Astro2020 Science White Paper

Understanding the nature of populations behind source-subtracted cosmic infrared background

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: Outline what new data would make progress possible (including WFIRST, EUCLID, JWST in conjunction with new X-ray missions eROSITA, Athena, etc), and argue how this cannot be done in any other way. 1. Need wide field deep observations to get enough ability to remove individual galaxies, and to see the scales at which the measured and predicted excesses are found. 2.Can use data taken for other purposes, IF they are structured to enable good stitching together of small-field observations, using self-calibration algorithms. 3. These CIB fluctuations are a pathway to finding sources that are not observable in any other way. The correlation with X rays is so important it needs to be measured again and better.

1. Introduction

Cosmic infrared background (CIB) includes emissions from objects inaccessible to direct telescopic studies [see review by 23, and refs therein]. However, direct measurements of the CIB intensity provide only upper limits at most near- to mid-IR wavelengths because of uncertainties in the contributions of Galactic and zodiacal foregrounds. A complementary approach is to characterize the spatial fluctuations of the source-subtracted CIB [27]. This analysis can employ data sets without an accurate determination of the absolute zero point, and avoids some of the difficulties in modeling the foreground contributions [26, 25, 19, 42]. The spatial power spectrum of the source-subtracted CIB fluctuations depends on the clustering of the remaining sources, and their integrated emission. Together these measurements can be used to infer the nature and redshifts of the contributors to the source-subtracted CIB.

Lower limits on the CIB mean flux can be made by integrating source counts in various bands, and upper limits can be estimated from measurement of the γ-ray opacity caused by the CIB (Fig. 1). All these estimates are generally consistent, and the present uncertainties show the range of the allowed CIB contribution from sources fainter than detected in the surveys. The source-subtracted CIB is that which remains after subtraction of the contribution from individually resolved sources, and is the key observable information on an otherwise unseen portion of the Universe.

The efforts over the past decade and a half identified source-subtracted CIB fluctuations in deep *Spitzer* and *Akari* data from *new* unknown populations. The measurements [30, 31, 33, 6, 43, 15] span 2–5μm; at shorter wavelengths there is currently significant uncertainty with conflicting results from, chronologically ordered, deep 2MASS, HST/NICMOS, CIBER and HST/WFC3 analyses [28, 48, 51, 52, 59, 45]. The source-subtracted CIB from deep *Spitzer* data appears highly coherent with soft cosmic X-ray background (CXB) [11, 12, 46, 41] implying a significant presence of accreting black holes (BHs) among the new CIB sources. See review by [36].

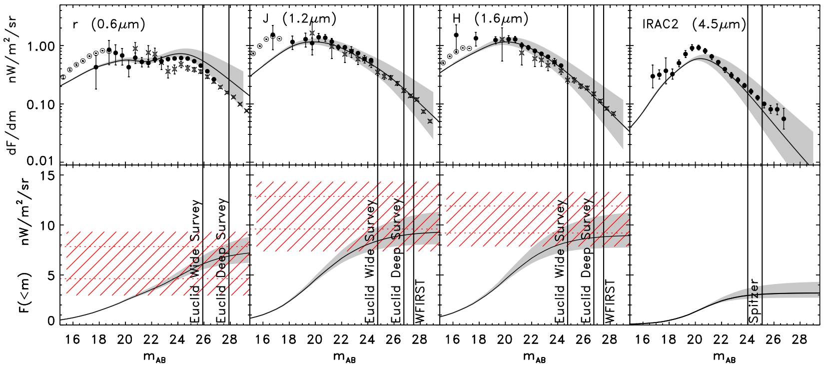

Figure 1: **Top**: Data points show the differential contribution to the mean background flux for galaxy count surveys. The line and shaded uncertainty band show the reconstruction provided by the models of [20]). **Bottom**: These models are integrated to provide the cumulative EBL vs. magnitude. The dotted lines and hatched band show the 1 and 2 σ ranges on EBL estimates from γ-ray opacity [16]. The range between the lowest limit from the integrated counts and the highest limit of the γ rays is the possible intensity of the source-subtracted extragalactic light.

The CIB fluctuation signal appears to imply new populations below the (faint) flux limit of the maps (AB$\simeq$24–25) with significant implications for cosmology. Theoretically such CIB signal was predicted to arise from the first starts era (FSE) [29, 13]. The sources responsible for it can come from Population III, predicted to be very massive stars forming, for standard ΛCDM model, in first collapsed minihaloes of $10^{6-9}M_\odot$ at $z > 10$ [9, 10, 1]; the faint minihalos will have high projected surface density lying largely in the confusion noise of the next decade telescopes [35]. The early epochs could also contain abundant BHs of various origins, contributing at both IR and X-ray [3, 56, 57, 58, 24, 38]. Also there may be contributions from new stellar populations at low to intermediate z as well as from a new particle decay [8, 15, 18]. The populations cannot be observed in direct telescopic studies, but could be probed via source-subtracted CIB fluctuations.

