Development and applications of terahertz hot electron bolometers

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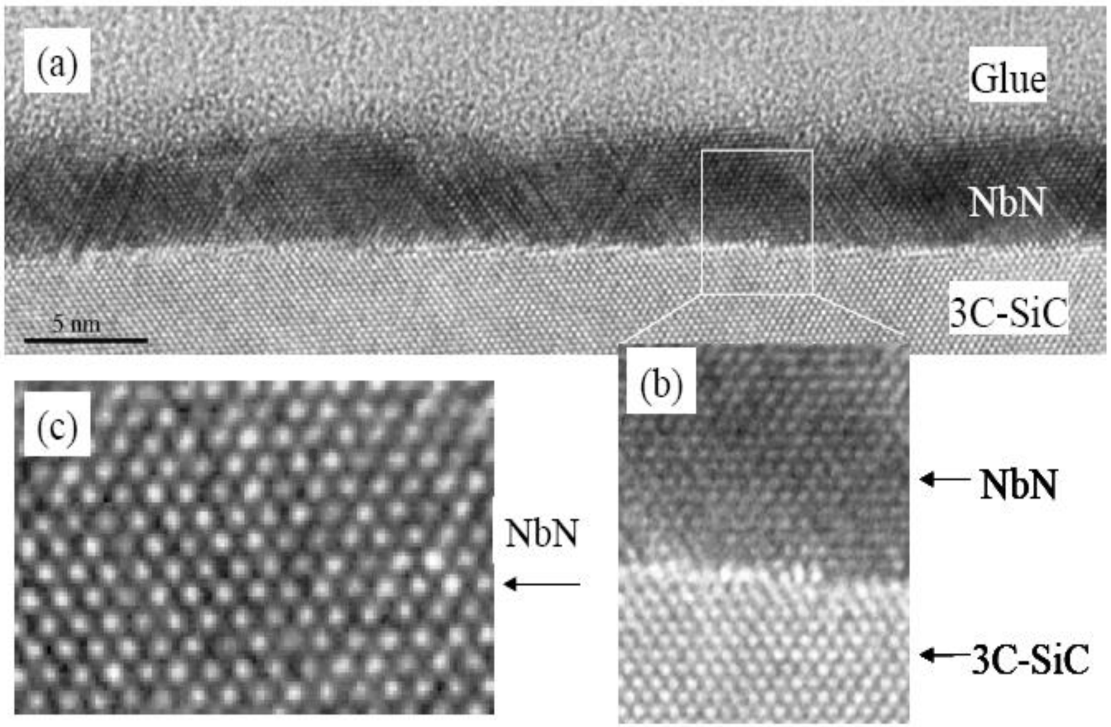
Outline

- Introduction: Heterodyne receiver based on superconducting hot electron bolometer (HEB) mixer, first applications in THz radioastronomy.
- Overview of current HEB involved THz projects: GUSTO, DATE5, GREAT and future HEB involving THz projects: OST, Millimetron, Smiles.
- NbN HEB mixer utilizing a GaN buffer layer: wider gain bandwidth
- MgB_2 HEB mixer technology: 15K operation temperature and wider gain bandwidth
- HEB as a direct detector is a precursor of single photon detector.
- Superconducting Single-Photon Detector (SSPD) – promotion of technology for counting photons from IR to THz range: direct and heterodyne detection
- Conclusions

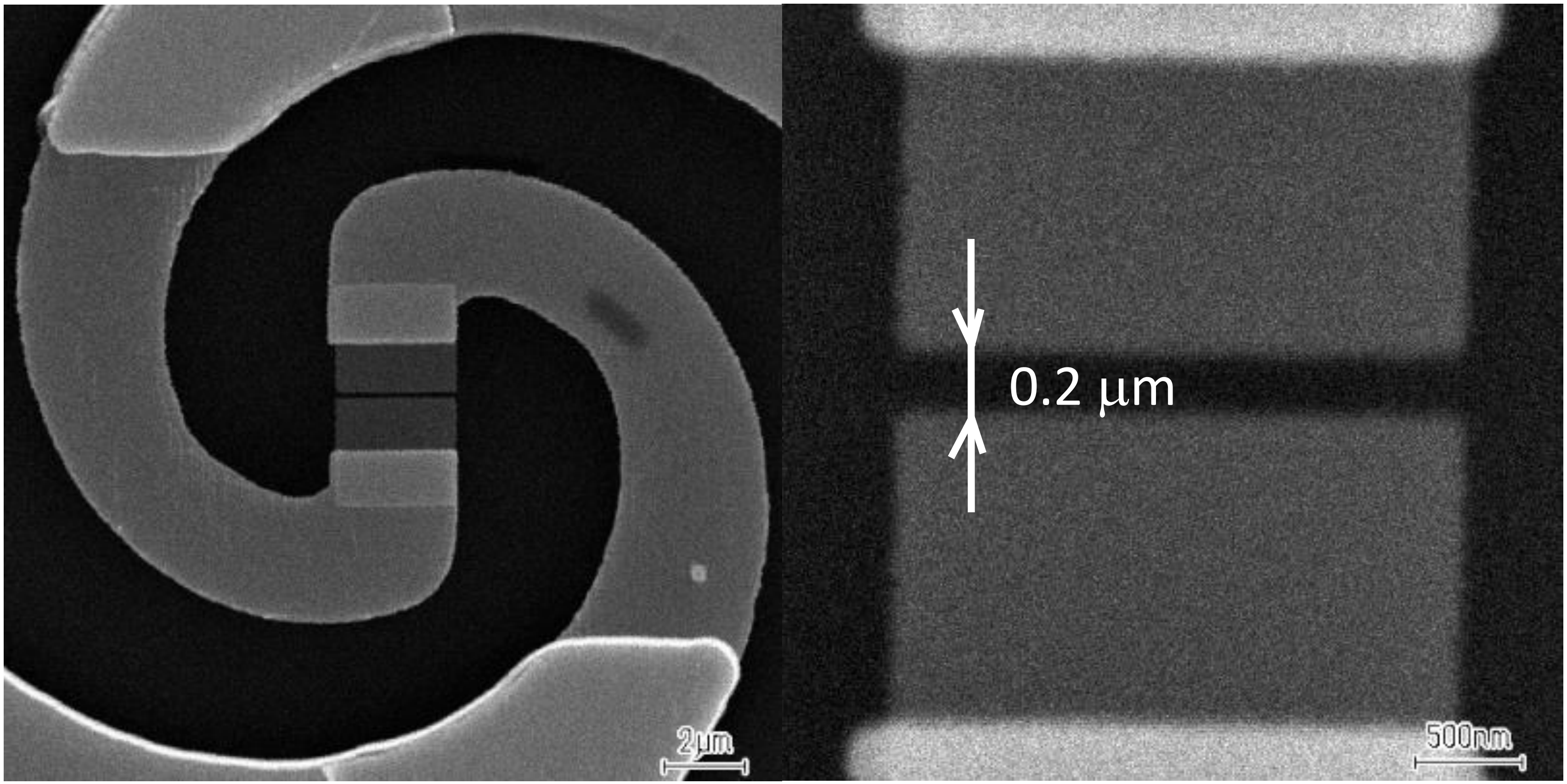
Ultrathin superconducting NbN film as unique material for sensitive and fast THz and IR detectors and mixers

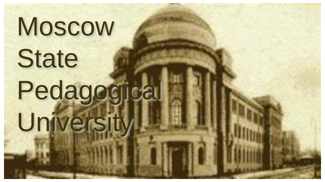
Technology of superconducting ultra-thin films of metals and compounds a few atomic layers thick with high-quality crystal structure and superconducting properties is developed



Transmission electron microscopy of 4 nm thick NbN film deposited on 3C-SiC substrate. Transition temperature $Tc > 10K$, and critical current density $jc = 10^7\ A/cm^2$ correspond to the properties of the bulk material, and allows us to produce planar nanostructures with unique properties.

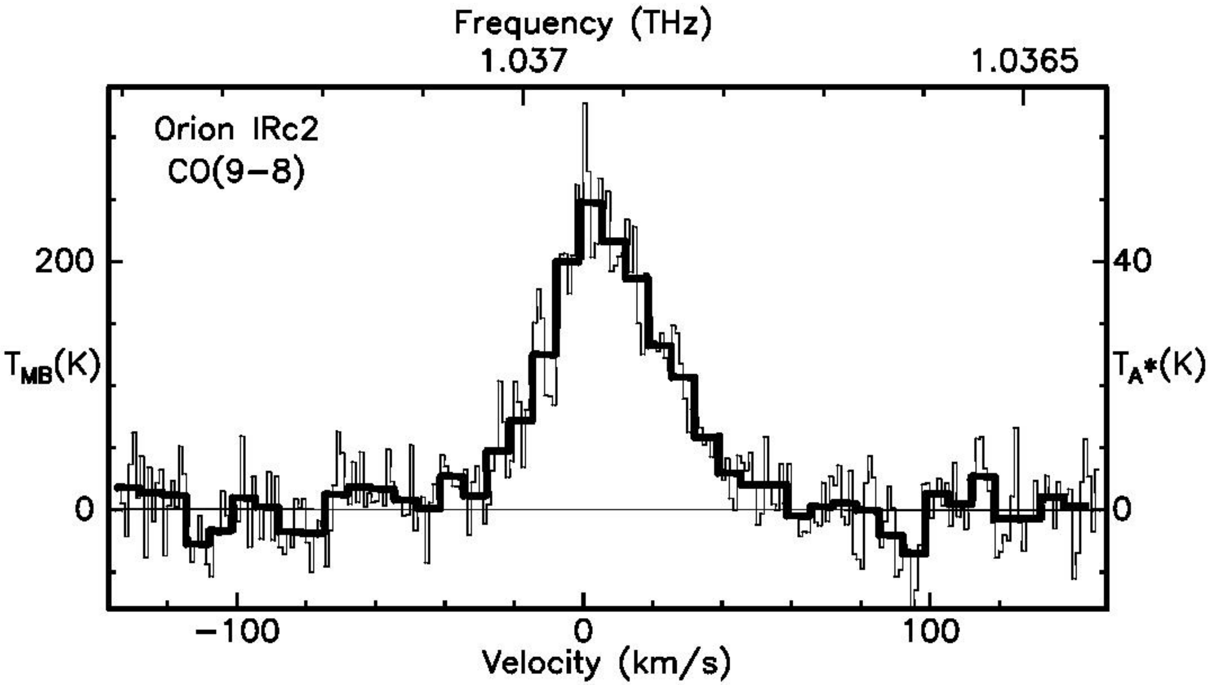
SEM micrographs of the central area of HEB mixer chip

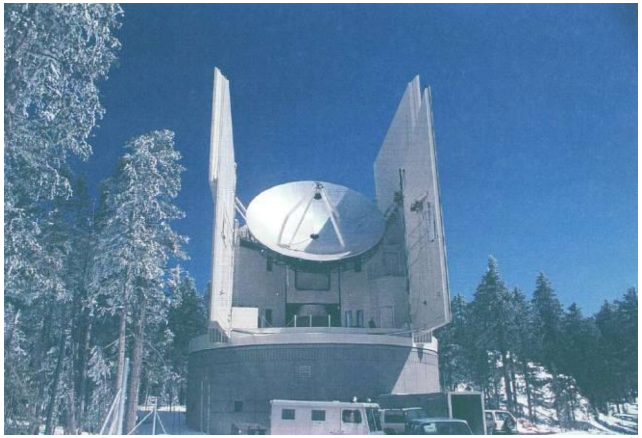




HEB mixer application in ground-based radioastronomy

Harvard – Smithsonian Center for Astrophysics





10-meter the Heinrich Hertz Telescope (HHT) on Mt. Graham (Arizona, USA).

