Terahertz Array Development for Astronomical Applications

Jenna Kloosterman
NASA Postdoctoral Program Fellow
Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Collaborating People and Institutions

Jet Propulsion Laboratory
California Institute of Technology

Jenna Kloosterman
Jonathan Kawamura
Bruce Bumble
Paul Goldsmith
Choonsup Lee
Robert Lin
Imran Mehdi
Alejandro Peralta
Jose Siles

l'Observatoire de Paris

Faouzi Boussaha

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Pietro Bernasconi
Bliss Carkhuff
Michael Carpenter
Harry Eaton
Jason Gorczyca
Jonah Gottlieb
Katherine Stambaugh

SRON

Darren Hayton
Jian-Rong Gao

THE UNIVERSITY OF ARIZONA

Ruben Dominguez
Brian Duffy
Craig Kulesa
David Lesser
William Peters
Brandon Swift
Christopher Walker
Abram Young

ASU
ARIZONA STATE UNIVERSITY

Kristina Davis
Christopher Groppi

The Beginning of Radio Astronomy

- Starts at Bell Labs in 1931 with an engineer name Karl Jansky
- Jansky was tasked with studying sources of noise on Transatlantic phone calls

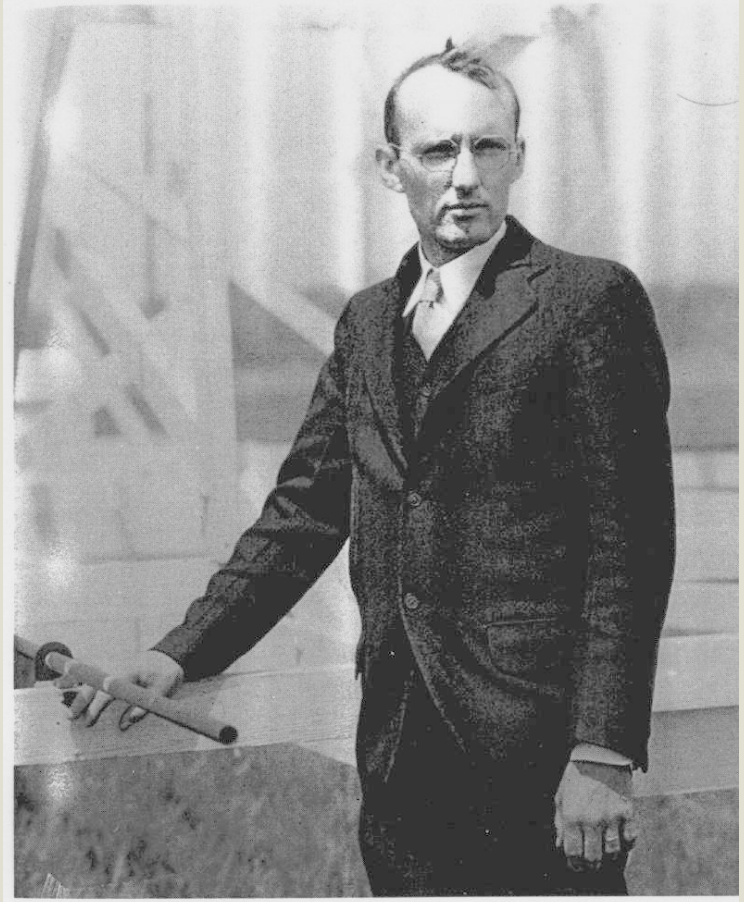


FIG. 1—Karl Guthe Jansky, about 1933.

Photo Credit: Krauss

The Beginning of Radio Astronomy

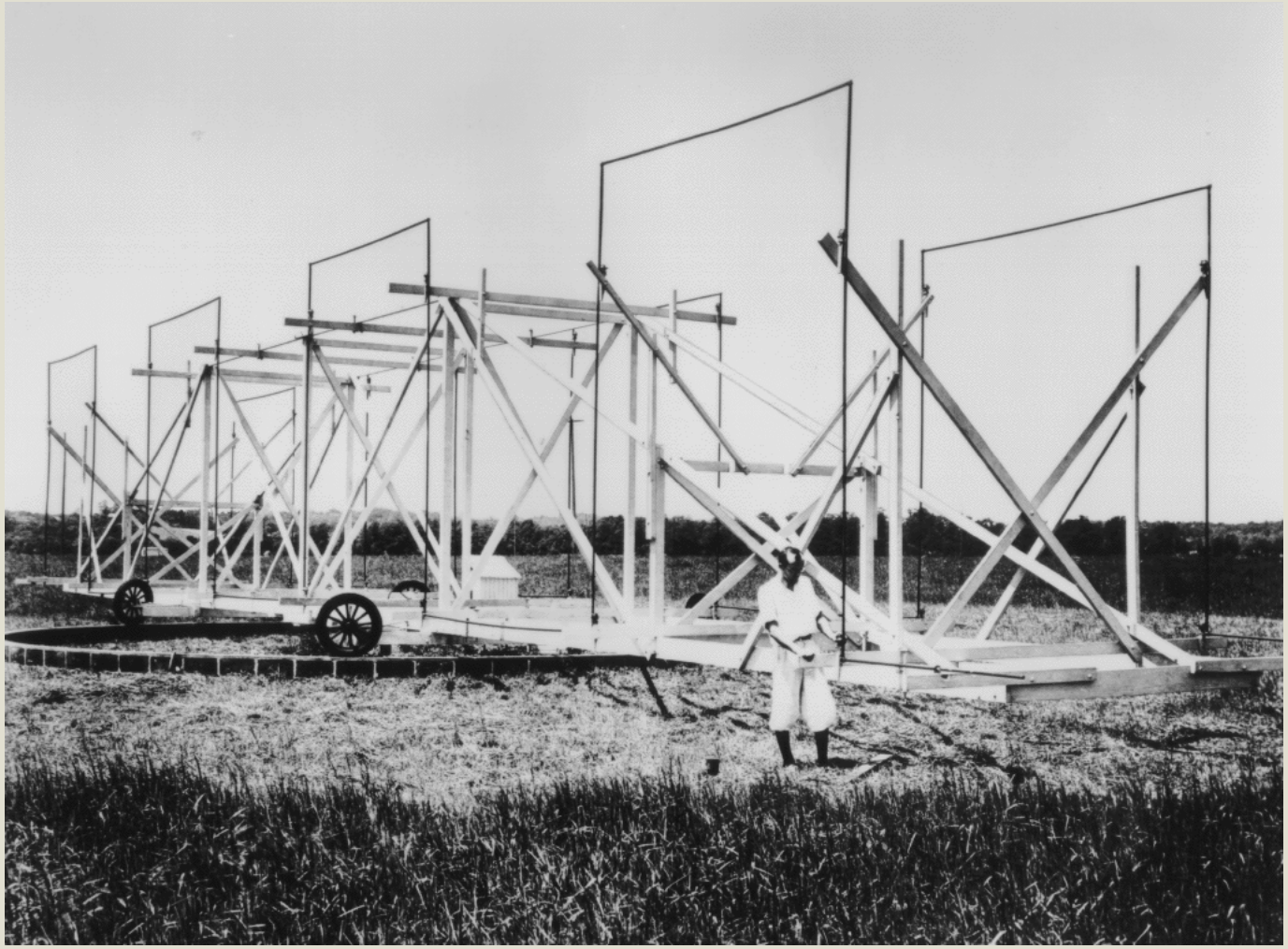


Photo Credit: Krauss

The Beginning of Radio Astronomy

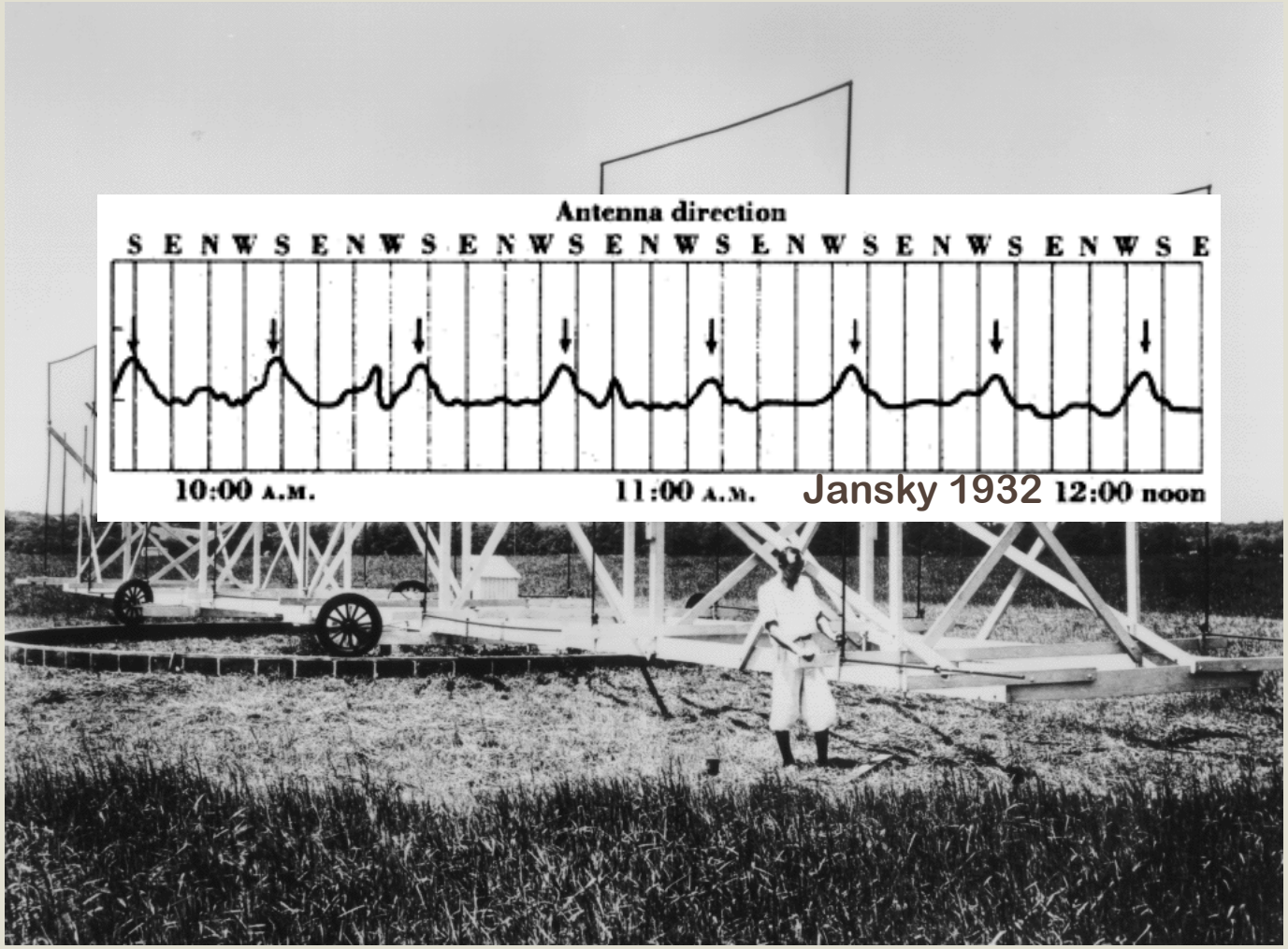


Photo Credit: Krauss

But the story doesn't end there…

Grote Reber, an electrical engieer, picked up Jansky's work with a radio dish he built in his own back yard

Photo Credit: Krauss

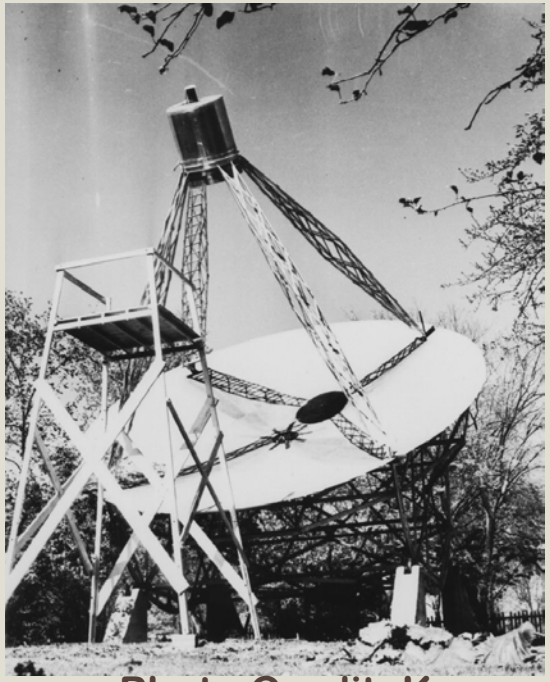
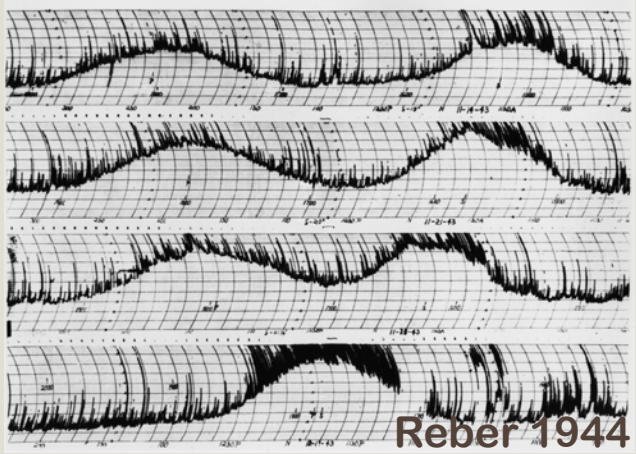
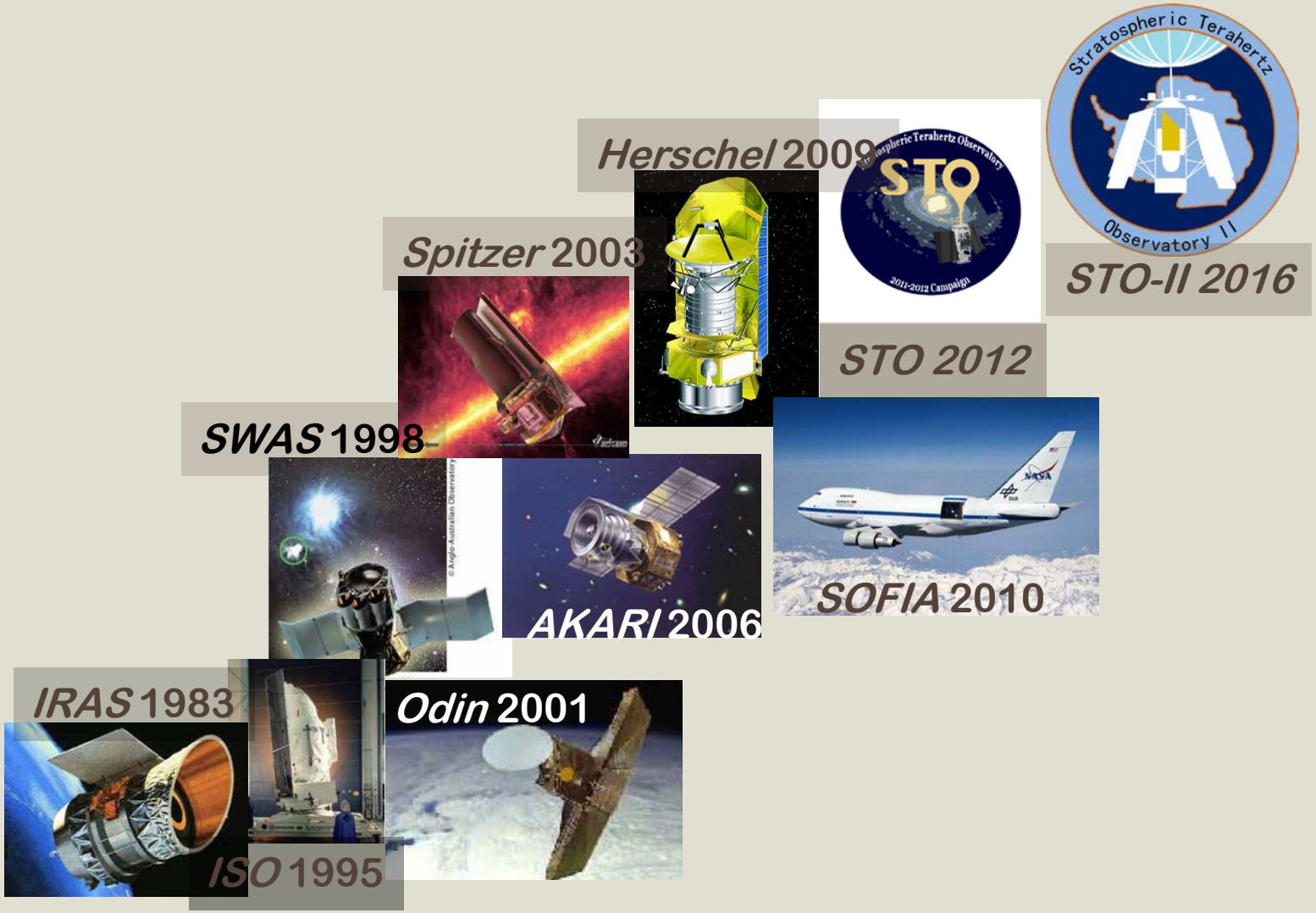


Photo Credit: Krauss



160 MHz signals from Grote Reber's backyard telescope

THz/IR Missions



Results from Herschel….

Andromeda in optical light
Image credit: R. Gendler

Andromeda in FIR. Image credit:
ESA/Herschel/SPIRE/HELGA

Life Cycle of Interstellar Medium (ISM)

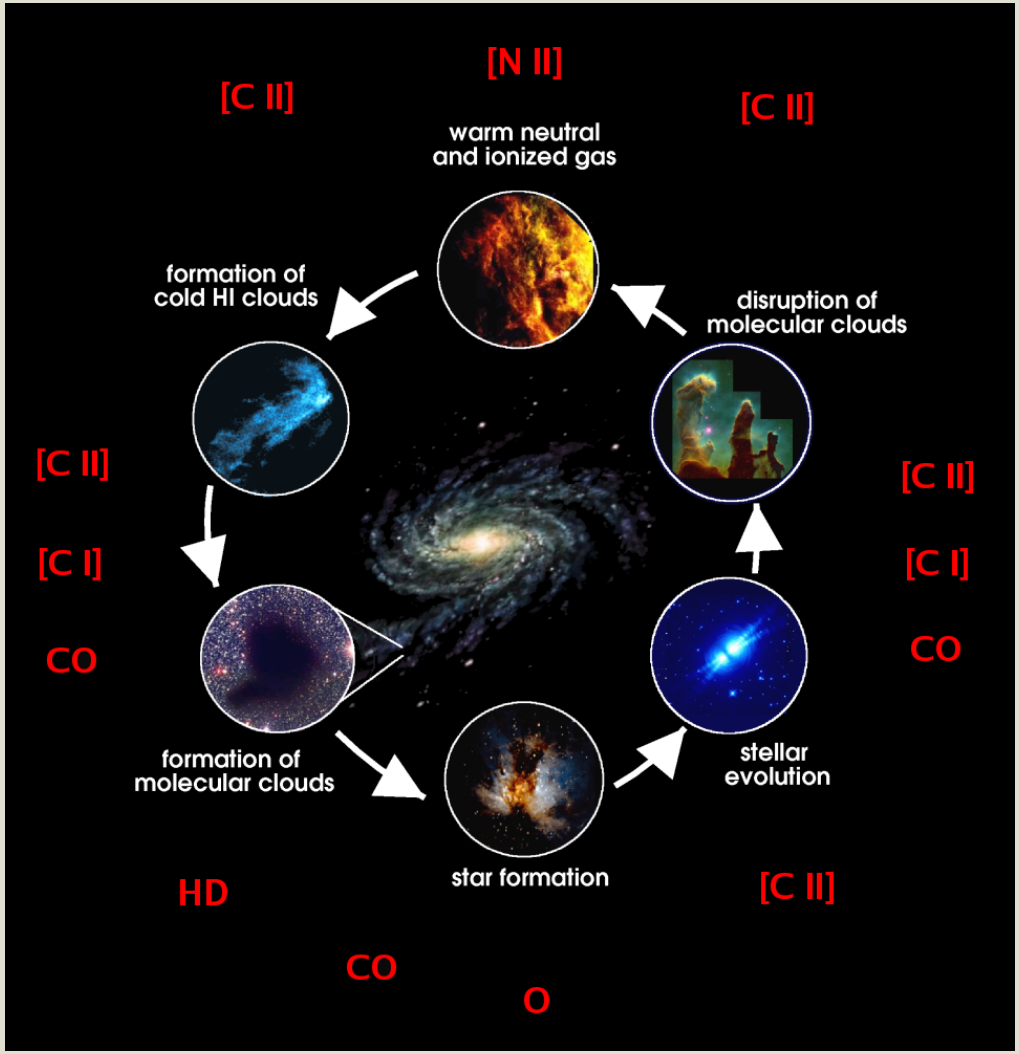
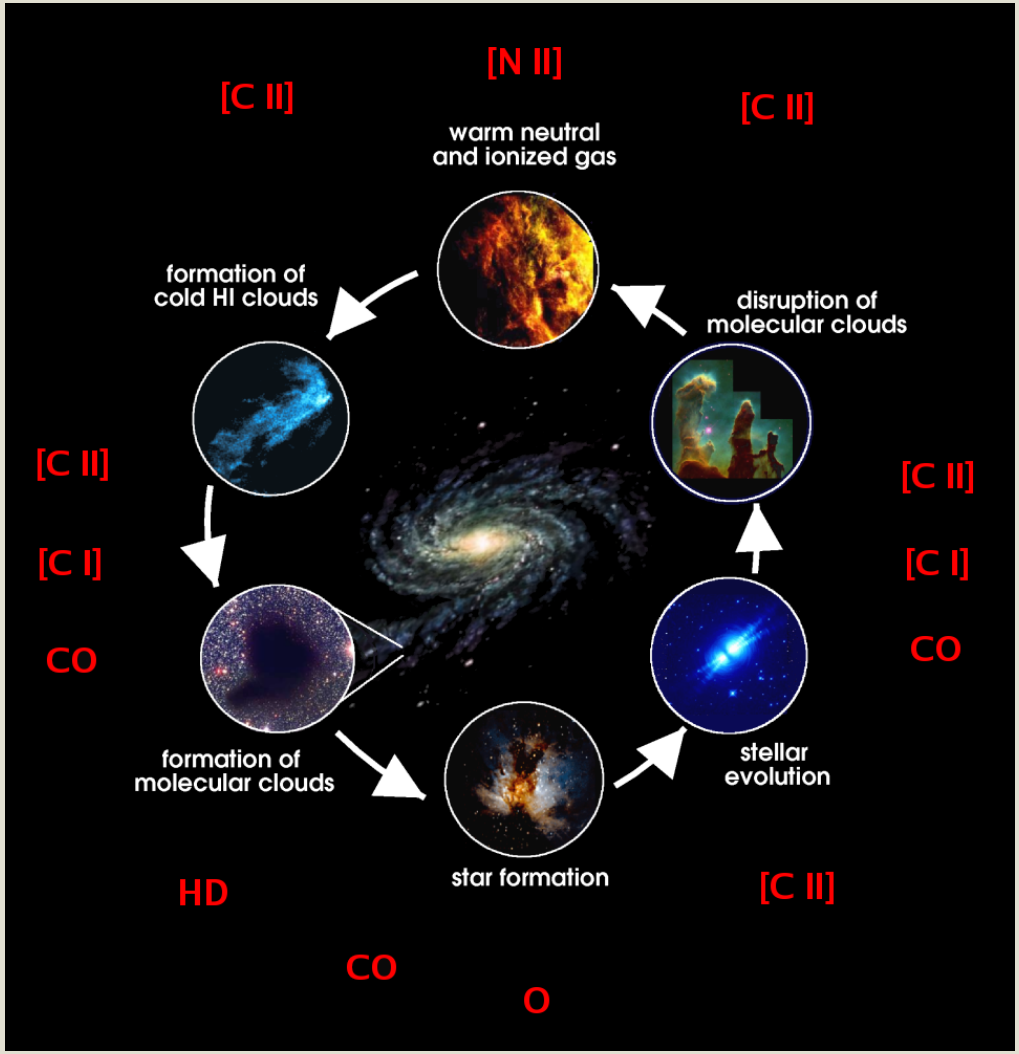


Image Credit: Kulesa and Walker

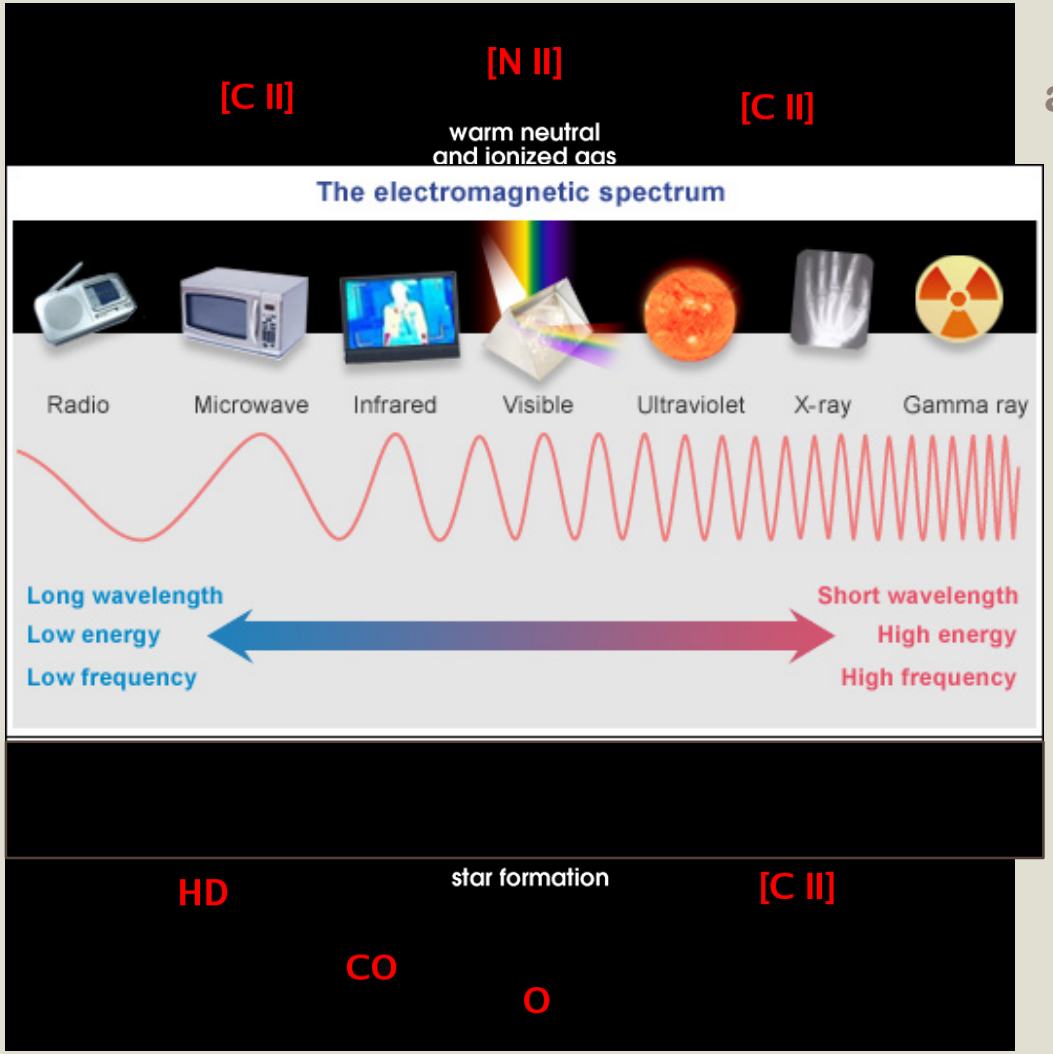
Life Cycle of Interstellar Medium (ISM)



What do all of these atomic and molecular tracers have in common?

