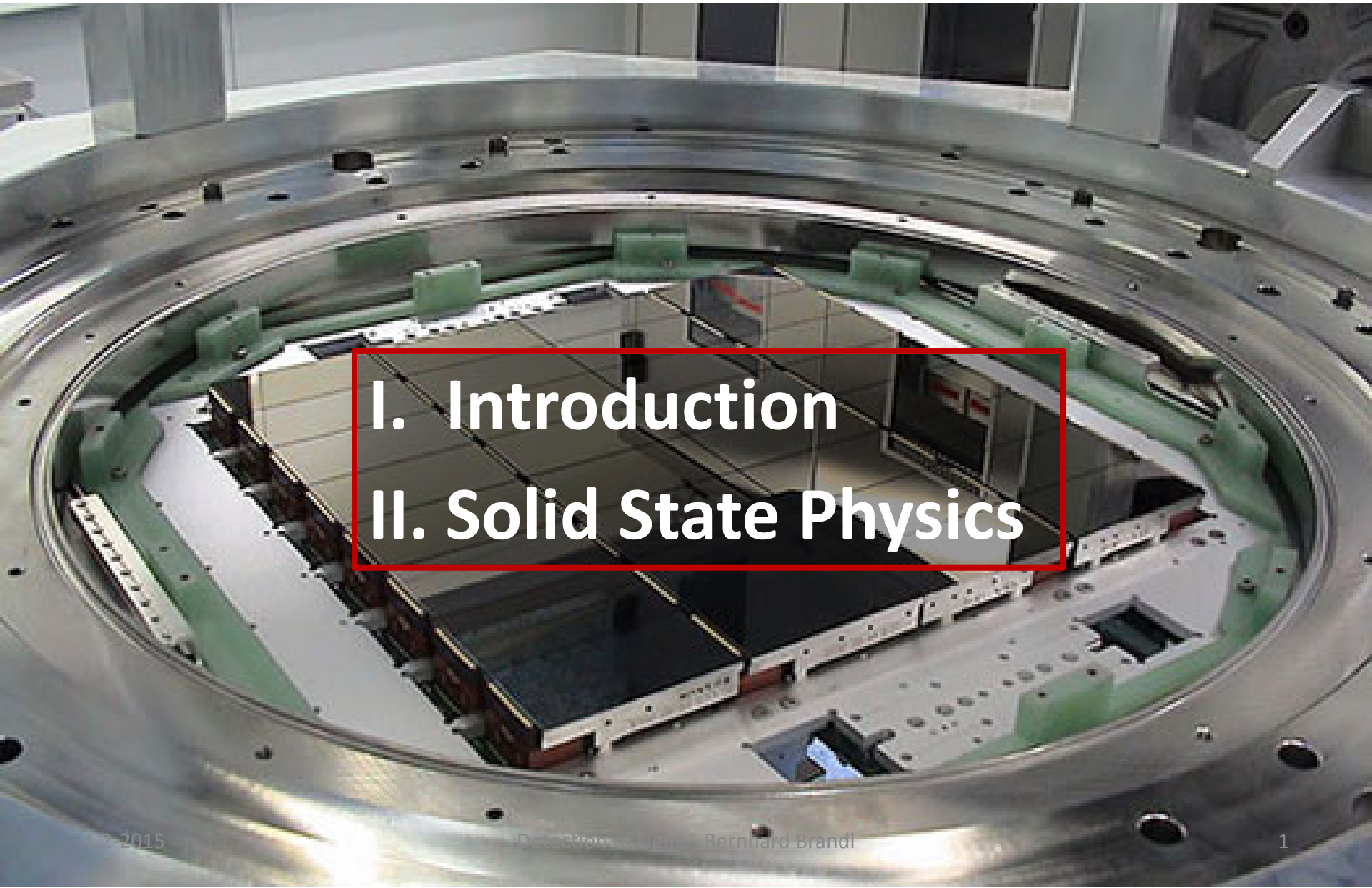
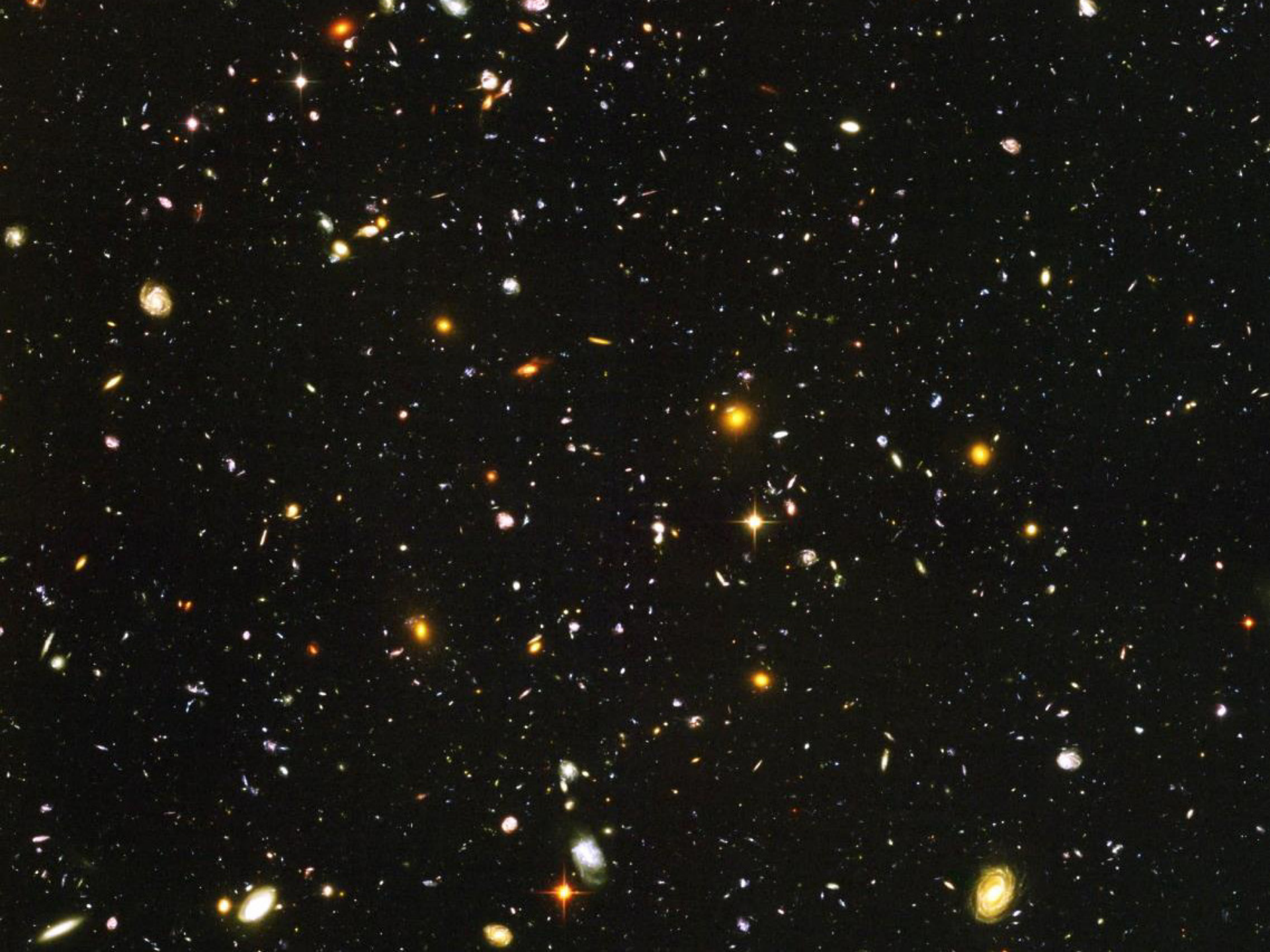
Detection of Light



I. Introduction

II. Solid State Physics

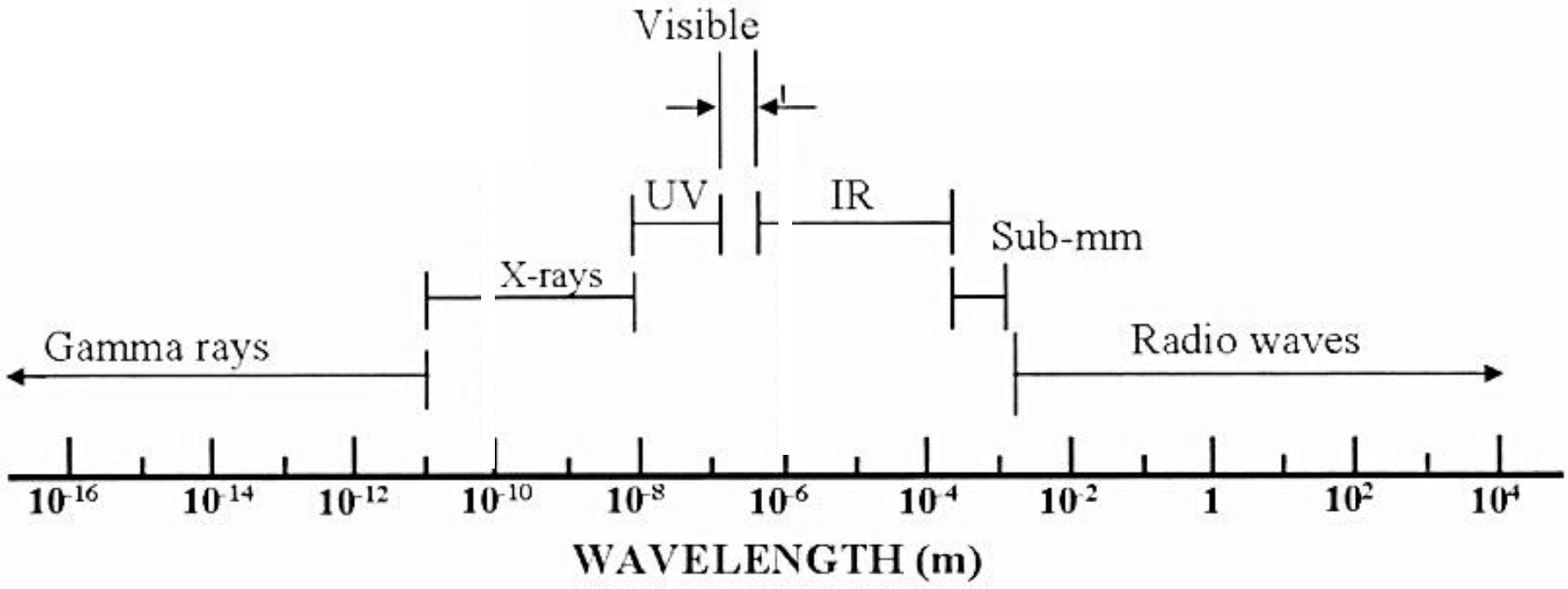
Introduction



Information Carriers in Astronomy

- In situ (planetary spacecraft)
- Gravitational Waves
- Neutrinos
- Photons / electromagnetic waves

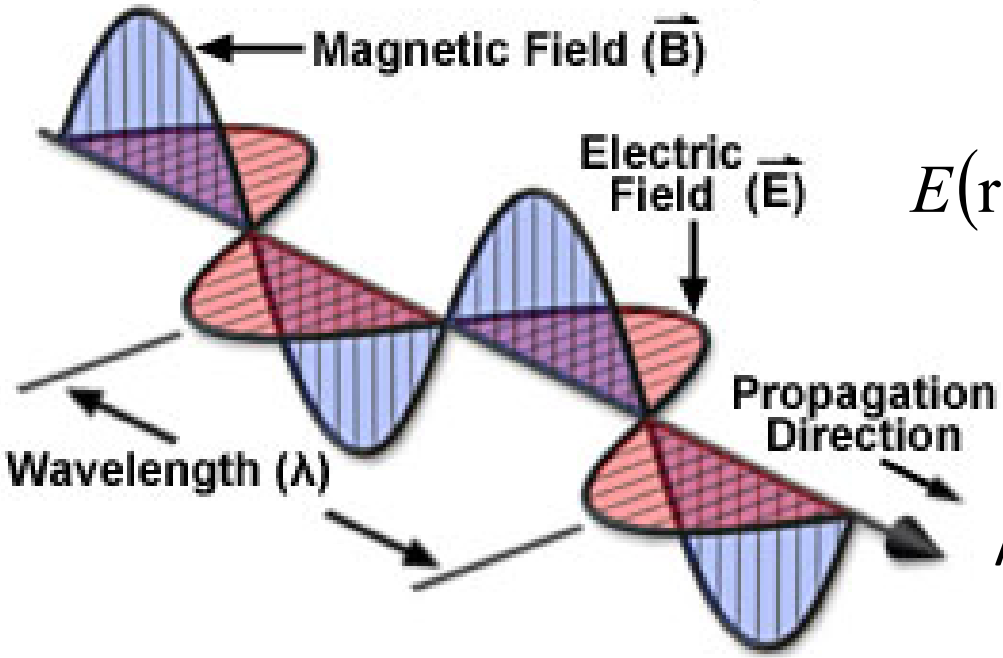
The Electromagnetic Spectrum



Photons

Waves

Light as a Wave



Time Space

$$E(\mathrm{r},t) = \frac{1}{\mathrm{r}} E_0 \cdot \sin(\omega t - \mathrm{k}\cdot\mathrm{r} + \phi_0)$$

