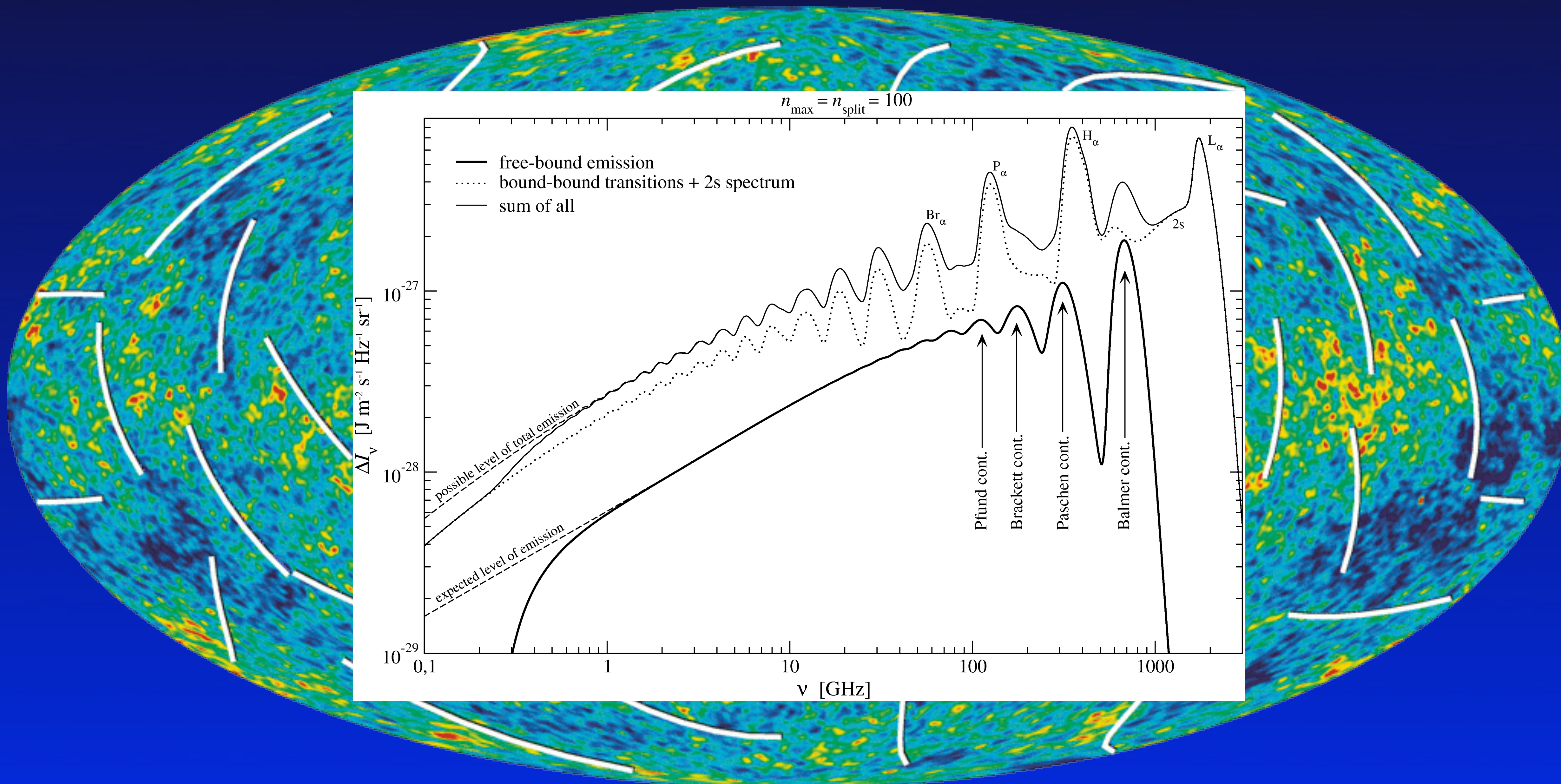
The Cosmological Recombination Spectrum: So What?



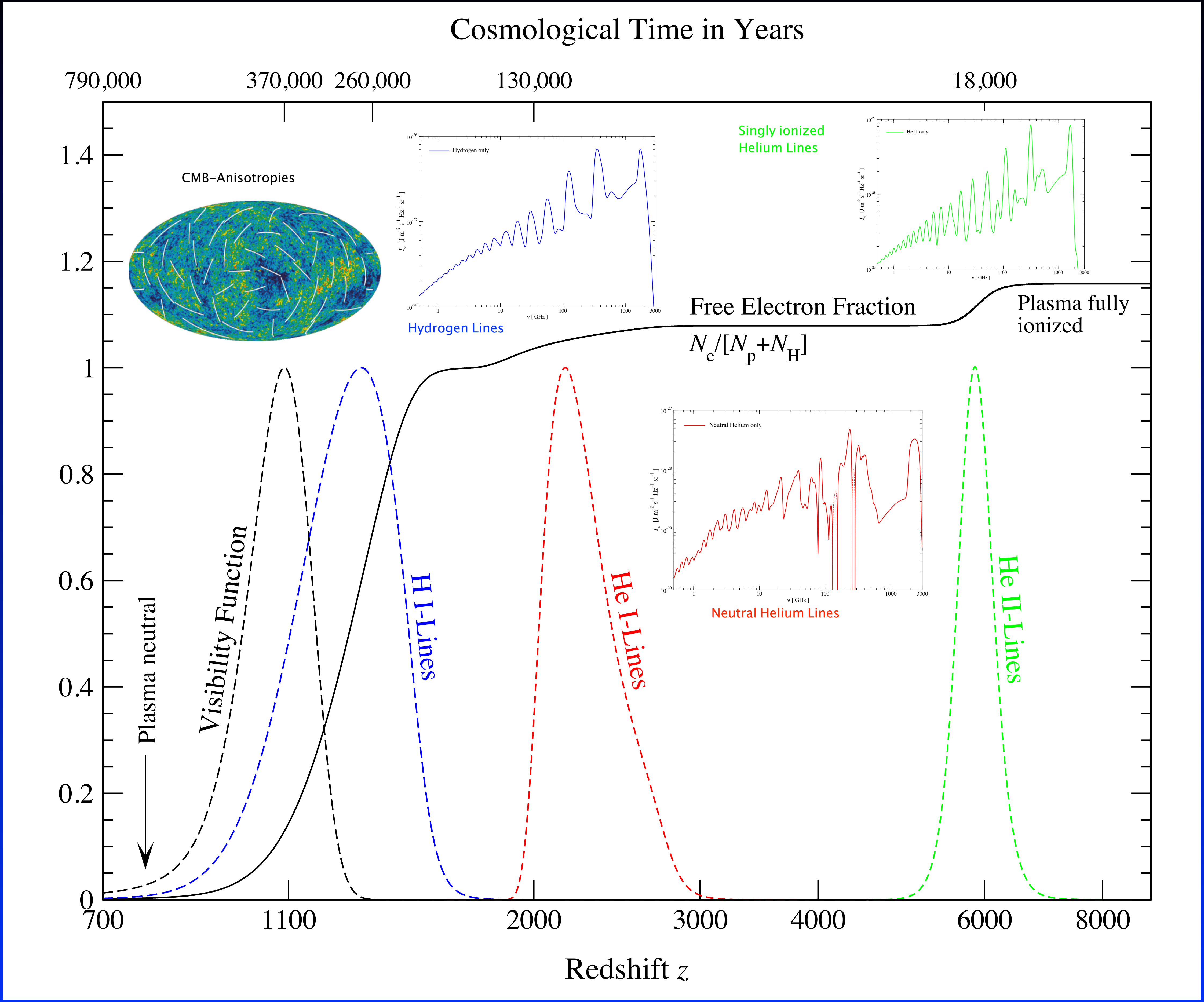
J. Chluba

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

Workshop on "The First Billion Years"

August 17, 2010, Pasadena

Collaborators: R.A. Sunyaev (MPA) and J.A. Rubiño-Martín (IAC)


Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized Helium Lines
He II only
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Neutral Helium only
Neutral Helium Lines
Visibility Function
Plasma neutral
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 can one learn by doing such a hard job?

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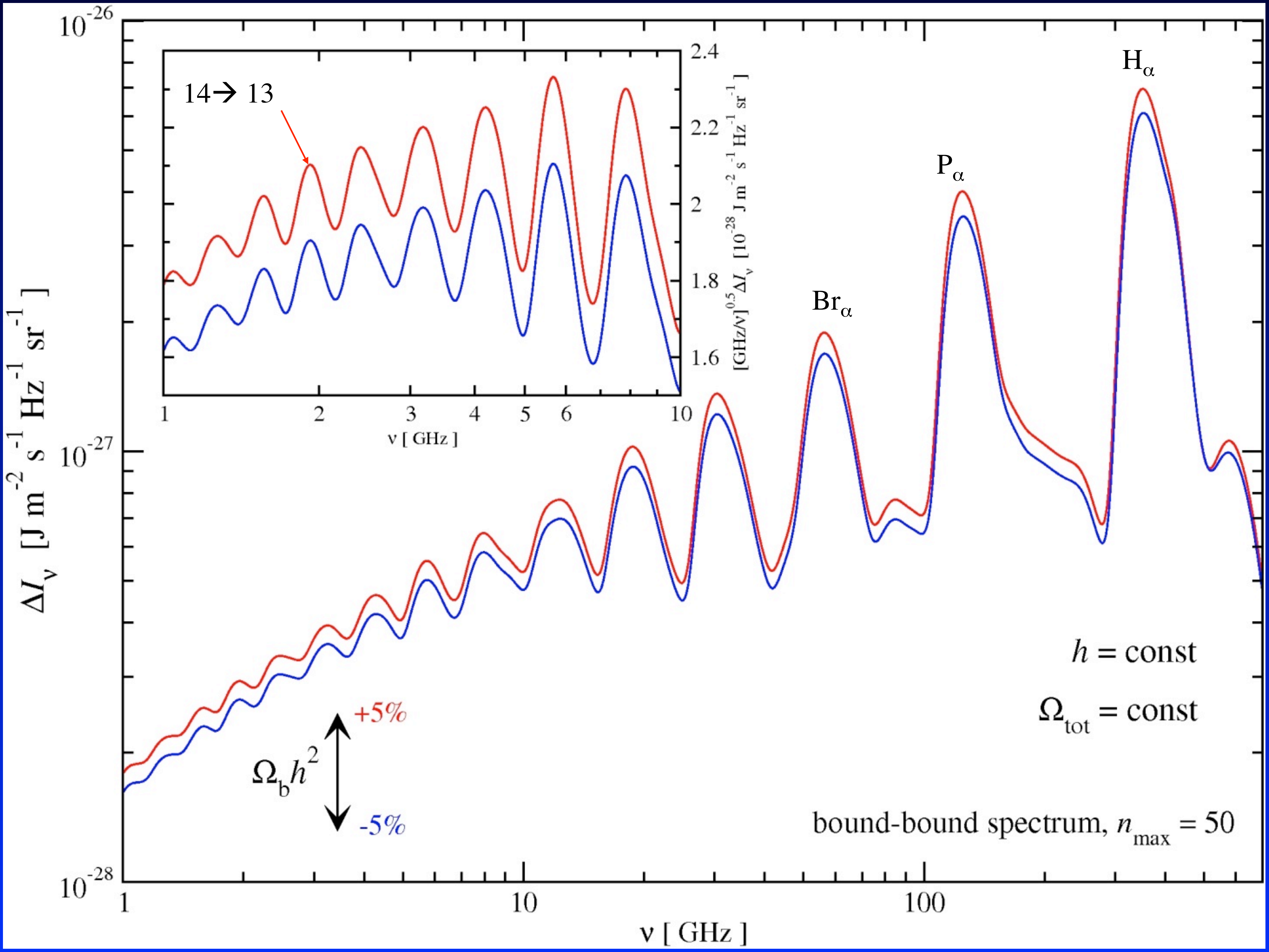
- Dependence on normal cosmological parameters

  → number of hydrogen atoms determines number of H photons ⇔ $\Omega_b h^2$

Hydrogen recombination spectrum: *dependence on $\Omega_b h^2$*



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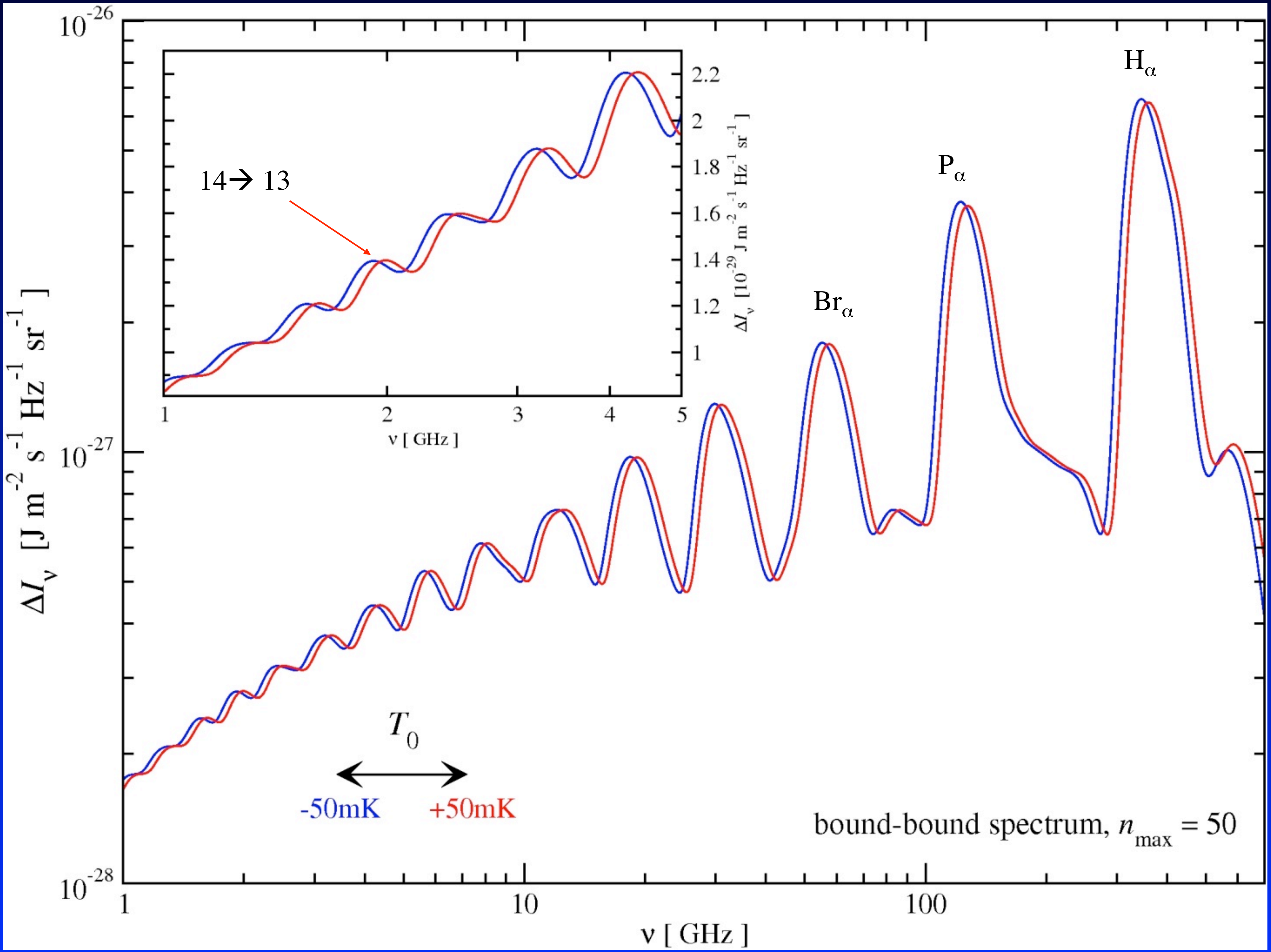
Hydrogen recombination spectrum: *dependence on T_0*



