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THz heterodyne sensors based on MgB_2

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IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019.
Invited presentation 1EOr2B-01 given at ASC 2018, October 28-November 02, 2018, Seattle, (USA).

The objective

Advancing the state-of-the-art of THz hot-electron bolometer (HEB) mixers for high-resolution molecular line spectroscopy by using MgB_2 superconducting thin films

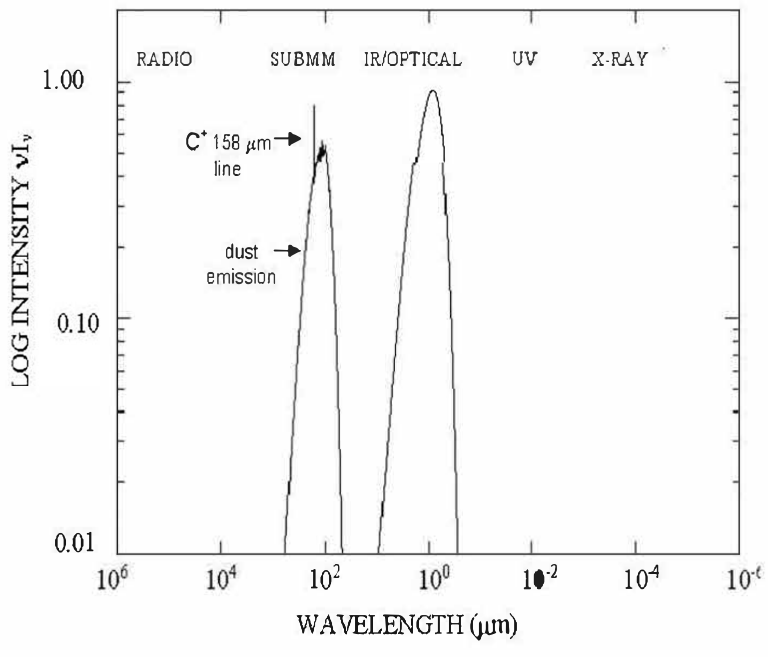
- Large IF bandwidth (~ 7 GHz)
- High operating temperature (≈ 15-20 K)
- Monolithic array architecture

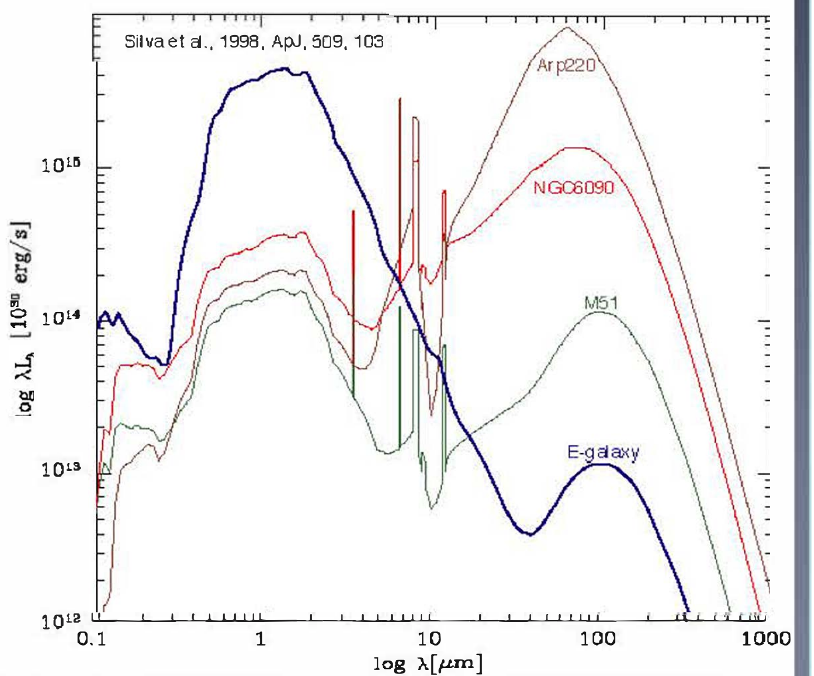
Outline

- THz heterodyne spectroscopy in space
- Benefits of the MgB_2 films
- Thin film fabrication
- HEB mixer devices & data
- Josephson junction device & data
- Waveguide based array mixer
- New application: mid-IR broadband mixer
- Summary

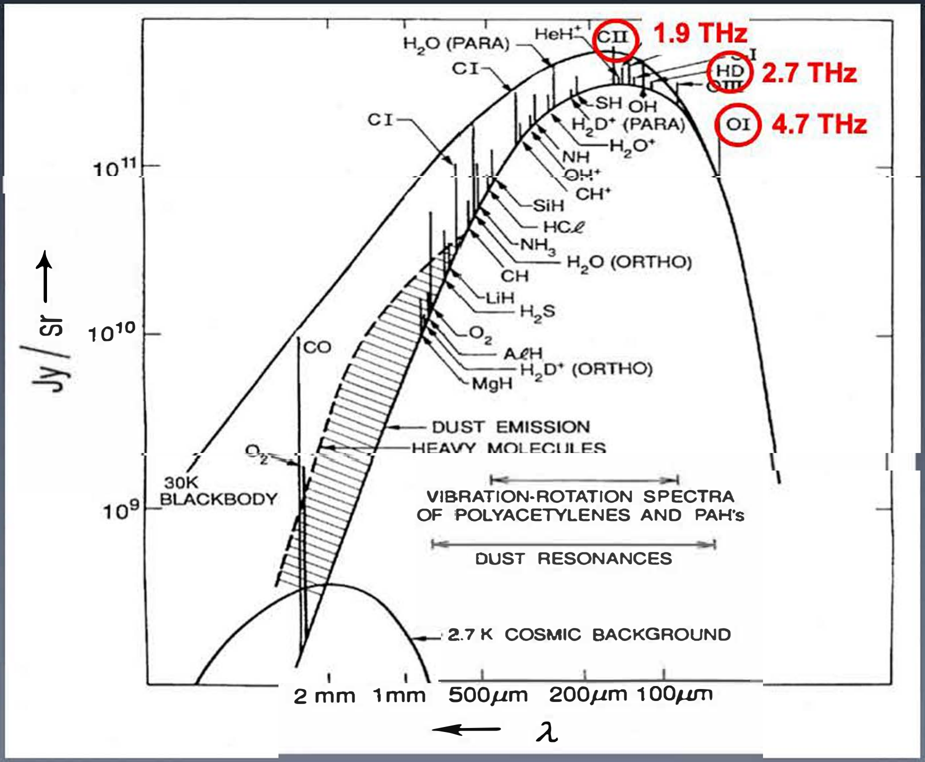
Far-IR galactic emission

- Half the luminosity and 98% of the photons falls into the far-IR region
- Red shifted galaxies from the early universe emit in the of far-IR





THz line emission spectrum



- THz is the primary frequency range for line and continuum radiation from cool (50-100 K) gas (ions, atoms and molecules) and dust
- High resolution ($\nu/\Delta\nu$ = 10^6-10^7) spectroscopy provides information about abundance of gas-phase species and their chemistry in regions of star- and galaxy formation

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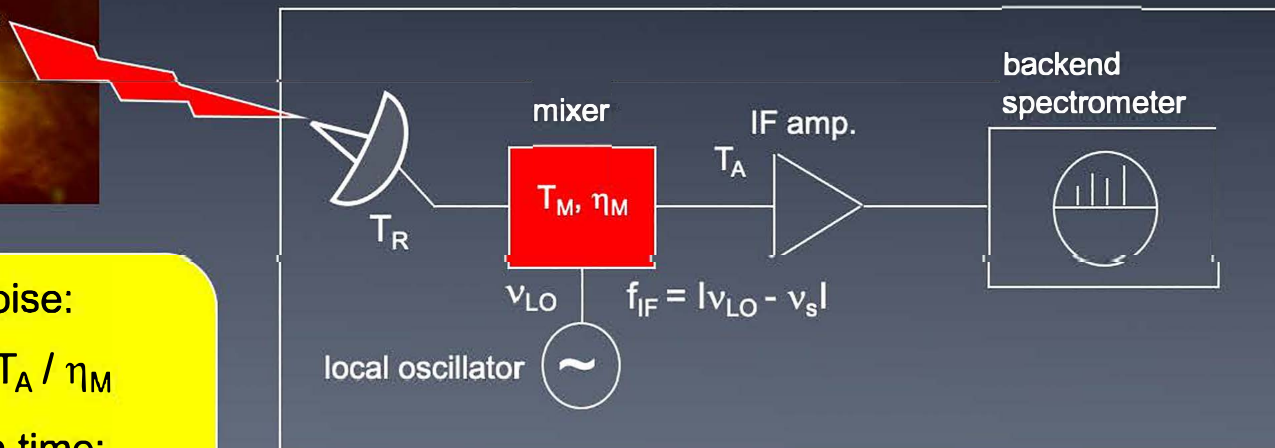
High resolution heterodyne spectroscopy

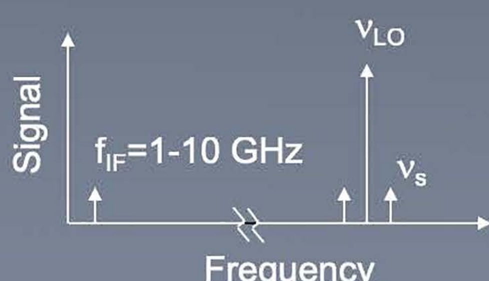


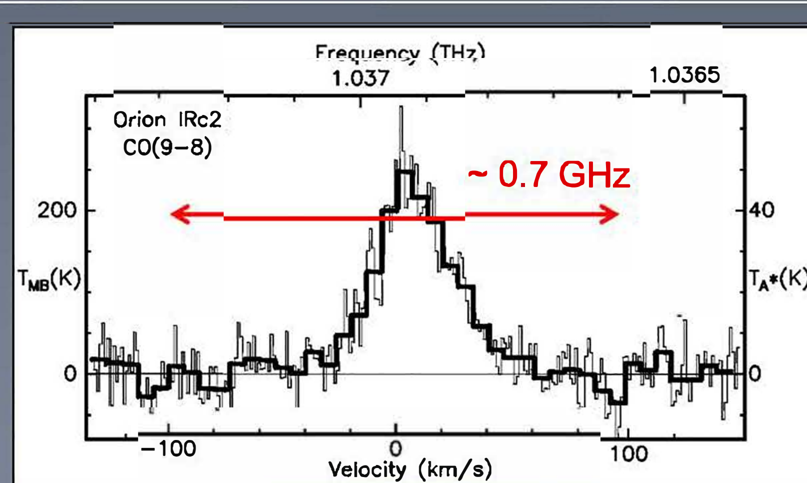
- receiver noise:

  $T_R = T_M + T_A / \eta_M$

- integration time:

  $\tau_{in} \sim (T_R)^2$





Herschel Space Observatory (HSO)

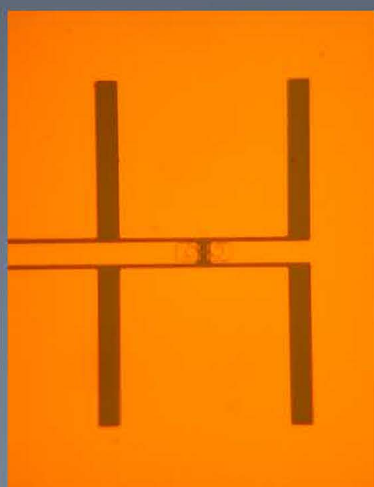
Heterodyne Instrument for Far-IR (HIFI)

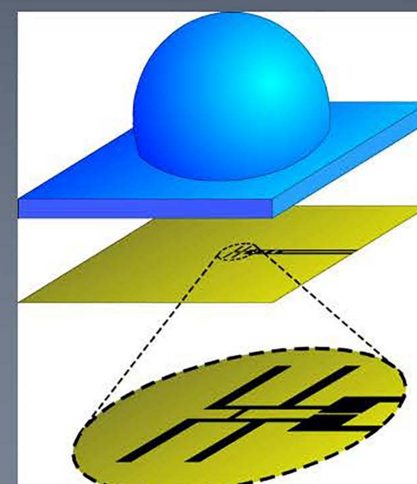
Band	Mixer	LF (GHz)	HF (GHz)
1	SIS	480	640
2	SIS	640	800
3	SIS	800	960
4	SIS	960	1120
5	SIS	1120	1250
6L	HEB	1400	1600
6H	HEB	1600	1910

