Extremely Faint Millimeter Sources Identified by Multi-Field Deep ALMA Survey and Subaru Follow-up Spectroscopy

Fujimoto et al. 2016 (ApJS, 222, 1)
Fujimoto et al. in prep.

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- Resolve the Cosmic Infrared Background light (CIB)

- Origin of the Faint mm Source
This work:

Largest dataset of multi-field deep ALMA

-> Resolve CIB / Physical origins
Sample Selection

**DATA: ALMA Band 6 & 7 (~submm/mm)**

- **Our quite deep** 4 ALMA data (Ouchi+13, etc)
- **ALL** ALMA data so far archived (2012/12-2015/7)

**Criteria:**

- Noise level < 0.1 mJy
- No too Bright/Extended Sources

**Total:** 67 deep maps

Obs. hrs ~100 hrs (cf. typical obs. hrs ~4 hrs)
Cluster Data (1 map)

- Multiple image: Diego+14
- Optical Catalog: Diego+14, Coe+10
- Software: GLAFIC (Oguri 10)
  (e.g., Ishigaki+15)
Field Data (66 maps)

Examples

Detected Example

-5σ

FWHM of PB

0.6 x 0.8

Detection Example

* Original Target Sources Removed

Total Sources: 133

Intro Data/Analysis Number Counts Resolving CIB Galaxy Bias Counterpart Subaru

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Data Analysis

Resolve CIB -> Derive **Number Counts**

\[ N_{\text{eff}} = \frac{1 - R_s(S/N)}{C(S/N)} \]

- **\( N_{\text{eff}} \): Effective Number**
- **\( R_s(S/N) \): Spurious Source Rate**
- **\( C(S/N) \): Completeness**

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**Positive & Negative Peaks**

- Deep (A)

**Completeness**

- ID6 (A)
- ID61 (B)
- ID67 (C)

**Survey Area**

(e.g., Hatsukade+13, Ono+14, Carniani+15)

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We successfully derive number counts in the range of 0.018 - 1.2 mJy.
Resolve the CIB

- Almost fully (104±30%) resolve the CIB
- < 0.02 mJy sources would be negligible

-> 1) Flattening
   2) Truncation below 0.02 mJy

What are the faint ALMA sources?

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1. **Statistical Approach: Cluster Analysis**

**Examples**

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<tr>
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<th>1</th>
<th>0</th>
<th>3</th>
<th>3</th>
<th>0</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Field-to-Field Scatter**

\[ Field-to-Field Scatter = Galaxy Bias + Poisson error \]

**Counts-in-Cells**

\[
\frac{b_g^2}{2} \approx \frac{\sigma_N^2 - \bar{N}}{\bar{N}^2 \sigma_V^2(z)}
\]

\( b_g \): galaxy bias  \( \sigma_V \): matter variance  
\( \sigma_N \): dispersion of source counts  
\( N \): mean source counts

**Faint ALMA Sources**

\( b_g < 3.5 \)  
\( (\Lambda CDM->) M_{DH} < 5 \times 10^{12} M_{\odot} \)

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1. Statistical Approach: Cluster Analysis

- Faint ALMA Sources
  \( b_g < 3.5 \)

- SMGs / DRGs / pBzK
  \( b_g \sim 5 - 7 \)

- sBzK / LBGs / LAEs
  \( b_g \sim 2 - 3 \)

Faint ALMA Sources = sBzK, LBGs, LAEs?
2. **Individual**: Opt.-NIR Counterparts

- Multi-wavelength data (X-ray, Optical, IR, radio)
- Opt.-NIR Counterparts

\[ \sim 60 \pm 20\% \]

**Source Flux vs Count. fraction**

Faint ALMA Sources (red contour) w/o opt. counterparts (B,r,z)
Photometric Properties

BzK Color Diagram

- $z \sim 2$
- $z \sim 3-5$

BX/BM Color Diagram

- $z \sim 3-5$
- $z \sim 2$

Majority of Faint ALMA Sources

$\rightarrow$ sBzK / LBG(BX/BM)
Photometric Properties

1. Clustering (Statistical)

Faint ALMA Sources

$\rightarrow$ x AGN
\[ \circ \text{Optically selected SFG} \]

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Subaru NIR Spectroscopy

- Five faint ALMA sources
- To determine redshift, $Z$

Date: 6/19-6/21/2016
Mode: MORICS/HK500

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Subaru NIR Spectroscopy

Other 3 faint ALMA sources …
• No lines are detected

z=2.50
12+log(O/H) ≤ 8.2

z=2.63
(Jullo+10)
12+log(O/H) ≤ 8.2

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Summary

Largest ALMA Dataset (133 down to 0.02 mJy)

- Resolve the CIB ~100%
- Statistical / Individual
  - galaxy bias: $b_g < 3.5$
  - Opt.-NIR counterparts:
    - (60%) Opt. SF galaxies $z \sim 2-3$
    - (40%) unknown

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