High-Sensitivity Superconducting Mixers and Detectors for THz Astronomy

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Purple Mountain Observatory, CAS
Key Lab of Radio Astronomy, CAS

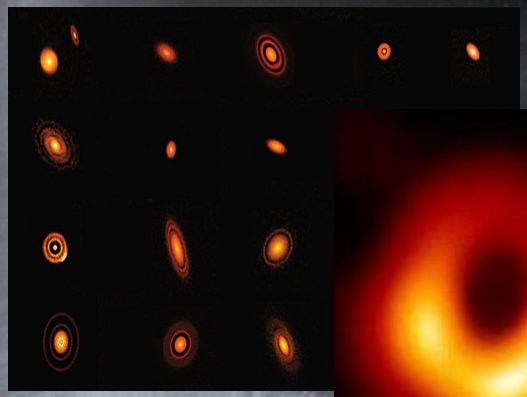
Background image credit: NRAO

Outline

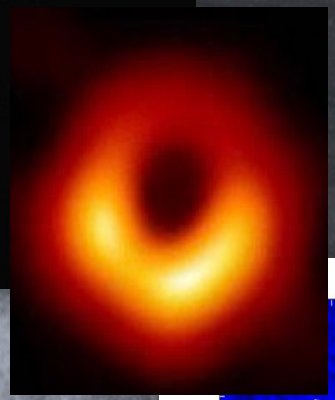
- Introduction
- Fabrication & measurement of CFRP panel & a scaled antenna
- Development of superconducting heterodyne receivers & detectors
- Summary

Background image credit: NRAO

Superconducting Mixers & Detectors for Mm/Submm/THz Astronomy

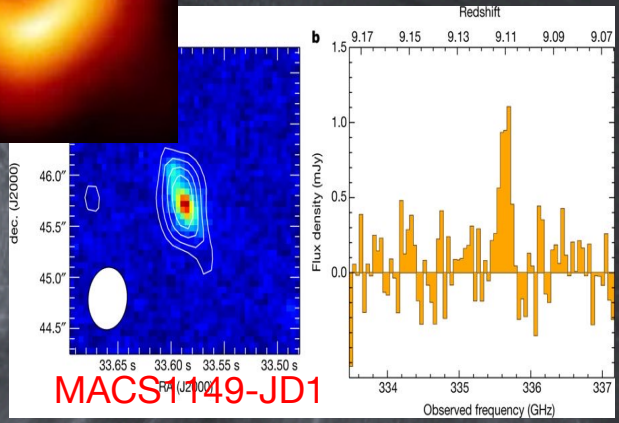


Proto planetary disks



Black hole taken by EHT

OIII @ z=9.11



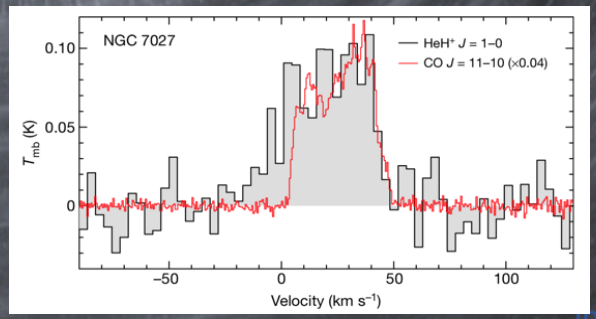
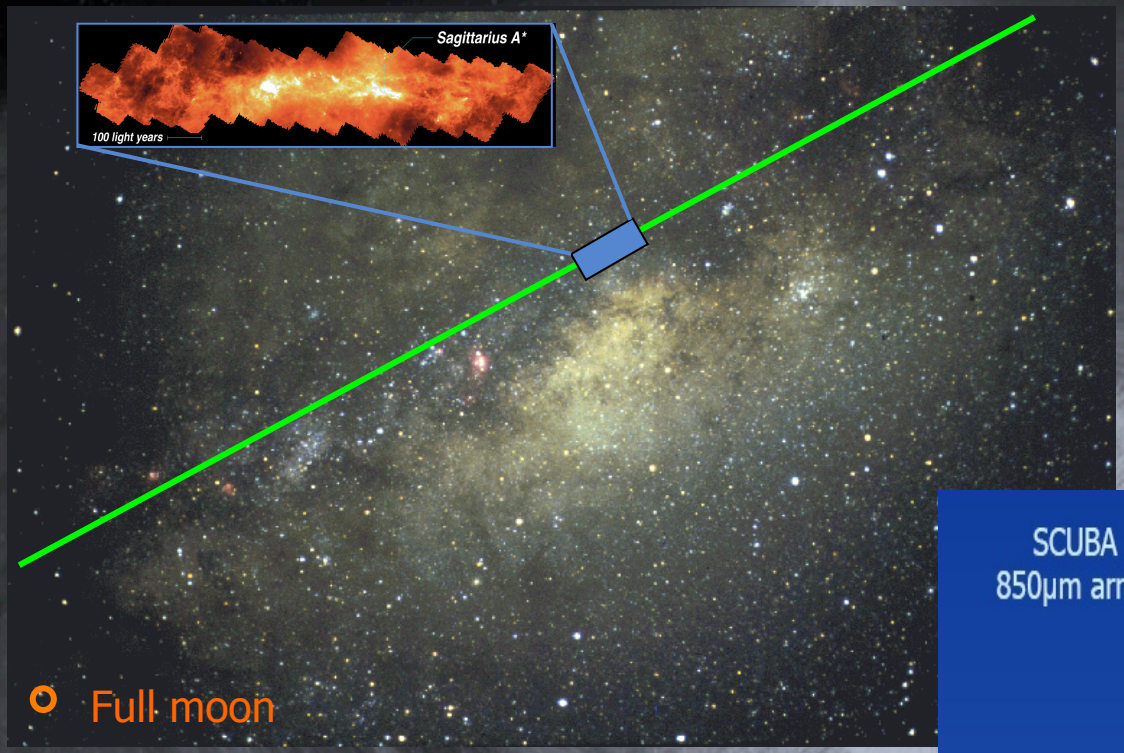


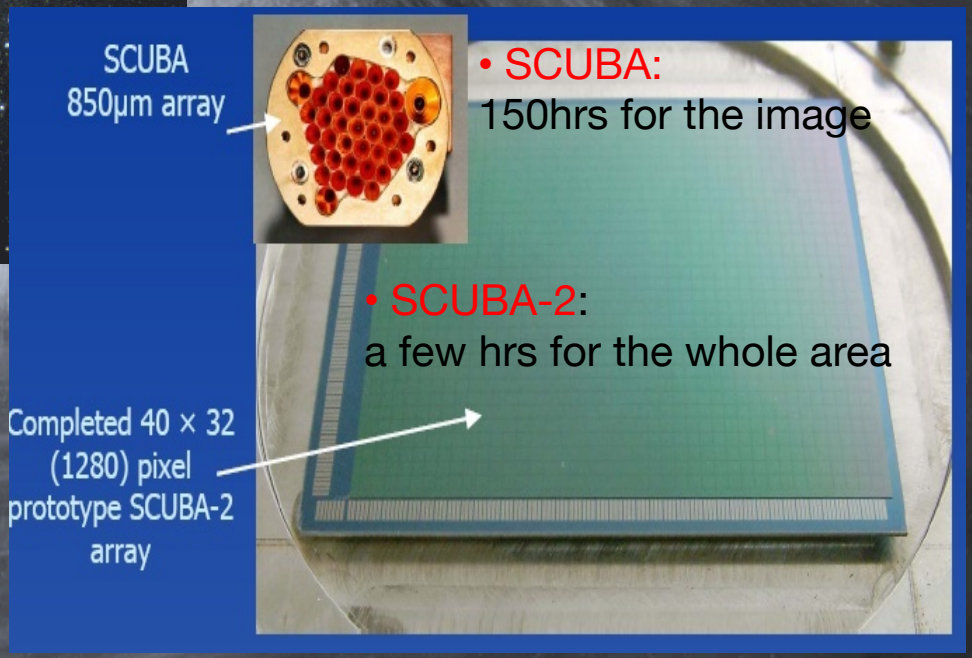
Image credit: ALMA/SOFIA

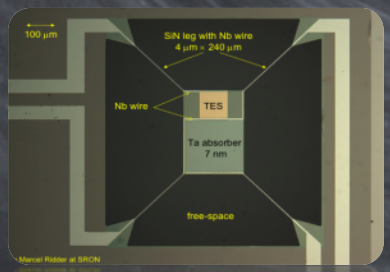
Superconducting Mixers & Detectors for Mm/Submm/THz Astronomy