Identifying with high accuracy the properties of source-subtracted CIB and understanding the nature of its populations is feasible with upcoming instruments and should be one of the major goals in cosmology for the coming decade.

2. Properties of source-subtracted CIB anisotropies and cosmological implications

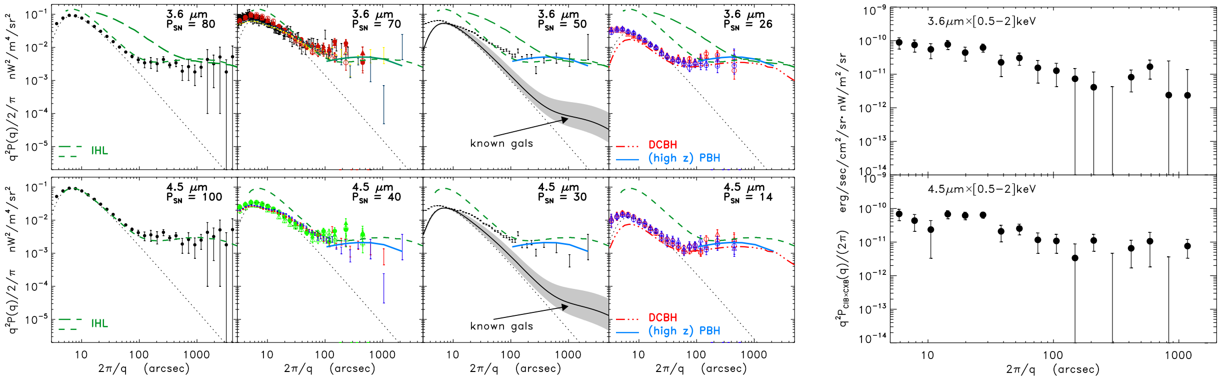

Figure 2: Adapted from [36]: $P(q)$ is the power at angular scales $2\pi/q$. **Left**: *Spitzer*/IRAC-based measurements of source-subtracted CIB fluctuations at different shot-noise levels [30, 31, 33, 15] at 3.6μm and 4.5 μm. *No decrease of the large-scale clustering component yet appears at these shot-nose levels*, marked in nJy·nW/m^2/sr. Contribution from remaining known galaxies is shown from [20]. IHL models at low z, green short dashes from [14] and green long dashes [59] , in their presented form appear inconsistent with the CIB data and cannot account for the CIB-CXB cross-power shown in right panels. BH-based models can account for the data at all shot-noise levels and the observed CIB-CXB cross-power. The DCBH model [56] is shown with red dash-triple-dotted lines, the LIGO-type PBH model [24] is shown with blue solid line. **Right**: The cross-power between the IRAC 3.6μm CIB and Chandra soft CXB is shown for the actual CXB signal (top) and a randomized CXB noise estimate [12].

Efforts over the past decade and a half identified source-subtracted CIB fluctuations in deep *Spitzer* and *AKARI* data, which originate from new unknown populations. The measurements at 2–5μm [30, 31, 33, 6, 43, 15] cover 2–5 μm; their main established properties have been summarized in [36, Sec. V.B.3] and are summed up below with Fig. 2 showing their most relevant for the present discussion highlights. Specifically:

