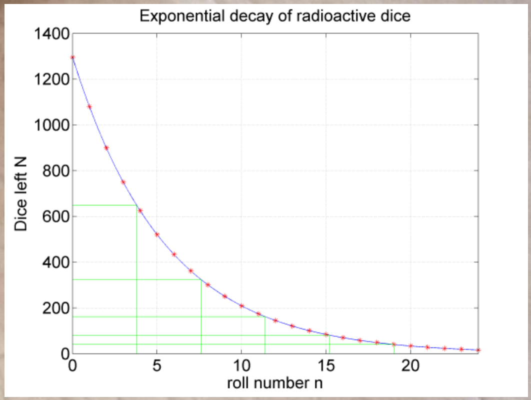
Radioactive Dice

Dr Andrew French

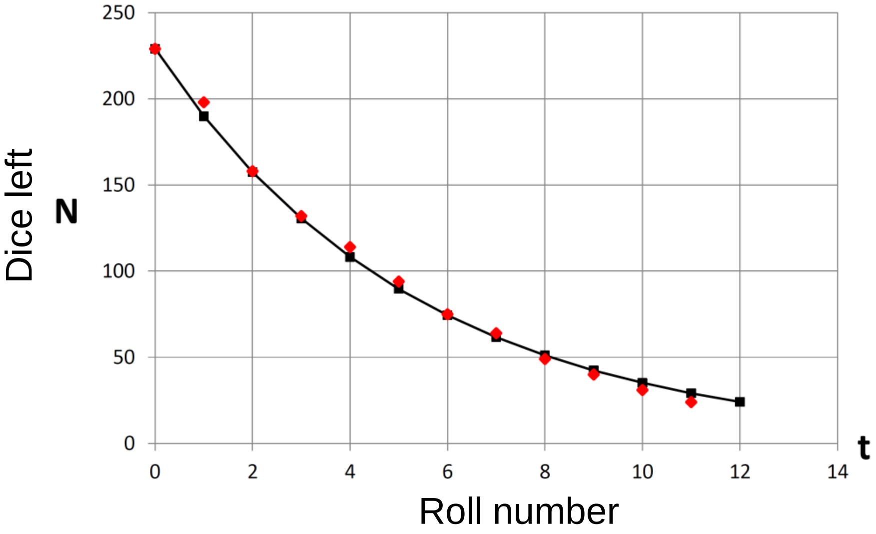
July 2017



This experiment will get you thinking about **atoms** and **radioactivity** – which is the *random decay of atomic nuclei into smaller parts.*

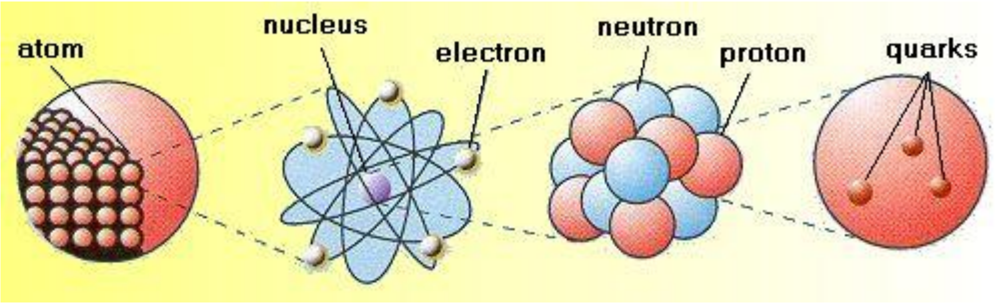
Radioactivity is a *high energy process* (about a million times more energetic than chemical reactions), so to keep things safe we will use **dice** instead!
This is an example of a physical *model* of what we are trying to understand.

- We'll hand out lots of dice (over 200)
- An atomic decay shall be *modelled* by a **rolling of a six**
- We'll all roll the dice together and I'll collect in the sixes each time.
- For each round I'll record in `Excel` the total number of dice held by each person.
- We'll then plot the **total number of dice left** vs **roll number.**
- We should obtain an **exponential decay curve**, from which we can determine the **half-life** for the radioactive dice



But first …. What are atoms? How big are they? How do we know they exist if we can’t see them?

