Photon Counting Terahertz Interferometry (PCTI)

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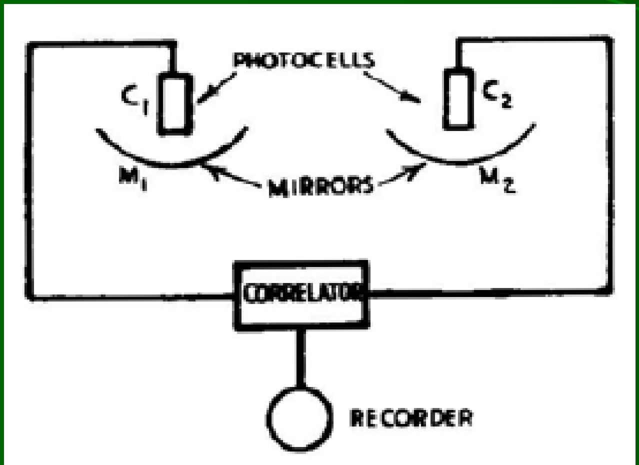


Hanbury-Brown and Twiss Experiment (1956)

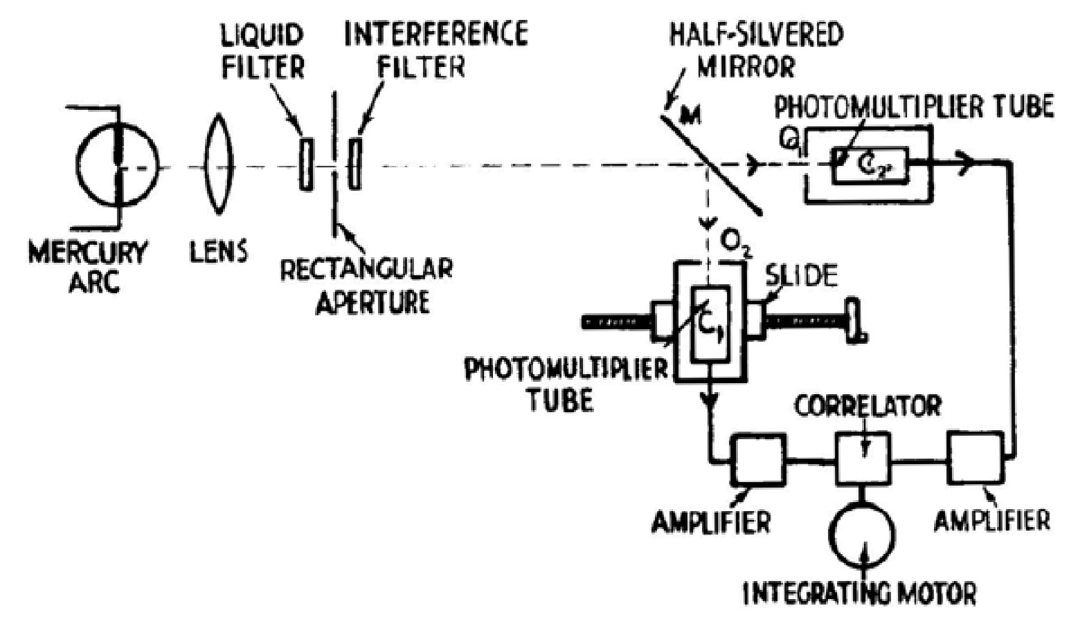
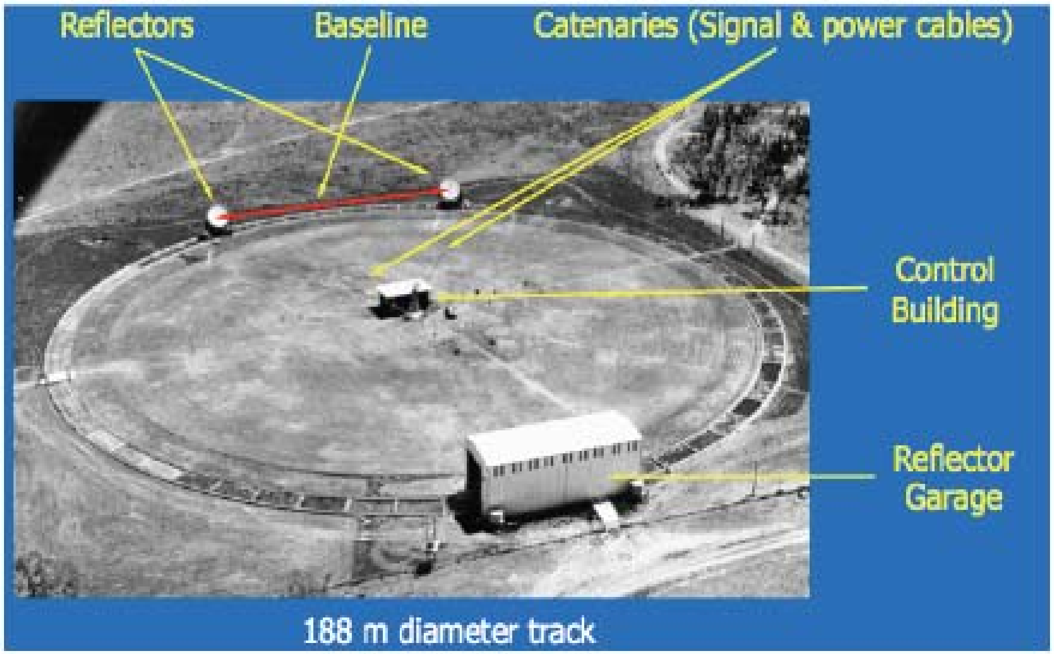


