Terahertz frequencies: perspectives and opportunities

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Outline

I **Introduction**

- Waves
- The electromagnetic spectrum
- Radio waves versus optical waves

II **The terahertz frequency range**

- Applications
- Challenges

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Waves…

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Waves…

Let's think a little bit…

1 - What is a "wave"?

2 – List some examples of waves

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Waves…

Time periodic oscillations that travel along space

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Waves…

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Waves…

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Let's take a snapshot of the background waves…

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Waves…

Time periodic oscillations that travel along space

Let's take a snapshot of the background waves…

And look at the water height versus position along the wave propagation direction.

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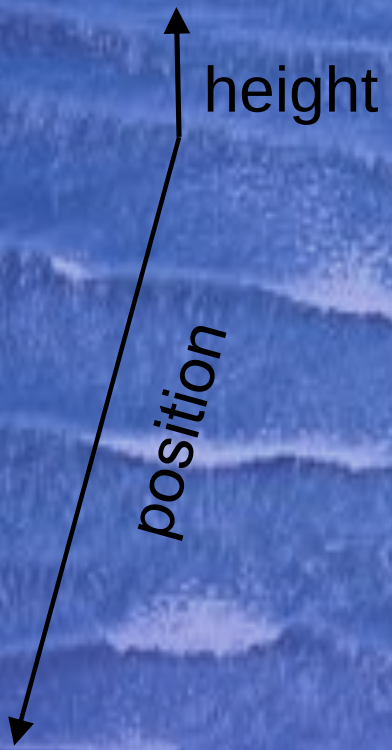
Waves…

Water height versus position along the wave propagation direction.



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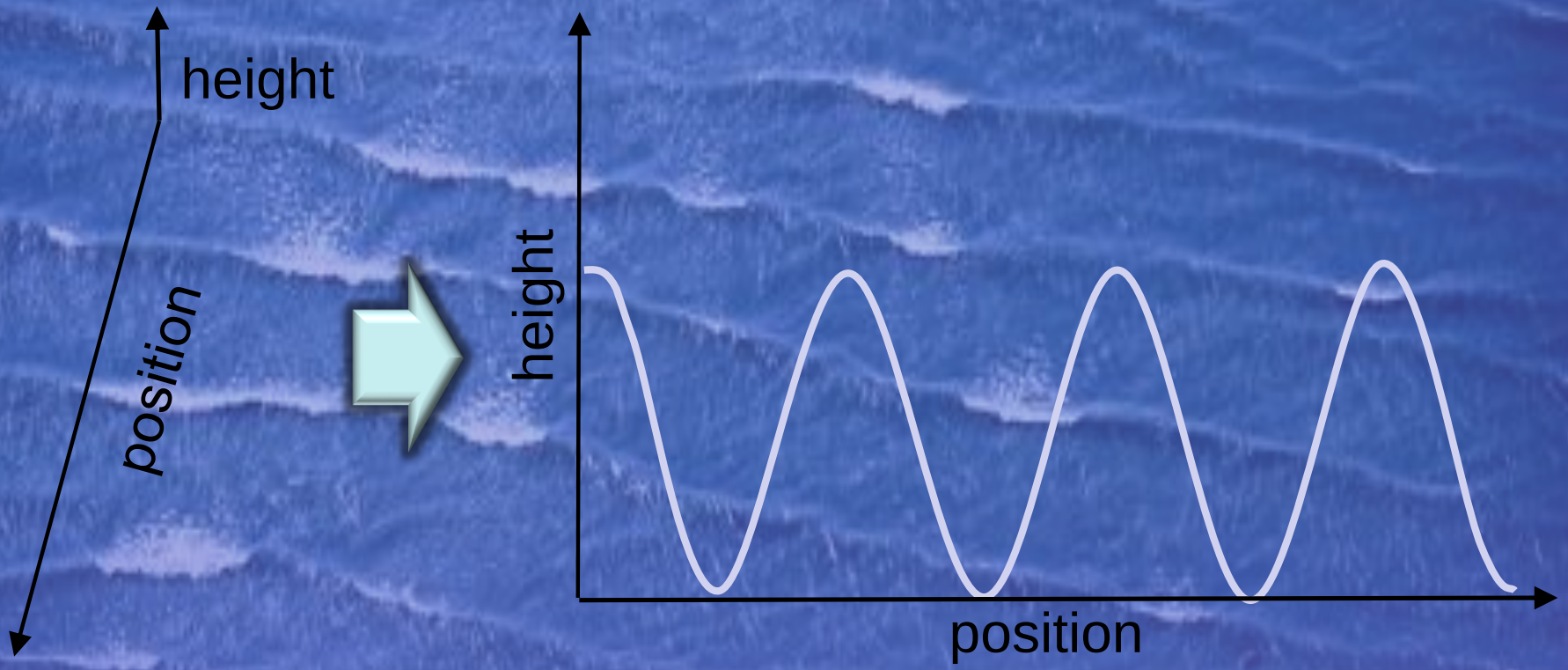

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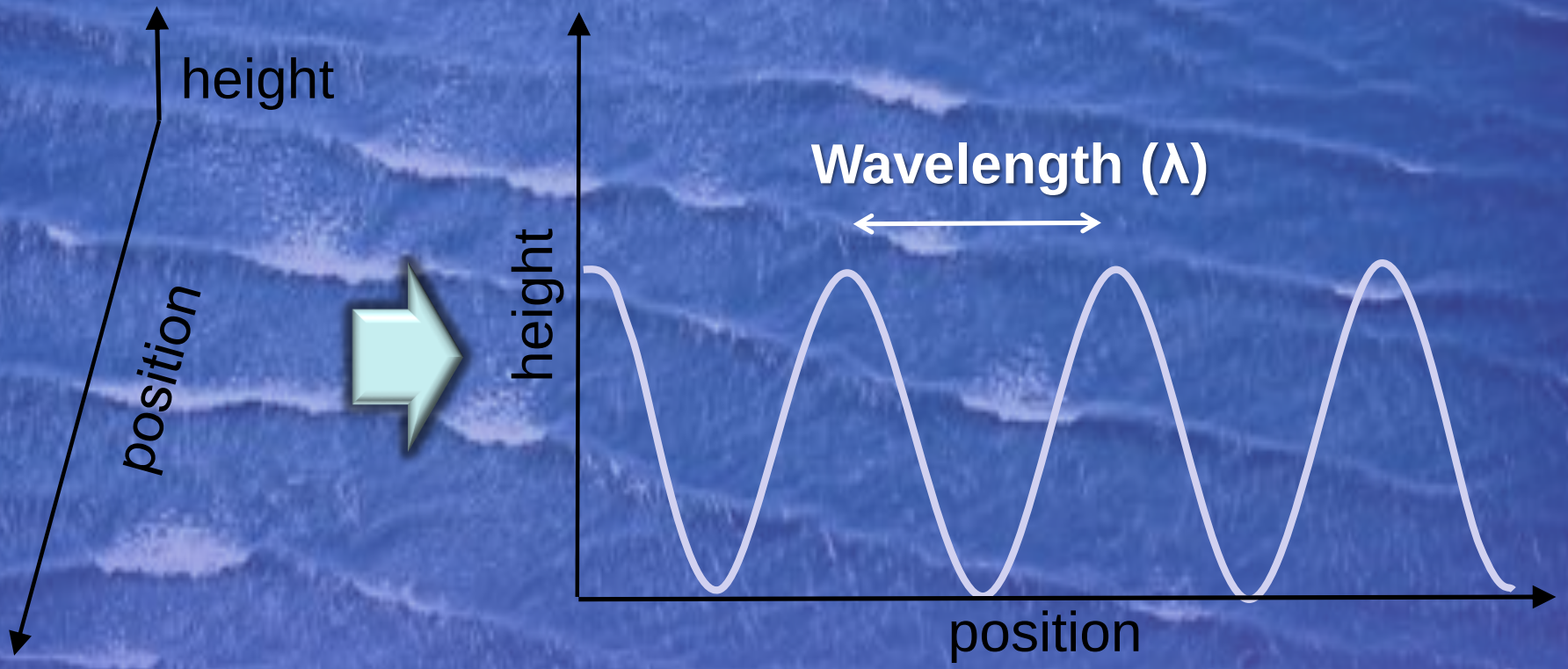

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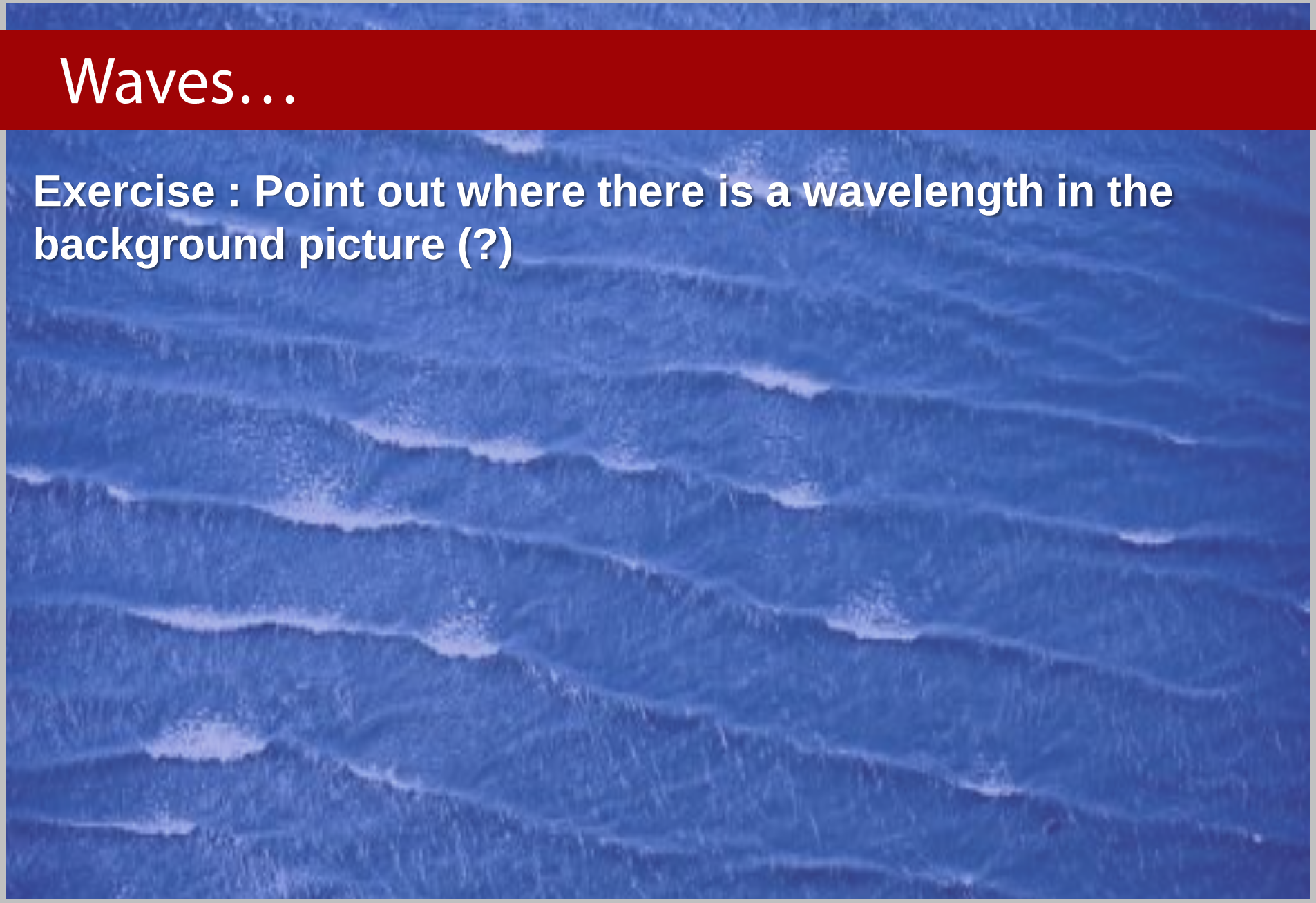

Exercise : Point out where there is a wavelength in the background picture (?)

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Exercise : Point out where there is a wavelength in the background picture (?)

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Time periodic oscillations that travel along space

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Time periodic oscillations that travel along space

observer

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Waves…

Time periodic oscillations that travel along space

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Look at the water height versus time at a fixed point in space along the wave propagation direction.

