# "Nuclear Physics: application to medicine"

INFN-LNL
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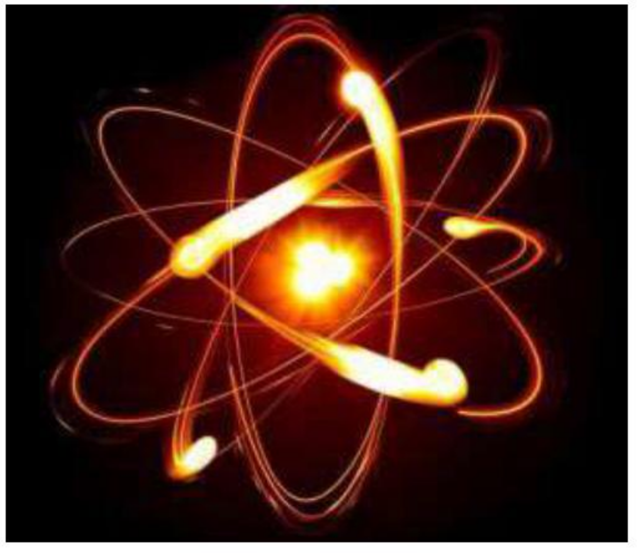
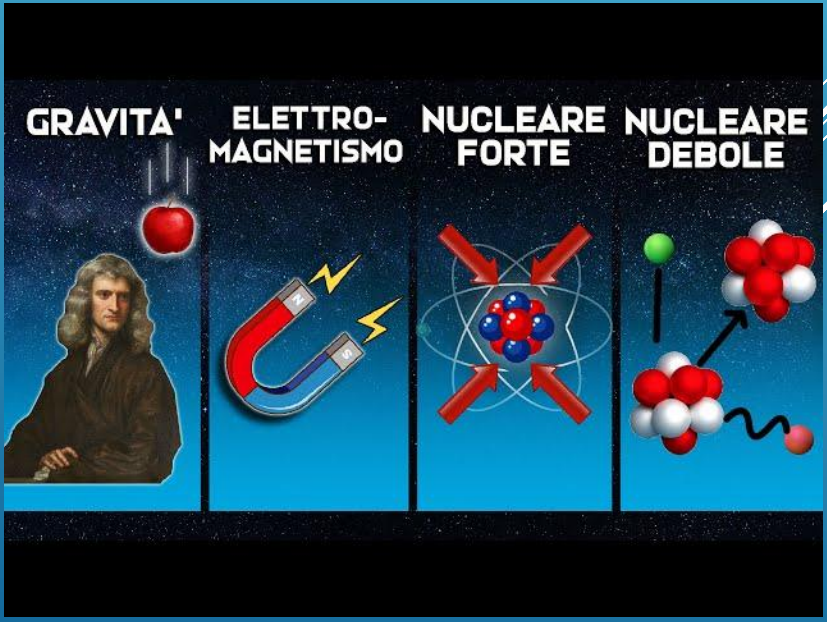
# Nuclear Physics



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

Nuclear Physics has been developed at the end of the 19° 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

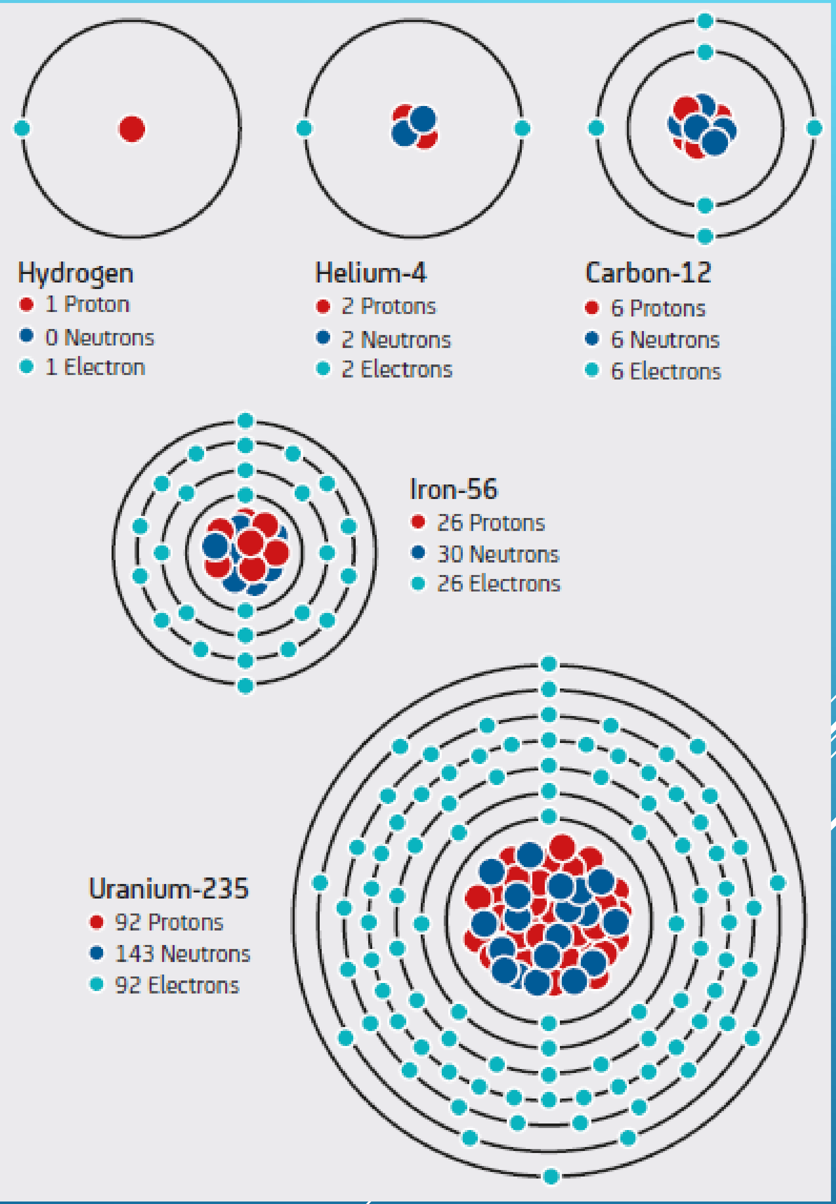
Atom dimension : ~ $10^{-10}$ m (Å)
Nucleus dimension : ~ $10^{-15}$ m (fm)

Neutron Mass ≈ Proton Mass
Proton Mass ≈ 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

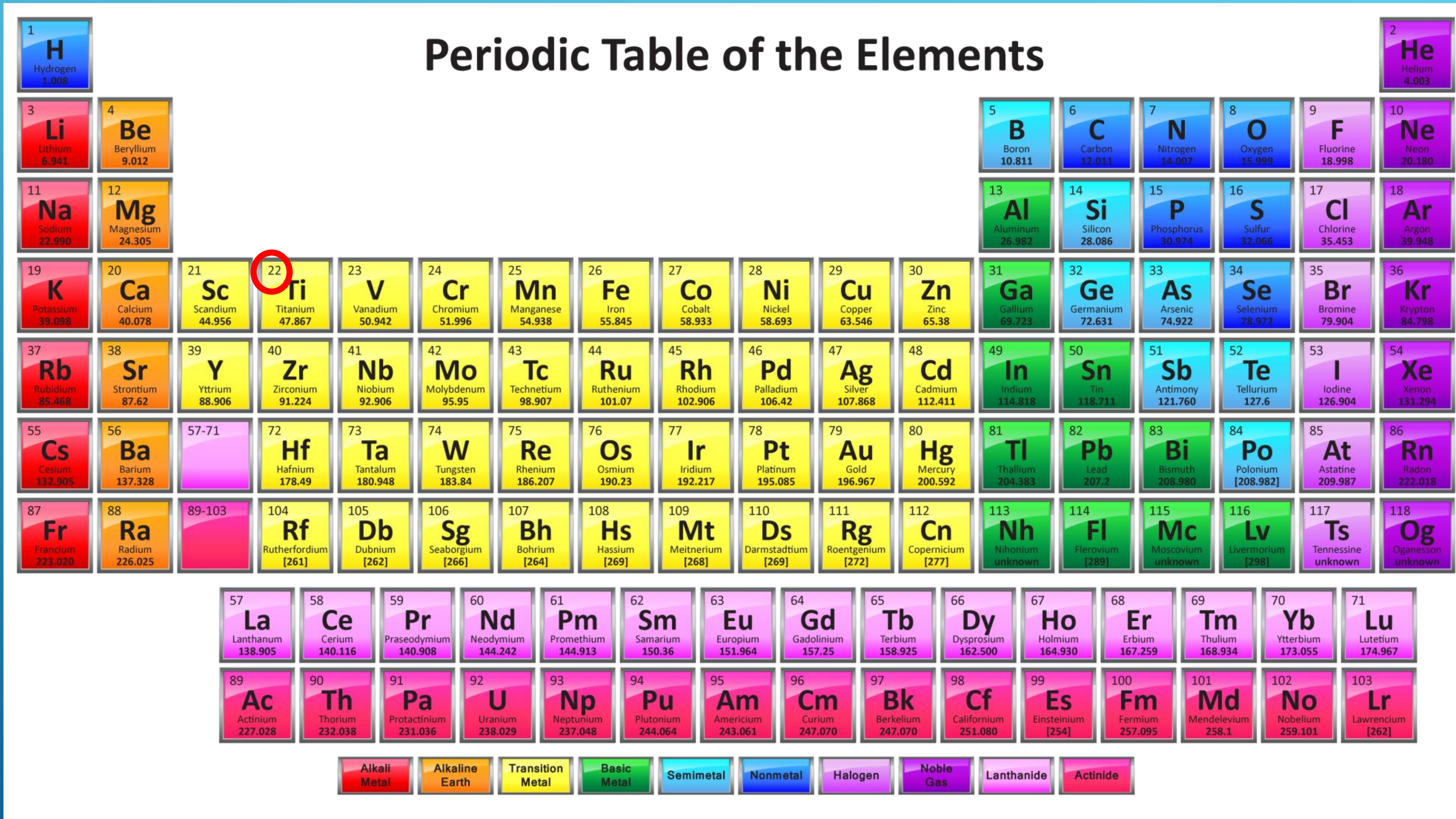
Z=8 Oxigen
N=8 $^{16}O$
N=9 $^{17}O$
N= 7 $^{15}O$




