Astro2020 Science White Paper

Populations behind the source-subtracted cosmic infrared background anisotropies

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

Principal Author:
Name: A. Kashlinsky
Institution: Code 665, Observational Cosmology Lab, NASA Goddard Space Flight Center, Greenbelt, MD 20771 and SSAI, Lanham, MD 20770
Email: Alexander.Kashlinsky@nasa.gov
Phone: 301-286-2176

Co-authors: R. G. Arendt (GSFC and UMBC), M. Ashby (CfA), F. Atrio-Barandela (U. Salamanca), V. Bromm (UT Austin), N. Cappelluti (U. Miami), S. Clesse (UCLouvain), A. Comastri (INAF), G. Fazio (CfA), S. Driver (UWA), A. Ferrara (Pisa), A. Finoguenov (U. Helsinki), J. Garcia-Bellido (IFT-UAM/CSIC), D. Fixsen (GSFC and UMCP), G. Hasinger (ESA), K. Helgason (U. Iceland), R. J. Hill (GSFC), R. Jansen (ASU), J. Kruk (GSFC), J. Mather (GSFC), P. Natarajan (Yale), N. Odegard (GSFC and ADNET), M. Ricotti (UMCP), M. Sahlen (U. Uppsala), E. Switzer (GSFC), R. Windhorst (ASU), E. Wollack (GSFC), Bin Yue (NAOC)

Abstract: Although the advent of ever-larger and more sensitive telescopes in the coming decade will reveal correspondingly fainter, more distant galaxies, a question will persist: what more is there that these telescopes cannot see? One answer is the source-subtracted Cosmic Infrared Background (CIB). The CIB is comprised of the collective light from all sources remaining after known, resolved sources are accounted for. A crucial point: unlike the cosmic microwave background, the CIB arises from discrete sources. Ever-more-sensitive surveys will identify the brightest of these, allowing them to be removed, and – like peeling layers off an onion – reveal deeper layers of the CIB. In this way it is possible to measure the contributions from populations not accessible to direct telescopic observation. Measurement of fluctuations in the source-subtracted CIB, i.e., the spatial power spectrum of the CIB after subtracting resolved sources, provides a robust means of characterizing its faint, and potentially new, populations. Studies over the past 15 years have revealed source-subtracted CIB fluctuations on scales out to $\sim 100'$ which cannot be explained by extrapolating from known galaxy populations. Moreover, they appear highly coherent with the unresolved Cosmic X-ray Background, hinting at a significant population of accreting black holes among the CIB sources. **Characterizing the source-subtracted CIB with high accuracy, and thereby constraining the nature of the new populations, is feasible with upcoming instruments and would produce critically important cosmological information in the next decade.** New coextensive

deep and wide-area near-infrared, X-ray, and microwave surveys will bring decisive opportunities to examine, with high fidelity, the spatial spectrum and origin of the CIB fluctuations and their cross-correlations with cosmic microwave and X-ray backgrounds, and determine the formation epochs and the nature of the new sources (stellar nucleosynthetic or accreting black holes).

1. Introduction

The cosmic infrared background (CIB) includes emissions from objects inaccessible to direct telescopic studies [see review by 25, 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 [29]. 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 [28, 27, 21, 45, 7]. The spatial power spectrum of CIB fluctuations depends on the clustering of the remaining sources, and their integrated emission.

Lower limits on the extragalactic background (EBL) flux come from integrating source counts in various bands; upper bounds can be estimated from the γ-ray opacity caused by the CIB/EBL (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 surveys. The source-subtracted CIB is that remaining 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 [32, 34, 33, 36, 6, 46, 16] span 2–5μm; at shorter wavelengths there is currently significant uncertainty with conflicting results from, in chronological order, deep 2MASS, *HST*/NICMOS, CIBER and *HST*/WFC3 analyses [30, 52, 55, 56, 63, 49]. The source-subtracted CIB from deep *Spitzer* data appears highly coherent with soft cosmic X-ray background (CXB) [12, 13, 50, 44] implying a significant presence of accreting black holes (BHs) among the new CIB sources. (See review by [39].)

The CIB fluctuation signal implies new populations below the (faint) flux limit (AB$\gtrsim$25) with significant implications for cosmology. *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.*

Theoretically such CIB signal was predicted to arise from the first stars era (FSE) [31, 14]. The sources responsible for it can come from Population III, predicted to be very massive stars that, for the standard ΛCDM model, form in first collapsed minihalos of $10^{6-9} M_\odot$ at $z > 10$ [10, 11, 1]; the faint minihalos will have high projected surface density lying largely in the confusion noise of the next decade telescopes [38]. The early epochs could also contain abundant BHs of various origins, contributing at both IR and X-ray [3, 60, 61, 62, 26, 41]. Also there may be contributions from new stellar populations at low to intermediate z as well as from a new particle decay [9, 16, 20]. The

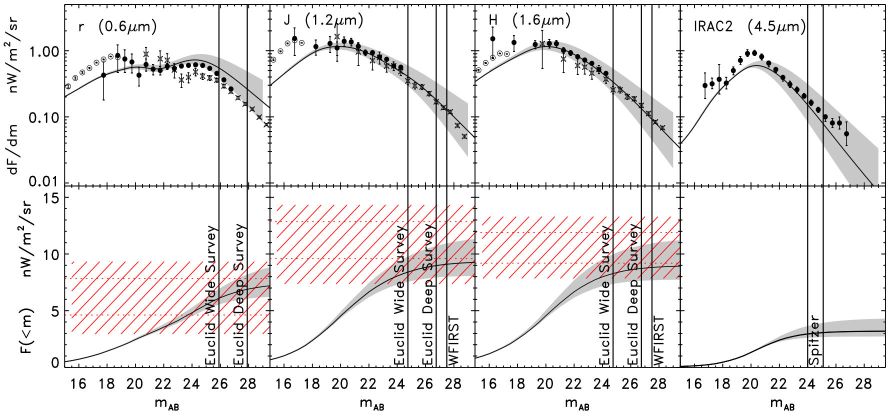

Figure 1: **Top**: Data points show the differential contribution to the mean background flux for galaxy count surveys [17]. The line and shaded uncertainty band are the mean flux provided by the reconstruction of [22]. **Bottom**: The reconstruction in black shows the net EBL flux vs. magnitude. The red dotted lines (hatched band) show the 1σ (2σ) range on EBL estimates from γ-ray opacity [18] (the 4.5μm limits are not constraining and are not shown). 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.

