Far-Infrared Technology for Spaceborne Applications

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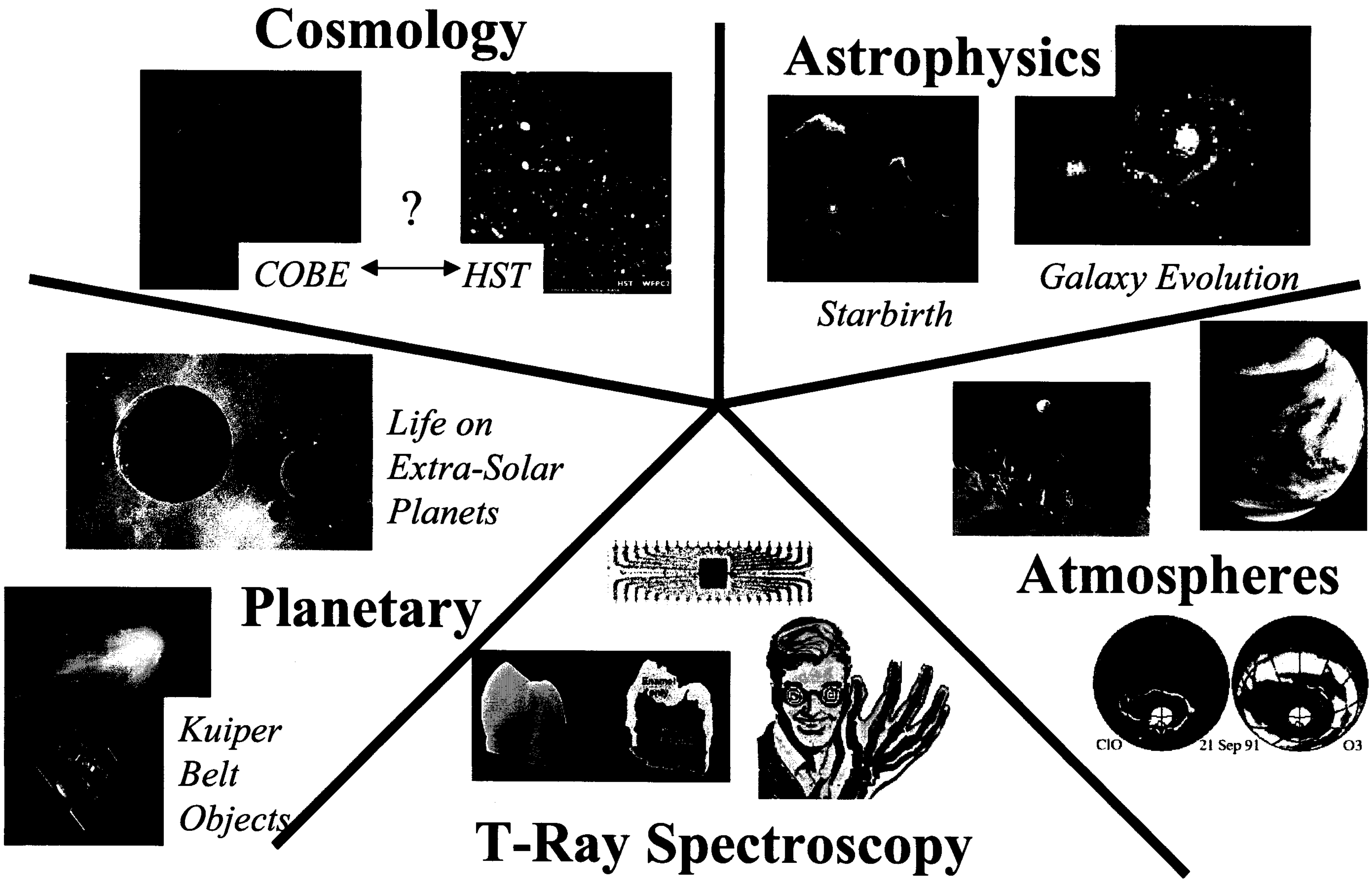
Flight: John Oswald (Group Leader): Mike Gaidis, Karen Lee, Robert Lin, David Pukala, Raymond Tsang, Tigran Karsian

Goals of this talk

- Convey the importance of the FIR/THz/Submm spectral region, and show its great potential for ***breakthrough discoveries***
- Review the common ***THz detectors*** with an eye to the future (not enough time to cover sources today)
- Review what the ***science community needs*** from you

What can you do with FIR?



Galdis, IEEE Frequency June 7, 2000 JPL

Astrophysics: Photons in the Far-Infrared

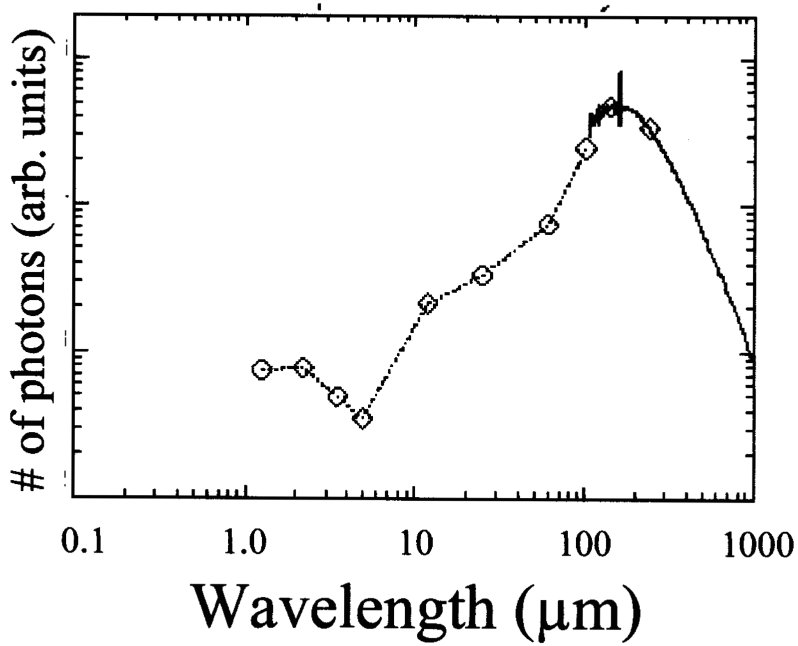
Common processes which produce FIR radiation:

- thermal emission from interstellar dust
- fine structure line emission from atoms and ions
- rotational line emission from molecules
- synchrotron and bremßtrahlung from hot electrons

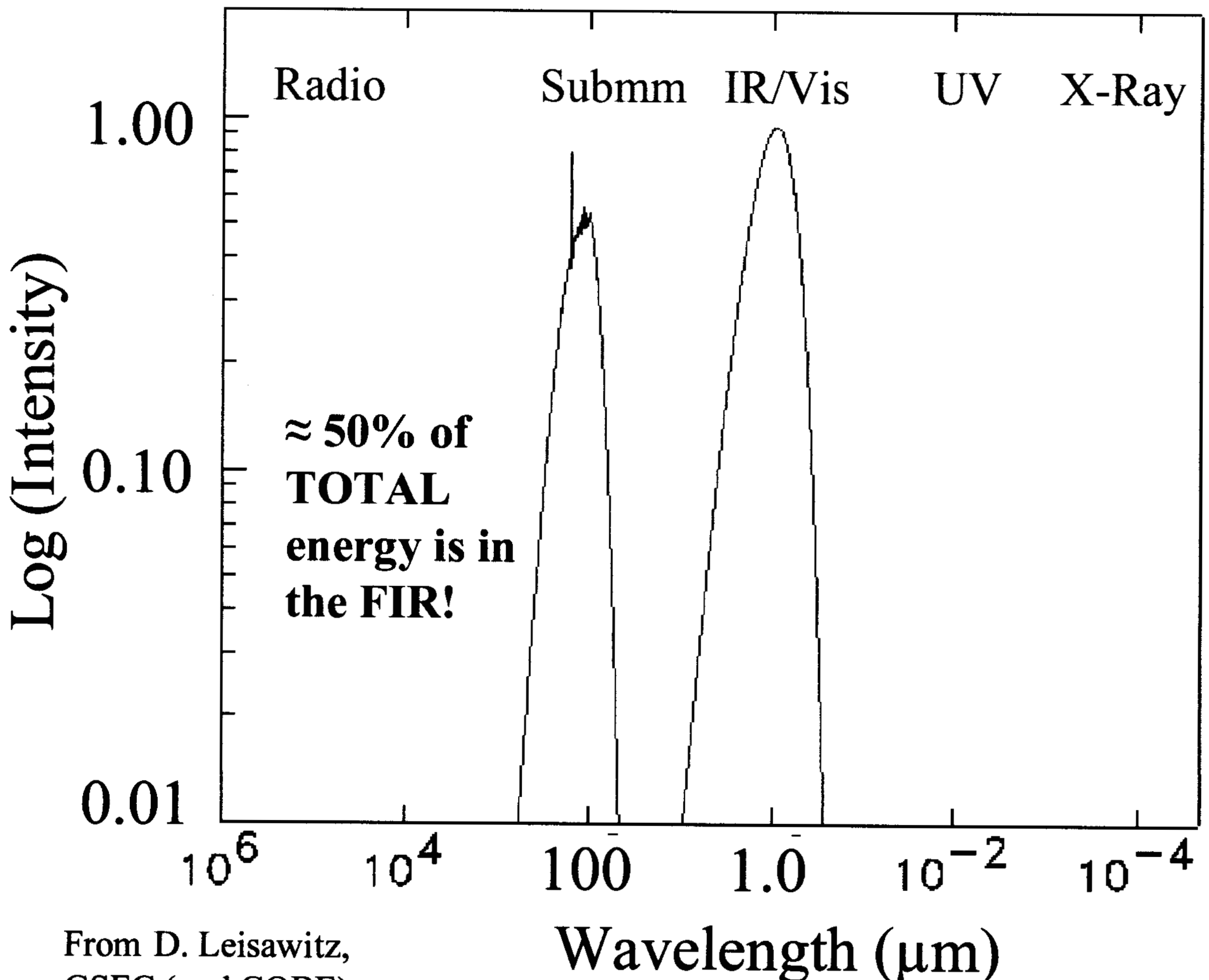
98% of post-Big Bang photons are in the FIR!

D. Leisawitz, GSFC

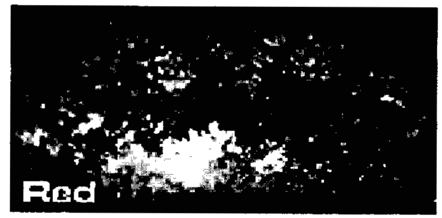
COBE Spectrum of the Galaxy



Energy of Photons in the Milky Way

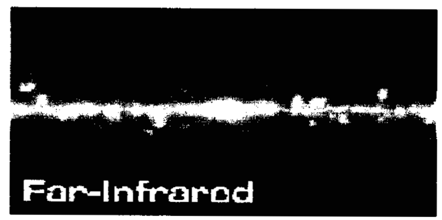


From D. Leisawitz, GSFC (and COBE)



from IPAC

radiation from stars is emitted in IR/Visible



energy is absorbed, re-radiated in FIR

Astrophysics: What are the questions?

from "The Submm Frontier…" by J.C. Mather *et al.*

- When was "first light"? Did the first generation of stars form in early galaxies or before such systems existed? (Did star formation = galaxy formation?)

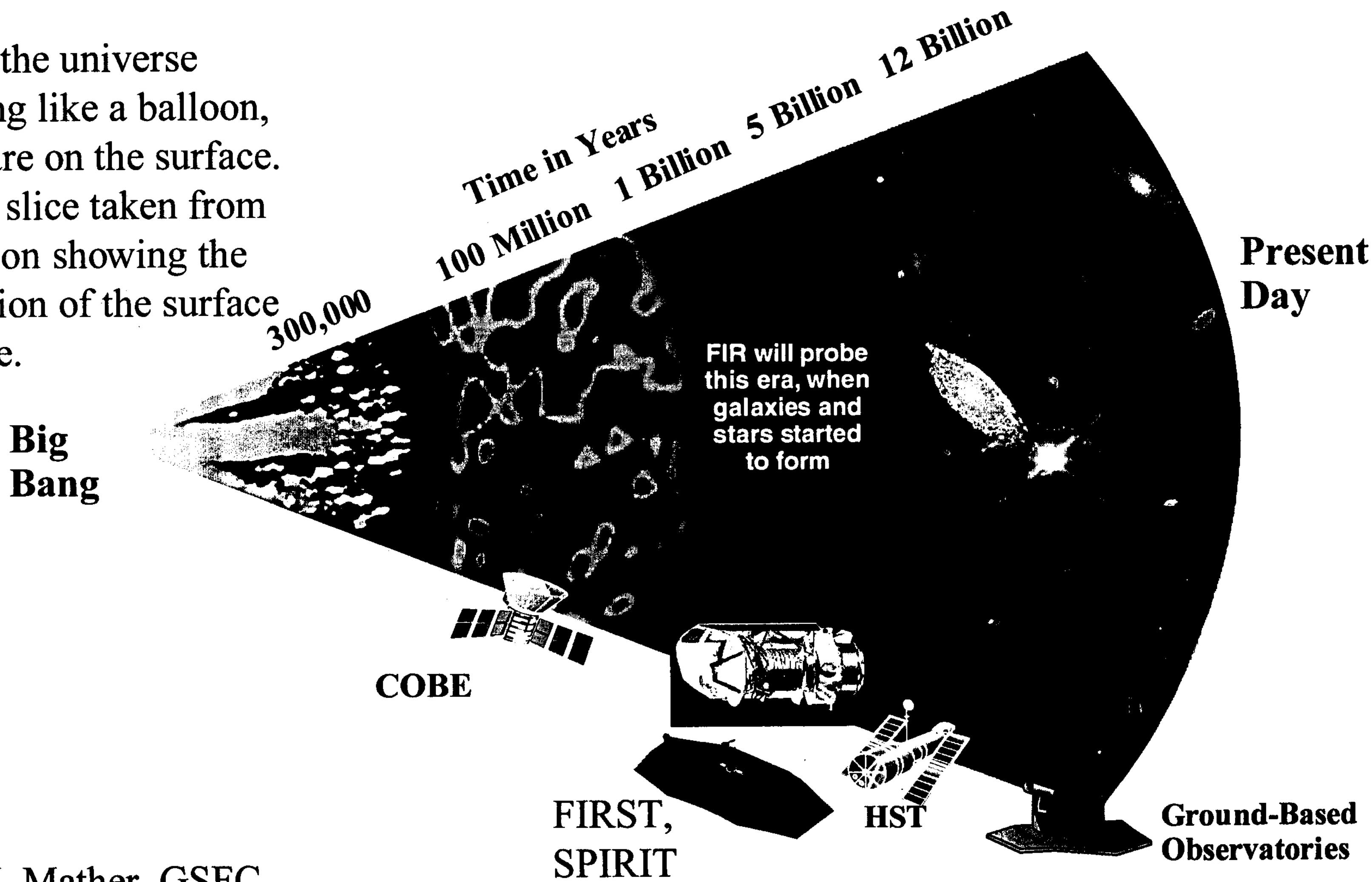
- What is the history of energy release and nucleosynthesis in the universe? How did carbon, oxygen, other heavy elements, and dust build up over time? What dispersed the metals?

