Future Steps in Cosmology using CMB Spectral Distortions

Jens Chluba

PPC 2017
Corpus Christi, May 22, 2017

Primordial Distortions

Cosmological Recombination lines

\[ G_\nu(z > 0) = 10^{-18} \text{ W m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \]

temperature-shift, \( z_h > \text{few} \times 10^6 \)

\( \mu \)-distortion at \( z_h \approx 3 \times 10^5 \)

\( \gamma \)-distortion, \( z_h < 10^4 \)

* CMB \( \equiv \) Cosmic Microwave Background
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

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

Planck all-sky temperature map
CMB provides another independent piece of information!

\[
T_0 = (2.726 \pm 0.001) \text{ K}
\]

**COBE/FIRAS**

Absolute measurement required!

One has to go to space...

- CMB monopole is 10000 - 100000 times larger than the fluctuations

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

\[ T_0 = 2.725 \pm 0.001 \text{K} \]
\[ |y| \leq 1.5 \times 10^{-5} \]
\[ |\mu| \leq 9 \times 10^{-5} \]


Nobel Prize in Physics 2006!
Standard types of primordial CMB distortions

**Compton y-distortion**

\[ x = \frac{\kappa y}{\kappa T_e} \quad (T_e >> T_y) \]

- Also known from thSZ effect
- Up-scattering of CMB photon
- Important at late times \((z<50000)\)
- Scattering inefficient

**Chemical potential \(\mu\)-distortion**

- Important at very times \((z>50000)\)
- Scattering very efficient

---

Sunyaev & Zeldovich, 1980, ARAA, 18, 537

Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect
CMB distortions probe the thermal history of the Universe at \( z < \text{few} \times 10^6 \).
CMB distortions probe the thermal history of the Universe at $z < \text{few} \times 10^6$.

Measurements of CMB spectrum will open a new unexplored window to the early Universe!
The image illustrates the pre- and post-recombination epoch with a focus on the \( \mu \)-era and \( y \)-distortion era. The timeline spans from the Big Bang to today, with key events marked, such as the creation of dark matter and the formation of galaxies. The \( y \)-distortion era is highlighted, showing the progression of intensity over wavelength (cm).
What does the spectrum look like after energy injection?

Intensity signal for different heating redshifts

- Temperature-shift, $z_h > \text{few } \times 10^6$
- $\mu$-distortion at $z_h \sim 3 \times 10^5$
- $y$-distortion, $z_h < 10^4$

Response function:
energy injection $\Rightarrow$ distortion

JC, 2013, ArXiv:1304.6120
What does the spectrum look like after energy injection?

**Intensity signal for different heating redshifts**

- Temperature-shift, $z_h > \text{few } 10^6$
- $\mu$-distortion at $z_h \sim 3 \times 10^5$
- $y$-distortion, $z_h < 10^4$

**Response function:**
energy injection $\Rightarrow$ distortion

- High-z SZ effect
- Full thermalization
- Hybrid distortion probes time-dependence of energy-release history

---

JC, 2013, ArXiv:1304.6120
What does the spectrum look like after energy injection?

**Intensity signal for different heating redshifts**

- **Temperature-shift,** $z_h > \text{few } 10^6$
- **$\mu$-distortion at** $z_h \sim 3 \times 10^5$
- **$\gamma$-distortion,** $z_h < 10^4$

**Response function:**

- energy injection
- distortion

**Distortion contains much more information than previously thought!**

Hybrid distortion probes the time-dependence of energy-release history

---

JC, 2013, ArXiv:1304.6120
pre-recombination epoch

µ-era

y-distortion era

post-recombination epoch

T-era

y-distortion
$\mu$-distortion

$\mu$-distortion era

$\mu$--era

$\mu$+$y$-era

$y$-distortion era

New hybrid era

pre-recombination epoch

post-recombination epoch

$\nu$-distortion

$\nu$-distortion at $\nu \sim 3 \times 10^5$

$\nu$-distortion, $\nu \ll 3 \times 10^5$

$\nu$-distortion, $\nu > 3 \times 10^5$

Temperature-shift, $\nu > 3 \times 10^5$

$y$-distortion

$y = 0.15$

$x = \frac{c_p}{c_p'}$

$T$-era

$0$ seconds

$10^{32}$ seconds

$10^{-30}$ seconds

1 second

100 seconds

100 years

1 year

380,000 years

200 million years

1 billion years

10 billion years

13.82 billion years

Today

Big Bang

Formation of the first atomic nuclei

Formation of the first stars and galaxies

Formation of the first gas clouds and stars

Formation of the first gas clouds

Formation of the first gas

Formation of the first particles

Formation of the first gas particles
CMB spectrum adds another dimension to the problem!

pre-recombination epoch

post-recombination epoch

T-era

μ-era

μ-y-era

y-distortion era

New hybrid era
CMB spectrum adds another dimension to the problem!