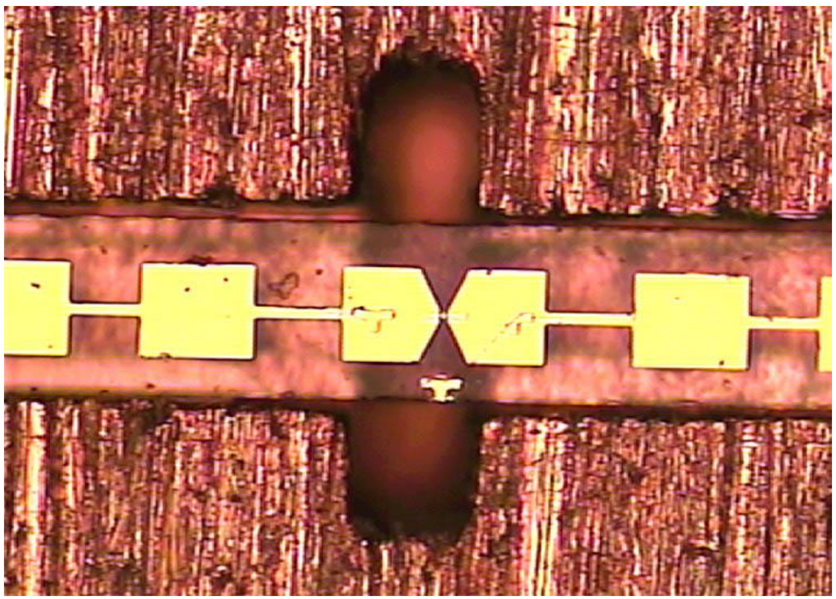
First fully-resolved ground-based detection of a terahertz spectral line from an astronomical source (CO 9-8 in Orion BN/KL) was obtained with the HEB receiver (January 2000). **The first ground-based heterodyne detection in the terahertz band.**

http://www.cfa.harvard.edu/srlab/rxlabHEB.html

http://www.cfa.harvard.edu/srlab/secure/rxlabTerahertzScience.html

From waveguide mixer chip to practical receiver up to 1.5 THz and astronomical observations in Chile from an altitude of 5525 meters

Superconducting waveguide hot-electron bolometer (HEB) mixer at 1.5 THz frequency



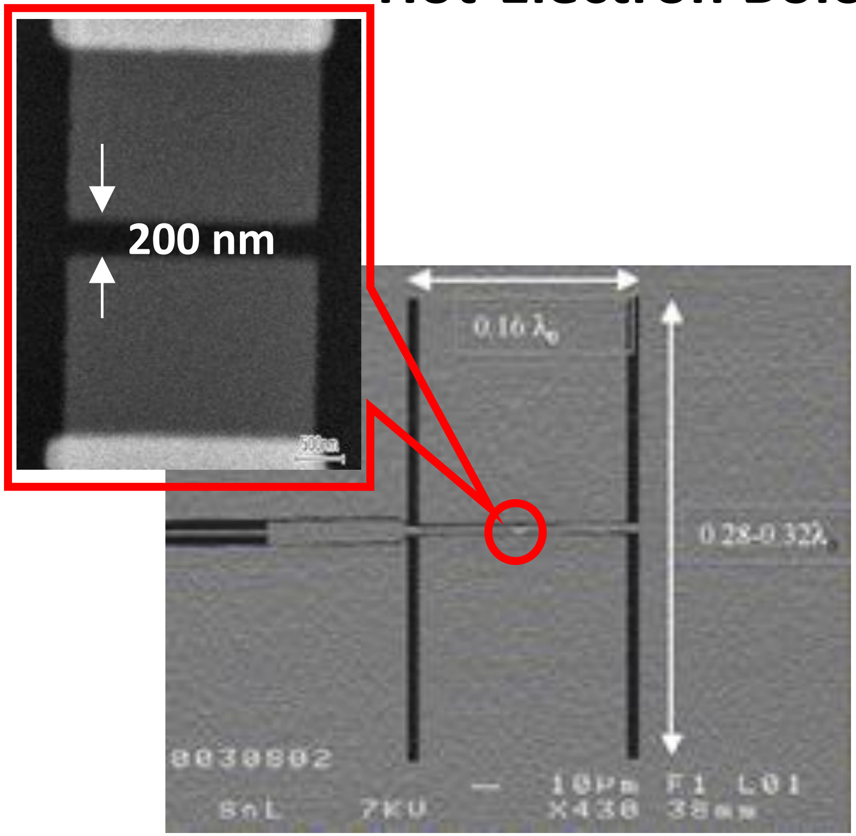
The 1.5 THz chip's sizes are 72 um wide, 1100 um long and 18 um thick

The Receiver Lab Telescope of the **Harvard-Smithsonian Center for Astrophysics** is the first ground-based radio telescope designed for operation at frequencies above 1 THz.

Observations since 2002 from an altitude of 5525 meters in Chile at 0.8-1.5 THz

Our NbN films are space-qualified

Hot-Electron Bolometer (HEB) mixer



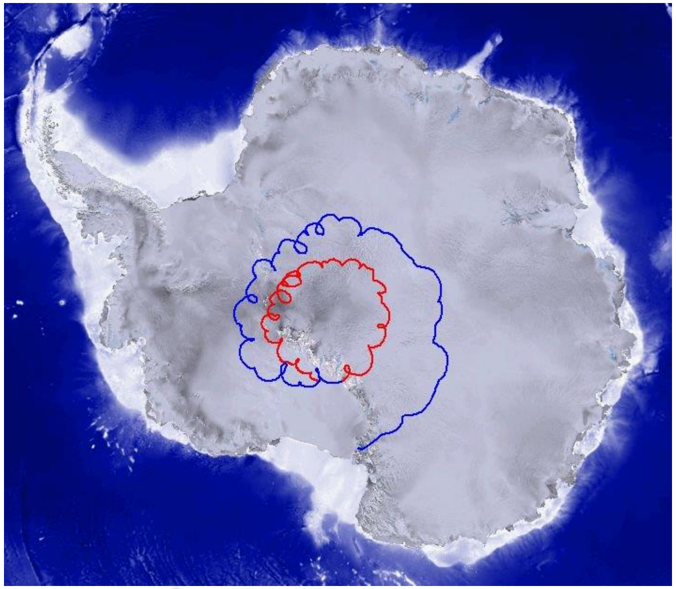
Herschel Space Observatory launched, May 2009
HEB mixers in Bands 6 and 7 of the HIFI instrument: 1.41 THz – 1.91 THz

2005 is the year of foundation of «Superconducting nanotechnology» JSC (Scontel)
http://www.scontel.ru

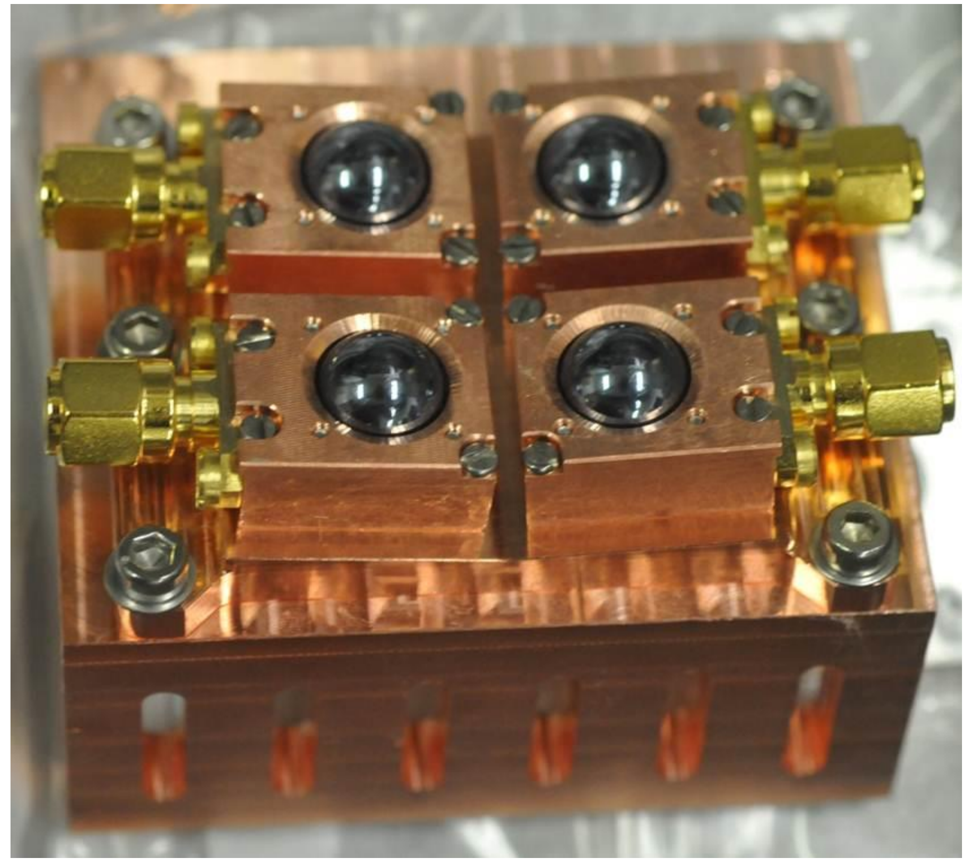
Scontel products
Detection systems for terahertz radiation

Type	1	1a	2	2a	3	3a
Frequency range, THz	0.1-6		1-12(40)		25-100	
Noise equivalent power (NEP) $W \cdot Hz^{-1/2}$	$5\text{-}7 \cdot 10^{-14}$	$3\text{-}5 \cdot 10^{-13}$	$1\text{-}2 \cdot 10^{-11}$	$6\text{-}8 \cdot 10^{-11}$	$1\text{-}2 \cdot 10^{-12}$	$4\text{-}5 \cdot 10^{-12}$
Response time, ns	1	0.05	1	0.1	1	0.1
Dynamic range, µW	0.1		50		2	
Bandwidth of amplifier, MHz	0.01-200	1-3500	0.01-200	1-3500	0.01-200	1-3500

