

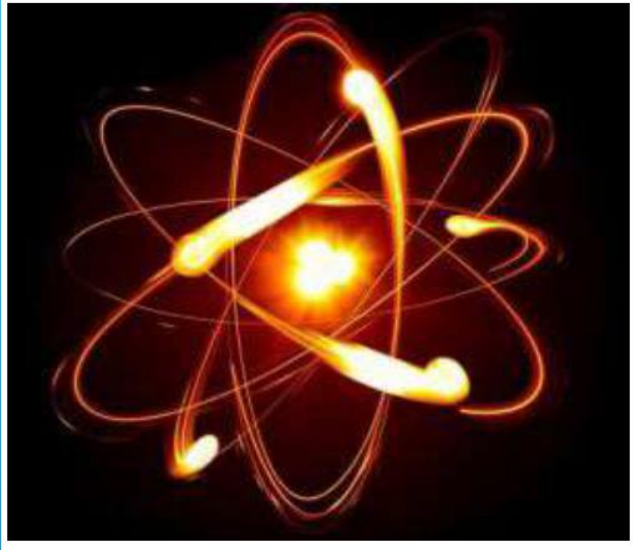
“Nuclear Physics: application to medicine”

INFN-LNL
July 17, 2025

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INFN –Sezione di Catania



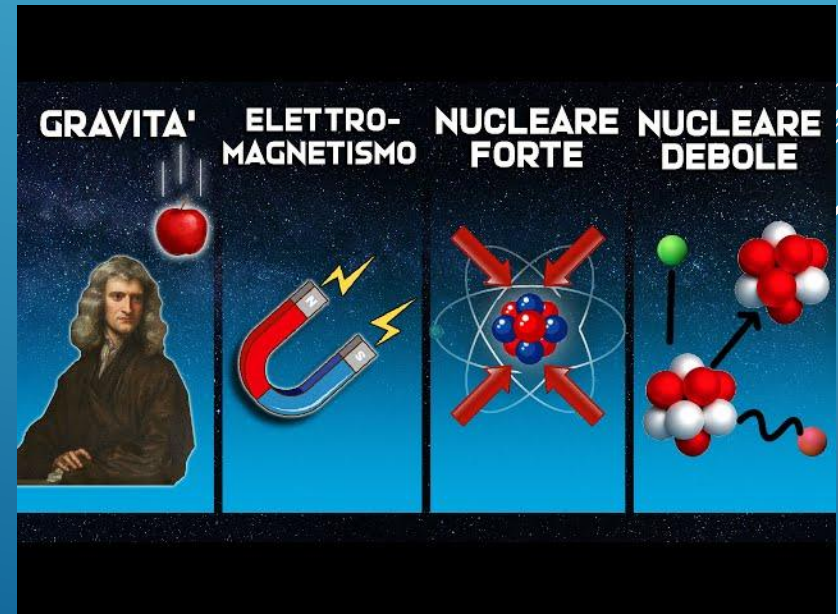
Nuclear Physics



Nuclear Physics studies the **ATOMIC NUCLEI**, their constituents (**neutrons and protons**) and their interactions (**nuclear forces**)

Nuclear Physics has been developed at the end of the 19th century starting with the discovery of radioactivity (Pier Curie and Marie Sklodowska), and then reinforced in 1936 with the discovery of the nuclear fission by Enrico Fermi

The study of nuclear physics has led to the understanding of the **weak** and **strong nuclear** forces, that with **gravitation** and **electromagnetic** forces are the four known fundamental interactions of nature



ATOM

Atom dimension : $\sim 10^{-10}$ m (Å)

Nucleus dimension : $\sim 10^{-15}$ m (fm)

Neutron Mass \approx Proton Mass

Proton Mass \approx 2000 Electron mass

Nucleus = neutrons and protons bound by
Nuclear Force - Strong Interaction

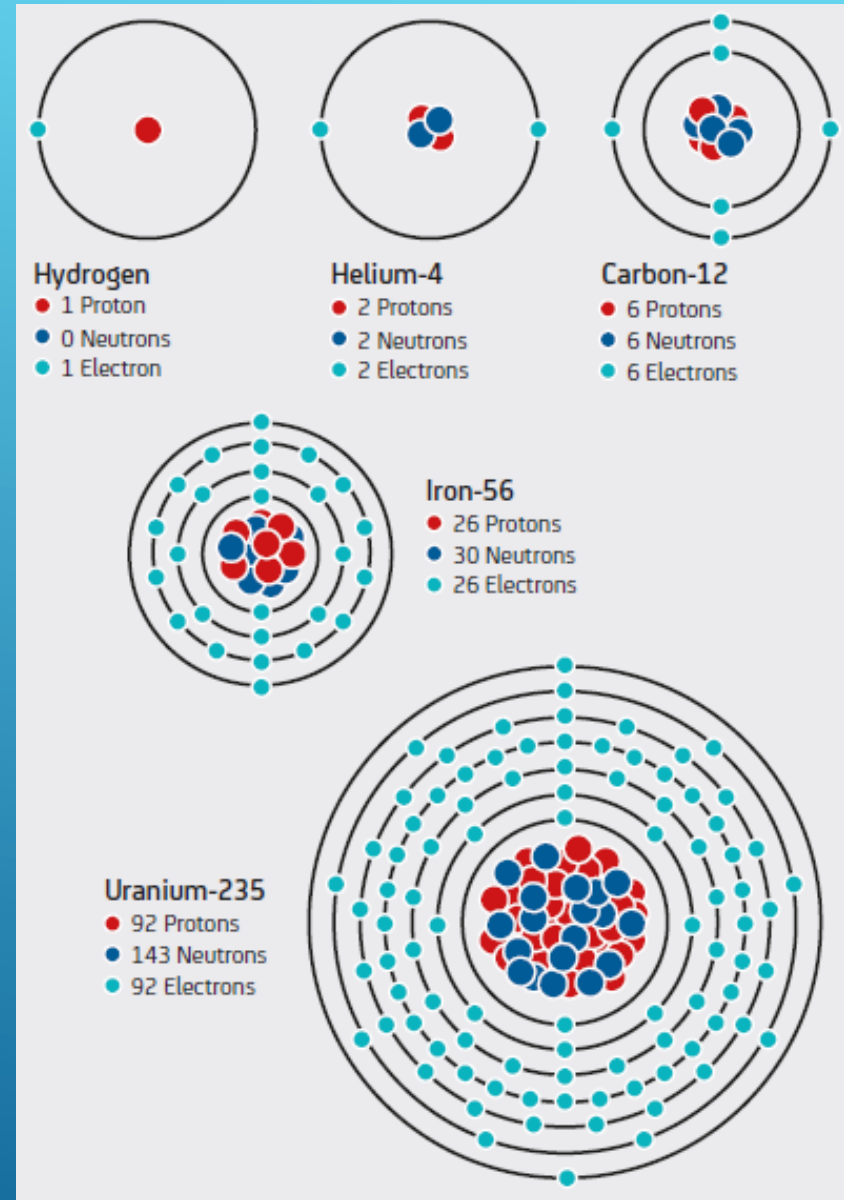
The number of protons Z , identifies the
chemical element, and the number of
neutrons N , identifies different isotopes of
that element

$Z=8$ Oxygen

$N=8$ ^{16}O

$N=9$ ^{17}O

$N=7$ ^{15}O



All the elements existing in nature are
organized in two important tables, both are alive

ATOMS and NUCLEI

The number of protons Z in the nucleus (named **ATOMIC NUMBER**) characterizes each **CHEMICAL ELEMENT**

<h1>Periodic Table of the Elements</h1>																																	
1 H Hydrogen 1.008																		2 He Helium 4.003															
3 Li Lithium 6.941	4 Be Beryllium 9.012																	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180										
11 Na Sodium 22.990	12 Mg Magnesium 24.305																	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948										
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798																
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294																
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018																
87 Fr Francium 223.028	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [298]	117 Ts Tennessine unknown	118 Og Oganesson unknown																
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967																			
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]																			
Alkali Metal		Alkaline Earth		Transition Metal		Basic Metal		Semimetal		Nonmetal		Halogen		Noble Gas		Lanthanide		Actinide															

Dmitrij Ivanovic Mendeleev, 1869

ATOM and NUCLEUS

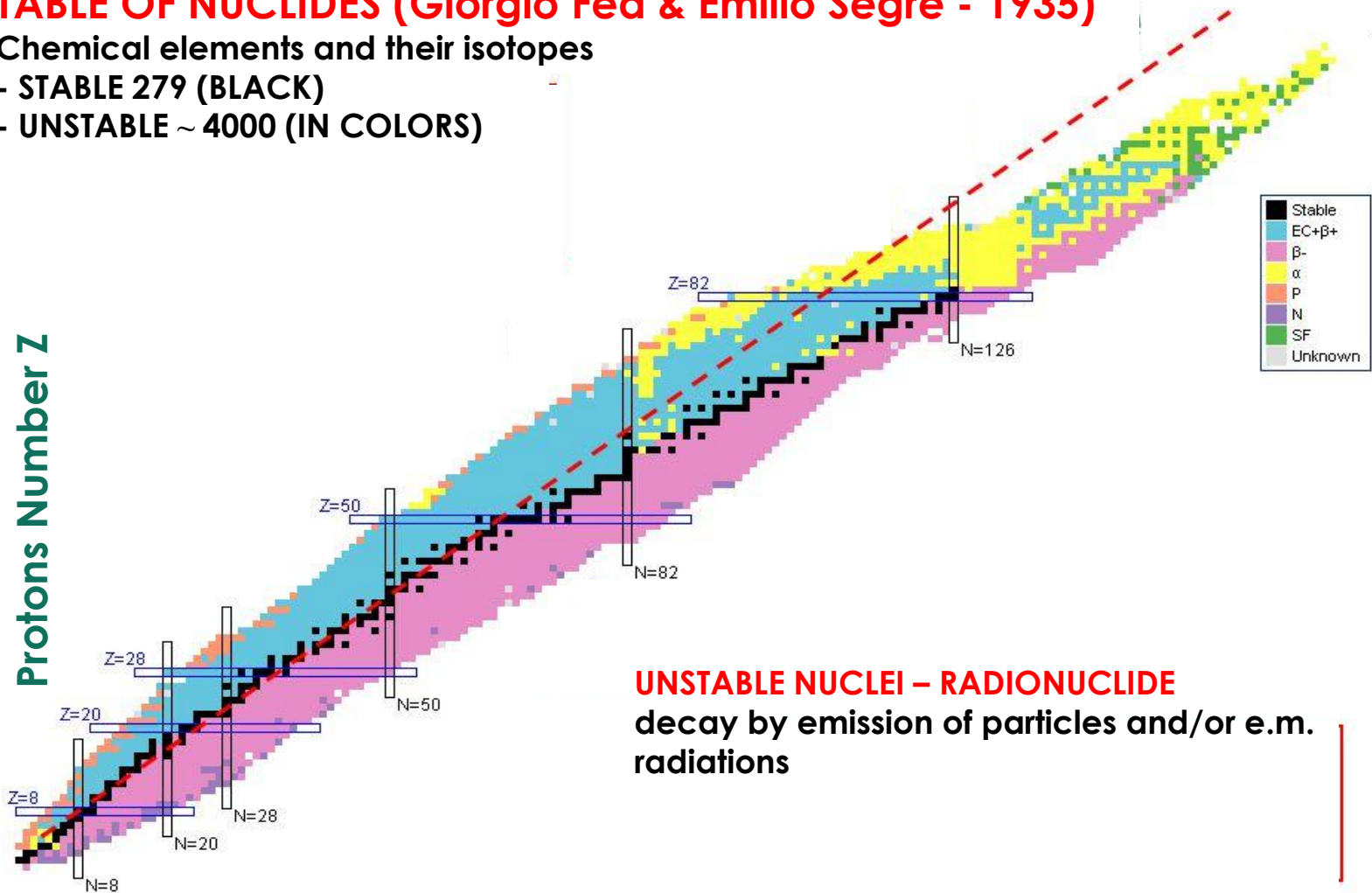
The number of protons, Z , and of neutrons, N , in the nucleus characterizes the different ISOTOPES

