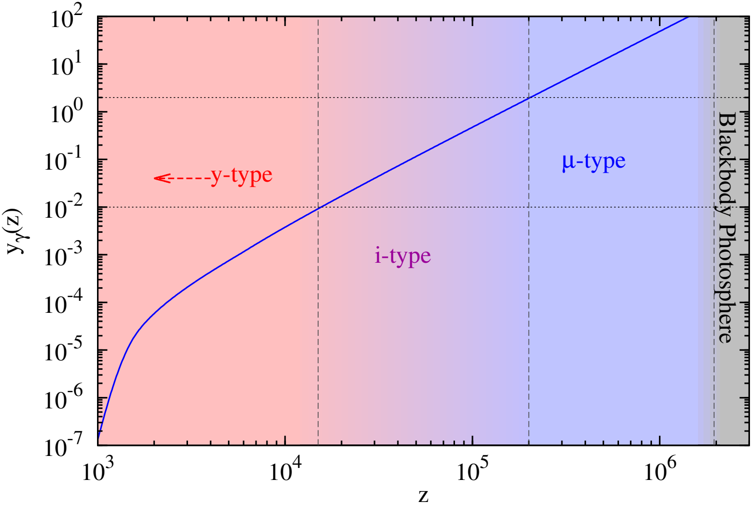
Efficiency of energy transfer between electrons and photons



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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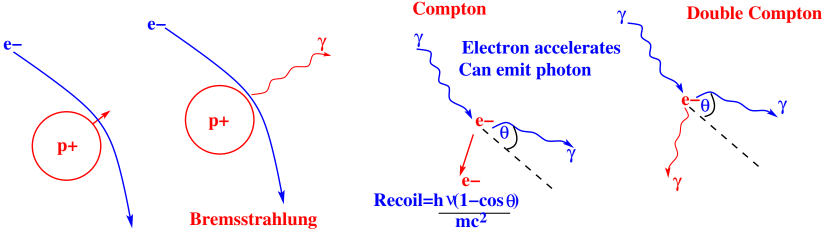
Idea behind analytic solutions:

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



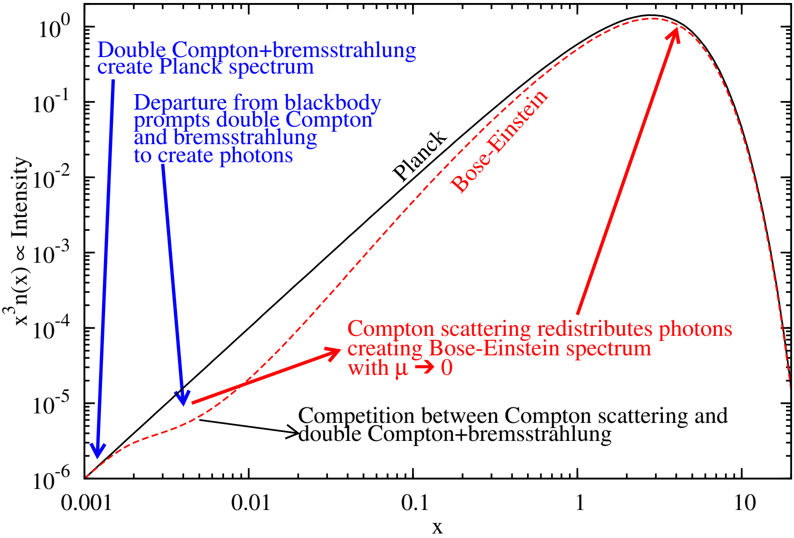
Compton

Electron accelerates
Can emit photon

Recoil$=\frac{h\nu(1-\cos\theta)}{mc^2}$

Double Compton

Creation of CMB Planck spectrum



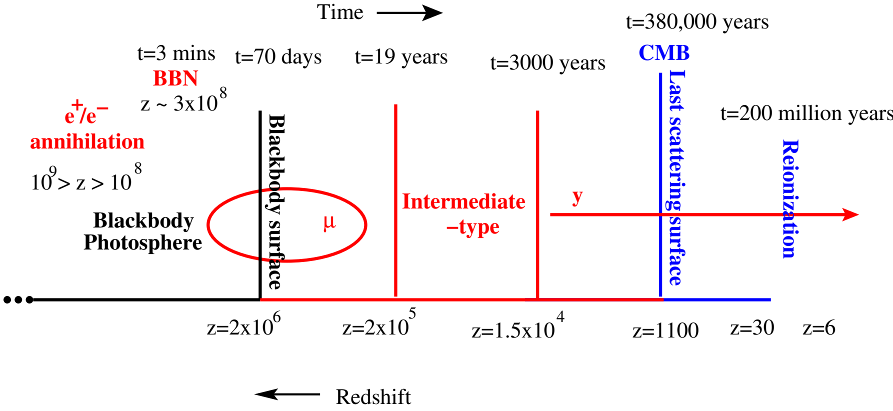
Double Compton+bremsstrahlung create Planck spectrum

Departure from blackbody prompts double Compton and bremsstrahlung to create photons

