Lines in the CMB spectrum from the epoch of Cosmological Recombination

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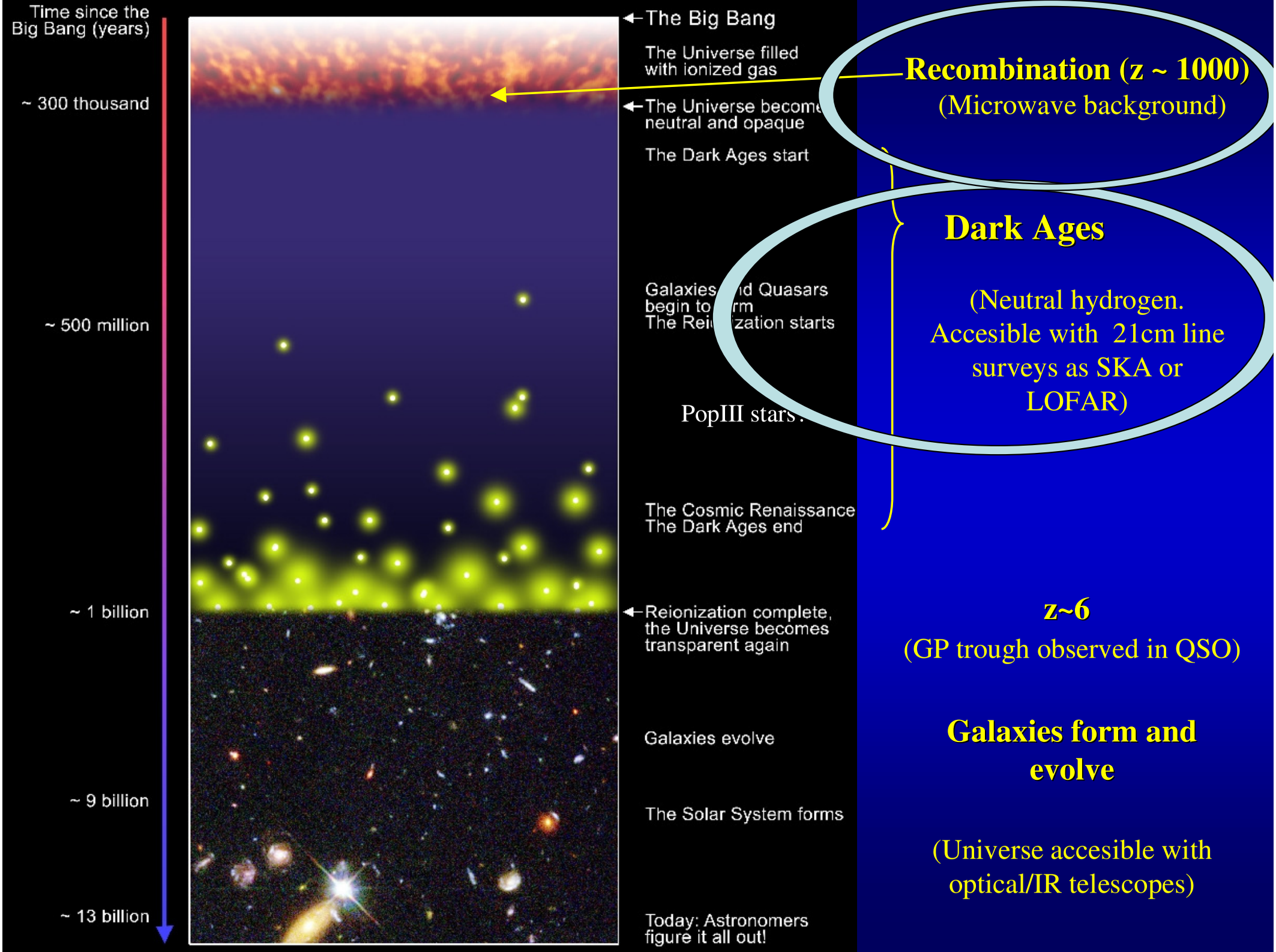
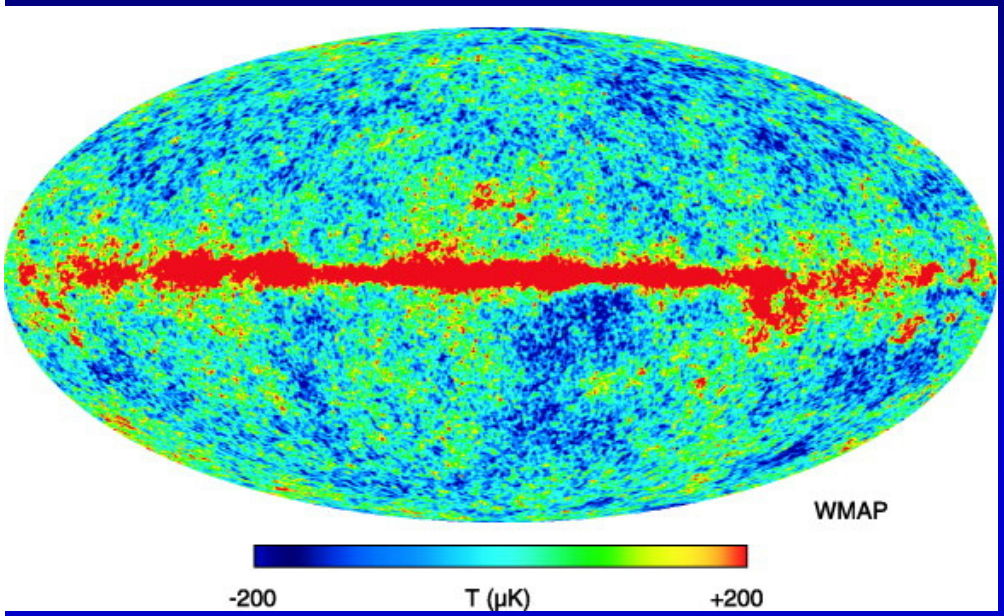
Benasque, August 4th, 2006

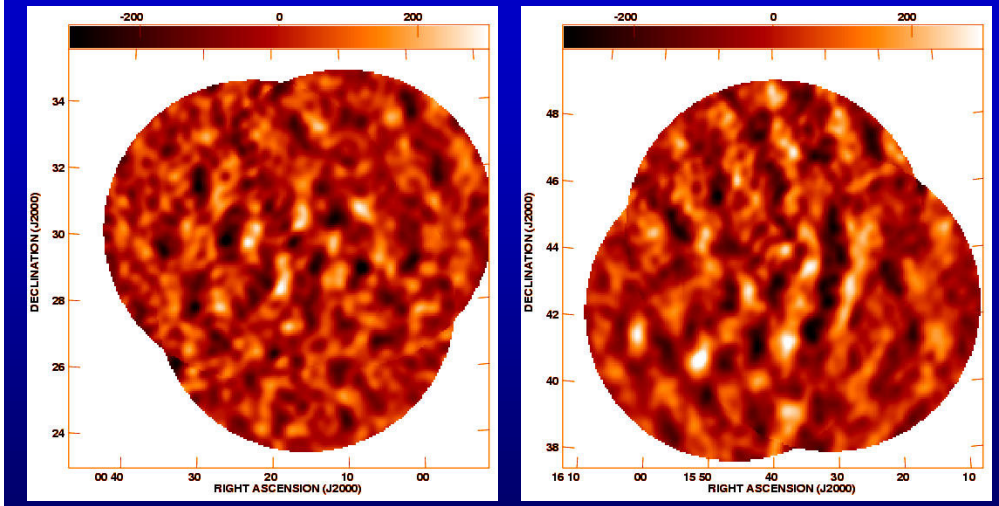

Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becom neutral and opaque
The Dark Ages start
Galaxies d Quasars begin to rm
The Rei zation starts
PopIII stars
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
Recombination (z ~ 1000)
(Microwave background)
Dark Ages
(Neutral hydrogen. Accesible with 21cm line surveys as SKA or LOFAR)
z~6
(GP trough observed in QSO)
Galaxies form and evolve
(Universe accesible with optical/IR telescopes)

Angular fluctuations of the CMB

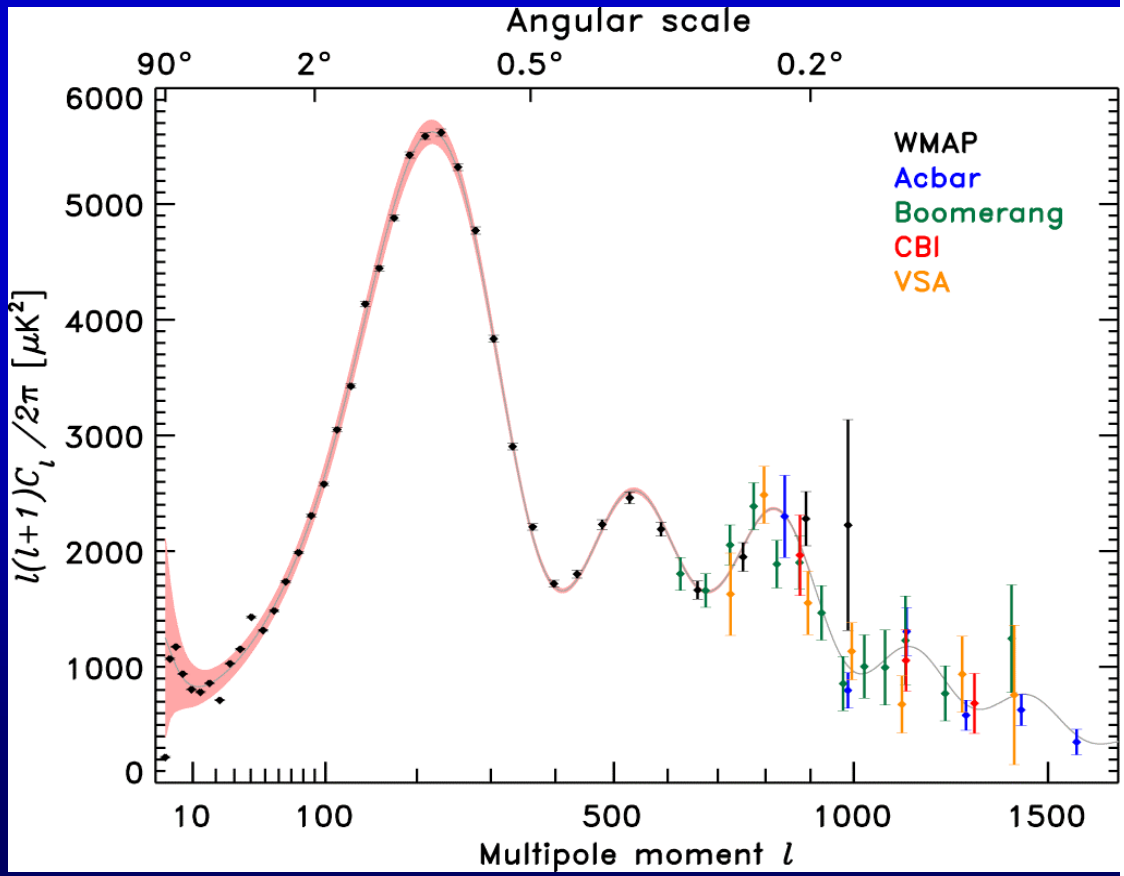


CMB anisotropies: Dynamics

- Initial conditions (inflation)
- Cosmological parameters

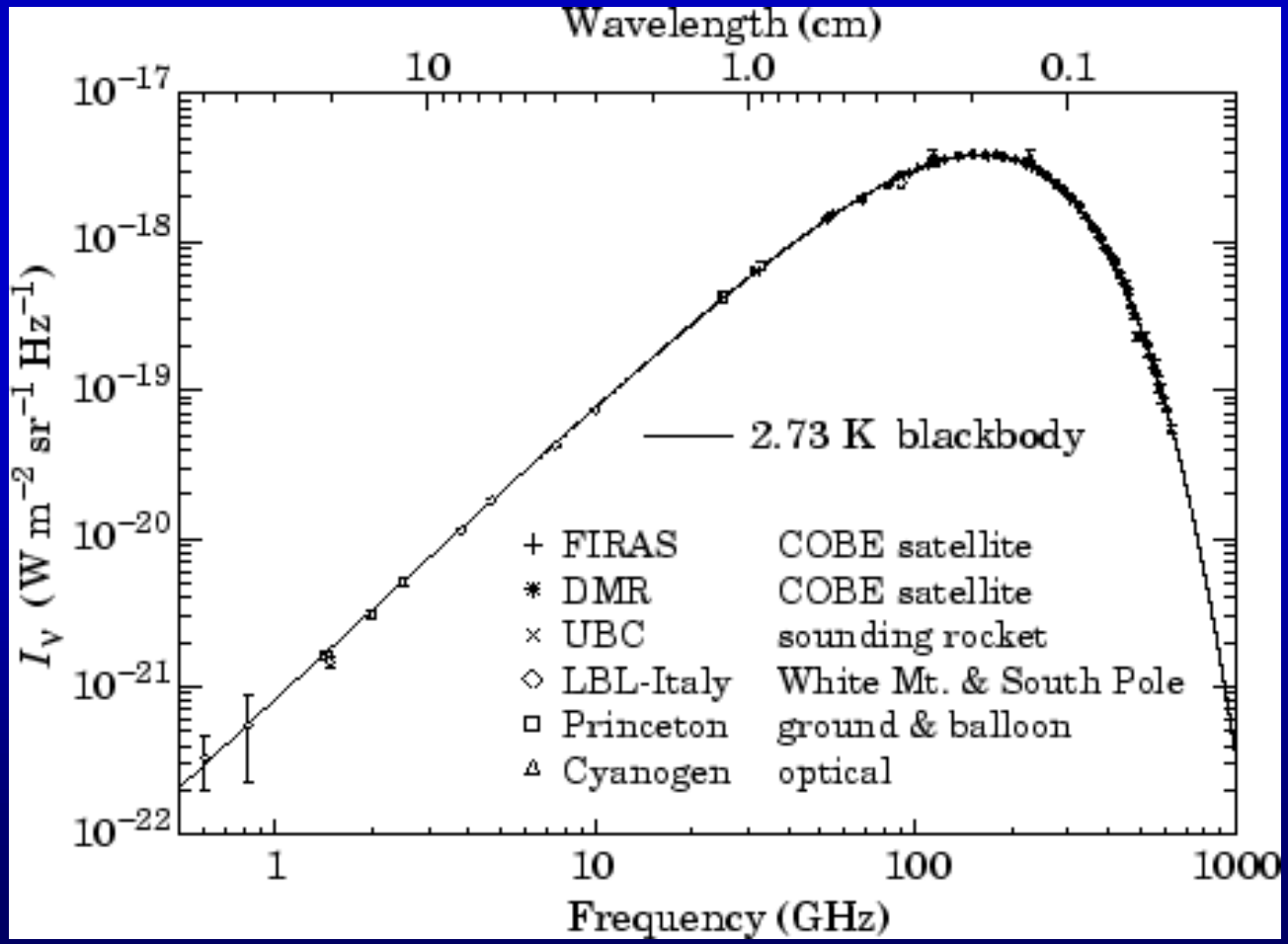


VSA



The CMB Spectrum

• Encodes information about **energetics** in the Universe (phase transitions in early universe; relic decay DM particles; reionization).

