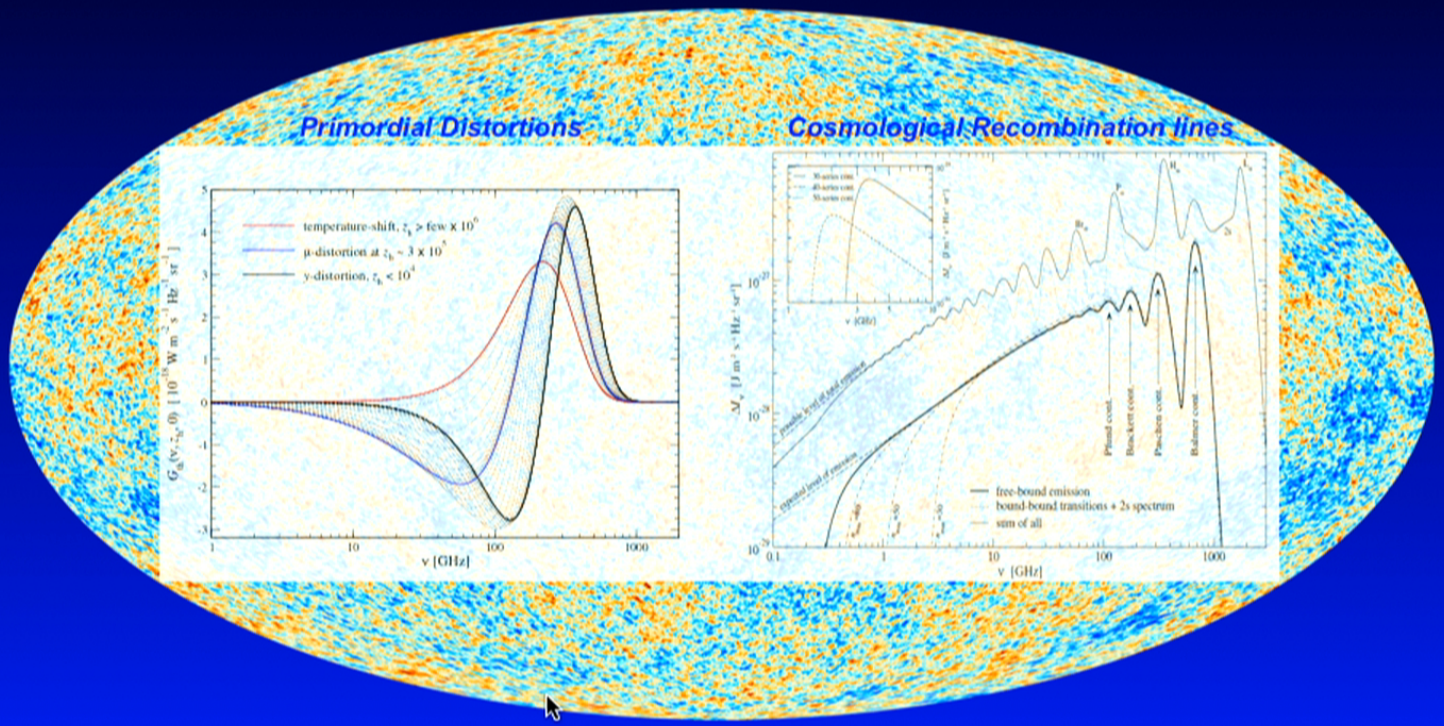
Title: CMB spectral distortions within LCDM

Date: May 12, 2016 11:00 AM

URL: http://pirsa.org/16050024

Abstract: Spectral distortions of the CMB provide a powerful new probe of early Universe processes. Even if so far no average spectral distortion has been seen, LCDM does predict several signals that are within reach of current technology. In this talk, I will give a broad brush overview of our most recent understanding of the formation and evolution of distortions in the early Universe, highlighting guaranteed LCDM signals and what we hope to learn from them about the Universe we live in.

CMB Spectral Distortions within ΛCDM



Jens Chluba

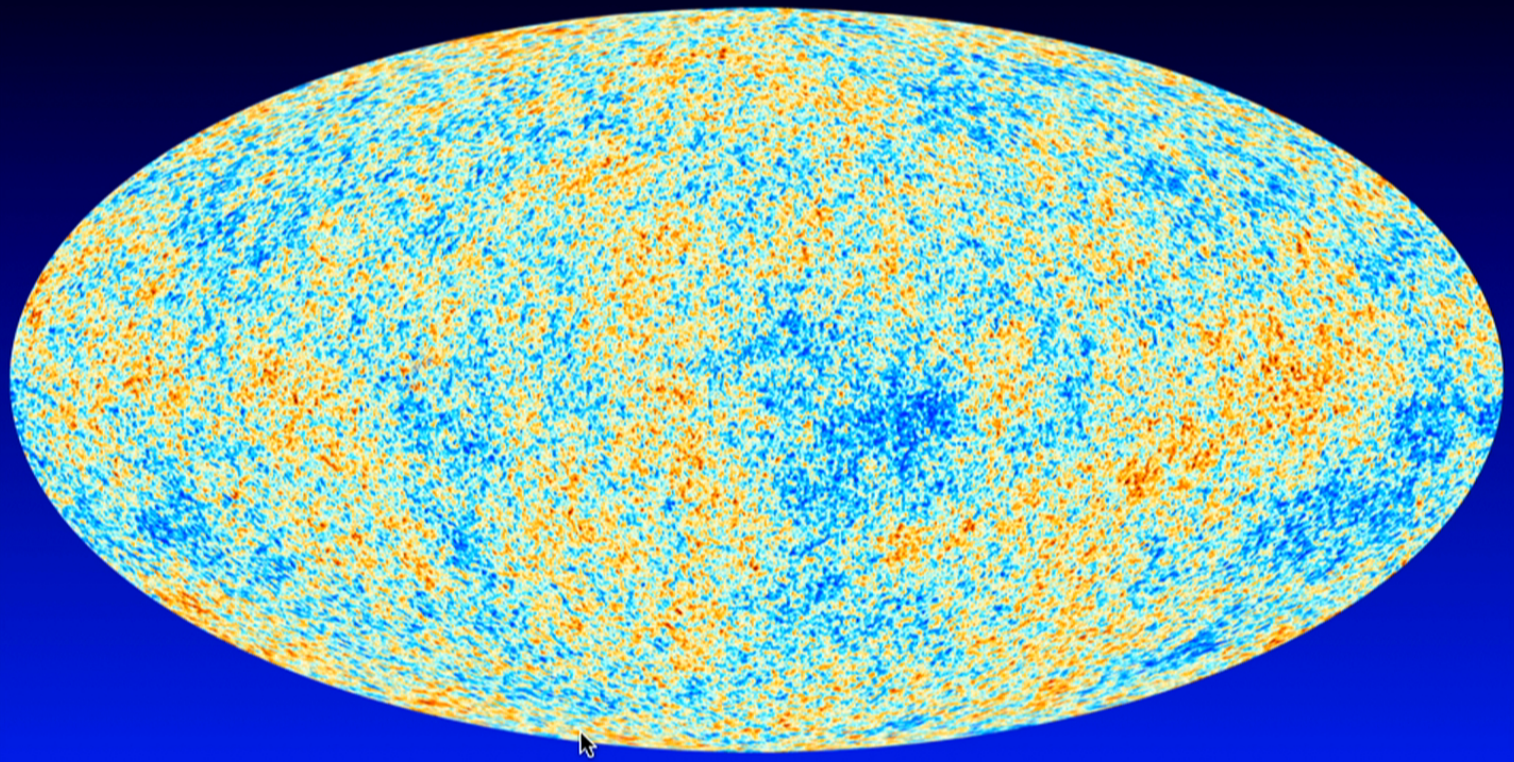
MANCHESTER 1824
The University of Manchester

Cosmology & Gravitation Seminar

Perimeter Institute, Waterloo, May 12th, 2016

THE ROYAL SOCIETY

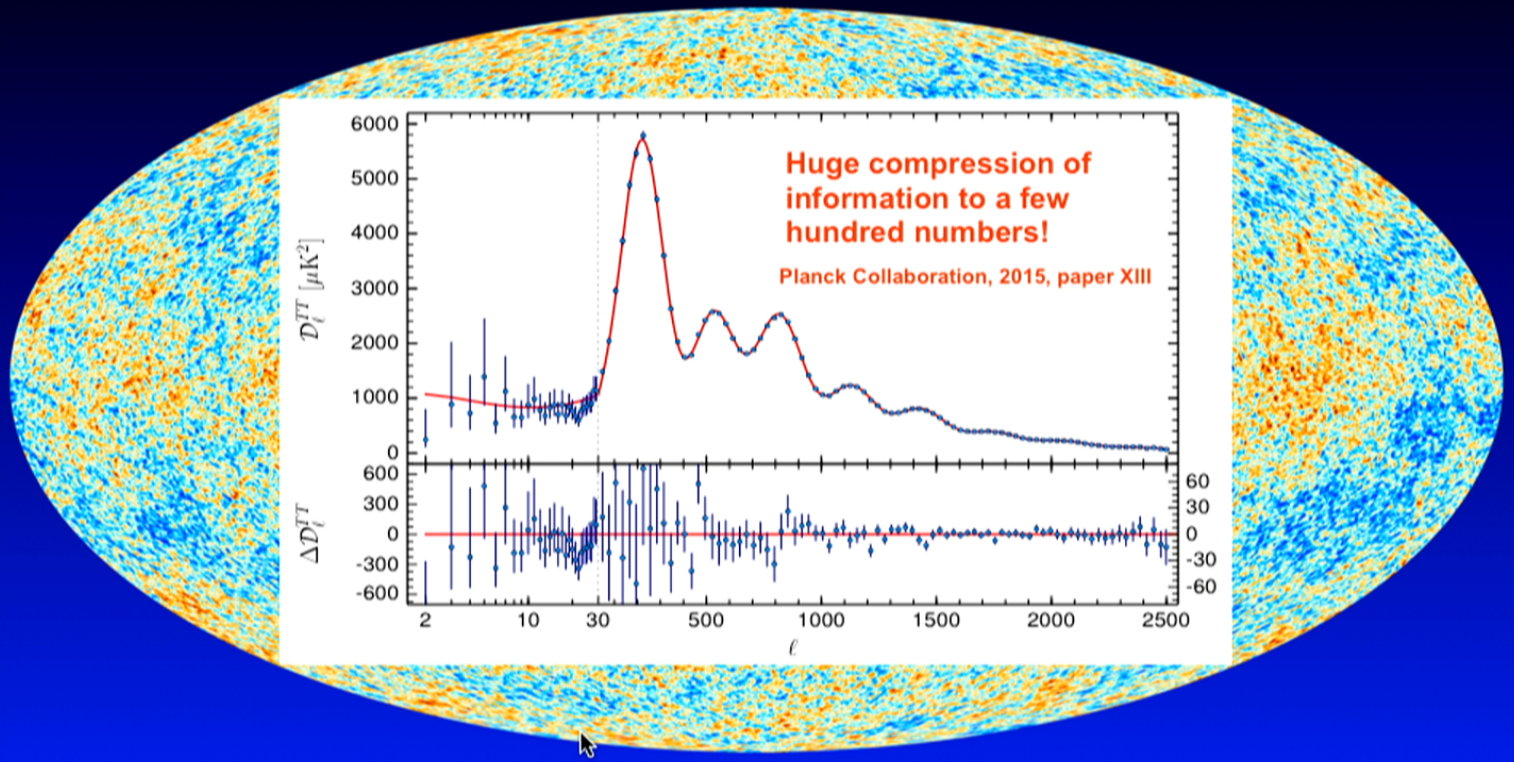
Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

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

Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

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

CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!

- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter ("CDM")
- accelerated expansion today ("Λ")
- Standard BBN scenario → $N_{\rm eff}$ and $Y_{\rm p}$
- Standard ionization history → $N_{\rm e}$ as a function of z

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_{\rm b}h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_{\rm c}h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{\rm MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10}A_{\rm s})$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
$n_{\rm s}$	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

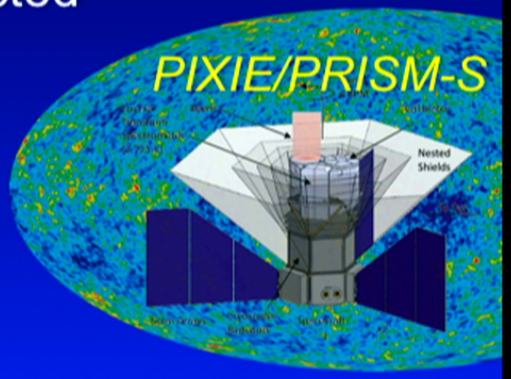
Planck Collaboration, 2015, paper XIII

What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-*l*
  - better constraint on τ from large scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional 'proof of inflation'
- CMB anomalies
  - stationarity of E and B-modes, lensing potential, etc across the sky
- SZ cluster science
  - large cluster samples and (individual) high-res cluster measurements

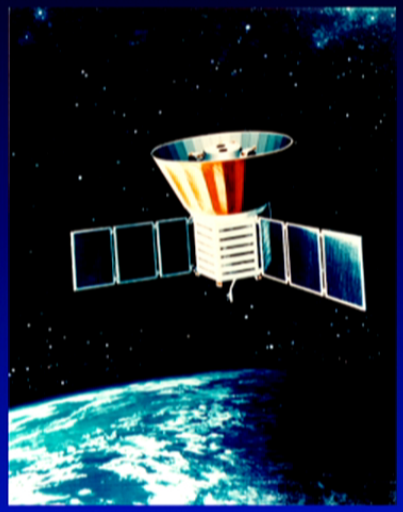
What can CMB spectral distortions add?

- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected
  - y-distortion from low redshifts
  - damping signal & recombination radiation
- Test various *inflation* models
  - damping of the small-scale power spectrum
- *Discovery* potential
  - decaying particles and other exotic sources of distortions



All this largely without any competition from the ground!!!

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

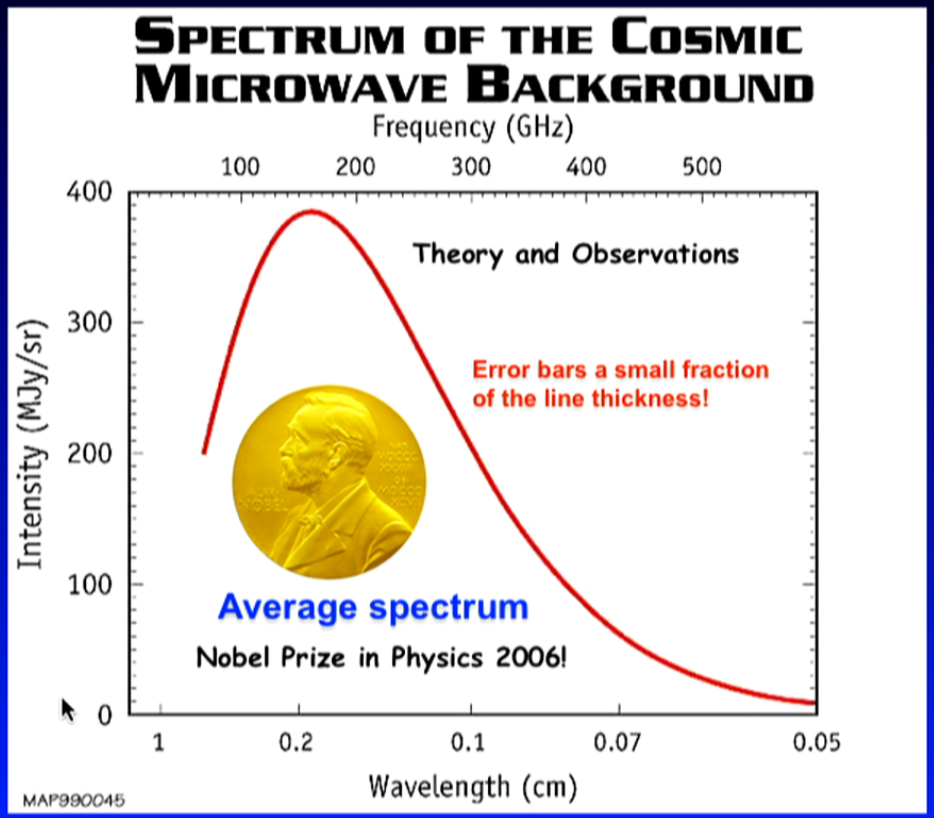


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

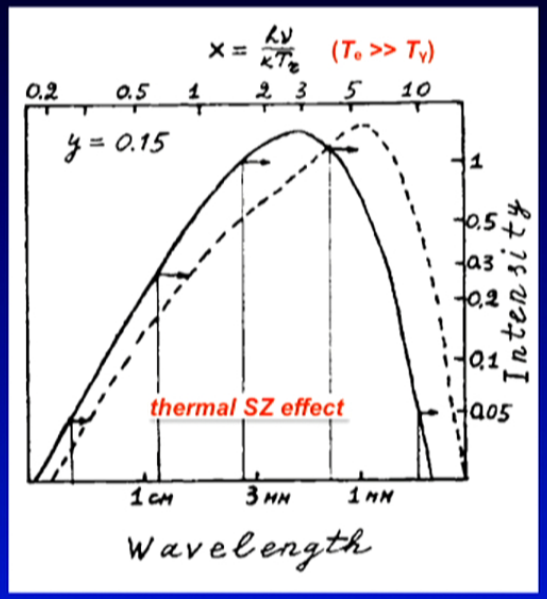
$$|\mu| \leq 9\times10^{-5}$$

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



Standard types of primordial CMB distortions

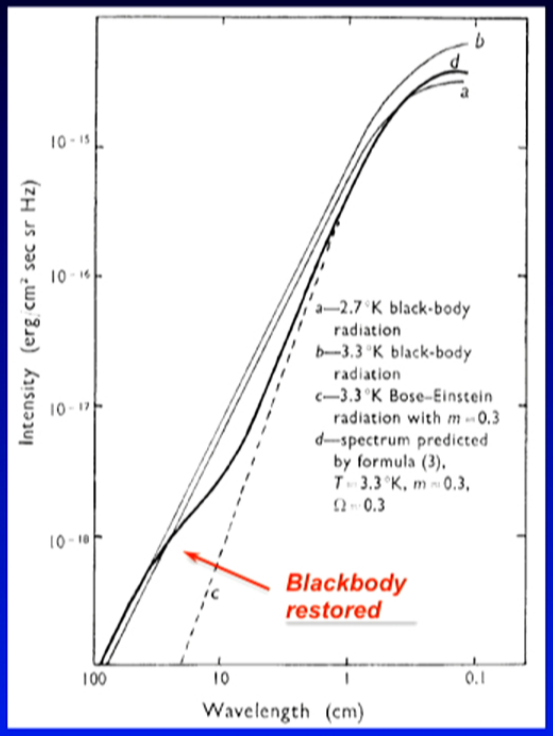
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering inefficient

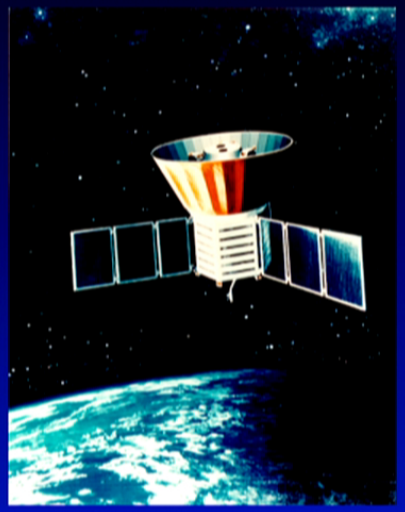
Chemical potential μ-distortion



Sunyaev & Zeldovich, 1970, ApSS, 2, 66

- important at very times (z>50000)
- scattering very efficient

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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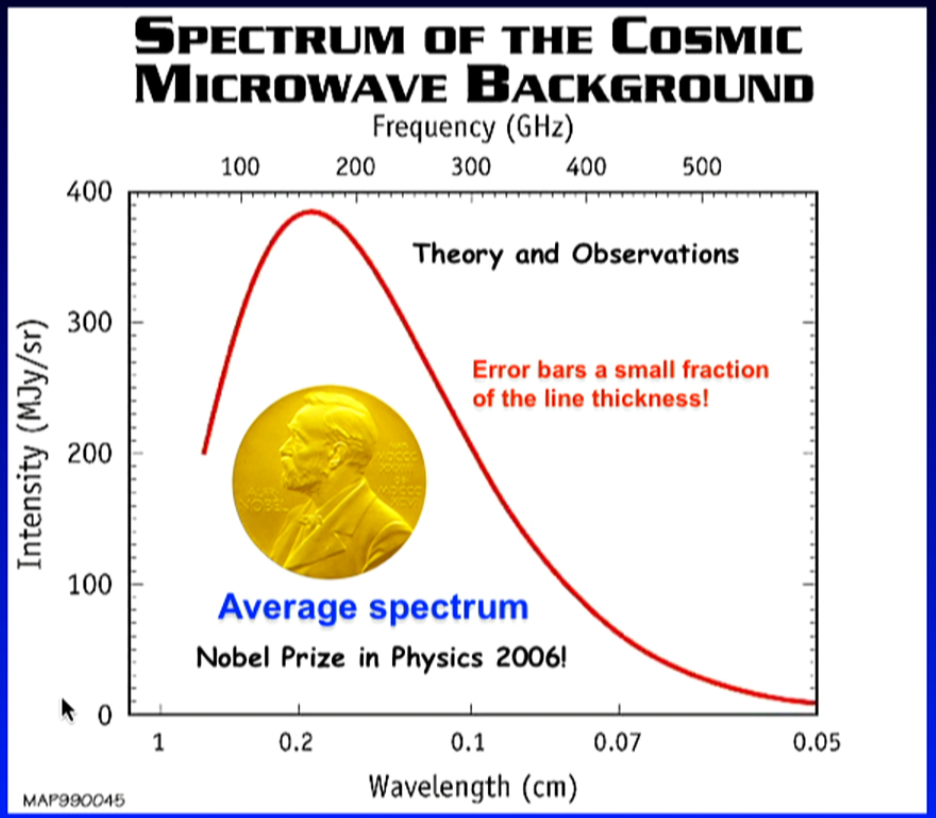


Only very small distortions of CMB spectrum are still allowed!