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




Dmitrij Ivanovic Mendeleev, 1869

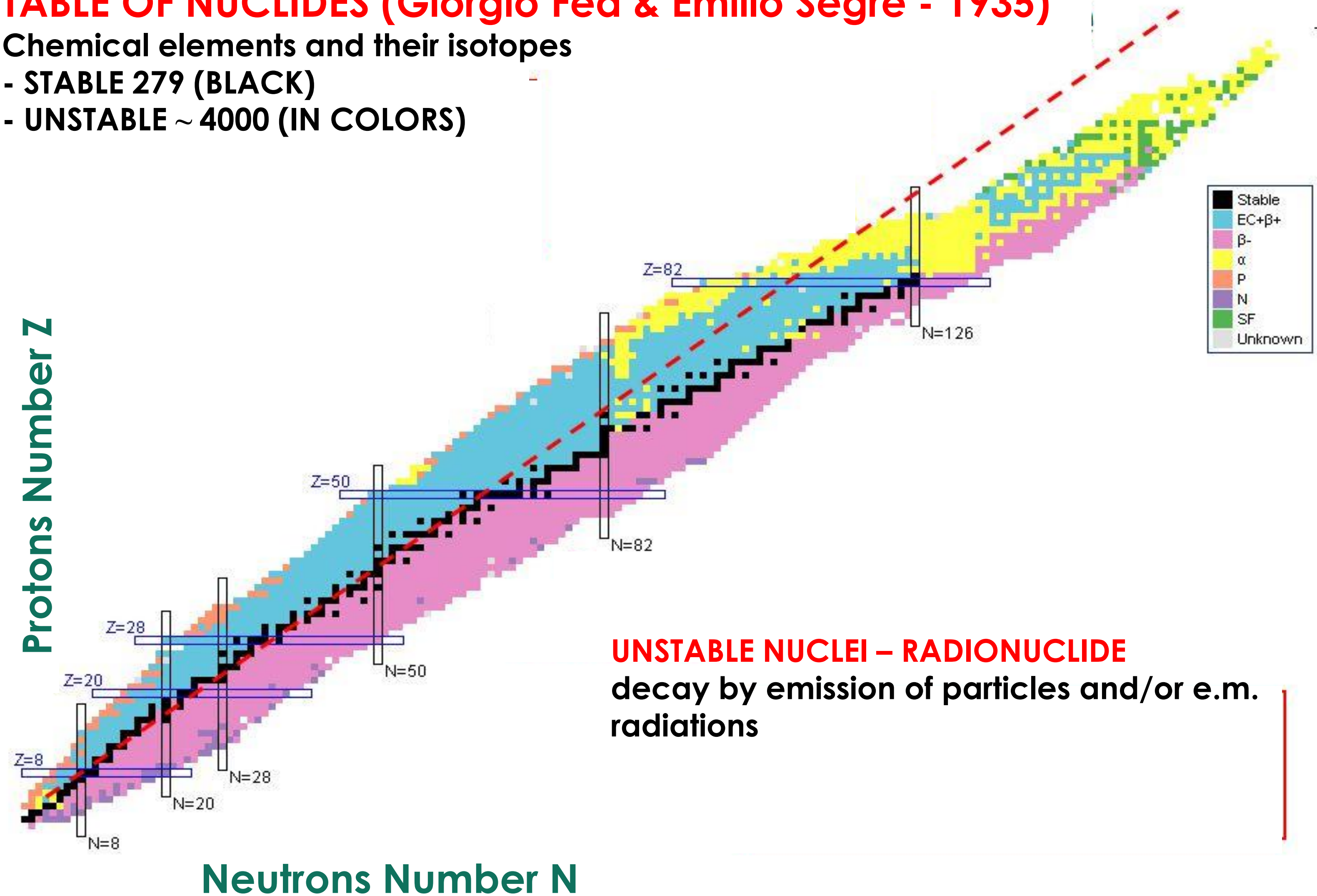
# ATOM and NUCLEUS

## 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)**

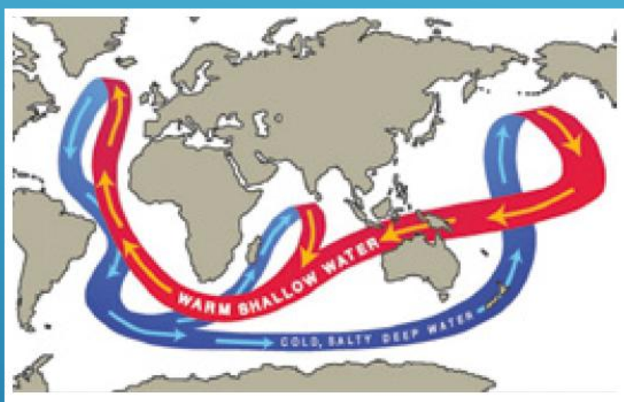



**UNSTABLE NUCLEI – RADIONUCLIDE**

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

**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**

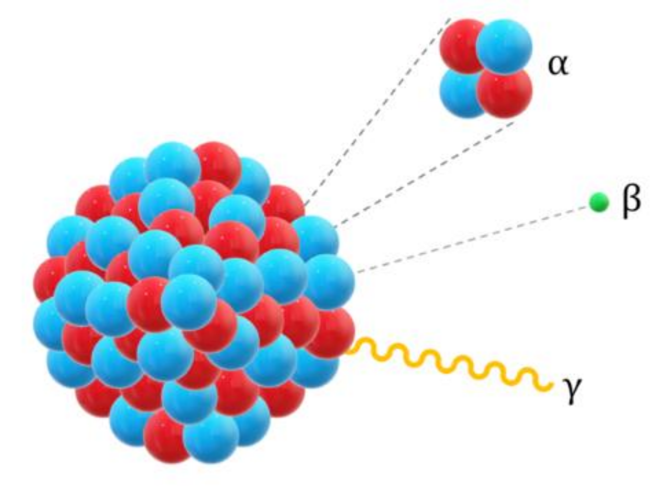



# Application of Nuclear Physics To Medicine

## 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).



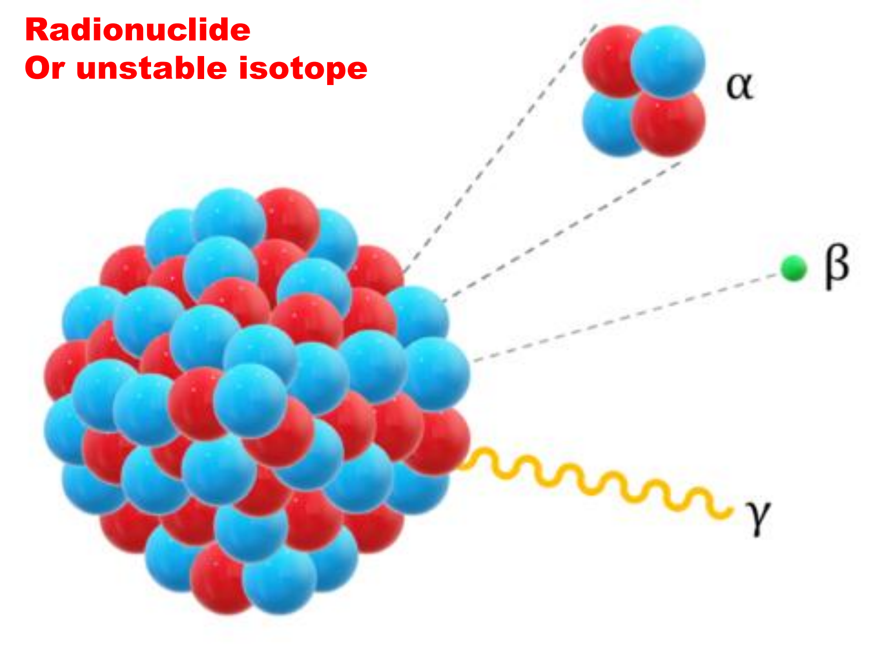

**Radionuclide are Used for Therapy and Diagnostic**

### 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**

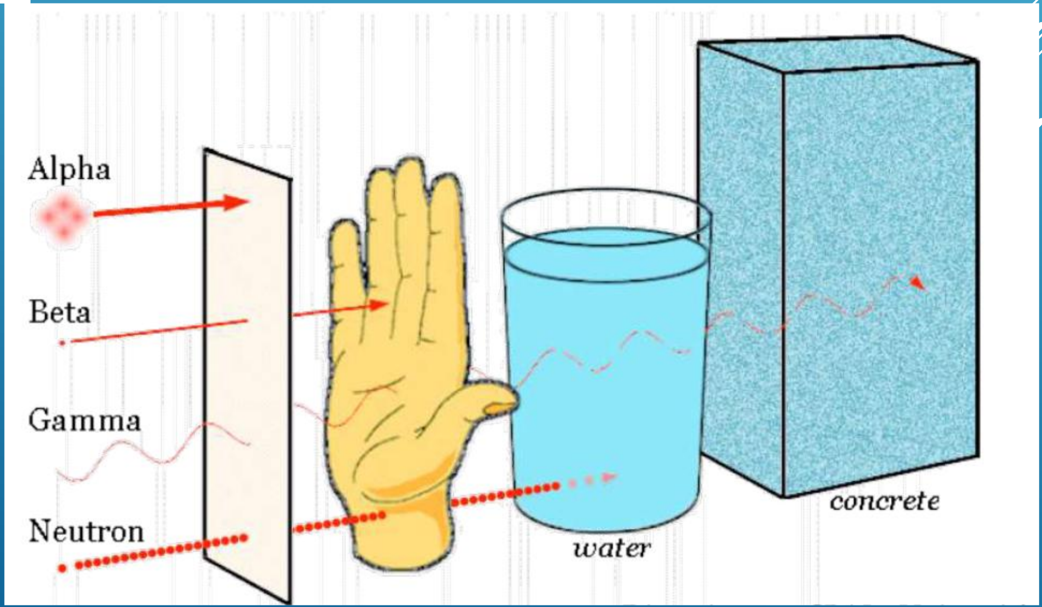
# RADIOACTIVITY




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

α particle → 2n+2p He Nucleus
β particle → 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 $10^9$ 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*

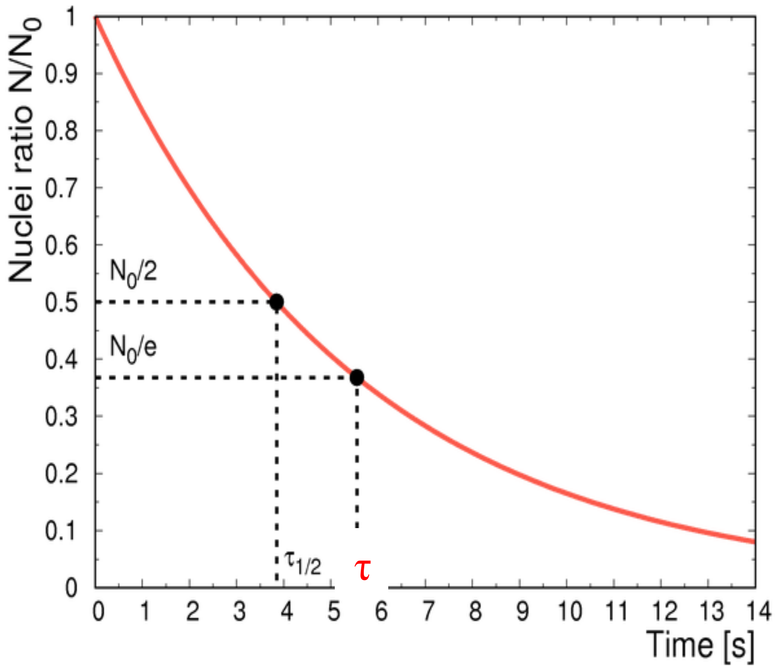
**$\tau$ , mean life** = it is the required time to reduce the number of nuclei in the system by a factor *e* *(Nepero number, 2.72)*