- Launched on May 14, 2009. Exhausted LHe on April 29, 2013
- HIFI used HEB mixers made from NbN films

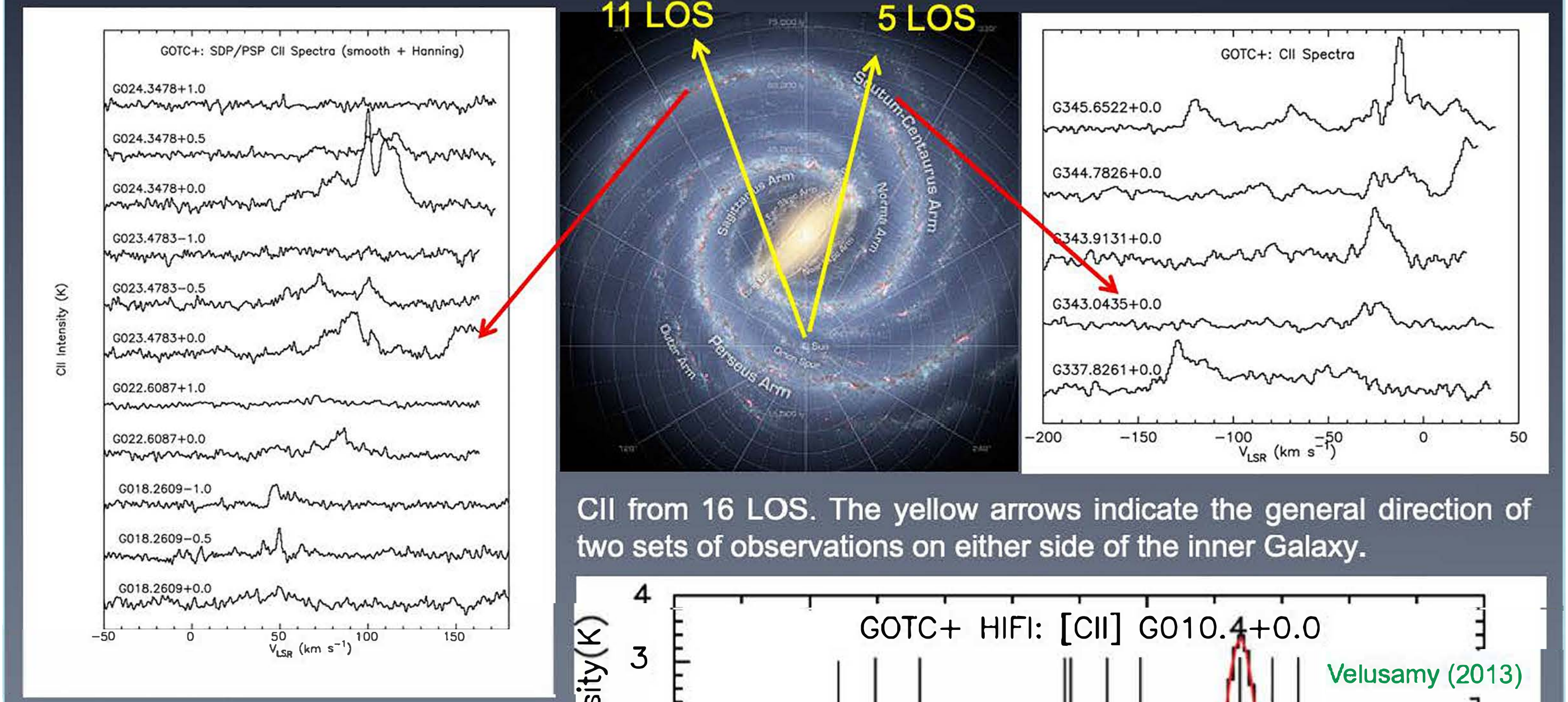
Quasioptical THz HEB mixers

Herschel HIFI Band 5 and 6 mixers

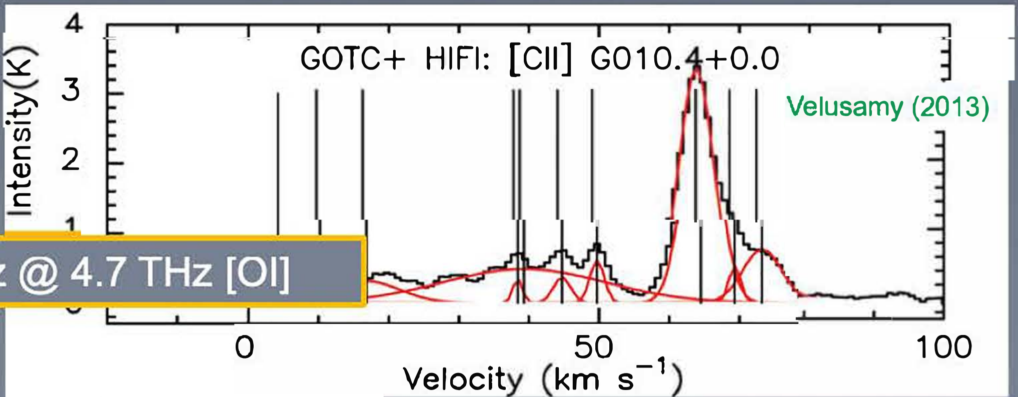




Galactic observation of THz [CII] line

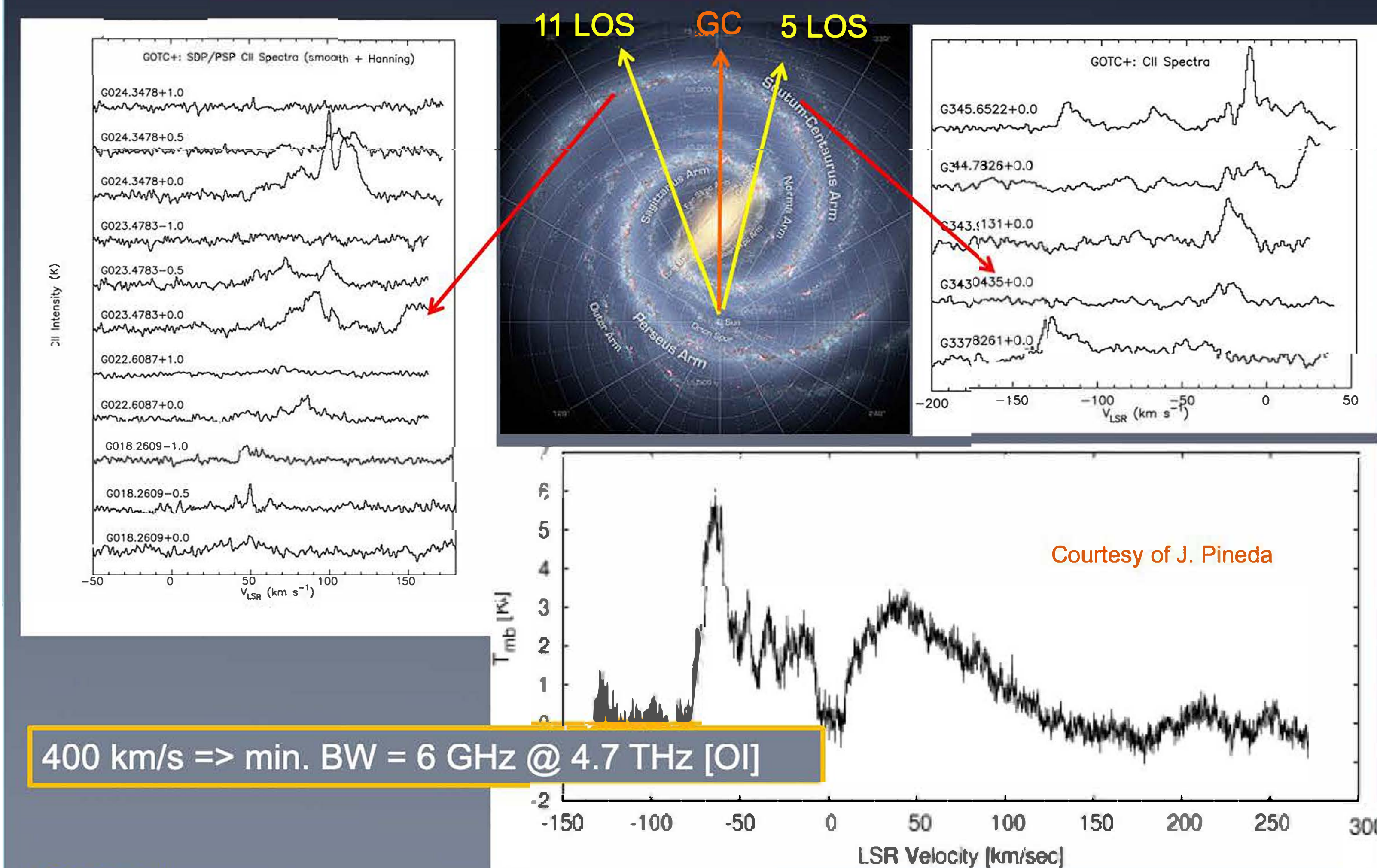


CII from 16 LOS. The yellow arrows indicate the general direction of two sets of observations on either side of the inner Galaxy.



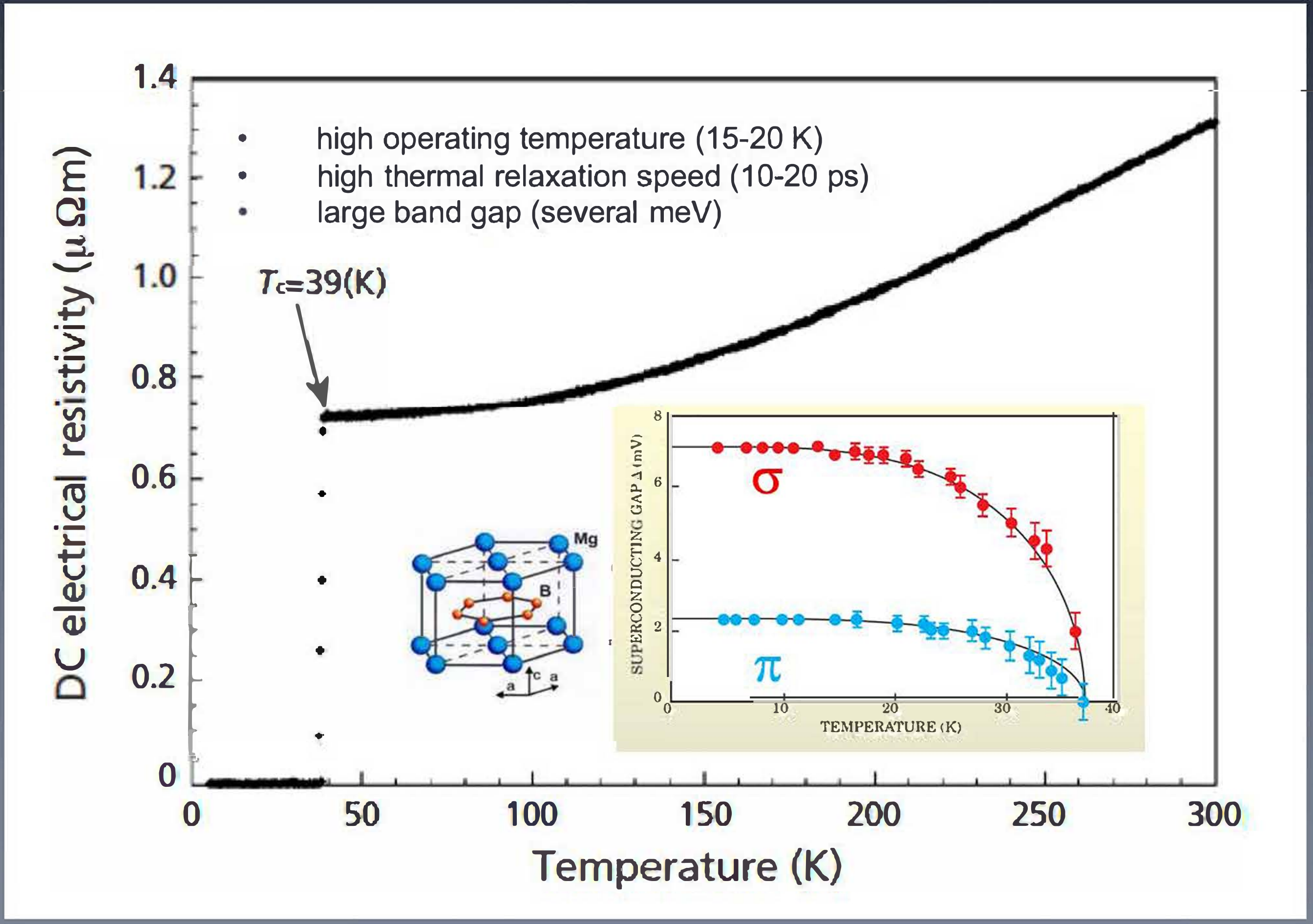
400 km/s => min. BW = 6 GHz @ 4.7 THz [OI]