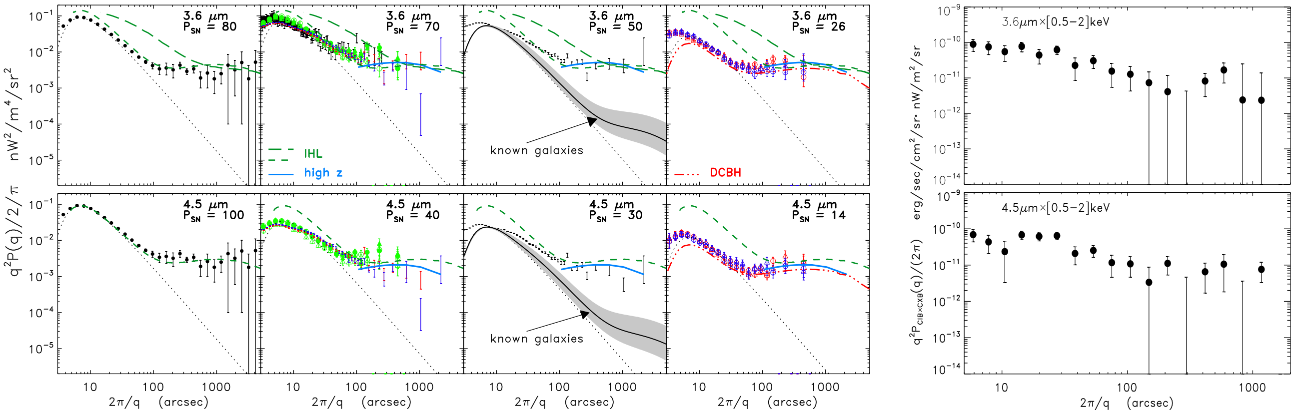

Figure 2: Mean squared fluctuation, $q^2P(q)/(2\pi)$, at angular scale $2\pi/q$. **Left**: *Spitzer*-based source-subtracted CIB fluctuations at different shot-noise power levels [32, 34, 36, 16] at 3.6μm and 4.5 μm. *No decrease of the large-scale clustering component with shot noise yet appears at these shot-noise levels*, its power marked in nJy·nW/m^2/sr. Contribution from remaining known galaxies is shown from [22]. The intrahalo light (IHL) models at low z, green short dashes from [15] and green long dashes [63] , 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 [60] is shown with red dash-triple-dotted lines, the LIGO-type PBH model [26] is shown with blue solid line. Adapted from [39]. **Right**: The CIB-CXB cross-power between the IRAC 3.6 and 4.5 μm CIB and Chandra soft CXB [13].

populations cannot be observed directly by existing telescopes, but could be probed via source-subtracted CIB anisotropies (or fluctuations).

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

The source-subtracted CIB fluctuations uncovered in deep *Spitzer* data, are displayed in Fig. 2, left. They contain two terms: 1) shot-noise, or the convolved white noise, and 2) the clustering term which originates from new unknown populations. The *Spitzer*- and *Akari*-based measurements [32, 34, 36, 6, 46, 16] cover 2–5 μm; their main established properties are summed up below with Fig. 2 showing their most relevant properties [see ref. 39, Sec. V.B.3]:

- The shot noise component, $P_{\rm SN}{=}\int_{m_0}^{\infty} S^2(m)dN$, dominates small angular scales (dotted lines in Fig.2, left panels). It still 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 [25, 22]. The excess power from clustering appears isotropic on the sky consistent with a cosmological origin [34, 36].
- 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 [35].
- 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 [46].
- *Spitzer/AKARI* band-integrated CIB fluctuations are $\delta F_{2-5\mu{\rm m}}(5')$ $\simeq$0.1 nW/m^2/sr [39], corresponding to the mean CIB flux $\sim$1 nW/m^2/sr [35] 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 [18].
- The CIB clustering component is strongly coherent with the (soft) cosmic X-ray background (CXB) [12, 13, 50, 44]. The cross-power, $P_{\rm CIB\times CXB}$, cannot be explained by remaining known galaxies [23]. The emerging CXB-CIB coherence, $\mathcal{C} \equiv P^2_{\rm CIB\times CXB}/P_{\rm CIB}/P_{\rm CXB}$, exceeds $\mathcal{C} \gtrsim$0.04 [13] suggesting a significant abundance of accreting BHs among the CIB-producing sources.

