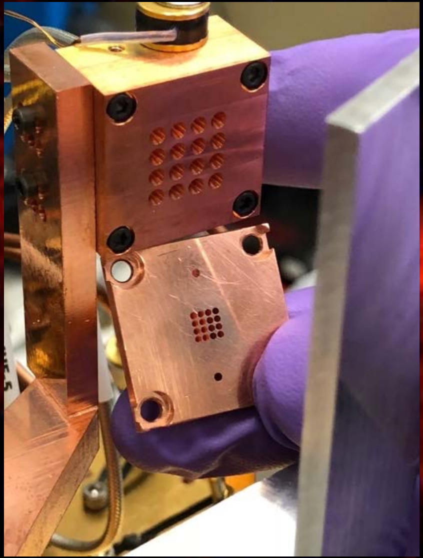

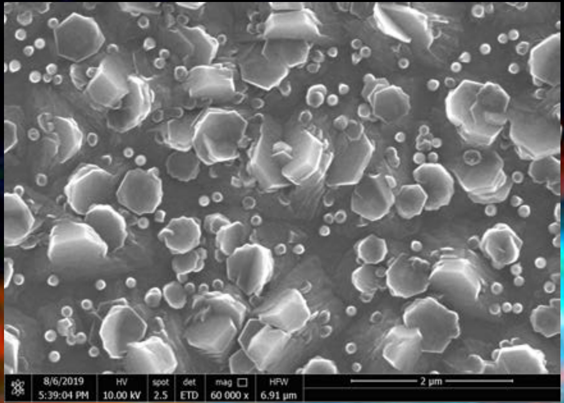

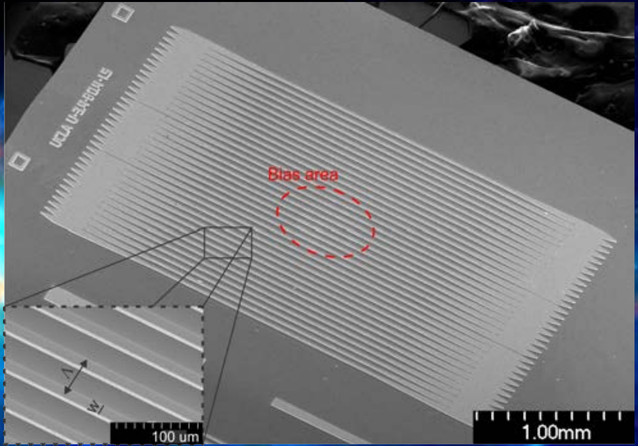

Virtual Research Presentation Conference

Ultrabroadband 5 THz Heterodyne Array Receiver for Extragalactic and Galactic Mapping

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Program: Strategic Initiative

Jet Propulsion Laboratory
California Institute of Technology

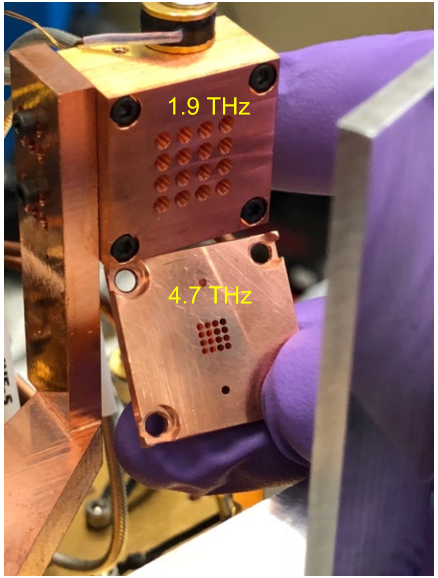
Assigned Presentation # RPC-104

Tutorial Introduction

Abstract

High-resolution THz spectroscopy is a vital tool for studying star formation and evolution; JPL has a long, strong tradition in this area of astronomical research, with major contributions to both science and technology. We develop terahertz (THz) superconducting heterodyne receivers for astrophysics, with the focus on technology for building large-array receivers throughout the THz regime and providing a wide instantaneous spectral bandwidth. Large arrays are needed to study extended fields in molecular clouds, and the wide bandwidth is required for study of objects with high velocity dispersion, such as seen in the central regions of nearby galaxies as well as the center of our Galaxy. The large bandwidth is also required for future projects in THz interferometry.