Image Credit: Kulesa and Walker

Life Cycle of Interstellar Medium (ISM)



What do all of these atomic and molecular tracers have in common?

Transitions in the THz/Sub-millimeter!

Image Credit: Kulesa and Walker

Life Cycle of Interstellar Medium (ISM)

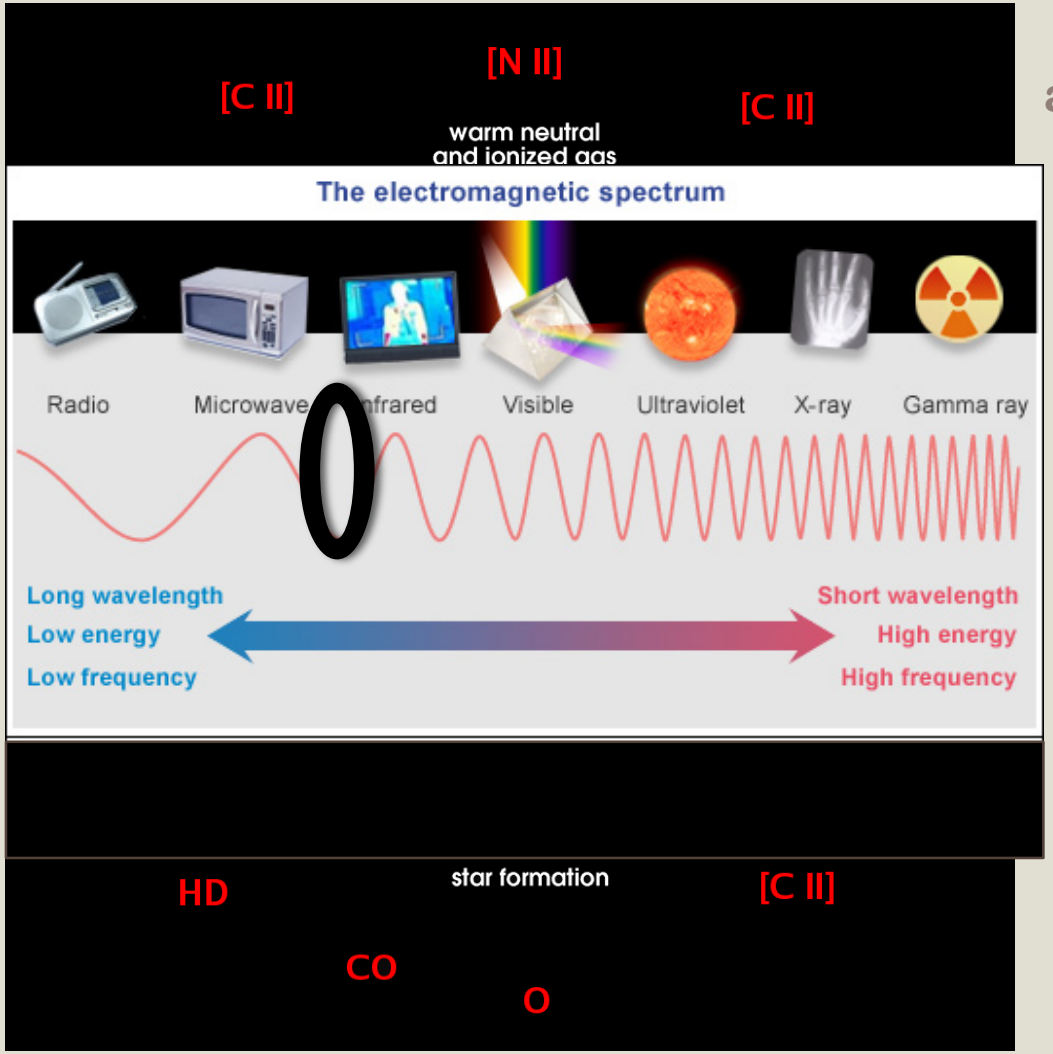


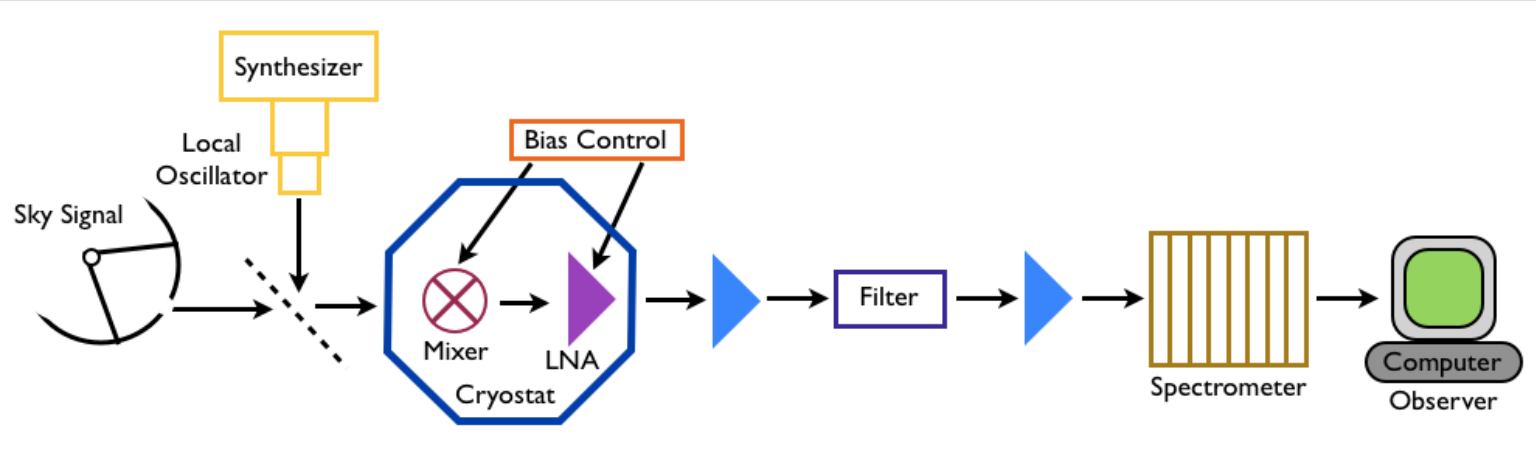
Image Credit: Kulesa and Walker

What do all of these atomic and molecular tracers have in common?

Transitions in the THz/Sub-millimeter!

Large scale THz spectroscopic surveys are needed to study the kinematics of large gas clouds in the Milky Way => heterodyne arrays needed!

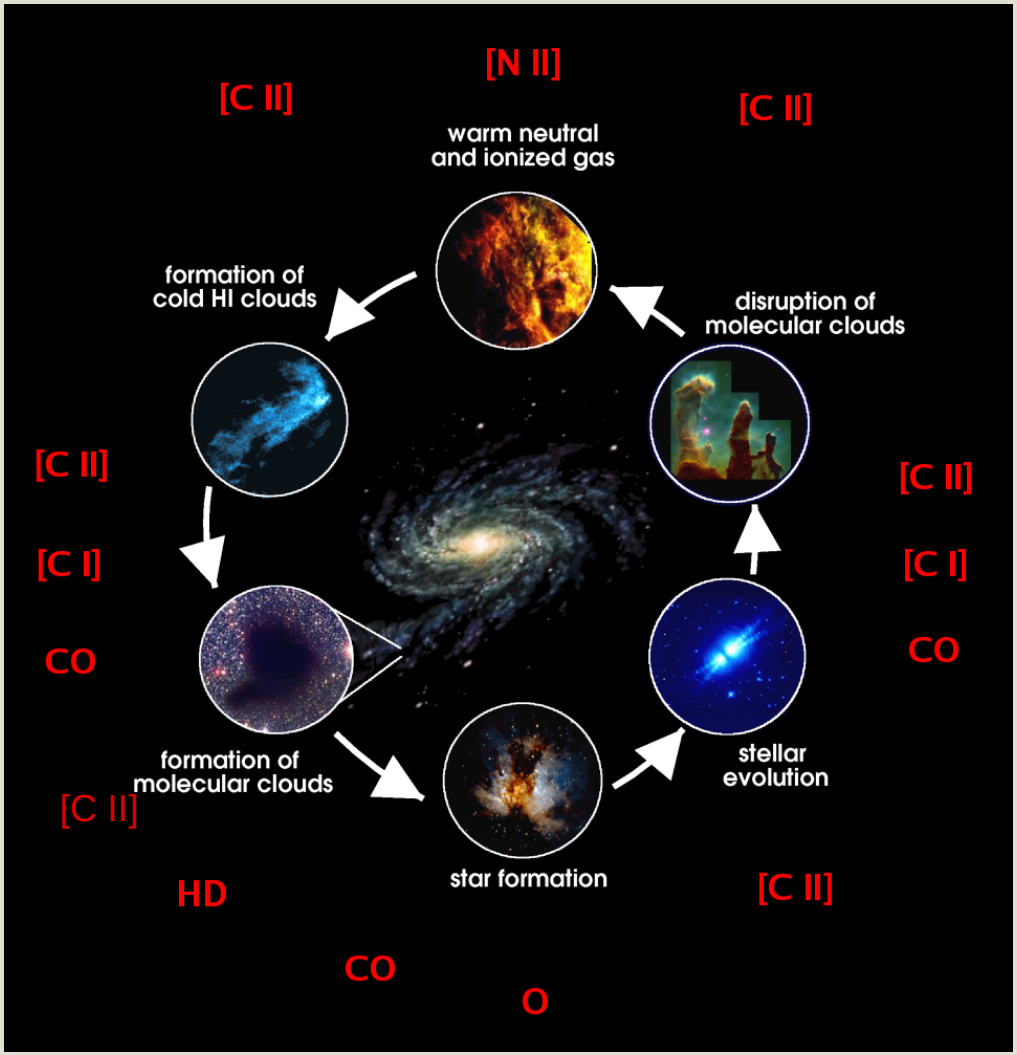
Superconducting THz Heterodyne Receiver



Kloosterman 2014

- Coherent detection
- High spectral resolution ($R=10^7$)
- Sensitivity
- SIS or HEB Mixers

Life Cycle of Interstellar Medium (ISM)



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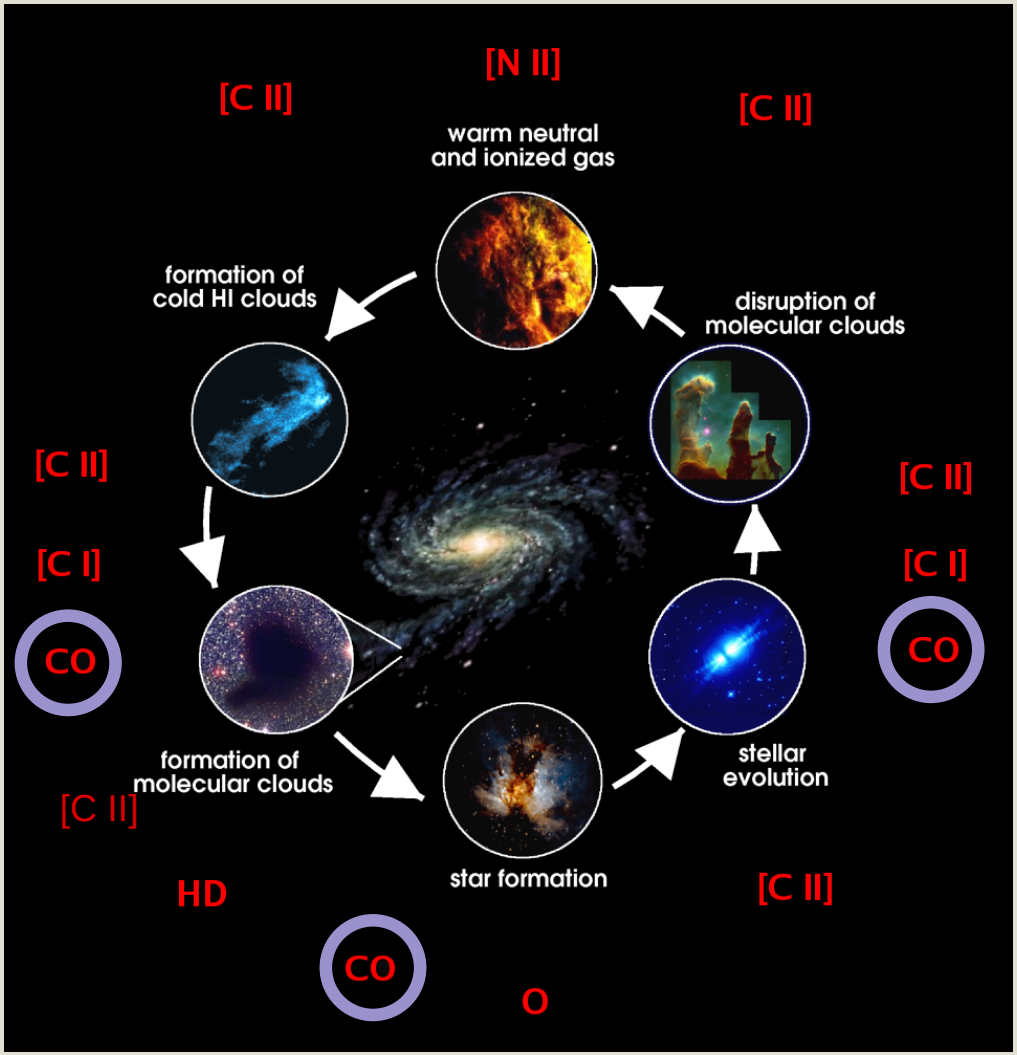
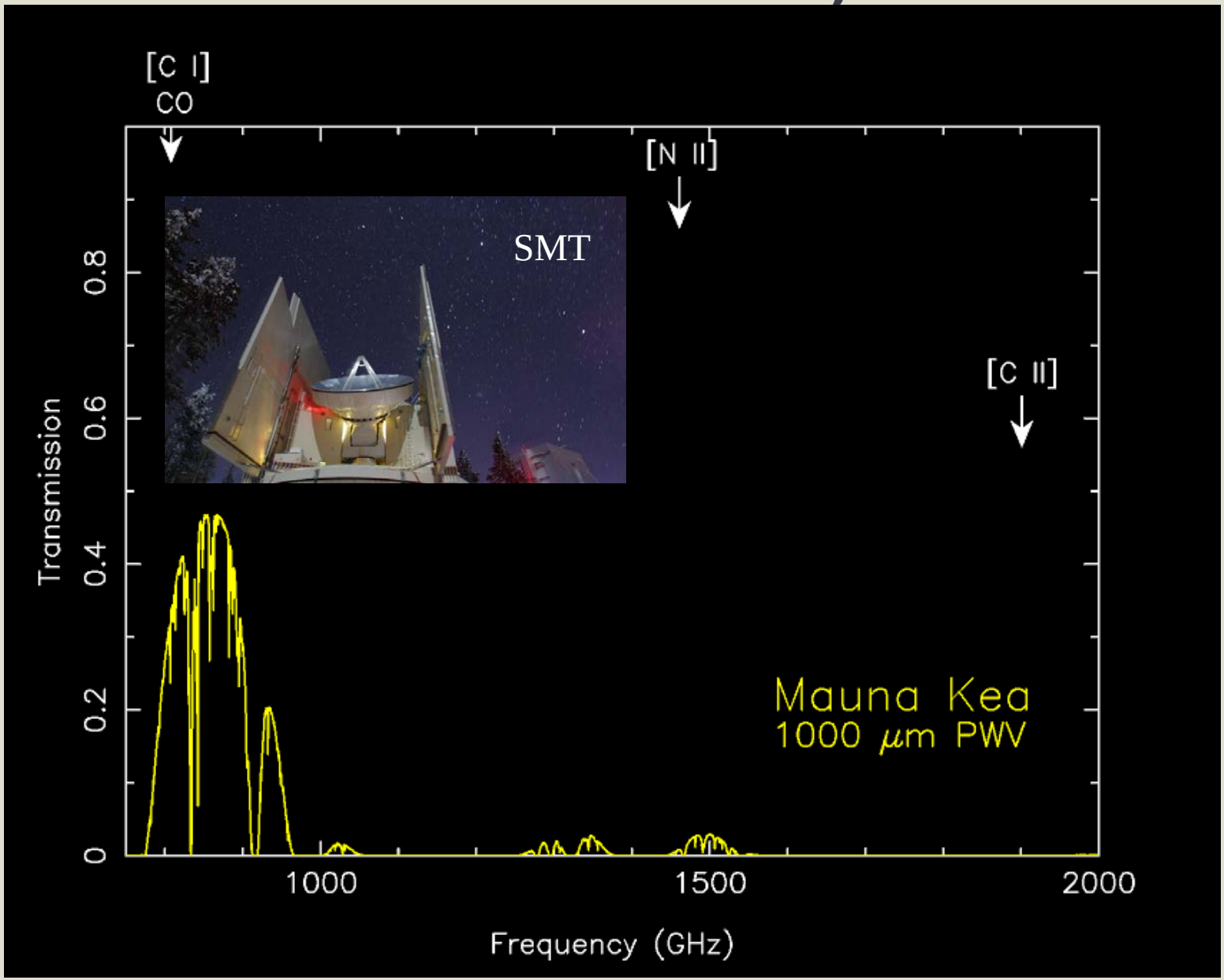
Life Cycle of Interstellar Medium (ISM)



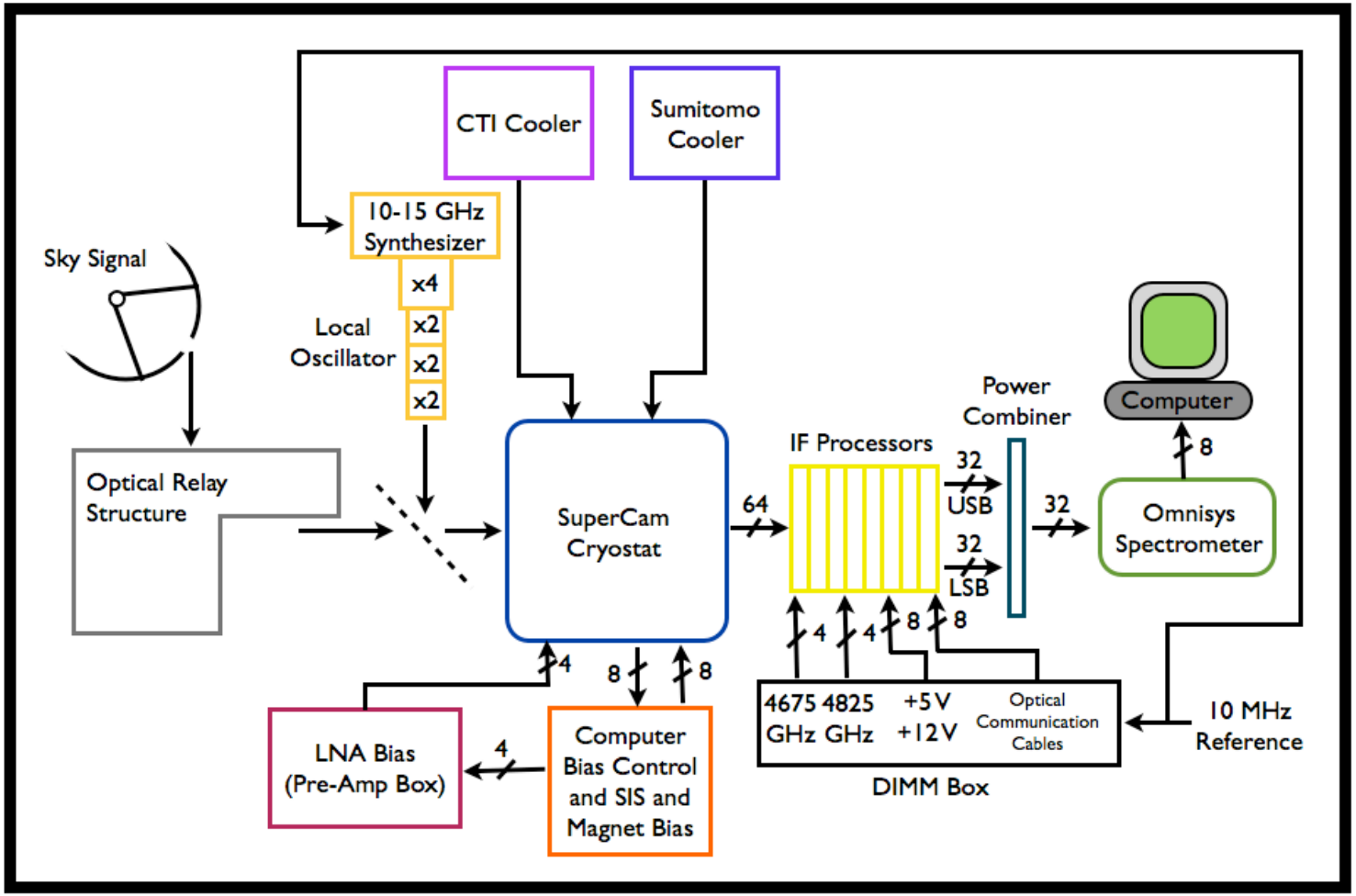
SuperCam
CO: λ = 0.8 mm, ν = 345 GHz

Image Credit: Kulesa and Walker

Atmospheric Transmission (Best Sites in North America)



