U.T.E.F.
2024 - 2025

Contributi della Fisica alla Diagnostica Medica

Prof. Mauro Gambaccini

Un po' di storia

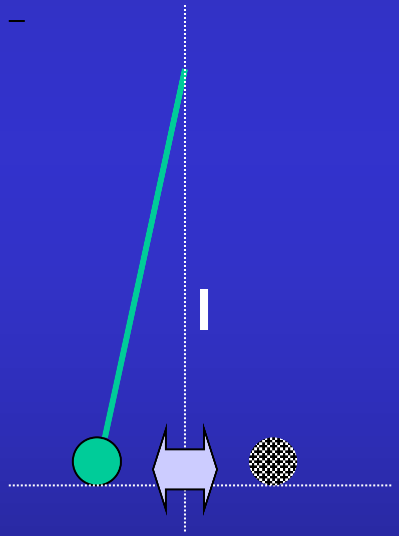
- ✓ In passato la FISICA e la MEDICINA non avevano una ben definita linea di demarcazione
- ✓ La medicina quantitativa venne introdotta nel 17° secolo
- ✓ Questo tipo di medicina cercava di seguire il metodo sperimentale proprio di Galileo
- ✓ La sede che per prima usò questo tipo di approccio fu l'Università PADOVA dove Galileo fu studente di Medicina prima di passare allo studio della Matematica

GALILEO

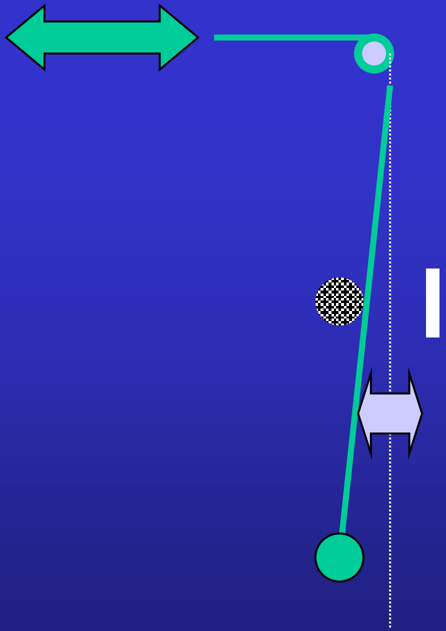
SANTORIO

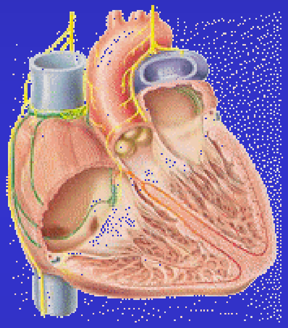
Verifica l'isocronia delle oscillazioni del pendolo col proprio ritmo cardiaco

Misura le pulsazioni di pazienti con un pendolo a lunghezza variabile



$$T = 2\pi \sqrt{(l/g)}$$

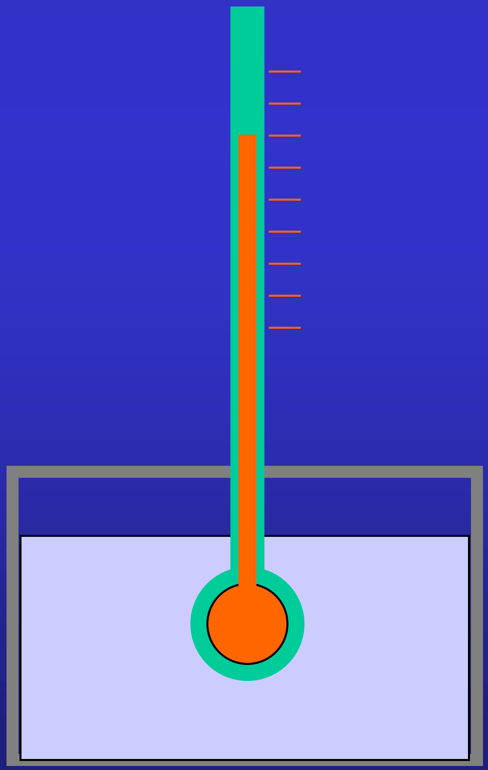




batt/ minuto	L(cm)
40	55,9
50	35,7
60	24,8
70	18,2
80	13,9
90	11
100	8,9
110	7,39
120	6,2

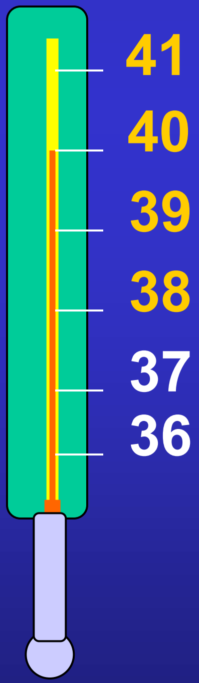
GALILEO

Studiando l'espansione dei liquidi inventa un termometro ad alcool



SANTORIO

Modifica il termometro e lo utilizza per la misura della febbre



Col progredire della Scienza e delle conoscenze altre discipline assumono importante identità nell'ambito scientifico

SCIENZE

BIOLOGICHE
MEDICHE

SCIENZE

MATEMATICHE
FISICHE
CHIMICHE

FISICA

Fisica Nucleare
Fisica delle Particelle Elementari
Astrofisica
Fisica Teorica
Fisica dello Stato Solido
Fisica Medica
Fisica Ambientale
- ecc.
-

Fisica Medica

Branca della fisica applicata alla medicina e alla biologia

Sviluppo di strumenti per verificare il corretto funzionamento degli organi (DIAGNOSI)

Sviluppo di dispositivi per ripristinare il corretto funzionamento degli organi (TERAPIA)

Questa branca della Fisica ha ricevuto un grande impulso da

grazie a due importanti scoperte:

1894	Raggi X.	Wilhelm Conrad Roentgen
1896.	Radioattività.	Henry Bequerel & Coniugi Curie

APPLICAZIONI NELL TERAPIA ONCOLOGIA

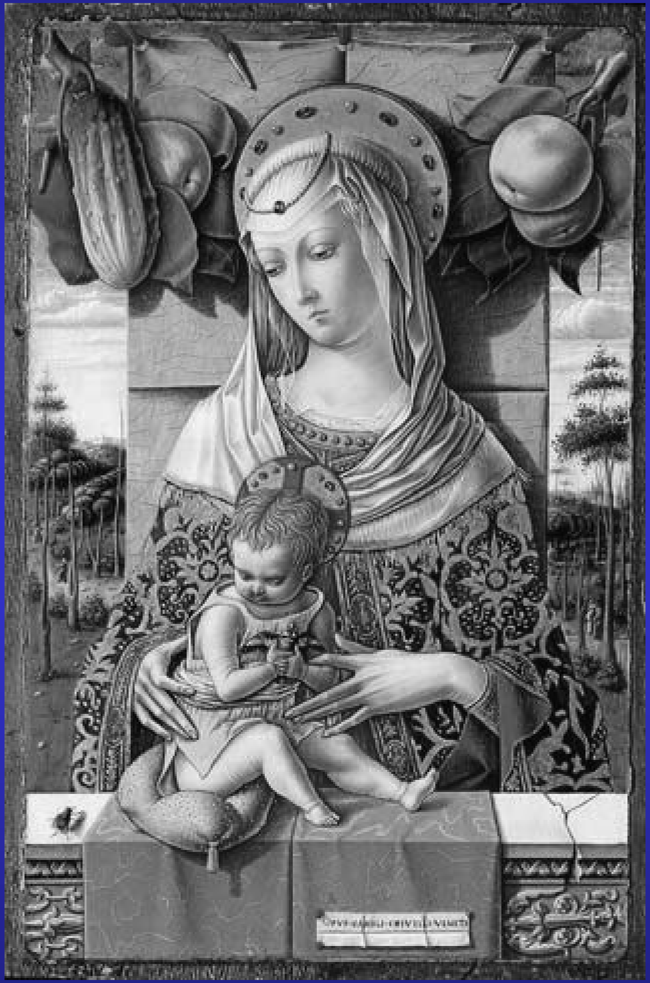
Radioterapia

APPLICAZIONI NELLA DIAGNOSTICA MEDICA

Radiologia	Diagnostica per immagini
Medicina Nucleare	Diagnostica per immagini

IMMAGINE DIGITALE (BIANCO E NERO)

Livelli di grigio



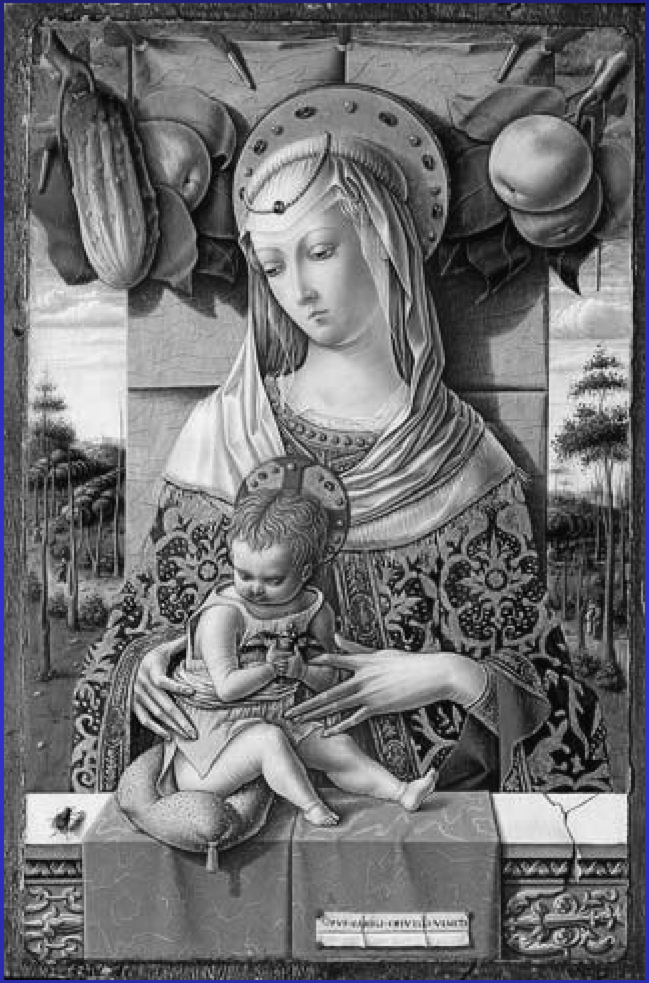
MATRICE NUMERICA

COLONNE

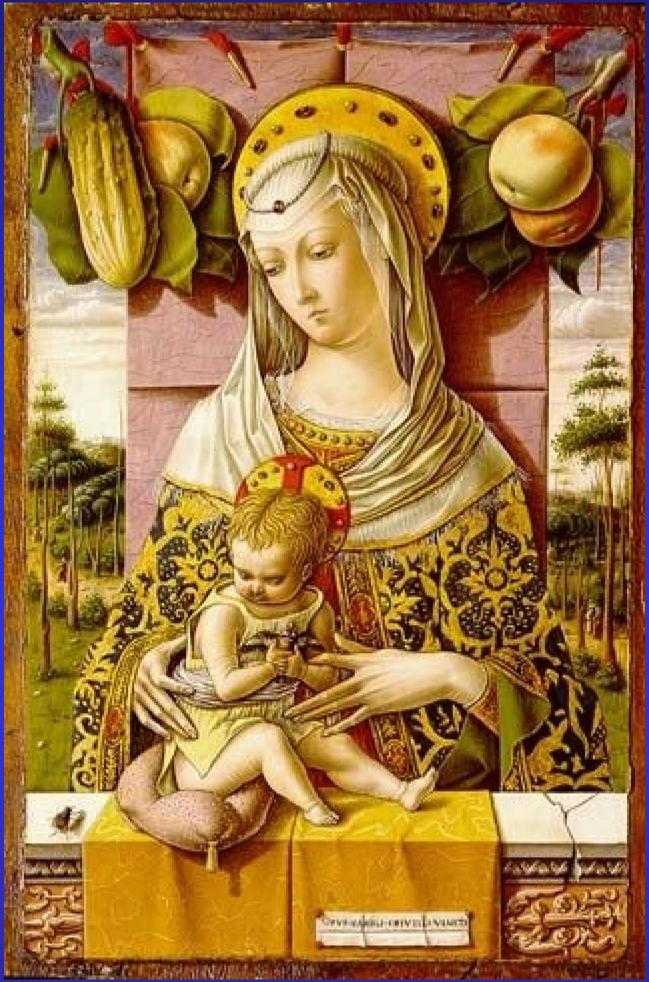
RIGHE

	123	163	264	186	163	150	186	264	186	163	163	123	150	186	163
	163	133	150	163	186	264	163	150	163	186	186	163	264	163	186
	186	163	186	186	264	150	264	186	186	264	264	186	150	264	264
	264	186	163	264	150	163	186	163	264	150	150	264	163	186	150
	150	264	18	150	186	163	150	18	150	186	186	150	163	150	186
	186	150	16	186	163	264	186	16	186	163	163	186	264	186	163
	163	186	163	186	264	186	163	150	133	163	264	163	186	163	163
	264	163	186	264	148	150	264	264	163	264	163	264	150	264	264
	150	186	264	186	163	186	186	264	150	264	186	150	186	186	264
	186	264	186	163	186	150	148	163	186	186	264	186	150	148	186
	186	150	163	186	264	186	163	150	133	16	150	186	186	163	16
	163	186	186	264	16	18	16	186	148	18	186	163		16	18
	186	186	264	163	186	163	186	264	186	163	163	186	163	186	163
	[illegible]	[illegible]	[illegible]	264	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	

IMMAGINI DIGITALI

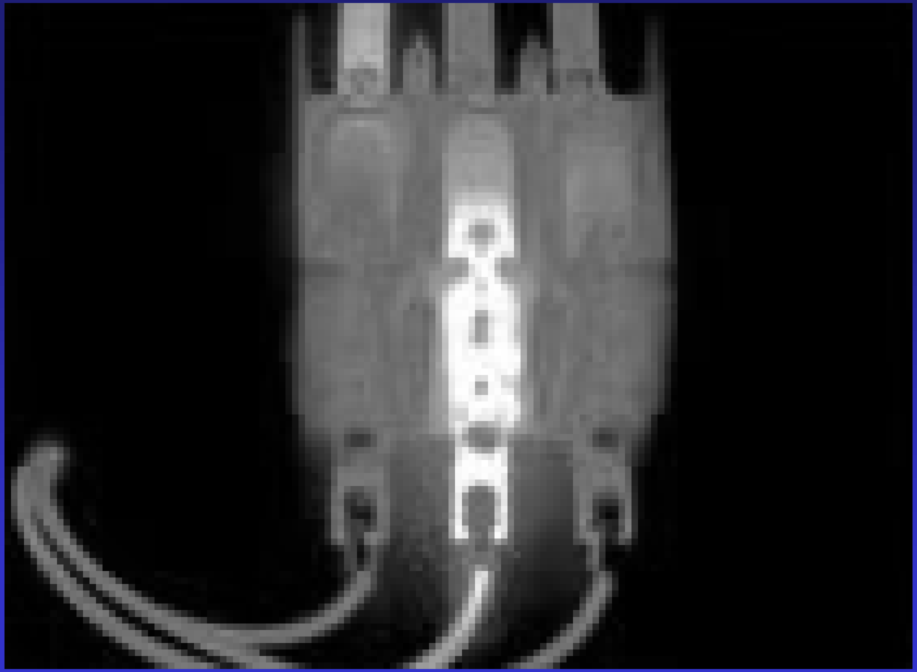


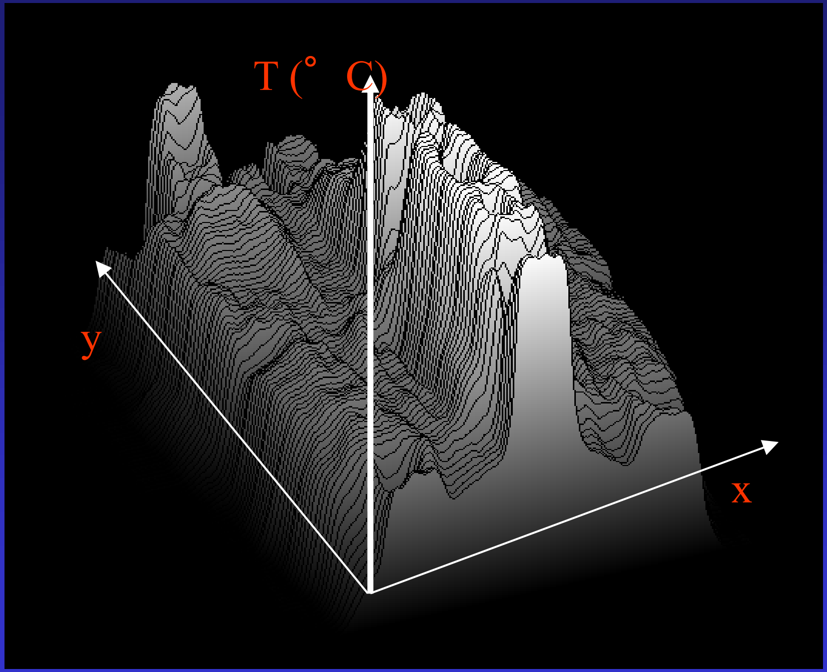
⬜	▒	▓	⬛
250	186	94	1

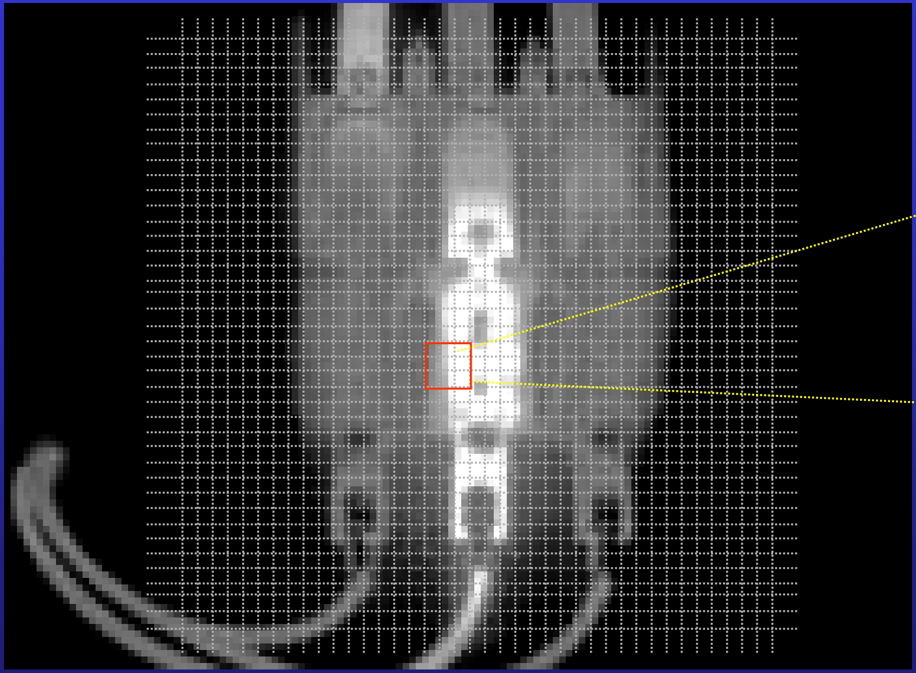


R	G	B
48	134	212

IMMAGINI DIGITALI O NUMERICHE

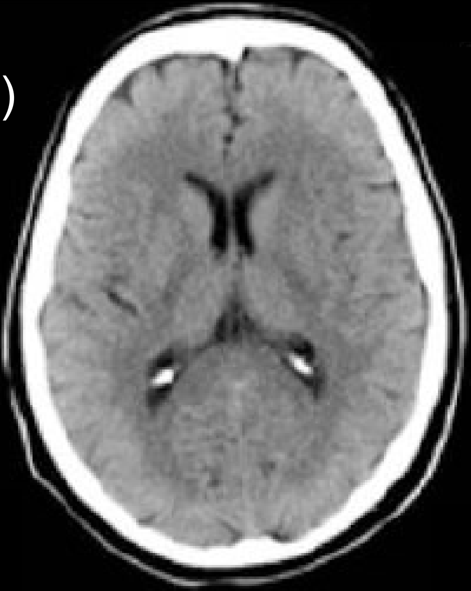




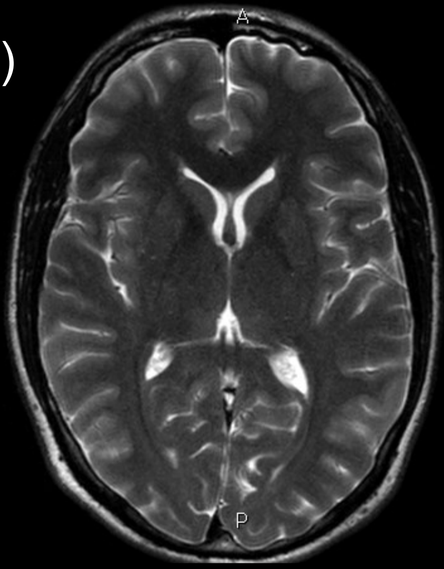


Temperatura ° C

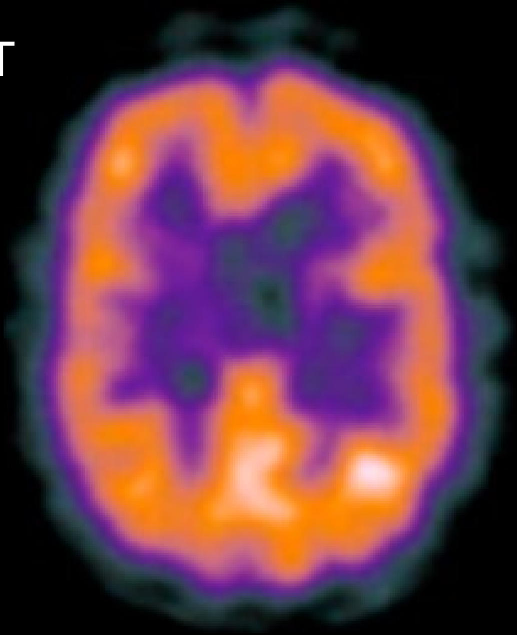
32.8	34.6	42.5	42.0	41.2
38.1	38.4	42.5	42.1	41.1
39.5	37.9	42.2	42.5	40.9
38.4	38.2	42.6	42.4	41.0
37.9	42.1	42.1	42.5	42.1
38.2	42.5	42.5	42.2	42.5



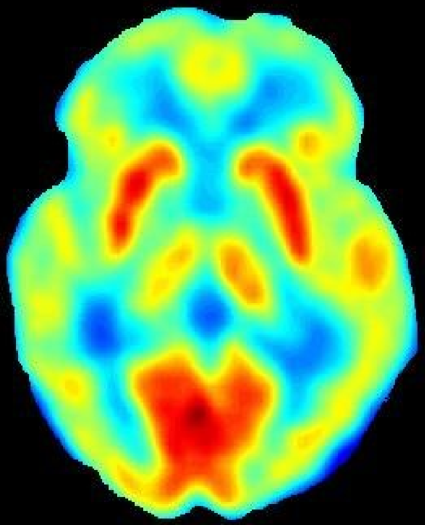
CT
(TAC)



NMR
(risonanza)

