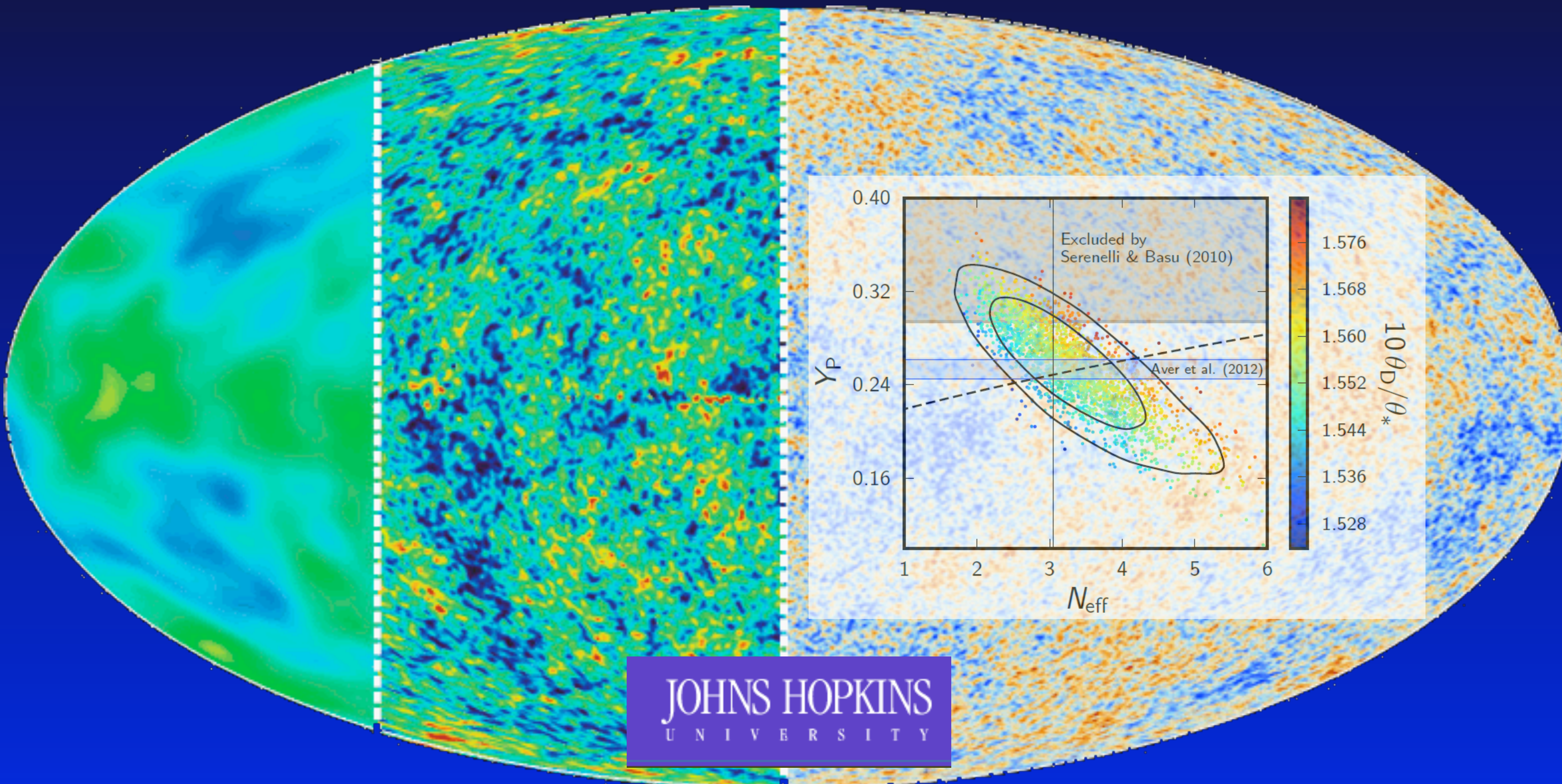
CMB Cosmology, Particle Physics and What all this has to do with Recombination



JOHNS HOPKINS UNIVERSITY

Jens Chluba

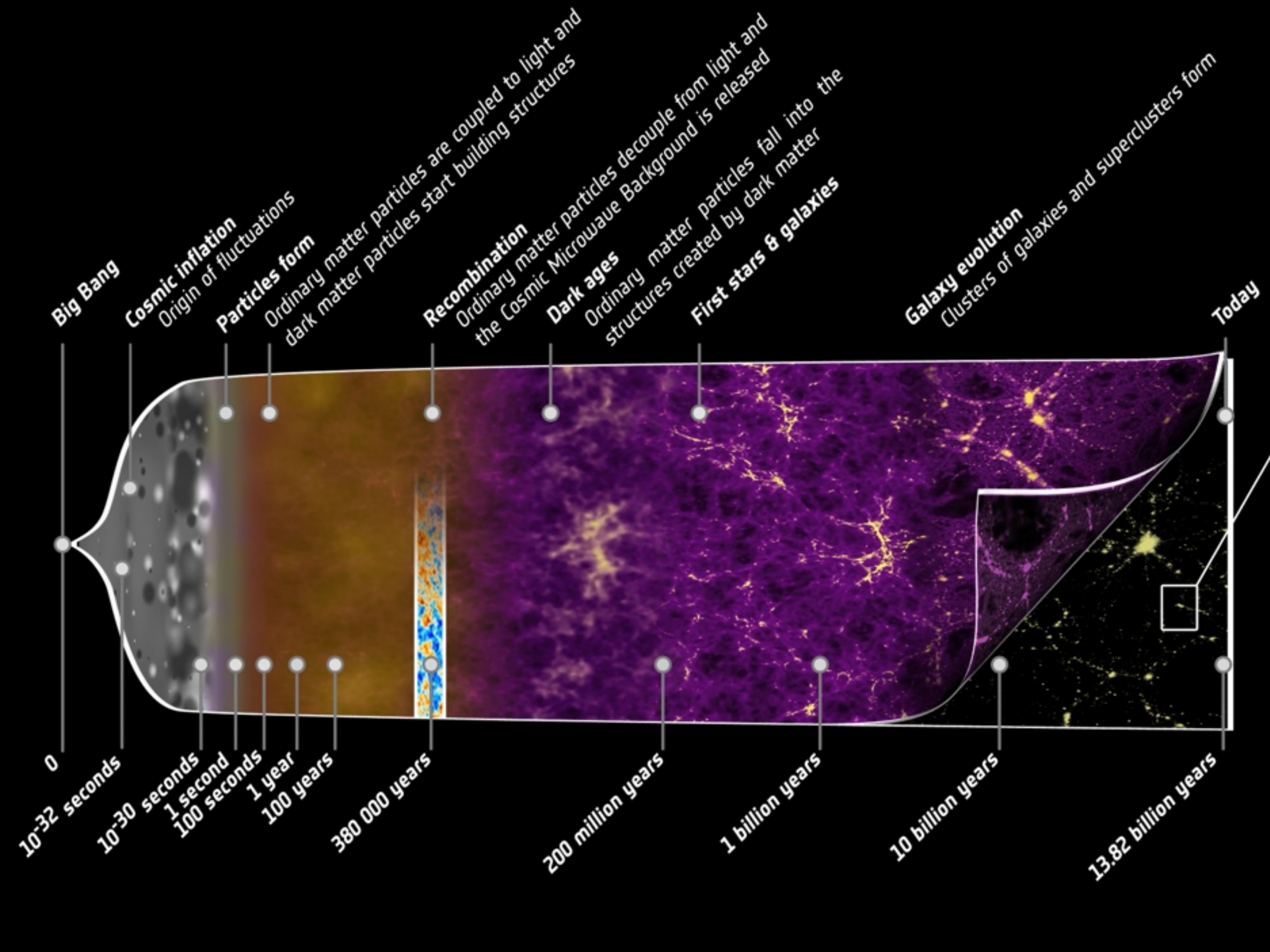
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

KEK Theory Meeting on Particle Physics Phenomenology

KEK, Japan, Sept 30th - Oct 3rd, 2013

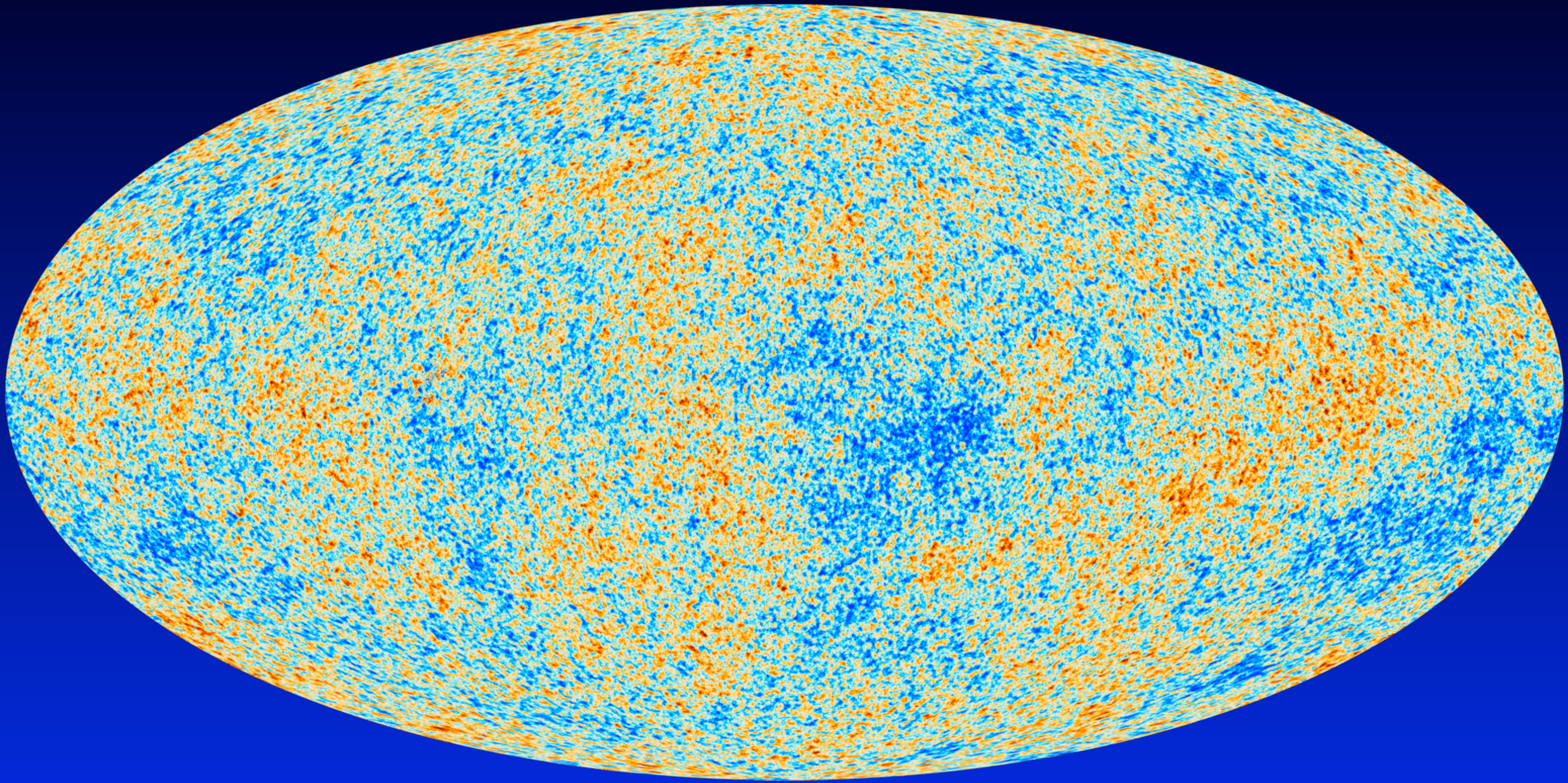
Main Goals for this Lecture

- Give an overview of some of the recent CMB results
- Explain why the CMB anisotropies link early-universe, particle and recombination physics
- Motivate how CMB spectral distortion (in particular from $z{\sim}1000$) could help disentangling effects in the future
- Convince you that the CMB holds many additional treasures for us, promising an exciting future for CMB cosmology



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Cosmic Microwave Background Anisotropies

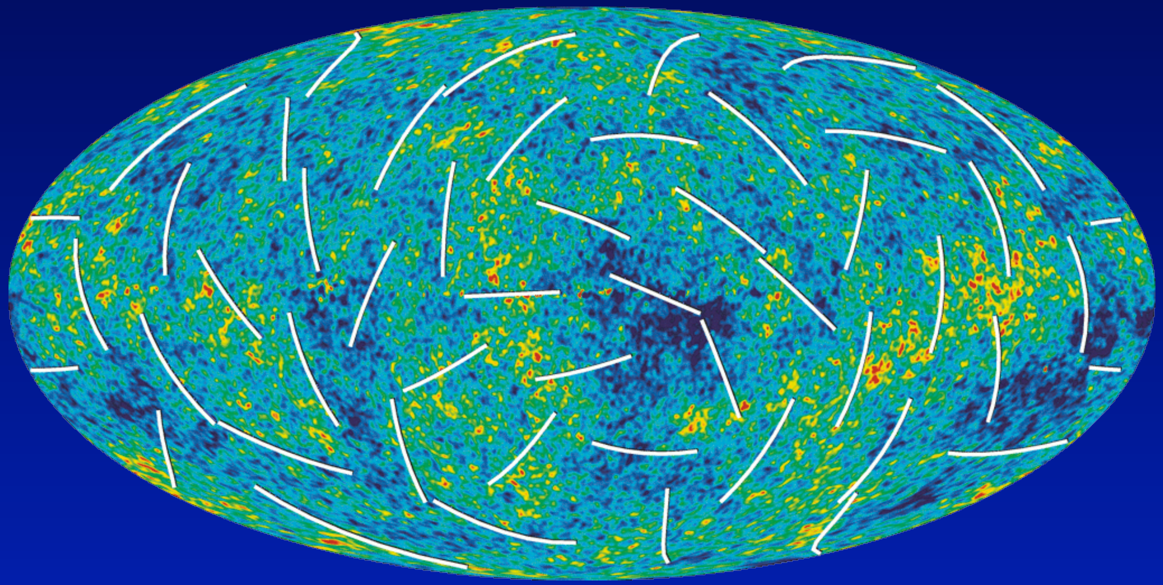


Planck all sky map

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

CMB Sky → Cosmology

WMAP CMB Sky



CMB Sky → Cosmology

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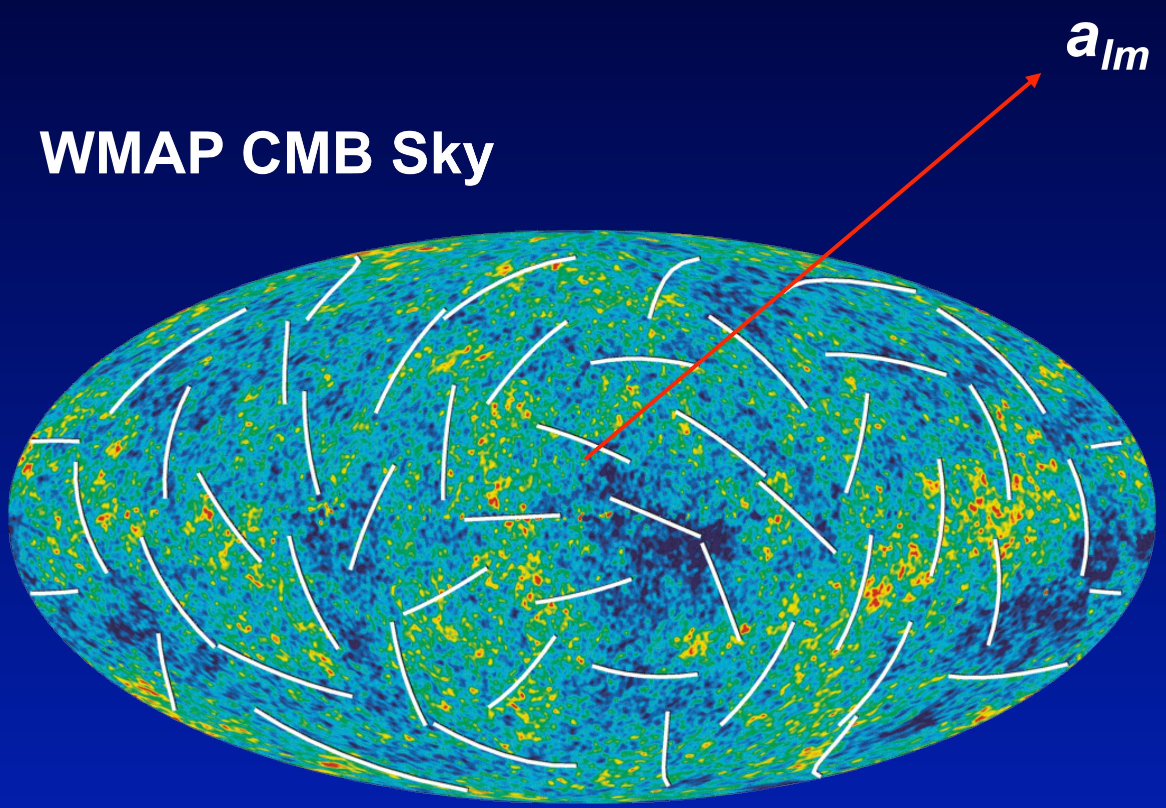
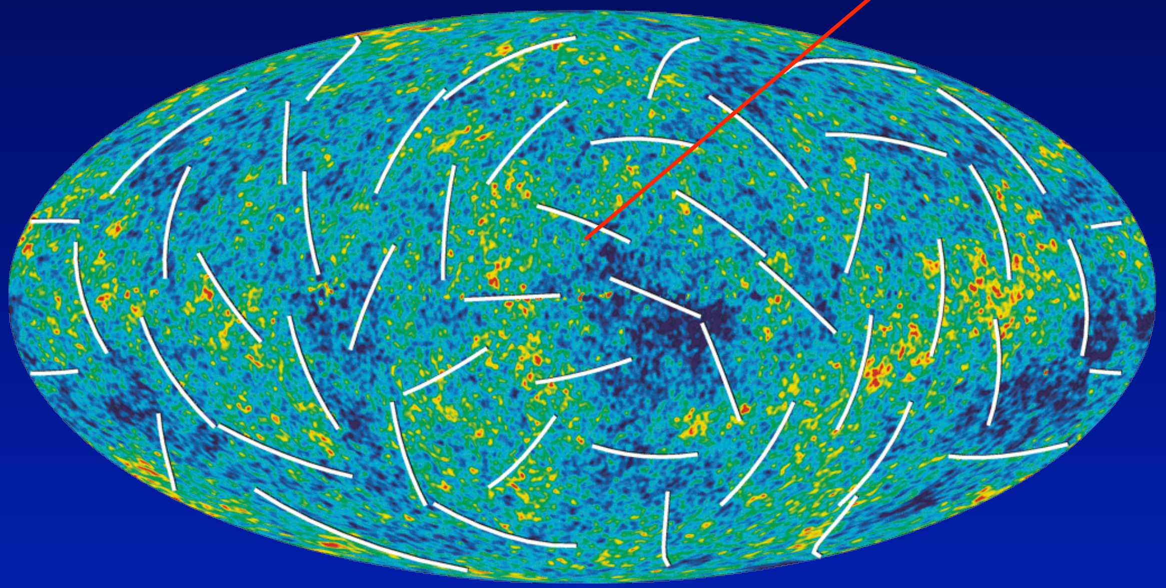


CMB Sky → Cosmology

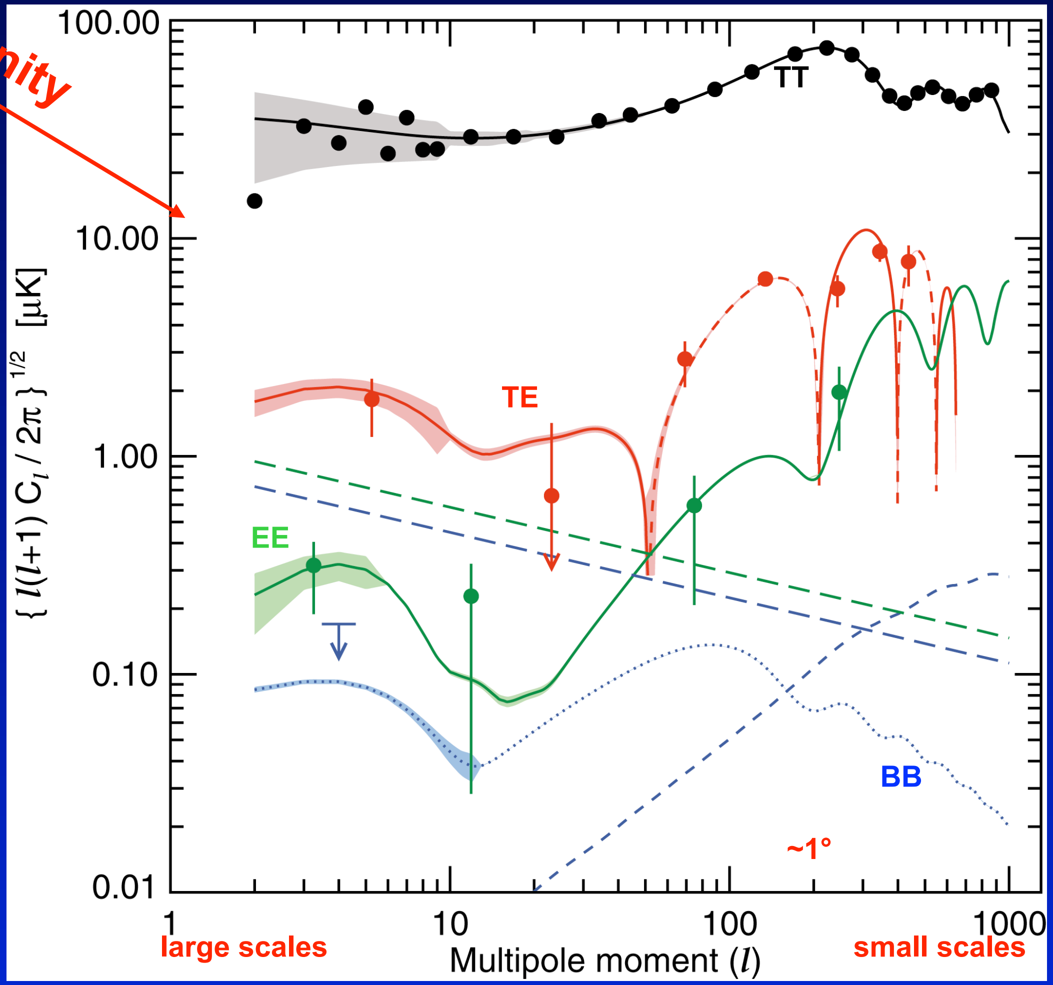
WMAP CMB Sky



a_{lm}

Gaussianity

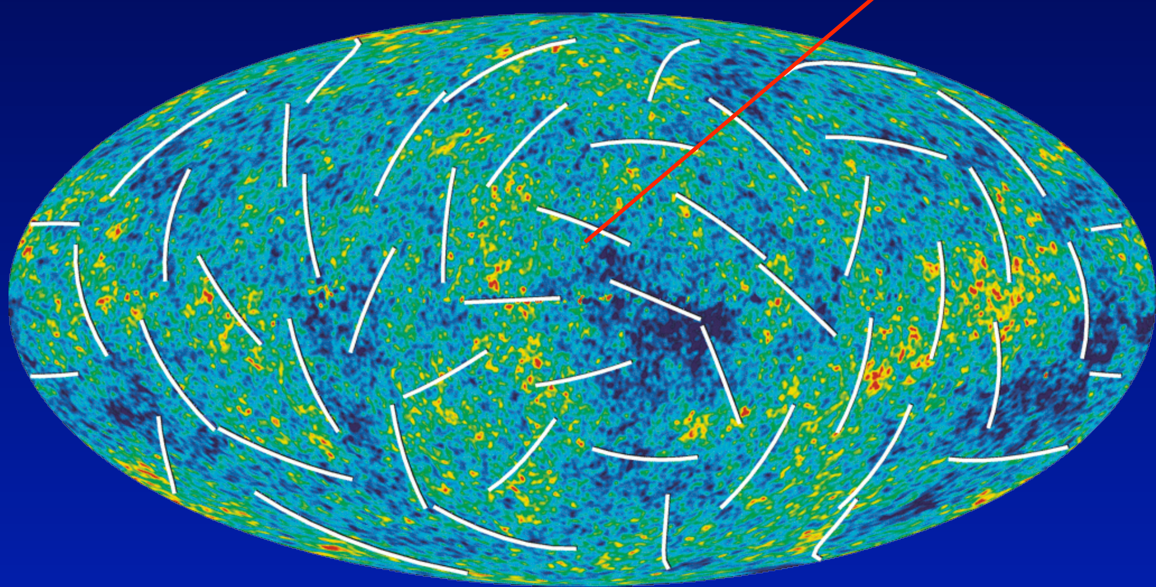
Power spectra



CMB Sky → Cosmology

a_{lm}

WMAP CMB Sky



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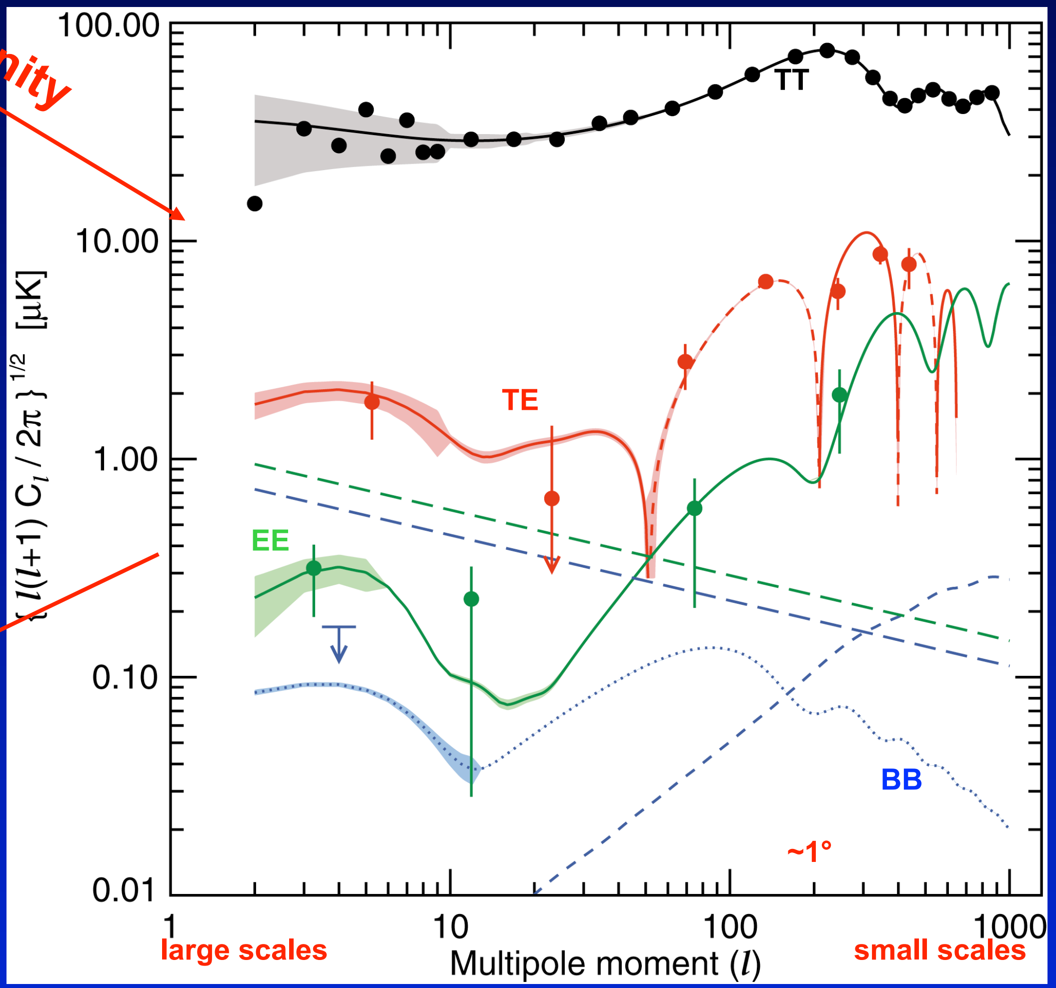


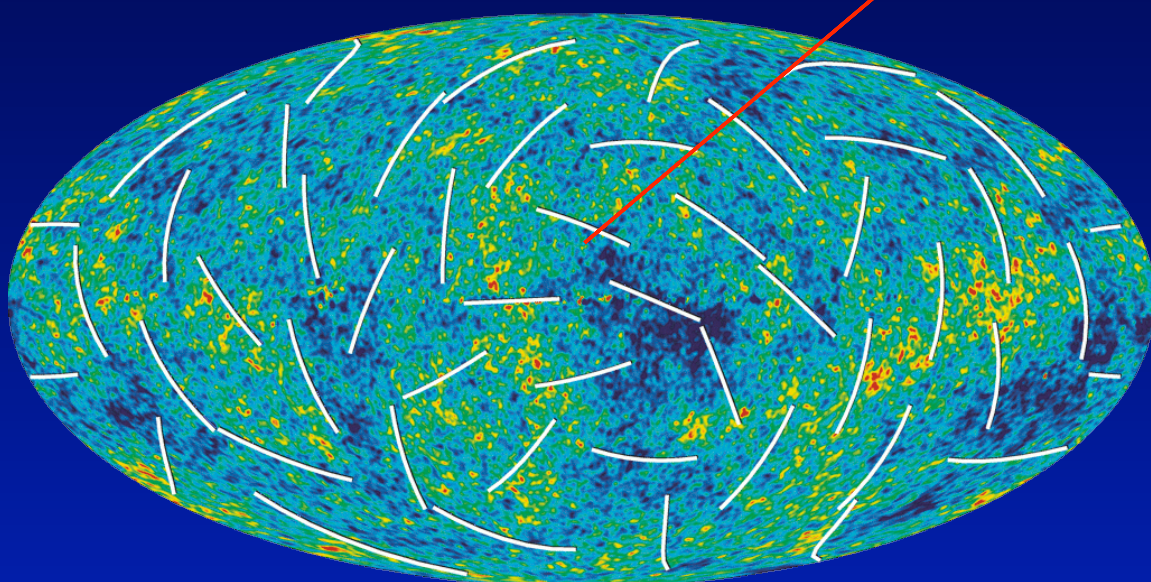
(Joint) analysis

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

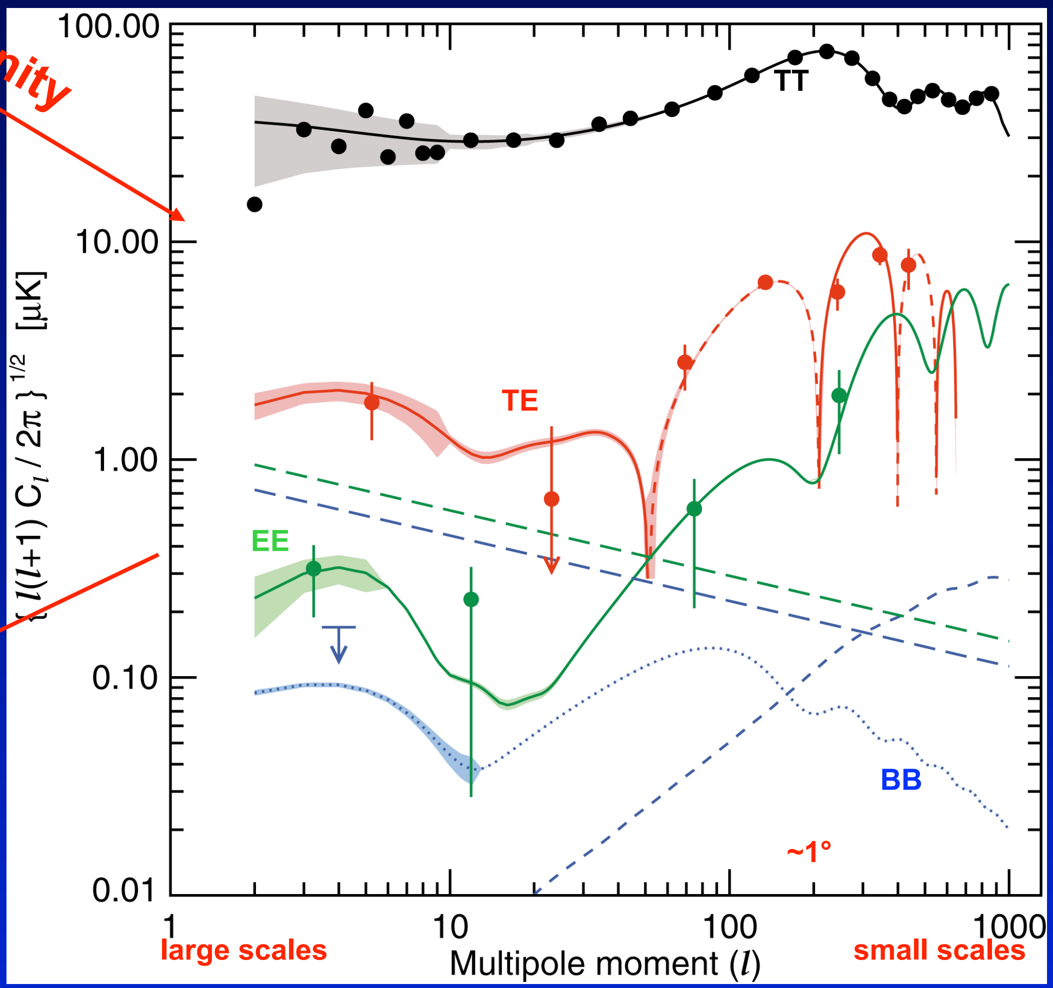
WMAP CMB Sky



a_{lm}

Gaussianity

Power spectra



(Joint) analysis

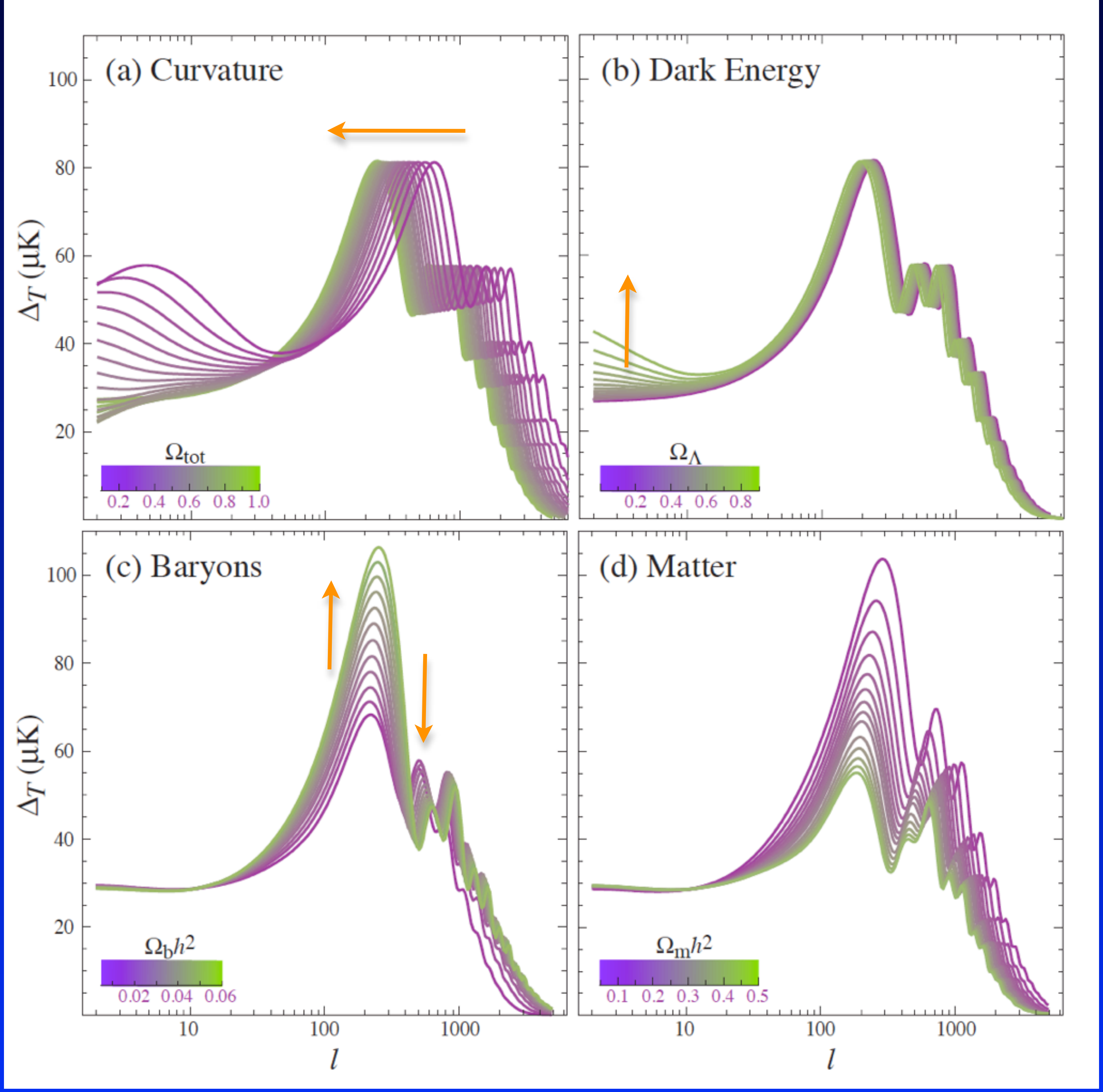
Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

