

Medical radioisotopes

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ESIPAP

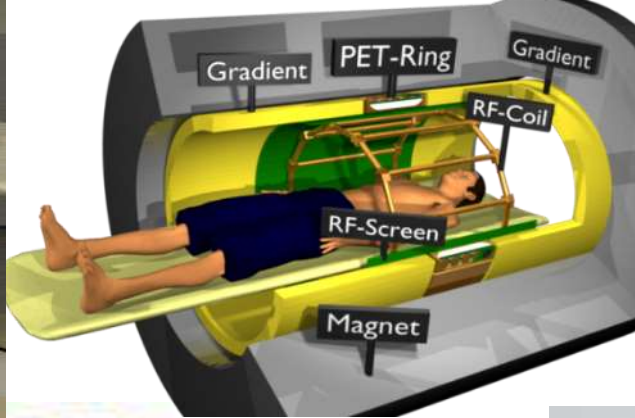
8 March 2021

Grands Instruments Européens

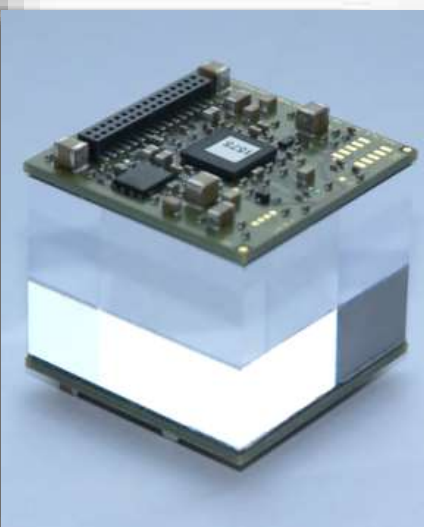
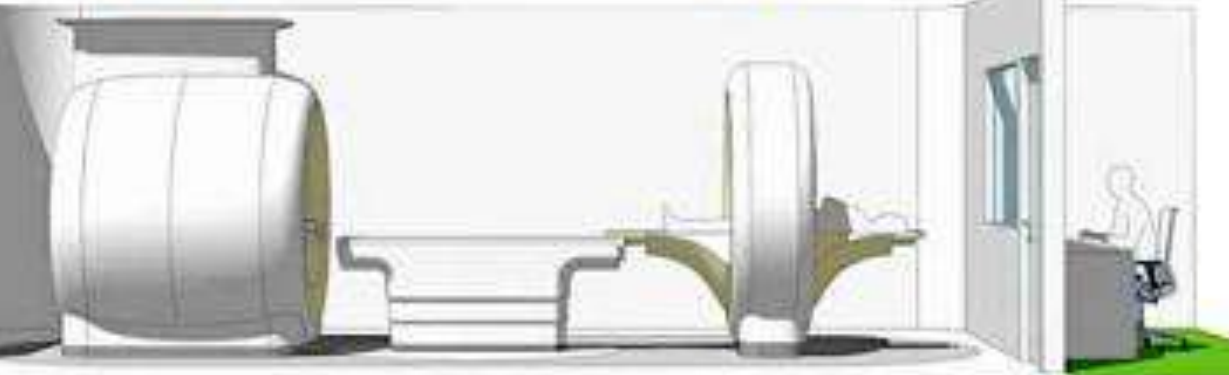
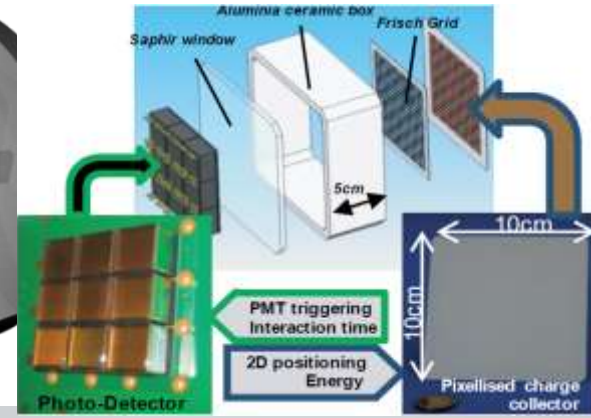




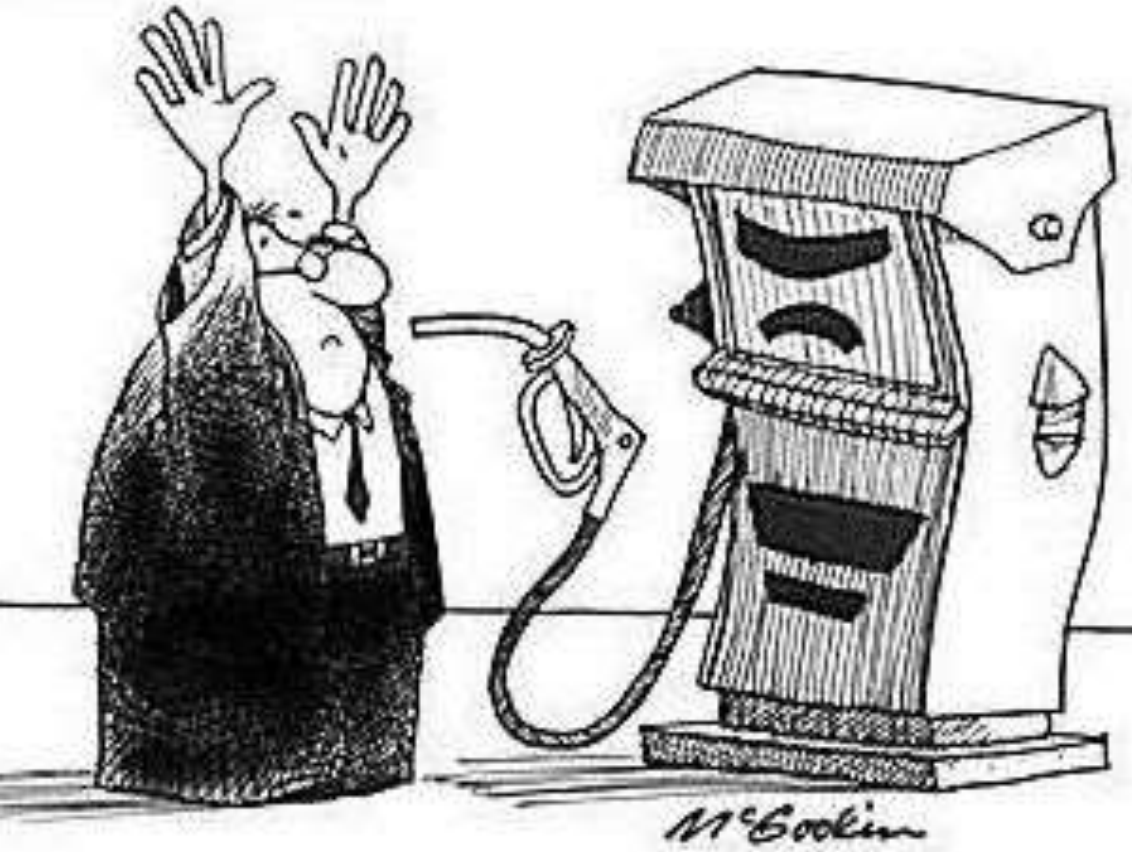
IRM



PET



Don't forget the fuel!

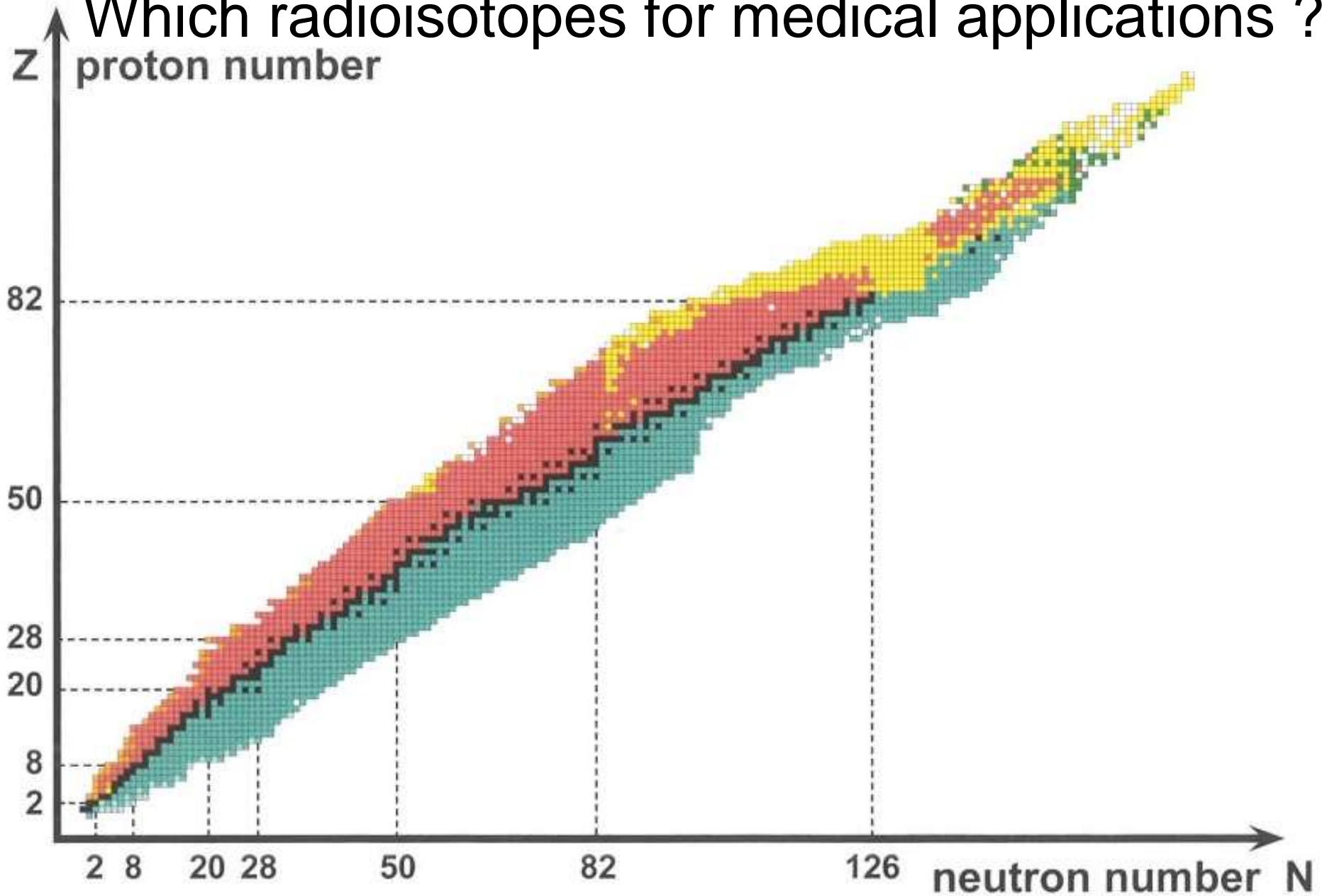


Radioisotopes: the “fuel” for nuclear medicine

1. What is the optimum fuel for an application ?
2. Are we using the optimum fuel today ?
3. Where does this fuel come from ?

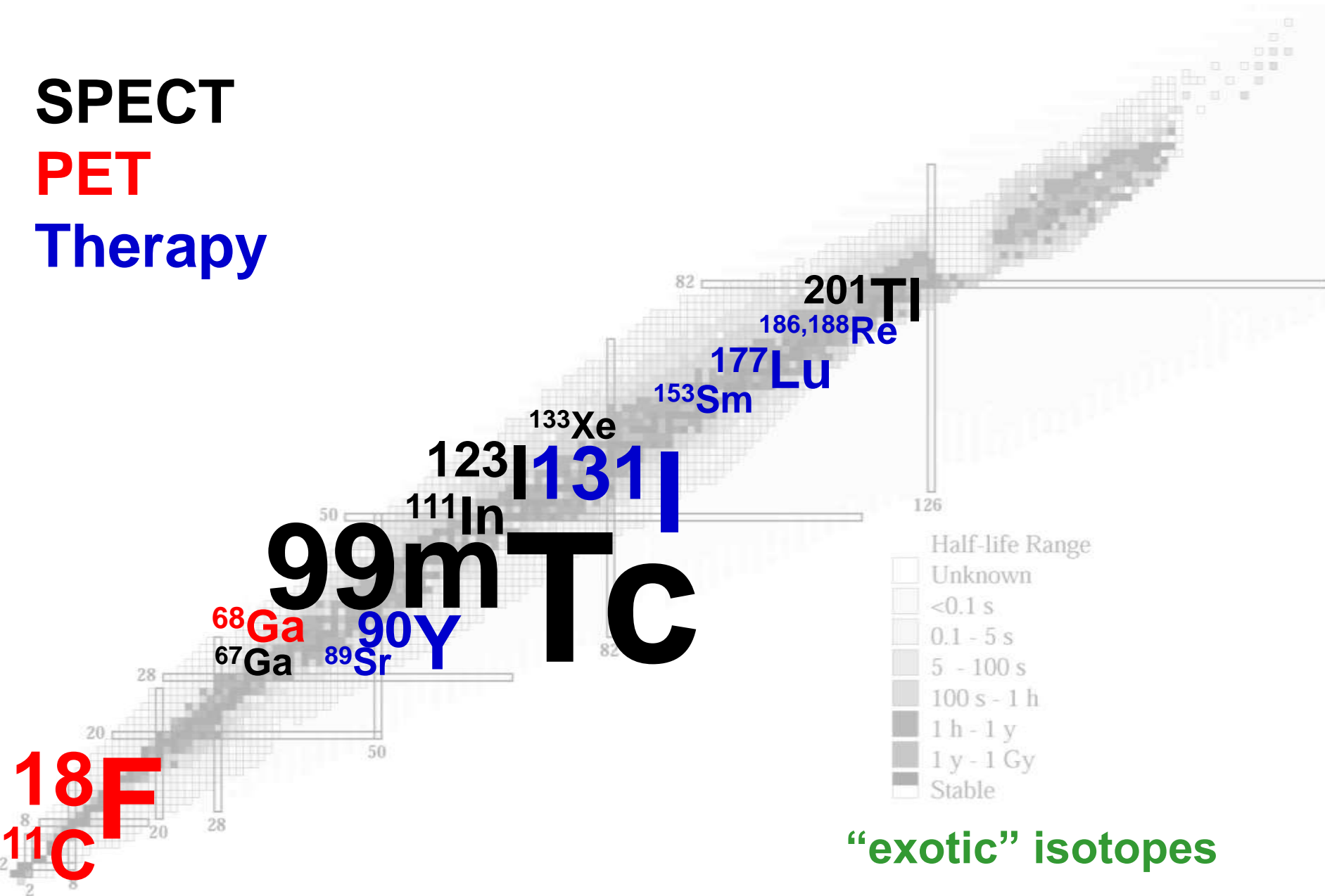
Question

Which radioisotopes for medical applications ?



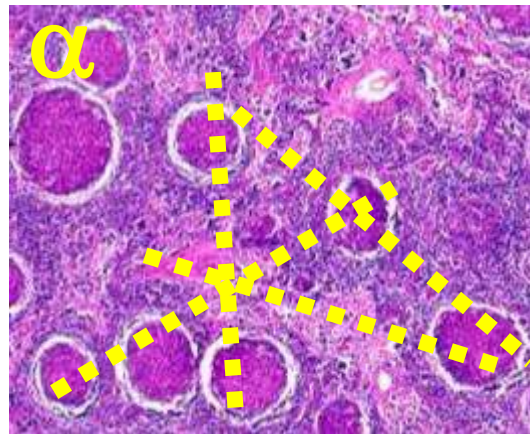
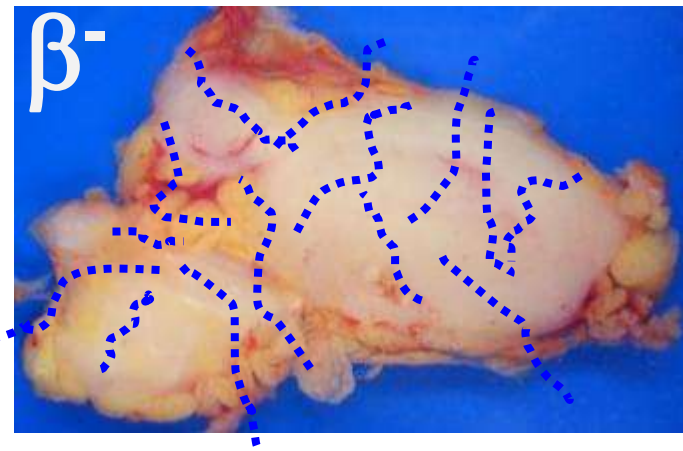
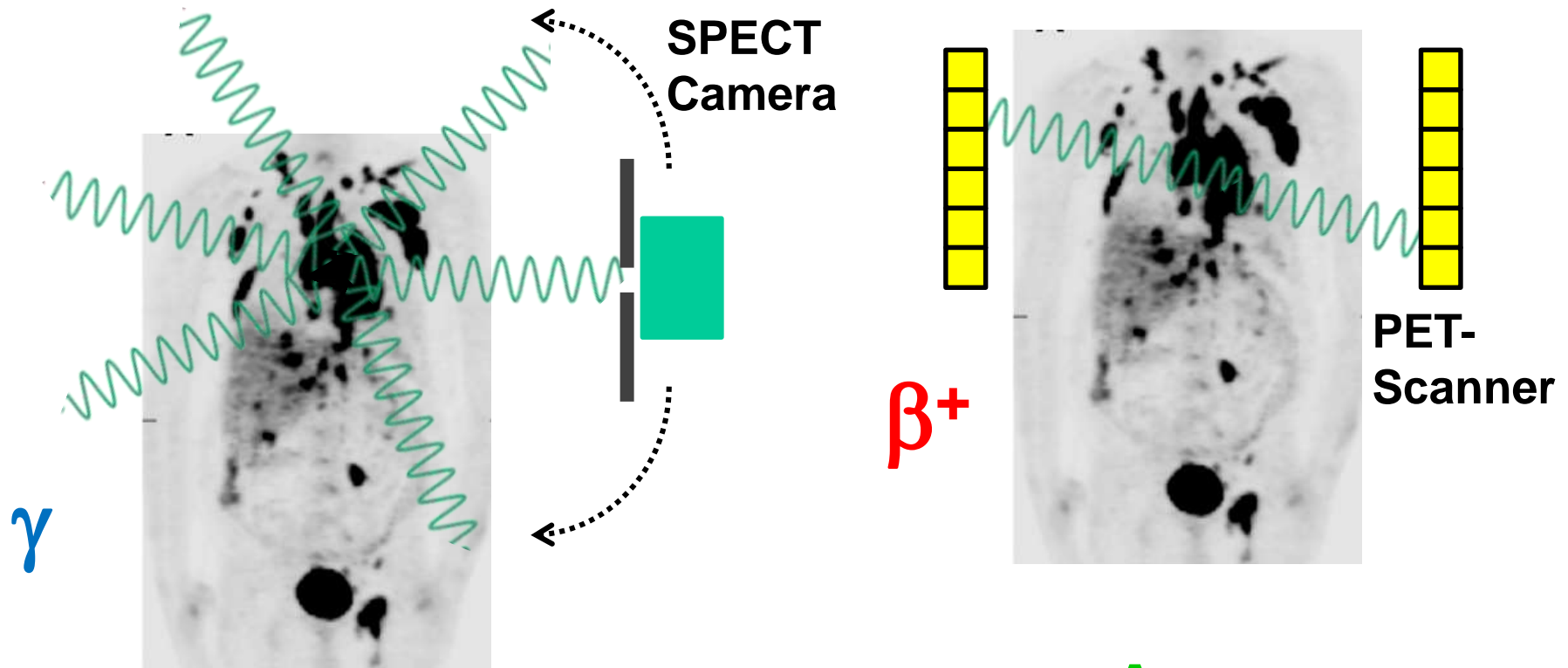
The chart of nuclides – nuclear medicine perspective

SPECT
PET
Therapy

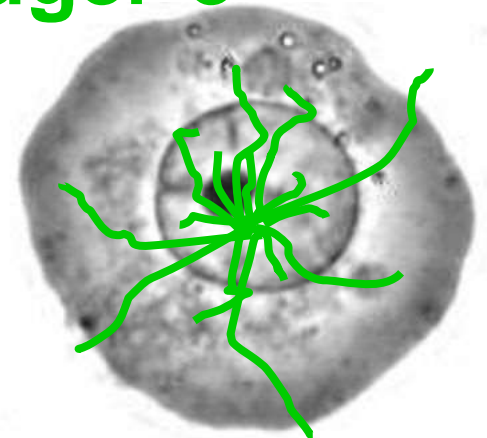


“exotic” isotopes

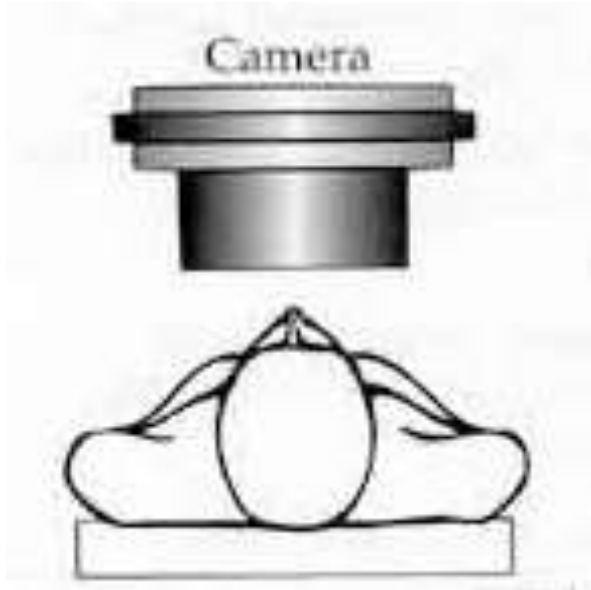
The Nuclear Medicine Alphabet



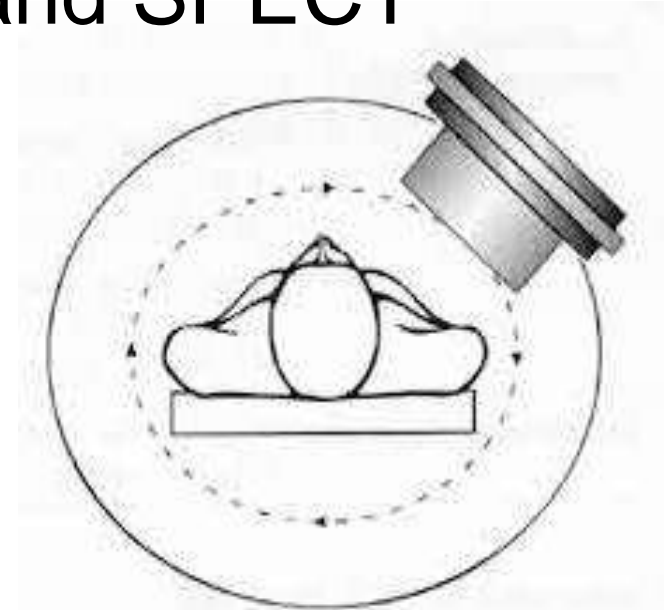
Auger- e^-



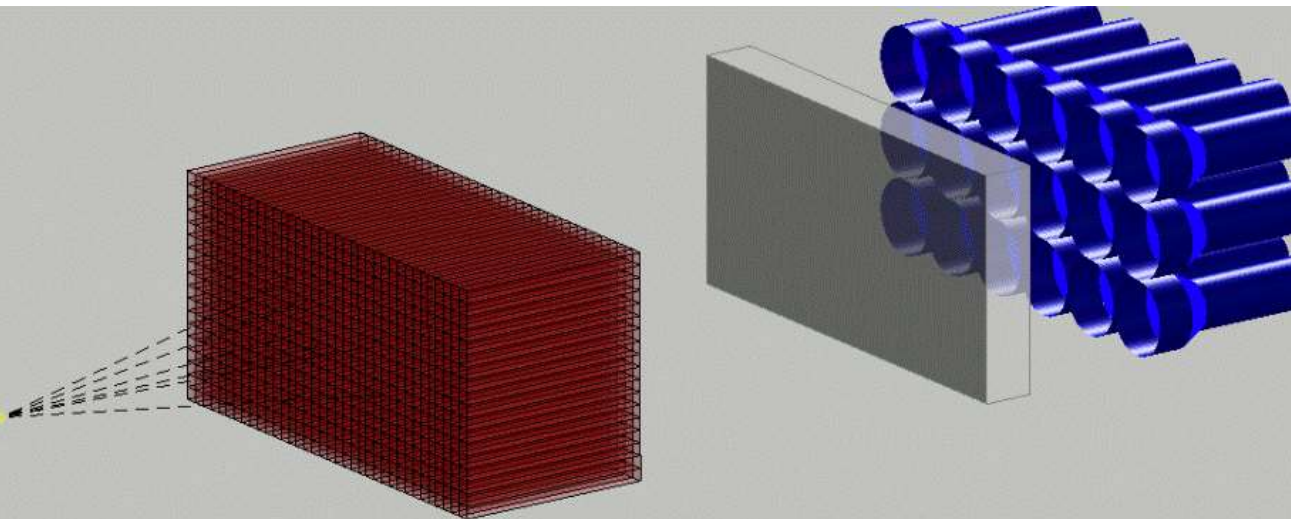
Scintigraphy and SPECT



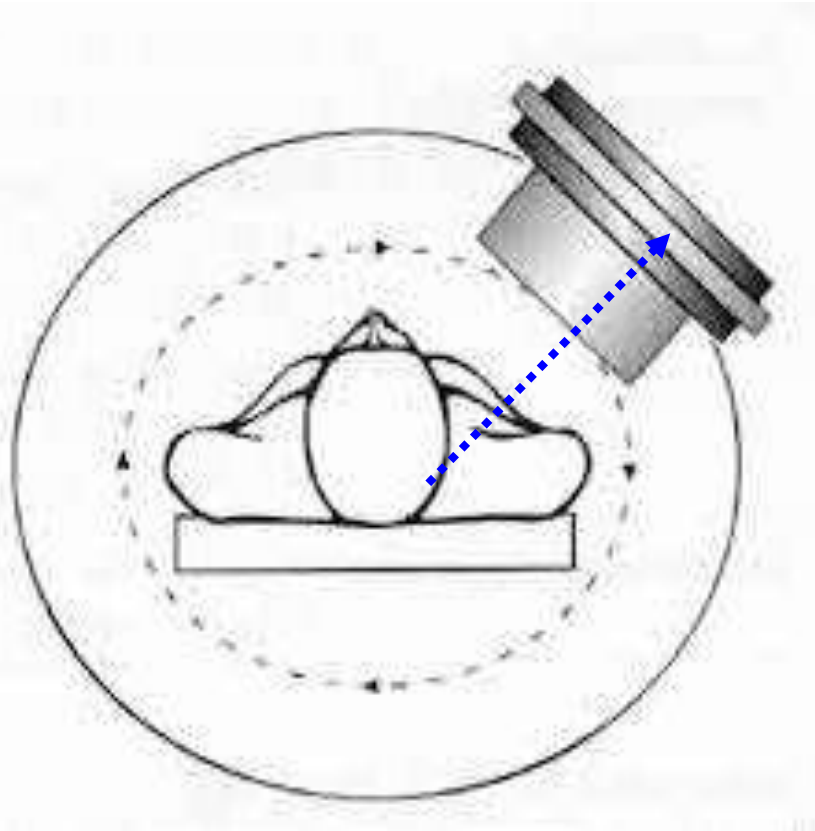
**2D: planar scan
(Gamma camera)**



**3D: SPECT: Single Photon Emission
Computed Tomography**



Question: Ideal gamma ray energy for scintigraphy/SPECT?