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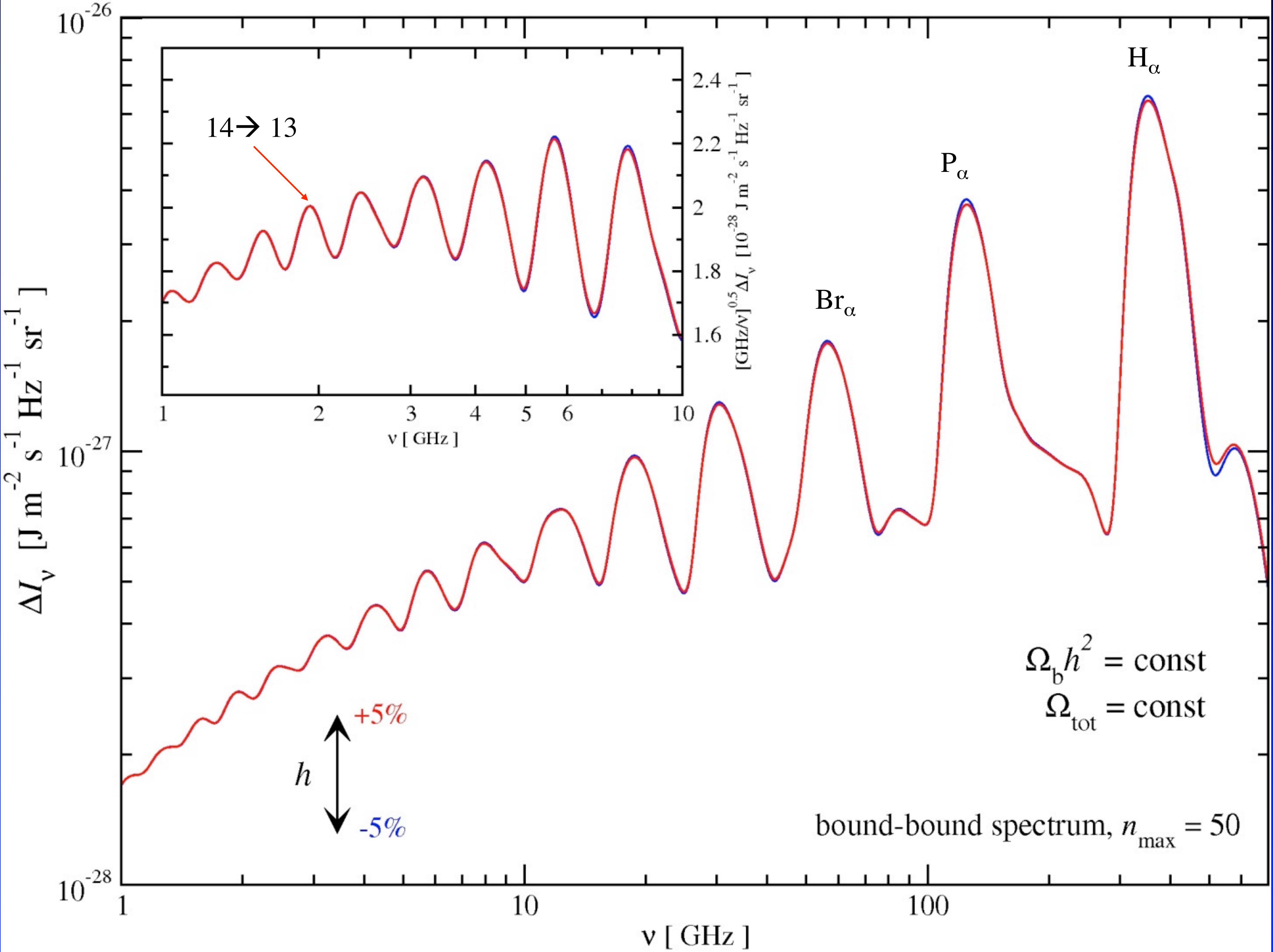
Hydrogen recombination spectrum: *dependence on h*



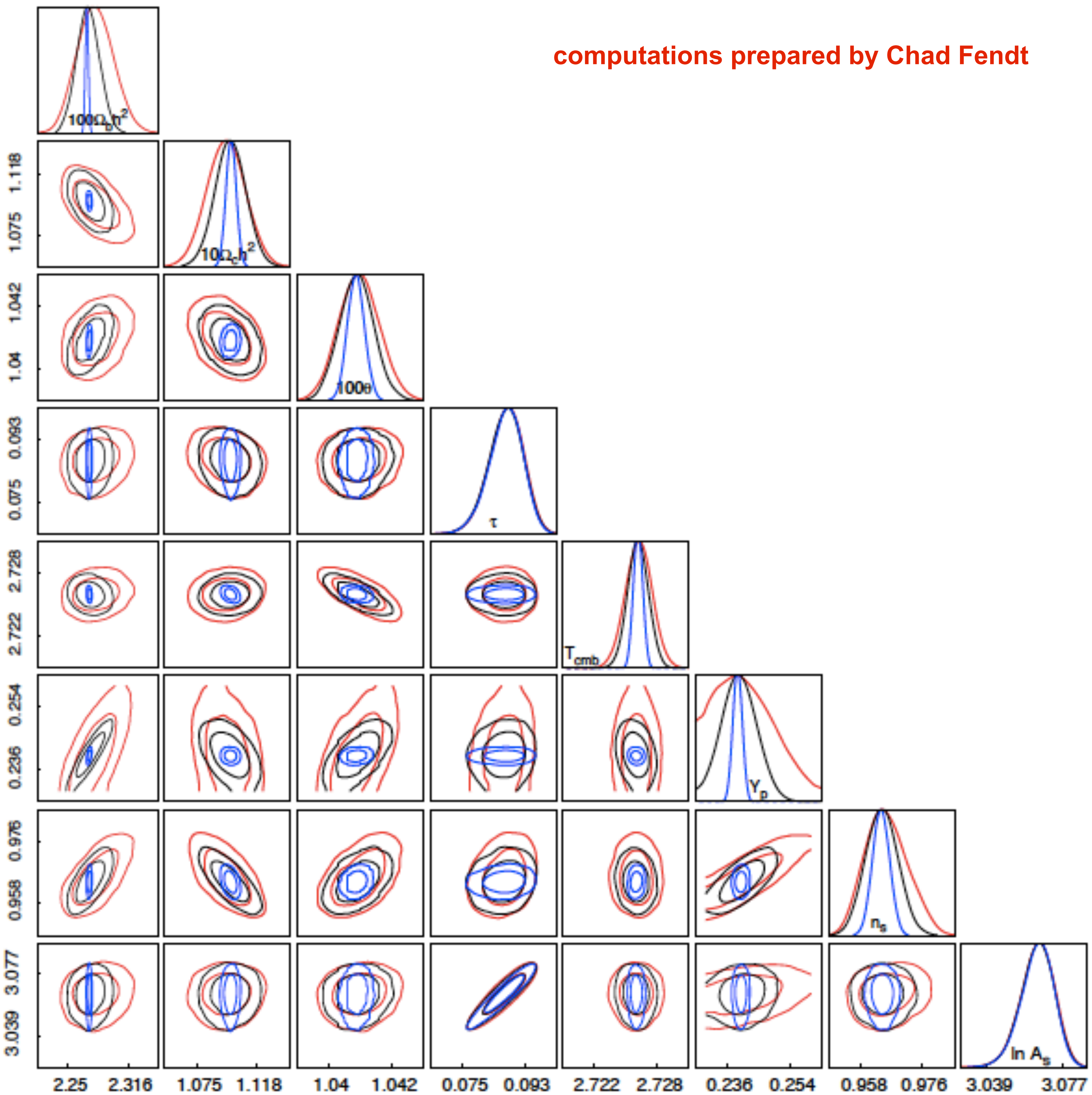
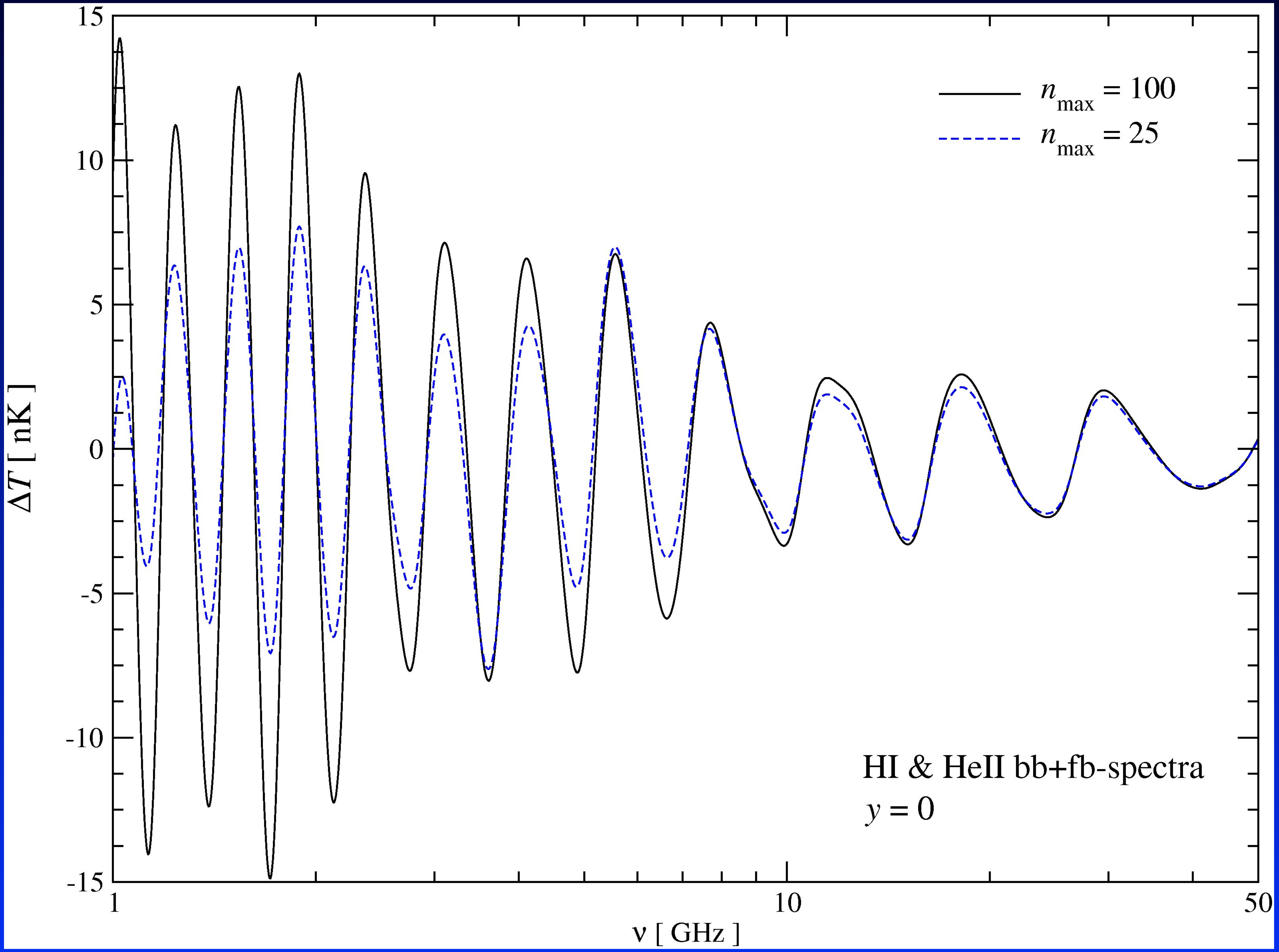
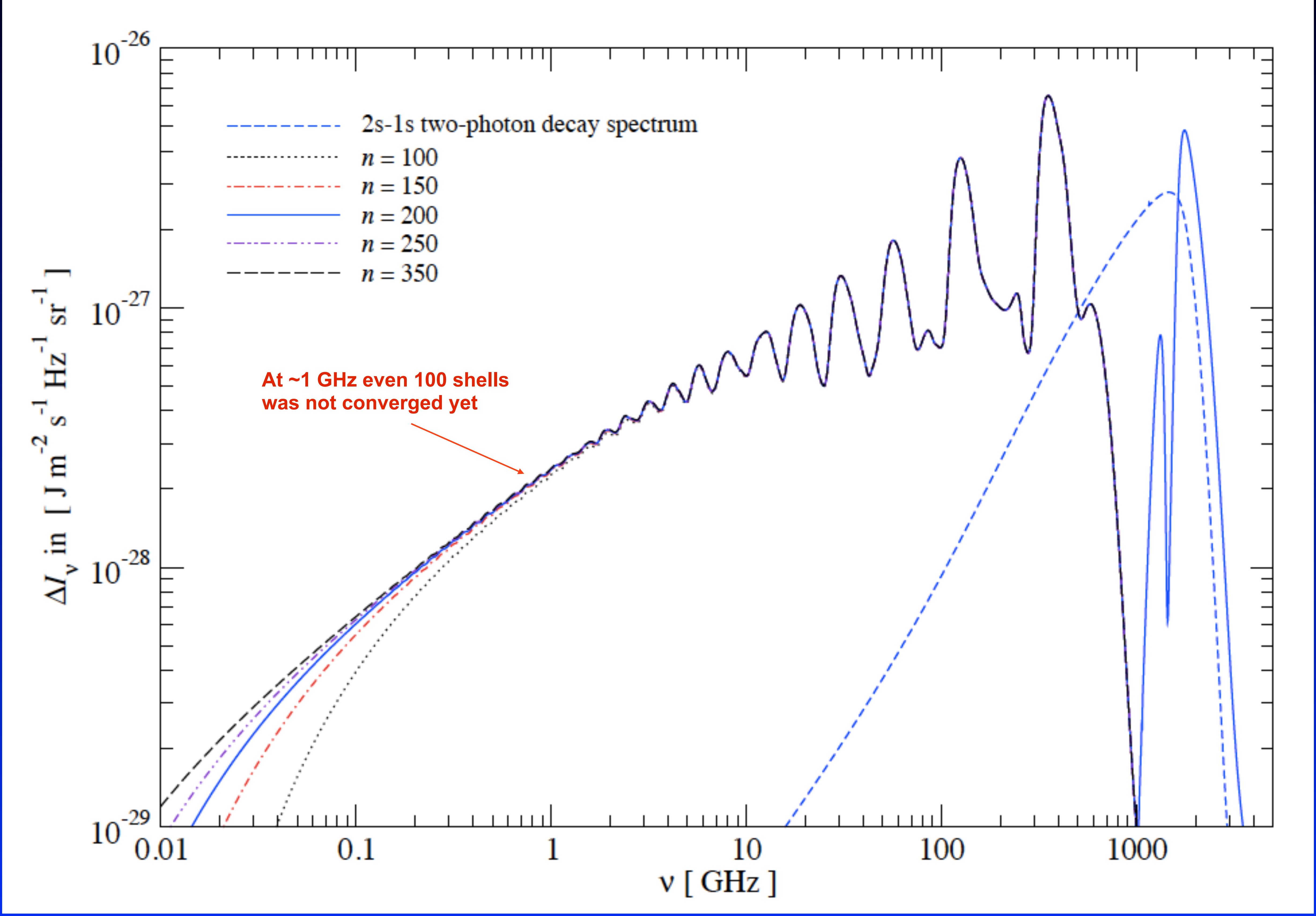


Figure 7.3: The 1 and 2 dimensional marginalized parameter posterior using the CMB spectral distortions. All three cases constrain the CMB power spectrum using a Gaussian likelihood based on Planck noise levels. The black line adds constraints due to a 10% measurement of the spectral distortions, while the blue line assumes a 1% measurement. The red line does not include the data from the spectral distortions.

- CMB based cosmology alone
- Spectrum helps to break some of the parameter degeneracies
- Planning to provide a module that computes the recombination spectrum in a fast way
- detailed forecasts: which lines to measure; how important is the absolute amplitude; how accurately one should measure; best frequency resolution;

How does the signal actually look?





2s-1s two-photon decay spectrum
n = 100
n = 150
n = 200
n = 250
n = 350
At ~1 GHz even 100 shells
was not converged yet
ΔI_ν in [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
10^-29
0.01
0.1
1
10
100
1000

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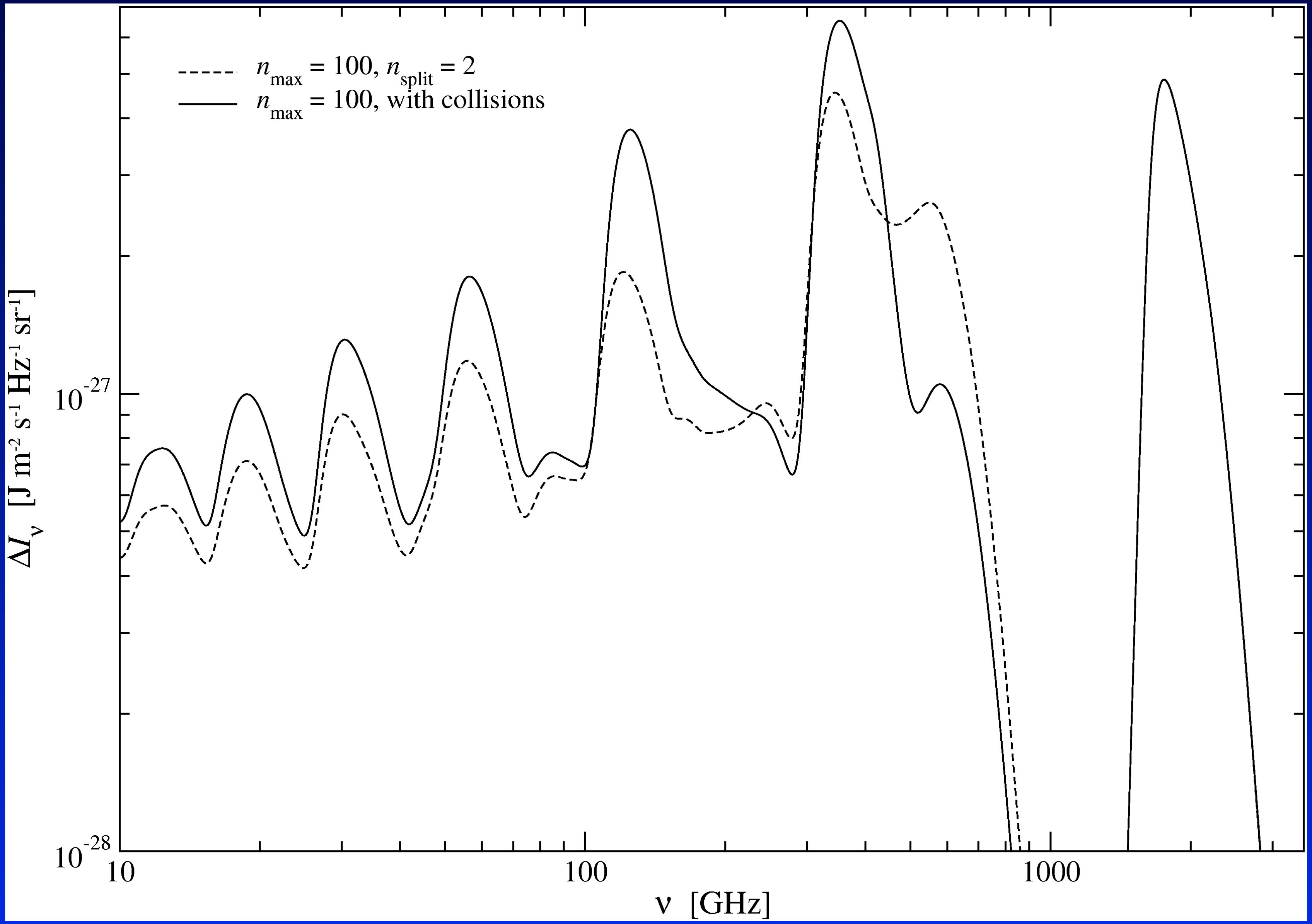
- Dependence on recombination dynamics and physics