Phase angle

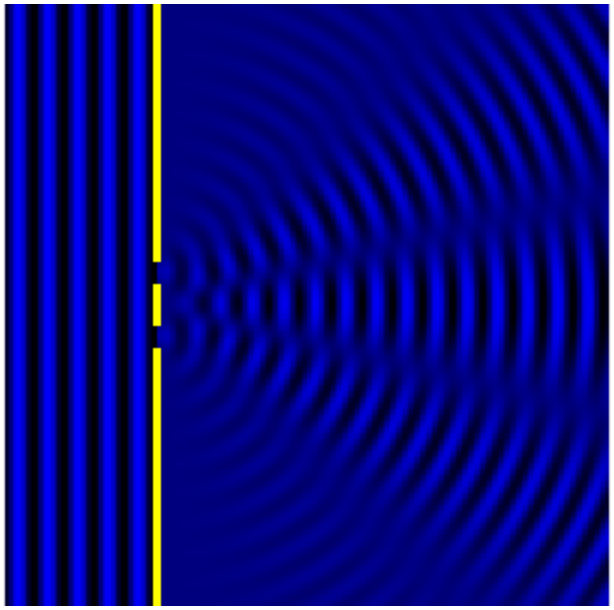
Angular frequency $\omega = 2\pi f$

Wavenumber $k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$

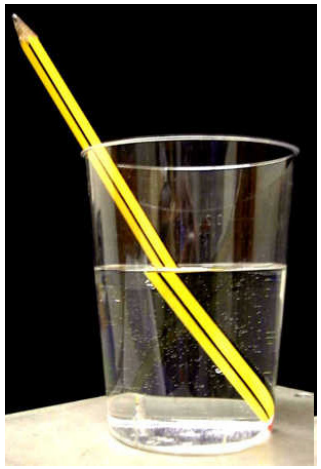
Intensity $\propto (E_0)^2$

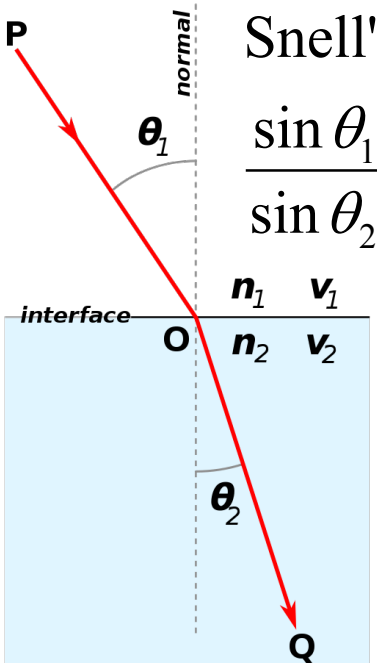
Manifestation as Wave

Diffraction & interference



Refraction



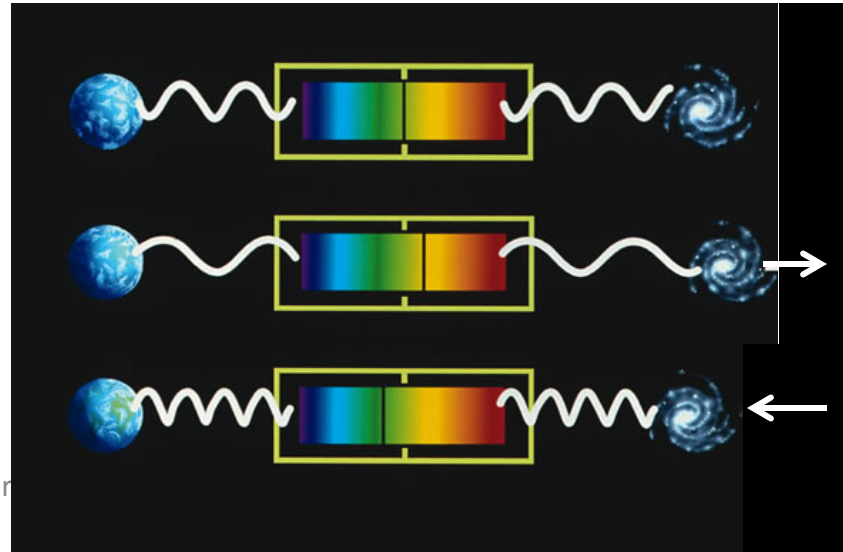


Snell's law :

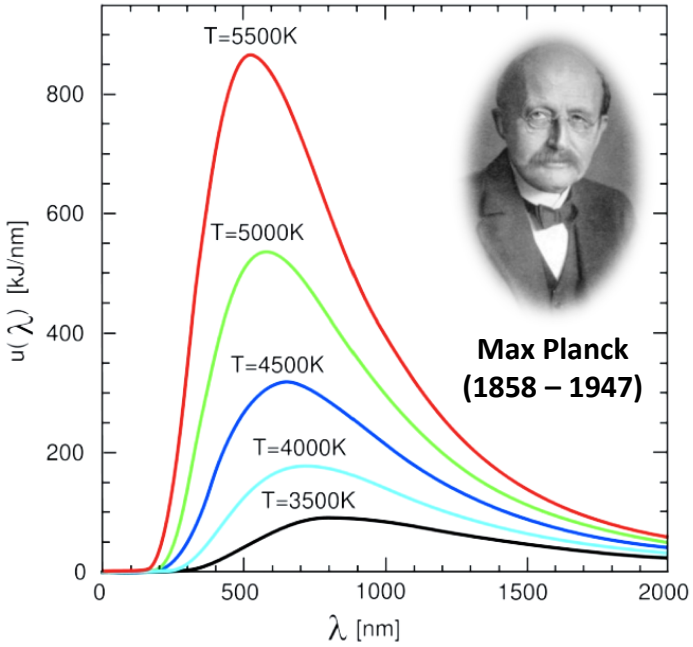
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Doppler effect (non-relativistic)

$$\lambda = \lambda_0\left(1+\frac{v}{c}\right) \quad \text{or} \quad \nu = \nu_0\left(1+\frac{v}{c}\right)$$

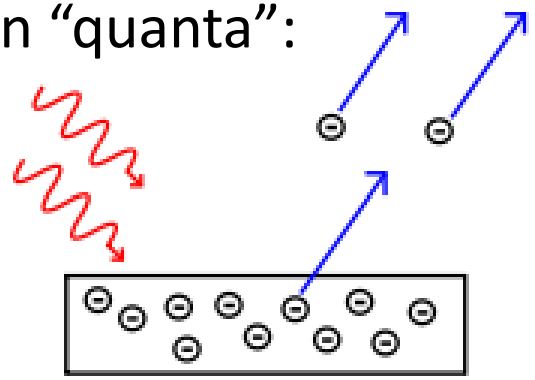


Light as a Particle



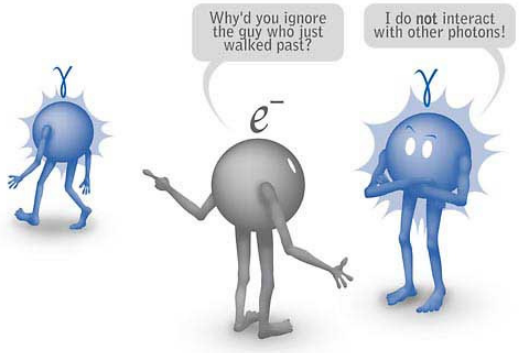
$$I_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1}$$

Photoelectric effect –observed by Hertz (1887) and explained by Einstein (1905): light comes in "quanta":

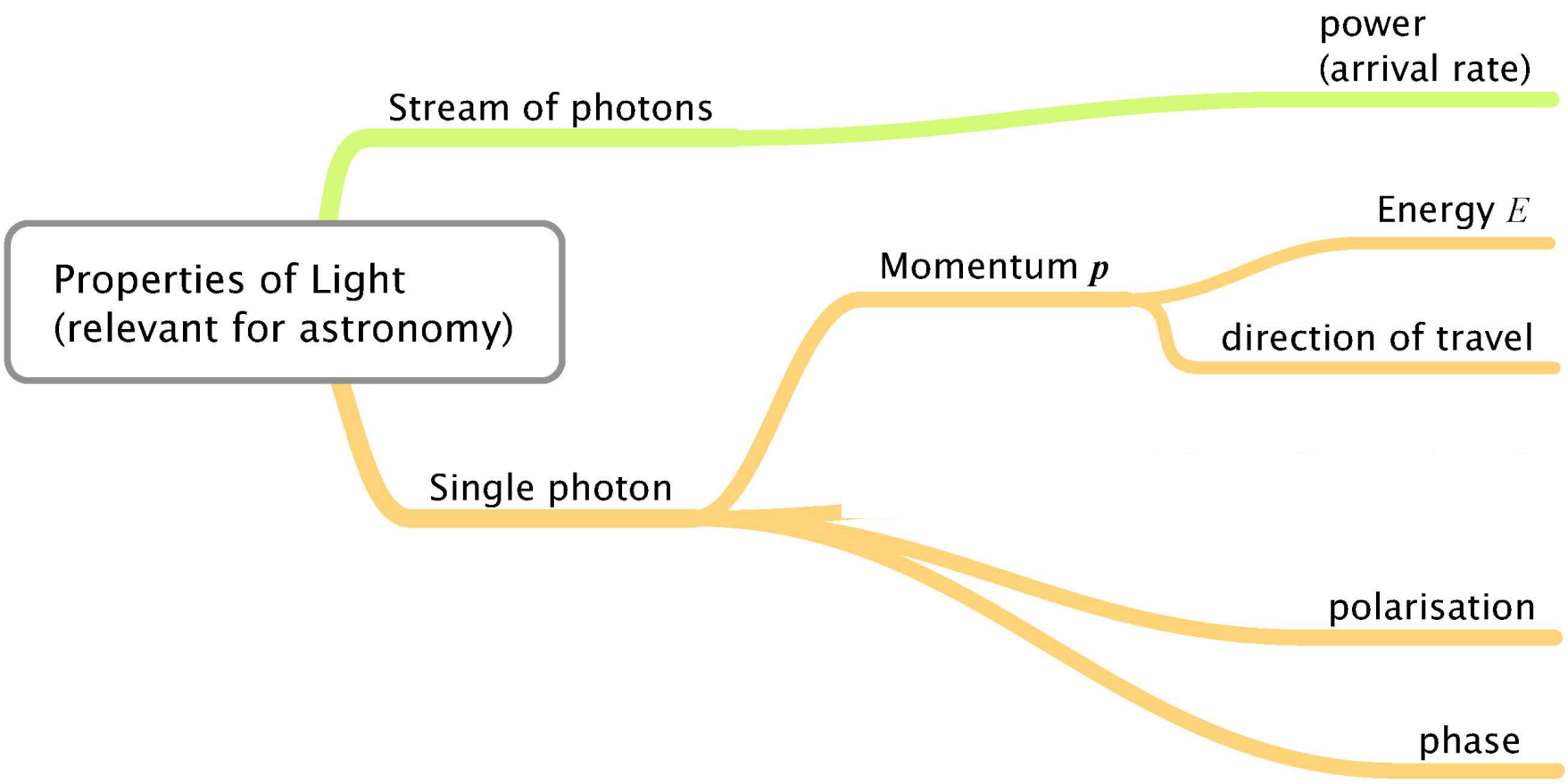


Energy $E = h\nu = \frac{hc}{\lambda}$

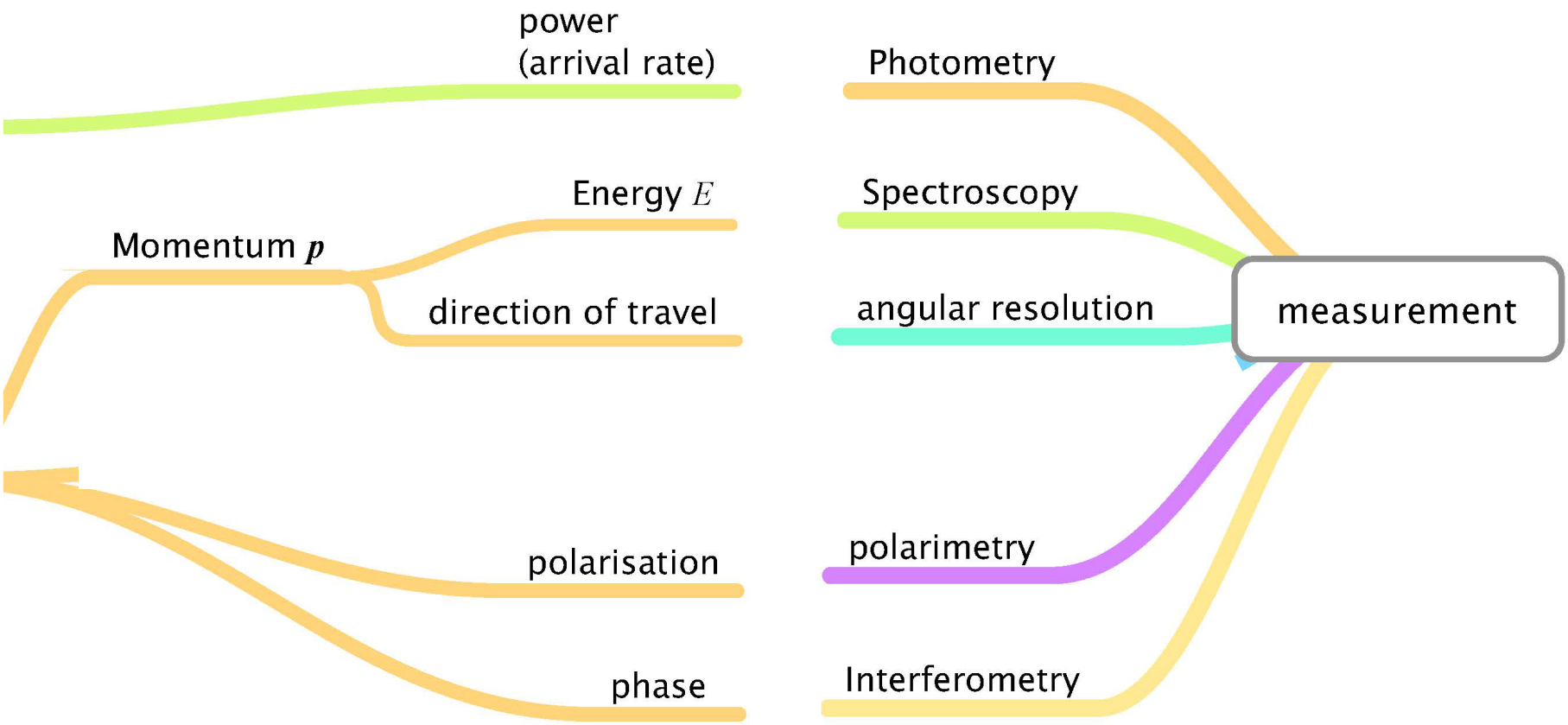
Momentum $p = \frac{h\nu}{c} = \frac{h}{\lambda}$



