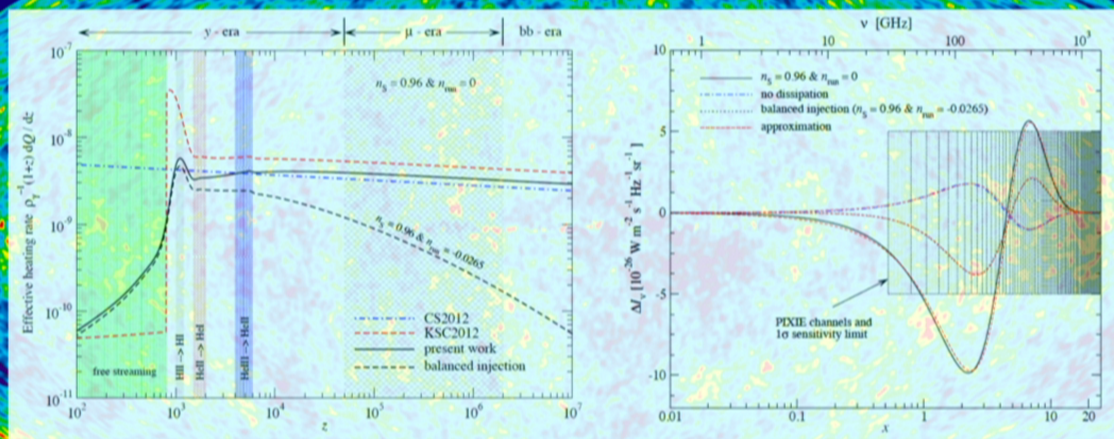
Title: Spectral distortions of the CMB and what we might learn about early universe physics

Date: Sep 11, 2012 11:00 AM

URL: http://pirsa.org/12090060

Abstract: The spectrum of the cosmic microwave background (CMB) is known to be extremely close to a perfect blackbody. However, even within standard cosmology several processes occurring in the early Universe lead to distortions of the CMB at a level that might become observable in the future. This could open an exciting new window to early Universe physics. In my talk I will then explain in more detail why the cooling of matter in the early Universe causes a negative mu- and y-type distortion and how the damping of primordial small-scale perturbations before recombination could allow placing interesting constraints on different inflationary models.

Spectral Distortions of the CMB and What We Might Learn About Early Universe Physics



CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

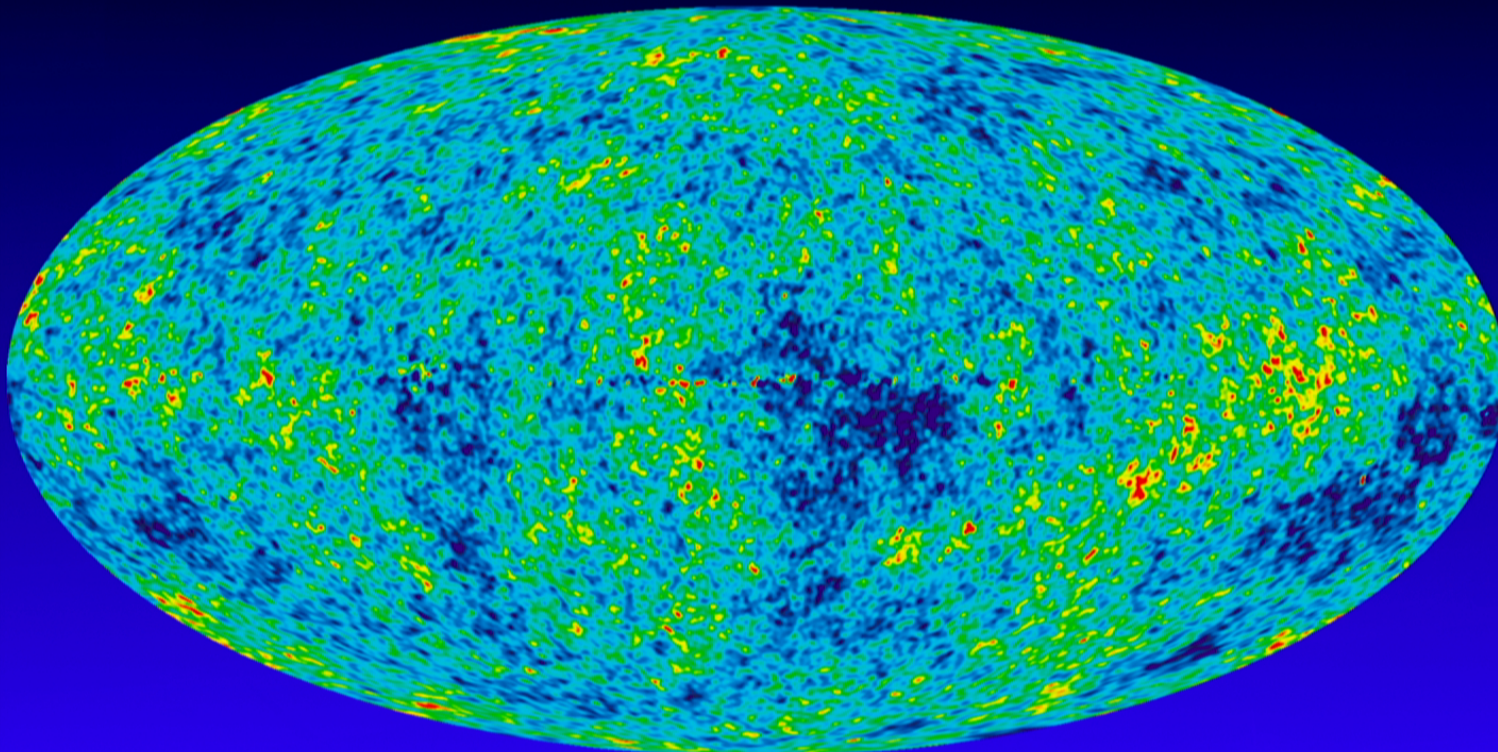
Jens Chluba

Cosmology Seminar

Sept. 11, 2012, Perimeter Institute, Waterloo

Collaborators: ***R.A. Sunyaev & Rishi Khatri (MPA) and Adrienne Erickcek & Ido Ben-Dayan (CITA)***

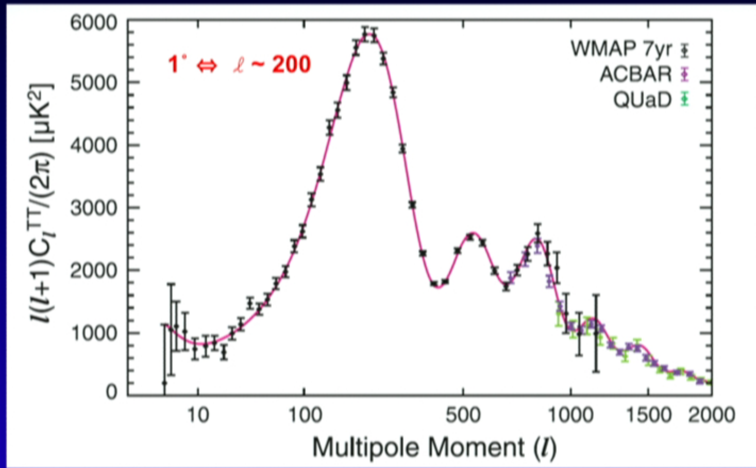
Cosmic Microwave Background Anisotropies

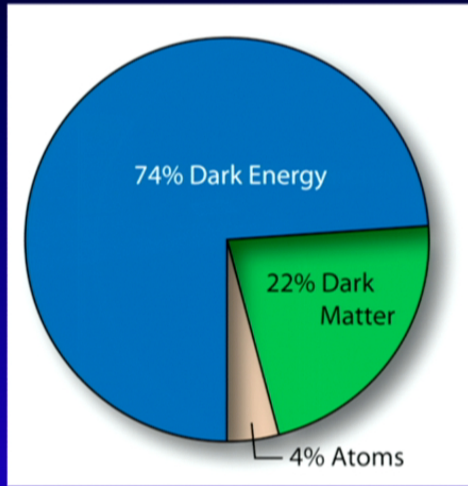


Example: WMAP-7

- CMB has a blackbody spectrum in every direction
- Variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

CMB anisotropies clearly have helped us a lot to learn about the Universe we live in!



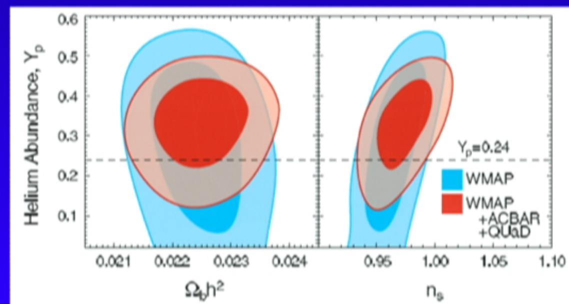


Precision cosmology — **Tiny error bars!**

TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.
[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).
[e] The present-day age of the universe.



e.g. Komatsu et al., 2011, ApJ, arXiv:1001.4538v1
Dunkley et al., 2011, ApJ, arXiv:1009.0866v1

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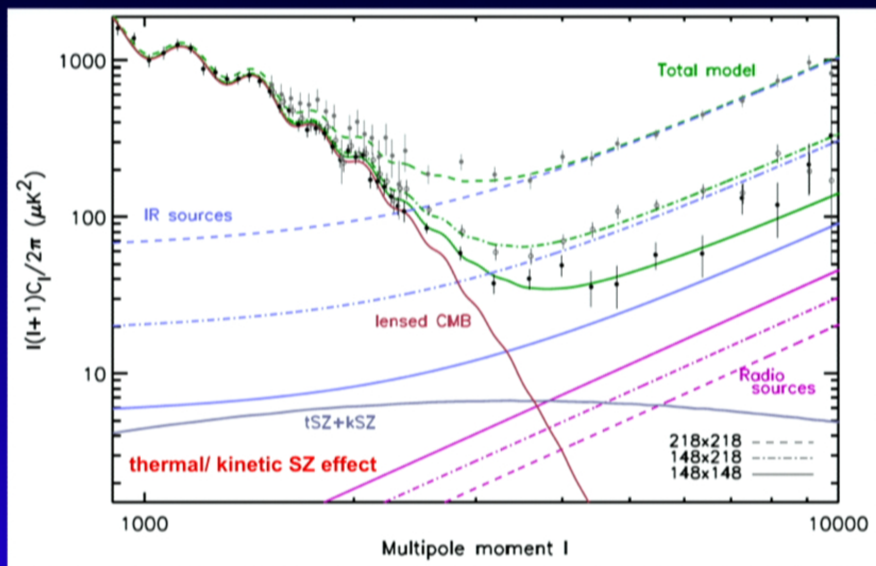

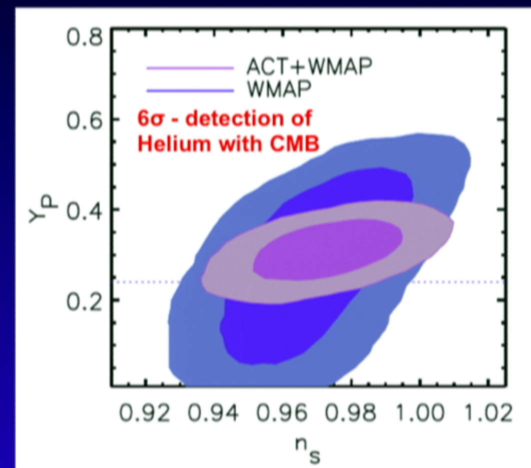

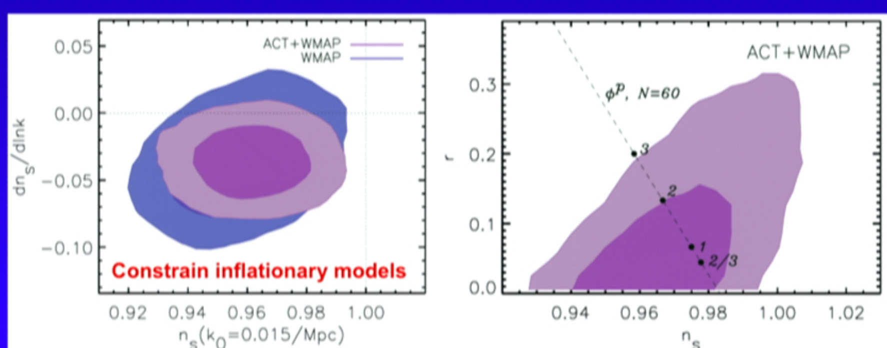

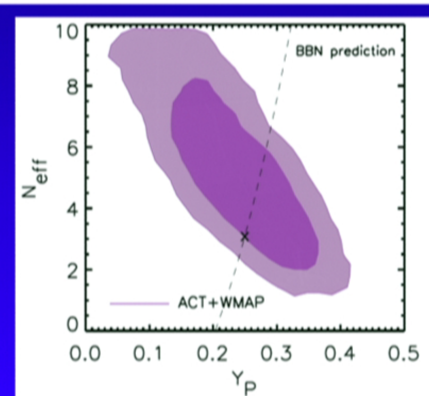

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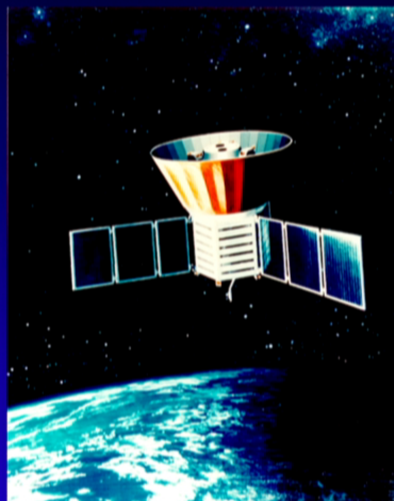
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

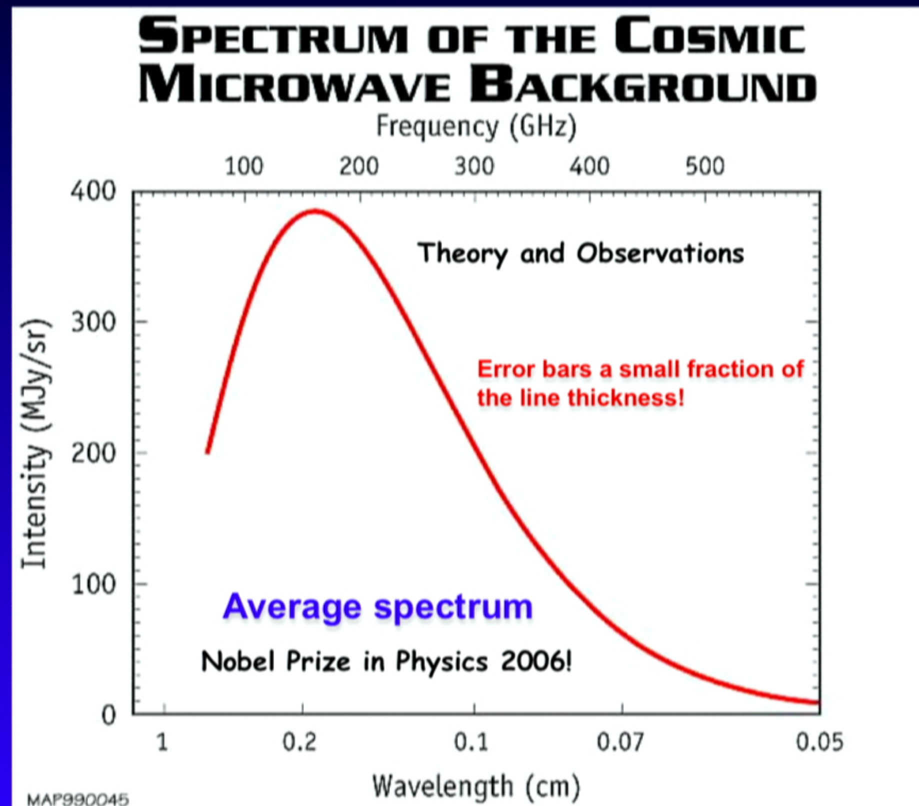


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \le 1.5\times10^{-5}$$

$$|\mu| \le 9\times10^{-5}$$

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67



Only very small distortions of CMB spectrum are still allowed!

Why should one expect some spectral distortion?

Full thermodynamic equilibrium (certainly valid at very high redshift)

- CMB has a blackbody spectrum at every time (not affected by expansion)
- Photon number density and energy density determined by temperature T_γ
  - $T_\gamma \sim 2.725\,(1+z)$ K
  - $N_\gamma \sim 410\ \mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$
  - $\rho_\gamma \sim 5.1\times10^{-7}\,m_e c^2\ \mathrm{cm}^{-3}\,(1+z)^4 \sim \rho_b \times (1+z)/925$

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Perturbing full equilibrium by

- Energy injection (*matter* ←→ *photons*)
- Production of energetic photons and/or particles (i.e. change of entropy)

→ CMB spectrum deviates from a pure blackbody

→ thermalization process (partially) erases distortions

(Compton scattering, double Compton and Bremsstrahlung in the expanding Universe)

Physical mechanisms that lead to release of energy

- *Cooling by adiabatically expanding ordinary matter*: $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
  - continuous *cooling* of photons until redshift z~150 via Compton scattering
  - due to huge heat capacity of photon field distortion very small ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)
- *electron-positron annihilation and BBN* (z~ 10^8-10^9)
  - too early to leave some important traces (completely thermalized)
- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, neutrino fraction, (at low redshifts: environments), ...
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012)
  - rather fast, quasi-instantaneous energy release
- *Dissipation of primordial acoustic modes*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994)
- *Cosmological recombination* — „high" redshifts

„low" redshifts

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; Effects of Reionization (Heating of medium by X-Rays, Cosmic Rays, etc)

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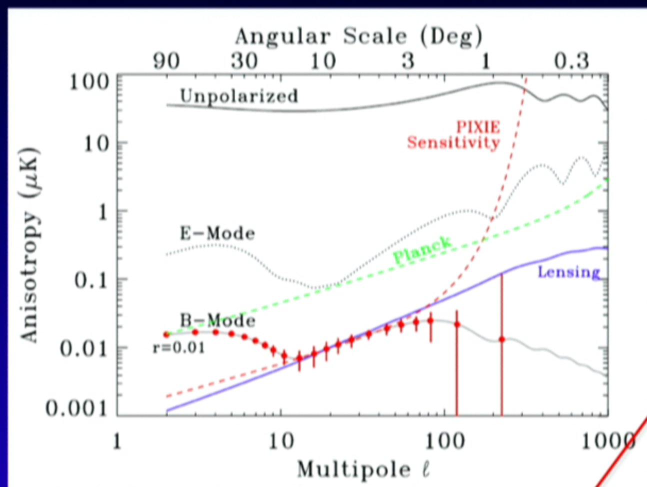
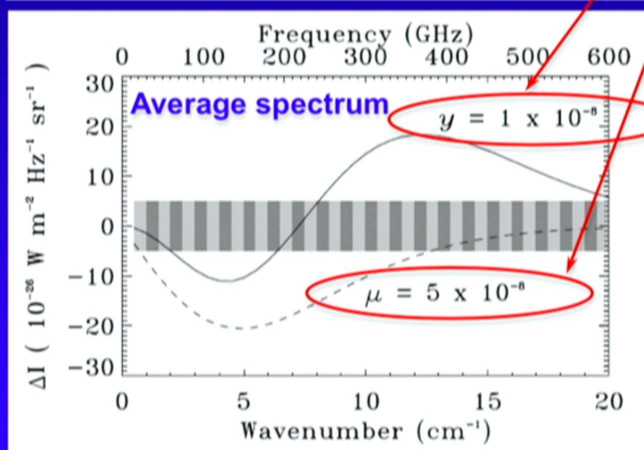
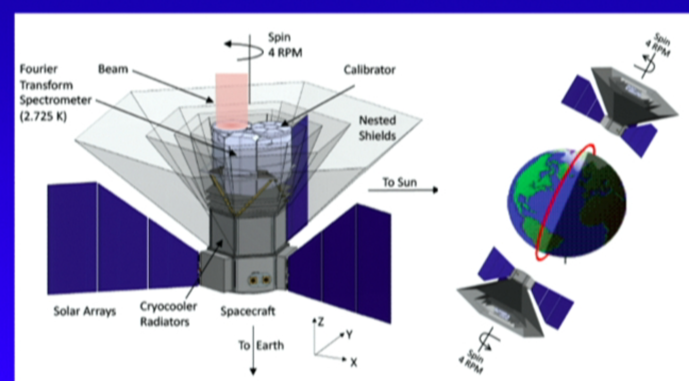
PIXIE: Primordial Inflation Explorer



- 400 spectral channel in the frequency range 30 GHz and 6THz ($\Delta\nu \sim$ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~120-180M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044

How does the thermalization process work?