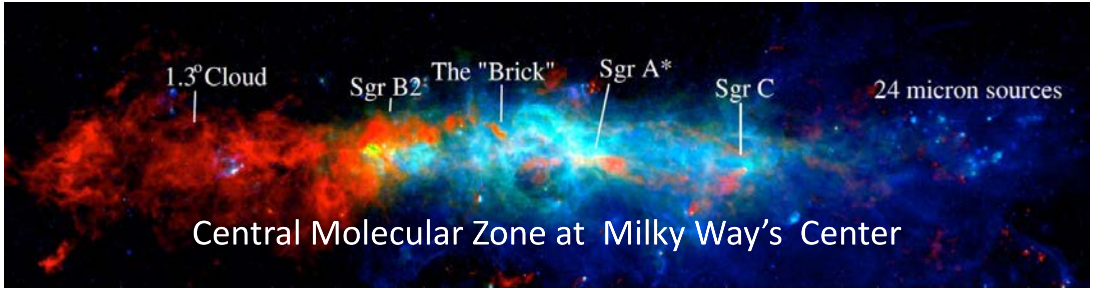
This task resulted in several important advancements in “super-THz” heterodyne arrays (~ 5 THz) where few receivers have been built so far and provided important demonstrations of new enabling technologies (mixers, local oscillators) for a THz heterodyne receiver suitable for the **G**alactic **E**cosystem **M**apping **S**mallSat (**GEMS**) mission. The research made use of brand-new device technologies, in particular, the hot-electron bolometric (HEB) mixer made from high-T_c superconductor MgB_2 [1] and the high-power, frequency tunable Quantum Cascade Vertical-External-Cavity Surface-Emitting-Laser (QC-VECSEL) local oscillator (LO) invented by UCLA [2].



Broadband High-Resolution Spectroscopy at 4.7 THz

- The center of galaxies is an important laboratory for studying the dynamical interaction of the interstellar medium with the gravitational potential produced by super massive black holes.
- Sources like the central molecular zone in the Milky's Way center emit spectral lines spread over 250 km/sec.
- The [OI] line at 4.7 THz is an important tracer of the high density gas in the galactic center that is illuminated by strong far-ultraviolet fluxes. High spectral resolution images of this line can be used to study the dynamics of the gas in galaxy centers.
- Multi-pixels receivers with sufficient spectral bandwidth are required for enabling large scale mapping of [OI] line **in the galactic center and the centers of nearby galaxies**.
- Observation of other lines above 2 THz (e.g., [HD] @ 2.7 THz, [OIII] @ 3.4&5.2 THz, [NIII] @ 5.8 THz) will also require larger IF bandwidth.

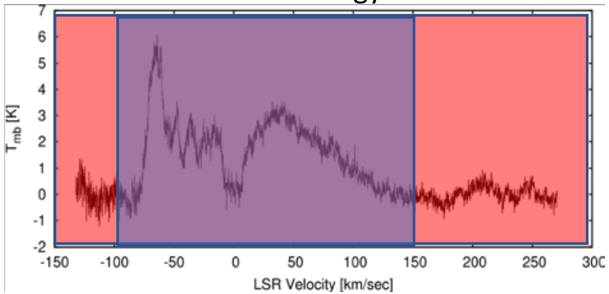
500 km/s@ 5THz → $\Delta f_{IF} \approx$ 8 GHz → MgB_2 HEB mixer