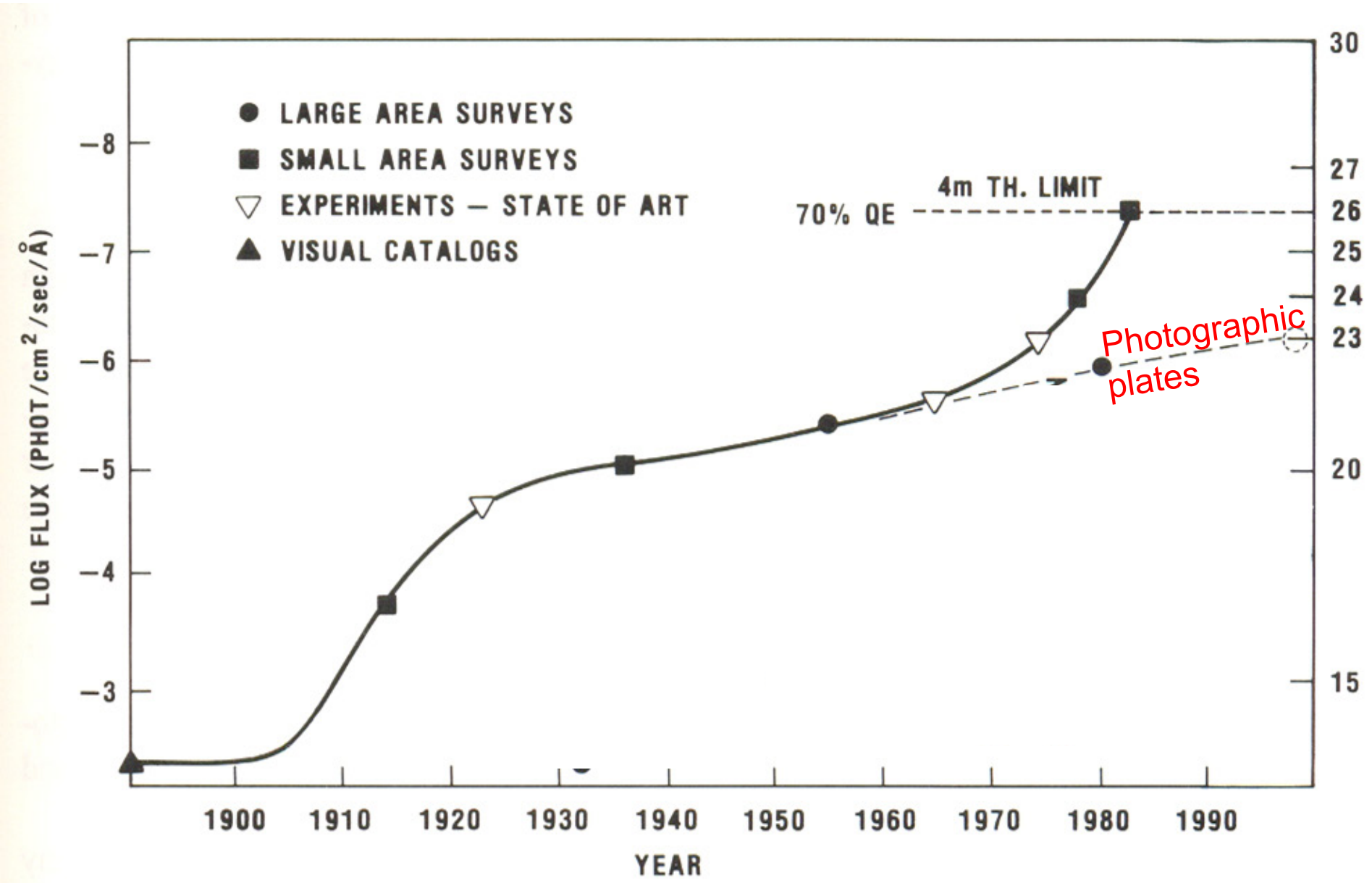
Information carried by Light …



… and Measurements of that Information



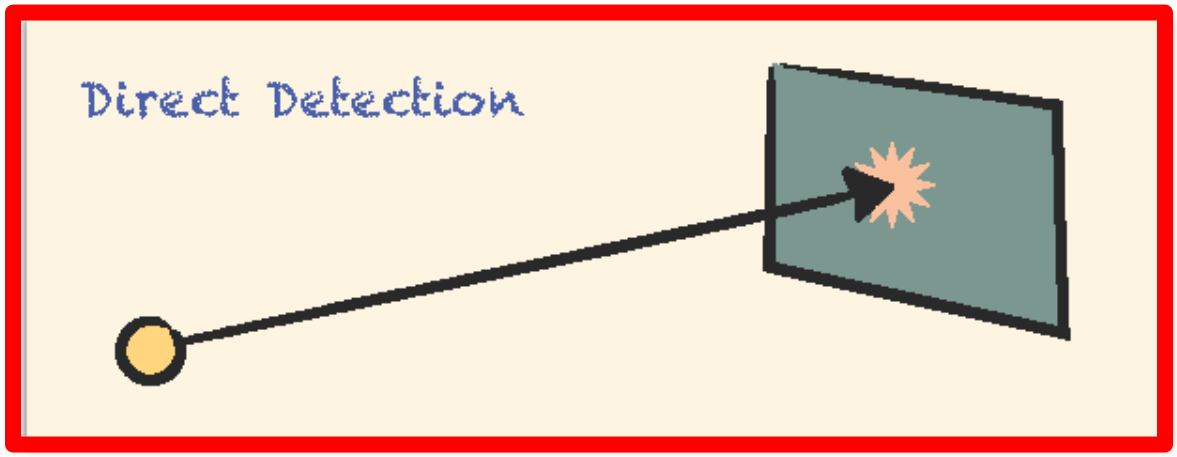
Detector Technology ⇔ Astronomy



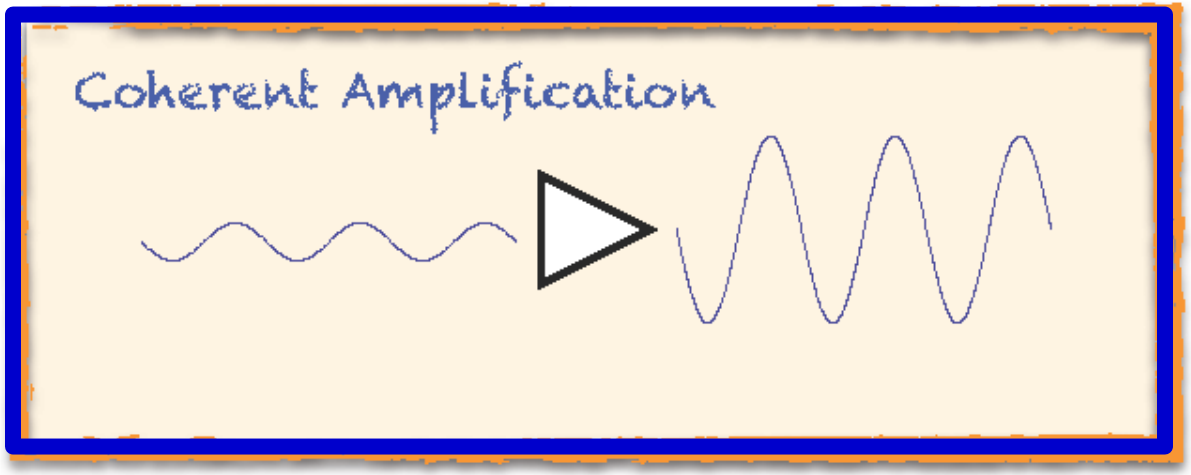
Fundamental Types of Detectors

Two Fundamental Principles of Detection

Respond to individual photon energy



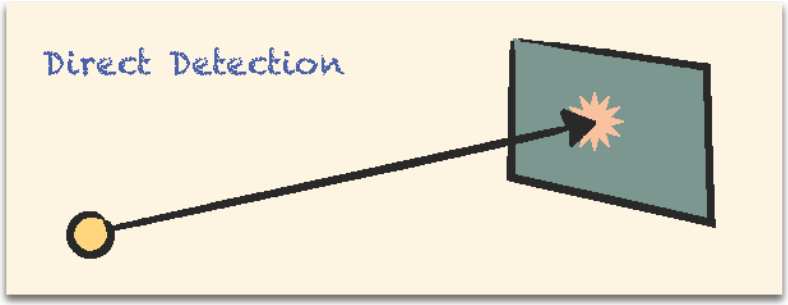
Photons



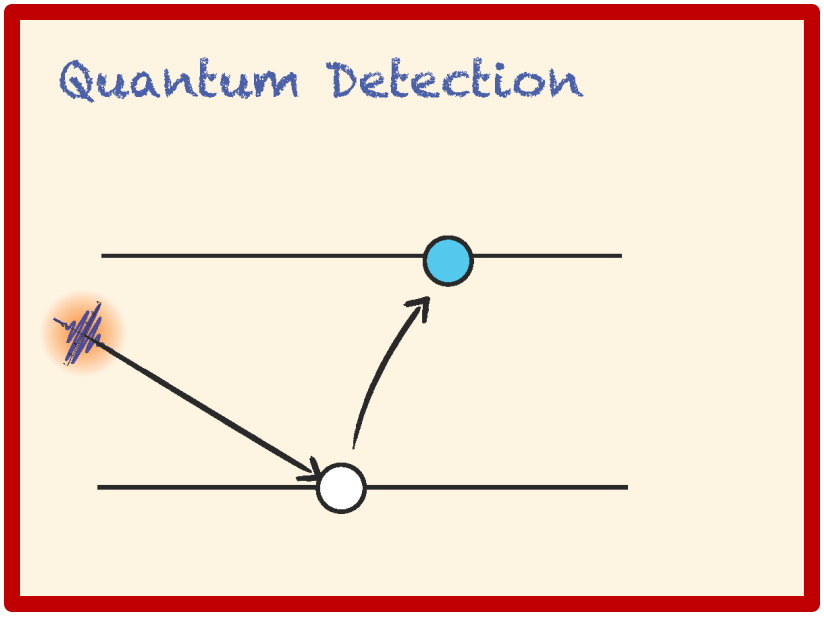
Waves

Respond to electrical field strength and preserve phase

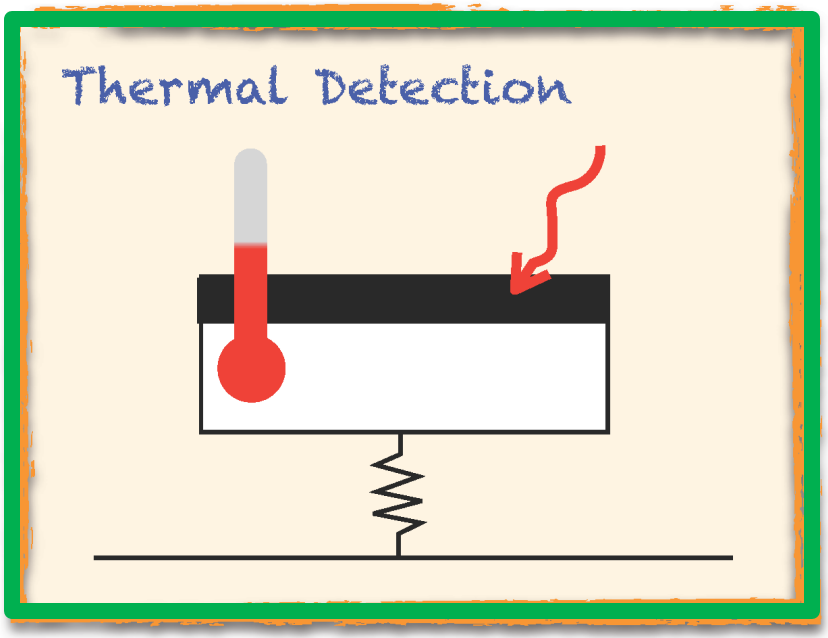
Two Types of *Direct* Detection



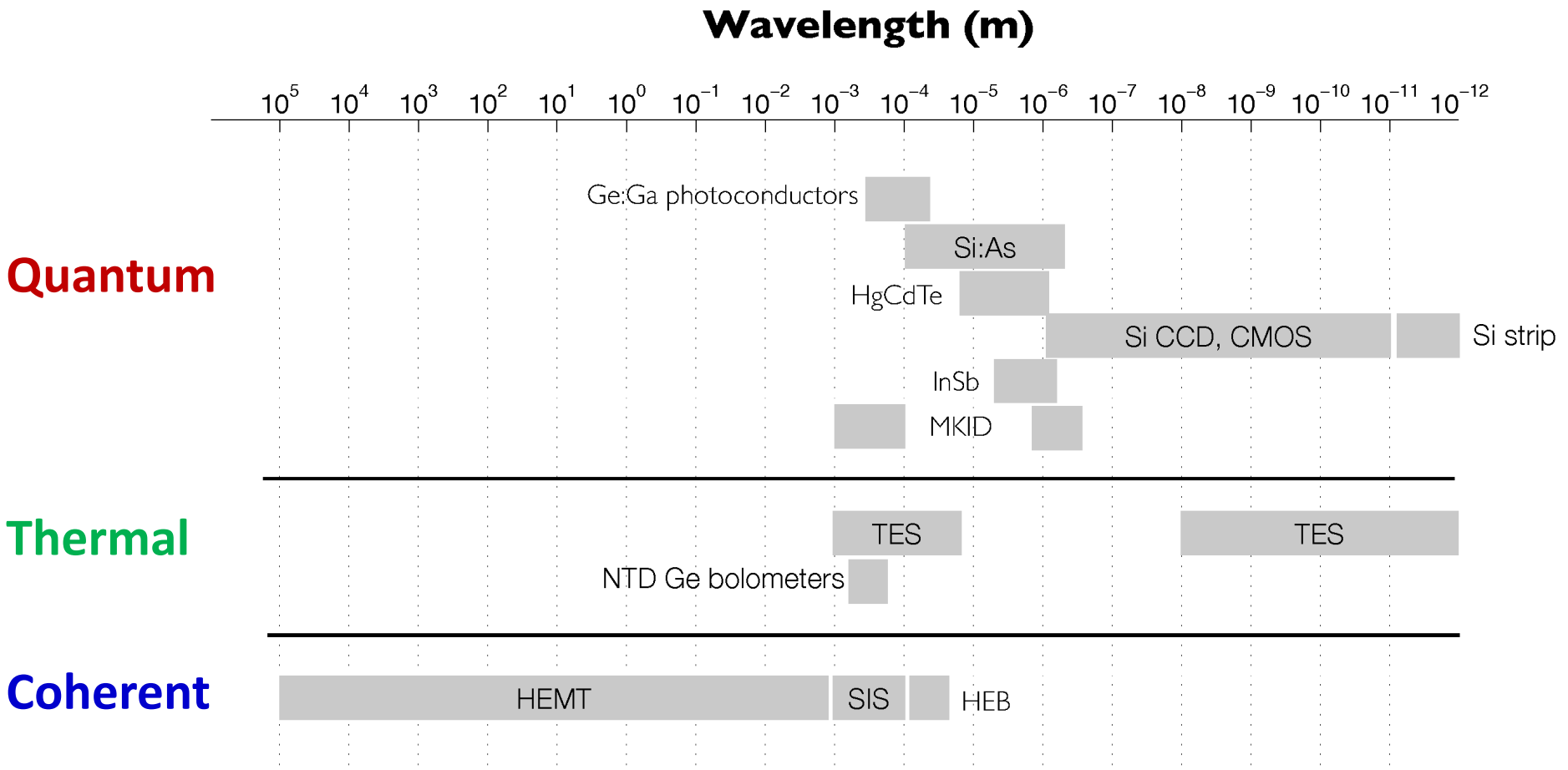
Based on photoelectric effect
(release of bound charges)