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 [25] posited that the signal is from the first stars era, while later [16] proposed that it comes from an 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 [63] appears in tension with the the newest γ-ray absorption limits [18]. Massive Pop III stars at $z \gtrsim 10$ can account for the CIB fluctuations only with somewhat "optimistic" efficiencies of formation (5-10%) inside the first minihalos [24]. With the discovery of the CIB-CXB coherence, two suggestions have been made for the origin of these fluctuations, both involving BHs at high z: 1) direct collapse BHs (DCBHs) [60] and 2) LIGO-type primordial BHs (PBHs) making up dark matter [26]. CIB fluctuations are thus a critical tool for the understanding of: i) new populations that cannot be detected directly; ii) the physics of the pregalactic Universe; iii) the nature of the first sources and, potentially, reionization; iv) BH activity; and v) the 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 can 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 observational configuration required to isolate the Lyman break must reach AB$\gtrsim$25 since at brighter magnitudes the CIB power below $\sim 1\mu$m from remaining known galaxies, and its systematic uncertainty strongly dominates that observed from the new populations at 2–5μm [38].

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 Lyman tomography by examining, suitably subtracting, the relative brightness of the large-scale fluctuations in a series of adjacent spectral bands.With increasing wavelength, such comparisons are sensitive to the fraction of the population lying at increasingly high redshifts [38, 37]. These studies require deep imaging (to remove foreground sources) over large areas (to obtain high S/N power spectra at large scales) in many 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 not sufficiently 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 [24, 60, 37, 59].

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. See Figure 4,left.

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

The IGM plasma would produce weak 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 [8].

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

Lyman tomography uses measurements of the CIB fluctuations over large areas at multiple wavelengths to derive high-precision measurements of the CIB power spectrum as a function of redshift at $z > 10$. This in turn may enable probing the baryonic acoustic oscillations (BAOs) at redshifts beyond those that can be probed by other means, opening a brand new window on the standard cosmological model to obtain constraints from the high redshift universe [37].

4. Outlook to the coming decade

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 [19, 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 [42, 43] will 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 probe 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, after subtraction of sources to the AB≃25–26 magnitude limits. In the H band, 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 if due to high z sources, and only the power of the unresolved known populations should be detected. The right panels of Fig.3 show that the 3 near-IR bands will enable Lyman tomography to explore the history of the emission (Q2), and the large areas will allow sufficient S/N to probe the BAO imprint in the power spectrum, addressing (Q6).

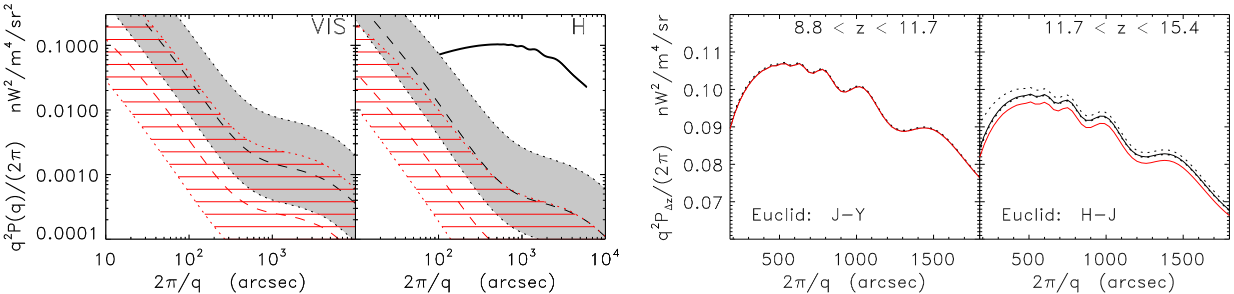

Figure 3: **Left**: CIB fluctuations from known galaxies remaining in the *Euclid* VIS and NISP bands (grey shaded area for Wide Survey and red lined area for Deep Survey). Thick solid line is a high-z CIB, which fits *Spitzer* 3.6, 4.5 μm CIB fluctuations. **Right**: The Lyman-tomography reconstruction of the CIB emission history and BAOs for *Euclid*'s (Y,J,H) filters and Wide Survey depth at each z-range. Red line shows the underlying CIB fluctuations by sources in the marked z-range from high-z stellar populations reproducing *Spitzer* measurements. Black lines include also the contributions from known remaining galaxies [22] with its uncertainty marked by dotted lines. Adapted from [39].

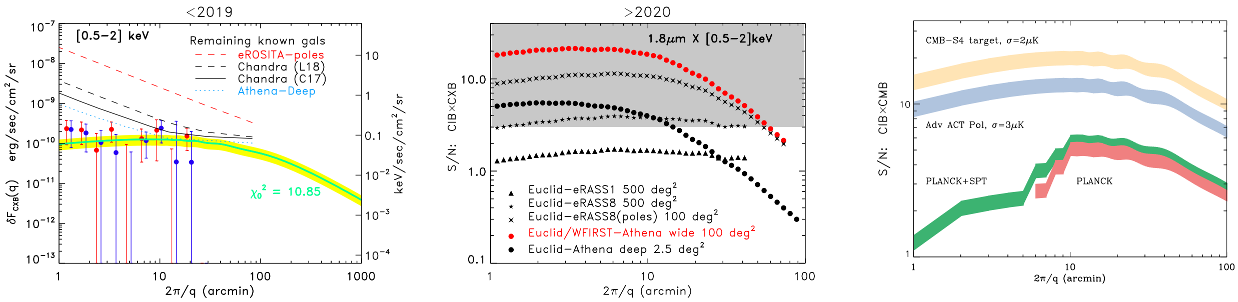

Figure 4: **Left**: Residual CXB, $\delta F_{\rm X} \equiv (q/\sqrt{2\pi}) P_{\rm CIB\times CXB}/\sqrt{P_{\rm CIB}}$, from the new populations [40]. Blue (3.6 μm) and red (4.5 μm) circles are derived using the IRAC/*Chandra* measurements [13]. Solid green line is the best fit for the 3D ΛCDM power template at $d_A = 7$ Gpc (z=15); the yellow regions marks 1σ deviation of the fit which gives $\chi_0^2 = 10.85$ for the 18 data points. The angular scales shown here are where clustering component dominates, and at the same 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. From [40]. **Middle**: 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 $S/N \geq 3$. From [40]. **Right**: Filled regions show the range of the S/N of the CIB-TSZ cross power over the Euclid Wide Survey region for the marked experimental configurations for an IGM temperature of $T_{\rm e}$=10^4K; the value of $S/N \propto T_{\rm e}$. From [8, 39].

