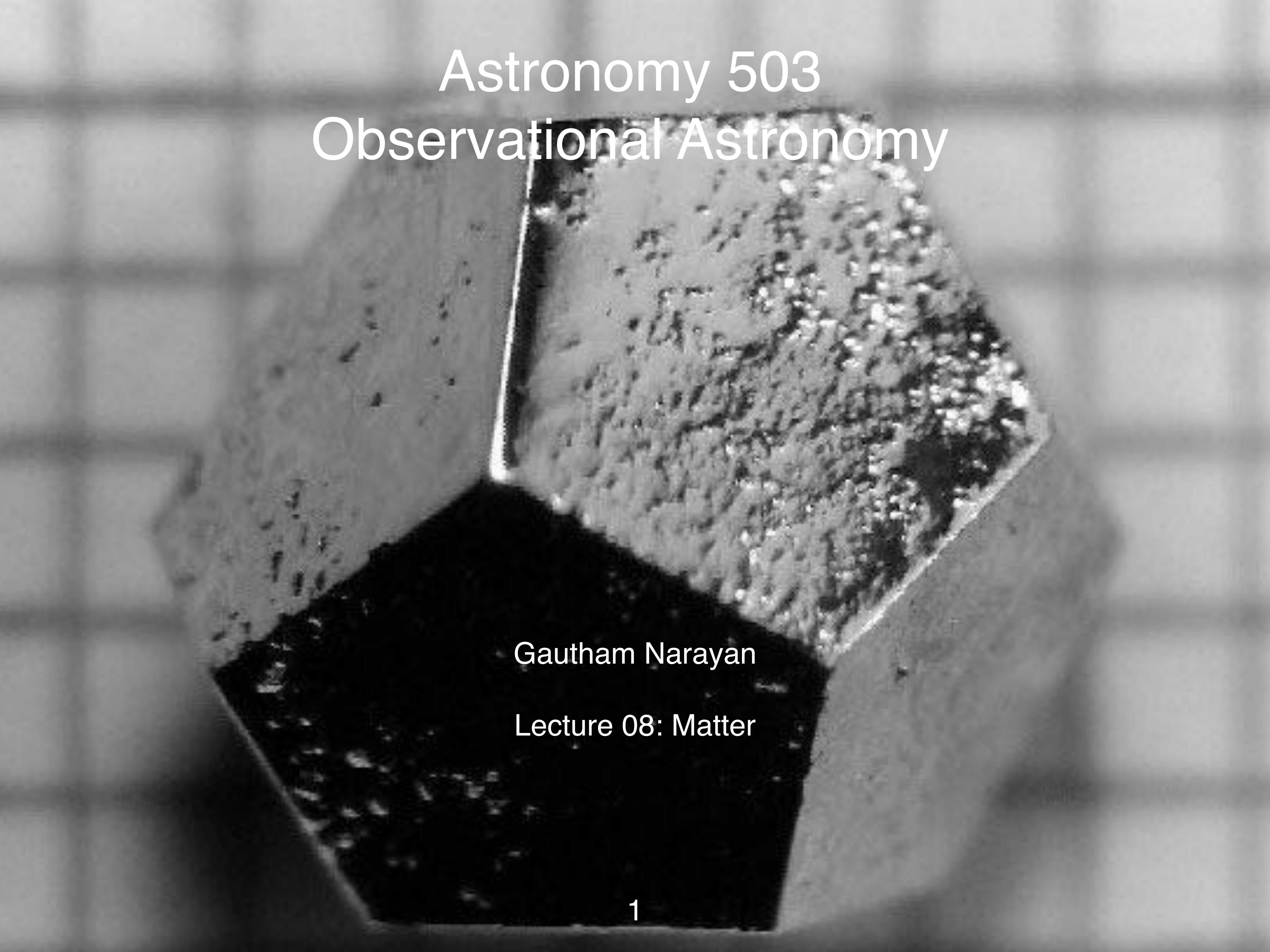
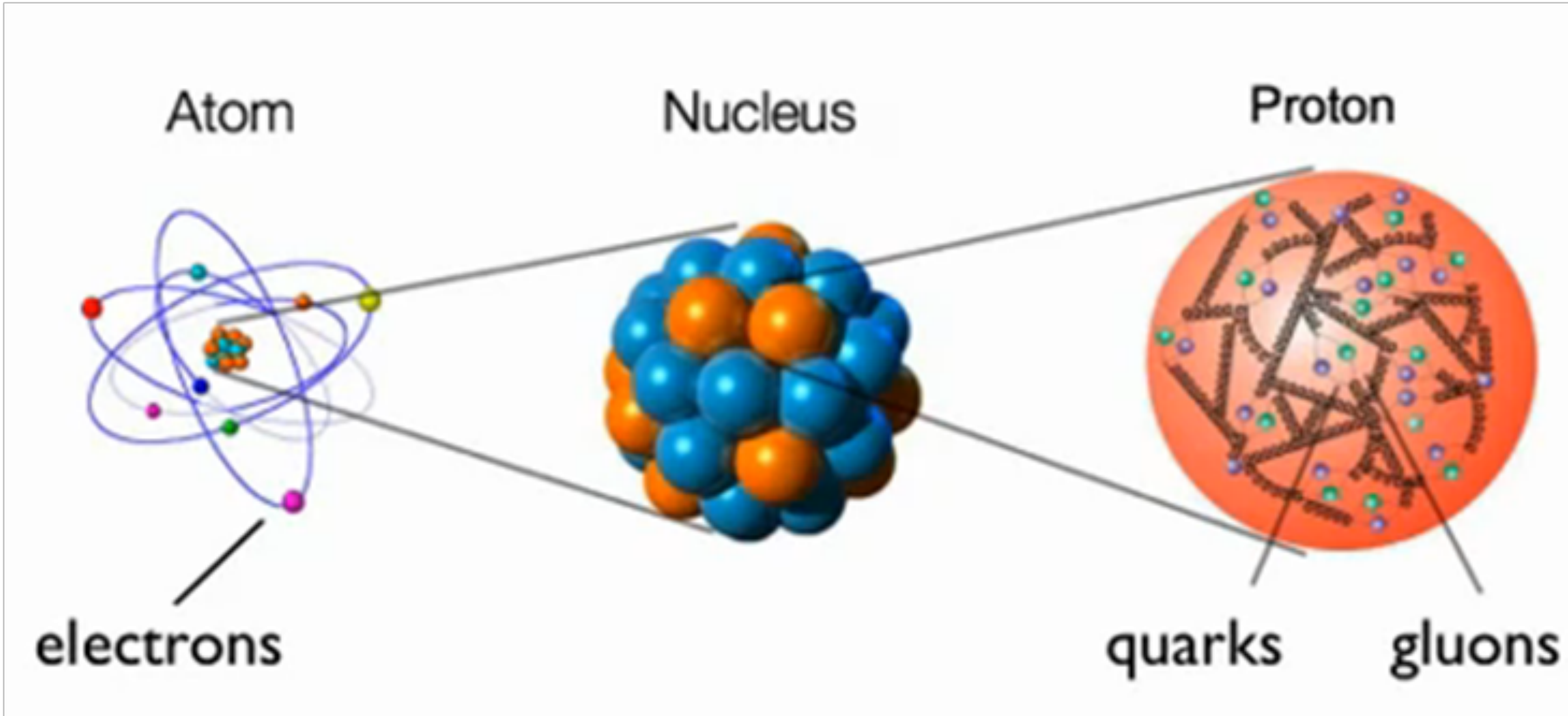


Astronomy 503
Observational Astronomy

Gautham Narayan

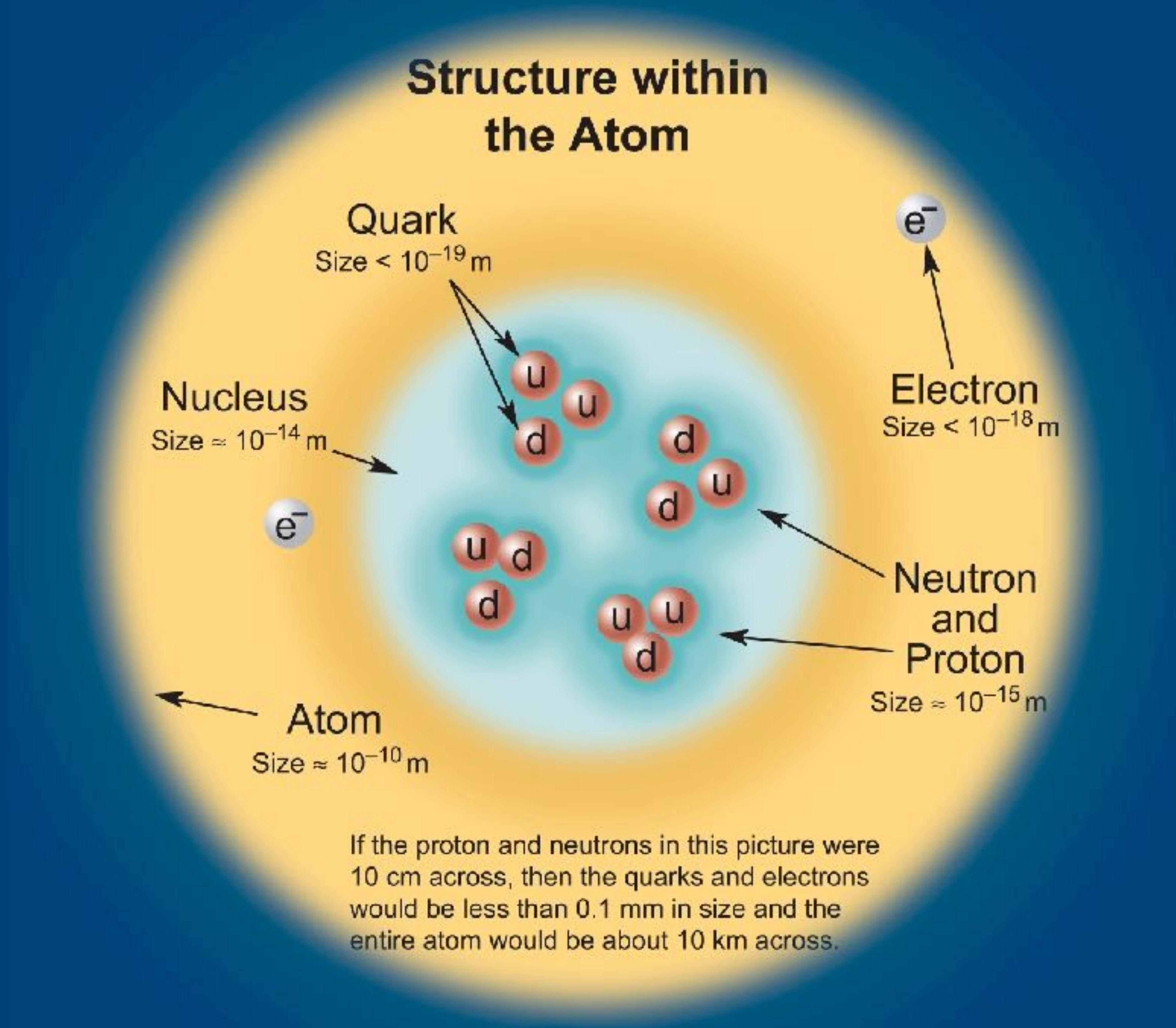
Lecture 08: Matter



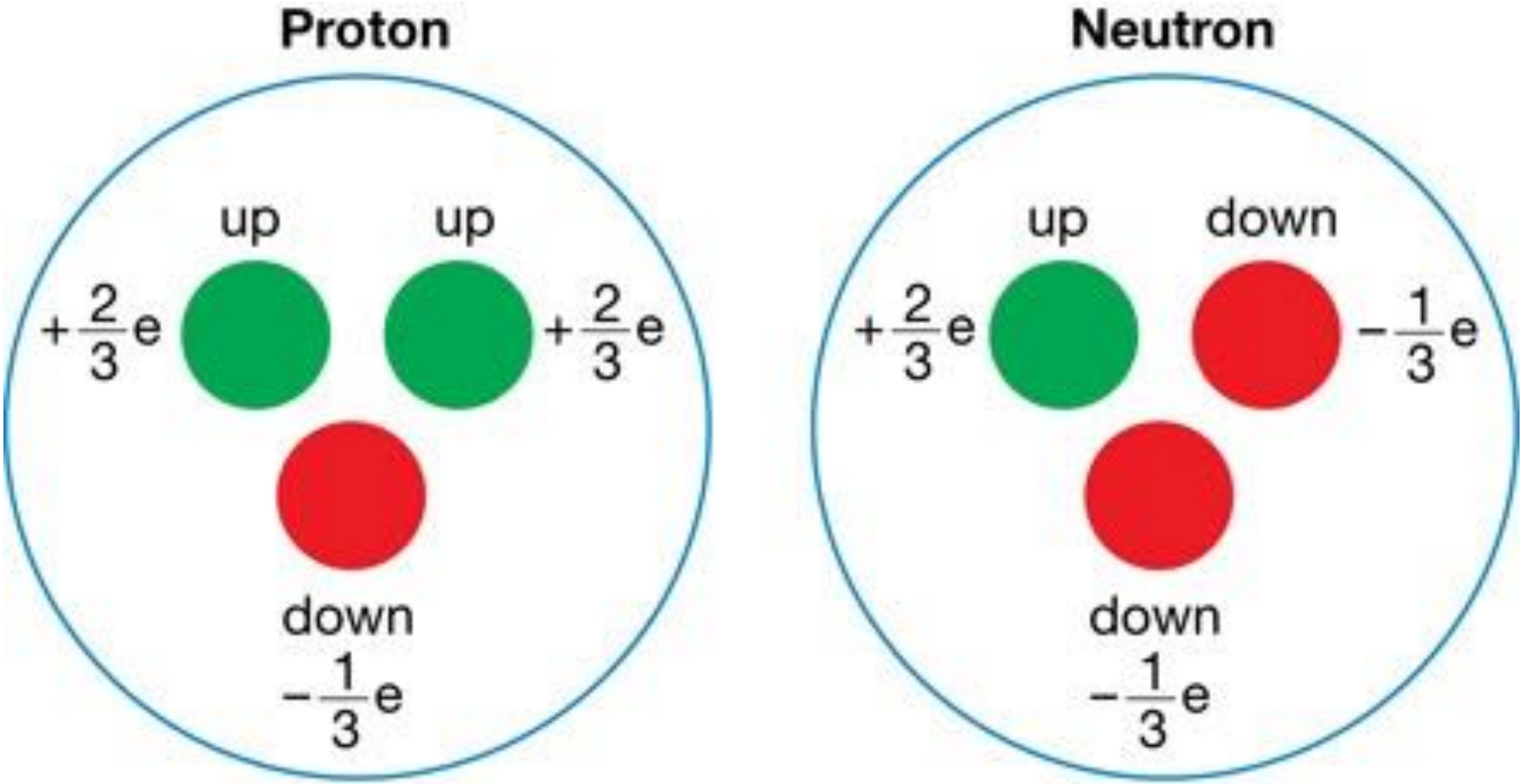
10^{-10} m
1 Å
0.1 nm

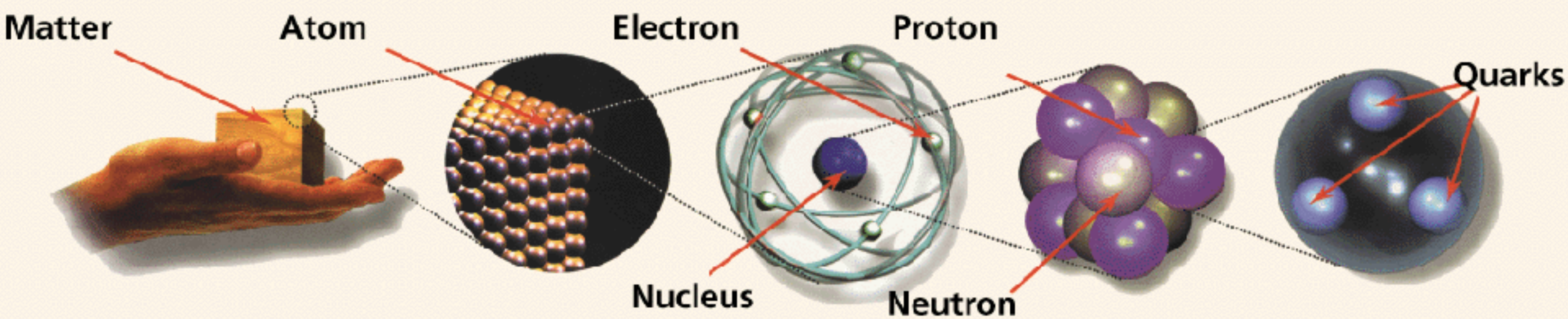
~10^{-14} m
1-10 fm
10^{-5} nm

10^{-15} m
1 fm
10^{-6} nm



Structure within the Atom
Quark
Size < 10^{-19} m
e⁻
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
u
d
d
u
d
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.


Proton
up
up
+2/3 e
+2/3 e
down
−1/3 e
Neutron
up
down
+2/3 e
−1/3 e
down
−1/3 e



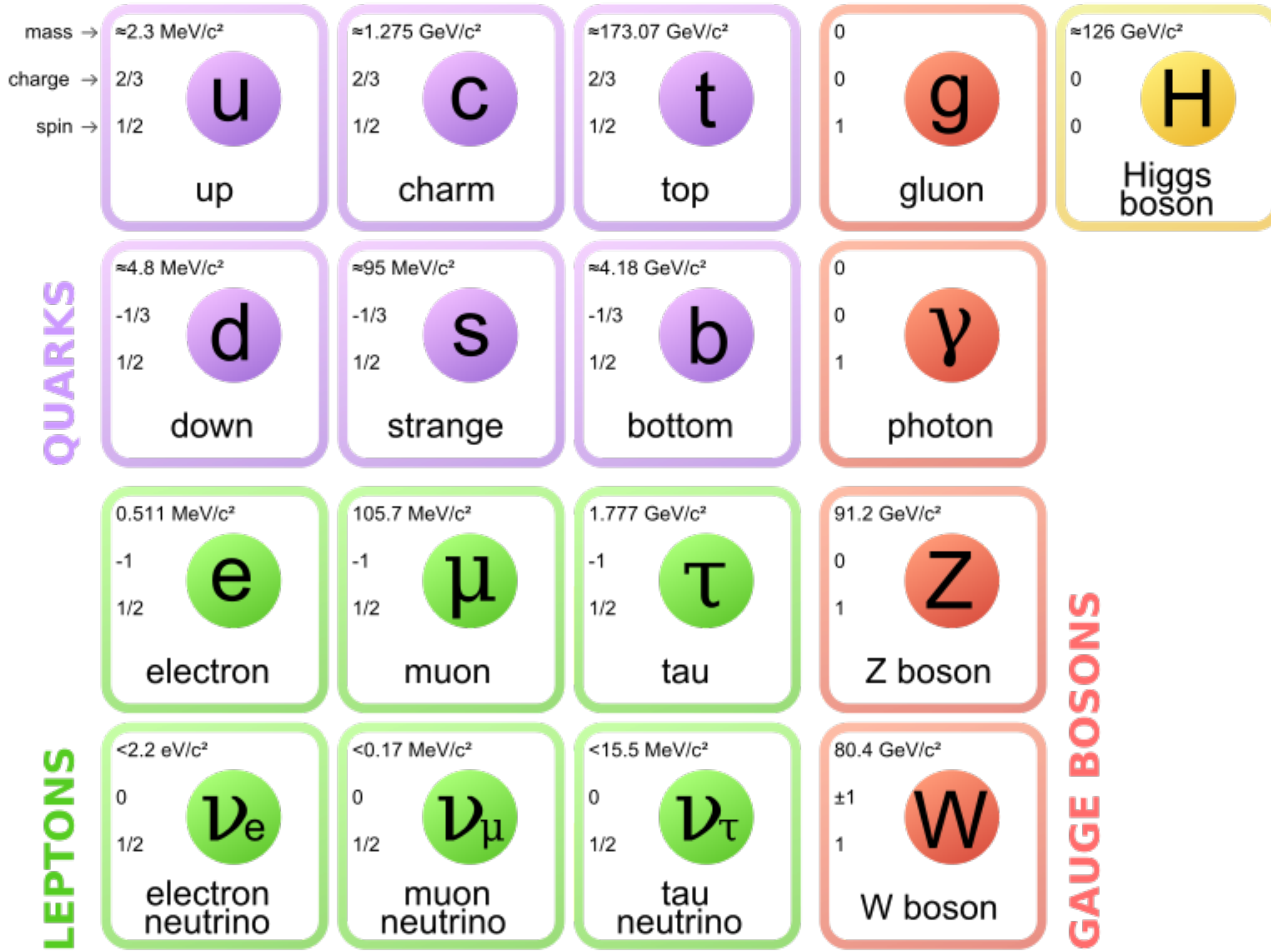
Matter Particles

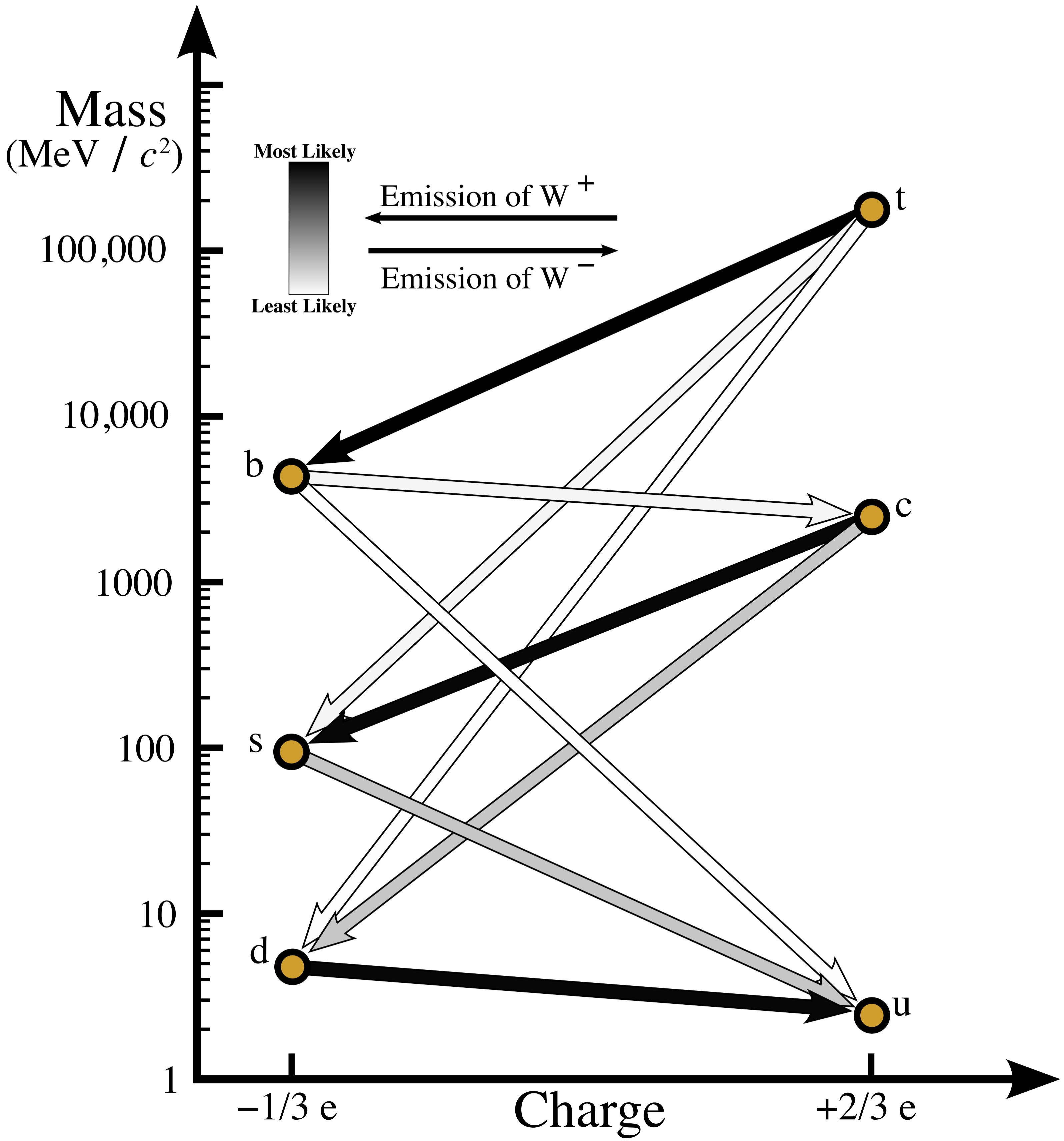
All ordinary particles belong to this group

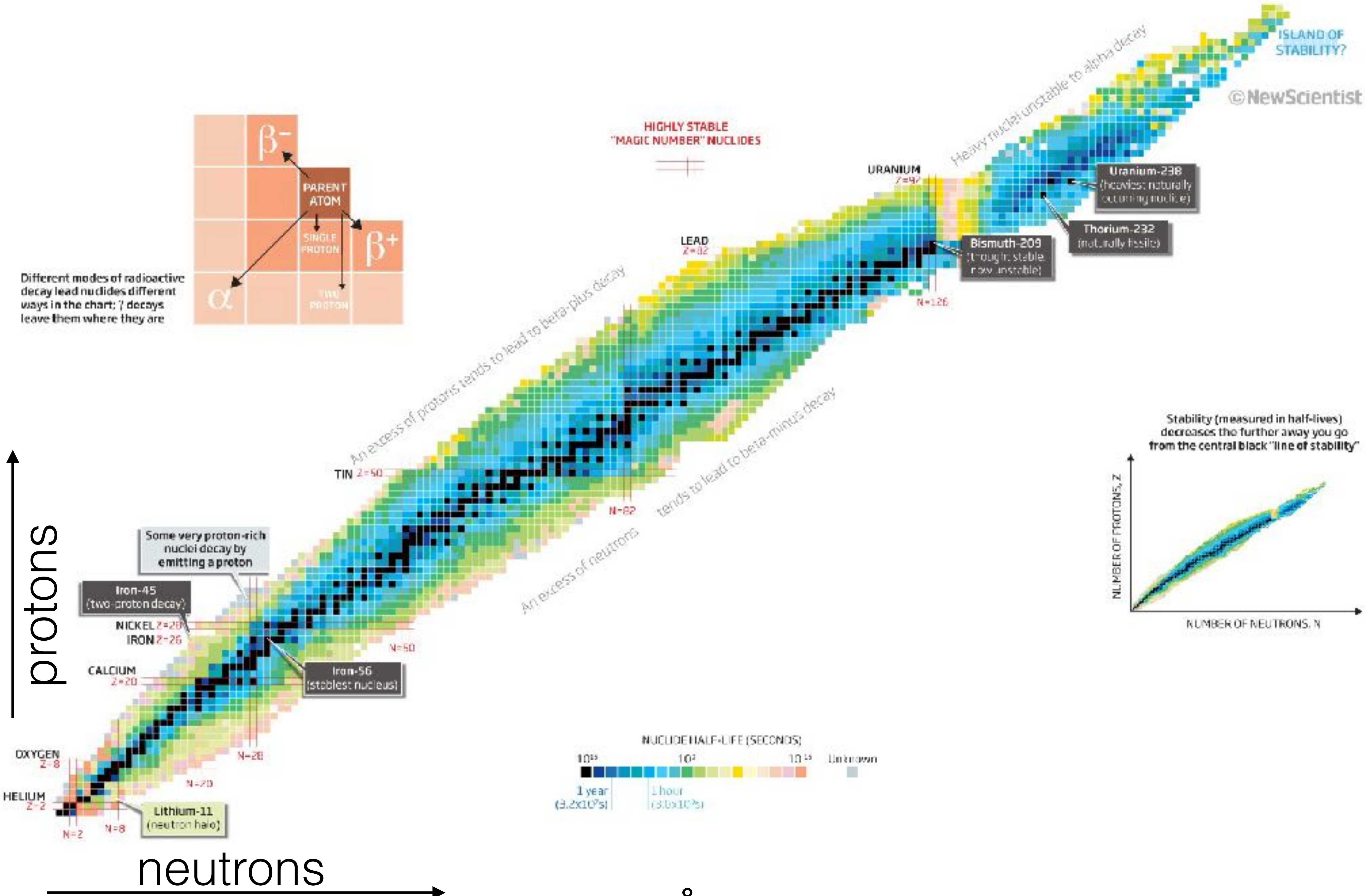
These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators.

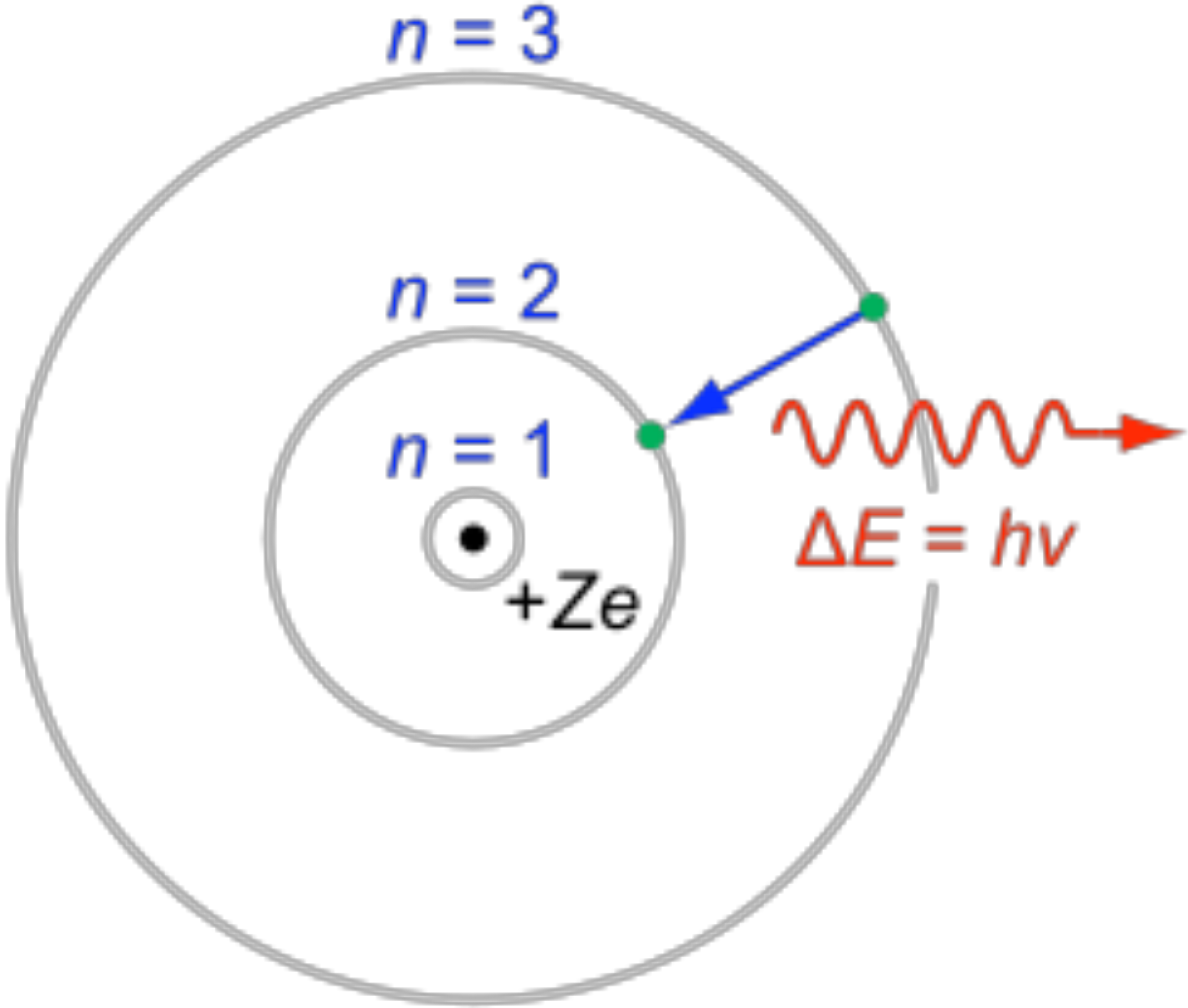
	LEPTONS		QUARKS	
FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of −1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second	**Up** Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay	**Charm** A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1974
THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** Not yet discovered but believed to exist	**Top** Heavier still; found in 1995	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

The (known) Fundamental Particles in Nature:




Mass
(MeV / c^2)
100,000
10,000
1000
100
10
1
Most Likely
Least Likely
Emission of W +
Emission of W −
t
b
c
s
d
u
−1/3 e
Charge
+2/3 e