JCMT observation toward Sagittarius A*

Large format camera & 3D broadband imaging spectrometer





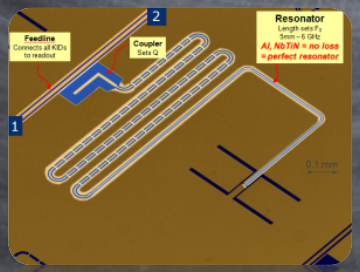
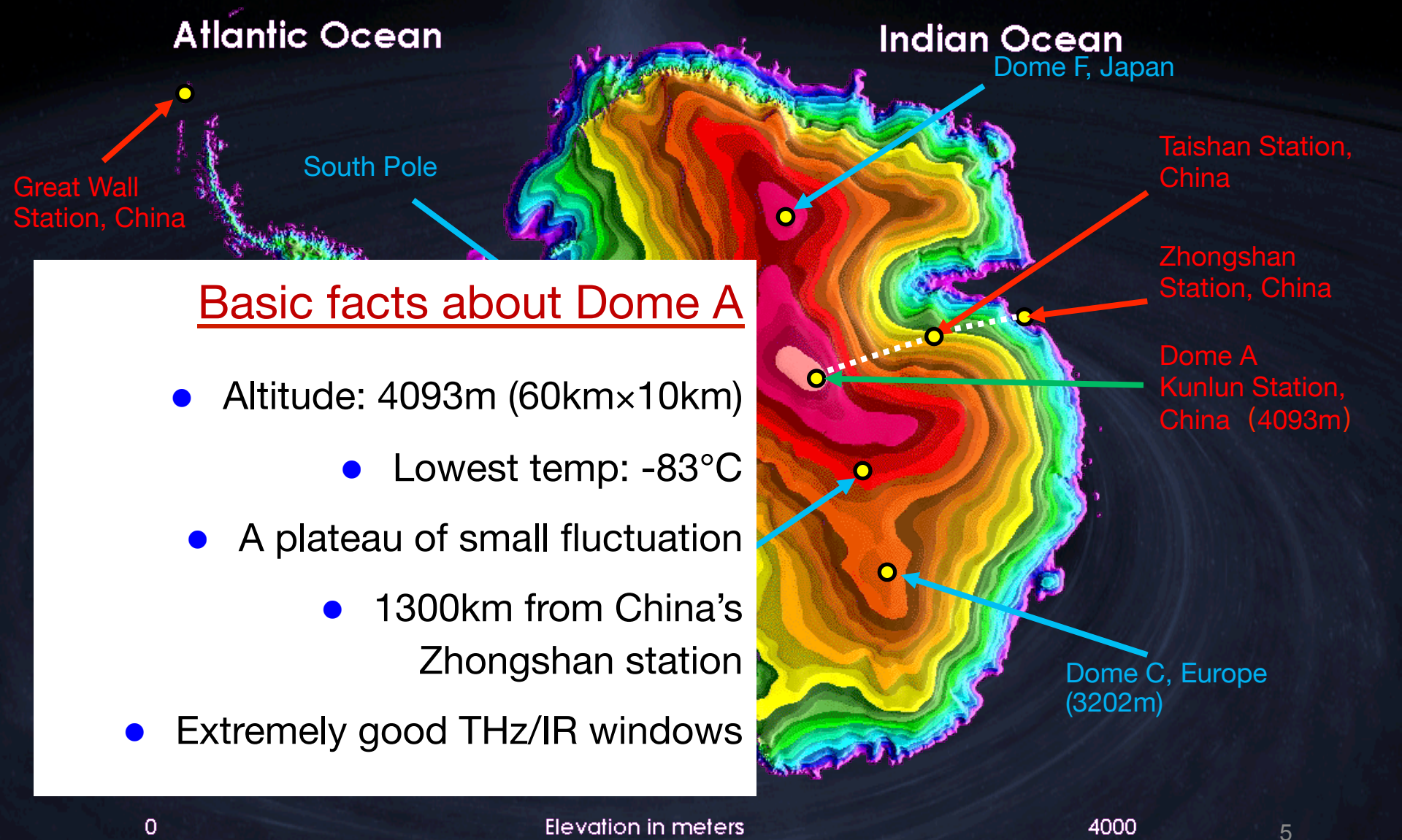


Image credit: JCMT/SRON/TuDelft

Dome A in Antarctic



Basic facts about Dome A

- Altitude: 4093m (60km×10km)
- Lowest temp: -83°C
- A plateau of small fluctuation
- 1300km from China's Zhongshan station
- Extremely good THz/IR windows

Road to Dome A in Antarctic

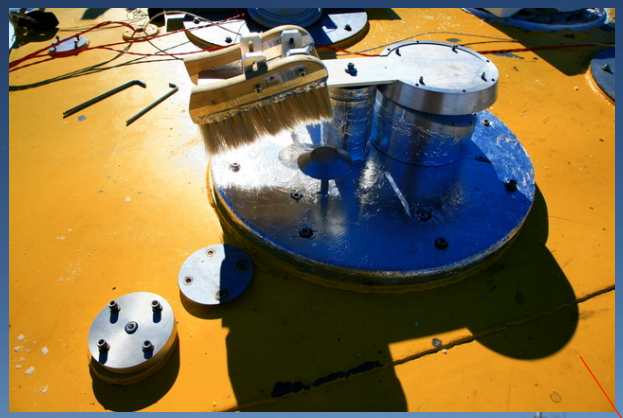
Chinese Antarctic Observatory at KunLun Station

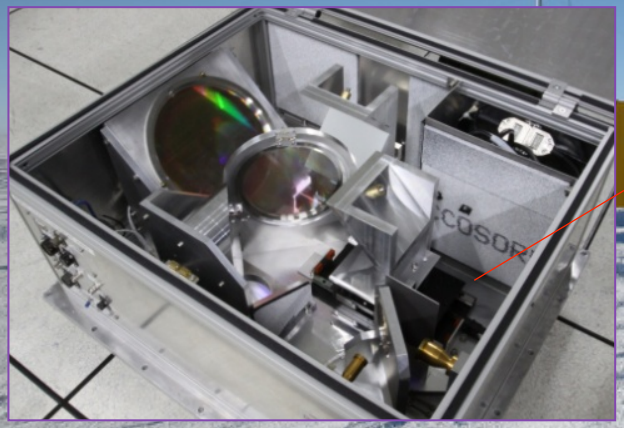
Timeline & Status

- 2005/1/9, arriving at Dome A (21th CHINARE)
- 2008/1, starting the site survey at Dome A
- 2009/1/27, constructing the Kun-Lun station (25th CHINARE)
- 2013/2, govermental announcement of 16 selected mega-science proposals for 2012-2030, including Chinese Antarctic Observatory
- 2013/7, CAS proposal for Chinese Antarctic Observatory
- 2016/11/9, negotiation between CAS and SOA, with PI switched to SOA
- 2017/8, SOA proposal for Chinese Antarctic Observatory
- 2019/3~, proposal revising & re-submission by MONR

Terahertz and far-infrared windows opened at Dome a in Antarctica

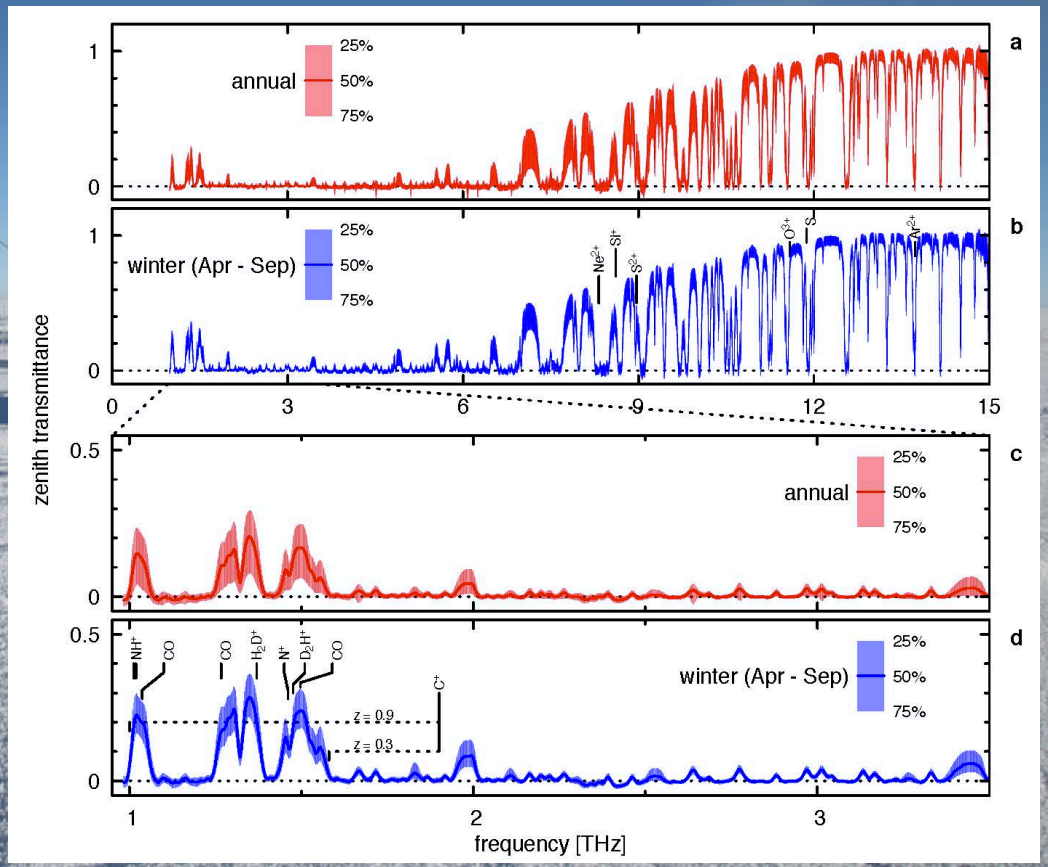
Sheng-Cai SHI et al., Nature Astronomy 1, 0001 (2016)