100-shell hydrogen atom and continuum
Non-equilibrium effects on the bound-bound-spectrum

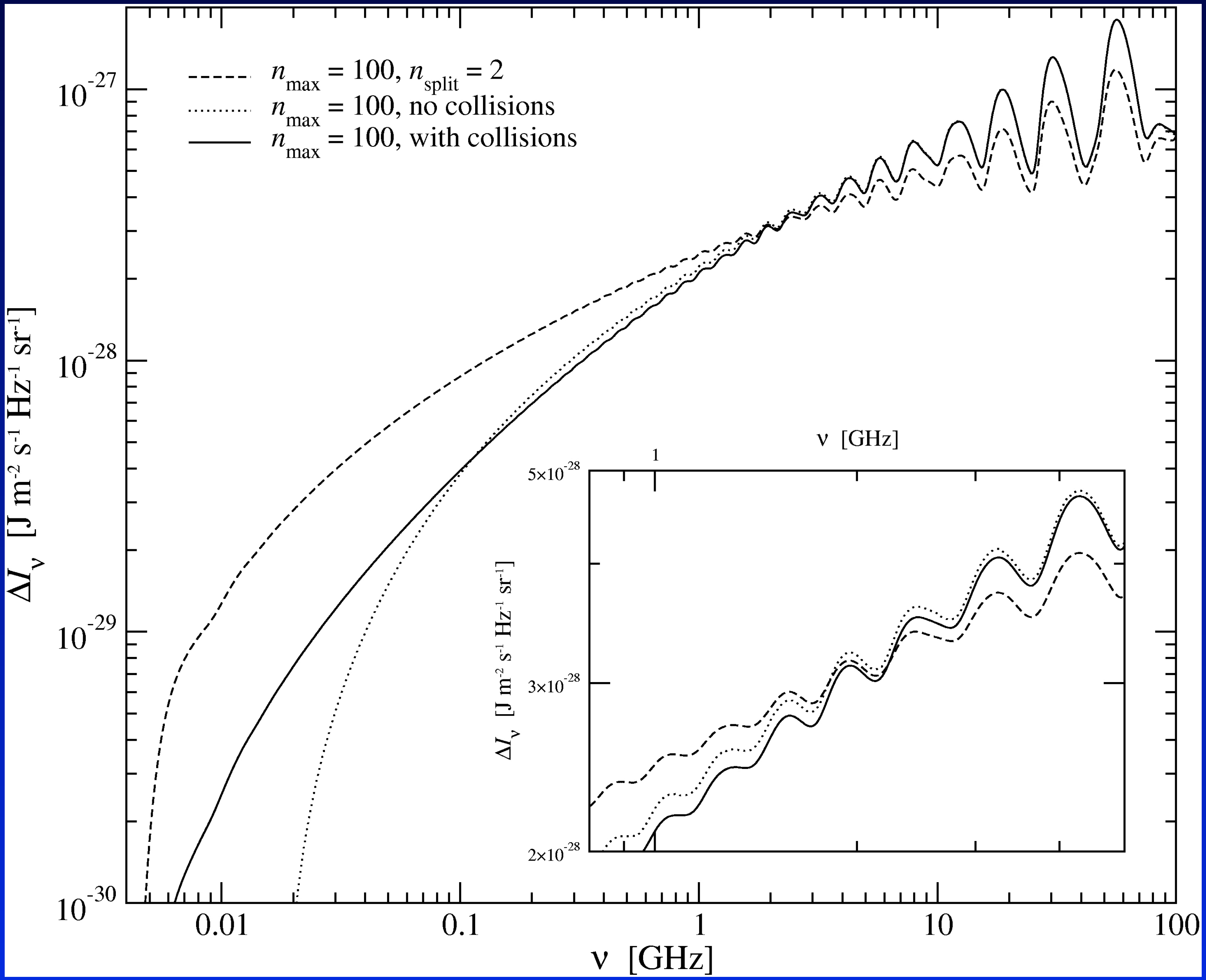


- Lyman- α unchanged
- Balmer-series:
  - B $_\alpha$ lower for n_{split}=2
  - for n_{split}=2 second peak more than 2 times higher
  - ratio first to second peak decreases from 6 → 2
- higher series:
  - n_{split}=2 → emission lower
- collision are negligible!

Rubiño-Martín, JC & Sunyaev, 2006, astro-ph/0607373
JC, Rubiño-Martín & Sunyaev, 2006, astro-ph/0608242

100-shell hydrogen atom and continuum

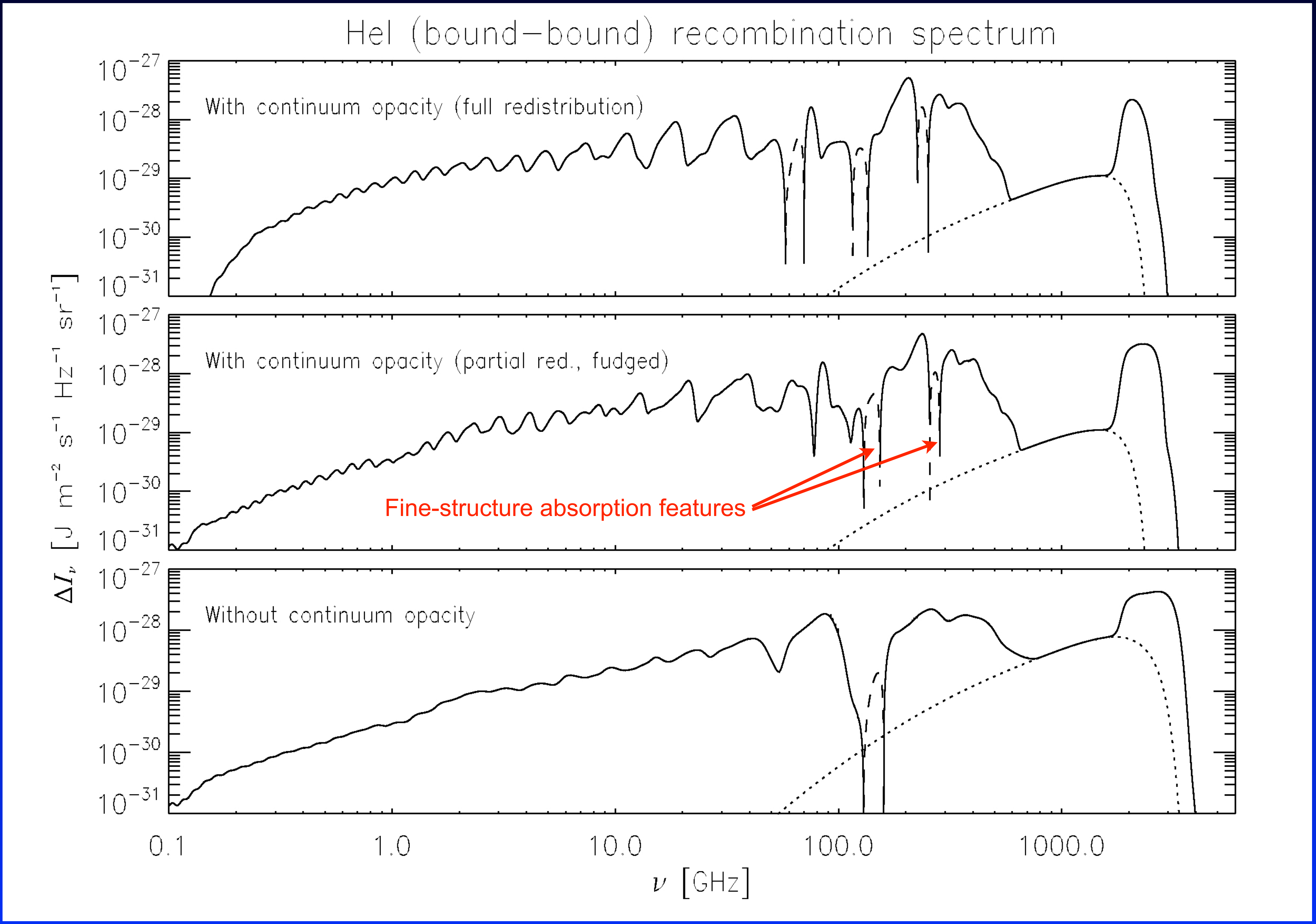
Effect of l-changing collisions on the b-b spectrum



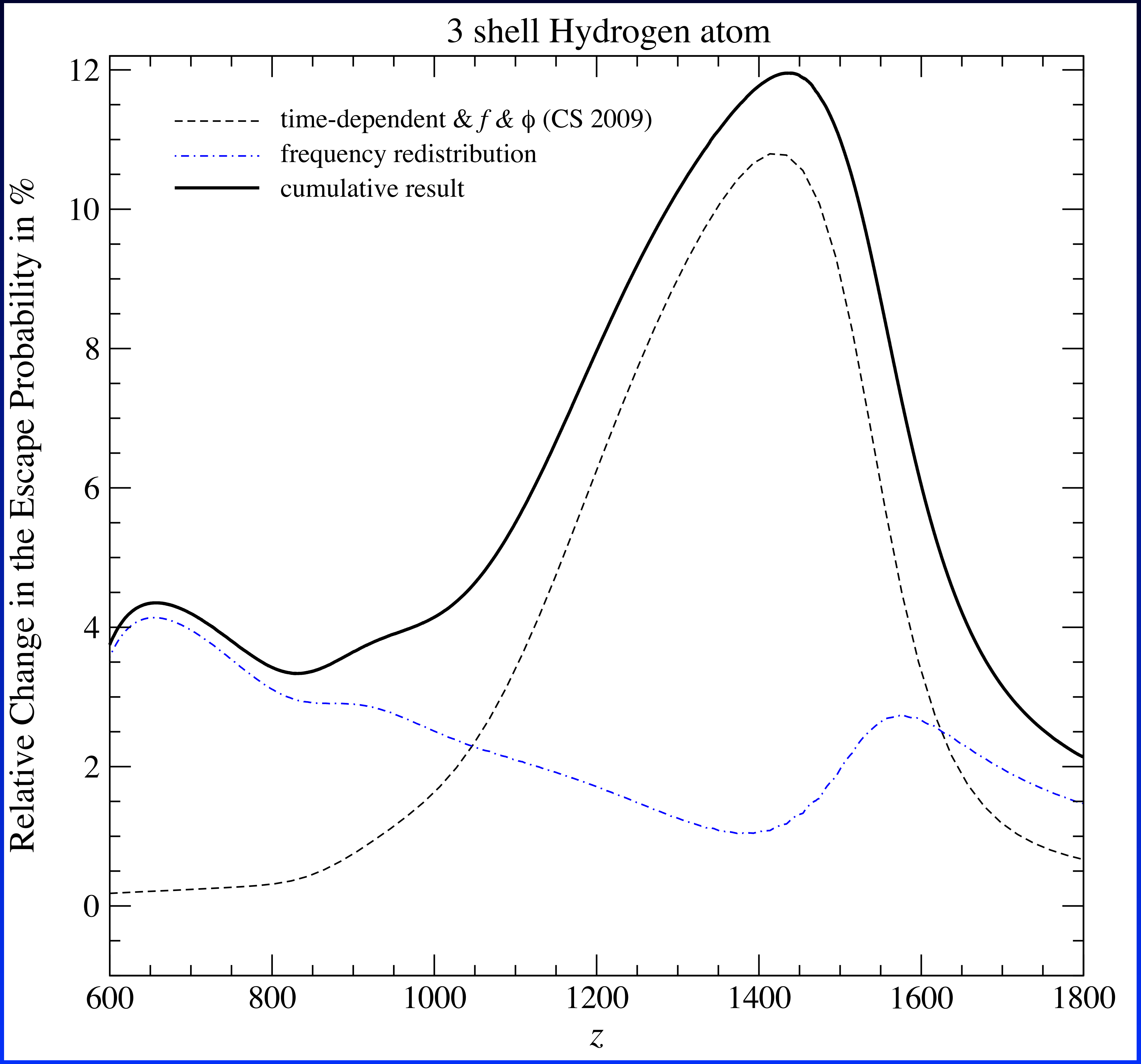
JC, Rubiño-Martín & Sunyaev, 2006, astro-ph/0608242

- collisions start to be important for *n* above ~ 40
- at low frequencies solution for n_{split}=2 lies above those with n_{split}=100
- difference in the low frequency slope robust (0.35 ↔ 0.46)
- large *n* → transitions with Δ*n* ~ *n* favoured for n_{split}=100

The importance of HI continuum absorption



Changes in the Lyman α escape probability



- Changes in Ly α escape probability *directly* translate into changes of the CMB Ly α distortion
- $\Delta P/P$=10% ⇒ $\Delta I_\nu/I_\nu$=10%
- Since Ly α line controls dynamics of recombination also all other lines will be affected by this process

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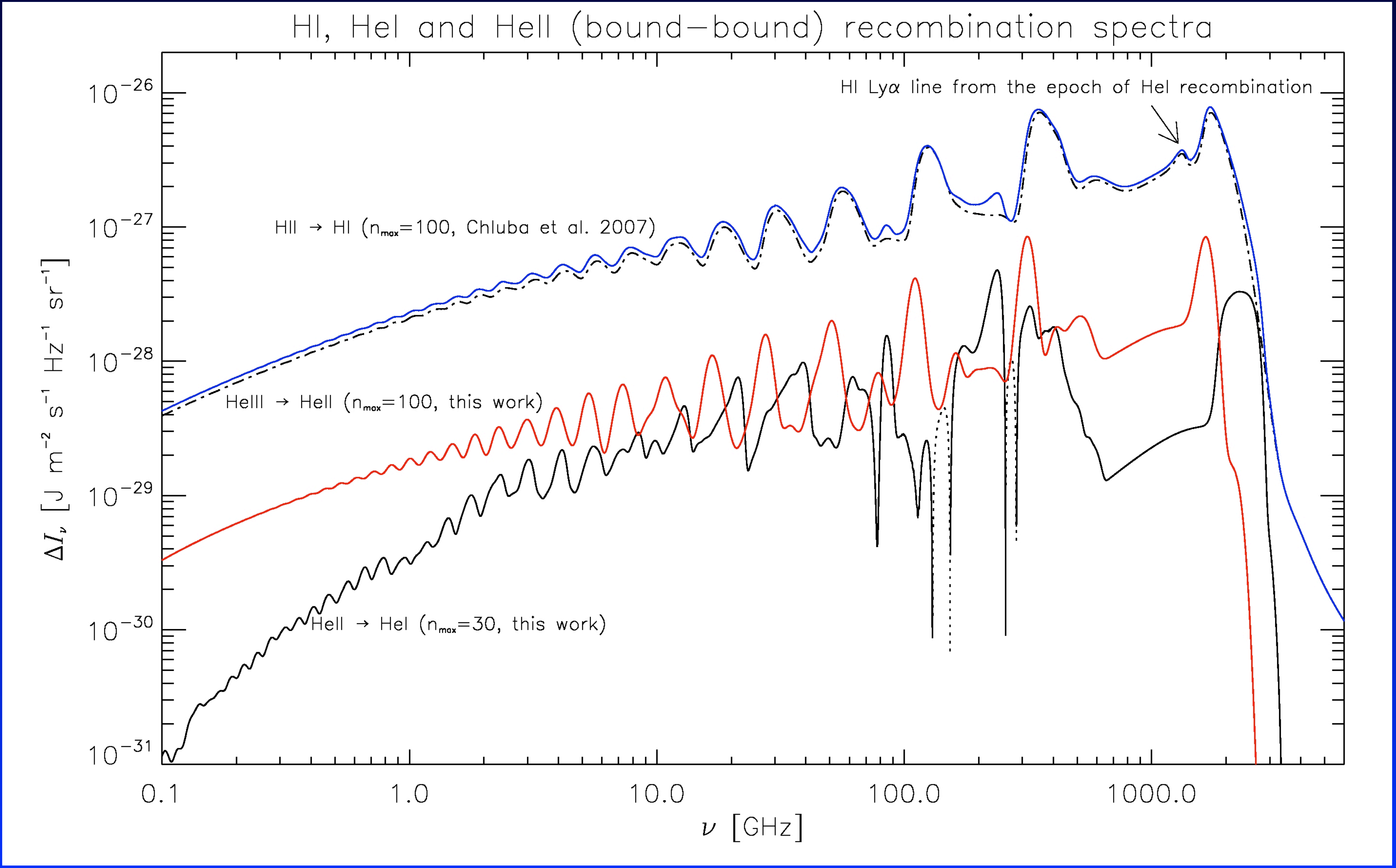
- Dependence on recombination dynamics and physics

  → allows us to check the recombination model

  → critical question: how well one will have to do to even if the 'response' is more direct?