- Did the process or rate of star formation change over the course of cosmic history? How might changes in the star formation process be attributed to the gradual enrichment of the interstellar medium with heavy elements? Are stars different today than they were at first light?

- What are the processes of structure formation in the universe? When and how did the first bulges, spheroids, and disks form? How did galaxies in today's universe form?

Astrophysics: FIR sees the First Stars and Galaxies

Imagine the universe expanding like a balloon, and we are on the surface. This is a slice taken from the balloon showing the progression of the surface with time.



From J. Mather, GSFC
NGST web site

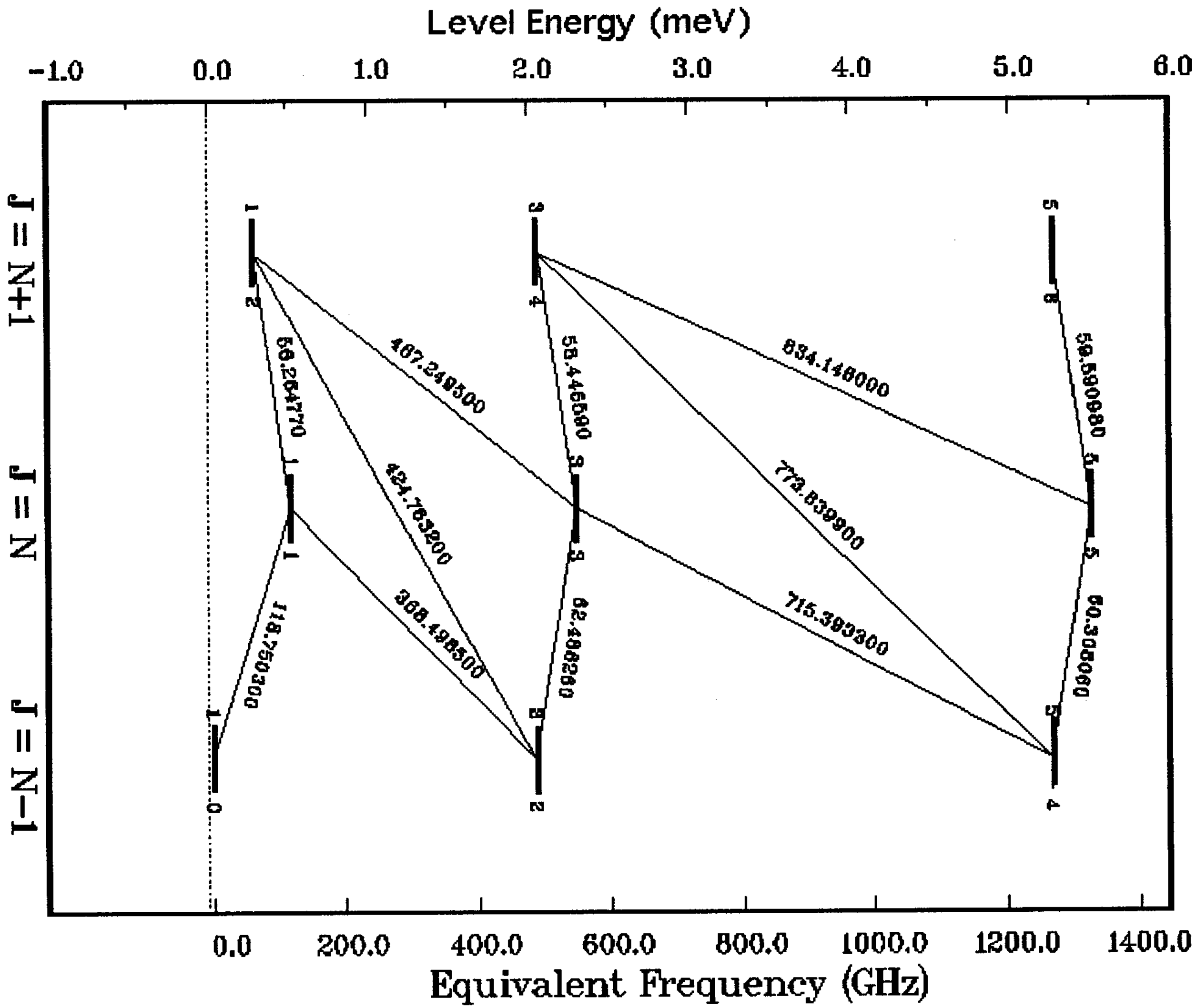
Astrophysical Sources and their Spectra

Type of Radiation	Wavelength Range (nanometers [10^{-9} m])	Radiated by Objects at this Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^{8} K	Few astronomical sources this hot; some gamma rays produced in nuclear reactions
X-rays	0.01 - 20	10^{6} - 10^{8} K	Gas in clusters of galaxies; supernova remnants, solar corona
Ultraviolet	20 - 400	10^{5} - 10^{6} K	Supernova remnants, very hot stars
Visible	400 - 700	10^{3} - 10^{5} K	Exterior of stars
Infrared	10^{3} - 10^{6}	10 - 10^{3} K	Cool clouds of dust and gas; planets, satellites
Radio	More than 10^{6}	Less than 10 K	Dark dust clouds

Atmospheric & Planetary Research in the FIR

- Ozone Depletion Studies on Earth
- Cloud Ice, Global Warming
- Aerosols, volcanic eruptions, dust…
- Search for H_2O in solar system bodies
- Chemical mapping of Venus, Titan,… atmospheres
- Comet outflows and composition

Molecular Oxygen (O_2) Transitions



≈ 70 K

* note that the temperature of the observed object does not necessarily correspond to the frequency of emitted/absorbed radiation

Galdis, IEEE Frequency June 7, 2000 JPL

Important Atmospheric Components Measured by EOS-MLS on NASA's AURA Spacecraft

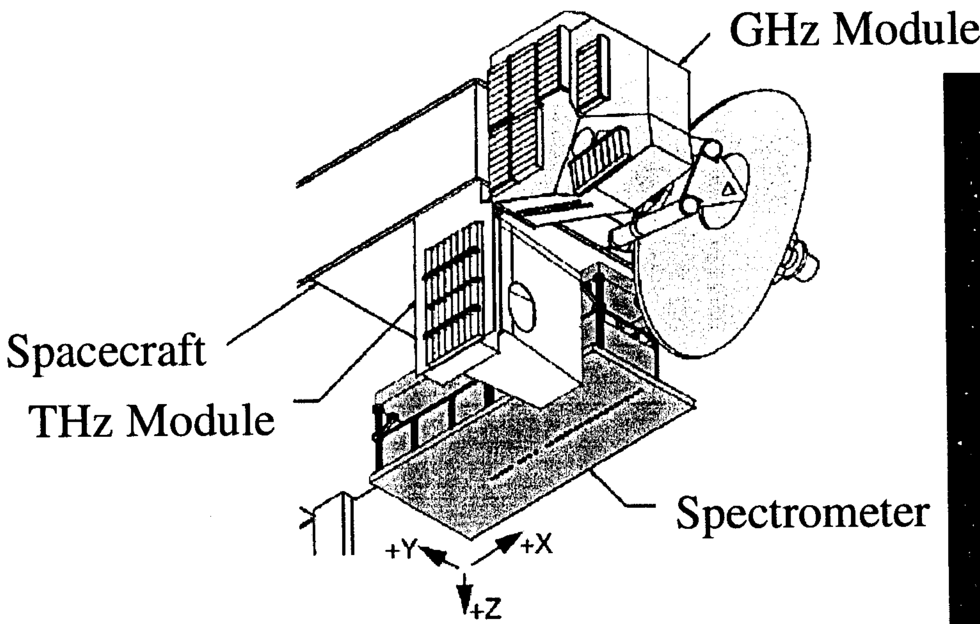
temperature and pressure

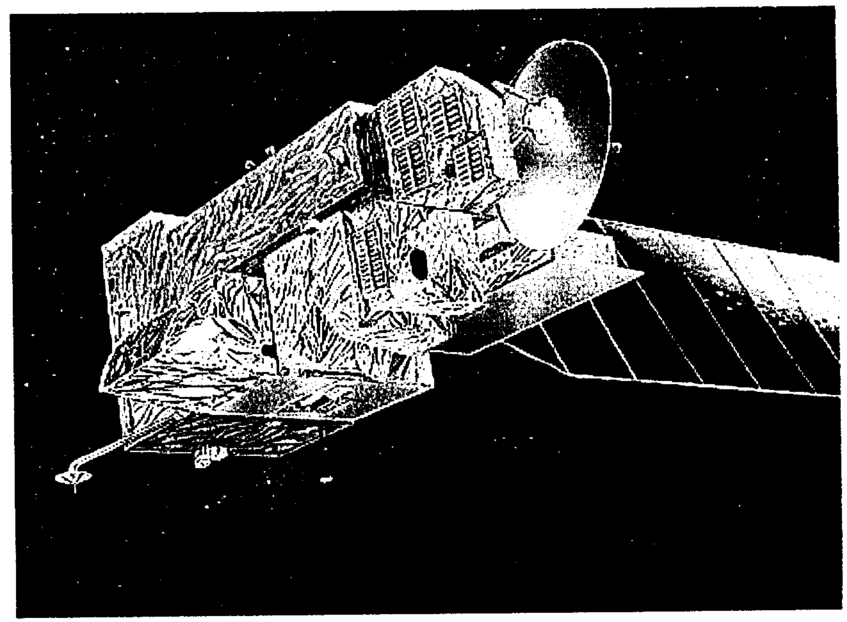
190 GHz → H_2O, HNO_3

240 GHz → O_3 and CO

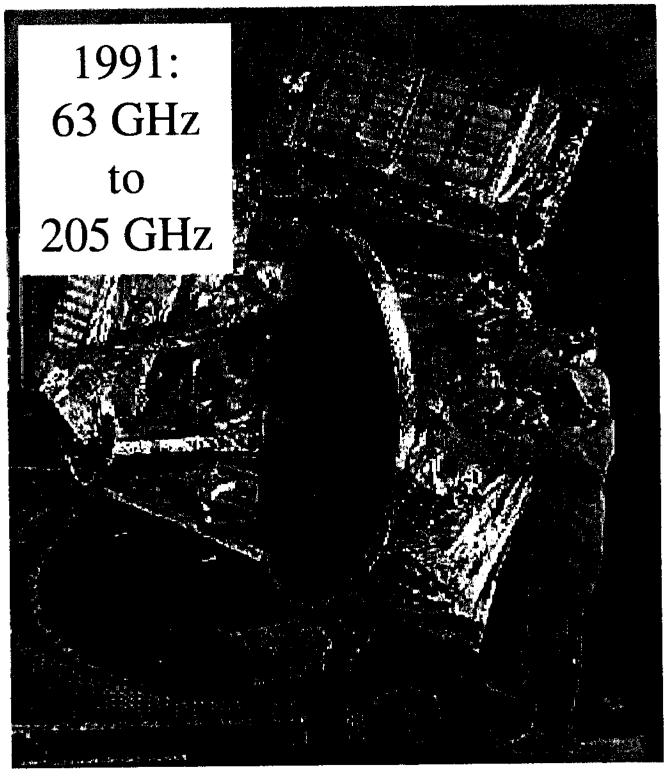
640 GHz → N_2O, HCl, ClO, HOCl, BrO, HO_2, and SO_2