Balloon based telescope GUSTO by SRON

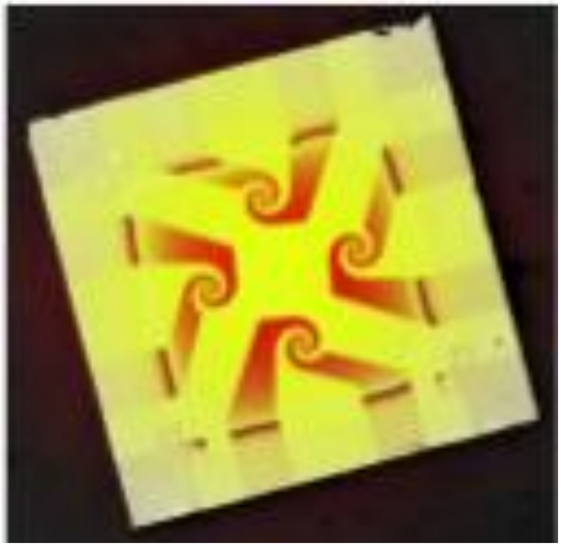


0.8 m telescope
39 km above Antarctica
22 days flight in December 2016

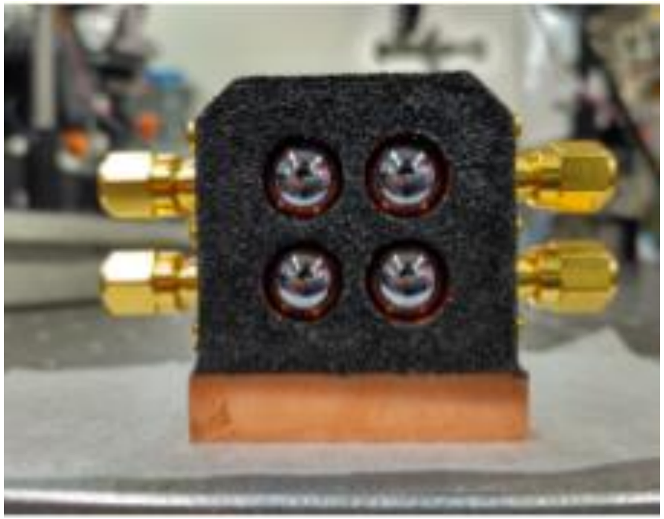


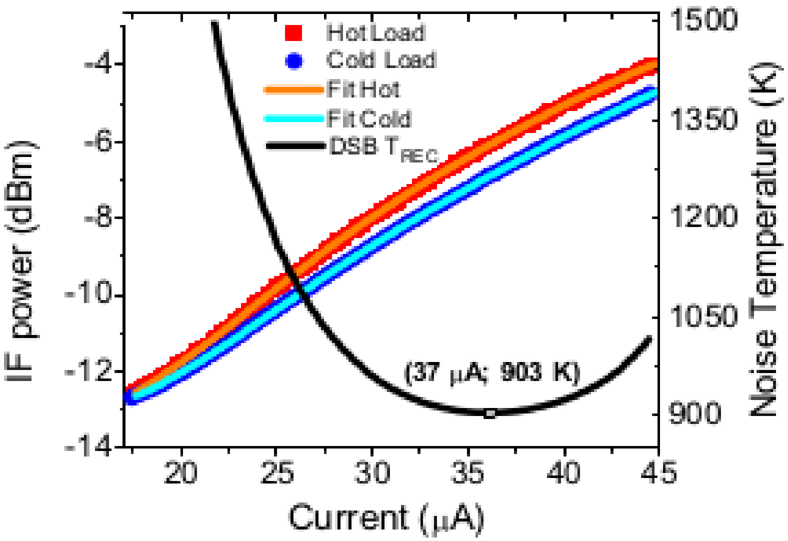
2 × 1.4THz and 2 × 1.9THz HEB mixers

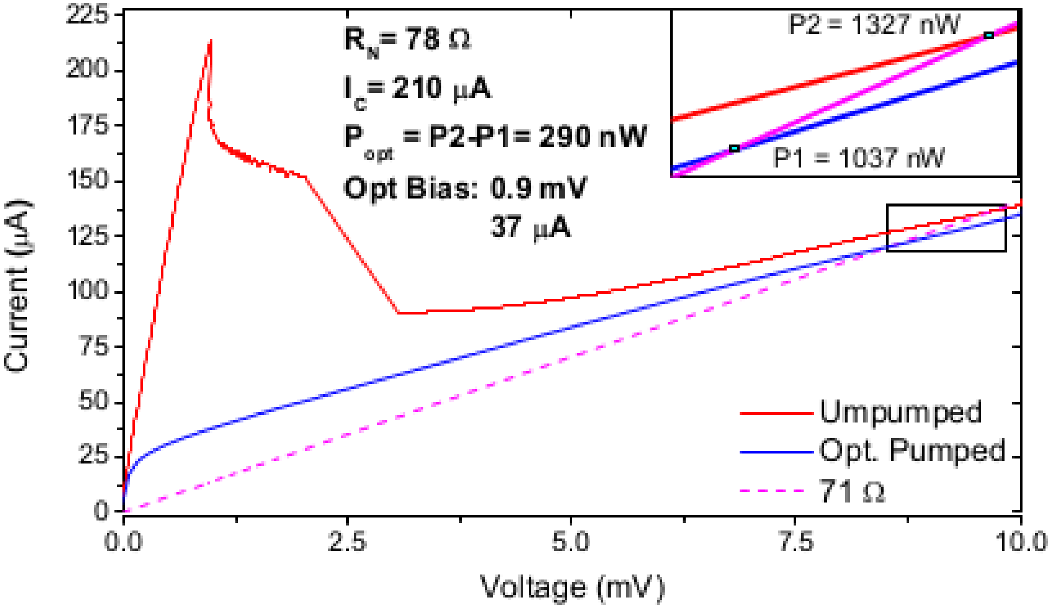
GUSTO 2x2 array 1.4 THz by SRON



Films were fabricated in Scontel - MSPU

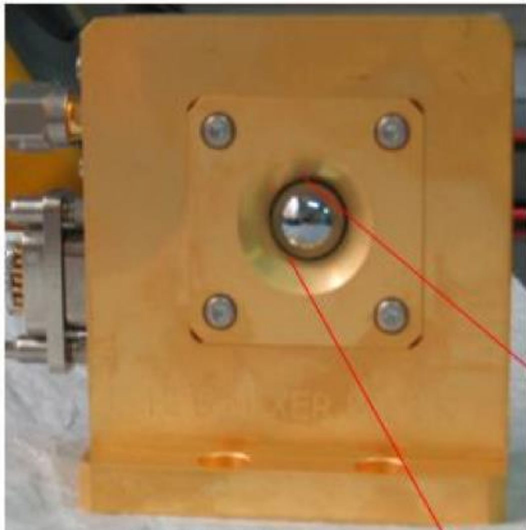






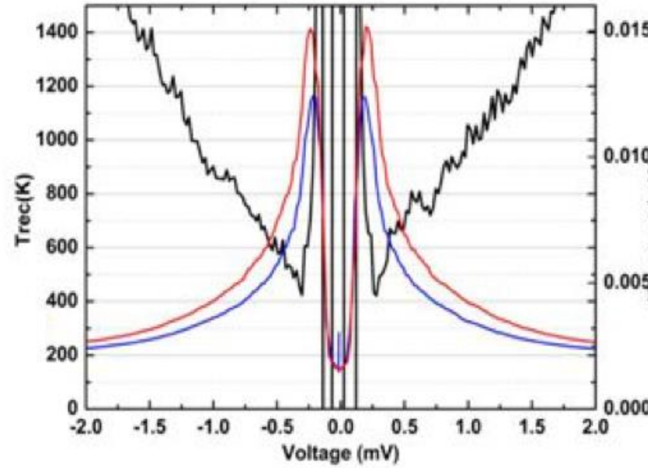
JRG Silva "Study on the viability of a 4x2 HEB mixer array at super-THz based on a Fourier phase grating LO for space applications" Master dissertation, 2016.

DATE5 – 5 m terahertz telescope at Dome A South pole by PMO

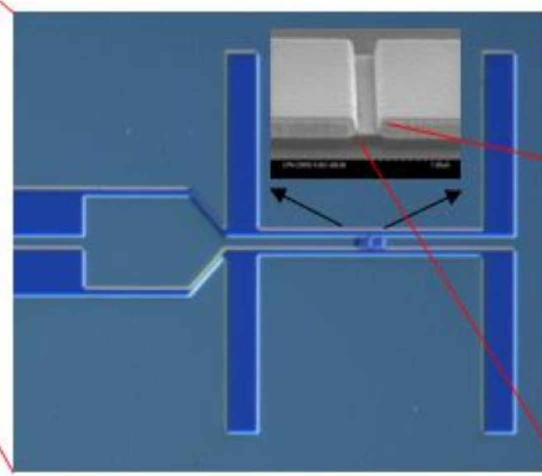


H200 HEB mixer

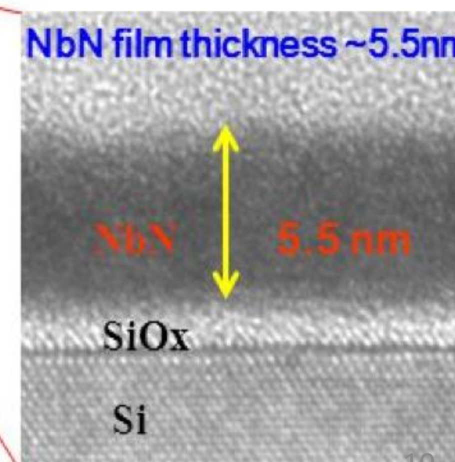
HEBs operate at 1.4 THz
Characterized at 1.3 THz
Uncorrected Tn ~ 600K
Corrected Tn ~ 300K



Noise temperature @ 1.26THz



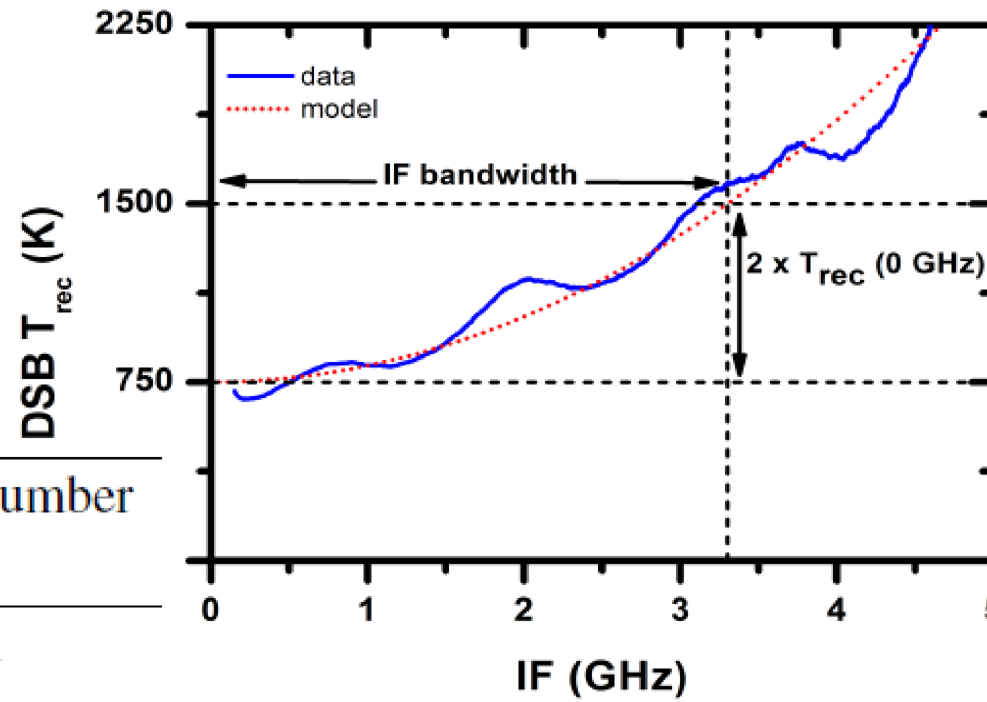
H200 HEB mixer chip



TEM image of the HEB microbridge

Films were fabricated in Scontel - MSPU

GREAT instrument operates on the Stratospheric Observatory for Infrared Astronomy (SOFIA) in the range of 1.2 - 4.7 THz by University of Cologne