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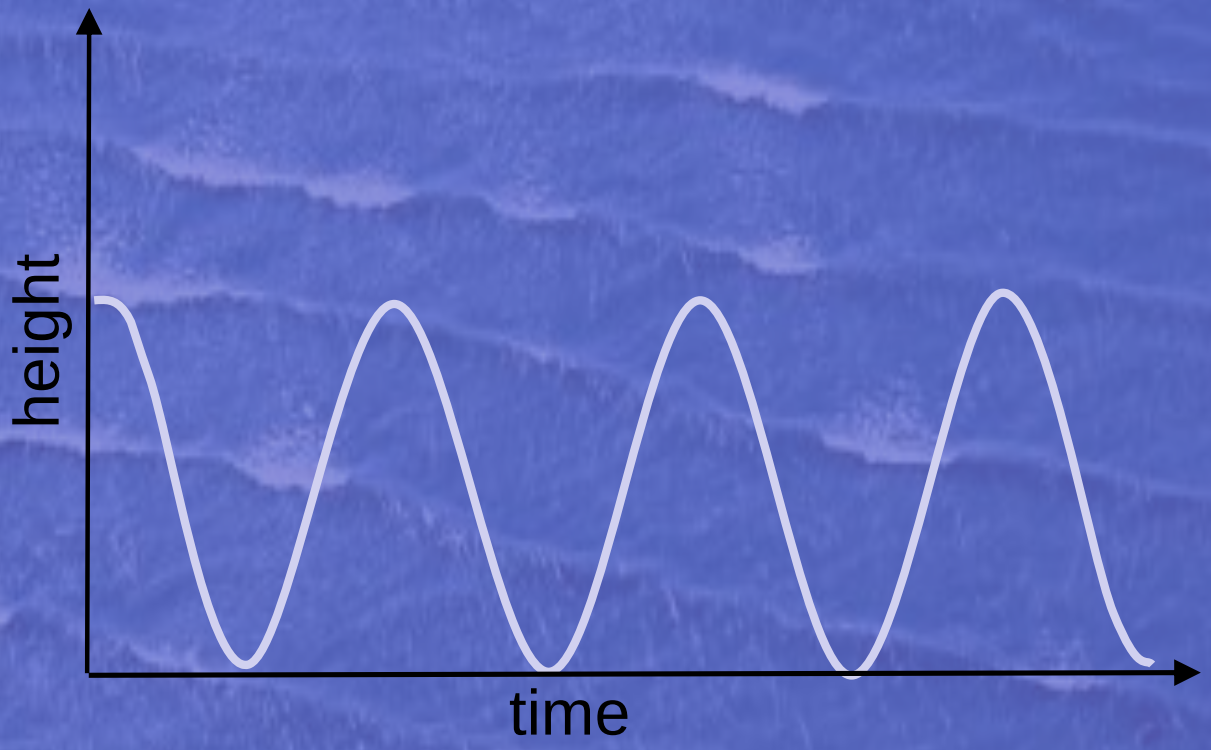

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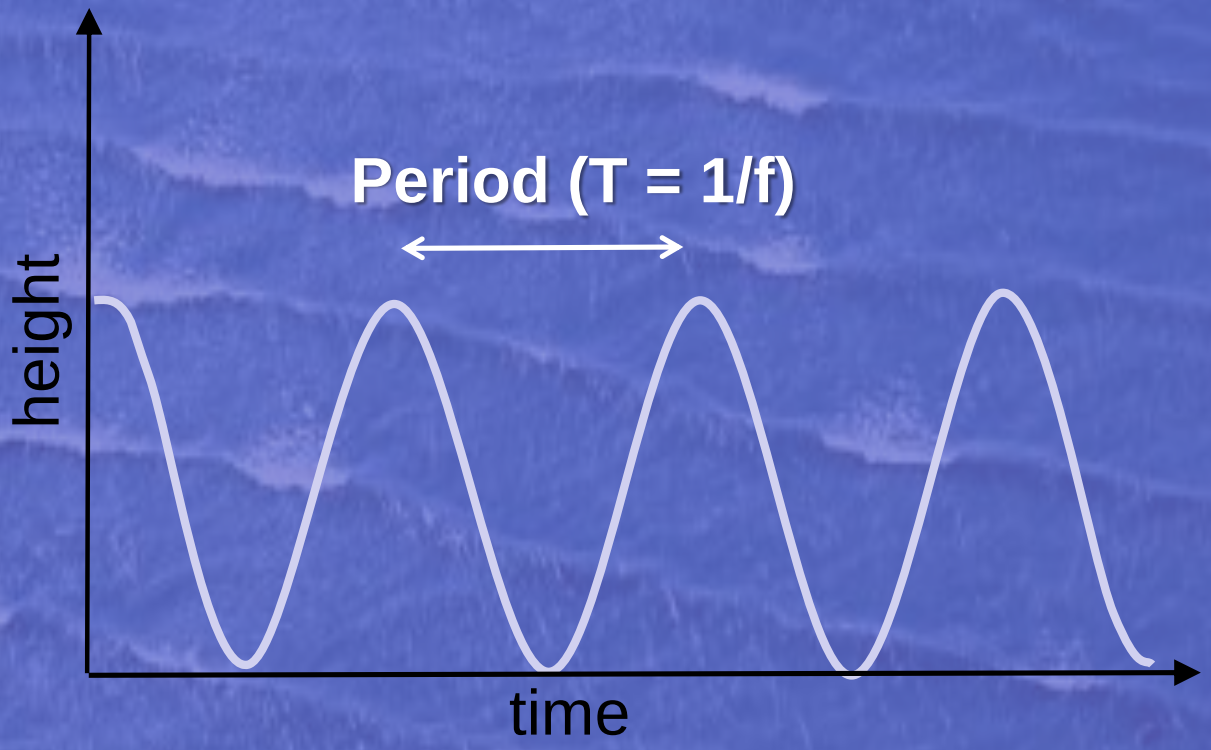

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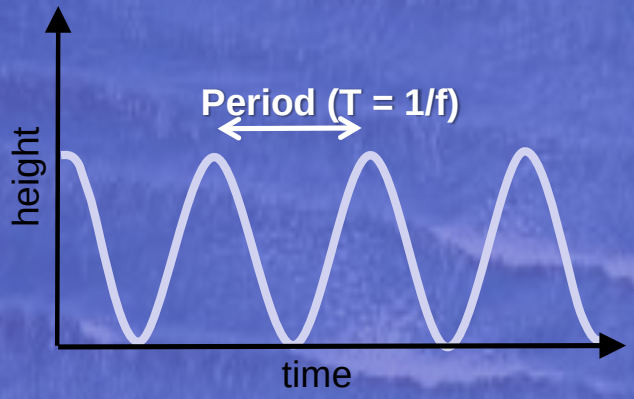

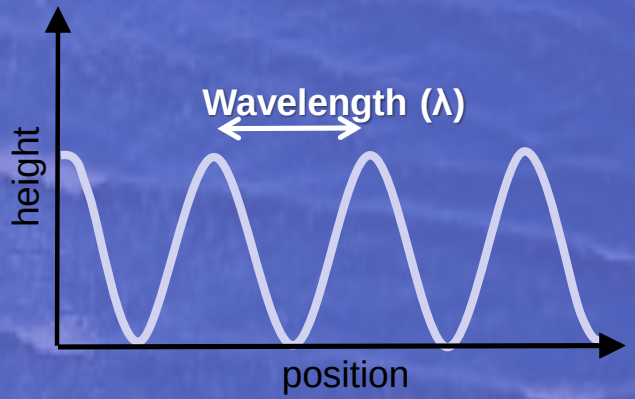

Once a maxima passes through the observation point, it takes (T) seconds for the next maximum to pass through.

The distance between these two maxima is (λ) meters, therefore a maximum travels (λ) meters in (T) seconds.

The wave velocity is : $v = \lambda / T = \lambda \cdot f$

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Waves…

Let's think a little bit…

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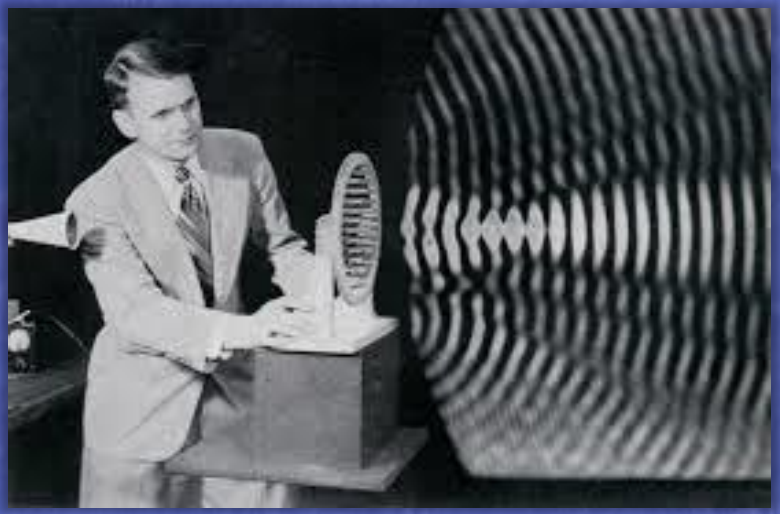
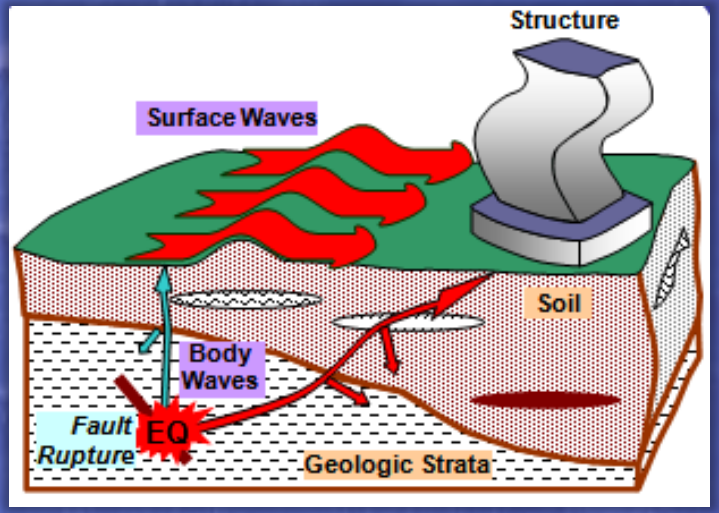
Waves…

Water waves, sound waves, earthquake waves….





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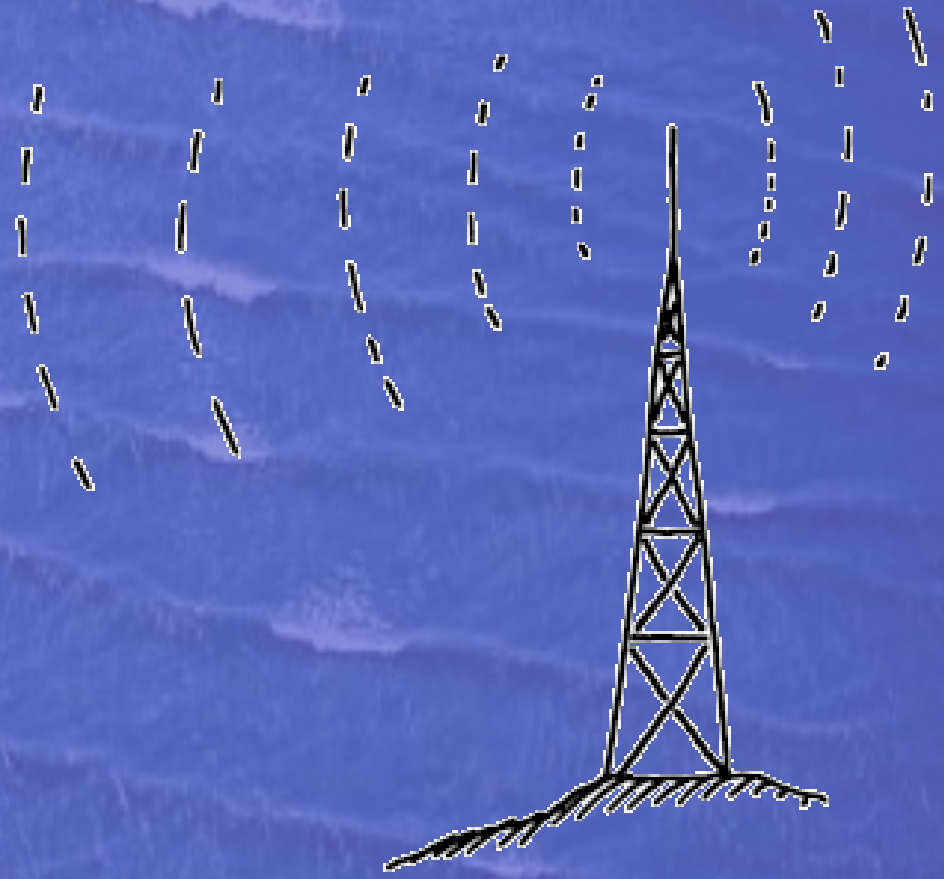
Waves…

Electromagnetic waves ….



…"Electric field oscillations"

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The electromagnetic spectrum

Let's think a little bit… electromagnetic waves of different wavelength are called differently depending on the region of the spectrum where they belong, example: radio-waves, X-rays, etc.