Thermalize photon energy



Wavelength ⇔ Technology



Course Organization

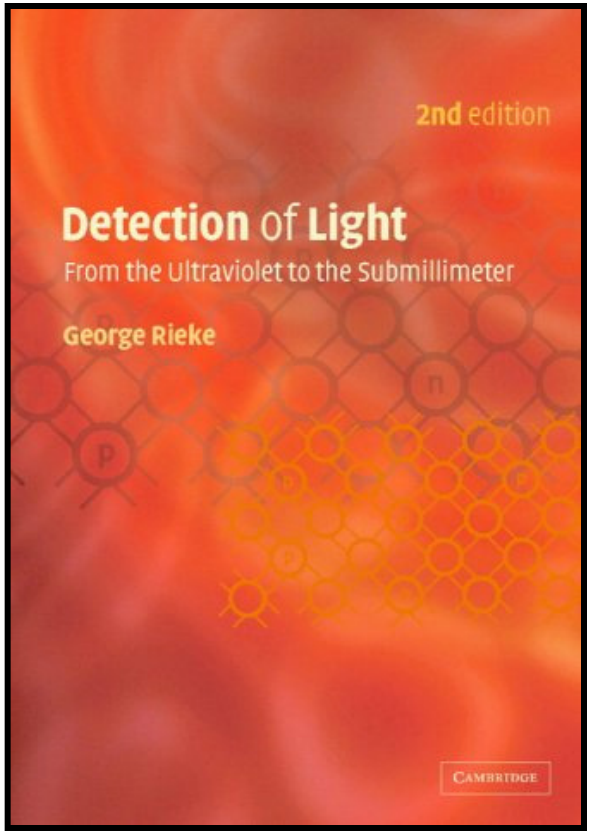
Course Topics & Lectures

#	Date	Title	Topics	Homework
1	4-Feb-15	Intro & Solid State Physics	General: grading, exercises, book, nature of light, EM spectrum, technology, photographic plate, overview of detectors principles and types; solid state physics: atomic energy levels, crystal: bands, (animation!), conductors and semi-condd., k-vector, Fermi energy	Homework
2	11-Feb-15	Intrinsic Photoconductors & Noise	general principle, box diagram, conductivity, mobility, tau, gain, quantum efficiency and responsivity; intro noise: poisson & Gaussian & 1/f noise; detector noise: Johnson, kTC, 1/f, BLIP	Homework
3	18-Feb-15	Extrinsic Photoconductors	energy bands, doping, wavelength ranges, limitations, drawbacks and comparisons; BIB detectors, photodiodes, avalanche diodes	Homework
4	4-Mar-15	IR Arrays, CCDs & Readouts	IR arrays: principle, construction, readout electronics; CCDs: principle, back/front illuminated, thinned, readout, CTE, CT architectures, GAIA example, variants	Homework
5	11-Mar-15	Operations and Artifacts	Readout schemes: SUR, Fowler, linearity & dynamic range, data rates; cryogenics: cryo-vac environments, cooling requirements	Homework
6	18-Mar-15	Bolometers	Basic operation, time constants, superconducting, edged; comparison: responsivity, noise, NEP	Homework
7	25-Mar-15	Heterodyne Detectors	general principle, IF, mixing, sidebands, bandwidth, components (HEB, SIS); performance: throughput, S/N, noise and antenna temperature, comparison coherent-incoherent detectors	Homework
8	1-Apr-15	New Technologies & Summary	EM CCDs, OTCCDs, (SIS) TESs, MKIDs, …; Summary	Homework

Lecture slides (“handouts”) will be posted on the site

Homework and solutions will be posted on the site

Literature



Main resource:

Detection of Light - from the Ultraviolet to the Submillimeter,

by George Rieke, 2nd Edition, 2003, Cambridge University Press, ISBN 0-521-01710-6.

Further reading:

- Introduction to Solid State Physics (8th Edition) by Charles Kittel;
- Electronic Imaging in Astronomy: Detectors and Instrumentation (2nd Edition) by Ian S. McLean;
- Observational Astrophysics by P. Lena, Francoise Lebrun & Francois Mignard;

Course Organization

- 3 ECTS, Level 500 – you need to register in uSis
- Lecture room: Huygens #106/7 from 9:00 - 10:45 hr
- Lecture period: 4 February – 1 April
- Lecturer: Dr. Bernhard Brandl, office: #535
- TA: Michael Wilby, office: #570
- Grade = 80% written exam + 20% mandatory homeworks
- Exam date: 13 April, 14:00 - 16:00 hr.

Course Website

http://home.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html

Location & Time

The lectures take place in the **Huygens building #106/7** on **Wednesdays** from **9:00 - 10:45 hr** (unless otherwise noted - see schedule below). The lectures run from 4 February through 1 April (no joke!).

Lecturer

The lecturer is Dr. Bernhard Brandl, office: #535 (Oort building), phone (071) 527-5830, email. The teaching assistant is Michael Wilby, office: #570, email .

Course content

Detectors are the crucial link between the astronomical target and the observer. As astronomers are aiming at fainter and fainter objects the quality and calibration of the detector systems have become increasingly important. The main goal of this course is to provide an overview of the various physical principles and techniques to detect electromagnetic radiation, from the UV to the sub-millimeter. Course topics are intrinsic and extrinsic photo-conductors, photodiodes and other junction-based detectors, detector arrays, bolometers, coherent receivers, and submillimeter- and millimeterwave heterodyne receivers. The course will not only provide the physical background of the various detector technologies but also cover practical aspects, which are of general interest to the observer, such as cosmetic quality and detector artifacts, linearity and dynamical range, spectral response and bandwidth, quantum efficiency and noise. For more details see schedule below.

Credits for the course: **3 ECTS**. Course level is 500. The course language is English.

Literature

The course will be heavily based on the book Detection of Light - from the Ultraviolet to the Submillimeter, by George Rieke, 2nd Edition, 2003, Cambridge University Press, ISBN 0-521-01710-6. *It is recommended that students get their own copy of this book.*

Recommended for further reading are:

- Introduction to Solid State Physics (8th Edition) by Charles Kittel;
- Electronic Imaging in Astronomy: Detectors and Instrumentation (2nd Edition) by Ian S. McLean;
- Observational Astrophysics by P. Lena, Francoise Lebrun & Francois Mignard;

Grading

The **final grade** is based to 80% on the written exam and 20% on the mandatory homeworks. The **exam date is 13 April**, 14:00 - 16:00 hr. It is a written, "closed book" exam. Pocket calculators are required at the exam.

Schedule

#	Date	Title	Topics	Homework
1	4-Feb-15	Intro & Solid State Physics	General: grading, exercises, book, nature of light, EM spectrum, technology, photographic plate, overview of detectors principles and types; solid state physics: atomic energy levels, crystal: bands,	Homework

Course TA: Michael Wilby

Office: 570 (Oort Building)
Email: wilby@strw.leidenuniv.nl

Weekly Exercises:

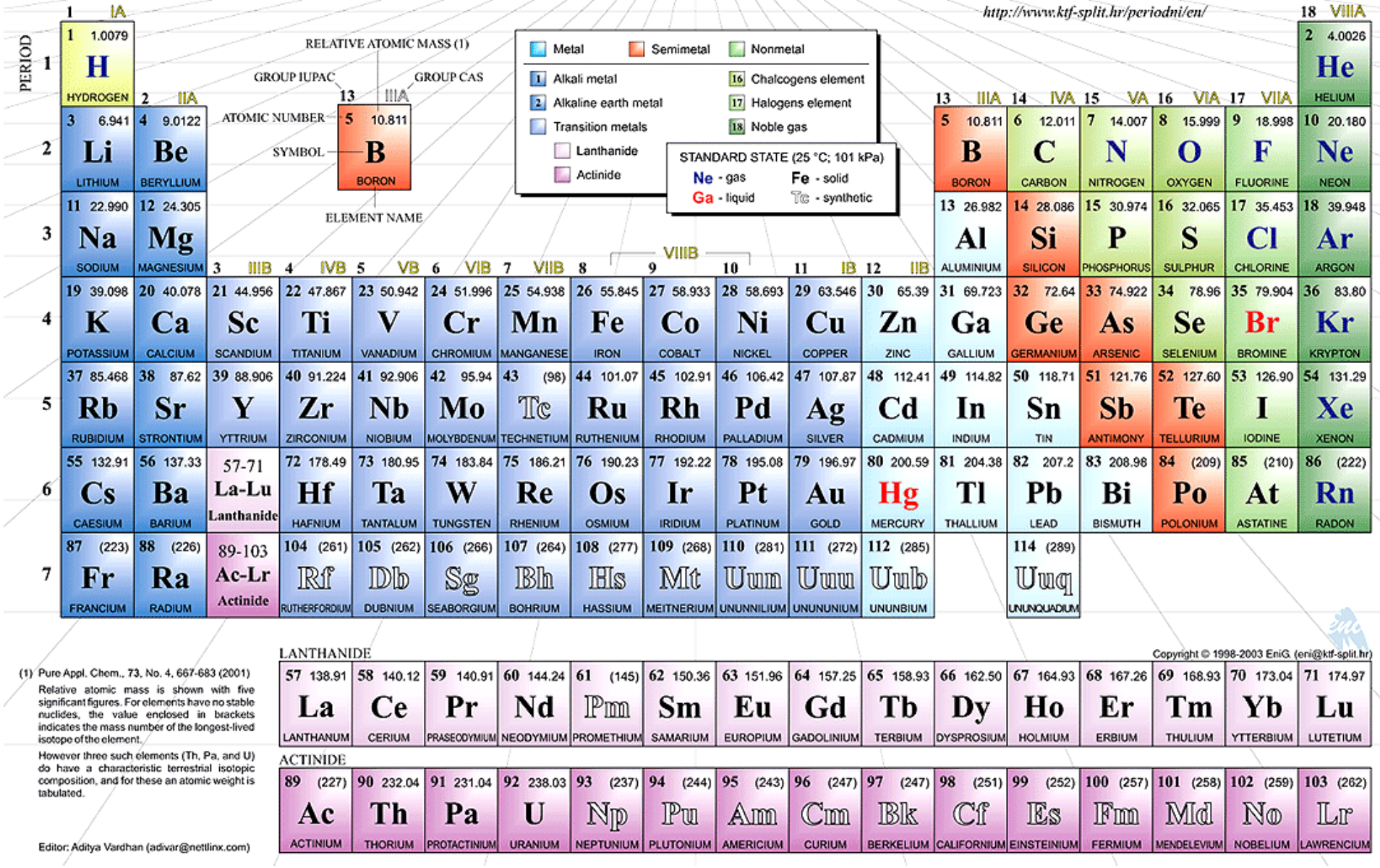
- 7 sets, 1 per week (20% of final grade)
- Distribution: Friday following each lecture (via email and course website)
- Deadline: 17:00 Friday, 1 week after distribution, to my pigeon hole (Kaiser lounge) or in person
- Marked exercises handed back in the next lecture

Any administrative or exercise-related questions:
drop by my office or send me an email!
(Please direct more detailed questions on course content to Dr. Brandl)

Basics of Solid State Physics

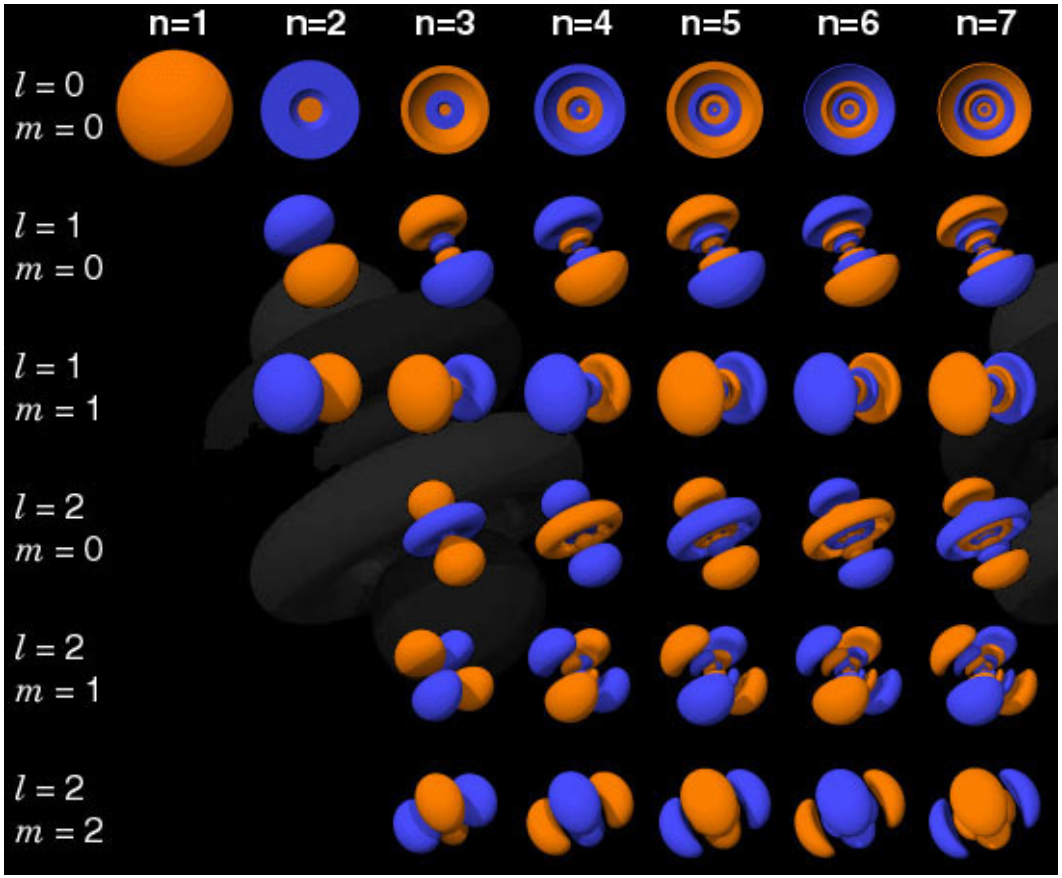
Electronic Levels

Nucleons define the Period Table of the Elements



Electrons lead to Atomic Lines and Bands

- Electrons are described by probability clouds (“orbitals”) with specific energies.
- An electron around a positively charged nucleus has one unique set of four quantum numbers (QN).