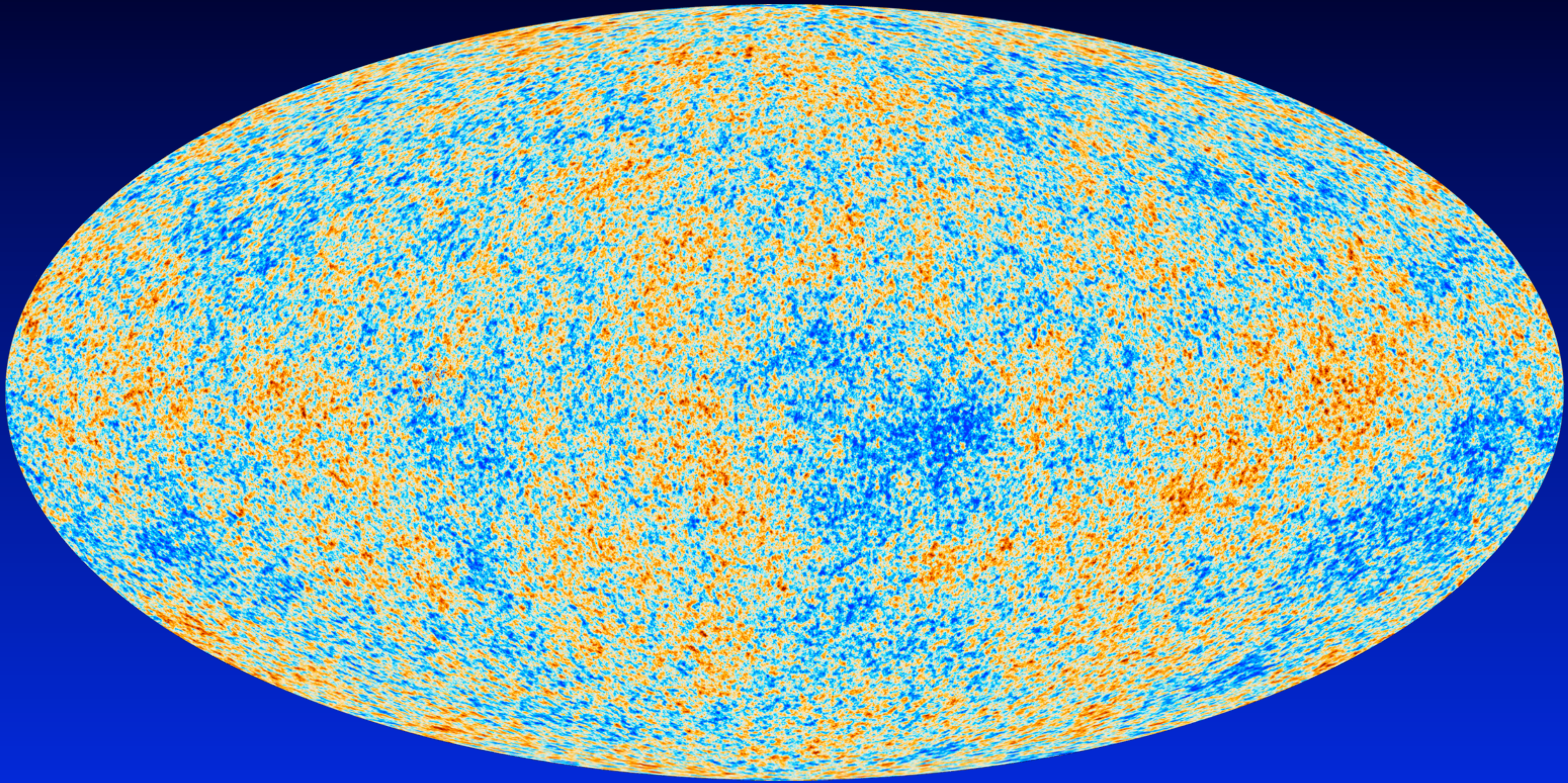
Dependence of the Power Spectrum on the Main Cosmological Parameters



- Total density (curvature)
  → positions of peaks
- dark energy
  → ISW at large scales
- Baryon density
  → damping tail / ratio of peaks
- dark matter
  → gravitational driving / enhancement of third peak over second
- spectral index n_S
  → tilt of the overall power spectrum
- Thomson optical depth τ
  → large scale E-mode polarization
  → damping tail

Hu & Dodelson, 2002, ARAA

Cosmic Microwave Background Anisotropies



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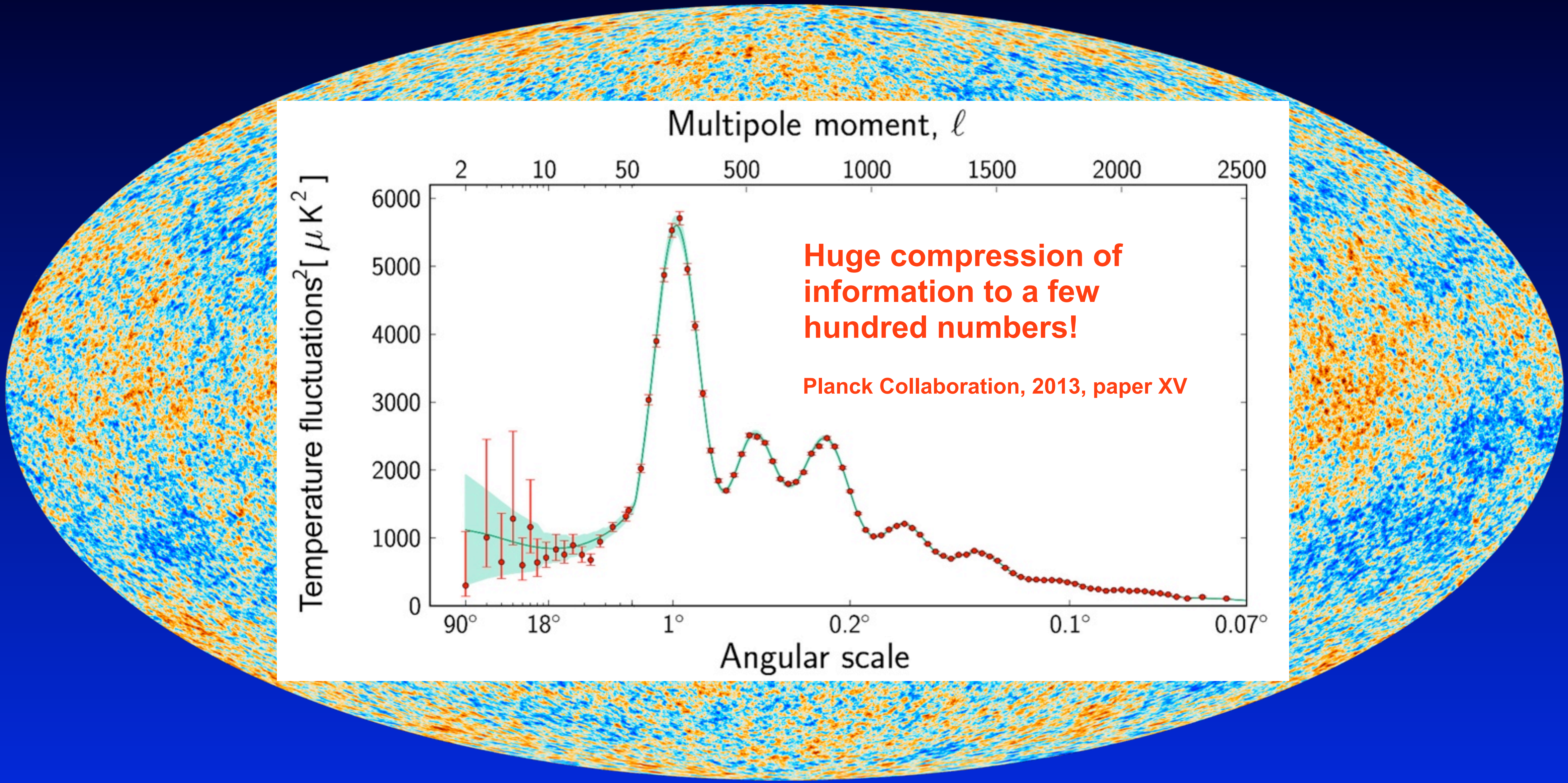
Cosmic Microwave Background Anisotropies



Planck all sky map

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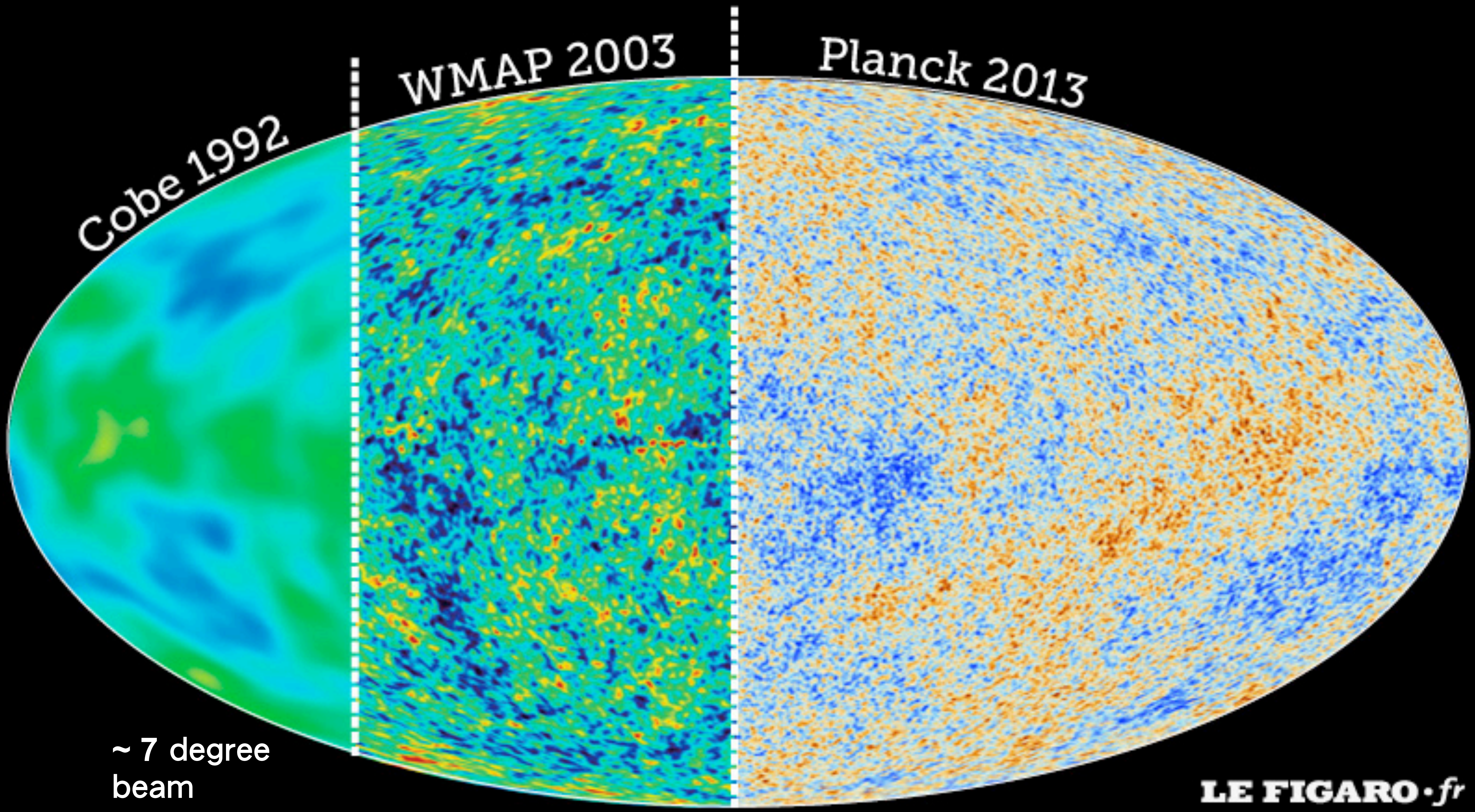
Dramatic improvements in angular resolution and sensitivity over the past decades!

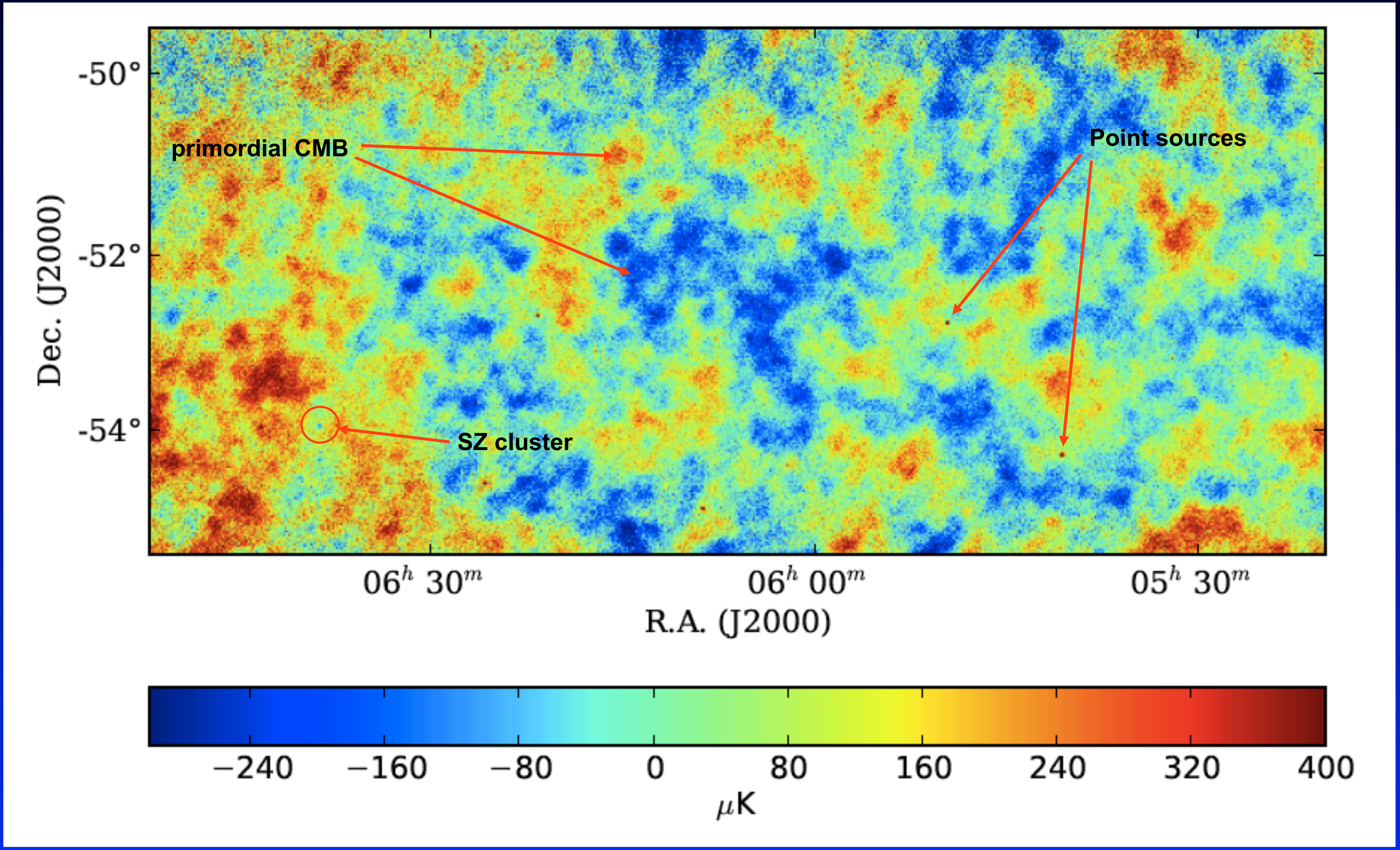


~ 7 degree beam

~ 0.3 degree beam

~ 0.08 degree beam

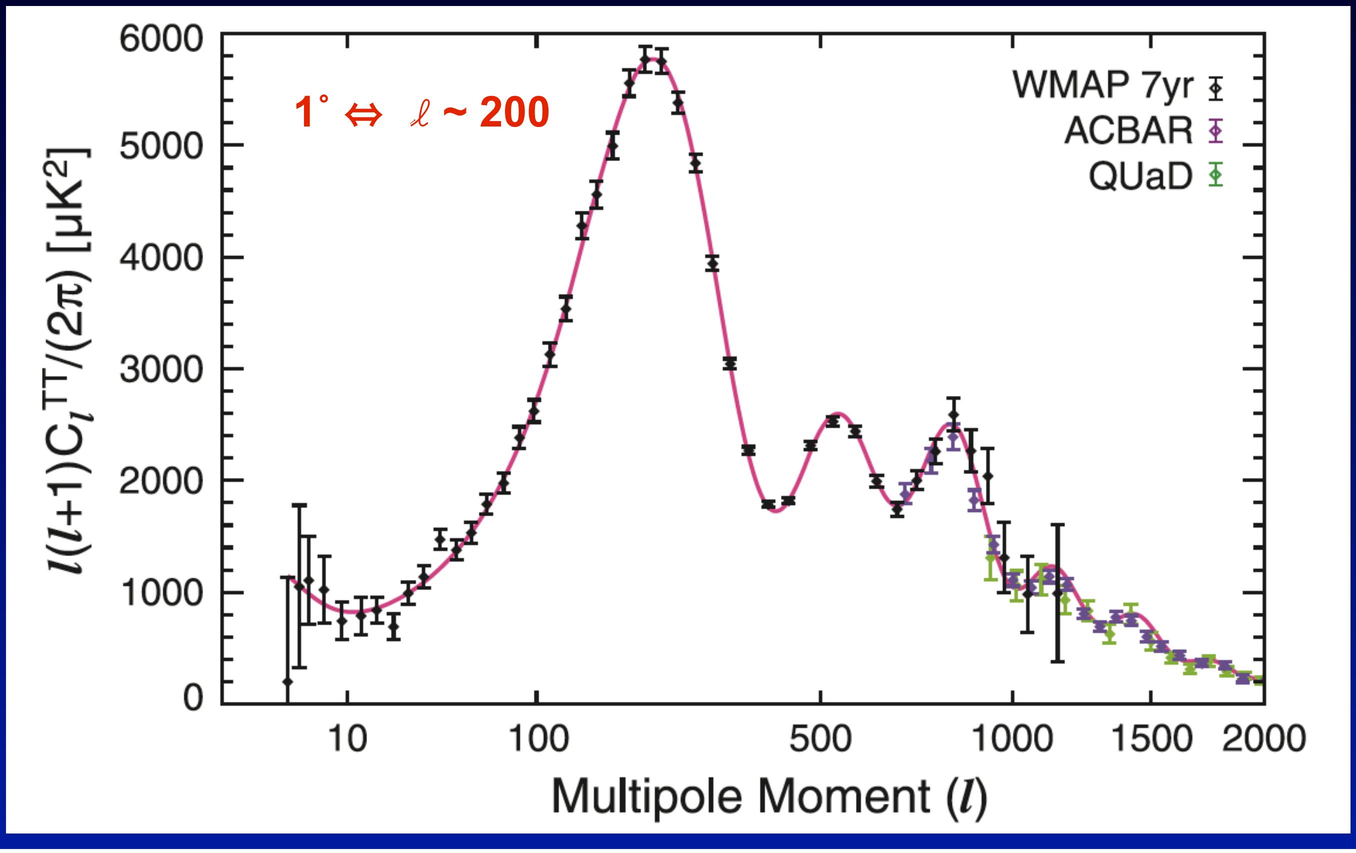
Cosmic Microwave Background Anisotropies with ACT

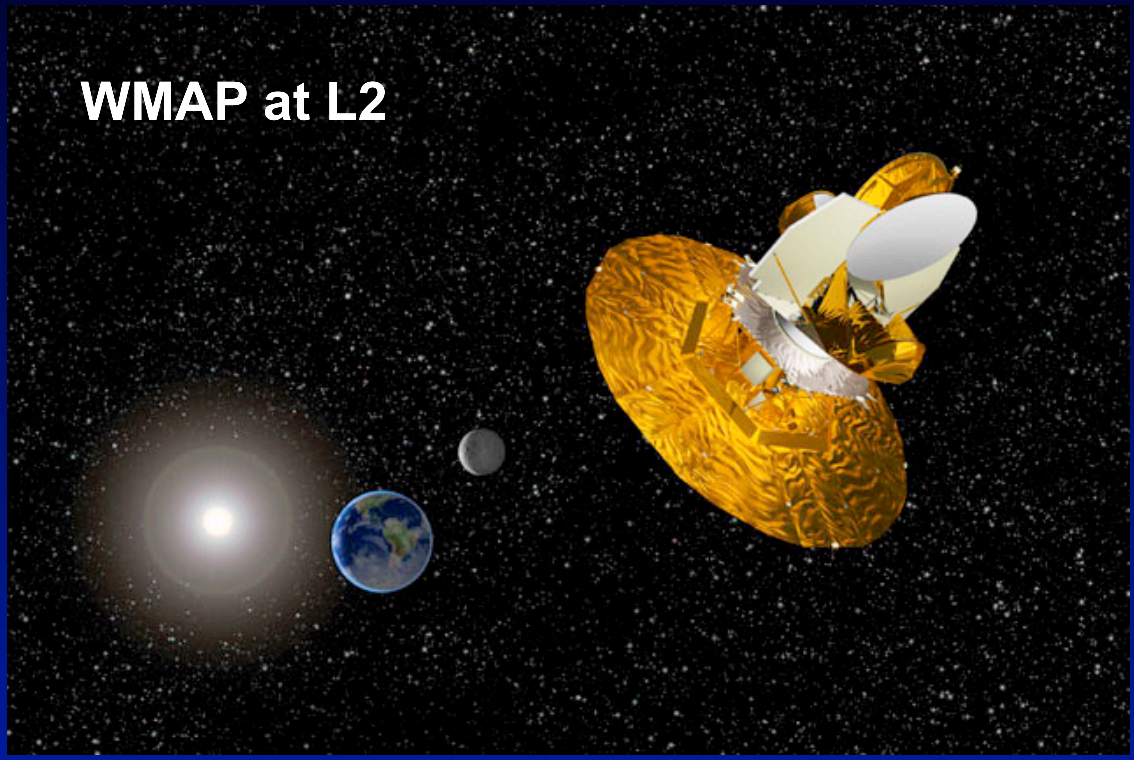


ACT - collaboration, 148 GHz Map, Hajian et al. 2010

~ 0.02 degree beam!

CMB anisotropies clearly taught us a lot about the Universe we live in!





Precision cosmology

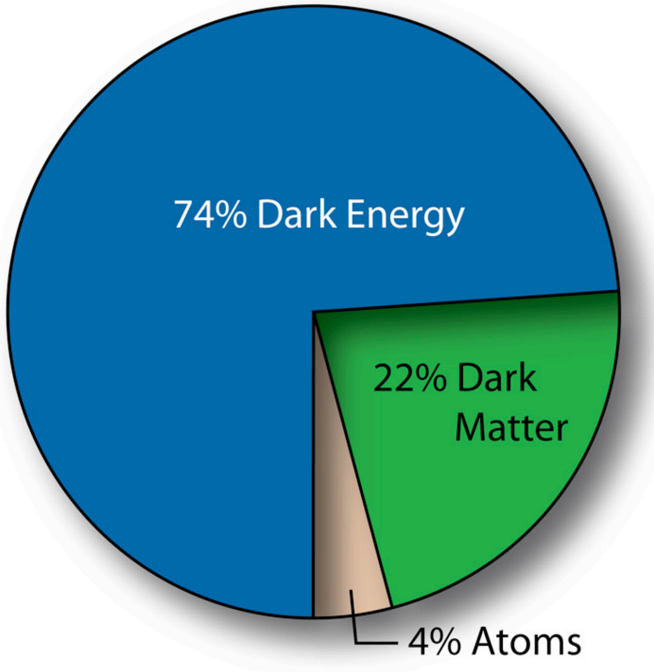
Tiny error bars!

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

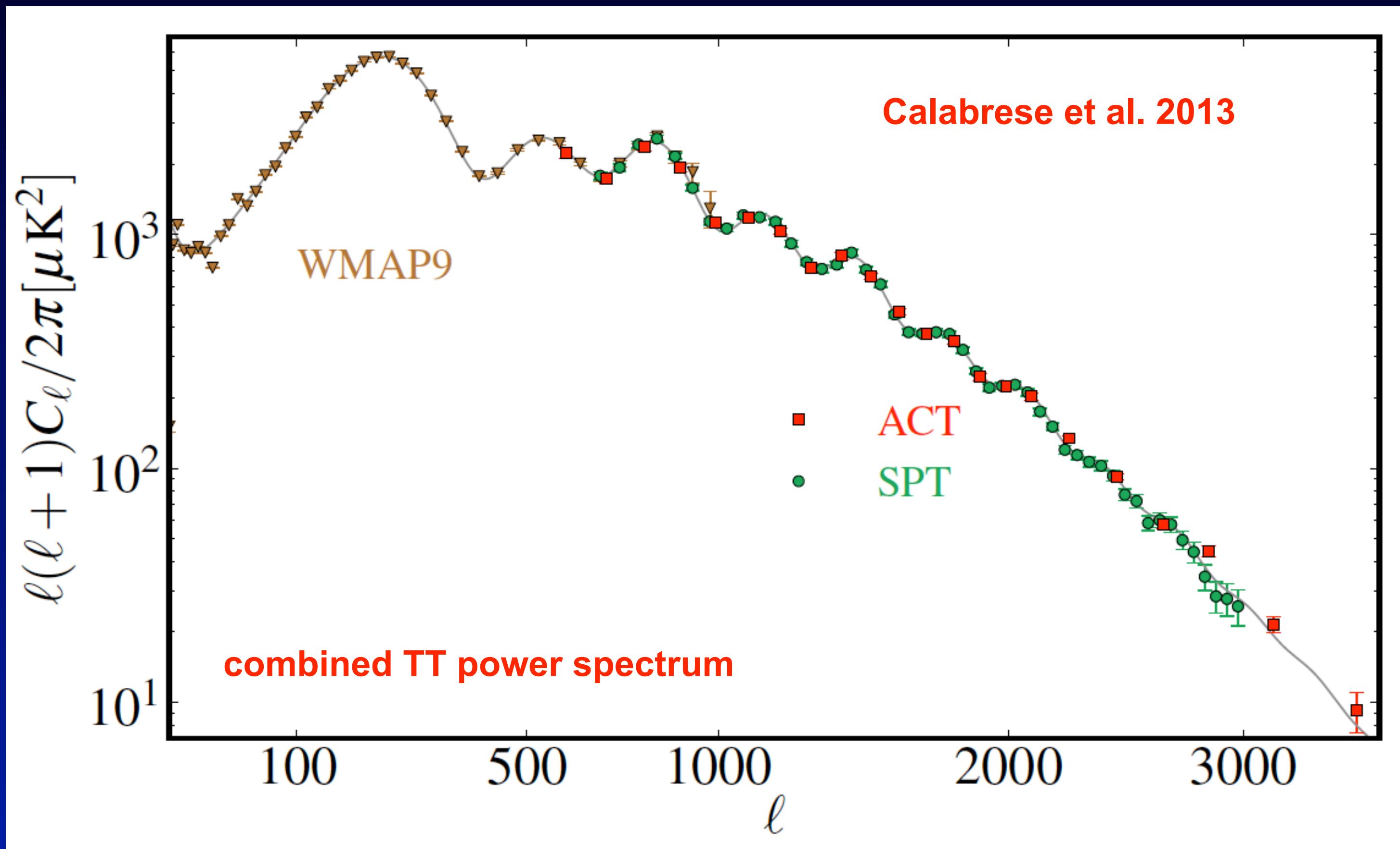
[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ 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.

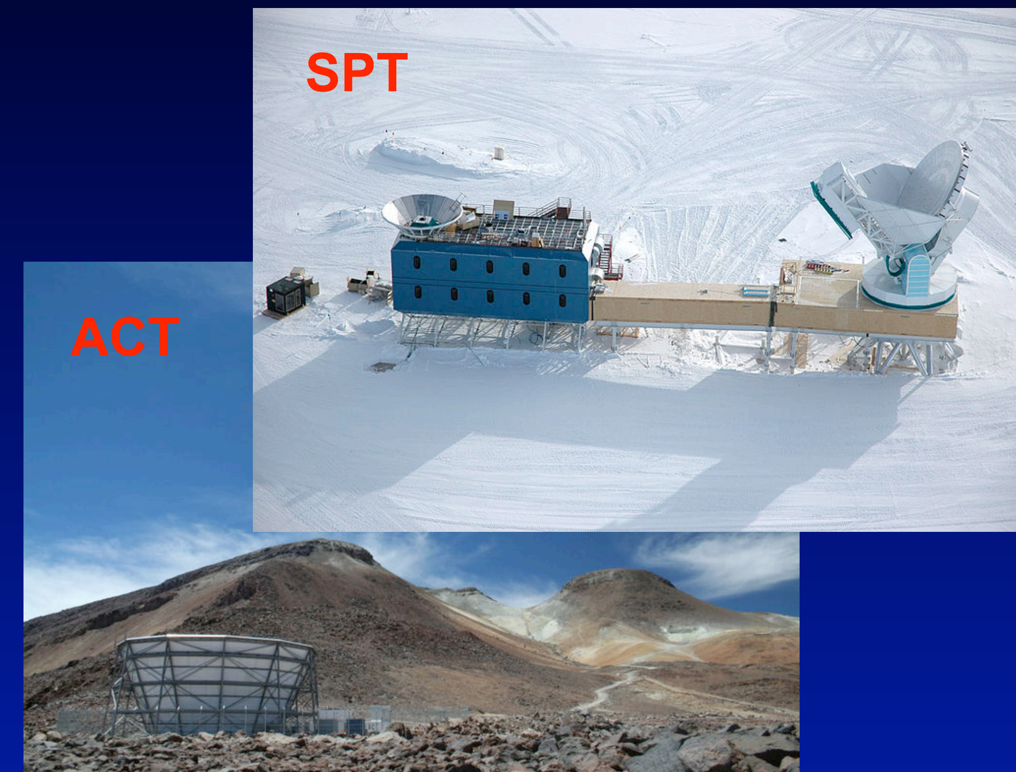
Pie-chart of the Universe



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

CMB anisotropies clearly taught us a lot about the Universe we live in!





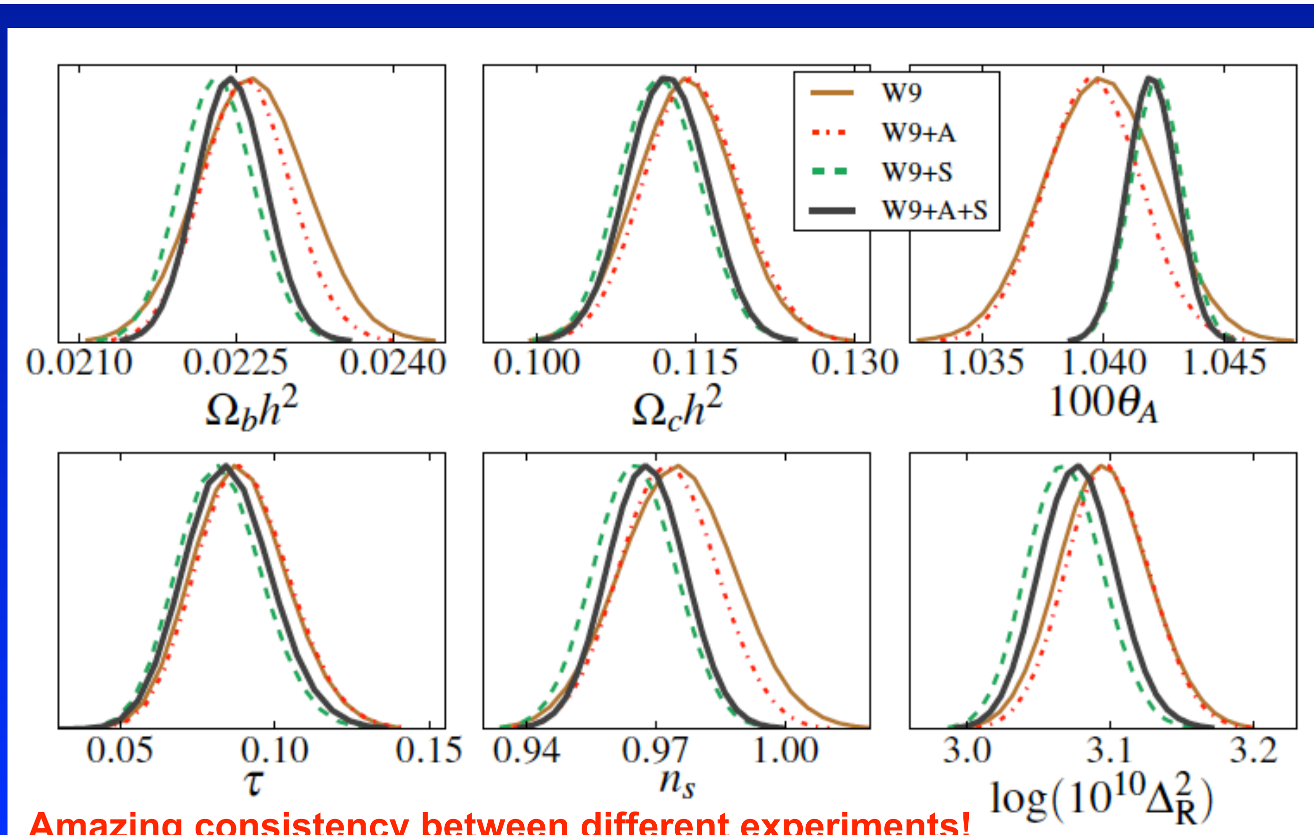


TABLE I. Standard ΛCDM parameters from the combination of WMAP9, ACT and SPT.

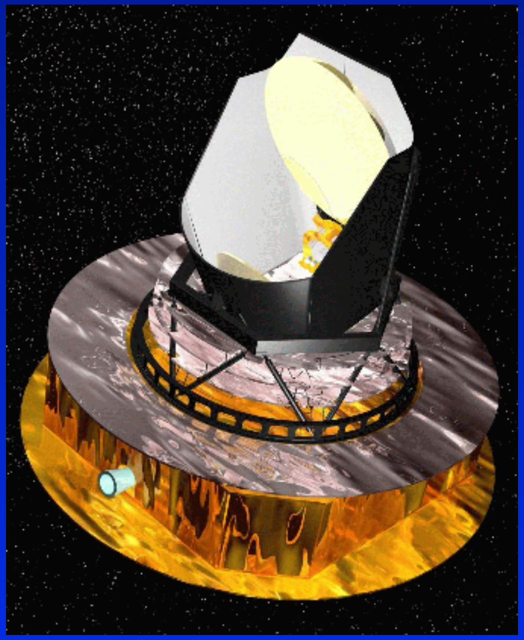
Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.245 ± 0.032
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.23 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0420 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9678 ± 0.0088
$10^9\Delta^2_{\mathcal{R}}$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
Ω_Λ [a]	0.716 ± 0.024	0.737 ± 0.019	0.734 ± 0.019
σ_8	0.830 ± 0.021	0.808 ± 0.018	0.814 ± 0.017
t_0	13.752 ± 0.096	13.686 ± 0.065	13.682 ± 0.063
H_0	69.7 ± 2.0	71.5 ± 1.7	71.2 ± 1.6
$100r_s/D_{V\,0.57}$	7.50 ± 0.17	7.65 ± 0.14	7.65 ± 0.14
$100r_s/D_{V\,0.35}$	11.29 ± 0.31	11.56 ± 0.26	11.55 ± 0.26
best fit χ^2	7596.0	7617.1	7660.0

Precision Cosmology with Planck

	Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
Standard parameters	$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
	$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
	$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
	τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
	n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
	$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
Foregrounds and secondaries	A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
	A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
	A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
	A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
	A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
	A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
	$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
	$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
	γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
	$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
	A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Derived parameters	Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
	σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
	z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
	H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
	Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
	$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
	r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

Planck Collaboration, 2013, paper XV

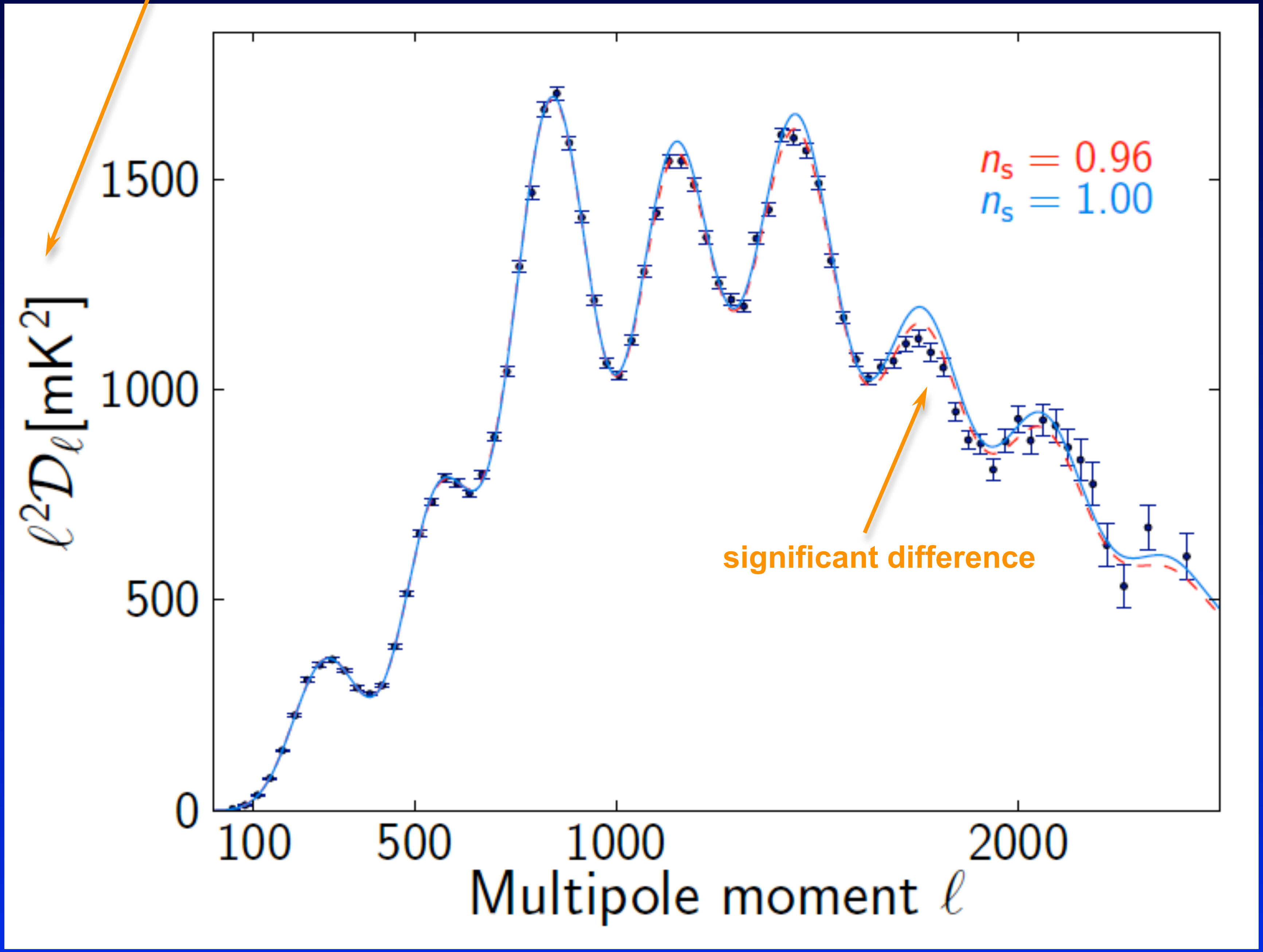
- Massive amount of information! (close to 30 Planck papers in March 2013)
- Impressive consistency between different experiments!
- Amazing confirmation of ΛCDM