2.5 THz → OH

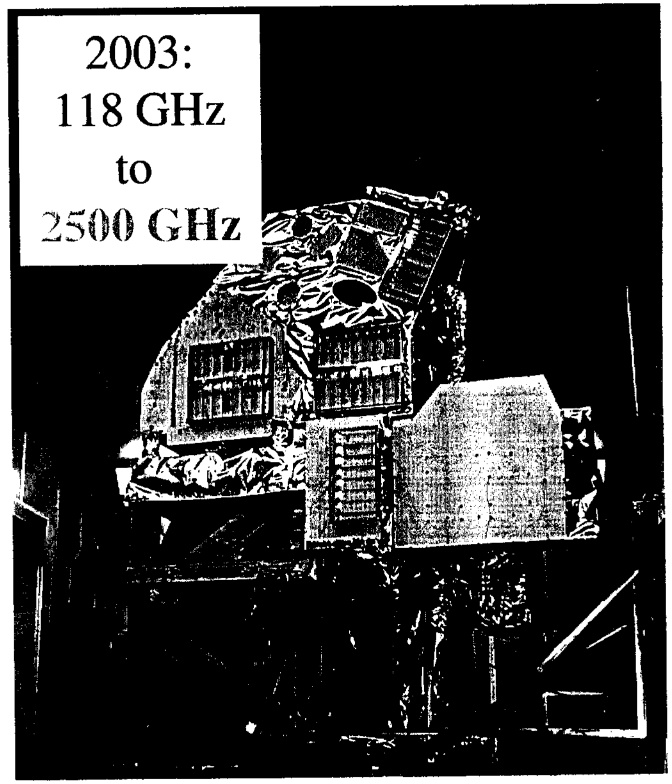




Progress in Heterodyne Sensors for Atmospheric Studies

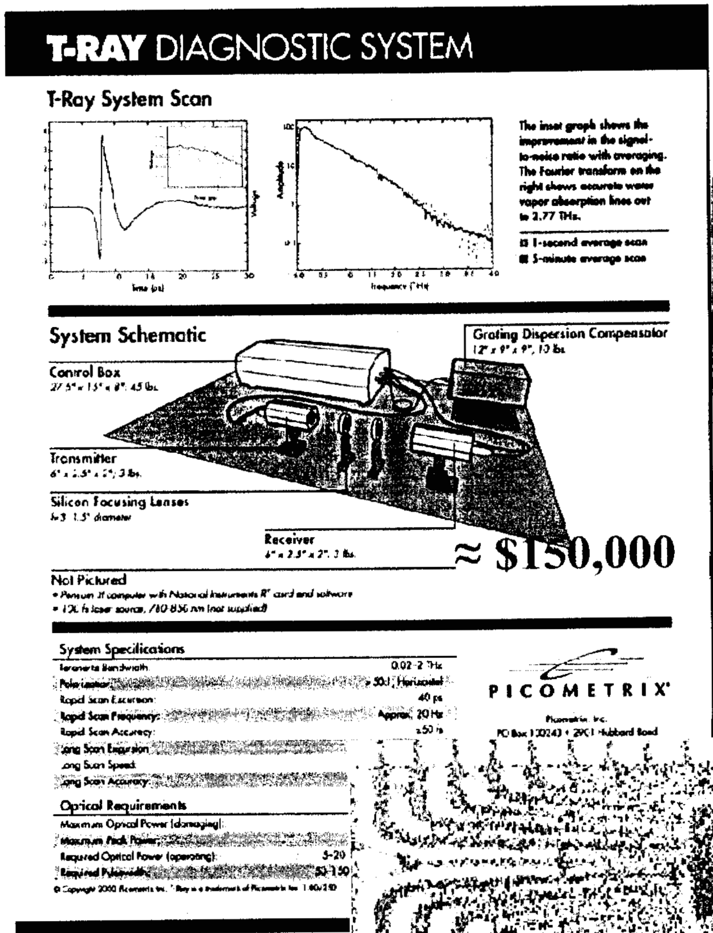


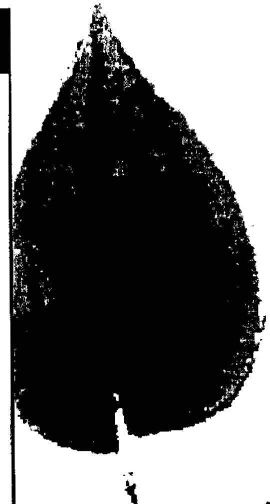
UARS - MLS
prior to S/C integration

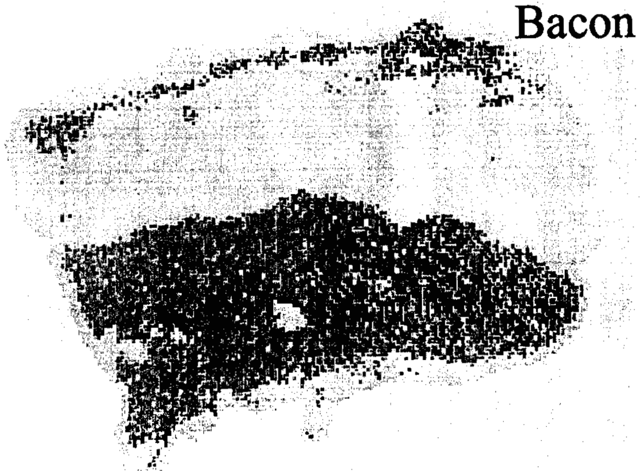


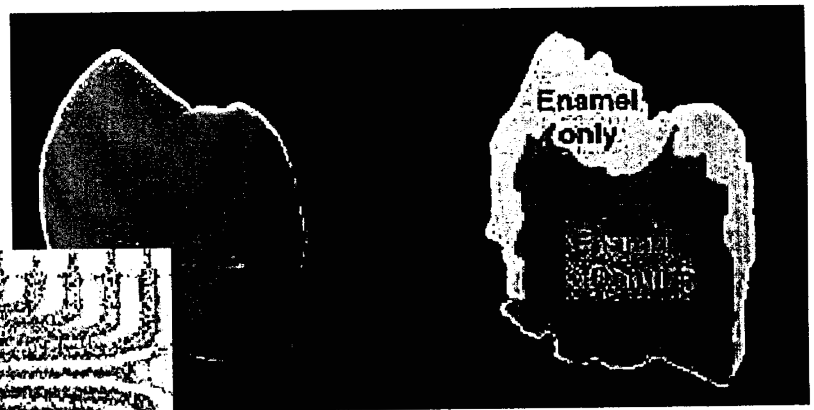
EOS - MLS
in thermal vacuum test chamber

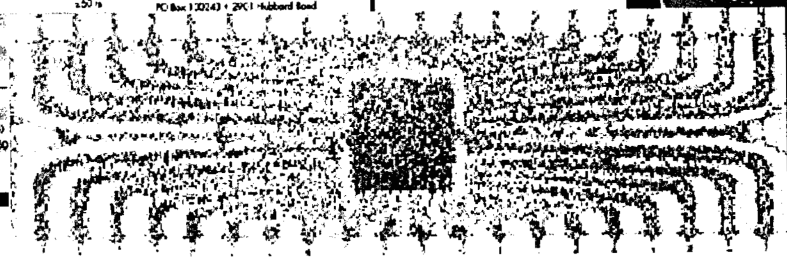
T-Rays











Picometrix, Bell Labs, and Toshiba Cambridge Research Lab

Energy/Temperature Scales

	CMB ≈ 2.7K	$k_B T$	≈ 0.2 meV	2.7 K
0.6 THz	$\lambda = 500\ \mu m$	$h\nu$	≈ 2.5 meV	28 K
	Nb Superconducting Gap	2Δ	≈ 3 meV	35 K
	GaAs Donor Ionization	E_d	≈ 6 meV	70 K
1.9 THz	Ionized Carbon (CII)	$h\nu$	≈ 8 meV	93 K
	Interstellar Clouds		0.85 - 8.5 meV	10 - 100 K
2.5 THz	OH Radical	$h\nu$	≈ 10 meV	120 K
6 THz	$\lambda = 50\ \mu m$	$h\nu$	≈ 25 meV	290 K
	Room Temp ≈ 295 K	$k_B T$	≈ 26 meV	295 K
	Si Carrier Ionization	E_a, E_d	≈ 50 meV	[illegible]

THz devices: electrons or photons?

waves or particles?

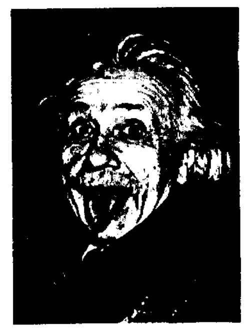
μ-Wave
HEMTs
Electrons!

500 μm
600 GHz

50 μm
6 THz

Infrared
CCDs
Photons!

at this time, *neither* approach works very well in the THz region!



Materials in the THz regime

Cannot assume ***anything*** is benign!

☹ Superconductors: Cooper pairs are split by THz photons ($\Delta \approx$ THz)

😐 Metals: anomalous skin effect (e^- mfp > skin depth); acoustic phonons absorb

☹ Semiconductors: free carriers and acoustic phonons absorb; plasma f $\approx$ THz

☹ Dielectrics: $n_{optical} \neq n_{THz}$ ➔ alignment difficult; strong phonon absorption

☹ Polymers & Plastics: intermolecular modes absorb strongly (but $n_{optical} \approx n_{THz}$)

☹ Liquids: molecules' vibration and rotation strongly absorb THz

☹ Gasses: simple molecules vibrate/rotate at THz; water absorption is horrendous

☹ Dust, Aerosols: grains the size of THz wavelengths scatter

☹ Surfaces: conventional machining can be rough on λ scales

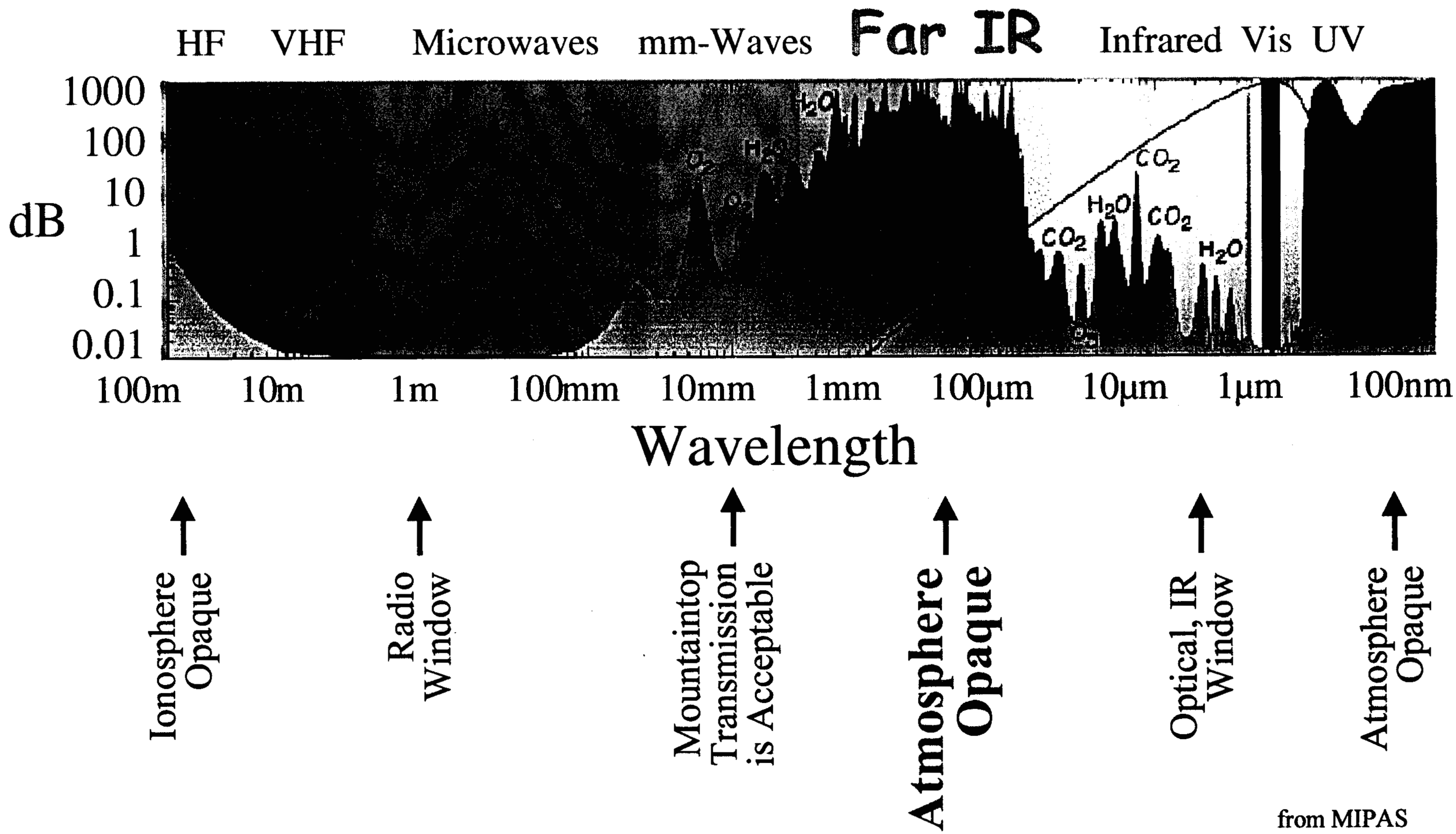
☺ Absorbers: *this* is not too difficult to find!

However, the savvy innovator can capitalize on these properties to create new applications and new instrument concepts

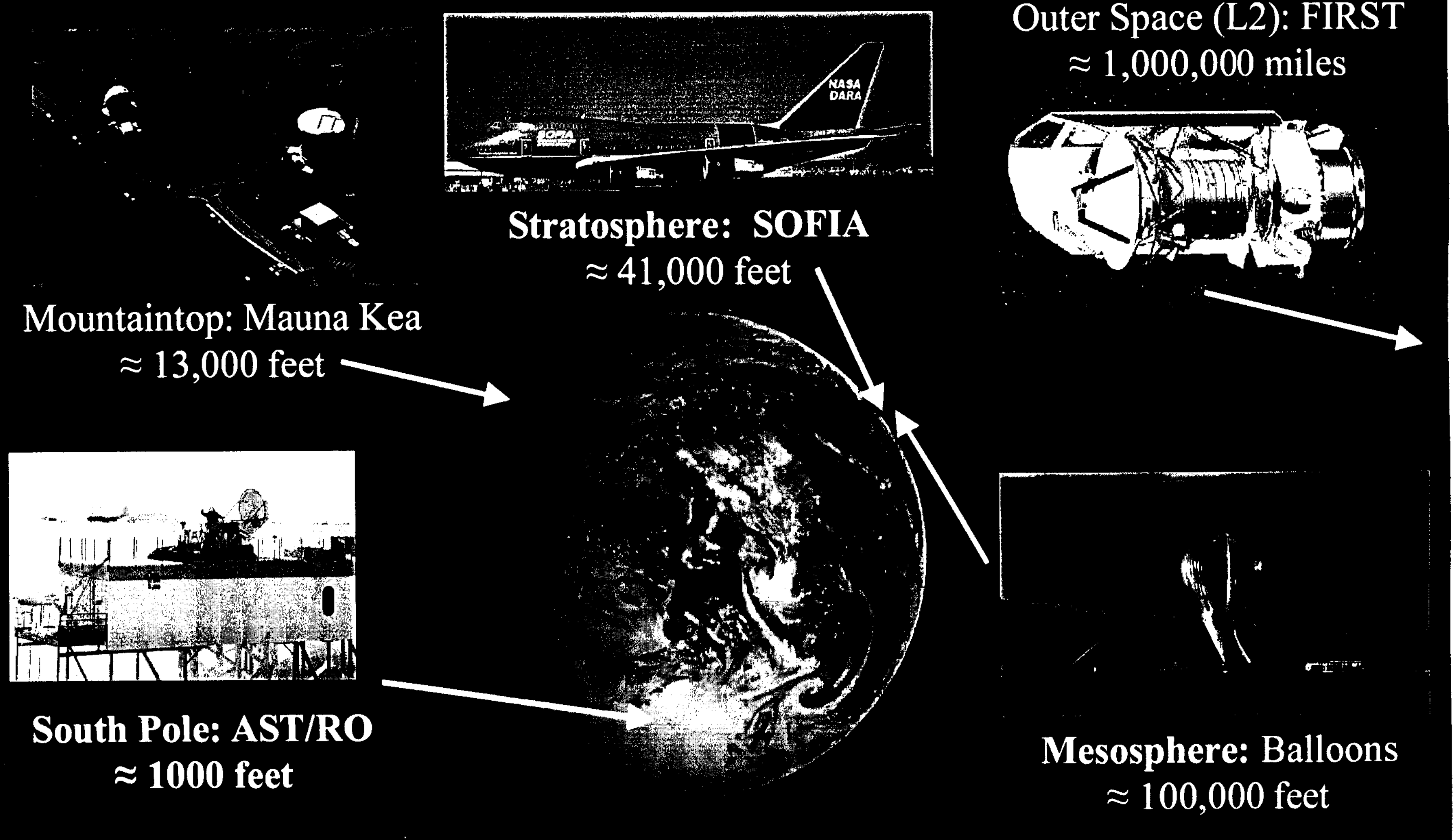
Capitalizing on Materials Properties

Material Type	Property	Use
Superconductor	THz breaks Cooper Pairs	Photon-based direct detector similar to diode
Semiconductor	Plasma frequency, free carrier absorption	Diagnostic in semiconductor processing (carrier concentration, etc.)
Polymers & Plastics	Strong phonon absorption; characteristics different for different materials	Specific spectral signature can be used for analysis of materials (TDS)
Liquids	THz coupling to molecular excitations	Chemical analyses
Gas	THz vibrational/rotational modes	Remote sensing
Gas (H_2O)	Strong absorption	Minimize communication signal interference (LANs)
Biochemical	Strong absorption; characteristics vary widely for different materials	Medical imaging
Ice Crystals	Interaction with THz radiation depends on crystal size	Quantify cloud ice effects in Earth's thermal balance