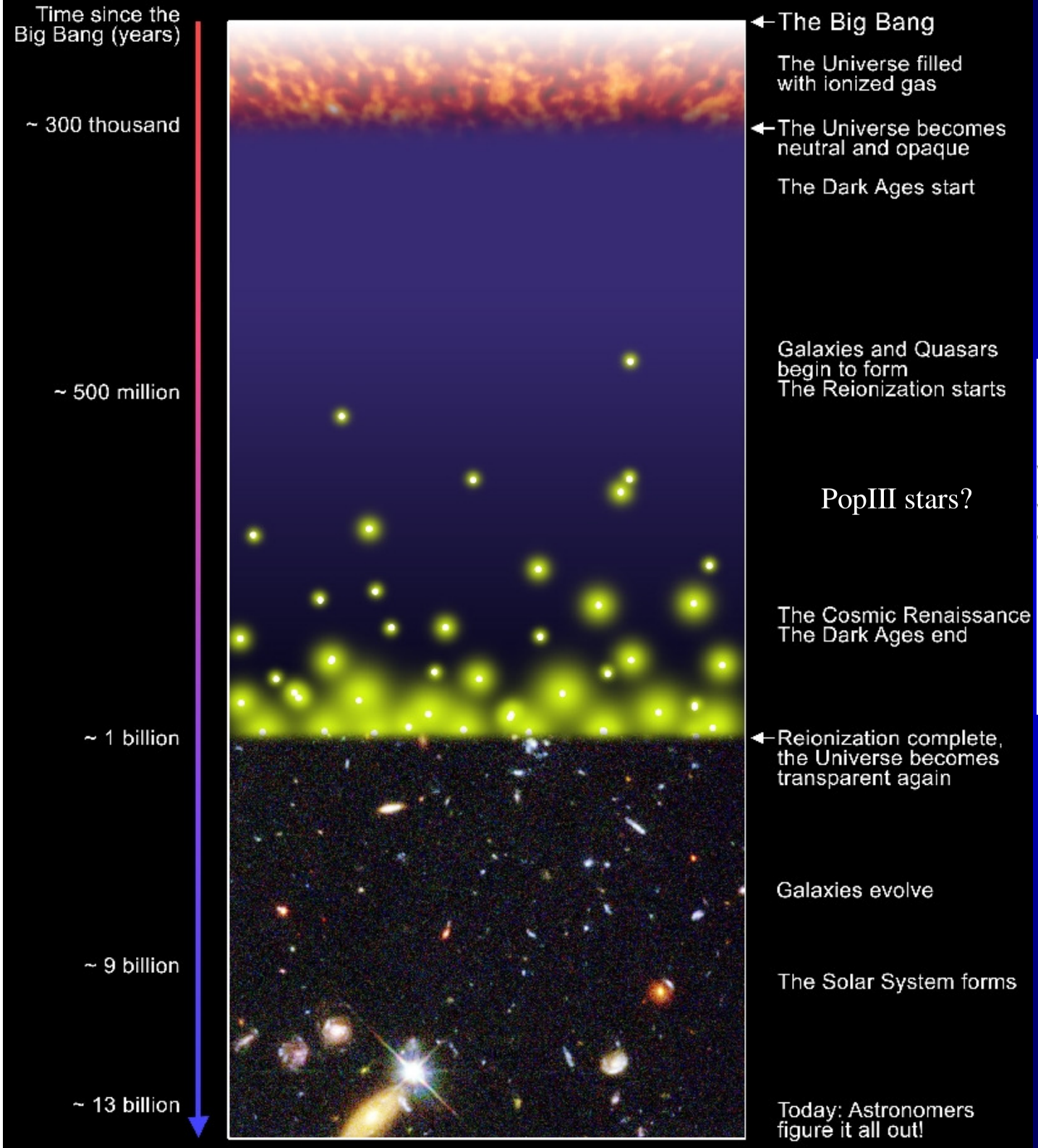


Blackbody spectrum with extremely high precission
(FIRAS, Fixsen & Mather 2002)

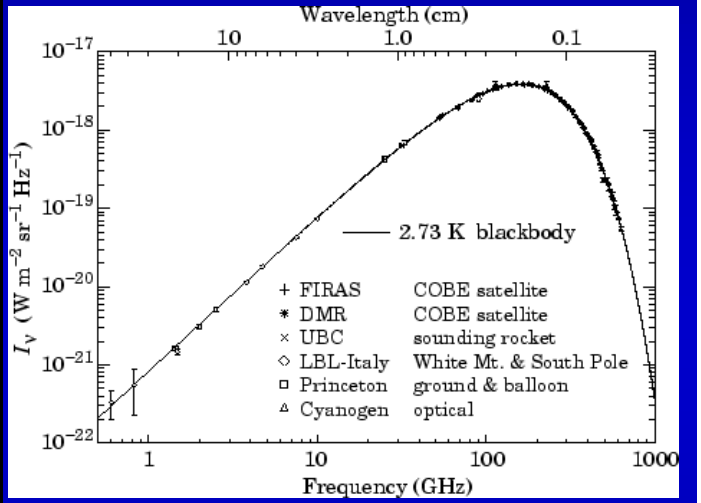
$T_0 = 2.725 \pm 0.001$ K

$|\mu| < 9 \times 10^{-5}$ (95% CL)

$|y| < 15 \times 10^{-6}$ (95% CL)



Is is possible to obtain spectral infomation from the epoch of recombination?



Or, in other words:

Where are the Ly-α photons from the epoch of recombination?

Overview

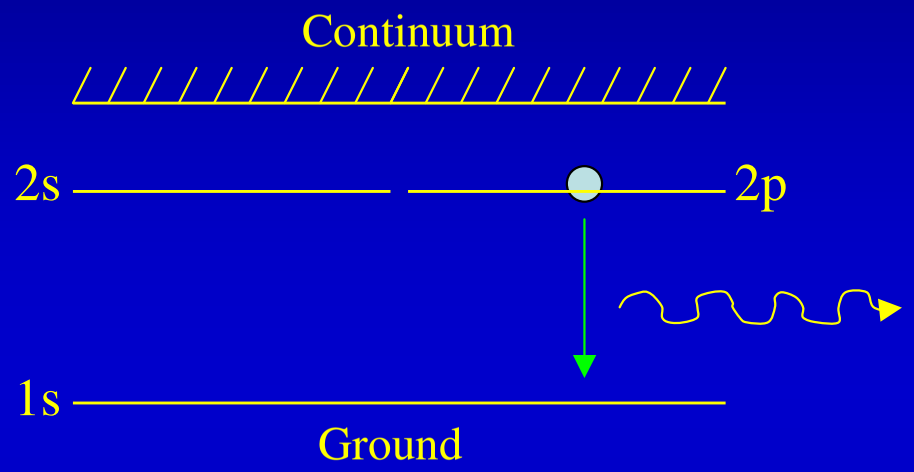
- Introduction. The Cosmological Hydrogen Recombination.
- Observing spectral features from recombination.
  - Hydrogen Spectrum from Recombination.
  - Effect on the angular power spectrum.
- Observability of the lines.
- Conclusions

How did the Universe became neutral?

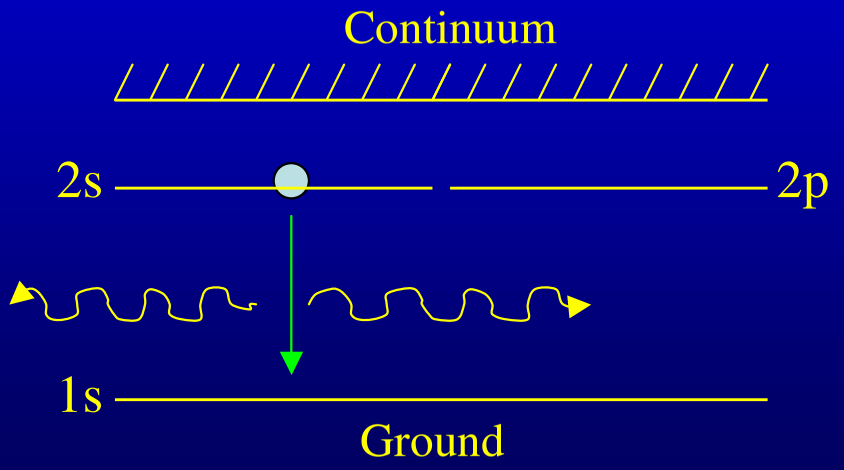
- Zel´dovich, Kurt & Sunyaev (1968) and Peebles (1968) were the first describing how the recombination occurs in the Universe.
- Two main arguments to understand Recombination:
  - Due to the high entropy of the Universe (~1.6×10^9 photons per baryon) recombination occurs at z= 1000. (Note that 13.6eV = 157800 K, but 3000K = 0.26eV). In addition, collisional processes are not important.
  - The Lyman-alpha photons are optically thick (Case B recombination). The main channel of the recombination is the 2s two-photon decay.

How did the Universe became neutral? (II)

a) Ly-α photon is absorbed by other atom



b) Two photons can escape.



- Effective 3-level atom.
- Direct recombinations to ground state do not produce a net recombination.
- Ly-α photons are optically thick and can not redshift before being re-absorbed. Level 2 overpopulated.
- Two photon 2s decay is the main channel, but the Einstein A-coefficient is

$$A_{2s1s}=8.22\ s^{-1}.$$

RECOMBINATION IS DELAYED

Where are the Ly-α photons from the epoch of recombination?

In the Wien tail of the Blackbody spectrum.

No. 1, 1968 PRIMEVAL PLASMA 9

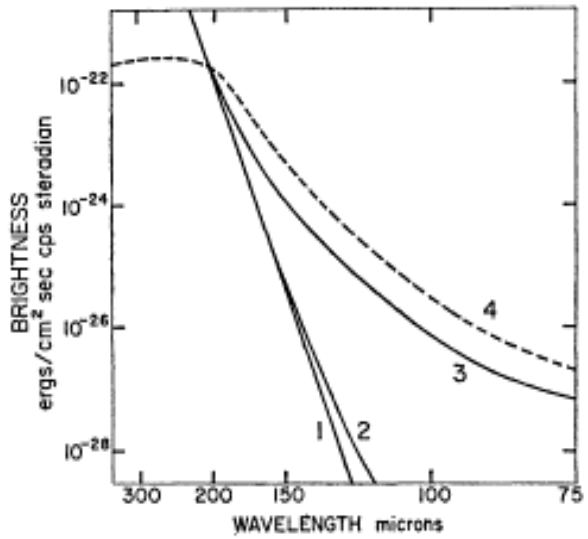
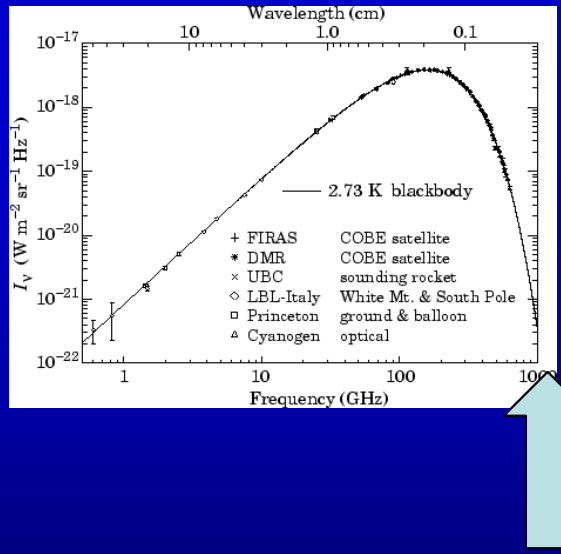
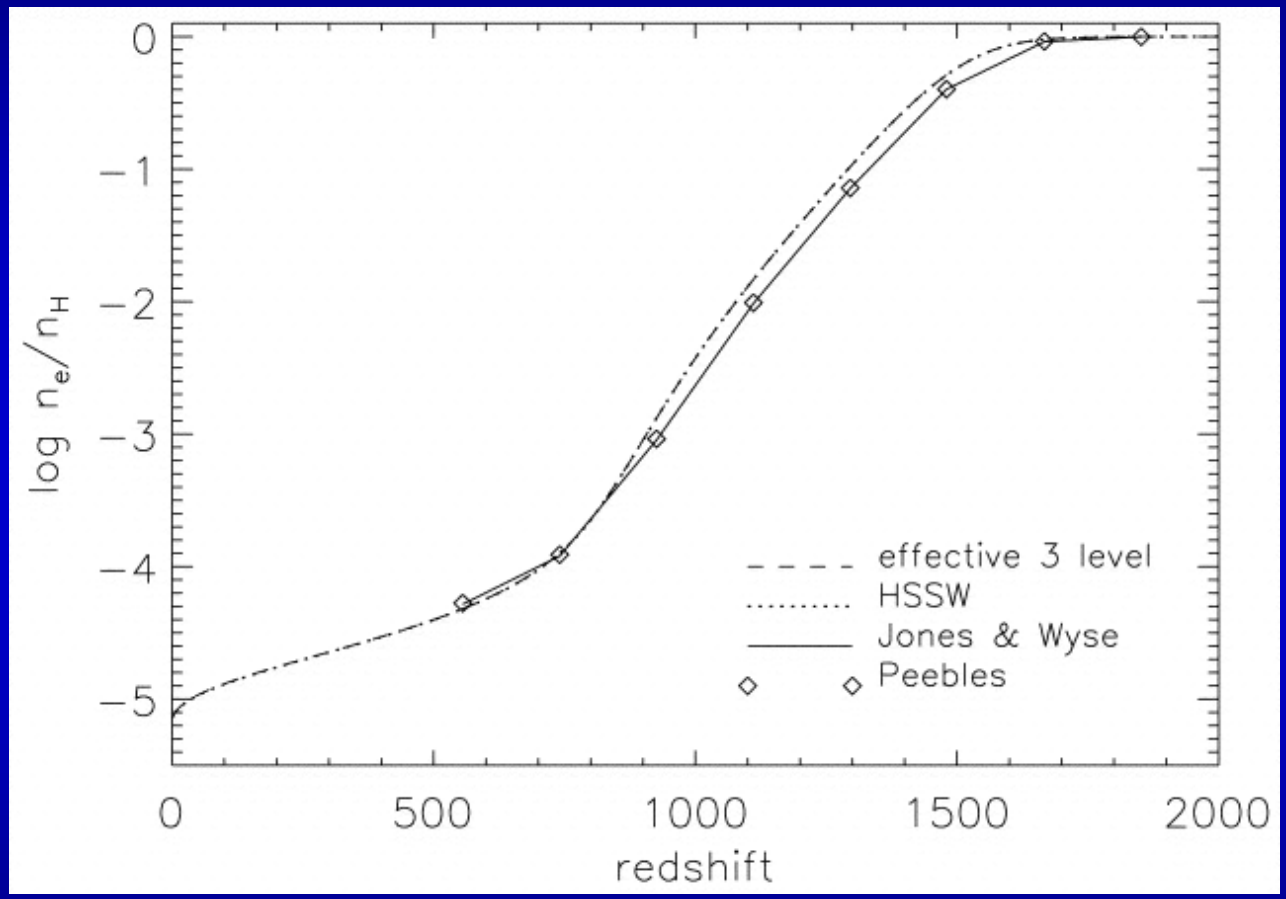


FIG. 1.—Spectrum of the Primeval Fireball radiation as it would be observed now is shown for a purely thermal spectrum (curve *1*), taking account of the redshifted ionizing recombination radiation (curve *2*), and taking account of the redshifted resonance line radiation (curve *3*). The dashed curve (*4*) shows the separate contribution due to two-quantum decay. The curves are computed for the flat cosmological model.



The problem is that in this spectral region, dust emission dominates (CIB).

How the Universe became neutral? (III)

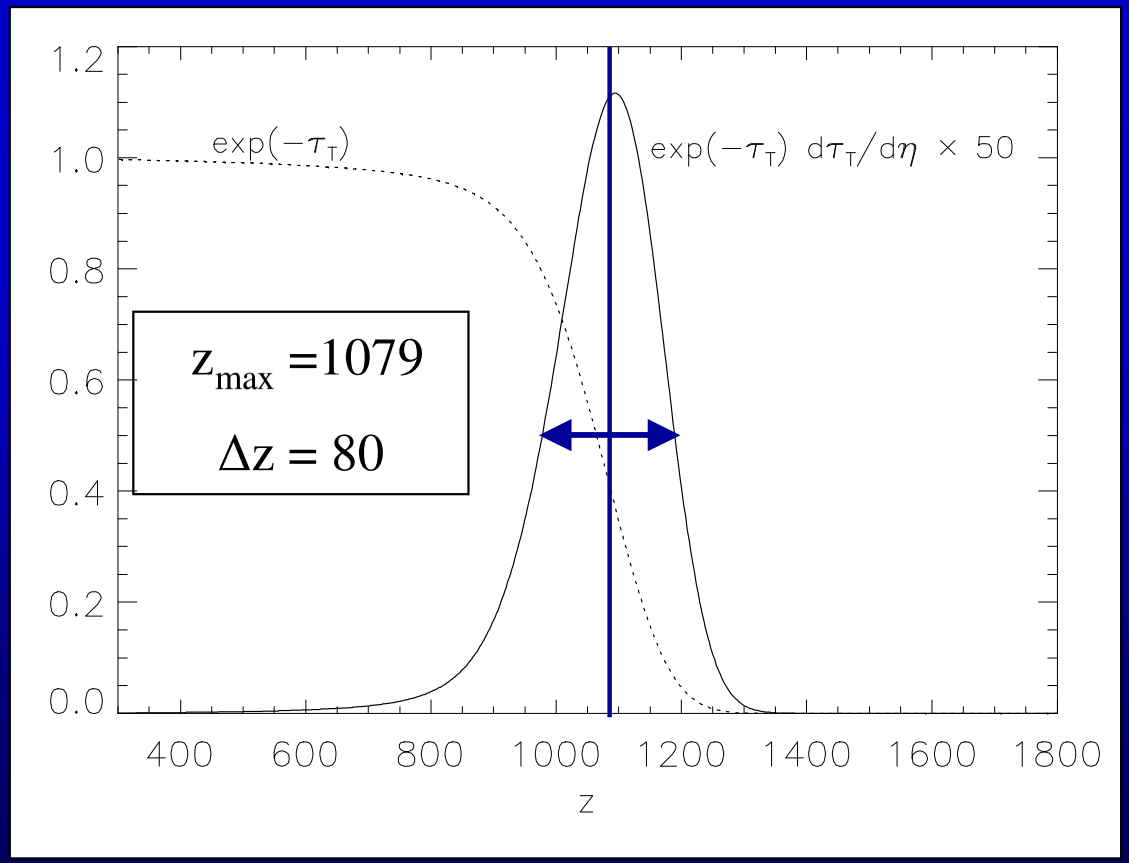


- Zel´dovich, Kurt & Sunyaev (1968)
- Peebles (1968)
- Lyubarsky & Sunyaev (1983)
- Jones & Wyse (1985)
- Hu et al. (1995, HSSW)
- Seager, Sasselov & Scott (1999, 2000).