Galactic observation of THz [CII] line

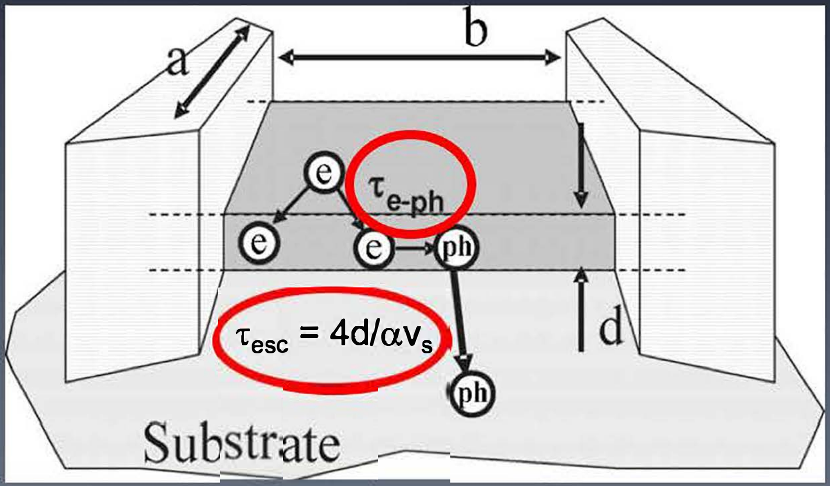


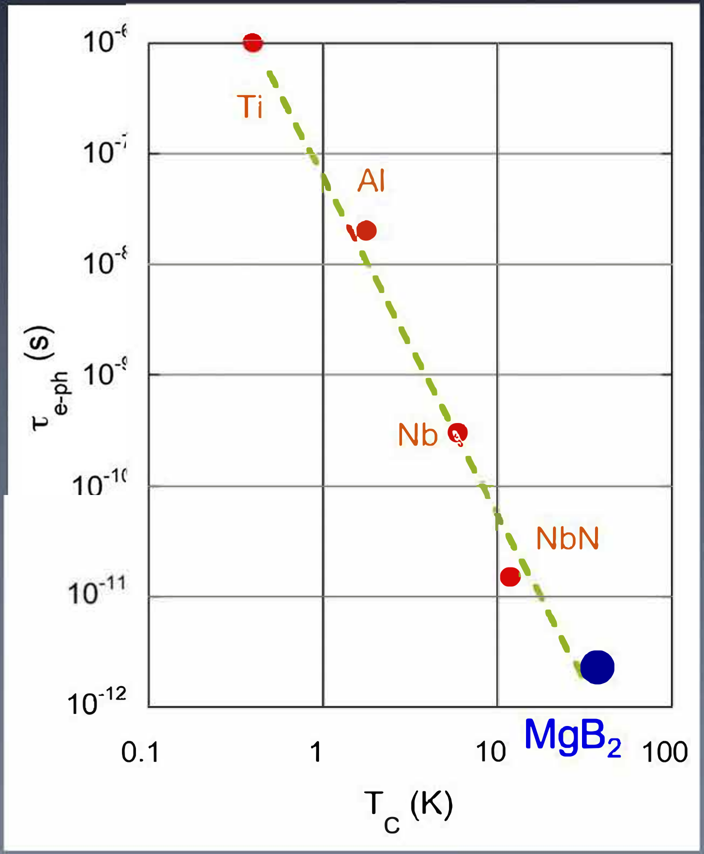
400 km/s => min. BW = 6 GHz @ 4.7 THz [OI]

MgB_2


high operating temperature (15-20 K)
high thermal relaxation speed (10-20 ps)
large band gap (several meV)
Tc=39(K)
DC electrical resistivity (μΩm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
Temperature (K)
Mg
B
a
c
a
σ
π
SUPERCONDUCTING GAP Δ (mV)
8
6
4
2
0
0
10
20
30
40
TEMPERATURE (K)

Electron energy relaxation in thin films

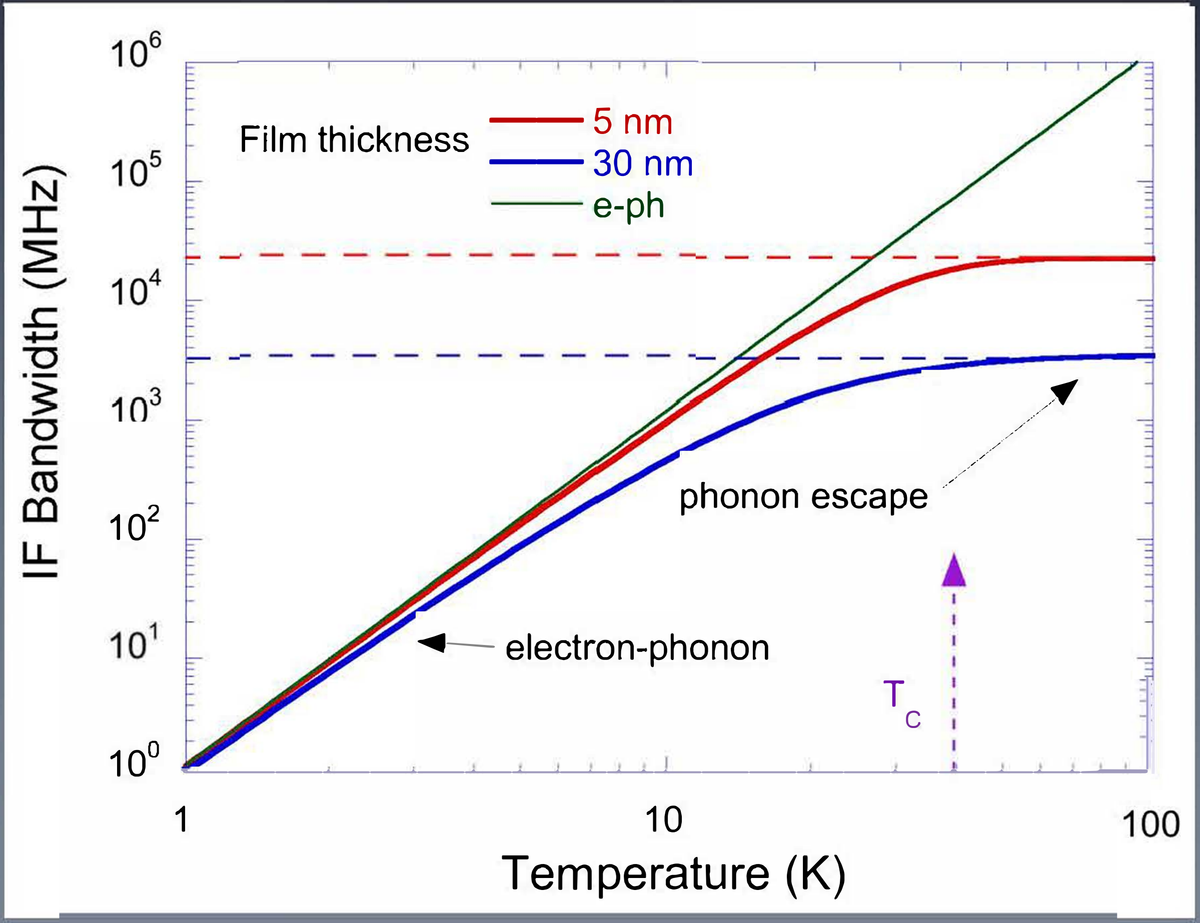




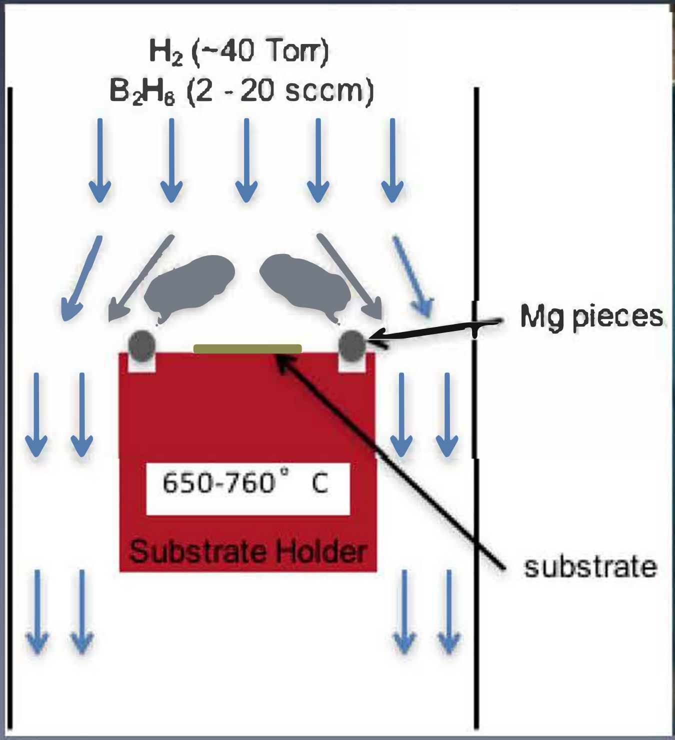
- at T > 4K, phonons partially escape film but partially return energy to electrons
- very thin films and good acoustic transparency at the film-substrate interface are needed to accelerate the phonon escape

Material	MgB_2	NbN
v_s (km/s)	7.8	2.5

Electron energy relaxation in MgB_2 film



Hybrid Physical-Chemical Vapor Deposition (HPCVD)

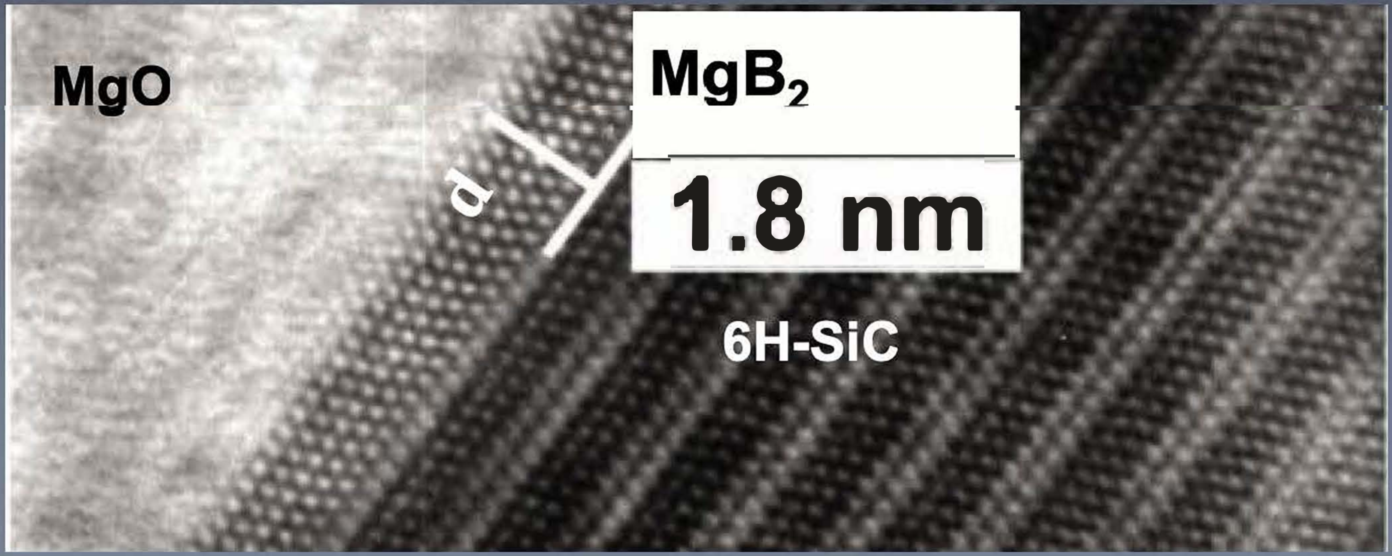


- c-axis oriented films on 6H-SiC
- thinnest films (≤ 10 nm) with high T_C and moderate resistivity (~10s μΩ cm)