Is the Cosmological Recombination Spectrum Really Interesting Enough?



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- Effects of intrinsic y-distortions

Another Example: Energy Release in the Early Universe

Full thermodynamic equilibrium (certainly valid at very high redshifts)

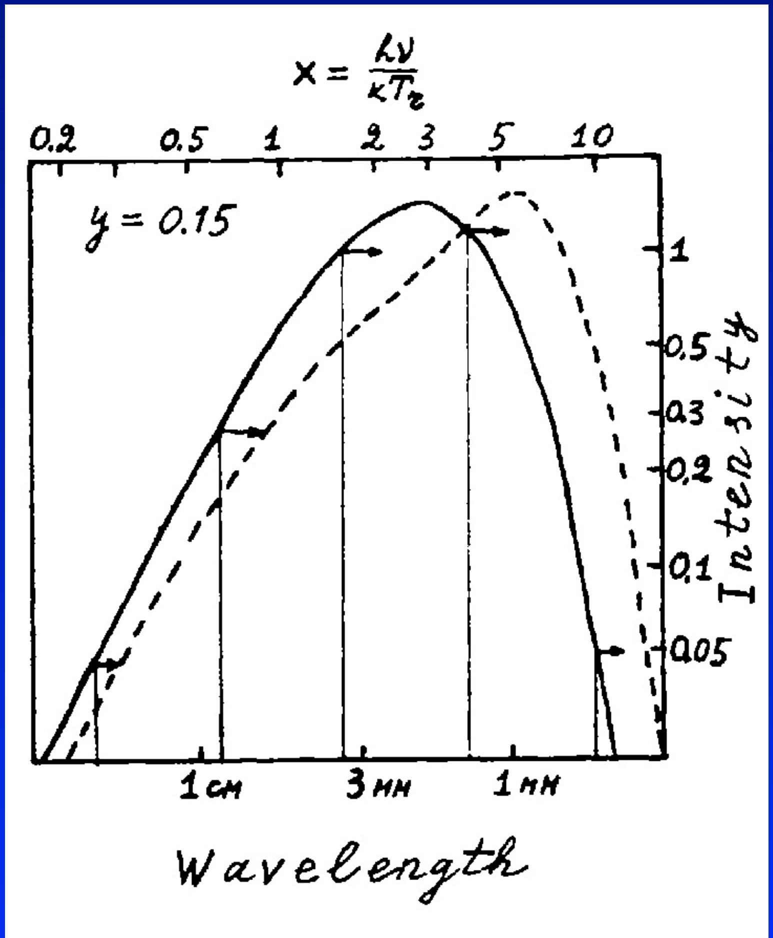
- CMB has a blackbody spectrum at every time (not affected by expansion!!!)
- Photon number density and energy density determined by temperature T_γ

Disturbance of full equilibrium for example by

- Energy injection (e.g. *decaying* or *annihilating particles* or *phase transitions*)
- Production of (energetic) photons and/or particles

→CMB spectrum would deviate from a pure blackbody today!

- „Early" energy release ($z \gtrsim 50000$)
  ⇒ μ-type distortion (another talk...)
- „Late" energy release ($z \lesssim 50000$)
  ⇒ *y*-type distortion
- Cobe/Firas spectral measurements
  (Mather et al., 1996; Fixsen et al. 1996; Fixsen et al. 2002)
  → $|y| \leq 1.5 \times 10^{-5}$



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

Energy injection ⇒ CMB Spectral Distortions

How easy is it actually to learn something interesting about the thermal history?

- CMB distortion can be predicted for different energy injection histories and mechanisms (e.g. Hu & Silk,1993a&b; Burigana & Salvaterra, 2003)

  → Spectral distortions are *broad* and *featureless*

  → Absolute (COBE-type) measurements are required

- Different injection histories yield very similar spectral distortion!

  Simplest example: *pre-* and *post-recombinational y-type distortions*

  - energy release at redshifts $1000 < z < 50000$
  - SZ-effect e.g. due to unresolved clusters, supernova remnants, shockwaves, etc.

  } ⇒ y-distortion

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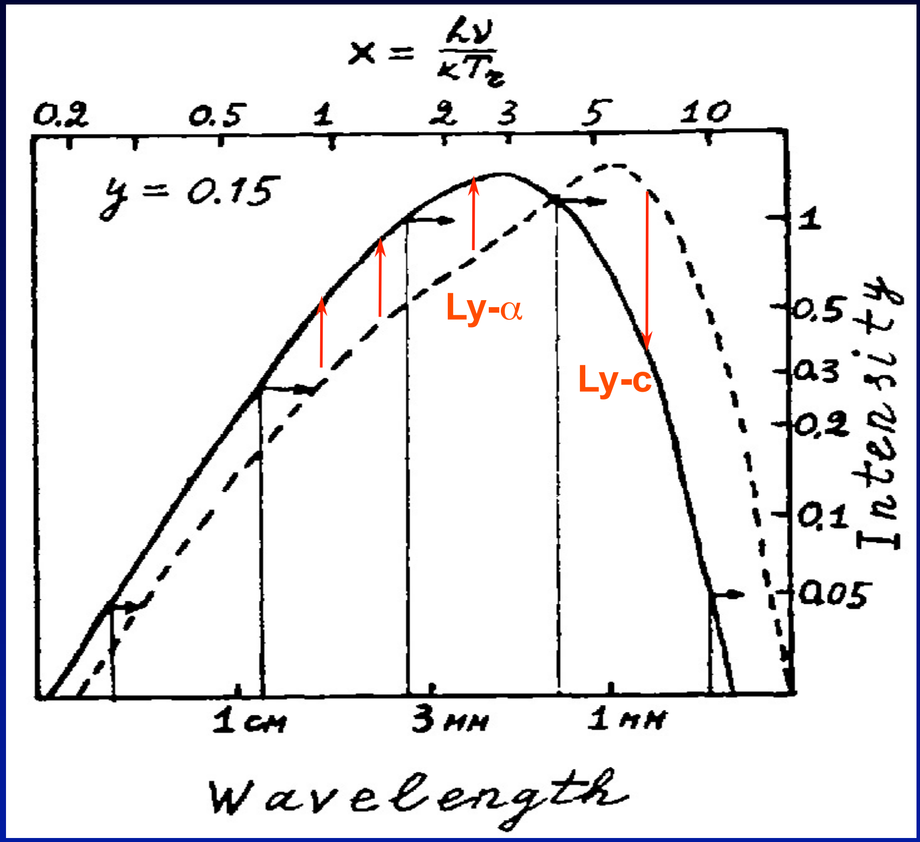
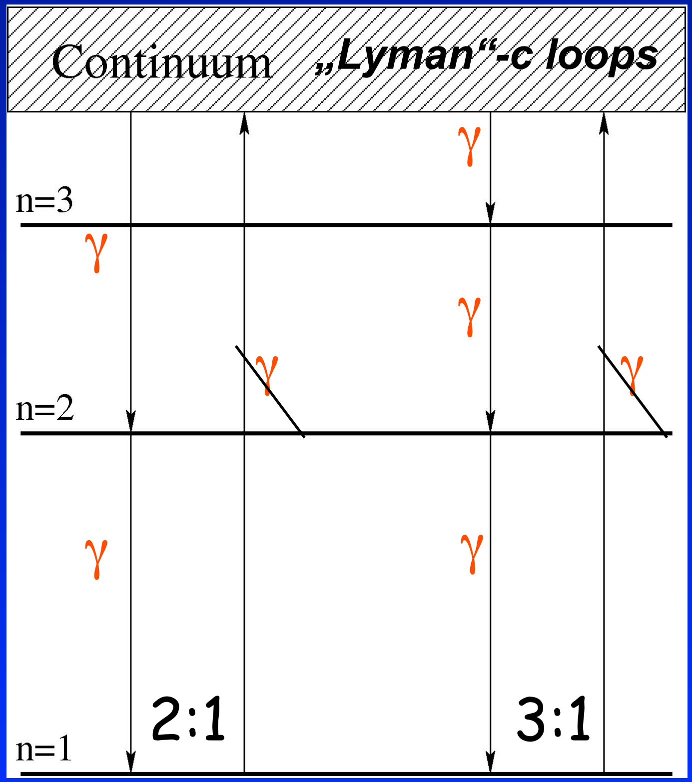
Absence of *narrow spectral features* makes it very hard to understand real details!!!

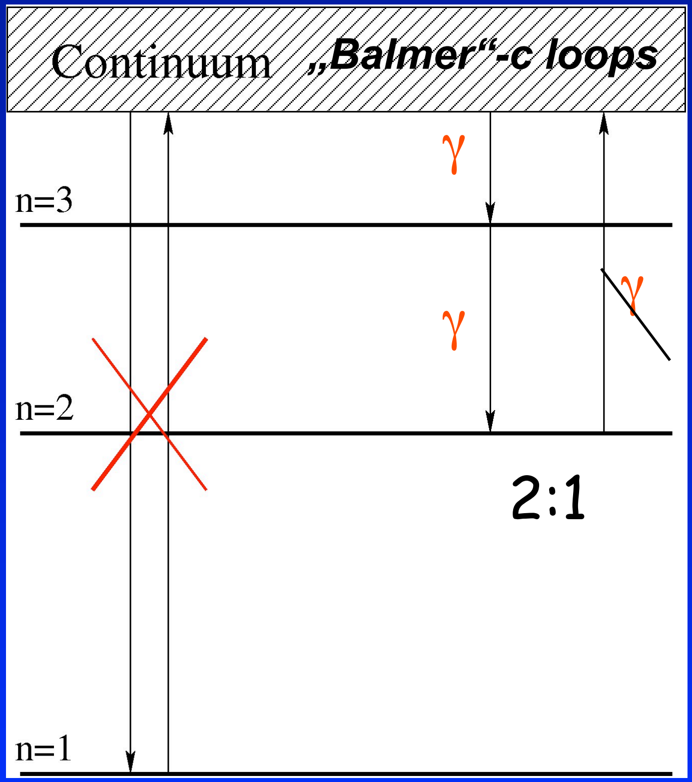
Pre-recombinational atomic transitions after possible early energy release

- pure blackbody CMB
  → *no net emission or absorption of photons before recombination epoch!*

- non-blackbody CMB
  (Lyubarsky & Sunyaev, 1983)
  → atoms "try" to restore full equilibrium
  → *atomic loops* develop (cont.→ bound → cont.)
  → "splitting" of photons
  → loops mainly end in Lyman-continuum
  → Balmer-cont. loops work just before recombination



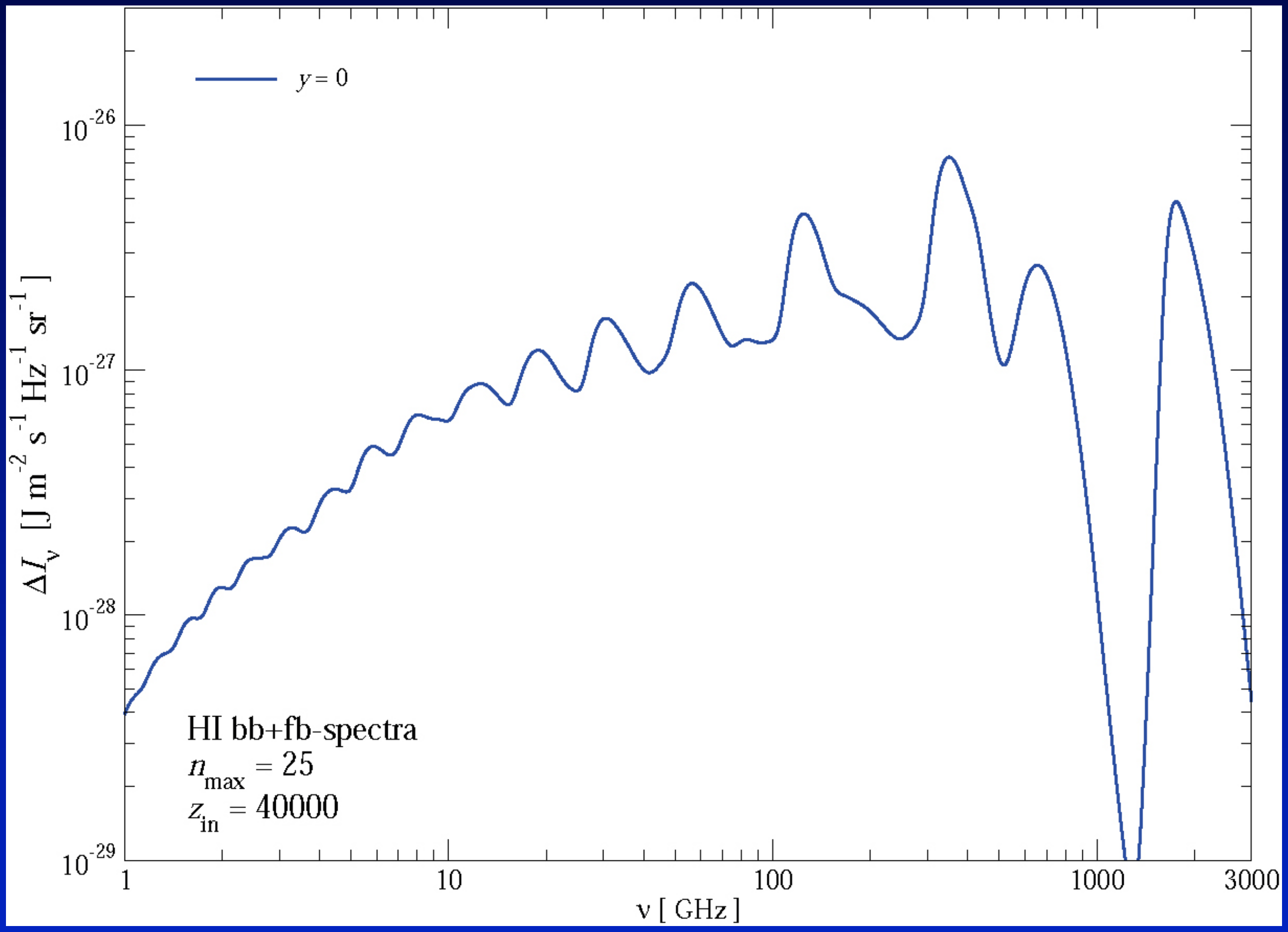




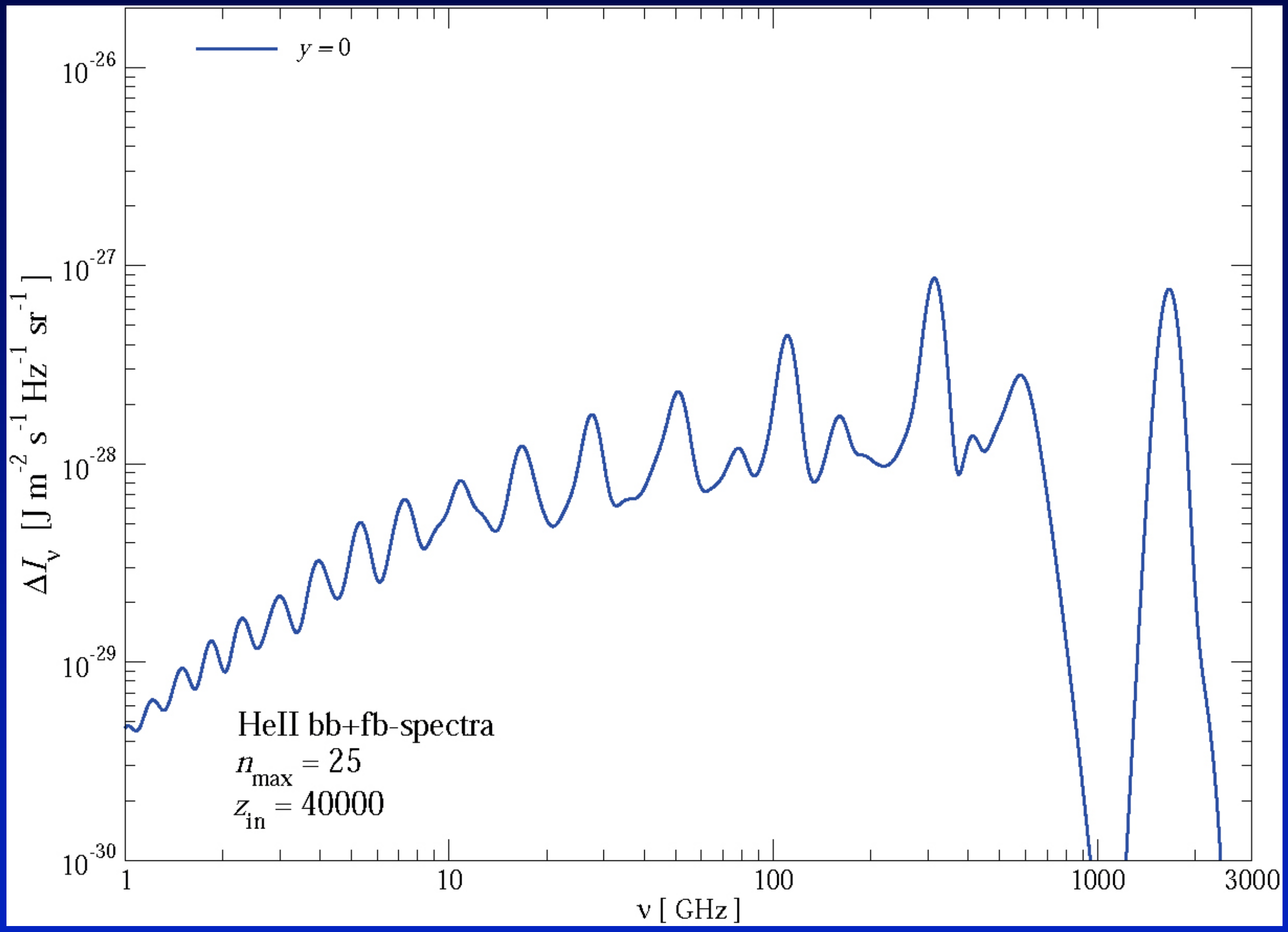
CMB spectral distortions after single energy release