SuperCam Block Diagram



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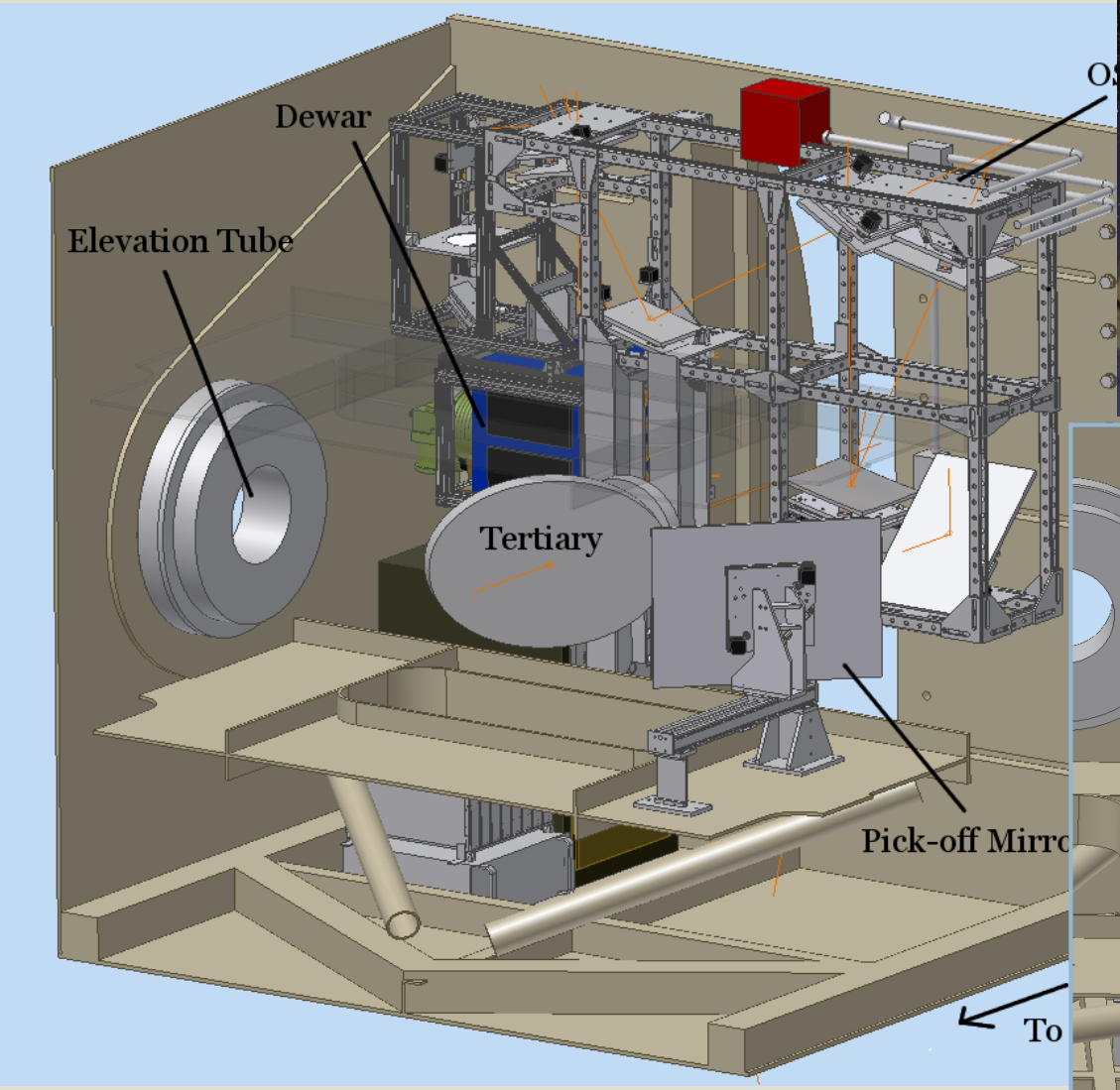
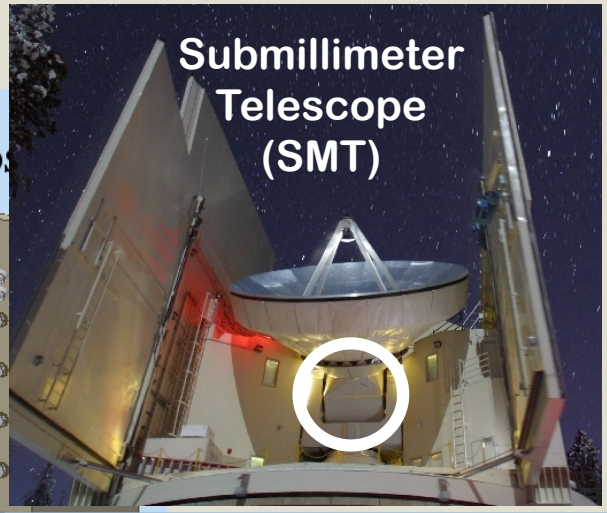
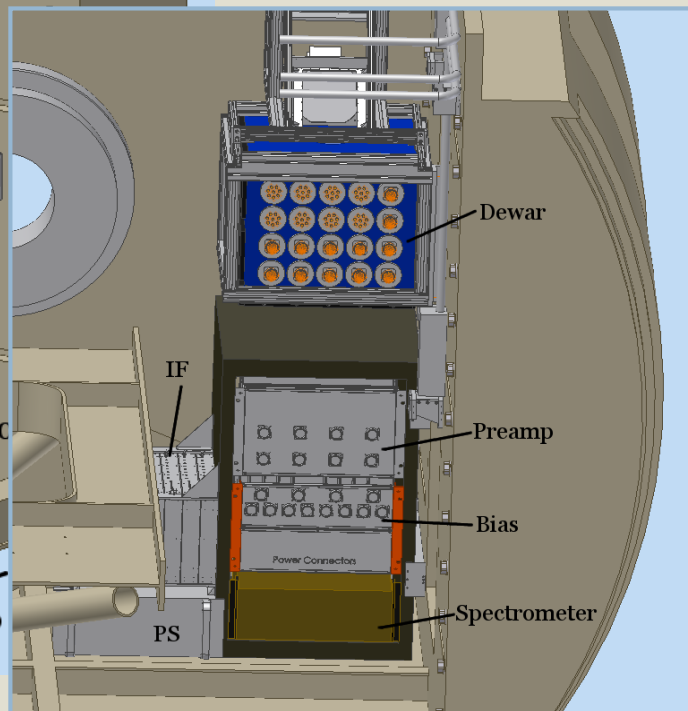
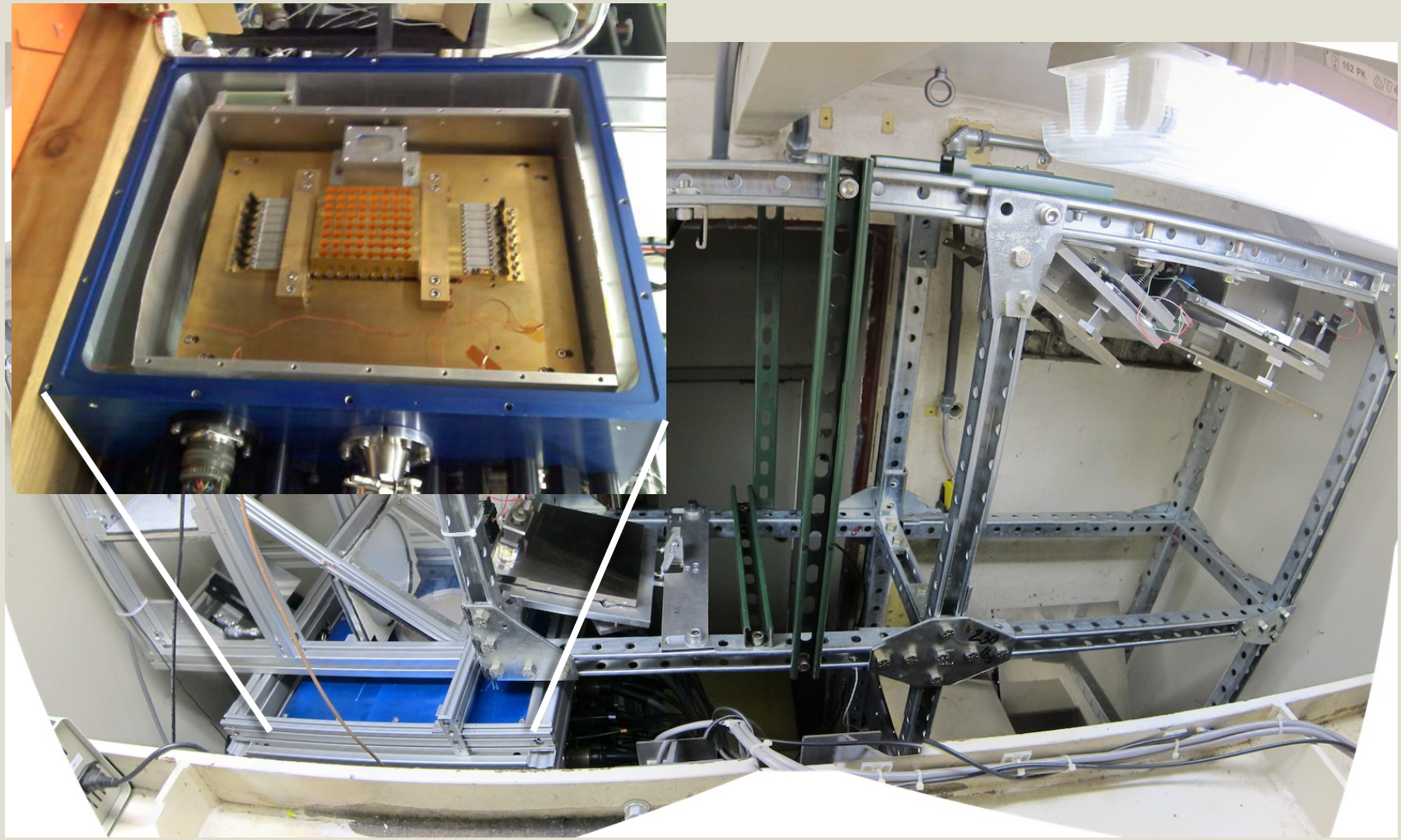
SuperCam: A 64-pixel imaging spectrometer at 345 GHz



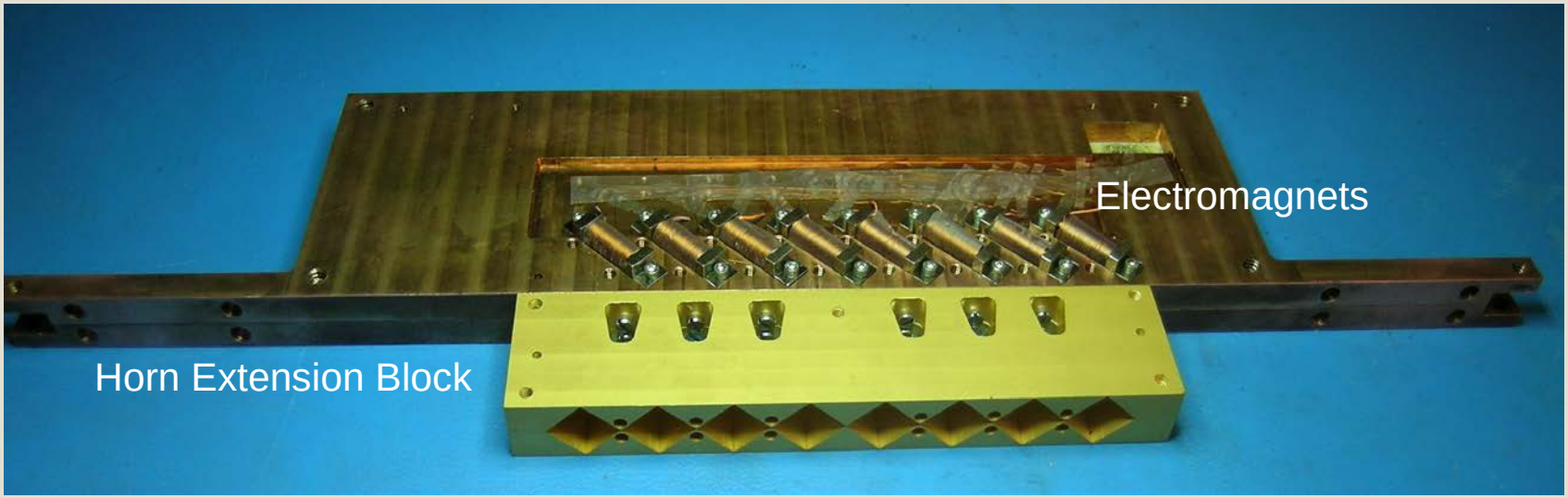


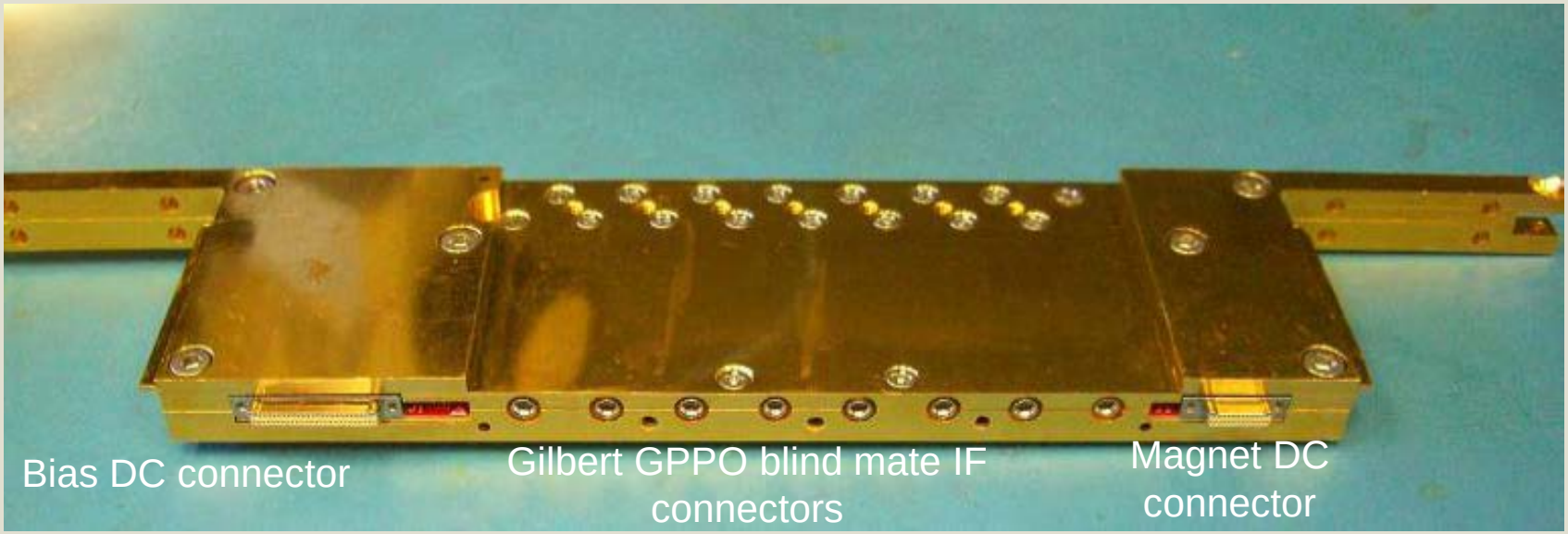


SuperCam Installed in the Apex Room of the SMT



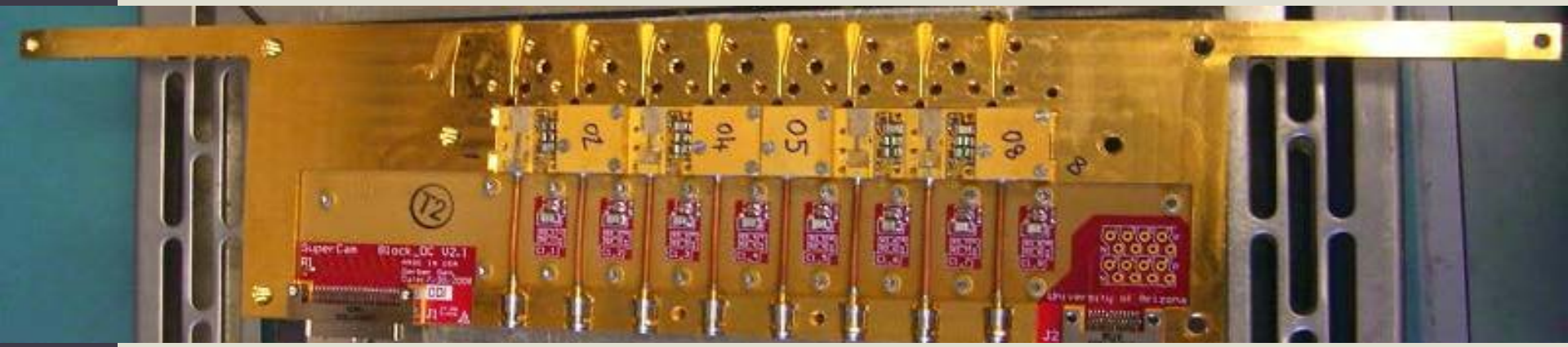
1x8 Mixer Module





Groppi et al. 2010

Anatomy of a 1x8 SuperCam Subarray



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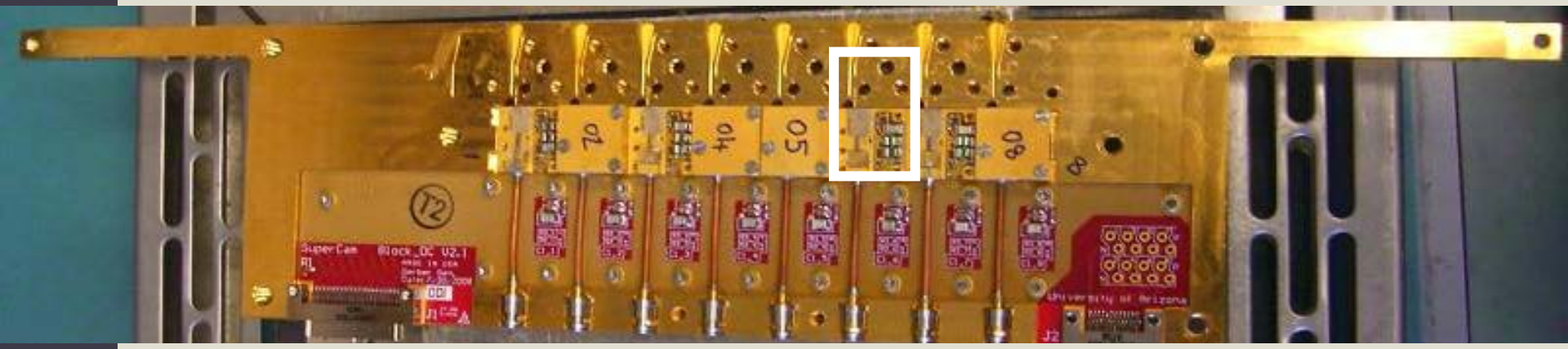

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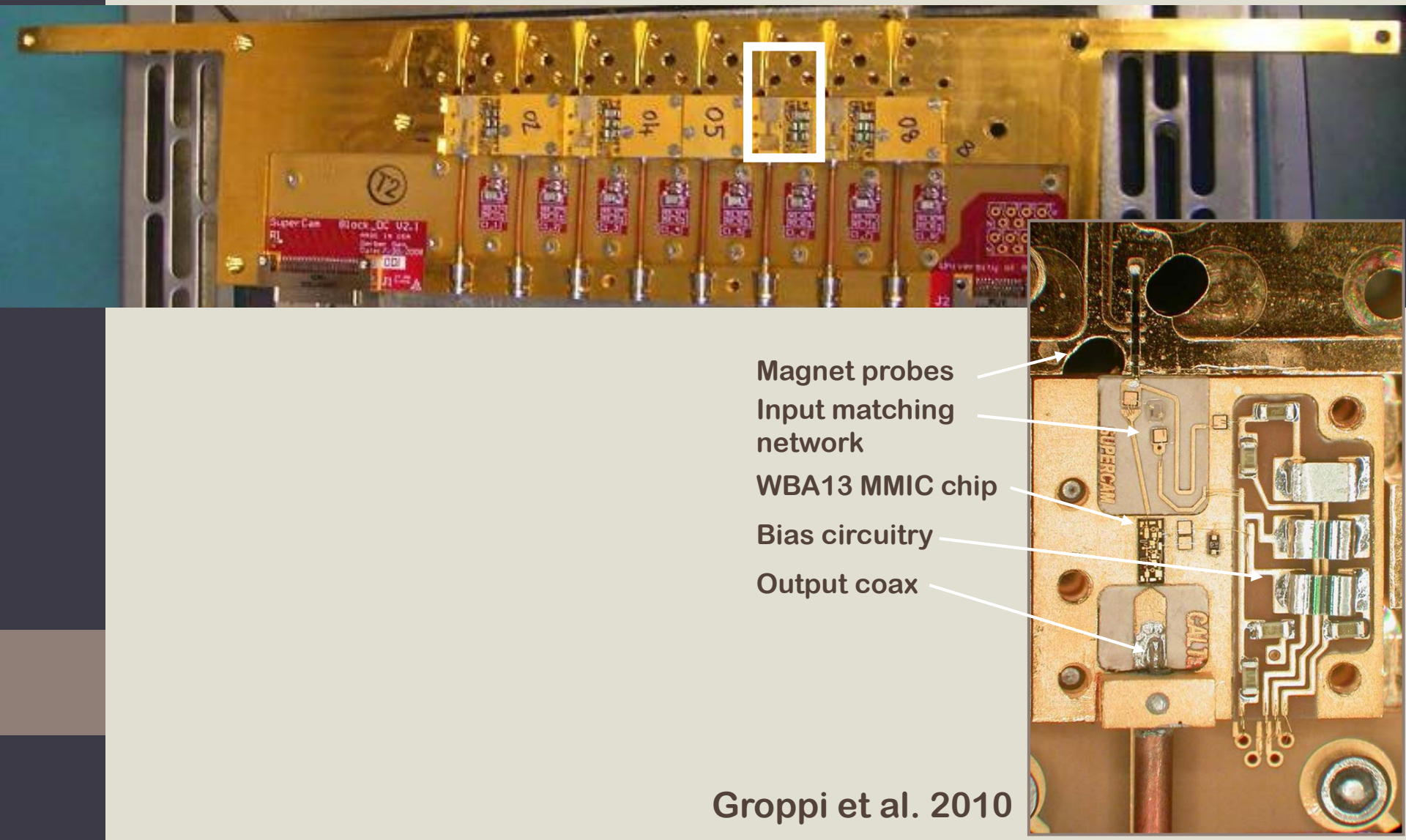

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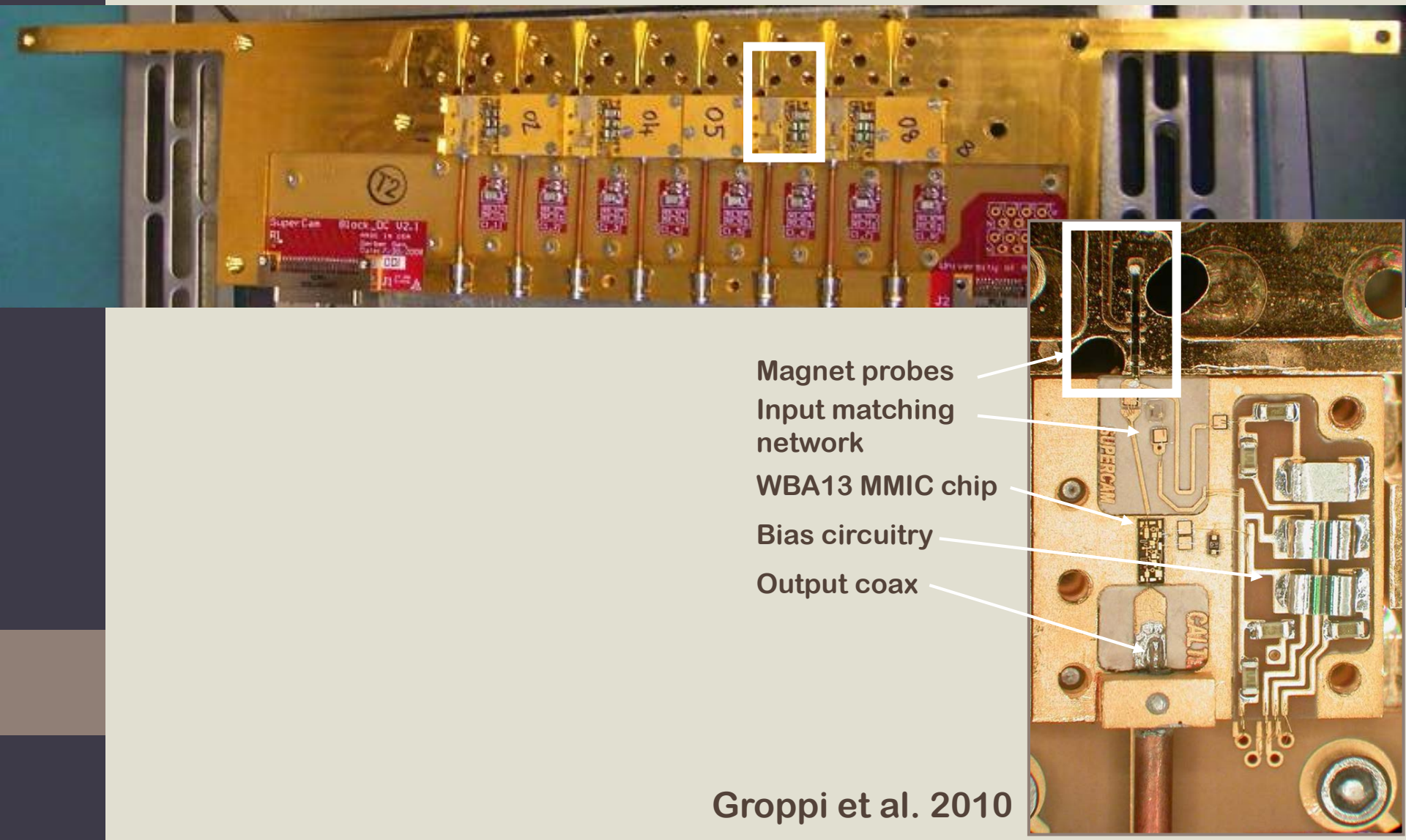