## 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

| Radionuclide | Physical Half-Life | Activity | Use |
|---|---|---|---|
| Cesium-137 | 30 yrs | $1.5\times10^{6}$ Ci | Food Irradiator |
| Cobalt-60 | 5 yrs | 15,000 Ci | Cancer Therapy |
| Plutonium-239 | 24,000 yrs | 600 Ci | Nuclear Weapon |
| Iridium-192 | 74 days | 100 Ci | Industrial Radiography |
| Hydrogen-3 | 12 yrs | 12 Ci | Exit Signs |
| Strontium-90 | 29 yrs | 0.1 Ci | Eye Therapy Device |
| Iodine-131 | 8 days | 0.015 Ci | Nuclear Medicine Therapy |
| 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 MeV (radiotherapy )

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

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

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

# NUCLEAR REACTIONS

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

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

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

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

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

# 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 recostructing 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

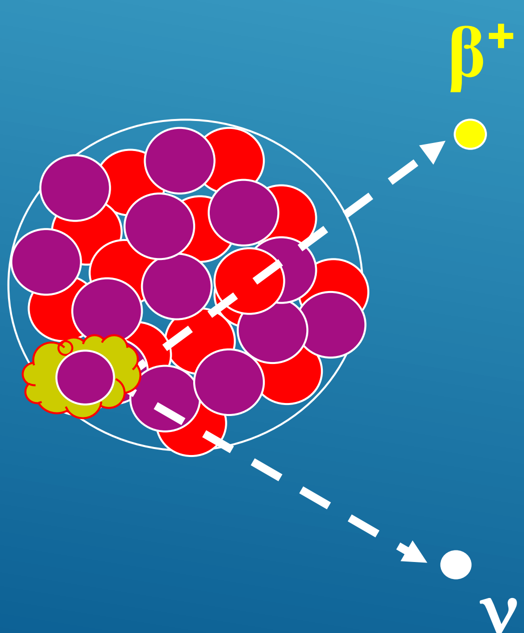
- PET
- SPECT

# PET = Positron emission tomography

Used Radionuclides are $\beta$+ (positron) emitter

$^{11}$**C** ($\tau$~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.



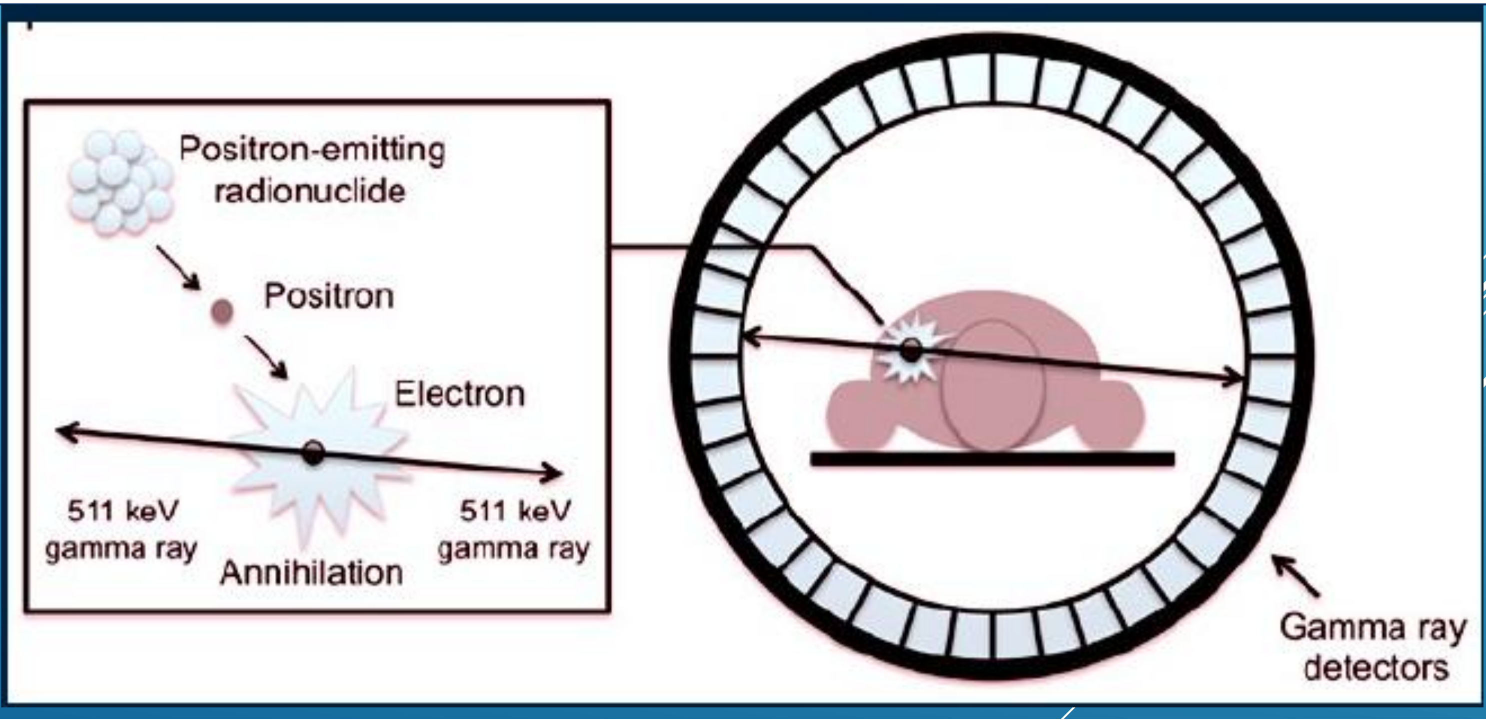

$$p \rightarrow n + \beta^+ + \nu$$

$$({}^{15}O \rightarrow {}^{15}N + \beta^+ + \nu)$$

# 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.

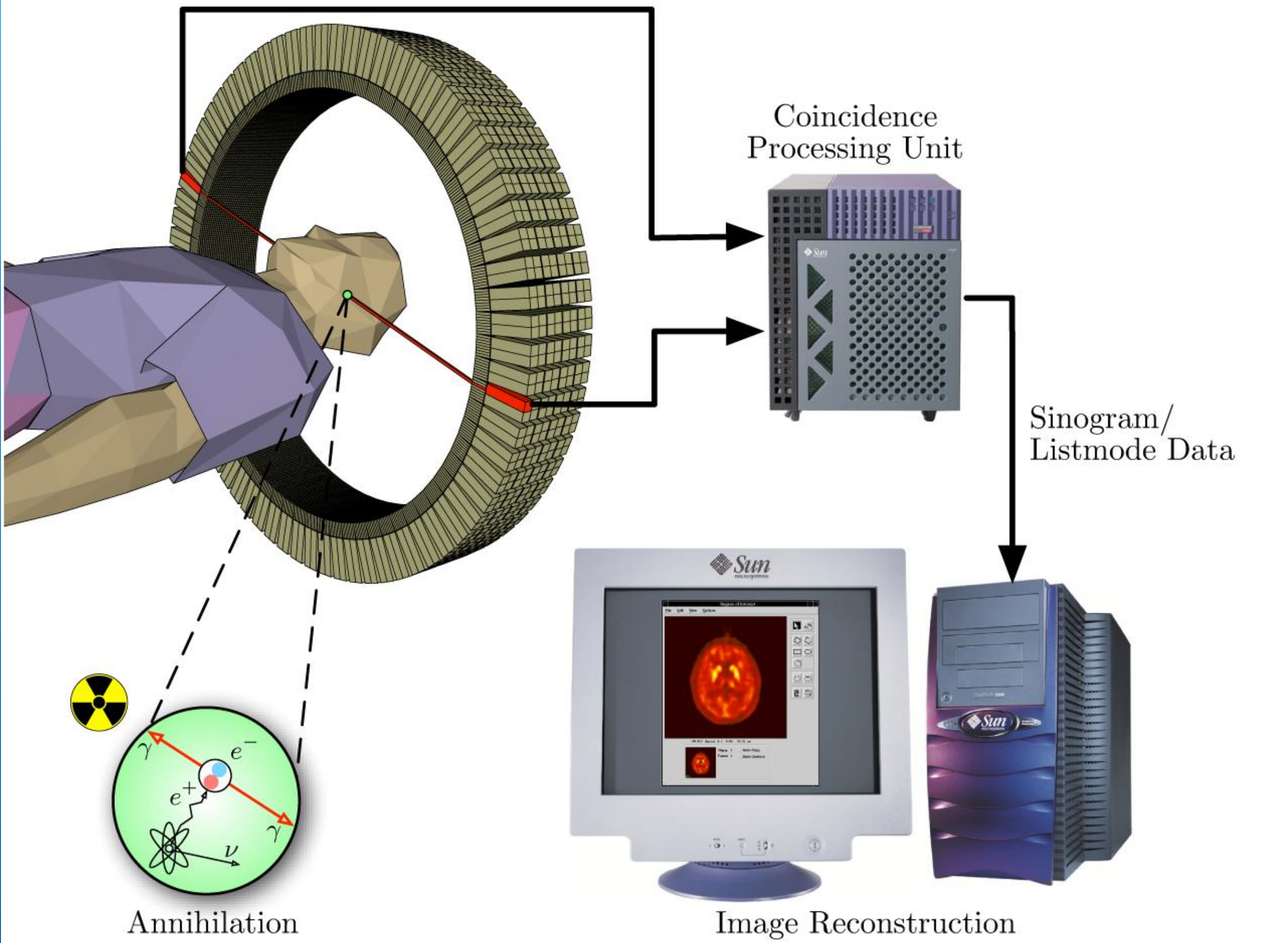
Then the radionuclide emits positron that interacts with an electron of the body (annihilation process) with emission of two gamma rays of E=511KeV in opposite directions.