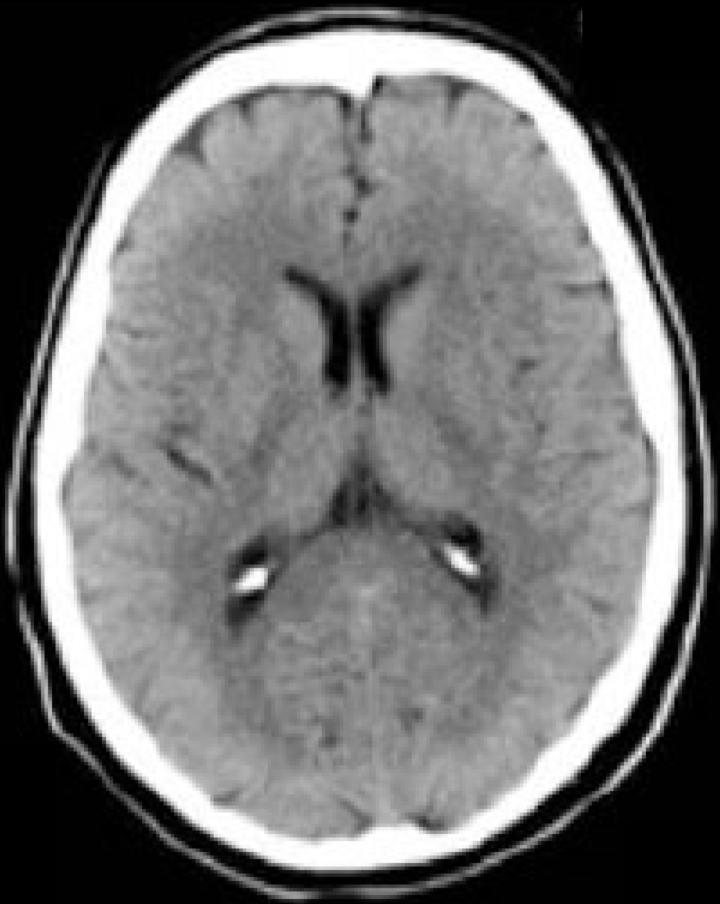


SPECT

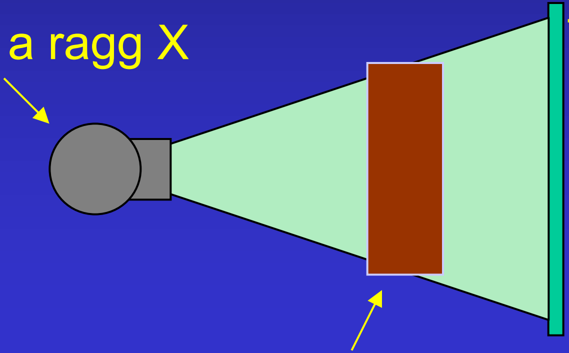


PET

CT (TAC)



Più di un secolo fa’ la prima radiogafia



Tubo a ragg X

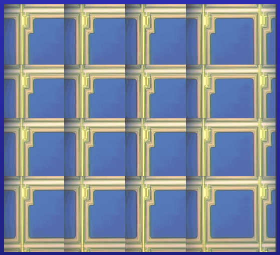
film radiografico

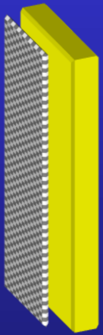
oggetto

1970
Schermi fluorescenti

1995
rivelatore a-Si pixel

(100 - 200 micron)



