Future Steps in CMB* Cosmology

Jens Chluba

53rd Rencontres de Moriond
La Thuile, March 21st, 2018

* CMB ≙ Cosmic Microwave Background
Some of the “big” questions in Cosmology:

• What is the Universe made of?
• How did it start? What are the initial condition?
• How did all the structures form?
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 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 ("\(^{\wedge}\)"")
- Standard BBN scenario \(\rightarrow N_{\text{eff}}\) and \(Y_p\)
- Standard ionization history \(\rightarrow N_e(z)\)

Planck Collaboration, 2015, paper XIII
Polarization signal is caused by physics of Thomson scattering.
Beautiful measurements of CMB E-modes!

- **E-modes generated by scalar and tensor perturbations**
- **B-modes sourced by tensors**
  - gravitational waves / inflation
- observed E-modes match model predicted from best-fit temperature power spectrum!
Thermal SZ effect is now routinely observed!

~ 1230 objects
CMB lensing

Higher order statistics of CMB reveal presence of gravitational lenses

40 σ measurement!

Power spectrum of lensing potential

CMB serves as background light
First real map of the lensing potential!

Distribution of mass in the Universe at large scales

Planck Collaboration, 2015, paper XV
Lots of amazing progress over the past decades!

COBE

ACT

Boomerang

VSA, DESI, MAXIMA, Keck Array, BICEP, Polarbear, EBEX, and many more...

WMAP

Planck

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

- *Primary* CMB temperature kind of finished...
Status of primary CMB TT measurements

Cosmic Variance limited
Can be improved
Only ~ 10% of sky measured

Fit by standard $\Lambda$CDM - only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ $\theta_s$ $A_s$ $n_s$ $\tau_e$

SZ clusters kick in here

Figure from Planck 2015 Results XI
What are the *main* next targets for CMB anisotropies?

- **Primary** CMB temperature kind of finished...
- **E modes** cosmic variance limited to high-$l$
  - better constraint 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
What are the main next targets for CMB anisotropies?

- **Primary** CMB temperature kind of finished...
- E modes cosmic variance limited to high-\(l\)
  - better constraint 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’
E and B mode signals and targets

- *no clear target for B-mode amplitude!*
- *foreground challenge is extreme*
- to obtain constraints on $n_T$ recombination bump is needed
- Still quite a long way to go to reach primordial B-modes…

**Figure 6.** Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: $r=0.001$ and $r=0.05$.

The contribution to tensor B modes from scattering at recombination peaks at $\ell \approx 80$ and from reionization at $\ell < 10$. Also shown are expected values for the contribution to B modes from gravitationally lensed E modes (green). Current measurements of the B-mode spectrum are shown for BICEP2/Keck Array (light orange), POLARBEAR (orange), and SPTPol (dark orange). The lensing contribution to the B-mode spectrum can be partially removed by measuring the E and exploiting the non-Gaussian statistics of the lensing.

**2.3 Sensitivity forecasts for $r$**

Achieving the CMB-S4 target sensitivity of $(r) \approx 10^{-3}$ will require exquisite measurements of the B-mode power spectrum. It is expected that CMB-S4 will target the degree-scale recombination feature rather than the tens-of-degree-scale reionization feature (see Fig. 6), because these largest scales are difficult to access from the ground due to atmosphere and sidelobe pickup (though some Stage-3 ground-based experiments are attempting this measurement, notably CLASS [24]).

As can be seen from Fig. 6, the first requirement for this level of sensitivity to $r$ is a substantial leap forward in raw instrument sensitivity. For ground-based bolometric detectors, which are individually limited in sensitivity by the random arrival of background photons, this means a large increase in detector count. The forecasts in this section use a baseline of 250,000 detectors operating for four years (or $10^6$ detector years), dedicated solely to maximizing sensitivity to $r$. It will be necessary to split this total effort among many electromagnetic frequencies, to separate the CMB from polarized Galactic foregrounds. The forecasts here assume eight frequency bands, ranging from 30 to 270 GHz. Contamination from gravitationally lensed E modes must also be mitigated. While a precise prediction for the cosmological mean of the lensing B-mode power spectrum can be made and subtracted from the observed spectrum, there will be a sample variance residual between this prediction and the real lensing B modes on a particular patch of sky. To suppress this sample variance, it will be necessary to “delens” the B-mode maps with a prediction for the lensing.
What are the *main* next targets for CMB anisotropies?