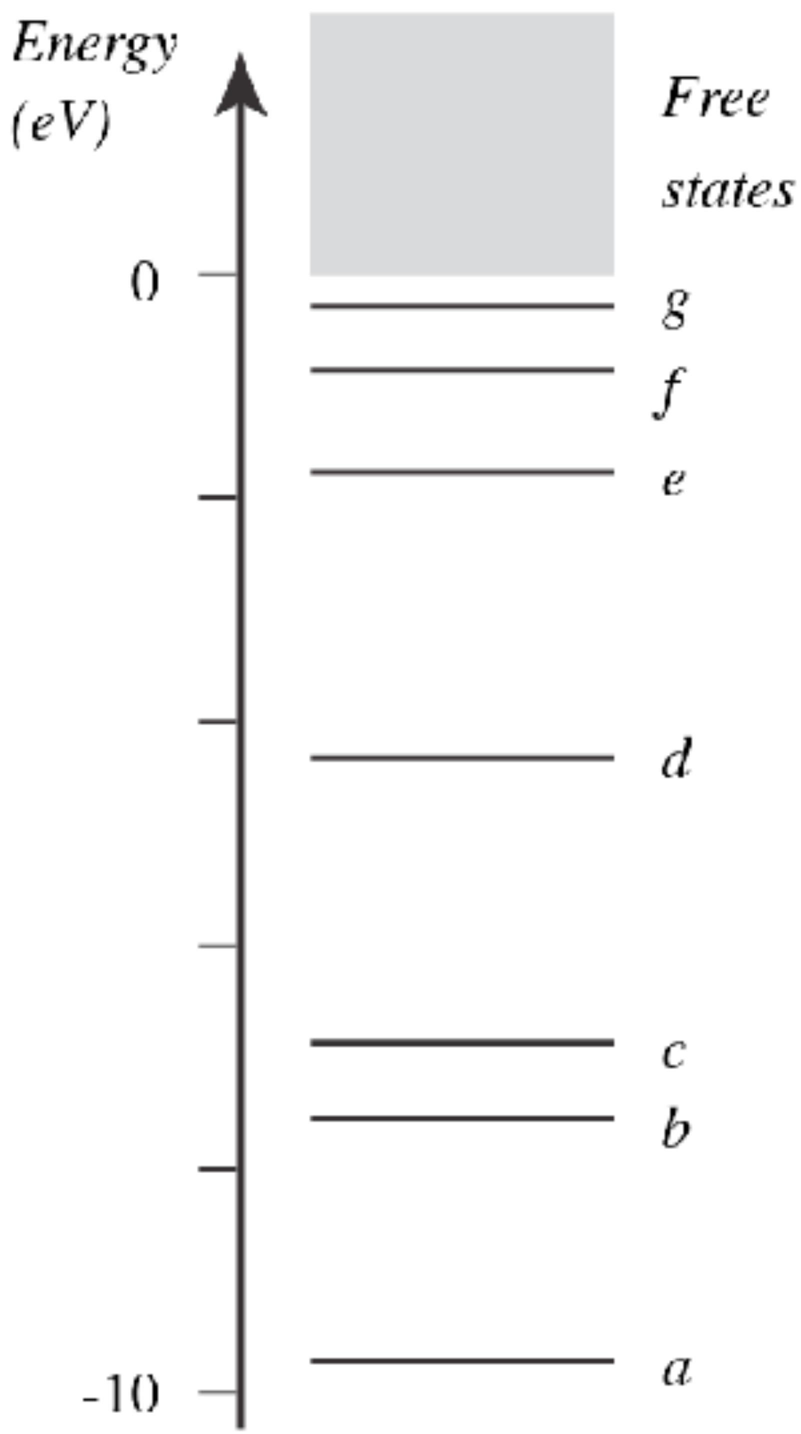

protons
neutrons
ISLAND OF STABILITY?
©NewScientist
HIGHLY STABLE "MAGIC NUMBER" NUCLIDES
PARENT ATOM
SINGLE PROTON
TWO PROTON
β-
β+
α
Different modes of radioactive decay lead nuclides different ways in the chart; γ decays leave them where they are
Heavy nuclei unstable to alpha decay
An excess of protons tends to lead to beta-plus decay
An excess of neutrons tends to lead to beta-minus decay
URANIUM Z=92
LEAD Z=82
TIN Z=50
NICKEL Z=28
IRON Z=26
CALCIUM Z=20
OXYGEN Z=8
HELIUM Z=2
N=2
N=8
N=20
N=28
N=50
N=82
N=126
Uranium-238 (heaviest naturally occurring nuclide)
Thorium-232 (naturally fissile)
Bismuth-209 (thought stable, now unstable)
Some very proton-rich nuclei decay by emitting a proton
Iron-45 (two-proton decay)
Iron-56 (stablest nucleus)
Lithium-11 (neutron halo)
Stability (measured in half-lives) decreases the further away you go from the central black "line of stability"
NUMBER OF PROTONS, Z
NUMBER OF NEUTRONS, N
NUCLIDE HALF-LIFE (SECONDS)
Unknown
1 year
1 hour


n = 3
n = 2
n = 1
+Ze
ΔE = hv

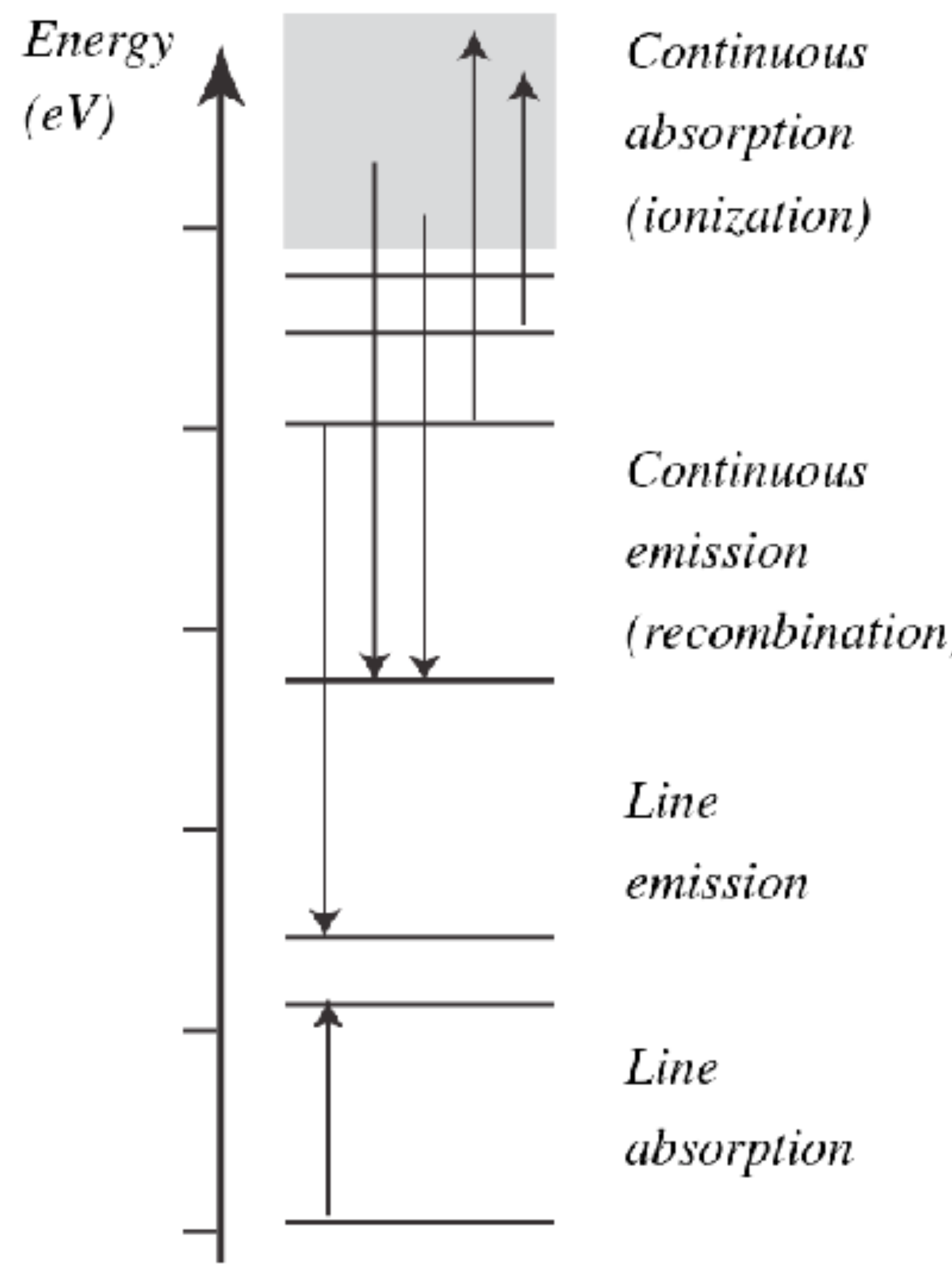
Energy levels in atoms

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

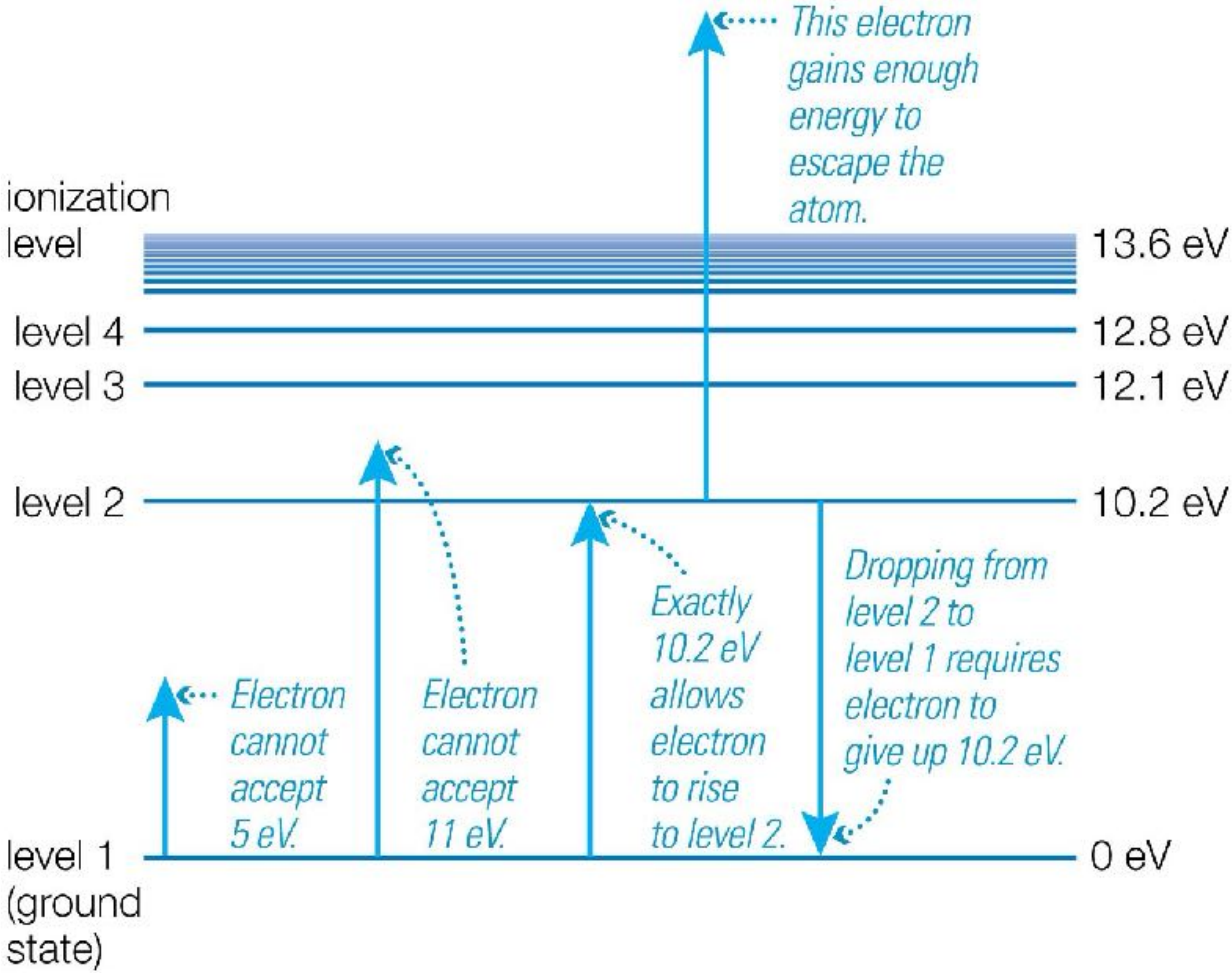
$$\lambda_{ab} = \frac{hc}{\Delta E_{ab}}$$

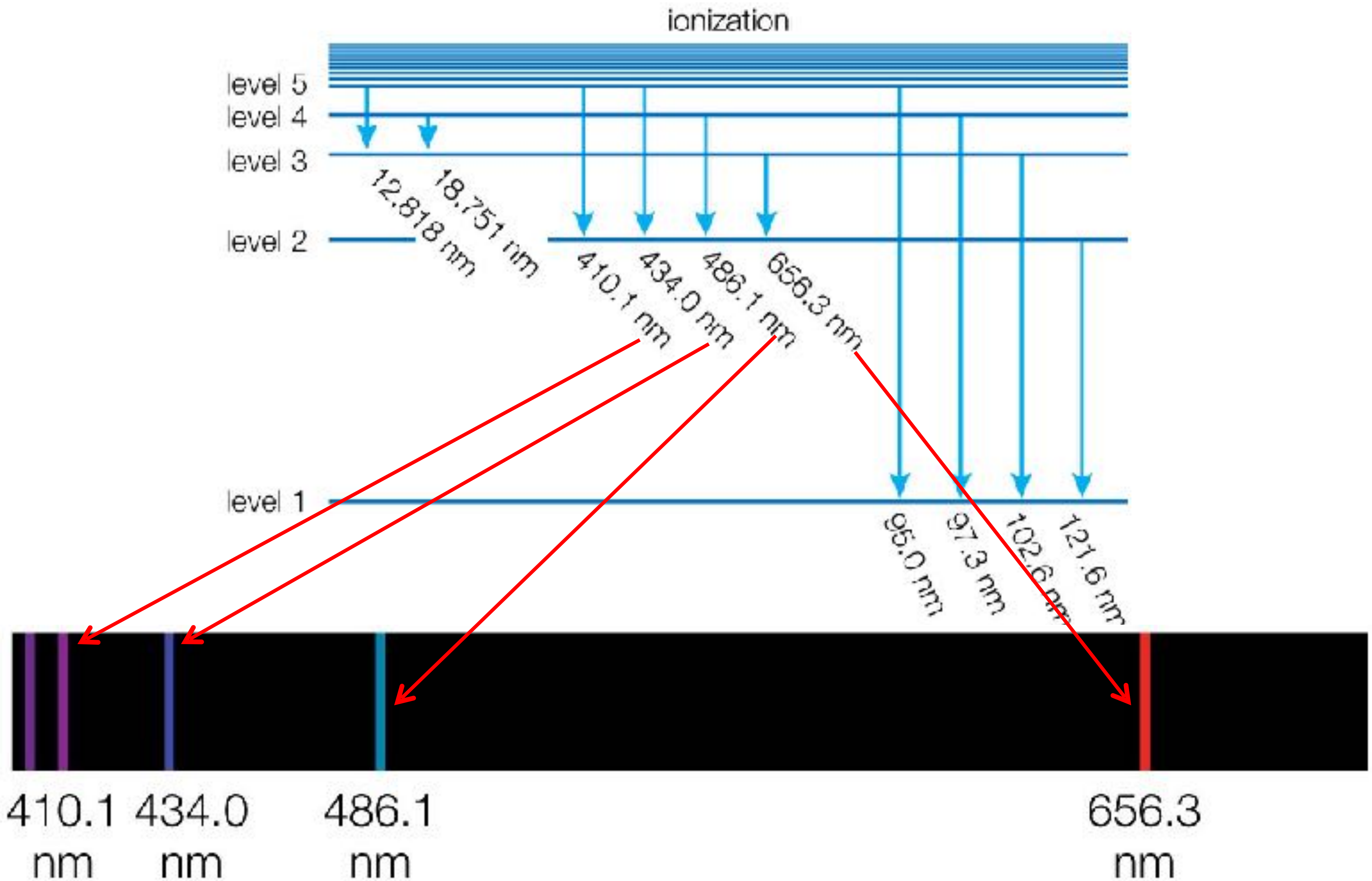


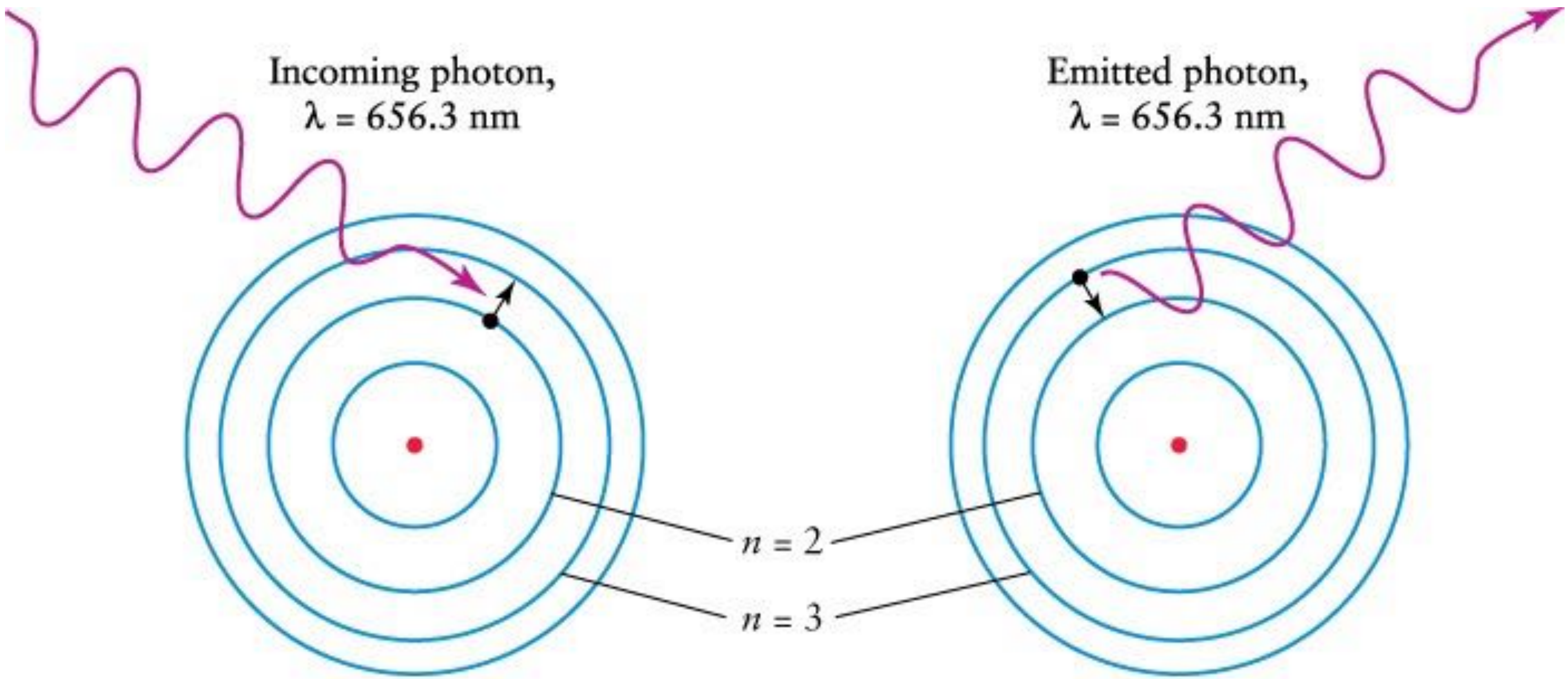
Energy levels



Electromagnetic transistions

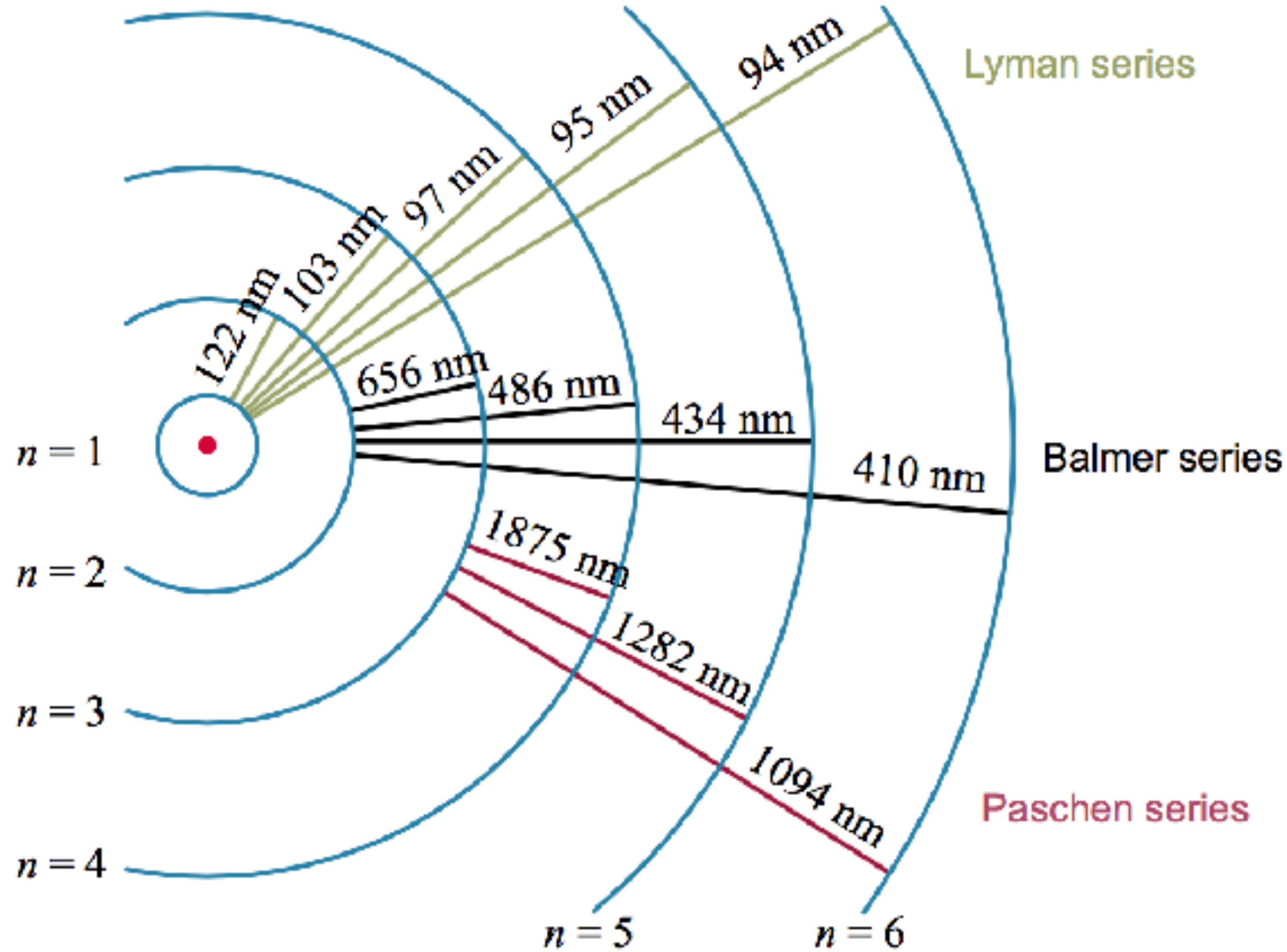

This electron gains enough energy to escape the atom.
ionization level
13.6 eV
level 4
12.8 eV
level 3
12.1 eV
level 2
10.2 eV
Electron cannot accept 5 eV.
Electron cannot accept 11 eV.
Exactly 10.2 eV allows electron to rise to level 2.
Dropping from level 2 to level 1 requires electron to give up 10.2 eV.
level 1 (ground state)
0 eV

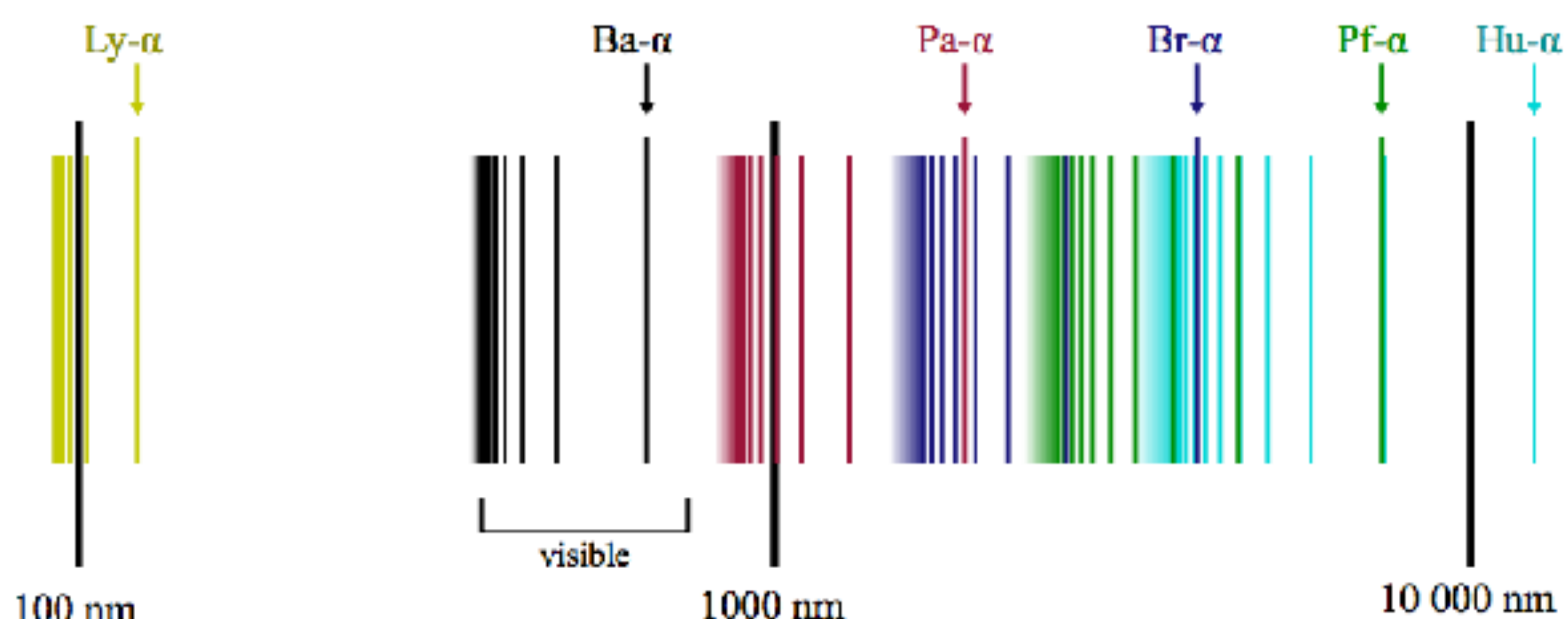

ionization
level 5
level 4
level 3
level 2
level 1
12,818 nm
18,751 nm
410.1 nm
434.0 nm
486.1 nm
656.3 nm
95.0 nm
97.3 nm
102.6 nm
121.6 nm
410.1 nm
434.0 nm
486.1 nm
656.3 nm



(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up the $n = 3$ orbit

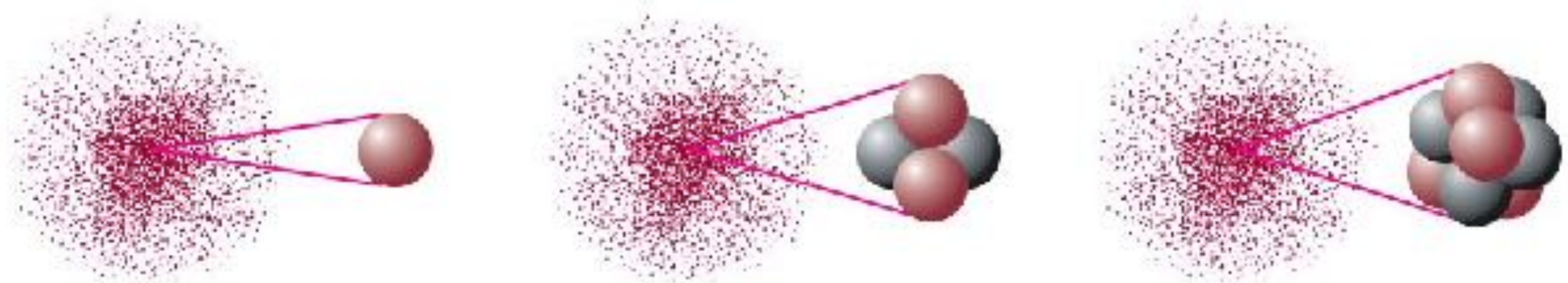
(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon


Lyman series
94 nm
95 nm
97 nm
103 nm
122 nm
656 nm
486 nm
434 nm
410 nm
Balmer series
1875 nm
1282 nm
1094 nm
Paschen series
$n = 1$
$n = 2$
$n = 3$
$n = 4$
$n = 5$
$n = 6$


Ly-α
Ba-α
Pa-α
Br-α
Pf-α
Hu-α
visible
100 nm
1000 nm
10 000 nm

atomic number *= number of protons*
atomic mass number *= number of protons + neutrons*
(A neutral atom has the same number of electrons as protons.)

Hydrogen (^{1}H)	Helium (^{4}He)	Carbon (^{12}C)

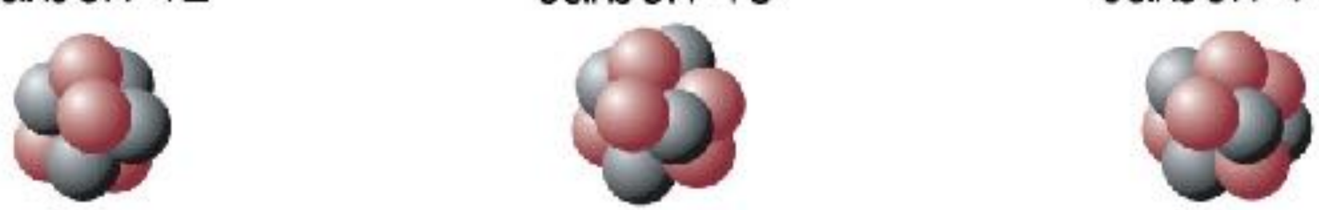


atomic number = 1	atomic number = 2	atomic number = 6
atomic mass number = 1	atomic mass number = 4	atomic mass number = 12
(1 electron)	(2 electrons)	(6 electrons)

Different ***isotopes*** *of a given element contain the same number of protons, but different numbers of neutrons.*

Isotopes of Carbon

carbon-12	carbon-13	carbon-14



^{12}C	^{13}C	^{14}C
(6 protons + 6 neutrons)	(6 protons + 7 neutrons)	(6 protons + 8 neutrons)

Quantum numbers

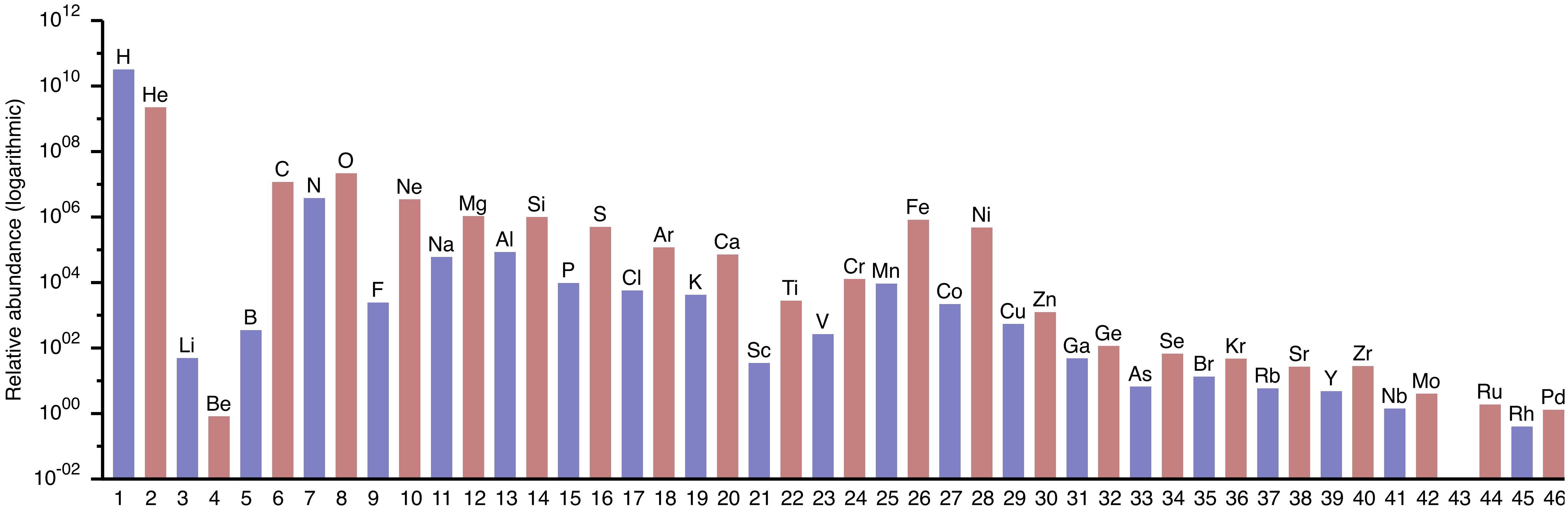
The state of every bound electron is specified by four quantum numbers (*n, ℓ, m, s*).

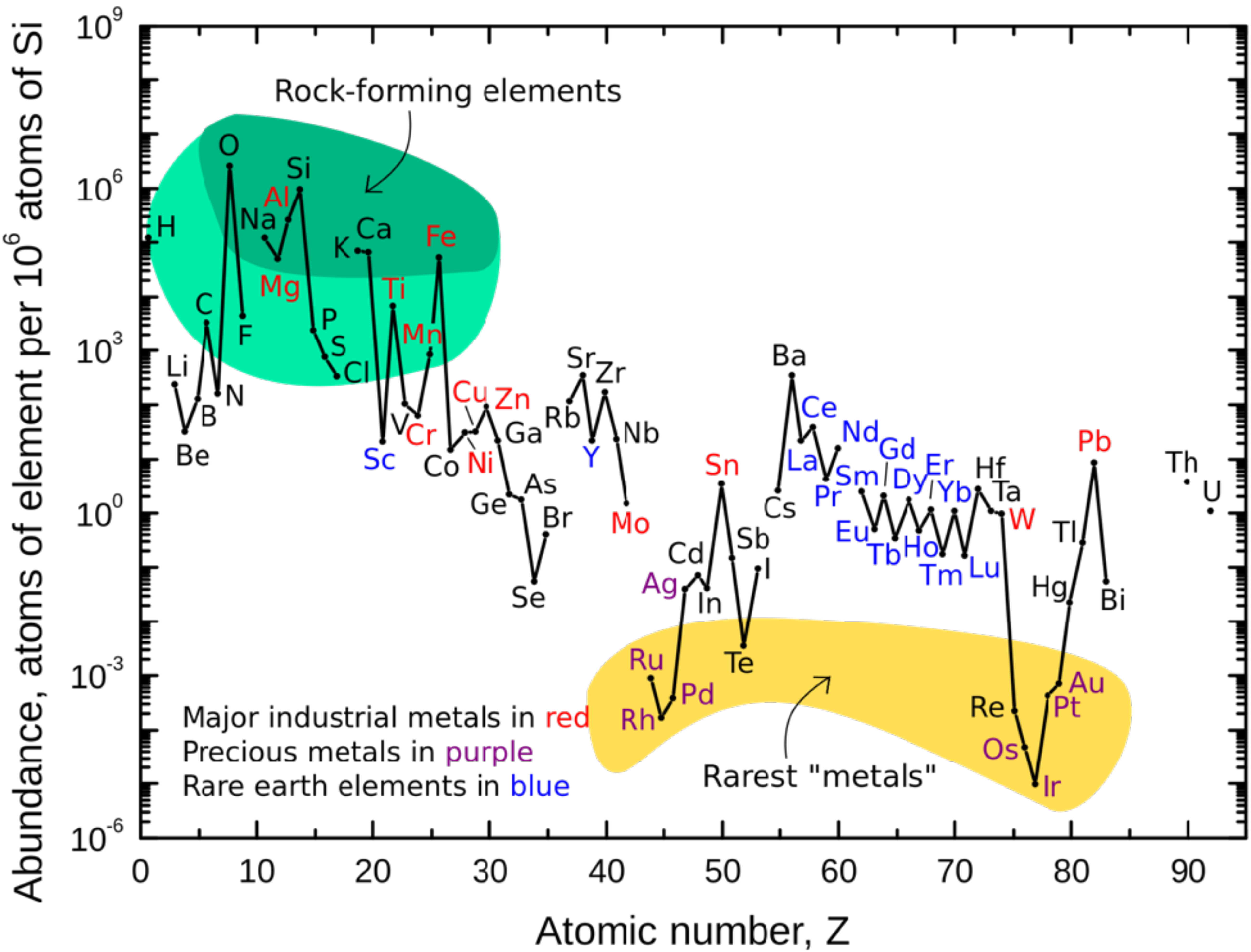
No two electrons bound in an atom may have the same 4 *n, ℓ, m, s*. (Pauli exclusion principle)

- *n* = principal quantum number. positive integer values. specifies the shell. n = 1,2,3, …
- *ℓ* = azimuthal quantum number describing the angular distribution. *ℓ* = 0,1,2,…*n*-1
- *m* = magnetic quantum number, describes integration with electron spin and external magnetic fields. *m* = 0, ±1, ±2 …±*ℓ*
- *s* = electron spin quantum number, +½, -½

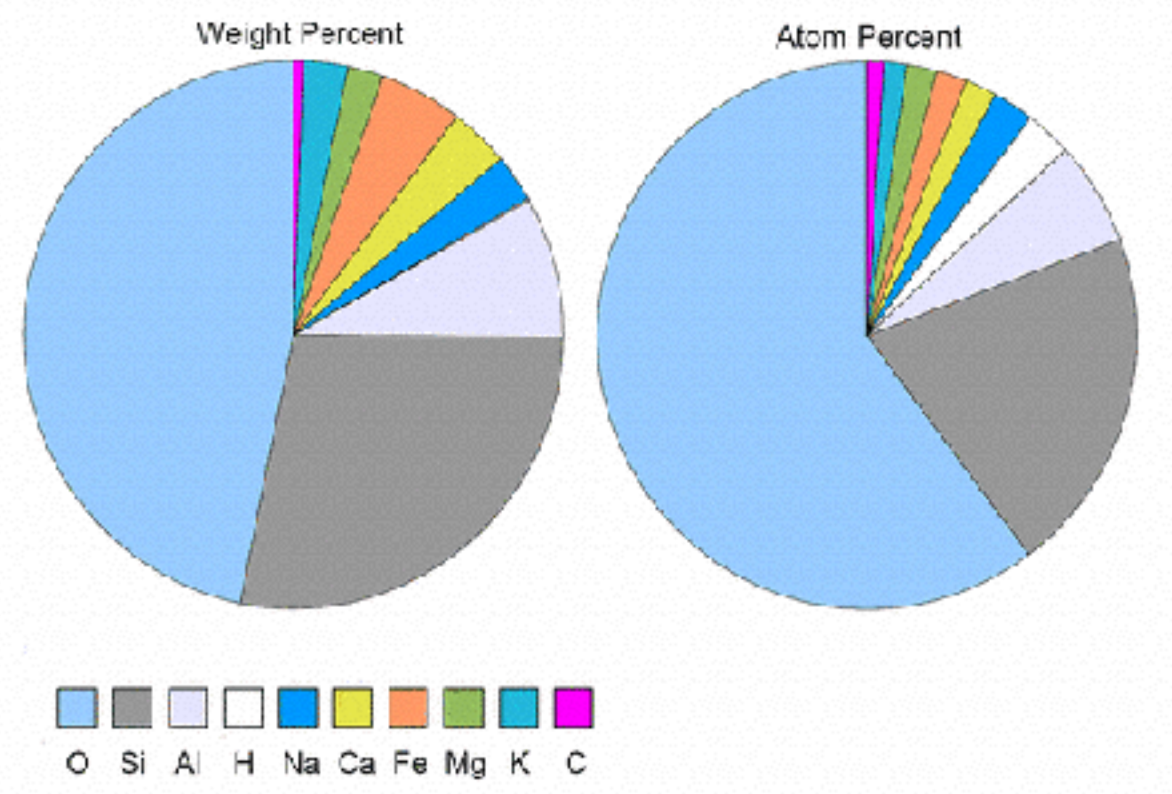
Quantum numbers					
n	*l*	*m*	*s*	Name of configuration	Number of states
1	0	0	±1/2	1s	2
2	0	0	±1/2	2s	2
2	1	−1	±1/2		
		0	±1/2	2p	6
		+1	±1/2		
3	0	0	±1/2	3s	2
3	1	−1	±1/2		
		0	±1/2	3p	6
		+1	±1/2		
3	2	−2	±1/2		
		−1	±1/2		
		0	±1/2	3d	10
		+1	±1/2		
		+2	±1/2		
4	0	0	±1/2	4s	2