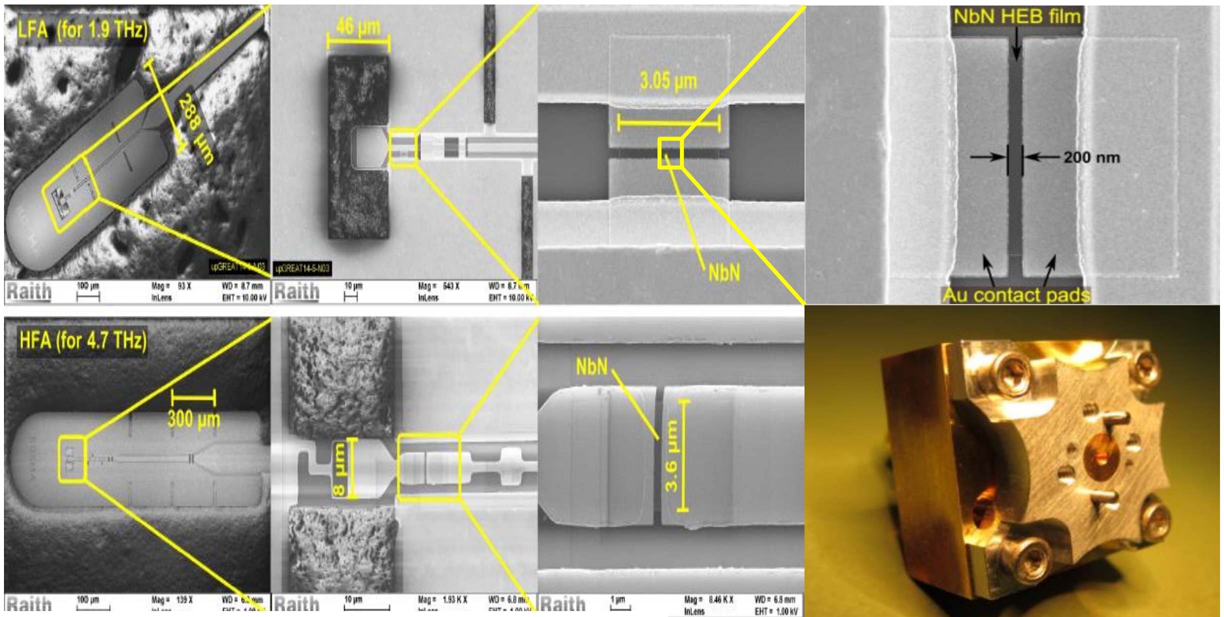
$T_{n,DSB}$ at 1.9THz of NbN mixer

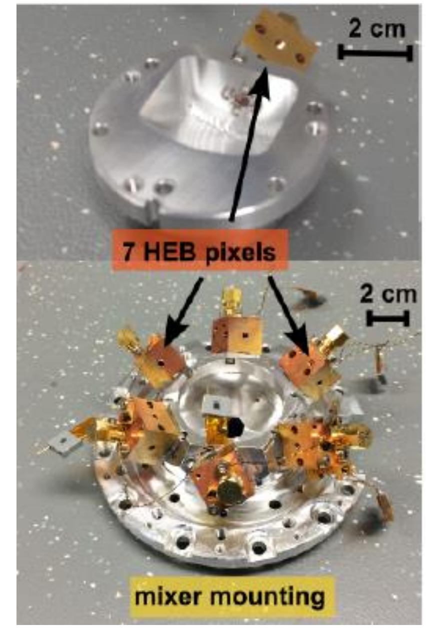
receiver channel	frequency (THz)	pixel number
L1	1.25 - 1.52	1
L2	1.81 - 1.91	1
M	2.4 - 2.7	1
H	4.7	1
LFA	1.83 - 2.54	2x7
HFA	4.7	1x7

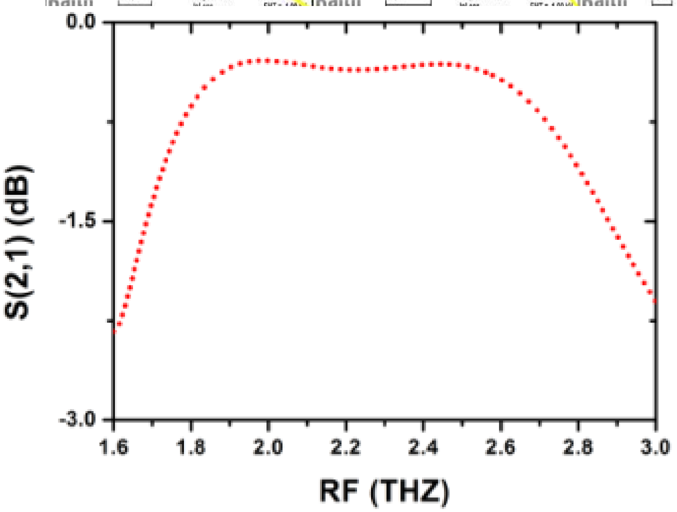
Arrays of HEB Mixers

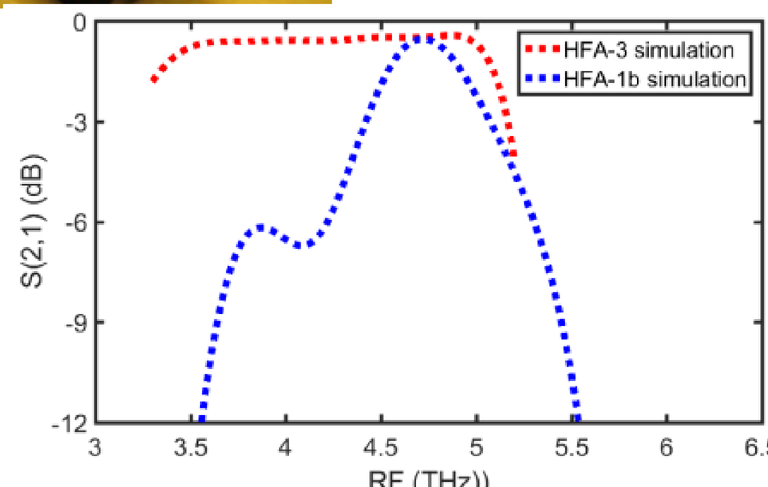
Hot Electron Bolometer Mixers for THz Arrays, Dissertation, Denis Fabian Büchel, Köln, 2017

GREAT instrument: waveguide mixers, mounts and THz matching









HEB based Low Frequency Array and High Frequency Array THz matching

Hot Electron Bolometer Mixers for THz Arrays, Dissertation, Denis Fabian Büchel, Köln, 2017

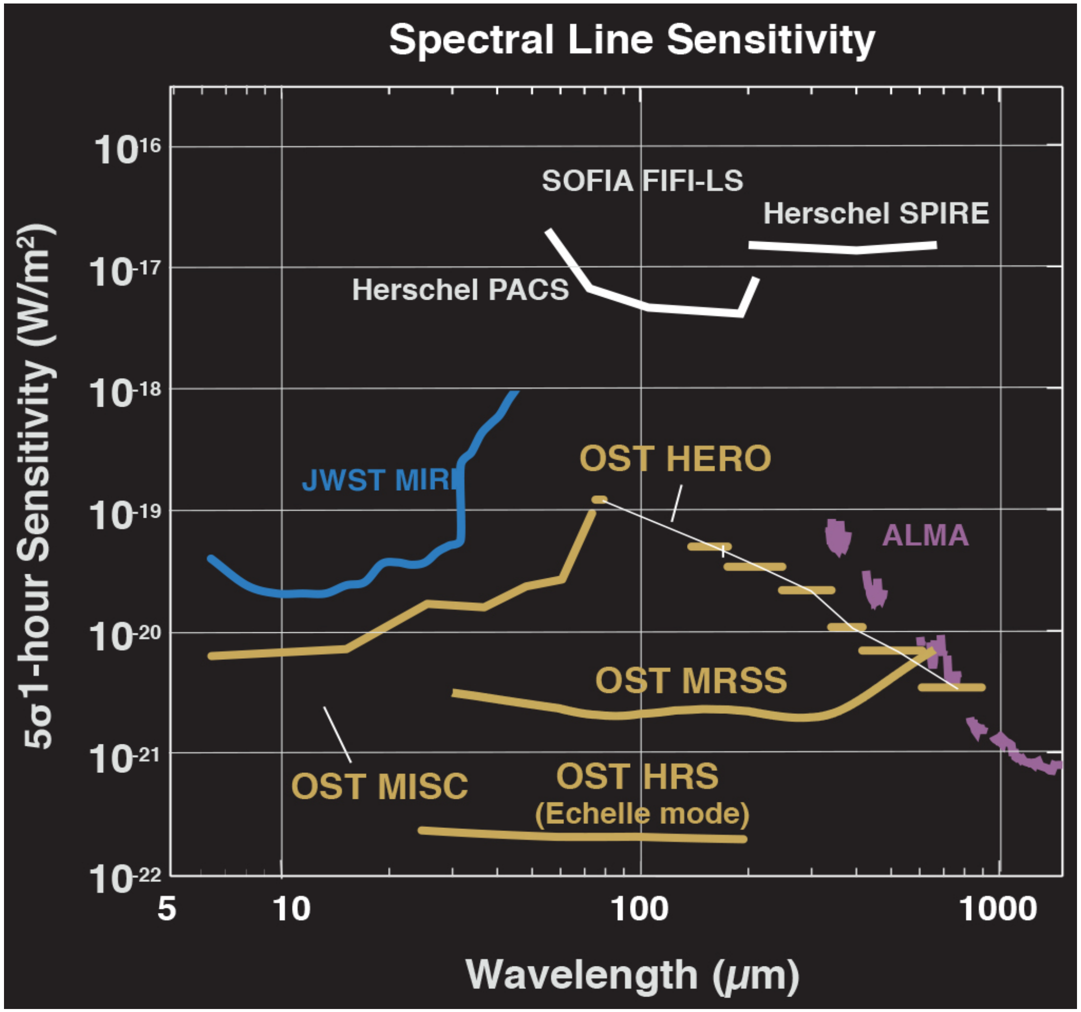
OST (Origins Space Telescope)

