

# Life, the Universe and Everything

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12 November 2019

# Institut Max von Laue – Paul Langevin

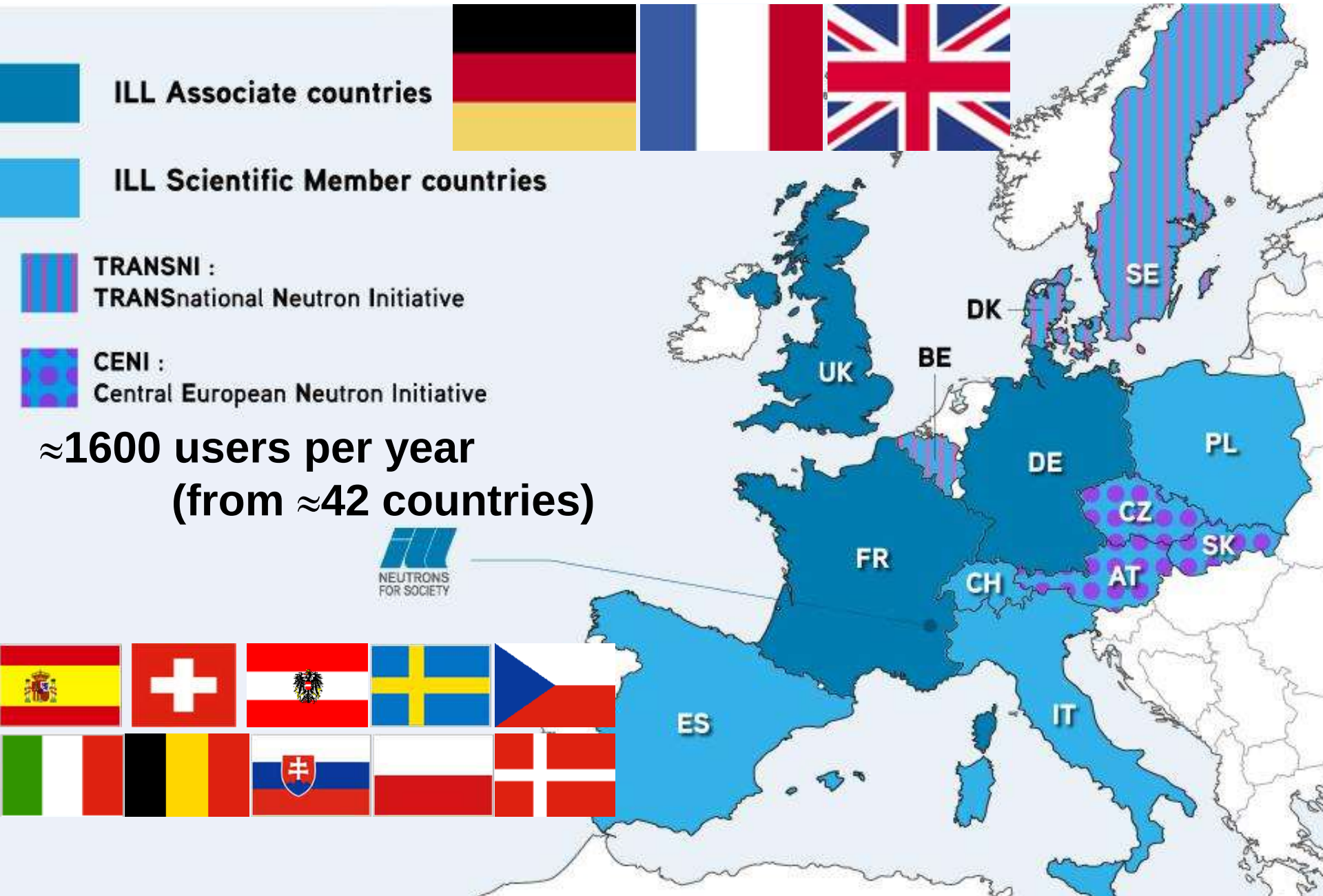


Max von Laue  
(1879-1960)  
Nobel Prize 1914  
**Diffraction** of X-rays

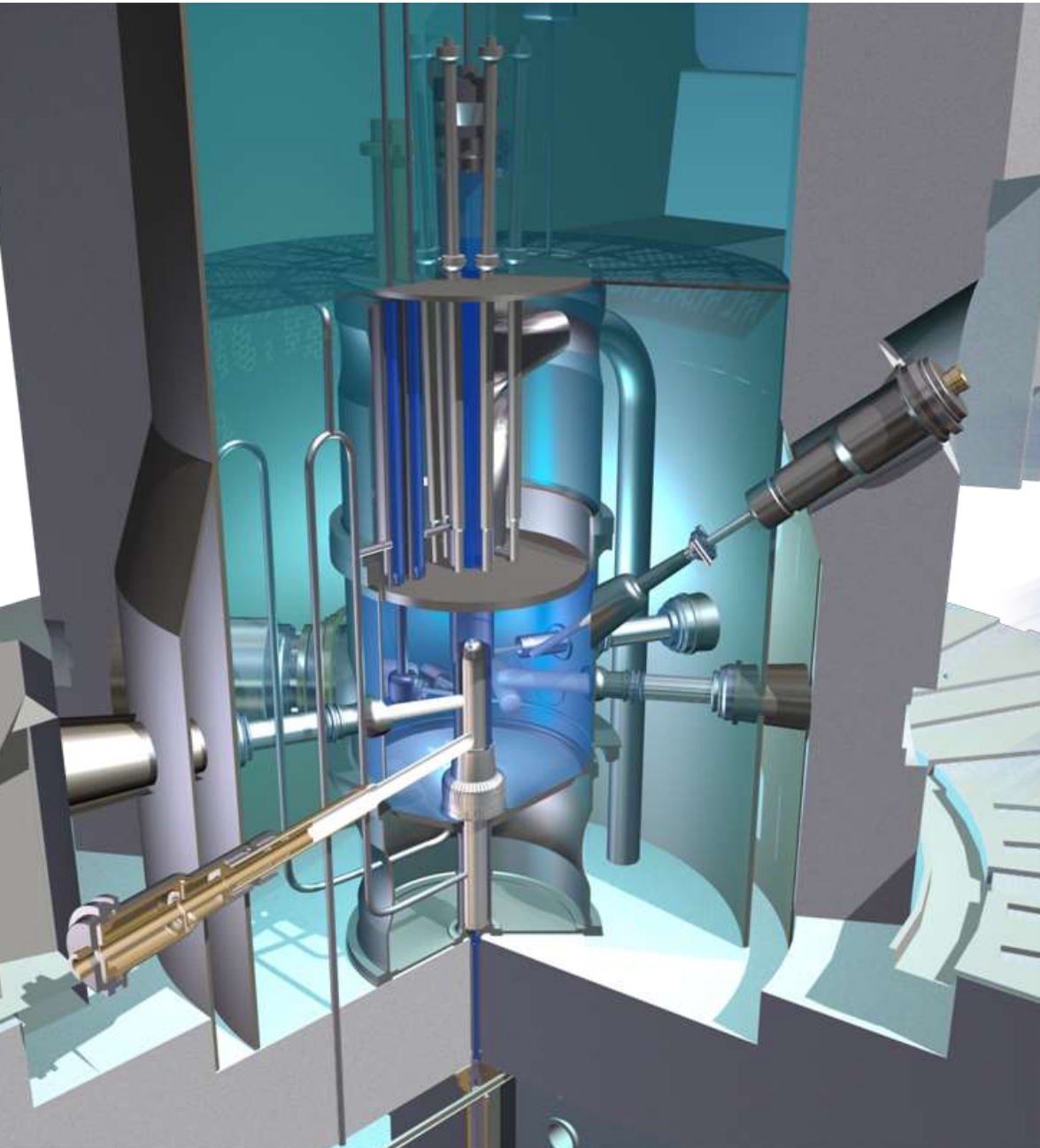


Paul Langevin  
(1872-1946)  
**Langevin dynamics**  
**Magnetism**, etc.

# An international user facility: $\approx 13$ member states

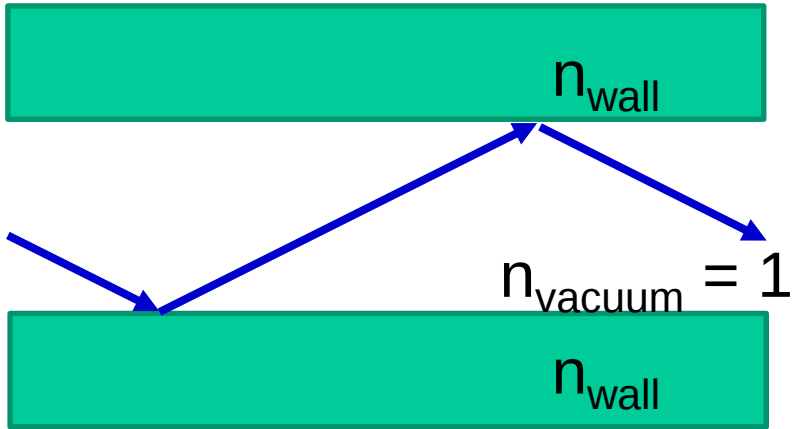


# The ILL Reactor



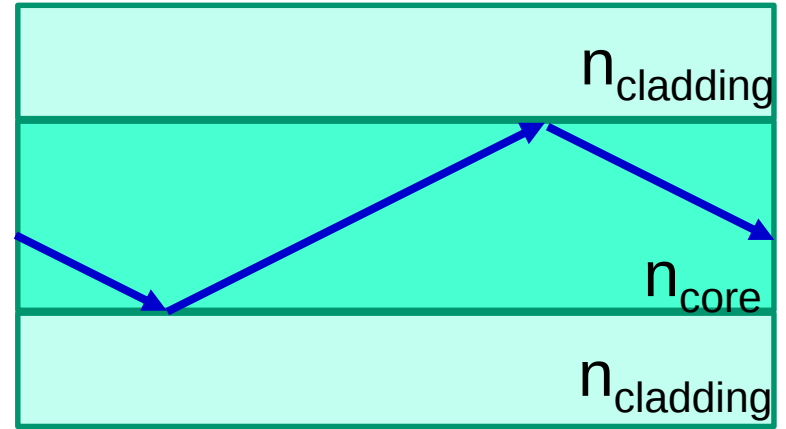
**$5 \cdot 10^{18}$  neutrons/s  
generated at 57 MW**

# Neutron guides vs. light guides



Neutron guide:

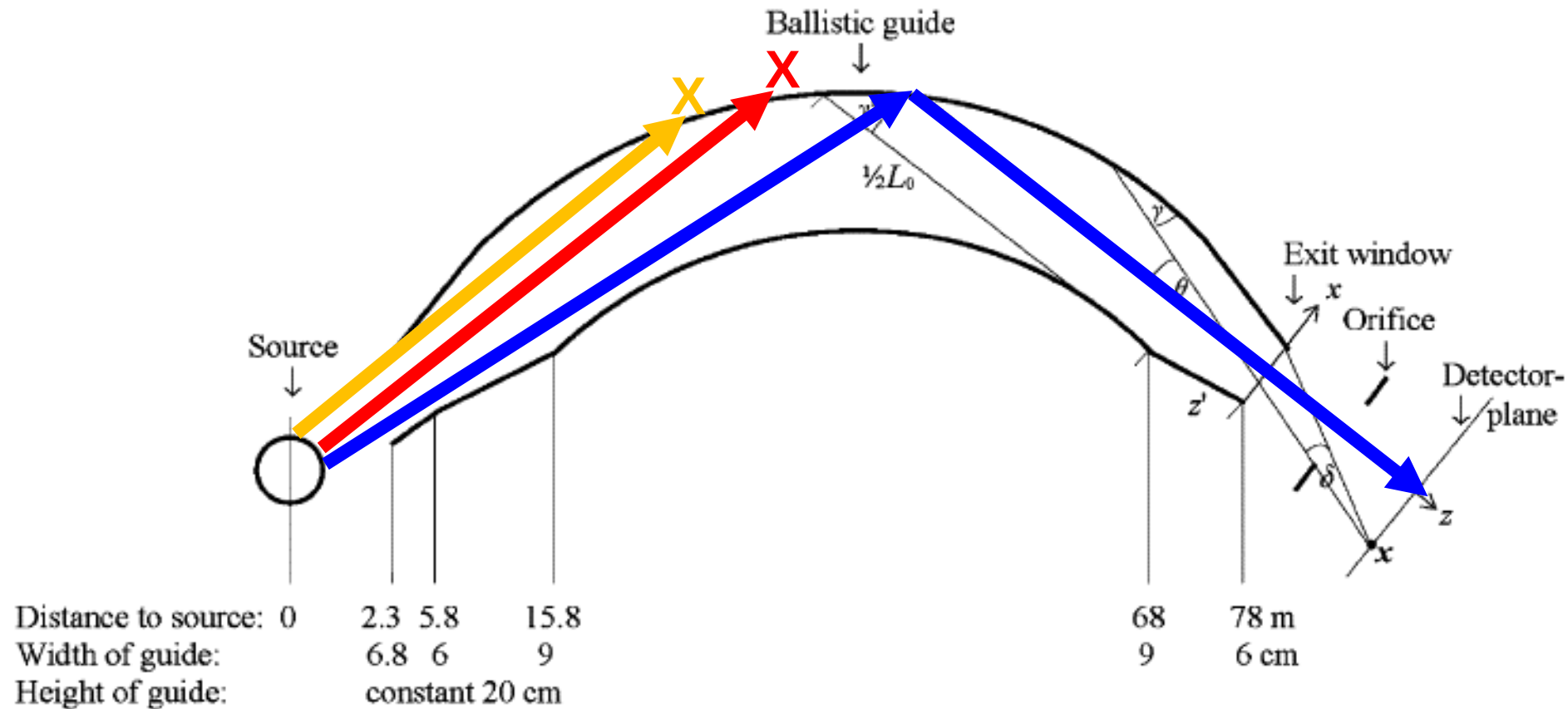
$$n_{\text{wall}} < n_{\text{vacuum}} = 1$$