- Their shot noise, $P_{\rm SN}{=}\int_{m_0}^{\infty} S(m)^2 dN$, dominates small angular scales. It comes mainly from the known sources below the limiting flux S of magnitude $m_0\simeq$24–25 (related to survey flux limits).
- There is a clear excess of CIB clustering power (scales $\gtrsim 100''$) at 3.6 and 4.5 μm over that from known remaining galaxies [23, 20]. The excess power from clustering appears isotropic on the sky consistent with it being cosmological [31, 33].
- The clustering component does not yet appear to drop with decreasing shot-noise suggesting it is produced by very faint sources with 3.6 and 4.5 μm flux densities $\lesssim$20nJy [32].
- The CIB fluctuations at *AKARI* wavelengths suggest a Rayleigh-Jeans energy spectrum for the power at 2–5μm, i.e. $P\propto\lambda^{-2n}$ with $n{\sim}3$ [43].
- *Spitzer/AKARI* band-integrated CIB fluctuations are $\delta F_{2-5\mu{\rm m}}(5')\simeq$0.1 nW/m^2/sr [36], corresponding to the mean CIB intensity $\sim$1 nW/m^2/sr [32] if at high z, which added to known populations is consistent with the γ-ray absorption measurements of $11.6^{+2.6}_{-3.1}$ nW/m^2/sr (2σ) at 1.4 μm [16].
- The CIB clustering component is strongly coherent with the (soft) cosmic X-ray background (CXB) [11, 12, 46, 41]. The cross-power, $P_{\rm CIB\times CXB}$, cannot be explained by remaining known galaxies [21]. The emerging CXB-CIB coherence, $\mathcal{C}\equiv P^2_{\rm CIB\times CXB}/P_{\rm CIB}/P_{\rm CXB}$, appears to exceed $\mathcal{C}\gtrsim 0.04$ [12] suggesting significant abundance of accreting BHs among the CIB-producing populations.

3. Questions posed by the CIB fluctuation measurements

The current theoretical proposals for the origin of the sources behind the CIB fluctuations differ in the epochs populated by these sources: the original discovery by [23] posited that the signal is from the first stars era, while later [15] proposed that it comes from intrahalo light (IHL) of normal stars stripped away in galactic mergers at low to intermediate z. The IHL proposals (Fig. 2), as presented, do not fit the CIB fluctuations at lower shot noise levels, do not account for the CIB-CXB coherence, and the modelling in [59] appears in tension with the the newest γ-ray absorption limits [16]. Massive Pop3 stars at $z \gtrsim 10$ can account for the CIB fluctuations only with somewhat "optimistic" efficiencies of formation (5-10%) inside the first minihalos [22]. With the discovery of the CIB-CXB coherence, two suggestions have been made for the origin of these populations, both involving BHs at high z: 1) direct collapse BHs (DCBHs) [56] and 2) LIGO-type primordial BHs (PBHs) making up dark matter [24]. CIB fluctuations are thus a critical tool for the understanding of: i) new, undetectable directly, populations; ii) the physics of the pregalactic Universe; iii) the nature of the first sources and, potentially, reionization; iv) BH activity; and v) possible connection to the nature of dark matter and LIGO-type BHs.

The specific questions that need to be answered, and the required configurations, are:

Q1: *What are the epochs of the sources producing the CIB fluctuations?*

The redshift of the sources producing the CIB fluctuations may be estimated by identifying a Lyman break in the spectrum of the sources, in much the same way that individual galaxy redshifts can be estimated from photometric dropouts. However, to be effective for the CIB, there must be a relatively sharp cutoff for the minimum z of the sources, and the foreground sources that would not show a Lyman break must be minimized. Observations in the visible and near-IR are needed, as sources whose epoch ends at $z \sim 10$ would show a Lyman break at $\sim 1\ \mu$m. The configuration required for this study is to reach AB$\gtrsim$25 since at brighter magnitudes the CIB power below $\sim$1μm from remaining known galaxies, and its systematic uncertainty strongly dominates that observed from the new populations at 2–5μm [35].

Q2: *How does the CIB from these sources evolve over cosmic time?*

The redshift evolution of the CIB fluctuations can be isolated in further detail via the Lyman tomography by examining the relative brightness of the large-scale fluctuations in a series of adjacent spectral bands, the subsequent wavelength then probing additional emissions from an extra range of z. With increasing wavelength, such comparisons are sensitive to the fraction of the population lying at increasingly high redshifts [35, 34]. These studies require deep imaging (to remove foreground sources) over large areas (to obtain high S/N power spectra at large scales) in mean adjacent filters (to explore as a function of z).

Q3: *What are the relative contributions of stars and BHs to the CIB fluctuations?*

The CIB-CXB cross-correlation appears real, but poorly constrained at present. Improved measurements of the correlations at large and small angular scales can better resolve the CIB fraction produced by sources that are associated with the X-ray emission. Whether this correlation is found only in the large-scale clustering component or also extends to small angular scales due to intrinsic coherence of the CIB and CXB shot noise from the new sources, will indicate the extent to which the IR and X-ray sources are physically the same objects or whether they are distinct objects (emission mechanisms) that are grouped together through the cosmic structure [22, 56, 34, 55].

Q4: *What is the contribution of the new sources to the CXB fluctuations?*

In the event that the intrinsic CIB-CXB coherence is high and the CIB fluctuations are measured with better S/N than the CXB fluctuations, the CIB fluctuations can be used to make a better estimate of the CXB fluctuations from the correlated sources than is possible from the X-ray observations alone. An example of this is shown in Figure 4,left.