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

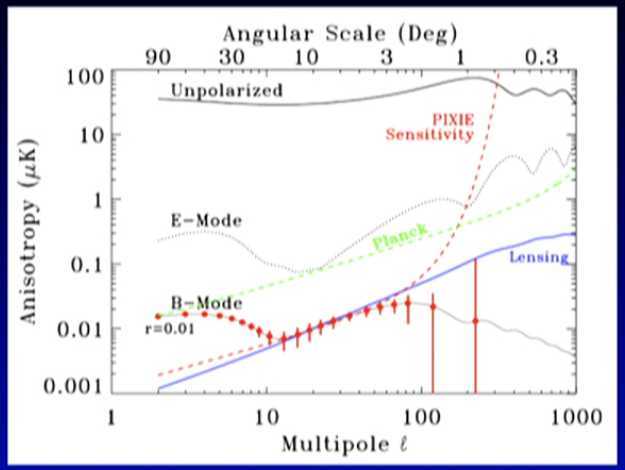
„high" redshifts

„low" redshifts

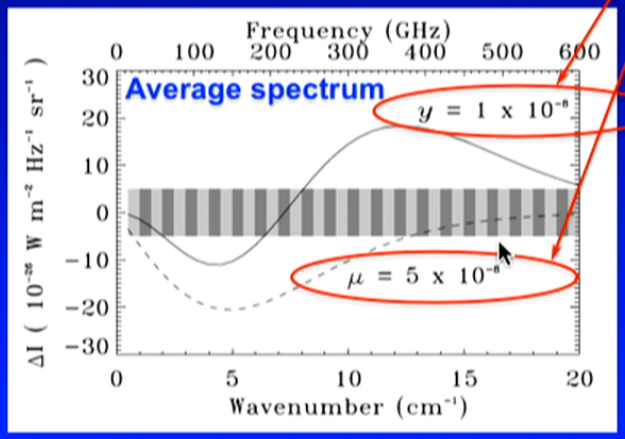
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- more exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

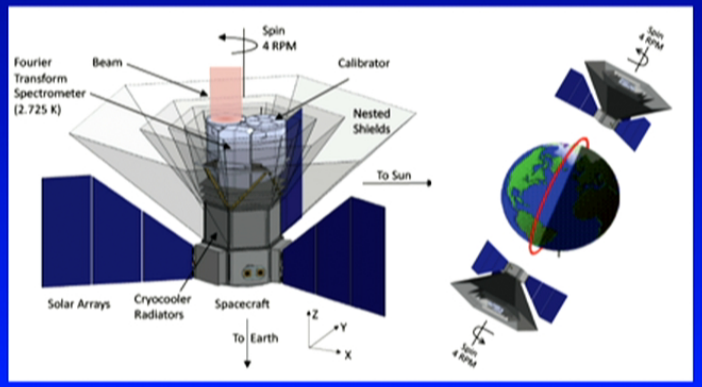
post-recombination

PIXIE: Primordial Inflation Explorer

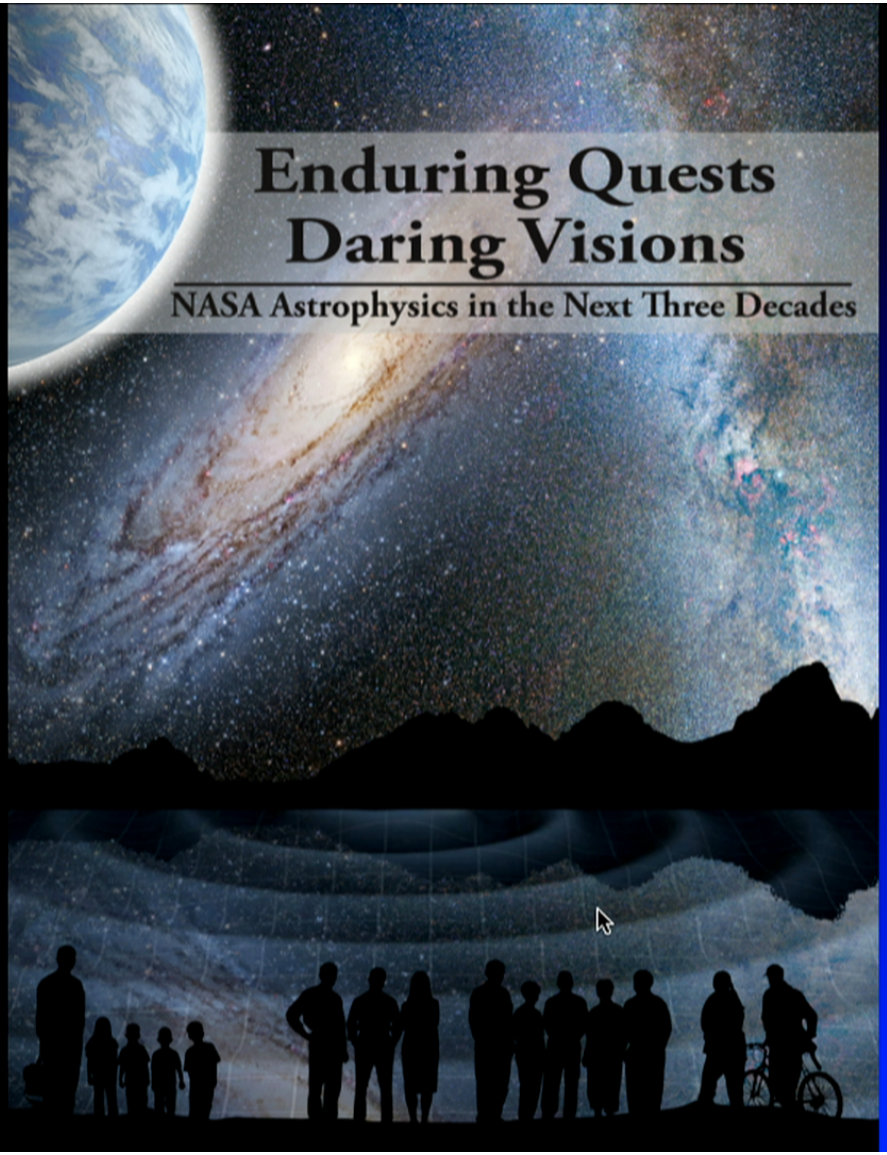


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δν ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

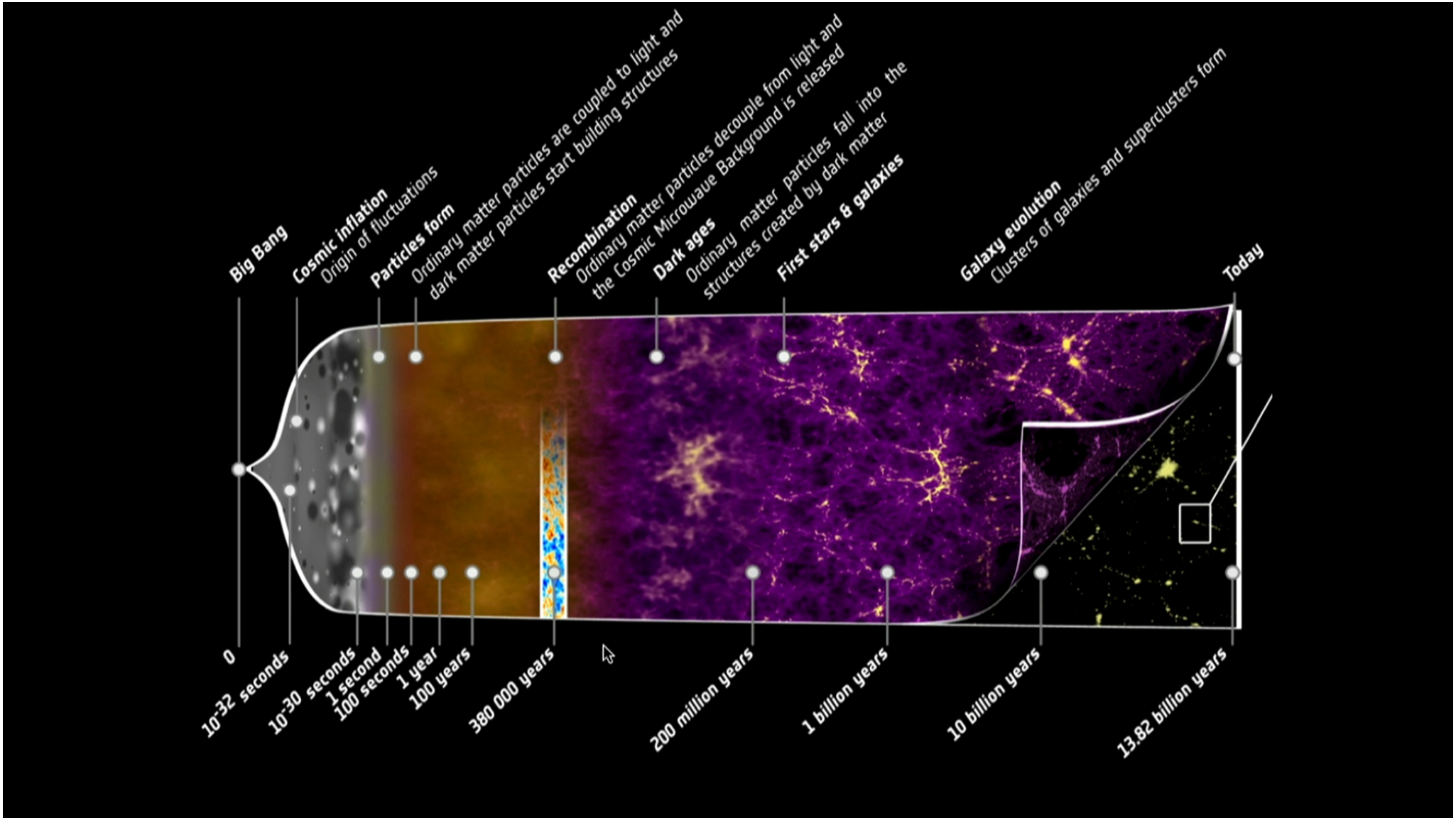
(published Dec 2013)

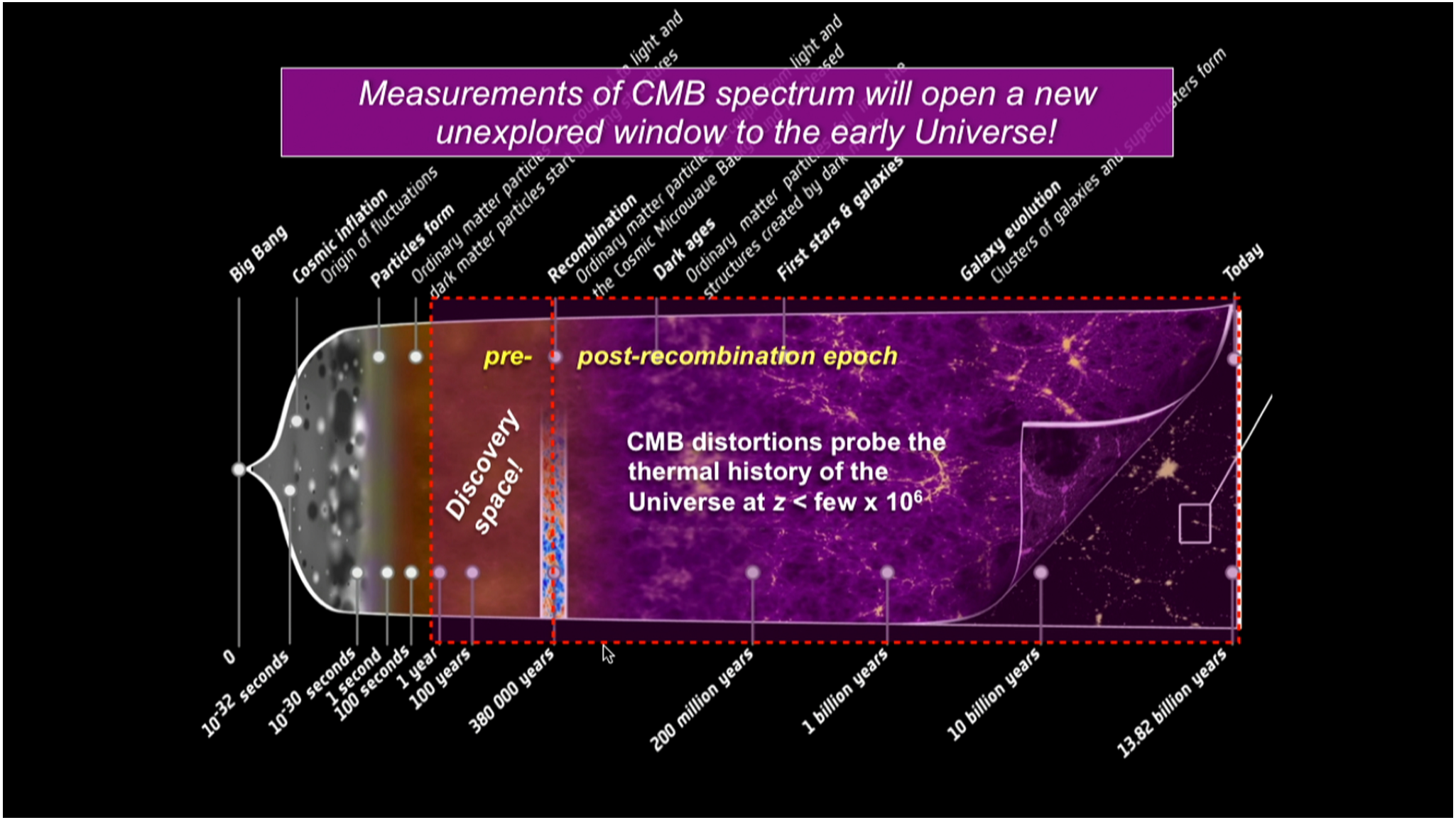
How does the Universe work?

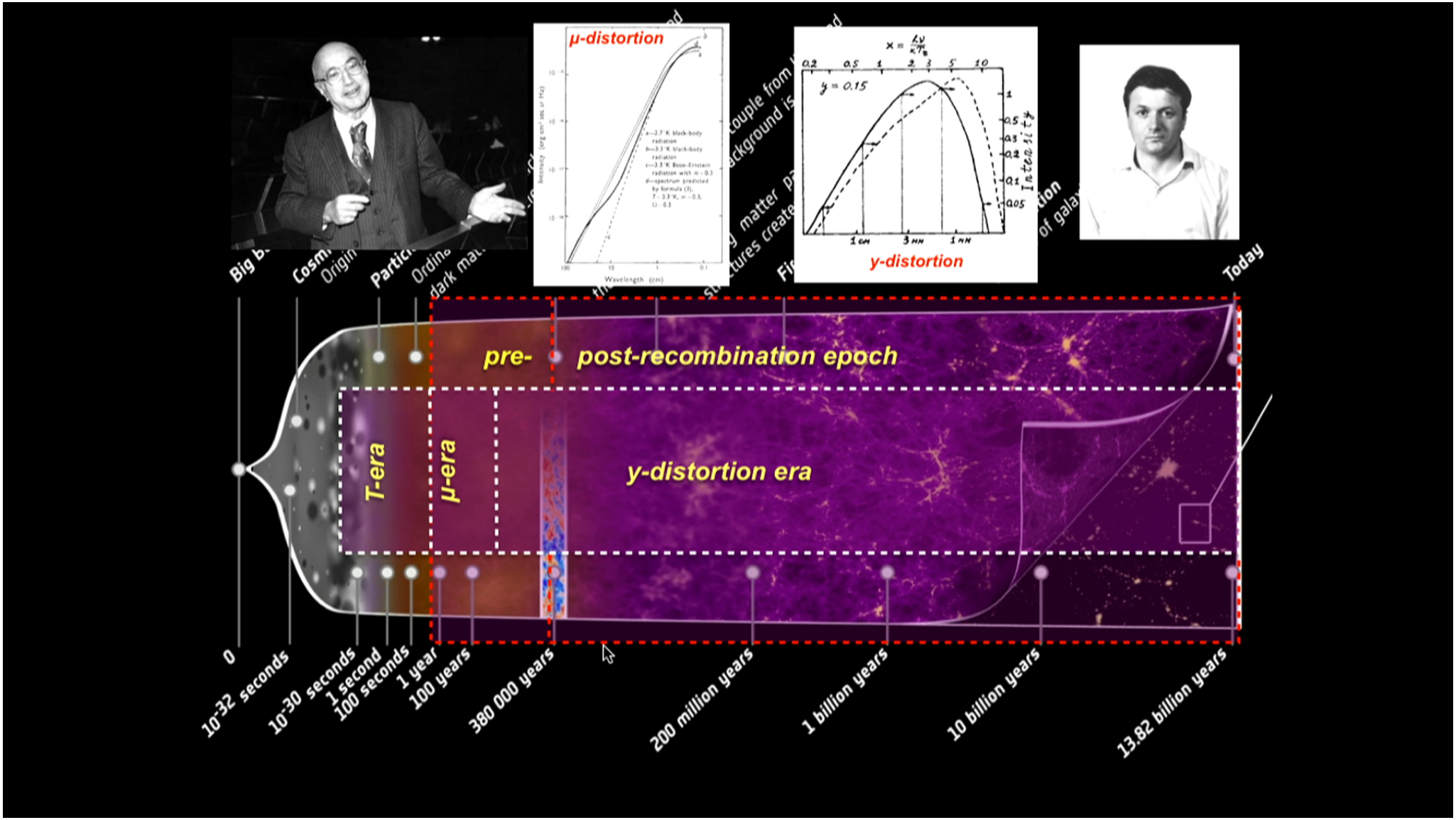
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

New call from NASA expected end 2016


Energy release distortions primer


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


Measurements of CMB spectrum will open a new unexplored window to the early Universe!
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Recombination
Dark ages
First stars & galaxies
Galaxy evolution
Clusters of galaxies
Today
pre-
post-recombination epoch
Discovery space!
CMB distortions probe the thermal history of the Universe at z < few x 10^6
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


μ-distortion
y-distortion
Today
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
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

Simple estimates for the distortion μ- and y-parameters caused by energy release

- Generalization of classical approximations:

$$y = \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y = \frac{1}{4}\int_0^\infty \mathcal{J}_y(z')\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

$$\mu = 1.401\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu = 1.401\int_0^\infty \mathcal{J}_\mu(z')\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

Energy release history

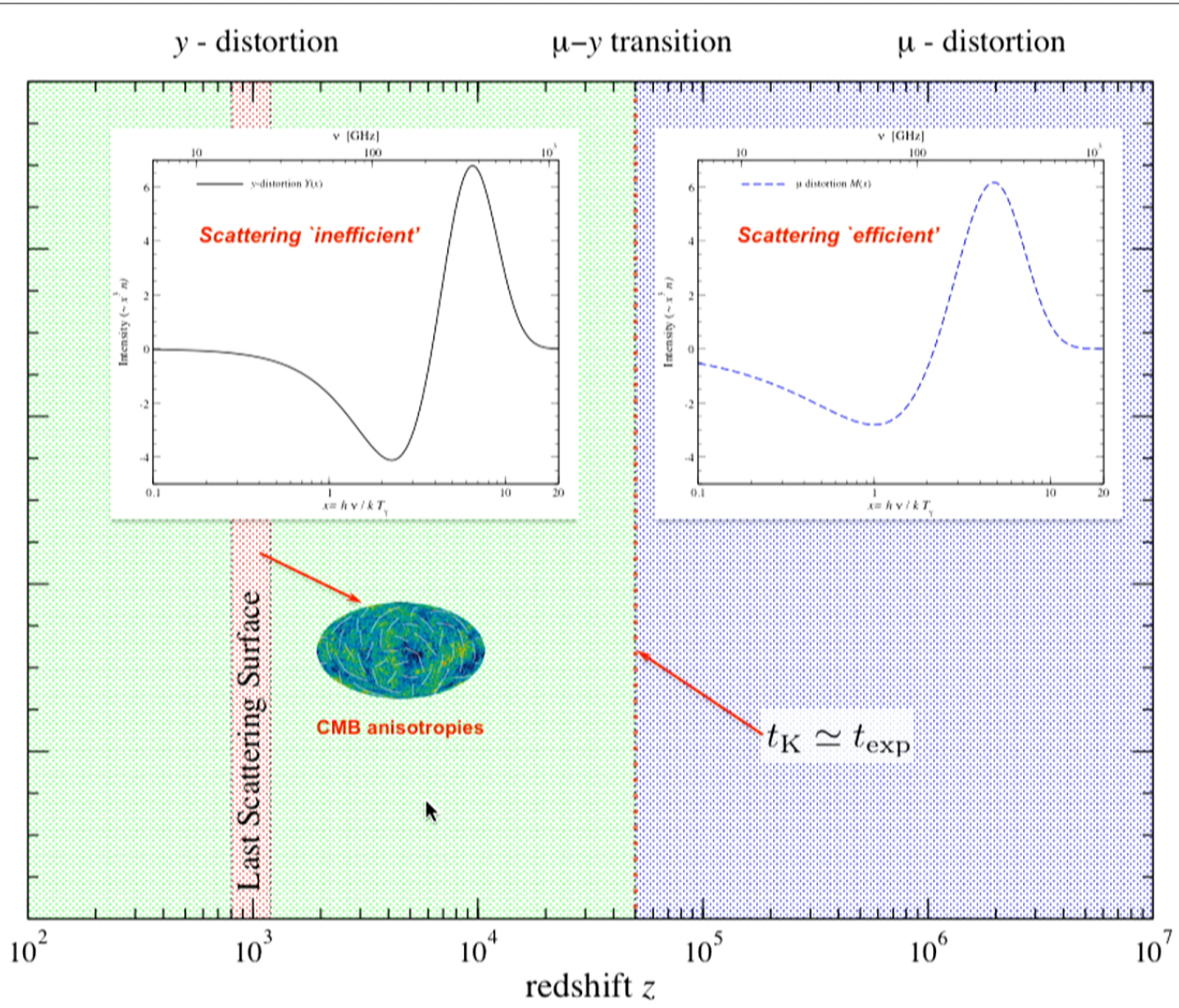
- Differences in the approximations are due to *visibility functions*
- An overview can be found in ArXiv:1603.02496
- One *commonly* used approximation (e.g., see Hu&Silk, 1993):

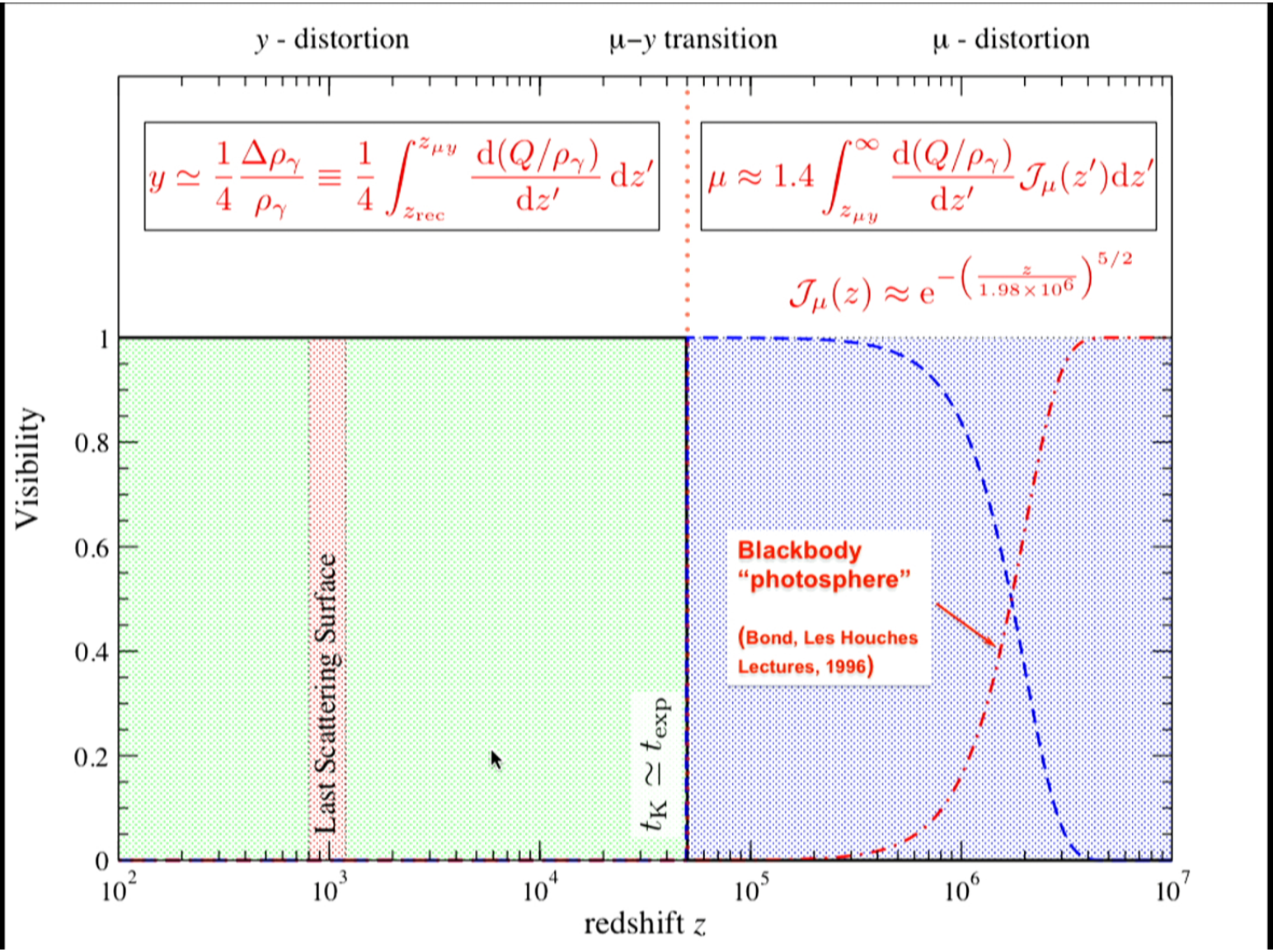
$$\mathcal{J}_y(z) = \begin{cases} 1 & \text{for } z_{\rm rec} \le z \le z_{\mu y} \\ 0 & \text{otherwise} \end{cases}$$

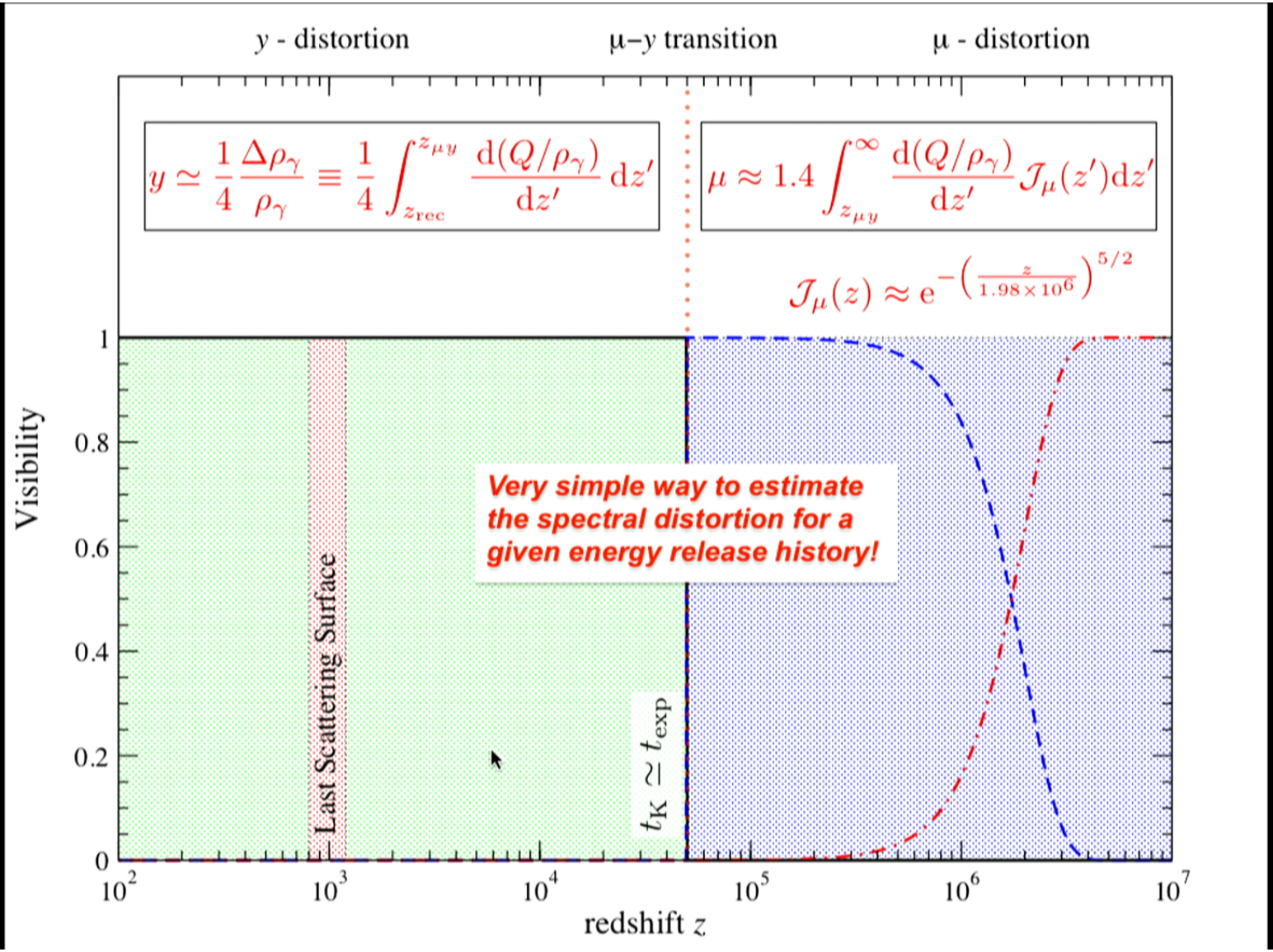
$$\mathcal{J}_\mu(z) = \begin{cases} \mathcal{J}_{\rm bb}(z) & \text{for } z_{\mu y} \le z \\ 0 & \text{otherwise.} \end{cases}$$