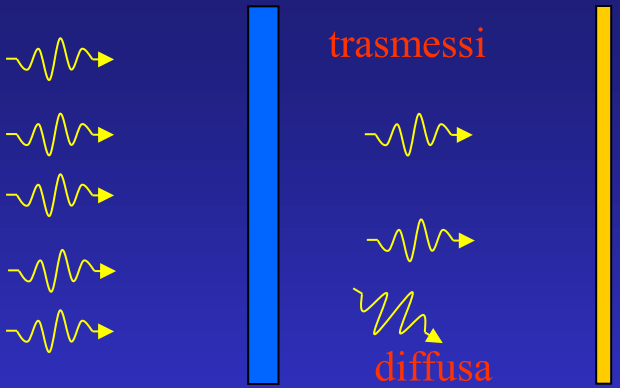


Schermo
fluorescente

ERA
della
DIGITALE RADIOGRAFIA

RAGGI X

incidenti



oggetto

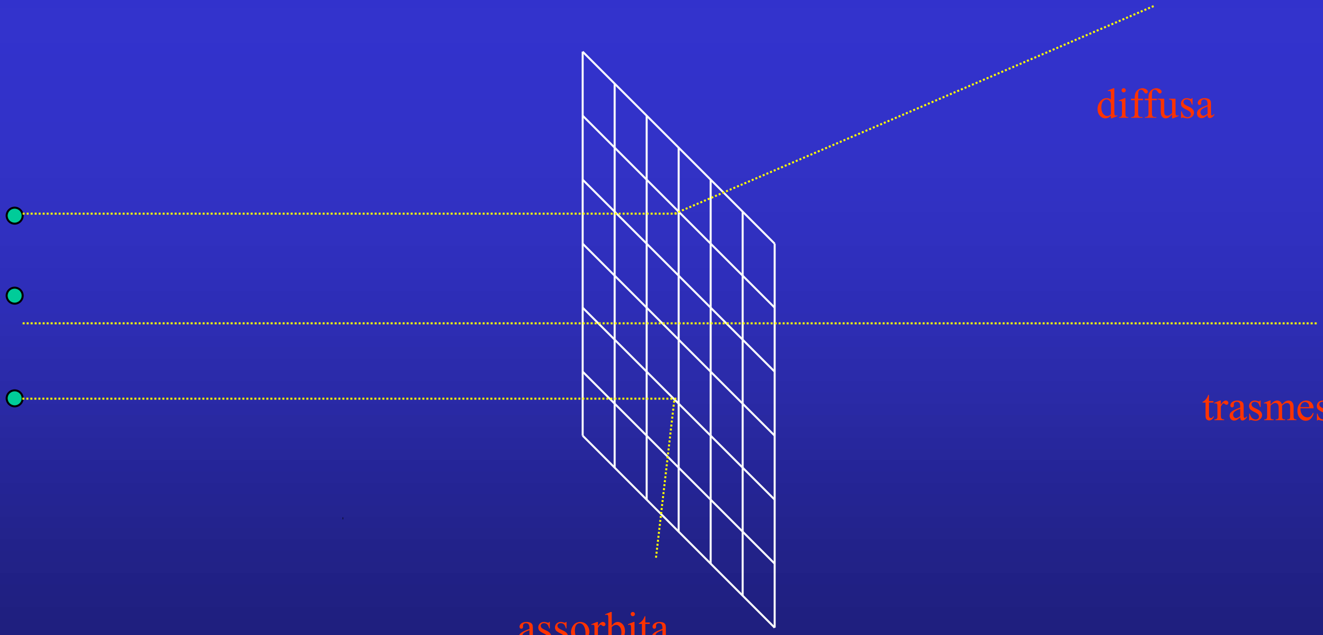
rivelatore

trasmessi

assorbiti

diffusa

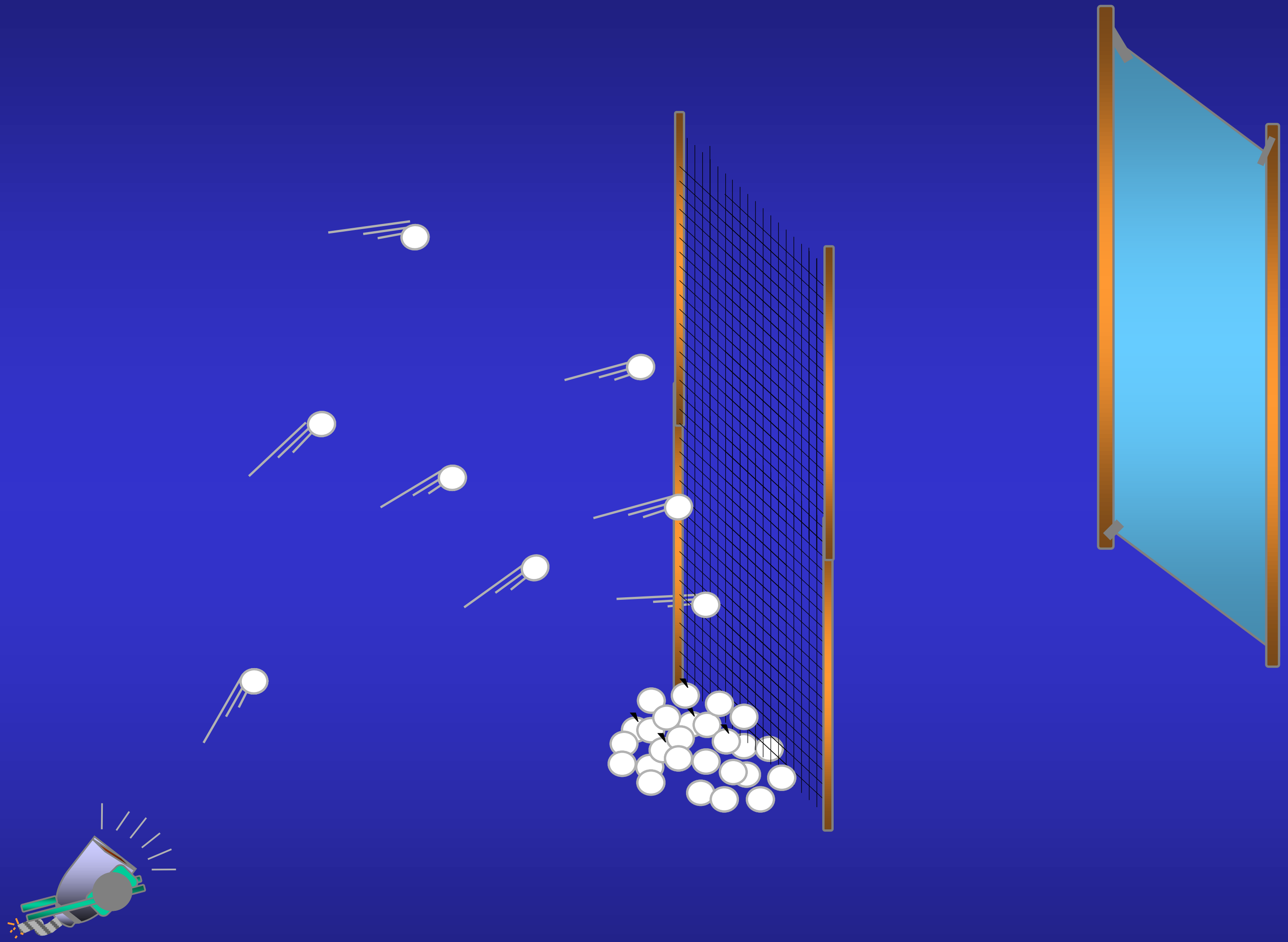
MODELLO

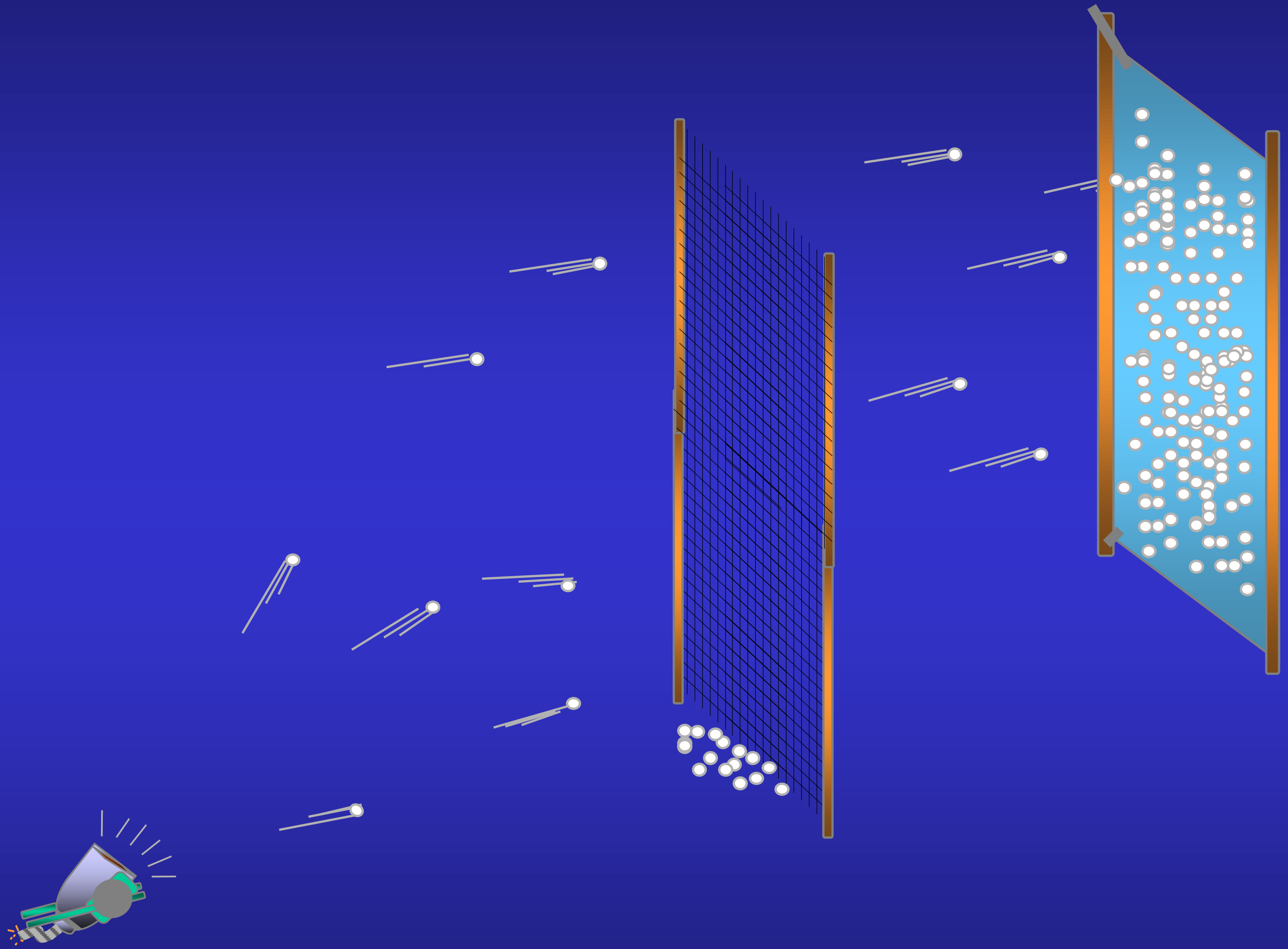


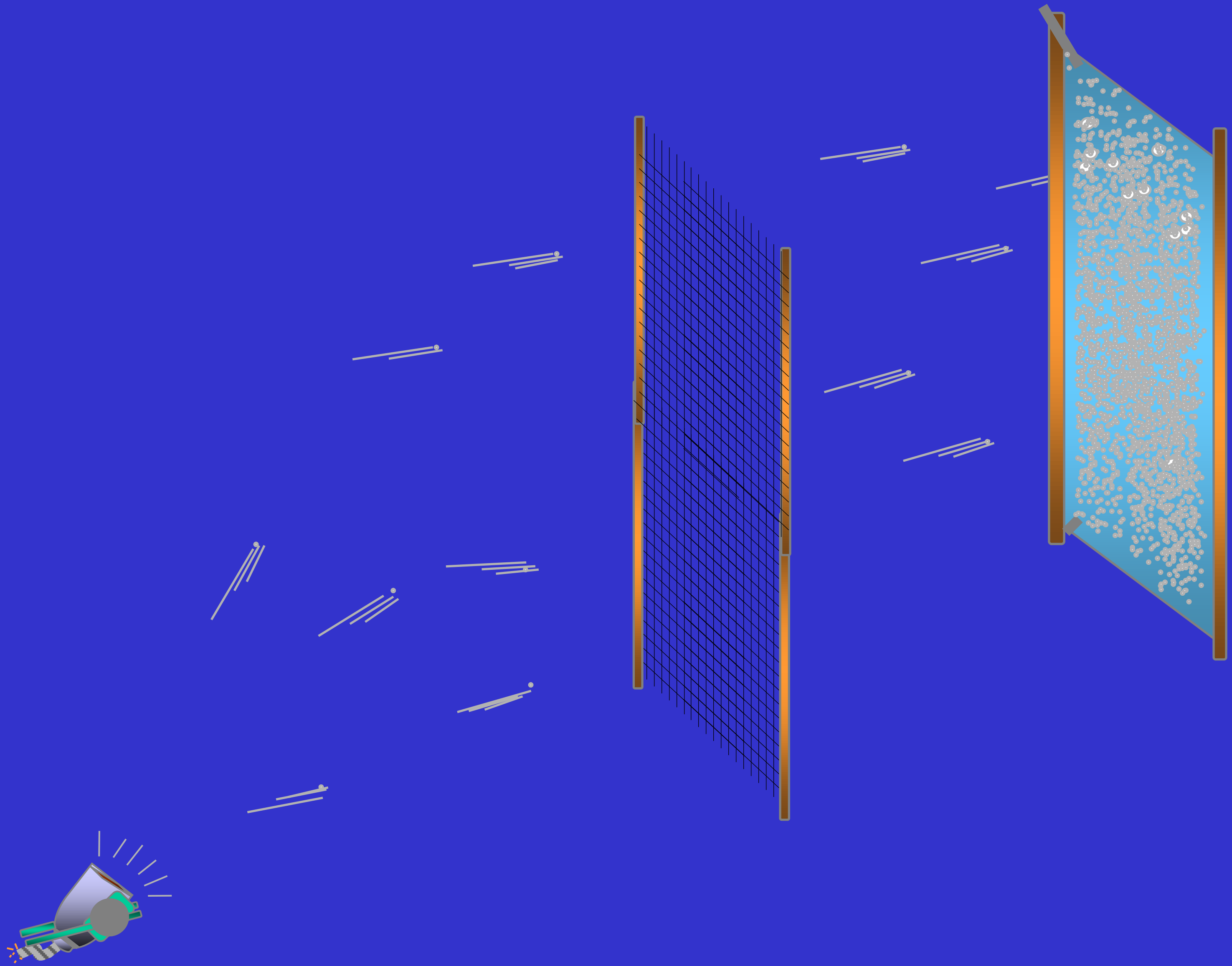
diffusa

trasmessa

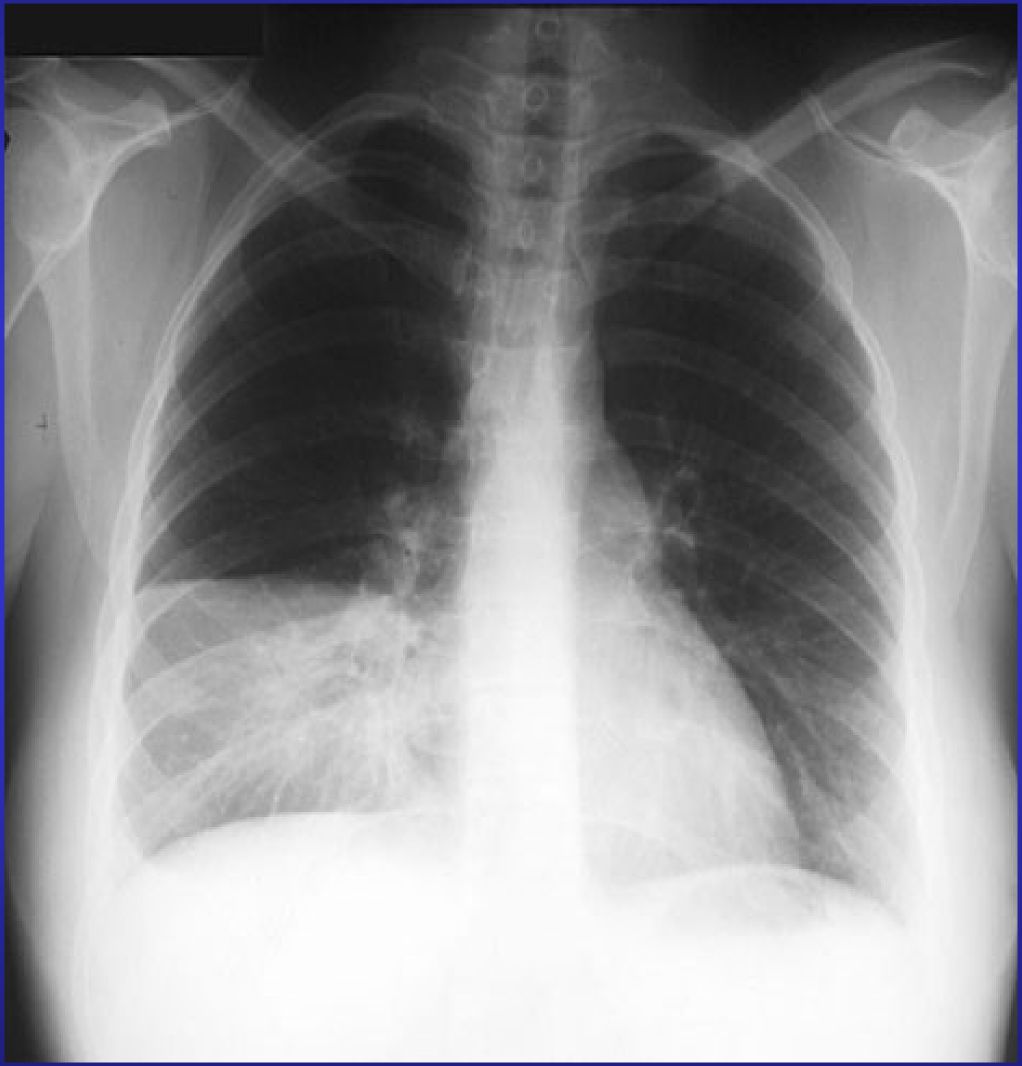
assorbita

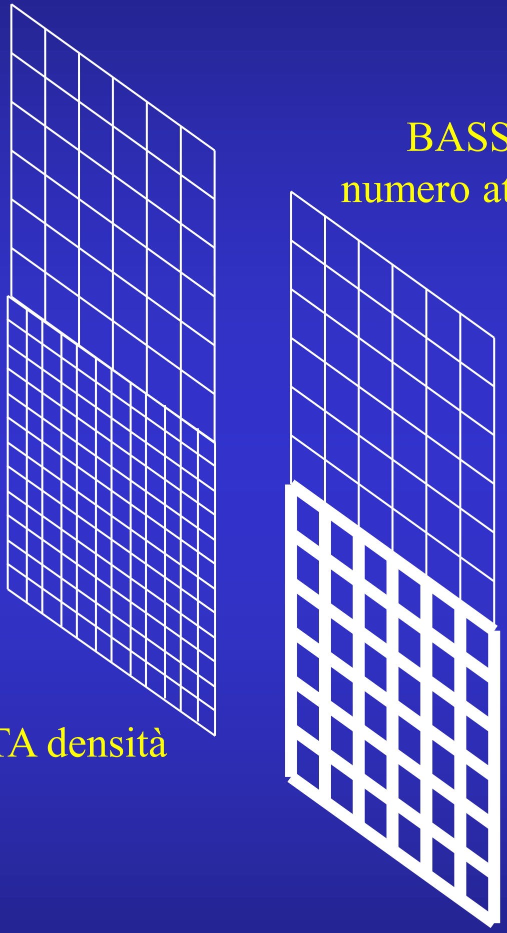






Esame radiografico del torace



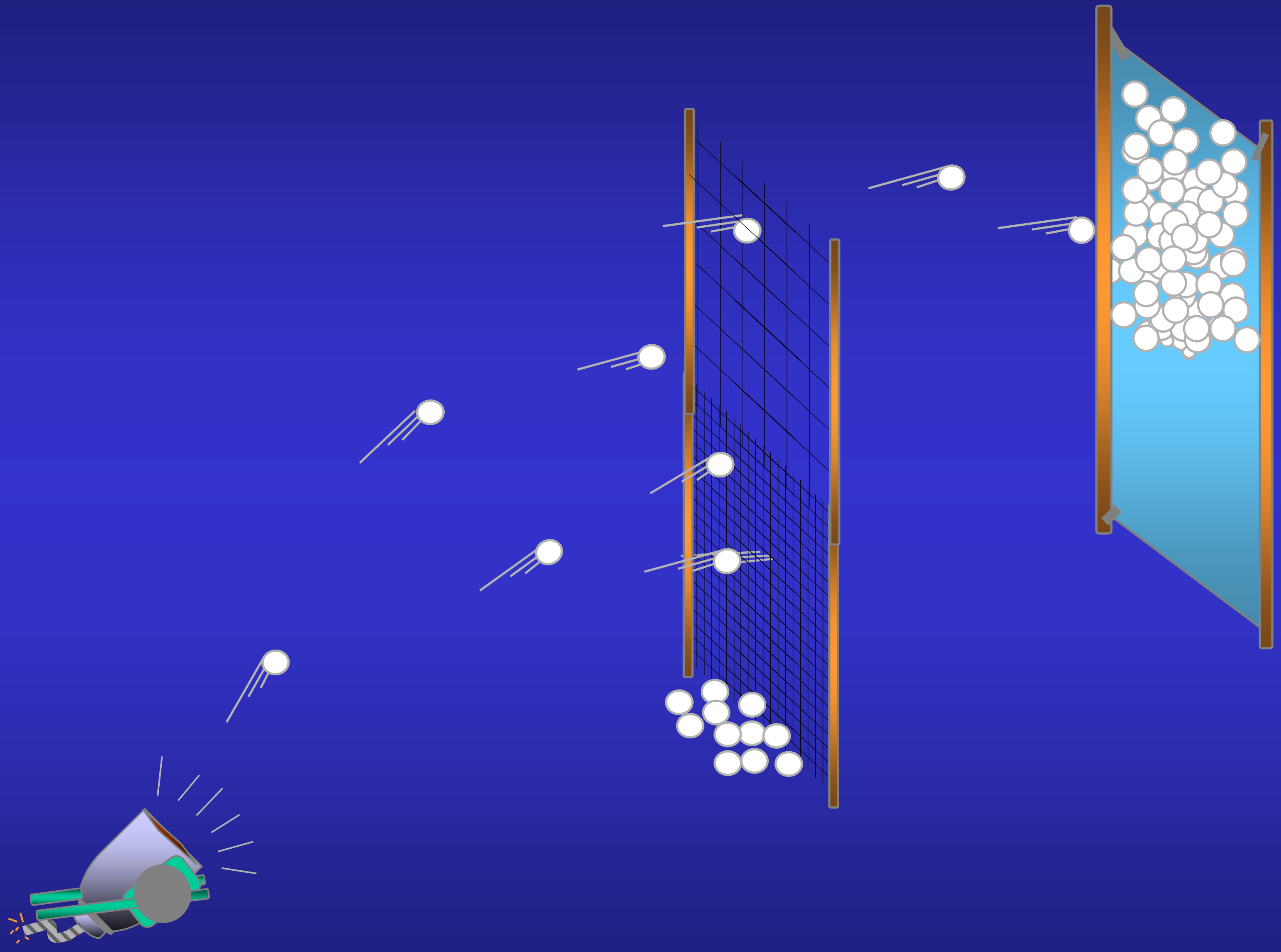


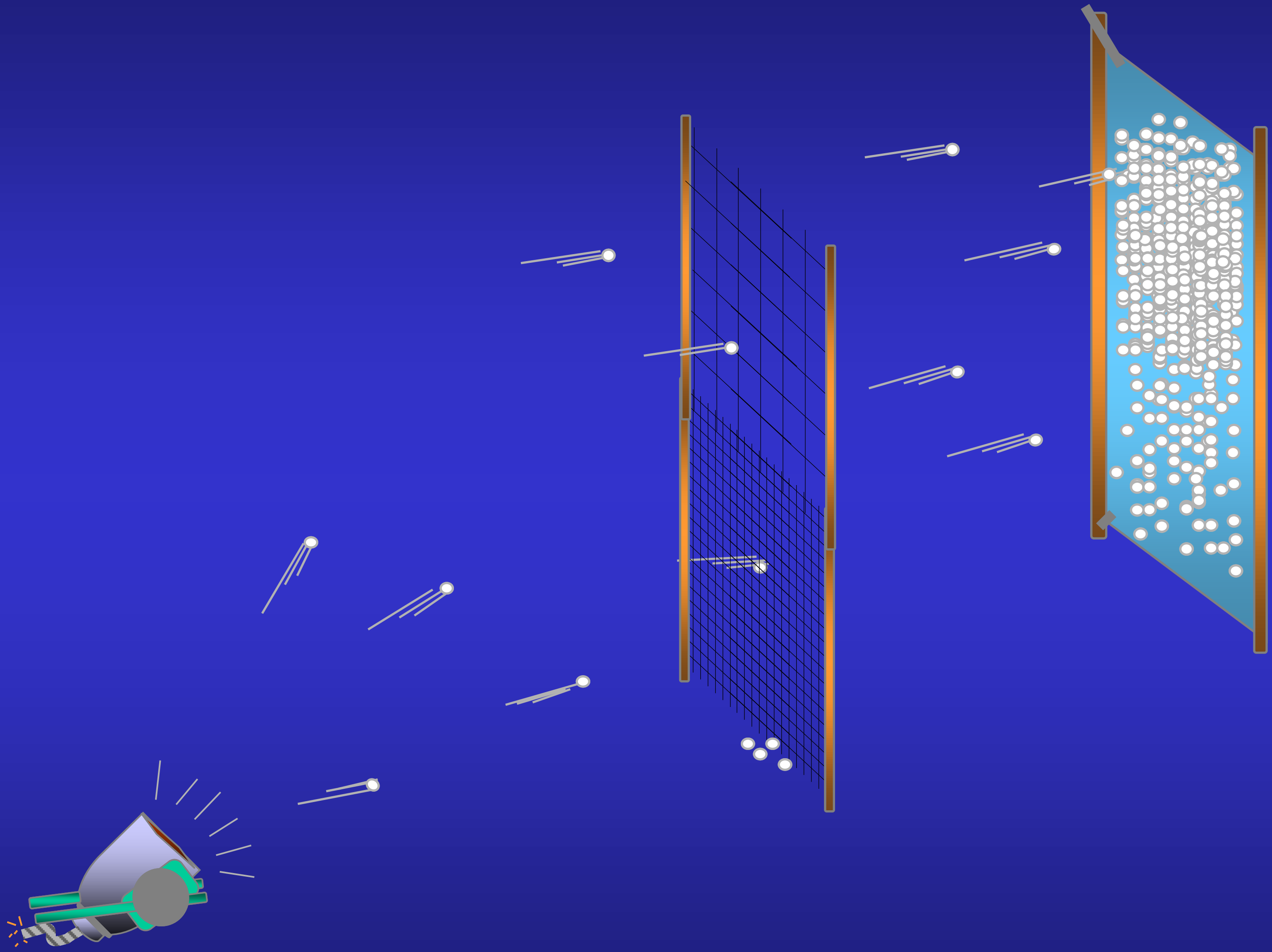
BASSA densità

BASSO
numero atomico

ALTA densità

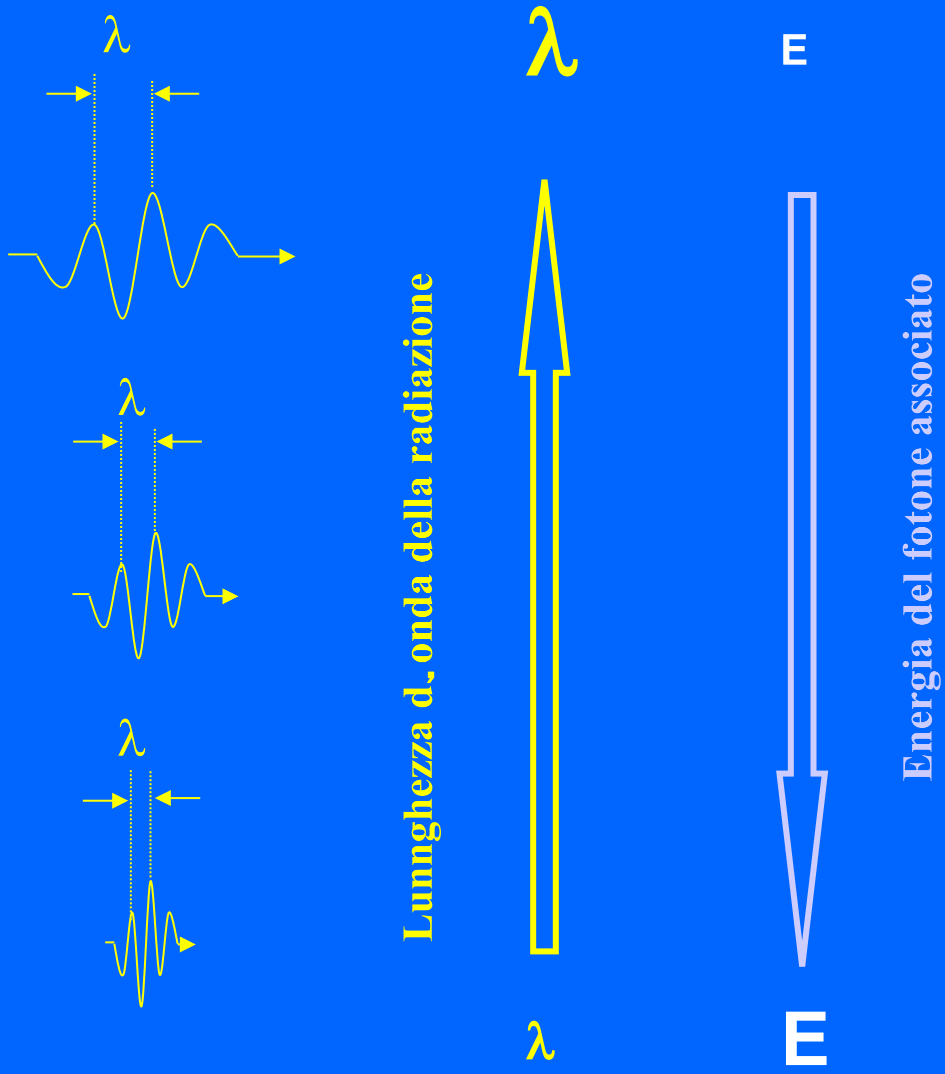
ALTO
numero atomico



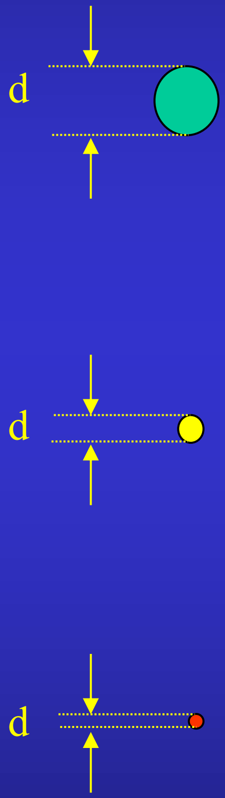


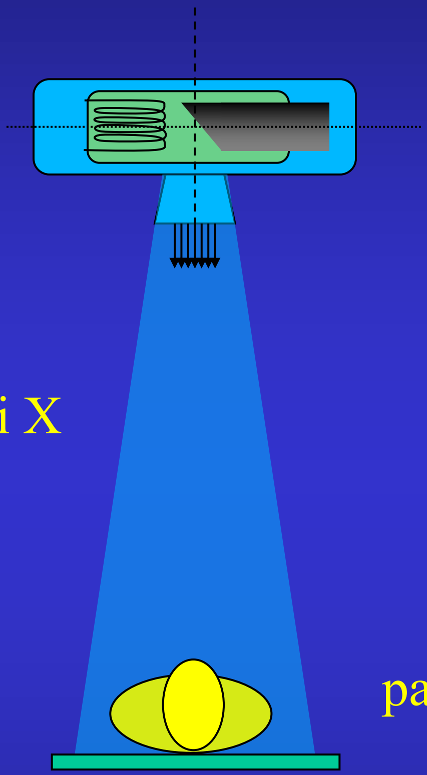
Raggi X

fotone
$E = hc/\lambda$


λ
λ
λ
λ
E
Lunnghezza d, onda della radiazione
Energia del fotone associato
λ
E

Palline



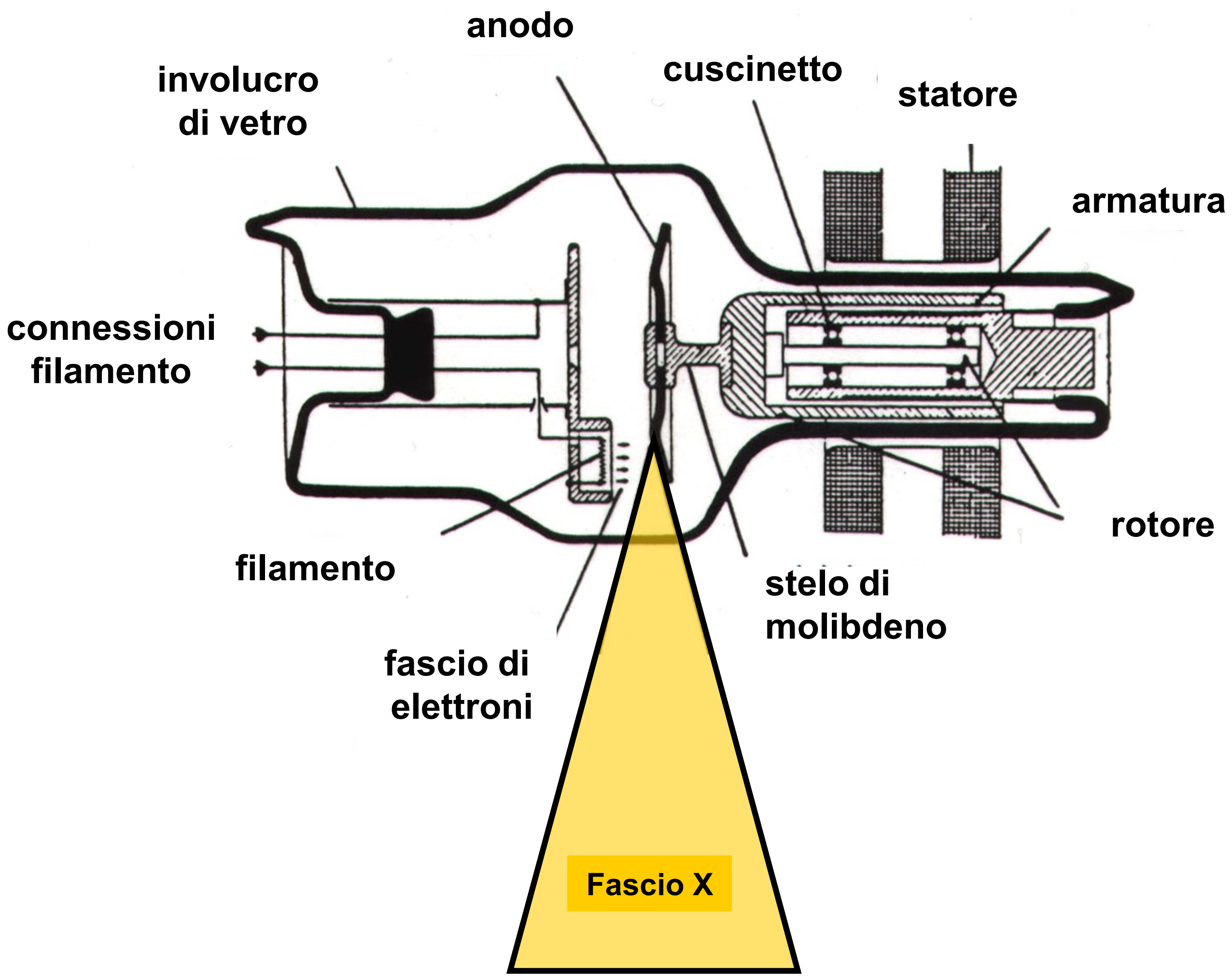


tubo a raggi X

Raggi X

paziente

rivelatore

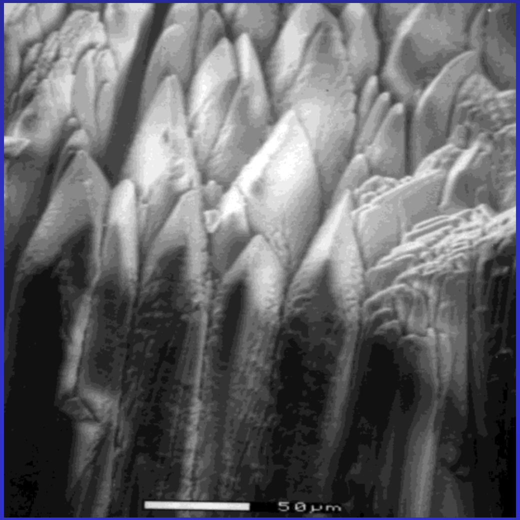

anodo
involucro di vetro
cuscinetto
statore
armatura
connessioni filamento
rotore
filamento
stelo di molibdeno
fascio di elettroni
Fascio X

kV (tensione)

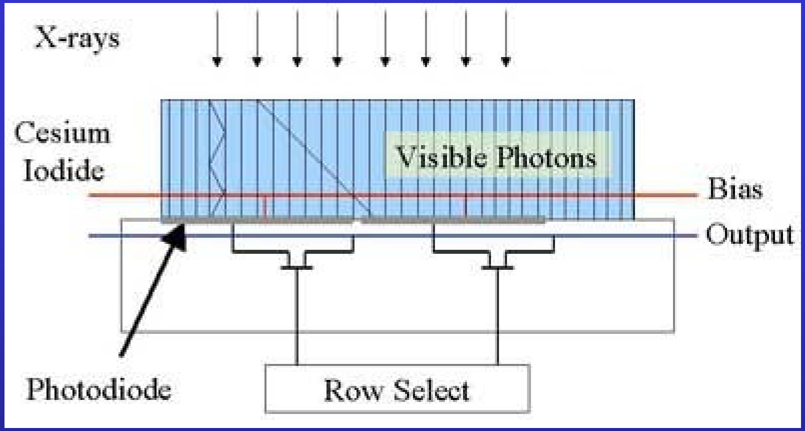
mA (corrente anodica)

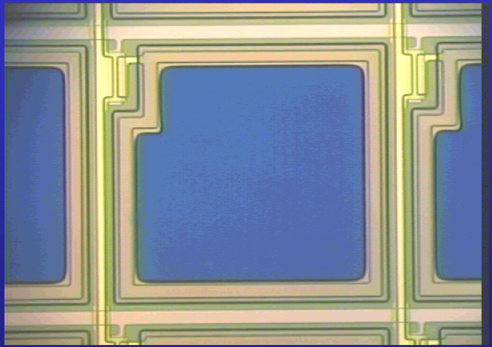
s (tempo di esposizione)

1929 x 2304 pixel
0.1 mm pitch
14 bit



CsI (Tl)
Ioduro di cesio

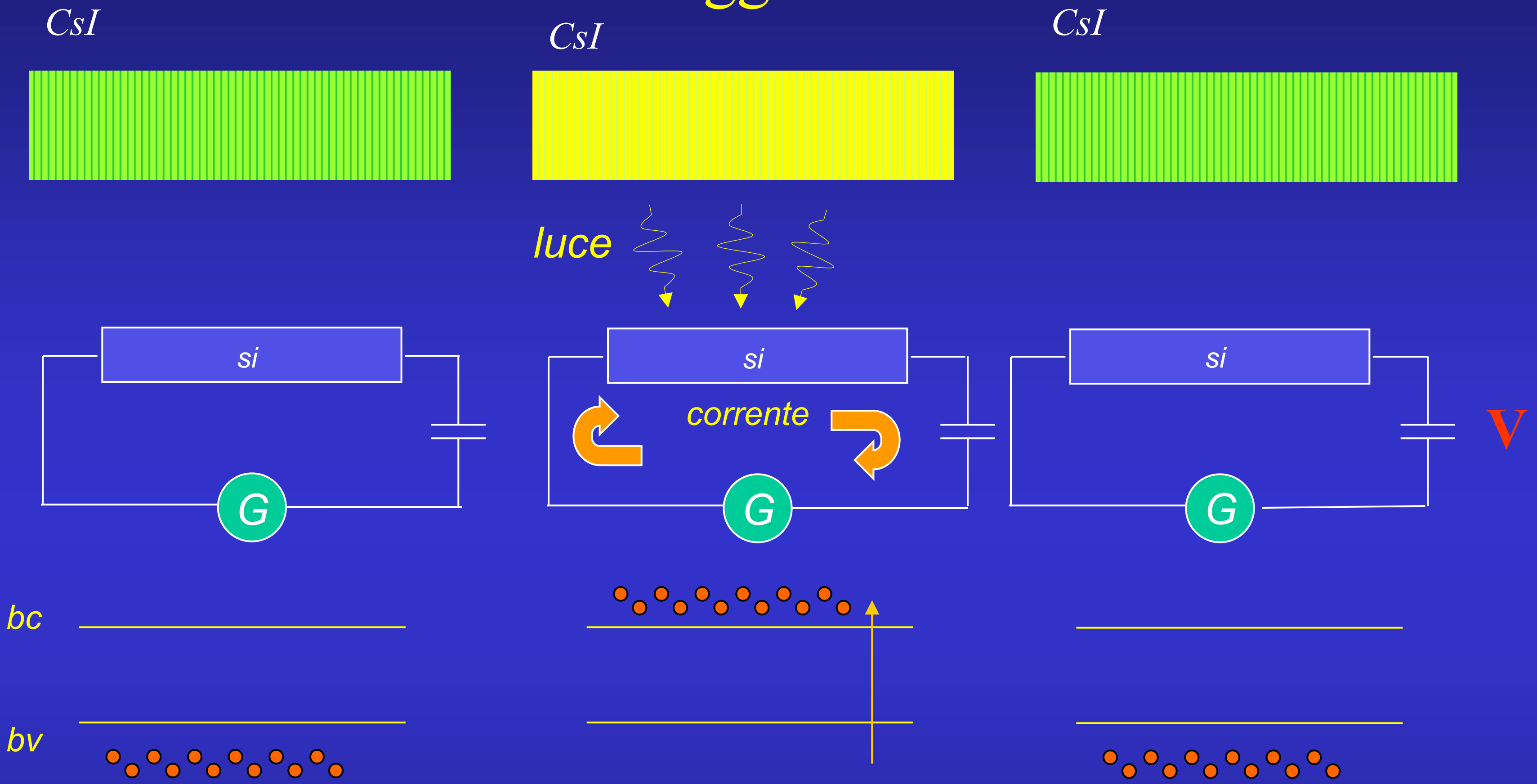

X-rays
Cesium Iodide
Visible Photons
Bias
Output
Photodiode
Row Select



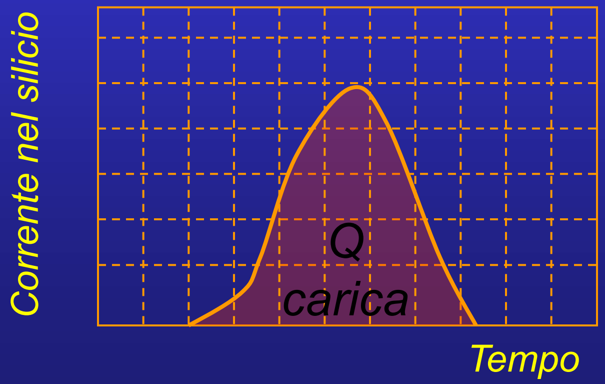
Si
silicio

Pixel (100 micron)

Raggi X


CsI
CsI
CsI
luce
si
si
si
corrente
G
G
G
V
bc
bv

FOTOCONDUTTIVITA’

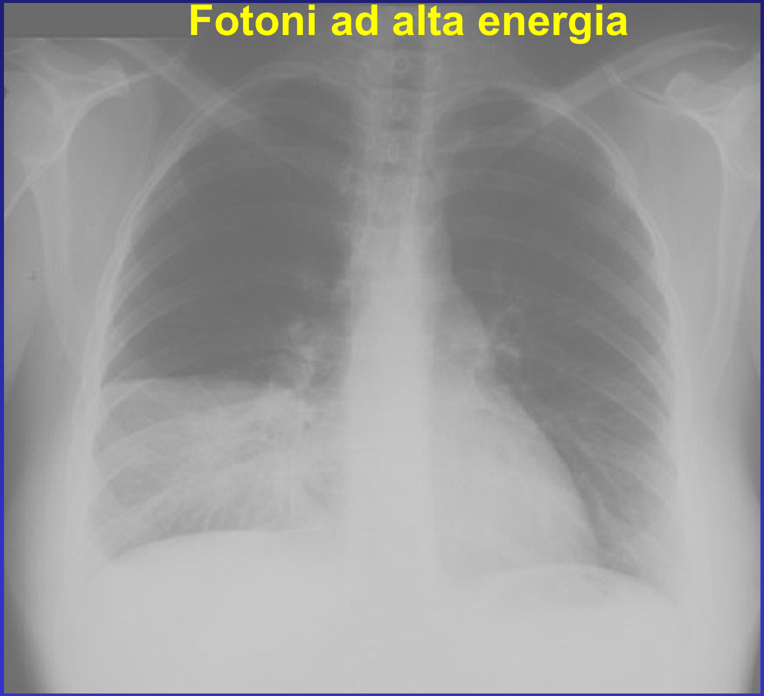


La carica è proporzionale alla quantità di raggi X assorbiti nello schermo sopra al silicio

