

Concept camera for the next-generation mm-wave cosmological surveys

Attila Kovács^a, Garrett Keating^a, and Timothy Norton^a

^aCenter for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA, U.S.A.

ABSTRACT

Past millimeter-wave galaxy surveys have probed the brightest starburst galaxies only and suffered heavily from confusion. The interpretation of existing surveys has also been hindered by the lack of reliable redshift indicators for measuring distances for the entire sample. Thanks to recent advances in mm-wave detector technologies we can now overcome these limitations, and conduct the first truly volumetric surveys of star-forming galaxies at mm-wavelengths down to the L_* luminosities of typical galaxies, with ~ 1000 redshift slices spanning most of the Cosmic star-forming volume ($z \sim 1-12$) with nearly uniform mass and luminosity selection. We describe an instrument concept capable of delivering such surveys with the technologies available today, which can be built and operated on a ground-based mm-wave facility in the near future. Such spectrometer cameras can resolve and redshift identify up to 25,000 star-forming galaxies per year even when operated on a 10-m class telescope. On a larger aperture it can do the same faster or probe even deeper. We propose a loose, open-source collaboration to design, build, and operate one or several such cameras through the shared contributions of leading experts and telescopes from around the globe.

Keywords: far-infrared instrumentation, integral-field spectroscopy, cosmological star-formation survey, volumetric galaxy survey, line intensity mapping, cosmic star-formation history, imaging spectroscopy

1. INTRODUCTION

Stars form in dusty environments, obscured from direct view at the optical wavebands.^{1,2} The optical/UV light from the young stellar populations is absorbed by the dust, and then re-emitted as cold (~ 35 K) thermal radiation in the far-infrared (FIR) bands, peaking near $\lambda \sim 100 \mu\text{m}$ in the rest frame.³ Even the Milky Way – with modest star-formation rates of $\sim 1 M_\odot/\text{year}$ – radiates about half of its total bolometric luminosity in the FIR bands as a result, while galaxies with significantly higher star-formation rates emit over 99% of the luminosities at FIR wavelengths, and are difficult to spot optically, especially at higher redshifts.

Cosmic star formation has peaked around redshift $z \sim 2-3$.^{4,5} The bulk of the stars we see today formed during intense starbursts in that era, when galaxies would have been at their most luminous (thanks to short-lived populations of massive OB stars), yet largely obscured at optical wavelengths. To catch galaxies during their intense episodes of star-formation, we really must study them at FIR wavelengths.

Due to a strongly negative K -correction on the Rayleigh-Jeans side of the thermal spectral energy distribution (SED), a star-forming galaxy will appear similarly bright at ~ 1 mm wavelength regardless of its distance at $z \sim 1-12$ (Fig. 1). This flat mass-luminosity selection^{3,6} allows us to conduct unbiased luminosity-limited surveys of star-formation in the mm-band that spans much of the Cosmic history in which galaxies formed and evolved. This effect has been exploited for a number of FIR galaxy surveys.⁷⁻⁹ The Herschel Multi-tiered Extragalactic Survey (HerMES)⁸ alone has detected on the order of a 100,000 FIR galaxies with its long-wavelength (200–500 μm) SPIRE¹⁰ instrument.

However, the flat selection at mm-wavelength is a mixed blessing. Because every line of sight can see star-forming galaxies at all distances equally, the detections alone do not inform us about the redshift of these objects; and the fields quickly get crowded (confused) as extremely bright galaxies fill up every beam on sky well before one could hope to individually detect the fainter, more typical Milky-Way-like galaxy populations. Attempts to use photometry as a way to guesstimate redshifts for these galaxies have proven ineffective at best,¹¹ while spectroscopic follow-ups often rely on heavily biased cross-identifications¹² and can target at most a tiny fraction of the galaxies detected by the continuum surveys overall.

Further author information: Send correspondence to attila.kovacs@cfa.harvard.edu

2. FUTURE SURVEYS

One way to address the confusion is to conduct surveys with larger telescope apertures. Increasing of aperture diameter by a factor X allows detecting X^2 more sources before the confusion limit is reached. And with SMG number number counts $\partial N/\partial S \propto S^{-3.2}$ typically for the (bright) submillimeter galaxy (SMG) populations,⁷ the confusion flux limit (i.e. mass-luminosity selection threshold) will scale inversely as $S_{\min} \sim X^{-0.6}$. So larger apertures can help probe a little deeper, but they cannot magically solve the redshift identification issue.

The only way to provide redshift identification for the SMG population without introducing extreme bias is through spectroscopy in the (sub)millimeter bands directly, targeting the principal cooling lines such as those of the bright CO rotational ladder in molecular gas, or else those in atomic or ionized species such as CI (492 GHz and 809 GHz), CII (158 μm), or similar. Because galactic lines are broad (many hundreds of km/s typically), a moderate degree of spectral resolution ($R \sim 200\text{--}1000$) is typically sufficient for the quasi-optimal detection of such transitions from spatially unresolved galaxies.

