Passive terahertz imaging with superconducting antenna-coupled microbolometers

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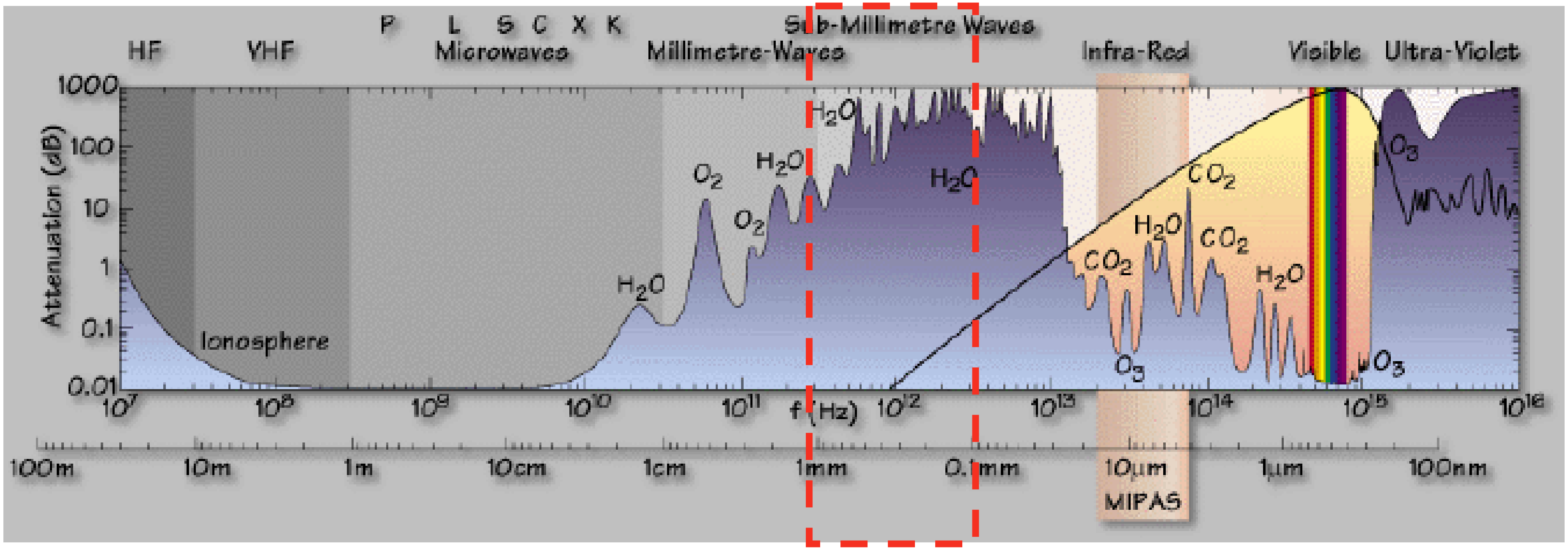
Outline

- Terahertz radiation - characteristics
- Application - stand-off detection of concealed weapons & explosives
    - Passive vs active modalities
    - Indoors vs outdoors
- Existing technologies: signal-starved & expensive
- Introduction to bolometers
- Spectral imaging - potential
- Experiments: Electrical & optical characteristics
- Single pixel raster scanned passive images
- New developments
    - NbN bolometers
    - Arrays
- Conclusions

Terahertz radiation?



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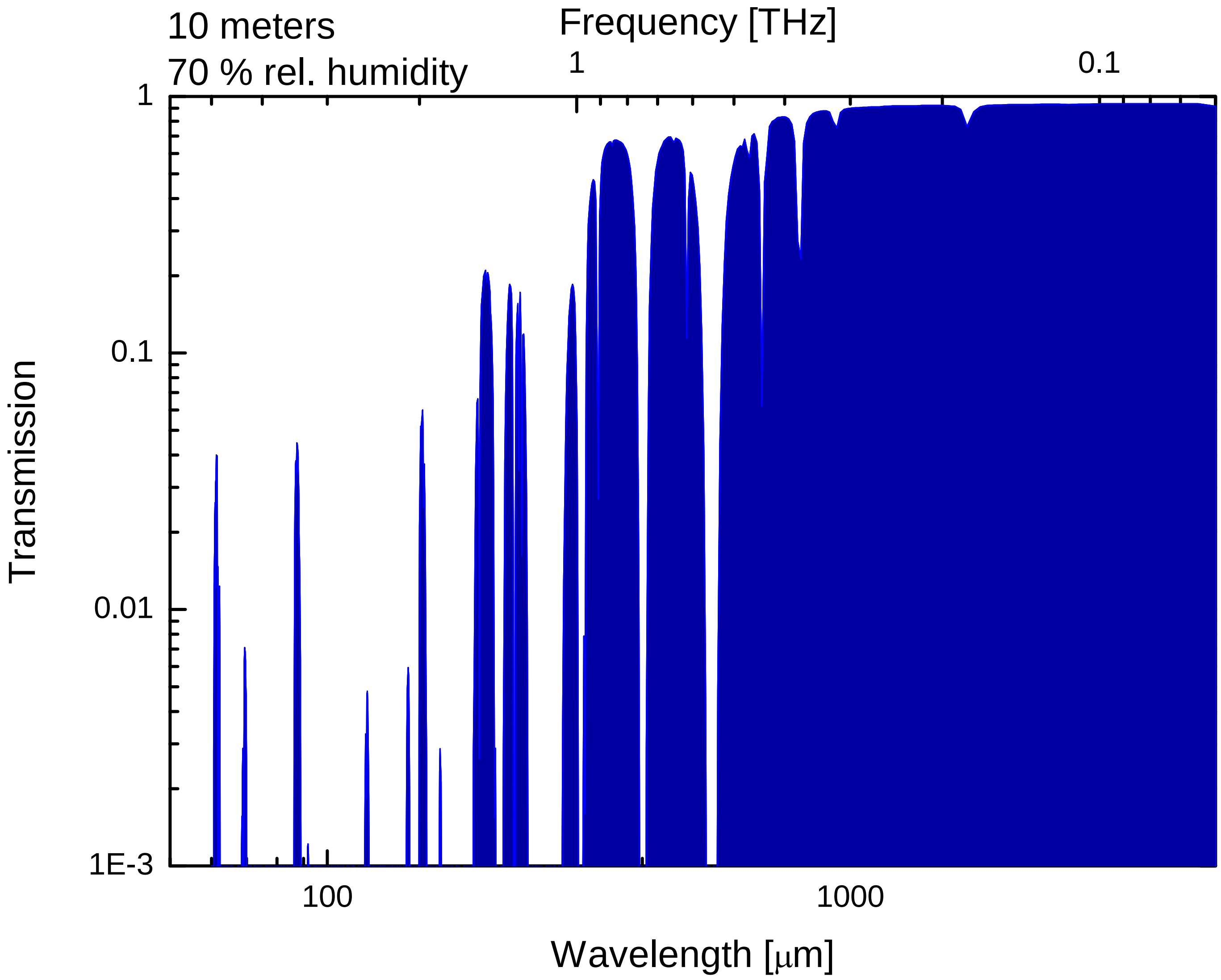
10 meters
70 % rel. humidity
Frequency [THz]
1
0.1
1
0.1
0.01
1E-3
Transmission
100
1000
Wavelength [μm]

Terahertz radiation

- Characterised by a wavelength ~100 μm < λ < 1 mm (300 GHz < f < 3 THz, 14 K < T < 144 K, 1.2 meV < $h\nu$ < 12 meV)
- Relatively good penetration through dielectric materials
- Focussing possible with reasonable (D<1 m) apertures
- No known health effects
- The spectral range contains a *vast* number of characteristic spectral lines that correspond to the torsional, rotational & twisting modes of molecules
    - Sharp spectral features only in low-pressure gases
    - Resonances are broad in solid materials & liquids
- Detection & generation (especially at ambient temperatures) remains a challenge ($h\nu \approx k_B T$)

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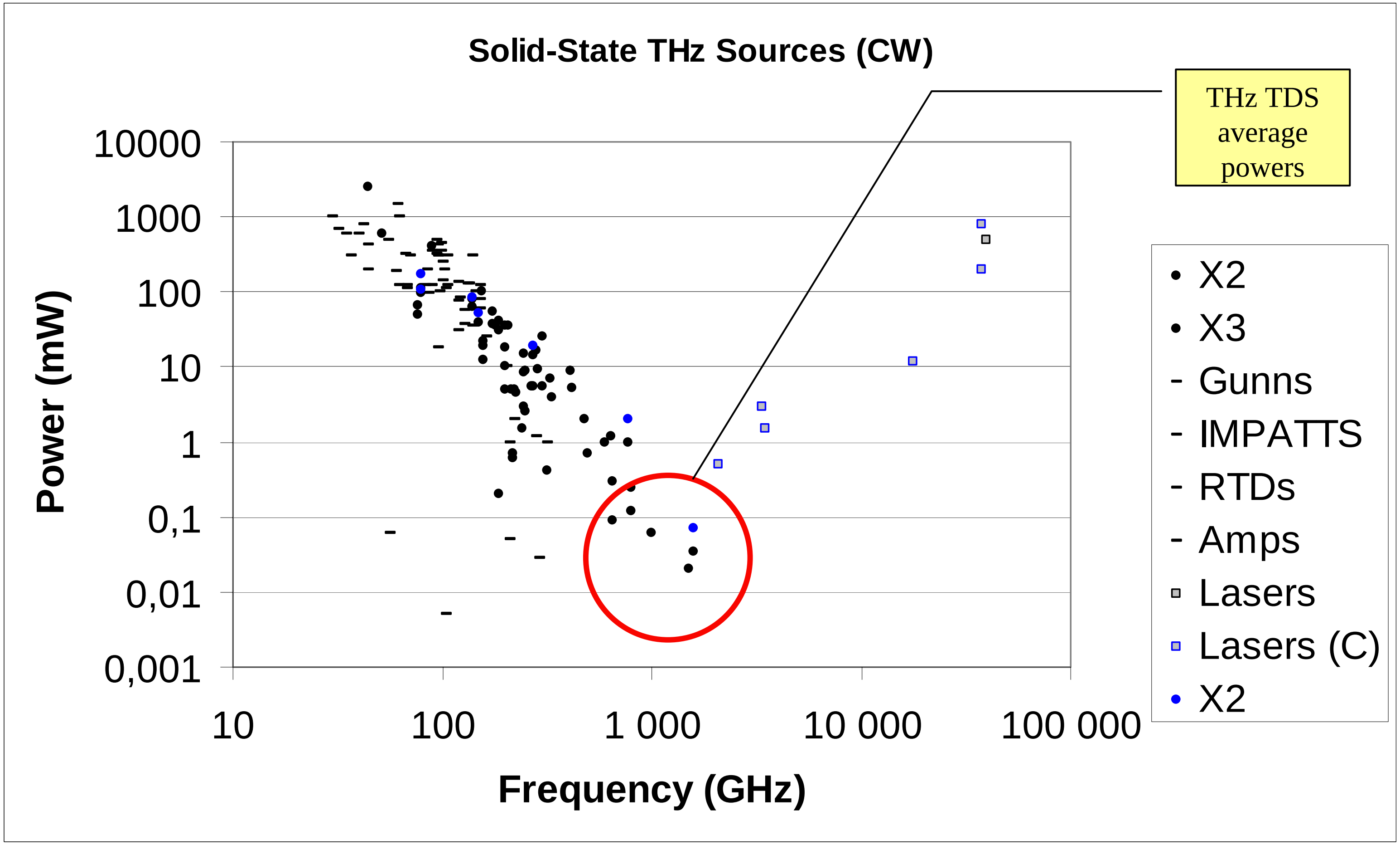
The THz "gap"



graph courtesy of Tom Crowe (VDI/UVA)

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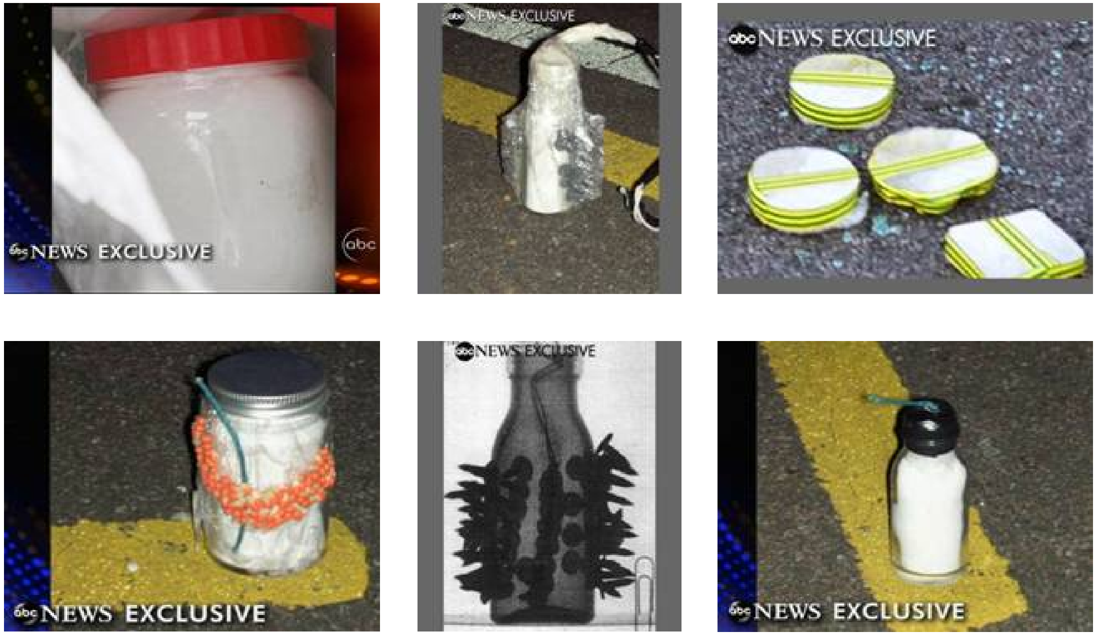
Our goals

- Our short term goals:
    - To demonstrate nearly background - limited direct detectors that are array compatible in the 0.2 to ~3 THz range
    - To show that refrigeration to 4 K with COTS closed-cycle cryorefrigerators is indeed a viable solution
    - Fully utilize the capabilities that are available for these sensitive direct detectors: hyperspectral operation at minimum front-end cost
- Our medium term goals:
    - Demonstrate passive video-rate operation with scanned linear arrays
- …and long term:
    - Cryogenic multiplexers
    - Large format 2D arrays

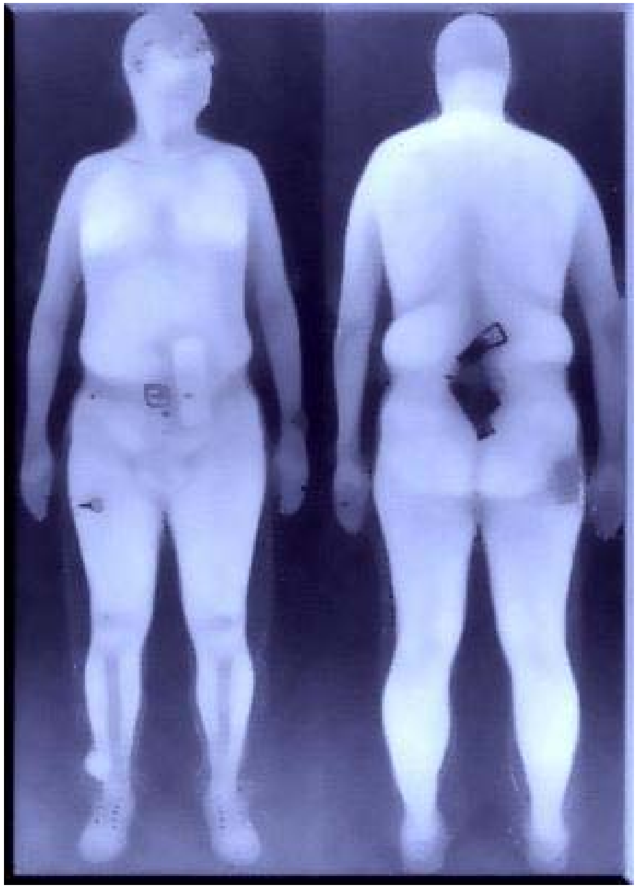
Motivation: Concealed Weapons Detection at a stand-off distance

- Millimetre & THz imaging identified as one possible solution to the detection of concealed weapons & explosives at a stand-off distance of several meters
- Non-metallic weapons onboard airplanes
- Explosive devices with little metal content
- Sheet explosives



CWD Imagers are out in the market - why bother?

