Thermal Sunyaev-Zel’dovich effect from high redshift \((z > 2)\) structures

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Thermal Sunyaev-Zel’dovich effect from high redshift (z > 2) structures

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An overview of the hot gas detection at high redshift

Hot gas structures

- $z > 3$
- $3 > z > 2$
- $2 > z > 1$
- $1 > z > 0$

Detection of galaxy clusters/hot gas structures?

Coma cluster

$z = 0.02$
An overview of the hot gas detection at high redshift

Hot gas structures

\[ z > 3 \quad 3 > z > 2 \quad 2 > z > 1 \quad 1 > z > 0 \]

Detection: (Thermal) Sunyaev-Zel'dovich effect

CMB photon → Scattered photon

\[ \Delta S^\nu (z) \]

Coma cluster

\[ z = 0.02 \]
An overview of the hot gas detection at high redshift

Hot gas structures

- $z > 3$
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Coma cluster

$z = 0.02$

Catalogues of clusters (Planck, SPT, ACT...)

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An overview of the hot gas detection at high redshift

Hot gas structures

- \( z > 3 \)
- \( 3 > z > 2 \)
- \( 2 > z > 1 \)
- \( 1 > z > 0 \)

- Mantz et al. 2014
  - CARMA
  - \( z = 1.9 \)

- Gobat et al. 2011
  - XMM
  - \( z = 2.07 \)

- Coma cluster
  - \( z = 0.02 \)

Catalogues of clusters (Planck, SPT, ACT...)

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Mantz et al. 2014
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Coma cluster
- z = 0.02

Proto-clusters?

Catalogues of clusters (Planck, SPT, ACT...)

An overview of the hot gas detection at high redshift

Hot gas structures

\[ z > 3 \quad 3 > z > 2 \quad 2 > z > 1 \quad 1 > z > 0 \]

Detecting of hot gas structures at high redshift? Millimeter maps + independent tracers.
An overview of the hot gas detection at high redshift

Hot gas structures

- **z > 3**
  - Data: Planck maps
    - *Ruan et al 2015*
  - tSZ at 5σ

- **3 > z > 2**
  - Data: ACT maps
    - *Gralla et al 2014*
  - tSZ at 5σ

- **2 > z > 1**
  - Quasars from SDSS-DR7/DR10 3.5 > z > 0.5
    - Data: ACT + Herschel maps
      - *Crichton et al 2015*
    - tSZ at 3-4σ
  - tSZ at 3.6σ

- **1 > z > 0**
  - Quasars from SDSS-DR7 2.5 > z > 0.1
  - Radio sources from FIRST and NVSS < z > ~1
  - Galaxies from BCS and VHS 1.5 > z > 0.5

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## Hot gas structures

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<th>z &gt; 3</th>
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### Our tracers: Quasars from SDSS-DR12 5 > z > 0.1

### Our data: Planck maps
(70, 100, 143, 217, 353, 545 and 857 GHz)
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Thermal Sunyaev-Zel’dovich effect from high redshift (z > 2) structures
First step: what is the nature of the signal at QSO positions?

- Extract a flux at the position of the QSOs with a matched filter.
- To increase the signal-to-noise, work with the **average flux** for a given sample of QSOs.
A significant signal at QSO positions

Formal description of a Planck map

\[ m_\nu(\vec{x}) = F_\nu \cdot \tau_\nu(\vec{x} - \vec{x}_0) + n_\nu(\vec{x}) \]  with

- \( m_\nu(\vec{x}) \), the Planck map at \( \vec{x} = (RA, DEC) \),
- \( F_\nu \), the flux from the structure (QSO and hot gas),
- \( \vec{x}_0 \) the QSO's position,
- \( \tau_\nu(\vec{x}) \) the spatial profile of the cluster (convolved with the Planck beam) and
- \( n_\nu(\vec{x}) \) the instrumental and astrophysical noise.

\( F_\nu \) + errors extracted with a single-frequency matched filter.
A significant signal at QSO positions

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A significant signal at QSO positions

**Average flux**

Average filtered maps centered on QSO positions. Size of the maps: $10^\circ \times 10^\circ$. 

![Average filtered map at 70 GHz](image1)

![Average filtered map at 100 GHz](image2)

![Average filtered map at 143 GHz](image3)

![Average filtered map at 217 GHz](image4)

![Average filtered map at 353 GHz](image5)

![Average filtered map at 545 GHz](image6)

![Average filtered map at 857 GHz](image7)
A significant signal at QSO positions
A significant signal at QSO positions

\[ \langle \hat{f} \rangle [\text{mJy}] \]

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

\[ \approx \]

\[ \approx \]

\[ \text{SZ}(\nu) \]

\[ \text{dust}(T, \beta, \nu) \]
Low-frequency tSZ extraction

**Find a signal (1) [DONE]**

First step: what is the nature of the signal at QSO positions?

- Extract a flux at the position of the QSOs with a matched filter.
- To increase the signal to noise, work with the **average flux** for a given sample of QSOs.

**Find a signal (2)**

Second step: assume the tSZ is the dominant signal and extract its amplitude.

