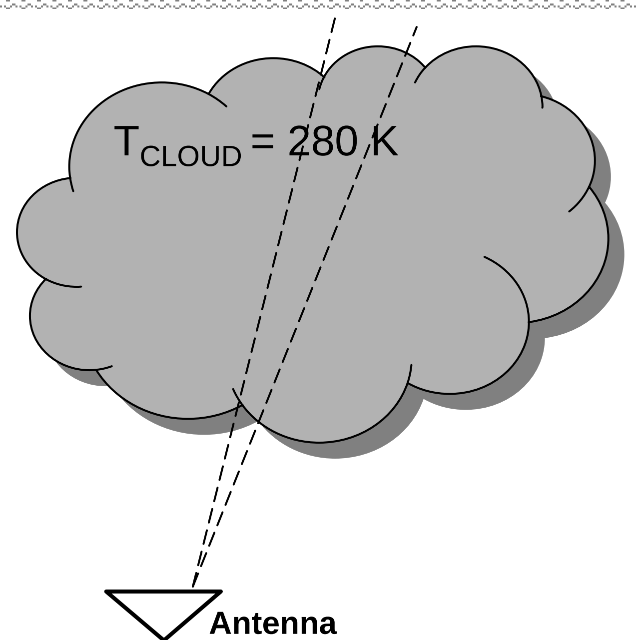
# Analysis of Canonical Receiver Architectures and Some Active THz Systems

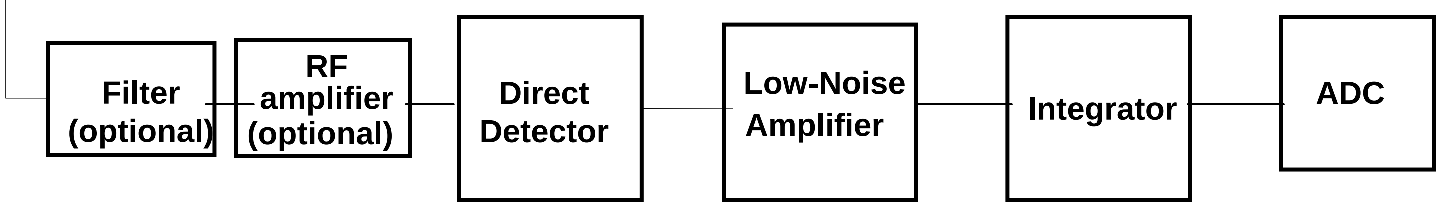
# THz Passive Incoherent (Direct) Radiometer

$T_{SKY}$ = 290 K




- Filter is long-wavelength pass (IR blocking)
- Best THz direct detectors are bolometers or rectifying diodes

| Detector Type | Operating Temperature | Electrical NEP |
|---|---|---|
| Semimetallic Air Bridge Bolometer | 300 K | ~ $50 \times 10^{-12}$ W-Hz$^{-1/2}$ |
| Silicon Composite Bolometer | ~4.2 K | ~ $1 \times 10^{-14}$ W-Hz$^{-1/2}$ |
| Schottky Diode Rectifier (Zero-Bias) | 300 K | ~ 1-$10 \times 10^{-12}$ W-Hz$^{-1/2}$ |



# Direct Detection Issues

- The block diagram of a generic direct receiver is shown on the previous chart. The incoming radiation from the target, be it thermal emission or transmitted power from the sensor itself, is collected by the receiver where it is transformed from RF (THz) to baseband by a “direct” detector. In most practical cases the baseband is defined by amplitude or frequency modulation of the incoming signal to reduce the effect of gain drifts and 1/f noise that occurs in the THz electronics. The rectified THz signal is then amplified and demodulated down to DC using synchronous detection. For cw AM modulation the synchronous detection is often carried out using a lock-in amplifier. For short duty-cycle pulse modulation, synchronous detector can be carried out with a boxcar integrator or similar gated receiver.

- A key factor in all direct detectors is spectral bandwidth. As in most analyses of signal processing, we assume here that this is band limited between $\nu_o$ and $\nu_o + \Delta\nu$. This can be a real bandwidth defined by a THz bandpass filter, or it might be an approximation to a real spectrum.

# More on THz Direct Detector Types

- In the THz region the direct detector is almost always a power-to-voltage or power-to-current converting device. That is, it is a device that puts out a voltage or current in proportion to the incoming power. There are many examples of such devices, but the most popular are field detectors and bolometers. Field detectors, such as Schottky diodes, respond directly to the THz electric field and generate an output current or voltage through a quadratic term in their current-voltage characteristic.
- Bolometers are composite devices consisting of a THz absorber and a thermistor. The THz absorber is generally isolated thermally from the environment so that the absorbed THz power raises the temperature both of the absorbing layer and an attached thermistor. The thermistor is, by definition, a device that displays a large change of resistance to a small change of temperature. In some bolometers, such as the composite type, the absorber and thermistor are separate elements. In other bolometers, such as the hot electron type, they are integrated into the same device.

# Analysis of Direct Detection Receiver

**An approximate expression for the NEP of a THz direct detector can be derived in terms of absorbed radiation fluctuations and the electrical NEP. Given the Rayleigh-Jeans limit and assuming all spatial modes have the same value of $\eta$, this expression is given by**

$$NEP_{AD} \approx \frac{1}{\eta}\sqrt{2\cdot\overline{(\Delta P_{ABS})^2}\cdot\Delta f/\Delta\nu+(NEP_{elect})^2}$$

$$=\sqrt{2\cdot(k_B T_{eff})^2\cdot M\cdot\Delta f\cdot\Delta\nu/\eta+(NEP_{elect}/\eta)^2}$$

**From the expression above we have $dP_{inc}/dT_B = M\cdot k_B\cdot\tau_A\cdot\Delta\nu$, so the NE$\Delta$T is given by**

$$NE\Delta T \equiv \frac{NEP_{AD}}{dP_{inc}/dT_B} = \tau_A^{-1}\sqrt{2\cdot T_{eff}^2\Delta f/(M\cdot\eta\cdot\Delta\nu)+[NEP_{elect}/(\eta\cdot M\cdot k_B\cdot\Delta\nu)]^2}$$

