Light and the known UNIVERSE

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Presentation Outline

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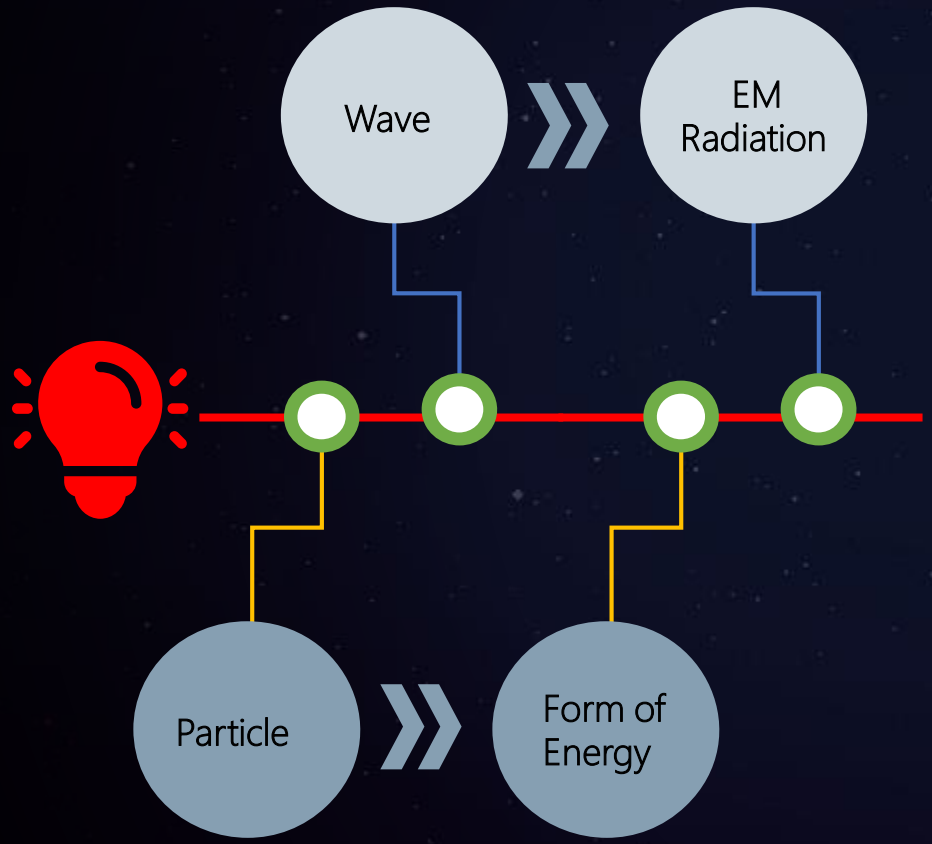
1. What is Light?
2. Quantum Theories of Light
3. Classical Theories of Light
4. Origin and Extent of the Universe
5. Anthropology of Light and Life
6. Advances in Light-based Technologies
7. Ideas for Space Exploration with Light
8. Interactive Discussions

Abstract

Light, a unique substance or wave is an important constituent of physical existence, formation of life and the universe. Human quest to understand the universe, its extent and dynamics of its integrant is closely related to the understanding of light and its properties.

This seminar will dive deep into our current knowledge of the quantum characteristics of light as well as in the classical domain. The state-of-the-art in light-based technologies will be highlighted while ideas and concepts of how they could enhance deep-space exploration will be introduced.