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

- E modes cosmic variance limited to high-\(l\)
  - better constraint 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
What are the main next targets for CMB anisotropies?

- **Primary CMB temperature** kind of finished...
- **E modes** cosmic variance limited to high-\(l\)
  - better constraint 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
What are the *main* next targets for CMB anisotropies?

- *Primary* CMB temperature kind of finished...
- E modes cosmic variance limited to high-$l$
  - better constraint 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 competition!
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 $\Delta T/T \sim 10^{-5}$
CMB provides another independent piece of information!

**COBE/FIRAS**

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

Absolute measurement required!

One has to go to space...

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

$T_0 = 2.725 \pm 0.001 \text{ K}$

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

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

Standard types of primordial CMB distortions

**Compton y-distortion**

- 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

\[ x = \frac{y \nu}{kT_e} \quad (T_e >> T_Y) \]

\[ y = 0.15 \]


Blackbody restored
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 $z < \text{few } \times 10^6$.
δT

\[ \frac{\Delta T}{T} \approx \frac{1}{4} \left( \frac{\Delta \rho_\gamma}{\rho_\gamma} \right)_T \]

\[ \mu \approx 1.4 \left( \frac{\Delta \rho_\gamma}{\rho_\gamma} \right)_\mu \]

\[ y \approx \frac{1}{4} \left( \frac{\Delta \rho_\gamma}{\rho_\gamma} \right)_y \]
What does the spectrum look like after energy injection?

Intensity signal for different heating redshifts

- Red line: temperature-shift, $z_h > \text{few} \times 10^6$
- Blue line: $\mu$-distortion at $z_h \sim 3 \times 10^5$
- Black line: $\gamma$-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, $z_h > \text{few} \times 10^6$
- $\mu$-distortion at $z_h \sim 3 \times 10^5$
- $y$-distortion, $z_h < 10^4$

Response function: energy injection $\Rightarrow$ distortion

- 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, \( z_h > \text{few} \times 10^6 \)
- \( \mu \)-distortion at \( z_h \approx 3 \times 10^5 \)
- \( y \)-distortion, \( z_h < 10^4 \)

Response function:
- Energy injection
- Distortion

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

Hybrid distortion probes time-dependence of energy-release history

JC, 2013, ArXiv:1304.6120
**µ-distortion**

-2.7 K black-body radiation
-0.3 K black-body radiation
-0.3 K Bose-Einstein radiation with n = -0.3
-4 spectrum evaluated by formula (1),
-7.27 K, n = -0.3, n = 0.3

\[ G(\nu, z_h, 0) \left[ 10^{-18} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \right] \]

<table>
<thead>
<tr>
<th>Temperature-shift, ( z_h )</th>
<th>µ-distortion at ( z_h \approx 3 \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z_h \approx 5 \times 10^7 )</td>
<td></td>
</tr>
</tbody>
</table>

- µ-distortion at \( z_h \approx 5 \times 10^7 \)

\[ x = \frac{\nu y}{k T} \]

\( y = 0.15 \)

\[ y = 0.15 \]

**µ+y + residual distortion**

\[ G(\nu, z_h, 0) \left[ 10^{-18} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \right] \]

<table>
<thead>
<tr>
<th>µ-distortion at ( z_h \approx 3 \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ-distortion, ( z_h &lt; 10^4 )</td>
</tr>
</tbody>
</table>

**New hybrid era**

<table>
<thead>
<tr>
<th>pre-recombination epoch</th>
</tr>
</thead>
<tbody>
<tr>
<td>post-recombination epoch</td>
</tr>
</tbody>
</table>

| T-era |
| µ-era |
| µ-y-era |

**y-distortion era**

Big Bang
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
Today

The diagram illustrates the evolution of the universe from the Big Bang to the present day, highlighting key epochs and their characteristics, including the pre- and post-recombination epochs, the T-era, µ-era, and µ-y-era. The y-distortion era is also emphasized, with detailed annotations and graphs showing changes in intensity and temperature-shift over time. The new hybrid era is marked as a transition phase.
CMB spectrum adds another dimension to the problem!

\[ G_{\text{th}}(\nu, z_h, 0) \left[ 10^{-18} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \right] \]

Temperature-shift, \( z_h > \text{few} \times 10^5 \)
\[ \mu \text{-distortion at } z_h \approx 3 \times 10^5 \]
\[ y \text{-distortion, } z_h < 10^4 \]

\[ G_{\text{th}}(\nu, z_h, 0) \left[ 10^{-18} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \right] \]

\[ x = \frac{\nu y}{k T} \]

New hybrid era

pre-

post-recombination epoch

\( y \)-distortion era
CMB spectrum adds another dimension to the problem!