Compton scattering redistributes photons creating Bose-Einstein spectrum with $\mu \rightarrow 0$

Competition between Compton scattering and double Compton+bremsstrahlung

μ-type distortions



Time →

t=3 mins

BBN

z ~ 3x10^8

t=70 days

t=19 years

t=3000 years

t=380,000 years

CMB

t=200 million years

e$^+$/e$^-$ annihilation

10^9 > z > 10^8

Blackbody Photosphere

Blackbody surface

μ

Intermediate –type

y

Last scattering surface

Reionization

z=2x10^6

z=2x10^5

z=1.5x10^4

z=1100

z=30

z=6

← Redshift

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

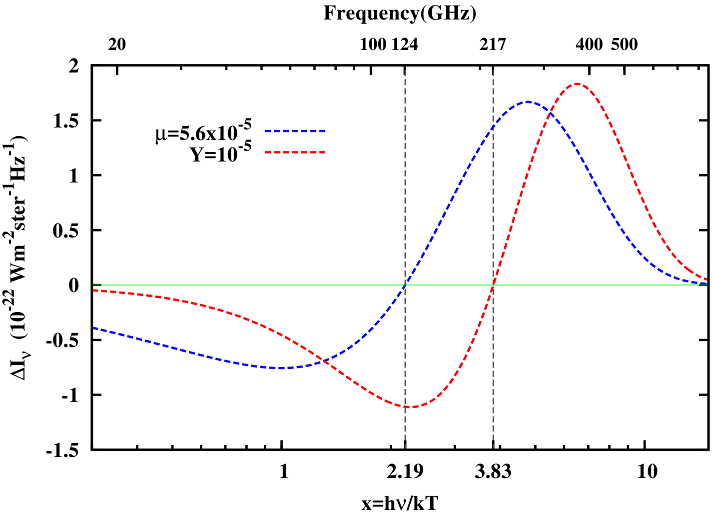
Numerical studies: Illarionov and Sunyaev 1975, Burigana, Danese, de Zotti 1991, Hu and Silk 1993, Chluba and Sunyaev 2012

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)*



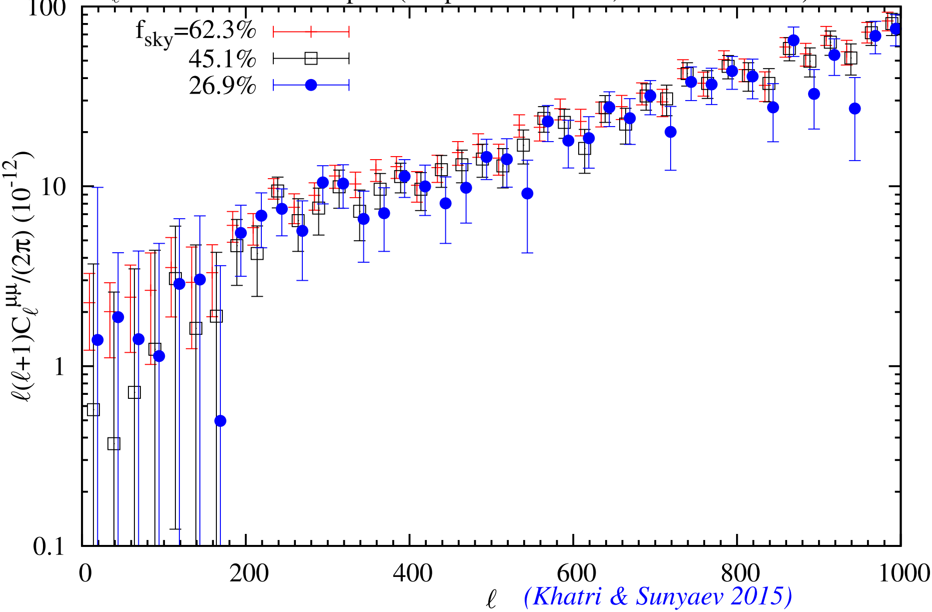
Upper limit on the μ-distortion fluctuations

- 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)*

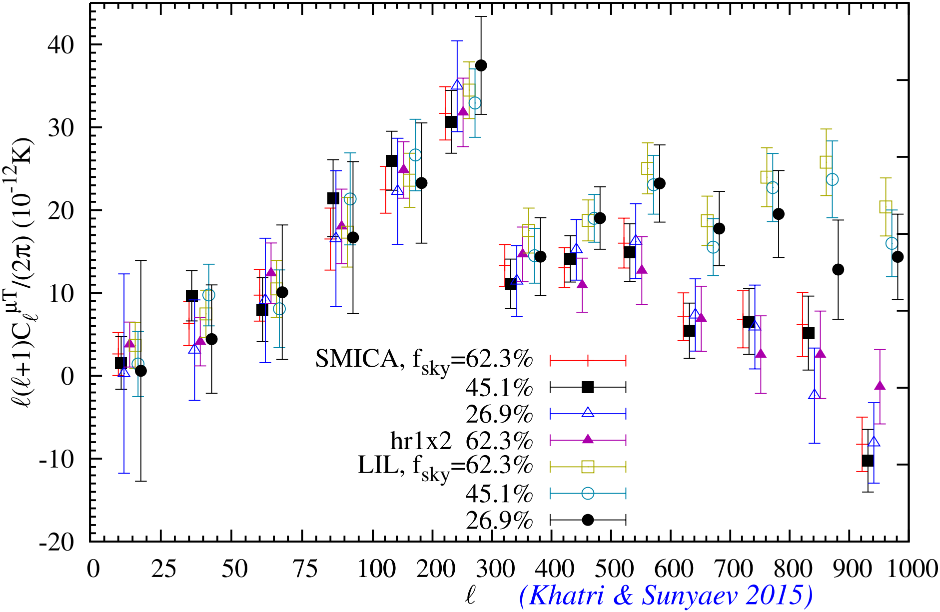
Power spectrum: $C_\ell^{\mu\mu}|_{\ell=2-26} = (2.3 \pm 1.0) \times 10^{-12}$