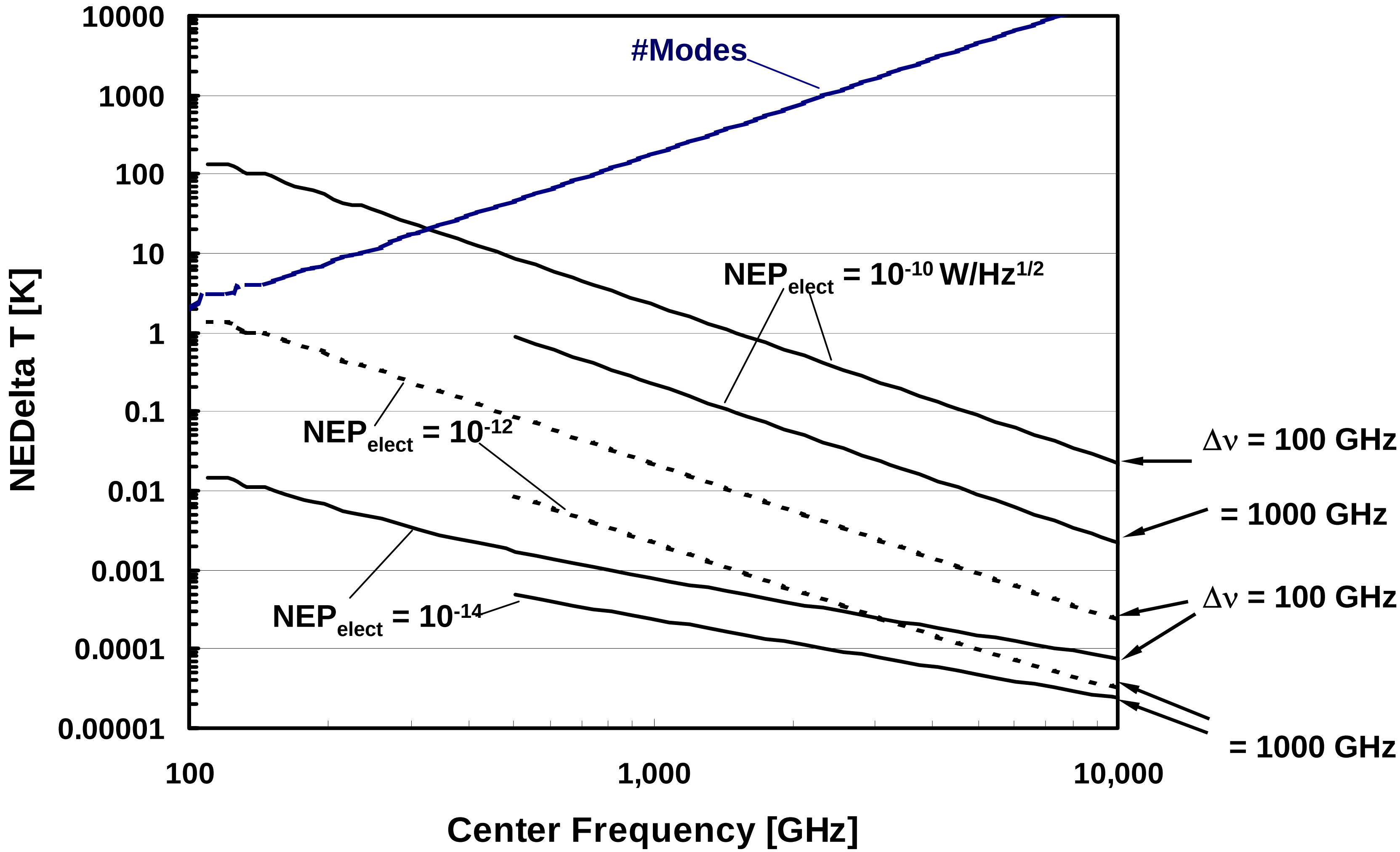
**In the event that the first term in the in the radicand dominates, we obtain**

$$NE\Delta T = \frac{T_{eff}}{\tau_A}\sqrt{2\cdot\Delta f\cdot(M\cdot\eta\cdot\Delta\nu)^{-1}}$$

# Analysis of Direct Detection Receiver (cont)

- These expressions are useful in evaluating the performance of direct-detection sensors once the parameters are known. The number of spatial modes can be estimated using $M \approx \Omega_{FOV}/\Omega_B \approx \mathrm{Int}(\nu_0/\nu_R)^2 + 1$ where $\nu_R$ is a reference frequency, assumed here to be 75 GHz. The external coupling efficiency per mode is assumed to be $\eta = 0.5$. The post-detection bandwidth is assumed to be 30 Hz consistent with live-video requirements. The center frequency $\nu$, instantaneous bandwidth $\Delta\nu$, and atmospheric transmission are best left as parameters since these are the most flexible or variable parameters from an engineering or phenomenology standpoint. The figure shows the NE$\Delta$T vs $\nu_0$ for three different $NEP'_{elect}$ values and two different $\Delta\nu$ values. Also shown is the number of modes vs $\nu_0$ for $\nu_R$ = 75 GHz. In all cases NE$\Delta$T drops monotonically with $\nu_0$ simply because M increases quadratically – there is no other $\nu_0$ dependence in Eqn 51. An increase of $\Delta\nu$ decreases NE$\Delta$T at any given $\nu_0$ , but a decrease in $NEP_{elect}$ is effective only down to roughly $10^{-13}$ W/Hz$^{1/2}$. This is because of the radiation noise arising from the 290-K source and atmosphere. The reader may note that the literature is replete with cryogenic mm-wave and THz bolometers having far lower values of NEP, consistent with operation in upper-atmospheric and astronomical sensing where the background radiation noise is far lower than in the present scenario

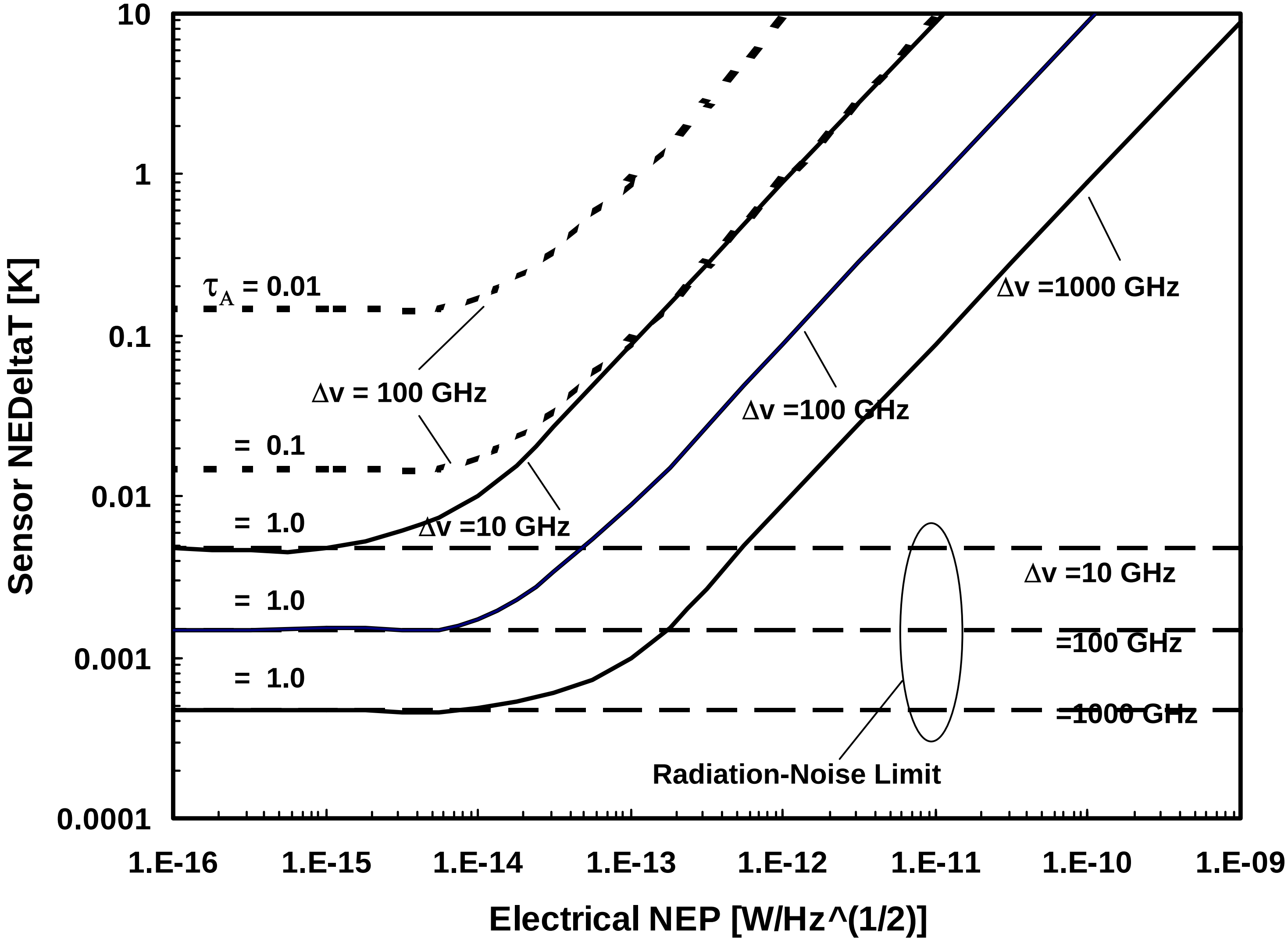
# Sensitivity in Direct Detection



# Sensitivity vs Center Frequency in Direct Detection

- The previous plot also reiterates the point of how important center frequency is to sensitivity. A detector having $NEP'_{elect} = 10^{-9}$ W/Hz$^{1/2}$ is relatively easy to obtain for room-temperature operation, but can provide an NE$\Delta$T only between roughly 1 and 20 K at a 1000-GHz center frequency – not considered sensitive enough for most applications. But this same detector can provide NE$\Delta$T between about 0.01 and 0.2 K if operated at a center frequency of 10 THz ($\lambda$ = 30 $\mu$m). The explanation is, again, the increase in the number of spatial modes, which also explains why "uncooled" detectors can be used as the basis for sensitive cameras at roughly $\lambda$ = 10 $\mu$m and shorter wavelengths. But the student should note that the present analysis assumes all spatial modes contribute both signal and noise, which is increasingly difficult to achieve when the frequency goes well into the infrared.