Light guide:

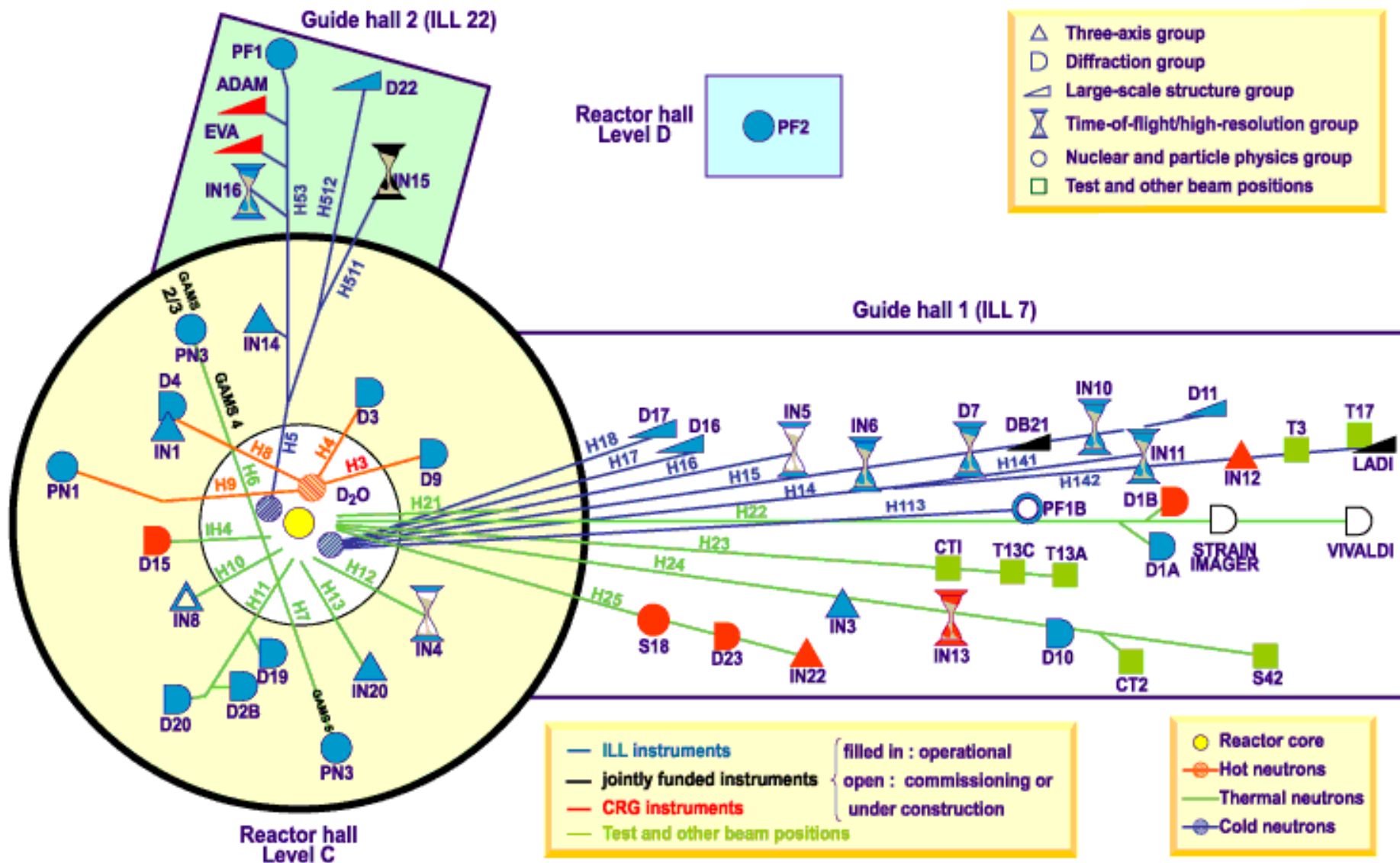
$$n_{\text{core}} > n_{\text{cladding}} > 1$$

# Guided neutron beams are “clean”



Fast neutrons and gamma rays are not transported.

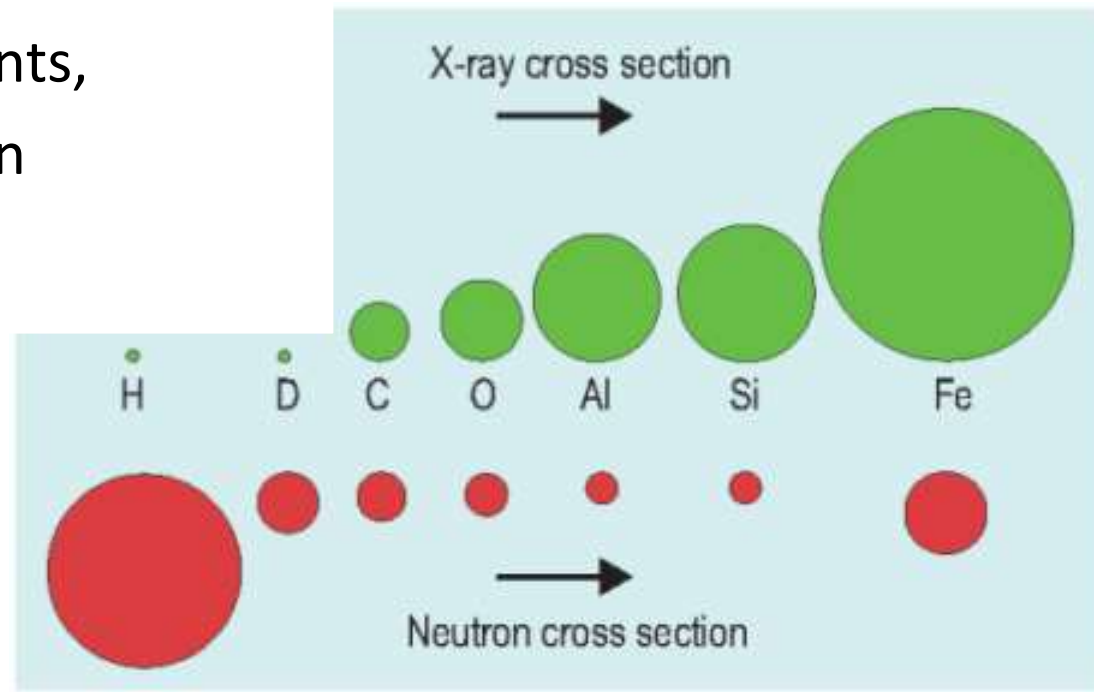
# ILL instruments

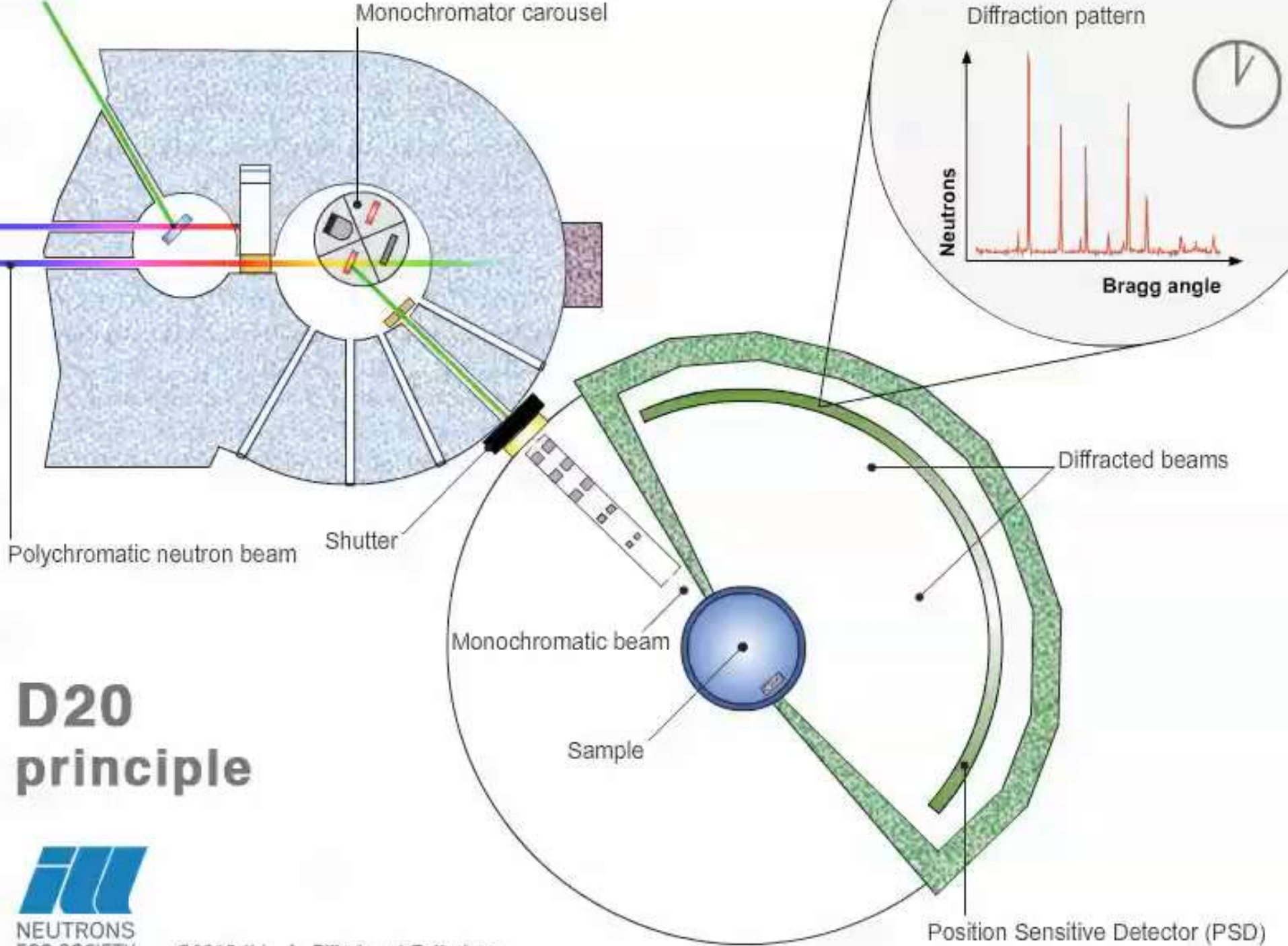


>40 instruments running simultaneously for 150-200 days per year  
 Neutron beams with up to  $2 \cdot 10^{10} \text{ n.cm}^{-2}\text{s}^{-1}$  flux and up to  $320 \text{ cm}^2$  area

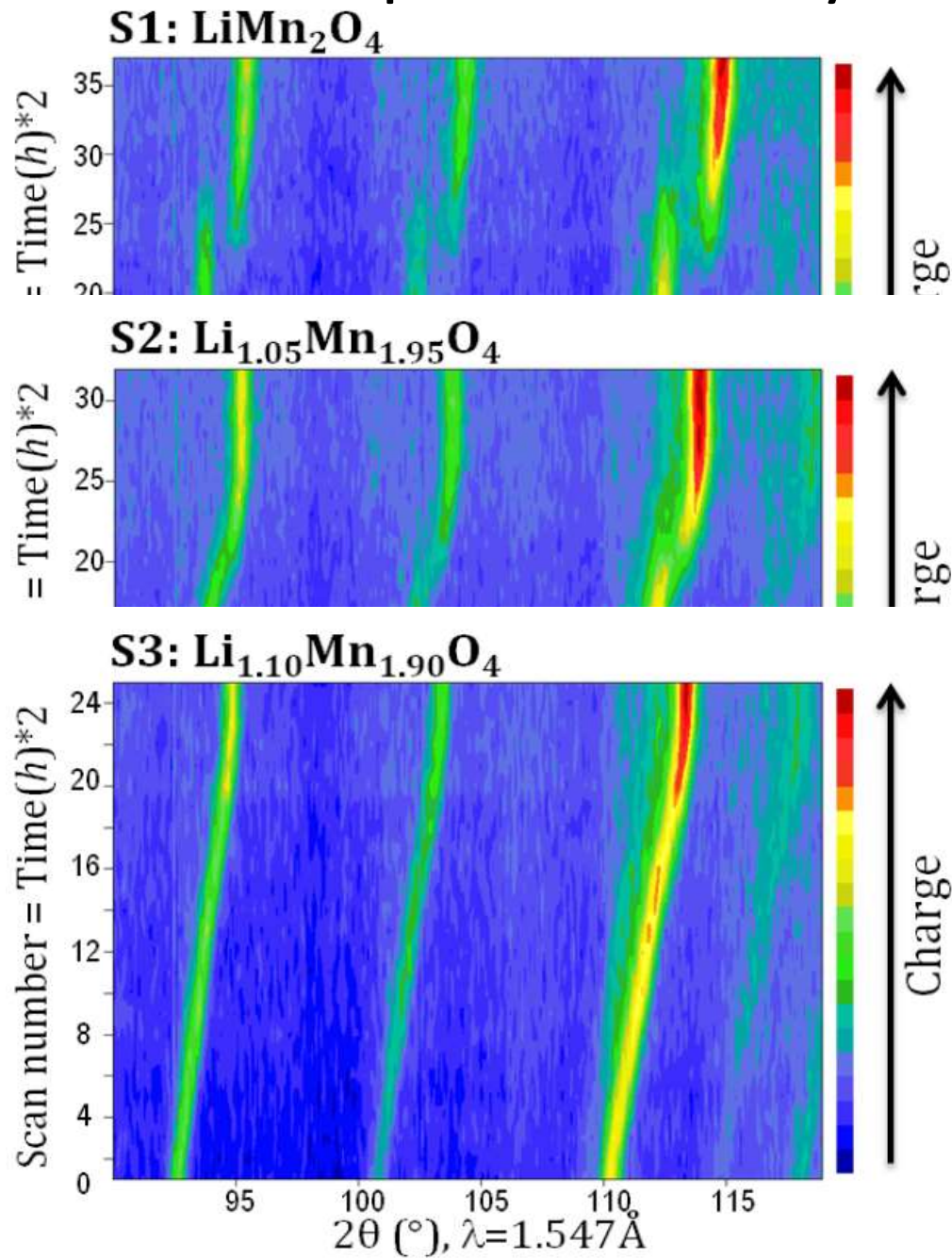
# Why neutrons ?