Relative Abundances of the Elements

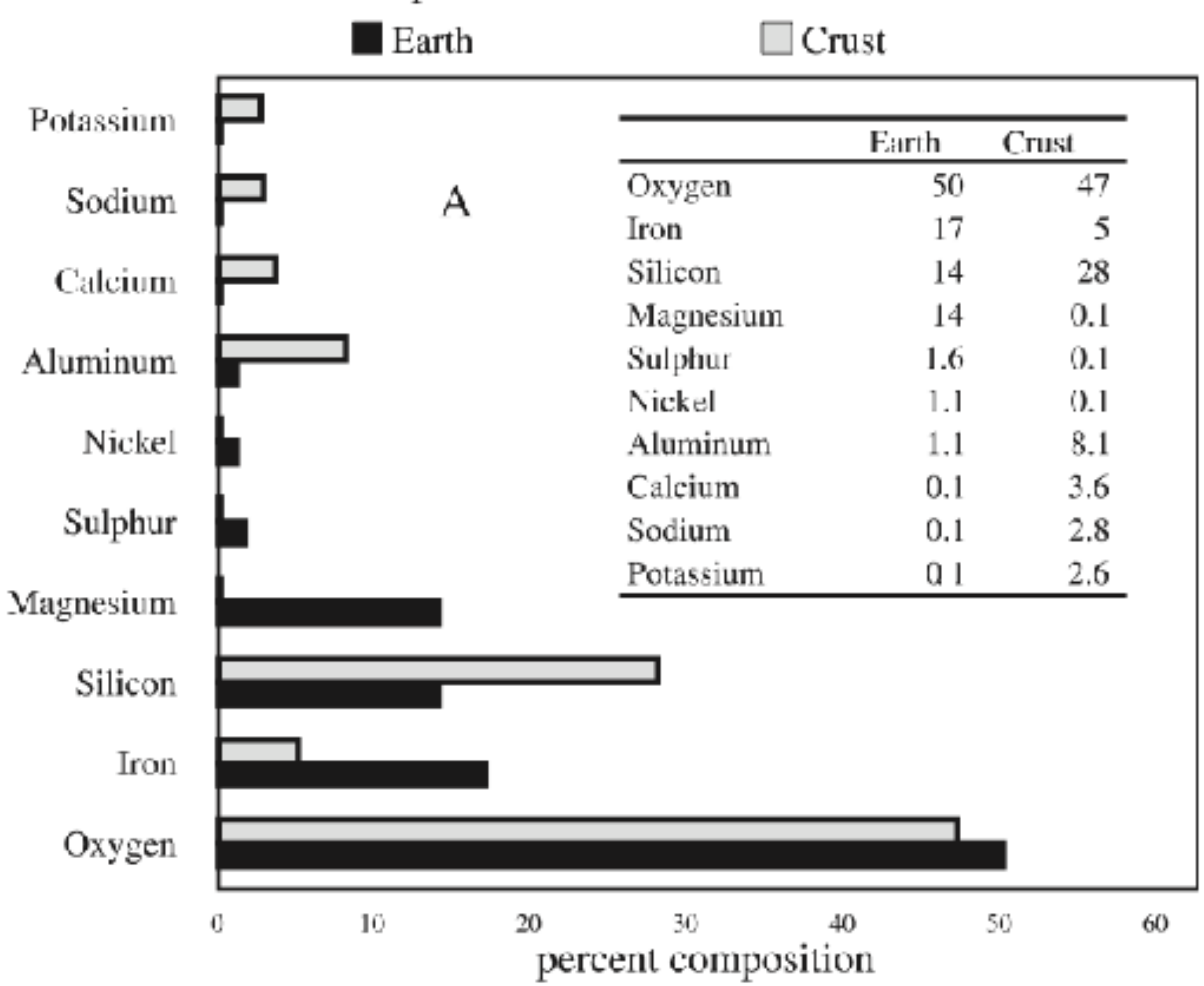




Rock-forming elements
Rarest "metals"
Major industrial metals in red
Precious metals in purple
Rare earth elements in blue
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
H
Li
Be
B
C
N
O
F
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U



Percent Composition of Earth and Crust



	Earth	Crust
Oxygen	50	47
Iron	17	5
Silicon	14	28
Magnesium	14	0.1
Sulphur	1.6	0.1
Nickel	1.1	0.1
Aluminum	1.1	8.1
Calcium	0.1	3.6
Sodium	0.1	2.8
Potassium	0.1	2.6

B

Humans	%
Hydrogen	61
Oxygen	26
Carbon	10.5
Nitrogen	2.4
Calcium	0.23
Phosphorus	0.13
Sulphur	0.13

C

Atmosphere	%
Nitrogen	78
Oxygen	21
Argon	0.93
Carbon	0.03
Neon	0.0018
Helium	0.0005

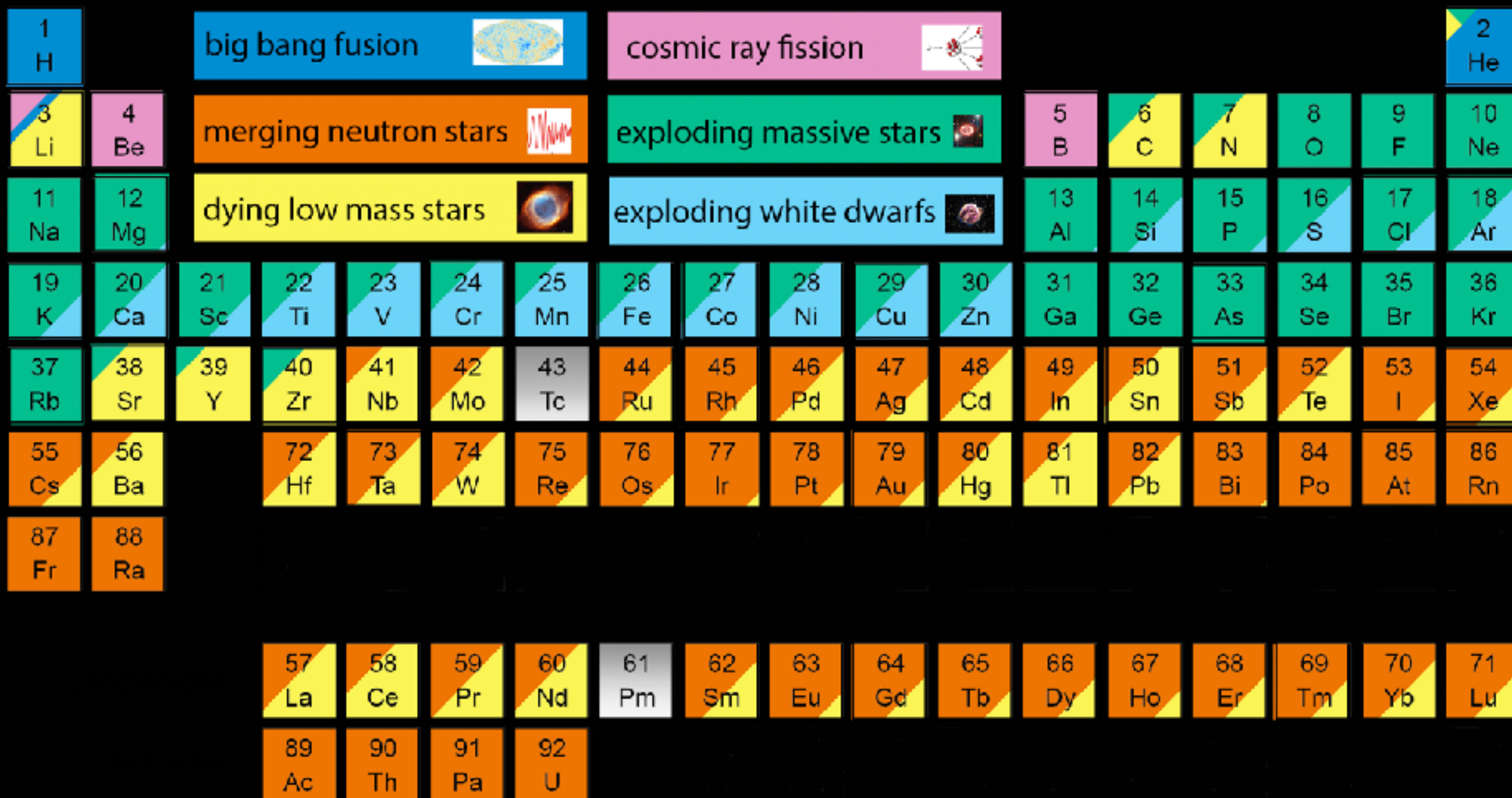
D

Universe	%
Hydrogen	92.47
Helium	7.4
Oxygen	0.06
Carbon	0.03
Nitrogen	0.01
Neon	0.01
Others	0.01

E

Sun	%
Hydrogen	90.99
Helium	8.87
Oxygen	0.078
Carbon	0.033
Neon	0.011
Nitrogen	0.01
Magnesium	0.004

The Origin of the Solar System Elements



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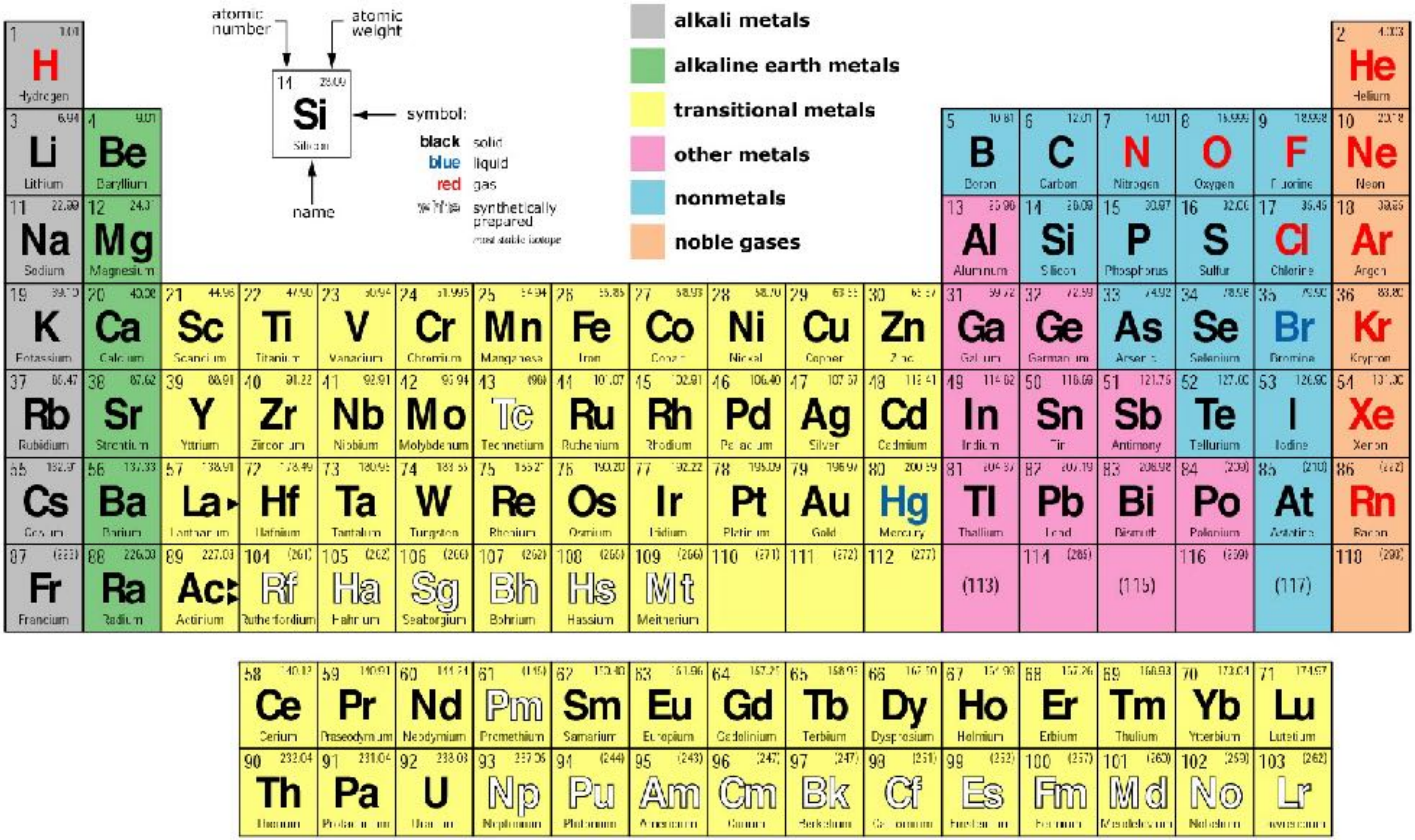
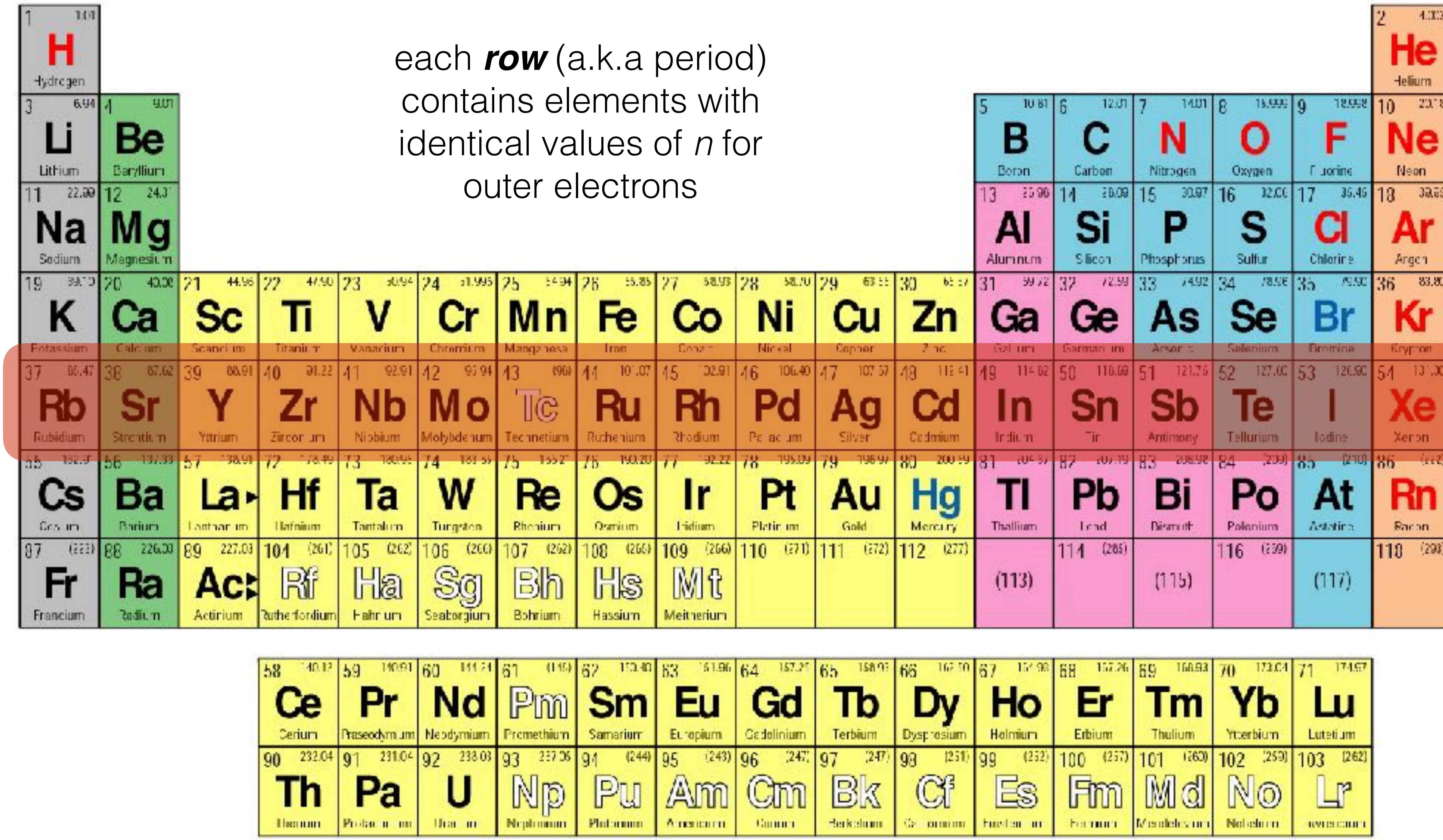
Graphic created by Jennifer Johnson

Periodic Table of the Elements



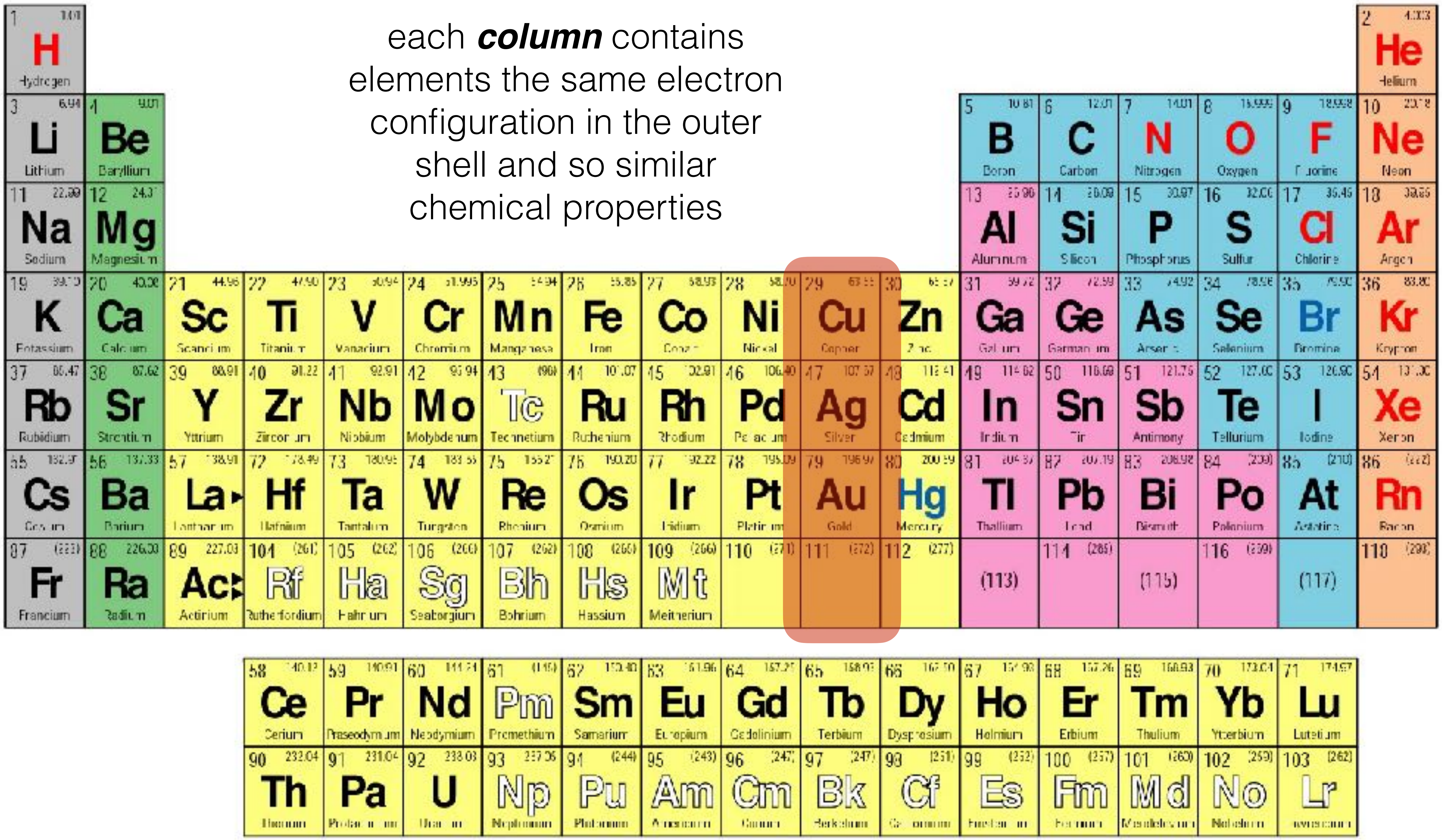
Periodic Table of the Elements

each ***row*** (a.k.a period) contains elements with identical values of *n* for outer electrons



Periodic Table of the Elements

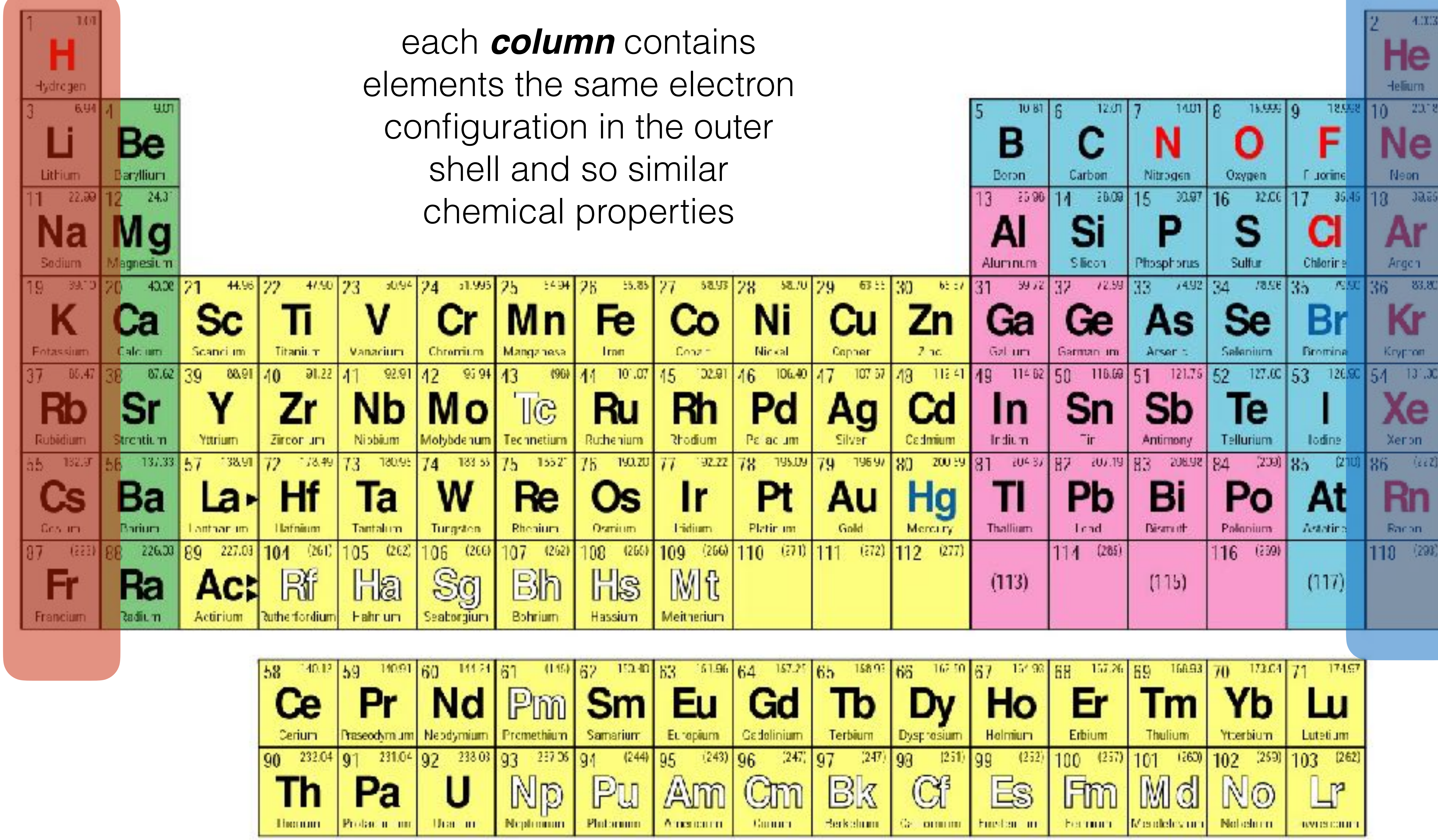
each ***column*** contains elements the same electron configuration in the outer shell and so similar chemical properties



MORE reactive

LESS reactive

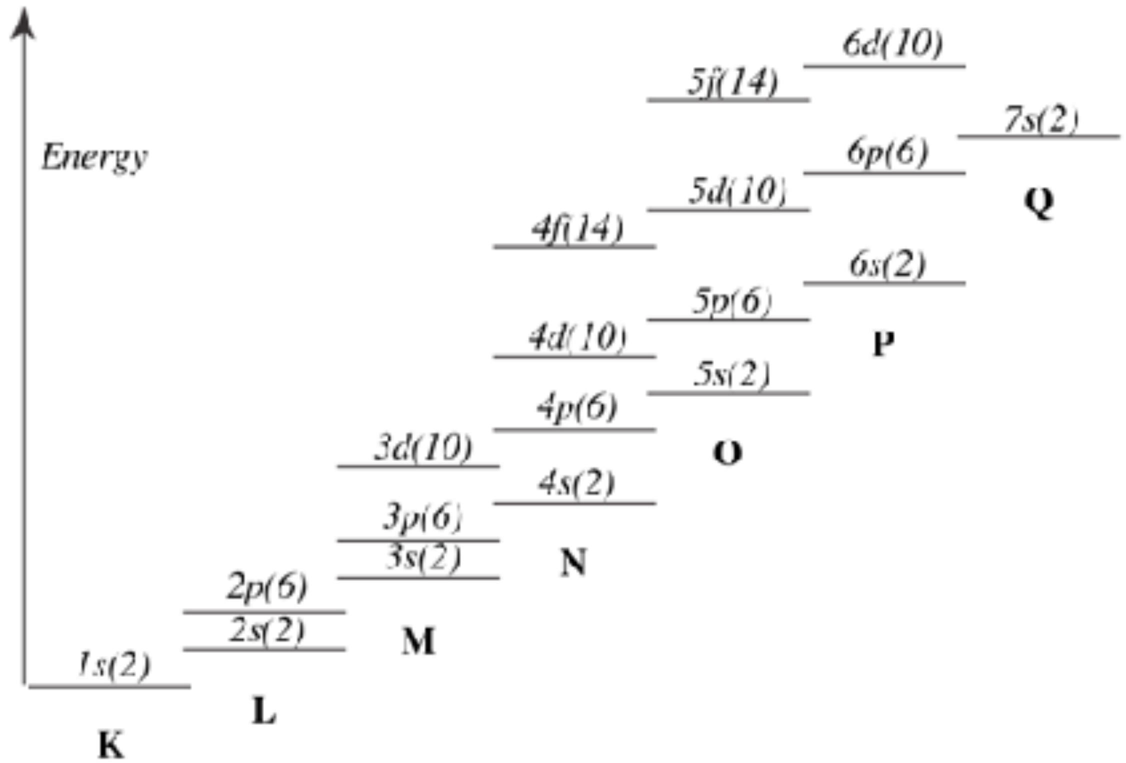
Periodic Table of the Elements



each ***column*** contains elements the same electron configuration in the outer shell and so similar chemical properties

Specification of energy levels

Element	Atomic number	Electron configuration of the ground state
Hydrogen	1	$1s^1$
Helium	2	$1s^2$
Boron	5	$1s^2\ 2s^2\ 2p^1$
Neon	10	$1s^2\ 2s^2\ 2p^6$
Silicon	14	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$
Argon	18	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6 = [Ar]$
Potassium	19	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1 = [Ar]\ 4s^1$
Scandium	21	$[Ar]\ 3d^1\ 4s^2$
Germanium	32	$[Ar]3d^{10}\ 4s^2\ 4p^2$
Krypton	36	$[Ar]3d^{10}\ 4s^2\ 4p^6 = [Kr]$
Rubidium	37	$[Kr]\ 5s^1$



electron configurations

energy levels

notation:

ny^x

n is principle quantum number

x is number of electrons in the level

y is the value of ℓ

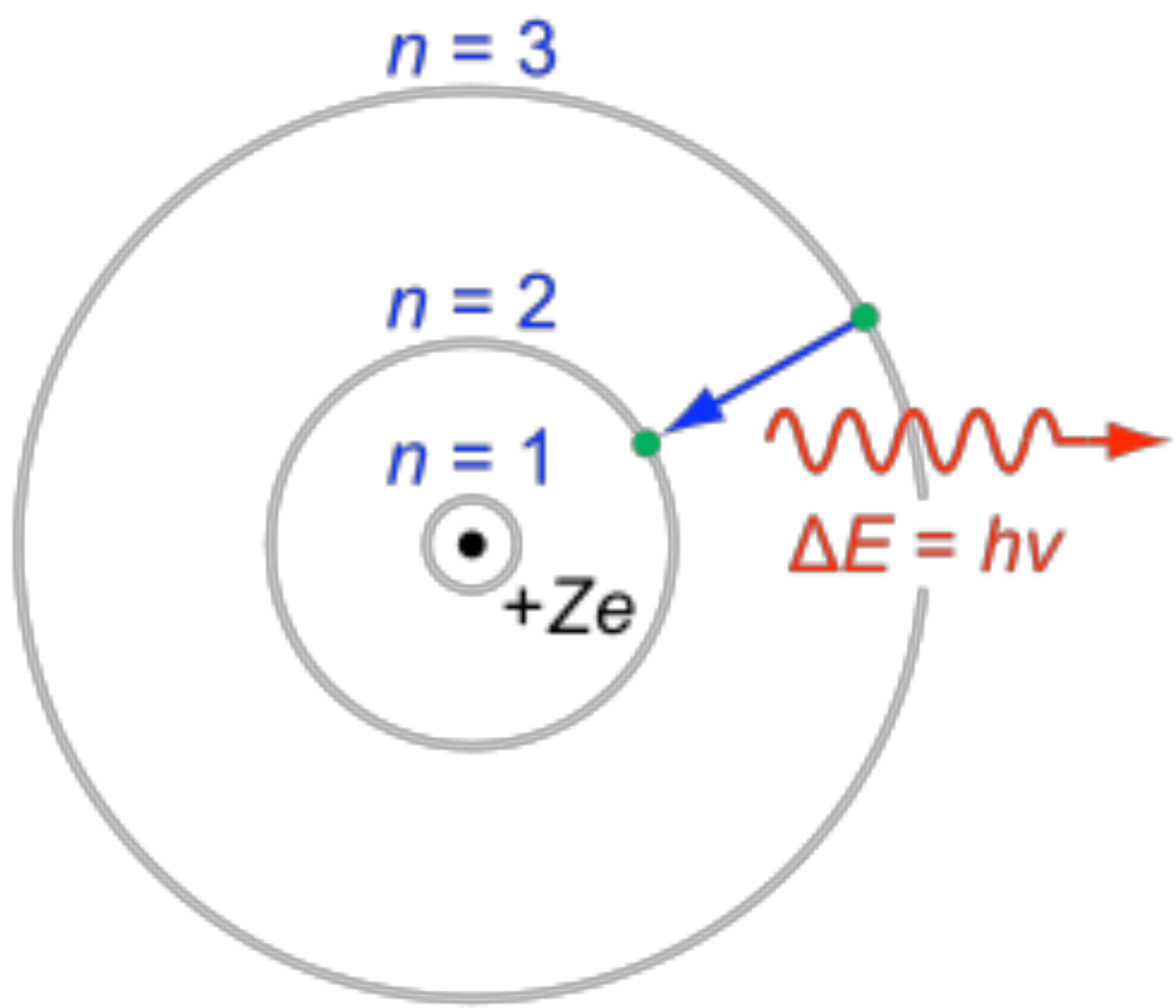
l	0	1	2	3	4	5	6	7, 8, ...
Designation	s	p	d	f	g	h	i	k, l, etc.

De-excitation

Excited atoms typically de-excite on the order of 10^{-8}s

The emit a photon and the electrons fall to the lowest available energy level.

So why aren't all atoms in the lowest energy level?



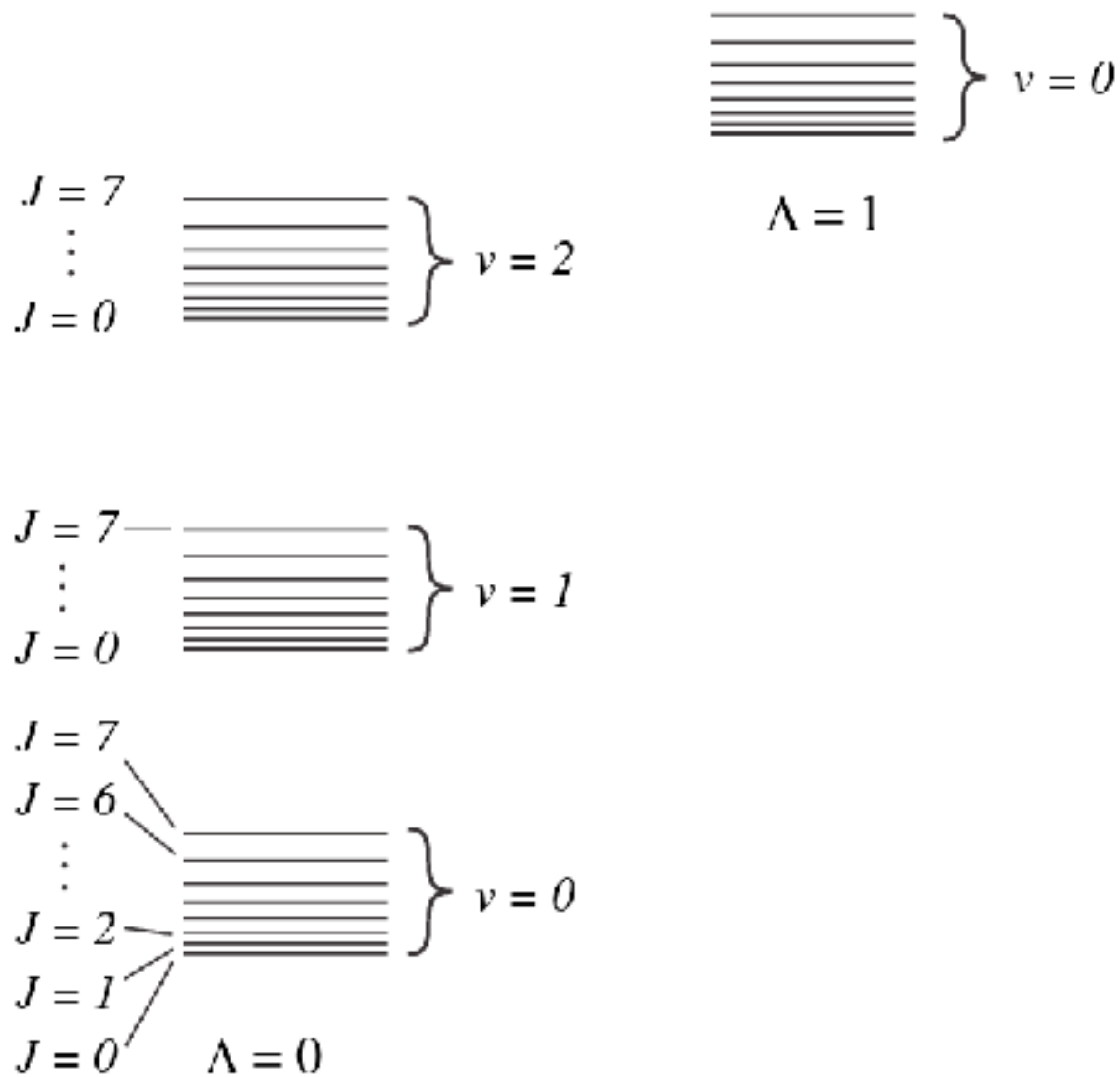
Thermal Excitation

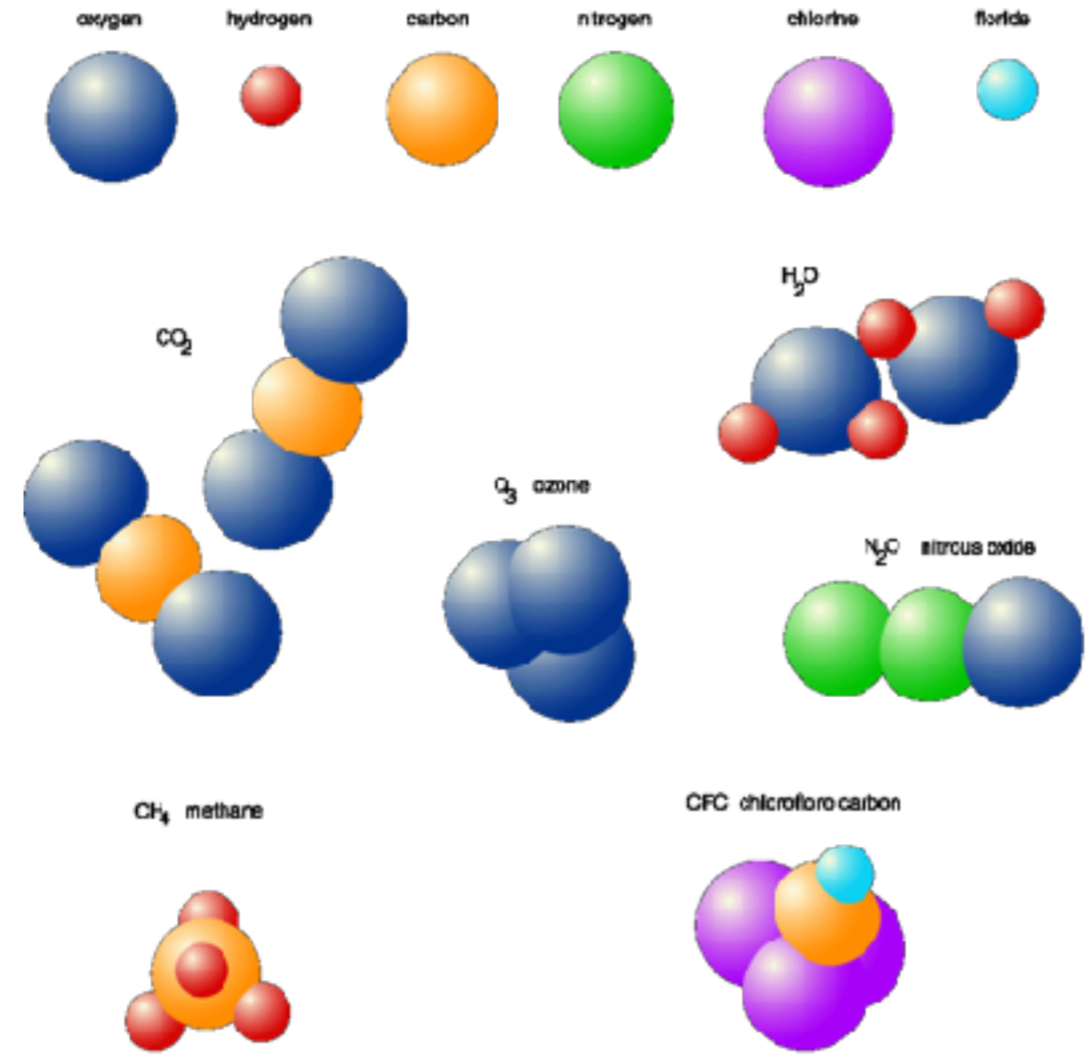
Atoms are typically not in isolation
Atoms are in thermodynamic equilibrium described by the Boltzmann distribution

$$\frac{n_i}{n_j} = \frac{g_i}{g_j} \exp\left\{\frac{E_j - E_i}{kT}\right\}$$

E is the energy level of each state
n is the number of atoms in each state
g are statistical weights of each distinct quantum state at the specified energy