TABLE OF NUCLIDES (Giorgio Fea & Emilio Segrè - 1935)

Chemical elements and their isotopes

- STABLE 279 (BLACK)
- UNSTABLE ~ 4000 (IN COLORS)

Protons Number Z



UNSTABLE NUCLEI – RADIONUCLIDE

decay by emission of particles and/or e.m. radiations

Neutrons Number N

In more than 100 years of study many **Nuclear Physics Applications** have been developed in different fields :
CLIMATE AND ENVIROMENT – ENERGY - HEALT – FOOD –
MATERIAL -FORENSICS AND HERITAGE -SPACE



Application of Nuclear Physics To Medicine

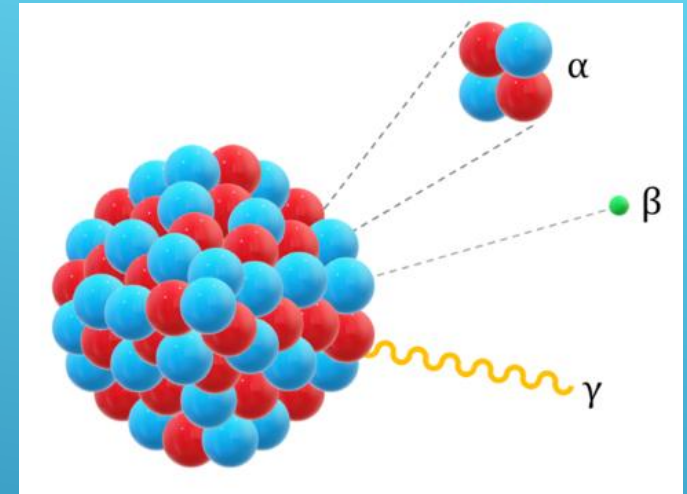


For the application of Nuclear Physics to Medicine,
we have to know two important processes.

1 RADIOACTIVITY

it is the process in which spontaneously a nucleus (**radionuclide**) emits particles (p , n , α , β) or e.m. radiations (X or γ -rays).

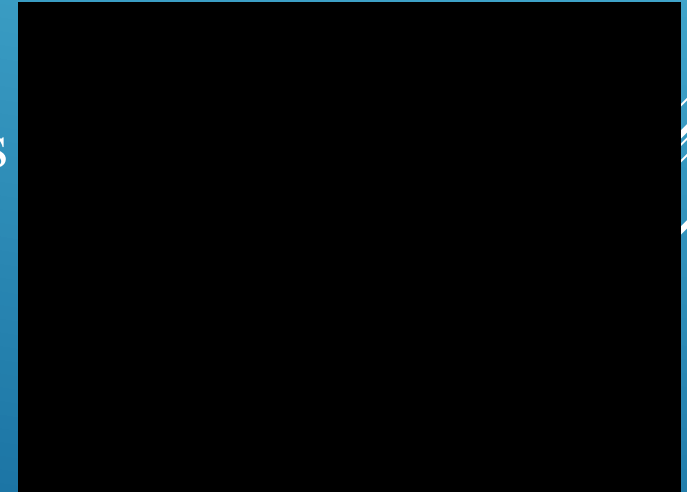
**Radionuclide are
Used for Therapy and Diagnostic**



2. NUCLEAR REACTION

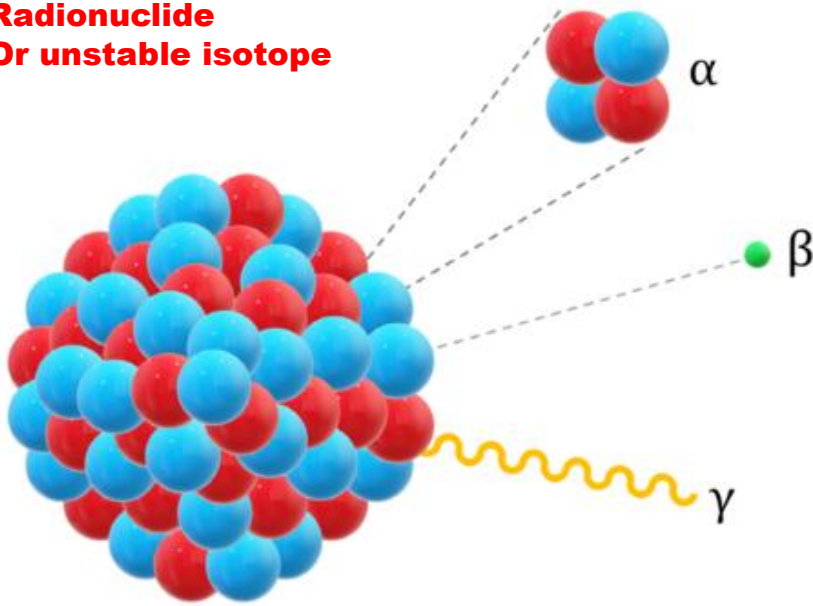
It is the process in which a beam of particles delivered by an accelerator hits a target (others nuclei or cells) with different effects

**Beams of particles are used to
produce radionuclides and
also directly for Therapy**



RADIOACTIVITY

**Radionuclide
Or unstable isotope**



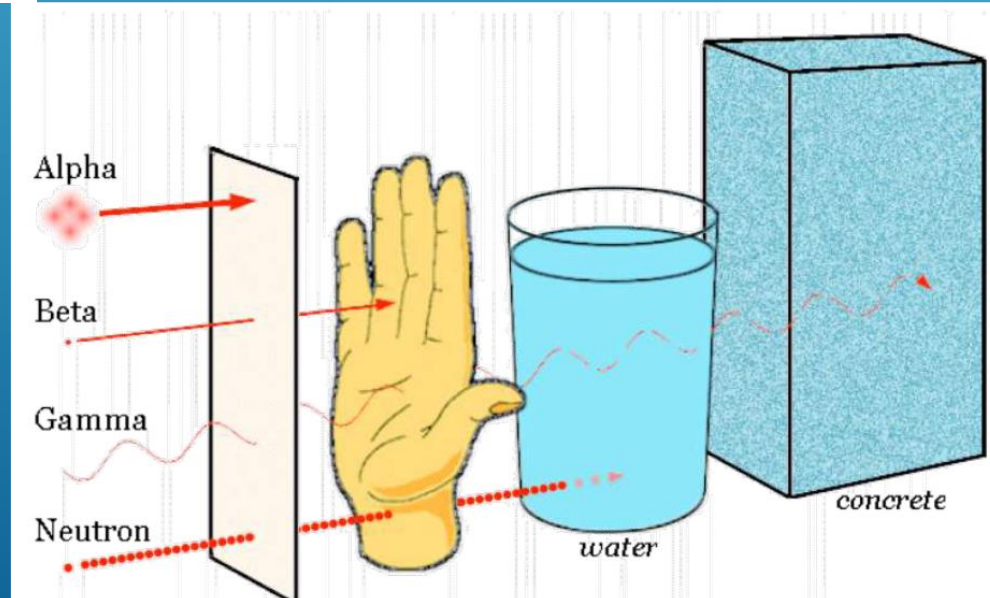
The nucleus spontaneously decay with emission of a particle or e.m radiation

α particle $\rightarrow 2n+2p$ He Nucleus

β particle \rightarrow electron or positron

X or γ radiation

The emitted particles and e.m. radiations have a different penetrating power, depending by the nature of the radiation and its energy



RADIOACTIVITY - Important quantity

ACTIVITY = it is the number of decay in the time unit (1 Curie= $3,7 \cdot 10^9$ decay/sec)

$T_{1/2}$, half time = it is the required time to reduce the number of nuclei in the system by a factor 2

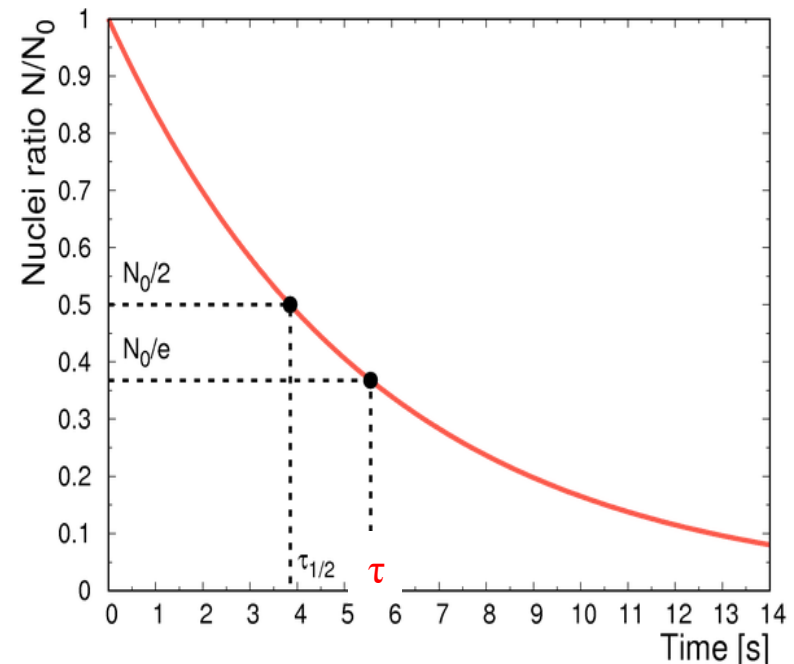
τ , mean life = it is the required time to reduce the number of nuclei in the system by a factor e (Nepero number, 2.72)

Radioactivity decay law

$$N(t) = N_0 e^{-t/\tau}$$

N_0 = initial number of nuclei $t=0$

$N(t)$ = number of nuclei $t=t$





Examples of Radioactive Materials

<u>Radionuclide</u>	<u>Physical Half-Life</u>	<u>Activity</u>	<u>Use</u>
Cesium-137	30 yrs	1.5×10^6 Ci	Food Irradiator
Cobalt-60	5 yrs	15,000 Ci	Cancer Therapy
Plutonium-239	24,000 yrs	600 Ci	Nuclear Weapon
Iridium-192 Radiography	74 days	100 Ci	Industrial
Hydrogen-3	12 yrs	12 Ci	Exit Signs
Strontium-90	29 yrs	0.1 Ci	Eye Therapy Device
Iodine-131 Therapy	8 days	0.015 Ci	Nuclear Medicine
Technetium-99m	6 hrs	0.025 Ci	Diagnostic Imaging
Americium-241	432 yrs	0.000005 Ci	Smoke Detectors
Radon-222	4 days	1 pCi/l	Environmental Level

^{60}Co γ -rays $E = 1.2 \text{ MeV}$
(radiotherapy)

^{131}I γ rays $E = 365 \text{ keV}$
(thyroid radiotherapy)

$^{99\text{m}}\text{Tc}$ γ -rays $E = 140 \text{ keV}$
(diagnostic)

**Most of the Radionuclides are produced
by nuclear reactions**

NUCLEAR REACTIONS

Accelerators, for ex.
Cyclotron, produce a
beam of particles



The beam hits a target that can
be a nucleus or a human cell

New nuclei can be
produced (reaction
products) as for ex.