- wavelength of thermal neutrons  $\approx$  interatomic distances (sol., liq.)  
 $\Rightarrow$  good for scattering
- neutron mass  $\approx$  atom mass  
 $\Rightarrow$  large momentum transfer possible
- weakly interacting  $\Rightarrow$  good penetration (thicker samples...)
- good to “see” light elements,  
in particular hydrogen
- magnetic moment  
 $\Rightarrow$  magnetic scattering





# In operando study of lithium batteries

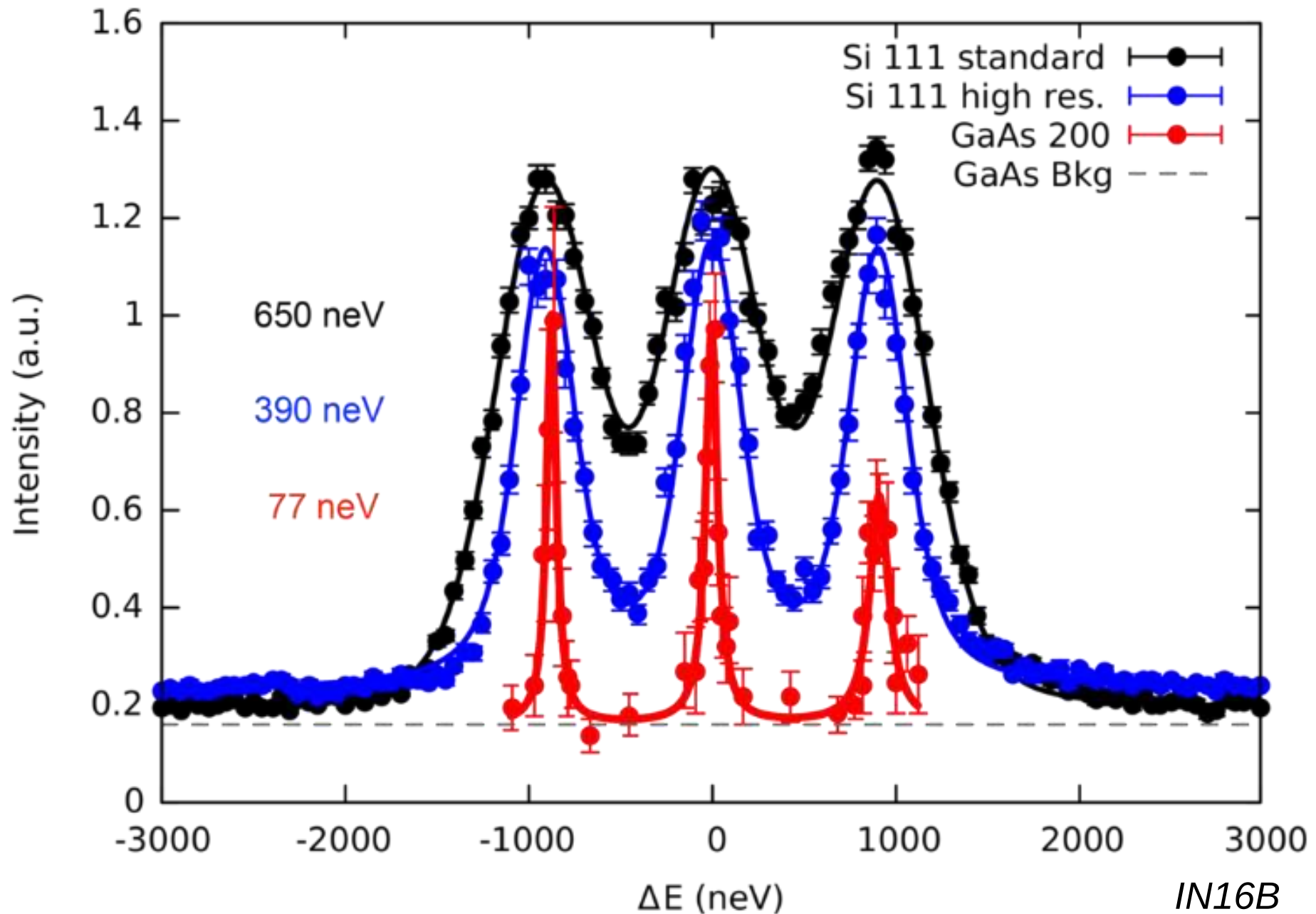


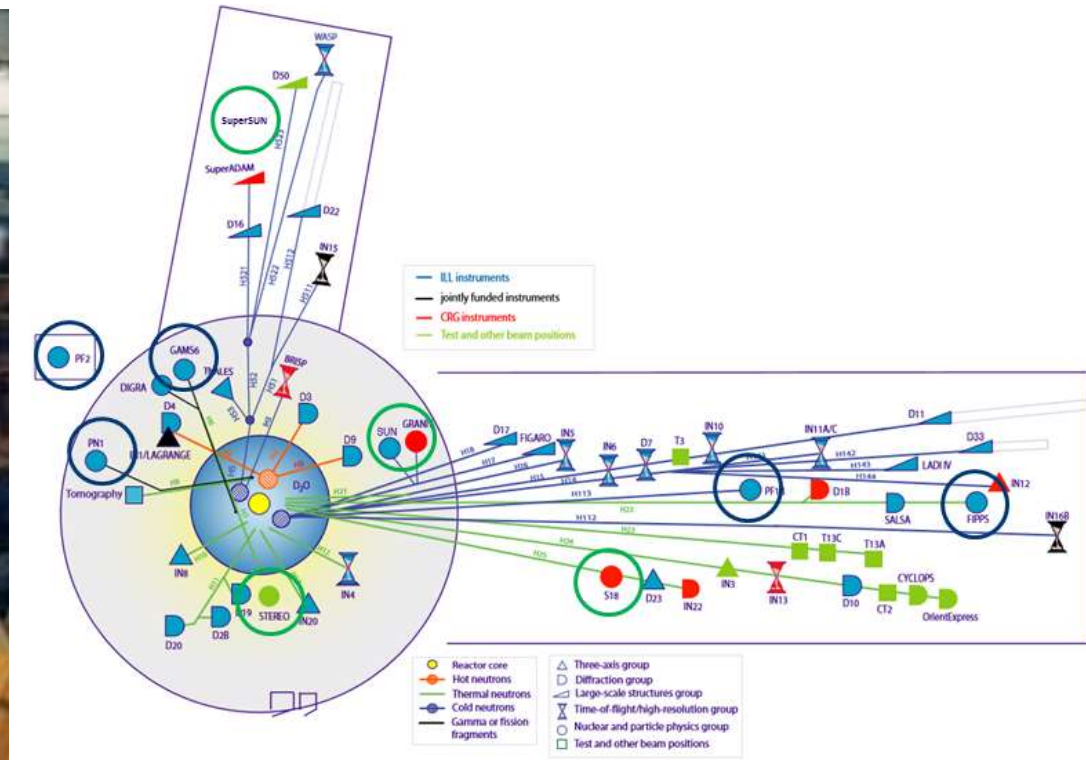
Also:

- hydrogen (biological samples !)
- magnetism
- reflectometry
- SANS
- inelastic neutron scattering

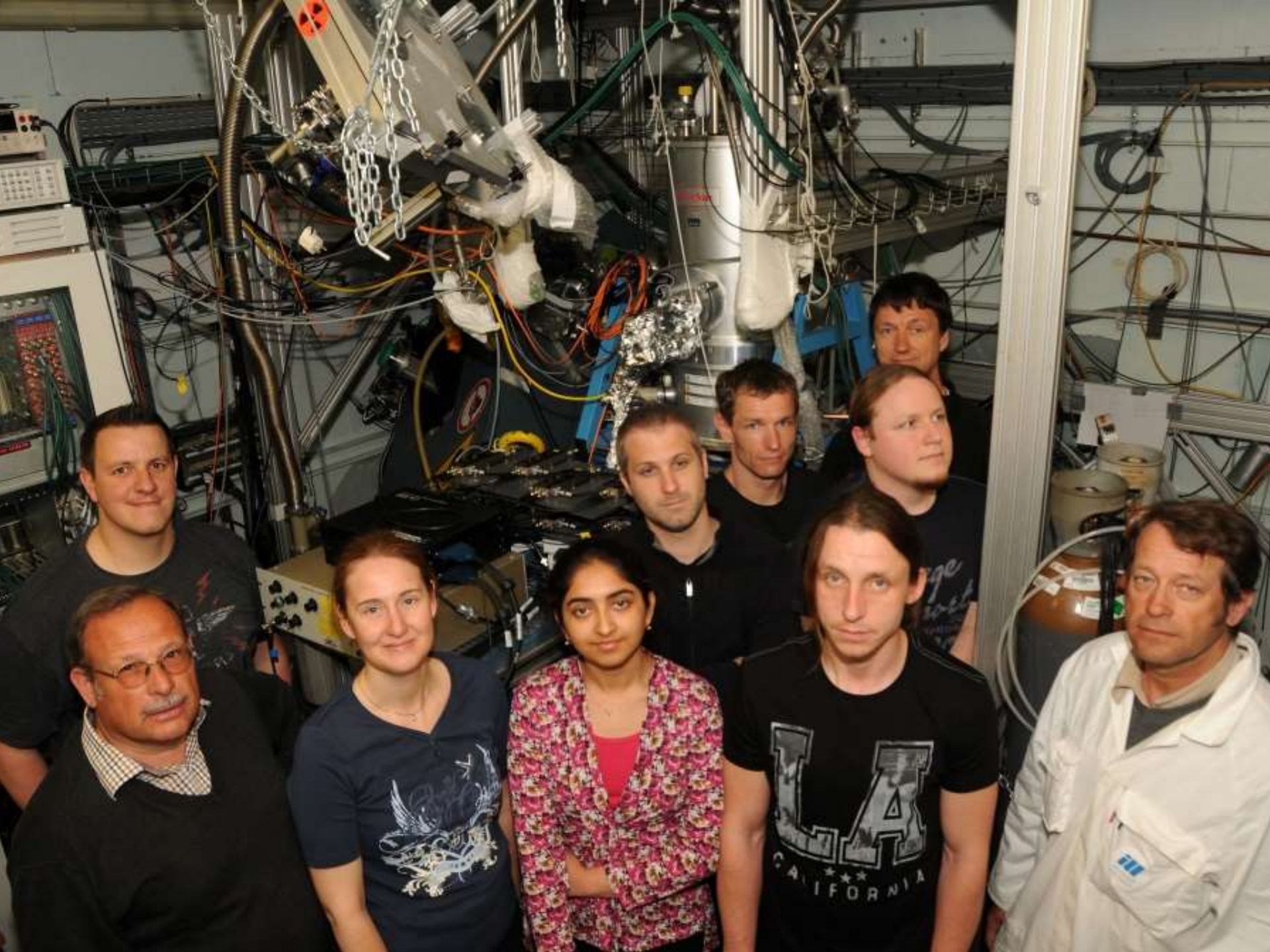
M. Bianchini et al.  
JPC C 2014;118:25947.