- step-function transition between μ and *y* around $z_{\mu y} \simeq 5\times 10^4$
- accounts for thermalization efficiency with *distortion visibility*

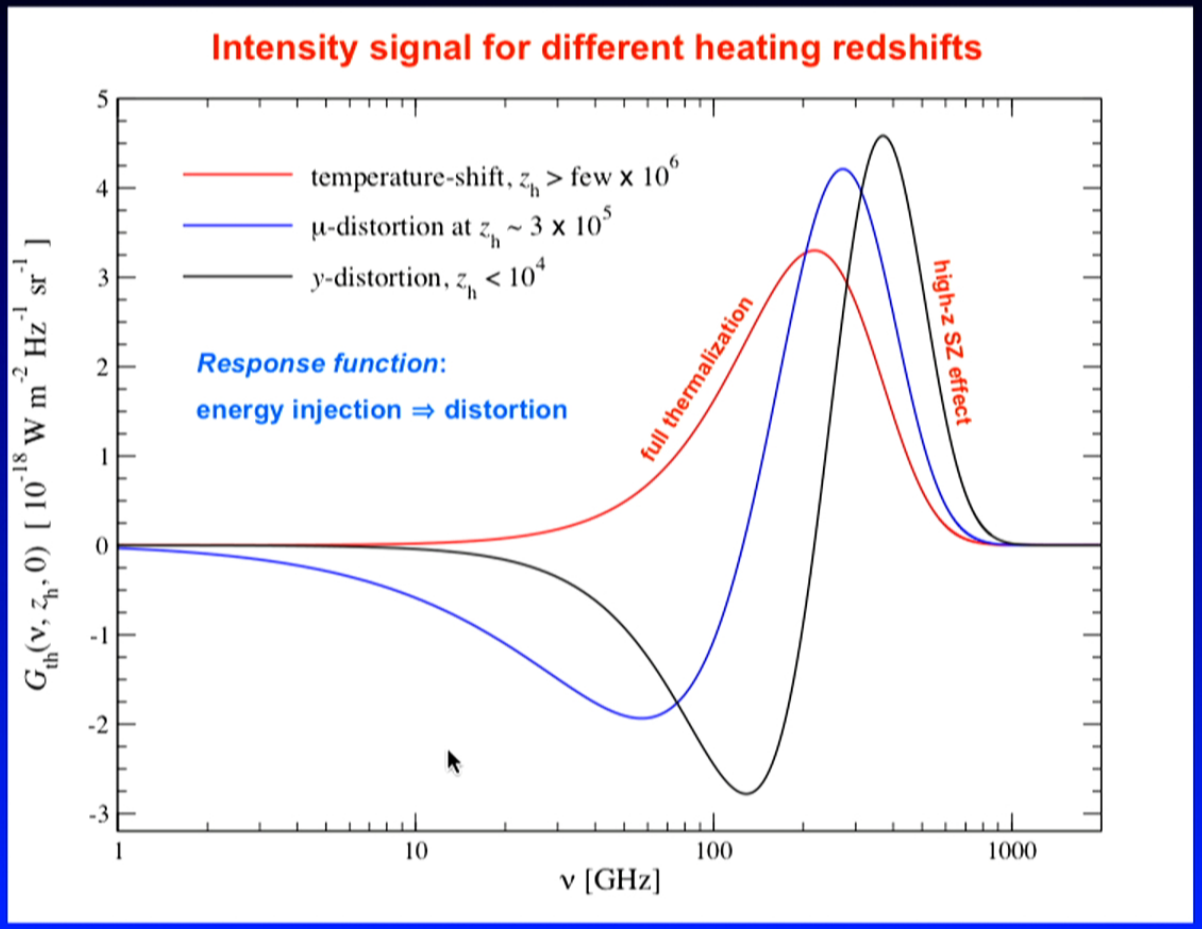
$$\mathcal{J}_{\rm bb}(z) \approx \mathrm{e}^{-(z/z_{\rm th})^{5/2}} \qquad z_{\rm th} \approx 1.98\times 10^6$$


y - distortion
μ–y transition
μ - distortion
ν [GHz]
y-distortion Y(x)
Scattering `inefficient'
Intensity (~ x³ n)
x≡ h ν / k T
ν [GHz]
μ distortion M(x)
Scattering `efficient'
Intensity (~ x³ n)
x≡ h ν / k T
Last Scattering Surface
CMB anisotropies
$t_{\rm K} \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,\mathcal{J}_\mu(z'){\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
Blackbody "photosphere"
(Bond, Les Houches Lectures, 1996)
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

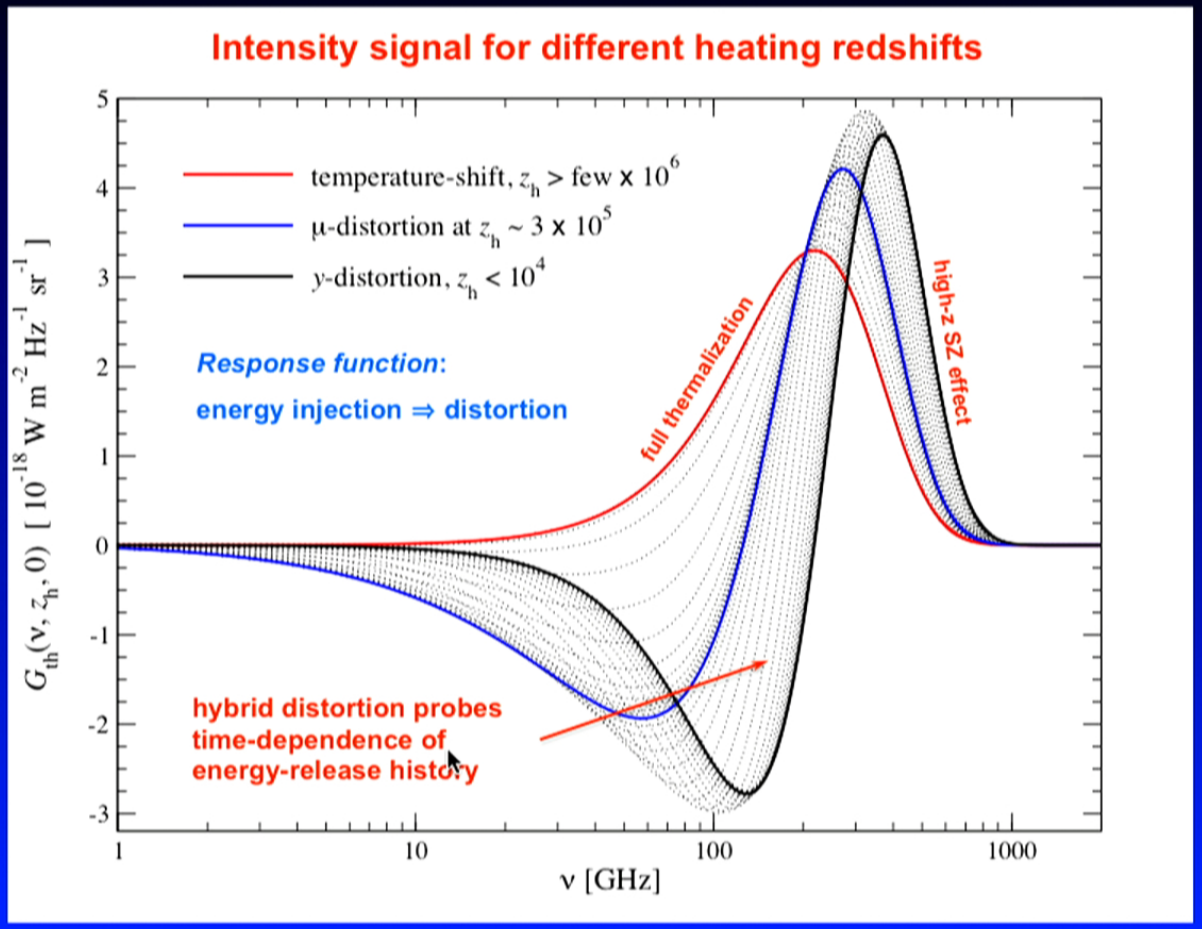

y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4\int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,\mathcal{J}_\mu(z'){\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
Very simple way to estimate the spectral distortion for a given energy release history!
$t_{\rm K} \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

Distortion Green's function for energy release



JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

Distortion Green's function for energy release



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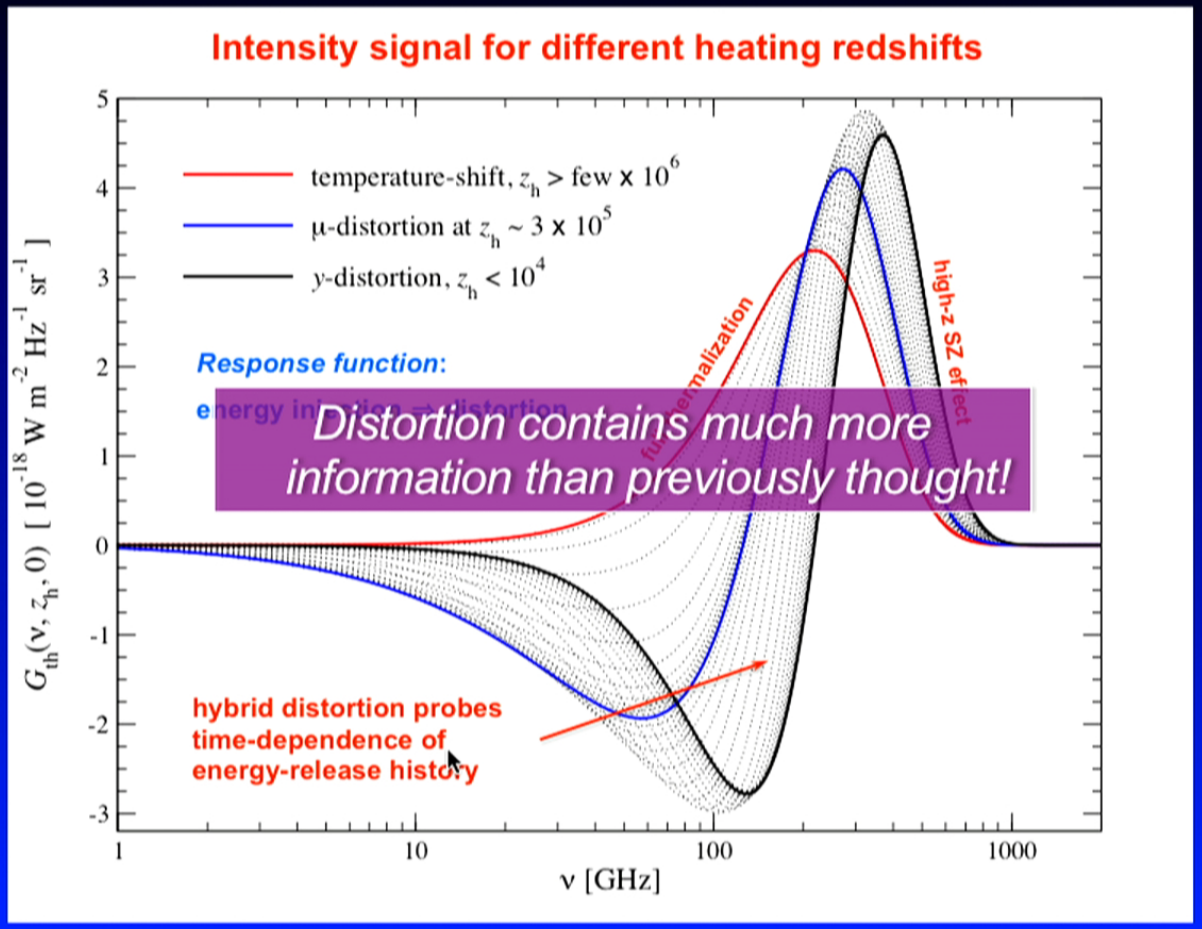
Distortion Green's function for energy release



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Transition from y-distortion → μ-distortion

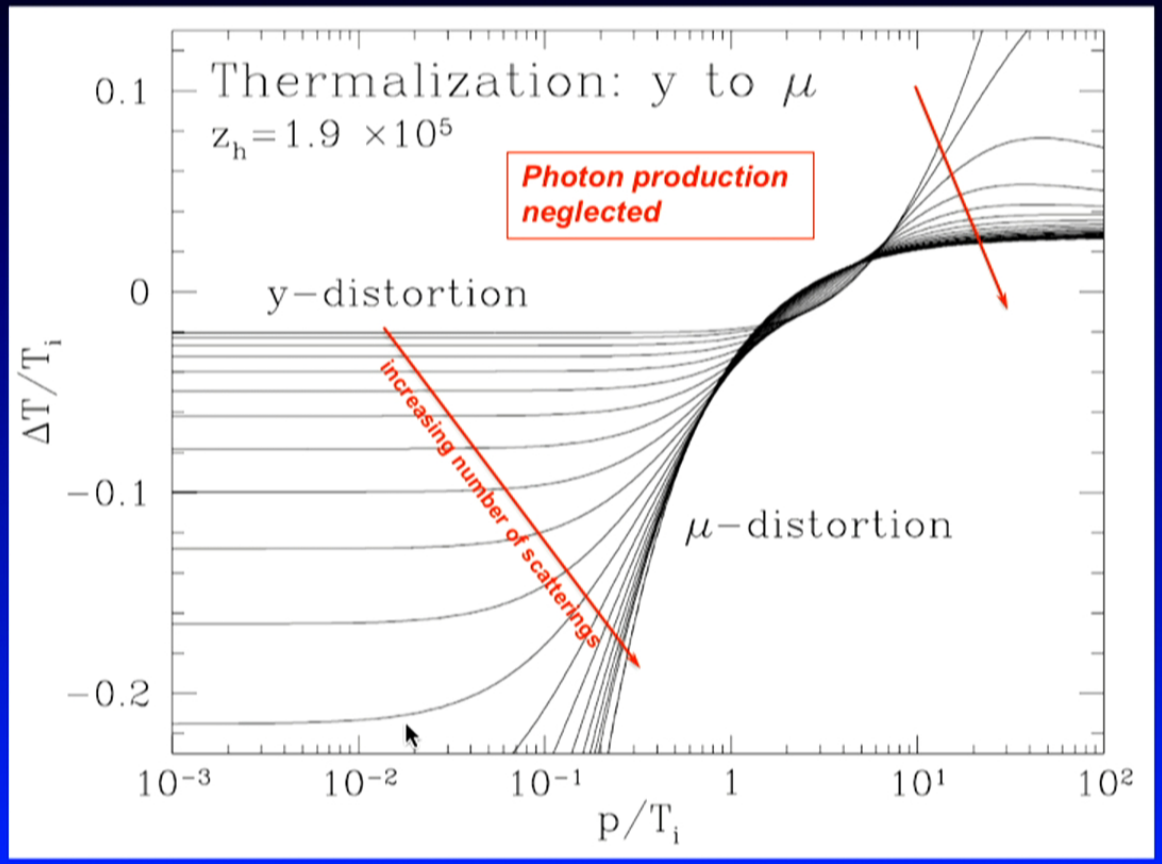
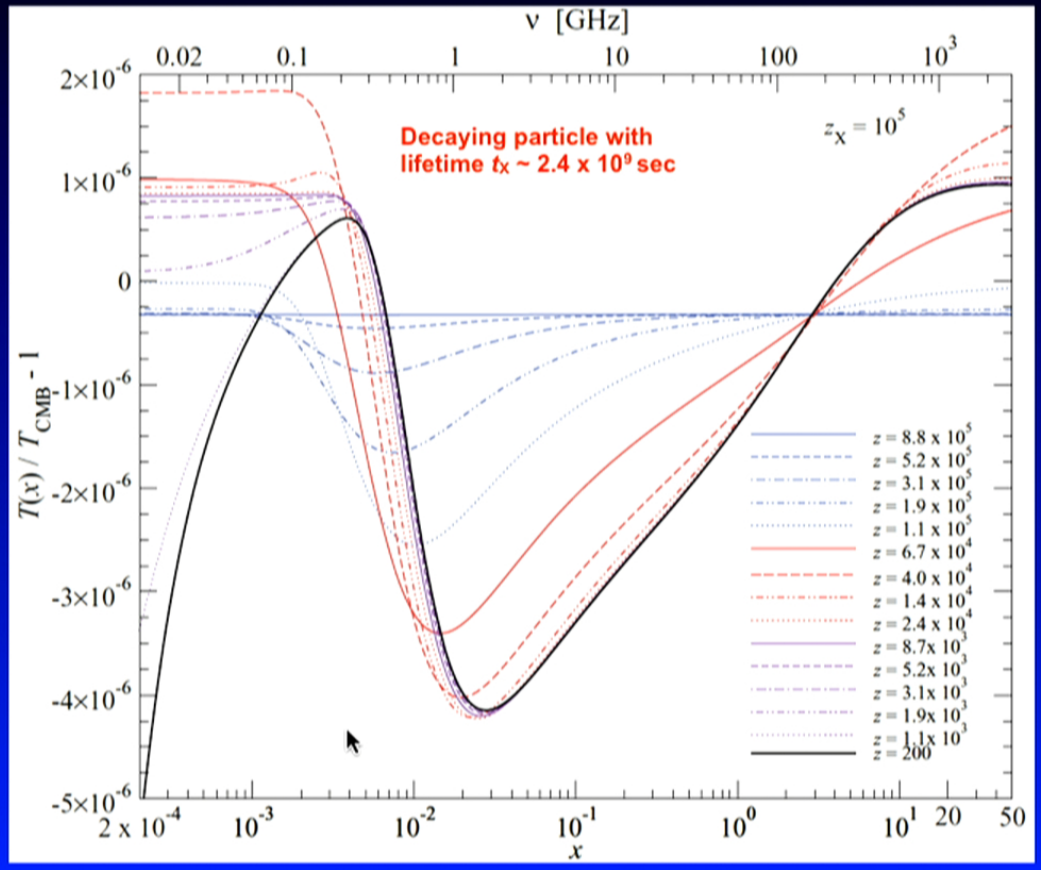


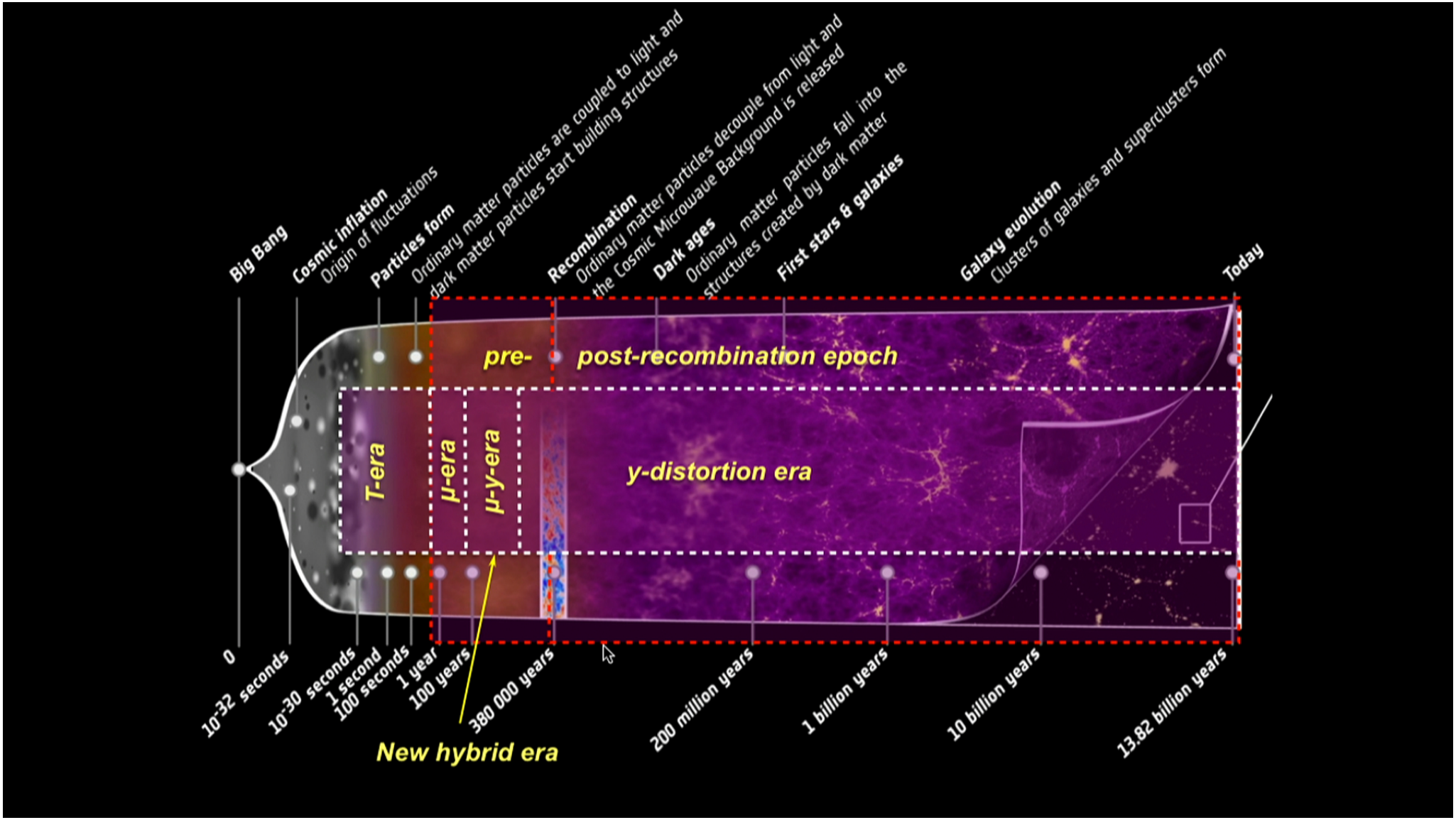
Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

Distortion *not* just superposition of μ and y-distortion!