Radionuclides

^{18}F ,
 ^{15}O , ^{13}N ,
 ^{11}C , ^{60}Co

Beams of particles can
also be used to destroy
directly bad molecules
(cancer)

HADRON THERAPY

Nuclear Physics application for diagnostic and therapy

- Radionuclides that emit particles and e.m. radiation can be used both in **DIAGNOSTIC** and **THERAPY**



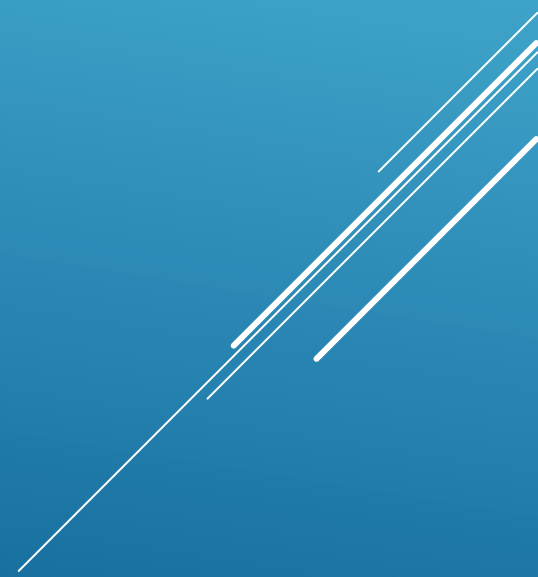
Radio
pharmaceutical

- Particle beams (p or ions) can be used in **THERAPY**



Treatment
room

DIAGNOSTIC



TRADITIONAL DIAGNOSTIC:

TAC – RADIOGRAPHY – RMN are diagnostic systems based on traditional methods, that allow reconstructing the morphology of the organs

DIAGNOSTIC FOR IMAGING (using radionuclides):

PET - SPECT are diagnostic systems based on imaging, that allow to see the functionality of the organs (ex. metabolism) and help in the understanding of the evolution of the disease

- **PET**
- **SPECT**

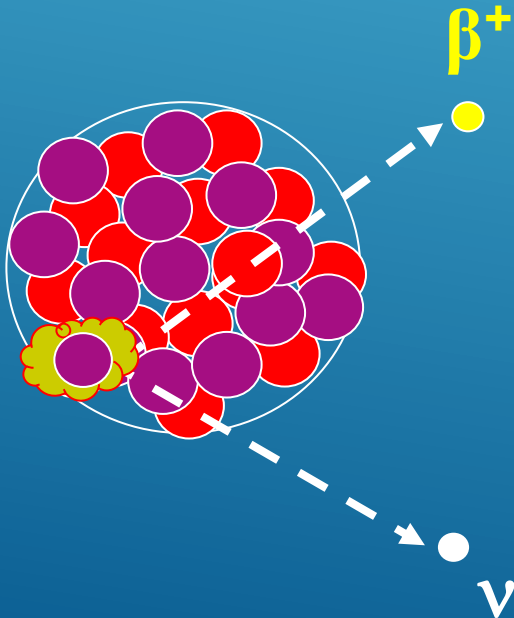


PET = Positron emission tomography

Used Radionuclides are β^+ (positron) emitter

^{11}C ($\tau \sim 20$ m), ^{13}N (~ 10 min), ^{15}O (~ 2 min), ^{18}F (~ 110 min)

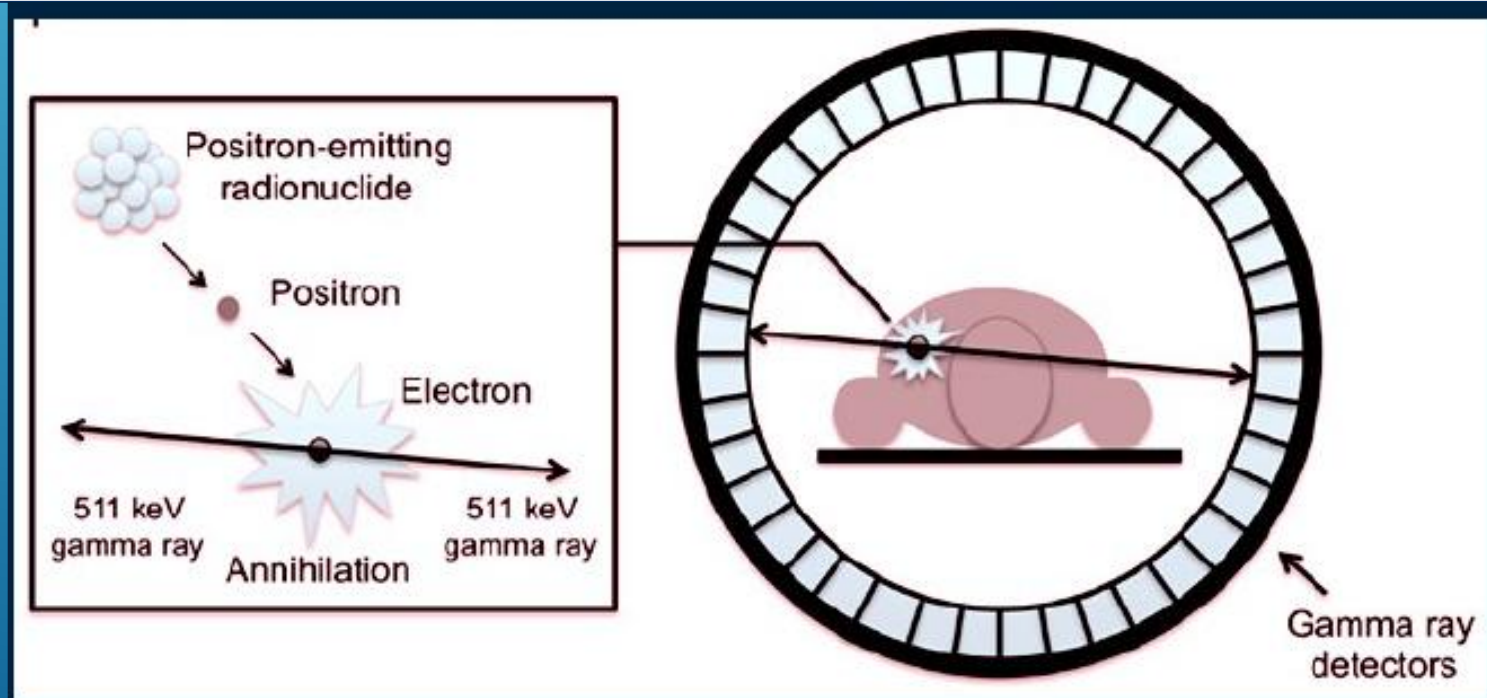
Due to the short half-lives of most positron-emitting radioisotopes, have been produced using a cyclotron in close proximity to the PET imaging facility.



PET = Positron emission tomography

The radionuclide, combined with glucose, is **injected** into the body. Cancer and metastasis are hungry of glucose so inside them we get the higher concentration of radionuclide.

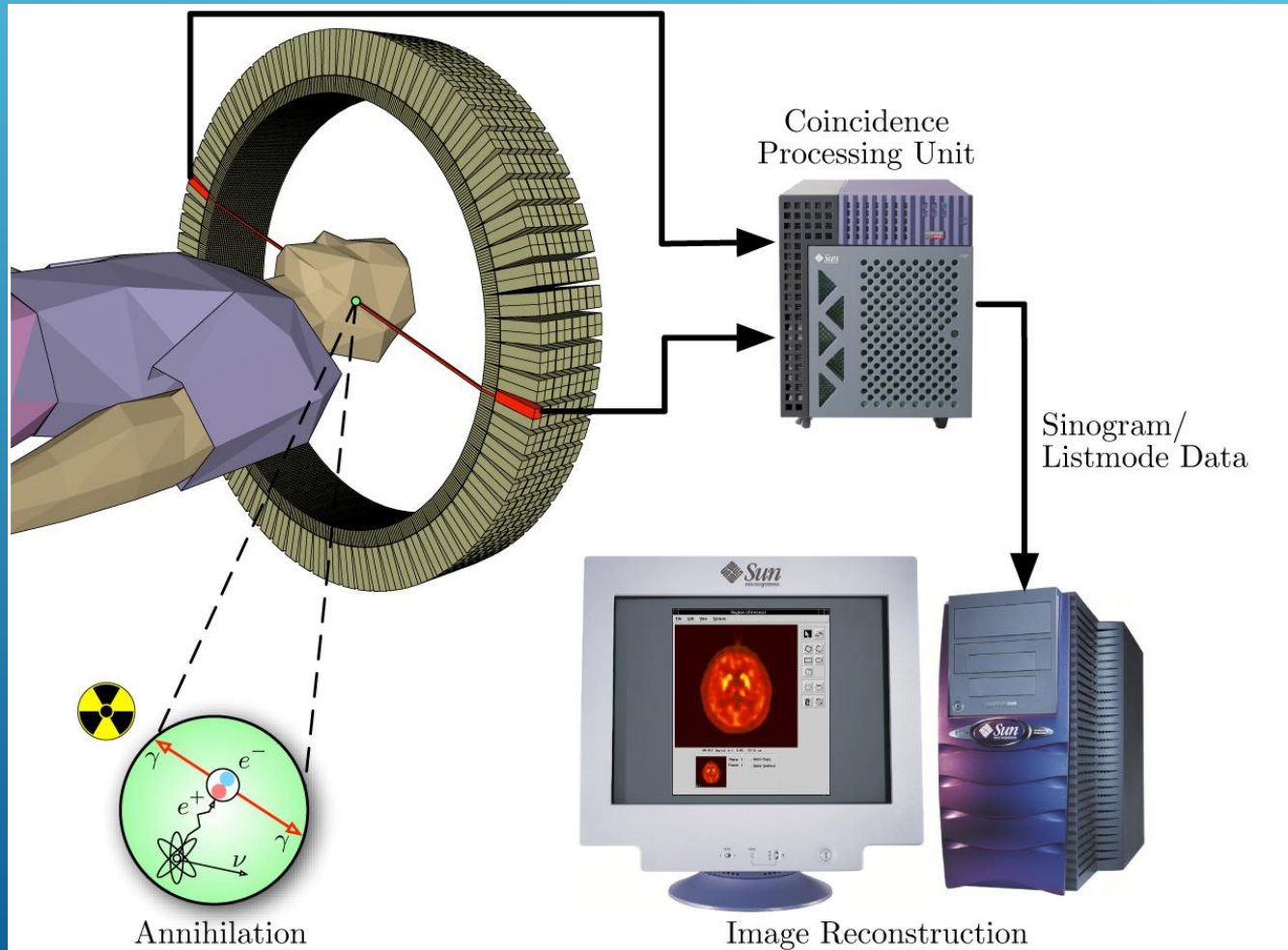
Then the radionuclide emits positron that interacts with an electron of the body (annihilation process) with emission of **two gamma rays of $E=511\text{KeV}$** in opposite directions.