- **µ-distortion era**
  - Temperature-shift, \( z_h > 10^5 \)
  - y-distortion, \( z_h < 10^4 \)

- **µ+γ + residual distortion**
  - \( \nu \) [GHz]
  - \( G_{\nu}(\nu, z_h, 0) \) [10^{-18} W m^{-2} Hz^{-1} sr^{-1}]

- **post-recombination epoch**
  - Extra time-slicing at recombination

- **New hybrid era**
$T_0 = 2.725 \pm 0.001$ K

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

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


Only very small distortions of CMB spectrum are still allowed!

Nobel Prize in Physics 2006!

Error bars a small fraction of the line thickness!
Physical mechanisms that lead to spectral distortions

- **Cooling by adiabatically expanding ordinary matter**

- **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**

- **Cosmological recombination radiation**
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

- **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)

- **Additional exotic processes**
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)
Physical mechanisms that lead to spectral distortions

- **Cooling by adiabatically expanding ordinary matter**
  

- **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**
  

- **Cosmological recombination radiation**
  
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

- **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)

- **Additional exotic processes**
  
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)
Dramatic improvements in angular resolution and sensitivity over the past decades!
Dramatic improvements in angular resolution and sensitivity over the past decades!

Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!
PIXIE: Primordial Inflation Explorer

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

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.”

PIXIE was proposed to NASA in Dec 2016. Decision this year!
Physical mechanisms that lead to spectral distortions

- **Cooling by adiabatically expanding ordinary matter**
  

- **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**
  

- **Cosmological recombination radiation**
  
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

- **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)

- **Additional exotic processes**
  
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)
Average CMB spectral distortions

- Low redshift $y$-distortion for $y = 2 \times 10^{-6}$
- PIXIE sensitivity
- Reionization & structure formation
Average CMB spectral distortions

low redshift $y$-distortion for $y = 2 \times 10^{-6}$

relativistic correction to $y$ signal

Relativistic correction signal

Hill et al. 2015

PIXIE sensitivity

Dissipation of small-scale acoustic modes
Dissipation of small-scale acoustic modes

The figure shows the power spectrum $D_\ell [\mu K^2]$ as a function of the multipole moment $\ell$. The spectrum is displayed for different angular scales, ranging from 90° to 0.05°. The data points are represented by markers, with error bars indicating the uncertainty. The angular scale is shown on the top of the graph, with logarithmic scales for both the multipole moment $\ell$ and the $D_\ell [\mu K^2]$ values.

The graph includes data from multiple sources: Planck, ACT, and SPT. Each source has a different color and marker style, allowing for easy differentiation. The data points are spread across the multipole moment range, with variations depending on the angular scale.

The figure also includes residuals, which are displayed in the lower panels, showing the difference between the data and the best-fit model. The residuals are presented with error bars, indicating the uncertainty in the measurements.

The y-axis represents the power spectrum $D_\ell [\mu K^2]$ on a logarithmic scale, ranging from $10^{-4}$ to $10^4$. The x-axis represents the multipole moment $\ell$, ranging from 2 to 4000. The y-axis is labeled as $D_\ell [\mu K^2]$, and the x-axis is labeled as Multipole moment $\ell$.
Dissipation of small-scale acoustic modes

Silk-damping is equivalent to energy release!

Distortion due to mixing of blackbodies

Blackbody spectra

Photon Energy

Intensity

$T_1 < T_2$

$T_b = (T_1 + T_2)/2$

$T_1$

$T_2$

$T_b$

Photon mixing

Blackbody + y-distortion

Intensity

Photon Energy

$y$-type distortion visible in the Wien tail

JC, Hamann & Patil, 2015
Average CMB spectral distortions

- Low redshift $y$-distortion for $y = 2 \times 10^{-6}$
- Relativistic correction to $y$ signal
- Damping signal

Computed directly with CosmoTherm
(with description of JC, Khatri & Sunyaev, 2012 for heating)

Late time absorption

PIXIE sensitivity

Average CMB spectral distortions

\[ \Delta I [\text{Jy sr}^{-1}] \]

- low redshift \( y \)-distortion for \( y = 2 \times 10^{-6} \)
- relativistic correction to \( y \) signal
- Damping signal

**Computed directly with** CosmoTherm
(with description of JC, Khatri & Sunyaev, 2012 for heating)

Planck 2015
TT,TE,EE + lowP

\[ y = 3.63^{+0.17}_{-0.17} \times 10^{-9} \]
\[ \mu = 2.00^{+0.14}_{-0.13} \times 10^{-8} \]

Distortions provide general power spectrum constraints!