Atmospheric Absorption



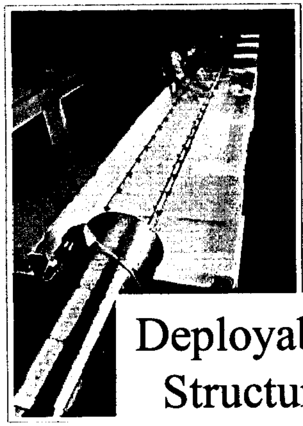
Avoiding Atmospheric Absorption



Designing for Space

Radiation,
Space Environment

Launch
Vibration

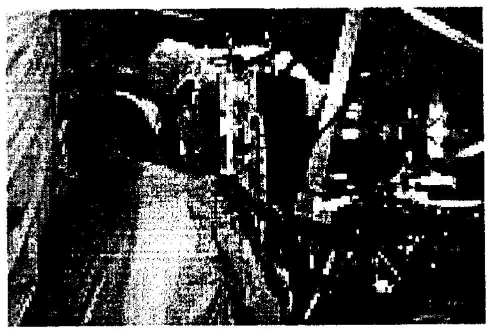


Deployable
Structures

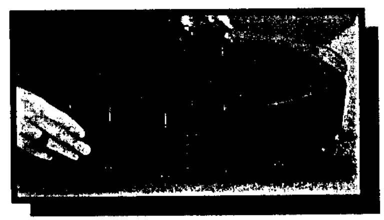
Paperwork,
Red Tape

Vacuum
Operation

No Repairs



Precise, Careful Engineering



Light-Weight
Structures

Detector Types: Tradeoffs

Note: the previous slides do not tell the whole story!

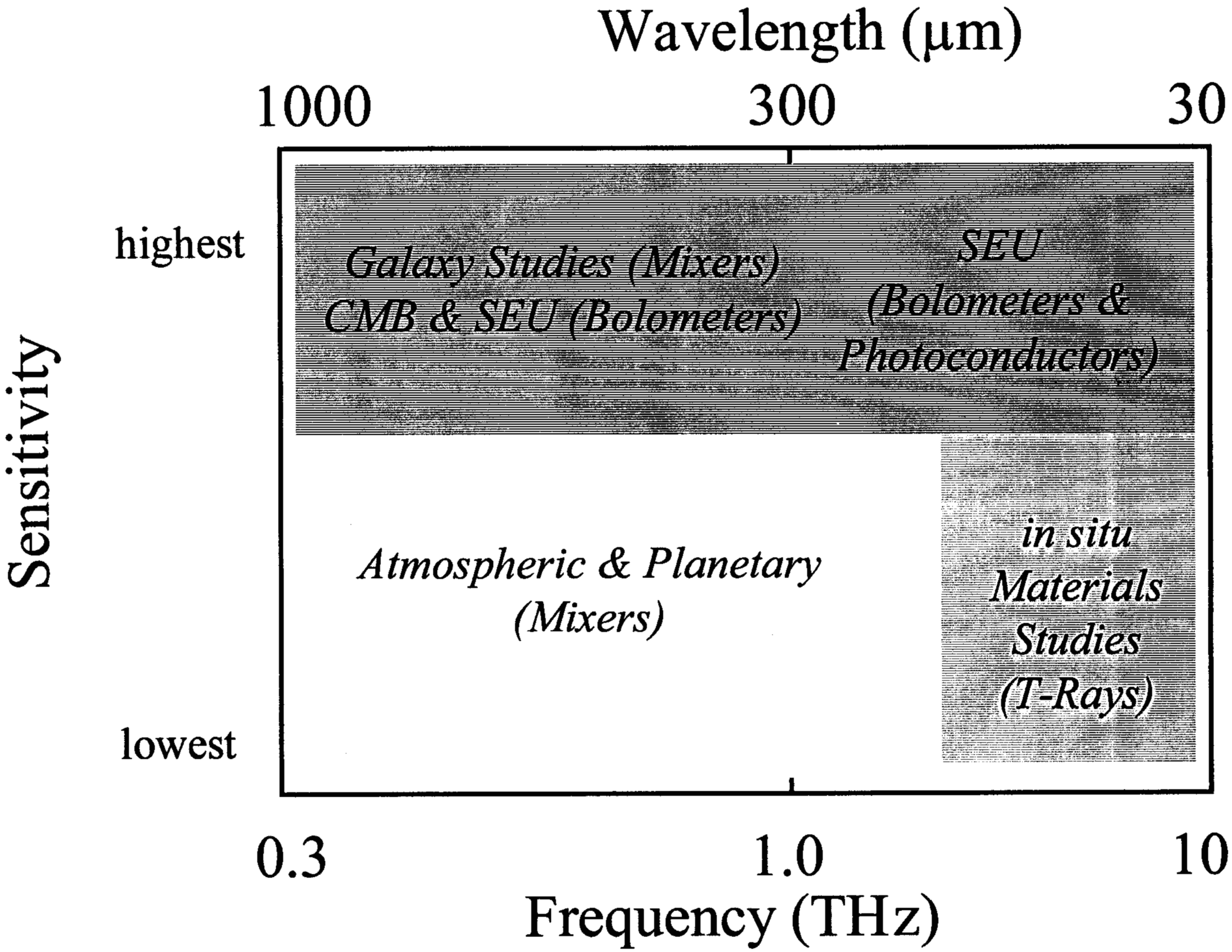
(very simplistic generalizations)

Many tradeoffs to consider:

1) observing frequency
2) background noise (telescope, object, atmosphere)
3) required sensitivity and dynamic range
4) integration time and detector fluctuations or response time
5) spectral resolution
6) spectral coverage
7) spatial resolution
8) spatial coverage and beam pattern
9) detector availability, complexity, and cost
10) instrument lifetime (cryogen use, opportunity for repair,…)
11) instrument power requirements (local oscillators, coolers,…)
12) instrument mass and volume
13) sensitivity to the environment (thermal, radiation, EMI, …)
14) heritage; past successes and failures

Dominant FIR/Submm Detector Applications:

Sensitivity vs. Wavelength

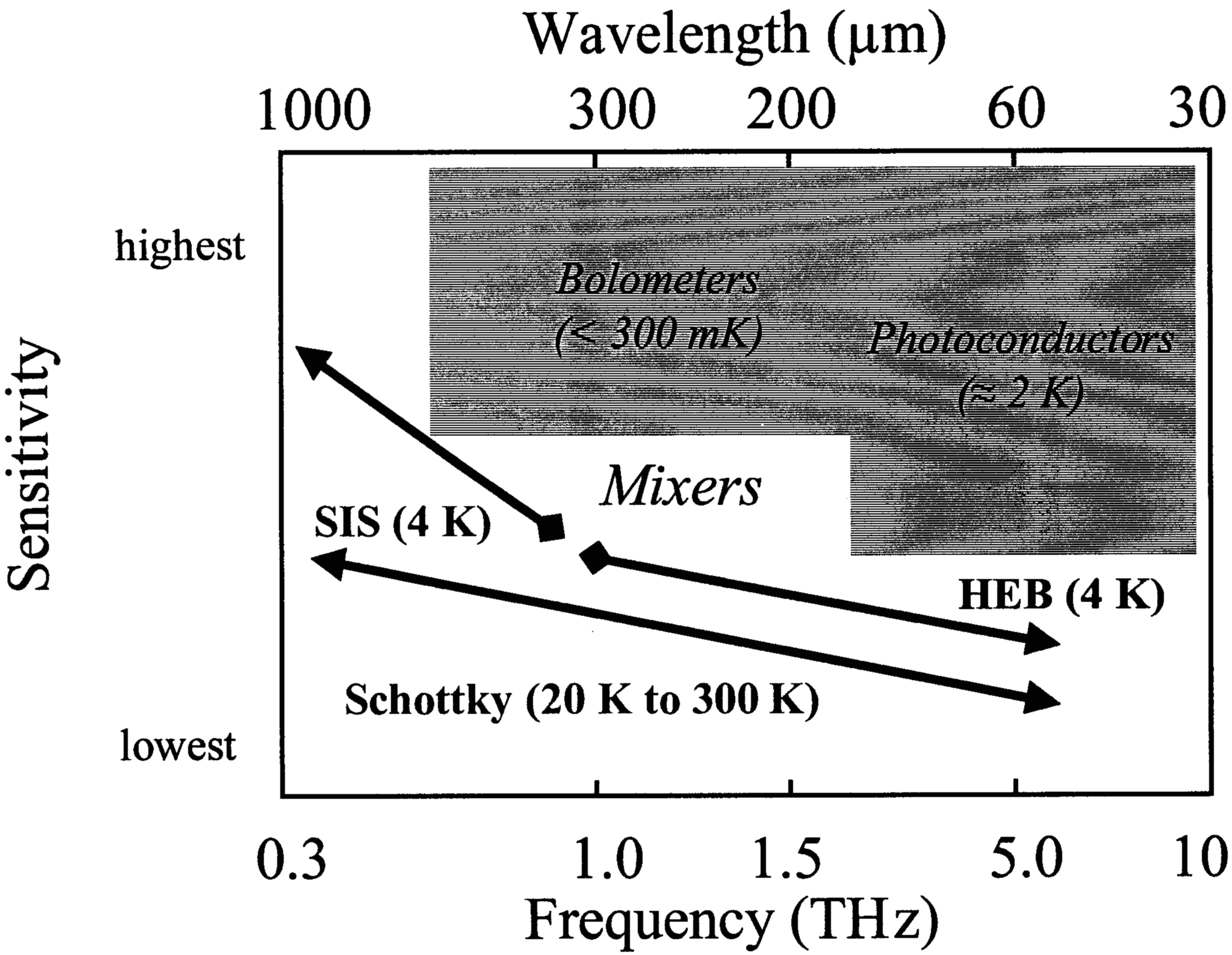


CMB =
Cosmic Microwave
Background

SEU =
Structure & Evolution
of the Universe

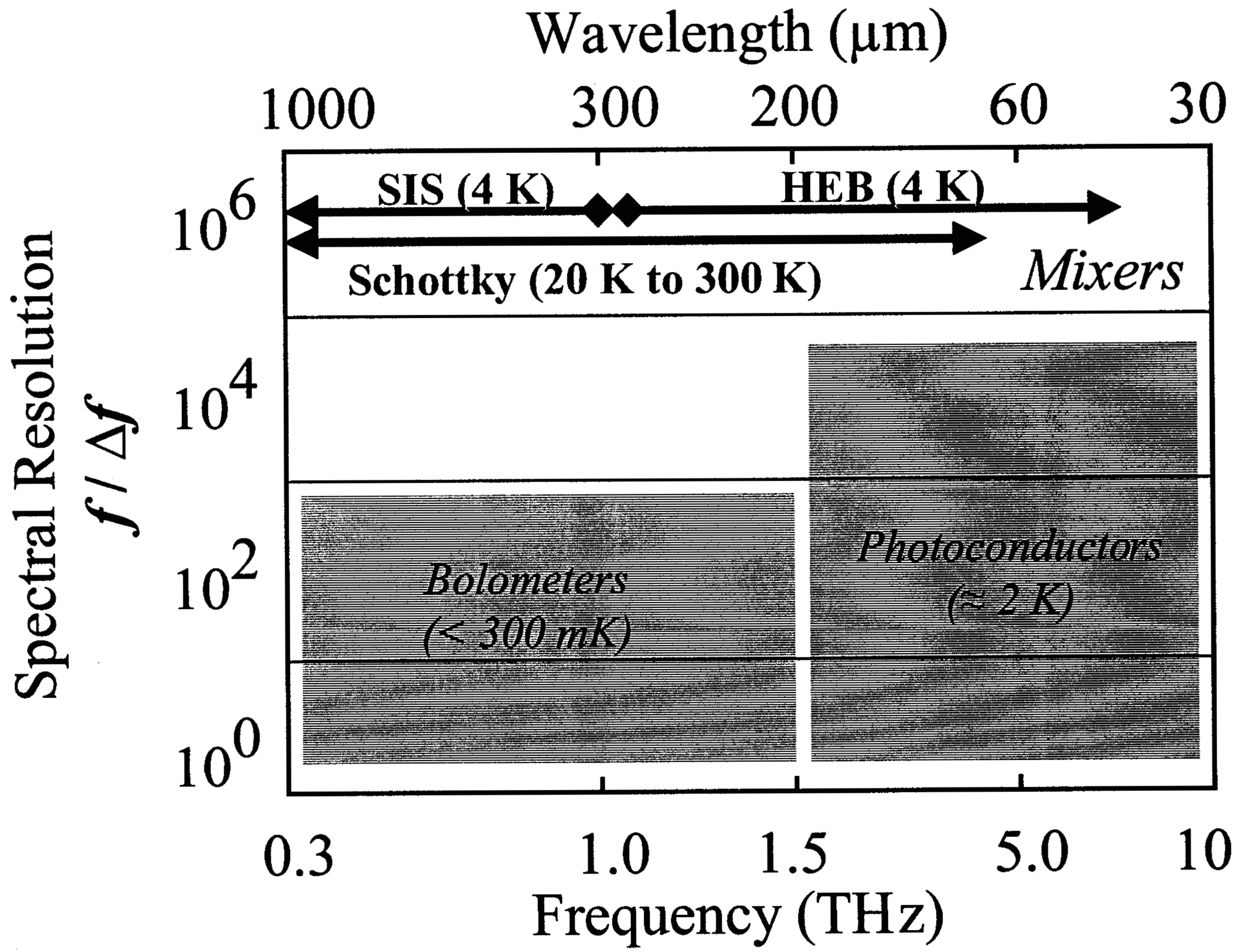
Dominant FIR/Submm Detector Niches:

Sensitivity vs. Wavelength



Dominant FIR/Submm Detector Niches:

Spectral Resolution vs. Wavelength

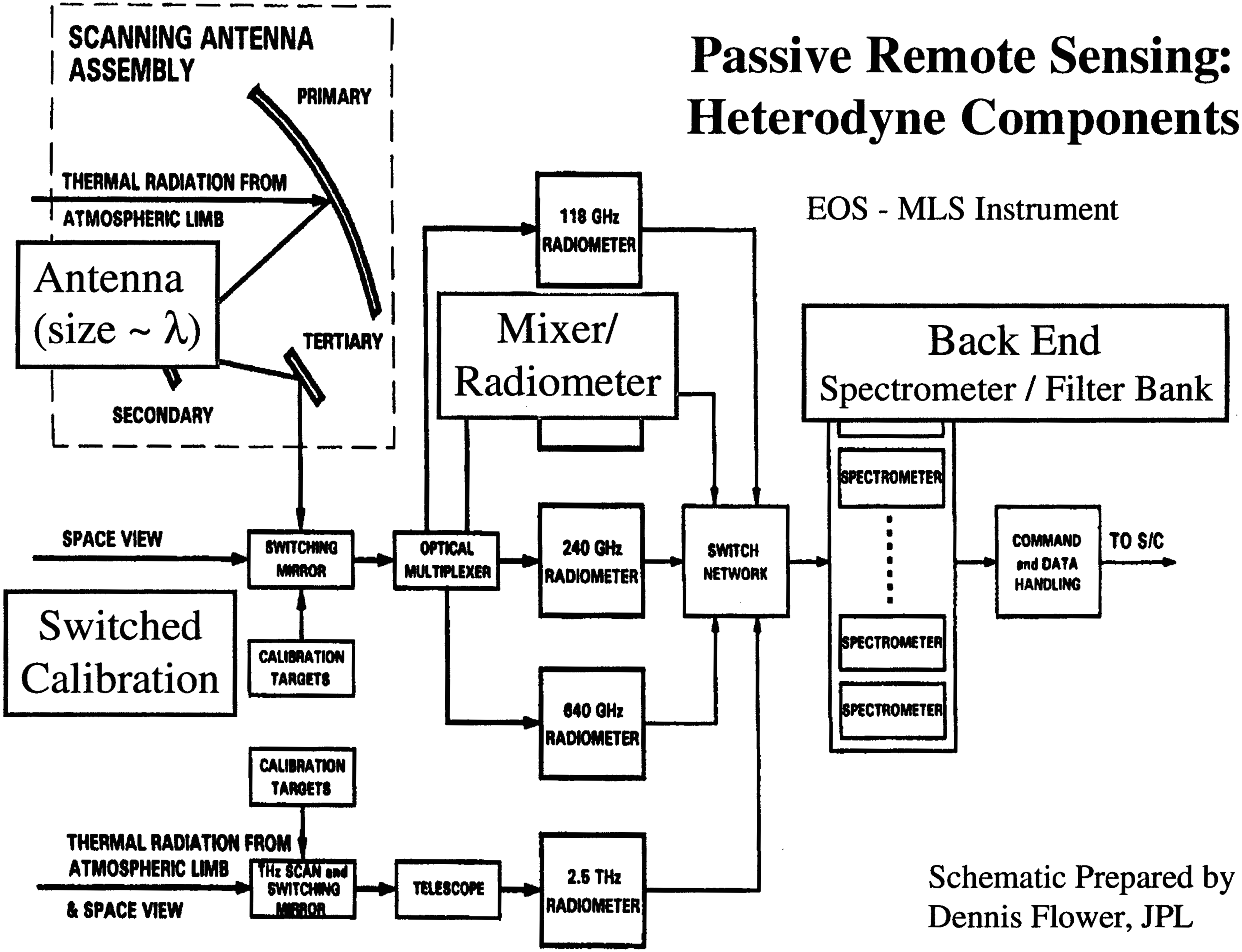


Noise Sources

- Photon noise (like shot noise)
- Confusion noise (infrared cirrus, high-Z objects)
- Atmospheric transmission noise (like attenuator at T>0)
- Optics noise (reflector loss or dielectric absorption is like an attenuator at T>0)
- Detector noise
  - Heterodyne Detectors: *i.e. Electronic "wave" detectors*
    - Quantum noise (associated with phase sensitive detection)
    - Shot noise
    - Thermal (Johnson) noise
    - Gain fluctuations
  - Direct Detectors: *i.e. Photon "particle" detectors*
    - Bolometers
      - Thermal (Johnson) noise
      - Phonon shot noise
    - Photoconductors
      - Shot noise

Passive Remote Sensing: Heterodyne Components

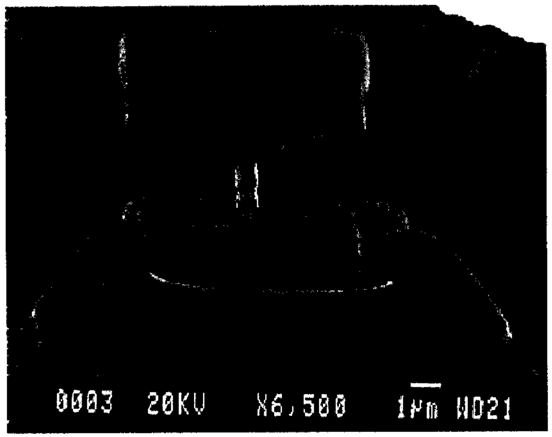
EOS - MLS Instrument



Schematic Prepared by Dennis Flower, JPL

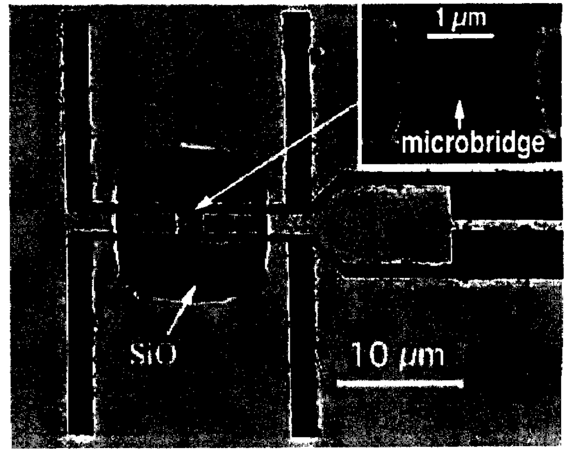
THz Heterodyne Mixers; Y2K

MOMED (JPL)
GaAs Schottky @ RT
≥ 800 GHz



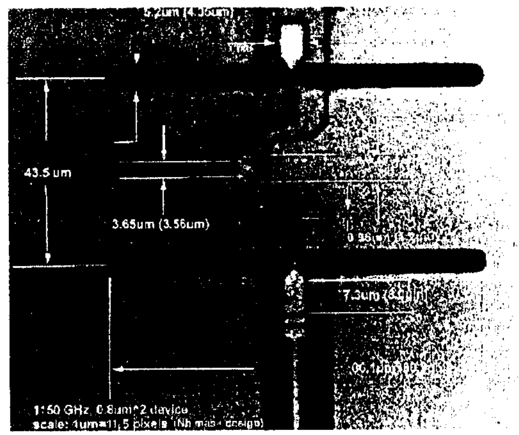
Waveguide mount; airbridge minimizes C

HEB (JPL)
Nb Hot Electrons @ 4 K
≈ 1 THz and up



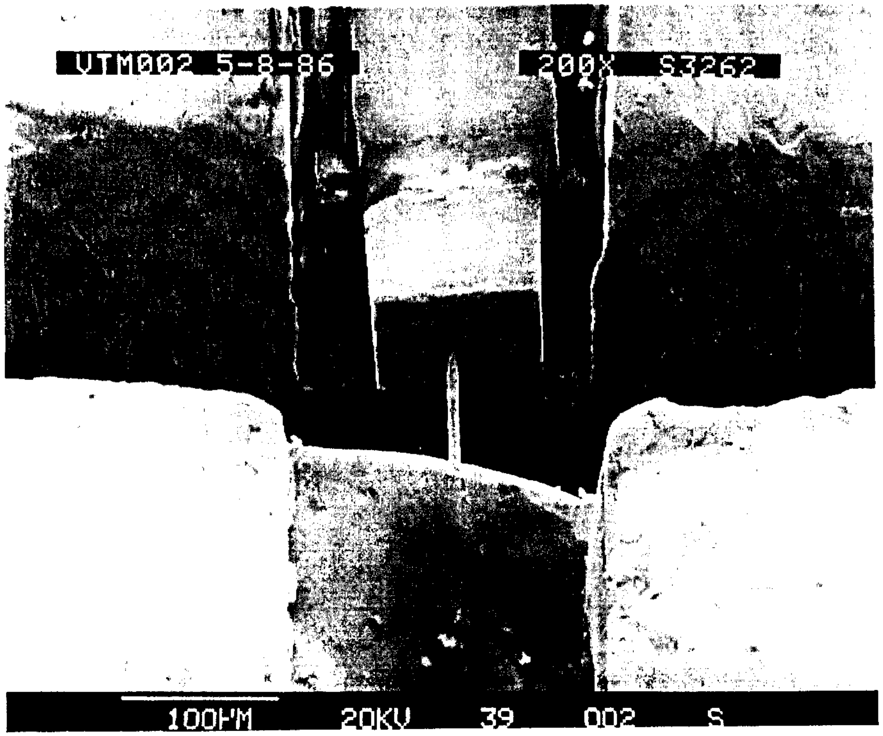
Quasi-optic coupling with twin-slot antennas

SIS (Caltech, JPL)
NbTiN superconductor @ 4 K
≈ 100 GHz to ≈ 1.2 THz

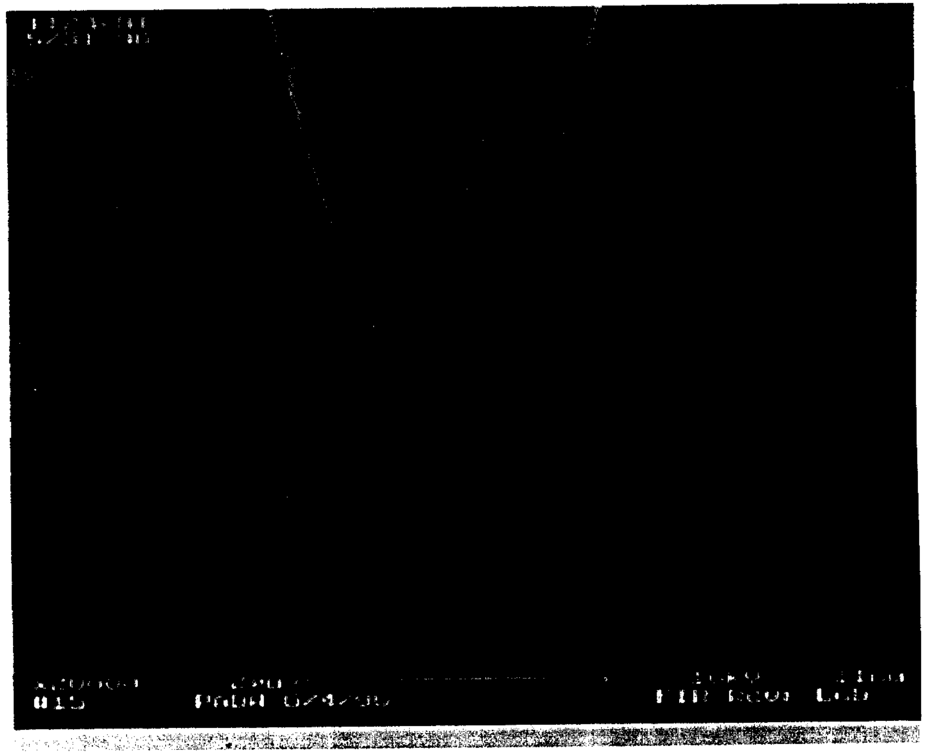


OLD: Whisker contacted Schottky Barrier Diodes

used for both heterodyne downconversion (mixing) and local oscillator power generation (varactor multiplication) for UARS



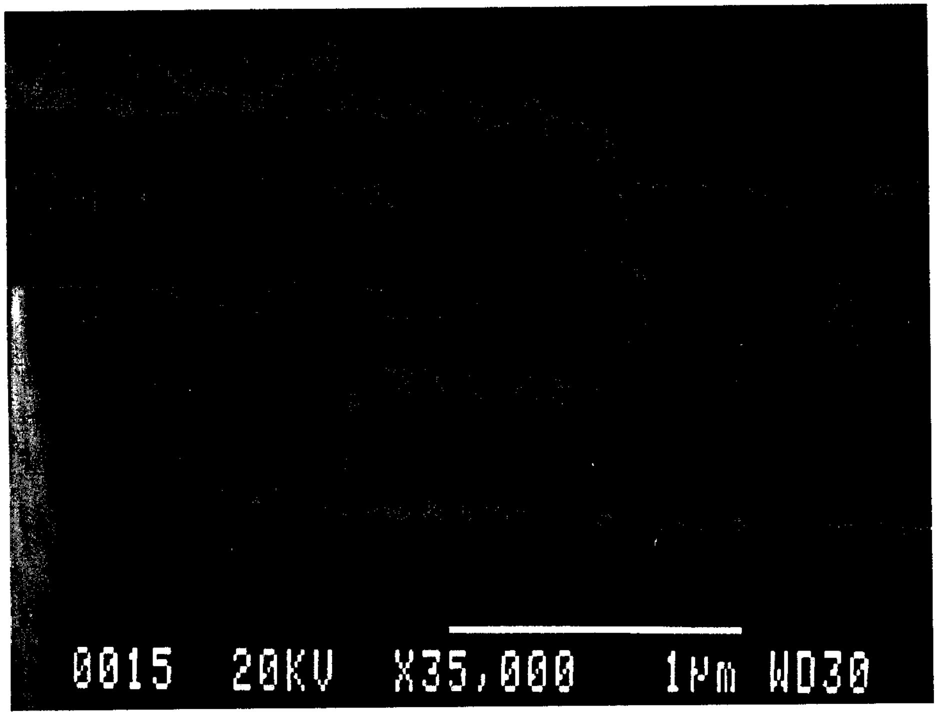
UVa point-contact GaAs Schottky diode for 200 GHz mounted in metallic waveguide mixer block

