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California Institute of Technology
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RUTGERS

A Photon Counting Hot-Electron Bolometer for Space THz Spectroscopy

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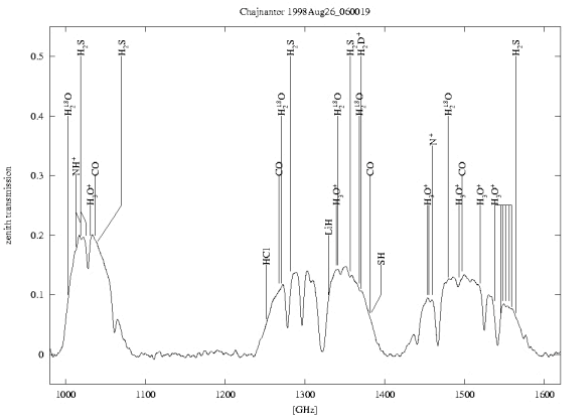
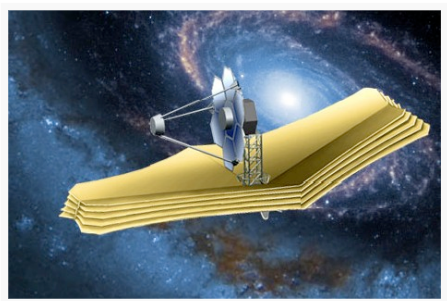
THz astronomy from the ground is strongly limited by the atmosphere opacity

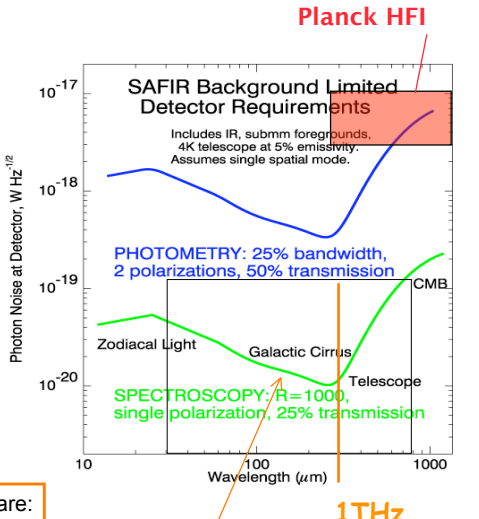


Better THz detectors are needed for space spectroscopy



Single-Aperture FIR Observatory -- SAFIR

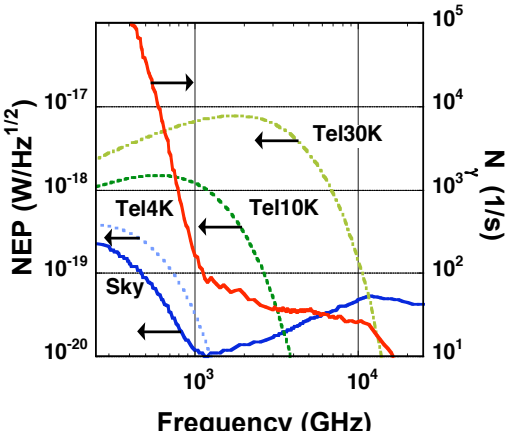
10-m mirror, 4K



Other examples of the future missions are: CMBPol (imaging photometry), SPECS (high-resolution spectroscopy using interferometry)

Requires photon-counting detectors

The ultralow background calls for photon-counting techniques at THz

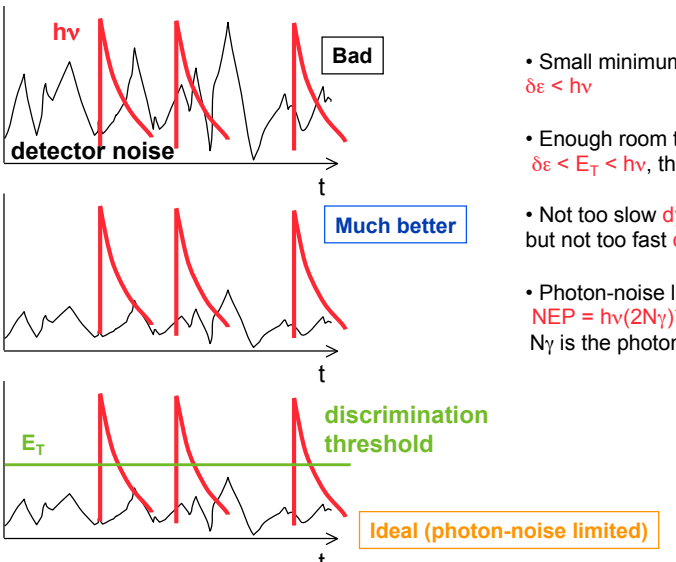


The photon statistics predicts $NEP_\gamma = h\nu(2N_\gamma)^{1/2}$

The combination of the low NEP and of the long integration time cannot be achieved with integrating detectors => THz photon counting