The CO rotational ladder offers perhaps the best tool for redshift identification. The lower- J CO transitions are typically thermalized with a $S(\nu) \sim \nu^2$ spectrum on the Rayleigh-Jeans side of their pseudo-blackbody spectral energy distributions (SEDs). SMGs are known to exhibit thermalized emission into the morerately high- J (~ 10) transitions.^{13,14} The observed spacing of the CO ladder is $\Delta\nu \sim 115.3 \text{ GHz } (1+z)^{-1}$ for a source at redshift z . Thus, the number of transitions detectable in a broad-band spectrometer scales as $N_{\text{CO}}(z) \sim (1+z)$ at higher z , while the measurement noise from co-adding fluxes from the necessary channels increases as $\sqrt{N_{\text{CO}}}$. As such, the detectability of redshift, through the combination of multiple CO transitions in band, benefits from a negative K -correction also with an effective emissivity index $\beta = 0.5$ due to the multiplicity of available transitions.

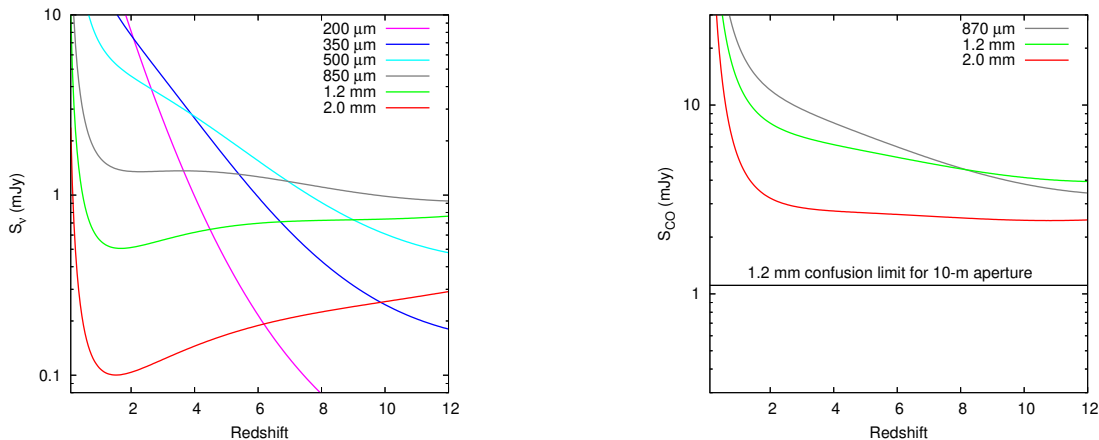


Figure 1. Typical redshift selection curves for a star-forming galaxies with $L \sim 10^{12} L_{\odot}$ at various wavelengths. *Left*: continuum selection curves.³ *Right*: Estimated combined CO-selection curves assuming thermalized CO transitions. As the high- J CO transitions may be sub-thermally excited, the actual selection curves will likely fall somewhat below this prediction at high z . The 1.2 mm confusion limit for an $R \sim 200$ spectrometer on a 10-m class telescope is also shown.

The ultimate result of which is that CO redshifts have a similarly flat mass-luminosity selection thresholds at millimeter wavelengths as the dust continuum (Fig. 1). CO emission is also highly correlated with the thermal dust continuum in extragalactic star-forming environments,¹⁵ both being equally effective tracers of the star-forming gas. As such, there is no fundamental need to detect SMGs by their far-infrared continuum emission separately, when detection via the CO ladder alone yields effectively the same mass-luminosity measure for star-forming sources. (Arguably, the CO selects star-formation more purely, since the mm-wave continuum may be contaminated by synchrotron emission, such as from active galactic nuclei [AGNs].)

2.1 Volumetric Galaxy Surveys

Because the CO ladder from a distant galaxy leaves a unique spectral imprint as a function of redshift, an $R \sim 200\text{--}1000$ spectrometer covering octave-scale bandwidths can effectively sample 1000–5000 redshift slices

above $z_{min} \sim 230 \text{ GHz} / \Delta f - 1$. Here z_{min} is the minimum redshift at which at least 2 CO transitions are detected in the observable bandwidth. Even if two galaxies overlap spatially, they will leave distinct spectral imprints so long as they are separated by $\Delta v_{rest} > c/R$ in the rest-frame velocity space (or $dz/(1+z) > 1/R$ in redshift space). That alone reduces confusion dramatically when compared to continuum surveys with comparable beam sizes. As a result, an $R \sim 200\text{--}1000$ survey instrument could detect up to 100–500 times more sources per beam than a continuum camera operated at the same wavelength before the spectral confusion limit is reached. Hence, an $R \sim 200\text{--}1000$ survey can probe star-forming galaxies to a mass / luminosity threshold an order-of-magnitude below that of a continuum survey at the same wavelengths for the same-sized telescope.

To put it into perspective, an $R \sim 200$ spectroscopic survey at $\lambda \sim 1.2 \text{ mm}$ on a 10-m class telescope, would be confused at a mass / luminosity threshold that is **~ 20 times below** what *Herschel*/SPIRE could probe at its longest wavelength $500 \mu\text{m}$ channel, while also peering further back in time. Consequently, it would resolve not only the most extreme ULIRG / HLIRG populations from before, but could for the first time systematically dip into the L_* populations¹⁶ that dominate the makeup of galaxies overall – while providing an unambiguous redshift identification for *every single detected source* also. On a 30-m aperture it could reach a factor of ~ 2 deeper still.