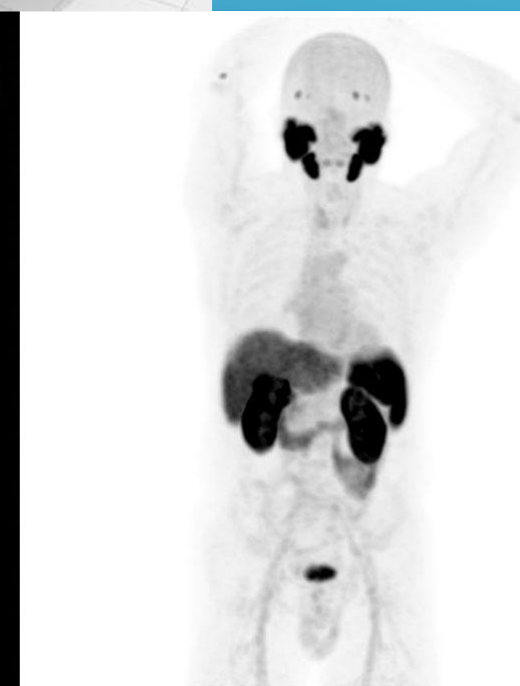

**A system of detectors around the body allows to detect the emitted gamma rays**

# PET positron emission tomography

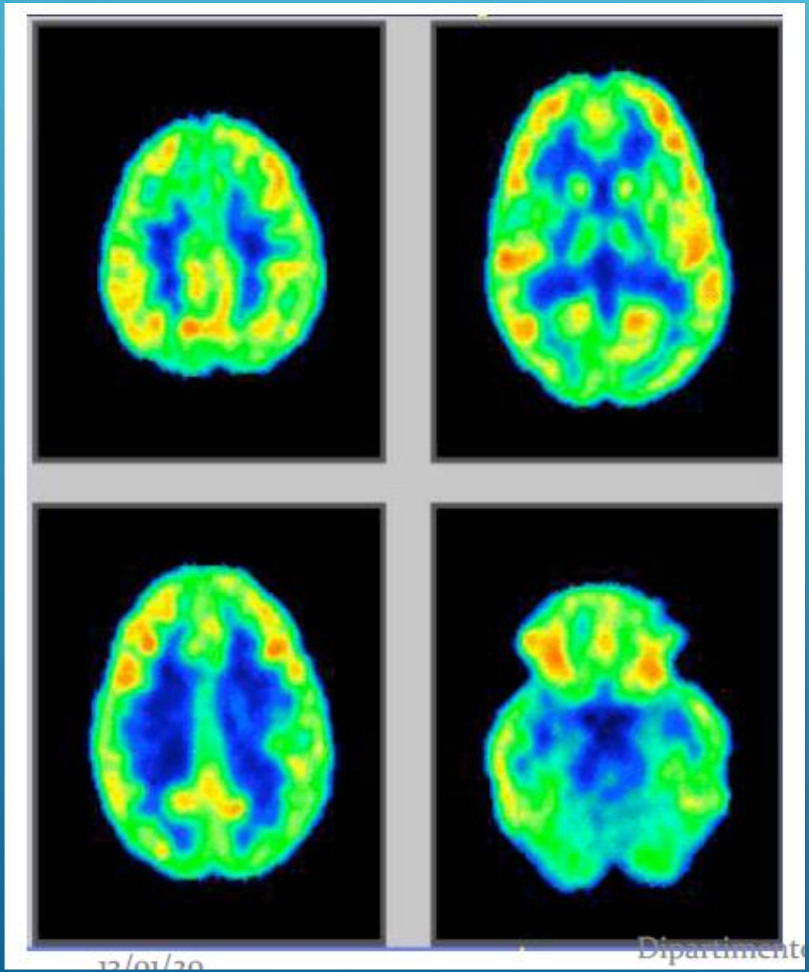
The system detects pairs of gamma rays emitted. Three-dimensional images of radionuclide concentration within the body are then constructed by computer analysis. This produces a functional imaging to observe metabolic processes in the body. Useful for diagnostic of cancer, and also of neurologic and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