Fig. 2. Simplified diagram of the apparatus

Table 1. COMPARISON BETWEEN THE THEORETICAL AND EXPERIMENTAL VALUES OF THE CORRELATION

	Cathodes superimposed ($d = 0$)		Cathodes separated ($d = 2\alpha = 1.8$cm)	
	Experimental ratio of correlation to r.m.s. deviation $S_e(0)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(0)/N$	Experimental ratio of correlation to r.m.s. deviation $S_e(d)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(d)/N$
1	+ 7.4	+8.4	−0.4	~ 0
2	+ 6.6	+8.0	+0.5	~ 0
3	+ 7.6	+8.4	+1.7	~ 0
4	+ 4.2	+5.2	−0.3	~ 0

Narrabri Stellar Intensity Interferometer



Narrabri Stellar Interferometer

Hanbury-Brown et al. (1974)
Diameter of 32 early-type stars were measured.

Limitation of intensity interferometers

- Low efficiency for optical observations
  - Observation of very early type stars only
- Phase information is missing
  - Measurement of stellar diameters only

Intensity Interferometry in THz frequency
-> Photon Counting Terahertz Interferometry (PCTI)

Fluctuation of thermal radiation

$$\Delta n = \sqrt{n + n^2}\ ,\quad \text{where}\quad n = \frac{1}{e^{h\nu/kT} - 1}$$

$$n : \text{photon occupation number}$$

$$A\Omega = \lambda^2$$

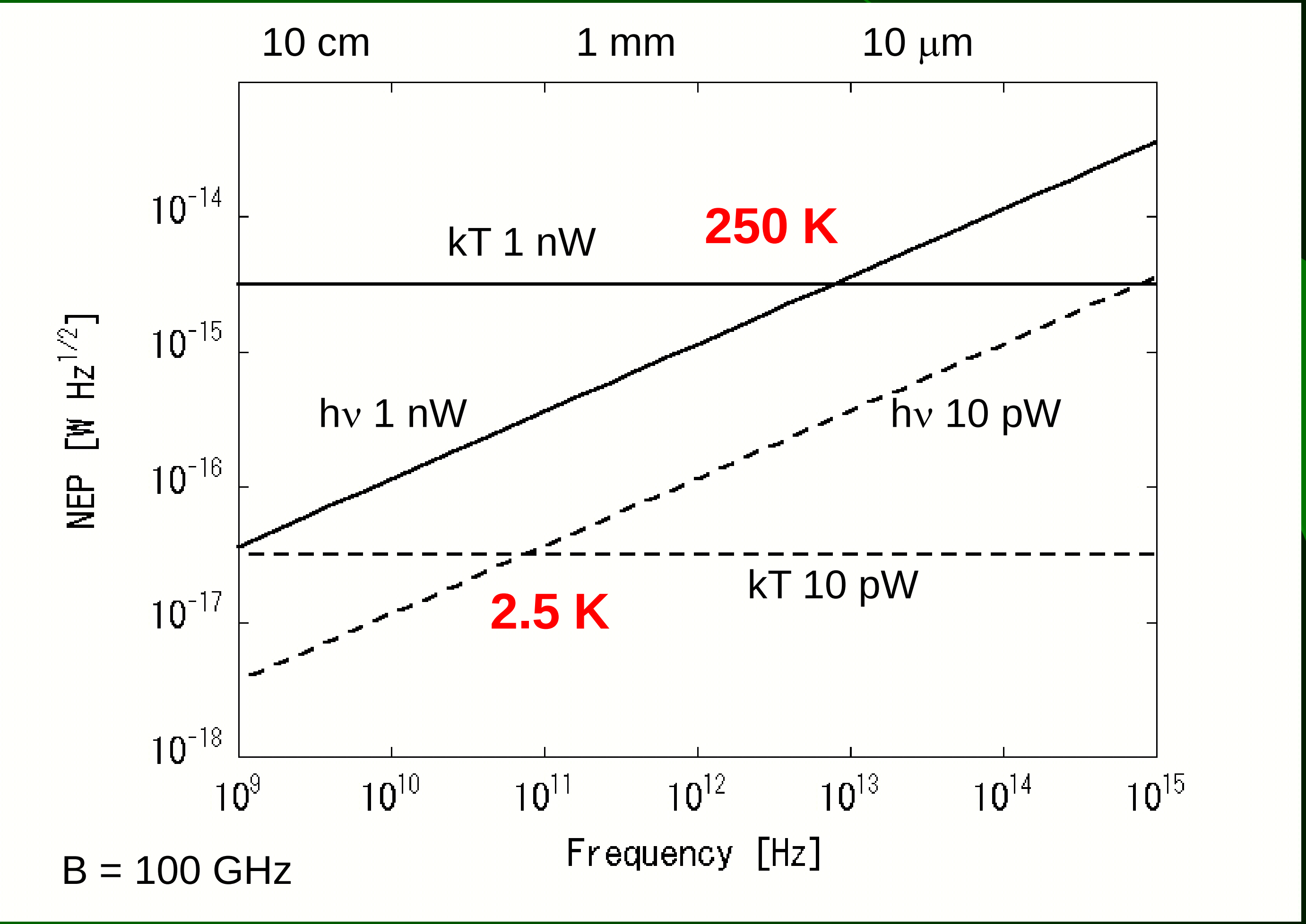
$$\text{NEP} = \sqrt{2P \cdot \left(h\nu + kT_B\right)}\,[\text{W}/\sqrt{\text{Hz}}\,]$$