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

First explicit calculation that showed that there is more!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Ordinary matter particles are coupled to light and dark matter particles start building structures
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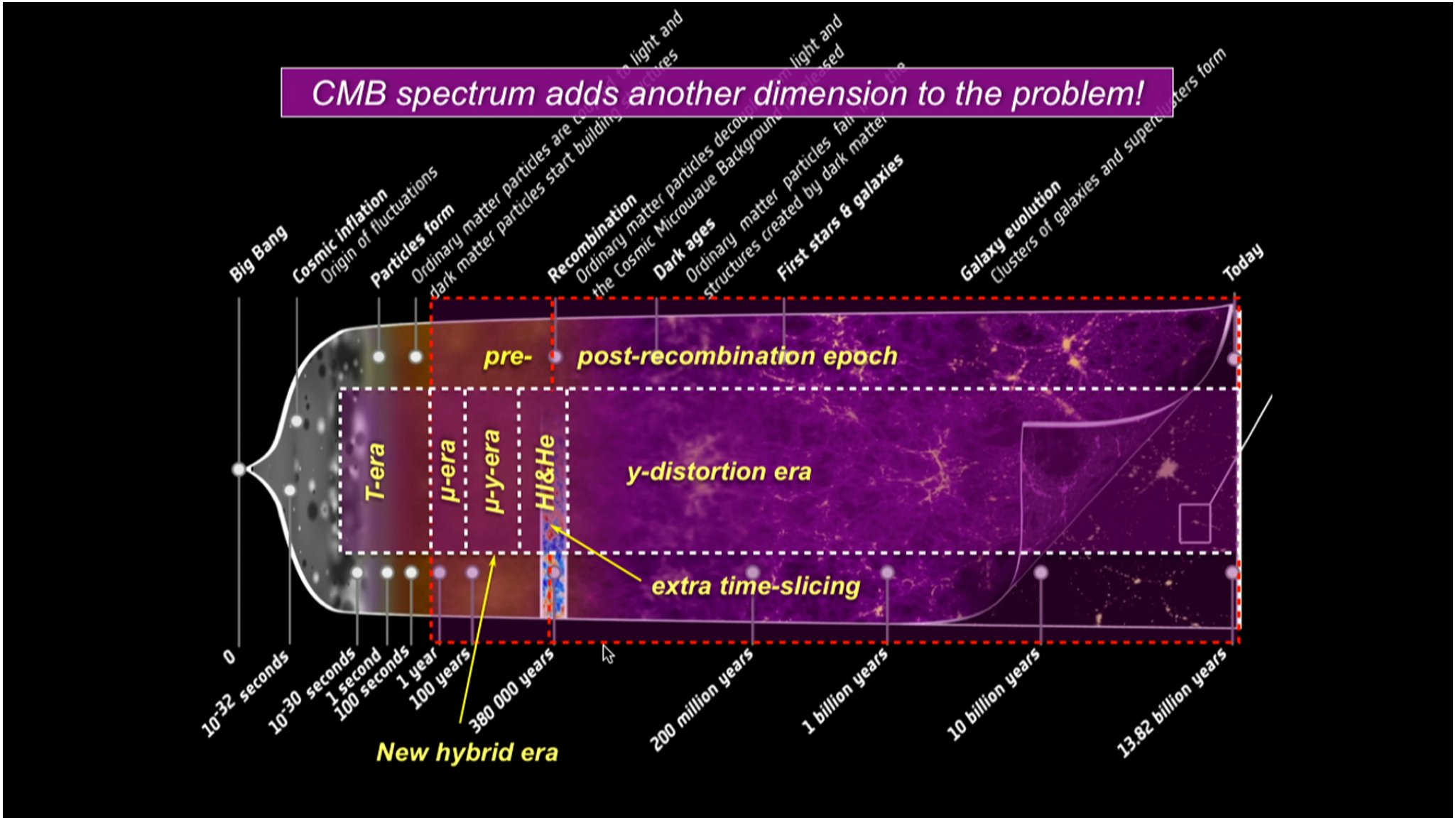
T-era
μ-era
μ-y-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13,82 billion years
New hybrid era


CMB spectrum adds another dimension to the problem!
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Recombination
Dark ages
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing
New hybrid era
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10-32 seconds
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100 seconds
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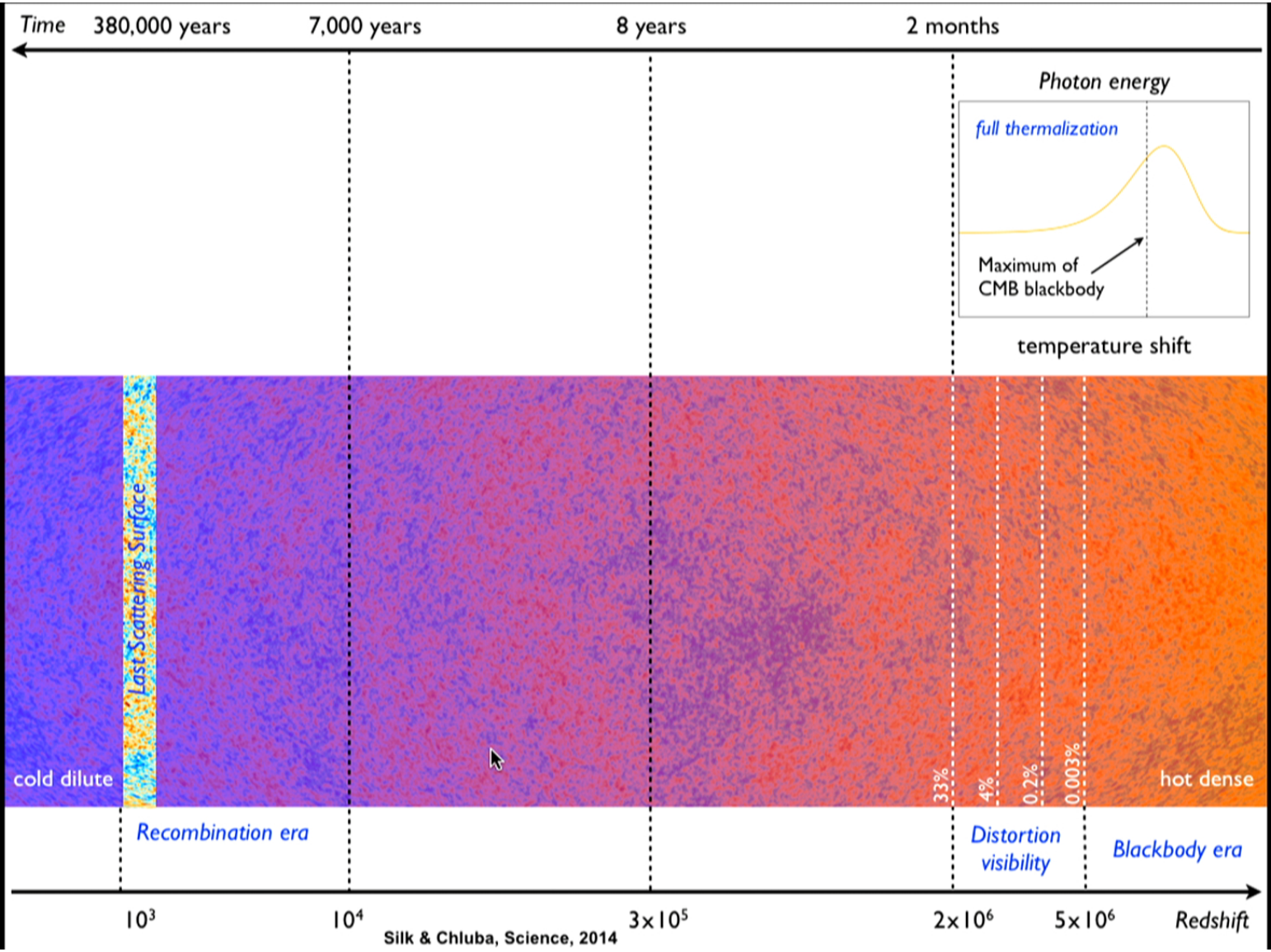
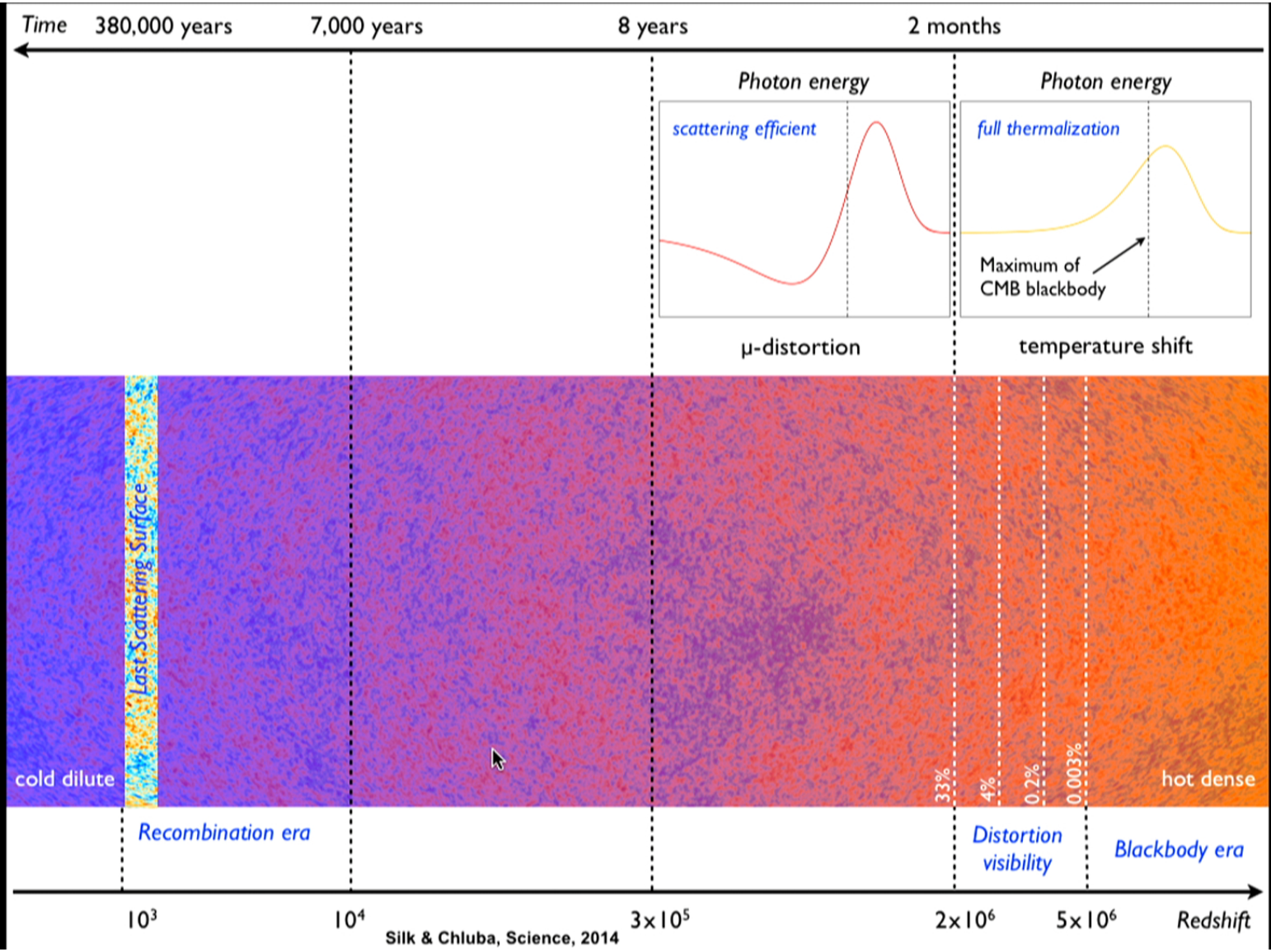
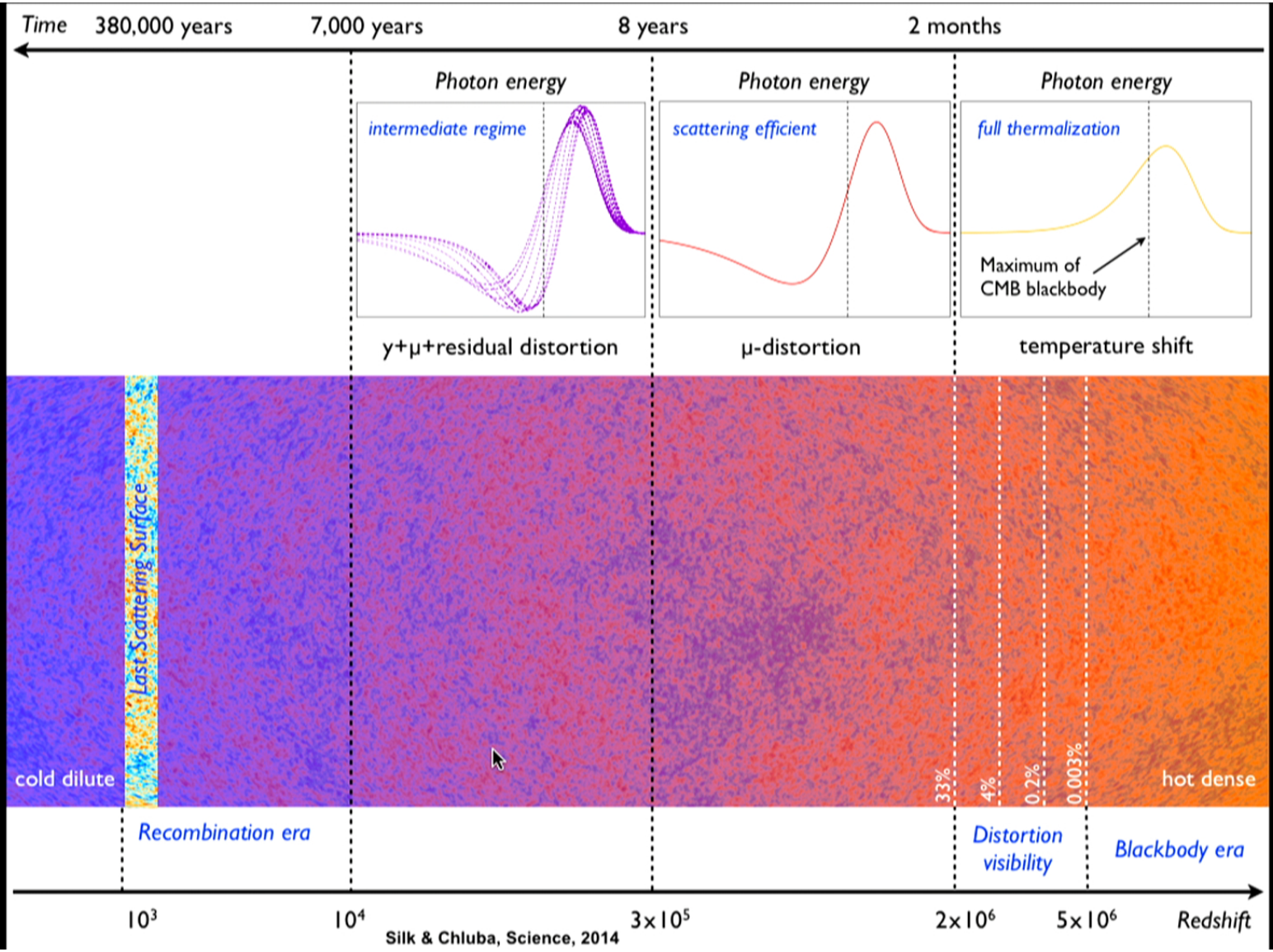
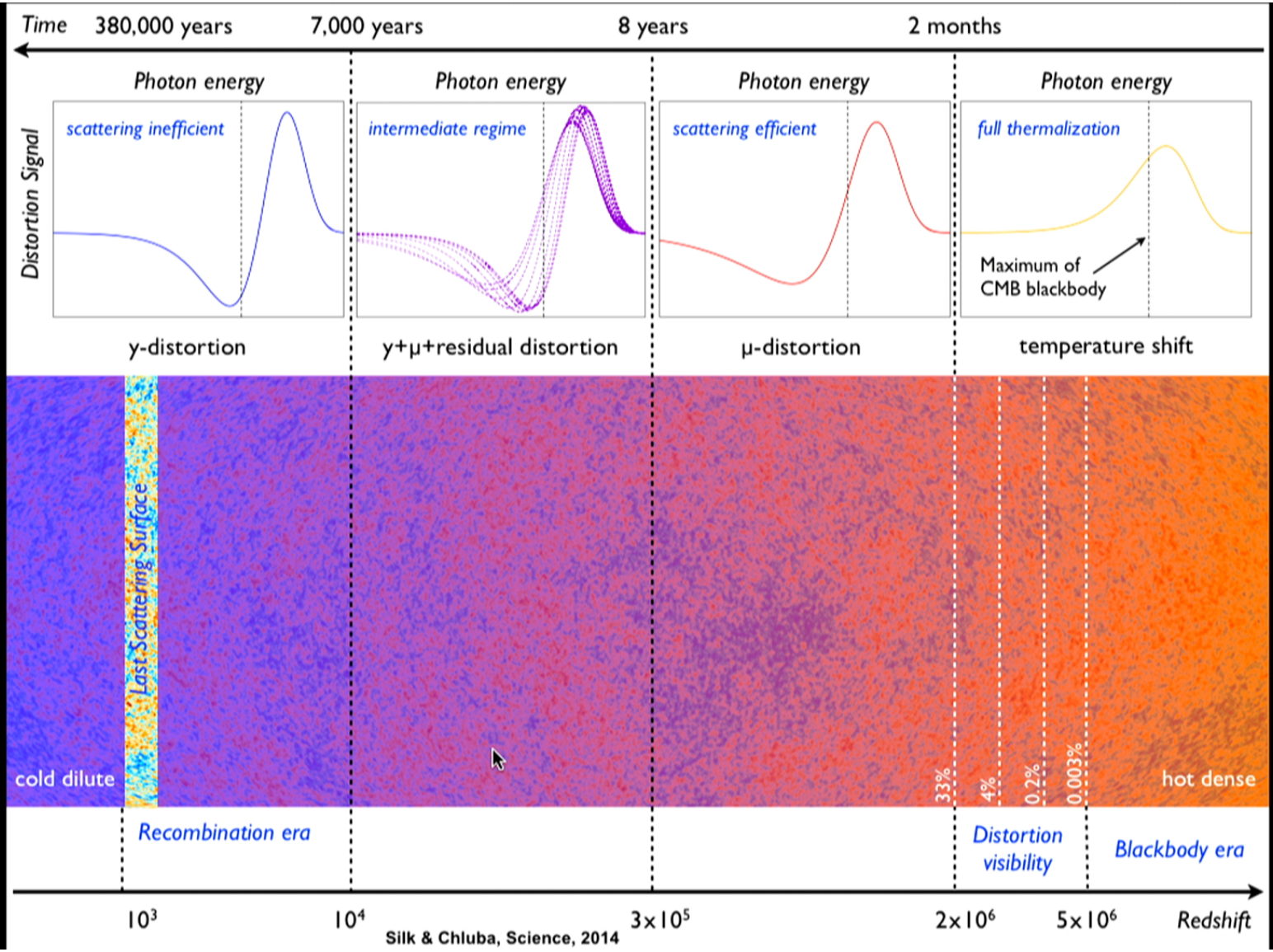
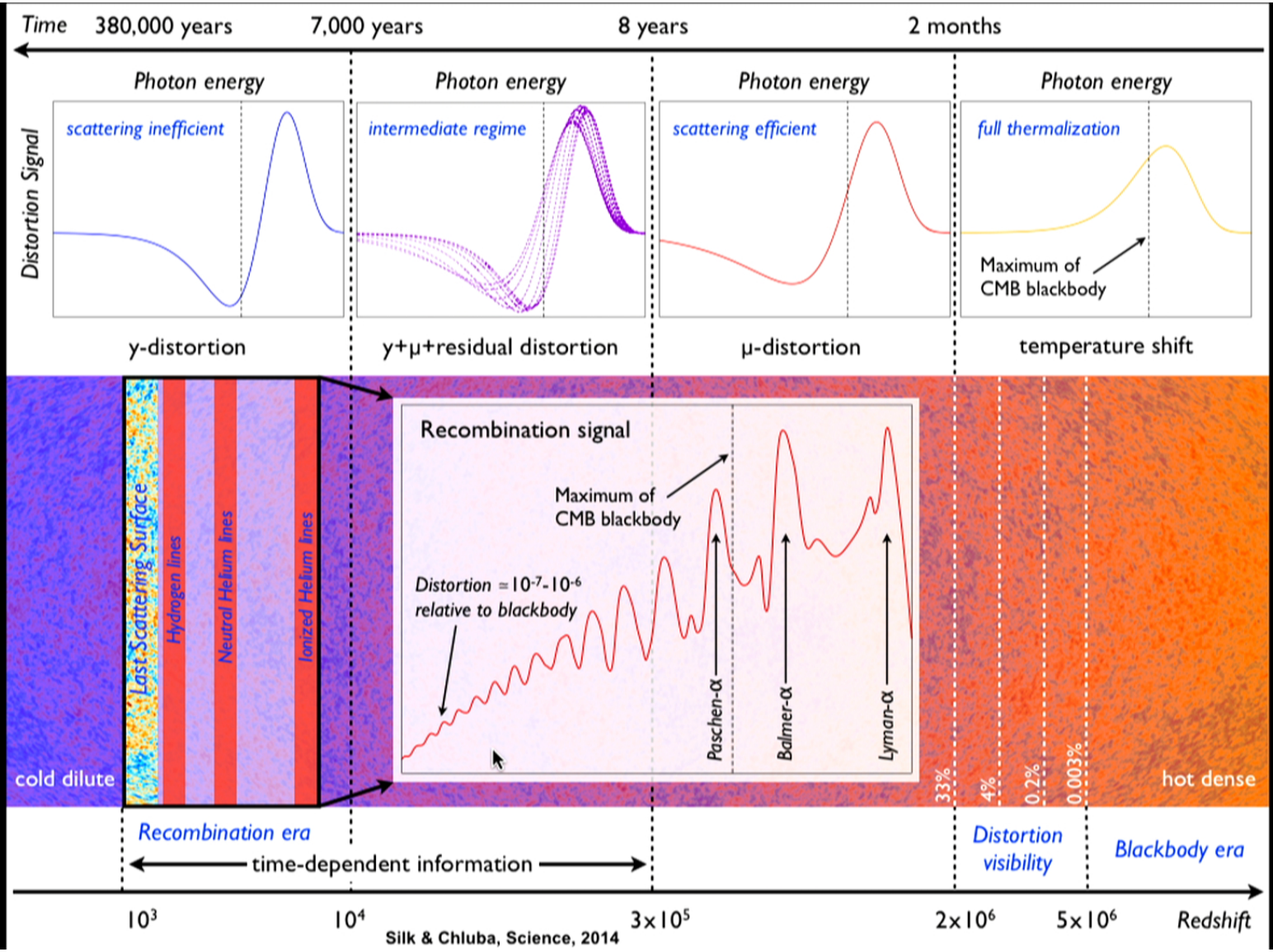
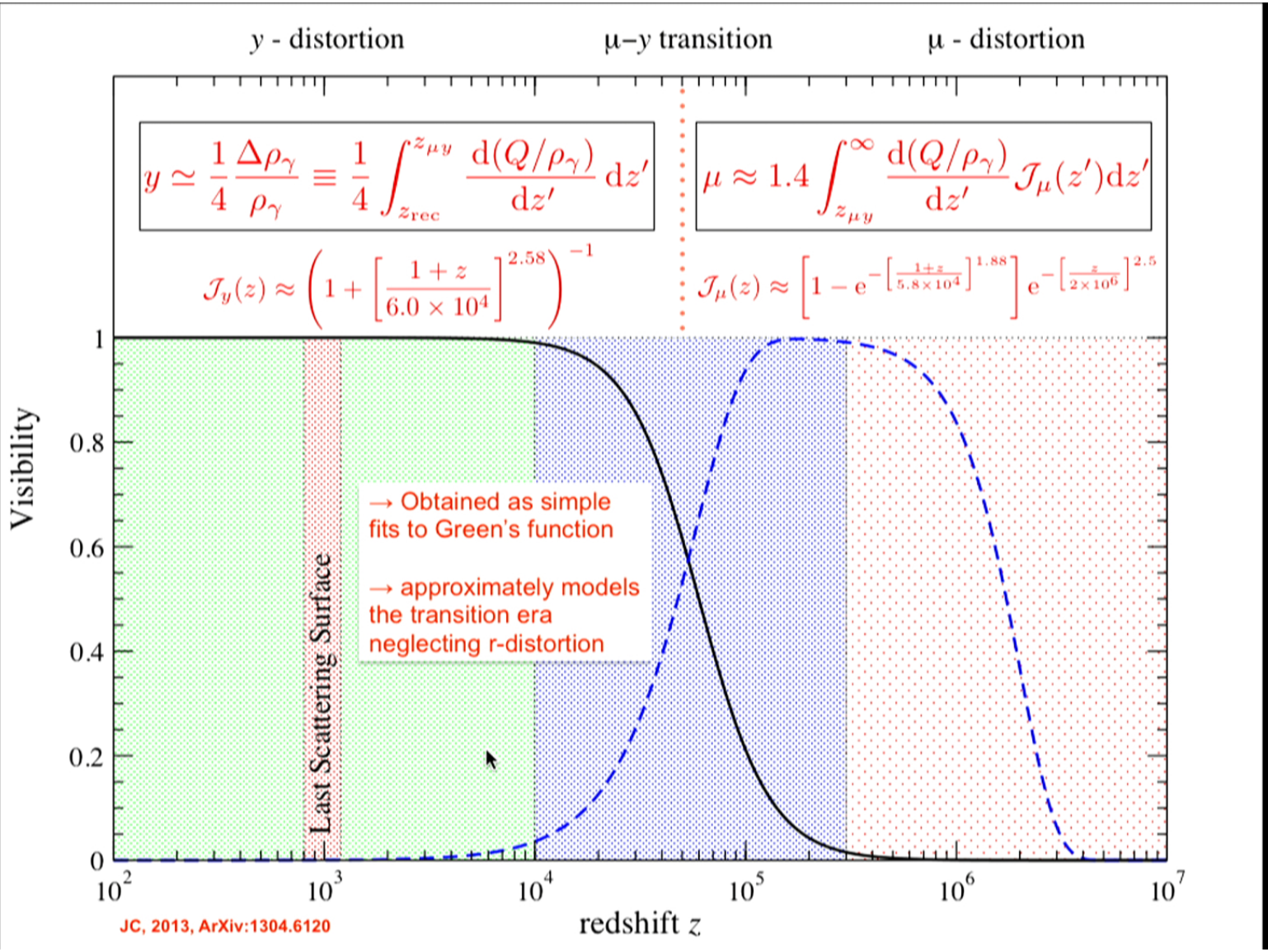

Time
380,000 years
7,000 years
8 years
2 months
Photon energy
full thermalization
Maximum of
CMB blackbody
temperature shift
Last Scattering Surface
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
Distortion
visibility
Blackbody era
10^3
10^4
3x10^5
2x10^6
5x10^6
Redshift
Silk & Chluba, Science, 2014