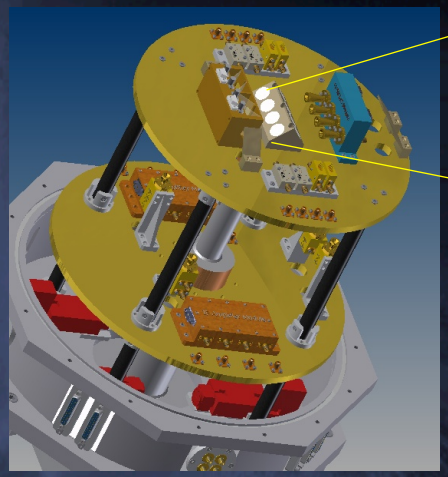
Unmanned Dome A FTS deployed to Dome A

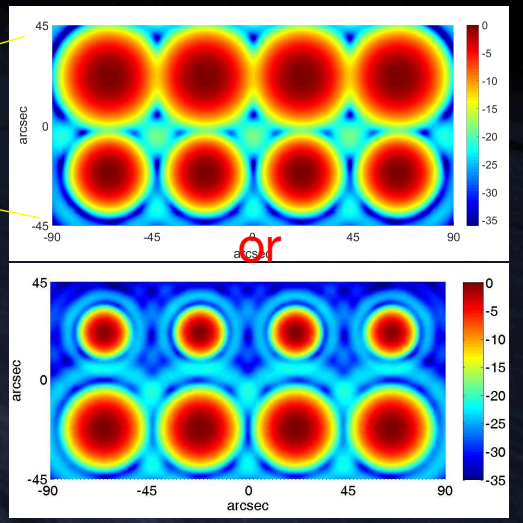
In collaboration with CfA/ UNSW/NAOJ/NAOC/…



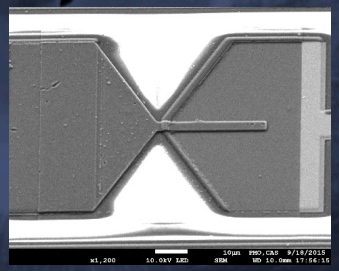
Measured THz/FIR transmission at Dome A in Antarctic

DATE5 Telescope & Instruments

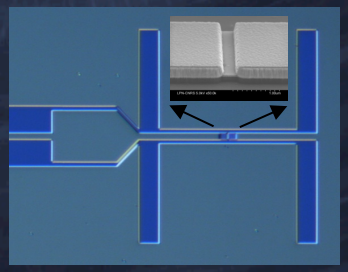




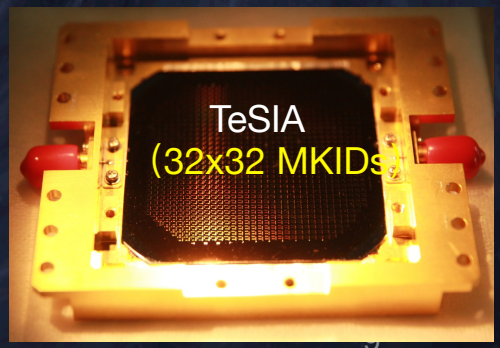
Antenna	Cassegrain
Diameter	5m, with rms accuracy <10μm
Band	450/350/200μm
Rx/Camera	1x4 SIS & 1x4 HEB mixer/TeSIA
IF BW	4GHz x 4 beams x 2 bands
FOV	5′×5′ (200μm)
Pointing	≤2"



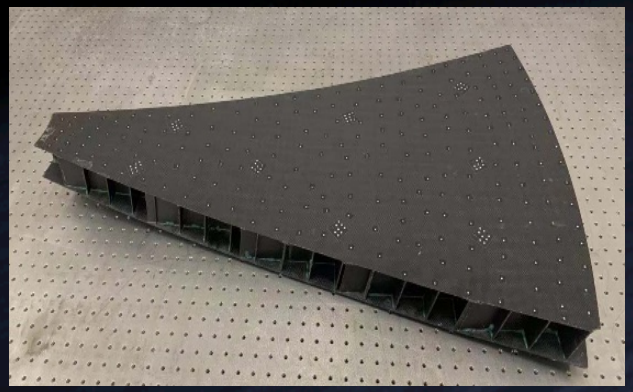
0.66/0.85 THz SIS



1.4THz HEB

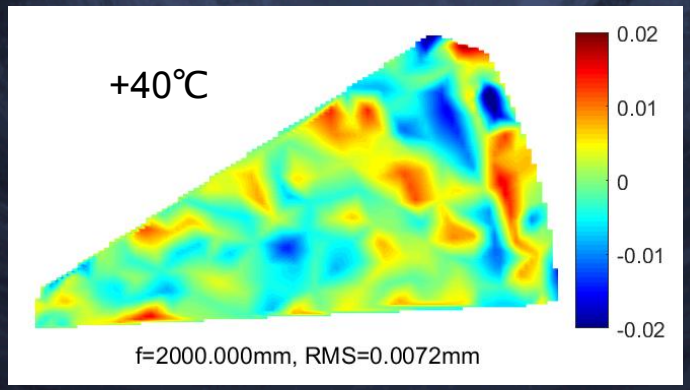


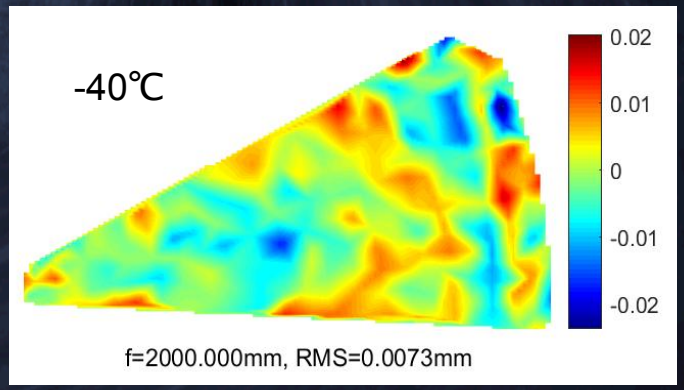
Fabrication & Measurement of CFRP Panel



A new sandwiched prototype CFRP panel with lattice core

- Size:1m×0.6m
- Surface Density :15kg/m^2
- Auto-heating for anti-icing



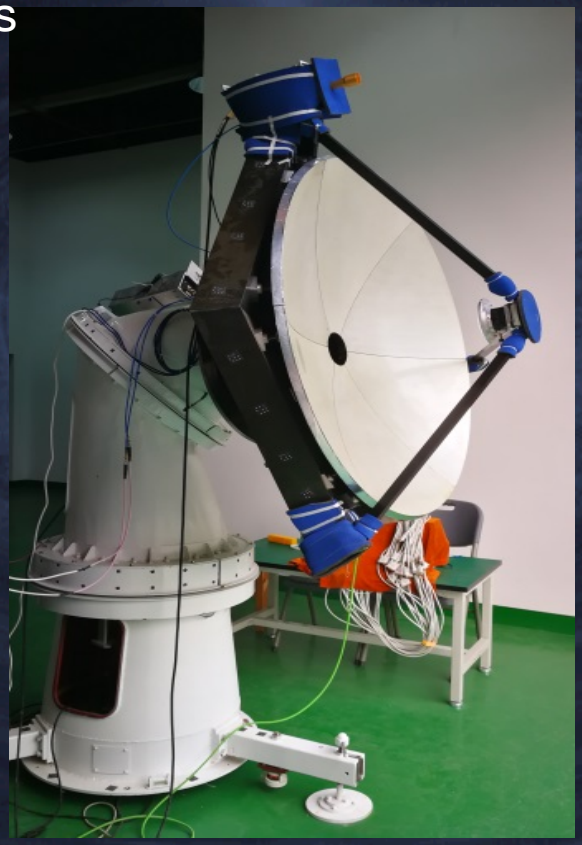


Surface accuracy measurement of prototype panel at ambient temperature of 40 degrees and -40 degrees

A Scaled Antenna for DATE5

Major Specifications

- Aperture: 1.2m (CFRP Reflector)
- Surface: 20μm rms
- Pointing: 3 arcmin rms
- Tracking: 2 arcmi rms