Principal QN (**n**) = electron shell

Orbital QN (**l**) = angular momentum

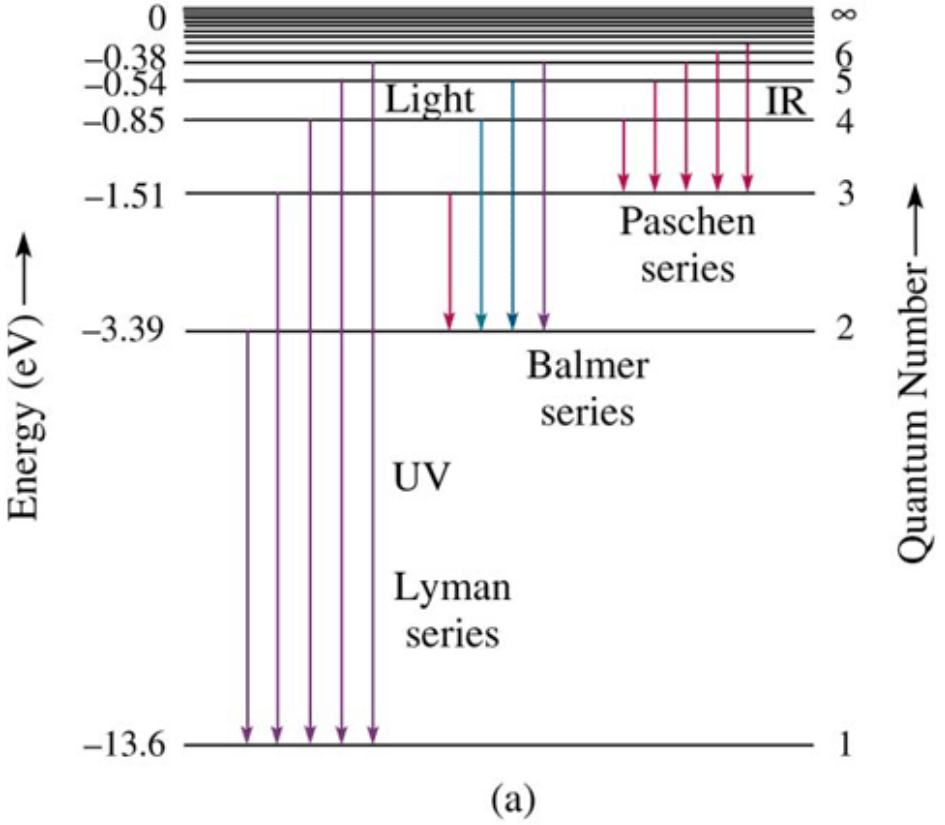
Magnetic QN ($\mathbf{m_l}$)

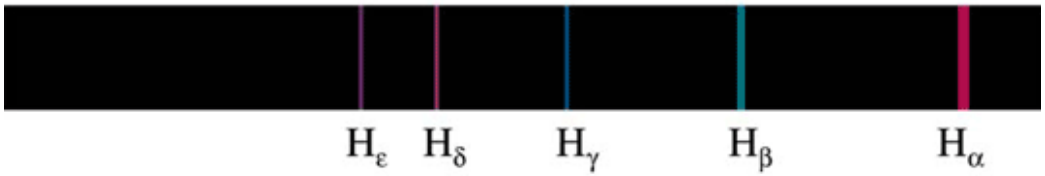
Spin QN ($\mathbf{m_s}$)

Electronic Energy Levels

- An atom can absorb or emit photons of specific energies
- In this process, electrons change their energy levels ("orbitals")

Example:
hydrogen atom
with one electron

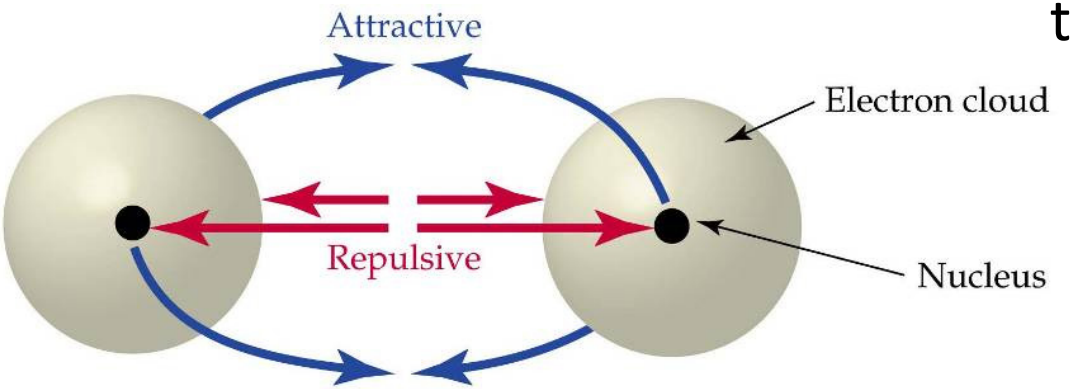


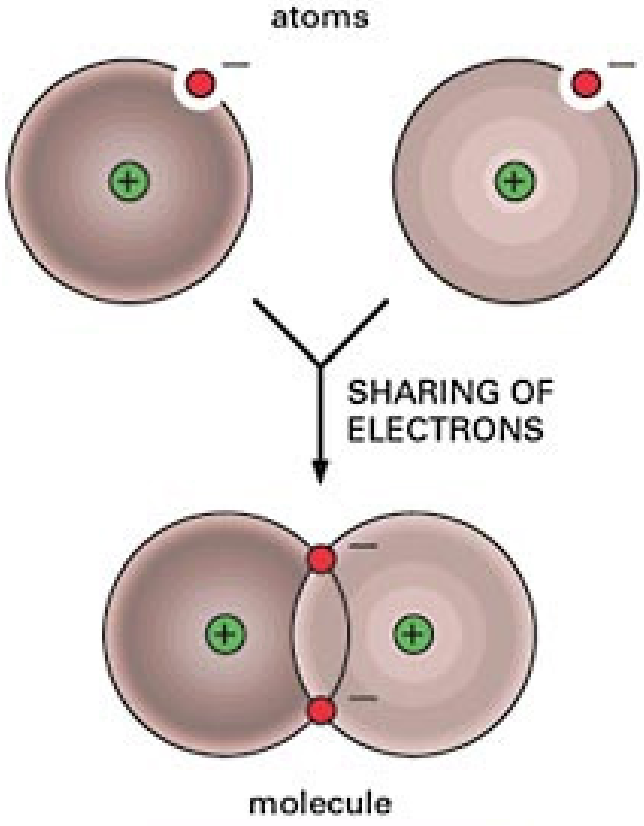


Crystal Lattices

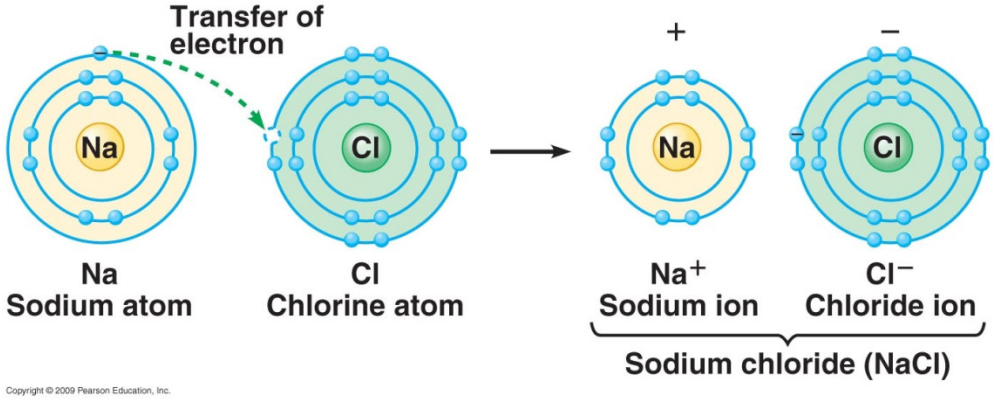
Electronic Bonding

Atoms with “incomplete” (= less than eight electrons) outer shells want to form a stable configuration





This can lead to transfer of electrons (→ salts) or sharing of electrons (→ covalent bonds)



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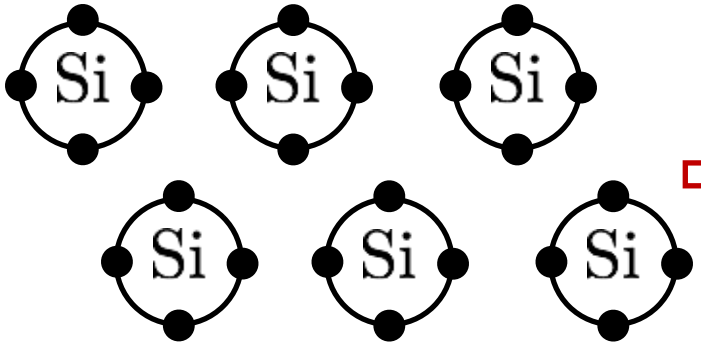
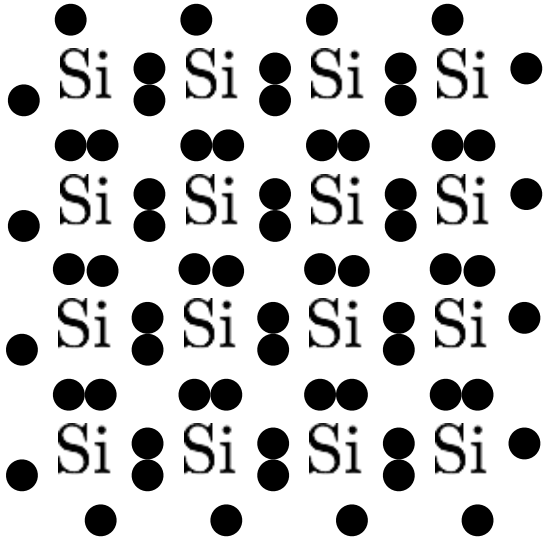
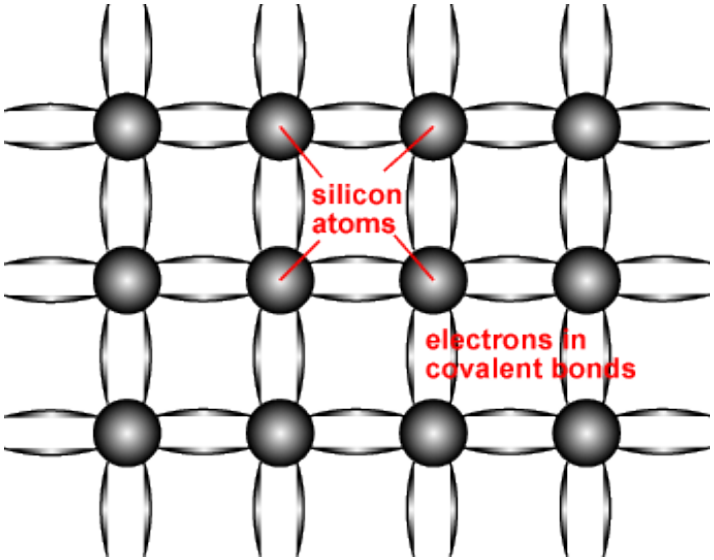
The Diamond Lattice

Elements with 4 e^- (e.g., C, Si, Ge) form crystals with a diamond lattice structure (each atom bonds to four neighbors).

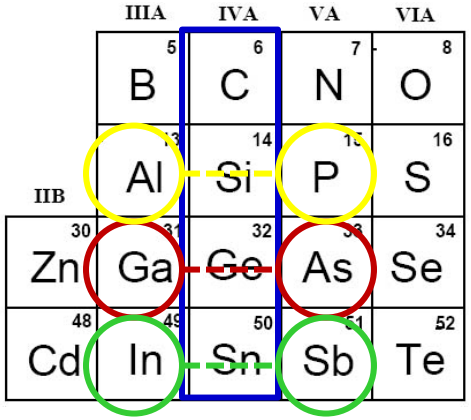




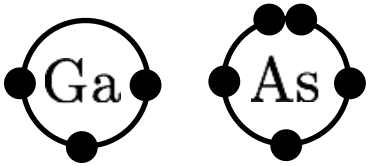


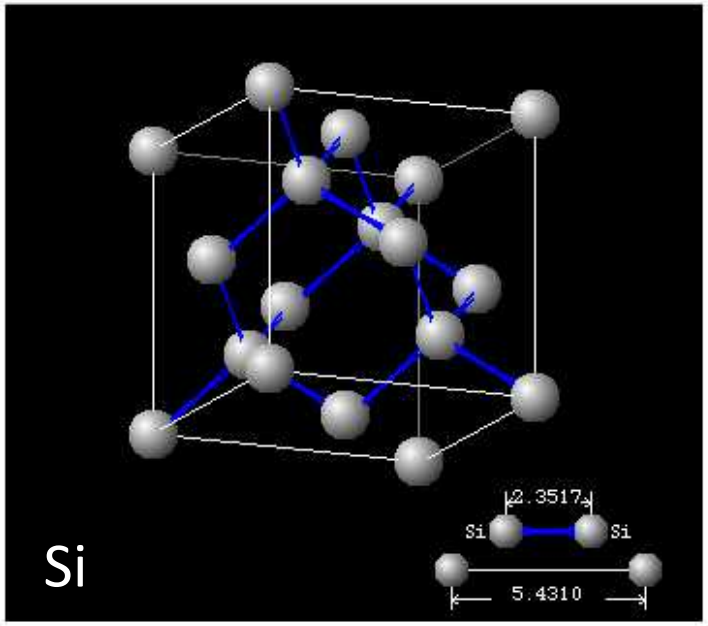
III – IV Semiconductors

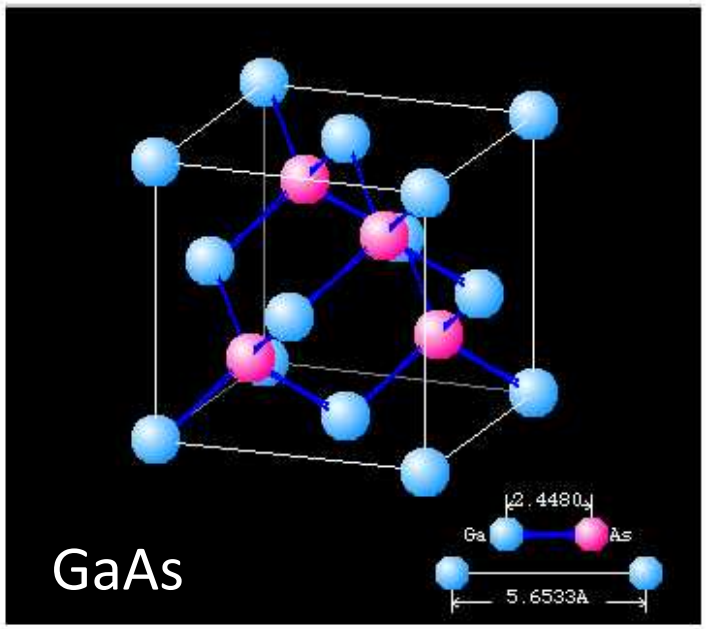
A diamond lattice can not only be formed by IV elements (C, Si, Ge) but also by elements from the 3rd and 5th group of elements.