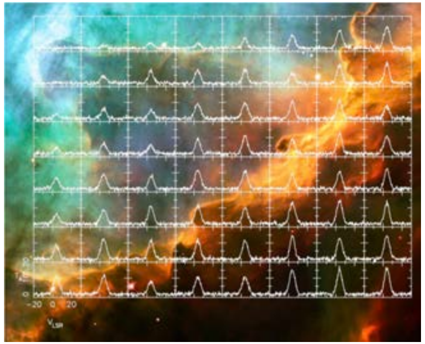
← 2 degrees →

← MgB_2 Technology →

← NbN Technology →

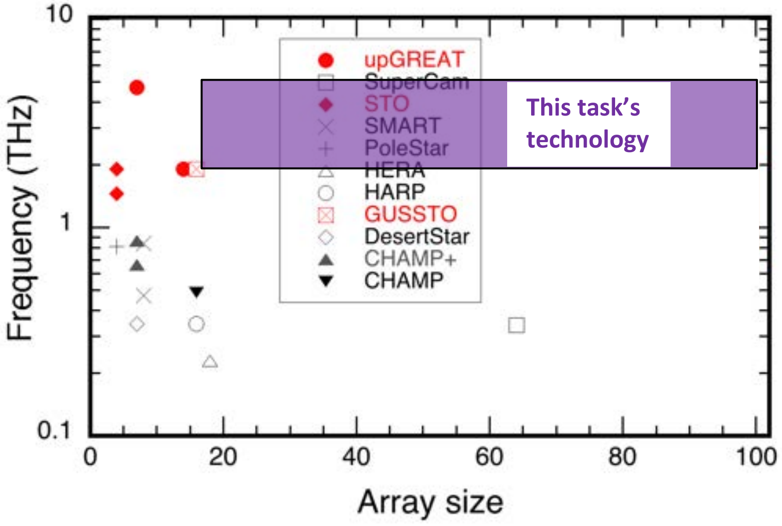


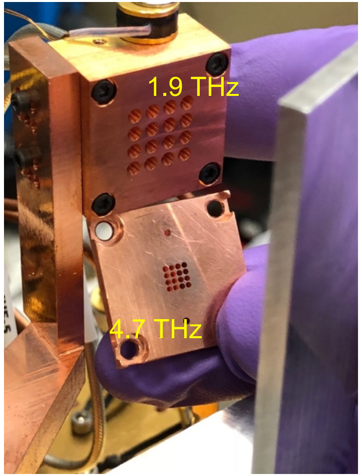
The [CII] 1.9THz line shown above at the galactic center is an indicator of the expected velocity span of the [OI] line.

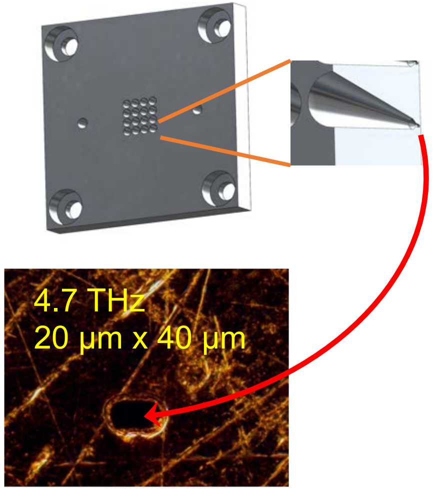


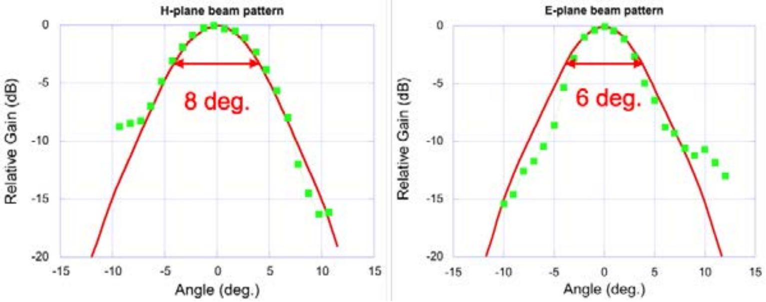
Model [OI] spectra in the vicinity of M17 [3]