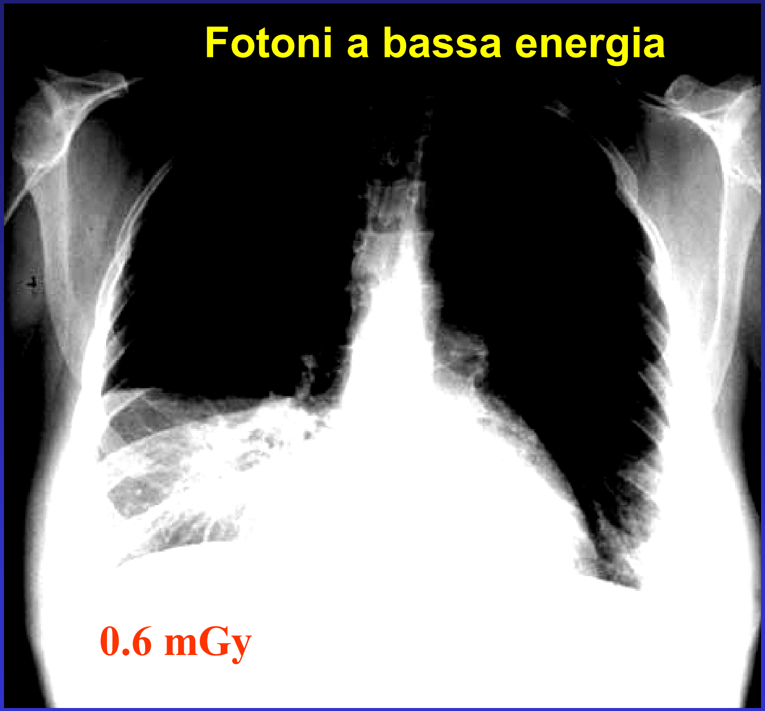
COLONNE

RIGHE

123	163	264	186	163	150	186	264	186	163	163	123	150	186	163
163	133	150	163	186	264	163	150	163	186	186	163	264	163	186
186	163	186	186	264	150	264	186	186	264	264	186	150	264	264
264	186	163	264	150	163	186	163	264	150	150	264	163	186	150
150	264	18	150	186	163	150	18	150	186	186	150	163	150	186
186	150	16	186	163	264	186	16	186	163	163	186	264	186	163
163	186	163	186	264	186	163	150	133	163	264	163	186	163	163
264	163	186	264	148	150	264	264	163	264	163	264	150	264	264
150	186	264	186	163	186	186	264	150	264	186	150	186	186	264
186	264	186	163	186	150	148	163	186	186	264	186	150	148	186
186	150	163	186	264	186	163	150	133	16	150	186	186	163	16
163	186	186	264	16	18	16	186	148	18	186	163		16	18
186	186	264	163	186	163	186	264	186	163	163	186	163	186	163

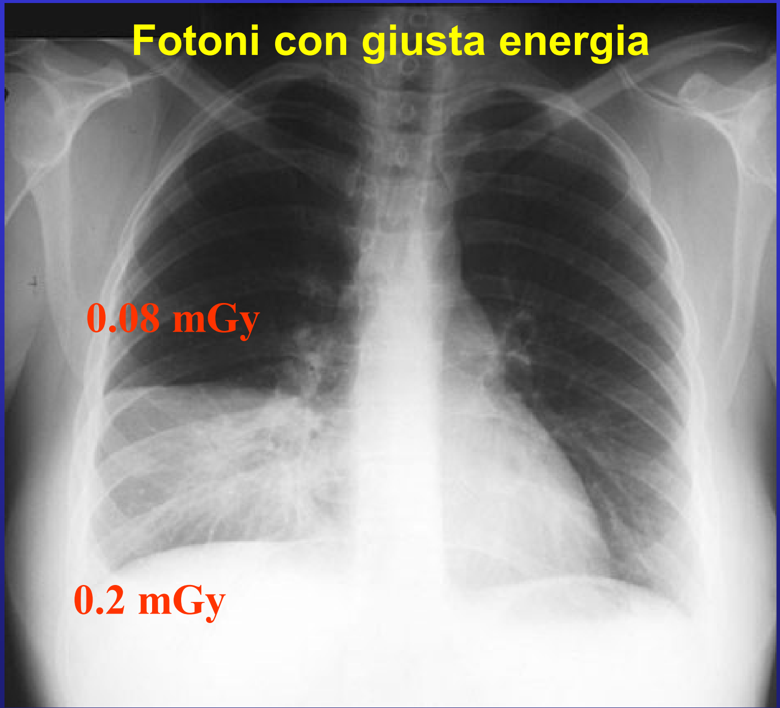


Fotoni ad alta energia



Fotoni a bassa energia

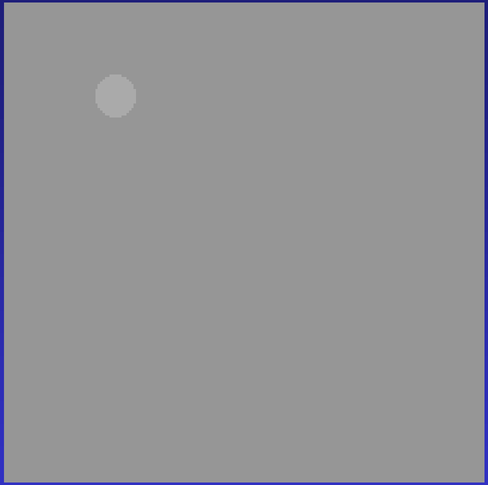
0.6 mGy



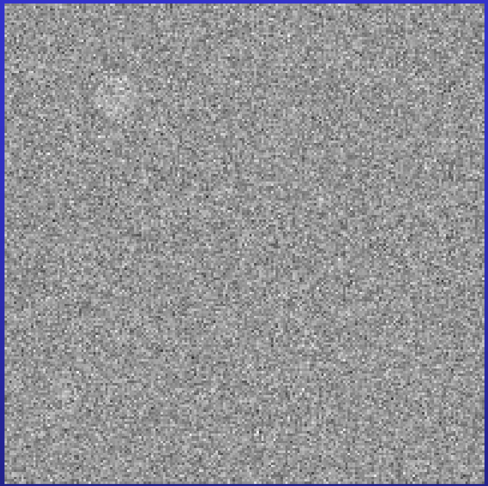
Fotoni con giusta energia

0.08 mGy

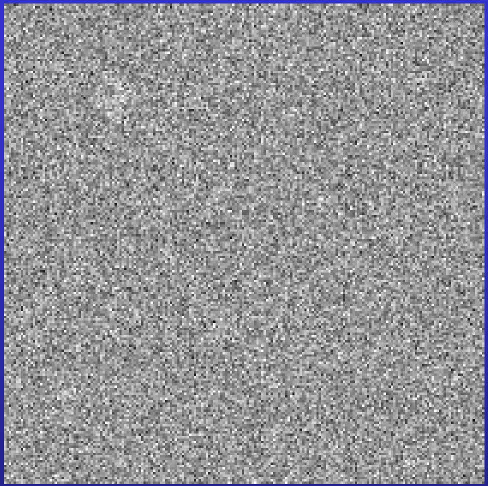
0.2 mGy



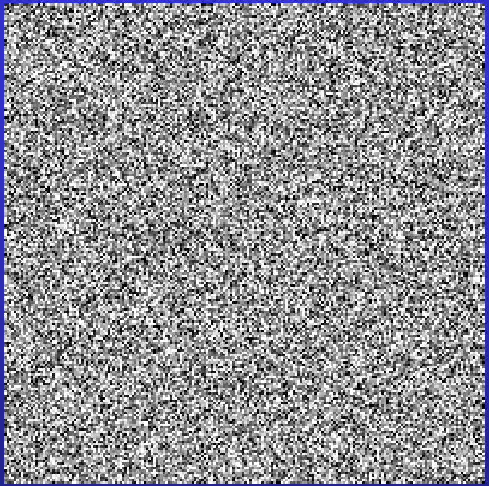
effetto del numero di fotoni usati per ottenere l’immagine



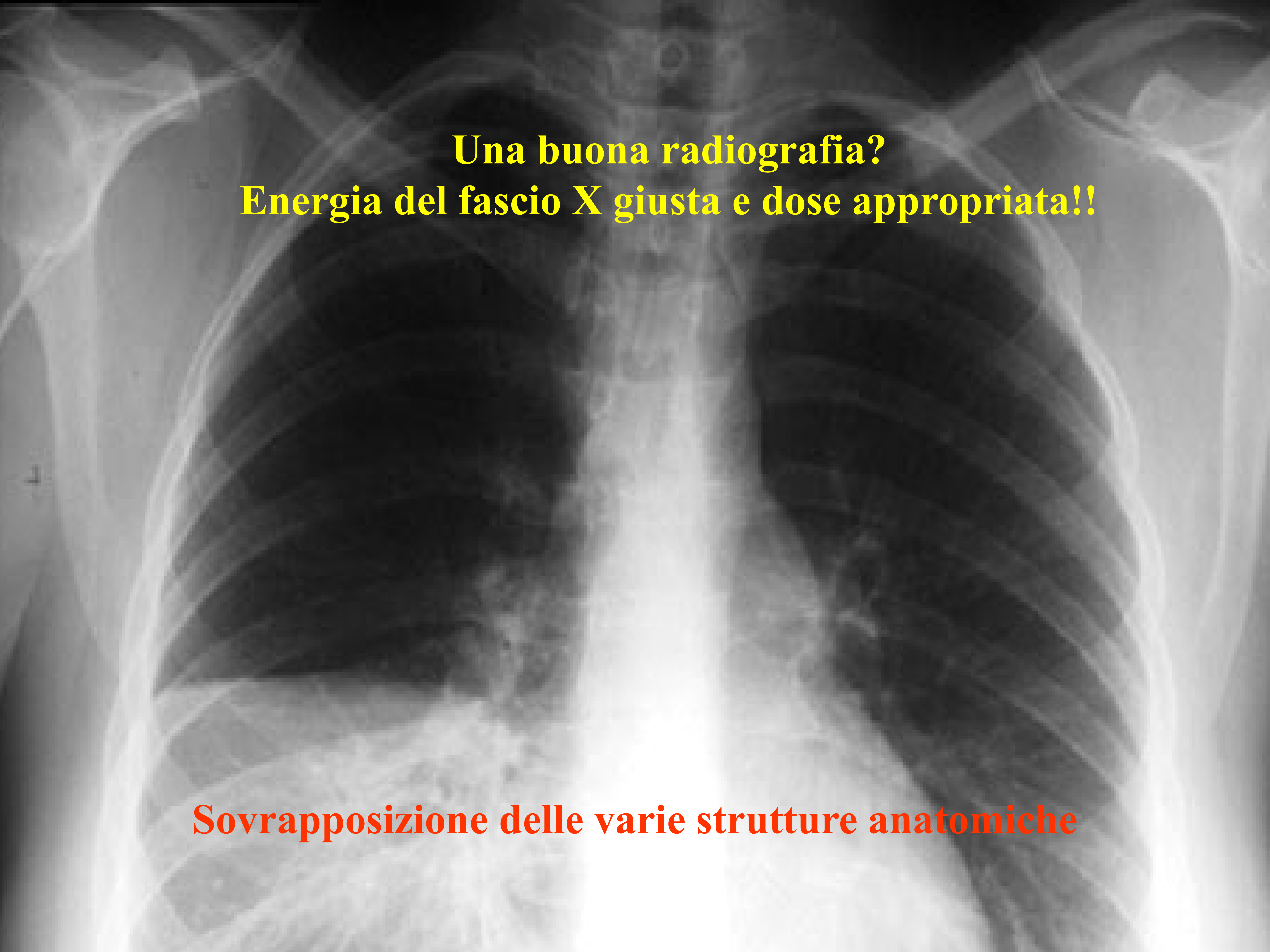
Dose = 1



Dose = 1/10



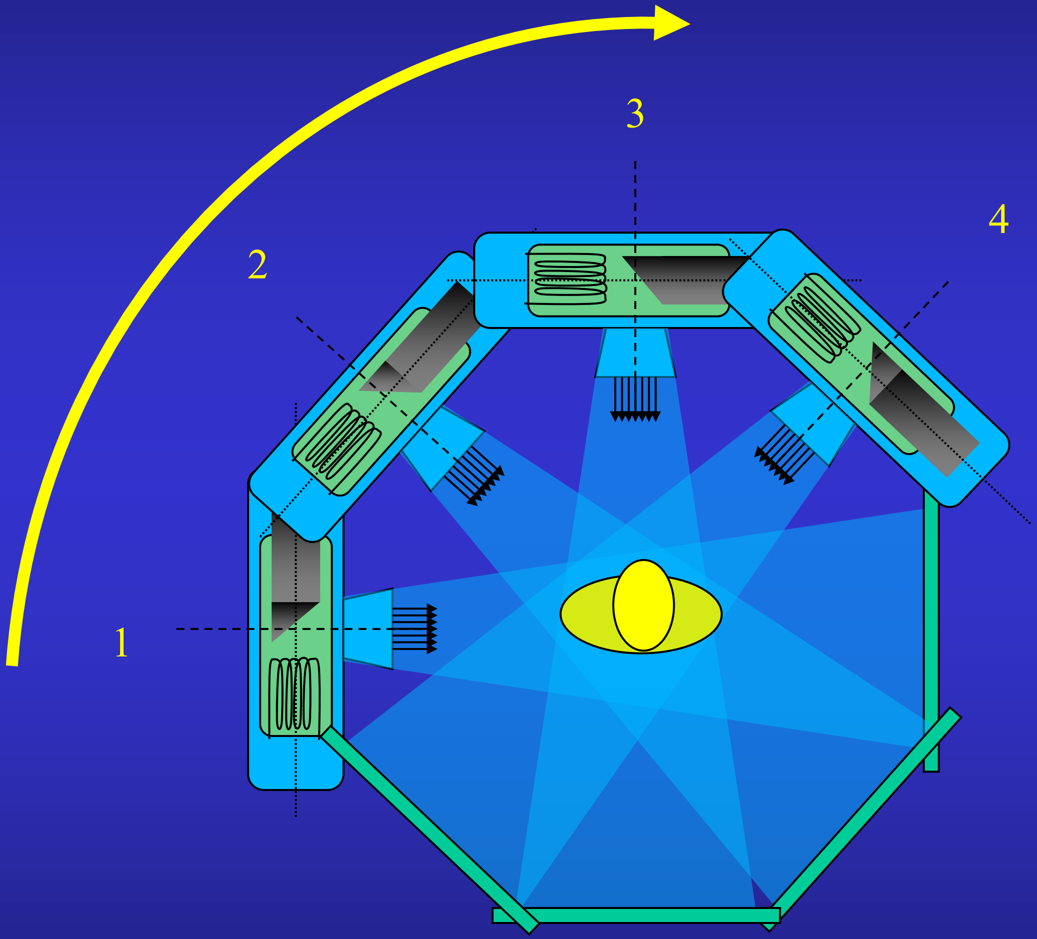
Dose = 1/100



Una buona radiografia?
Energia del fascio X giusta e dose appropriata!!

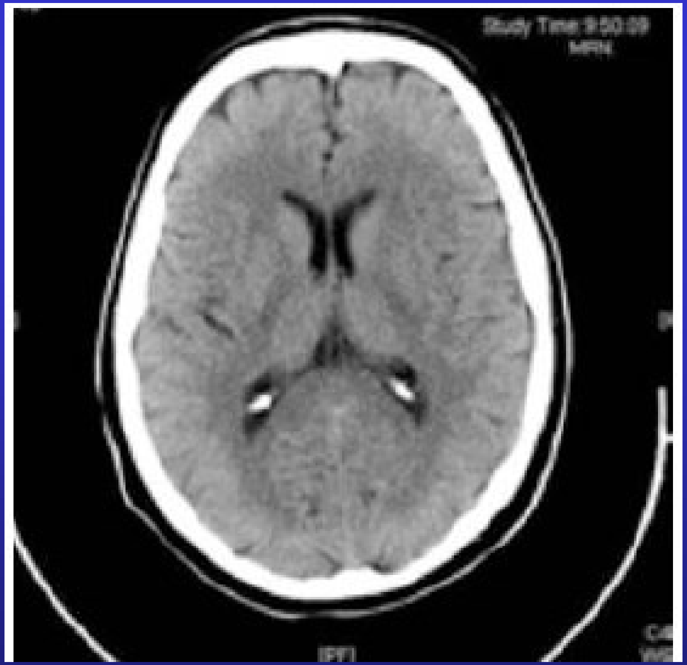
Sovrapposizione delle varie strutture anatomiche

E’ necessario fare più proiezioni



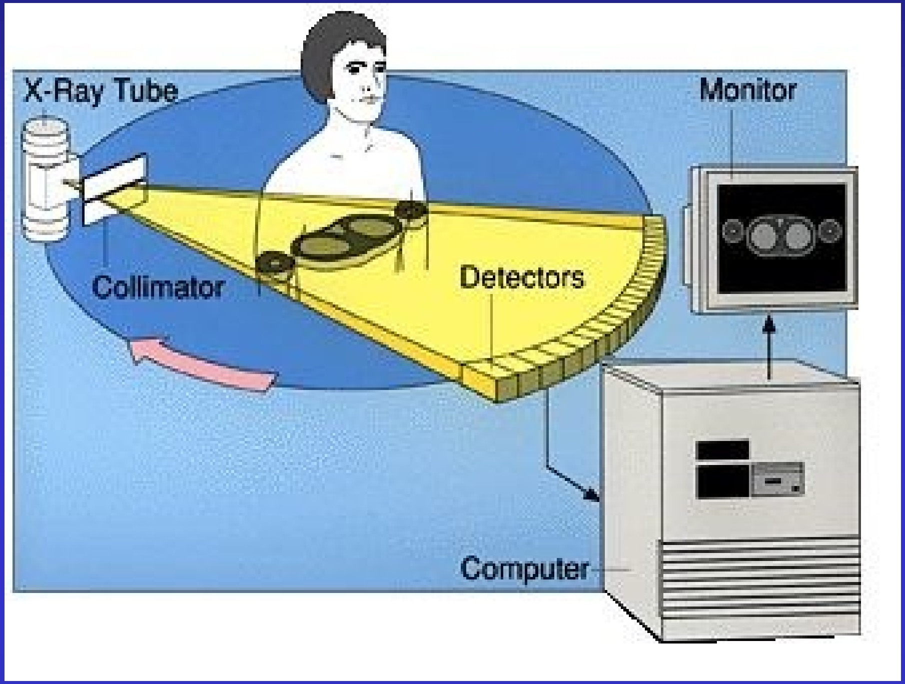
Tomografia Assistita dal Computer

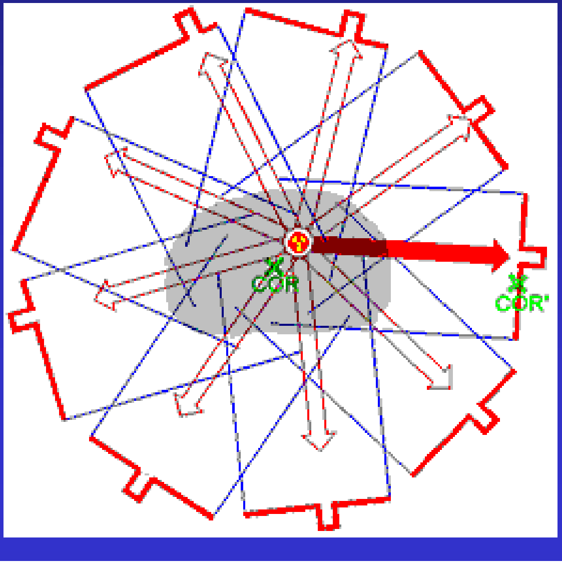
La TAC è un esame diagnostico che combina l'uso dei raggi X con le tecnologie di calcolo.

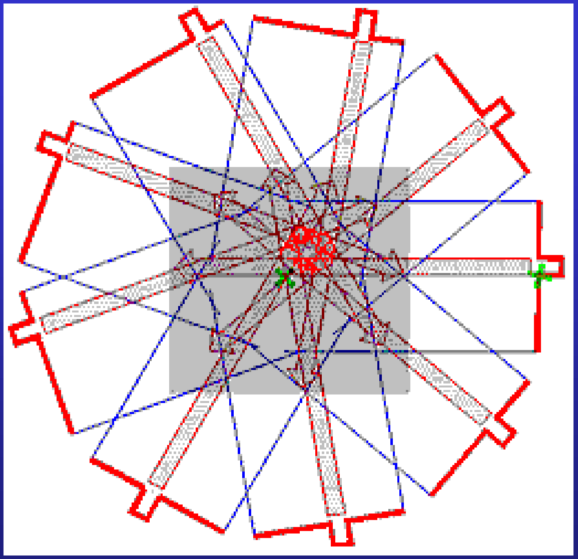

Study Time 9:50:09
MRN

TAC

Tomografia Assistita dal Computer


X-Ray Tube
Monitor
Collimator
Detectors
Computer

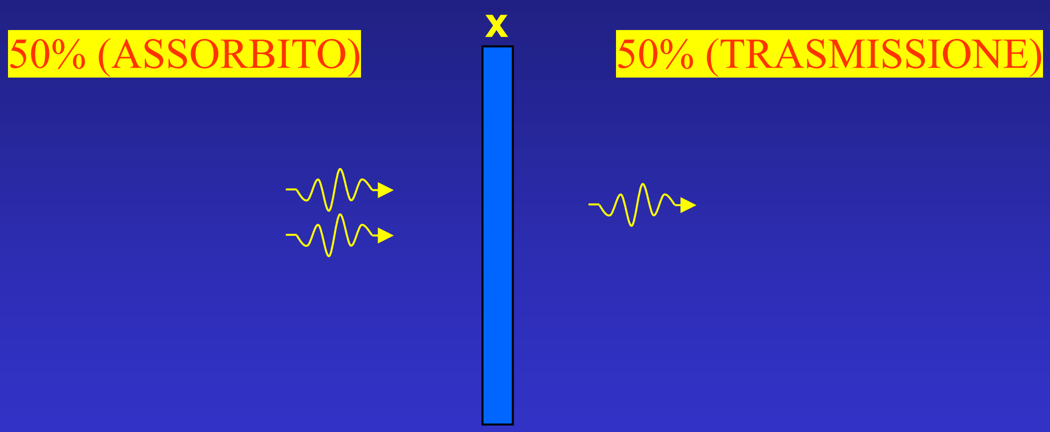




Si accquisiscono profili di trasmissione dei raggi X

Le dimensioni dei rivelatori definiscono lo spessore della sezione

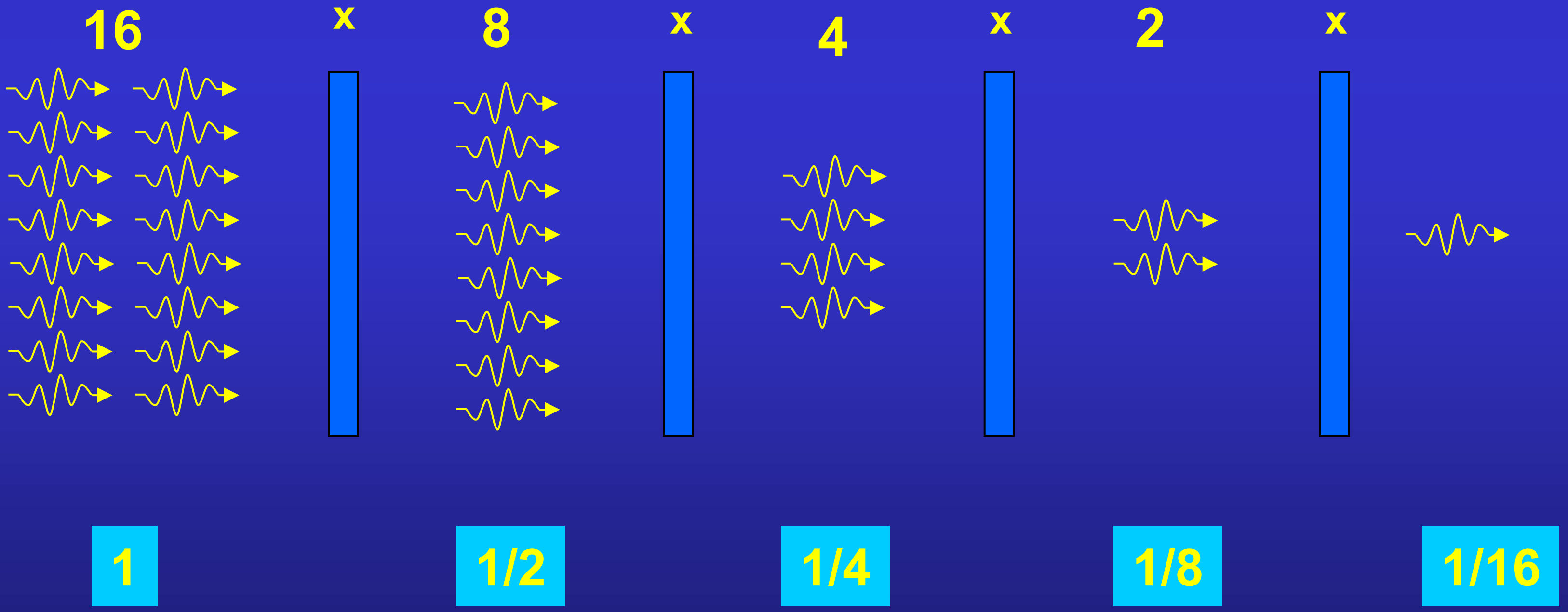
Oggetto



50% (ASSORBITO)

x

50% (TRASMISSIONE)