Planck Satellite

CMB anisotropies directly probe early-universe physics / inflation

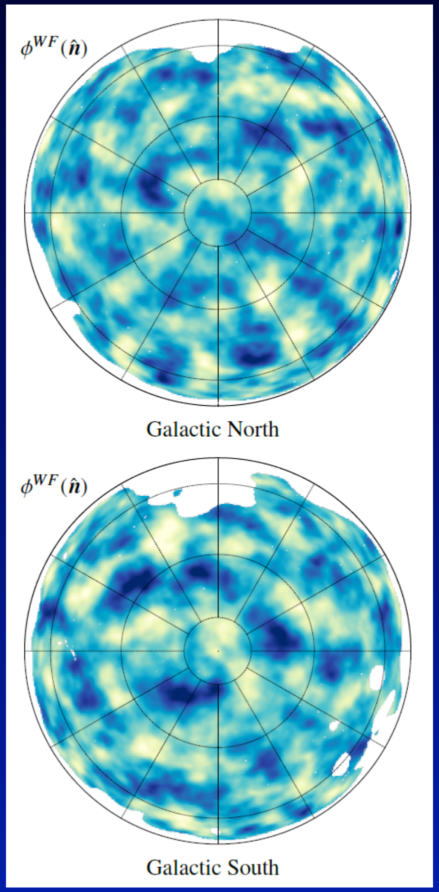
Another way to plot small-scale power spectrum

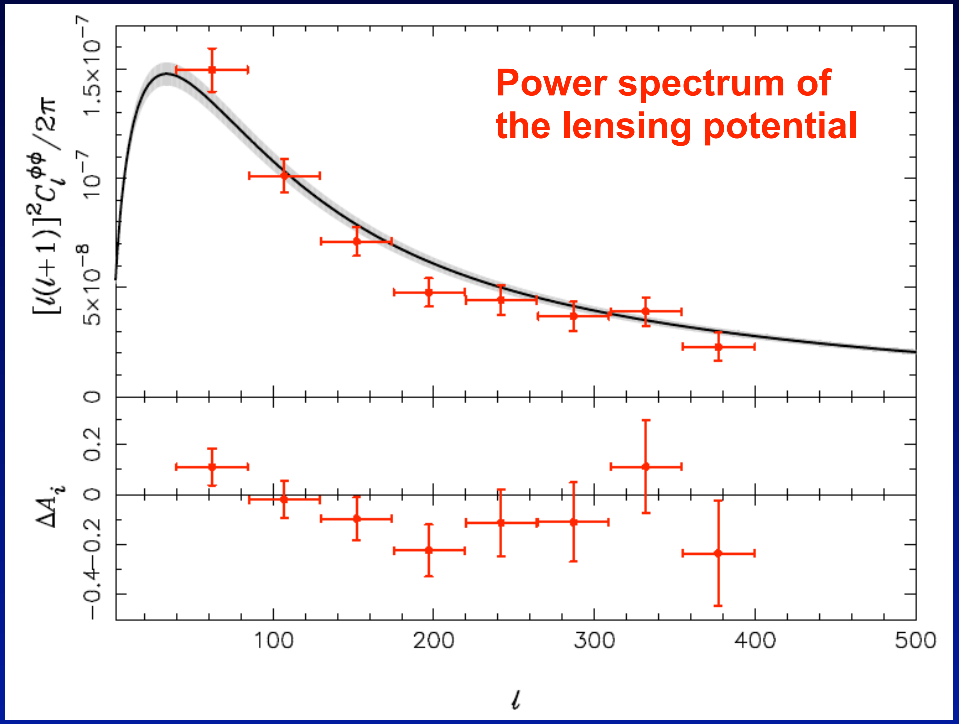


Planck Collaboration, 2013, paper XV

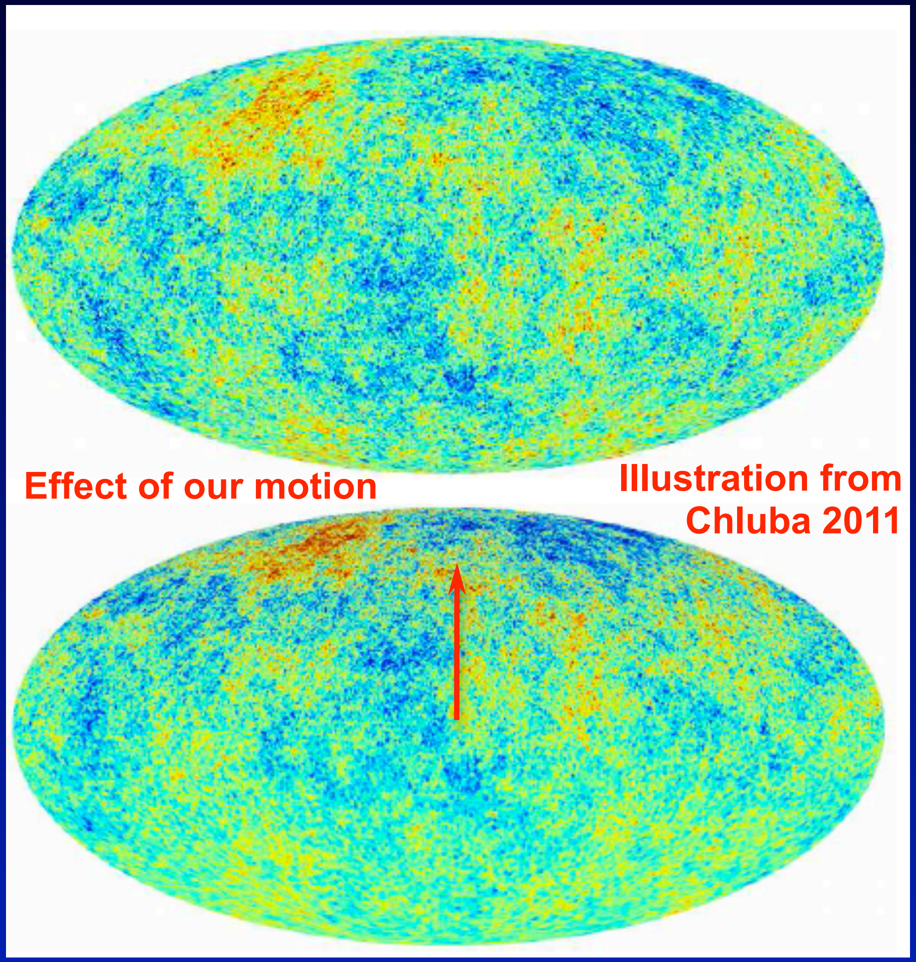
- 6σ deviation from scale-invariance (previously ~ 3σ)
- single-field inflation predicts departure from scale-invariance (e.g., Mukhanov 2007)
- *Degeneracies* with, e.g., effective number of relativistic degrees of freedom, N_{eff}, Helium abundance, Y_p, and recombination physics!
- *The power spectrum at small scales thus directly links early-Universe, particle and recombination physics!*

All kind of fun science with the CMB (no time for this though)



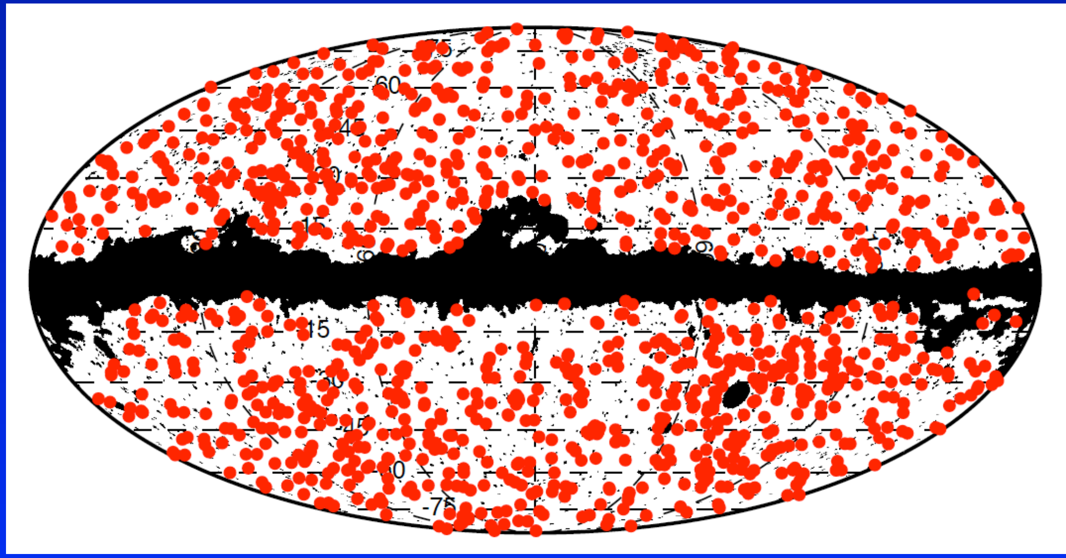


Planck Collaboration, 2013, paper XVII



Planck Collaboration, 2013, paper XXVII

SZ clusters on the sky



Planck Collaboration, 2013, paper XXIV

- *Non-Gaussianity* (test of inflation models)
- *Topology*
- *CMB anomalies*
- *CIB* and *Galactic science*

Extension of ΛCDM and why these link early-universe, particle and recombination physics

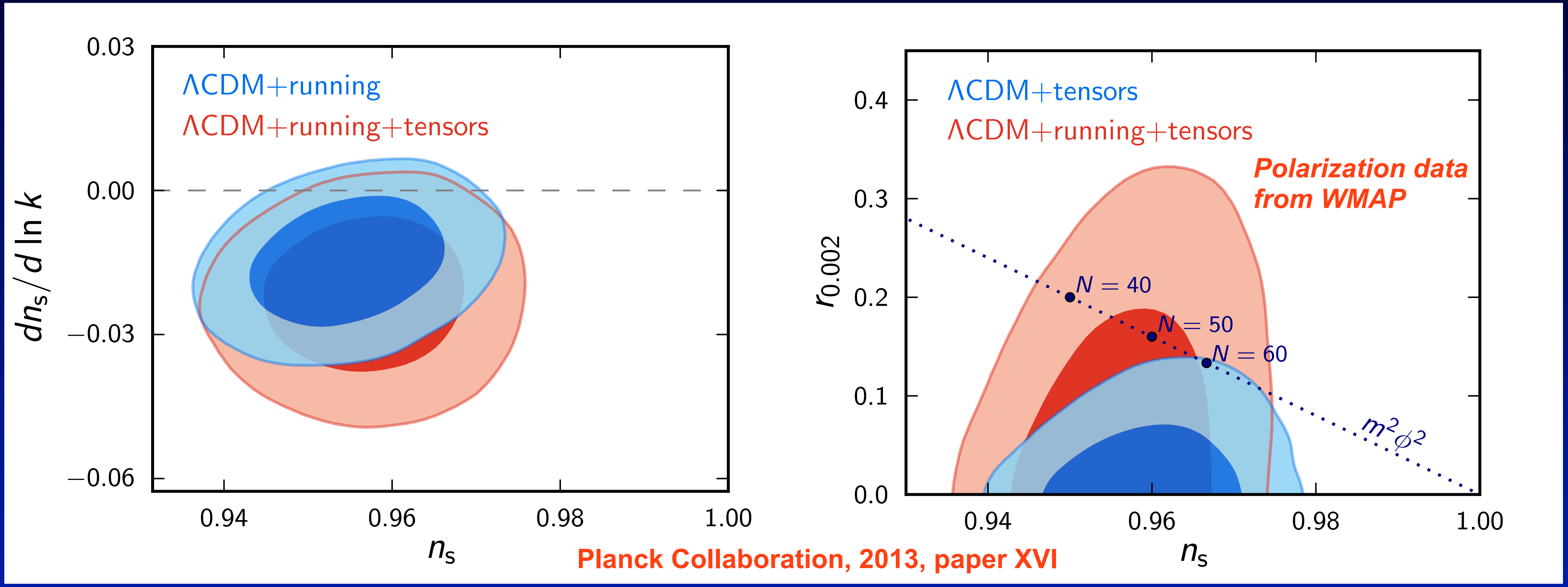
Simplest one parameter extensions of ΛCDM

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\mathrm{s}}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Planck Collaboration, 2013, paper XV

- *All consistent with standard ΛCDM*
- *slight tensions between different experiments (e.g., Neff, Yp and running)*

CMB anisotropy constraints on running and the tensor to scalar ratio



Planck Collaboration, 2013, paper XVI

- Single-field inflation: $\mathrm{d}n/\mathrm{d}\ln k \simeq (n_S - 1)^2$
- *Big future goal:* detection of B-polarization
- Plenty of progress in the next few years:

  ground/balloon: SPTpol, ACTpol, Spider, ...

  space: Planck, LiteBIRD, PIXIE, PRISM, ...?

Other experiments:

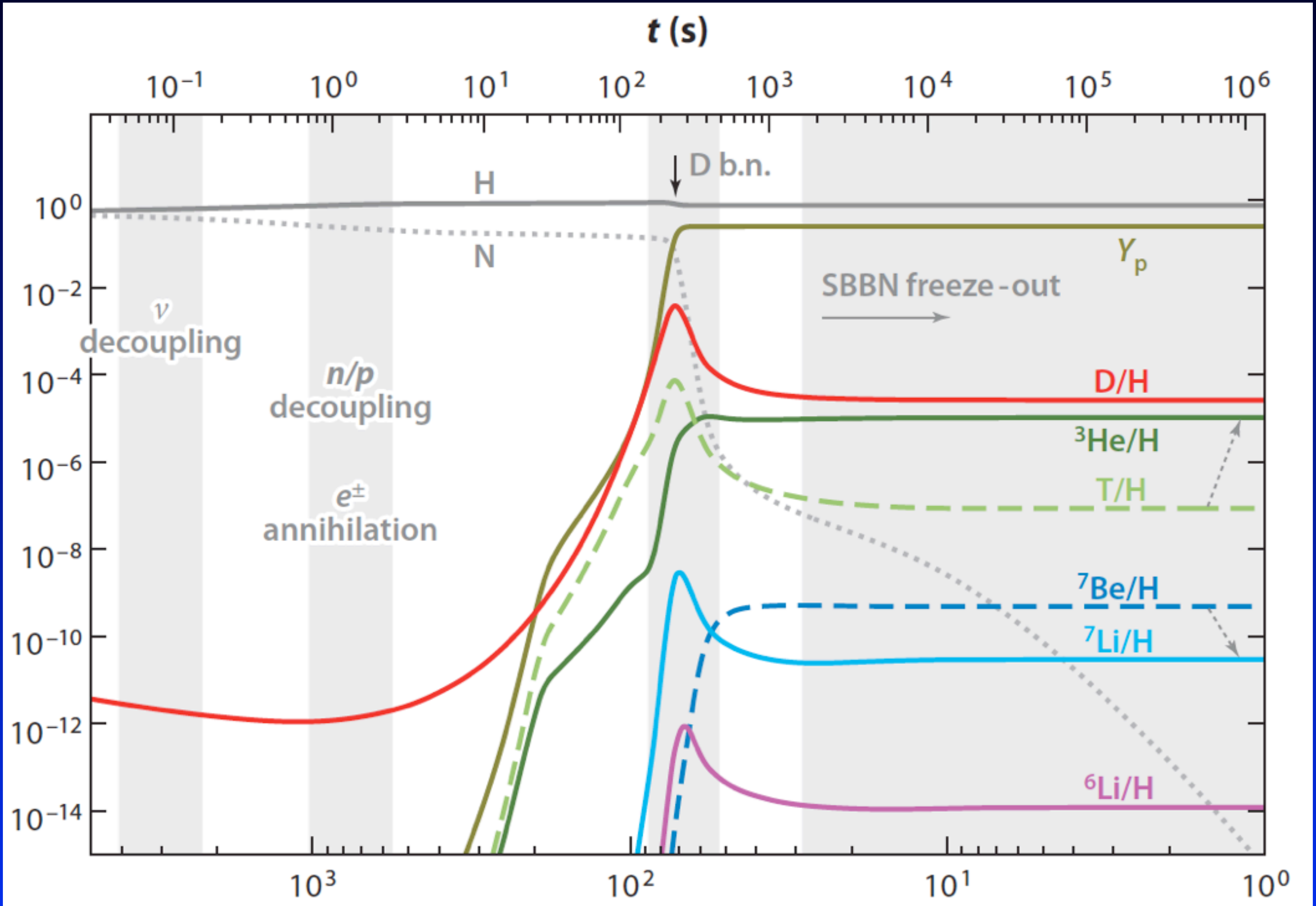
$\mathrm{d}n/\mathrm{d}\ln k = -0.022 \pm 0.012$
Dunkley et al 2011 & Keisler et al 2011

$\mathrm{d}n/\mathrm{d}\ln k = -0.003 \pm 0.013$
Sievers et al 2013

$\mathrm{d}n/\mathrm{d}\ln k = -0.024 \pm 0.011$
Hou et al 2012

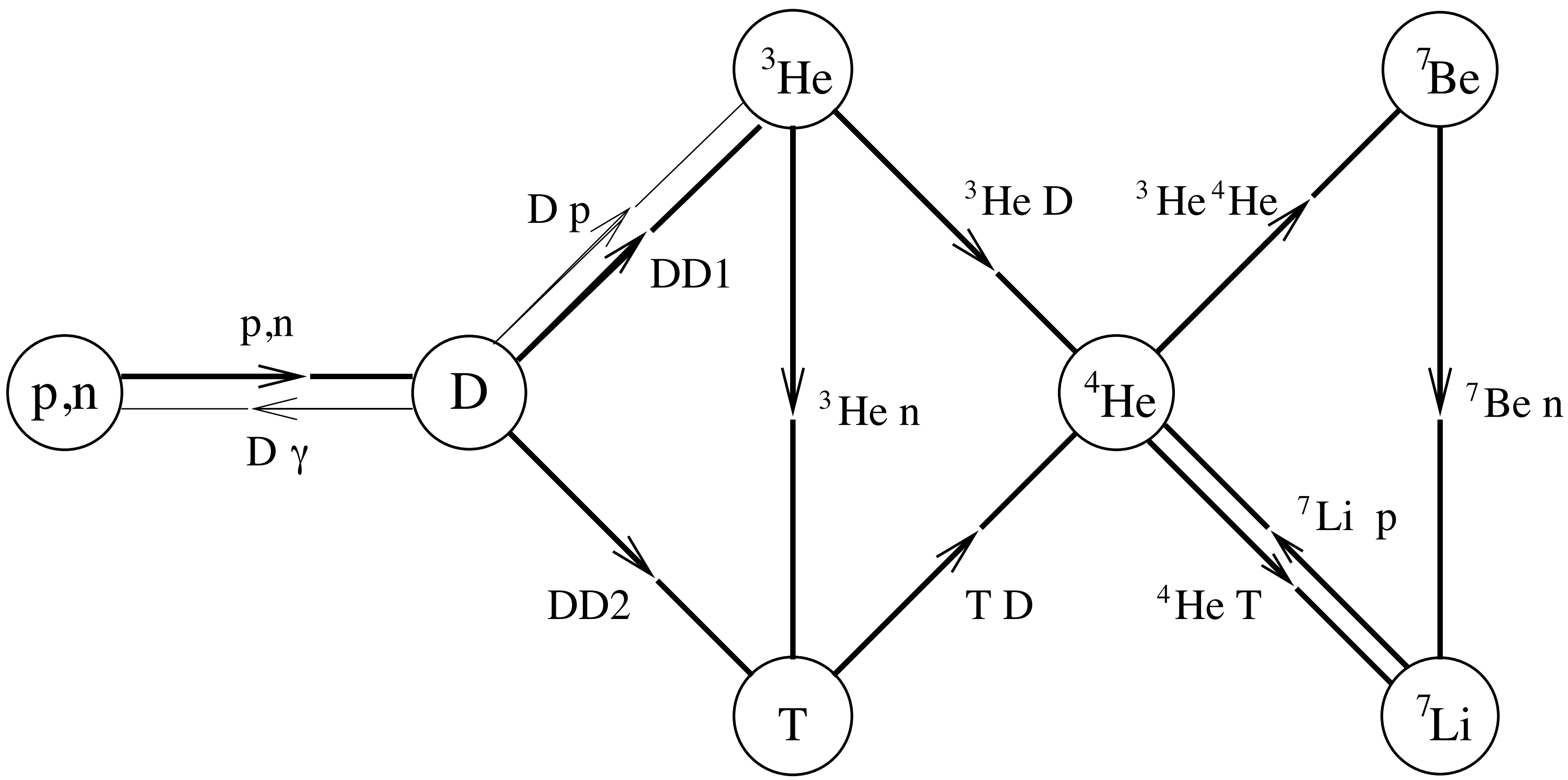
CMB as a test for BBN

Standard Big Bang Nucleosynthesis (SBBN)



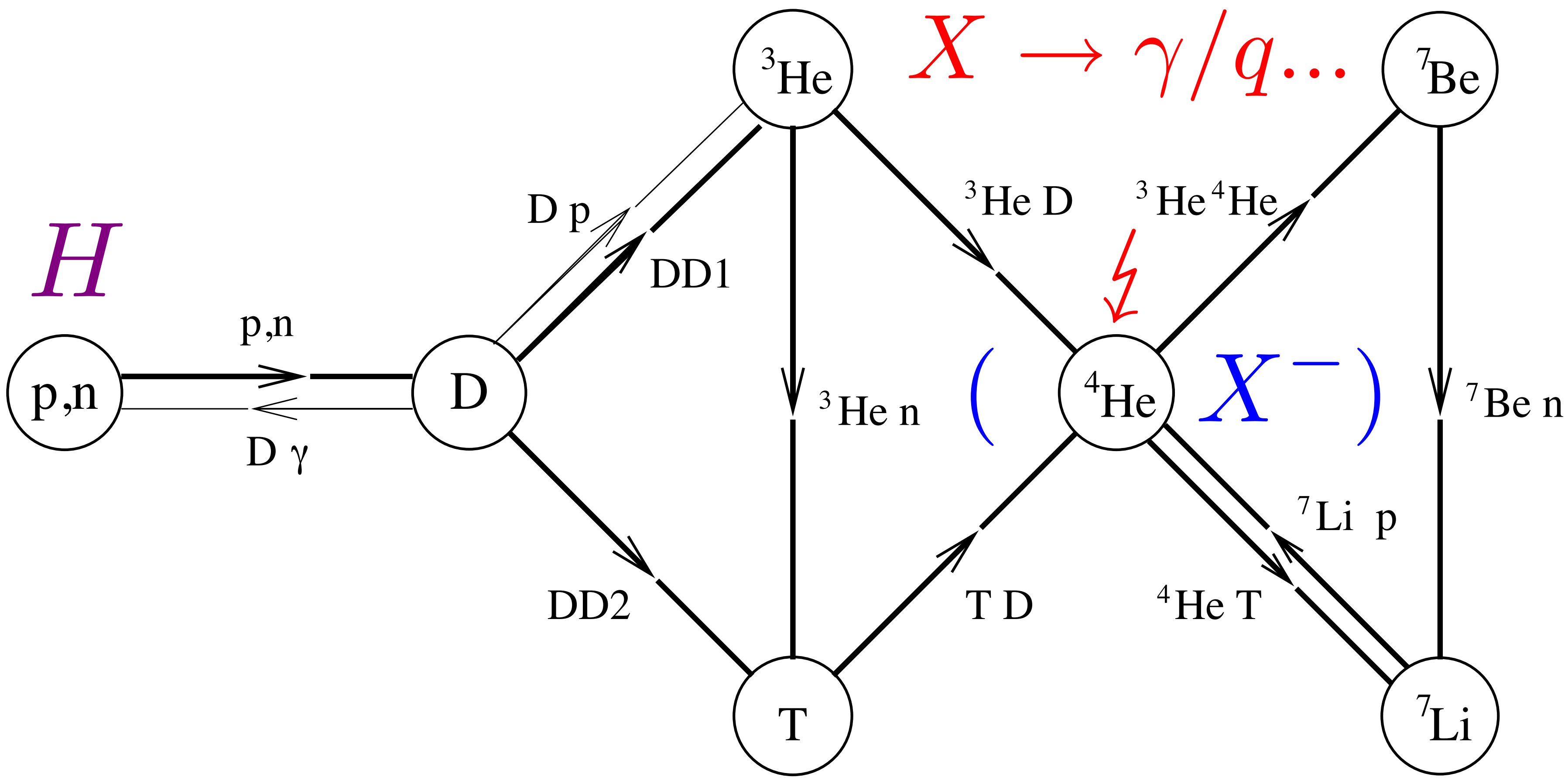
From review of Pospelov & Pradler, 2010

Beyond SBBN



Courtesy: to Josef Pradler

Beyond SBBN



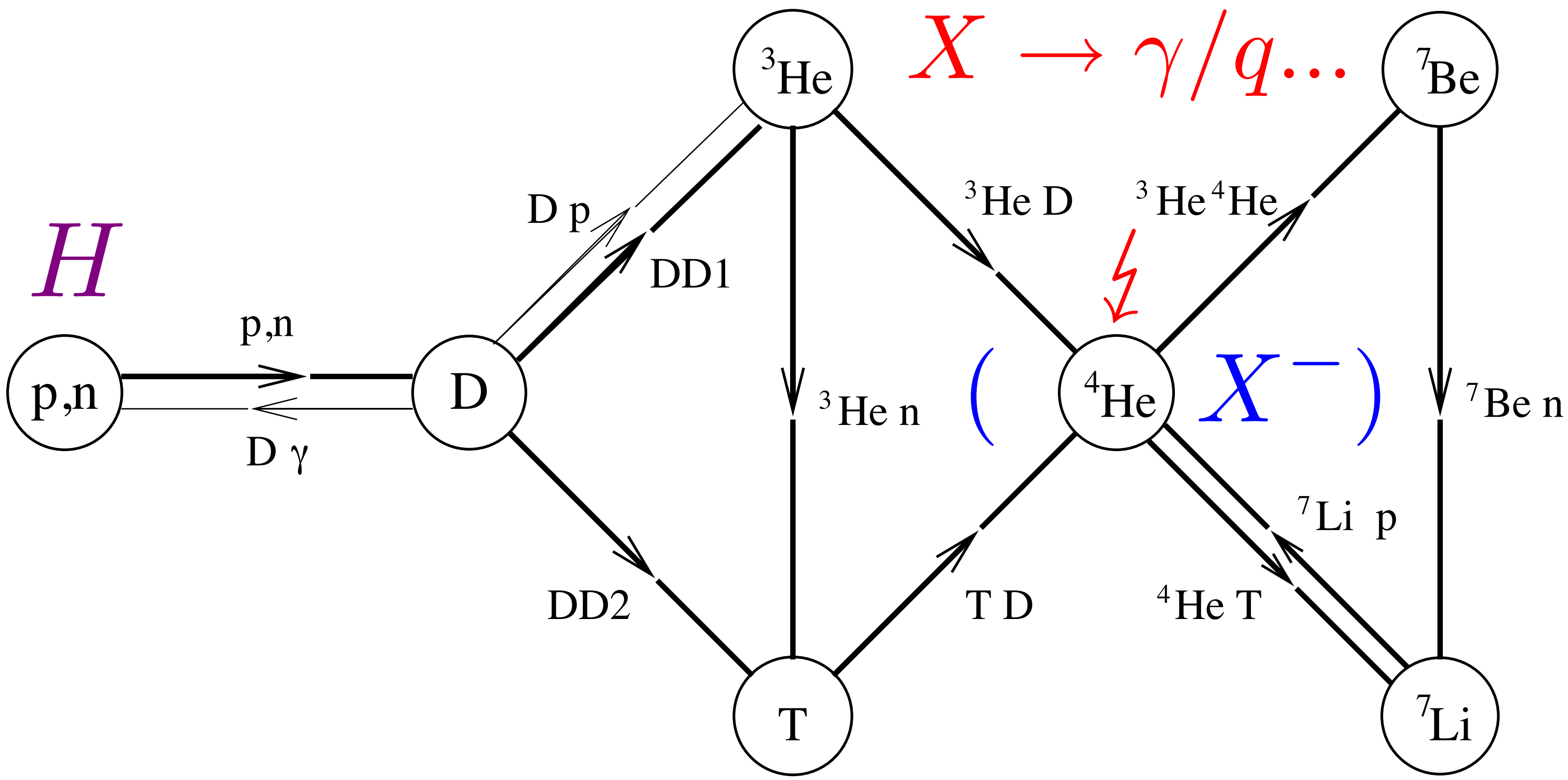
Change in timing

non-equilibrium BBN

catalyzed BBN

Courtesy: to Josef Pradler

Beyond SBBN

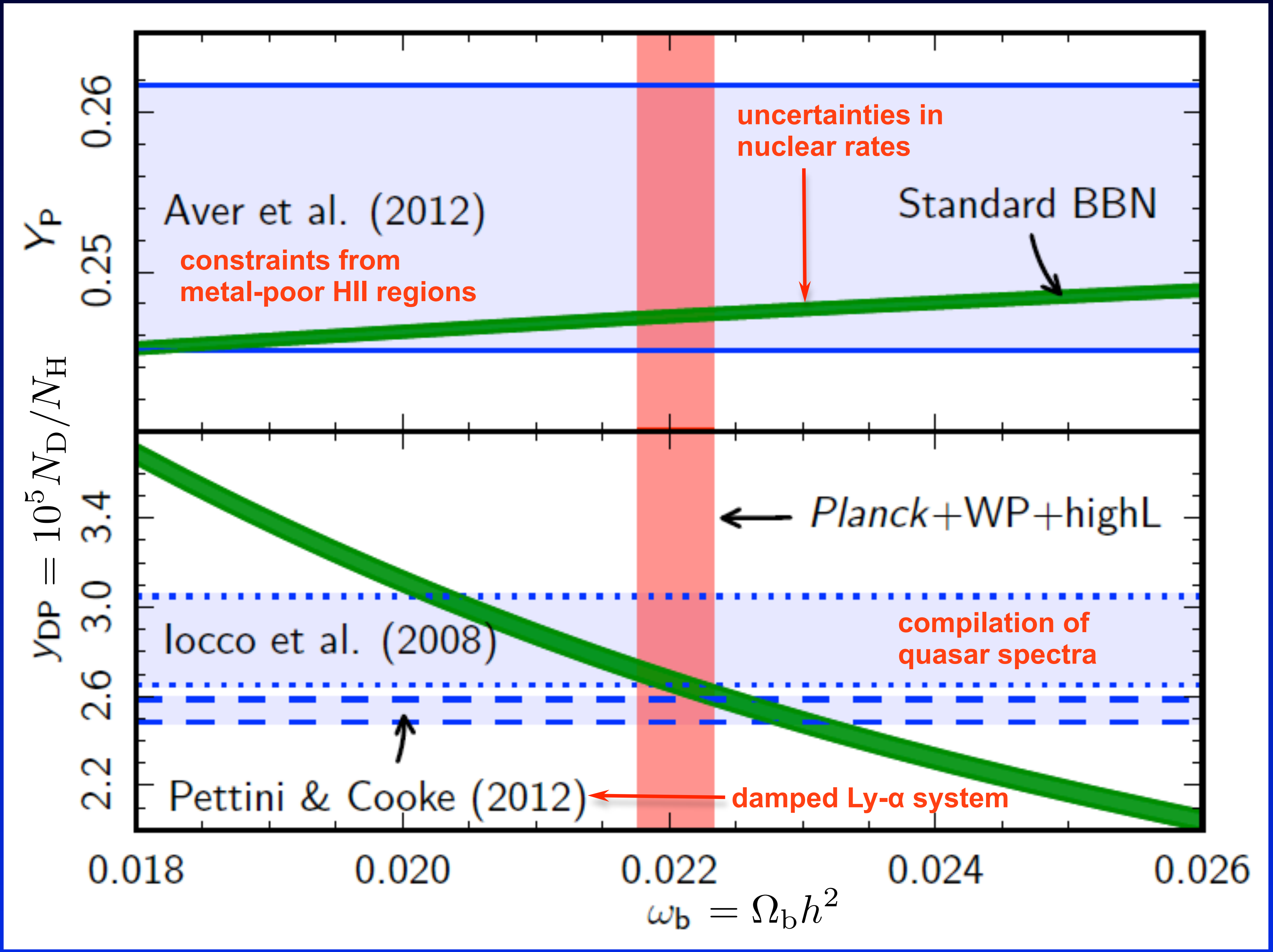


Abundances of light-elements provide a unique test of non-standard BBN!

Change in timing | non-equilibrium BBN | catalyzed BBN

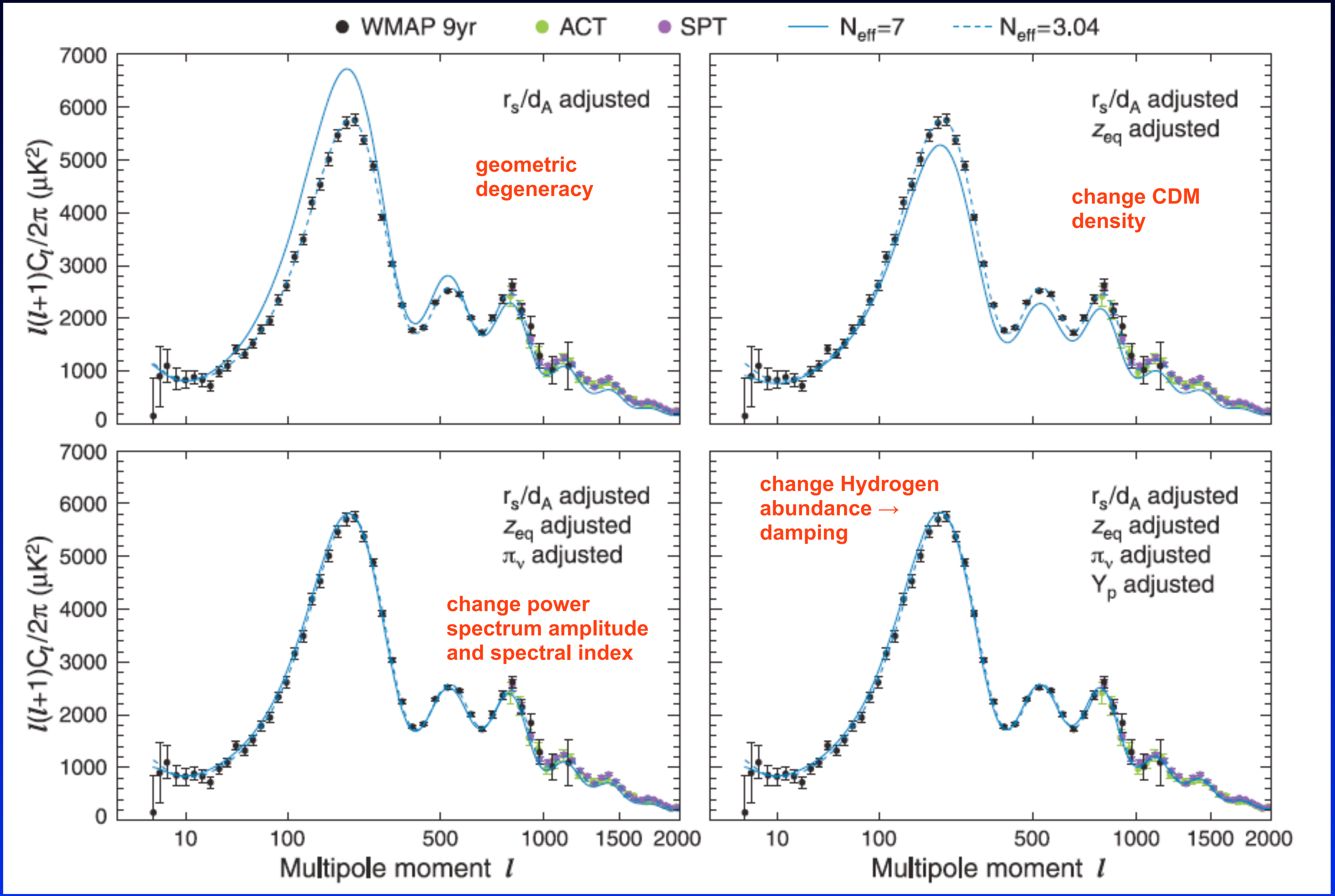
Courtesy: to Josef Pradler

SBBN Predictions for Helium and Deuterium



Planck Collaboration, 2013, paper XV

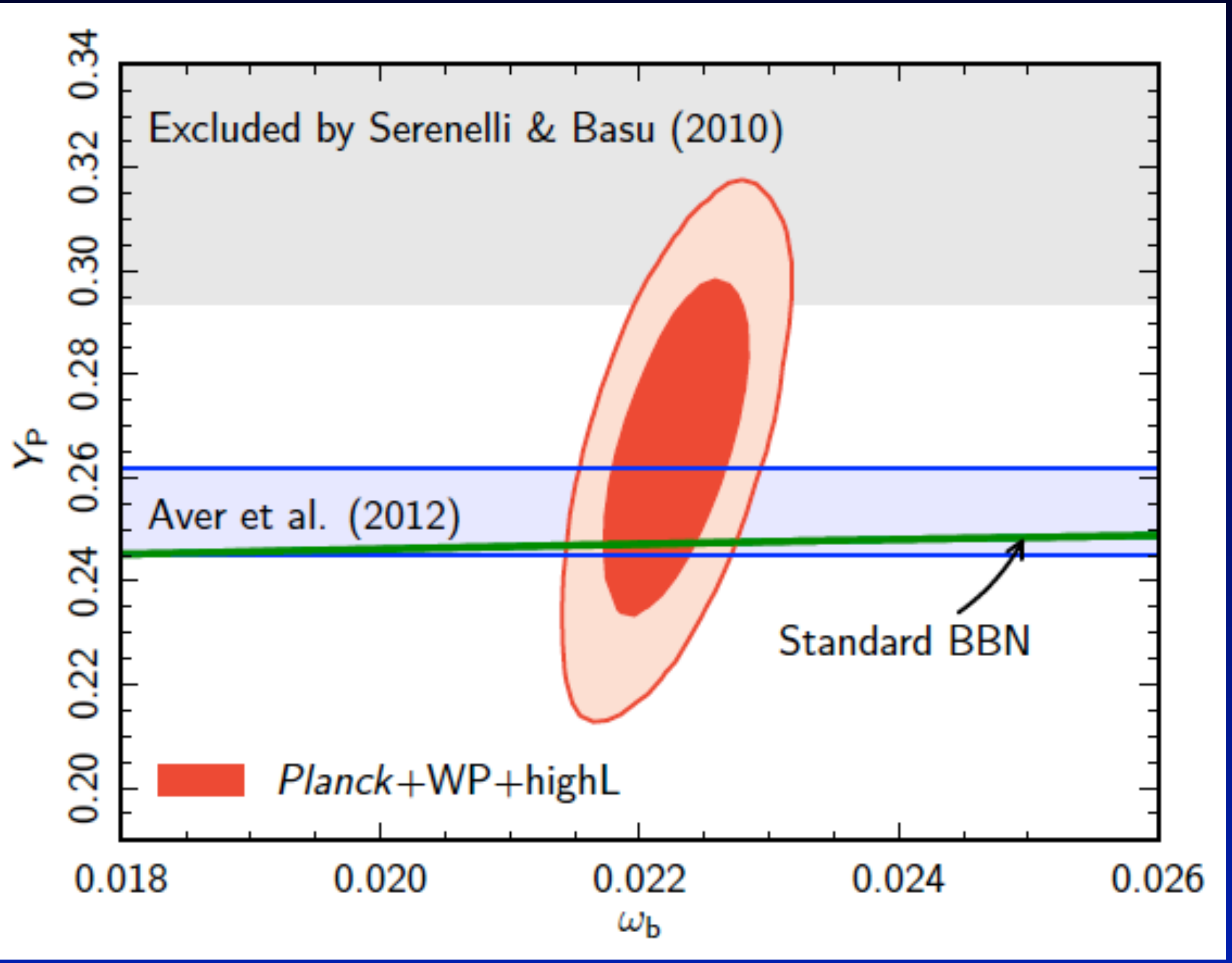
Interplay of N_{eff} and Y_p and other parameters