- Low energy X-ray backscatter (Rapiscan Systems Secure-1000)
- Exquisite image quality
- BUT:
  - Even though the Δ dose is extremely small, still ionizing radiation
  - Image quality can in fact be too good - privacy concerns
  - *Lacks stand-off capability*
  - *Slow throughput*



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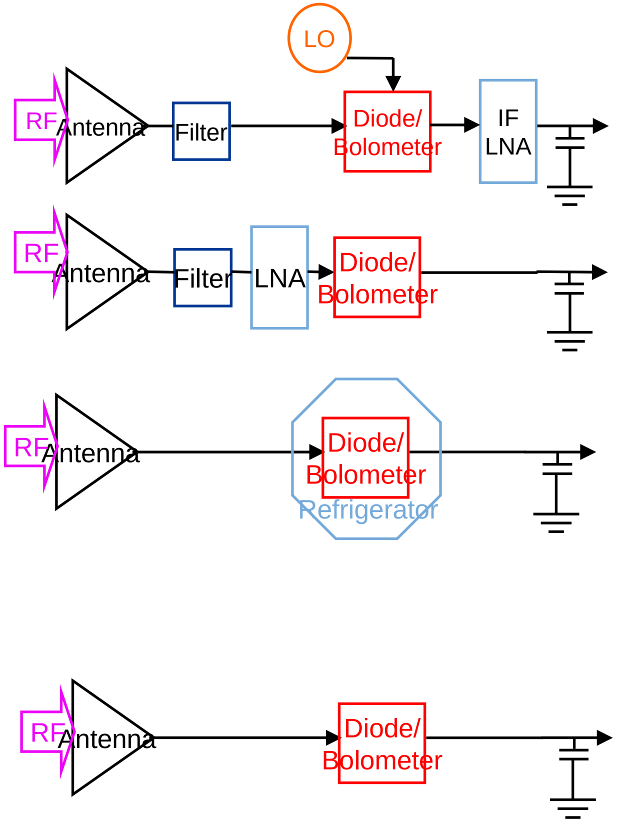
THz/MMW Radiometry: technology matrix

- Context: **Passive** kilopixel imaging at video rates at mm/sub-mm waves



Technology	Sensitivity	Price
Coherent heterodyne	**Good**	**Huge**
Coherent direct (with MMIC preamplification)	**Good**	**Large**
Cryogenic Microbolometers	**Excellent**	**Moderate**
Incoherent direct (i.e. diodes, no preamplification)	**Moderate**	**Small**
Antenna coupled microbolometers	**Poor (active only)**	**Tiny**

Decreasing complexity
Decreasing sensitivity
Increasing detector requirements

Maximum frequency

~200 GHz	**600 GHz**	**> 1THz**

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Figures of Merit

- For direct (incoherent) detectors, typically Noise Equivalent Power (NEP) [W/Hz$^{1/2}$]

$$\Longrightarrow \quad \mathrm{SNR} = \frac{\eta P_{sig}}{NEP_e}\sqrt{2\tau_{\mathrm{int}}}$$

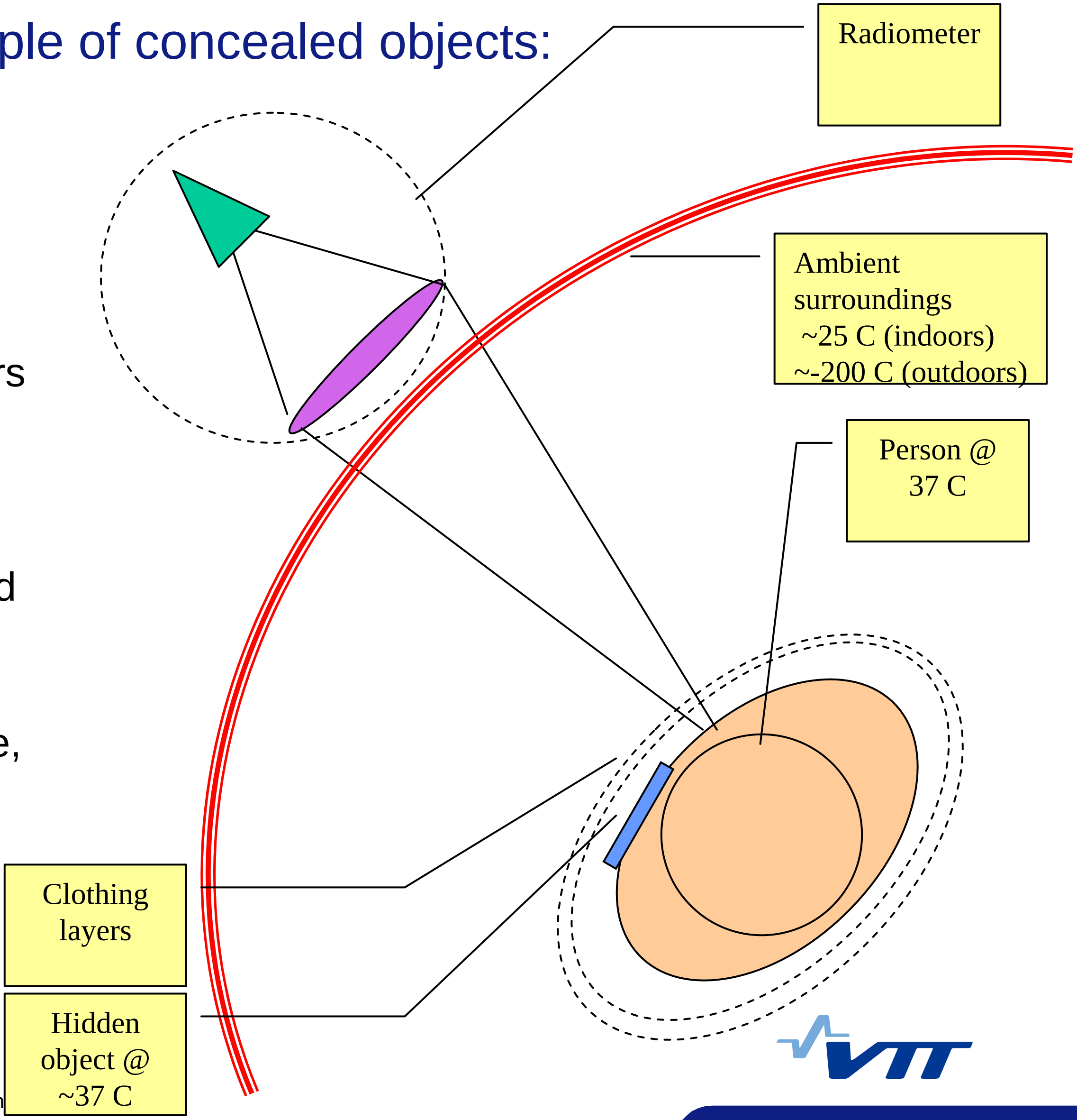
- For passive detection of thermal (continuum) targets, Noise Equivalent Temperature Difference (NETD) is most useful (includes detection bandwidth)
  - Typically assumes 30 ms integration time

$$\Longrightarrow \quad NETD = \frac{NEP}{\partial P / \partial T_{\mathrm{target}}\sqrt{2\tau_{\mathrm{int}}}} \approx \frac{NEP}{nk_B \Delta\nu\sqrt{2\tau_{\mathrm{int}}}}, [\mathrm{K}]$$

In Rayleigh-Jeans limit

Detection principle of concealed objects:

- Emissivity of human skin ~50 % @ 100 GHz (close to 1 at higher frequencies)
- Metallic objects almost perfectly reflecting, other materials fall between perfect reflectors/absorbers
- Clothing materials ~transparent at mmw frequencies
- A radiometric temperature contrast between the background (body) and the object, which reflects the temperature of the surroundings
- If surroundings at body temperature, no contrast - illumination required
- Figure of merit of the radiometer: Noise Equivalent Temperature Difference (Radiometric resolution) [K]



Radiometer

Ambient surroundings
~25 C (indoors)
~-200 C (outdoors)

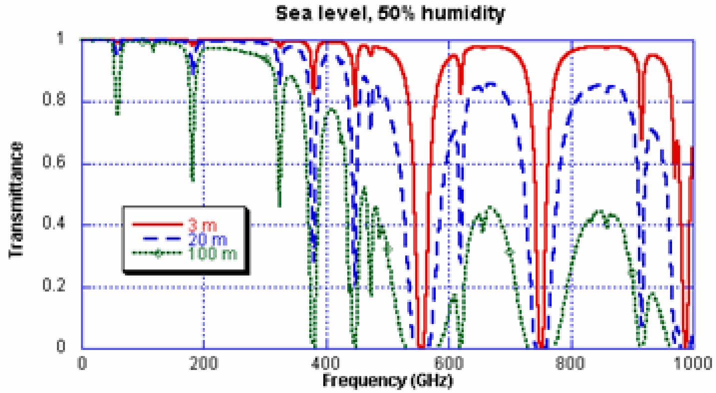
Person @ 37 C

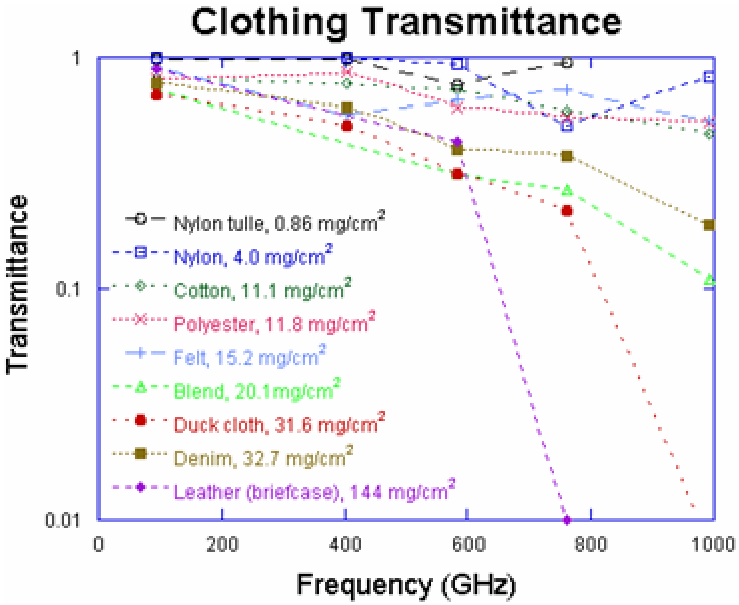
Clothing layers

Hidden object @ ~37 C

Millimetre-wave imaging vs. submillimetre (or THz) imaging

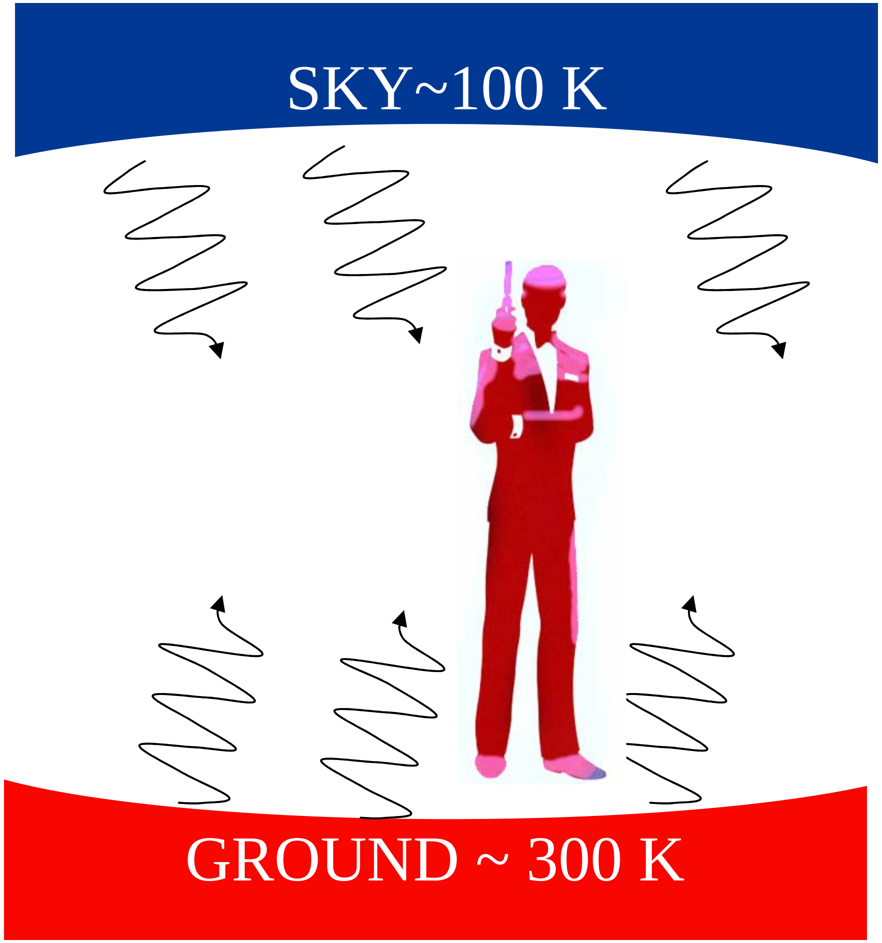
- Optimum operating frequency for CWD determined by several factors:
  - Range
  - Spatial resolution
  - Thermal (or power) resolution
  - Target scenario (thickness of clothing materials etc)
  - Bandwidth
- Higher frequencies:
  - better spatial resolution for a given aperture size (1 m considered max. practical)
  - Most typical clothing materials transmit well up to ~0.6 THz
  - Atmospheric attenuation not an issue at short ranges (~<10 m) For longer ranges, operation at atmospheric windows necessary
- *For stand-off CWD at ~10-50 m, optimum f~0.6 THz*
- *Limited technology options available*





Outdoors passive millimetre wave (100 GHz or below) imagery

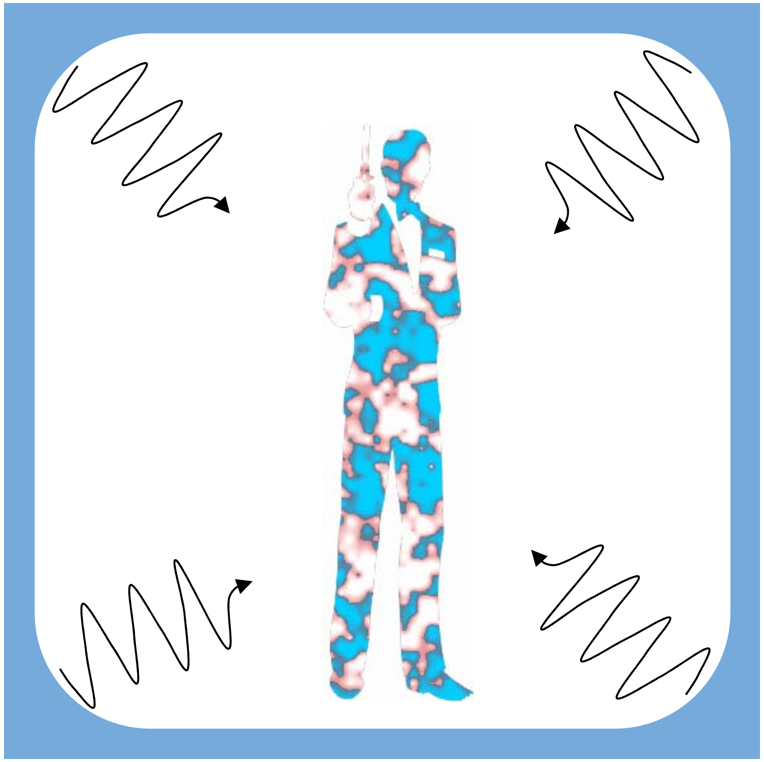
- Outdoors contrasts in the mmw scene can be very large (cold sky vs. ground ~200 K)
- Contrast between body & concealed weapons ~10 K
- Sky/ground provides 'illumination' to the scene--> bi-modal illumination
- Sufficient sensitivity of passive radiometers ~1-5 K
- Sky is like a giant cold lamp that illuminates the scene; Instead of being emitted by the person, detected signal is due to the reflection from surroundings



Millimeter wave outdoors images (Qinetiq, UK)

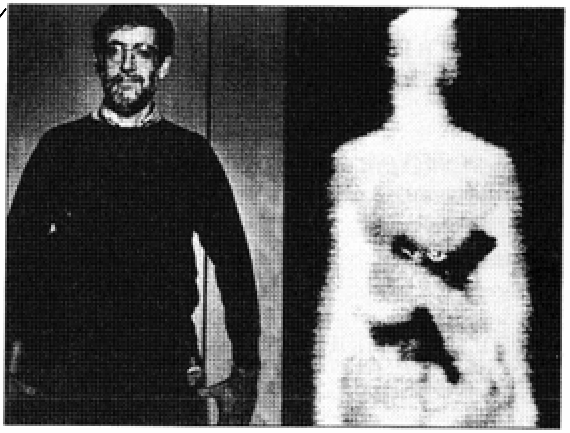
Indoors passive millimetre wave imagery

- Contrasts at max ~(37-20) K~15 K, with losses much less
- One tenth of available signal power as compared to outdoors imaging
- With losses in clothing materials, contrast between a weapon and the body ~ 1 K or less
- Required NETD 0.5 K or less
- Remedies (for existing detector technology)
  - Active illumination (lack of sources!)
    - Oscillators
    - Noise sources
  - "passive" illumination
    - Artificial enhancement of the scene contrast by a large blackbody, a window through the ceiling, etc
- All illumination schemes require "angle diversity"



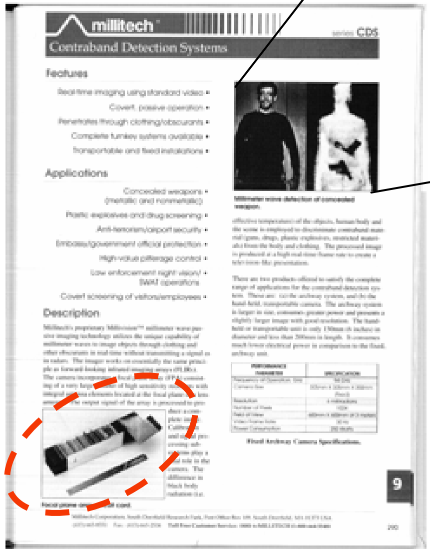
Passive mm-wave imaging is old-hat, isn’t it ?

- Single pixel scanned image
- 30 minutes acquisition time
- Switched heterodyne receiver, scanned across the target (8 pixels)
- Technology transfer from millimetre-wave astronomy to the airport…?



Millimeter wave detection of concealed weapon.

• 1995: Millitech catalog



millitech series CDS

Contraband Detection Systems

Features

- Real-time imaging using standard video
- Covert, passive operation
- Penetrates through clothing/obscurants
- Complete turnkey systems available
- Transportable and fixed installations

Applications

- Concealed weapons (metallic and nonmetallic)
- Plastic explosives and drug screening
- Anti-terrorism/airport security
- Embassy/government official protection
- High-value pilferage control
- Law enforcement night vision/ SWAT operations
- Covert screening of visitors/employees

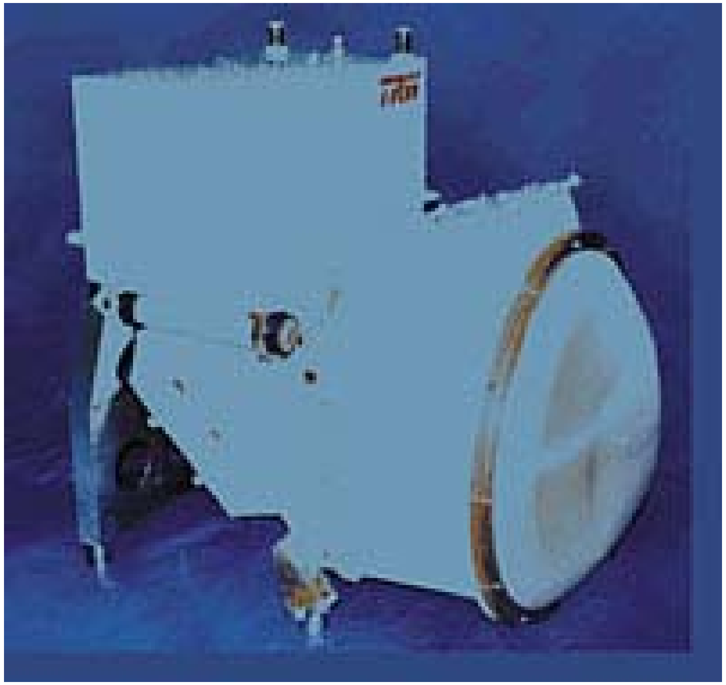
Description

Millimeter wave detection of concealed weapon.

