CMB Spectroscopy: What Spectral Distortions Could Add (PIXIE, COSMO, APSERa and PRISTINE)

Jens Chluba
CMB Foregrounds for B-mode Studies
Tenerife, 15-18th October 2018

Primordial Distortions

Cosmological Recombination lines

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

Cosmological Recombination lines

Free-bound emission
Bound-bound transitions + 2s spectrum
Sum of all
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 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 ("^\wedge")
- Standard BBN scenario \( \rightarrow N_{\text{eff}} \) and \( Y_p \)
- Standard ionization history \( \rightarrow N_{e}(z) \)

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

Planck Collaboration, 2015, paper XIII
What are the main next targets for CMB anisotropies?

• *Primary* CMB temperature kind of finished...

• E modes cosmic variance limited to high-$l$
  - CVL-limit on Thomson optical depth 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

A bright and exciting future with lots of activity!
CMB provides another independent piece of information!

**COBE / FIRAS** (Far InfraRed Absolute Spectrophotometer)

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

Initial conditions

CMB anisotropies

Large-scale E & B-modes

CMB Lensing

SZ effect
CMB distortions probe the thermal history of the Universe at $z < \text{few} \times 10^6$.
\[ \frac{\Delta T}{T} \approx \frac{1}{4} \frac{\Delta \rho_\gamma}{\rho_\gamma} \quad \mu \approx 1.4 \quad y \approx \frac{1}{4} \frac{\Delta \rho_\gamma}{\rho_\gamma} \]
CMB spectrum adds another dimension to the problem!

- µ-distortion era
- µ+γ-era
- HI&He
- three different time-slicing at recombination

New hybrid era
$T_0 = 2.725 \pm 0.001 \text{ K}$

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

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

Only very small distortions of CMB spectrum are still allowed!


Nobel Prize in Physics 2006!

Error bars a small fraction of the line thickness!

Theory and Observations

Average spectrum
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)
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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 & 2016 as NASA EX mission (i.e. cost ~ 200-250 M$)

**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 mission concepts:**

- **PRISTINE (France)**
- **CMB-Bharat (India)**

**Decadal Survey**

White papers for Jan 2019
Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion

About APSERa

The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSEFa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval plasma in the early Universe adds broad spectral lines to the relic Cosmic Radiation. The lines are extremely wide because recombination is stalled and extended over redshift space. The spectral features are expected to be isotropic over the whole sky.

The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby radio-quiet locations and relocated to a remote site for long duration exposures to detect the subtle features in the cosmic radio background arising from recombination. The observing site would be appropriately chosen to minimize RFI from geostationary satellites and to be able to observe towards sky regions relatively low in foreground brightness.

Details in Rao et al., ArXiv:1501.07191
COSMO at Dome C

Concordia station at Dome-C

Concordia station:
- 75° 06' S – 123° 21' E
- 3233 m a.s.l.
- <T>=-50°    ;    min(T)=-85°
- High altitude but fully logistical supported
- 16 crew-members during winter.
- Maximum 80 people during summer
- Diffusely site tested at all wavelengths and continuous atmospheric monitoring
- Water Vapour Content ~75% of the time below 0.4mm PWV (Tremblin et al., 448 A65 A&A 2012)

• Circular and linear polarizations constrained to
  - CP<0.19%;
  - LP<0.11% (Battistelli et al., 423 1293 MNRAS  2012)

Taken from a talk by Elia Battistelli
Probing fundamental physics with CMB spectral distortions

12 Mar 2018, 00:30 → 16 Mar 2018, 19:00 Europe/Zurich

503-1-001 - Council Chamber (CERN)

CMB Spectral Distortion Science Book, First Edition

Main initiators: Al Kogut, Subodh Patil, Emanuela Dimastrogiovanni & JC
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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

Reionization & structure formation

- negative branch
- positive branch
- PIXIE sensitivity
- Relativistic correction signal

- Constrain total energy output
- Average temperature of the medium
- Constrain feedback mechanisms

$\nu$ [GHz]
Dissipation of small-scale acoustic modes

The figure shows the angular scale and multipole moment of the CMB power spectra, with data from Planck, ACT, and SPT. The spectra are displayed on a logarithmic scale, with angular scales ranging from 90° to 0.05° and multipole moments from 2 to 4000. The Planck data are shown in blue, ACT in red, and SPT in green. The residuals and data being fitted are displayed in the lower panels, with error bars corresponding to the diagonal elements of the covariance matrix.
Dissipation of small-scale acoustic modes

Silk-damping is equivalent to energy release!

**Distortion due to mixing of blackbodies**

$$T_1 < T_2$$

$$T_b = \frac{T_1 + T_2}{2}$$

- Photon mixing

$$B_\nu(T_1) + B_\nu(T_2) \neq B_\nu(T_1 + T_2)$$

- **y-type distortion visible in the Wien tail**

**Mixing is mediated by Thomson scattering ⇒ Silk damping**
Early power spectrum constraints from FIRAS

- based on classical estimate for heating rate
- Tightest / cleanest constraint at that point!
- simple power-law spectrum assumed
- $\mu \approx 10^{-8}$ for scale-invariant power spectrum
- $n_s \leq 1.6$

**Fig. 1.**—Spectral distortion $\mu$, predicted from the full eq. (11), as a function of the power index $n$ for a normalization at the mean of the COBE DMR detection $(\Delta T/T)_{0.0} = 1.12 \times 10^{-5}$. With the uncertainties on both the DMR and FIRAS measurements, the conservative 95% upper limit is effectively $\mu < 1.76 \times 10^{-4}$ (see text). The corresponding constraint on $n$ is relatively weakly dependent on cosmological parameters: $n < 1.60$ ($h = 0.5$) and $n < 1.63$ ($h = 1.0$) for $\Omega_0 = 1$ and quite similar for $0.2 < \Omega_0 = 1 - \Omega_\Lambda < 1$ universes. These limits are nearly independent of $\Omega_\Lambda$. We have also plotted the optimistic 95% upper limit on $\mu < 0.63 \times 10^{-4}$ for comparison as discussed in the text.
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)

If we do not see this signal then $\Lambda$CDM is in trouble!