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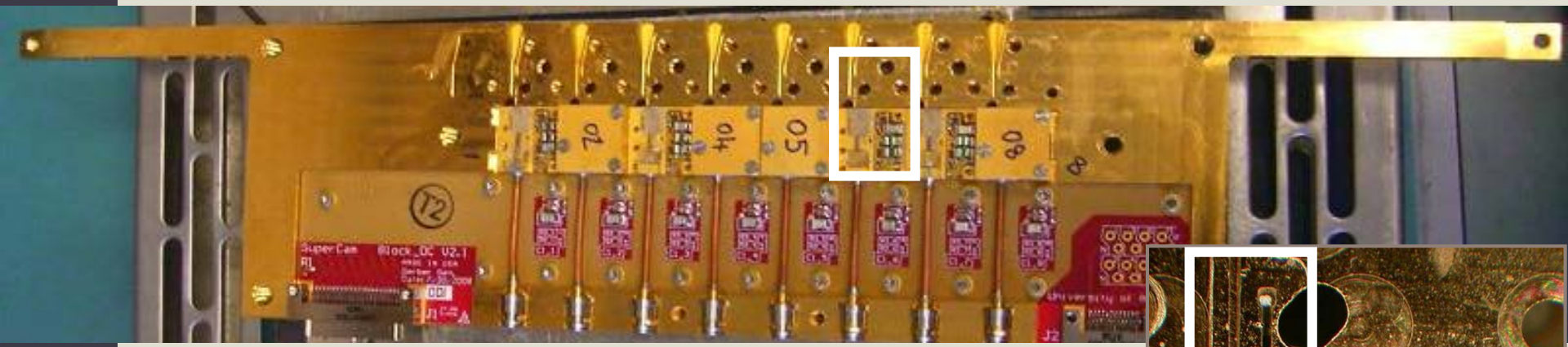
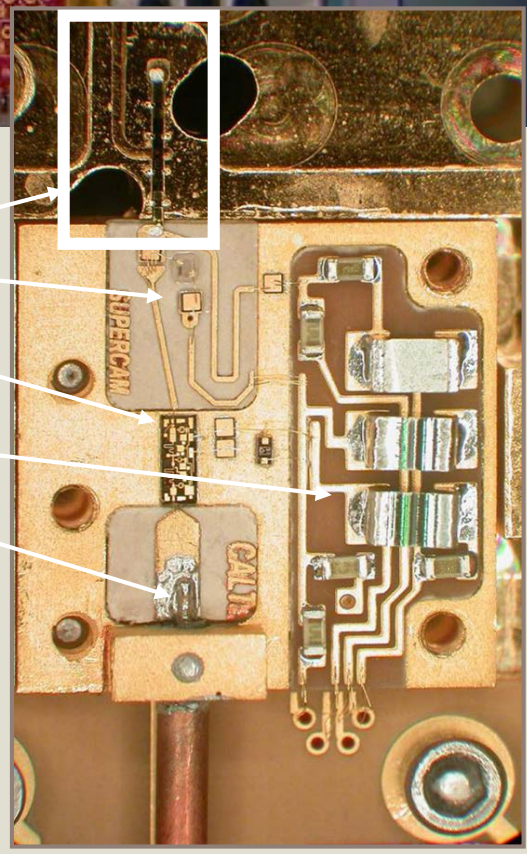
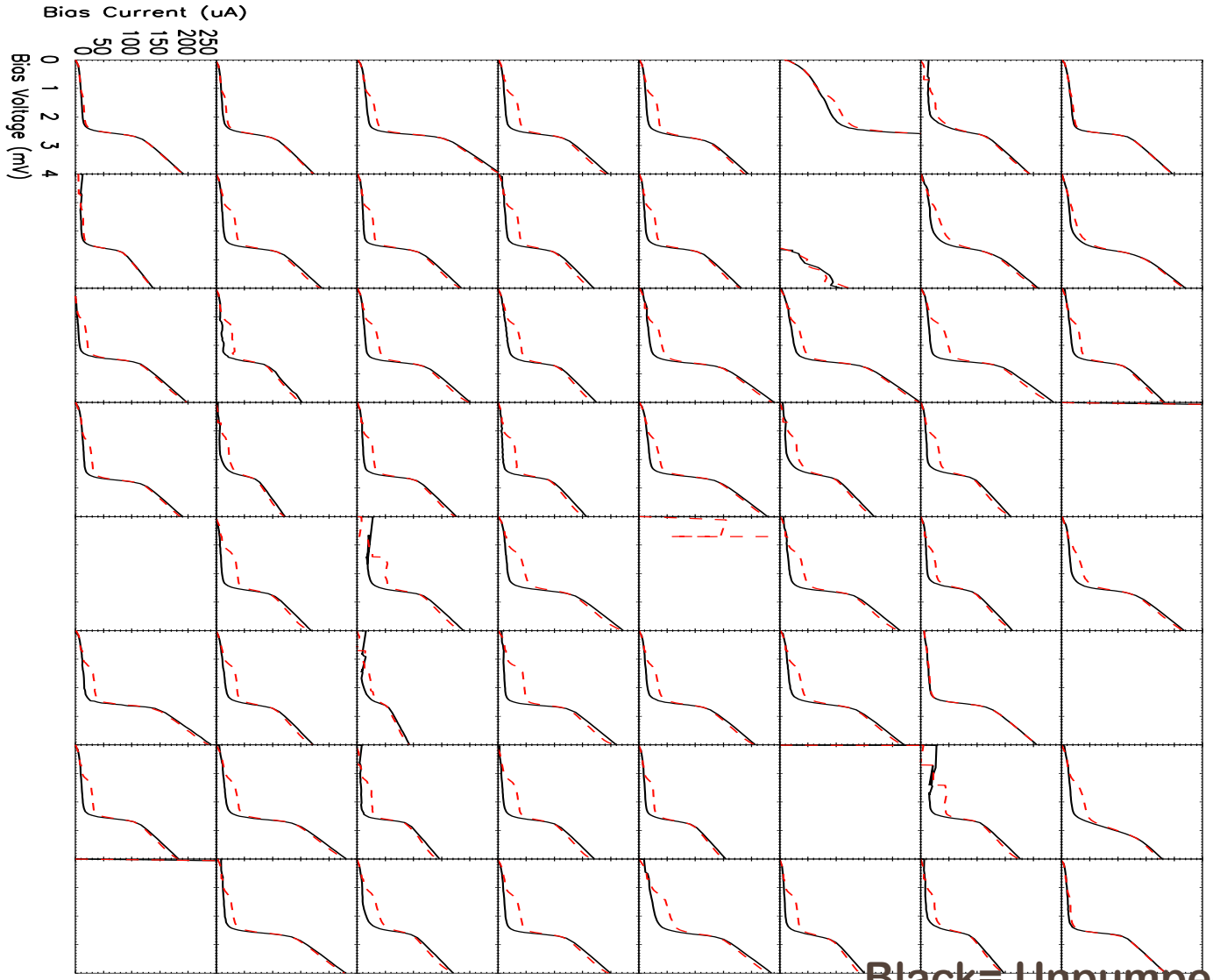




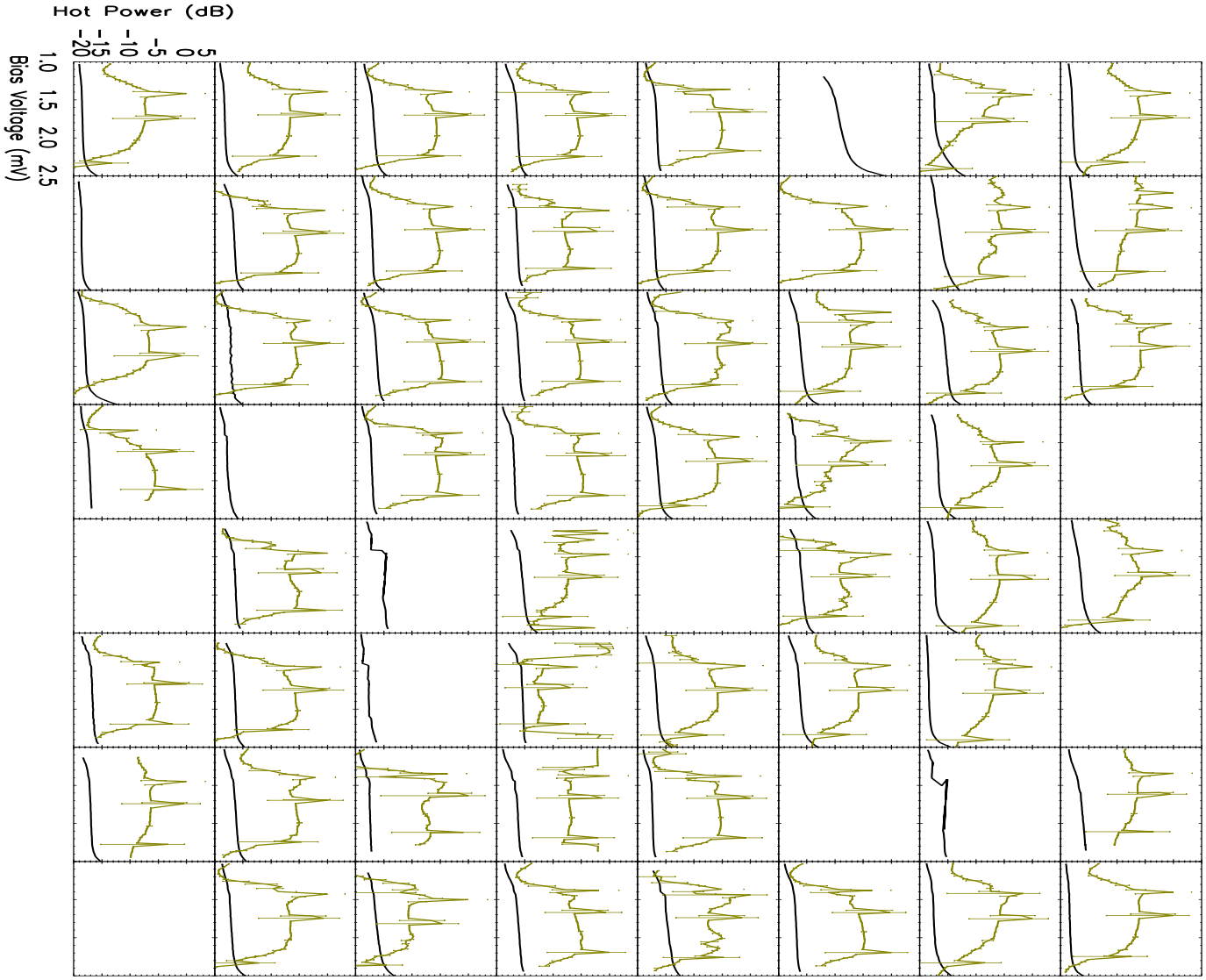
Groppi et al. 2010

SuperCam I-V Curves



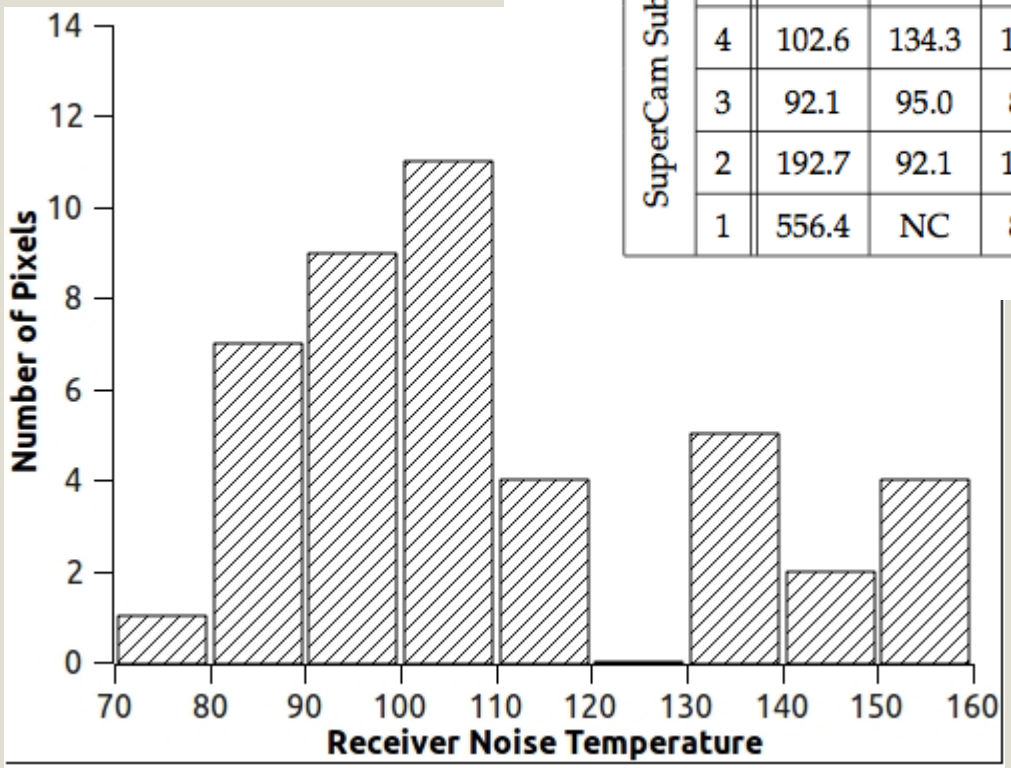
Black= Unpumped
Red=Pumped

SuperCam Power Curves



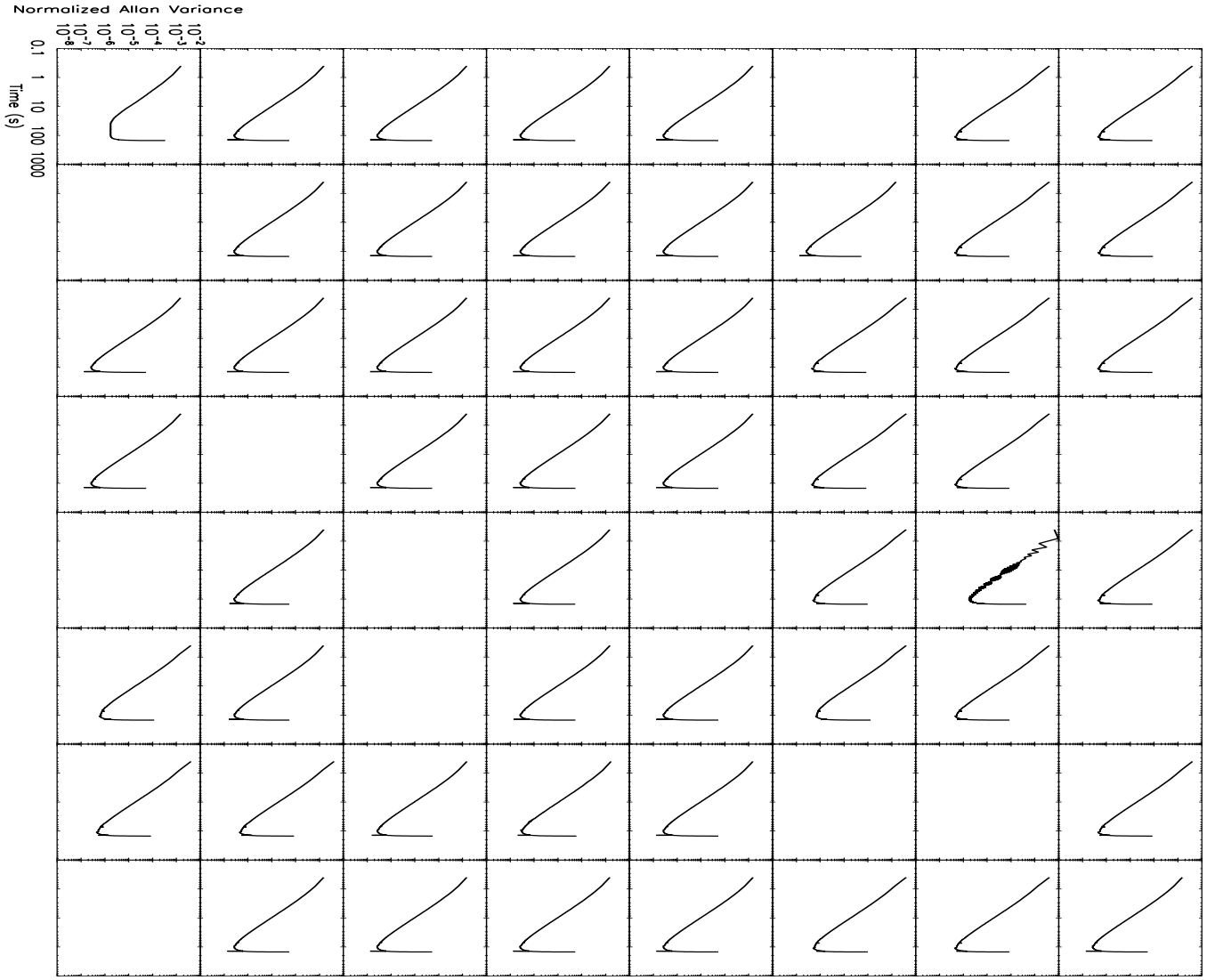
Receiver Noise Temperature

SuperCam Subarray Number	Pixel Number 1	2	3	4	5	6	7	8
8	458.5	228.8	153.3	NC	156.0	NC	109.2	253.3
7	153.3	243.1	110.9	132.1	116.3	458.5	NC	141.1
6	NC	79.1	148.3	156.0	102.6	138.8	NC	132.1
5	95.0	86.7	102.6	93.6	NC	105.8	118.1	107.5
4	102.6	134.3	105.8	102.6	81.5	95.0	420.0	89.4
3	92.1	95.0	88.0	85.4	NC	NC	92.1	104.2
2	192.7	92.1	102.6	NC	92.1	136.5	116.3	99.5
1	556.4	NC	89.4	84.1	NC	105.8	340	NC

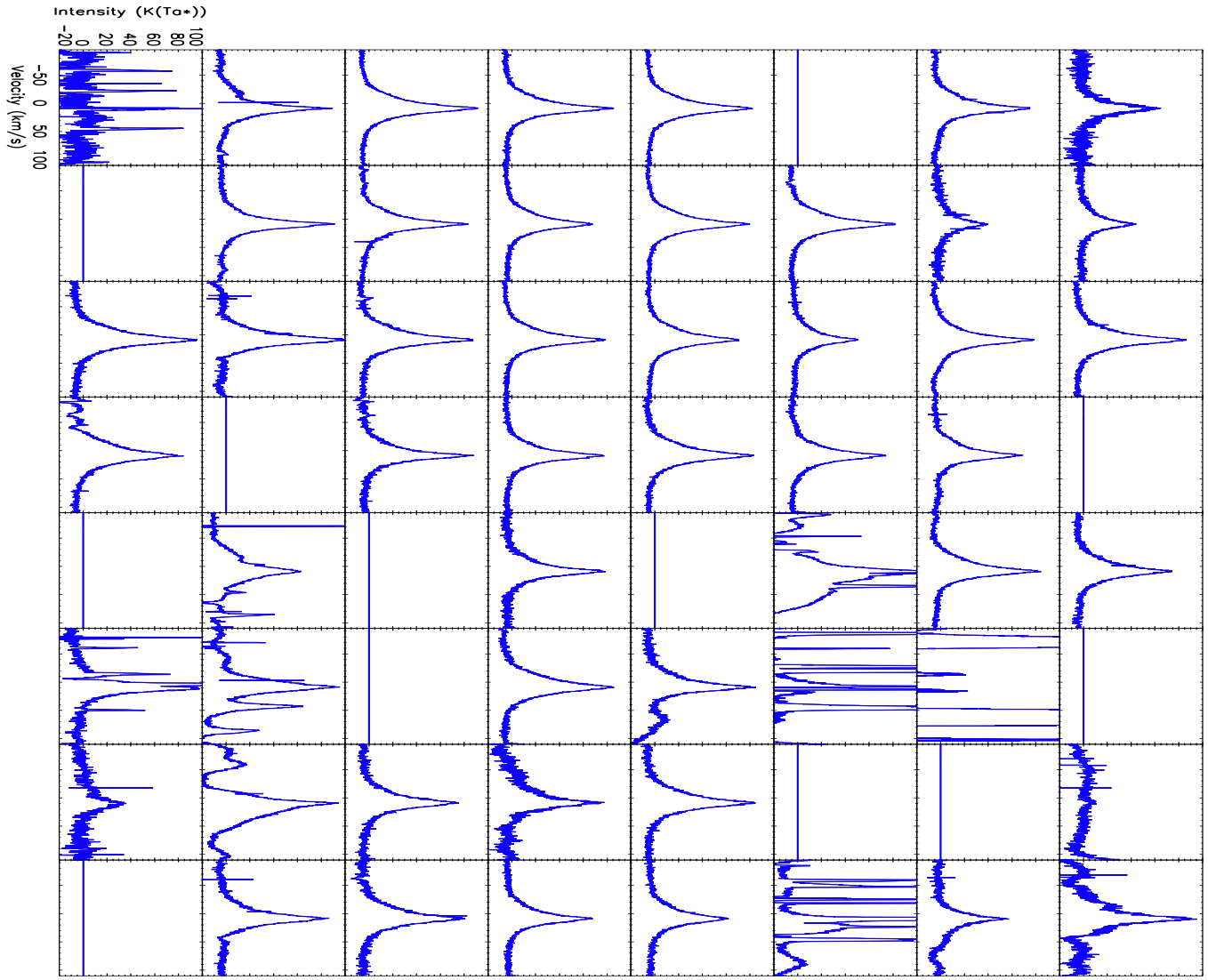


- 81% of pixels working!!!
- Noise-weighted median T_{rx} = 104 K

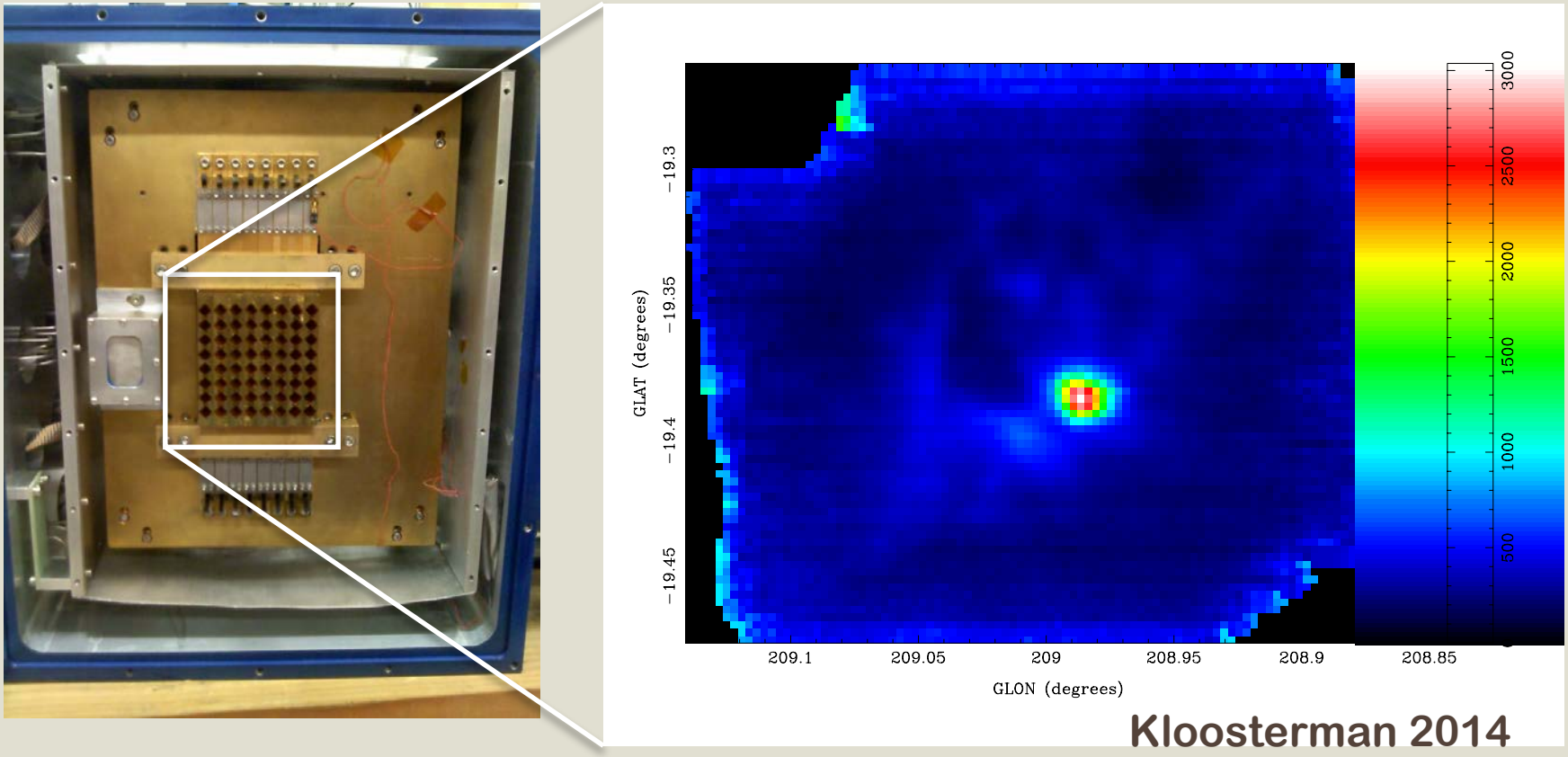
SuperCam Allan Variance



SuperCam Spectra of Orion A



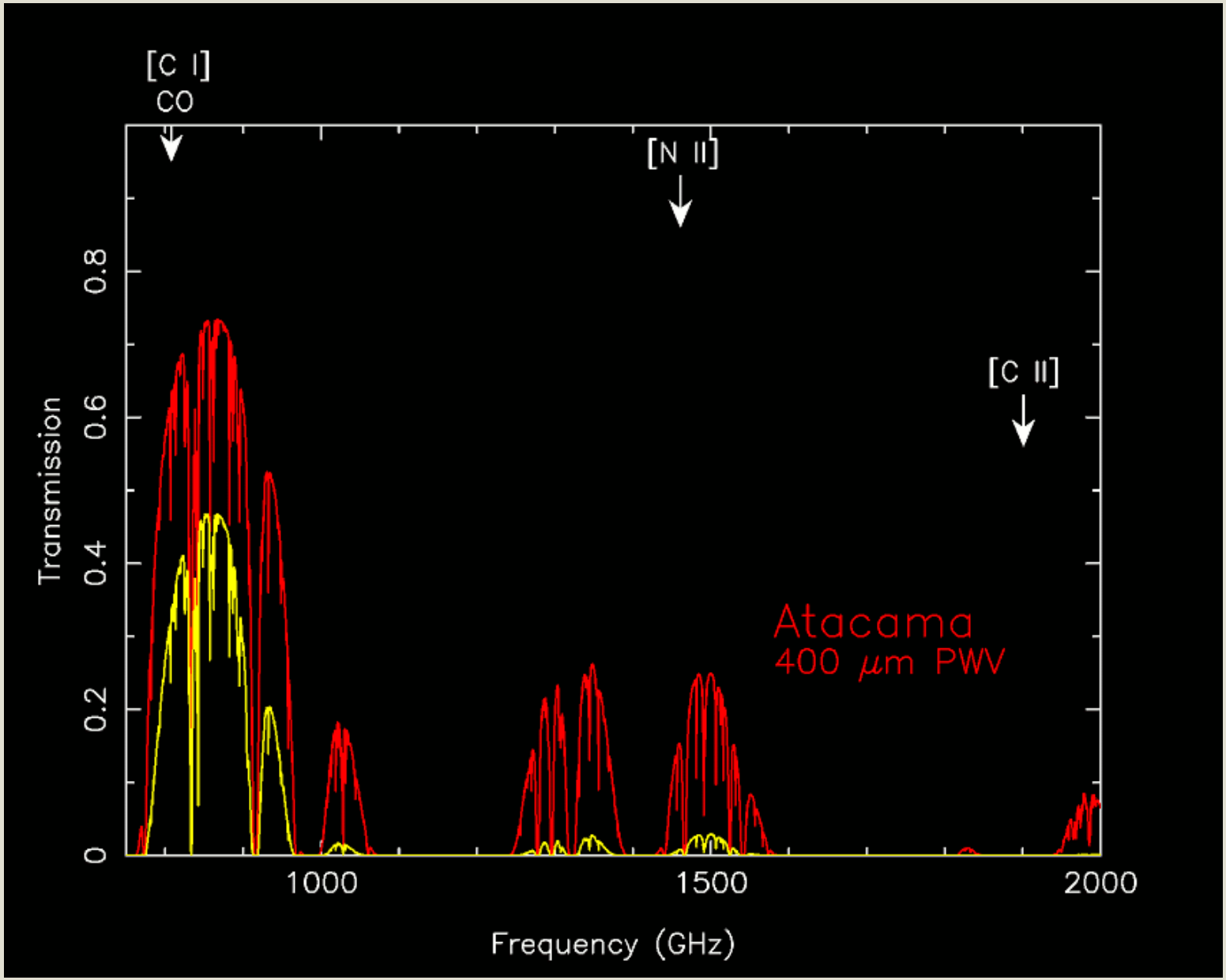
SuperCam



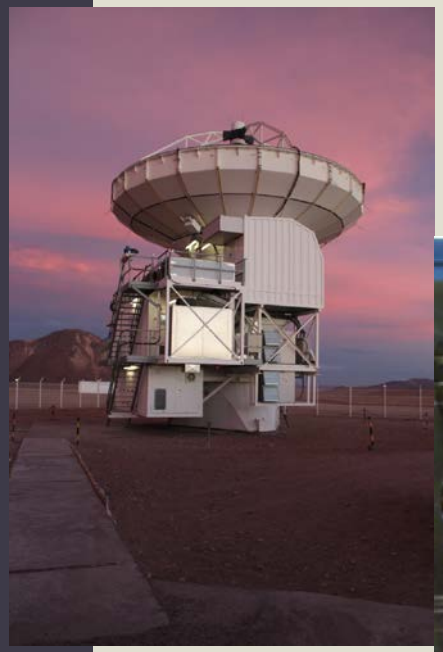
Kloosterman 2014

SuperCam Map of Orion A Molecular Cloud from the SMT, May 2013

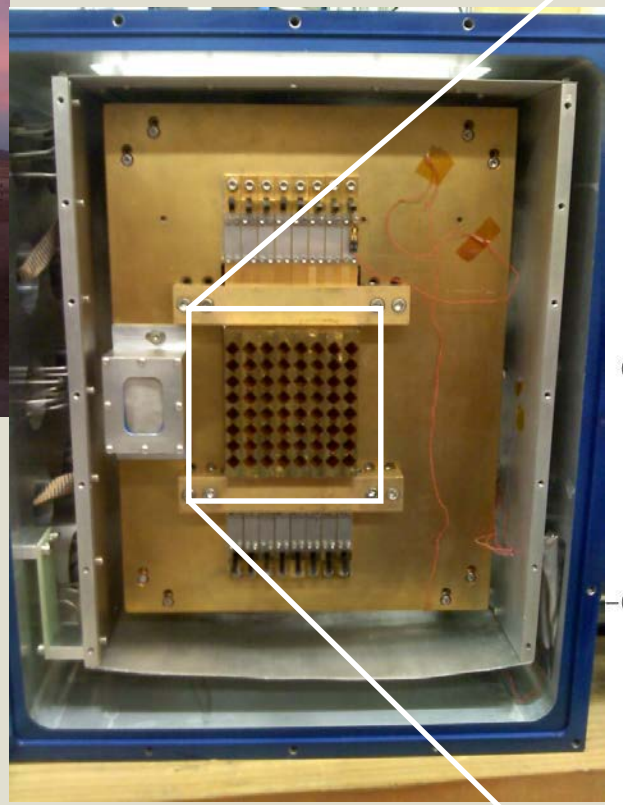
Atmospheric Transmission
(Best Site Reasonably Accessible Site in the World)