References

A. Einstein (1909)
J. Mather (1984)
J.M. Lamarre (1986)
J. Zmuidzinas (2003)

THz photon fluctuation

$$\mathrm{NEP} = \sqrt{2P\cdot\left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

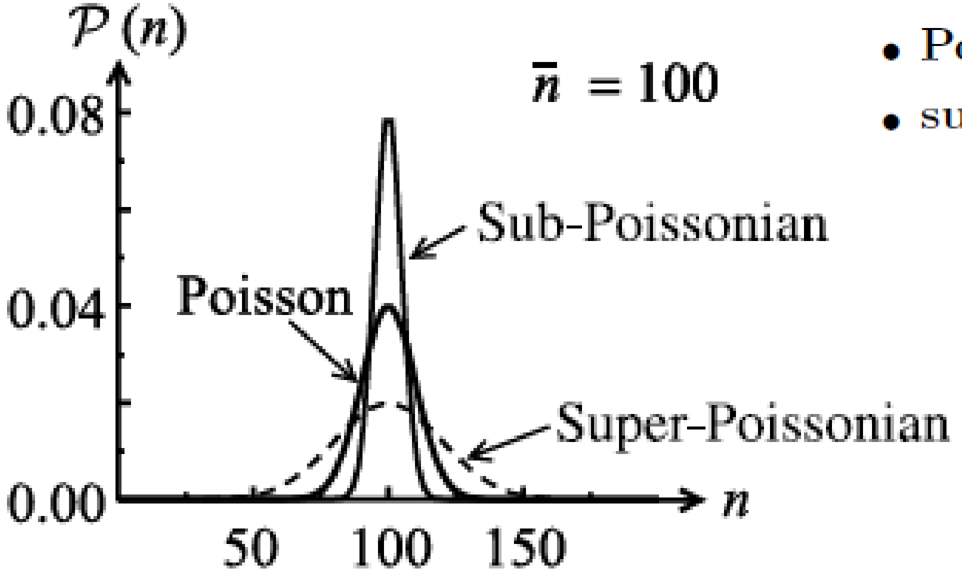


Introduction of Quantum Optics

from “Quantum Optics” by Mark Fox (2006)

Photon Statistics

- sub-Poissonian statistics: $\Delta n < \sqrt{\overline{n}}$,
- Poissonian statistics: $\Delta n = \sqrt{\overline{n}}$,
- super-Poissonian statistics: $\Delta n > \sqrt{\overline{n}}$.



$$\Delta n = \sqrt{n + n^2}$$

$$n = \frac{1}{e^{h\nu/kT} - 1}$$

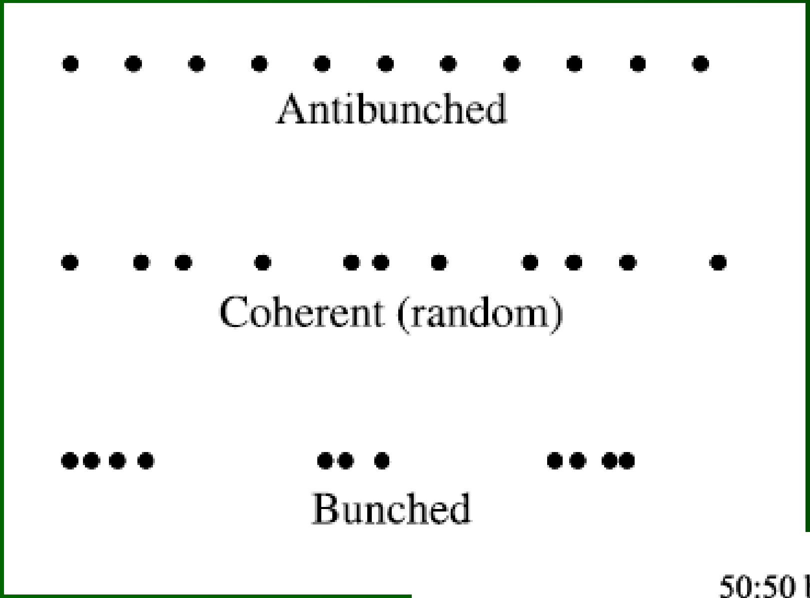
First order correlation function

$$g^{(1)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}(t+\tau)\rangle}{\langle |\mathcal{E}(t)|^2\rangle}.$$