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Some important conditions

- Plasma fully ionized before recombination
  - → free electrons, protons and helium nuclei
  - → photon dominated (~2 Billion photons per baryon)
- Coulomb scattering $e + p \leftrightarrow e' + p$
  - → electrons in full thermal equilibrium with baryons
  - → electrons follow thermal Maxwell-Boltzmann distribution
  - → efficient down to very low redshifts (z ~ 10)

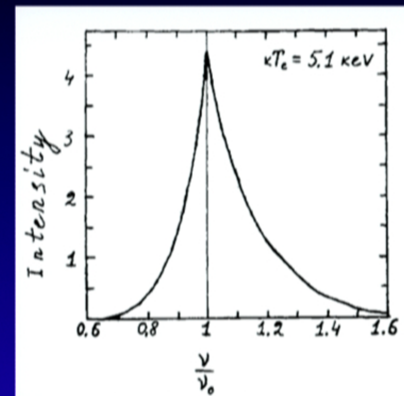
Redistribution of photons by Compton scattering

- Compton scattering $e + \gamma \leftrightarrow e' + \gamma'$

  → *redistribution* of photons in frequency

  - up-scattering due to the ***Doppler*** effect for $h\nu < 4kT_e$
  - down-scattering because of ***recoil*** (and stimulated recoil) for $h\nu > 4kT_e$
  - ***Doppler*** broadening $\frac{\Delta\nu}{\nu} \simeq \sqrt{\frac{2kT_e}{m_e c^2}}$

  → strongly couples (free) electrons to the CMB photon down to redshifts z~150

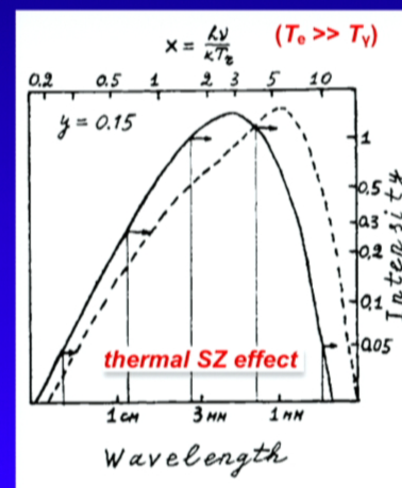


- *Kompaneets Equation* → 'pure' ***y*-distortion**

$$\frac{\Delta I_\nu}{I_\nu} \simeq y \, \frac{x e^x}{e^x - 1} \left[x \frac{e^x + 1}{e^x - 1} - 4 \right],$$

Temperature difference

where $x = \frac{h\nu}{kT_\gamma}$ and $y = \int \frac{k(T_e - T_\gamma)}{m_e c^2} \sigma_T n_e \mathrm{d}l << 1$



Sunyaev& Zeldovich, 1980, Ann. Rev. Astr. Astrophy., 18, pp.537

Adjusting the photon number

- Bremsstrahlung $e + p \leftrightarrow e' + p + \gamma$
  - → 1. order α correction to *Coulomb* scattering
  - → production of low frequency photons
  - → important for the evolution of the distortion at low frequencies and late times ($z < 2 \times 10^5$)
- Double Compton scattering
  (Lightman 1981; Thorne, 1981)
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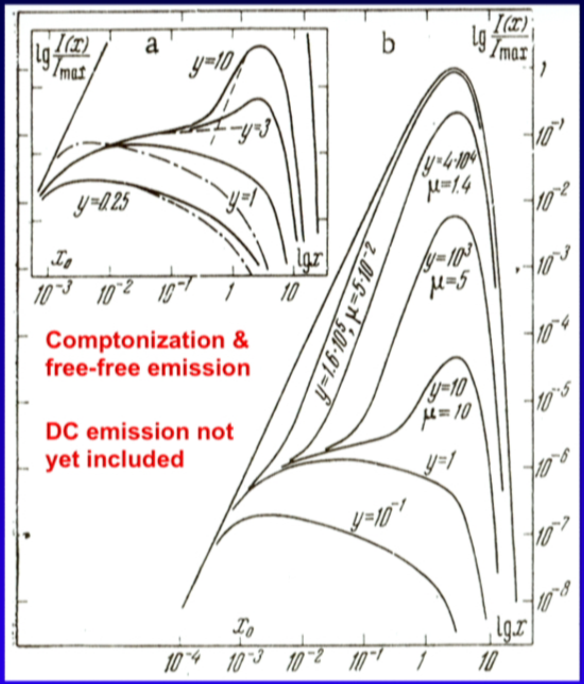

Illarionov & Sunyaev, 1975, Sov. Astr, 18, pp.413

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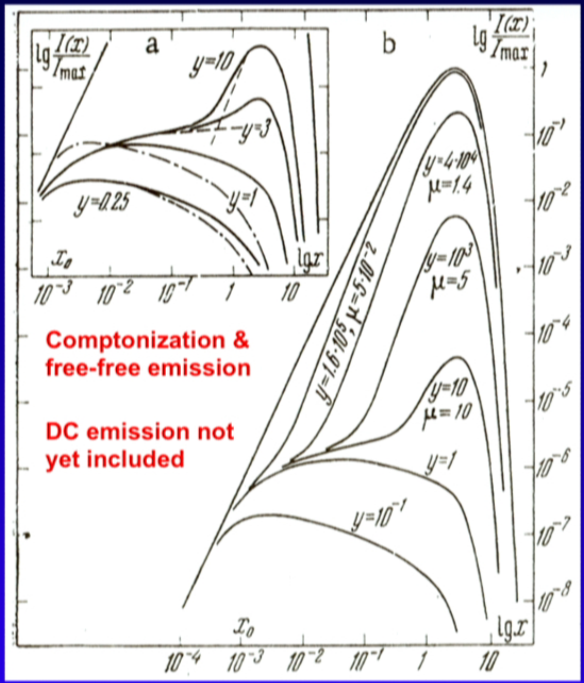

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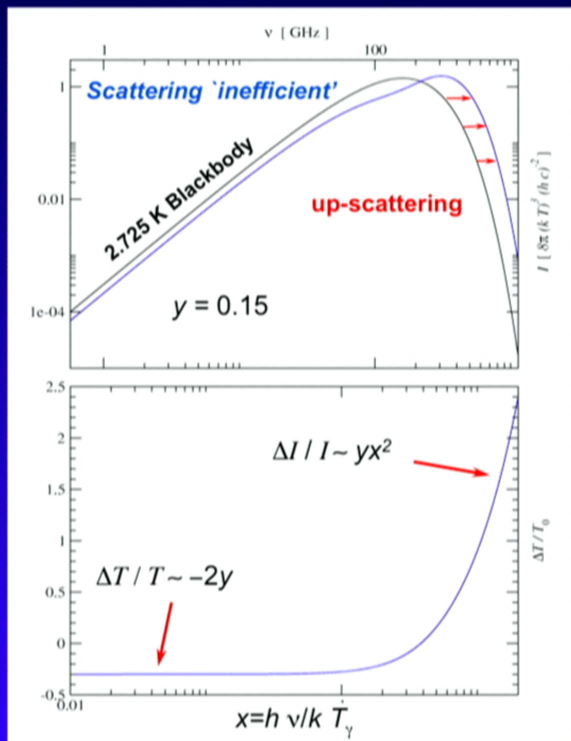
Compton *y* and chemical potential (μ) distortions

'Late' Energy Release ($z \lesssim 50000$)

→ y-type spectral distortion



Zeldovich & Sunyaev, 1969, Ap&SS, 4, pp. 301

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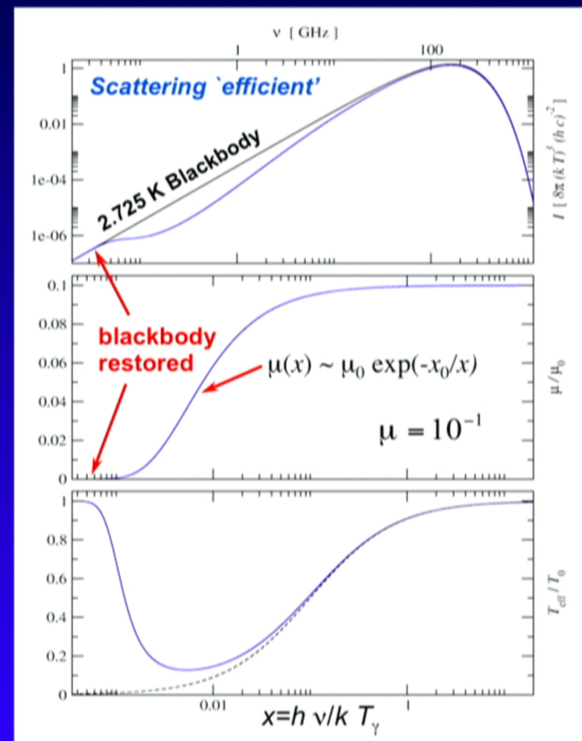

Sunyaev & Zeldovich, 1970, Ap&SS, 7, pp.20-30
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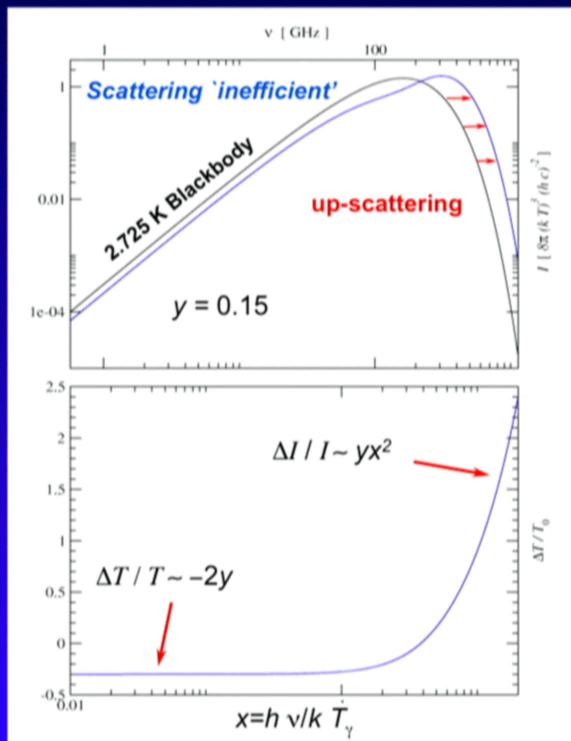

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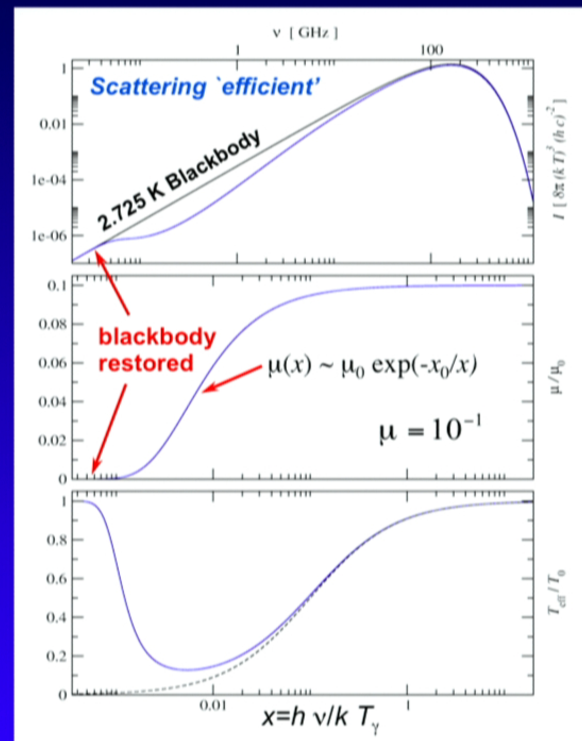

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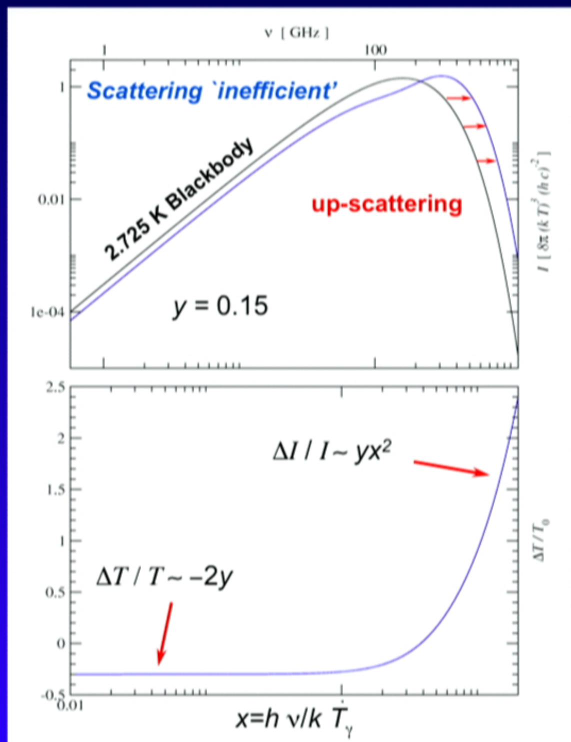

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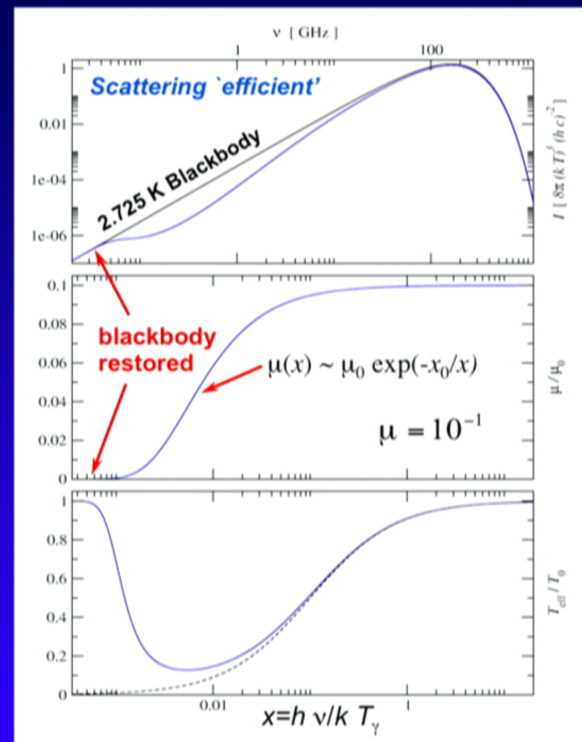

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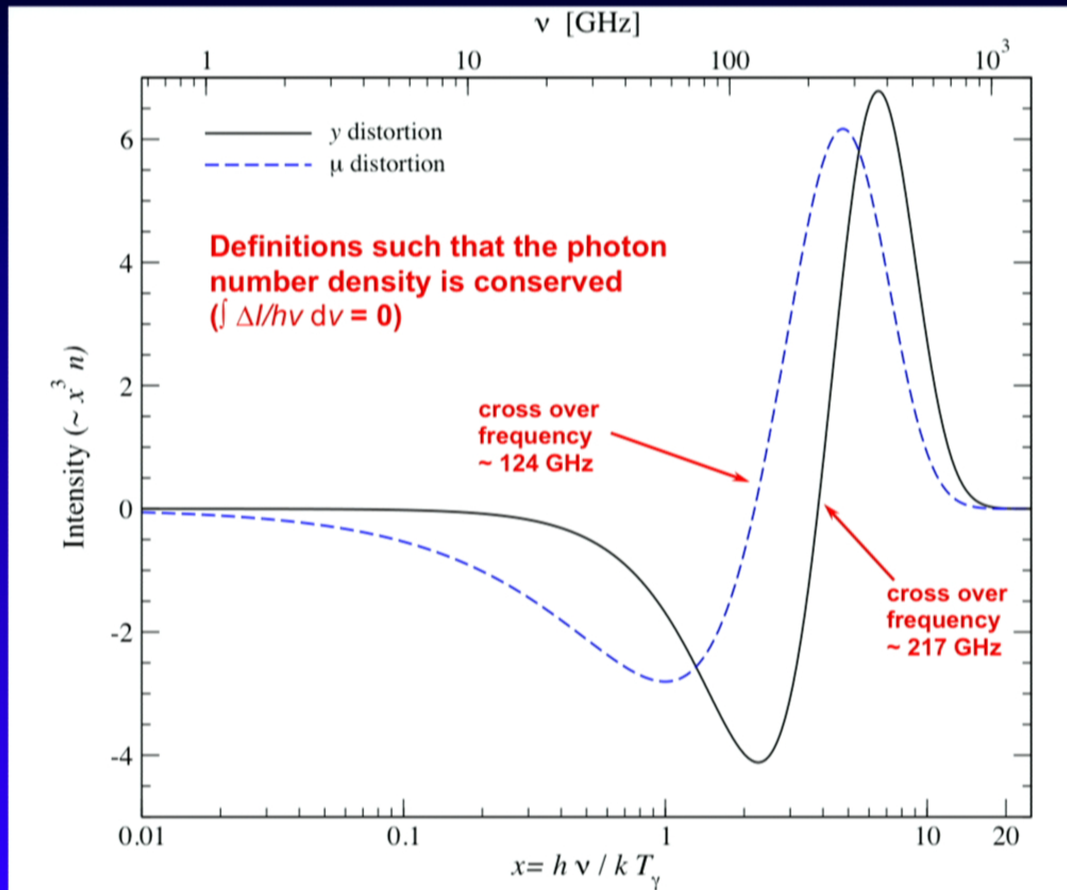
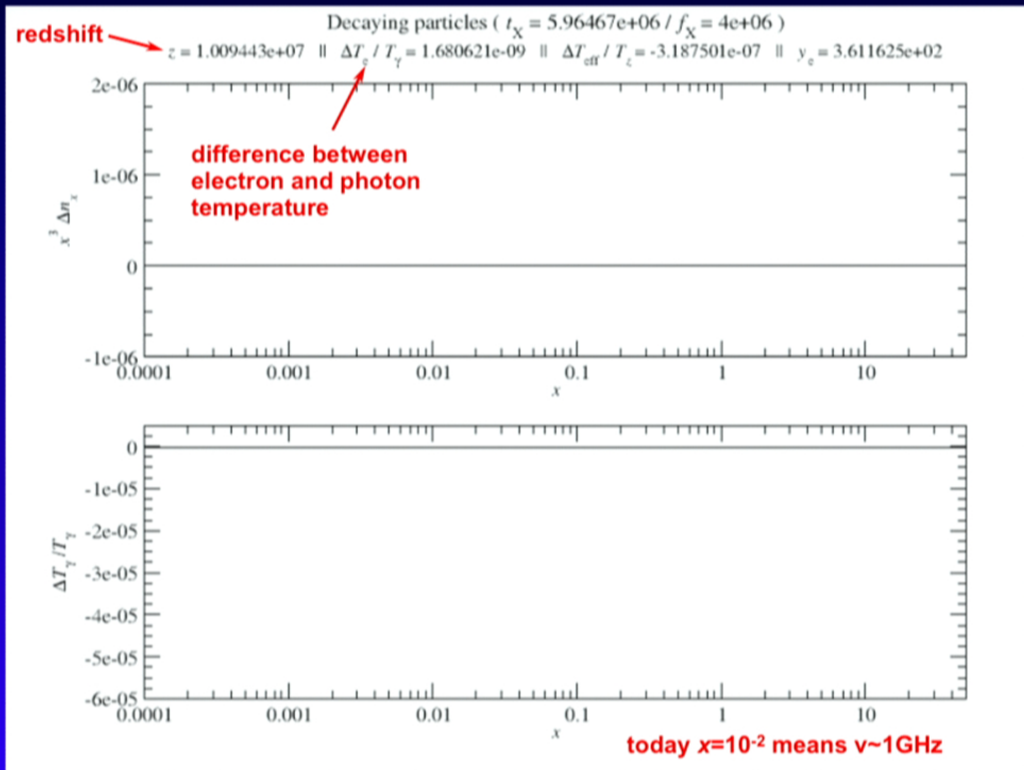
Comparison of *y* and μ distortion at high frequencies



Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3 \times 10^{-6}$
- most of energy release around: $z_X \sim 2 \times 10^6$
- positive μ-distortion
- late ($z<10^3$) free-free absorption at very low frequencies ($T_e<T_\gamma$)

Computation carried out with *CosmoTherm*
(JC & Sunyaev 2011)

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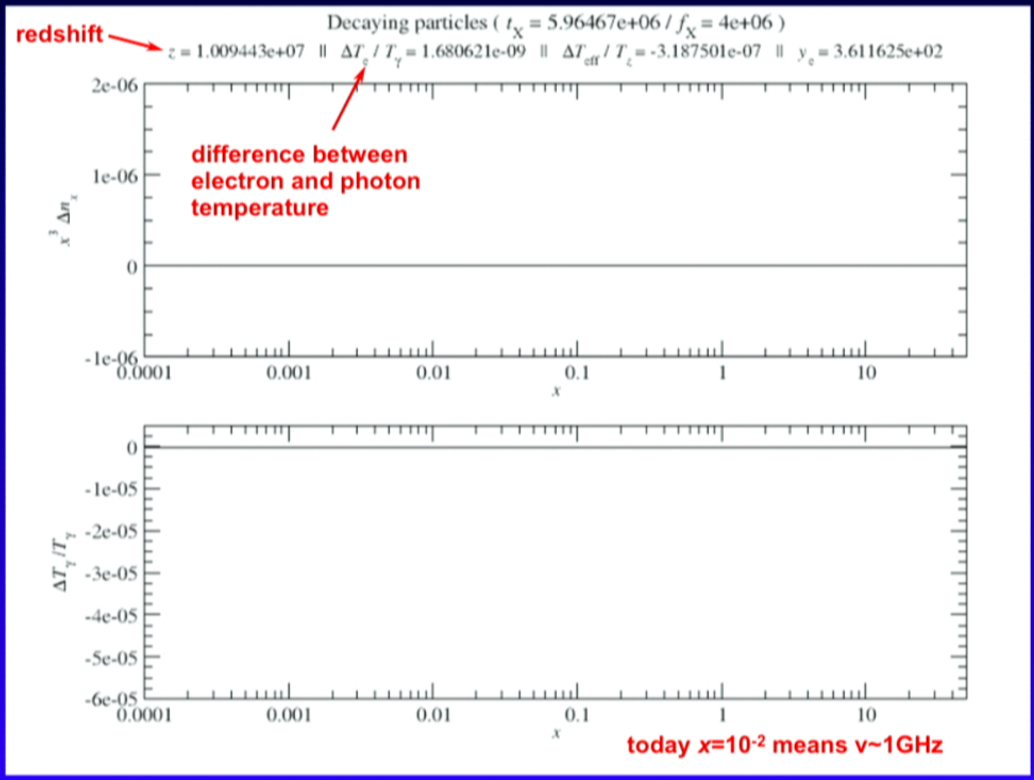