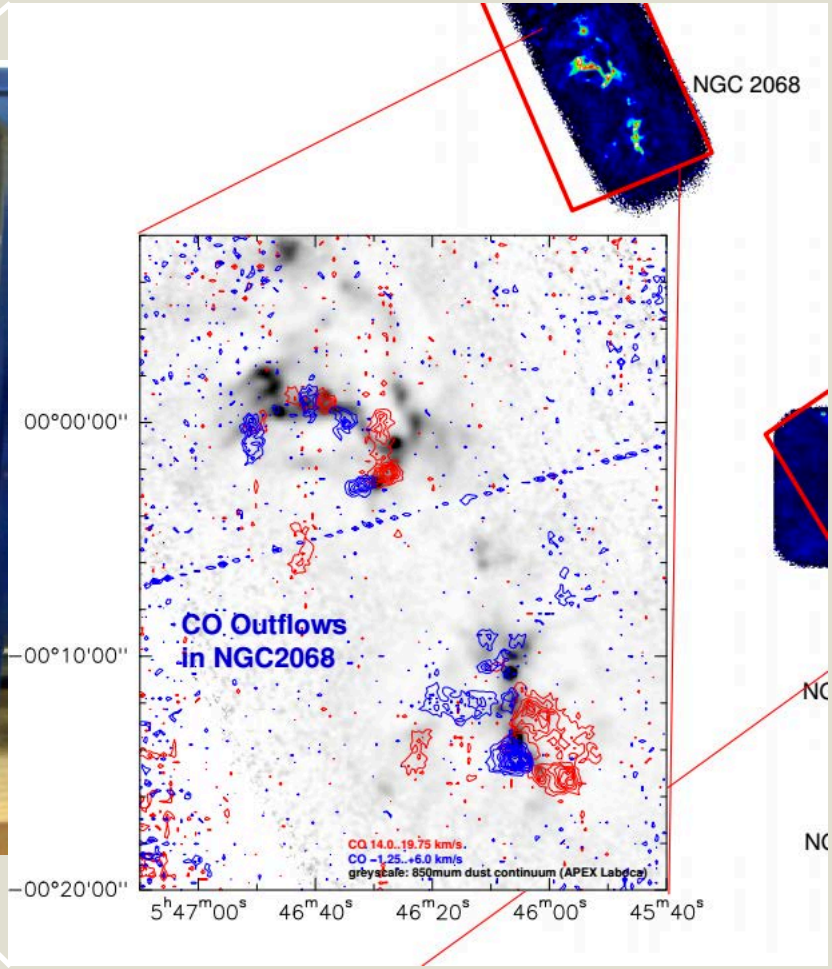
CO Survey Instrument: SuperCam



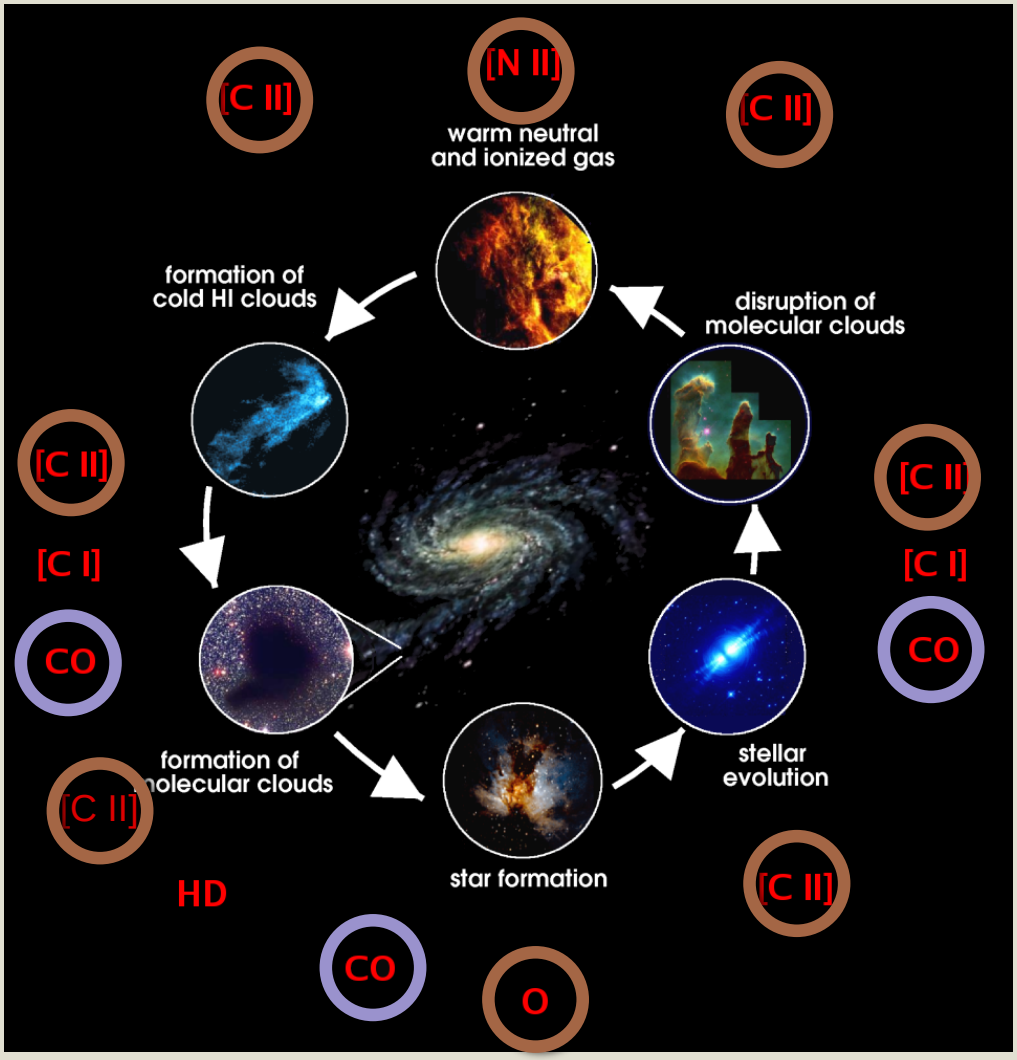
APEX



Stanke et al., 2015, *in prep*



Life Cycle of Interstellar Medium (ISM)

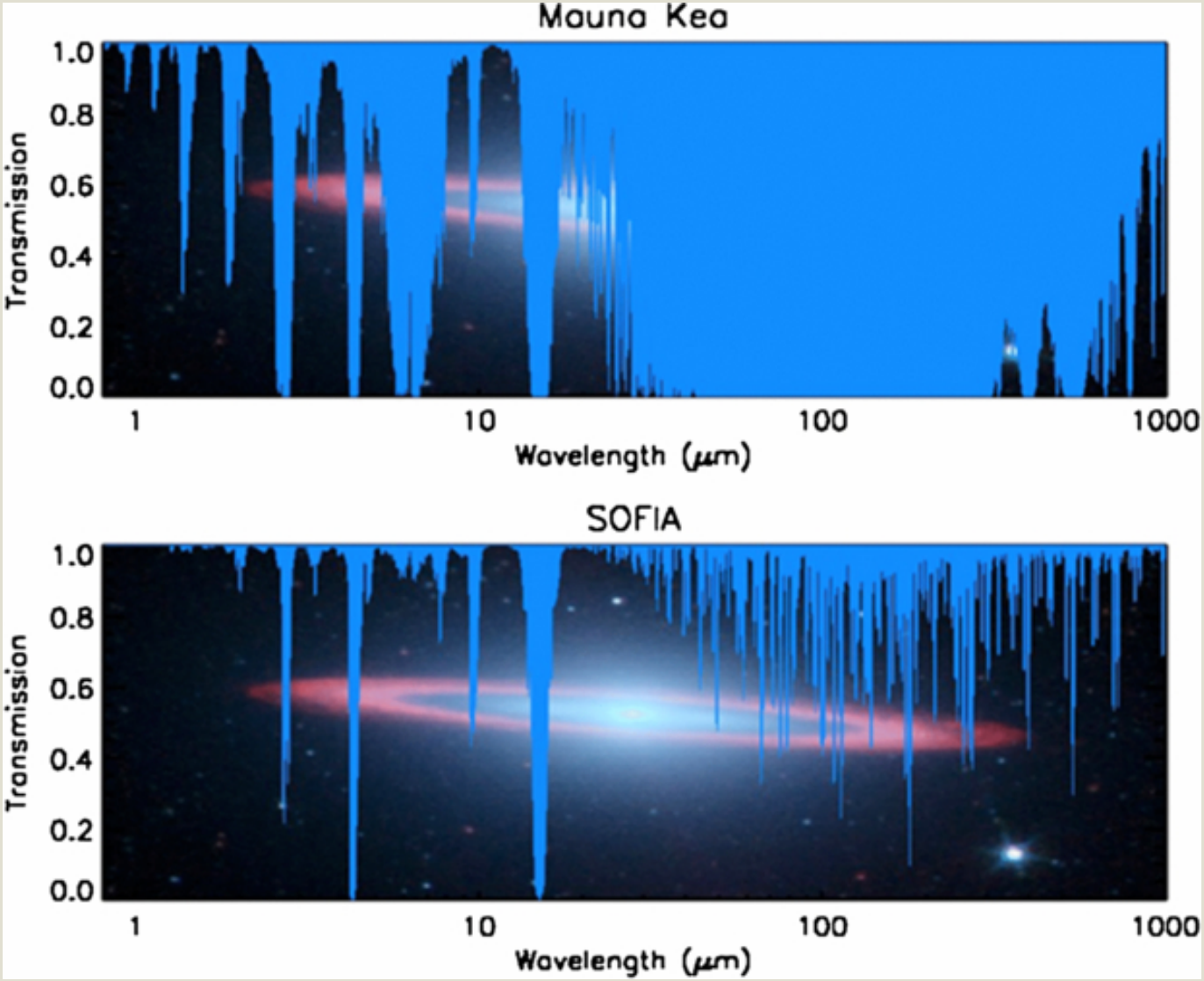


SuperCam
CO: λ = 0.8 mm, ν = 345 GHz

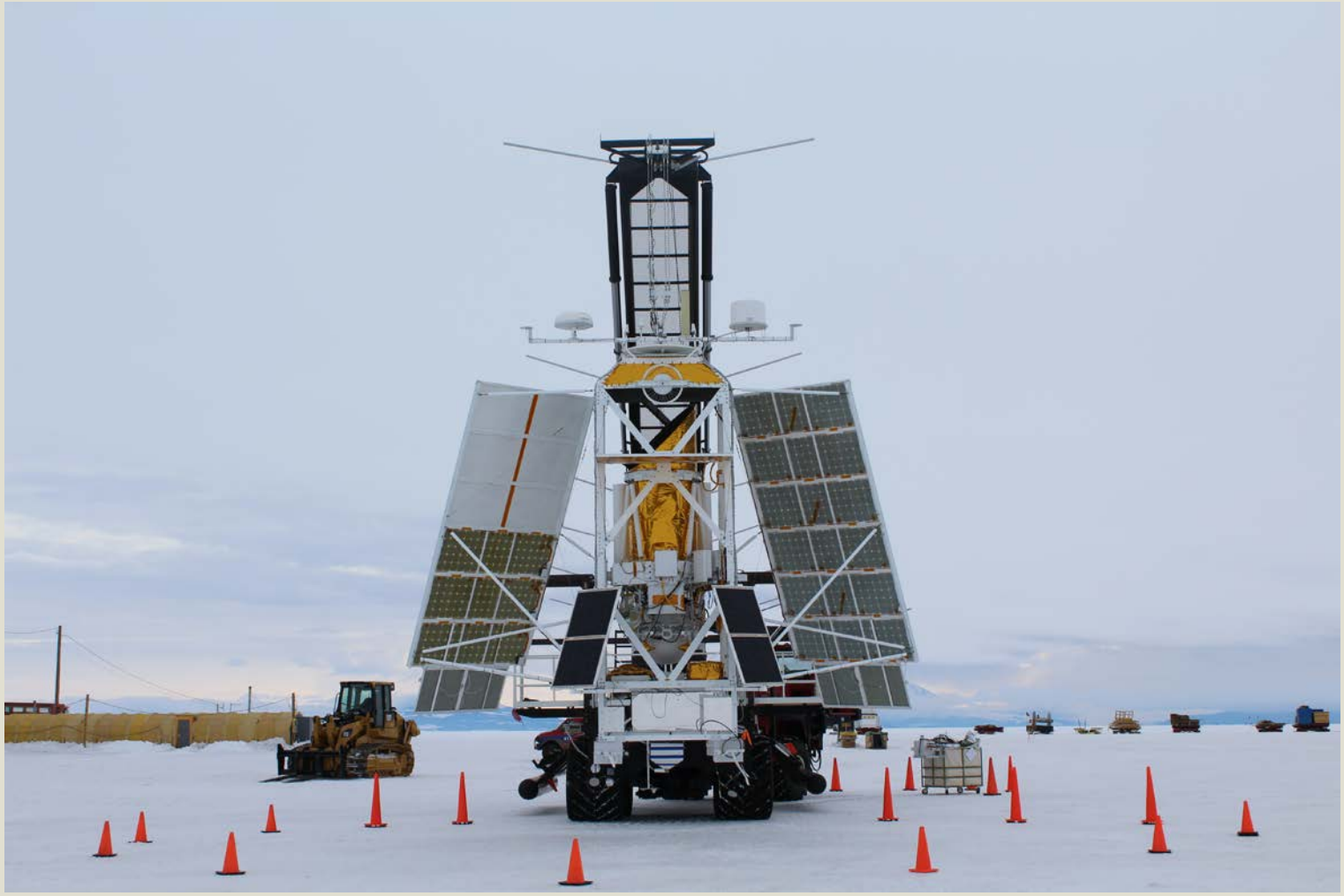
STO/STO-2/GUSTO/SHASTA
[NII]: λ = 205 μm, ν = 1.5 THz
[CII]: λ = 158 μm, ν = 1.9 THz
[OI]: λ= 63 μm, ν = 4.74 THz

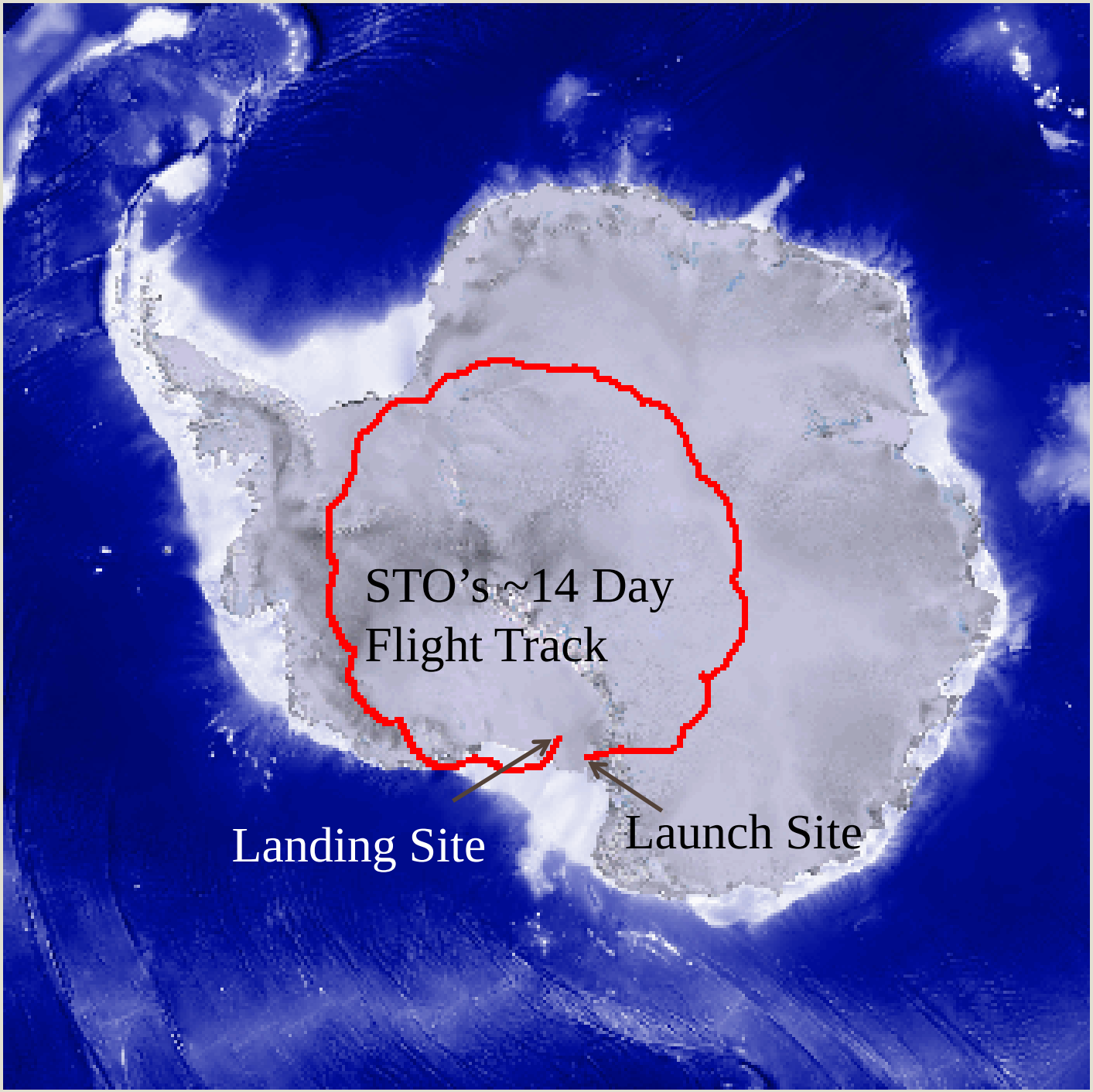
Image Credit: Kulesa and Walker

Atmospheric Transmission (SOFIA/Sub-Orbital)