Q5: *What is the contribution of the new sources to reheating and reionization of the IGM?*

The IGM plasma would produce faint temperature anisotropies in the cosmic microwave background (CMB) via the Sunyaev-Zeldovich (SZ) effect. While these SZ anisotropies are too faint to be detected, the cross-correlation of maps of specific source-subtracted CIB fluctuations with suitably constructed microwave maps at different frequencies, can probe the physical state of the gas during reionization and test/constrain models of the early CIB sources [7].

Q6: *Can the CIB fluctuations constrain the cosmological model at high z?*

The Lyman tomography from a suitable set of instruments can isolate the CIB as function of redshift at $z > 10$ and measurements of the CIB fluctuations over large sky area can lead to high-precision determination of it power spectrum. This in turn may enable probing the baryonic acoustic oscillations (BAOs) at the range of redshifts where it cannot be probed by other means, opening a further window on the standard cosmological model [34].

4. Outlook to the coming decade

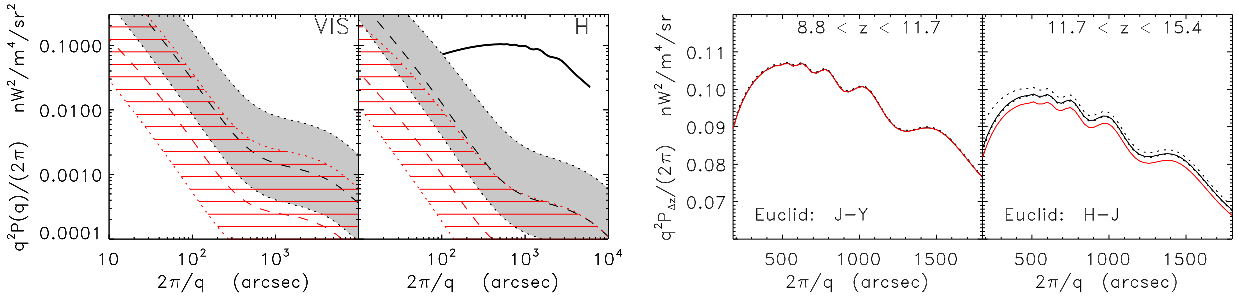

Figure 3: Adapted from [36]. **Left**: CIB fluctuations from known galaxies remaining in the *Euclid* VIS and NISP bands (grey shaded area for Wide Survey and red lined area for Deep Survey). The thick solid line is a high-z CIB, which fits *Spitzer* 3.6, 4.5 μm CIB fluctuations. **Right**: The Lyman-tomography reconstruction of the CIB emission history and BAOs for *Euclid*'s (Y,J,H) filters and Wide Survey depth at each z-range. Red line (starting near bottom on left) shows the underlying CIB fluctuations by sources in the marked z-range from high-z stellar populations reproducing *Spitzer* measurements. Black lines show the contributions by known remaining galaxies with its uncertainty marked by dotted lines.

In the next decade, new observations of the CIB fluctuations will need to meet several requirements to significantly help answer Q1 and Q2, above. First, the observations will need to be made over large areas, on order of 10^3 deg^2. This is needed to obtain the best possible S/N out to the largest possible angular scales. The data must be collected and processed by means which accurately capture large scale structure [17, 4, 5]. Second, observations in multiple near-IR bands are needed to study the SED of the fluctuations to probe the cutoff redshift (Q1), and to determine the cosmic history of the emission of the CIB sources. Third, the data should have sufficient sensitivity and angular resolution to detect and subtract as much of the total CIB as possible.

Fig.3 shows how the data from the upcoming *Euclid* mission [39, 40] is expected to provide very useful results via the NASA selected LIBRAE (Looking at Infrared Background Radiation Anisotropies with *Euclid*) project (`https://www.euclid.caltech.edu/page/Kashlinsky%20Team`). *Euclid*'s NISP instrument will allow the measurement of CIB fluctuations in Y, J, and H near-IR bands, and VIS which will do the same in a single broad visible light band. The left panels of Figure 3 show the expected contributions of remaining galaxies in the CIB power spectrum obtained from *Euclid's* Wide and Deep surveys. The AB≃25–26 magnitude limits allow suppression of the known remaining galaxies. In the H bands, the extrapolated large-scale fluctuation is expected to be much stronger than that of faint known galaxies. In the VIS band, the clustering component will drop out and only the power of the unresolved known populations should be detected if the clustering power is due to high z sources. Fig.3,right show that the multiple bands will enable “Lyman tomography” to explore the history of the emission (Q2), and the large areas will allow sufficient S/N to probe details in the power spectrum (e.g. BAOs) addressing (Q6).