C_ℓ calculated with PolSpice (Szapudi et al. 2001, Chon et al. 2004)



(Khatri & Sunyaev 2015)

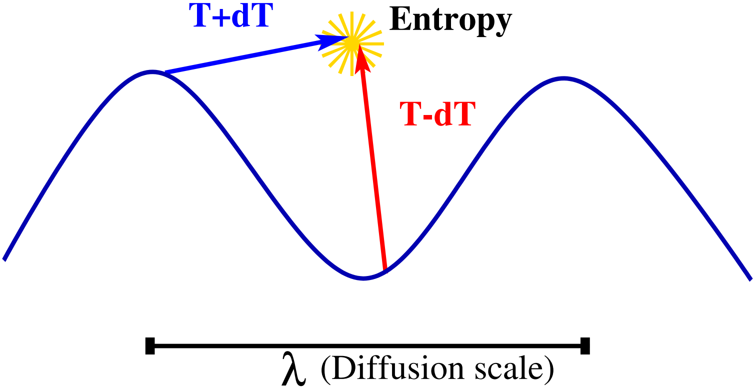
Power spectrum: $C_\ell^{\mu T}|_{\ell=2-26} = (2.6 \pm 2.6) \times 10^{-12}$ K



(Khatri & Sunyaev 2015)

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

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

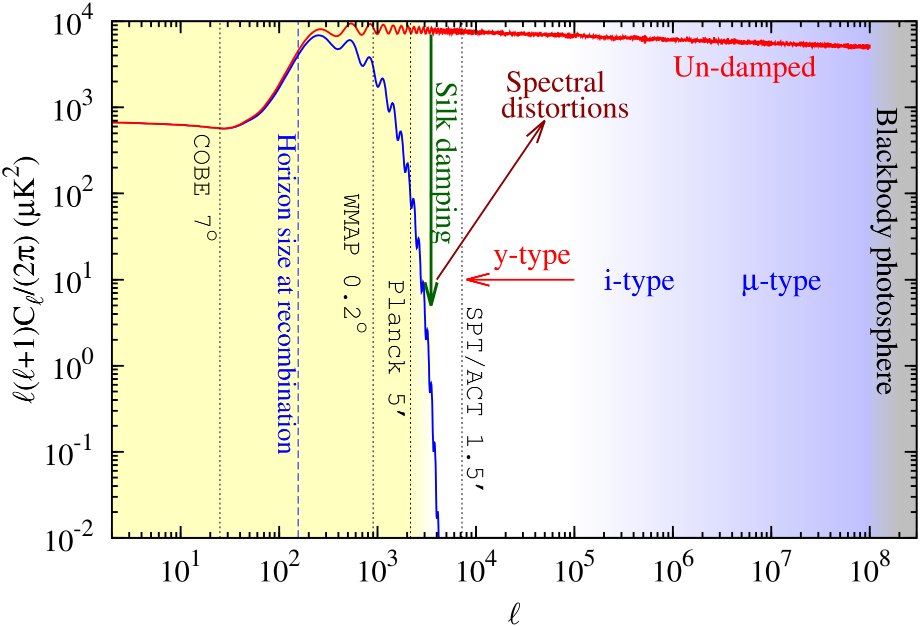
$$\tau_{\mathrm{NL}} < 10^{11}$$

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

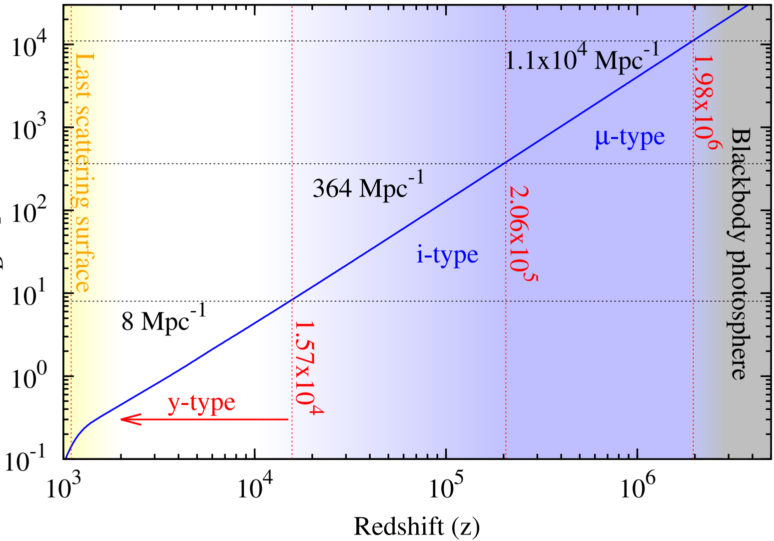
Only other comparable constraints from primordial black holes

Byrnes, Copeland, & Green 2012

Silk damping: 17 e-folds of inflation!