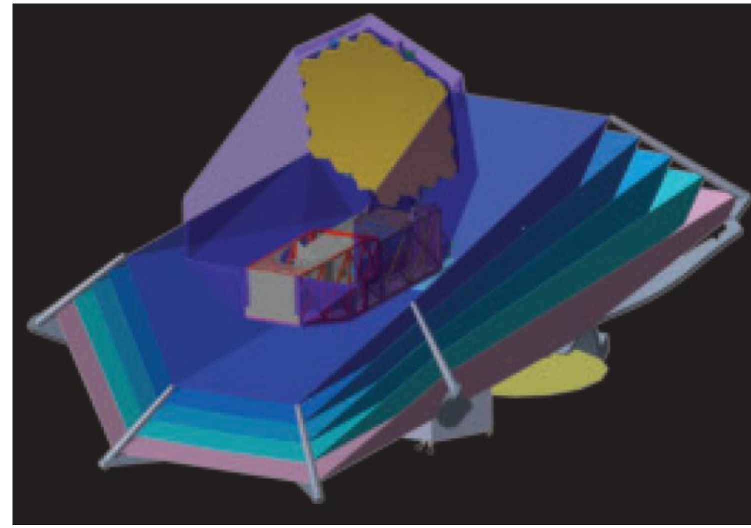
The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study by NASA

9.1 m off-axis primary mirror Cold (4K) telescope Operation frequencies 0.45 - 60THz Launch 2030s Includes 5 different instruments					
Instruments	MICS Mid-Infrared Imager, Spectrometer, Coronagraph	”MRSS” Medium Resolution Survey Spectrometer - IFU	“”FIP” Far-Infrared Imager and Polarimeter	“HERO” Heterodyne Receiver for OST	“HRS” High Resolution Spectrometer

HERO (Heterodyne Receiver for OST)	**63-66, 111-610 um**	**Multi-beam spectroscopy**

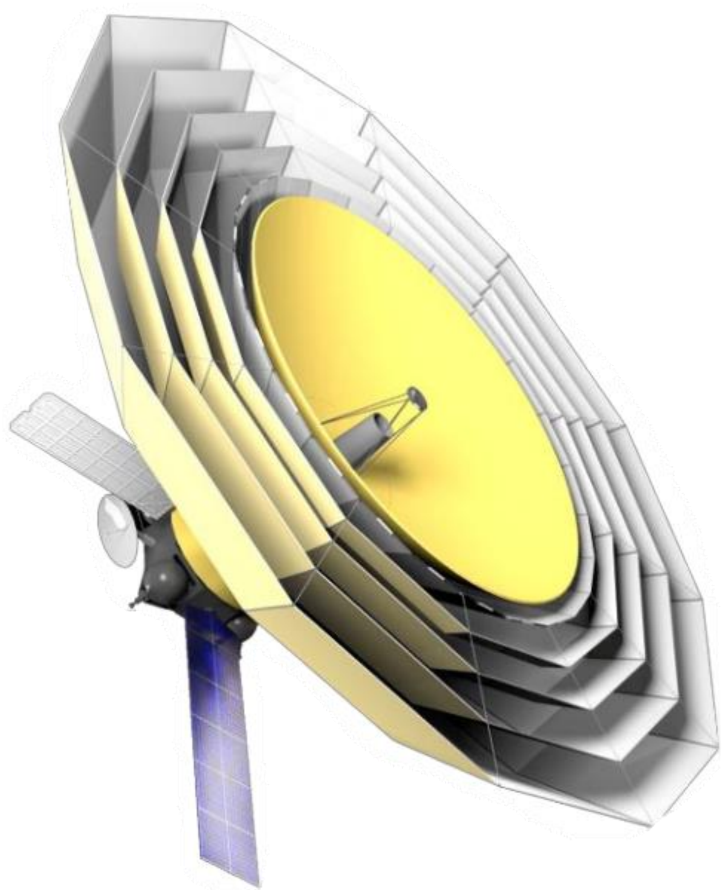
OST performance





HERO instrument will consist of 128 pixels between 900 - 2700 GHz and at 4.7 THz, and 32 pixels for the 468 to 900 GHz range.

Part of Millimetron instruments

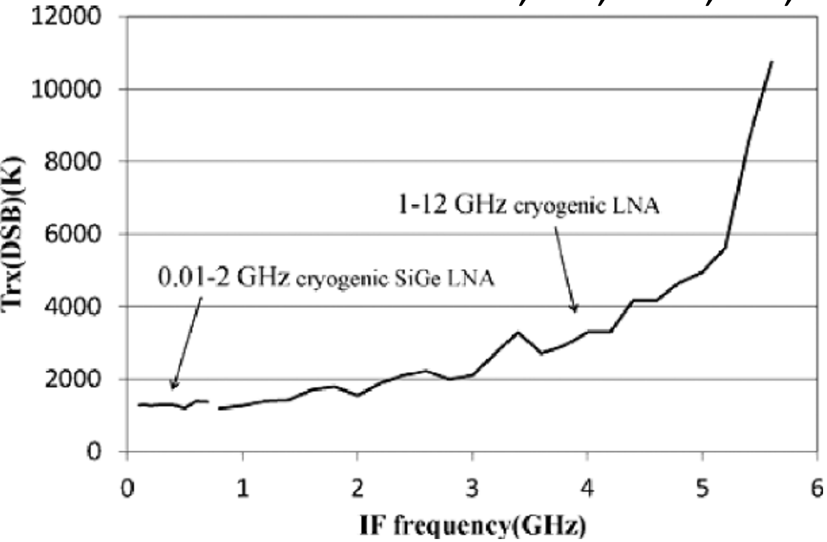


W. Wild, et. al., “Instrumentation for Millimetron - a large space antenna for THz astronomy” Proceeding 19th International Symposium on Space Terahertz Technology

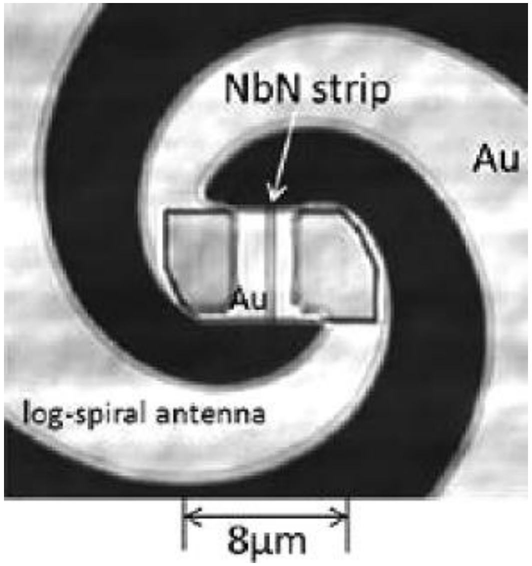
Instrument	Frequency wavelength	Detector technology	Sensitivity
Heterodyne receivers			
HET-1	480 – 700 GHz	SIS 2x2 mixer array with multiplier LO (IREE RAS)	Tsys < 100 K
	1100 – 1400 GHz		Tsys < 200 K
HET-2	1650 – 2000 GHz	HEB mixers with multiplier or QCL LO (MSPU)	Tsys < 500 K
	2600 – 2700 GHz		Tsys < 700 K
	4700 – 4800 GHz		Tsys < 1000 K
Far-Infrared imaging photometer/spectrometer			
M-PACS	60 – 210 μm	Photoconductor arrays	2×10^{-18} Wm^{-2}

HEB in SMILES-2 mission by JAXA

The SMILES-2 mission will have four SIS/**HEB** receivers with bands near 487, 527 GHz, 557, 576 GHz, 623, 653 GHz, and **1.8, 2 THz** to observe spectral lines of atomic oxygen, **OH**, **atomic-O**, O3, O2, H2O, CO, NO, NO2, N2O, ClO, HCl, and BrO.



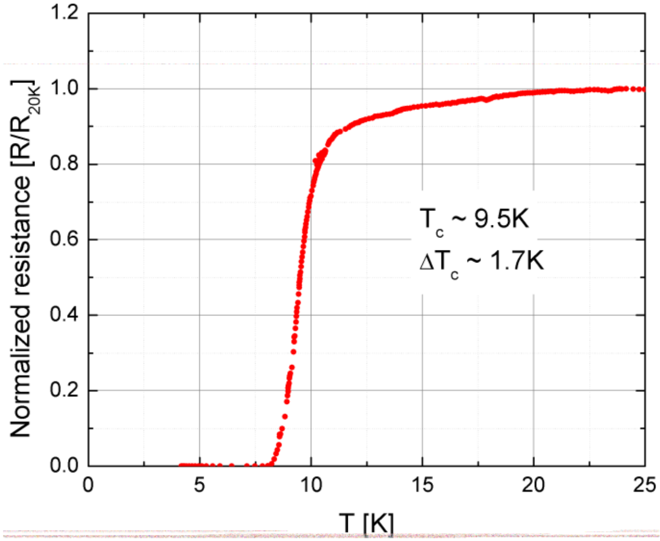
Spectral bands and related products			
Band	Frequency , GHz	Product	Tsys
HEB1	1837.05-1838.05 1834.05-1835.05	OH OH,O_3	990K
HEB2	2056.8-2057.8 2059.8-2060.8	O_3 Wind, O, T	