This curve is a key ingredient to predict the angular power spectrum of the CMB, because it directly gives the fraction of free electrons.

The (Thomson) visibility function

Prior to the recombination epoch, the photons and the electrons are tighly coupled due to Thomson scattering. When the number density of electrons decreases, the photons are released and the CMB is formed.



•The relevant quantity is the Thomson optical depth.

$$\tau = \int \sigma_T \, n_e \, dl$$

•The **visibility function** gives the probability that a photon observed now was last scattered at redshift z:

$$V = \exp(-\tau) \, d\tau/d\eta$$

Recombination. Basic equations

1. The radiation field. Given by the **radiative transfer equation**. For an homogeneous and isotropic (I -> J) expanding medium:

$$\frac{dJ(\nu, t)}{dt} = \frac{\partial J(\nu, t)}{\partial t} - \nu H(t) \frac{\partial J(\nu, t)}{\partial \nu}$$
$$= -3H(t)J(\nu, t) + c[j(\nu, t) - \kappa(\nu, t)J(\nu, t)] ,$$

This equation is in its most general form and is difficult to solve, but we can do two assumptions:

- The spectral distortions are very small (FIRAS: Fixsen et al. 1996, showed that $\Delta I/I_0 < 10^{-4}$). Thus, J(ν,t)=B(ν,t).
- Quasi-static solution for spectral-line profile is valid (Rybicki & Dell´Antonio 1994). We can use the Sobolev escape probability method to deal with the evolution of all lines.

Basic equations (II)

2. The rate equations.

$$a(t)^{-3}\,\frac{d[n_i(t)a(t)^3]}{dt} = [n_e(t)n_c(t)P_{ci} - n_i(t)P_{ic}] + \sum_{j=1}^{N}[n_j(t)P_{ji} - n_i(t)P_{ij}]\ ,$$

- Collisional rates are of minor importance (Peebles 68, Seager et al. 2000).
- Photoionization/Photorecombination **radiative** rates are computed by integrating the blackbody radiation field, e.g.

$$R_{ic} = 4\pi\int_{\nu_0}^{\infty}\frac{\sigma_{ic}(\nu)}{h_P\,\nu}\,J(\nu,\,t)d\nu\ .$$

$$\sum_{i>1}^{N} n_e\,n_c\,R_{ci} = n_e\,n_c\sum_{i>1}^{N}\left(\frac{n_i}{n_e\,n_c}\right)^{\rm LTE} 4\pi\int_{\nu_0}^{\infty}\frac{\sigma_{ic}(\nu)}{h_P\,\nu} \times\left(\frac{2h_P\,\nu^3}{c^2} + B(\nu,\,T_R)\right)e^{-h_P\,\nu/k_B\,T_M}\,d\nu\ .$$

Basic equations (III)

3. **Sobolev escape probability method**. The net bound-bound rate is:

$$\Delta R_{ji} = p_{ij}\{n_j[A_{ji} + B_{ji}\,B(\nu_{ij}, t)] - n_i\,B_{ij}\,B(\nu_{ij}, t)\}\ .$$

The escape probability p_{ij} encodes the probability that photons associated to the considered transition will "escape" without being further scattered or absorbed. The concept is similar to stellar atmospheres.

In this case, it can be shown that (Seager et al. 2000; Dubrovich & Grachev 2004)

$$\tau_S = \frac{A_{ji}\,\lambda_{ij}^3[n_i(g_j/g_i) - n_j]}{8\pi H(z)}\ .$$

$$p_{ij} = \frac{1 - \exp\,(-\tau_S)}{\tau_S}\ .$$

Basic equations (IV)

4. **Matter temperature** evolution (Compton cooling + adiabatic expansion)

$$(1+z)\frac{dT_M}{dz} = \frac{8\sigma_T U}{3H(z)m_e c}\frac{n_e}{n_e + n_H + n_{He}} \times (T_M - T_R) + 2T_M$$

5. Other equations.
    1. Hubble constant evolution
    2. Helium recombination.

Recombination. Status of the art (I)

- After ZKS68 and P68, many authors have refined the computation of the recombination process, based on the effective 3-level atom model (e.g. Jones & Wyse 1985).
- To solve the complete set of ODEs (ordinary differential equations) is computationally difficult. The problem is very stiff, and the accuracy requierements are very high.
- If one is not interested in the lines, but in the total electron fraction, the accuracy requierements can be relaxed.
- In addition, one can assume statistical equilibrium between the l-substates, i.e. that the sublevels are populated according to $N(n,l)=(2l+1)\,N(n,l=0)$. This is not obvious for the cosmological recombination, where collisions are not important.
- Best determination to date: Seager, Sasselov & Scott (1999, 2000), used a 300-level hydrogen atom (statistical equilibrium between l-substates assumed). This is the **RECFAST** code. Focused on n_e.

Recombination. Status of the art (II)

• Dubrovich (1975) proposed to look for spectral distortions for higher transitions.

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• Ma lupenko et al. 200 l with the equa mplitude of the l

• On nio 1993), but the r

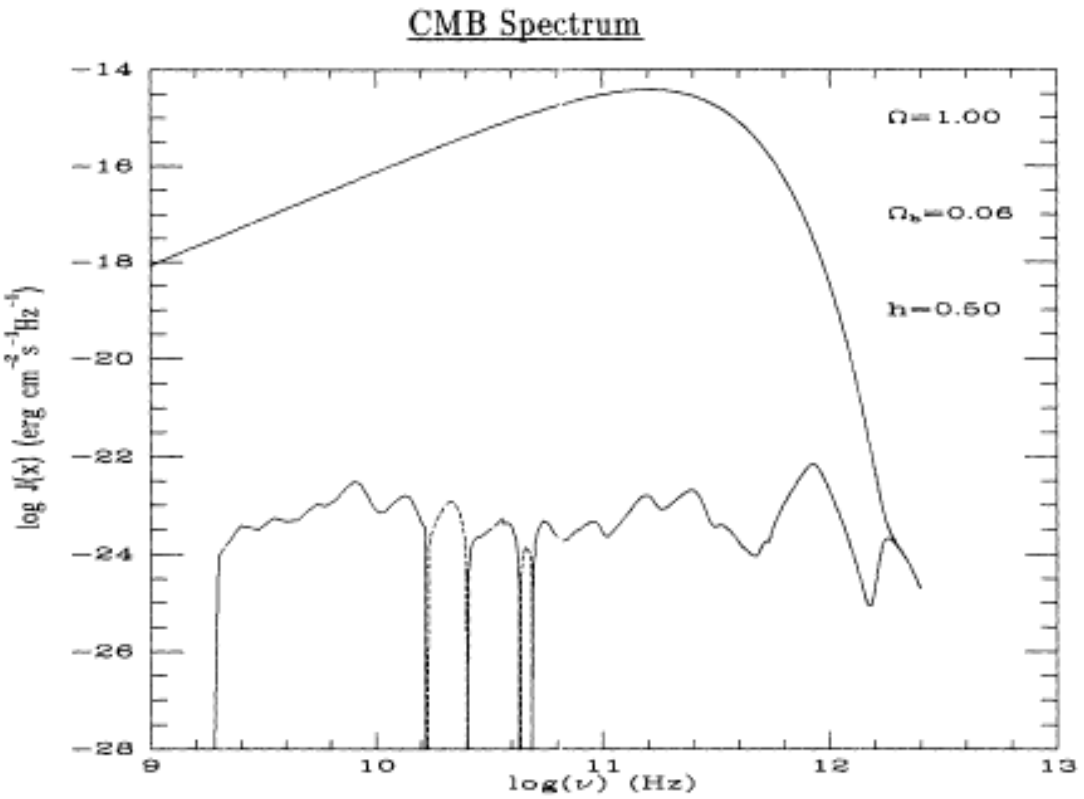


Figure 2. The spectral distortions in the CMB in a sample run. The upper line represents the total spectrum, the lower line the distortions. The dotted lines show the absorption features.

Our work: how to observe spectral features from the epoch of recombination

- **Frequency Spectrum**. We have computed the spectral distortions to the blackbody arising from H recombination in the frequency range 1- 3500 GHz.
- **Resonant (coherent) scattering of CMB photons**. Use angular fluctuations and observations at different frequencies.

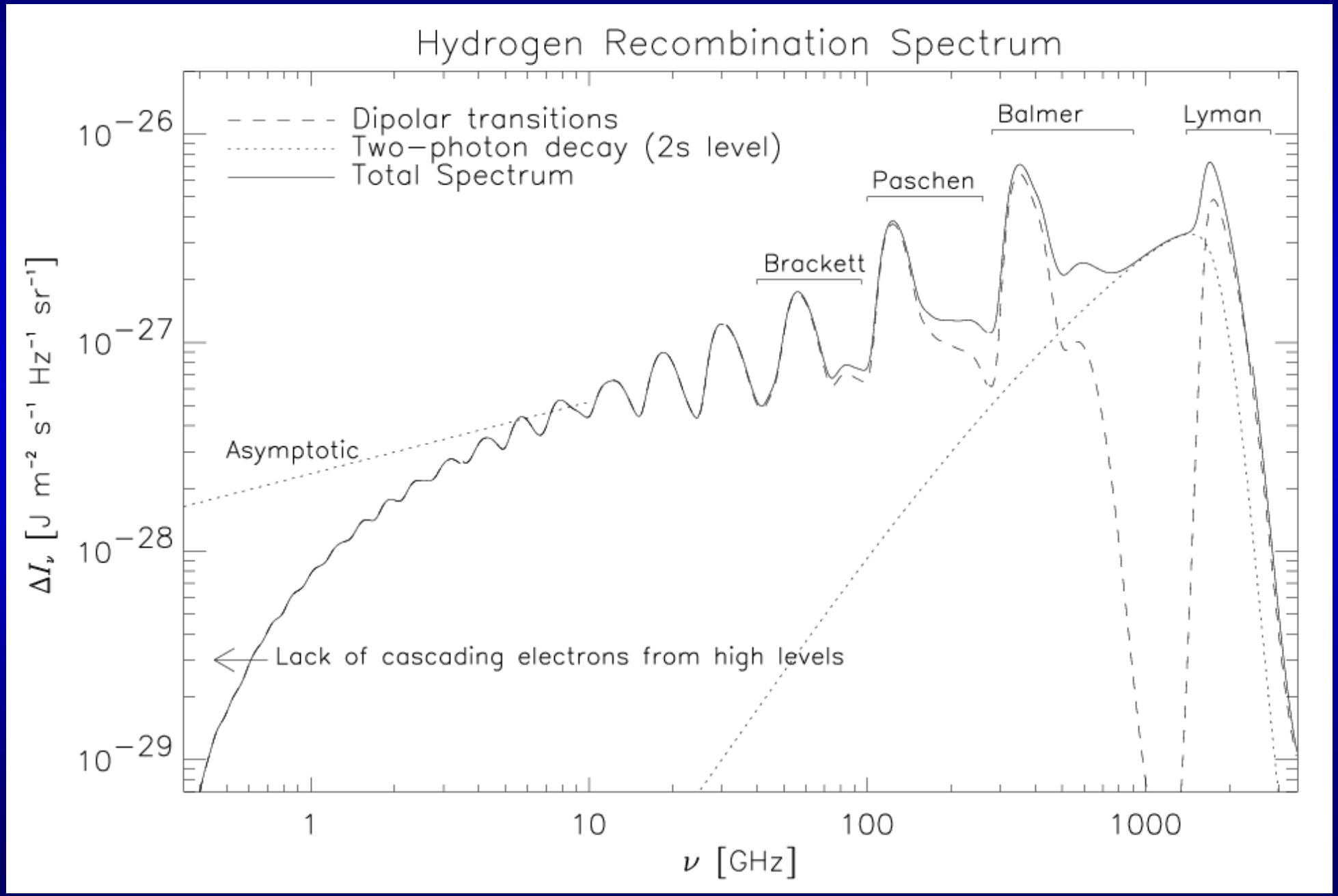
Hydrogen Recombination Spectrum

(Rubiño-Martín, Chluba & Sunyaev 2006 MNRAS accepted, astro-ph/0607373)

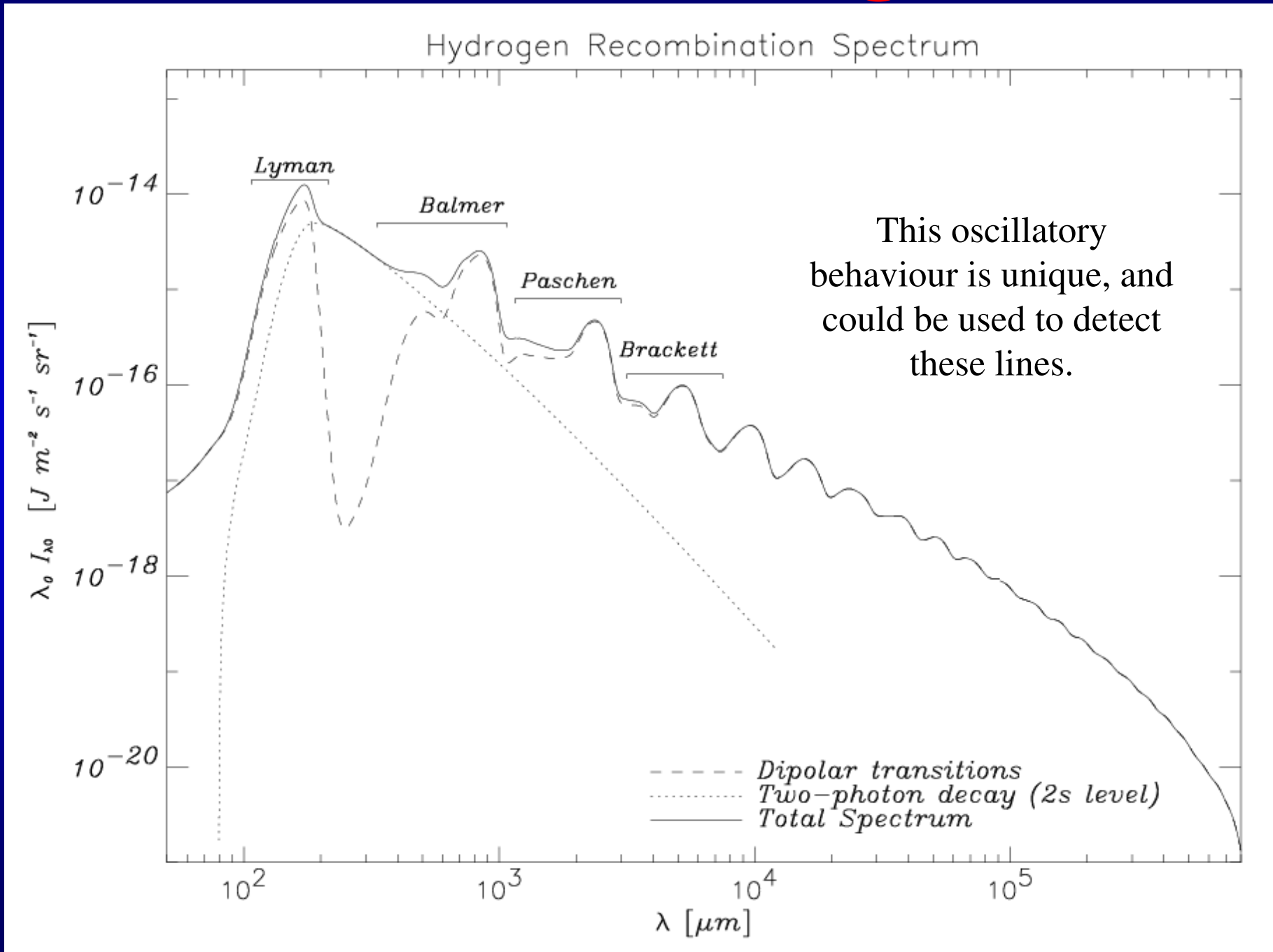
- All states (including angular momentum sublevels) treated in detail up to n=30. Thus, 465 levels are solved simultaneously for the hydrogen atom. (We use a variable-order, variable-step method implementing the backward differentiation formulae).
- Integration range in redshift: [500, 3500]
- Spectral distortion due to the 2s two photon decay included.
- Lines (bound-bound transitions) are computed as:

$$\Delta I_{ij}(\nu) = \frac{ch}{4\pi} \frac{\Delta R_{ij}(z_{\rm em})}{H(z_{\rm em})\,[1+z_{\rm em}]^3}\,,$$