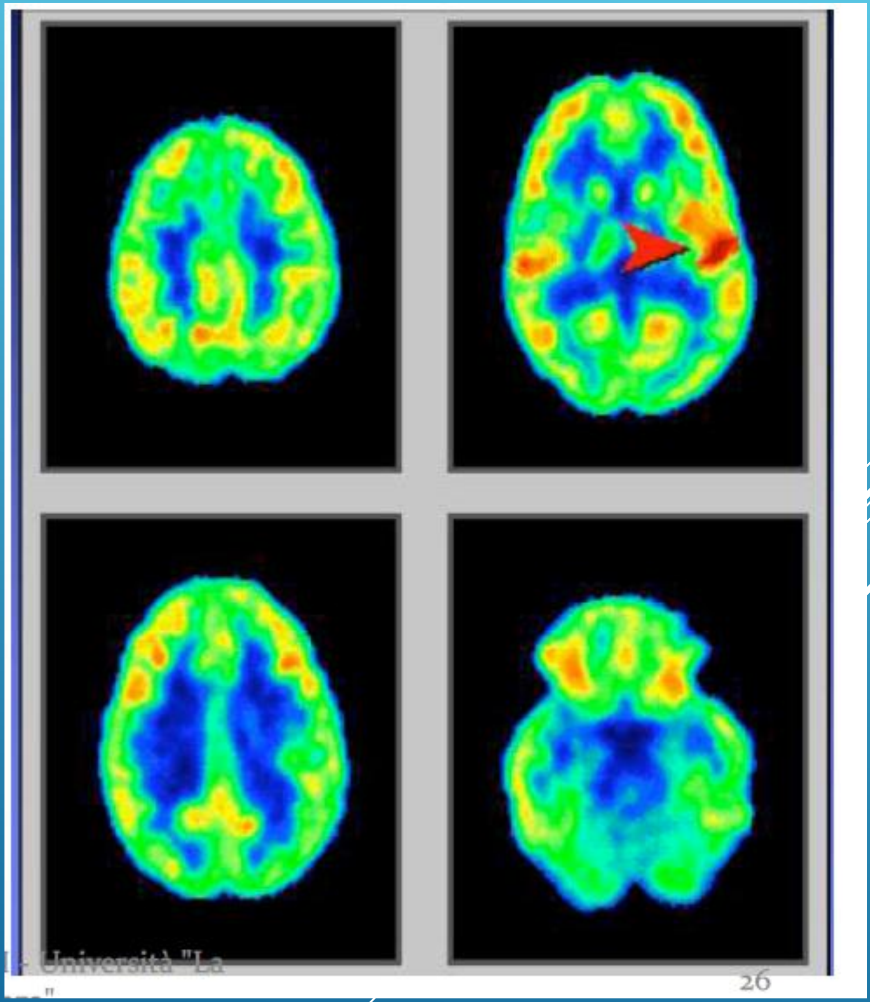
# PET tomograph



# Brain at rest

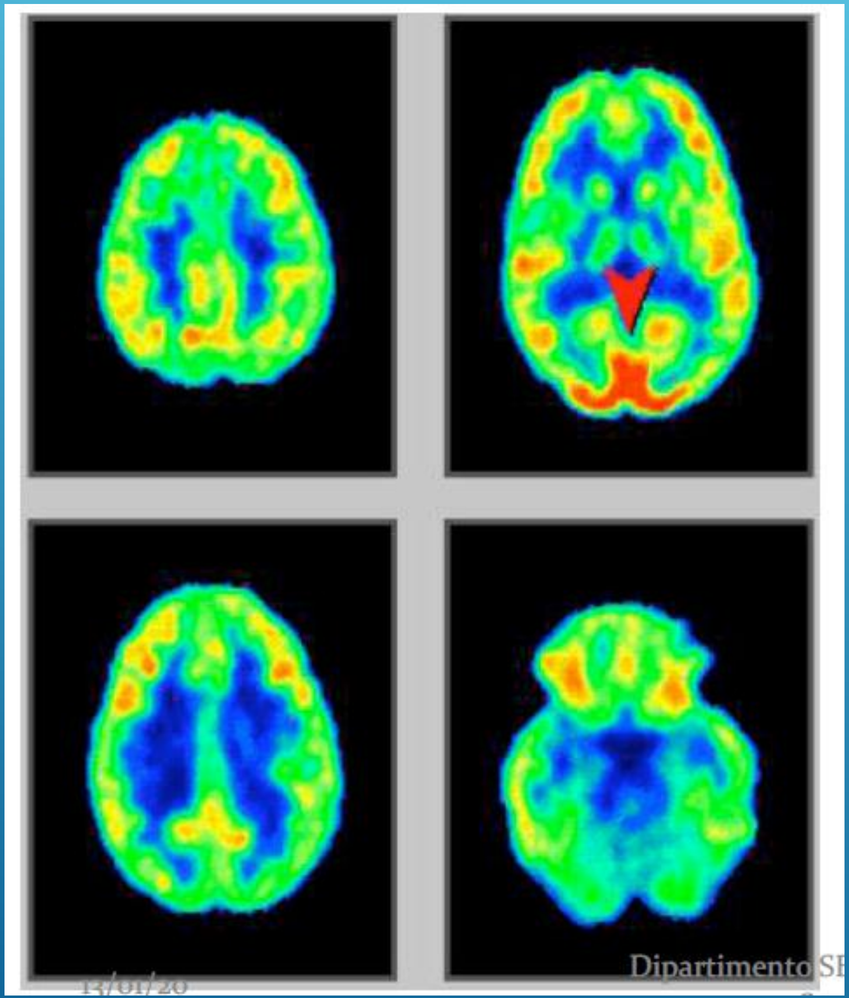


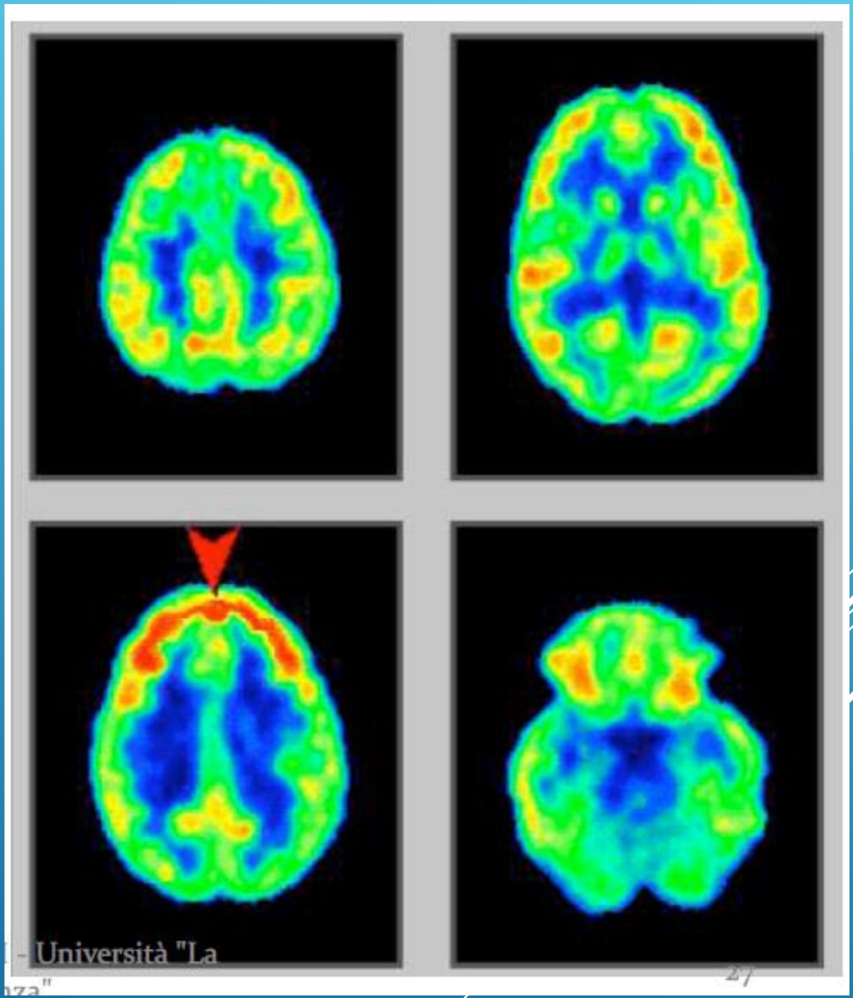

# Brain listening music



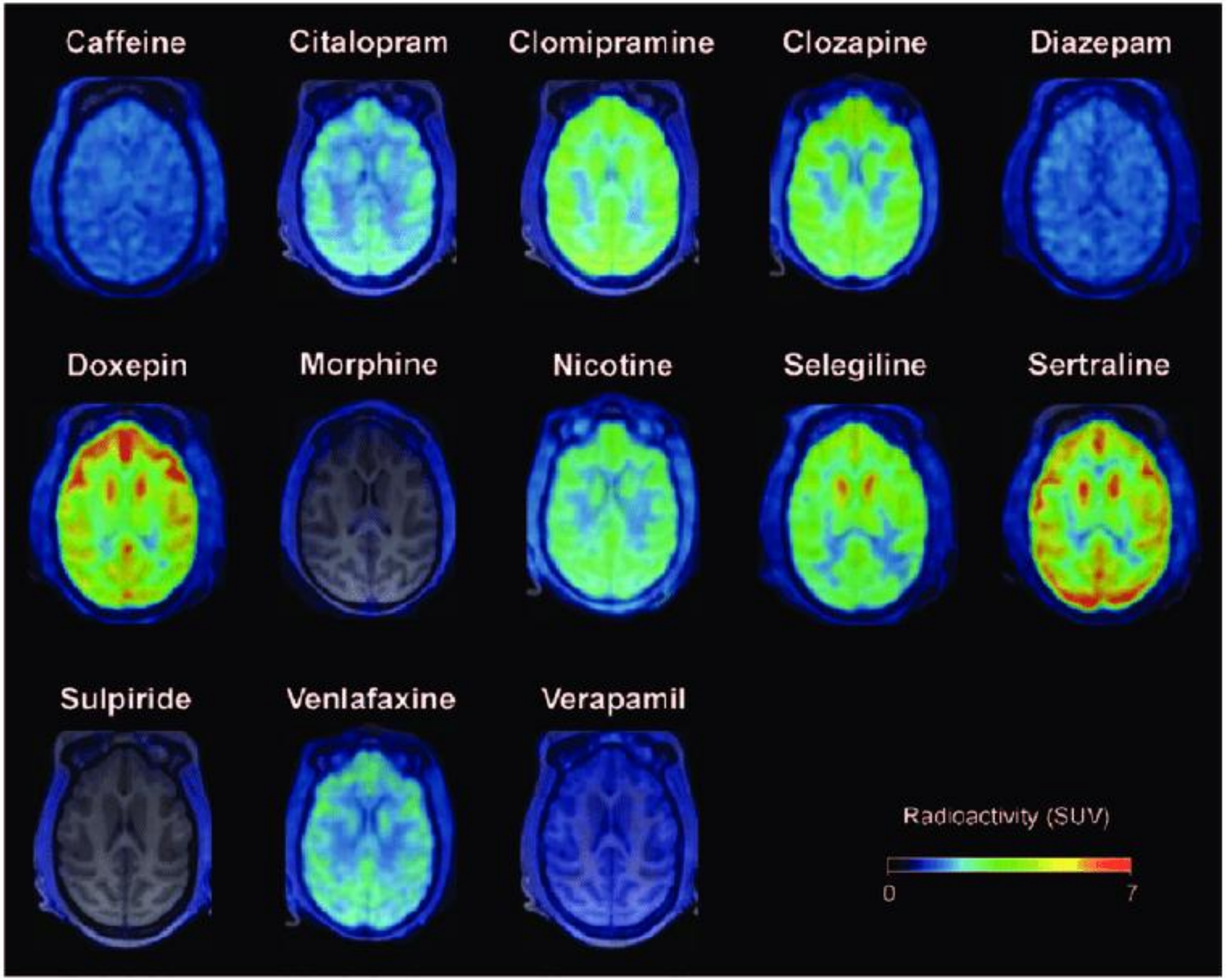
**Brain**
**visual stimulation**

**Brain**
**intellectual activity**



# Drugs


Caffeine
Citalopram
Clomipramine
Clozapine
Diazepam
Doxepin
Morphine
Nicotine
Selegiline
Sertraline
Sulpiride
Venlafaxine
Verapamil
Radioactivity (SUV)
0
7

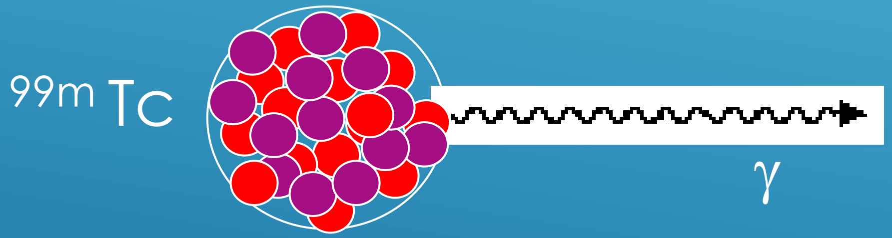
# SPECT- Single Photon Emission Computed Tomography

Used radionuclides are $\gamma$ (gamma rays) emitter

$^{99m}$**Tc** ($\tau$~6h)      $E\gamma = 140 KeV$

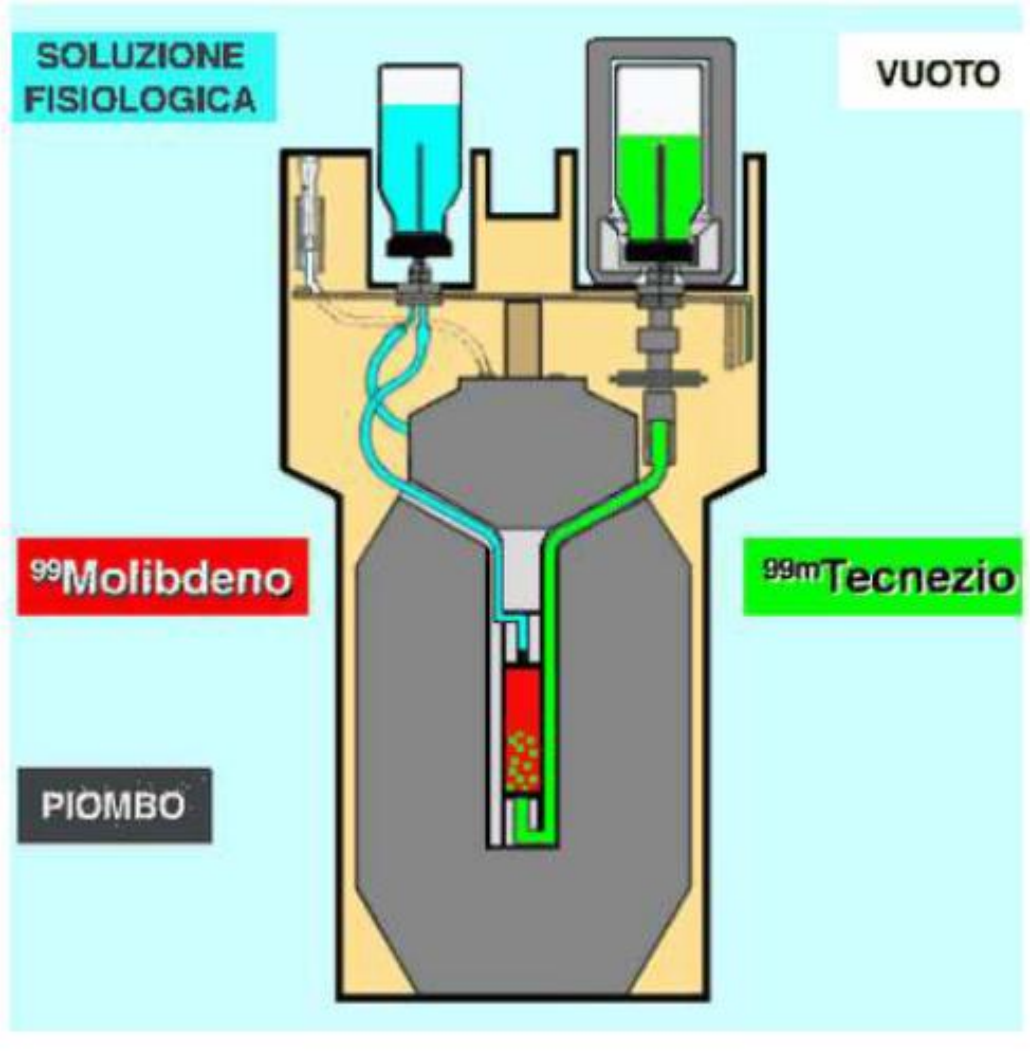
$^{99}$Technetium is obtained from the decay of $^{99}$Molibdenum