# High resolution inelastic neutron spectroscopy





***P. Armbruster et al.,  
Nucl Instr Meth 1976;39:213.***



# Life, the Universe and Everything



# Structural imaging versus functional imaging molecular imaging

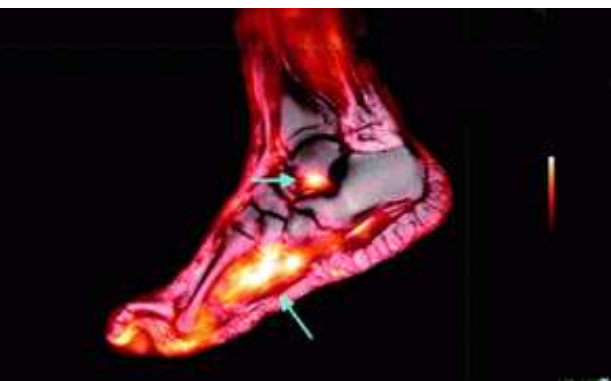
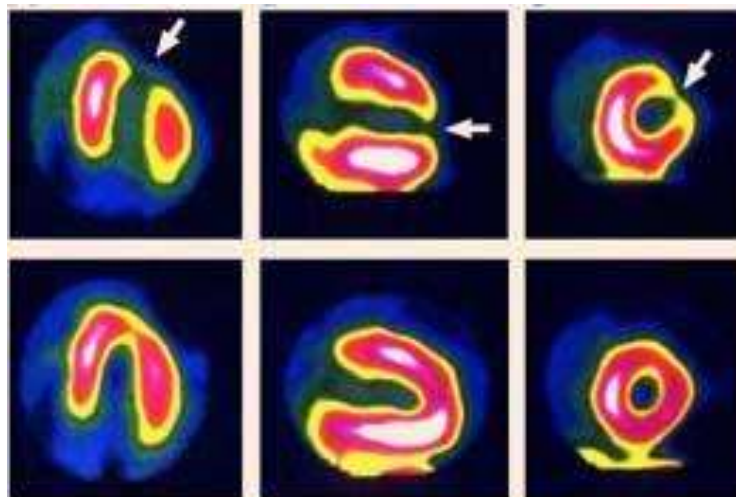
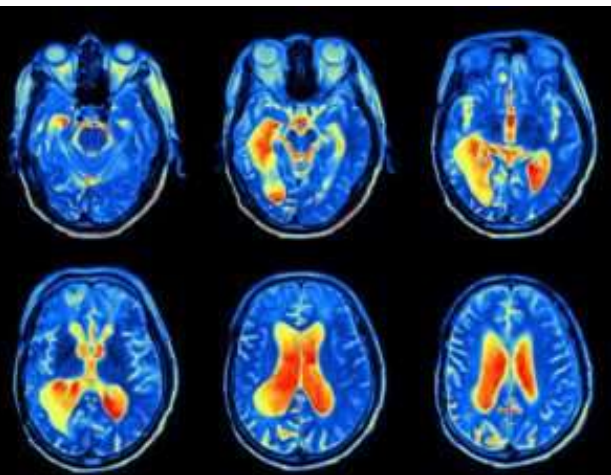


Radiology



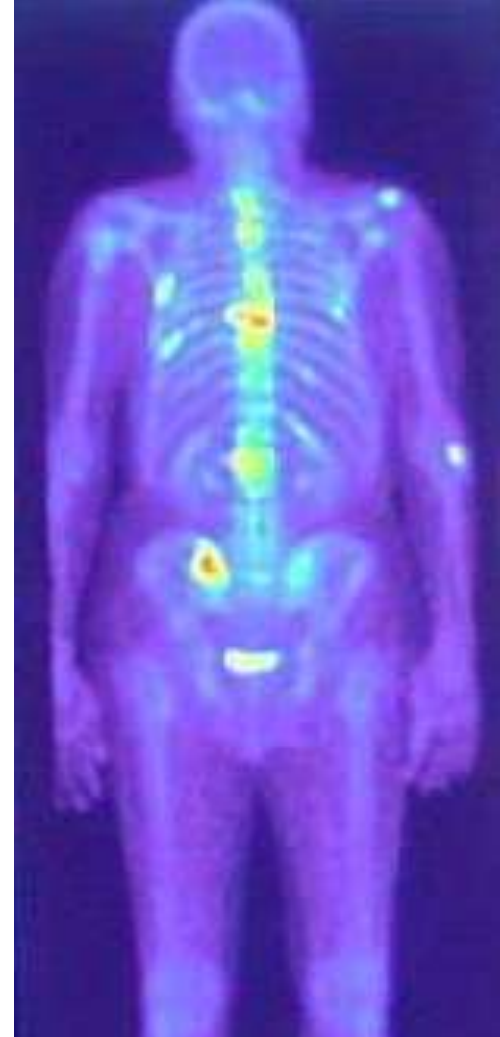
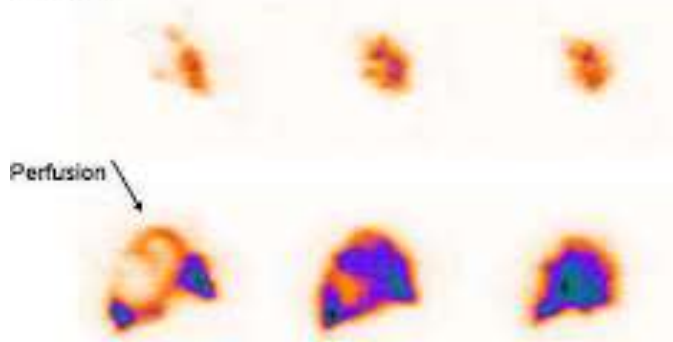
Nuclear Medicine

# Molecular imaging



Ventilation:

Perfusion



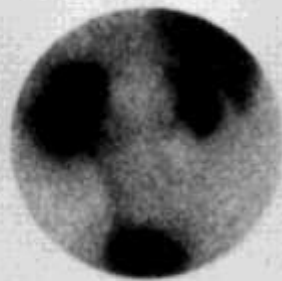
FL



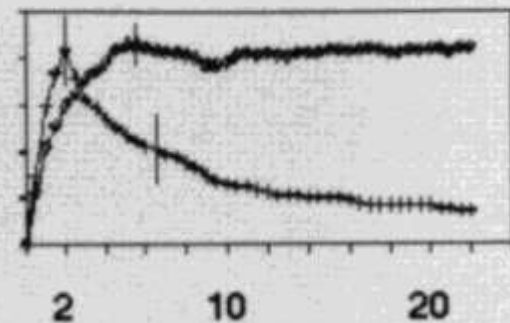
2



30



30 E



# What is Theranostics ?

**Therapy** based on **diagnostics**  
personalized medicine, stratified medicine



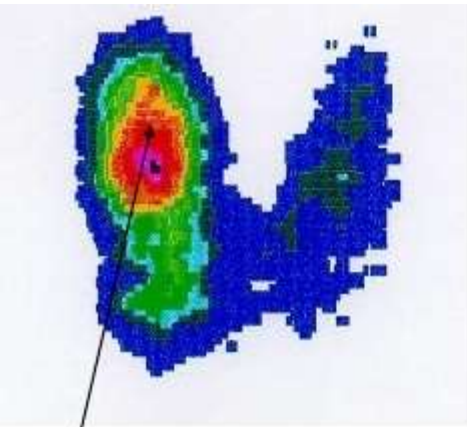
**Saul Hertz** (Massachusetts General Hospital):

1936 proposes iodine radiotracer

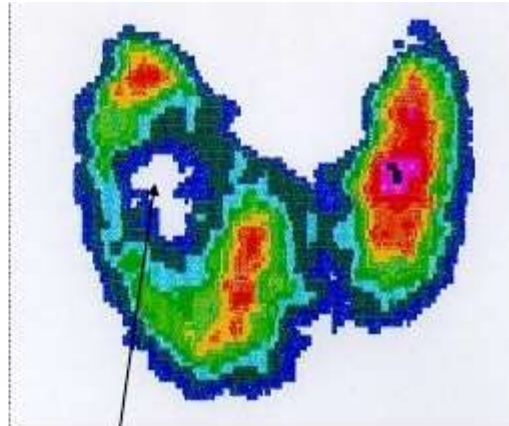
1937 rabbit studies with  $^{128}\text{I}$

1941 clinical therapy studies with  $^{130}\text{I}$

# Thyroid scintigraphy and therapy



Hot nodule – Rt. lobe



Cold nodule – Rt. lobe

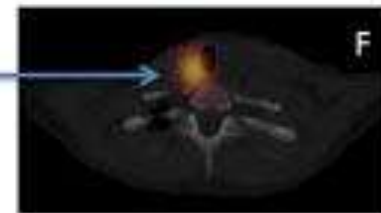
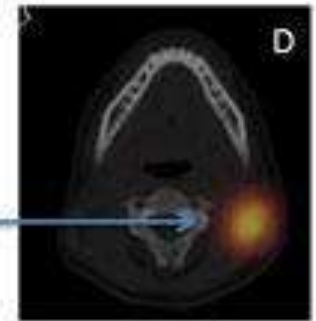
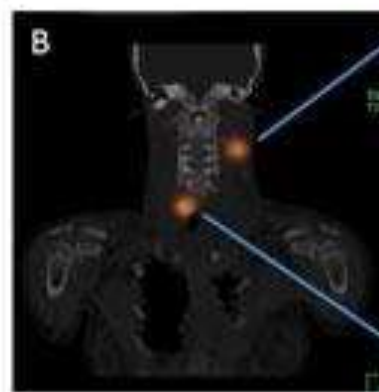
$I^{123}$

13.2 h

$\epsilon$   
no  $\beta^+$   
 $\gamma$  159

$I^{123}$ -I Diagnostic  
Whole Body  
Scan

$I^{123}$ -I DxWBS with  
SPECT-CT



$I^{131}$

8.0 d

$\beta^-$  1.0, 1.8,...  
 $\gamma$  364, 637...

$I^{123}$ -,  $I^{131}$ - or  $^{99m}TcO_4^-$  for scintigraphy

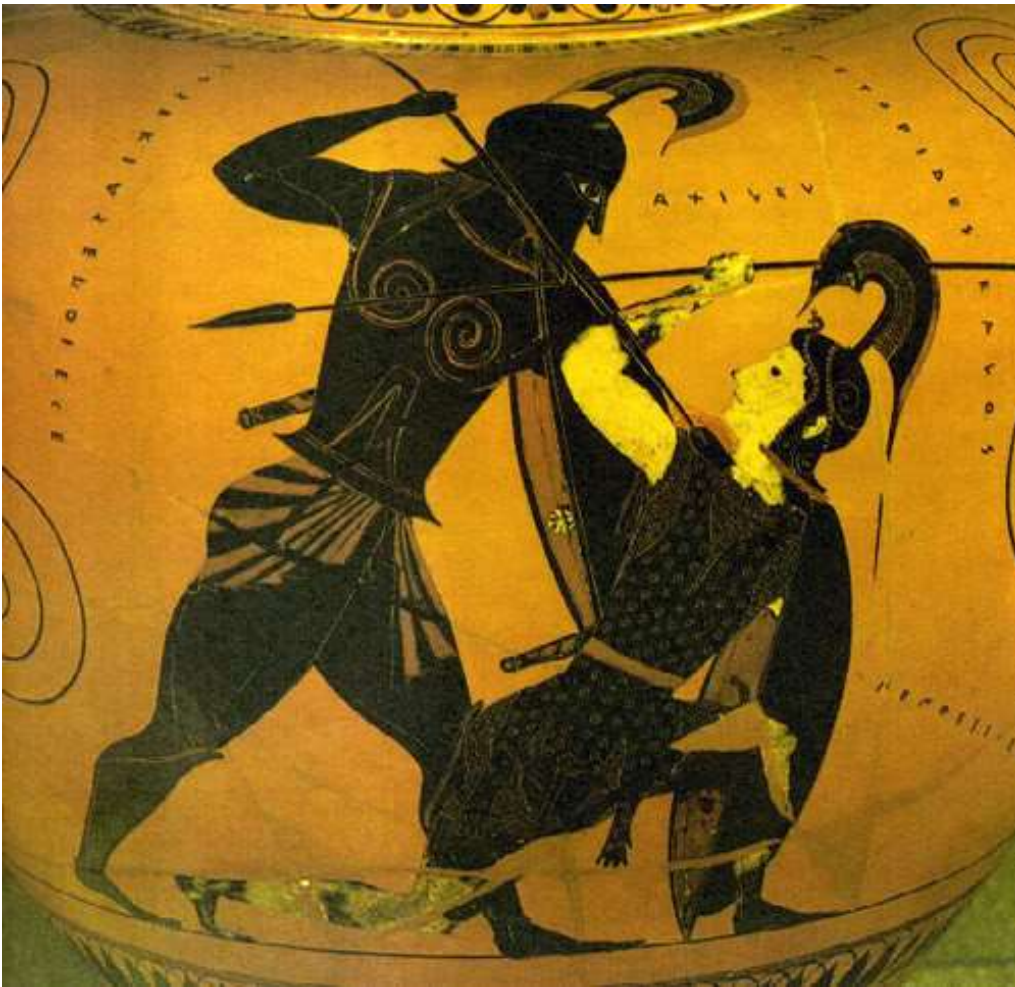
$I^{131}$ - for therapy

(Papillary) thyroid cancer has the **highest survival** of all malignant cancers!

How can one treat such patients?