9

Passive mm-wave imaging is old-hat, isn’t it ?

- Second generation: TRW passive millimetre wave camera (1997)
- 1040 MMIC radiometers
- *Unit cost >1 MUSD (production line, not prototype!)*
- Power consumption ~1 kW, water cooled
- 89 GHz, NETD (17 Hz) ~1 K



- InP HEMT- based MMIC low noise amplifiers remain expensive
- Frequency of operation limited by the availability of low noise transistors to ~250 GHz
- Our philosophy: reduce front-end complexity by refrigeration

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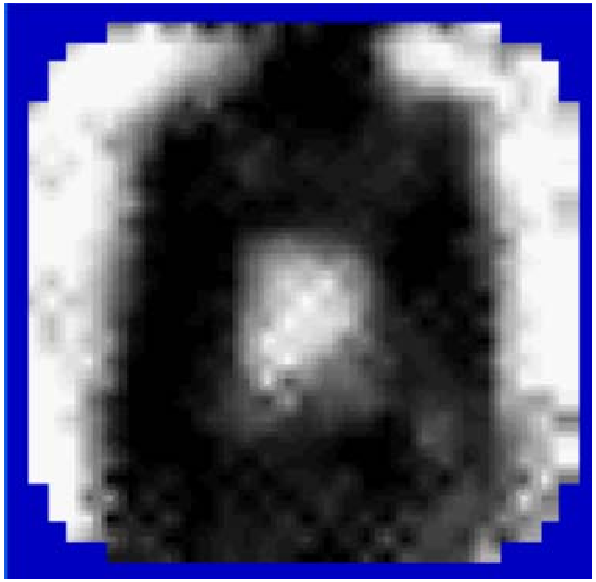
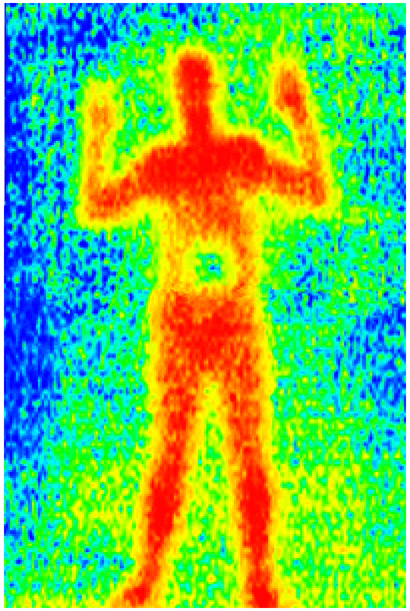
Passive indoors imagery, Heterodyne/direct detection receivers

- Comparison: Indoors imagery by Millivision (a frame from a real-time movie)



thruvision™

3 frames/sec



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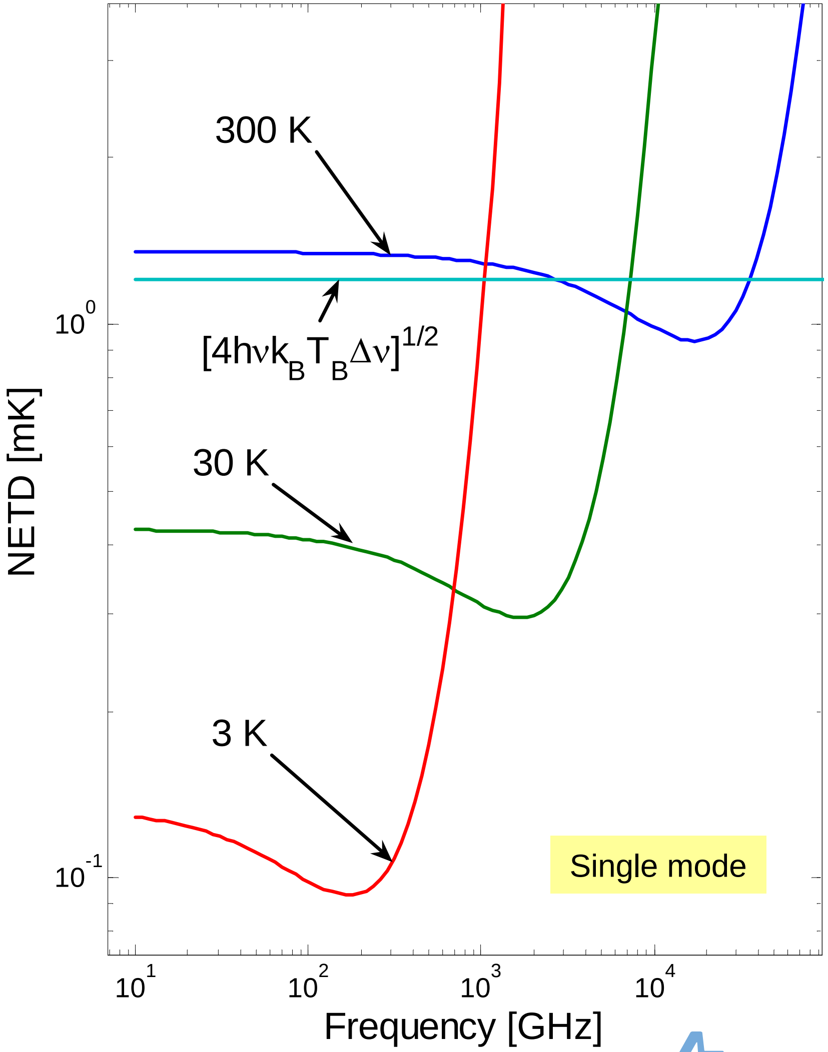
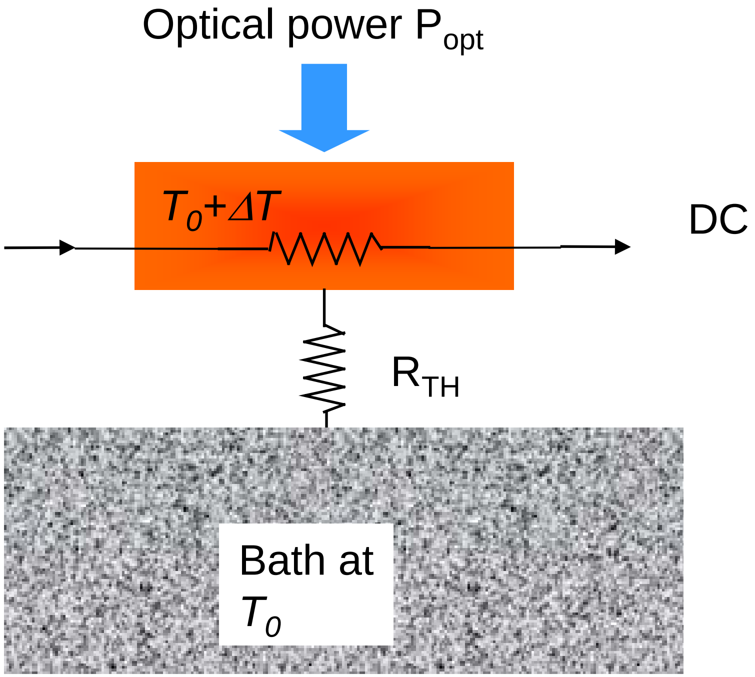
Fundamental limits for incoherent direct detection

- Assuming parameters:
  - ν_c=500 GHz
  - $\Delta\nu/\nu_c$=2/3 (1 octave)
  - τ_{int}=30 ms (video-rate)
- → Theoretically NETD =1.3 mK achievable
- However, in real-life also other sources of noise (e.g. atmosphere, scene clutter etc.)
- ***Only cryogenic direct detectors have the potential to reach this NETD***



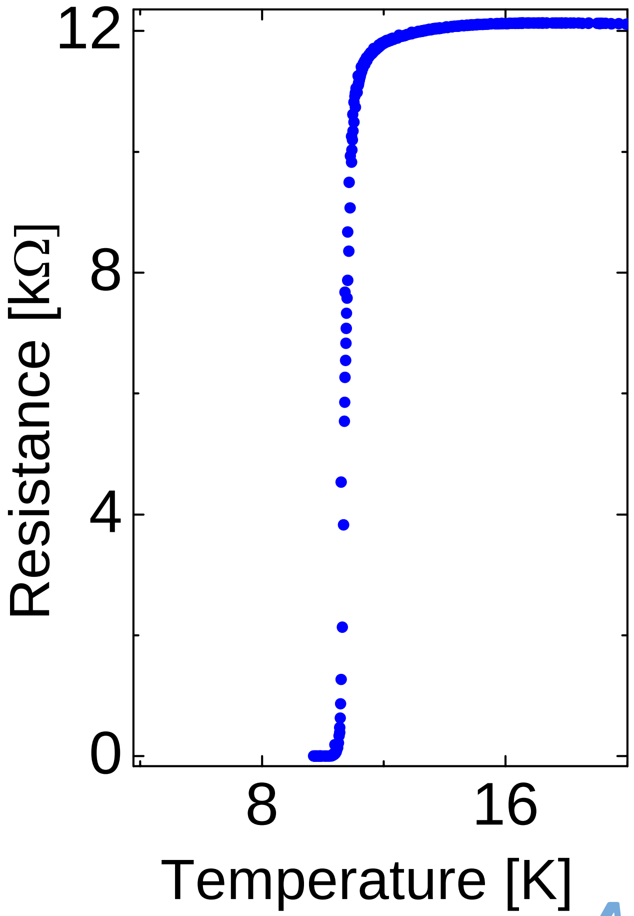
Bolometers - an introduction

- Invented by Samuel Pierpoint Langley 1880
- "Detected a cow moving across the field at 1/4 mile away" using a platinum thermometer within a Wheatstone bridge
- Simple principle:
    - absorbed radiation (of any kind, really) causes variations in the temperature *T* of an isolated heat capacity *C*.
    - Sensitive thermometer measures the temperature variation
    - Steady-state change in temperature: $\Delta T=\Delta P_{opt}R_{th}$
    - Thermal time constant $\tau_{th}=R_{th}C$



Bolometers - an introduction

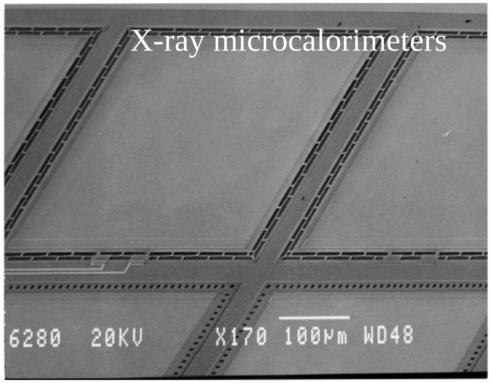
- Various methods of thermometry:
    - Resistive
    - Capacitive (e.g. pyroelectric devices)
    - Inductive
    - Mechanical
- Supercondutors: Thermometry at the S-N transition
- Cryogenic bolometers (T~300 mK or below) are *the most sensitive direct radiation detectors that exist*



Bolometers: Optical Coupling

- Various schemes of radiation coupling
  - Infrared → γ-rays : surface absorbing (lossy "antenna")
  - As wavelength increases, large thermally isolated (suspended structures become unpractical)
  - … → infrared : Antenna - coupled

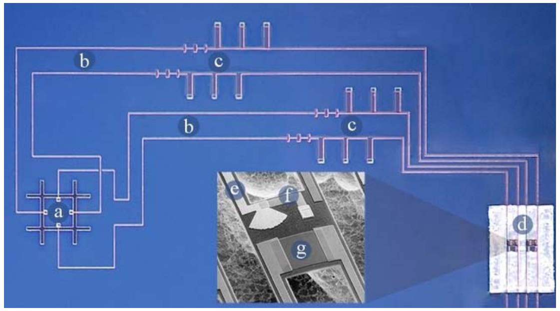
- Speed = $C_{th}R_{th}$
- $C_{th} \propto 1/f$
- → decrease thermally active volume while maintaining sensitivity

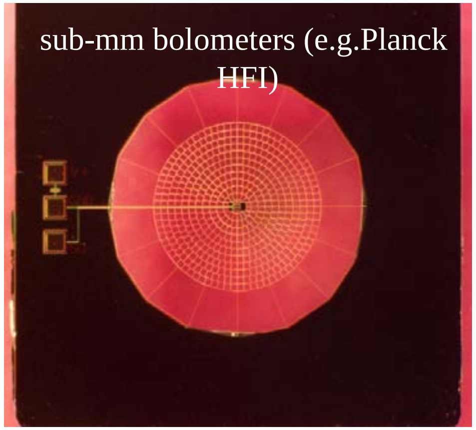

X-ray microcalorimeters

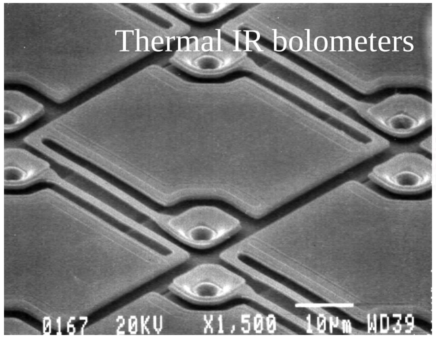
Increasing wavelength

Earlier work on ACMBs

Tong	1983
Rebeiz	1990
Hu	1996




sub-mm bolometers (e.g.Planck HFI)


Thermal IR bolometers

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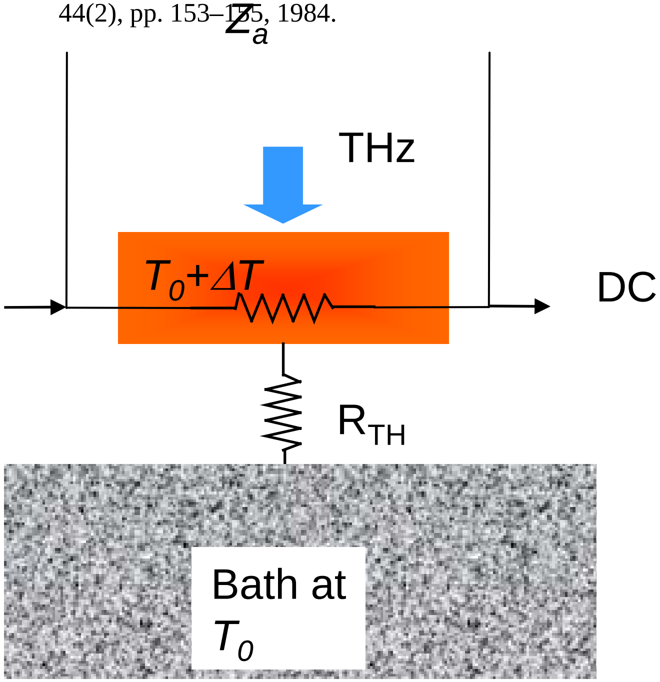
Bolometers - an introduction

- A thermally isolated, radiation absorbing lump of material: a bolometer
- Change ΔP_{opt} in incident signal power results to a change $\Delta T = \Delta P_{opt} R_{th}$ of the isolated element
- Add thermometry → obtain ΔP_{opt}
- A thermally isolated termination of a lithographic antenna
- **NEP of bolometers *independent* of frequency**
    - In practive NETD *improves with frequency*
- Noise sources
    - Phonon (or thermal fluctuation) noise $\propto \mathbf{T}^{3/2}$ (for W-F law limited thermal conductance in an isolated bridge)
    - Johnson noise
    - (1/f noise)
- Unique advantage over MMICs, diodes: **bandwidth** (even $\Delta f/f$ ~2 possible) due to the *Bode-Fano Criterion*

T.-L. Hwang, S. Schwarz, and D. Rutledge, "Microbolometers for infrared detection," Appl. Phys. Lett. 34(11), pp. 773–776, 1979.
6. D. P. Neikirk, W. W. Lam, and D. B. Rutledge, "Far-infrared microbolometer detectors," International journal of infrared and millimeter waves 5(3), pp. 245–278, 1983.
7. D. P. Neikirk and D. B. Rutledge, "Air-bridge microbolometer for far-infrared detection," Appl. Phys. Lett. 44(2), pp. 153–155, 1984.