The Silk damping scale



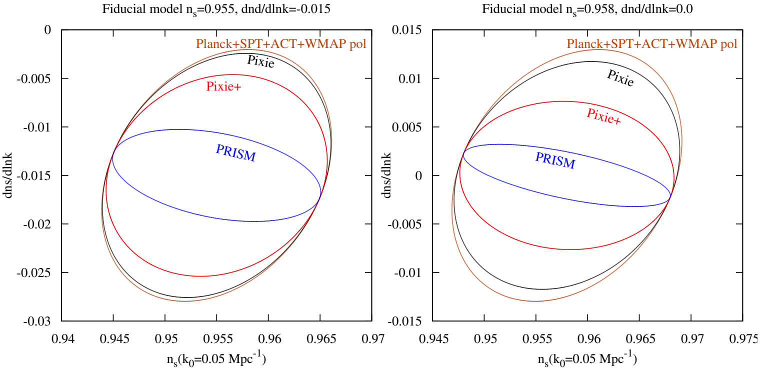
Fisher matrix f orecasts with Planck+SPT+ACT+WMAP-pol

(Khatri and Sunyaev 2013)

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

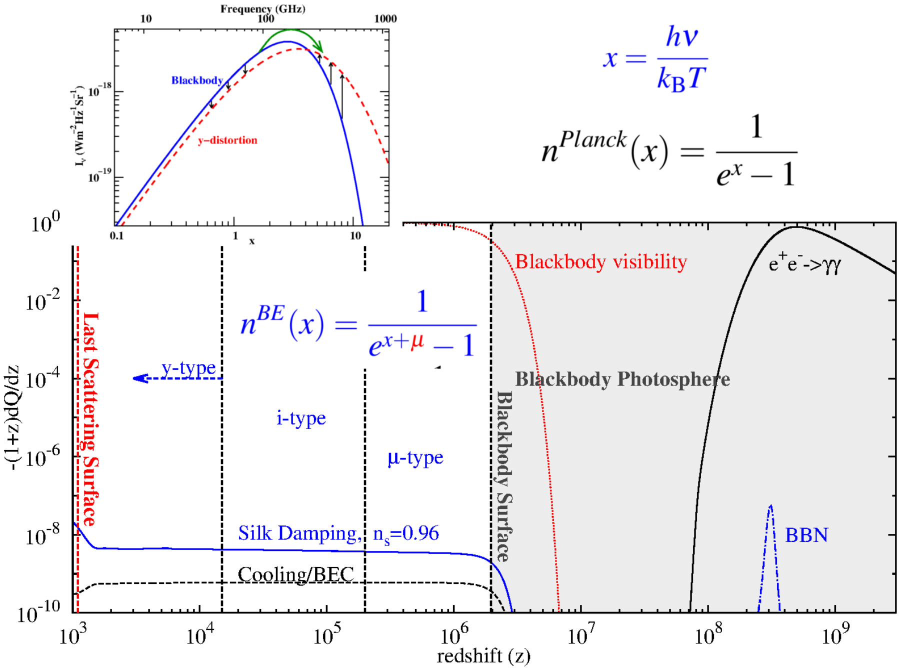
(x,y) ≡ (Resolution GHz , $\delta I(\nu) = 10^{-26}\mathrm{Wm^{-2}Sr^{-1}Hz^{-1}}$)

Pixie=(15,5)