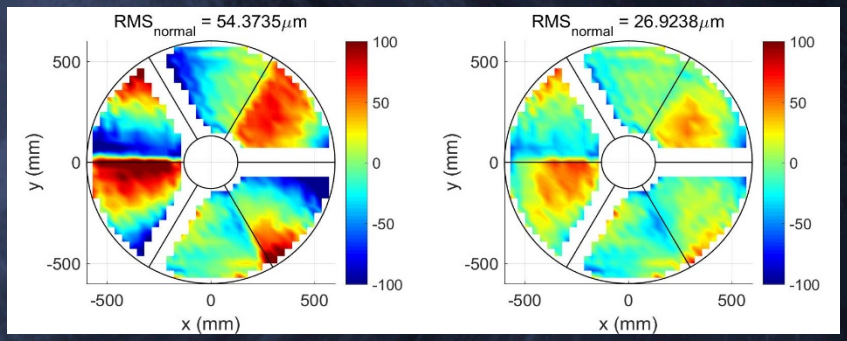
Demonstrations on

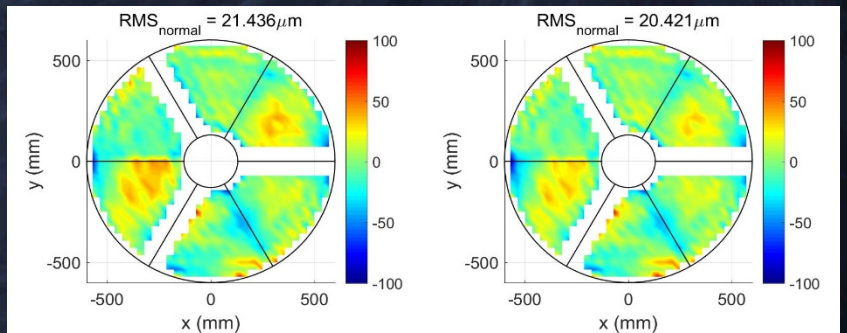
- Holography
- Thermal control
- Slant-axis mount

Near-field Holography Measurements

- **Near-field measurements on the scaled antenna**
  - Primary-focus mode
  - Cassegrain-focus mode

- **Correction for various error sources**
  - Rotation-center displacement
  - Beam self-rotation of the slant-axis
  - Polarization mismatch
  - Diffraction of the subreflector



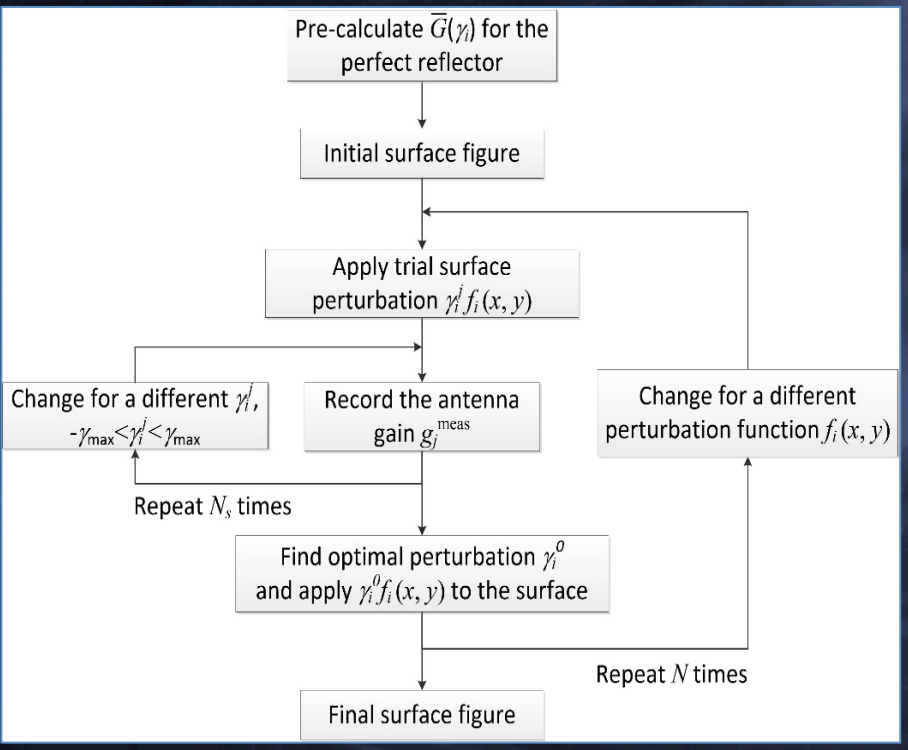


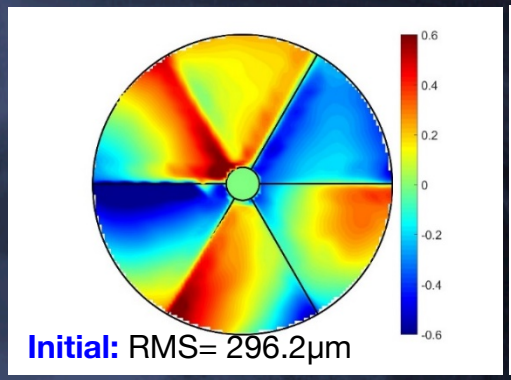
Surface error after consecutive settings

→ 20 μm

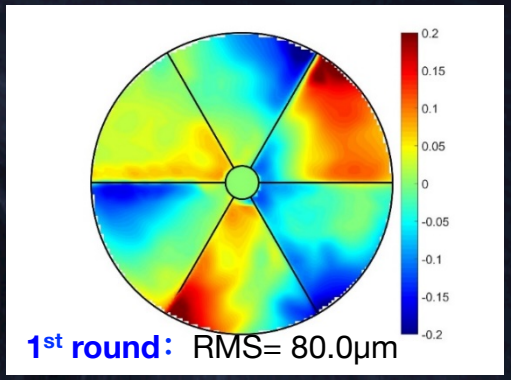
Surface Alignment Based on Antenna Gain Measurements

- Proposed a new alignment technique based on antenna gain measurement
- Tested on the scaled antenna, achieved accuracy of λ/100 @ 3mm
- Potential application on DATE5 and other telescopes