1 What is Light?



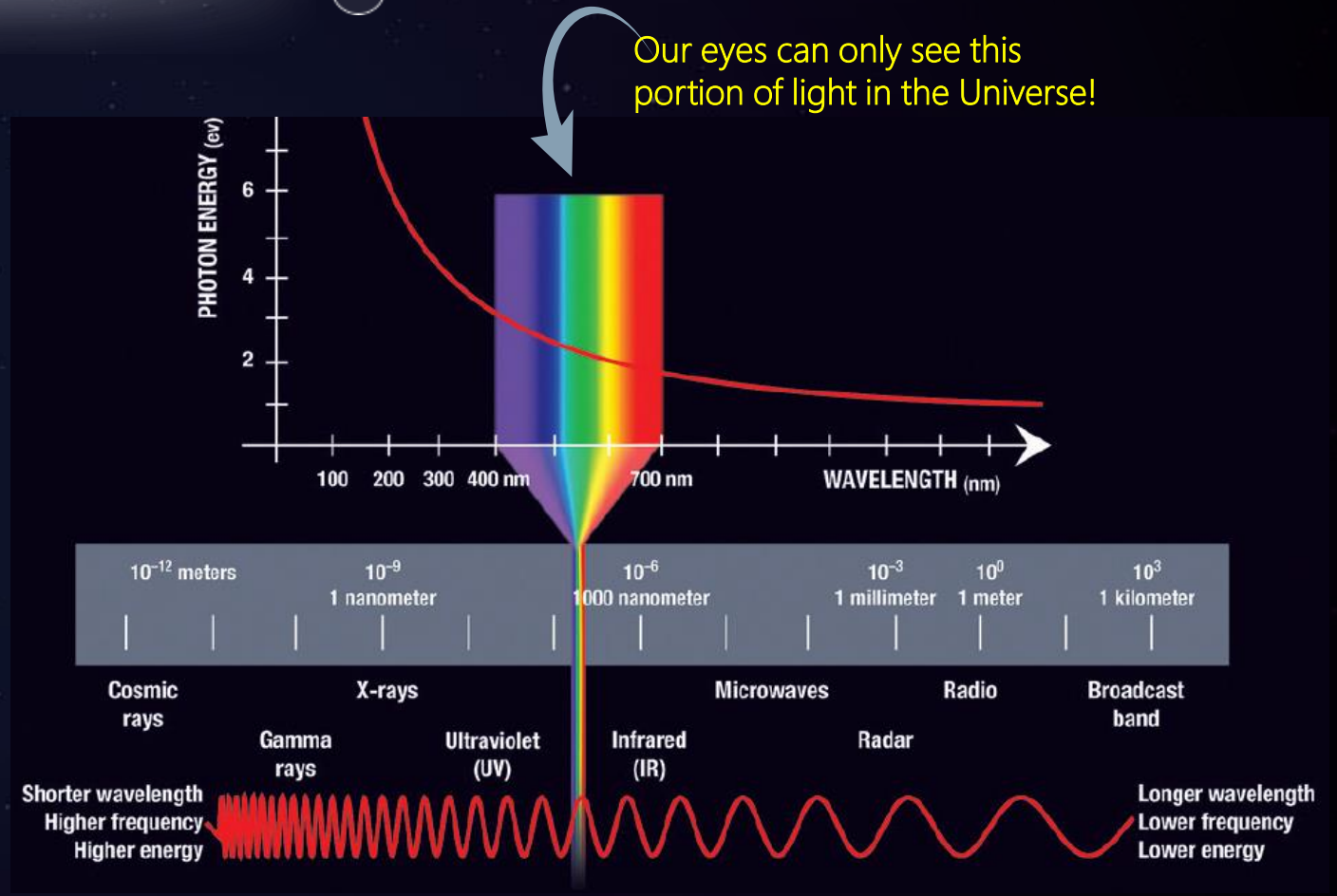


Image credit : SPIE

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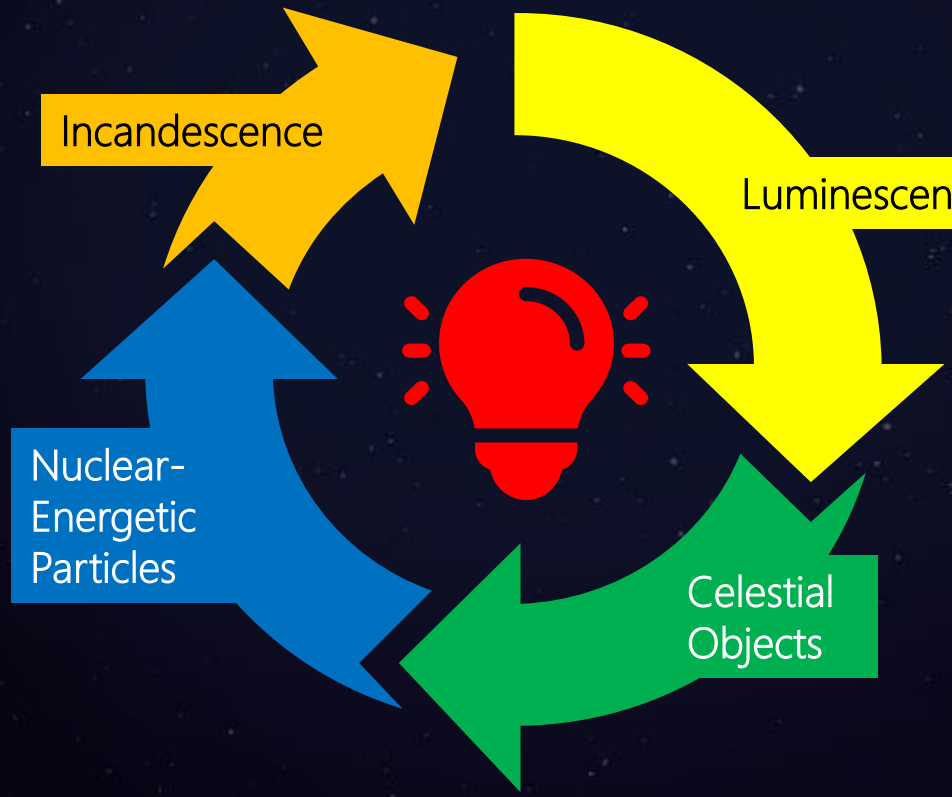
Known Sources of Light



- Electronic Devices
- Biological Organisms
- Chemical Reactions
- Electrochemical
- Cathode Discharge
- Cryogenics
- Crystals
- Photoluminous Materials
- Mechanical-Piezo-Sono
- Electrostatic-Gas Discharge
- Radio Ionization
- Thermal Emissions

1 Photon of Light

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- Photon is the fundamental particle of light, a quantised, discrete packet of energy generated when electrons move from conduction to valence band, a higher energy level to lower energy level
- Photons have a rest mass of zero and has no charge with spin value of 1
- The energy, E carried by a single photon is dependent on its electromagnetic frequency

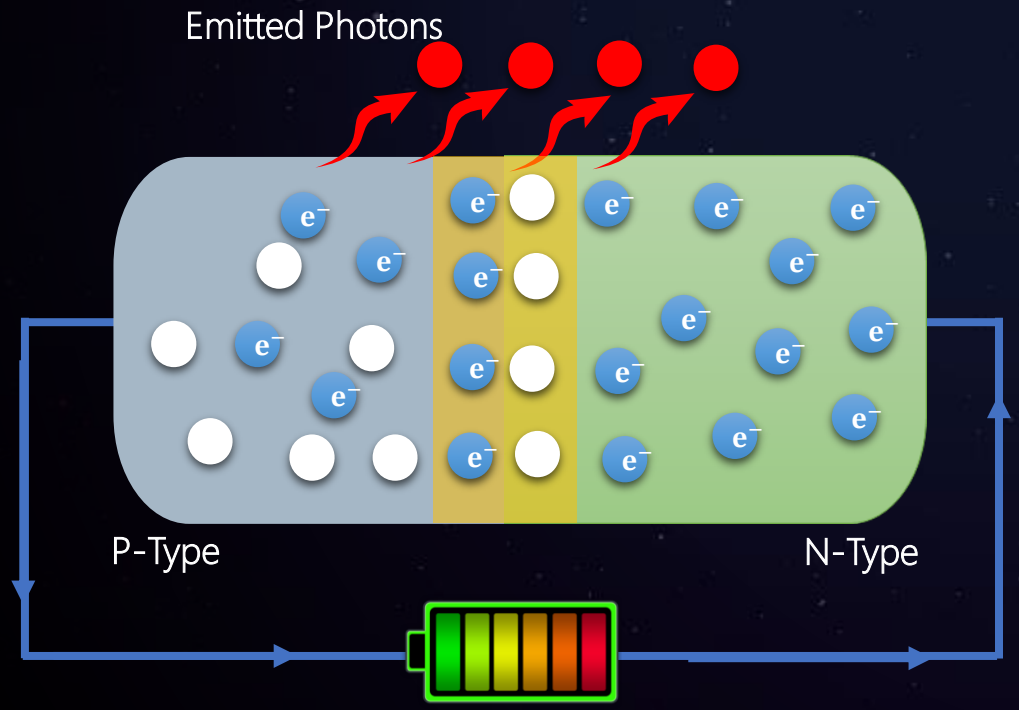
Planck-Einstein Equation

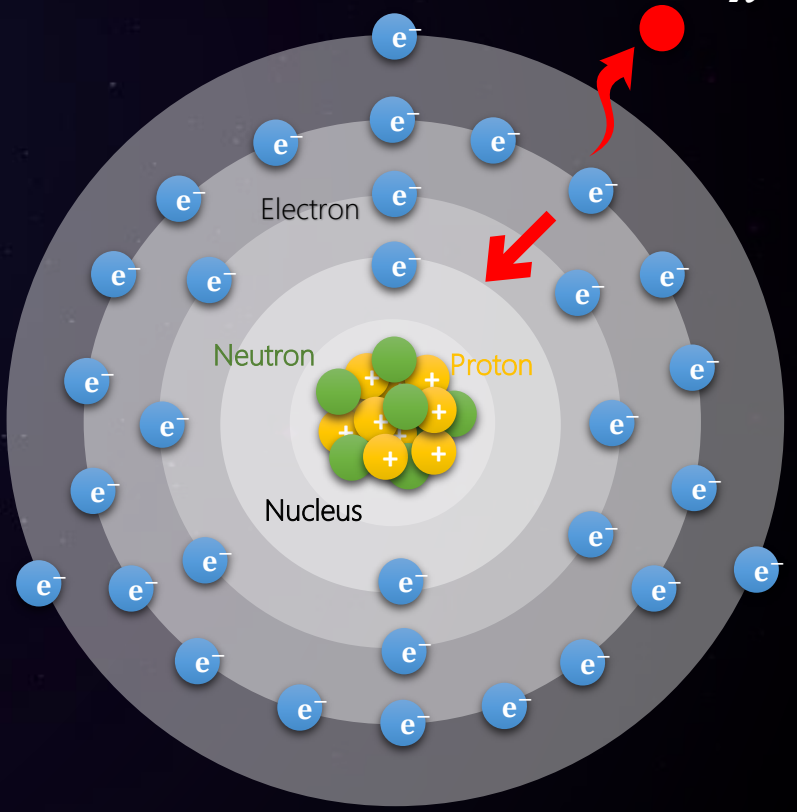
$$E = hf = \frac{hc}{\lambda}$$

$$1eV = 1.602 \times 10^{-19} J$$

$$h = 6.62607015 \times 10^{-19} J.s$$

$$c = 2.99792458 \times 10^{8} m/s$$





Gallium Atom [31 Protons, 39 Neutrons, 31 Electrons-2-8-18-3]