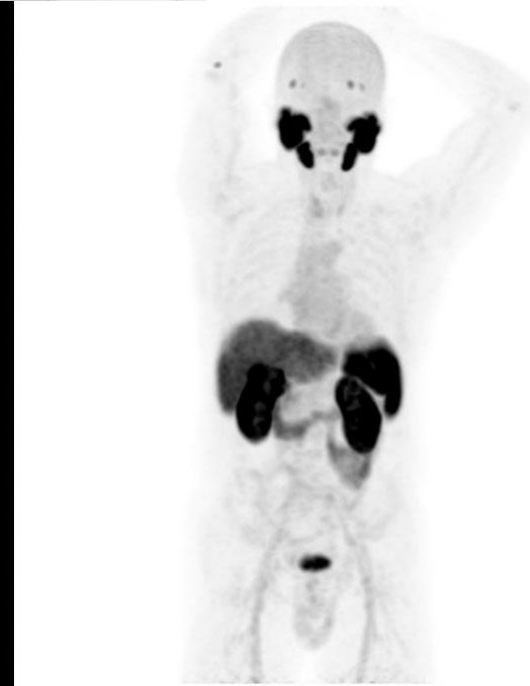
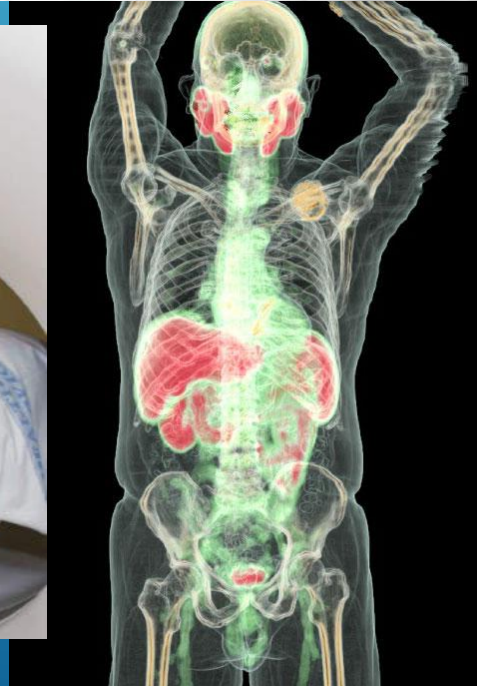
A system of detectors around the body allows to detect the emitted gamma rays

PET positron emission tomography

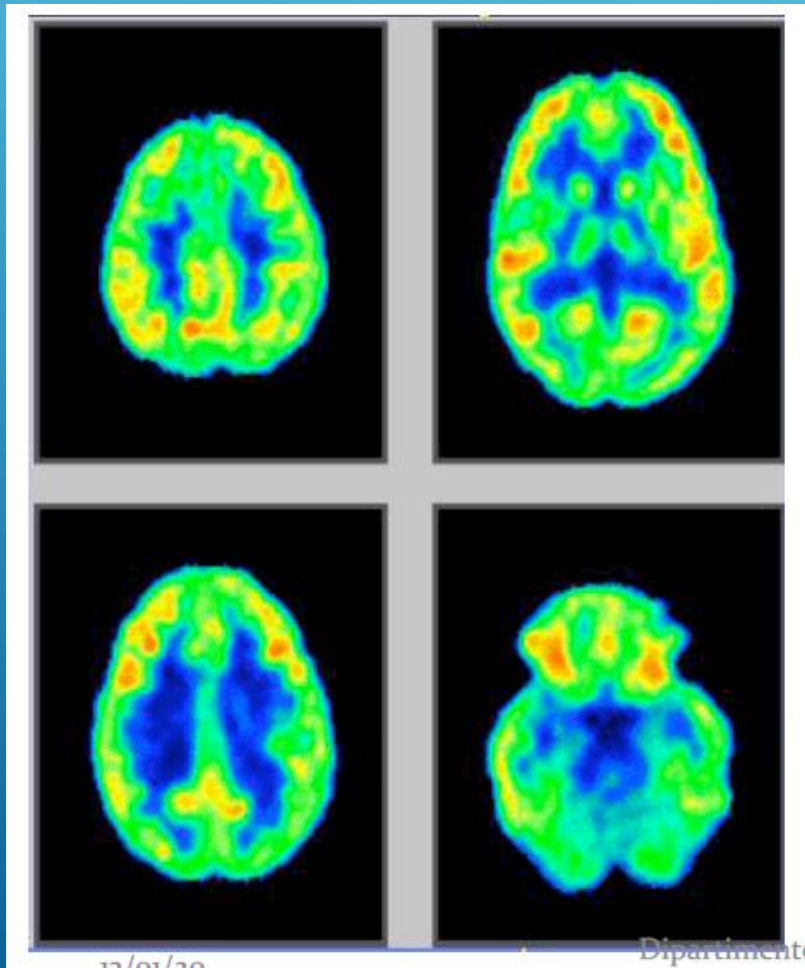
The system detects pairs of gamma rays emitted. Three-dimensional images of radionuclide concentration within the body are then constructed by computer analysis. This produces a functional imaging to observe metabolic processes in the body. Useful for diagnostic of cancer, and also of neurologic and cardiac diseases.