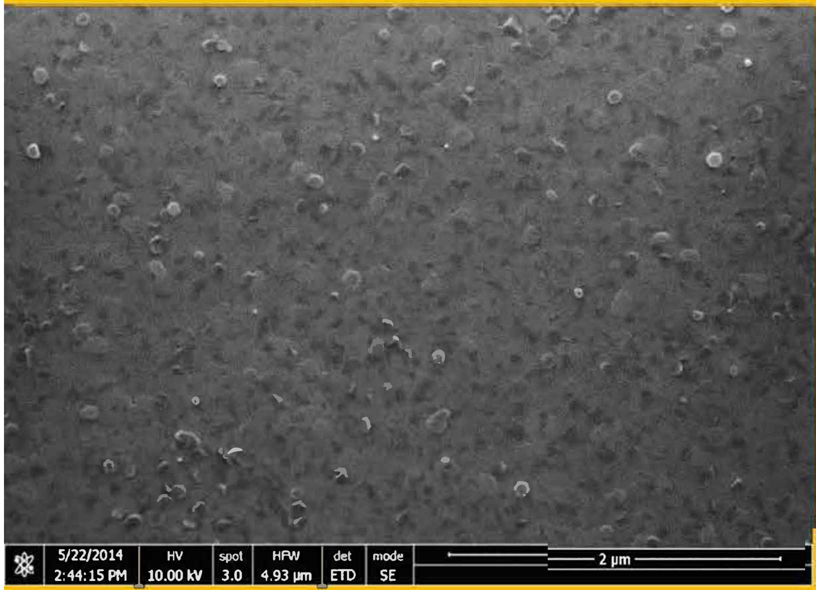
Fast escape of phonons from MgB_2 to SiC

phonon escape ($\tau_{es} = 4d/v_s\alpha$) is the bottleneck for the energy relaxation in MgB_2 HEB

Material	MgB_2	NbN
v_s (km/s)	8-10	2.5



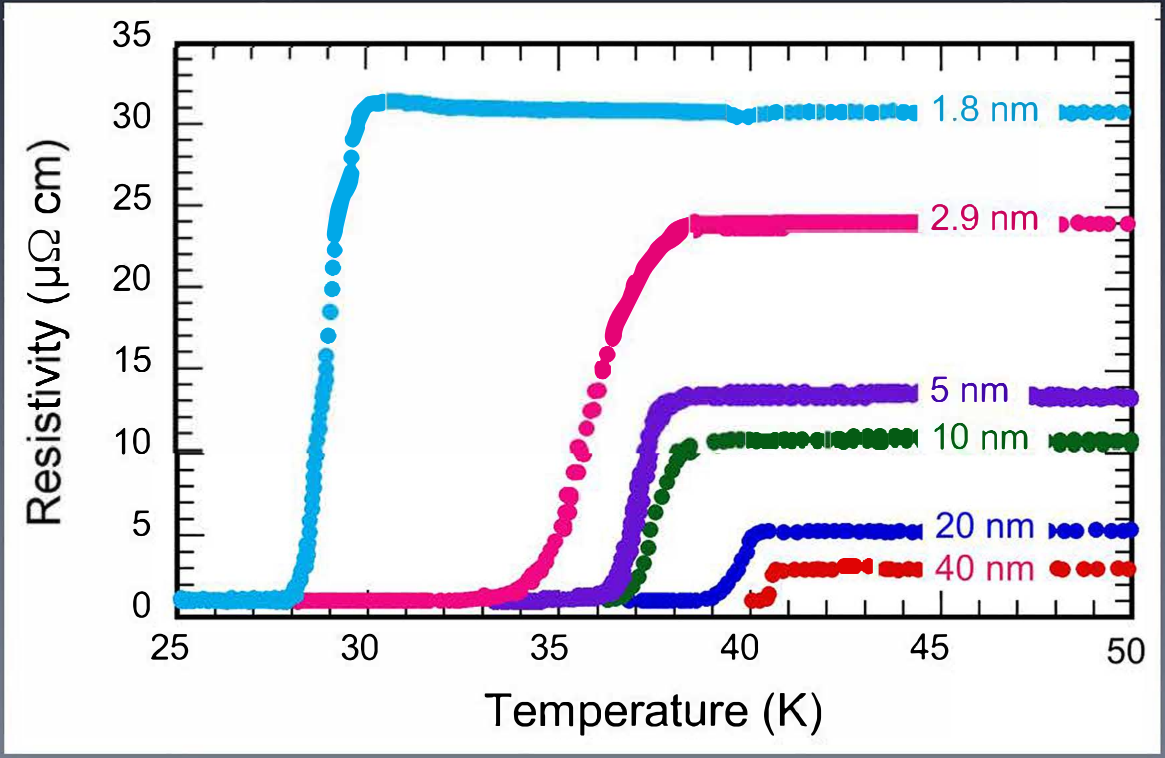
As-grown and ion milled 15 nm thick films



HPCVD alone

HPCVD+ion mill

Ion-milled thin films with high T_C

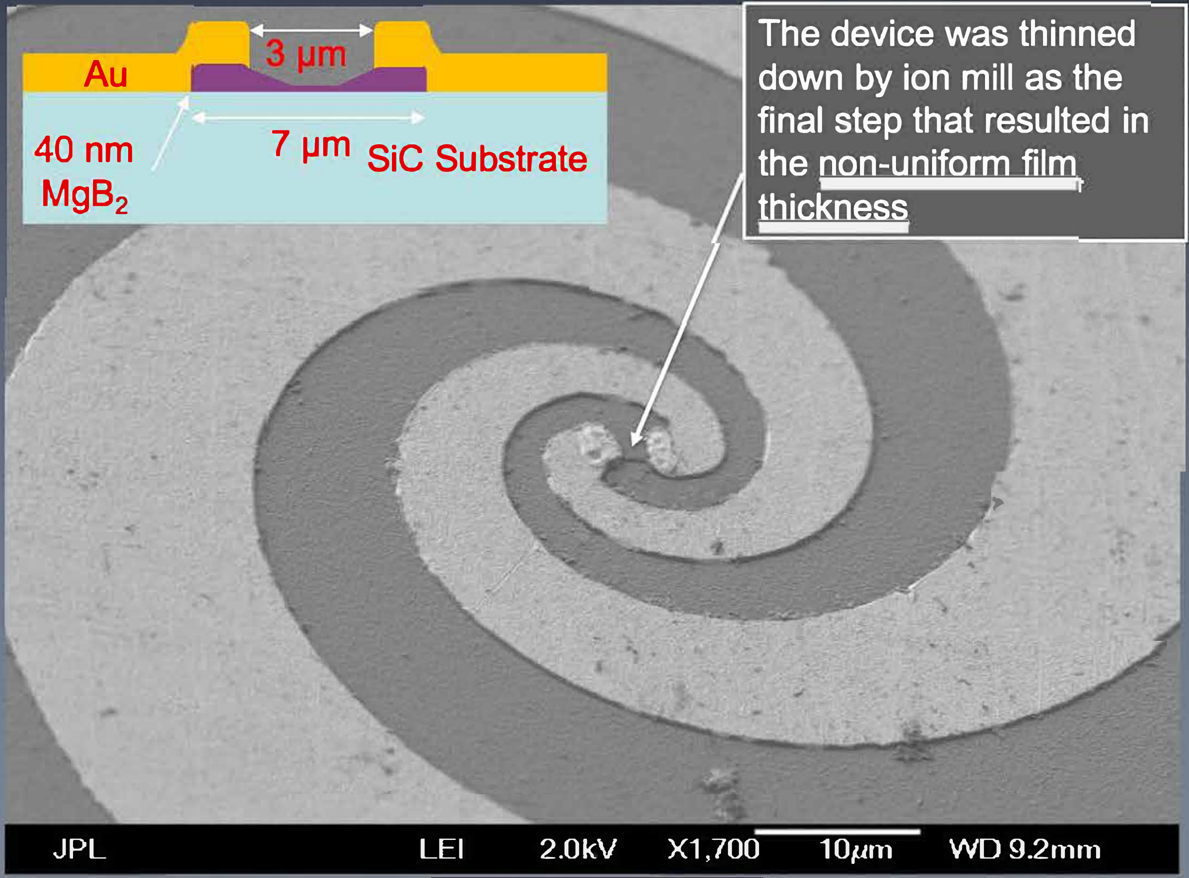


- very thin as-grown films (< 10 nm) lose continuity
- ultrathin films were achieved using ion mill of thicker (~ 40 nm) continuous films
- Good quality superconducting material ($j_C \sim 10^7$ A/cm^2)