Substantial improvements in the CIB-CXB cross-power will be provided by the *Euclid* CIB data and *eROSITA* [47] X-ray maps. These would bring decisive probes of the cross-power signal [40] particularly from the deep *eROSITA* coverage of 140 deg^2 at the poles. ESA's *Athena* [51], 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 [12, 50, 13, 44]. Figs.4,left/middle show the expected progress for answering Q3,Q4. The large areas covered by *eROSITA* and *Athena* with good energy resolution will allow probing the CIB-CXB cross-power at hard X-ray energies, enabling further insights into Q3,Q4 and the new sources.

If they are 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 a cross-correlation of the source-subtracted CIB from *Euclid* with multifrequency CMB maps, suitably constructed to remove primary and kinematic SZ CMB terms [8]. 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 [58, 57, 54] and CMB-S4 [2].

Further CIB information will be available from *WFIRST* to be launched in 2nd half of 2020's [53] which will map 2,000 deg^2 with 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. The areal coverage of *JWST* surveys will be too limited to provide a detailed probe of the clustering signal in the power spectrum. However *JWST* will provide the deepest possible direct survey of contributors to the CIB. A configuration covering 1 deg^2 to $m_{\rm AB} = 28$ in all 7 NIRCAM wide filters will take ∼400 hrs of *JWST*'s time and was proposed by [38] to result in significant new information (Q1,Q2) on the new CIB sources, including their energy spectrum over 0.6–6μm.

New ground-based telescopes can provide very deep and wide surveys of the resolved galaxy populations, but are not well-suited for measuring CIB fluctuations at the scales and wavelengths of interest. The study of CIB fluctuations will perfectly complement ongoing neutral hydrogen 21 cm line intensity mapping studies (e.g. PAPER, EDGES, HERA, LOFAR, MWA, SKA), where the 21 cm global or power spectrum signals characterize the topology and z-evolution of the IGM [48, and refs therein]. Since CIB is more sensitive to the nature and properties of early sources, the combination of the two approaches will provide a complete picture at the time of the first light.

References

[1] T. Abel, G. L. Bryan, and M. L. Norman. The Formation of the First Star in the Universe. *Science*, 295:93–98, January 2002. doi: 10.1126/science.295.5552.93.

[2] M. H. Abitbol, Z. Ahmed, D. Barron, R. Basu Thakur, A. N. Bender, B. A. Benson, C. A. Bischoff, S. A. Bryan, J. E. Carlstrom, C. L. Chang, D. T. Chuss, A. Cukierman, T. de Haan, M. Dobbs, T. Essinger-Hileman, J. P. Filippini, K. Ganga, J. E. Gudmundsson, N. W. Halverson, S. Hanany, S. W. Henderson, C. A. Hill, S.-P. P. Ho, J. Hubmayr, K. Irwin, O. Jeong, B. R. Johnson, S. A. Kernasovskiy, J. M. Kovac, A. Kusaka, A. T. Lee, S. Maria, P. Mauskopf, J. J. McMahon, L. Moncelsi, A. W. Nadolski, J. M. Nagy, M. D. Niemack, R. C. O'Brient, S. Padin, S. C. Parshley, C. Pryke, N. A. Roe, K. Rostem, J. Ruhl, S. M. Simon, S. T. Staggs, A. Suzuki, E. R. Switzer, K. L. Thompson, P. Timbie, G. S. Tucker, J. D. Vieira, A. G. Vieregg, B. Westbrook, E. J. Wollack, K. W. Yoon, K. S. Young, and E. Y. Young. CMB-S4 Technology Book, First Edition. *ArXiv e-prints*, June 2017.

[3] B. Agarwal, S. Khochfar, J. L. Johnson, E. Neistein, C. Dalla Vecchia, and M. Livio. Ubiquitous seeding of supermassive black holes by direct collapse. *MNRAS*, 425:2854–2871, October 2012. doi: 10.1111/j.1365-2966.2012.21651.x.

[4] R. G. Arendt, D. J. Fixsen, and S. H. Moseley. Dithering Strategies for Efficient Self-Calibration of Imaging Arrays. *ApJ*, 536:500–512, June 2000. doi: 10.1086/308923.

[5] R. G. Arendt, D. J. Fixsen, and S. H. Moseley. A Practical Demonstration of Self-Calibration of NICMOS HDF North and South Data. In D. A. Bohlender, D. Durand, and T. H. Handley, editors, *Astronomical Data Analysis Software and Systems XI*, volume 281 of *Astronomical Society of the Pacific Conference Series*, page 217, 2002.

[6] R. G. Arendt, A. Kashlinsky, S. H. Moseley, and J. Mather. Cosmic Infrared Background Fluctuations in Deep Spitzer Infrared Array Camera Images: Data Processing and Analysis. *ApJS*, 186:10–47, January 2010. doi: 10.1088/0067-0049/186/1/10.

[7] R. G. Arendt, A. Kashlinsky, S. H. Moseley, and J. Mather. Cosmic Infrared Background Fluctuations and Zodiacal Light. *ApJ*, 824:26, June 2016. doi: 10.3847/0004-637X/824/1/26.