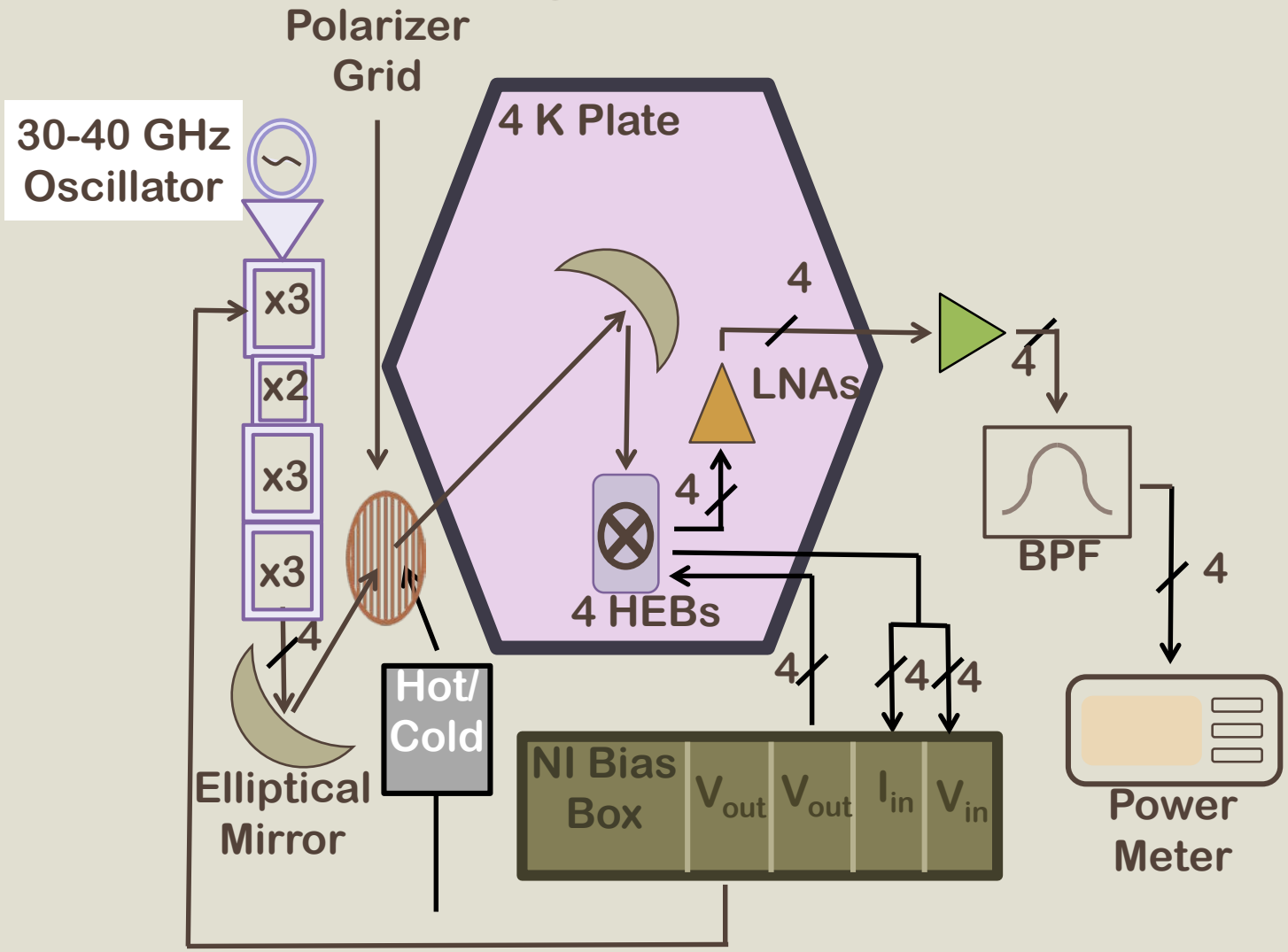


STO-2 Hang Test

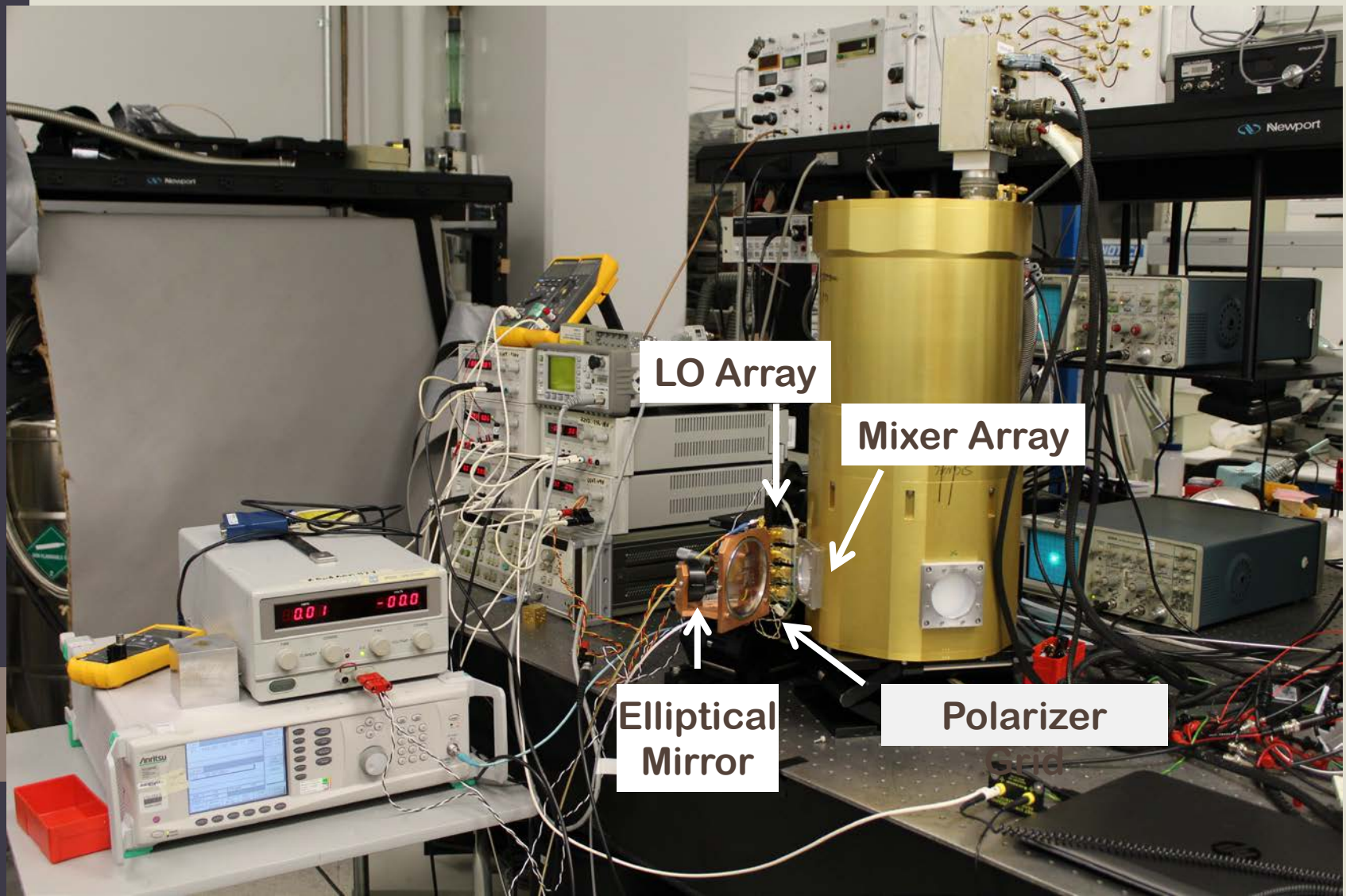



STO's ~14 Day
Flight Track
Landing Site
Launch Site

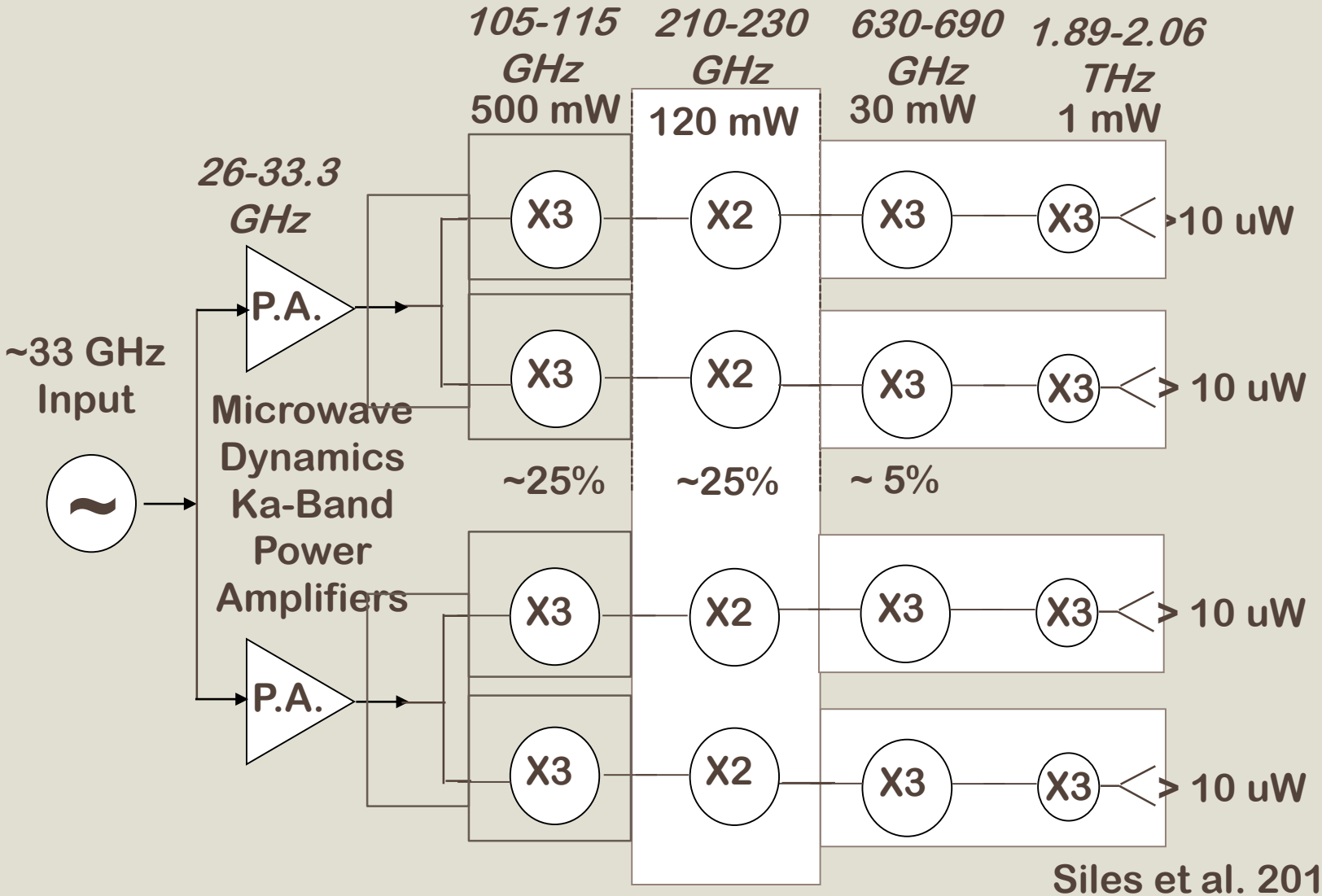
Lab Setup for Prototype Array at 1.9 THz