Gallium has 3 electrons, Arsenic has 5 electrons:







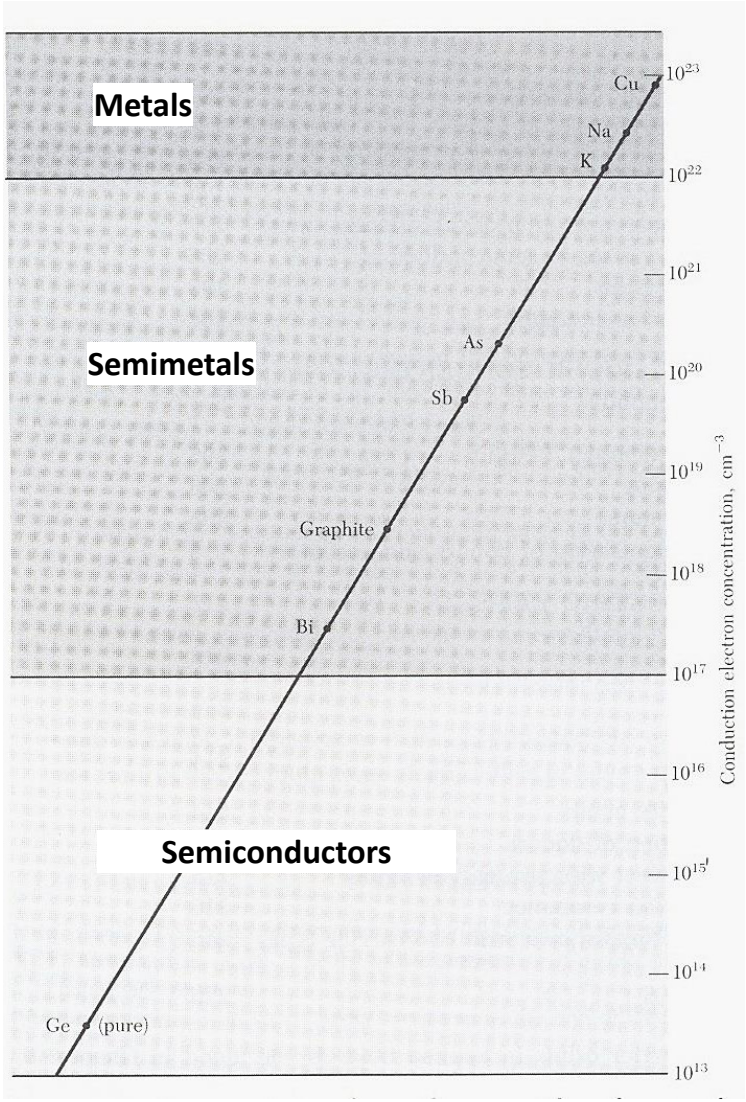
Common Semiconductor Materials

(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaN	CdS
			GaP	CdSe
			GaAs	CdTe
			GaSb	
			InP	
			InAs	
			InSb	

Electronic States and Bands

Metals, Semiconductors and Insulators

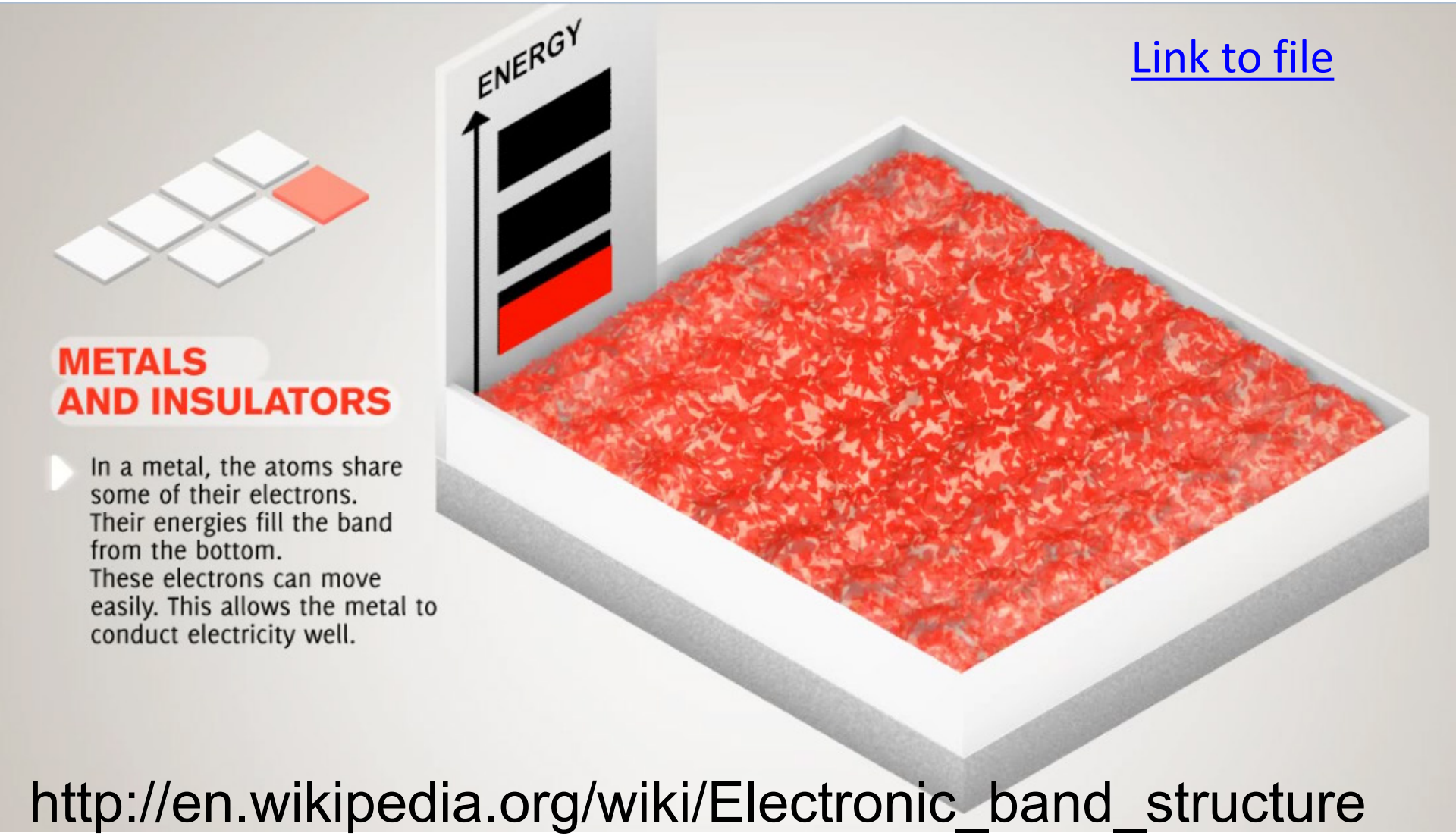


Metals have high electrical conductivity and consist of positive ions in a crystal lattice surrounded by delocalized electrons.

Semiconductors have electrical resistivity between metals and insulators, which is temperature dependent.

Insulators (also called dielectrics) resist the flow of electric current.

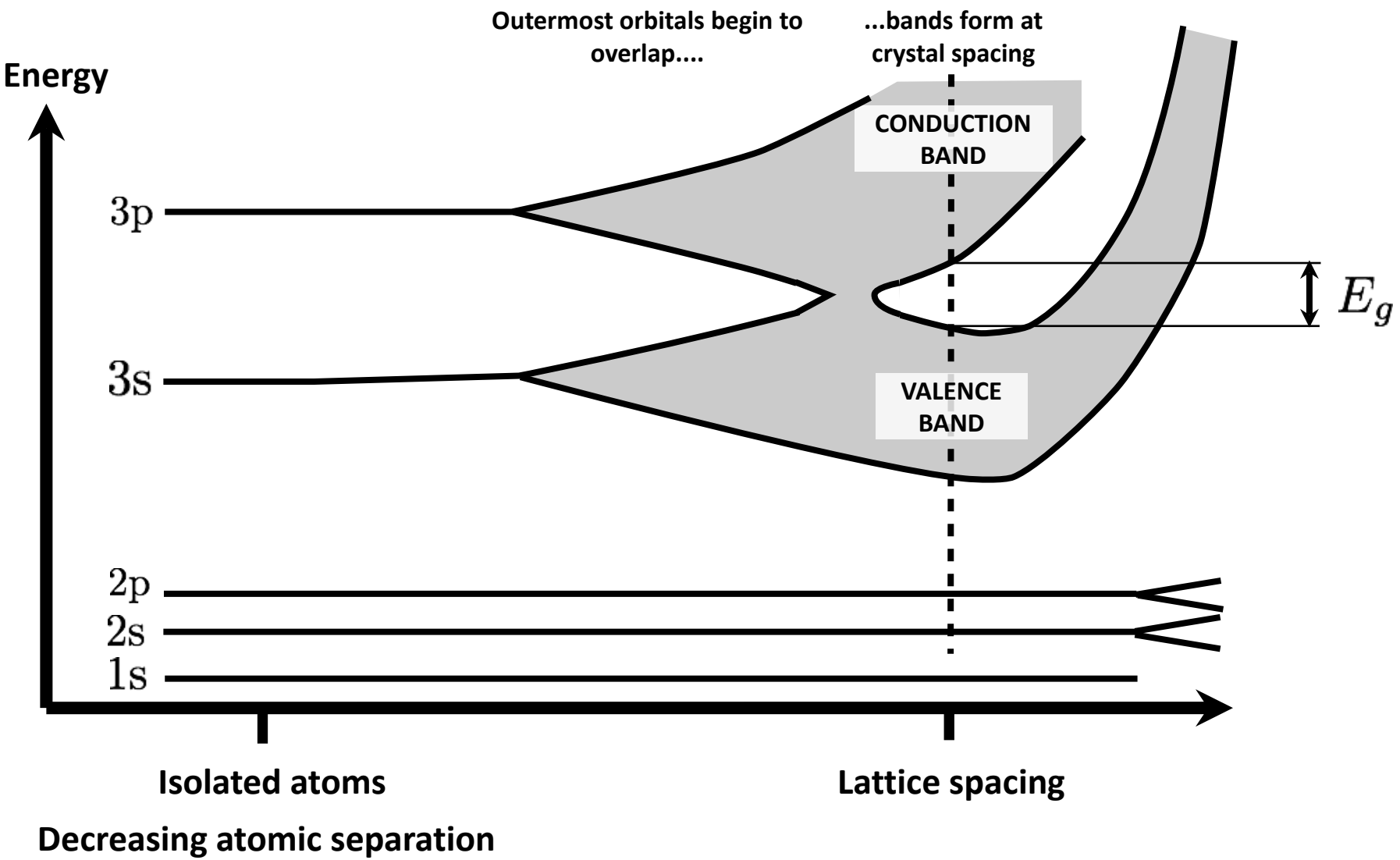
Animation: Electronic States and Bands



Link to file

http://en.wikipedia.org/wiki/Electronic_band_structure

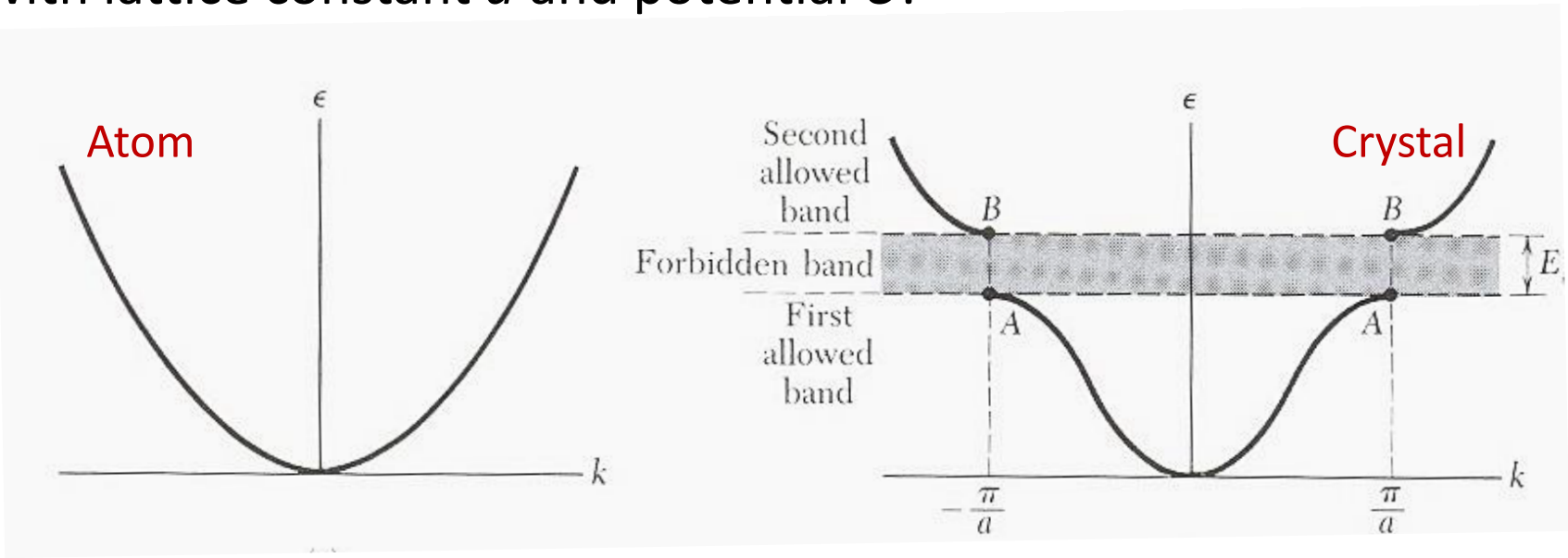
Atomic Orbitals overlap → Electronic Bands



Bands in a periodic Crystal Lattice

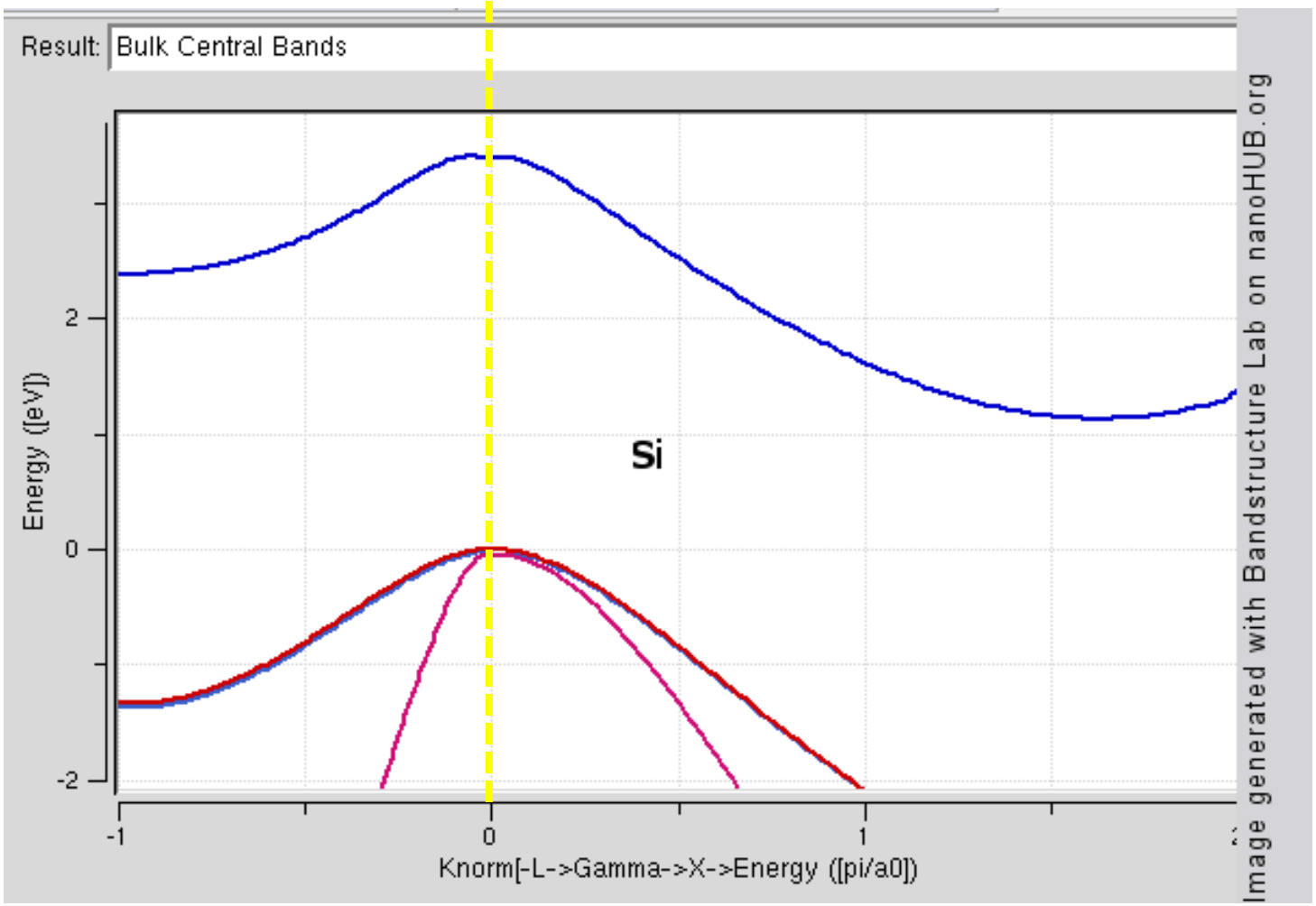
The so-called k-vector of an electron or hole in a crystal is the wave-vector of its quantum-mechanical wavefunction $\psi_k = U(k,r)e^{(ik.r)}$

The electron moves* with momentum $p = \hbar k$ in a periodic lattice with lattice constant *a* and potential *U*.