Results: Monolithic THz heterodyne array for 4.7 THz



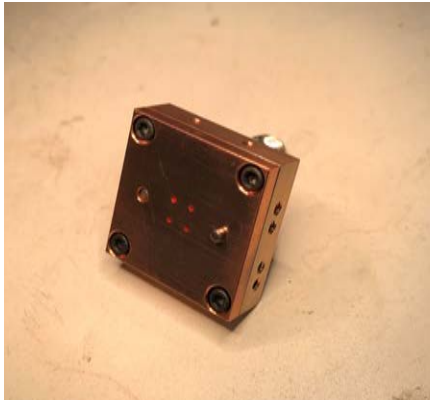


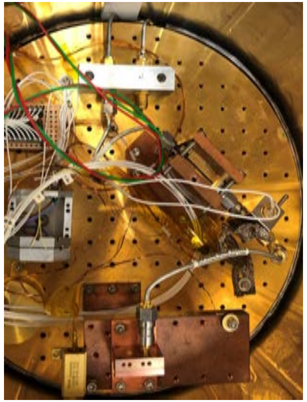


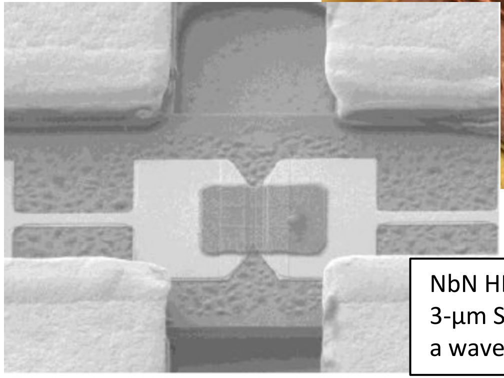


A multi-pixel array receiver can be implemented using monolithic array technology [4] resulting in **less volume**, **less mass**, and less complicated fore-optics. A front-end for 4.7 THz has been produced by this SRTD task

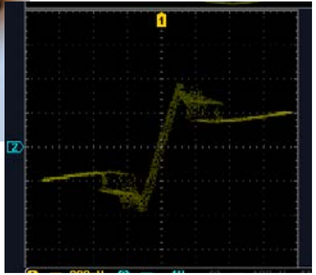
Results: Demonstration of a 4.3 THz HEB pixel



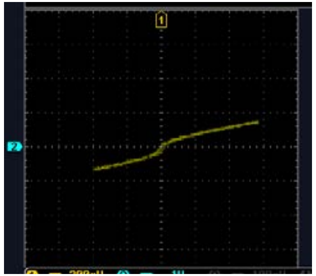




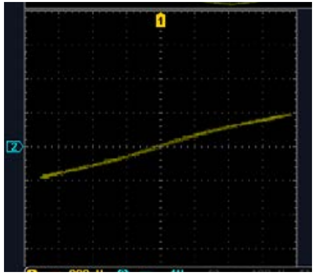
NbN HEB mixer on a 3-µm Si membrane in a waveguide [4]



Unpumped IV curve at 4.2 K



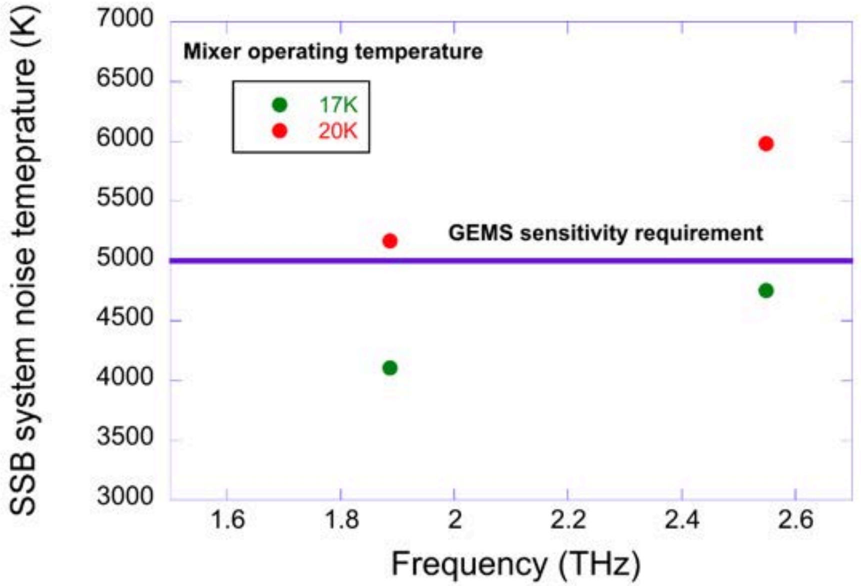
4.3 THz optimally pumped.