# Sensitivity vs NEP in Direct Detection

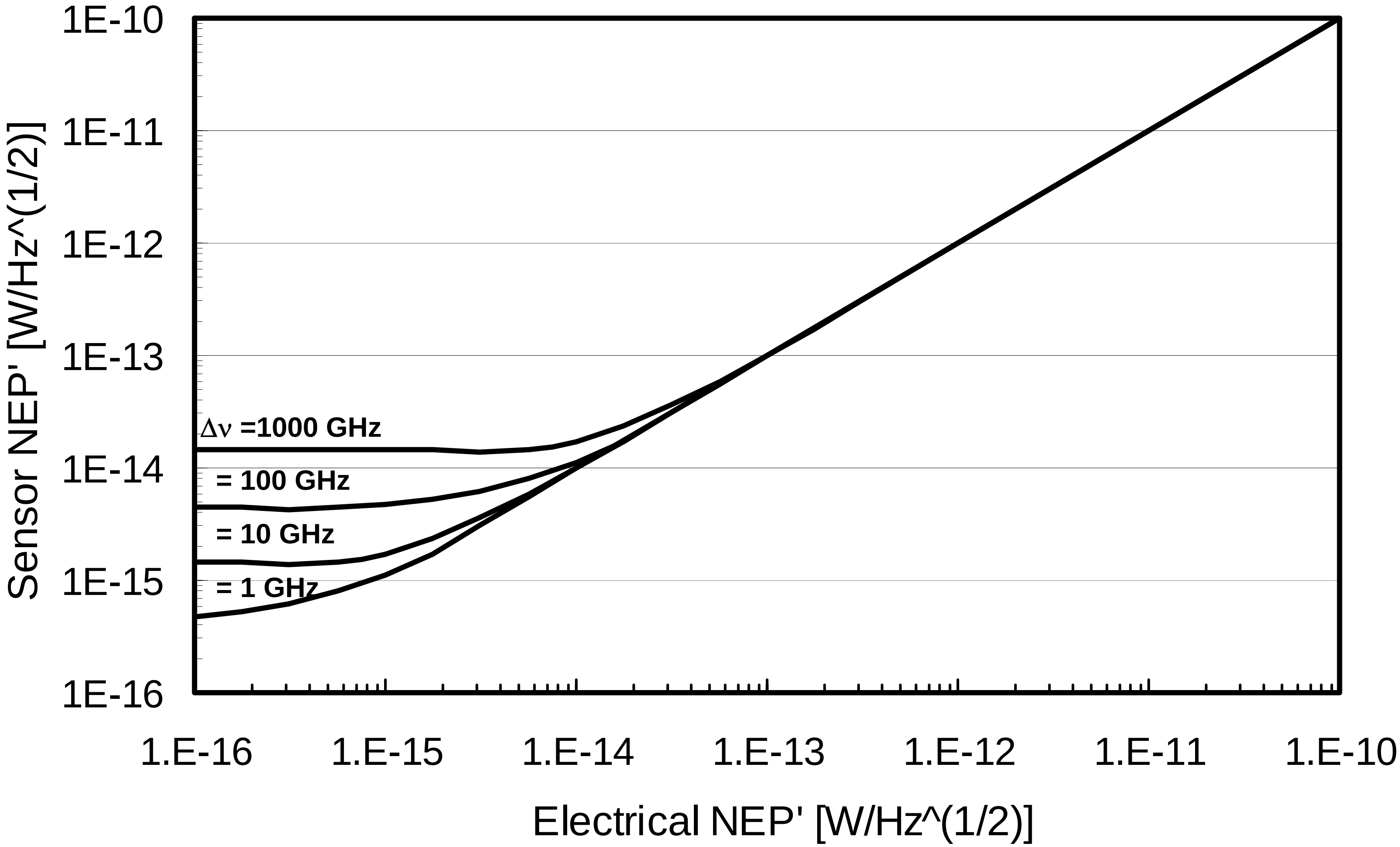


## Sensitivity vs NEP in Direct Detection (cont)

- This previous plot shows NE$\Delta$T vs NEP'$_{elect}$ , parametrized by $\Delta\nu$ and $\tau_A$ . The center frequency, number of modes, and mode coupling are fixed at 500 GHz, M=45, and $\eta$ = 0.5, respectively. The resulting curves in show, again, the asymptotic approach toward the radiation-noise-limited NE$\Delta$T for NEP'$_{elect}$ $\leq 10^{-13}$ W/Hz$^{1/2}$ . To get a useful sensitivity of, say NE$\Delta$T ~ 0.1 K with $\tau_A$ = 1.0, the NEP'$_{elect}$ can be no worse than about $10^{-11}$ W/Hz$^{1/2}$ – a performance that is hard to achieve at room temperature if one also requires M = 45 and $\eta$ = 0.5. As $\tau_A$ degrades, the required NEP'$_{elect}$ also drops until $\tau_A$ ~ 0.01 (-20 dB), when the radiation noise then limits the NE$\Delta$T to values above 0.1 K. Hence for passive thermal imaging it is imperative in the THz region to choose the center frequency carefully as a trade-off between NEP$_{elect}$, number of modes, and atmospheric transmission. From the atmospheric transmission, a compelling choice of center frequency would be the highest-frequency "good window" centered around 9 cm$^{-1}$ (270 GHz).