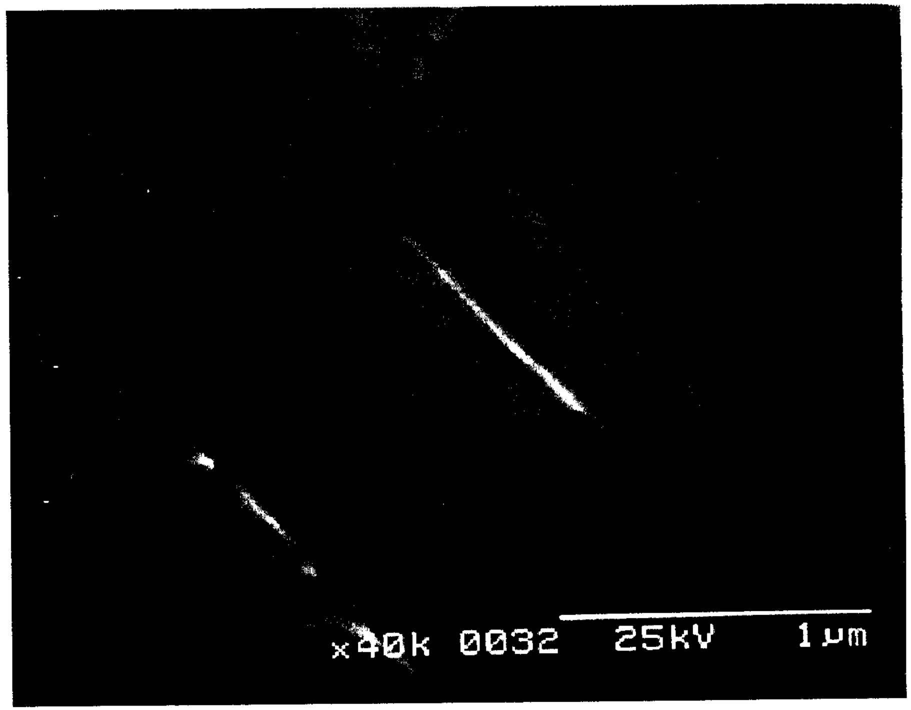


UVa point-contact GaAs Schottky diode for 2 THz operation (submicron anodes)

NEW: T-Gate Schottky Anode Geometry

Reduces parasitic resistance by as much as 2X without increasing capacitance and allows submicron anode area (<.05 μm^2) for >15 THz cutoff frequencies.

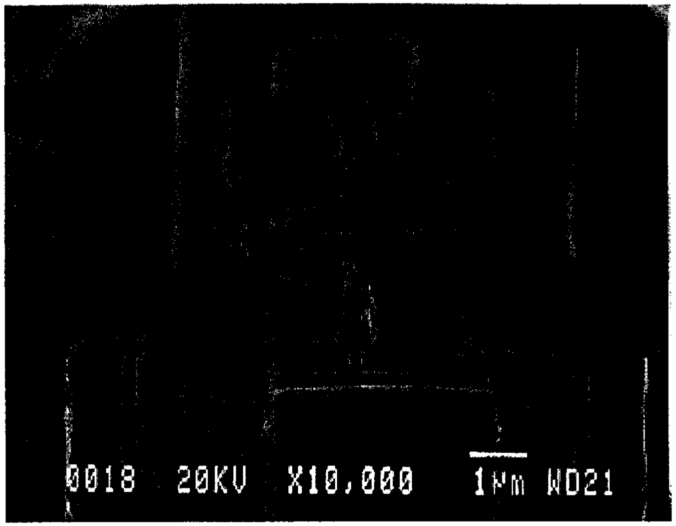


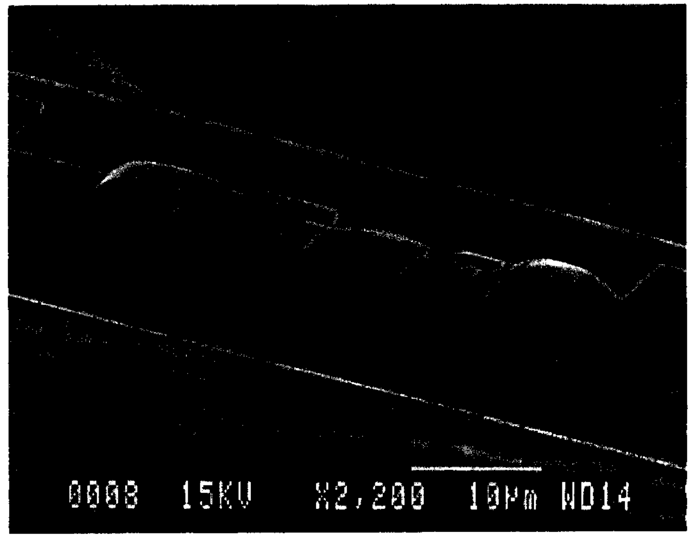


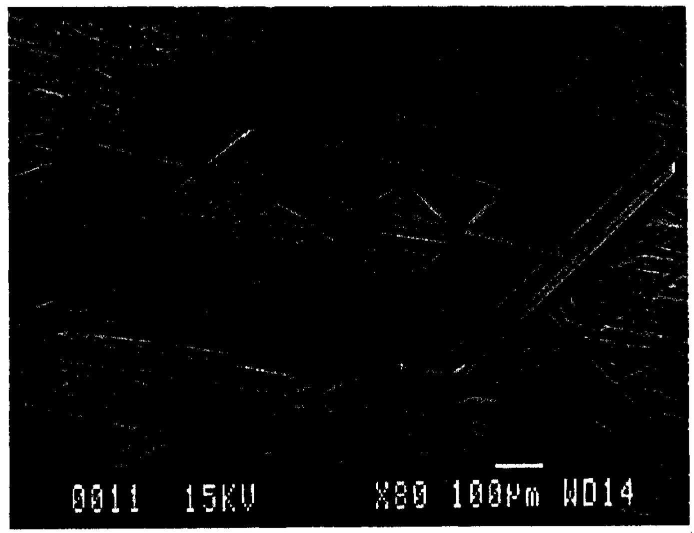
SEM's of JPL submicron T-gate style Schottky anode for 2.5 THz mixing applications.

Advances in planar diode and circuit topology have helped establish the credibility of THz space-borne heterodyne instruments – several of which are now in production.

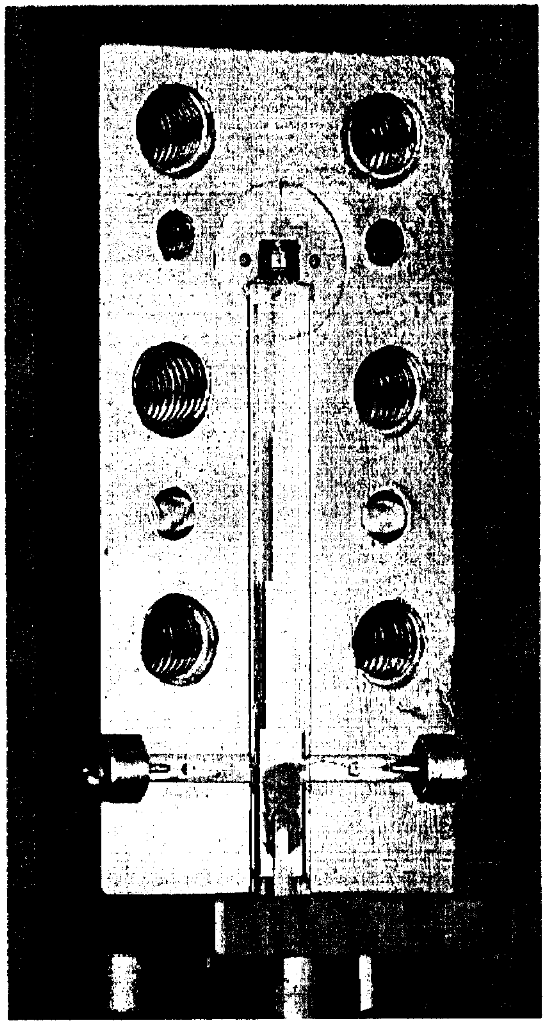
JPL Mixer: Planar Diode on Membrane Devices



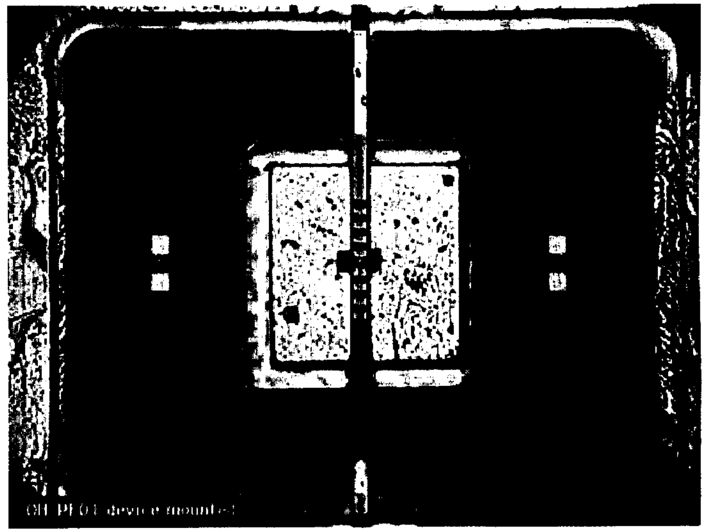


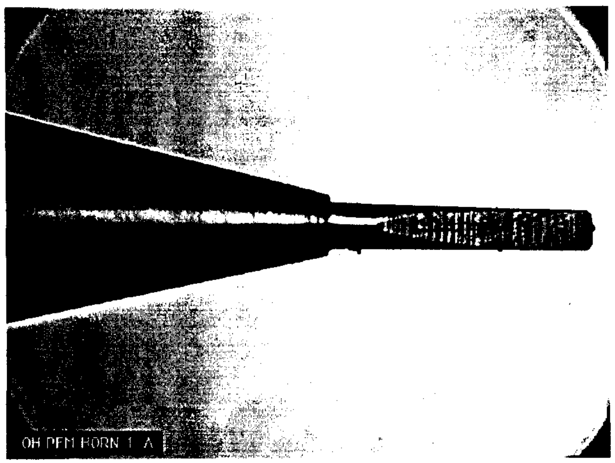


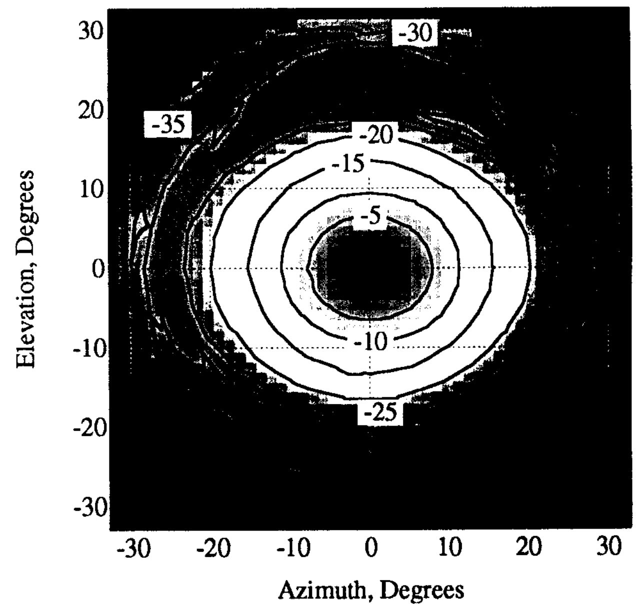
Monolithic Membrane Device (MOMED) Mixer at 2520 GHz



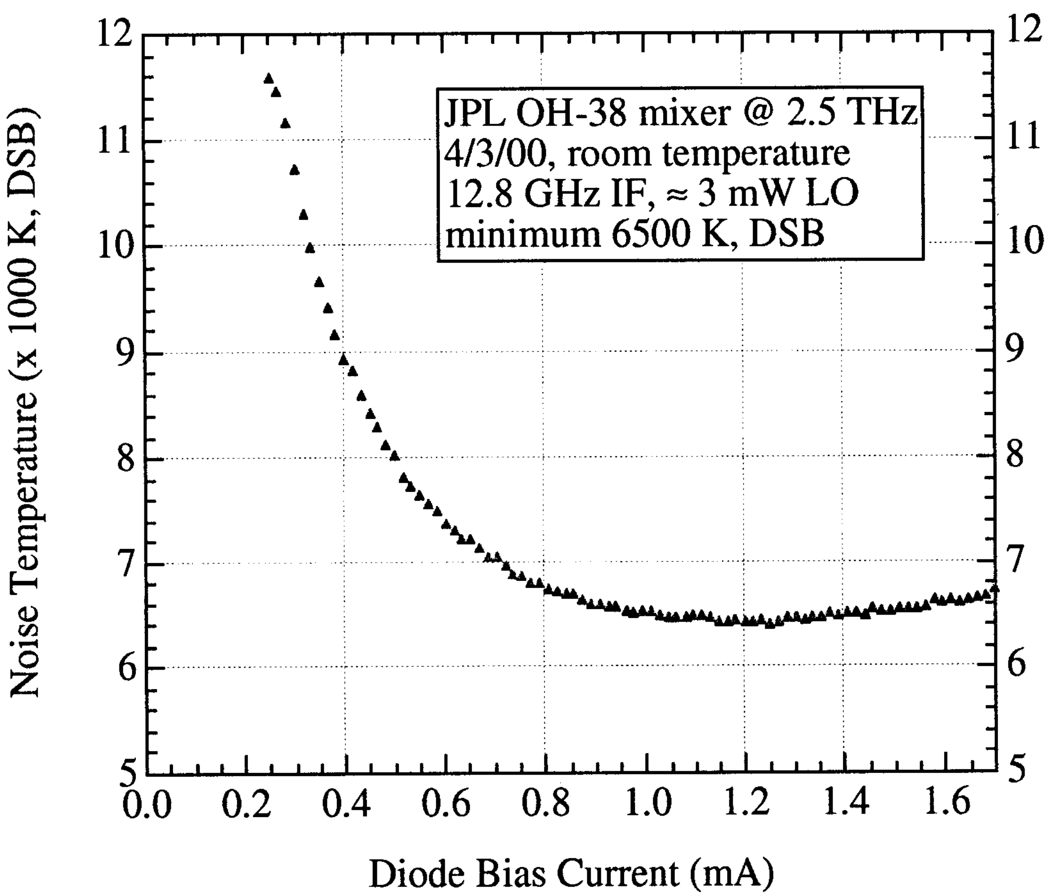
Top Right: Close up of 2.5 THz waveguide (50x100μm).
Below: Dual mode 2.5 THz feedhorn mandrel.
Below Right: Beam pattern of horn & MOMED at 2520 GHz