25 shell HI and HeII bb&fb spectra: dependence on y

Hydrogen



Helium +



JC & Sunyaev, 2008, astro-ph/0803.3584

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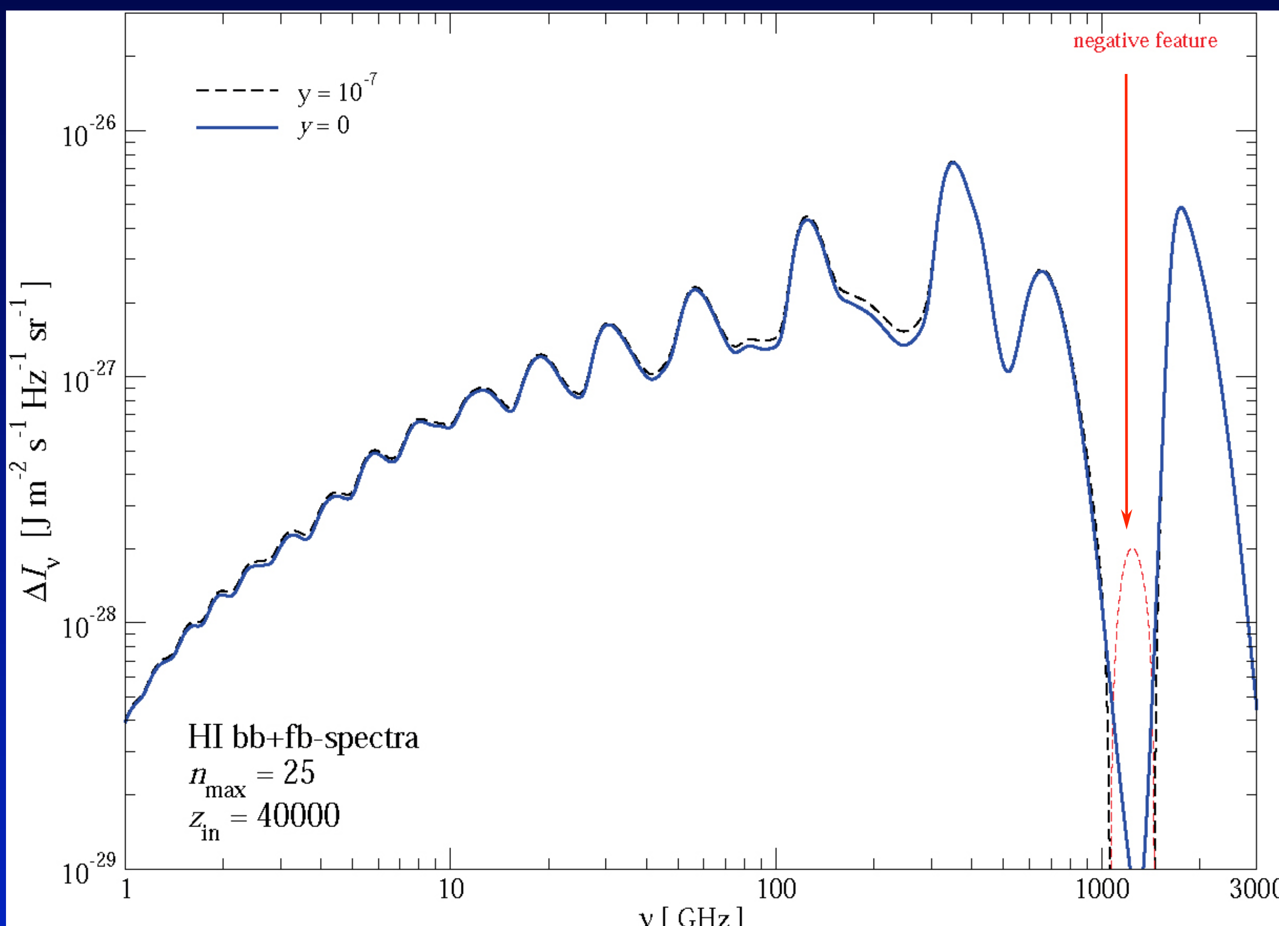

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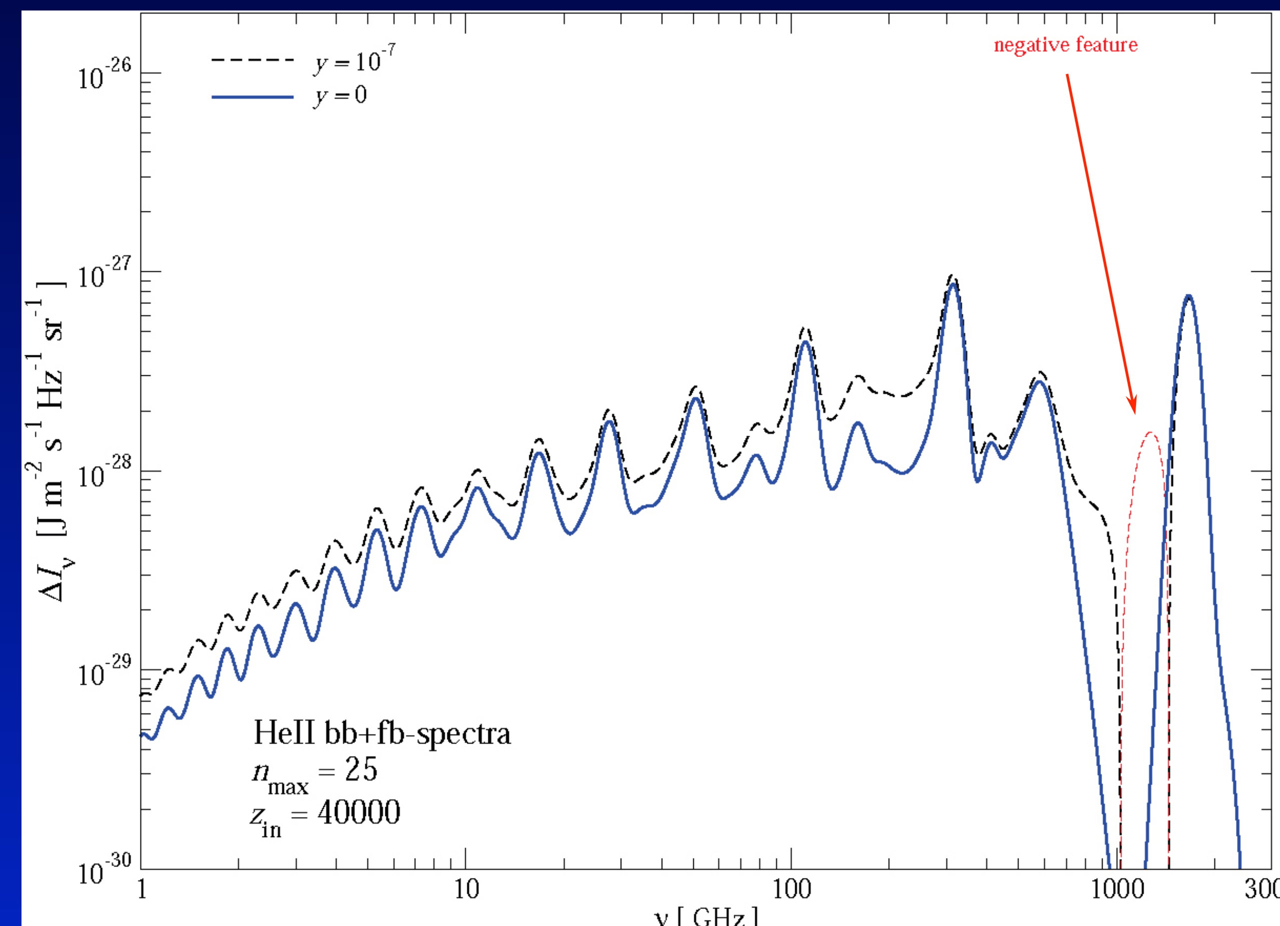

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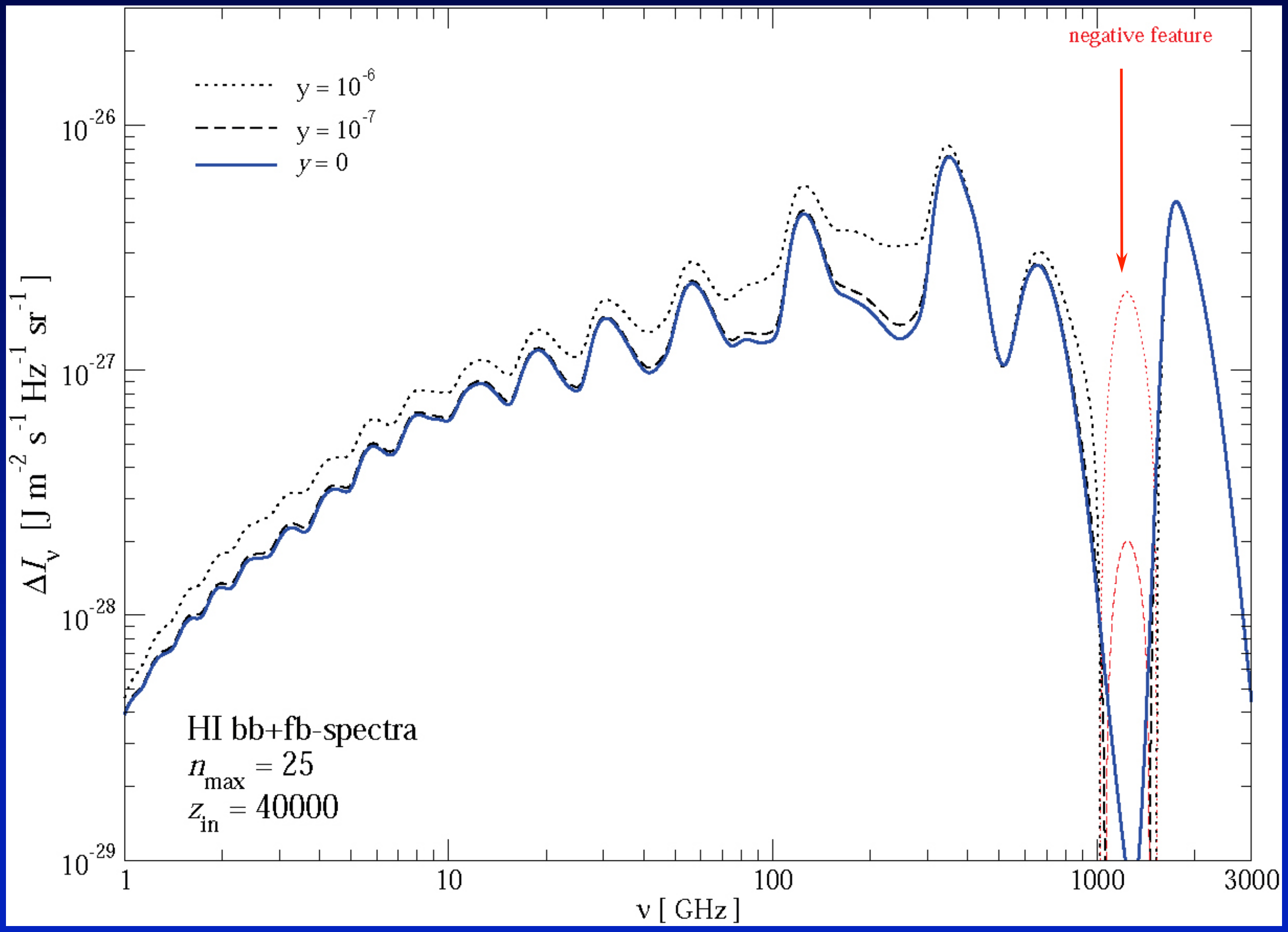

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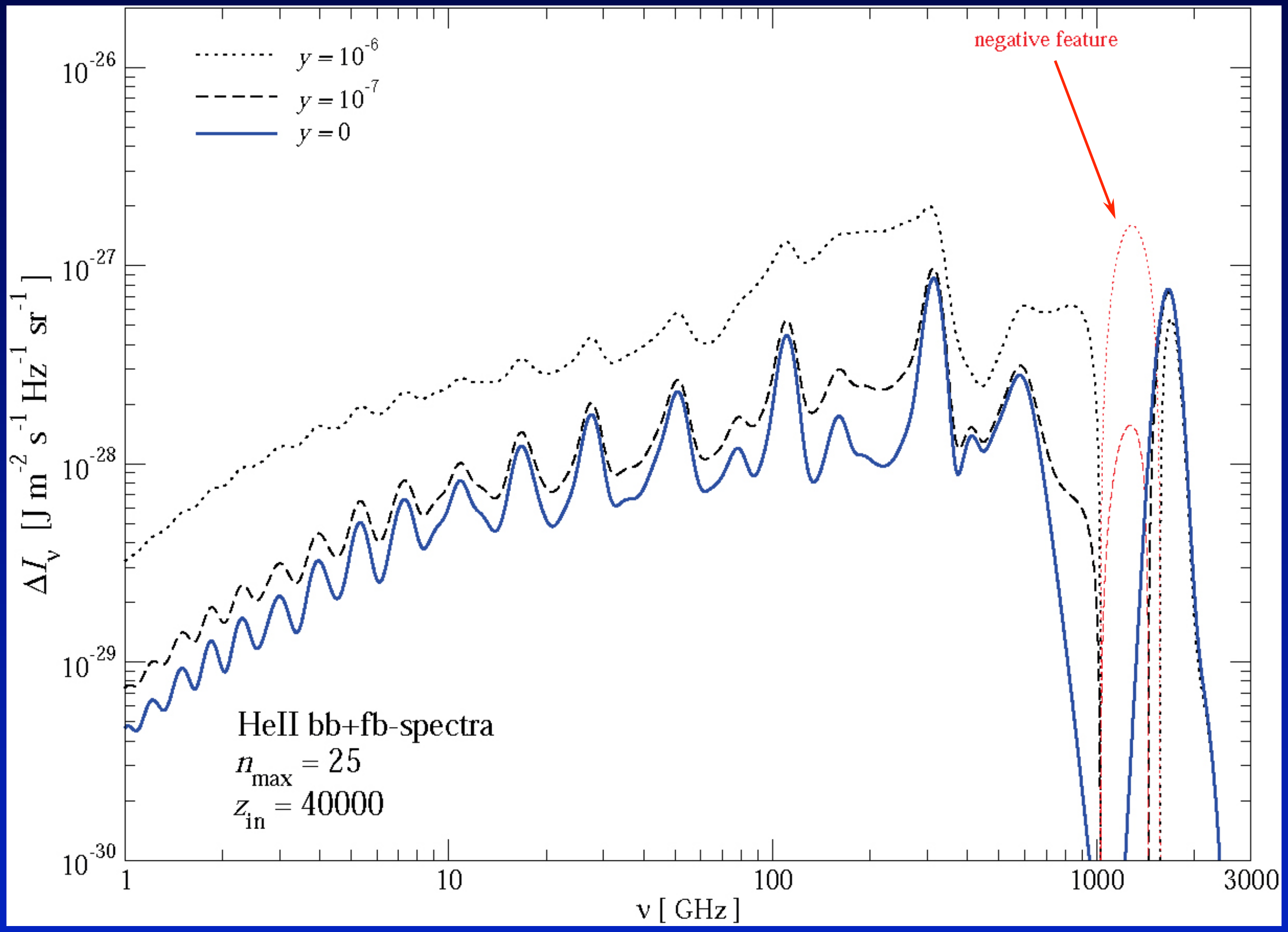