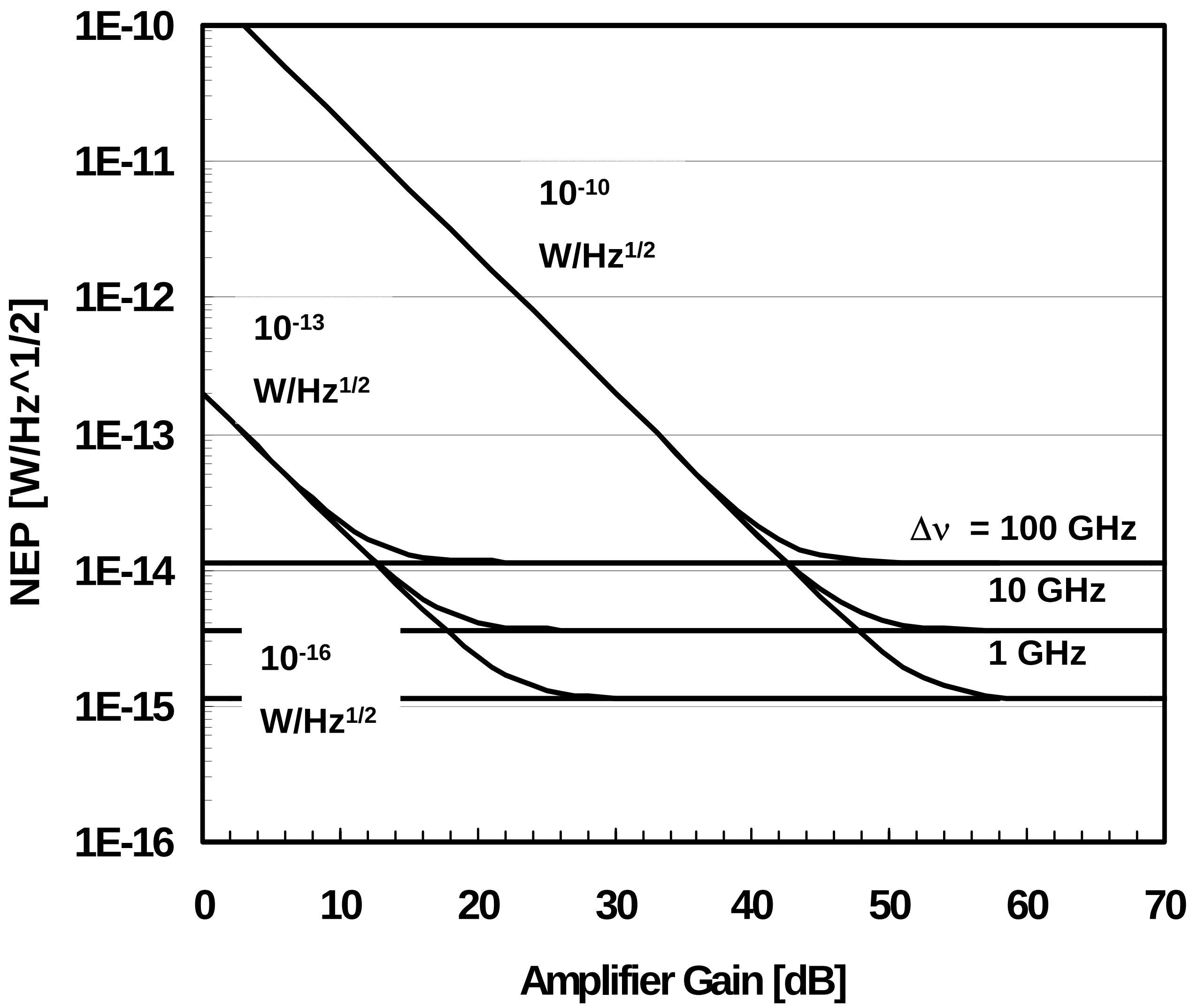
# Quantum Limit in Direct Detection

**(of academic interest except for cryogenic operation)**

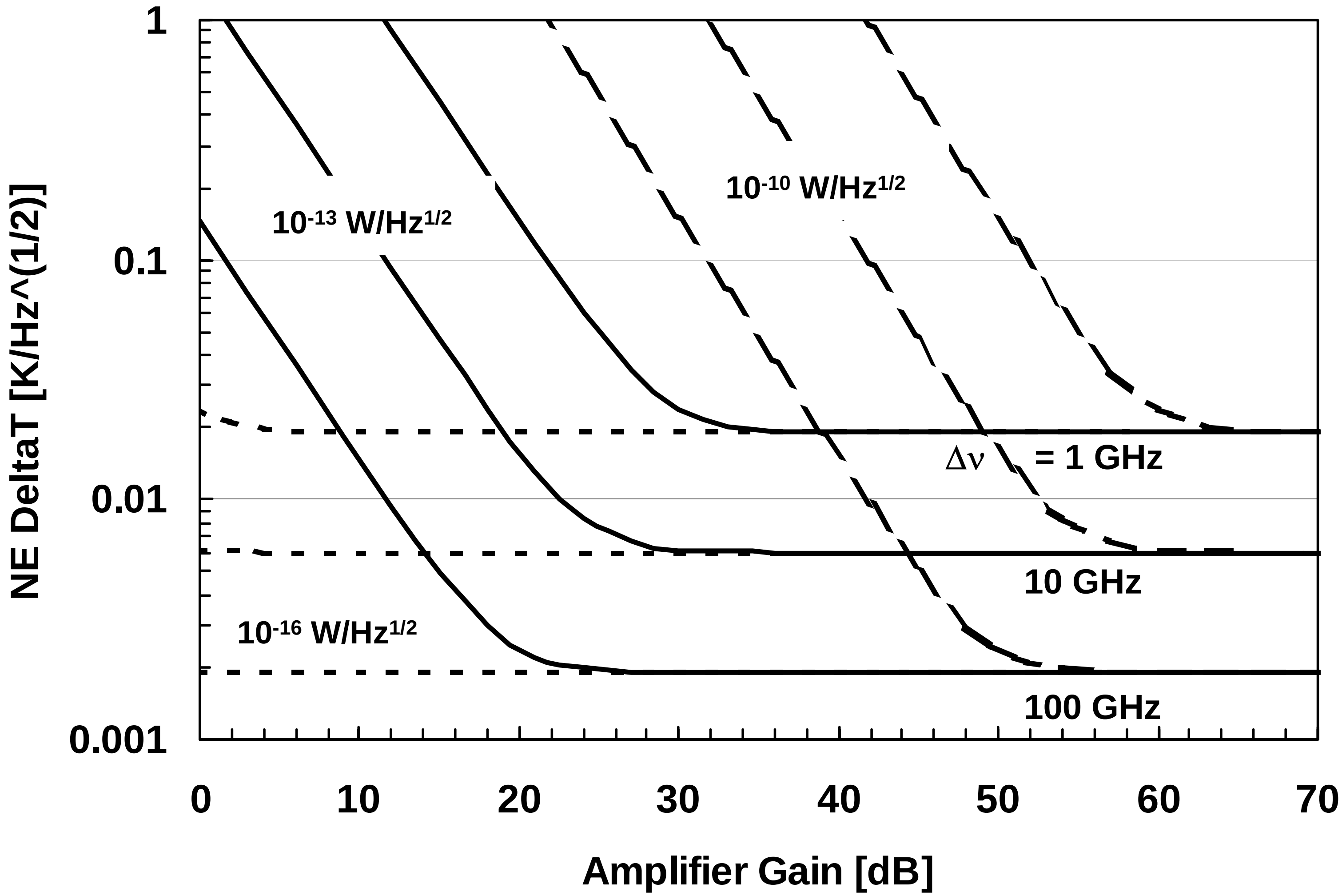


# System NEP with Preamplified Direct Detection

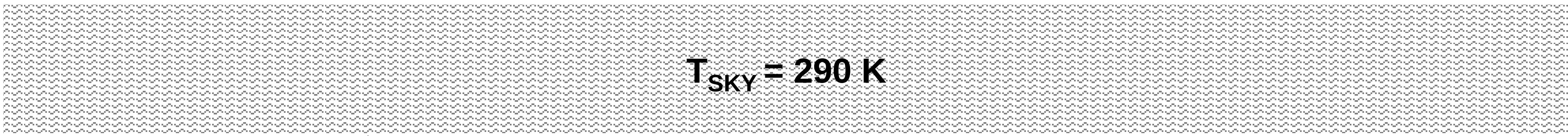
$$\left(\frac{S}{N}\right)_{AD} = \frac{(\Re \cdot P_{inc} \cdot \eta_R \cdot G)^2}{2\Re^2 \cdot \{\ \eta_R \cdot G^2 \cdot (k_B T_B \cdot \Delta\nu)^2 + [G \cdot (F-1) \cdot k_B T_{300} \cdot \Delta\nu]^2\ \} \cdot (\Delta f / \Delta\nu) + \left(\Re \cdot NEP'_{elec}\right)^2 \cdot \Delta f}$$