2.2 Line Intensity Mapping (LIM)

A related application, for the same or very similar spectrometer camera, is Line Intensity Mapping (LIM).¹⁷ In this case, the goal is not the detection and unique redshift identification of individually resolved galaxies, but rather the statistical (unresolved) detection of entire populations, and the statistical (e.g. 3D) correlations that characterize them. Because LIM targets galaxies with similar properties (e.g. velocity dispersion) as the above described survey, its requirements are inherently similar, specifically with $R \sim 200\text{--}1000$ spectroscopic mapping.¹⁸ However, because the goal is not the individual detection of sources, LIM surveys probe much larger areas albeit at shallower depths.

While deep galaxy surveys that can be performed effectively in a single atmospheric window (e.g. at $\lambda \sim 1.2 \text{ mm}$), LIM is best conducted over as much total bandwidth as possible, covering as many molecular and/or hyperfine transitions as possible. Thus, the ultimate LIM survey would require the next-level camera upgrade, featuring simultaneous multi-band capability. An ideal mm-wave LIM camera would cover the 3 mm, 2 mm, 1.2 mm, and $850 \mu\text{m}$ atmospheric windows with fully populated focal plane spectrometers simultaneously. As such it may contain up to four separate focal-planes, with a correspondingly higher total detector count to match. A multi-band implementation will inevitably require a far more complicated optical and cryogenic configuration than what a single-band camera can get away with. Sufficient stray-light and out-of-band light rejection will be significantly more challenging to achieve. Nevertheless, it is possible with the right amount of ambition if one really wants it.

Both a single-band and multi-band spectroscopic camera could satisfy both science goals (not at the same time of course). It's a question on which it is designed to do more optimally. The resolved galaxy surveys and LIM are inherently complementary to one another, both in their survey modes (small-deep vs. large-shallow), and their scientific outputs (individually resolved galaxies vs. statistically identified unresolved populations). Ideally, we will be pursuing both science goals in the not too distant future.

2.3 Enabling Technologies

Moderate resolution $R \sim 200\text{--}1000$ spectroscopic surveys are a compelling way forward. They promise to overcome both limitations of past (sub)millimeter continuum surveys, with significantly lesser confusion *and* direct, unambiguous, in-band redshift identifications. To conduct such surveys, however, we would need multi-beam spectroscopic cameras with moderate spectral resolutions of $R \sim 200\text{--}1000$ at mm-waves, preferably fully populating the field-of-view of a designated 10-m class or larger telescope. That in turn requires the following enabling technologies (scoped for a ground-based instrument, operated at $\lambda \sim 1 \text{ mm}$, with $f/D \sim 3\text{--}10$):

1. moderate resolution spectral channelizing in a footprint that is comparable or smaller than the size of a focal-plane pixel ($\sim 1 \text{ cm}^2$). *

*Alternatively, a set of slits and gratings illuminating a 2D array of detectors could in principle also be used to provide

2. direct detectors with $\text{NEP} \sim 3 \cdot 10^{-18} \text{ W/Hz}^{1/2}$, with footprint $\leq 1 \text{ mm}^2$ to allow packing 200 detectors onto a focal-plane pixel.
3. multiplexed readout for order $\sim 20,000$ mm-wave detectors in total.

Recent advances in technology have readily provided us with all three prerequisites. On-chip mm-wave spectrometers, like SuperSpec^{20,21} or DESHIMA,^{22,23} with $R \sim 100\text{--}1000$ have been demonstrated. Crucially, the channelizer part of these is already much smaller than the typical $\sim 1 \text{ cm}^2$ of a mm-wave focal-plane pixel of an envisaged mm-wave camera (most of the real-estate taken up by the readout resonators of the KIDs for both). Highly sensitive KIDs that far surpass the NEP requirement for background-limited operation have been produced,²⁴ and KIDs that meet the size and multiplexing requirements are presently being deployed.^{25,26} All that remains is combining these advances in the form of a new mm-wave integral field spectrometer (IPS) camera that can fill the field-of-view (FoV) of a 10-m class or larger mm-wave telescope. It could be done 'today'.

3. INSTRUMENT CONCEPT

Spectroscopic galaxy surveys at mm-wavelengths could be conducted from ground-based facilities. The 1.2 mm atmospheric window is especially promising in terms of yielding the highest detection rates, through a combination of factors: (1) the widest fractional bandwidth observable from the ground ($\Delta f / \langle f \rangle \sim 0.5$), which also results in the (2) lowest z_{min} cutoff, (3) low atmospheric opacities most of the time even at moderate altitudes, and (4) allows for cm^2 -scale packed pixel footprints, and (5) a reasonably flat CO redshift selection for $z \sim 1.5\text{--}12$, being firmly on the Rayleigh-Jeans side of the SED even for sources of extreme redshift ($z > 6$). However, we'll consider designs for the neighboring 2 mm and $850 \mu\text{m}$ atmospheric windows also. See Tables 1–3 for details.