Molecules

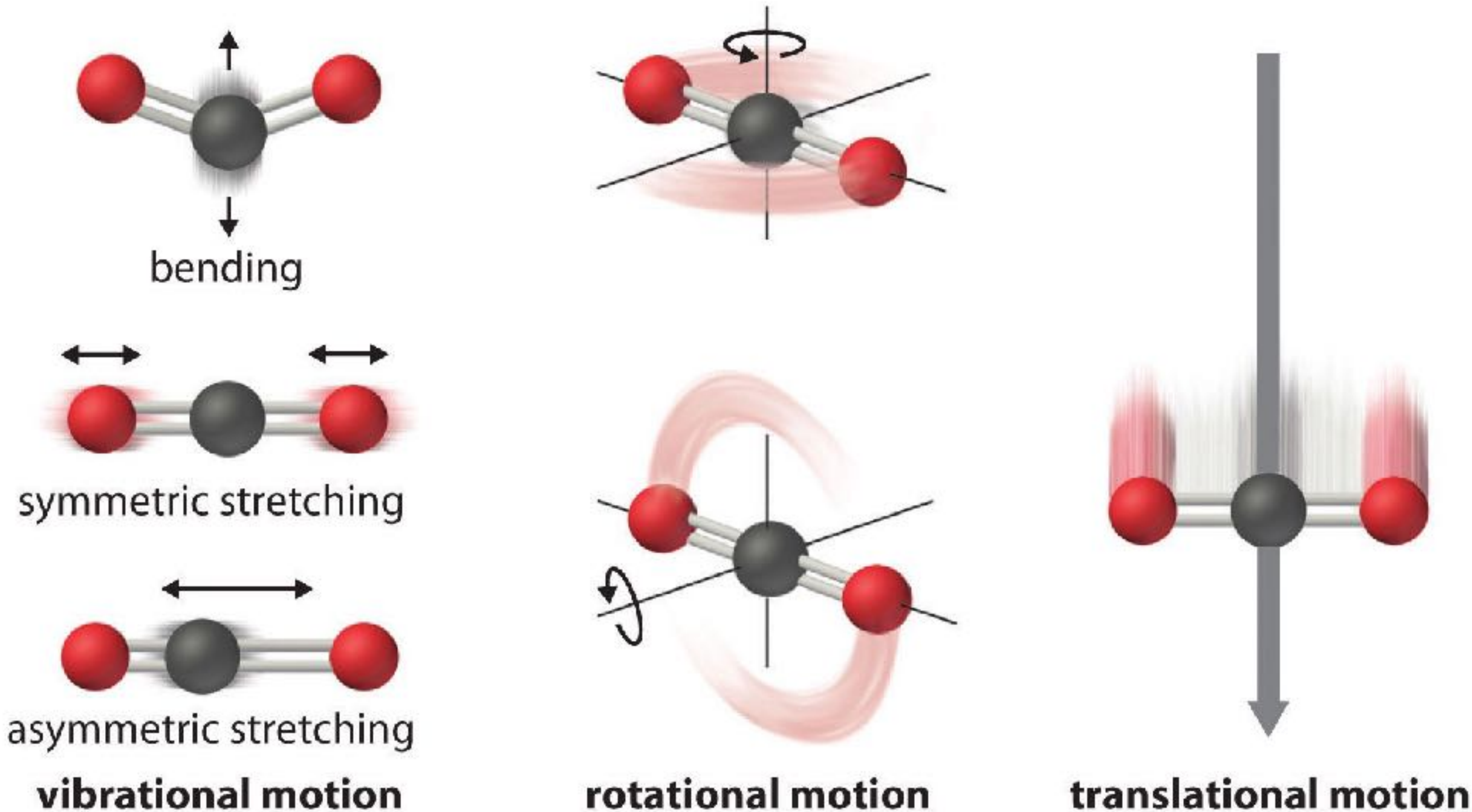




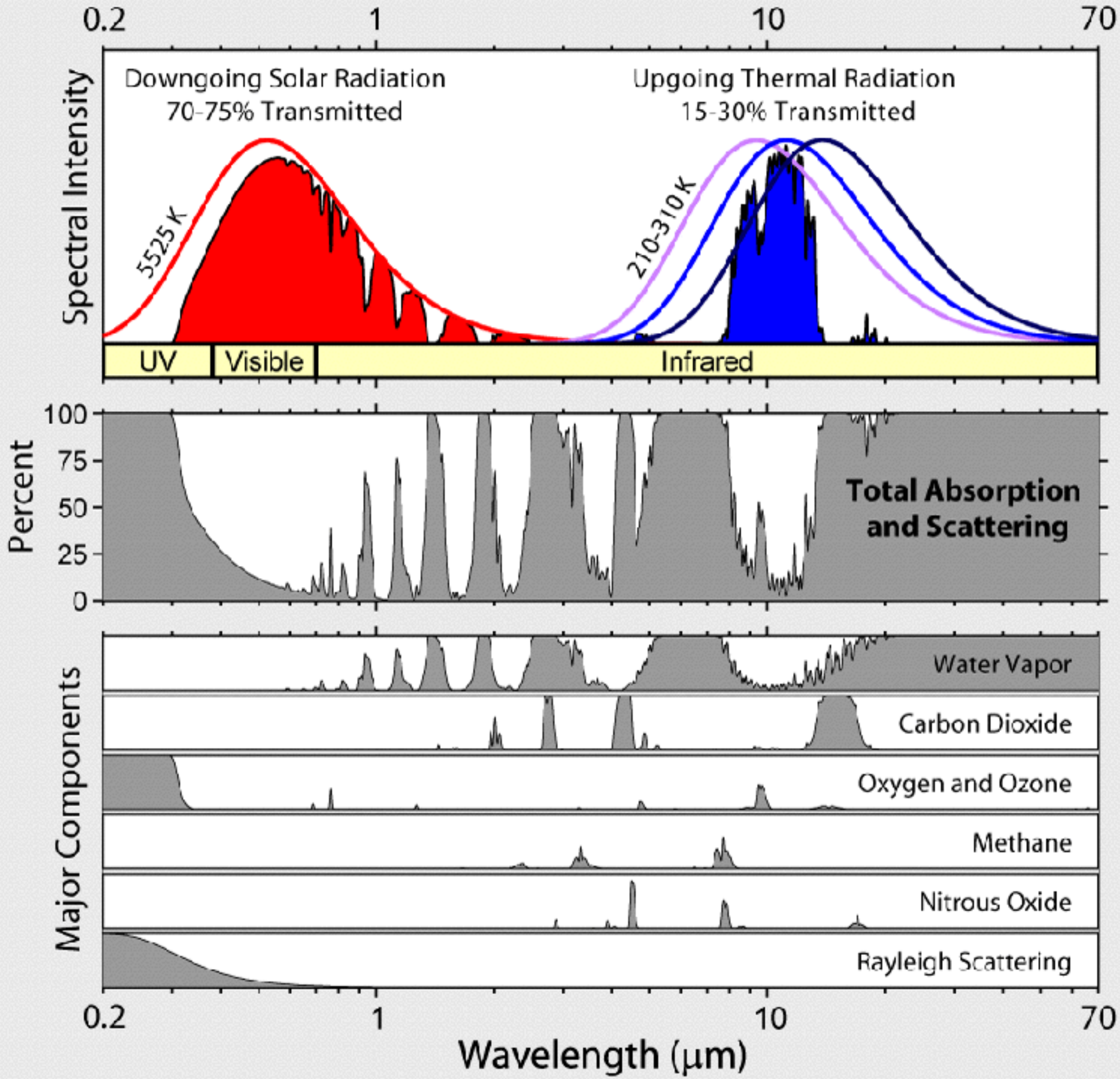
J is rotational state
v is vibrational state
Λ is electronic quantum state

$$E = E_{\text{electron}} + E_{\text{vibration}} + E_{\text{rotation}}$$

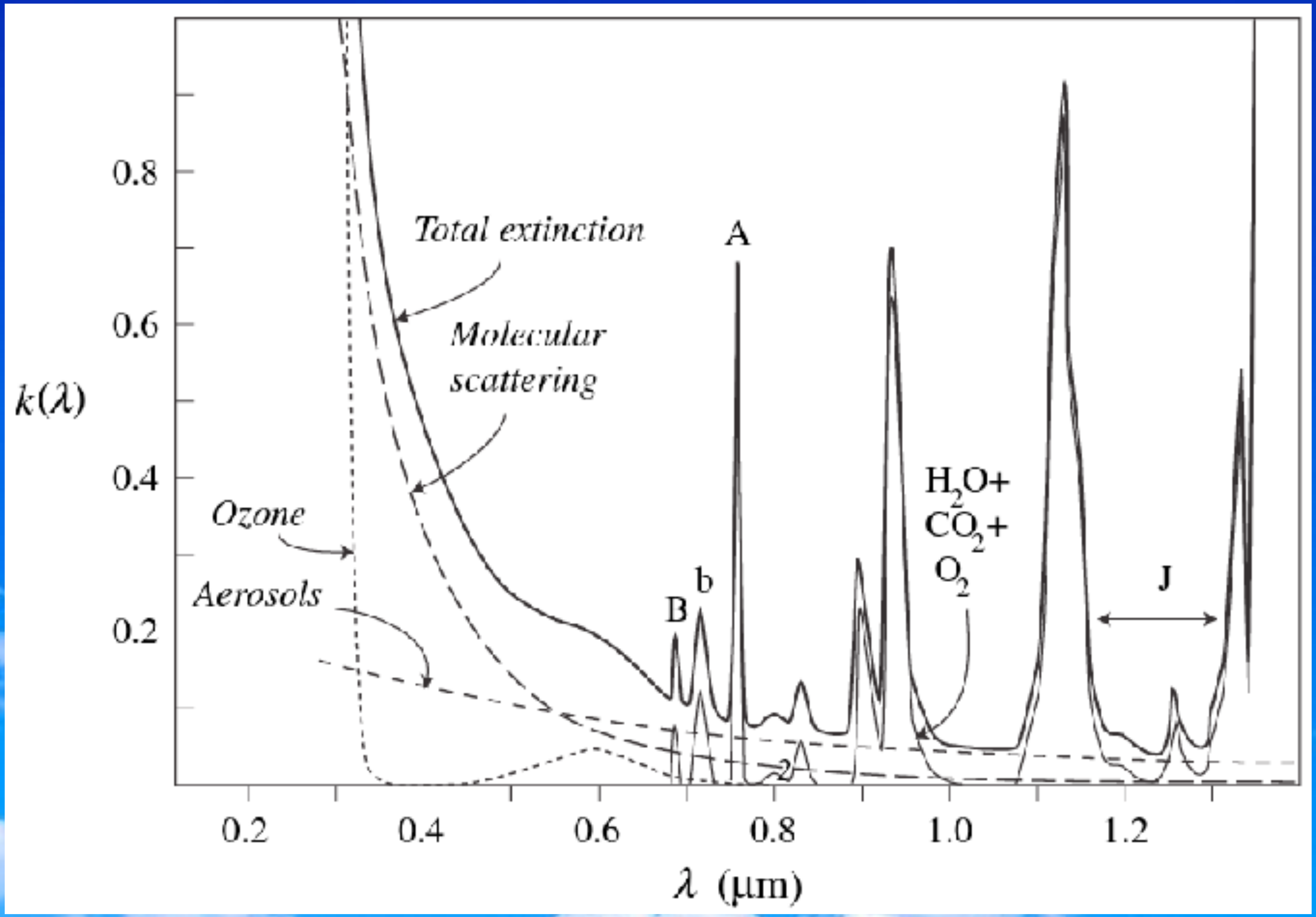
Molecules


bending
symmetric stretching
asymmetric stretching
vibrational motion
rotational motion
translational motion

Radiation Transmitted by the Atmosphere

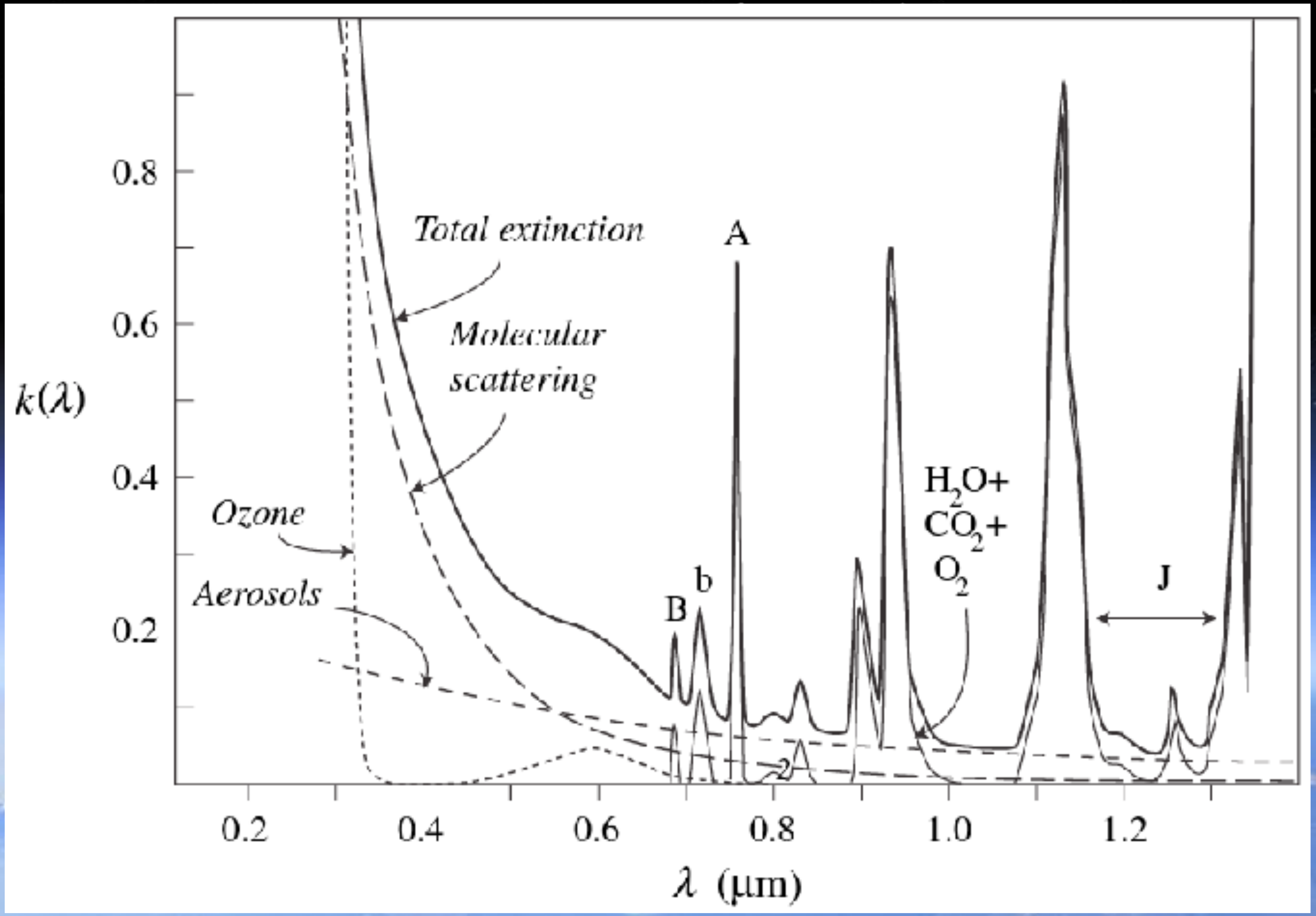


Rayleigh Scattering



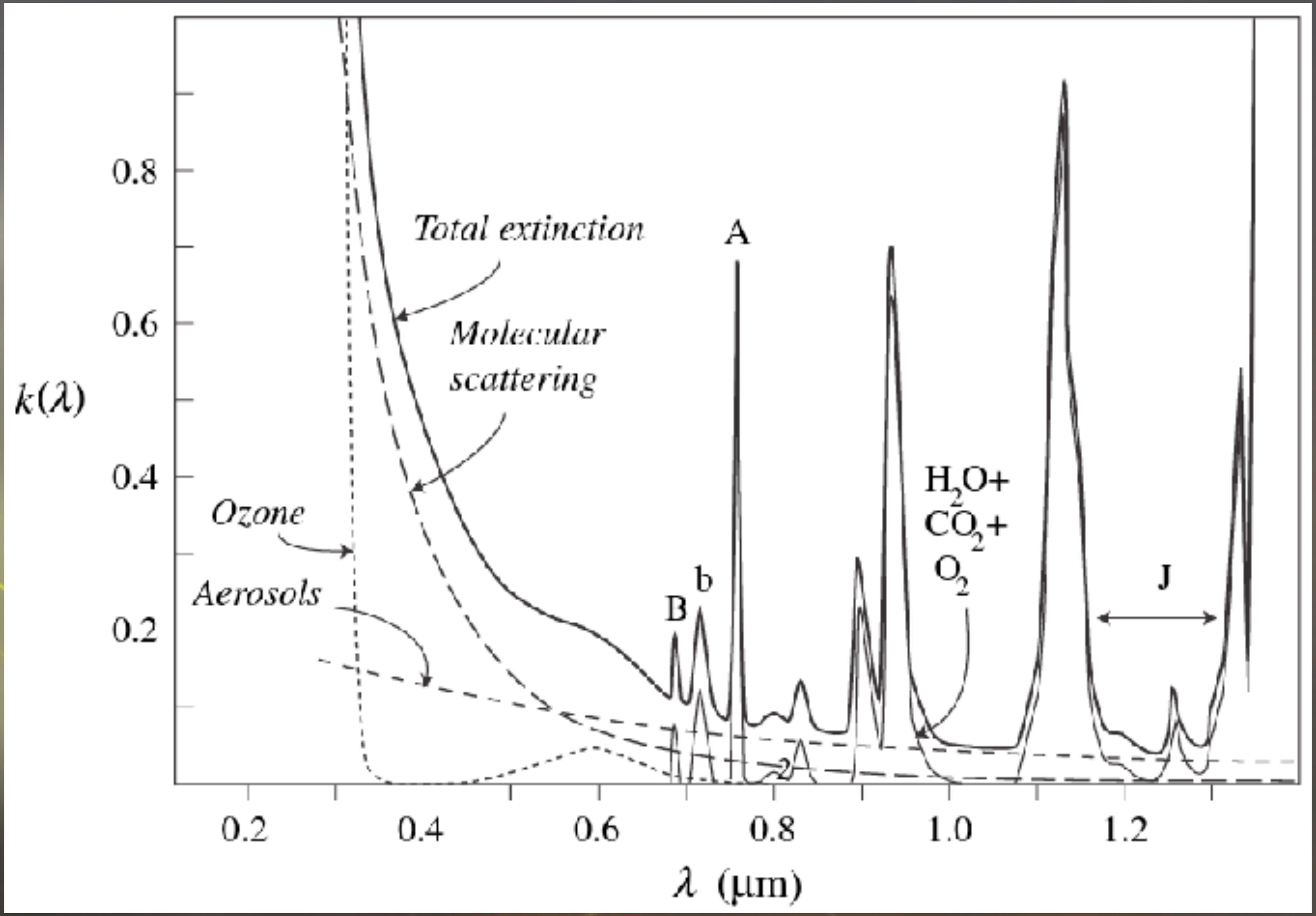
- scattering by molecules
- probability ∝λ^{-4} —> short wavelengths affected —> why sky is blue
- stable over time
- magnitude scales with pressure —> higher altitudes more transparent

Ozone



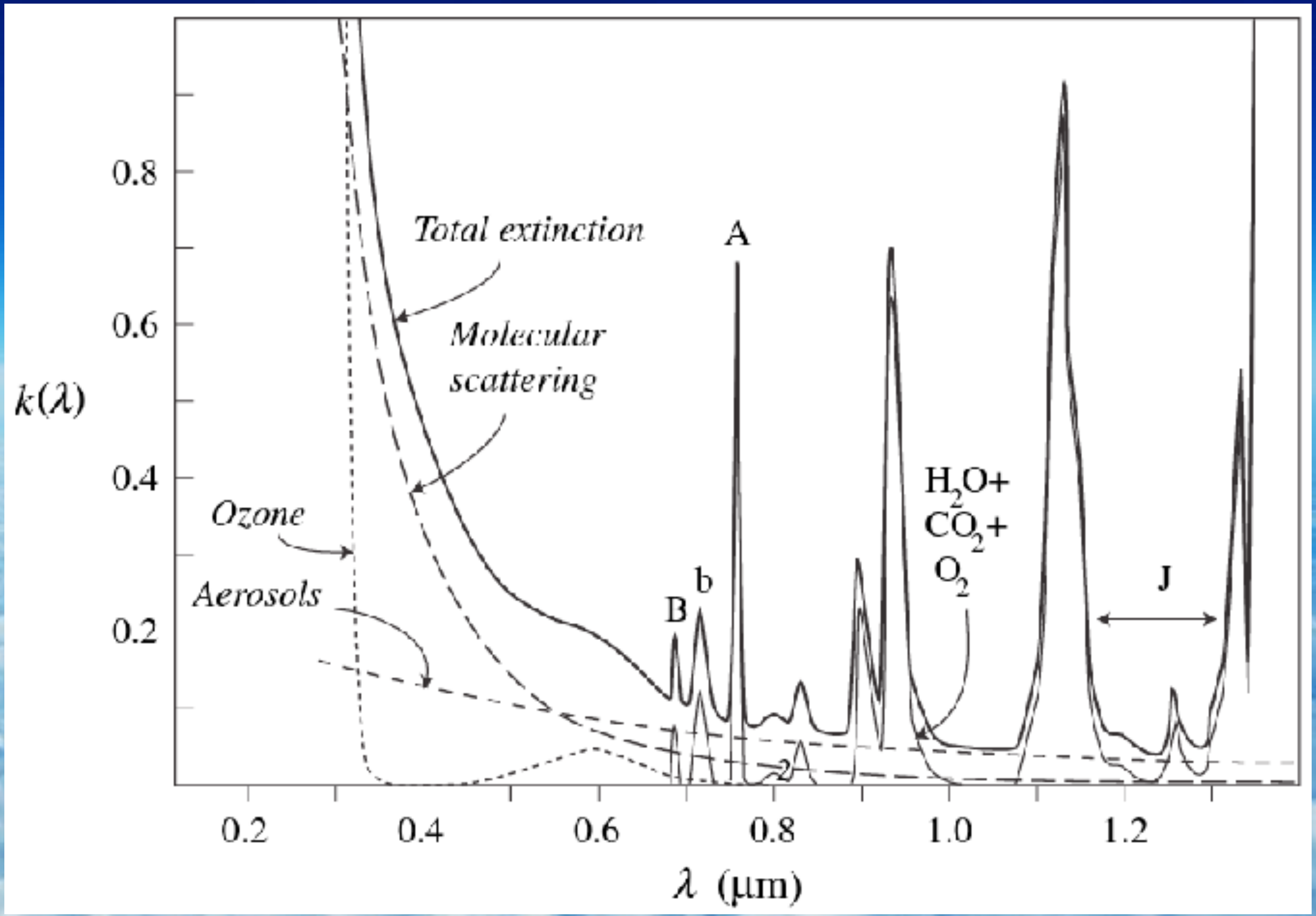
- O_3 absorption in upper atmosphere sharply cuts off λ<320nm
- concentrates in the stratopause ~25km —> mountains won't help !
- varies seasonally and by latitude, but not on short time scales
- FYI, don't hate. Necessary for life.

Aerosols

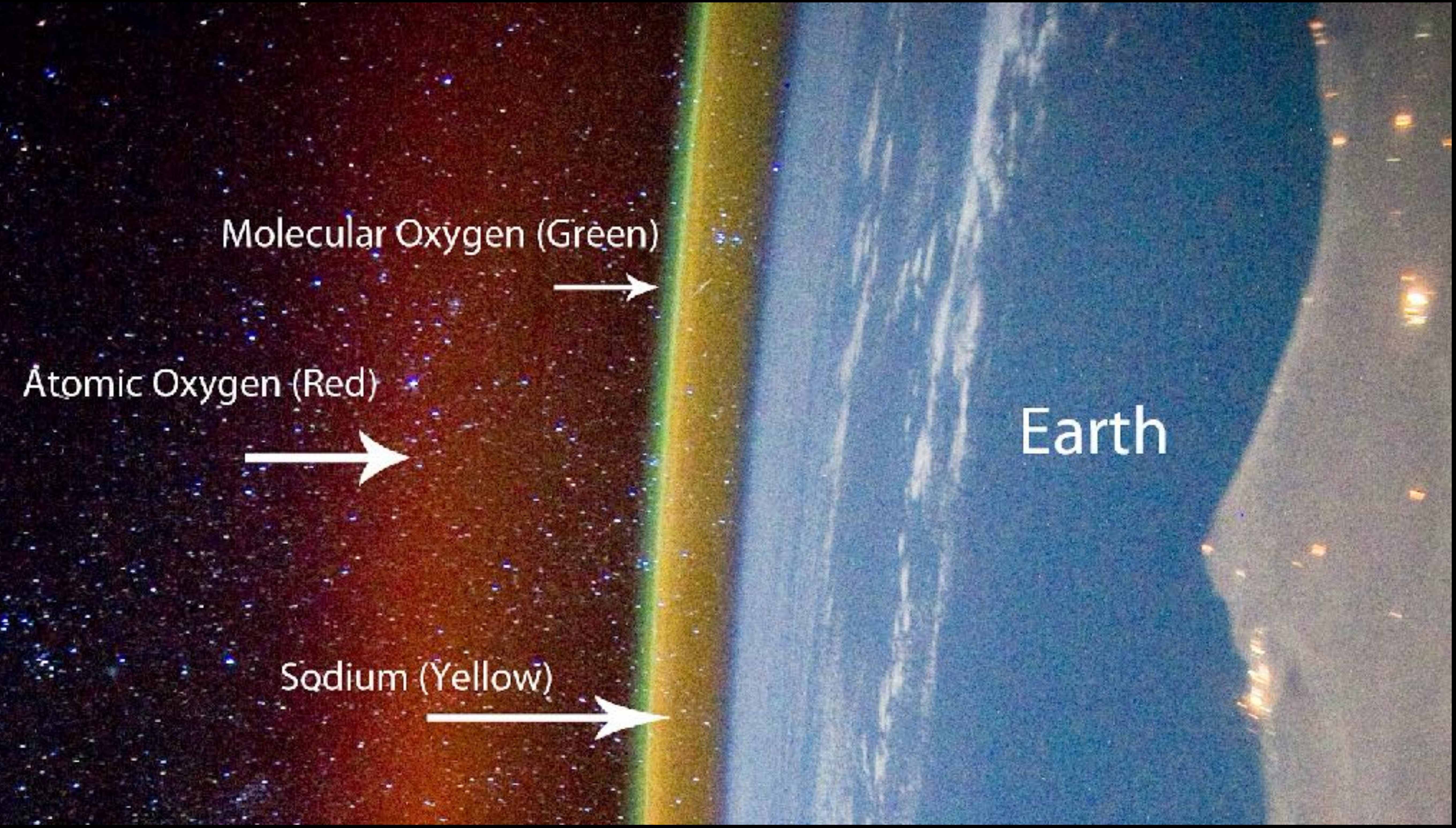


- small particles, larger than molecules up to ~50µm
- e.g. salt grains from sea spray, winds over desert make dust, volcanic ash, burning fossil fuels
- produce grey extinction (λ^{-1})
- makes sky pale blue instead of deep blue
- can vary on short time scales and be at all levels of atmosphere

Molecules

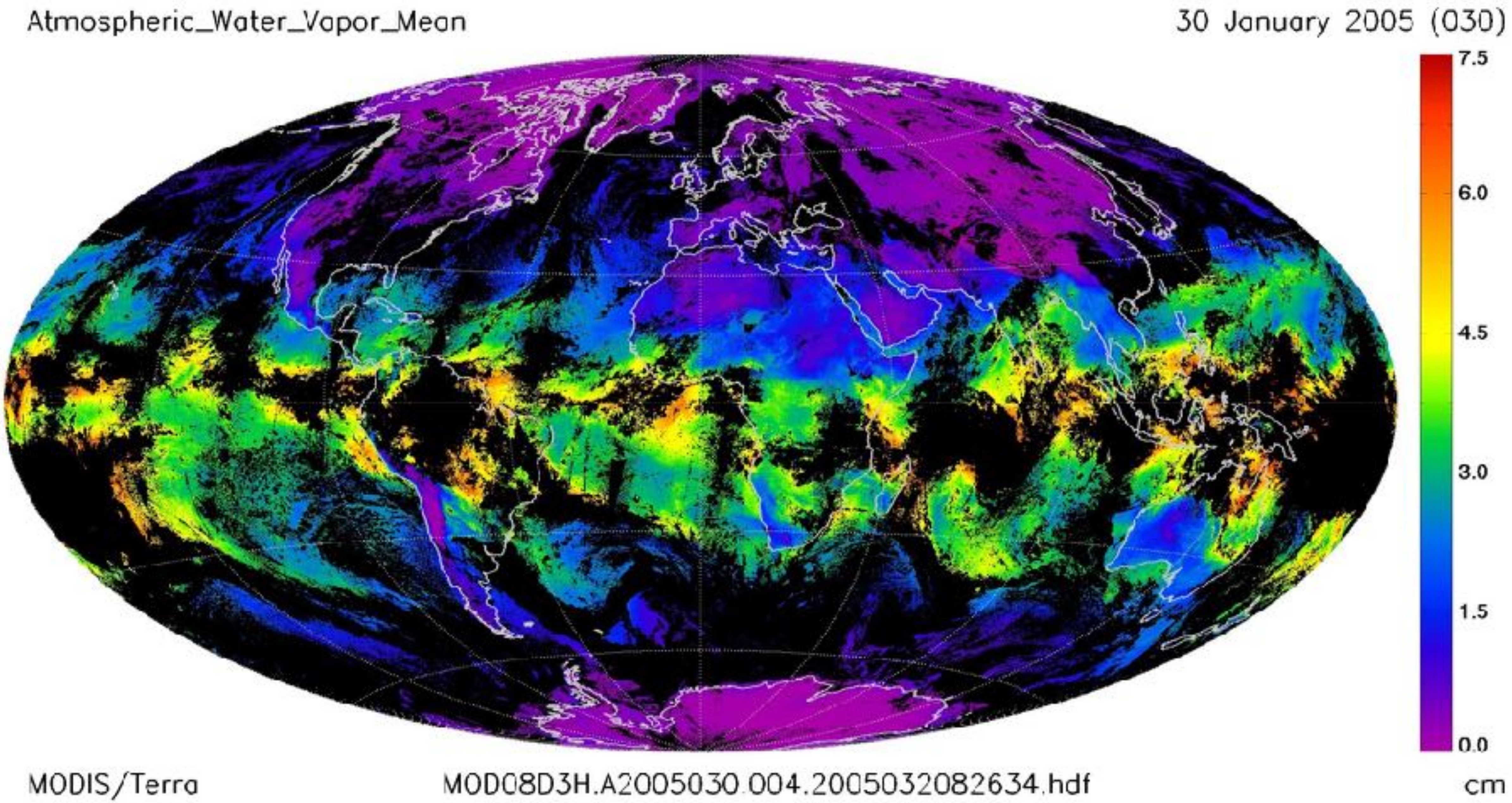


- main molecular absorbers are H2O, CO2, O2, O3
- CO2 is well mixed with altitude —> can't do anything about it
- H2O concentrates near the surface and is highly variable.
- At sea level, ~ 10mm precipitable water H2O
- On Mauna Kea, ~1 mm precipitable H2O
- At South Pole, 0.15 mm
- Balloons even lower