Temperature-shift, $z_h > 10^5$

$\mu$-distortion at $z_h \sim 3 \times 10^5$

$y$-distortion, $z_h < 10^4$

$\mu + y + \text{residual distortion}$

New hybrid era

$\mu$-era

$\mu$-y-era

HI & He

extra time-slicing at recombination

pre- post-recombination epoch

$T$-era

$\mu$-era

$\mu$-y-era

HI & He

extra time-slicing at recombination

New hybrid era
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

\[ T_0 = 2.725 \pm 0.001 \text{ K} \]

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

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


Only very small distortions of CMB spectrum are still allowed!
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-Martín 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-Martín 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)

**Standard sources of distortions**
Dramatic improvements in angular resolution and sensitivity over the past decades!

- **Cobe 1992**: ~7 degree beam
- **WMAP 2003**: ~0.3 degree beam
- **Planck 2013**: ~0.08 degree beam
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 ($\Delta v \sim 15$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 (i.e. cost $\sim 200$ M$\$$)

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. Sadly not selected :(

NASA 30-yr Roadmap Study
(published Dec 2013)
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 - APSERa - 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.
Concordia station at Dome-C

COSMO at Dome C

Cosmological Monopole Observer

Taken from a talk by Elia Battistelli

Concordia station:

- 75° 06' S – 123° 21' E
- 3233 m a.s.l.
- <T>=-50°    ;    min(T)=-85°
- High altitude but fully logistical
- 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)
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)
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 $\nu$-distortion for $\nu = 2 \times 10^{-6}$

Reionization & structure formation

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

$\nu$ [GHz]
Average CMB spectral distortions

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

- Low redshift \( y \)-distortion for \( y = 2 \times 10^{-6} \)
- Reionization & structure formation
- Negative branch
- PIXIE sensitivity
- Signal detectable with very high significance using present day technology!
Average CMB spectral distortions

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

- Signal detectable with very high significance using present day technology!

- $\Rightarrow$ relativistic corrections measurable! (Hill et al. 2015)

- Reionization & structure formation

- PIXIE sensitivity
Average CMB spectral distortions

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

\[ \nu \quad [\text{GHz}] \]

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

\( \Delta I \) for negative branch

\( \Delta I \) for positive branch

PIXIE sensitivity

Relativistic correction signal

Hill et al. 2015

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

The Planck Collaboration XIII including ACT and SPT for the baseline produced, with little additional cosmological information added by the errors on the extracted dependent and do not benefit from ACT and SPT. As a result, contaminants are the Poisson sources, which are treated as independent and do not benefit from ACT and SPT. As a result, contaminants are the Poisson sources, which are treated as independent and do not benefit from ACT and SPT. The main contribution of ACT and SPT is to constrain these ACT and SPT bandpowers have an overall calibration uncertainty larger than that of Planck and are well described by the Planck prior based on the 2013 data. The main contribution of ACT and SPT is to constrain these ACT and SPT bandpowers have an overall calibration uncertainty larger than that of Planck and are well described by the Planck prior based on the 2013 data.
Dissipation of small-scale acoustic modes

Silk-damping is equivalent to energy release!