Hydrogen Recombination Spectrum

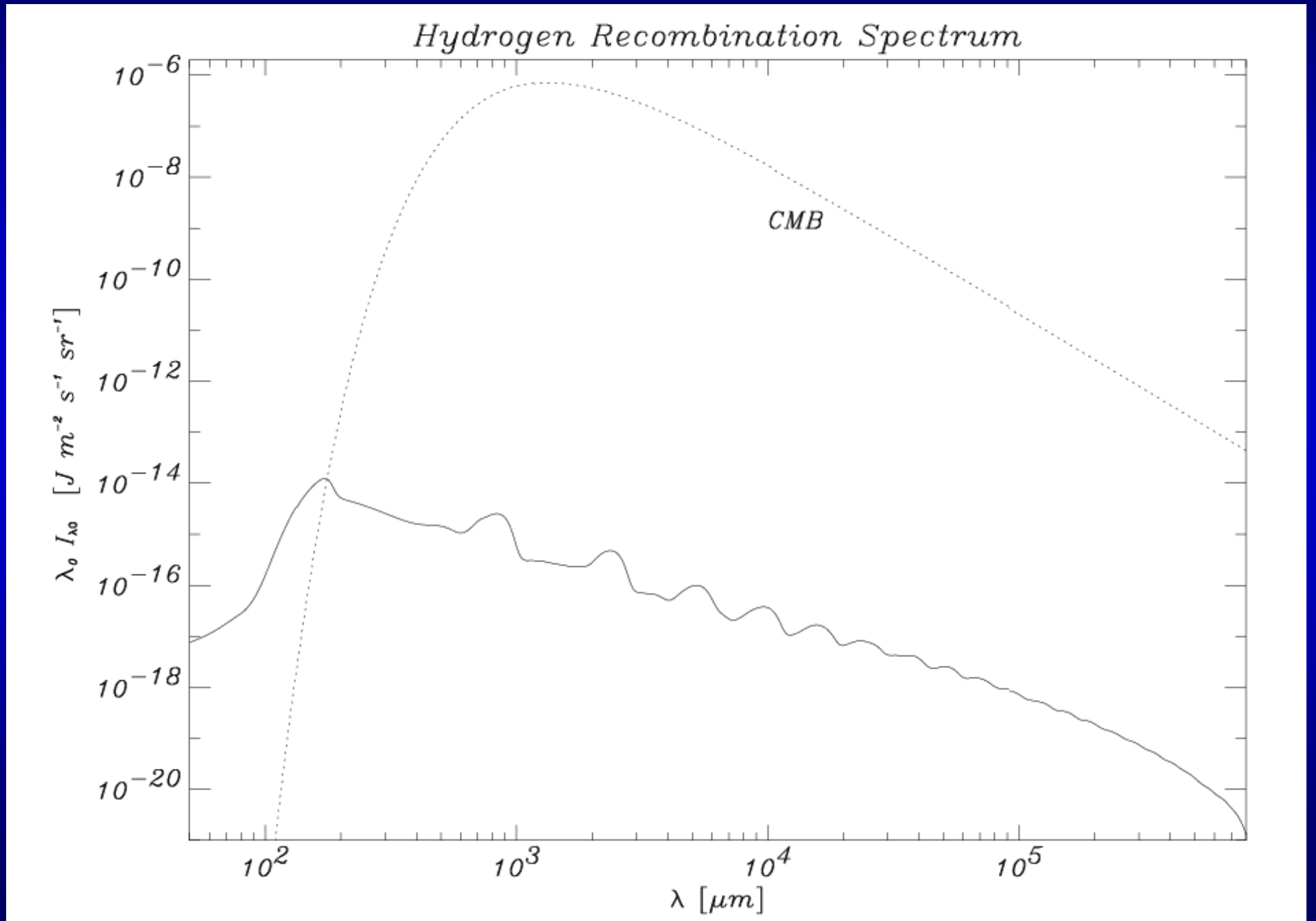


... or in wavelengths

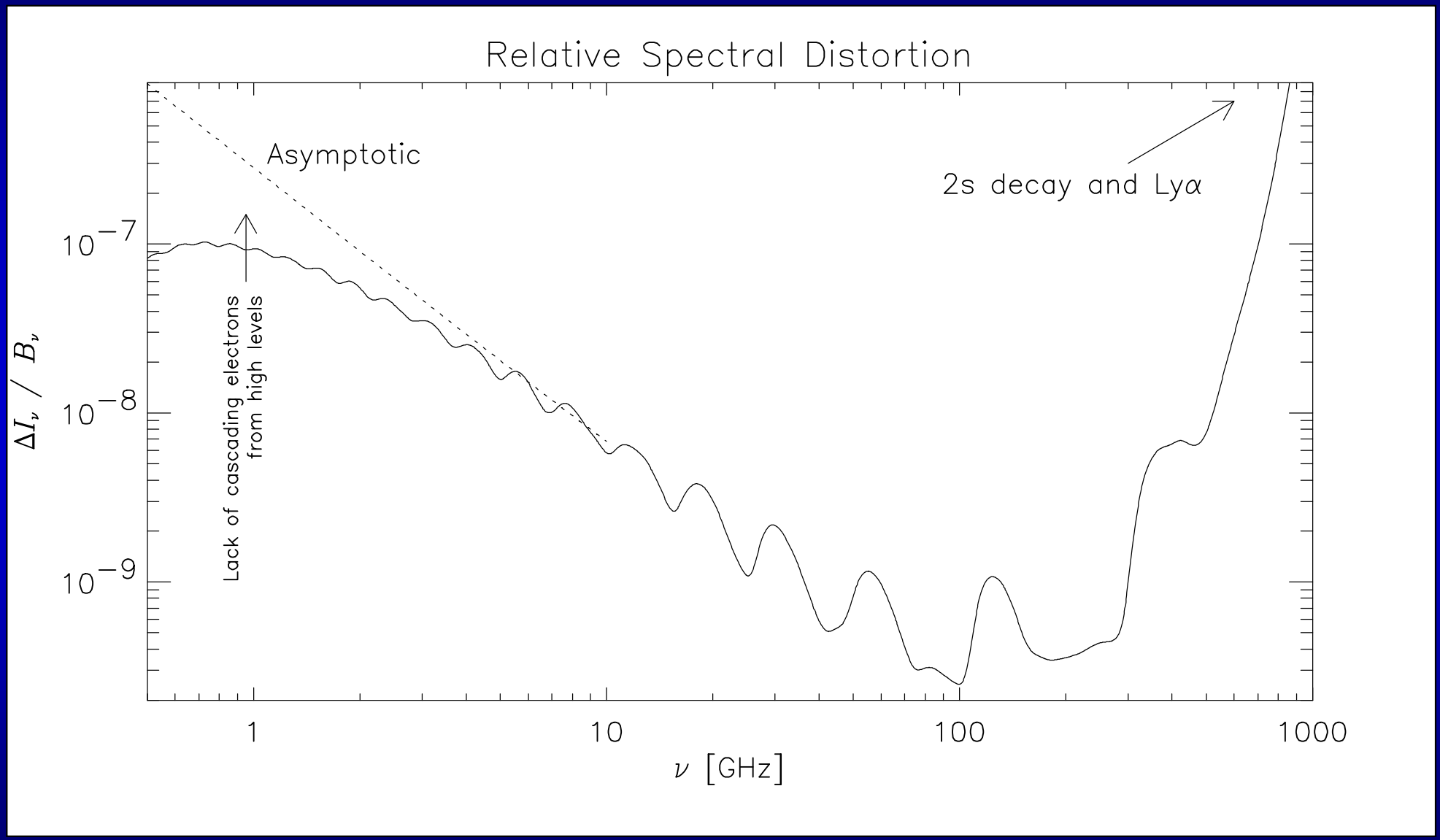


This oscillatory behaviour is unique, and could be used to detect these lines.

Relative intensity of the lines



Relative intensity of the lines



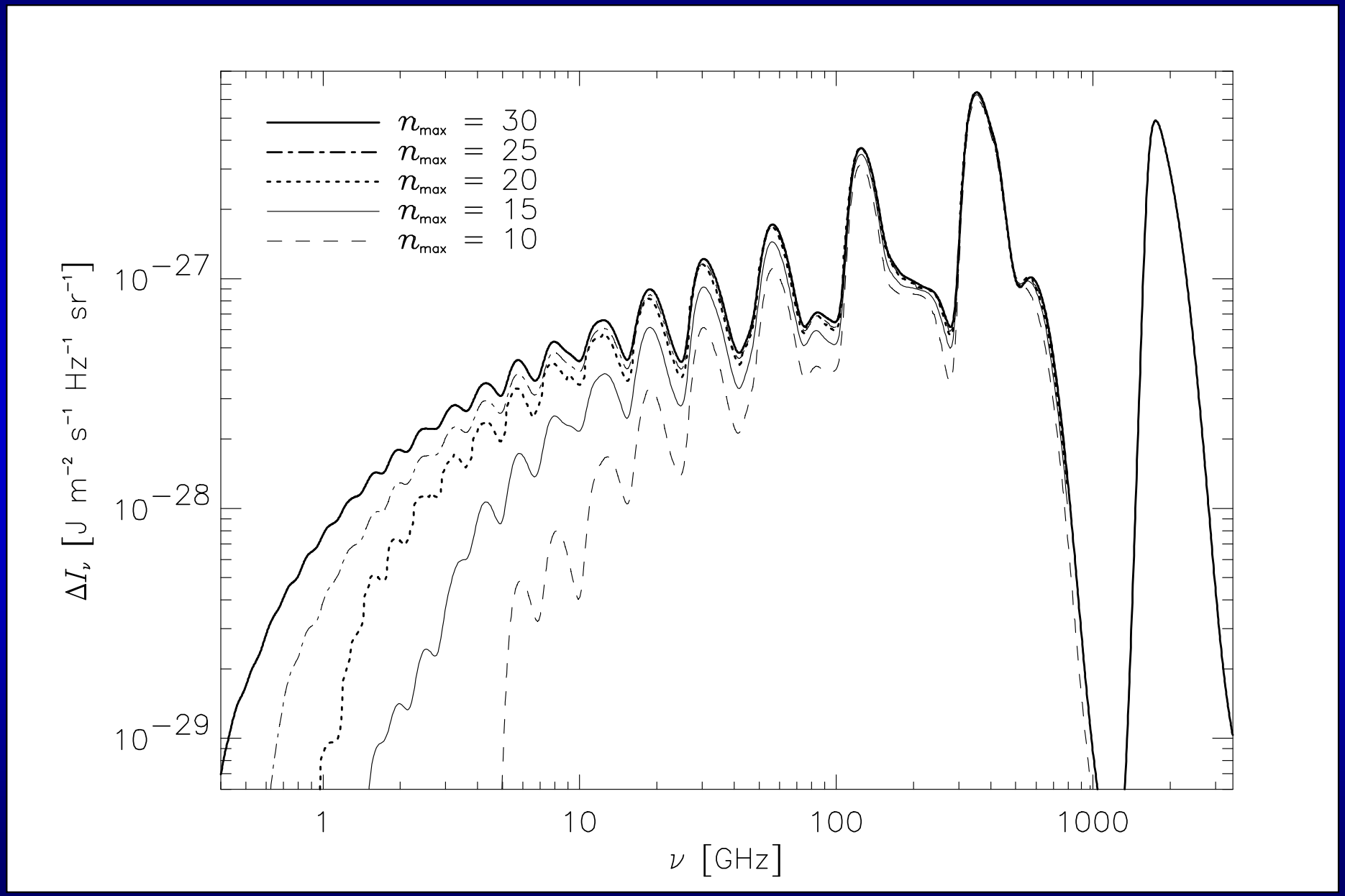
Positions and widths of the features

Table 1. Positions and amplitudes of the main features shown in Fig. 1. We show the central frequency (ν_0) and wavelength (λ_0) as observed today, the relative width at half maximum ($\Delta\nu/\nu$) and the peak intensity for the features corresponding to the first five series of hydrogen. For comparison, the last five columns show the central redshift of formation, the central frequency, the relative width, the peak and relative amplitude of the corresponding α-transition (i.e. $\Delta n = 1$) when considered separately.

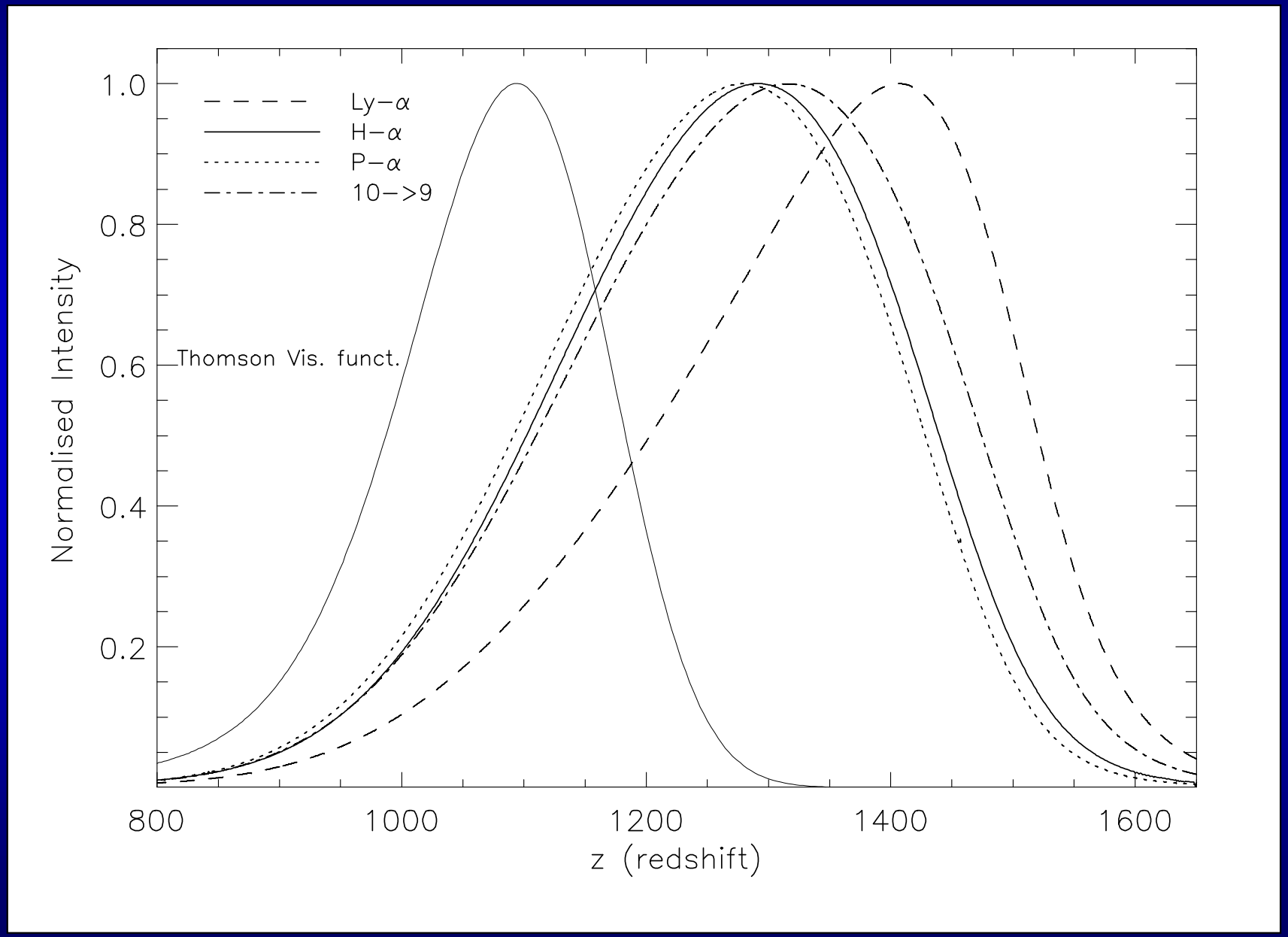
Series	n	ν_0 [GHz]	λ_0 [μm	$\Delta\nu/\nu$	ΔI_ν(peak) [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]	z_α	ν_α [GHz]	$(\Delta\nu/\nu)_\alpha$	ΔI_α [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]	$\Delta I_\alpha/\Delta I_\nu$ [%]
Lyman	1	1732	17	0.28	7.4×10^{-27}	1407	1752	0.23	4.8×10^{-27}	65
Balmer	2	353	84	0.37	7.2×10^{-27}	1274	358	0.26	6.5×10^{-27}	93
Paschen	3	125	239	0.31	3.8×10^{-27}	1259	127	0.26	3.3×10^{-27}	87
Brackett	4	56	535	0.36	1.8×10^{-27}	1304	57	0.27	1.2×10^{-27}	67
Pfund	5	30	9993	0.39	1.2×10^{-27}	1312	31	0.27	7.3×10^{-28}	61

They are broad features. Electron broadening is not changing this picture.