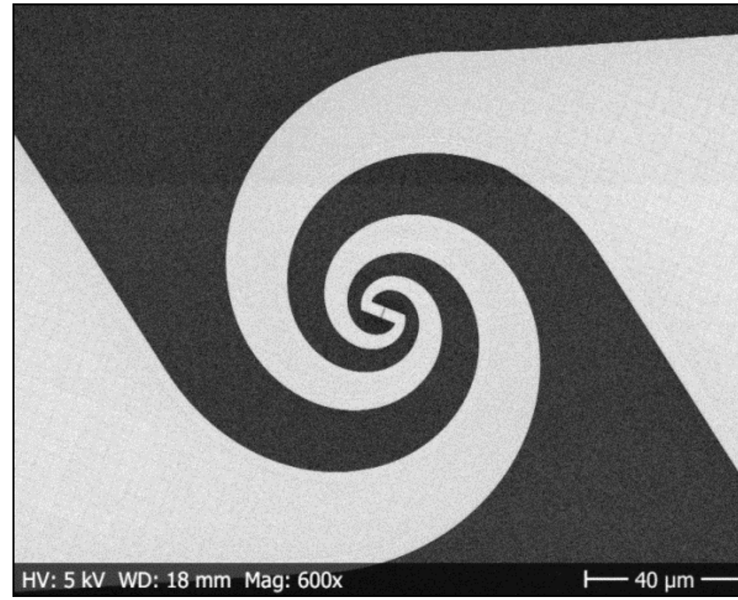


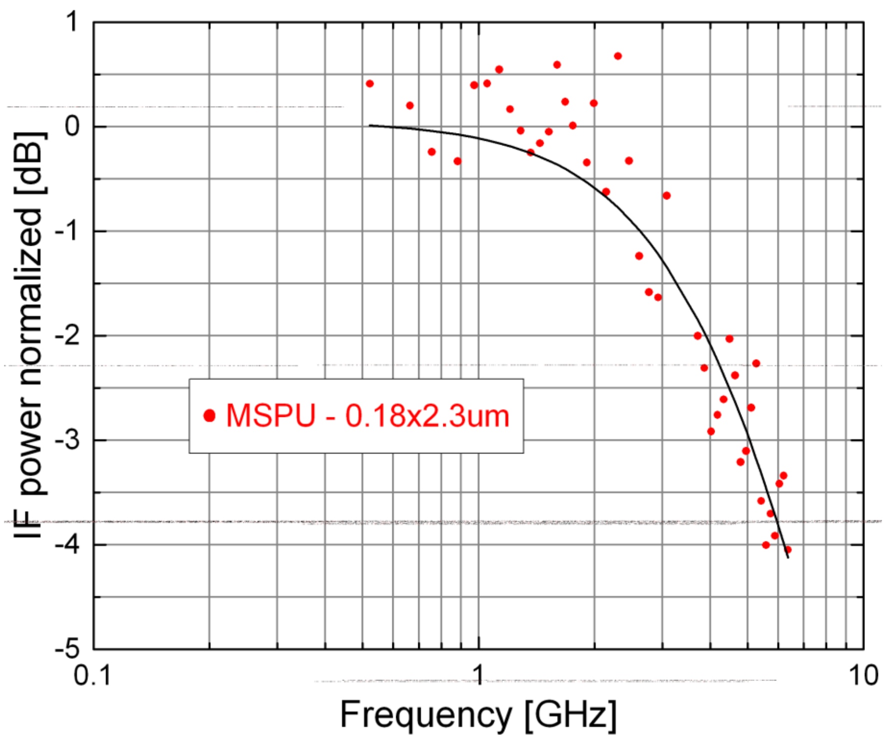
The band HEB1 is dedicated to the measurement of OH at 1.8 THz, a key observation for studying the chemistry in the upper stratosphere and mesosphere.
The atomic oxygen line in band HEB2 is used to sense the lower thermosphere (90−160 km).

Y. Irimajiri, et al., “Development of a Superconducting Low-Noise 3.1- THz Hot Electron Bolometer Receiver,” IEEE Trans. THz Sci. Tech., 5, 6, 1154–1159, 2015.

NbN HEB mixer utilizing a GaN buffer layer in MSPU







NbN/GaN buffer layer:

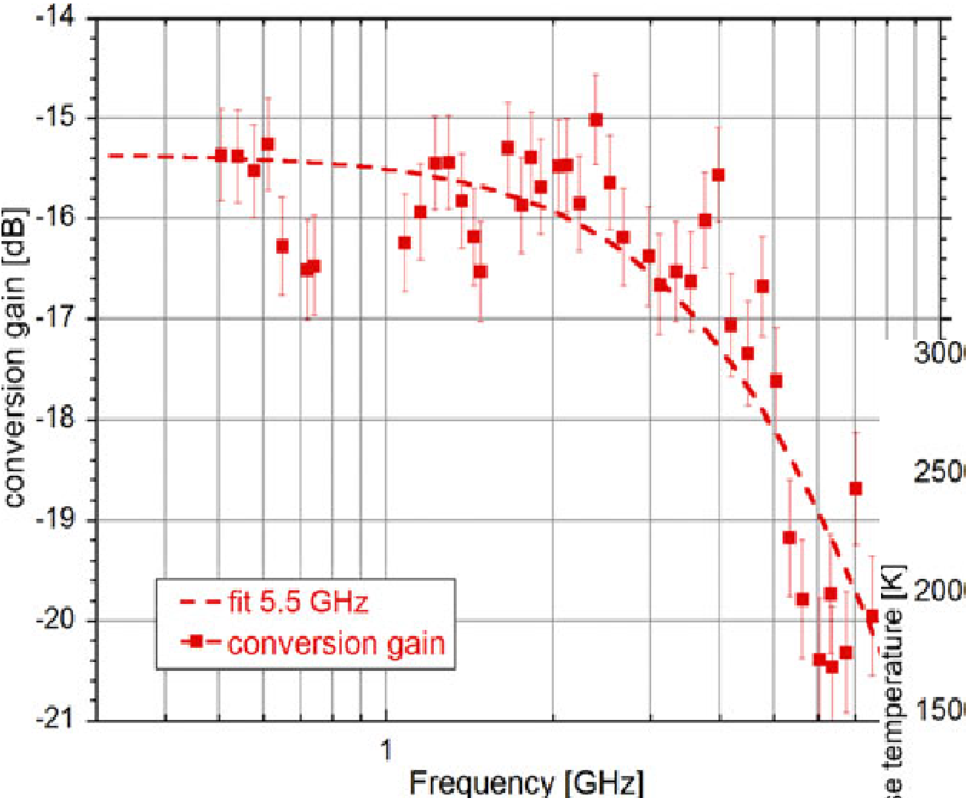
Grown at MSPU, Tc ~ 10 K

Device size: 4.5nm x 0.18um x 2.3um

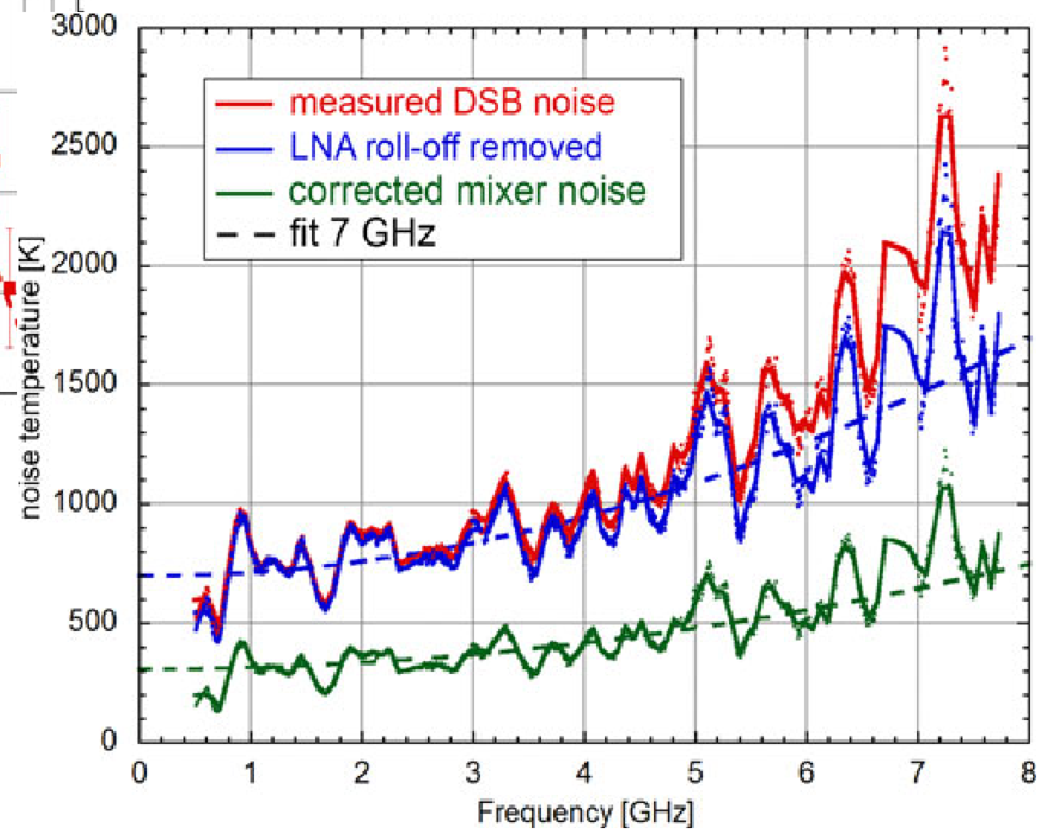
Measured at 2.02 THz with QCL LO

IF gain bandwidth ~ 5 GHz

NbN HEB mixer utilizing a GaN buffer layer in Chalmers Uni. of Tech.



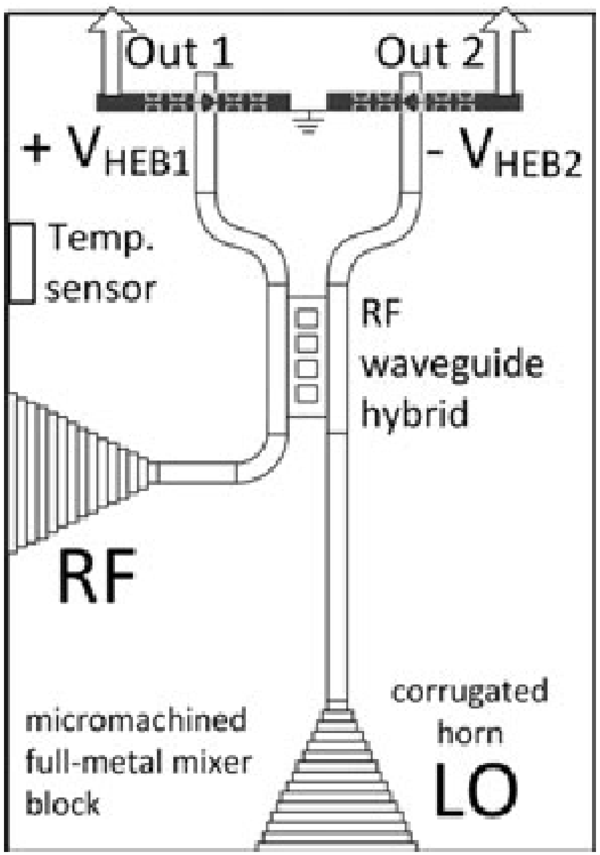
Gain bandwidth 3 dB roll-off:
~ 5.5 GHz
Noise bandwidth 3 dB roll-off :
~ 7 GHz

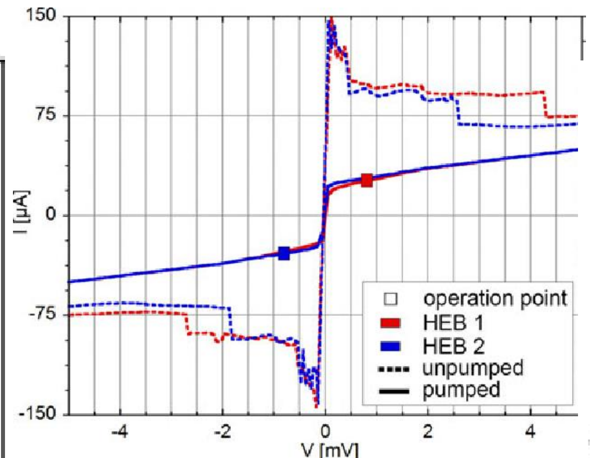


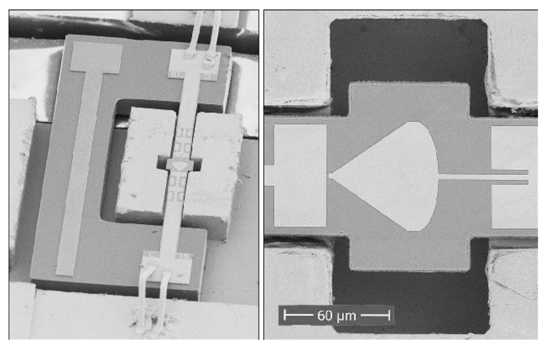
LO frequency: 1.4 THz
Uncorrected DBS T_n: ~ 750 K
(1 GHz IF bandwidth);
Corrected DBS T_n : ~ 300 K
(1 GHz IF bandwidth)