Distortion due to mixing of blackbodies

$T_1 < T_2$

$T_b = (T_1 + T_2)/2$

$\Rightarrow$ Distortion due to mixing of blackbodies

Mixing is mediated by Thomson scattering $\Rightarrow$ Silk damping
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)

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


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

Recent discussion of caveats:
Gosenca, Adamek, Byrnes & Hotchkiss, ArXiv:1710.02055!


e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013
Distortions provide new 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
- CMB spectral distortions would extend our lever arm to $k \sim 10^4 \text{ Mpc}^{-1}$
- very complementary piece of information about early-universe physics

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
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
Shedding Light on the ‘Small-Scale Crisis’

A primordial suppression would result in a very small $\mu$-distortions
Spectral distortion measurements might be able to test this question

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

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

Nakama, JC & Kamionkowski, ArXiv:1703.10559
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations

- Uniform heating (e.g., dissipation in Gaussian case or quasi-uniform energy release) → distortion practically the same in different directions
- Spatially varying heating rate (e.g., due to ultra-squeezed limit non-Gaussianity or cosmic bubble collisions) → distortion varies in different directions → probe of scale-dependent non-Gaussianity at k~10 Mpc\(^{-1}\) and \(~750\) Mpc\(^{-1}\)

Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013; JC et al., 2016
Distortions could shed light on decaying (DM) particles!

\[ f_X/z_X \text{ [eV]} \]

\[ t_X \text{ [sec]} \]

\[ \Delta \rho/\rho_\gamma \]

Kawasaki et al., 2005

\(^3\text{He} / \text{D} \text{ bound}

Estimated 1σ detection limits for PIXIE

JC & Jeong, 2013
Distortions could shed light on decaying (DM) particles!

![Graph showing parameter space covered by decaying particles and the detection limits for PIXIE.](image)

- **Direct measurement of particle lifetime may be possible!**
- **Estimated 1σ detection limits for PIXIE**
- **3He / D bound**
- **Kawasaki et al., 2005**

**JC & Jeong, 2013**
Distortion constraints on DM interactions through adiabatic cooling effect

![Graph showing distortion constraints on DM interactions](image)

- We have set forth a new avenue to study DM interactions through cooling effects on the background spectrum of photons.
- Distortion constraints are obtained from the cooling effect of DM particles on the photon background spectrum.

### Equations

Eqs. (15) and (10):

- The DM-photon cross section is obtained similarly from Eqs. (15) and (4).

### Constraints

- The upper dashed curve indicates the approximate forecasted sensitivity constraint from FIRAS measurements.
- The dotted curve indicates the approximate sensitivity due to PIXIE satellites.

### Data Points

- For DM-proton collisions in the limit of sub-GeV DM with cooling effect, the constraints on DM-electron scattering from XENON10 are shown.

### Analysis

- The constraints are obtained from the cooling effect of DM particles on the photon background spectrum, providing a probe of DM-nuclei interactions.
- Detection experiments only constrain DM-nucleon cross sections with power-law dependence on the baryon-DM mass.

### Reference

Ref. [6] have set the first constraints on the scattering cross section of sub-GeV DM with cooling effect. For comparison, we also show the forecasted constraints for the sensitivity of the DM mass given the FIRAS measurements. We present independent cross sections with power-law dependence on the baryon-DM mass.
Rich phenomenology of photon injection distortions

[Graphs showing the behavior of $G_m(\nu, x, z)$ for different $z$ values and $x$ values: $x_1 = 0.001$, $x_1 = 1$, and $x_1 = 15$.]

$G_m(\nu, x, z) \left[ 10^{18} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \right]$
Cosmological Time in Years

Redshift $z$

Visibility Function
- H I-Lines
- He I-Lines
- He II-Lines

Free Electron Fraction
$N_e / [N_p + N_H]$

CMB-Anisotropies

Singly ionized Helium Lines
Neutral Helium Lines
He II-Lines

Plasma fully ionized
Plasma neutral
Hydrogen only
Hydrogen and Helium

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
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
- cooling effect
- CRR

Late time absorption

Average CMB spectral distortions

**ΔI [Jy sr\(^{-1}\)]**

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

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

Conclusions

• *Exciting future with CMB anisotropies*
  - Extract all information from E-modes
  - Main target B-modes from inflation
  - Neutrino mass, SZ effect and CMB lensing science

• *CMB spectral distortions open new window*
  - Several guaranteed signals (→ y-distortion & recombination)
  - Probe of inflation paradigm (→ damping signal)
  - Discovery potential (→ decaying particles, axions, etc)

• *In both cases: foreground challenge huge!*
  - We are entering the large “Noise to Signal” era
  - New experimental designs and analysis methods are required
  - Synergetic approaches (→ ground, balloon and space)
  - Strong international coordination is needed!

Lots of fun science to look forward to!
Many thanks for your attention and ‘Ski Heil’!