[8] F. Atrio-Barandela and A. Kashlinsky. Probing the Epoch of Pre-reionization by Cross-correlating Cosmic Microwave and Infrared Background Anisotropies. *ApJL*, 797:L26, December 2014. doi: 10.1088/2041-8205/797/2/L26.

[9] J. R. Bond and G. Efstathiou. Cosmic background radiation anisotropies in universes dominated by nonbaryonic dark matter. *ApJL*, 285:L45–L48, October 1984. doi: 10.1086/184362.

[10] V. Bromm and R. B. Larson. The First Stars. *Ann. Rev. Astron. Astropys.*, 42:79–118, September 2004. doi: 10.1146/annurev.astro.42.053102.134034.

[11] V. Bromm, A. Ferrara, P. S. Coppi, and R. B. Larson. The fragmentation of pre-enriched primordial objects. *MNRAS*, 328:969–976, December 2001. doi: 10.1046/j.1365-8711.2001.04915.x.

[12] N. Cappelluti, A. Kashlinsky, R. G. Arendt, A. Comastri, G. G. Fazio, A. Finoguenov, G. Hasinger, J. C. Mather, T. Miyaji, and S. H. Moseley. Cross-correlating Cosmic Infrared and X-Ray Background Fluctuations: Evidence of Significant Black Hole Populations among the CIB Sources. *ApJ*, 769:68, May 2013. doi: 10.1088/0004-637X/769/1/68.

[13] N. Cappelluti, R. Arendt, A. Kashlinsky, Y. Li, G. Hasinger, K. Helgason, M. Urry, P. Natarajan, and A. Finoguenov. Probing Large-scale Coherence between Spitzer IR and Chandra X-Ray Source-subtracted Cosmic Backgrounds. *ApJL*, 847:L11, September 2017. doi: 10.3847/2041-8213/aa8acd.

[14] A. Cooray, J. J. Bock, B. Keatin, A. E. Lange, and T. Matsumoto. First Star Signature in Infrared Background Anisotropies. *ApJ*, 606:611–624, May 2004. doi: 10.1086/383137.

[15] A. Cooray, Y. Gong, J. Smidt, and M. G. Santos. The Near-infrared Background Intensity and Anisotropies during the Epoch of Reionization. *ApJ*, 756:92, September 2012. doi: 10.1088/0004-637X/756/1/92.

[16] A. Cooray, J. Smidt, F. de Bernardis, Y. Gong, D. Stern, M. L. N. Ashby, P. R. Eisenhardt, C. C. Frazer, A. H. Gonzalez, C. S. Kochanek, S. Kozłowski, and E. L. Wright. Near-infrared background anisotropies from diffuse intrahalo light of galaxies. *Nature*, 490:514–516, October 2012. doi: 10.1038/nature11474.

[17] S. P. Driver, S. K. Andrews, L. J. Davies, A. S. G. Robotham, A. H. Wright, R. A. Windhorst, S. Cohen, K. Emig, R. A. Jansen, and L. Dunne. Measurements of Extragalactic Background Light from the Far UV to the Far IR from Deep Ground- and Space-based Galaxy Counts. *ApJ*, 827:108, August 2016. doi: 10.3847/0004-637X/827/2/108.

[18] Fermi-LAT Collaboration, S. Abdollahi, M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, J. Becerra Gonzalez, R. Bellazzini, E. Bissaldi, R. D. Blandford, E. D. Bloom, R. Bonino, E. Bottacini, S. Buson, J. Bregeon, P. Bruel, R. Buehler, R. A. Cameron, R. Caputo, P. A. Caraveo, E. Cavazzuti, E. Charles, S. Chen, C. C. Cheung, G. Chiaro, S. Ciprini, J. Cohen-Tanugi, L. R. Cominsky, J. Conrad, D. Costantin, S. Cutini, F. D'Ammando, F. de Palma, A. Desai, S. W. Digel, N. Di Lalla, M. Di Mauro, L. Di Venere, A. Domínguez, C. Favuzzi, S. J. Fegan, J. Finke, A. Franckowiak, Y. Fukazawa, S. Funk, P. Fusco, G. Gallardo Romero, F. Gargano, D. Gasparrini, N. Giglietto, F. Giordano, M. Giroletti, D. Green, I. A. Grenier, L. Guillemot, S. Guiriec, D. H. Hartmann, E. Hays, K. Helgason, D. Horan, G. Jóhannesson, D. Kocevski, M. Kuss, S. Larsson, L. Latronico, J. Li, F. Longo, F. Loparco, B. Lott, M. N. Lovellette, P. Lubrano, G. M. Madejski, J. D. Magill, S. Maldera, A. Manfreda, L. Marcotulli, M. N. Mazziotta, J. E. McEnery, M. Meyer, P. F. Michelson, T. Mizuno, M. E. Monzani, A. Morselli, I. V. Moskalenko, M. Negro, E. Nuss, R. Ojha, N. Omodei, M. Orienti, E. Orlando, J. F. Ormes, M. Palatiello, V. S. Paliya, D. Paneque, J. S. Perkins, M. Persic, M. Pesce-Rollins, V. Petrosian, F. Piron, T. A. Porter, J. R. Primack, G. Principe, S. Rainò, R. Rando, M. Razzano, S. Razzaque, A. Reimer, O. Reimer, P. M. Saz Parkinson, C. Sgrò, E. J. Siskind, G. Spandre, P. Spinelli, D. J. Suson, H. Tajima, M. Takahashi, J. B. Thayer, L. Tibaldo, D. F. Torres, E. Torresi, G. Tosti, A. Tramacere, E. Troja, J. Valverde, G. Vianello, M. Vogel, K. Wood, and G. Zaharijas. A

gamma-ray determination of the Universe's star formation history. *Science*, 362:1031–1034, November 2018. doi: 10.1126/science.aat8123.