Convergence of the result

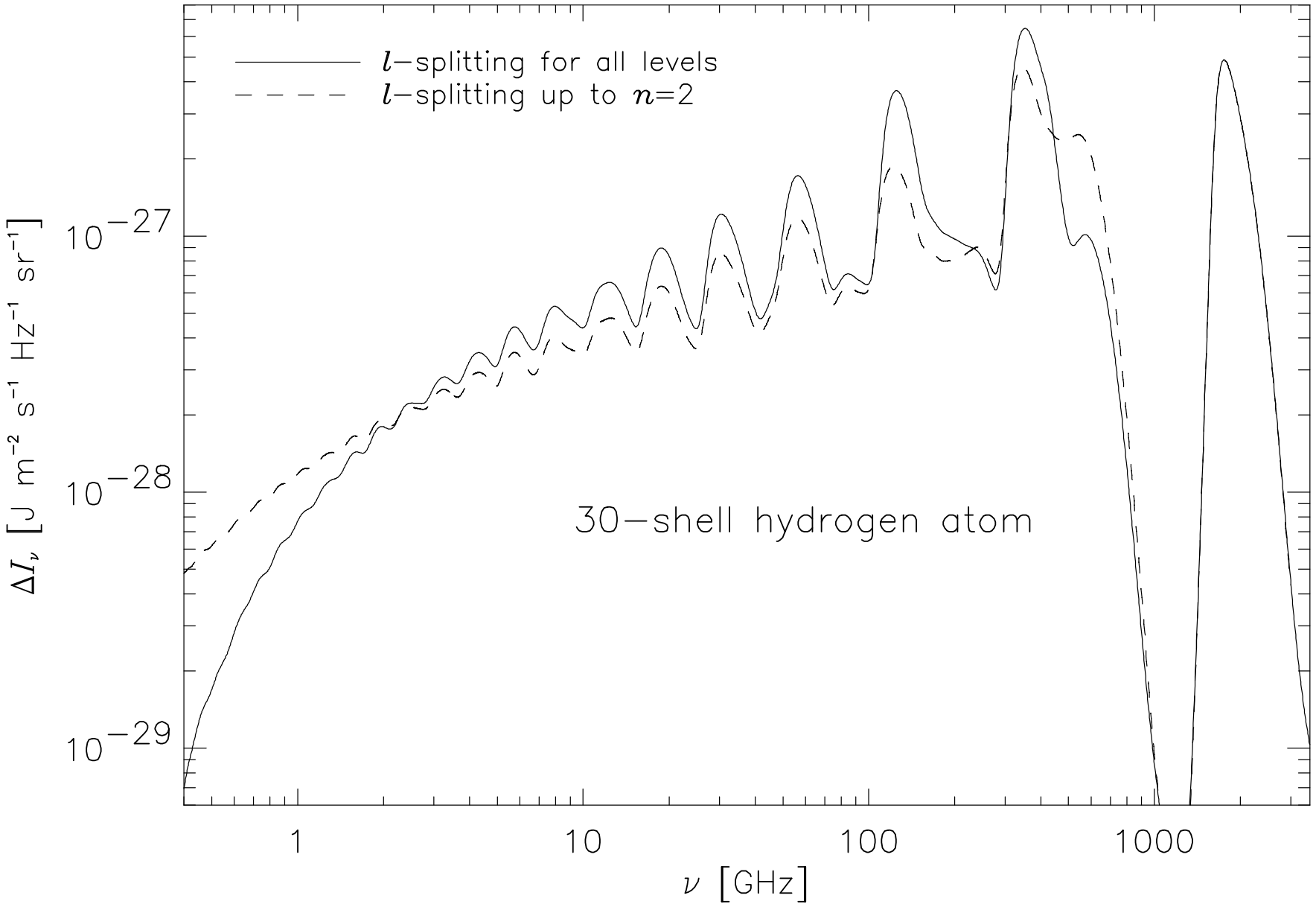


Redshift of formation of the lines

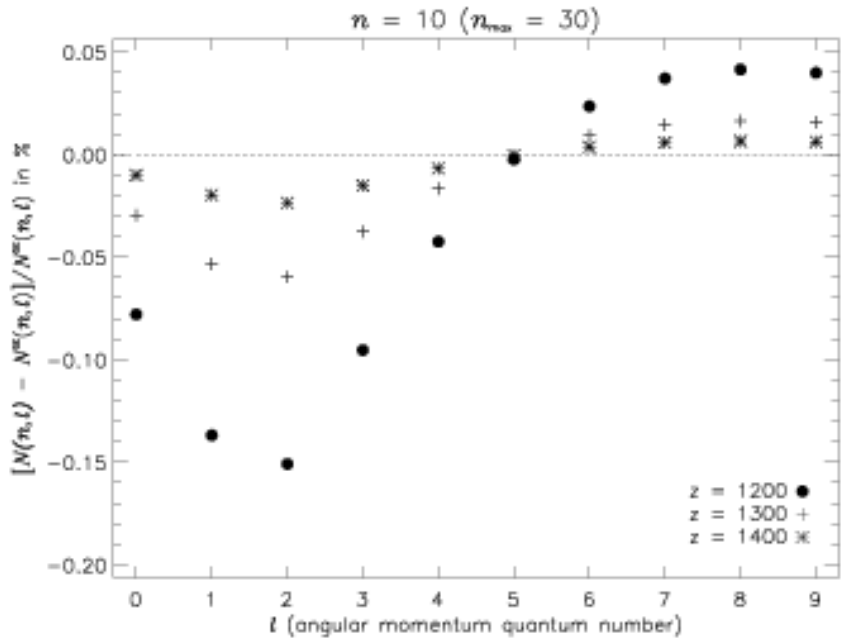


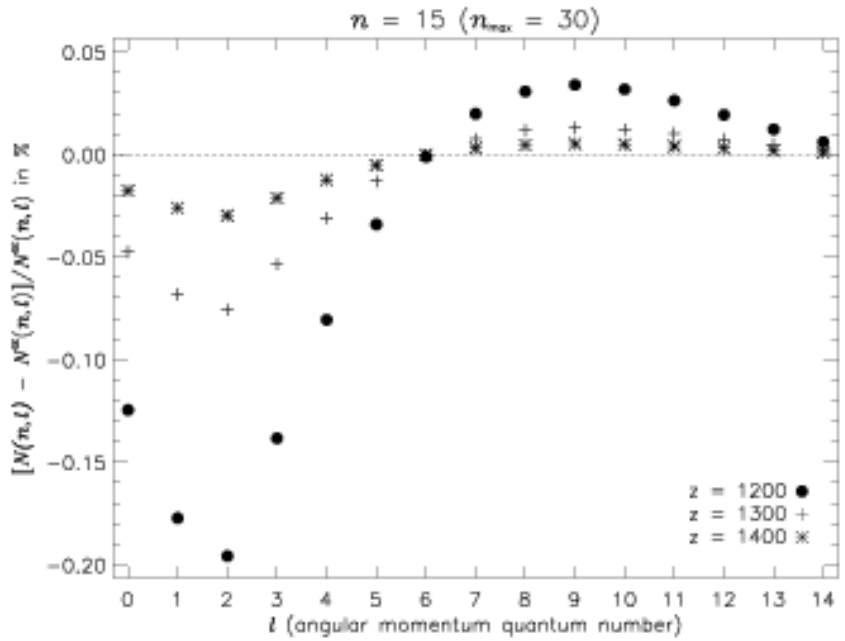
Lines are formed prior to the epoch of recombination

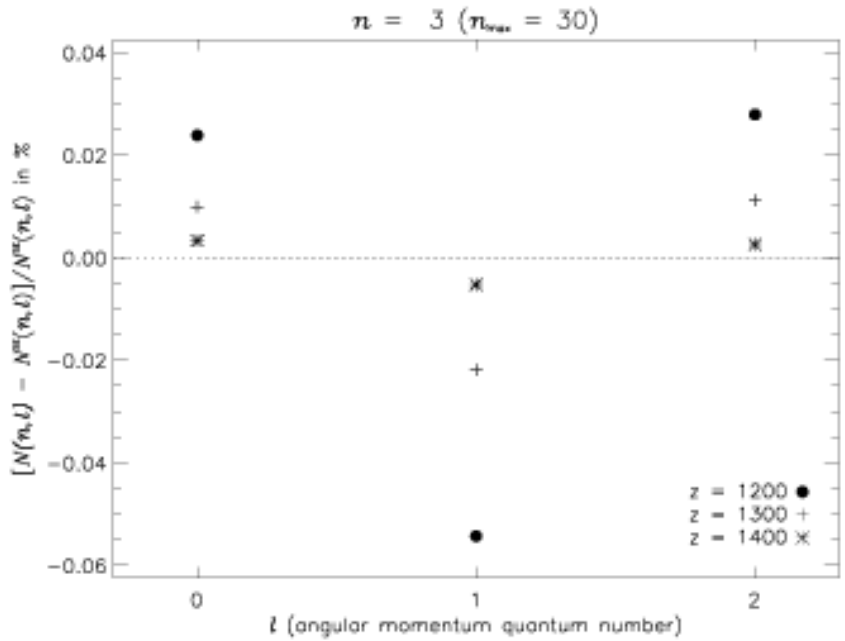
Importance of detailed l-treatment

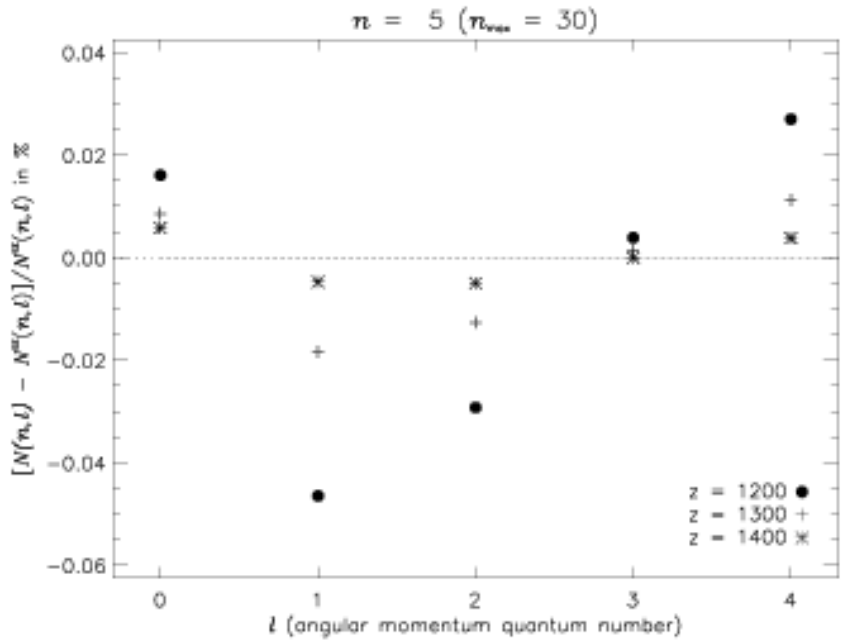


Importance of detailed l-treatment









Impact on the residual electron fraction

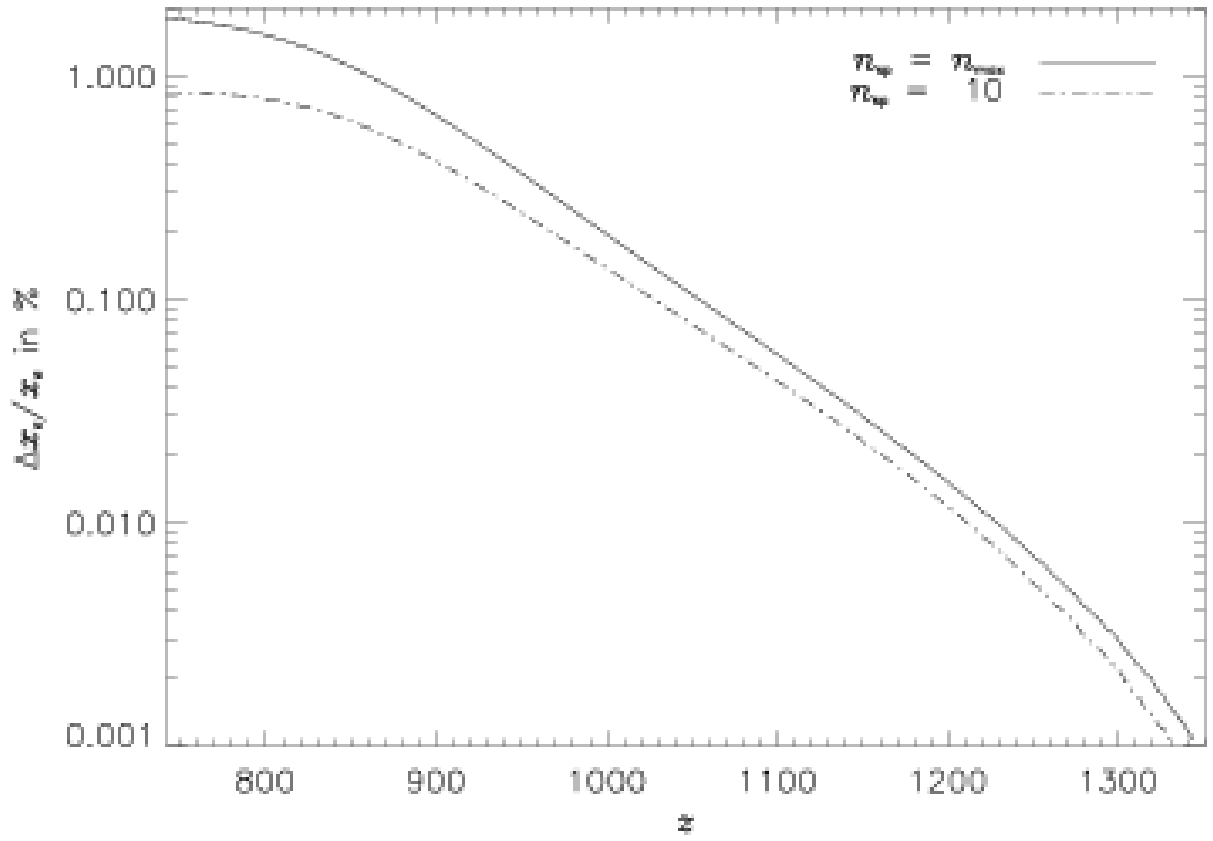
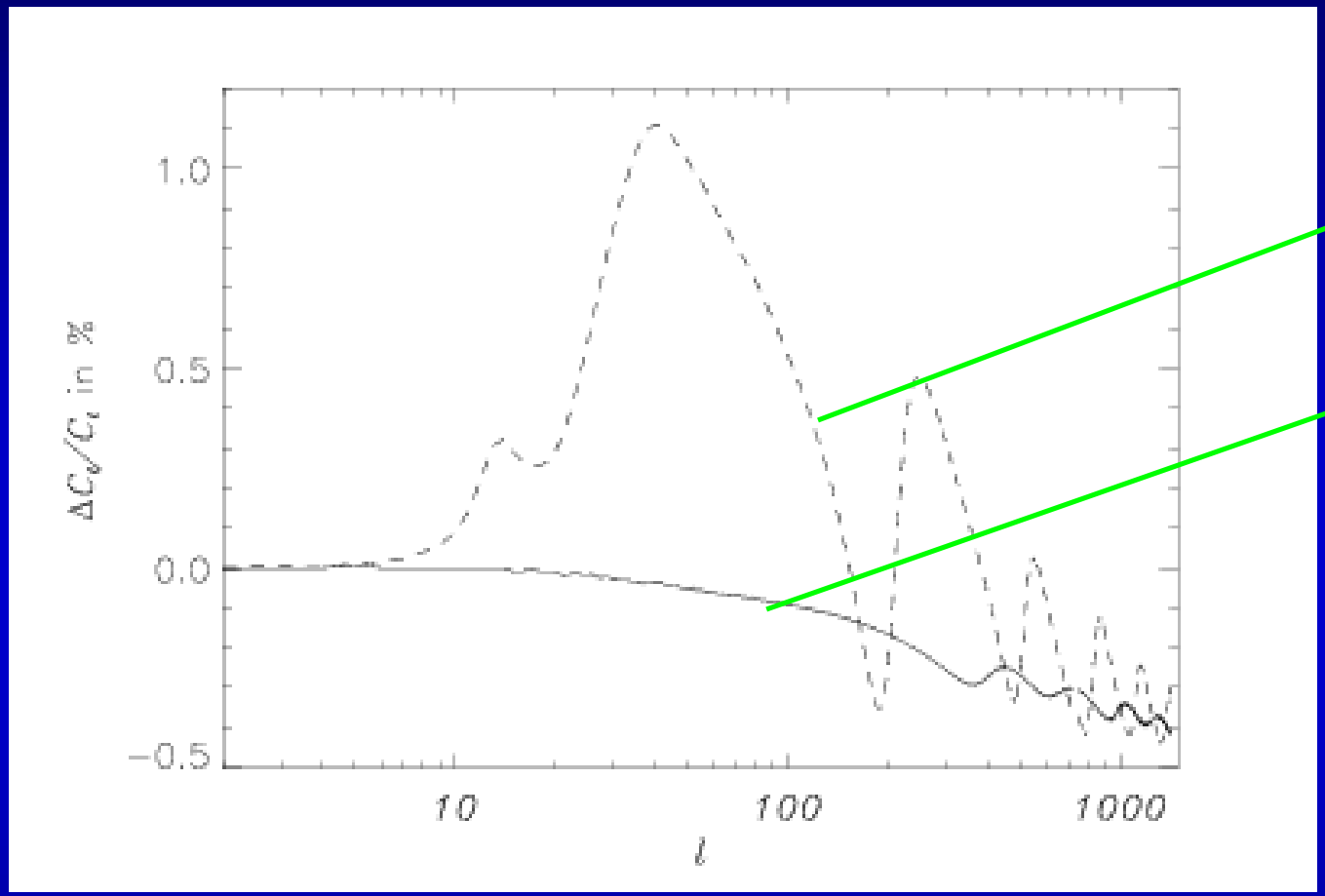