We initially target $R \sim 200$ spectral resolution for practical reasons. While the most optimal detection of typical extragalactic CO linewidths (which we guess to be in the range of $\Delta v \sim 300\text{--}600 \text{ km/s}$ on average) may push for R in the 500–1000 range, it would require packing 2.5–5 times as many channels on a focal-plane pixel than an $R \sim 200$ design. Thus, while an $R \sim 200$ resolution may be somewhat less optimal for the detection of star-forming galaxies on average, it is significantly more feasible technologically, at least for now.

Table 1. $R=200$ spectrometer pixel properties.

λ (mm)	Band (GHz)	Bandwidth (GHz)	z_{min}	octaves	channels (count)
2	125 – 175	50	0.31	0.5	200
1.2	190 – 310	120	0.15	0.7	280
0.87	330 – 360	30	2.9	0.13	52

We baseline the camera concept for a 10-m class telescope. These are the smallest of the 'large' mm-wave telescopes, which abound thanks to many ALMA prototypes (e.g. APEX,²⁷ GLT²⁸), as well as existing telescopes of other designs (e.g., LCT²⁹ or SPT³⁰). The point is to show that a 10-m class telescope is perfectly capable delivering the transformative science when equipped with a background-limited $R \sim 200$ spectrometer camera, and operated from a site where PVW $\sim 2 \text{ mm}$ is typical. Larger telescopes (e.g. JCMT, IRAM 30-m,³¹ LMT,³² or AtLAST³³) could do the same thing faster and/or go deeper still. A 50-m class telescope may also provide astrometry of the sources at the 1–2'' level, which is sufficient for direct follow-up in most other bands.

We will assume a 10 arcmin FoV, which is achievable for most 10-m class mm-wave telescopes (e.g. in the Cassegrain cabin of APEX prototypes) without major modifications. Telescopes that offer a smaller field-of-view are not ruled out either – but their mapping speeds would be reduced proportionally to the area that can be imaged instantaneously. (This penalty, however, may be more than compensated by gains from a larger aperture size, e.g. for a 30-m telescope). Conversely, a larger field-of-view can increase the speed and yield of surveys, provided that it can be populated with the necessary number of detectors also.

an $R \sim 200$ spectrometer with a 2D field of view also, expanding on the design of HIRMES¹⁹ but with an additional tiling of slits and gratings, and hence spectra. However, we consider that approach both more complex and less proven, and hence we do not consider it here in detail.

For the concept, we will assume $f/D=5$ optical configuration, which is not atypical for existing mm-wave cameras. The $f/5$ is used merely to estimate the physical size of 'pixels' in the focal plane. Accordingly, the 10 arcmin field-of-view translates to around 12 cm on the focal plane, which is just below the size of a 5-inch wafer that is typically used for lithography. For larger focal planes, it may be necessary to tile multiple wafers to provide the desired total field of view. The concept is easily adjusted for different optical configurations also, and larger F numbers are can accommodate larger physical pixels, hence provide more room for the integrated spectrometers.

Table 2. Estimated $R=200$ channel performance at $PWV\sim 2$ mm.

λ (mm)	NEFD (mJy s ^{1/2})	CO confusion limit (mJy)	Conf. exposure (h)
2	86	0.55	6.8
1.2	220	1.1	11
0.87	450	1.9	16

The in-pixel $R\sim 200$ channelizing of the incident radiation necessitates an antenna-coupled design, whereby light is coupled into a lithographic transmission line filterbank. Because of the relatively narrow-band ($R\sim 200$) flux measurement, we want to focus as much of the incident light from a point-source onto a single pixel to achieve the best sensitivities. The incident radiation may be focused on the antenna by a suitable feedhorn or a lens. The most efficient coupling to the telescope beam is likely achieved with feedhorns packed at a $2F\lambda$ spacing. To maximize sensitivity, ideally we couple both orthogonal linear polarizations for a given channel into the same total-power detector. Such dual-polarization driving ought to be possible for kinetic inductance detectors (KIDs), where a single detector could absorb power from two separate channelizer structures originating from orthogonally polarized antenna inputs. The dual-polarization coupling would be a novelty, but it is also an non-essential. Without it, the effective survey speed will be reduced by a factor of ~ 2 , but the survey data quality will be unaffected otherwise, since the CO emission is not expected to be strongly polarized.

Given the above parameters (10-m telescope, 10 arcmin FoV, $\lambda\sim 1.2$ mm, $F=5$, $2F\lambda$ pixel spacing), a suitable spectrometer camera would have around 100 pixels, arranged in a hexagonal pattern at $2F\lambda$ spacing, fully populating the available field-of-view. Each pixel, with a physical area of ~ 1.1 cm², must fit an $R\sim 200$ channelizer for ~ 280 Nyquist sampled channels, and a matching number of detectors per pixel, or 25 thousand detectors in all. Like for SuperSpec,²¹ the channelizer can be provided via thin-film microstrip transmission lines, on an area that is ≤ 20 μ m wide and $R\lambda/\epsilon_r$ long. For the 1.2 mm band that translates to an area of ≤ 0.5 mm² assuming a suitable dielectric with $\epsilon_r\geq 10$. Accordingly, around 99% of the focal-plane real-estate can be used by the 280 detectors per pixel, which sets the size of individual detectors to ≤ 0.44 mm² (or equivalently $\leq [0.66$ mm]²). That detector area is not too different from that of the KIDs currently being deployed in the high-frequency array (HFA) of the APEX MKID camera.^{25, 26}

3.1 Challenges

While there are no technological gaps that would prevent the realization of a spectroscopic survey camera as described, a successful implementation is expected to encounter a number of practical challenges nevertheless:

Stray-light and out-of-band radiation: The camera concept is based on broad-band power detectors (such as KIDs), which are coupled to the incident radiation from a celestial source through the telescope and instrument optics, an antenna, and a network of lithographic transmission lines. However, the detectors may also respond

Table 3. $R=200$ $f/5$ camera and survey overview.