1) **List several types of electromagnetic waves you have heard of…**

2) **Order these by increasing frequency**

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The electromagnetic spectrum

- Radio-waves (kHz-MHz),
- Microwaves (GHz),
- Millimeter-waves (100's GHz),
- Terahertz (few THz),
- Infrared (10's of THz),
- Visible light (100's THz),
- Ultraviolet (few PHz),
- X-rays(few EHz),
- Gamma rays(100's EHz)

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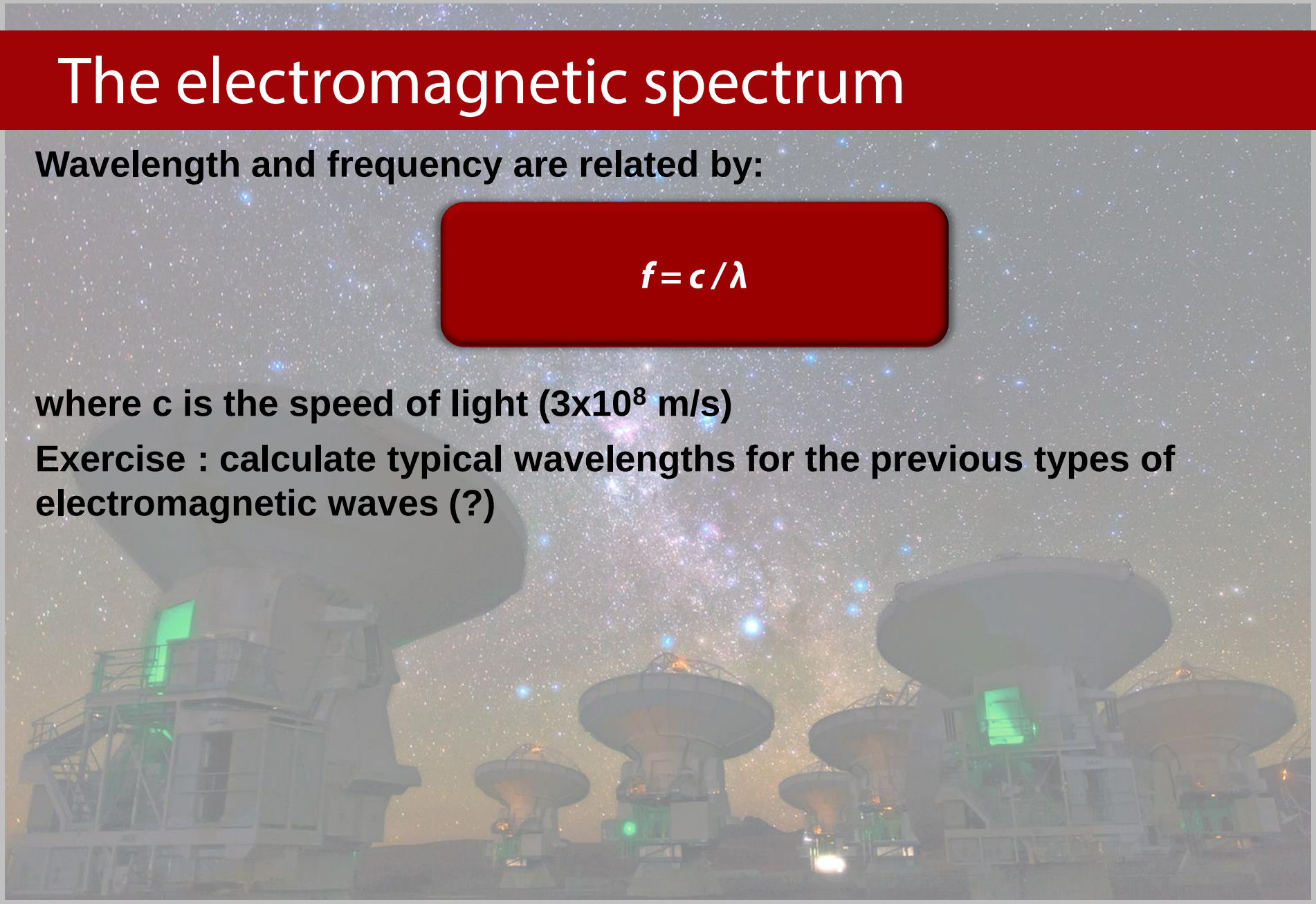
The electromagnetic spectrum

Wavelength and frequency are related by:

$$f = c / \lambda$$

where c is the speed of light (3×10^8 m/s)

Exercise : calculate typical wavelengths for the previous types of electromagnetic waves (?)



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Exercise : calculate typical wavelengths for the previous types of electromagnetic waves (?)

- **Radio-frequency : 300 MHz**
- **Microwaves : 3 GHz**
- **Millimeter-waves : 300 GHz**
- **Terahertz : 3 THz**
- **Infrared : 30 THz**
- **Visible : 600 THz**
- **Ultraviolet : 3 PHz**
- **X-rays : 3 EHz**

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Exercise : calculate typical wavelengths for the previous types of electromagnetic waves (?)

• Radio-frequency	:	300	MHz	→	1	m
• Microwaves	:	3	GHz	→	10	cm
• Millimeter-waves	:	300	GHz	→	1	mm
• Terahertz	:	3	THz	→	100	μm
• Infrared	:	30	THz	→	10	μm
• Visible	:	600	THz	→	500	nm
• Ultraviolet	:	3	PHz	→	100	nm
• X-rays	:	3	EHz	→	0.1	nm

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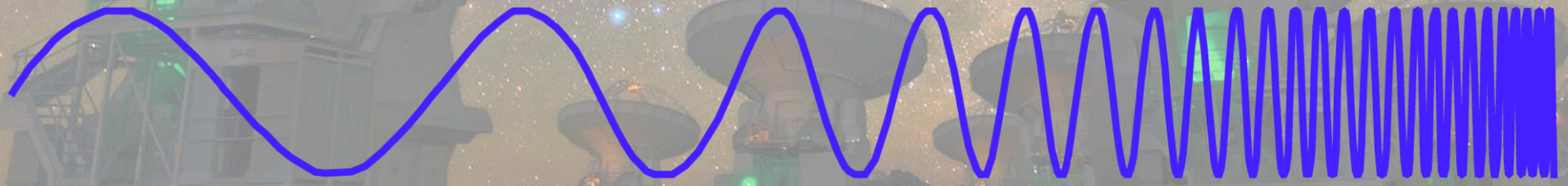
The electromagnetic spectrum



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The electromagnetic spectrum

Question : with electromagnetic waves of which wavelength do the following devices interact?

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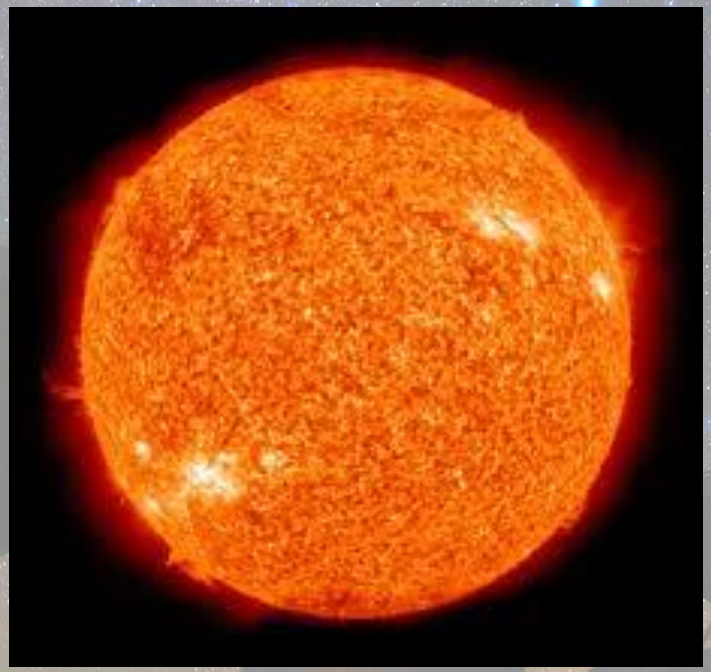
Radio waves vs. optical waves

Since the beginnings of mankind, people has wondered about light…



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Radio waves vs. optical waves

There are obvious sources of light in nature…

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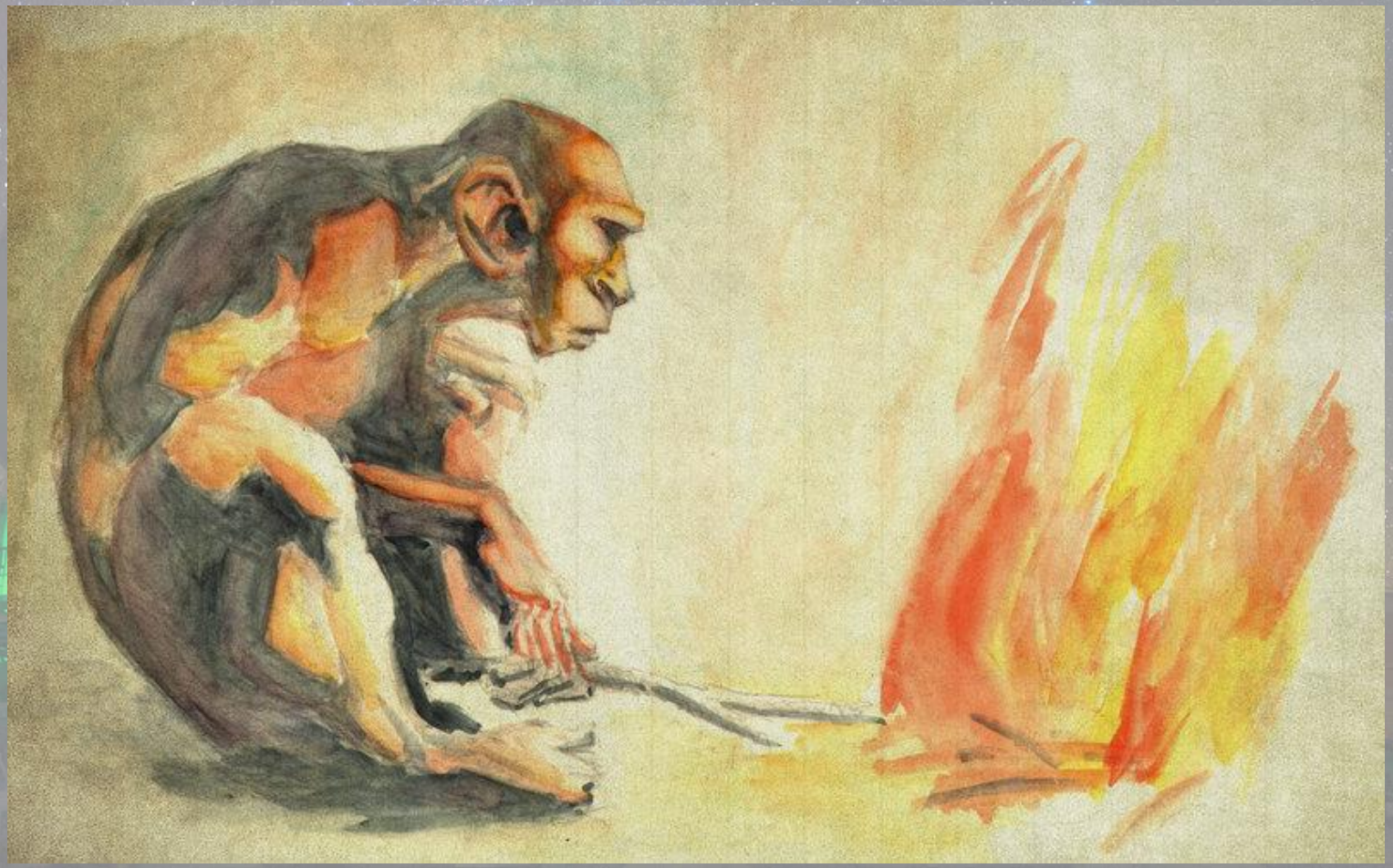
Radio waves vs. optical waves

Which man eventually managed to harness…



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Radio waves vs. optical waves

Over history humanity deepened its understanding about light and how light interacts with matter…

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Radio waves vs. optical waves

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Radio waves vs. optical waves