2 Quantum Theories of Light

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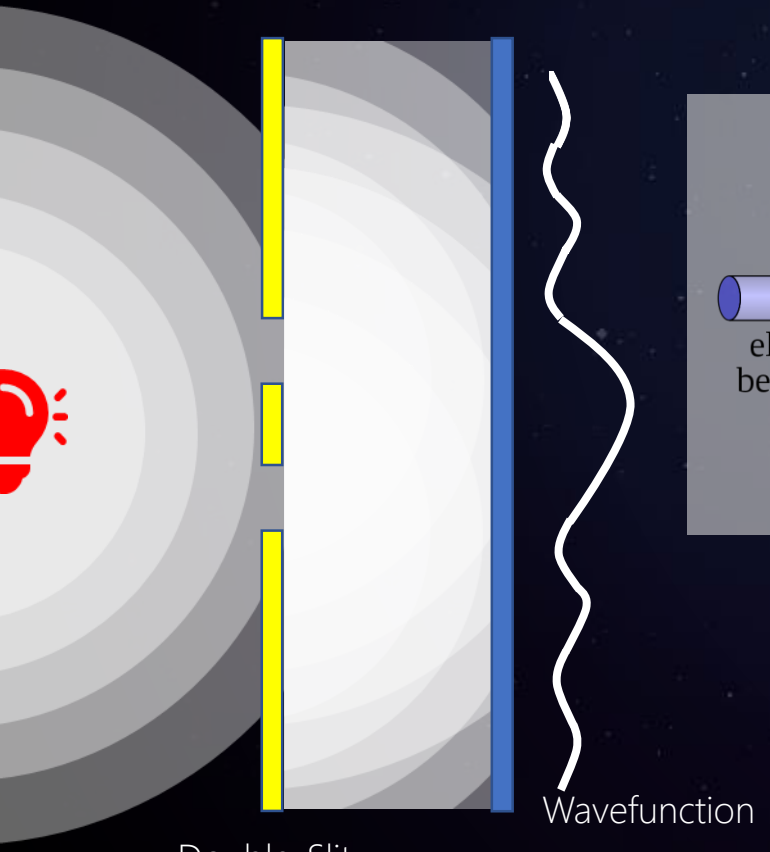
- Wave-Particle duality nature of light shows that a bunch of photons behave like mechanical waves e.g. sound waves while also behaving like electrons. Electrons and Protons are considered particles because they have masses but photons have zero mass and yet can eject photoelectrons from metallic surfaces at its characteristic threshold frequency, $\boldsymbol{v_0}$ (Photoelectric Effect)!



Young's double-slit interferometer

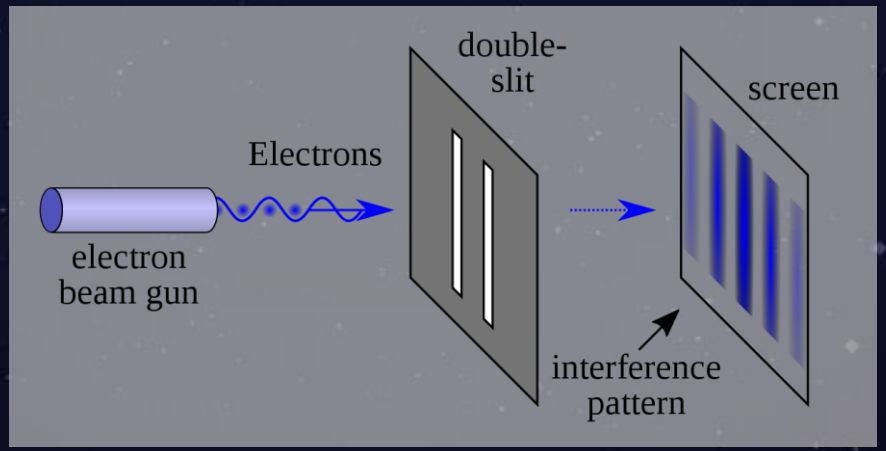


Image credit : Wiki

Einstein's Photoelectric Effect

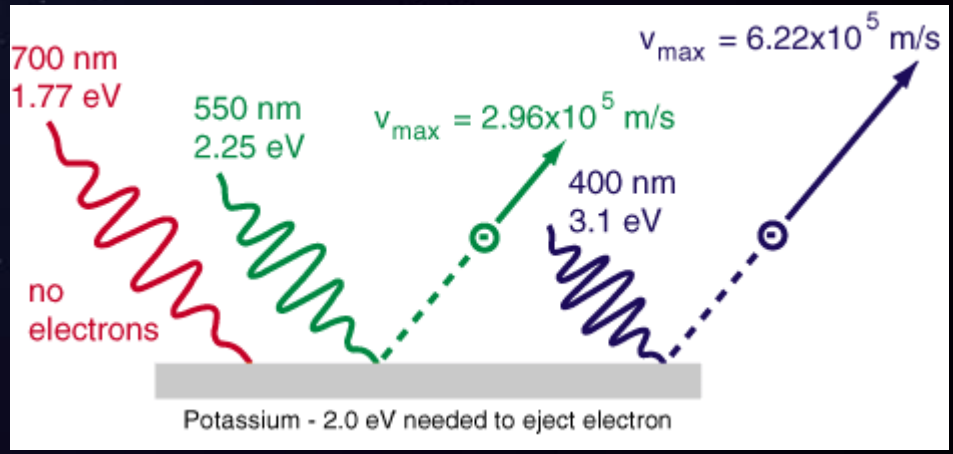


Image credit : Sites.Google

$$qV_O = E_{max} = h(f - v_O)$$

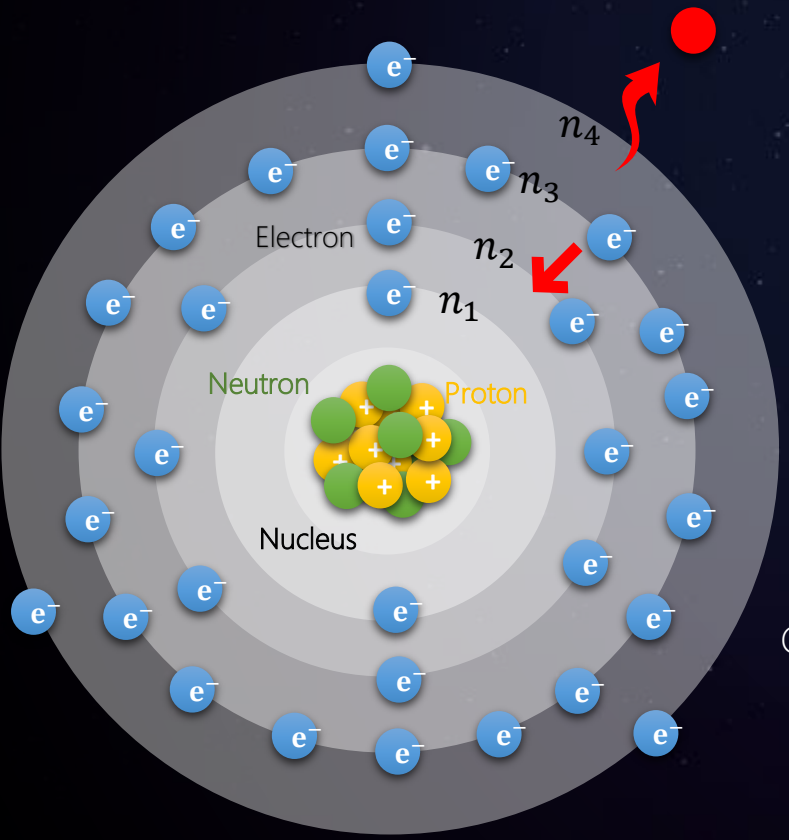
$$q = 1.60217662 \times 10^{-19} c$$

V_O = Stopping Potential

2 Particle Position & Momentum

- Wave-Particle duality nature of light shows that a bunch of photons behave like mechanical waves e.g. sound waves while also behaving like electrons. Electrons and Protons are considered particles because they have masses but photons have zero mass and yet can eject photoelectrons from metallic surfaces at its threshold frequency (Photoelectric Effect) !