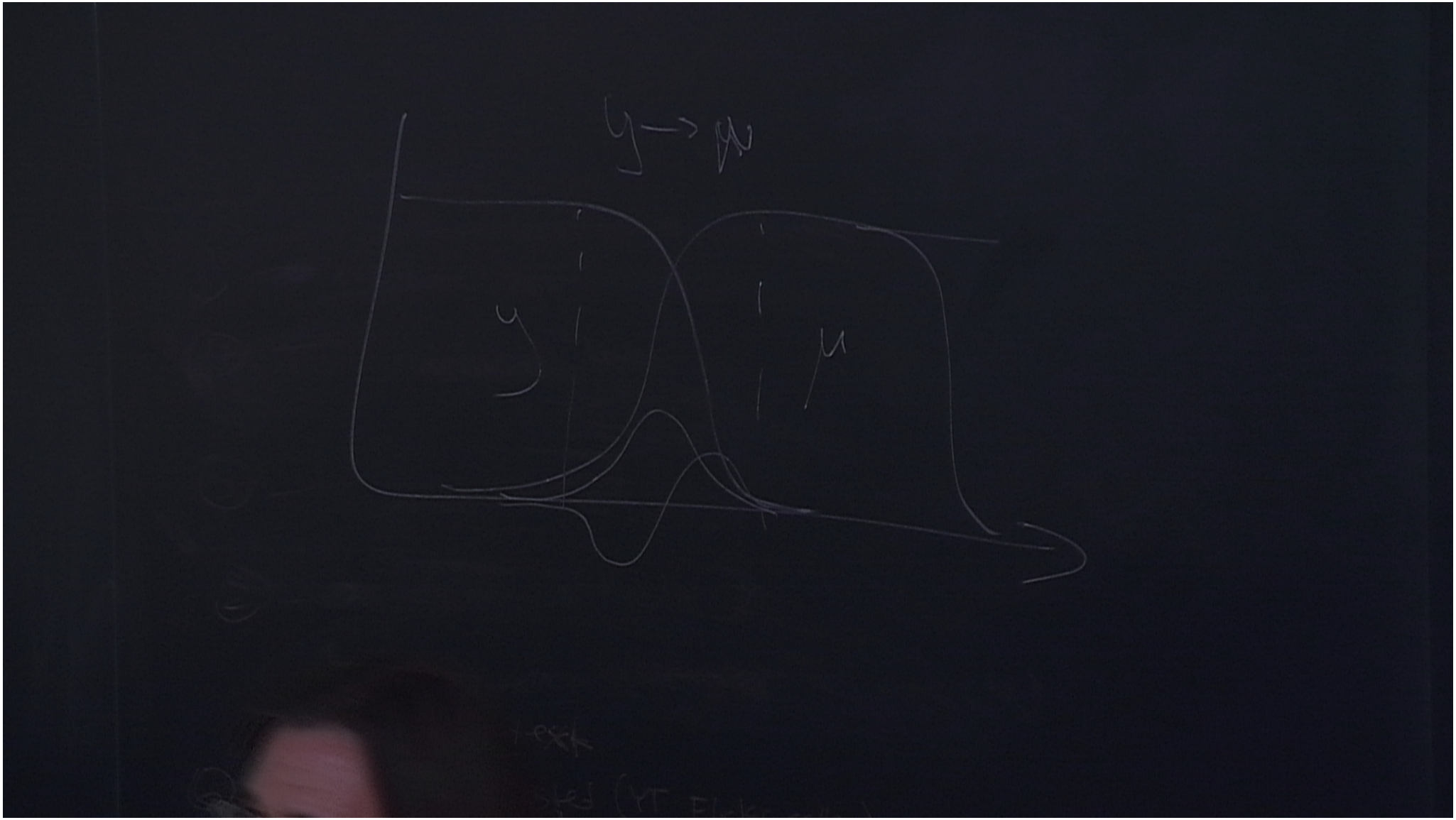

Time
380,000 years
7,000 years
8 years
2 months
Photon energy
scattering efficient
Photon energy
full thermalization
Maximum of
CMB blackbody
μ-distortion
temperature shift
Last Scattering Surface
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
Distortion
visibility
Blackbody era
10^3
10^4
3x10^5
2x10^6
5x10^6
Redshift
Silk & Chluba, Science, 2014


Time
380,000 years
7,000 years
8 years
2 months
Photon energy
intermediate regime
Photon energy
scattering efficient
Photon energy
full thermalization
Maximum of
CMB blackbody
y+μ+residual distortion
μ-distortion
temperature shift
Last Scattering Surface
cold dilute
33%
4%
0.2%
0.003%
hot dense
Recombination era
Distortion
visibility
Blackbody era
10^3
10^4
3x10^5
2x10^6
5x10^6
Redshift
Silk & Chluba, Science, 2014


Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
intermediate regime
scattering efficient
full thermalization
Maximum of
CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
cold dilute
Last Scattering Surface
33%
4%
0.2%
0.003%
hot dense
Recombination era
Distortion
visibility
Blackbody era
10^3
10^4
3x10^5
2x10^6
5x10^6
Redshift
Silk & Chluba, Science, 2014


Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
intermediate regime
scattering efficient
full thermalization
Maximum of
CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Recombination signal
Maximum of
CMB blackbody
Distortion ≈ 10-7-10-6
relative to blackbody
Last Scattering Surface
Hydrogen lines
Neutral Helium lines
Ionized Helium lines
Paschen-α
Balmer-α
Lyman-α
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
time-dependent information
Distortion
visibility
Blackbody era
10³
10⁴
3x10⁵
2x10⁶
5x10⁶
Redshift
Silk & Chluba, Science, 2014


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\mathcal{J}_\mu(z'){\rm d}z'$
$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mathcal{J}_\mu(z) \approx \left[1-{\rm e}^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]{\rm e}^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
→ Obtained as simple fits to Green's function
→ approximately models the transition era neglecting r-distortion
10^2
10^3
10^4
10^5
10^6
10^7
redshift z
JC, 2013, ArXiv:1304.6120



Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

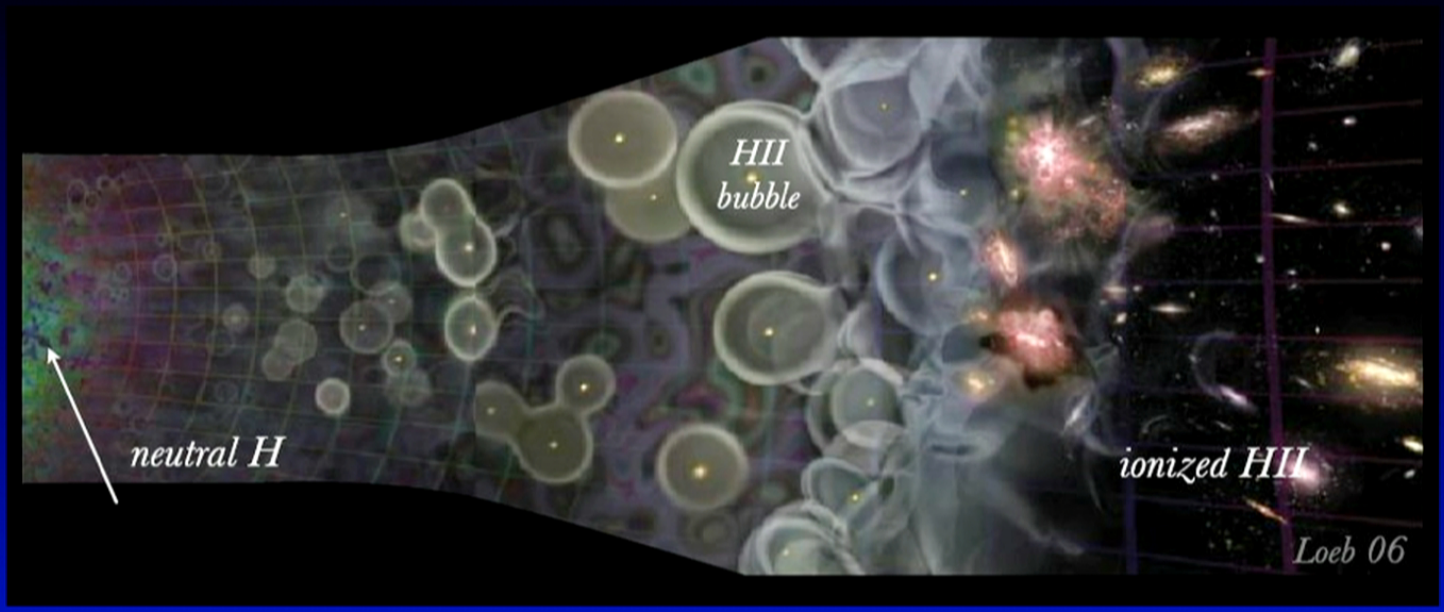
„high" redshifts

„low" redshifts

post-recombination

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- more exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Simple estimates for the distortion

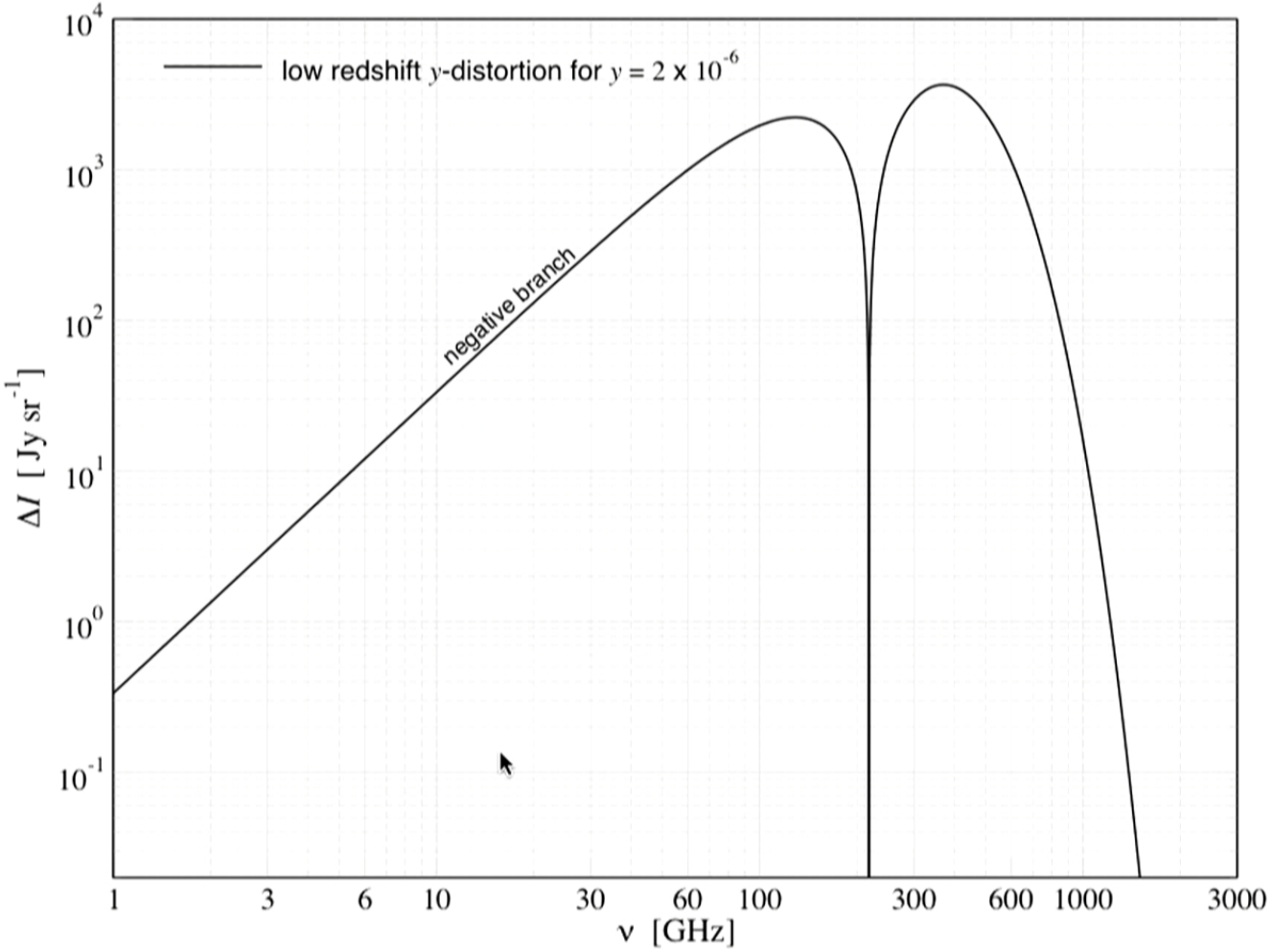


- Gas temperature $T \simeq 10^4$ K
- Thomson optical depth $\tau \simeq 0.1$

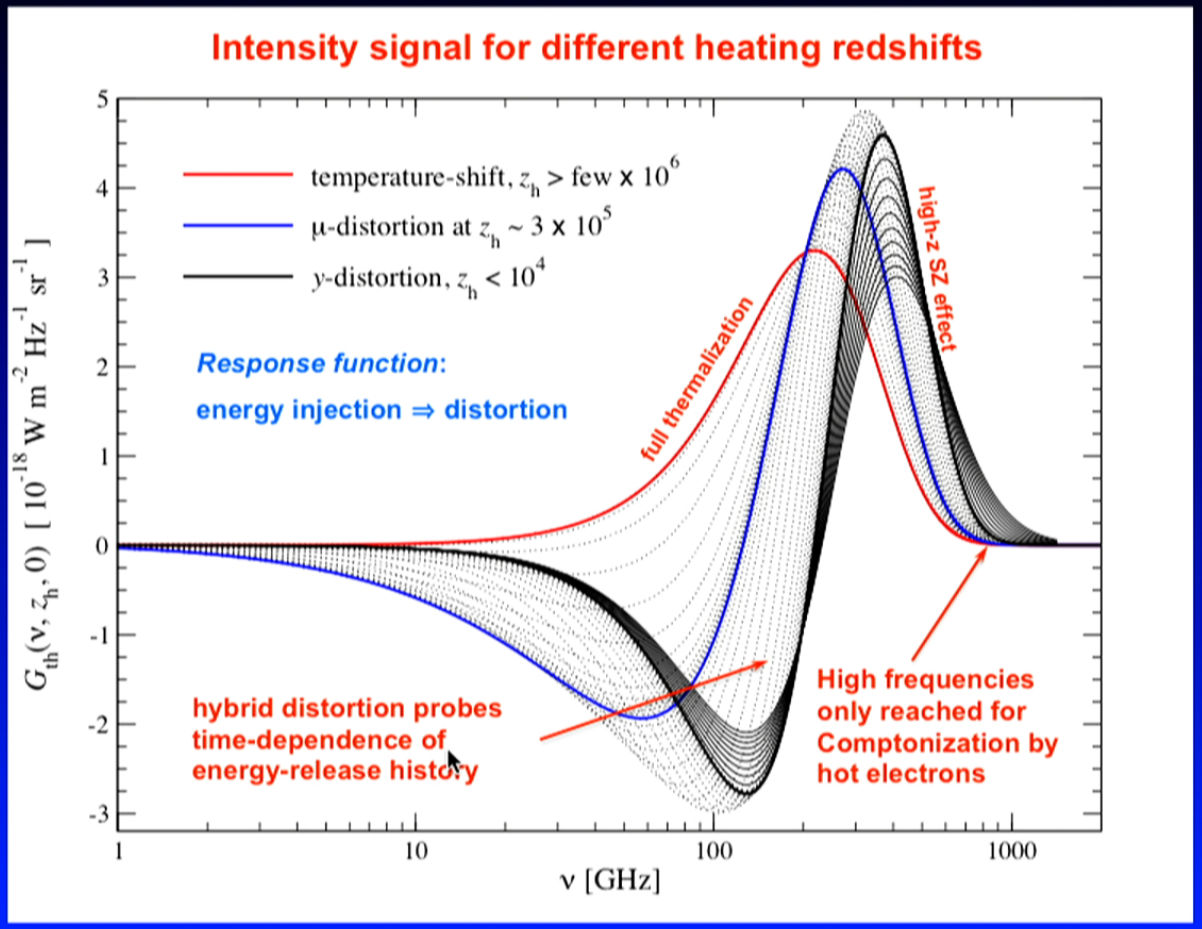
$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau \approx 2 \times 10^{-7}$$

- second order Doppler effect $y \simeq$ few x 10^{-8}
- structure formation / SZ effect (e.g., Refregier et al., 2003) $y \simeq$ few x 10^{-7}-10^{-6}

Average CMB spectral distortions

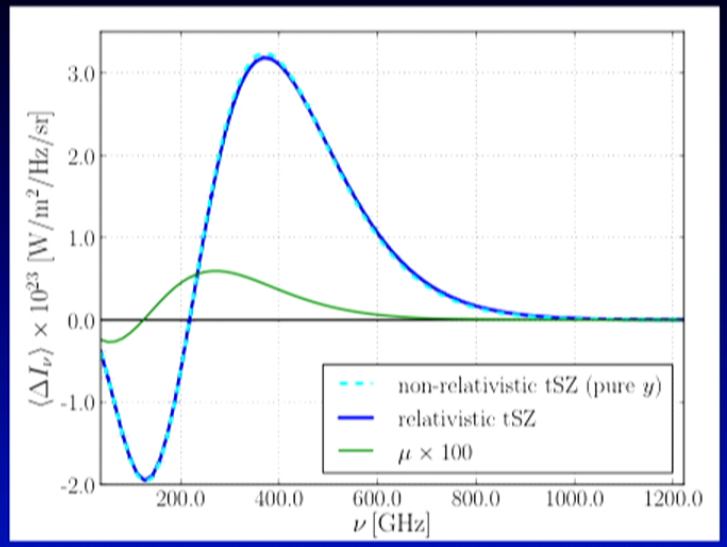


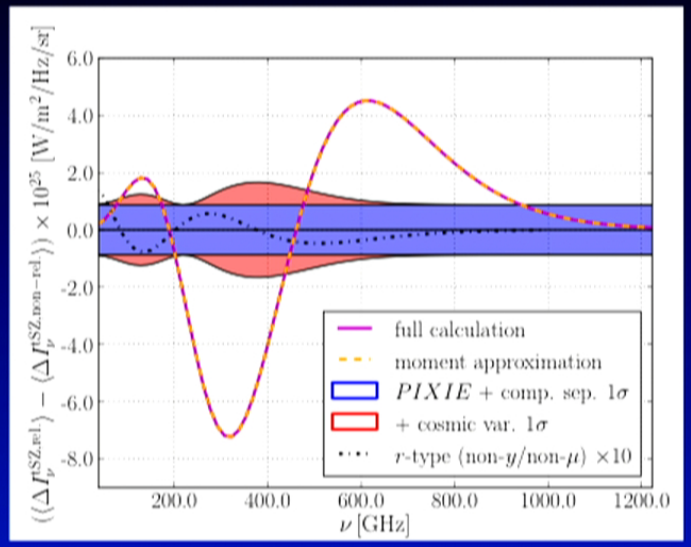
Distortion Green's function for energy release



JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

Taking the Universe's temperature

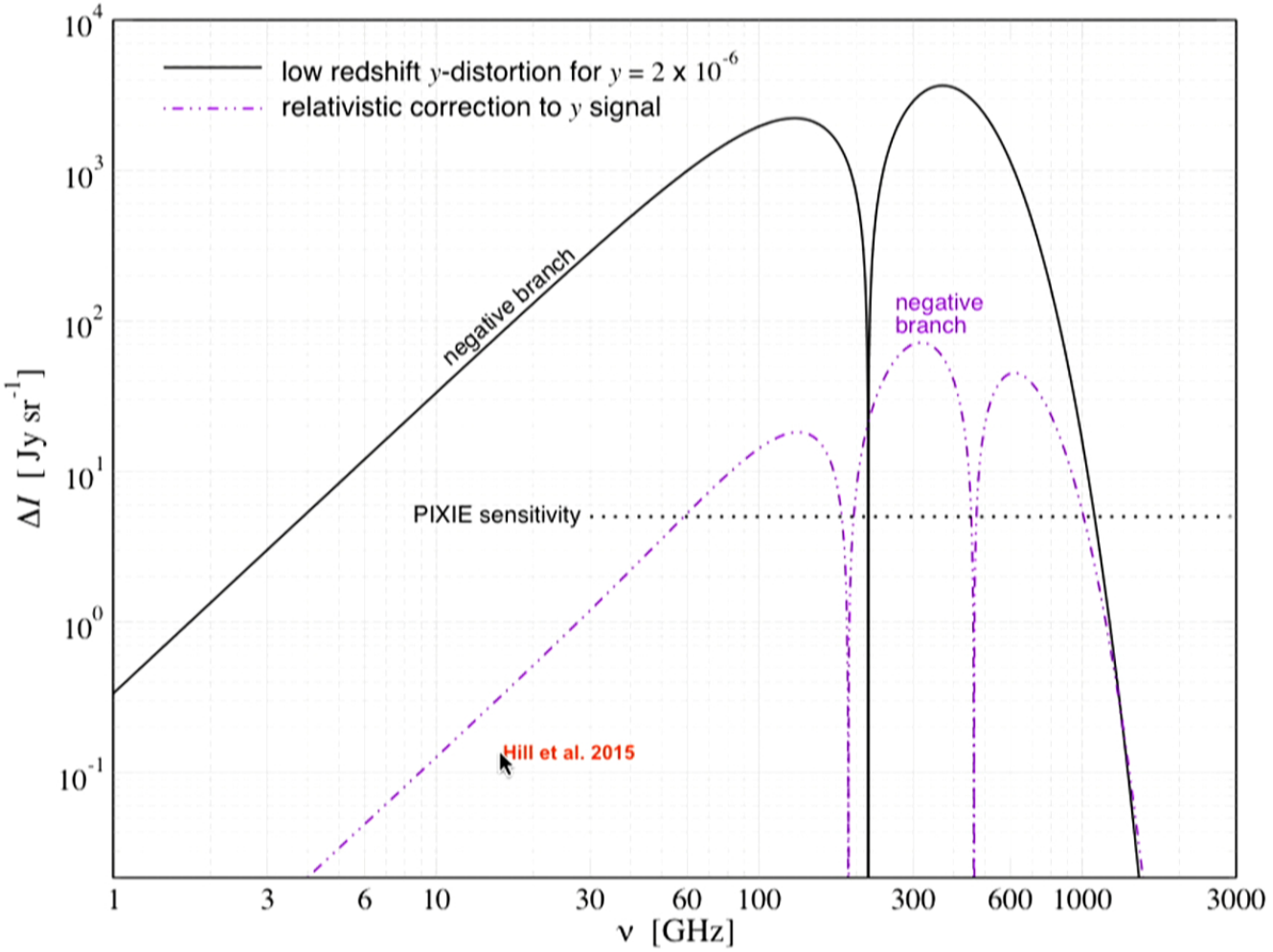




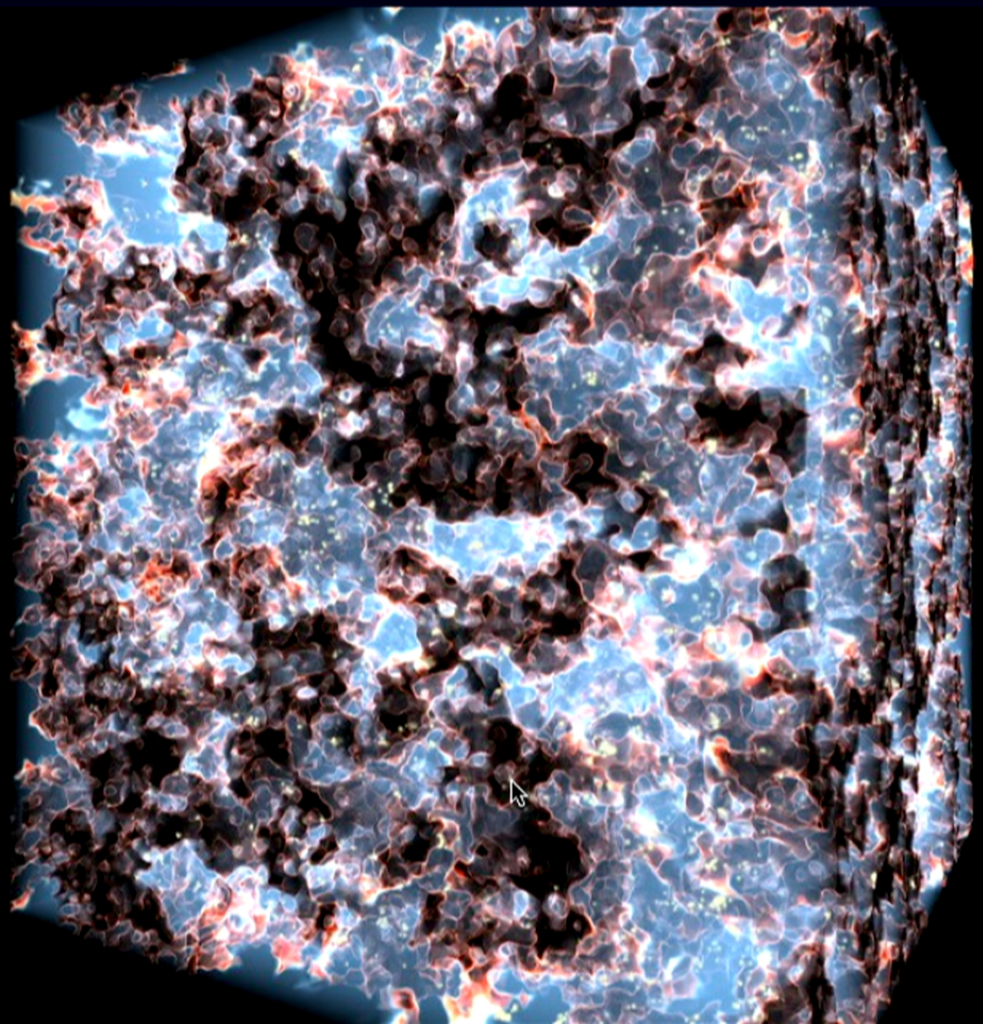
- $\langle y \rangle \simeq 1.8 \times 10^{-6}$ (~ 10% from IGM and reionization rest from ICM)
- > 1000 σ detection with PIXIE-type experiment
- optical depth-weighted temperature: $\langle kT_{\rm e} \rangle_\tau \simeq 0.208\,{\rm keV} (\equiv 2.4 \times 10^6\,{\rm K})$
- ~ 30 σ detection with PIXIE-type experiment