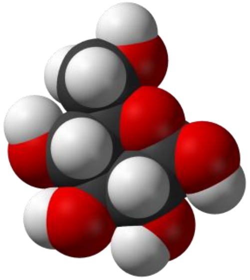
Length scales



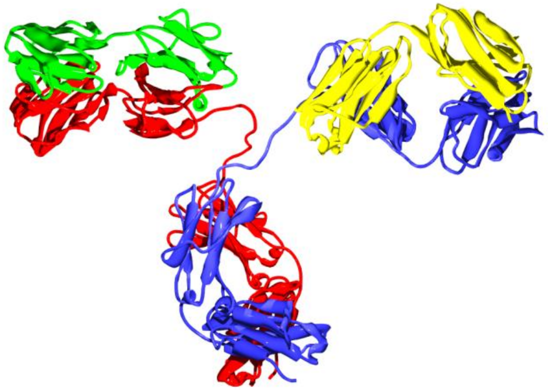
10^{-10} m

10^{-15} m

Glucose molecule

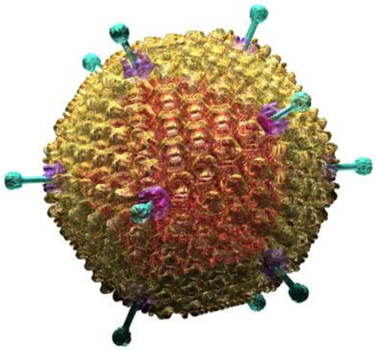


10^{-9} m



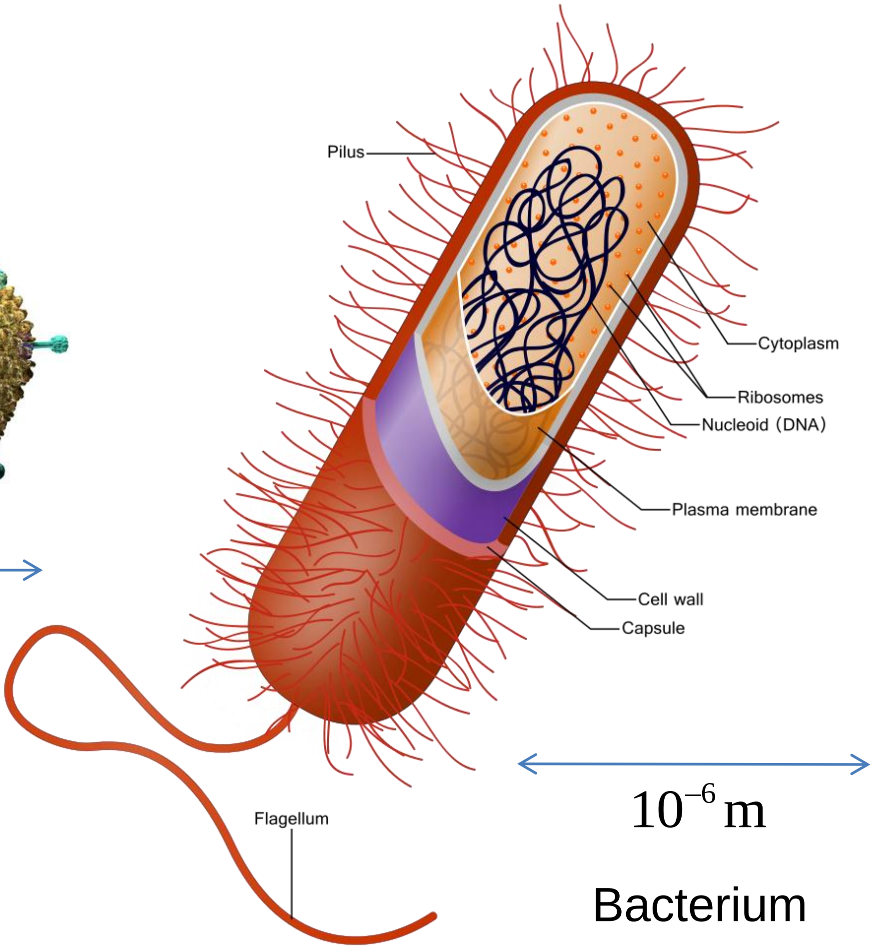
10^{-8} m

Antibody



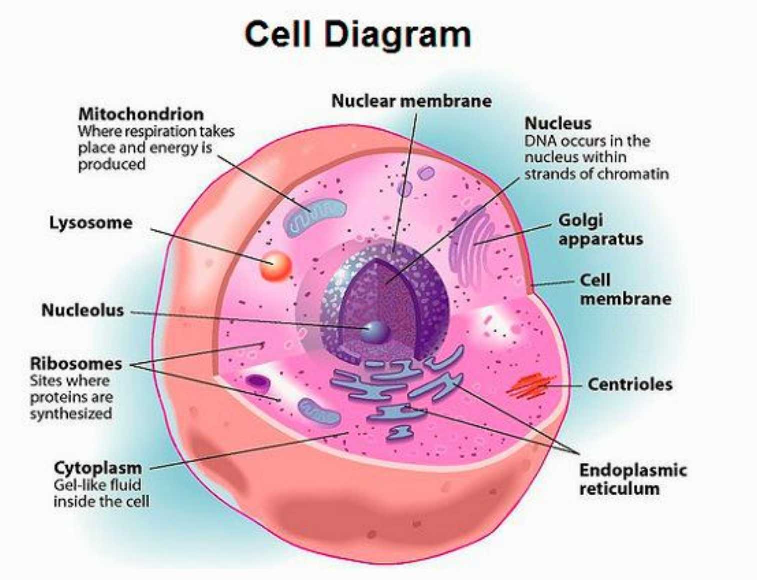
10^{-7} m

Virus



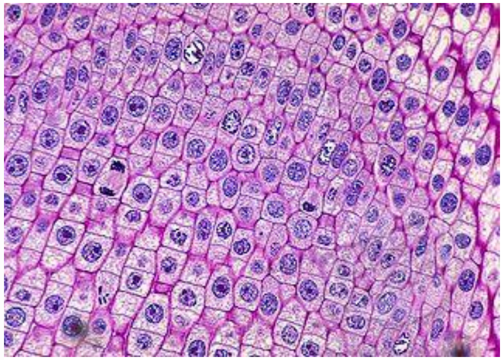
10^{-6} m

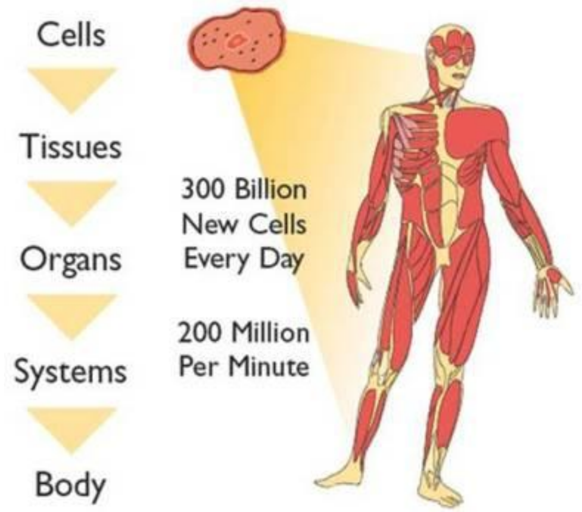
Bacterium



10^{-5} m

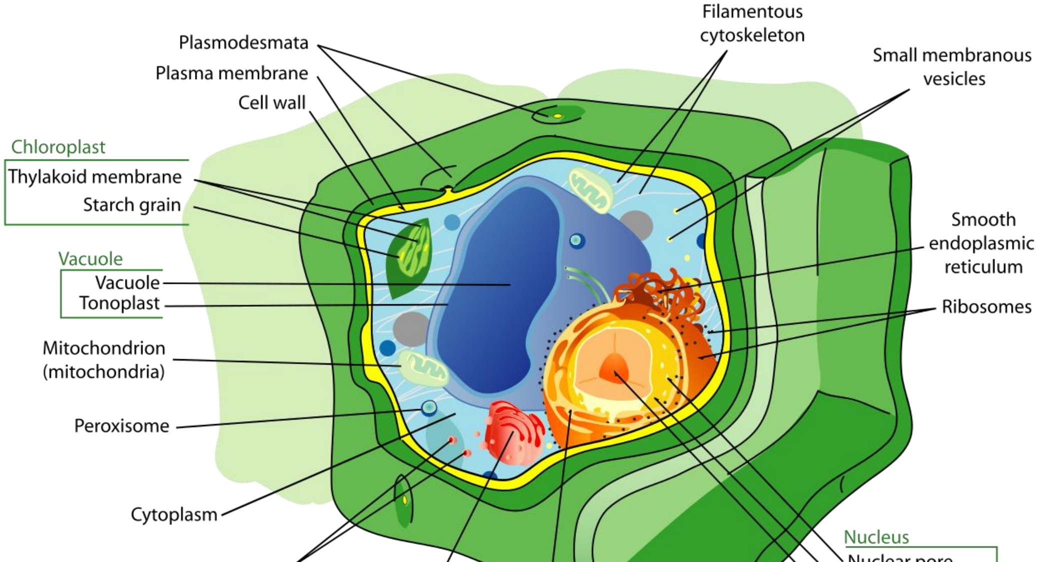
Human cell



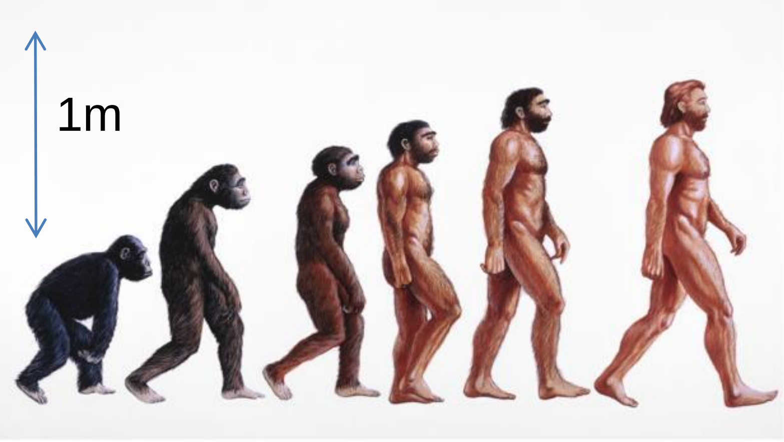


10^{-2} m

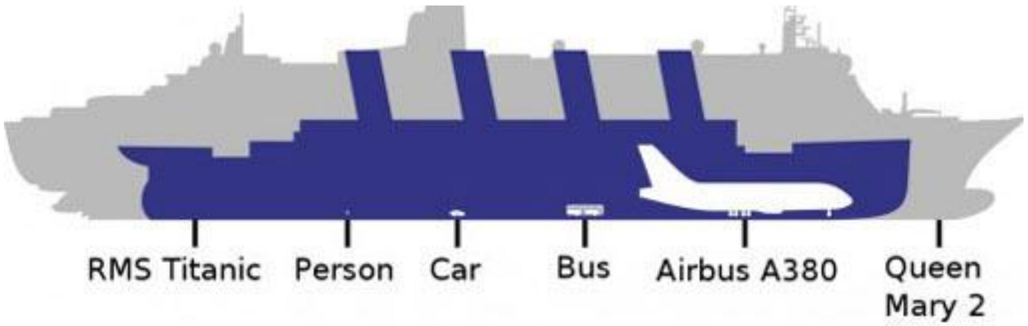
Human eye



Plant cell

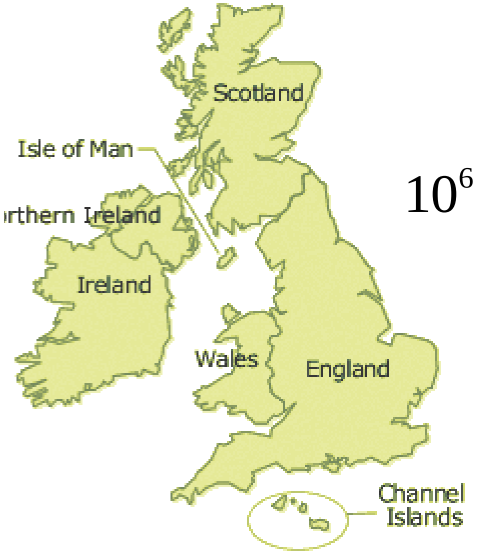


1m

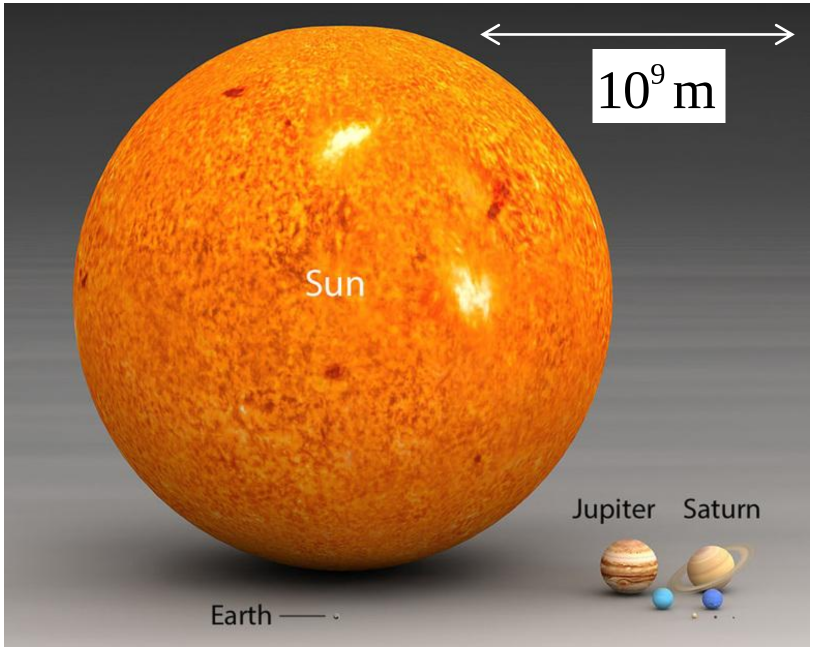


10^2 m

10^4 m

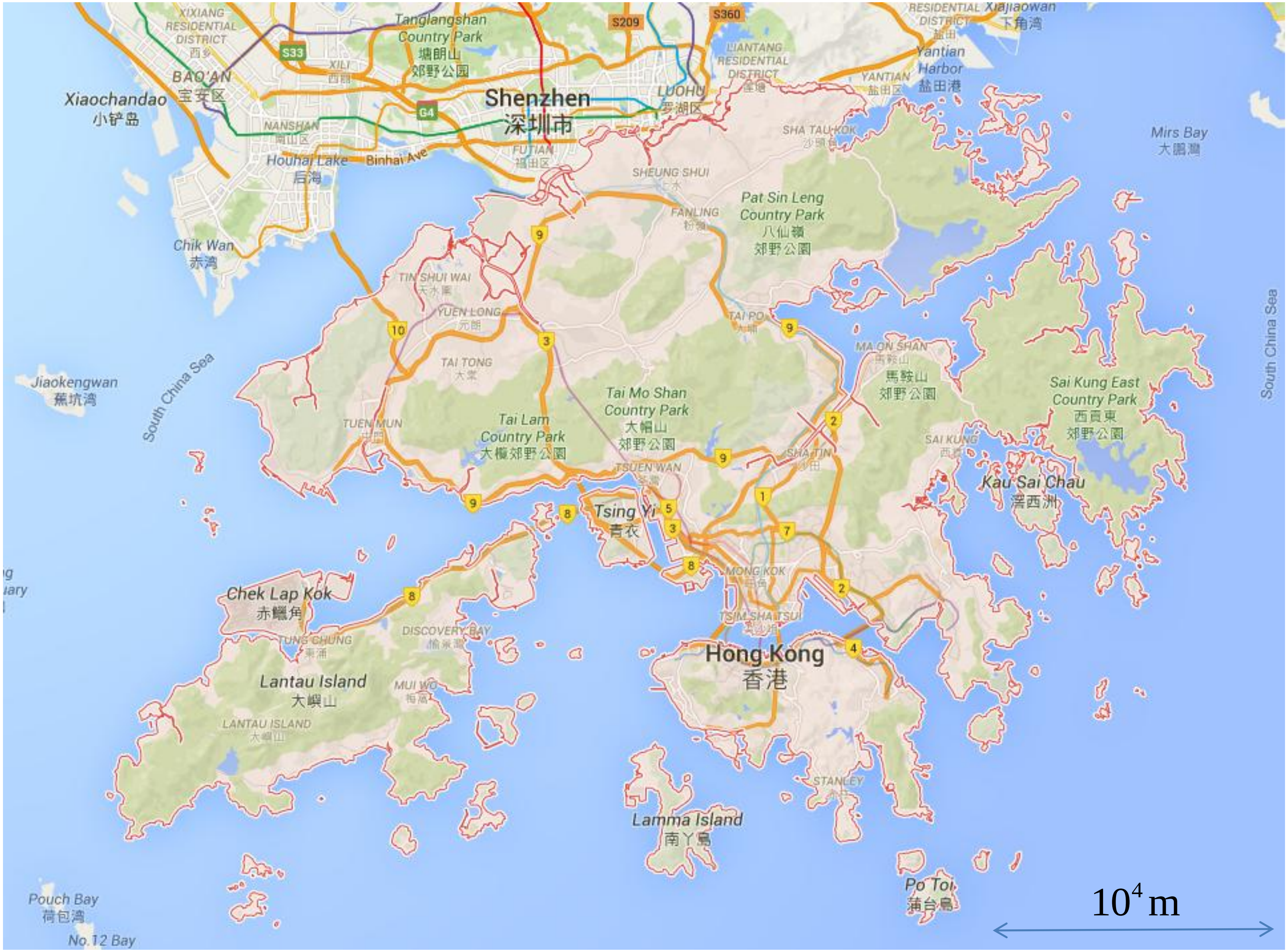


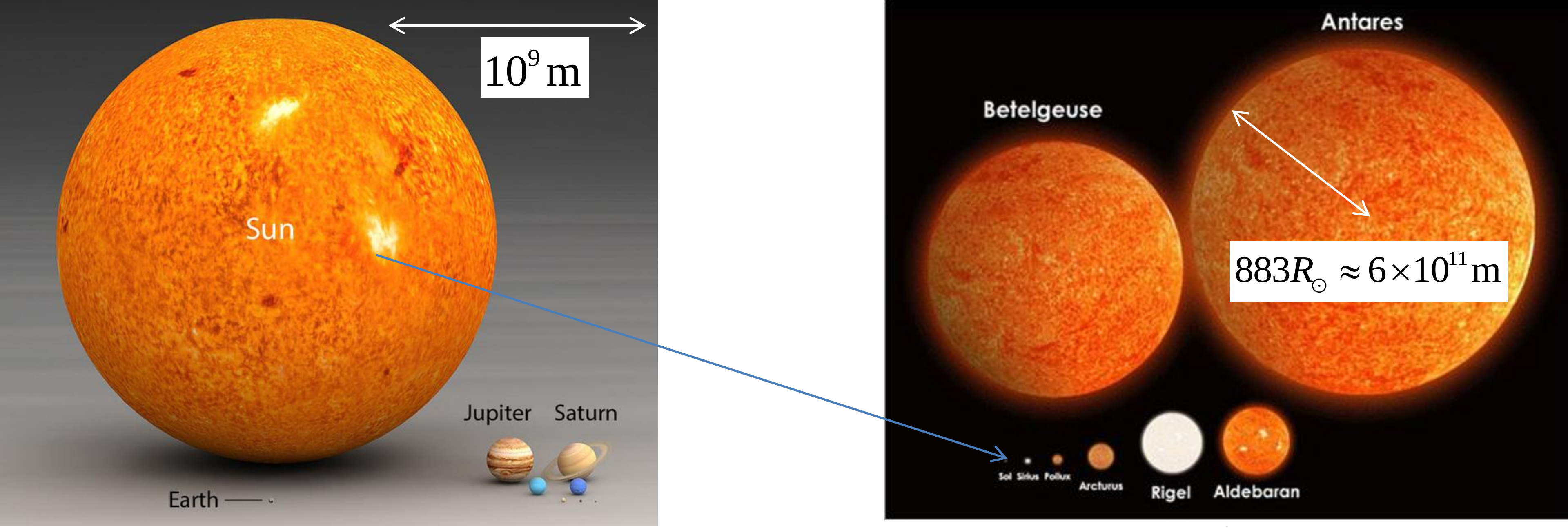
10^6 m

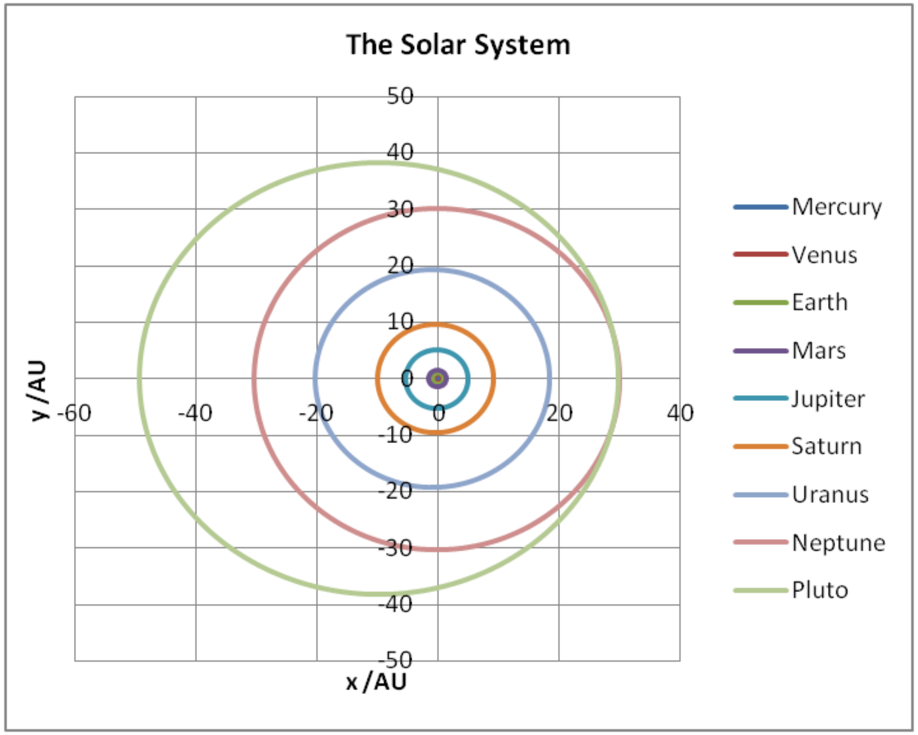


10^7 m

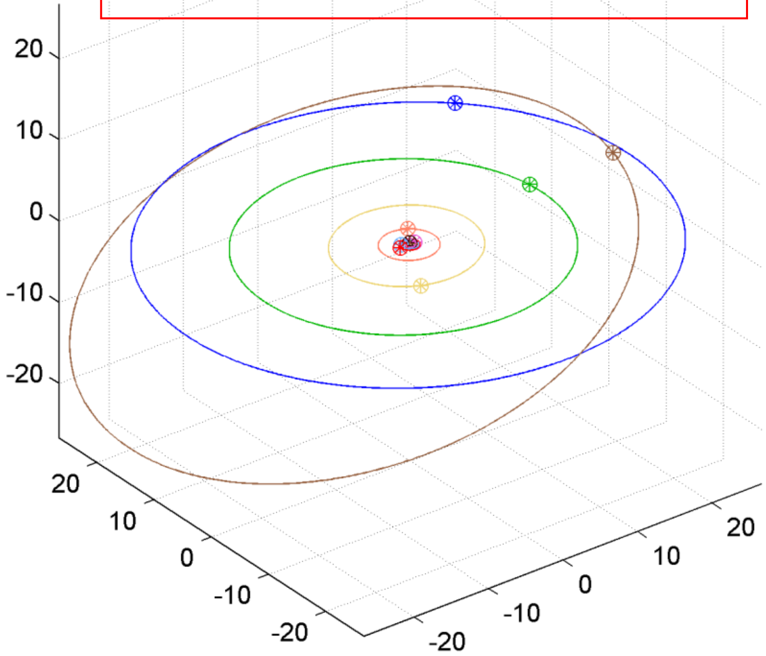
Earth diameter
= 12,756km

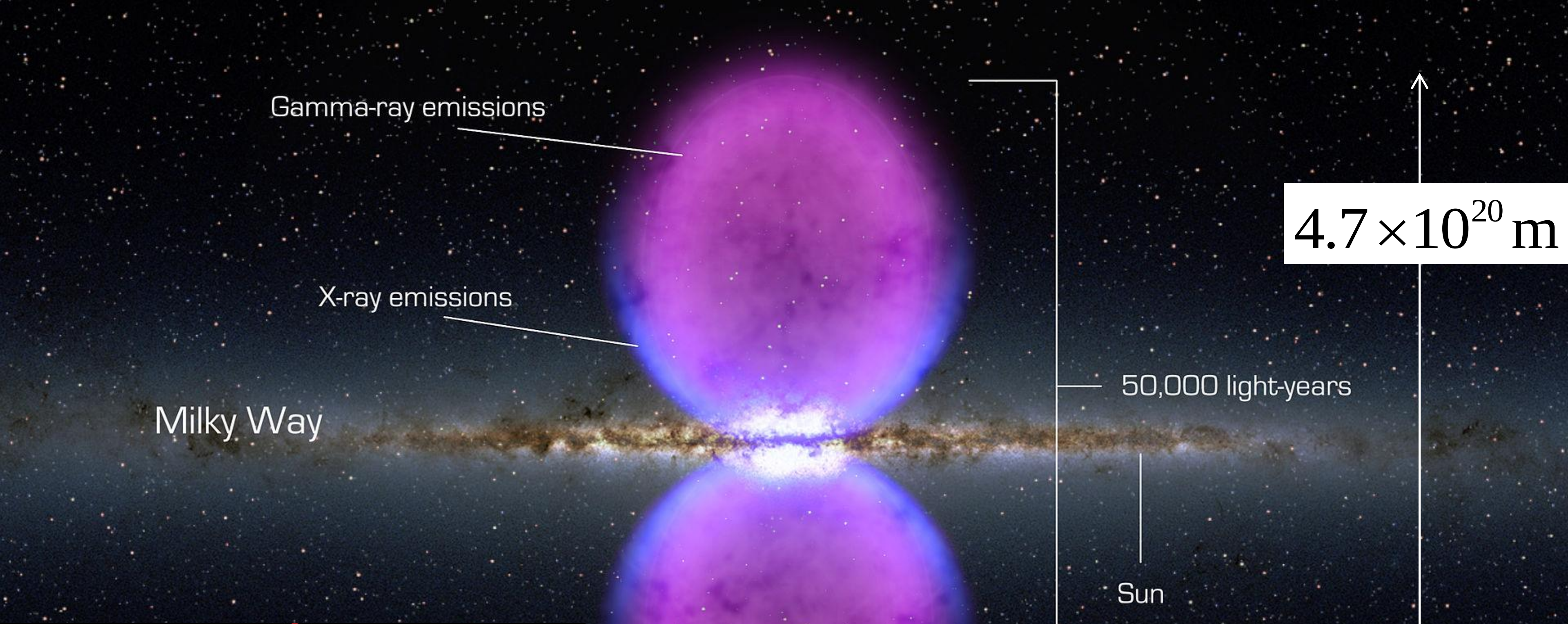

Xixiang Residential District 西乡
Tanglangshan Country Park 塘朗山郊野公园
S209
S360
Residential District
Xiajiaowan 下角湾
S33
Xili 西丽
Bao'an 宝安区
Liantang Residential District
Yantian Harbor 盐田港
Yantian 盐田区
Xiaochandao 小铲岛
G4
Shenzhen 深圳市
Luohu 罗湖区
Nanshan 南山区
Futian 福田区
Sha Tau Kok
Mirs Bay 大鵬灣
Houhai Lake 后海
Binhai Ave
Sheung Shui
Pat Sin Leng Country Park 八仙嶺郊野公園
Fanling
Chik Wan 赤湾
Tin Shui Wai 天水圍
Yuen Long 元朗
Tai Po 大埔
10
3
9
Ma On Shan
馬鞍山郊野公園
Jiaokengwan 蕉坑湾
South China Sea
Tai Tong 大棠
Tai Mo Shan Country Park 大帽山郊野公園
Sai Kung East Country Park 西貢東郊野公園
Tuen Mun
Tai Lam Country Park 大欖郊野公園
2
Sai Kung
Sha Tin
Tsuen Wan
Kau Sai Chau 滘西洲
1
5
8
Tsing Yi 青衣
7
Mong Kok
Chek Lap Kok 赤鱲角
Tung Chung
Discovery Bay
Tsim Sha Tsui
4
Hong Kong 香港
Lantau Island 大嶼山
Mui Wo
Lantau Island
Stanley
Lamma Island 南丫島
Po Toi 蒲台島
Pouch Bay 荷包湾
No.12 Bay
South China Sea
10^4 m