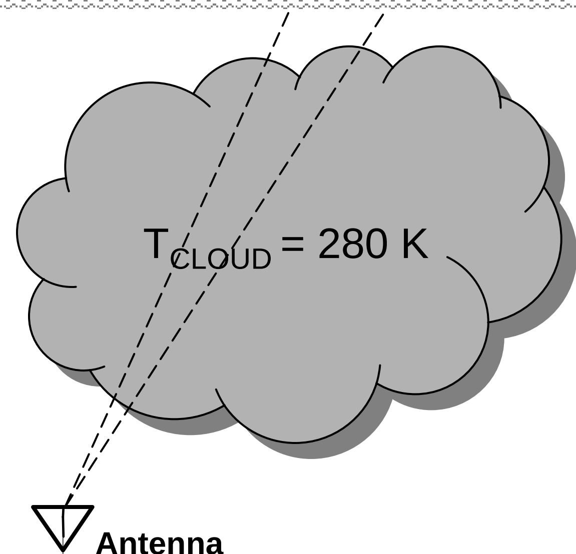


# System NE$\Delta$T with Preamplified Direct Detection

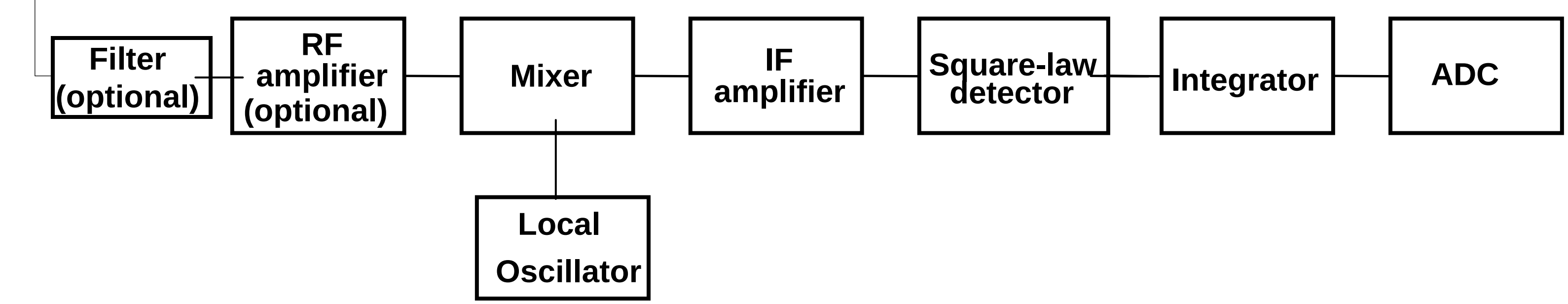


# THz Passive Coherent (Heterodyne) Radiometer



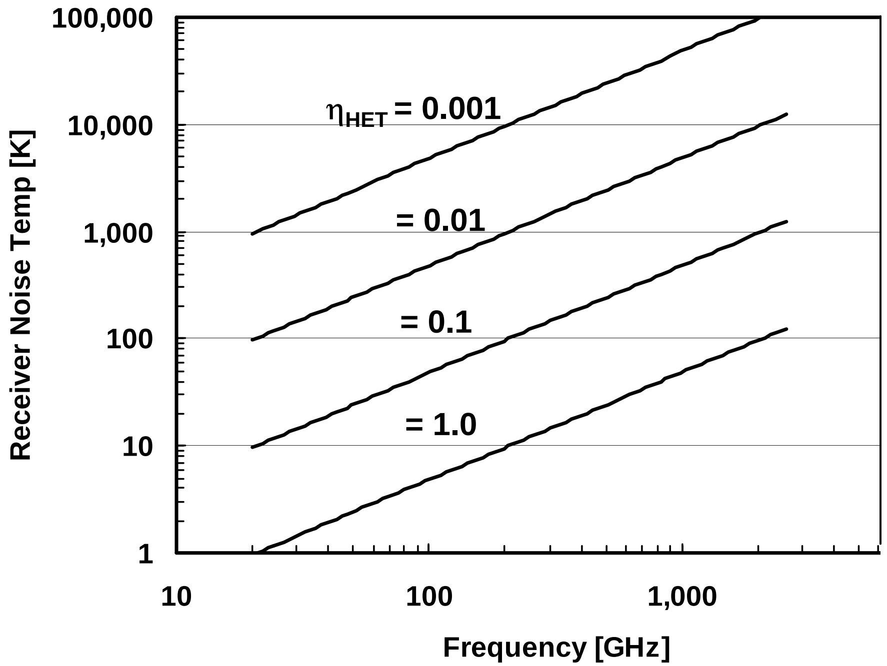

- **RF Amplifiers up to approx 300 GHz; mixers above 300 GHz**
- **Quantum efficiency = $h\nu/kT_n$ , ~ 0.1 between 200 and 600 GHz (cryogenic operation)**

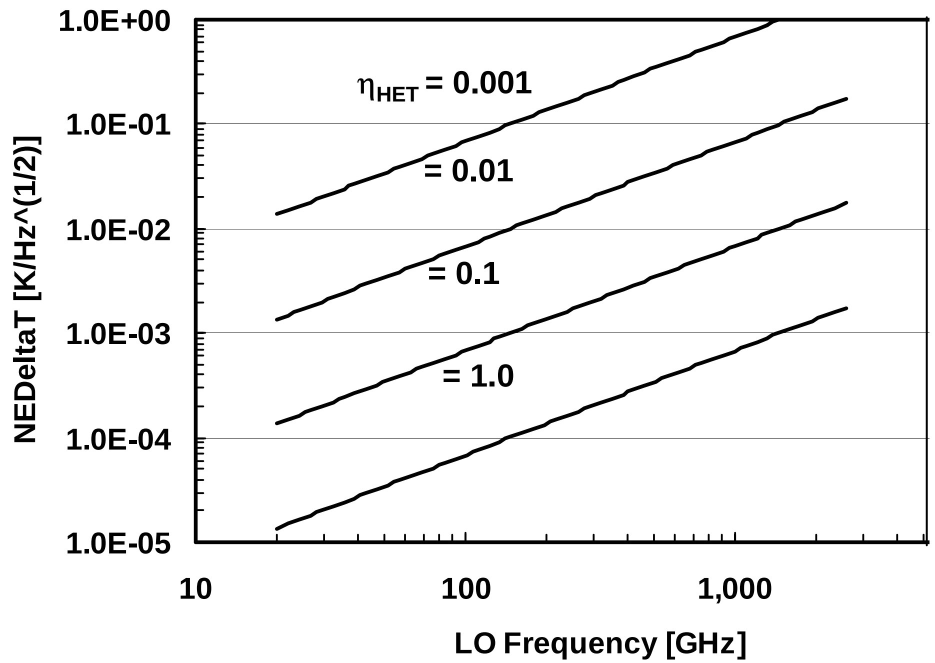


# THz Passive Heterodyne Radiometer Issues

- As we have already discussed, but it's worth re-stating, coherent down-conversion has several unique features that distinguish it from direct detection. First, mixing a weak signal with a relatively strong LO effectively amplifies the received signal relative to the receiver noise floor, which can greatly improve the sensitivity compared to direct detection. Second, for the typically weak signals in the THz region, the mixing process is linear. That is, the signal power at the IF frequency is linearly proportional to the signal power at the input. Therefore, the receiver passband can be defined by an IF band pass filter, which is generally much lower in cost and has much higher performance than any THz filter. This feature tends to make coherent receivers the favored approach in applications requiring high spectral resolution, such as molecular spectroscopy. But as will be shown below, the direct receiver tends to be preferable in wideband applications such as thermal imaging because of its superior spectral bandwidth and simplicity.