- Frequencies kept for the analysis: 100 GHz and 143 GHz (where tSZ is negative and dust emission is weaker).
- Assume $F_\nu = y \cdot SZ(\nu)$
- $Y_{500} = y \cdot E^{-2/3}(z) \cdot \left( \frac{D_A(z)^2}{500\text{Mpc}} \right) = f(M_{\text{gas}})$
Averaging on the whole QSO population

\[ \begin{align*}
\tau_{\nu}(\vec{x}) & \quad \rightarrow \quad m_{\nu}(\vec{x}) \\
\Psi & \quad \rightarrow \quad \hat{y} \\
\vec{x}_0 & \quad \rightarrow \quad R_{\nu} \\
\text{Multi-frequency Matched Filter} & \quad \rightarrow \quad \sigma^2(\hat{y}) \\
SZ(\nu) & \quad \rightarrow \quad \chi^2 \\
\hat{Y}_{500} & \quad \rightarrow \quad < \hat{Y}_{500} >
\end{align*} \]

\[ R_{\nu} = \hat{F}_{\nu} - \hat{y} \cdot SZ(\nu) \]
Low-frequency tSZ extraction
Higher frequencies required

- No significant tSZ signal detected.
- Need leverage at high frequency for removing dust.
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Evidence for a tSZ signal for z>2 quasars

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Find a signal (3)

Third step: extract the dominant component of the signal, the dust emission and the sub-dominant tSZ signal.
- Assume \( F_\nu = D \cdot dust(T_{\text{dust}}, \beta, \nu) + y \cdot SZ(\nu) \) with \( dust(T_{\text{dust}}, \beta, \nu) = \nu^\beta \cdot B_\nu(T_{\text{dust}}) \).
- \( M_{\text{dust}} = f(T_{\text{dust}}, \beta, D, z) \) (Beelen et al 2006)
Evidence for a tSZ signal for z>2 quasars

Averaging on the whole QSO population

\[
\begin{align*}
\tau_\nu(\vec{x}) & \Rightarrow \hat{D} & \Rightarrow \hat{M}_{\text{dust}} & \Rightarrow \langle \hat{M}_{\text{dust}} \rangle \\
m_\nu(\vec{x}) & \Rightarrow \hat{y} & \Rightarrow \hat{Y}_{500} & \Rightarrow \langle \hat{Y}_{500} \rangle \\
\vec{x}_0 & \Rightarrow \text{Cov}(\hat{D}, \hat{y}) & \Rightarrow R_\nu & \Rightarrow \chi^2(T_{\text{dust}}, \beta)
\end{align*}
\]

Multi-component Multi-frequency Matched Filter

\[
\begin{align*}
\text{SZ}(\nu) & \Rightarrow \text{dust}(T, \beta, \nu) & \Rightarrow T_{\text{dust}}, \beta & \Rightarrow R_\nu = \hat{F}_\nu - \hat{D} \cdot \text{dust}(T, \beta, \nu) - \hat{y} \cdot \text{SZ}(\nu)
\end{align*}
\]
Evidence for a tSZ signal for z>2 quasars
Evidence for a tSZ signal for z>2 quasars

Averaging on the whole QSO population

Marginalization on T and $\beta$

Multi-frequency Matched Filter

$SZ(\nu) \rightarrow dust(T, \beta, \nu)$

$T_{dust}, \beta$

$\chi^2(T_{dust}, \beta)$

$\frac{\nu}{x_0}$

$\tau_{\nu}(\bar{x}) \rightarrow M_S$

$\hat{D} \rightarrow \hat{M}_{dust}$

$\langle \hat{M}_{dust} \rangle \rightarrow M_{dust}$

$\langle \hat{Y}_{500} \rangle \rightarrow \bar{Y}_{500}$

$\nu \rightarrow Cov(D, \hat{y})$
Evidence for a tSZ signal for $z>2$ quasars

![Graph showing evidence for a tSZ signal for high redshift quasars]
Evidence for a tSZ signal for z>2 quasars

Interesting sub-population of QSO: \( z \in [2.5, 4] \), no radio counterpart (from FIRST)

- Significant signal from the hot gas: \( Y_{500} = (10.86 \pm 1.46) \times 10^{-6} \text{arcmin}^2 \) (7 \( \sigma \)).
- Cluster mass estimated at \( 1.71 \pm 0.13 h^{-1} 10^{13} M_\odot \) (assuming tSZ from virialized clusters and standard redshift evolution). Consistent with the QSO clustering analysis \( 1.41 \pm 0.6 h^{-1} 10^{13} M_\odot \) (Richardson et al 2012).
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Conclusion

Evidence for hot gas in high redshift structures

- Significant signal at QSO positions in the Planck maps.
- Signal dominated by dust emission.
- Evidence for a sub-dominant tSZ signal using the radio quiet sub-sample between 2.5<z<4.
- No tSZ signal is found if the analysis is restricted to low frequency (ν<217 GHz) maps.
- High frequencies (ν>217GHz) are required to disentangle dust emission from tSZ.
Conclusion

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Origin of the tSZ signal difficult to determine

- Hot gas gravitationally heated in potential wells of QSO halos? Or gas from AGN feedback?
- Proper modeling of the AGN required to decide between the two hypotheses.
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**Origin of the tSZ signal difficult to determine**
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**Low mass halos contamination**
Understanding the mixture of components (tSZ, dust, etc) in low mass halos ($M \sim 10^{13} M_\odot$) may be important to understand the selection function of future millimeter surveys (CMB-S4, COre+, ?).
Thanks for your attention!