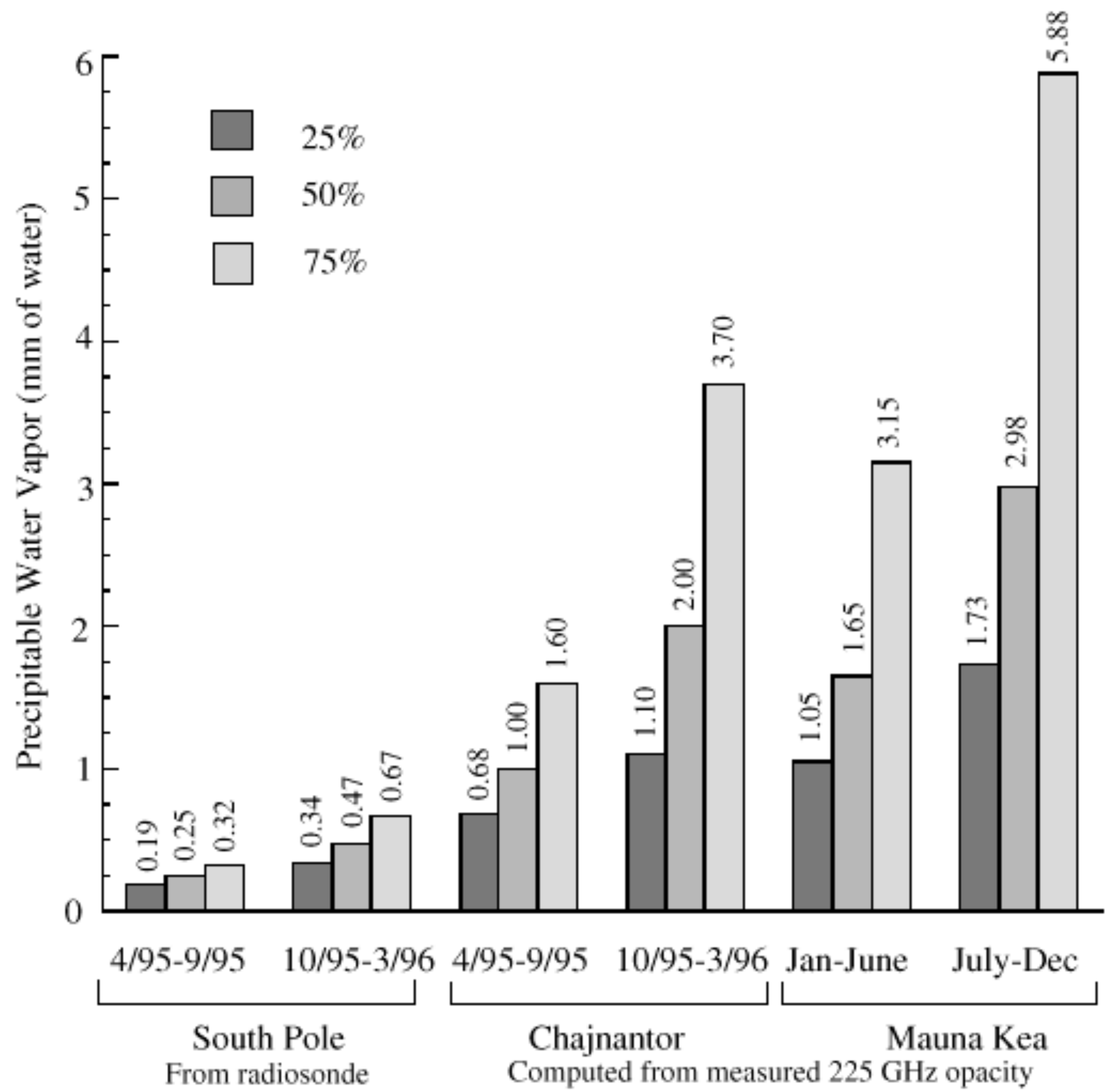

Molecular Oxygen (Green)
Atomic Oxygen (Red)
Sodium (Yellow)
Earth

O
O_2
Na

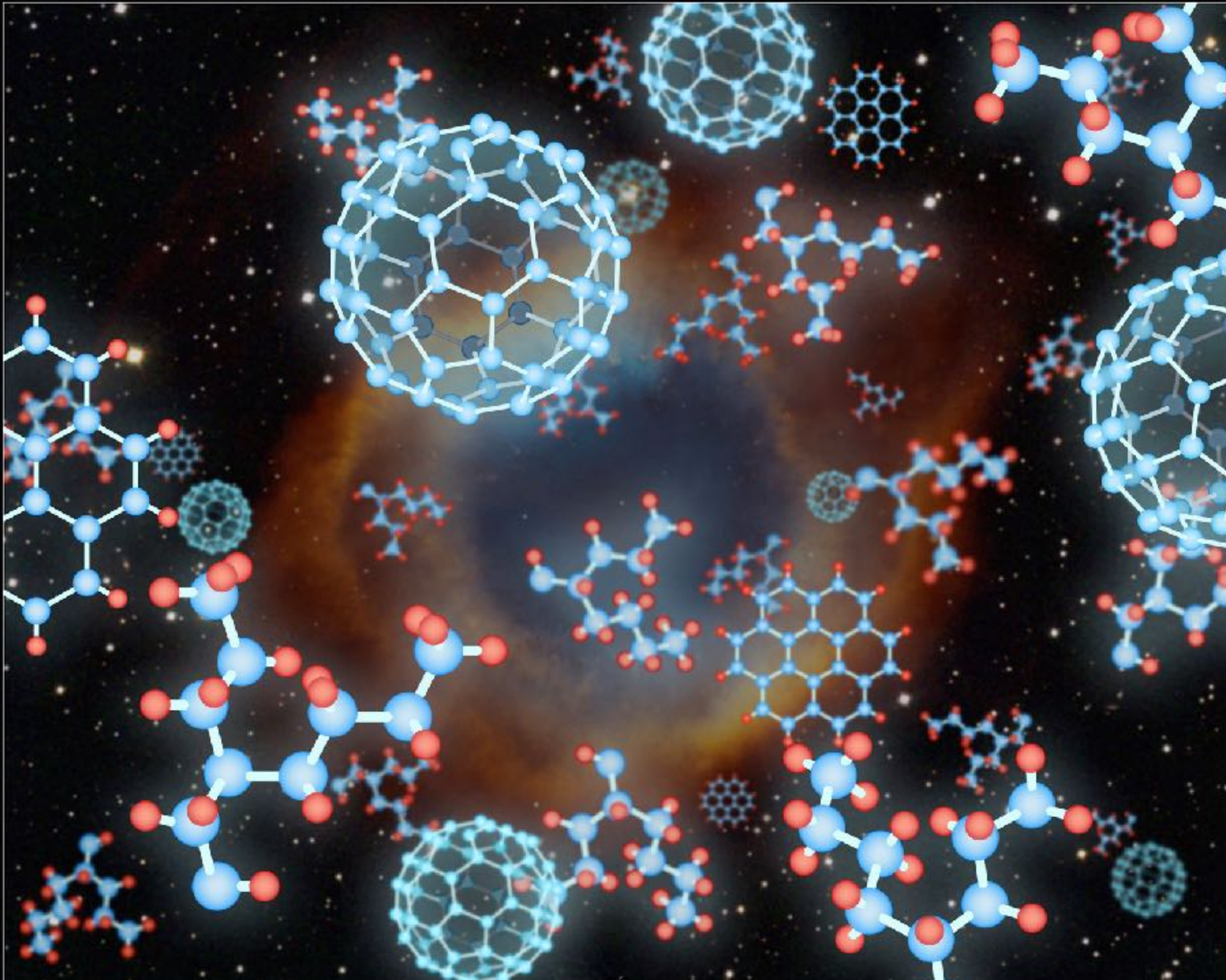
Atmospheric water vapor

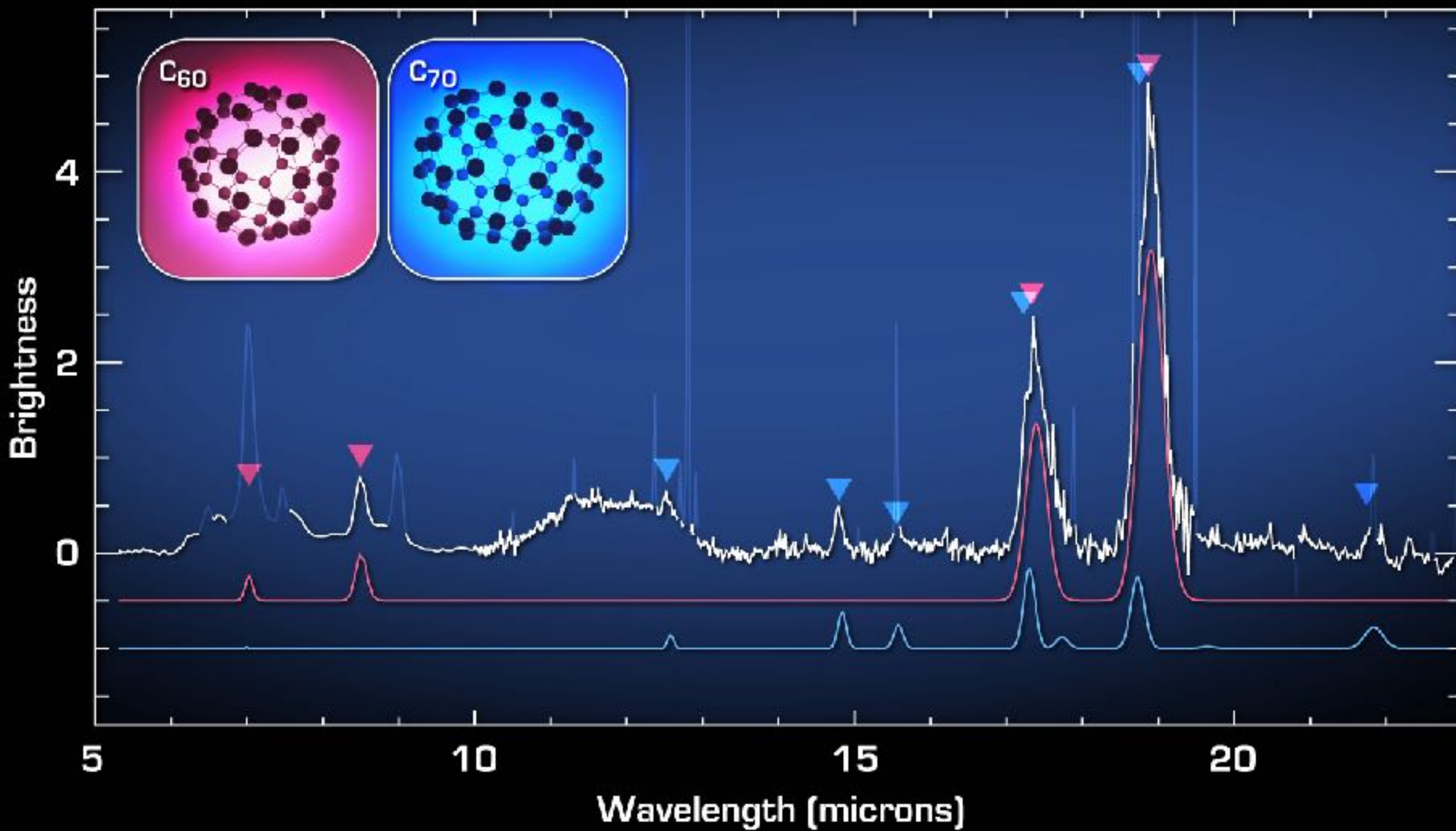


(NASA)



Precipitable Water Vapor (mm of water)
0
1
2
3
4
5
6
25%
50%
75%
0.19
0.25
0.32
0.34
0.47
0.67
0.68
1.00
1.60
1.10
2.00
3.70
1.05
1.65
3.15
1.73
2.98
5.88
4/95-9/95
10/95-3/96
4/95-9/95
10/95-3/96
Jan-June
July-Dec
South Pole
From radiosonde
Chajnantor
Mauna Kea
Computed from measured 225 GHz opacity



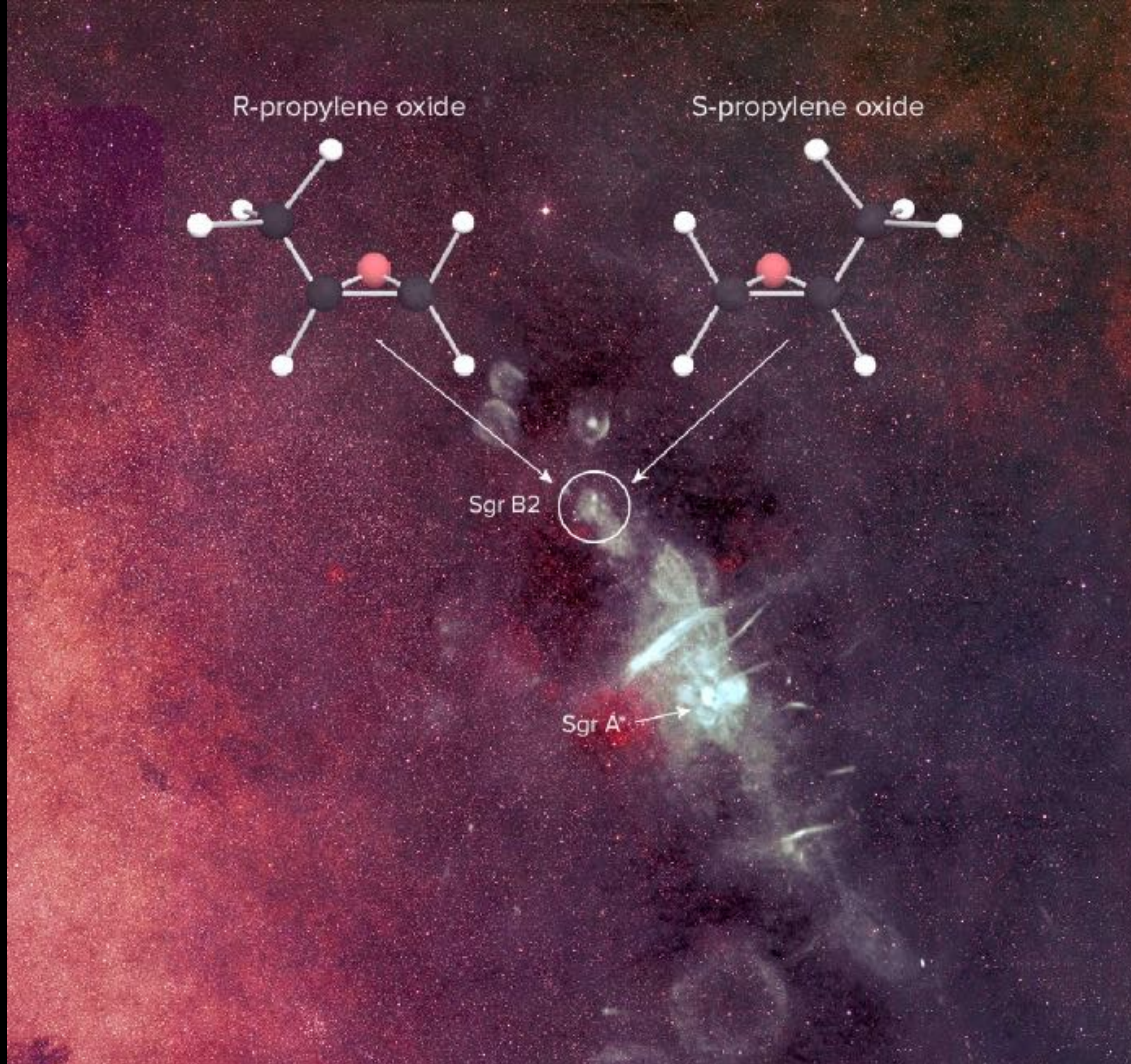


Buckyballs In A Young Planetary Nebula

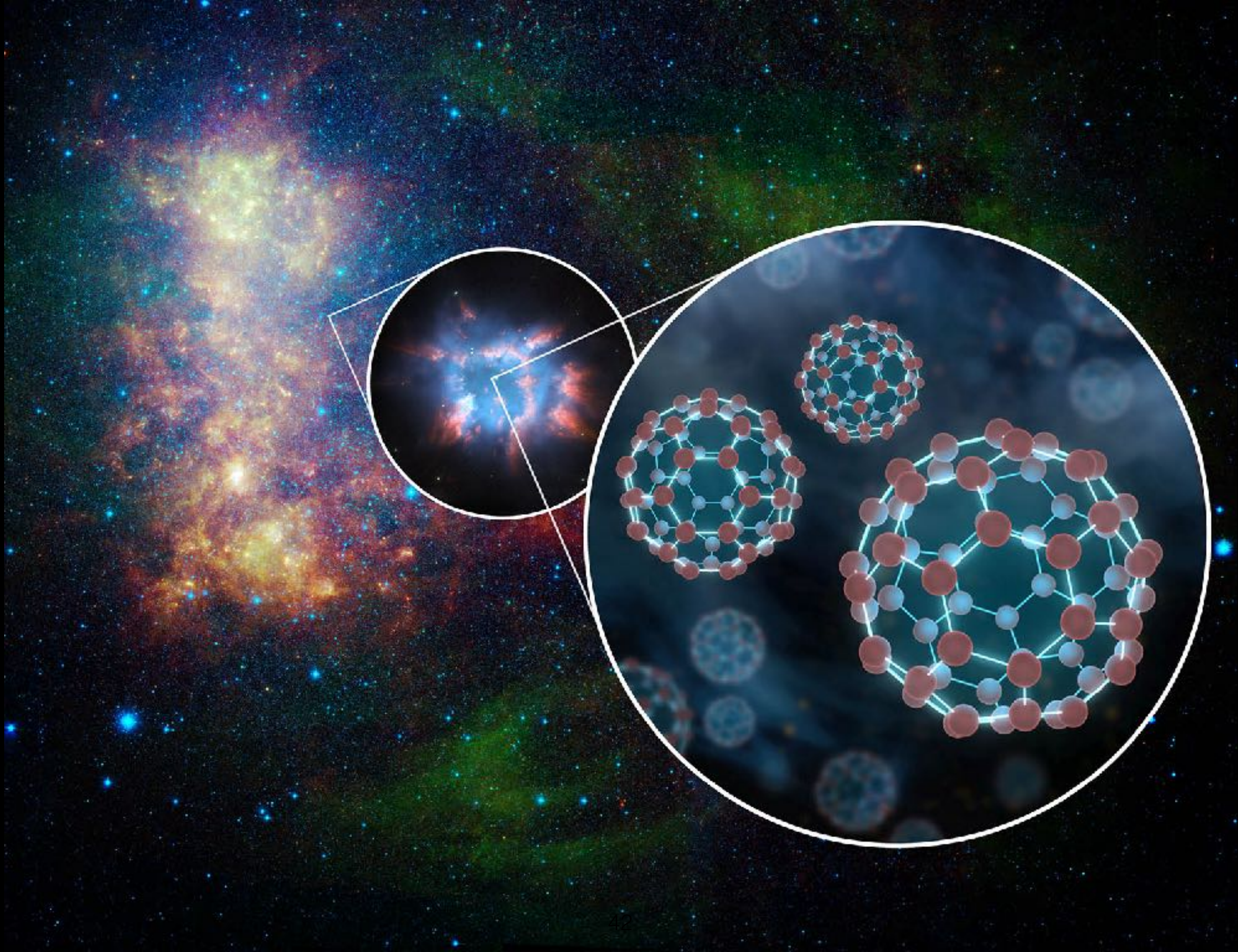
NASA / JPL-Caltech / J. Cami (Univ. of Western Ontario/SETI Institute)

Spitzer Space Telescope • IRS

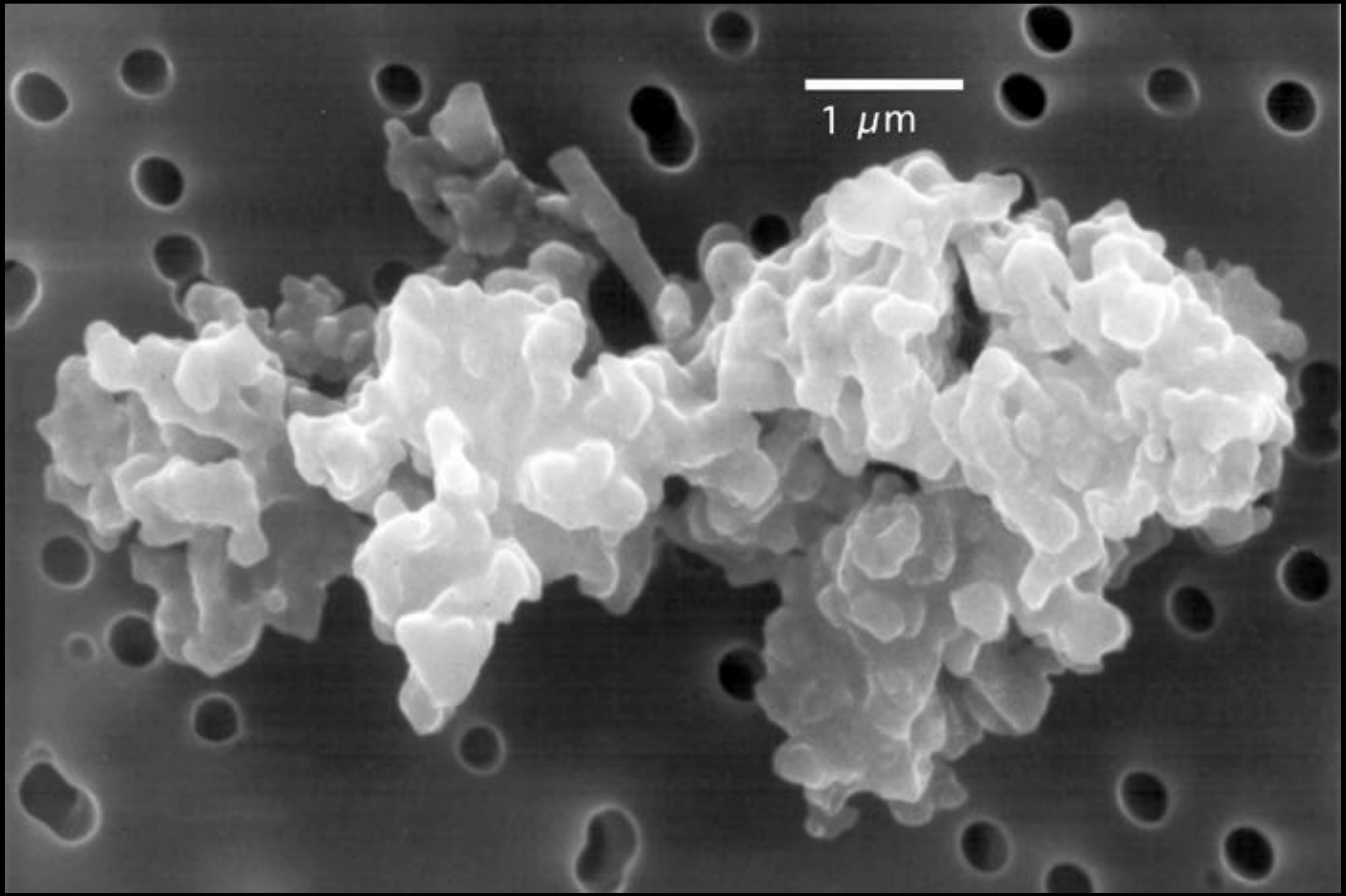
ssc2010-06a

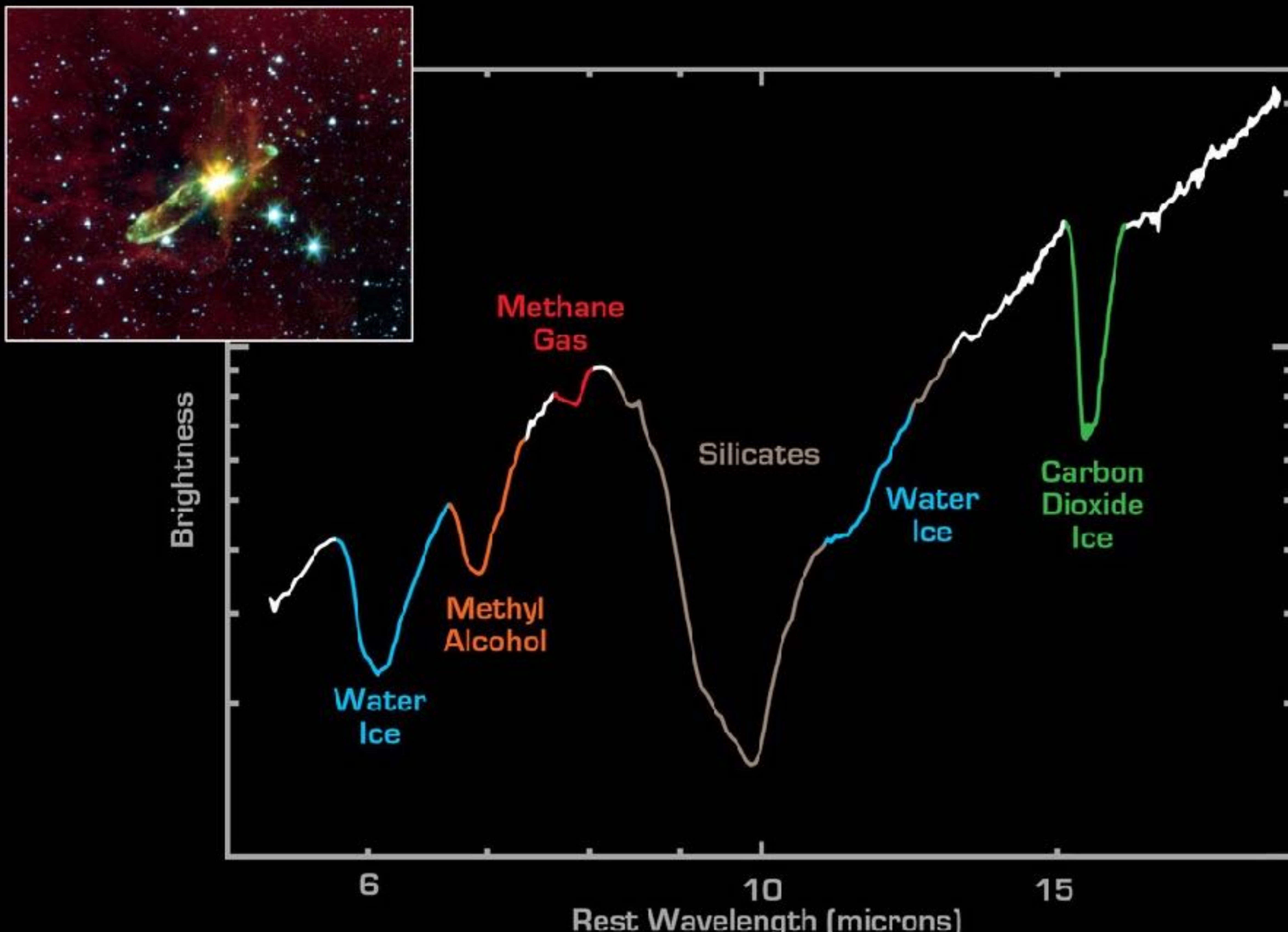


complex left-handed chiral organic molecules
in the galactic center



dust grains





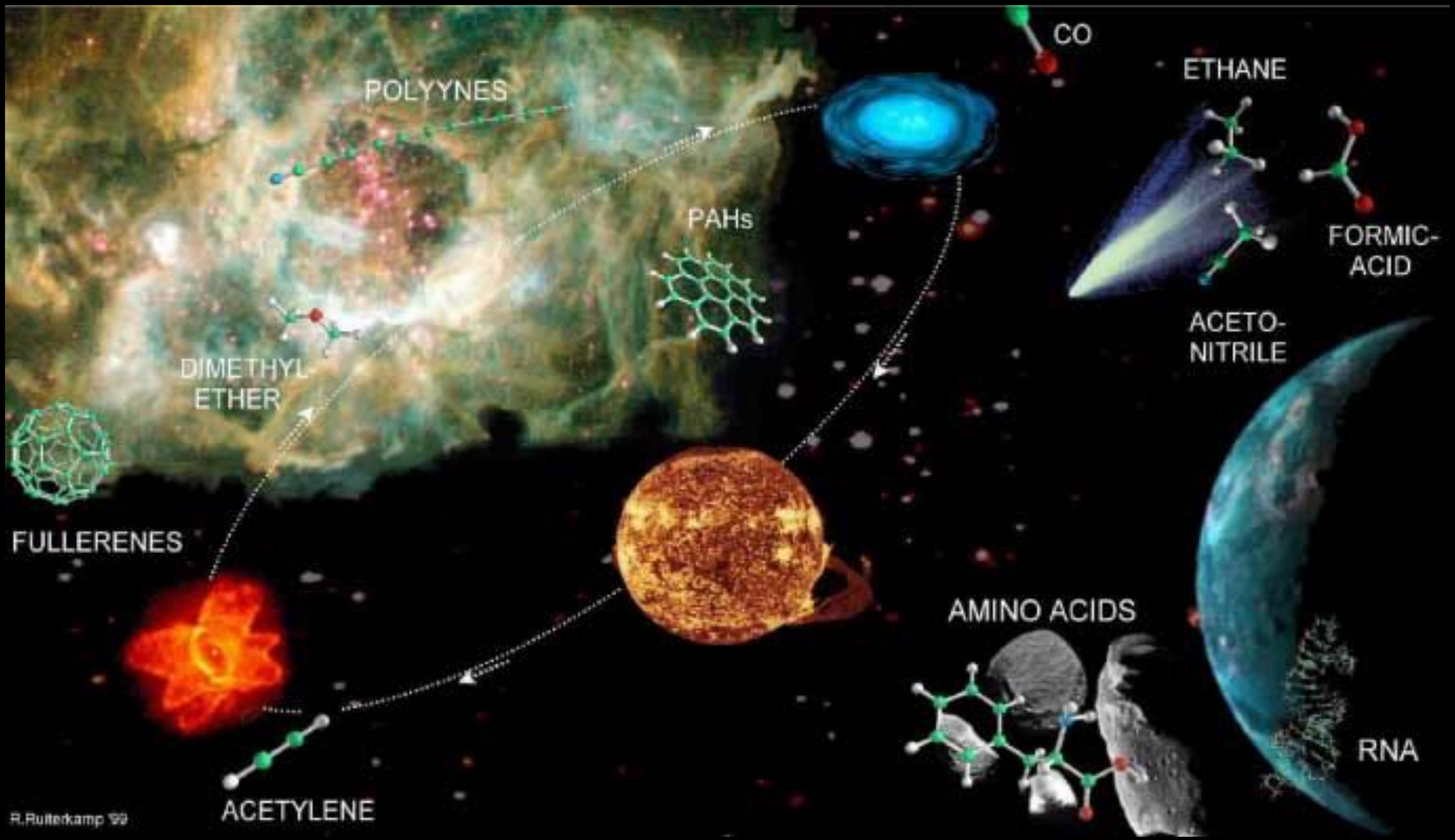
Embedded Outflow in HH 46/47

Spitzer Space Telescope • IRS • IRAC

NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)

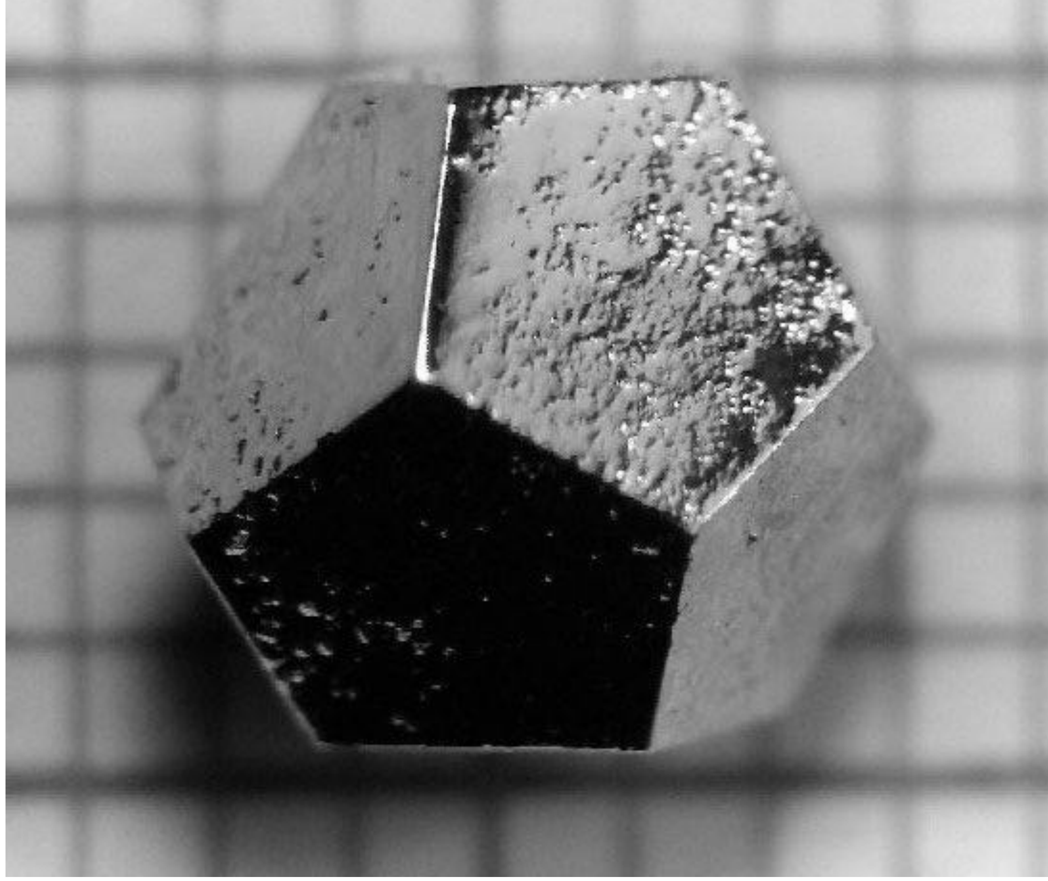
ssc2003-06g

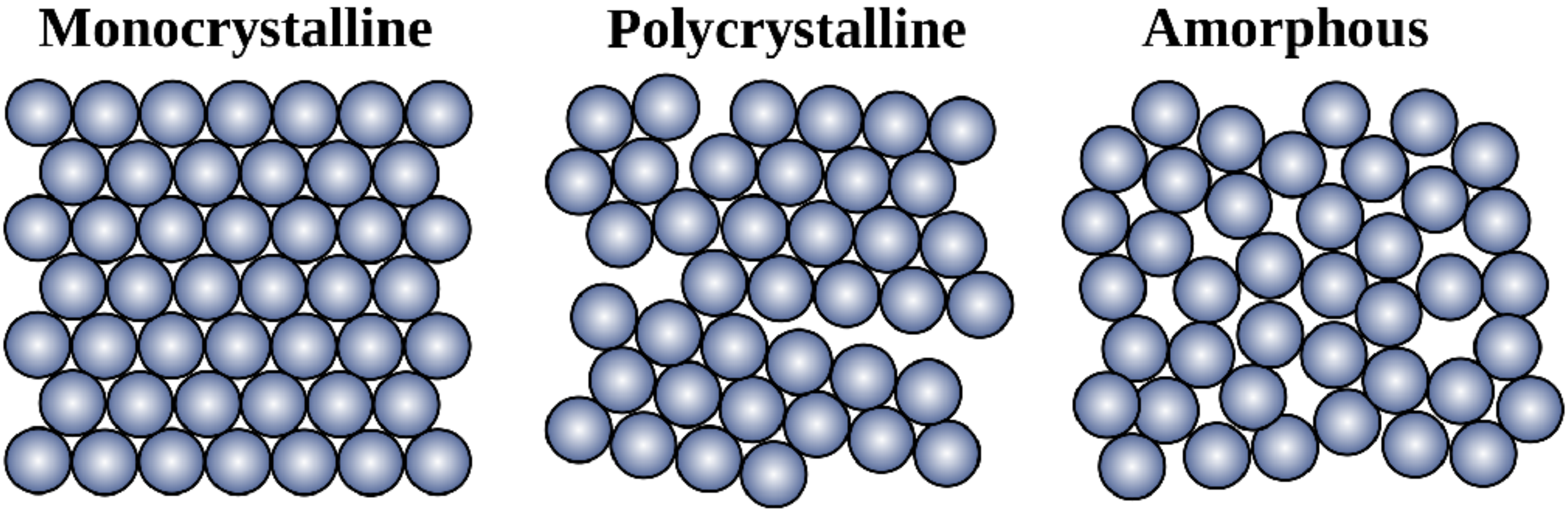
astro chemical cycles



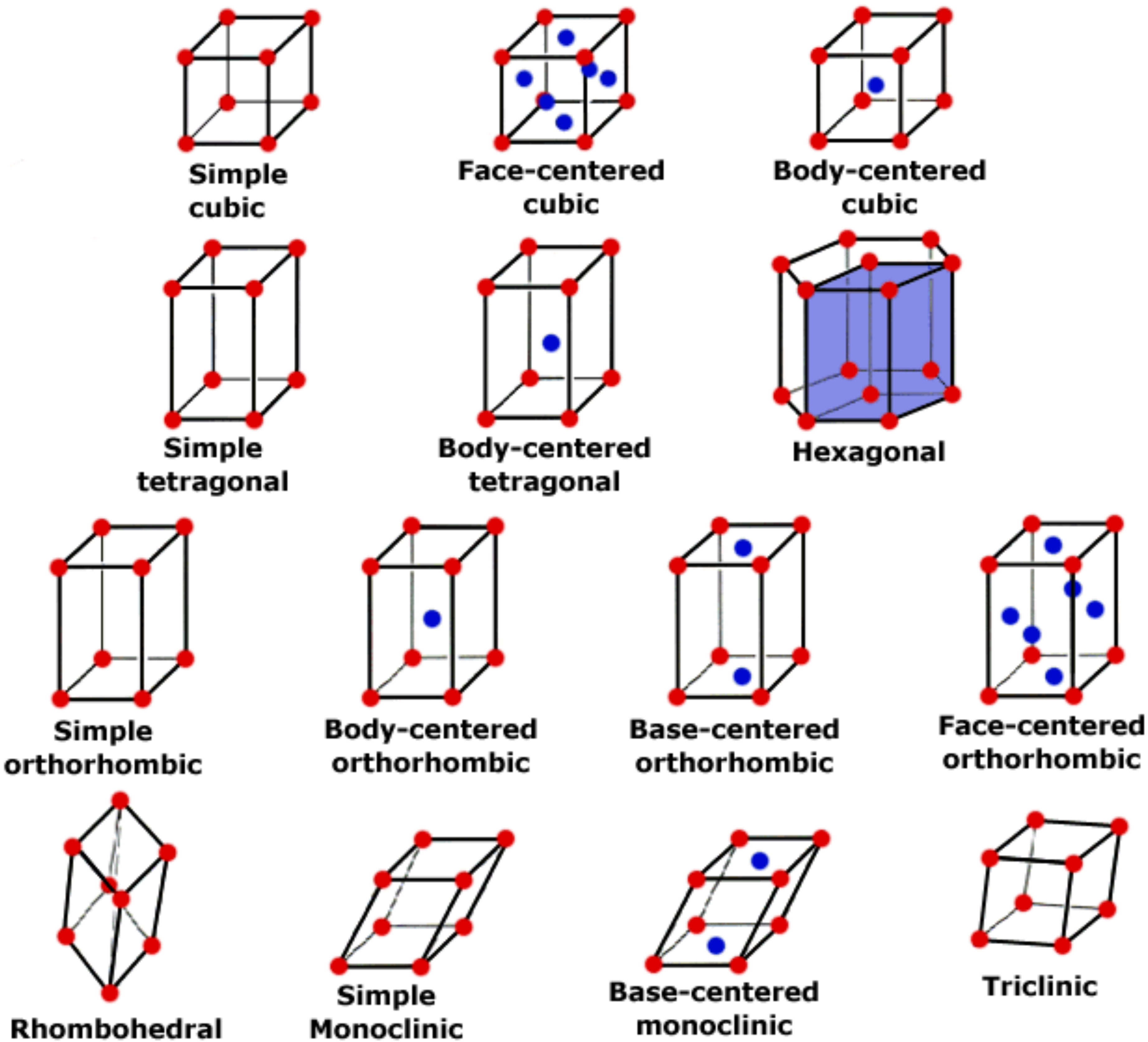
Crystals

A crystal is a mega molecule where the pattern of atoms and bonds repeats periodically with location