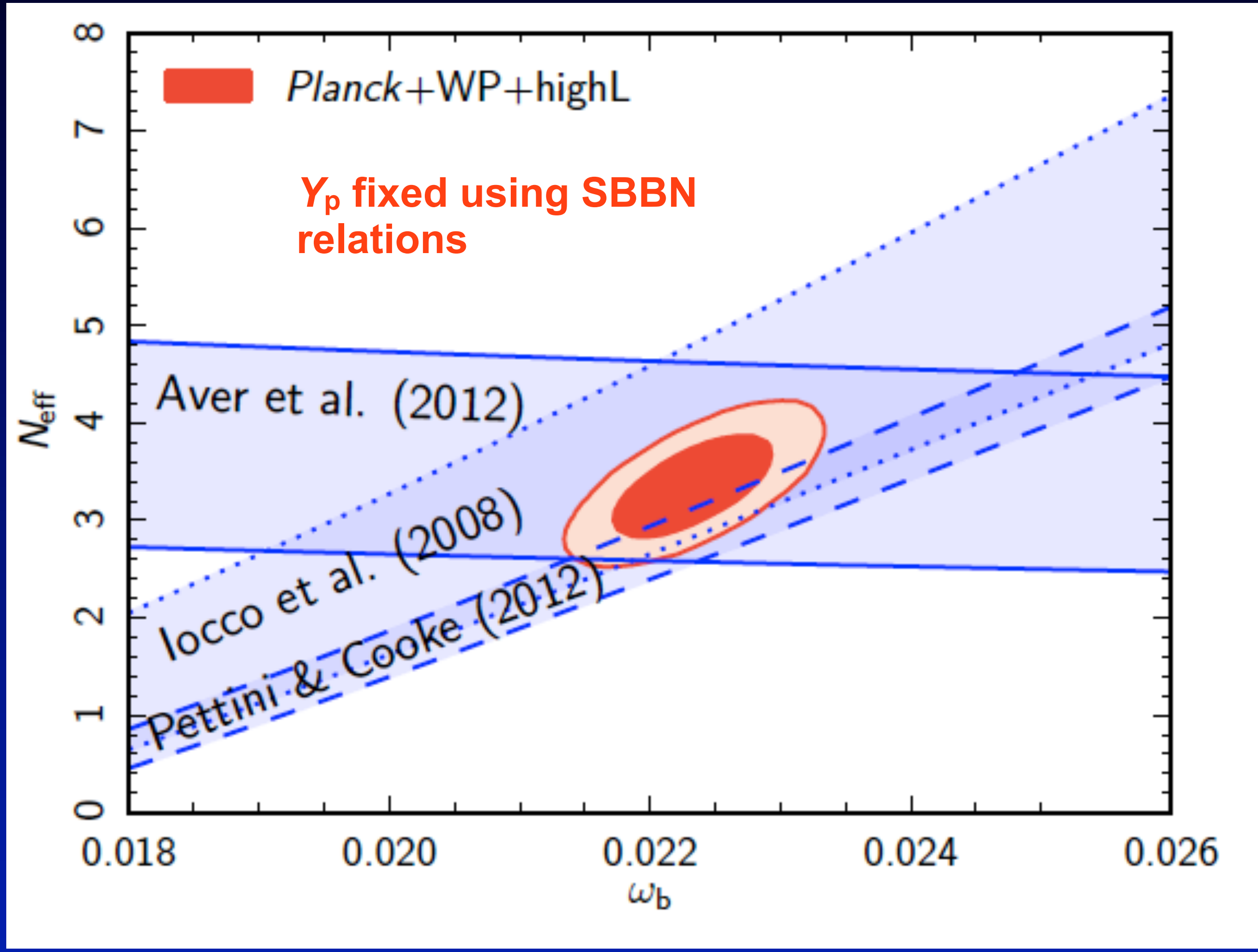


Hinshaw et al, 2012 (WMAP-9yr)

Bottom line: changes in the damping tail can be mimics by combination of many parameters

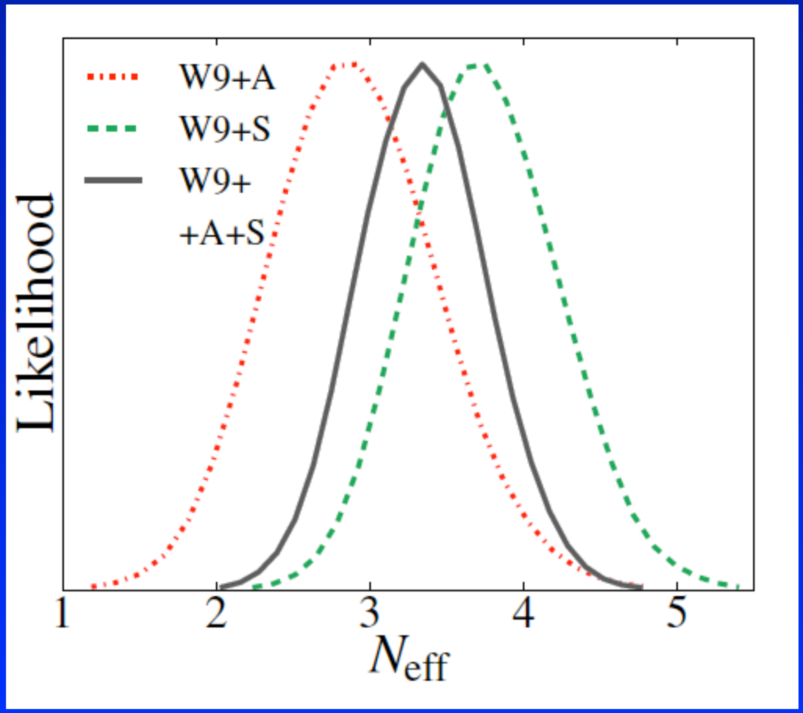
CMB constraints on N_{eff} and Y_p





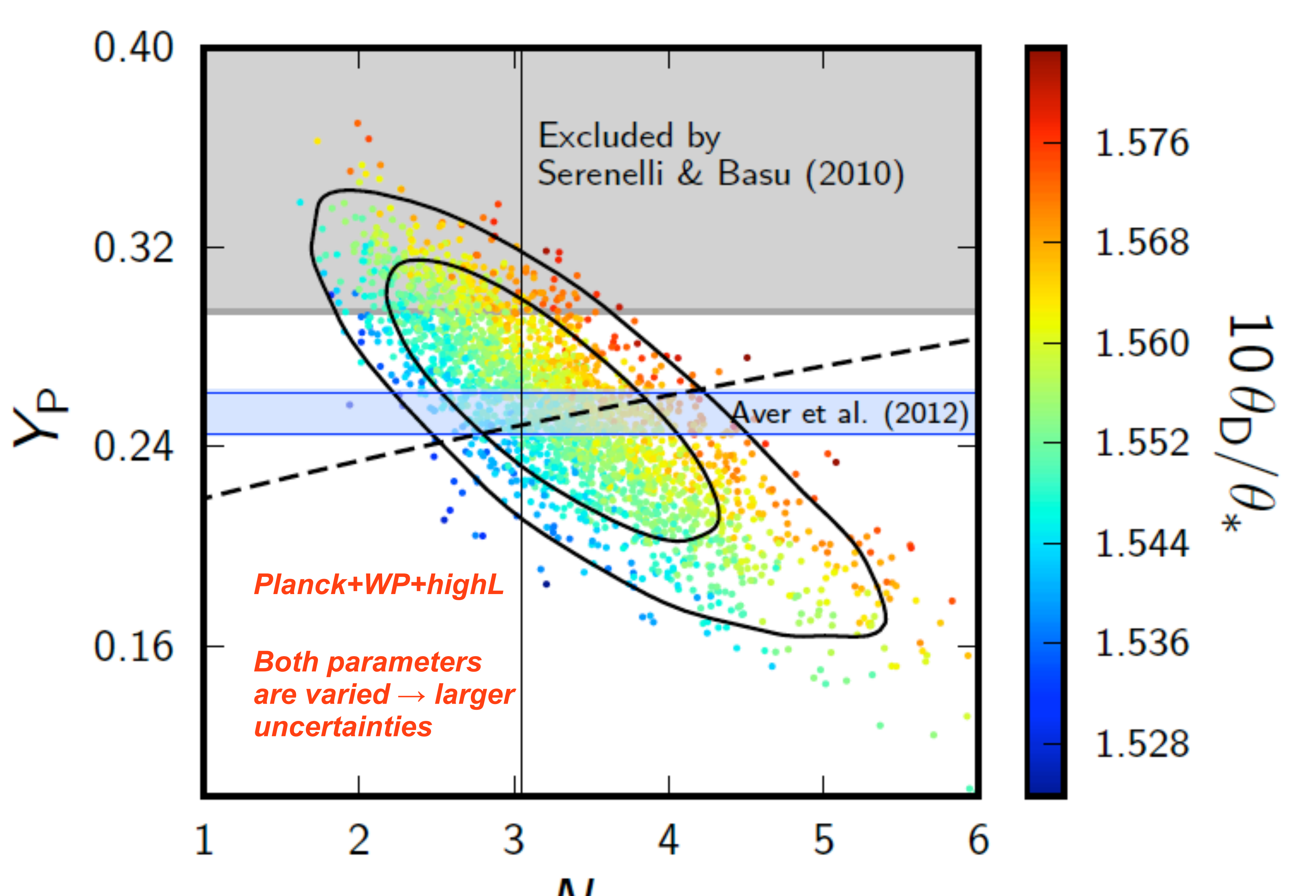
Planck Collaboration, 2013, paper XV

- *Helium determination from CMB consistent with SBNN prediction*
- *CMB constraint on N_{eff} competitive*
- *Partial degeneracy with Y_p and running*
- *Some tension between different data sets*



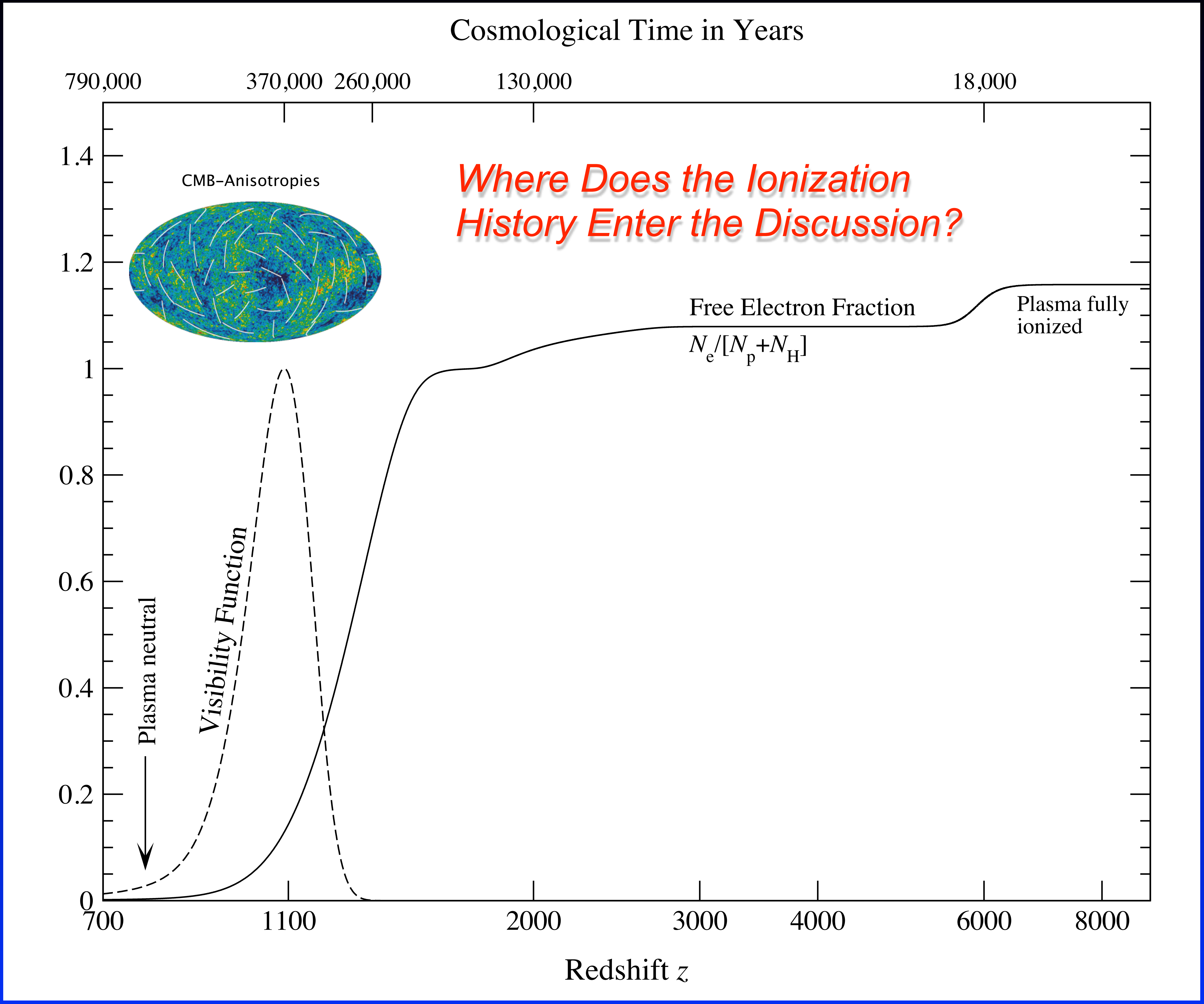
Calabrese et al. 2013

CMB constraints on N_{eff} and Y_{p}

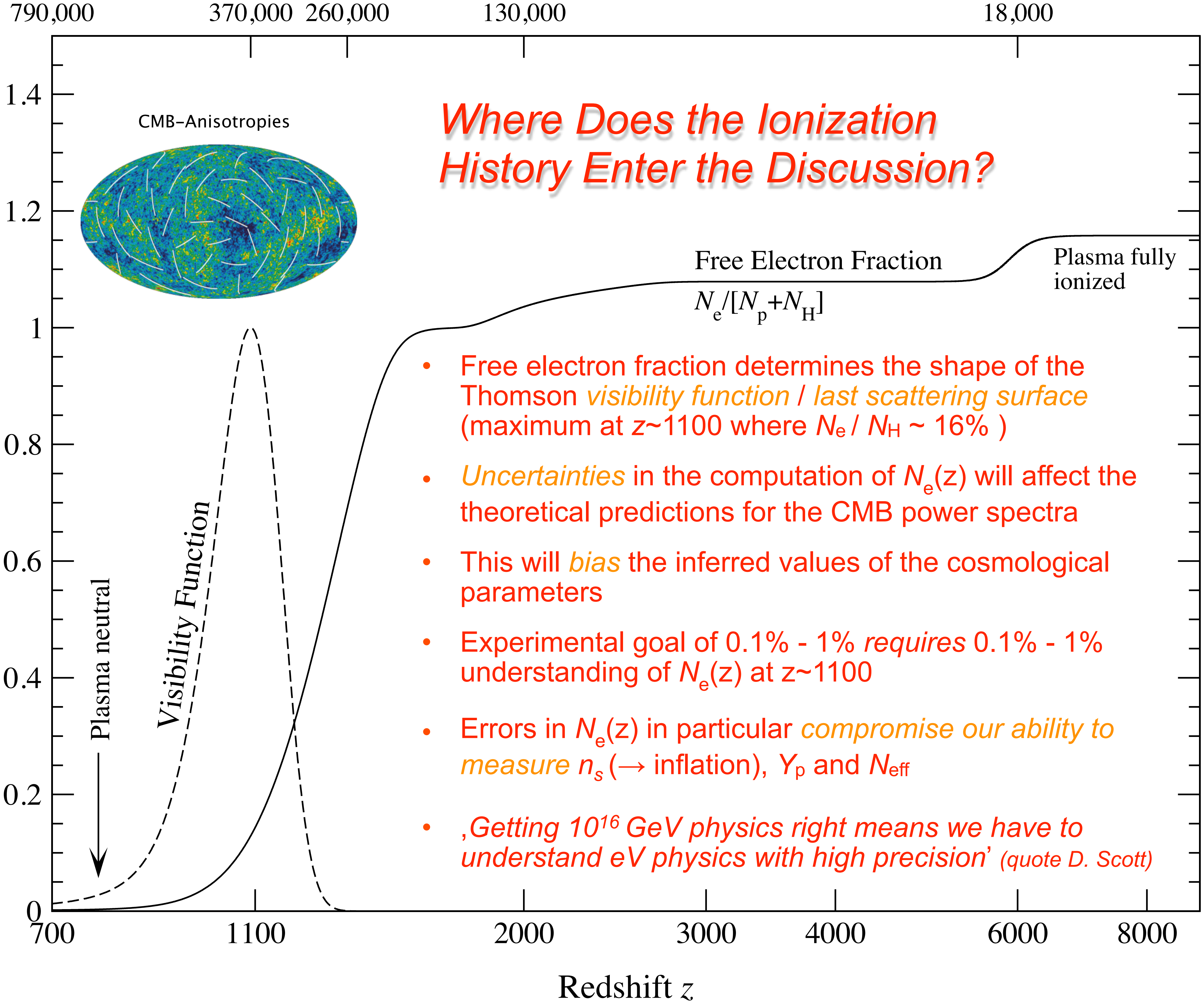


Planck Collaboration, 2013, paper XV

- *Consistent with SBBN and standard value for N_{eff}*
- *Future CMB constraints (SPTPol & ACTPol) on Y_{p} will reach 1% level*


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

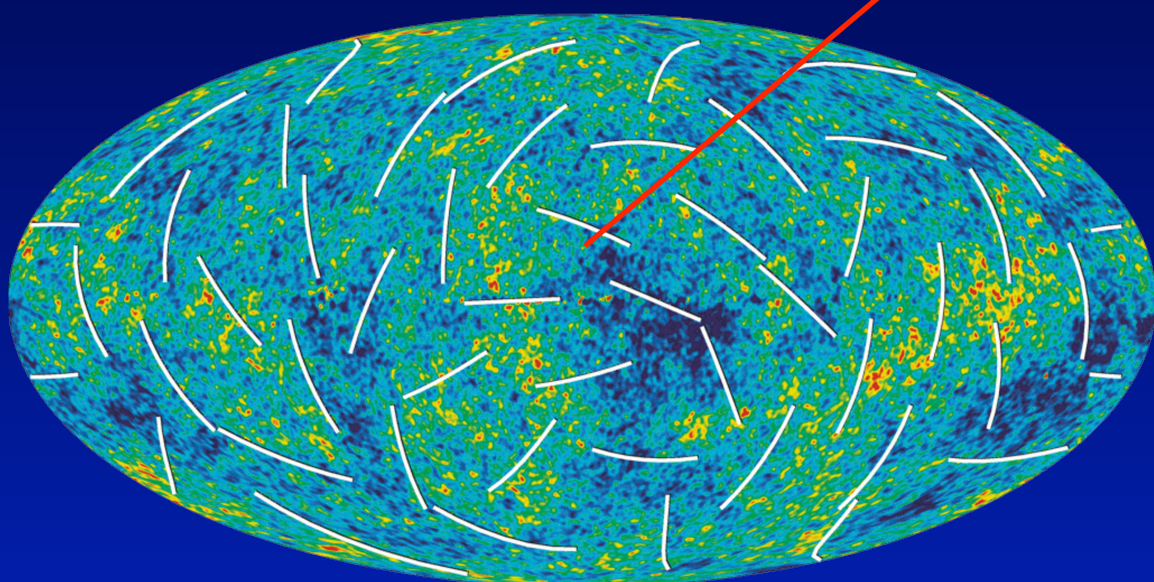
Where Does the Ionization History Enter the Discussion?



- Free electron fraction determines the shape of the Thomson *visibility function* / *last scattering surface* (maximum at z~1100 where N_e / N_H ~ 16%)
- *Uncertainties* in the computation of N_e(z) will affect the theoretical predictions for the CMB power spectra
- This will *bias* the inferred values of the cosmological parameters
- Experimental goal of 0.1% - 1% *requires* 0.1% - 1% understanding of N_e(z) at z~1100
- Errors in N_e(z) in particular *compromise our ability to measure* n_s (→ inflation), Y_p and N_{eff}
- *‚Getting 10^{16} GeV physics right means we have to understand eV physics with high precision*' *(quote D. Scott)*

CMB Sky → Cosmology

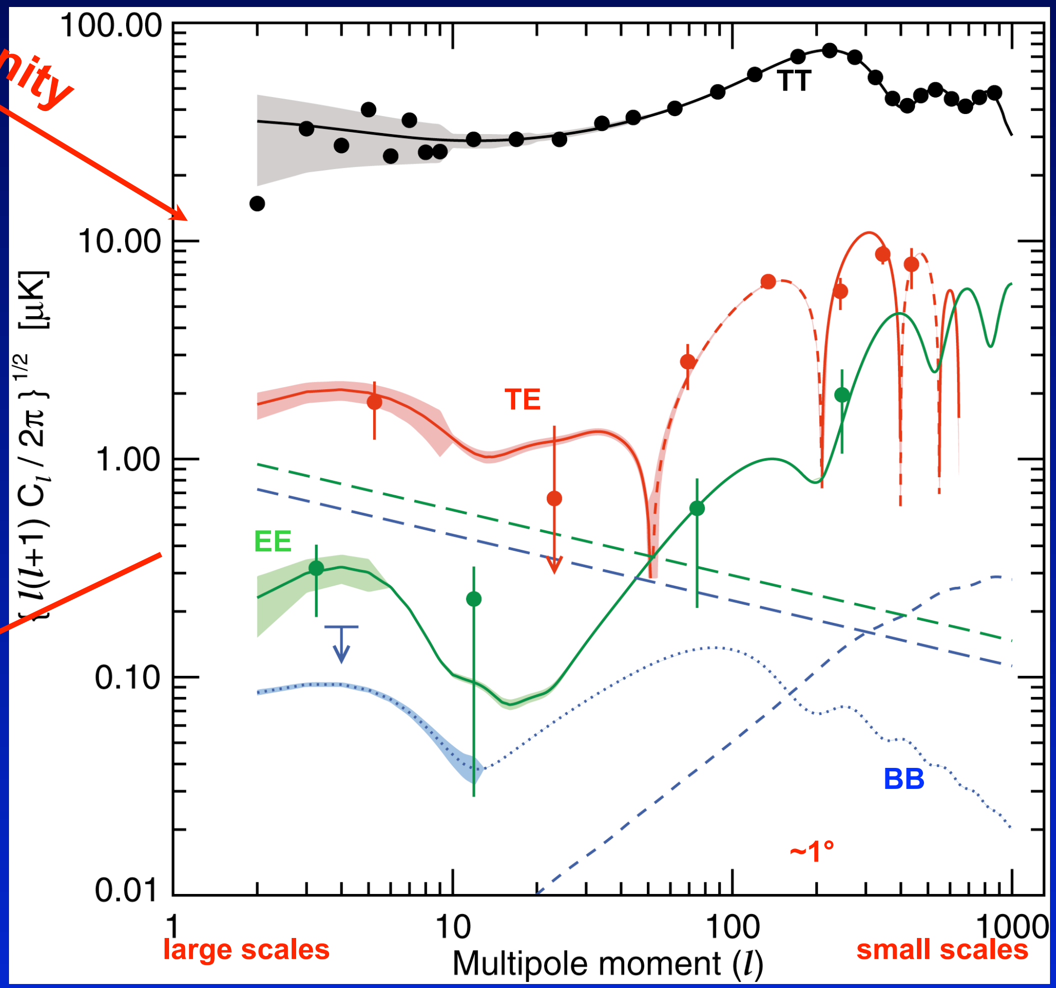
WMAP CMB Sky



a_{lm}

Gaussianity

Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

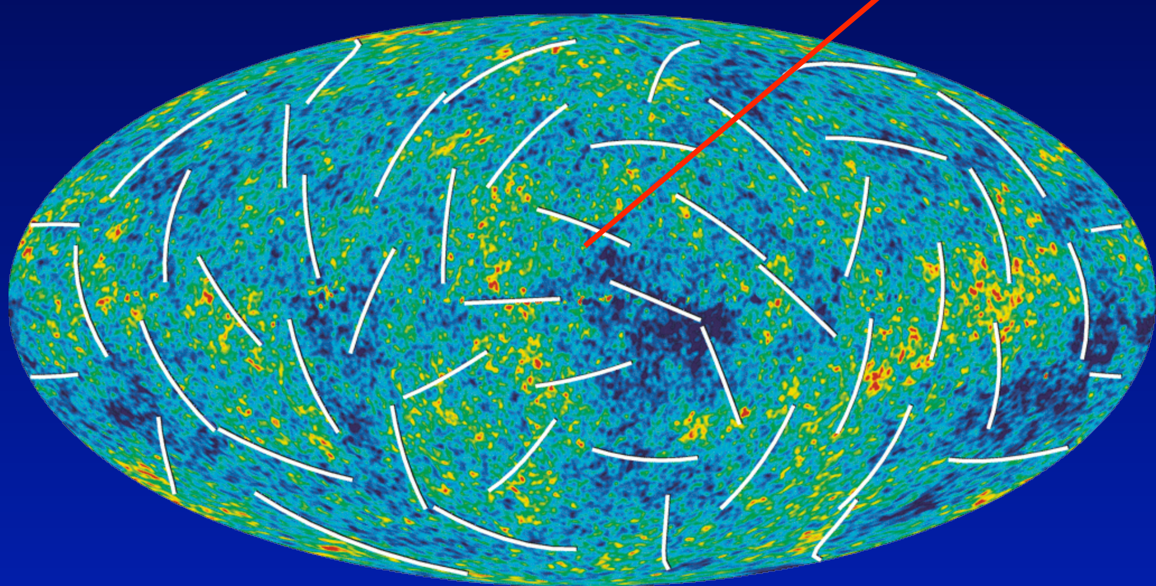
CMB Sky → Cosmology

$N_e(z)$ is an important input

Power spectra

a_{lm}

WMAP CMB Sky



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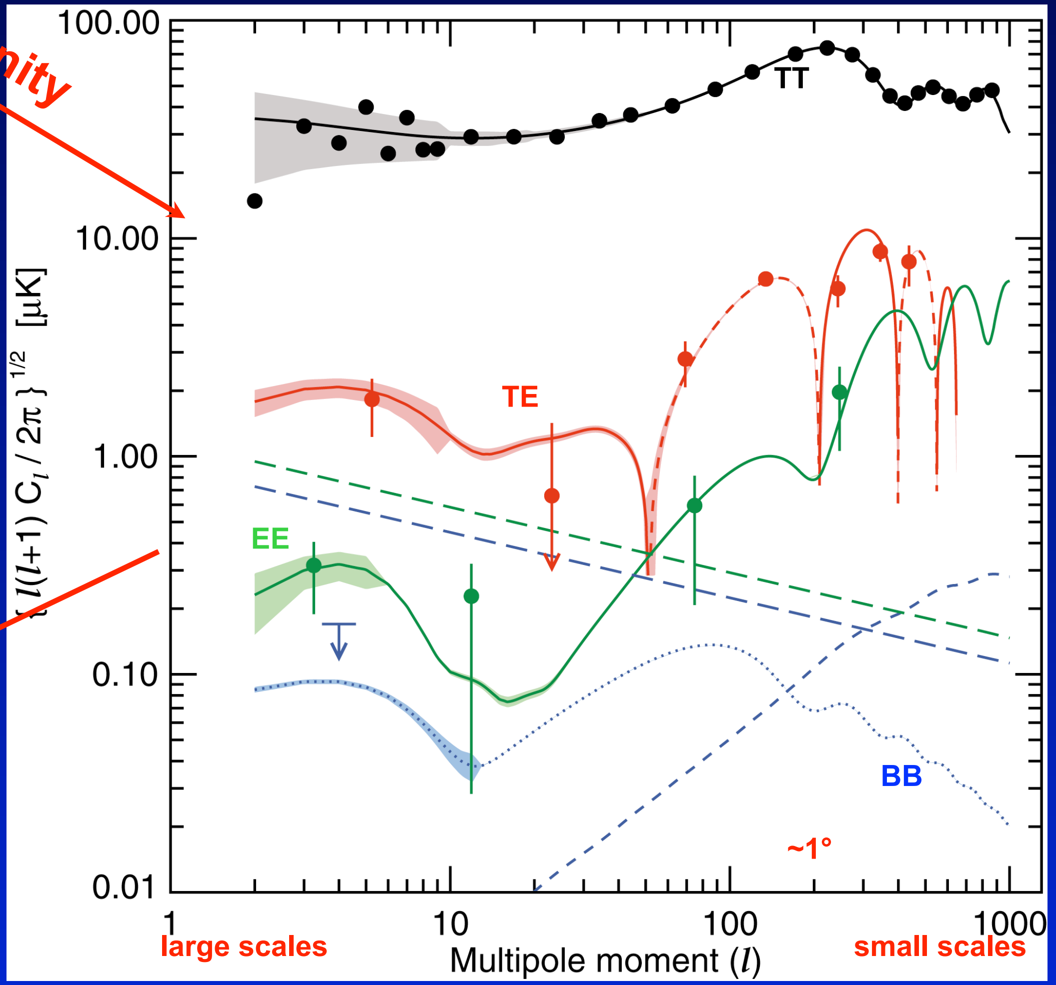

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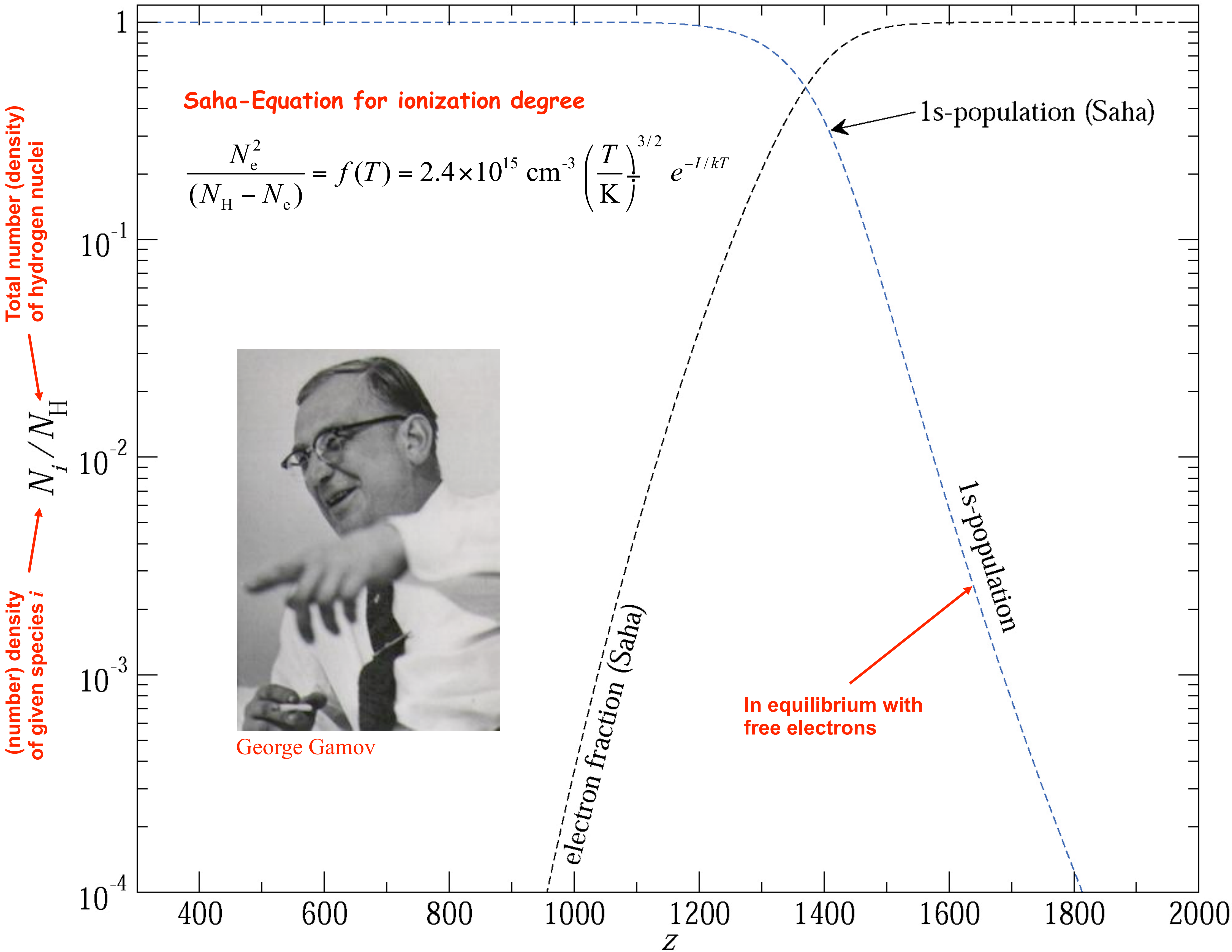
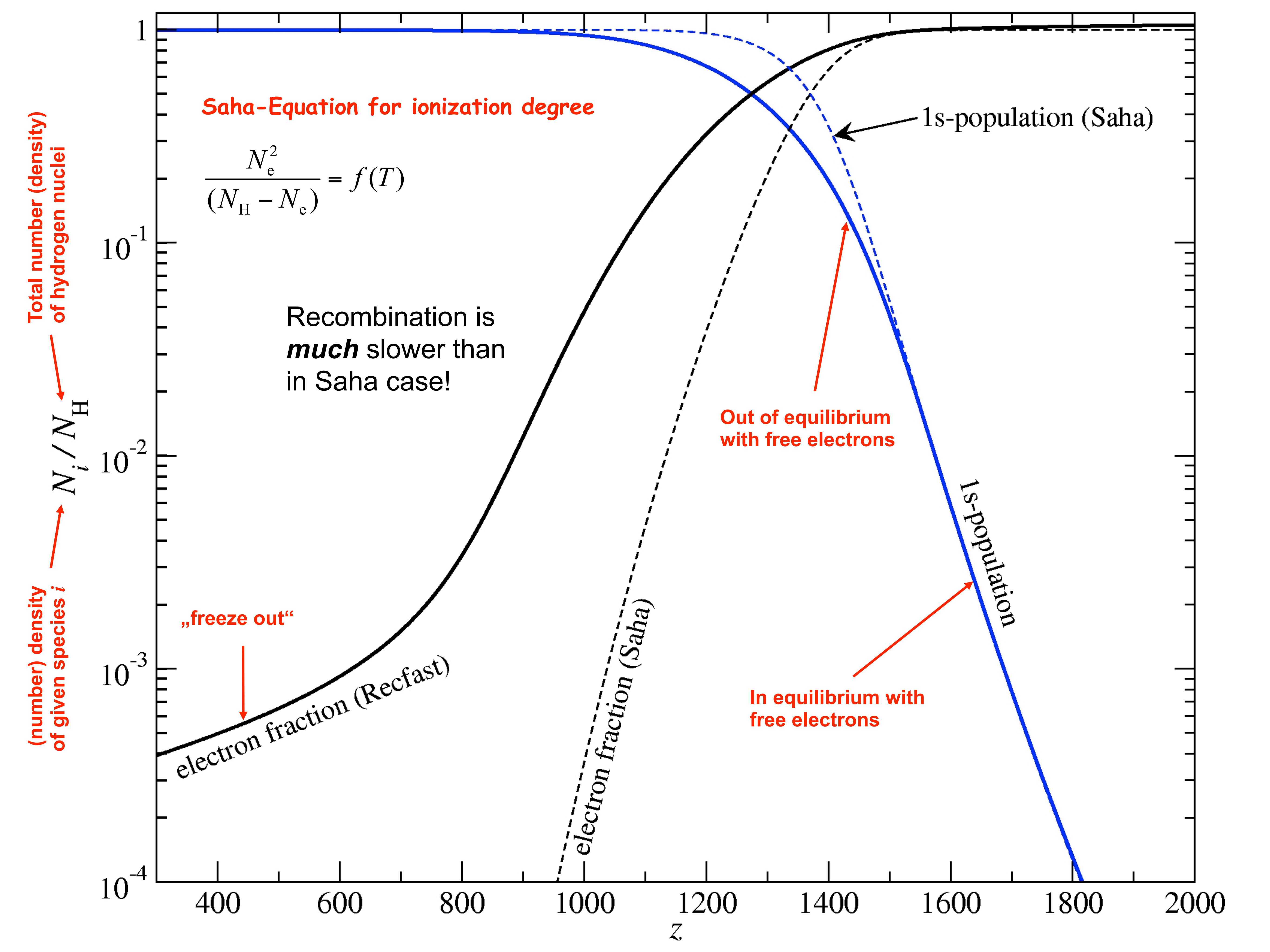
How does cosmological recombination work?