PET tomograph



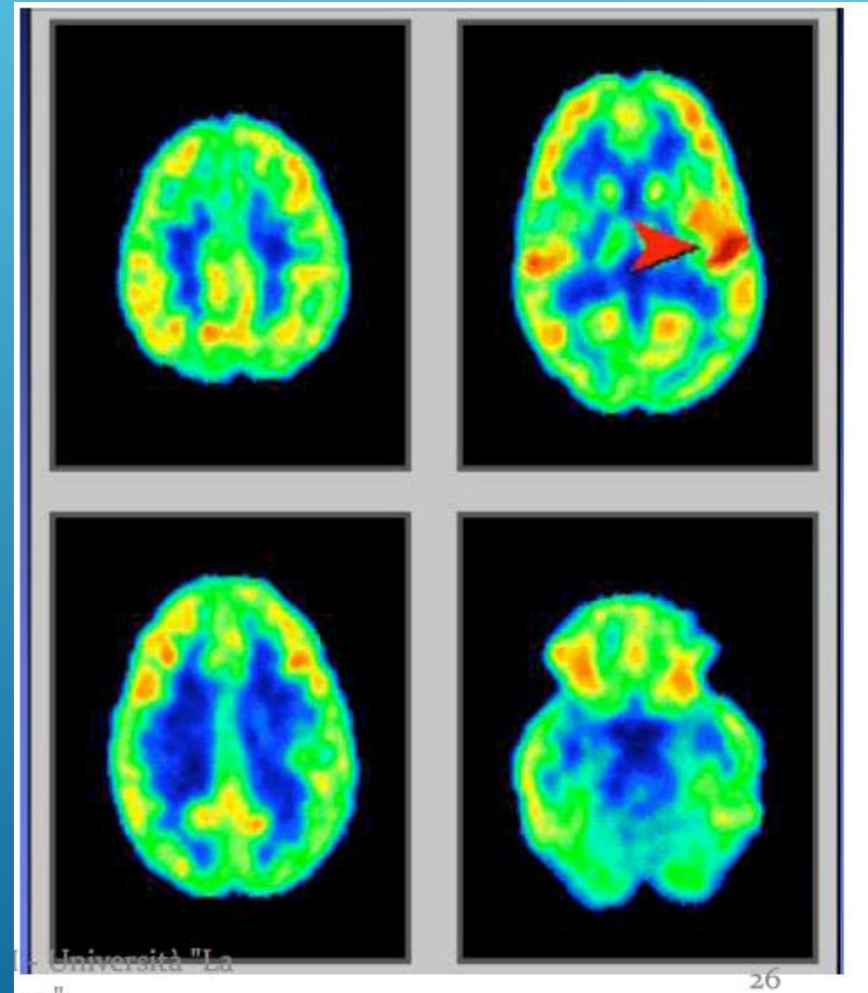
Brain at rest



12/01/20

Dipartimento

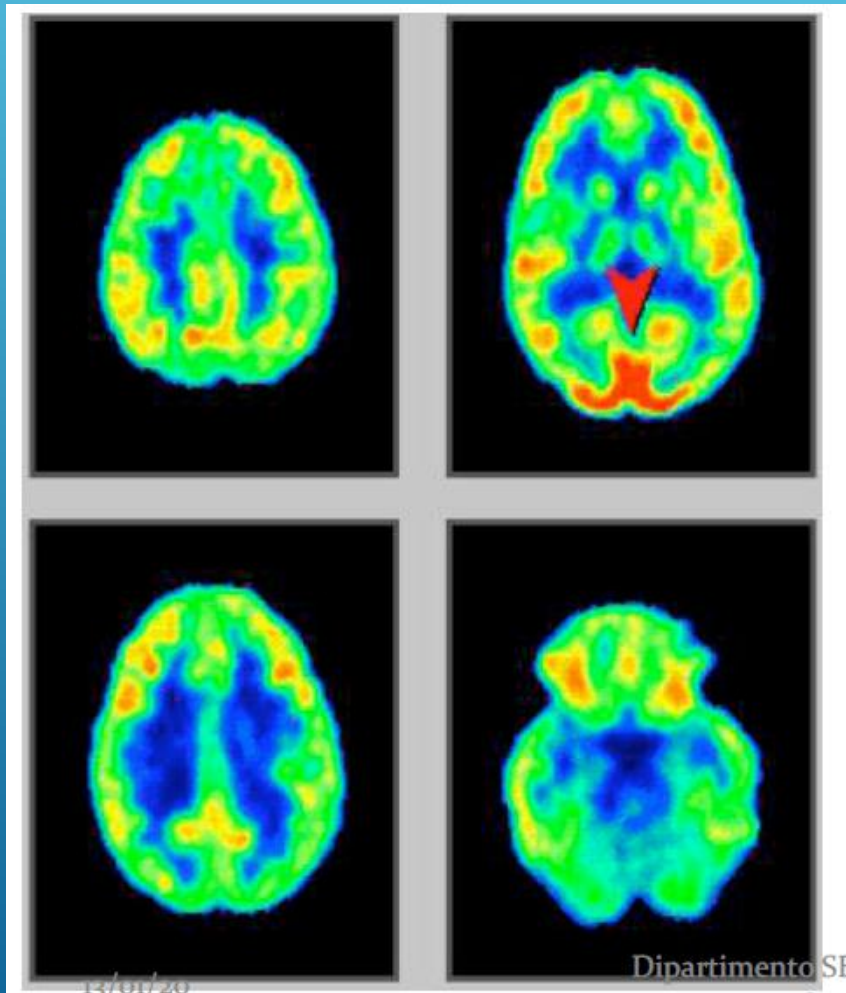
Brain listening music



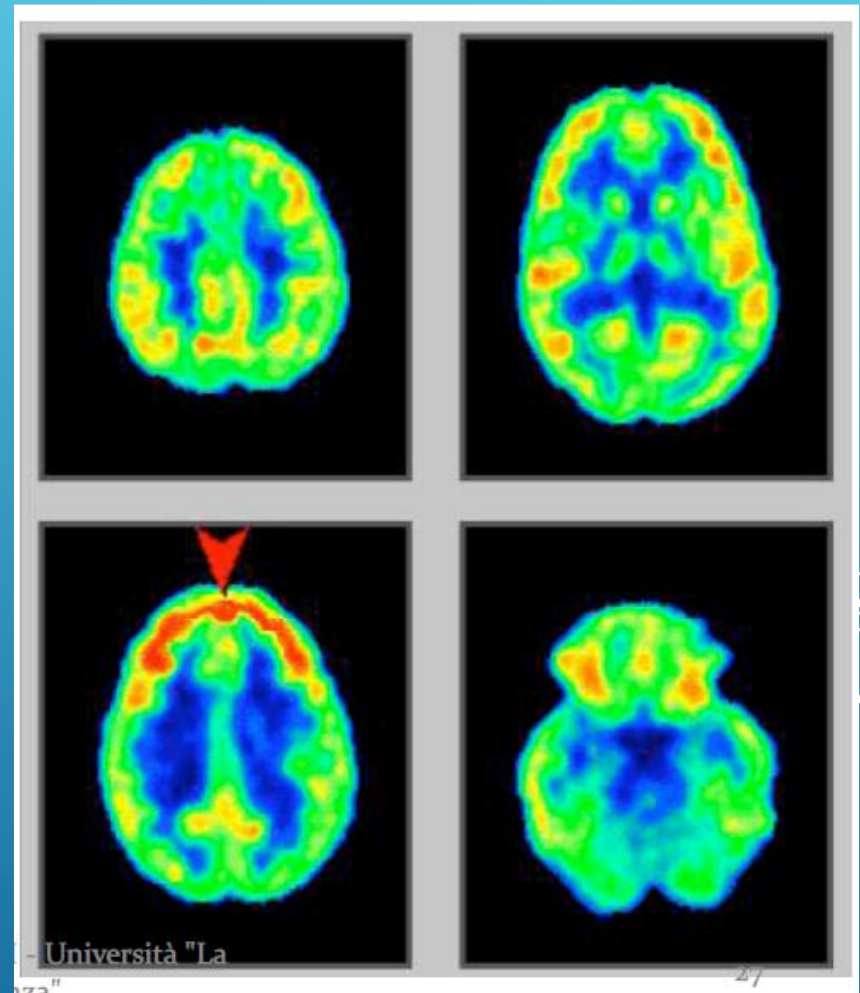
Università "La

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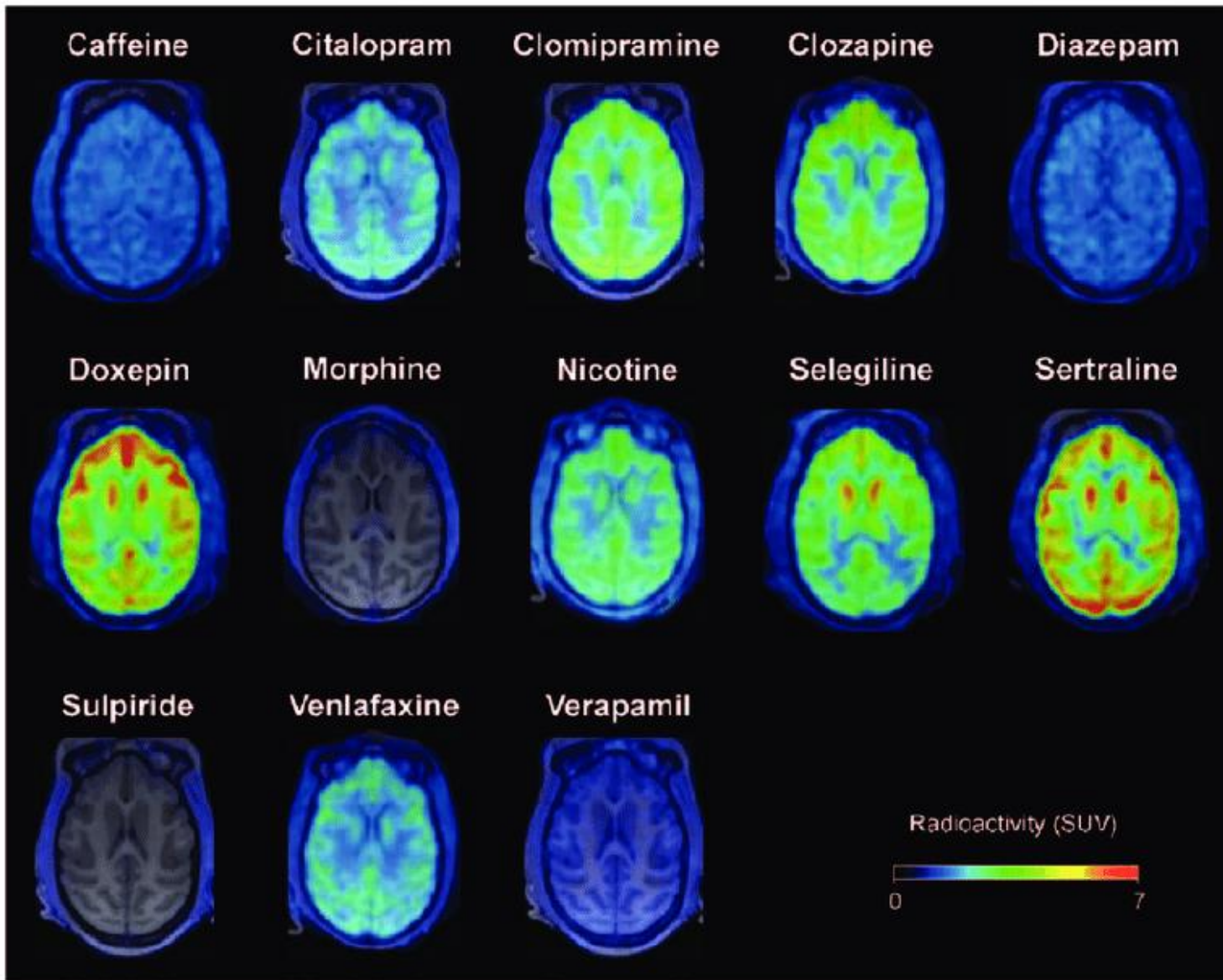
Brain visual stimulation



Brain intellectual activity



Drugs



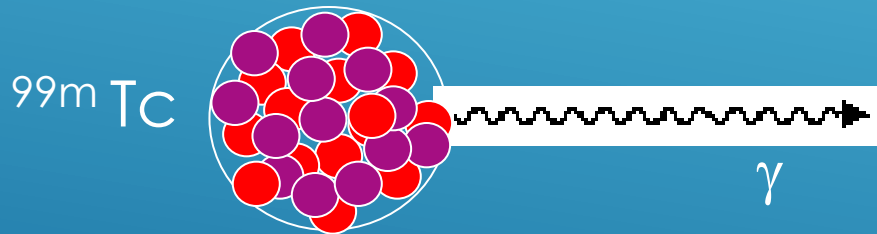
SPECT- Single Photon Emission Computed Tomography

Used radionuclides are γ (gamma rays) emitter

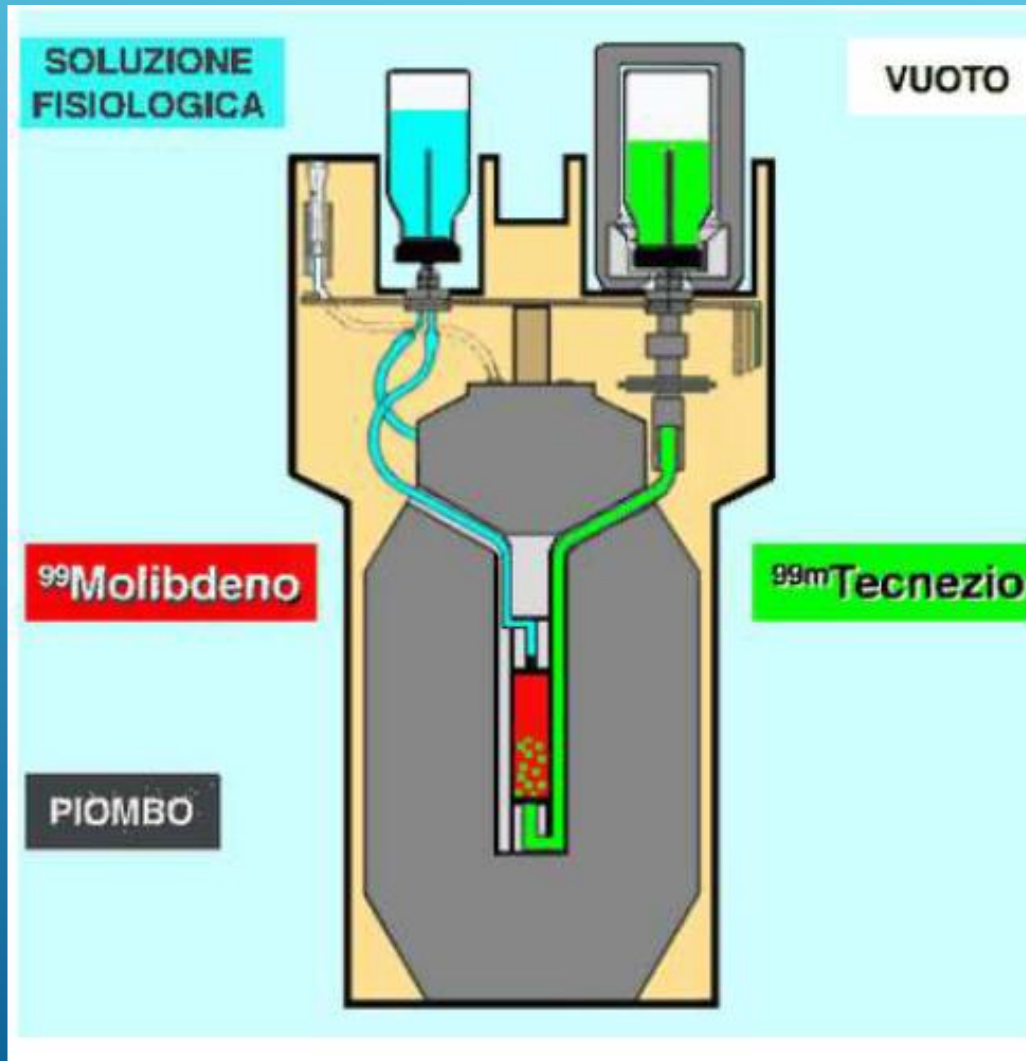
^{99m}Tc ($\tau \sim 6\text{h}$) $E_\gamma = 140\text{KeV}$

^{99}Tc is obtained from the decay of ^{99}Mo

It is used in ten of million of procedure/day!!!