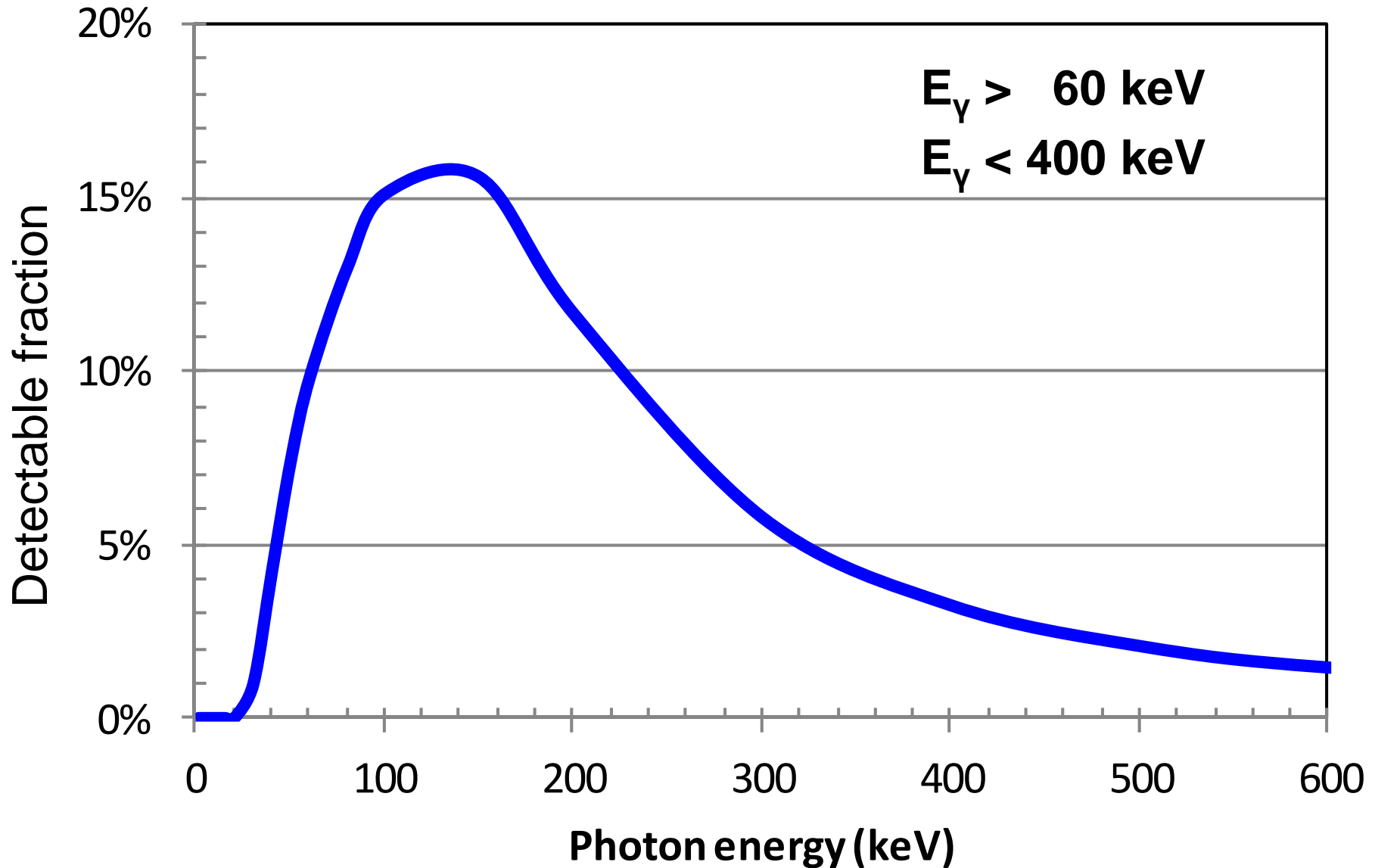
$$N = N_0 e^{-\int_0^d \mu(x) dx}$$

10 cm soft tissue

0.2 cm aluminium (detector encapsulation)

1 cm NaI

Ideal gamma ray energy for scintigraphy/SPECT



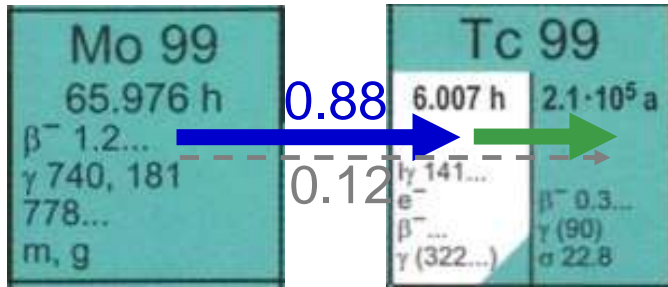
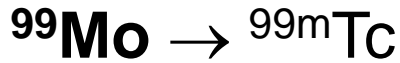
10 cm soft tissue, 0.2 cm aluminium (detector encapsulation), 1 cm NaI

^{99m}Tc : ideal for SPECT and gamma cameras

Ru 98 1.87 $\sigma < 8$	Ru 99 12.76 $\sigma 4$	Ru 100 12.60 $\sigma 5.8$	Ru 101 17.06 $\sigma 5$	Ru 102 31.55 $\sigma 1.2$
Tc 97 92.2 d $4.0 \cdot 10^5 \text{ a}$ $\beta^- (97)$ e^-	Tc 98 $4.2 \cdot 10^6 \text{ a}$ $\beta^- 0.4$ $\gamma 745; 652$ $\sigma 0.9 + ?$	Tc 99 6.0 h $2.1 \cdot 10^5 \text{ a}$ $\beta^- 141 \dots$ e^- $\beta^- \dots$ $\gamma (322 \dots)$	Tc 100 15.8 s $\beta^- 3.4 \dots$ ϵ $\gamma 540; 591 \dots$	Tc 101 14.2 m $\beta^- 1.3 \dots$ $\gamma 307; 545 \dots$
Mo 96 16.68 $\sigma 0.5$	Mo 97 9.56 $\sigma 2.5$ $\sigma_n, \alpha 4E-7$	Mo 98 24.19 $\sigma 0.14$	Mo 99 66.0 h $\beta^- 1.2 \dots$ $\gamma 740; 182;$ 778... m; g	Mo 100 9.67 $1.15 \cdot 10^{19} \text{ a}$ $2\beta^-$ $\sigma 0.19$

- IT with 89% 140.5 keV gamma ray, $T_{1/2} = 6 \text{ h}$
- decays to quasi-stable daughter
- ^{99m}Tc fed in 88% of β^- decays of ^{99}Mo , $T_{1/2} = 66 \text{ h}$
- produces nearly carrier-free product

The Bateman equations



$$dN_1/dt = -\lambda_1 N_1$$

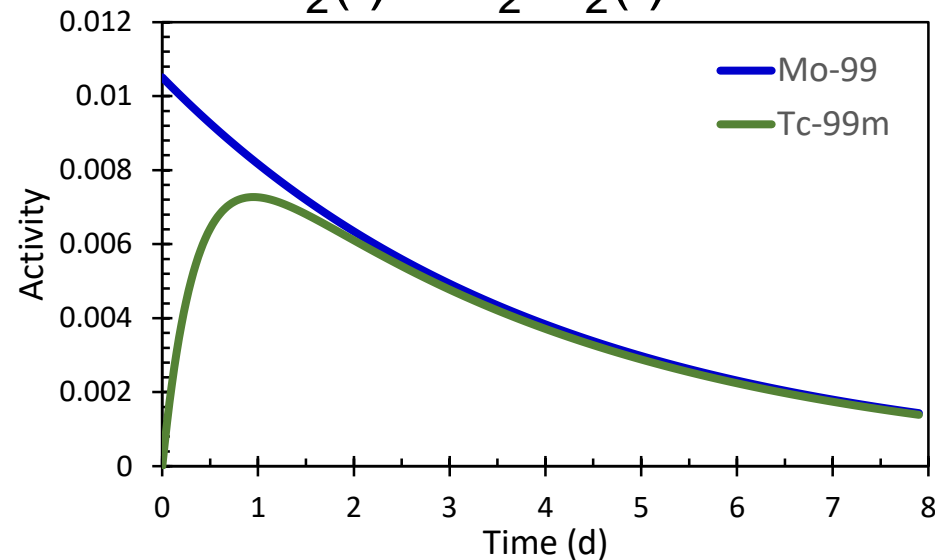
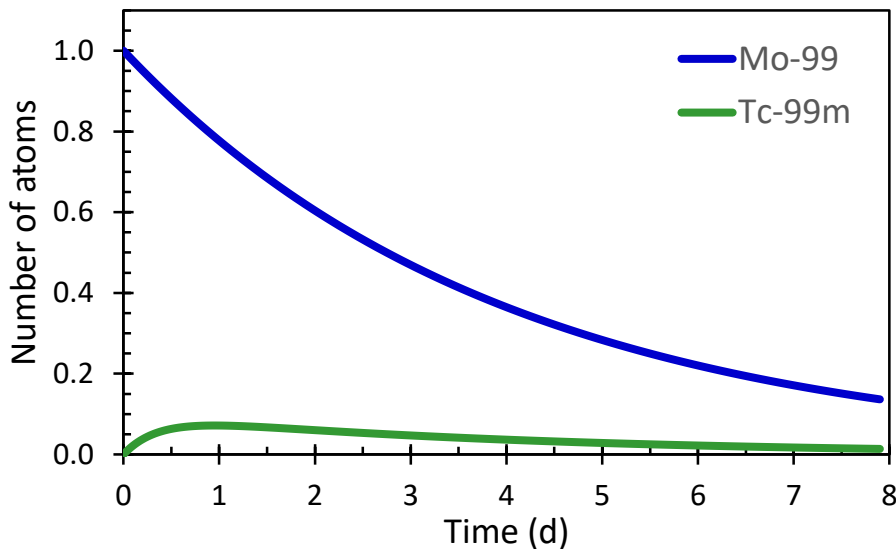
$$N_1(t) = N_1(0) \exp(-\lambda_1 t)$$

$$A_1 = \lambda_1 N_1 = \lambda_1 N_1(0) \exp(-\lambda_1 t)$$

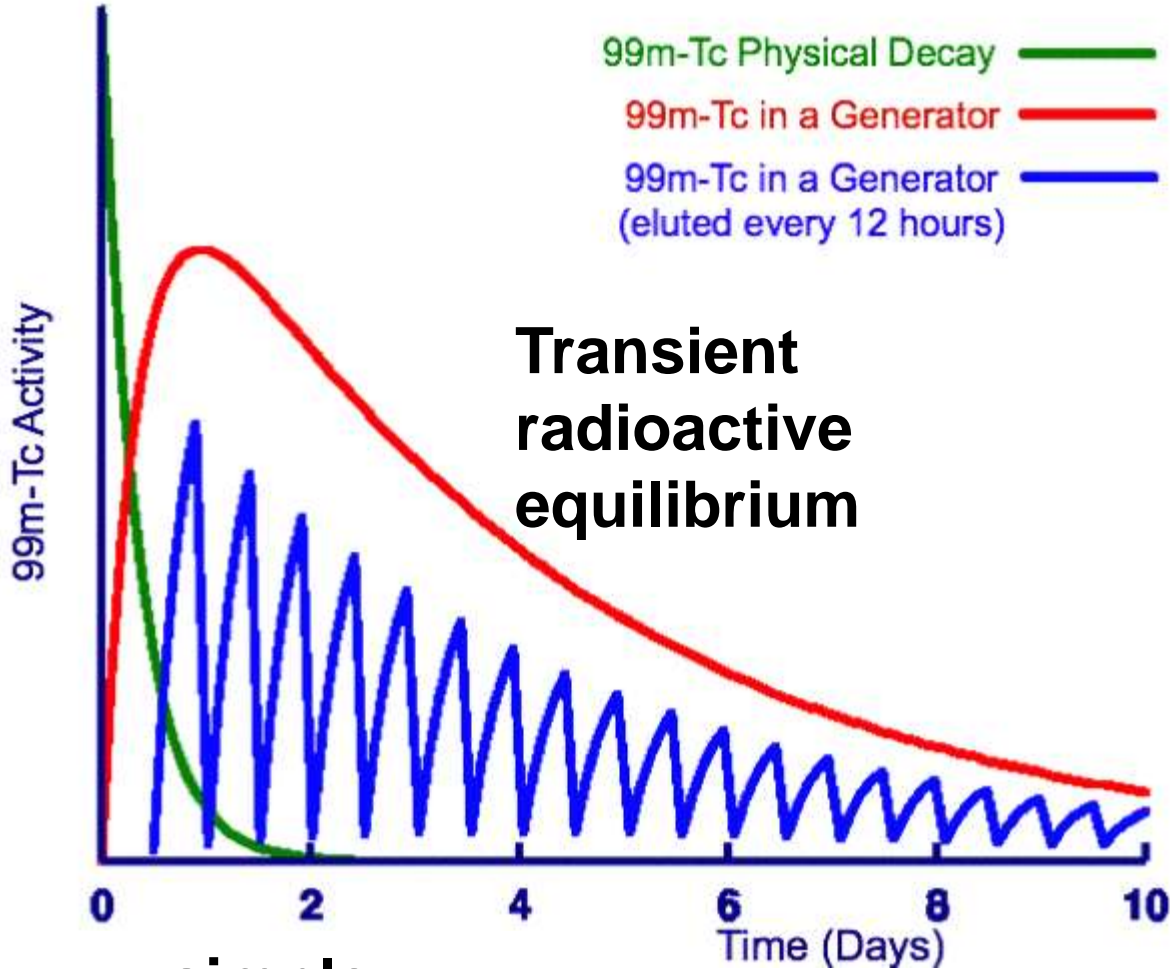
$$dN_2/dt = \lambda_1 N_1 - \lambda_2 N_2$$

$$N_2(t) = N_2(0) \exp(-\lambda_2 t) + \frac{\lambda_1}{\lambda_2 - \lambda_1} N_1(0) [\exp(-\lambda_1 t) - \exp(-\lambda_2 t)] * 0.88$$

$$A_2(t) = \lambda_2 N_2(t)$$



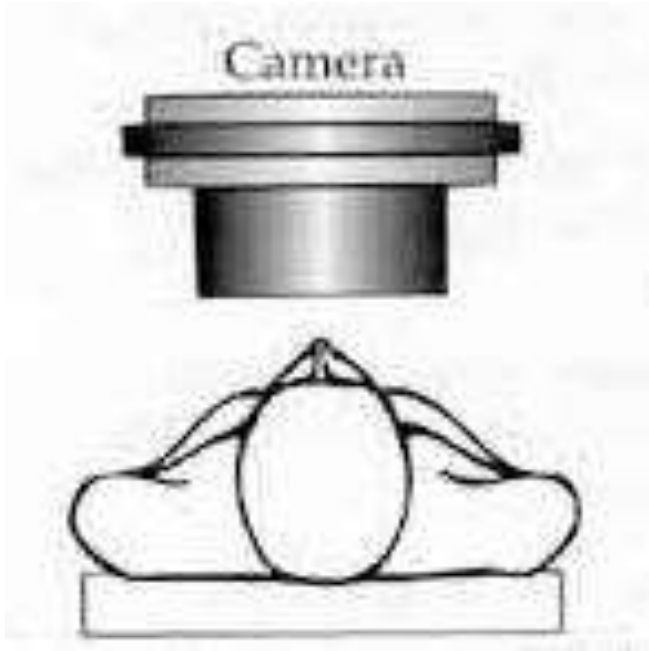
$^{99}\text{Mo}/^{99\text{m}}\text{Tc}$ generator



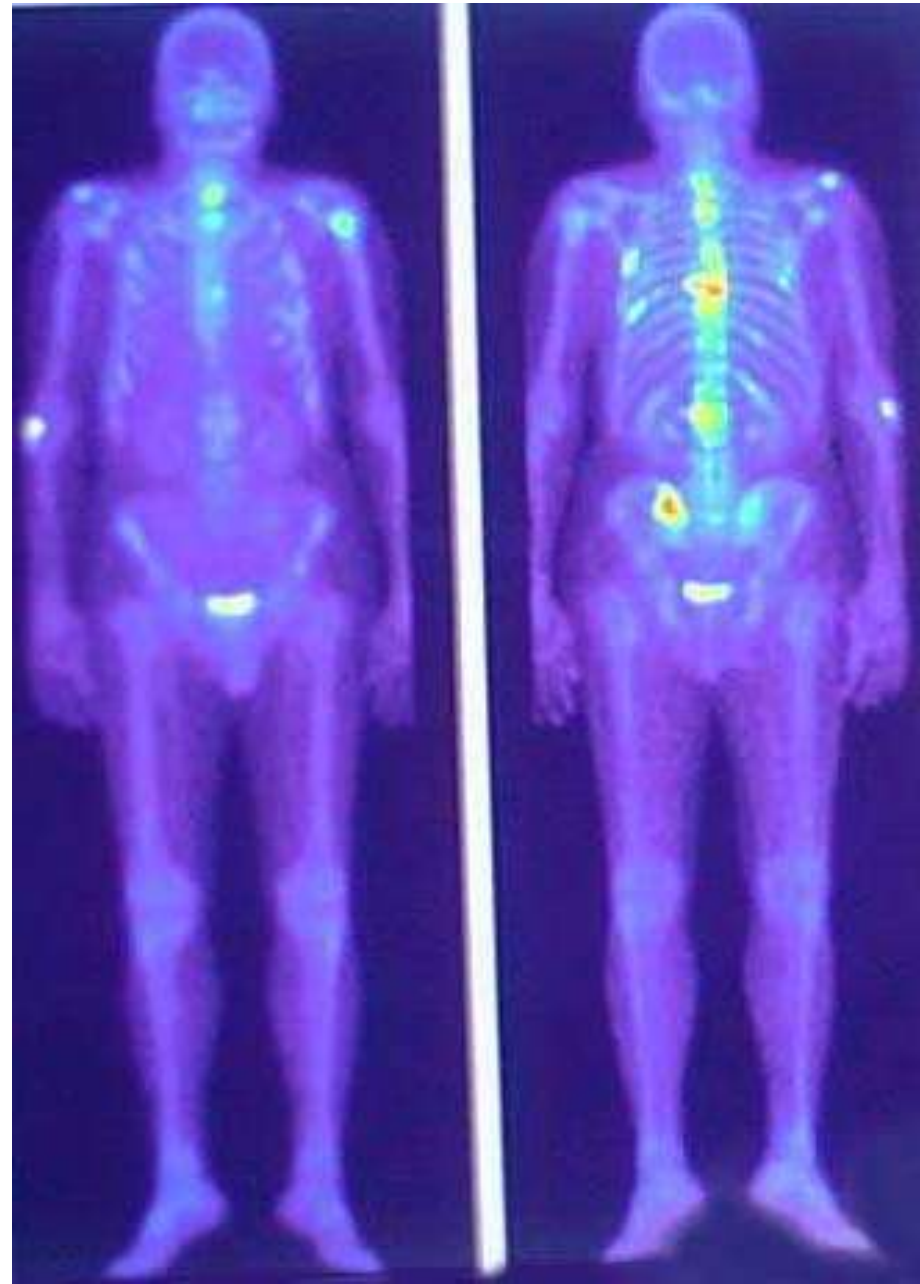
- **simple**
- **reliable**
- **portable**
- **self-shielded**



Bone metastases



- planar or SPECT scan for bone metastases
- differentiate between local and generalized disease
- decide on treatment options: surgery or radiation therapy versus systemic therapy





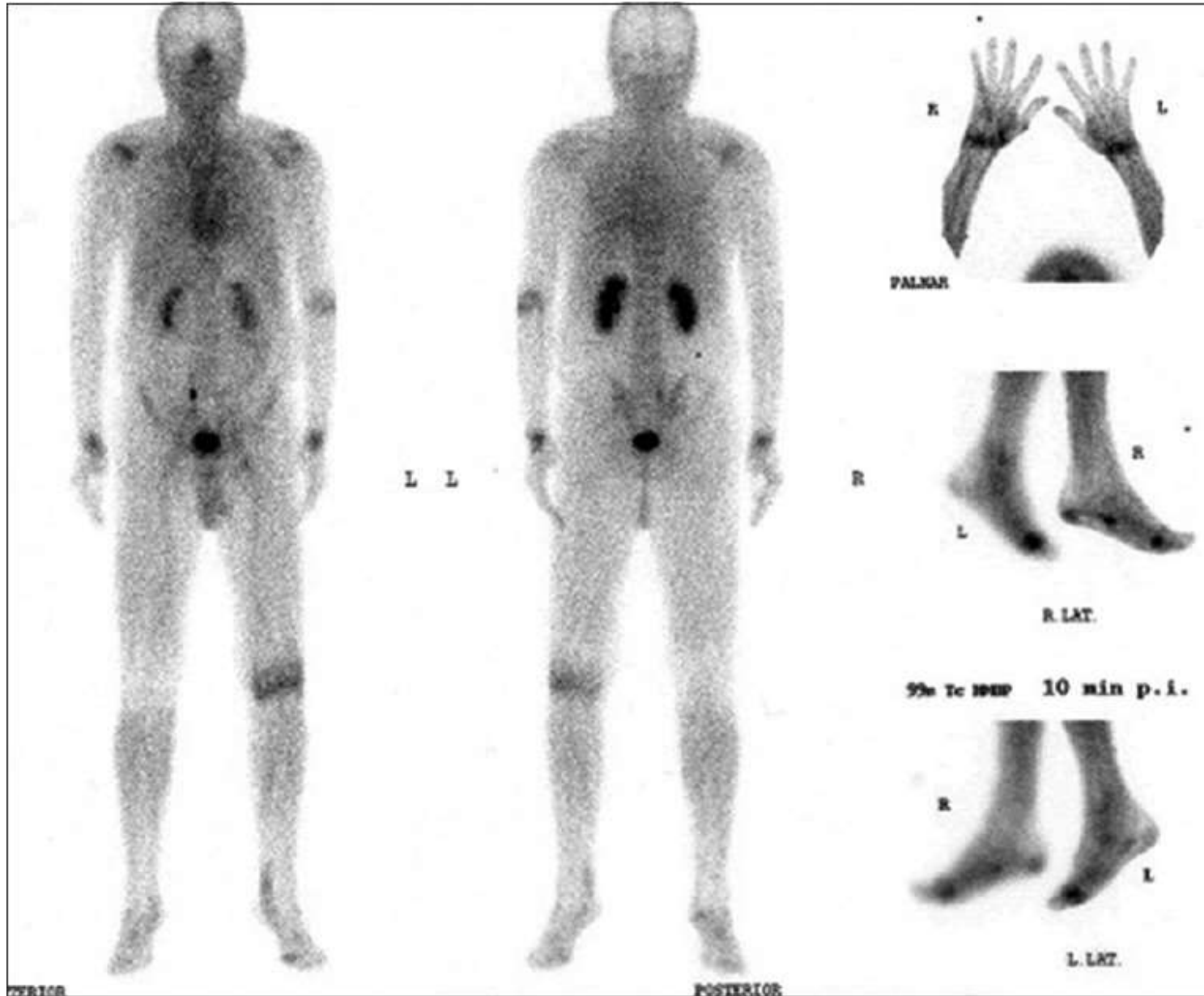
Bone scans: 35% of NM procedures in Europe

Even-Sapir E et al., J Nucl Med 2006; 47: 287.