Hill et al., 2015, ArXiv:1507.01583

Average CMB spectral distortions



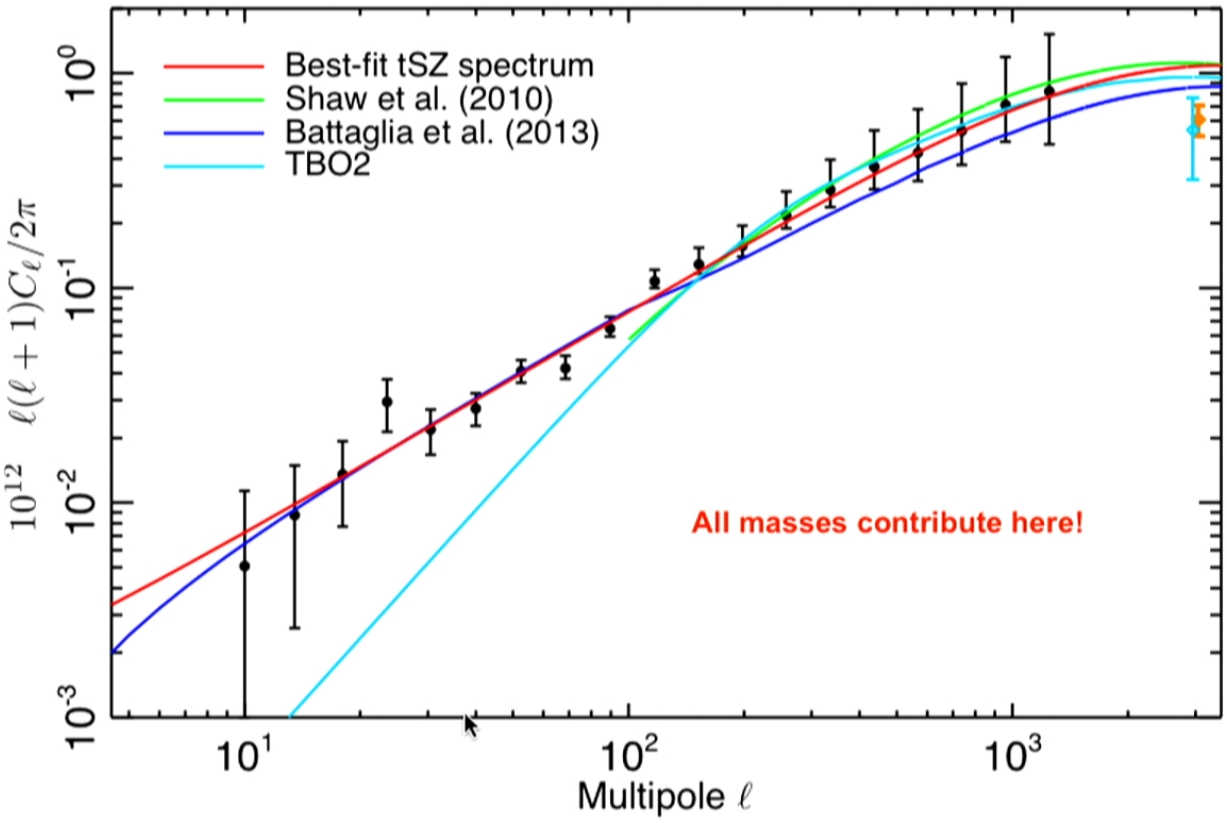
Fluctuations of the y-parameter at large scales



- spatial variations of the optical depth and temperature cause small-spatial variations of the y-parameter at different angular scales
- could tell us about the reionization sources and structure formation process
- additional independent piece of information!
- Cross-correlations with other signals

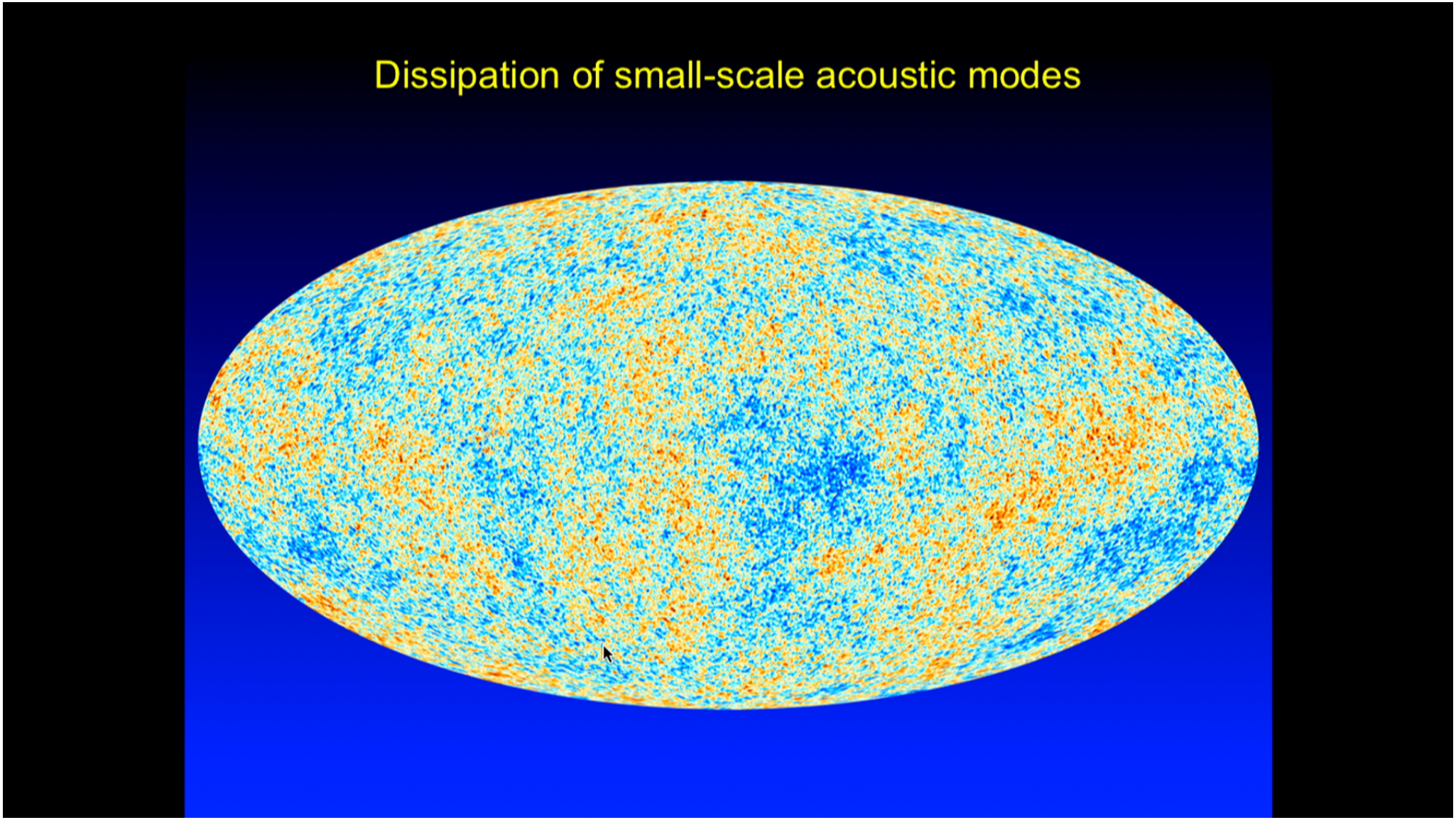
Example:
Simulation of reionization process (1Gpc/h) by *Alvarez* & *Abel*

Measured power spectrum for y-parameter

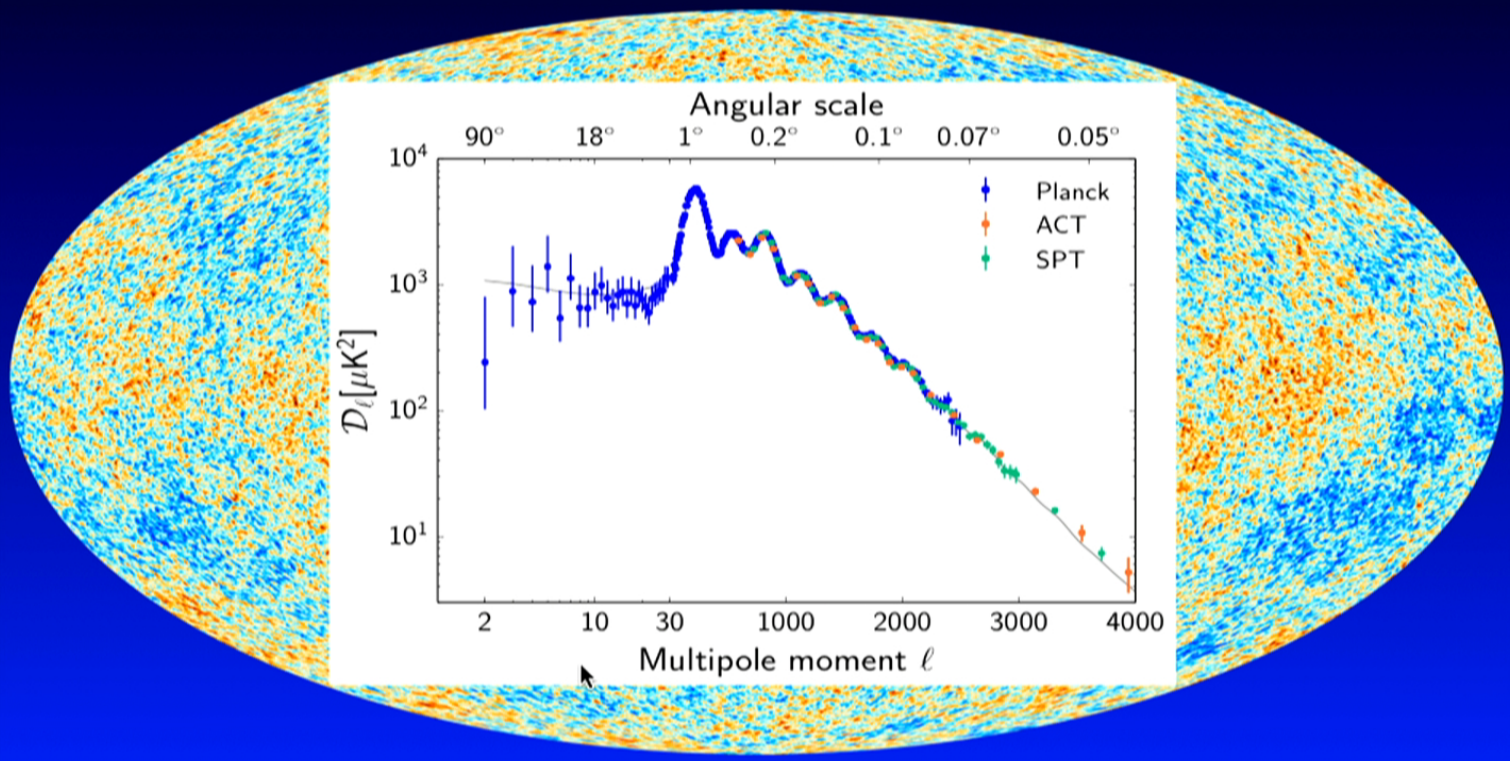


Planck Collaboration, 2015, XXII


The dissipation of small-scale acoustic modes


Dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



Energy release caused by dissipation process

'Obvious' dependencies:

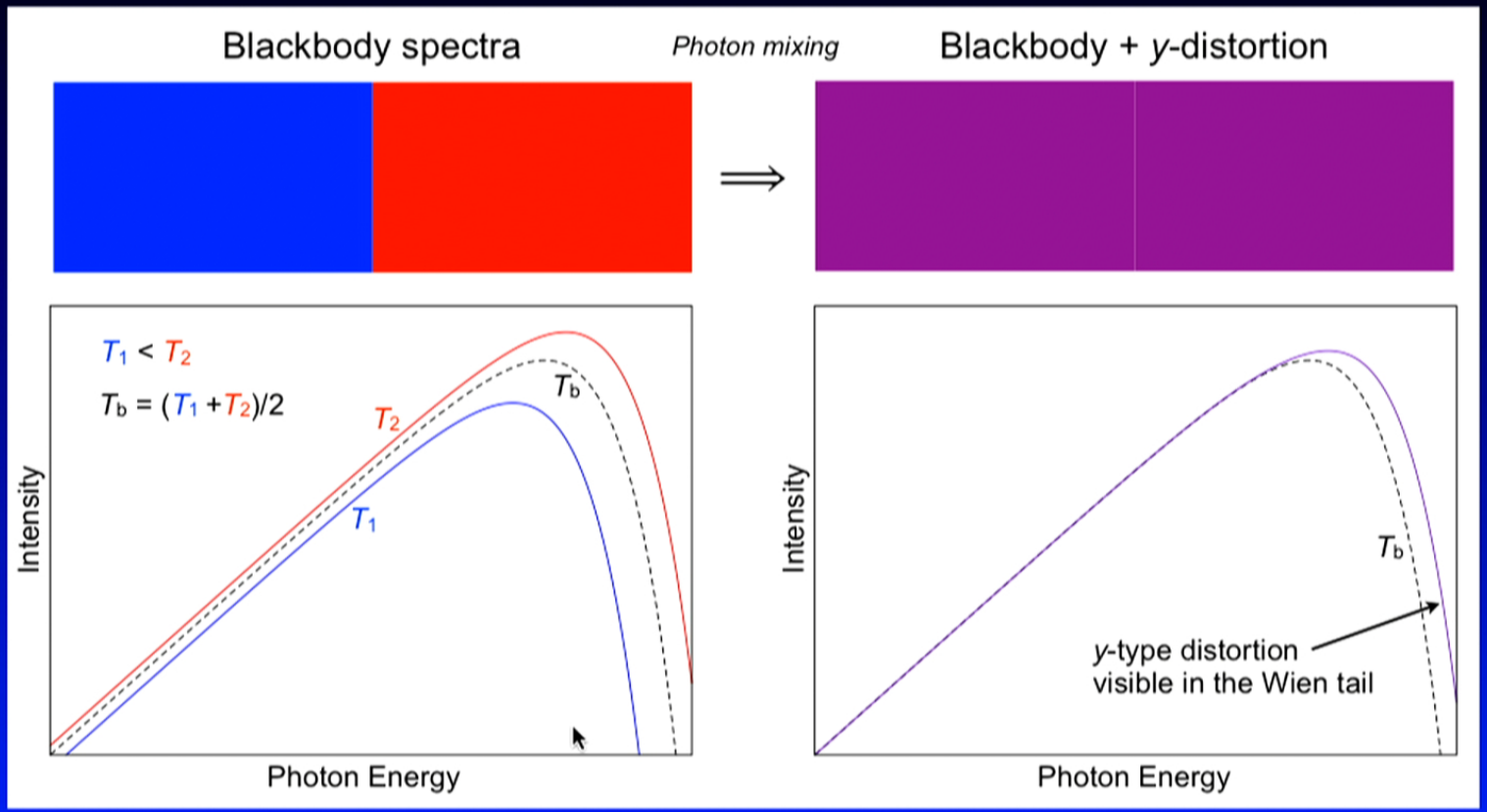
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* $\rightarrow k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

not so 'obvious' dependencies:

- *primordial non-Gaussianity* in the ultra squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- *Type* of the perturbations (adiabatic ↔ isocurvature)
  (Barrow & Coles, 1991; Hu et al., 1994; Dent et al, 2012, JC & Grin, 2012)
- *Neutrinos* (or any extra relativistic degree of freedom)

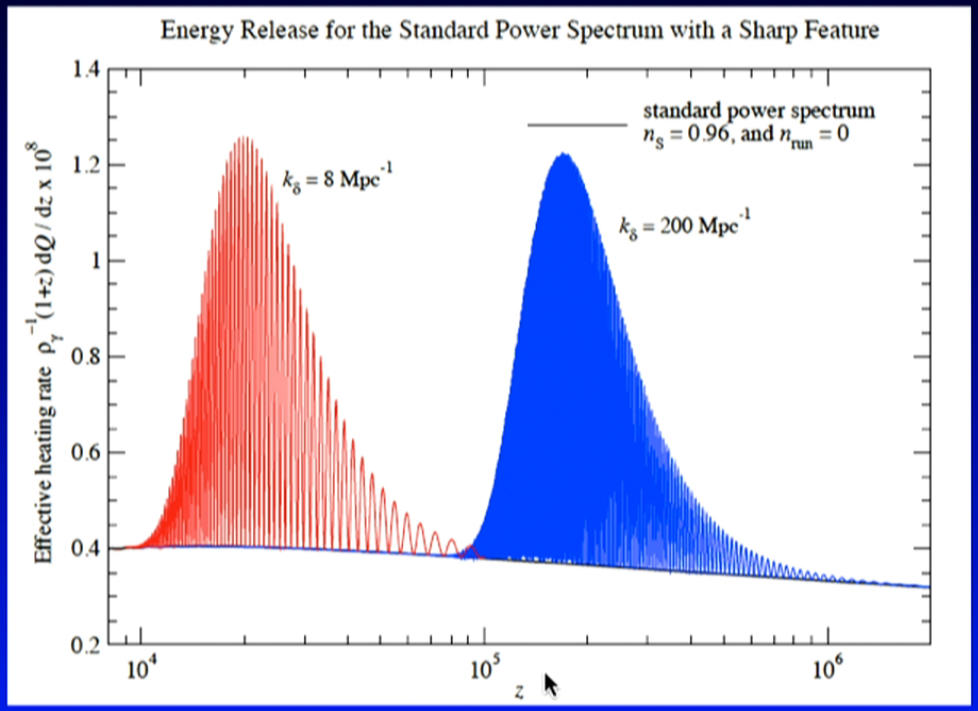
CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

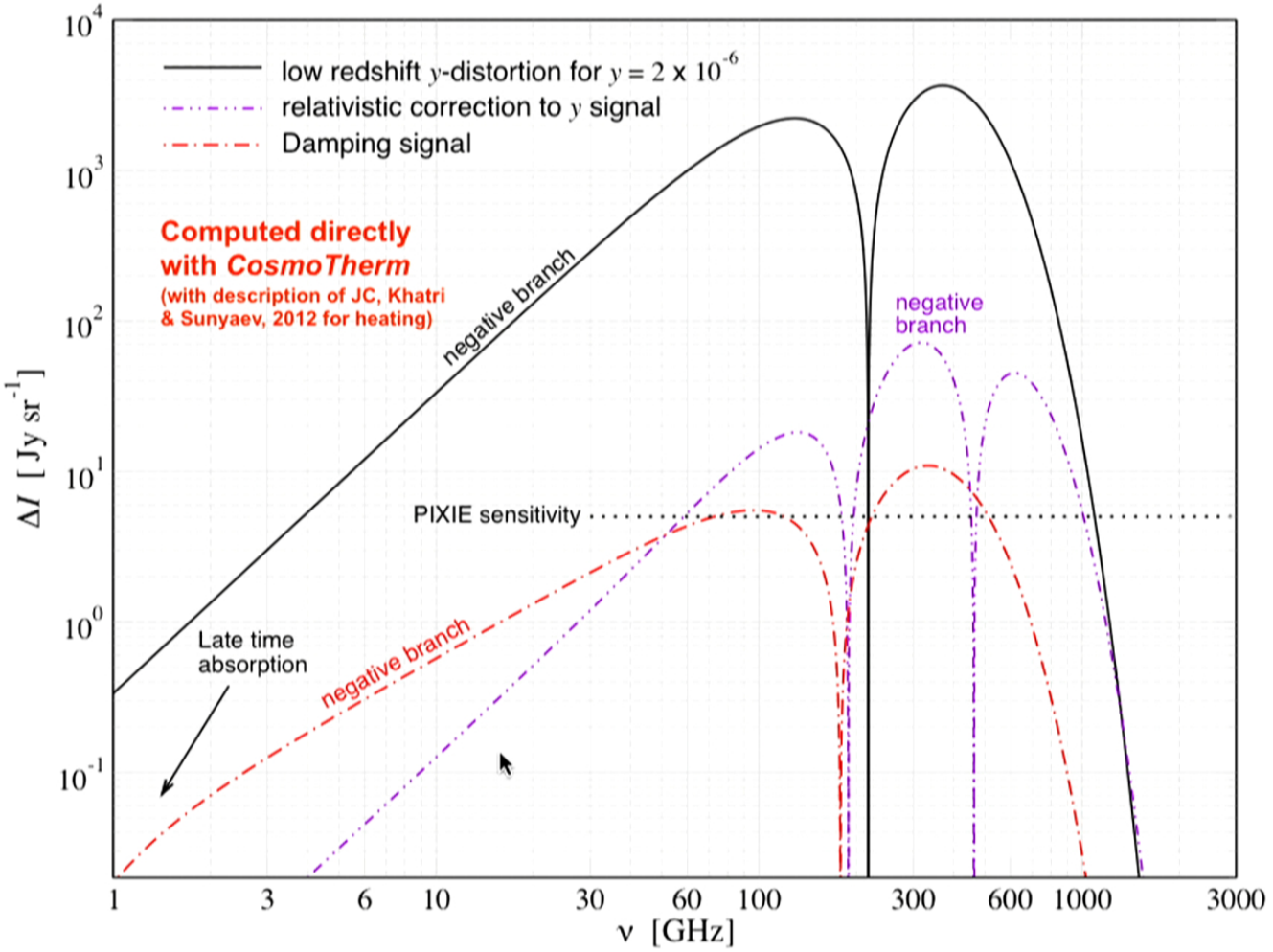
- Single mode with wavenumber k dissipates its energy at

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

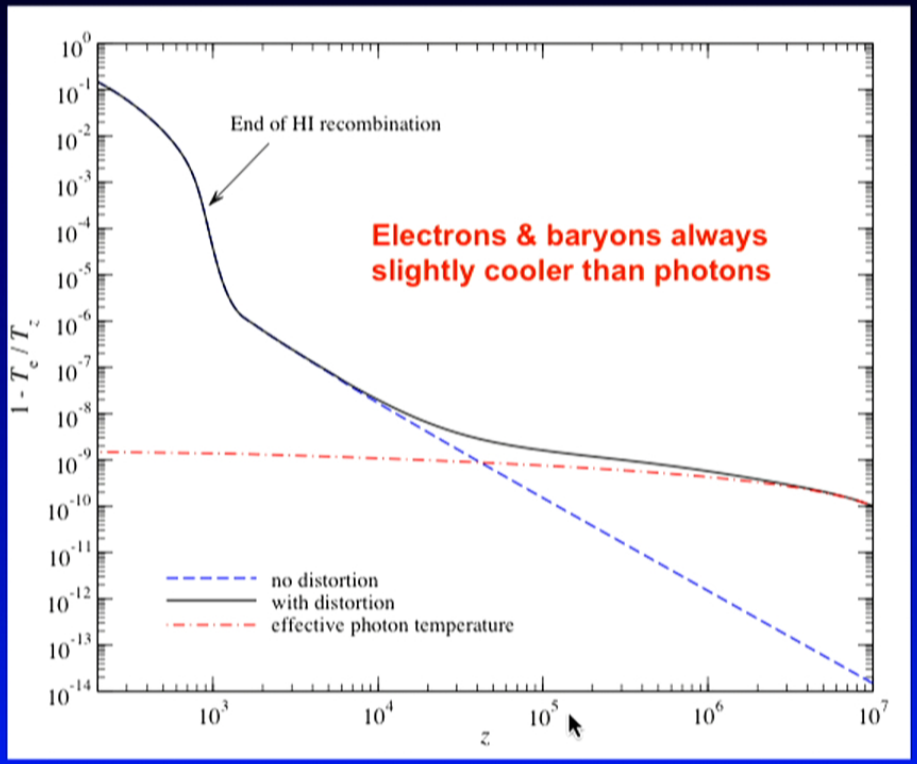
- Modes with wavenumber $50\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$ dissipate their energy during the μ-era
- Modes with $k < 50\ \mathrm{Mpc}^{-1}$ cause y-distortion

So what does one expect within ΛCDM?