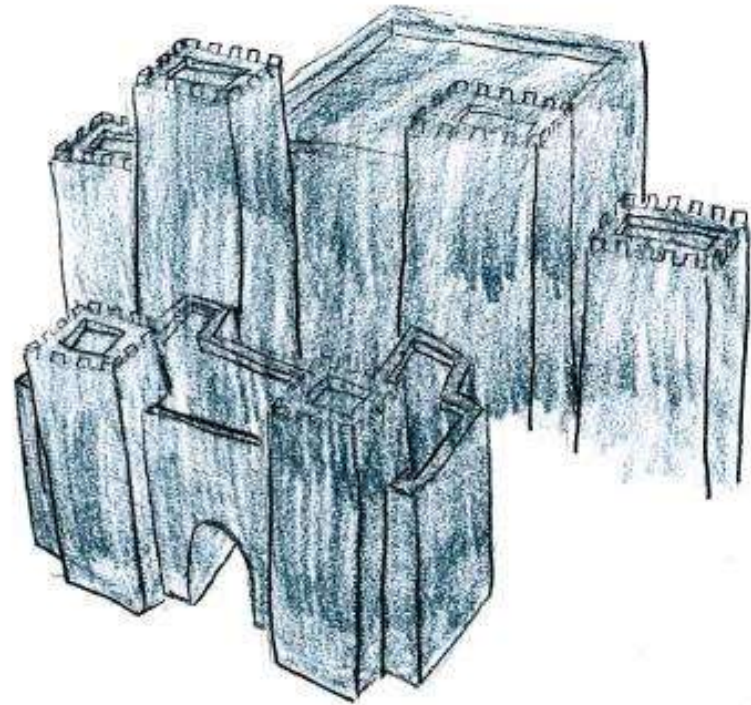


# Learning from history

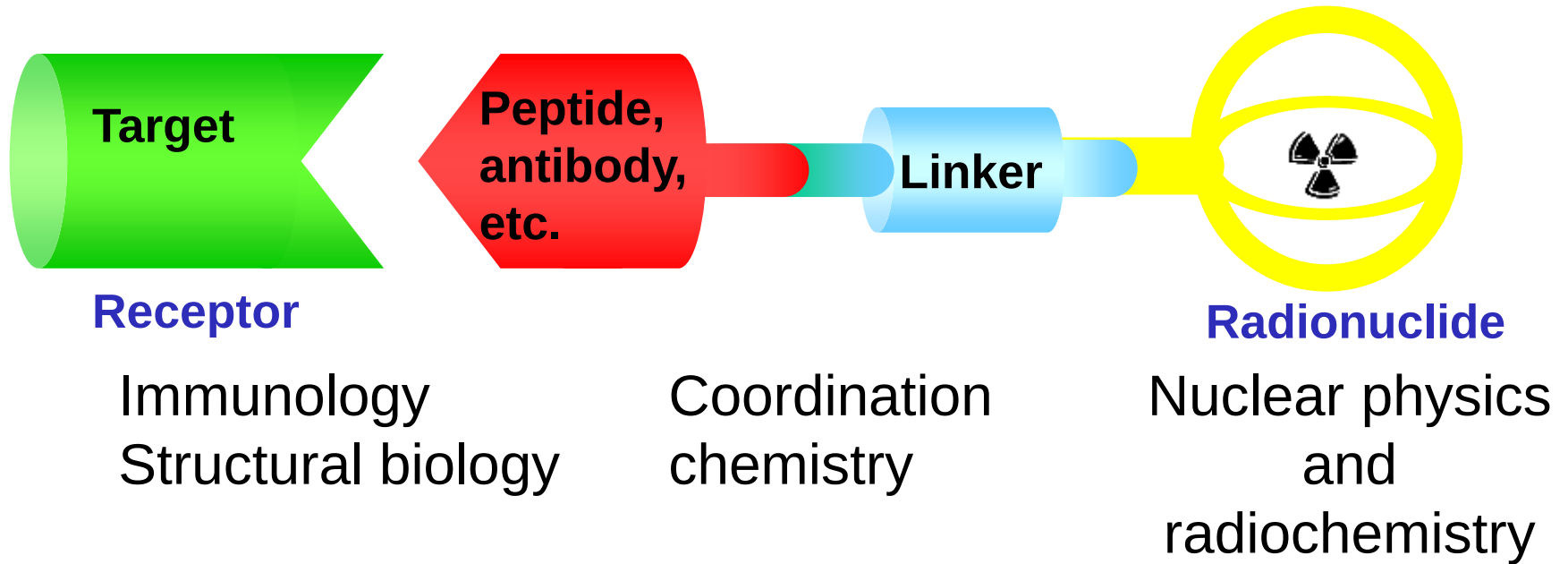


# The principle of targeted therapies

- “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

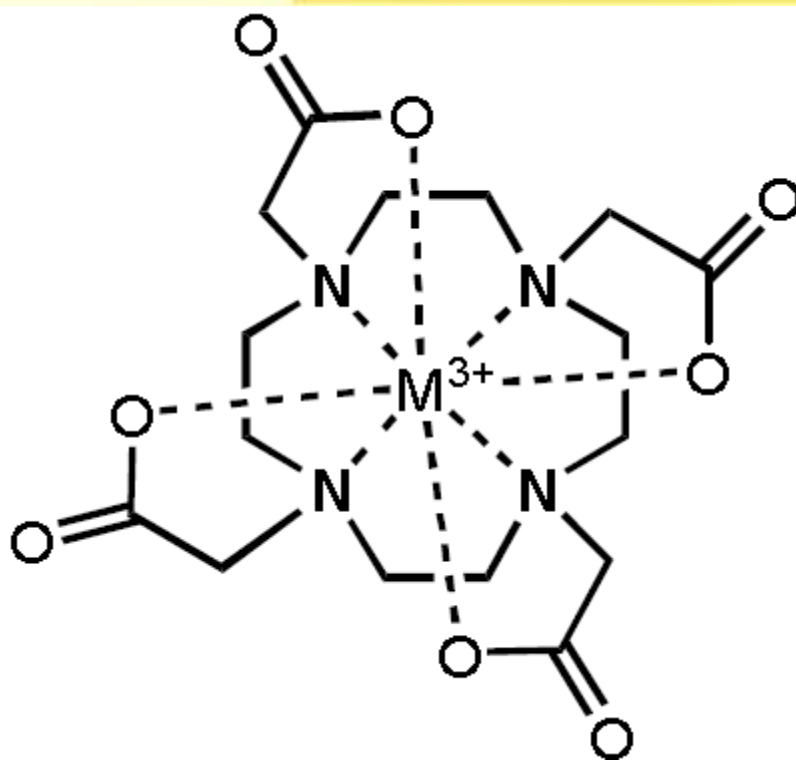


# Multidisciplinary collaboration to fight cancer

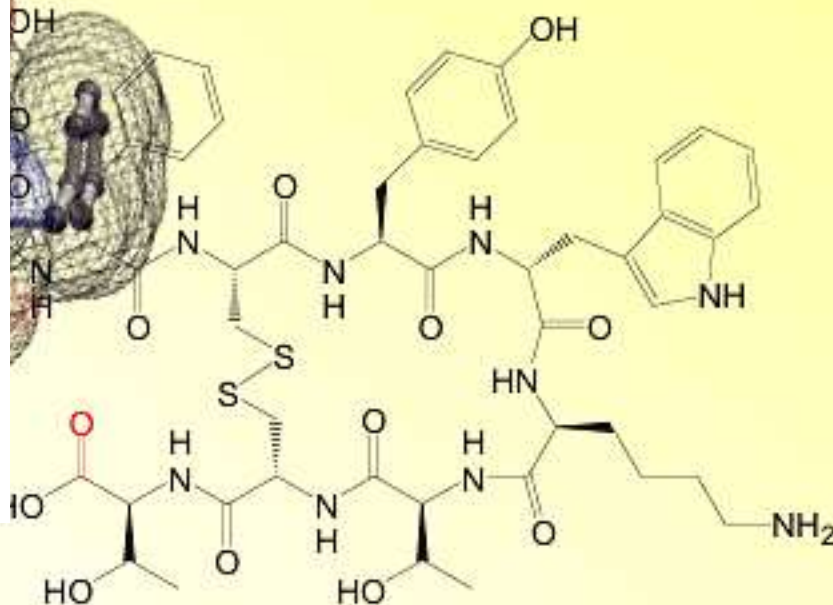


Nuclear medicine and medical physics

# Structural Formula of DOTA-TOC/TATE



DOTA-TATE



1,4,7,10-tetraazacyclododecantetraacetate

$^{111}\text{In}$

$^{90}\text{Y}$

$^{67}\text{Ga}$

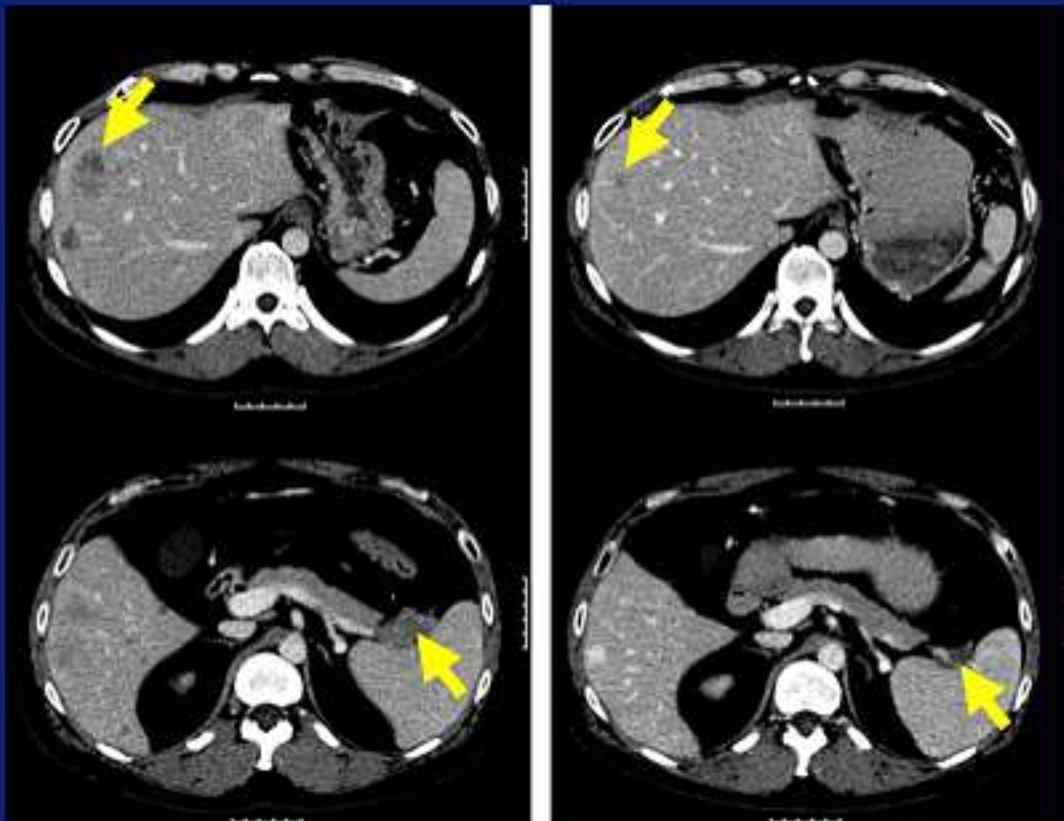
$^{177}\text{Lu}$

$^{68}\text{Ga}$

$^{213}\text{Bi}$

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

*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  $^{177}\text{Lu}$ -  
octreotate and  
capecitabine