# THz Passive Heterodyne Radiometer Performance




$$T_R \equiv NEP_{in} / (k_B B_{IF})$$

$$\eta_{HET} \equiv NEP_{QL} / NEP_{in} = h\nu / NEP_{in}$$

**e.g., at $\nu$ = 1.0 THz, $h\nu$ = 4.1 meV = $6.6\times10^{-22}$ J = $6.6\times10^{-22}$ W/Hz**

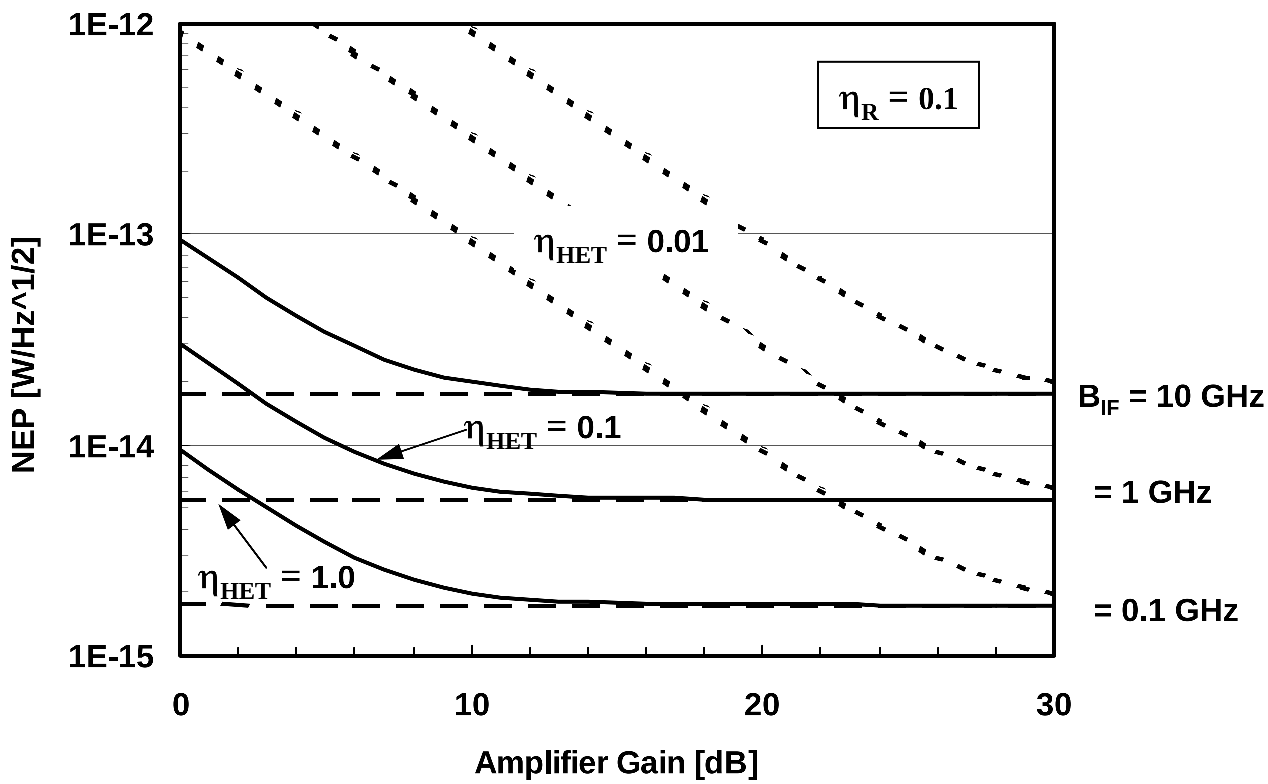
# THz Passive Heterodyne Radiometer Aspects

- The previous plots show the $NEP_{HET}$ before detection and the $NE\Delta T_{AD}$ after detection for various values of $\eta_{HET}$ and $B_{IF}$. Several of the popular detector types can operate in both as direct detector and mixers. A good example is the Schottky diode. Based on the above analysis, the following rule-of-thumb relationship between the heterodyne and direct NEP values can be found: $NEP'_{HET} \approx (NEP'_{AD})^2/P_{LO}$ . From the analysis of the generic Schottky diode, we would have a room-temperature direct $NEP'_{AD}$ of about $3x10^{-12}$ $W/Hz^{1/2}$ at 300 GHz. Then given a local oscillator power of 1 mW, one would predict a heterodyne NEP of $9x10^{-21}$ W/Hz, corresponding to a $\eta_{HET}$ value of 0.02. These numbers are all reasonably close to the experimental reality.

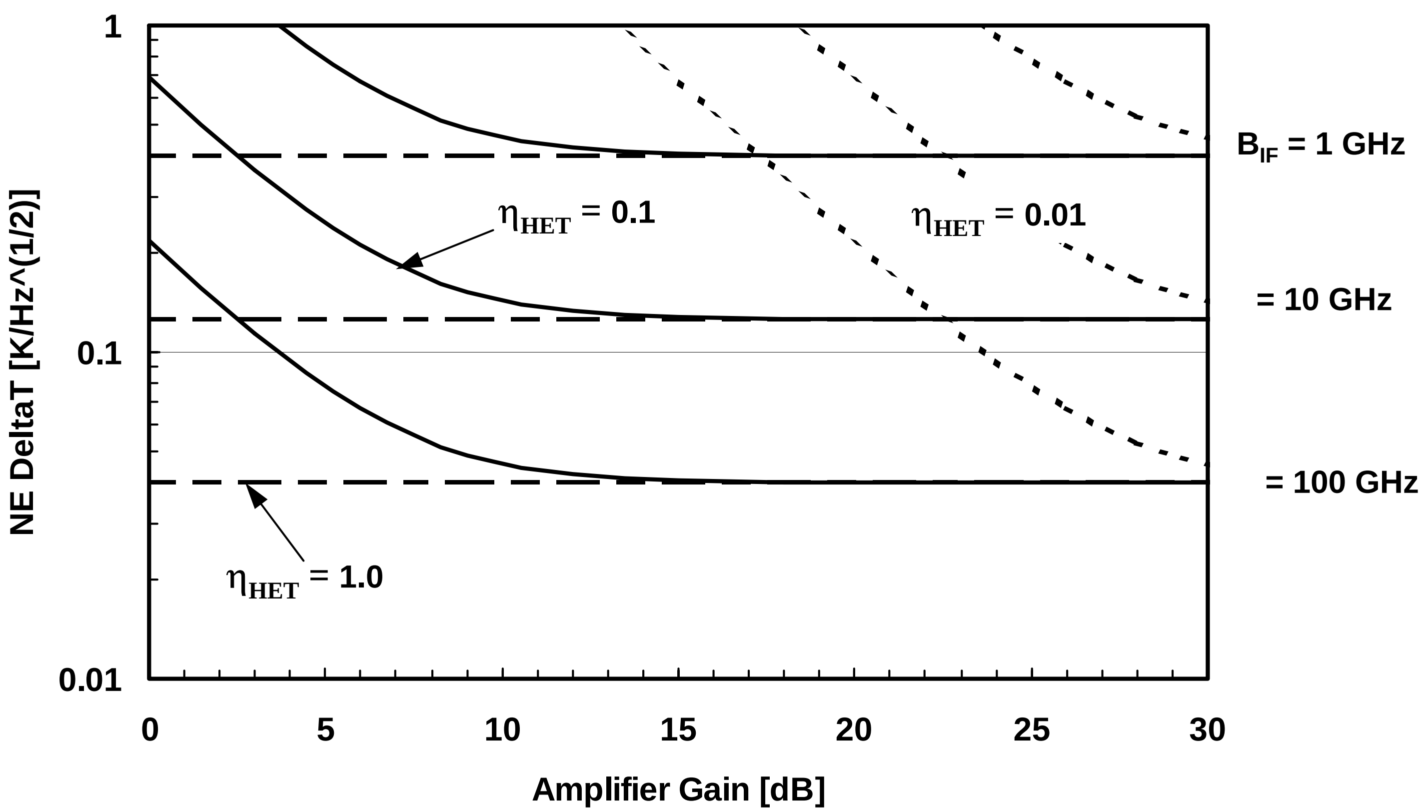
# Preamplified Coherent THz Radiometer

- An intriguing possibility in the millimeter-wave band and lower end of the THz range is a preamplifier feeding a mixer element. With recent advances in MMIC solid-state power amplifiers and the possibility of integrating them with high-frequency Schottky mixers monolithically, one can envision a receiver in which an antenna couples radiation to an LNA that, in turn, is coupled to a high-frequency mixer. The mixer then down-converts the radiation to whatever IF band makes sense, be it narrowband for spectroscopic applications, or wider band for thermal imaging applications. Intuitively, one could design the LNA with just enough gain so that the overall receiver sensitivity was not affected significantly by the mixer or following IF electronics. As will be shown later, this provides excellent overall performance if the LNA noise figure is acceptably low. And not surprisingly, it is the same architecture used at lower frequencies in communications and radar receivers alike, perhaps most commonly in the handsets of nearly every mobile telephone made today at PCS wireless frequencies.