Materials properties (i.e. refractive index) depend on wavelength

prism➔ different refraction for different wavelengths

therefore :

white light can be separated into colors

this was Newton's discovery of the spectrum of light

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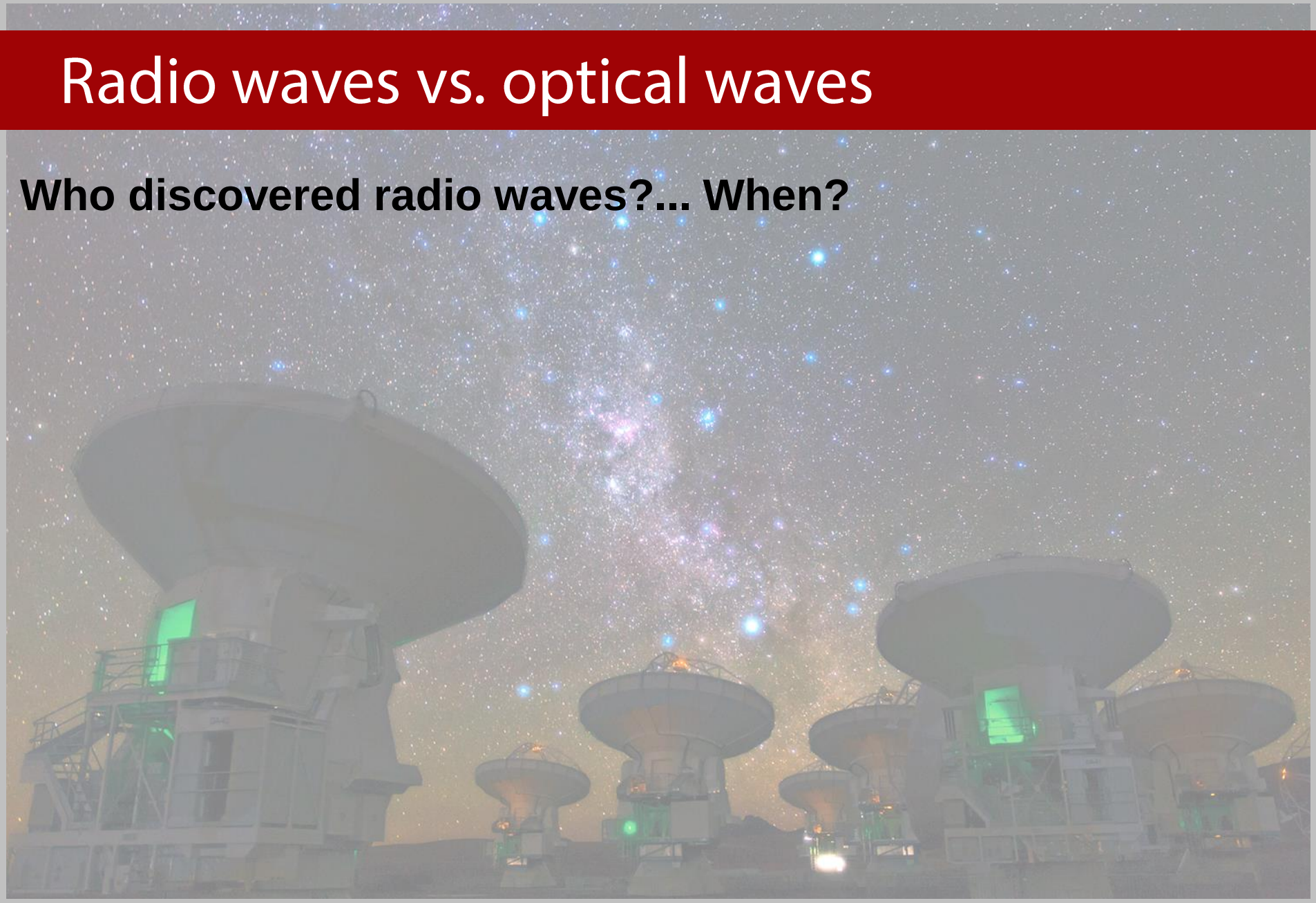
Radio waves vs. optical waves

Who discovered radio waves?... When?



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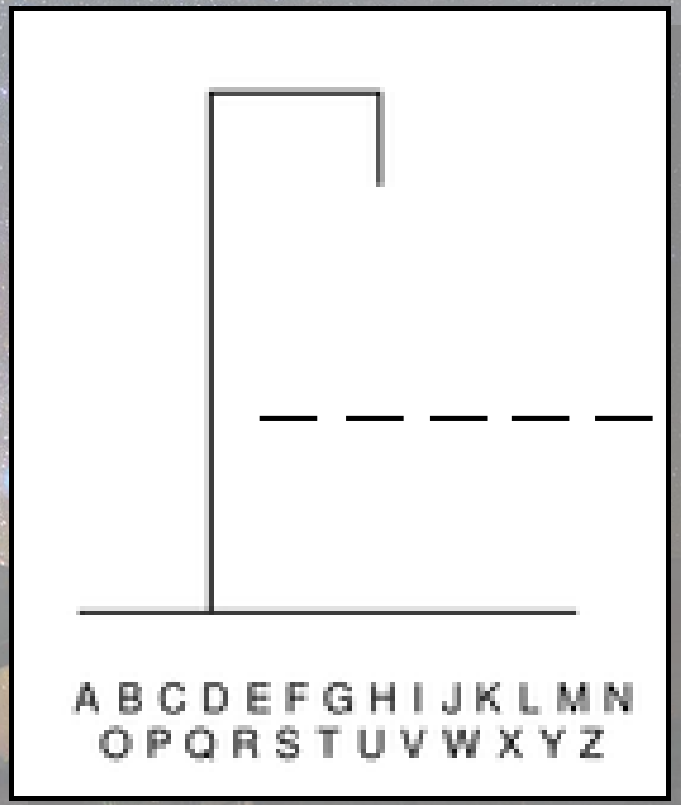

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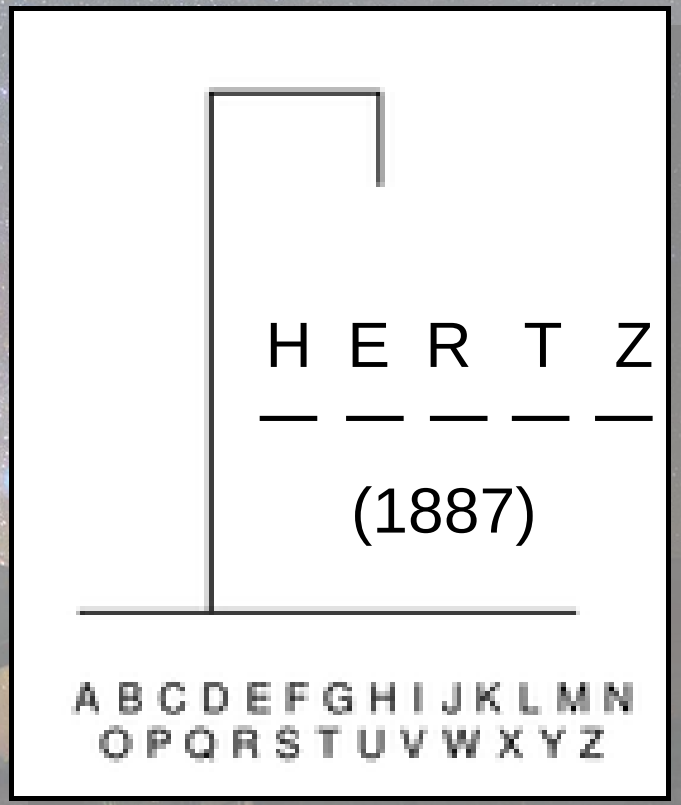

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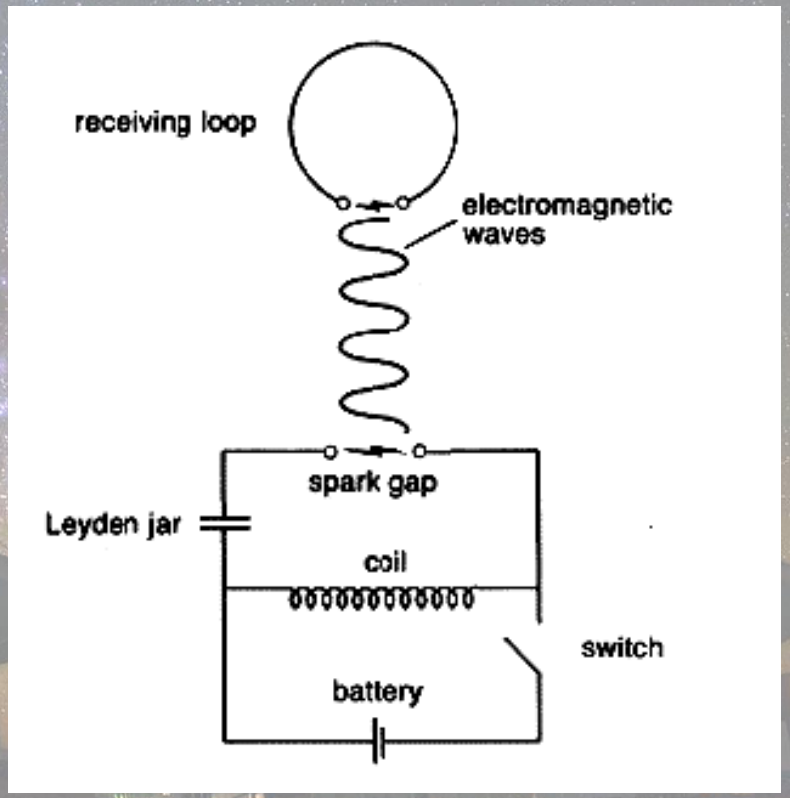

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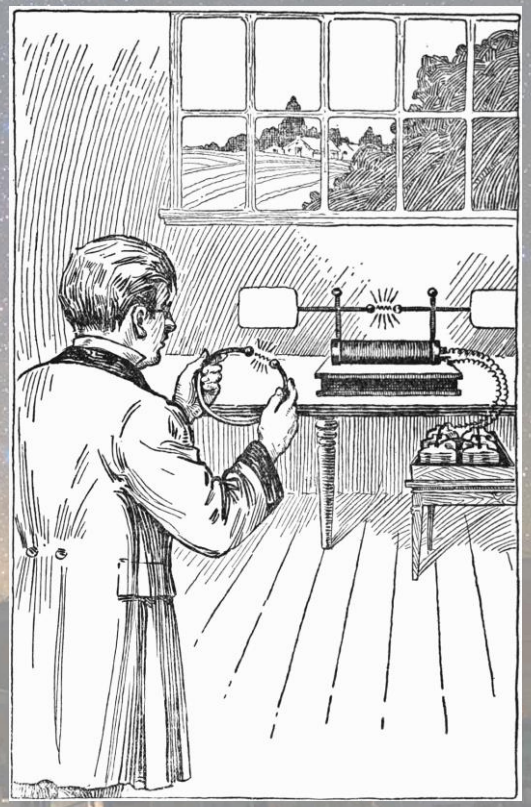

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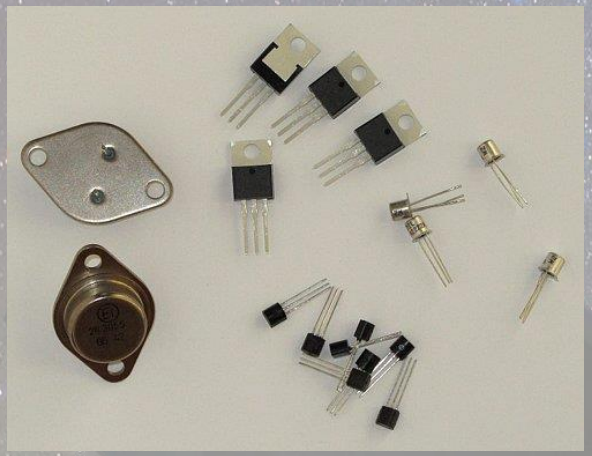
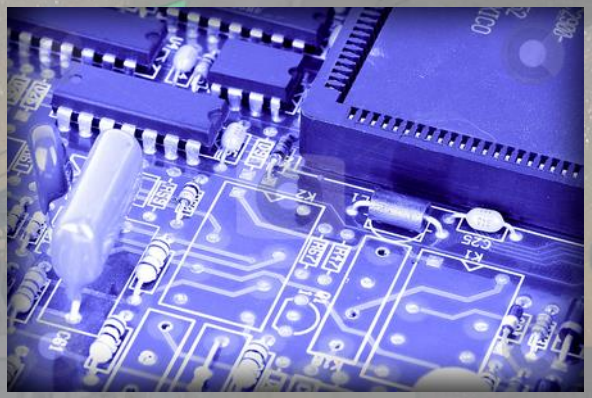
Radio waves vs. optical waves

Today… RF electronics and optical devices





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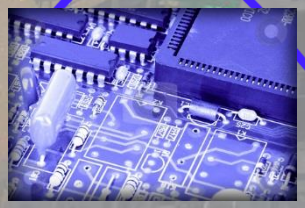

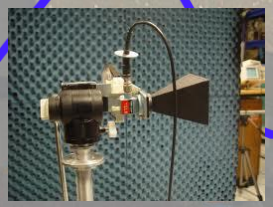

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The THz frequency range

HEAT RAYS OF GREAT WAVE LENGTH.

By Heinrich Rubens and E. F. Nichols.

SINCE we have become accustomed to think of waves of electrical energy and light waves as forming component parts of a common spectrum, the attempt has often been made to extend our knowledge over the wide region which has separated the two phenomena, ...