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Bolometers as X-ray detectors

- Cryogenic thermal detectors currently hold the world record with respect to energy resolution at X-ray & Gamma-ray energies
- Example - NIST Transition-edge microcalorimeter (~100 mK)
- ΔE_{FWHM}=2.38 eV @ 5.89 keV
- But - sub-kelvin operation essential (can not compete with photodiodes above a few kelvins)

Francesco Giazotto, Tero T. Heikkilä, Arttu Luukanen, Alexander M. Savin, and Jukka P. Pekola, *Thermal properties in mesoscopics: physics and applications from thermometry to refrigeration*, Reviews of Modern Physics, 78, 1, pp. 217-274 (2006)

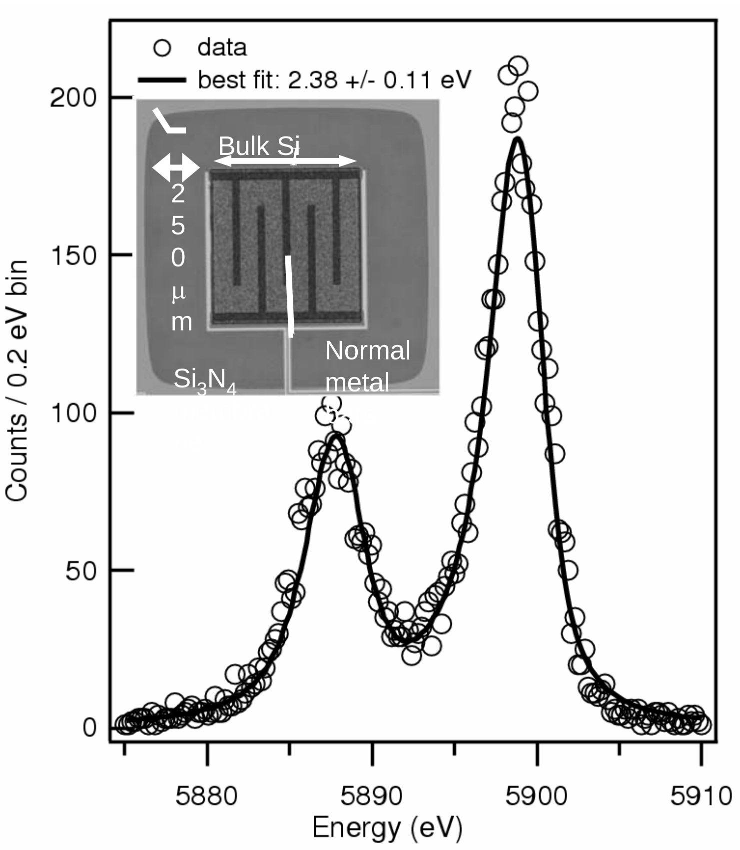
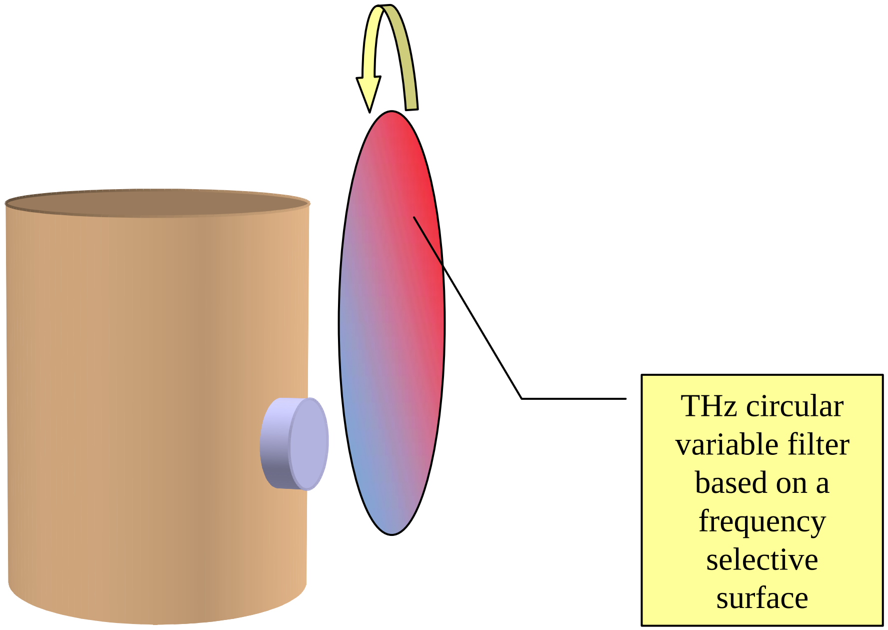
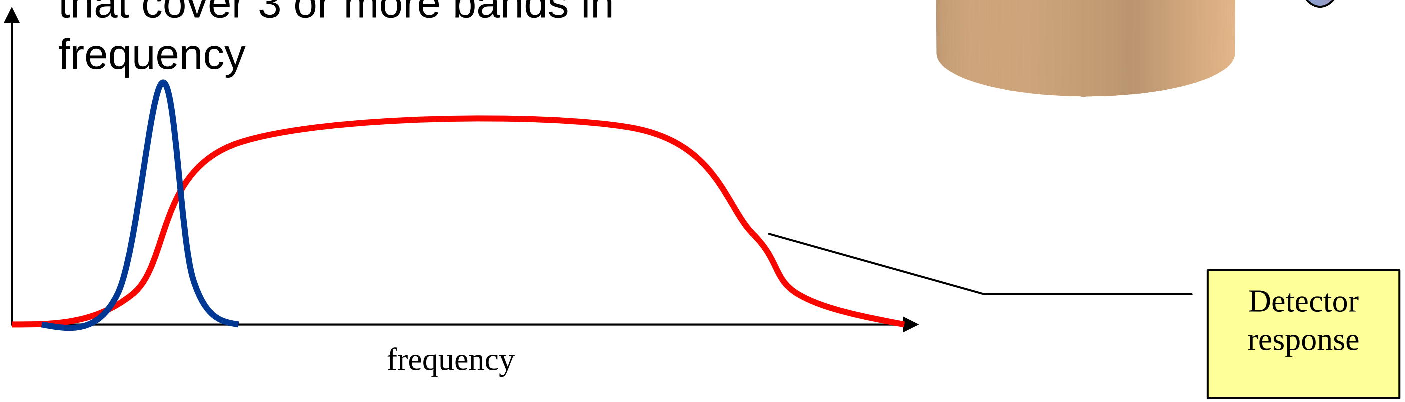


Figure courtesy of Joel Ullom, NIST Quantum Electrical Metrology Division
Boulder, CO

What does sensitivity (NEP) coupled with bandwidth buy?

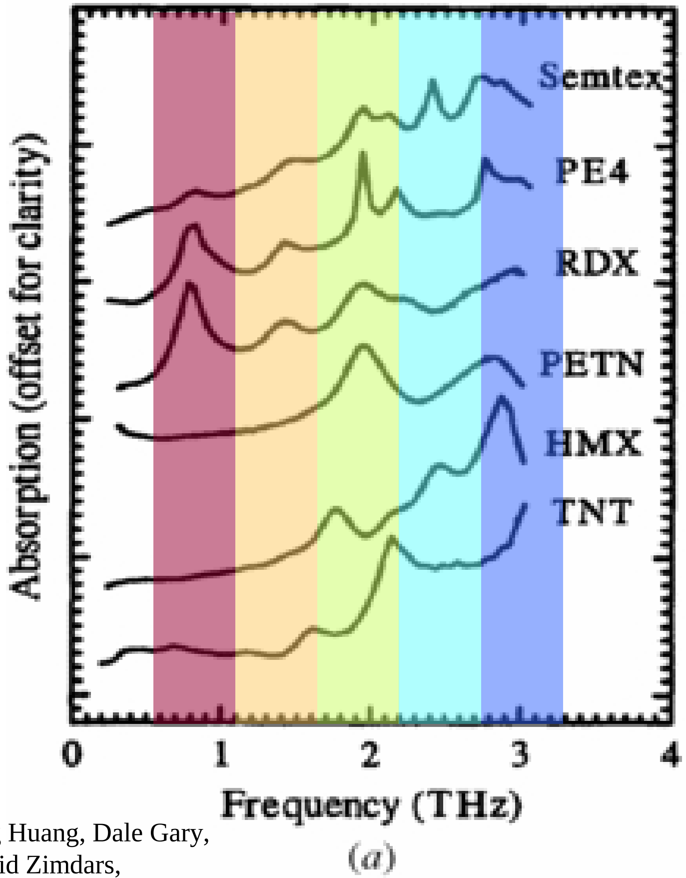
- Spectral features of solids & gases in stp are *broad*.
- Combination of a broadband bolometric detector & tunable filter → low resolution spectroscopy for materials identification
- Alternatively: Design "RGB" pixels that cover 3 or more bands in frequency





THz imaging with superconducting antenna-coupled microbolometers: *Unique* capabilities

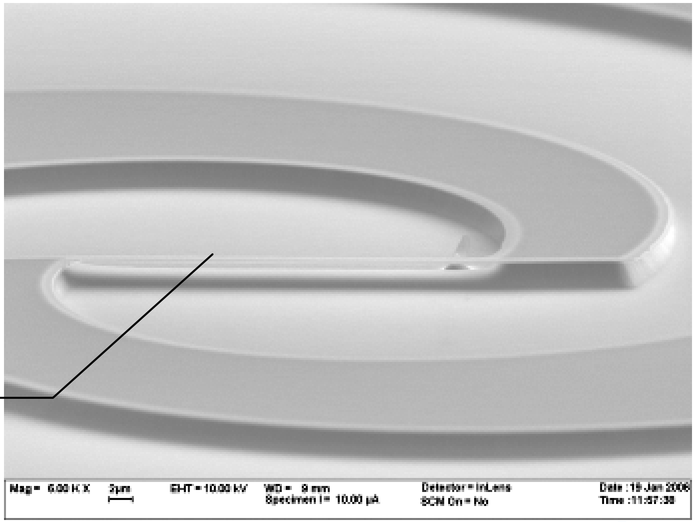
- Almost perfect frequency agility: can be used to construct full-"colour" imagers: use THz CVF or multi-colour arrays
- Possibility for spectral imaging for remote identification of concealed explosives
- Not limited to frequencies below ~300 GHz (as MMIC technologies currently are)



Kemp *et al* , Proc SPIE
John F Federici, Brian Schulkin, Feng Huang, Dale Gary, Robert Barat, Filipe Oliveira and David Zimdars, *Semicond. Sci. Technol.* 20 No 7 (July 2005) S266-S280

Superconducting Antenna-coupled microbolometers for passive THz imaging

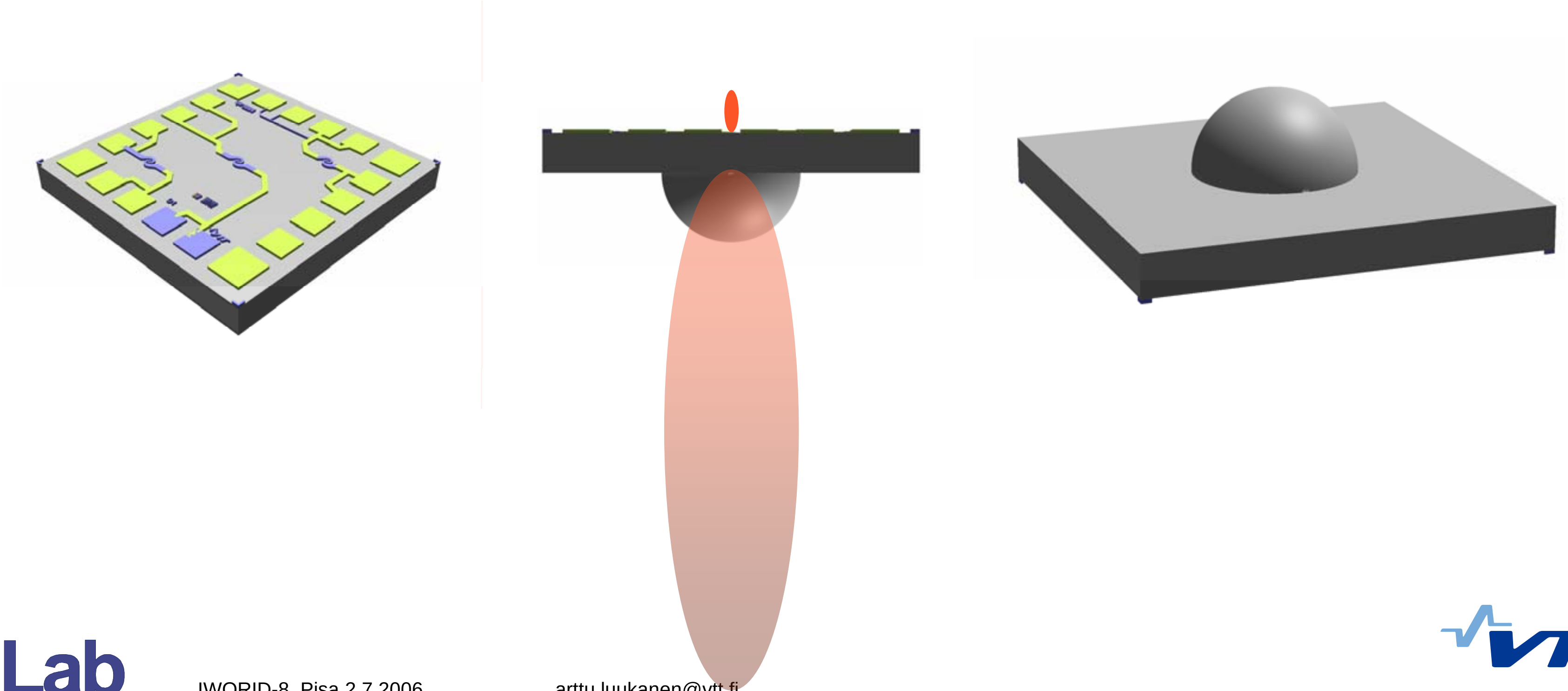
- Broadband (0.1 - 1 THz lithographic antenna) on Si
- Bolometer material
    - Nb for 1st generation devices
    - NbN for 2nd generation
- Similar to a Transition Edge Sensor; but with a large temperature gradient
- V-bias + T-gradient→ phase separation
- Bias + RF dissipation (DC) takes place in the N state region, some RF dissipated also in the superconducting region (gap varies across the bridge)
- Bias power modulates the size of the hot-spot → modulation of *R* → modulation of current through the bridge
- Electrical measurements in 2003; $\text{NEP}_e = 14\ \text{fW/Hz}^{1/2}$
- *Extremely* simple to fabricate
- Speed requirement? Real time scanned imagery: 30 Hz × 200 scan positions ~ 6 kHz



$36\text{x}1\text{x}0.05\ (\mu\text{m})^3$
suspended Nb
Bridge

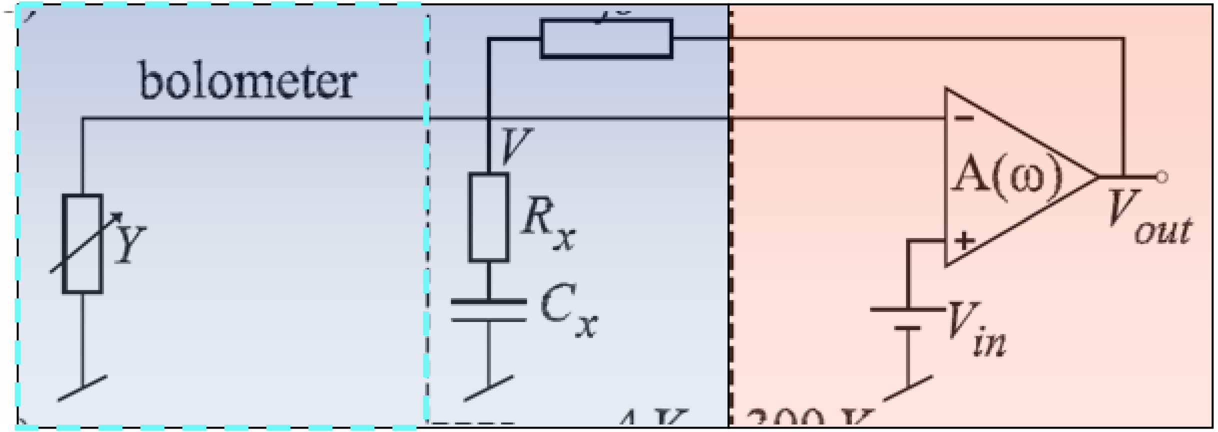
A. Luukanen, J.P. Pekola, Applied Physics Letters, Volume 82, Issue 22, pp. 3970-3972 (2003).
Arttu Luukanen, Robert H. Hadfield, Aaron J. Miller, Erich N. Grossman, Proc. SPIE Vol. 5411, p. 121-126, Terahertz for Military and Security Applications II; R. Jennifer Hwu, Dwight L. Woolard; Eds. (2004)

Radiation coupled through a Si substrate lens



The room-temperature read-out

- Readout architecture developed by VTT Technical Research Center of Finland (J. S. Penttilä, H. Sipola, P. Helistö, and H. Seppä, “*Low-noise readout of superconducting bolometers based on electrothermal feedback*,” Superconductor Science and Technology 19(4), pp. 319–322, 2006.)
- External feedback circuit employed that provides constant V
- V-bias at frequencies above the electronics BW provided by an RC shunt
- Bias point set at the bottom of the V-I → large dV/dI allows for noise matching to a room temperature JFET (T_N=4.7 K)
- COTS video-frequency electronics: Everything except the JFET can be integrated to an ASIC



Theory vs experiment

- Thermal behaviour really *very* simple to model
- Thermal conductance of Nb devices obtained from fit: 2 nW/K
- Implies a phonon-noise limited NEP of 10^{-15} W/Hz^{½}

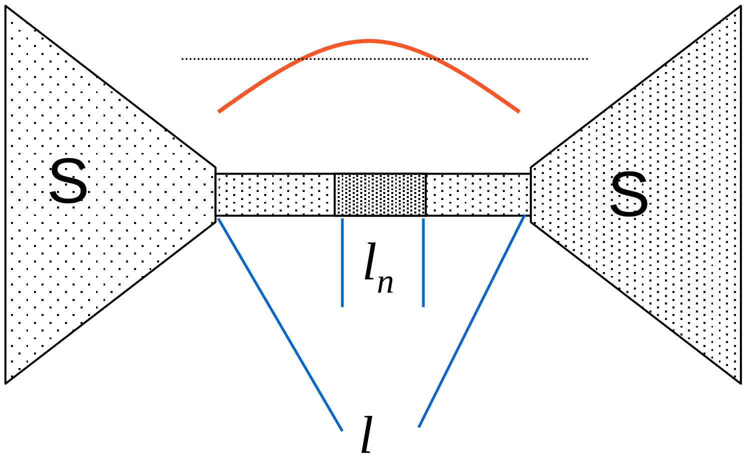
$$I(V)=\frac{V}{R_N}\left[1+\frac{2}{(p_0+p_e-1)+\sqrt{(p_0+p_e+1)^2-4p_0}}\right]$$

$$p_o=P_{opt}\Big/G(T_c-T_{bath}),\; p_e=V^2\Big/R_N G(T_c-T_{bath})$$

in the limit $P_{opt}\to 0$ reduces to

$$I(V)=\frac{G\Delta T}{V}+\frac{V}{R_N}$$

$$L=\frac{G\Delta T R_N}{V^2}$$



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- Implies a phonon-noise limited NEP of 10^{-15} W/Hz^{½}