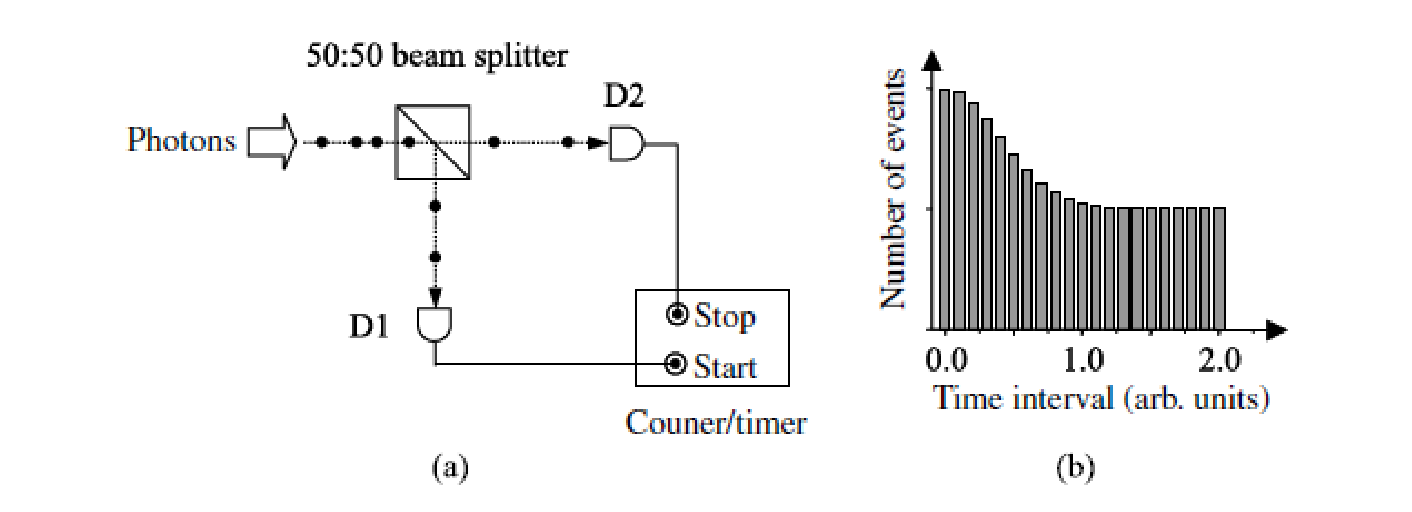
Second order correlation function

$$g^{(2)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\mathcal{E}(t)\rangle}{\langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle\langle \mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\rangle} = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle},$$

Photon Bunching, Anti-bunching



- bunched light: $g^{(2)}(0) > 1$,
- coherent light: $g^{(2)}(0) = 1$,
- antibunched light: $g^{(2)}(0) < 1$.



From M. Fox
Quantum Optics

THz photon bunches measured from a Synchrotron Source

$YBa_2Cu_3O_{7-\delta}$ thin film detectors for picosecond THz pulses

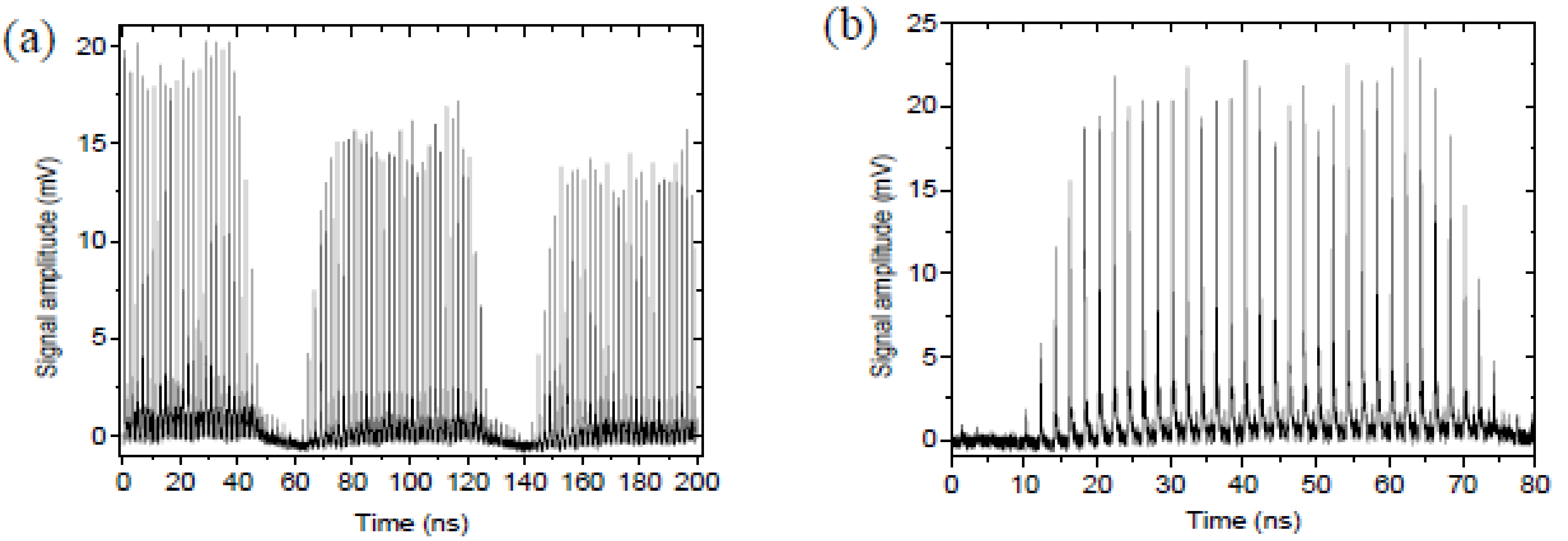


Fig. 3 (a) Measured detector signal of a 15 nm YBCO THz HEB over time. The distance between two trains is 20 ns (50 MHz). In (b) one train with 33 bunches is depicted in detail.

Probst et al., Journal of Low Temp. Phys. (2012)

The use of photon bunching ?