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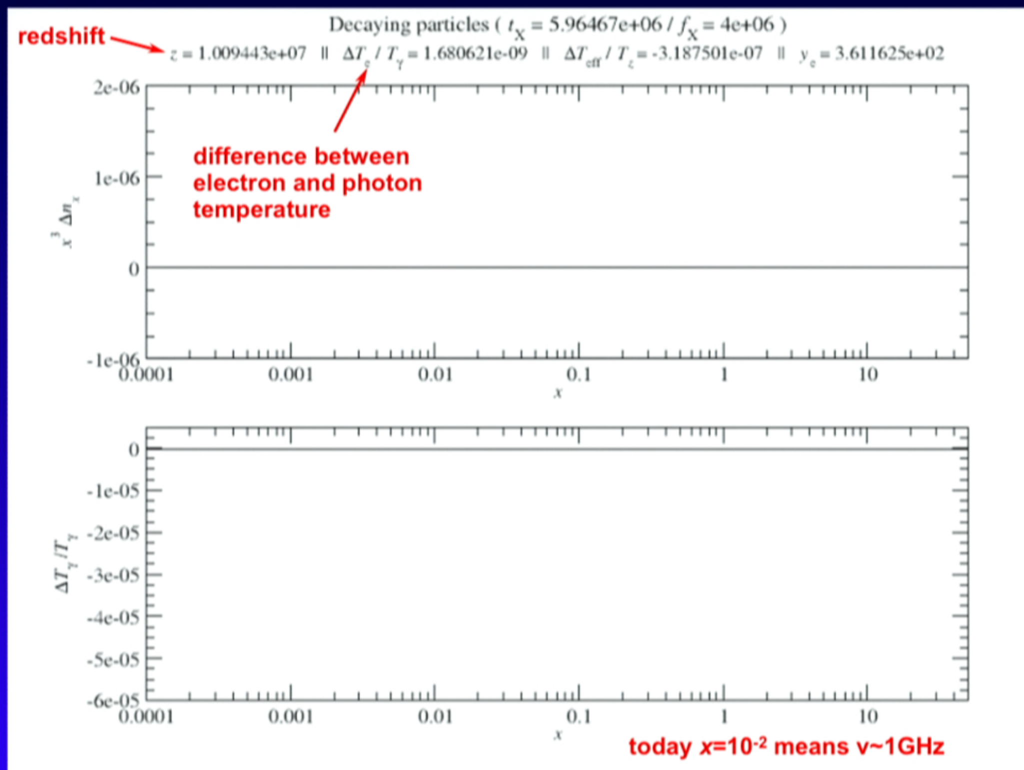

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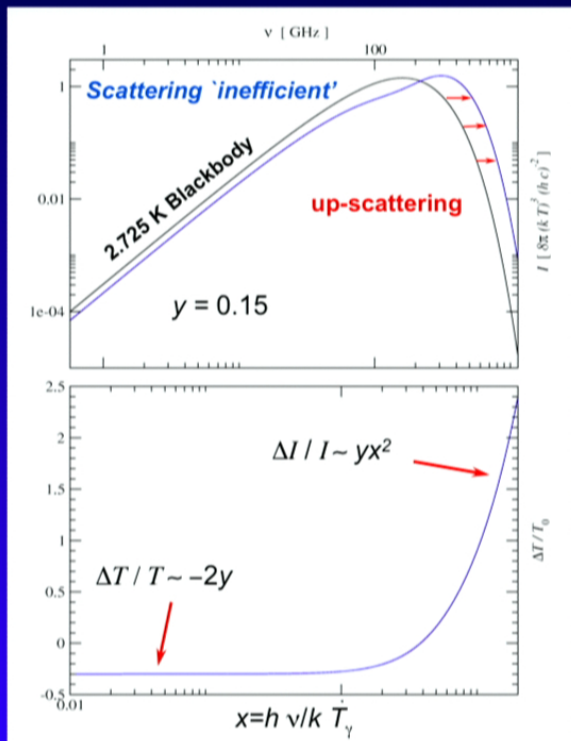
'Late' Energy Release ($z \lesssim 50000$)

→ y-type spectral distortion



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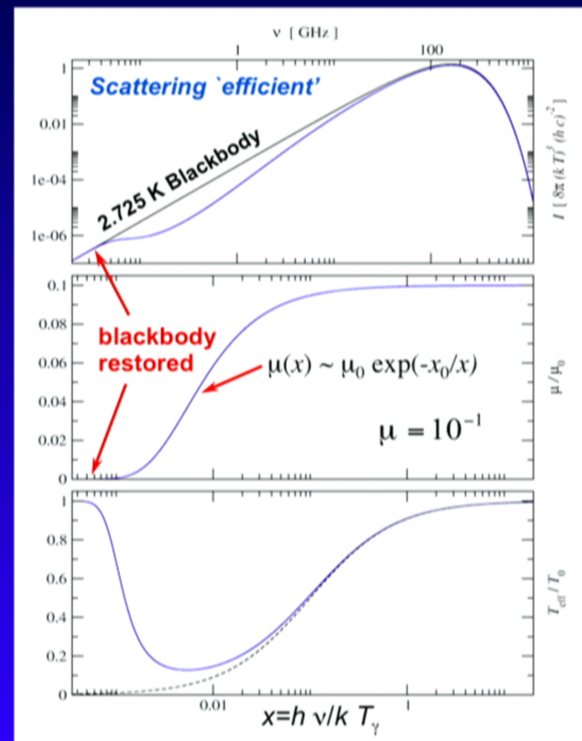

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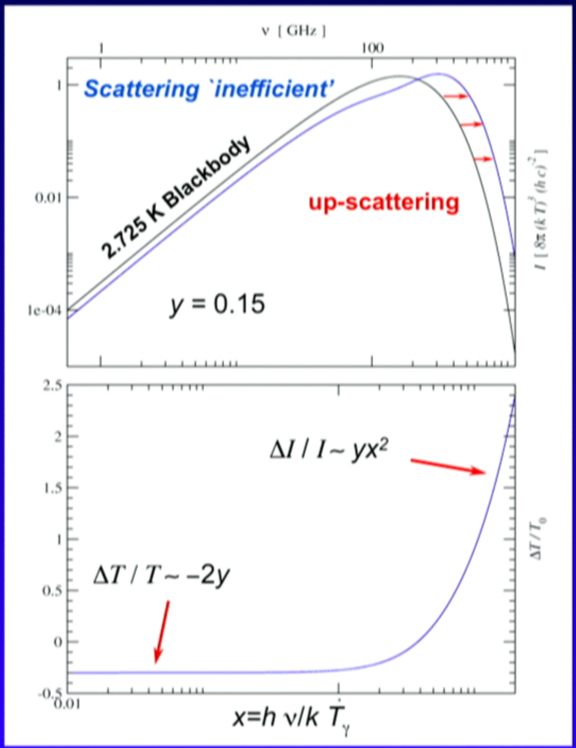

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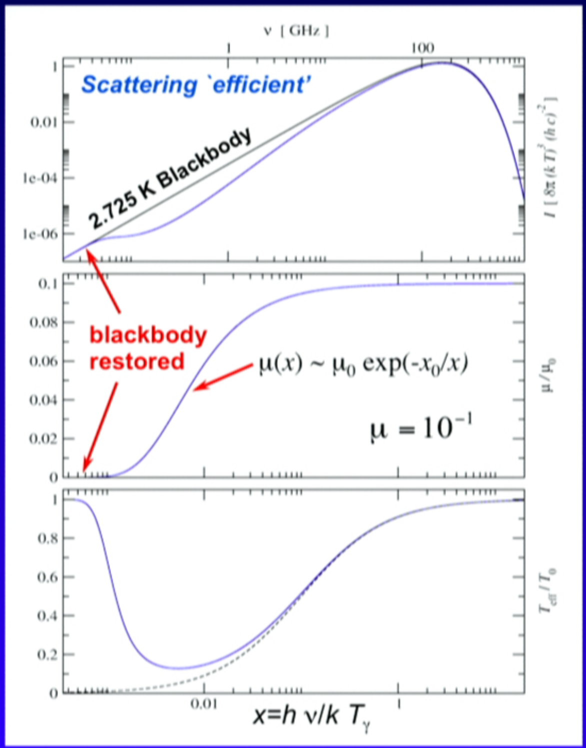

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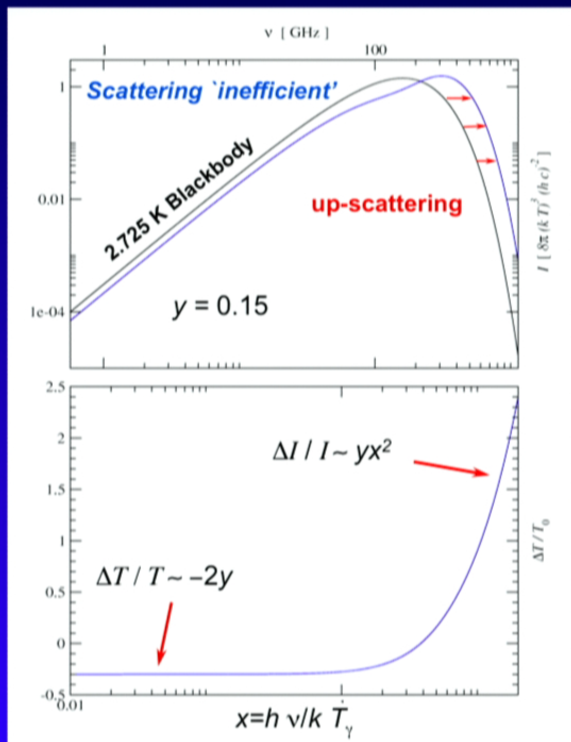
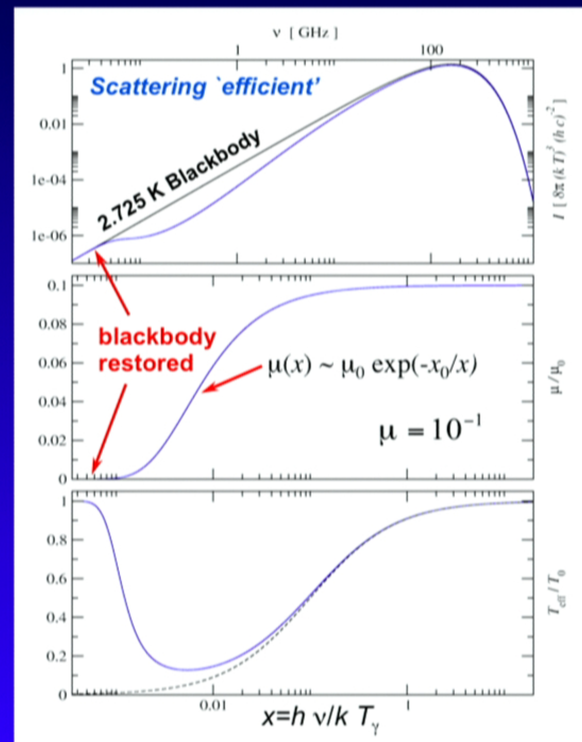


Zeldovich & Sunyaev, 1969, Ap&SS, 4, pp. 301

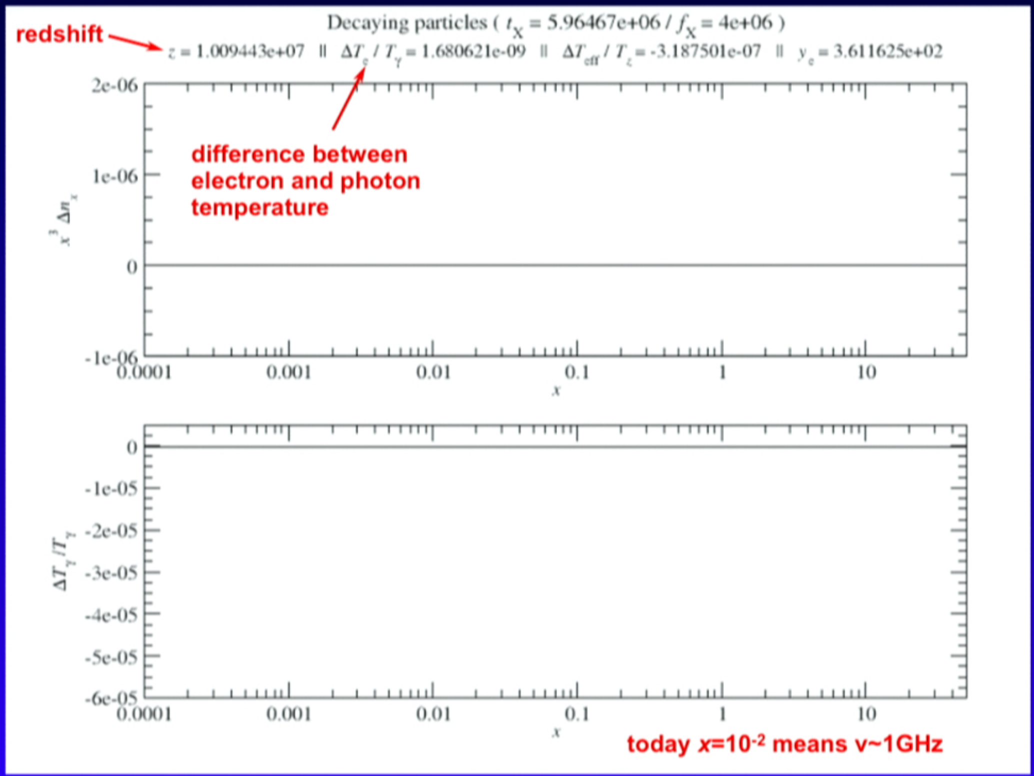
'Early' Energy Release ($z \gtrsim 50000$)

→ μ-type spectral distortion



Sunyaev & Zeldovich, 1970, Ap&SS, 7, pp.20-30
Illarionov & Sunyaev, 1975, Sov. Astr., 18, pp. 413
Danese & de Zotti, 1982, A&A, 107, 39-42

Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3\times10^{-6}$
- most of energy release around: $z_X \sim 2\times10^6$
- positive μ-distortion
- late ($z<10^3$) free-free absorption at very low frequencies ($T_e<T_\gamma$)

Computation carried out with *CosmoTherm*
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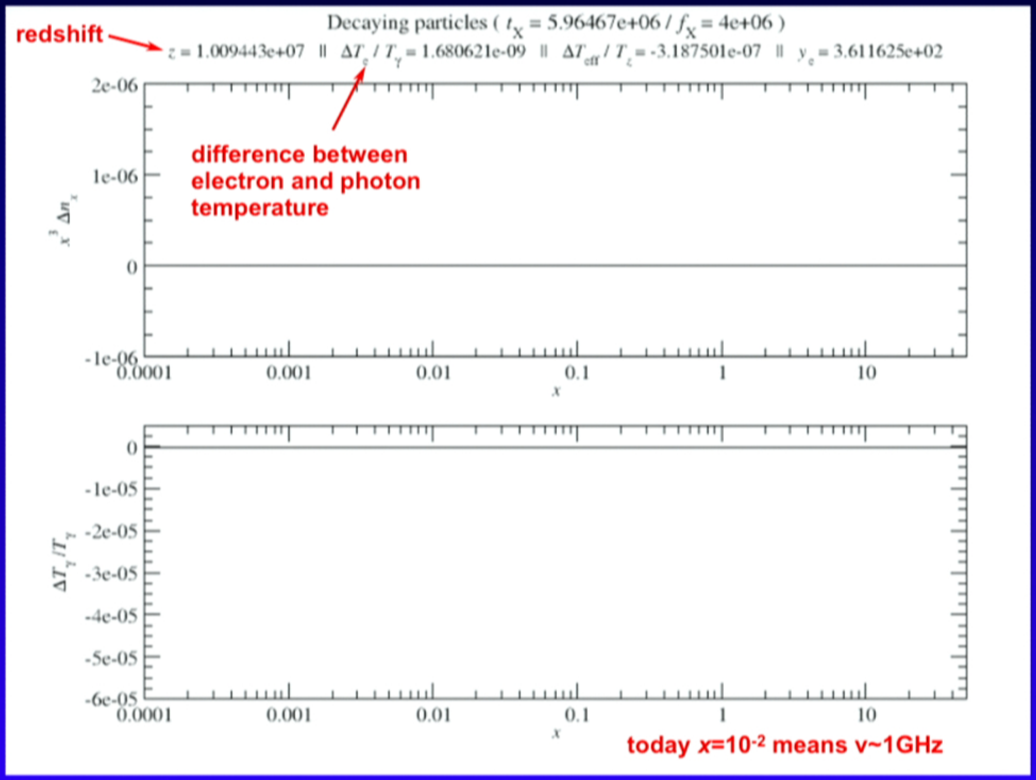

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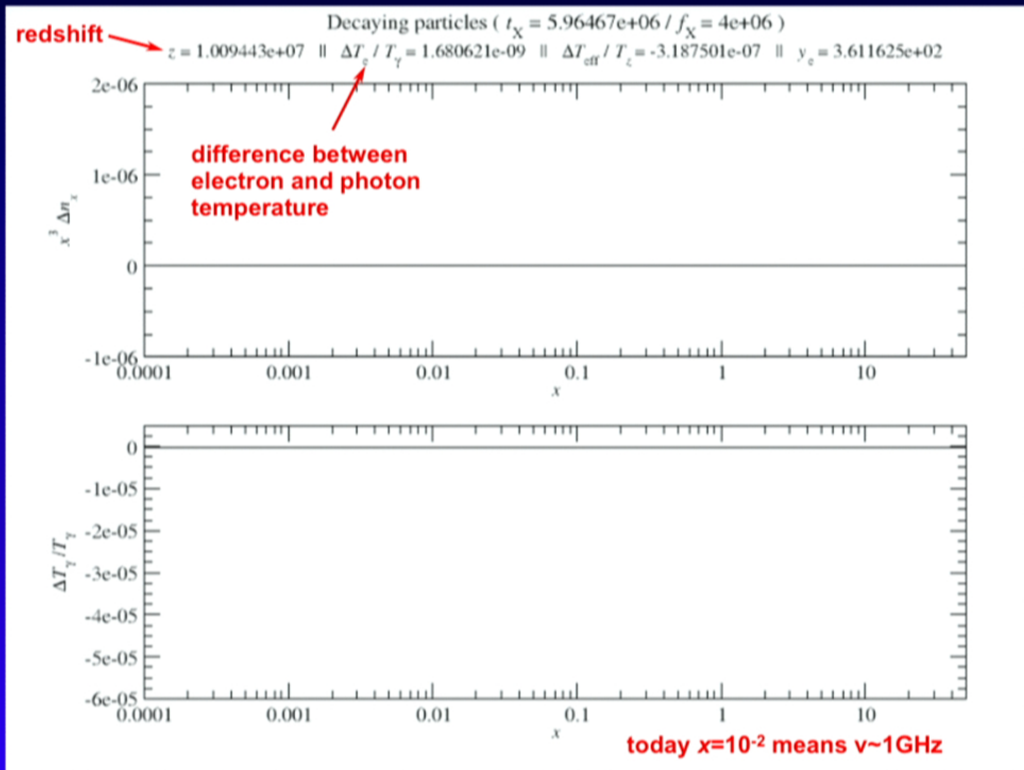

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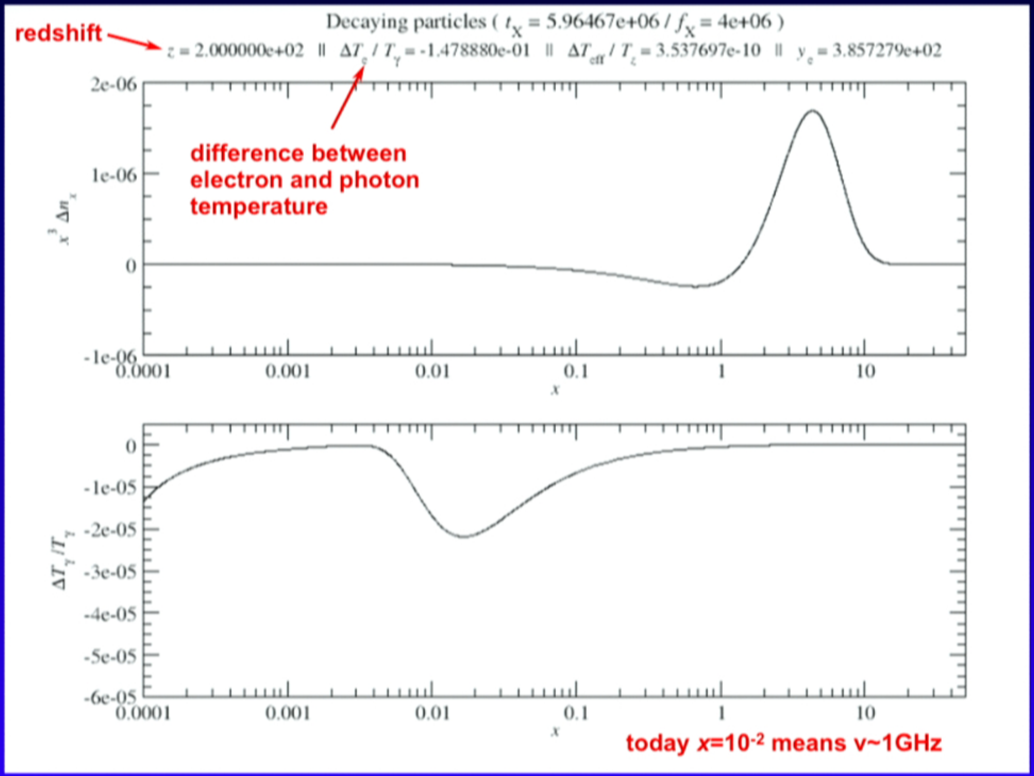