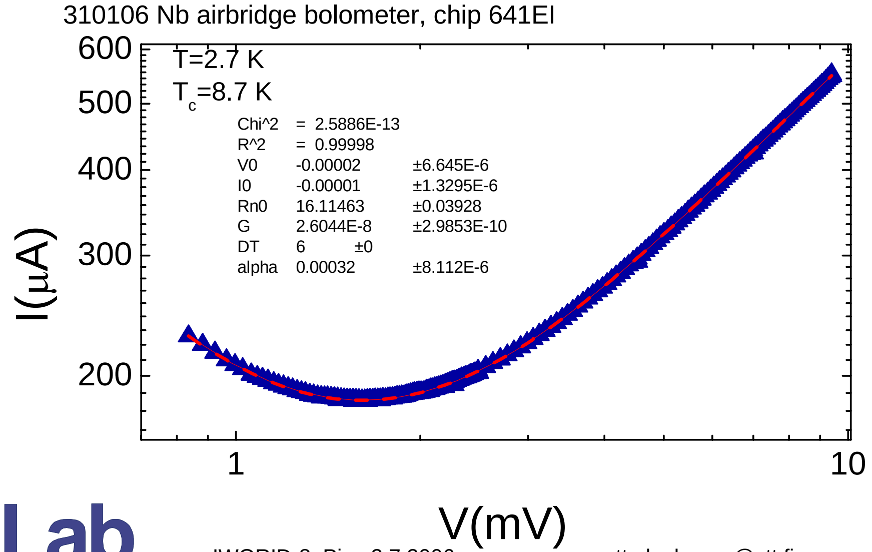
$$I(V) = \frac{V}{R_N}\left[1 + \frac{2}{(p_0 + p_e - 1) + \sqrt{(p_0 + p_e + 1)^2 - 4p_0}}\right]$$

$$p_o = P_{opt} \big/ G(T_c - T_{bath}),\ p_e = V^2 \big/ R_N G(T_c - T_{bath})$$

in the limit $P_{opt} \rightarrow 0$ reduces to

$$I(V) = \frac{G\Delta T}{V} + \frac{V}{R_N}$$

$$L = \frac{G\Delta T R_N}{V^2}$$



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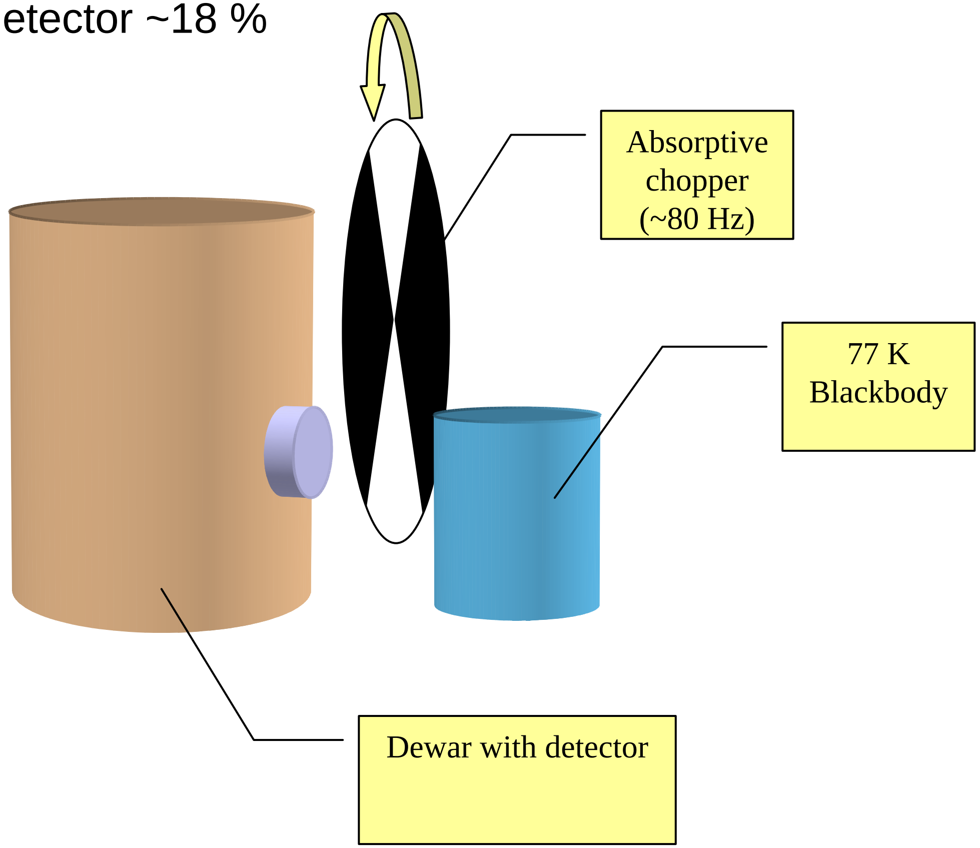
Optical characterization (Nb devices)

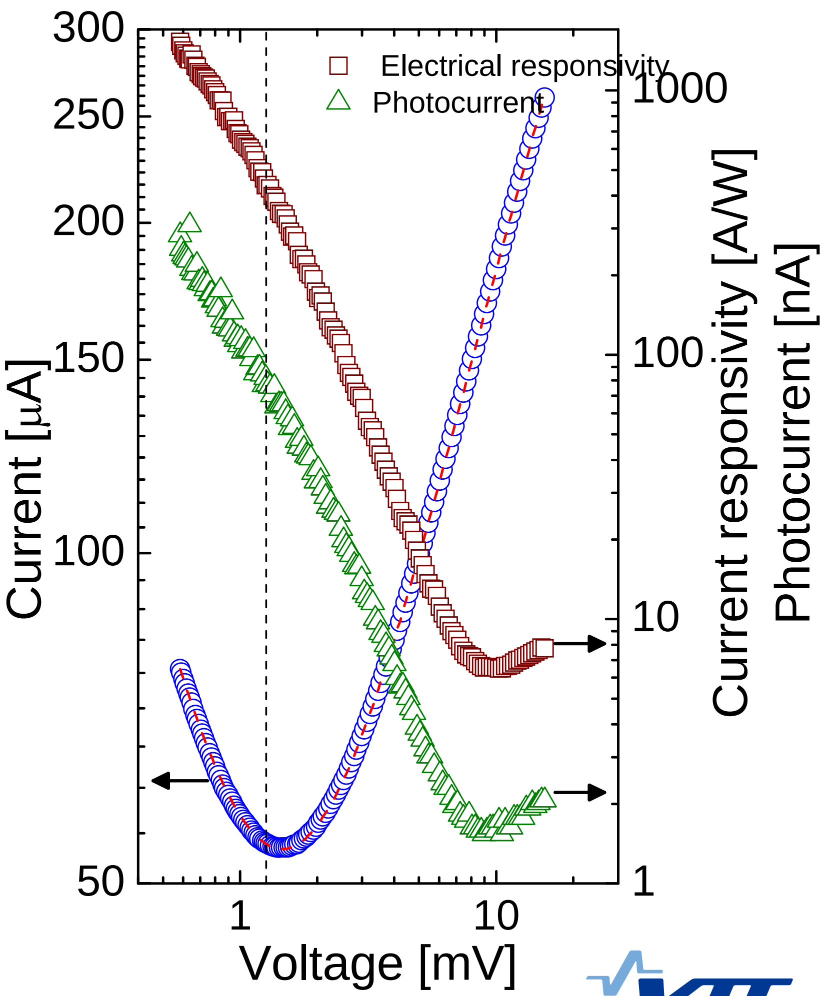
- I_{sig} vs responsivity: very good qualitative agreement
- Optical coupling efficiency referred to the detector ~18 %



Absorptive chopper (~80 Hz)

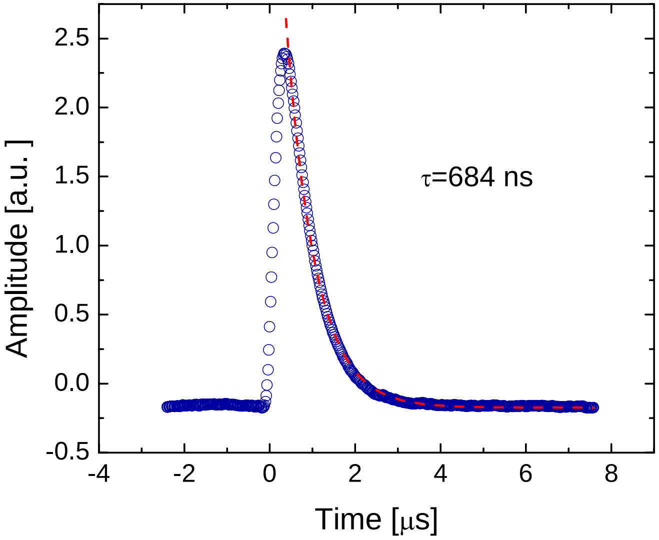
77 K Blackbody

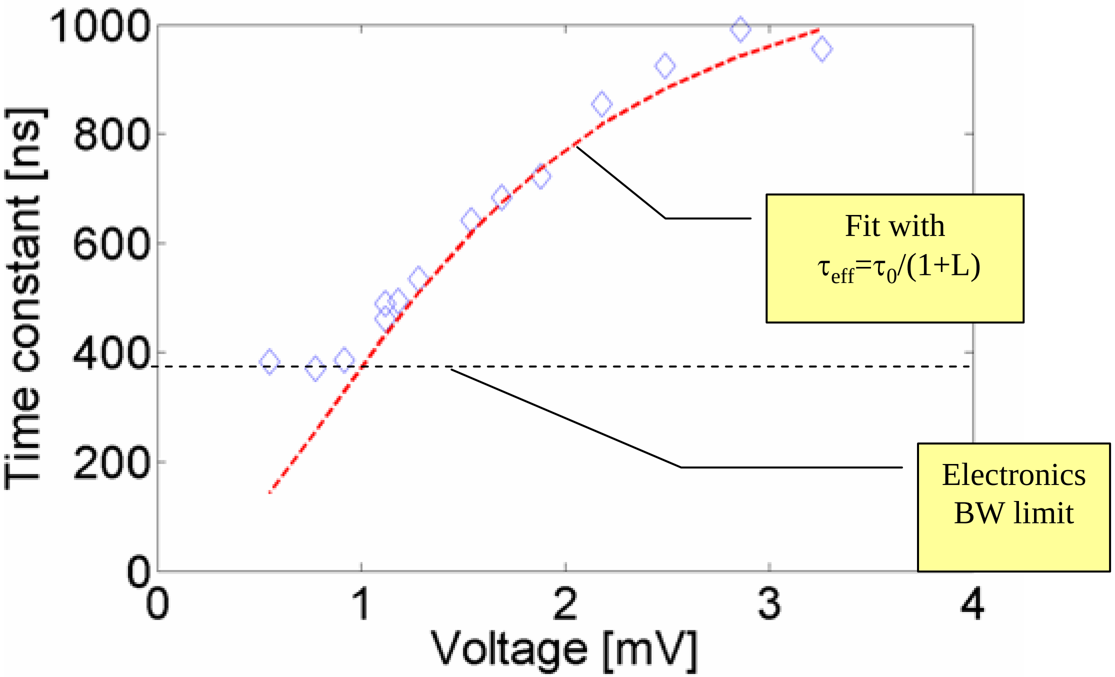
Dewar with detector



Speed?

- Response to a heavily attenuated pulsed (100 ns) IMPATT -oscillator (95 GHz)
- Intrinsic time constant 1.2 μs → fast enough for scanning architectures





Fit with $\tau_{eff}=\tau_0/(1+L)$

Electronics BW limit

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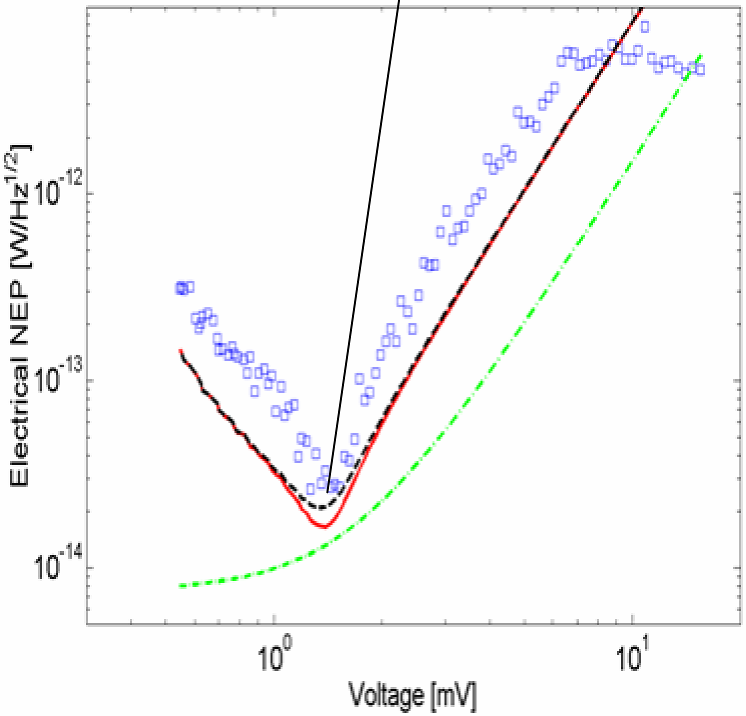
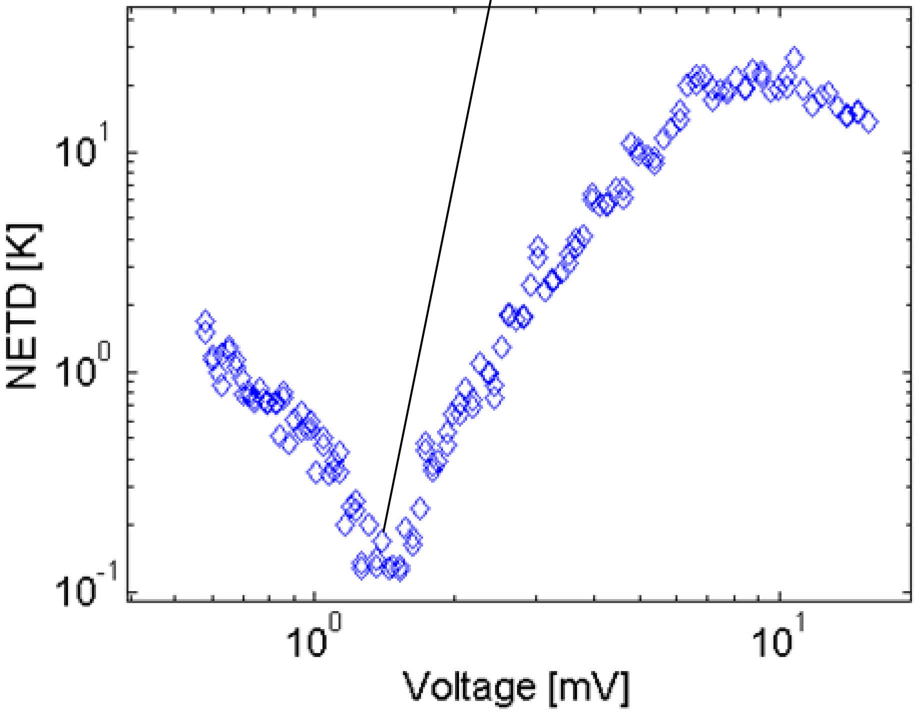
NEP, NETD (Nb devices)