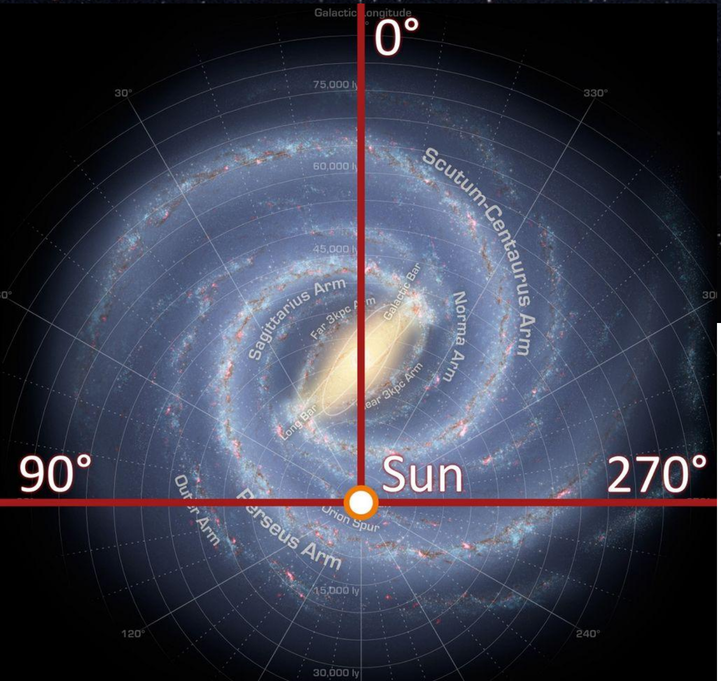


$$1\text{AU} = 1.496\times10^{11}\text{m}$$





4.7×10^{20} m



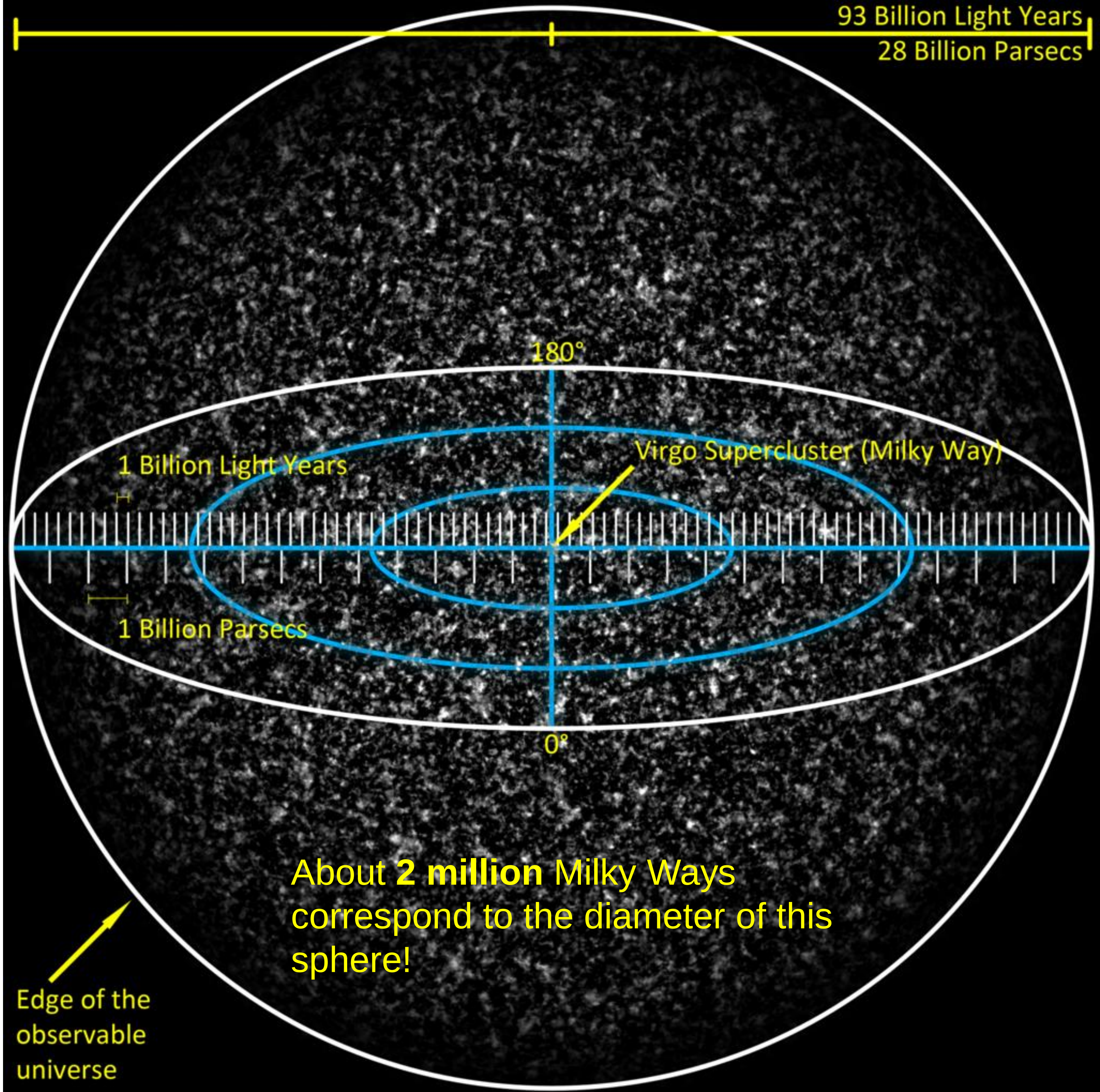
1 light year

9.461×10^{15} m

10^{26} m

1 light year

9.461×10^{15} m



About **2 million** Milky Ways correspond to the diameter of this sphere!

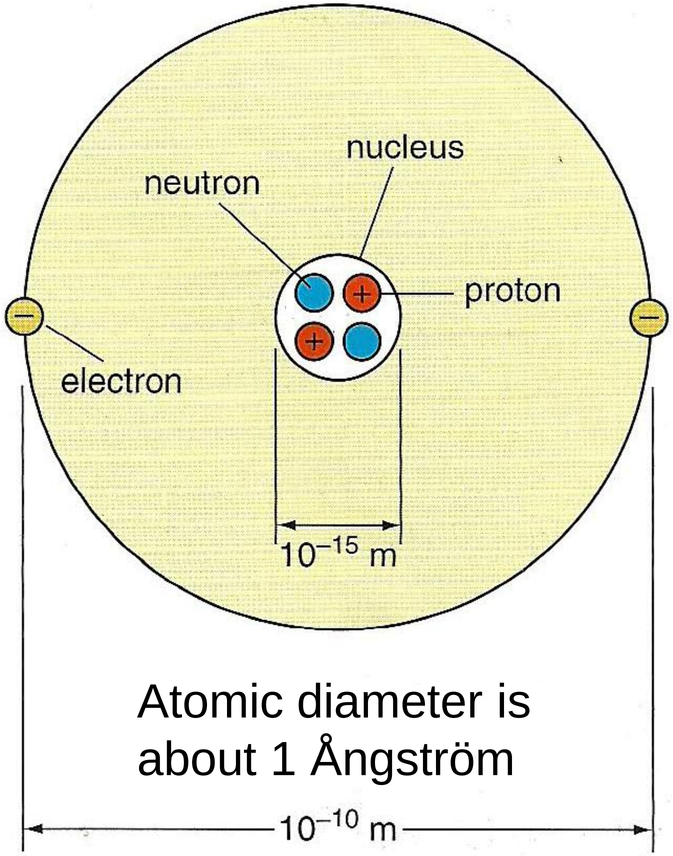
The size of an atom

Earth diameter
= 12,756km

Marble diameter =
3.6cm

$$\left(\frac{1.2756\times10^{7}}{3.6\times10^{-2}}\right)^{3}\approx\boxed{4.4\times10^{25}}$$

Volume of Earth in marbles



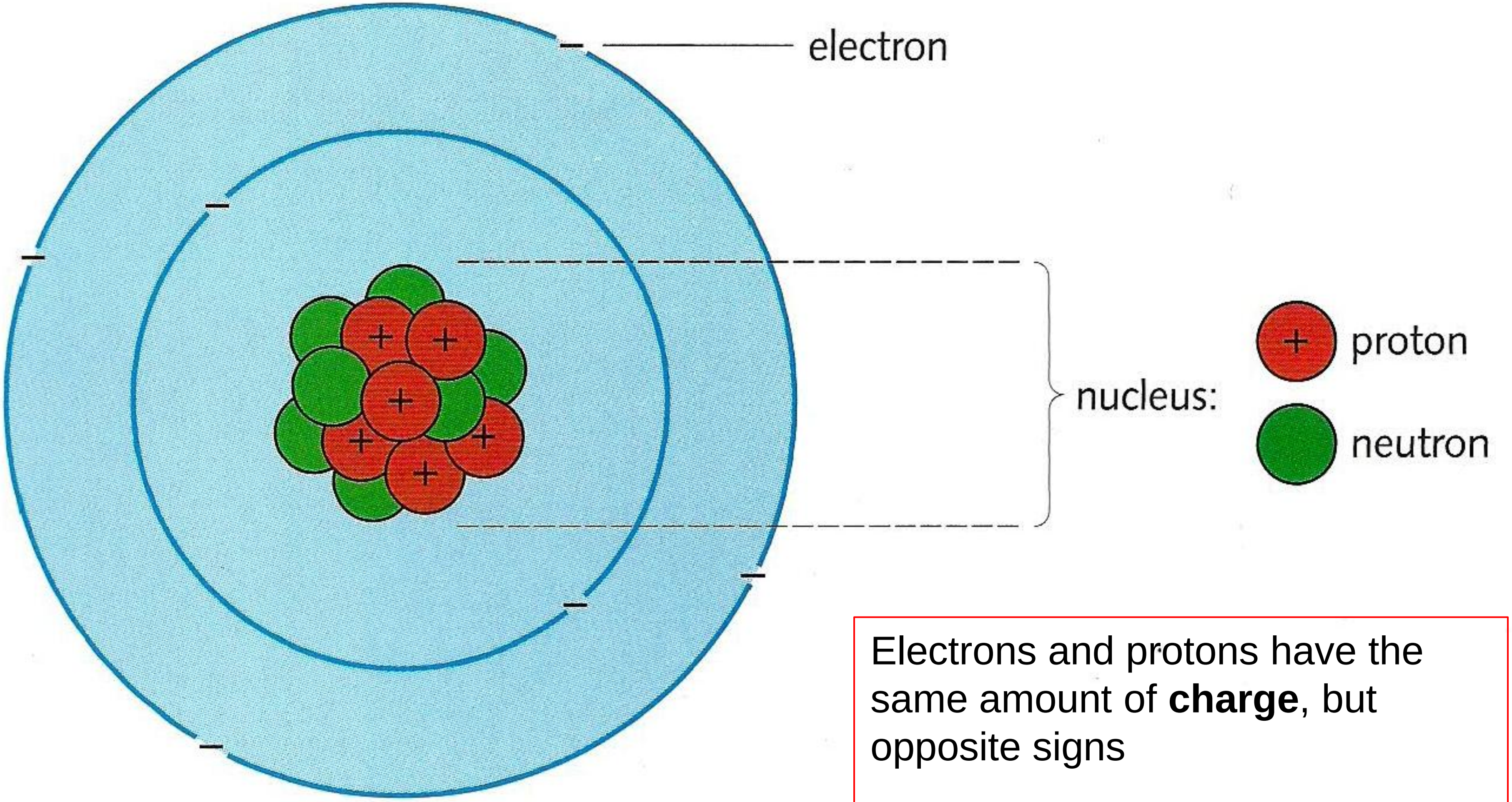
Atomic diameter is
about 1 Ångström

$$\left(\frac{3.6\times10^{-2}}{1\times10^{-10}}\right)^{3}\approx\boxed{4.7\times10^{25}}$$

Number of atoms in a marble

There are as many atoms in a marble as an Earth made of marbles!