Partial remission



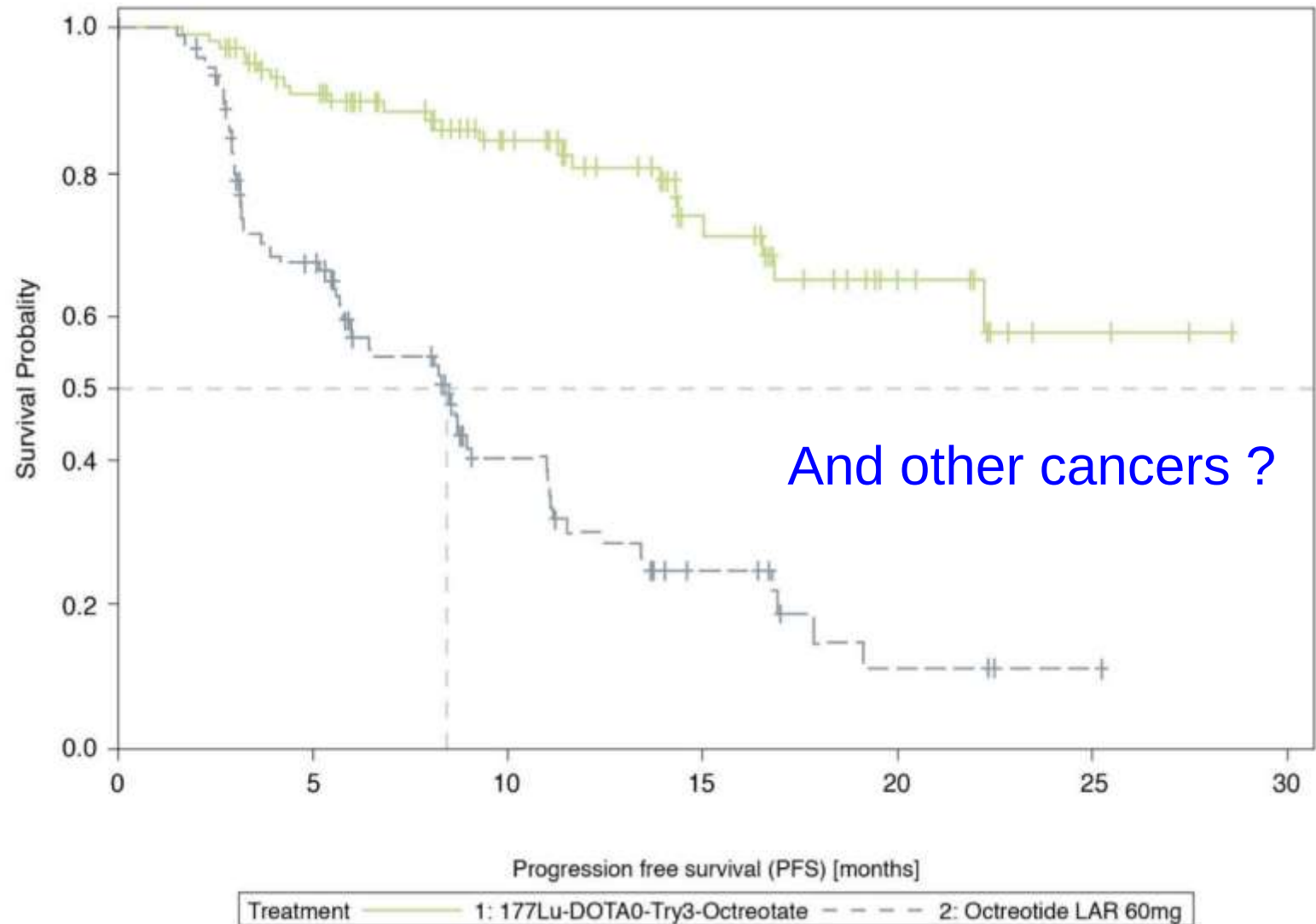
1<sup>st</sup> therapy



4<sup>th</sup> therapy

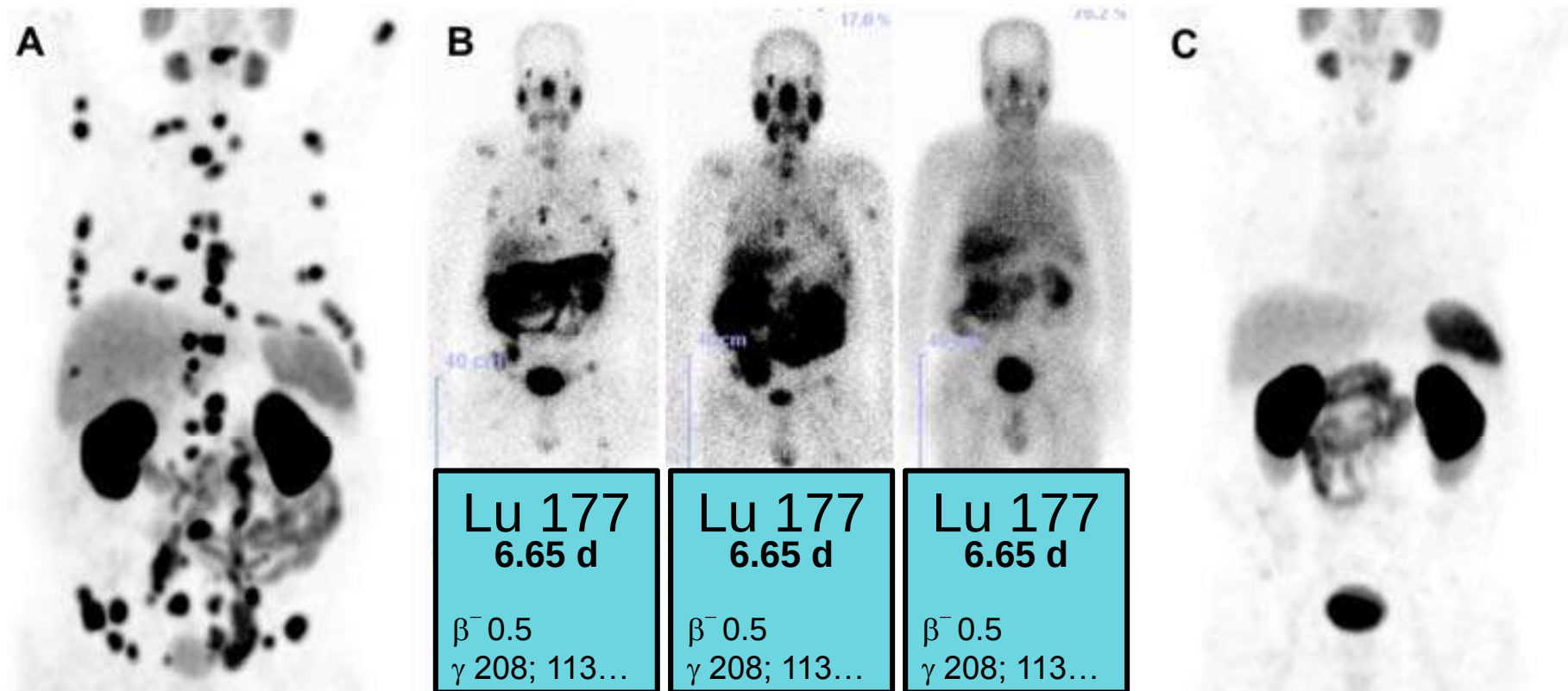
*Roelf Valkema, EANM-2008.*

# $^{177}\text{Lu}$ -Peptide Receptor Radionuclide Therapy of midgut neuroendocrine tumors



*J. Strosberg et al., N Engl J Med 2017;376:125.*

# $^{177}\text{Lu}$ -radioligand therapy of advanced prostate cancer



C. Kratochwil et al., *Eur J Nucl Med Mol Imaging* 2015;42:987.

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.

M.S. Hofman et al., *Lancet Oncol* 2018;19:825.

M.M. Heck et al., *Eur Urol* 2019;75:920.

T.W. Barber et al., *J Nucl Med* 2019; 60:955.

# The “gold standard” for radionuclide therapy



Institut Laue-Langevin 2018:  
≈ **1600** scientific users came to ILL  
≈ **4000** patients got  $^{177}\text{Lu}$  from ILL



# Radionuclides for Radioligand Therapy

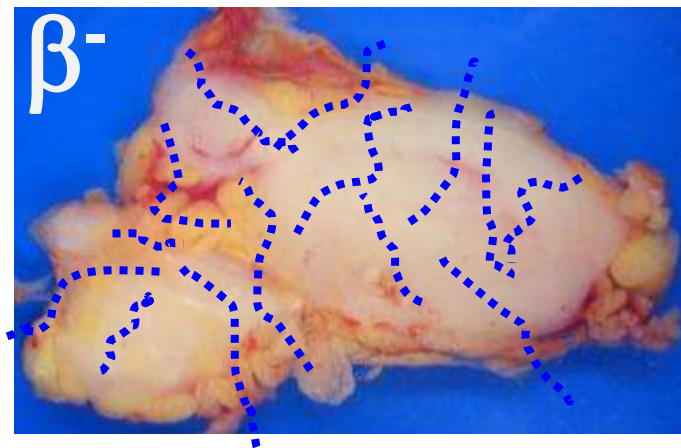
| Radio-nuclide | Half-life | E mean (keV) | E $\gamma$ (B.R.) (keV) | Range        |
|---------------|-----------|--------------|-------------------------|--------------|
| <b>Y-90</b>   | 2.67 d    | 934 $\beta$  | -                       | <b>12 mm</b> |
| <b>I-131</b>  | 8.02 d    | 182 $\beta$  | 364 (82%)               | <b>3 mm</b>  |
| <b>Lu-177</b> | 6.65 d    | 134 $\beta$  | 208 (10%)<br>113 (6%)   | <b>2 mm</b>  |

**cross-fire**

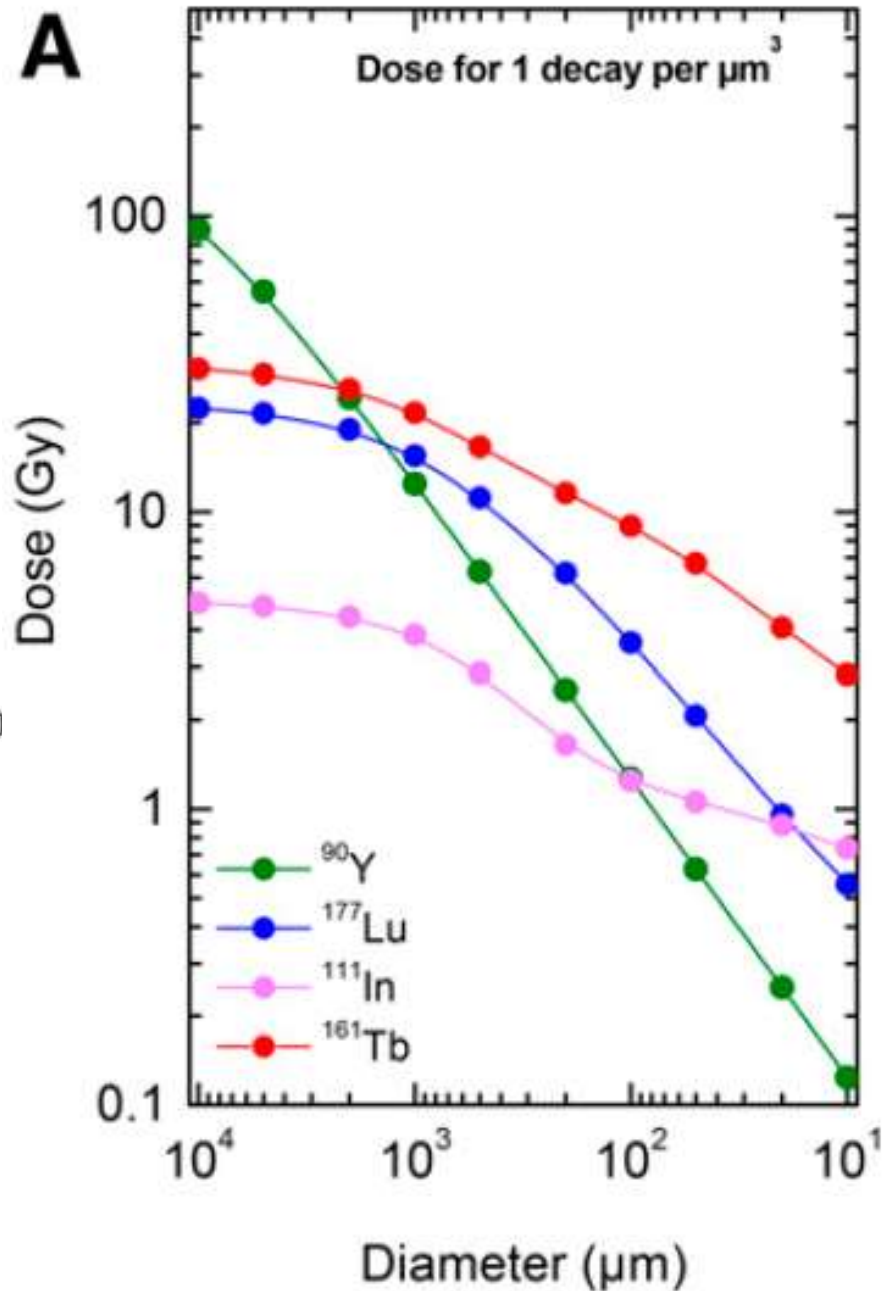
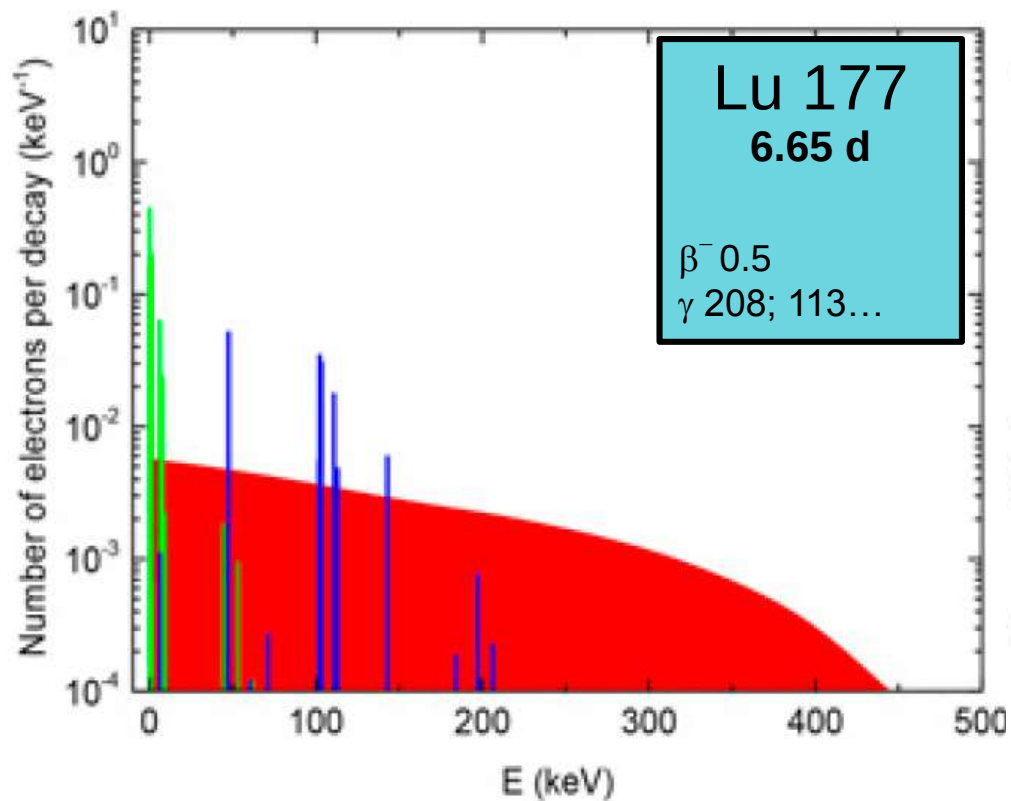
**Estab-  
lished  
isotopes**