^{99m}Tc -MDP planar

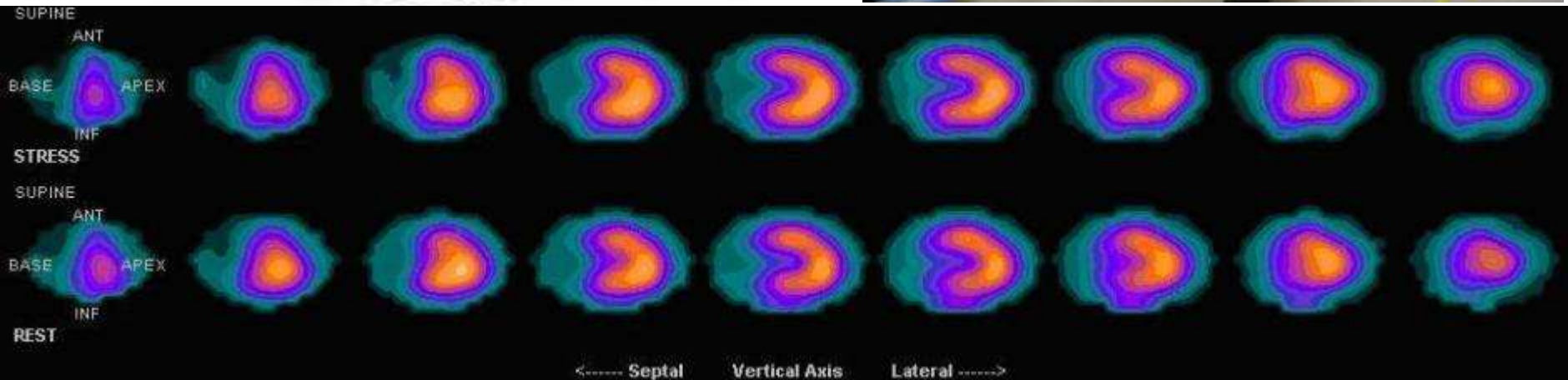
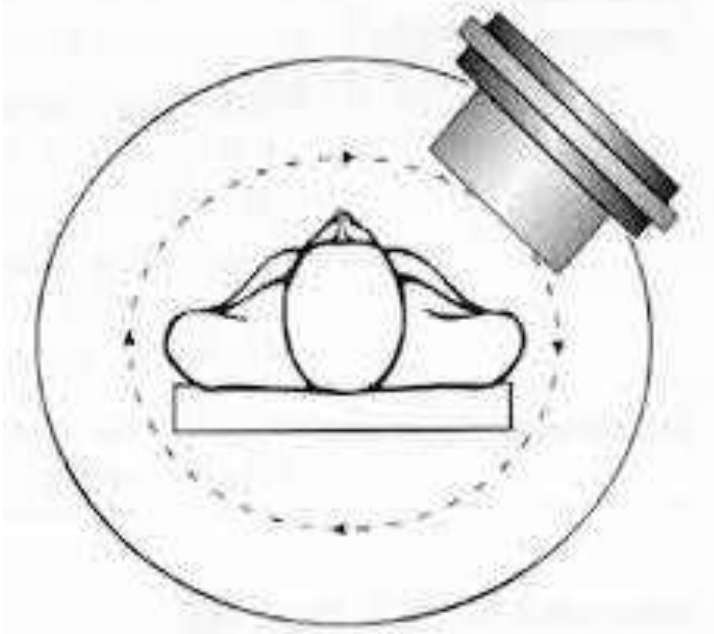
^{99m}Tc -MDP SPECT

Rheumathoid arthritis

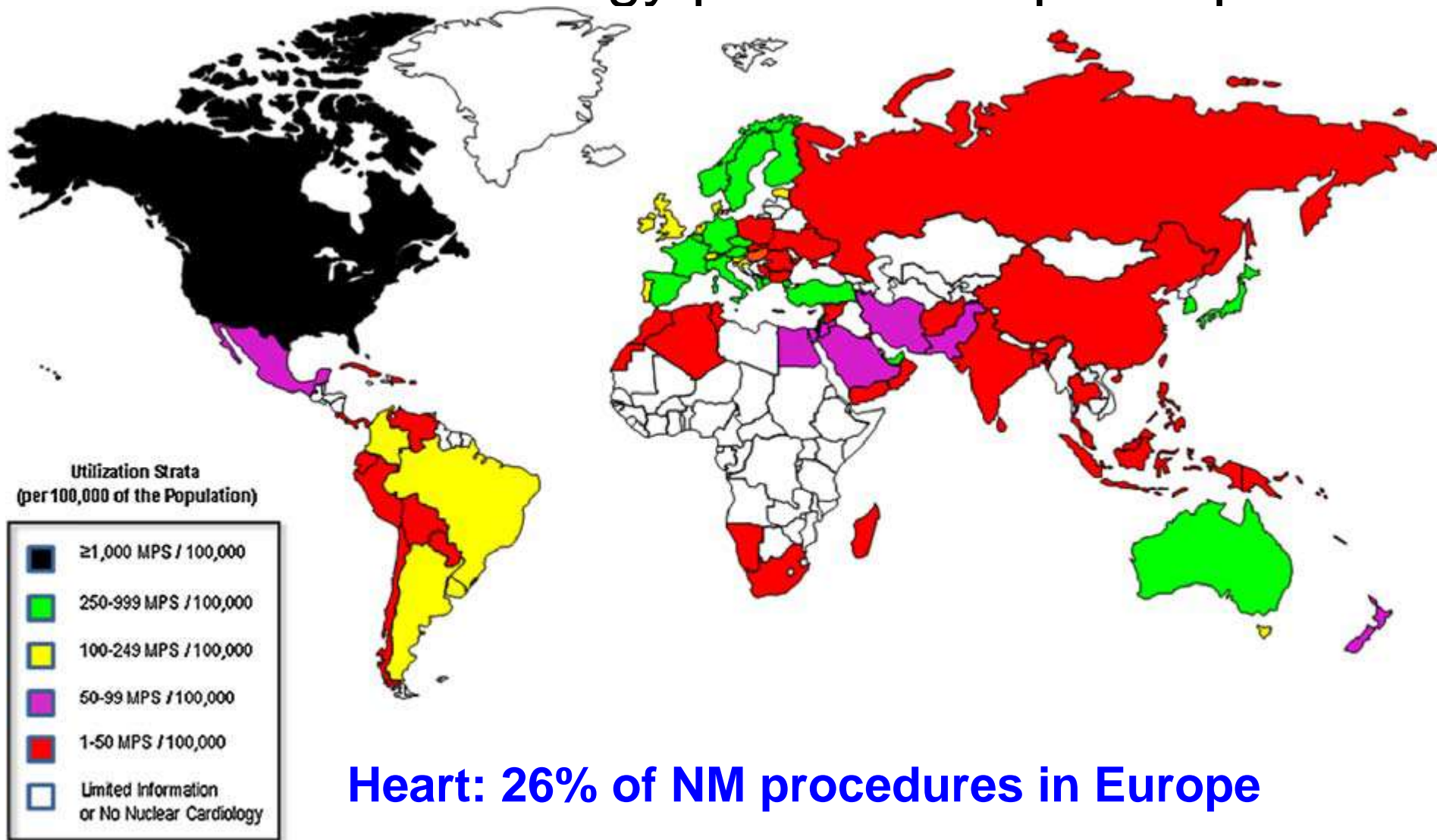


Ischemic heart disease

- diagnose by ECG and cardiac stress test with SPECT
- treatment by medication, angioplasty or bypass surgery



Nuclear cardiology procedures per capita

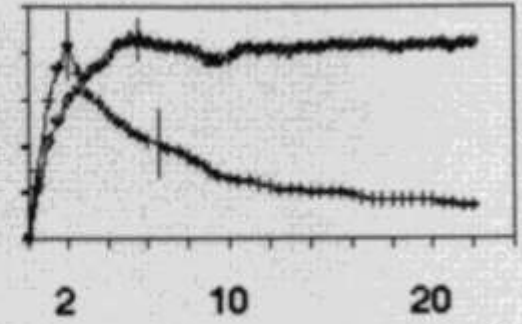
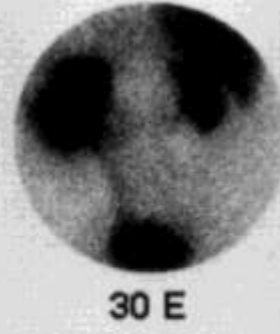


Heart: 26% of NM procedures in Europe

2007: 8.54M myocardial perfusion SPECT
procedures reimbursed in the USA

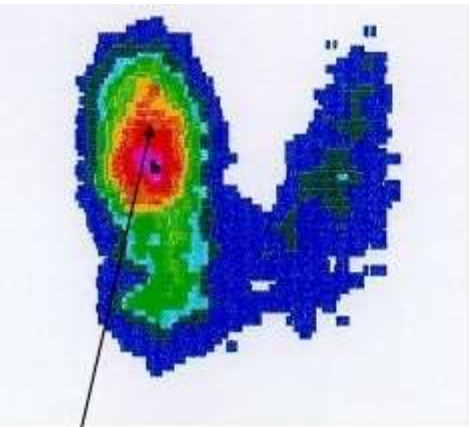
J.V. Vitola et al., J Nucl Cardiol 2009;16:956.

Scintirenography

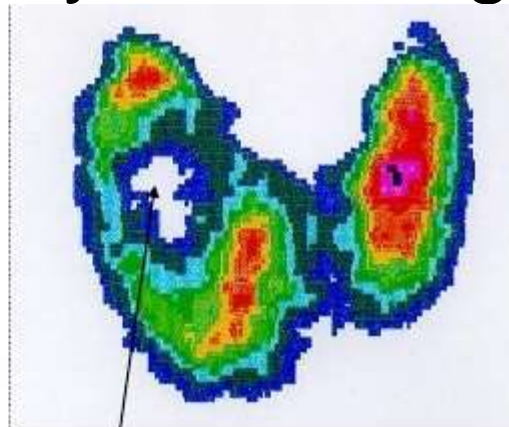


Kidney: 13% of NM procedures in Europe

Thyroid scintigraphy



Hot nodule – Rt. lobe

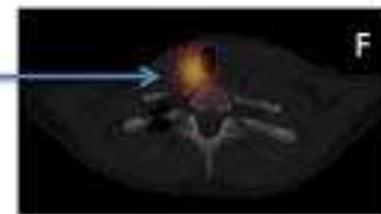
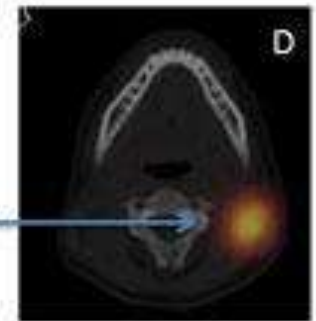
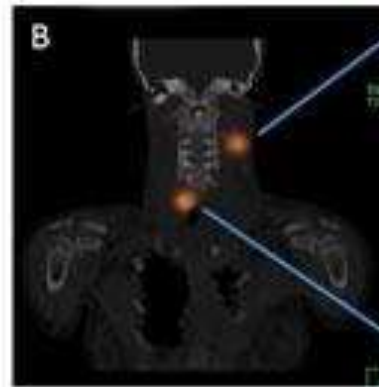


Cold nodule – Rt. lobe

^{123}I Diagnostic Whole Body Scan



^{123}I DxWBS with SPECT-CT



$^{123}\text{I}^-$, $^{131}\text{I}^-$ or $^{99\text{m}}\text{TcO}_4^-$

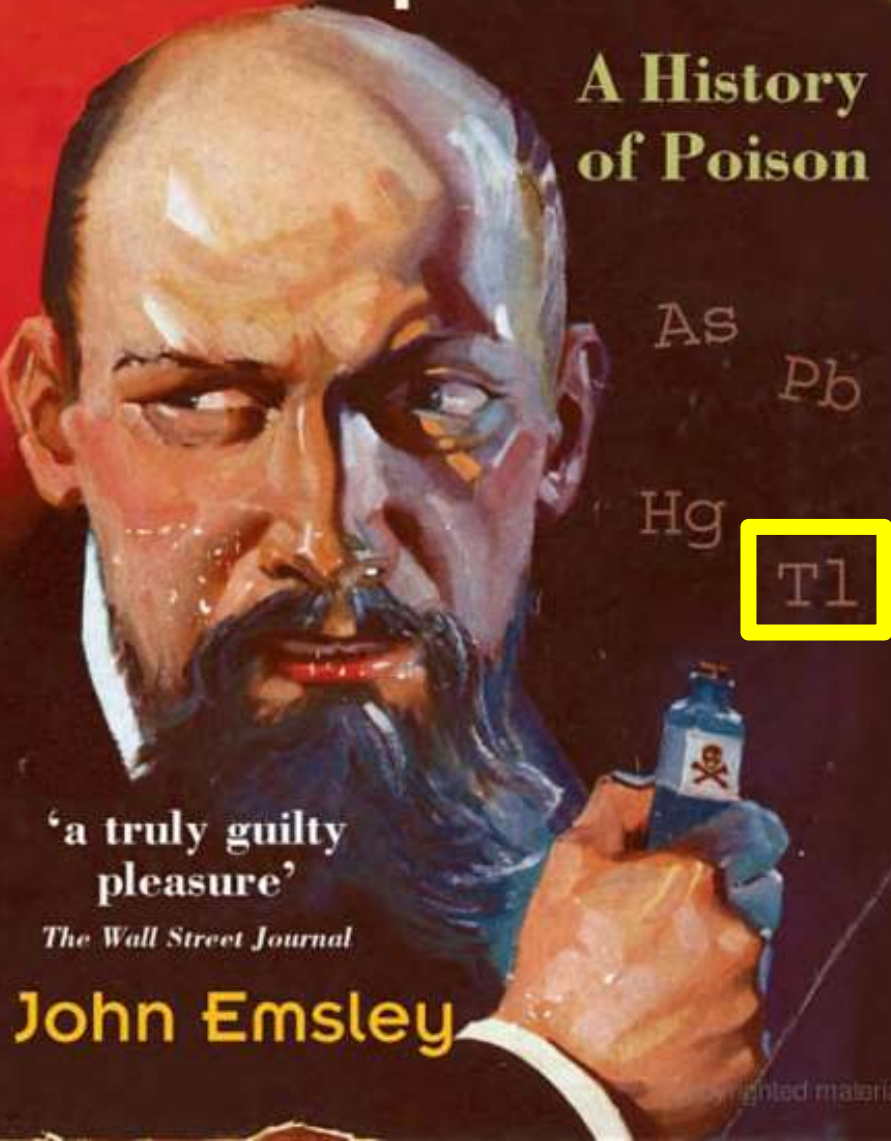
Thyroid: 12% of NM procedures in Europe

SPECT isotopes

Radio-nuclide	Half-life (h)	E _γ (keV)	I _γ (%)	Decay type
Ga-67	78	93 185	42 21	EC
Kr-81m	0.004	190	64	IT
Tc-99m	6	141	89	IT
In-111	67	171 245	91 94	EC
I-123	13	159	83	EC
Xe-133	126	81	38	β ⁻
Tl-201	73	70 167	59 10	EC
I-131	192	364	82	β ⁻
Lu-177	161	113 208	6 10	β ⁻

The Elements of Murder

A History of Poison



'a truly guilty pleasure'

The Wall Street Journal

John Emsley

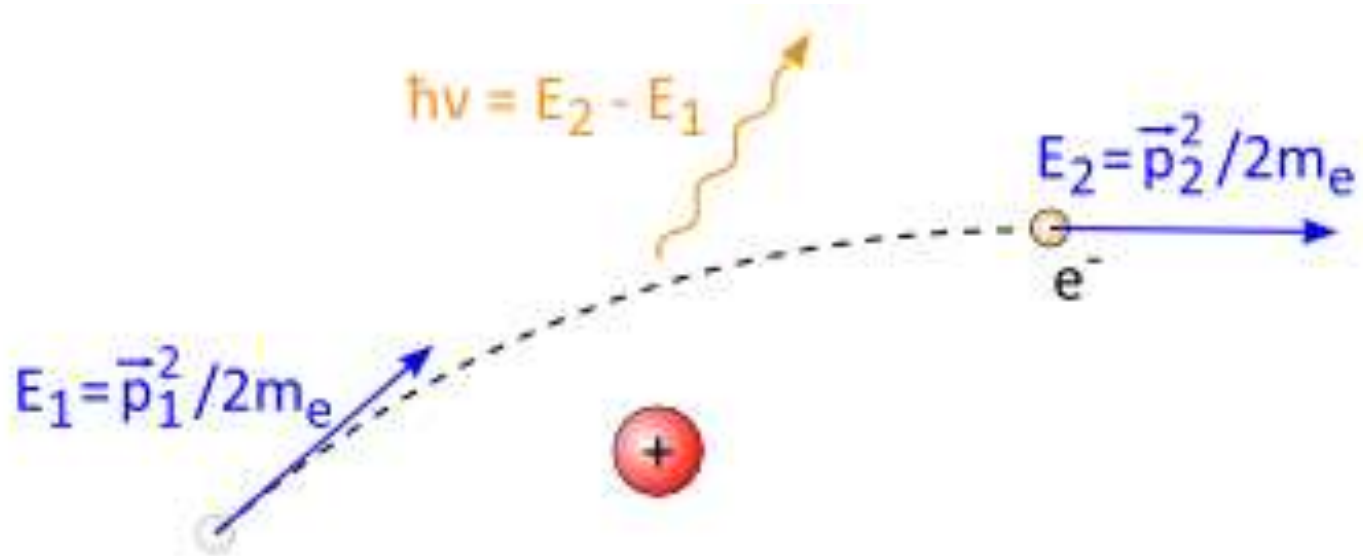
Thallium for patients ?

- MBq to GBq activities correspond to ng to μg
- no chemical toxicity at this level
- provided stable isotopes are absent ("carrier-free") or relatively low abundant ("non-carrier-added")
- **high specific activity** is frequently a decisive quality criterion for nuclear medicine applications!

$$A/m = \lambda N_A/M = N_A \ln(2)/(M \cdot T_{1/2})$$

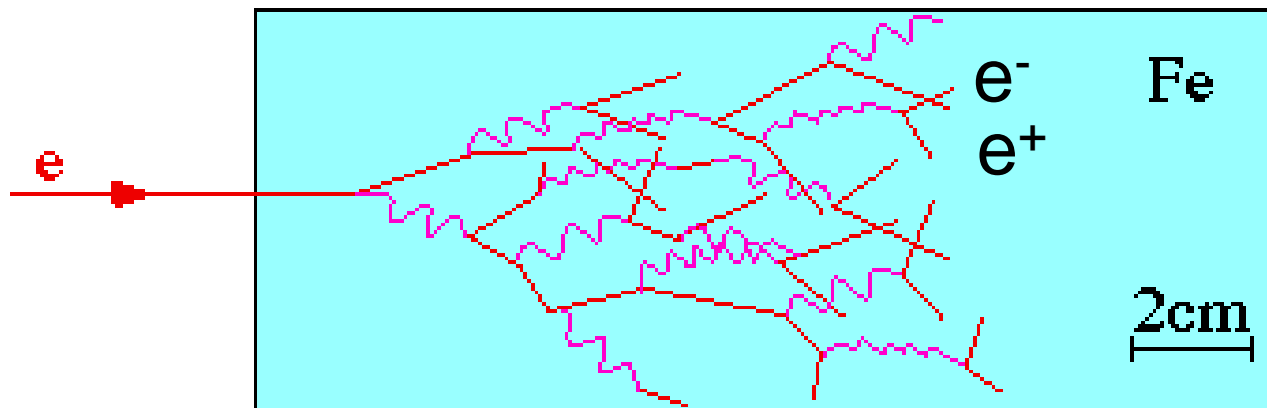
specific activity (Bq/g)

Bremsstrahlung

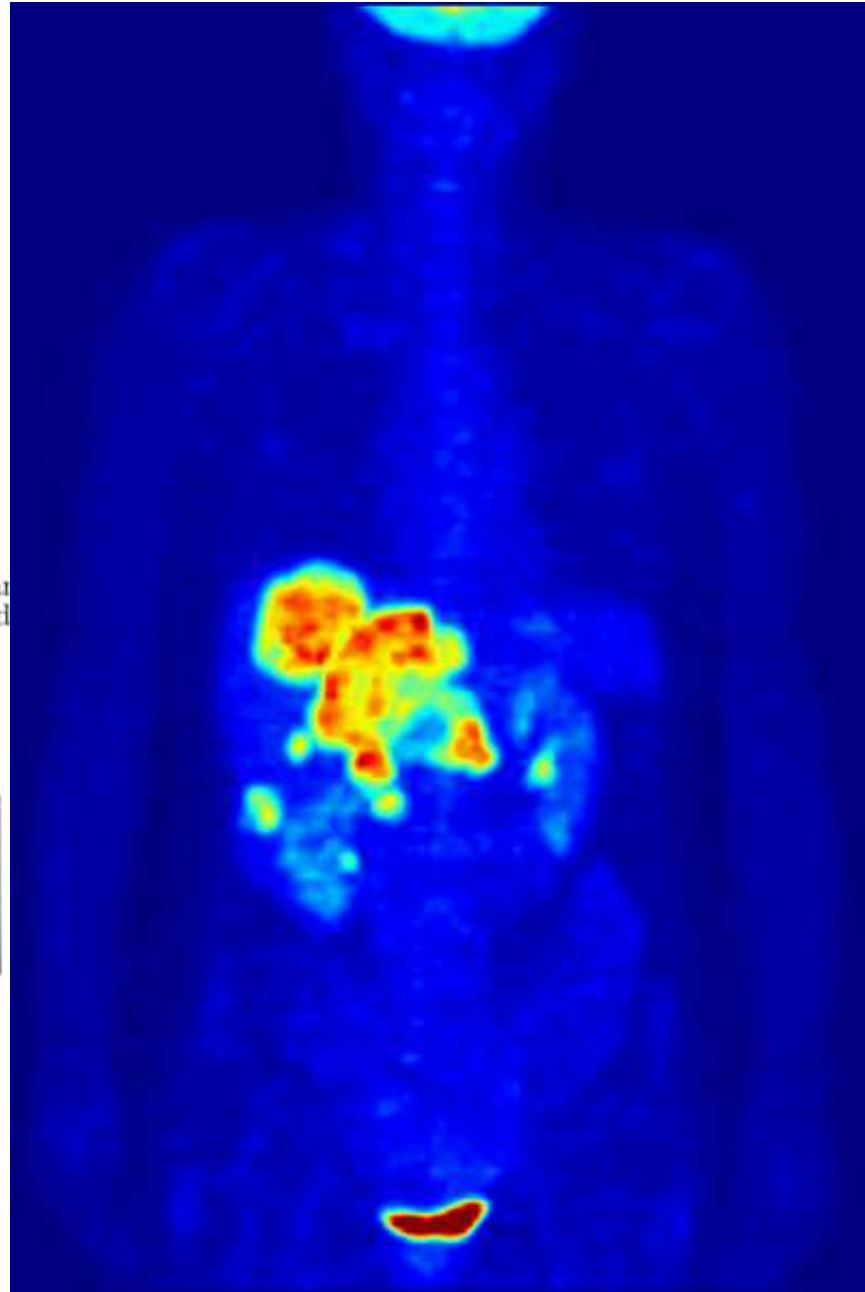
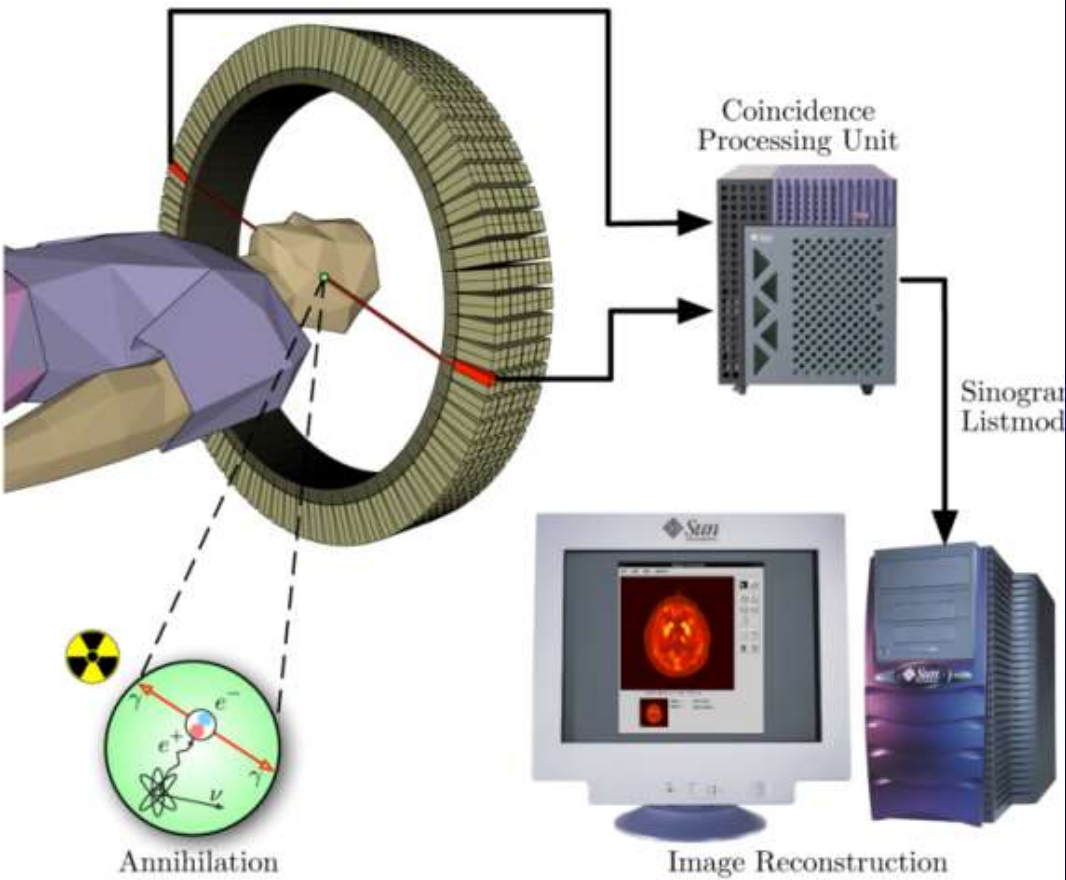


$$\left. \frac{dE}{dx} \right|_{BS} = -\frac{E}{X_0} \quad X_0 \propto \frac{A}{Z^2} \quad \text{radiation length}$$