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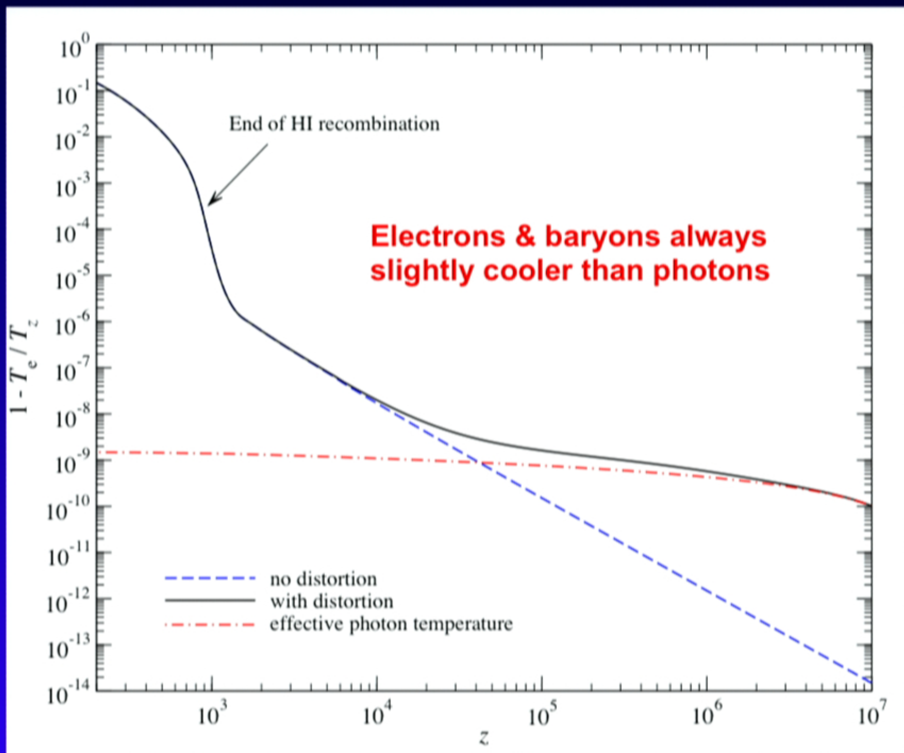
Spectral distortion caused by the cooling of ordinary matter



- adiabatic expansion

⇒ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as annihilation ($\propto N_X^2$)

⇒ cancellation possible

JC, 2005; JC & Sunyaev, 2012
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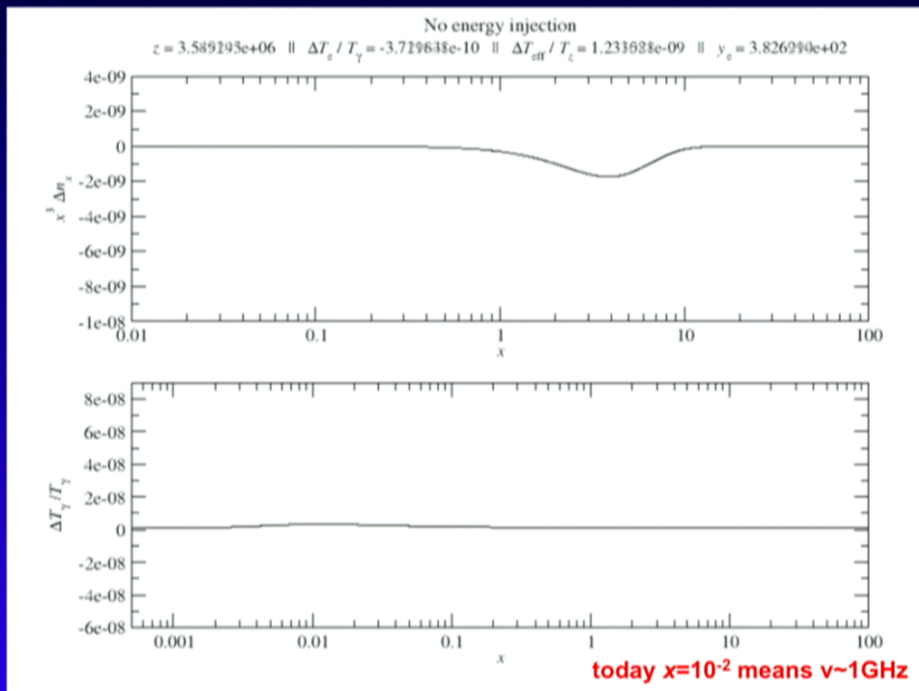

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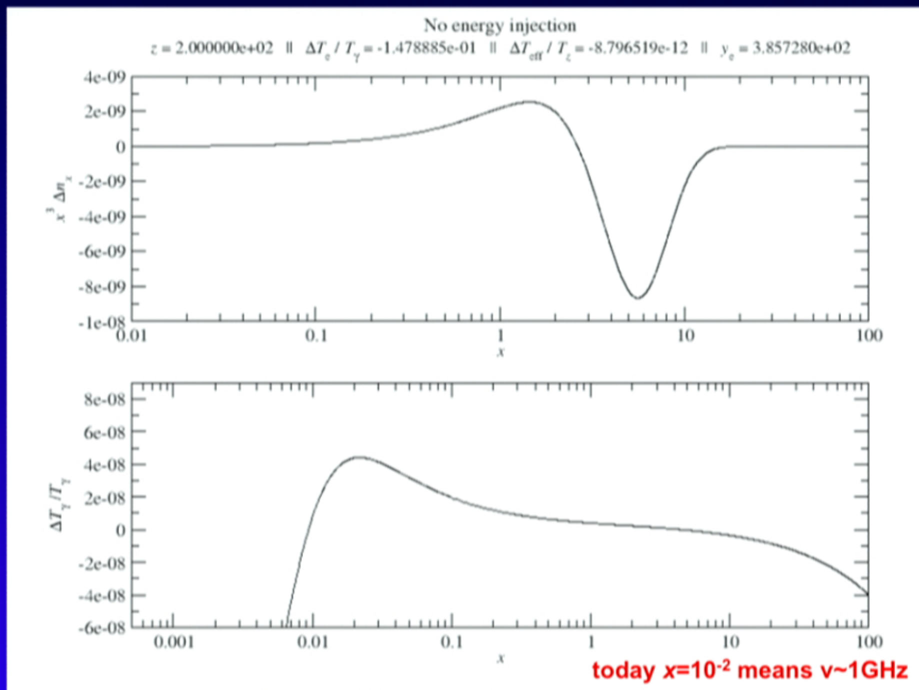

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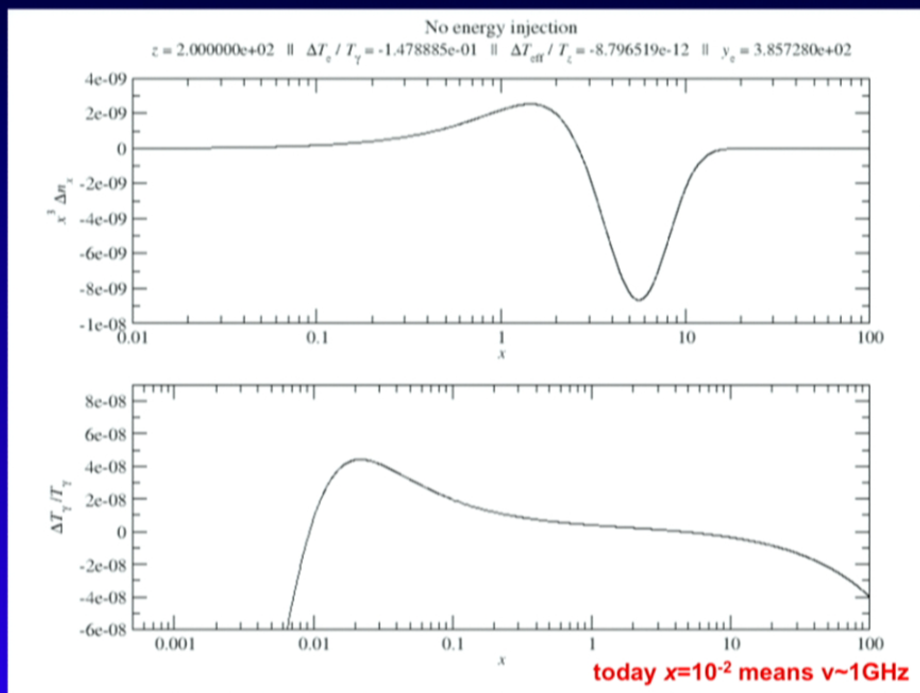

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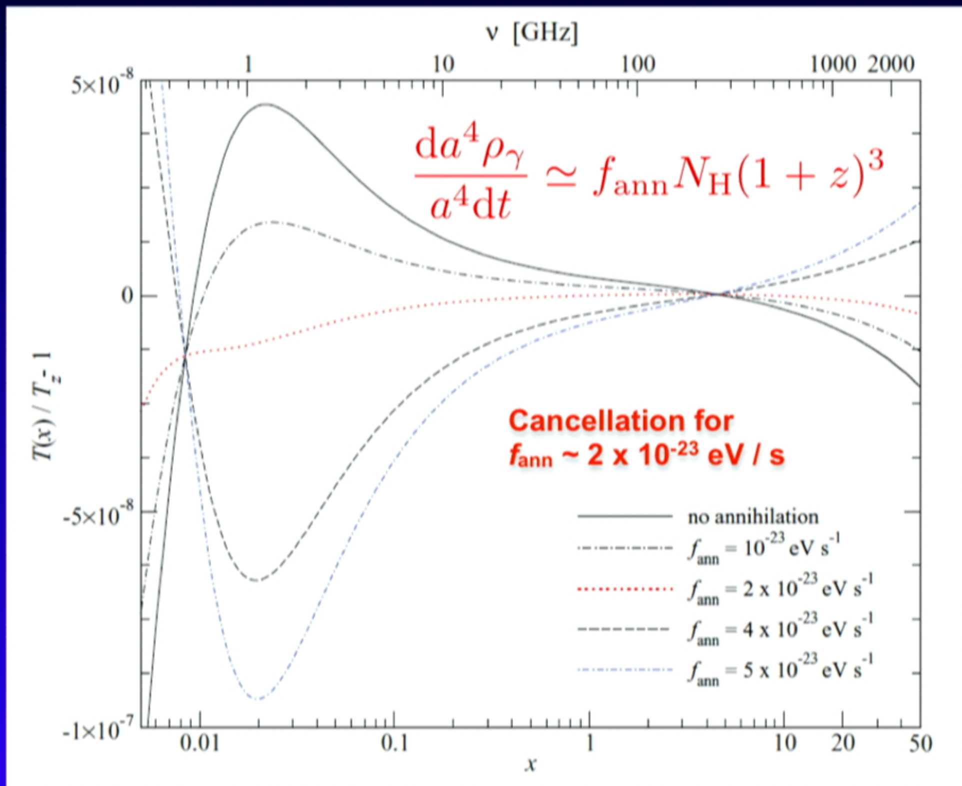
Cancellation of cooling by heating from annihilation



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  (Padmanabhan & Finkbeiner, 2005; JC 2010)
- CMB anisotropy constraint

  $$f_{\rm ann} \lesssim 2 \times 10^{-23} {\rm eV s^{-1}}$$

  (Galli et al., 2009; Slatyer et al., 2009; Huetsi et al., 2009, 2011)
- Limit from Planck satellite will be roughly *6 times stronger* → more precise prediction for the distortion will be possible
- uncertainty dominated by particle physics
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JC & Sunyaev, 2012

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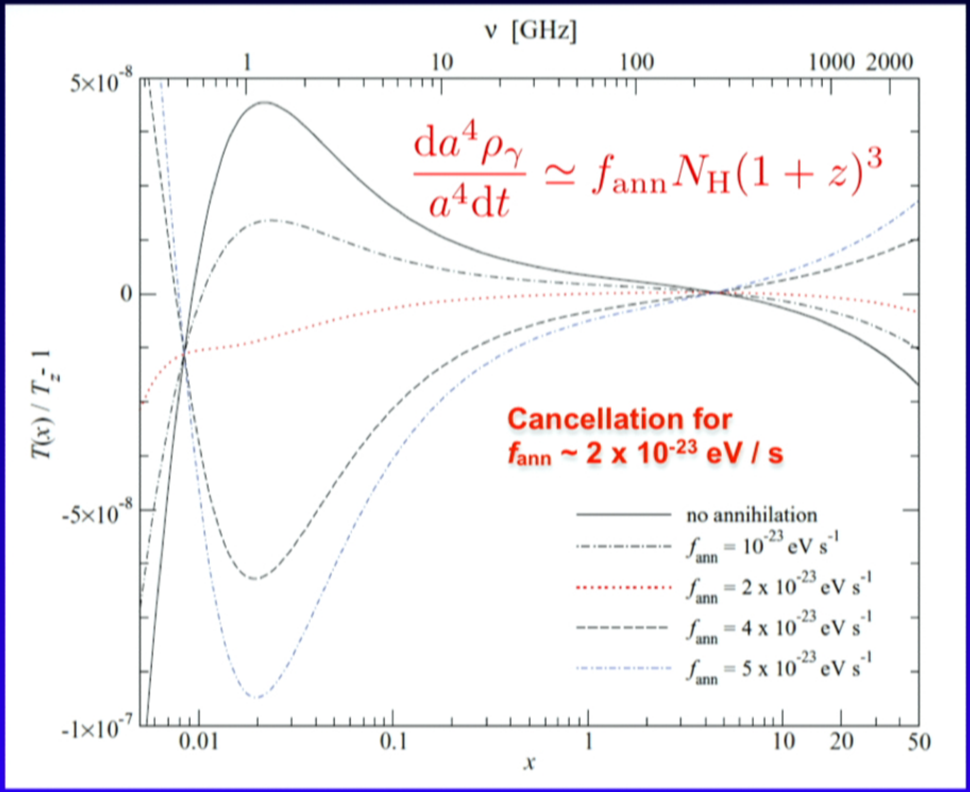

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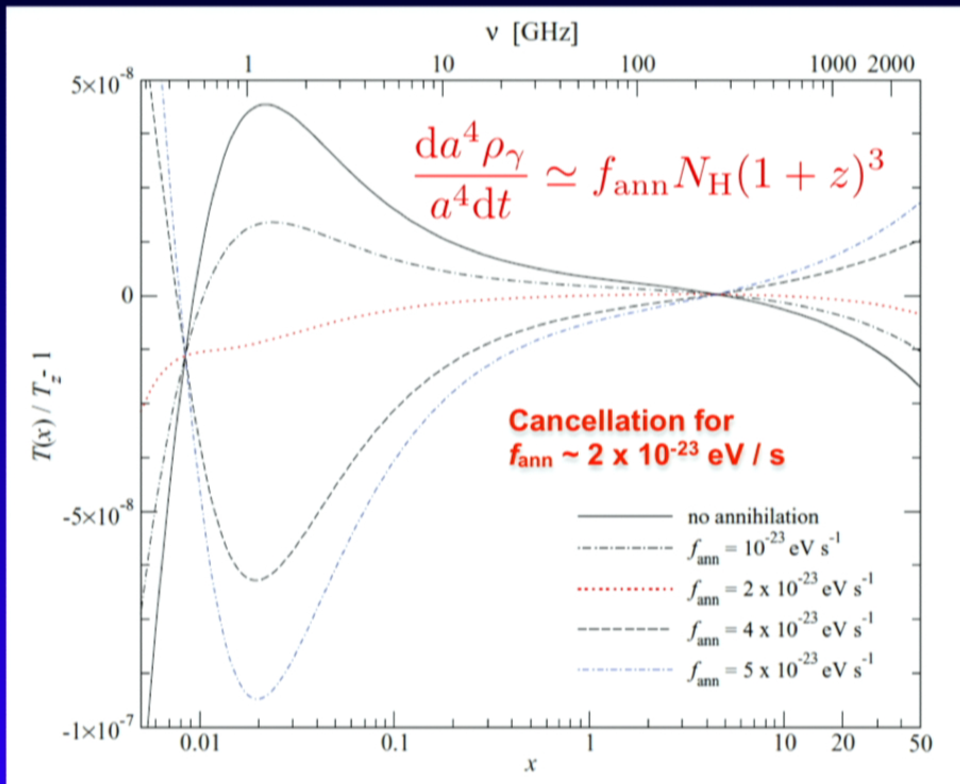

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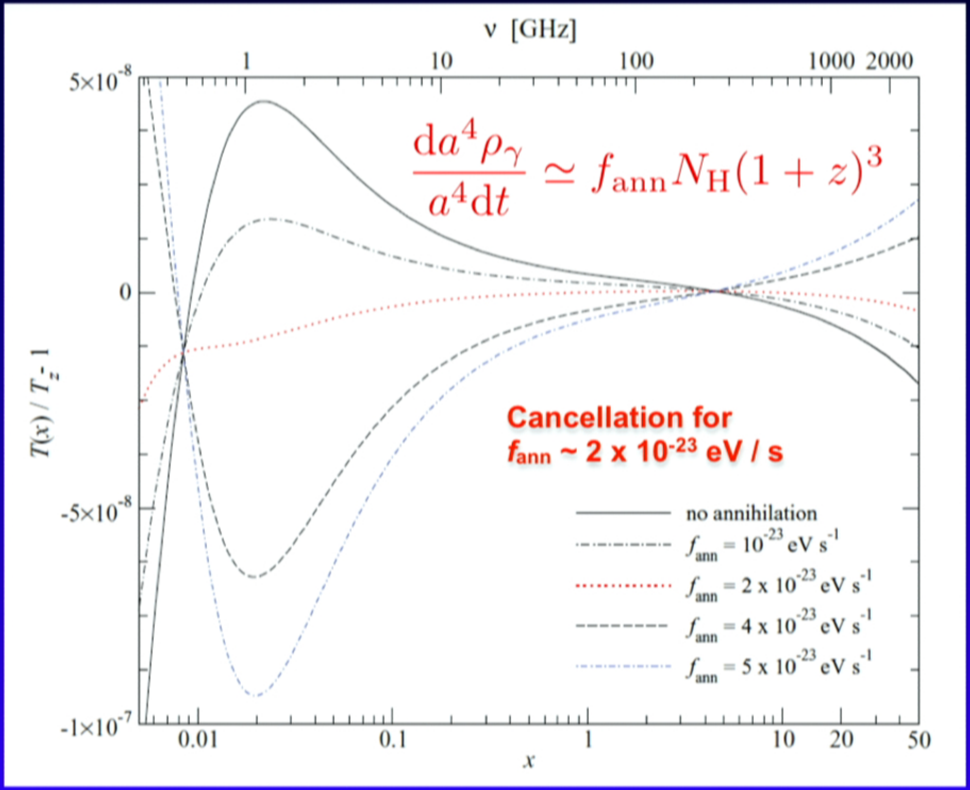