**Emerging  
isotopes**

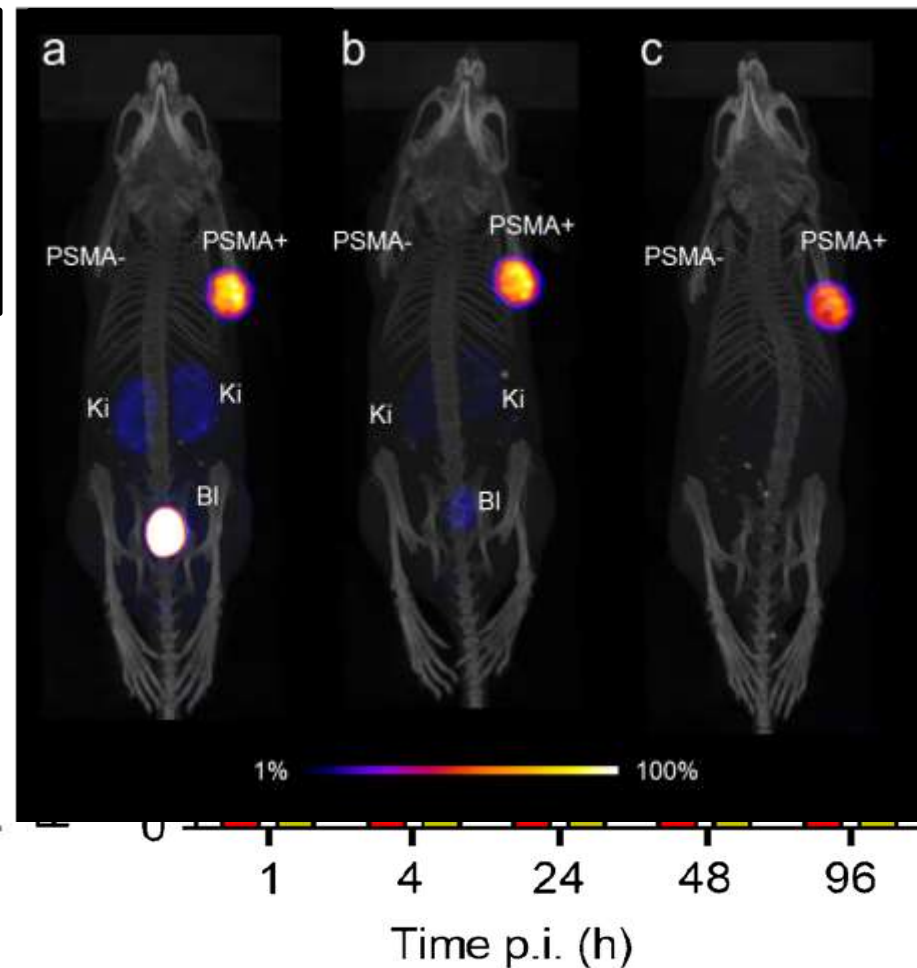
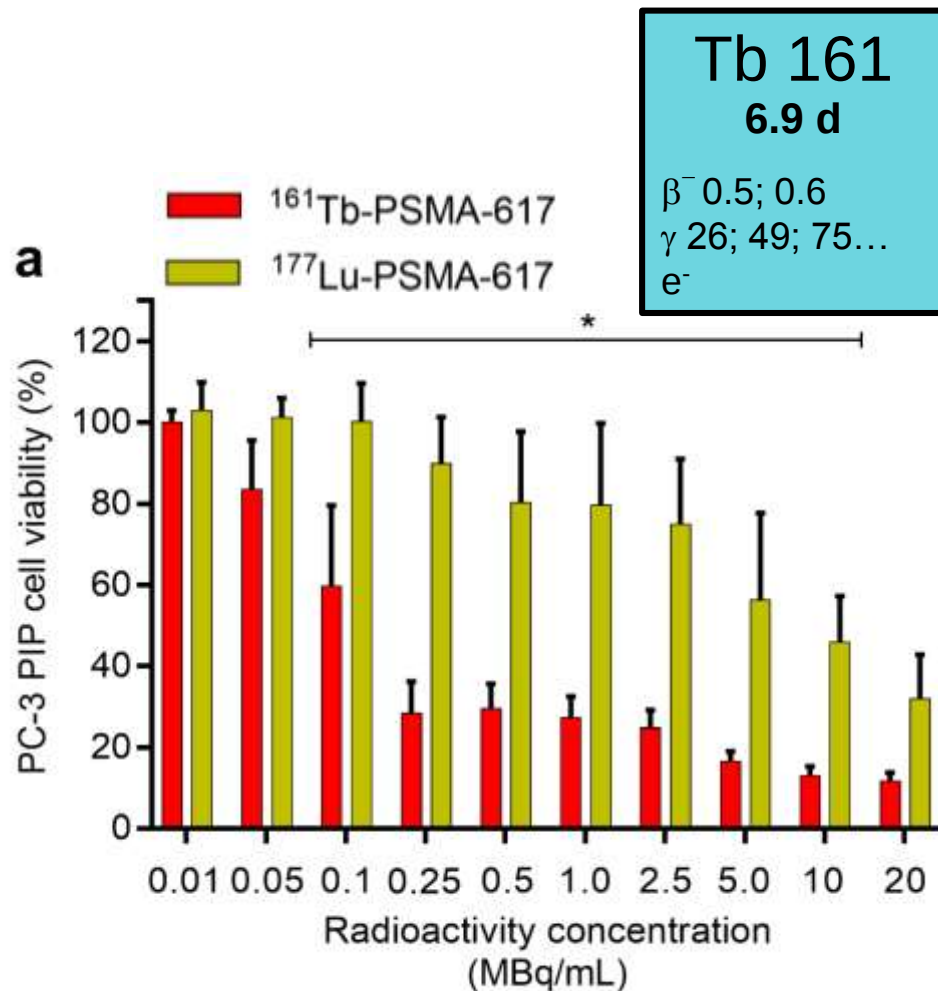
**localized**