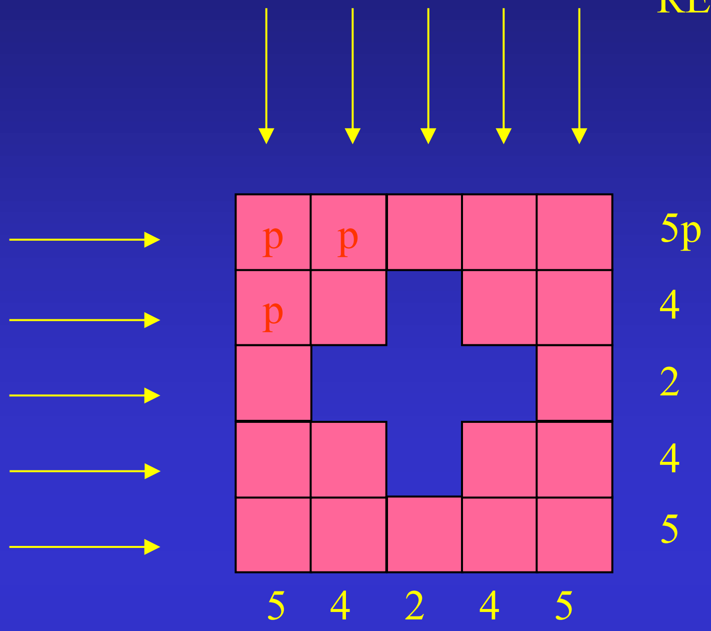
16 x 8 x 4 x 2 x

1 1/2 1/4 1/8 1/16

ASSOBIMENTO ESPONENZIALE DECRESCENTE

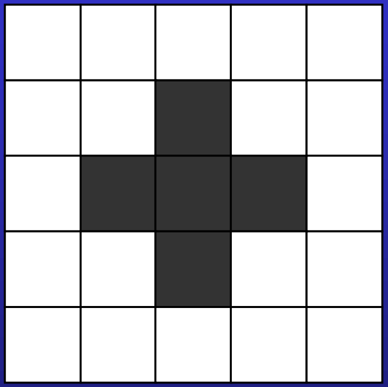
RICOSTRUZIONE DELL' IMMAGINE

RETRO PROIEZIONE FILTRATA

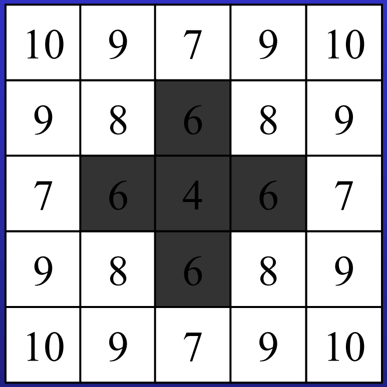


Retroproiezione dei profili

5	4	2	4	5	
10	9	7	9	10	5
9	8	6	8	9	4
7	6	4	6	7	2
9	8	6	8	9	4
10	9	7	9	10	5

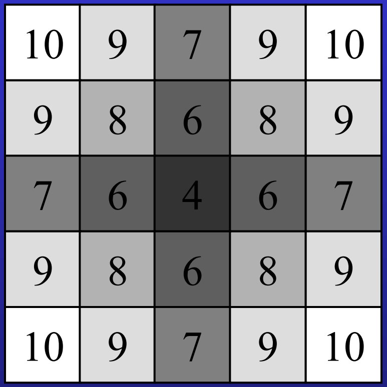


immagine



10	9	7	9	10
9	8	6	8	9
7	6	4	6	7
9	8	6	8	9
10	9	7	9	10

filtraggio

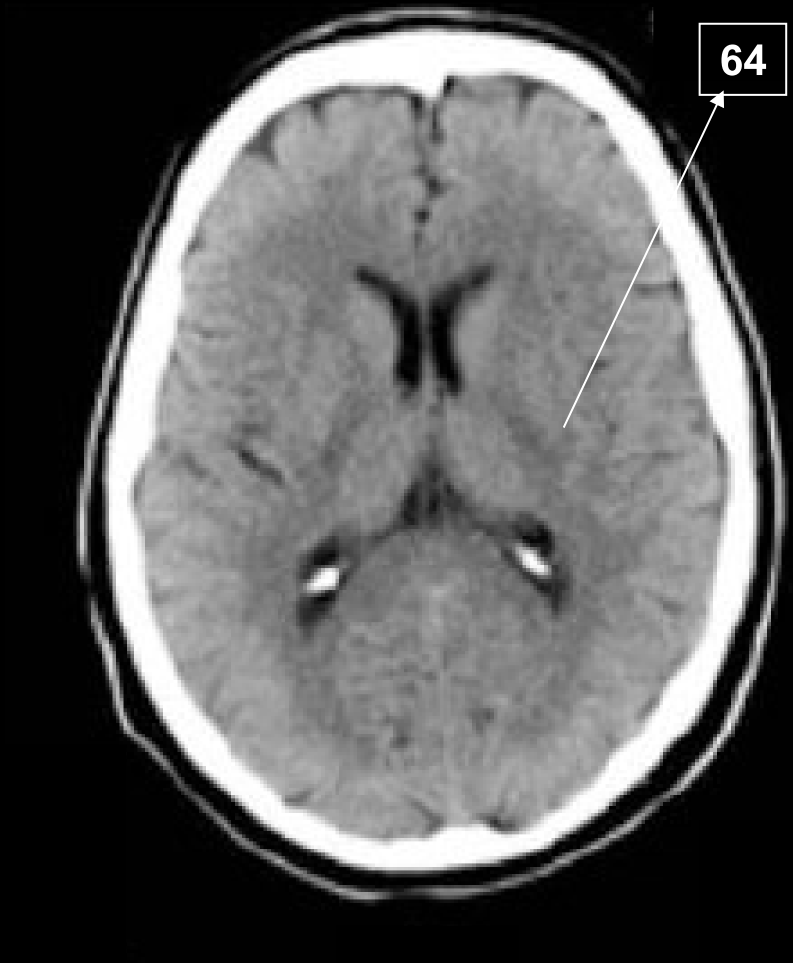


10	9	7	9	10
9	8	6	8	9
7	6	4	6	7
9	8	6	8	9
10	9	7	9	10

conversione in
livelli di grigi

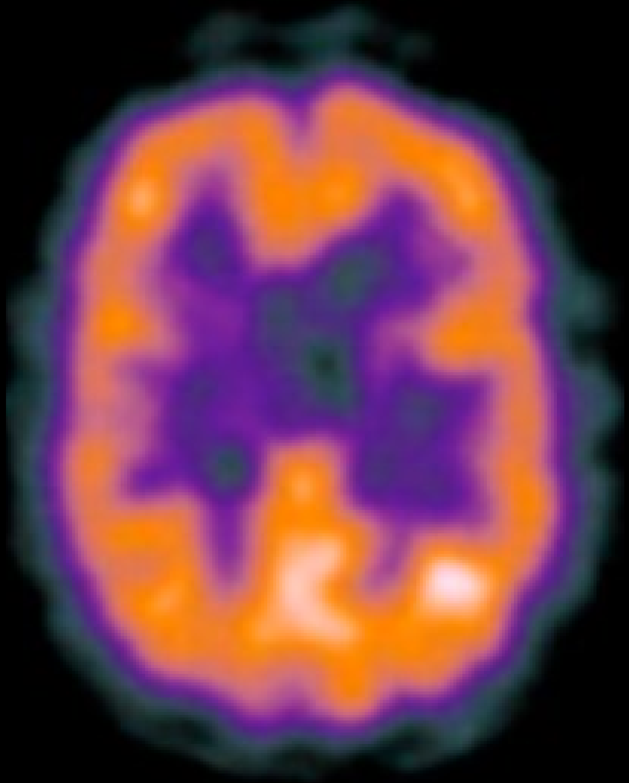
CT (TAC)

numero legato alla probabilità dei raggi X di essere assorbiti dal tessuto presente in quel punto (COEFFICIENTE DI ASSORBIMENTO)



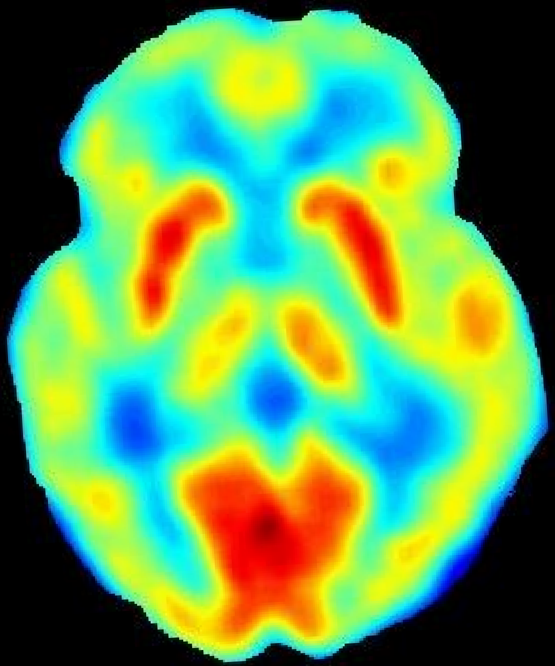
SPECT

Radioisotopi γ emittenti



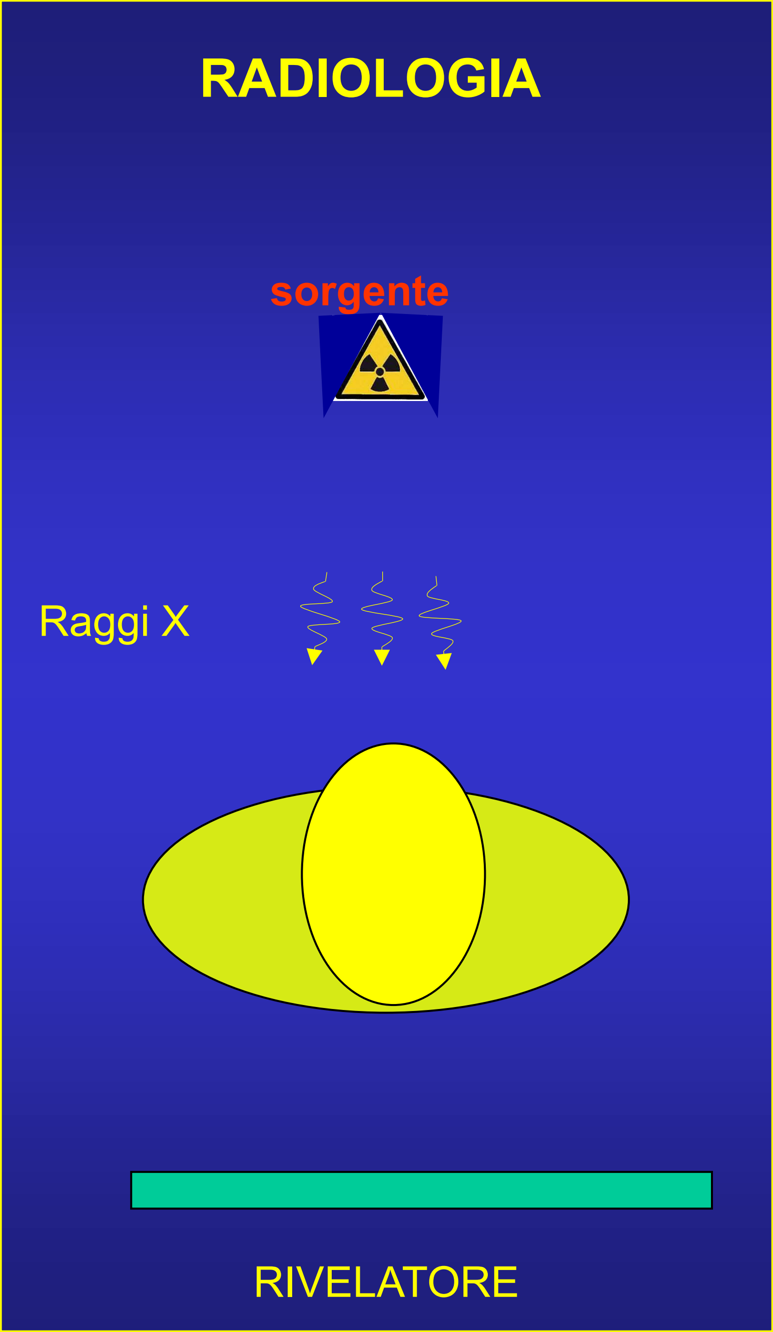
PET

Radioisotopi β^+ emittenti



- Tecniche tomografiche
- Fanno uso di radioisotopi (radiofarmaci)
- Medicina Nucleare

RADIOLOGIA

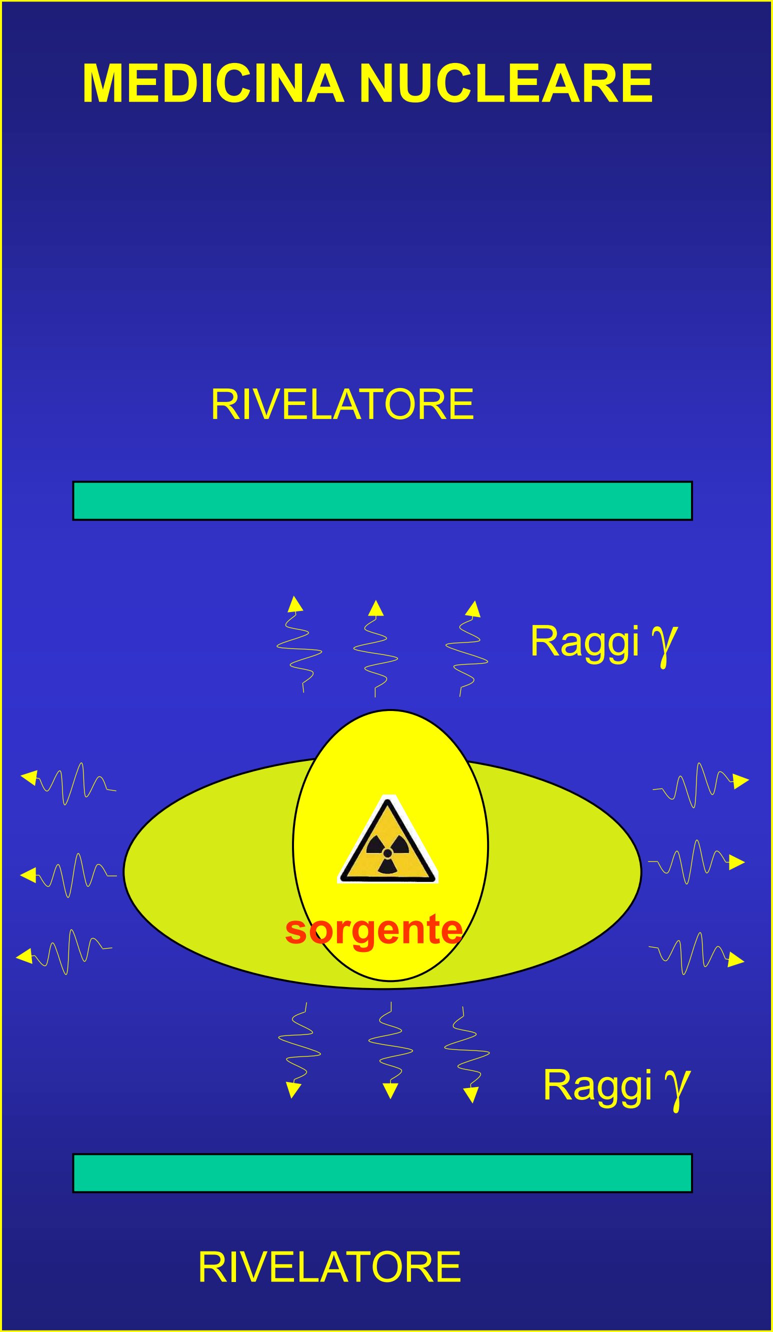


sorgente

Raggi X

RIVELATORE

MEDICINA NUCLEARE



RIVELATORE

Raggi γ

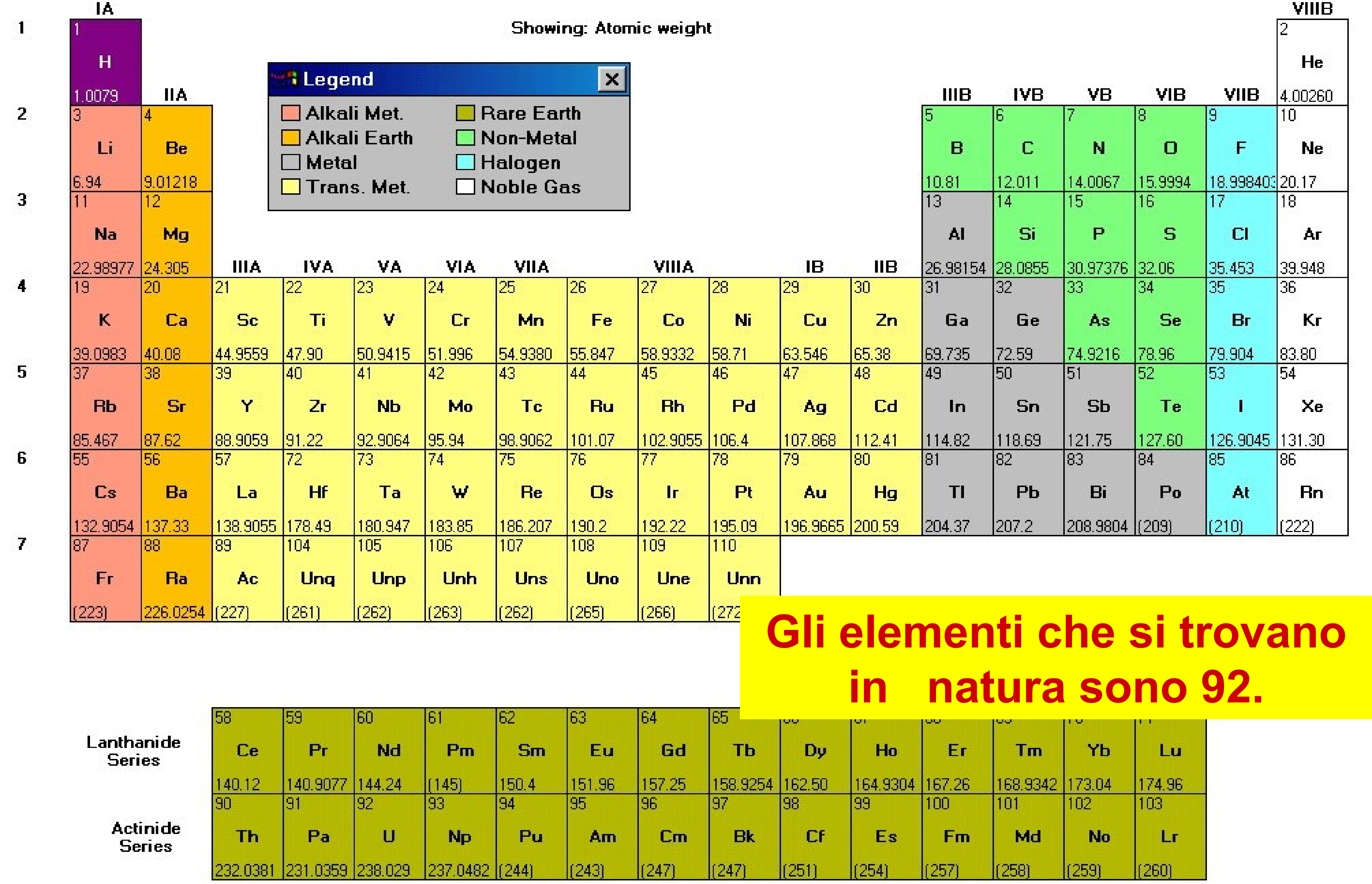
sorgente

Raggi γ

RIVELATORE

la radioattività

Tavola periodica degli elementi



Showing: Atomic weight

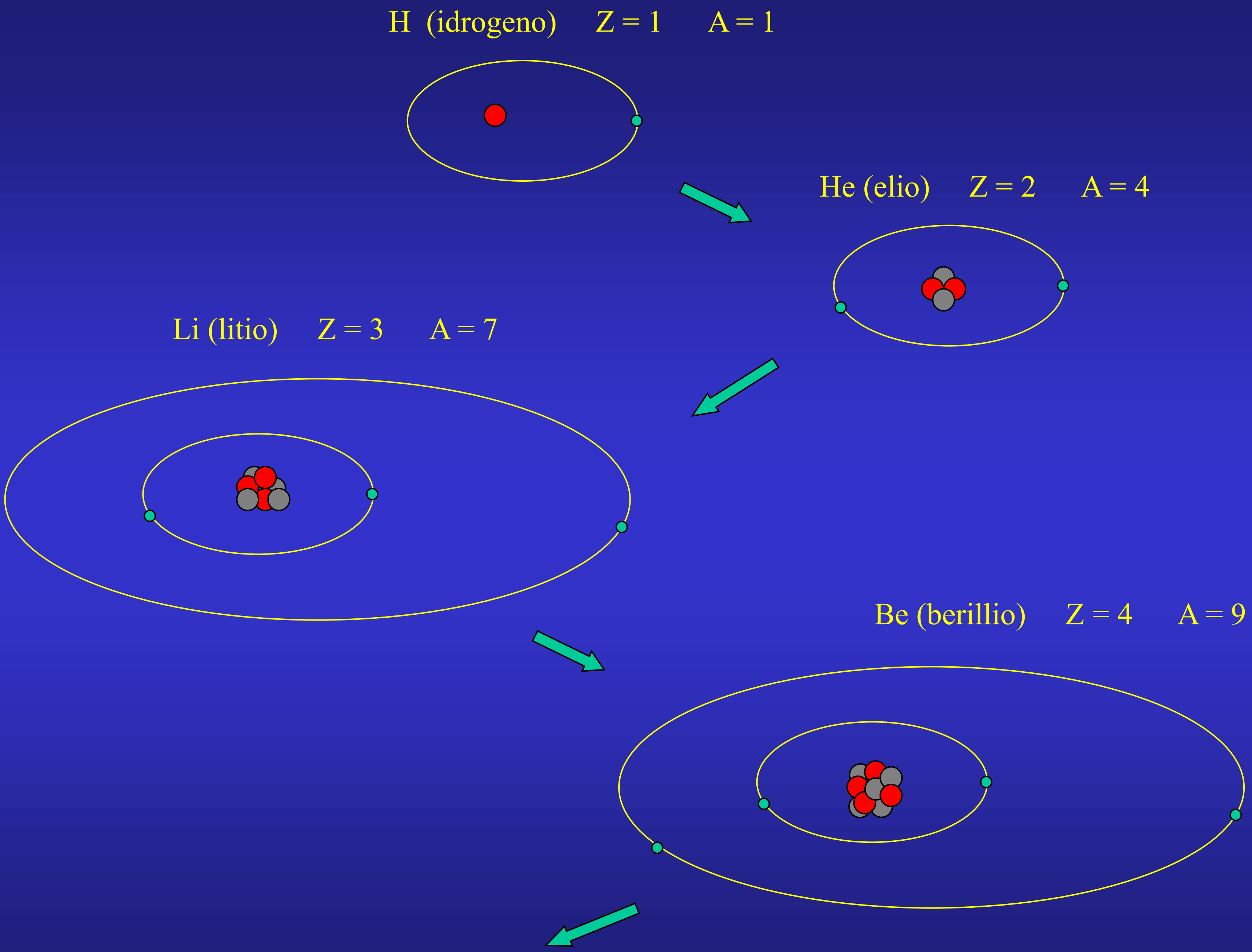
Legend ✕

🟥 Alkali Met.
🟧 Alkali Earth
▨ Metal
🟨 Trans. Met.
🟫 Rare Earth
🟩 Non-Metal
🟦 Halogen
⬜ Noble Gas

	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIIIB
1	1 H 1.0079																	2 He 4.00260
2	3 Li 6.94	4 Be 9.01218											5 B 10.81	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.17
3	11 Na 22.98977	12 Mg 24.305											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.90	23 V 50.9415	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.546	30 Zn 65.38	31 Ga 69.735	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.467	38 Sr 87.62	39 Y 88.9059	40 Zr 91.22	41 Nb 92.9064	42 Mo 95.94	43 Tc 98.9062	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.4	47 Ag 107.868	48 Cd 112.41	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.9045	54 Xe 131.30
6	55 Cs 132.9054	56 Ba 137.33	57 La 138.9055	72 Hf 178.49	73 Ta 180.947	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.09	79 Au 196.9665	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.0254	89 Ac (227)	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)	110 Unn (272								

Lanthanide Series	58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 Tb 158.9254	Dy 162.50	Ho 164.9304	Er 167.26	Tm 168.9342	Yb 173.04	Lu 174.96
Actinide Series	90 Th 232.0381	91 Pa 231.0359	92 U 238.029	93 Np 237.0482	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

Gli elementi che si trovano in natura sono 92.