Physical Conditions during Recombination

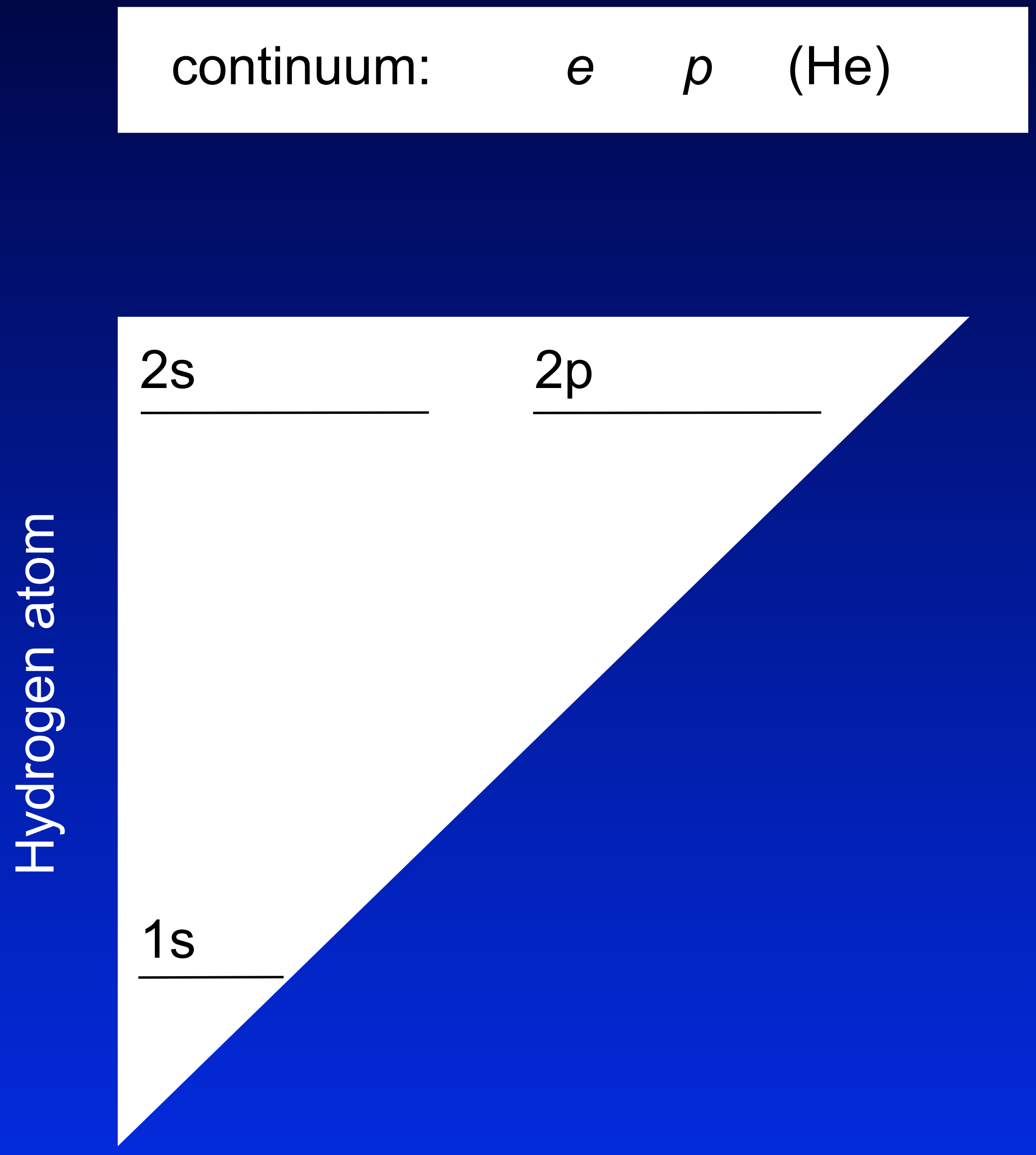
- Temperature $T_\gamma \sim 2.725\,(1+z)$ K ~ 3000 K
- Baryon number density $N_b \sim 2.5 \times 10^{-7}\,\mathrm{cm}^{-3}\,(1+z)^3 \sim 330\,\mathrm{cm}^{-3}$
- Photon number density $N_\gamma \sim 410\,\mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$
  $\Rightarrow$ photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until $h\nu_\alpha \sim 40\,kT_\gamma$
- Collisional processes negligible (completely different from stars!!!)
- Rates dominated by radiative processes
  (e.g. stimulated emission & stimulated recombination)
- Compton interaction couples electrons very tightly to photons until $z \sim 200 \Rightarrow T_\gamma \sim T_e \sim T_m$



Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$
1s-population (Saha)
electron fraction (Saha)
1s-population
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen nuclei
(number) density of given species i
N_i / N_H
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000
z


Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T)$$
1s-population (Saha)
Recombination is
much slower than
in Saha case!
Out of equilibrium
with free electrons
1s-population
In equilibrium with
free electrons
„freeze out“
electron fraction (Recfast)
electron fraction (Saha)
Total number (density)
of hydrogen nuclei
(number) density
of given species *i*
N_i / N_H
z
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000

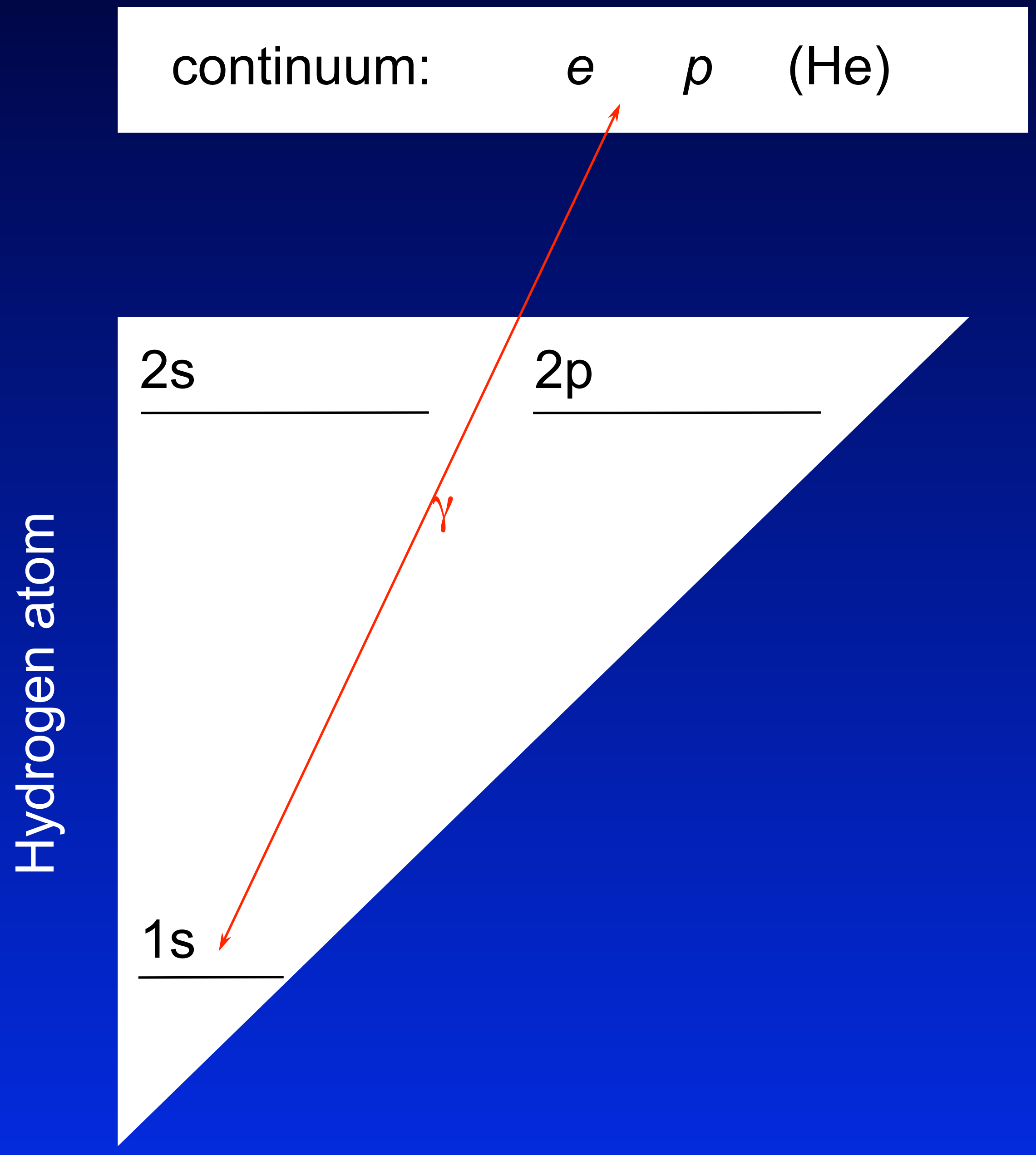
3-level Hydrogen Atom and Continuum



Routes to the ground state ?

Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

3-level Hydrogen Atom and Continuum



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  - **Emission of photon is followed by immediate re-absorption**

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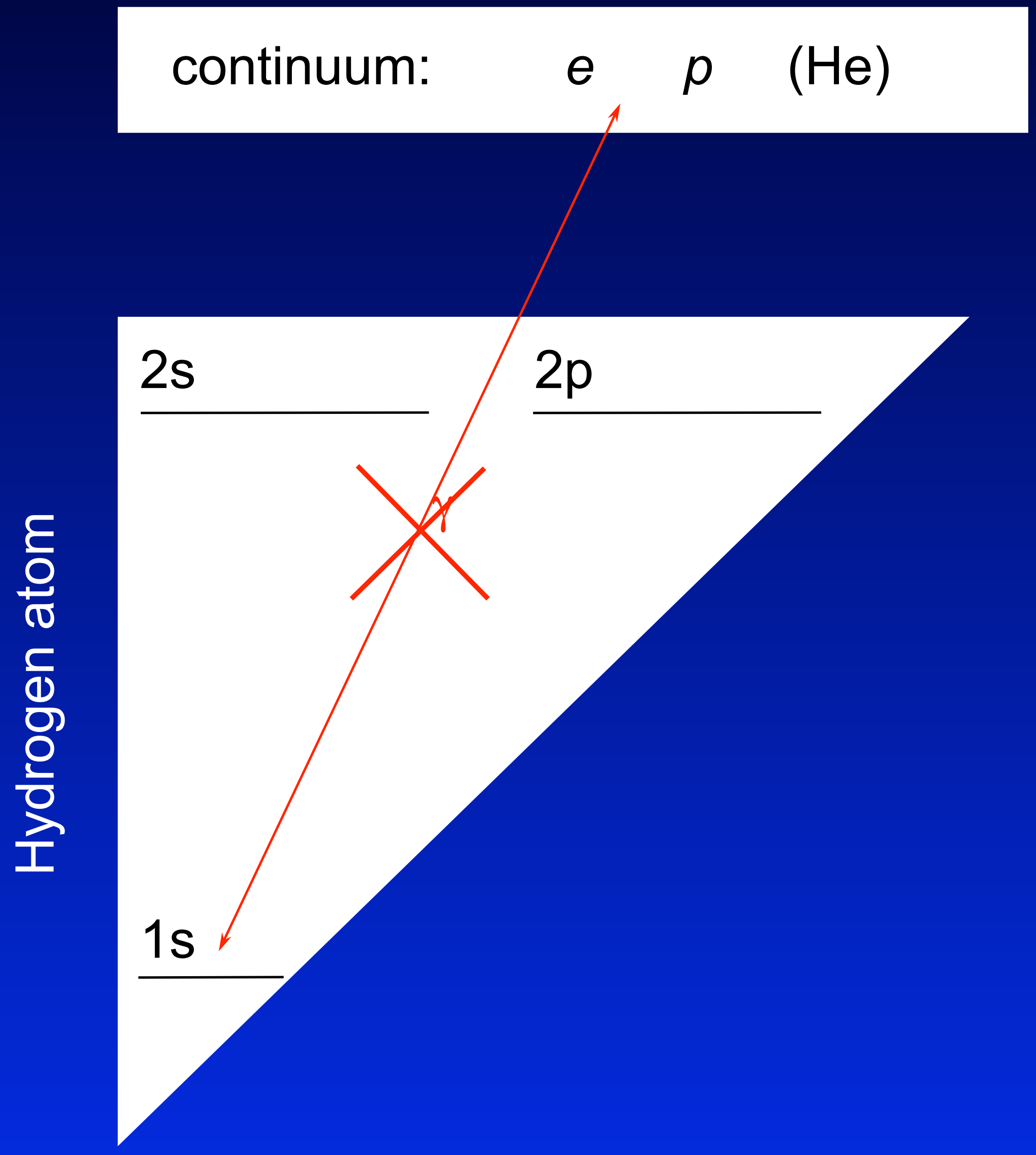

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No

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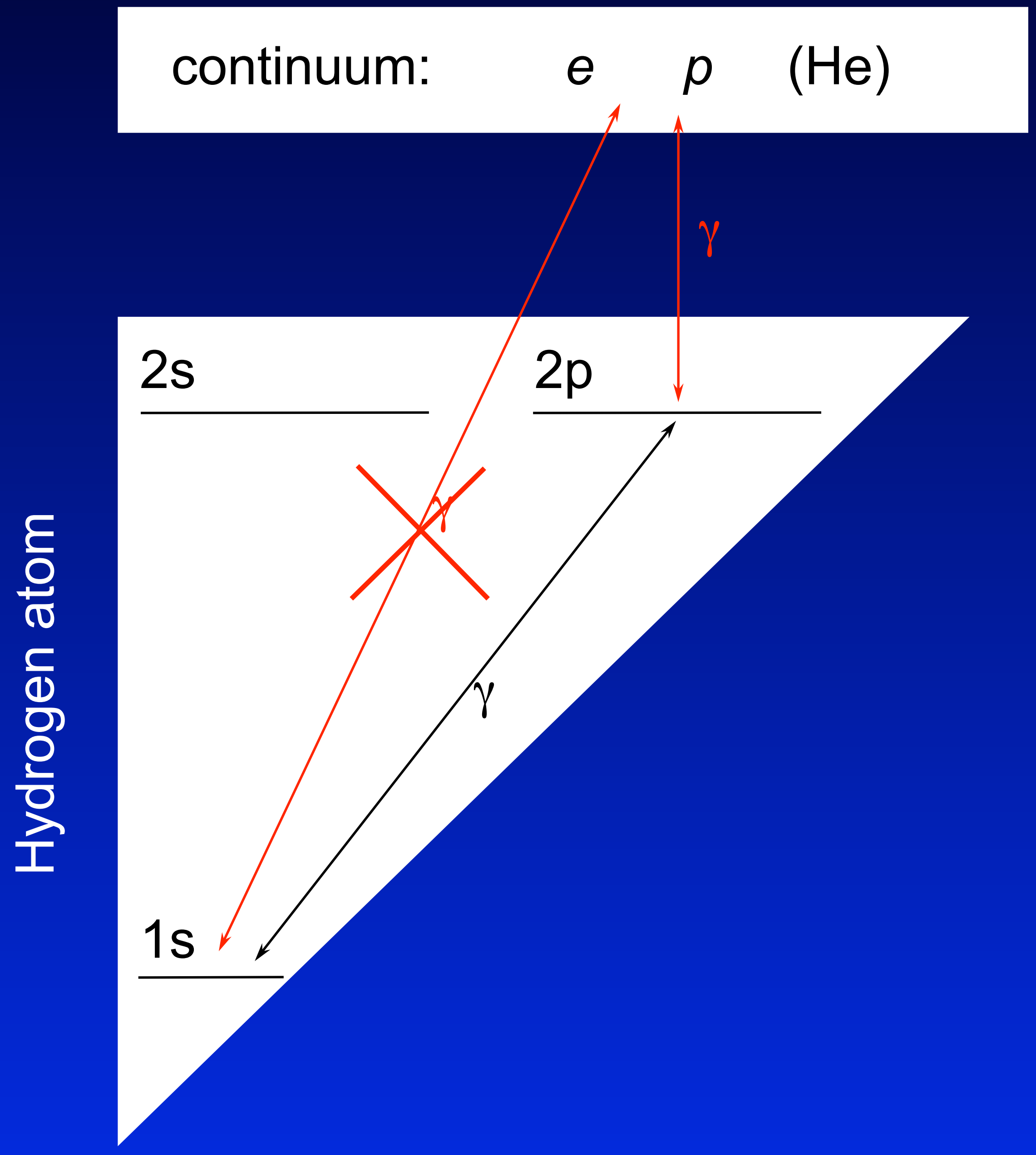

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- **recombination to 2p followed by Lyman-α emission**
  - **medium optically thick to Ly-α phot.**
  - **many resonant scatterings**
  - **escape very hard (*p* ~10^{-9} @ *z* ~1100)**

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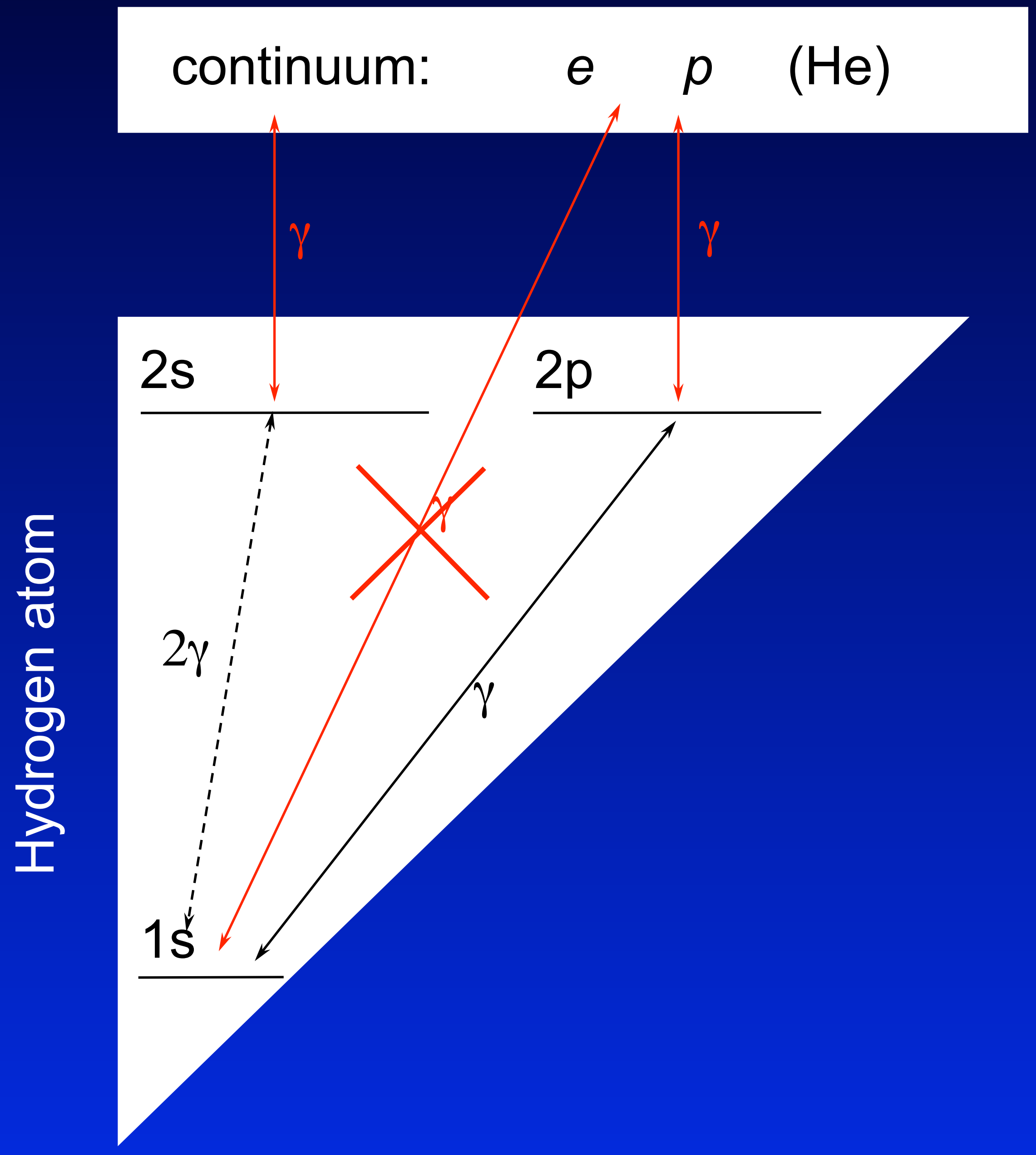

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  - **2s → 1s ~10^8 times slower than Ly-α**
  - **2s two-photon decay profile → maximum at $\nu \sim 1/2\, \nu_\alpha$**
  - **immediate escape**

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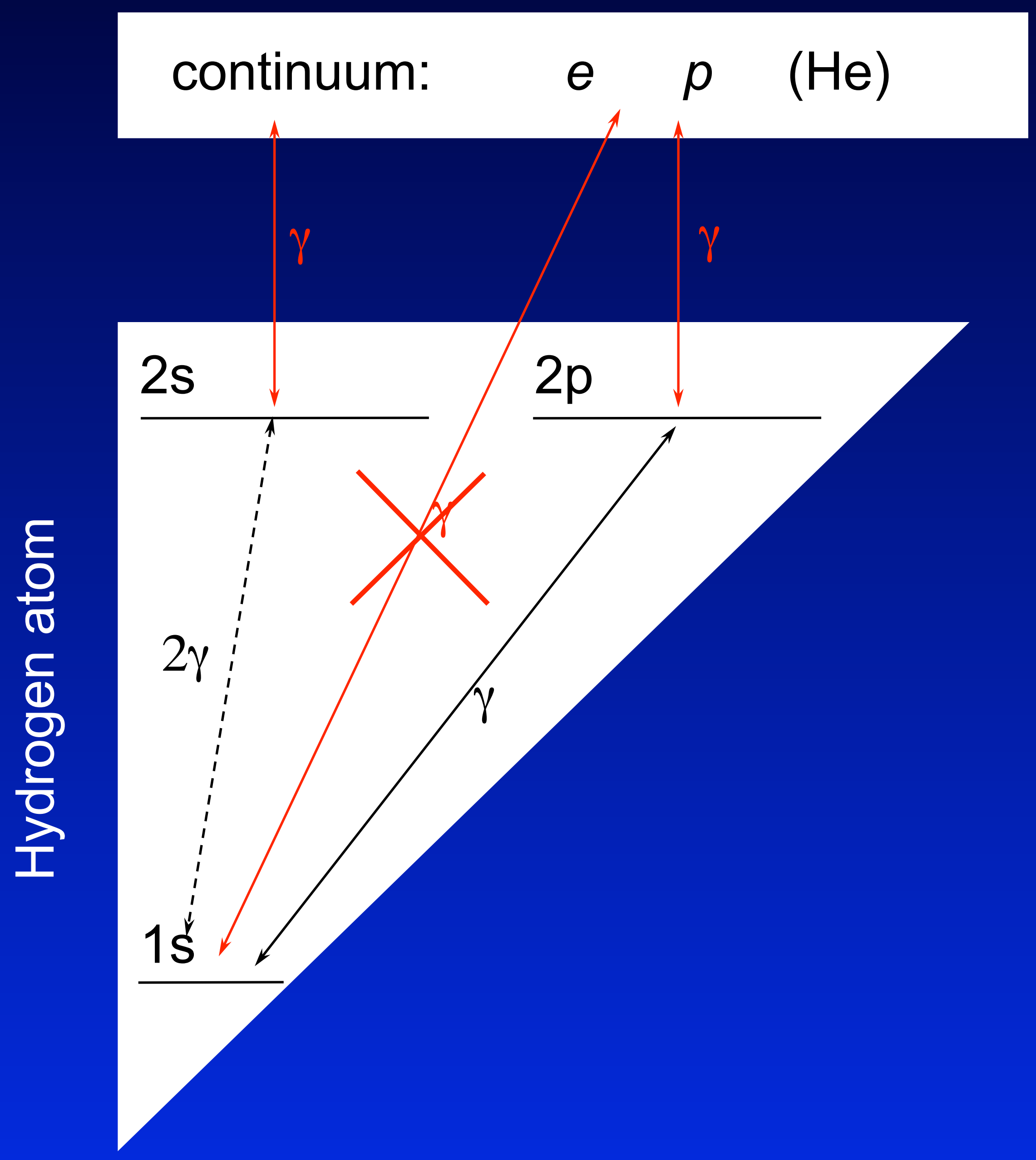

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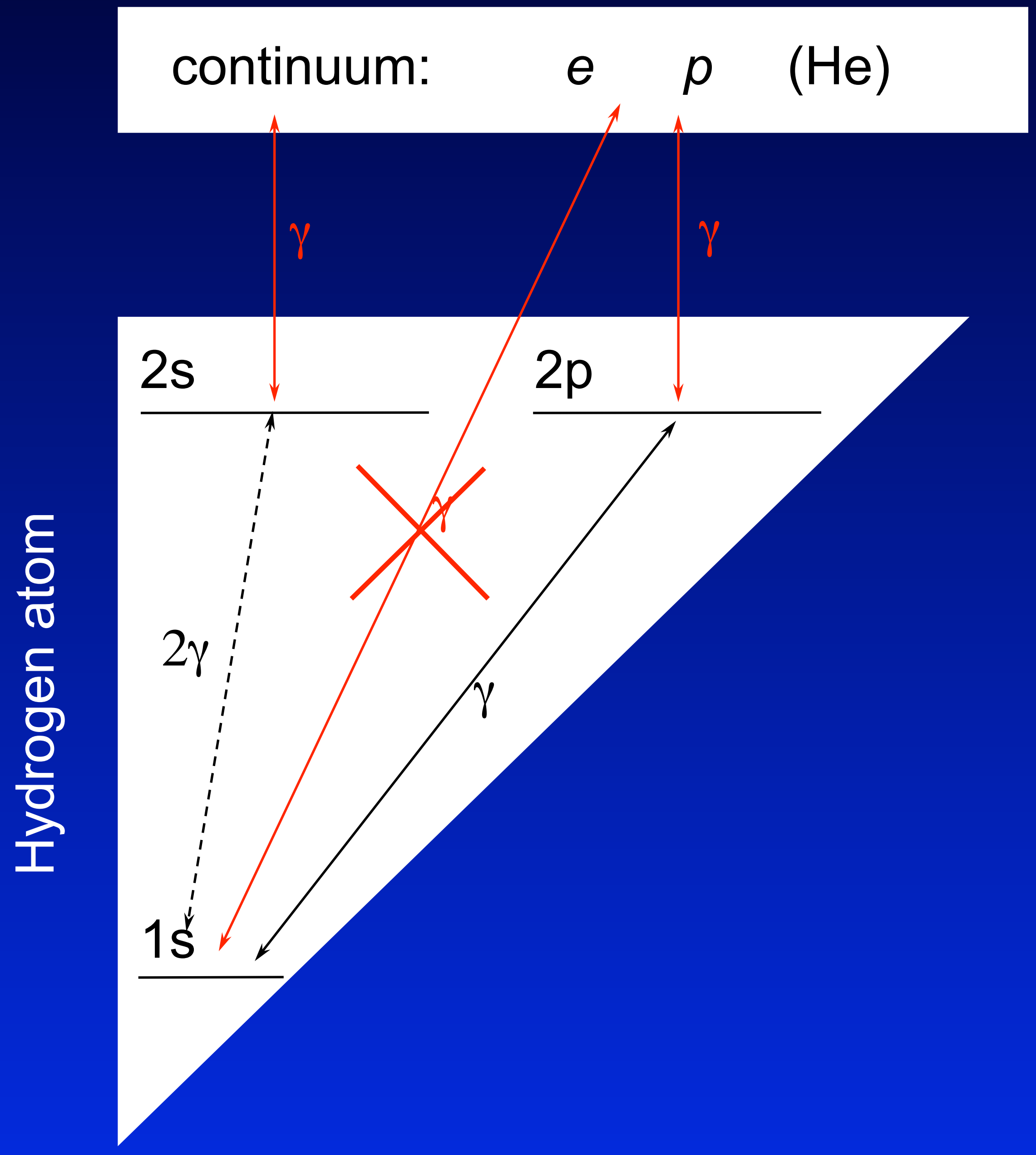

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Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

$\Delta N_e \;/\; N_e \sim 10\% - 20\%$

First recombination computations completed in 1968!

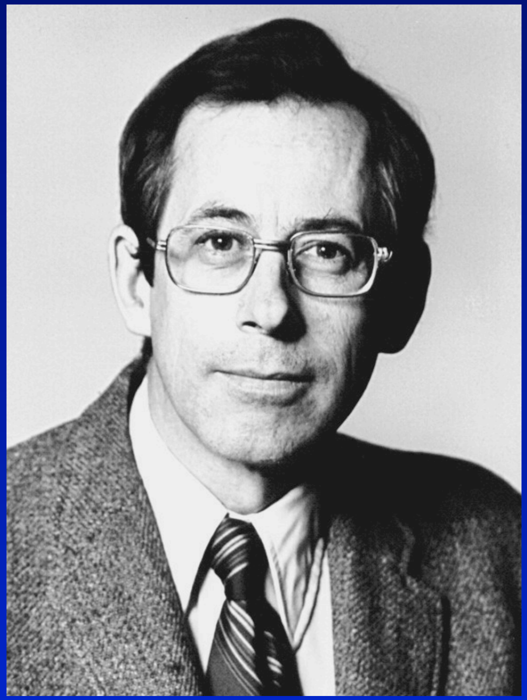
Yakov Zeldovich

Vladimir Kurt
(UV astronomer)

Moscow

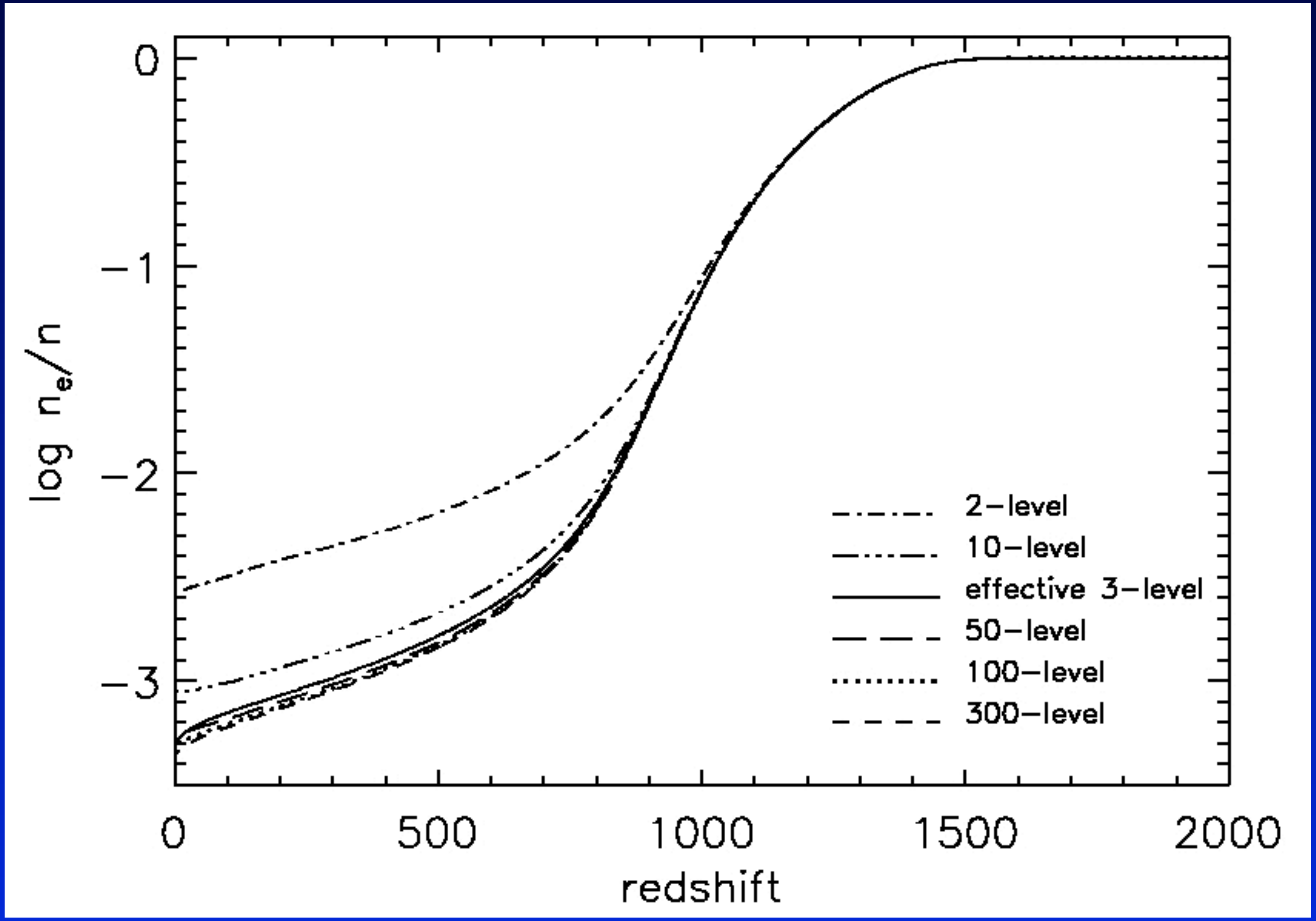
Rashid Sunyaev

Princeton



Jim Peebles

Multi-level Atom ⇒ The Recfast-Code



Seager, Sasselov & Scott, 1999, ApJL, 523, L1
Seager, Sasselov & Scott, 2000, ApJS, 128, 407

Output of N_e/N_H

Hydrogen:

- up to 300 levels
- only 2s & 2p separately
- n>2 → full SE for l-sub-states

Helium:

- HeI 200-levels (z ~ 1400-1500)
- HeII 100-levels (z ~ 6000-6500)
- HeIII 1 equation

Low Redshifts:

- H chemistry (important at low z)
- cooling of matter (Bremsstrahlung, collisional cooling, line cooling)

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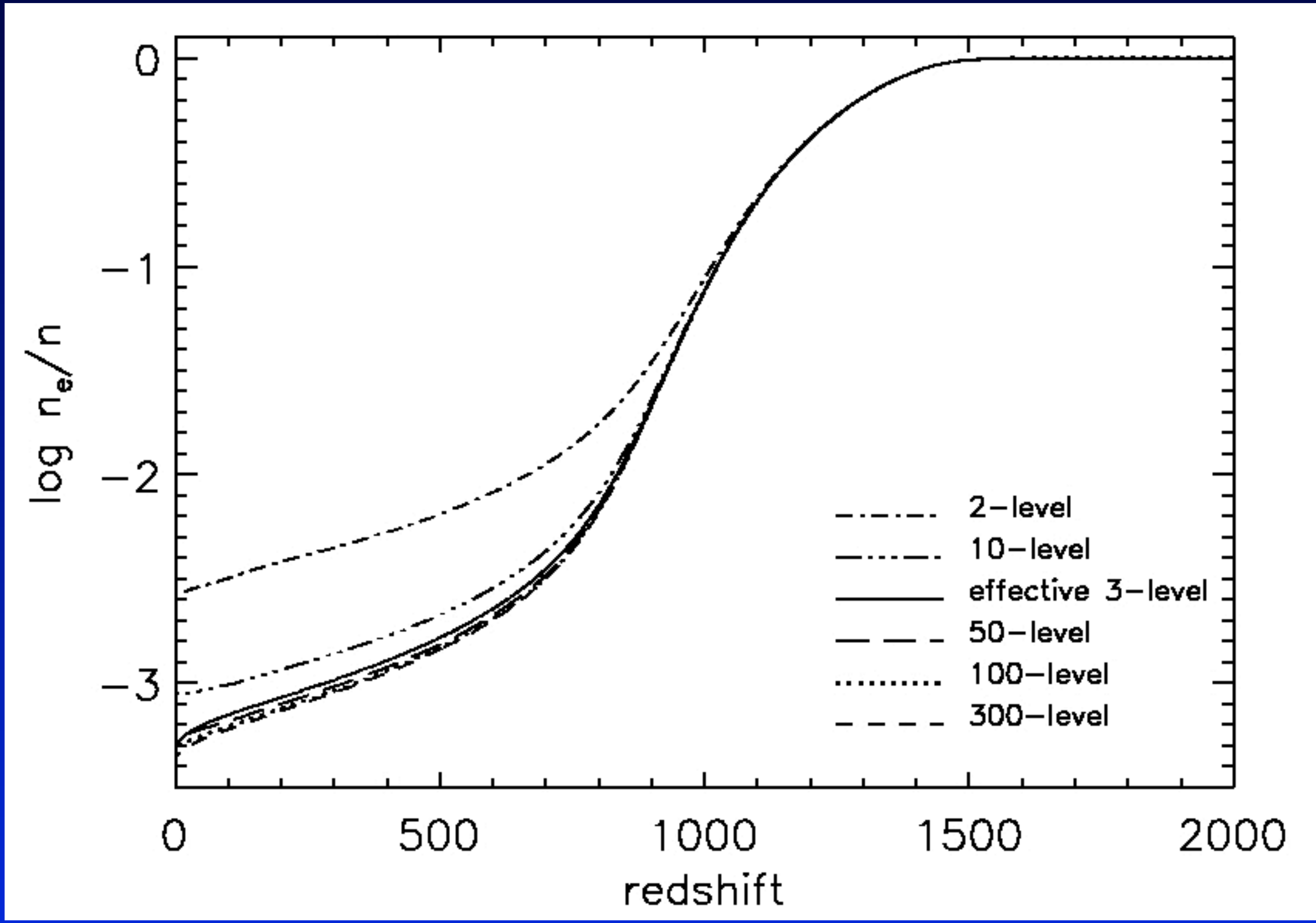

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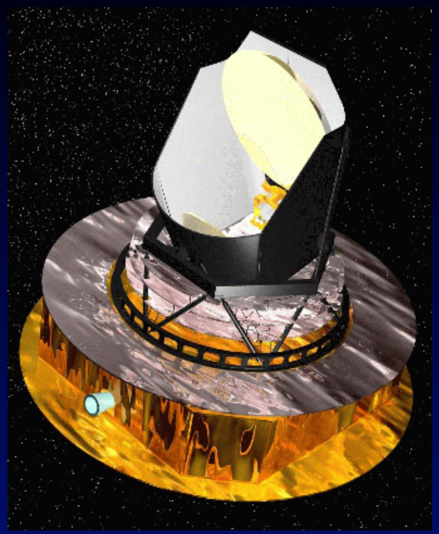
- cooling of matter (Bremsstrahlung, collisional cooling, line cooling)