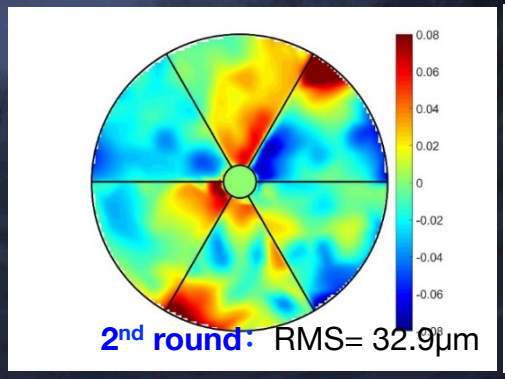




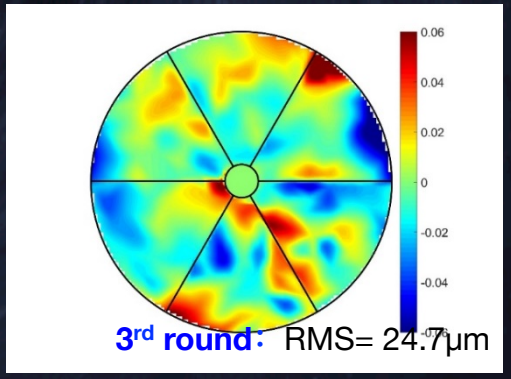
Initial: RMS= 296.2μm



1st round: RMS= 80.0μm



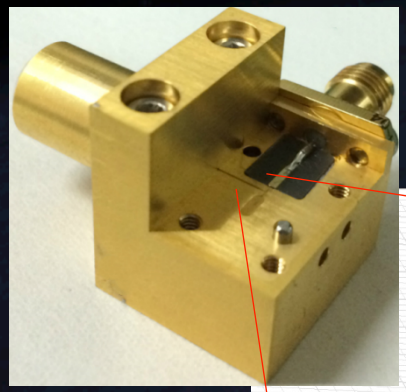
2nd round: RMS= 32.9μm



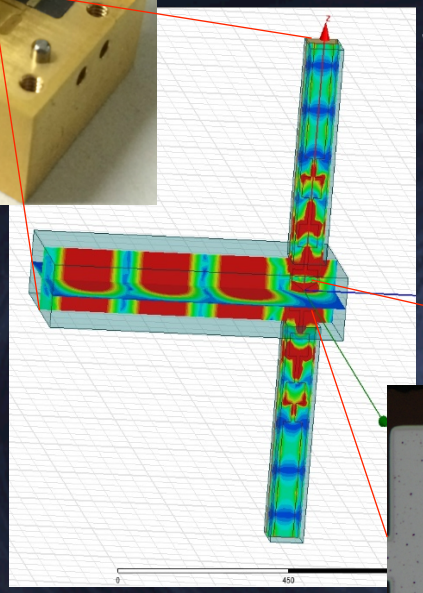
3rd round: RMS= 24.7μm

Z. Lou et al., JATIS 5(2), 2019

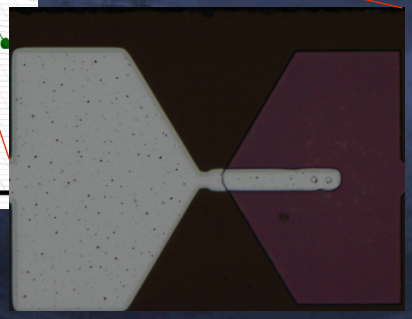
A 0.85-THz Waveguide SIS Mixer



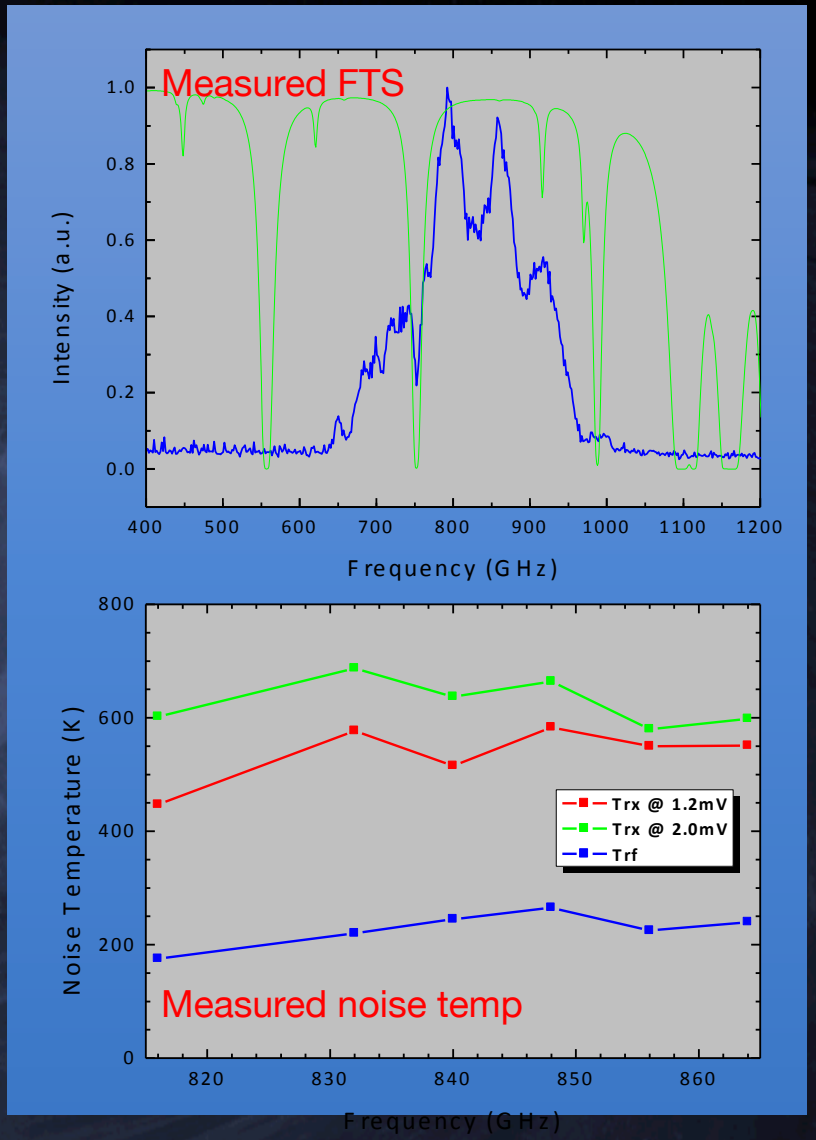
0.85-THz SIS mixer



Simulated E-field

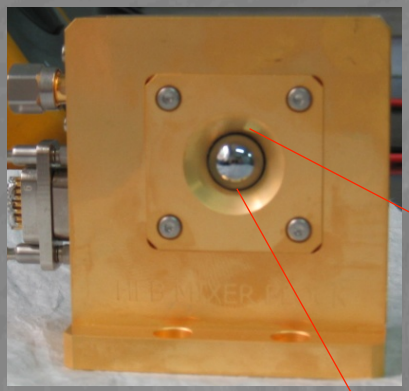


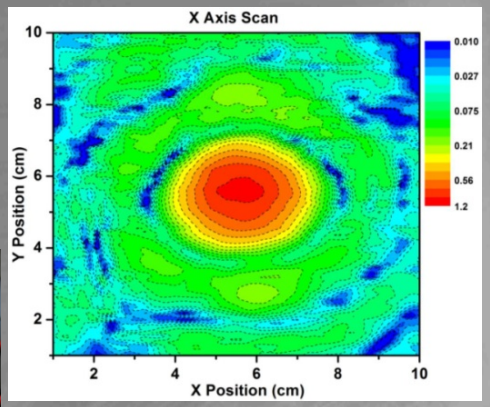
PCTJ w/ Nb/AlN/NbN

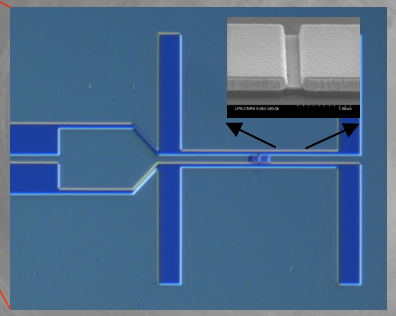


In collaboration with IREE, Russia

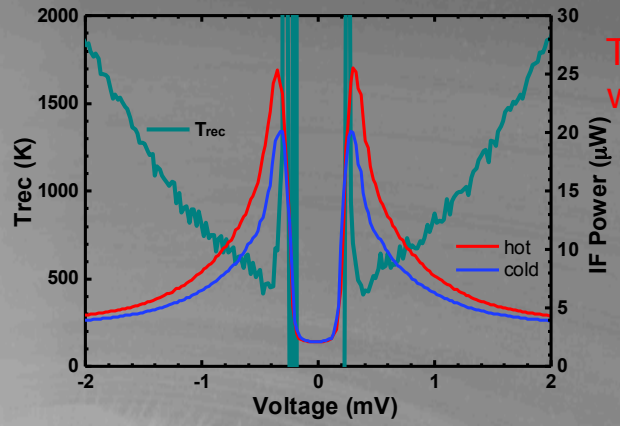
A 1.4-THz Quasi-optical HEB Mixer



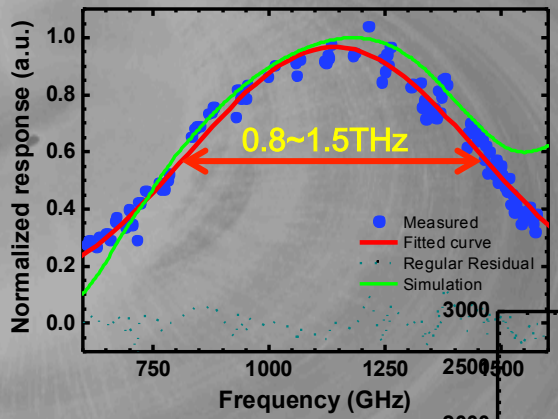




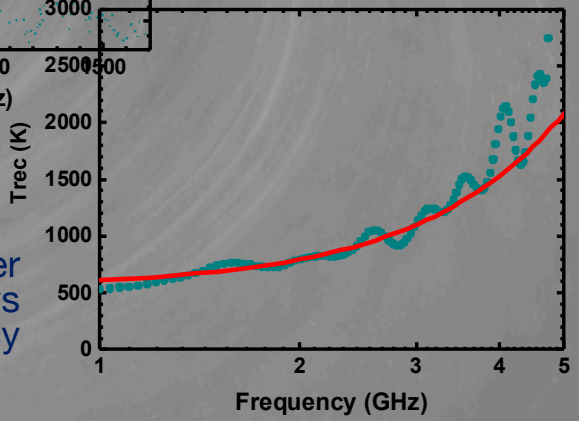
1.4THz superconducting HEB mixer
for DATE5



Trx=450K @ 1.3THz
w/ coated lens



Measured &
simulated frequency
response



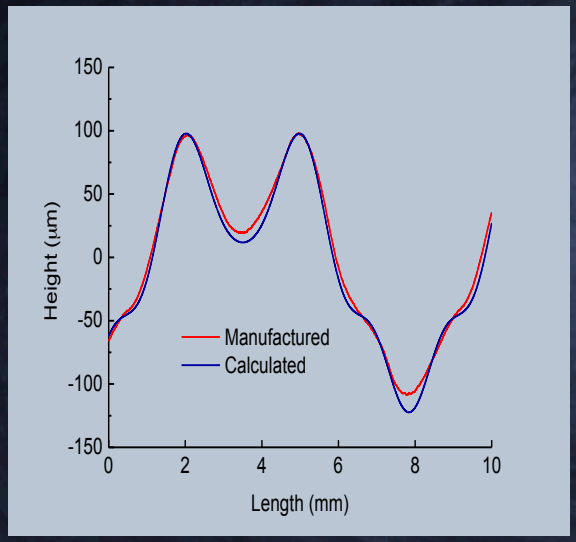
Measured receiver
noise temperature vs
IF frequency

In collaboration with LERMA, France

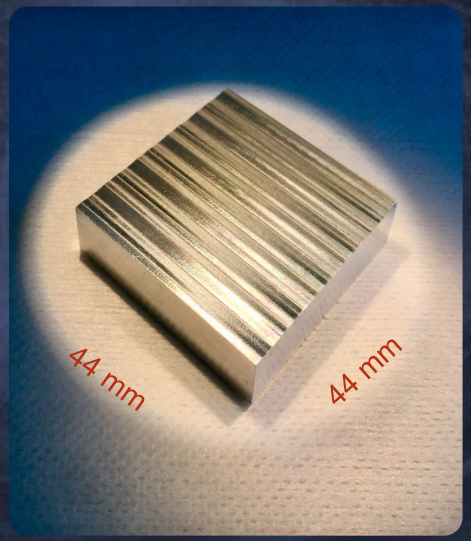
THz Fourier Phase Grating

- Frequency： 450 μm
- 1x4 beams
- Unit size: 9.33 mm
- 5 x 5 units
- Fourier series: 5