Average CMB spectral distortions



Spectral distortion caused by the cooling of ordinary matter



$$\mu \simeq 1.4\,\frac{\Delta\rho_\gamma}{\rho_\gamma}\bigg|_\mu \approx -3\times10^{-9} \qquad y \simeq \frac{1}{4}\,\frac{\Delta\rho_\gamma}{\rho_\gamma}\bigg|_y \approx -6\times10^{-10}$$

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

- adiabatic expansion

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

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

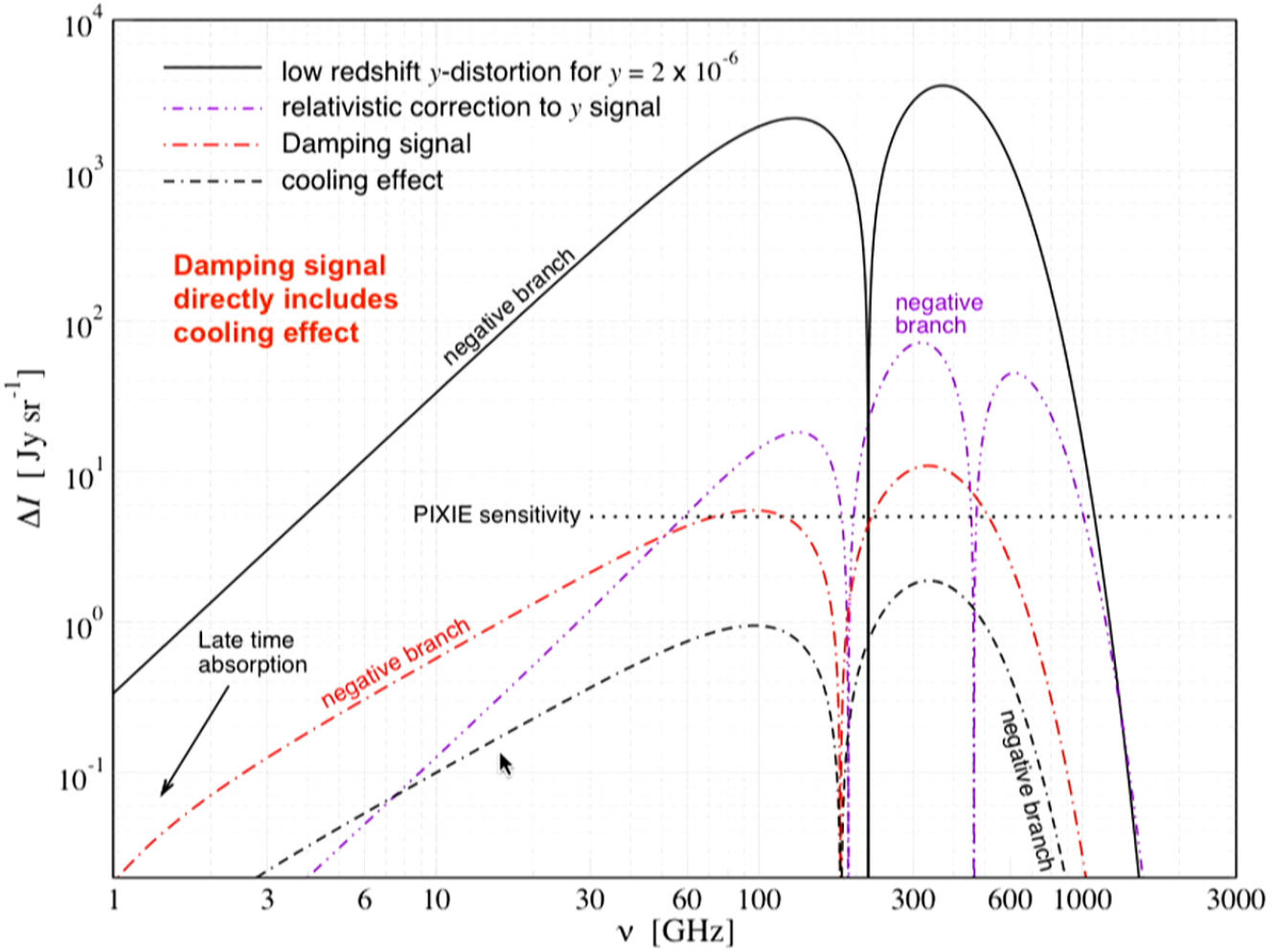
$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

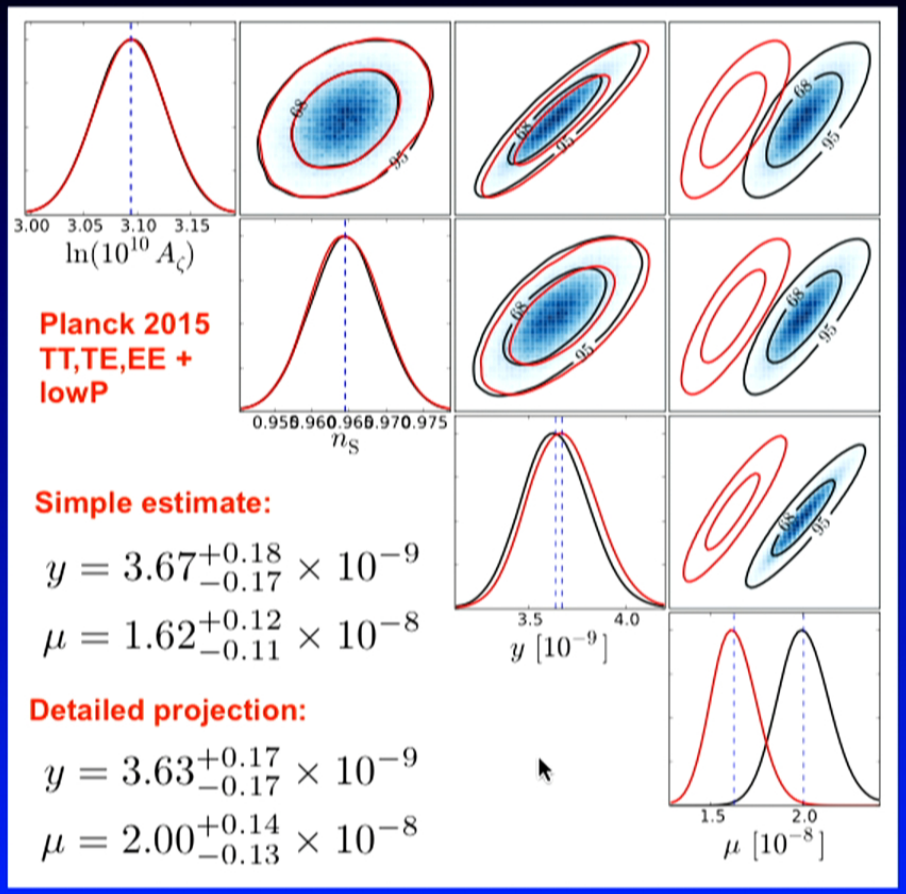
⇒ partial *cancellation*

- *negative* μ and y distortion
- late free-free absorption at very low frequencies
- Distortion a few times below PIXIE's current sensitivity

Average CMB spectral distortions



Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

Simple estimate:

$$y = 3.67^{+0.18}_{-0.17} \times 10^{-9}$$

$$\mu = 1.62^{+0.12}_{-0.11} \times 10^{-8}$$

Detailed projection:

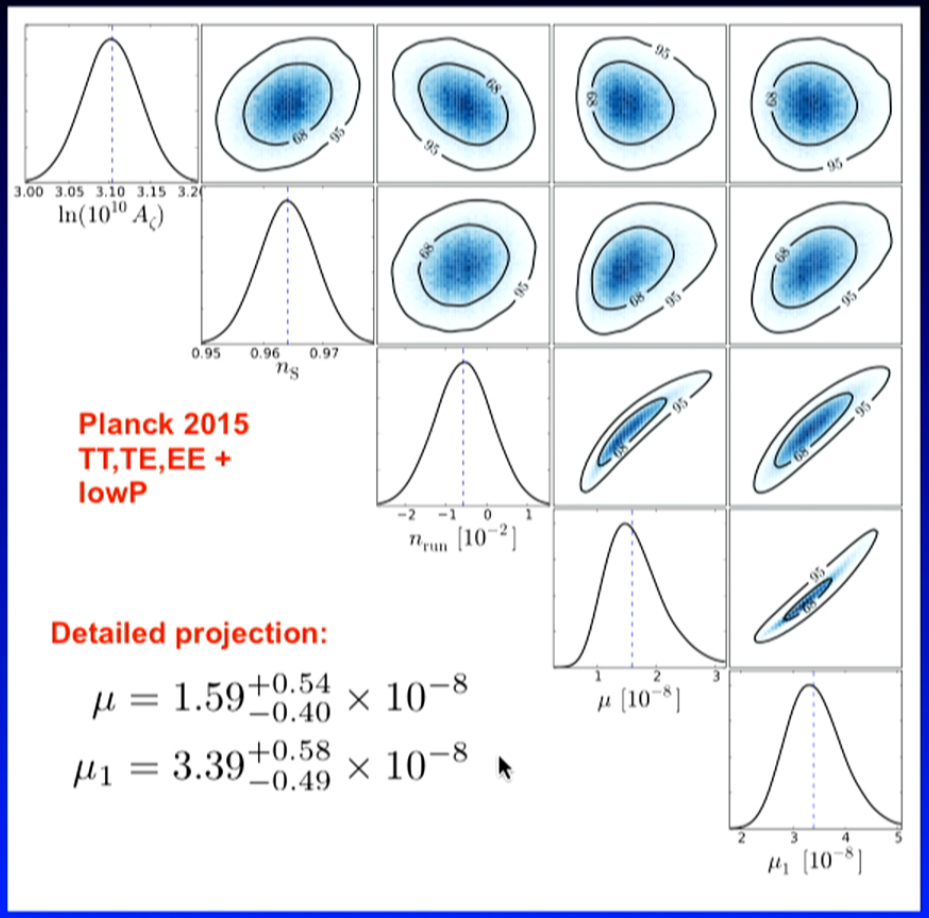
$$y = 3.63^{+0.17}_{-0.17} \times 10^{-9}$$

$$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$$

- *Errors dominated by power spectrum parameters*
- Detailed projections give slightly higher value for μ (~ 2.6σ)
- y-part swamped by low redshift distortion
- μ could be detectable at 1.5σ with PIXIE in current setting
  (see also JC, Khatri & Sunyaev, 2015)
- a factor of ~3.4 short of clear 5σ detection

JC 2016, ArXiv:1603.02496

Allowing for running of the spectral index



Planck 2015 TT,TE,EE + lowP

Detailed projection:

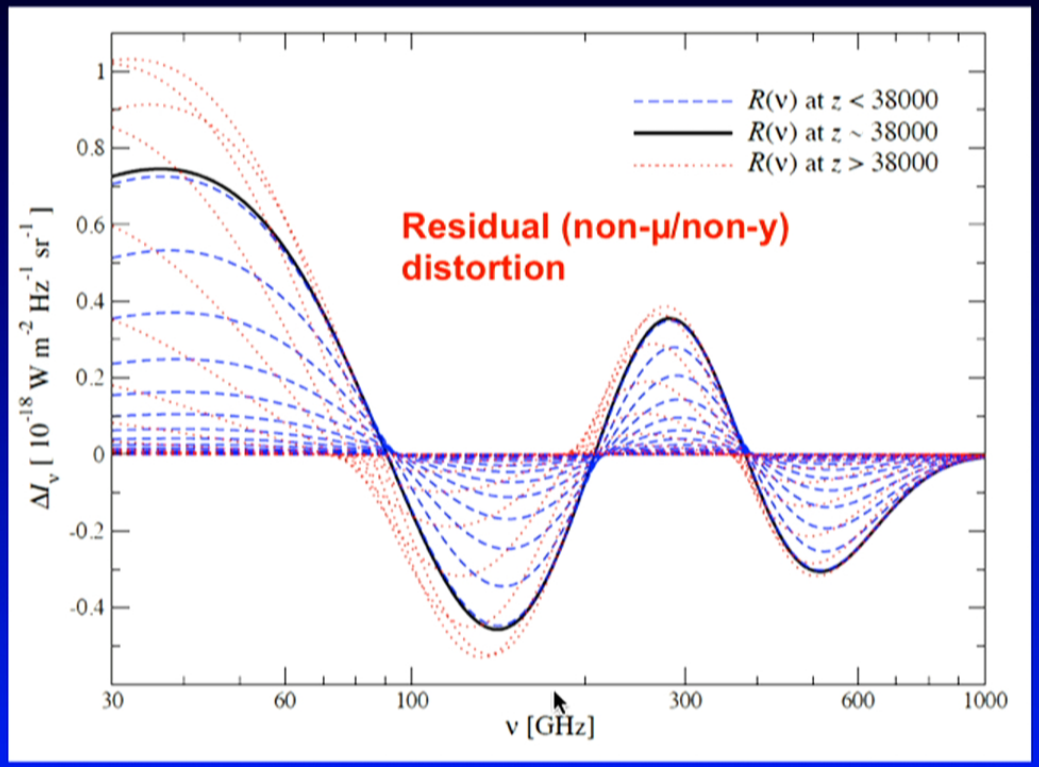
$$\mu = 1.59^{+0.54}_{-0.40} \times 10^{-8}$$

$$\mu_1 = 3.39^{+0.58}_{-0.49} \times 10^{-8}$$

- Posteriors more non-Gaussian
- *extended scenario*
- *small* negative running → *lower* value of μ
- μ signal ~1σ above current PIXIE sensitivity
- first residual distortion parameter μ_1 ~ 0.3σ for current PIXIE sensitivity

JC 2016, ArXiv:1603.02496

Using signal eigenmodes to compress the distortion data

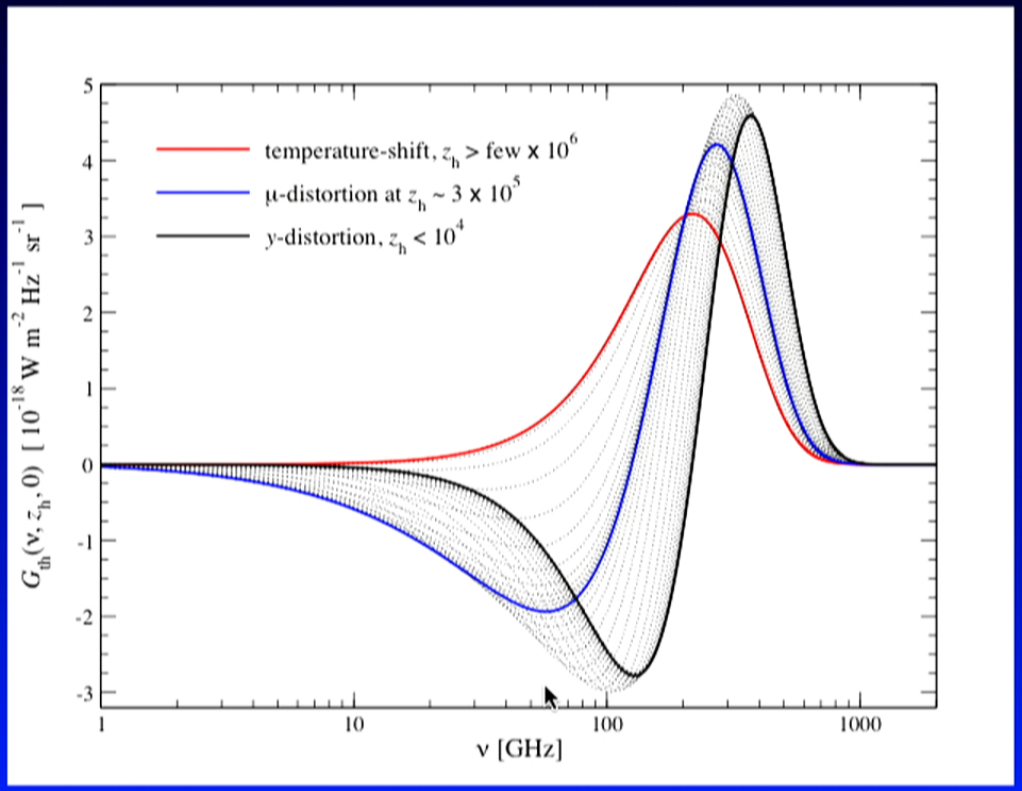


JC & Jeong, 2013

- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

  $p=\{y, \mu, \mu_1, \mu_2, \ldots\}$
- model-comparison + forecasts of errors very simple!

Using signal eigenmodes to compress the distortion data



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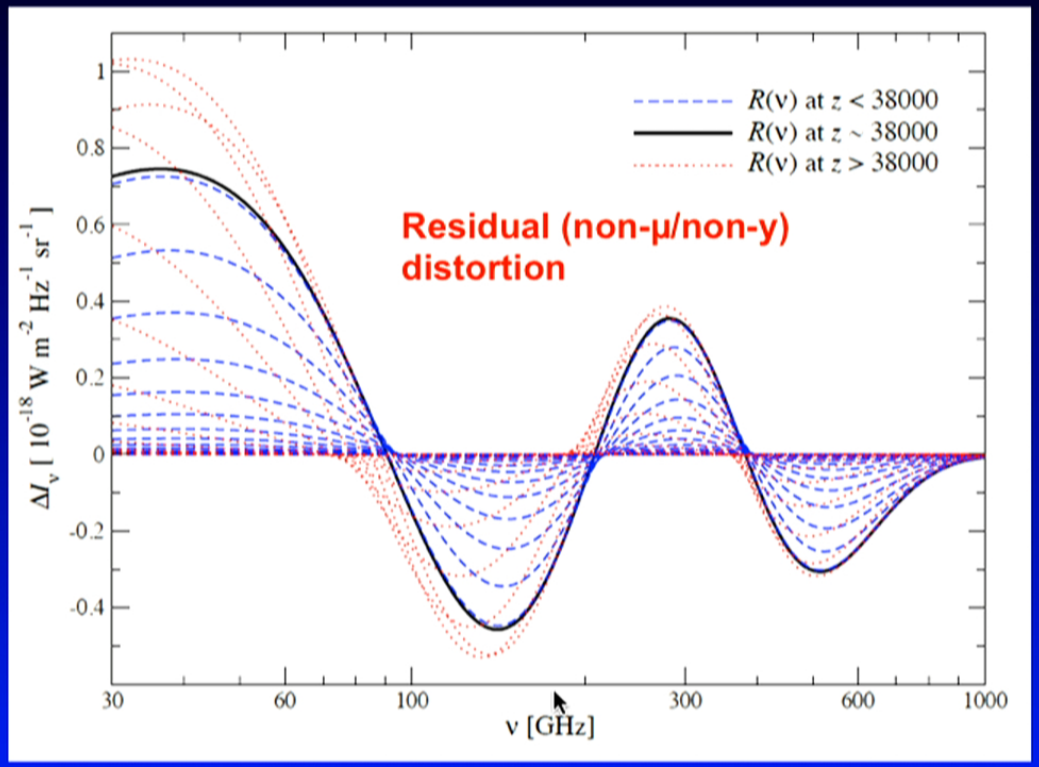
JC & Jeong, 2013

Using signal eigenmodes to compress the distortion data



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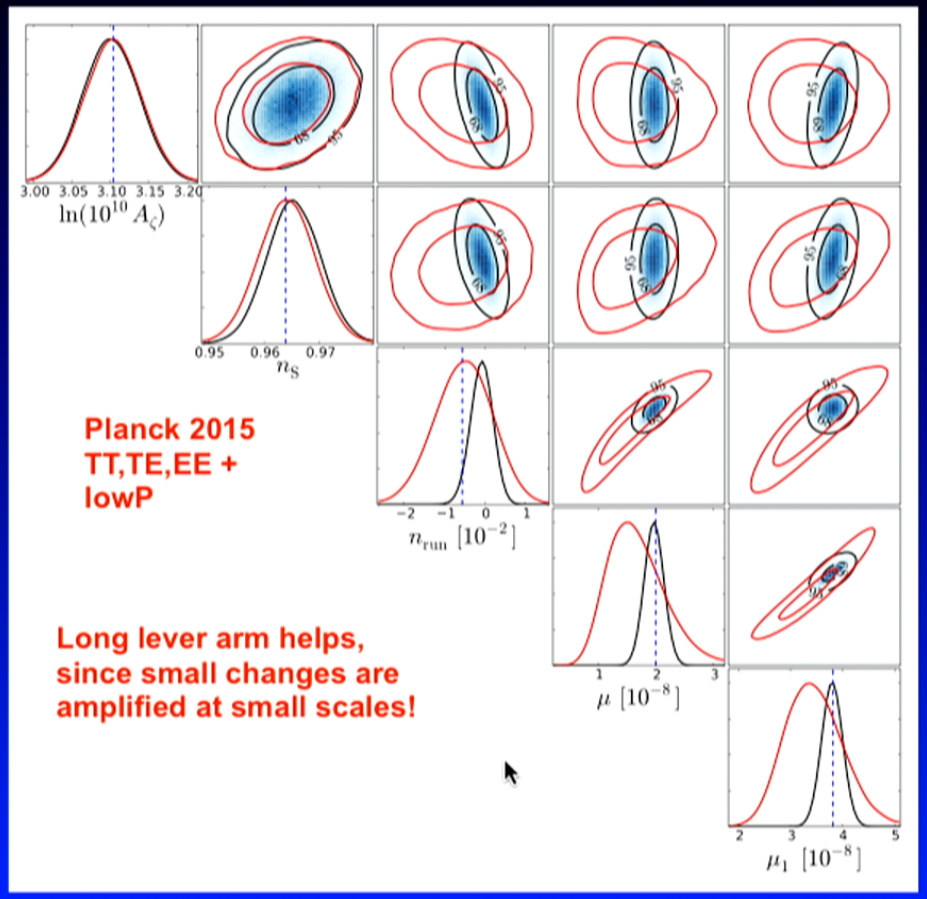
- compression of the useful information given instrumental settings
- new set of observables

  $p=\{y, \mu, \mu_1, \mu_2, \ldots\}$
- model-comparison + forecasts of errors very simple!

JC & Jeong, 2013

Ultimately this may be the only way to learn more!

Testing running with distortions



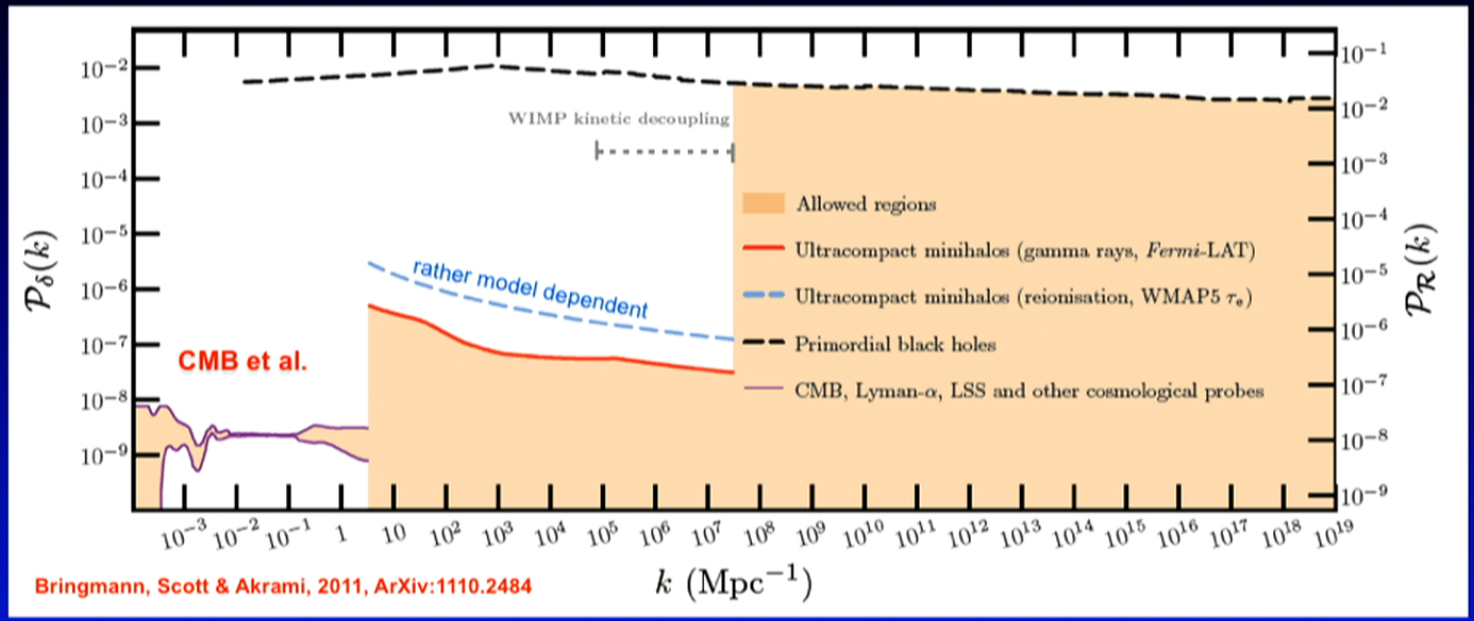
Planck 2015 TT,TE,EE + lowP

Long lever arm helps, since small changes are amplified at small scales!