Bohr Atomic Model



$$\Delta E = E_2 - E_1 = hf$$

Electron's Quantised Angular Momentum

$$L = n\hbar$$

Electron Orbital Velocity

$$v_n = \frac{e^2}{n\hbar}$$

Radius of Orbit

$$r_n = \frac{n^2\hbar^2}{me^2}$$

Coulomb Force=Centrifugal Force

$$\frac{e^2}{r} = \frac{mv^2}{r}$$

de Broglie's Hypothesis

$$\hbar = \frac{h}{2\pi} \quad \omega = 2\pi f \quad E = \hbar\omega$$

Linear Momentum of material particles

$$P = \frac{h}{\lambda}$$

For non-relativistic Particle De Broglie's wavelength

$$\lambda = \frac{h}{\sqrt{2mE}}$$

Heisenberg Uncertainty Principle

Standard deviations of position and momentum

$$\sigma_x \sigma_{px} \geq \frac{h}{4\pi}$$

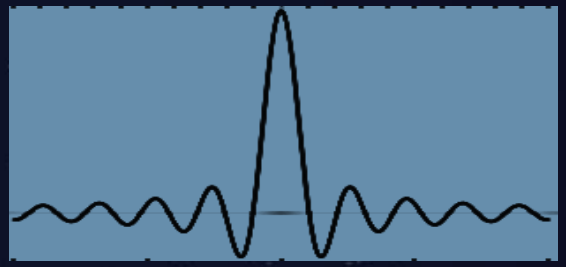
2 The Wavefunction $\psi(x,t)$

- The position and behaviour of a particle with respect to time is defined by the Wavefunction. The square of the Wavefunction gives the probability density of locating the particle within an interval x and x+dx during Δt.

The Schrodinger Time-Dependent Wave Equation

One dimensional equation

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V(x,t)\psi(x,t)$$



Three dimensional equation in Cartesian coordinates

$$i\hbar\frac{\partial\psi(r,t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi(r,t) + V(r,t)\psi(r,t)$$

Time-Dependent Solution

$$\psi = C_1\psi_1(x,t) + C_2\psi_2(x,t) + \cdots + C_n\psi_n(x,t) = \sum_{i=1}^{n} C_i\psi_i(x,t)$$

$$\psi_n(x,t) = \Phi_n(x)e^{-\frac{iE_nt}{\hbar}}$$

Wavefunction properties $\int_{-\infty}^{\infty}|\psi(x,t)|^2dx < \infty$

1D Probability Density Function $dP(x,t) = |\psi(x,t)|^2\,dx$

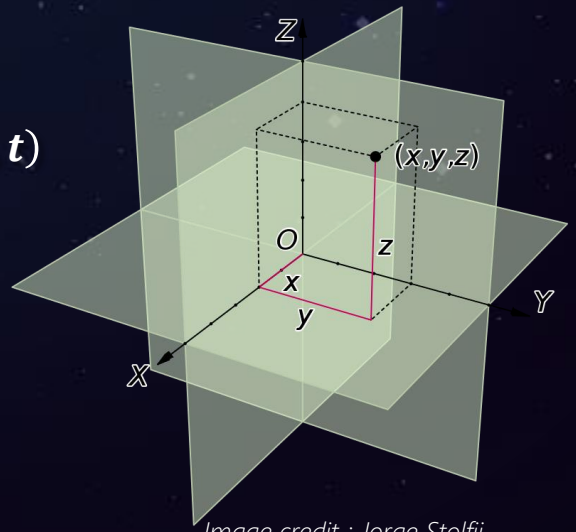


Image credit : Jorge Stolfii

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

3D Probability Density Function

$$dP(r,t) = |\psi(r,t)|^2\,d^3r$$

$$d^3r = \partial x\partial y\partial z$$

2 The Wavefunction $\Phi(x)$

- The time-invariant version of the wave equation reveals the stationary phase of the Wavefunction, tends itself to easy simplification and thus expressed as follows

The Schrodinger Time-Invariant Wave Equation

One dimensional equation

$$E\Phi(x) = -\frac{\hbar^2}{2m}\frac{\partial^2\Phi(x)}{\partial x^2} + V(x)\Phi(x)$$

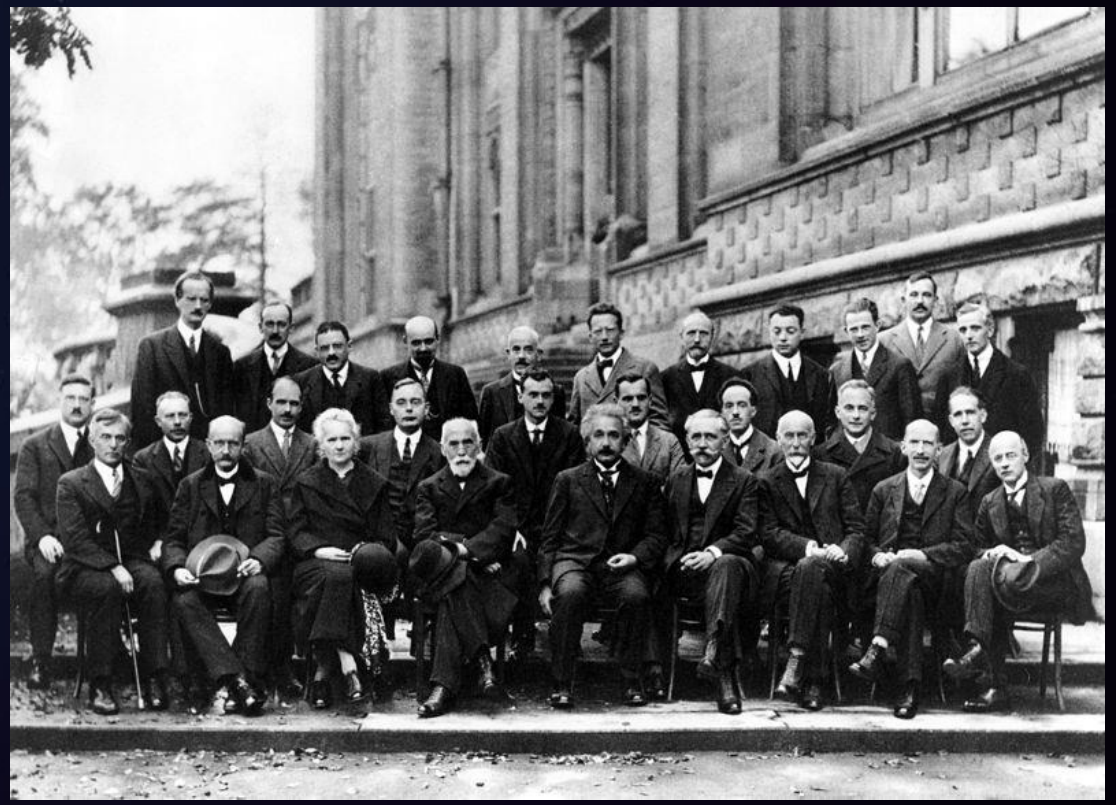
Probability Density Function

$$|\Phi(x)|^2 = \Phi^*(x) + \Phi(x)$$

Three dimensional equation

$$E\Phi(r) = -\frac{\hbar^2}{2m}\nabla^2\Phi(r) + V(r)\Phi(r)$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$