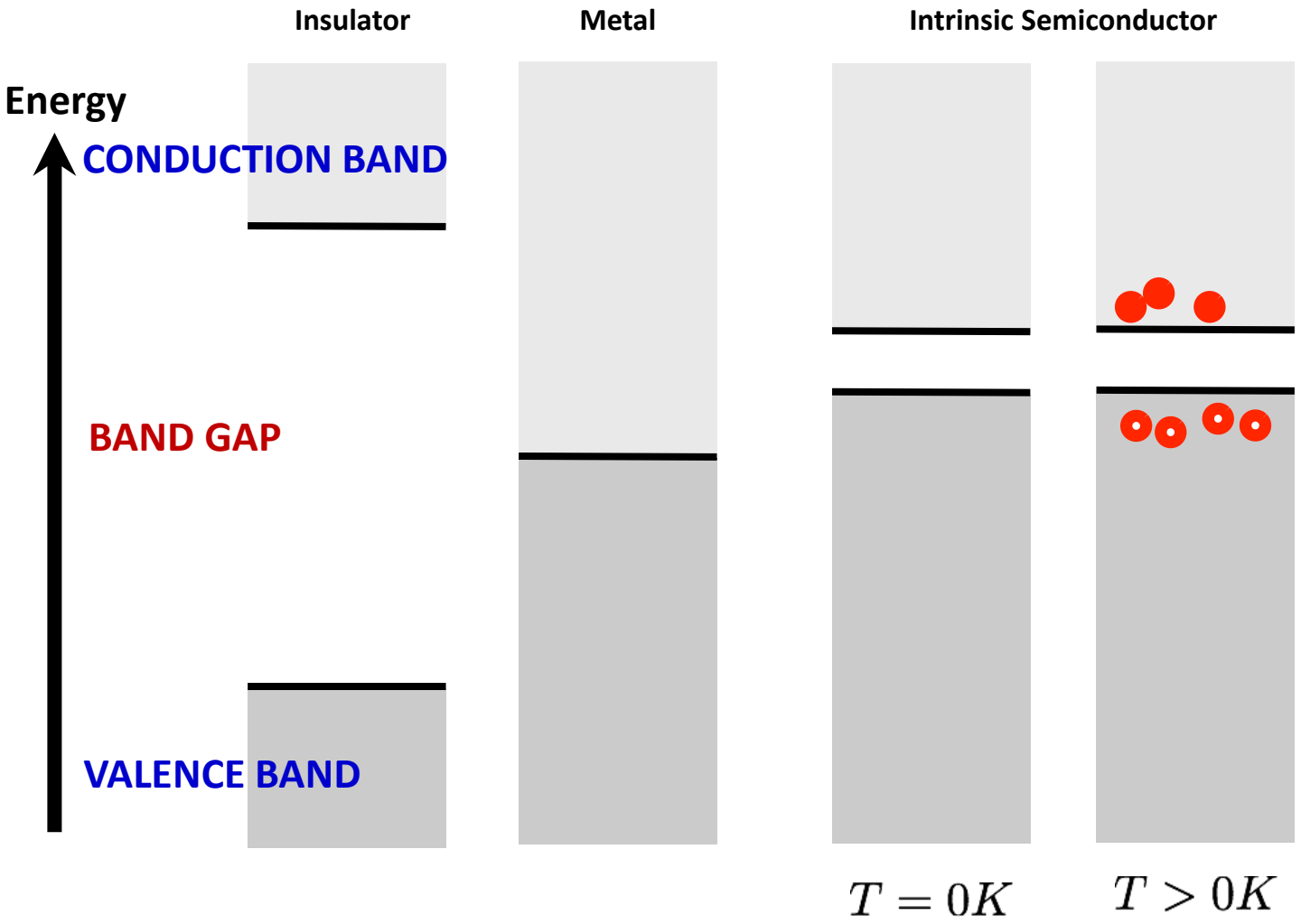
*note that even in a crystal with T=0, the electrons have momentum

Real Band Structures

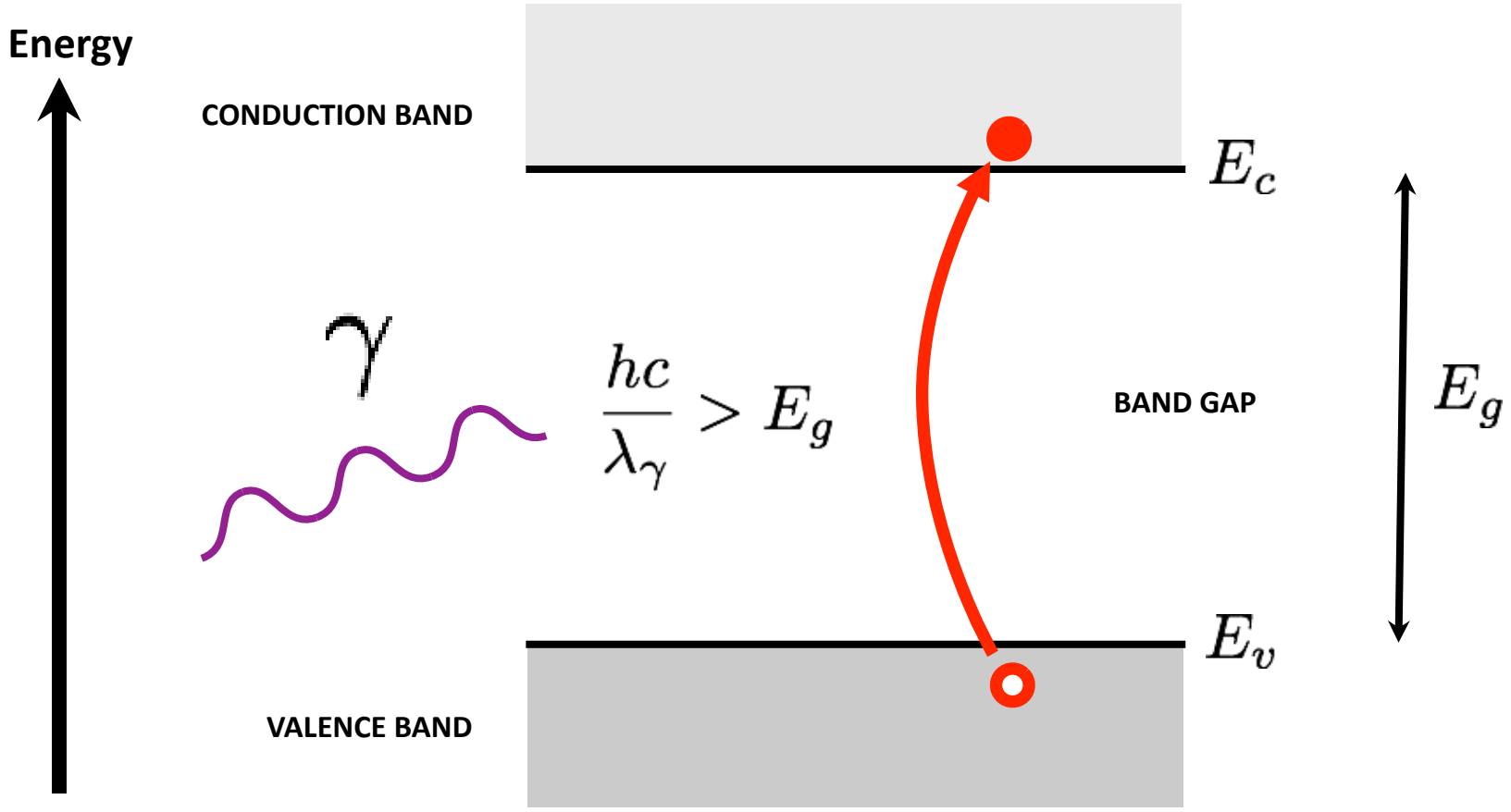


"Bulkbandstructure" by Saumitra R Mehrotra & Gerhard Klimeck - Bandstructure Lab on nanoHUB.org Link: http://nanohub.org/resources/8814. Licensed under CC BY 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Bulkbandstructure.gif#mediaviewer/File:Bulkbandstructure.gif

Band Gaps of Isolators, Metals and Semiconductors



What makes a Detector work …:



That photon of energy $\frac{hc}{\lambda_\gamma} > E_g$ may be our astronomical signal.

However, note that electrons can also get thermally excited ← cooling

Fermi Energy and Distribution

The Fermi Energy

In a 1D, periodic potential, the electronic energy states are given by $E_n = \frac{\hbar^2}{2m}\left(\frac{n\pi}{a}\right)^2$

The Pauli principle requires that no two electrons have exactly the same quantum numbers.

The energy corresponding to the *highest occupied quantum state* in a system of N electrons is the Fermi energy:

$$E_F = \frac{\hbar^2}{2m}\left(\frac{N\pi}{2a}\right)^2$$

At T = 0 K the Fermi energy is the same as the chemical potential μ.

The Energy Distribution of Electrons (1)

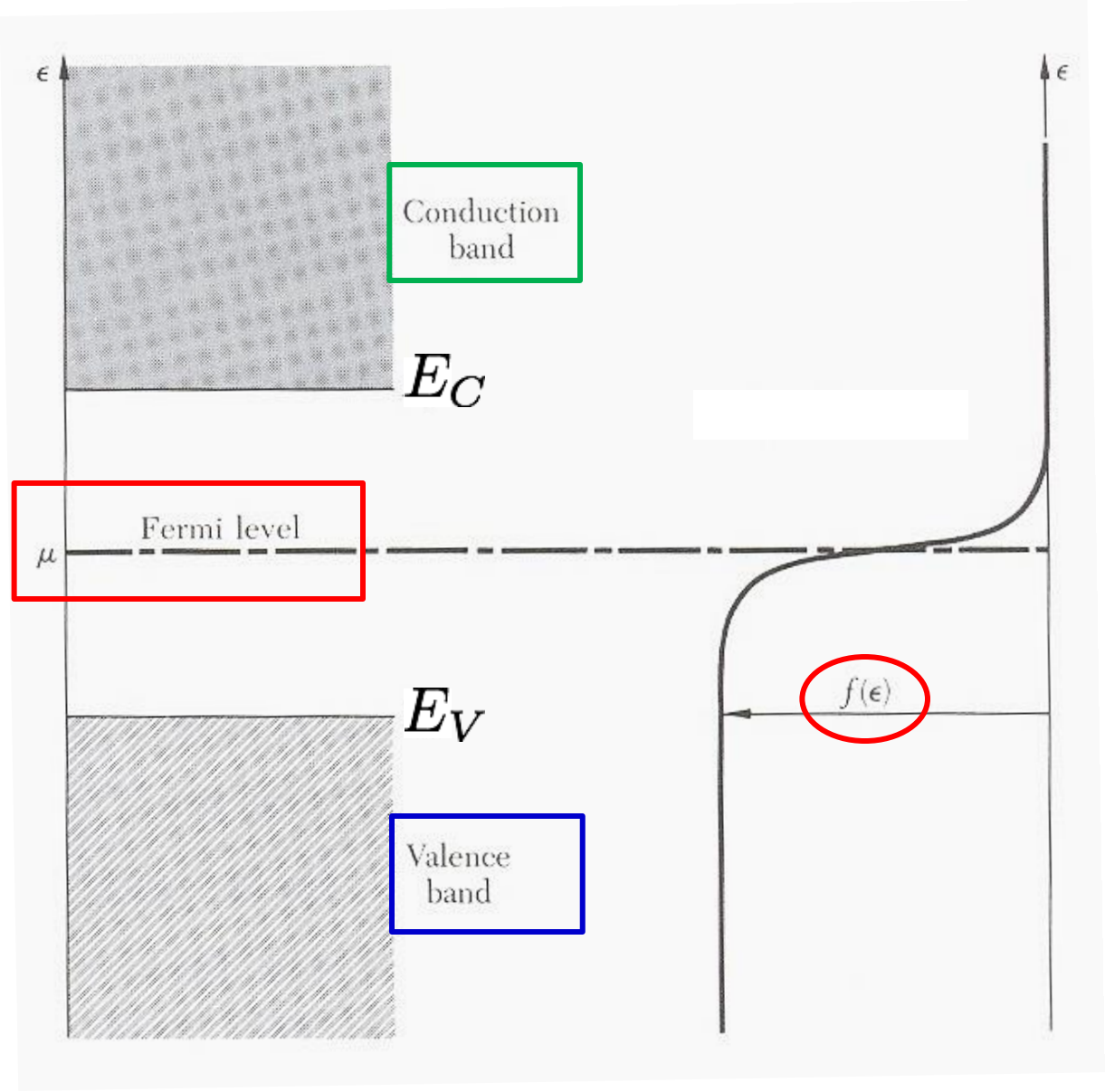
In the classical picture, the energetic distribution of electrons would be given by the Maxwell-Boltzmann statistics:

$$\frac{n_2}{n_1} = e^{-(E_2-E_1)/kT} = e^{-E_g/kT}$$

In the QM picture the concentration of electrons in the conduction band is given by: $n_0 = \int_{E_c}^{\infty} f(E)N(E)\,\mathrm{dE}$

...where N(E) dE is the density of states and f(E) the Fermi distribution (Fermi-Dirac statistics): $f(E) = \frac{1}{1+e^{\frac{E-E_F}{kT}}}$