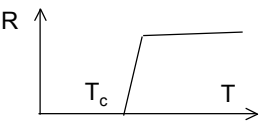
THz photons are extremely difficult to detect => requires new detectors with the single-electron sensitivity or large multiplication gain

An optimal photon counter

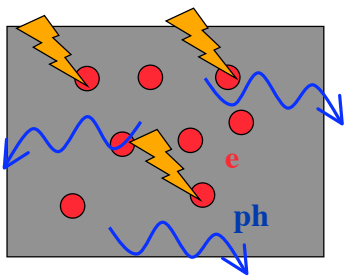


- Small minimum resolved energy $\delta\varepsilon < h\nu$
- Enough room to insert the threshold $\delta\varepsilon < E_T < h\nu$, that is, $\delta\varepsilon << h\nu$
- Not too slow dynamic range $\sim \tau^{-1}$ but not too fast dark current rate $\sim \tau^{-1}$
- Photon-noise limited performance $NEP = h\nu(2N\gamma)^{1/2}$ $N\gamma$ is the photon arrival rate

The superconducting hot-electron THz calorimeter



A photon energy distributes quickly between many electrons => large intrinsic gain



Thin (~10nm) disordered superconducting film => **long $\tau_{e\text{-}ph}$, small C_e**

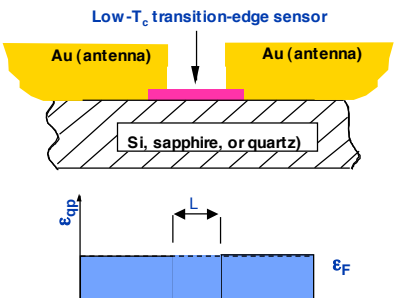
Low-T_c => **long $\tau_{e\text{-}ph}$, small C_e**

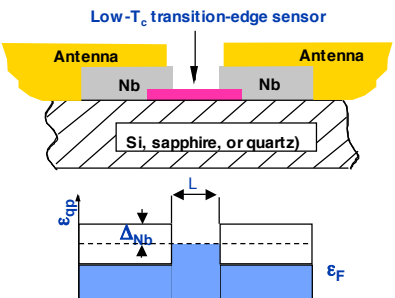
Small (subμ) lateral dimensions => **small C_e**

$$\tau = \tau_{e-ph}(T,\ell)$$

$$\delta\varepsilon \sim (k_B T_c^2 C_e)$$

Diffusion cooling vs phonon cooling





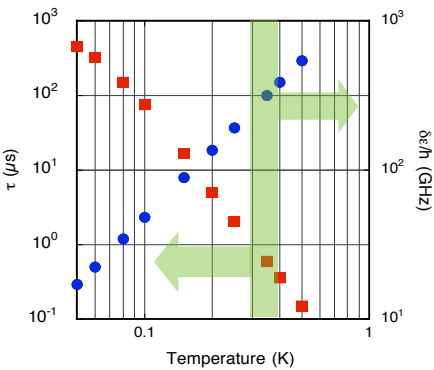
Hot electrons diffuse into normal contacts.

The relaxation time $\tau_{diff.} \approx L^2/\pi^2 D$ in subμ devices (10's ps) is too short to keep the dark count rate low.

Andreev contacts stop diffusion of hot electrons.

The relaxation time is ~ $\tau_{e\text{-}ph}$ (1-10 μs at 0.3 K). This turns out to be optimal for achieving the "ideal" THz photon counter conditions.