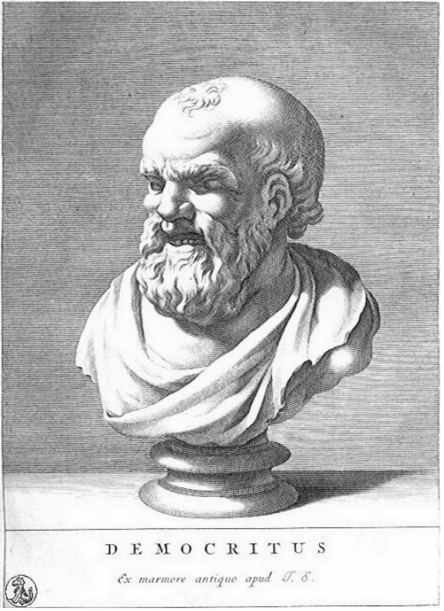
The Atomic model



Electrons and protons have the same amount of **charge**, but opposite signs

A *charged* atom with electrons removed (or added) is called an **ion**

Charge on the electron is 1.6 x 10^{-19} coulombs



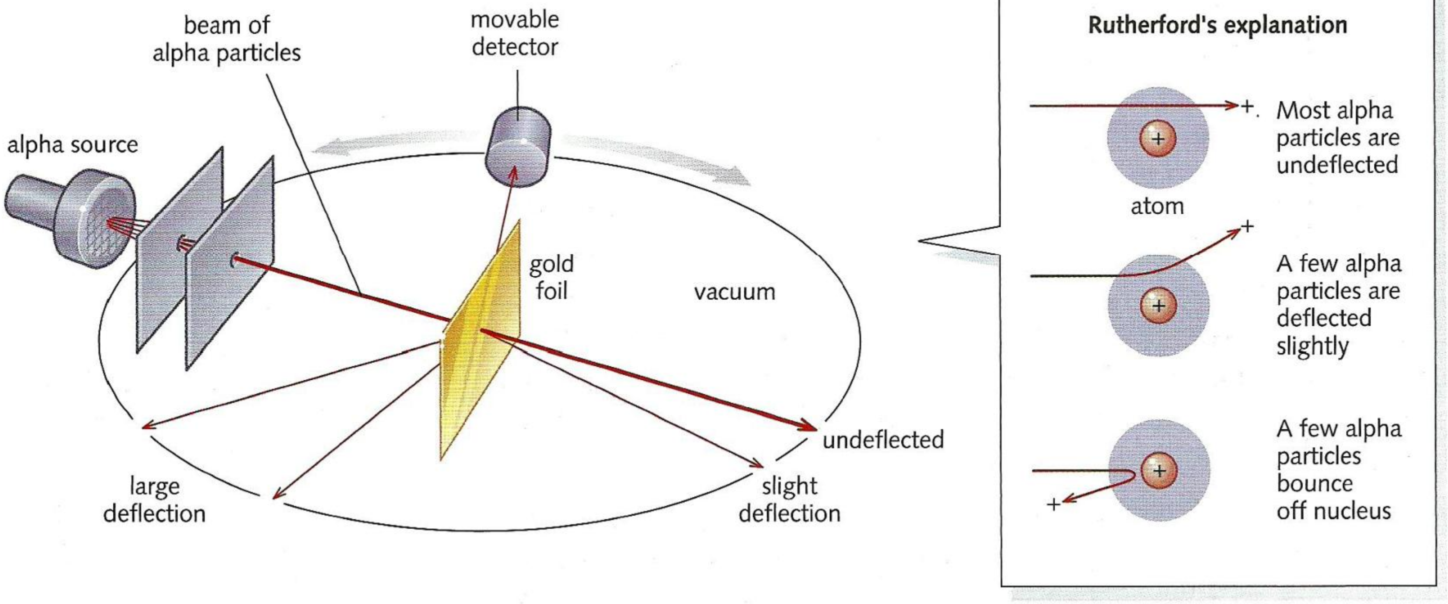
Democritus
460BC-370BC
Abdera, Thrace

Ernest Rutherford

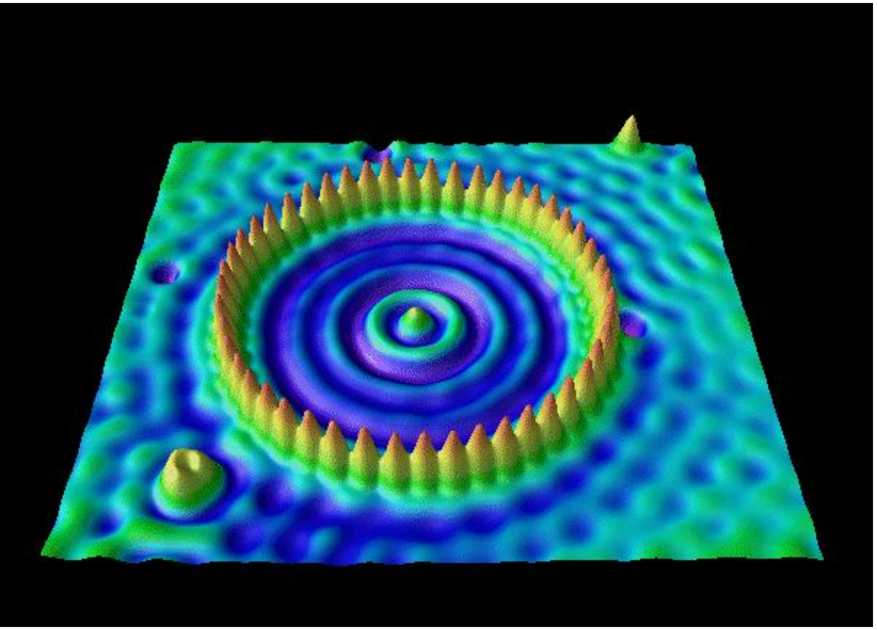
Hans
Geiger

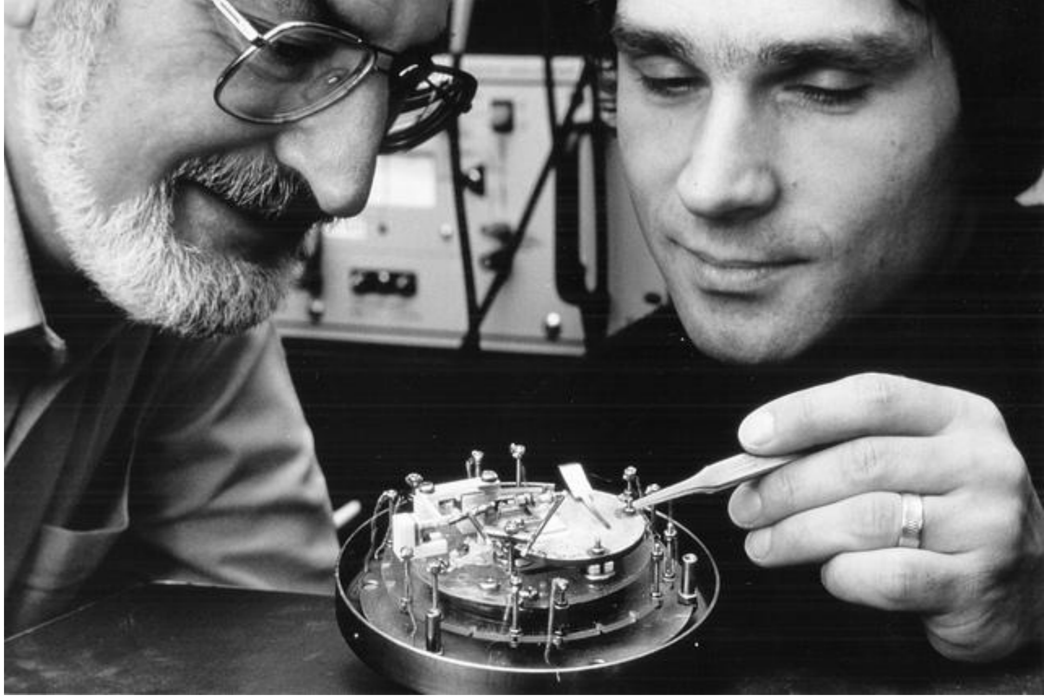
Ernest
Marsden

Experiments performed 1908-1913
at the University of Manchester

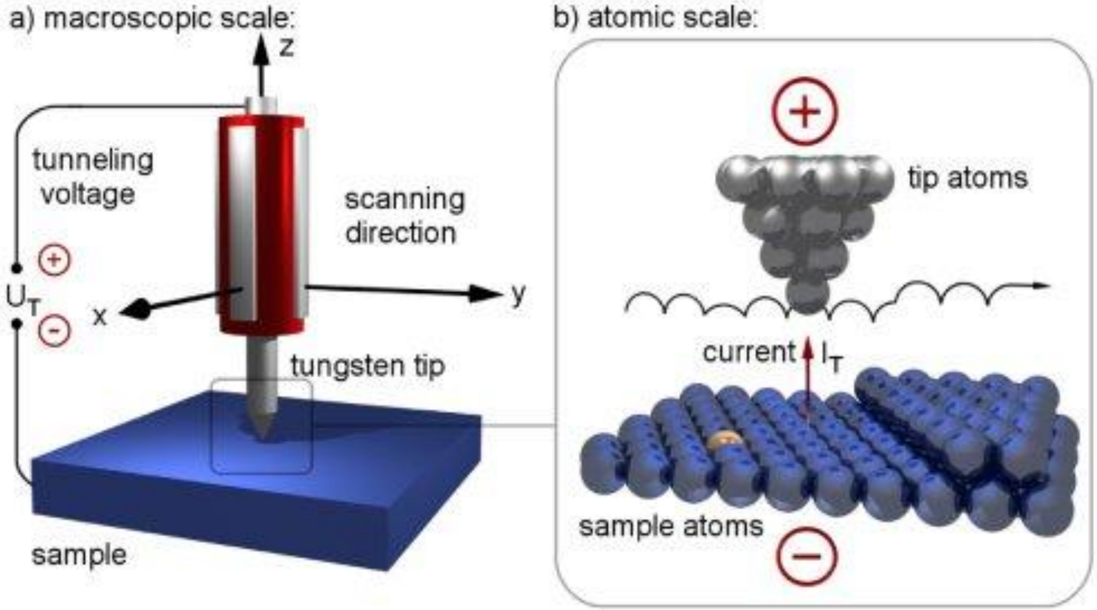


‘Seeing’ atoms





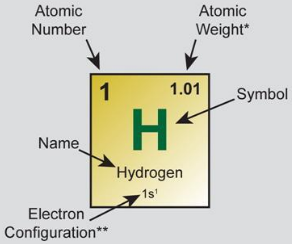
Heinrich Rohrer and Gerd Binnig
Nobel Prize winners 1986



Scanning Tunnelling Microscope (STM)

Periodic Table of the Elements

- 🟫 Alkali Metals
- 🟦 Alkaline Earth Metals
- 🟩 Transition Metals
- 🟨 Non-metals
- 🟥 Lanthanide Series
- 🟪 Actinide Series
- 🟦 Halogens
- 🟧 Inert Gases
- ⬛ Other Metals



Period \ Group	1 Ia	2 IIa	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8	9 ← VIIIb →	10	11 Ib	12 IIb	13 IIIa	14 IVa	15 Va	16 VIa	17 VIIa	18 0
1	1 1.01 **H** Hydrogen $1s^1$																	2 4.00 **He** Helium $1s^2$
2	3 6.94 **Li** Lithium $1s^2 2s^1$	4 9.01 **Be** Beryllium $1s^2 2s^2$											5 10.81 **B** Boron $1s^2 2s^2 p^1$	6 12.01 **C** Carbon $1s^2 2s^2 p^2$	7 14.01 **N** Nitrogen $1s^2 2s^2 p^3$	8 16.00 **O** Oxygen $1s^2 2s^2 p^4$	9 19.00 **F** Fluorine $1s^2 2s^2 p^5$	10 20.18 **Ne** Neon $1s^2 2s^2 p^6$
3	11 22.99 **Na** Sodium $[Ne]3s^1$	12 24.31 **Mg** Magnesium $[Ne]3s^2$											13 26.98 **Al** Aluminum $[Ne]3s^2 p^1$	14 28.09 **Si** Silicon $[Ne]3s^2 p^2$	15 30.97 **P** Phosphorus $[Ne]3s^2 p^3$	16 32.07 **S** Sulfur $[Ne]3s^2 p^4$	17 35.45 **Cl** Chlorine $[Ne]3s^2 p^5$	18 39.95 **Ar** Argon $[Ne]3s^2 p^6$
4	19 39.10 **K** Potassium $[Ar]4s^1$	20 40.08 **Ca** Calcium $[Ar]4s^2$	21 44.96 **Sc** Scandium $[Ar]3d^1 4s^2$	22 47.87 **Ti** Titanium $[Ar]3d^2 4s^2$	23 50.94 **V** Vanadium $[Ar]3d^3 4s^2$	24 52.00 **Cr** Chromium $[Ar]3d^5 4s^1$	25 54.94 **Mn** Manganese $[Ar]3d^5 4s^2$	26 55.85 **Fe** Iron $[Ar]3d^6 4s^2$	27 58.93 **Co** Cobalt $[Ar]3d^7 4s^2$	28 58.69 **Ni** Nickel $[Ar]3d^8 4s^2$	29 63.55 **Cu** Copper $[Ar]3d^{10} 4s^1$	30 65.39 **Zn** Zinc $[Ar]3d^{10} 4s^2$	31 69.72 **Ga** Gallium $[Ar]3d^{10} 4s^2 p^1$	32 72.61 **Ge** Germanium $[Ar]3d^{10} 4s^2 p^2$	33 74.92 **As** Arsenic $[Ar]3d^{10} 4s^2 p^3$	34 78.96 **Se** Selenium $[Ar]3d^{10} 4s^2 p^4$	35 79.90 **Br** Bromine $[Ar]3d^{10} 4s^2 p^5$	36 83.80 **Kr** Krypton $[Ar]3d^{10} 4s^2 p^6$
5	37 85.47 **Rb** Rubidium $[Kr]5s^1$	38 87.62 **Sr** Strontium $[Kr]5s^2$	39 88.91 **Y** Yttrium $[Kr]4d^1 5s^2$	40 91.22 **Zr** Zirconium $[Kr]4d^2 5s^2$	41 92.91 **Nb** Niobium $[Kr]4d^4 5s^1$	42 95.94 **Mo** Molybdenum $[Kr]4d^5 5s^1$	43 (98) **Tc** Technetium $[Kr]4d^5 5s^2$	44 101.07 **Ru** Ruthenium $[Kr]4d^7 5s^1$	45 102.91 **Rh** Rhodium $[Kr]4d^8 5s^1$	46 106.42 **Pd** Palladium $[Kr]4d^{10}$	47 107.87 **Ag** Silver $[Kr]4d^{10} 5s^1$	48 112.41 **Cd** Cadmium $[Kr]4d^{10} 5s^2$	49 114.82 **In** Indium $[Kr]4d^{10} 5s^2 p^1$	50 118.71 **Sn** Tin $[Kr]4d^{10} 5s^2 p^2$	51 121.76 **Sb** Antimony $[Kr]4d^{10} 5s^2 p^3$	52 127.60 **Te** Tellurium $[Kr]4d^{10} 5s^2 p^4$	53 126.90 **I** Iodine $[Kr]4d^{10} 5s^2 p^5$	54 131.29 **Xe** Xenon $[Kr]4d^{10} 5s^2 p^6$
6	55 132.91 **Cs** Cesium $[Xe]6s^1$	56 137.33 **Ba** Barium $[Xe]6s^2$	♦	72 178.49 **Hf** Hafnium $[Xe]4f^{14} 5d^2 6s^2$	73 180.95 **Ta** Tantalum $[Xe]4f^{14} 5d^3 6s^2$	74 183.84 **W** Tungsten $[Xe]4f^{14} 5d^4 6s^2$	75 186.21 **Re** Rhenium $[Xe]4f^{14} 5d^5 6s^2$	76 190.23 **Os** Osmium $[Xe]4f^{14} 5d^6 6s^2$	77 192.22 **Ir** Iridium $[Xe]4f^{14} 5d^7 6s^2$	78 195.08 **Pt** Platinum $[Xe]4f^{14} 5d^9 6s^1$	79 196.97 **Au** Gold $[Xe]4f^{14} 5d^{10} 6s^1$	80 200.59 **Hg** Mercury $[Xe]4f^{14} 5d^{10} 6s^2$	81 204.38 **Tl** Thallium $[Xe]4f^{14} 5d^{10} 6s^2 p^1$	82 207.20 **Pb** Lead $[Xe]4f^{14} 5d^{10} 6s^2 p^2$	83 208.98 **Bi** Bismuth $[Xe]4f^{14} 5d^{10} 6s^2 p^3$	84 (209) **Po** Polonium $[Xe]4f^{14} 5d^{10} 6s^2 p^4$	85 (210) **At** Astatine $[Xe]4f^{14} 5d^{10} 6s^2 p^5$	86 (222) **Rn** Radon $[Xe]4f^{14} 5d^{10} 6s^2 p^6$
7	87 (223) **Fr** Francium $[Rn]7s^1$	88 (226) **Ra** Radium $[Rn]7s^2$	★	104 (265) **Rf** Rutherfordium $[Rn]5f^{14} 6d^2 7s^2$	105 (268) **Db** Dubnium $[Rn]5f^{14} 6d^3 7s^2$	106 (271) **Sg** Seaborgium $[Rn]5f^{14} 6d^4 7s^2$	107 (270) **Bh** Bohrium $[Rn]5f^{14} 6d^5 7s^2$	108 (277) **Hs** Hassium $[Rn]5f^{14} 6d^6 7s^2$	109 (276) **Mt** Meitnerium $[Rn]5f^{14} 6d^7 7s^2$	110 (281) **Ds** Darmstadtium $[Rn]5f^{14} 6d^9 7s^1$	111 (280) **Rg** Roentgenium $[Rn]5f^{14} 6d^9 7s^2$	112 (285) **Cn** Copernicium $[Rn]5f^{14} 6d^{10} 7s^2$	113 (284) **Uut** Ununtrium $[Rn]5f^{14} 6d^{10} 7s^2 7p^1$	114 (289) **Fl** Flerovium $[Rn]5f^{14} 6d^{10} 7s^2 7p^2$	115 (288) **Uup** Ununpentium $[Rn]5f^{14} 6d^{10} 7s^2 7p^3$	116 (293) **Lv** Livermorium $[Rn]5f^{14} 6d^{10} 7s^2 7p^4$	117 (294) **Uus** Ununseptium $[Rn]5f^{14} 6d^{10} 7s^2 7p^5$	118 (294) **Uuo** Ununoctium $[Rn]5f^{14} 6d^{10} 7s^2 7p^6$

♦	57 138.91 **La** Lanthanum $[Xe]5d^1 6s^2$	58 140.12 **Ce** Cerium $[Xe]4f^1 5d^1 6s^2$	59 140.91 **Pr** Praseodymium $[Xe]4f^3 6s^2$	60 144.24 **Nd** Neodymium $[Xe]4f^4 6s^2$	61 (145) **Pm** Promethium $[Xe]4f^5 6s^2$	62 150.36 **Sm** Samarium $[Xe]4f^6 6s^2$	63 151.96 **Eu** Europium $[Xe]4f^7 6s^2$	64 157.25 **Gd** Gadolinium $[Xe]4f^7 5d^1 6s^2$	65 158.93 **Tb** Terbium $[Xe]4f^9 6s^2$	66 162.50 **Dy** Dysprosium $[Xe]4f^{10} 6s^2$	67 164.93 **Ho** Holmium $[Xe]4f^{11} 6s^2$	68 167.26 **Er** Erbium $[Xe]4f^{12} 6s^2$	69 168.93 **Tm** Thulium $[Xe]4f^{13} 6s^2$	70 173.04 **Yb** Ytterbium $[Xe]4f^{14} 6s^2$	71 174.97 **Lu** Lutetium $[Xe]4f^{14} 5d^1 6s^2$
★	89 (227) **Ac** Actinium $[Rn]6d^1 7s^2$	90 232.04 **Th** Thorium $[Rn]6d^2 7s^2$	91 231.04 **Pa** Protactinium $[Rn]5f^2 6d^1 7s^2$	92 238.03 **U** Uranium $[Rn]5f^3 6d^1 7s^2$	93 (237) **Np** Neptunium $[Rn]5f^4 6d^1 7s^2$	94 (244) **Pu** Plutonium $[Rn]5f^6 7s^2$	95 (243) **Am** Americium $[Rn]5f^7 7s^2$	96 (247) **Cm** Curium $[Rn]5f^7 6d^1 7s^2$	97 (247) **Bk** Berkelium $[Rn]5f^9 7s^2$	98 (251) **Cf** Californium $[Rn]5f^{10} 7s^2$	99 (252) **Es** Einsteinium $[Rn]5f^{11} 7s^2$	100 (257) **Fm** Fermium $[Rn]5f^{12} 7s^2$	101 (258) **Md** Mendelevium $[Rn]5f^{13} 7s^2$	102 (259) **No** Nobelium $[Rn]5f^{14} 7s^2$	103 (262) **Lr** Lawrencium $[Rn]5f^{14} 7s^2 7p^1$

Aa - Solid
Aa - Gas
Aa - Liquid
Aa - Synthetically Prepared

* Based on Carbon-12. (###) represents most stable or most stable expected isotope.

** Some electron configurations are based on theoretical expected arrangements.

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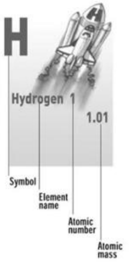
- TRANSITION METALS
- OTHER METALS
- OTHER NONMETALS
- HALOGENS
- NOBLE GASSES
- RARE EARTH METALS

At room temperature the element is:

- 🟨 Gas
- 🟦 Liquid
- 🟥 Natural solid
- ⬛ Man-made solid [synthetic]

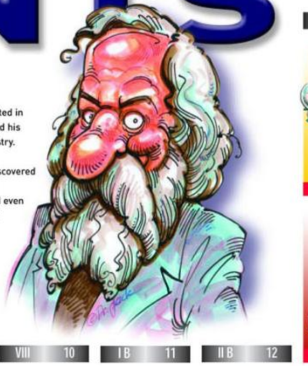


DMITRI MENDELEYEV (1834 – 1907)

The Russian chemist, Dmitri Mendeleyev, was the first to observe that if elements were listed in order of atomic mass, they showed regular (periodical) repeating properties. He formulated his discovery in a periodic table of elements, now regarded as the backbone of modern chemistry.

The crowning achievement of Mendeleyev's periodic table lay in his prophecy of then, undiscovered elements. In 1869, the year he published his periodic classification, the elements gallium, germanium and scandium were unknown. Mendeleyev left spaces for them in his table and even predicted their atomic masses and other chemical properties. Six years later, gallium was discovered and his predictions were found to be accurate. Other discoveries followed and their chemical behaviour matched that predicted by Mendeleyev.

This remarkable man, the youngest in a family of 17 children, has left the scientific community with a classification system so powerful that it became the cornerstone in chemistry teaching and the prediction of new elements ever since.
In 1955, element 101 was named after him: Md, Mendelevium.