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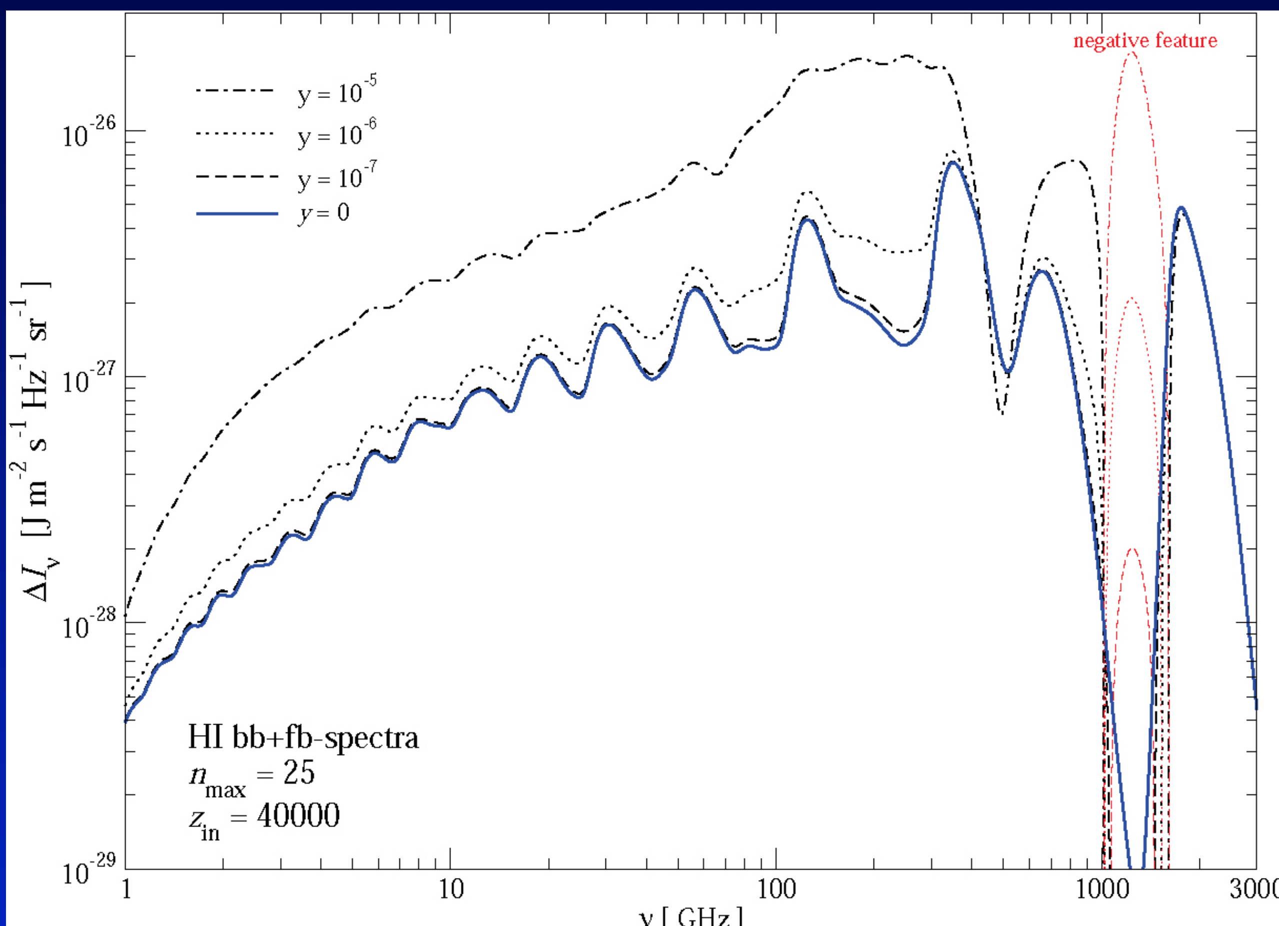

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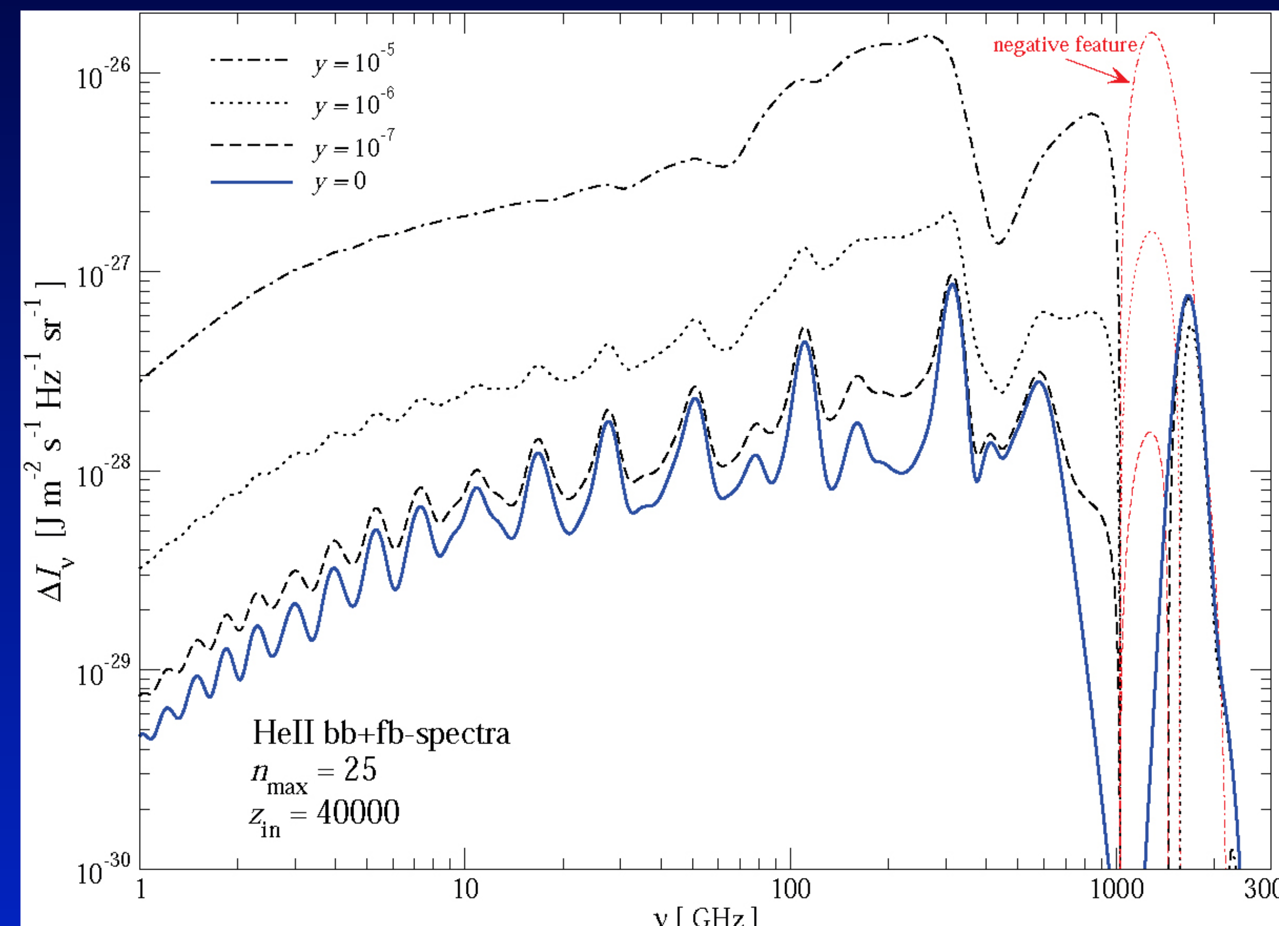

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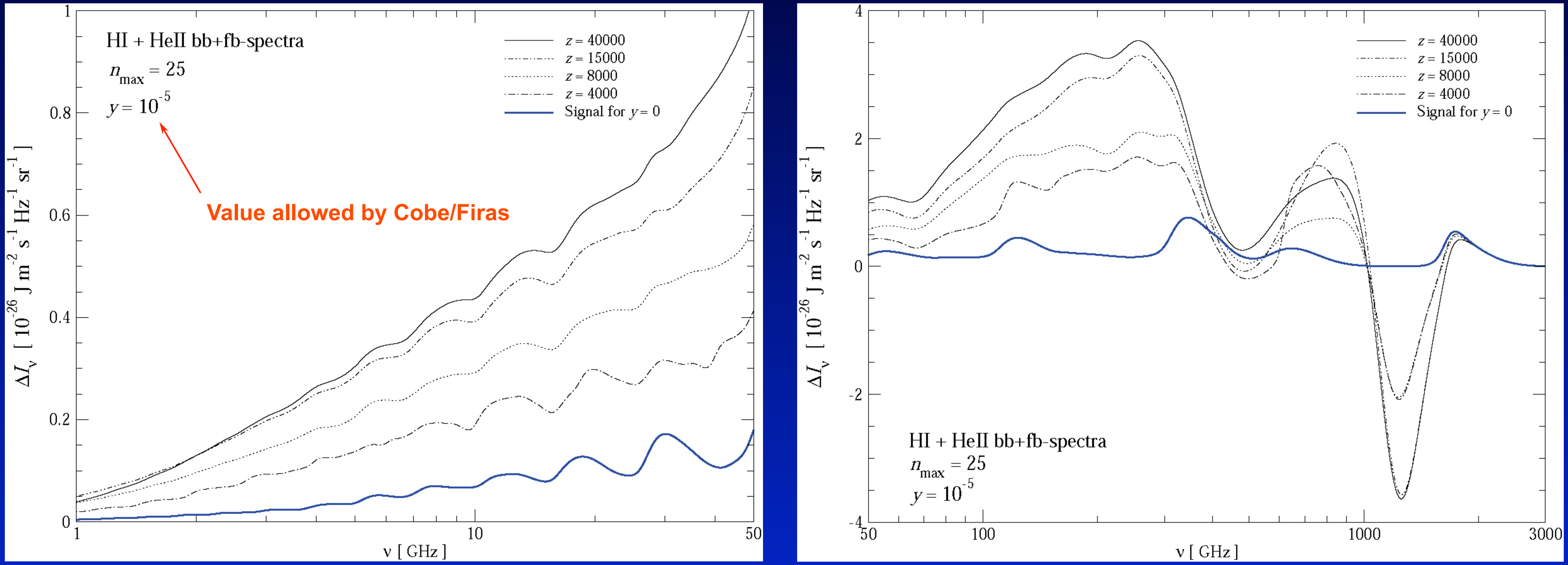
- Large increase in the total amplitude of the distortions with value of *y*!
- Strong emission-absorption feature in the Wien-part of CMB (absent for *y*=0!!!)
- HeII contribution to the pre-recombinational emission as strong as the one from Hydrogen alone !

CMB spectral distortions after single energy release
25 shell HI and HeII bb&fb spectra: dependence on z

Hydrogen and Helium +



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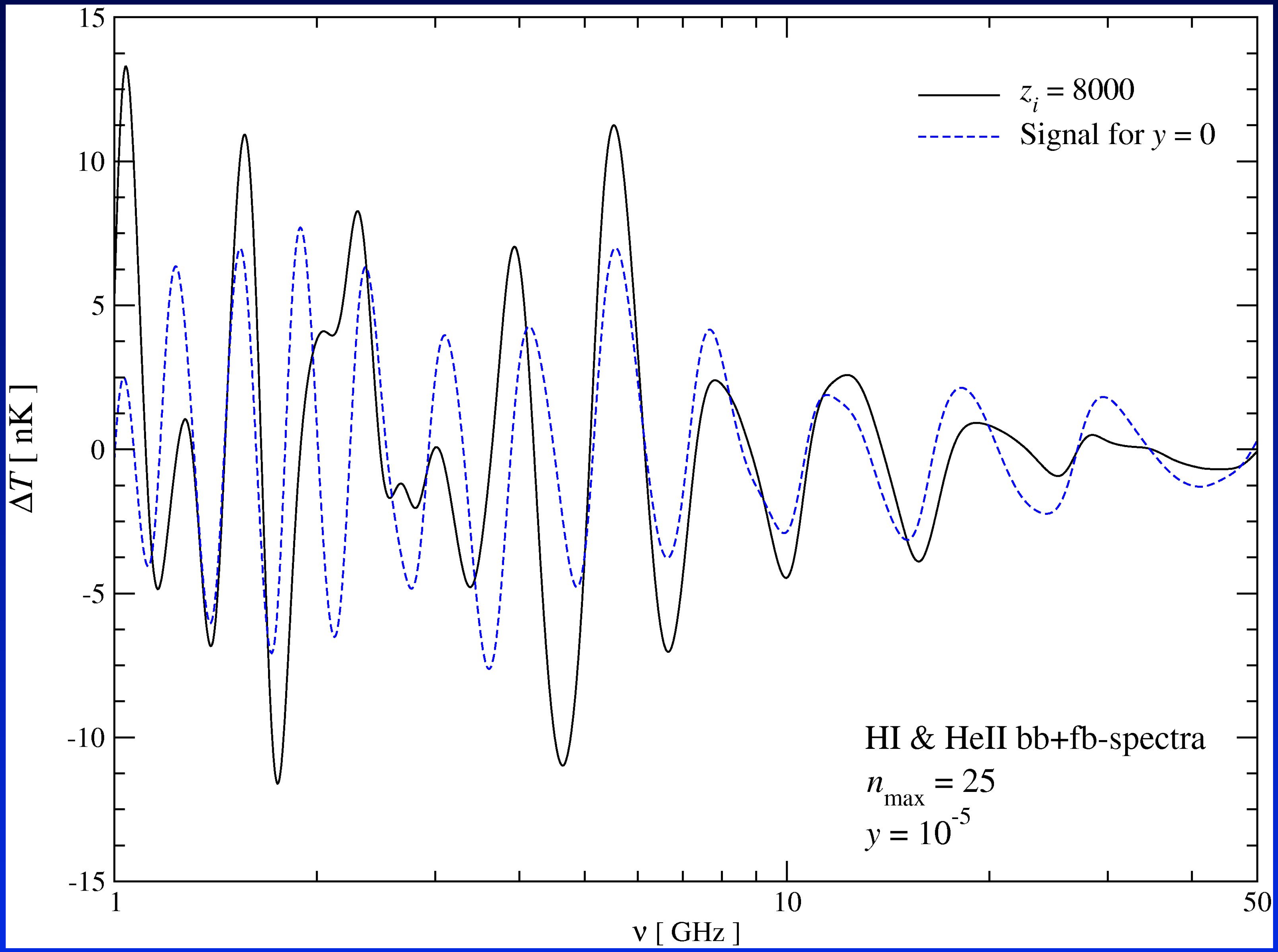
- Large increase in the total amplitude of the distortions with injection redshift!
- Number of spectral features depends on injection redshift!
- Emission-Absorption feature increases ~2 for energy injection z ⇒11000

CMB spectral distortions after single energy release
Changes in the low-frequency variability