- combined constraint Planck & PIXIE not affected much by distortion information
- at ~3.4 x PIXIE, constraint on running improved ~1.5 times
- centroid moves towards fiducial model
- at 10 x PIXIE, constraint on running improved 3 times over Planck alone
- μ could be detected at ~15σ and μ_1 at ~2.6σ
- combining with future imager (e.g., COrE+) *distortions* could still improve constraint on running (e.g., JC & Jeong, 2014)

JC 2016, ArXiv:1603.02496

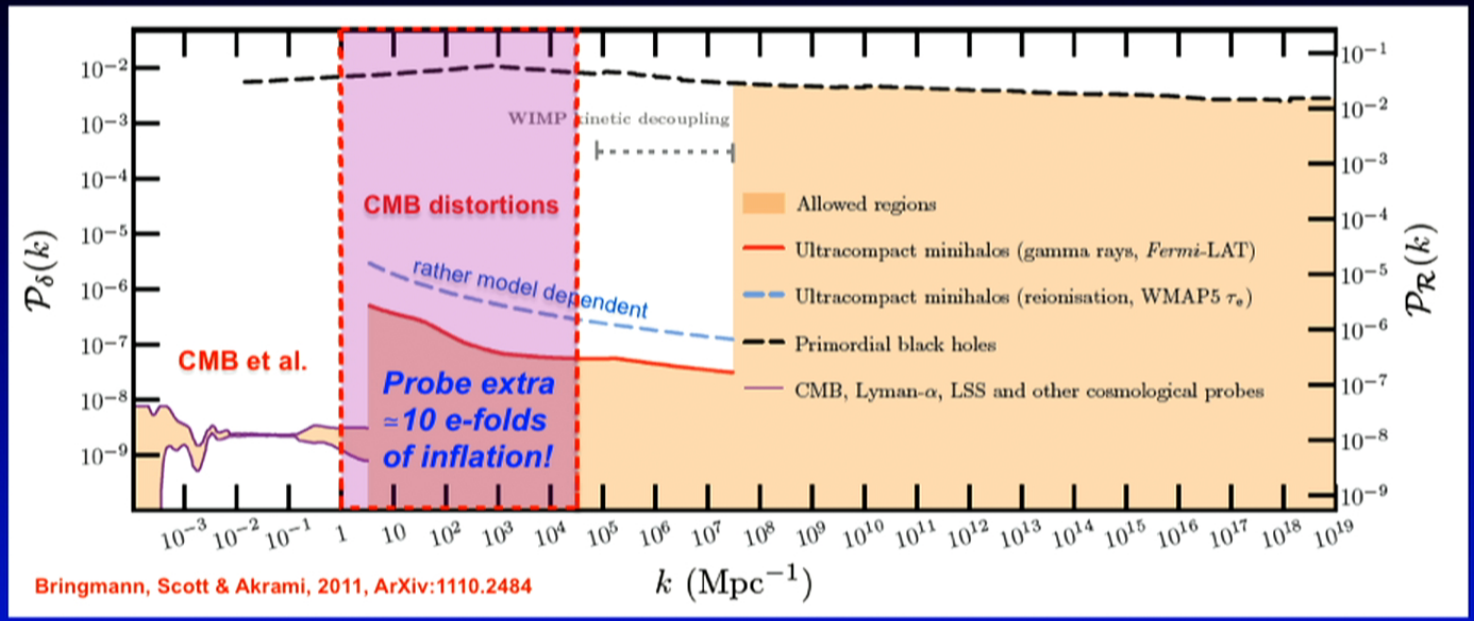
Distortions provide general power spectrum constraints!



- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*

e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

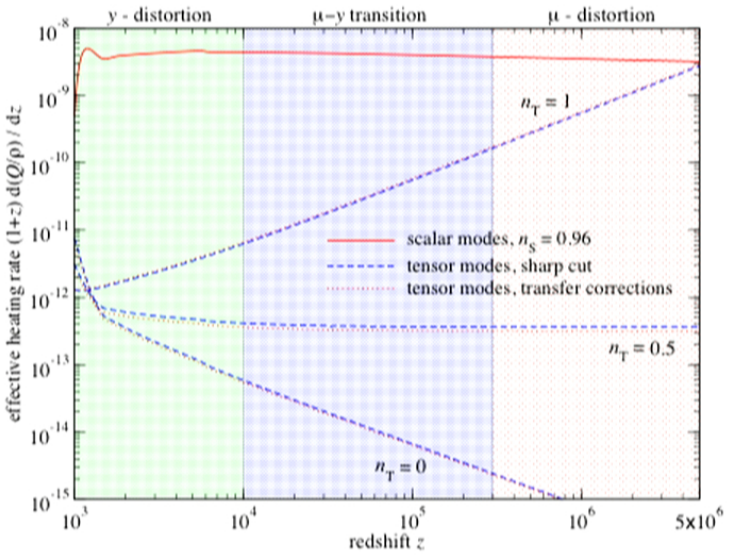
Distortions provide general power spectrum constraints!



- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about early-universe physics

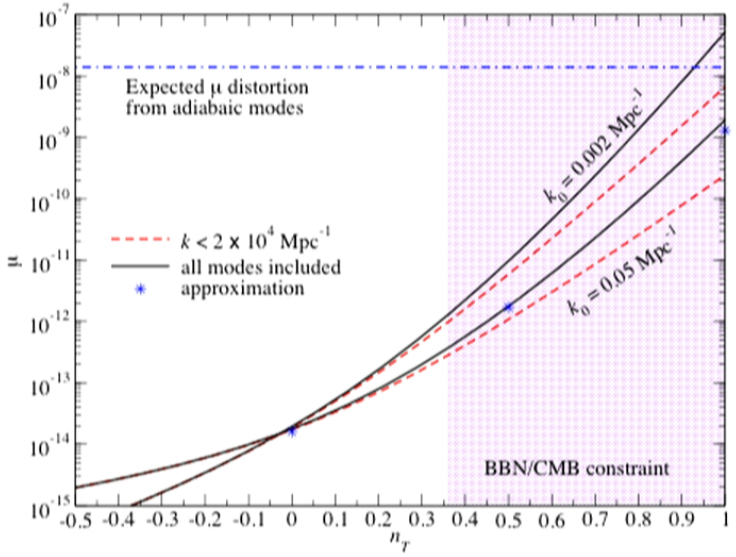
e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

Dissipation of tensor perturbations



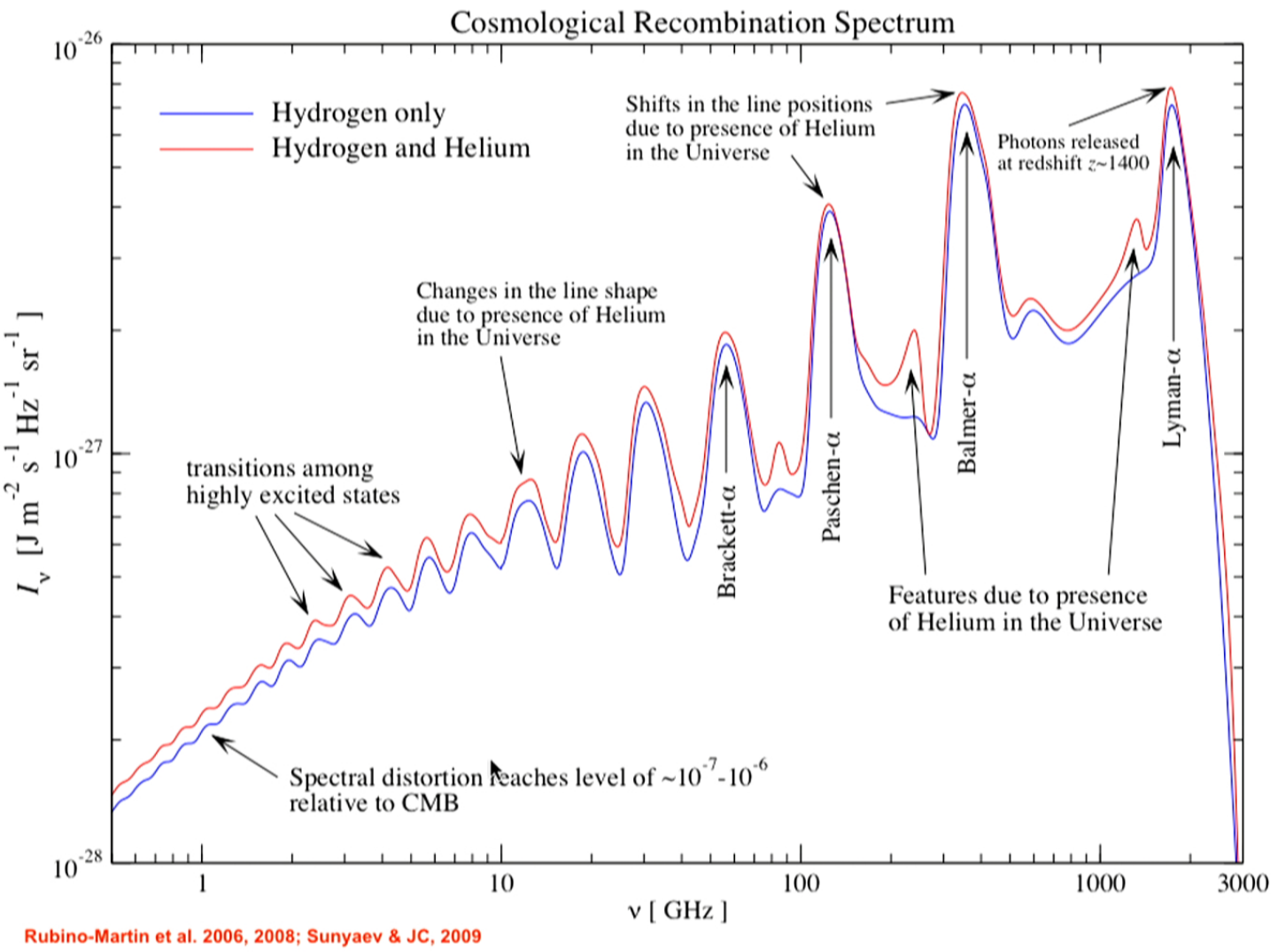
- heating rate can be computed similar to adiabatic modes
- heating rate much smaller than for scalar perturbations
- roughly constant per dlnz for n_T~0.5

- distortion signal very small compared to adiabatic modes
- no severe *contamination* in simplest cases
- models with 'large' distortion already constrained by BBN/CMB



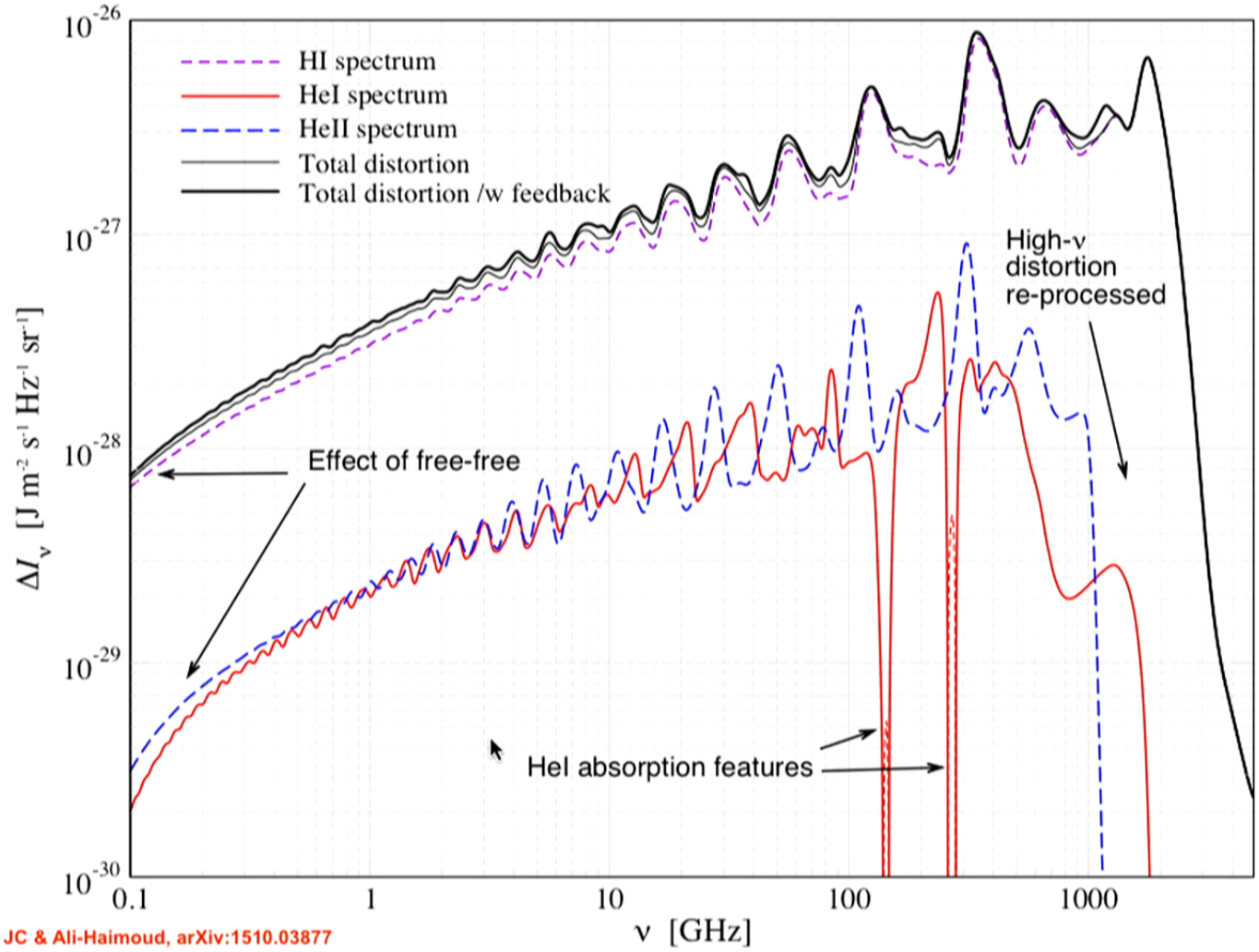
JC, Dai, Grin et al., 2014, ArXiv:1407.3653

The cosmological recombination radiation



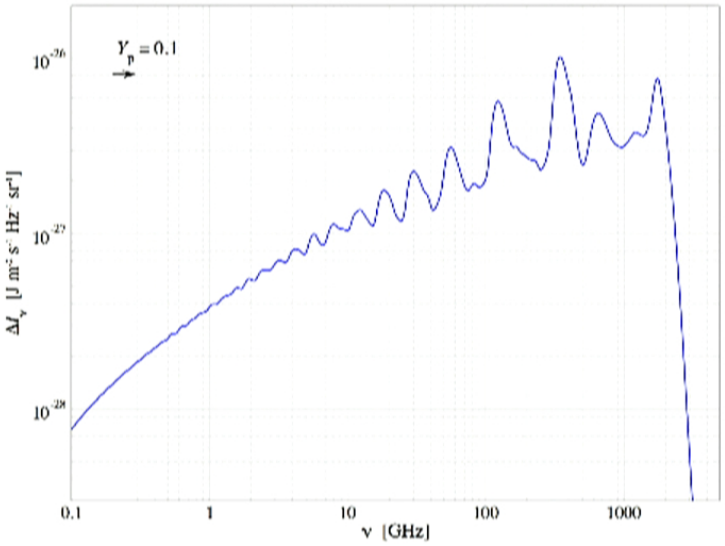
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

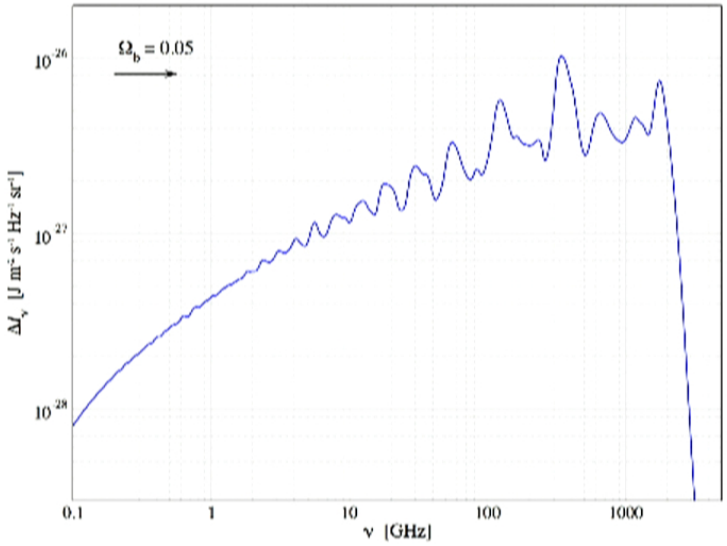
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR





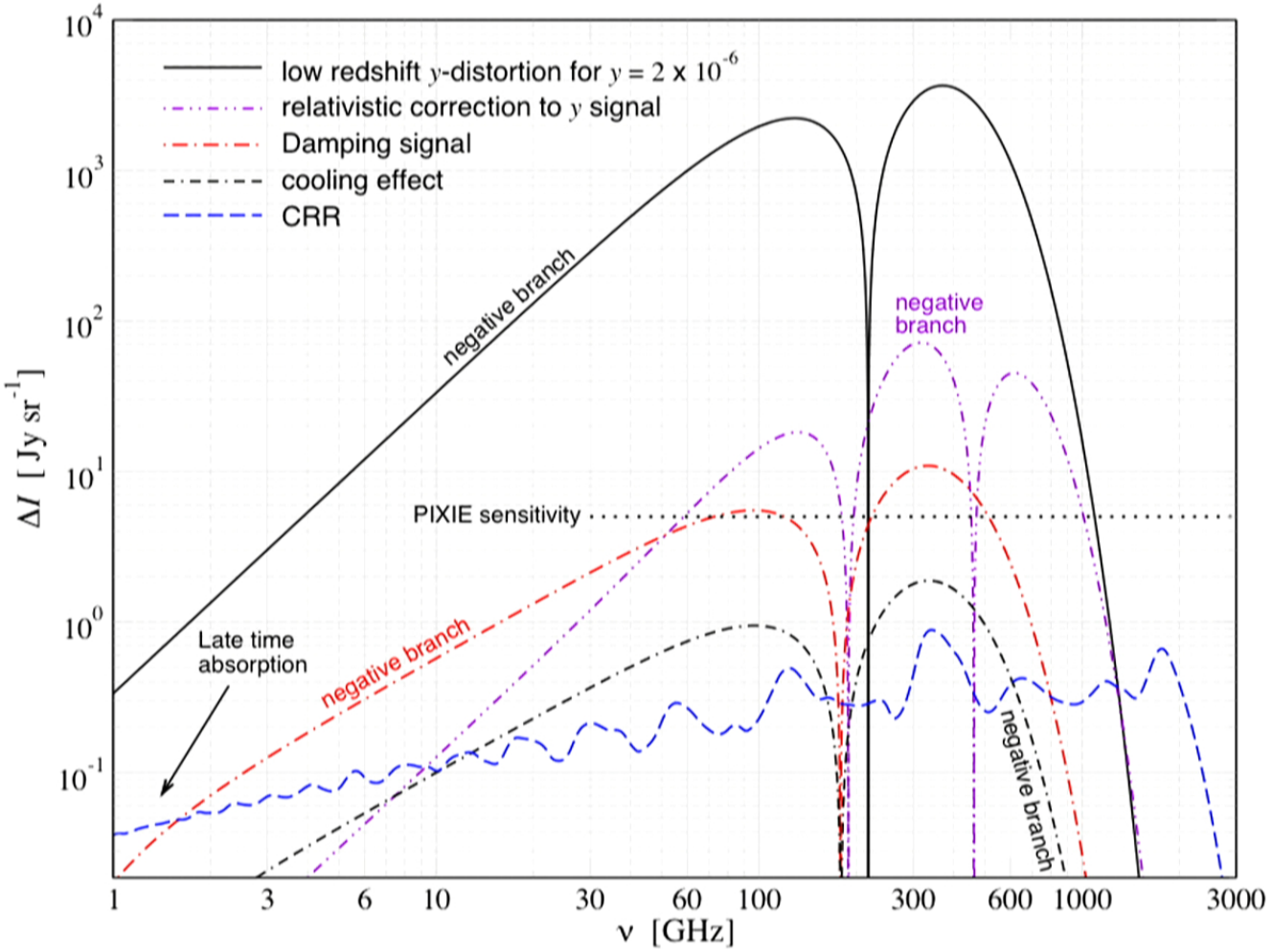
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

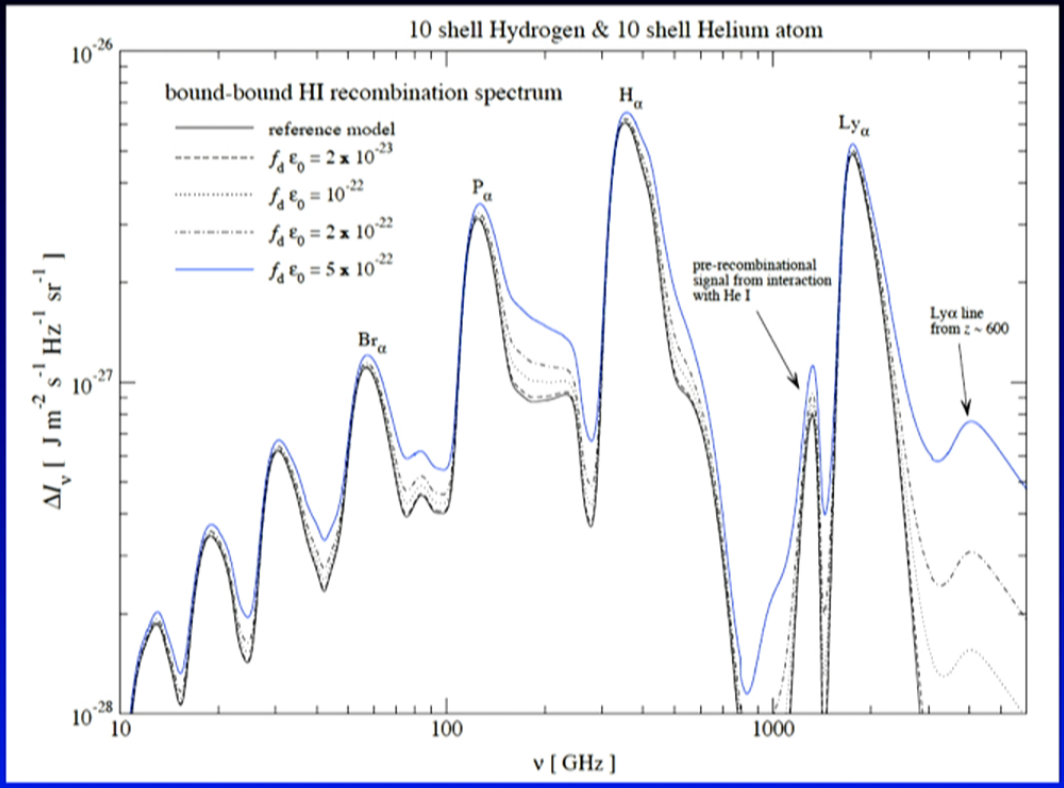
www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

Average CMB spectral distortions

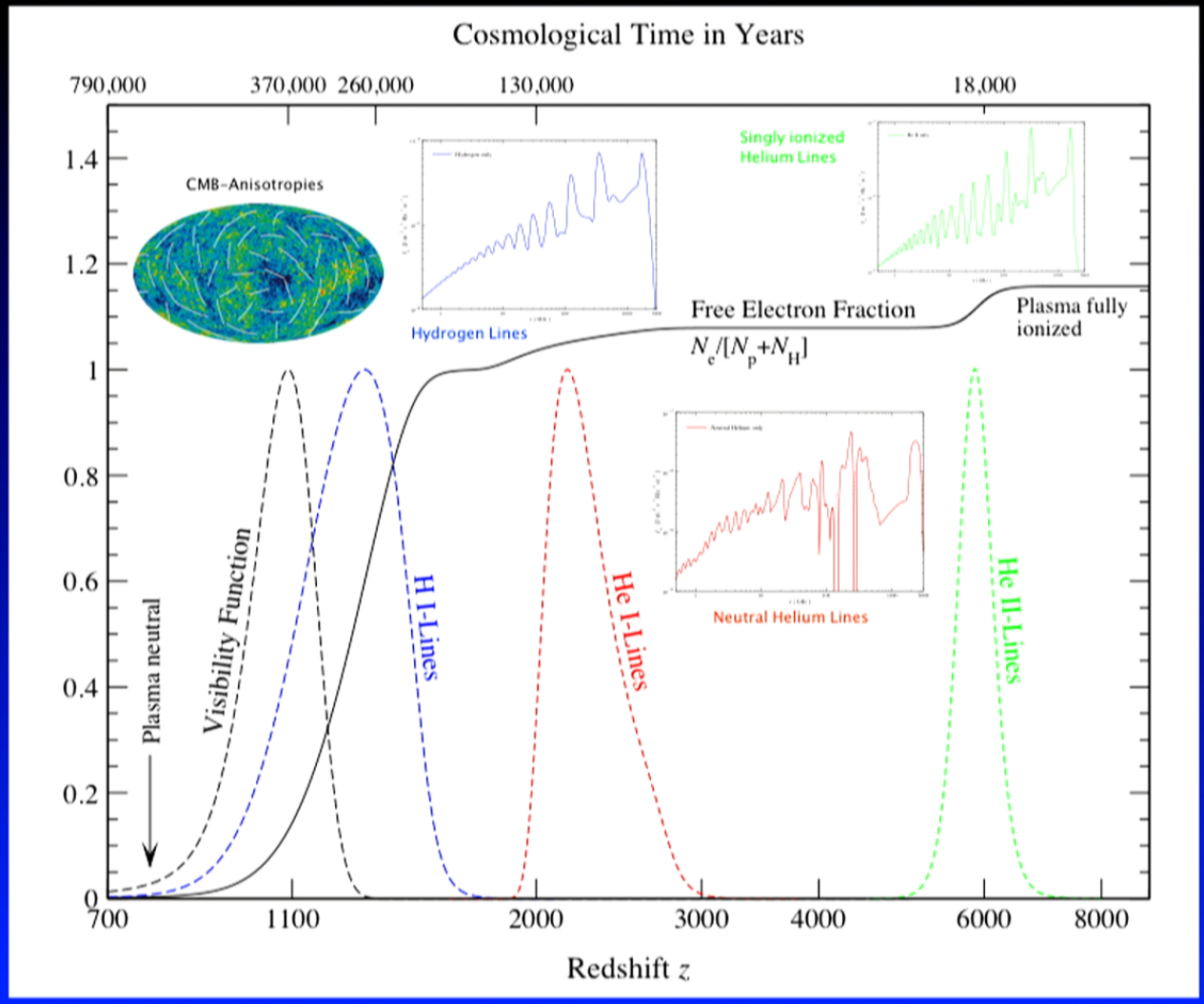


Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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


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