λ (mm)	FWHM (arcsec)	pixels (count)	detectors (count)	A_{det} (mm ²)	Mapping Speed (deg ² /year)	N_{gals} (count/year)
2	42	37	7,400	1.52	0.82	10,800
1.2	25	91	25,480	0.44	0.45	23,300
0.87	18	169	8,788	1.29	0.30	5,500

to unintended sources of direct illumination. Because direct illumination may be broad band, in contrast to the $R \sim 200$ channels coupled via the antenna and filterbank, they must be suppressed ~ 200 times below of what would be sufficient for a broad-band continuum camera. To avoid an undesired loss of sensitivity, the utmost care must be taken to avoid stray light and/or blue-leak contamination of the detectors, within the instrument, and in the telescope optical environment in which the camera will operate.

Standing waves: Standing wave patterns, both on pixel and before it, can severely disrupt the spectrometer performance, resulting in a highly uneven and/or unstable spectral response across the observed pixel bandwidths. Signals typically travel an $\sim R\lambda$ total path length along the channelizer structure of the pixel alone. To avoid undesired standing waves developing along that long 'cavity', it may be necessary to terminate the channelizer structure with a broad-band absorber to prevent reflection at its end, which could adversely affect the performance of the spectrometer chip. One must also be careful to avoid on-axis reflections along all optical elements of the telescope and the instrument also, each of which could result in a similar performance degradation also.

Phononic isolation of the detectors may be necessary, both to keep power in the detectors localized long enough for effective translation into electronic signals, and to prevent cross-talk among the thousands of detectors residing on the same substrate. Given the number of detectors per pixel and overall, the cross-detector leakage of non-thermal phonons within a pixel needs to be suppressed at the ≥ 30 dB level, while across pixels it may need to be suppressed at the ≥ 50 dB to avoid an increase in the effective background noise levels due to cross-contamination.

Magnetic shielding: KIDs (and other superconducting detectors) can be sensitive to magnetic fields, especially during the cooldown phase, and therefore effective magnetic shielding of the detectors in the focal plane may be critical for achieving the nominal detector performance in a real-world operation.

Cryogenics: Achieving the necessary detector NEPs for background limited operation from the ground may require operation near or below 100 mK, although the non-thermal detection mechanism of KIDs may also allow operating them at a higher temperature, such as 260–280 mK without a significant performance degradation. Depending on the telescope it is operated on, the camera may have to be installed in the Cassegrain focus, in which case the dewar will tilt with telescope elevation, and pose additional challenges to maintaining cryogenic performance at the range of typical tilt angles during observations.

Multi-band capability: If a multi-band instrument is desired with LIM as its primary science driver, all of the above will likely become significantly more challenging still. It is probably wisest to demonstrate and perfect a single-beam spectroscopic camera first, before taking the leap to an ambitious multi-band implementation.

Readout: The small pixel footprint will likely require readout multiplexing at the ~ 10 GHz regime for KIDs. As such it may involve additional up- and downconverters to interface with digital-to-analog waveform outputs and the digitization of signals at a lower baseband.

At the same time, a spectroscopic imager is exempt from some of the constraints that affect similar single-beam spectrometers, like SuperSpec. Notably, a multi-beam spectrometer does not require that all spectral channels are operational on any given pixel, or that channels are spaced at closely regular intervals in frequency, or that they provide closely uniform sensitivities. As the celestial source is scanned across many/all pixels during an observation,³⁴ spectral information can be reconstructed effectively and uniformly as long as any given spectral 'channel' is 'typically' present, with a 'typical' sensitivity, among the ensemble of pixels. As such, detector yields as low as 70–80% and/or gaps in the frequency coverage of individual pixels are generally tolerable, while non-uniformities will average out in the mapping process.