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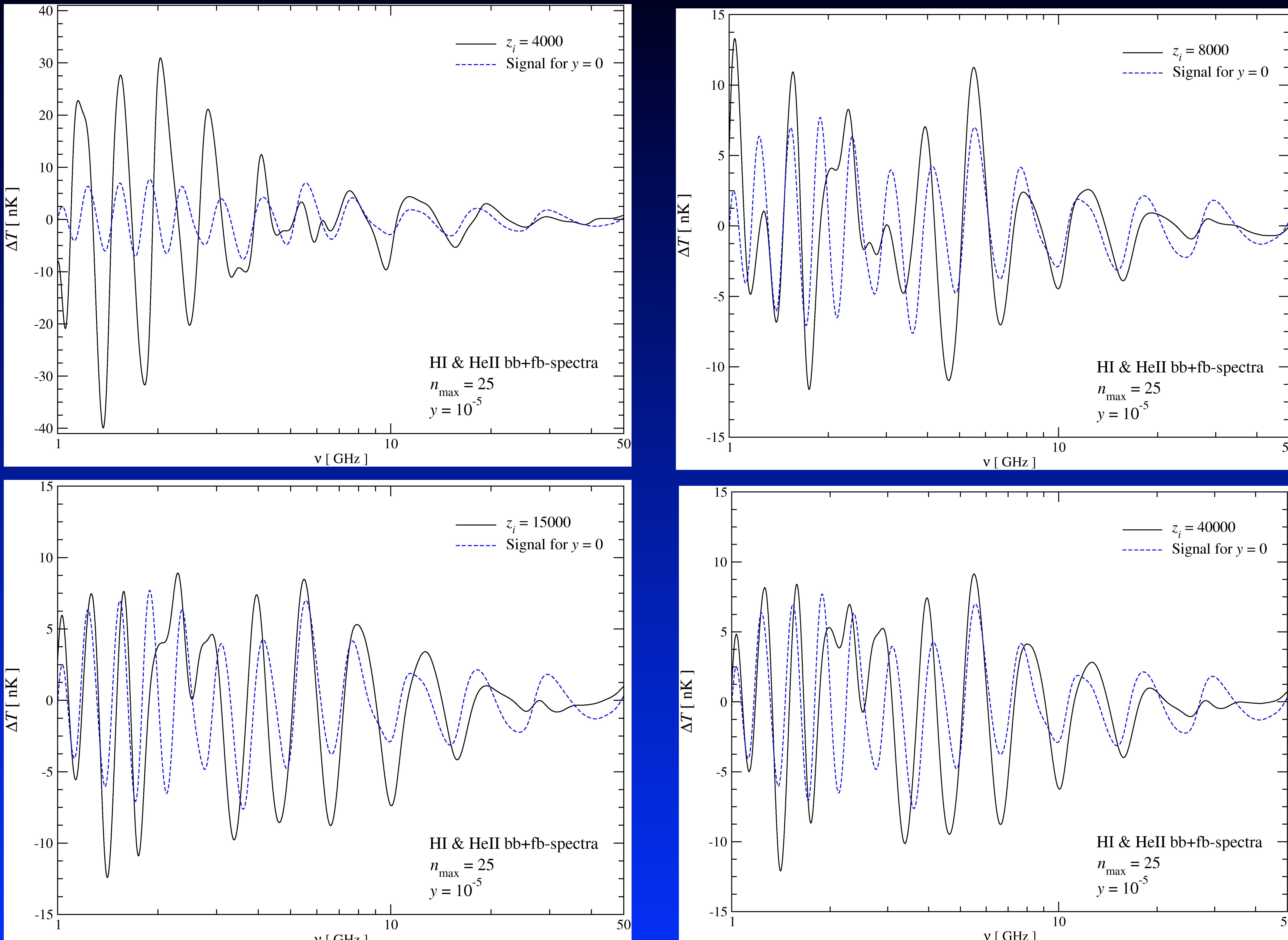
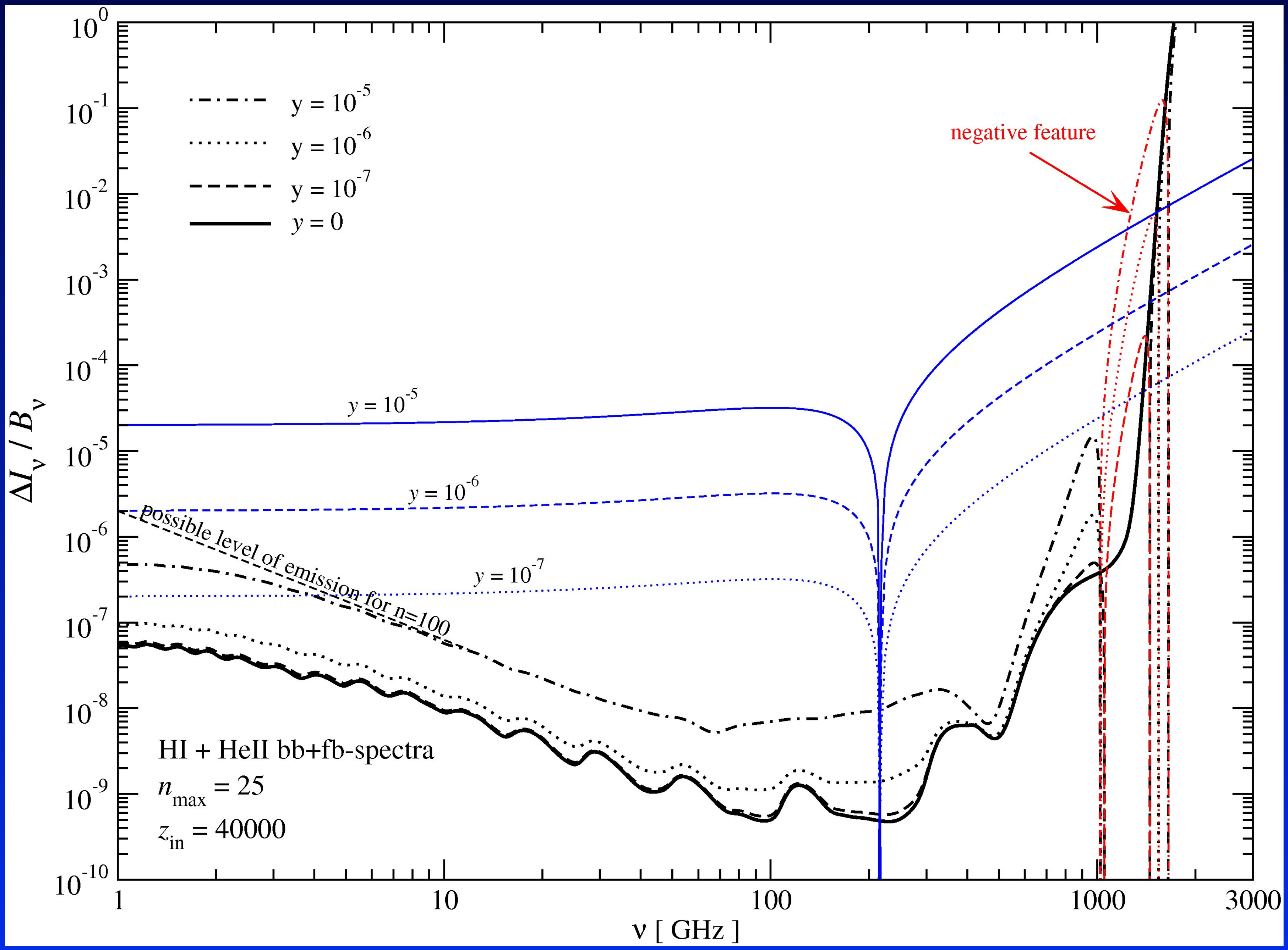
- increase of the peak-peak amplitude by up to a factor of 2!
- non-trivial phase-shifts
- additional features



z_i = 4000
Signal for y = 0
HI & HeII bb+fb-spectra
n_{max} = 25
$y = 10^{-5}$
ΔT [nK]
ν [GHz]
z_i = 8000
Signal for y = 0
HI & HeII bb+fb-spectra
n_{max} = 25
$y = 10^{-5}$
ΔT [nK]
ν [GHz]
z_i = 15000
Signal for y = 0
HI & HeII bb+fb-spectra
n_{max} = 25
$y = 10^{-5}$
ΔT [nK]
ν [GHz]
z_i = 40000
Signal for y = 0
HI & HeII bb+fb-spectra
n_{max} = 25
$y = 10^{-5}$
ΔT [nK]
ν [GHz]

CMB spectral distortions after single energy release
Comparison with intrinsic y-distortion



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Distortion exceeds intrinsic y-distortion at very low and very high frequencies!

Atomic loops may even help restoring blackbody there!

Question about collisions....

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  → critical question: how well one will have to do to even if the 'response' is more direct?

- Effects of intrinsic y-distortions

  → lines are 'thermometer' at different redshift

  → could allow us to 'date' the y-type distortion

  → additional source of low frequency photons that could help erasing distortions

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- Dark matter annihilation or decaying particles during recombination

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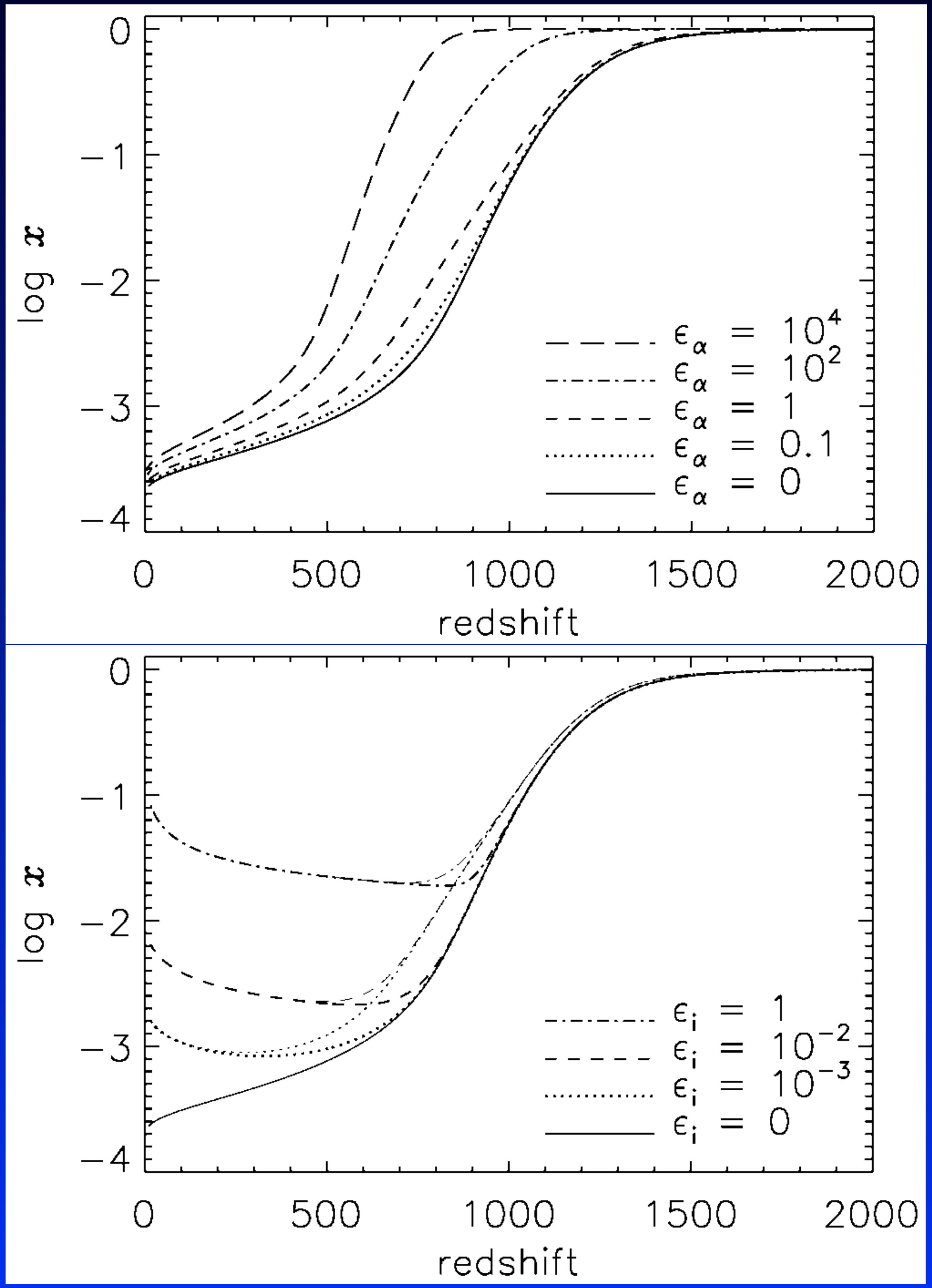
Extra Sources of Ionizations or Excitations

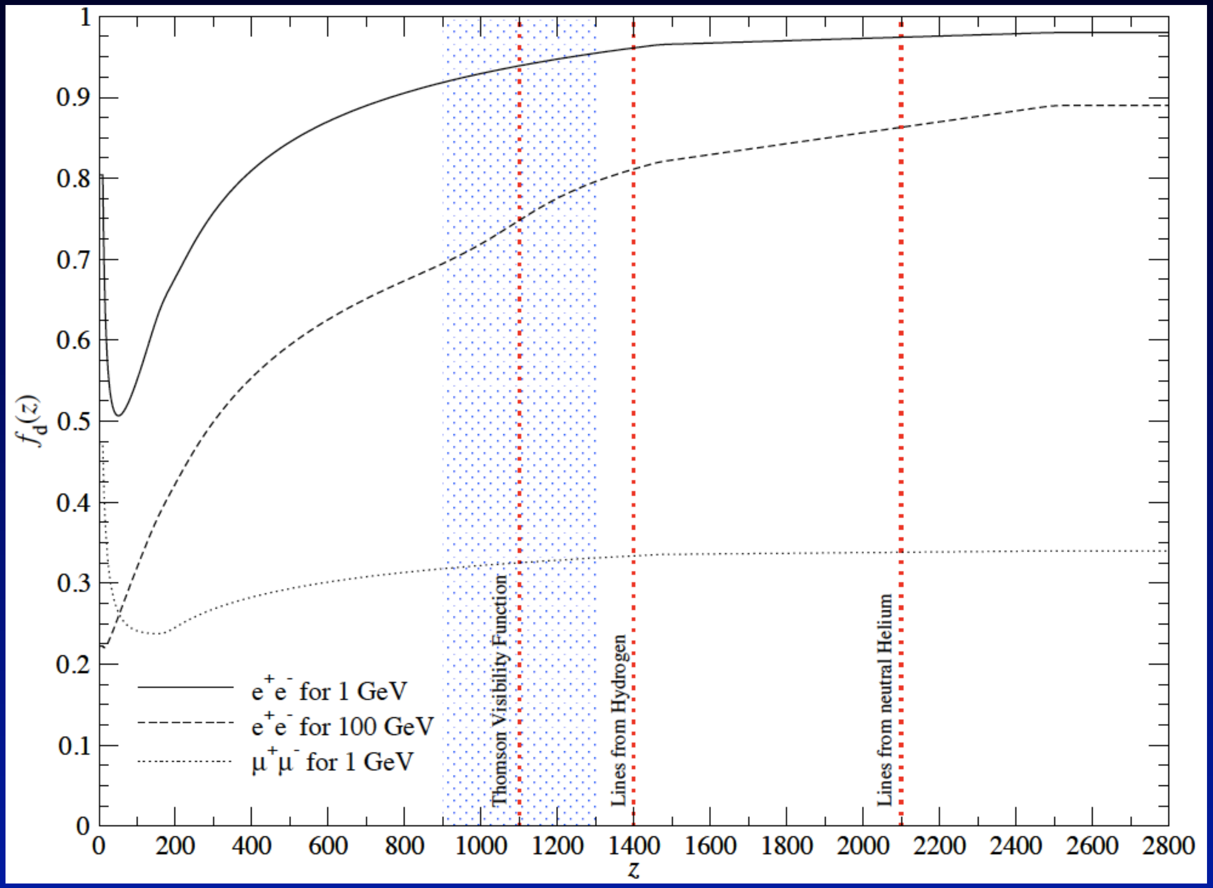


Peebles, Seager & Hu, ApJ, 2000

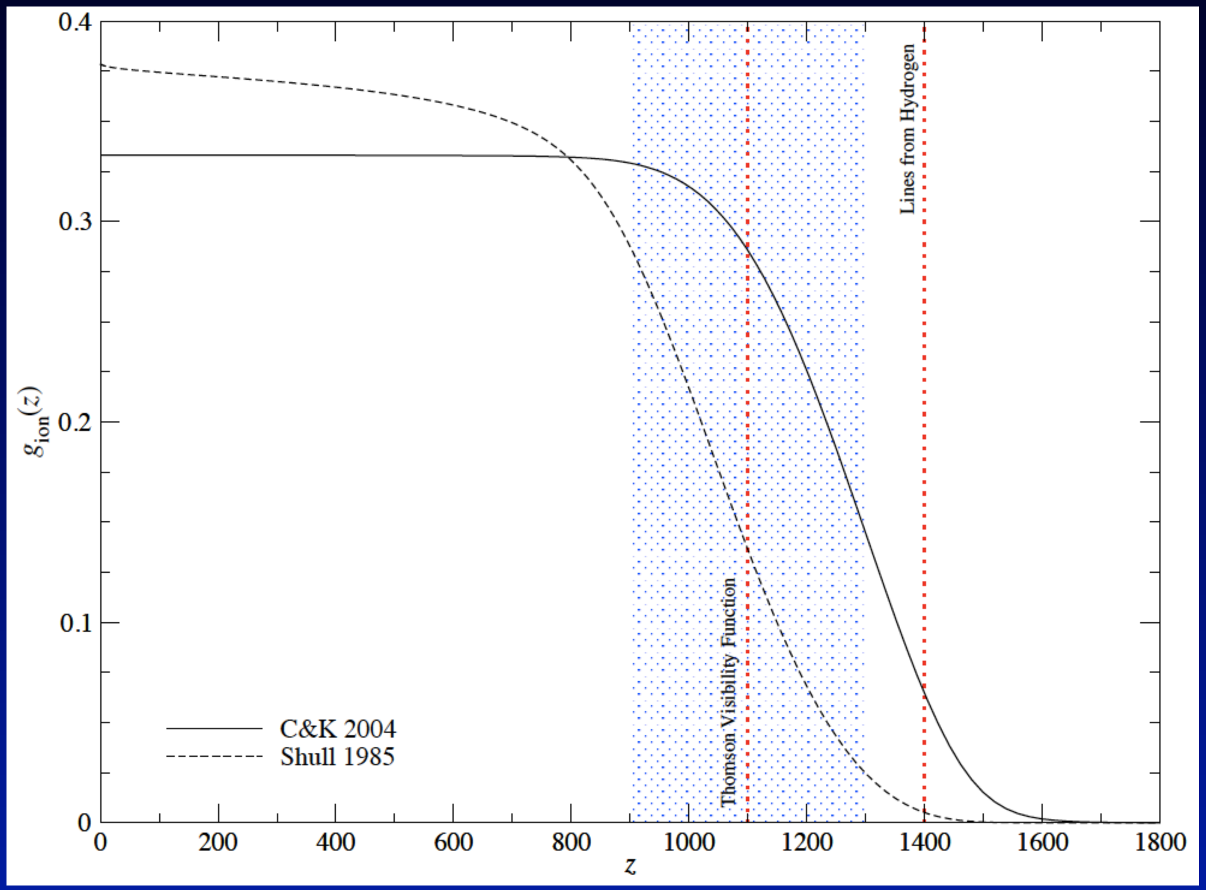
- ‚Hypothetical' source of extra photons parametrized by ε_α & ε_i
- Extra excitations ⇒ delay of Recombination
- Extra ionizations ⇒ affect 'freeze out' tail
- This affects the Thomson visibility function
- From WMAP ⇒ $\varepsilon_\alpha < 0.39$ & $\varepsilon_i < 0.058$ at 95% confidence level (Galli et al. 2008)

- Extra ionizations & excitations should also lead to additional photons in the recombination radiation!!!
- This in principle should allow us to check for such exotic sources of photons at z~1000

Example: Dark Matter Annihilations (I)