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




$$^{99m}Tc^* \rightarrow {}^{99m}Tc + \gamma$$

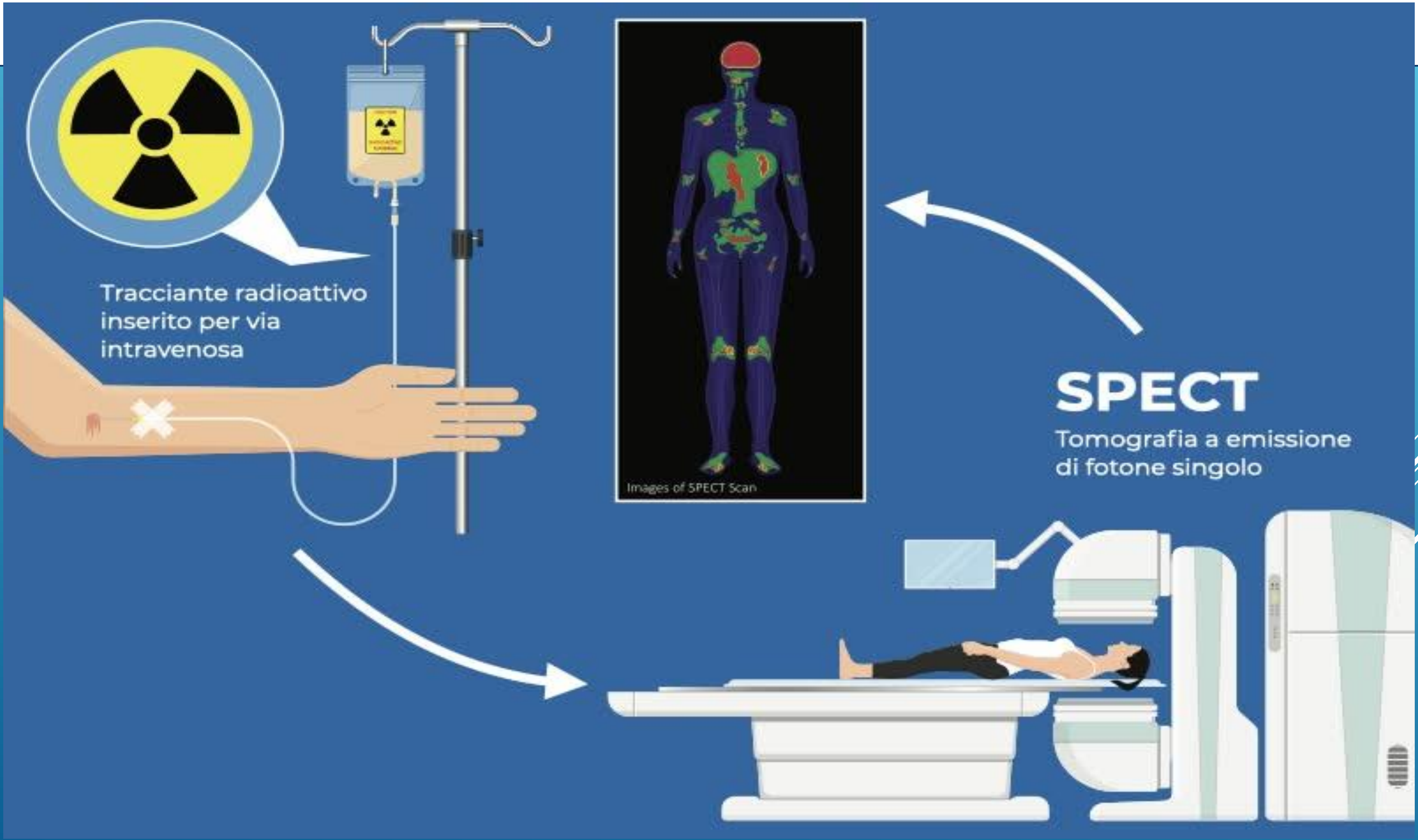
# $^{99m}$Tc generator




$^{99}Mo \rightarrow {}^{99m}Tc + \beta$

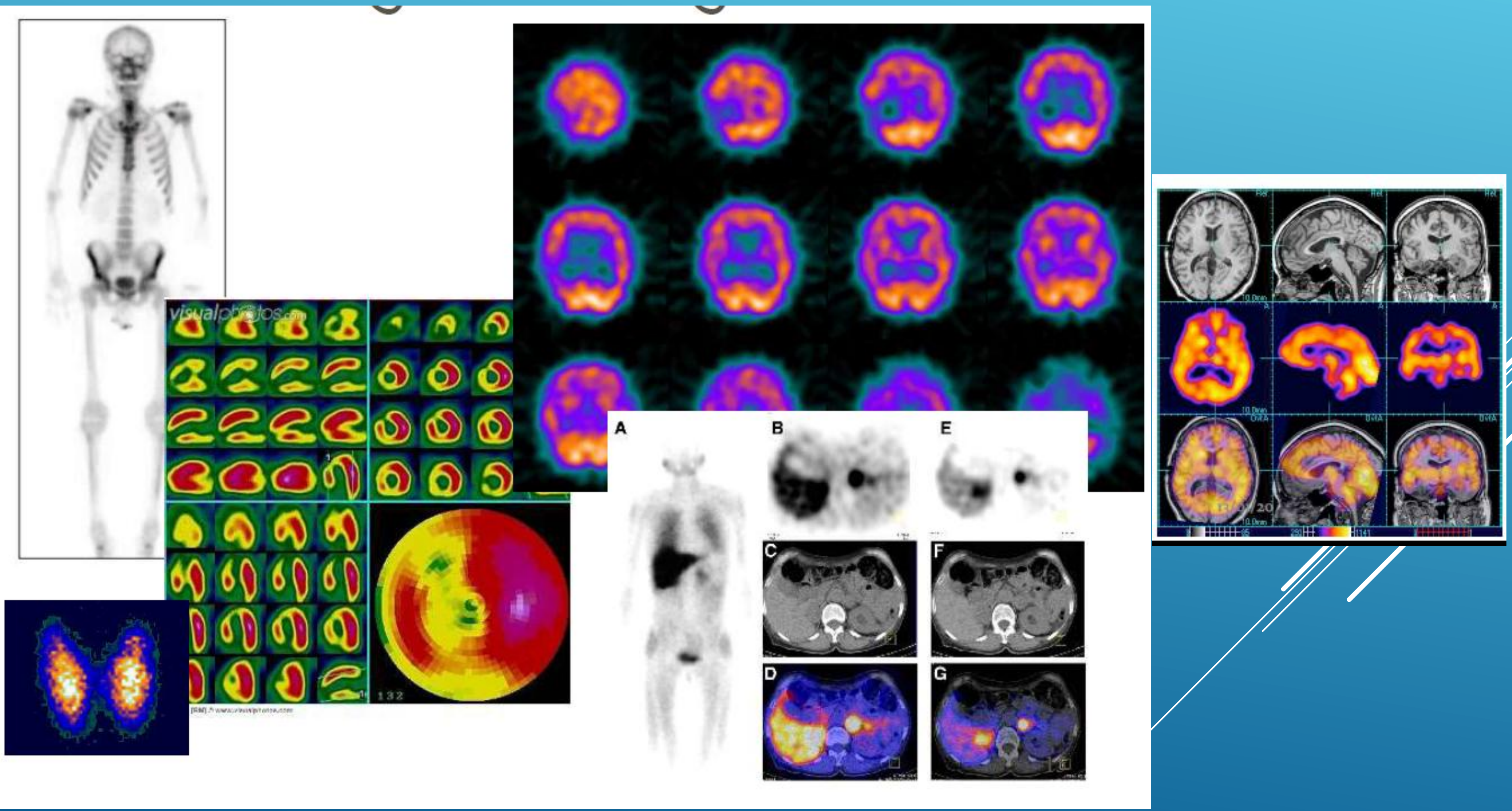
# SPECT = Single-Photon Emission Computed Tomography

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

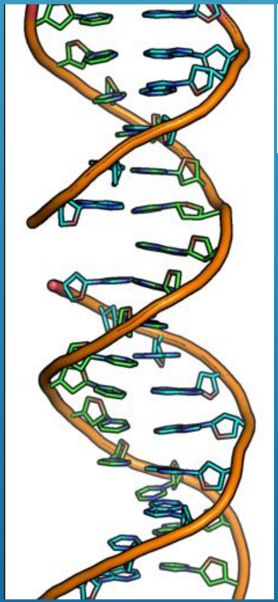
# RADIOTHERAPY

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

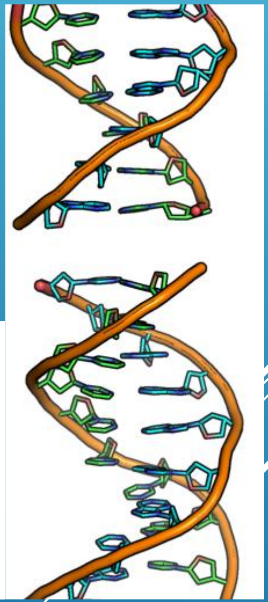
beams of proton or C ions at high energy, delivered by accelerators, are headed in direction of the disease, relasing they energy and destroying ill cells, and only **very few healty cells** along the trajectory are destroyed