3.2 Scoping

There is not one way to realize the spectroscopic imaging camera for the galaxy or LIM surveys. Depending on the availability of funding, resources, telescope, and the degree of ambition, there is ample room for adjusting the concept for specific needs or constraints. For example, one may scope (or descope) specific aspects of the camera concept:

- Any number of bands (1–4), and any mm-wave band ($850\ \mu\text{m} - 3\ \text{mm}$) can be scientifically interesting and useful – for deep CO galaxy surveys and LIM application alike.
- Spectral resolution can be interesting and useful anywhere between $R \sim 150$ ($\Delta v \sim 2000\ \text{km/s}$) and $R \sim 1000$ ($\Delta v \sim 300\ \text{km/s}$). Low R values may suffer from the dilution of the CO signal, when the line widths of the star-forming gas in the targeted galaxies do not fill the spectral channels. High R values too may result in loss sensitivity if the galactic lines spread over multiple spectral bins. Optimal sensitivities are reached when the channel widths closely match the typical (mean) projected velocity dispersion of the star-forming gas. Assuming that $\pm 250\ \text{km/s}$ projected velocity spreads are typical, $R \sim 600$ may be more optimal from a sensitivity perspective alone, but other constraints may push toward targeting different R values.
- The camera’s field-of-view may be scaled to match what the host telescope optics can deliver. As the survey speed scales with the camera’s FoV, it is generally desirable to fill the available FoV with pixels to the maximal extent, if possible.
- The pixel packing can be adjusted. The $2F\lambda$ spacing maximizes the survey speed for a fixed number of pixels,³⁵ and relaxes the NEP requirement by focusing a full telescope beam on an individual pixel. However, smaller, more tightly packed pixels are also viable provided that the necessarily lower detector NEP values can be achieved for background-limited operation.
- We envision a feedhorn-coupled design illuminating the antenna(s) on pixels, because horns provide a naturally effective way for rejecting stray and out-of-band light. However, lens coupling may be viable also, provided that the necessary degree of rejection of stray and out-of-band light can be achieved otherwise.
- It is not necessary for the camera to have dual-polarization sensitivity. A single-polarization instrument can do the same survey science. It just needs twice the time to reach equivalent sensitivities.
- The F number may be chosen to any convenient value for the implementation, and suitable re-imaging optics can interface the camera to the telescope, as appropriate.

4. IMPLEMENTATION

The proposed instrument is sufficiently complex that implementation within a single institution may prove challenging, as demonstrated by the most recent wave of large cameras with similar scope and complexity.^{25,36,37} It is increasingly rare that a single institution would have all the resources (financial and human), as well as all the in-house expertise, necessary to cover every aspect of design, production, and fielding optimally; and to deliver flawless instrumentation on the typical timescales of funding cycles (3–5 years).

We therefore propose a new approach. It relies on the loose, open-source collaboration of partners, and benefits from the contribution of leading experts from all over the world. Participants who join shall generally agree to the following foundational principles:

- The collaboration is open to all who wish to contribute to it.
- Participants agree to abide by a code of honor. (We are in this together because we all want to see the best spectrometer camera(s) be built and operated based on the concepts and designs we develop together.)
- All information shared with the collaboration is considered private knowledge, not to be re-shared outside of the collaboration without the explicit consent by those who contributed the information.

- Any participant in the collaboration may freely use, adapt, modify, or innovate any aspect of the camera concept in any way they deem appropriate, as long as they re-share all relevant new information (e.g. designs, simulations, lab measurements, documentation, publications) with the the rest of collaboration.
- Any participant is free to work independently, secure their own funding, or form their own working partnerships within the collaboration, for example to build and operate a particular implementation of the shared concepts. There is no need for approval or even coordination with other participants of the collaboration on their individual activities.
- Any participant is free to publish or present their own work to the public, as they see fit, and with the list of authors they deem appropriate, as long as they simply acknowledge the collaboration, and appropriately cite or acknowledge the contributions of others.

These principles are meant to protect innovation while fostering a free-spirited collaboration among the partners. All information shared within the collaboration will likely be through a properly authenticated version control system (e.g. GitHub[†]), such that once information is shared it remains accessible to all involved, but not to outside the collaboration. (The details of the version control system, organization, and workflows are to be identified later, and may evolve with the project.) Apart from sharing ideas, designs, and measurements, the collaboration will support its participants in any way possible to help them achieve their goals.

4.1 Modular Designs

While there is a uniting concept centered around a spectrometer camera capable of delivering the next-generation cosmological surveys of star-formation, it is not limited to the realization of a singular instrument or design that alone is capable of delivering on that goal. For every design choice one can make, alternative choices may be viable also. As such, our aim is to compile a small library of designs and components from which an instrument builder may draw to assemble a particular implementation of the camera concept. We may, therefore, have multiple alternatives for the detectors, focal-plane units, focusing elements, etc. And each module may in turn have sub-versions optimized somewhat differently, offering varying trade-offs. (Hopefully, common sense will guide us to converge on no more than a few alternative designs for the critical components).

As we progress, we may want to agree on certain specific standards (such as physical dimensions, or other specifications) for the components to allow swapping one design with another easily, e.g. to accommodate changing requirements or budgetary constraints, or to support variant implementations. As the collaboration grows and evolves, we shall identify areas where such standardization is desirable or necessary, in order to facilitate continued progress.

5. CONCLUSION

We envision that a mm-wave spectroscopic imaging camera can be designed, developed, and built on a ~ 5 -year timescale, and deployed to a suitable 10-m class (or larger) ground-based mm-wave telescope to conduct the first truly volumetric surveys of star-formation in the Universe, in a dedicated effort over 1–3 years of operation. Such cameras can for the first time deliver a complete census of star-formation at $z \sim 1-12$, individually detecting tens of thousands of star-forming galaxies above a mass-luminosity threshold, complete with spectroscopic redshifts for each and every one. These cameras will be able to probe an order of magnitude deeper in star-forming galaxy masses and luminosities than any previous degree-scale mm-wave survey to date, and for the first time approach the L_* galaxy populations that represent that bulk of the galaxies in the Universe. The same or similar camera can conduct Line Intensity Mapping (LIM) also, and the two complementary surveys can be conducted in a time-sharing arrangement for maximum scientific impact.