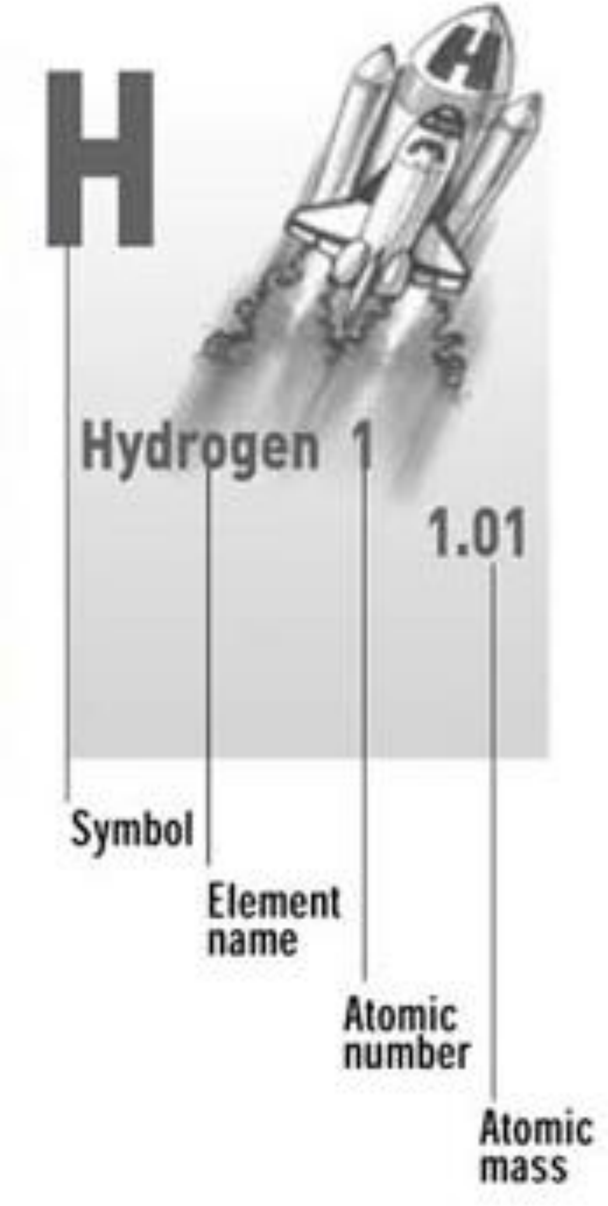


	IA 1	IIA 2	IIIB 3	IVB 4	VB 5	VIB 6	VIIB 7	VIII 8	VIII 9	VIII 10	IB 11	IIB 12	IIIA 13	IVA 14	VA 15	VIA 16	VIIA 17	VIIIA 18
1	H Hydrogen 1 1.01																	He Helium 2 4.00
2	Li lithium 3 6.94	Be Beryllium 4 9.01											B Boron 5 10.81	C Carbon 6 12.01	N Nitrogen 7 14.01	O Oxygen 8 16.00	F Fluorine 9 19.00	Ne Neon 10 20.18
3	Na Sodium 11 22.99	Mg Magnesium 12 24.31											Al Aluminium 13 26.98	Si Silicon 14 28.09	P Phosphorus 15 30.97	S Sulphur 16 32.06	Cl Chlorine 17 35.45	Ar Argon 18 39.95
4	K Potassium 19 39.10	Ca Calcium 20 40.08	Sc Scandium 21 44.96	Ti Titanium 22 47.88	V Vanadium 23 50.94	Cr Chromium 24 52.00	Mn Manganese 25 54.94	Fe Iron 26 55.85	Co Cobalt 27 58.93	Ni Nickel 28 58.69	Cu Copper 29 63.55	Zn Zinc 30 65.39	Ga Gallium 31 69.72	Ge Germanium 32 72.61	As Arsenic 33 74.92	Se Selenium 34 78.96	Br Bromine 35 79.90	Kr Krypton 36 83.80
5	Rb Rubidium 37 85.47	Sr Strontium 38 87.62	Y Yttrium 39 88.91	Zr Zirconium 40 91.22	Nb Niobium 41 92.91	Mo Molybdenum 42 95.94	Tc Technetium 43 (98)	Ru Ruthenium 44 101.07	Rh Rhodium 45 102.91	Pd Palladium 46 106.42	Ag Silver 47 107.87	Cd Cadmium 48 112.41	In Indium 49 114.82	Sn Tin 50 118.71	Sb Antimony 51 121.76	Te Tellurium 52 127.60	I Iodine 53 126.90	Xe Xenon 54 131.29
6	Cs Caesium 55 132.91	Ba Barium 56 137.33	Lanthanide Series	Hf Hafnium 72 178.49	Ta Tantalum 73 180.95	W Tungsten 74 183.85	Re Rhenium 75 186.21	Os Osmium 76 190.23	Ir Iridium 77 192.22	Pt Platinum 78 195.08	Au Gold 79 196.97	Hg Mercury 80 200.59	Tl Thallium 81 204.38	Pb Lead 82 207.20	Bi Bismuth 83 208.98	Po Polonium 84 (209)	At Astatine 85 (210)	Rn Radon 86 (222)
7	Fr Francium 87 (223)	Ra Radium 88 (226)	Actinide Series	Rf Rutherfordium 104 (261)	Db Dubnium 105 (262)	Sg Seaborgium 106 (263)	Bh Bohrium 107 (262)	Hs Hassium 108 (265)	Mt Meitnerium 109 (266)									

La Lanthanum 57 138.91	Ce Cerium 58 140.12	Pr Praseodymium 59 140.90	Nd Neodymium 60 144.24	Pm Promethium 61 (145)	Sm Samarium 62 150.36	Eu Europium 63 151.96	Gd Gadolinium 64 157.25	Tb Terbium 65 158.92	Dy Dysprosium 66 162.50	Ho Holmium 67 164.93	Er Erbium 68 167.26	Tm Thulium 69 168.93	Yb Ytterbium 70 173.04	Lu Lutetium 71 174.96
Ac Actinium 89 227.02	Th Thorium 90 232.03	Pa Protactinium 91 231.03	U Uranium 92 238.02	Np Neptunium 93 (237)	Pu Plutonium 94 (244)	Am Americium 95 (243)	Cm Curium 96 (247)	Bk Berkelium 97 (247)	Cf Californium 98 (251)	Es Einsteinium 99 (254)	Fm Fermium 100 (257)	Md Mendelevium 101 (258)	No Nobelium 102 (259)	Lr Lawrencium 103 (260)

Public Understanding of Science Engineering and Technology

FEST
Foundation for Education, Science & Technology



Each different type of atom is called a **nuclide**

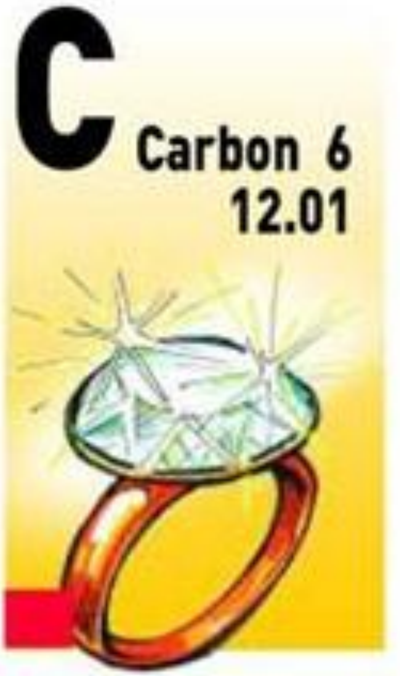
Atomic number (Z) = *number of protons*. This defines an **element**

The *number of neutrons* defines an **isotope** of an element

The **atomic mass** (A) is approximately the number of protons + the number of neutrons *but not exactly....*

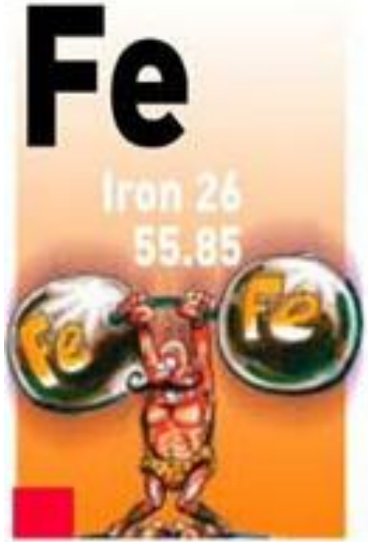
Carbon 12 has:

- 6 protons
- 6 electrons
- 6 neutrons



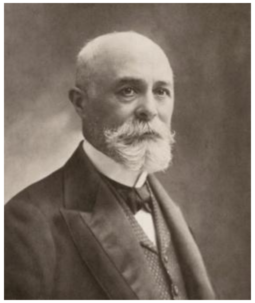
Iron 56 has:

- 26 protons
- 26 electrons
- 30 neutrons



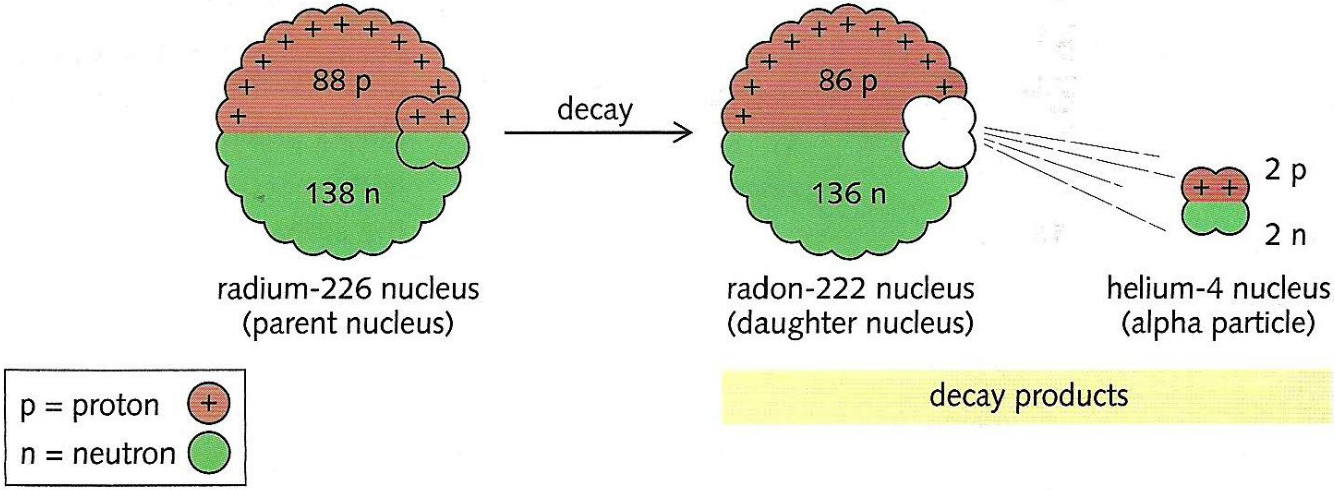
Binding energy

Radioactive decay



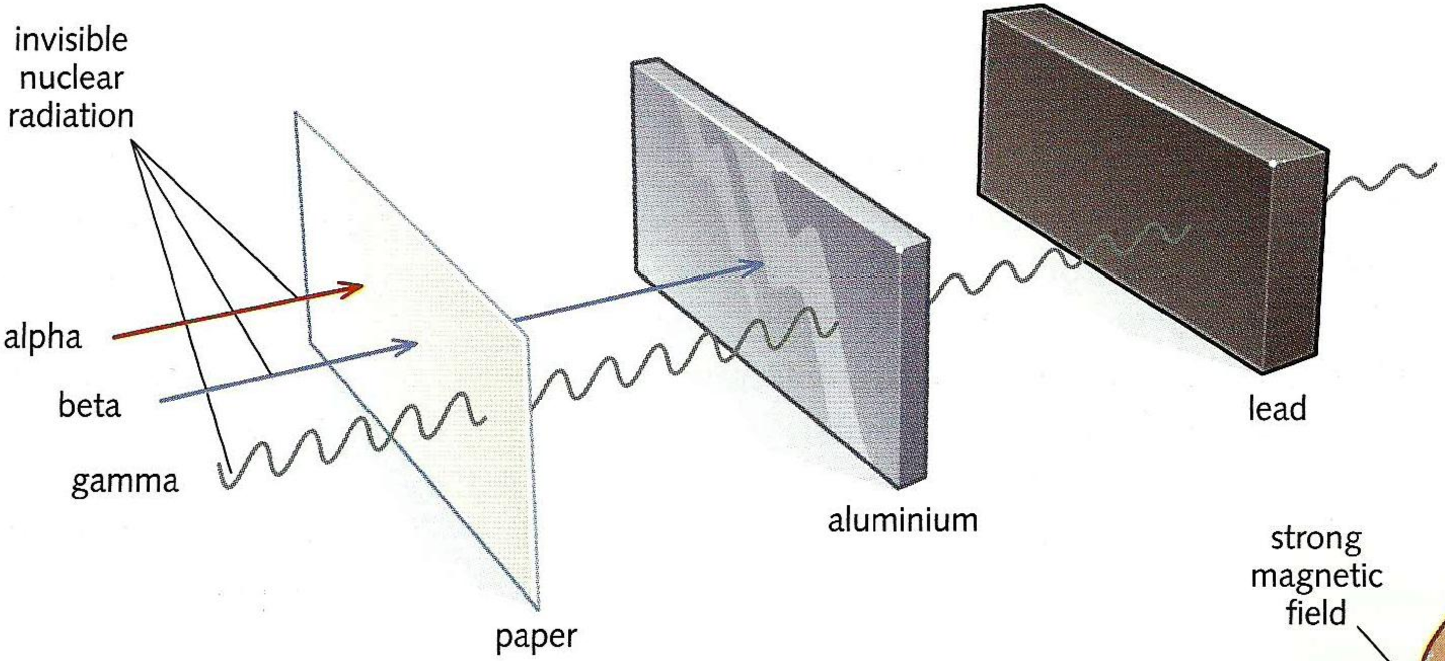
Antoine Henri Becquerel
1852-1908
Spontaneous radioactivity
in Uranium salts

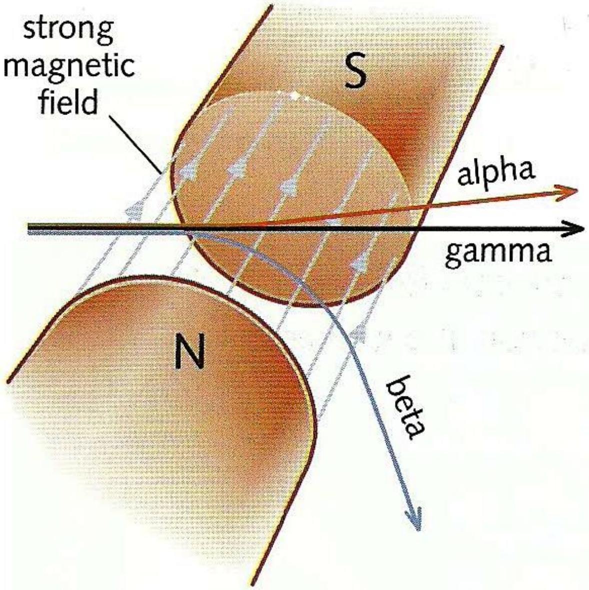
Marie Curie
1867-1934
Theory of radioactivity
Isolation of isotopes

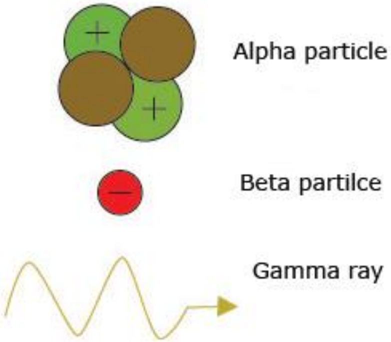


Alpha, beta, and gamma radiation

There are three main types of nuclear radiation: **alpha particles**, **beta particles**, and **gamma rays**. Gamma rays are the most penetrating and alpha particles the least, as shown below:





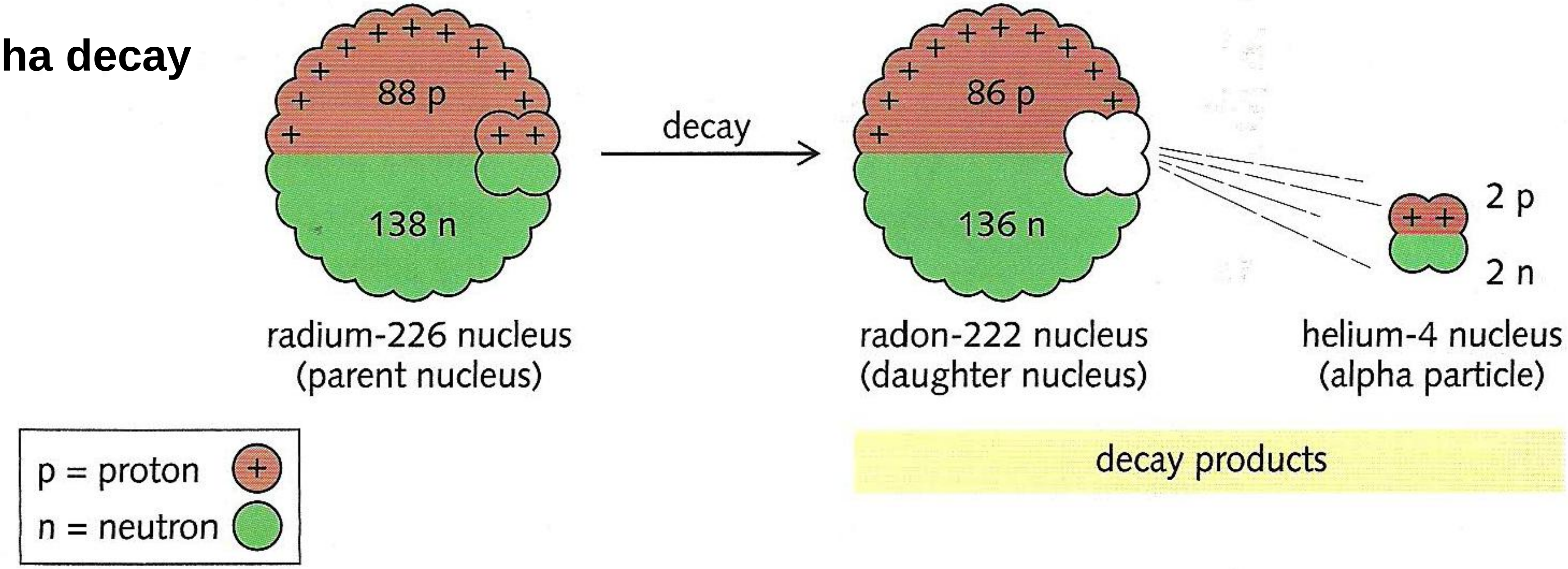


He^{2+}

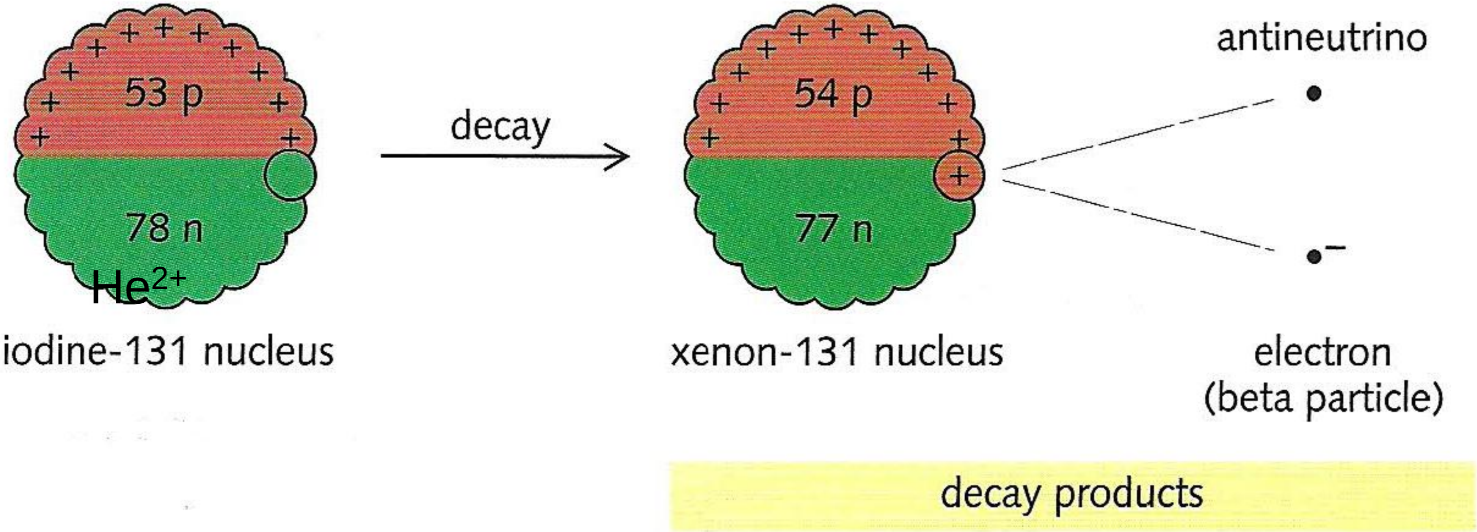
e^{-}

Very high frequency radiation

Alpha decay



Beta decay



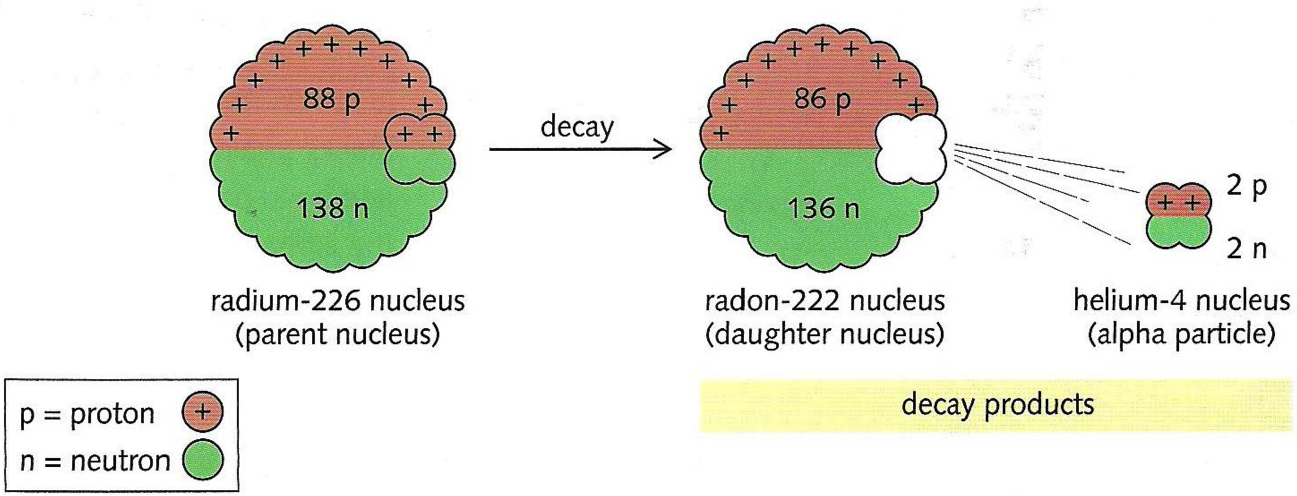
Alpha decay

$$ {}^{Z+N}_{\quad Z}X \rightarrow {}^{Z+N-4}_{\quad Z-2}Y + \alpha $$

e.g. $$ {}^{229}_{\ 90}\mathrm{Th} \rightarrow {}^{225}_{\ 88}\mathrm{Ra} + \alpha $$

Atomic number (Z) *reduces* by 2

Mass number *reduces* by 4



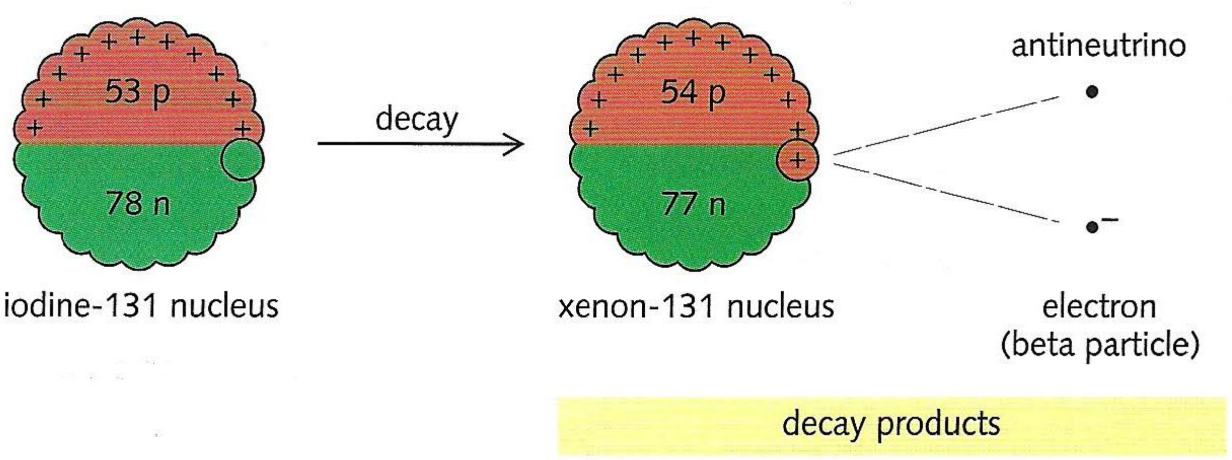
Beta decay

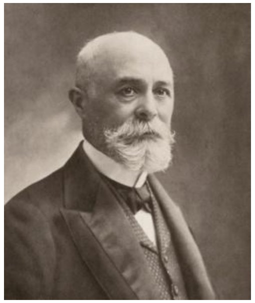
$${}^{Z+N}_{\ \ \ \ Z}\mathrm{X} \rightarrow {}^{Z+N}_{Z+1}\mathrm{Y} + \beta$$

e.g.

$${}^{14}_{\ 6}\mathrm{C} \rightarrow {}^{14}_{\ 7}\mathrm{N} + \beta$$

Atomic number (Z) *increases* by 1
Mass number *stays the same*





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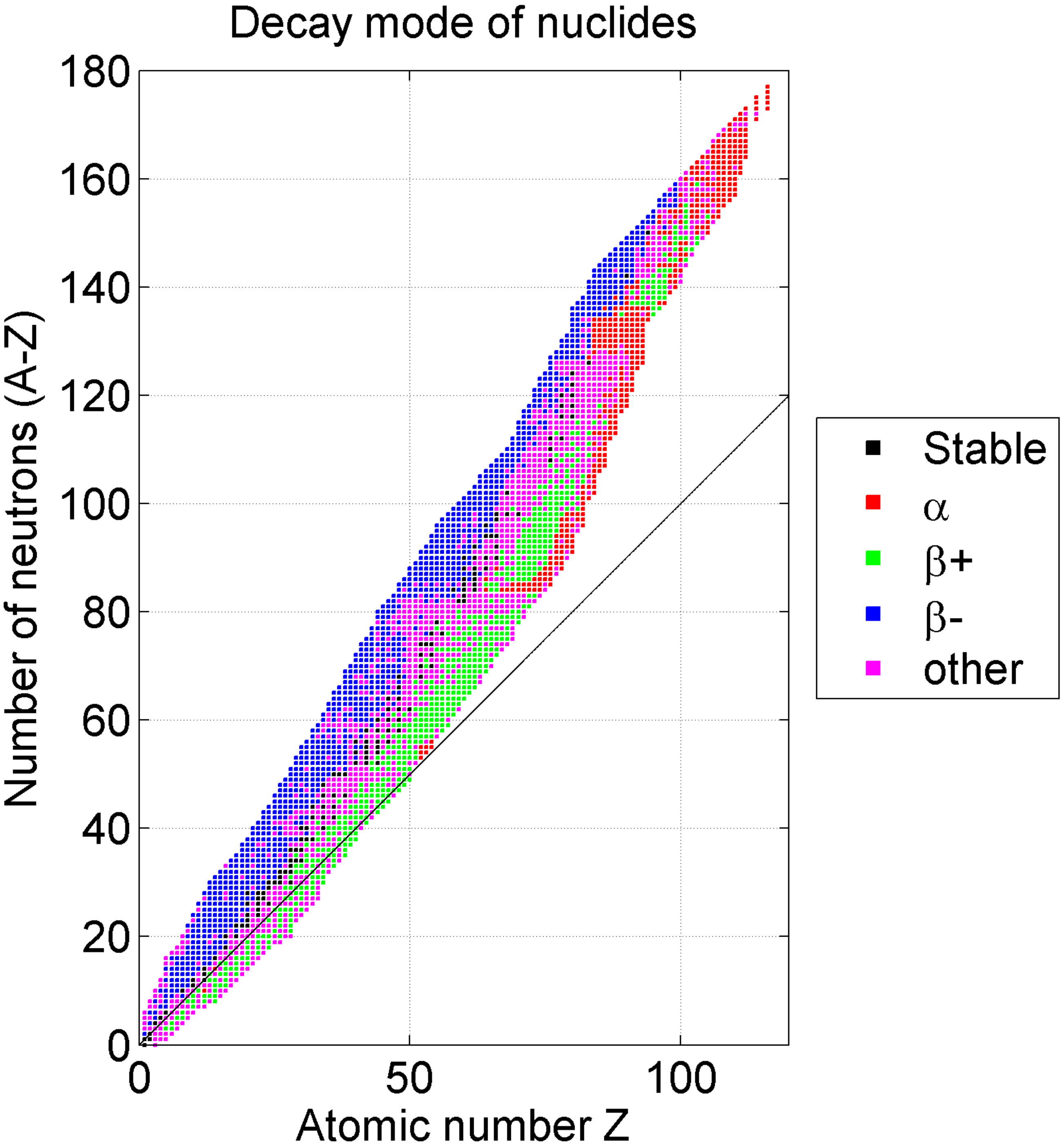
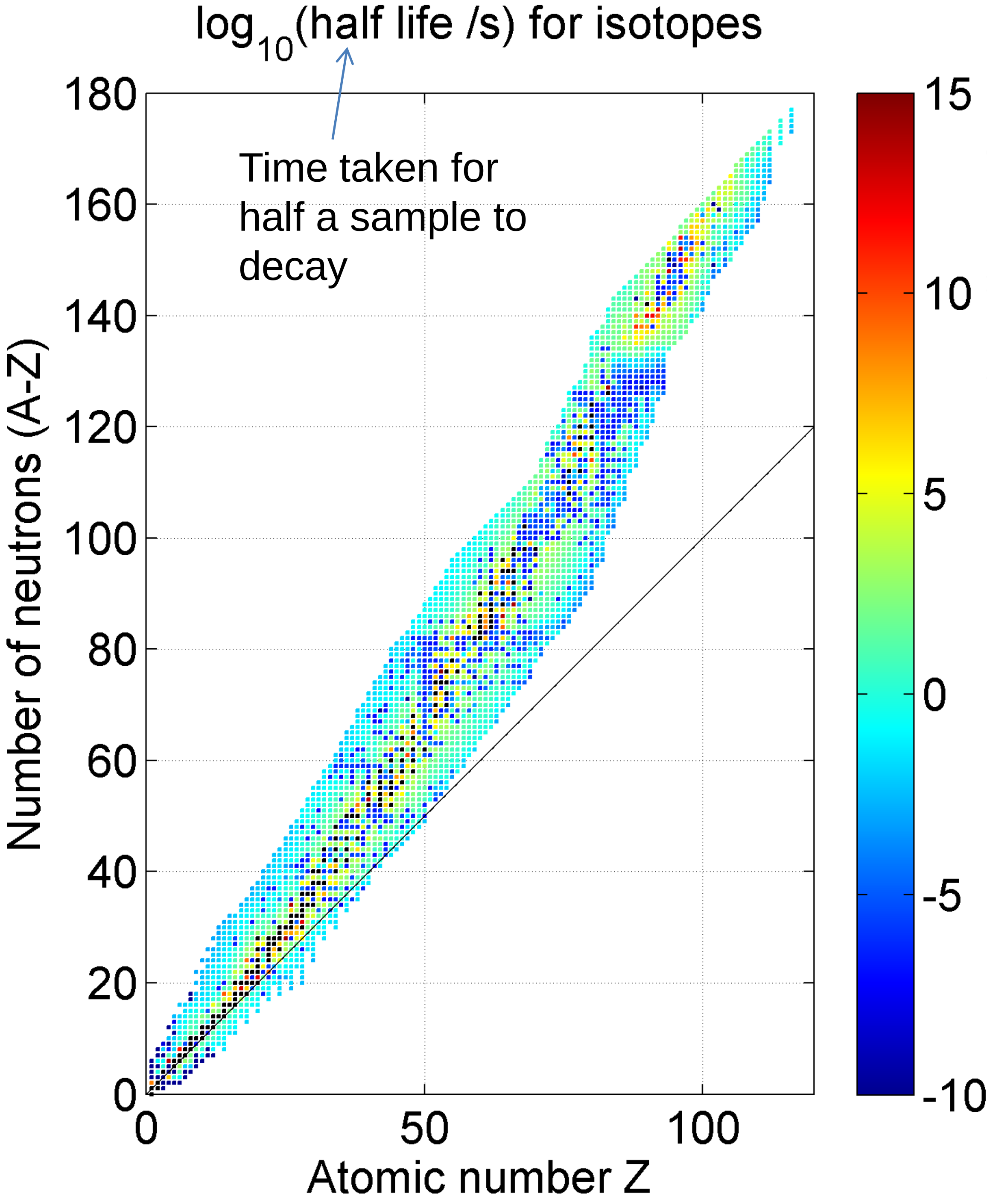
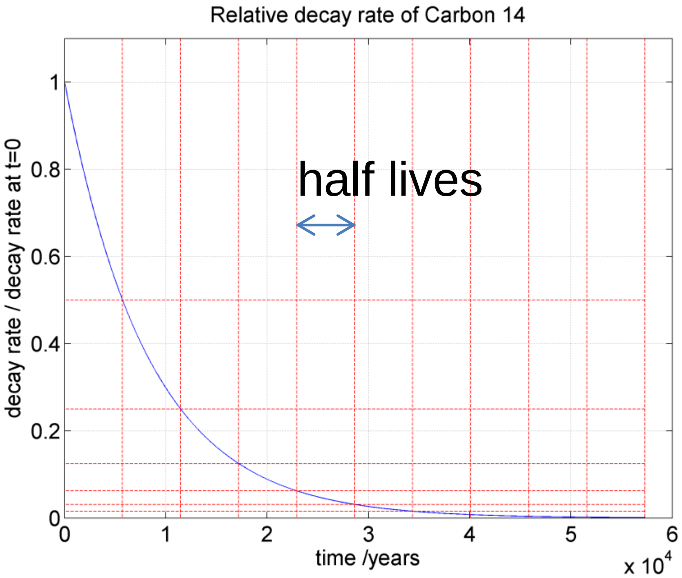