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 new 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\(^{-1}\)
- complementary piece of information about early-universe physics

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e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013
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- FIRAS (JC, Erickcek & Ben-Dayan, 2012)
- CMB et al.
- PIXIE (Abitbol, JC, Hill and Johnson, 2017)
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 $z \sim 1400$

Features due to presence of Helium in the Universe

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

transitions among highly excited states

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

Another way to do CMB-based cosmology!

Direct probe of recombination physics!

Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009
Cosmological Time in Years

Redshift $z$

CMB-Anisotropies

Visibility Function

Free Electron Fraction

$N_e / (N_p + N_H)$

Hydrogen Lines

Singly ionized Helium Lines

Neutral Helium Lines

He II-Lines

Hydrogen Lines

Singly ionized Helium Lines

Neutral Helium Lines

He II-Lines
Average CMB spectral distortions

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

APSERa

What can CMB spectral distortions teach us?

• **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 CMB 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

*We should really make use of this information!*
Steps forward on CMB spectral distortions

• **Pioneering** work from the ground
  - Improved constraints on $\mu$ and $y$
  - Possible detection of average late-time $y$-distortion
  - Discovery potential (e.g., ARCADE excess, EDGES)

  ➡ COSMO at Dome-C and APSERa

• **Low-frequency foregrounds**
  - One of the main problems for distortions (Abitbol, JC, Hill and Johnson, 2017)
  - Capitalize on *existing experience* (e.g., C-Bass, Quijote)
  - One of the *important inputs* for B-mode searches

• **Advancing the frontier from space**
  - Probe of *inflation* and early-Universe physics
  - Complementary science to B-modes + *guaranteed signals*
  - Absolutely calibrated multi-frequency maps incredibly valuable (e.g., calibration issues, foreground separation)

  ➡ PRISTINE, PIXIE-prime, CMB-Bharat
What is PRISTINE?

Polarized Radiation Interferometer for Spectral distortions and INflation Exploration
Aims, boundary conditions and collaboration

• Measure both CMB polarisation and distortions
• From design of COBE/FIRAS and PIXIE optimise and adapt the science case and instrument design for a small mission
  – $y$-type distortions
  – Do from space what can best be done from space
  – Complementarity with other missions and ground based projects
  – Do not have the ambition of a definitive CMB mission

European and US Consortium

Max Abitbol
Jonathan Aumont
François Bouchet
Jens Chluba
Hervé Dole
Marian Douspis
Josquin Errard
Ken Ganga
Julien Grain
Vincent Guillet

Ariel Haziot
Guilaine Lagache
Mathieu Langer
Juan Macias-Perez
Bruno Maffei
Jean-Pierre Maillard
Anna Mangilli
Luca Pagano
Etienne Pointecouteau
Jean-Loup Puget

Louis Rodriguez
Gérard Rouillé
Abdellah Roussafi
Giorgio Savini
Jean-Luc Starck
Valentin Sauvage
Andrea Tartari
Neil Trappe
Sébastien Triqueneaux
Gérard Vermeulen

PI: Nabila Aghanim

Courtesy: Bruno Maffei
**Instrument Philosophy**

**Optimised imaging** polarised FT Spectro. based on PIXIE concept

- Two telescopes of 36 cm each
- Frequency range 90 to 2000 GHz
  - 2 THz decreases largely the noise contribution from dust and mitigates degeneracy with CIB, and correlation with synchrotron
  - 90 GHz improves spatial resolution and constraints size of optical elements
- Spectral resolution of 5 GHz
  - Mitigates contamination from lines and optimises legacy ISM & galaxies
- Spatial resolution 0.75 deg equivalent Gaussian
- Array of 7 dual polarised pixels (x 2, one for each output port)
- Sensitivity similar to PIXIE /10
- Internal absolute photometric calibrator
- Try to reduce risks and have high TRL

- Slow spinning

**Proposal to be submitted to ESA (F-class)**

*Courtesy: Bruno Maffei*
Instrument concept

Courtesy: Bruno Maffei
Detector array at ~ 100mK
7 horn-coupled dual-polarisation bolometers on curved focal surface
Potential internal calibration mechanism

G. Savini
JP Maillard
Science with PRISTINE

Spectral distortion forecasts by Max Abitbol:

- Significant detection of $y (>10 \sigma)$
- Close to detecting average rel. thSZ
- Improved limit on $\mu$

B-mode forecasts by Mathieu Remazeilles and Josquin Errard:

- $20 \sigma$ detection of $\tau$ and E-mode reconstruction at $2 \leq l \leq 50$
- $5 \sigma$ detection of $r = 10^{-2}$

Additional science and Foregrounds

- Large-angle CIB and CO intensity mapping
- Absolutely calibrated maps of the sky at many frequencies
- Goldmine for foreground studies
- Could be crucial for B-mode searches
Uniqueness of CMB Spectral Distortion Science

Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

Silk & Chluba, Science, 2014

PIXIE

APSERa

PRISTINE
COSMO
CMB-Bharat