N. Acharya et al., *APL Mater.* **4**, 086114 (2016)

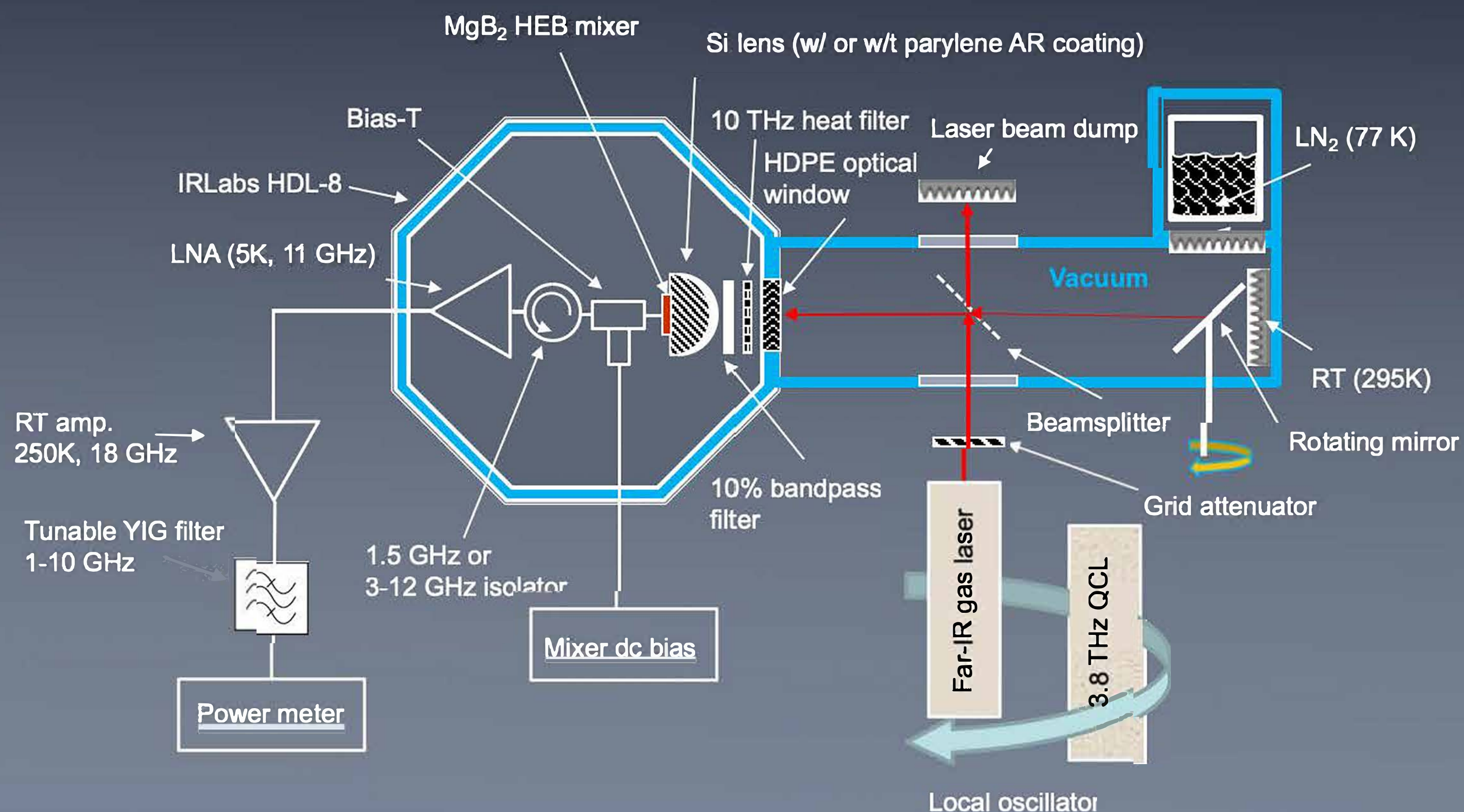
Antenna-coupled HEB devices

Prior to the device fabrication, films are *ex-situ* passivated with SiO_2 or Au

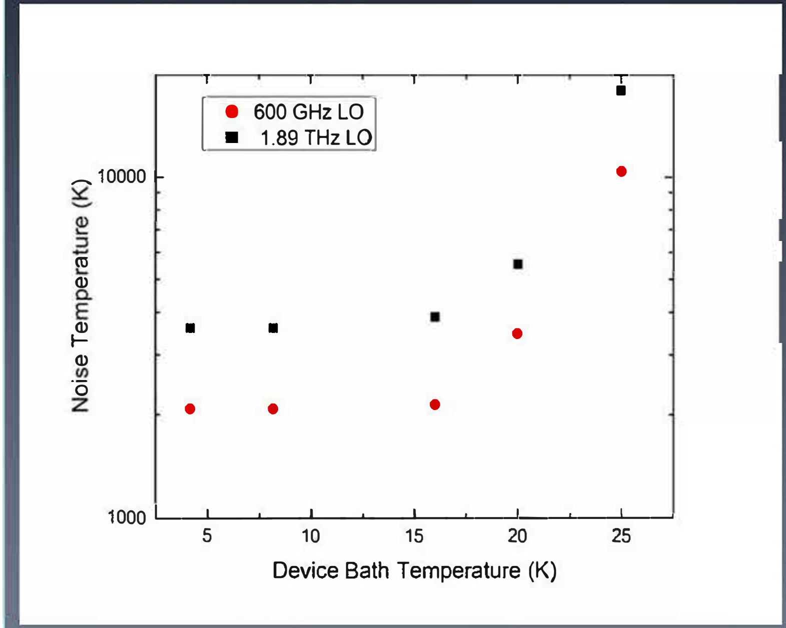


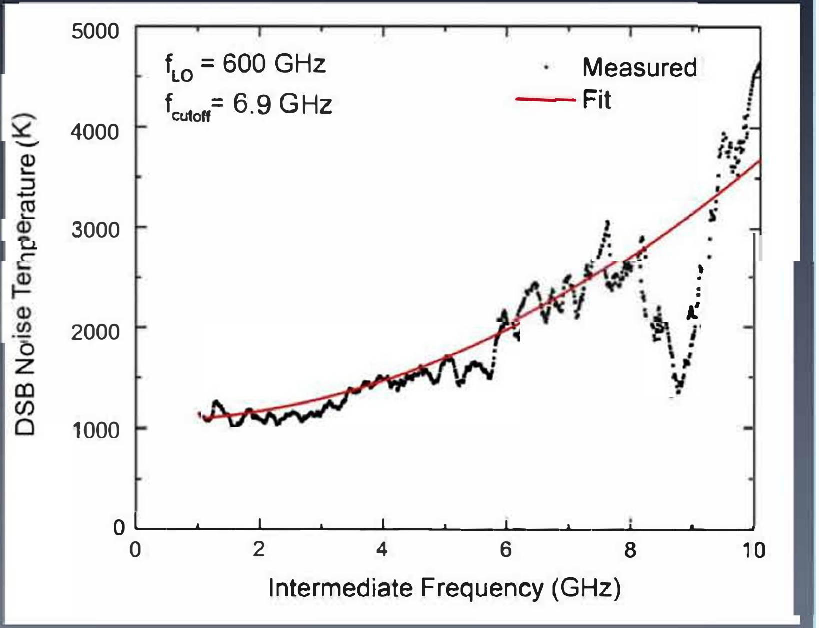
The device was thinned down by ion mill as the final step that resulted in the non-uniform film thickness

THz test setup



Noise temperature and bandwidth

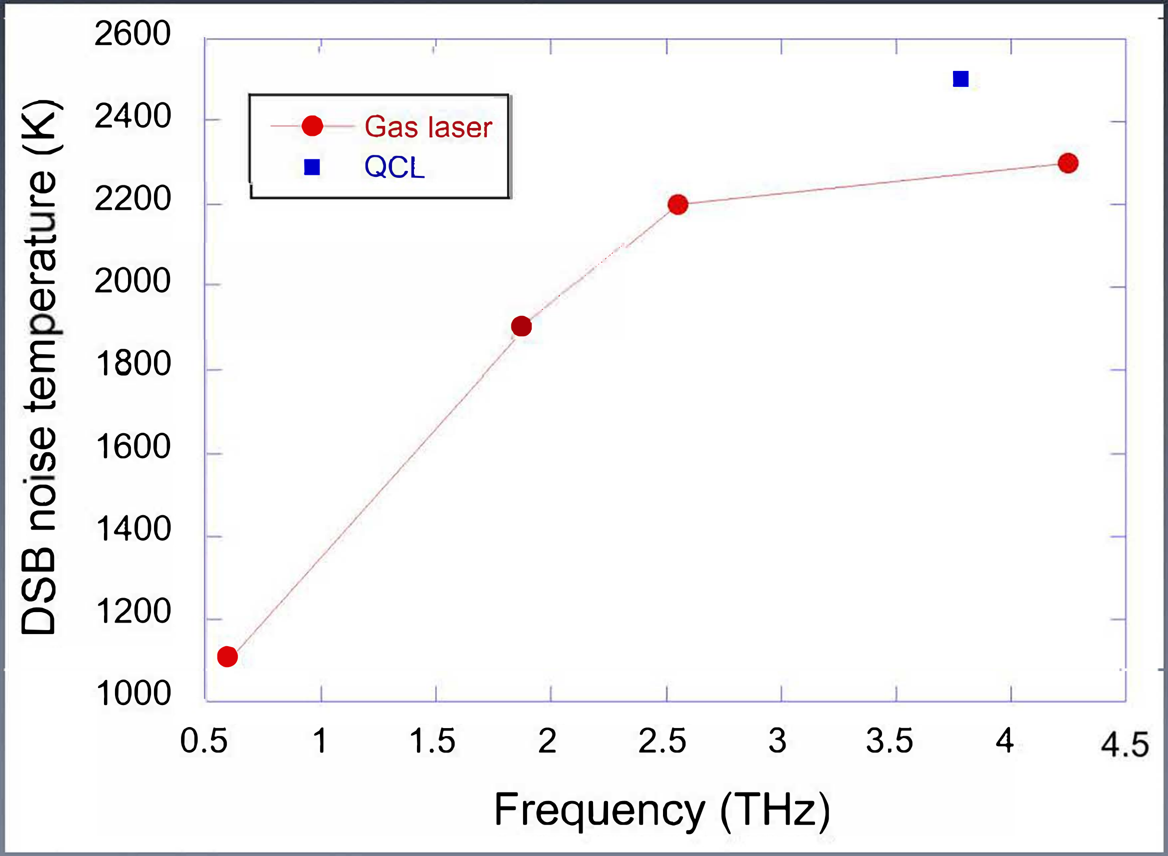




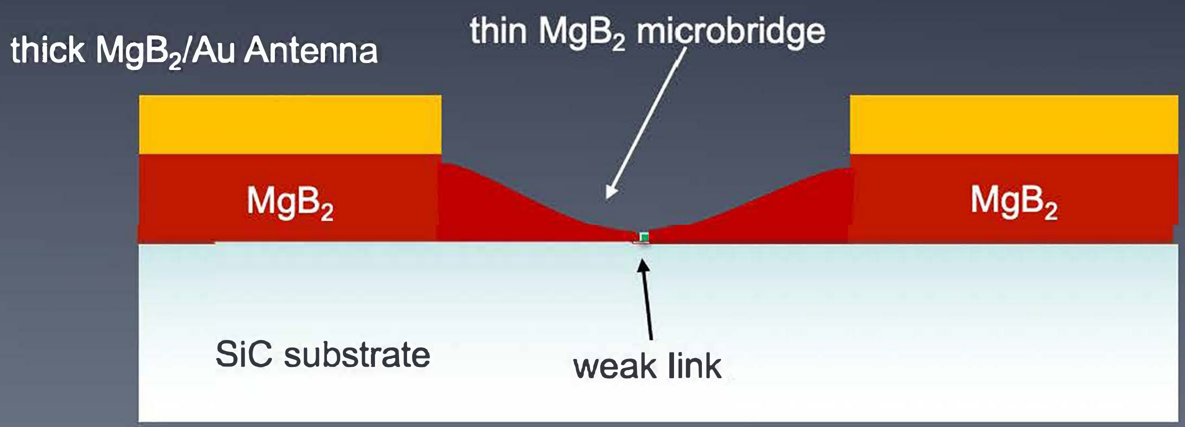
- No noise temperature degradation up to at least 15 K. Acceptable increase at 20 K.
- A 6.9 GHz noise bandwidth.

D. Cunnane et al., *IEEE TAS* **27**, 2300304 (2017)

Summary of the noise temperature data

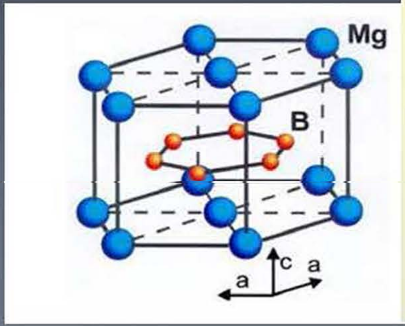


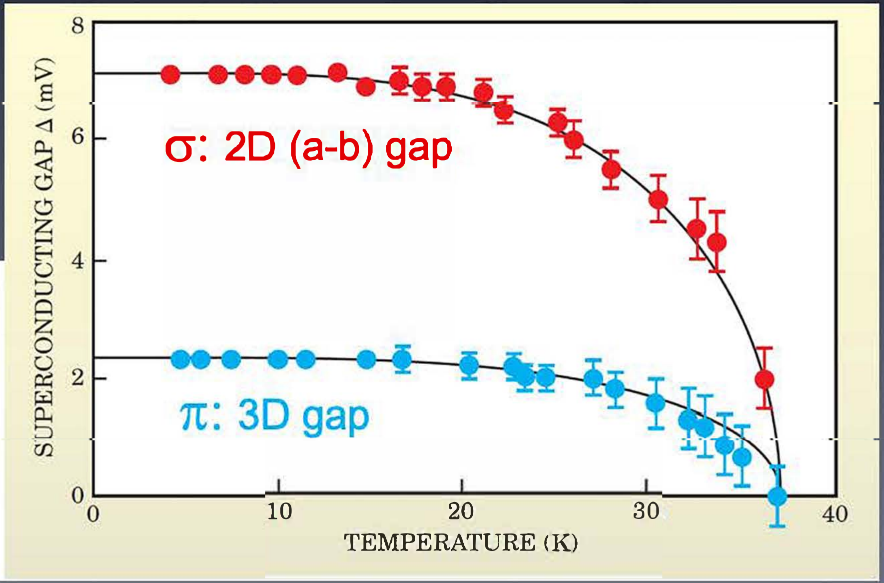
In-plane Josephson junction



- in-plane (a-b) WL junction is due to the overetch of the film during the ion mill process
- similar technique using Focused Ion Beam (FIB) was employed for fabrication of YBCO JJ Cybart et al., *NatNANO* **10**, 598 (2015)
- because of the strong c-axis orientation of the film, σ-gap contributes in Josephson tunneling