- Brightness temperature measurements
  - $T_B \sim 10^8$ K in X-ray
  - $T_B \sim 10^5$ K in optical
  - $T_B \sim 100$ K in terahertz
  - Application to CMB
- Application to Terahertz Interferometry
  - FIR atomic lines, black holes, stars, exo-planets

Brightness temperature measurements

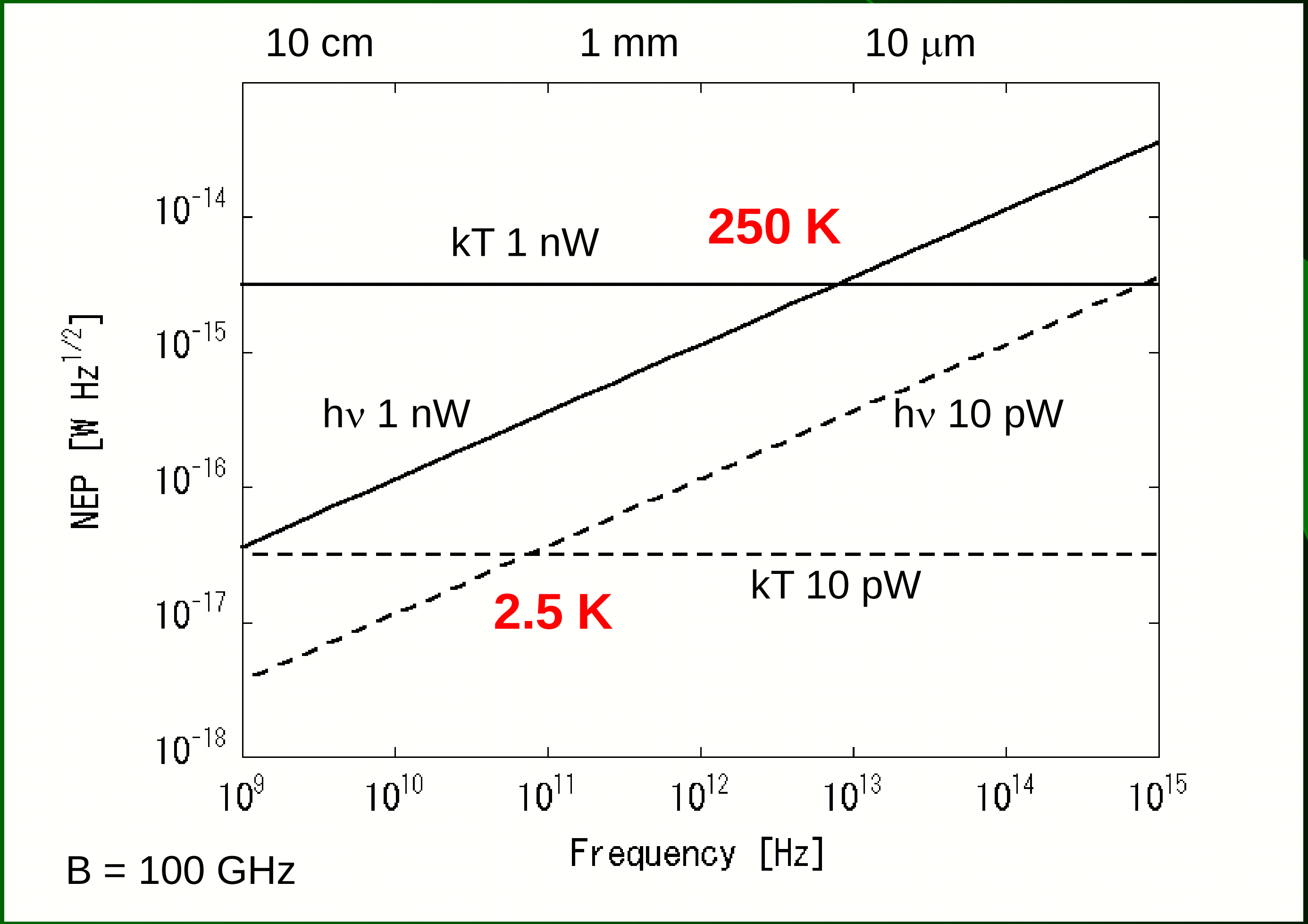
$$\mathrm{NEP} = \sqrt{2P \cdot \left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

$$T_B = \left(\frac{\mathrm{NEP}^2}{2P} - h\nu\right) \times \frac{1}{k}\ \ [\mathrm{K}]$$

de Bernardis and Masi (1982)

THz photons are bunched

$$\mathrm{NEP} = \sqrt{2P\cdot\left(h\nu + kT_B\right)}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}\,]$$



Photon Counting THz Interferometry (PCTI)

- Thermal THz photons are highly bunched
  - High efficiency measurement
- Bunches in two detectors can be used to measure delay
  - Complex visibility can be measured
- Wide bandwidth recording enables
  - Photon Counting VLBI