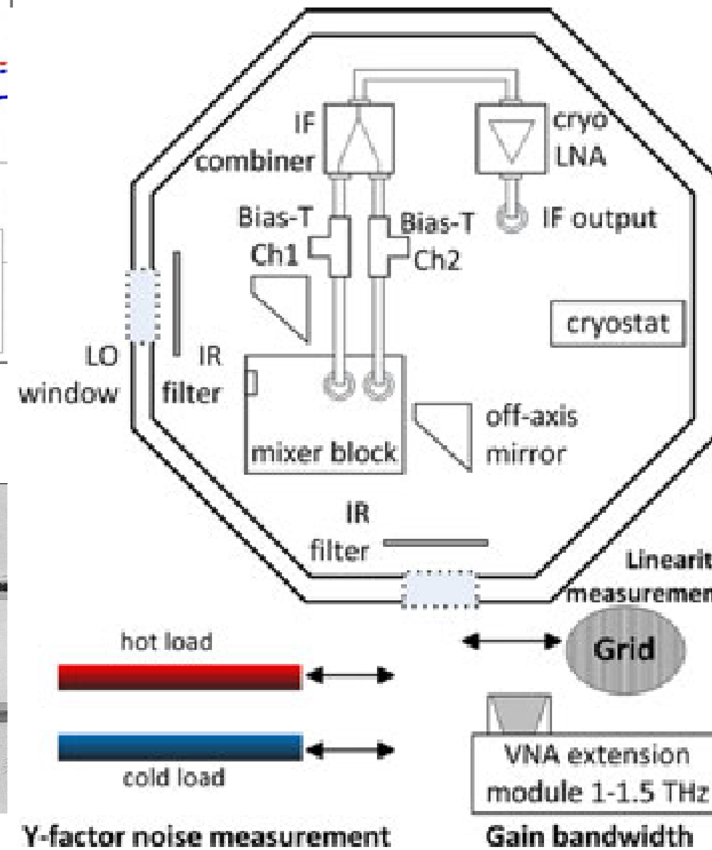
Krause S, Meledin D, Desmaris V, Belitsky V 2018 Noise and IF gain bandwidth of a balanced waveguide NbN/GaN hot electron bolometer mixer operating at 1.3 THz *IEEE Transactions on Terahertz Science and Technology* 8(3) 365-371

1.3 THz balanced waveguide NbN HEB mixer utilizing a GaN buffer layer by Chalmers University of Technology





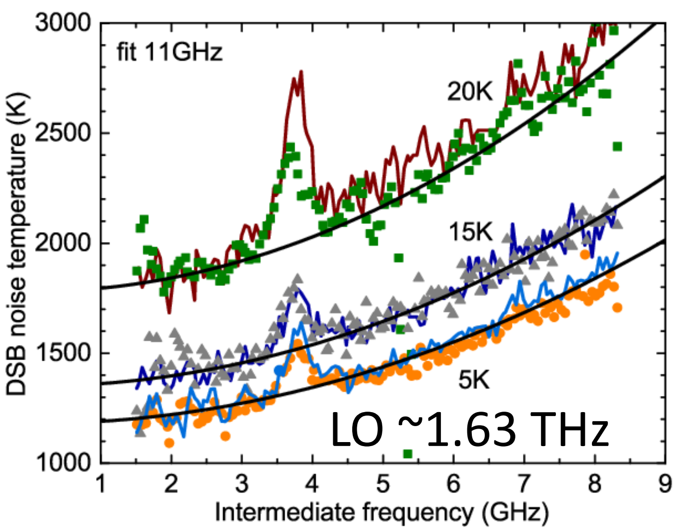


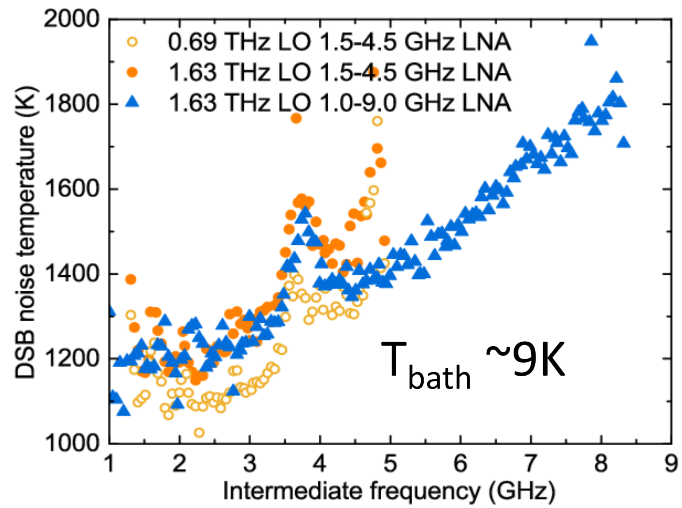


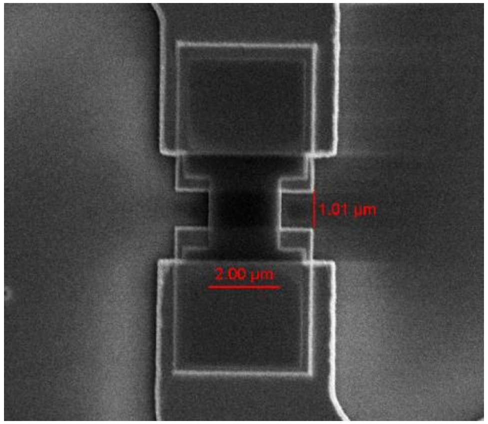
Krause S, Meledin D, Desmaris V, Belitsky V 2018 Noise and IF gain bandwidth of a balanced waveguide NbN/GaN hot electron bolometer mixer operating at 1.3 THz *IEEE Transactions on Terahertz Science and Technology* 8(3) 365-371

MgB$_2$ HEB mixer technology in Chalmers University of Technology

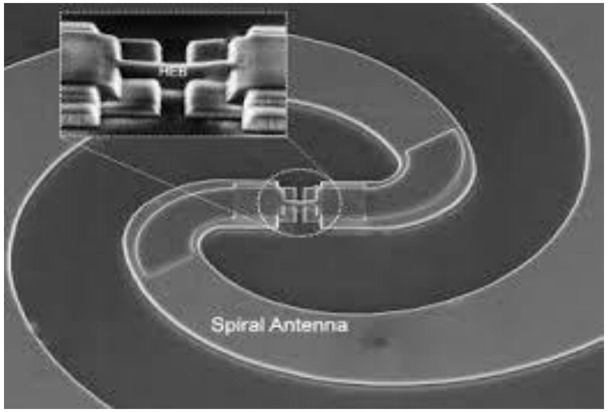
DSB noise temperature of 930 K and 1400 K at 1.63 THz and 2.55 THz LO frequencies S. Cherednichenko, et. al. 29th IEEE Int. Symposium on Space THz Technology (ISSTT2018)







(a) (b)

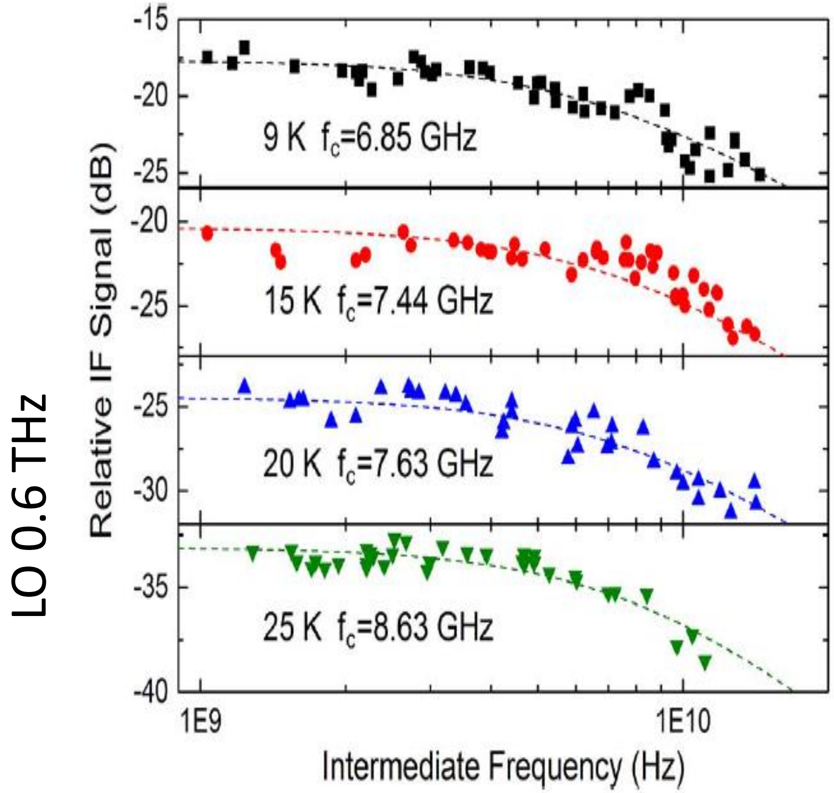


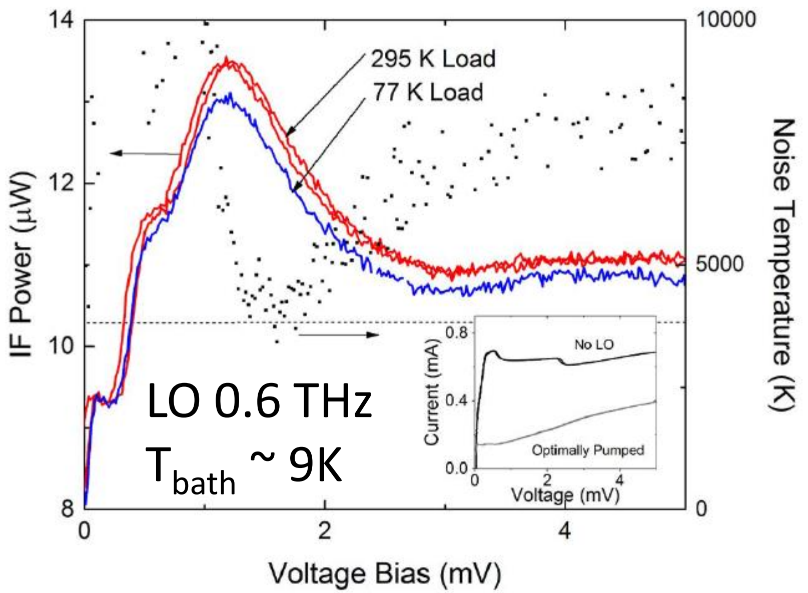
Evgenii Novoselov and Sergey Cherednichenko, Gain and Noise in THz MgB2 Hot-Electron Bolometer Mixers With a 30-K Critical Temperature, IEEE Transactions on Terahertz Science and Technology, vol. 7, no. 6, November 2017

MgB_2 HEBs for Array Receivers
Jet Propulsion Laboratory, California Institute of Technology

Best mixer devices demonstrate a noise temperature ≈ 2000 K from 0.6 THz to 4.3 THz, with an LO power < 1µW.