Progenitors of Quantum Theory at the Solvay Conference of 1927

2 Quick Derivation

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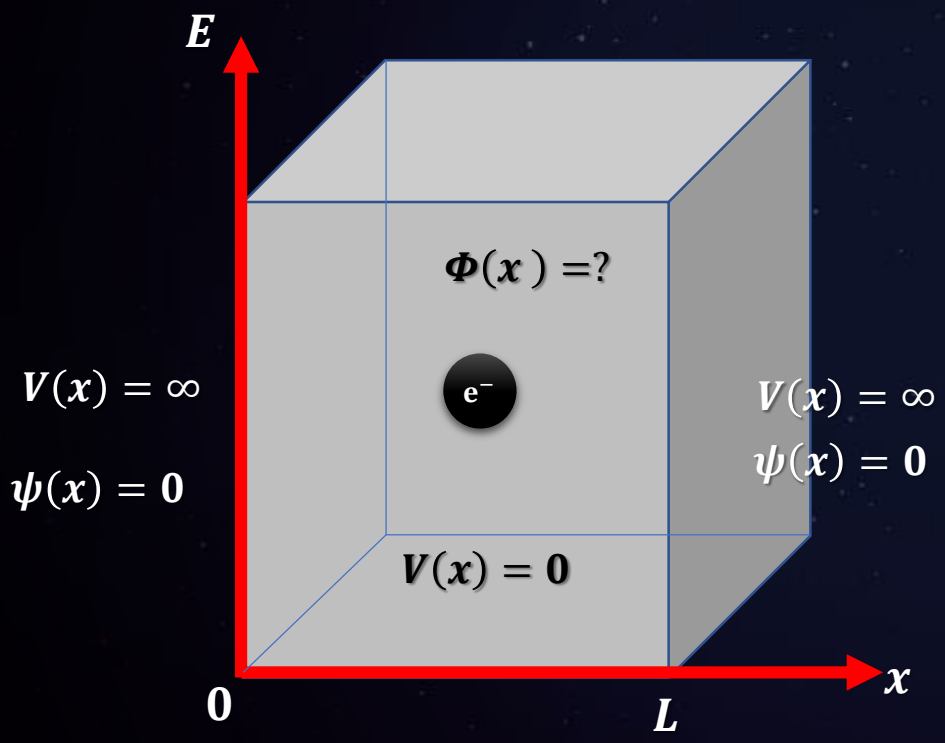
- Consider an electron trapped in a quantum potential well bouncing in the trapped volume. Let us derive an equation that predicts the motion i.e. position and momentum of the particle in the box



Total energy of the particle

$$E = P.E + K.E$$

$$E = V(x) + \frac{1}{2}mv^2$$

$$p = mv$$

$$E = V(x) + \frac{p^2}{2m}$$

Multiply both sides by Φ

$$E\Phi = V(x)\Phi + \frac{p^2\Phi}{2m}$$

Wavenumber, $k = \frac{2\pi}{\lambda}$

$$n = 1, 2, 3 \ldots$$

From De Broglie,

$$P = \frac{h}{\lambda}$$

$$h = 2\pi\hbar$$

$$P = \frac{2\pi\hbar}{\lambda}$$

$$P = \hbar k$$

$$k = \frac{P}{\hbar}$$

$$\psi = e^{-i(kx-\omega t)}$$

$$\frac{\partial\psi}{\partial x} = ike^{(kx-\omega t)} = ik\Phi$$

$$\frac{\partial^2\psi}{\partial x^2} = i^2k^2e^{(kx-\omega t)} = -k^2\Phi$$

$$\frac{\partial^2\Phi}{\partial x^2} = -\frac{P^2}{\hbar^2}\Phi$$

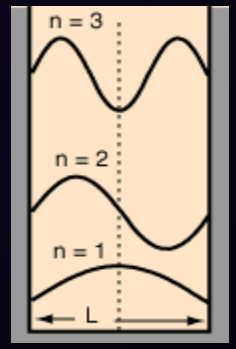
$$-\hbar^2\frac{\partial^2\Phi}{\partial x^2} = P^2\Phi$$

$$E\Phi = V(x)\Phi - \frac{\hbar^2}{2m}\frac{\partial^2\Phi}{\partial x^2}$$

$$\Phi(x) = \sqrt{\frac{2}{L}}\cos\left(\frac{\pi n x}{L}\right) \quad n = 1, 3 \ldots$$

$$\Phi(x) = \sqrt{\frac{2}{L}}\sin\left(\frac{\pi n x}{L}\right) \quad n = 2, 4 \ldots$$

$$E = \frac{\hbar^2 n^2 \pi^2}{2mL^2}$$



3 Classical Theories of Light

- Classical theories treats light as a wave instead of a particle.
- Light behaves like other electromagnetic radiations such as radio and microwaves
- Maxwell Equations is an aggregation of Ampere's Law, Faraday's Law, Lenz Law and Gauss Law

Maxwell Equations of Electromagnetic Radiation

$$\nabla \times \vec{E}(r,t) = -\frac{\partial}{\partial t}\vec{B}(r,t)$$

$$\nabla \times \vec{B}(r,t) = C^{-2}\frac{\partial}{\partial t}\vec{E}(r,t)$$

$$\nabla . \vec{E}(r,t) = 0$$

$$\nabla . \vec{B}(r,t) = 0$$

Electromagnetic Radiation Propagates at the Speed of Light

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = f\lambda$$

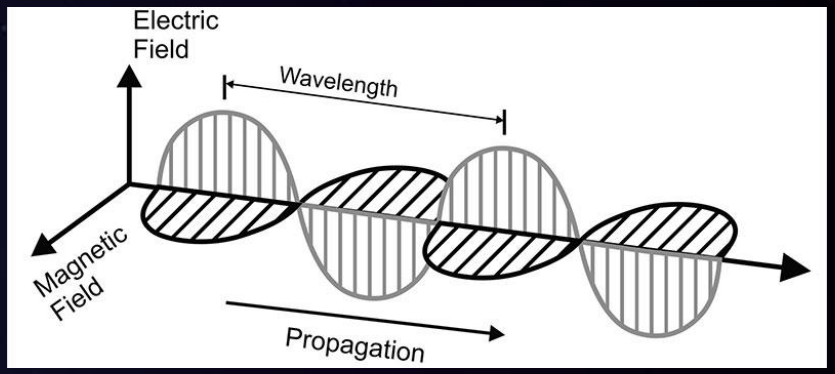


Image credit: Nutsvolt.com

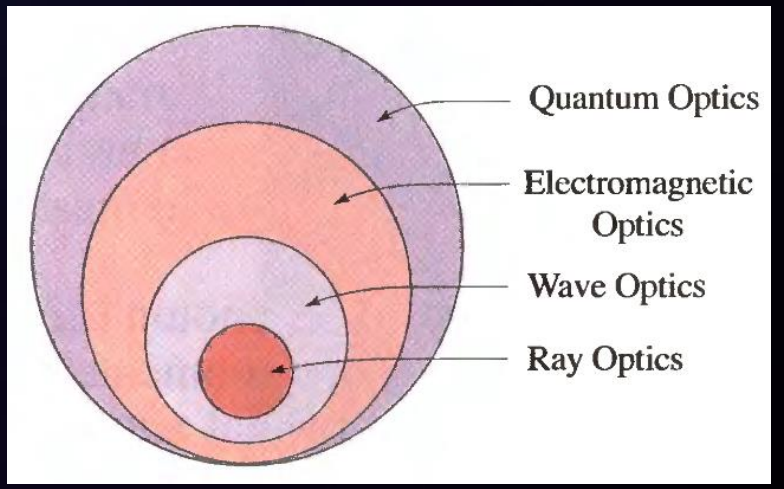


Image credit: Saleh & Teich Fundamentals of Photonics

3 Classical Theories of Light

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Geometrical Optics

- Snell's law laid the foundation of geometrical optics by describing light propagation in rectilinear form as rays
- Light rays exhibit the following properties

Reflection
Refraction
Dispersion
Total Internal Reflection
Interference
Diffraction
Scattering
Polarization
Absorption

Light in Astronomical Context

- Gravitational force and huge masses in outer space interacts with and influences properties of light in strange ways different from geometrical optics
- The robust field of Astronomy is entirely dedicated to understanding the dynamics of the components of the universe
- Since the distant planets, stars and galaxies are not within reach of human and robotic transportation, scientists rely solely on studying how the cosmic objects generates light or how they affect the light within their surroundings

Gravitational Lensing
Aberration of Starlight
Redshift-Doppler Effect Hubble's Law
Parallax