τ and $\delta\varepsilon$ in the Ti photon counter



Experimental $\tau_{e\text{-}ph}$ data are from Gershenson et al., *Appl. Phys. Lett.* 2001

$\tau \approx \tau_{e\text{-}ph}/20$ due to the effect of the negative electro-thermal feedback typical in transition-edge sensors

- Titanium films magnetron sputtered on sapphire substrates or e-beam evaporated on Si

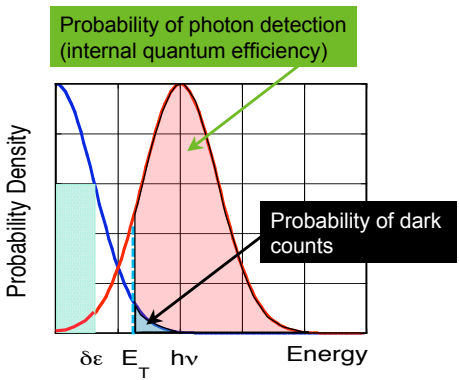
- Thickness d = 20-30 nm
  Sheet resistance R = 15-20 Ω
  Critical temperature T_c = 0.3-0.4 K
  Electron diffusivity D = 2.5 cm^2/s

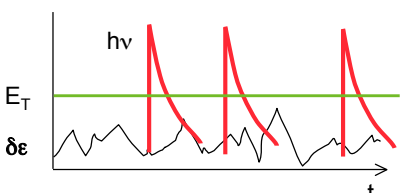
- τ-data were extracted from the measurements with large samples

- Device dimensions 0.5μm × 0.15μm × 0.03μm have been already achieved

- **$\delta\varepsilon \approx$ 170 GHz, BW ≈ 80 kHz**

Photon statistics and NEP@1THz

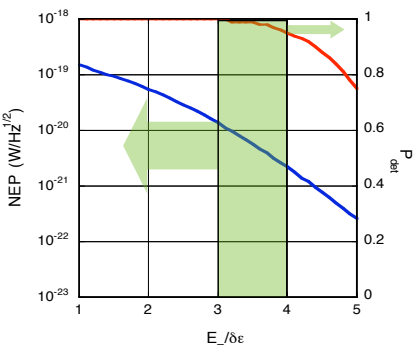




$$P_{\det} = \frac{1}{\sqrt{2\pi}} \cdot \int_{(E_T - h\nu)/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right) dx$$

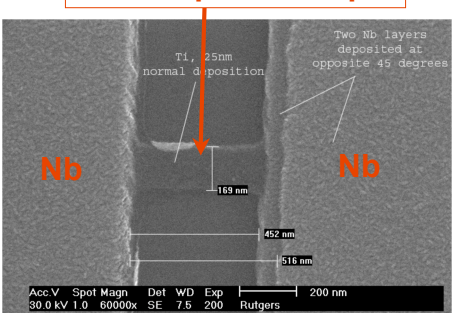
$$P_{dark} = \frac{1}{\sqrt{2\pi}} \cdot \int_{E_T/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right) dx$$

$$NEP = h\nu\sqrt{2P_{dark}B}$$

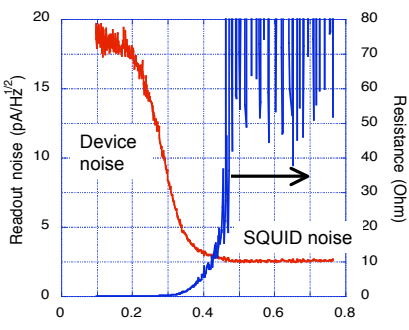


A subμm Ti photon-counter device

Ti: 0.45 μm x 0.17 μm

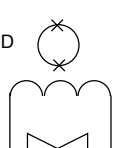


R(T) via the noise thermometry



A power of 0.1-0.3 fW saturates
the device => hard to use wired circuits

dc SQUID

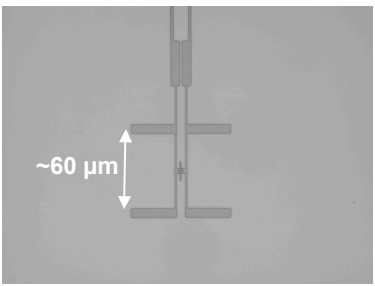


The device

$$\frac{I_n}{\sqrt{df}} = \sqrt{\frac{4k_BT}{R}}$$

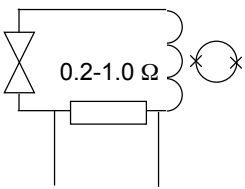
Input detector circuit and readout

A 1 THz twin-slot antenna



A 1000-pixel array is needed for SAFIR

- A SQUID readout will have an sufficiently small noise and broad bandwidth



- Novel multiplexing solutions based on SQUIDs or RSFQ will be required

Conclusions

☐ A THz photon counter closely meeting the "ideal" photon detector requirements can be made using a submicron size Ti hot-electron superconducting calorimeter

☐ The detector would operate at 0.3 K (easy cryocooling in space)

☐ Superconducting Ti devices with Nb contacts have been fabricated and are being tested