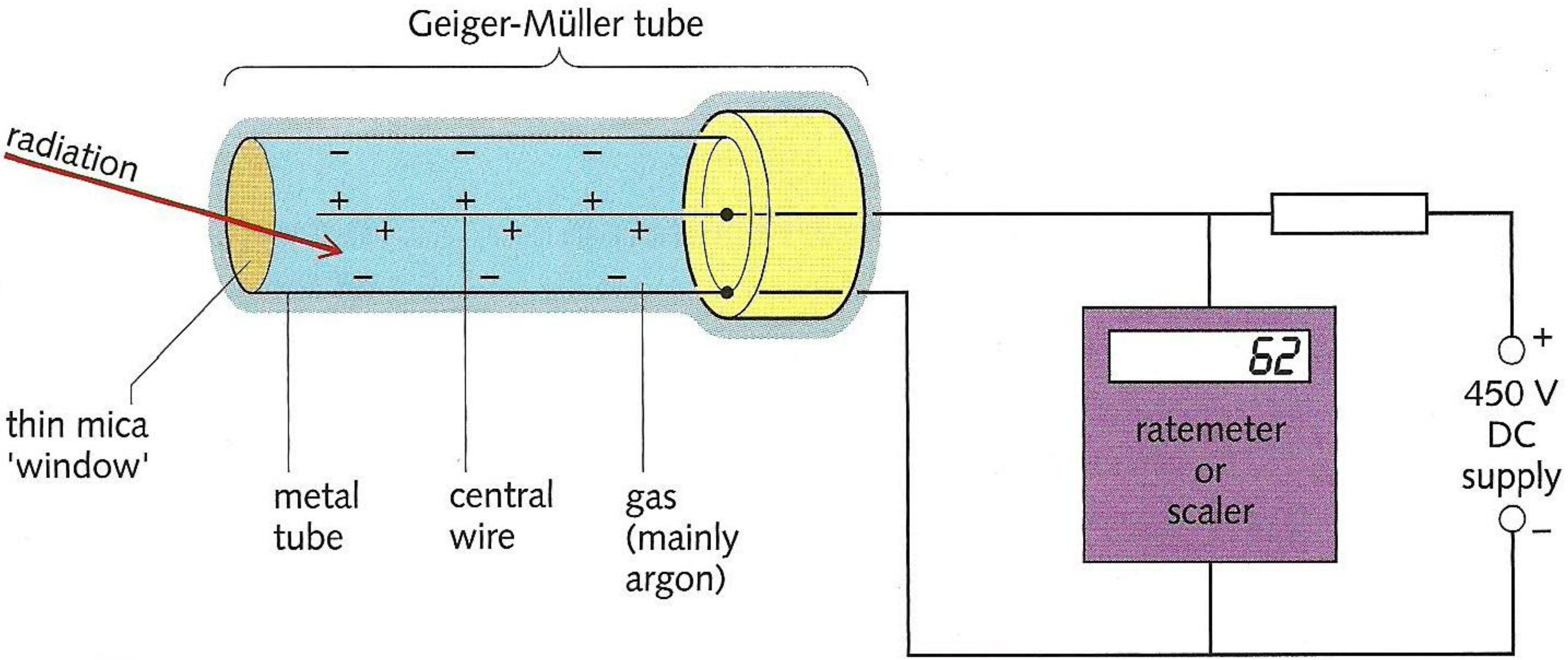
Time taken for half a sample to decay



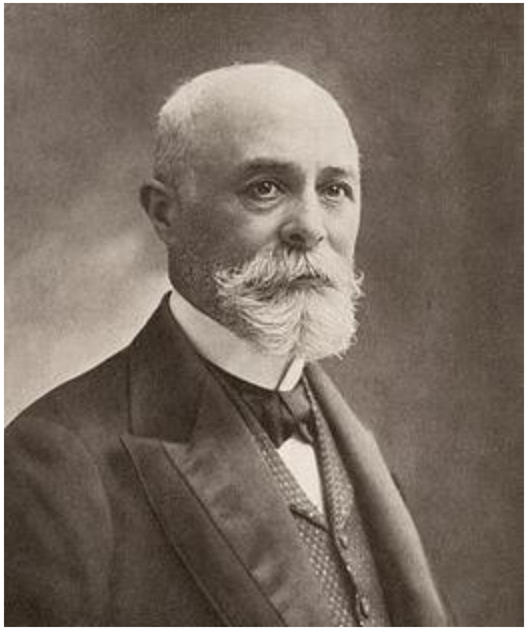
The decay of atomic nuclei is a *random process*

The *decay rate* is proportional to the number of radioactive elements in a sample

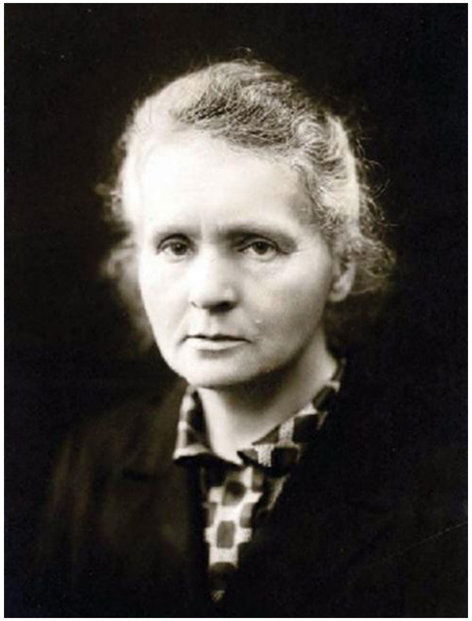
Detecting radiation



Quantifying radioactivity



Antoine Henri Becquerel
1852-1908



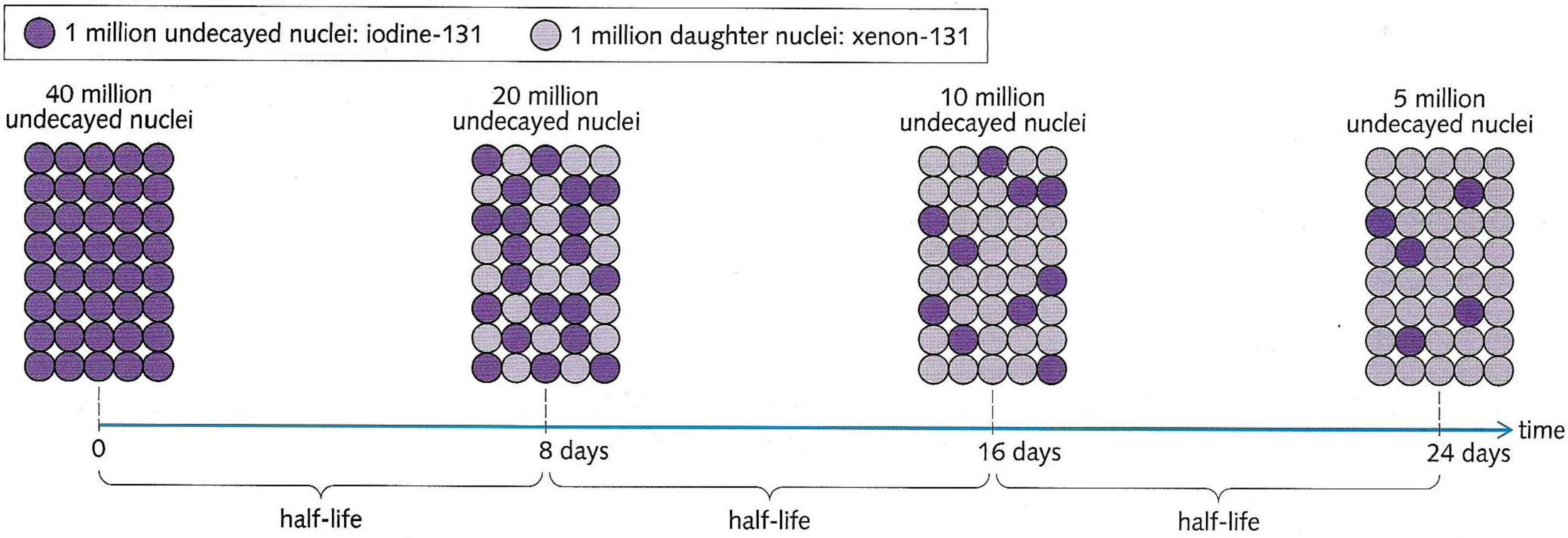
Marie Curie
1867-1934

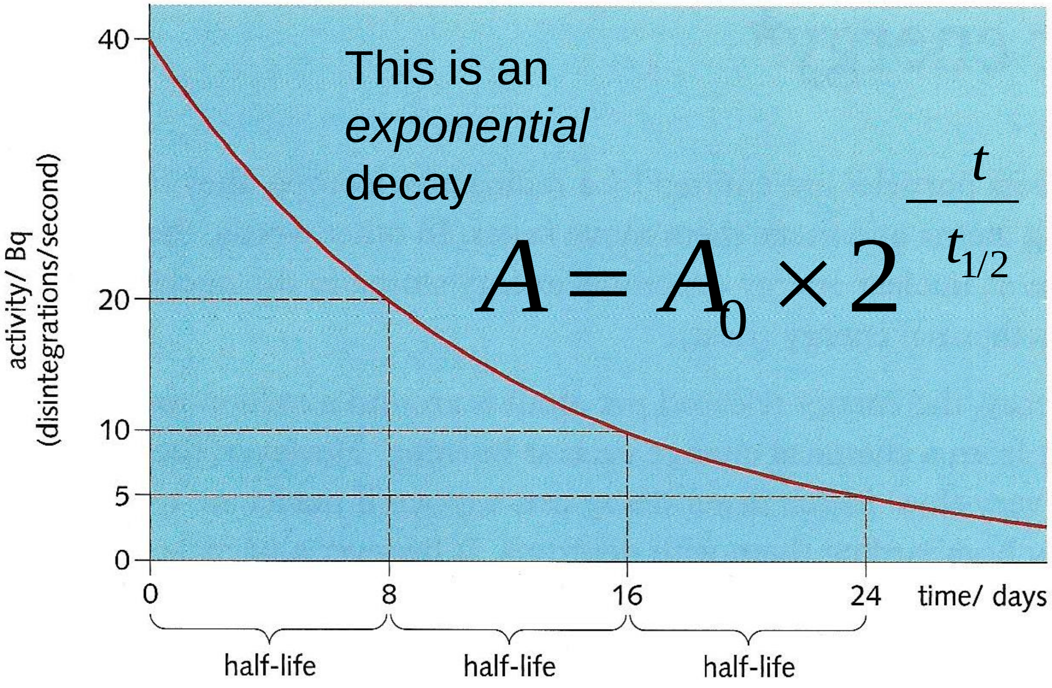
1 Becqueral (Bq) is 1 radioactive decay per second

1 Curie (Ci) = 37GBq

$$1\text{Ci} = 3.7 \times 10^{10}\,\text{Bq}$$

Isotope	Half life	Ci /gram
^{232}Th	1.405×10^{10} years	1.1×10^{-7}
^{238}U	4.471×10^{9} years	3.4×10^{-7}
^{40}K	1.25×10^{9} years	7.1×10^{-6}
^{235}U	7.038×10^{8} years	2.1×10^{-6}
^{129}I	15.7×10^{6} years	0.00018
^{99}Tc	211×10^{3} years	0.017
^{239}Pu	24.11×10^{3} years	0.063
^{240}Pu	6563 years	0.24
^{226}Ra	1601 years	0.99
^{241}Am	432.6 years	3.49
^{14}C	5730 years	4.5
^{238}Pu	88 years	18.5
^{137}Cs	30.17 years	83
^{90}Sr	28.8 years	139
^{241}Pu	14 years	121.2
^{60}Co	1925 days	1132
^{210}Po	138 days	4484
^{3}H	12.32 years	9708
^{131}I	8.02 days	125000
^{123}I	13 hours	2000000



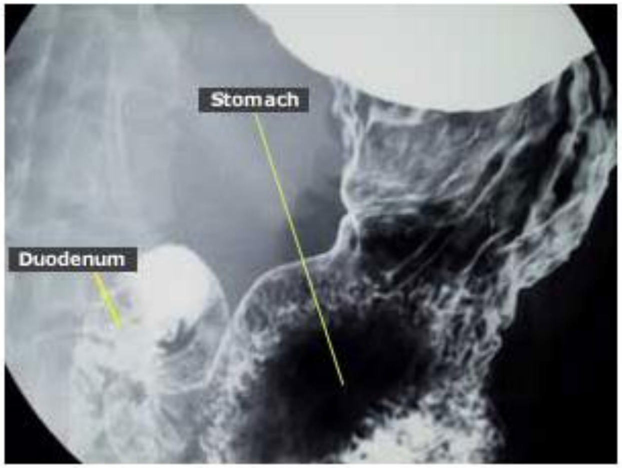
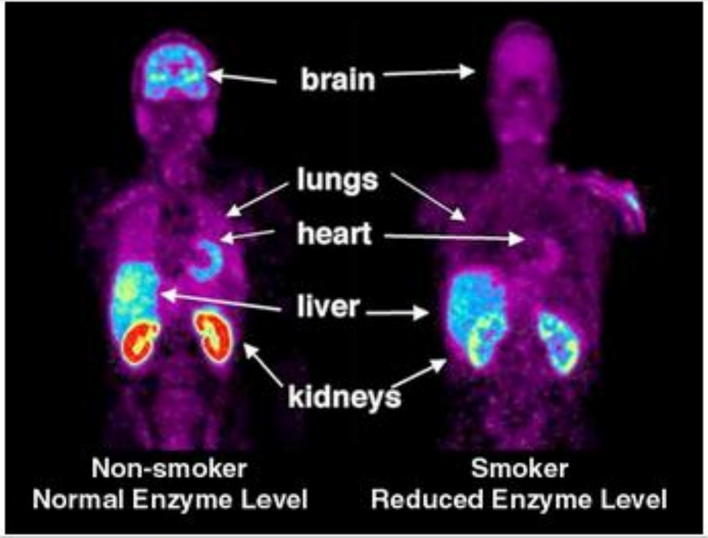
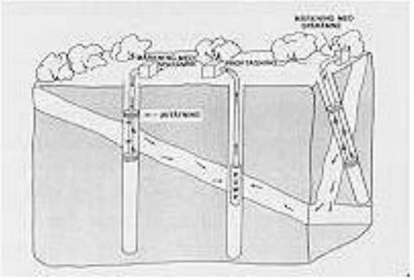


This is an *exponential* decay

$$A = A_0 \times 2^{-\frac{t}{t_{1/2}}}$$

radioactive isotope	half-life
boron-12	0.02 seconds
radon-220	52 seconds
iodine-128	25 minutes
radon-222	3.8 days
strontium-90	28 years
radium-226	1602 years
carbon-14	5730 years
plutonium-239	24 400 years
uranium-235	7.1×10^8 years
uranium-238	4.5×10^9 years

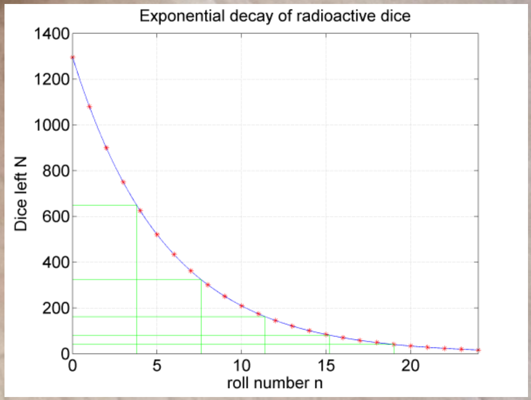
Uses of radioactivity

		
How old is this religious artifact? Carbon dating tells us about 500 years.	A Barium meal before an X ray gives a much better picture	Positron Emission Tomography is a fantastic new imaging technique
		
Geologists use radioactive tracers to look at underground water flow	Smoke alarms contain an alpha source.	Gamma radiation is used to kill cancerous cells

http://www.stokesleyscience.org/A level Physics/Radioactivity/uses_of_radioactivity.htm

Back to....