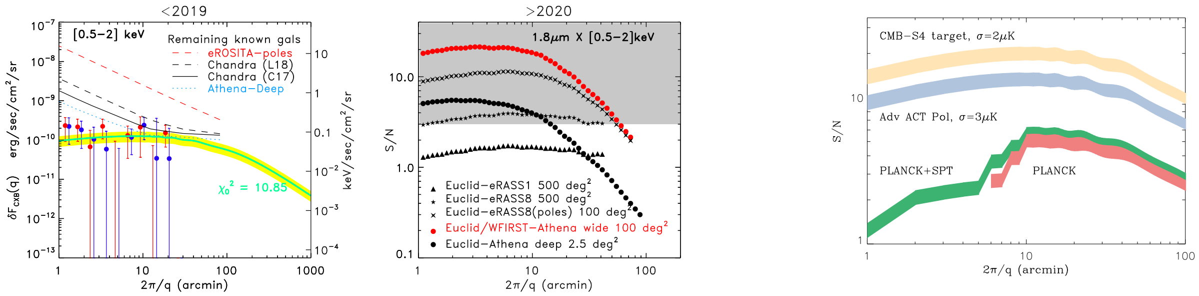

Figure 4: **Left**: From [37]. Residual CXB, $\delta F_{\rm X} \equiv (q/\sqrt{2\pi}) P_{\rm CIB\times CXB}/\sqrt{P_{\rm CIB}}$, from the new populations [37]. Blue (3.6μm) and red (4.5μm) circles are derived using the IRAC/*Chandra* measurements [12]. Solid green line is the best fit for the 3D ΛCDM power template at $d_A = 7$ Gpc (z=15); the yellow regions marks 1σ deviation of the fit which gives $\chi^2_0 = 10.85$ for the 18 data points. The angular scales where clustering component dominates exceeds the contributions from known sources at $> 5\sigma$ level for both IR bands. The CXB fluctuations from known sources remaining in the marked configurations are shown to be above the signal if probed directly. **Middle**: From [37]. Overall S/N for the signal in the right panel through CIB-CXB cross-power measurements from *Euclid-eROSITA* and *Euclid-Athena* configurations. Shaded area marks $S/N \geq 3$. **Right**: From [7]. TBD

Substantial improvements in the CIB-CXB cross-power will be provided by the *Euclid* CIB data and *eROSITA* [44] X-ray maps. These would bring decisive probes of the cross-power signal [37] particularly from the deep *eROSITA* coverage of 140 deg^2 at the poles. ESA's *Athena* [47], to be launched later in the next decade, will bring further refinements in the measurement, particularly if it covers a wide area of ~100 deg^2 at the depth corresponding to the current *Chandra* integrations in [11, 46, 12, 41]. See the expected progress for answering Q3,Q4 in Figs.4,left/middle.

If they turn out to at high-z further probe of the CIB sources will involve testing their impact on the state of IGM at reionization by measuring the thermal SZ component using cross-correlation of the source-subtracted CIB from *Euclid* with multifrequency CMB maps, suitably constructed to remove primary and kinematic SZ CMB terms [7]. The prospects here are illustrated in Fig. 4,right which shows the possibility of probing IGM temperature to well below 10^4K with multifrequency CMB maps of low noise and high resolution from AdvACTPol [54, 53, 50] and CMB-S4 [2].

Further CIB information will be available from *WFIRST* to be launched in 2nd half of 2020's [49] which will map 2,000 deg^2 at 4 filters from 0.9 to 2 μm. The area covered will be smaller, but observed more deeply than in the *Euclid* surveys. The *WFIRST* wavelength coverage will extend to longer wavelengths allowing the probe of potentially higher-z components. *JWST* will be too limited in the area covered to provide as detailed probe on the clustering part of the power spectrum. However *JWST* will provide the deepest possible direct survey of contributors to the CIB. A configuration covering 1 deg^2 to AB=28 in all 7 NIRCAM wide filters will take ~400 hrs of *JWST*'s time and was proposed by [35] to result in significant new information (Q1,Q2) on the new CIB sources, including their energy spectrum over 0.6–6μm.

TBD: New theoretical advances are likely needed? Significant X-ray component, effects on reionization, first star formation with PBHs as DM, etc.

Prospects for ground-based: going fainter, but wide, with EELT, LSST.

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