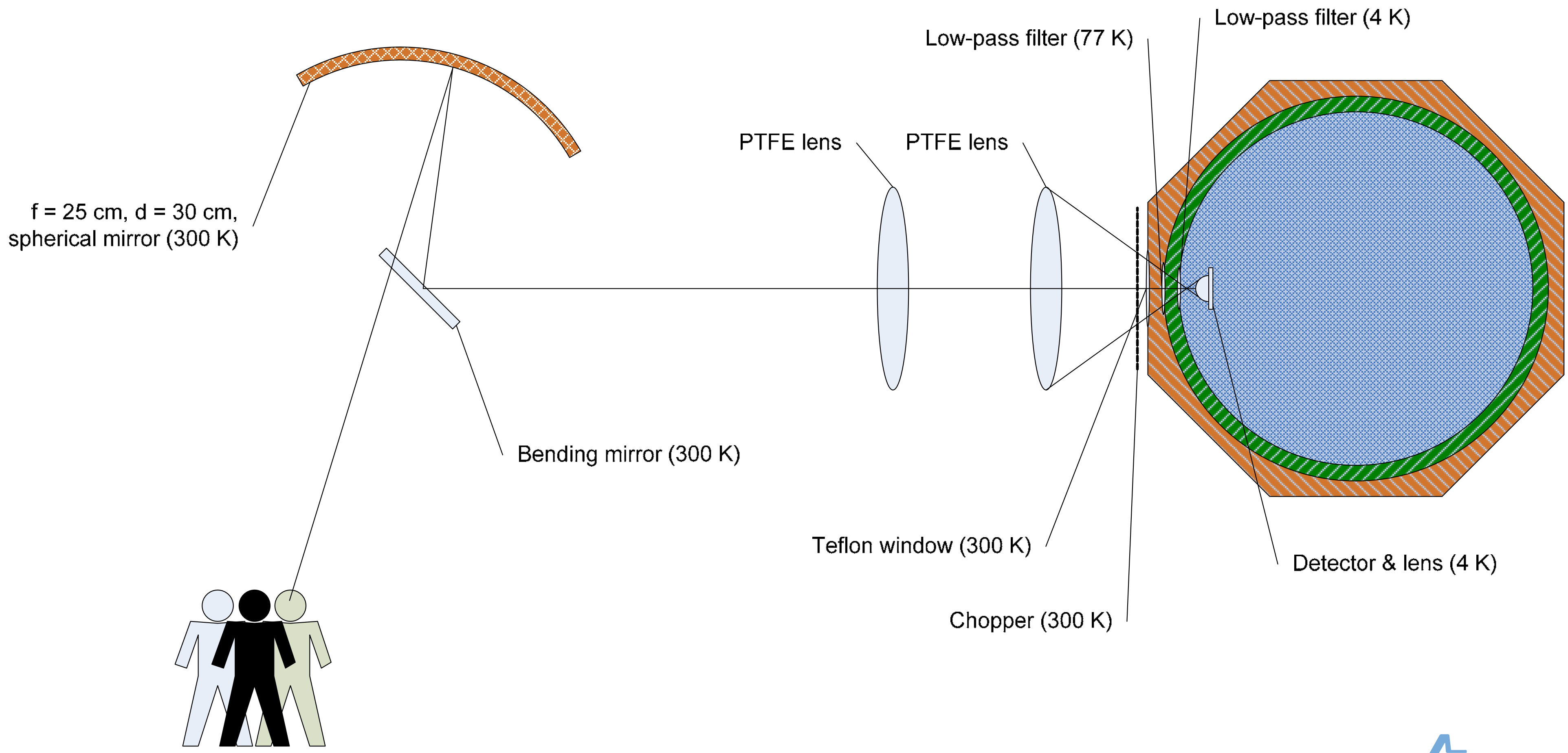


26 fW/Hz$^{1/2}$



125 mK

Scanned single pixel imagery with Nb devices



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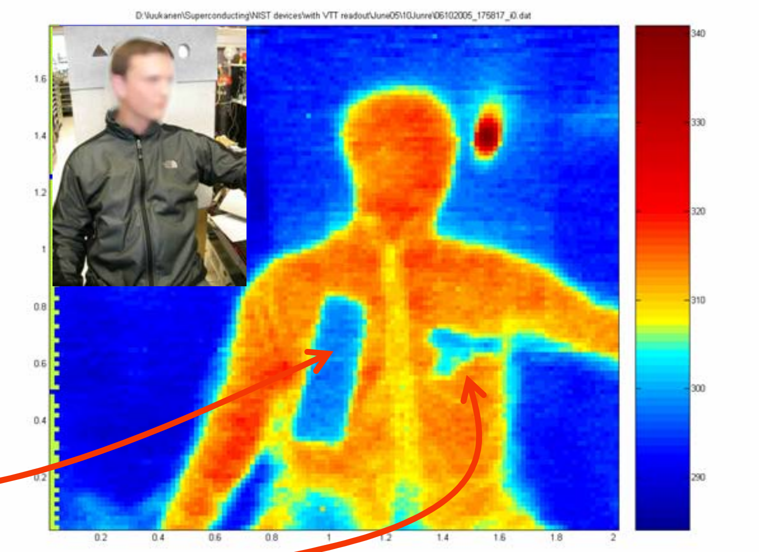
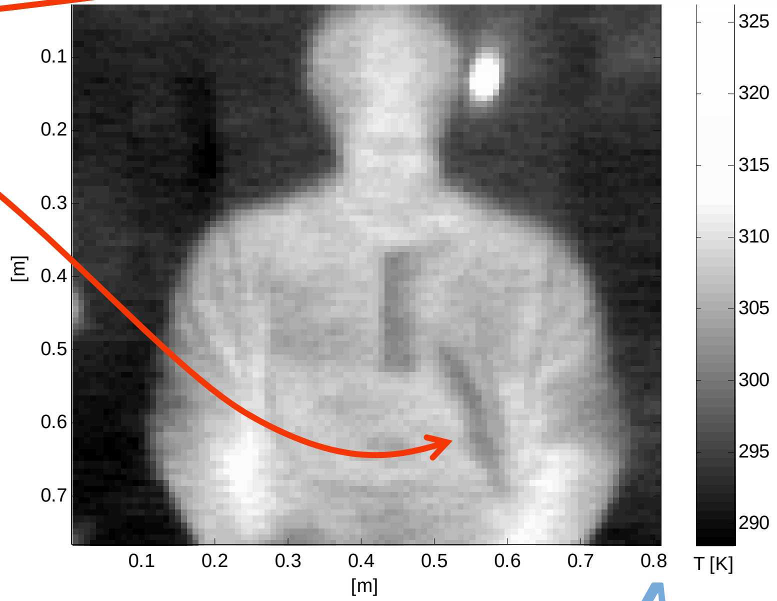
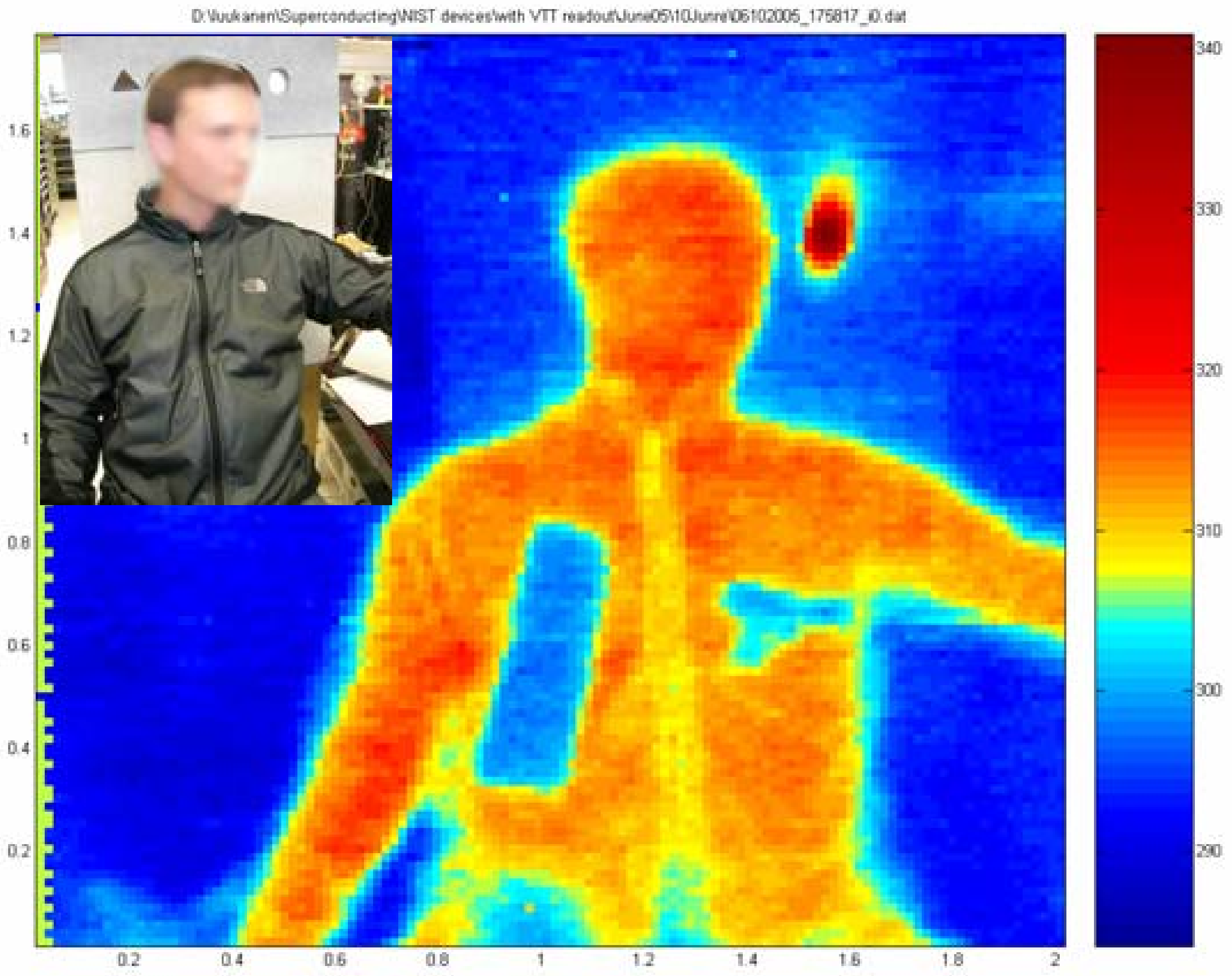
VTT

Examples of acquired images (single pixel, Nb device)

- General parameters:
  - Distance: 0.8–2 m
  - Spatial pixel size: ~ 4–8 mm square
  - Pixel integration time: 10 ms
  - Calibration: hot water & background average area
  - Clothing variations: cotton, polyester, windblocker jacket, thermal sweater
  - Concealed objects:
    - RAM (AN-72)
    - metal gun
    - ZrO_2 knife
- Measured fluctuation in smooth background of images
  - 200-500 mK depending on area and image
- Important measured temperature contrasts
  - 8K: concealed threat objects
  - 5K: zippers, thick clothing overlap
  - 0.5-1.5K: wrinkles/folds in clothes, i.e., clutter
- Observed spatial resolution
  - ~ 1 cm features plainly resolved







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Examples of acquired images (single pixel, Nb device)

- General parameters:
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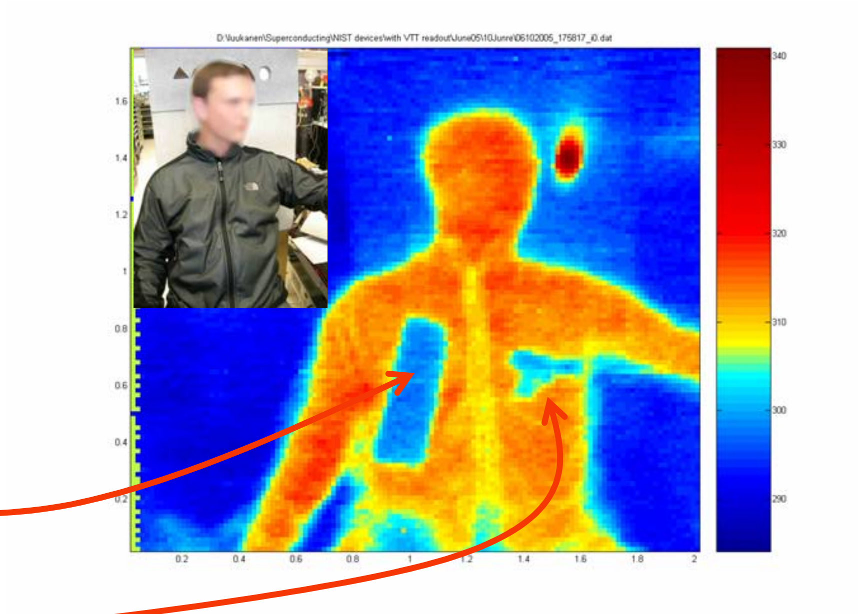
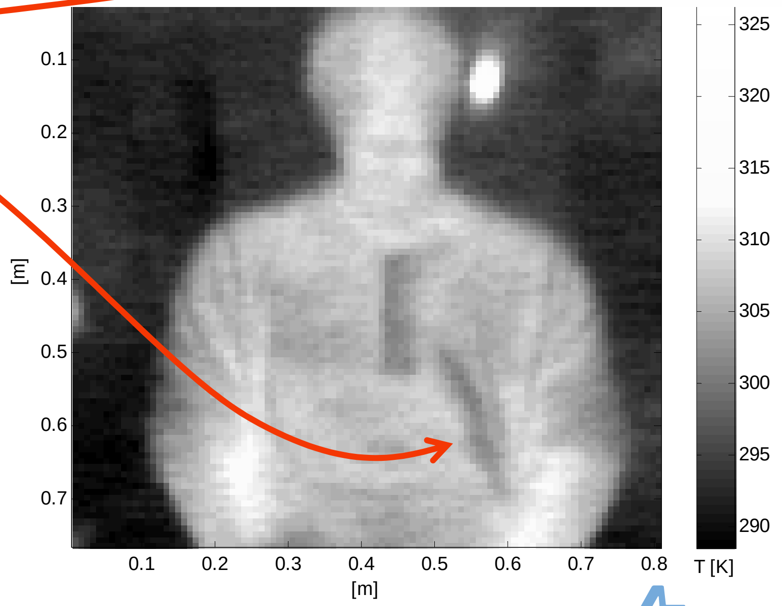
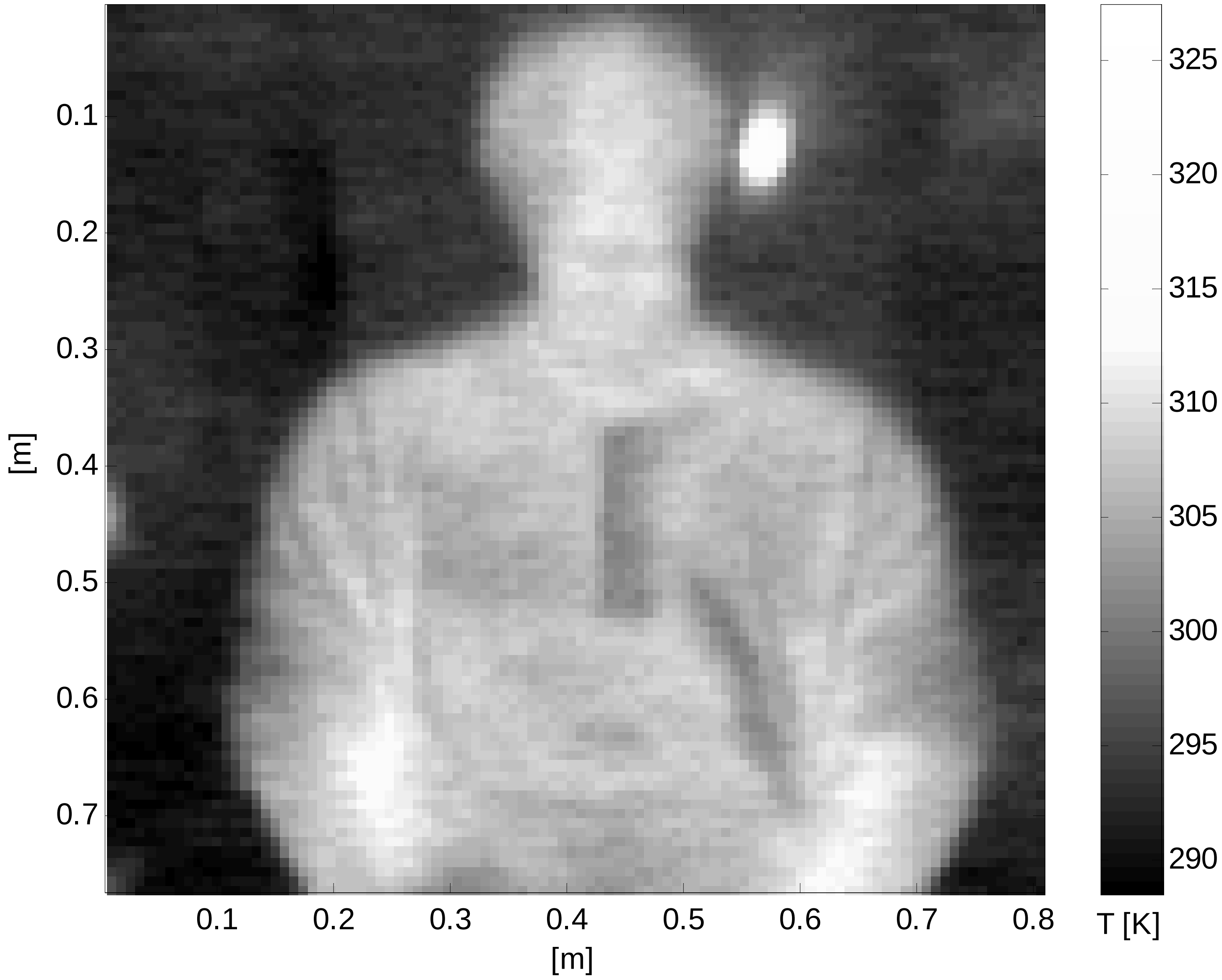
  - Calibration: hot water & background average area
  - Clothing variations: cotton, polyester, windblocker jacket, thermal sweater
  - Concealed objects:
    - RAM (AN-72)
    - metal gun
    - ZrO_2 knife
- Measured fluctuation in smooth background of images: 200 mK
- Important measured temperature contrasts
  - 8K: concealed threat objects
  - 5K: zippers, thick clothing overlap
  - 0.5-1.5K: wrinkles/folds in clothes, i.e., clutter
- Observed spatial resolution
  - ~ 1 cm features plainly resolved

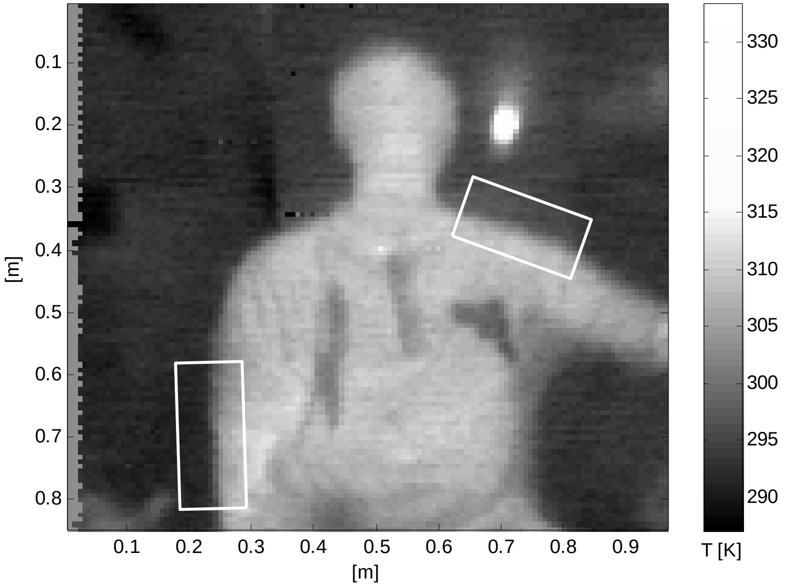


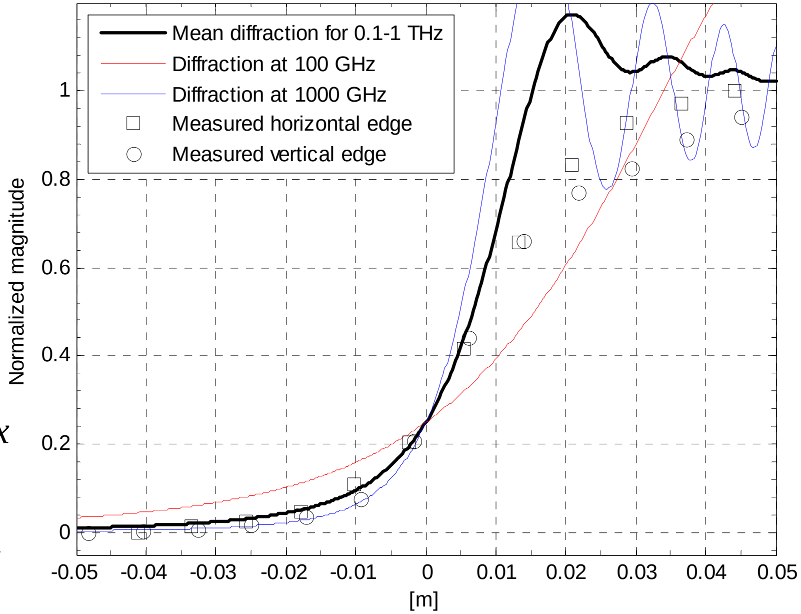



0.1
0.2
0.3
0.4
0.5
0.6
0.7
[m]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
[m]
325
320
315
310
305
300
295
290
T [K]

Effective frequency?