H (idrogeno) Z = 1 A = 1

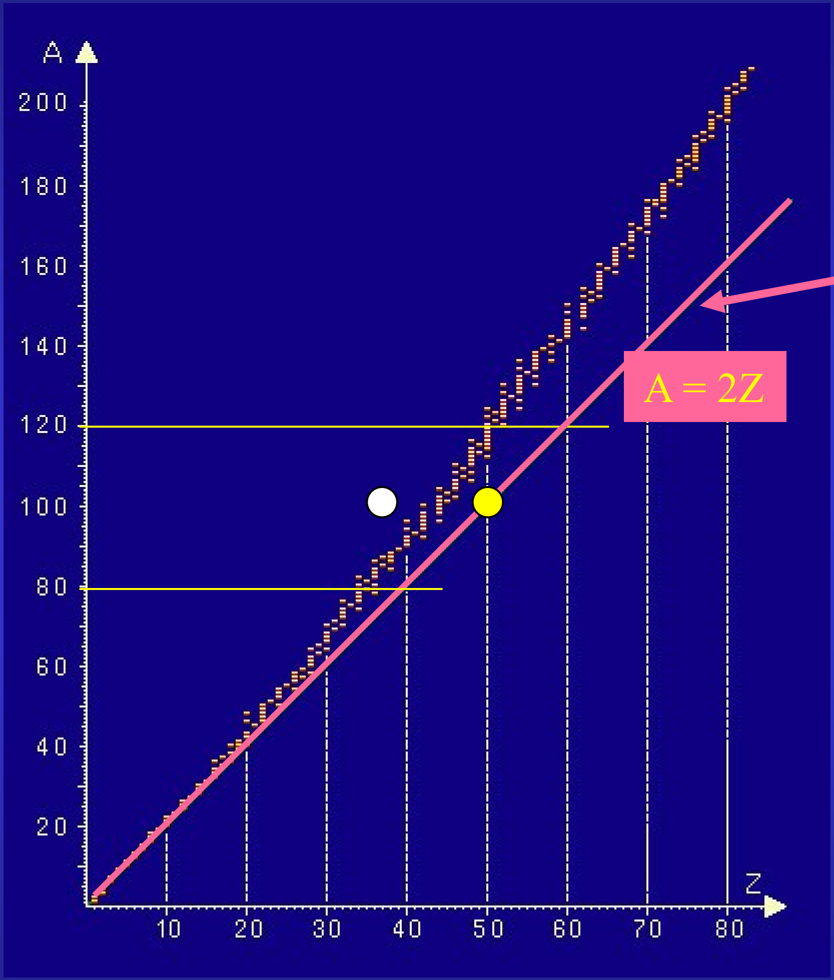
He (elio) Z = 2 A = 4

Li (litio) Z = 3 A = 7

Be (berillio) Z = 4 A = 9

Diagramma di stabilità degli elementi

MASSA NUCLEO



Numero di protoni nel nucleo

Retta che rappresenta la posizione
Nuclei aventi lo stesso numero
di neutroni e protoni

$N_n = Np$

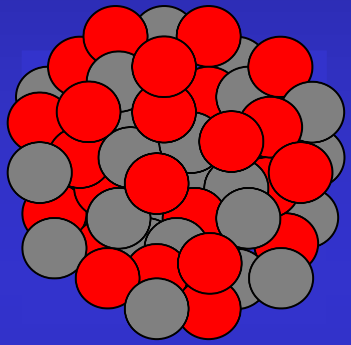
← $p \dashrightarrow n + e^+ + \nu$

Decadimento β⁺

→ $n \dashrightarrow p + e^- + \underline{\nu}$

Decadimento β⁻

decadimento beta - gamma



^{24}Na radioattivo

^{24}Mg stabile

elettrone

antineutrino

radiazione gamma

Radionuclidi per scintigrafia

Radionuclide	particella emessa	energia (keV)	emivita $(t_{1/2})$
Gallio-67	γ	93,185,300	78.3 h
Tecnezio-99m	γ	142	6.02 h
Indio-111	γ	173, 247	67.3 h
Iodio-123	γ	159	13 h
Iodio-131	γ	364, b 606	8.05 d
Tallio-201	γ	135,167, X 68-82	73.5 h

Decadimento ^{99}Mo – ^{99}Tc^{m} - (gamma puro)- ^{99}Tc

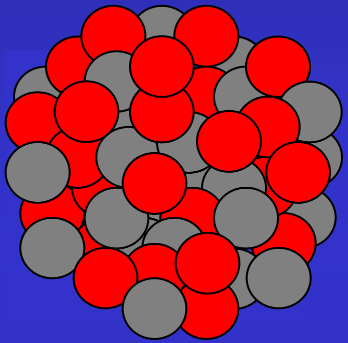
tecnetos = artificiale

τεχνετοσ

^{99}Mo radioattivo

^{99}Tc^{m} radioattivo metastabile

^{99}Tc stabile



elettrone

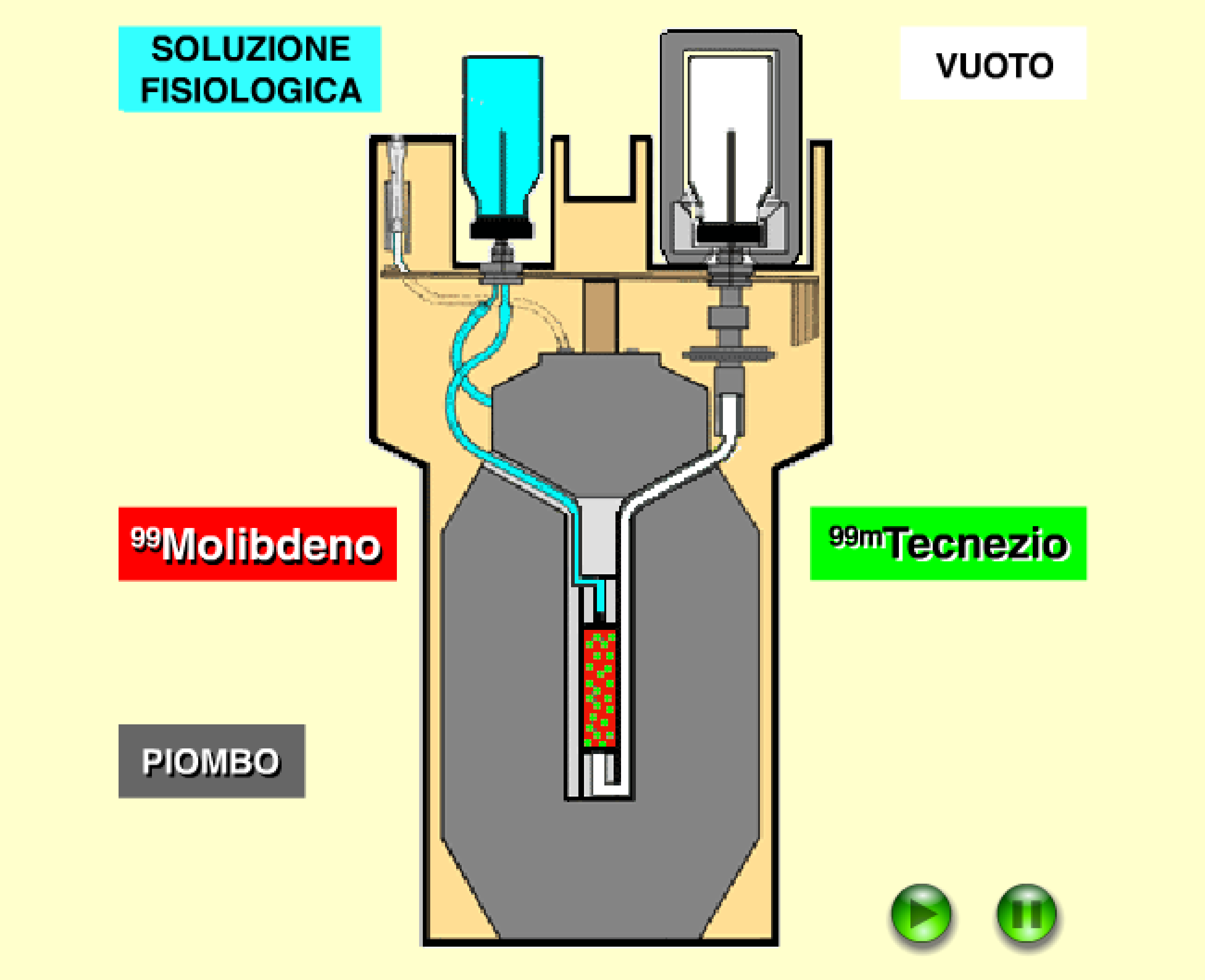
antineutrino

radiazione gamma

La presenza dello stato metastabile è importantissima:

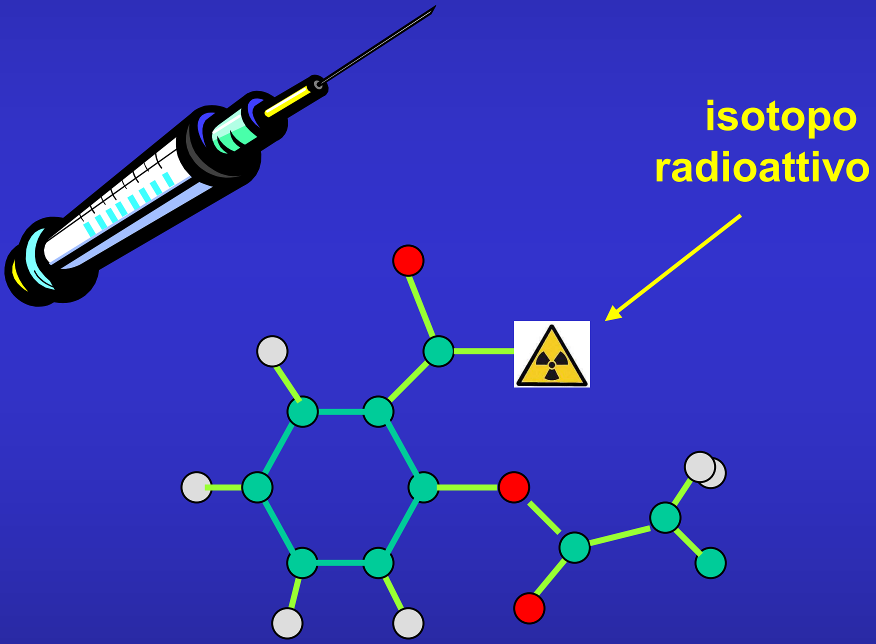
1. l’emissione beta non avviene nel paziente (riduzione dose)
2. tempo per la prepazione del radiofarmaco

Generatore portatile di Tc-99m

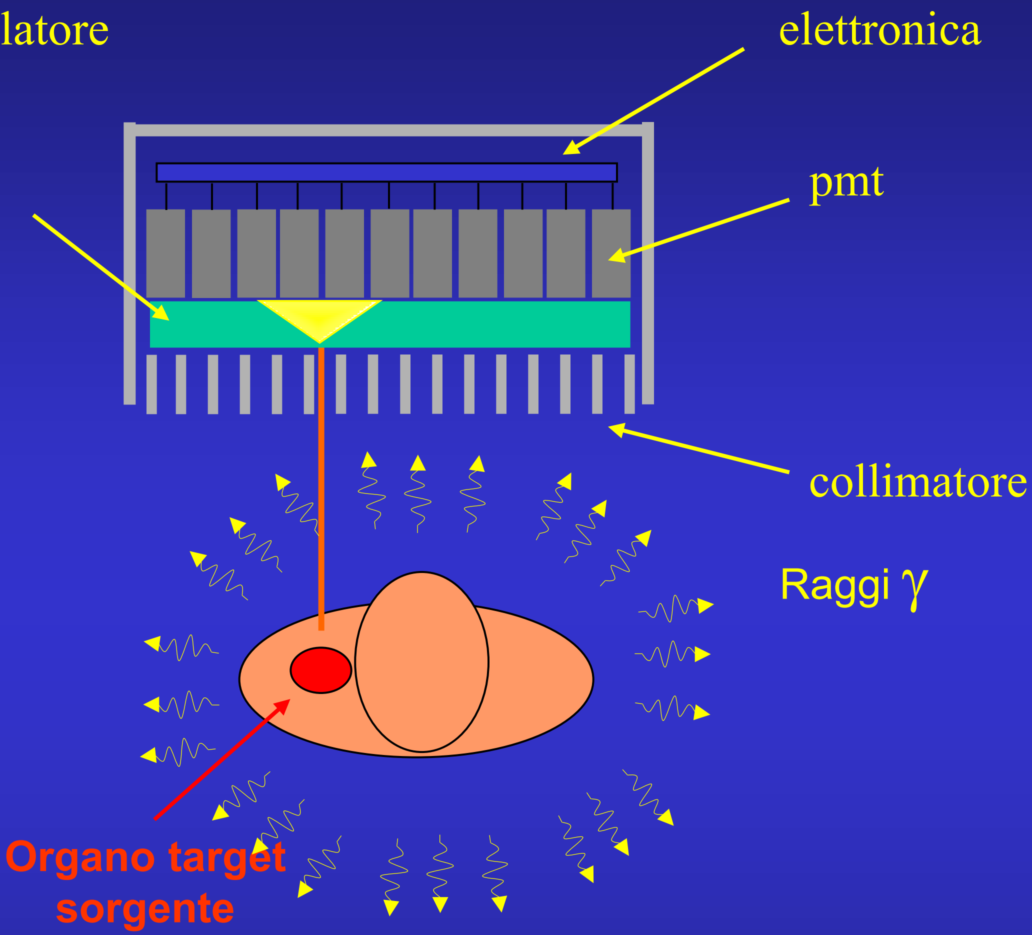

SOLUZIONE FISIOLOGICA
VUOTO
99Molibdeno
99mTecnezio
PIOMBO

Radiofarmaco

Iniezione
radiofarmaco


isotopo
radioattivo

gamma camera



Cristallo scintillatore

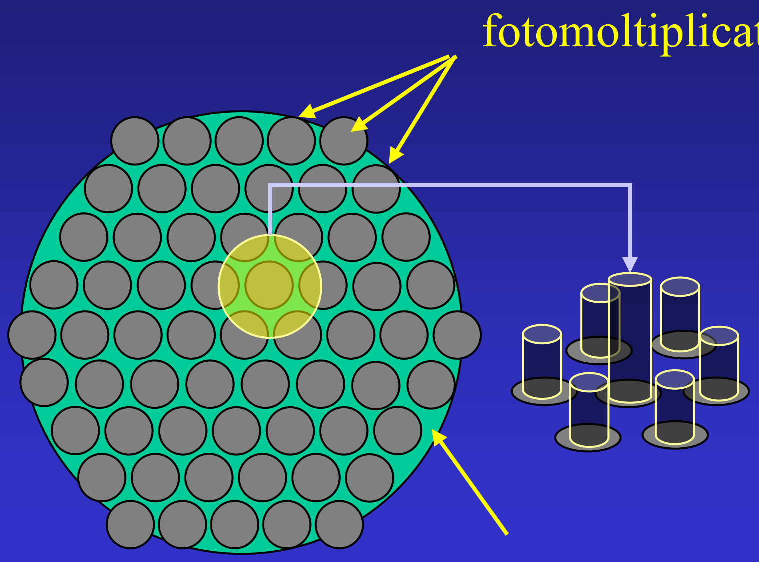
elettronica

pmt

collimatore

Raggi γ

Organo target sorgente



fotomoltiplicatori

cristallo scintillatore

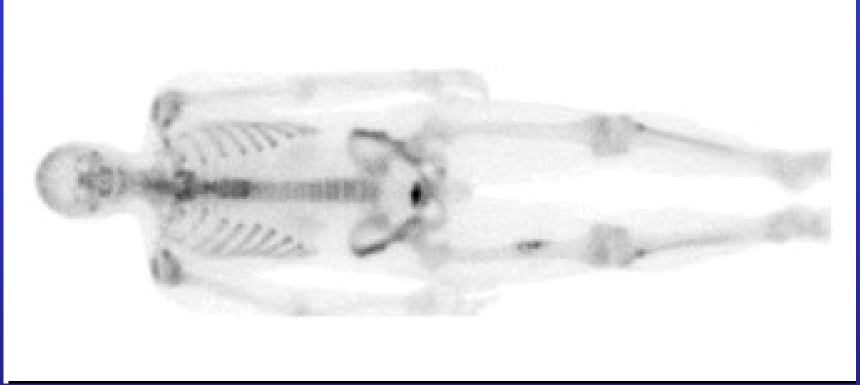
la posizione (x,y) è ottenuta come il baricentro delle intensità luminose viste dai fototubi