4 Origin and Extent of the Universe

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The Big Bang Theory

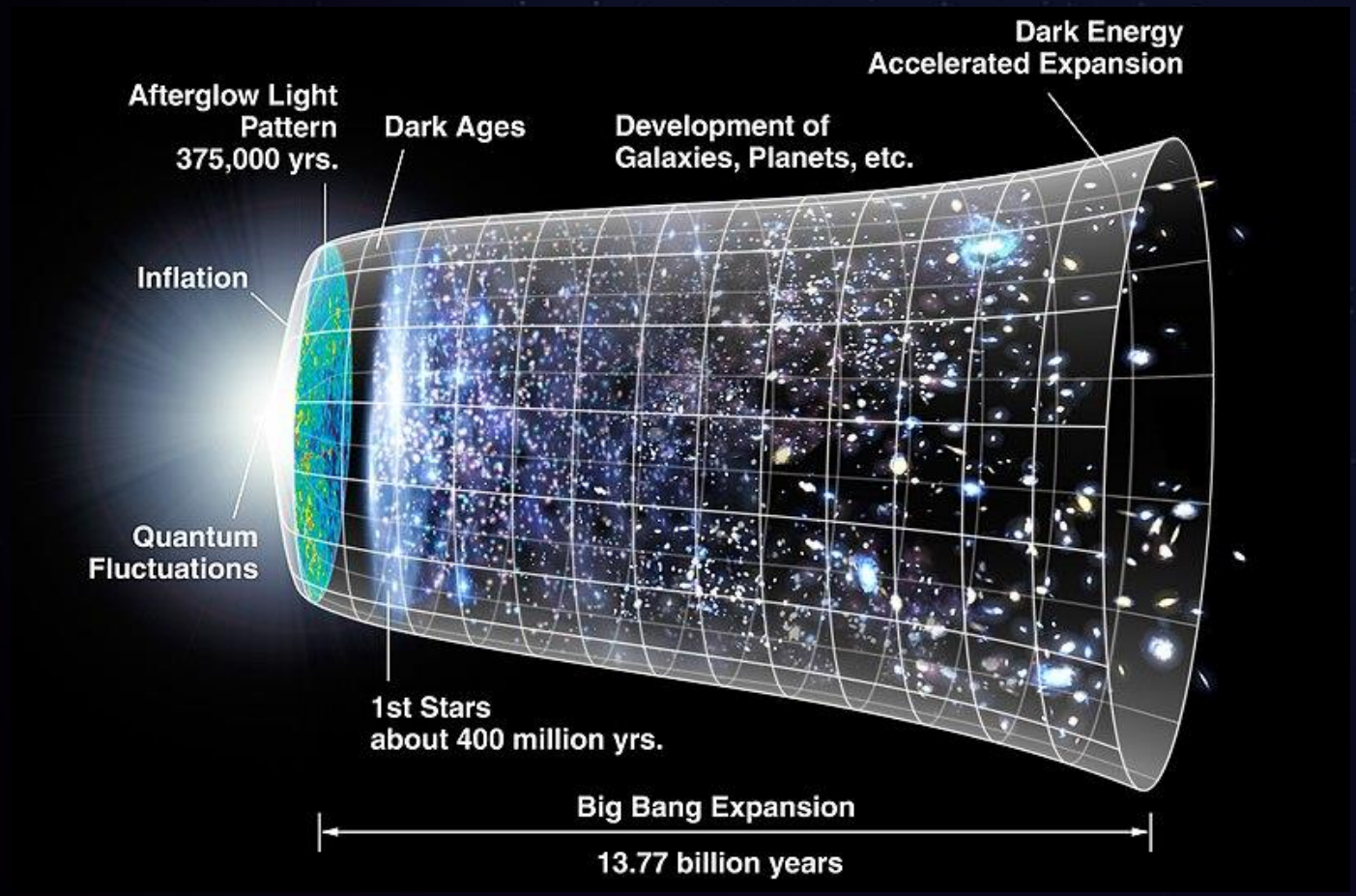


Image credit: NASA/WMAP Science Team & Cherkash

Modern Cosmology

Time	Temperature	Radius	Event
0	Infinite	zero	Singularity
		10^{-56} cm	Four forces are united and all exist as radiation energy
10^{-43} sec	10^{32} K		Gravity separates from other forces
10^{-35} sec	10^{27} K	Sudden expansion from volume of atom to volume of cherry pit	Strong nuclear separates Inflation
10^{12} sec	10^{15} K	Volume: a few cubic meters	Weak and electromagnetic forces separate Particle era begins
10^{-4} sec	10^{12} K	150 m	Quarks combine to form protons and neutrons
10 sec	10^{10} K		Radiation era begins
3 min	10^{9} K		Atomic nuclei form
500,000 years	2000 K		Matter era begins Atoms form Universe becomes transparent
1 billion years			Galaxies form
10 billion years			Planets form
10 billion years			Microscopic life
15 billion years	3 K		Today

History of the Universe. SourceHarry Poe and Jimmy Davis: Science & Faith, 2000.

4 Origin and Extent of the Universe

Shape of the Universe

- From General Relativity, the density parameter, Ω reveals how mass and energy bends the curvature of space-time
- If Ω = 1, the universe is flat
- If Ω > 1, there is positive curvature
- if Ω < 1 there is negative curvature

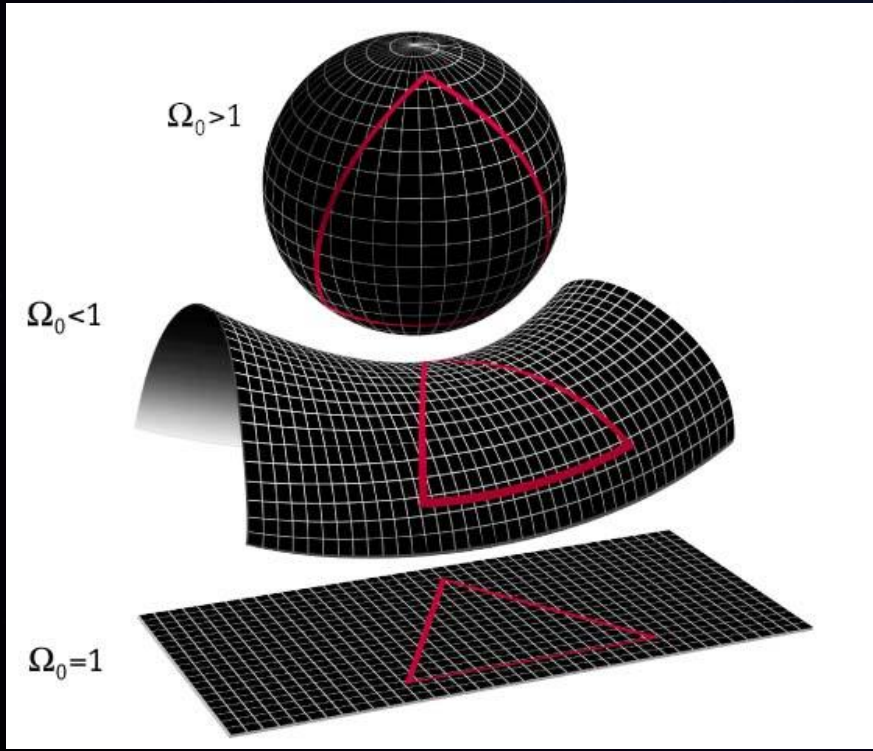


Image credit: Wiki

Expanding Universe

- Cosmic Microwave Background Radiation

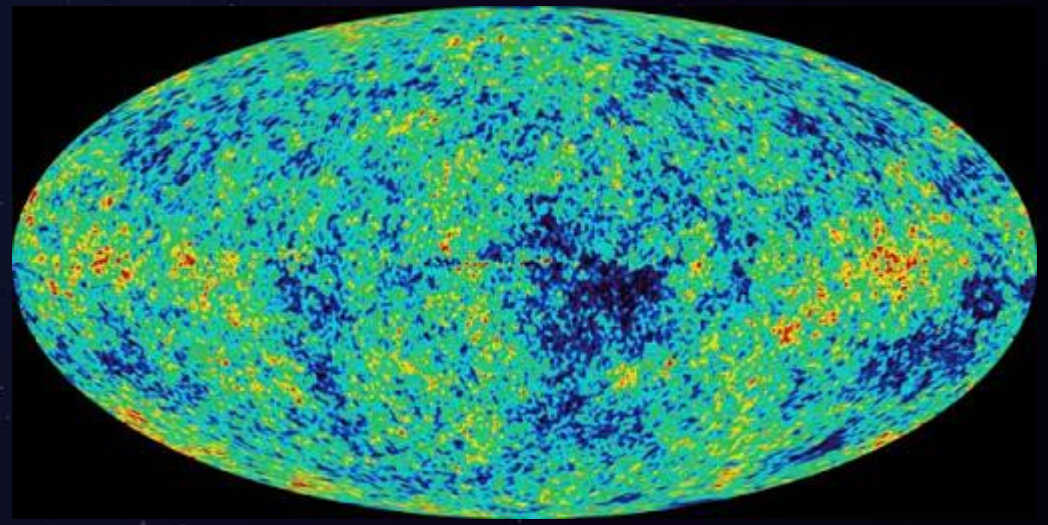


Image credit: Wiki

The Universe = Ordinary Matter + Dark Matter + Energy + Dark Energy + Particles + Empty Space

- Of all the particles, we can only see photons and it lend itself easily as a tool for observing and exploring the universe!