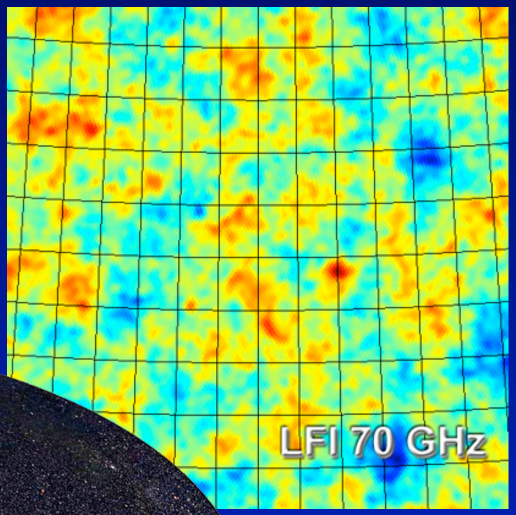
$\Delta N_e \,/\, N_e \sim 1\% - 3\%$

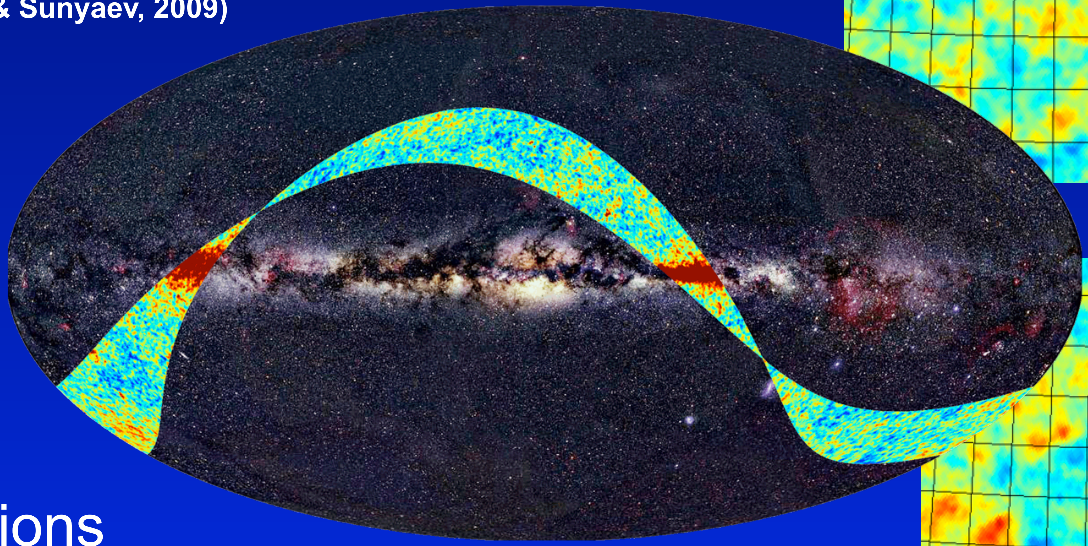
Getting Ready for Planck



Hydrogen recombination

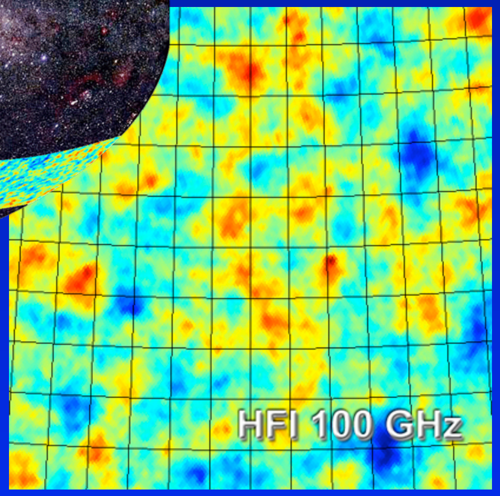
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption rate
  (Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
  (Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons (Ly[n] → Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman-α escape problem (*atomic recoil, time-dependence, partial redistribution*)
  (Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Raman scattering
  (Hirata 2008; JC & Thomas , 2010; Haimoud & Hirata, 2010)





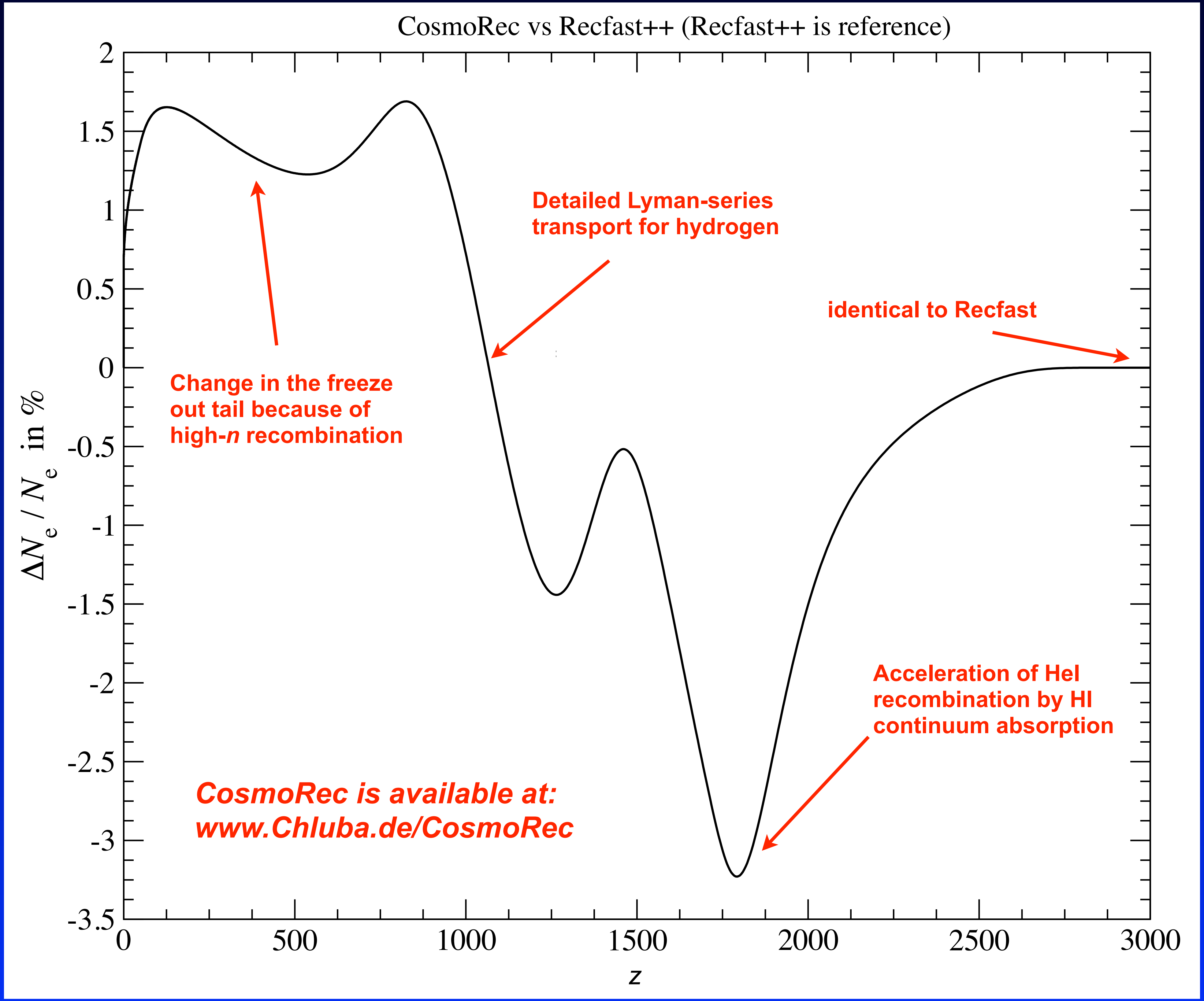
Helium recombination

- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
- Hydrogen continuum opacity during He I recombination
  (Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007; Rubiño-Martín, JC & Sunyaev, 2007)
- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS)



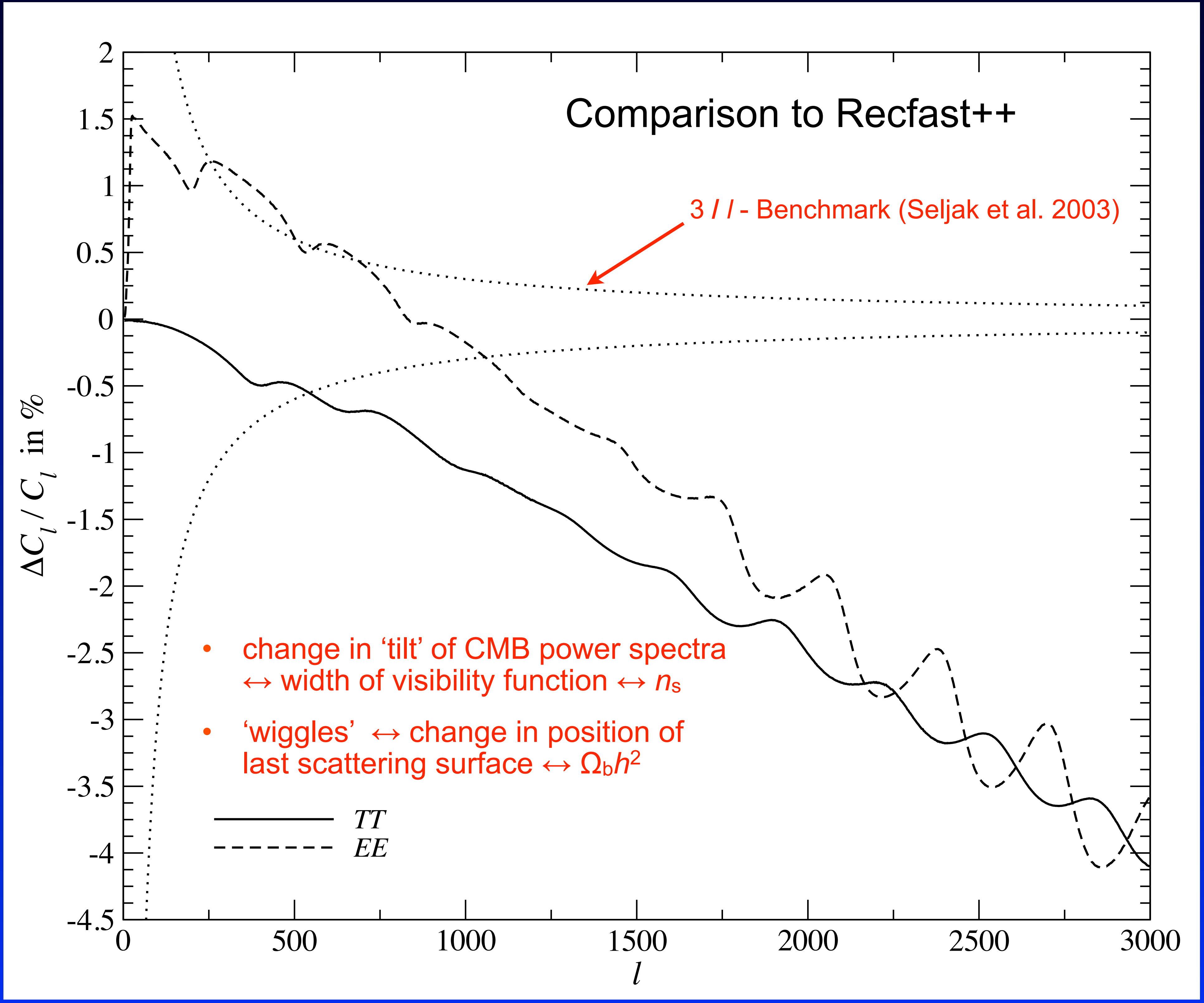
$\Delta N_e / N_e \sim 0.1\ \%$

Cumulative Changes to the Ionization History



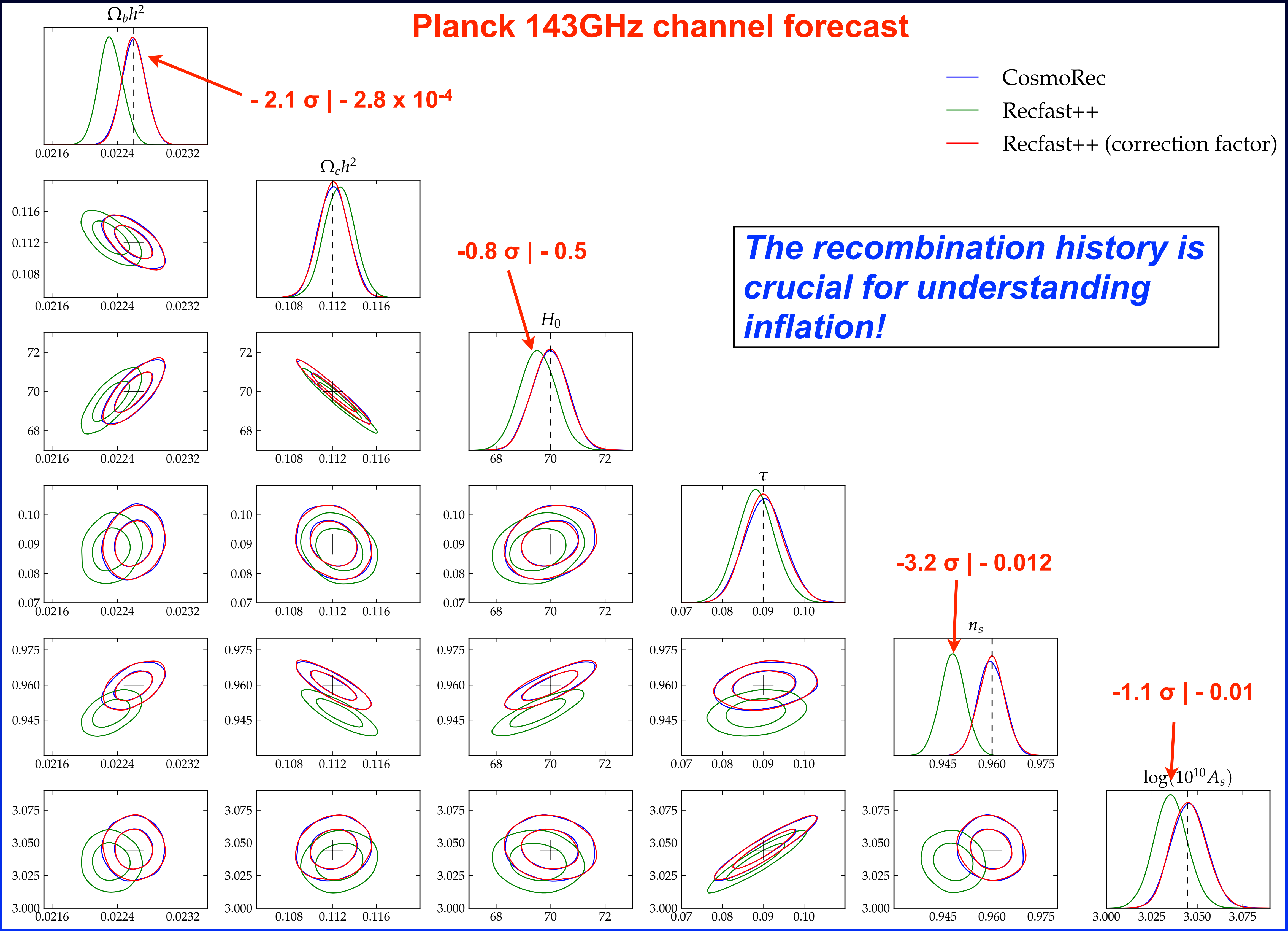
JC & Thomas, MNRAS, 2010; Shaw & JC, 2011

Cumulative Change in the CMB Power Spectra



CITA ICAT Shaw & JC, 2011

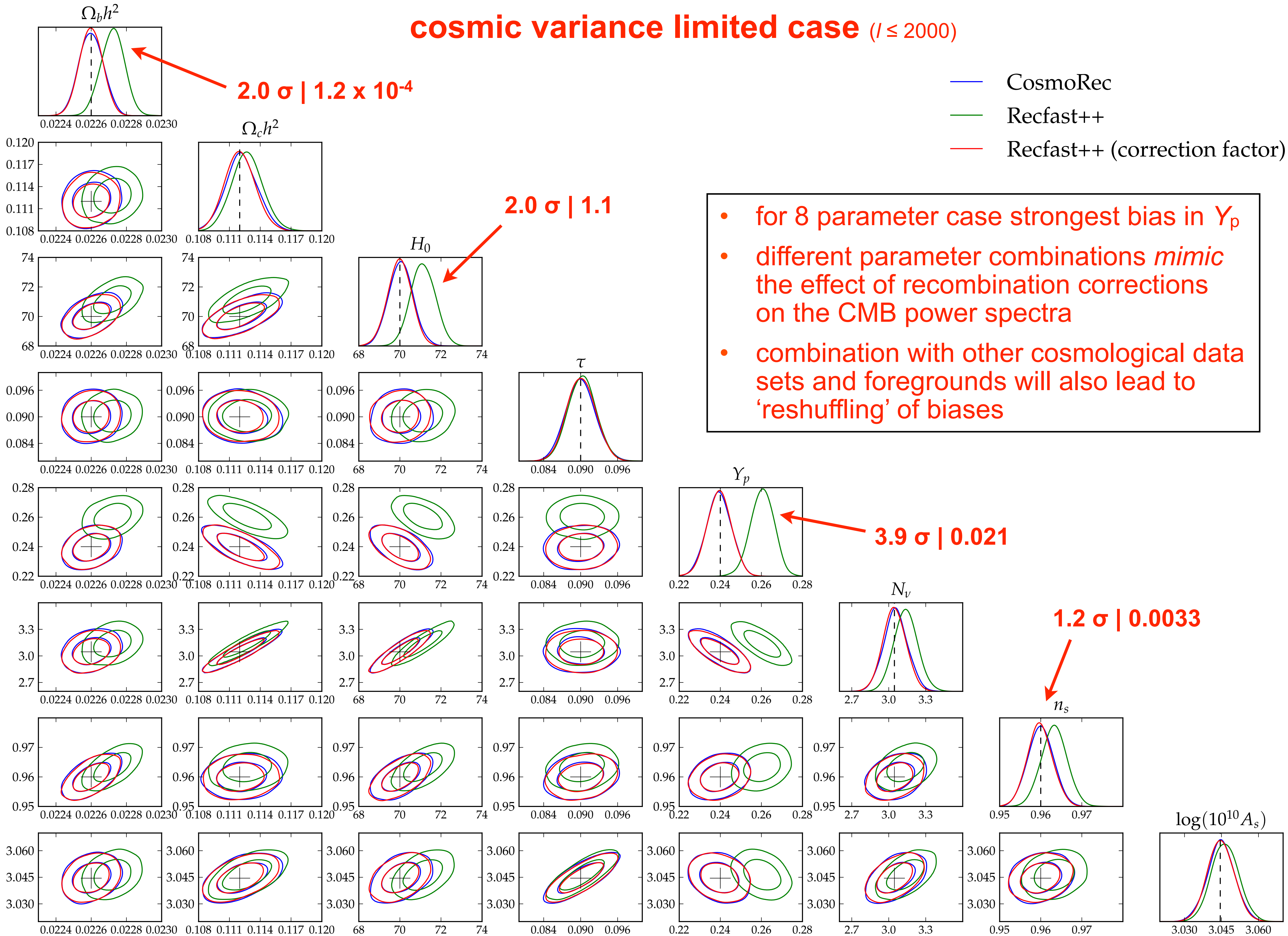
Importance of recombination for inflation



Shaw & JC, 2011, and references therein

Importance of recombination for measuring helium

cosmic variance limited case ($l \leq 2000$)



- for 8 parameter case strongest bias in Y_p
- different parameter combinations *mimic* the effect of recombination corrections on the CMB power spectra
- combination with other cosmological data sets and foregrounds will also lead to 'reshuffling' of biases

CITA ICAT Shaw & JC, 2011, and references therein

What if something unexpected happened?

- **E.g., something** *standard* **was missed, or something** *non-standard* **happened !?**
- **A** *non-parametric estimation* **of possible** *corrections* **to the recombination history would be very useful →** *Principle component analysis* **(PCA)**

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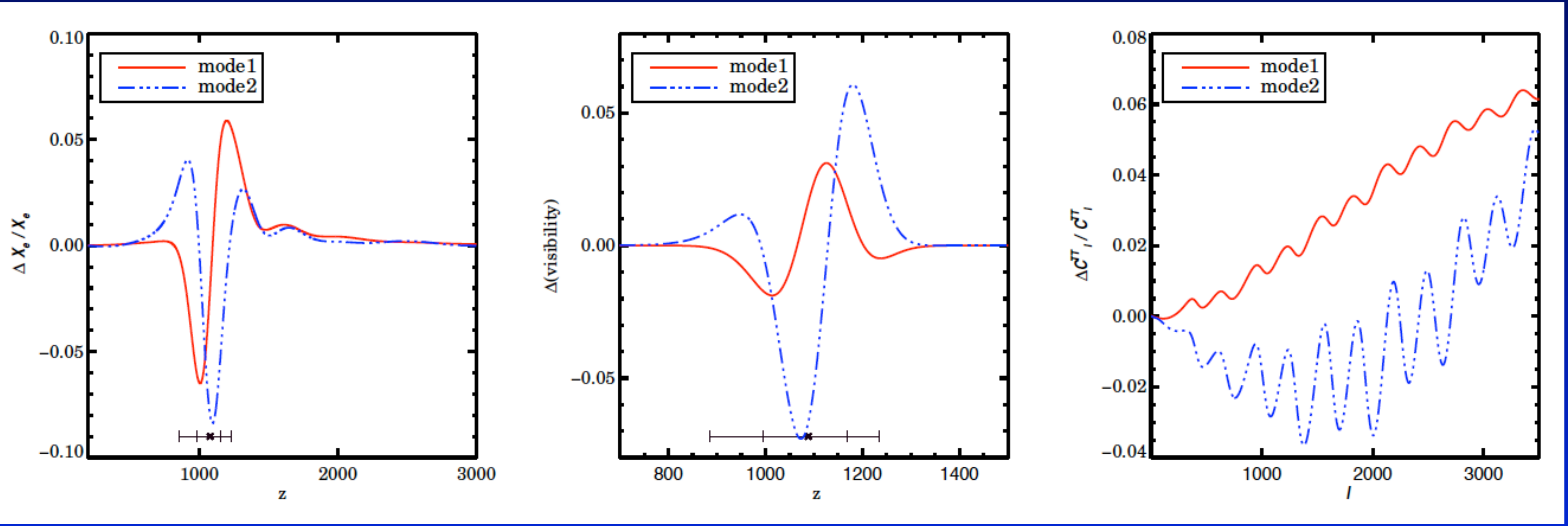


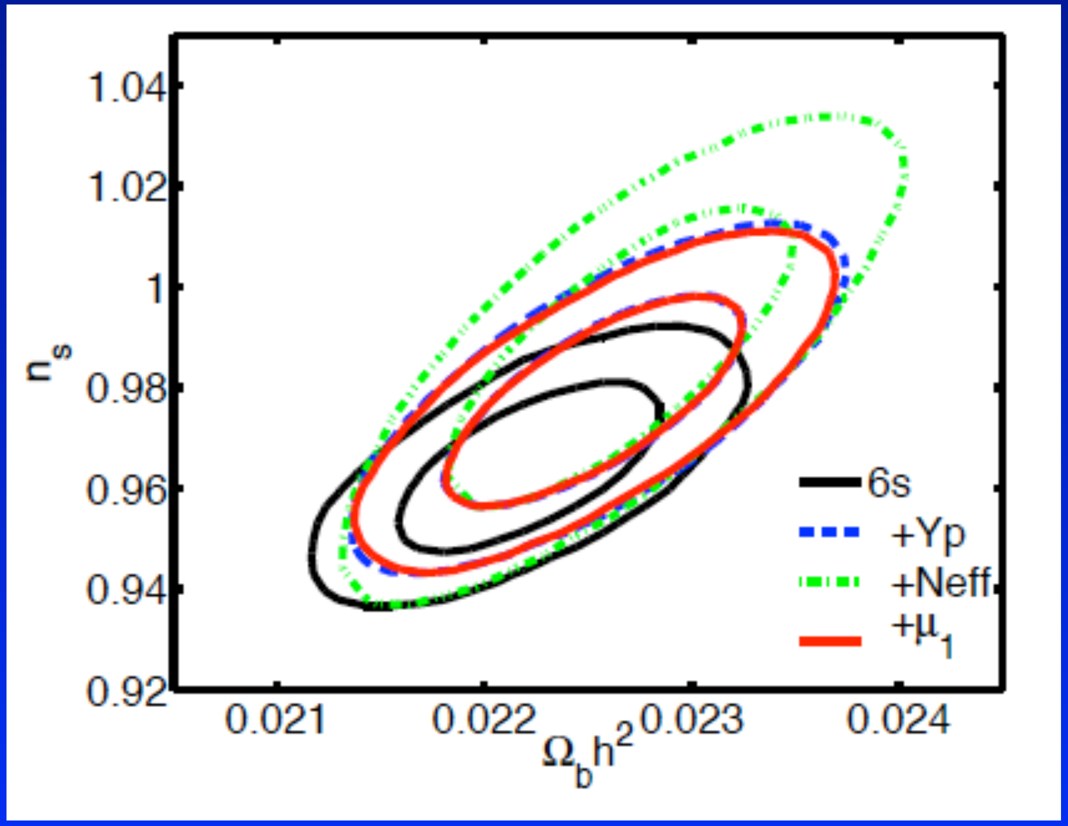
Farhang, Bond & JC, 2012

Measured mode amplitudes for ACT & SPT

parameters	SPT+WMAP7 6s	SPT+WMAP7 + mode 1	SPT+WMAP7 + mode 2	ACT+WMAP7 6s	ACT+WMAP7 + mode 1	ACT+WMAP7 + mode 2
$100\Omega_b h^2$	2.221 ± 0.042	2.253 ± 0.046	2.249 ± 0.047	2.219 ± 0.051	2.240 ± 0.050	2.236 ± 0.053
$\Omega_c h^2$	0.1110 ± 0.0048	0.1123 ± 0.0049	0.1118 ± 0.0052	0.1121 ± 0.0052	0.1155 ± 0.0056	0.1121 ± 0.0061
$100\theta_s$	1.041 ± 0.002	1.041 ± 0.002	1.040 ± 0.003	1.039 ± 0.002	1.039 ± 0.002	1.035 ± 0.004
τ	0.086 ± 0.015	0.089 ± 0.015	0.089 ± 0.015	0.086 ± 0.015	0.089 ± 0.015	0.0875 ± 0.015
n_s	0.964 ± 0.011	0.977 ± 0.013	0.975 ± 0.016	0.963 ± 0.013	0.976 ± 0.015	0.960 ± 0.019
$10^9 \Delta^2_{\mathcal{R}}$	2.43 ± 0.10	2.40 ± 0.10	2.40 ± 0.10	2.45 ± 0.11	2.43 ± 0.11	2.45 ± 0.11
μ_1	(0)	-0.77 ± 0.46	-0.76 ± 0.47	(0)	-1.27 ± 0.74	-1.67 ± 0.86
μ_2	(0)	(0)	-0.39 ± 1.09	(0)	(0)	-3.5 ± 2.7
σ_8(derived)	0.807 ± 0.024	0.825 ± 0.027	0.818 ± 0.032	0.814 ± 0.028	0.841 ± 0.031	0.802 ± 0.040
$\delta z_{dec}/z_{dec}$ [a]	–	-0.6%	-0.7%	–	-1.0%	-1.7%
$\delta\sigma_{z,dec}/\sigma_{z,dec}$ [b]	–	1.5%	-0.5%	–	2.6%	-14.0%
$(\lvert\delta x_e\rvert/x_e)_{max}$ [c]	–	5% $(z \sim 1196)$	5% $(z \sim 1039)$	–	8% $(z \sim 1006)$	31% $(z \sim 1076)$
$\Delta\chi^2$	–	2.5	2.5	–	2.1	2.5

[a] relative change in the redshift of maximum visibility where $z_{dec} = 1088$ is the fiducial maximum visibility point.
[b] relative change in the width of the visibility function.
[c] maximum relative change in the ionization fraction. The redshift corresponding to this maximum change is also included.

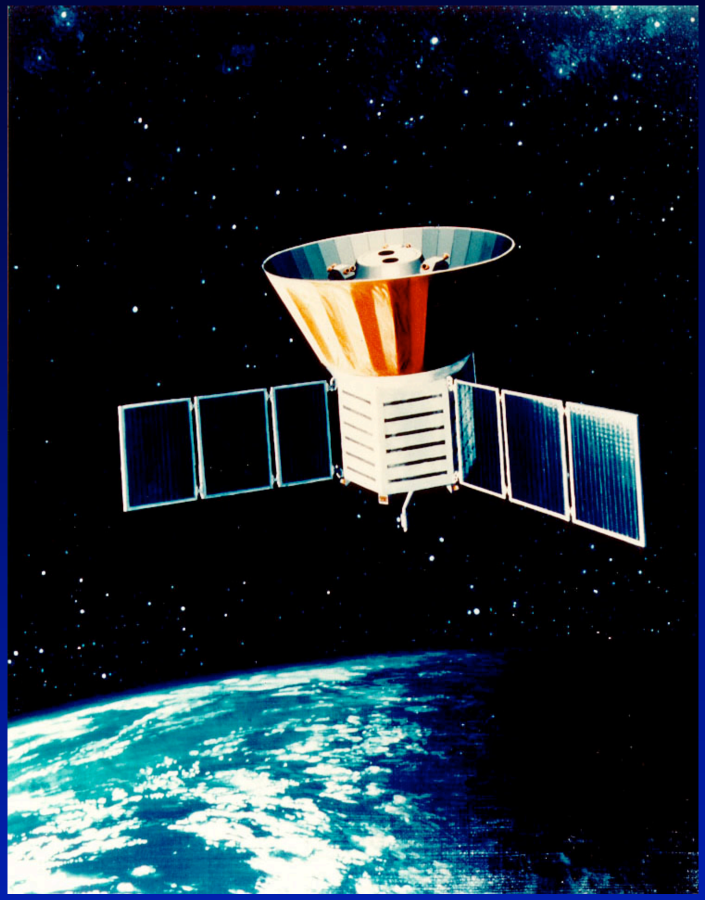
- *First mode detected at ~ 2σ*
- *Similar for current Planck data*
- *Effect very similar to the one of helium*
- *In the future 2-3 modes detectable*



Farhang, Bond & JC, 2012

Is there another more direct way to constrain the cosmological recombination history?

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

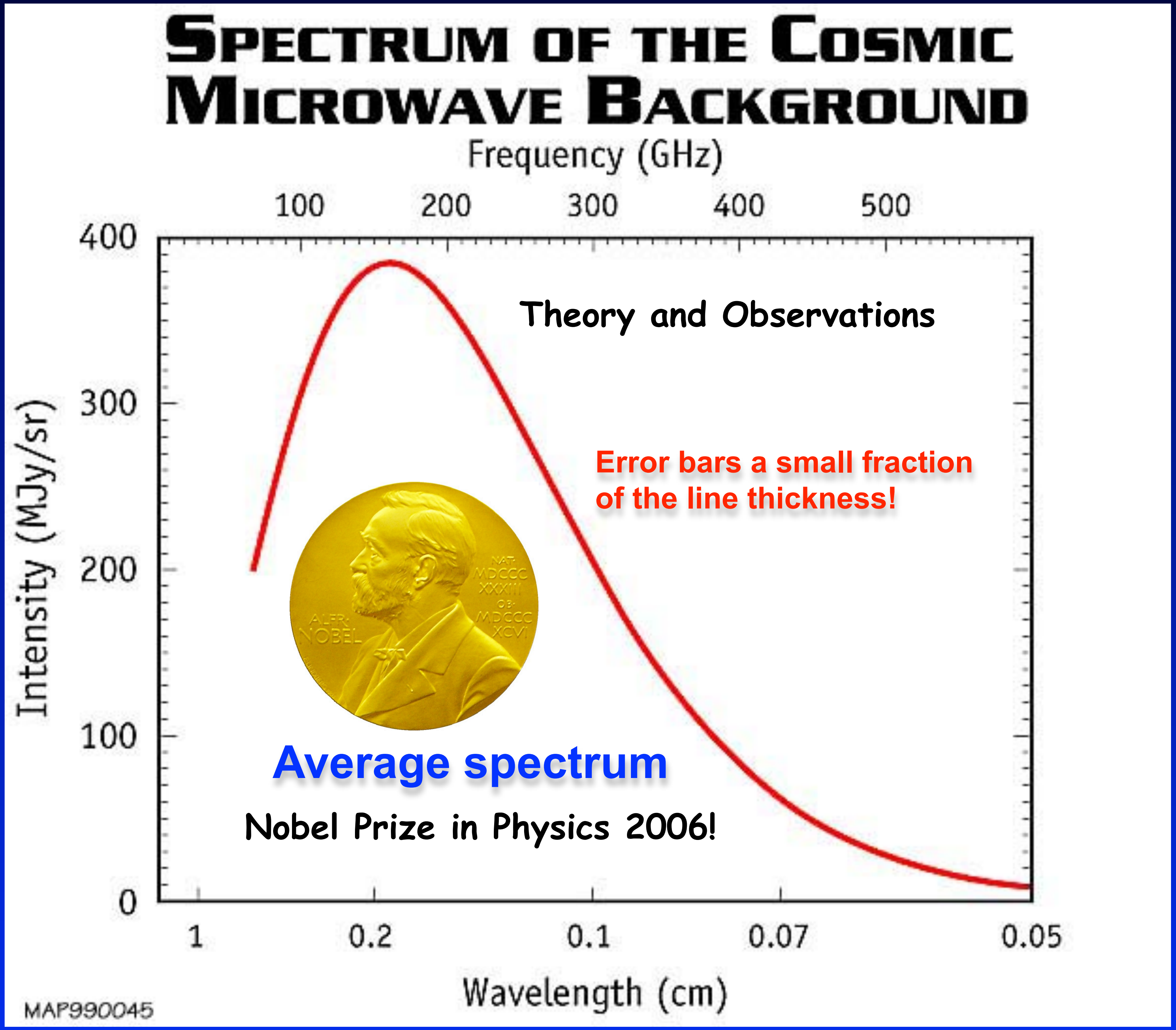


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|\,y\,| \leq 1.5 \times 10^{-5}$$

$$|\,\mu\,| \leq 9 \times 10^{-5}$$

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



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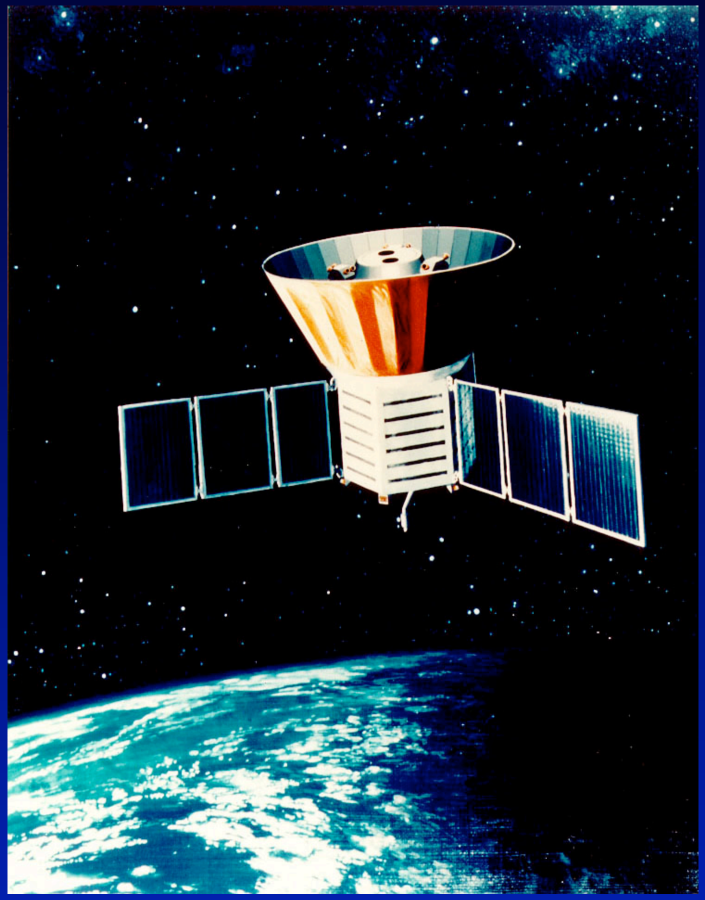

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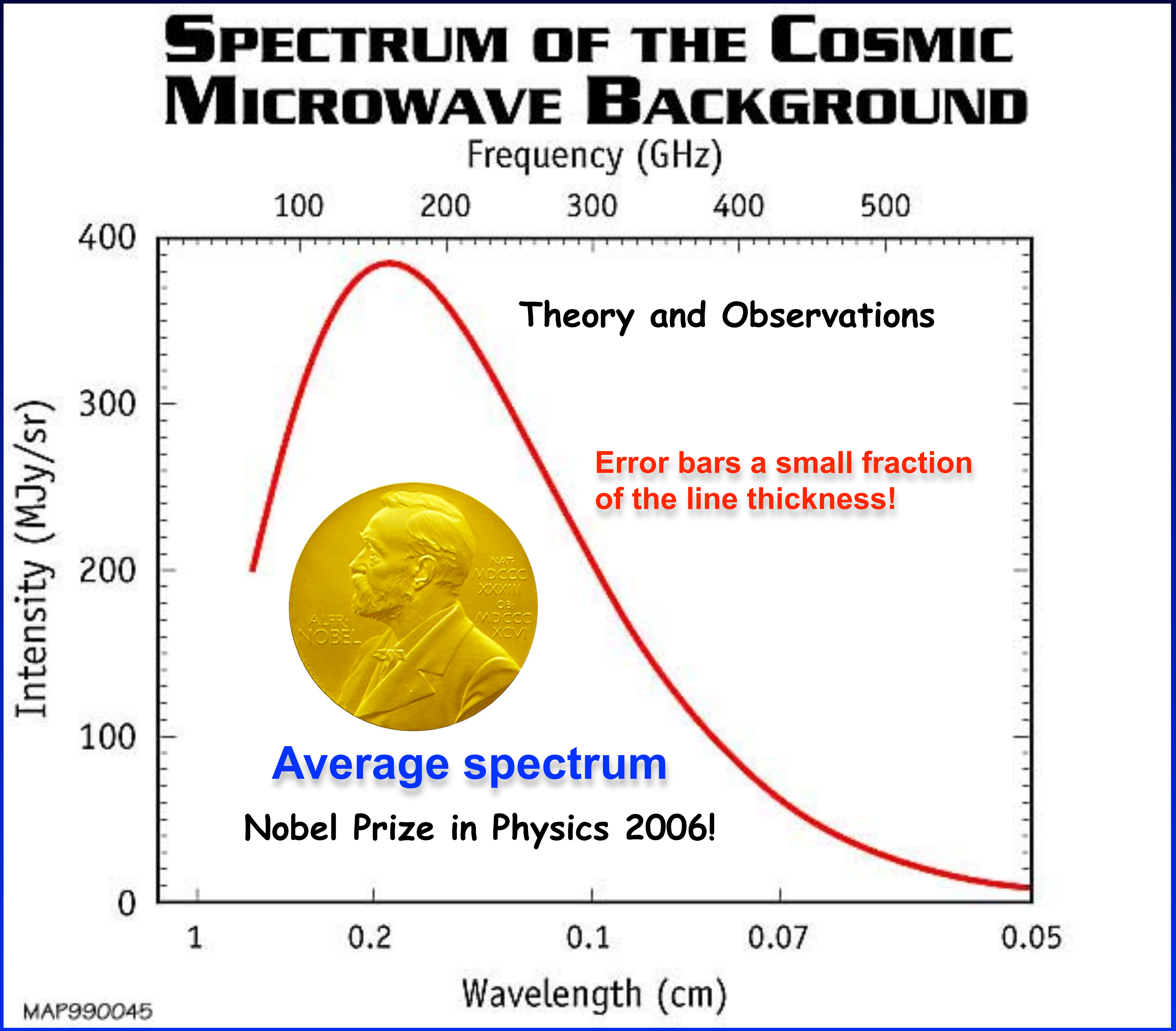


Only very small distortions of CMB spectrum are still allowed!