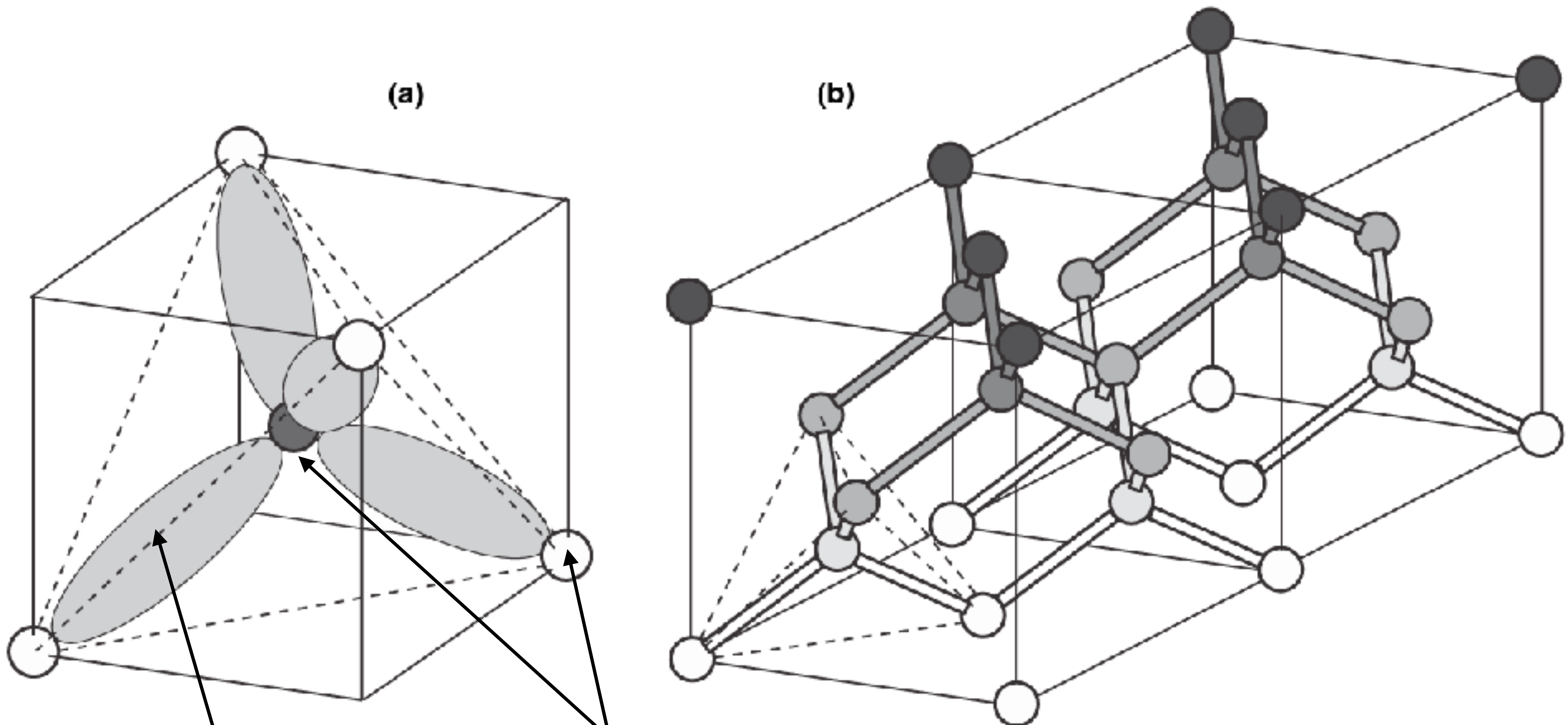


Crystals



Simple cubic
Face-centered cubic
Body-centered cubic
Simple tetragonal
Body-centered tetragonal
Hexagonal
Simple orthorhombic
Body-centered orthorhombic
Base-centered orthorhombic
Face-centered orthorhombic
Rhombohedral
Simple Monoclinic
Base-centered monoclinic
Triclinic

Crystals



atom

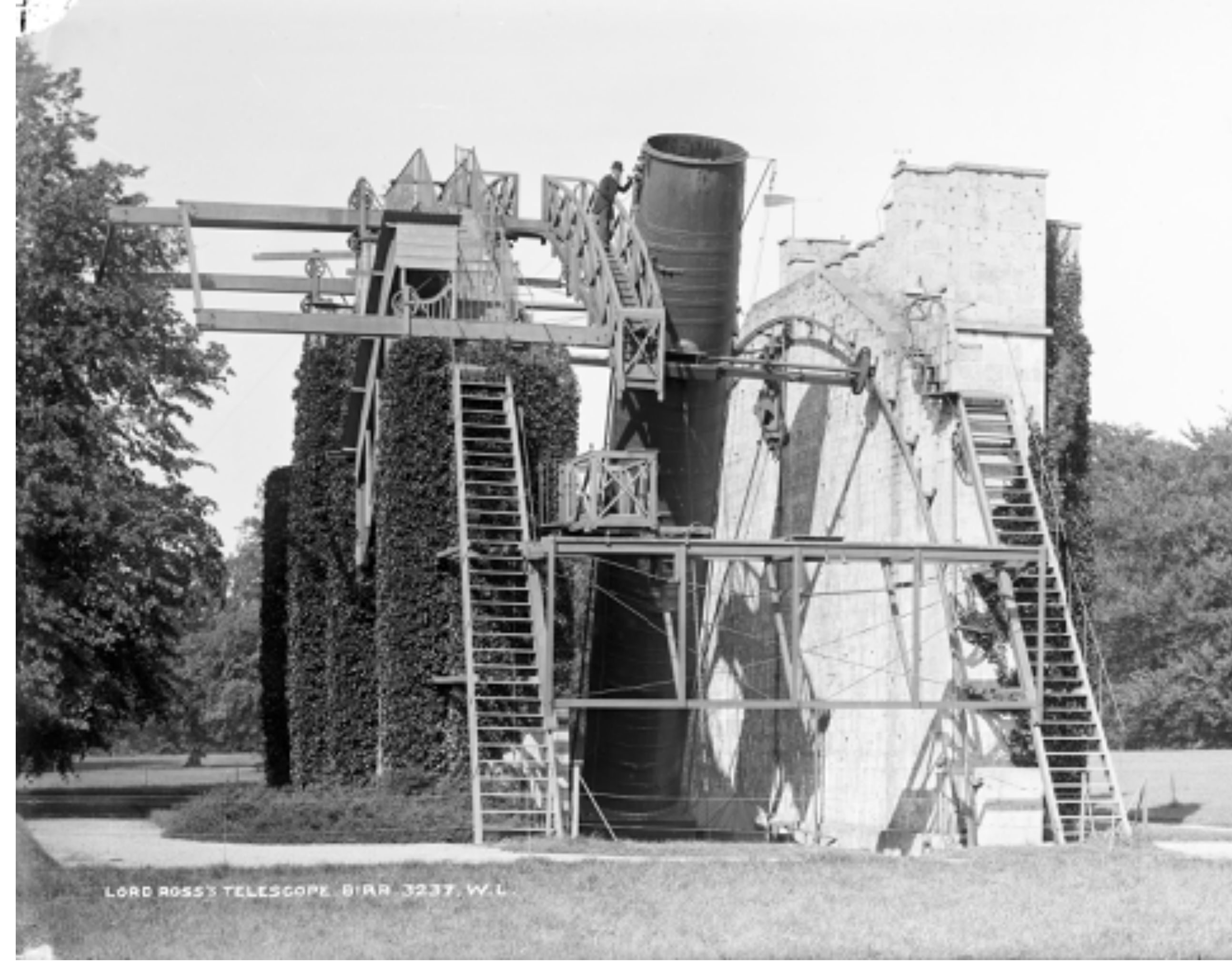
probability of finding electron

Strength & Weight

- steel = iron + carbon
- aluminum

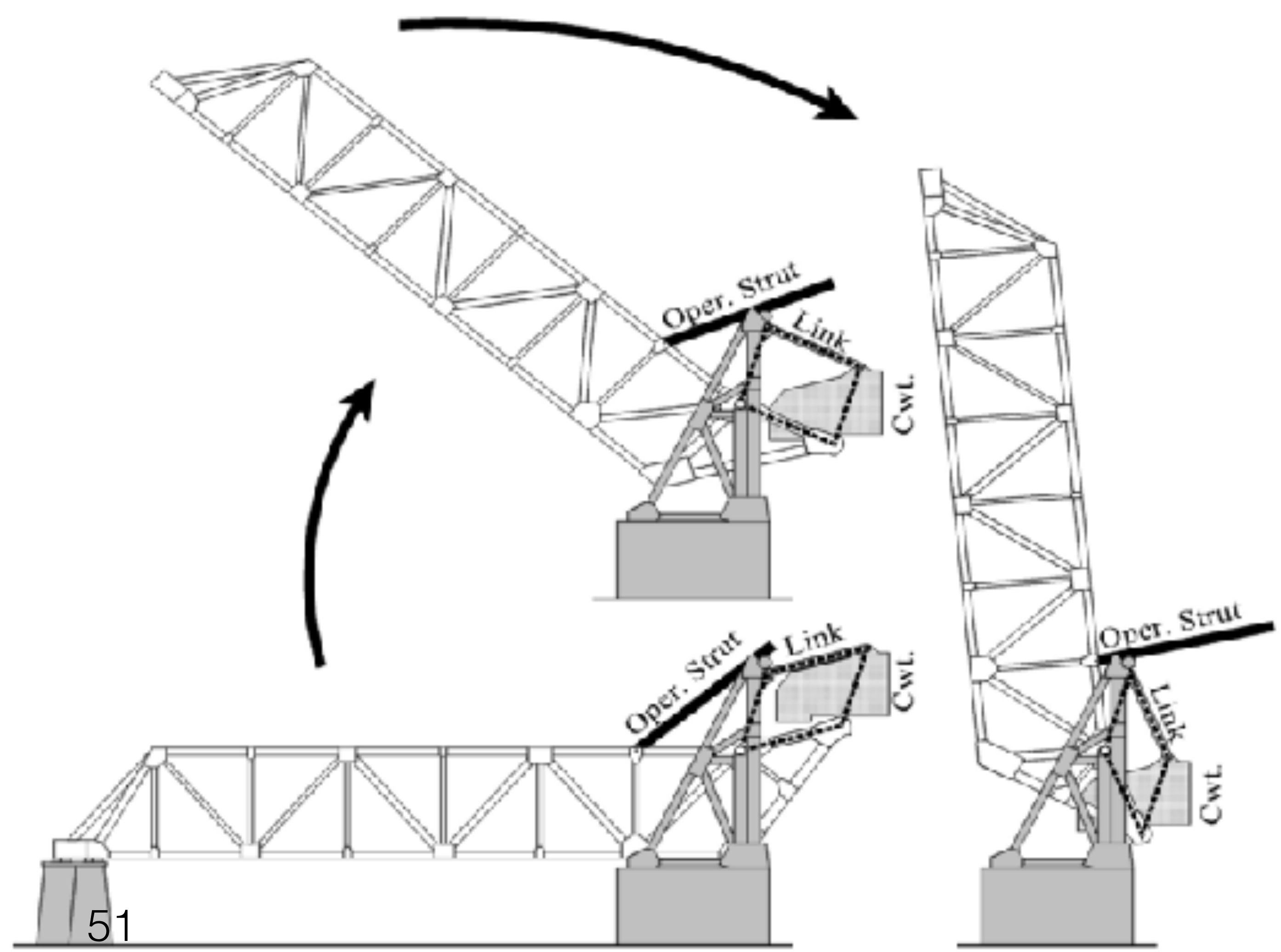
Lord Rosse's Leviathan of Parsontown

- Built 1843-1845
- 6 foot telescope (1.8m)
- Largest in the world until Hooker Telescope in 1917
- mirror made of speculum metal: copper + tin



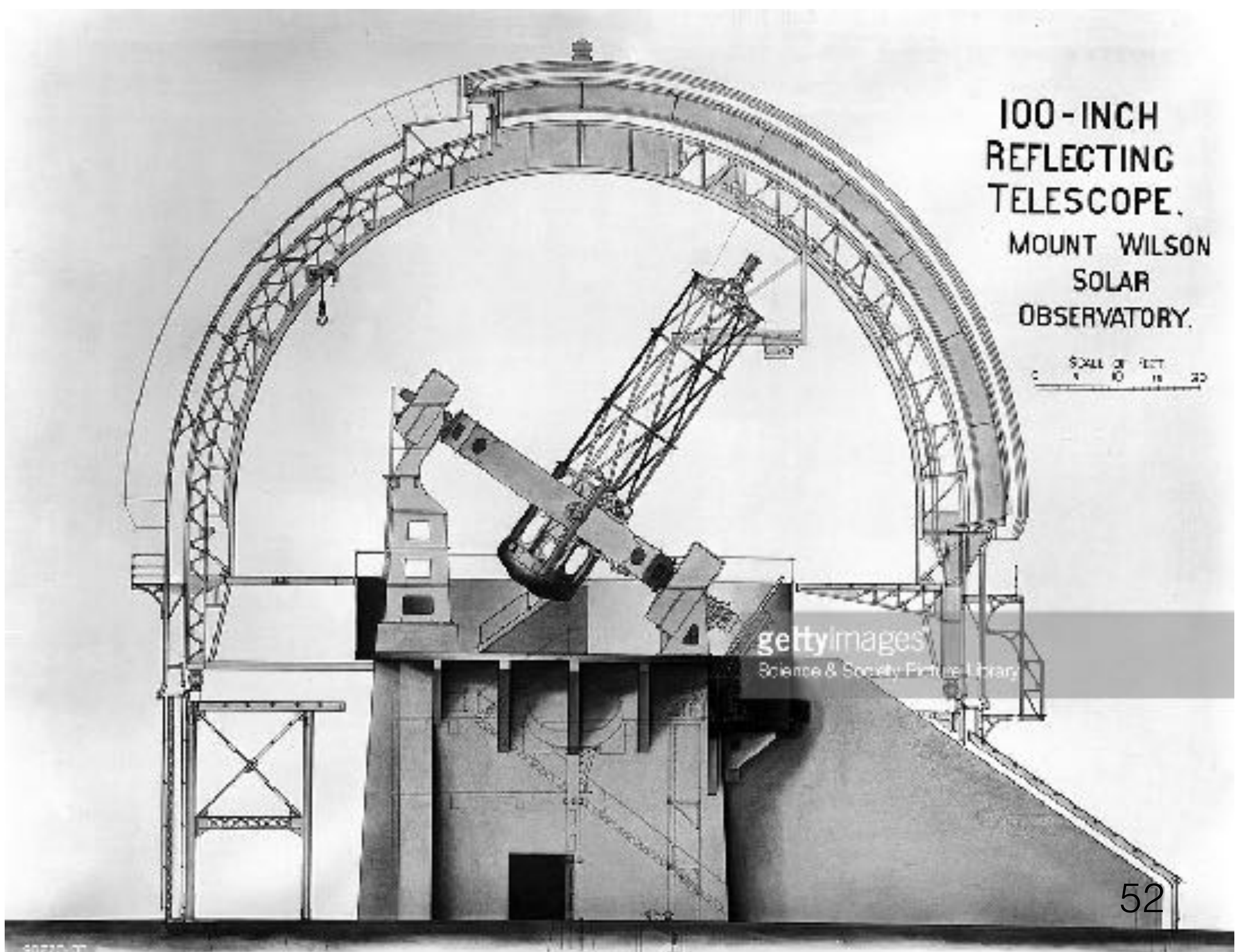
Chicago Kenzie Street Railroad Bridge

- Built in 1908
- World's longest and heaviest movable bridge



Hooker 100-inch Reflecting Telescope

- Built 1917. Largest until 1949.
- 100-inch (2.5m)
- Hubble used it to discover the Universe



Specific tensile strength of various materials

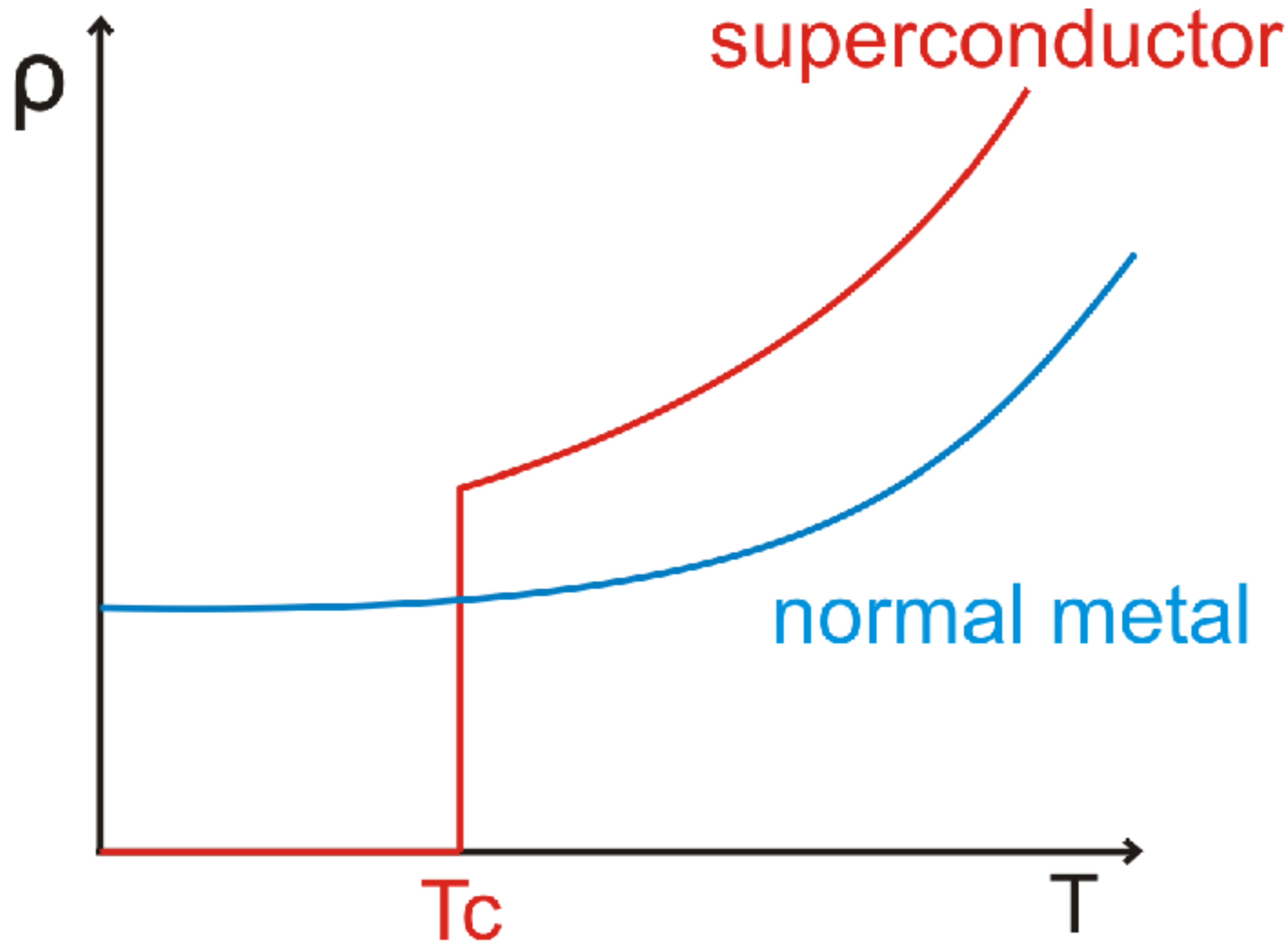
Material	Tensile strength (MPa)	Density (g/cm³)	Specific strength (kN·m/kg or KYuri)
Concrete	12	2.30	5.22
Rubber	15	0.92	16.3
Copper	220	8.92	24.7
Polypropylene	25-40	0.90	28-44
Stainless steel (304)	505	8.00	63.1
Brass	580	8.55	67.8
Nylon	78	1.13	69.0
Oak	90	0.78-0.69	115-130
Inconel (X-750)	1250	8.28	151
Magnesium alloy	275	1.74	158
Aluminium alloy (7075-T6)	572	2.81	204
Titanium	1300	4.51	288
Bainite	2500	7.87	321
Balsa	73	0.14	521
Carbon-epoxy composite	1240	1.58	785
Spider silk	1400	1.31	1069
Silicon carbide fiber	3440	3.16	1088
Glass fiber	3400	2.60	1307
Basalt fiber	4840	2.70	1790
1 µm iron whiskers	14000	7.87	1800
Vectran	2900	1.40	2071
Carbon fiber (AS4)	4300	1.75	2457
Kevlar	3620	1.44	2514
Dyneema (UHMWPE)	3600	0.97	3711
Zylon	5800	1.54	3766
Carbon nanotube (see note below)	62000	.037-1.34	46268-N/A
Colossal carbon tube	6900	.116	59483
Fundamental limit			9×10^{13}

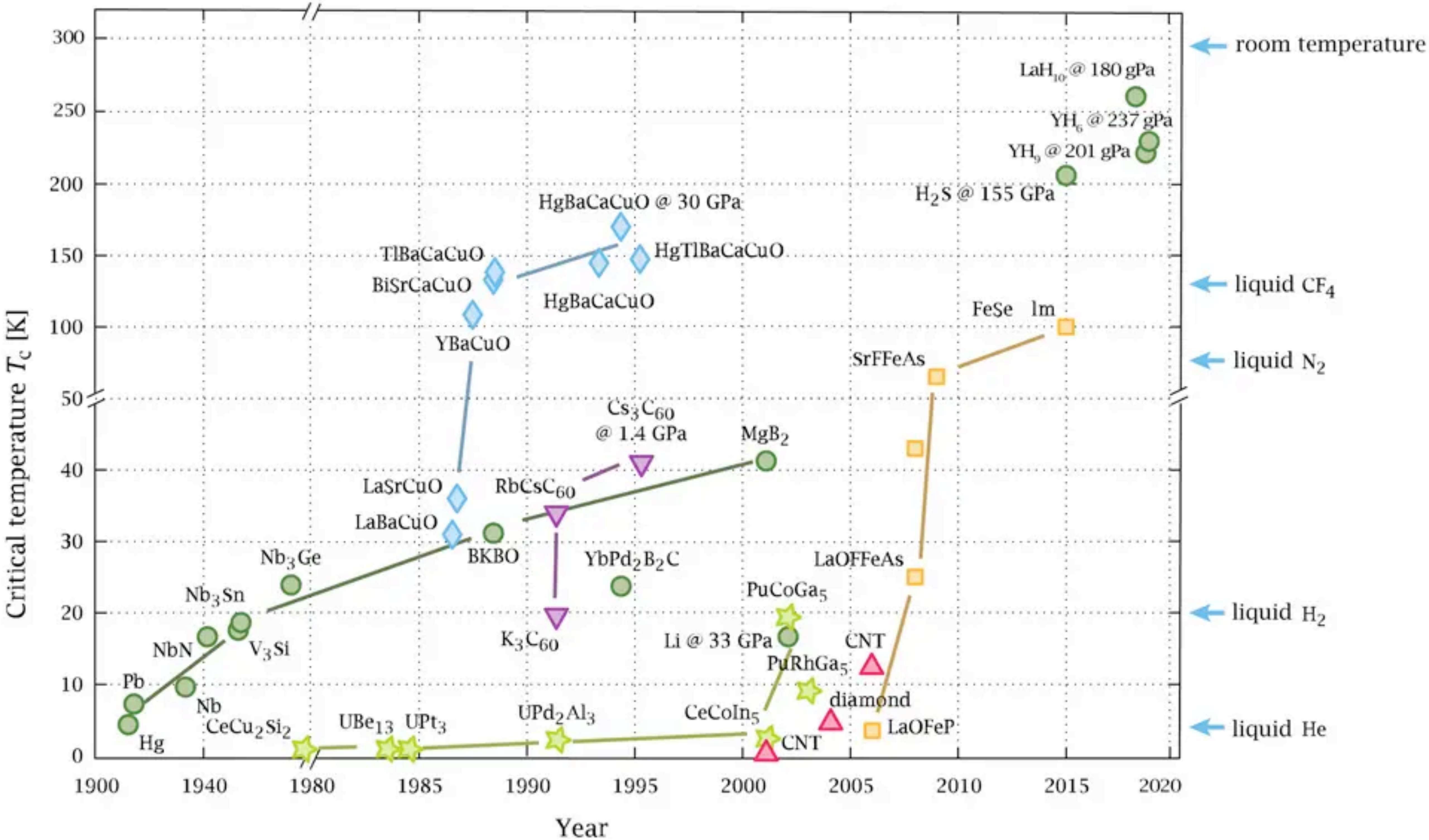
Electrical Conductivity

- gold, silver, copper
- superconductors, discovered in 1911 by Onned in Leiden with Mercury

How to get cold

Element	boiling [K]	Ice [K]	pumped [K]
N	77	63	
He4	4.2		1
He3	3.2		0.25


superconductor
ρ
normal metal
Tc
T



Green circles = Low-temperature metallic BCS • Light green stars = Heavy-fermions-based • Blue diamonds = Ceramics/cuprates
Purple inverted triangle = Buckminsterfullerene-based • Red triangle = Carbon-allotrope • Yellow squares = Iron-based
Adapted from PJRay, CC BY-SA 4.0.

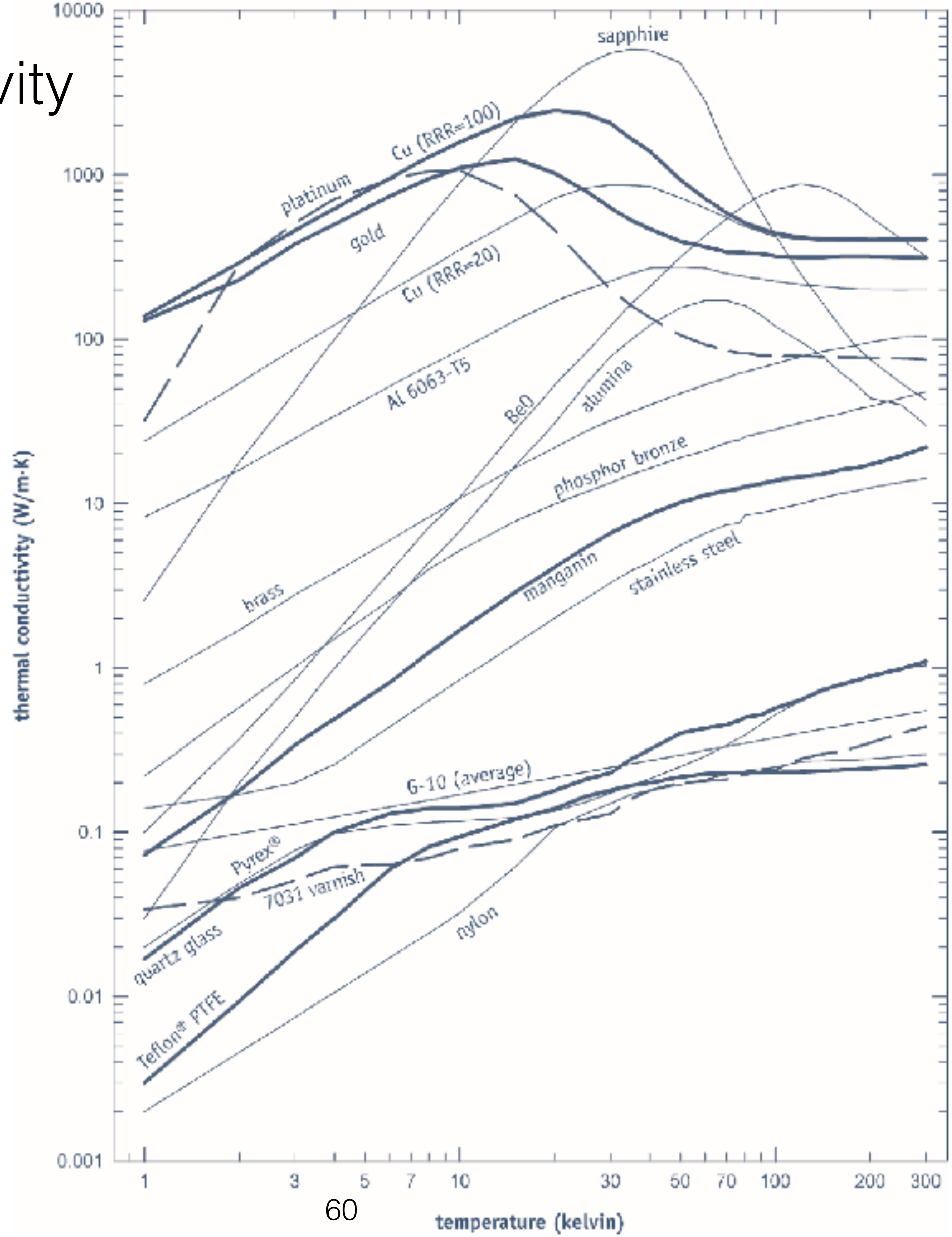
Useful Superconductors

Element	Symbol	Tc [K]	atomic number
Niobium	Nb	9.26	41
Niobium-Titanium	NbTi	9.2	—
Lead	Pb	7.19	82
Solder 60/40	Sn/Pb	5	—
Tantalum	Ta	4.48	73
Mercury	Hg	4.15	80
Tin	Sn	3.72	50
Indium	In	3.4	49
Aluminum	Al	1.20	13
Molybdenum	Mo	0.92	42
Zinc	Zn	0.88	30
Titanium	Ti	0.39	22

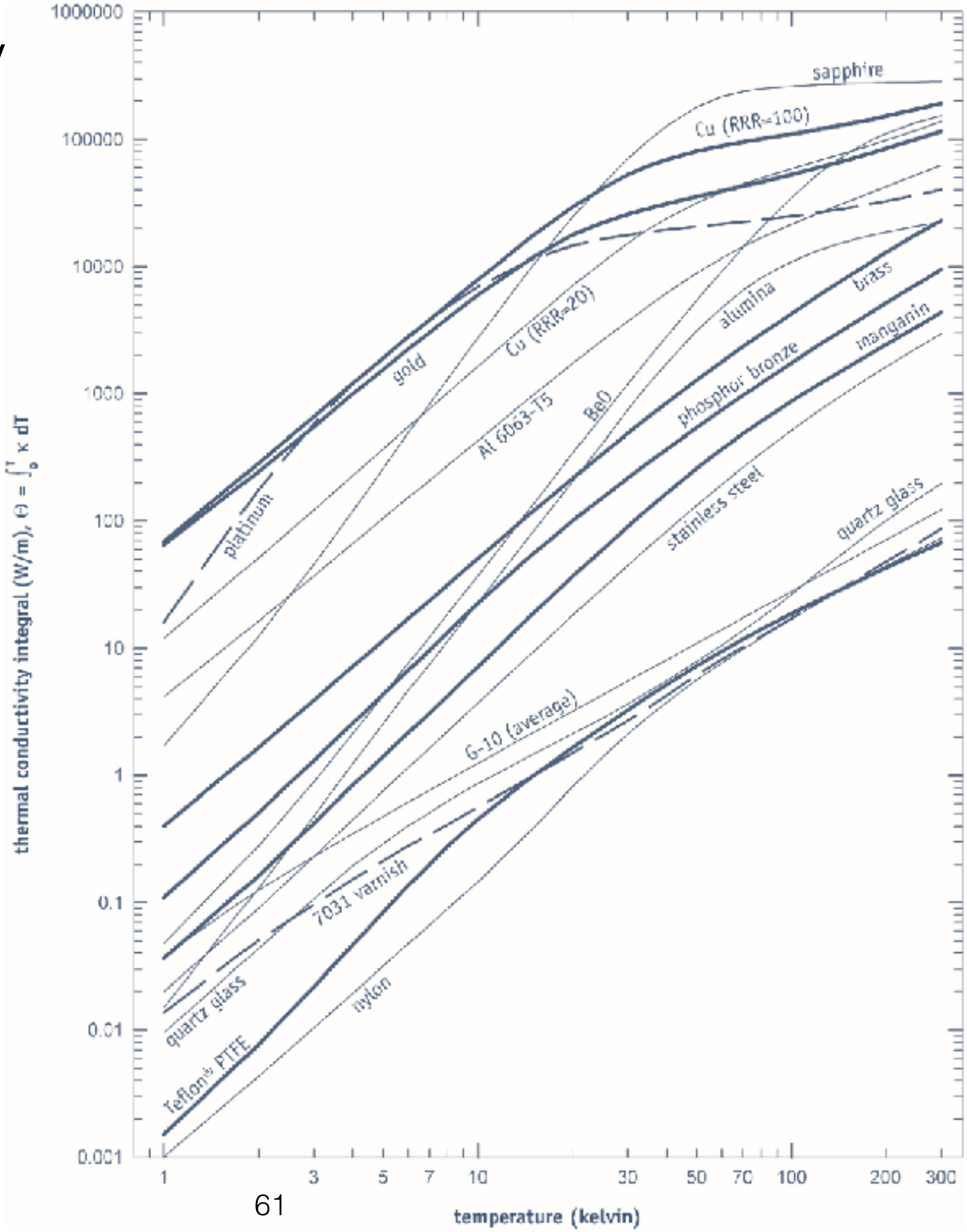
Thermal Conductivity

- High: Gold, Copper, aluminium
- Low: Stainless steel, G10, carbon fiber

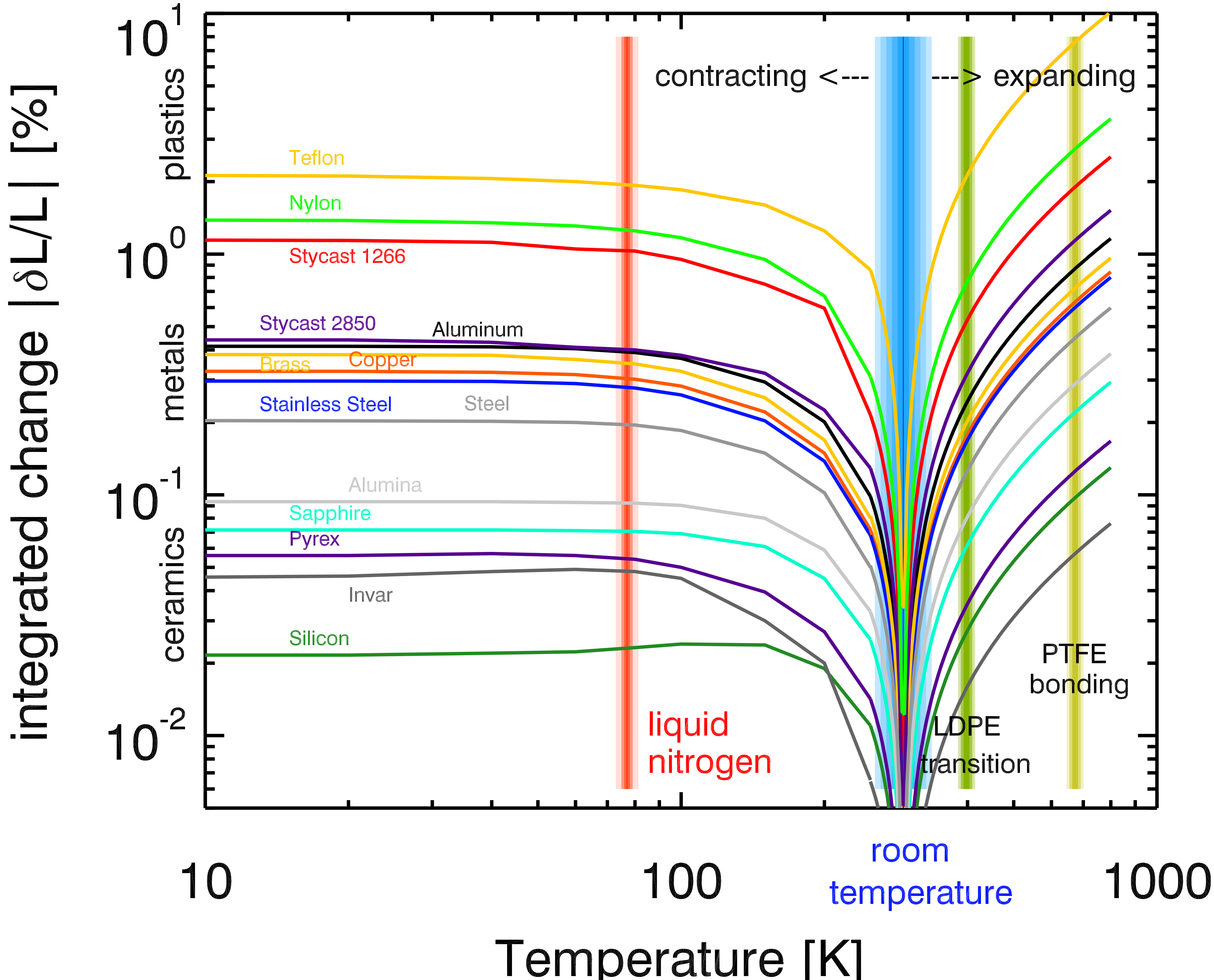
Thermal conductivity



Thermal conductivity Integral



Thermal Expansion of Materials



Modern Mirror Materials

Property	Unit	Aluminum 6061-T6	Beryllium I-70	Ceraform SiC	Silicon	ULE	Desired Value
ρ, Density	g/cm^3	2.71	1.85	2.92	2.33	2.21	Low
E, Young's Modulus	GPa	68.3	303	310	130	67.6	High
ν, Poisson's Ratio	----	0.33	0.07	0.19	0.26	0.17	Low
α^2, Thermal Expansion	ppm/°C	22.7	11.4	2.44	2.62	±0.03	Low
$\Delta\alpha$, CTE	ppb/°C	100	100	30	10	10	Low
κ, Thermal Conductivity	W/°C	156	216	157	135	1.31	High
C_p, Specific Heat	J/Kg°C	879	1820	670	713	766	Low
σ, Design Stress	MPa	124	17	70	62	7	High

Materials

Elements:

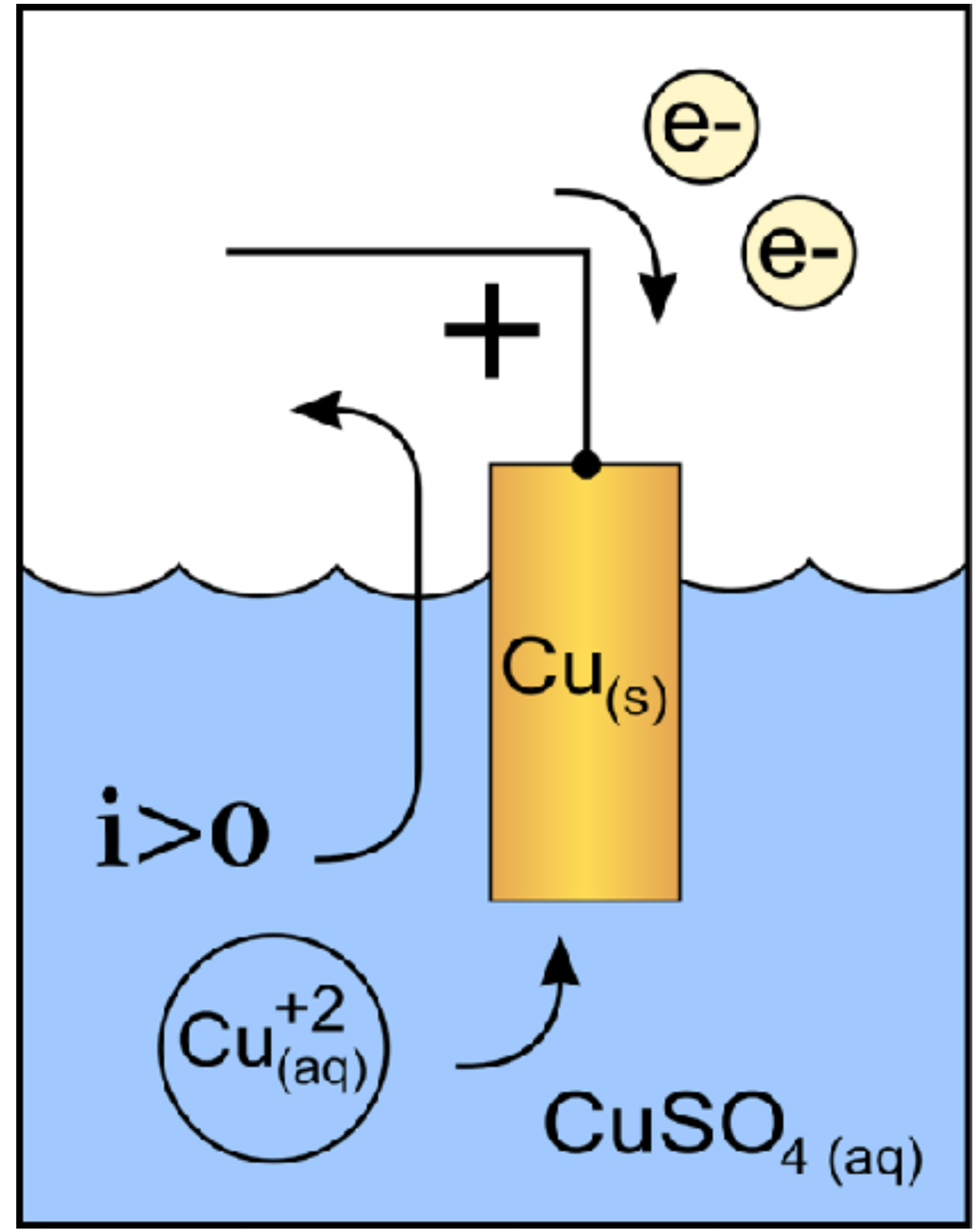
- **Gold** - Best thermal conductor. Good electrical conductor, but doesn't superconduct. Inert. Soft. Expensive.
- **Copper** - Good thermal conductor. Difficult to weld. Not easy to machine. Heavy. Can easily get 99.99% pure oxygen-free high-thermal conductivity copper (OFHC). Very reactive.
- **Aluminum** - OK thermal conductor. Superconducts at 1.2K. Easy to machine and weld. Relatively cheap. Large thermal contraction. In very pure form, can conduct very well. Band gap is ~ 80GHz. Oxidizes immediately. 6061 for strength. 1100 for thermal conductivity.
- **Titanium** - Light, strong, weldable. Difficult to machine. Superconductors at 0.4K. Forms oxide layer in a few hours.
- **Niobium** - Superconducts at 9.26K. Hard metal. Used for electronic striplines. Lossless out to ~THz. Highest natural superconducting transition.
- **Lead** - Superconducts at 7.2K. Soft. Low melting point. Leads to brain damage.
- **Tin** - Superconducts at 3.7K.
- **Indium** - Superconducts at 3.4K. Very soft. Low melting point. Can make contacts between wafers.
- **Silicon** - Used for device fabrication. Grown in crystals. Transparent above 1.1. um. Cheap.