# Beam of particles or em radiation hits a DNA double elix



**Single break**
**REPARAIBLE IN SOME CASES**

**Double break**
**PERMANENT DAMAGE**
**IRREPARABLE**



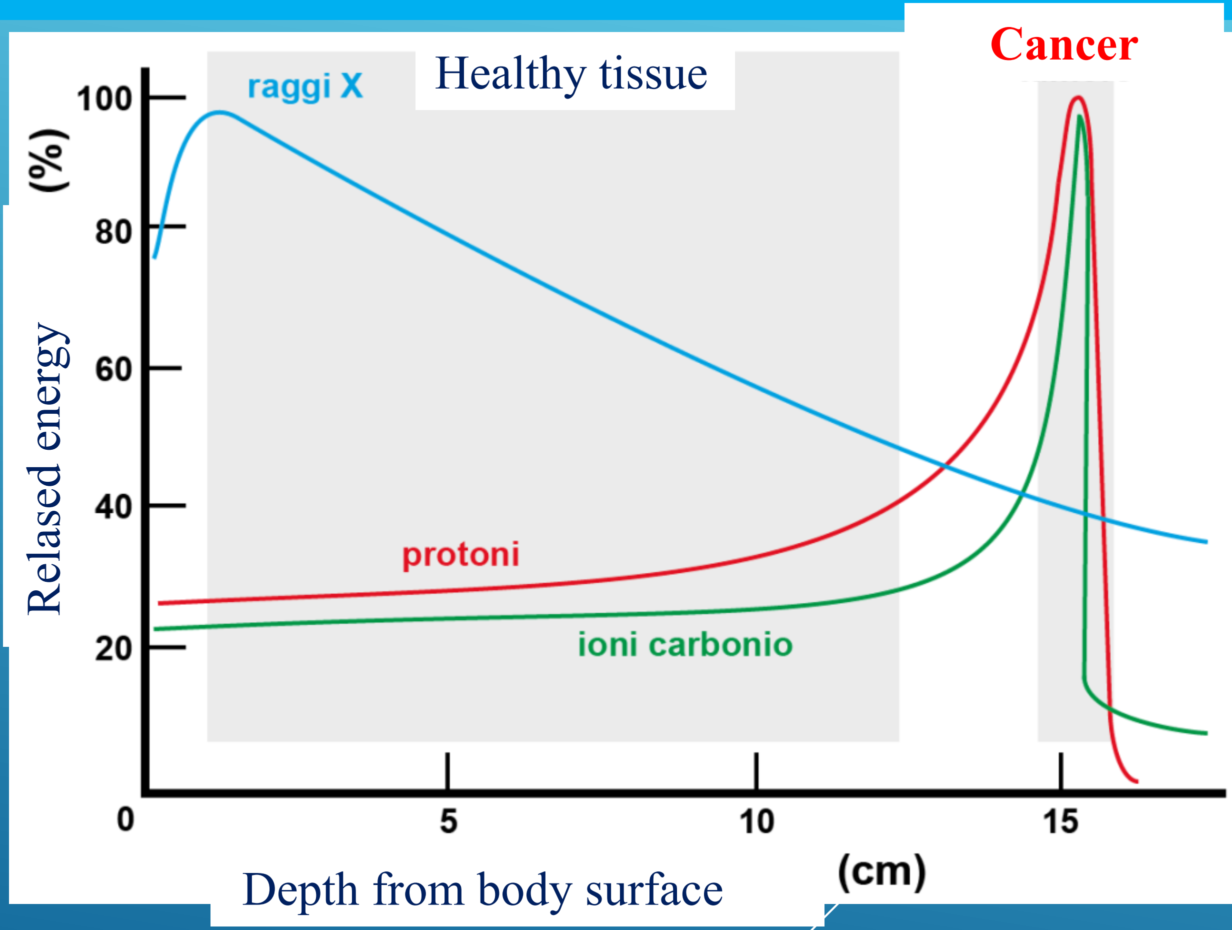
**e.m. radiation X or γ ray**

**Proton or Carbon beam**

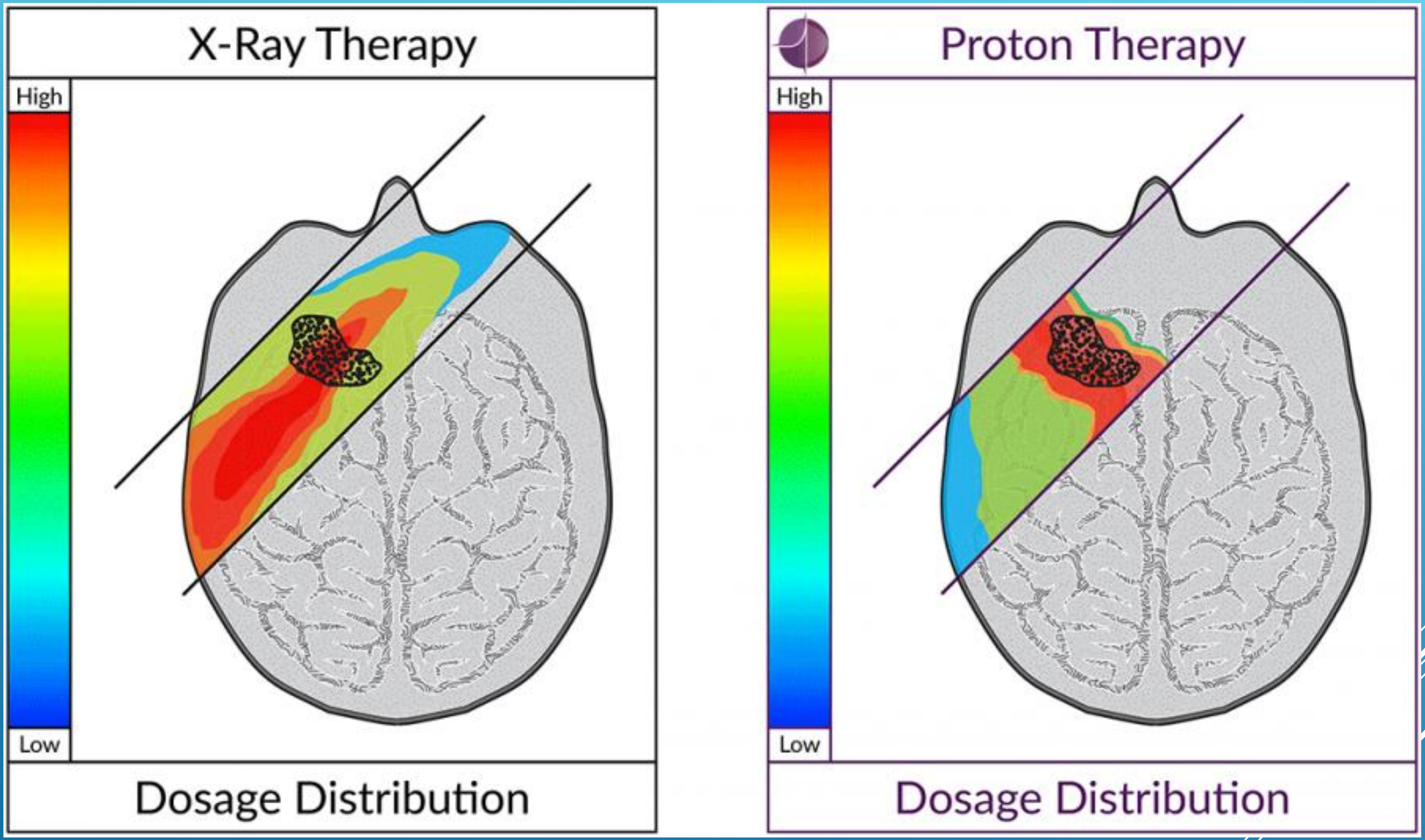
# Difference of Relased Energy in the body by radiotherapy and hadrontherapy

Hadrontherapy respect to the conventional radiotherapy is

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

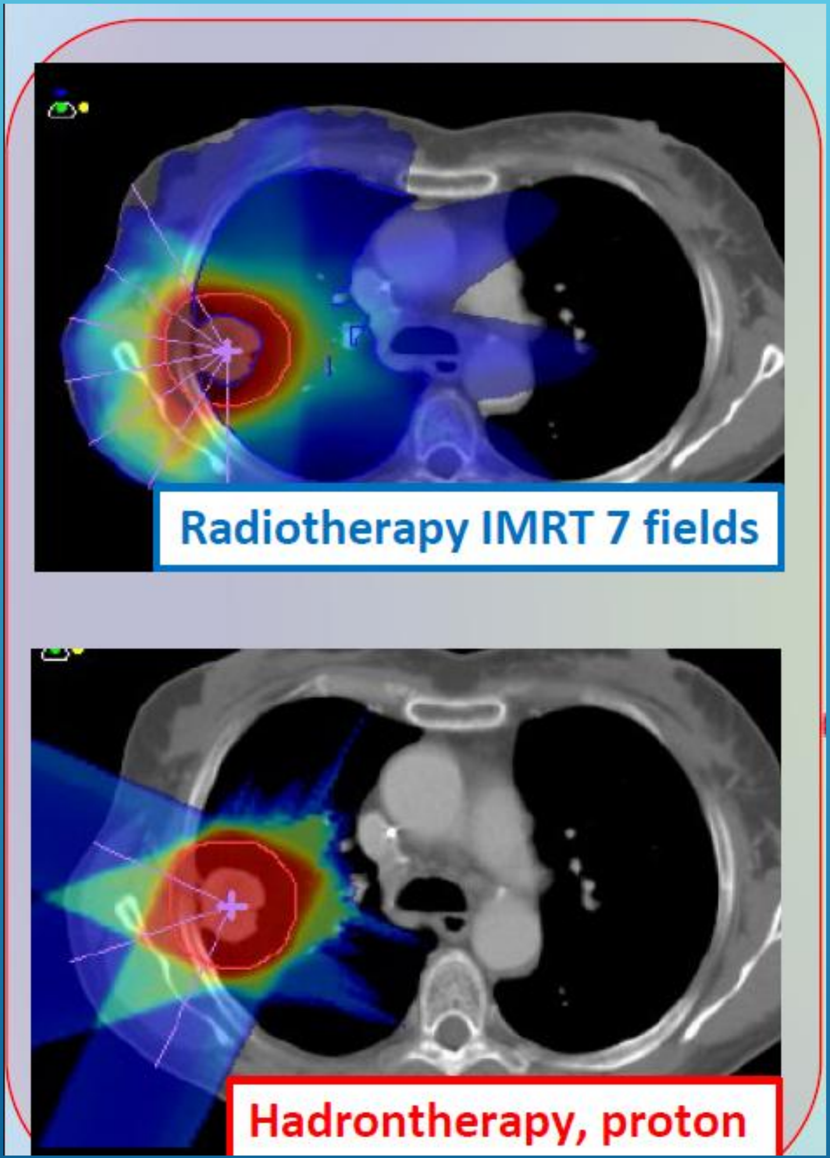


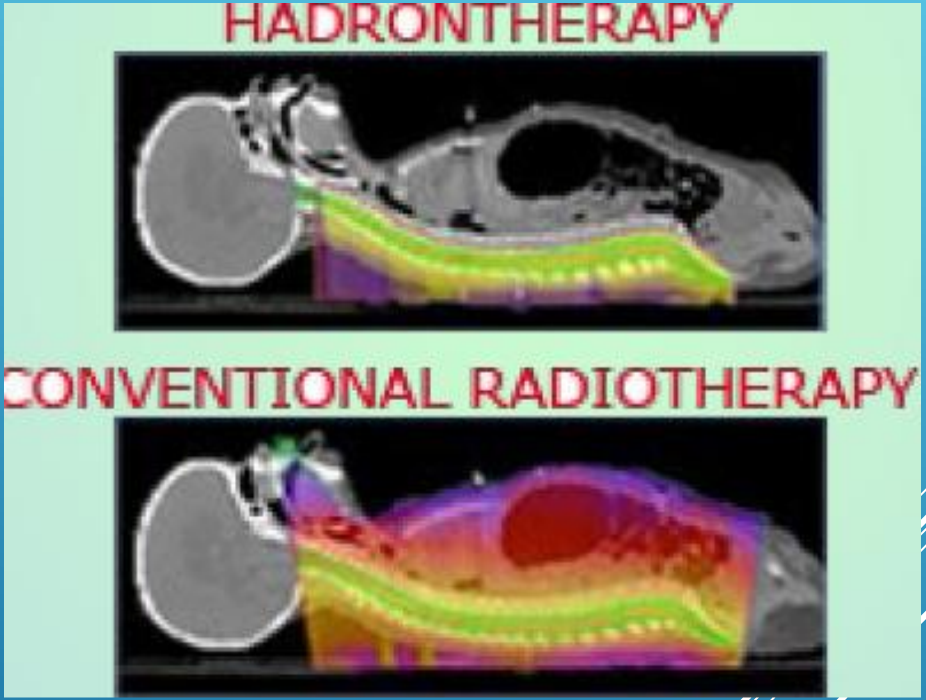
# X-γ radiotherapy vs hadronterapy




**Vantage : a smaller good healt 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 radionaclide to fight deep cancer

- Today high energy radiations, in combination with chemotherapy and surgey, are usualy employed.