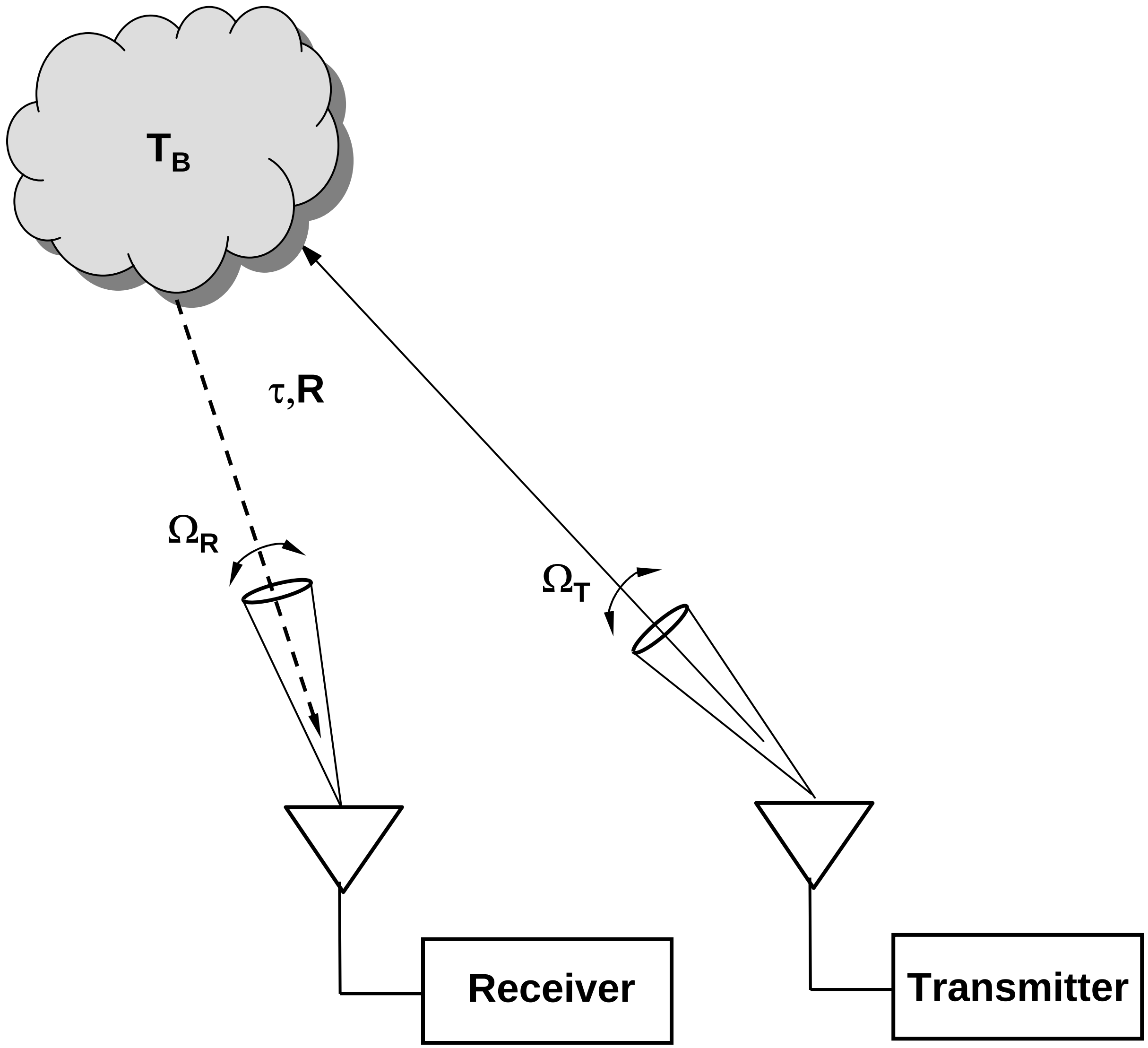
# Preamplified Coherent THz Radiometer Performance



# Preamplified Coherent THz Radiometer Performance (cont)



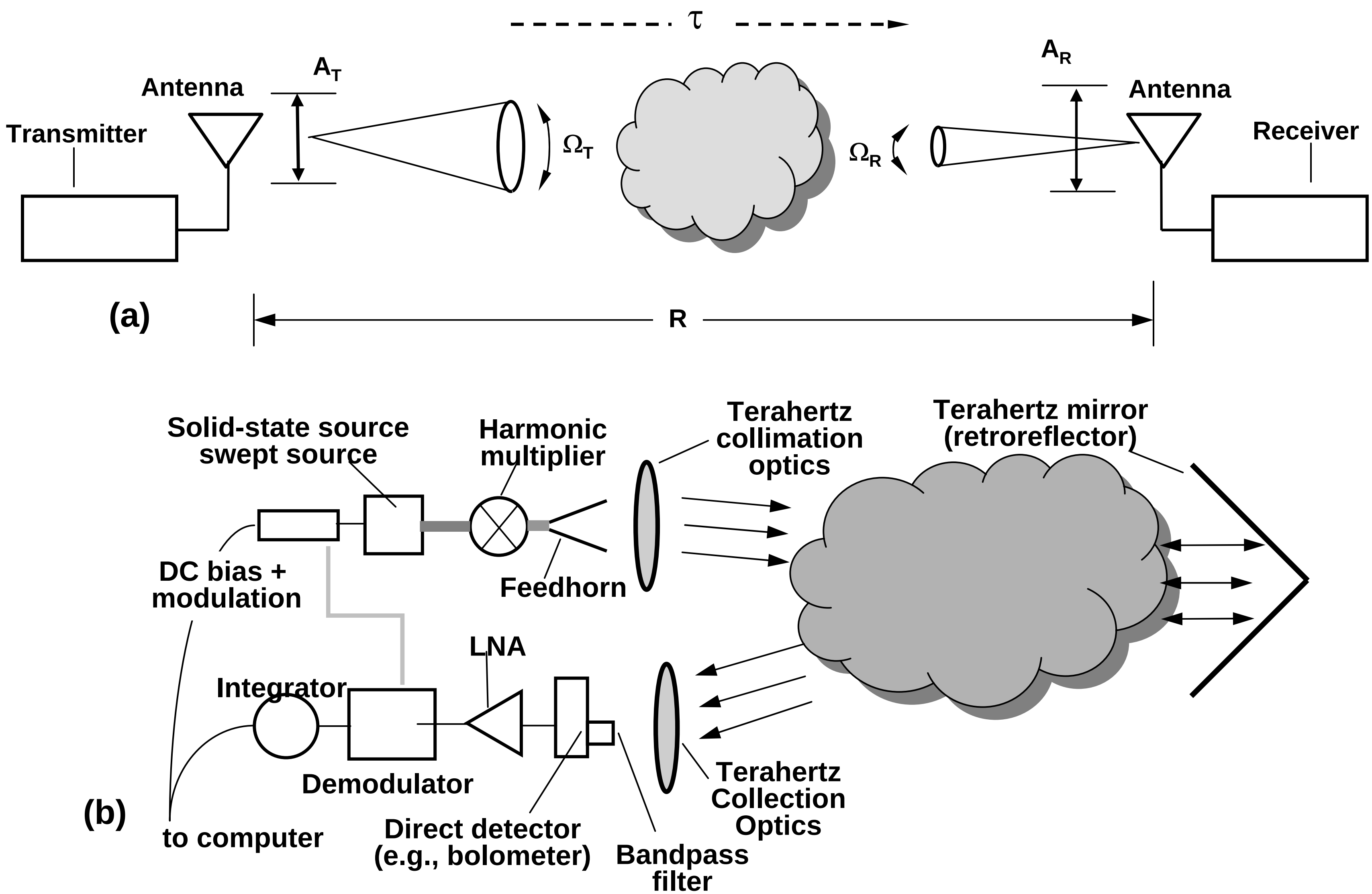
# THz Active Sensor Scenario



## THz Active Sensor Scenario (cont)

- By combining a transmitter (Tx) with a receiver (Rx) oriented as shown above, a coherent or quasi-coherent signal is sent out by the Tx, is reflected or transmitted by the object or target, and is then collected by the Rx where it is rectified from RF (THz) to baseband either by a direct or coherent receiver. The target might be a cloud or a partially transparent object, for example. To maximize the received signal, the relative orientation of the Tx and Rx is important.
- To get the receiver SNR and NEP performance, one first needs to know how much of the transmitted power is collected by the receiver. For scatter-free atmospheric propagation, the instantaneous signal power at the receiver (Rx) can be estimated analytically given reasonable assumptions about the Tx power and beam patterns. For simplicity, we make the following three assumptions: (1) the Tx radiates only the one fundamental spatial mode of its antenna, (2) the width of the Tx and Rx beams are much smaller than the lateral extent of the target at every point where they pass through, and (3) the Tx and Rx antennas are perfectly aligned such that the peaks of their patterns are collinear. The Rx incident power can then be approximated by the Friis formula in the case of perfect beam and polarization alignment