Alloys:

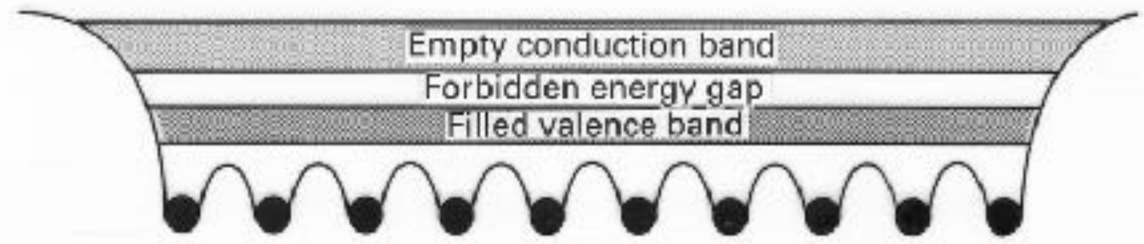
- **Lead/Tin solder** — 60/40 Sn/Pb. Superconducts at ~6K.
- **Steel** - Iron and carbon. Strong. Easily weldable. Cheap. Oxidizes (rusts).
- **Brass** - Copper and zinc. Super easy to machine.
- **Invar** - Steel and 36% nickel. Strong, difficult to machine. No thermal contraction. Nobel prize in 1920.
- **Stainless Steel** - Steel alloy with chromium. Inert. Weldable. Low thermal conductivity.
- **Sapphire** - Aluminum Oxide (Al_2O_3). Can also be grown in crystals and used for fabrication. Also amorphous as a ceramic. High thermal conductivity. Difficult to machine. bi-refringent, so useful for polarized optics. transparent from optical through mm waves.

Cathode and Anode

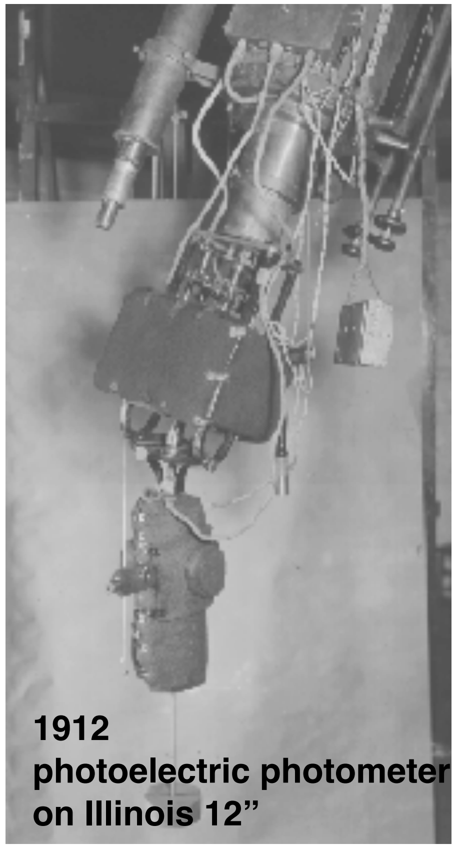
- defined in the 1830s
- current is negative flow
- electrons flow into the cathode and out of the anode. (but the sign convention of the current is opposite)
- cathode is usually the positive side, but not always
- in a discharging cell, cathode is positive; in a recharging battery, cathode is negative
- In a diode, the cathode is the negative terminal



The photovoltaic effect



- In 1839 Becquerel discovered photovoltaic effect which showed relation between light and electric properties of materials
- Light absorbed onto a material excites the electrons and moves them from a bound to a free state.
- So, put a constant current, shine light. Measure voltage, measure light !
- In 1903 Dr Joel Stebbins arrived at Illinois from Lick Observatory. Studied binary stars. Wife said: “Someday we will do this with electricity”
- In 1907 Stebbins put a photoelectric selenium cell onto the 12” and measured faint binary stars. (Selenium cells are the guts of a light meter in photography)
- In 1912 Stebbins and physicists observe with a new photoelectric photometer. We now call these photoelectric cells “solar panels.”
- That is why the 12” is a National Historic Landmark.



1912 photoelectric photometer on Illinois 12”

Joel Stebbins

Joel Stebbins and early electronic astronomical instrumentation

Joel Stebbins in Wisconsin in 1925 with his invention, the photoelectric photometer

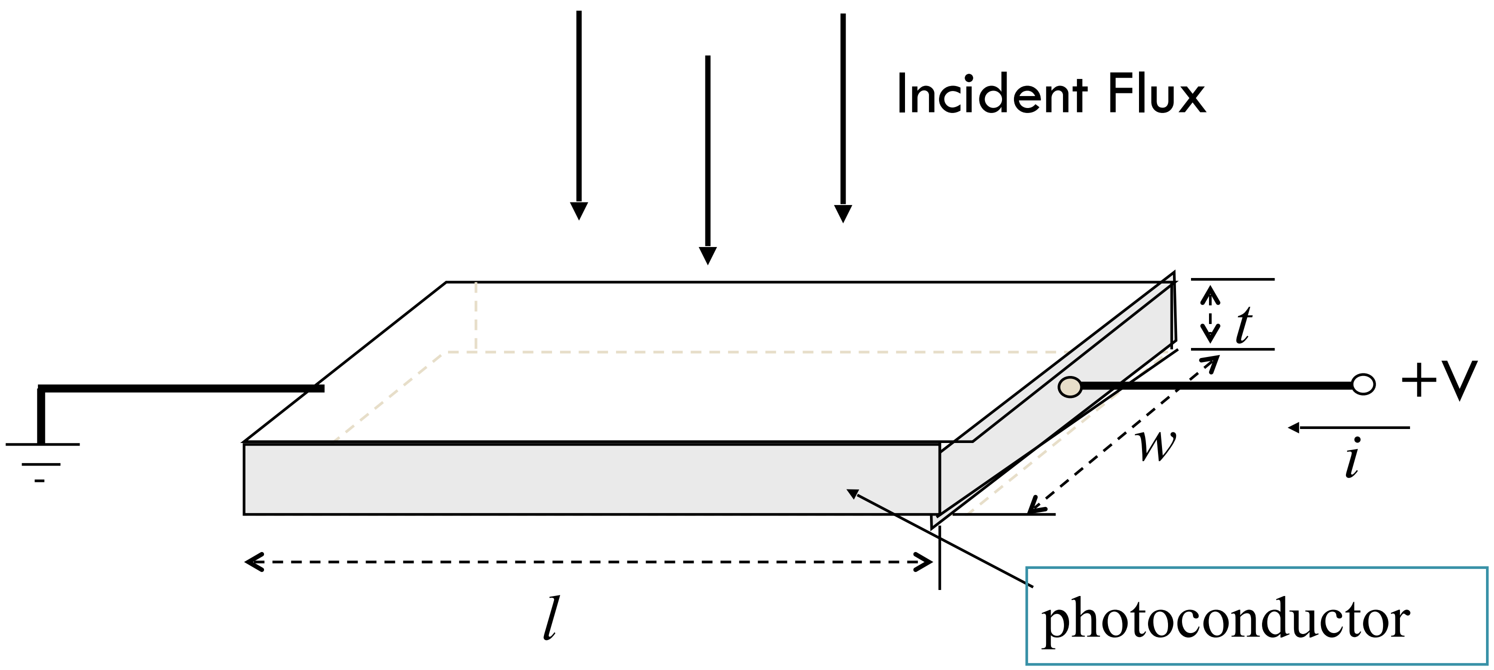
The photometric program went along well enough for a couple of years until we got a bride in our household, and then things began to happen. Not enjoying home alone, she (May Stebbins) found that if she came to the observatory and acted as recorder, she could get me home earlier.

She wrote down the numbers as the observer called them, but after some nights of recording a hundred readings to get just one magnitude, she said it was pretty slow business. I responded that someday we would do this by electricity. That was a fatal remark. Thereafter she would often prod me with the question: "When are you going to change to electricity?"

It happened that within a two or three months the department of physics gave an open house, and one of the exhibits was in charge of a young instructor F.C. Brown. He showed how when he turned on a lamp to illuminate a selenium cell, a bell would ring; when the lamp was off, the bell would stop. Here was the idea; why not turn a star on to a cell on a telescope and measure the current?

(Stebbins, *Early Photometry*, 507)

Photoconductors



(McLean 2008)

Lifetime before recombination: τ

Incident power: P

Quantum efficiency: η

Electron drift velocity: $v_{drift} = \mu E$

Electron mobility: μ

Electric field: $E = \dfrac{V}{l}$

Electron charge: e

Photoelectron volume density: $n_e = \eta\left(\dfrac{P}{h\nu}\right)\tau\left(\dfrac{1}{lwt}\right)$

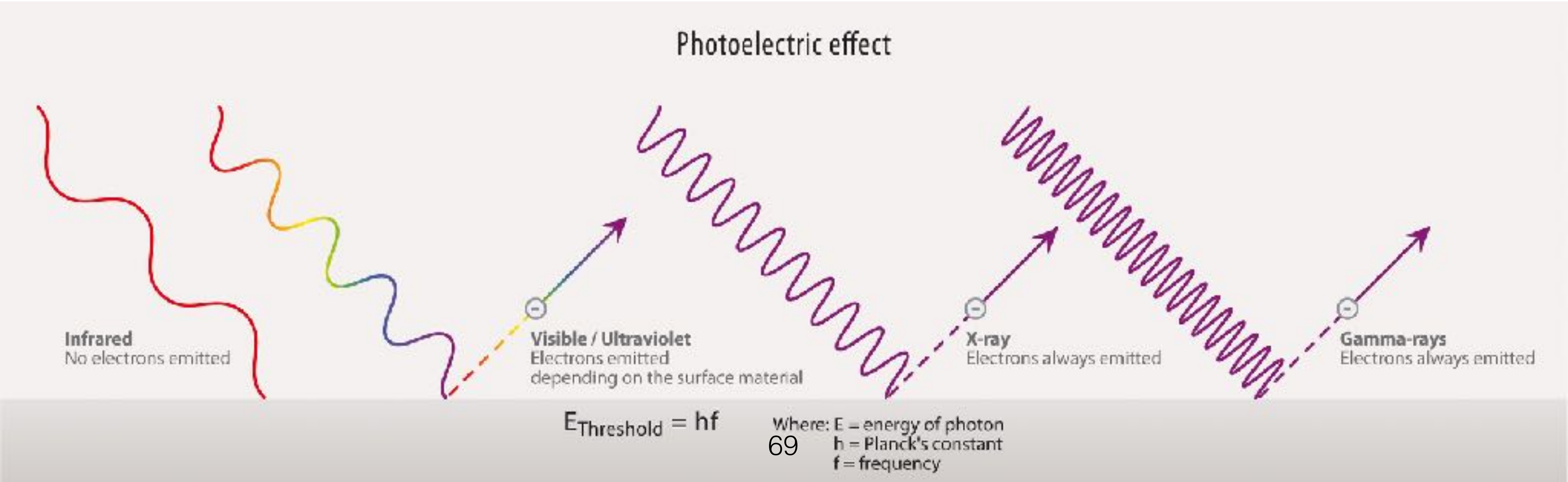
Induced current: $i = e(n_e wt)v_{drift} = \left(\dfrac{e\eta P}{h\nu}\right)\left(\dfrac{\nu\tau}{l}\right)$

Photoconductive gain: $G = \left(\dfrac{\nu\tau}{l}\right)$

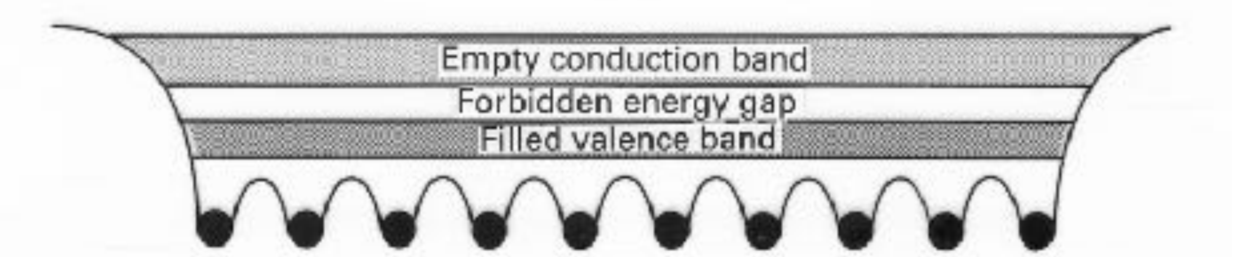
Ratio of mean carrier lifetime to transit time.

The photoelectric effect

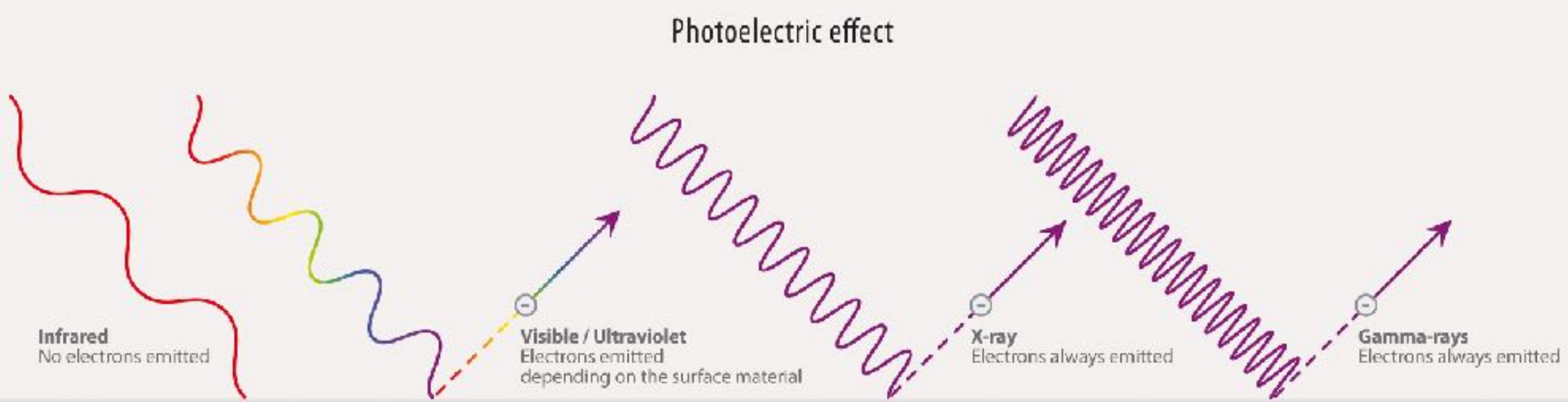
- In 1887 Hertz and Hallwachs noticed that light shined on a charged surface could emit charged particles.
- Only worked for light above a given threshold wavelength, e.g. UV light.
- Shine a light on a material (or gas). As frequency increases into UV, electrons are released. Gas is ionized. Measure electrons.
- This light discharged charged particles with the same nature as cathode rays
- In 1899 J.J. Thompson discovered these were the same thing as electrons
- In 1902 Leonard observed that the energy of the electrons was proportional to the wavelength of light.
- This was at odds with Maxwell's theory which said $E_e \propto$ intensity, not λ
- In 1905, Einstein proposed quanta of light ("photons") and won the nobel prize in 1921



The photoelectric effect



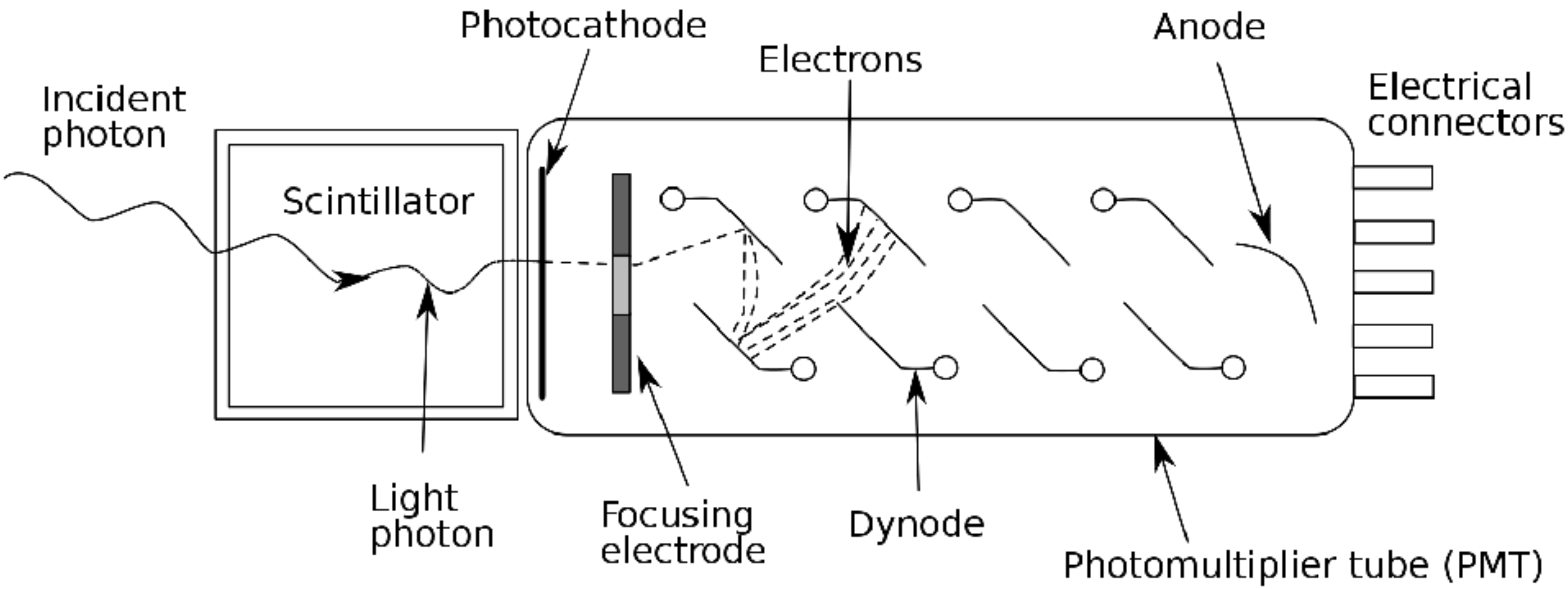
- There is a threshold energy for removing a bound electron from an atom
- This is the ionization potential, which depends on the atom and the shell (k,l,m… for n=1,2,3…)
- For Hydrogen, n=1 is a famous UV photon at 91.2 nm or 13.6 eV
- For solids in vacuum, e.g. a crystal, ionization potential is the work function. Thresholds can be ~1eV
- In a semiconductor, think of it as a big weird atom, where a photon "ionizes" and makes a "free" electron where it stays in the conduction band of the lattice. Thresholds are 0.01-1 eV



$E_{Threshold} = hf$

Where: E = energy of photon
h = Planck's constant
f = frequency

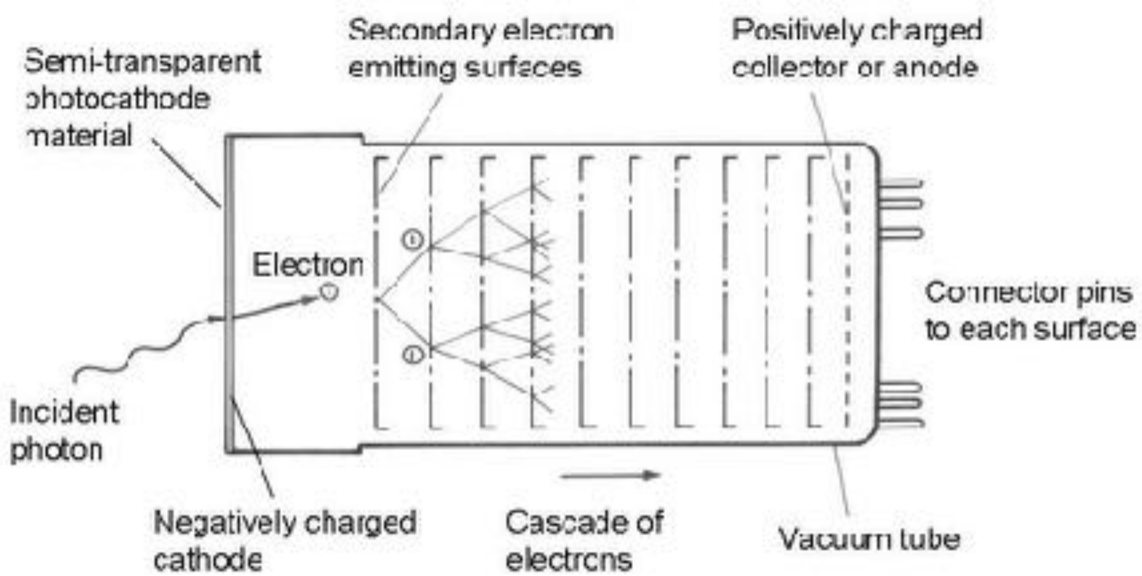
Photo Multiplier Tube (PMT)



cathode is something like Cesium or antimony … a metal with a low work function.

The first was silver-oxygen-cesium in 1929. Sensitive from 300 nm to 1200 nm

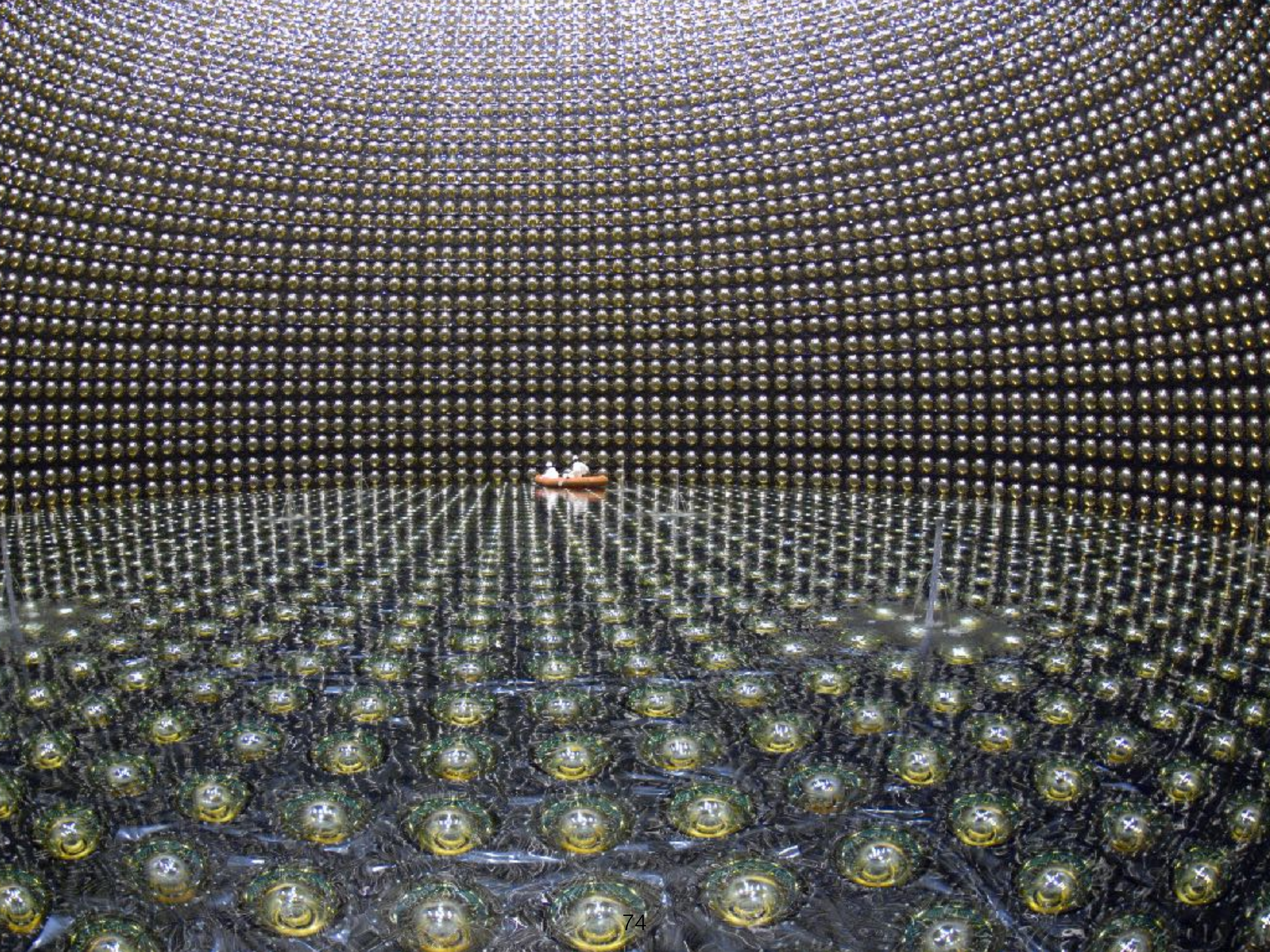
Photoemission detector: the photomultiplier tube



Total voltage of 1,500 V (or 1.5 kV) across a tube with 10 stages.

- Photocathode efficiency ~20%, that is, 1 electron out for 5 photons in.
- Each succeeding dynode at ~150 V more positive electrical potential.
  - Accelerates electrons to next dynode, releasing q further electrons on impact.
  - Total pulse of electrons $Q = q^n$ over n dynodes for one initial photoemission event.
- Output pulses are counted over a certain time interval (or integration)
  - Photon counting.


RCA
CE-1P40
MADE IN U. S. A.



Photography

- Photography relies on a photochemical reaction of silver halide salts, (e.g. AgBr):

  $Ag^{+}Br^{-} + hv \rightarrow Ag^{+} + Br + e^{-}$

  $Ag^{+} + e^{-} \rightarrow Ag$

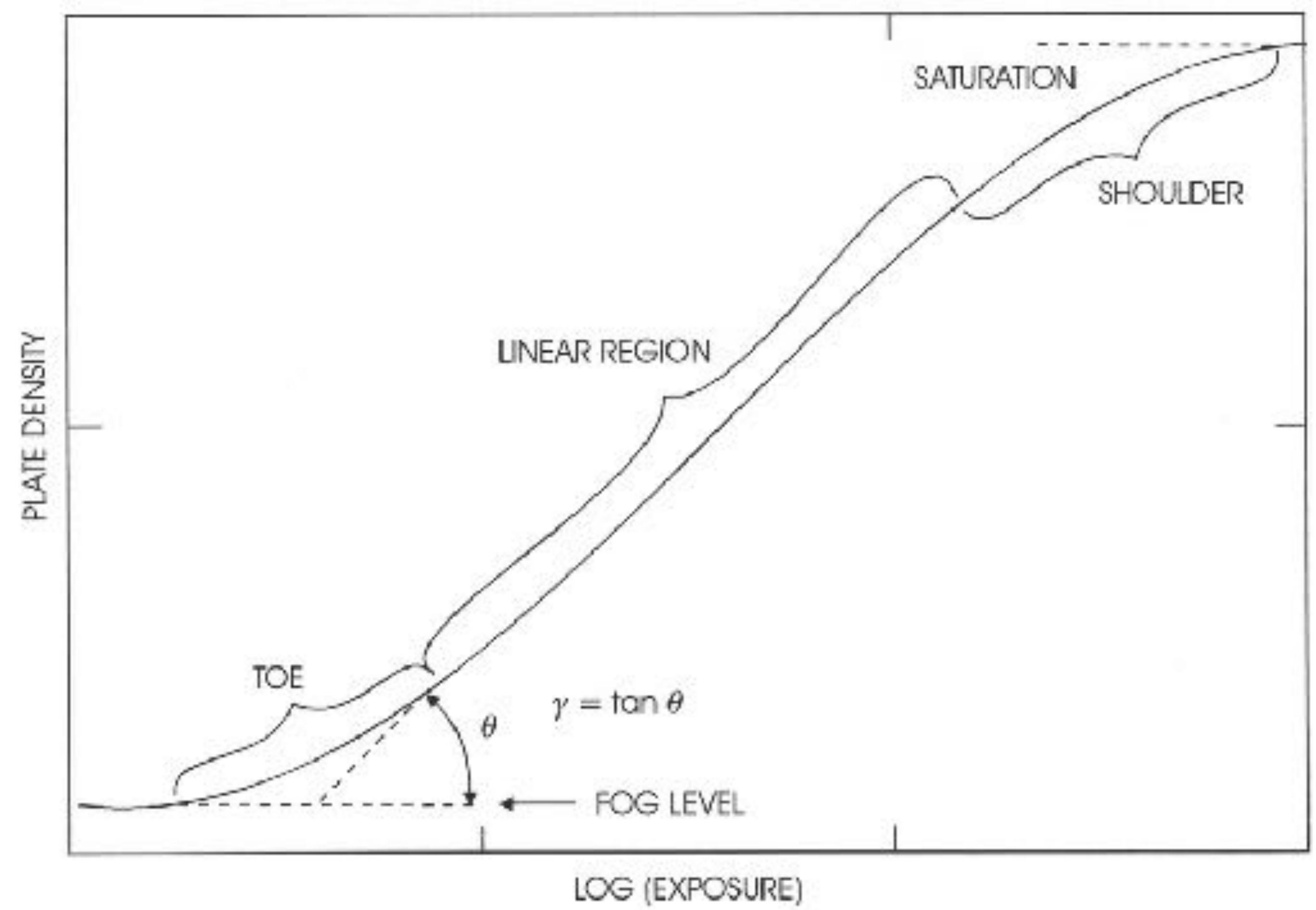
  producing a neutral silver atom; a “latent image”

- Chemical processing:
  - ***Development*** – amplify silver deposition.
  - ***Fixing*** – remove unexposed silver bromide.
  - Produces a ***negative.***

Ansel Adams (Tetons and Snake River)

Characteristic curve of photographic plate

- **Pros:**
  - Can integrate for much longer than the human eye.
  - Sensitive to greater wavelength range than the human eye.
- **Cons:**
  - Sensitivity varies across plate.
  - Saturates eventually from faint light from night sky.
  - Minimum density occurs for zero exposure – "fog".
  - Non-linear response function.
  - Analog – now replaced by electronic imaging detectors.



