Signatures of early structure formation at FIR/sub-mm wavelengths

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INTRODUCTION

First stars (Pop III) e.g. Bromm 2013

Reionization

First metals

Dust Formation

Strong negative feedback

Mini-halos (~10^6 M☉) at z>20

Atomic cooling halos (~10^7 – 10^8 M☉) at z~20-6 e.g. Bromm & Yoshida 2011

First long-lived stellar systems

First galaxies might have been composed of Pop II stellar systems, surrounded by mixed phase of gas and dust.
Interconnection FIR/sub-mm Radiation and First Galaxies

Primordial stellar populations

- Imprint on the NIR (peaking at $\lambda \sim 1\mu m$) (e.g. Bromm 2013).
- Widely studied in the literature.
- NIR-EBL excess suggests a significant contribution from early epochs (e.g. Kashlinksky 2005).

Dust emission

- UV radiation from primordial stars heated interstellar dust.
- Re-radiated dust emission contributes to the FIR/sub-mm part of the spectrum.
- Role of first galaxies as possible FIR/sub-mm sources poorly explored.

We ask to what extent the first galaxies may have contributed to the observed FIR/sub-mm radiation through redshifted dust emission.
Brief overview of dust model (De Rossi & Bromm 2017)

**Model galaxy**: *dark matter halo* hosting a central cluster of *Pop II stars*, surrounded by a mixed phase of *gas* and *dust*.

- **Different density profiles for the gas (e.g. isothermal power law).**
- **Spectral energy distribution associated to stars**: YGGDRASIL model grids (Zackrisson+2011).
- **Silicon-based dust models** (Cherchneff & Dwek 2010).
- **Grain-size distributions used in Ji et al. (2014)**: “standard” (Pollack+1994) and “shock” (Bianchi & Schneider 2007).
- **Dust temperature** ($T_d$) was determined assuming thermal equilibrium.
- **Dust emissivity** was estimated by applying the Kirchhoff’s law for the $T_d$ profile.

**Fiducial model**: dust-to-metal mass ratio $D/M=5 \times 10^{-3}$, gas metallicity of $Z_g=5 \times 10^{-3} Z_\odot$ and a star formation efficiency of $\eta = 0.01$. 
Dust emission from a model source at z=10

Peaks at $\lambda \sim 50\,\mu m$ or $\lambda_{\text{obs}} \sim 500\,\mu m$.

Point source sensitivities of current instruments not sufficient to allow detection.

Rare massive systems ($M_{\text{vir}} > 10^{14} M_\odot$, $L_\odot > 10^{12} L_\odot$) detectable but statistically difficult to find.

An increase of $D/M$, $Z_g$ or $\eta$ and the use of the shock SD would increase dust emission.

De Rossi & Bromm (2017)
Dust emission from a model source with $M_{\text{vir}} = 10^{10} M_\odot$

- Larger $L_\nu$ at higher $z$
- High-z systems, more concentrated.
- Higher temperature floor set by the CMB.
- Increase in dust temperature.
- Enhancement of heating efficiency associated with stellar radiation.
- FIR/sub-mm sources at $z > 7$ experience a strong negative K-correction.
- Observations in the FIR also sensitive to spectral features.

De Rossi & Bromm (2019)
Contrary to expectations, systems with similar masses brighter at higher $z$.

Strong negative K-correction

Characteristic sensitivity values covering the scope of future FIR surveys.

$M_{\text{min}} \sim 10^{11} - 10^{12} M_{\odot}$ ($M_{\text{min}} \sim 10^{13} - 10^{14} M_{\odot}$) required to reach sensitivity limits of $S \sim 0.1 \mu$Jy ($S \sim 10.0 \mu$Jy), with the exact value depending on dust properties.

$M_{\text{vir}} > M_{\text{min}}$ far from typical, highly biased overdensities.

Detection difficult with blind surveys.
The Redshift Horizon

For a given sky area ($\Delta \Omega$), $z_{\lim}$ is defined as the highest $z$ above which the projected number of sources above the sensitivity limit is $N \leq 1$.

At $z_{\lim} > 12$:

$$z_{\lim} = -4 \log_{10}(S/nJy) + z_{\lim}(S = 1 \text{ nJy})$$

De Rossi & Bromm (2019)
The Redshift Horizon

For a given sky area ($\Delta\Omega$), $z_{\text{lim}}$ is defined as the highest $z$ above which the projected number of sources above the sensitivity limit is $N \leq 1$.