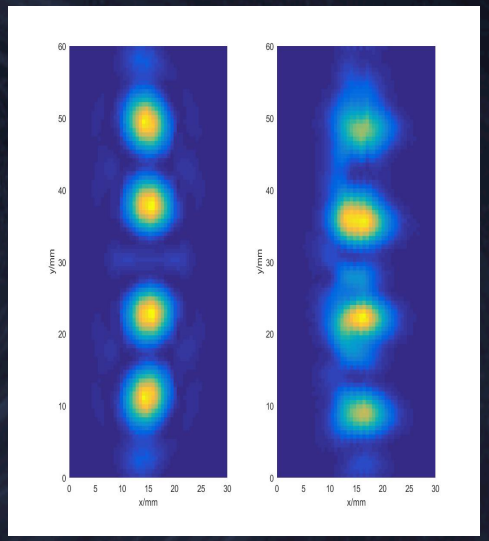
$$\Delta\phi(x)=\sum_{n=1}^{N} a_n \cos\left(n2\pi x/D\right)$$



Design



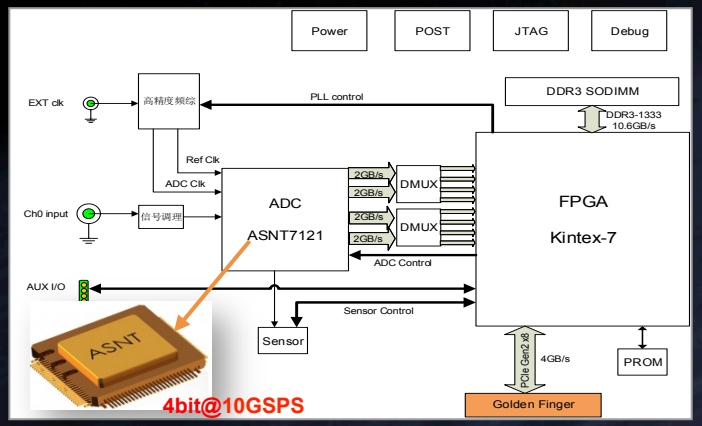
Manufactured FPG

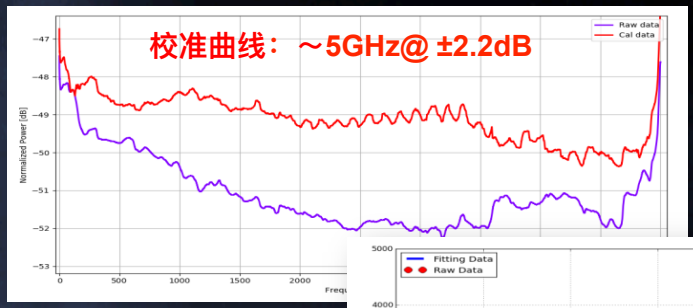


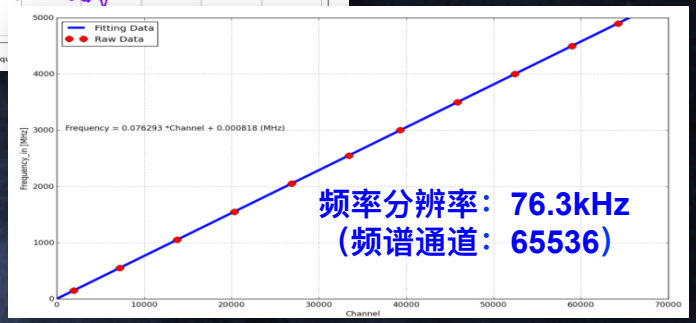
Simulation & Measurements

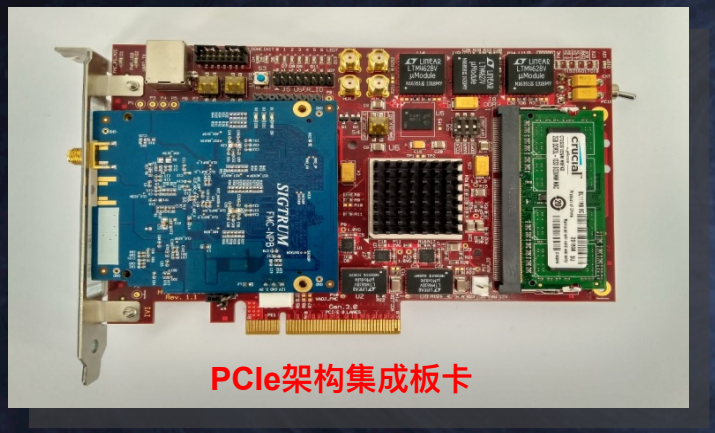
Fourier Phase Grating for H450 of DATE5, with efficiency > 84%

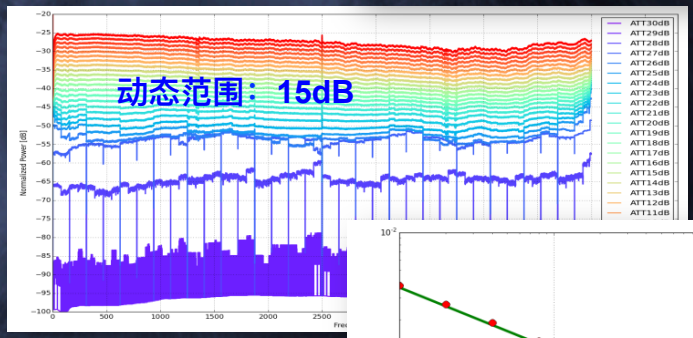
A 5-GHz Bandwidth FFTS

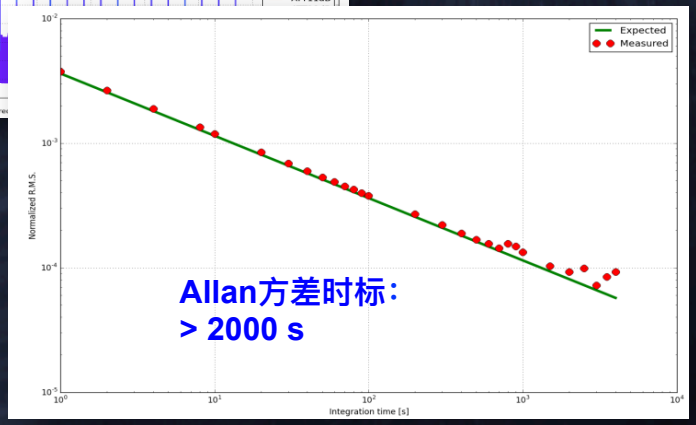


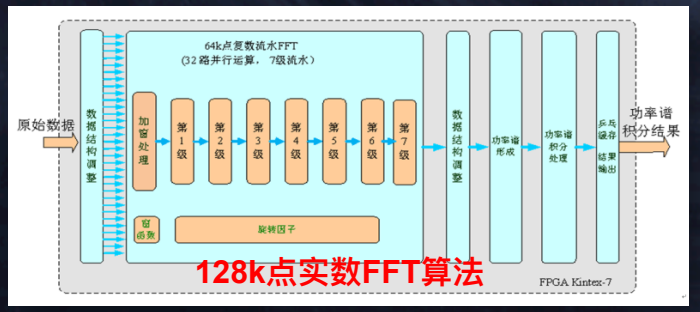






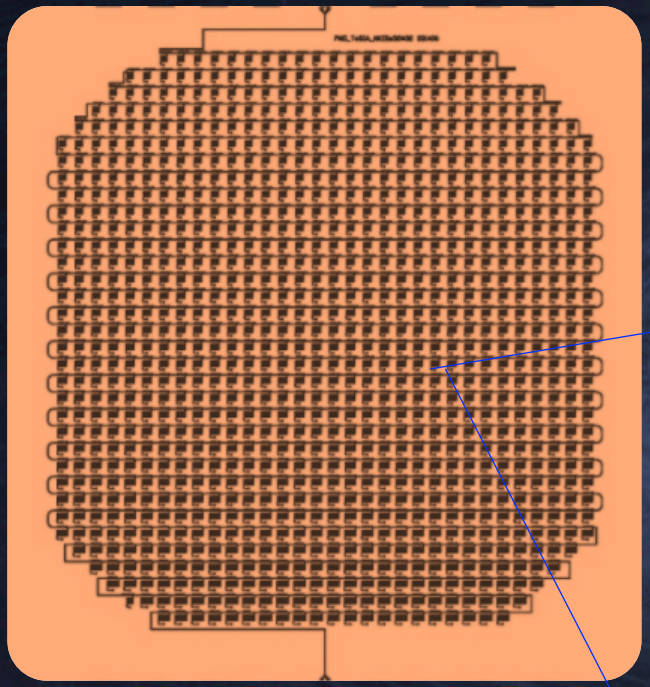




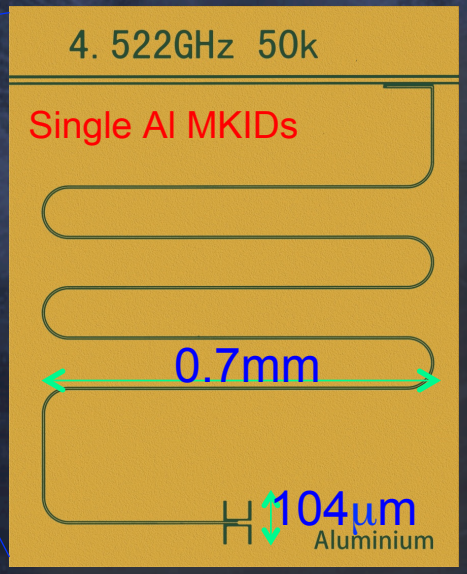


A 350μm/0.85THz 32x32 Al MKIDs Array

Detector	Al/TiN MKIDs
Format	32x32
Band	350 μm/850 GHz
NEP	$1x10^{-16}$ W/$Hz^{0.5}$