4.3 THz overpumped.

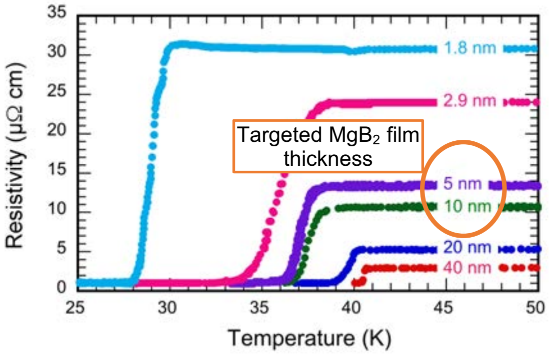
Feasibility for application on SmallSat (GEMS)

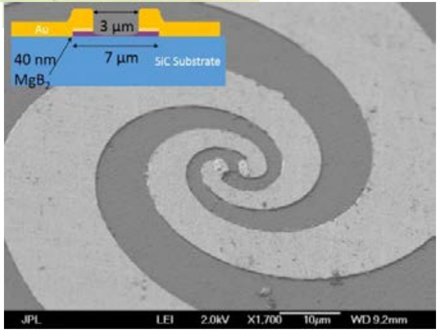
- The goal for GEMS is to produce large-scale maps of the [CII] (1900.526 GHz), [NII] 205µm (1461.134 GHz) and 122µm (2459.371 GHz) spectral lines above and below the plane of the Milky Way.
- MgB_2 HEB mixer enables the SmallSat application by
  - ❖ Operating at 17 K base temperature that can be achieved on a SmallSat. Meeting other SWaP requirements imposed by the SmallSat platform resources
  - ❖ Meeting the sensitivity (system noise temperature) requirement at 17K

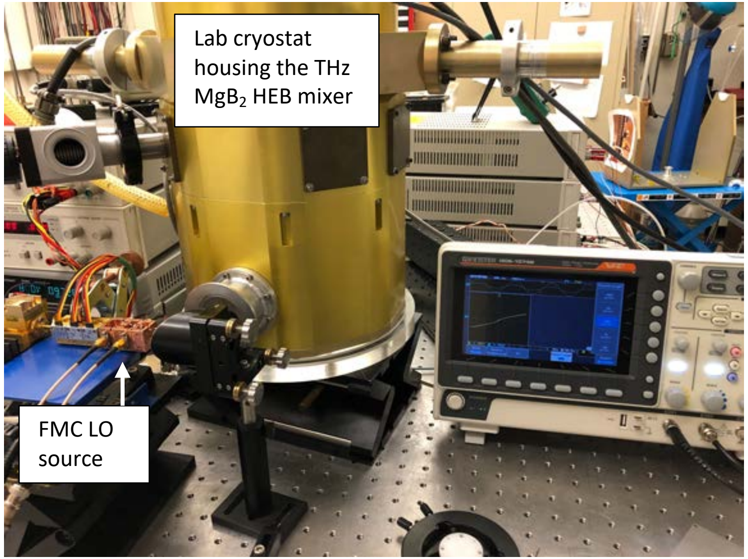


Results: Quasioptical MgB_2 HEB mixer

An MgB_2 HEB mixer (inside the cryostat) under the test using a novel frequency-multiplier-chain (FMC) LO source. A pumped current-voltage characteristic of the mixer is seen on the oscilloscope screen.