matrice dei conteggi

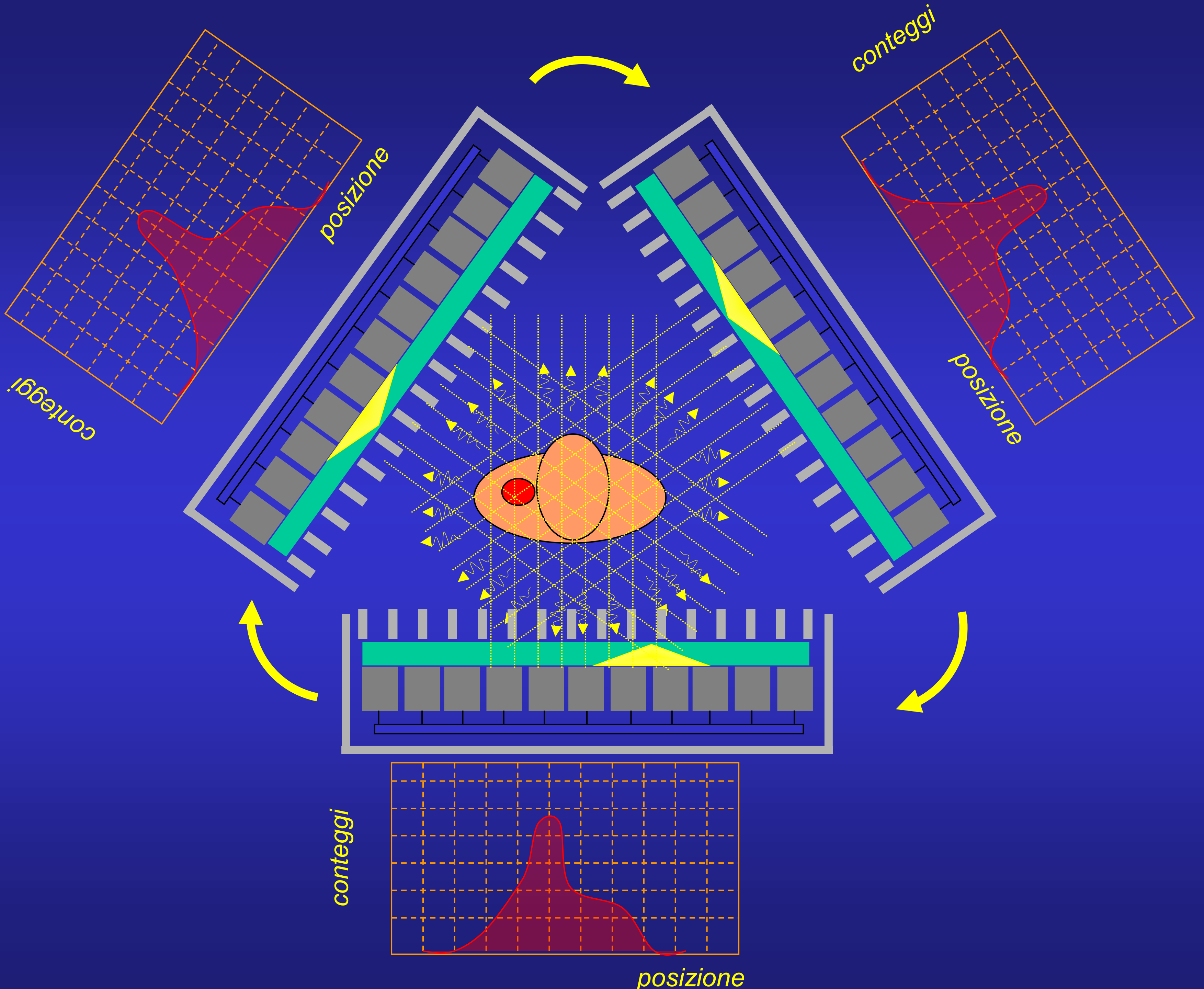
Y

234	432	256	623	844	956	855	321
123	390	289	525	901	1022	834	301

X

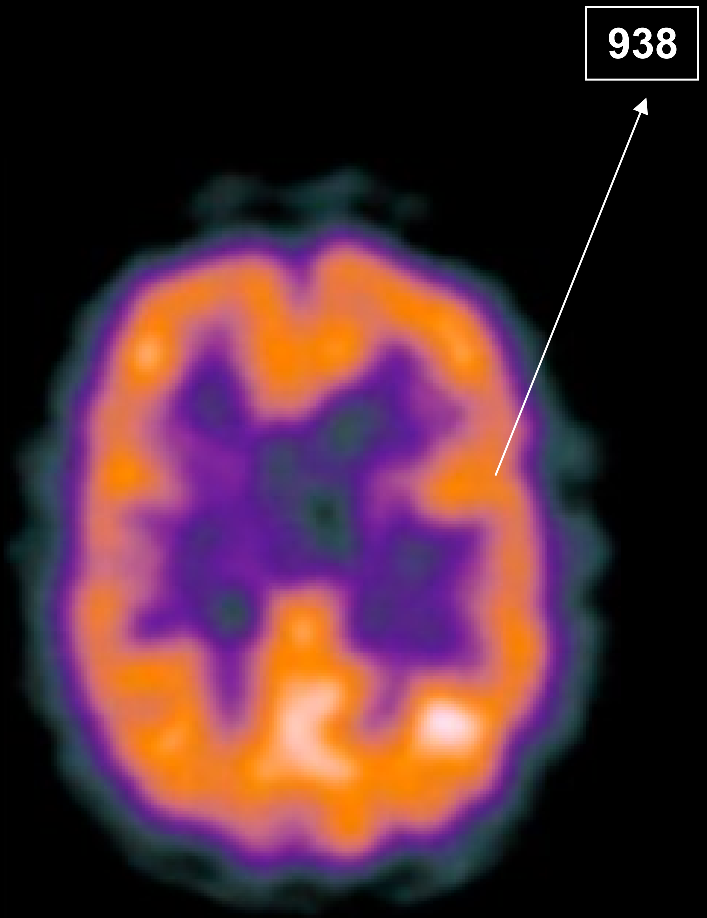


scintigrafia ossea


conteggi
posizione
conteggi
posizione
conteggi
posizione

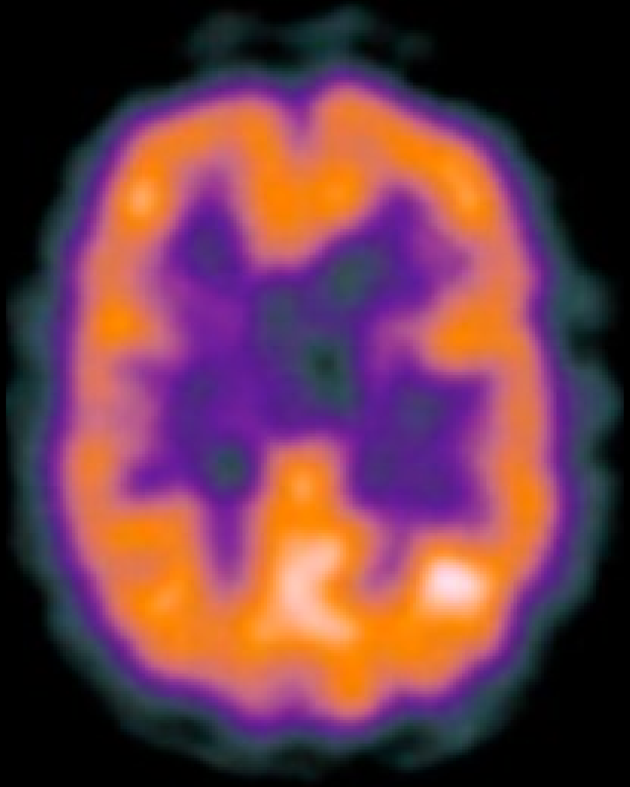
SPECT

numero legato alla radioattività γ presente in quel punto



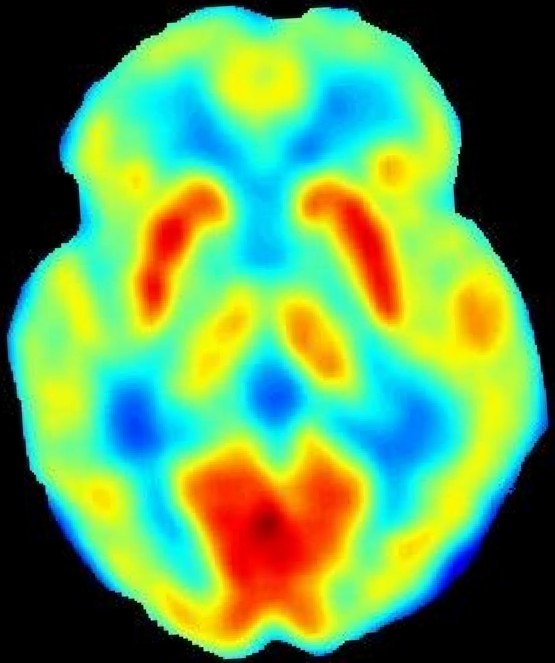
SPECT

Radioisotopi γ emittenti



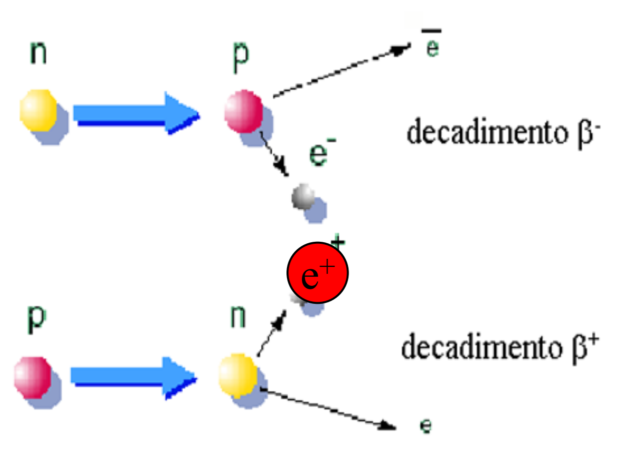
PET

Radioisotopi β^+ emittenti



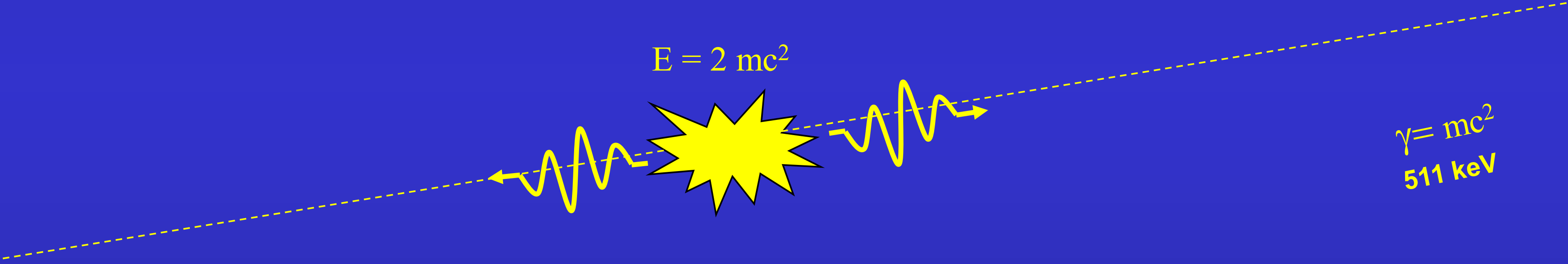
- Tecniche tomografiche
- Fanno uso di radioisotopi (radiofarmaci)
- Medicina Nucleare

Decadimenti β


n
p
$\bar{e}$
decadimento β^-
e^-
e^+
p
n
decadimento β^+
e

positrone

ANTIMATERIA



$E = 2\ mc^2$

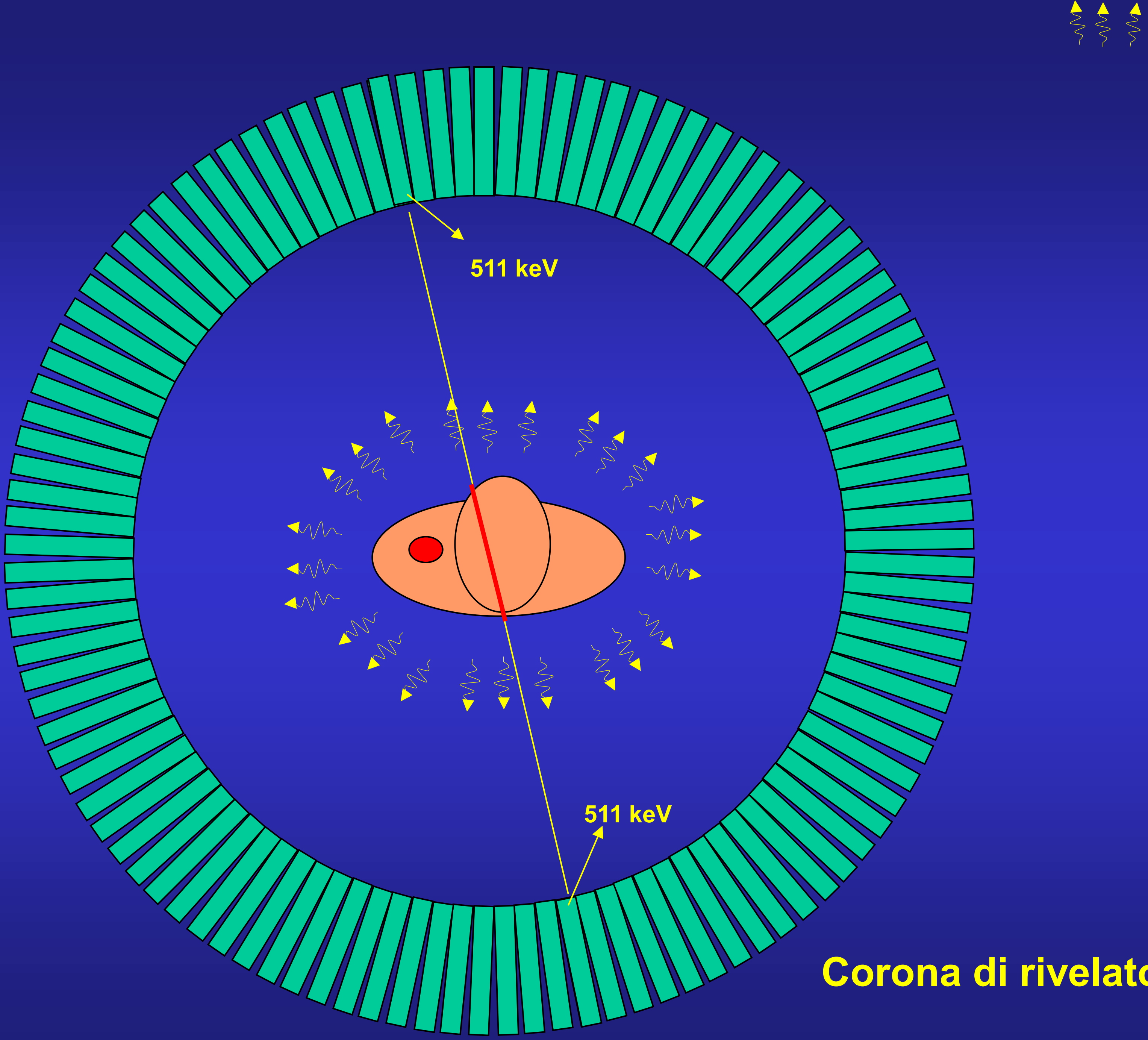
$\gamma = mc^2$

511 keV

$\gamma = mc^2$

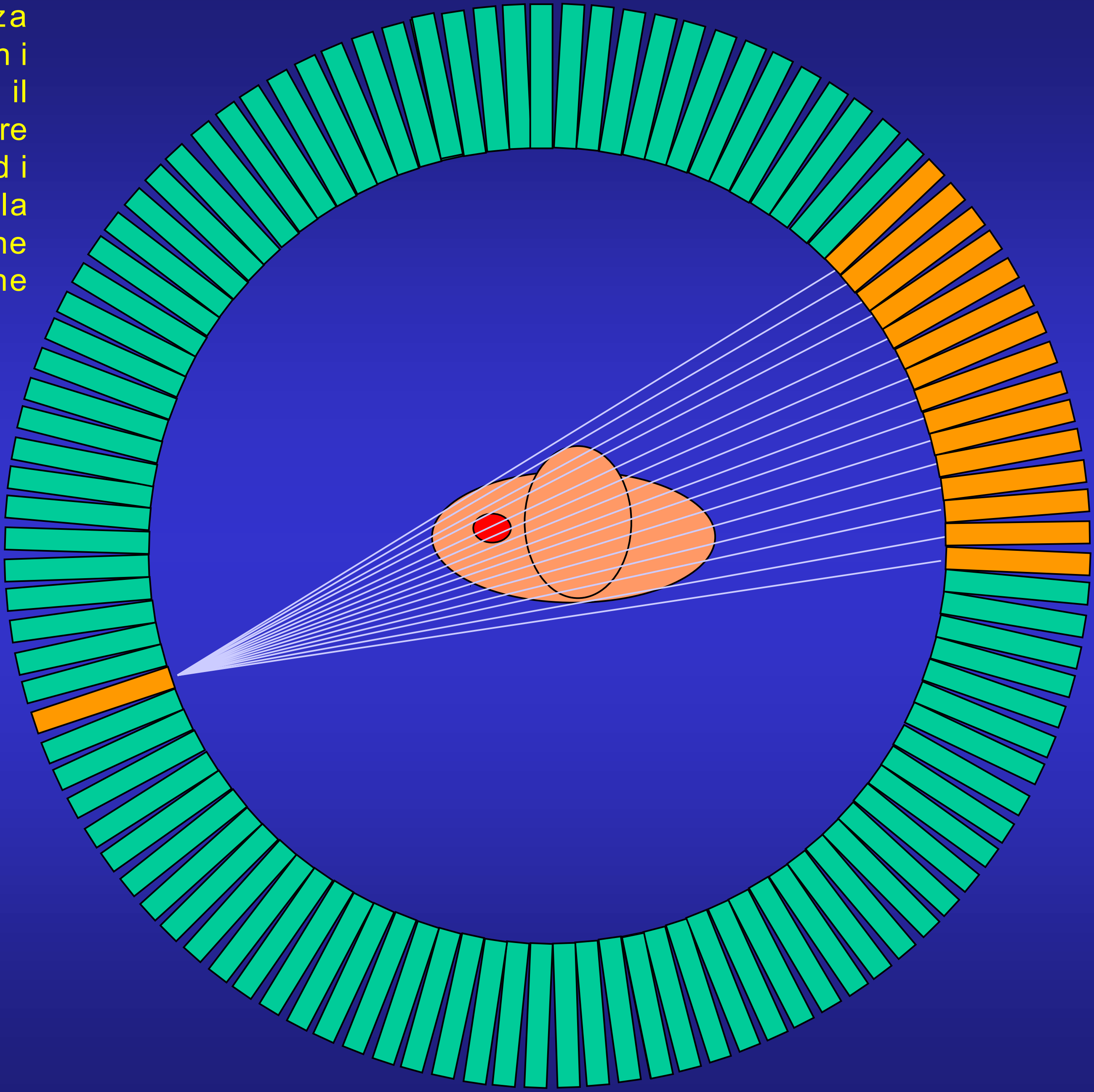
511 keV

ANNICHILAZIONE


511 keV
511 keV

Corona di rivelatori

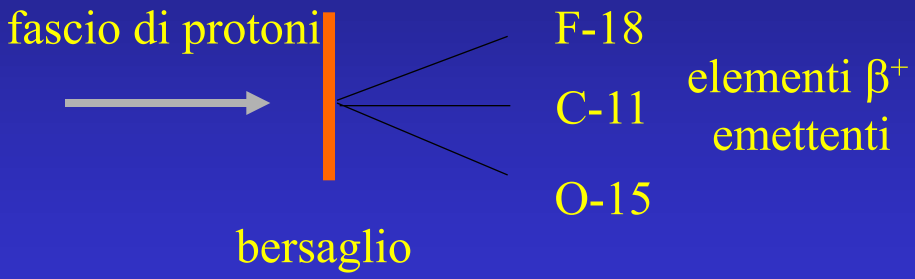
Mettendo in coincidenza ogni rivelatore dell’anello con i rivelatori che intercetteno il paziente si possono ottenere molti di profili di di radioattività utili per la ricostruzione dell’immagine con tecniche tomografiche



Radionuclidi PET

Radionuclide emivita	particella emessa	energia (keV)	($t_{1/2}$)
Carbonio-11	β^+	959	20.4 min
Azoto-13	β^+	1197	9.96 min
Ossigeno-15	β^+	1738	2.07 min
Fluoro-18	β^+	633	109.7 min

CICLOTRONE



fascio di protoni

bersaglio

F-18

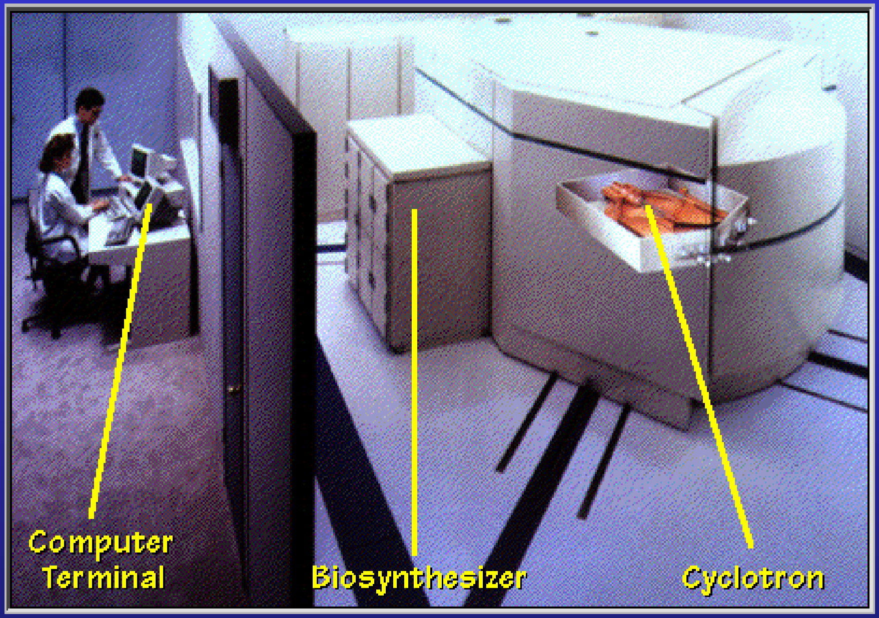
C-11

O-15

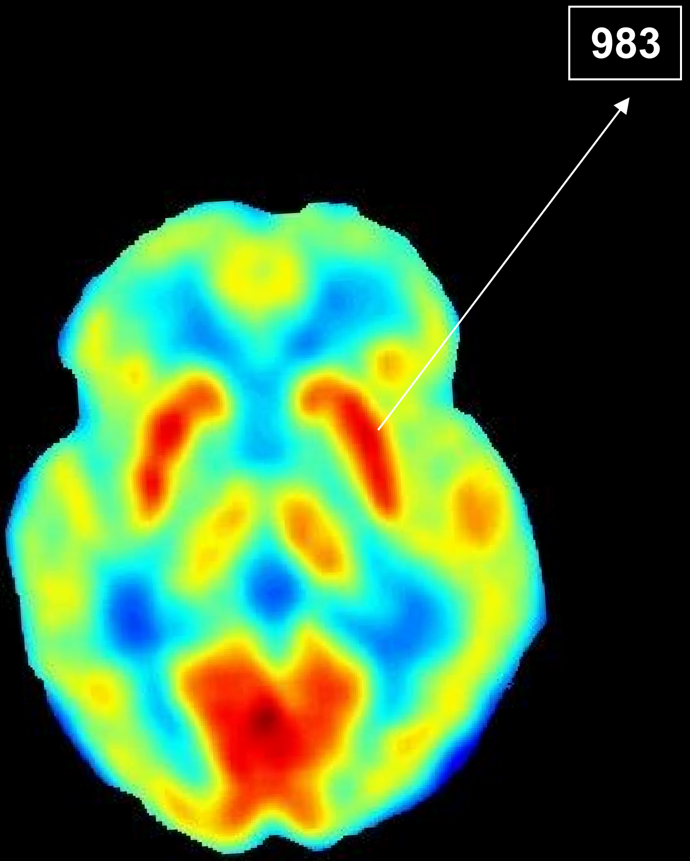
elementi β^+ emettenti

$^{14}N_7$ (p, α) ⟶ $^{11}C_6$

$^{18}O_8$ (p, n) ⟶ $^{18}F_9$


Computer Terminal
Biosynthesizer
Cyclotron

PET



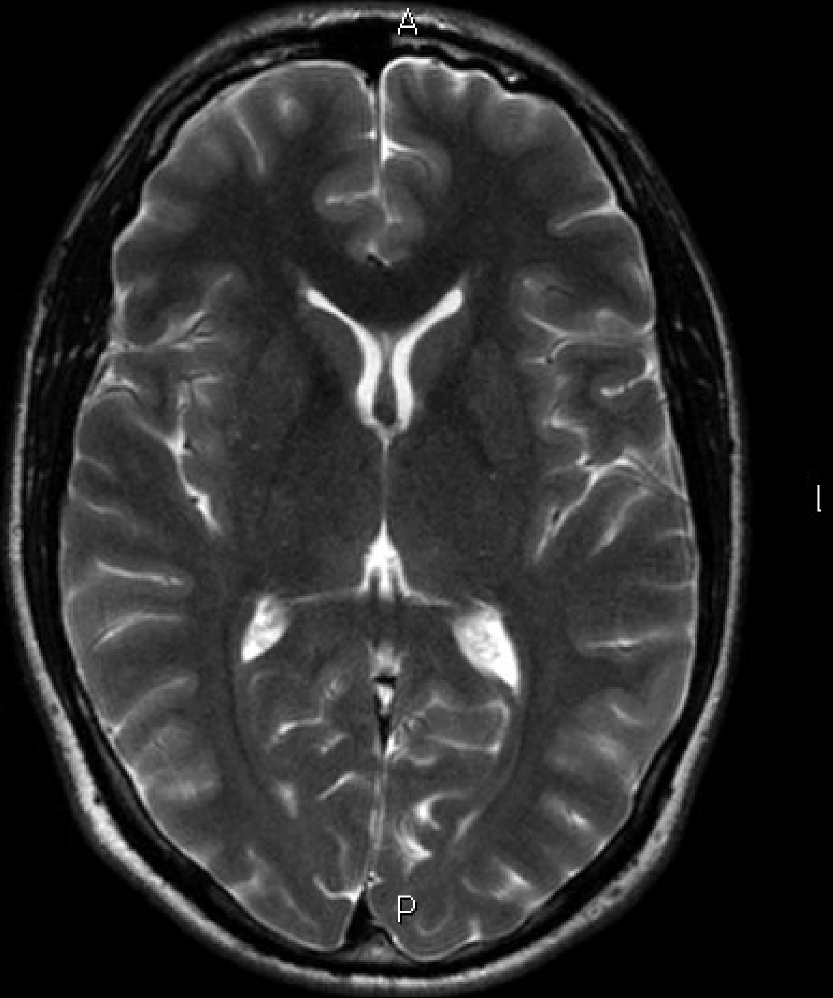
numero legato alla radioattività β^+ presente in quel punto

Radiazioni:

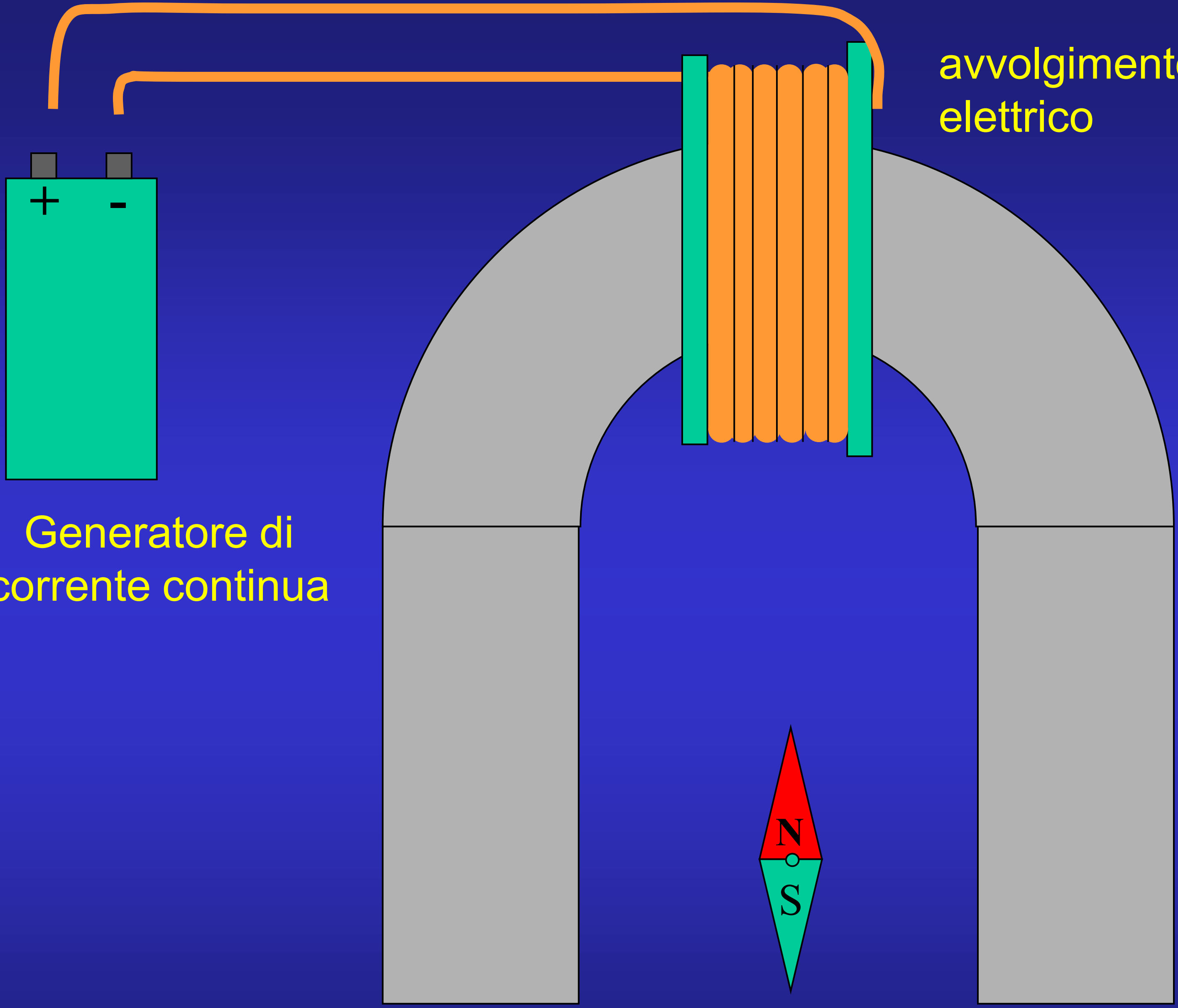
ionizzanti

non ionizzanti (NIR)