Phys. Rev. 4, 314-323 (1897)

-10 years after Heinrich Hertz's discovery of radio waves-

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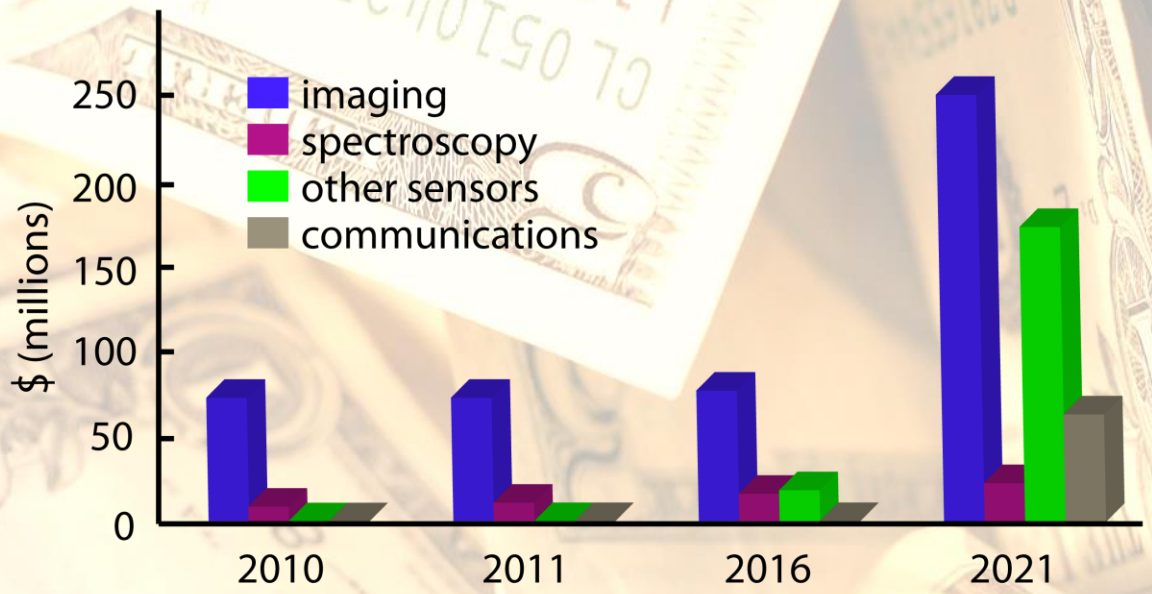
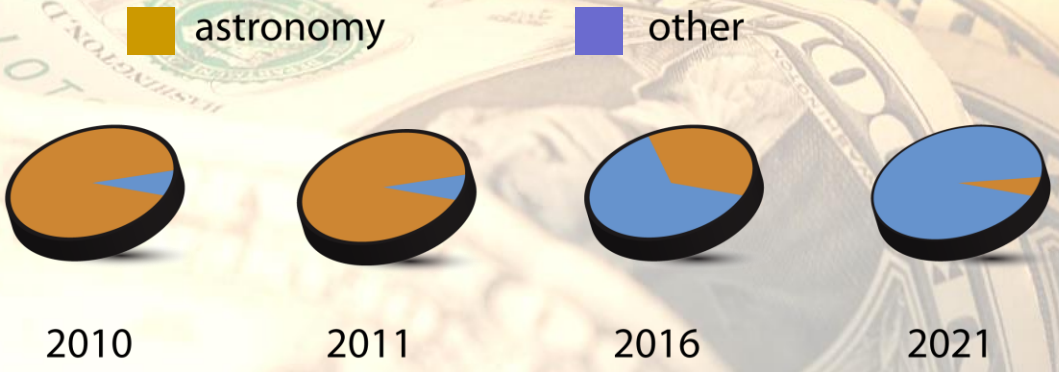
The THz frequency range



A growing market…



In transition…

Source: BCC research

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Applications of THz waves

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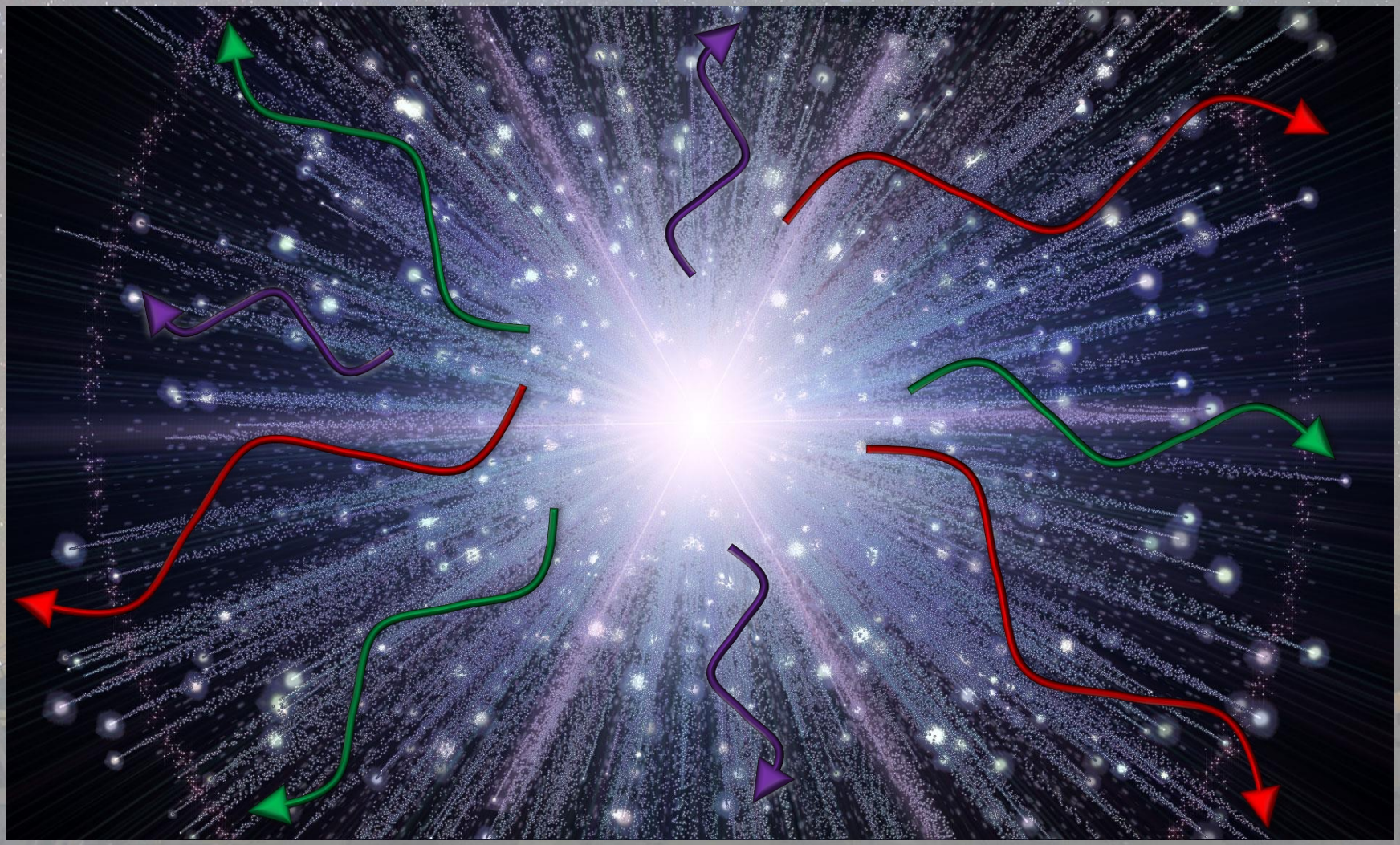

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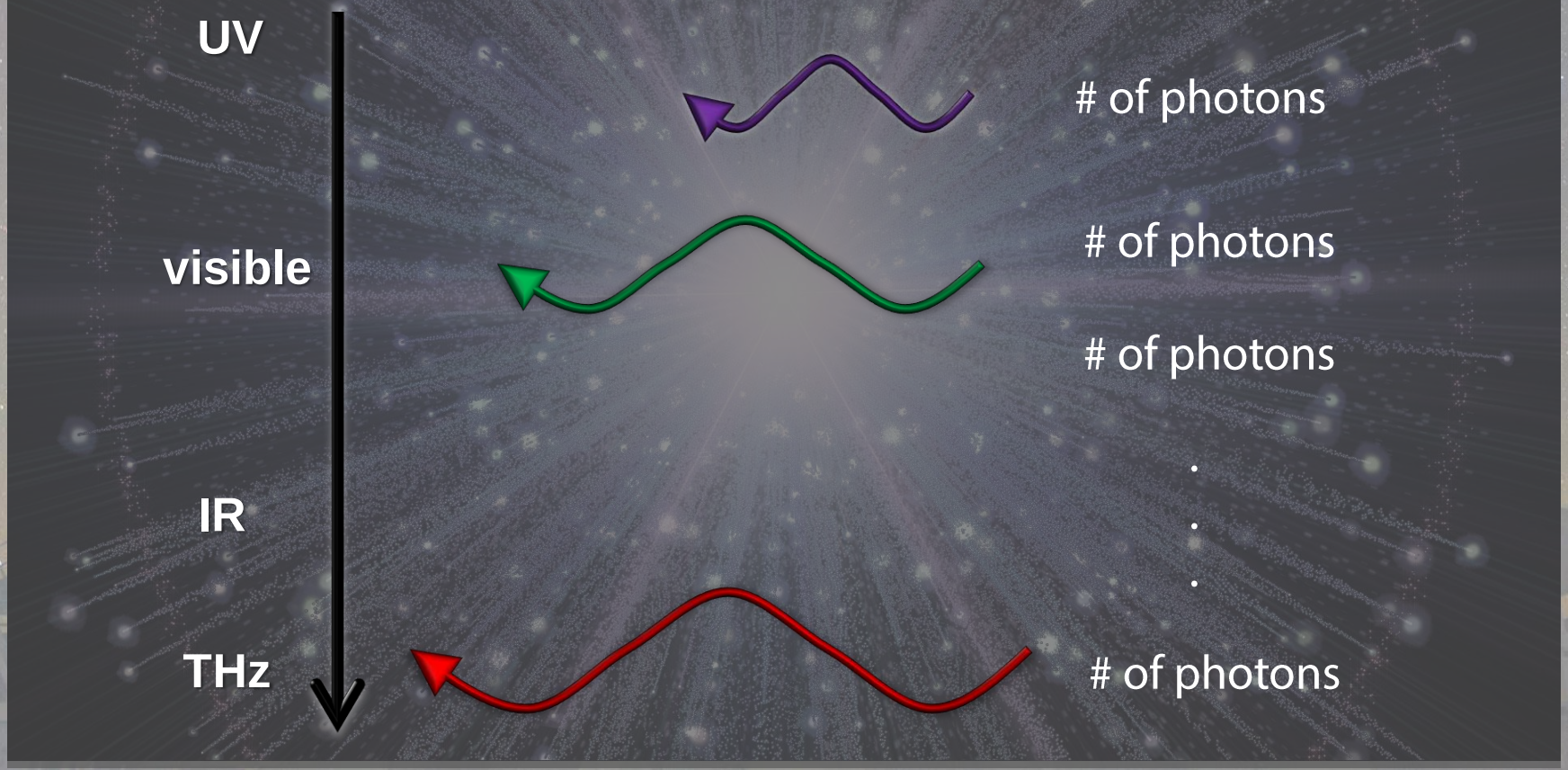
Applications of THz waves

Let's sort (per region of the electromagnetic spectrum) all the photons emitted since the beginning of the universe…



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Applications of THz waves

Results from the NASA Cosmic Background Explorer indicate that :

98 % **of the photons emitted since the big bang fall into the THz and far-IR ranges.**

Siegel, P. "Terahertz technology," *IEEE Trans. MTT*, vol. 50, no.3, pp.910-928, 2002

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Applications of THz waves

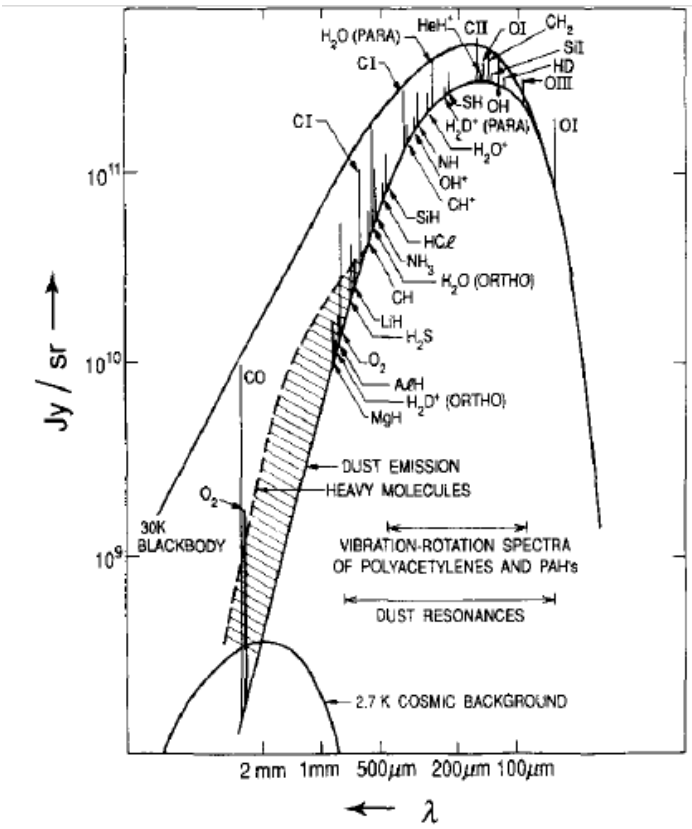

Fig. 1. A schematic presentation of some of the spectral content in the submillimeter band for an interstellar cloud. The spectrum includes dust continuum, molecular rotation line and atomic fine-structure line emissions.