At $z_{\text{lim}} > 12$:

$$z_{\text{lim}} = -4 \log_{10}(S/nJy) + z_{\text{lim}}(S = 1 \text{ nJy})$$

Probability of detecting typical first galaxies in blind surveys (FIR/sub-mm): very challenging, given the extreme sensitivities required.
The Redshift Horizon

For a given sky area ($\Delta \Omega$), $z_{\text{lim}}$ is defined as the highest $z$ above which the projected number of sources above the sensitivity limit is $N \leq 1$.

Probability of detecting one individual source: dependence on instrument sensitivity and survey area.

De Rossi & Bromm (2019)
The Redshift Horizon

For a given sky area ($\Delta \Omega$), $z_{\lim}$ is defined as the highest $z$ above which the projected number of sources above the sensitivity limit is $N \leq 1$.

Nature of primordial galaxies still uncertain. Observational prospects increase significantly with star formation efficiency, metallicity and dust-to-metal ratio.

Probability of detecting one individual source: dependence on instrument sensitivity and survey area.
An increase by one order of magnitude of $Z_g$, $\eta$ or $D/M$, relaxes the sensitivity limit for detection to similar order of magnitude.

Similar trends obtained if adopting survey areas of 0.1 and 10 deg$^2$. 

**Reference parameters**

- **Dust-to-metal mass ratio** $D/M=5 \times 10^{-3}$
- **Gas metallicity** $Z_g=5 \times 10^{-3}Z_\odot$
- **Star formation efficiency** $\eta = 0.01$

**De Rossi & Bromm (2019)**
Cosmic FIR Background

Peak: \( \sim 500 \mu \text{m} \)

Maximum intensities: \( \sim 10^{-4} \) and \( \sim 10^{-3} \) nW m\(^{-2}\) sr\(^{-1}\) for the standard and shock SD, resp.

Below the measured background by \( \sim 3-4 \) orders of magnitude.

Below average source-subtracted EBL by \( \sim 2-3 \) orders of magnitude.

Dust chemical composition does not significantly affect the main trends.

\[
I_{\nu}(\nu_{\text{obs}}) = \frac{c}{4\pi} \int_{z_{\text{min}}}^{z_{\text{max}}} \epsilon_{\nu}(\nu, z) \left| \frac{dt}{dz} \right| \, dz.
\]

\( \epsilon_{\nu} \): specific luminosity per comoving volume

\( \rightarrow \) Sheth-Tormen MF + dust luminosities predicted by our model.

De Rossi & Bromm (2017)
Impact of model parameters

Radiation intensity increases with D/M. For extreme D/M, ~1% of measured flux and ~100% of SS EBL.

SS EBL only reached if extremely high values are assumed for model parameters.

Radiation intensity increases with $\eta$. For extreme $\eta$, model EBL reaches the averaged observed EBL excess.

D/M and $Z_g$ are degenerate parameters.

- **Standard parameters**
  - Dust-to-metal mass ratio $D/M = 5 \times 10^{-3}$
  - Gas metallicity $Z_g = 5 \times 10^{-3} Z_\odot$
  - Star formation efficiency $\eta = 0.01$

De Rossi & Bromm (2017)
CONCLUSIONS

- We analysed the FIR/sub-mm signatures of first galaxies by implementing an analytical model for dust emission.

- Sources at z>7 experience a strong negative K-correction.

- Dust emission from dwarf galaxies at z~10 would peak at ~500μm, with observed fluxes below the capabilities of current observatories.

- For survey areas of 0.1 deg² and 10 deg², the redshift horizon would be above z ~ 7 for sensitivities <0.1 – 0.5 μJy and <0.5 – 3.0 μJy, respectively, with the exact values depending on the nature of dust.

- The FIR/sub-mm EBL peaks at ~500μm and it would not represent a significant percentage of the total observed EBL.

- Because the FIR/sub-mm radiation shows a strong dependence on D/M, Z_g and η, its study could help to constrain these quantities at early times.
Contribution of the first galaxies to the cosmic far-infrared/sub-millimeter background – I. Mean background level

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Redshift Horizon for Detecting the First Galaxies in Far-Infrared Surveys

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