# Two Easier Active Scenarios



# THz Active Sensor Issues

- If the object or target is best observed in transmission, then for good performance the Rx is best located along the direction of the transmitter radiation but on the opposite side of the object. An alternative is to place a retroreflector on the opposite side of the object and co-locate the Rx next to the Tx. If the object or target is best observed in reflection because of a strong back-scatter effect, then Tx is best configured to produce a quasi-collimated beam.
- A common goal of all three of these Tx-Rx orientations is that the received power, as defined in the Friis formula, should fall with separation r between the Tx and Rx slower than $1/r^4$. This is in contrast to the typical $1/r^4$ decay that occurs in conventional radar, where the $1/r^2$ factor from the far-field Tx radiation is multiplied by a second $1/r^2$ factor based on assumed isotropic scattering from the target or object. Although the $1/r^4$ factor is considered accurate for long-range radar, particularly at microwave frequencies and below, it is unnecessarily pessimistic for the short range applications being pursued with mm-wave and THz sensors.

# THz Active Sensing Analysis: Direct Detection

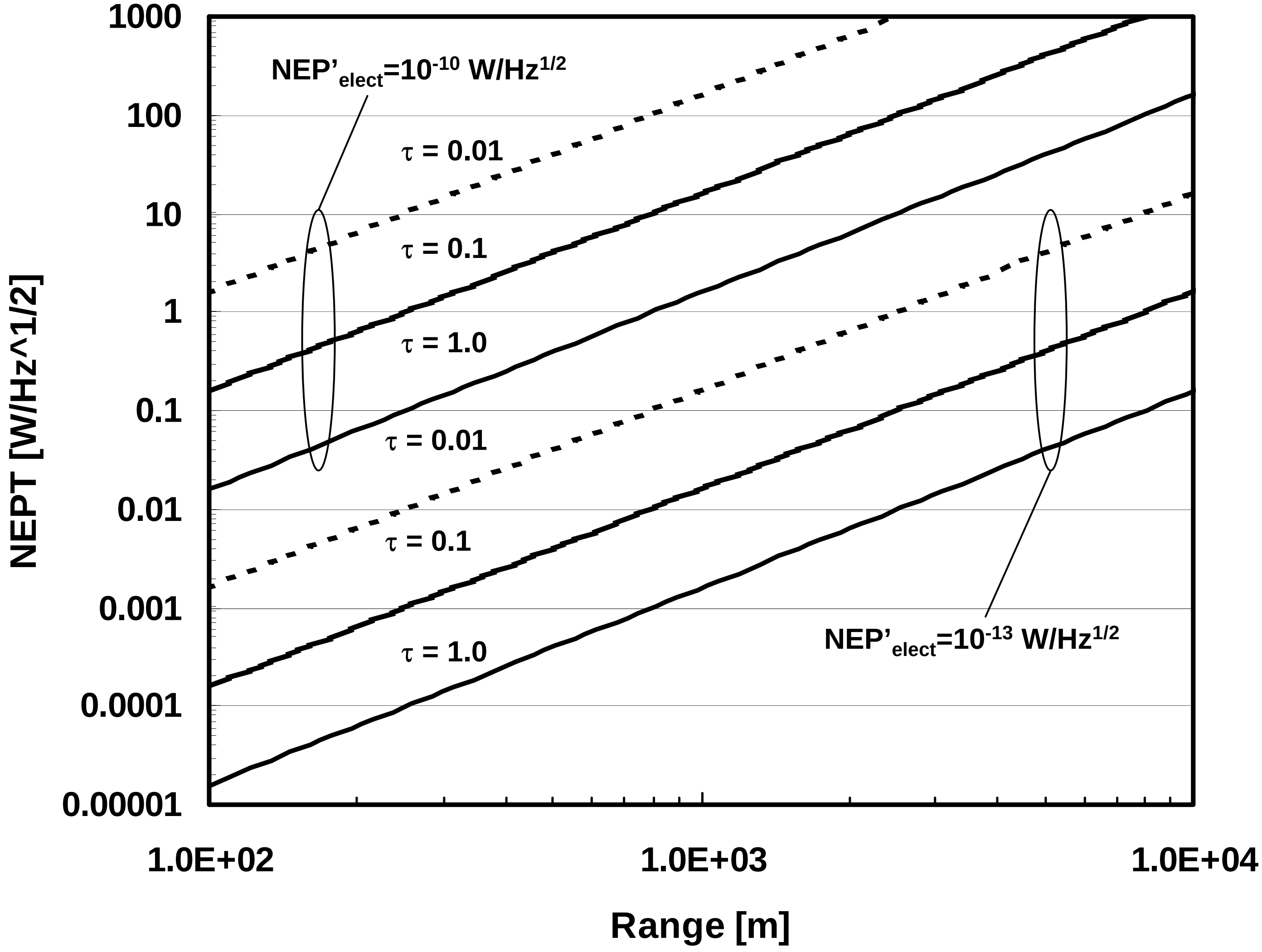
$$P_{inc}(\nu) = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2} \tau(\nu)$$

With direct detection:

$$\left(\frac{S}{N}\right)_{AD} = \frac{\left[\eta \cdot \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2} \tau(\nu)\right]^2}{2 \cdot \eta \cdot (k_B T_{eff} \cdot \Delta\nu)^2 \cdot (\Delta f / \Delta\nu) + (\eta \cdot NEP'_{elect})^2 \cdot \Delta f}$$

$$NEP'_T = \frac{(4\pi R)^2}{\tau \cdot G_T G_R \lambda^2} \sqrt{2 \cdot (k_B T_{eff})^2 \Delta\nu / \eta + (NEP'_{elect})^2} \qquad [\mathrm{W/Hz^{1/2}}]$$

# Active Sensor, Incoherent Receiver



# Active Sensor, Incoherent Receiver Issues

- This previous plot shows the noise equivalent transmit power for the active sensor with a direct-detection receiver as a function of range separating the transmitter and receiver. The lines are parametrized by the net atmospheric transmission factor $\tau$ and the direct-detector $NEP'_{elect}$. The other parameters in the curve are $G_T = G_R = 100$, $\eta = 0.5$.

- From this plot it is clear that even at moderate range, the worst-case direct detector having an $NEP'_{elect}$ of $10^{-12}$ can not provide useful sensitivity under any atmospheric condition unless the transmit power is >> 10 mW. So one would be advised in an active receiver with direct detection to use an NEP no worse than roughly $10^{-13}$ $W/Hz^{1/2}$ . According to Eqn 60 this produces an SNR of 1.0 with approximately 1 mW of transmit power at a range of 1 km

# THz Active Sensing Analysis: Coherent Detection

$$P_{inc}(\nu) = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2} \tau(\nu)$$

With coherent detection:

$$\left(\frac{S}{N}\right)_{AD} = \frac{\left\{ H \cdot {\eta_R}^2 \cdot \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2} \tau(\nu) \right\}^2}{2 \cdot \{\eta_R \cdot h\nu_{LO} + (\eta_R)^2 \cdot NEP'_{mixer}\}^2 \cdot (B \cdot \Delta f)} \equiv \frac{\left\{ H \cdot \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2} \tau(\nu) \right\}^2}{2 \cdot \{h\nu_{LO} / \eta_{HET}\}^2 \cdot (B \cdot \Delta f)}$$

H = 1 $\rightarrow$ heterodyne, H = 2 $\rightarrow$ homodyne

$$NEP'_T = \frac{(h\nu_{LO} / \eta_{HET})(4\pi R)^2 \sqrt{2 \cdot B}}{\tau \cdot G_T G_R \lambda^2} \qquad [\mathrm{W/Hz^{1/2}}]$$

# THz Active Coherent Sensor Performance