1024 Al MKIDs on 3” Si Wafer

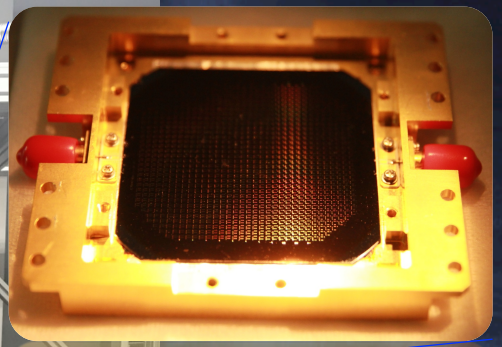


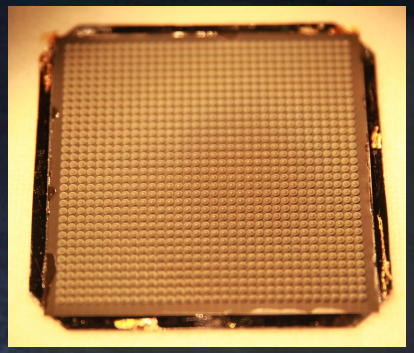
- Twin-slot antenna coupled
- CPW read-through line & resonators

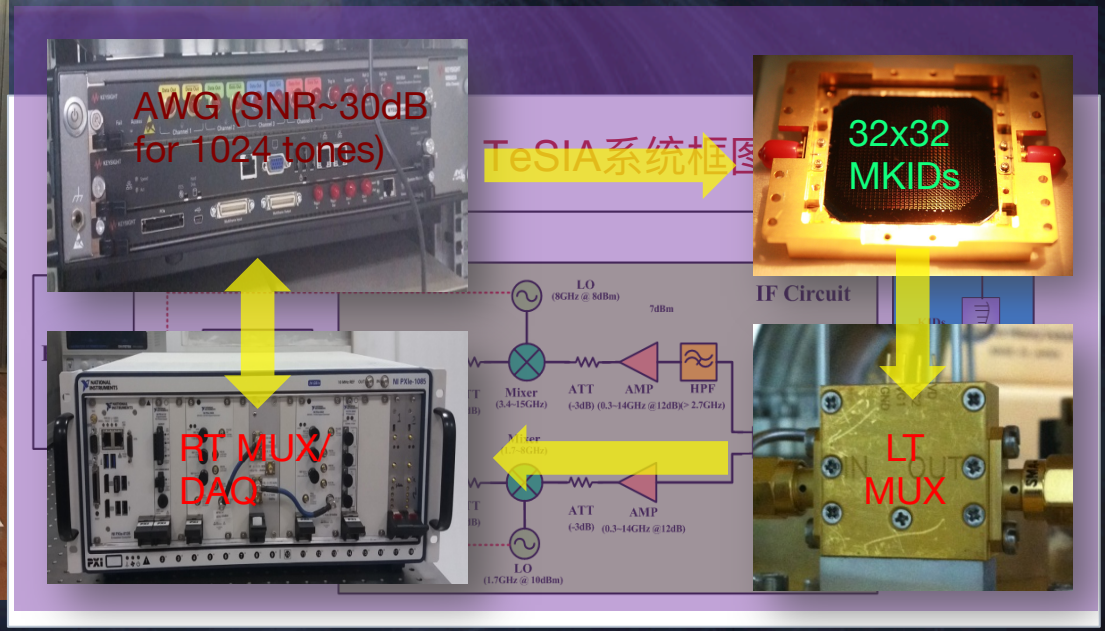
Qc	50-1000k
Freq step	3 MHz
Freq range	4-7.069 GHz
Bath temp	300 mK