$$x = \frac{h\nu}{k_B T}$$

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

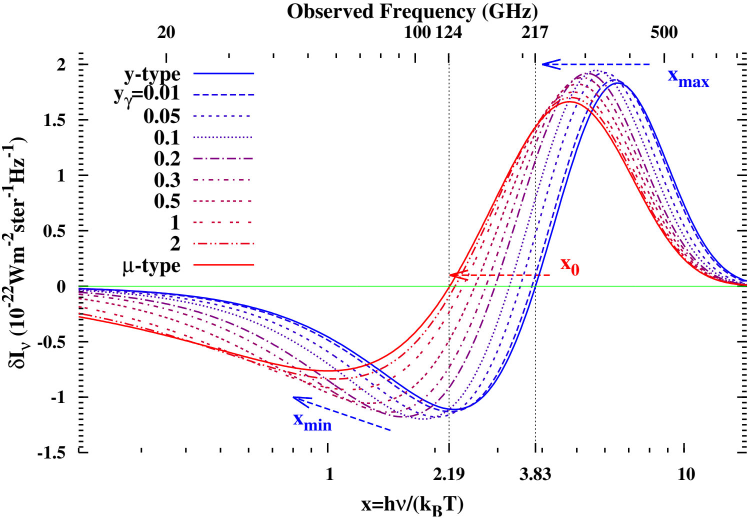


$$n^{BE}(x) = \frac{1}{e^{x+\mu} - 1}$$

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

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

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

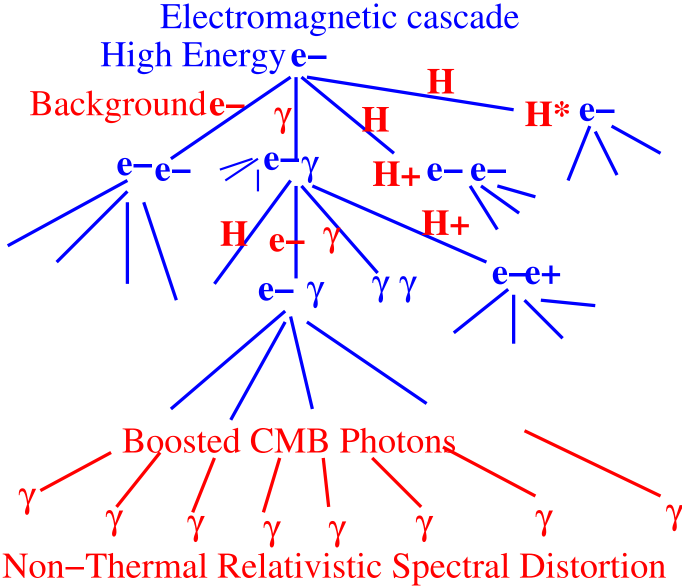


y and i-type distortions are non-relativistic solutions

Many processes in the early Universe inject relativistic particles. So far these have been studied assuming non-relativistic y-type distortions.

- 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)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Black holes: Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010

Particle cascades ⇒ Non-Thermal Relativistic Distortions



Electromagnetic cascade

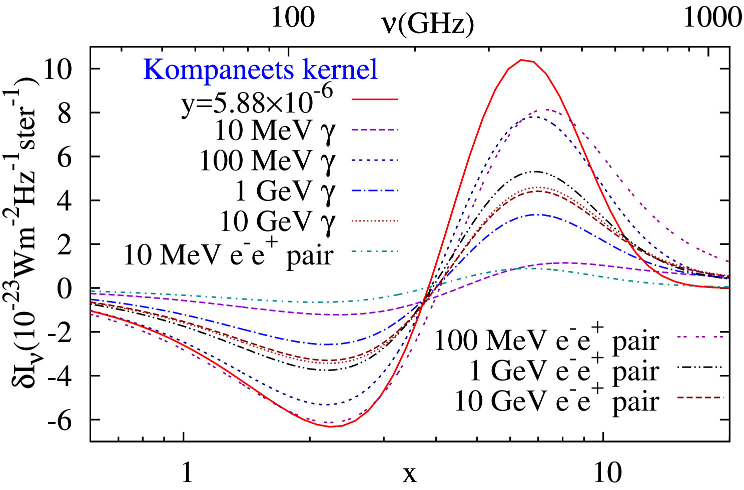
High Energy **e–**

Boosted CMB Photons

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 2019a



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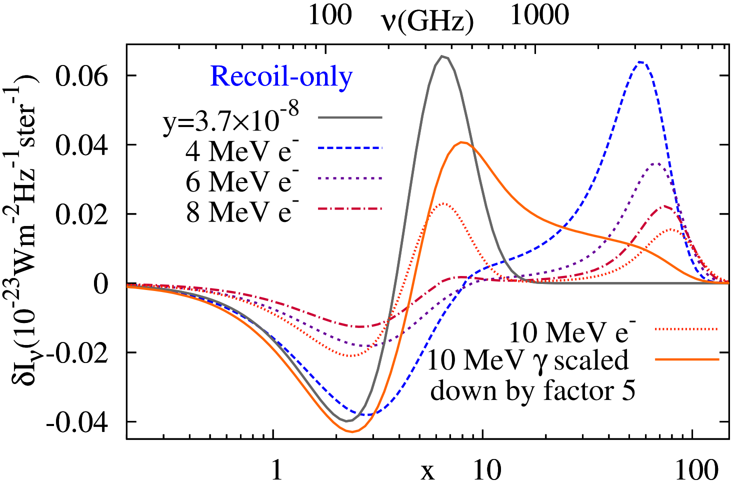
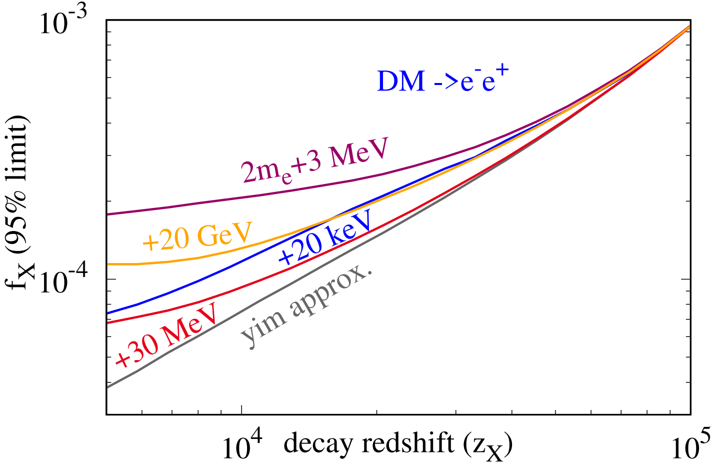