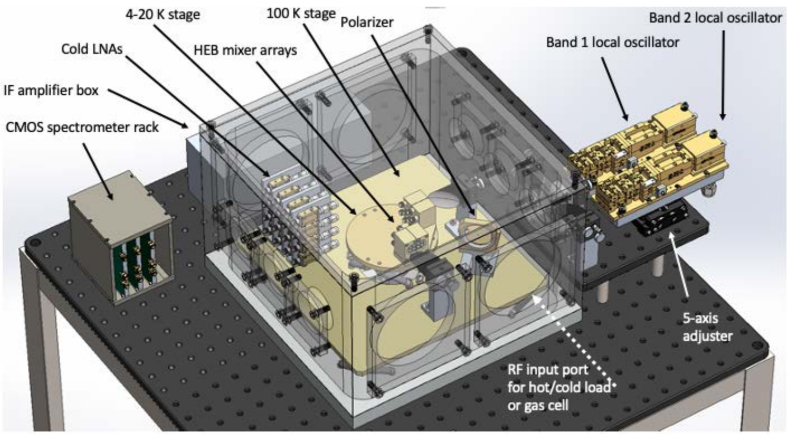


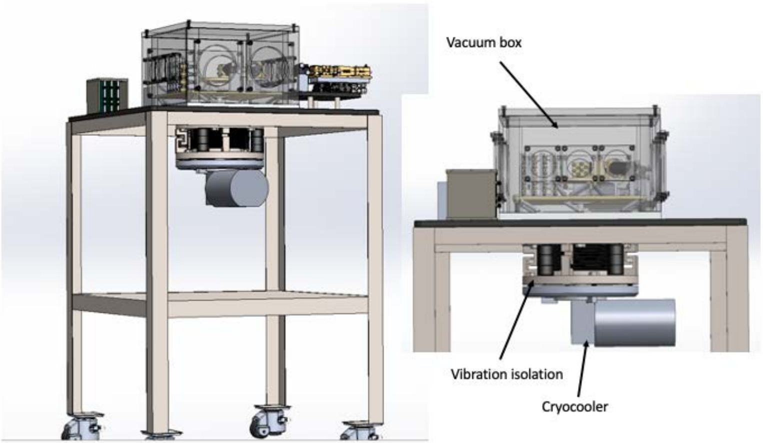




Results: GEMs Breadboard

- GEMS would use a 3-ch, 4-pixel, heterodyne receiver
- Each channels is a QO MgB_2 HEB with a frequency multiplier LO
- End-to-end demonstration of a channel (noise temperature) is important for proving the validity of the technical approach
- A brassboard demonstration is important for establishing TRL= 5 for GEMS receivers
- The brassboard will be important for prototyping MgB_2 based receiver for other applications (e.g., on balloons)
- The brassboard will allow for development of an integrated heterodyne receiver with an MgB_2 HEB mixer and QC-VECSEL placed inside the same cryopackage.

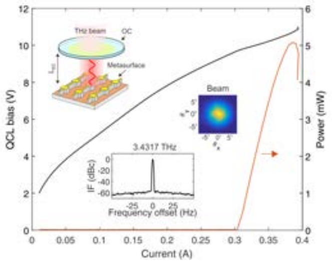




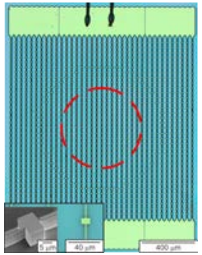
Results: Phase-lock of a 3.4 THz QC-VECSEL

- ❑ QC-VECSEL is the only practical approach to solid-state LO for arrays above 2 THz
- ❑ A single high-power (up to 10 mW) QC-VECSEL can be used for flood illumination of a monolithic mixer array

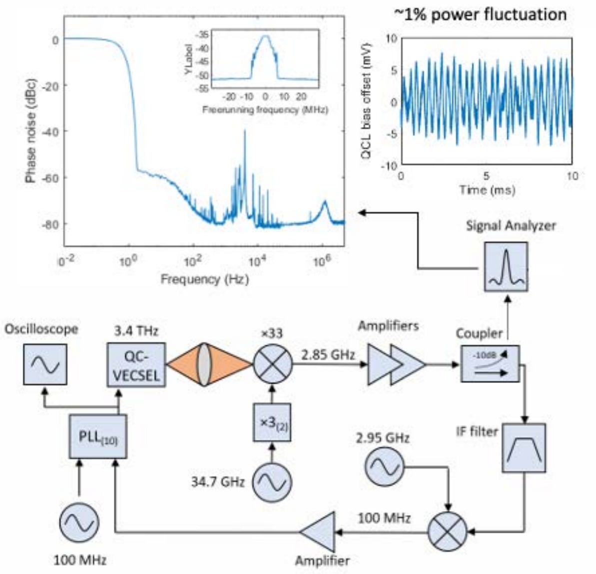
QCL current-voltage-power data:



Microscope and SEM images:



PLL block diagram and locked spectra



Ref. 5

- The QC-VECSEL is lasing at 3.4317 THz and outputs a maximum of ~5 mW of power at 77 K. Dissipated power ~3.5 W (0.15% WPE).
- Signal is down-converted from 3.4317 THz to 2.85 GHz using a diode mixer, and again down to 100 MHz using another diode mixer. The signal is **98.7% locked** (power in 1 Hz bandwidth / power in 5 MHz bandwidth).
- Bandwidth of the loop is ~1.5 MHz.
- Phase noise in the 100 Hz – 10 kHz range likely associated with mechanical noise in the external cavity.
- Bias on locked QCL fluctuates are on the order of 10 mV, corresponding to ~1% fluctuation in output power at maximum bias. Fluctuations agree with phase noise in the low kHz.