[19] D. J. Fixsen, S. H. Moseley, and R. G. Arendt. Calibrating Array Detectors. *ApJS*, 128: 651–658, June 2000. doi: 10.1086/313390.

[20] Y. Gong, A. Cooray, K. Mitchell-Wynne, X. Chen, M. Zemcov, and J. Smidt. Axion decay and anisotropy of near-IR extragalactic background light. *ArXiv e-prints*, November 2015.

[21] M. G. Hauser, R. G. Arendt, T. Kelsall, E. Dwek, N. Odegard, J. L. Weiland, H. T. Freudenreich, W. T. Reach, R. F. Silverberg, S. H. Moseley, Y. C. Pei, P. Lubin, J. C. Mather, R. A. Shafer, G. F. Smoot, R. Weiss, D. T. Wilkinson, and E. L. Wright. The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. I. Limits and Detections. *ApJ*, 508:25–43, November 1998. doi: 10.1086/306379.

[22] K. Helgason, M. Ricotti, and A. Kashlinsky. Reconstructing the Near-infrared Background Fluctuations from Known Galaxy Populations Using Multiband Measurements of Luminosity Functions. *ApJ*, 752:113, June 2012. doi: 10.1088/0004-637X/752/2/113.

[23] K. Helgason, N. Cappelluti, G. Hasinger, A. Kashlinsky, and M. Ricotti. The Contribution of $z \lesssim 6$ Sources to the Spatial Coherence in the Unresolved Cosmic Near-infrared and X-Ray Backgrounds. *ApJ*, 785:38, April 2014. doi: 10.1088/0004-637X/785/1/38.

[24] K. Helgason, M. Ricotti, A. Kashlinsky, and V. Bromm. On the physical requirements for a pre-reionization origin of the unresolved near-infrared background. *MNRAS*, 455:282–294, January 2016. doi: 10.1093/mnras/stv2209.

[25] A. Kashlinsky. Cosmic infrared background and early galaxy evolution [review article]. *Phys. Rep.*, 409:361–438, April 2005. doi: 10.1016/j.physrep.2004.12.005.

[26] A. Kashlinsky. LIGO Gravitational Wave Detection, Primordial Black Holes, and the Near-IR Cosmic Infrared Background Anisotropies. *ApJL*, 823:L25, June 2016. doi: 10.3847/2041-8205/823/2/L25.

[27] A. Kashlinsky and S. Odenwald. Clustering of the Diffuse Infrared Light from the COBE DIRBE Maps. III. Power Spectrum Analysis and Excess Isotropic Component of Fluctuations. *ApJ*, 528:74–95, January 2000. doi: 10.1086/308172.

[28] A. Kashlinsky, J. C. Mather, and S. Odenwald. Clustering of the Diffuse Infrared Light from the COBE DIRBE Maps: an All-Sky Survey of C(0). *ApJL*, 473:L9, December 1996. doi: 10.1086/310379.

[29] A. Kashlinsky, J. C. Mather, S. Odenwald, and M. G. Hauser. Clustering of the Diffuse Infrared Light from the COBE DIRBE Maps. I. C(0) and Limits on the Near-Infrared Background. *ApJ*, 470:681, October 1996. doi: 10.1086/177900.

[30] A. Kashlinsky, S. Odenwald, J. Mather, M. F. Skrutskie, and R. M. Cutri. Detection of Small-Scale Fluctuations in the Near-Infrared Cosmic Infrared Background from Long-Exposure 2MASS Fields. *ApJL*, 579:L53–L57, November 2002. doi: 10.1086/345335.

[31] A. Kashlinsky, R. Arendt, J. P. Gardner, J. C. Mather, and S. H. Moseley. Detecting Population III Stars through Observations of Near-Infrared Cosmic Infrared Background Anisotropies. *ApJ*, 608:1–9, June 2004. doi: 10.1086/386365.

[32] A. Kashlinsky, R. G. Arendt, J. Mather, and S. H. Moseley. Tracing the first stars with fluctuations of the cosmic infrared background. *Nature*, 438:45–50, November 2005. doi: 10.1038/nature04143.

[33] A. Kashlinsky, R. G. Arendt, J. Mather, and S. H. Moseley. Demonstrating the Negligible Contribution of Optical HST ACS Galaxies to Source-subtracted Cosmic Infrared Background Fluctuations in Deep Spitzer IRAC Images. *ApJL*, 666:L1–L4, September 2007. doi: 10.1086/521551.

[34] A. Kashlinsky, R. G. Arendt, J. Mather, and S. H. Moseley. New Measurements of Cosmic Infrared Background Fluctuations from Early Epochs. *ApJL*, 654:L5–L8, January 2007. doi: 10.1086/510483.

[35] A. Kashlinsky, R. G. Arendt, J. Mather, and S. H. Moseley. On the Nature of the Sources of the Cosmic Infrared Background. *ApJL*, 654:L1–L4, January 2007. doi: 10.1086/510484.

[36] A. Kashlinsky, R. G. Arendt, M. L. N. Ashby, G. G. Fazio, J. Mather, and S. H. Moseley. New Measurements of the Cosmic Infrared Background Fluctuations in Deep Spitzer/IRAC Survey Data and Their Cosmological Implications. *ApJ*, 753:63, July 2012. doi: 10.1088/0004-637X/753/1/63.