Receiver Noise: JPL Schottky MOMED



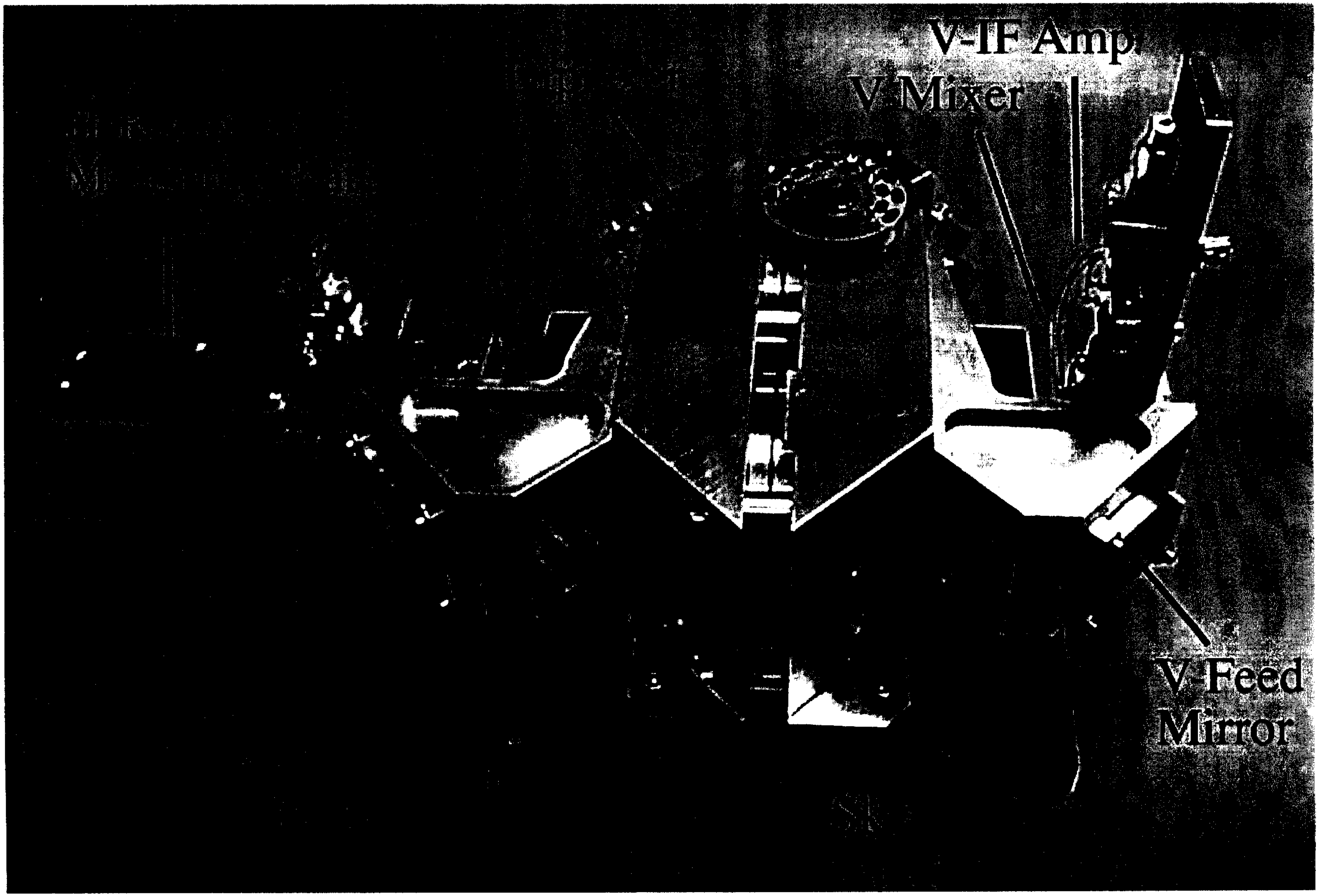
Signal Resolution:
$\Delta T_{sig} \approx T_n/\mathrm{sqrt}(B\tau)$

for $T_n = 6500$ K
$B = 10$ MHz
$\tau = 1$ second

....

$\Delta T_{sig} \approx 2$ K

EOS-MLS 2.5 THz Receiver Front End

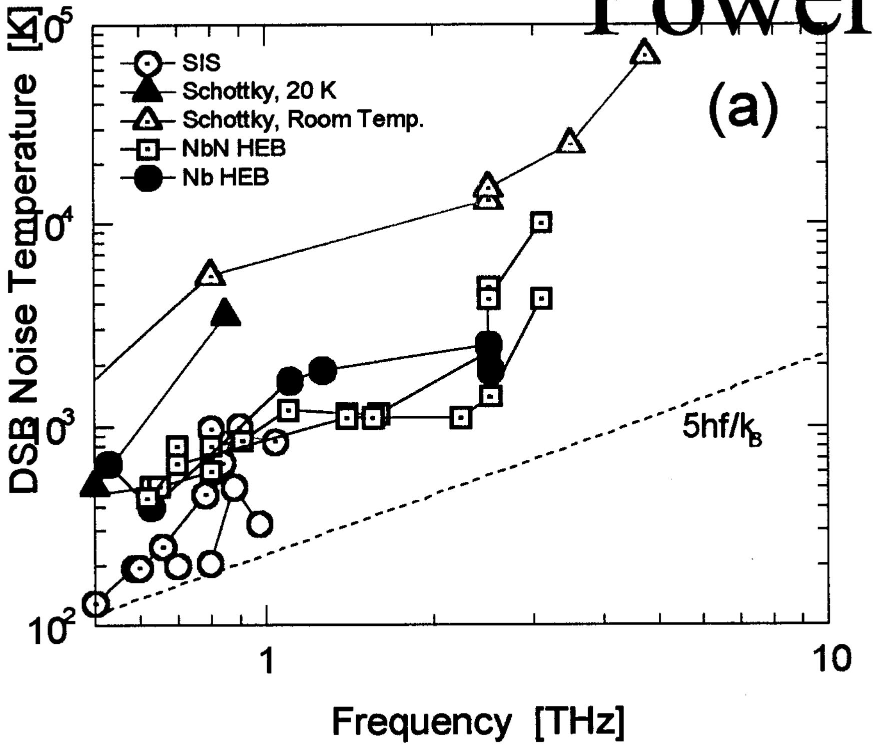


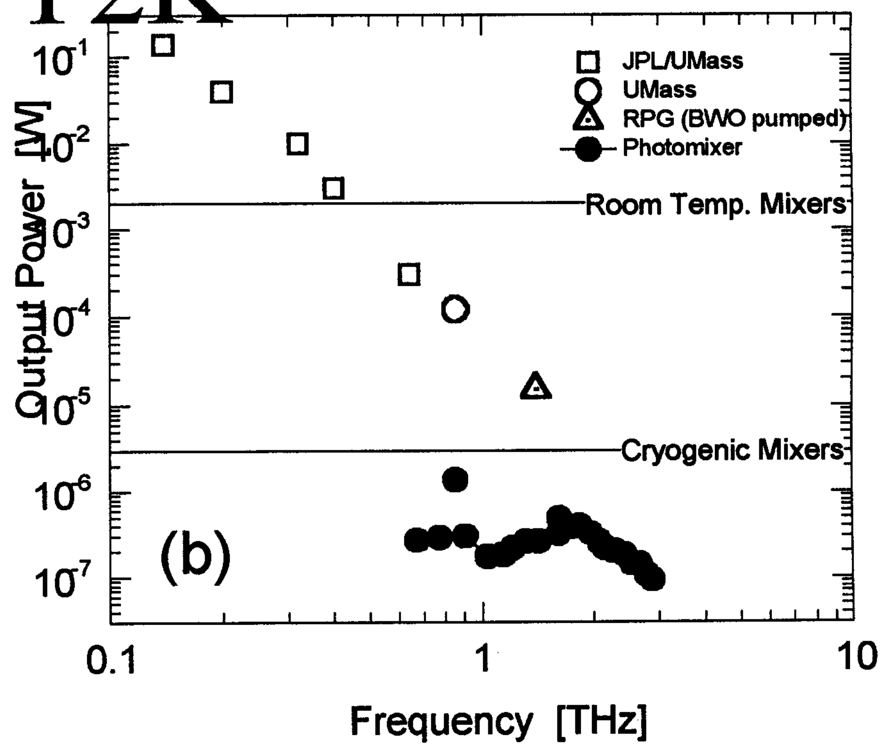
Summary of Submillimeter-Wave Receivers being built at JPL

JPL INSTRUMENT	PURPOSE	RADIOMETER CHANNELS	KEY MEASUREMENTS	IMPLEMENTATION
Earth Observing System Microwave Limb Sounder (EOS-MLS) Launch: 2003	Stratospheric and Tropospheric Ozone chemistry	5 Radiometer Bands: 118 GHz, 190 GHz, 240 GHz, 640 GHz, 2520 GHz	>20 key lines ClO, O_3, H_20, HCl, N_2O, HNO_3, OH, HCN, BrO, HOCl, SO_2, temp., press...	118: MMIC Amp (TRW) 190: Schottky (Aerojet) 240: Schottky QUID 640: Schottky QUID 2520: MOMED
Microwave Imager for Rosetta Orbiter (MIRO) Launch: 2003	Water and Carbon Monoxide on Comet Wirtanen	2 Radiometer Bands: 200 GHz, 557 GHz	CO and water in the head, tail. Temperature, isotope ratios.	190: Schottky planar chip mixer (Aerojet) 557: Schottky planar QUID SHP mixer
Far Infrared and Submm Space Telescope (FIRST) Launch: 2006	Molecular line survey in star forming regions, intra & extra galactic sources.	7 Radiometer Bands: 480-2700 continuous coverage.	>1000 spectral lines: CO, water, ionized carbon, HD, oxygen ...	480-1200: SIS mixers 1200-2700: HEB bolometer mixers Schottky planar mults.
Cloud Ice DC-8 Aircraft-2000	Measurement of ice content & size in cirrus clouds	4 Radiometer Bands: 183, 325, 450, 640 GHz	Continuum and water	183: Schotty chip 325/450: QUID SHP 640: QUID Fund. Mxr.
VESPER Venus Orbiter (proposal) Launch: 2005	Atmospheric chemistry on Venus	2 Radiometer Bands: 470, 557 GHz	>30 key lines: Water, SO, CO_2, SO_2, Oxygen, ...	470: Schottky QUID Subharmonic mixer 557: Schottky QUID Sub harmonic mixer

prepared by Peter Siegel

Heterodyne Receiver Noise and LO Power: Y2K





Obvious need for better sources!

Direct or Heterodyne: How do I choose?

If you want sensitivity...

Direct Detection: high frequency
Heterodyne: low frequency

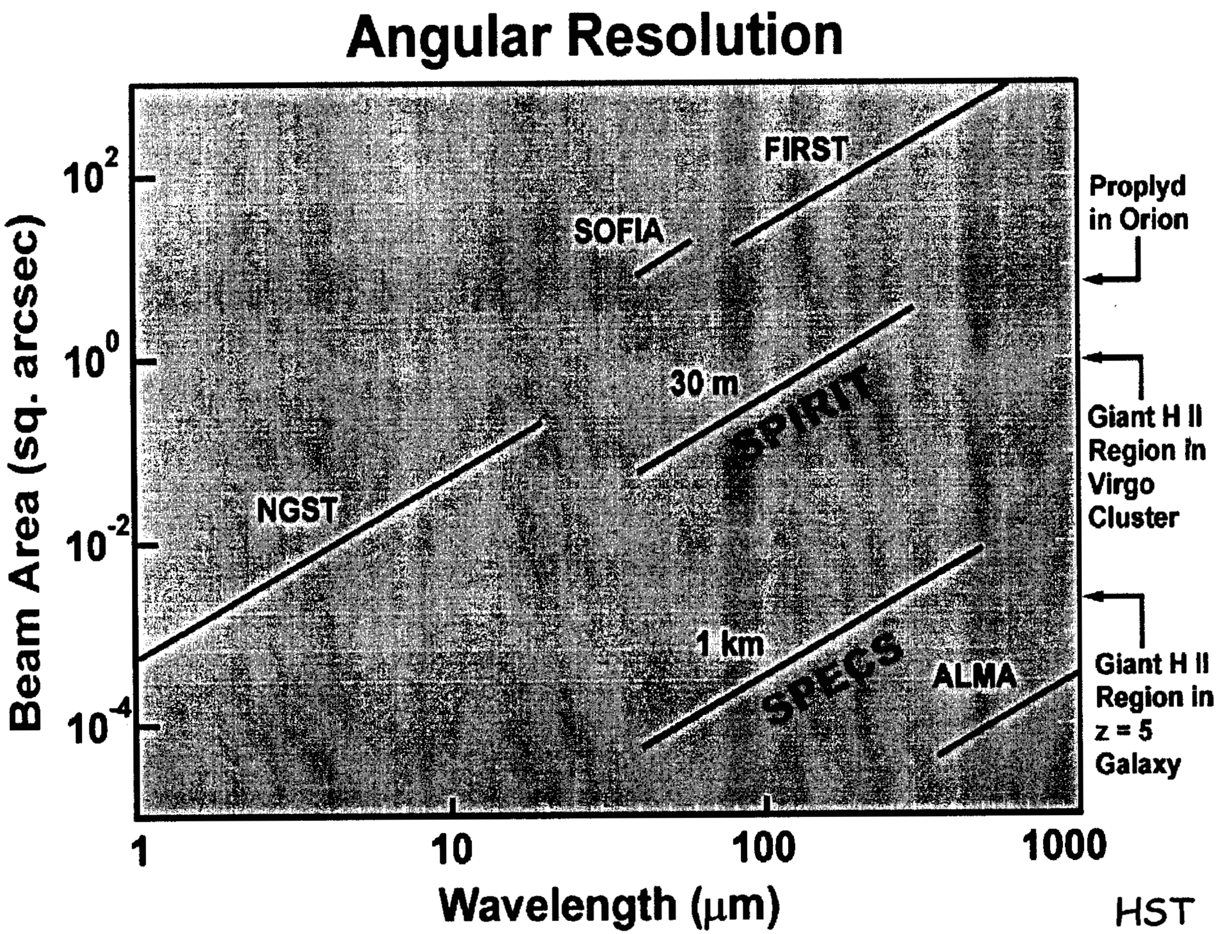
Crossover in techniques at frequency where
source thermal noise ≈ quantization noise

$k_BT \approx h\nu$

roughly, $\lambda \approx 100\ \mu m$ or $\nu \approx 3$ THz

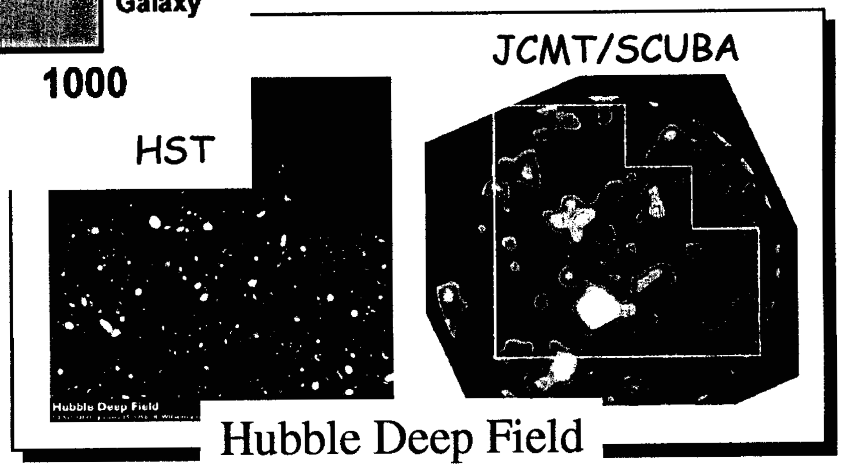
Direct vs. Heterodyne involves many tradeoffs, and the specific application will often make the choice for you.