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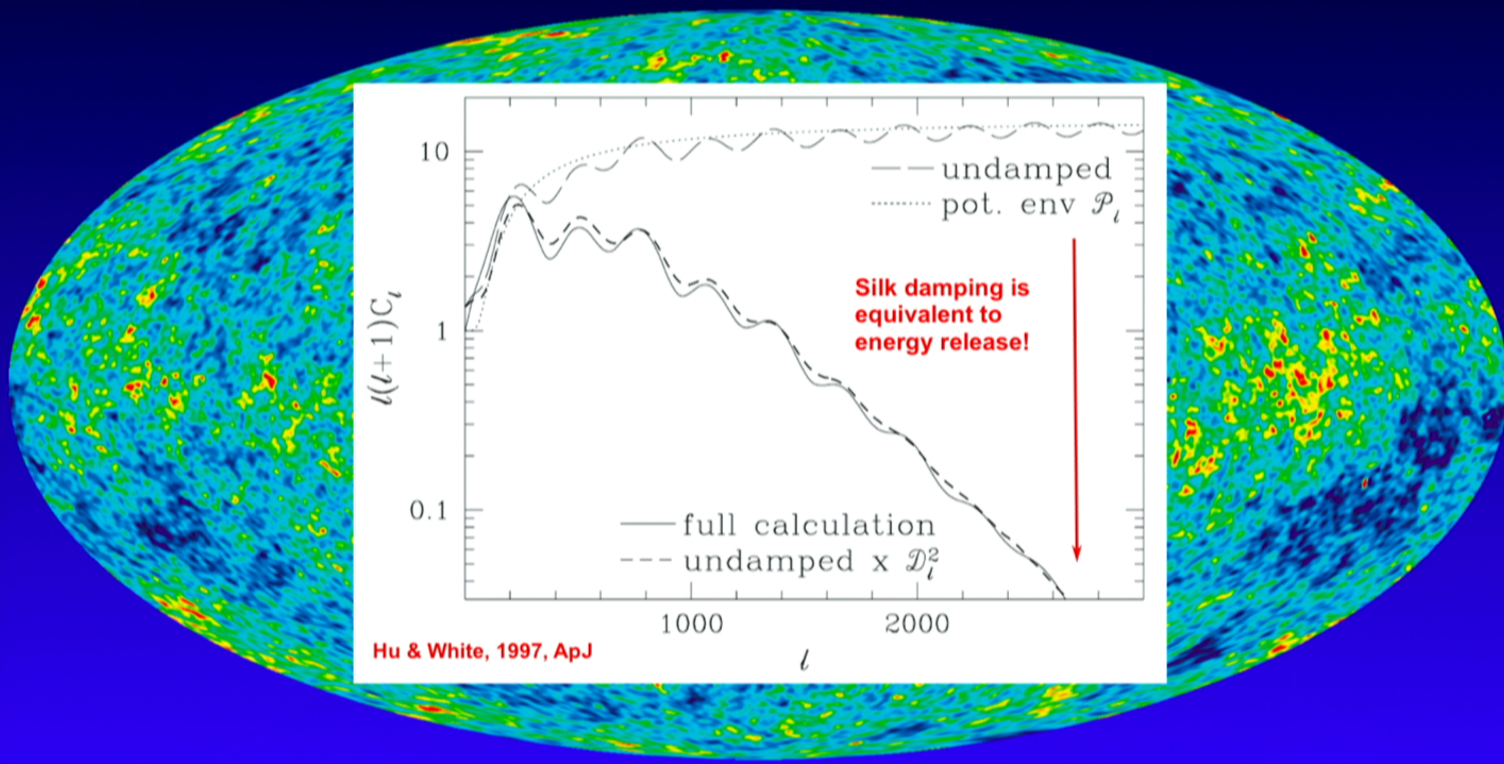
The dissipation of small-scale acoustic modes

Cosmic Microwave Background Anisotropies



Energy release caused by dissipation process

'Obvious' dependencies:

- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

not so 'obvious' dependencies:

- *primordial non-Gaussianity* in the squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
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Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

  Landau & Lifshitz, ‘Fluid Mechanics‘, § 65 ⇒ $Q \sim c_s^2\,\rho\,(\delta\rho/\rho)^2$

- expression for normal ideal gas where ρ is ‘*mass density*’ and c_s denotes ‘*sounds speed*’

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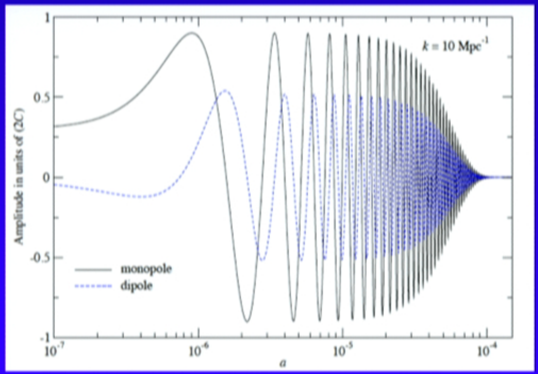

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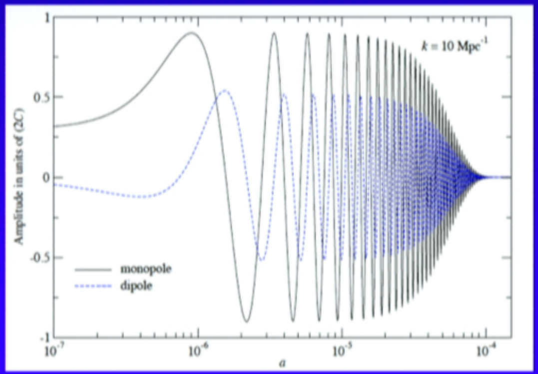

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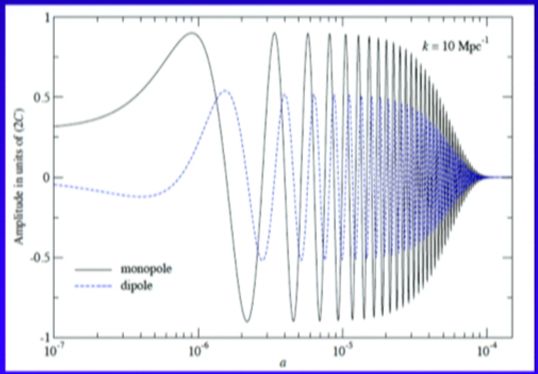
- Simple estimate for the total energy release does *not* capture all the physics of the problem:
  - *detailed treatment with Boltzmann equation shows that the total energy release is 9/4 ~ 2.25 times larger!*
  - *also only 1/3 of the released energy goes into distortions while 2/3 only adiabatically raise the average CMB temperature*



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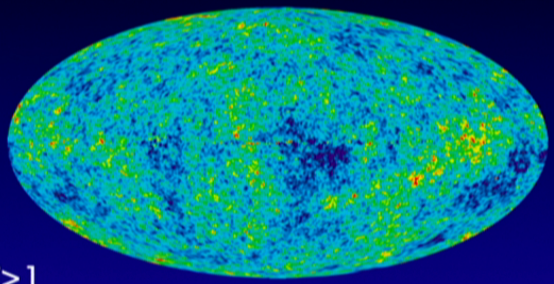
Dissipation of acoustic modes: 'microscopic treatment'

- after inflation: photon field has spatially varying temperature T
- average energy stored in photon field at any given moment

$$<\rho_\gamma> = a_R <T^4> \approx a_R <T>^4 [1 + 4<\Theta> + 6<\Theta^2>]$$

$<\Theta>$ == 0



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JC, Khatri & Sunyaev, 2012

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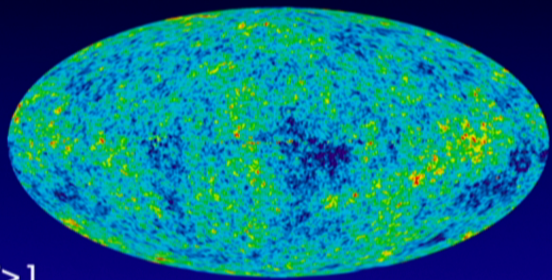

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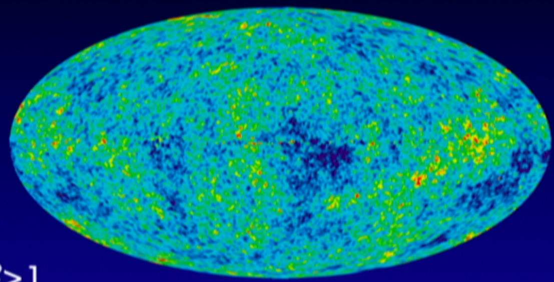

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- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release

JC, Khatri & Sunyaev, 2012

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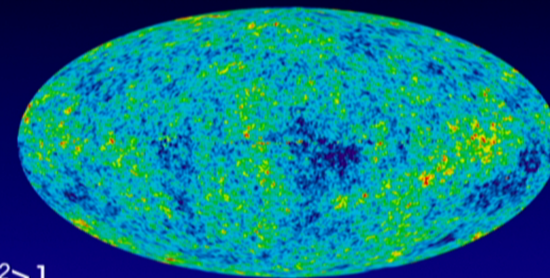

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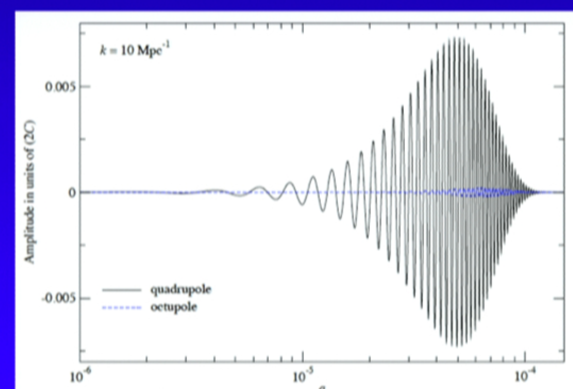
- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release
- At high redshifts ($z \geq 10^4$):
  - *net (gauge-invariant) dipole and contributions from higher multipoles are negligible*
  - *dominant term caused by quadrupole anisotropy*

$$\Rightarrow (a^4\rho_\gamma)^{-1}\, da^4 Q_{ac}/dt \approx -12\, d<\Theta_0^2>/dt$$

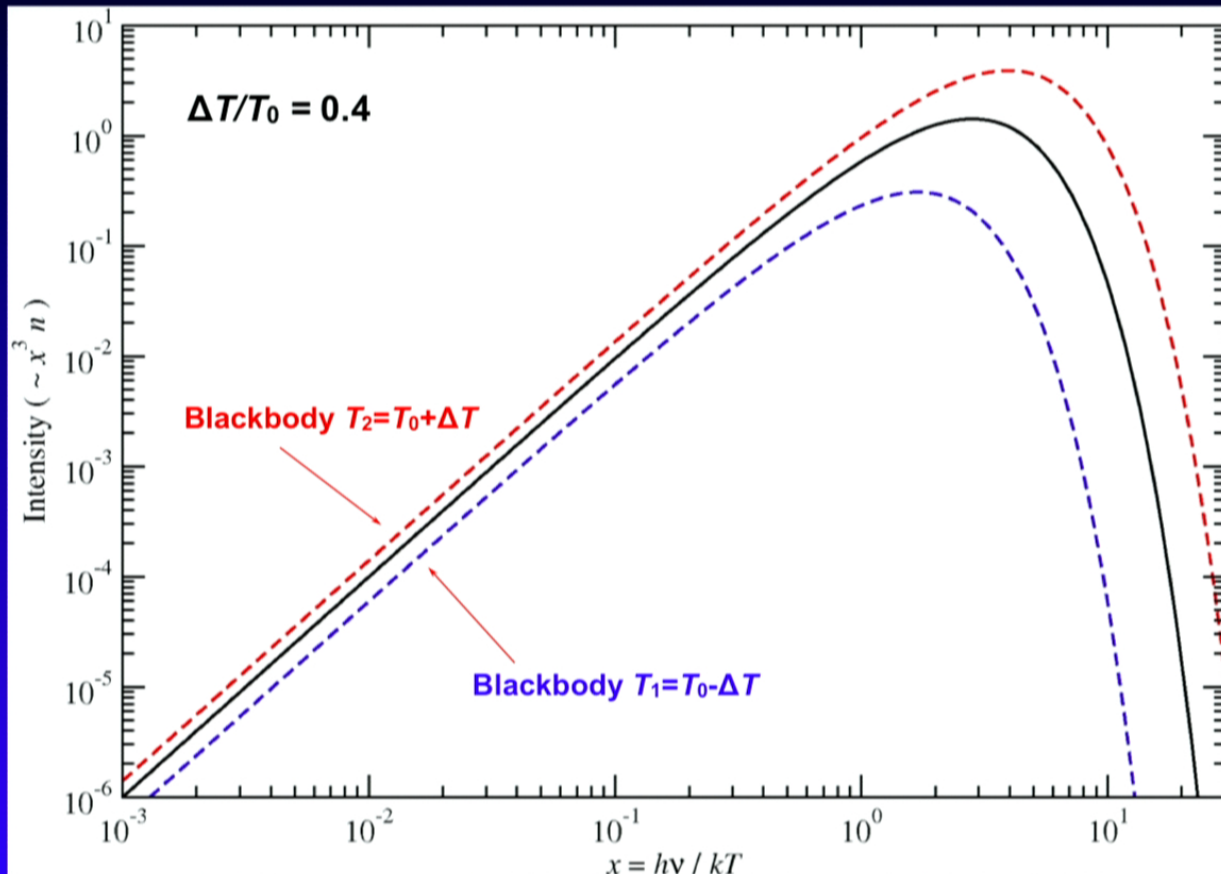
9/4 larger than classical estimate

JC, Khatri & Sunyaev, 2012



Where does the 2:1 ratio come from?

Superpositions of blackbody spectra



Zeldovich, Illarionov & Sunyaev, 1972
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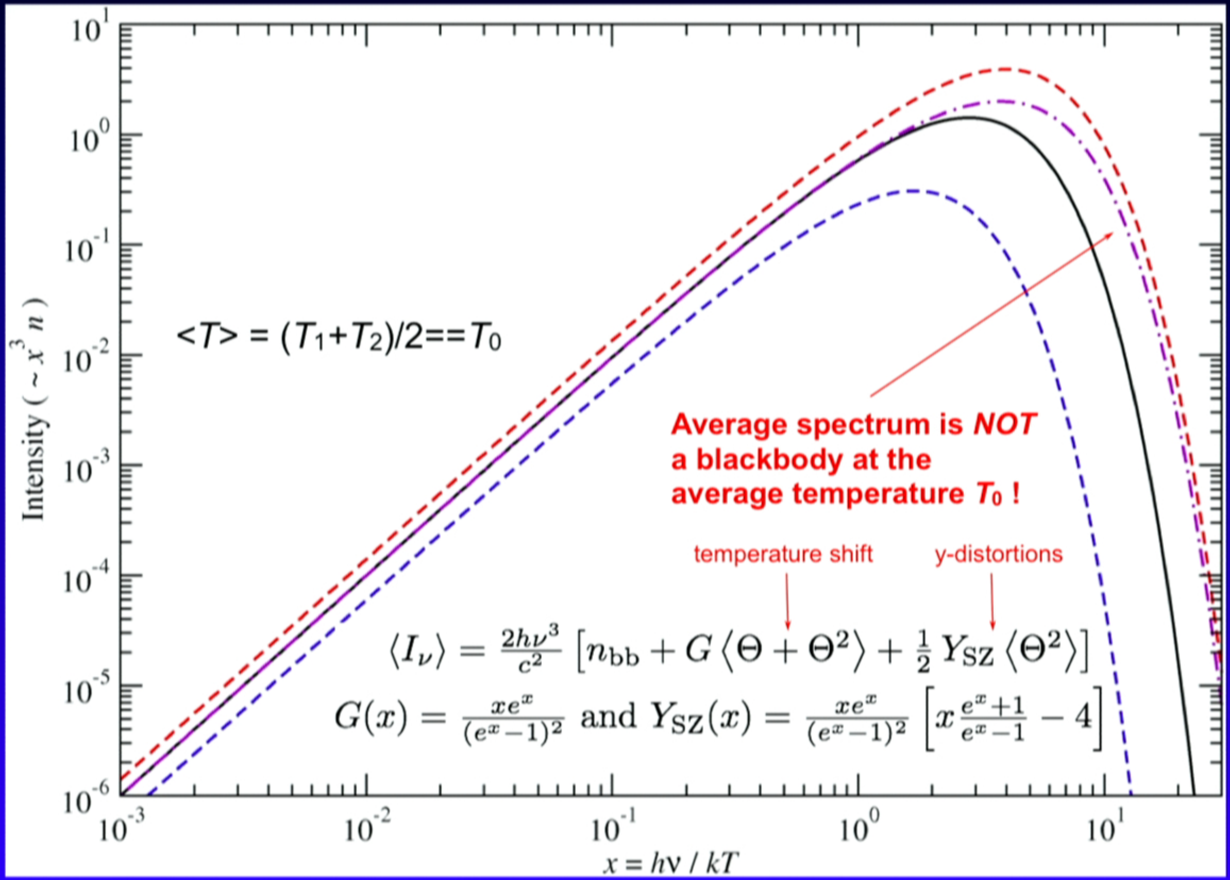

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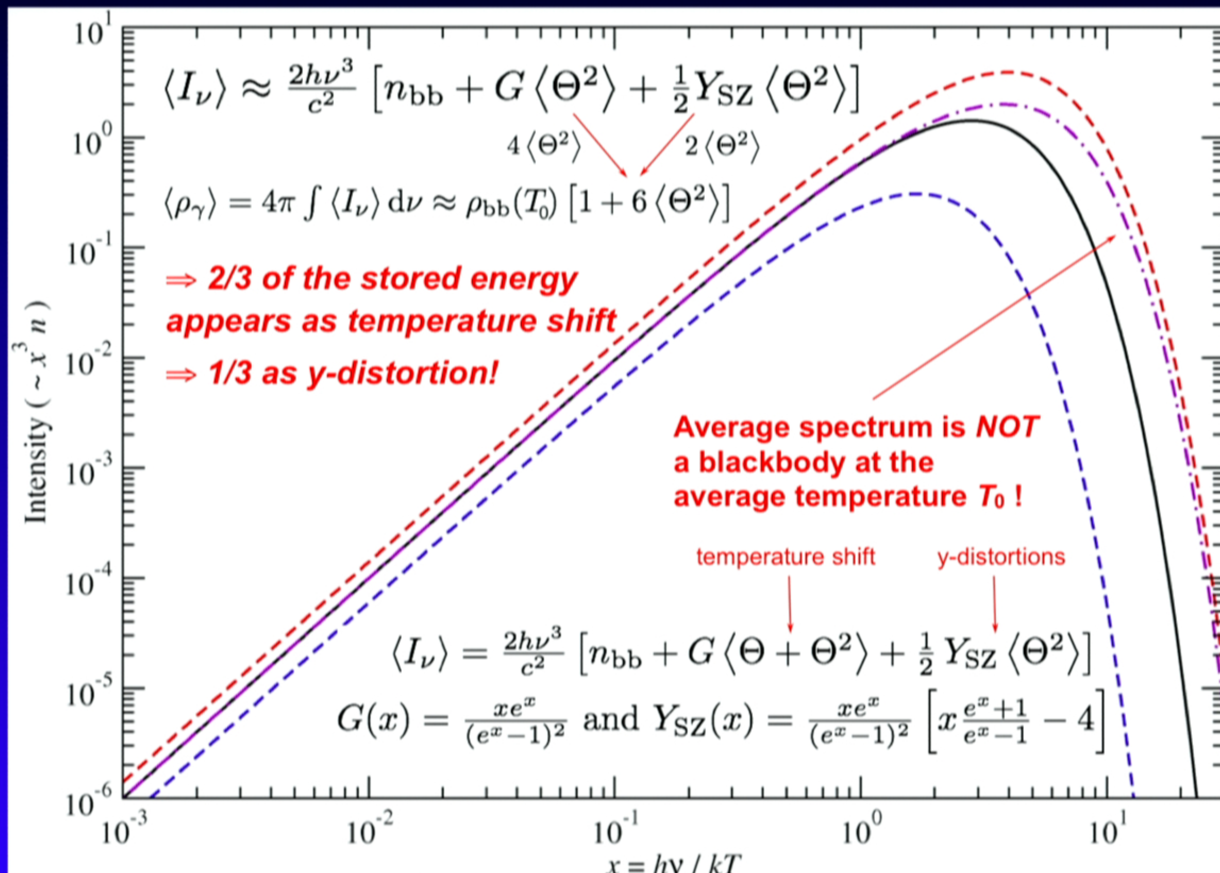

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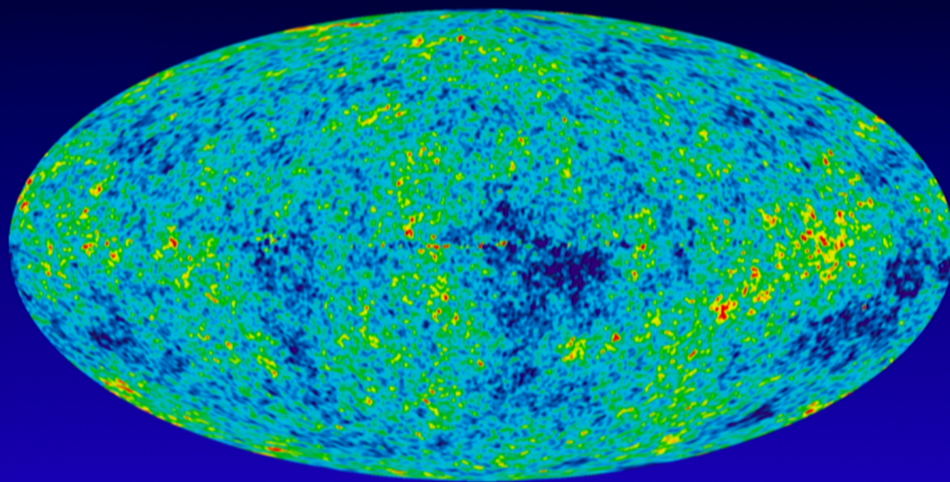
Distortion caused by superposition of blackbodies

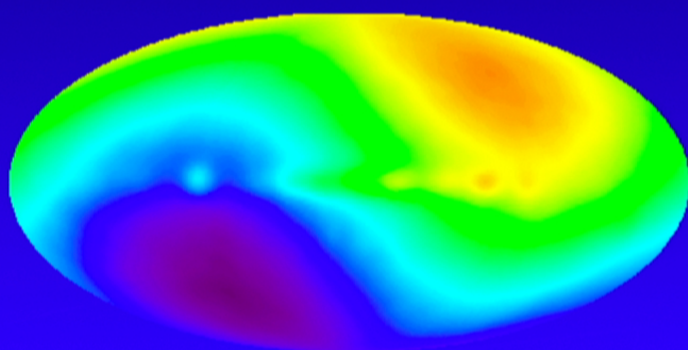


- average spectrum

$$\Rightarrow\ y \simeq \frac{1}{2}\left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 8\times10^{-10}$$

$$\Delta T_{\rm sup} \simeq T \left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 4.4{\rm nK}$$