Number of Photons expected

- 1Jy source ν=1THz   B=100GHz
- With 10m diameter telescope

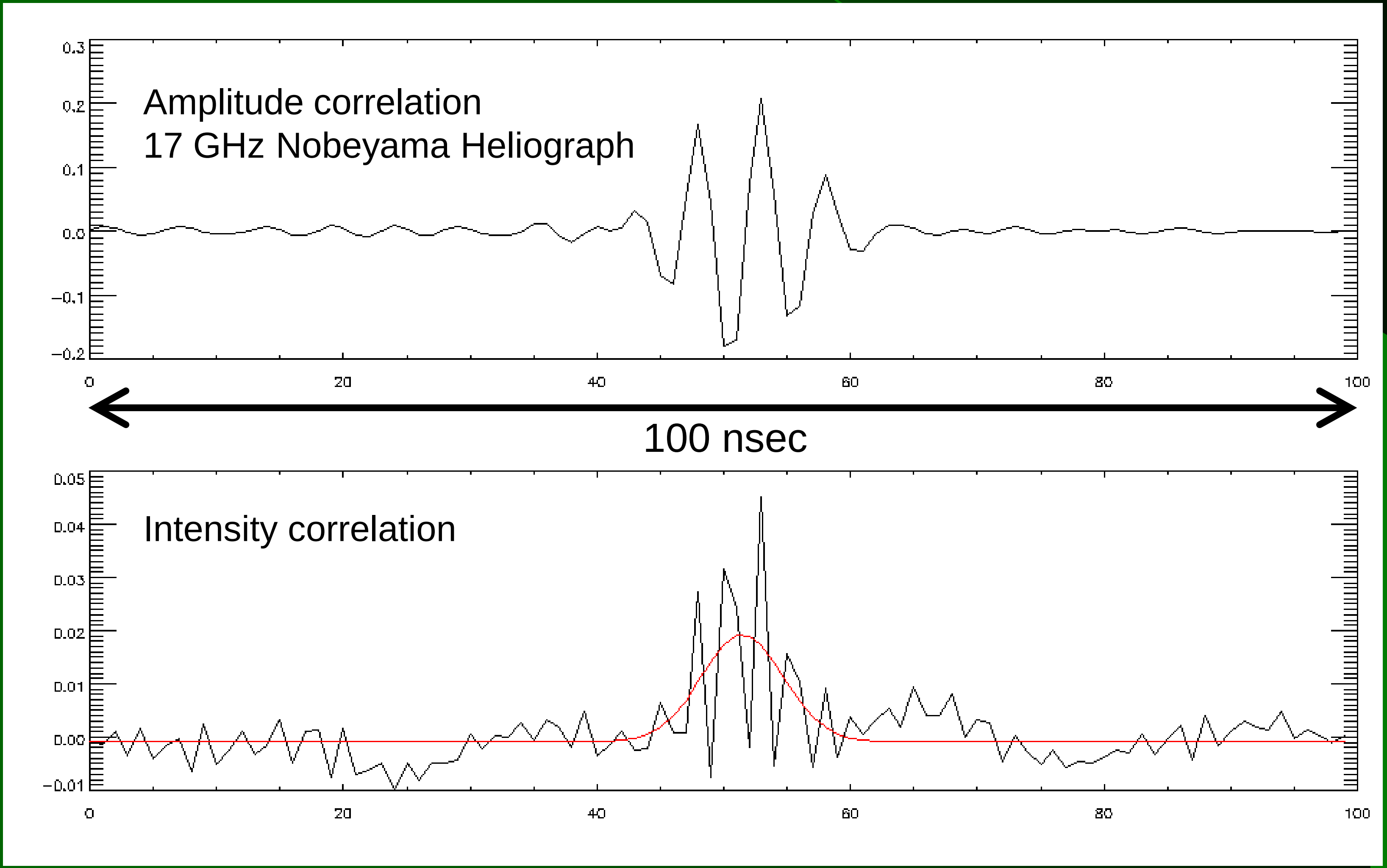
100 M photons/sec

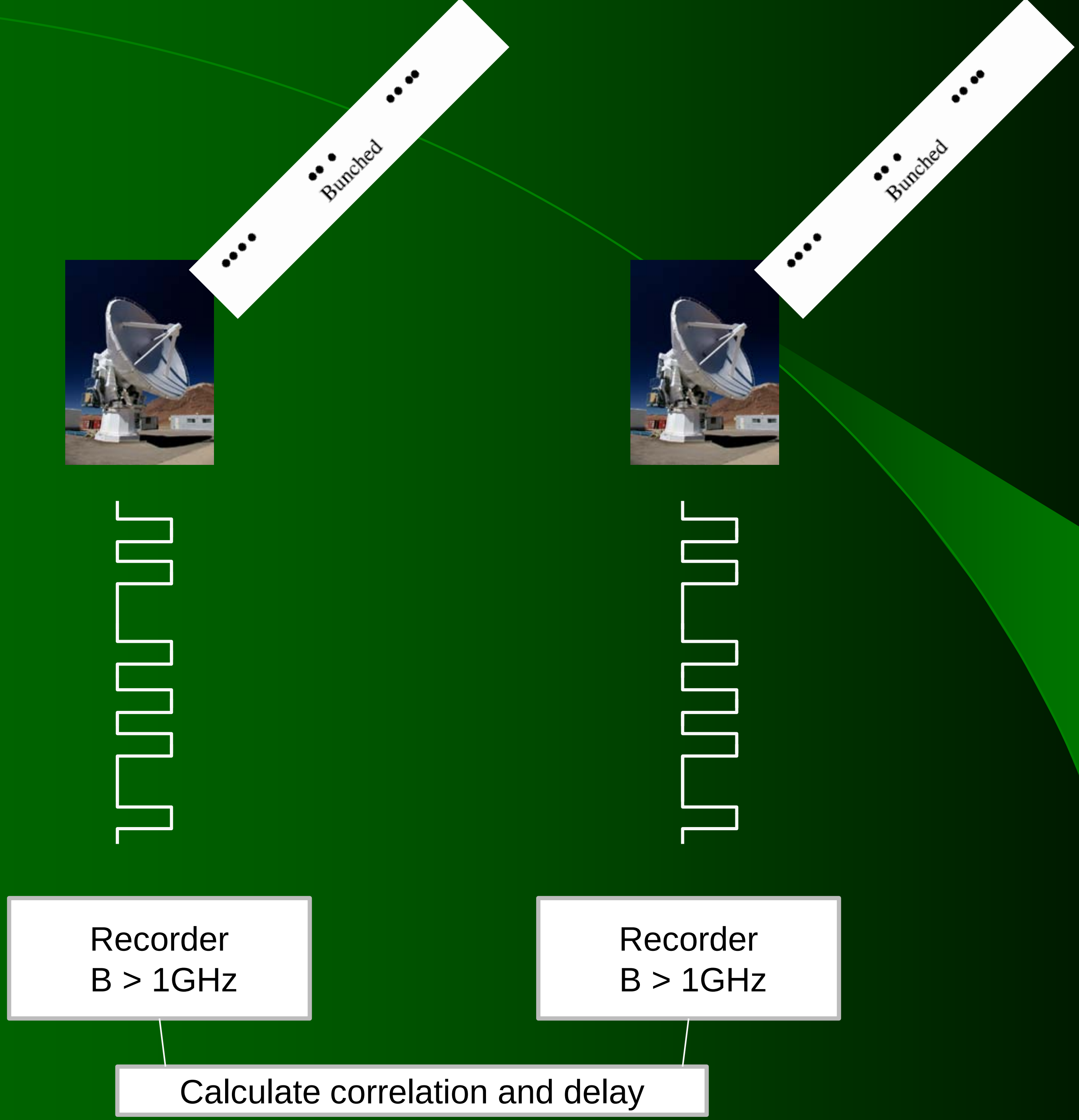
- FIR lines from massive star forming regions
- Nearby Stars and Planets
- AGNs
- CMB photons

Phase Measurement using Photon Bunches

- Photon rate of 100 MHz
  with 100 sec measurement,
  total number of photons 10^{10}.
- Timing accuracy for one photon is
  $1/100\text{MHz} = 10^{-8}$ sec.
- Statistical accuracy with 100 sec measurements
  $10^{-8} / \text{sqrt}(10^{10}) = 10^{-13}$ sec

An example of amplitude and intensity cross-correlation




Bunched
Bunched
Recorder
B > 1GHz
Recorder
B > 1GHz
Calculate correlation and delay

Science Cases