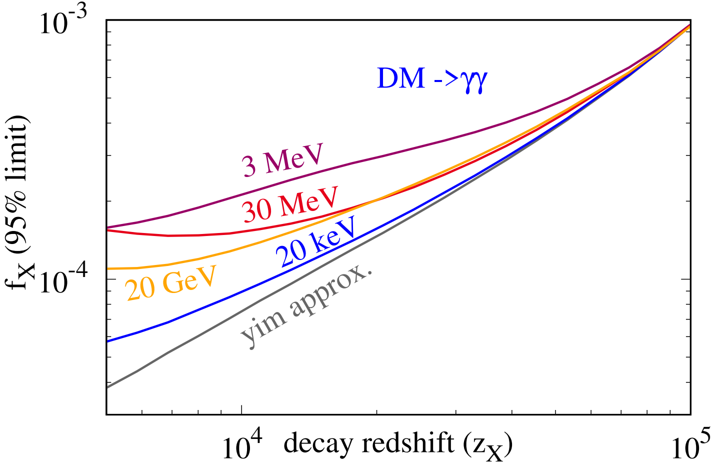
New COBE constraints on decaying dark matter: upto a factor of 5 correction

electron-positron channel *Acharya and Khatri 2019b*



New COBE constraints on decaying dark matter: upto a factor of 5 correction

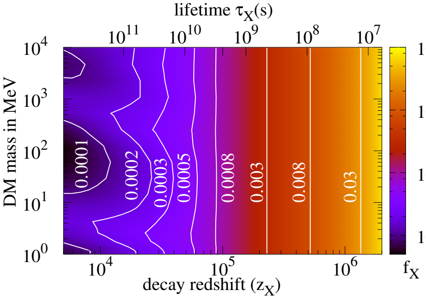
photon channel *Acharya and Khatri 2019b*



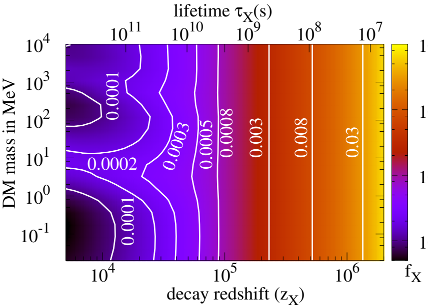
CMB spectral distortions are sensitive to the mass of decaying particle as well as the lifetime