- known with very high precision



- *CMB dipole* (β_c ~ 1.23×10^{-3})

$$\Rightarrow\quad y \simeq \frac{\beta_c^2}{6} \approx 2.6\times10^{-7}$$

$$\Delta T_{\rm sup} \simeq T\,\frac{\beta_c^2}{3} \approx 1.4\mu{\rm K}$$

- electrons are up-scattered
- can be taken out at the level of ~ 10^{-9}

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012

COBE/DMR: ΔT = 3.353 mK

Effective energy release caused by damping effect

- Effective heating rate from full 2x2 Boltzmann treatment **(JC, Khatri & Sunyaev, 2012)**

$$\frac{1}{a^4 \rho_\gamma} \frac{\mathrm{d}a^4 Q_{\rm ac}}{\mathrm{d}t} = 4\sigma_{\rm T} N_{\rm e} c \left\langle \frac{(3\Theta_1 - \beta)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_0^{\rm P} + \Theta_2^{\rm P}) + \sum_{l \geq 3}(2l+1)\Theta_\ell^2 \right\rangle$$

$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu) P_\ell(\mu)\mathrm{d}\mu$$

gauge-independent dipole

effect of polarization

higher multipoles

$$\langle XY \rangle = \int \frac{k^2 \mathrm{d}k}{2\pi^2} P(k) X(k) Y(k)$$

Primordial power spectrum

JC, Khatri & Sunyaev, 2012

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gauge-independent dipole — **effect of polarization** — **higher multipoles**

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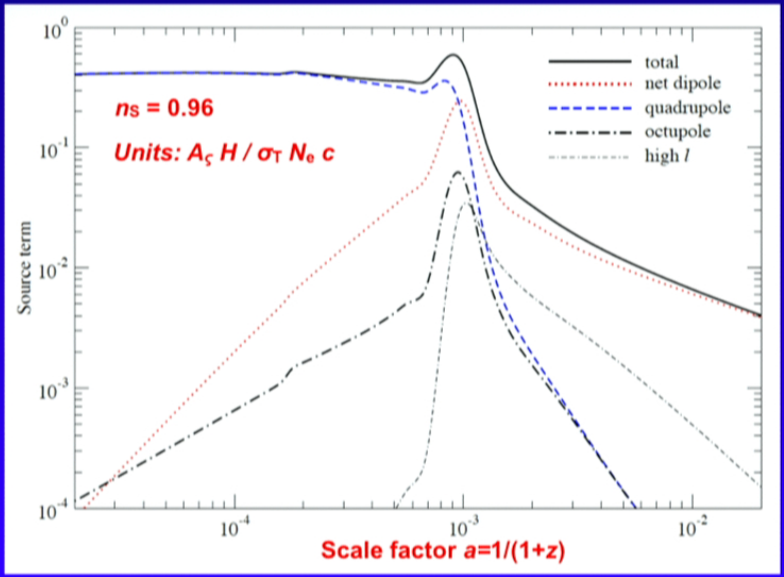
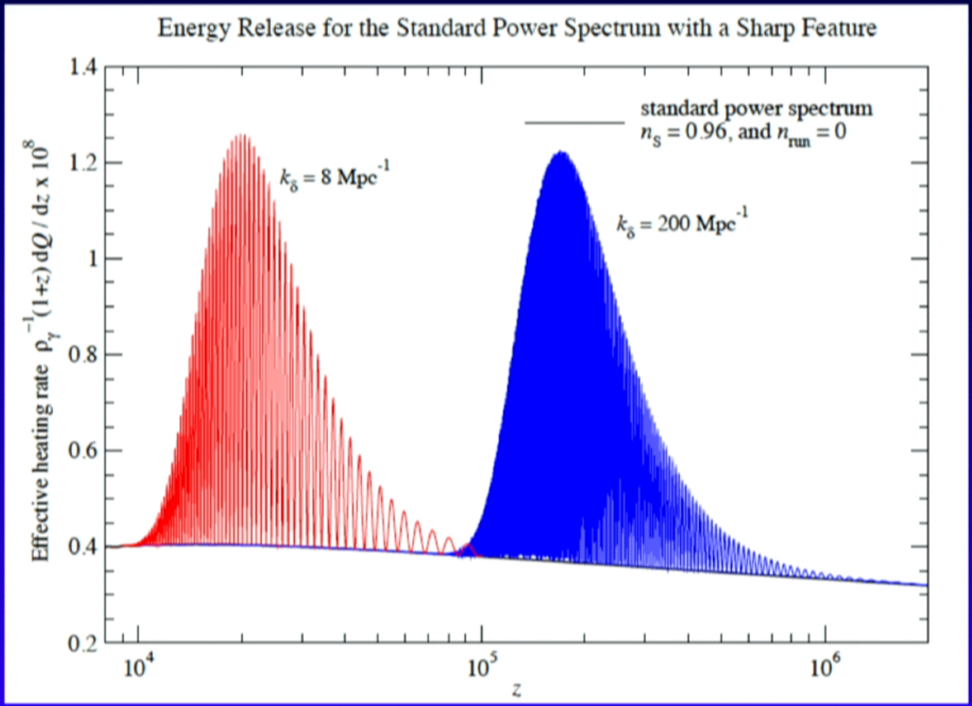
Primordial power spectrum

- *quadrupole* dominant at high *z*
- *net dipole* important only at low redshifts
- polarization ~5% effect
- contribution from higher multipoles rather small



JC, Khatri & Sunyaev, 2012

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

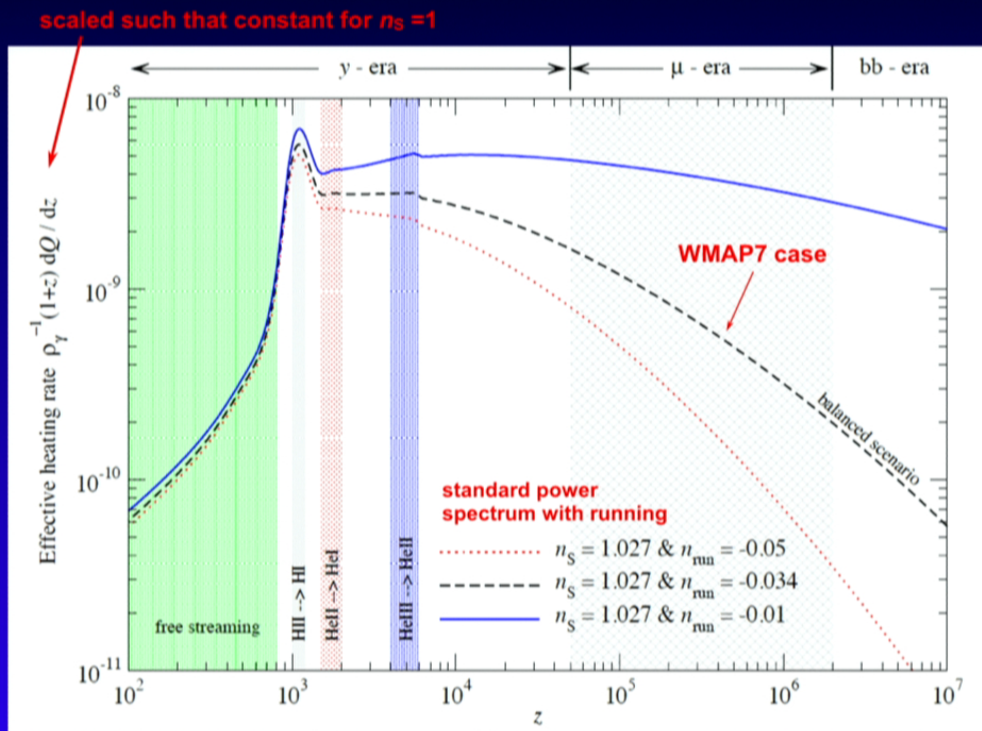
- Single mode with wavenumber *k* dissipates its energy at

  $z \sim 4.5\times10^5 (k\,\mathrm{Mpc}/10^3)^{2/3}$

- Modes with wavenumber $50\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$ dissipate their energy during the μ-era

- Modes with $k < 50\ \mathrm{Mpc}^{-1}$ cause y-distortion

Our computation for the effective energy release



- Amplitude of the distortion depends on the small-scale power spectrum
- 'balanced' energy release scenarios ↔ adiabatic cooling effect is canceled by acoustic damping process → $\mu \sim 0$
- **Computation carried out with *CosmoTherm***
  (JC & Sunyaev 2011)

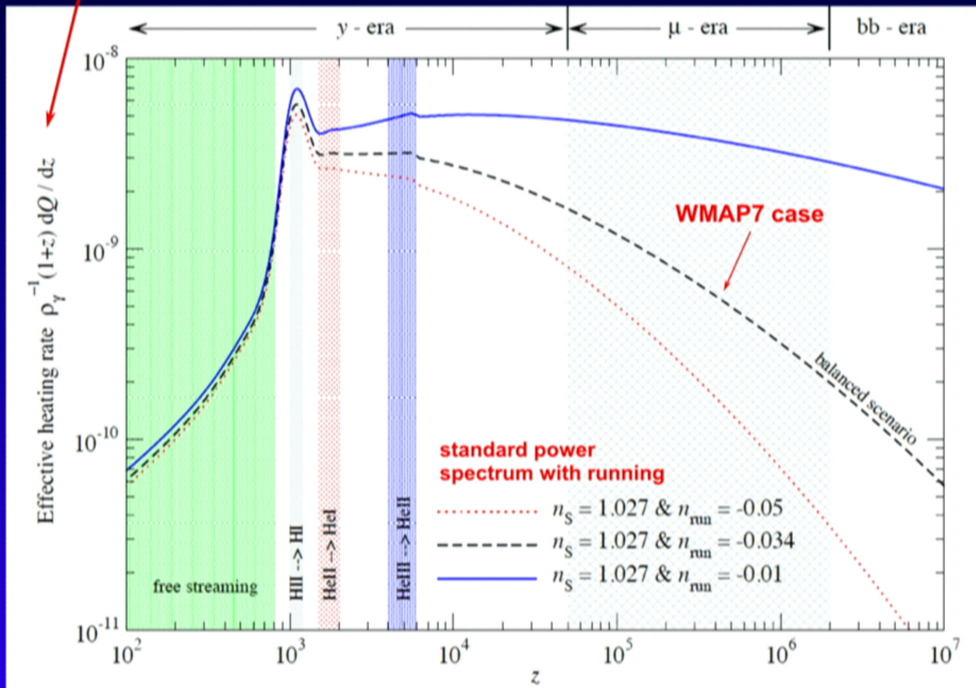
$$P_\zeta(k) = 2\pi^2 A_\zeta k^{-3}(k/k_0)^{n_S-1+\frac{1}{2}n_{\rm run}\ln(k/k_0)}$$

$$n_{\rm run}^{\rm bal} \approx -0.0336[1 + 5.22(n_S - 1) + 0.58(n_S - 1)^2]$$

JC, Khatri & Sunyaev, 2012

Our computation for the effective energy release

scaled such that constant for $n_S = 1$



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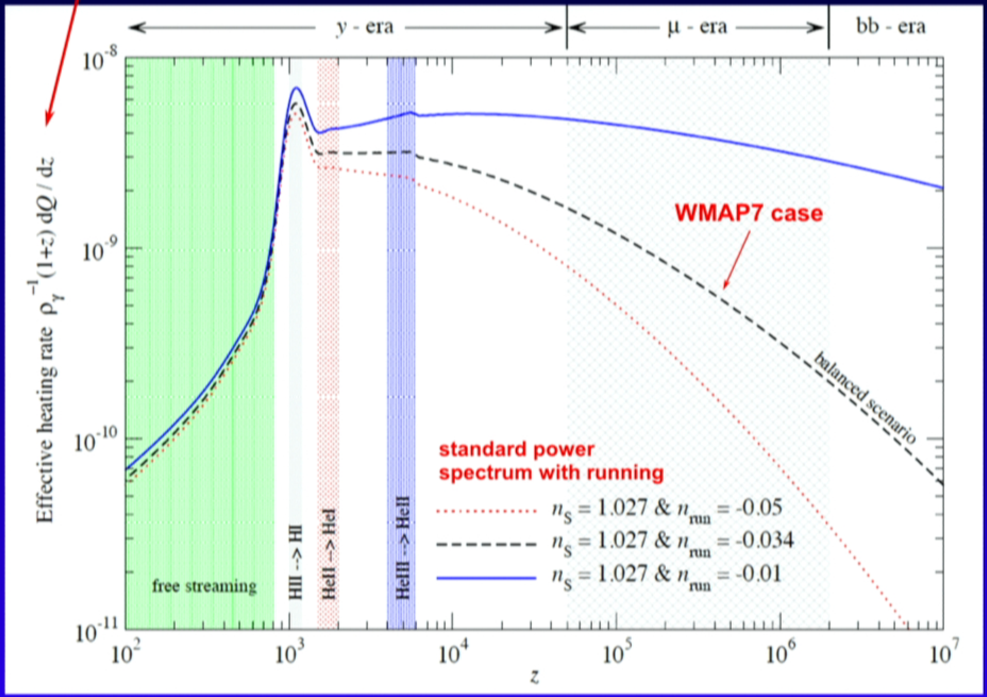

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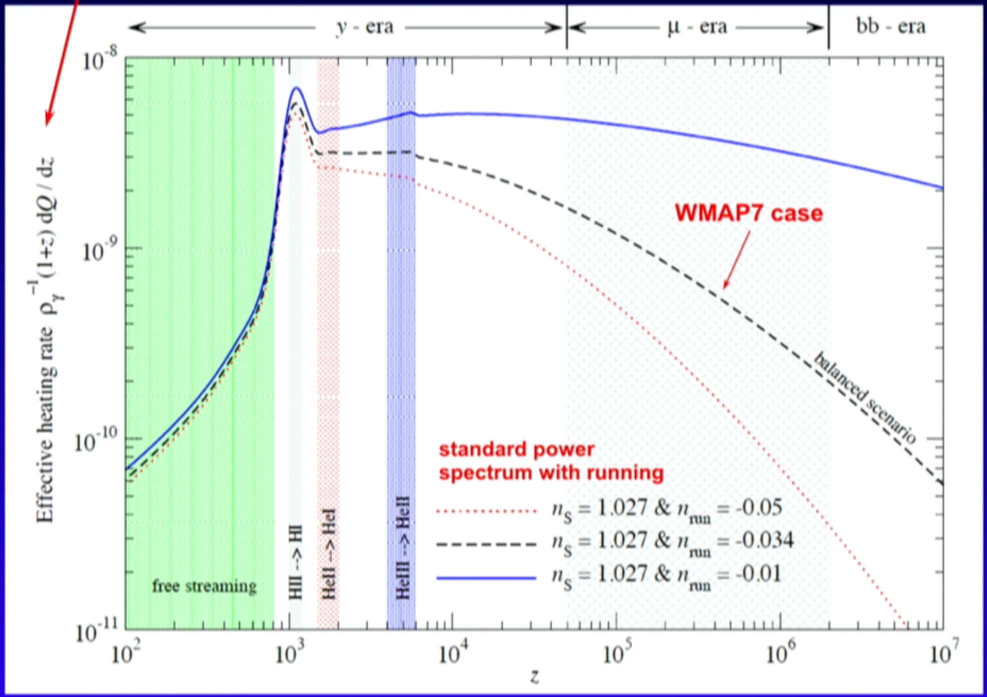

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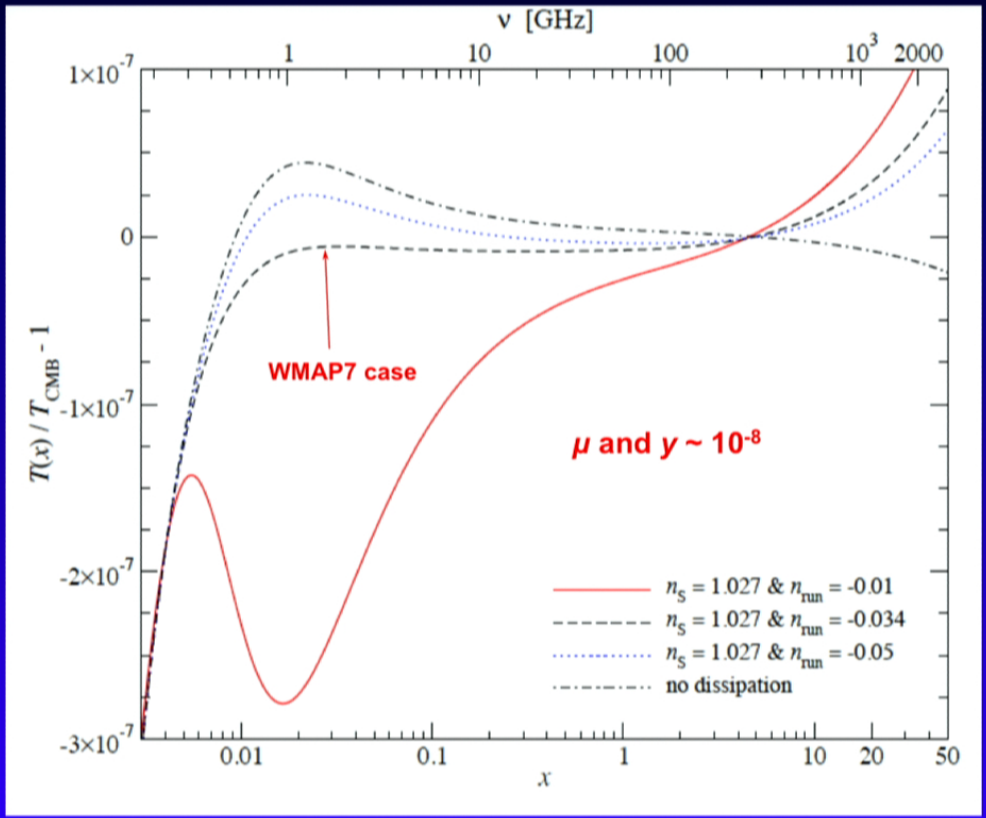

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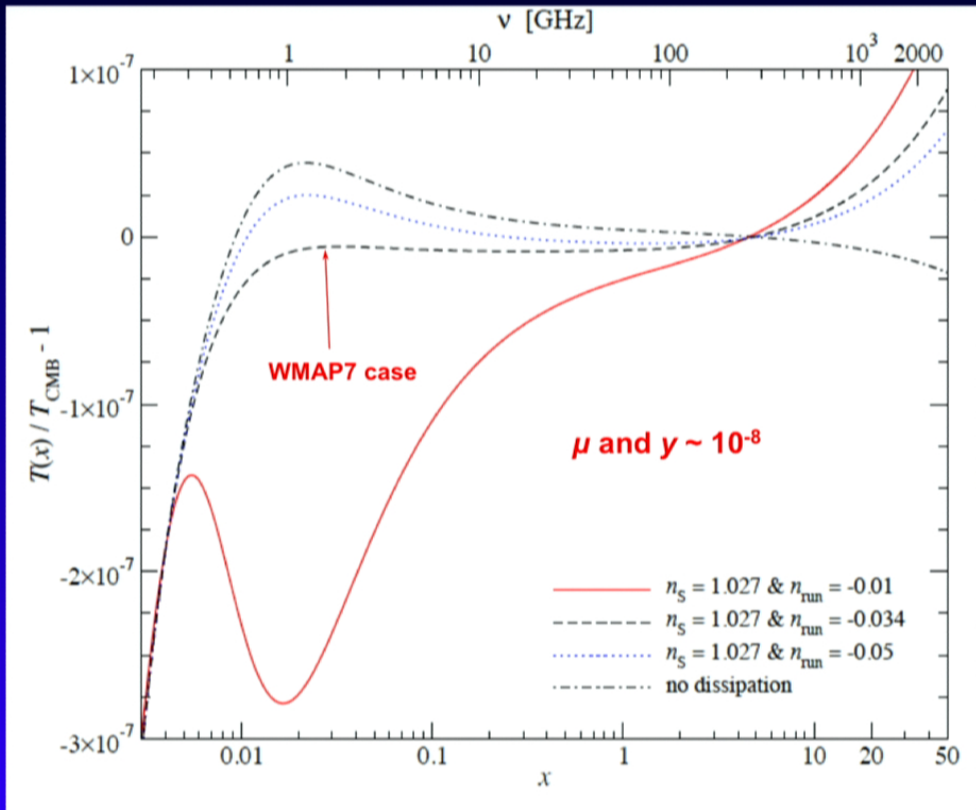