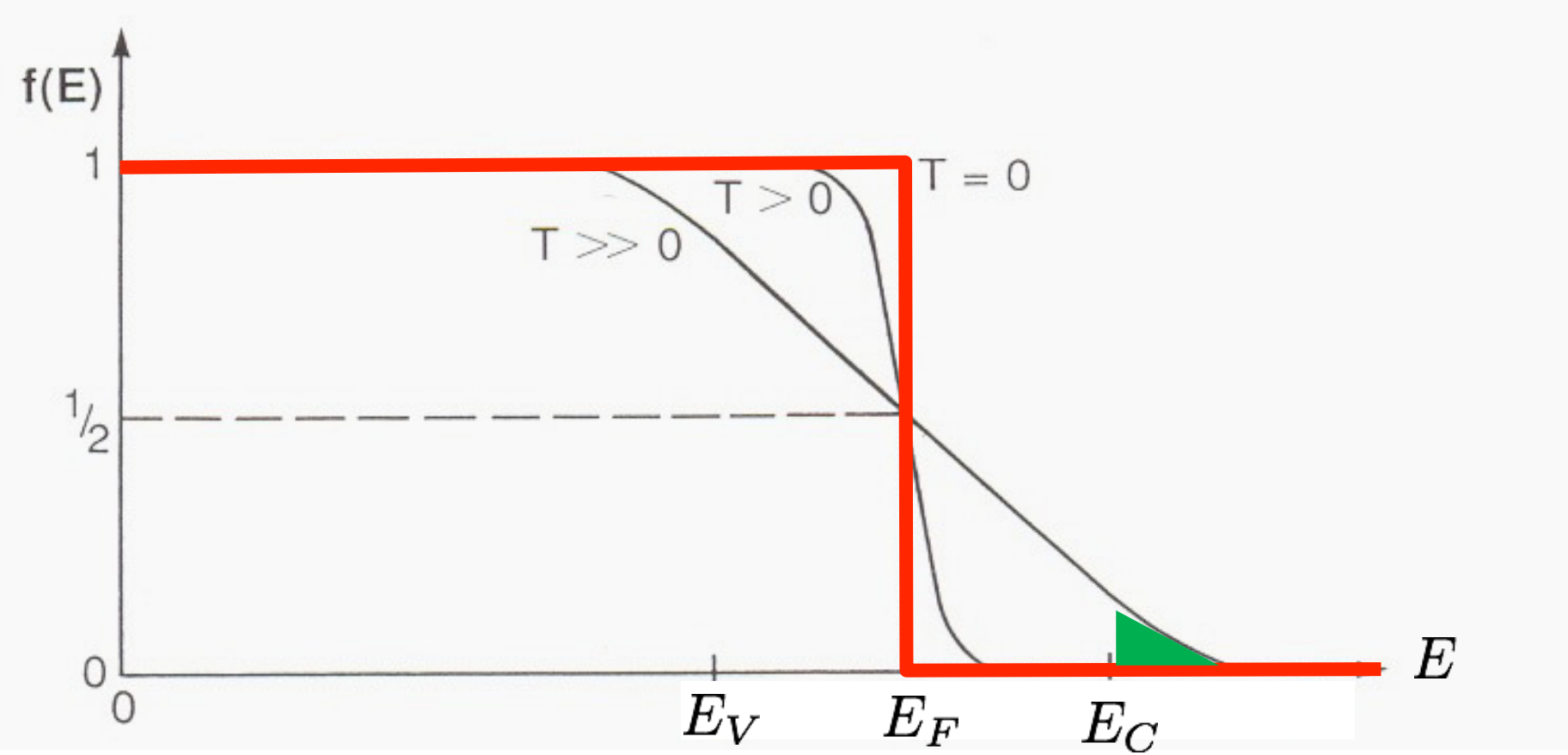
Fermi Energy and Distribution



Fermi Distribution and Temperature

At T = 0 K, the Fermi distribution is a step function

At T >> 0 K, the Fermi distribution flattens → electrons may reach the conduction band by thermal excitation.



The Energy Distribution of Electrons (2)

Even at room temperature, the conduction electrons occupy typically only the lowest states in the conduction band.

If f(E)N(E) is close to zero at E > E_c, it can be described by an average "effective density of states N_c" near E ~ E_c:

$$n_0 = N_c f(E_c) \text{ where } N_c = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2}$$

Hence the Fermi-Dirac statistics becomes:

$$f(E_c) = \frac{1}{1+e^{\frac{-(E_c-E_F)}{kT}}} \overset{E_c-E_F>>kT}{\approx} e^{\frac{-(E_c-E_F)}{kT}}$$

…and we get:

$$n_0 = N_c f(E_c) = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2} e^{-(E_c-E_F)/kT}$$

Fermi Energy ⇔ Chemical Potential

(http://www.physicsforums.com/archive/index.php/t-239923.html)

"If the Fermi energy is defined as the energy of the highest occupied state then the Fermi level would sit at the bottom of the gap by definition.

What does lie in the middle of the gap is the chemical potential μ, and because the chemical potential of a free gas of electrons is equal to its Fermi level as traditionally defined, one says that the Fermi level of the semiconductor considered is at the center of the gap.

If one redefines the Fermi level from "energy of highest occupied state" to "chemical potential" then the Fermi level will lie in the gap in the semiconductor case considered and the Fermi level will sit at the energy of the highest occupied state in the free gas in agreement with the more familiar definition."

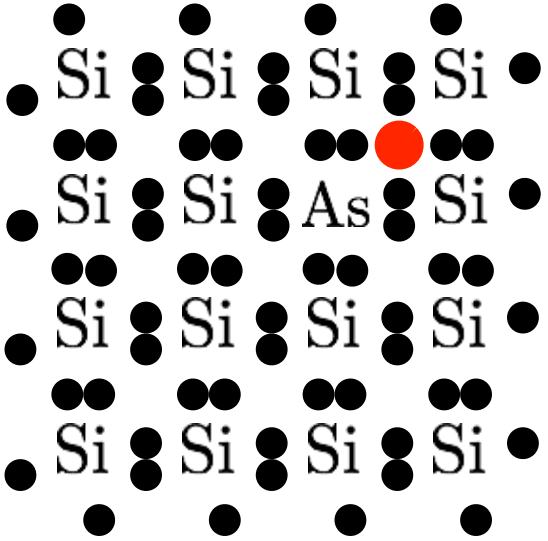
Doping

What can we do to reduce the Bandgap?

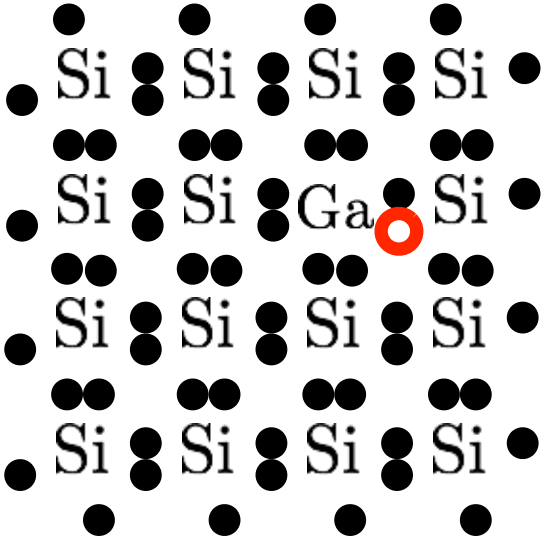
Goal: smaller bandgap = lower excitation energy = detection of lower energies = detection of longer wavelengths photons

Consider "doping" a pure silicon crystal with small amounts of Group V or Group III elements:

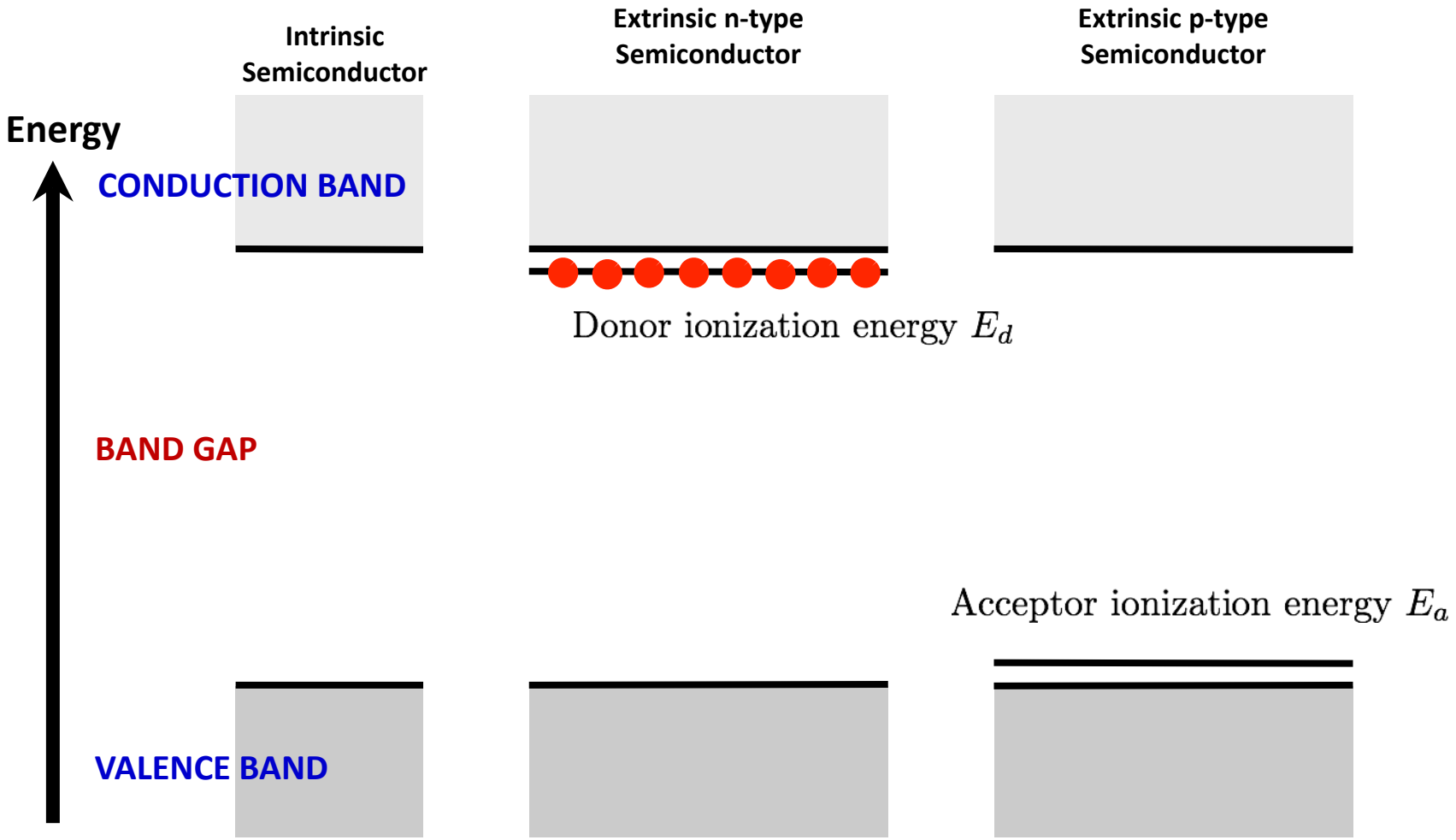
Adding a Group V element ("donor") adds conduction electrons → n-type Si



Adding a Group III element ("acceptor") adds a missing electron = "hole" → p-type Si

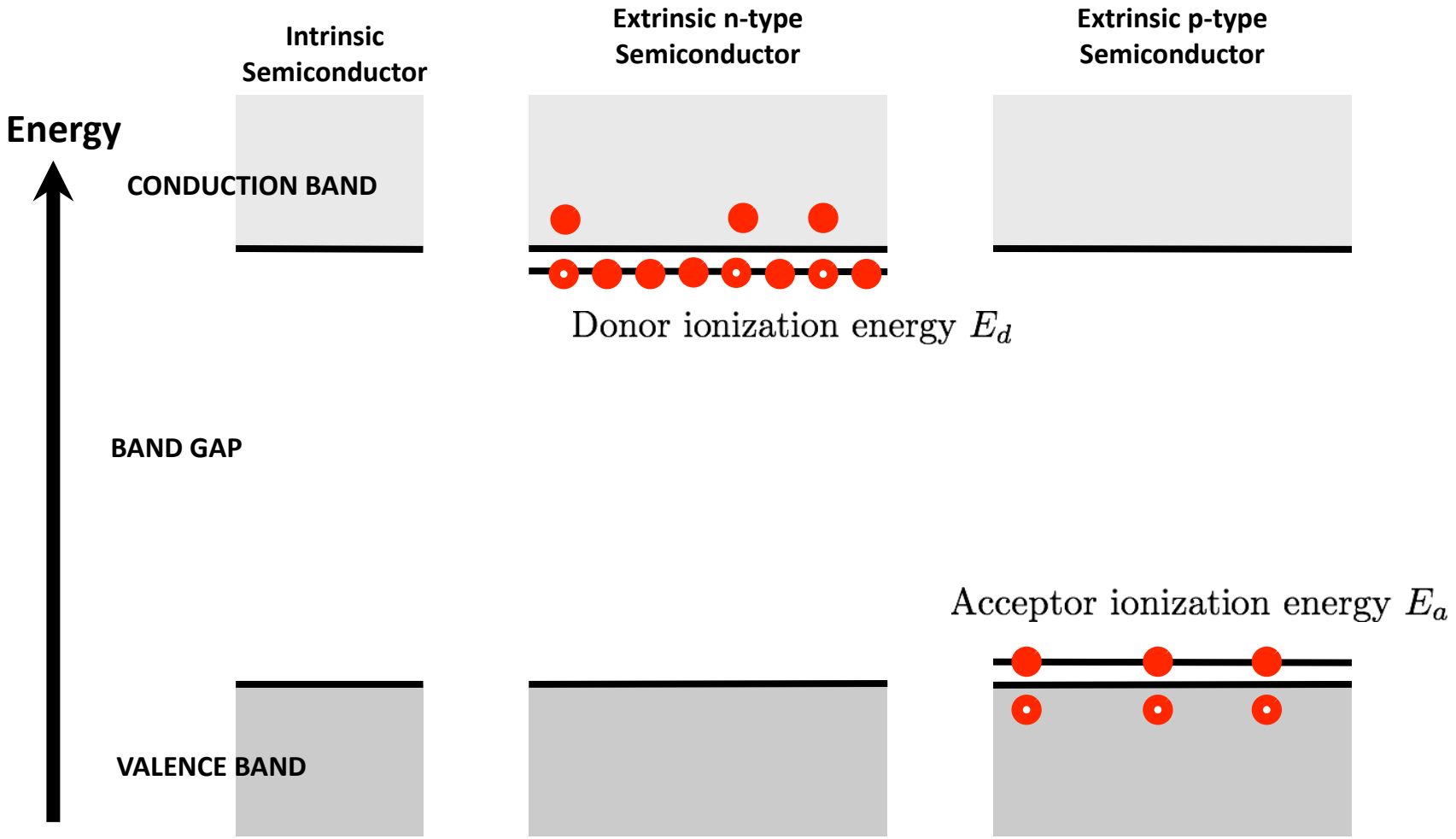


Energy Bandgaps at T = 0 K



Note: pure semiconductors are called intrinsic, doped semiconductors are called extrinsic.

Energy Bandgaps at T > 0 K



Bandgaps in extrinsic Semiconductors

Measured donor E_d and acceptor E_a ionization energies:

Donor	Si (meV)	Ge (meV)
intrinsic	1100	700
P	45	12
As	49	13
Sb	39	10
B	45	10
Ga	65	11
In	157	11

Note: 25 × smaller bandgap means 25 × longer wavelength coverage of the detector!

Note: for T = 300K, kT ~ 26 meV → cooling of detector is crucial