NMR
(risonanza)



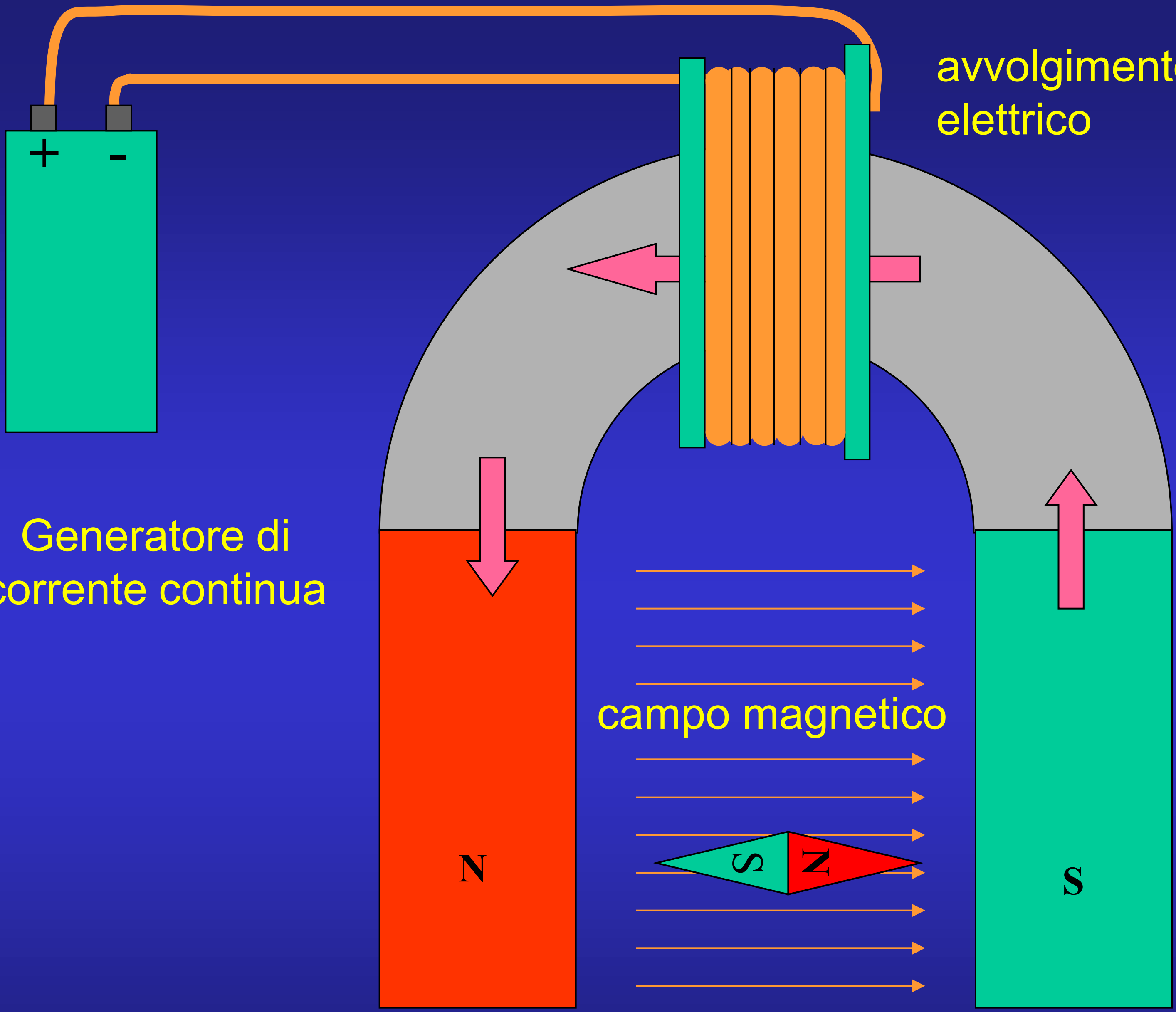
Intenso campo magnetico e onde radio



avvolgimento
elettrico

Generatore di
corrente continua

ago magnetico



avvolgimento
elettrico

Circuito
magnetico

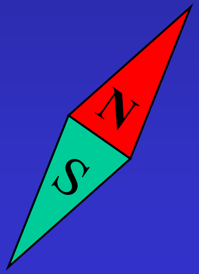
Generatore di
corrente continua

campo magnetico

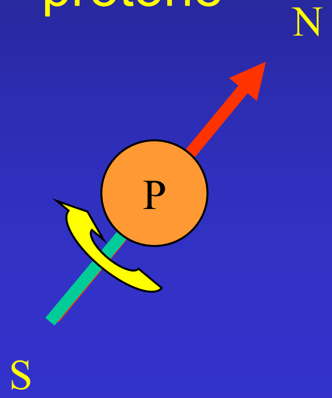
ago magnetico

MAGNETISMO E PARTICELLE

ago magnetico



protone

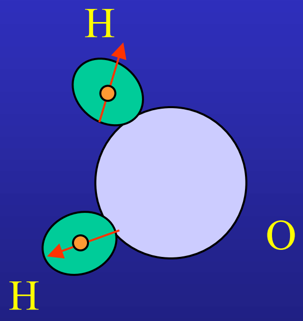


Il momento magnetico
delle particelle di chiama

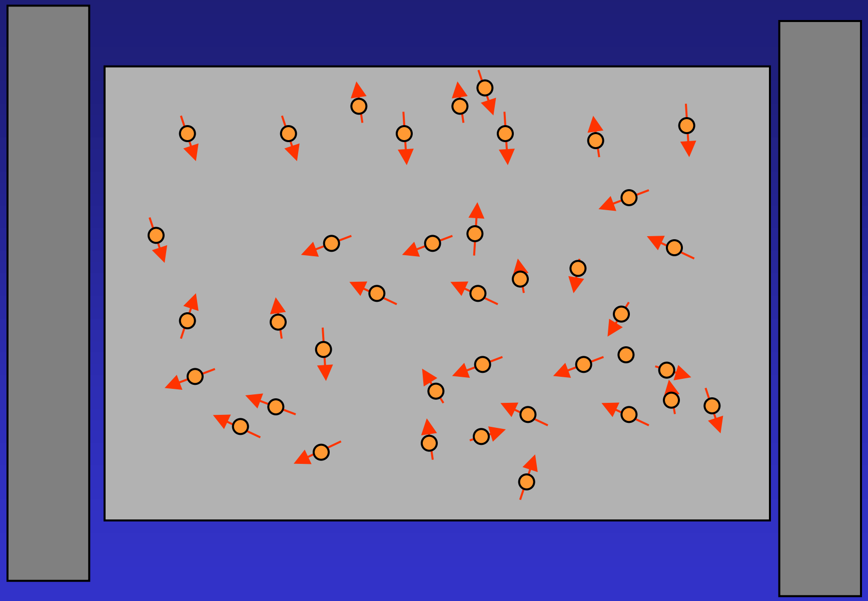
SPIN

Acqua

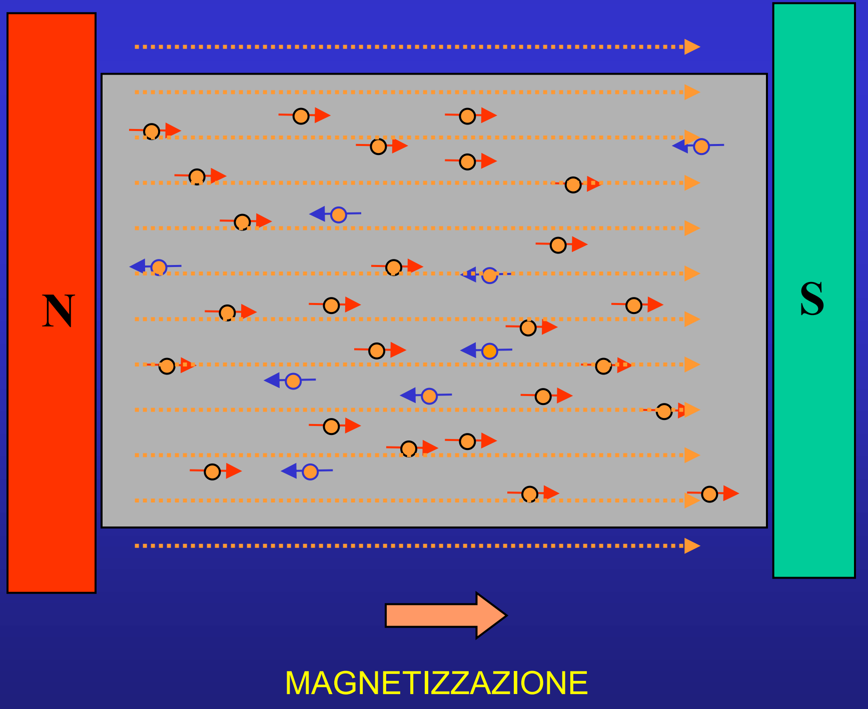
H_2O

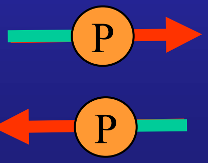


Nell'acqua gli spin dei vari protoni sono orientati a caso



se immergiamo l'acqua in un forte campo magnetico gli spin dei vari protoni si orientano col campo in un modo un po strano

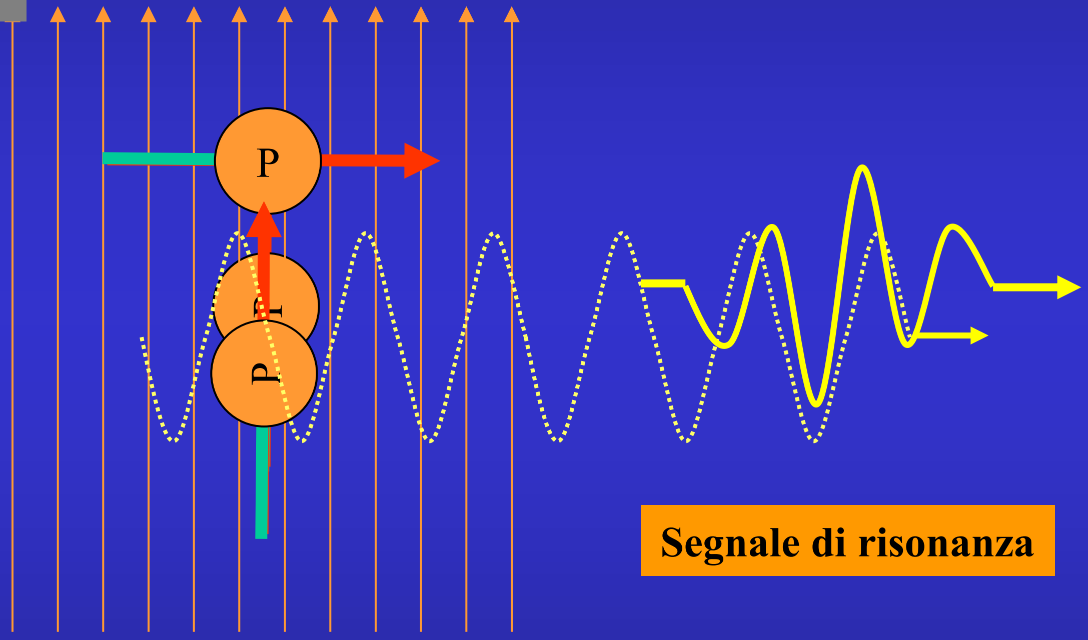

N
S
MAGNETIZZAZIONE



RISONANZA MAGNETICA

inviamo una radio onda con frequenza uguale a quella di risonanza

Protone con spin allineato al campo magnetico può entrare in risonanza



Segnale di risonanza

campo magnetico

B

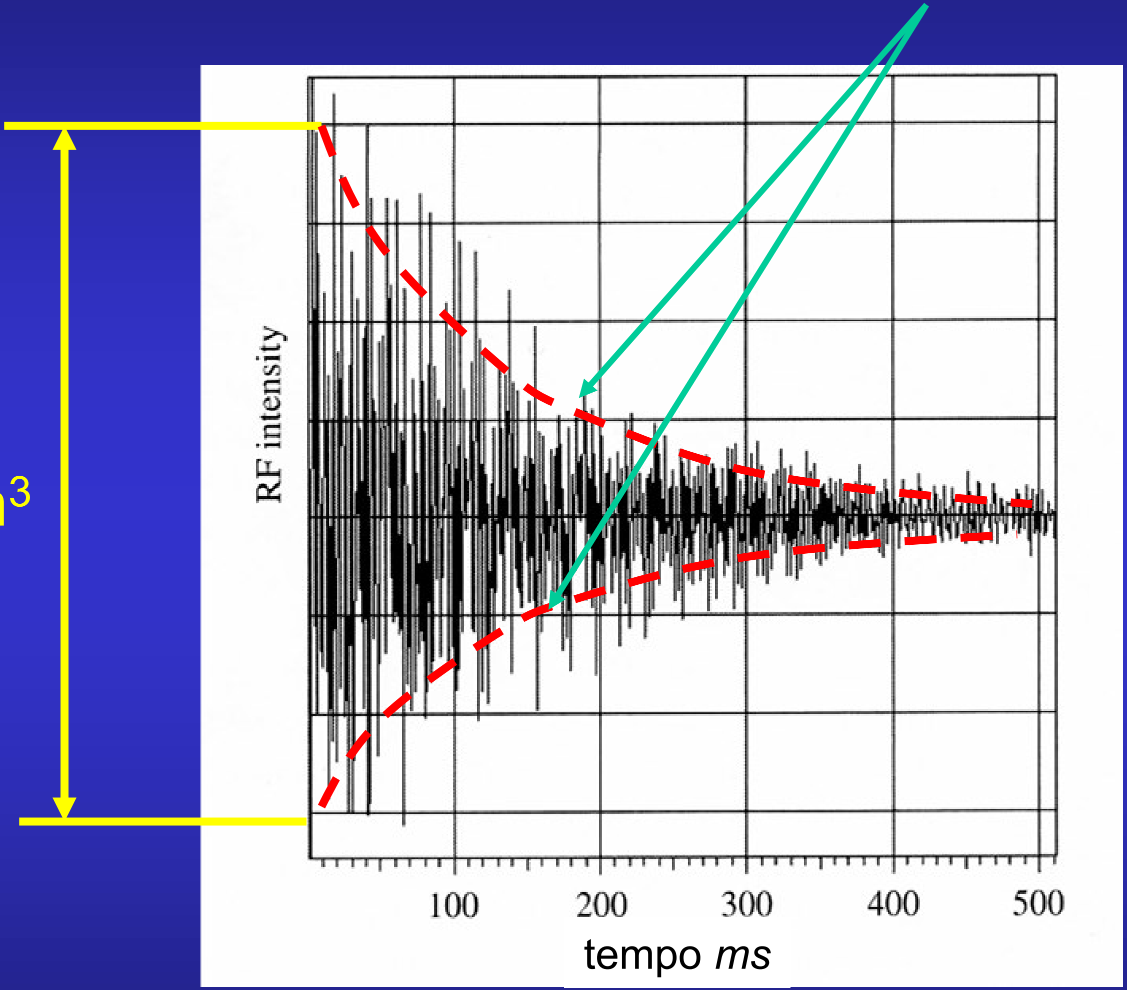
Larmor

$f_\ell = k B$

B = 2.5 T

$F\ell$ = 105 MHz

Emissione di una onda elettromagnetica di diseccitazione alla stessa frequenza della risonanza



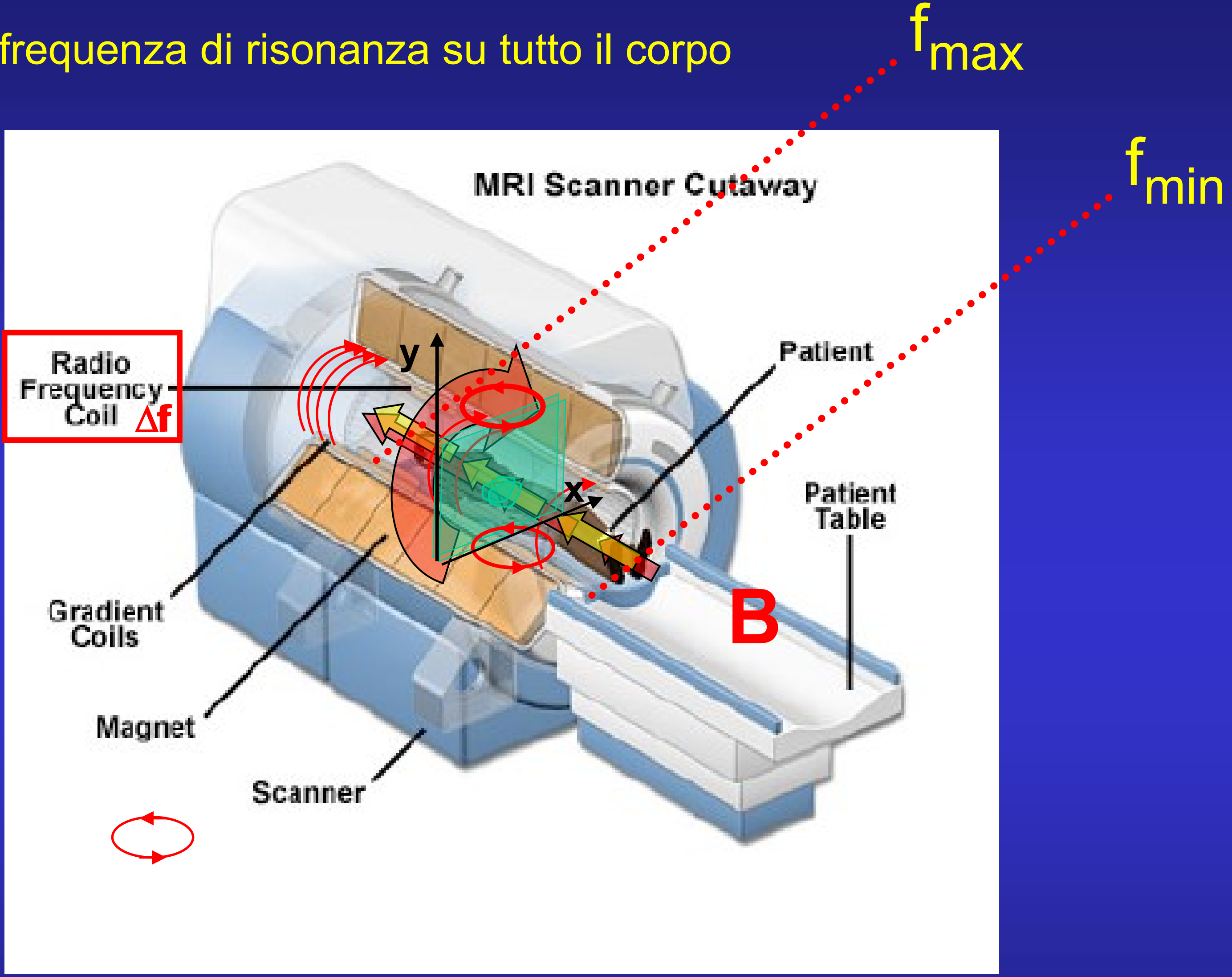
T1 rilassamento spin-reticolo
T2 rilassamento spin-spin

Densita
protonica
Protoni / cm^3

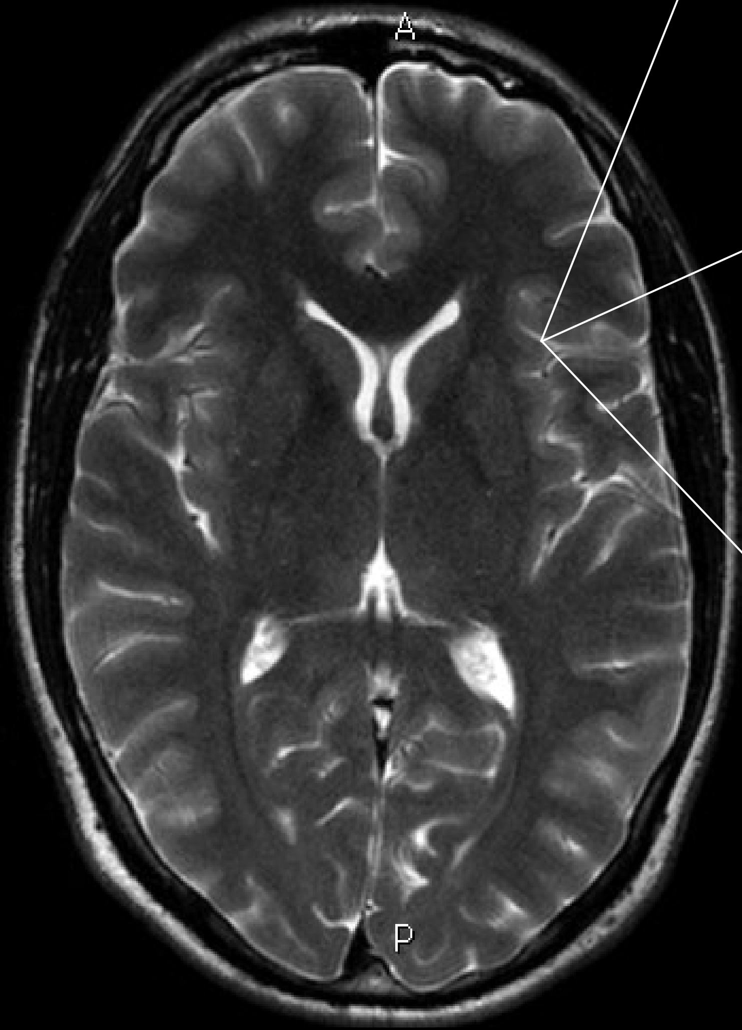
Tempo di rilassamento per alcuni tessuti a 20 MHz

	T1 (ms)	T2 (ms)
Sangue	900	200
Muscolo	500	35
Grasso	200	60
Acqua	3000	3000

unica frequenza di risonanza su tutto il corpo


f_{max}
f_{min}
MRI Scanner Cutaway
Radio Frequency Coil
Δf
y
x
Patient
Patient Table
Gradient Coils
Magnet
Scanner
B

NMR
(risonanza)



938

numero legato alla densità di protoni in quel punto

2854

numero legato al tempo di ritorno veloce dei protoni alle condizioni di equilibrio

365

numero legato al tempo di ritorno lento dei protoni alle condizioni di equilibrio

Grazie per l’attenzione

		123	163	264	186	163	150	186	264	186	163	163			
		163	133	150	163	186	264	163	150	163	186	186			
		186	163	186	186	264	150	264	186	186	264	264			
		264	186	163	264	150	163	186	163	264	150	150			
		150	264	18	150	186	163	150	18	150	186	186			
		186	150	16	186	163	264	186	16	186	163	163			
		163	186	163	186	264	186	163	150	133	163	264			
		264	163	186	264	148	150	264	264	163	264	163			
		150	186	264	186	163	186	186	264	150	264	186			

123	163	264	186	163	150	186	264	186	163	163
163	133	150	163	186	264	163	150	163	186	186
186	163	186	186	264	150	264	186	186	264	264
264	186	163	264	150	163	186	163	264	150	150
150	264	18	150	186	163	150	18	150	186	186
186	150	16	186	163	264	186	16	186	163	163
163	186	163	186	264	186	163	150	133	163	264
264	163	186	264	148	150	264	264	163	264	163
150	186	264	186	163	186	186	264	150	264	186
186	264	186	163	186	150	148	163	186	186	264
186	150	163	186	264	186	163	150	133	16	150
163	186	186	264	16	18	16	186	148	18	186
186	186	264	163	186	163	186	264	186	163	163