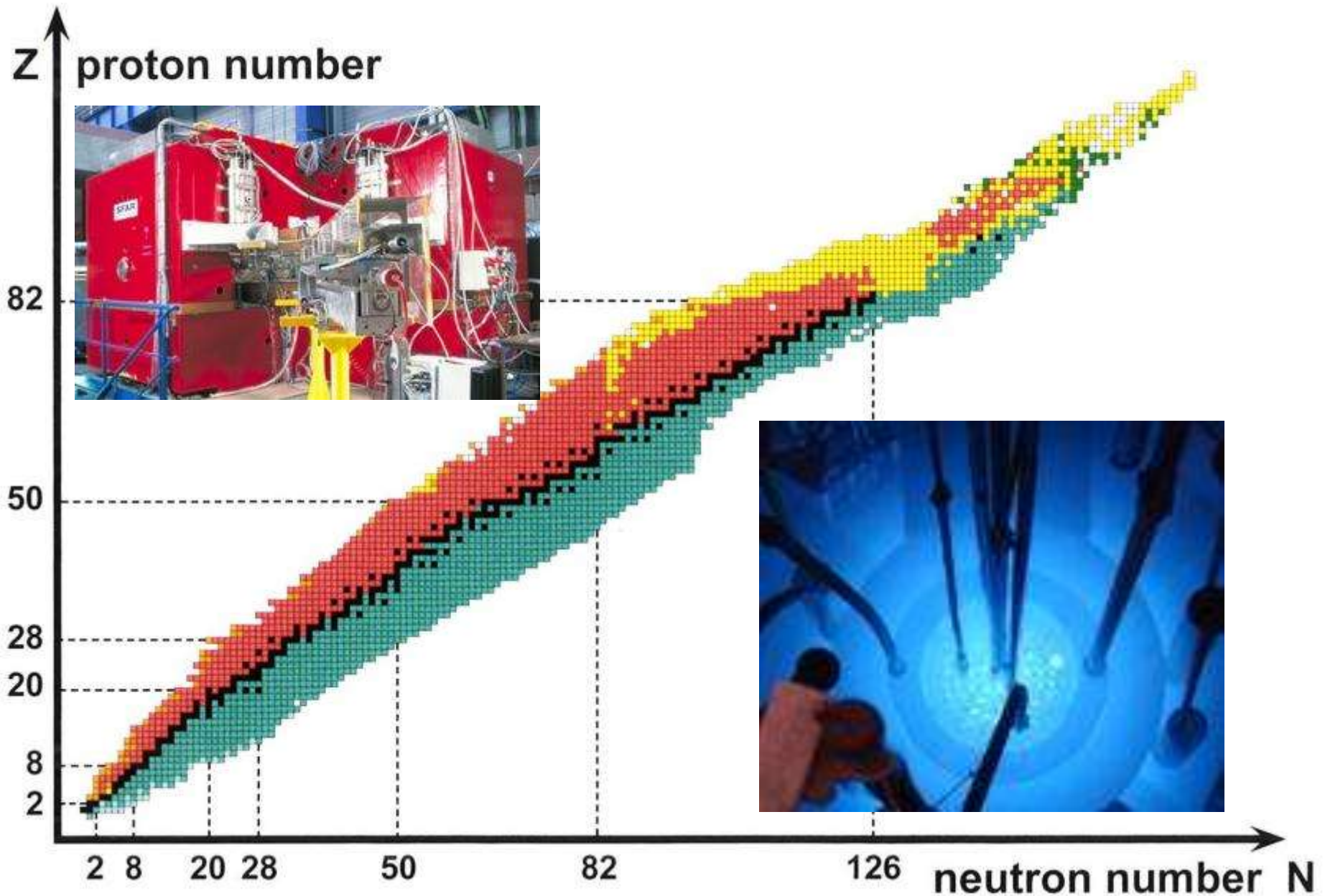
air 300 m, water 36 cm, Fe 1.8 cm, Pb 0.56 cm



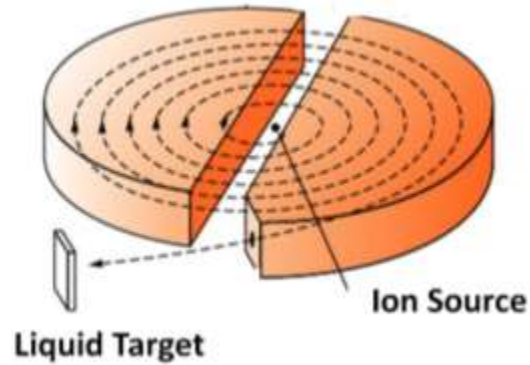
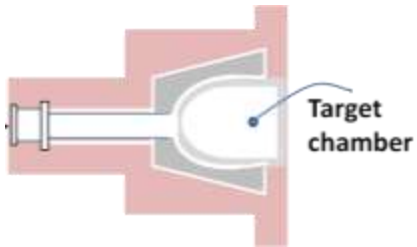
Positron Emission Tomography



The Tordesillas meridian of radioisotope production



^{18}F production via $^{18}\text{O}(p,n)$

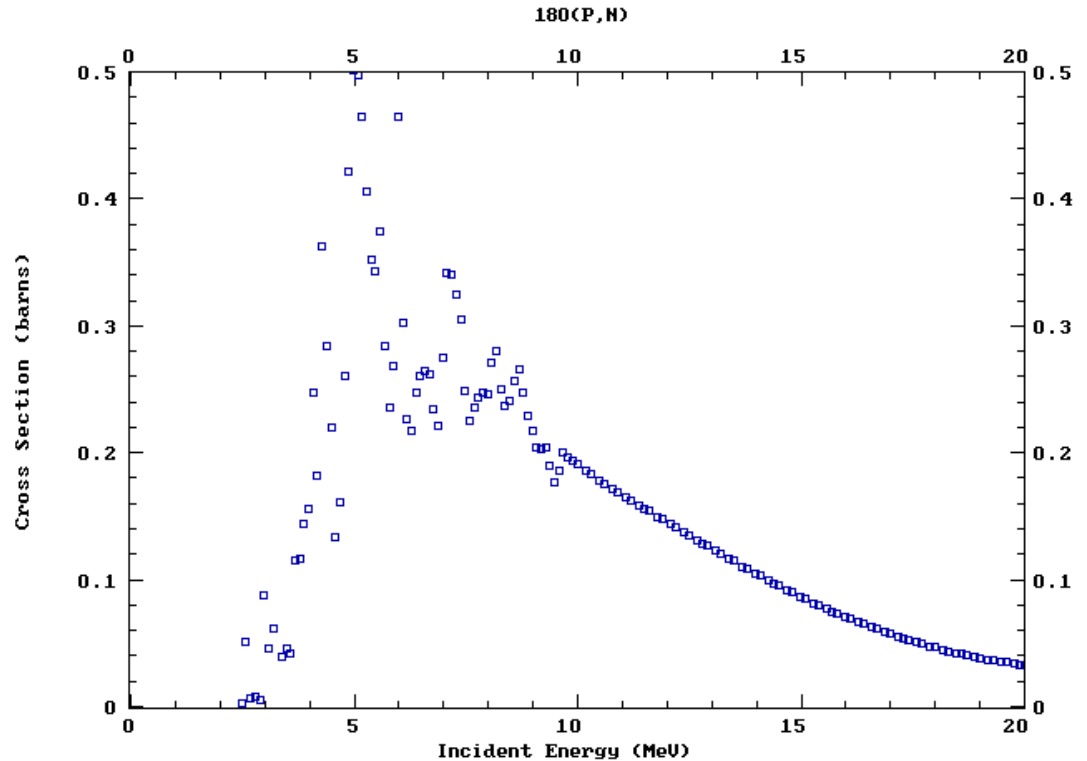


H_2^{18}O (water)

Cyclotron irradiation

Transformation into FDG

<p>Ne 18 1.67 s</p> <p>β^+ 3.4... γ 1042...</p>	<p>Ne 19 17.22 s</p> <p>β^+ 2.2... γ (110, 197, 1357)</p>	<p>Ne 20 90.48</p> <p>σ 0.039</p>
<p>F 17 64.8 s</p> <p>β^+ 1.7 no γ</p>	<p>F 18 109.728 m</p> <p>β^+ 0.633 no γ</p>	<p>F 19 100</p> <p>σ 0.0095</p>
<p>O 16 99.757</p> <p>σ 0.00019</p>	<p>O 17 0.038</p> <p>σ 0.00054 $\sigma_{n,\alpha}$ 0.257</p>	<p>O 18 0.205</p> <p>σ 0.00016</p>



PET isotopes

Radio-nuclide	Half-life (h)	Intensity β^+ (%)	E mean (MeV)	Range (mm)
C-11	0.34	99.8	0.39	1.3
N-13	0.17	99.8	0.49	1.8
O-15	0.03	99.9	0.74	3.2
F-18	1.83	96.7	0.25	0.7
Ga-68	1.13	89.1	0.83	3.8
Rb-82	0.02	95.4	3.38	20

^{18}F -Fluorodeoxyglucose (FDG)

Bone scans for bone metastasis screening



^{99m}Tc -MDP planar

^{99m}Tc -MDP SPECT

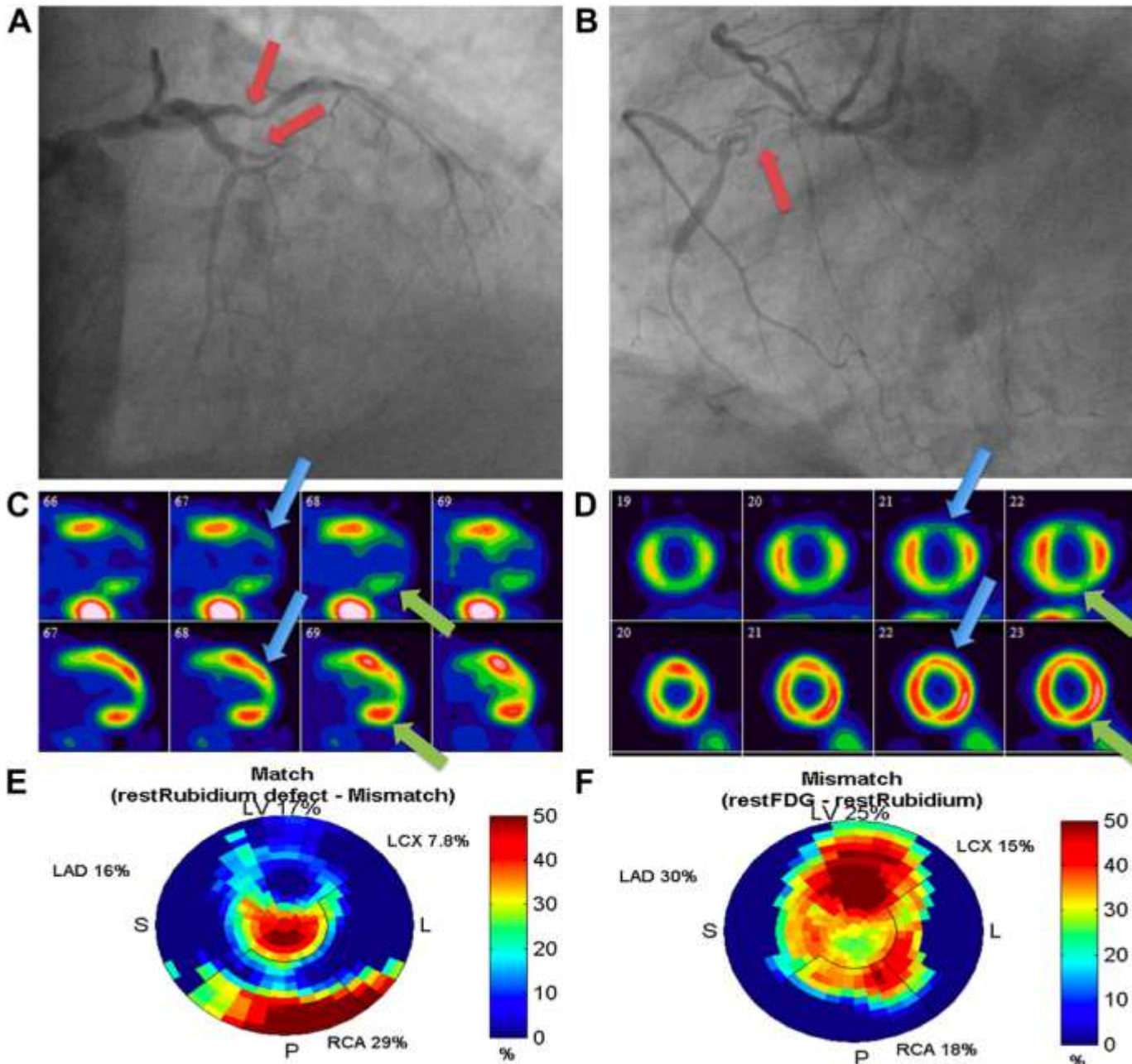
^{18}F - PET

^{68}Ga -BPAMD PET

PET isotopes

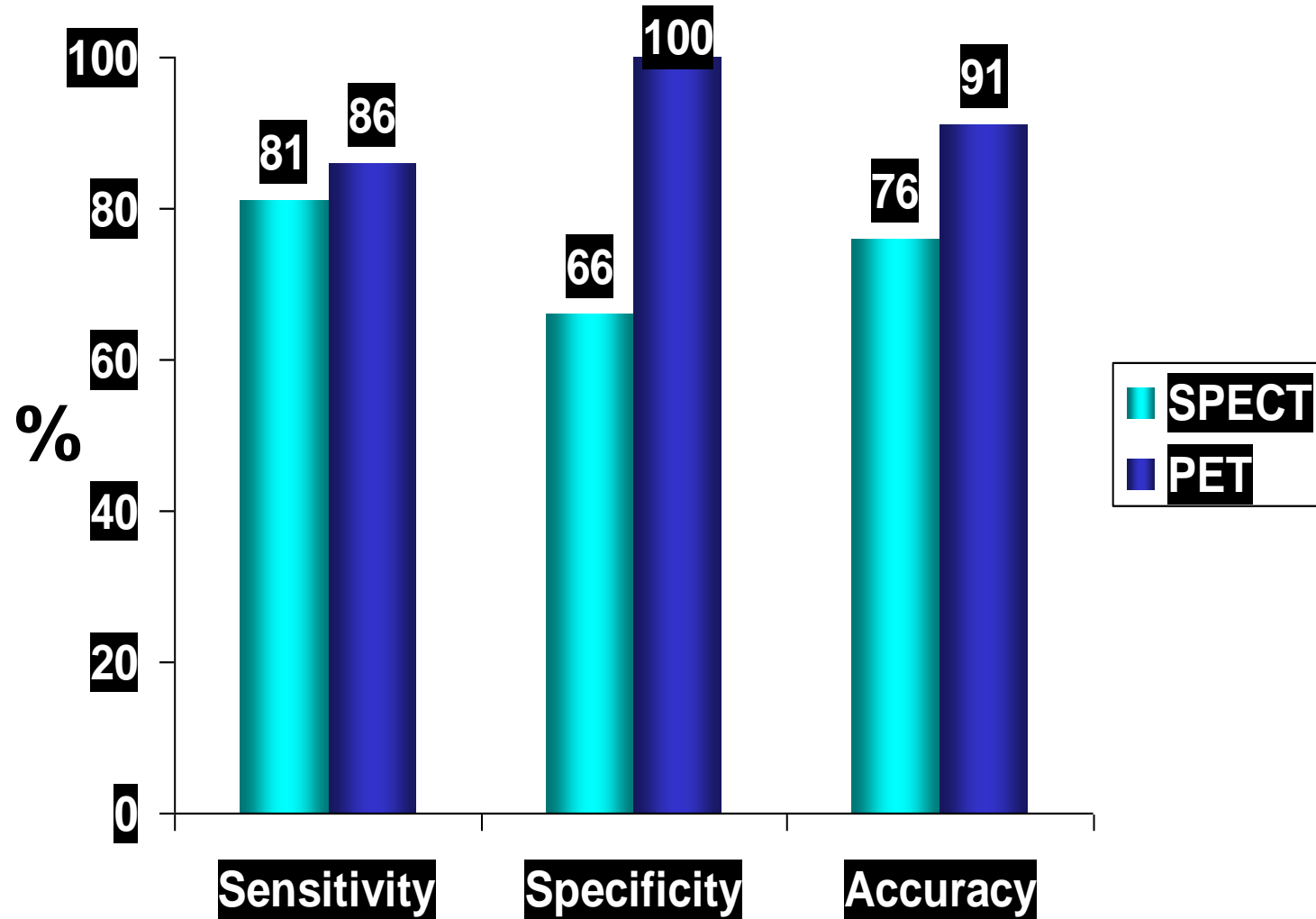
Radio-nuclide	Half-life (h)	Intensity β^+ (%)	E mean (MeV)	Range (mm)
C-11	0.34	99.8	0.39	1.3
N-13	0.17	99.8	0.49	1.8
O-15	0.03	Mother isotope: 271 d 25 d	0.74	3.2
F-18	1.83		0.25	0.7
Ga-68	1.13		0.83	3.8
Rb-82	0.02		3.38	20

Cardiology applications



*B.A. Mc Ardle,
Can. J. Cardiology
29 (2013) 399.*

Diagnostic Accuracy: ^{82}Rb PET vs $^{99\text{m}}\text{Tc}$ SPECT

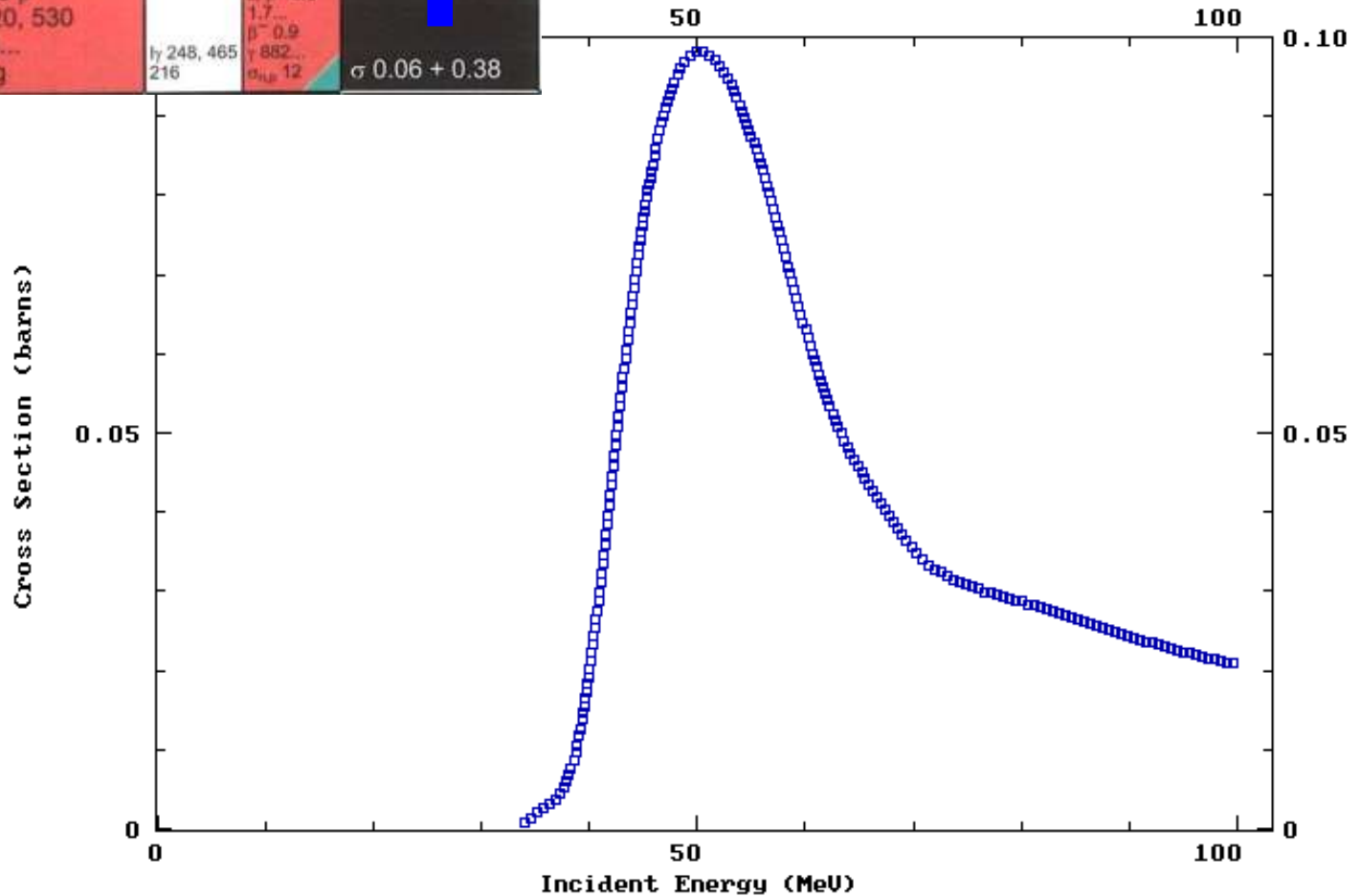


Bateman et al, J Nucl Cardiol 2006;13:24.