- FIR atomic fine structure lines from massive star-forming region
- Imaging AGNs
- Imaging nearby stars
- Exo-planet search and imaging

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Space-borne Photon Counting THz Interferometer

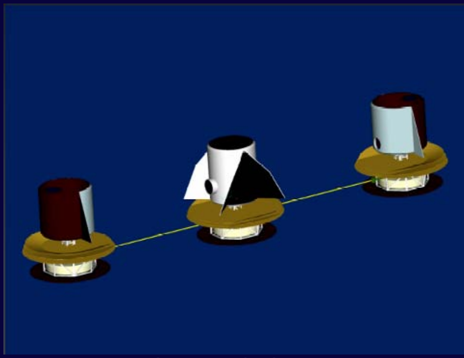
- Earth-like planet at 1.3 pc
  - With 6 m telescope at 2 THz (B=1 THz)
- Photon arrival rates are
  - 150 M photons/sec from the primary star
  - 150 k photons/sec from interstellar background
  - 500 photons/sec from the planet

Photons from planets are countable and bunched !

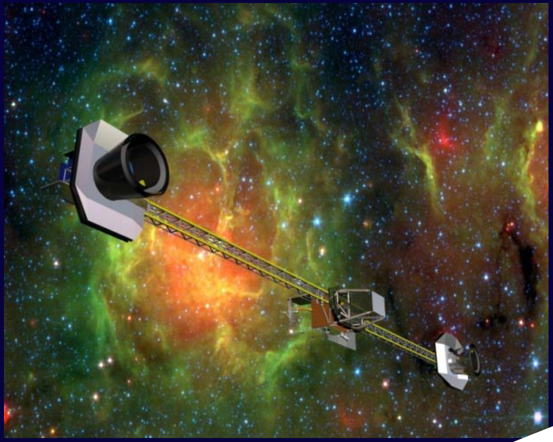
Technology Readiness ?

- Detector technologies
- Delay measurements
- Correlation efficiencies
- Formalism in quantum optics
- Aperture synthesis in lab.
- Ground-based demonstration
- PCTI in space