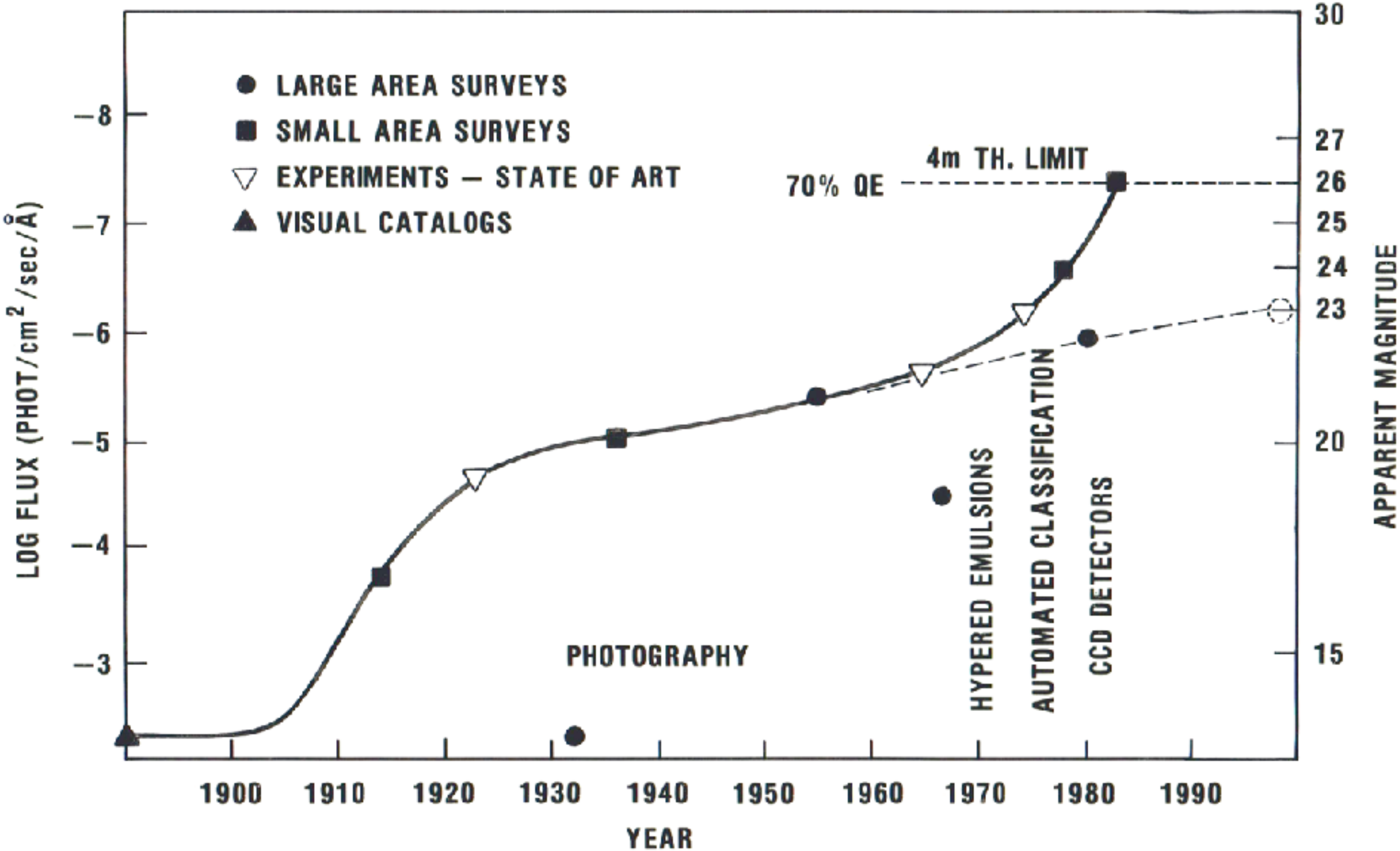
$$\text{Transmittance: } T = \frac{I_{out}}{I_{in}}$$

$$\text{"Opacity": } O = \frac{1}{T}$$

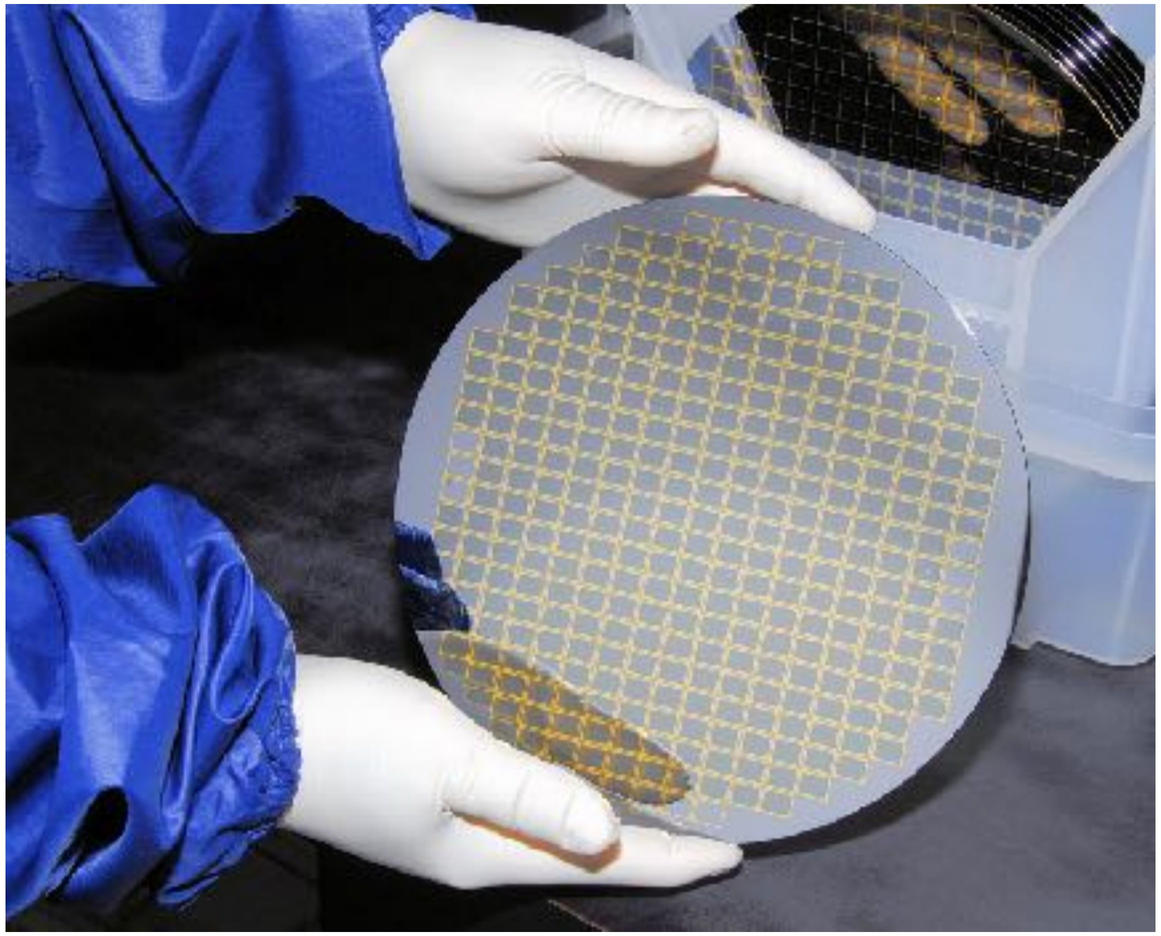
$$\text{Density: } D = \log(O) = -\log(T)$$

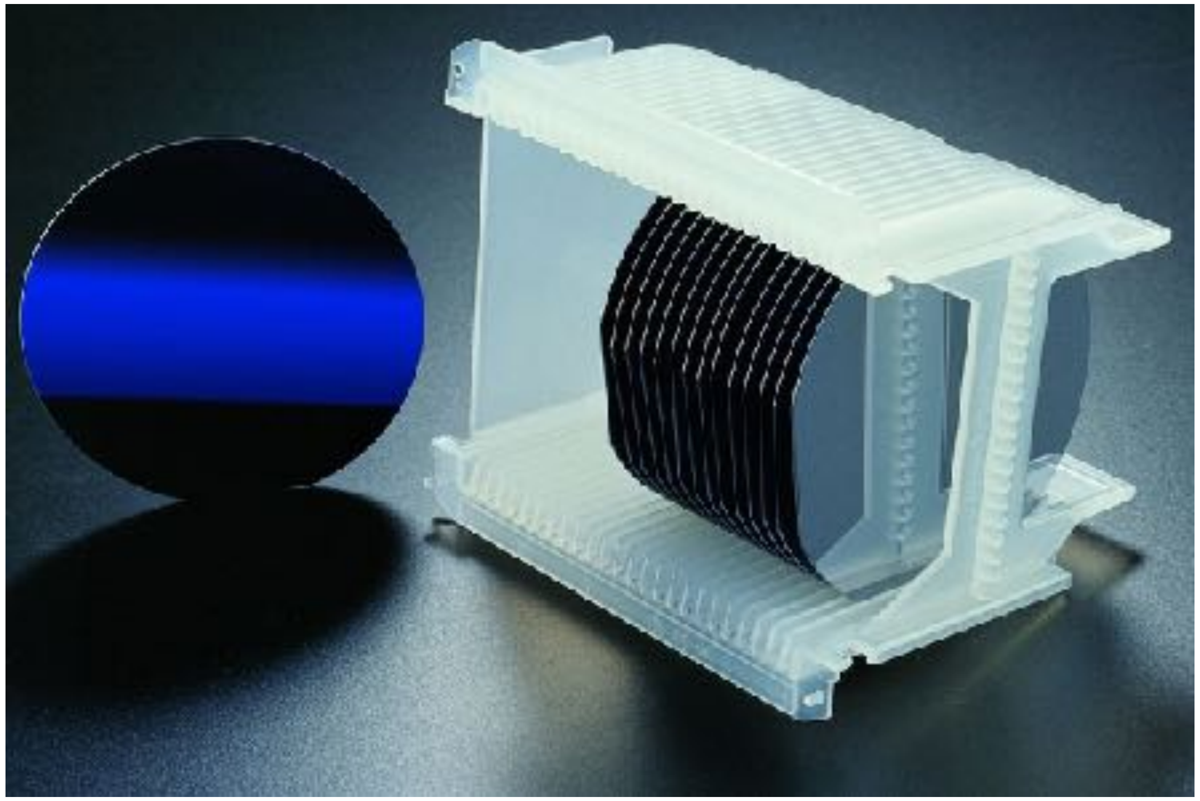
Exposure: proportional to fluence [J m^{-2}]

MODERN LIMITS FOR GALAXY PHOTOMETRY

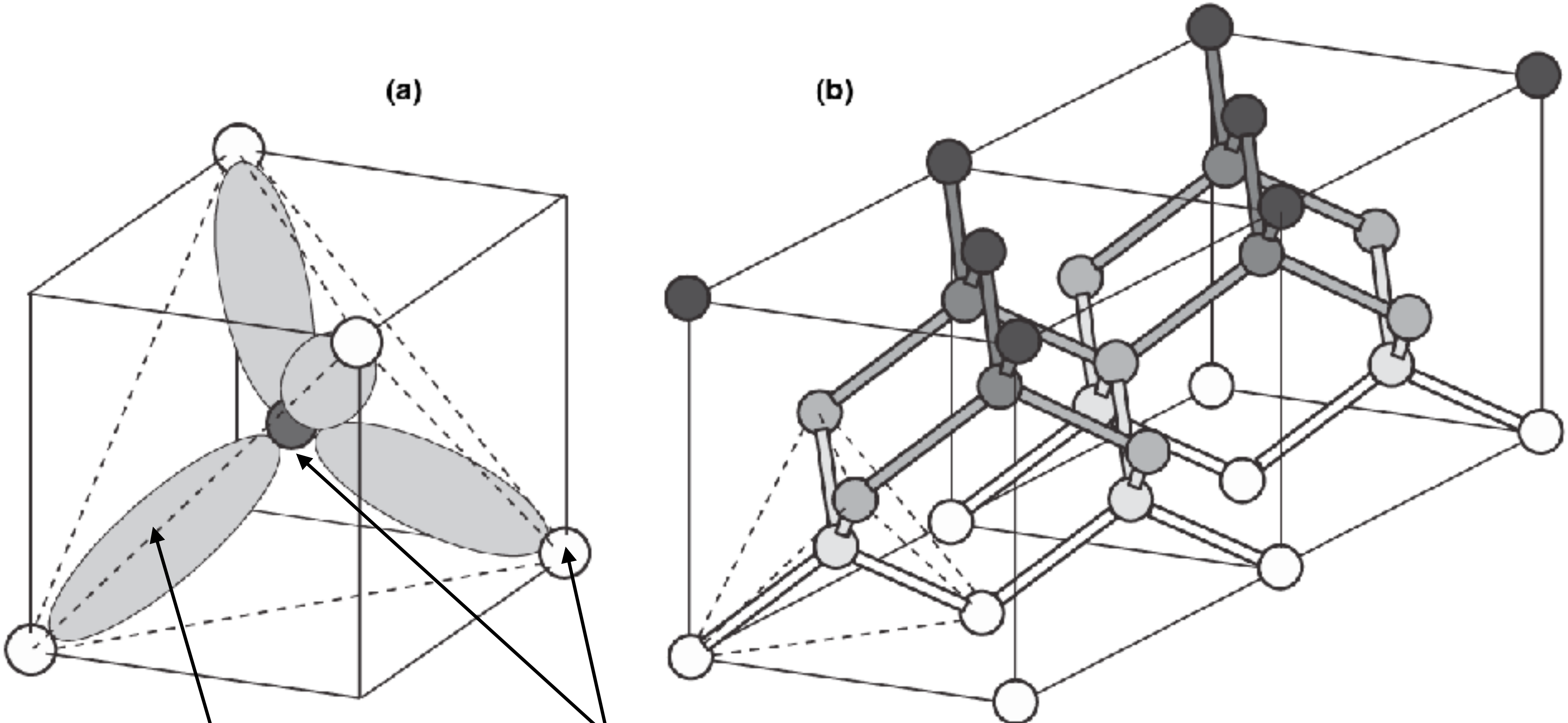


Silicon





Crystals



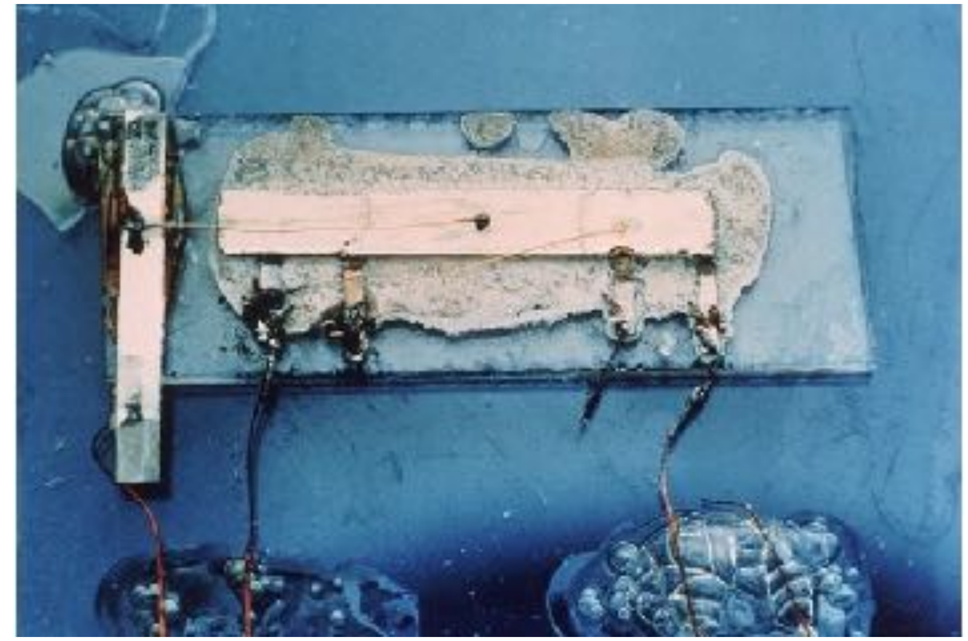
atom

probability of finding electron

Semiconductors I

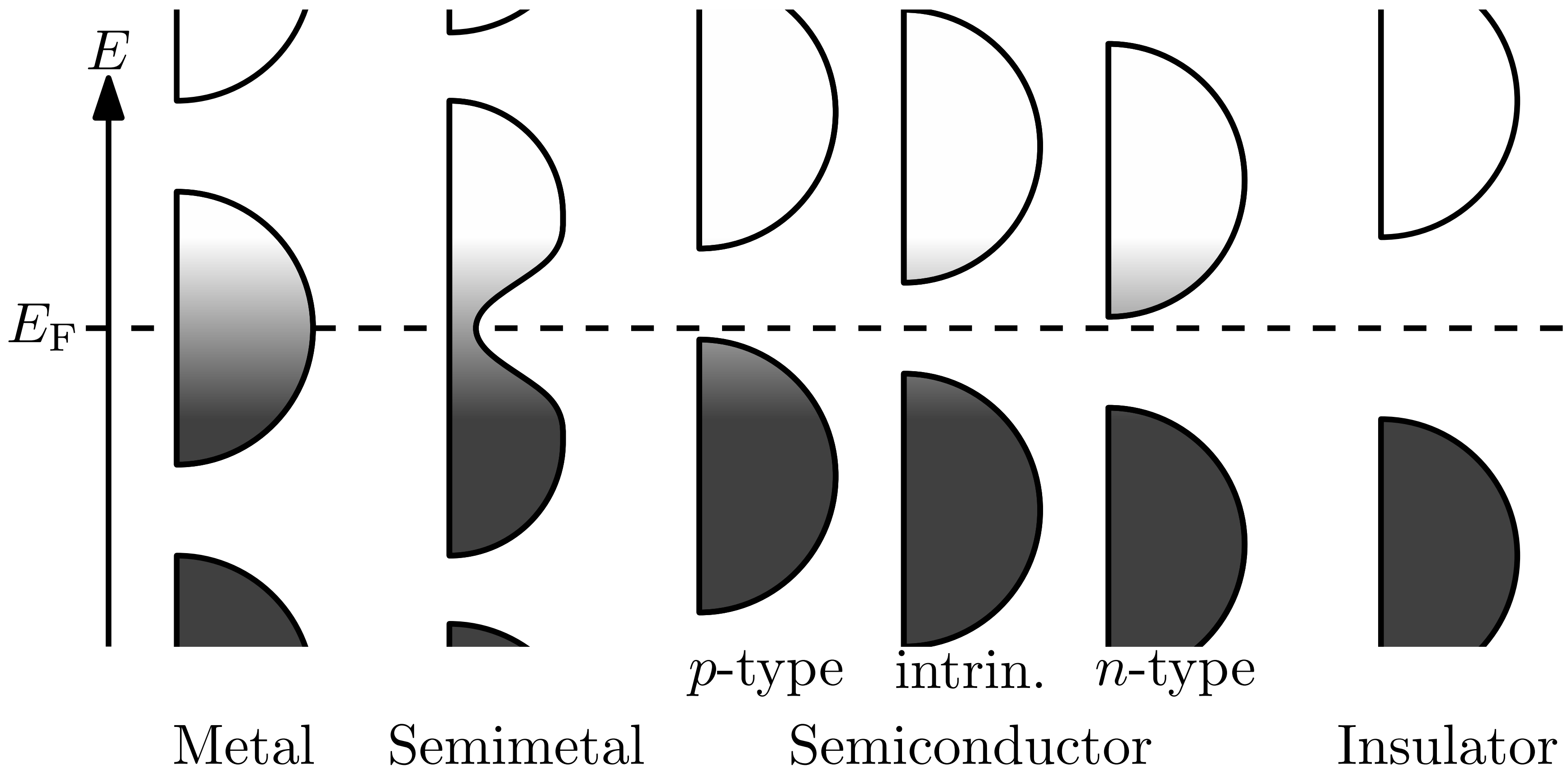
- Semiconductors are crystalline or amorphous solids with distinct electrical characteristics.
- They have high electrical resistance — higher than typical resistance materials, but still of much lower resistance than insulators.
- Their resistance decreases as their temperature increases, which is behavior opposite to that of a metal.
- Their conducting properties may be altered in useful ways by the deliberate, controlled introduction of impurities ("doping") into the crystal structure, which lowers its resistance but also permits the creation of semiconductor junctions between differently-doped regions of the extrinsic semiconductor crystal.
- The behavior of charge carriers which include electrons, ions and electron holes at these junctions is the basis of diodes, transistors and all modern electronics.
- Semiconductor devices can display a range of useful properties such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat.
- Because the electrical properties of a semiconductor material can be modified by doping, or by the application of electrical fields or light, devices made from semiconductors can be used for amplification, switching, and energy conversion.

Semiconductors II



- The modern understanding of the properties of a semiconductor relies on quantum physics to explain the movement of charge carriers in a crystal lattice.
- Doping greatly increases the number of charge carriers within the crystal.
- When a doped semiconductor contains mostly free holes it is called "p-type", and when it contains mostly free electrons it is known as "n-type".
- The semiconductor materials used in electronic devices are doped under precise conditions to control the concentration and regions of p- and n-type dopants.
- A single semiconductor crystal can have many p- and n-type regions; the p–n junctions between these regions are responsible for the useful electronic behavior.
- Although some pure elements and many compounds display semiconductor properties, silicon, germanium, and compounds of gallium are the most widely used in electronic devices.
- Some of the properties of semiconductor materials were observed throughout the mid 19th and first decades of the 20th century.
- The first practical application of semiconductors in electronics was the 1904 development of the Cat's-whisker detector, a primitive semiconductor diode widely used in early radio receivers.
- Developments in quantum physics in turn allowed the development of the transistor in 1947 and the integrated circuit in 1958.

Semiconductors III

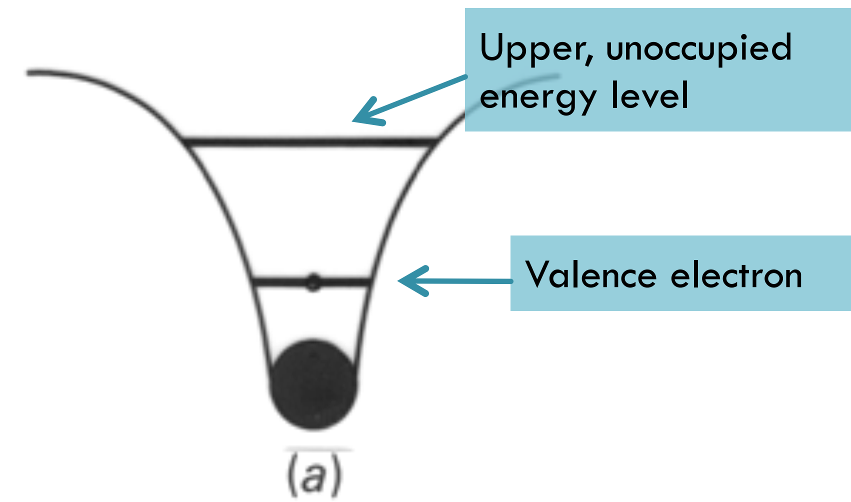


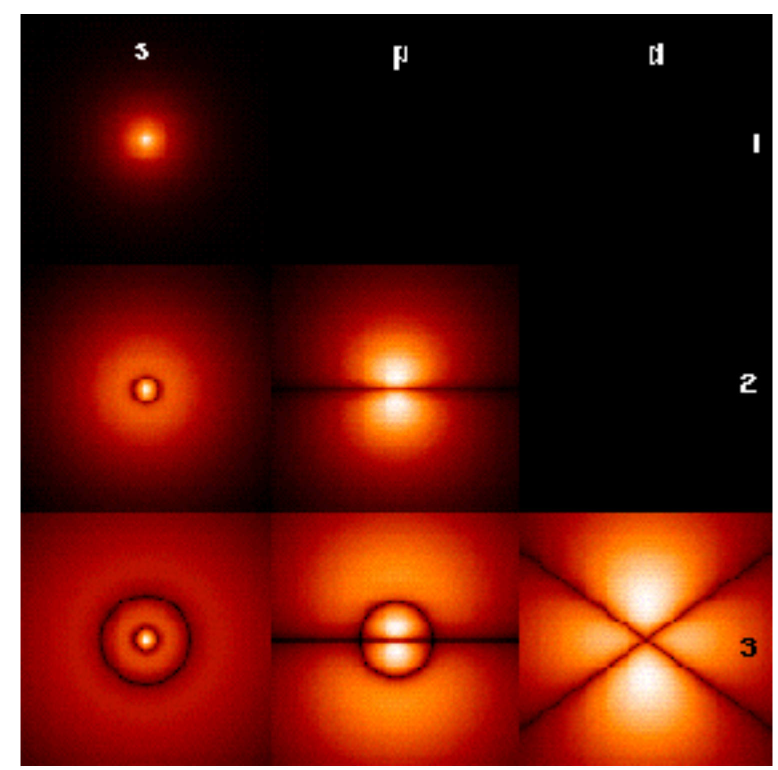
- Filling of the electronic states in various types of materials at equilibrium.
- Height is energy while width is the density of available states for a certain energy in the material listed.
- The shade follows the Fermi–Dirac distribution (black = all states filled, white = no state filled).
- In metals the Fermi level E_F lies inside at least one band.
- In insulators and semiconductors the Fermi level is inside a band gap.
- In semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes.

Key properties of semiconductors

- The properties of any solid material depend on:
  - The atomic structure of the atoms of the material, and
  - The way the atoms are arranged within the solid in a crystal structure.

- Atomic orbitals (*s,p,d,…)*
  - Quantized atomic energy levels.
  - Outer valence electrons.
    - E.g. ^{14}Si has four valence electrons.

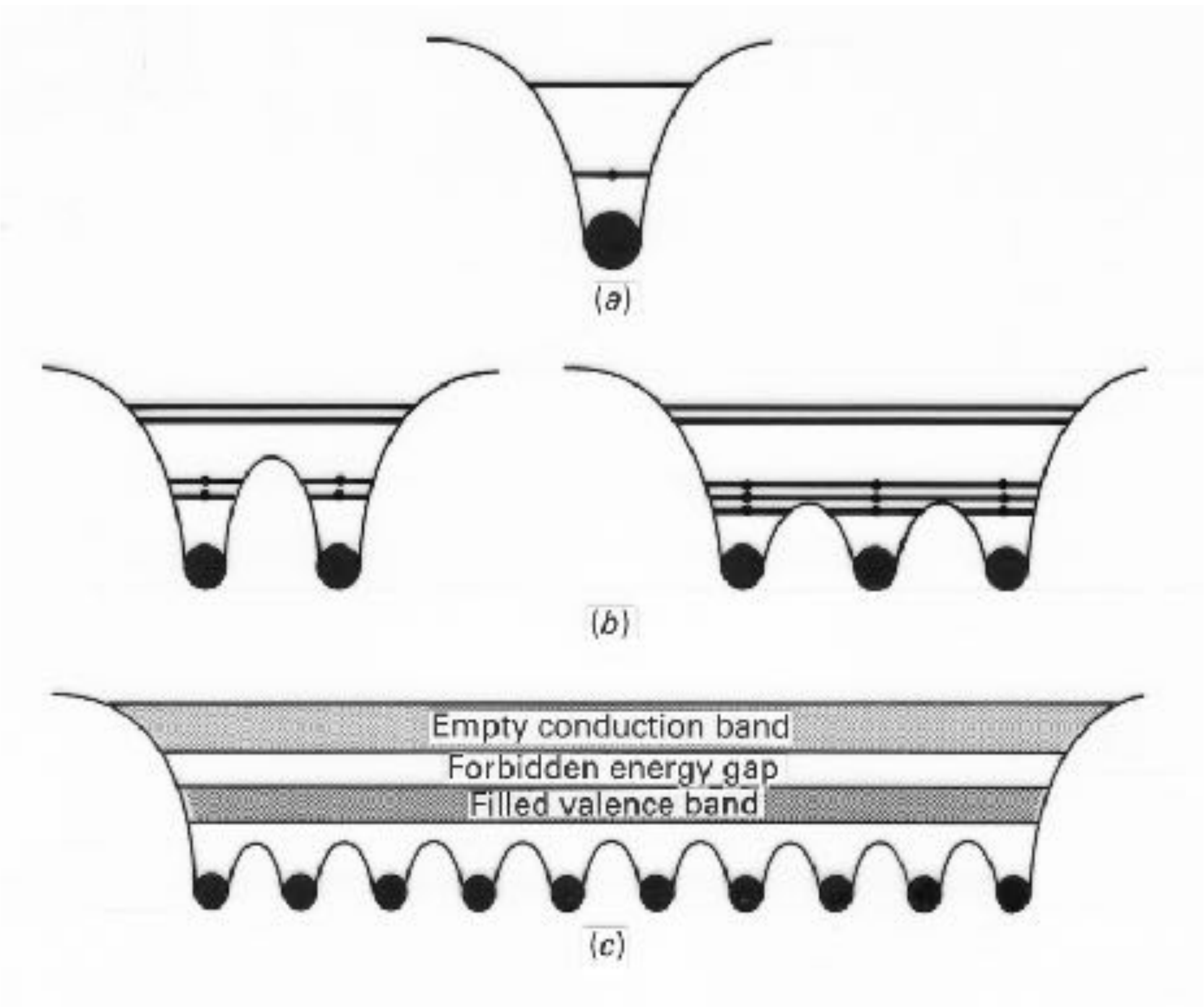




Hydrogen orbitals

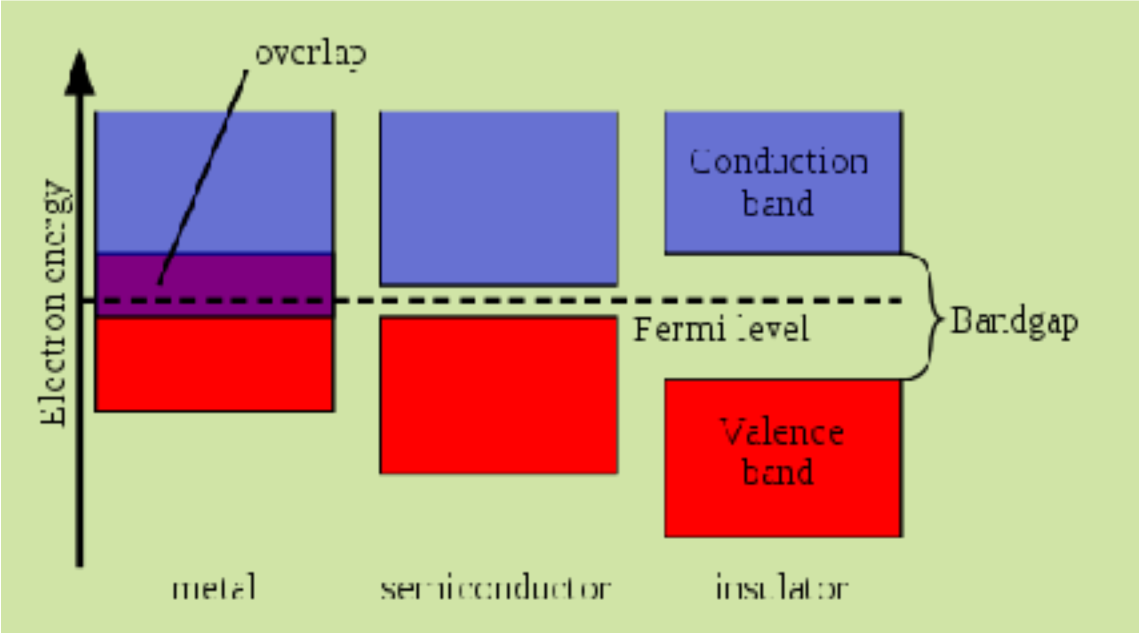
Semiconductor band structure

- Bringing atoms together in a crystalline structure causes the single atom energy levels to split in proportion to the number of atoms:
  - Valence electrons shared between nuclei; energy levels form a ***valence band***.
    - Filled, if atomic valence bands are filled.
  - Outer unoccupied atomic levels similarly form a band – the ***conduction band.***



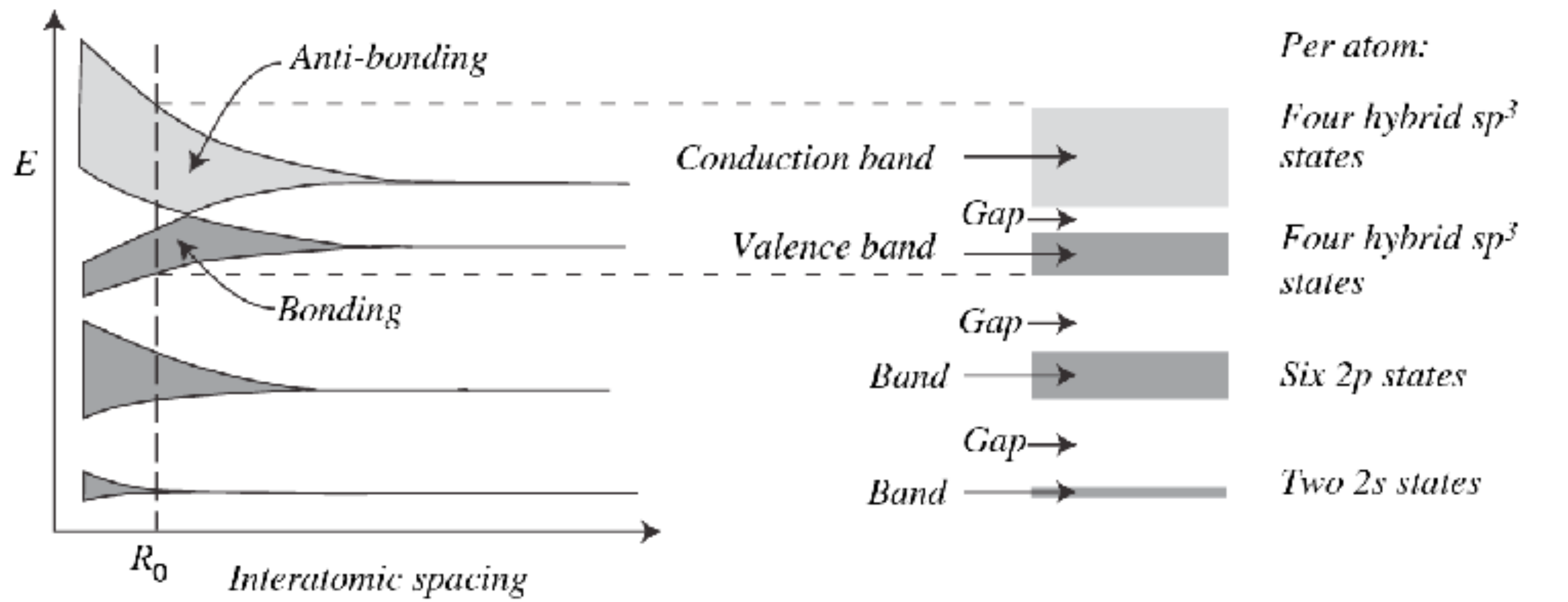
Semiconductor band structure

- Gap between valence and conduction band is the ***forbidden energy gap***:
  - For current to flow there must either be:
    - Electrons in the conduction band.
    - “Holes” in the valence band (previously occupied by electrons).
    - An applied electric field (a voltage across the semiconductor).
- ***<u>Conductors:</u>***
  - Overlapping valence and conduction bands.
- ***<u>Insulators:</u>***
  - Wide forbidden gap and no free electrons or holes.
- ***<u>Semiconductors:</u>***
  - Non-zero probability of electron-hole pairs forming and current conduction – properties lie between conductors and insulators.

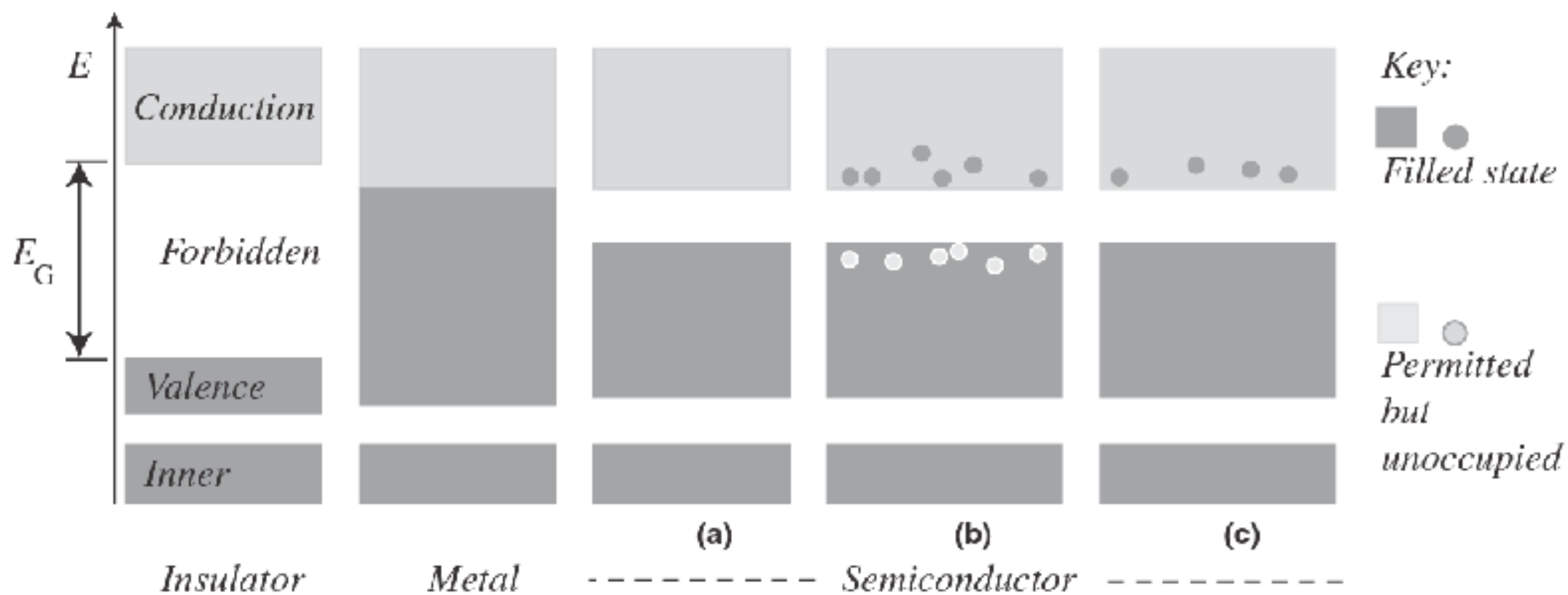


Fermi level: *energy at which there is a 50/50 probability of the electron energy state being occupied by an electron.*

Crystals



Anti-bonding
Bonding
E
R_0
Interatomic spacing
Conduction band
Gap
Valence band
Gap
Band
Gap
Band
Per atom:
Four hybrid sp^3 states
Four hybrid sp^3 states
Six 2p states
Two 2s states



E
Conduction
Forbidden
E_G
Valence
Inner
(a)
(b)
(c)
Insulator
Metal
Semiconductor
Key:
Filled state
Permitted but unoccupied