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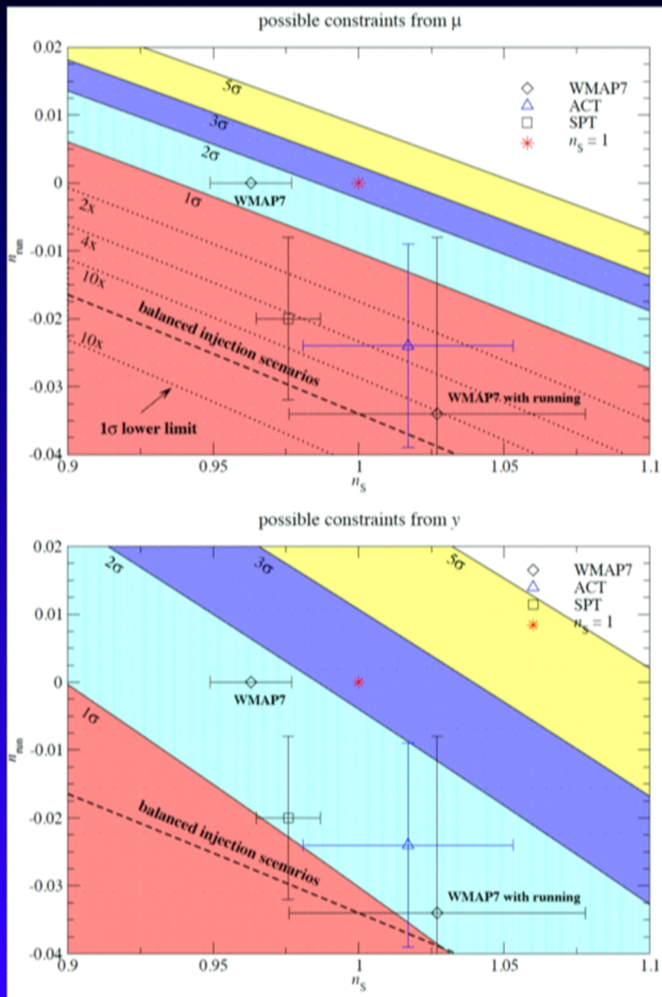
Constraints on the standard primordial power spectrum



- For *any* given power spectrum very precise predictions are possible!
- The *physics* going into the computation are *well understood*
- For the standard power spectrum PIXIE might detect the μ-distortion caused by acoustic damping at ~1.5σ level
- PIXIE could *independently* rule out a scale-invariant power spectrum at ~2.5σ level
- Most currently favoured models with running are close to *balanced injection scenarios*, for which PIXIE will only give upper limits
- y-distortion will be more hard to measure, since there are many *other astrophysical processes* that could cause y-distortions at low redshift

JC, Khatri & Sunyaev, 2012

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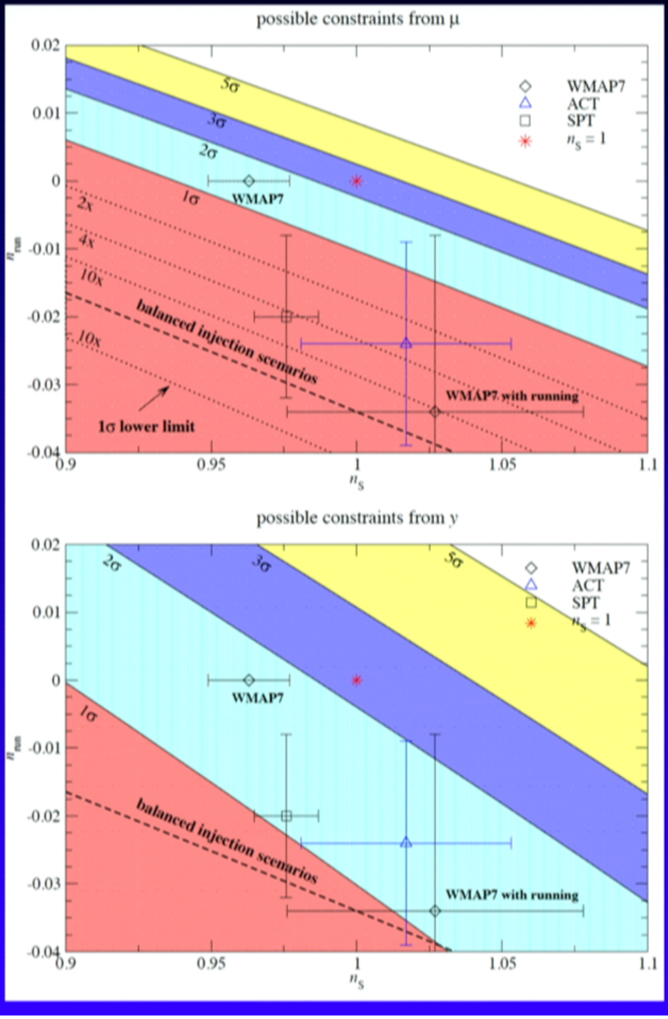

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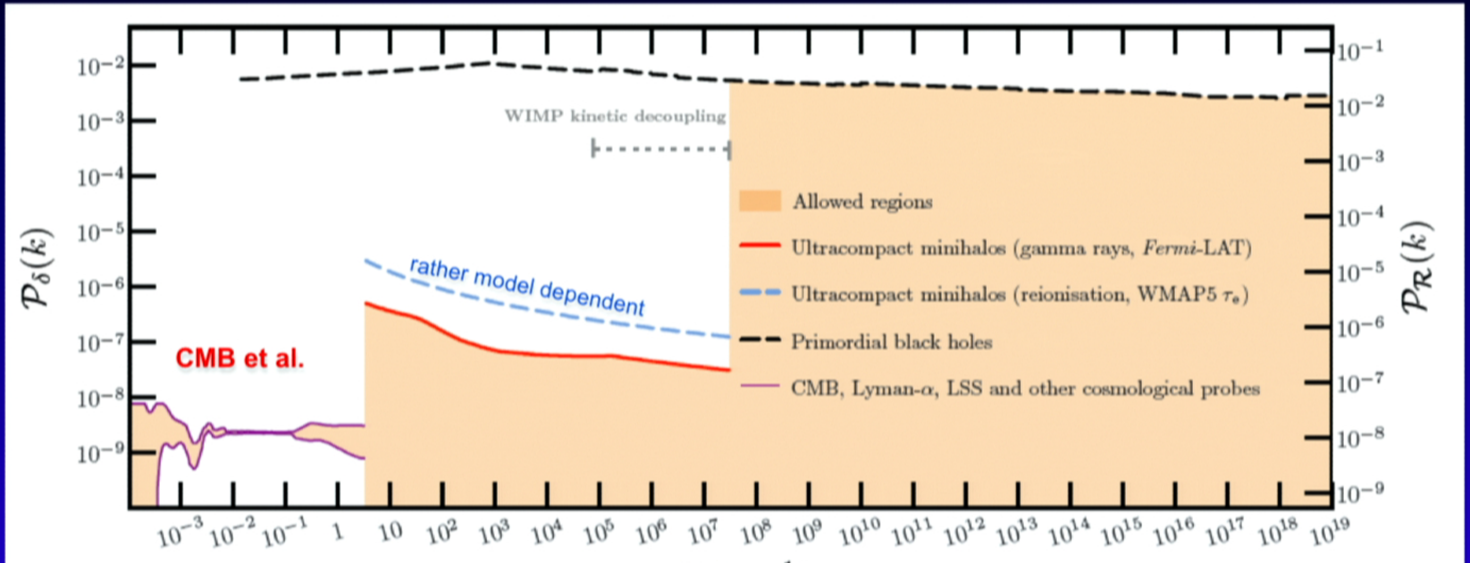
JC, Khatri & Sunyaev, 2012

Is this already all one can look at?

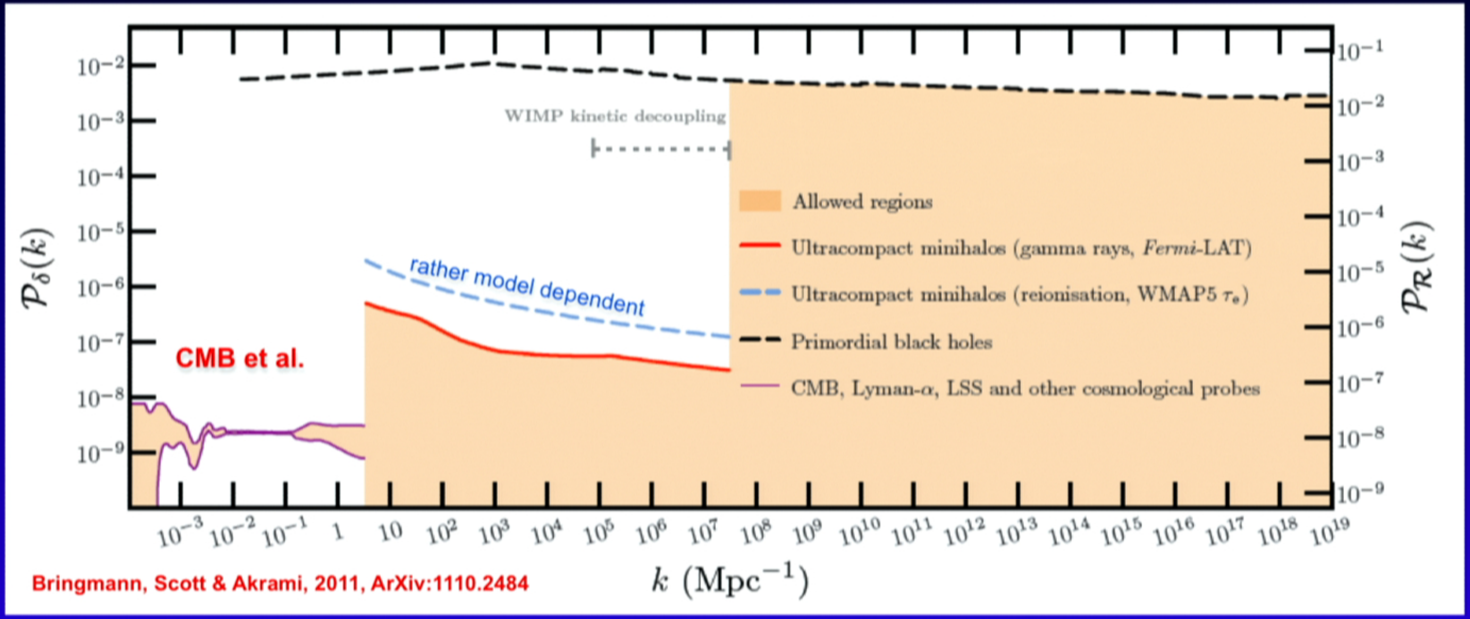
Power spectrum constraints



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improving limits at smaller scales would constrain inflationary models

Power spectrum constraints



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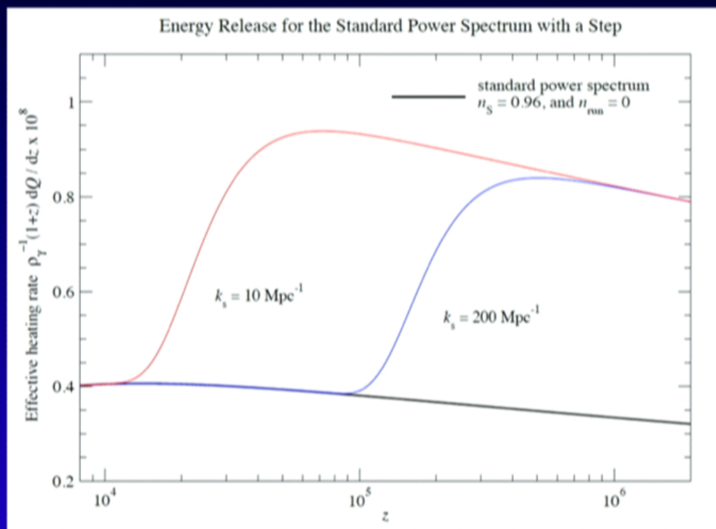
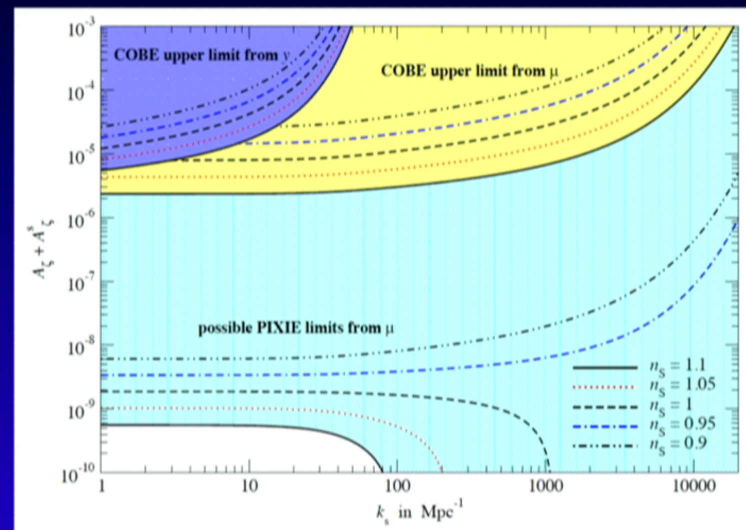
Primordial power spectra with 'step' at small scales





$$\mu \approx 2.2 \int_{k_{\min}}^{\infty} \mathcal{P}_\zeta(k) \left[\exp\left(-\frac{\hat{k}}{5400} \right) - \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \right] \mathrm{d} \ln k$$

$$y \approx 0.4 \int_{k_{\min}}^{\infty} \mathcal{P}_\zeta(k) \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \mathrm{d} \ln k,$$

Integral constraint on small-scale power

JC, Erickcek & Ben-Dayan, 2012

- simple formula to compute the effective μ and y-parameter
- COBE/FIRAS ⇒ amplitude of the small-scale power spectrum can't change by more than ~2x10^{-6} at wavenumber k ~ 1 Mpc^{-1}

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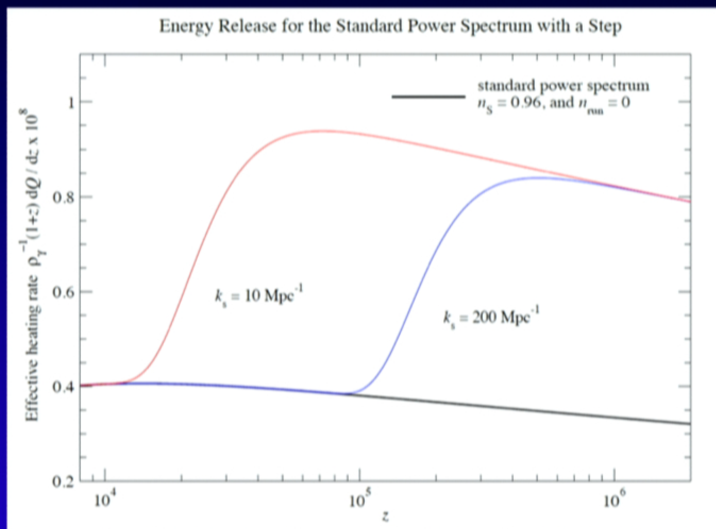

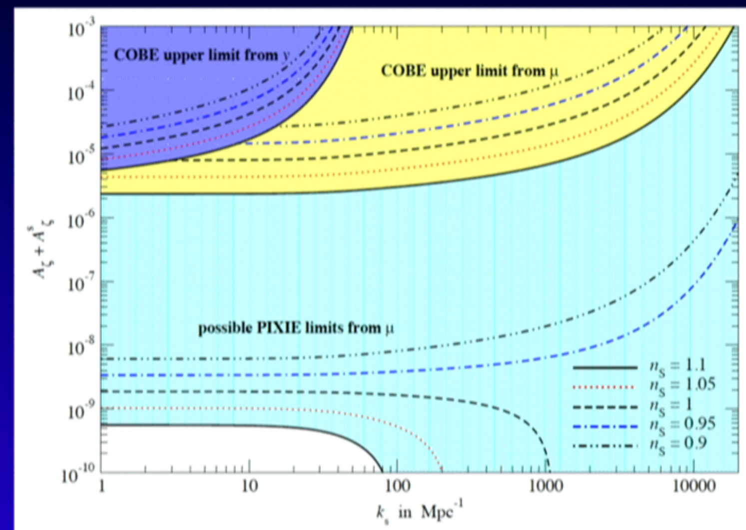

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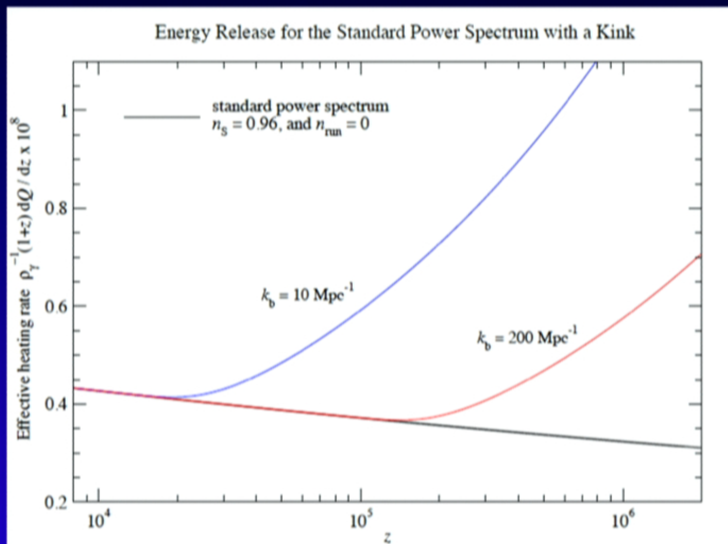
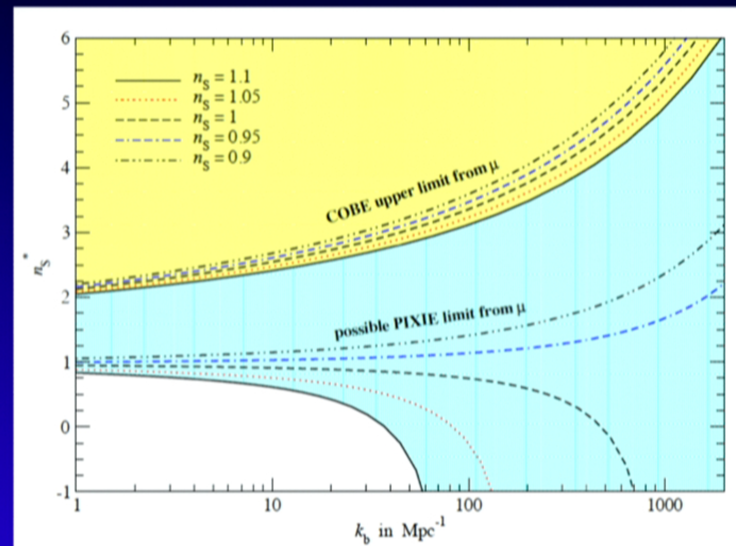
JC, Erickcek & Ben-Dayan, 2012

Primordial power spectra with 'bend' at small scales





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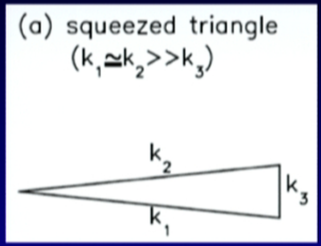
Integral constraint on small-scale power

JC, Erickcek & Ben-Dayan, 2012

- COBE/FIRAS ⇒ spectral index at $k \sim 1$ Mpc^{-1} cannot change by more than $\Delta n \sim 1$
- PIXIE will place very tight constraints on such models

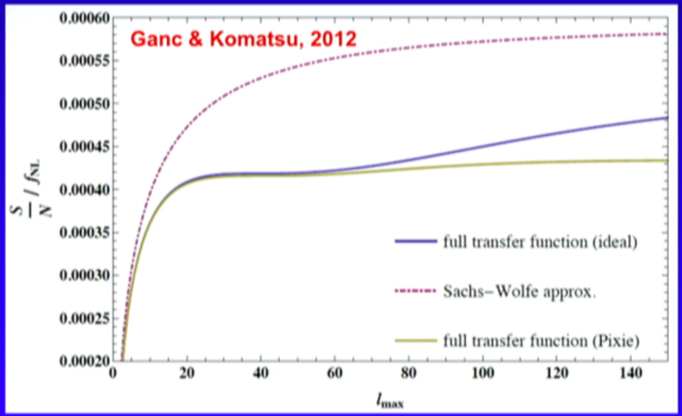
Modified μ-distortion in the squeezed limit

- Modes that dissipate energy have $k_1 \approx k_2 >> k_3$
- Non-Gaussian power spectrum → presence of positive long-wavelength mode enhances small-scale power
- More small-scale power → larger μ-distortion
- → Spatially varying μ-distortion caused by non-Gaussianity! (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- Non-vanishing μ-T correlation at large scales
- Might be detectable with PIXIE-type experiment for $f_{NL} > 10^3$



Requirements

- precise cross-calibration of frequency channels
- higher angular resolution does not improve cumulative S/N



What about the cosmological recombination epoch?

Simple estimates for hydrogen recombination

Hydrogen recombination:

- per recombined hydrogen atom an energy of ~ 13.6 eV in form of photons is released
- at z~1100 → $\Delta\varepsilon/\varepsilon \sim 13.6\text{ eV}\, N_b / N_\gamma\, 2.7kT_r \sim 10^{-9}\text{-}10^{-8}$

→ recombination occurs at redshifts $z < 10^4$

→ At that time the thermalization process does not work anymore!

→ There should be some *small* spectral distortion due to these additional photons!
(Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278; Peebles, 1968, ApJ, 153, 1)

→ In 1975 ***Viktor Dubrovich*** emphasized the possibility to observe the recombinational lines from n>3 and Δn<<n!