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 → $\Delta\varepsilon/\varepsilon \sim 13.6\text{ eV } N_b / (N_\gamma\, 2.7kT_r) \sim 10^{-9} - 10^{-8}$

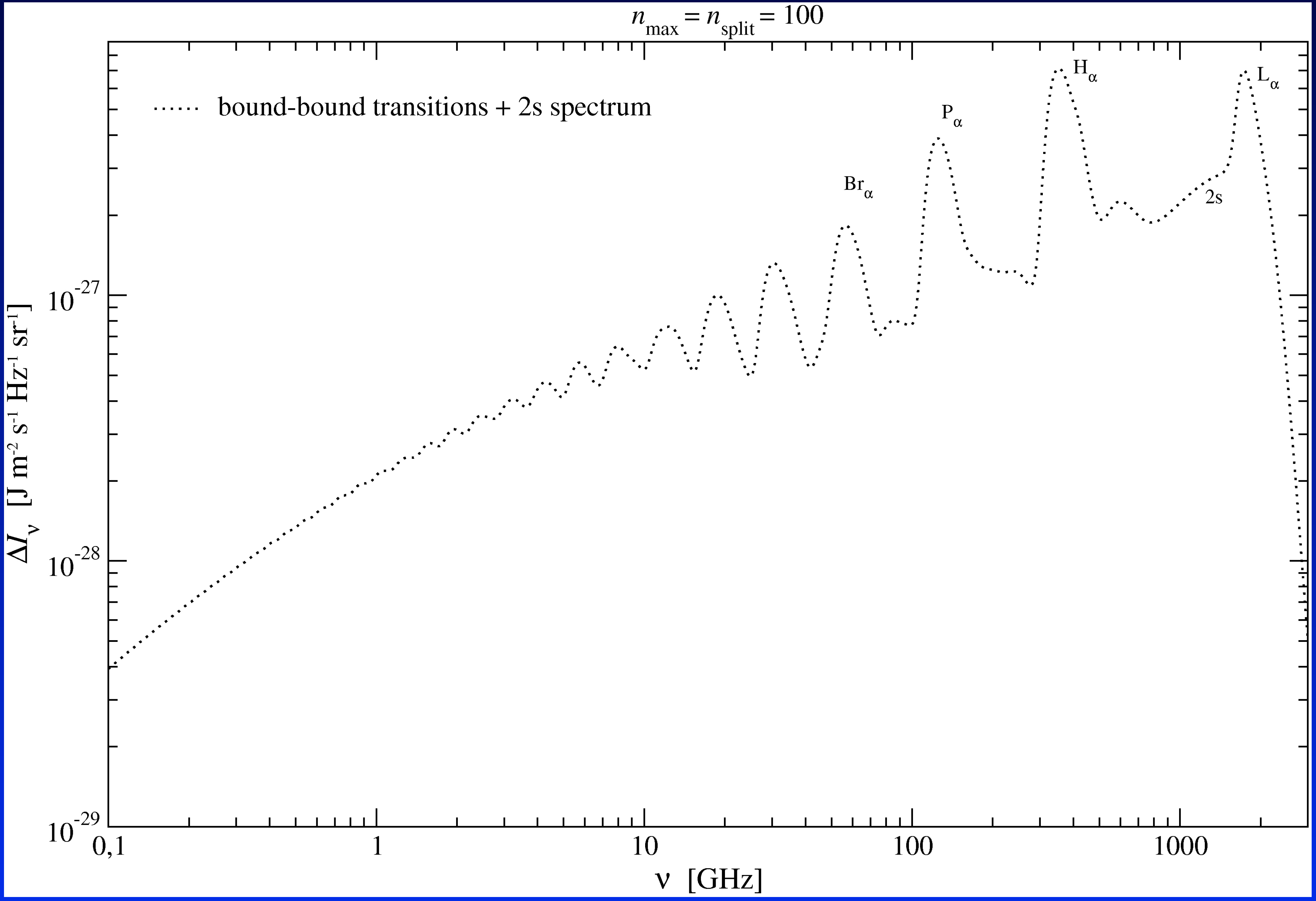
→ recombination occurs at redshifts $z < 10^4$

→ At that time the *thermalization* process doesn't work anymore!

→ There should be some *small* spectral distortion due to additional Ly-α and 2s-1s 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!

100-shell hydrogen atom and continuum
CMB spectral distortions

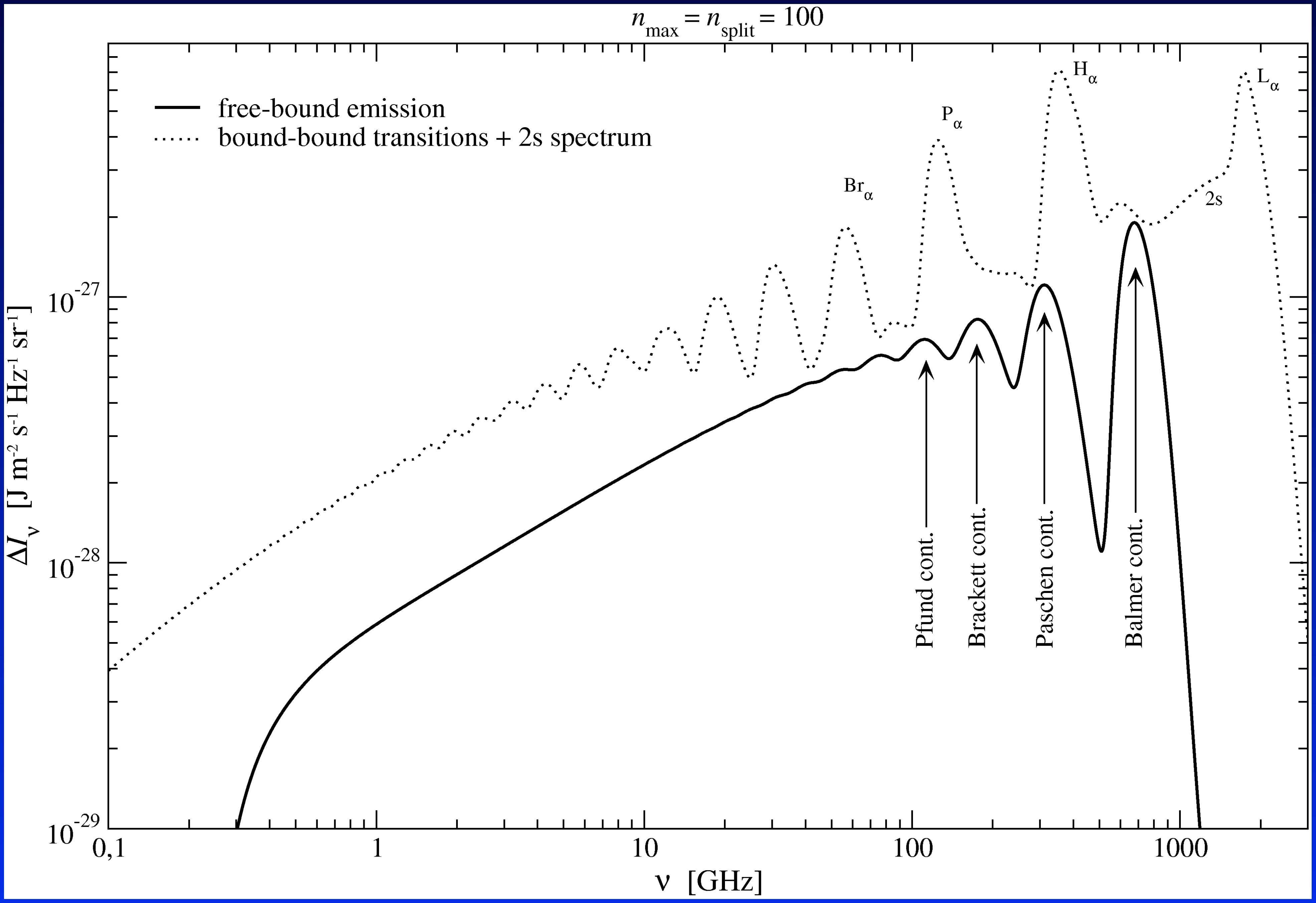


bound-bound & 2s:

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

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

100-shell hydrogen atom and continuum
CMB spectral distortions



bound-bound & 2s:

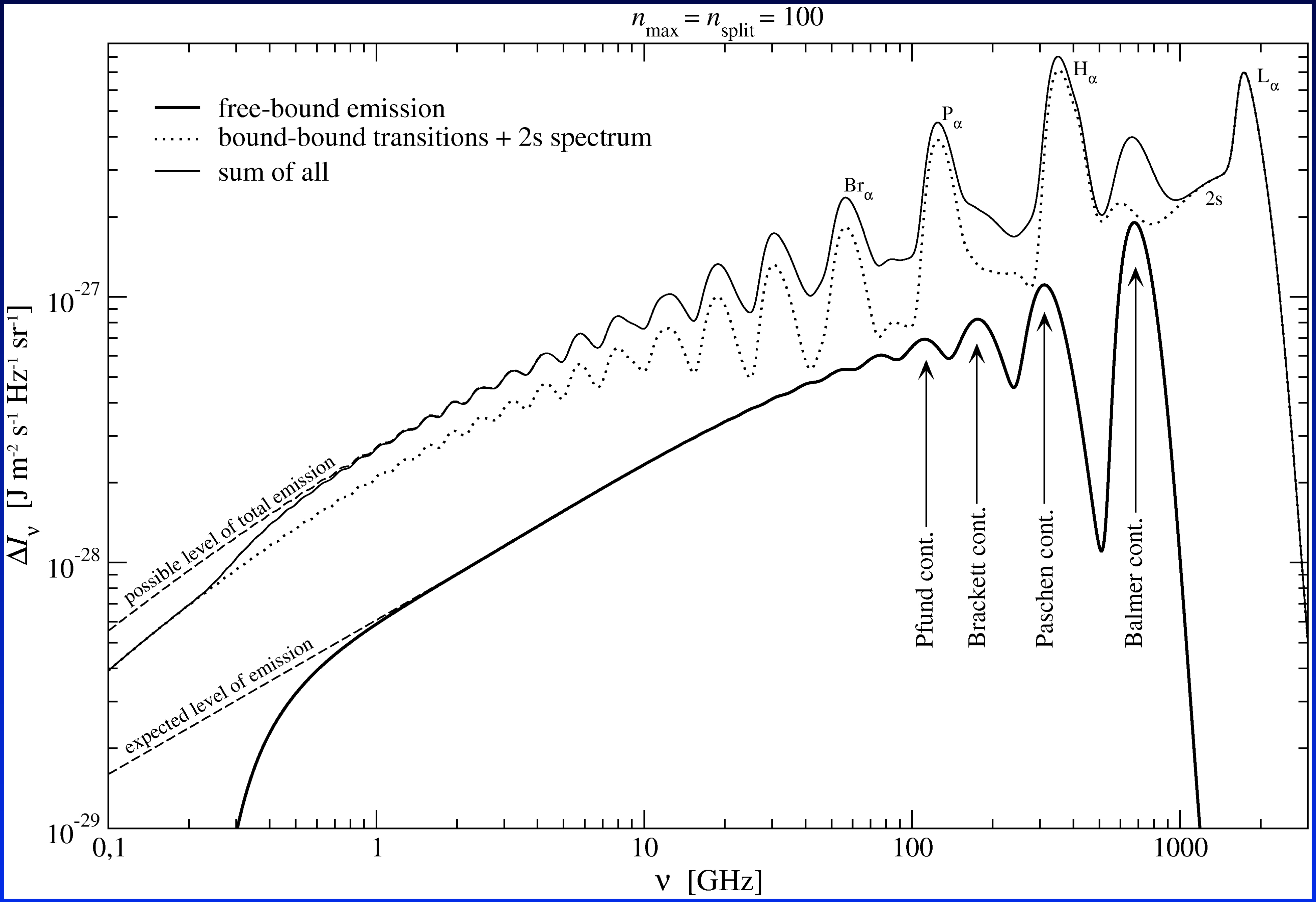
- at ν>1GHz: distinct features
- slope ~ 0.46

free-bound:

- only a few features distinguishable
- slope ~ 0.6

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

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

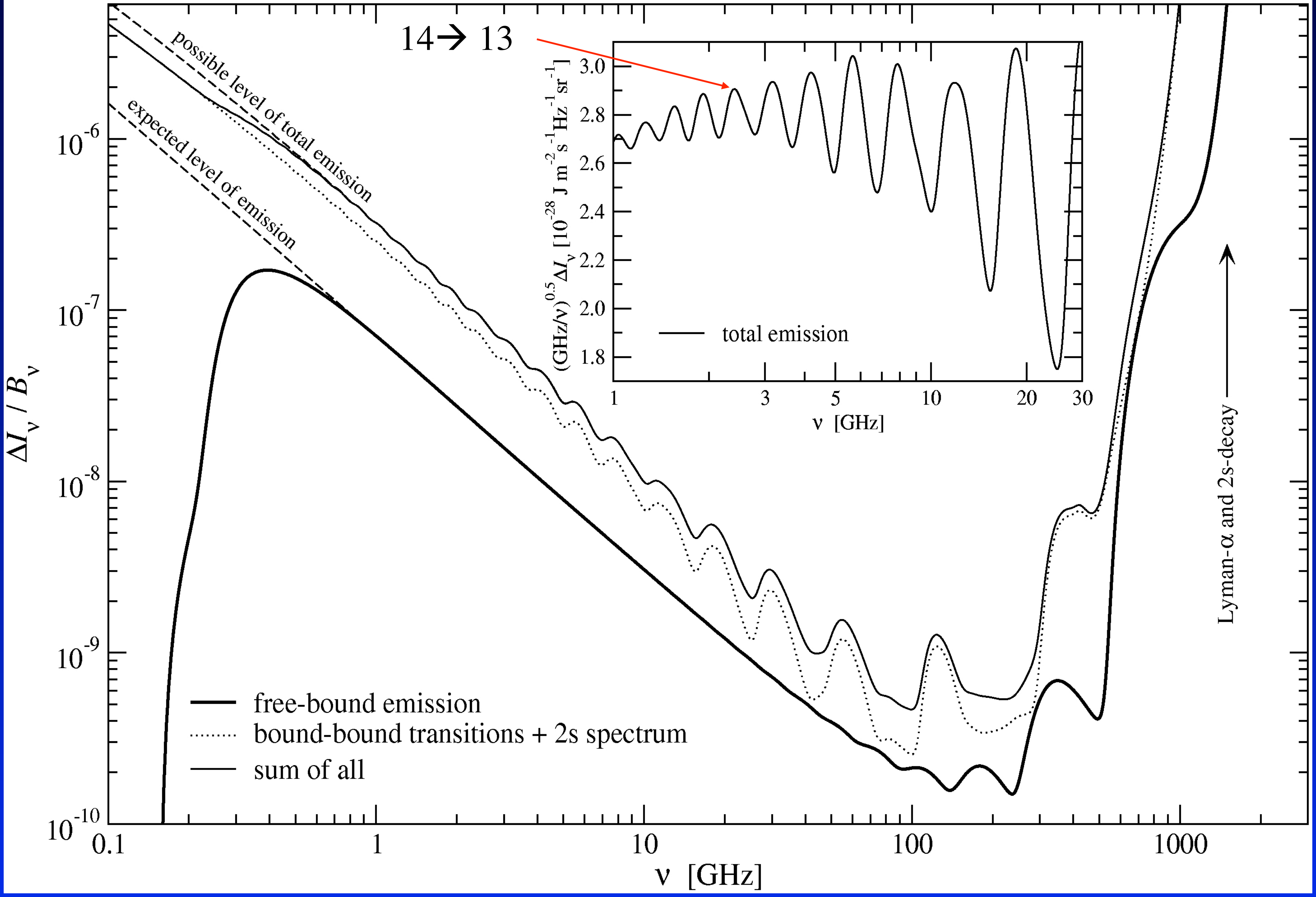
free-bound:

- 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
Relative distortions



Wien-region:

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

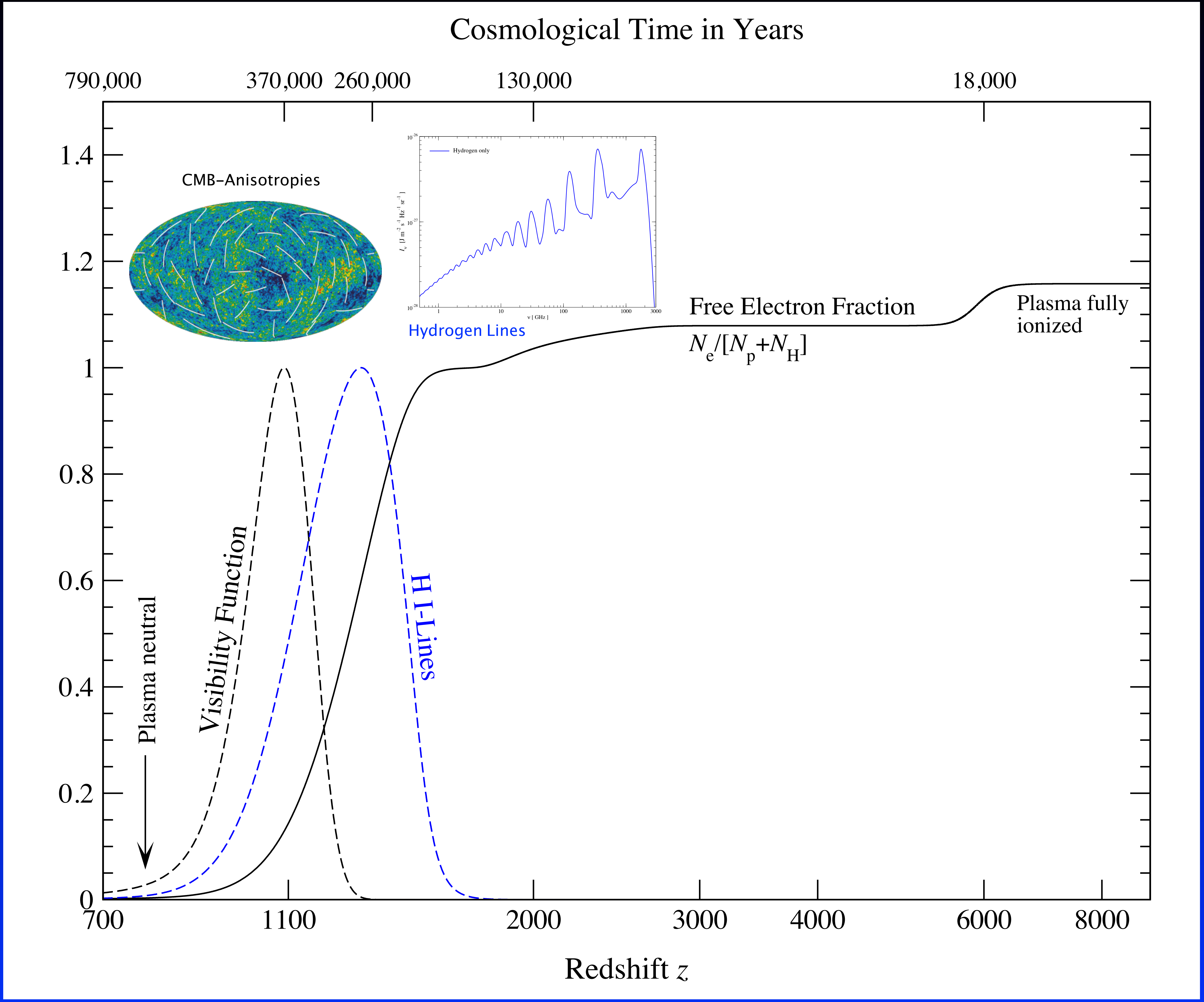
@ CMB maximum:

- 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*

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



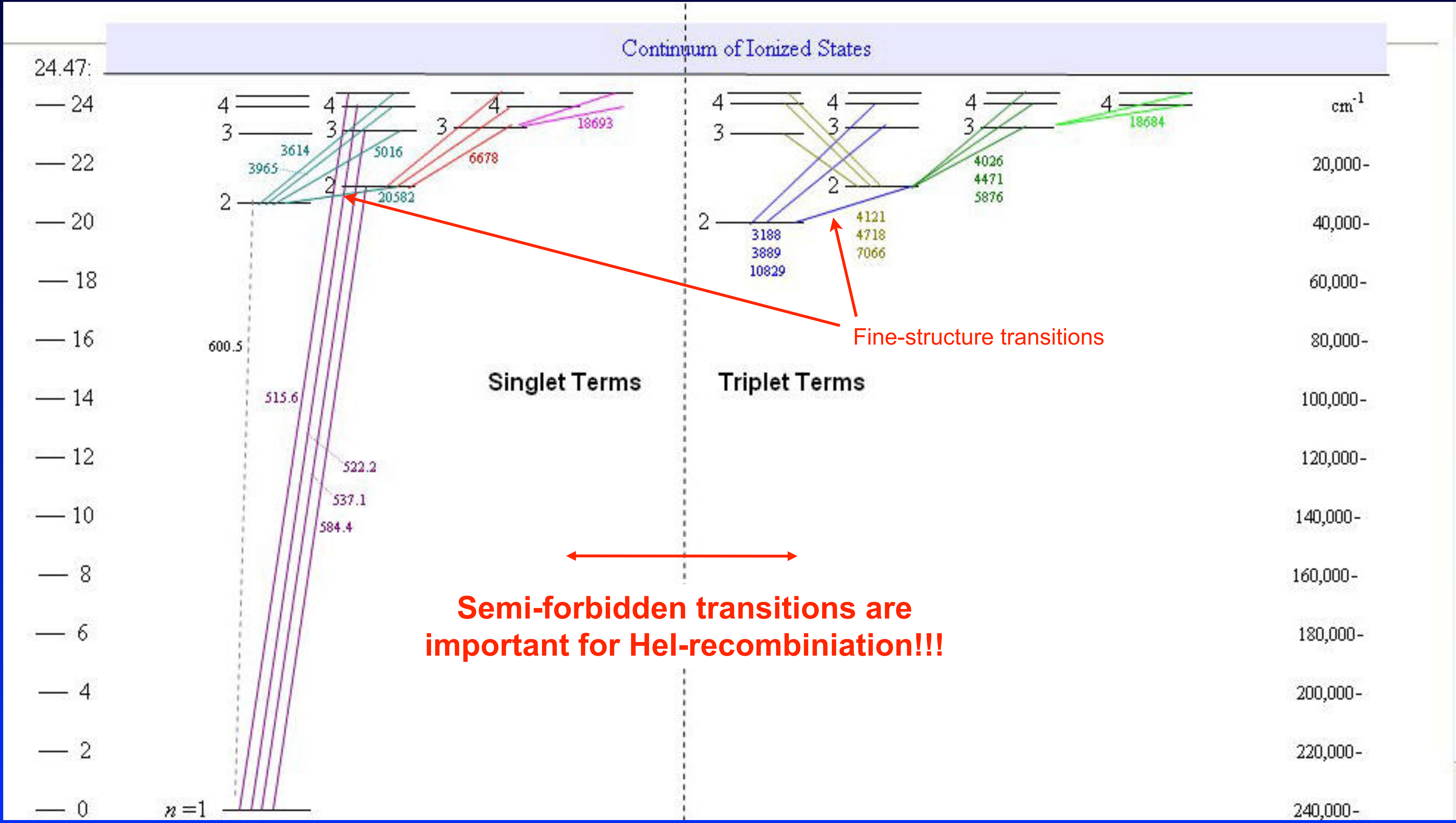
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Hydrogen only
Hydrogen Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
H I-Lines
700
1100
2000
3000
4000
6000
8000
Redshift z

What about the contributions from helium recombination?

- Nuclear reactions: Y_p~0.24 ←→ N_{HeI} / N_H ~8 %
  → expected photon number rather small
- ***BUT:***
  (*i*) *two* epochs of He recombination
  HeIII→HeII at *z*~6000 and HeII→HeI at *z*~2500
  (*ii*) Helium recombinations faster
  → more *narrow* features with *larger* amplitude
  (*iii*) non-trivial superposition
  → local amplification possible
  (*iv*) reprocessing of HeII & HeI photons by HeI and HI
  → increases the number of helium-related photons

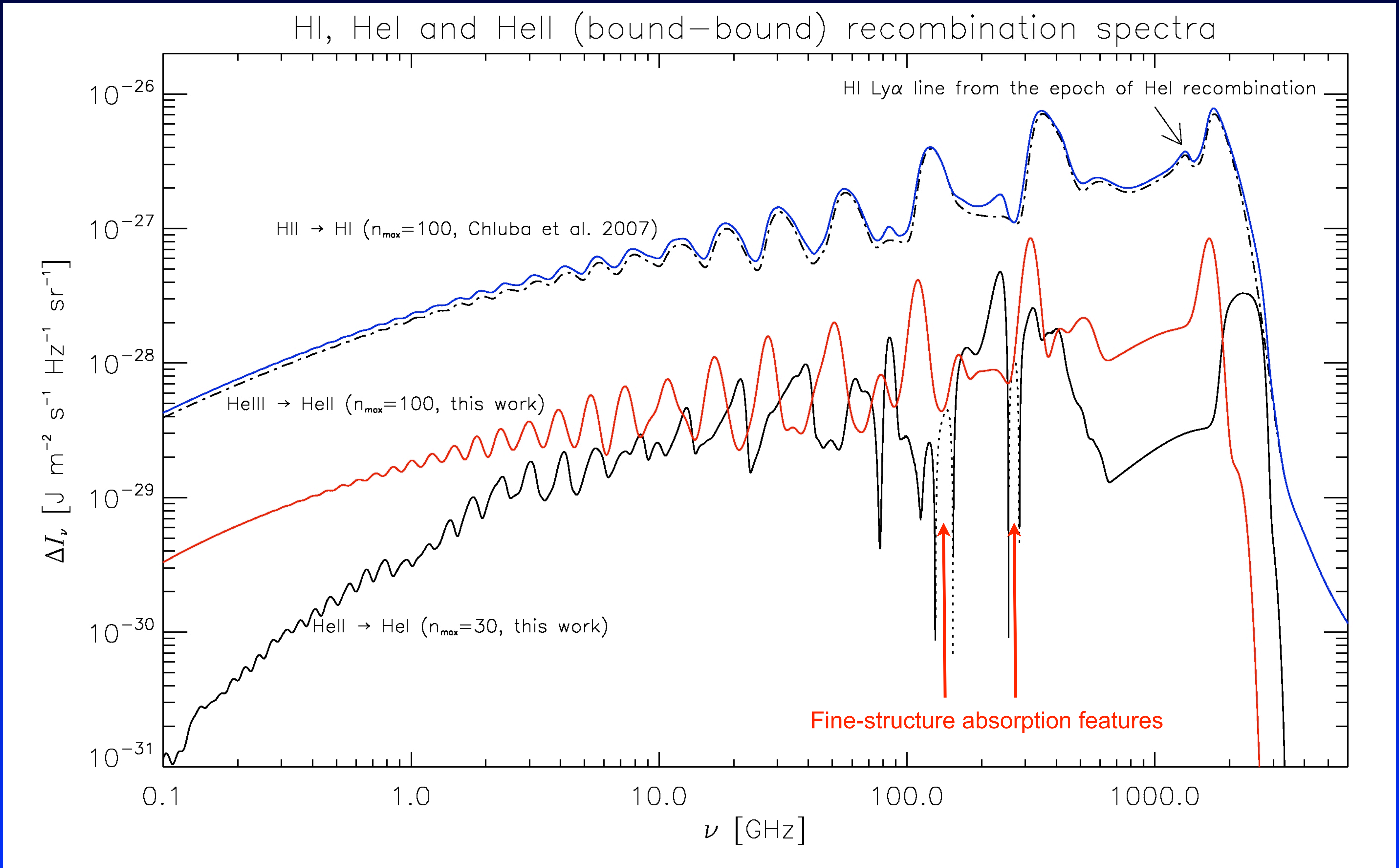
→ May opens a way to ***directly*** measure the primordial (pre-stellar!!!) helium abundance!

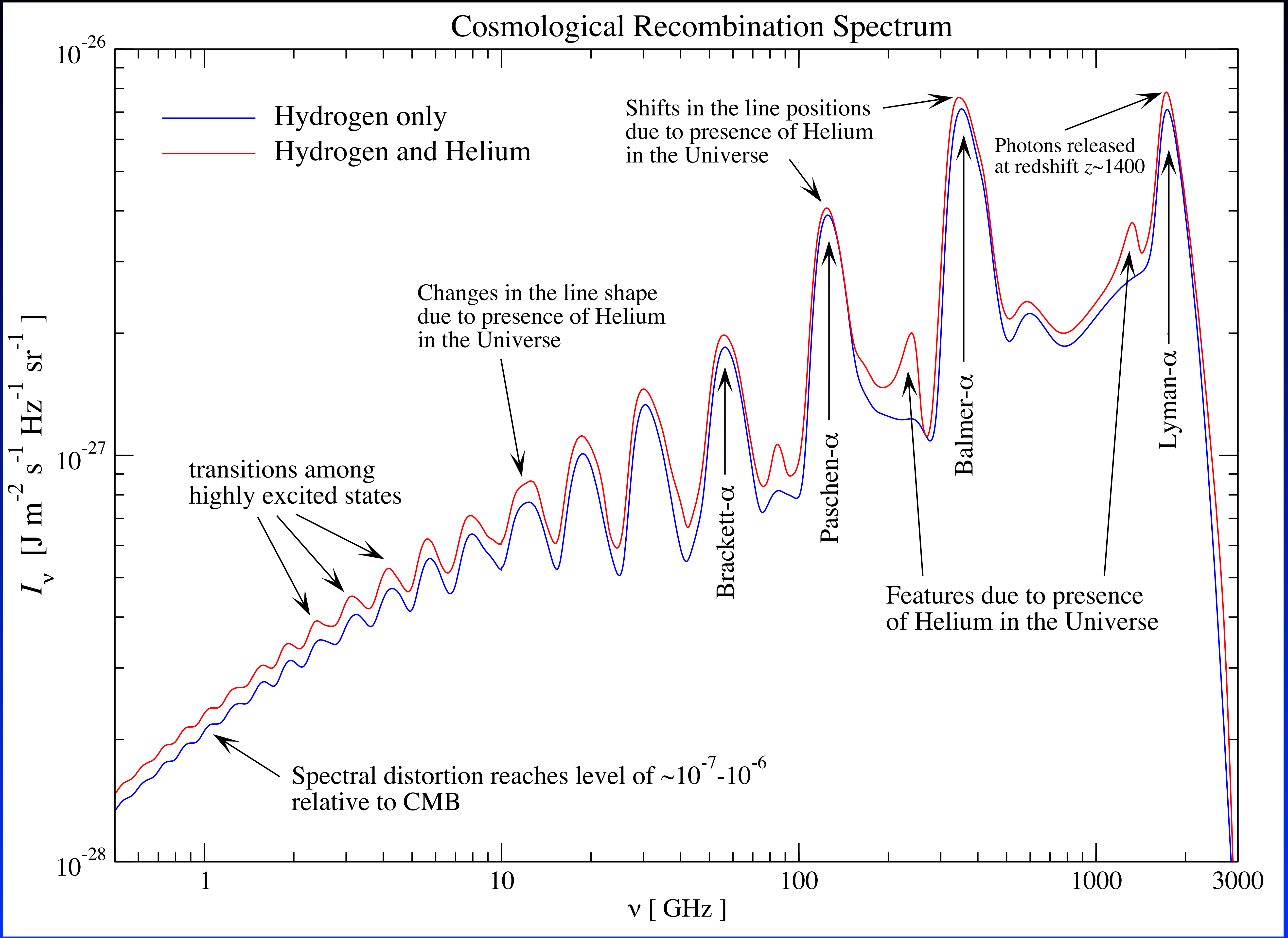
Grotrian diagram for neutral helium



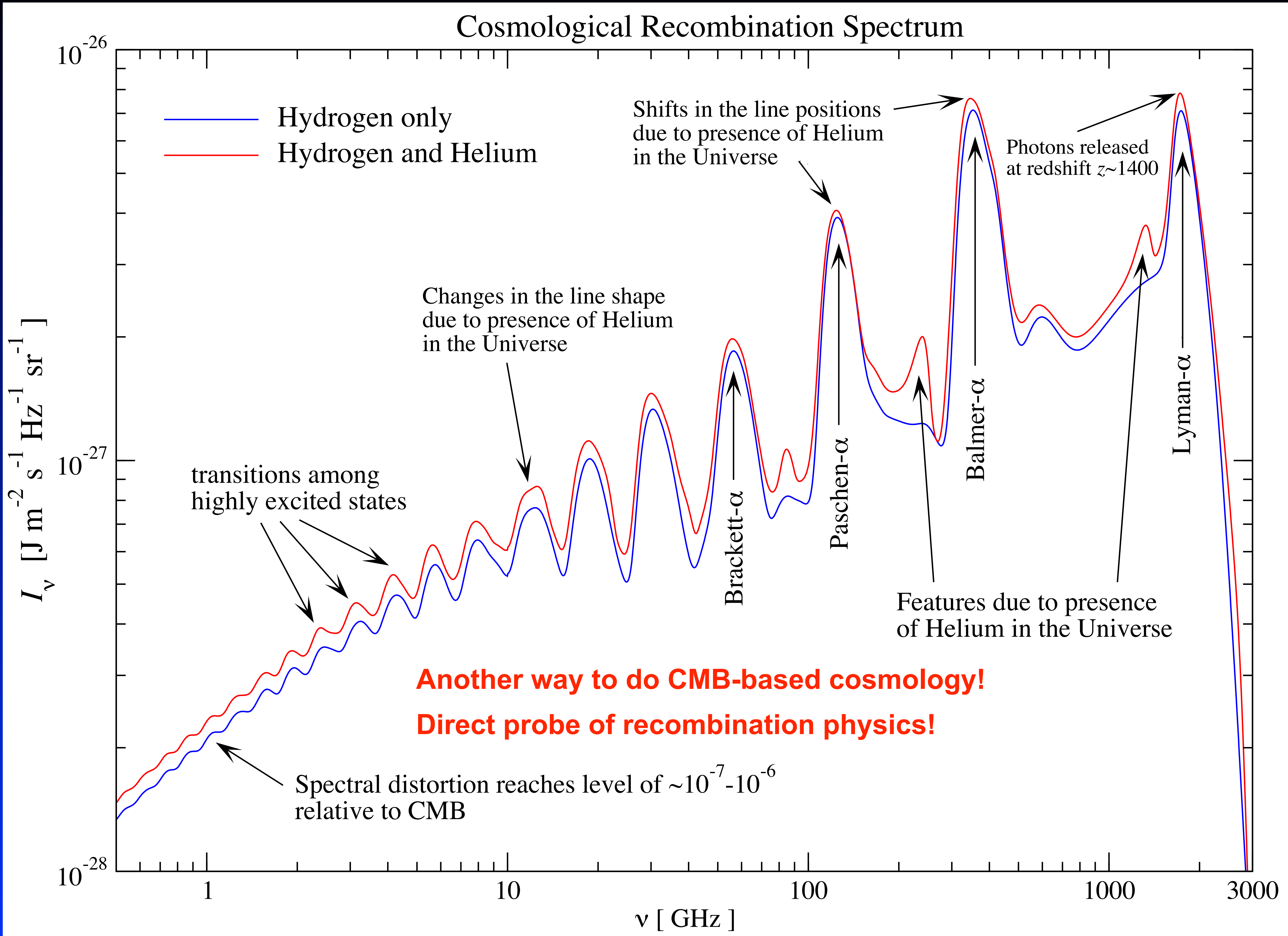
Semi-forbidden transitions are important for HeI-recombiniation!!!