Astronomy:
The most traditional application of THz technology

Radiated power versus wavelength for interstellar dust and its key molecular vibration lines.

Phillips, T.G.; Keene, J.; , "Submillimeter astronomy," *Proceedings of the IEEE*, vol. 80, no.11, pp.1662-1678, 1992

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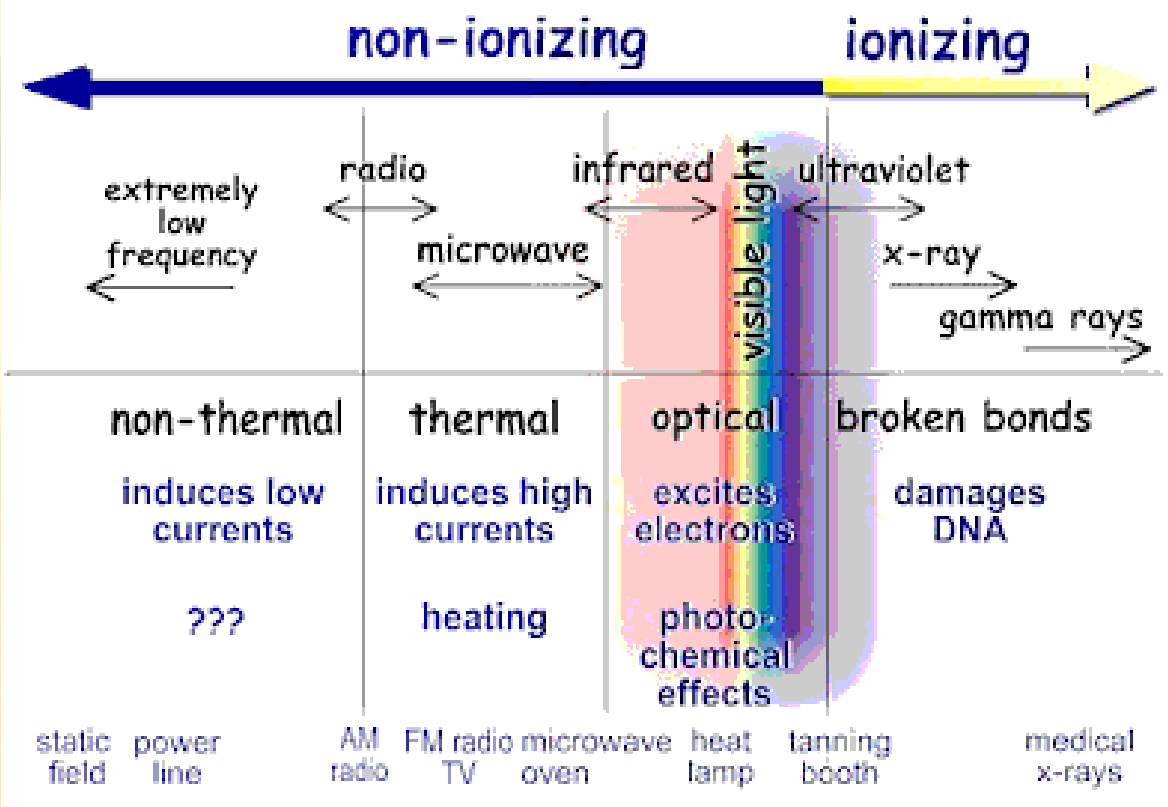
Applications



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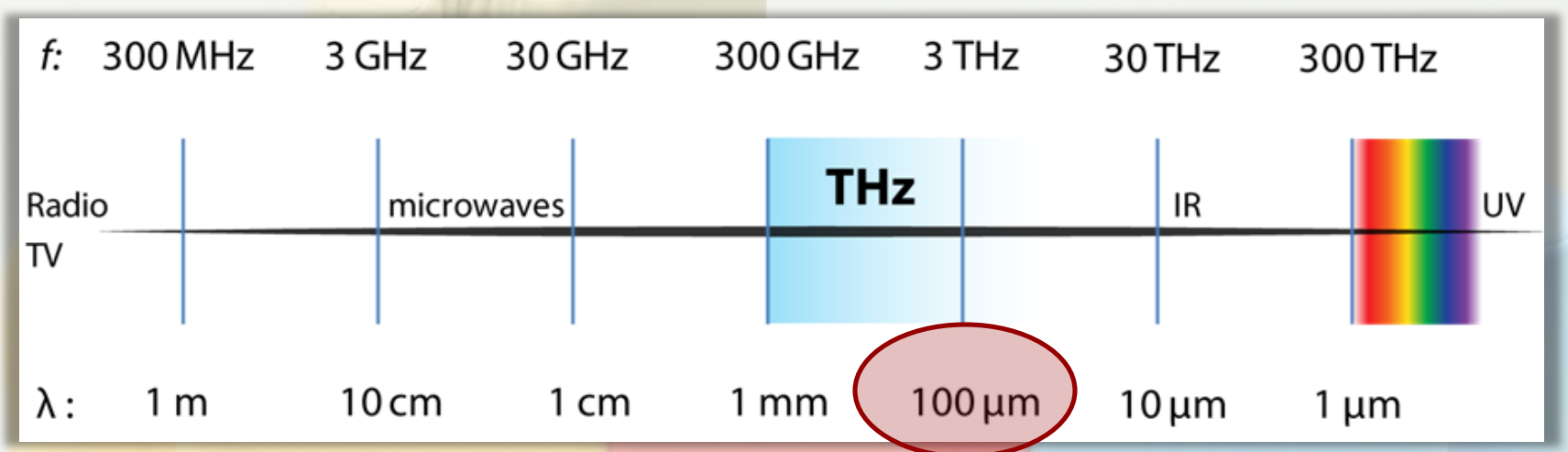
Applications



Imaging applications!!!

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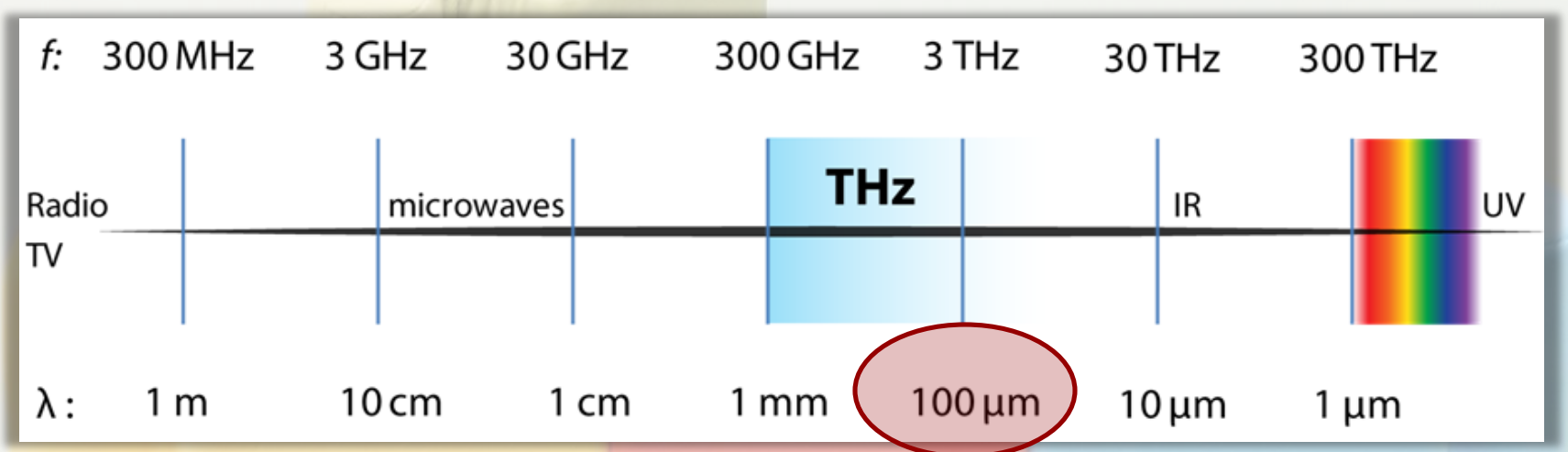

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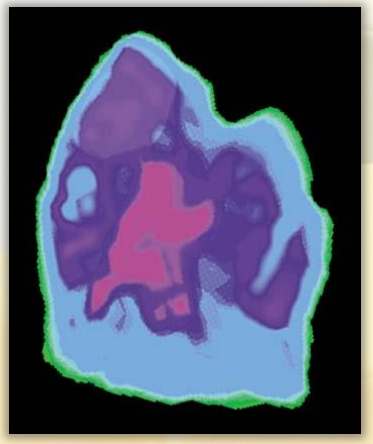
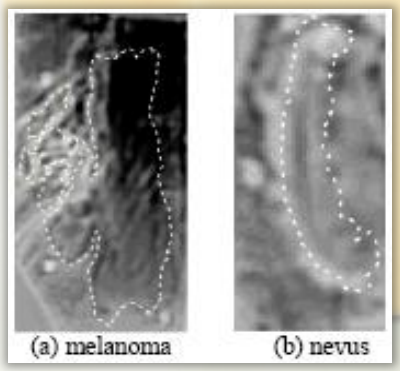
Applications

Medical imaging





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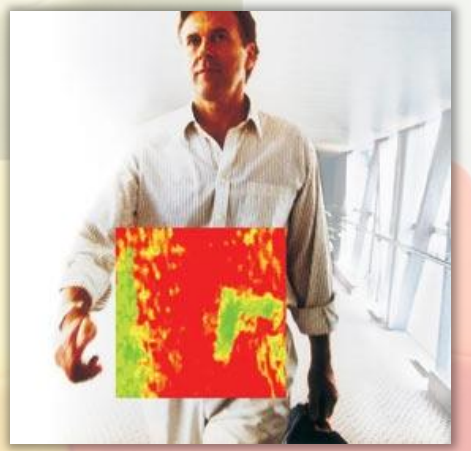
Applications

Security



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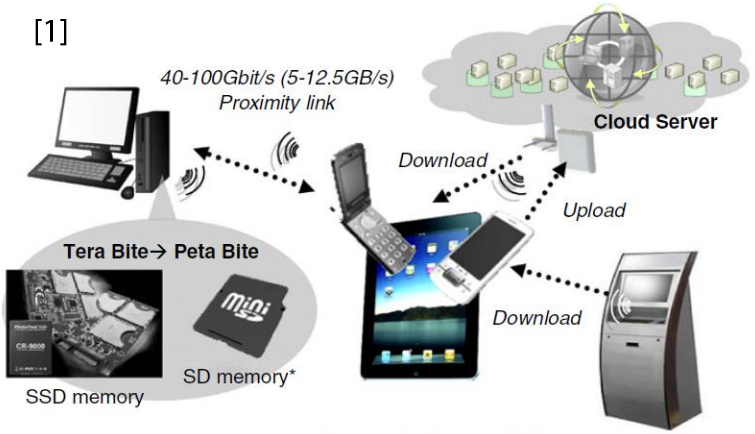
Applications

[1] J. Infrared Milli. Terahz. Waves 32, 143 (2011)
[2] JOSA A 29(2), 179 (2012)

- **Versus microwaves**
  - **Larger bandwidth**
  - **Atmospheric attenuation**
- **Versus IR**
  - **Less directional**
  - **Less susceptible to fog attenuation and scintillation** [2]

[1]



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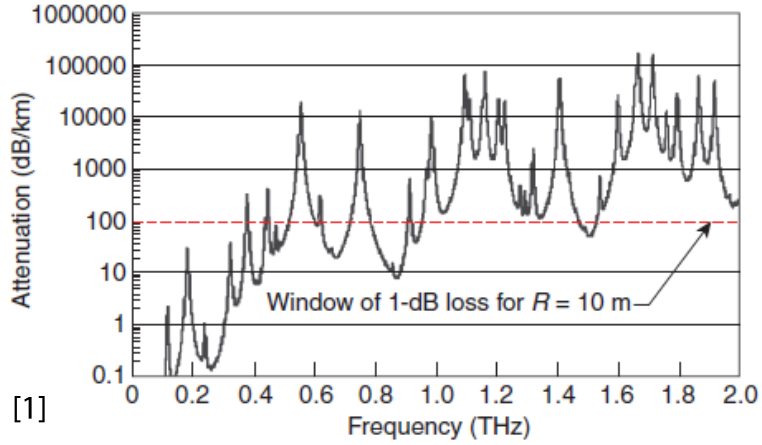

Figure 3. Atmospheric attenuation in the THz frequency range.