Lab Setup

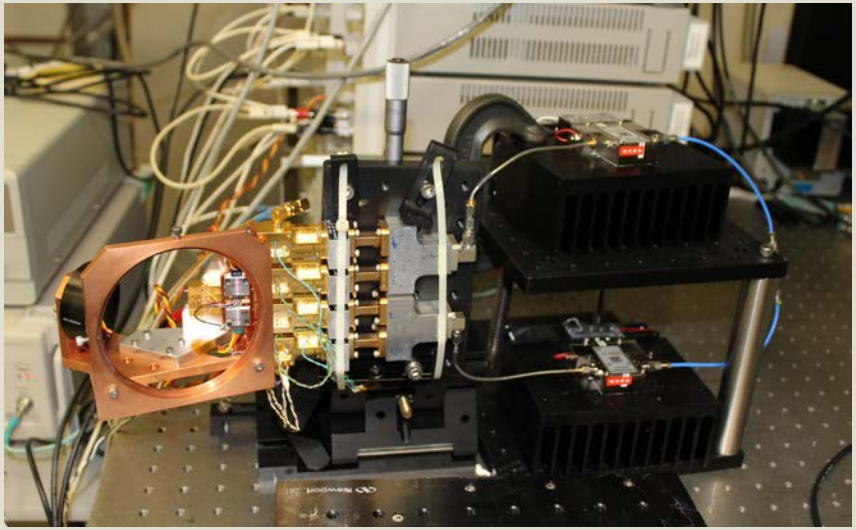

LO Array
Mixer Array
Elliptical Mirror
Polarizer Grid
Newport
Anritsu

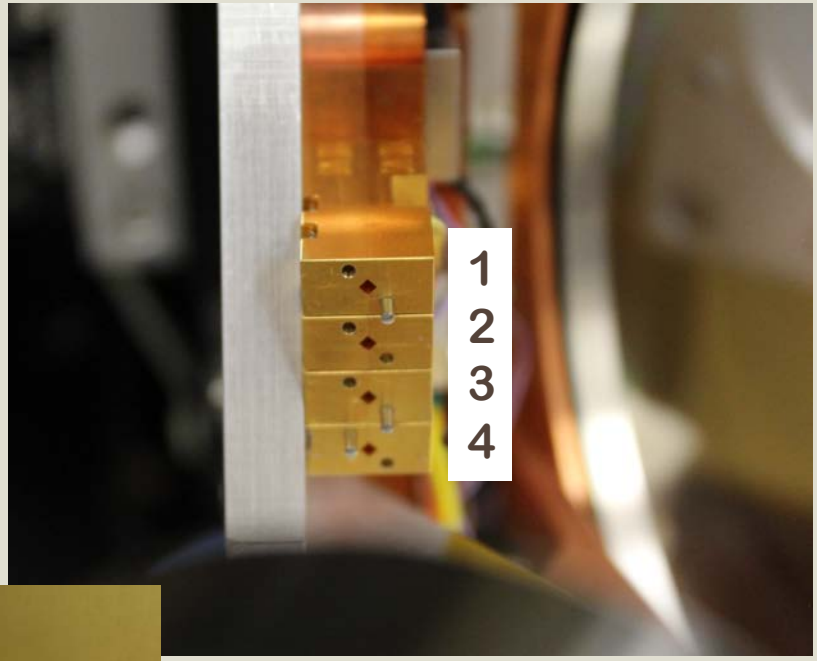
1.9 THz Local Oscillator

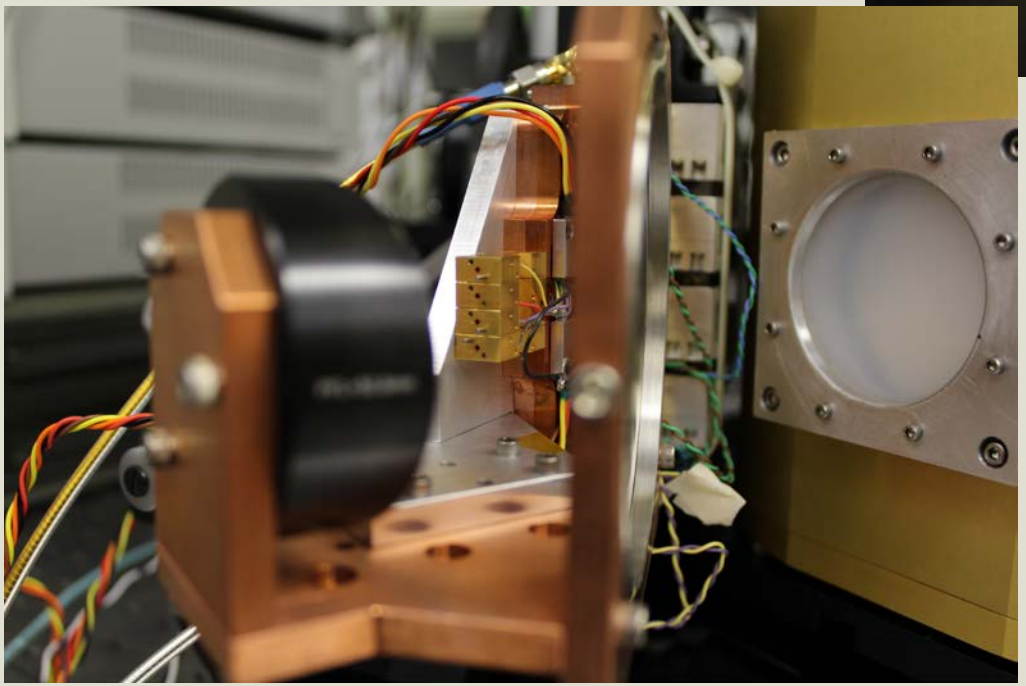


Siles et al. 2014

4-Pixel LO

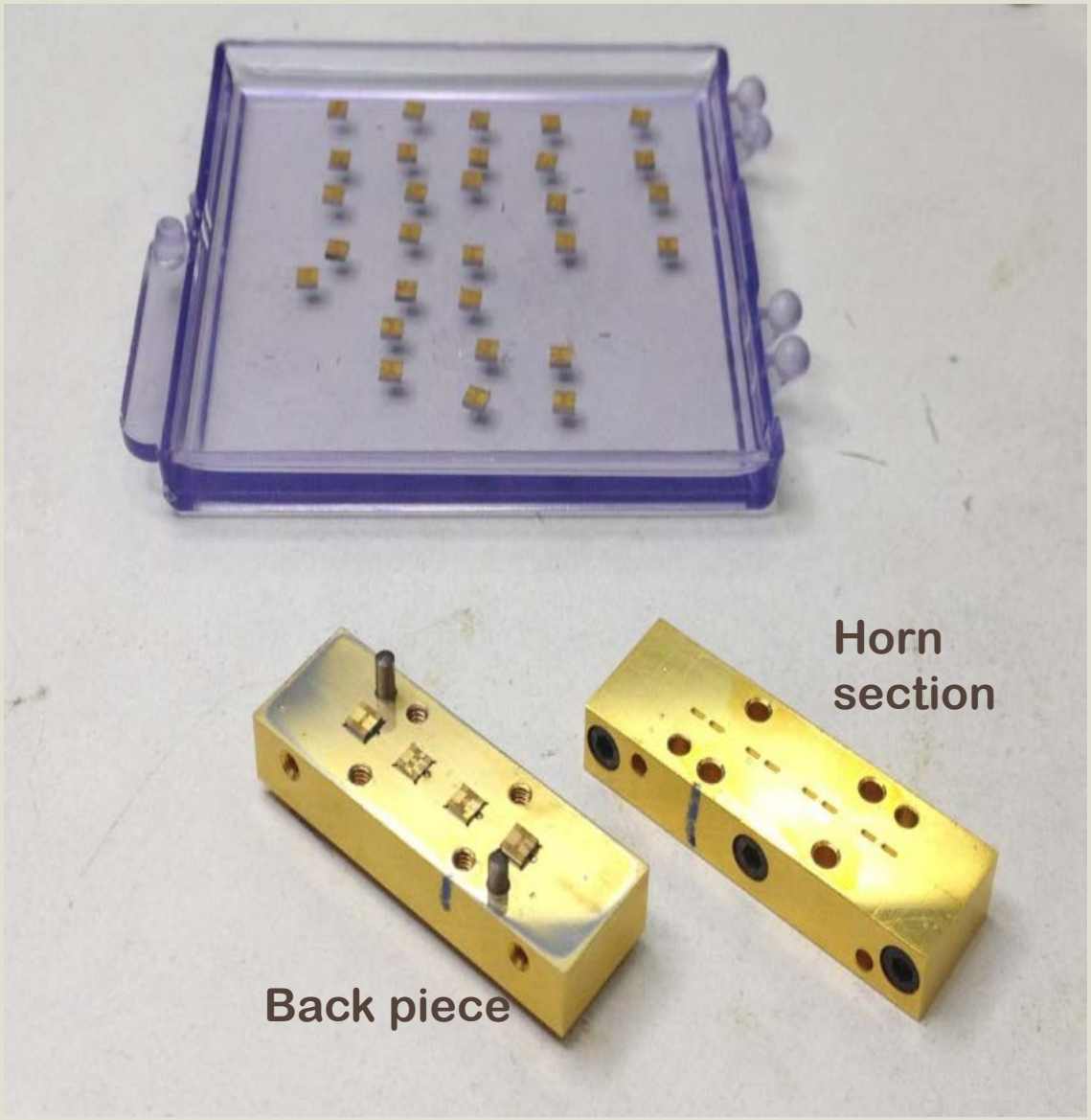






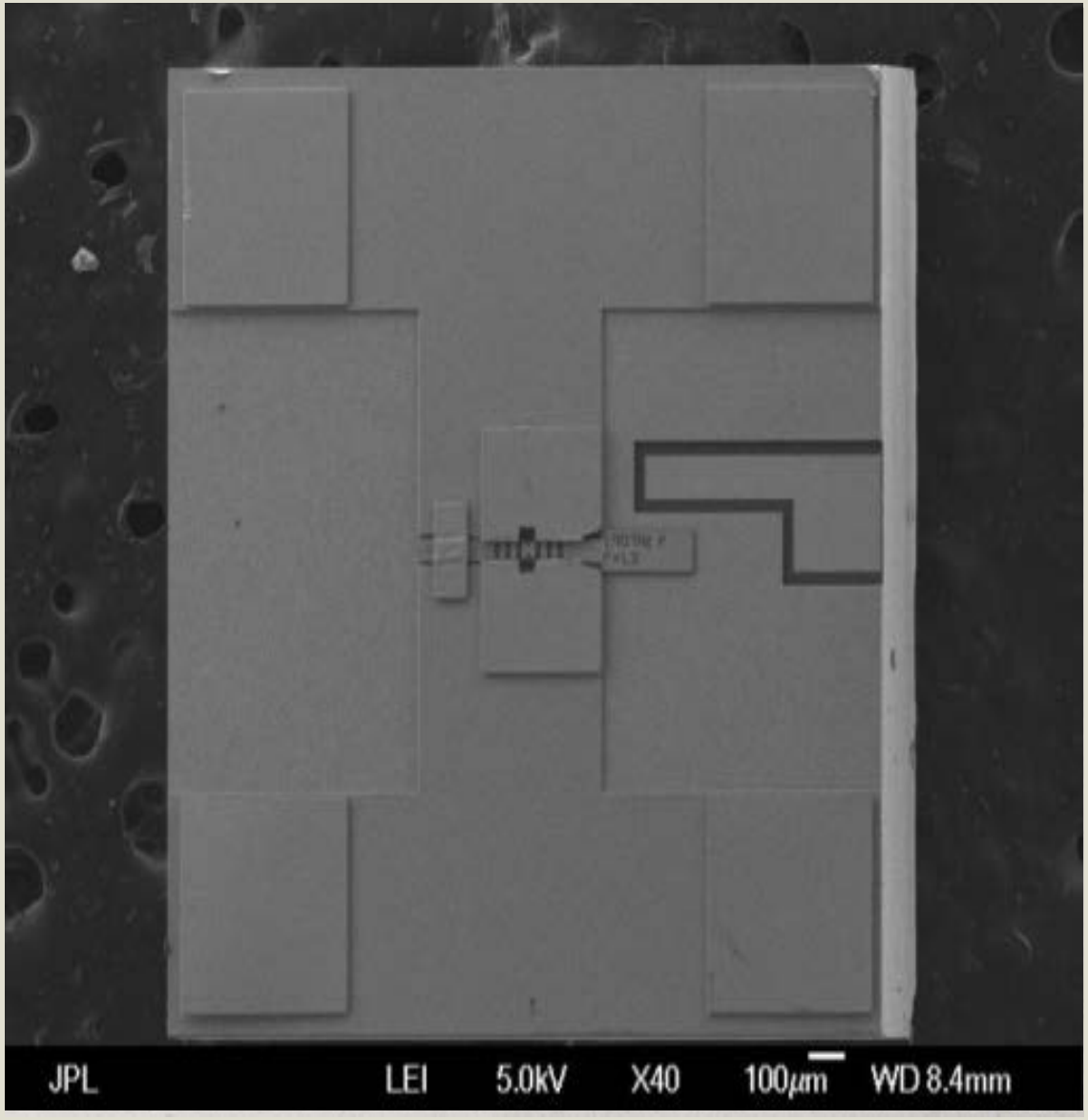
Mixers

SOI Chip-HEB Technology

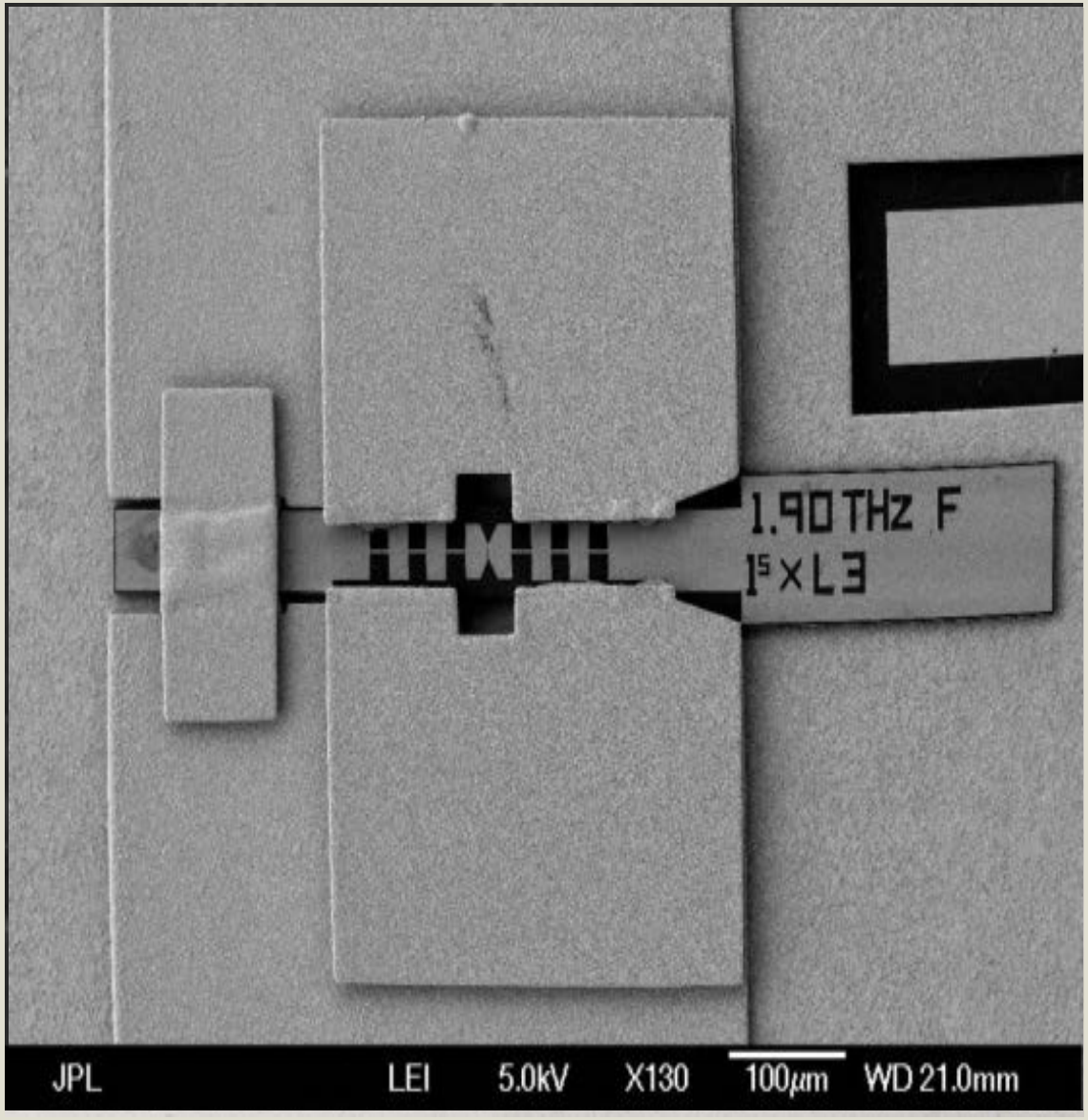


Mixers

SOI Chip-
HEB
Technology

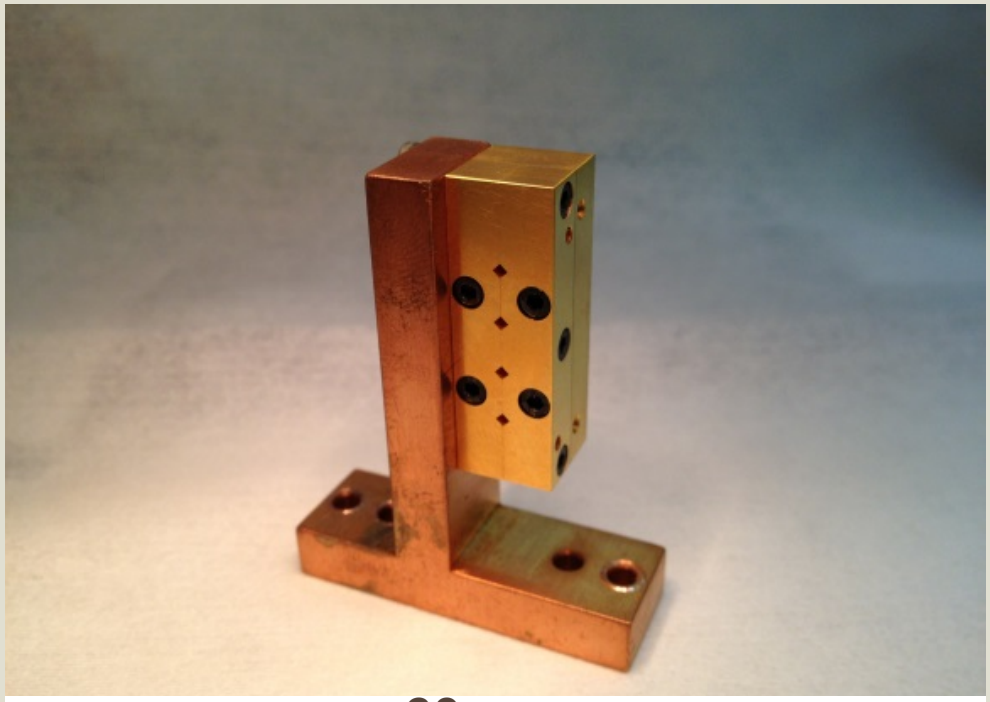


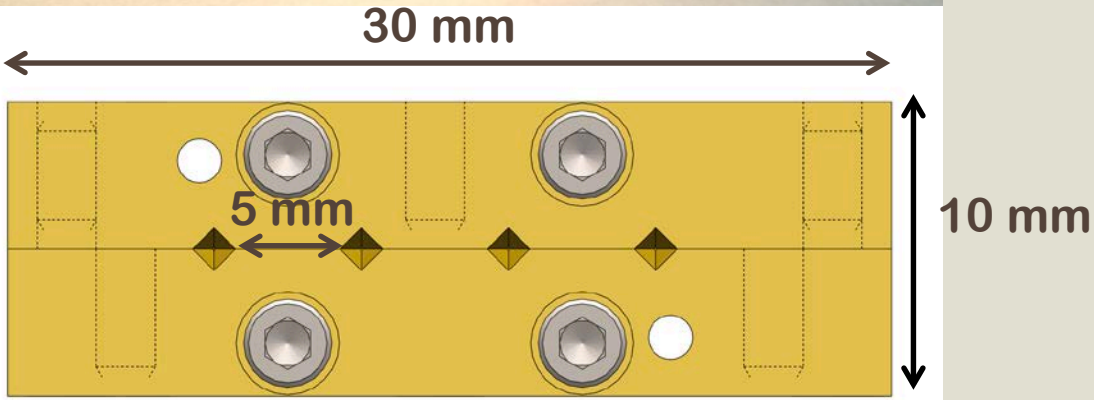
Mixers

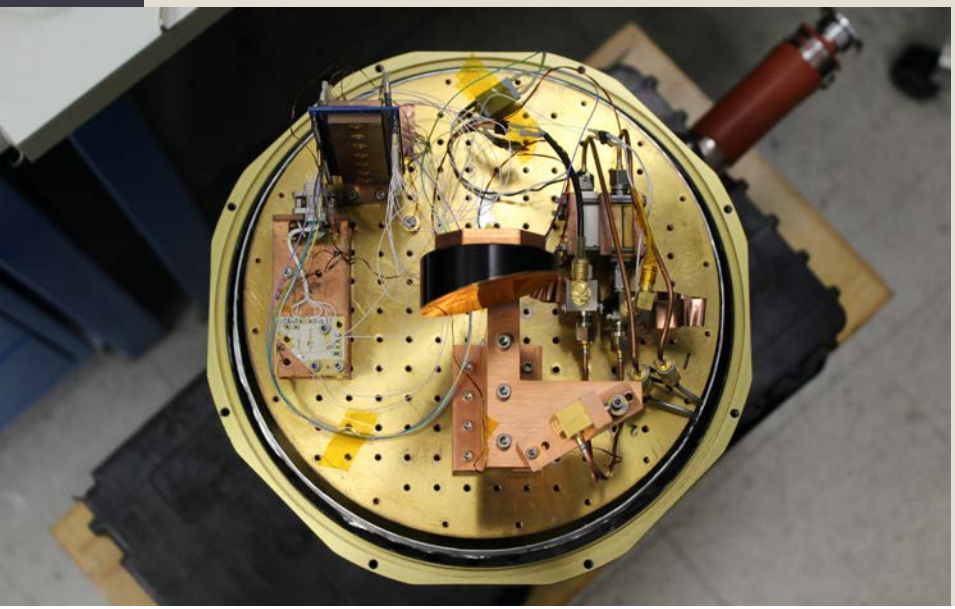


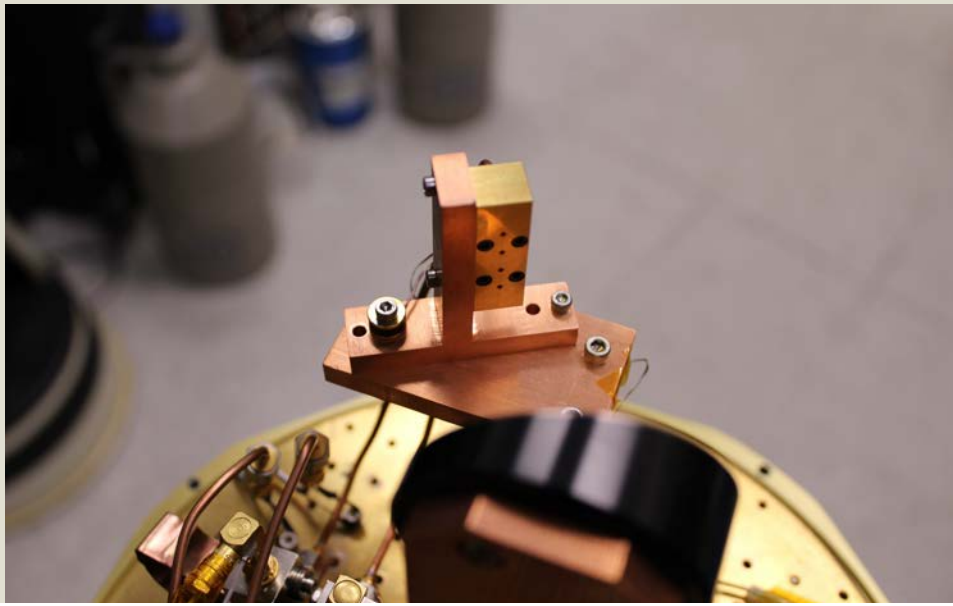
SOI Chip-HEB Technology

4-Pixel Mixer Block

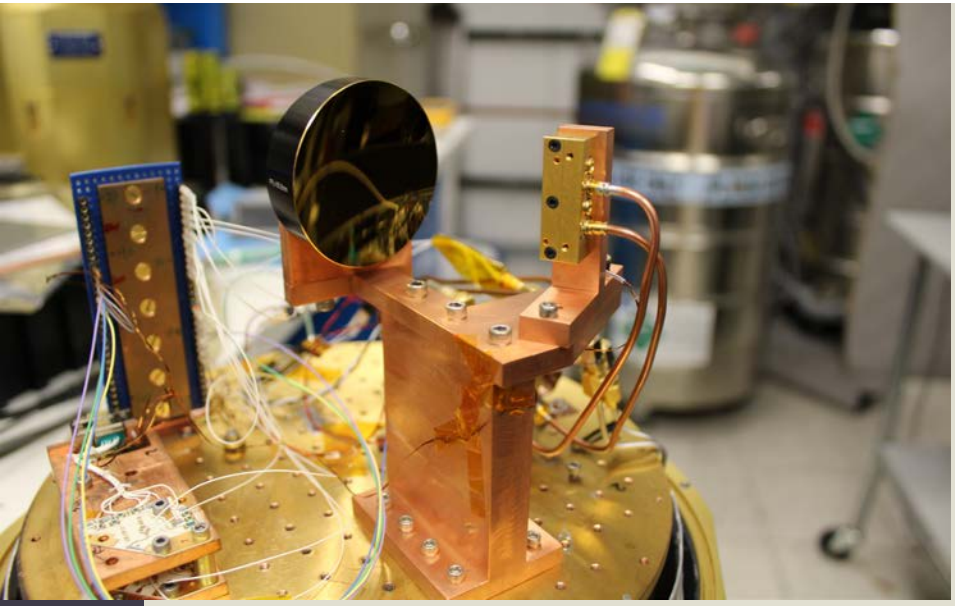


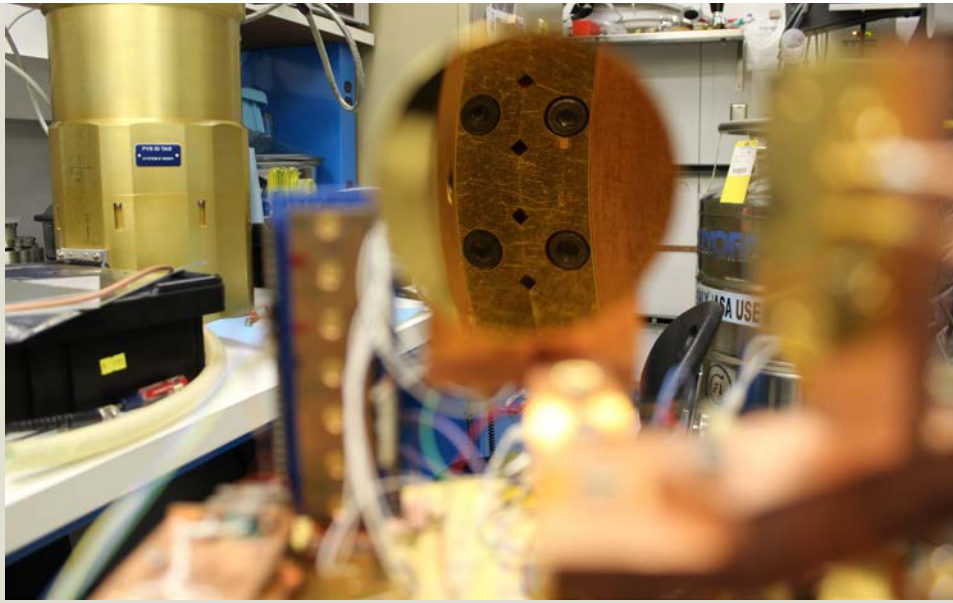






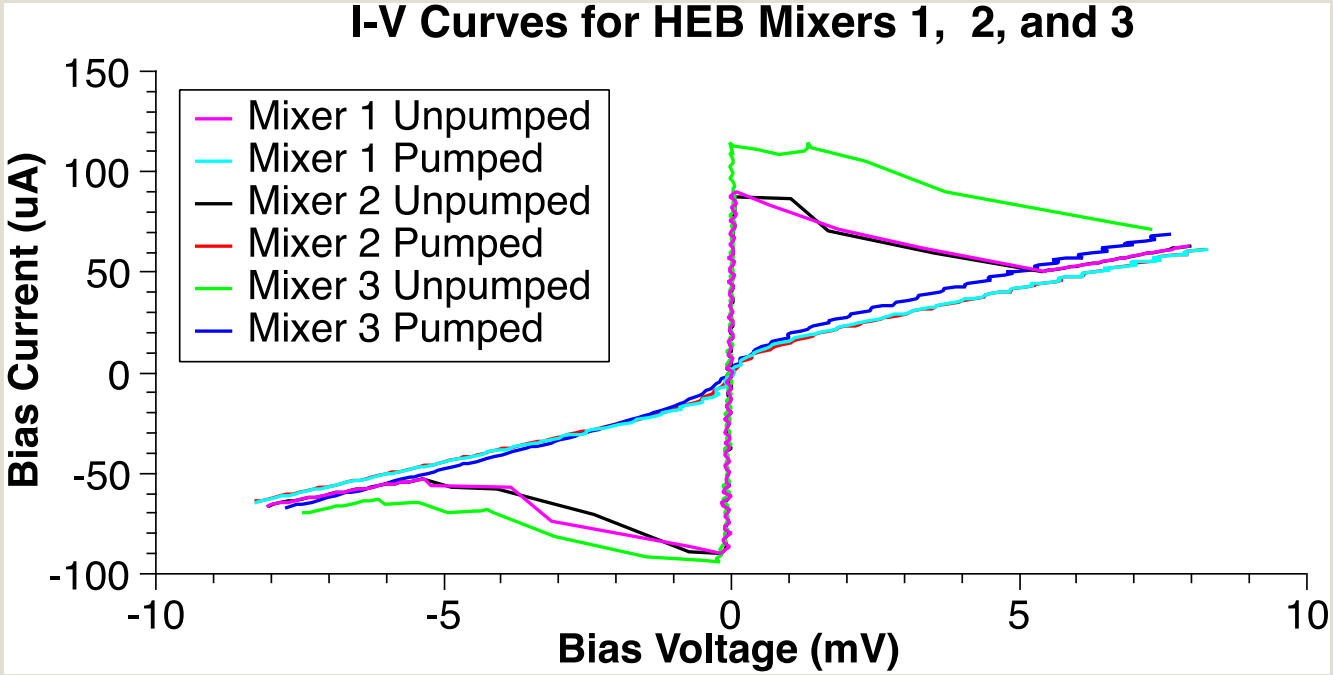
4 Pixel Array Inside the Cryostat



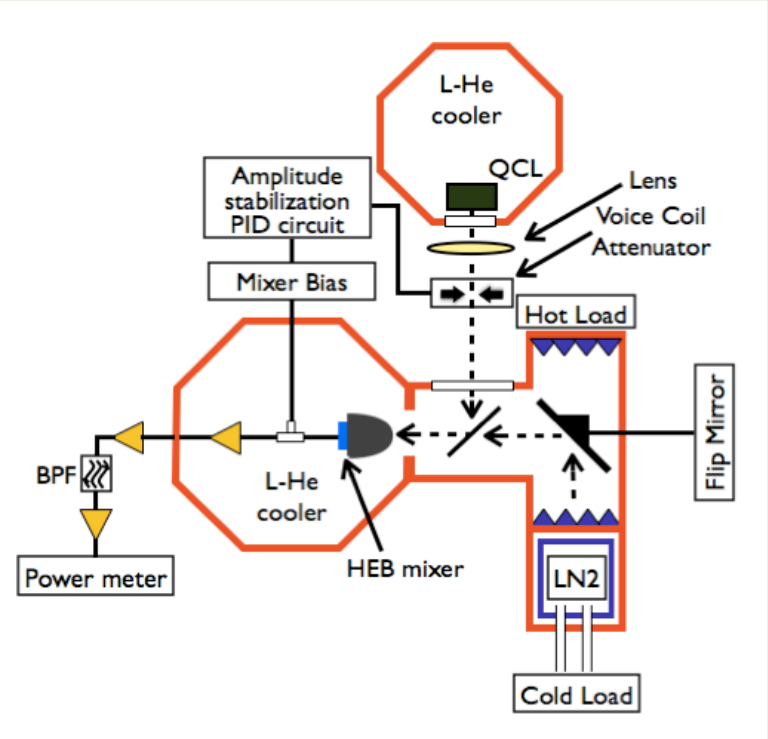


Results

	Ω_{RT}	$I_C(\mu A)$	$V_{BIAS}(mV)$	$I_{BIAS}(\mu A)$	$T_{RX}(K)$
Mixer 1	126	90.2	0.78	13.8	TBD
Mixer 2	114	89.6	0.69	8.6	840
Mixer 3	102	105.4	0.46	11.8	875
Mixer 4	0	NA	NA	NA	NA

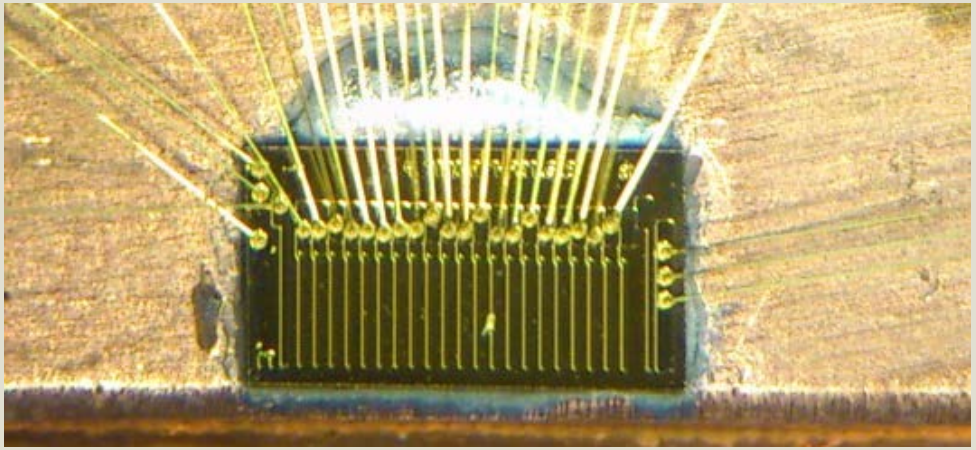


4.7 THz Heterodyne Receiver Laboratory Setup

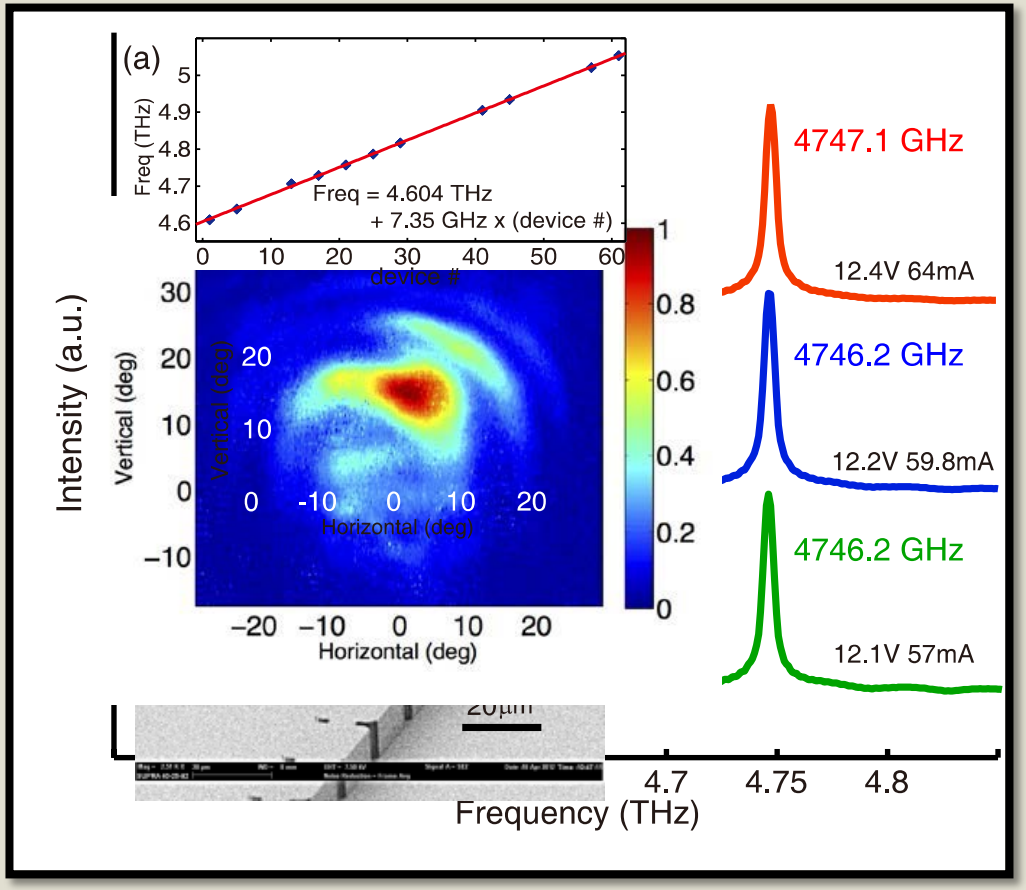


Results from Kloosterman et al. 2013

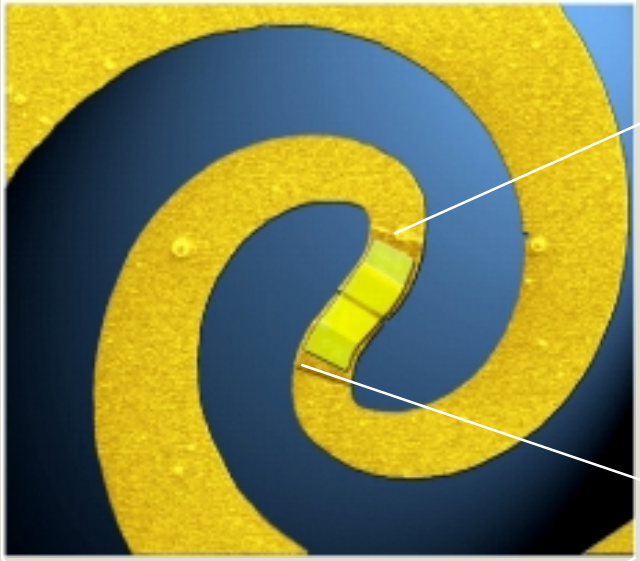
4.7 THz QCL

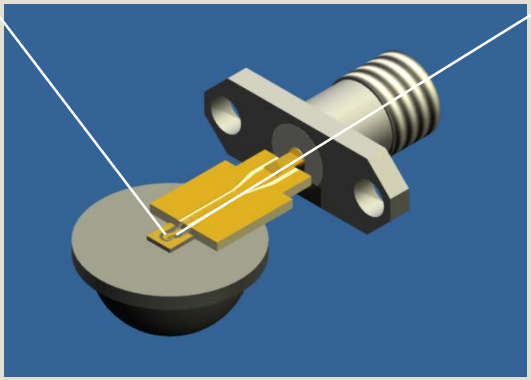


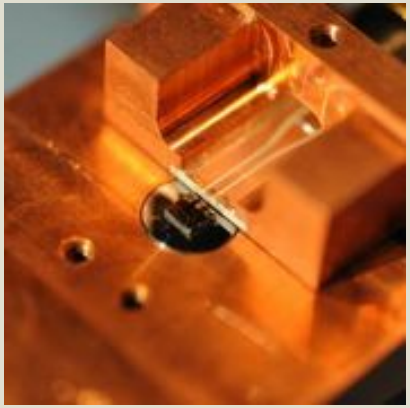
- Tuning range: 1.5 GHz
- Tuning coefficient: 2.4 GHz/V
- THz output: 0.25 mW
- Low power requirement: 0.8 W @ 15 K
- Operation up to 77 K



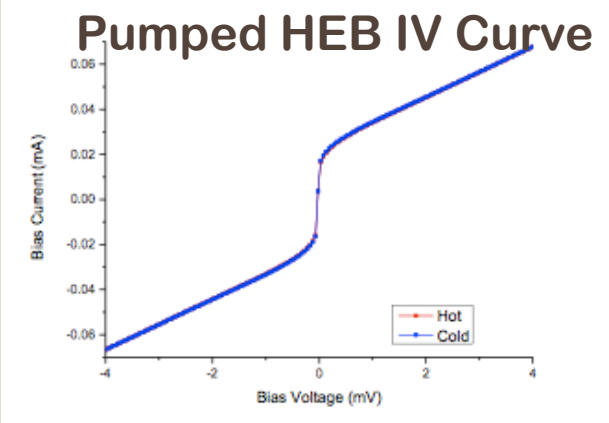
Mixer: Hot Electron Bolometer



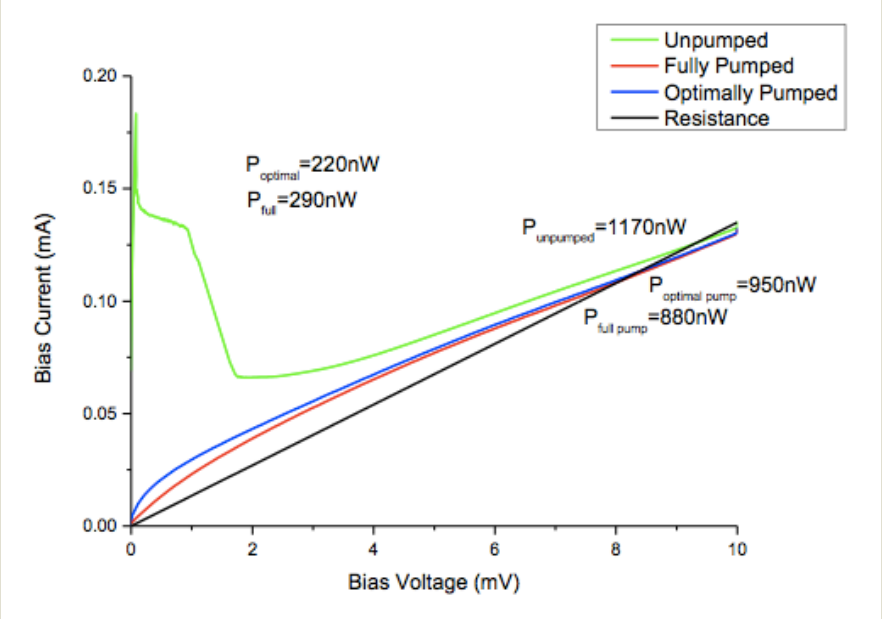




- NbN 2 x 0.2 μm^2 superconducting bridge
- Tight spiral antenna
- Coated Si lens for 4.3 THz



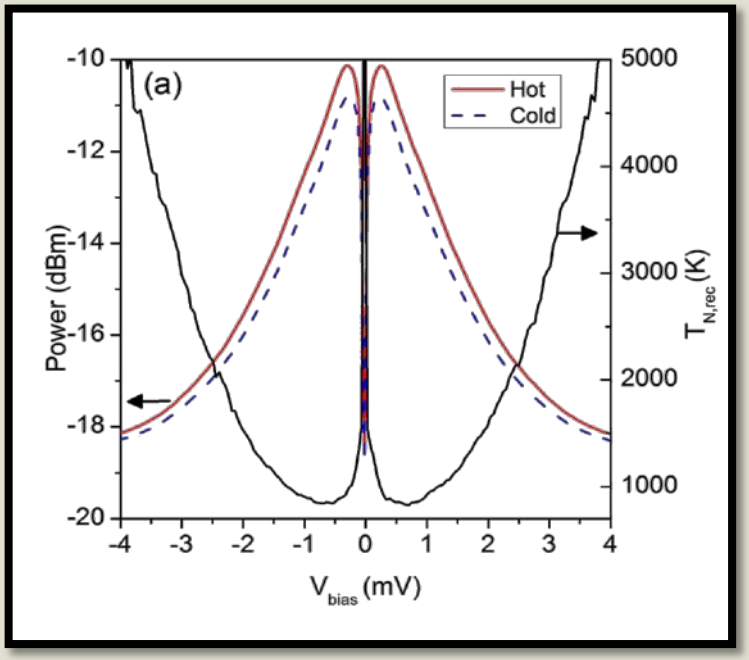
QCL-HEB Coupling Efficiency

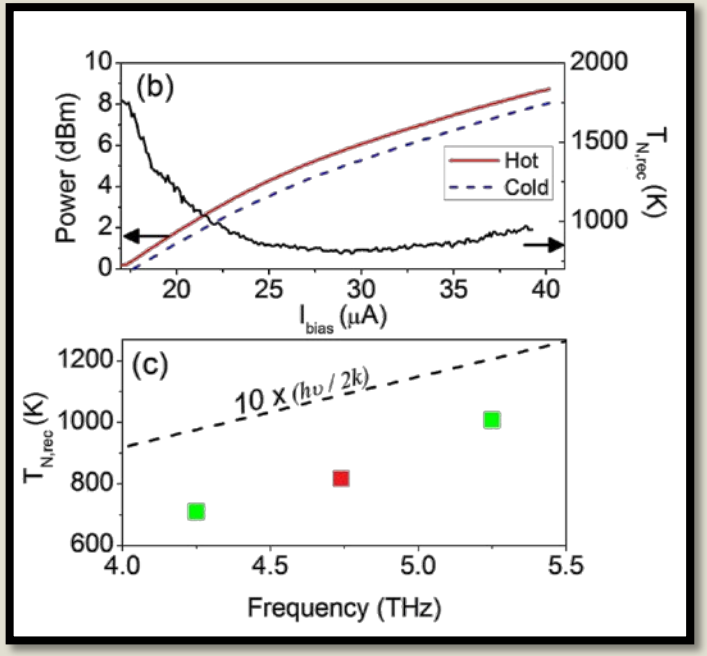


QCL Power Loss

- UHMW-PE lens and cryostat windows: **~3 dB**
- Air: **~3.5 dB**
- Mylar beam splitter: **~9 dB**
- IR filter: **~0.8 dB**
- Coated Si lens: **~1 dB**
- Spiral antenna polarization: **3 dB**
- Total: **~21 dB**