COBE Constraints *Acharya and Khatri 2019b*

electron-positron channel

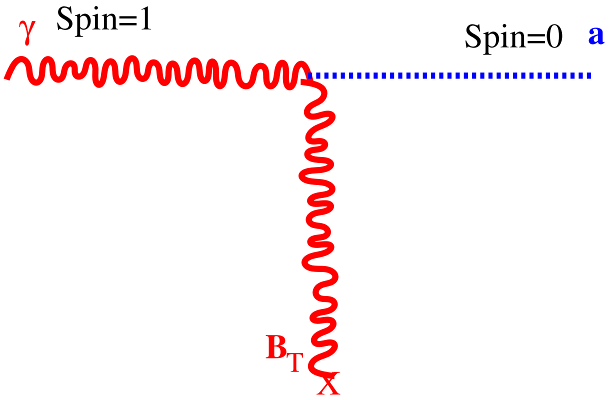


photon channel

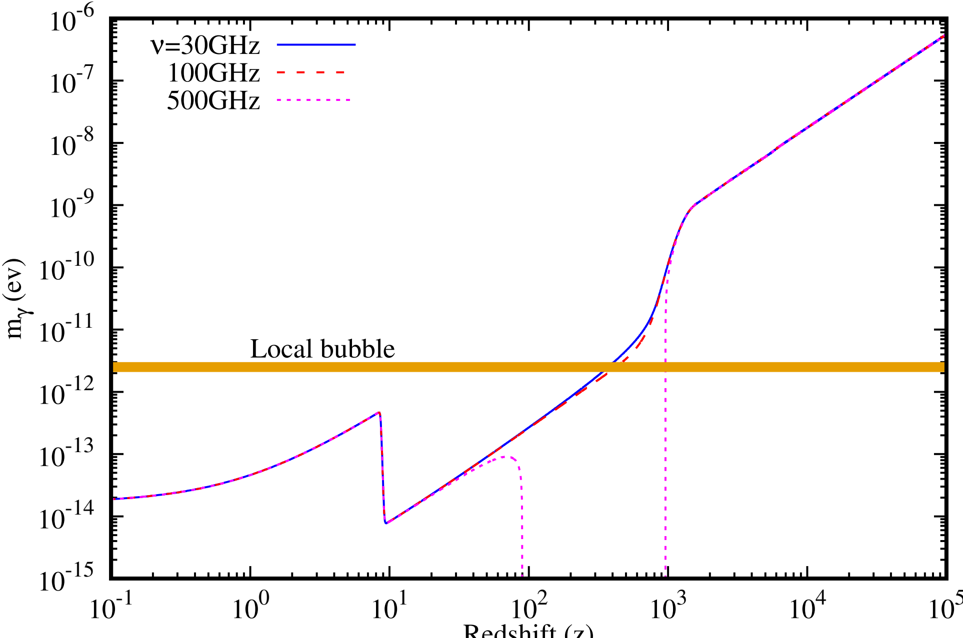


Photon-axion conversion

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

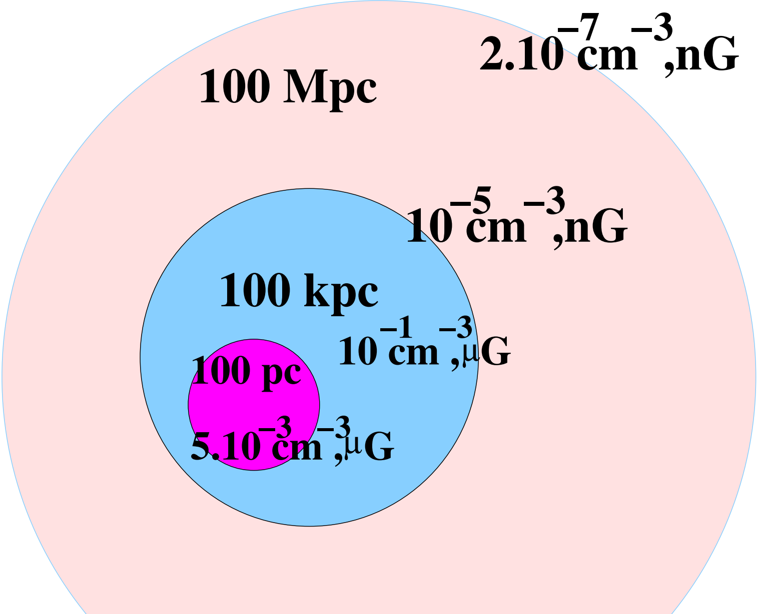


Evolution of the effective mass of the photon



Photon-axion conversion in MilkyWay magnetic field

Mukherjee, Khatri & Wandelt 2017 (n_{e}, B)