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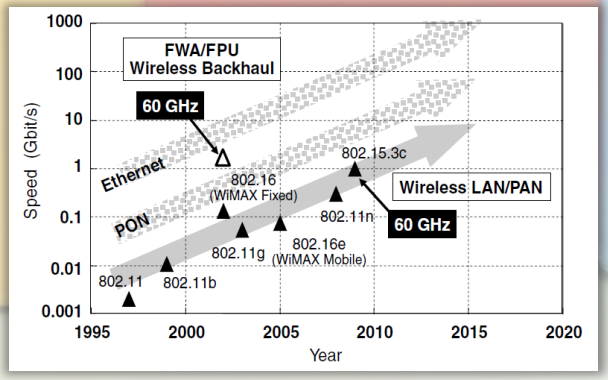
Applications

Communications



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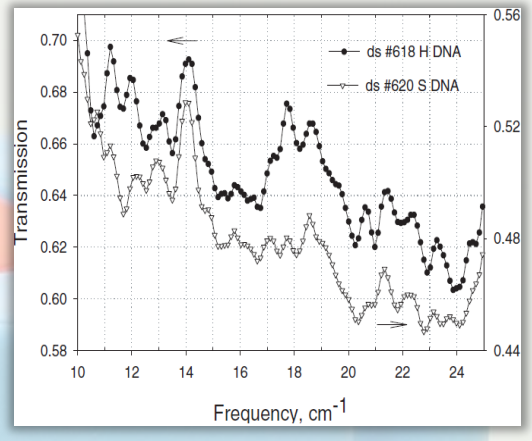
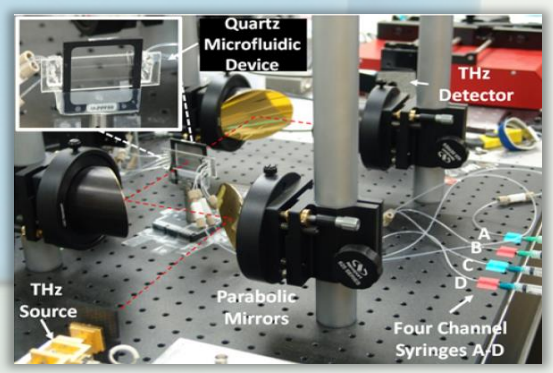
Applications

Spectroscopy





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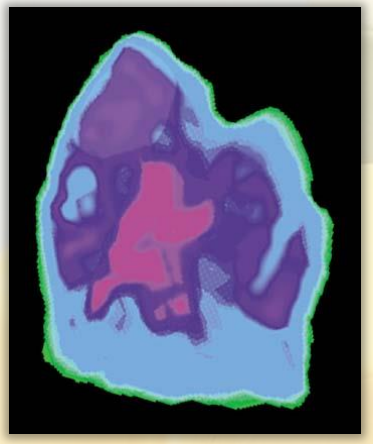
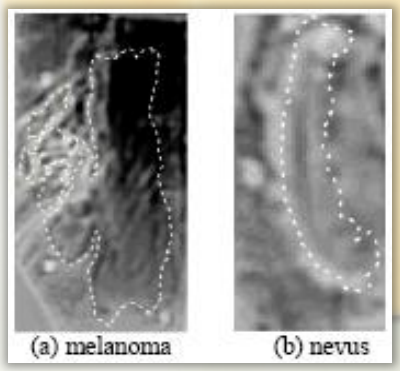
Applications

Medical imaging





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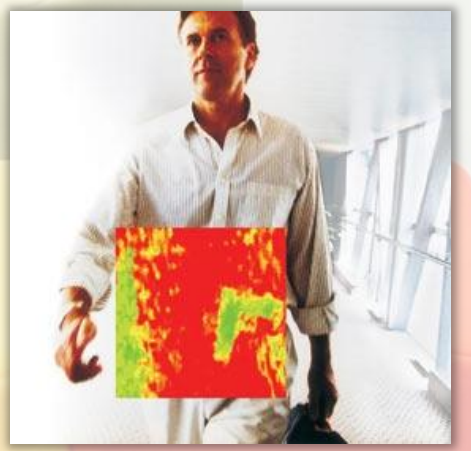
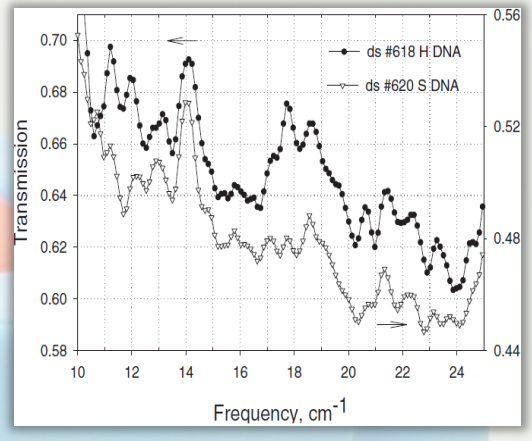
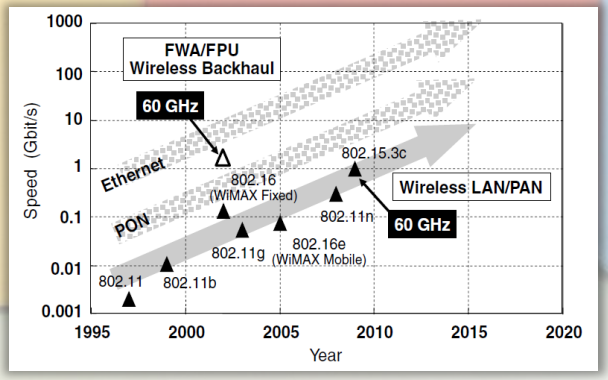
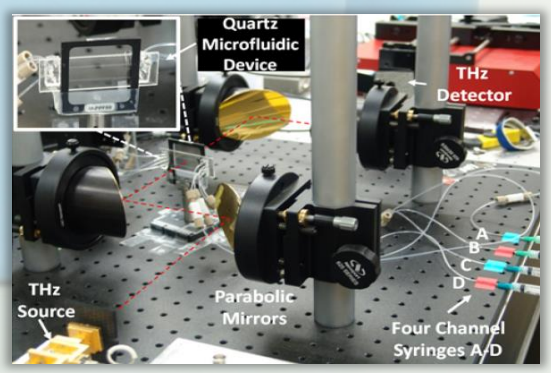


Spectroscopy



Communications





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Outline

I **Introduction**

- Waves
- The electromagnetic spectrum
- Radio waves versus optical waves

II **The terahertz frequency range**

- Applications
- Challenges

The THz gap

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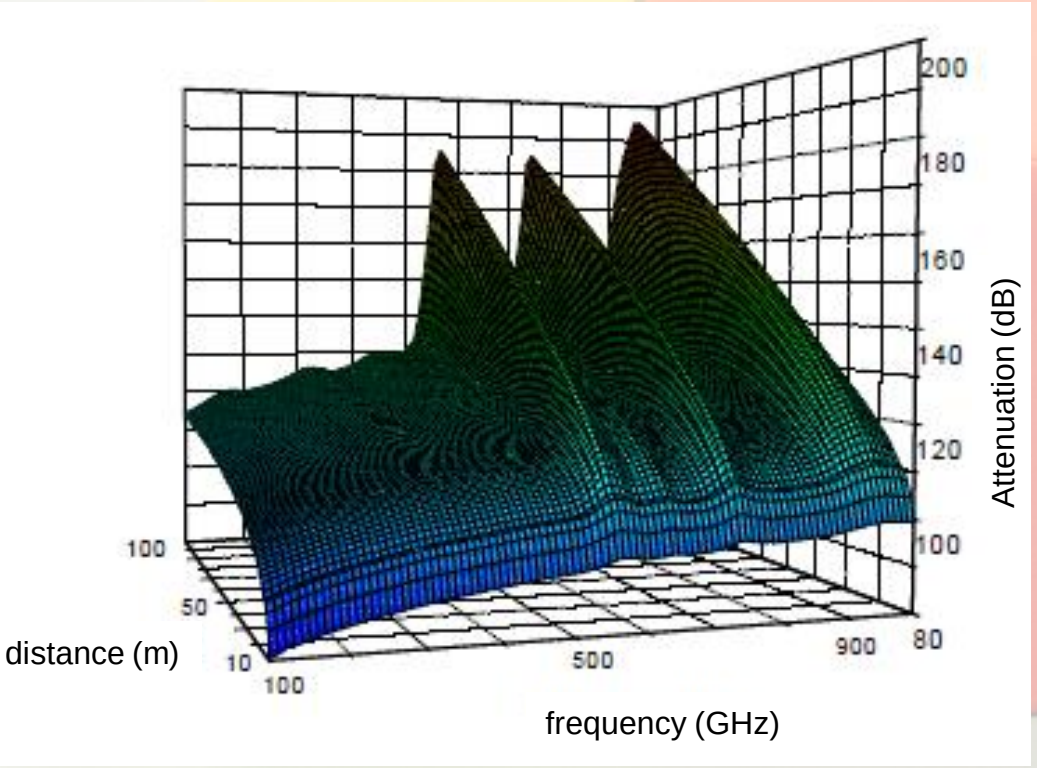
The THz gap



~100dB power attenuation @ 10 m from source! Need for powerful enough sources to counteract these losses!

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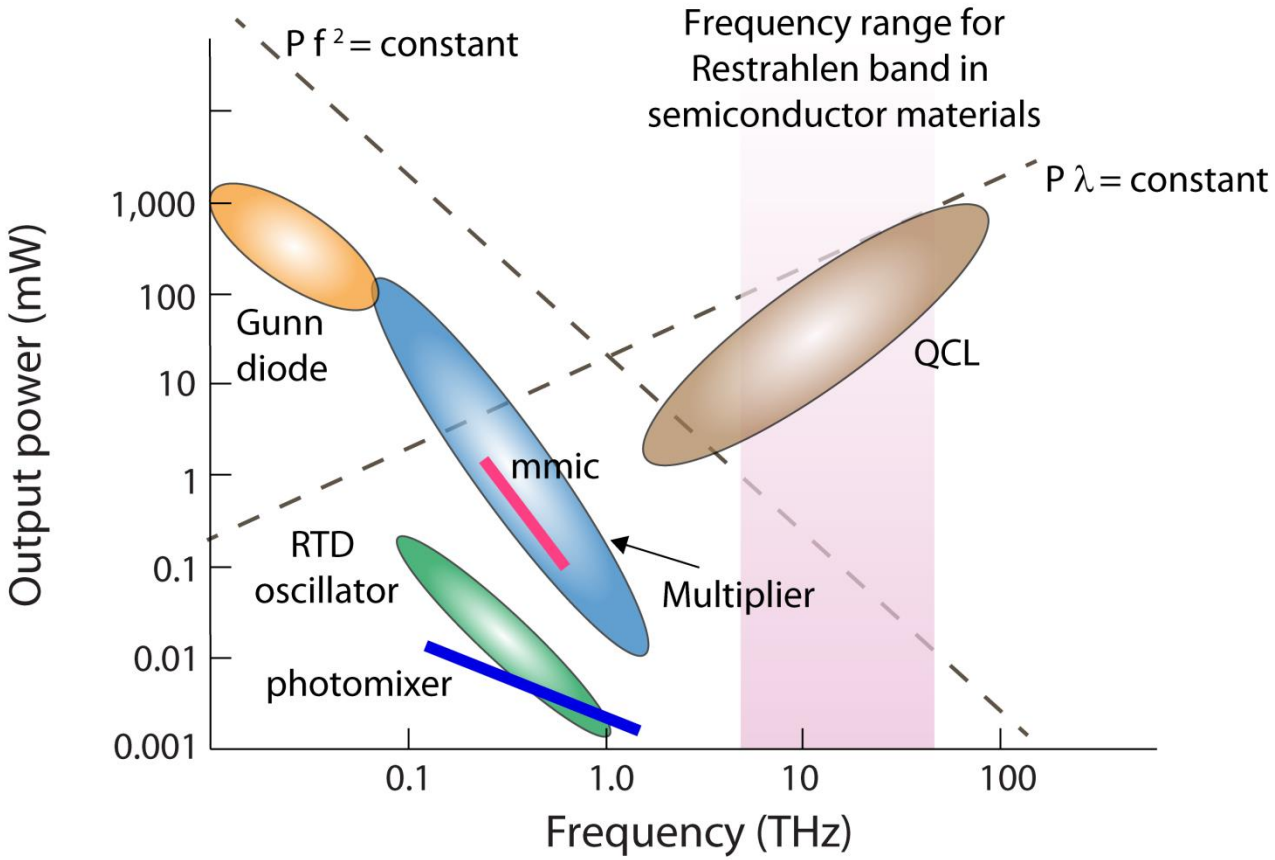
The THz gap