[37] A. Kashlinsky, R. G. Arendt, F. Atrio-Barandela, and K. Helgason. Lyman-tomography of Cosmic Infrared Background Fluctuations with Euclid: Probing Emissions and Baryonic Acoustic Oscillations at $z \gtrsim 10$. *ApJL*, 813:L12, November 2015. doi: 10.1088/2041-8205/813/1/L12.

[38] A. Kashlinsky, J. C. Mather, K. Helgason, R. G. Arendt, V. Bromm, and S. H. Moseley. Reconstructing Emission from Pre-reionization Sources with Cosmic Infrared Background Fluctuation Measurements by the JWST. *ApJ*, 804:99, May 2015. doi: 10.1088/0004-637X/804/2/99.

[39] A. Kashlinsky, R. G. Arendt, F. Atrio-Barandela, N. Cappelluti, A. Ferrara, and G. Hasinger. Looking at cosmic near-infrared background radiation anisotropies. *Reviews of Modern Physics*, 90(2):025006, April 2018. doi: 10.1103/RevModPhys.90.025006.

[40] A. Kashlinsky, R. G. Arendt, N. Cappelluti, A. Finoguenov, G. Hasinger, K. Helgason, and A. Merloni. Probing the Cross-power of Unresolved Cosmic Infrared and X-Ray Backgrounds with Upcoming Space Missions. *ApJL*, 871:L6, January 2019. doi: 10.3847/2041-8213/aafaf6.

[41] M. A. Latif and A. Ferrara. Formation of Supermassive Black Hole Seeds. *Pub. Astron. Soc. Aust.*, 33:e051, October 2016. doi: 10.1017/pasa.2016.41.

[42] R. Laureijs, J. Amiaux, S. Arduini, J. . Augueres, J. Brinchmann, R. Cole, M. Cropper, C. Dabin, L. Duvet, A. Ealet, and et al. Euclid Definition Study Report. *ArXiv e-prints*, October 2011.

[43] R. Laureijs, G. Racca, L. Stagnaro, J.-C. Salvignol, J. Lorenzo Alvarez, G. Saavedra Criado, L. Gaspar Venancio, A. Short, P. Strada, C. Colombo, G. Buenadicha, J. Hoar, R. Kohley, R. Vavrek, Y. Mellier, M. Berthe, J. Amiaux, M. Cropper, S. Niemi, S. Pottinger, A. Ealet, K. Jahnke, T. Maciaszek, F. Pasian, M. Sauvage, S. Wachter, U. Israelsson, W. Holmes, M. Seiffert, V. Cazaubiel, A. Anselmi, and P. Musi. Euclid mission status. In *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*, volume 9143 of *Proc. SPIE*, page 91430H, August 2014. doi: 10.1117/12.2054883.

[44] Y. Li, N. Cappelluti, R. G. Arendt, G. Hasinger, A. Kashlinsky, and K. Helgason. The SPLASH and Chandra COSMOS Legacy Survey: The Cross-power between Near-infrared and X-Ray Background Fluctuations. *ApJ*, 864:141, September 2018. doi: 10.3847/1538-4357/aad55a.

[45] T. Matsumoto, S. Matsuura, H. Murakami, M. Tanaka, M. Freund, M. Lim, M. Cohen, M. Kawada, and M. Noda. Infrared Telescope in Space Observations of the Near-Infrared Extragalactic Background Light. *ApJ*, 626:31–43, June 2005. doi: 10.1086/429383.

[46] T. Matsumoto, H. J. Seo, W.-S. Jeong, H. M. Lee, S. Matsuura, H. Matsuhara, S. Oyabu, J. Pyo, and T. Wada. AKARI Observation of the Fluctuation of the Near-infrared Background. *ApJ*, 742:124, December 2011. doi: 10.1088/0004-637X/742/2/124.

[47] A. Merloni, P. Predehl, W. Becker, H. Böhringer, T. Boller, H. Brunner, M. Brusa, K. Dennerl, M. Freyberg, P. Friedrich, A. Georgakakis, F. Haberl, G. Hasinger, N. Meidinger, J. Mohr, K. Nandra, A. Rau, T. H. Reiprich, J. Robrade, M. Salvato, A. Santangelo, M. Sasaki, A. Schwope, J. Wilms, and t. German eROSITA Consortium. eROSITA Science Book: Mapping the Structure of the Energetic Universe. *ArXiv e-prints*, September 2012.

[48] A. Mesinger, editor. *Understanding the Epoch of Cosmic Reionization*, volume 423 of *Astrophysics and Space Science Library*, 2016. doi: 10.1007/978-3-319-21957-8.

[49] K. Mitchell-Wynne, A. Cooray, Y. Gong, M. Ashby, T. Dolch, H. Ferguson, S. Finkelstein, N. Grogin, D. Kocevski, A. Koekemoer, J. Primack, and J. Smidt. Ultraviolet luminosity density of the universe during the epoch of reionization. *Nature Communications*, 6:7945, September 2015. doi: 10.1038/ncomms8945.

[50] K. Mitchell-Wynne, A. Cooray, Y. Xue, B. Luo, W. Brandt, and A. Koekemoer. Cross-correlation between X-ray and optical/near-infrared background intensity fluctuations. *ArXiv e-prints*, October 2016.

[51] K. Nandra, D. Barret, X. Barcons, A. Fabian, J.-W. den Herder, L. Piro, M. Watson, C. Adami, J. Aird, J. M. Afonso, and et al. The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena+ mission. *ArXiv e-prints*, June 2013.

[52] S. Odenwald, A. Kashlinsky, J. C. Mather, M. F. Skrutskie, and R. M. Cutri. Analysis of the Diffuse Near-Infrared Emission from Two-Micron All-Sky Survey Deep Integration Data: Foregrounds versus the Cosmic Infrared Background. *ApJ*, 583:535–550, February 2003. doi: 10.1086/345401.