Figure 14. Relative change in the free electron fraction ($x_e = N_e/N_H$). We consider the 25-shell atom and show the relative difference in x_e with respect to the standard computation ($\Delta x_e/x_e \equiv [x_e - x_e(n_{sp} = 2)]/x_e(n_{sp} = 2)$) for two cases: full computation ($n_{sp} = n_{max}$) and $n_{sp} = 10$.

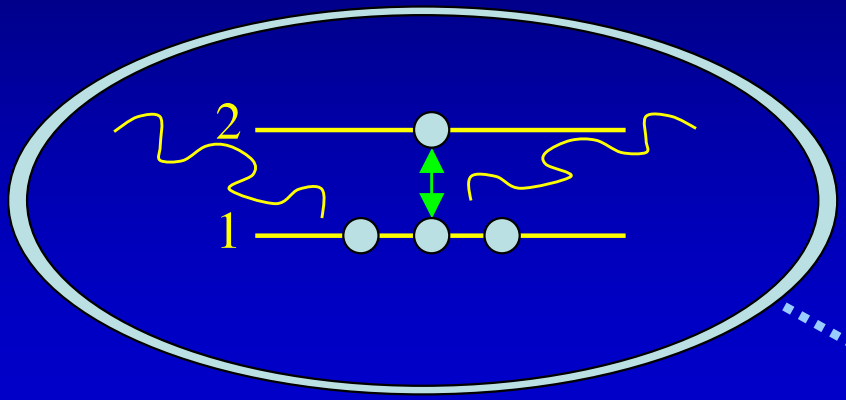
Effect of the l-treatment in the C_ls



- The effect is larger at low redshifts. The net (integrated) effect on the power spectrum is of the order of 1%.
- New paper in preparation including n=100 shells, plus detailed treatment of collisions.

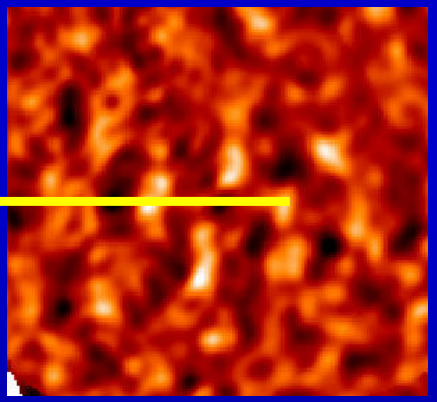
Coherent scattering of the CMB photons

(Rubiño-Martín, Hernández-Monteagudo & Sunyaev 2005 A&A 438, 461)



λ_{12} : Rest frame wavelength

CMB photon



z=0

Hydrogen atom at redshift z

z=1000

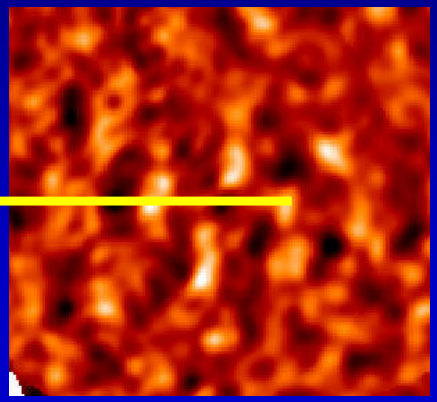
$$\frac{\Delta T}{T_0}(\theta) = e^{-\tau_\nu} \left.\frac{\Delta T}{T_0}(\theta)\right|_{orig.} + \left.\frac{\Delta T}{T_0}(\theta)\right|_{new}$$

$\lambda_{12}(1+z)$ ← λ_{12}

Coherent scattering of the CMB photons

(Rubiño-Martín, Hernández-Monteagudo & Sunyaev 2005)

CMB photon

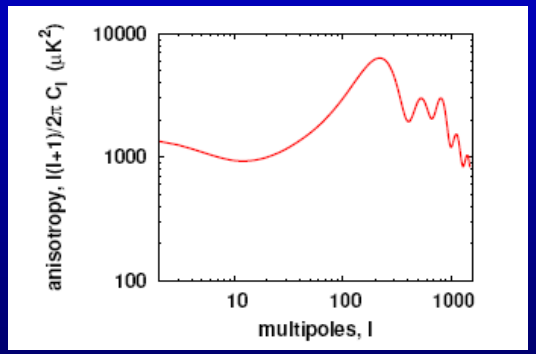


z=0

Hydrogen atom at redshift z

z=1000

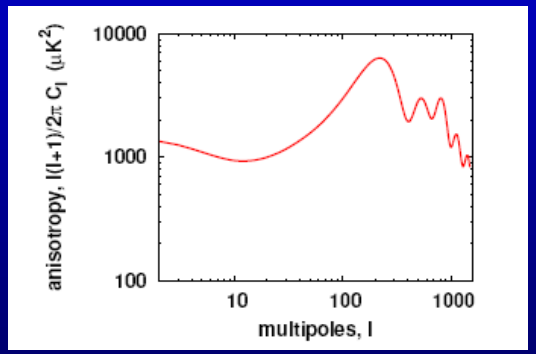
$\lambda_{12}\,(1+z)$ ← λ_{12}



$C_l + \delta C_l$

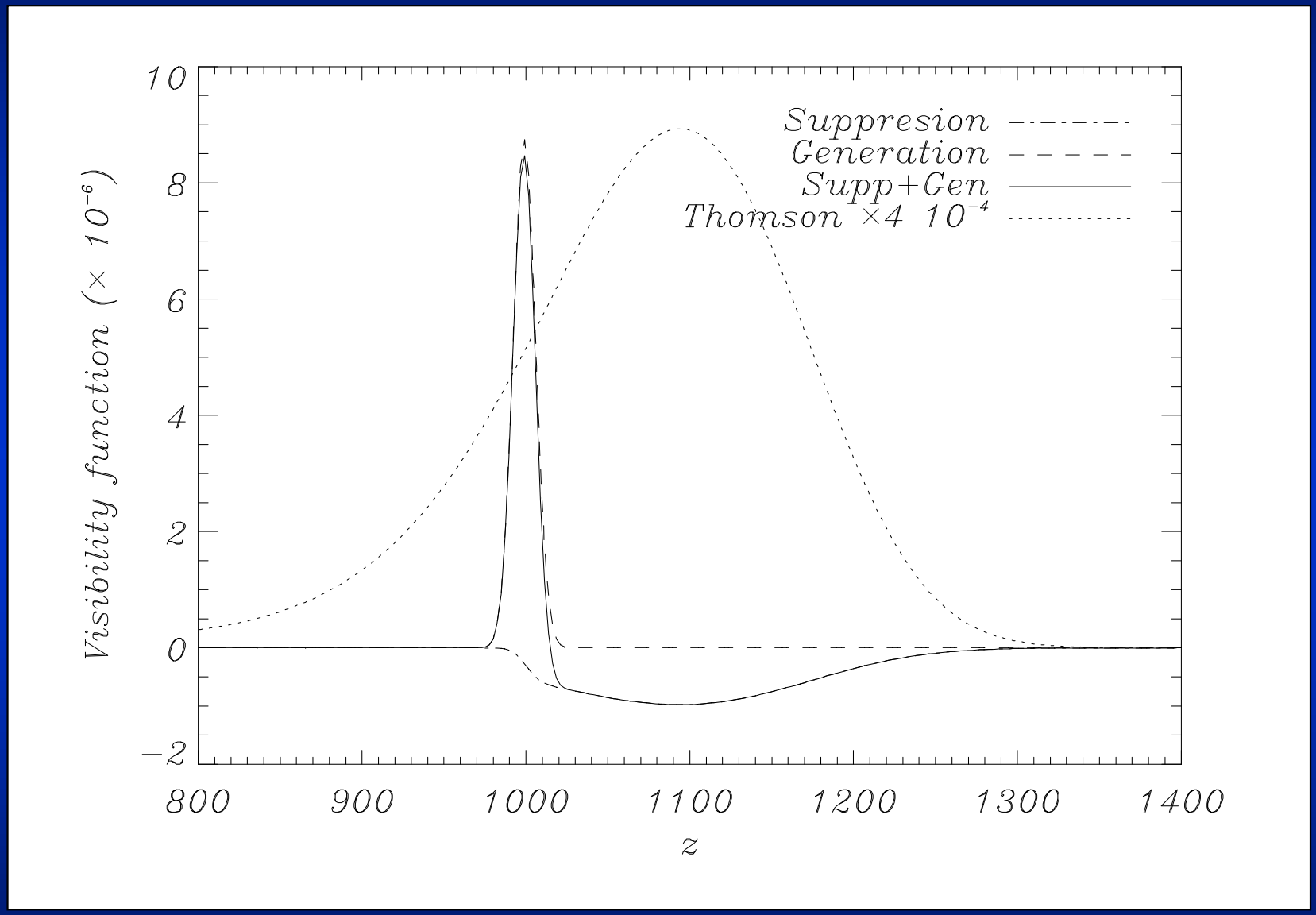
$$\delta C_\ell = \tau_{nn} \cdot C_1(\ell) + \tau_{nn}^2 \cdot C_2(\ell) + O\left(\tau_{nn}^3\right)$$

(Basu et al. 2005)



C_l

Coherent scattering of the CMB photons



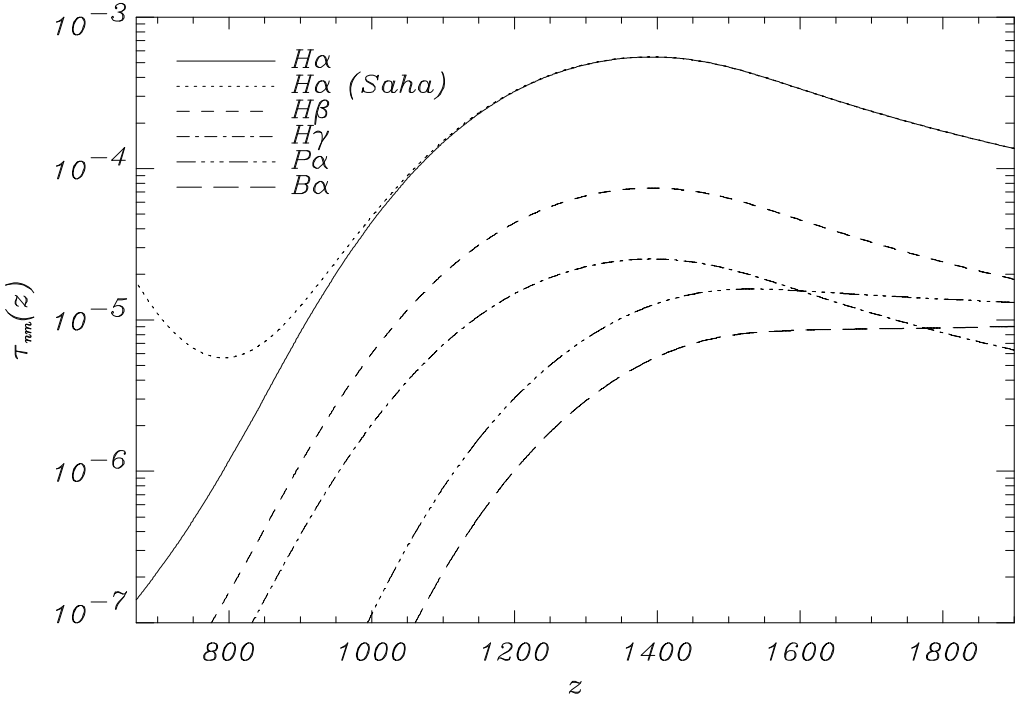
Computing the change in the C_l

- Compute the optical depth for the line of interest.
- Compute the linear term using an standard Boltzmann code to integrate the CMB anisotropies (CMBFAST)

$$\delta C_\ell = \tau_{nm} \cdot C_1(\ell) + \tau_{nm}^2 \cdot C_2(\ell) + O\left(\tau_{nm}^3\right)$$

- To observe the effect, we compare power spectra at two frequencies:

$$\delta C_l = C_l(\text{with line}) - C_l(\text{without line})$$



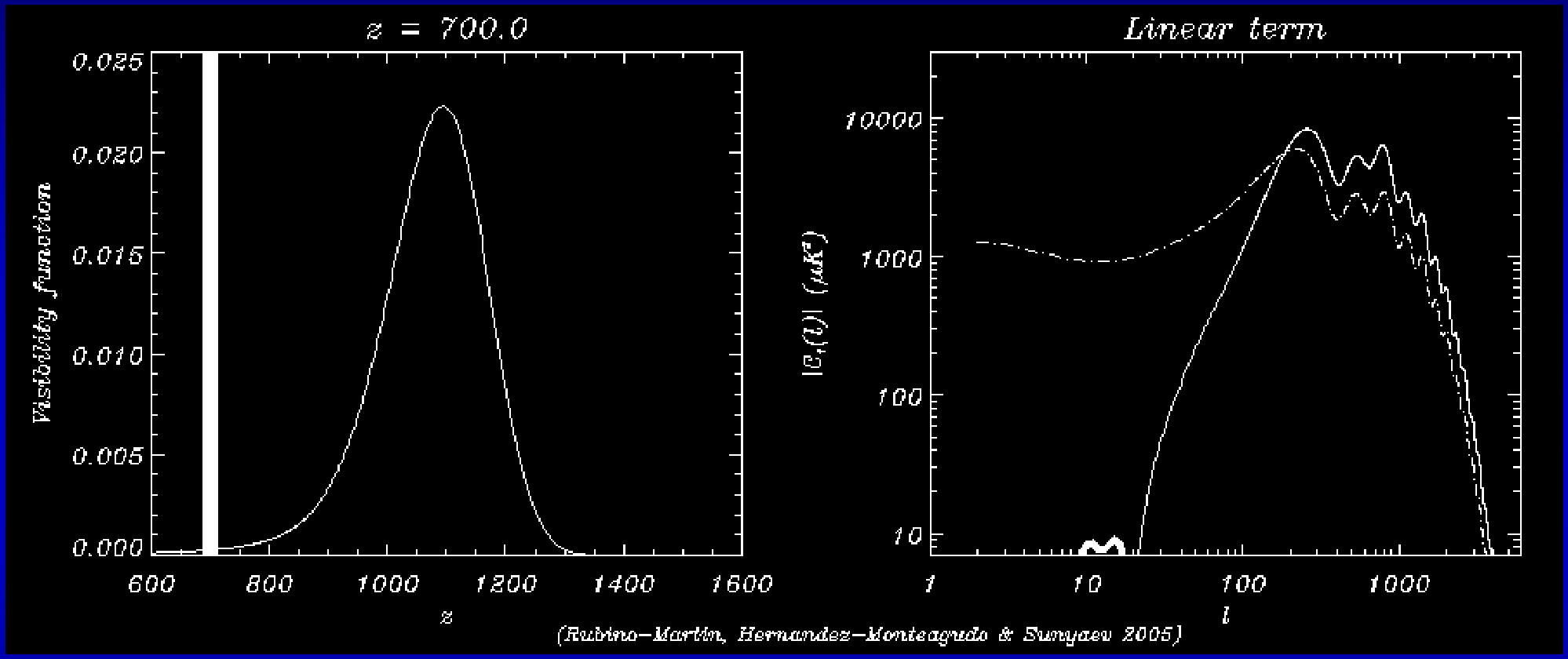
Transition	m	λ_{nm} (Å)	f_{nm}	$\nu_0(z = 1000)$ (GHz)	$\tau_{nm}(z = 1000)$
Balmer lines ($n = 2$)					
Hα	3	6562.8	0.6407	456.3	4.53×10^{-5}
Hβ	4	4861.3	0.1193	616.1	6.14×10^{-6}
Hγ	5	4340.5	0.0447	690.0	2.09×10^{-6}
Paschen lines ($n = 3$)					
Pα	4	18751.0	0.8421	159.7	1.17×10^{-7}
Pβ	5	12818.1	0.1506	233.6	1.47×10^{-8}
Pγ	6	10938.1	0.0558	273.8	4.75×10^{-9}
Brackett lines ($n = 4$)					
Bα	5	40512.0	1.0377	73.9	2.57×10^{-8}
Bβ	6	26252.0	0.1793	114.1	3.42×10^{-9}
Bγ	7	21655.0	0.0655	138.3	1.09×10^{-9}

Computations for this work

- All states (including angular momentum sublevels) treated in detail up to n=10.
- Optical depths for the main transitions: all very small.