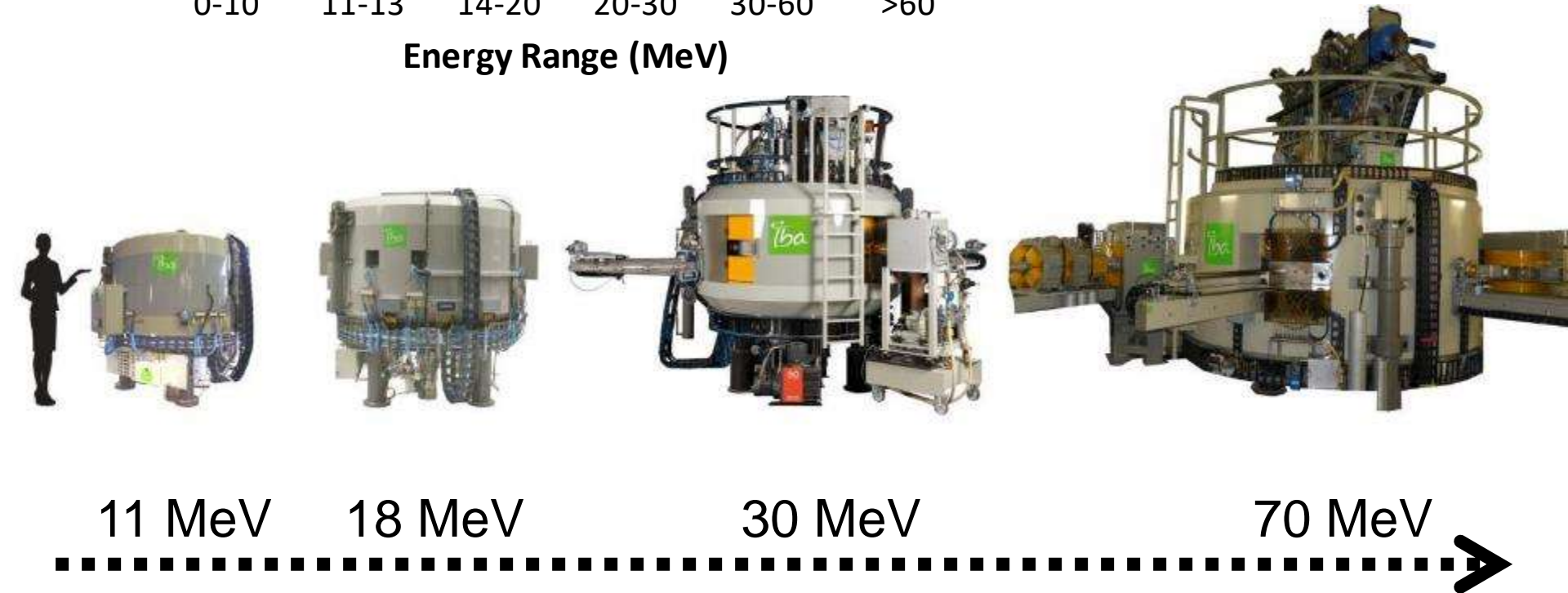
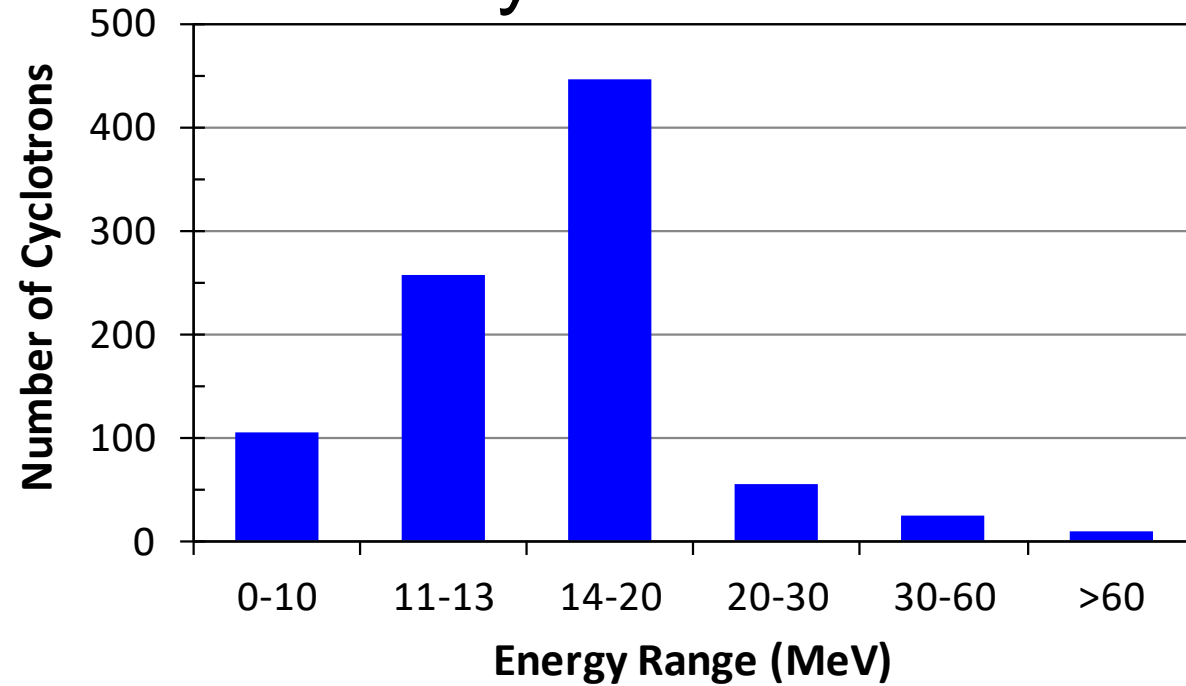
^{82}Sr production

Sr 82 25.34 d ϵ no β^+ no γ g	Sr 83 5.0 s 32.4 h β^+ 1.2... γ 763, 381 418... ly 259	Sr 84 0.56 σ 0.6 + 0.2	Sr 85 67.7 m 64.850 d ϵ , β^+ ... γ 151... σ 0.8...	Sr 86 9.86 σ 0.8... 23
Rb 81 30.3 m 4.58 h ly 86 e^- β^+ 1.4... γ (50...) g	Rb 82 6.3 1.27 m β^+ 0.8... γ 776, 554 619... β^+ 3.3... γ 776...	Rb 83 86.2 d ϵ , no β^+ γ 520, 530 553... m, g	Rb 84 20.26 m 32.8 d ϵ , β^+ 0.8 1.7... β^- 0.9 γ 882... ly 248, 465 216 σ_{th} 12	Rb 85 72.17 σ 0.06 + 0.38

37-RB-0(P,X)38-SR-82



Cyclotrons: the work horses



Facilities producing ^{82}Sr

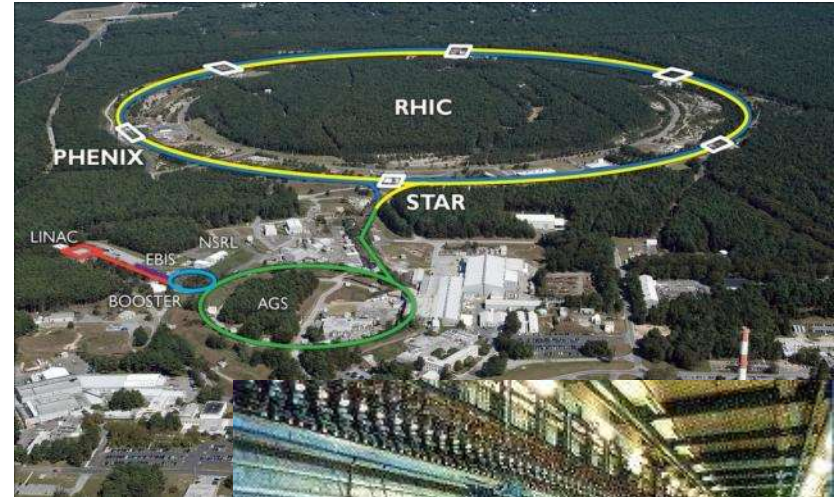
BNL, USA – 200 MeV, 100 μA

LANL, USA – 100 MeV, 200 μA

INR, Russia – 160 MeV, 120 μA

TRIUMF, Canada – 110 MeV, 70 μA

iThemba, South Africa – 66 MeV, 250 μA



Facilities producing ^{82}Sr

BNL, USA – 200 MeV, 100 μA

LANL, USA – 100 MeV, 200 μA

INR, Russia – 160 MeV, 120 μA

TRIUMF, Canada – 110 MeV, 70 μA

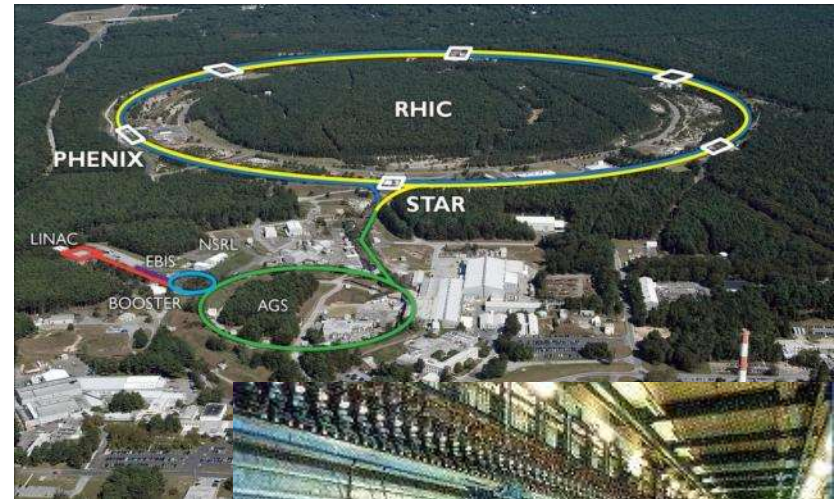
iThemba, South Africa – 66 MeV, 250 μA

ARRONAX, France – 70 MeV, < 750 μA

SPES, Italy – 70 MeV, < 1000 μA

Zevacor, USA – 70 MeV, < 750 μA

ZDNM, Russia – 70 MeV, < 750 μA

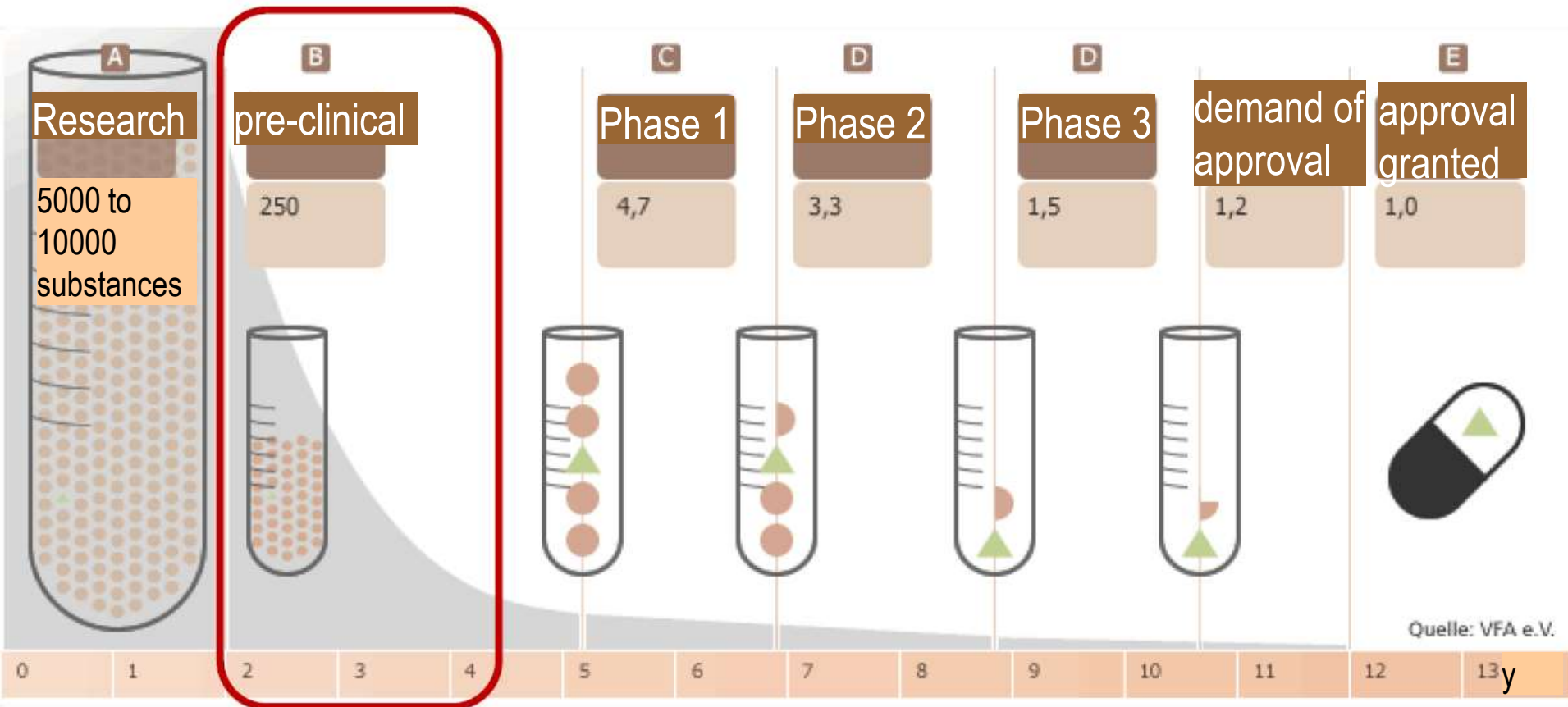


Longer-lived PET isotopes

Radio-nuclide	Half-life (h)	Intensity β^+ (%)	E mean (MeV)	Range (mm)
Sc-44	3.97	94.3	0.63	2.5
Cu-64	12.7	17.6	0.28	0.8
Br-76	16.2	55	1.18	6
Y-86	14.7	31.9	0.66	2.6
Zr-89	78.4	22.7	0.40	1.4
I-124	100	22.8	0.82	3.8

Molecular imaging without patients?

Development of pharmaceuticals



Quelle: VFA e.V.

**Screening in vitro tests
animal exp.**

tests with humans

toxicity
side effects

wanted effect

comparison
with standard

20-80 healthy volunteers
100-300 patients
x00-x000 patients

Pre-clinical studies (1)



Pre-clinical studies (2)



Pre-clinical studies (3)





Control



Treated



Control



Treated



Control



Treated



Control



Treated

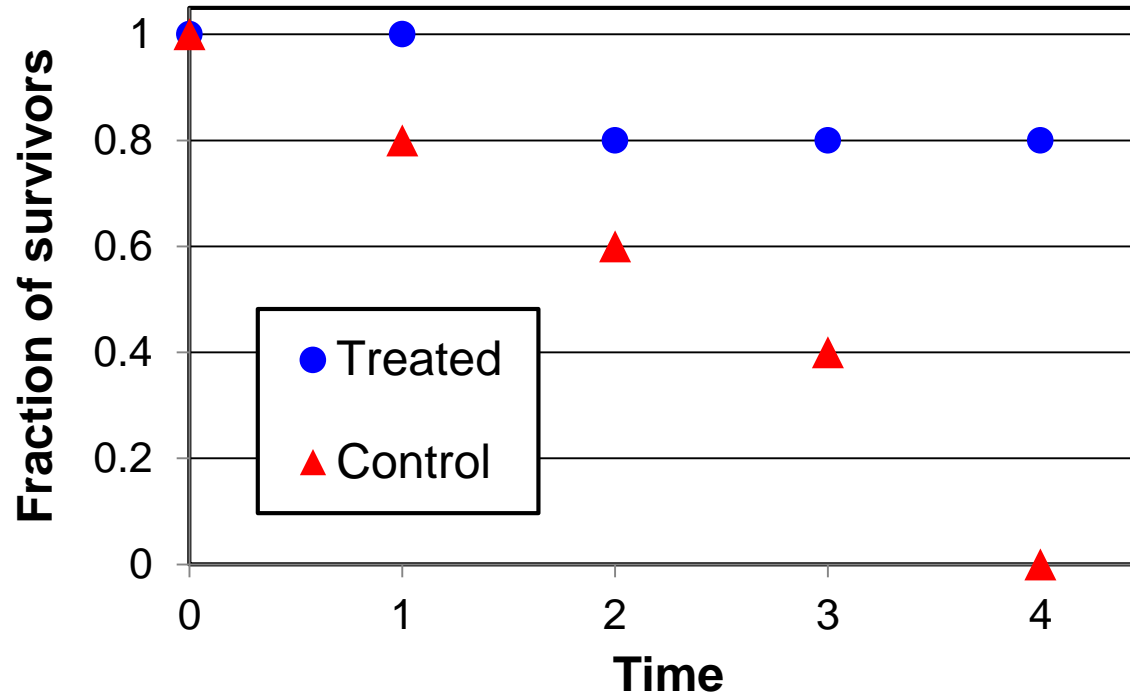


Control



Treated

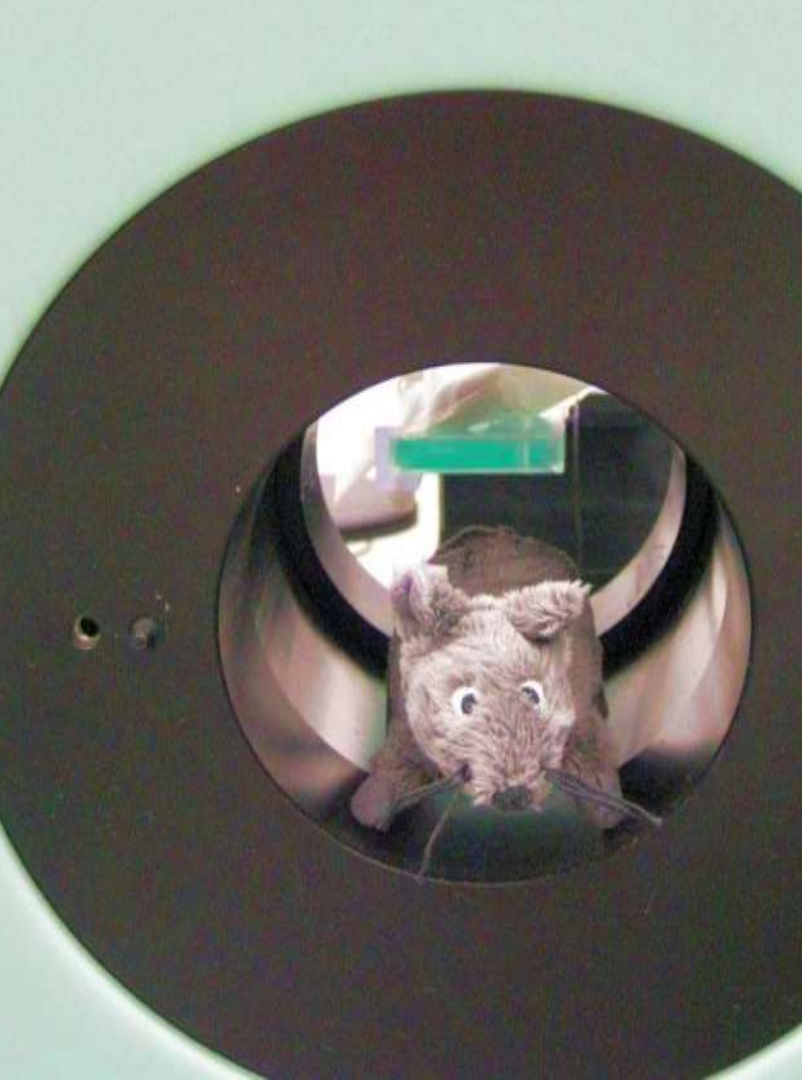
Survival curve



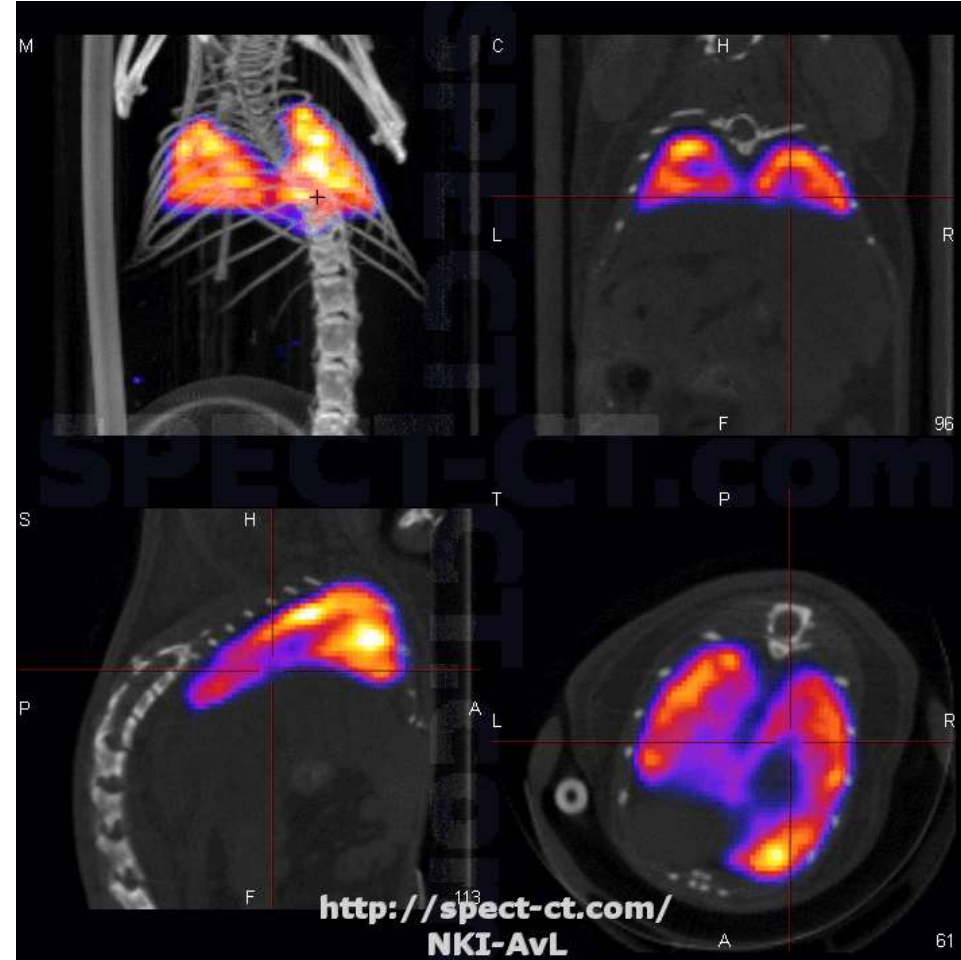
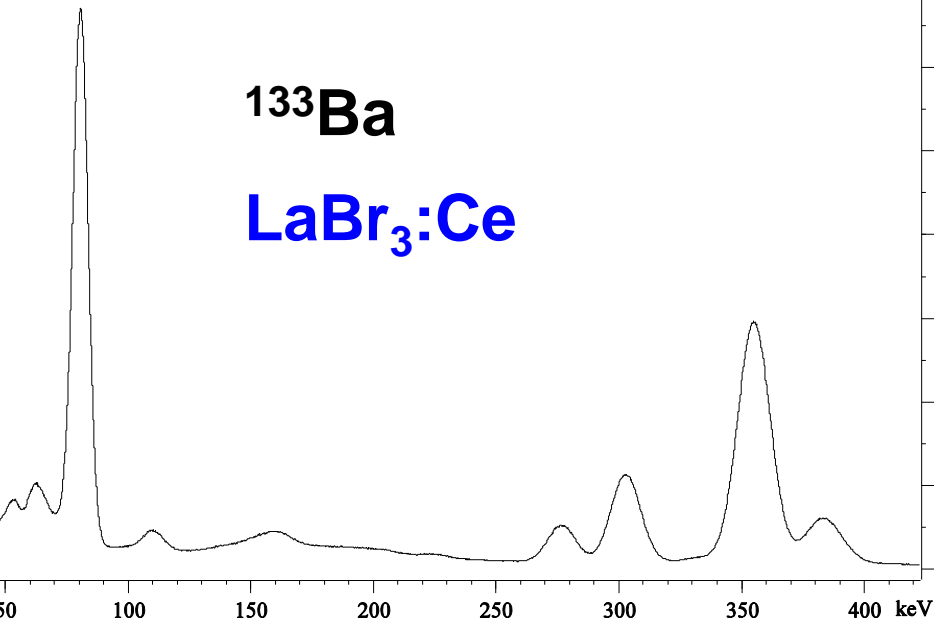
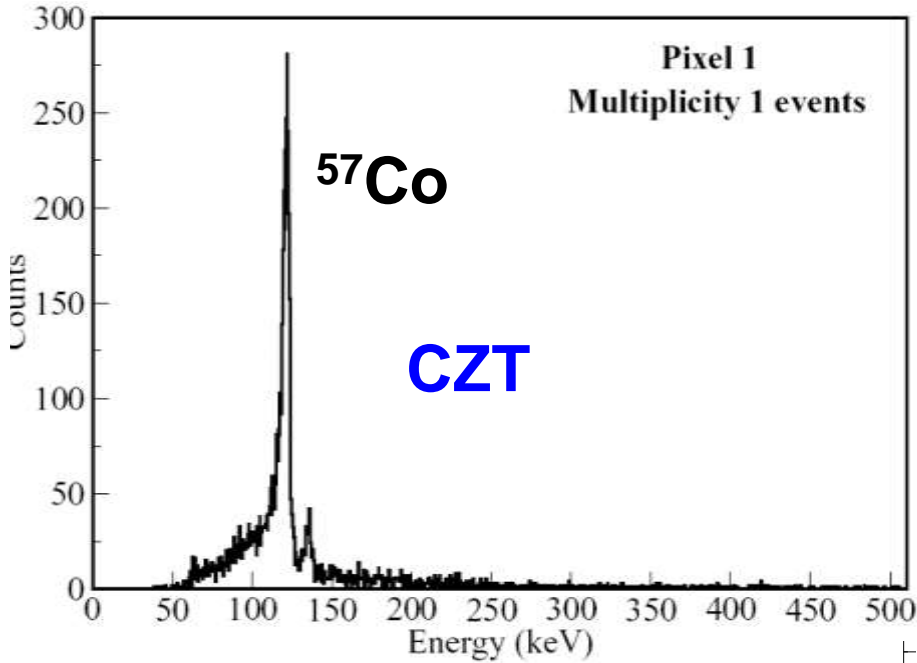
- medium survival time, median survival time, survival benefit
- shows final benefit but not detailed mechanism
- more information from **bio-distribution studies**
- preferentially **on-line with suitable radiotracers**
and small animal SPECT or PET

SIEMENS

Small animal imaging



New generation of small animal SPECT



systematic biodistribution studies with different radiotracers become possible with dedicated small animal SPECT

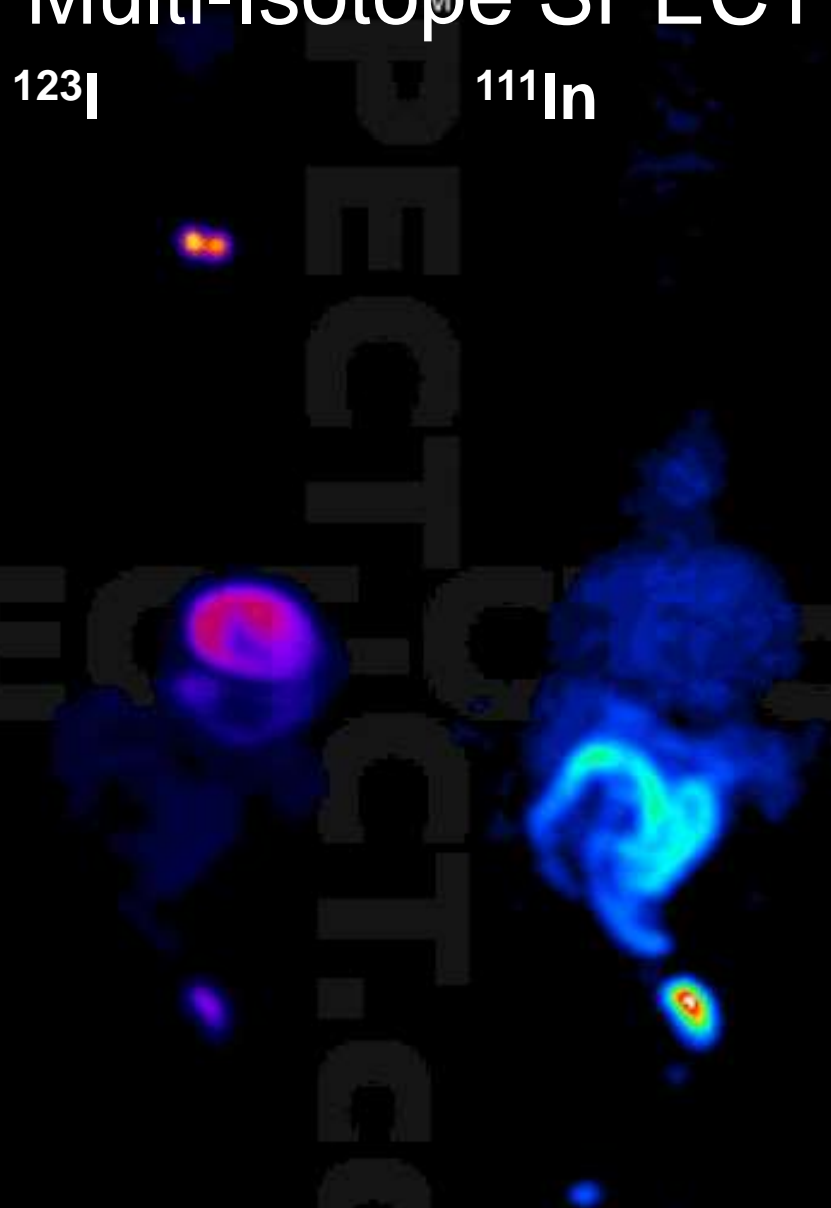
M Multi-Isotope SPECT M

M
 ^{99m}Tc

M
 ^{123}I

M
 ^{111}In

M
 ^{201}Tl



<http://spect-ct.com/>
University of New Mexico

From diagnostics

The death and the radiologist.