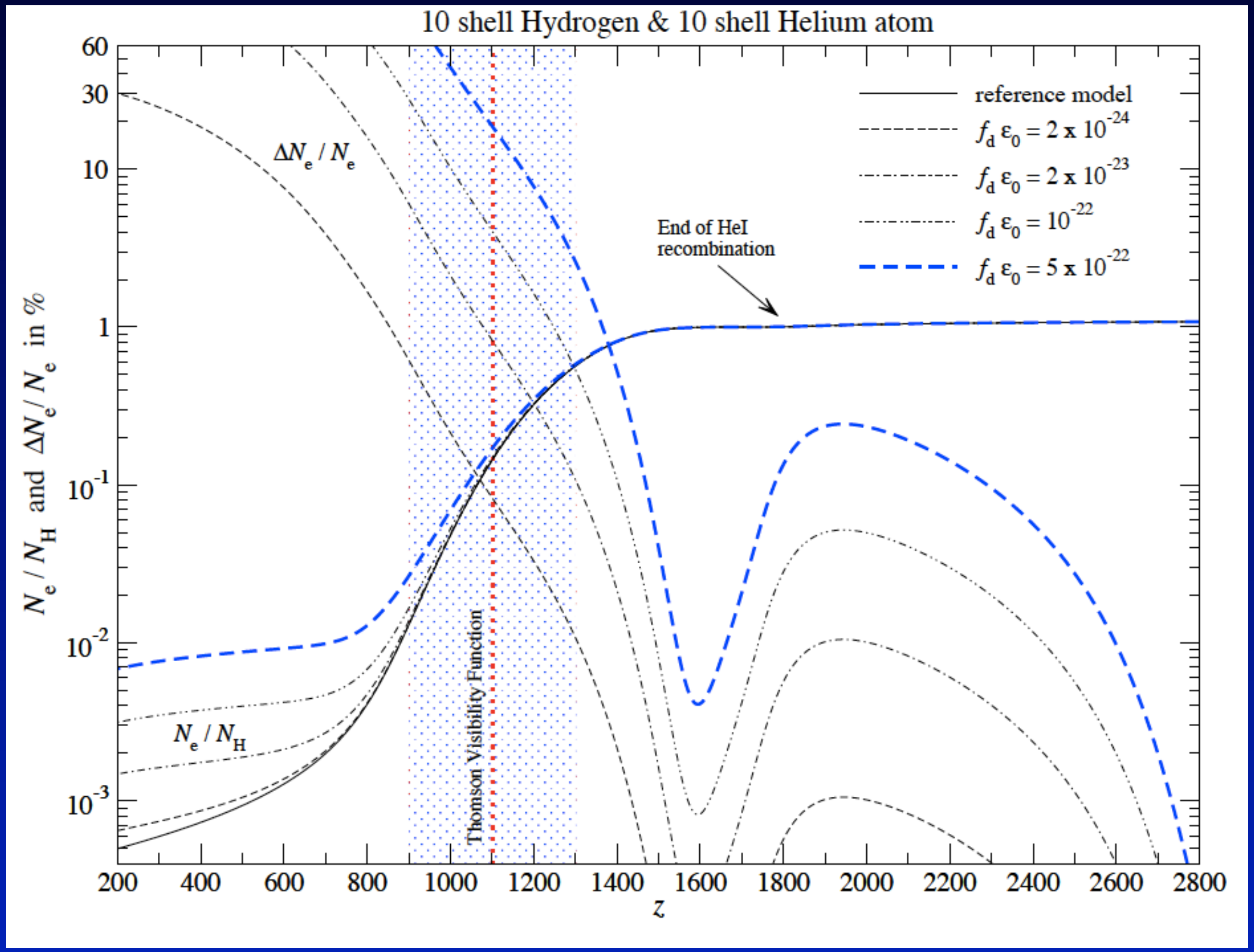
curves from Slatyer et al. 2009

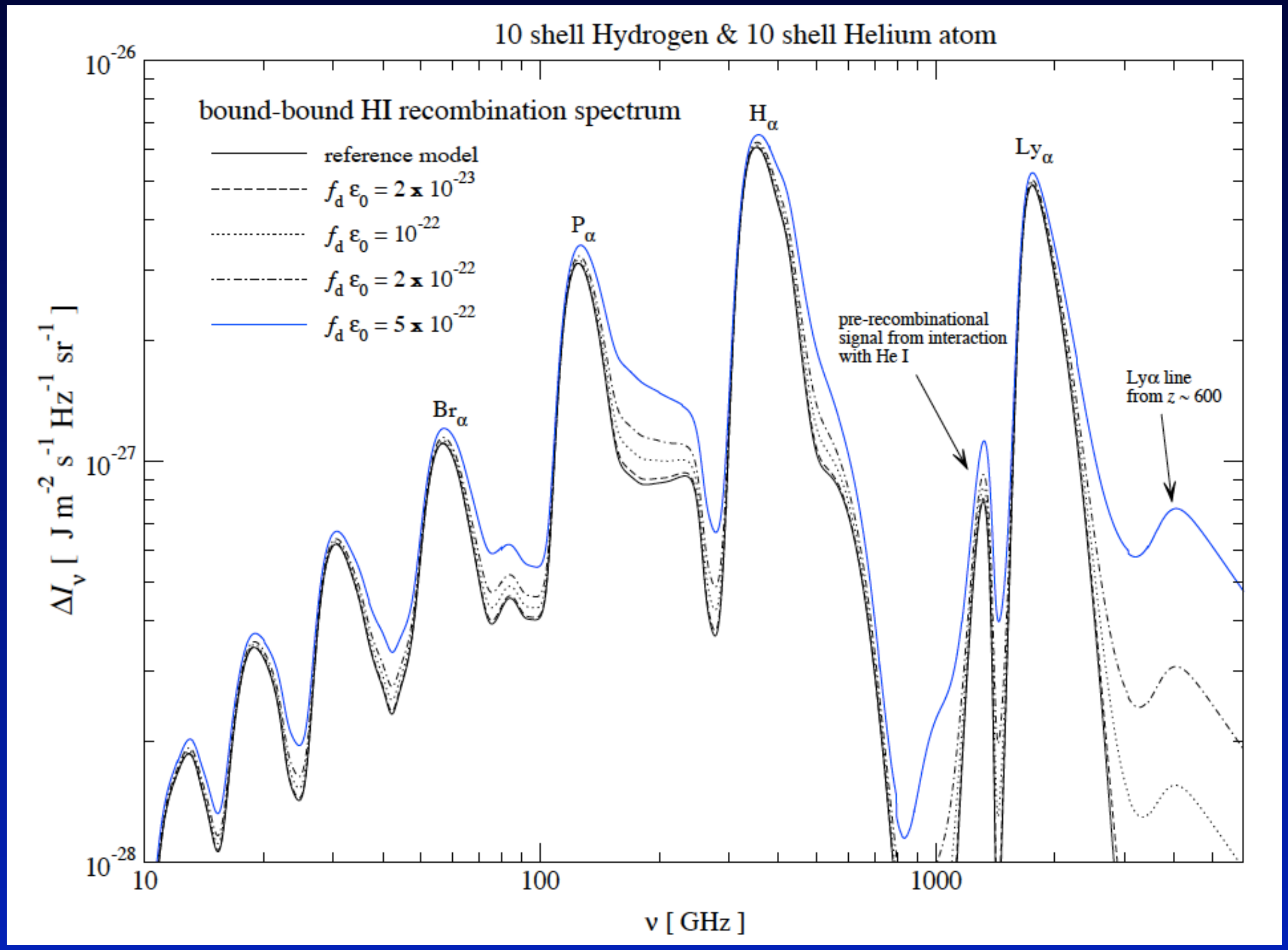


Efficiencies according to Chen & Kamionkowski, 2004 & Shull & van Steenberg 1985

- N^2 - dependence ⇒ $\mathrm{d}E/\mathrm{d}t \propto (1+z)^6$ and $\mathrm{d}E/\mathrm{d}z \propto (1+z)^{3...3.5}$
- continuous energy release ⇒ *tiny* μ & y-type distortion
- only part of the energy is really deposited (f_d ~ 0.1)
- Branching into *heating* (100% at high z), *ionizations* and *excitations* (mainly during recombination)
- Branching depends on considered DM model

Example: Dark Matter Annihilations (II)





- 'Delay of recombination'
- Affects Thomson visibility function
- Possibility of Sommerfeld-enhancement

- Additional photons at all frequencies
- Broadening of spectral features
- Shifts in the positions

see also Padmanabhan & Finkbeiner, Phys. Rev. D, 2005

JC, 2009, arXiv:0910.3663

Example: Dark Matter Annihilations (III)

- WMAP constraints on possible dark matter annihilation efficiencies already very tight (e.g. see Galli et al. 2009; Slatyer et al. 2009)
  - absolute changes to CMB power spectra have to be small (~ 1%-5%)
  - changes to cosmological recombination spectrum are of similar order

- So why bother anymore? What could the cosmological recombination spectrum teach us in addition? (JC, 2009, arXiv:0910.3663)
  - spectrum is sensitive to cases for which the C_l's are not affected!
  - DM annihilation parameters are ‚degenerate' with n_S & $\Omega_b h^2$
  - spectrum could help breaking this degeneracy
  - very direct way to check for sources of extra ionizations and excitations during *all three* recombination epochs

What can one learn by doing such a hard job?

- Dependence on normal cosmological parameters

  → number of hydrogen atoms determines number of H photons ⇔ $\Omega_b h^2$

  → number of helium atoms determines number of He photons ⇔ Y_p

  → changing Y_p also changes number of HI photon and the mixture of HeI spectrum and HI spectrum
  → changing T_0 shifts the positions of spectral features (‘real’ thermometer)
  → real shifts expected to be small, but the *question* is how easy it will be to measure the position of the line-template?
  → direct dependence on H_0 or $\Omega_m h^2$, etc rather small...

- Dependence on recombination dynamics and physics

  → allows us to check the recombination model
  → *critical question*: how well one will have to do to even if the ‘response’ is more direct?

- Effects of intrinsic y-distortions

  → lines are ‘thermometer’ at different redshift
  → could help us to ‘date’ y-type distortions; *Question*: is this problem really much harder otherwise?
  → additional source of low frequency photons that could help erasing distortions

- Dark matter annihilation or decaying particles during recombination

  → it is easy to perturb baryon, and the lines directly respond to tiny amounts of energy injection during recombination
  → spectrum sensitive even at times when the CMB anisotropies will not be affected at all!

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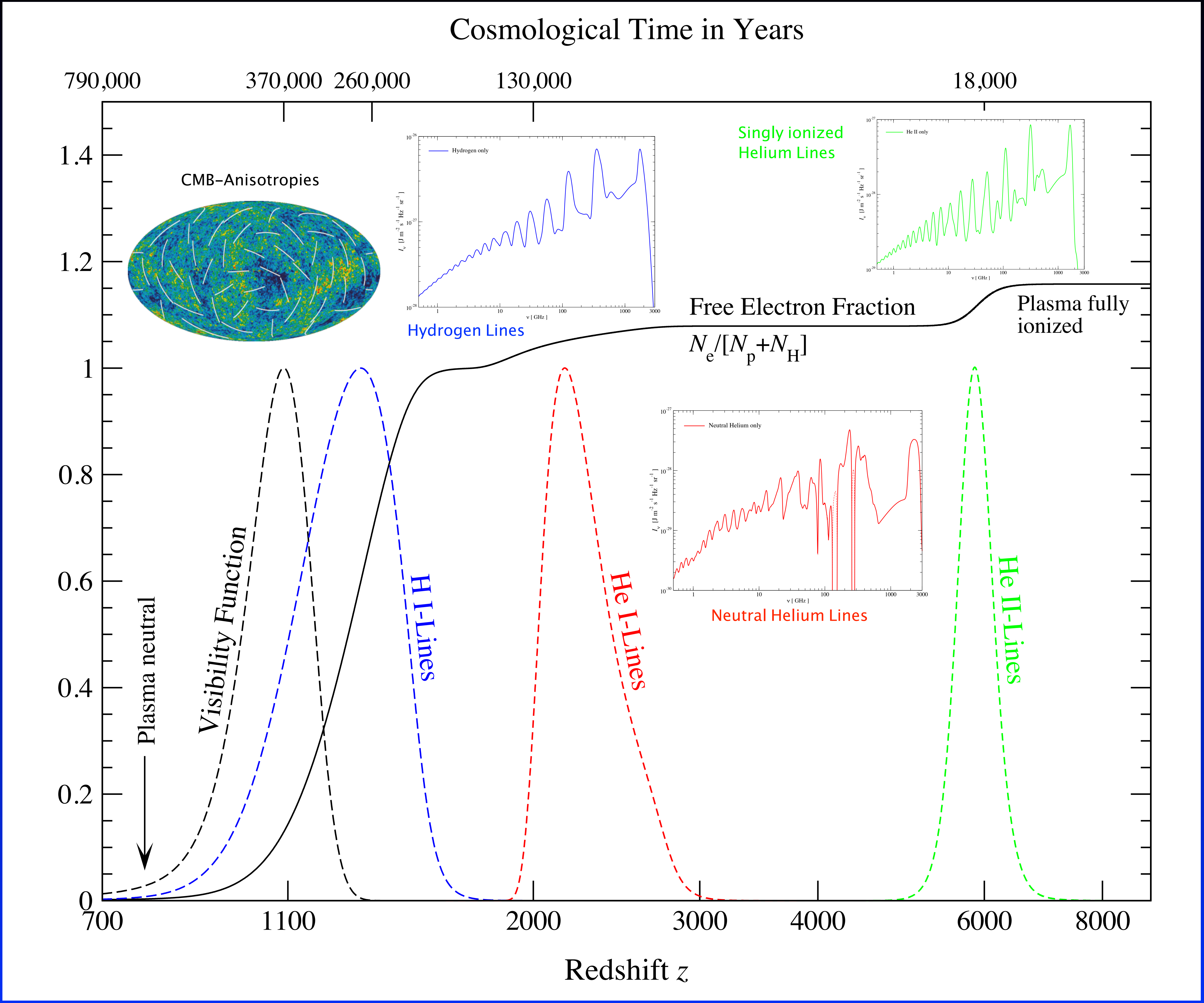
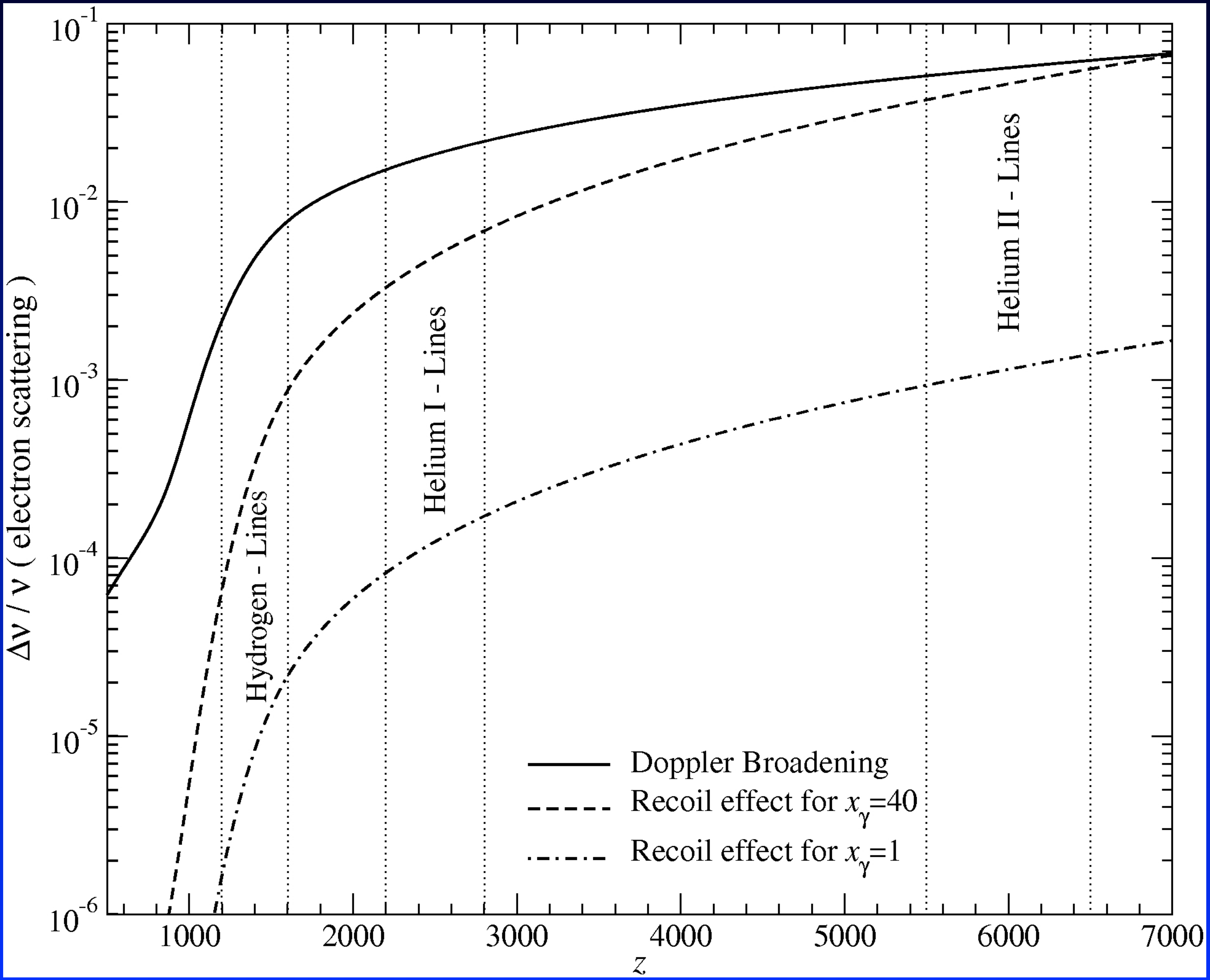
- Other stuff, which one still has to work out...

  → variation of fundamental constants during recombination (α, m_e, m_e/m_p ; position of features!)
  → non-standard BBN; Inhomogeneous Helium production (small scales; average spectrum different; width of the lines)


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

Effects due to electron scattering



Line broadening due to the Doppler-term