Space THz Interferometer
The Road Map



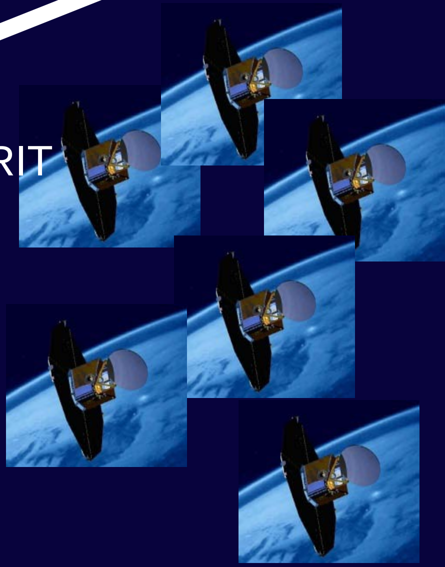
SPECS

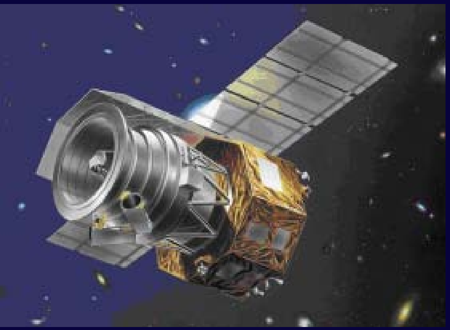


SPIRIT

SPICA

FIRI ESPRIT



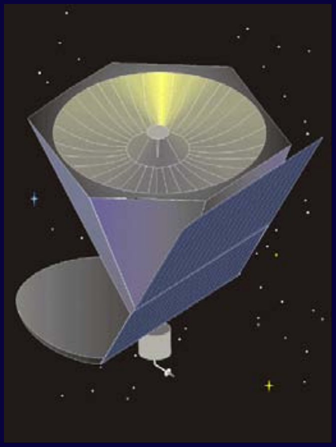


AKARI

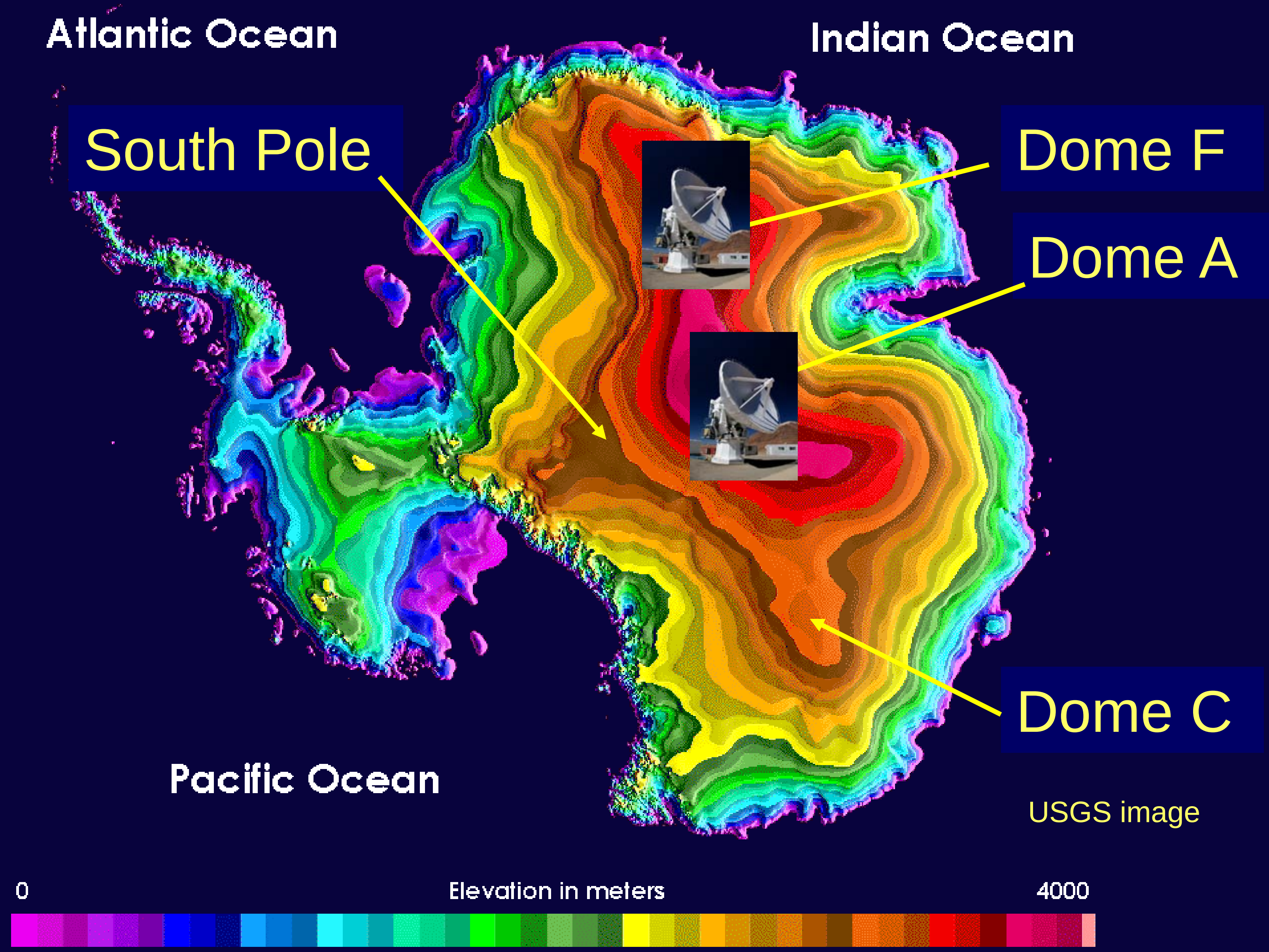
Millimetron

Herschel

Spitzer



南極大陸



Atlantic Ocean
Indian Ocean
South Pole
Dome F
Dome A
Dome C
Pacific Ocean
USGS image
0
Elevation in meters
4000

THz Gap of Spatial Resolution