Helium contributions to the cosmological recombination spectrum





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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Lyman-α
Features due to presence
of Helium in the Universe
Another way to do CMB-based cosmology!
Direct probe of recombination physics!
Spectral distortion reaches level of ~10^-7-10^-6
relative to CMB
I_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]
10^{-26}
10^{-27}
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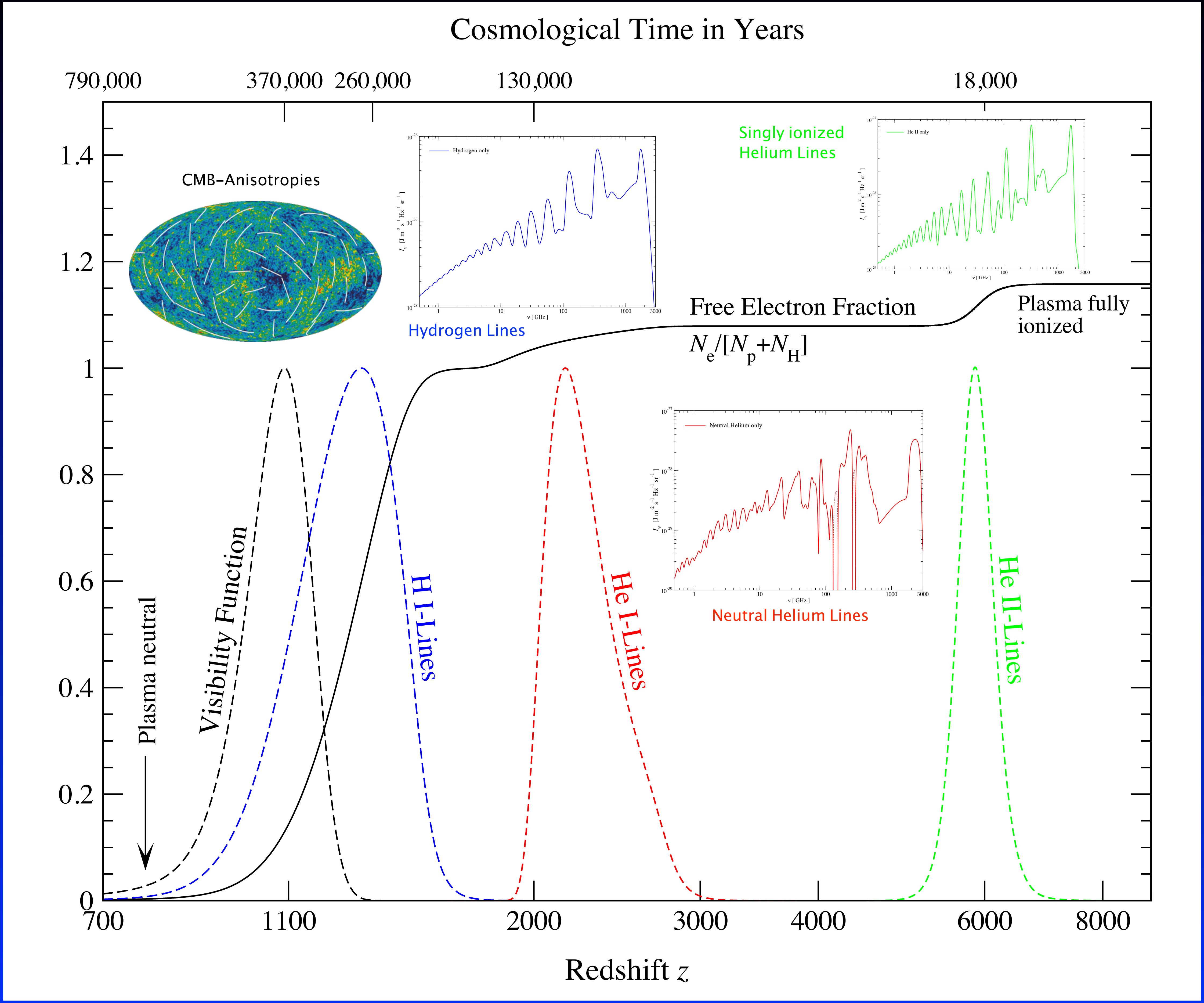
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Redshift z

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***

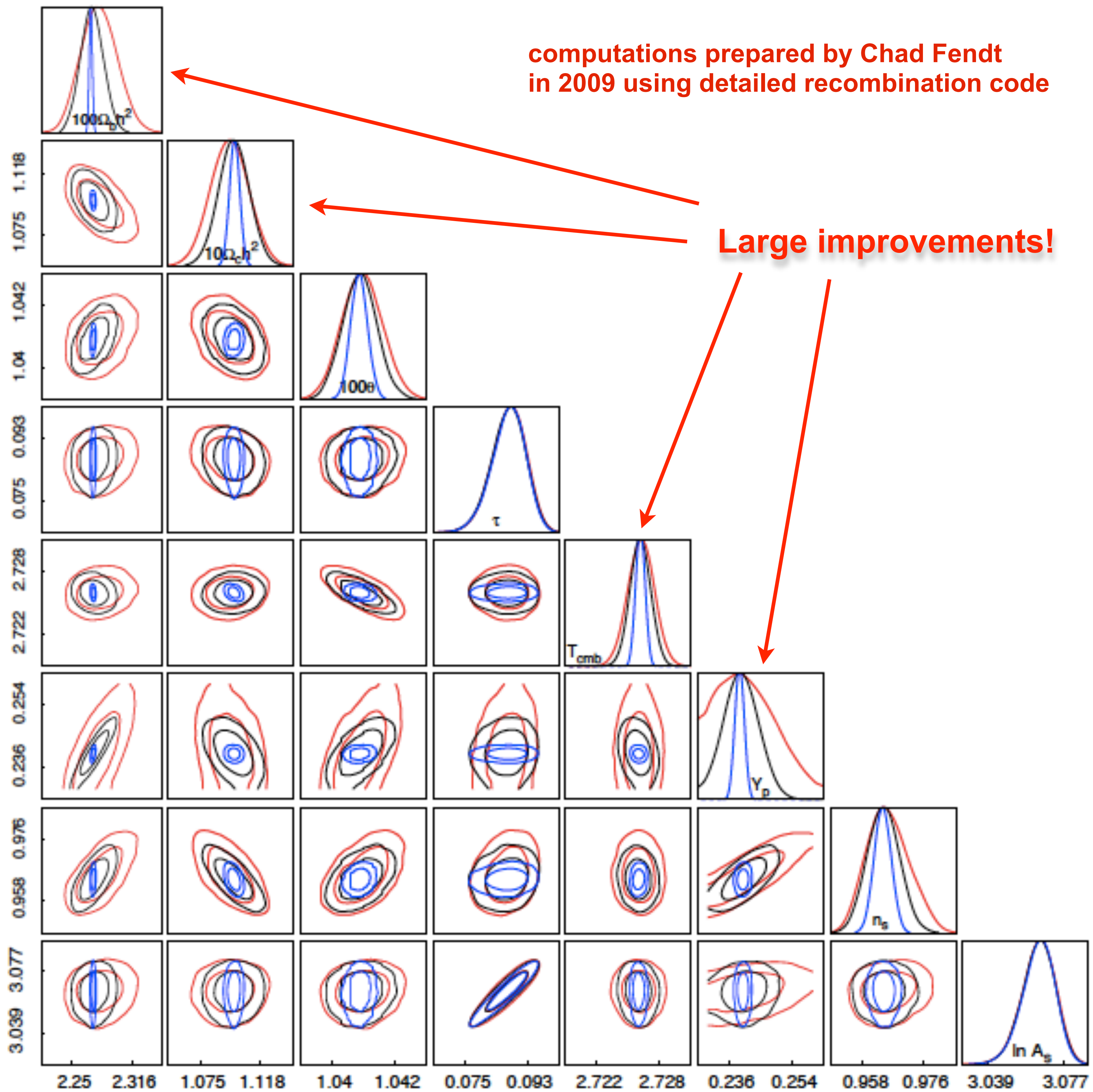

Figure 7.3: The 1 and 2 dimensional marginalized parameter posterior using the CMB spectral distortions. All three cases constrain the CMB power spectrum using a Gaussian likelihood based on Planck noise levels. The black line adds constraints due to a 10% measurement of the spectral distortions, while 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;

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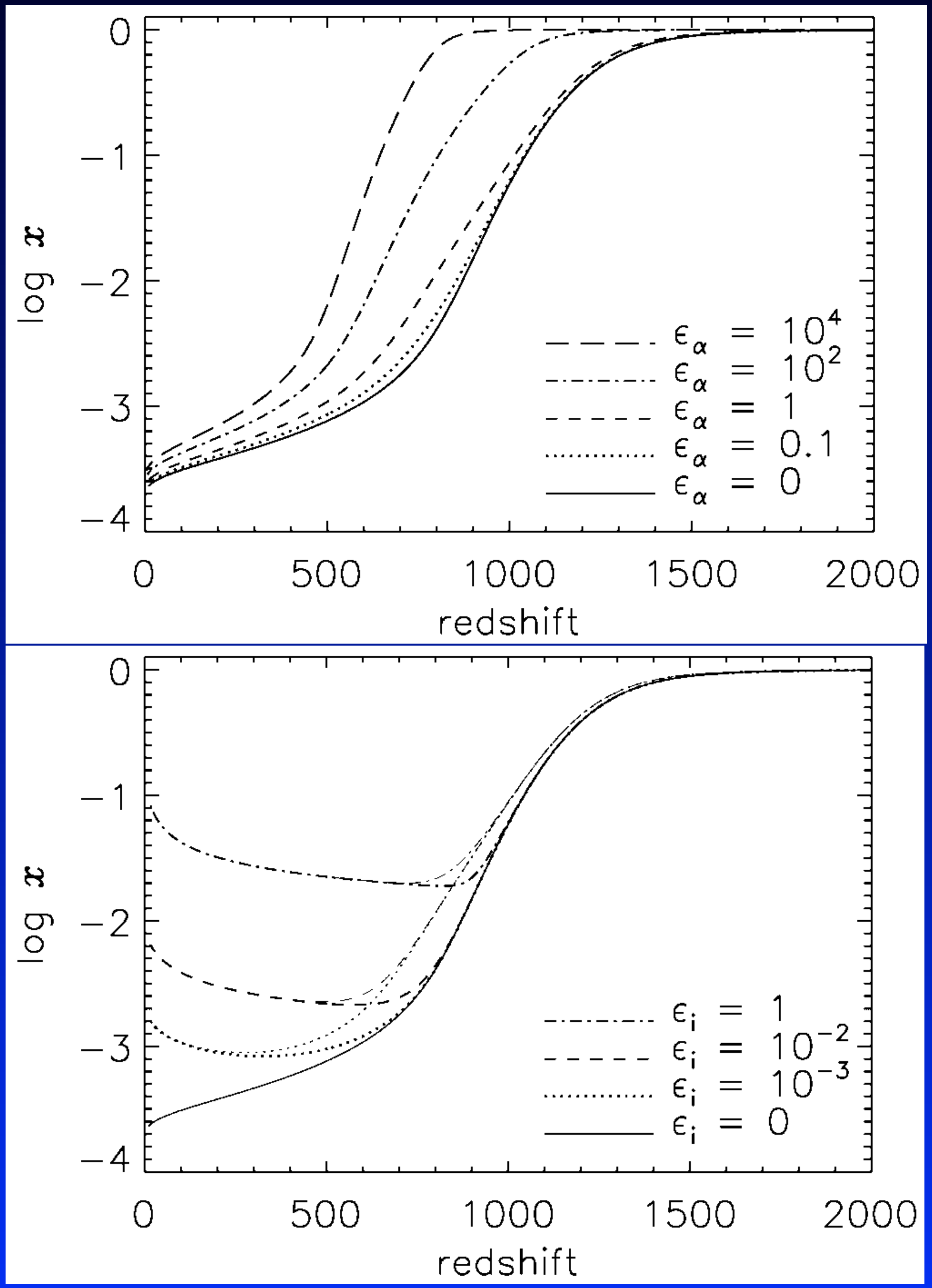
But is the *standard* cosmological recombination spectrum really interesting enough?

Extra Sources of Ionizations or Excitations

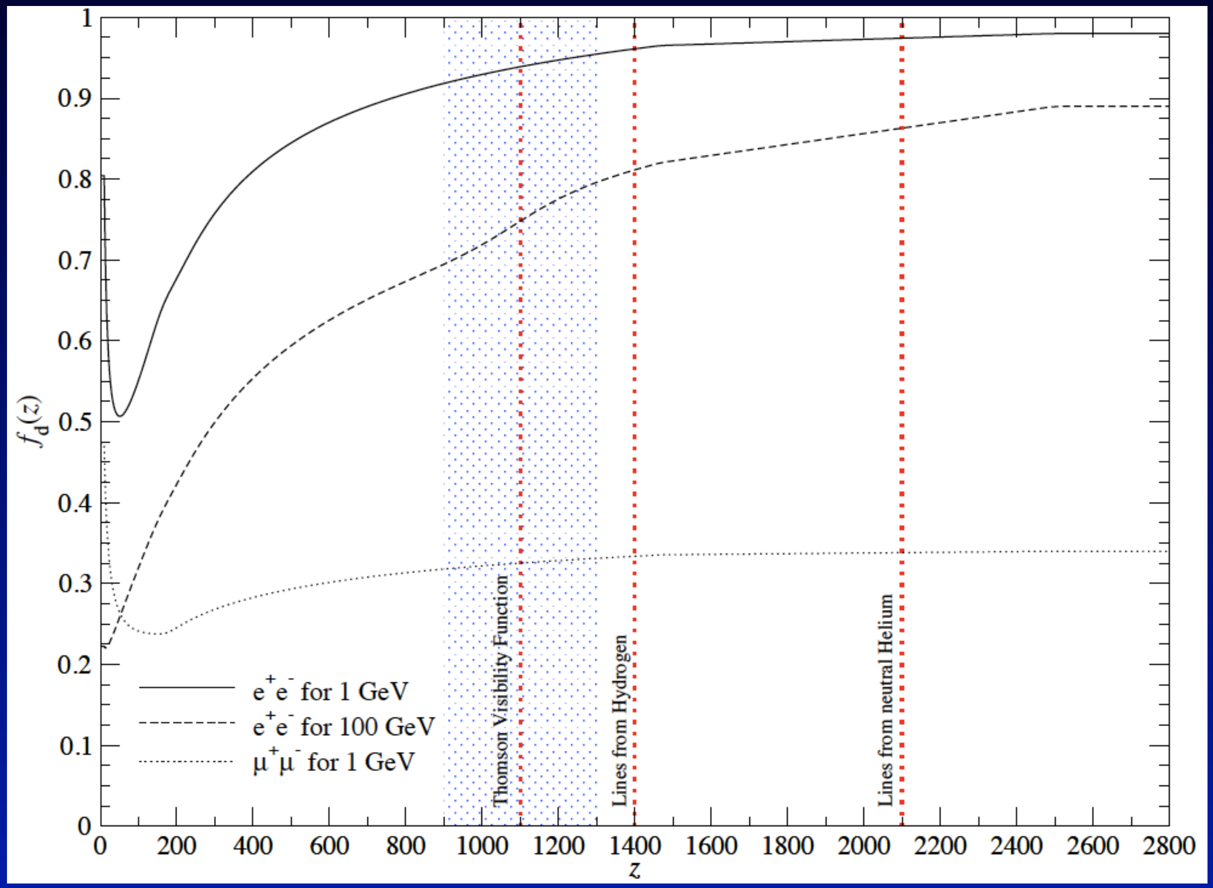


Peebles, Seager & Hu, ApJ, 2000

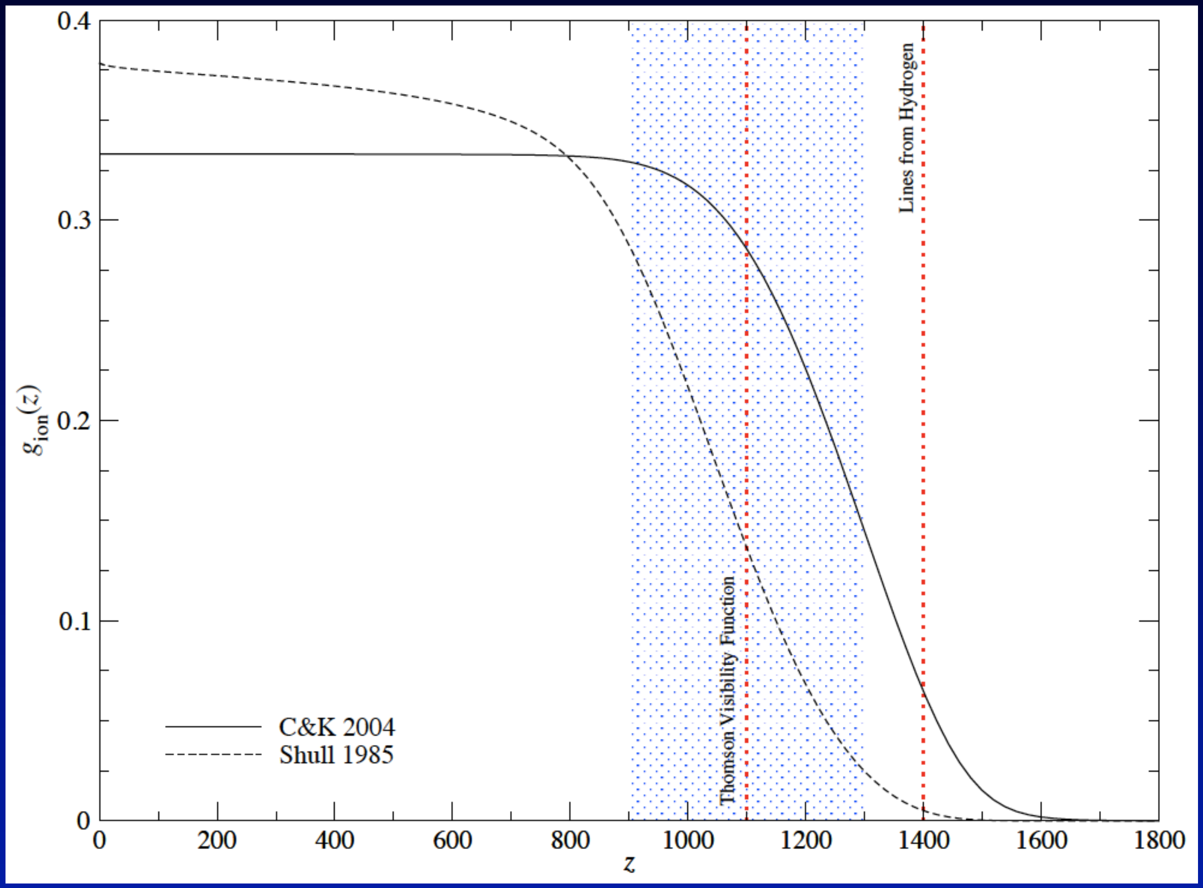
- ‚Hypothetical' source of extra photons parametrized by ε_α & ε_i
- Extra excitations ⇒ delay of Recombination
- Extra ionizations ⇒ affect 'freeze out' tail
- This affects the Thomson visibility function
- From WMAP ⇒ $\varepsilon_\alpha < 0.39$ & $\varepsilon_i < 0.058$ at 95% confidence level (Galli 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 sources at z~1000

Dark Matter Annihilation: Energy Branching Ratios



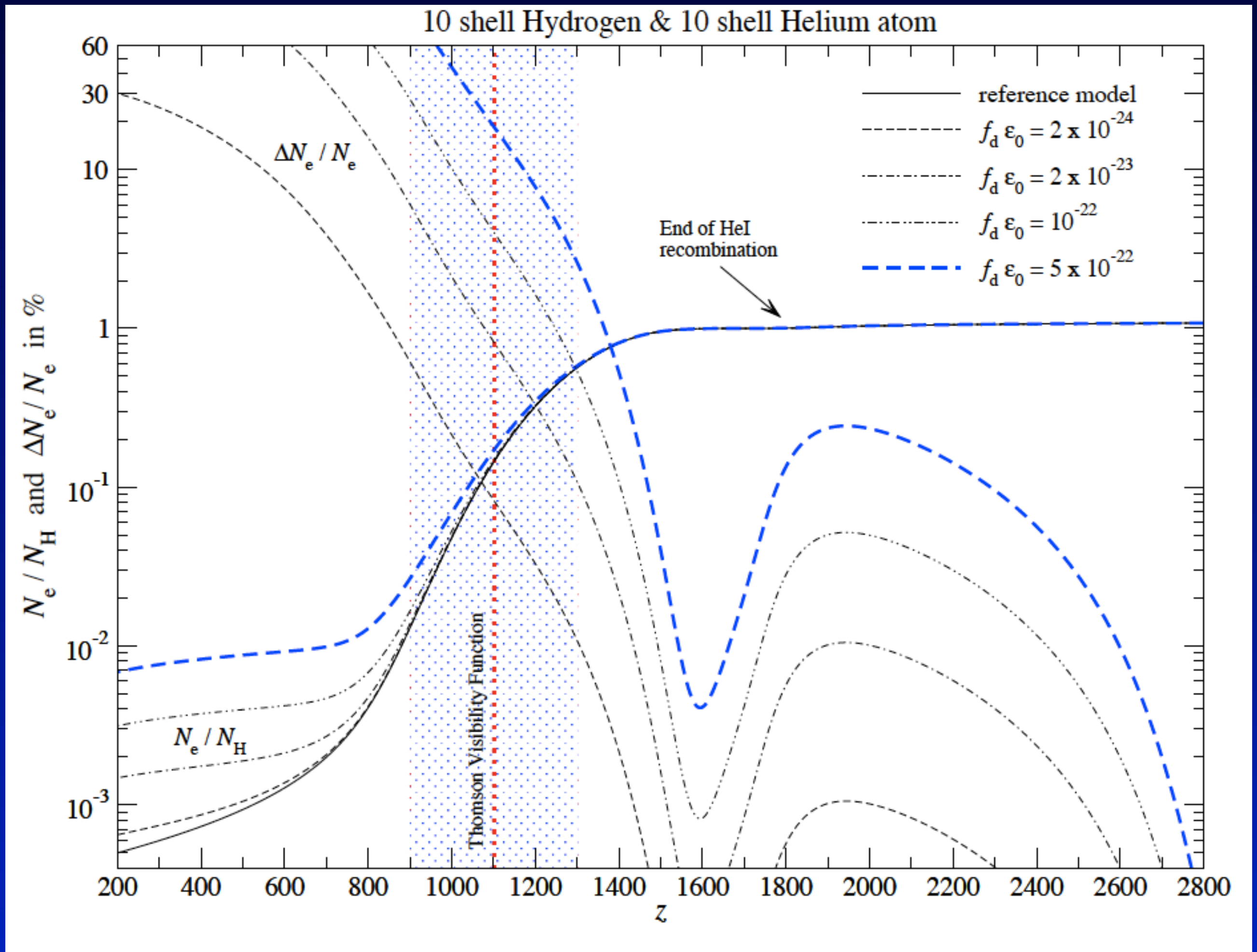
curves from Slatyer et al. 2009

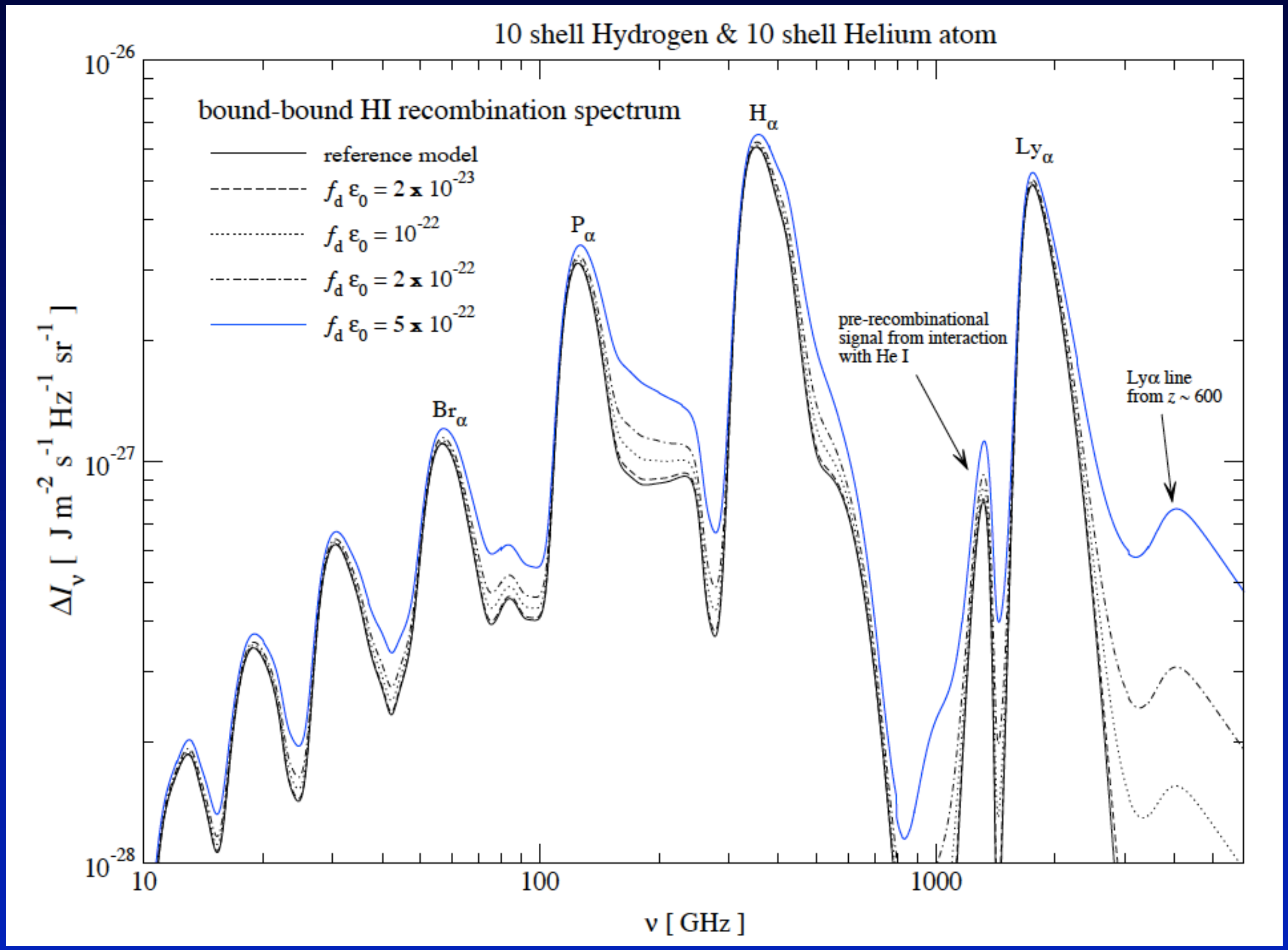


Efficiencies according to Chen & Kamionkowski, 2004 & Shull & van Steenberg 1985

- N^2 - dependence ⇒ dE/dt $\propto(1+z)^6$ and dE/dz $\propto(1+z)^{3...3.5}$
- only part of the energy is really deposited ($f_d \sim 0.1$)
- Branching into *heating* (100% at high z), *ionizations* and *excitations* (mainly during recombination)
- Branching depends on considered DM model

Dark Matter Annihilation: Effect on CMB Anisotropies and the Recombination Spectrum





- ‘Delay of recombination’
- Affects Thomson visibility function
- Possibility of Sommerfeld-enhancement
- Clumpiness of matter at z<100

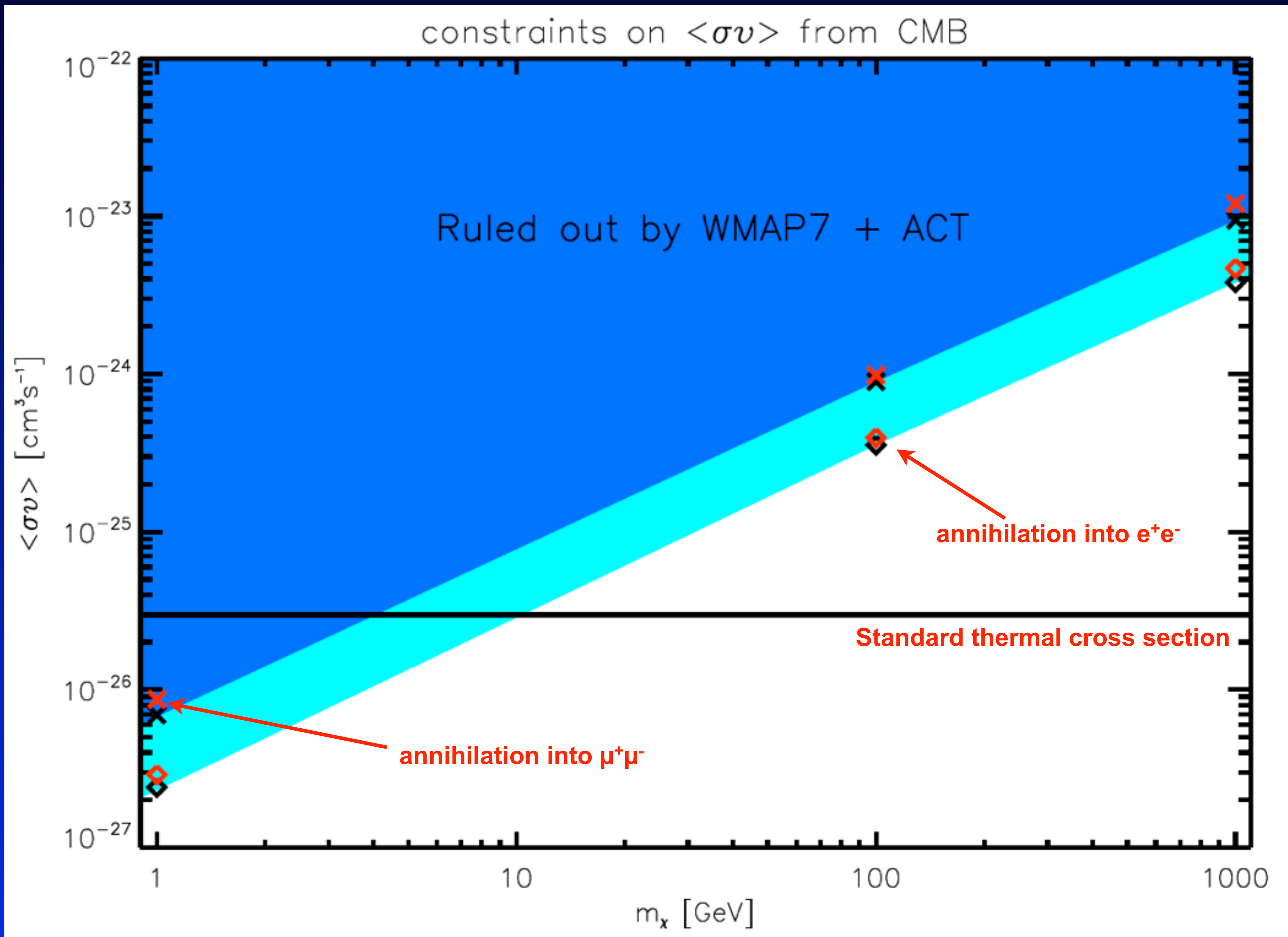
- Additional photons at all frequencies
- Broadening of spectral features
- Shifts in the positions

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

JC, 2009, arXiv:0910.3663

CMB limits on annihilation cross section

95% c.l.



- Planck limits still not as tight (polarization data)
- in the future factor of ~ 5-10 improvement possible
- constraints depend on DM model

Galli et al, 2011 (similar to Huetsi et al, 2011)

What could the recombination spectrum add?

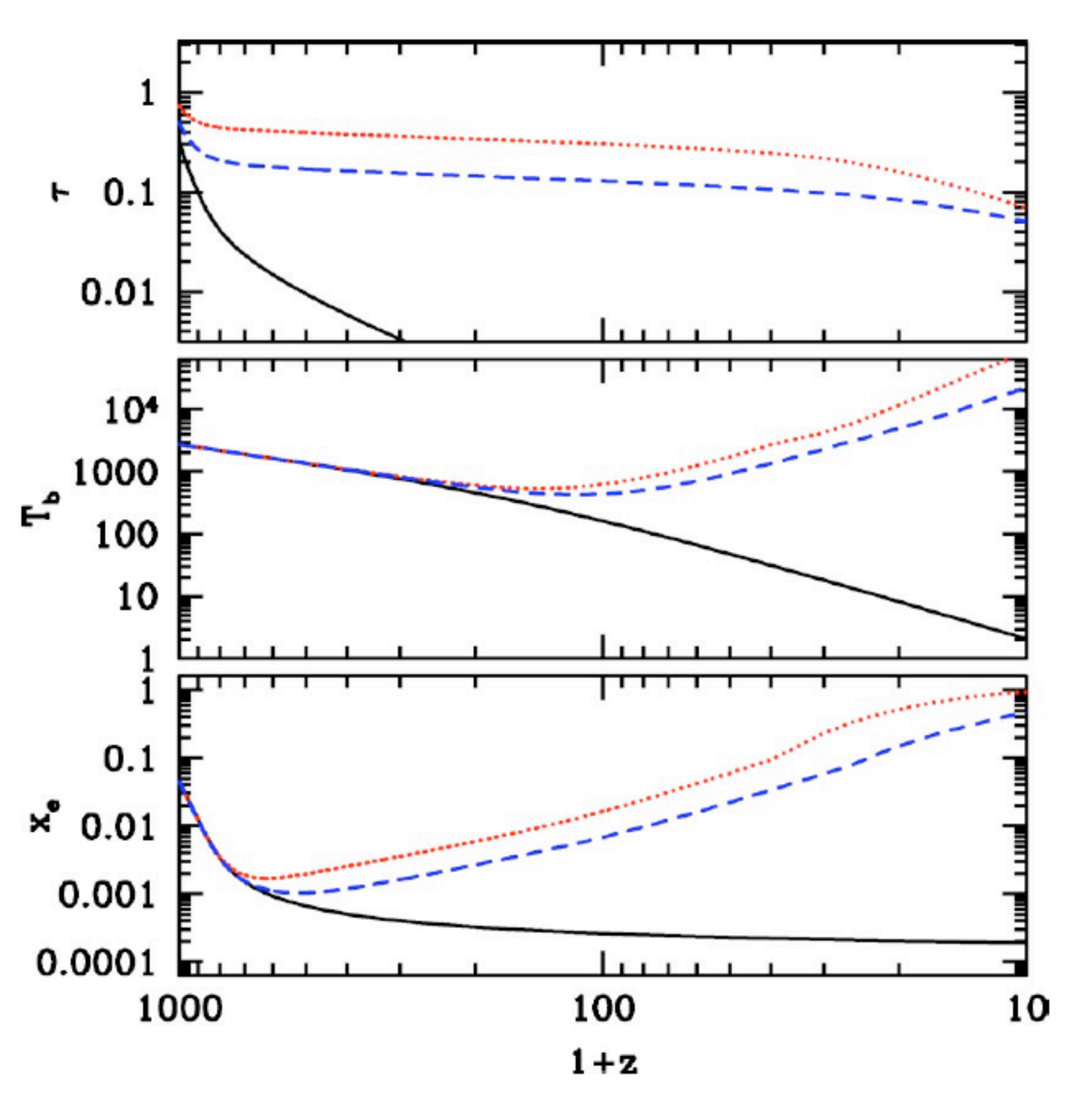
- WMAP constraints on possible dark matter annihilation efficiencies already very tight (e.g. see Galli et al. 2009; Slatyer et al. 2009, Huetsi et al., 2009, Huetsi et al. 2011, Galli et al. 2011)
  - absolute changes to CMB power spectra have to be small (~ 1%-5%)
  - changes to cosmological recombination spectrum are of similar order

What could the recombination spectrum add?

- WMAP constraints on possible dark matter annihilation efficiencies already very tight (e.g. see Galli et al. 2009; Slatyer et al. 2009, Huetsi et al., 2009, Huetsi et al. 2011, Galli et al. 2011)
  - 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
  - broad y and μ distortions will give another handle! (see tomorrow)

Decaying particle during & after recombination



Chen & Kamionkowski, 2004

- Modify recombination history
- this changes Thomson visibility function and thus the CMB temperature and polarization power spectra
- ⇒ CMB anisotropies allow

  probing particles with lifetimes $\gtrsim 10^{12}$ sec
- CMB spectral distortions provide complementary probe! (more tomorrow)

What would we actually learn by doing such hard job?

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→ ***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***

If something unexpected or non-standard happened:

→ ***non-standard thermal histories should leave some measurable traces***

→ ***direct way to measure/reconstruct the recombination history!***

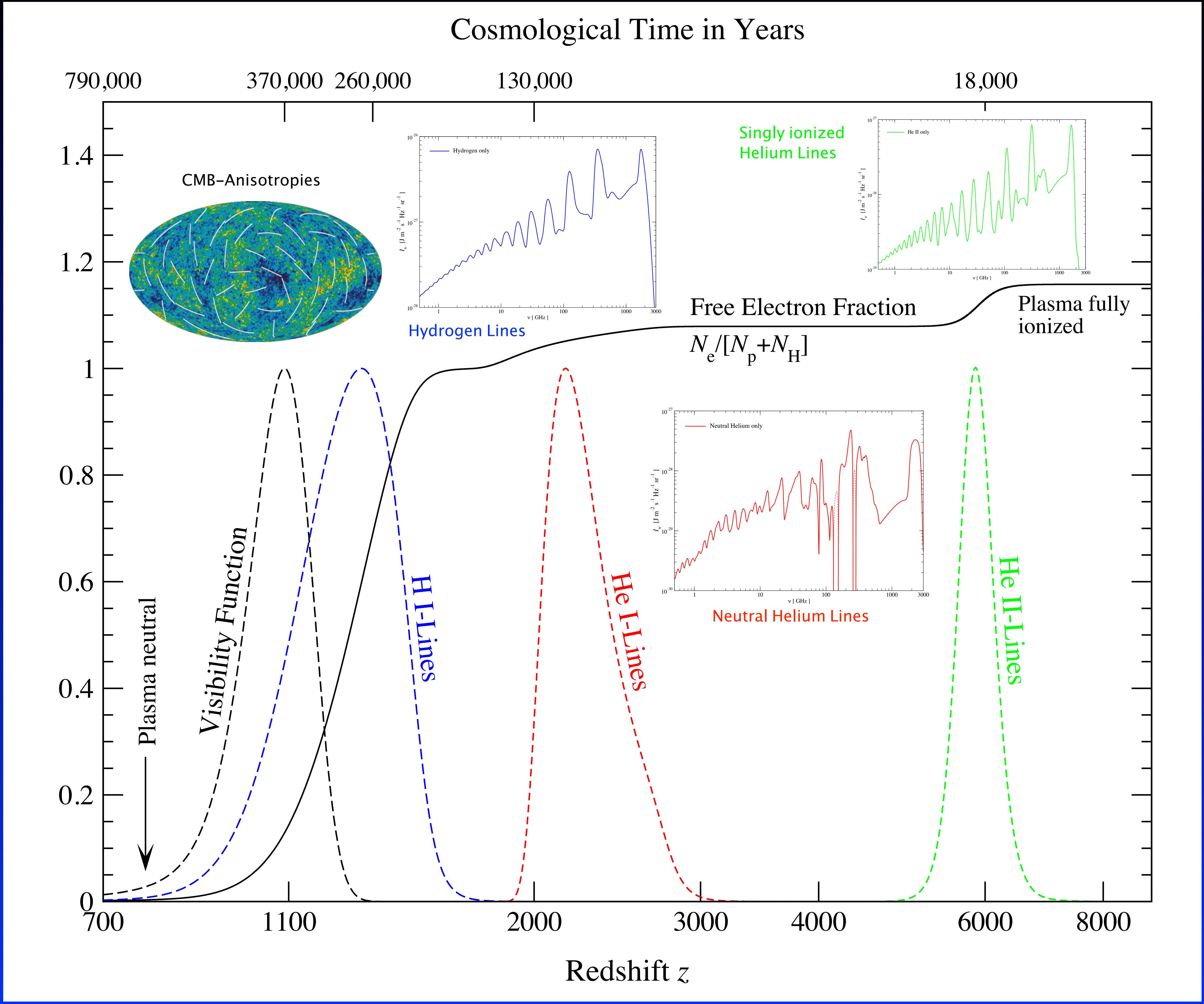
→ **possibility to distinguish *pre-* and *post-recombination y*-type distortions**

→ ***sensitive to energy release during recombination***

→ **variation of fundamental constants**

Conclusions

- CMB anisotropies provide an *outstanding confirmation* of ΛCDM cosmology
- The data has become so precise that one can start *testing SBBN* and *non-standard extensions* of ΛCDM
- The *recombination process* is crucial for the interpretation of the data at this level of precision
- Future observation of the *cosmological recombination radiation* will allow confirming the recombination model
- If something non-standard happened around z~1000, then this should show up in the recombination spectrum, allowing us to *break degeneracies* and providing *independent confirmation*



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