- Amplitude of power spectrum rather uncertain at $k > 3 \text{ Mpc}^{-1}$
- 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

*Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484*
Shedding Light on the ‘Small-Scale Crisis’

- ‘missing satellite’ problem
- ‘too-big-to-fail’
- Cusp-vs-core problem

⇒ Are these caused by a primordial or late-time suppression?

- A primordial suppression would result in a very small µ-distortions
- Spectral distortion measurements can test this question!
Average CMB spectral distortions

\[ \Delta I \text{ [Jy sr}^{-1}] \]

- low redshift \(\gamma\)-distortion for \(\gamma = 2 \times 10^{-6}\)
- relativistic correction to \(\gamma\) signal
- Damping signal
- cooling effect

Adiabatic cooling distortion
(JC & Sunyaev, 2012)

\[ T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2 \]

Distortion constraints on DM interactions through adiabatic cooling effect

\[
\text{max}(\sigma_0) \text{ [cm}^2\text{]} \quad \begin{cases} 
10^{-23} & \text{for } \chi \rightarrow \gamma, \\
10^{-27} & \text{for } \chi \rightarrow e, \\
10^{-31} & \text{for } \chi \rightarrow p.
\end{cases}
\]

- FIRAS
- PIXIE
- MW satellites
- XENON10

\[m_\chi \text{ [MeV]} \quad 0.001 \quad 0.01 \quad 0.1 \quad 1 \quad 10 \quad 100 \quad 1000\]
Cosmological Recombination Spectrum

$I_\nu \ [J \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}]$

- **Hydrogen only**
- **Hydrogen and Helium**

Shifts in the line positions due to presence of Helium in the Universe


differences in line shape due to presence of Helium in the Universe

transitions among highly excited states

Features due to presence of Helium in the Universe

Photons released at redshift $z \sim 1400$

Lyman-$\alpha$

Balmer-$\alpha$

Paschen-$\alpha$

Brackett-$\alpha$

Another way to do CMB-based cosmology!

Direct probe of recombination physics!

Spectral distortion reaches level of $\sim 10^{-7} - 10^{-6}$ relative to CMB

Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009
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 $\alpha$, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

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 $\alpha$, energy injection etc.)

CosmoSpec will be available here: [www.Chluba.de/CosmoSpec](http://www.Chluba.de/CosmoSpec)

Importance of recombination for inflation constraints

- Analysis uses refined recombination model (CosmoRec/HyRec)
Importance of recombination for inflation constraints

Without improved recombination modules people would be talking about different inflation models!
(e.g., Shaw & JC, 2011)

- Analysis uses refined recombination model (CosmoRec/HyRec)
Average CMB spectral distortions

\[ \Delta I \quad [\text{Jy sr}^{-1}] \]

- low redshift \( \gamma \)-distortion for \( \gamma = 2 \times 10^{-6} \)
- relativistic correction to \( \gamma \) signal
- Damping signal
- cooling effect
- CRR

Average CMB spectral distortions

Factor of > 10 needed to detect recombination lines...

What can CMB spectral distortions add?

- CMB spectral distortions *will* open a *new window* to the early Universe.
- new probe of the *inflation epoch* and *particle physics*
- *complementary* and *independent* source of information *not* just confirmation
- in *standard cosmology* several processes lead to *early energy release* at a level that will be detectable in the future
- extremely interesting *future* for CMB-based science!
What can CMB spectral distortions add?

- CMB spectral distortions will open a new window to the early Universe
- new probe of the inflation epoch and particle physics
- complementary and independent source of information not just confirmation
- in standard cosmology several processes lead to early energy release at a level that will be detectable in the future
- extremely interesting future for CMB-based science!

We should make use of all this information!
Photon energy

Distortion Signal

scattering inefficient

intermediate regime

scattering efficient

full thermalization

y-distortion

y+µ+residual distortion

µ-distortion

temperature shift

Time

380,000 years

7,000 years

8 years

2 months

Hydrogen lines

Neutral Helium lines

Ionized Helium lines

Last Scattering Surface

Recombination signal

Recombination era

time-dependent information

Blackbody era

Distortion visibility

Silk & Chluba, Science, 2014