Radioactive Dice



RADIOACTIVE (6 sided) DICE

Total number of dice left

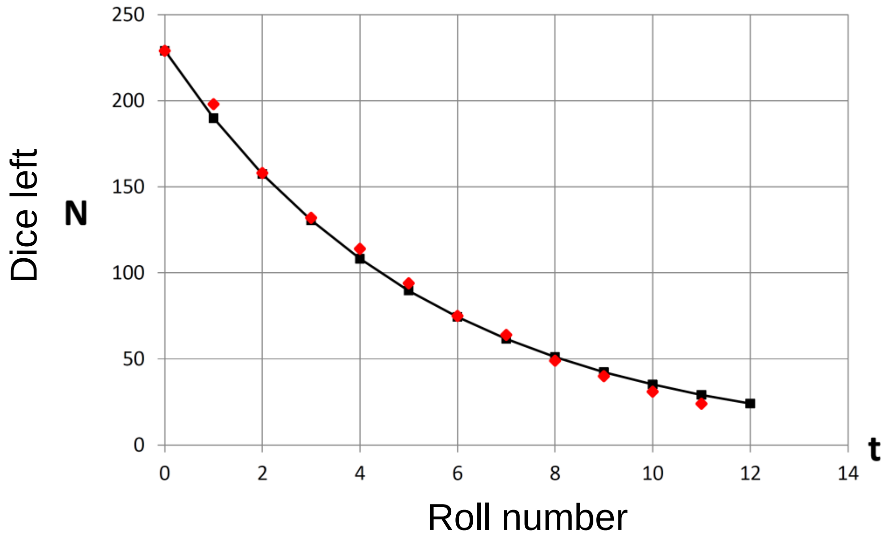
t	N	N	N	N	N	N	N	N	N	N	N	N total	N model
0	22	22	20	24	19	18	23	18	19	23	21	**229**	**229**
1	18	18	16	21	17	14	20	15	19	21	19	**198**	**190**
2	12	12	13	18	13	11	17	12	14	20	16	**158**	**157**
3	9	8	10	14	12	11	16	10	11	17	14	**132**	**131**
4	9	7	9	10	7	11	15	9	10	14	13	**114**	**108**
5	6	6	6	7	4	9	12	8	10	13	13	**94**	**90**
6	5	4	6	6	3	5	9	7	7	11	12	**75**	**74**
7	5	3	5	6	3	4	8	6	5	9	10	**64**	**62**
8	5	3	4	5	3	0	7	5	3	8	6	**49**	**51**
9	4	2	4	3	3	0	6	4	1	7	6	**40**	**42**
10	3	2	2	3	3	0	5	3	0	6	4	**31**	**35**
11	1	1	1	2	3	0	4	3	0	6	3	**24**	**29**
12	1	1	1	2	1	0	4	3	0	5	3	**21**	**24**

Roll number (this is our
model of **time** passing)

Dice left for each roll for each person

We expect an **exponential decay** of dice left with roll number.

Why? We expect a **constant probability (chance) of decay at any point in time for a given atom.** Therefore the rate of decay is **proportional to the number of atoms left.**



Let’s explore this for our dice. The chance of a six is 1/6 for each roll. Therefore we expect 5/6 of the dice to remain each roll. If we started with 216 dice:

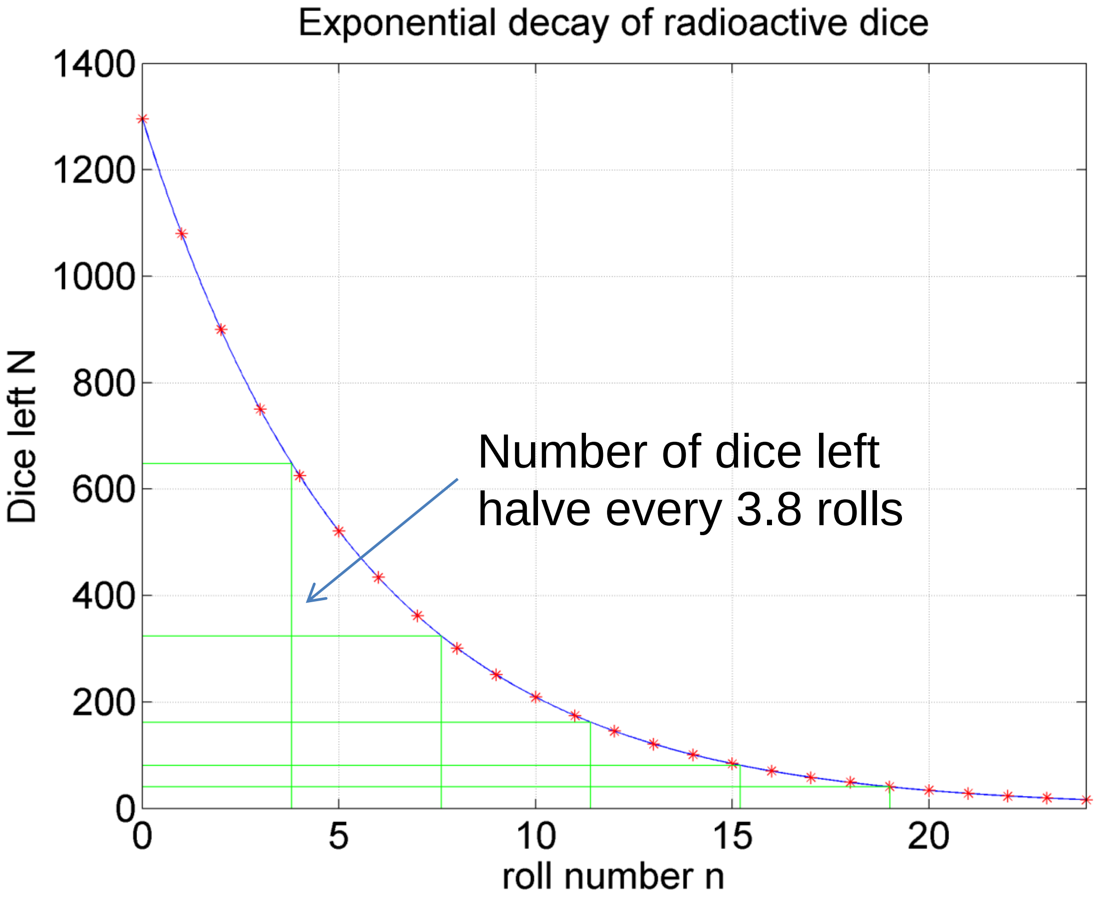
Expected number of dice left	**Roll number**
216	0
216 x 5/6 = 180	1
216 x 5/6 x 5/6 = 150	2
216 x 5/6 x 5/6 x 5/6 = 125	3
216 x 5/6 x 5/6 x 5/6 = 104.17	4
216 x 5/6 x 5/6 x 5/6 x	n

$$\boxed{N(n) = 216 \times \left(\frac{5}{6}\right)^{n}}$$

RADIOACTIVE DICE MODEL N = 1296 x (5/6)^n

Roll number = 0, Dice left N = 1296
Roll number = 1, Dice left N = 1080
Roll number = 2, Dice left N = 900
Roll number = 3, Dice left N = 750
Roll number = 4, Dice left N = 625
Roll number = 5, Dice left N = 521
Roll number = 6, Dice left N = 434
Roll number = 7, Dice left N = 362
Roll number = 8, Dice left N = 301
Roll number = 9, Dice left N = 251
Roll number = 10, Dice left N = 209
Roll number = 11, Dice left N = 174
Roll number = 12, Dice left N = 145
Roll number = 13, Dice left N = 121
Roll number = 14, Dice left N = 101
Roll number = 15, Dice left N = 84
Roll number = 16, Dice left N = 70
Roll number = 17, Dice left N = 58
Roll number = 18, Dice left N = 49
Roll number = 19, Dice left N = 41
Roll number = 20, Dice left N = 34
Roll number = 21, Dice left N = 28
Roll number = 22, Dice left N = 23
Roll number = 23, Dice left N = 20
Roll number = 24, Dice left N = 16

$$N(n) = 1296 \times \left(\frac{5}{6} \right)^n$$



Exponential decay of radioactive dice

Number of dice left halve every 3.8 rolls

Half Life

For radioactive decay this is **the amount of time it takes for the activity to halve.** Since the decay curve is *exponential*, this is a **fixed time** regardless of the starting activity*.

To explain this we can express the number of dice left as a **power of two** instead of 5/6.

$$N(n) = 1296 \times \left(\frac{5}{6}\right)^n = \frac{1296}{2^{\frac{n}{n_{1/2}}}}$$

i.e. when roll number is a multiple of 3.8, we divide the number of dice left by a whole number power of 2

$$\therefore \frac{5}{6} = \frac{1}{2^{\frac{1}{n_{1/2}}}}$$

$$\therefore n_{1/2} \approx 3.8$$

$$\boxed{N(n) = 1296 \times \left(\frac{5}{6}\right)^n \approx \frac{1296}{2^{\frac{n}{3.8}}}}$$

$$2^{\frac{1}{n_{1/2}}} = \frac{6}{5}$$

$$\frac{1}{n_{1/2}} \log 2 = \log \tfrac{6}{5}$$

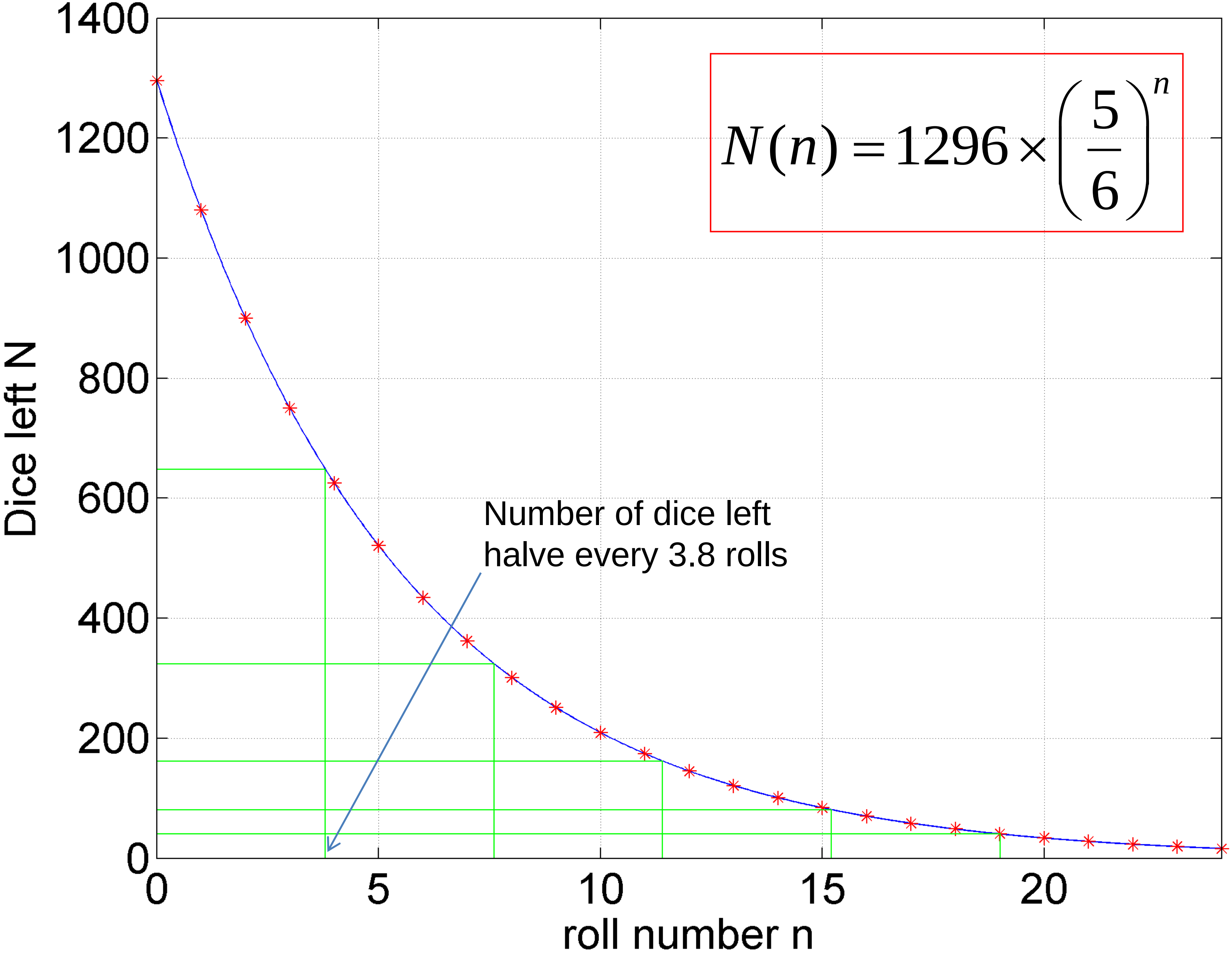
$$\frac{\log 2}{\log \tfrac{6}{5}} = n_{1/2}$$

$$3.80 = n_{1/2}$$

---

*As long as the activity is a large number! The exponential curve is not such a good model when we get down to a handful of atoms, since we can only have a whole number of decays per second.

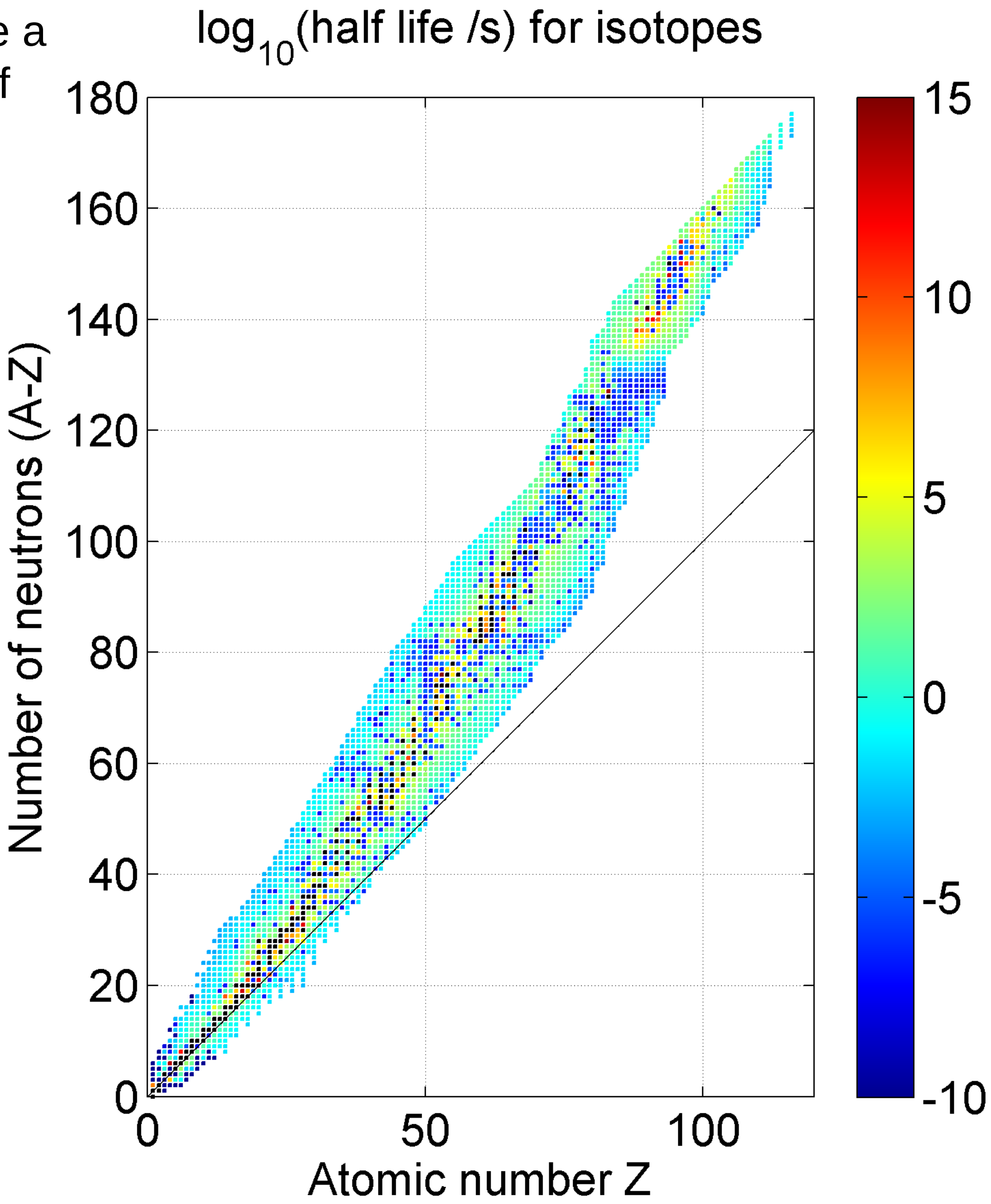
Exponential decay of radioactive dice



$$N(n) = 1296 \times \left(\frac{5}{6}\right)^n$$

Number of dice left halve every 3.8 rolls

Radioactive isotopes have a *huge range* of half lives



log$_{10}$(half life /s) for isotopes

Isotope	**Half life**
^{232}Th	1.405 × 10^{10} years
^{238}U	4.471 × 10^{9} years
^{40}K	1.25 × 10^{9} years
^{235}U	7.038 × 10^{8} years
^{129}I	15.7 × 10^{6} years
^{99}Tc	211 × 10^{3} years
^{239}Pu	24.11 × 10^{3} years
^{240}Pu	6563 years
^{226}Ra	1601 years
^{241}Am	432.6 years
^{14}C	5730 years
^{238}Pu	88 years
^{137}Cs	30.17 years
^{90}Sr	28.8 years
^{241}Pu	14 years
^{60}Co	1925 days
^{210}Po	138 days
^{3}H	12.32 years
^{131}I	8.02 days
^{123}I	13 hours