- Averaged edge transition from background to target, along edge
  - Performed on several images, in horizontal and vertical orientations
- Result:
  - Slope of measured edge agrees with theory at f = 450 GHz
    - Upper half of measured data does not “ring”, since the theory of diffraction from an edge does not include an optical system imaging the edge
    - Due to the PSF of an optical system, the ESF is a rounded step





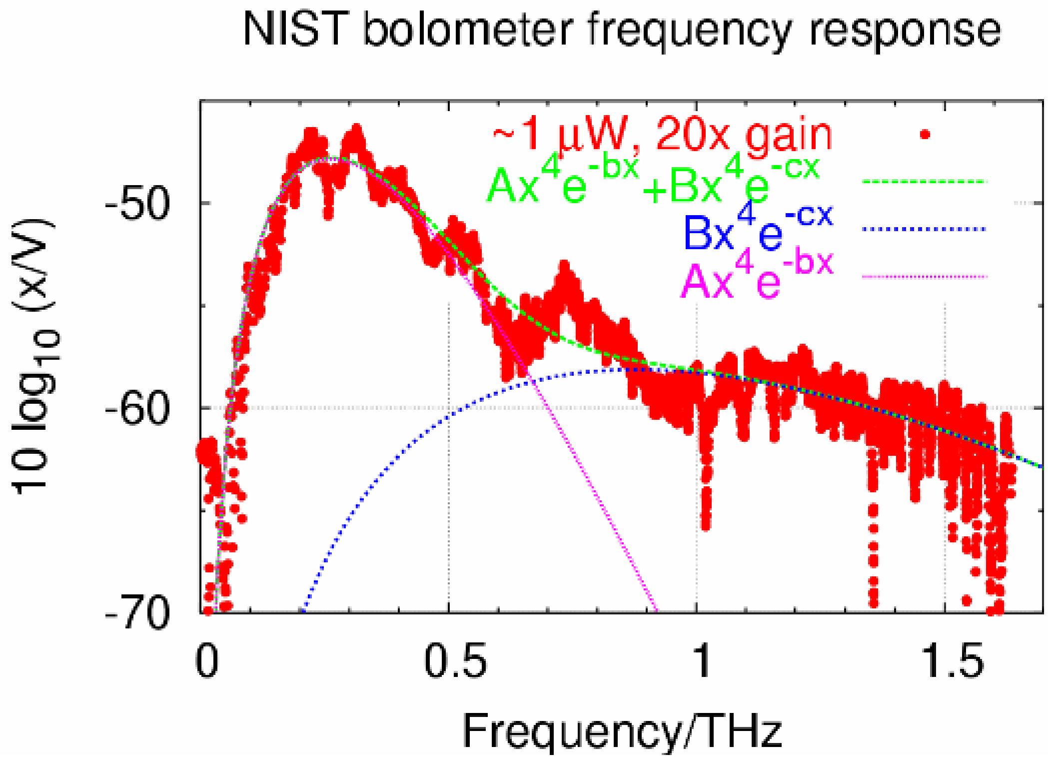
$$I = \frac{1}{2} I_0 \left\{ \left[C\left(u\sqrt{\frac{2}{\pi}} \right) - \frac{1}{2} \right]^2 + \left[S\left(u\sqrt{\frac{2}{\pi}} \right) - \frac{1}{2} \right]^2 \right\}$$

$$C(u) \equiv \int_0^u \cos\left(\pi x^2/2\right) dx$$

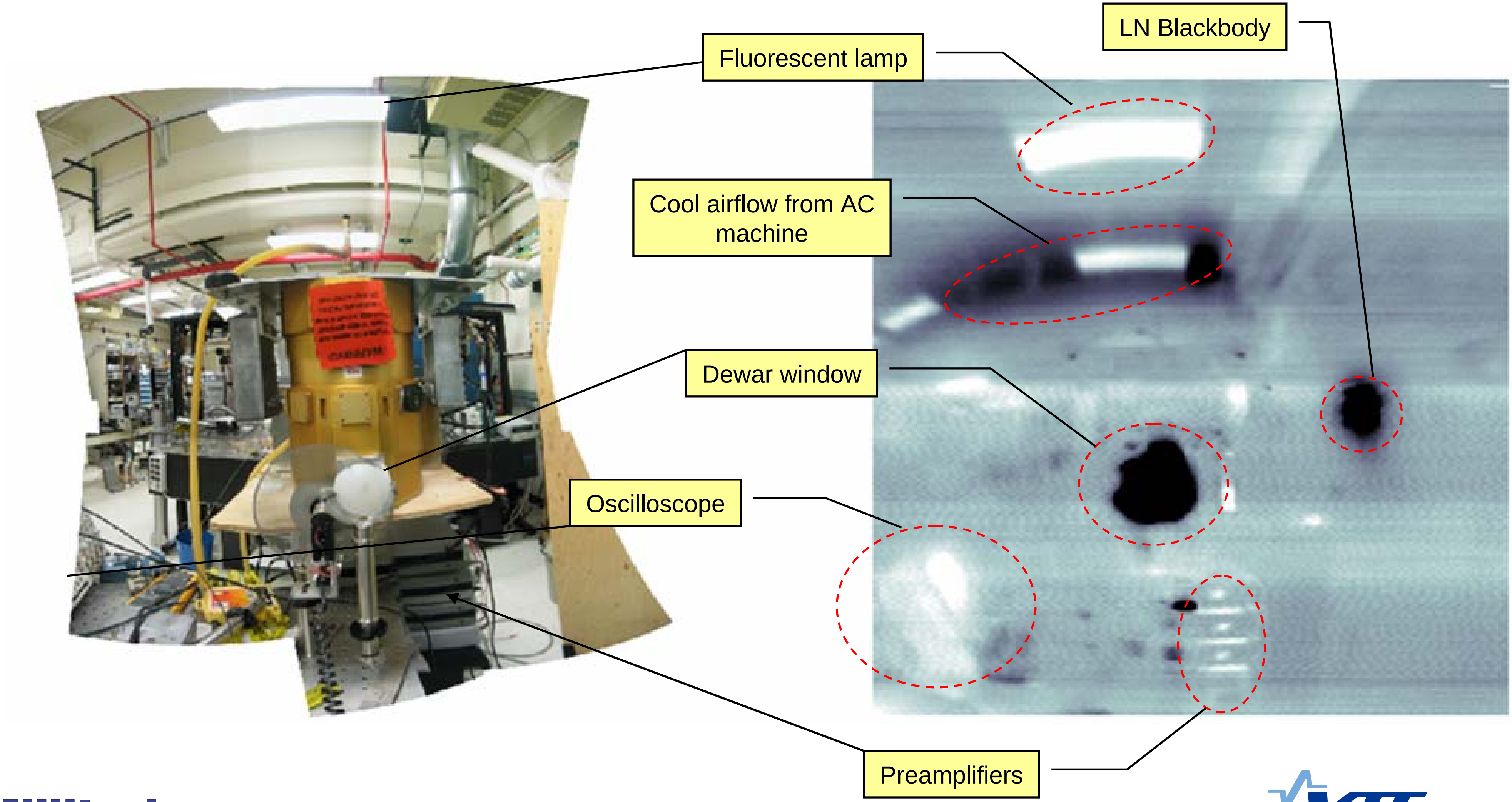
$$S(u) \equiv \int_0^u \sin\left(\pi x^2/2\right) dx$$

Effective frequency?

- Recent data obtained by Jon Bjarnason, Elliot Brown, UCSB, using their novel Er- based photomixer
- Effective frequency 446 GHz



The THz Lab

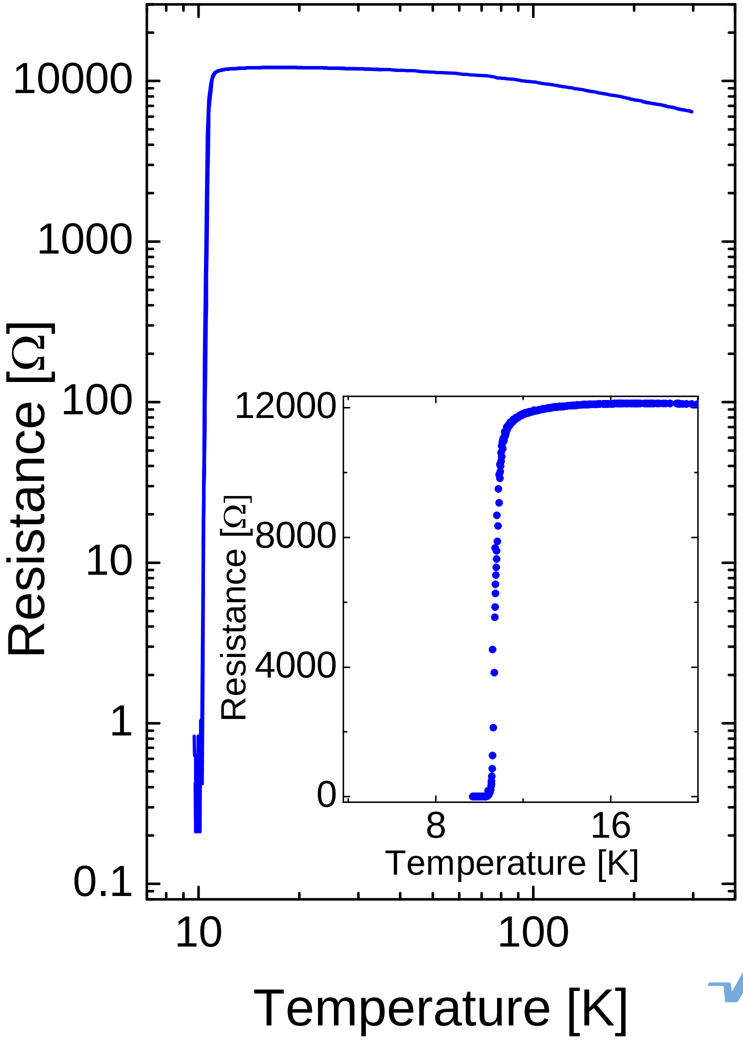

LN Blackbody
Fluorescent lamp
Cool airflow from AC machine
Dewar window
Oscilloscope
Preamplifiers

Bolometer optimization: from Nb to NbN

- Bolometers: improving thermal isolation improves performance
- In a vacuum-bridge: thermal resistance & DC resistance coupled via Wiedemann - Franz Law: $G \approx L_0 T_c / R_N \rightarrow \mathrm{NEP}_{\mathrm{TFN}} = (4 k_B T_c^3 L_0 / R_N)^{1/2}$
- But: can't increase R_N indefinitely:
  - Increasing geometric inductance with aspect ratio
  - Need to match the antenna ($Z_{a,}$, real) → coupling $\eta = 4 Z_a R_N / (Z_a + R_N)^2$
- NEP& Optimum $R_N = 6 Z_a$ (for a 75 Ω log-spiral = 450 Ω)
- Antenna impedance and bolometer NEP are coupled, *favours high impedance antennas*
- For an ideal 450 Ω device, optical NEP $\approx 4 \cdot 10^{-15}$ W/Hz$^{1/2}$ is possible (T_c=10 K)
- Square spiral antennas have higher impedance (250 Ω) (E.R. Brown *et al*)
  - $\mathrm{NEP}_{\mathrm{opt}} \approx 2 \cdot 10^{-15}$ W/Hz$^{1/2}$ achievable

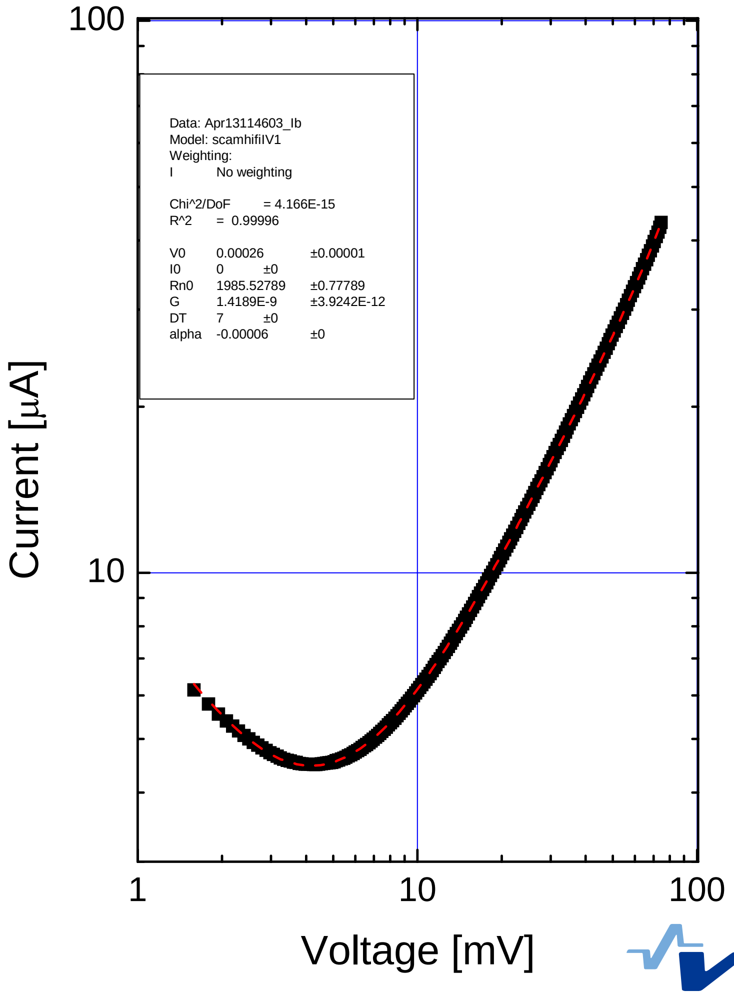
NbN devices: improved matching to the antenna

- First processing run of NbN test detectors (only *one* mask layer!) in March 2006
- Good NbN has a T_c=15 K; However, our NEP$\propto T_c^{3/2}$ → we want *bad* NbN (high resistivity, T_c~10 K)
- Fabricated films have a T_c=11 K, ρ≈2-4 mΩcm



NbN experimental results

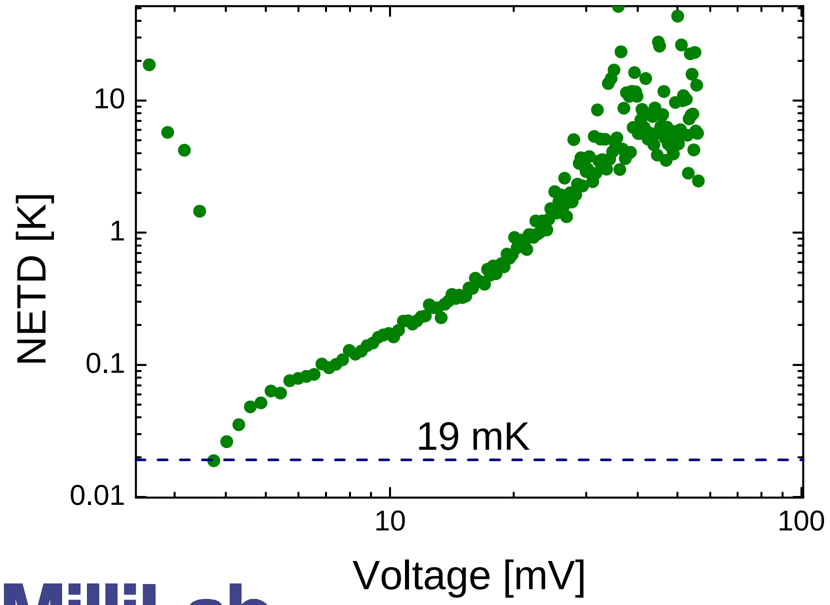
- I-V measurement: fitted value for G=1.4 nW/K (κ=34 mW/(Km))
- Resistivity 4.4 mΩcm (above T_c)
    - Electronic thermal conductance (W-F: ~0.5 nW/K) < lattice
- Thermal transport dominated by phonons

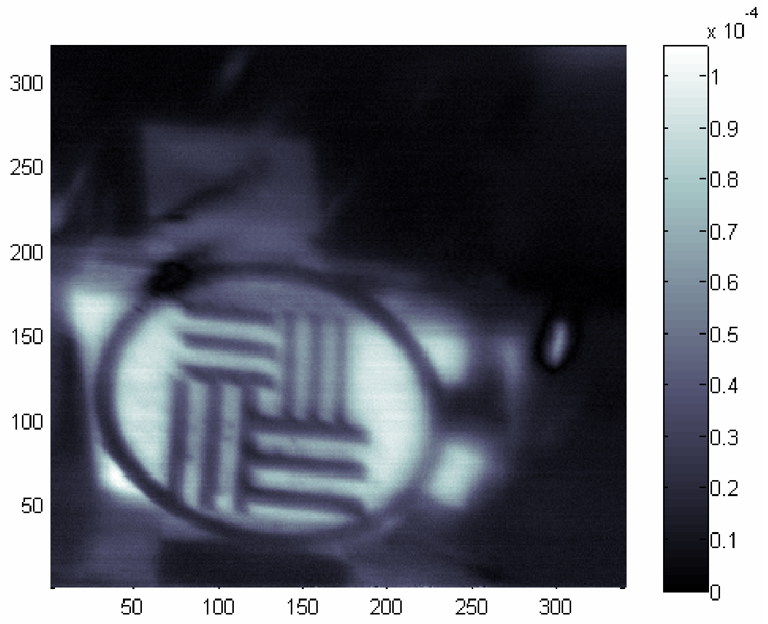


```
Data: Apr13114603_Ib
Model: scamhifiIV1
Weighting:
I          No weighting

Chi^2/DoF       = 4.166E-15
R^2      =  0.99996

V0       0.00026         ±0.00001
I0       0          ±0
Rn0      1985.52789      ±0.77789
G        1.4189E-9       ±3.9242E-12
DT       7          ±0
alpha    -0.00006        ±0
```

New material : NbN devices, optical characterisation

- Optical characterisation carried out recently jointly at NIST
- "Traditional" resistive (local Electrothermal FB) voltage bias (noise dominated by the amplifier noise)
- Direct optical NETD (30 ms) : ~20 mK
- Images of a bar target