[53] D. Spergel, N. Gehrels, C. Baltay, D. Bennett, J. Breckinridge, M. Donahue, A. Dressler, B. S. Gaudi, T. Greene, O. Guyon, C. Hirata, J. Kalirai, N. J. Kasdin, B. Macintosh, W. Moos, S. Perlmutter, M. Postman, B. Rauscher, J. Rhodes, Y. Wang, D. Weinberg, D. Benford, M. Hudson, W.-S. Jeong, Y. Mellier, W. Traub, T. Yamada, P. Capak, J. Colbert, D. Masters, M. Penny, D. Savransky, D. Stern, N. Zimmerman, R. Barry, L. Bartusek, K. Carpenter, E. Cheng, D. Content, F. Dekens, R. Demers, K. Grady, C. Jackson, G. Kuan, J. Kruk, M. Melton, B. Nemati, B. Parvin, I. Poberezhskiy, C. Peddie, J. Ruffa, J. K. Wallace, A. Whipple, E. Wollack, and F. Zhao. Wide-Field InfrarRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report. *ArXiv e-prints*, March 2015.

[54] The Simons Observatory Collaboration, P. Ade, J. Aguirre, Z. Ahmed, S. Aiola, A. Ali, D. Alonso, M. A. Alvarez, K. Arnold, P. Ashton, and et al. The Simons Observatory: Science goals and forecasts. *arXiv e-prints*, August 2018.

[55] R. I. Thompson, D. Eisenstein, X. Fan, M. Rieke, and R. C. Kennicutt. Evidence for a $z < 8$ Origin of the Source-subtracted Near-Infrared Background. *ApJ*, 666:658–662, September 2007. doi: 10.1086/520634.

[56] R. I. Thompson, D. Eisenstein, X. Fan, M. Rieke, and R. C. Kennicutt. Constraints on the Cosmic Near-Infrared Background Excess from NICMOS Deep Field Observations. *ApJ*, 657:669–680, March 2007. doi: 10.1086/511380.

[57] R. J. Thornton, P. A. R. Ade, S. Aiola, F. E. Angilè, M. Amiri, J. A. Beall, D. T. Becker, H.-M. Cho, S. K. Choi, P. Corlies, K. P. Coughlin, R. Datta, M. J. Devlin, S. R. Dicker, R. Dünner, J. W. Fowler, A. E. Fox, P. A. Gallardo, J. Gao, E. Grace, M. Halpern, M. Hasselfield, S. W. Henderson, G. C. Hilton, A. D. Hincks, S. P. Ho, J. Hubmayr, K. D. Irwin, J. Klein, B. Koopman, D. Li, T. Louis, M. Lungu, L. Maurin, J. McMahon, C. D. Munson, S. Naess, F. Nati, L. Newburgh, J. Nibarger, M. D. Niemack, P. Niraula, M. R. Nolta, L. A. Page, C. G. Pappas, A. Schillaci, B. L. Schmitt, N. Sehgal, J. L. Sievers, S. M. Simon, S. T. Staggs, C. Tucker, M. Uehara, J. van Lanen, J. T. Ward, and E. J. Wollack. The Atacama Cosmology Telescope: The Polarization-sensitive ACTPol Instrument. *ApJS*, 227:21, December 2016. doi: 10.3847/1538-4365/227/2/21.

[58] J. T. Ward, J. Austermann, J. A. Beall, S. K. Choi, K. T. Crowley, M. J. Devlin, S. M. Duff, P. A. Gallardo, S. W. Henderson, S.-P. P. Ho, G. Hilton, J. Hubmayr, N. Khavari, J. Klein, B. J. Koopman, D. Li, J. McMahon, G. Mumby, F. Nati, M. D. Niemack, L. A. Page, M. Salatino, A. Schillaci, B. L. Schmitt, S. M. Simon, S. T. Staggs, R. Thornton, J. N. Ullom, E. M. Vavagiakis, and E. J. Wollack. Mechanical designs and development of TES bolometer detector arrays for the Advanced ACTPol experiment. In *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, volume 9914 of *Proc. SPIE*, page 991437, July 2016. doi: 10.1117/12.2233746.

[59] R. A. Windhorst, F. X. Timmes, J. S. B. Wyithe, M. Alpaslan, S. K. Andrews, D. Coe, J. M. Diego, M. Dijkstra, S. P. Driver, P. L. Kelly, and D. Kim. On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits. *ApJS*, 234:41, February 2018. doi: 10.3847/1538-4365/aaa760.

[60] B. Yue, A. Ferrara, R. Salvaterra, Y. Xu, and X. Chen. Infrared background signatures of the first black holes. *MNRAS*, 433:1556–1566, August 2013. doi: 10.1093/mnras/stt826.

[61] B. Yue, A. Ferrara, R. Salvaterra, Y. Xu, and X. Chen. The brief era of direct collapse black hole formation. *MNRAS*, 440:1263–1273, May 2014. doi: 10.1093/mnras/stu351.

[62] B. Yue, A. Ferrara, and R. Salvaterra. Updated analysis of near-infrared background fluctuations. *ArXiv e-prints*, January 2016.

[63] M. Zemcov, J. Smidt, T. Arai, J. Bock, A. Cooray, Y. Gong, M. G. Kim, P. Korngut, A. Lam, D. H. Lee, T. Matsumoto, S. Matsuura, U. W. Nam, G. Roudier, K. Tsumura, and T. Wada. On the origin of near-infrared extragalactic background light anisotropy. *Science*, 346:732–735, November 2014. doi: 10.1126/science.1258168.