5 Anthropology of Light and Life

Origin of Life Versus Importance of Light

- There are many divergent theories that describes the formation of life in the universe
- Creationism, Abiogenesis, Evolution, Biogenesis etc are some of the schools of thoughts about the beginning of life
- Religion and sociocultural beliefs also add to the list
- This seminar do not intend to analyze or shortlist the best from among these numerous theories and ideologies
- However, it is interesting to underline the role of light in the sustainance of living organisms.
- Plants cannot live without photosynthesis, and its hard to imagine human life without light.
- Food cycle, ecological cycle and the entire universal ecosystem are heavily dependent on light for sustenance.
- Astronomers often priotize the goldilocks' zones around distant star systems as possible areas to find extraterrestrial life because of the available light and temperature

6 Advances in Light-Based Technologies

Augmented Reality Liquid Crystal 3D Displays

- Liquid Crystal Displays are everywhere: phones, TVs, computers, laptops, digital cameras etc. and have become the visual human-machine interface but mainly 2D capabilities
- Holographic 3D LCDs are been developed to render quality augmented reality images

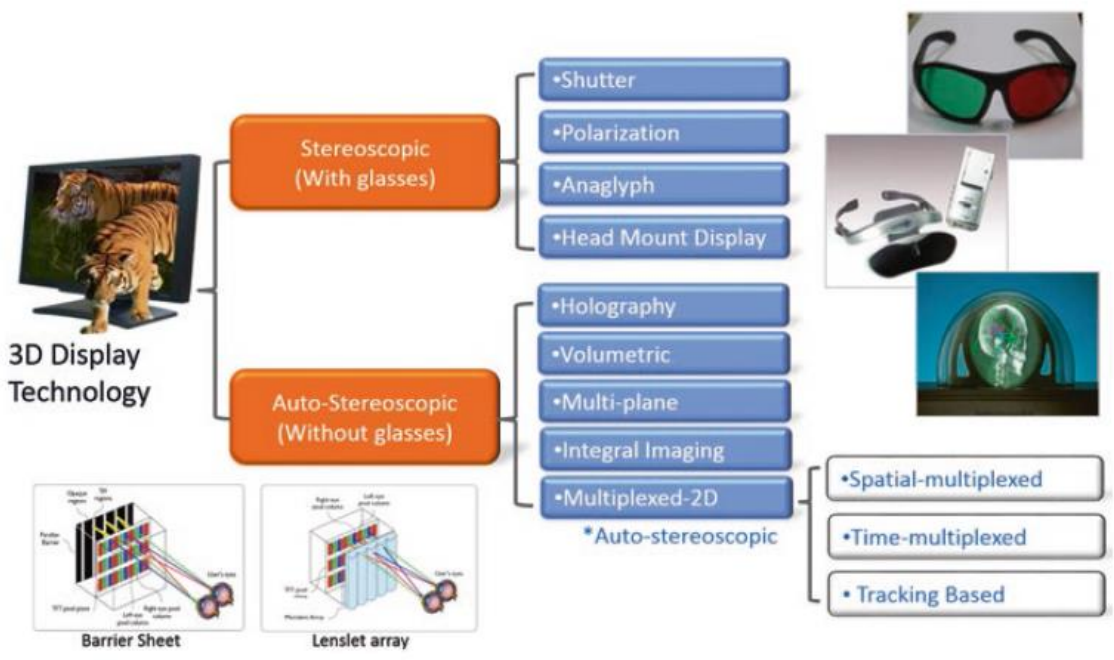
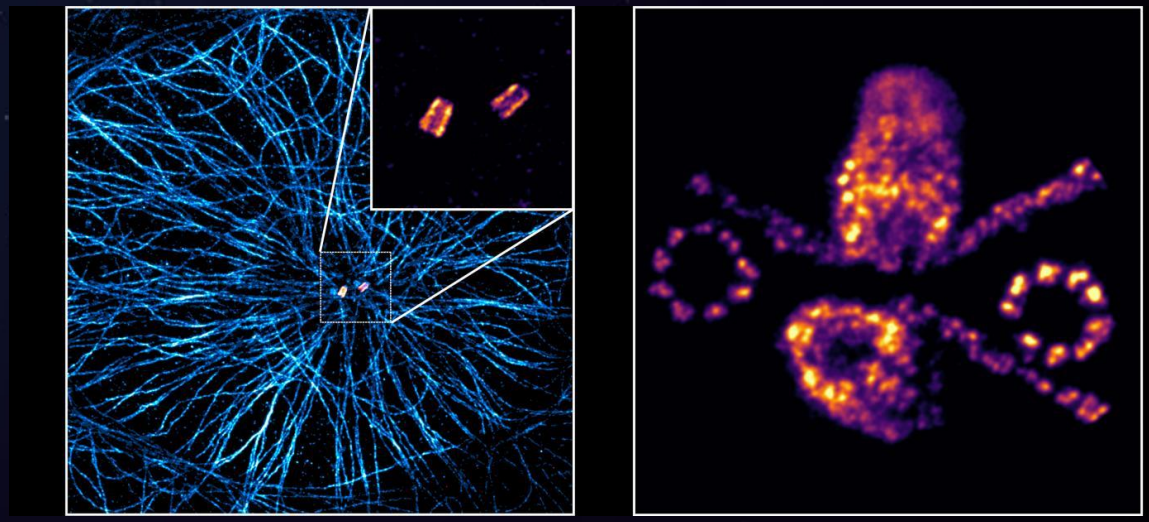


Image credit: Yi-Pai Huang

Super-Resolution Microscopy

- Microscopes are now becoming Nanoscopes
- Techniques and systems capable of depicting better than 200nm objects with 3D spatial viewing are now available



Expanded Human Cell Image credit: Fabian Zwettler. Markus Sauer

6 Advances in Light-Based Technologies

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Biophotonics

- Progress in biophotonics is connected with several applications in medical diagnosis, clinical tools, carcinogenesis, agriculture, biotechnology, genomics-DNA sequencing, forensics etc.
- Improvements include development of biosensors, non-invasive functional imaging, biophotonic instrumentation and nano-biophotonic devices