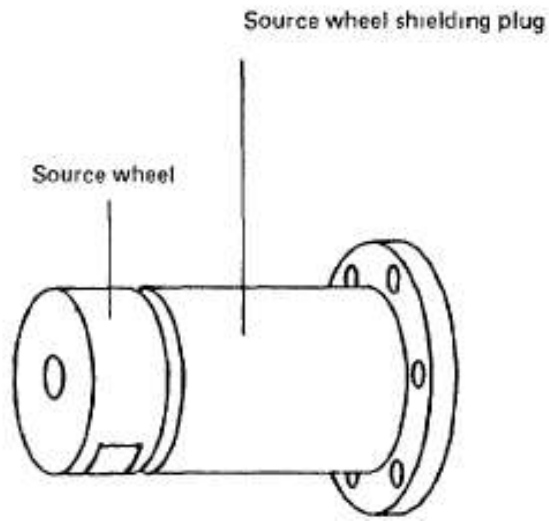
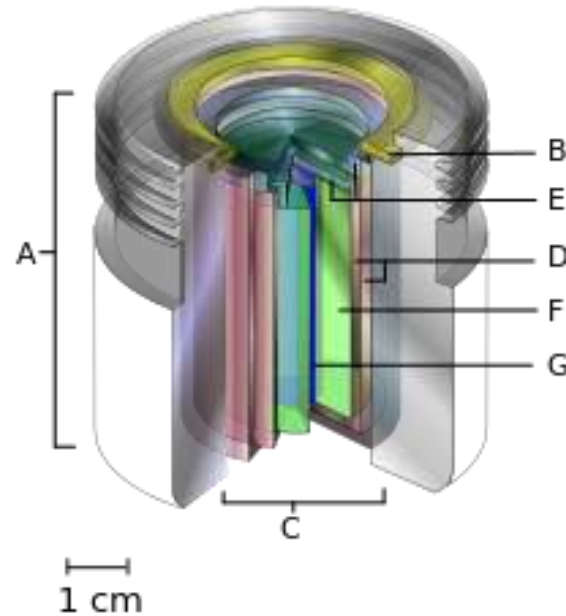
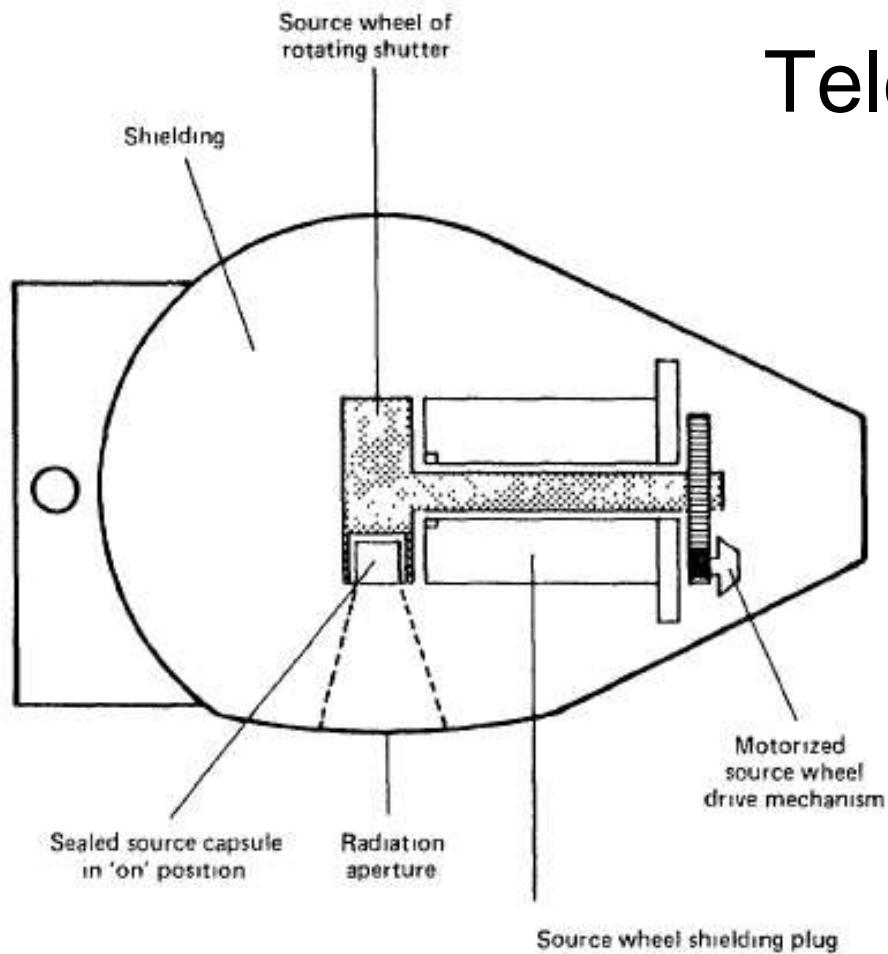
*Bad news:
you are going
to die soon.*

*Oh my God!
Where did you find
all these nude
photos of me?*



to therapy

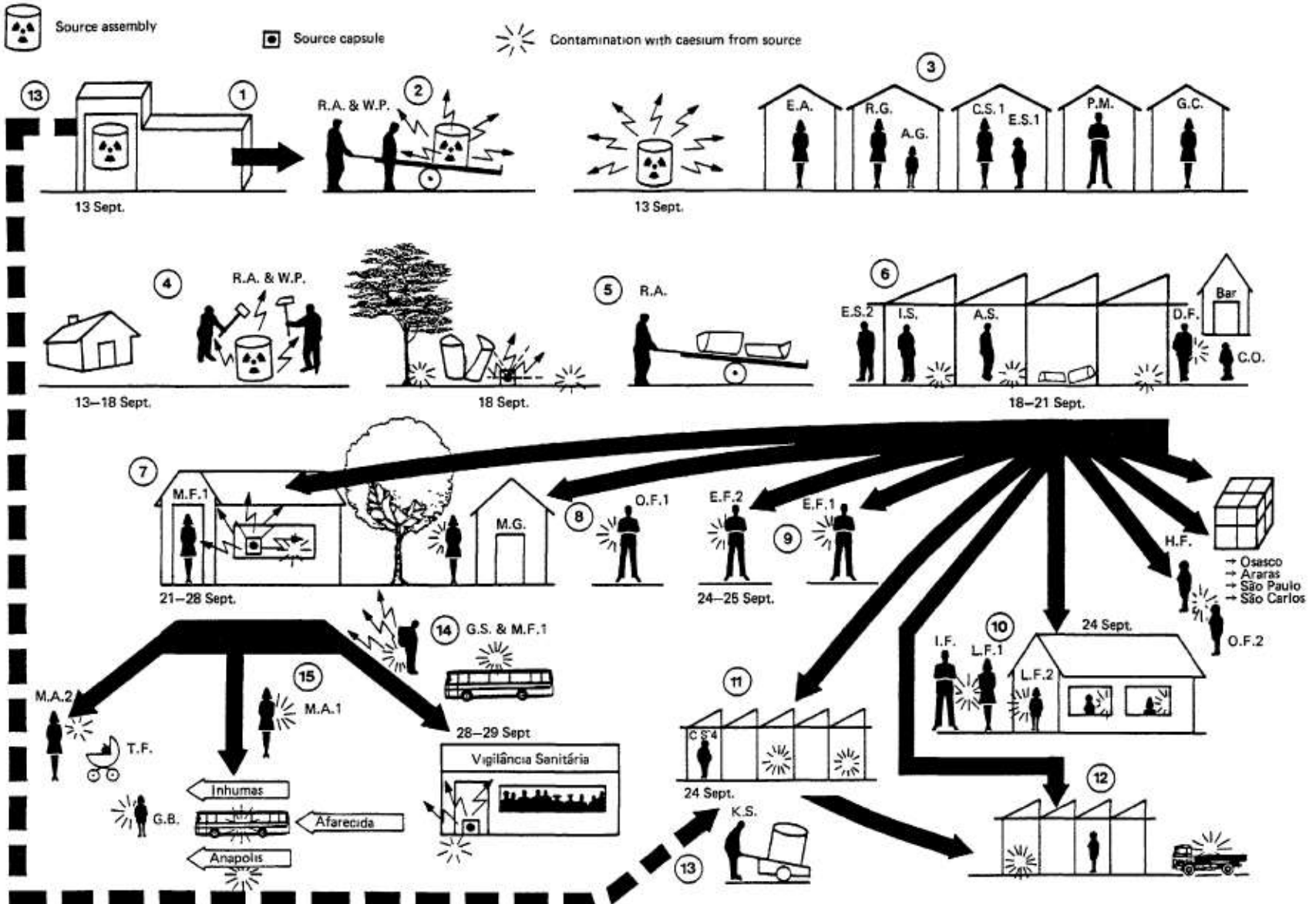
Teletherapy units



“Cobalt-bomb” or “Cesium-bomb”
 50 – 100 TBq of ^{60}Co or ^{137}Cs
 5 – 10 Gy/h at 1 m

Less operation and maintenance effort with respect to LINACs, BUT long-term legacy!

Civilian radiation accidents



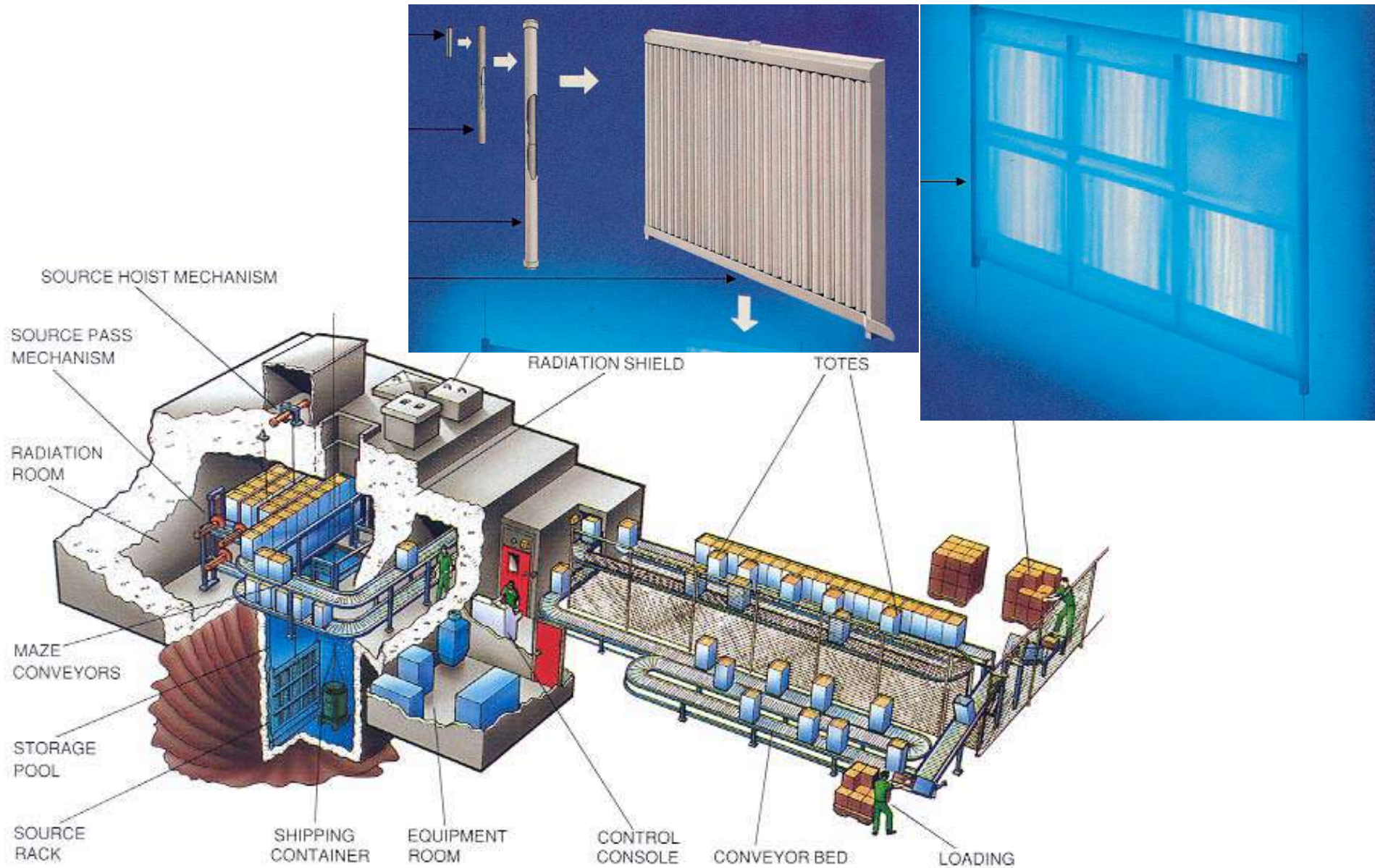
Goiania, Ciudad Juarez, Samut Prakan, etc.



10. A hole is made to remove a radiation hot spot giving a dose rate of $0.5 \text{ Sv}\cdot\text{h}^{-1}$.



Parenthesis: Radiation Sterilization of Medical Devices

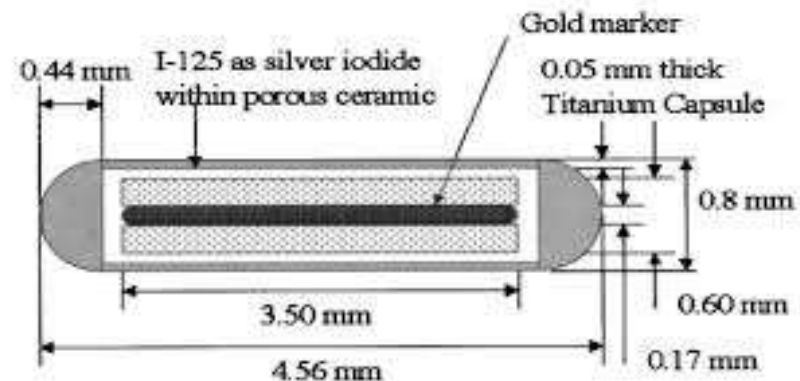


1 MCi = 37 PBq ^{60}Co sterilizes 650 kg/hour at 25 kGy

Brachytherapy

High Dose Rate (HDR) brachytherapy
short-term insertion of ^{60}Co , ^{137}Cs ,
 ^{169}Yb or ^{192}Ir sources

Low Dose Rate (LDR) brachytherapy
long-term insertion of ^{32}P , ^{103}Pd , ^{125}I ,
 ^{131}Cs , etc. sources (“seeds”)



Cancer and efficiency of treatments

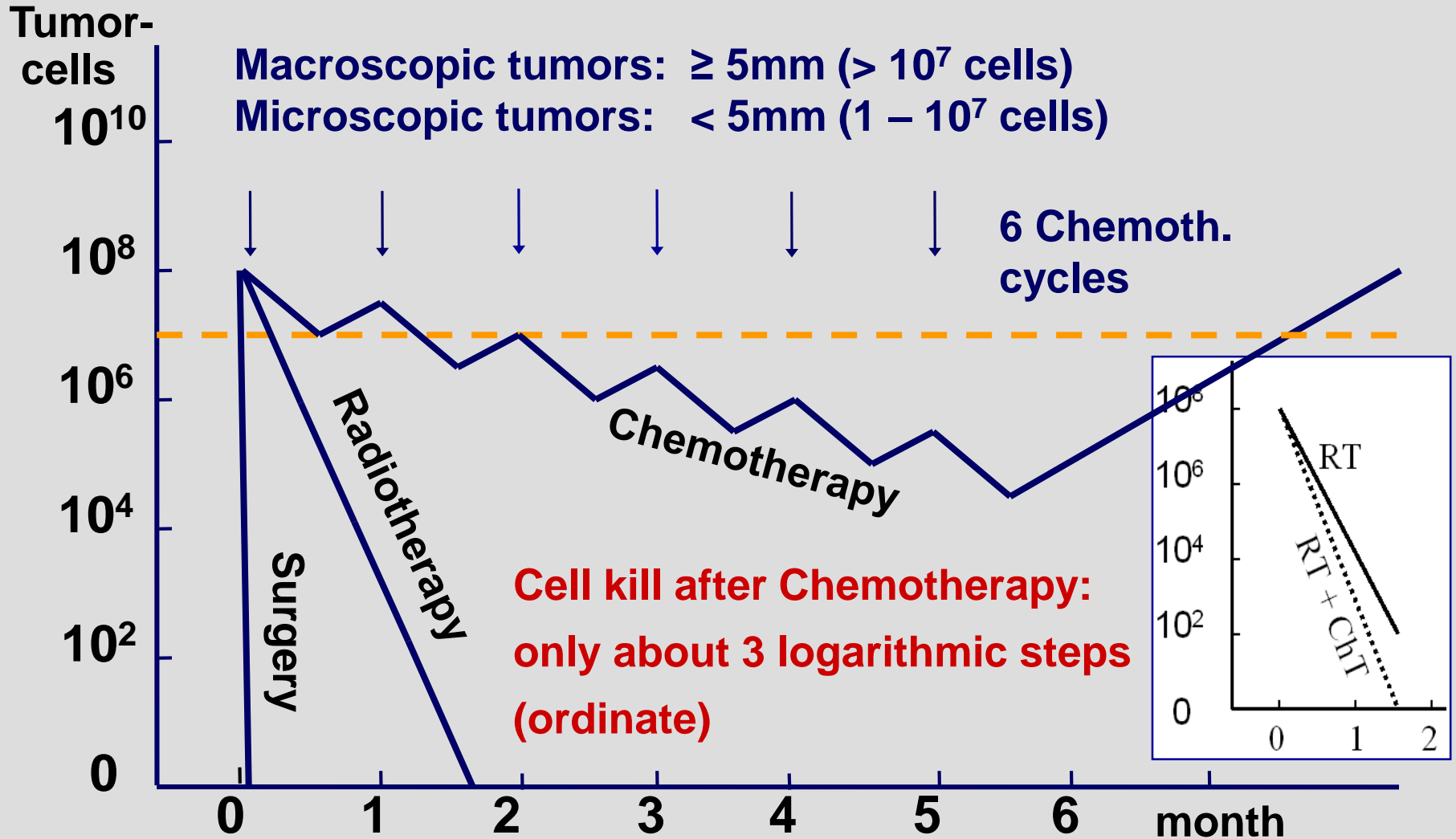
At time of diagnosis	Primary tumor	With metastases	Total
Diagnosed	58%	42%	100%
Cured by:			
Surgery	22%		
Radiation therapy	12%		
Surgery+radiation therapy	6%		
All other treatments and combinations incl. chemotherapy		5%	
Fraction cured	69%	12%	45%

Over **one million deaths per year** from cancer in EU.

⇒ improve early diagnosis

⇒ improve systemic treatments

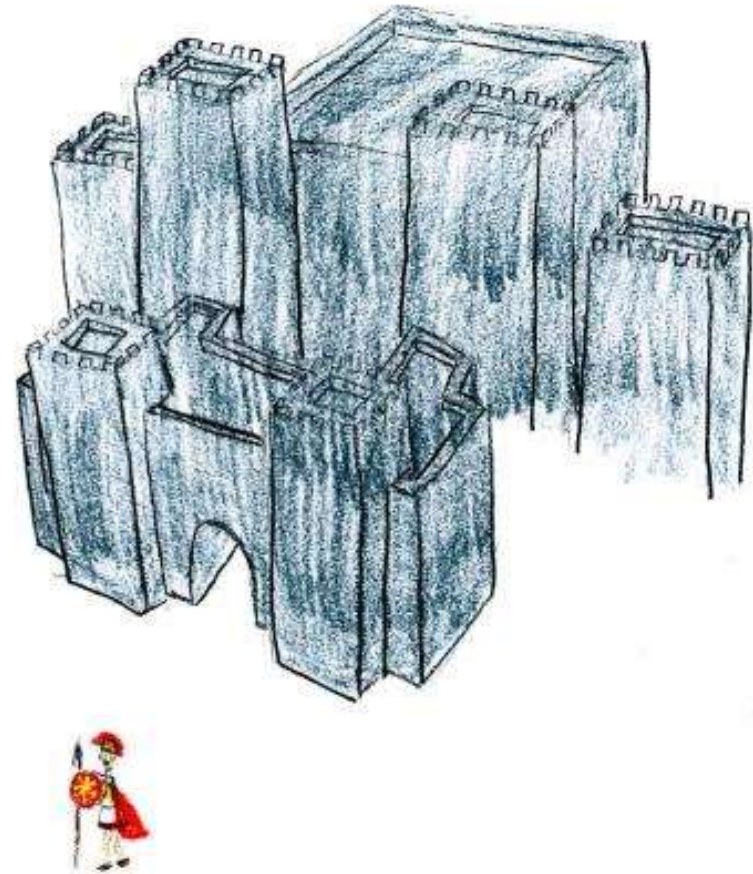
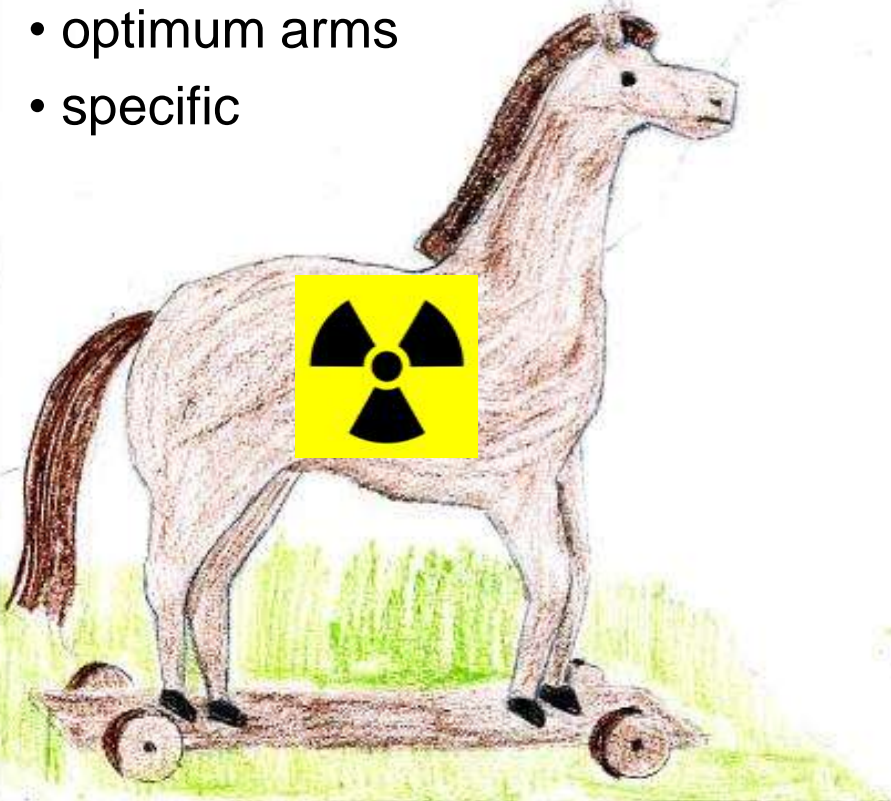
Comparison of Therapies



