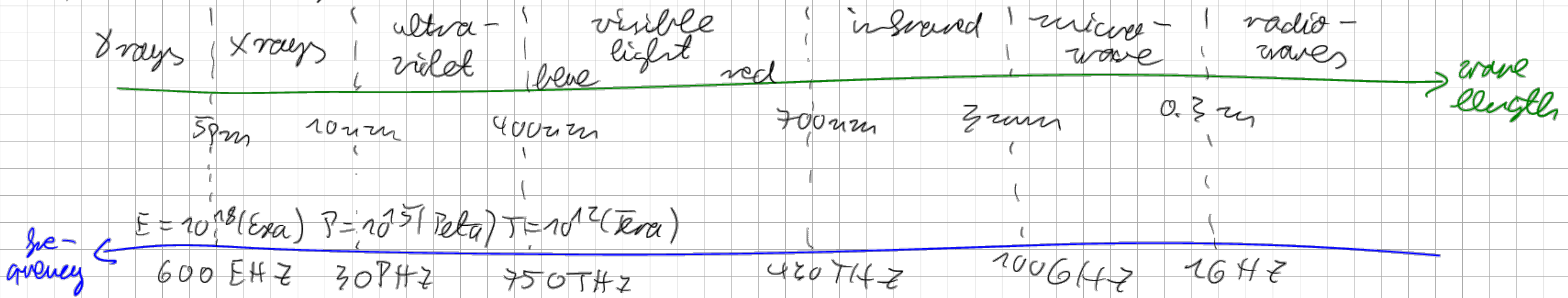
Quantum Optics

1. Introduction:

- Visible light: ubiquitous phenomenon
  => true nature has always puzzled mankind
- From a physical point of view: small fraction of electromagnetic spectrum perceived by human eye



- sometimes: "light" = electromagnetic radiation of any wavelength
- Light propagates as waves characterised by frequency, wavelength, amplitude, polarisation, intensity, direction of propagation and light velocity: $c = 299\ 792\ 458\ m/s$ (fundamental constants of nature, identical in all inertial systems due to Michelson-Morley experiment)
- Energy imparted by waves is absorbed at single locations the way particles are absorbed. Absorbed energy of an electromagnetic wave

is called a photon, a quantum of light. The location where the energy of the wave collapses in a location, where the photon arrives at, the wave function of the photon collapses.

- Light has, thus, both a wave-like and a particle-like nature: particle wave duality. Quantum optics studies the nature and effects of light as quantized photons → important and lively research in modern physics
- Initial developments:
  - 1900: Max Planck modelled black-body radiation spectrum under the hypothesis of light being emitted in discrete units of energy
  - 1905: Albert Einstein explained the photoelectric effect that an electromagnetic wave hits a material leads to the emission of electron thus providing evidence for corpuscular nature of light
  - 1913: Niels Bohr showed that hypothesis of quantized light corresponded to his theory of quantized energy levels in the atoms
  - Understanding of interaction of light and matter was fundamental for development of quantum mechanics. For many decades quantisation light was not treated as a topic by its own but was considered as a subfield of atomic physics.
- 1960: Theodore Maiman built the first laser
  - Device that emits light due to light amplification based on stimulated

emission of radiation

* laser science: principles and applications and design of lasers
- different lasers: gas lasers, solid-state lasers, fiber lasers, photonic crystal lasers, semiconductor lasers, free-electron lasers
  → operate at different wavelengths
- study of quantum mechanics of laser principles became important and then the name of quantum optics became more customary

- Theoretical foundations of quantum optics:
  - 1927 Paul Dirac laid the foundations of quantum field theory
  - Around Second World War: Freeman Dyson, Richard Feynman, Julian Schwinger and Shinichiro Tomonaga worked out quantum electrodynamics
    = relativistic treatment of light-matter interaction
  - 1950s/1960s: Roy Glauber, John Klauder, Leonard Mandel, George Sudarshan, and others; they applied the laws of quantum theory to the electromagnetic field in order to get a deeper understanding of the statistics of light as e.g. coherence
  - different states of light: thermal state, coherent state, exotic squeezed states

- Application side: many intriguing phenomena as for instance
  - mode-locked oscillator: generation of ultrashort laser pulse of duration of fs,

broadband spectrum, high intensity → nonlinear optics
- Applications in molecular and solid-state physics: e.g. Raman spectroscopy → detection of vibrational modes as spectral fingerprints
- Quantum information technology: quantum entanglement, quantum teleportation, quantum cryptography, quantum logic gates → building a quantum computer

- Ultracold atomic and molecular gases:
  - Application of mechanical forces of light on matter: levitate and position and atomic cloud in a magneto-optical trap
  - Laser and evaporative cooling
  - Experimental realization of a macroscopic quantum phenomenon, which was predicted 1925 by Albert Einstein based on a paper by Satyendra Nath Bose:
    → Bose-Einstein condensation
    1995: realized by Eric Cornell, Carl Wieman and Wolfgang Ketterle
    → Lecture Widera: Ultracold quantum gases

- Photon Bose-Einstein condensate (BEC)
  - Electromagnetic radiation in equilibrium does not show a BEC: rest mass of photons vanish, chemical is zero. Lowering the temperature photons go into ~~walls~~ cavity
  - Group of Martin Weitz at Bonn in 2010: photons in a dye-filled cavity

- Cavity mirrors provide a confining potential and non-vanishing photon mass: system is formally equivalent to a 2D gas of bosons with a finite mass ($\approx 10^{-10}\, m_{Rb}$).
- Absorption / emission of photons by dye molecules leads to thermalisation of photons at room temperature
- James Anglin: Particles of Light, Nature 468, 517 (2010)
- Experimental platforms: Bonn, London, Utrecht, Twente and now also in Kaiserslautern (Georg von Freymann)

This lecture: introduction into quantum optics from a theoretical point of view but also experimental set-ups and results are discussed

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4. Emission and Absorption of Light by Matter
- Non-relativistic matter (in contrast to QFT)
- Perturbative treatment: three elementary Einstein processes
- Rabi model: classical light-matter interaction
- Jaynes-Cummings model: quantum-mechanics light-matter interaction

5. Quantum Mechanical Equations of Motion for Light and Matter
- Without and with coupling to environment providing pumping/losses
- Semiclassical and quantum mechanical laser theory

6. Theory of Photon BECs
- experimental set-up and results
- Paraxial approximation in microcavity
- Kerr interaction
- Thermo-optic interaction

Conclusion: Lecture strives for
- providing a general overview of quantum optics
- compare specifically two light sources

laser		photon BEC
nonequilibrium phase transition	⟷	equilibrium phase transition