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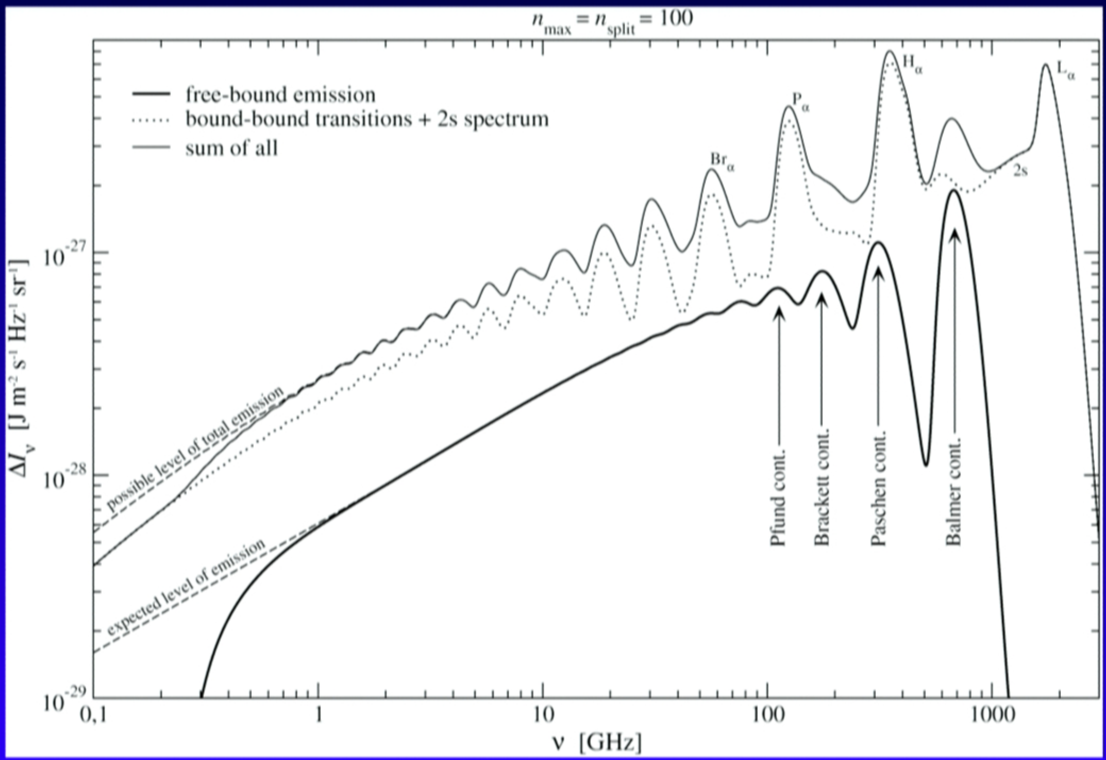
100-shell hydrogen atom and continuum

CMB spectral distortions



JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)

bound-bound & 2s:

- at ν>1GHz: distinct features
- slope ~ 0.46

free-bound:

- only a few features distinguishable
- slope ~ 0.6

Total:

- f-b contributes ~30% and more
- Balmer cont. ~90%
- Balmer: 1γ per HI
- in total 5γ per HI

100-shell hydrogen atom and continuum
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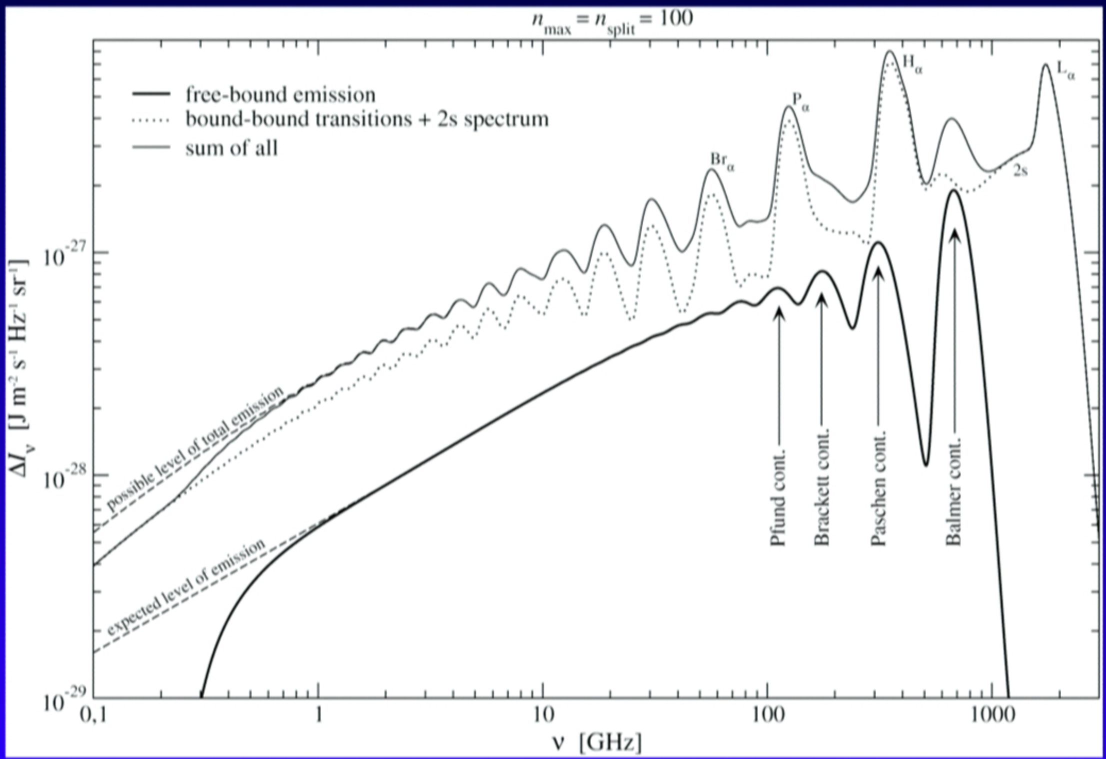

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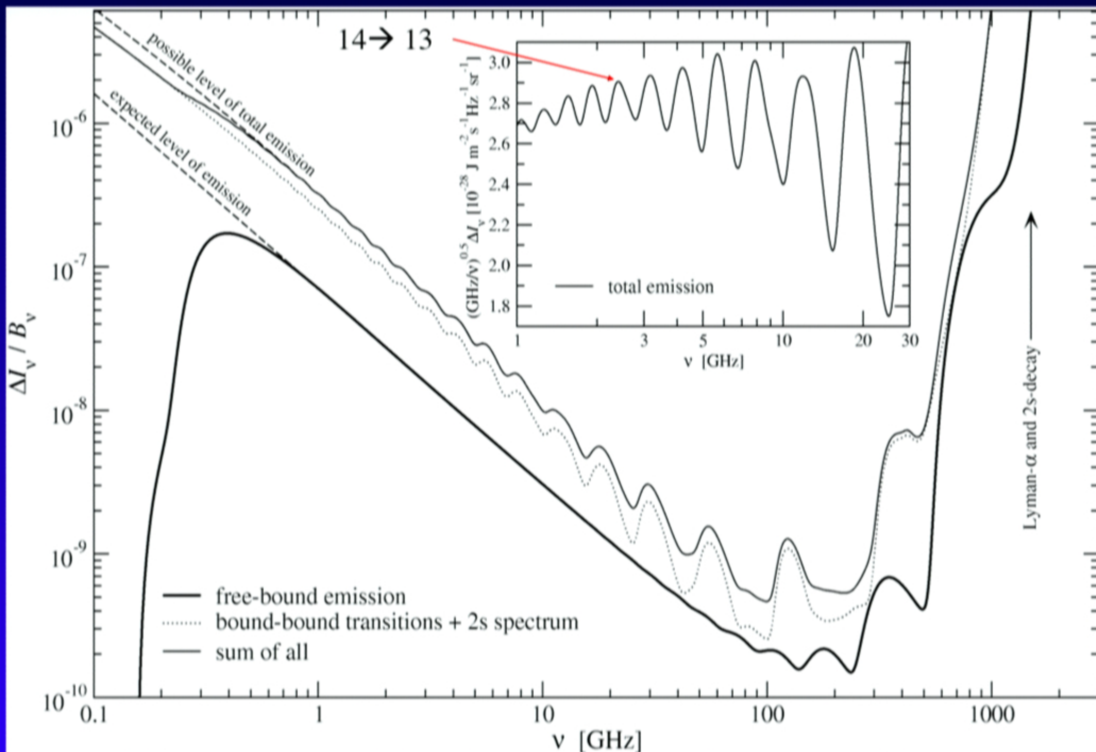
Relative distortions



JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)

Wien-region:

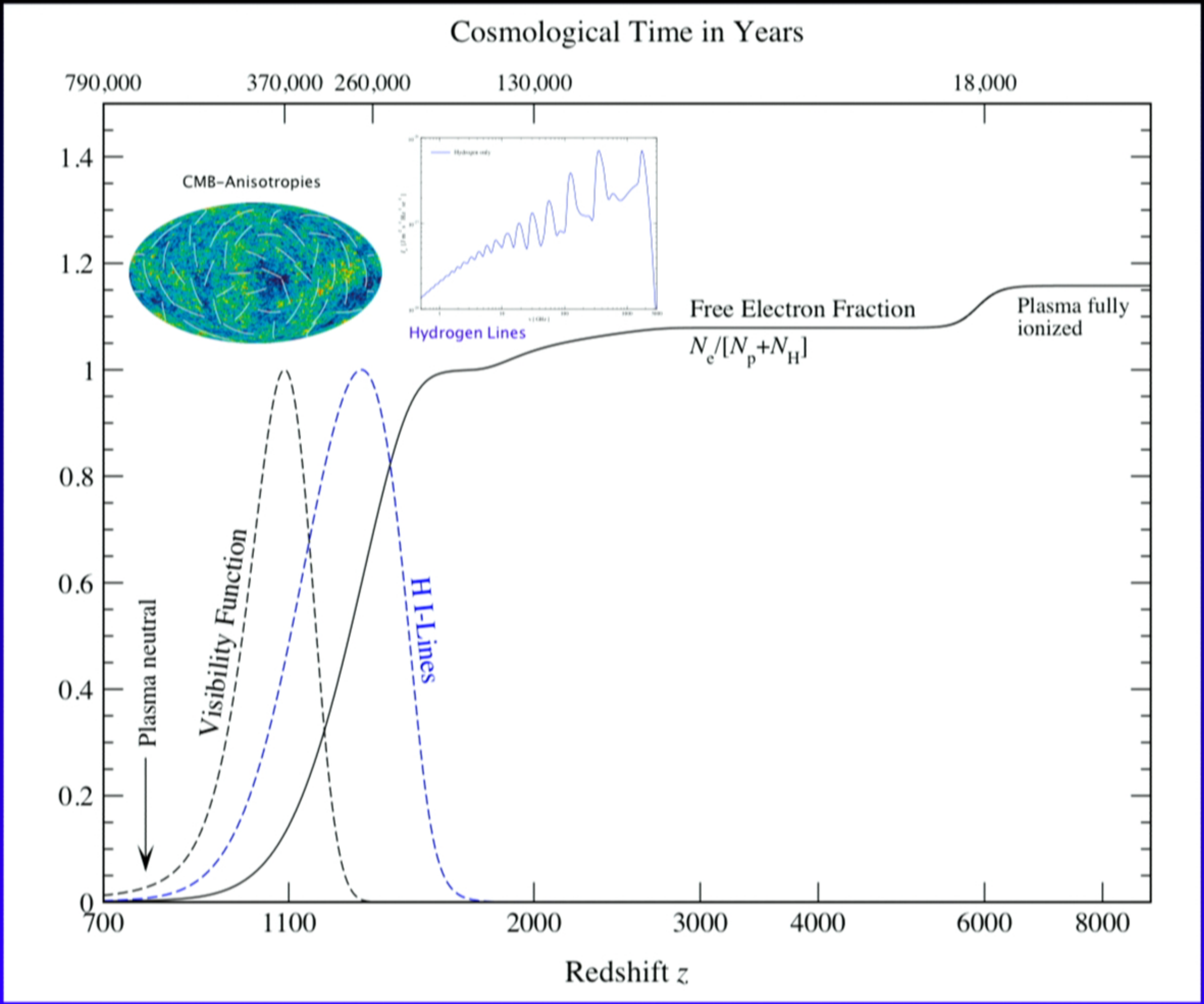
- L_α and 2s distortions are very strong
- but CIB more dominant

@ CMB maximum:

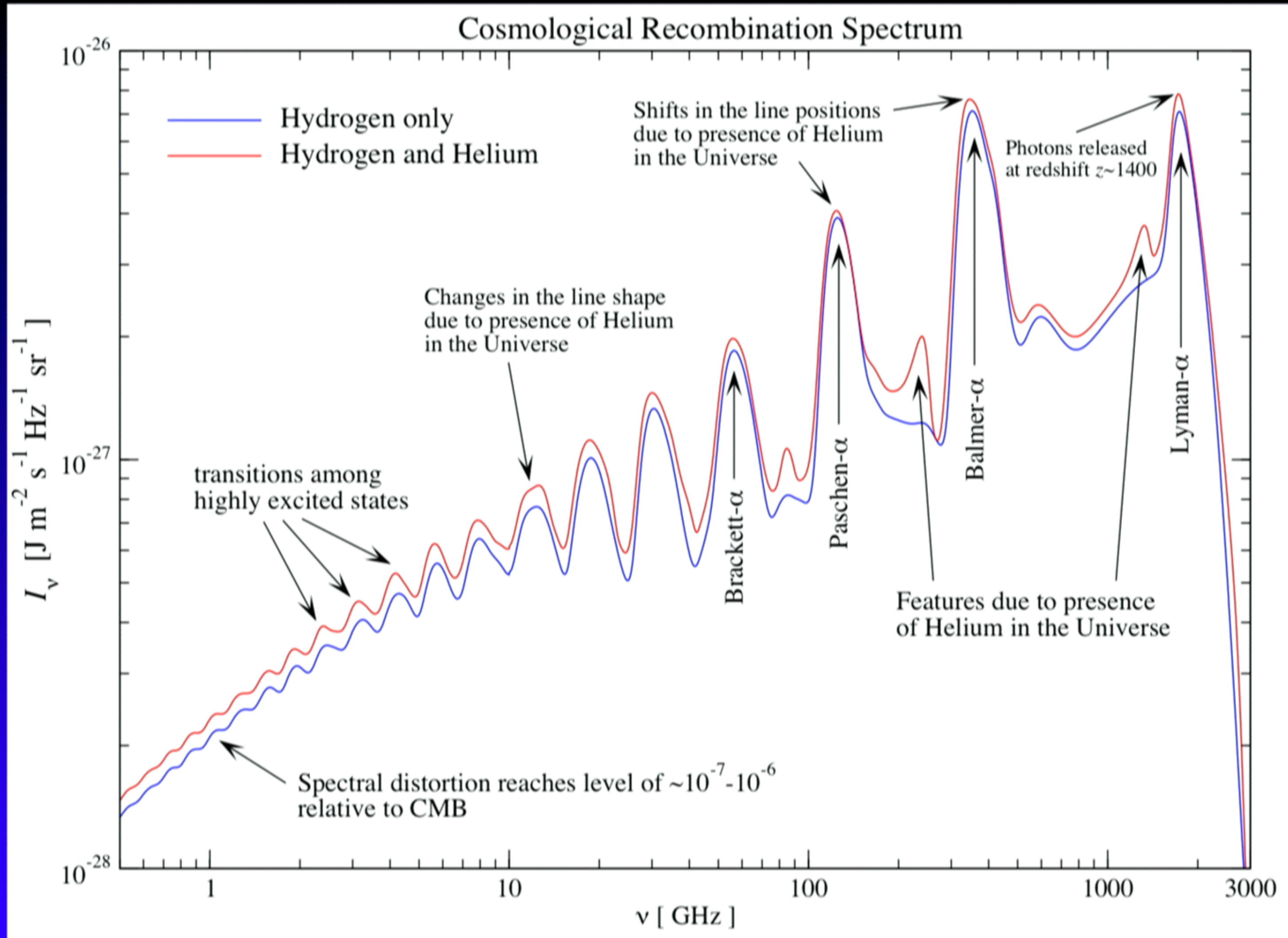
- relative distortions extremely small
- strong ν-dependence

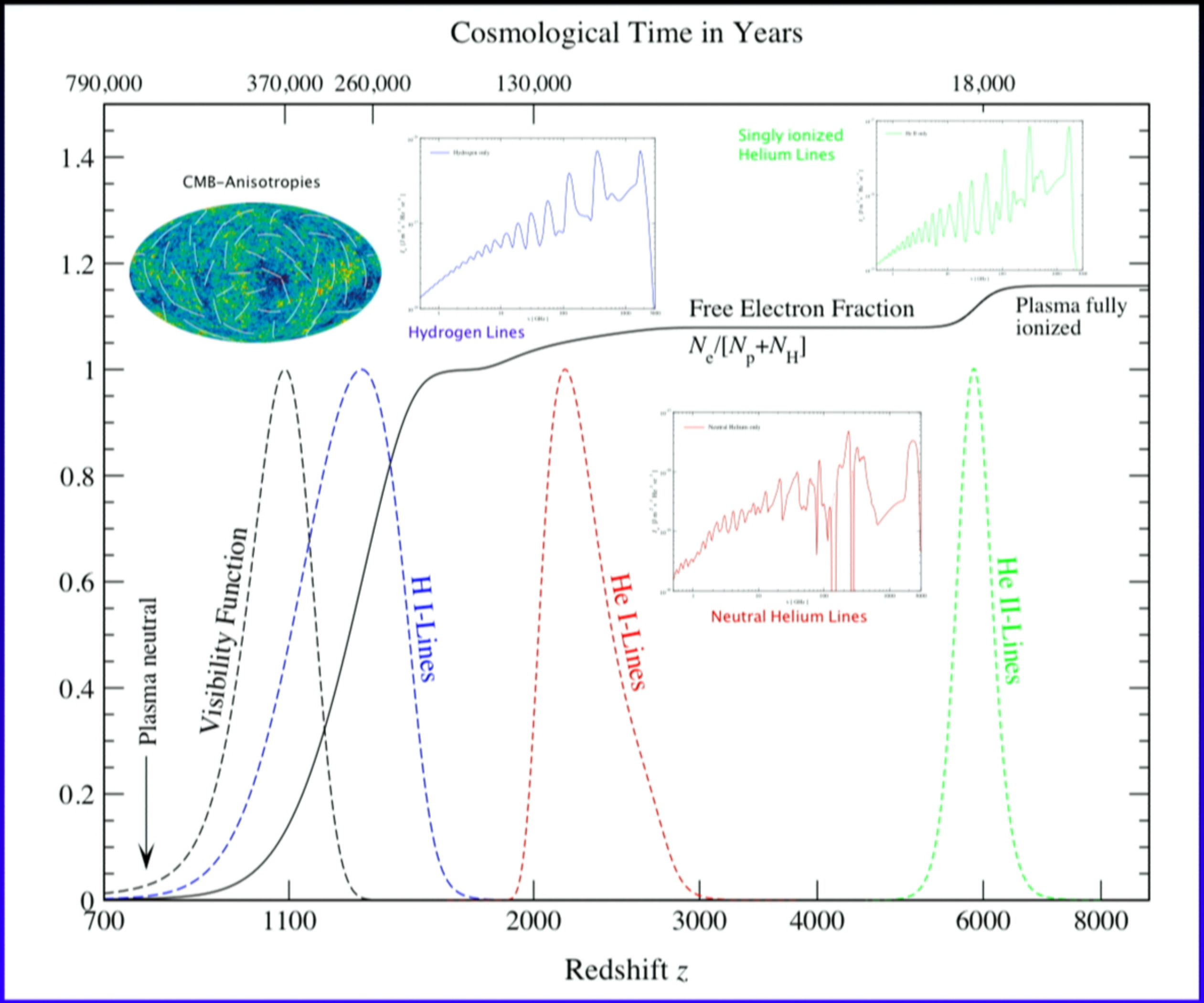
RJ-region:

- relative distortion exceeds level of ~10^{-7} below ν ~ 1-2 GHz
- oscillatory frequency dependence with ~1-10 percent-level amplitude:
- *hard to mimic by known foregrounds or systematics*



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
H I-Lines
Plasma neutral
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z


Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
1
10
100
1000
3000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Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

What would we actually learn by doing such hard job?

Cosmological Recombination Spectrum opens a way to measure:

- → **the specific *entropy* of our universe (related to $\Omega_b h^2$)**
- → **the CMB *monopole* temperature T_0**
- → ***the pre-stellar abundance of helium Y_p***
- → ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***
- → ***In principle allows us to directly check our understanding of the standard recombination physics***

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Conclusions

- CMB spectral distortions open a new window to the early Universe
- *complementary* source of information not just confirmation
- simplicity of thermalization physics in principle allows making very precise predictions for the distortions caused by different processes
- in *standard* cosmology several processes lead to *early energy release* at a level that could be detectable in the future
- measurements of μ & y-distortions help placing strong limits on the *small-scale power spectrum* at *very small scales*, corresponding to wavenumbers $1\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$
- this places an integral constraint on different inflationary models
- constraints on primordial non-Gaussianity in the squeezed limit might be obtained by considering the spatial variation of μ

JC, Rishi Khatri & Rashid Sunyaev, ArXiv:1202.0057
JC, Adrienne Erickcek & Ido Ben-Dayan, ArXiv:1203.2681