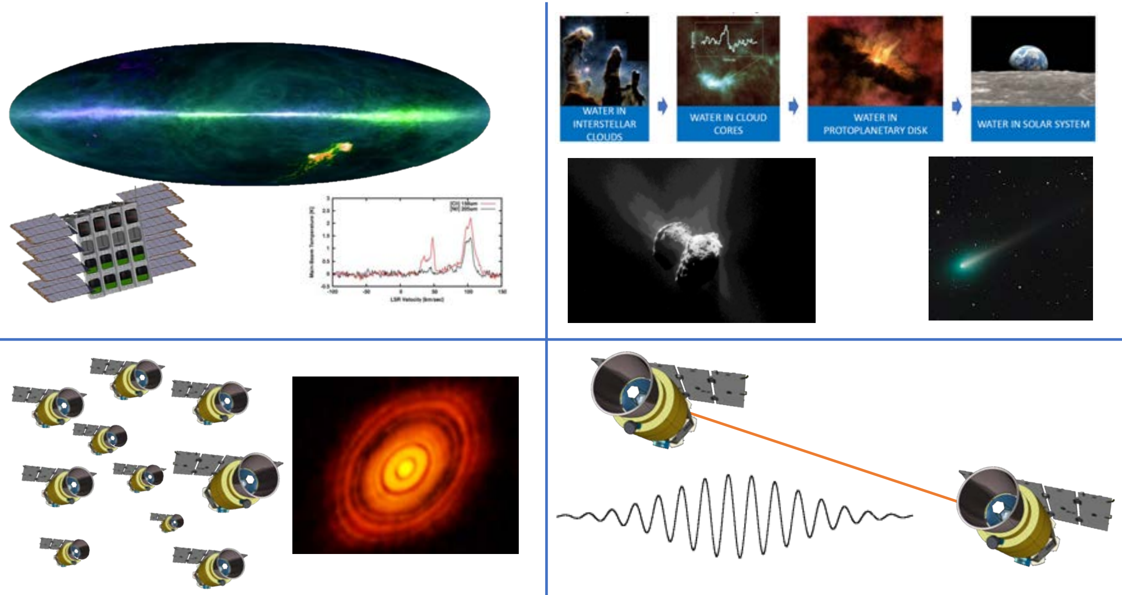
Significance and next steps

- The achieved results demonstrate the promise of the new heterodyne array architecture and the new mixer and LO devices for enabling new astrophysics instruments and exploring the very challenging range of the far-IR spectrum
- The new JPL technologies are unique and will create a competitive edge for the future instrument proposals
- The follow-up R&D and TRL advancing opportunities include:
  - SRTD (GEMS brassboard)
  - APRA (5+THz QCL)
  - ASTHROS hosted flight of MgB_2 HEB
  - Possible ‘23 AO

Mission Science and Enabling Future Missions

SmallSat ⇒ Galactic structure and star formation

MIDEX ⇒ Water science



Swarm Imaging Interferometer

Planetary disks

Interferometer PF

Publications and References

1. B. S. Karasik et al., *2019 44th Int. Conf. IR, MM & THz Waves (IRMMW-THz)* DOI: 10.1109/IRMMW-THz.2019.8874175.
2. C. Curwen et al., *Nat. Phot.* **13**, 855 (2019).
3. C. Walker et al, *Proc. SPIE* **7741**, 77410Z (2010).
4. F. M. Boussaha et al., *IEEE Trans. THz Sci.&Technol.* **2**, 284 (2012).
5. C. A. Curwen et al., *Int. Quantum Cascade Laser School & Workshop – IQCLSW 2020,* Zurich, Switzerland, Sep. 7-10, 2020.