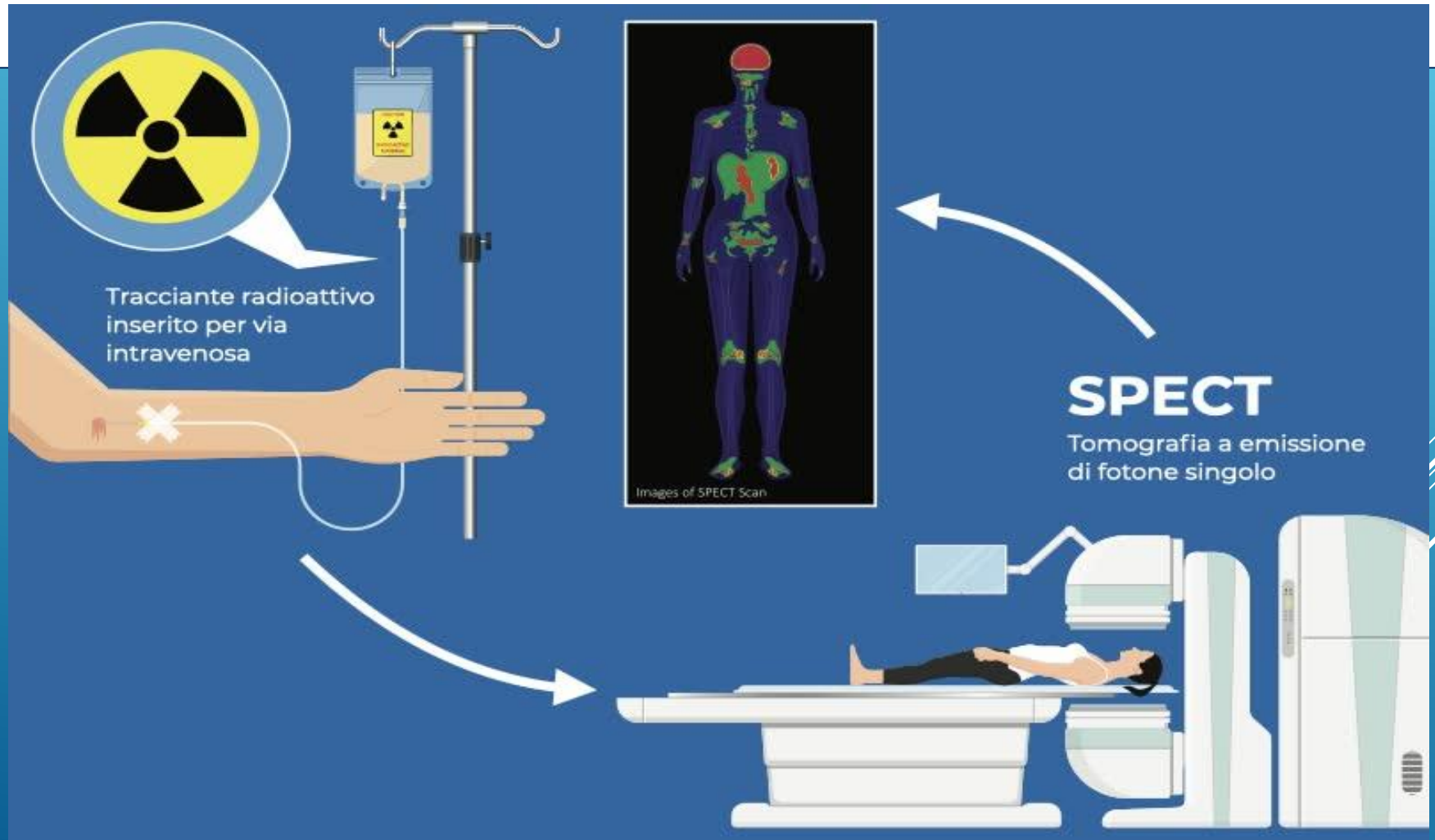


^{99m}Tc generator



SPECT = Single-Photon Emission Computed Tomography

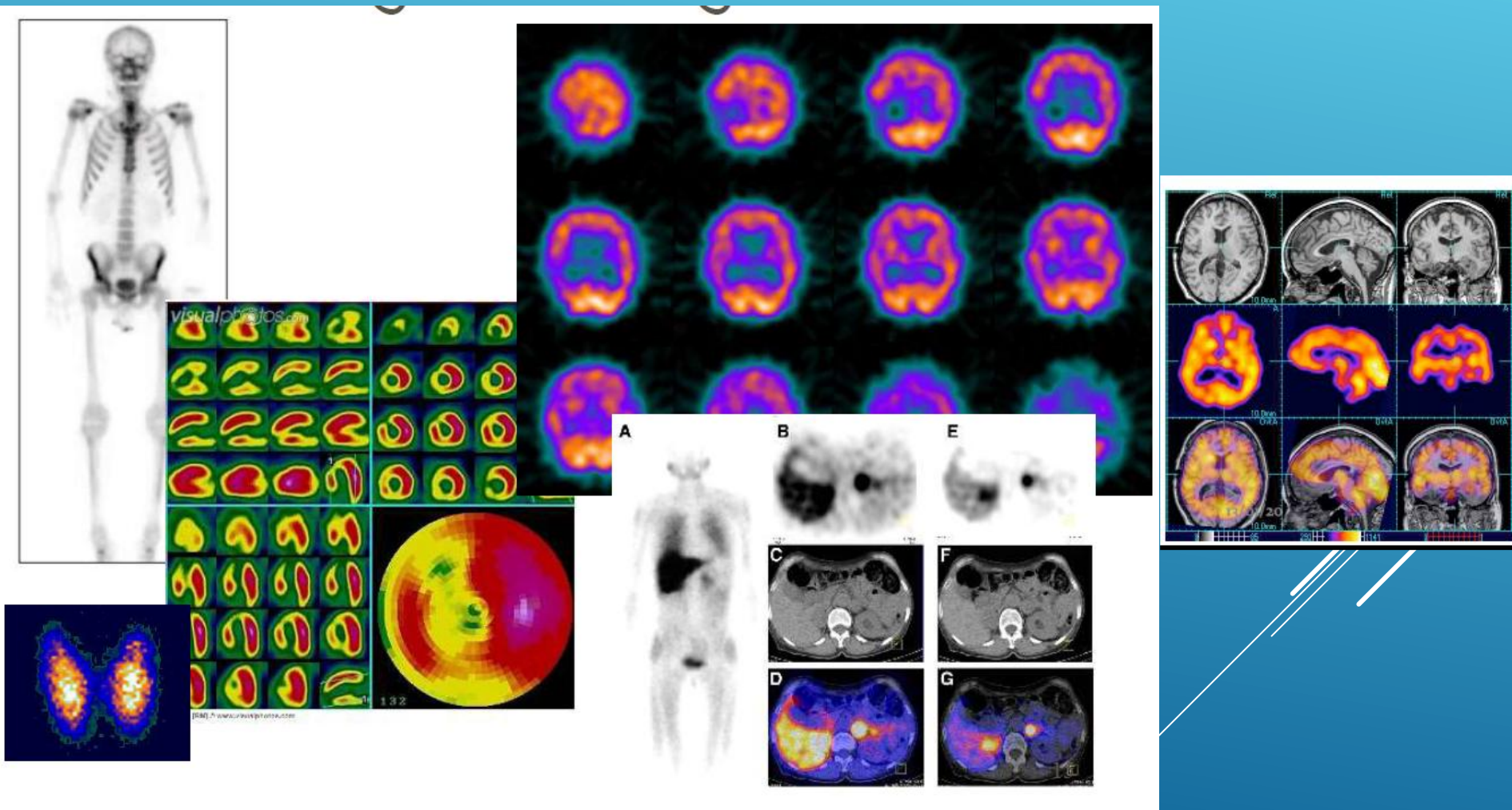
The radionuclide is **injected** into the bloodstream, then the emitted gamma rays from decay, these are detected by a system that produce images of the organs. It is able to provide 3D information.



SPECT = Single-Photon Emission Computed Tomography



SPECT allows to localize cancer in bones, kidneys, thyroid, myocardium, to verify the functionality of organs, to visualize the circulatory system in the heart and also to diagnose the Alzheimer



THERAPY



Nuclear Physics is applied in two types of therapies for cancer and diseases in general

RADIOTHERAPY

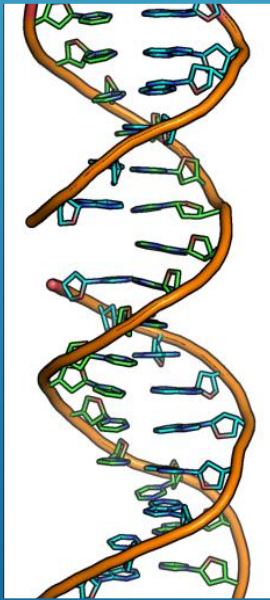
e.m. radiations emitted by a radionuclide are focalized in direction of the disease, releasing they energy and destroying ill cells, but also **many healthy cells** along the trajectory are destroyed



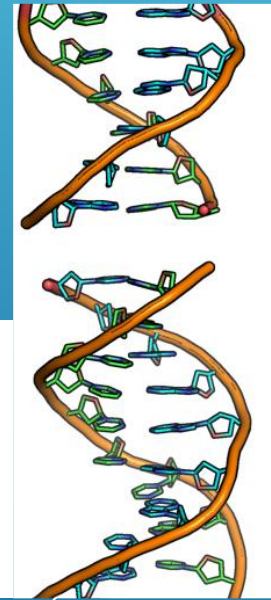
HADRONTHERAPY

beams of proton or C ions at high energy, delivered by accelerators, are headed in direction of the disease, relasing they energy and destroying ill cells, and only **very few healty cells** along the trajectory are destroyed