$2.10^{-7}\,\mathrm{cm}^{-3}$,nG

100 Mpc

$10^{-5}\,\mathrm{cm}^{-3}$,nG

100 kpc

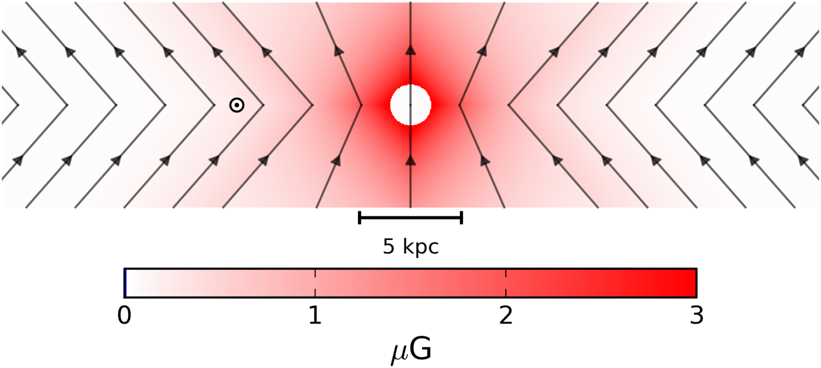
$10^{-1}\,\mathrm{cm}^{-3}$,$\mu$G

100 pc

$5.10^{-3}\,\mathrm{cm}^{-3}$,$\mu$G

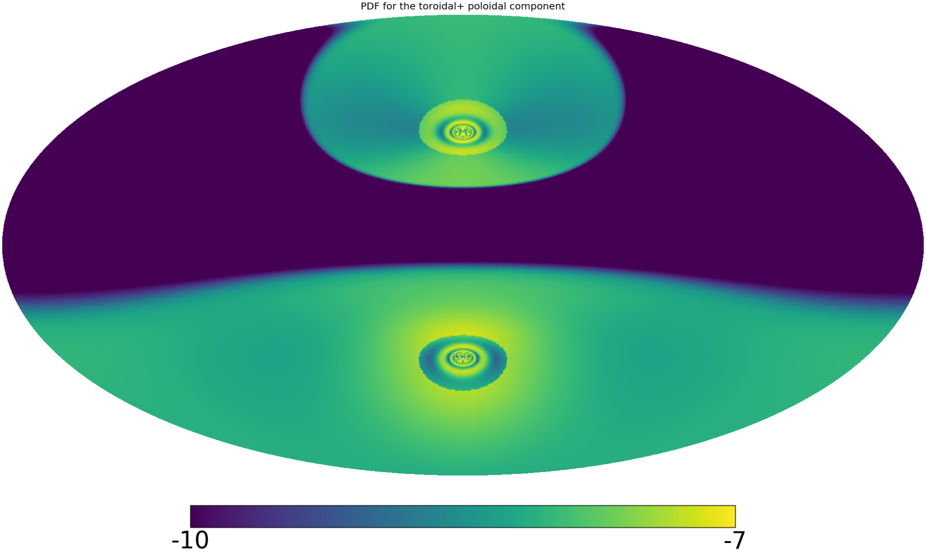
Galactic magnetic field: Poloidal field

Jansson& Farrar 2012



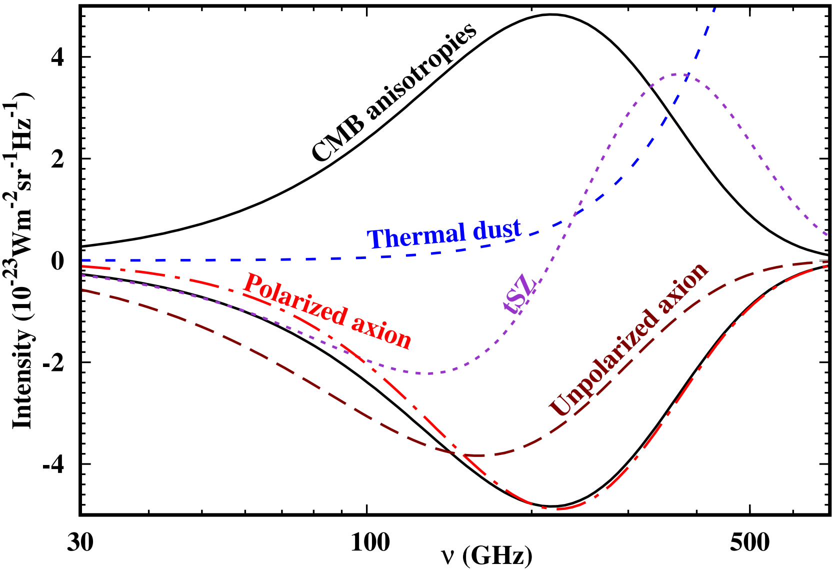
Axion distortions: Polarized & Anisotropic

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



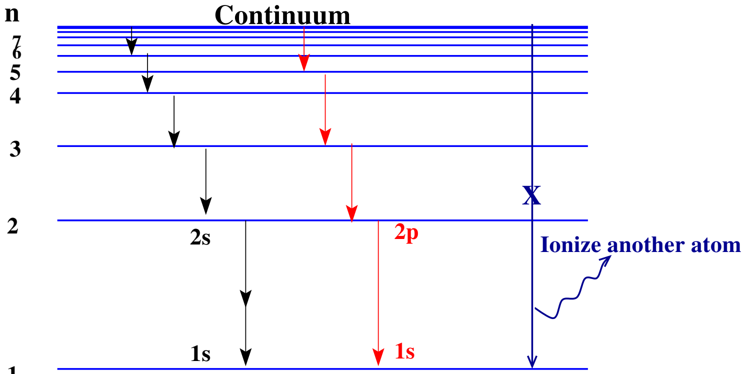
Axion distortions: Polarized & Anisotropic

Mukherjee, Khatri & Wandelt 2017



Cosmological recombination cascade

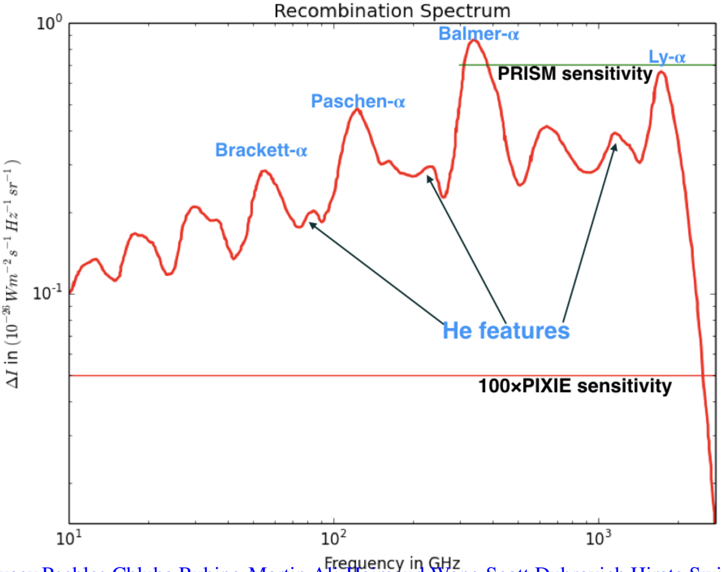
Several photons are emitted as electrons cascades down to the ground state



Recombination cascade

Cosmological recombination spectrum

Calculation by Debajyoti Sarkar



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

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

Future: Many orders of magnitude improvement in next decade
PIXIE (NASA), LiteBIRD (JAXA), ECHO (CMB-Bharat,ISRO India), CORE (ESA), PICO (NASA), PRISTINE (ESA)...