We believe that such a spectroscopic imaging camera, or family of cameras, are best built through a loose, open-source collaboration that involves a wide range of experts from around the globe, and in which participants are free to pursue their own specific goals and directions without being confined by the restrictive rules that are typical to consortia.

[†]<https://www.github.com>

We hope that you, the reader of this paper, will join this collaboration to contribute your expertise to make these cameras the best they can be. If you are an instrument builder, we hope that you join because you can draw on the knowledge shared in the collaboration to build your capable instrument, or component, to its utmost potential and without delays and detours. And, we hope telescope organizations will join because they want a share of the transformative science that these cameras will deliver when deployed on a telescope they run.

If you have questions about the collaboration, or wish to be a part of it, please contact us by email at the address provided on the title page of this article.

REFERENCES

- [1] Devlin, M. J., Ade, P. A. R., Aretxaga, I., et al., “Over half of the far-infrared background light comes from galaxies at $z \geq 1.2$,” *Nature* **458**, 737–739 (Apr. 2009).
- [2] Puget, J. L., “Planck Performances and Capabilities to Constrain the Dark-side,” in [*36th COSPAR Scientific Assembly*], **36**, 3881 (Jan. 2006).
- [3] Kovács, A., Omont, A., Beelen, A., et al., “Far-infrared Properties of Spitzer-selected Luminous Starbursts,” *ApJ* **717**, 29–39 (July 2010).
- [4] Chapman, S. C., Blain, A. W., Ivison, R. J., and Smail, I. R., “A median redshift of 2.4 for galaxies bright at submillimetre wavelengths,” *Nature* **422**, 695–698 (Apr. 2003).
- [5] Madau, P. and Dickinson, M., “Cosmic Star-Formation History,” *ARA&A* **52**, 415–486 (Aug. 2014).
- [6] Staguhn, J. G., Kovács, A., Arendt, R. G., et al., “The GISMO Two-millimeter Deep Field in GOODS-N,” *ApJ* **790**, 77 (July 2014).
- [7] Weiß, A., Kovács, A., Coppin, K., et al., “The Large Apex Bolometer Camera Survey of the Extended Chandra Deep Field South,” *ApJ* **707**, 1201–1216 (Dec. 2009).
- [8] Oliver, S. J., Bock, J., Altieri, B., et al., “The Herschel Multi-tiered Extragalactic Survey: HerMES,” *MNRAS* **424**, 1614–1635 (Aug. 2012).
- [9] Simpson, J. M., Smail, I., Swinbank, A. M., et al., “The East Asian Observatory SCUBA-2 Survey of the COSMOS Field: Unveiling 1147 Bright Sub-millimeter Sources across 2.6 Square Degrees,” *ApJ* **880**, 43 (July 2019).
- [10] Griffin, M. J., Abergel, A., Abreu, A., et al., “The Herschel-SPIRE instrument and its in-flight performance,” *A&A* **518**, L3 (July 2010).
- [11] Cox, P., Neri, R., Berta, S., et al., “z-GAL: A NOEMA spectroscopic redshift survey of bright Herschel galaxies. I. Overview,” *A&A* **678**, A26 (Oct. 2023).
- [12] Pope, A., Scott, D., Dickinson, M., et al., “The Hubble Deep Field-North SCUBA Super-map - IV. Characterizing submillimetre galaxies using deep Spitzer imaging,” *MNRAS* **370**, 1185–1207 (Aug. 2006).
- [13] Weiss, A., Downes, D., Walter, F., and Henkel, C., “CO Line SEDs of High-Redshift QSOs and Submm Galaxies,” in [*From Z-Machines to ALMA: (Sub)Millimeter Spectroscopy of Galaxies*], Baker, A. J., Glenn, J., Harris, A. I., Mangum, J. G., and Yun, M. S., eds., *Astronomical Society of the Pacific Conference Series* **375**, 25 (Oct. 2007).
- [14] Boogaard, L. A., van der Werf, P., Weiss, A., et al., “The ALMA Spectroscopic Survey in the Hubble Ultra Deep Field: CO Excitation and Atomic Carbon in Star-forming Galaxies at $z = 1-3$,” *ApJ* **902**, 109 (Oct. 2020).
- [15] Weiß, A., Kovács, A., Güsten, R., et al., “LABOCA observations of nearby, active galaxies,” *A&A* **490**, 77–86 (Oct. 2008).
- [16] Cooray, A. and Milosavljević, M., “What is L_* ? Anatomy of the Galaxy Luminosity Function,” *ApJ* **627**, L89–L92 (July 2005).
- [17] Moradinezhad Dizgah, A., Keating, G. K., Karkare, K. S., et al., “Neutrino Properties with Ground-based Millimeter-wavelength Line Intensity Mapping,” *ApJ* **926**, 137 (Feb. 2022).
- [18] Karkare, K. S. and Bird, S., “Constraining the expansion history and early dark energy with line intensity mapping,” *Phys. Rev. D* **98**, 043529 (Aug. 2018).
- [19] Kutyrév, A., Moseley, S. H., Melnick, G., et al., “HIRMES - High Resolution Mid-infrared Spectrometer for SOFIA,” in [*American Astronomical Society Meeting Abstracts #233*], *American Astronomical Society Meeting Abstracts* **233**, 354.15 (Jan. 2019).