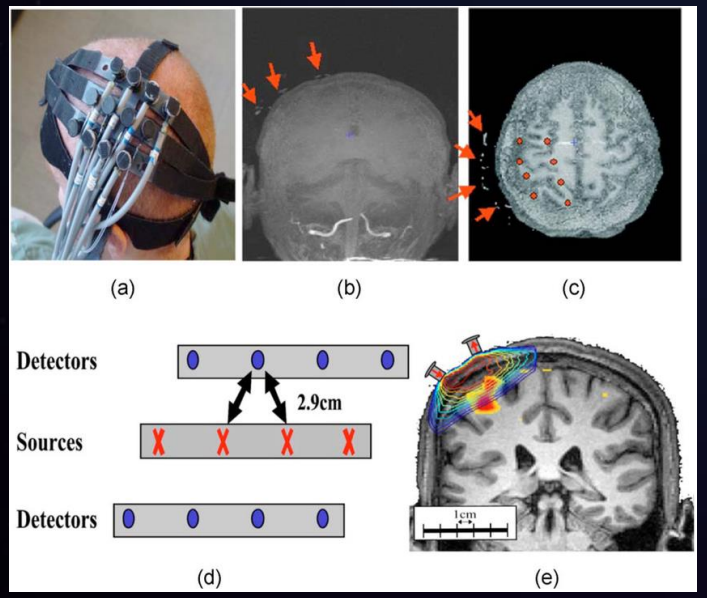
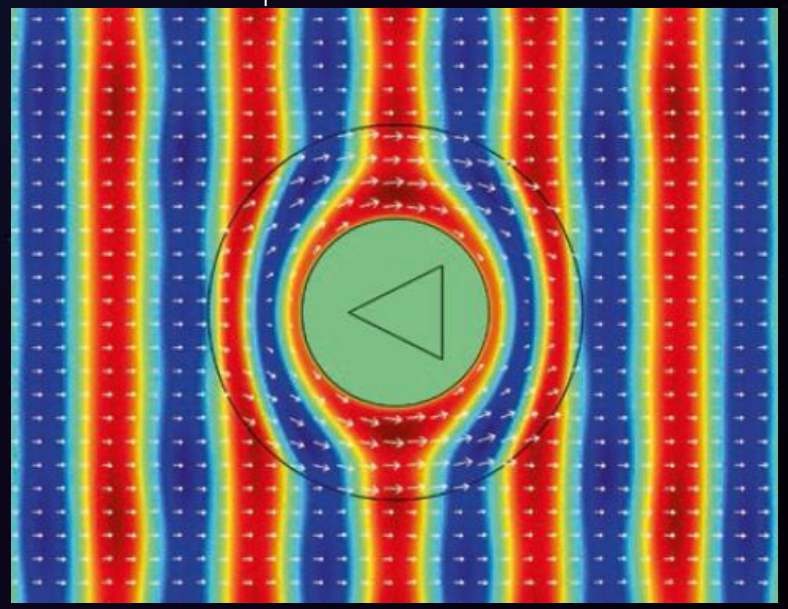


Image source: Theodore J Huppert et al

Metamaterial & Transformation Optics

- Metamaterials exhibits non-traditional electromagnetic properties such as negative permeability, negative refraction index, hyperbolic dispersion, sub-wavelength imaging, field enhancement etc.
- Invisibility cloaks, stealth coating, superlens, hyperlens are some devices that exploit advantages of Metamaterial and transformation optics



EM wave around a cloak. Image credit: : Yi-Pai Huang

6 Advances in Light-Based Technologies

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Solar Cells Technology

- Optical technology is been applied to improve characteristics and performance of solar cells for diverse applications.
- Higher efficiency, lower cost, lighter weight, flexibility and easy production process drives innovation and design of modern solar cells for mobile, wearable, domestic, industrial and space applications.
- Meaningful progress are been recorded in the follow types

Crystalline Silicon solar cells

Amorphous Silicon solar cells

III-V Semiconductor solar cells

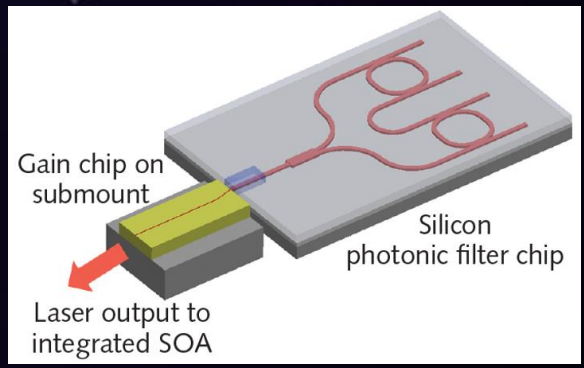
Thin-film solar cells

Dye-sensitized solar cells

Organic solar cells

Integrated Photonics and Optical Interconnects

- Metallic conductors and cables imposes resistive, capacitive and inductive losses in electronics circuits. These often results into signal attenuation, EM interference, increased noise figure and corruption of data or signal
- Miniaturized optical cables are immune to these problems and are gradually been introduced into electronic devices and systems.
- Integrated photonics is a very promising area where optical circuitry can be condensed into chip-scale and they represent the future of quantum computers.



Silicon photonics (SiPhol Chipmage. Image credit: Laserfocusworld.com

6 Advances in Light-Based Technologies

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Optical Communications

- Telecommunication technology has been experiencing rapid development since the era of wired telegraphy and Morse codes.
- Today, cable lines are completely phased out, while radio and microwave spectrum are congested and heavily regulated.
- As data processing and storage capacities are increasing so also is the need to increase data rate, reduce latency and protect the data from theft or interference during transmission
- The optical channel-visible, infrared and lasers are the current and continuing frontier for communication in current and coming centuries

Visible Light Communications

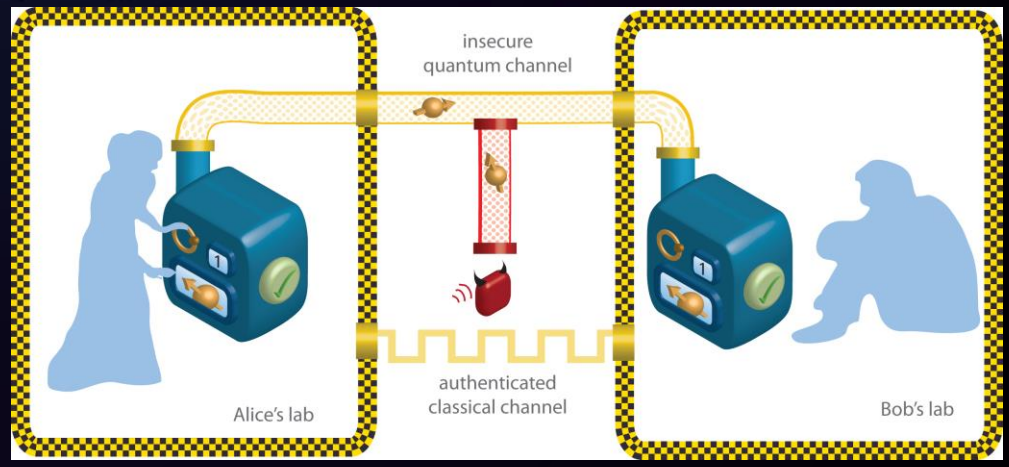
Fiber-Wireless Communications

Terrestrial Free Space Optical Comms

Satellite & Airborne Optical Communications

Quantum Cryptography

- Quantum Key Distribution exploits the quantum mechanical properties of photon to securely maintain a communication link between a transmitter and receiver without any possibility of an eavesdropper to intercept the messages.
- QKD networks are via optical fiber links gradually been deployed and has also been demonstrated between orbiting satellite and ground stations.
- Quantum cryptography receives lots of love from financial and military organizations.



Quantum encryption. Image credit: Phys.org

7 Ideas for Space Exploration with Light

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Space-Based Super-resolution Observation Telescopes & Cryogenic Ground-Based Telescope Array Network

Super Efficient, Multispectral & Radiation Tolerant Solar Cells

Optical-Laser Beamed Power Propulsion for Small Satellites in Deep Space

Fine Adaptive Optics & Detectors for Space-to-Ground Optical Communications

Deep Space Optical Networks

Improved Optical Navigation, Fiber-Optic Gyroscope and Optical Sensors for Spacecraft and Satellites

8 Interactive Discussions

- What triggered the big bang?
- In your opinion, how close can human-rated or robotic space flight technology get close to the speed of light ? How can we utilise black holes, dark matter to aid universal exploration?
- Do we really need to visit another star system or galaxy? What is the value and purpose of the universe?
- How far into the future from now do you think quantum computers will become available to everyone and what breakthrough technology do you think it needs to become feasible?

Thank You!