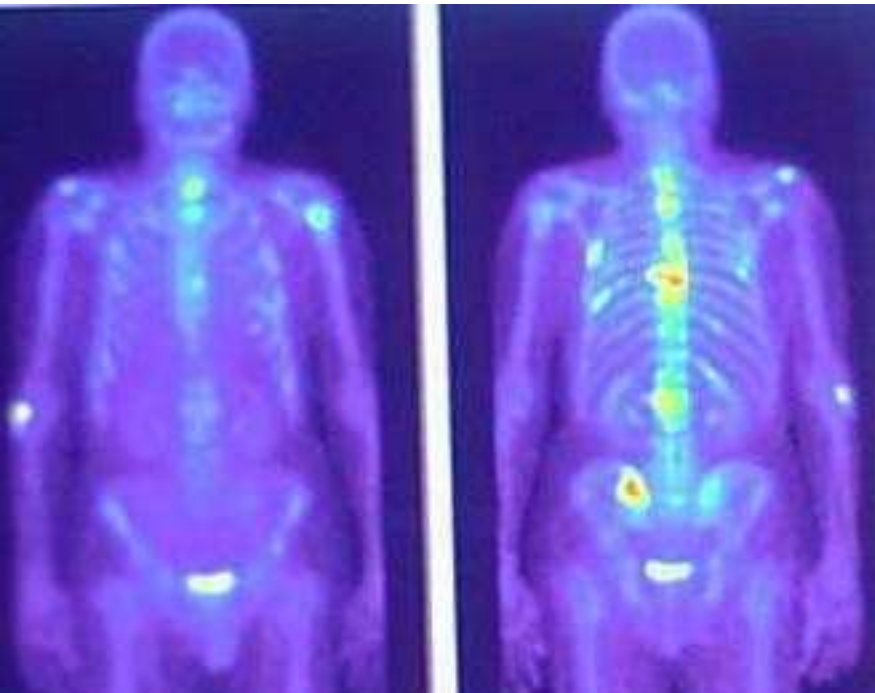
(Molls, TU München; according to Tannock: Lancet 1998, Nature 2006)

The principle of targeted therapies

- “attractive” vector > high uptake by the target
- transportable
- good in-vivo stability
- warriors “not visible”
- delayed uptake > suitable half-life
- limited space > high specific activity
- optimum arms
- specific



Metabolic targeting



Thyroid cancer

$^{123}\text{I}^-$ for imaging

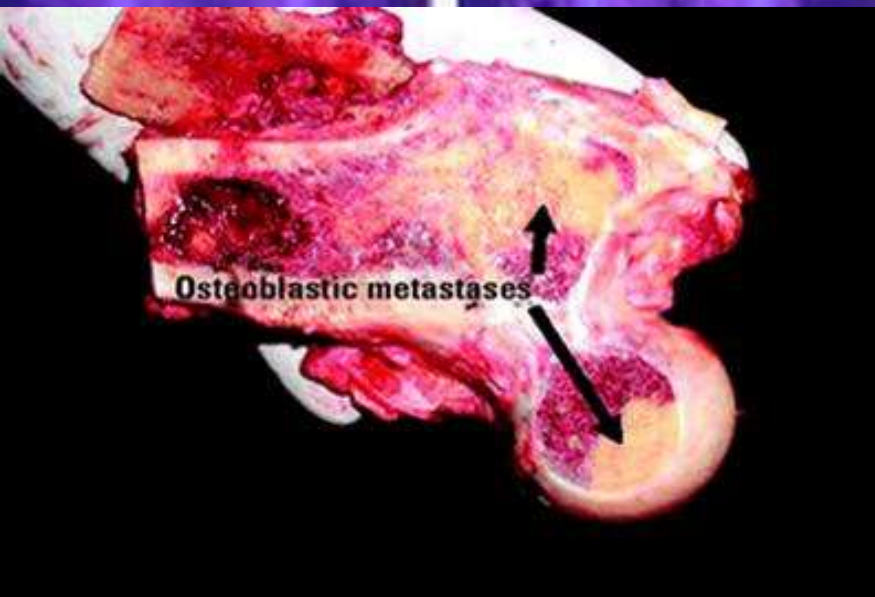
$^{131}\text{I}^-$ for therapy

Bone metastases

1.5 million patients world-wide

$^{99\text{m}}\text{Tc-MDP}$ for SPECT imaging

^{18}F for PET imaging



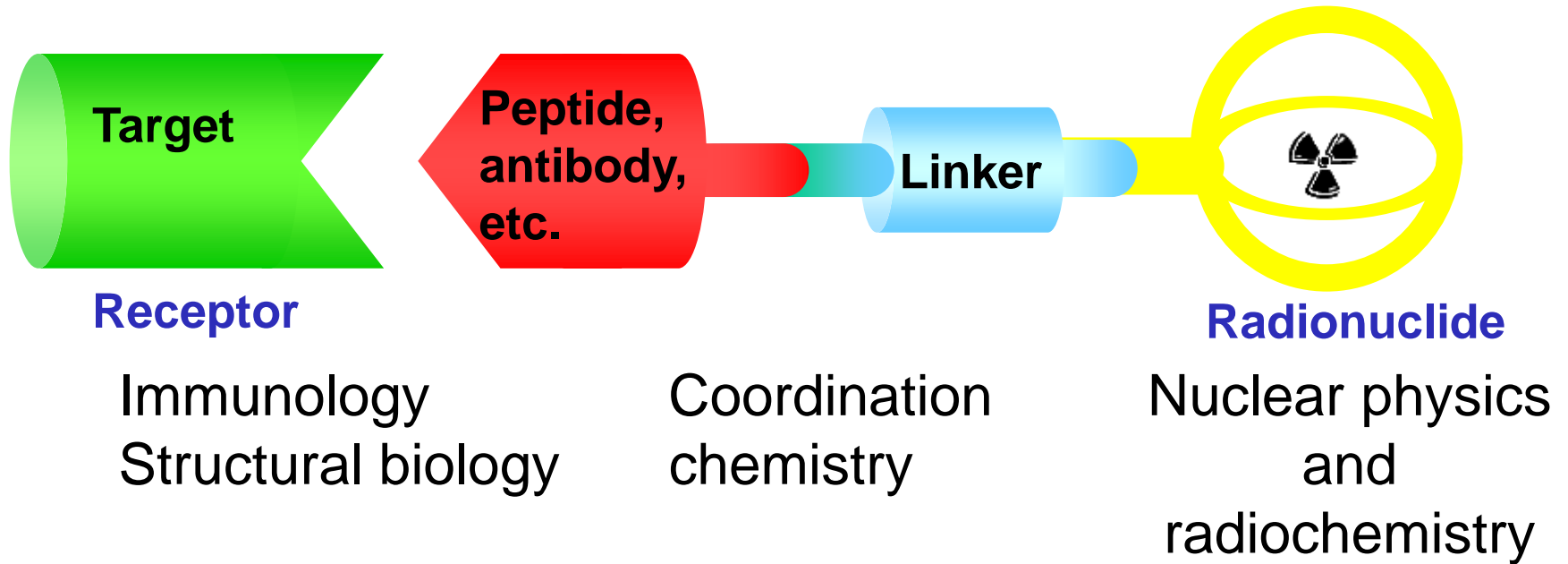
Therapy

$^{153}\text{Sm-EDTMP}$ (Quadramet)

$^{89}\text{Sr}^{2+}$ (Metastron)

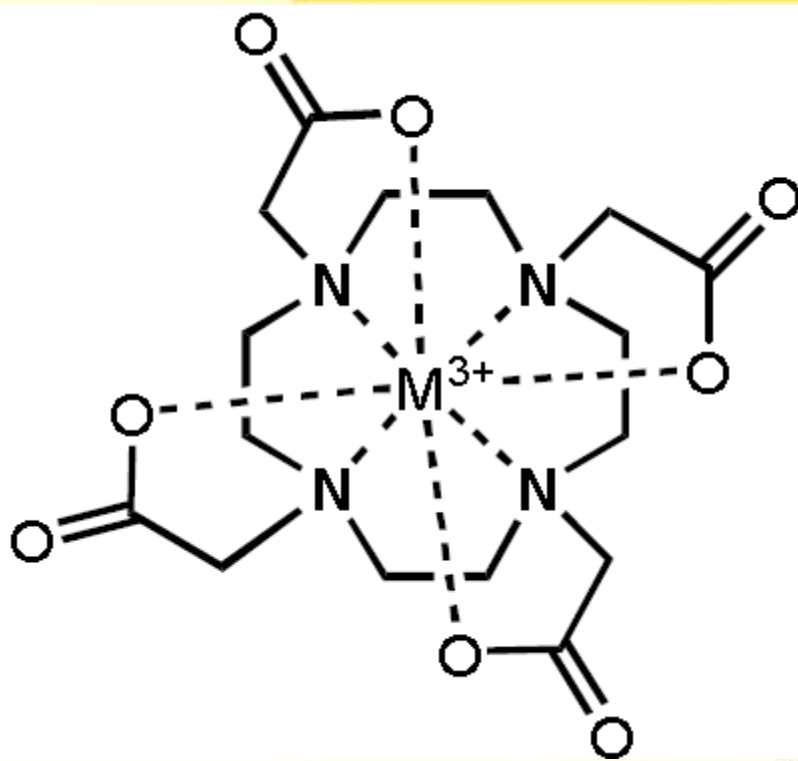
$^{223}\text{Ra}^{2+}$ (Xofigo/Alpharadin)

Multidisciplinary collaboration to fight cancer

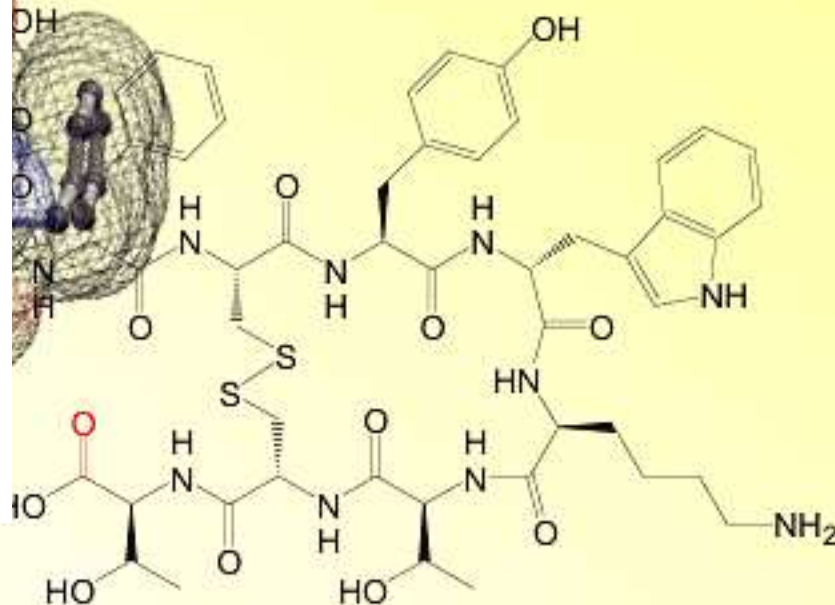


Nuclear medicine and medical physics

Structural Formula of DOTA-TOC/TATE



DOTA-TATE



1,4,7,10-tetraazacyclododecantetraacetate

^{111}In

^{90}Y

^{67}Ga

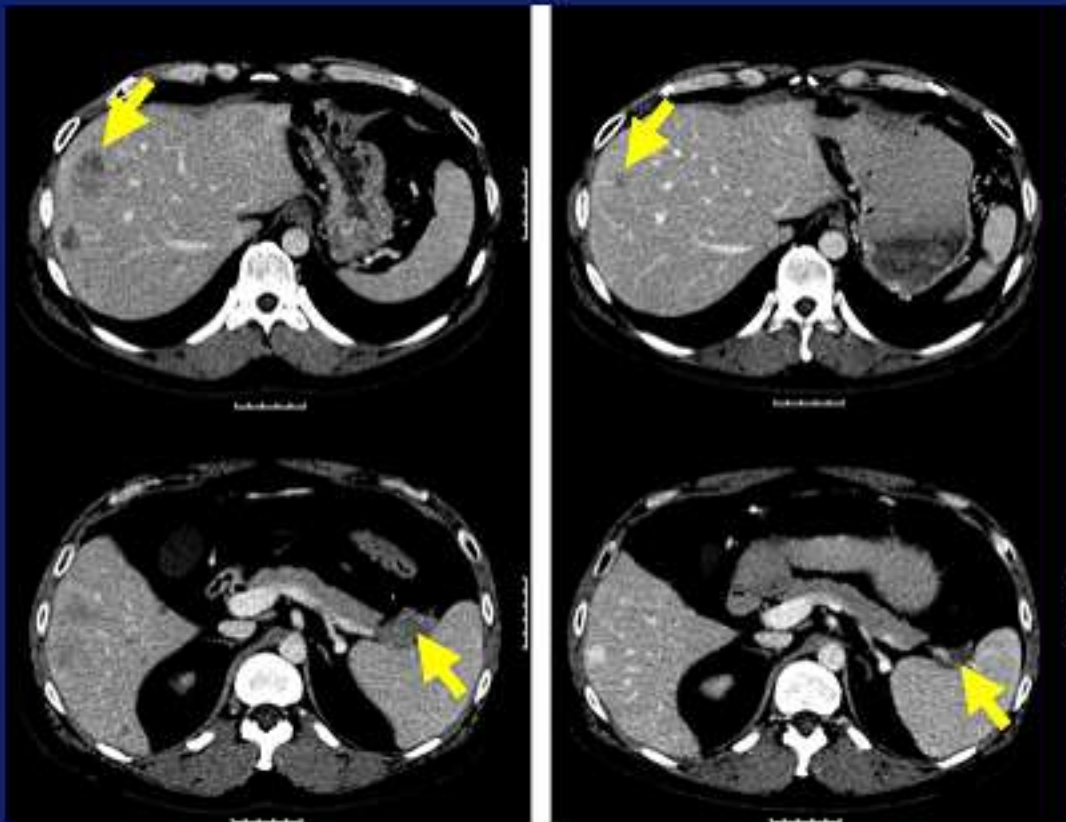
^{177}Lu

^{68}Ga

^{213}Bi

$\text{IC}_{50} (\text{Y}^{\text{III}}) = 1.6 \pm 0.4 \text{ nM}$

Helmut Maecke, EANM-2007.



Male

36 years of age

Small cell pancreatic
neuroendocrine
tumour

Liver metastases

Ki-67 index 10-15%
(liver biopsy)

4 cycles with ^{177}Lu -
octreotate and
capecitabine

Partial remission



Roelf Valkema, EANM-2008.

Lymphoma therapy: RITUXIMAB+¹⁷⁷Lu

E.B., 1941 (m): UPN 6

¹⁸FDG PET



1.9.2002

¹⁷⁷Lu-Scan



13.9.2002

¹⁸FDG PET



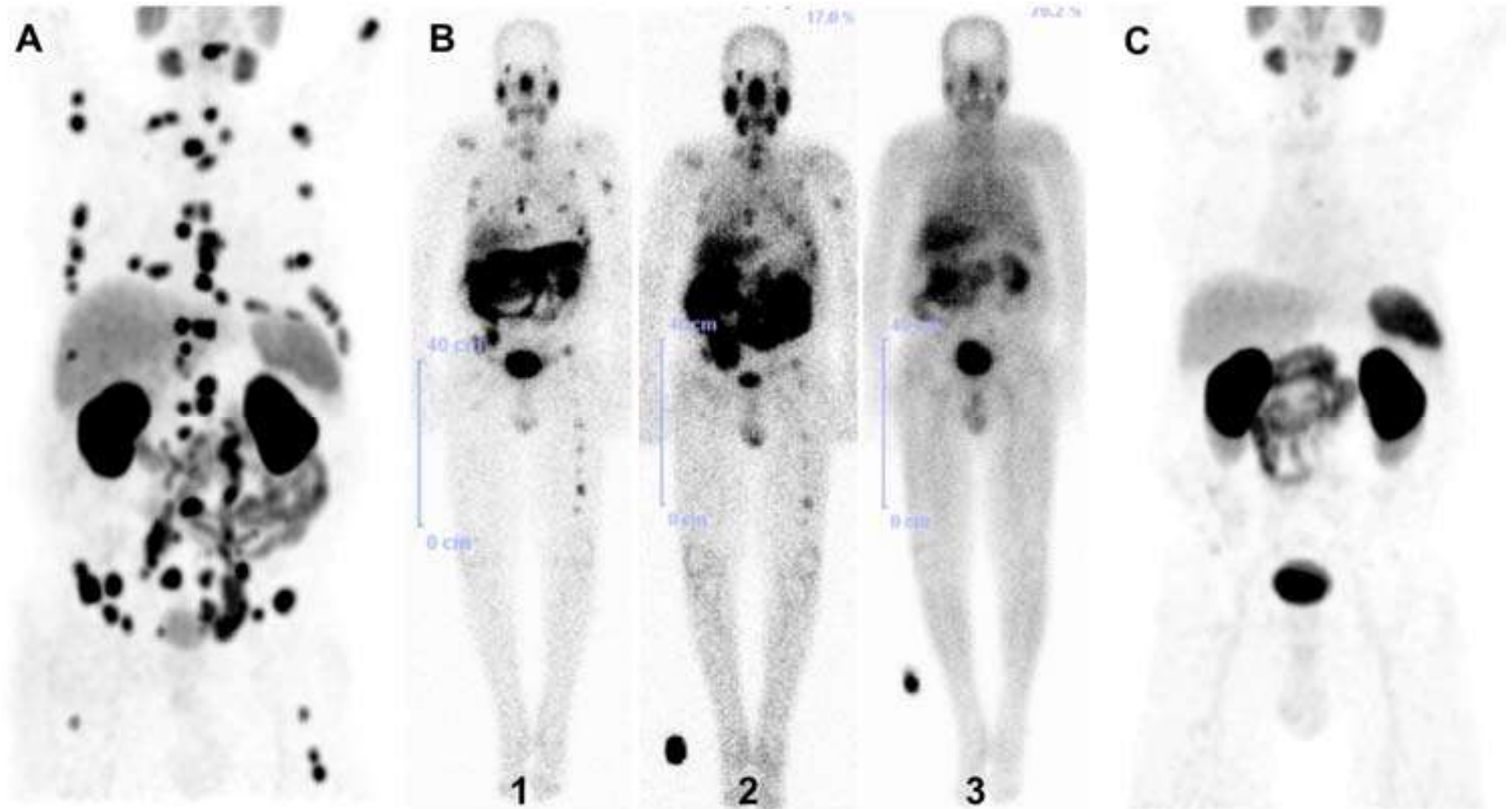
15.11.2002

**Still
in
CR**

15.9.2009

F. Forrer et al., J Nucl Med 2013;54:1045.

^{177}Lu -radioligand therapy of advanced prostate cancer



R.P. Baum et al., J Nucl Med 2016;57:1006.

C. Kratochwil et al., J Nucl Med 2016;57:1170.

K. Rahbar et al., J Nucl Med 2017;58:85.

Radionuclides for targeted radionuclide therapy

Radio-nuclide	Half-life (d)	E mean (keV)	E γ (B.R.) (keV)	Range	
Y-90	2.7	934 β	-	12 mm	Established isotopes
I-131	8.0	182 β	364 (82%)	3 mm	
Lu-177	6.7	134 β	208 (10%) 113 (6%)	2 mm	Emerging isotope

“Clean” production route to ^{177}Lu

Ta 175 10.5 h ϵ γ 207; 349; 267; 82; 126; 1793...	Ta 176 8.1 h ϵ β^+ ... γ 1159; 88; 1225...	Ta 177 56.6 h ϵ β^+ γ 113; 208... g	Ta 178 \leftarrow 9.25 m \rightarrow 2.45 h ϵ β^+ 0.9 γ 93; 1351; 1341... ϵ γ 332... m ₁	Ta 179 665 d ϵ no γ g σ 930	Ta 180 0.012 $> 10^{15}$ a $\sigma \sim 560$ ϵ β^- 0.7... γ 93; 104 g	Ta 181 99.988 σ 0.012 + 20 $\sigma_n, \alpha < 10^{-5}$
Hf 174 0.16 $2.0 \cdot 10^{15}$ a α 2.50 σ 600	Hf 175 70.0 d ϵ γ 343...	Hf 176 5.26 σ 23	Hf 177 51 m 1.1 s 18.60 ϵ γ 277; 295; 327... γ 208; 229; 379... σ 10 ⁻⁷ + 1 + 375	Hf 178 31 a 4.0 s 27.28 ϵ γ 574; 495; 217... γ 426; 326; 213; 89... σ 45 σ ? + 54 + 32	Hf 179 25 d 18.7 s 13.62 ϵ γ 454; 363; 123; 146... γ 214 σ 0.43 + 46	Hf 180 5.5 h 35.08 ϵ γ 332; 443; 215; 57... β^- ... σ 13 $\sigma_n, \alpha < 1.3 \cdot 10^{-5}$
Lu 173 1.37 a ϵ γ 272; 79; 101... e ⁻	Lu 174 142 d 3.31 a ϵ γ 45; 67... e ⁻ ; ϵ γ (992; 273...) β^+ ... γ 1242; 76...	Lu 175 97.41 σ 16 + 8	Lu 176 2.59 3.68 h 3.8 · 10 ¹⁰ a β^- 1.2; 1.3...; ϵ γ 88... e ⁻ σ 2 + 2100	Lu 177 160.1 d 6.71 d β^- 0.2 β^- 0.5... γ 414; 319; 122... 113... m ₁ g σ 3.2 σ 1000	Lu 178 22.7 m 28.4 m β^- 2.0... γ 93; 1341; 1310; 1269...; g β^- 1.2... γ 332...	Lu 179 4.6 h β^- 1.4... γ 214... g
Yb 172 21.83 $\sigma \sim 1.3$ $\sigma_n, \alpha < 1E-6$	Yb 173 16.13 σ 16 $\sigma_n, \alpha < 1E-6$	Yb 174 31.83 σ 63 $\sigma_n, \alpha < 0.00002$	Yb 175 4.2 d β^- 0.5... γ 396; 283; 114...	Yb 176 12 s 12.76 ϵ γ 293; 390; 190; 96... σ 3.1 $\sigma_n, \alpha < 1E-6$	Yb 177 6.5 s 1.9 h β^- 1.4... γ 150; 1080; 122; 1241 g σ 1.4...	Yb 178 74 m β^- 0.6... γ 391; 348;... g

- Free of long-lived isomer
- Non-carrier-added quality
- Requires high-flux reactor and advanced radiochemistry



The highest neutron flux in Western Europe

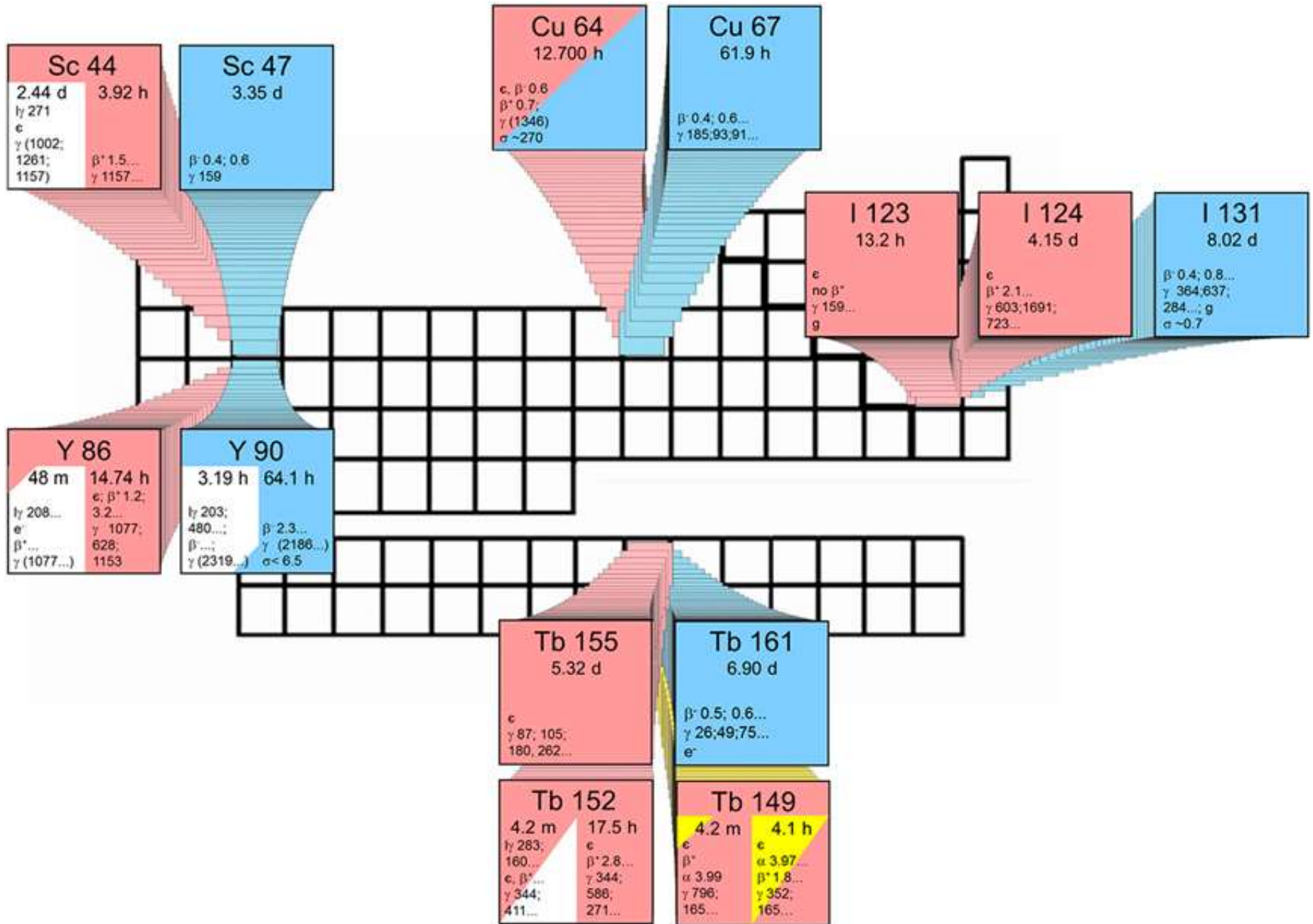
$1.5 \cdot 10^{15} \text{ n.cm}^{-2}\text{s}^{-1}$