Beam of particles or em radiation hits a DNA double helix



Single break
REPARABLE IN SOME CASES



Double break
**PERMANENT
DAMAGE
IRREPARABLE**

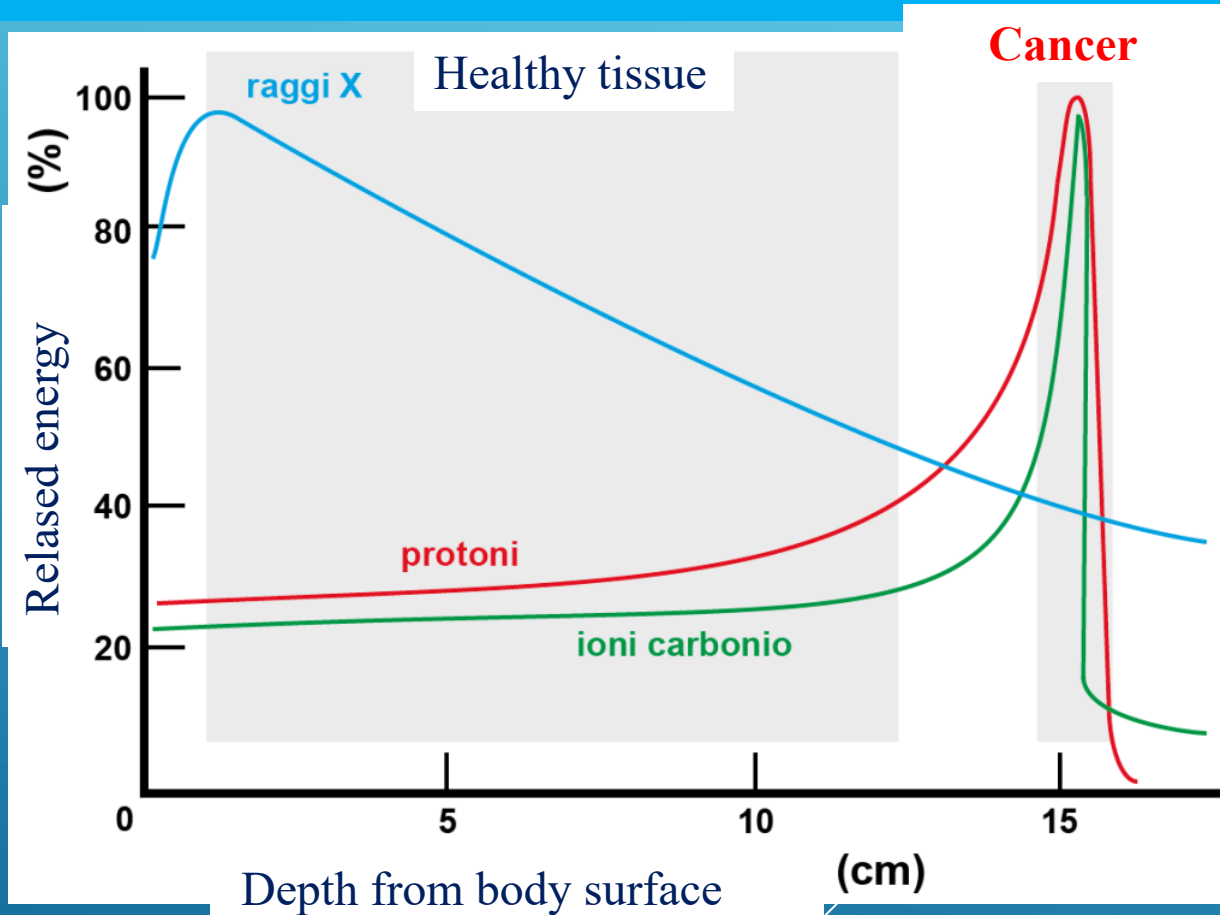
e.m. radiation X or γ ray

Proton or Carbon beam

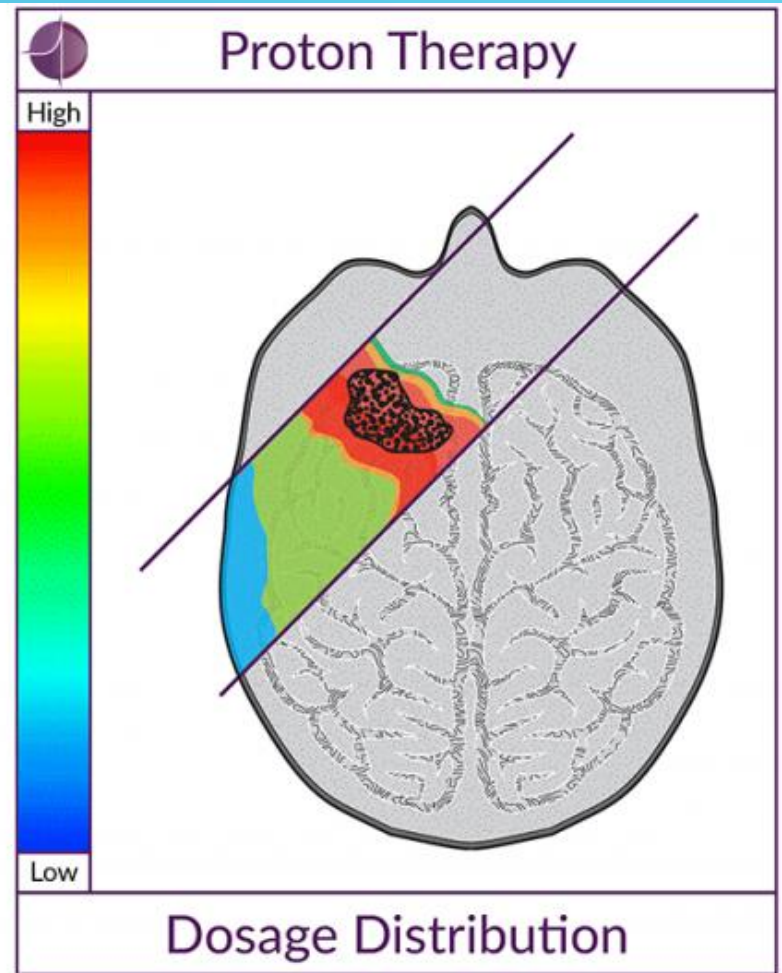
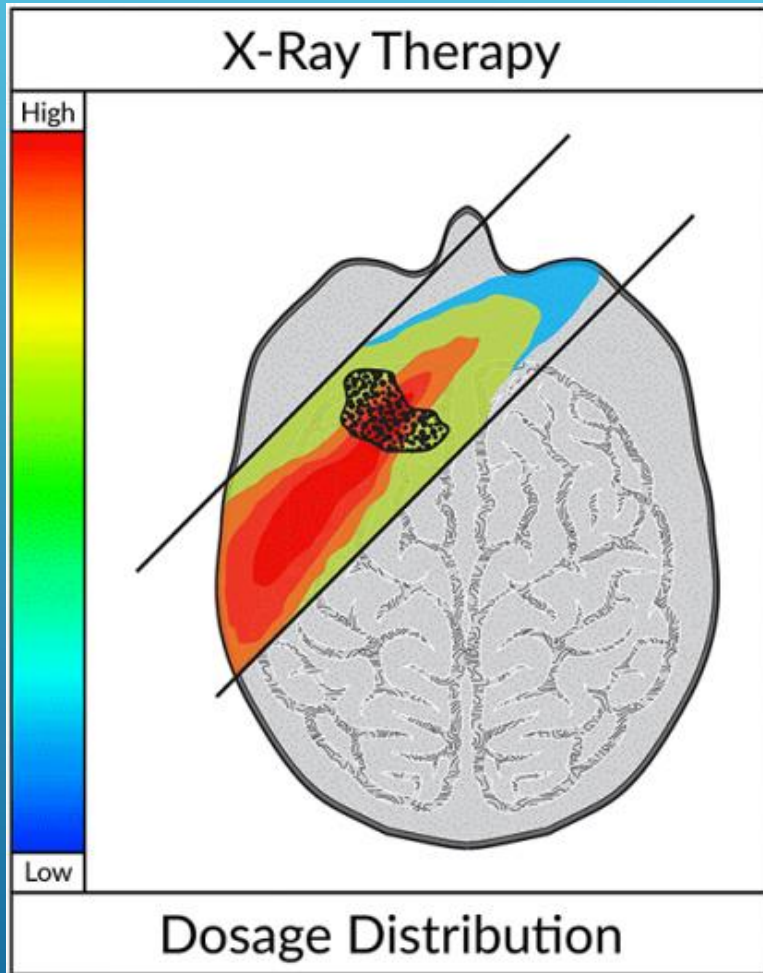
Difference of Released Energy in the body by radiotherapy and hadrontherapy

Hadrontherapy respect to the conventional radiotherapy is

- More efficient destroying the disease
- Less healthy tissue is destroyed
- less probability to get new cancer

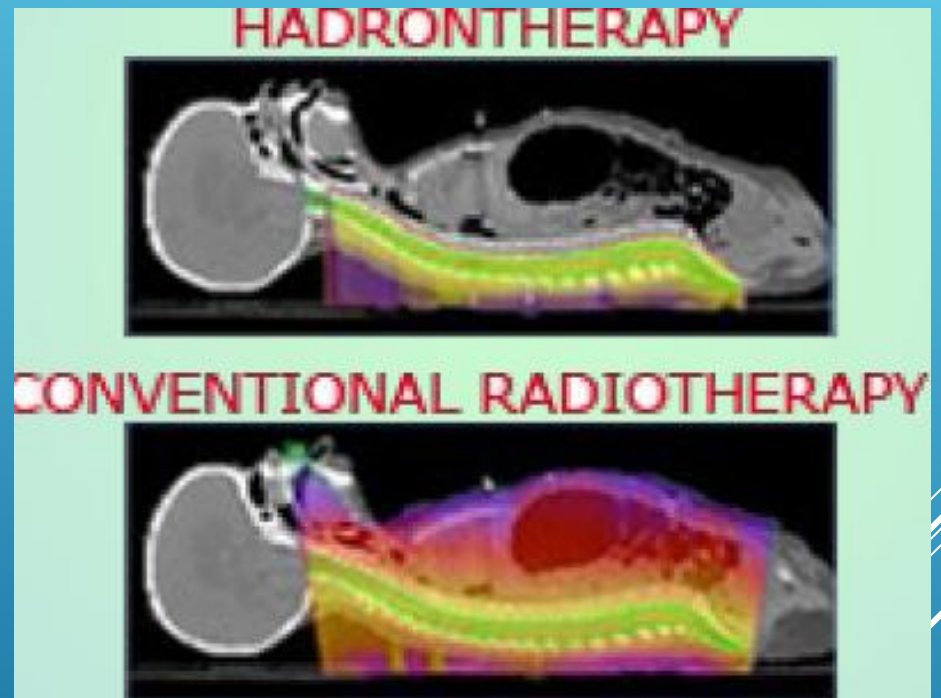
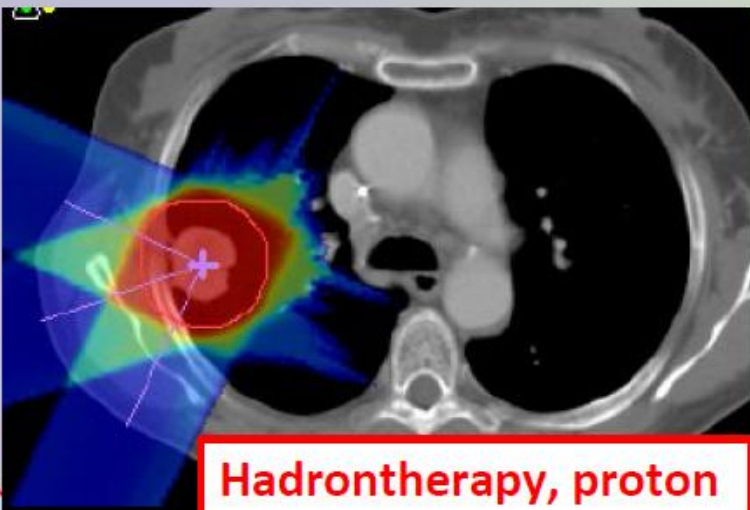
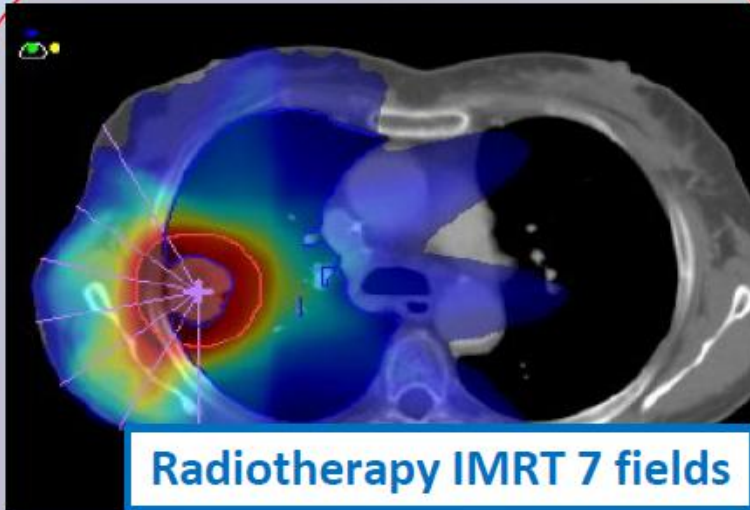


X- γ radiotherapy vs hadrontherapy



Vantage : a smaller good health region interested by radiations respect X or γ ray

X- γ radiotherapy vs hadrontherapy



RADIOTHERAPY

- Radiations have been applied for treatments since 1946 in USA by using **Iodine 131** that emitted γ and β radiations, on thyroid cancer.
- **Cobalt 60**, emitting high energy γ rays is one of the most common and efficient radionuclide to fight deep cancer
- Today high energy radiations, in combination with chemotherapy and surgery, are usually employed.