How far behind is THz?



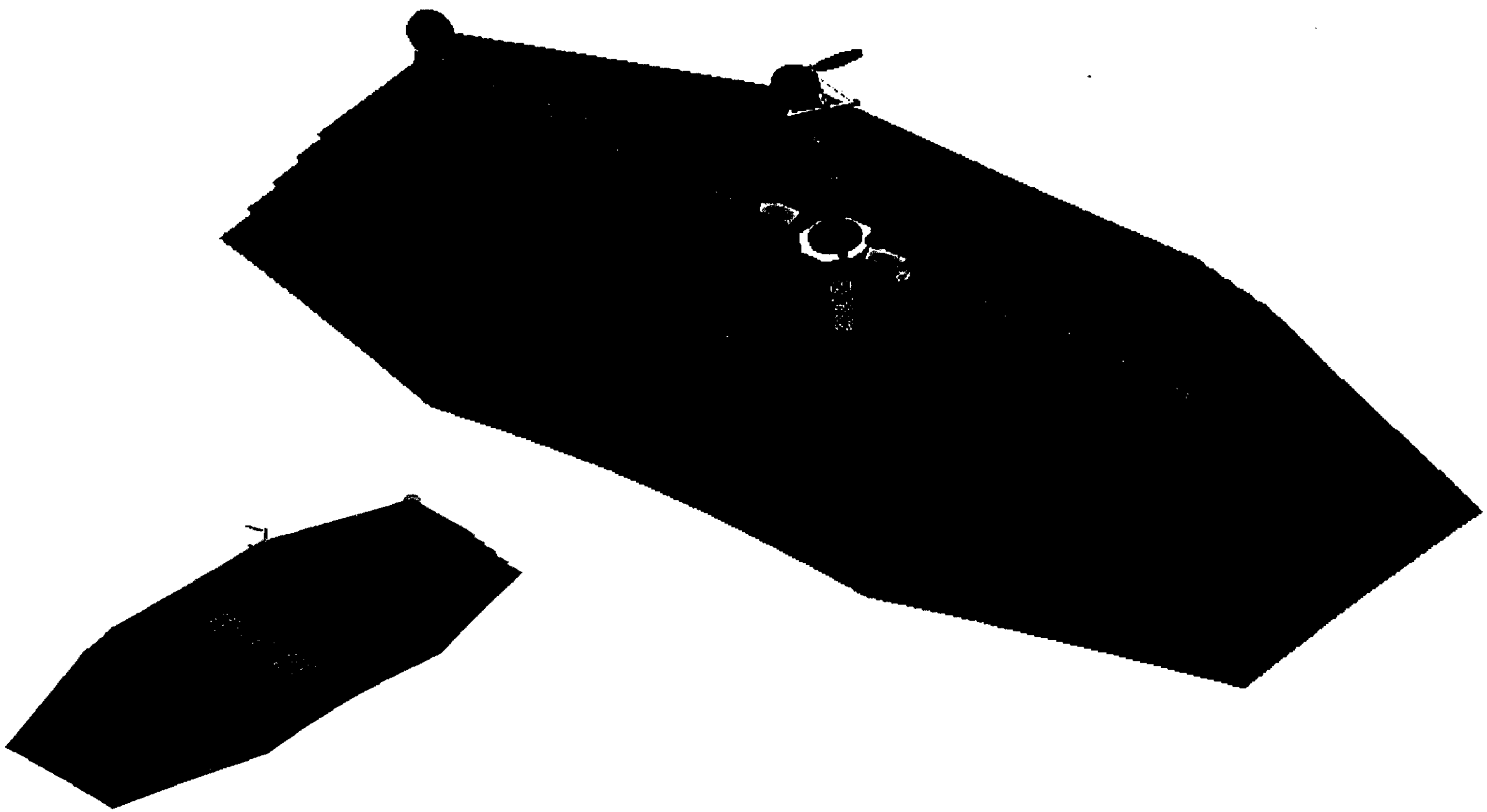
A 30 m baseline is needed to see individual high-z galaxies

A 1 km baseline is needed to resolve the young galaxies

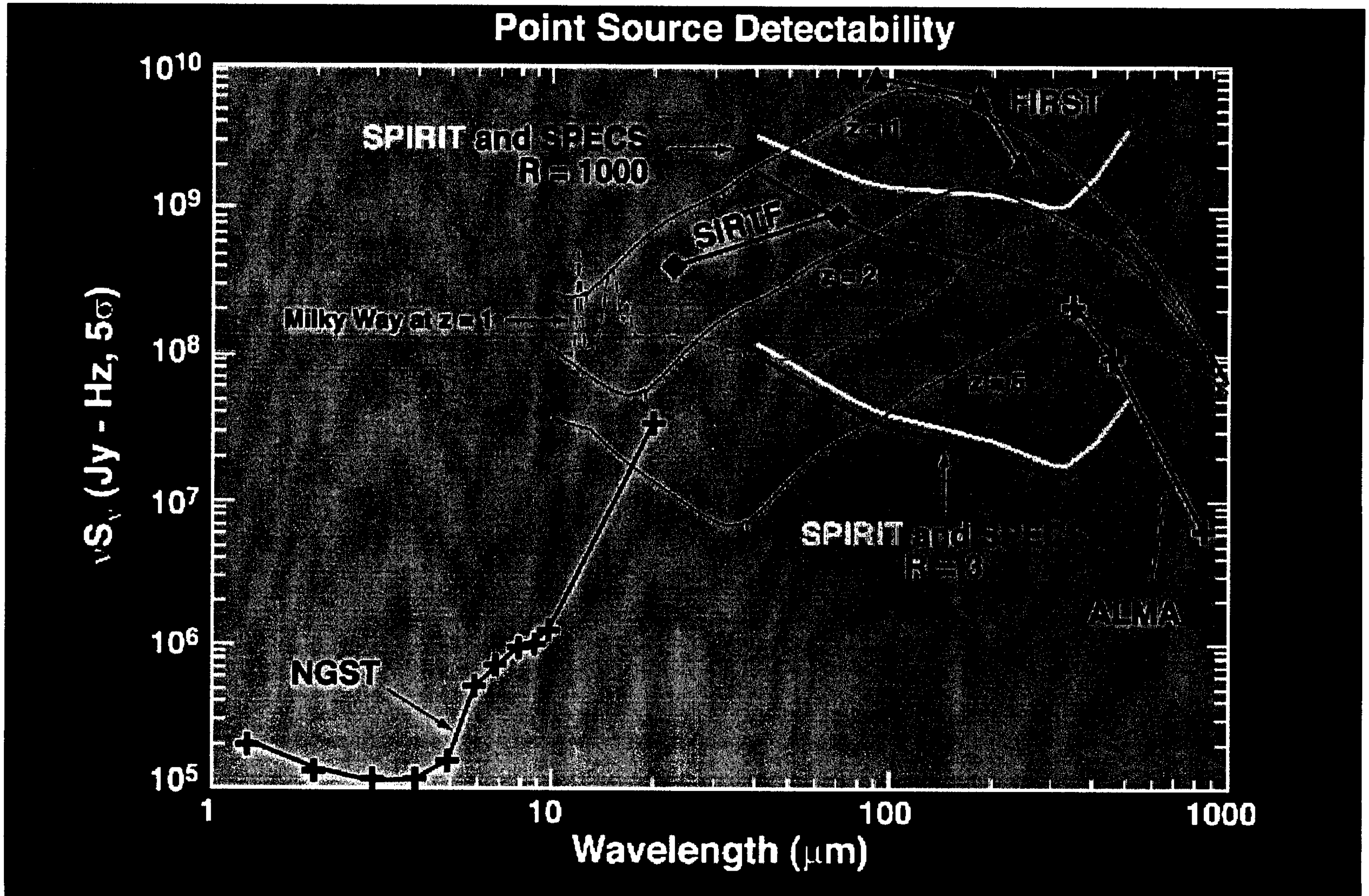


from D. Leisawitz, GSFC

SPIRIT – Submillimeter Interferometer



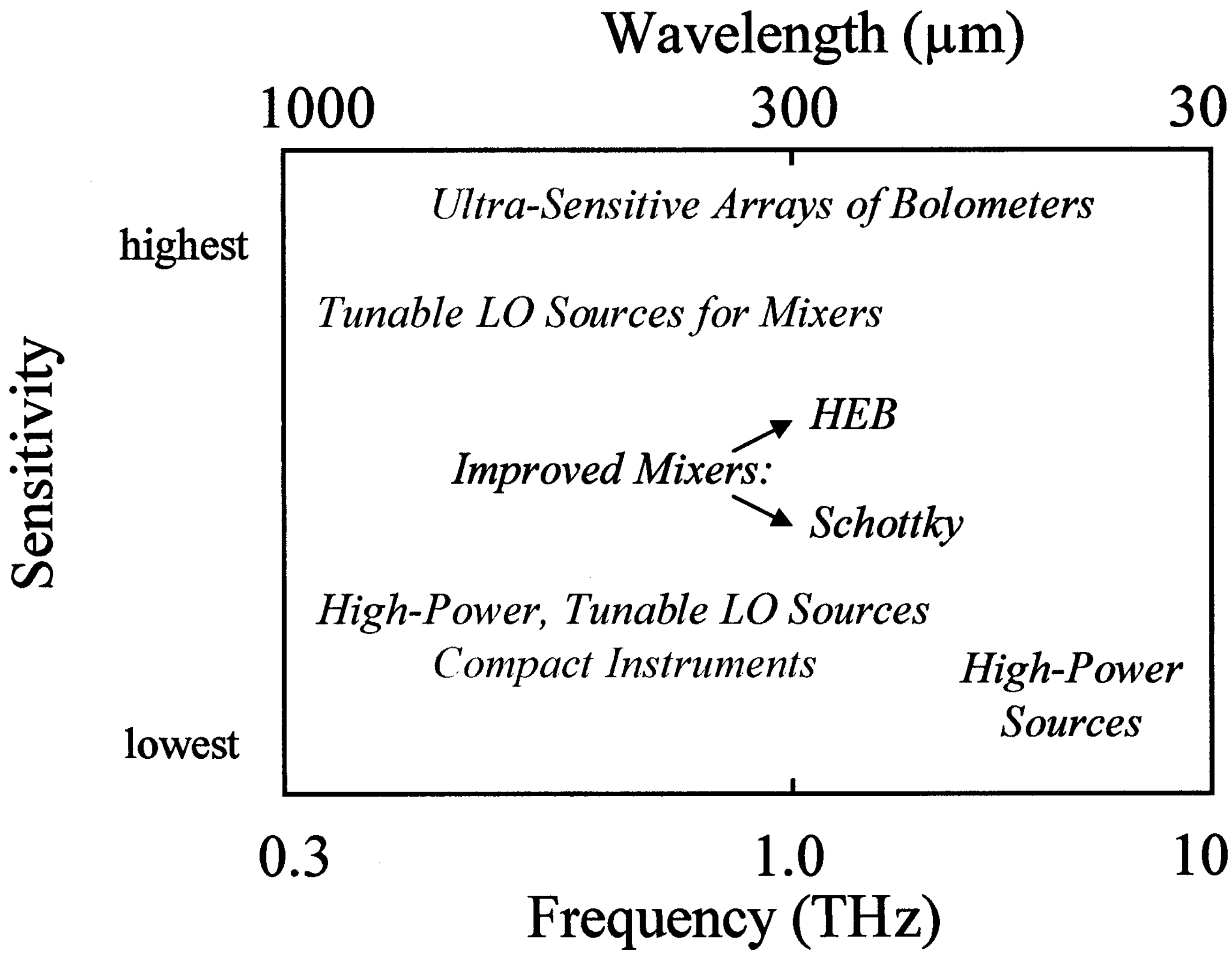
How far behind is THz? (continued)



from D. Leisawitz

Pressing FIR/Submm Detector Needs:

Sensitivity vs. Wavelength



The Present State of FIR Technology

Present state: similar to
optical astronomy in the 1950's !!

They've come a long way in 22 years!

- **Huge increase in sensitivity, and angular resolution over current and proposed missions is possible, unique in the EM spectrum**
- **Simultaneous spectral information provides great potential for BREAKTHROUGH discoveries!**

The *LAST* Viewgraph

This is a *fun and exciting* field!

- Revolutionary technology is being developed
  and will be rapidly implemented
- Factors of 2 to 10 improvement are common

It is challenging, but there is a BIG payoff

What legacy do YOU want to leave for future generations?

T-Rays can *stop terrorism*, cure *heart disease* and *cancer*, and alleviate *traffic congestion* (OK, maybe not "stop terrorism")