In-plane Josephson junction





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  Cybart et al., *NatNANO* **10**, 598 (2015)
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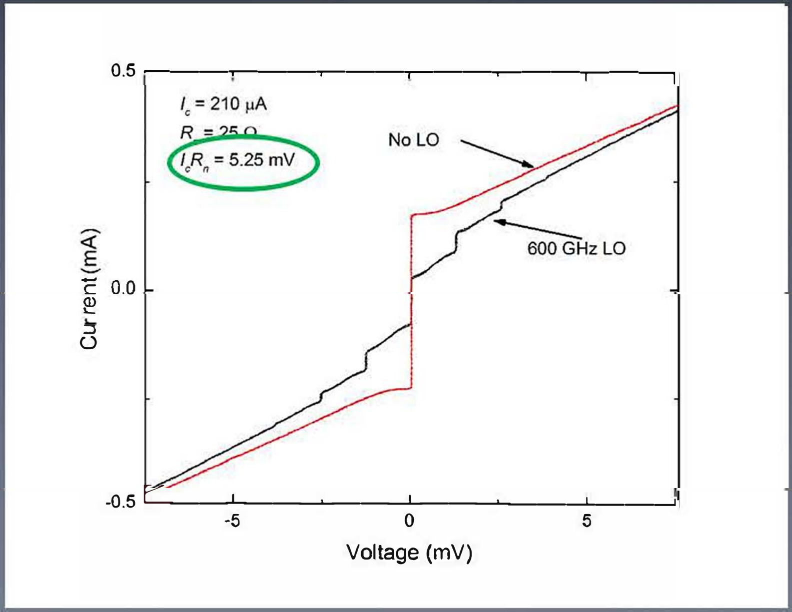
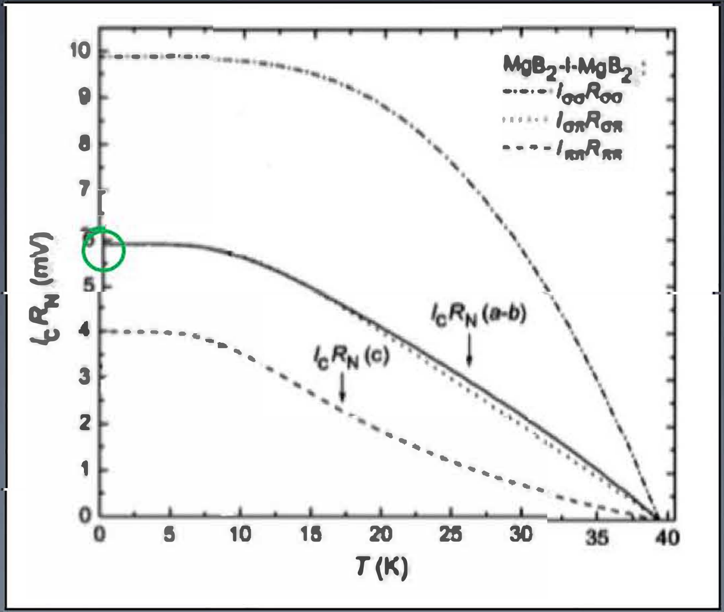
Josephson mixing at 600 GHz