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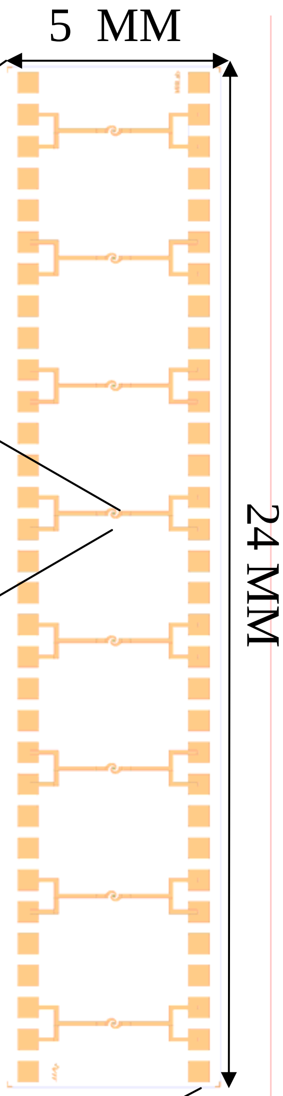
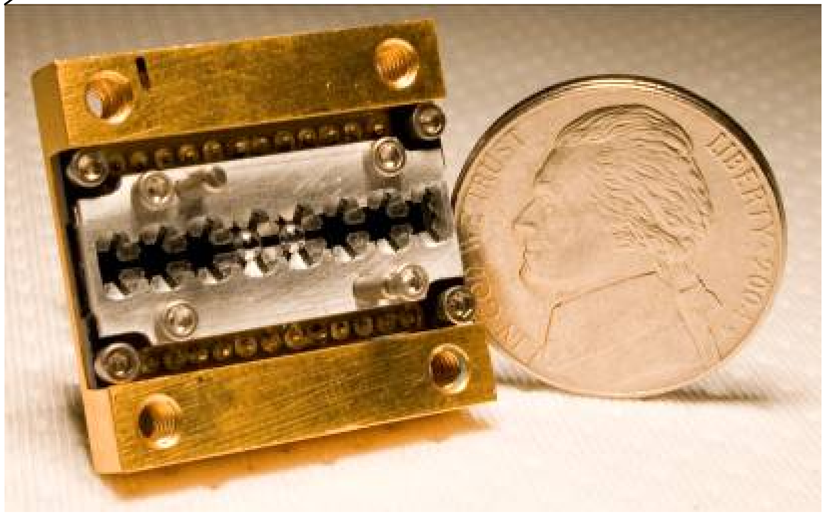
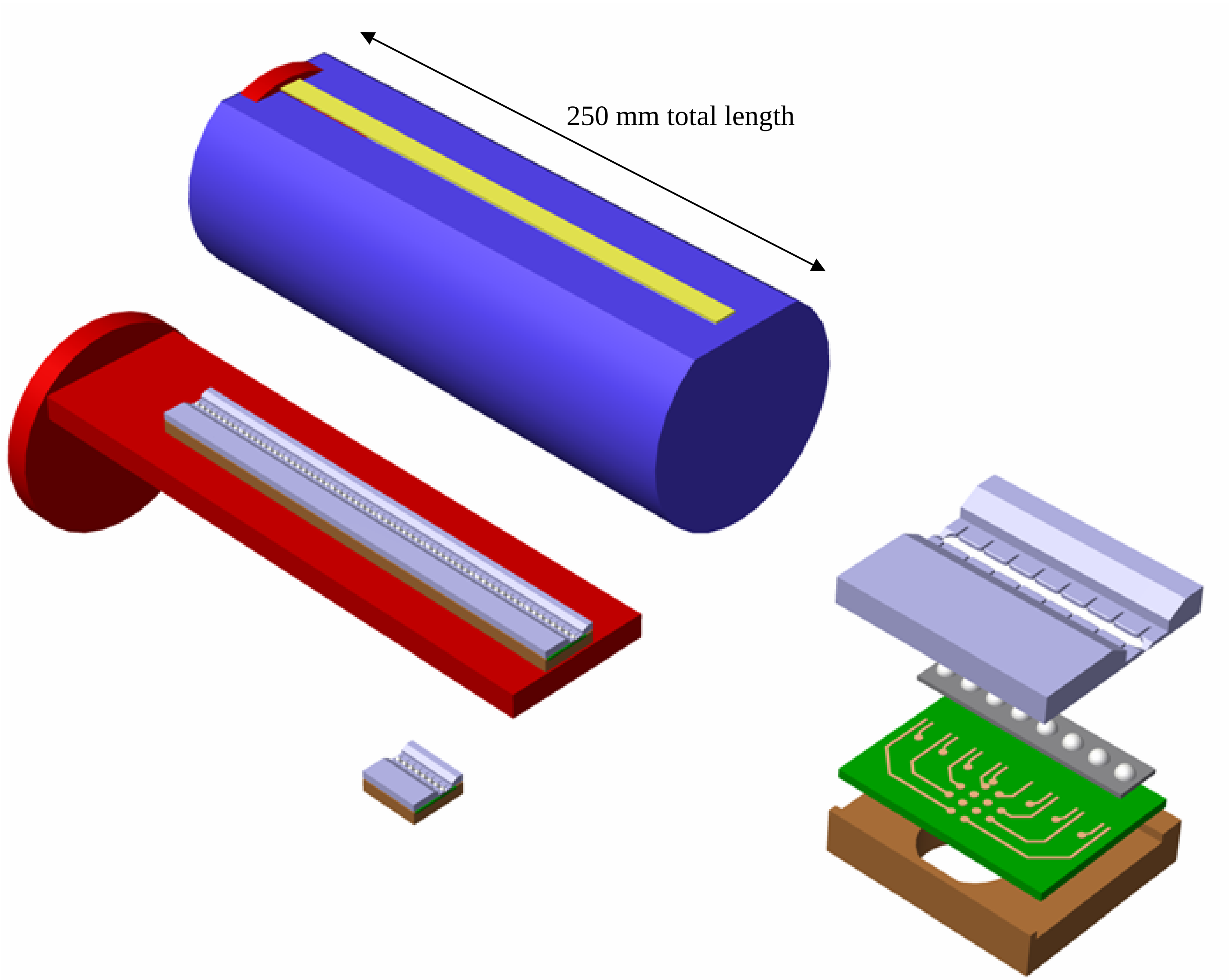
64 pixel arrays

- Linear array, 64 x 1 pixels
- Pixel-to-pixel separation: 3 mm
- Two designs for 2 bandwidths:
    - 0.2 THz to 1.8 THz
    - 0.2 THz to 3.6 THz
- Modular design: 8 pixel modules
- Brute-force scaling of electronics (need 4 wires/pixel → 256 RT to 4 K connections
- Conical scanning optics






250 mm total length

Migration to a cryogen-free Pulse Tube refrigerator

- Oxford Optisat AC-V12 (utilising Cryomech PT403):
  - Air or water cooled compressor, 3.3 kW (~50 cm x 50 cm x 50 cm), single phase
  - Cold-head: 250 mW cooling power at 4 K
  - MTF >~ 20 000 hrs
- Interfacing to RT electronics:
  - Worst-case: 64 pixels require 256 wires to room temperature
  - Custom-made low thermal conductivity cryoflex, 50 traces each. Low cost snap-on connectors
- Verification of noise performance
  - Effect of vibrations
  - Effect of temperature variations
  - EMI compatibility

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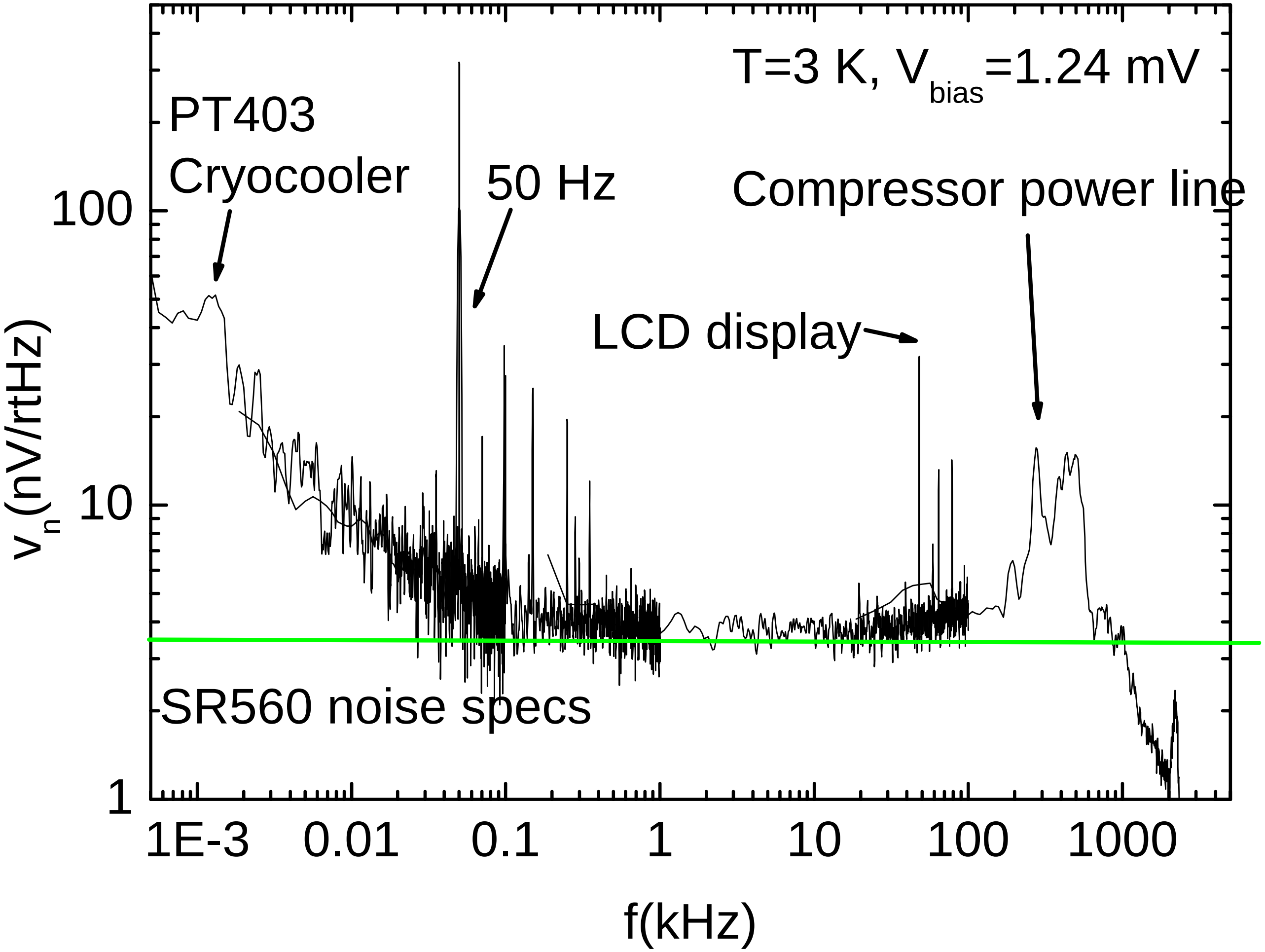
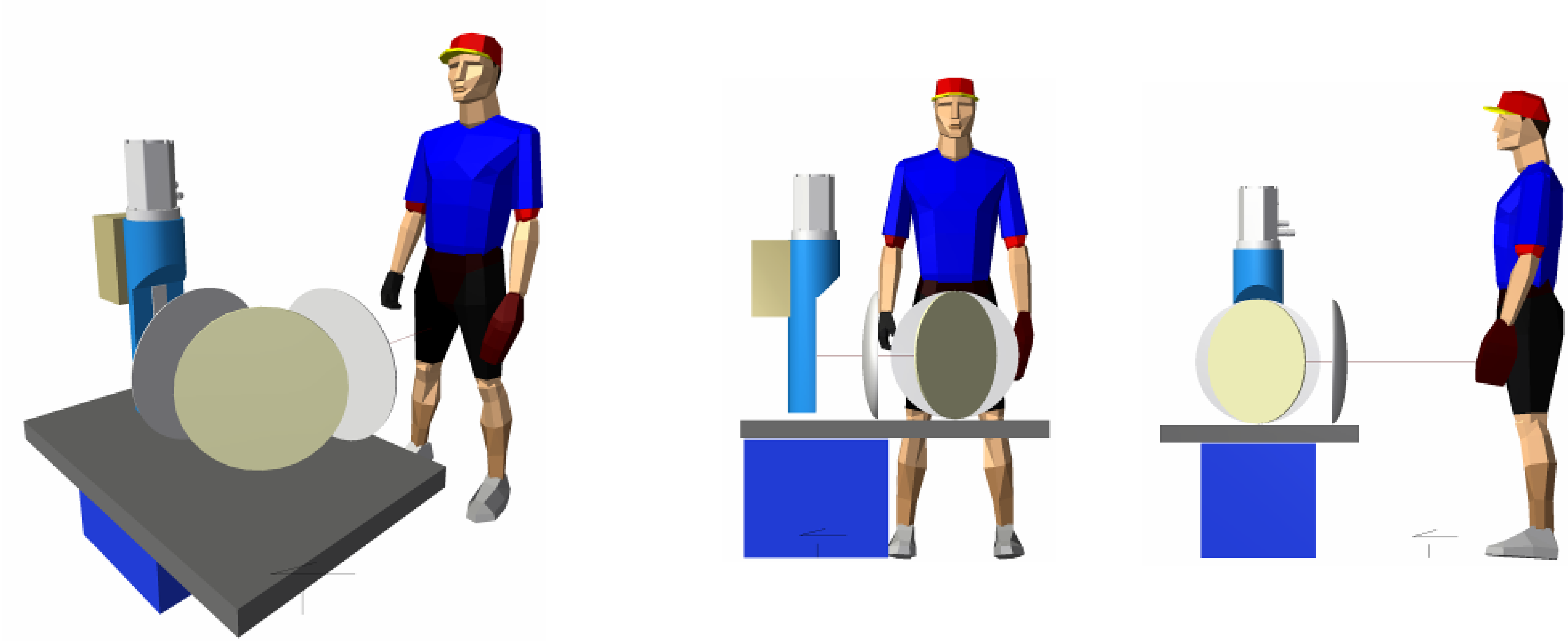
Some desirable features of Cryocoolers from the application standpoint

- Airport applications - Minimum impact on the infrastructure:
    - Single phase power
    - 25 A Fusing
    - Minimum footprint
    - Preferably no water cooling required
- Other:
    - MTTF: 20 000 or more hrs
    - On-site service
    - Acoustic noise: Aircooled units likely above limits
    - EMI Compatibility
    - Transportability
    - Backup in the case of a power failure ?

Noise at preamp input



Conceptual view of the passive THz imager



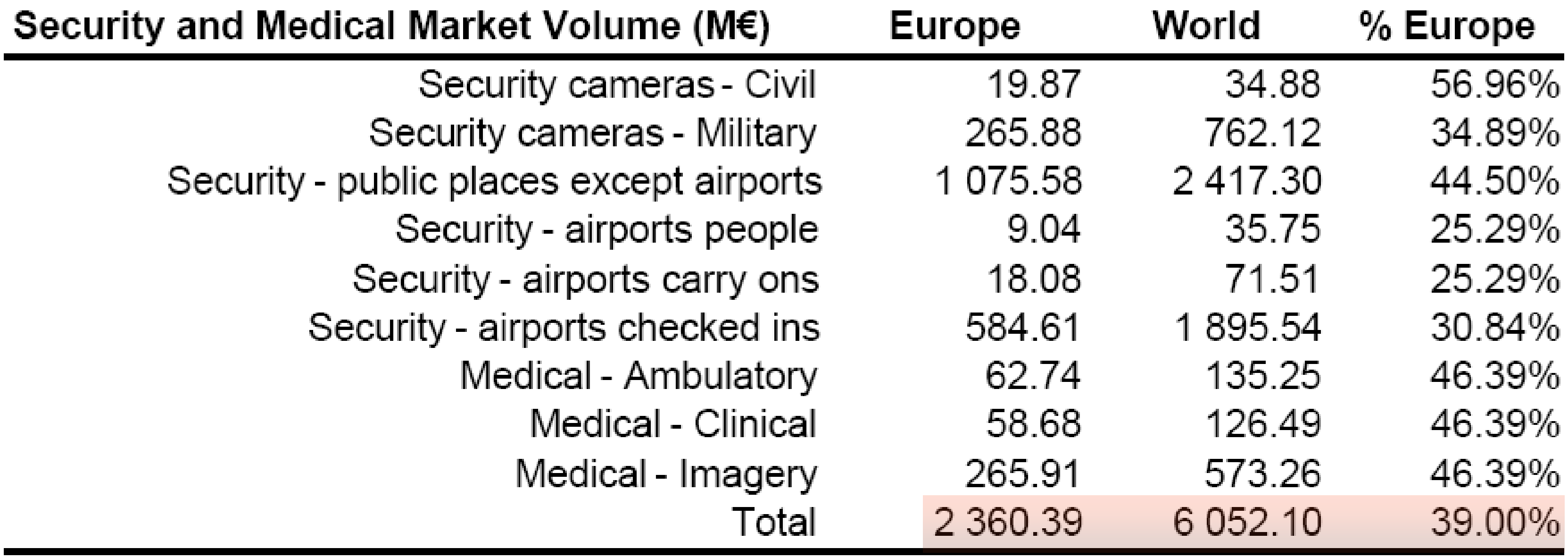
Conclusions

- Single pixels with 30 ms NETD below 20 mK demonstrated
  - Need less than 0.5 K NETD for passive indoors imagery; For a 128 pixel array, 200 scan locations/frame, 30 frames/second, scanned NETD=0.25 K projected for these detectors;
- Efforts now really more on systems integration level; Some interesting detector physics still remains, though (where is the 1/f noise knee?)
- A passive approach that allows for
  - Broadband coarse-resolution photospectrometry in the 0.1 to ~5 THz band (similar detectors demonstrated all the way to 30 THz)
  - Low production cost of the imaging arrays
  - Nearly flat cost vs pixel number curve
- Chicken & Egg problem with cryocoolers: At present, a limited market volume keeps unit cost high (~25 k$)
- Potentially a *very* large cryocooler market

Conclusions (2)

- Millimetrewave imaging is superior in terms of range (negligible atmospheric attenuation), but existing technologies require illumination when operated indoors
- Cryogenic microbolometers have the potential for truly passive imaging (indoors/outdoors) with lower system cost as compared to MMIC based technologies
- Major technology need: cryogenic MUX for large format 2D arrays
- MilliLab, VTT, Oxford Instruments Analytical & Rapiscan Systems collaborating within a new program towards a spectral real-time imager based on the bolometer technology (TEKES); Includes collaboration with NIST, Boulder (Erich Grossman)
- *If we can show that cryogenic detectors can solve the CWD problem with lower cost, better sensitivity, better specificity and that it is a practical solution - we have a winner*

Backup



Security and Medical Market Volume (M€)	Europe	World	% Europe
Security cameras - Civil	19.87	34.88	56.96%
Security cameras - Military	265.88	762.12	34.89%
Security - public places except airports	1 075.58	2 417.30	44.50%
Security - airports people	9.04	35.75	25.29%
Security - airports carry ons	18.08	71.51	25.29%
Security - airports checked ins	584.61	1 895.54	30.84%
Medical - Ambulatory	62.74	135.25	46.39%
Medical - Clinical	58.68	126.49	46.39%
Medical - Imagery	265.91	573.26	46.39%
Total	2 360.39	6 052.10	39.00%

Market study by Peter de Maagt, ESA-ESTEC