29th IEEE International Symposium on Space THz Technology (ISSTT2018), Pasadena, CA, USA, March 26-28, 2018

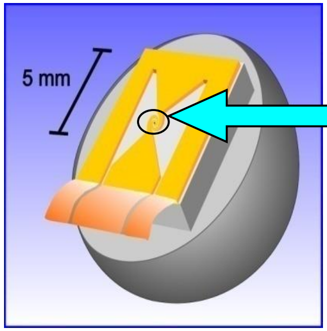


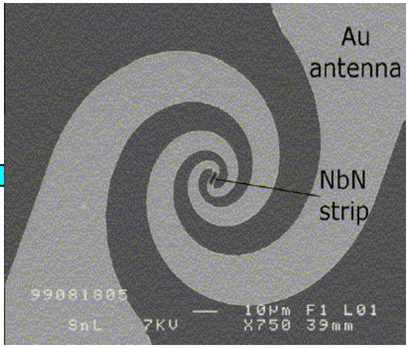


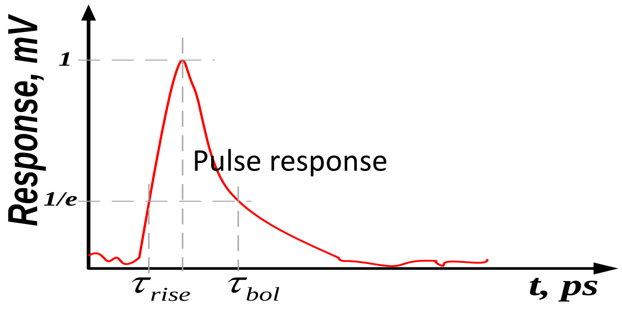
D. Cunnane ; J. H. Kawamura ; M. A. Wolak ; N. Acharya ; T. Tan ; X. X. Xi ; B. S. Karasik Characterization of MgB_2 Superconducting Hot Electron Bolometers IEEE Transactions on Applied Superconductivity (Volume: 25, Issue: 3, June 2015)

Hot electron bolometers as direct detectors are capable to detect *aJ* pulse energy at GHz rate

Spiral antenna coupled bolometer





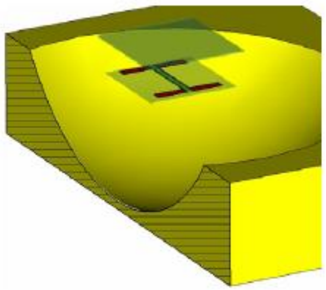


$t_{bol} \approx 50$ ps

NEP ≈ 10 $^{-13}$ W/√Hz

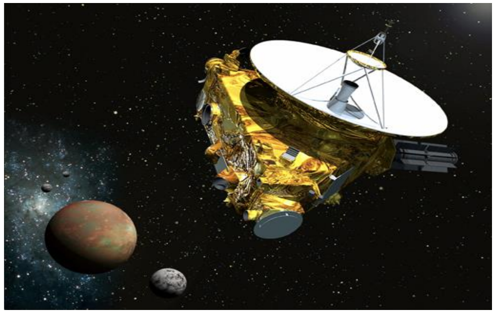
$$W_{pulse} = SNR \times NEP \times \sqrt{\tau_{bol}} \approx 1\ aJ$$

Signal to noise ratio (SNR) ≈ 5 is required for stable link



Double dipole antenna coupled bolometer

No photon shot noise in THz!



New Horizons: approaching Pluto

(artist's view, to happen in summer 2015)

2.1 m diameter dish antenna to communicate with Earth from 7.5 billion kilometers away

Credit: Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI)

First observation of single-photon response and first idea of SSPD physics

Picosecond superconducting single-photon optical detector

G. N. Gol'tsman,[a)] O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov
Department of Physics, Moscow State Pedagogical University, Moscow 119435, Russia

C. Williams and Roman Sobolewski[b)]
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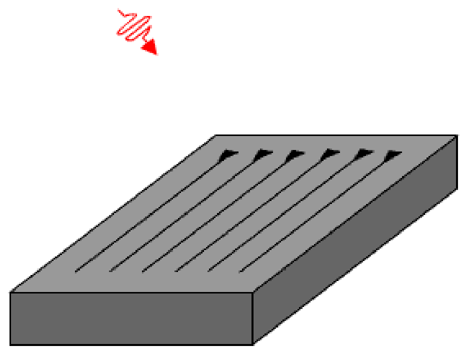

FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

Quantum detection by current carrying superconducting film

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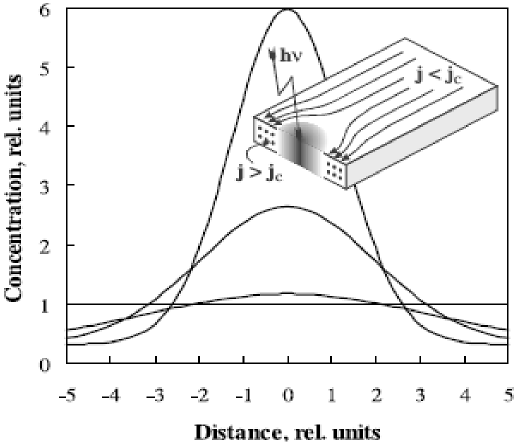
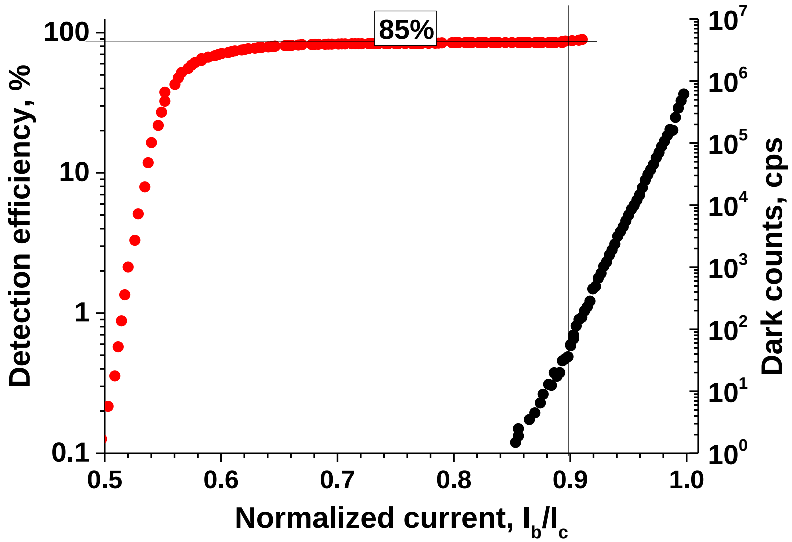


Fig. 1. Concentration of nonequilibrium quasiparticles across the width of the film at different moments after the photon has been absorbed. Time delays are 0.8, 2.0 and 5.0 measured in units of the thermalization time. Distance from the absorption site is shown in units of the thermalization length. Inset illustrates redistribution of supercurrent in the superconducting film with the normal spot – the basis of quantum detection. It shows the cross-section of the film drawn through the point where photon has been absorbed.

Practical single-photon receiver based on SSPD

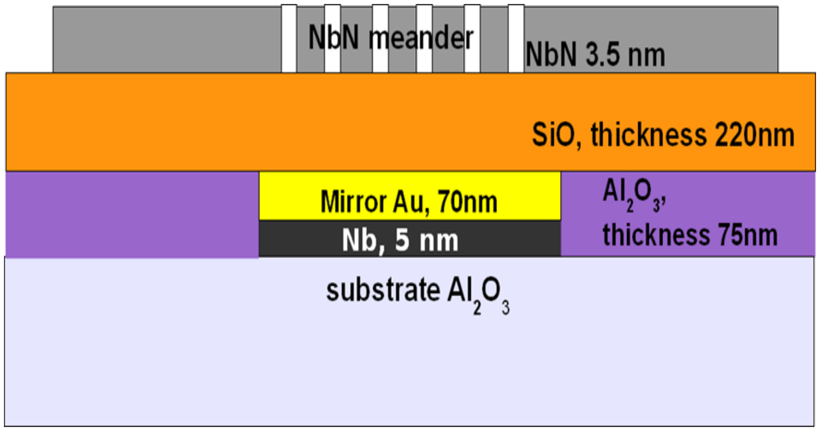
Direct detection: Quantum efficiency 80% at 1550nm, jitter 20ps, max. counting rate 100 MHz and dark count rate $10 s^{-1}$

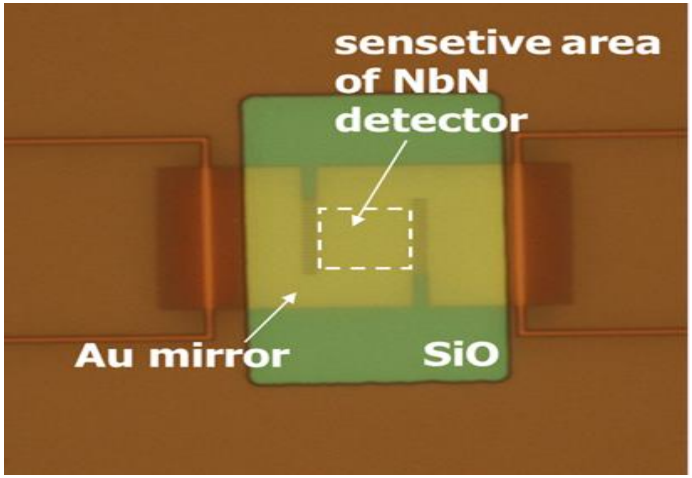
Heterodyne detection: $T_N \rightarrow$ quantum limit, Bandwidth ~ 1 GHz



Spectral range	Quantum efficiency (referred to optical input)
0.7 – 1.3 µm	85 %
1.3 – 1.6 µm	80 %
1.6 – 2.3 µm	50 %

Cavity-integrated SSPD





Conclusions

Superconducting Hot-Electron Bolometer Mixers based on ultrathin NbN films demonstrate the best performance in the frequency range higher than 1 THz. NbN HEB with GaN buffer layer demonstrates wider IF bandwidth. Next promising material is MgB2.

Space- and airborne telescopes with high resolution spectrometers based on HEB heterodyne receivers provide unprecedented sensitivity for observations in the THz range. Currently several international projects aimed to carry out high resolution THz observations are in progress.

Photon counting technology based on SSPD moves from IR to THz range, demonstrates high quantum efficiency, no intrinsic noise and a very large dynamic range.

Thank you for your attention!