The rising star
for therapy



Matched pairs for theranostics

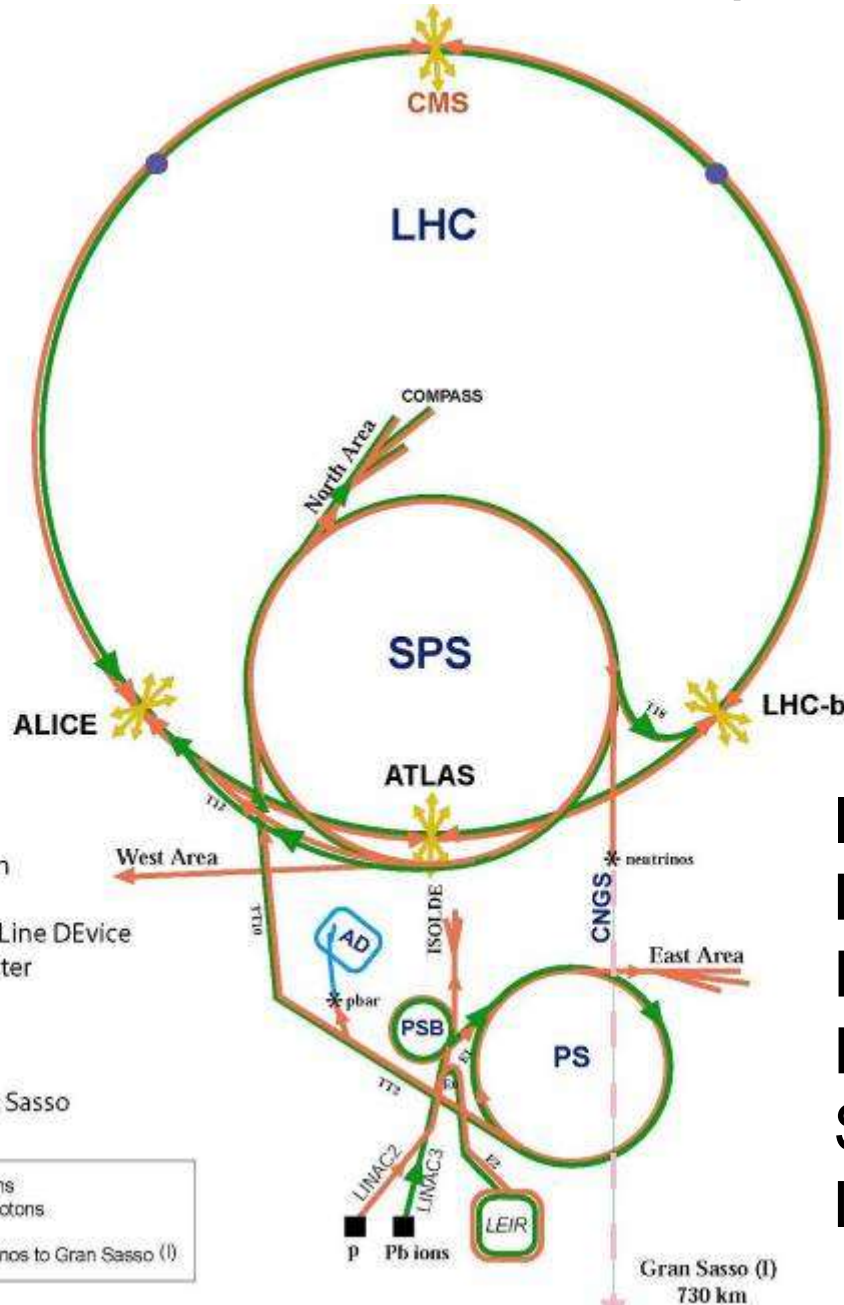


Terbium: a unique element for nuclear medicine

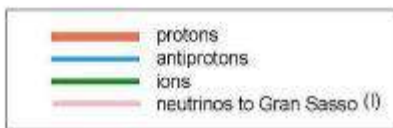


Dy 150 7.2 m ε; β ⁺ ... α 4.23 γ 397	Dy 151 17 m ε; α 4.07 γ 386; 49; 546; 176...	Dy 152 2.4 h ε α 3.63 γ 257	Dy 153 6.29 h ε; β ⁺ ... α 3.46... γ 81; 214; 100; 264	Dy 154 3.0 · 10 ⁶ a α 2.67	Dy 155 10.0 h ε β ⁺ 0.9; 1.1... γ 227...	Dy 156 0.056 α 33 σ _{n, α} < 0.009	Dy 157 8.1 h ε γ 326...	Dy 158 0.095 α 33 σ _{n, α} < 0.006	Dy 159 144.4 d ε γ 58; β ⁻ α 8000	Dy 160 2.329 α 60 σ _{n, α} < 0.0003	Dy 161 18.889 α 600 σ _{n, α} < 1E-6	Dy 162 25.475 α 170
Tb 149 4.2 m ε α 3.99 β ⁺ 3.8 γ 796; 352; 165...	Tb 150 4.1 h ε α 3.97 β ⁺ 3.8 γ 352; 165...	Tb 151 5.8 m 3.67 h ε; β ⁺ 3.1; α 49; β ⁺ 3.41 γ 252; 300; 287; 531...	Tb 152 4.2 m 17.5 h ε; β ⁺ ... α 2.9... γ 344; 506; 411...	Tb 153 2.34 d ε; β ⁺ ... α 2.9... γ 212; 170; 110; 102; 83...	Tb 154 23 h 9.0 h 21 h ε; β ⁺ ... α 2.9... γ 212; 170; 110; 102; 83...	Tb 155 5.32 d ε γ 87; 105; 180; 262...	Tb 156 24 h? 5.4 h 5.4 d ε; β ⁺ ... α 2.9... γ 212; 170; 110; 102; 83...	Tb 157 99 a ε (54) β ⁻	Tb 158 10.5 s 180 a ε β ⁻ 0.9 γ 944; 962; 80...	Tb 159 100 α 23.2	Tb 160 72.3 d β ⁻ 0.6; 1.7... γ 879; 299; 966... α 570	Tb 161 6.90 d β ⁻ 0.5; 0.6... γ 26; 49; 75... β ⁻
Gd 148 74.6 a α 3.183 σ 14000	Gd 149 9.28 d ε; α 3.016 γ 150; 299; 347...	Gd 150 1.8 · 10 ⁶ a α 2.72	Gd 151 120 d ε; α 2.60 γ 154; 243; 175...	Gd 152 0.20 1.1 · 10 ¹⁴ a α 2.14; σ 700 σ _{n, α} < 0.007	Gd 153 239.47 d ε γ 97; 103; 70... α 20000 σ _{n, α} 0.03	Gd 154 2.18 α 60	Gd 155 14.80 α 51000 σ _{n, α} 0.00008	Gd 156 20.47 α - 2.0	Gd 157 15.65 α 254000 σ _{n, α} < 0.05	Gd 158 24.84 α 2.3	Gd 159 18.48 h β ⁻ 1.0... γ 364; 59...	Gd 160 21.86 α 1.5

The accelerator complex of CERN

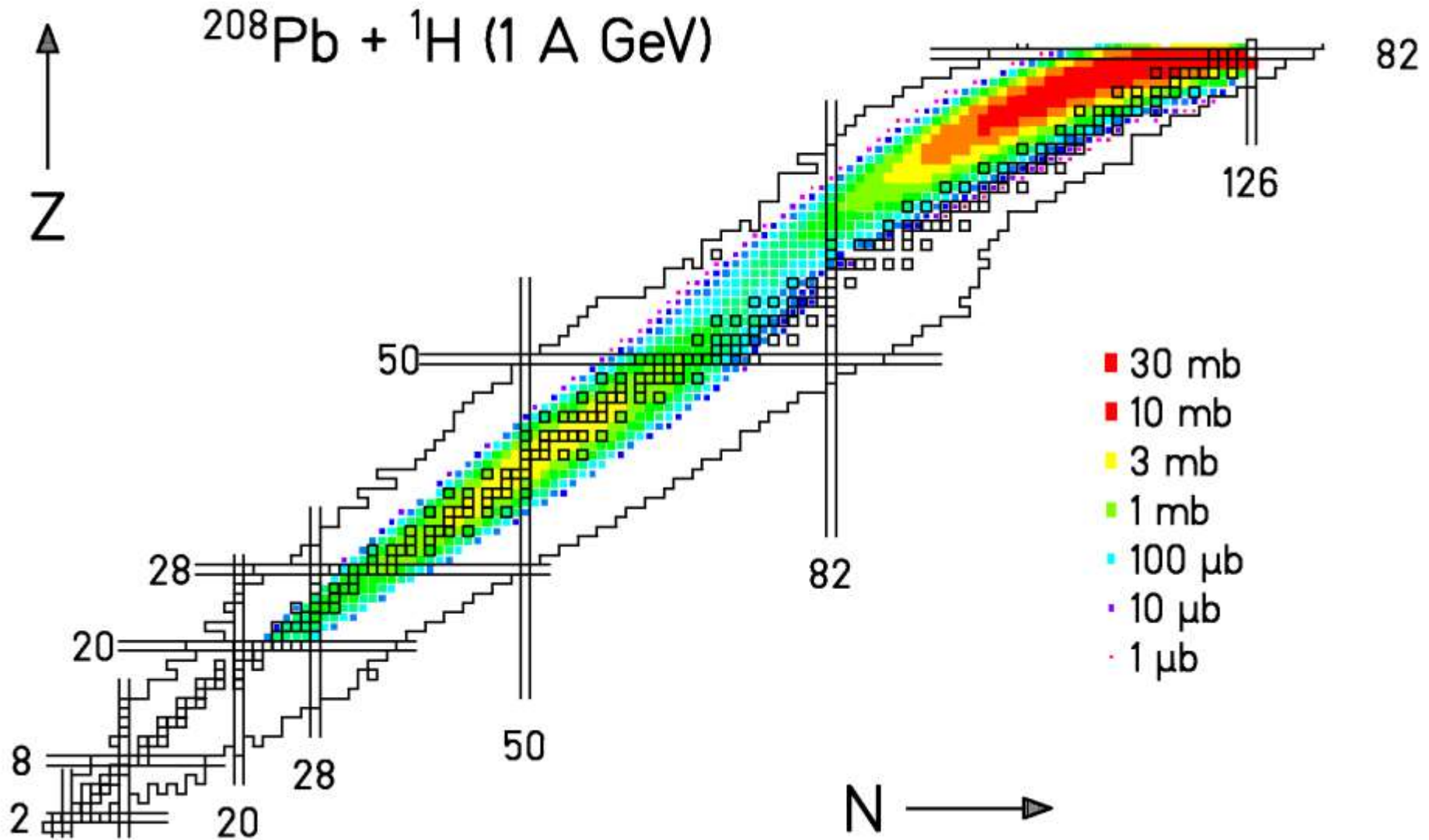


LHC: Large Hadron Collider
 SPS: Super Proton Synchrotron
 AD: Antiproton Decelerator
 ISOLDE: Isotope Separator OnLine DEvice
 PSB: Proton Synchrotron Booster
 PS: Proton Synchrotron
 LINAC: LINear ACcelerator
 LEIR: Low Energy Ion Ring
 CNGS: Cern Neutrinos to Gran Sasso



Ion source	90 keV
LINAC2	50 MeV
PSB	1.4 GeV
PS	25 GeV
SPS	450 GeV
LHC	6500 GeV

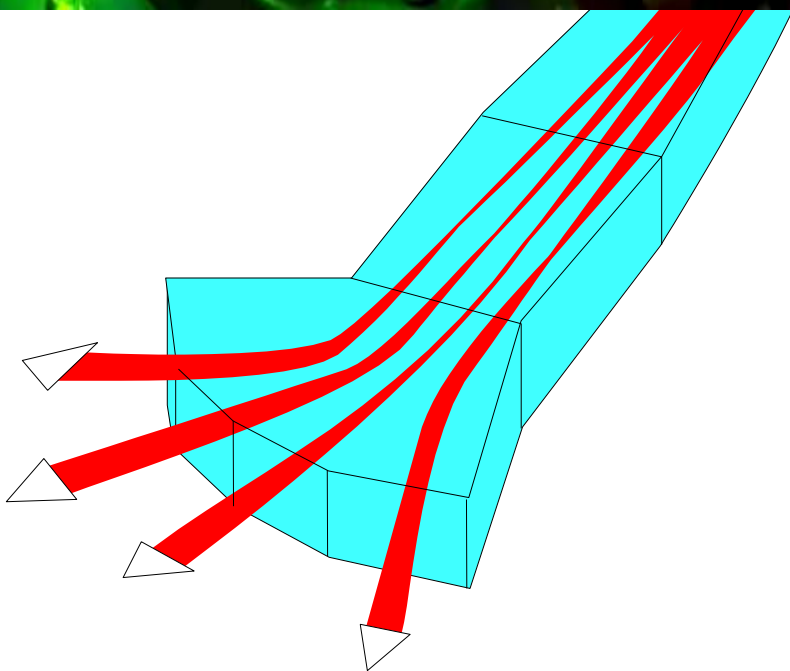
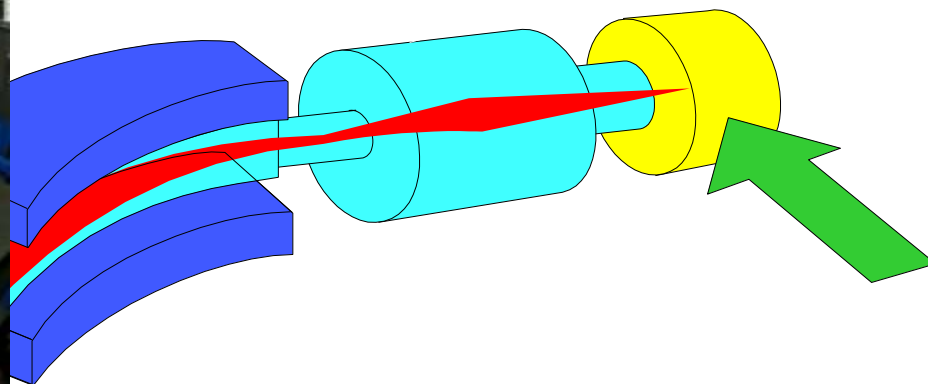
Spallation + Fragmentation + Fission



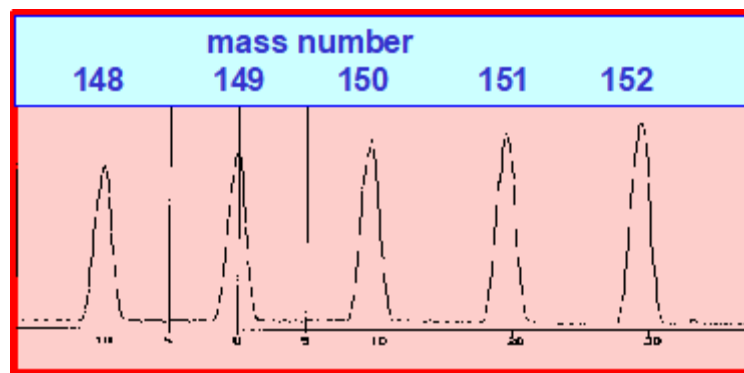
W. Wlazio et al., Phys. Rev. Lett. 84 (2000) 5736.

T. Enqvist et al., Nucl. Phys. A 686 (2001) 481.

Production of ^{149}Tb , ^{152}Tb and ^{155}Tb at ISOLDE



radioactive ion beams

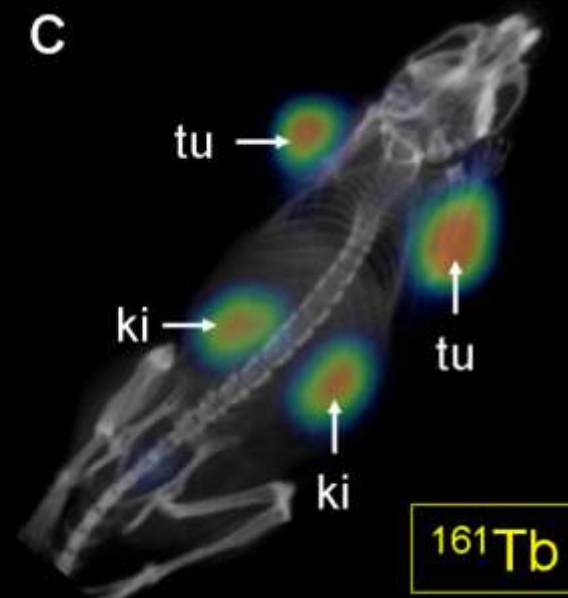
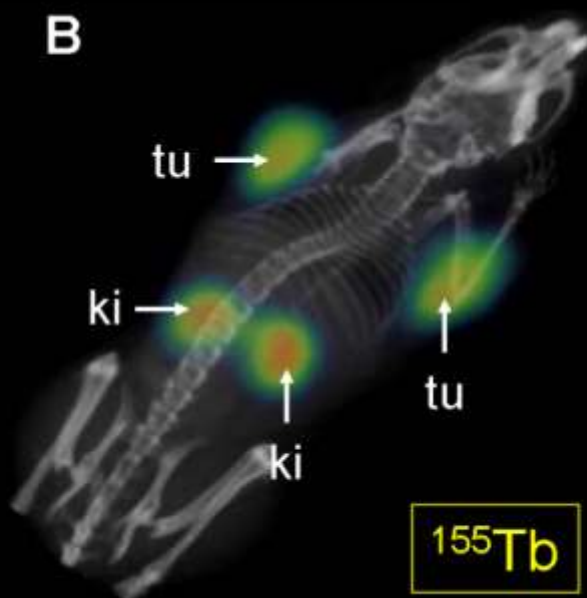
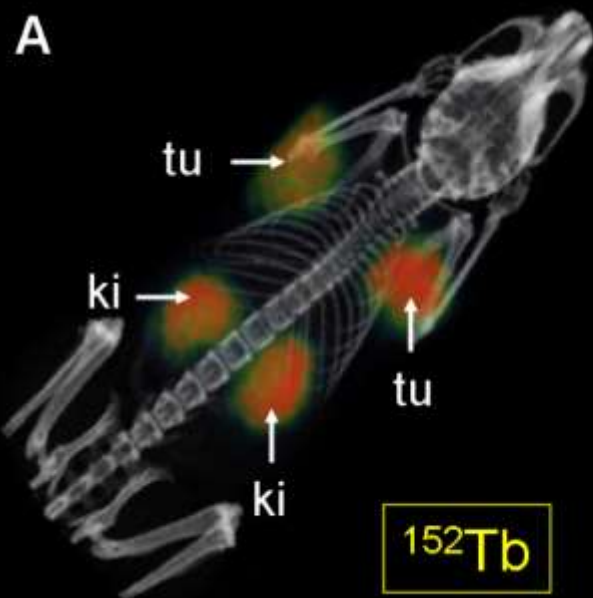


Theranostics with terbium isotopes

PET

SPECT

SPECT



ISOLDE

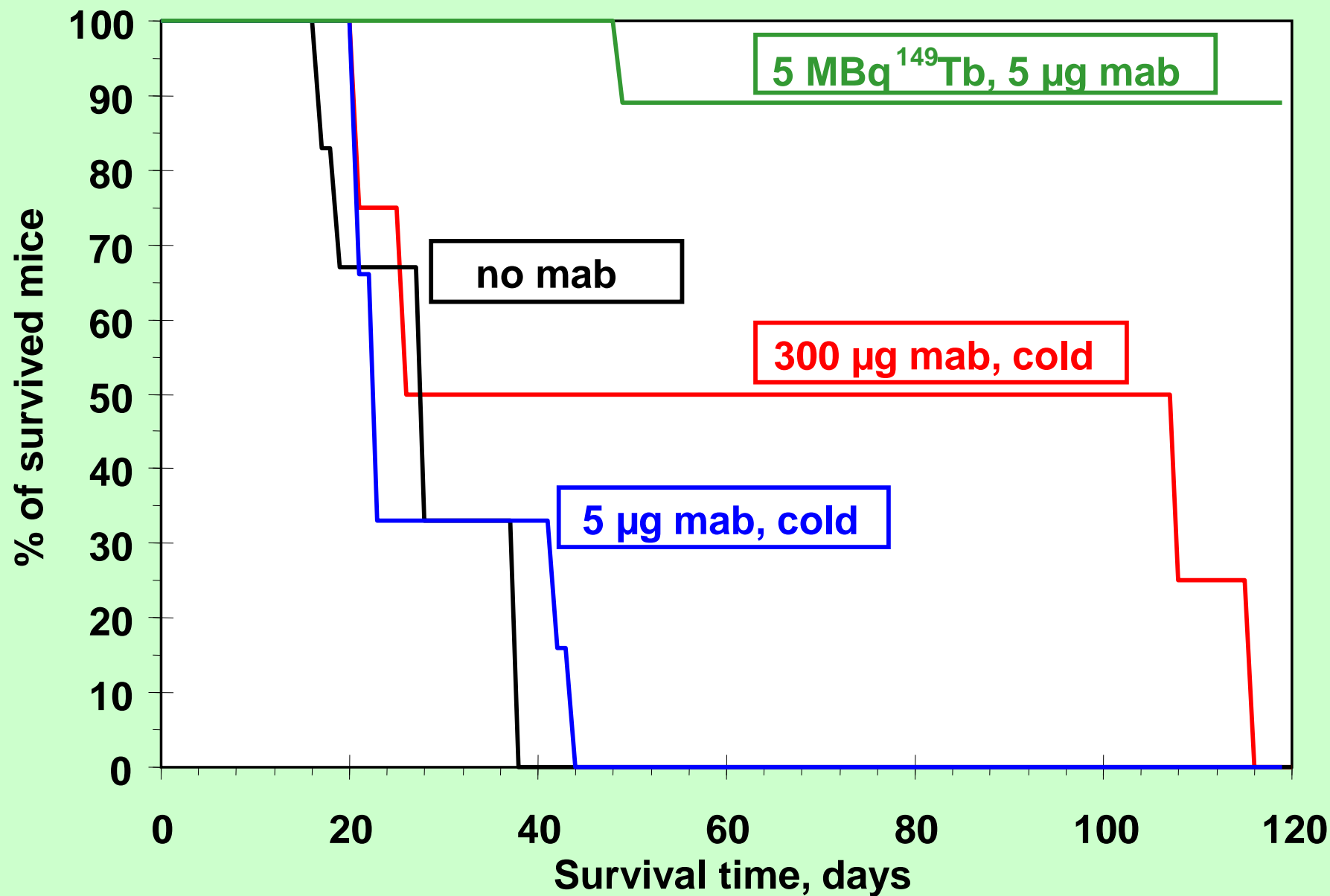


ISOLDE

PAUL SCHERRER INSTITUT
PSI

ILL
NEUTRONS
FOR SCIENCE

Preclinical study with lymphoma mouse model



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Many reports and guidelines from IAEA Vienna (free download):

- Nuclear Medicine Physics. A Handbook for Teachers and Students, IAEA Vienna 2014, STI/PUB/1617.
- Cyclotron Produced Radionuclides: Principles and Practice, IAEA Vienna 2008, Technical Report 465.
- Cyclotron Produced Radionuclides: Physical Characteristics and Production Methods, IAEA Vienna 2009, Technical Report 468.
- Lectures on Theranostics by Richard Baum:
<https://www.youtube.com/watch?v=Z0TIXH2dVi8>
<https://www.youtube.com/watch?v=S74LNxXOaSw>
- (Free) medical review papers from <http://pubmed.gov>
- Information on on-going clinical trials: <http://clinicaltrials.gov>