- [20] Kovács, A., Barry, P. S., Bradford, C. M., et al., “SuperSpec: design concept and circuit simulations,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI*], Holland, W. S. and Zmuidzinas, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8452**, 84522G (Sept. 2012).
- [21] Redford, J., Barry, P. S., Bradford, C. M., et al., “SuperSpec: On-Chip Spectrometer Design, Characterization, and Performance,” *Journal of Low Temperature Physics* **209**, 548–555 (Nov. 2022).
- [22] Endo, A., Werf, P., Janssen, R. M. J., et al., “Design of an Integrated Filterbank for DESHIMA: On-Chip Submillimeter Imaging Spectrograph Based on Superconducting Resonators,” *Journal of Low Temperature Physics* **167**, 341–346 (May 2012).
- [23] Taniguchi, A., Bakx, T. J. L. C., Baselmans, J. J. A., et al., “DESHIMA 2.0: Development of an Integrated Superconducting Spectrometer for Science-Grade Astronomical Observations,” *Journal of Low Temperature Physics* **209**, 278–286 (Nov. 2022).
- [24] Griffin, M., Baselmans, J., Baryshev, A., et al., “SPACEKIDS: kinetic inductance detectors for space applications,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*], Holland, W. S. and Zmuidzinas, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9914**, 991407 (July 2016).
- [25] Heyminck, S., Klein, B., Güsten, R., et al., “Development of a MKID Camera for APEX,” in [*Twenty-First International Symposium on Space Terahertz Technology*], 262 (Mar. 2010).
- [26] Reyes, N., Mayorga, I. C., Grutzeck, G., et al., “Characterization of Widefield THz Optics Using Phase Shifting Interferometry,” *IEEE Transactions on Terahertz Science and Technology* **13**, 614–621 (Nov. 2023).
- [27] Güsten, R., Nyman, L. Å., Schilke, P., et al., “The Atacama Pathfinder EXperiment (APEX) - a new submillimeter facility for southern skies -,” *A&A* **454**, L13–L16 (Aug. 2006).
- [28] Grimes, P. and Blundell, R., “The Greenland Telescope,” in [*Ground-based and Airborne Telescopes IV*], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8444**, 84441N (Sept. 2012).
- [29] Yao, Y.-W., Chen, W.-R., and Wang, Z., “Collaborative Simulation of Mechanical Structure and Control Systems of Leighton Chajnantor Telescope,” *Research in Astronomy and Astrophysics* **23**, 045013 (Apr. 2023).
- [30] Miknaitis, K., “The South Pole Telescope,” in [*APS April Meeting Abstracts*], *APS Meeting Abstracts*, Y11.005 (Apr. 2007).
- [31] Baars, J. W. M., Hooghoudt, B. G., Mezger, P. G., and de Jonge, M. J., “The IRAM 30-m millimeter radio telescope on Pico Veleta, Spain,” *A&A* **175**, 319–326 (Mar. 1987).
- [32] Young, J. S., Carrasco, L., and Schloerb, F. P., “The Large Millimeter Telescope (LMT),” in [*American Astronomical Society Meeting Abstracts #200*], *American Astronomical Society Meeting Abstracts* **200**, 64.02 (May 2002).
- [33] Klaassen, P. D., Mroczkowski, T. K., Cicone, C., et al., “The Atacama Large Aperture Submillimeter Telescope (AtLAST),” in [*Ground-based and Airborne Telescopes VIII*], Marshall, H. K., Spyromilio, J., and Usuda, T., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11445**, 114452F (Dec. 2020).
- [34] Kovács, A., “Scanning strategies for imaging arrays,” in [*Millimeter and Submillimeter Detectors and Instrumentation for Astronomy IV*], Duncan, W. D., Holland, W. S., Withington, S., and Zmuidzinas, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7020**, 702007 (July 2008).
- [35] Holland, W., Duncan, W., and Griffin, M., “Bolometers for Submillimeter and Millimeter Astronomy,” in [*Single-Dish Radio Astronomy: Techniques and Applications*], Stanimirovic, S., Altschuler, D., Goldsmith, P., and Salter, C., eds., *Astronomical Society of the Pacific Conference Series* **278**, 463–491 (Dec. 2002).
- [36] Holland, W. S., Bintley, D., Chapin, E. L., et al., “SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope,” *MNRAS* **430**, 2513–2533 (Apr. 2013).
- [37] Wilson, G. W., Abi-Saad, S., Ade, P., et al., “The TolTEC camera: an overview of the instrument and in-lab testing results,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy X*], Zmuidzinas, J. and Gao, J.-R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11453**, 1145302 (Dec. 2020).