# HADRONTERAPY IN ITALY

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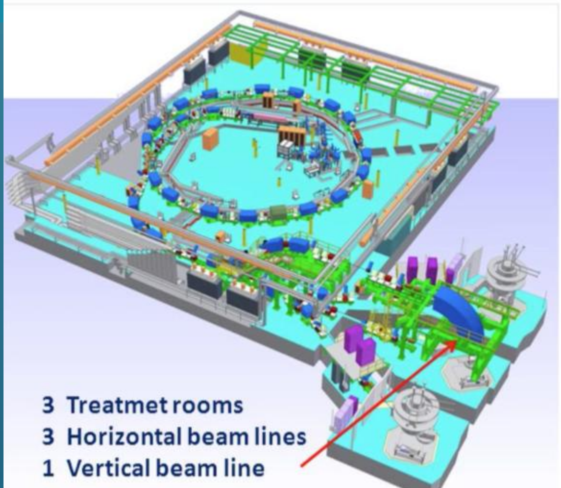
## CNAO (Centro Nazionale di Adroterapia Oncologica) @ Pavia




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

p E : [60, 250] MeV

$C^{6+}$ E : [120, 400] MeV/u

Syncrotron (26 m diameter)

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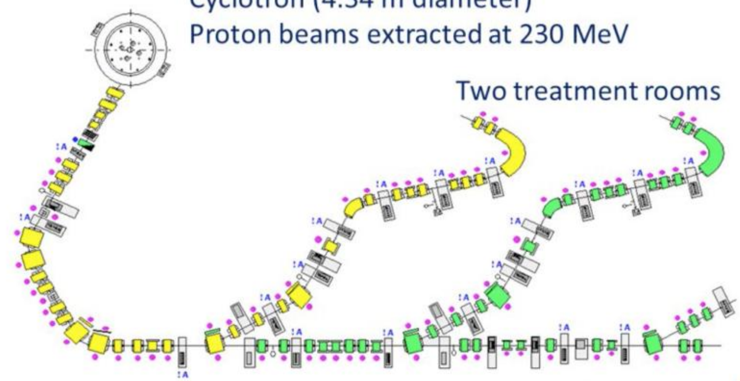
## ATreP (Agenzia Provinciale per la Protonterapia) @ Trento




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

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## CATANA (Centro di Adroterapia e Applicazioni Nucleari Avanzate) @ LNS (Laboratori Nazionali del Sud) - Catania

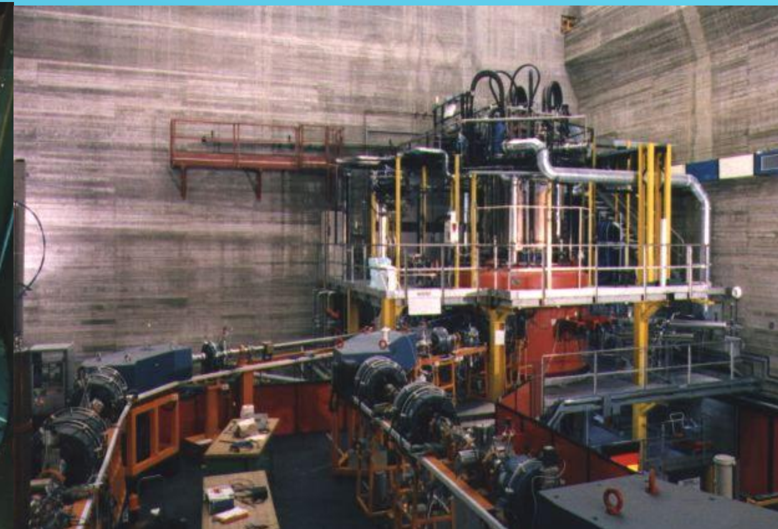
INFN

CATANA treatment room

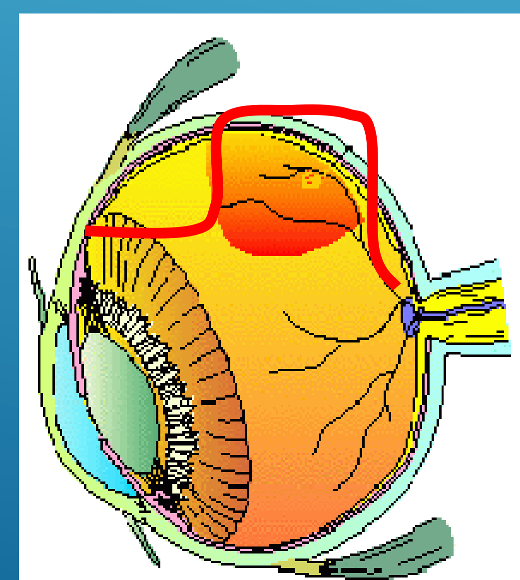
- Uses 62 MeV proton beams accelerated by the Cyclotron at LNS
- Allows the treatment of ocular tumors
- Operating since 2002 with approximately 500 patients treated to date

# Proton Therapy – INFN LNS - CATANA

# Proton Therapy – INFN LNS – «CATANA»



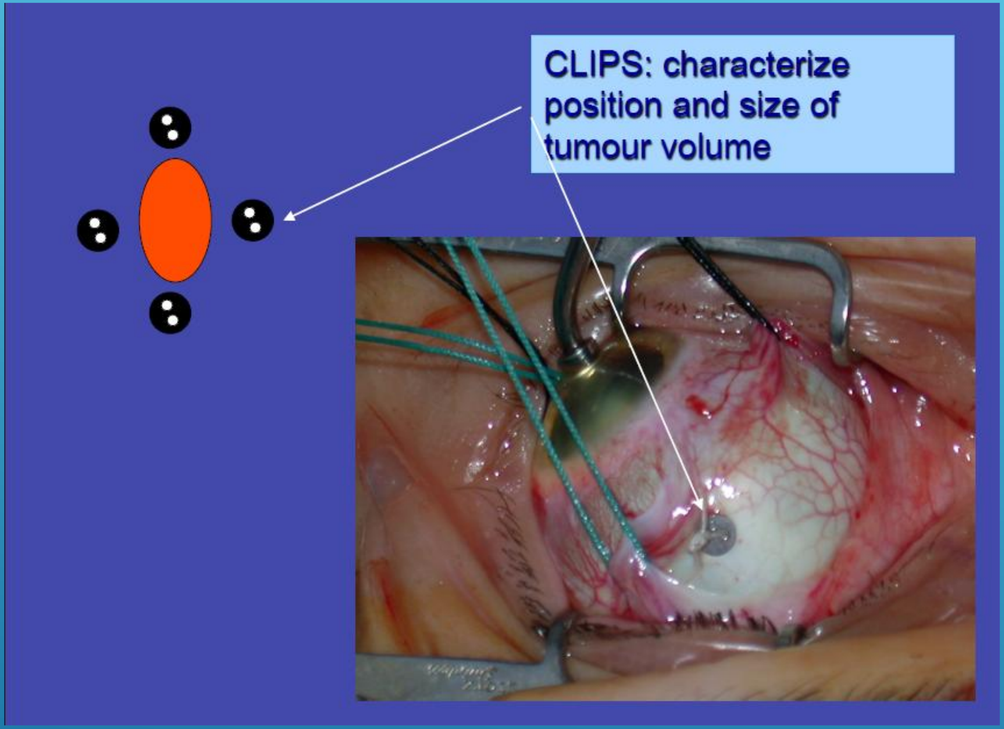
Protons with energy of 62 MeV, delivered by the cyclotron, are used against ocular melanoma



Maximum depth of 3 cm in the biological tissue

# Surgical Phase

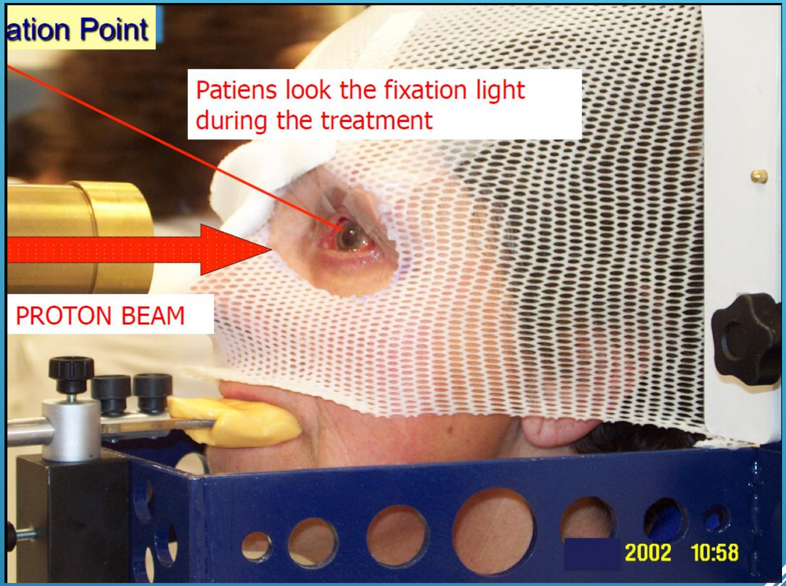
The surgeon applies four metal clips on the surface of the eye around the tumor.




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

# Treatment phase

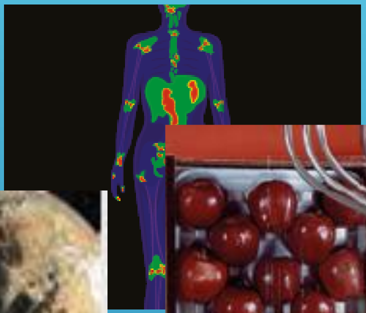
The patient is finally ready to undergo the treatment...

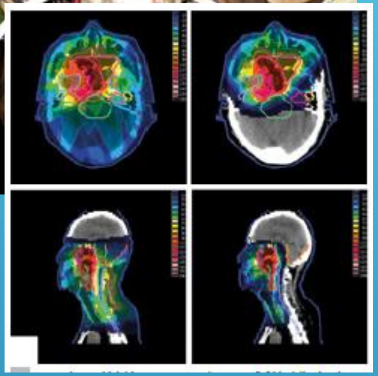



...divided into four sessions (one per day for four consecutive days), each lasting about a minute

# 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.**