Device efficiency drops at THz frequencies…



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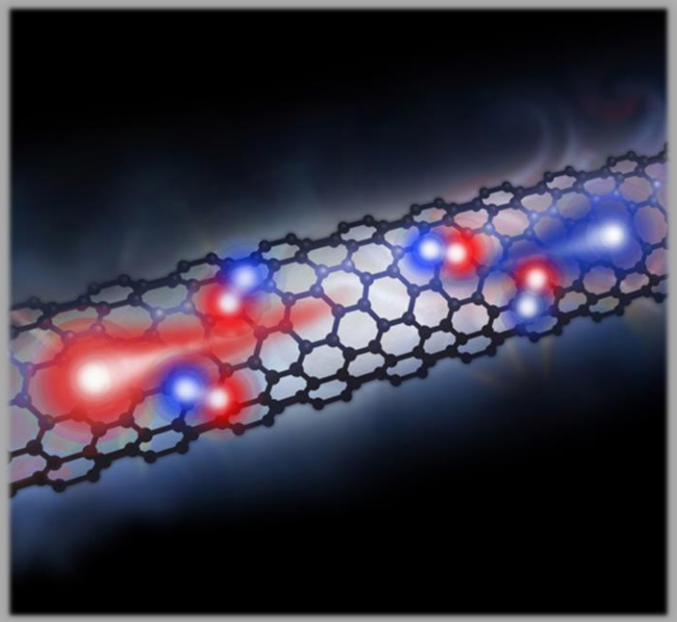
Limitations of HF electronics

Device/system speed is limited by the velocity in which **carriers** can be transferred



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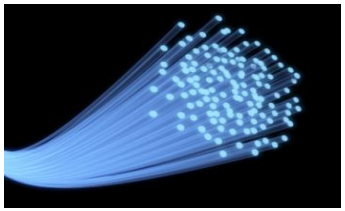
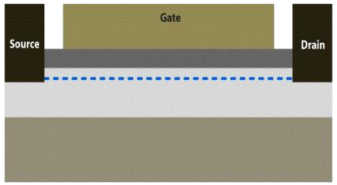


Optical fiber ; speed of light : $s = 3x10^{10}$ cm/s



FET ; electron drift velocity : $s = 2x10^{7}$ cm/s

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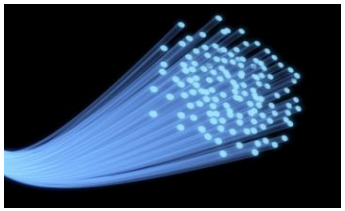

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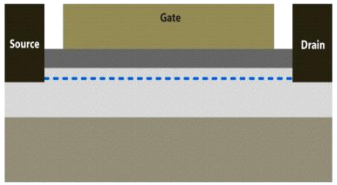

FET ; electron drift velocity : $s = 2x10^{7}$ cm/s

Question : in a 20nm device, which are the maximum achievable frequencies?

Suggestion calculate the time that takes for an electron to move along the transistor channel, estimate frequency from the inverse of this time.

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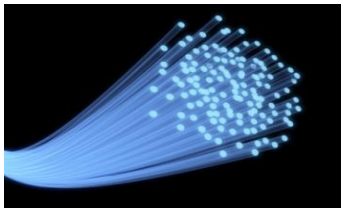
Limitations of HF electronics

Device/system speed is limited by the velocity in which **carriers** can be transferred



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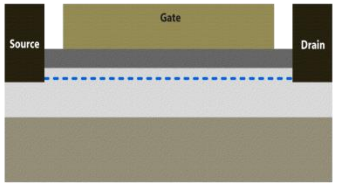

FET ; electron drift velocity : $s = 2x10^{7}$ cm/s

Challenge #1 :
How to engineer semiconductor electronic devices operating at speeds larger than what is limited by the electron drift velocity ???

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The THz gap

Let's think a little bit…

… what are the typical dimensions of antennas at different frequencies?

Suggestion : what's the size of a radio antenna, what about a cell-phone antenna… and what about a photodiode?

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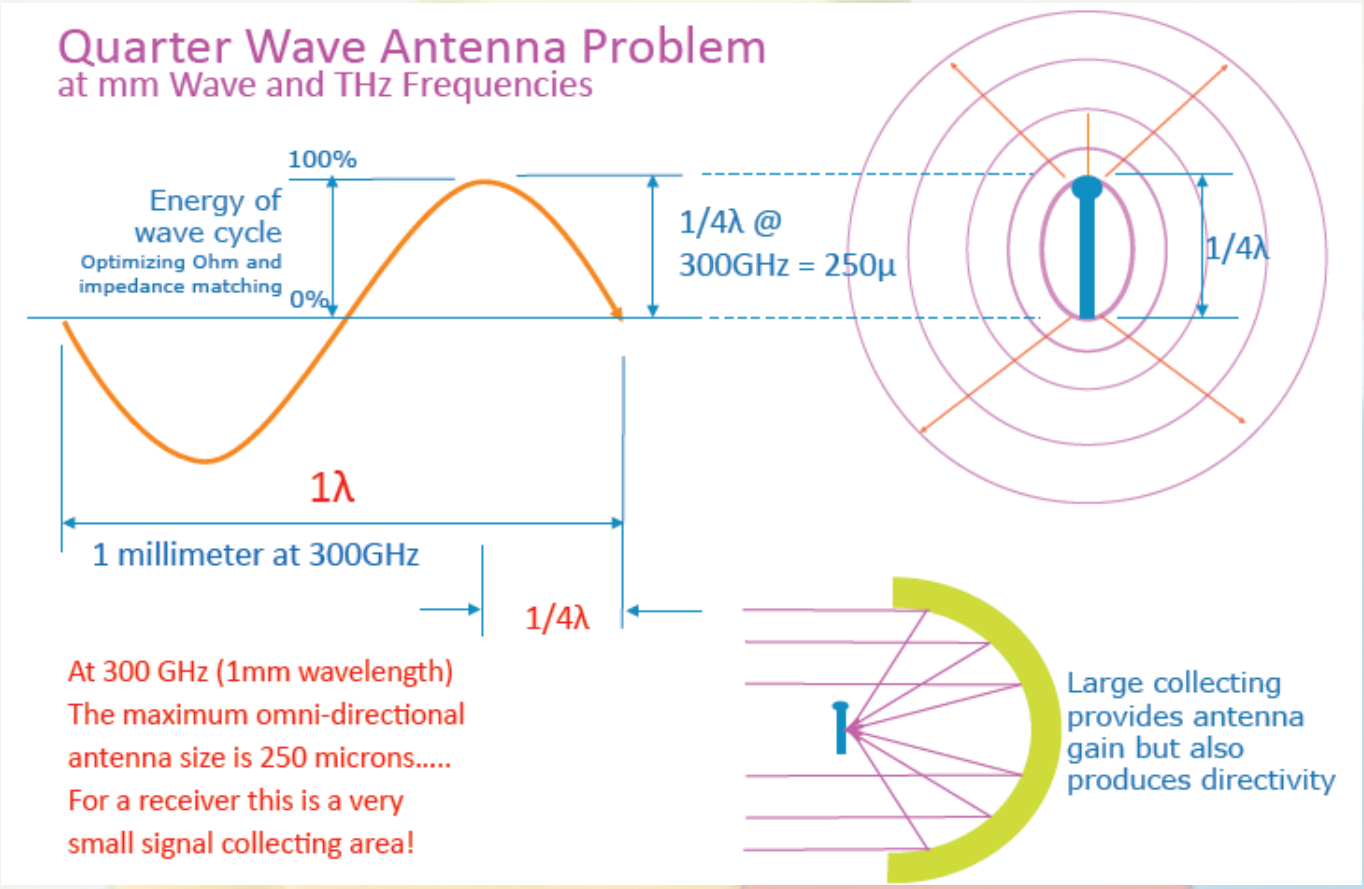

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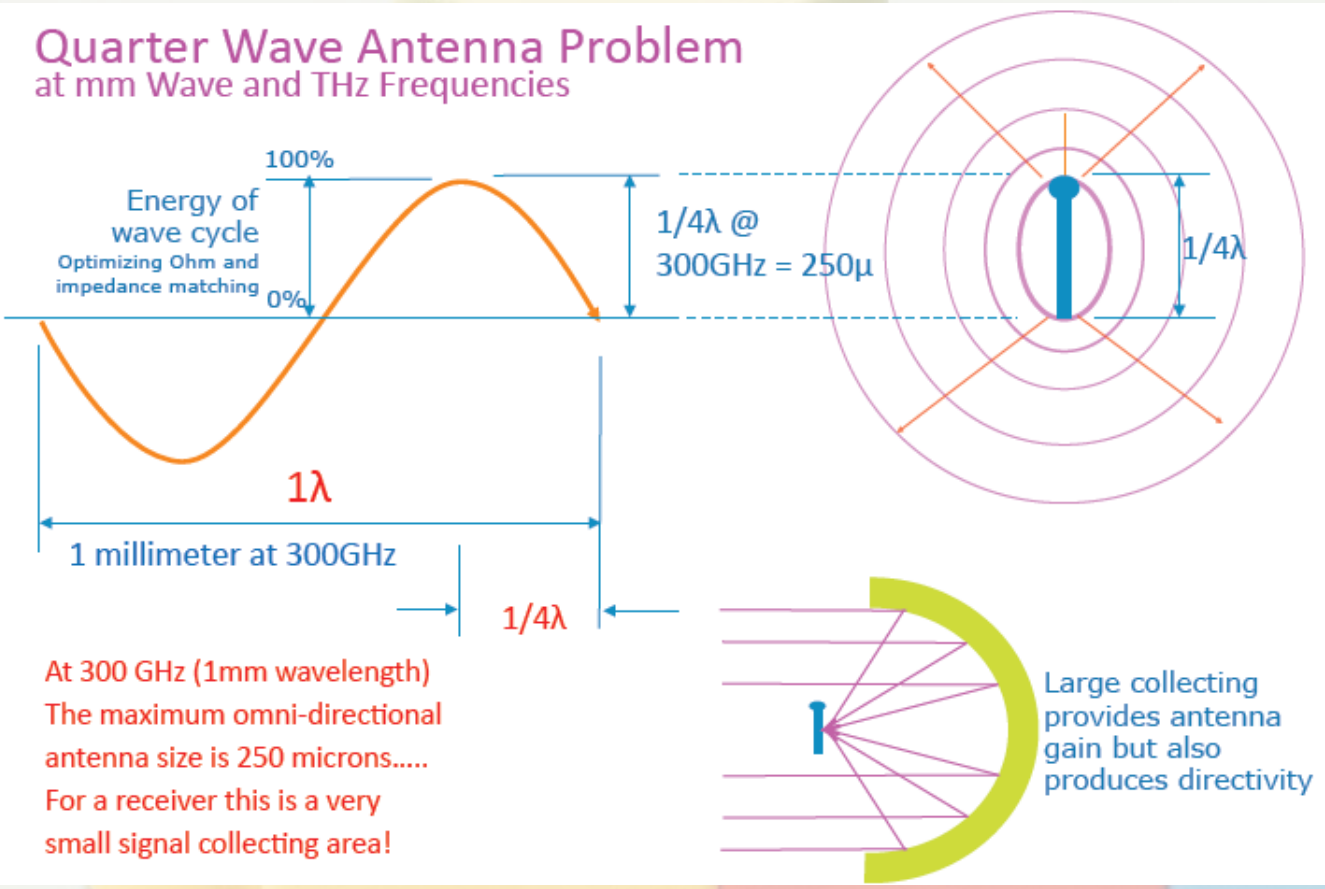

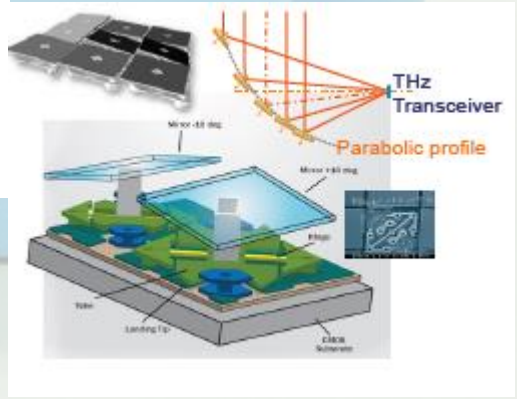

Challenge #2 : beam steering is needed in order to establish a link!

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The THz gap

Need for devices:

- Efficiently **operating at RT**
- Capable of **actively manipulating** THz waves (modulators, switches, active filters, active lenses,…)
- Capable of **responding to THz frequencies** (amplifiers, oscillators, detectors, switches,…)
- Other needs: integration, measurement techniques, interface, etc.

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