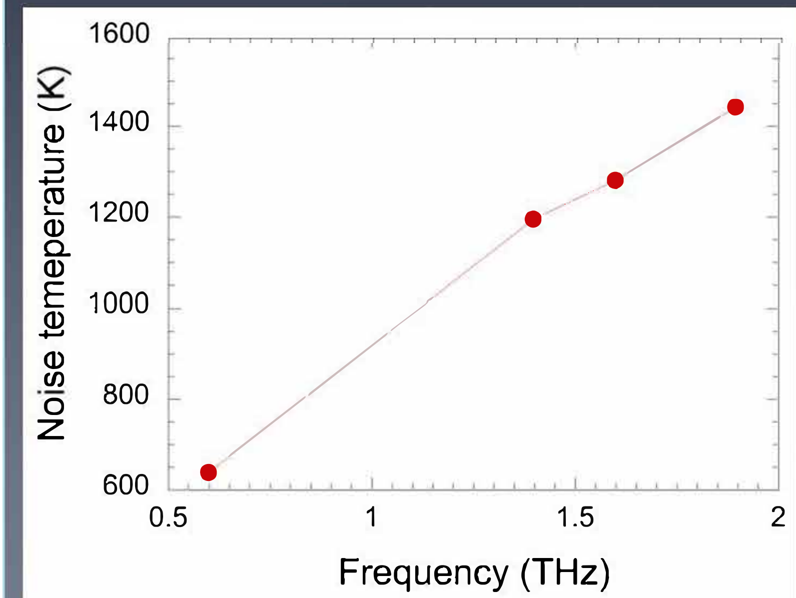


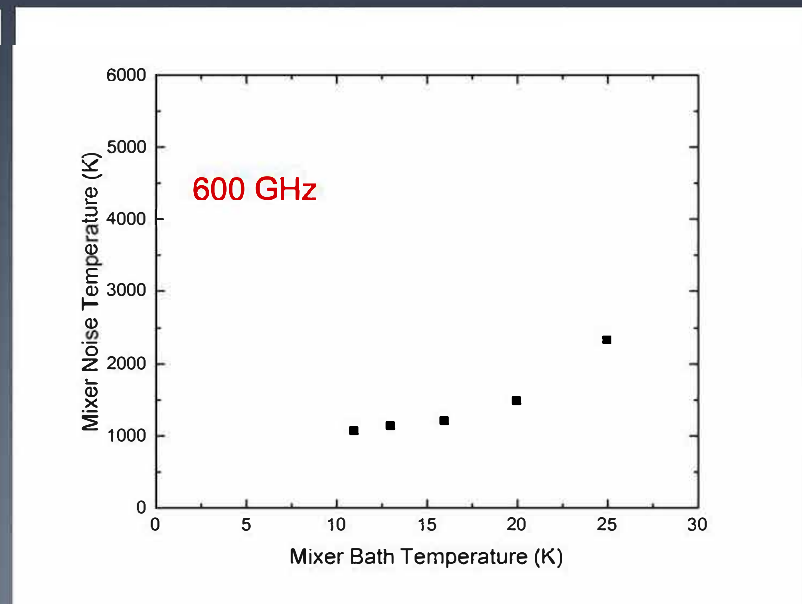


D. Cunnane et al., *Appl. Phys. Lett.* **109**, 112602 (2016) A. Brinkman et al., *Phys. Rev.* B **65**, 180517R (2002)

Shapiro steps at V = hν/2e

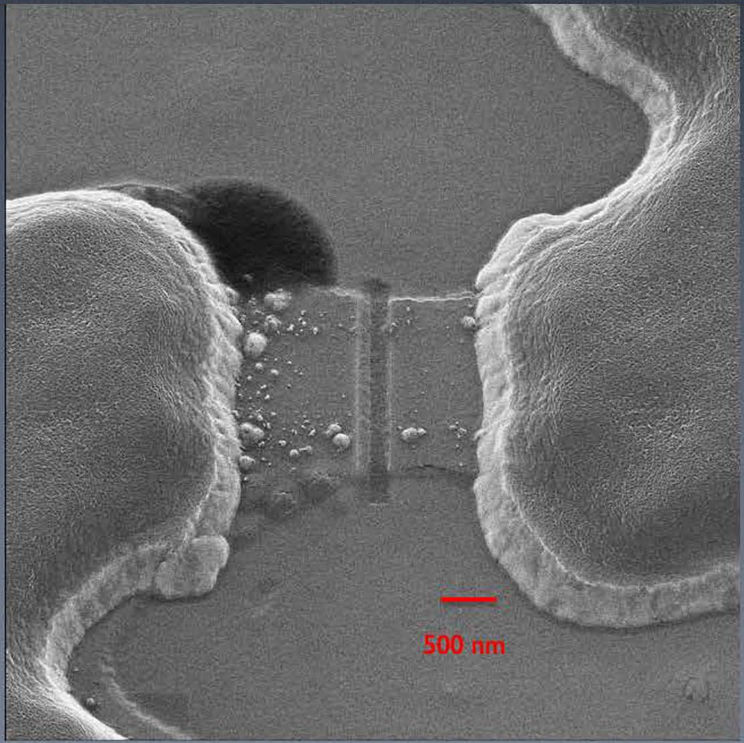
JJ mixer noise temperature

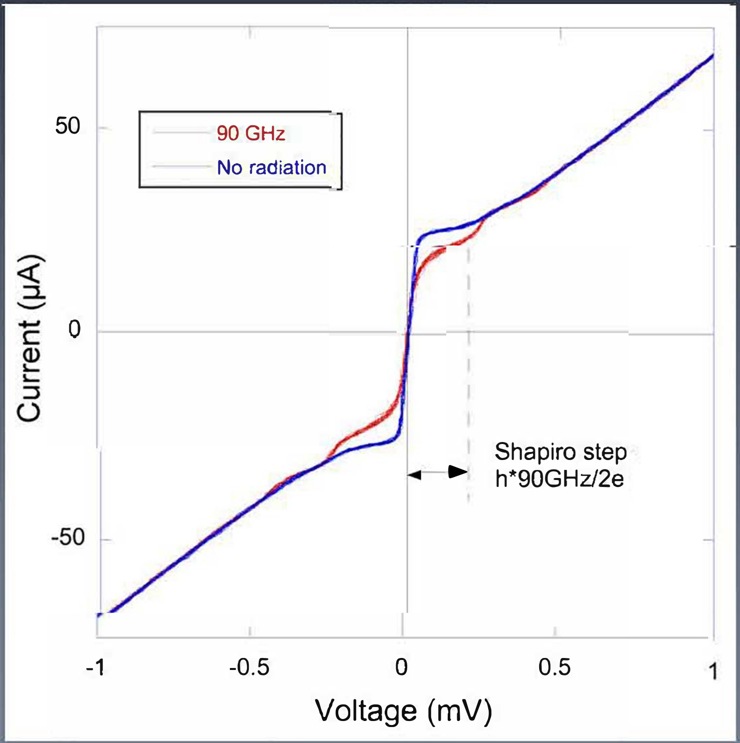




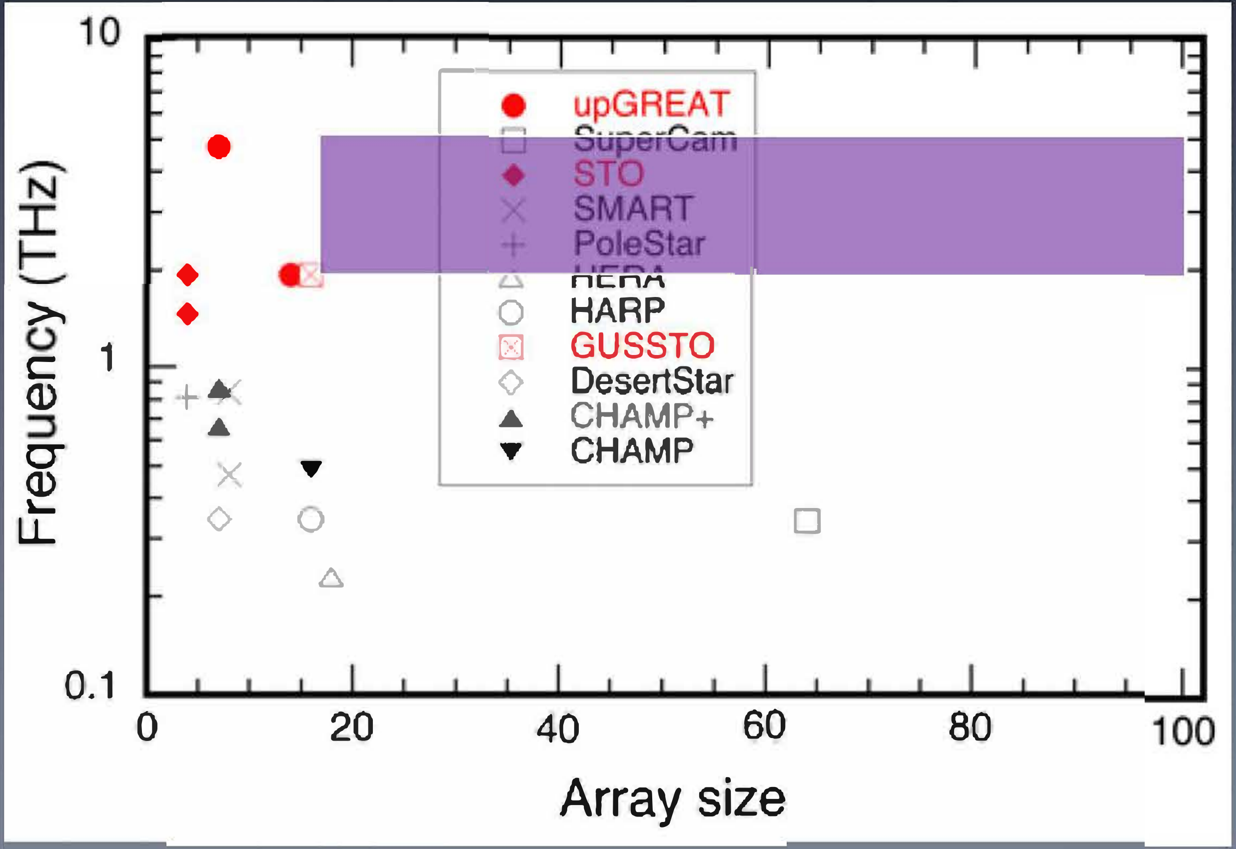
- NT ≈ 1,500 K has been measured at 1.9 THz
- focused development of this technology will likely improve NT

In-plane JJ using FIB technique



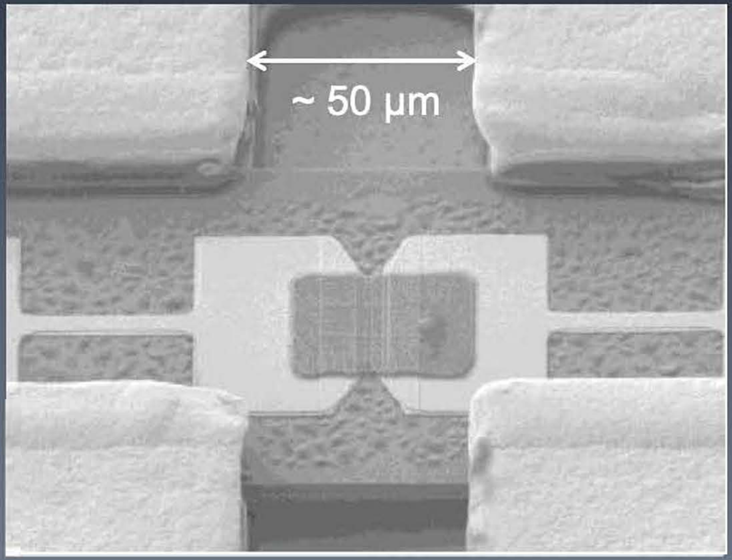


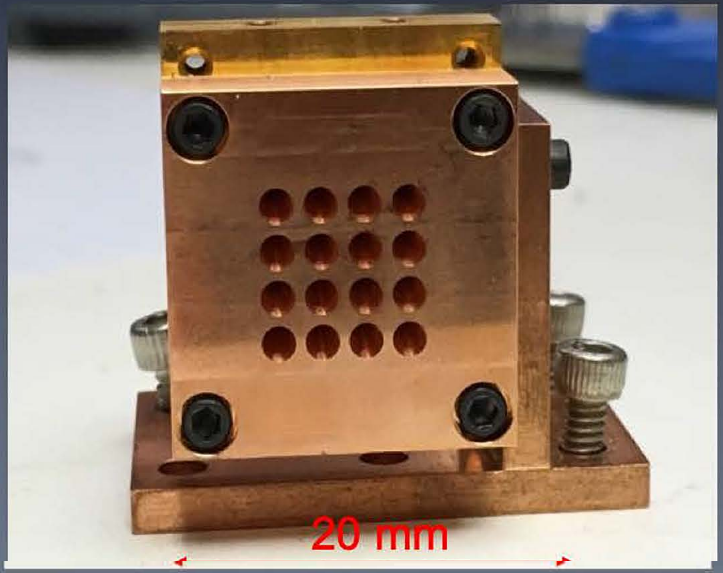
THz heterodyne arrays



Waveguide THz HEB mixers

2.7 THz / JPL



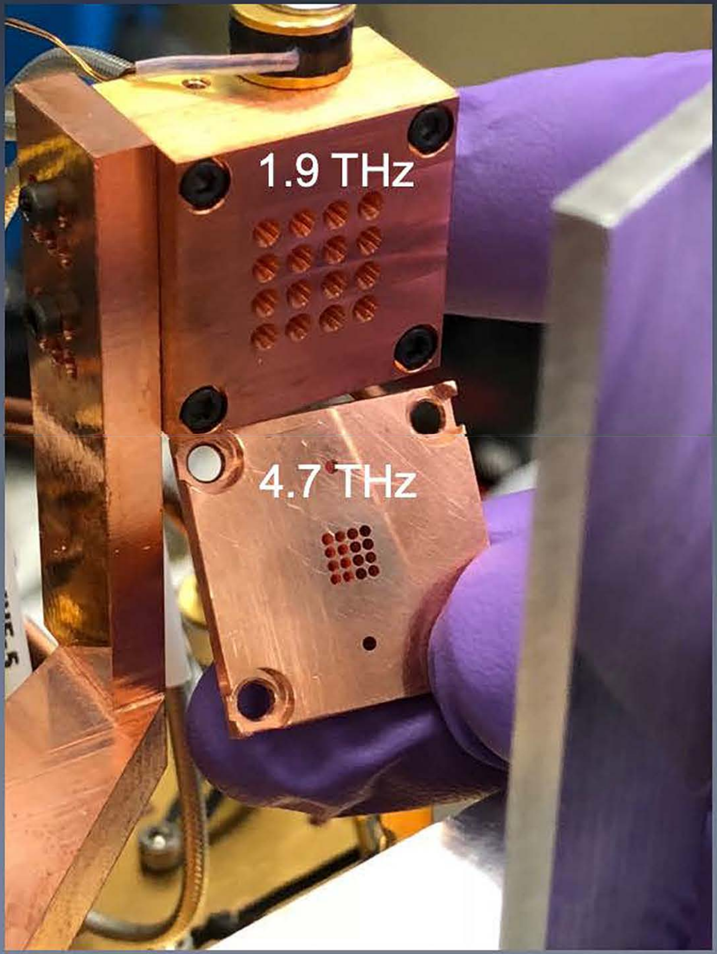


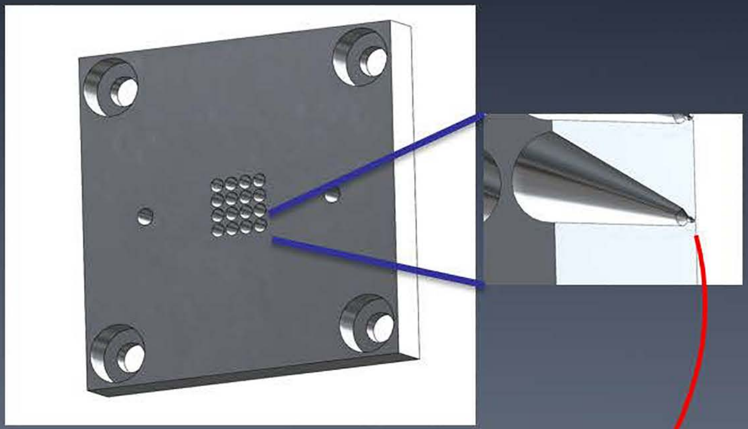
2.7 THz fixed-tuned HEB NbN mixer in a single-mode waveguide block. The mixer circuit is suspended with a ~ 2.3 µm thick Si substrate

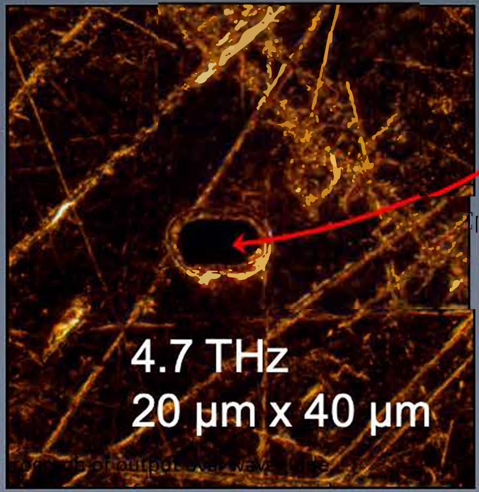
The JPL prototype 2 THz mixer has 16-pixels in a monolithic package with no practical limit to the number of pixels (the goal is 100 pixels)