HADRONTHERAPY IN ITALY

CNAO (Centro Nazionale di Adroterapia Oncologica) @ Pavia

- Treatments with protons started in september 2011
- Treatments with carbon ions started in november 2012

p E : [60, 250] MeV

C⁶⁺ E : [120, 400] MeV/u

Synchrotron
(26 m diameter)

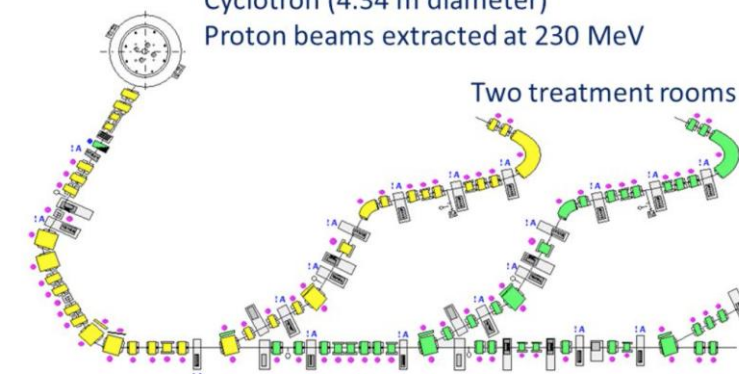
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3 Treatment rooms
3 Horizontal beam lines
1 Vertical beam line

ATreP (Agenzia Provinciale per la Protonterapia) @ Trento

Cyclotron (4.34 m diameter)
Proton beams extracted at 230 MeV

Two treatment rooms



Inaugurated in July 2013, after commissioning it's starting the clinical activity

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CATANA (Centro di Adroterapia e Applicazioni Nucleari Avanzate)

INFN @ LNS (Laboratori Nazionali del Sud) - Catania



CATANA treatment room

- Uses 62 MeV proton beams accelerated by the Cyclotron at LNS
- Allows the treatment of ocular tumors
- Operating since 2002 with approximately 500 patients treated to date

Proton Therapy – INFN LNS - CATANA

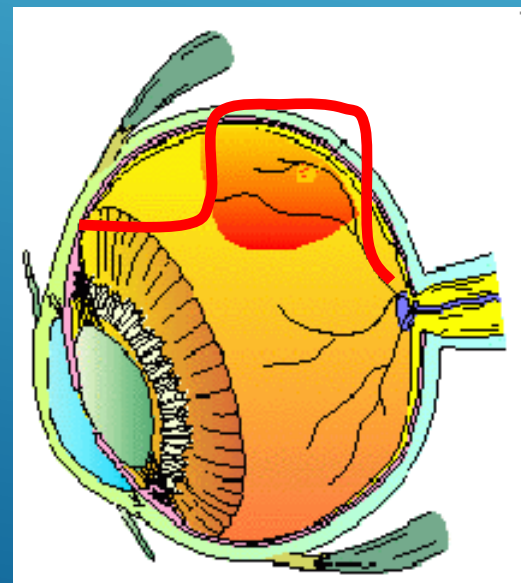


Proton Therapy – INFN LNS – «CATANA»



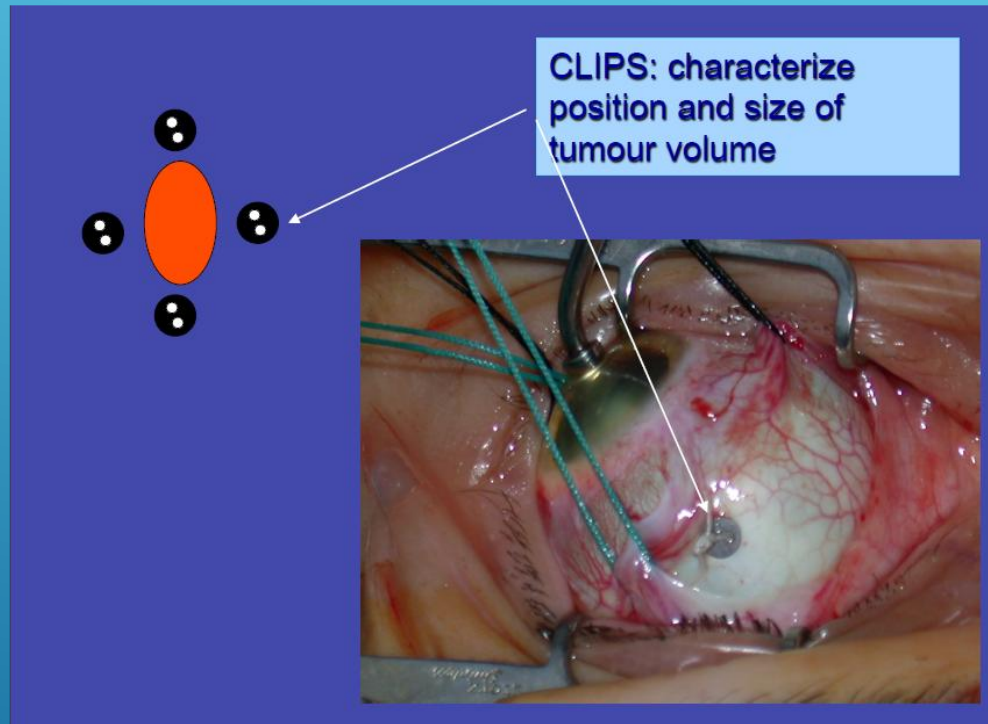
Protons with energy of 62 MeV, delivered by the cyclotron, are used against ocular melanoma

Maximum depth of 3 cm in the biological tissue



Surgical Phase

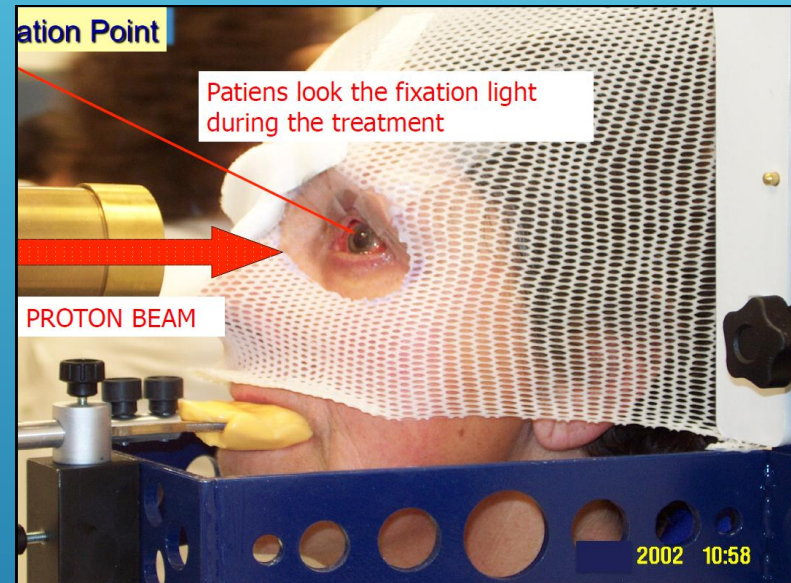
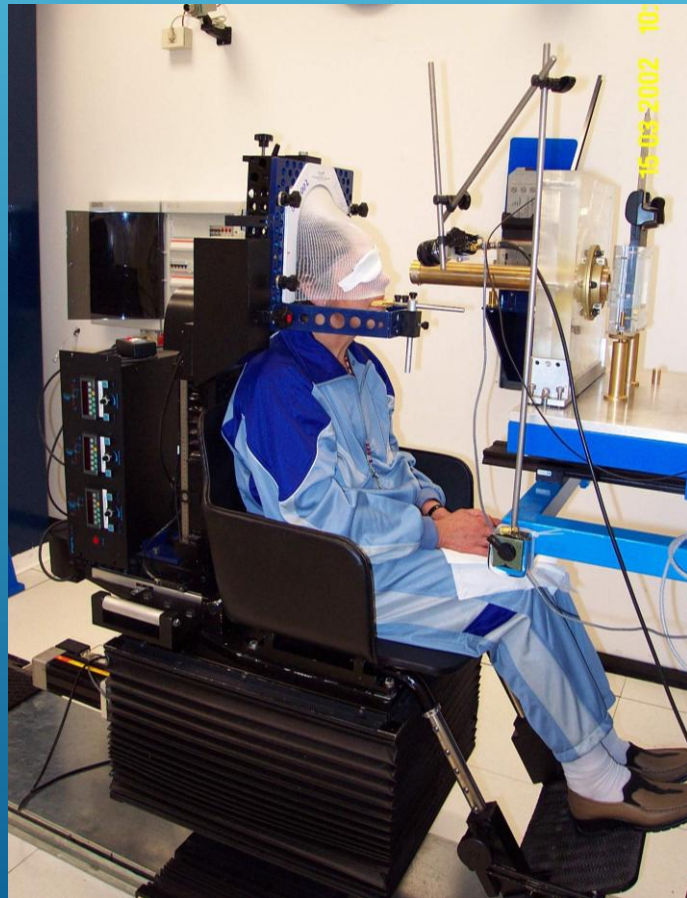
The surgeon applies four metal clips on the surface of the eye around the tumor.



.....which are be used to identify the position of the tumor simply by taking X-rays of the patient's eye

Treatment phase

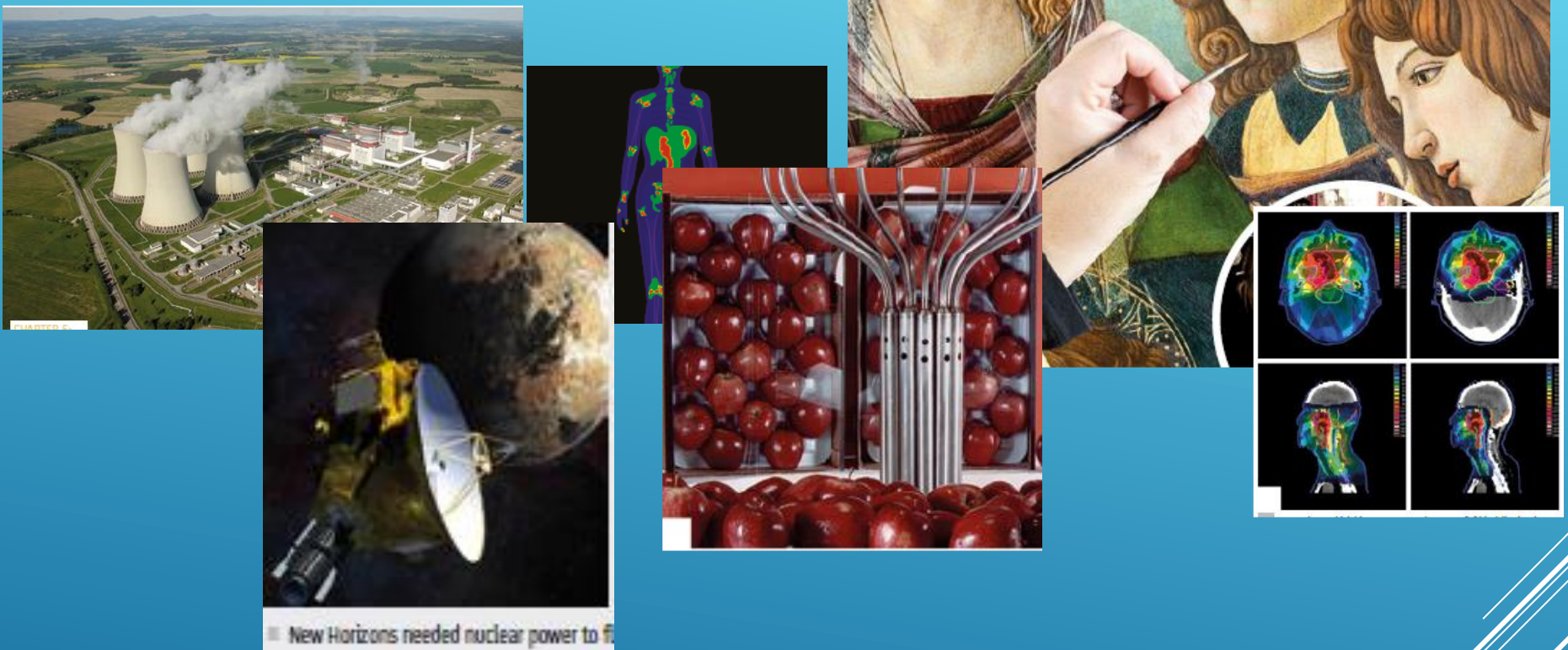
The patient is finally ready to undergo the treatment...



...divided into four sessions (one per day for four consecutive days), each lasting about a minute

CONCLUDING

We have seen applications of Nuclear Physics in Medicine, but it is applied also in many other fields



All these applications improve our life under different aspects.

But always it is important to fix in mind :
It is the study of the fundamental nuclear physics (nucleare structure, nuclear reactions, nuclear principia) that allows us to take advantages of NP for applications in many fields.