(Rubiño-Martín, Hernández-Monteagudo & Sunyaev 2005)

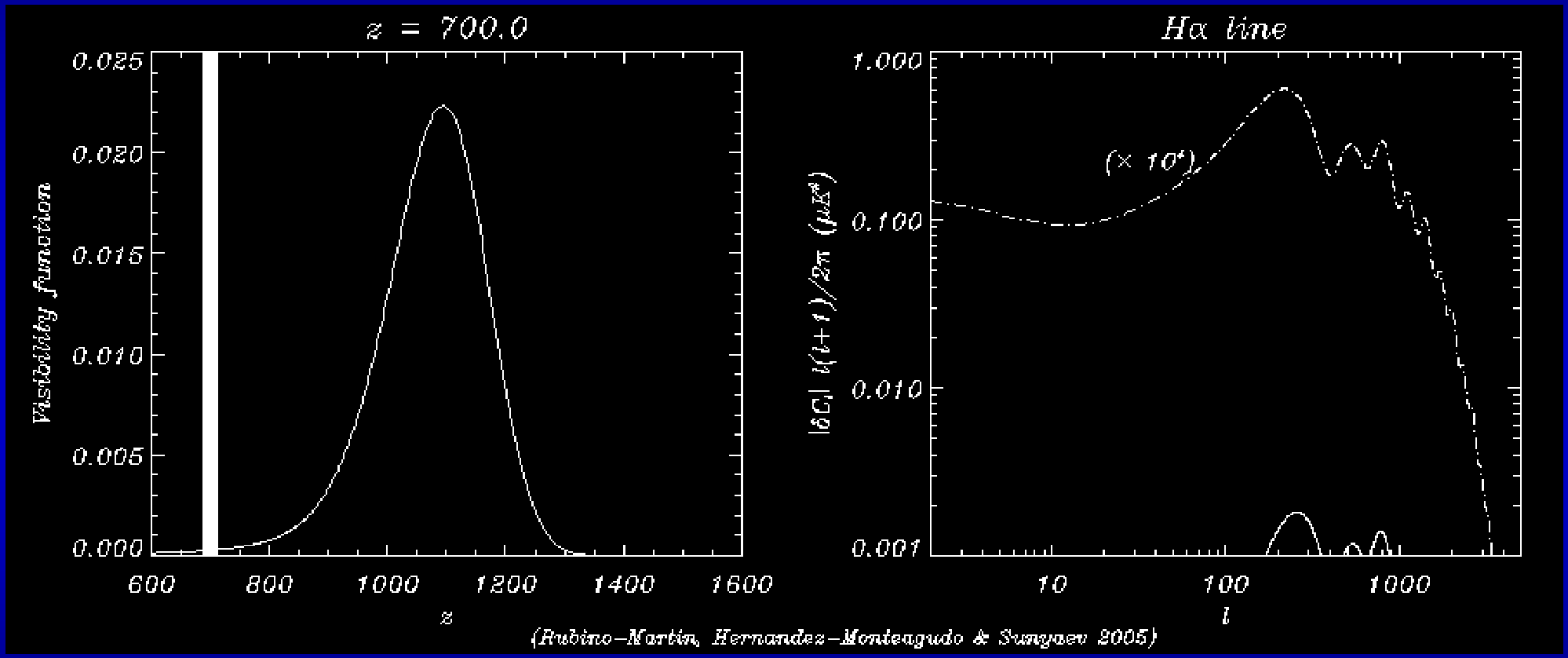
The linear term



- Optical depths in the lines are very small: this term is sufficient.
- For a given line, this redshift interval translates into frequency interval.

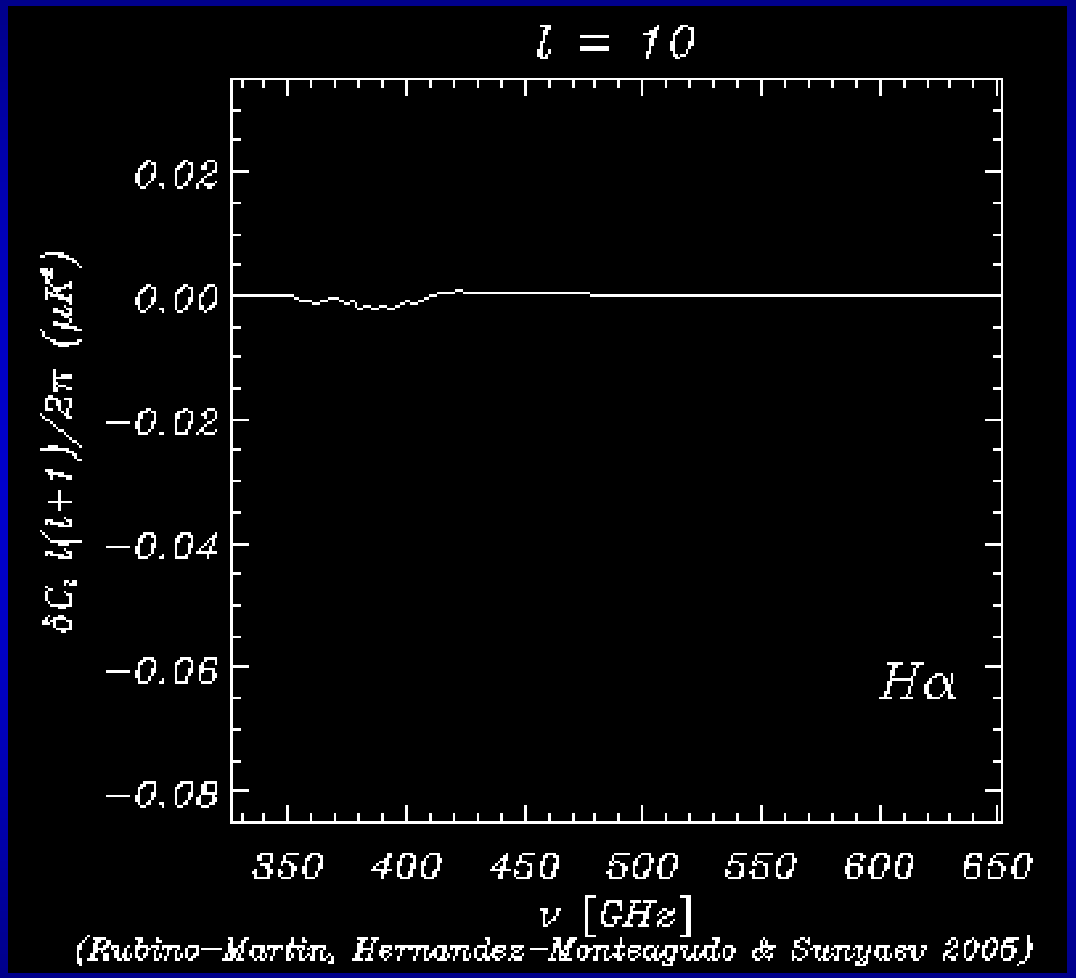
(see additional movies at http://www.iac.es/galeria/jalberto)

The Hα line

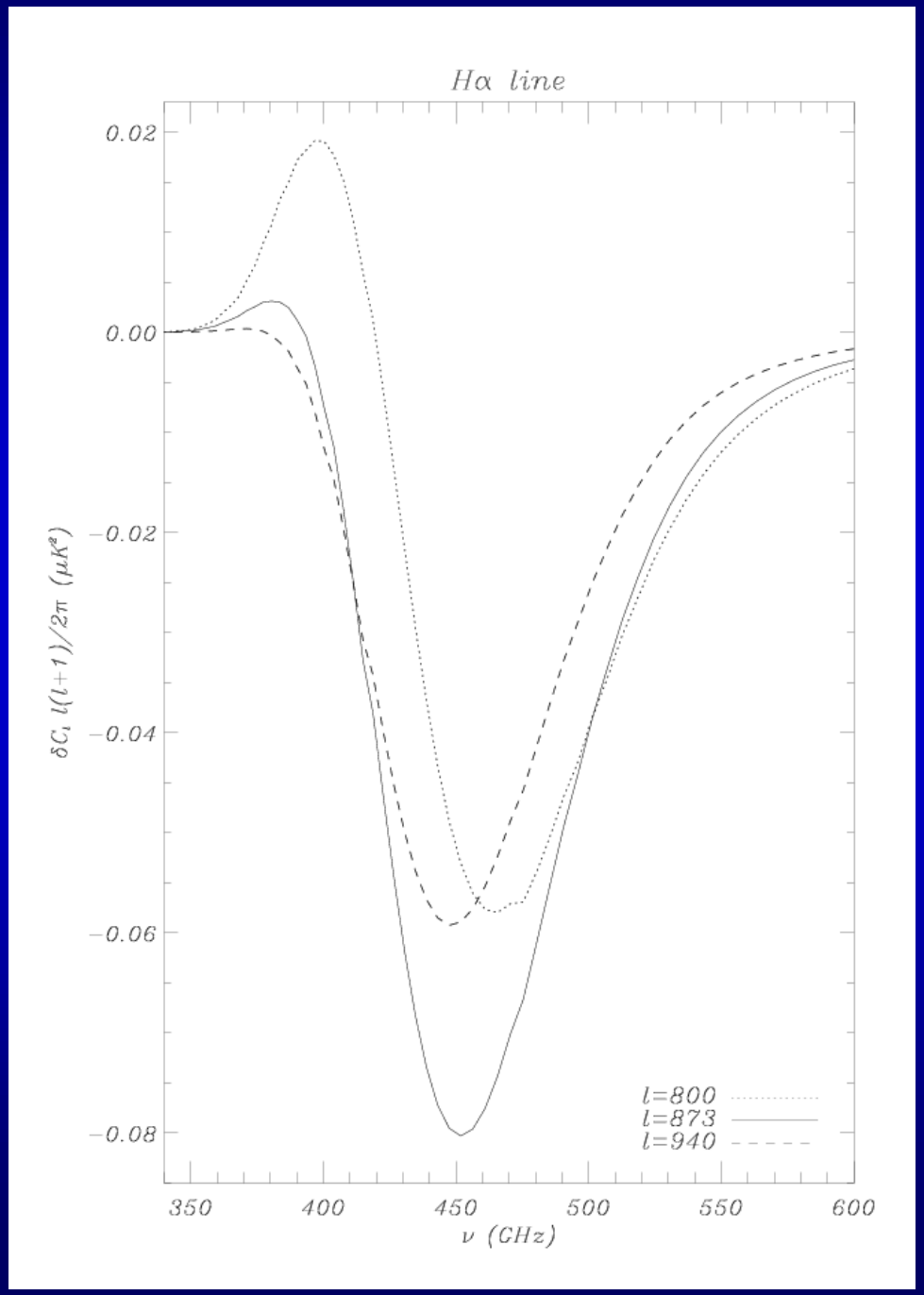


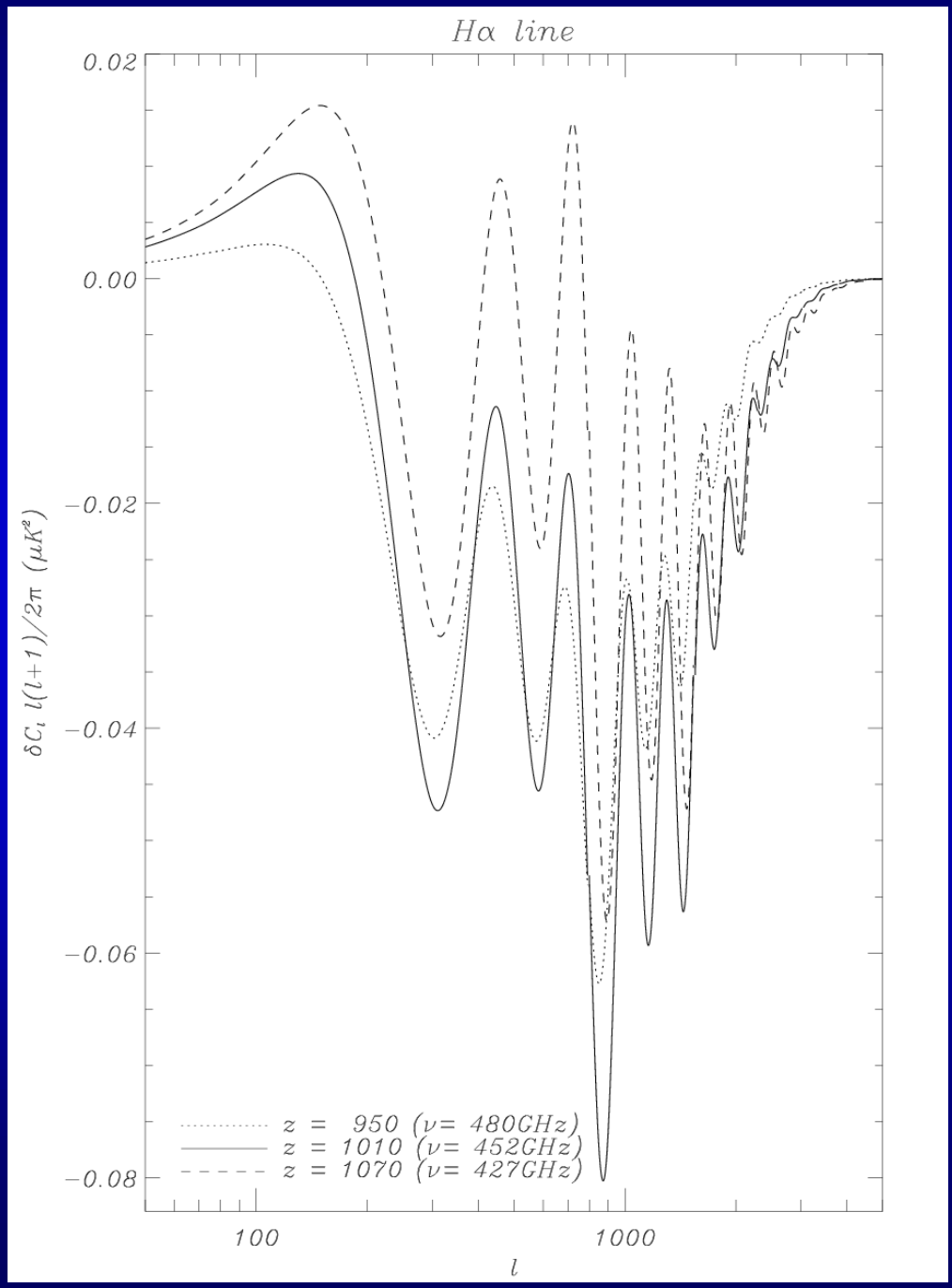
The redshift translates into frequency as 6562.8Å (1+z)

The Hα line (II)



The Hα line (III)