F. Boussaha et al., *IEEE Trans. TST.* **2**, 284 (2012)

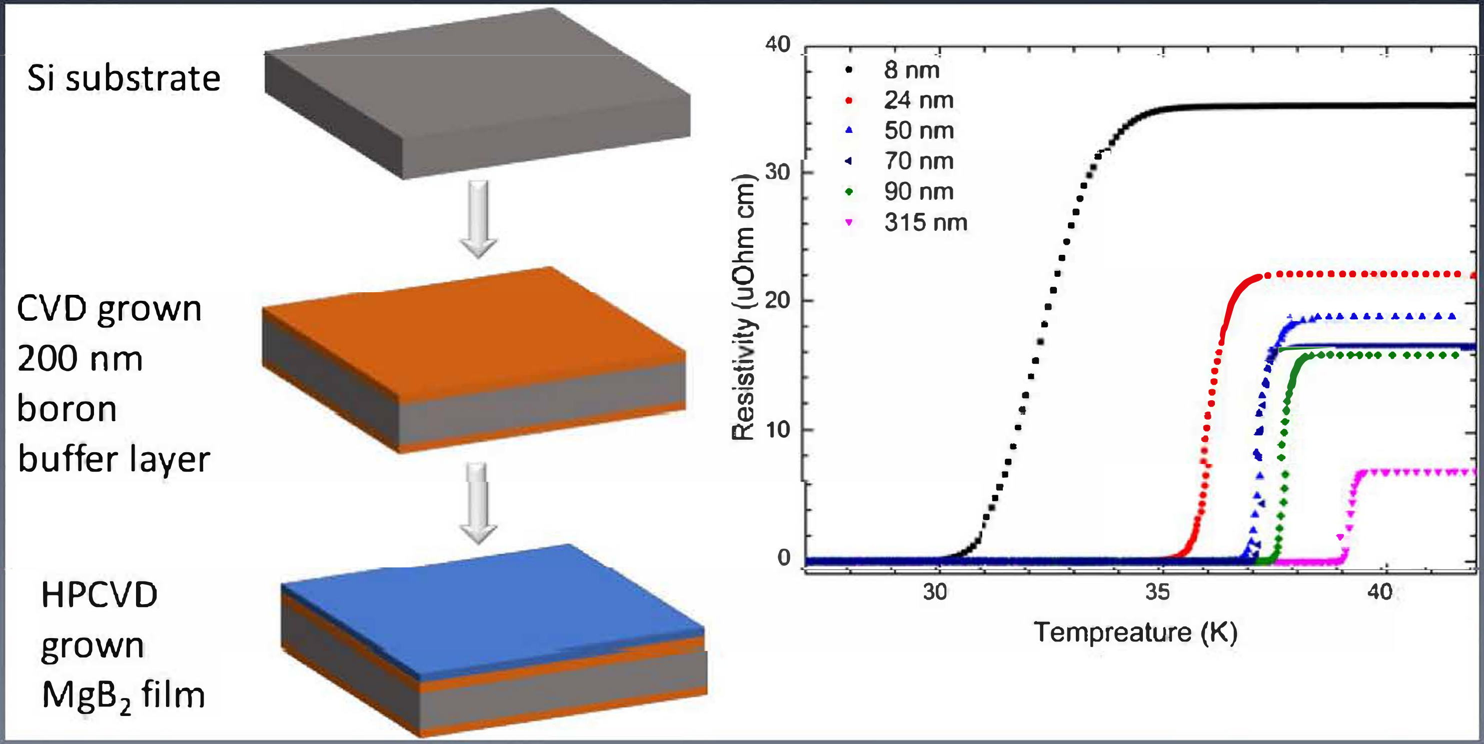
16-pixel horn-antenna block







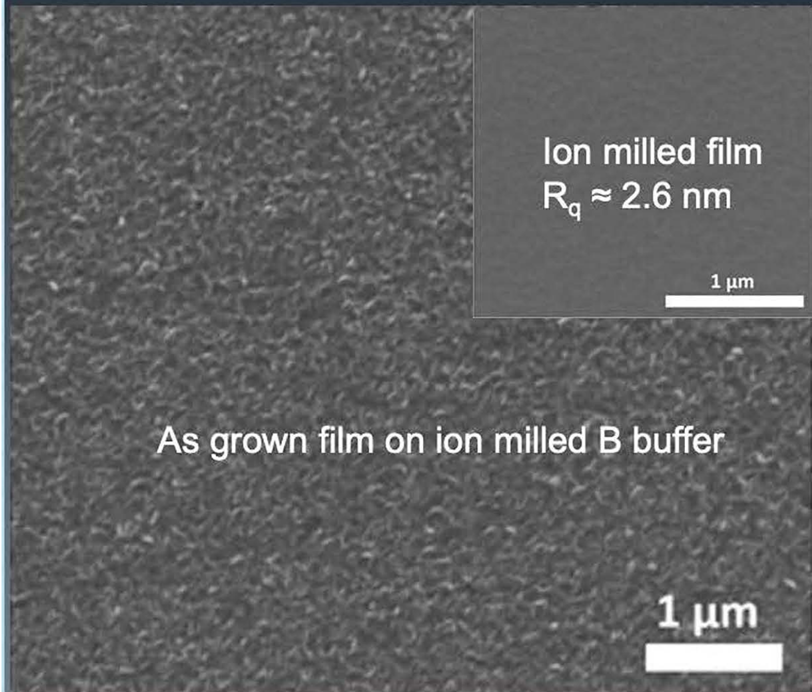
MgB_2 on Si

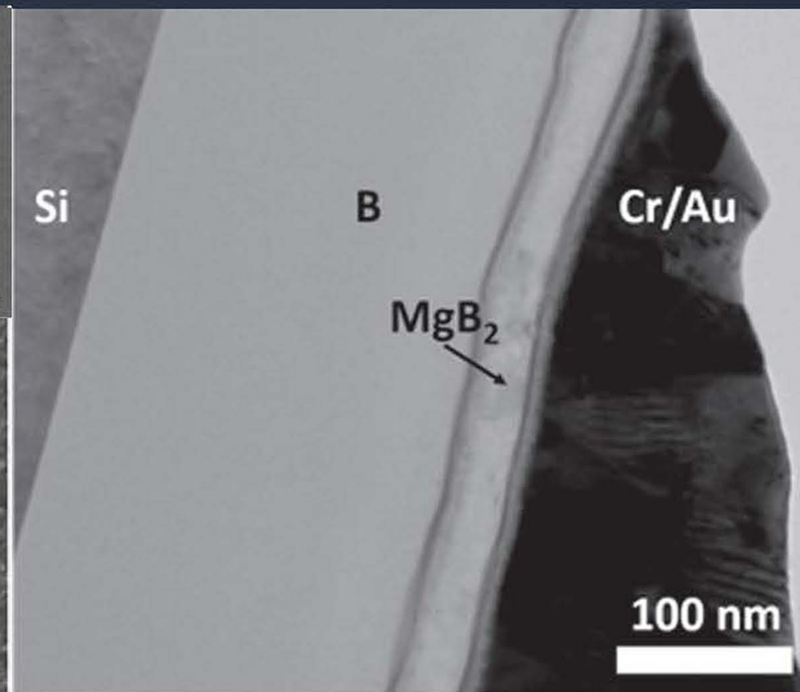


- Boron buffer layer protects Si against reaction with Mg at 700 C
- MgB_2 film on SOI wafer fabricated

W. Withanage et al., *SuST* **31**, 075009 (2018)

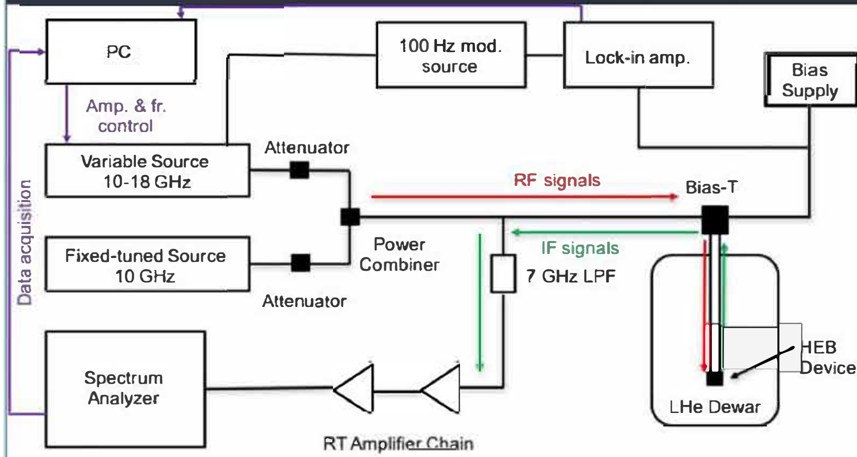
MgB_2 film on Si

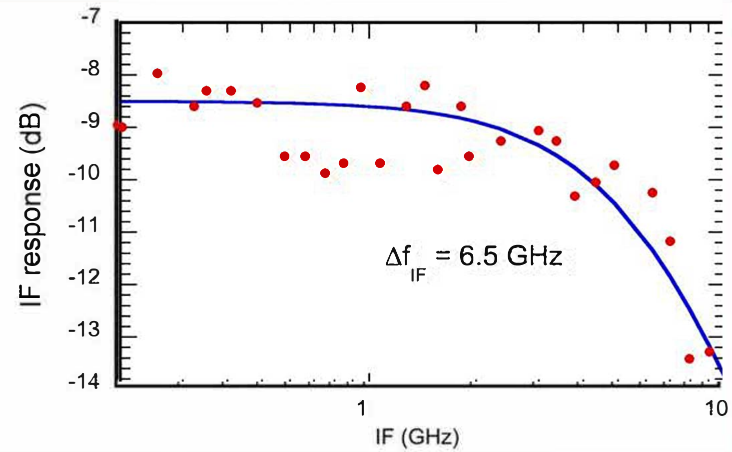




- Superconducting properties similar to those in films grown on SiC
- Clean interface between the film and the buffer

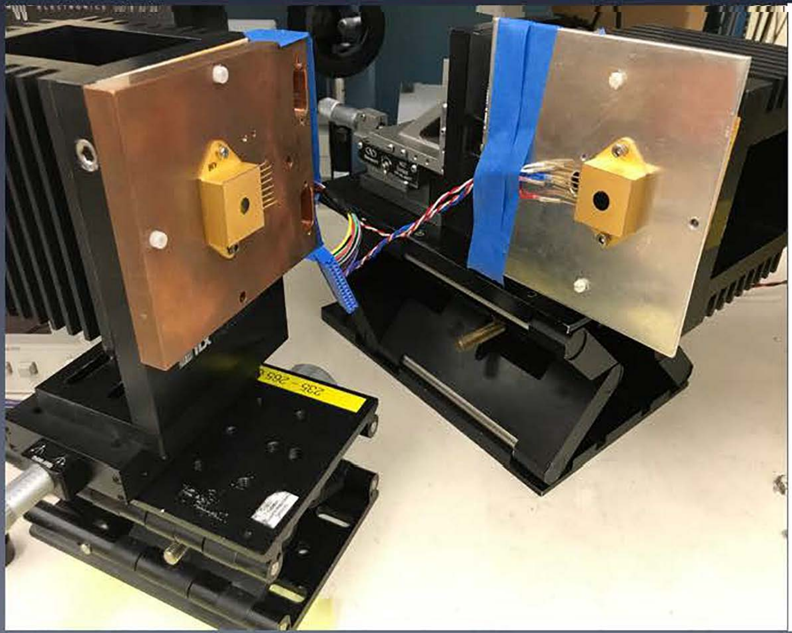
IF bandwidth in MgB_2 HEB on SOI

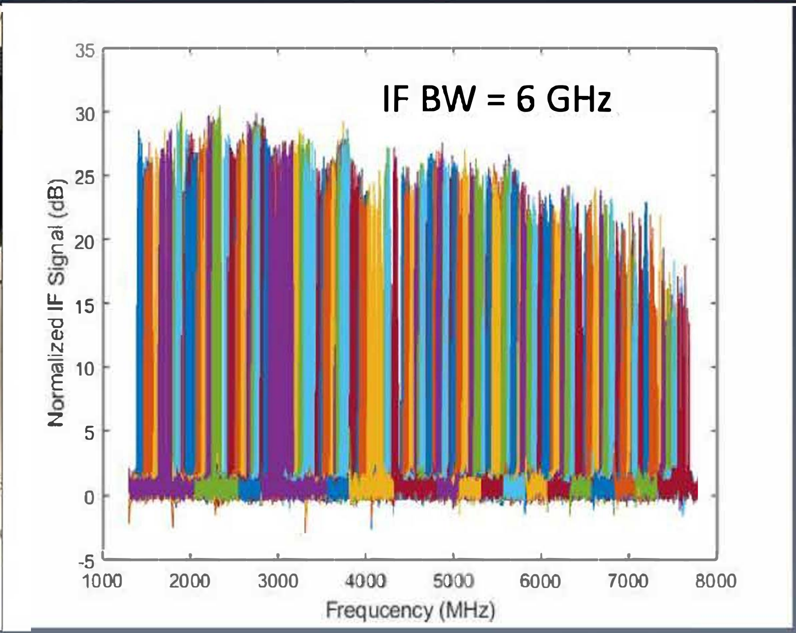




- Measurements of the bandwidth using two low-power microwave sources
- The device is biased just below TC to ensure a temperature sensitive, continuous IV characteristic
- The IF bandwidth figure is similar to that for SiC substrate

10-μm mixing using MgB_2 HEB





- SOA mid-IR heterodyne detectors (e.g., HgCdTe photo-diode) have a typical IF bandwidth ~ 1 GHz
- Applications in frequency-comb spectrometers, interferometers, and lidars require detectors with larger bandwidth, up to 10 GHz
- The IF bandwidth in HEB is a thermal property and does not depends on the radiation frequency
- Given the high power LO available at 10 μm, one can use large HEB devices cavity-coupled to radiation

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Summary

- Ultrathin MgB_2 films (HPCVD deposition + ion mill) are available for THz detector development
- QO HEB mixers made from these films demonstrate good noise performance up to 20 K throughout the entire THz range
- A noise bandwidth of about 7 GHz has been achieved in HEB mixers
- J mixer is a promising approach to the mixers at 1.9 THz requiring low LO power (needed for arrays)
- Ultrathin MgB_2 films on Si have been developed for achieving the waveguide based array mixer
- There is a potential for expansion of MgB_2 HEB mixers into the mid-IR range where large IF bandwidth is required for a number of applications

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