Receiver Noise Temperature



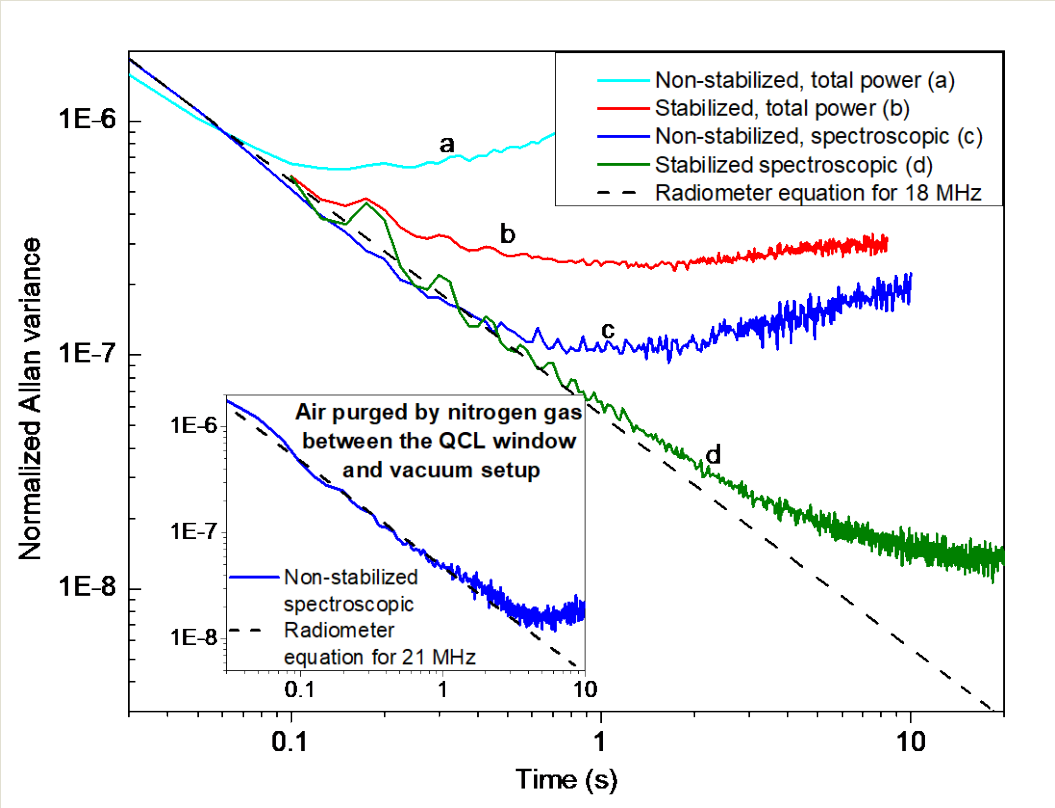


- 3 methods used to measure y-factor at 4.7-THz for an average T^{DSB} = 815 K!!!
- At 4.25 THz, measured 750 K
- At 5.25 THz, measured 950 K

$$T_{N,rec} = \frac{T_{eff,hot} - YT_{eff,cold}}{Y - 1}$$

Stability – Allan variance measurements

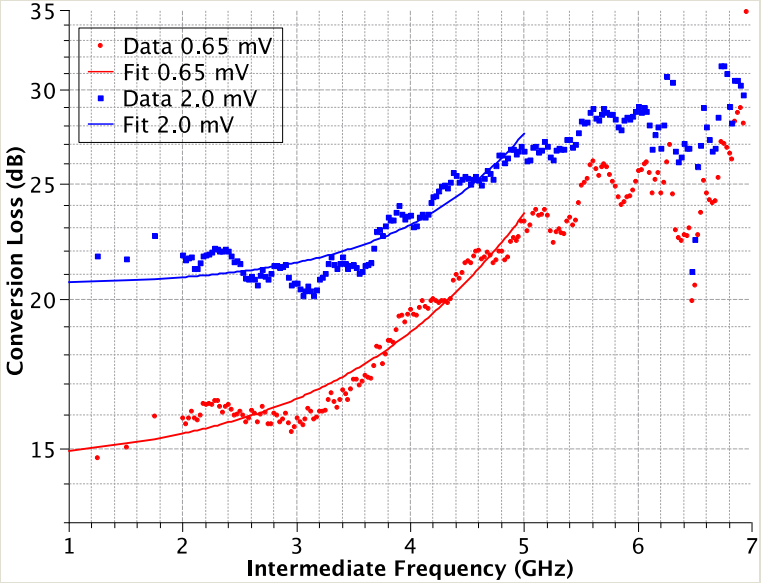
- Non-stabilized, spectroscopic Allan variance: ~1 second
- Stabilized spectroscopic Allan variance: ~15 seconds
- Nitrogen gas purged (non-stabilized) Allan variance: ~7 seconds
- Suggests that atmospheric turbulence may be a large contributor to instability of the system



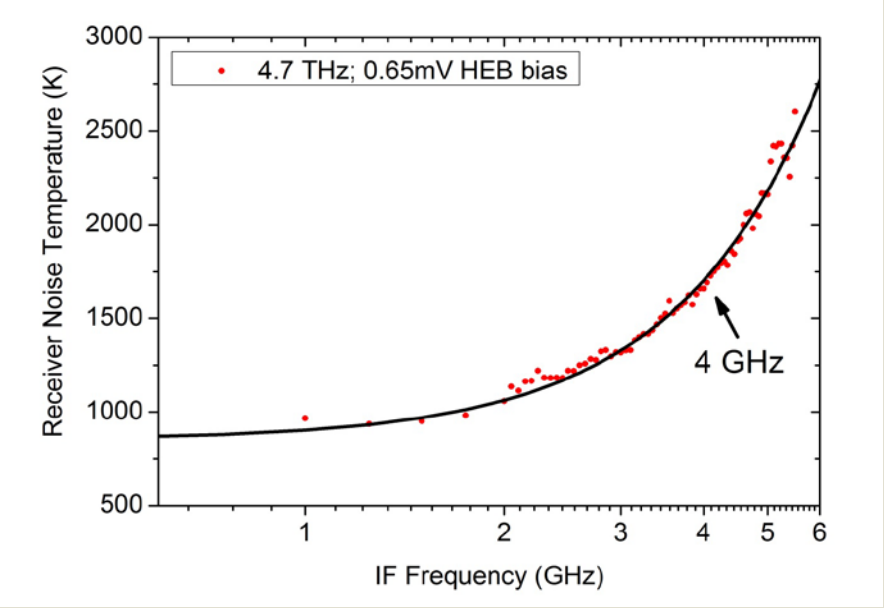
$$\sigma_A^2(\tau) = \frac{1}{2\tau^2(N-2n+1)} \sum_{k-1}^{N-2n+1} [x(t+2\tau) - 2x(t+\tau) + x(t)]^2$$

IF Bandwidth

Conversion Loss

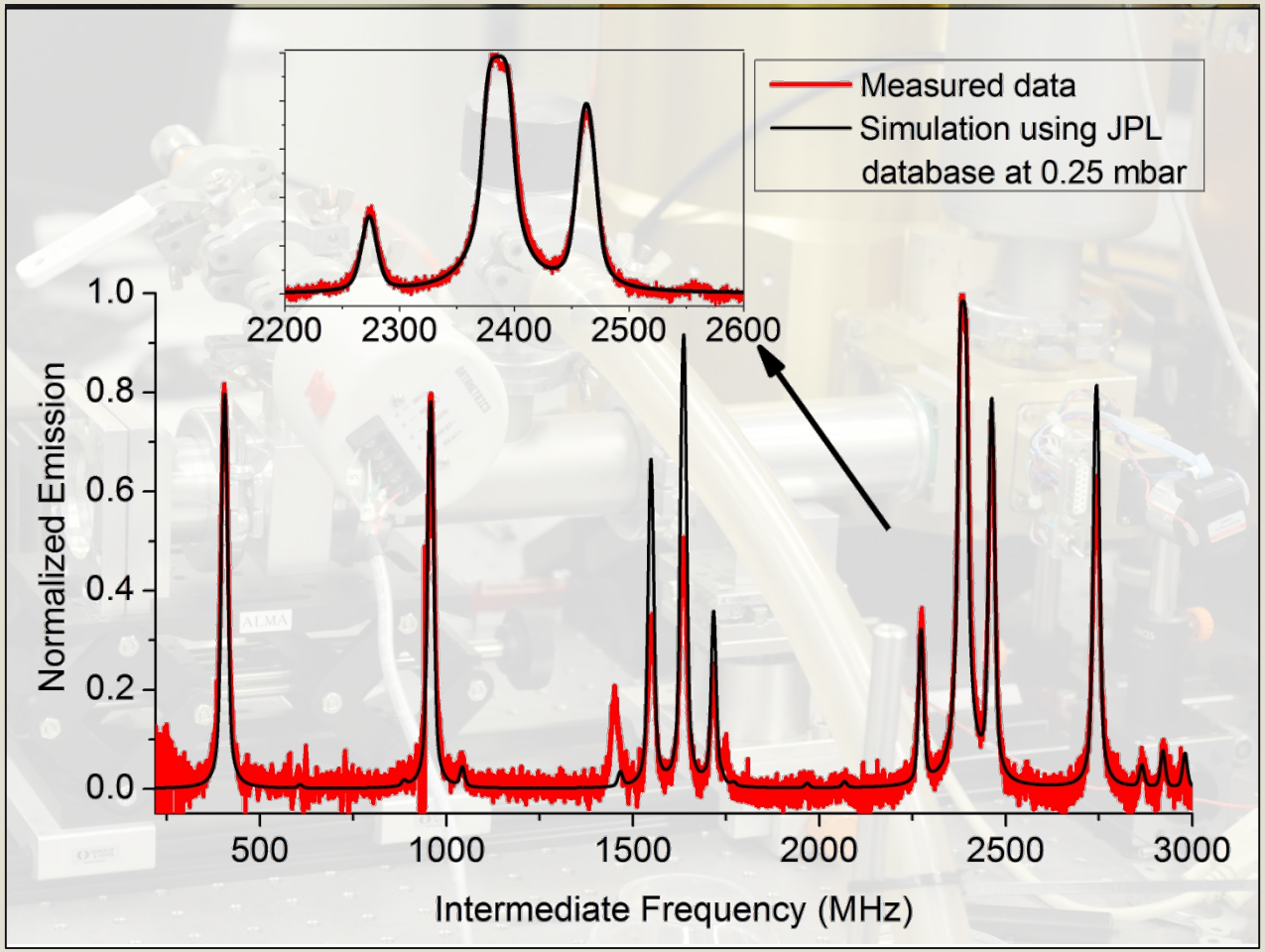


IF Noise Bandwidth



Methanol Gas Spectroscopy at 4.7 THz

Methanol gas spectroscopy used to verify performance



Good agreement with model demonstrates:

- HEB sensitivity
- IF linearity
- Receiver stability
- LO frequency

  QCL: 4.7404 THz

  [O I]: 4.7448 THz

  -> ~4.3 GHz IF

Next Steps To Arrays

New feedhorns

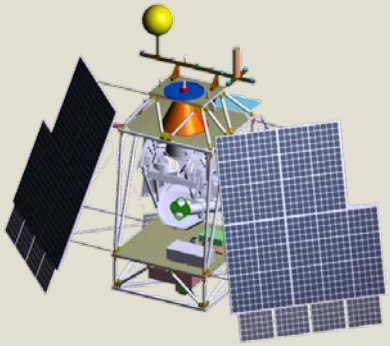
- Easier to machine, and assemble
- Lowers cross-polarization

Summary/Future of THz Astronomy

SuperCam

STO/STO-II

GUSTO

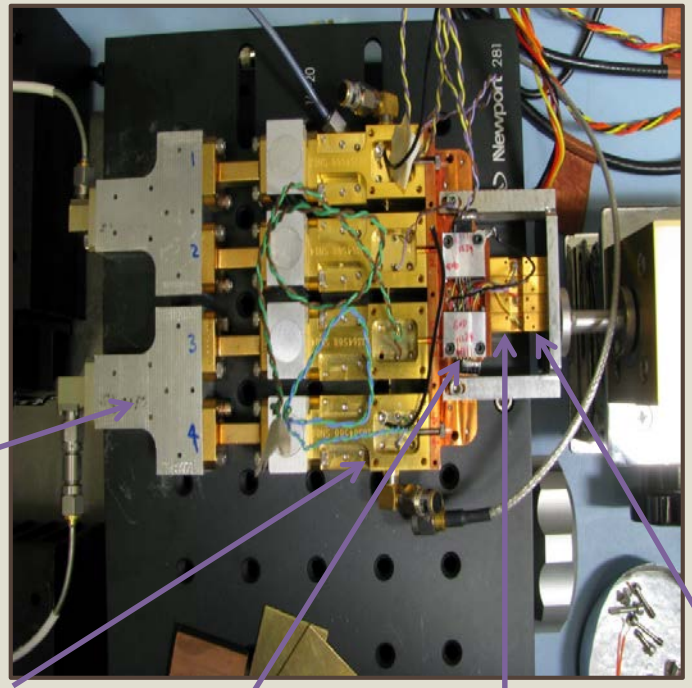


SHASTA

Extra Slides

Penguins!

1.9 THz Local Oscillator



18mm

10mm

Ka-band 2-way power dividers

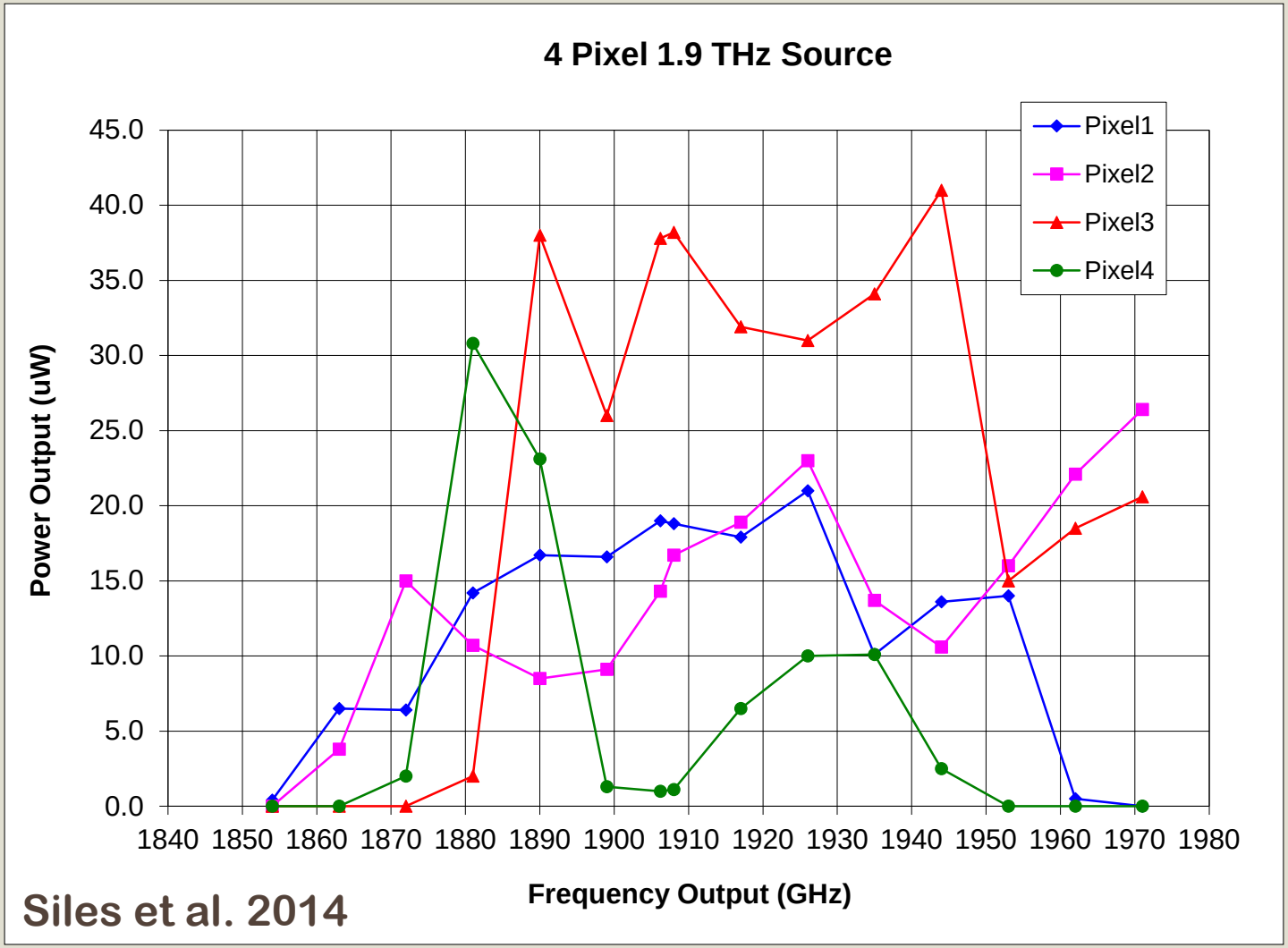
110 GHz tripler modules

225 GHz doubler modules

660 GHz tripler modules

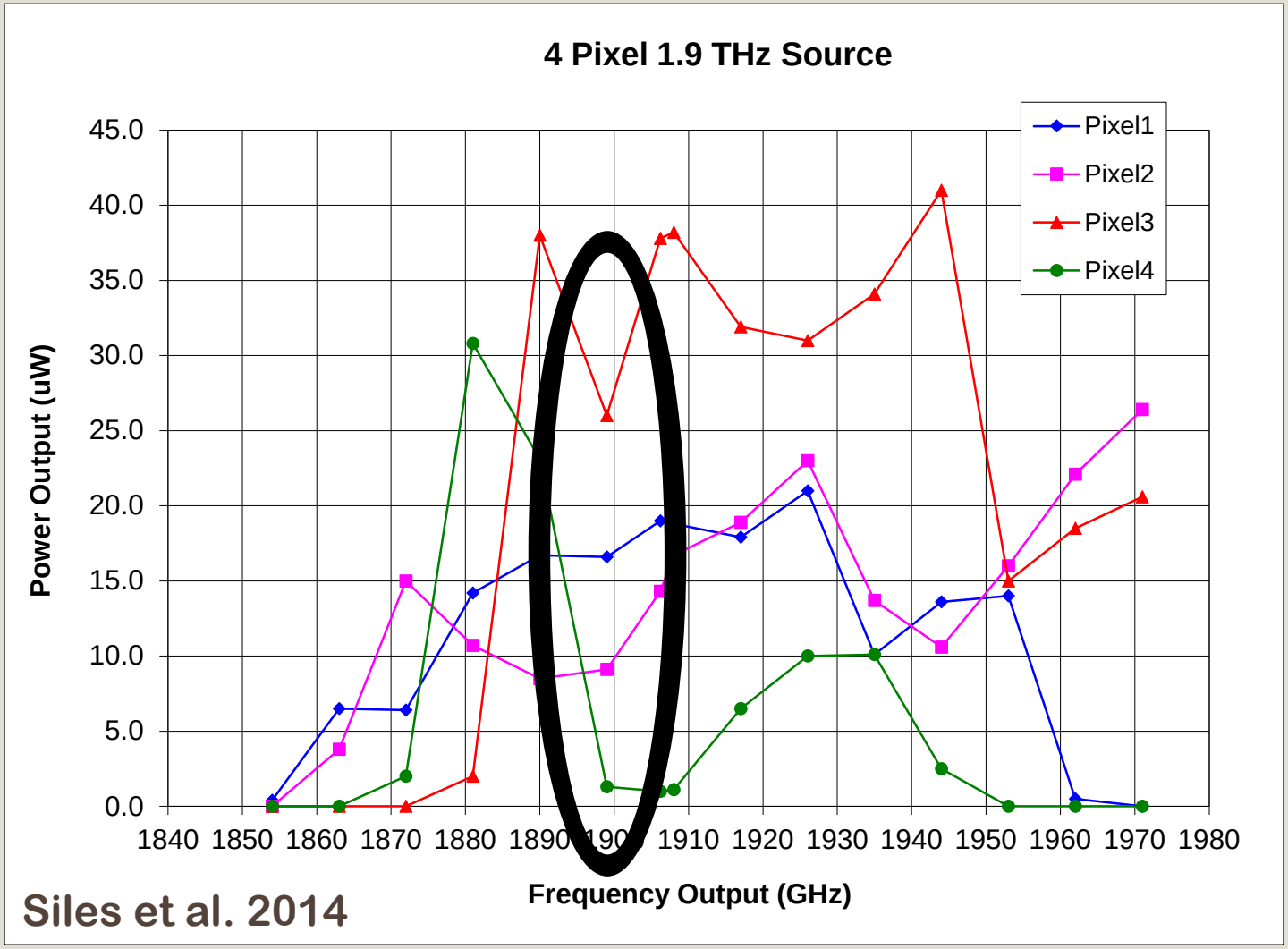
1.9 THz tripler modules

Power Output

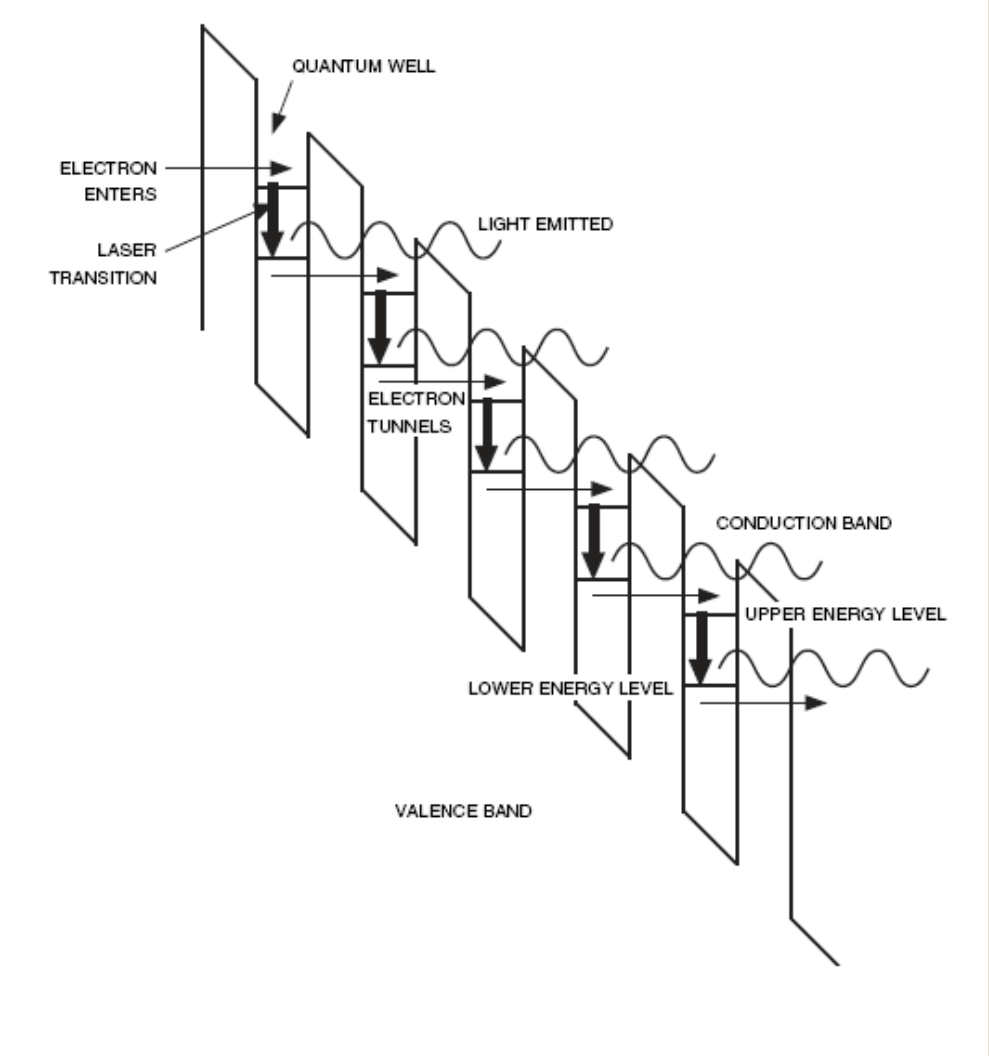


Siles et al. 2014

Power Output



Siles et al. 2014

Local Oscillator: Quantum Cascade Laser

- A voltage moves free electrons from the valence band to the conduction band
- These electrons tunnel through a quantum well
- A photon is released with the amount of energy lost by the electron
- Repeat