A 350μm/0.85THz 32x32 Al MKIDs Array

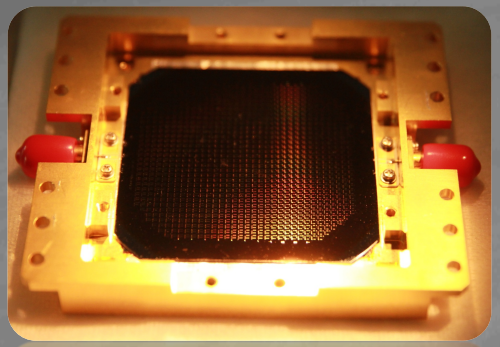
1024 Al MKIDs & micro-lens array



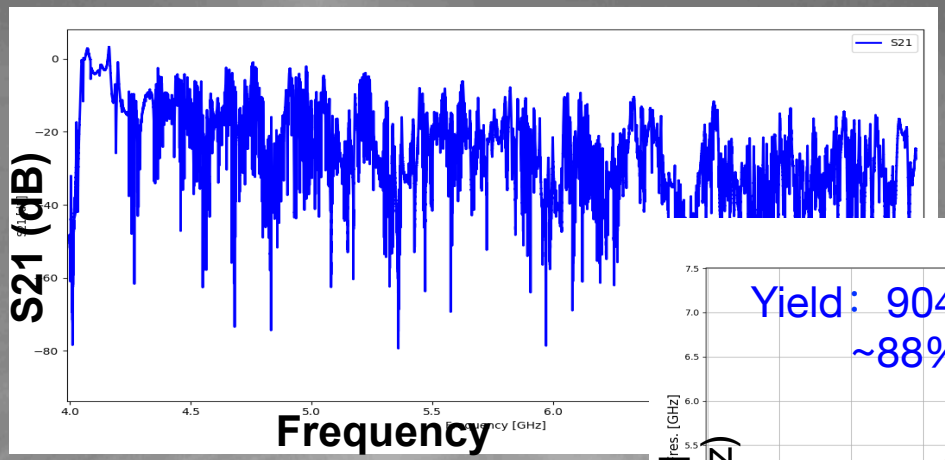




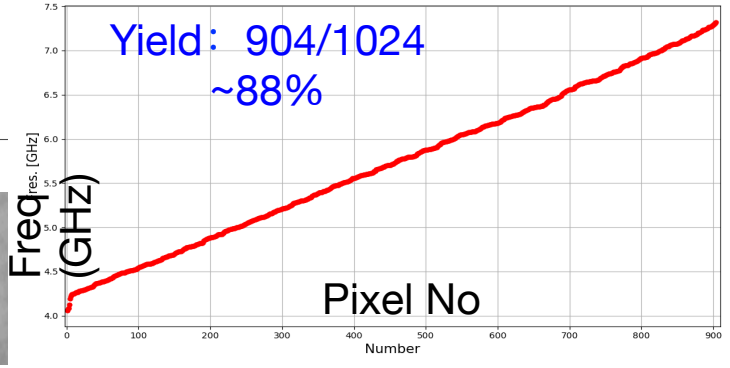
A 350μm/0.85THz 32x32 Al MKIDs Array



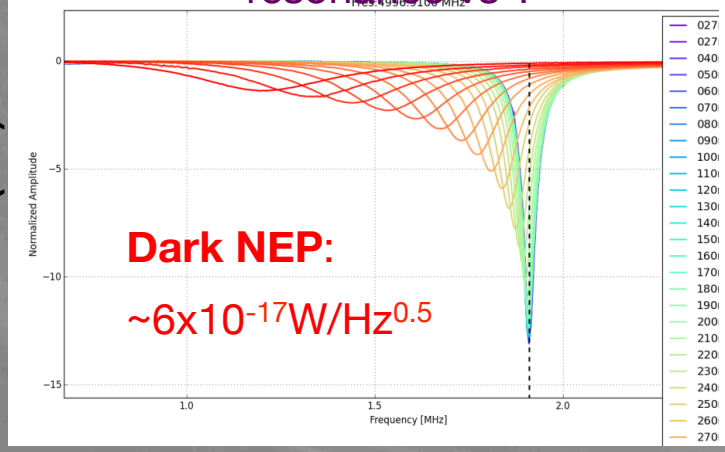
Measured by VNA

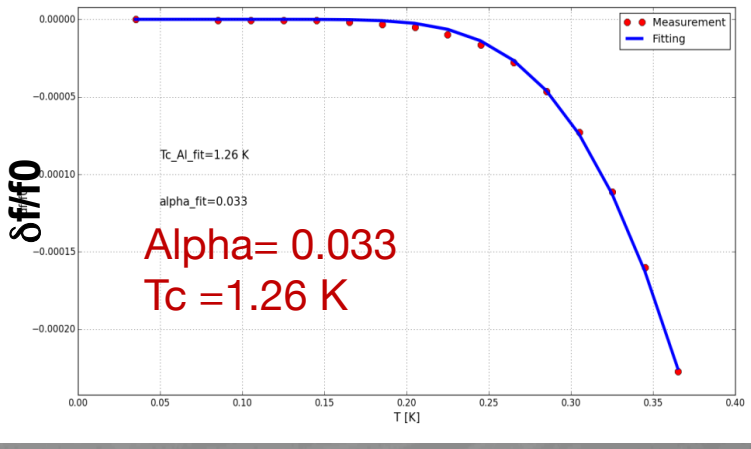


Measured S21 & counted resonances



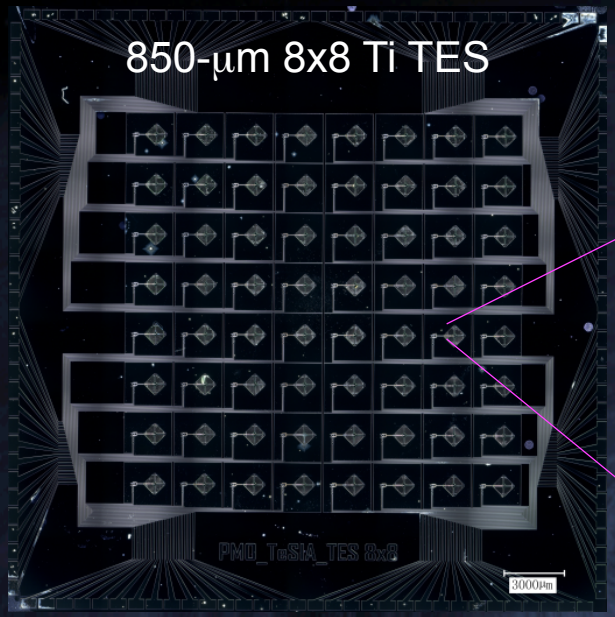
A typical example: measured resonance vs T

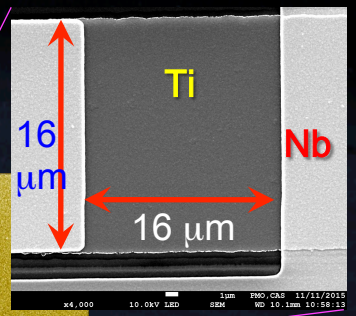




A typical example: measured & fitted resonance frequency shift vs T/Tc

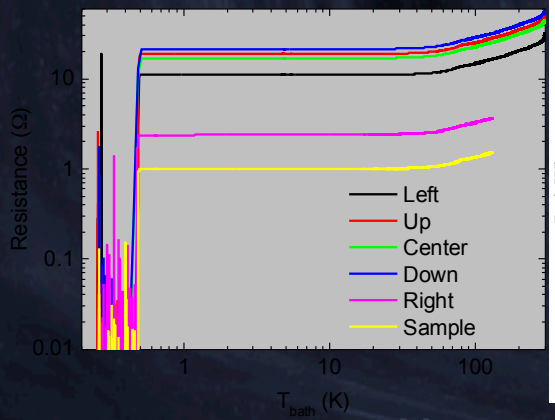
A 850μm/0.35THz 8x8 Ti TES Array

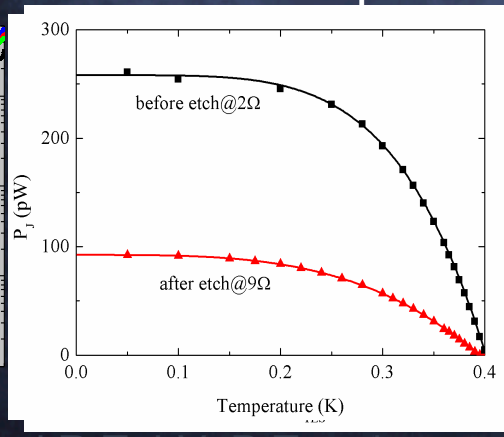


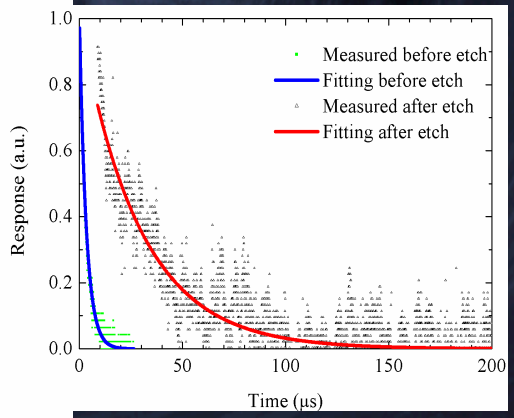


G=3000→800pW/K

τ=3→30μs





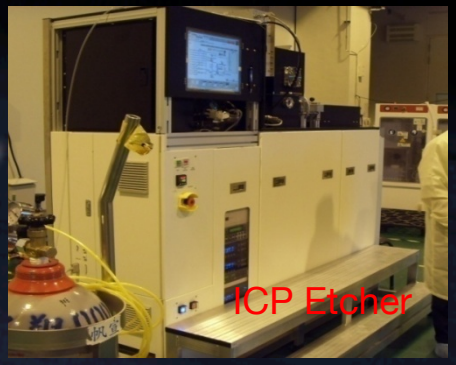


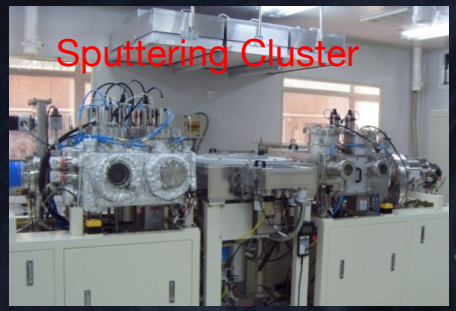
Dark NEP:

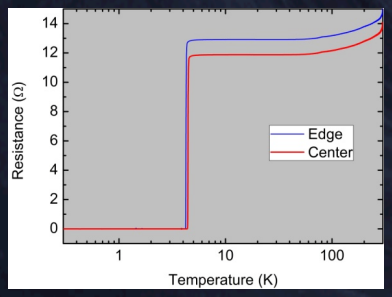
~6x10^{-17}W/Hz$^{0.5}$

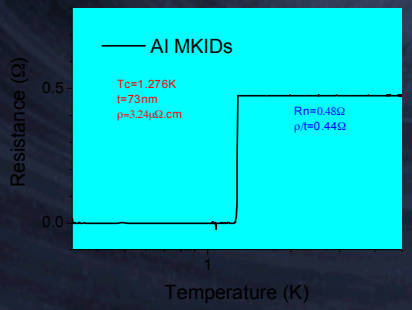
Measured R-T, I-V, P-T and response time

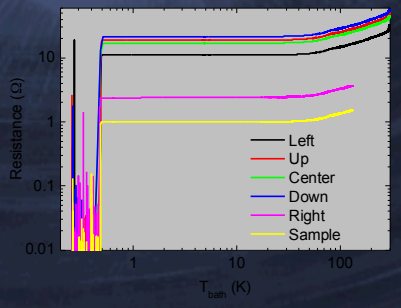
Superconducting Device Fabrication Lab



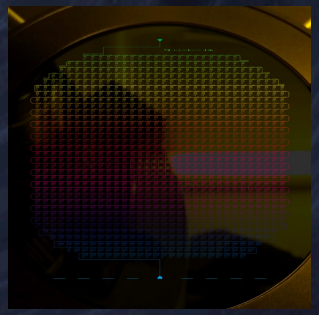


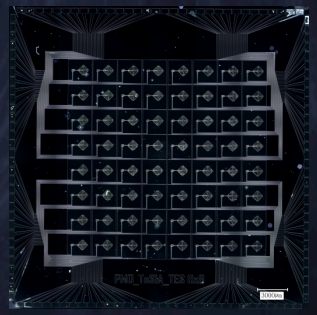






Measured R-T for the fabricated TiN/Al/Ti films





32x32 MKIDs & 8x8 TES

Summary

- Dome A in Antarctic is the best site for THz/FIR astronomy on the ground
- Pre-studies (antenna/receiver/backend) for DATE5 to be built at Dome A in Antarctic are undergoing
- Sensitive superconducting SIS and HEB mixers have been developed for DATE5
- PMO is building the capability of developing large format TES/MKIDs detectors

Acknowledgment

- Dome A FTS was supported by the Operation, Maintenance and Upgrading Fund for Astronomical Telescopes and Facility Instruments
- CCAA, Polar Institute (China) & PLATO Team for the deployment & operation of the instrument
- Blue Sky (Canada) and QMC (UK) for good cooperation in developing the instrument
- Team for CAS's Int. Collaboration Partnership Program

- NSFC & CAS funding for TeSIA and related projects
- Contribution from my colleagues & graduate students
- LERMA (Yan Delorme's group) for the fabrication of 1.4THz HEB chips
- IREE (V. Koshlets's group) for the fabrication of 850GHz SIS chips
- APC/IAS (Michel Piat's & Francois Pajot's groups) & ASIAA (Ming-Jye Wnag's group for the fabrication of TES devices
- RIKEN (Chiko Otani's group) for the fabrication of MKIDs devices
- Early collaboration with SRON/TUDelft on MKIDS with Akira, Jochem, Teun, …