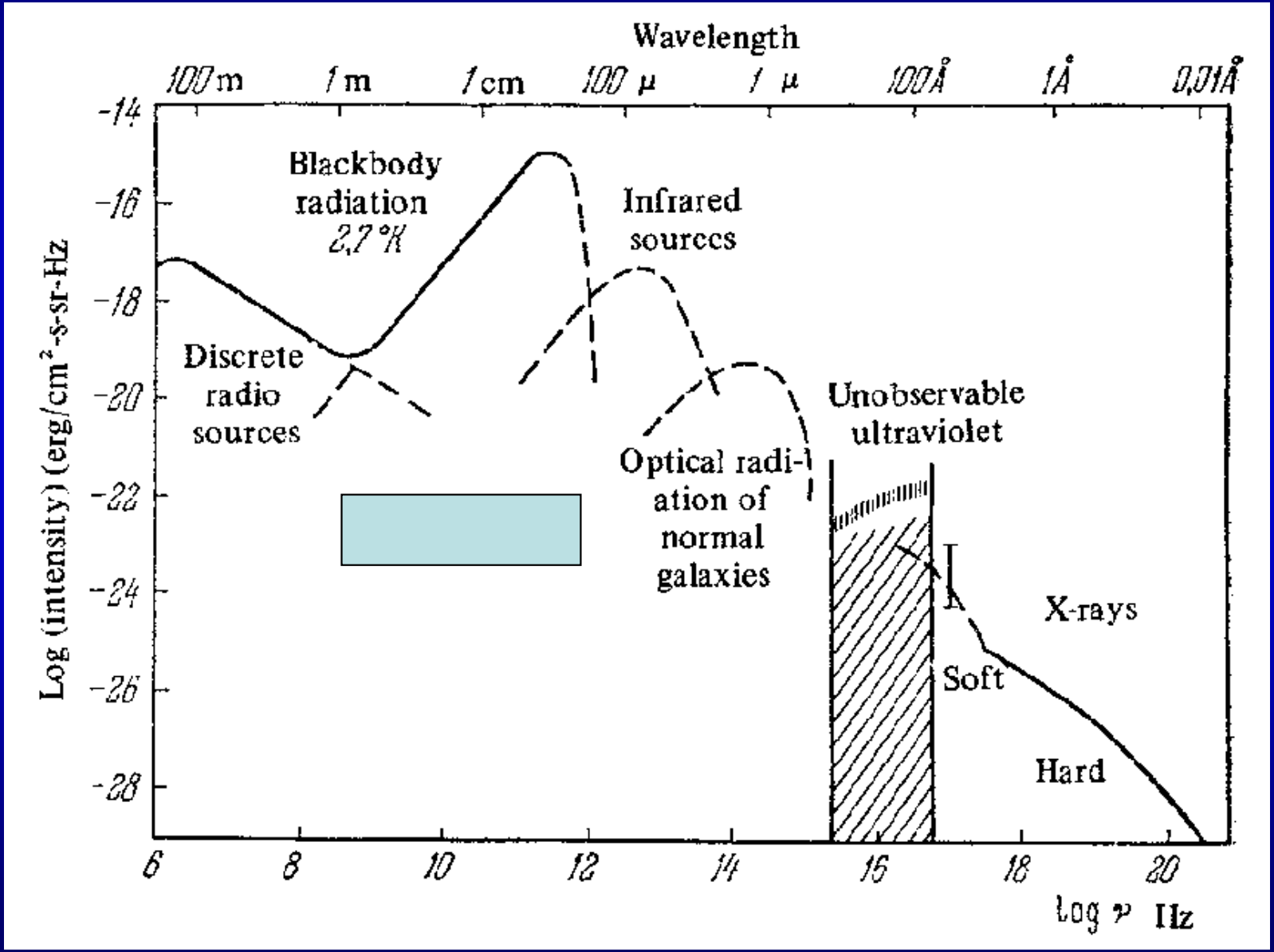


Observability of the effects

The effects that we are discussing are very small, but:

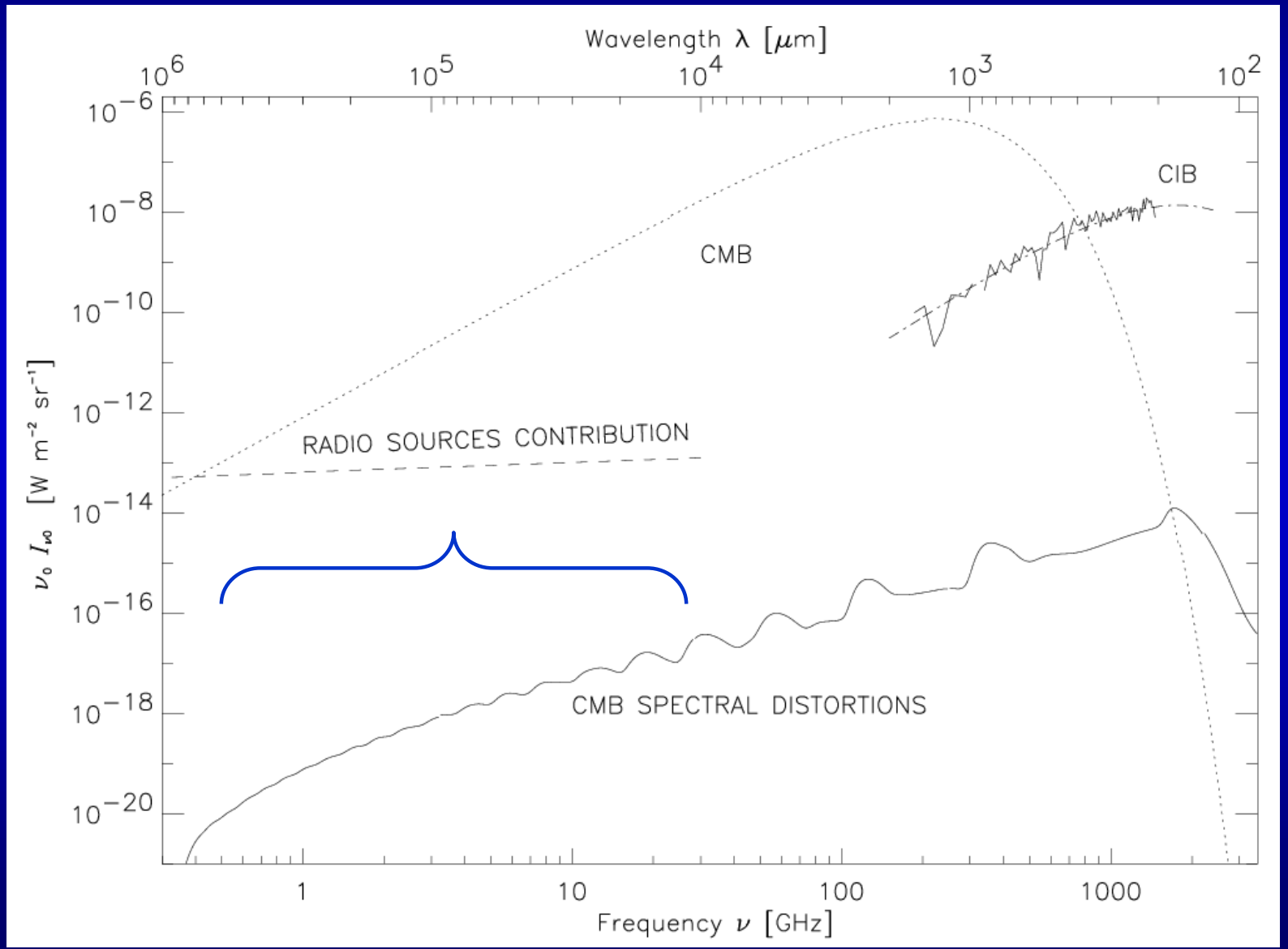
- Fixsen & Mather (2002) point out that current technology permit us to reach the level of 10^{-7} in broad regions of the frequency spectrum.
- Next generation of CMB instruments measuring B-modes (polarization) will reach levels of sub-microkelvin (0.01-0.1 μK), which is enough to detect these effects on the power spectrum.
- But we will be limited by the control of foregrounds (radiogalaxies, dust emission,...)
- However, NO FOREGROUND CAN MIMIC these features.

Observability of the effects



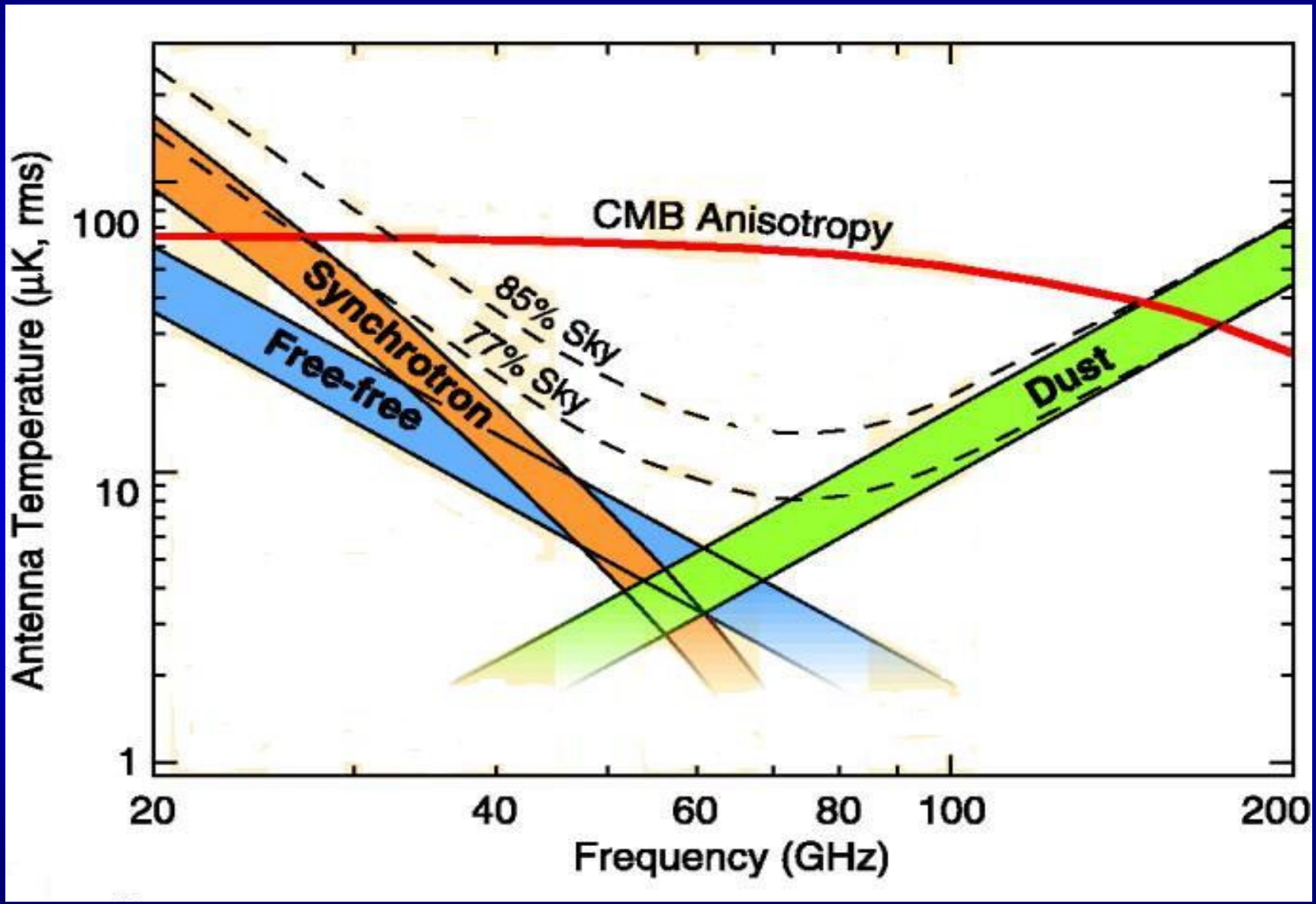
(Longair & Sunyaev 1972)

Observability of the spectral distortions

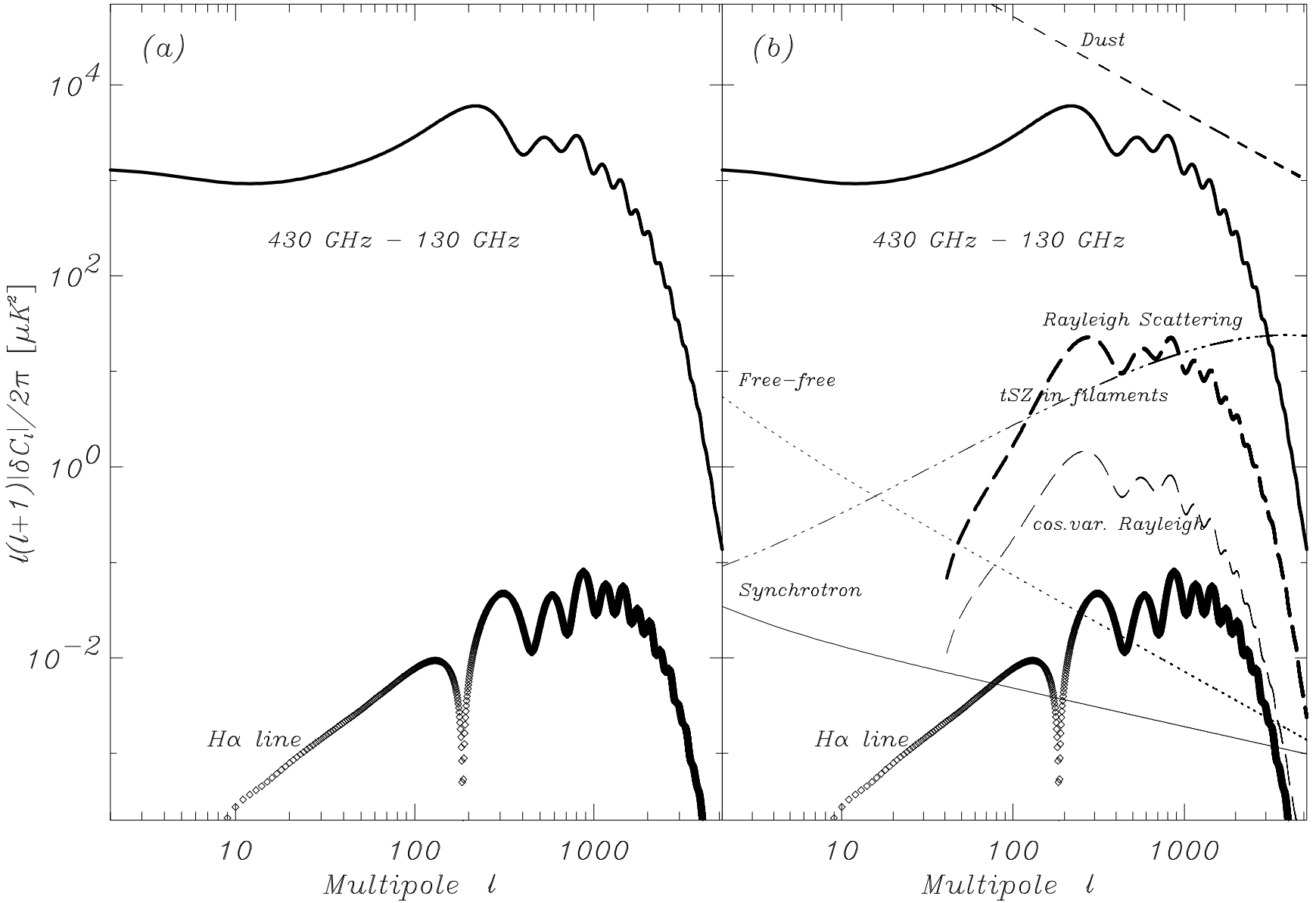


- Lyα is dominant, but the CIB is intense.
- However, the sensitivity is improving: e.g. Spitzer (Dole et al. 2006) have resolved practically ¾ of the MIB at 160 microns into luminous IR galaxies at z~1.
- The region around 21cm seems most promising. In addition, there is new physics there (decaying dark matter particles).

Observability of the effect on the C_l´s



Observability of the effect on the C_l´s



Conclusions

- We have obtained the most precise determination of the Cosmological Recombination spectrum to date.
- Spectral features from the epoch of Recombination are **very small**, being of the order of sub-microkelvins for power spectrum distortions, and 10^{-7}-10^{-8} for the spectrum itself.
- Exquisite control on foreground contamination is essential to measure these features, but ...
- All these features have a very peculiar oscillatory behaviour which can not be mimiced by any other foreground and might help in separating these lines.
- Observations of these spectral features provide a **direct measurement** of the epoch of recombination, as well as an independent determination of cosmological parameters.