# $^{161}\text{Tb}$ versus $^{177}\text{Lu}$

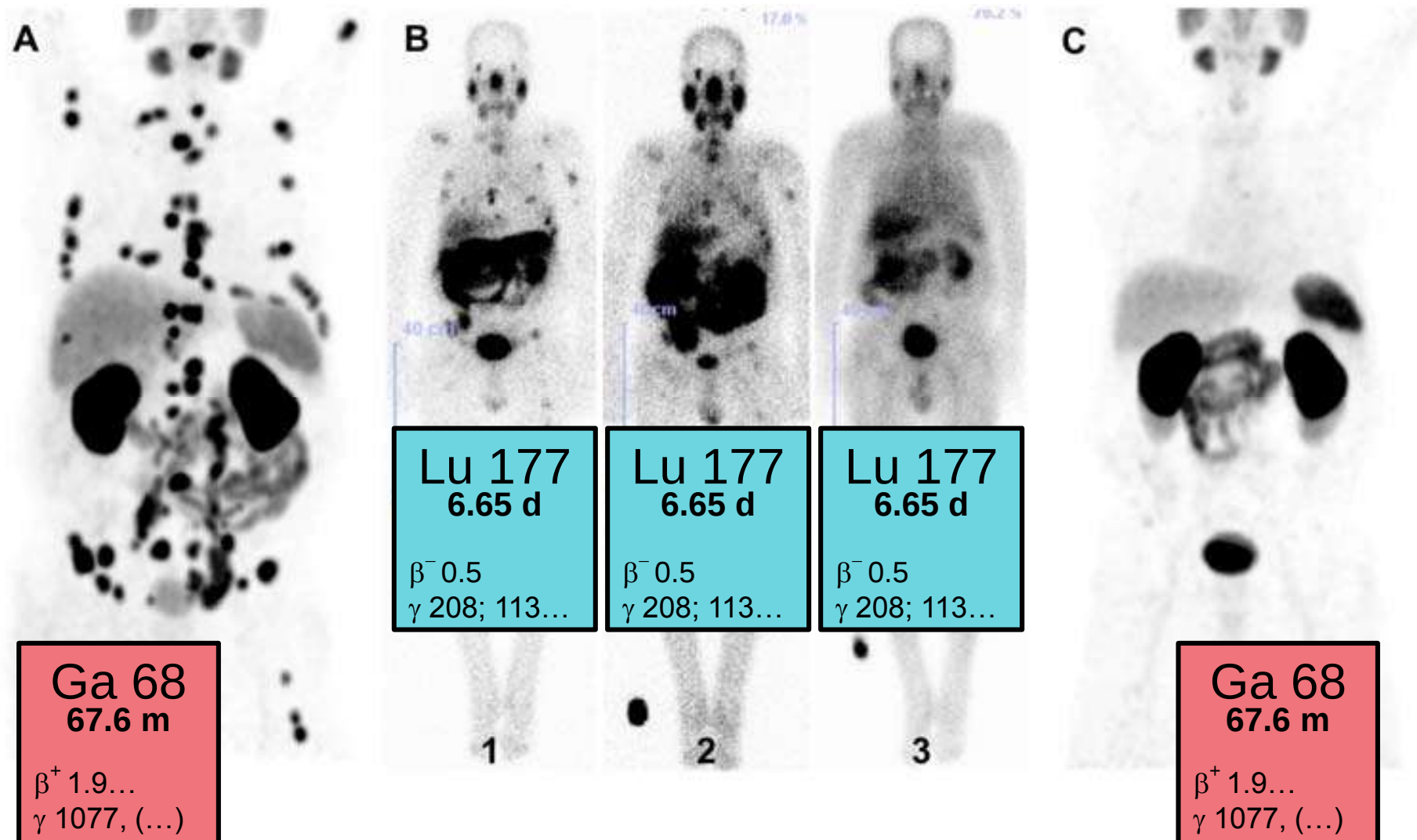


# $^{161}\text{Tb}$ -PSMA-617 vs. $^{177}\text{Lu}$ -PSMA-617

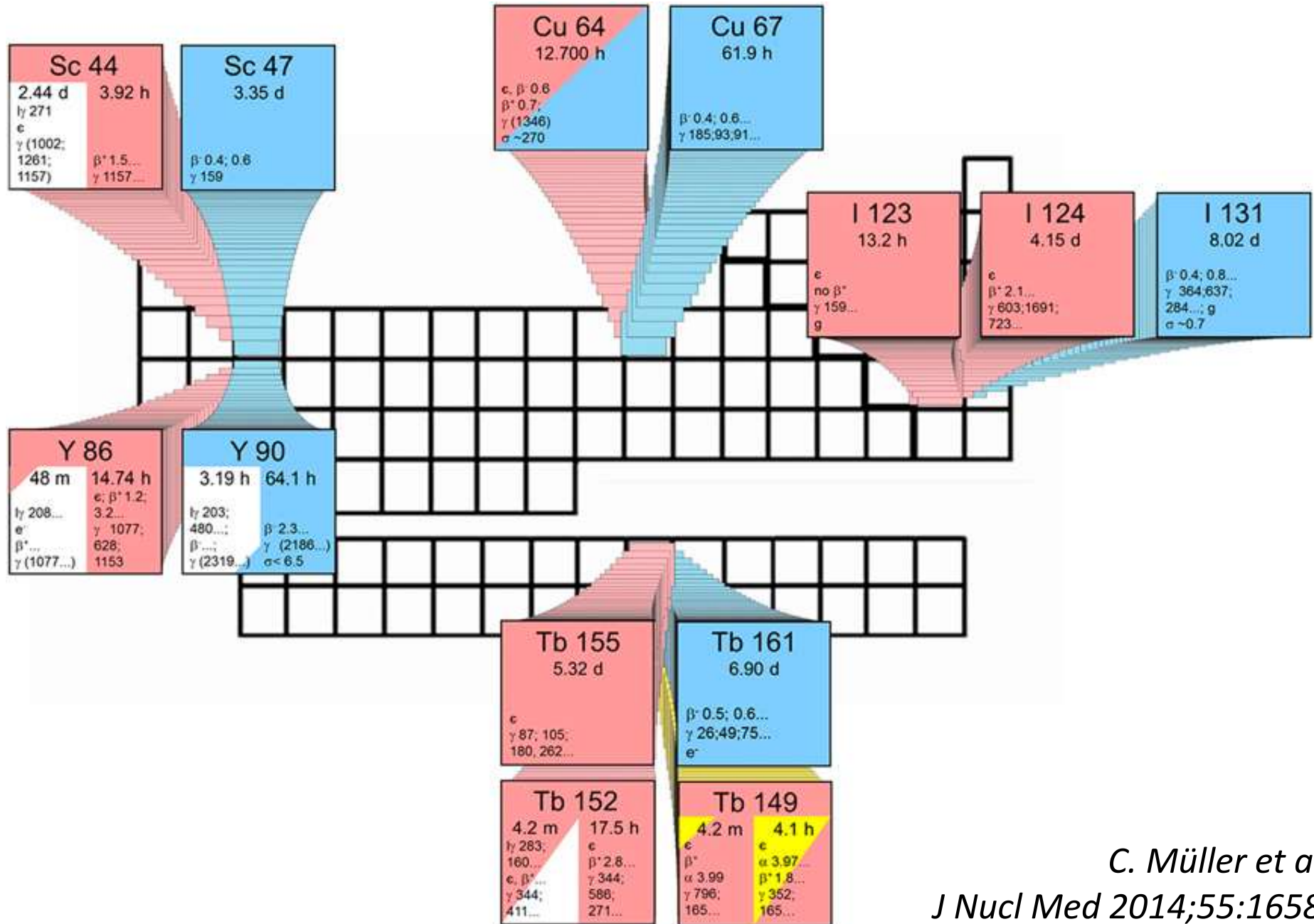


*C. Müller et al., Eur J Nucl Med Mol Imaging 2019;46:1919.*

# $^{177}\text{Lu}$ -radioligand therapy of advanced prostate cancer



# Matched pairs for theranostics

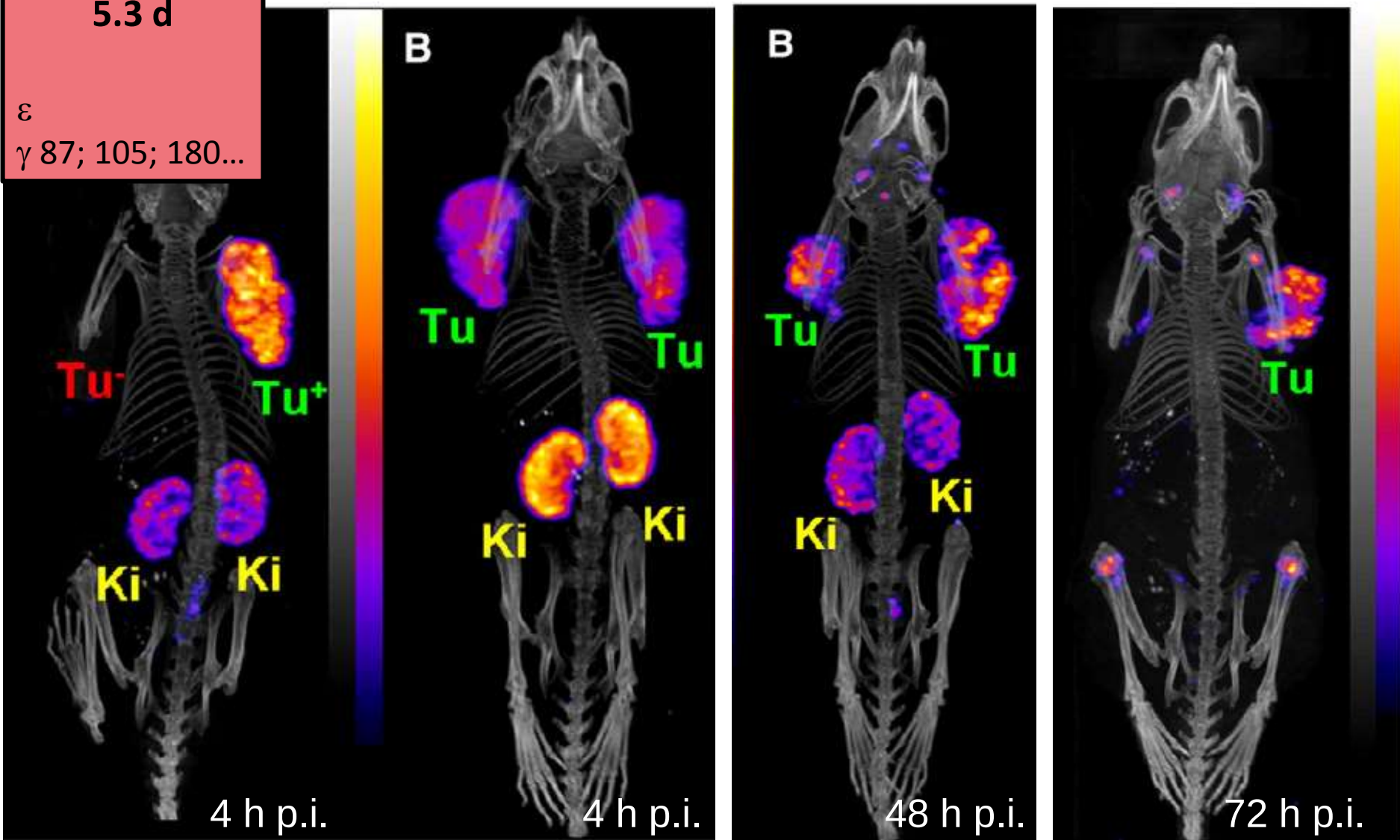


Tb 155  
5.3 d

$\varepsilon$

$\gamma$  87; 105; 180...

# $^{155}\text{Tb}$ for SPECT



minigastrin  
A431 tumor

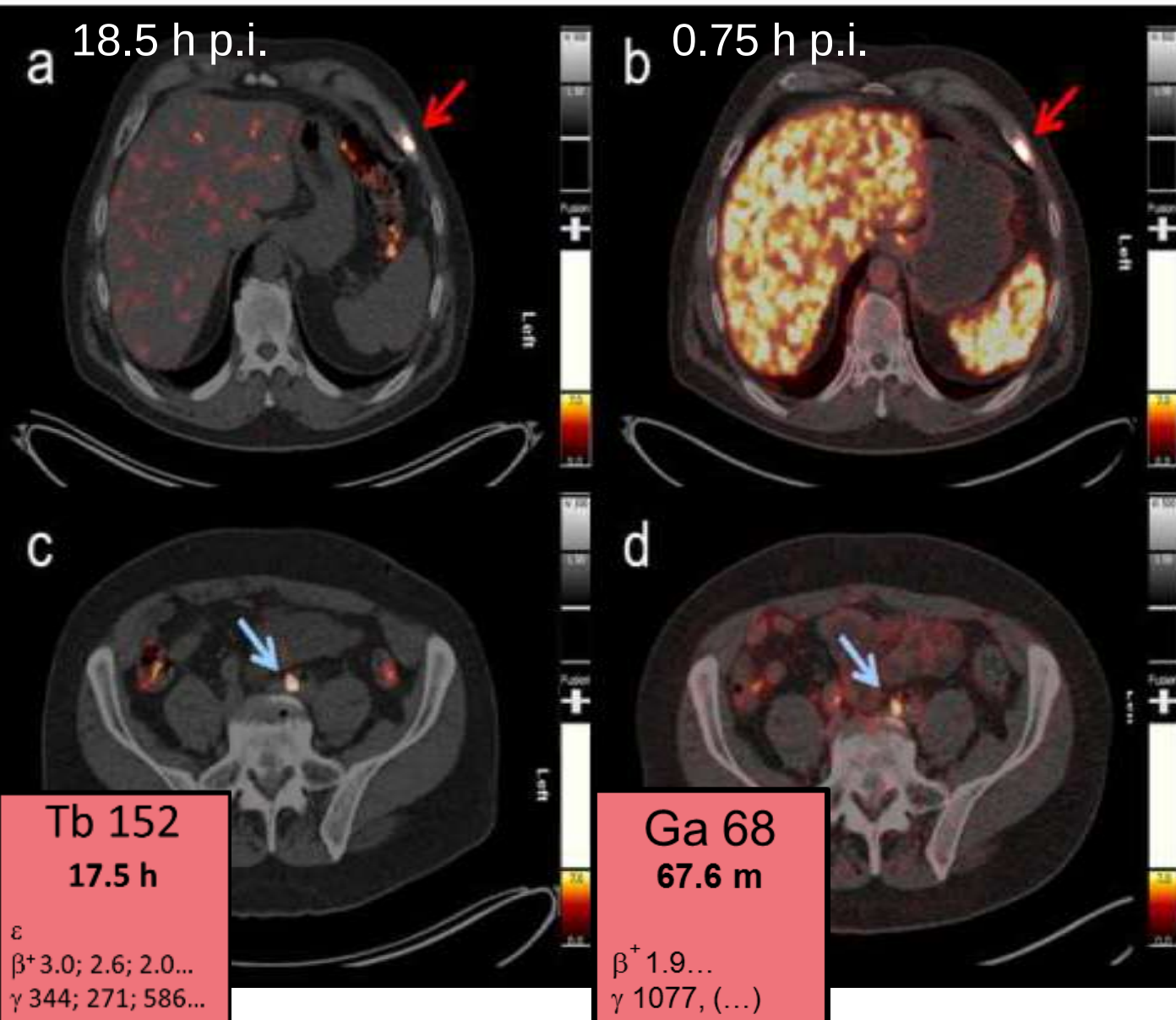
DOTATATE  
A431 tumor

cm09  
IGROV-1 tumor

chCE7  
SKOV-3ip tumor

*C. Müller et al. Nucl Med Biol 2014;41:e58.*

# First-in-human study with $^{152}\text{Tb}$ -PSMA-617



Zentralklinik Bad Berka

PAUL SCHERRER INSTITUT  
**PSI**

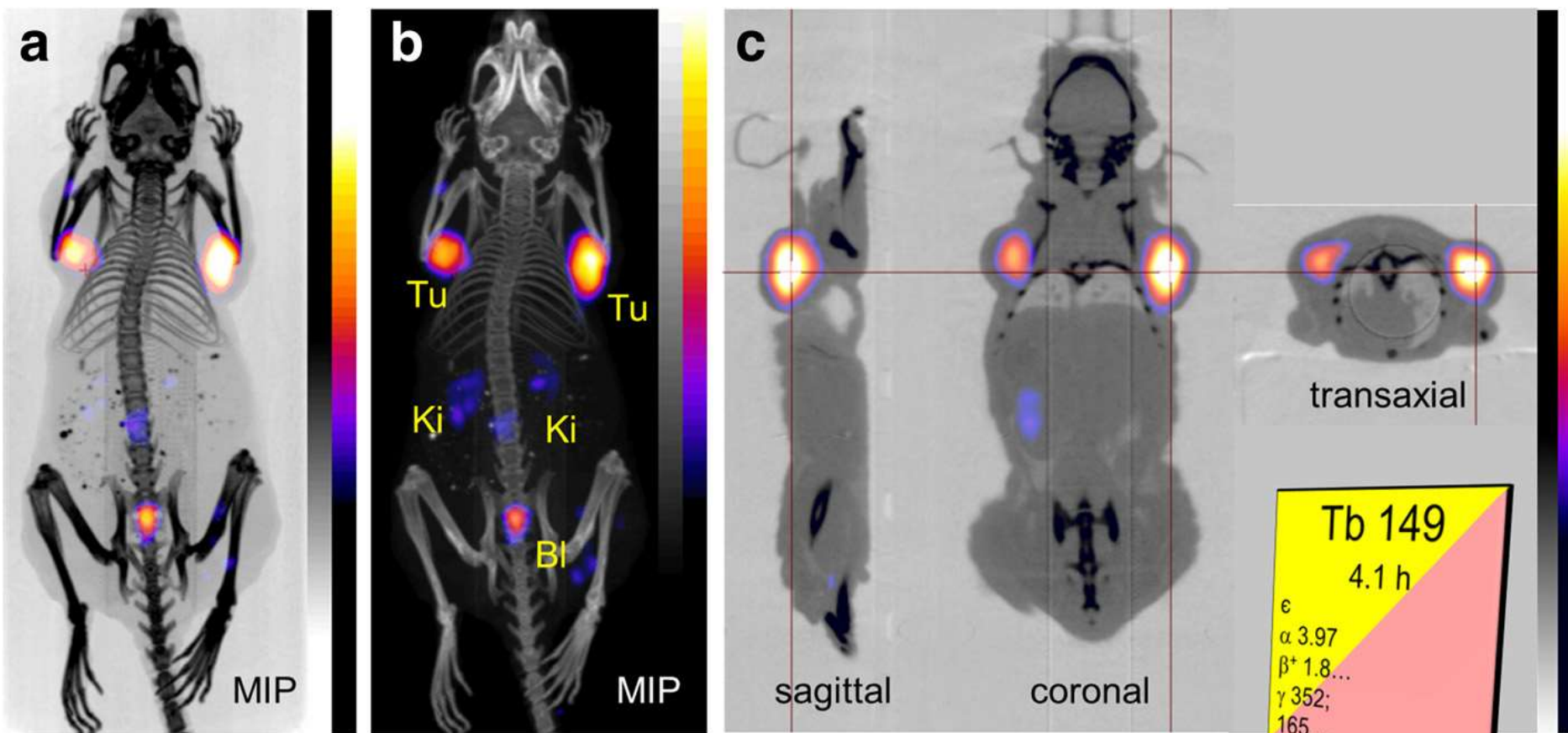
**ETH** zürich

**ISOLDE**

**ILL**  
NEUTRONS  
FOR SOCIETY

**ENSAR2**

# Alpha-PET with $^{149}\text{Tb}$



7 MBq  $^{149}\text{Tb}$ -DOTANOC 2 h p.i.

ISOLDE

PAUL SCHERRER INSTITUT

PSI

ETH zürich

NEUTRONS  
FOR SOCIETY

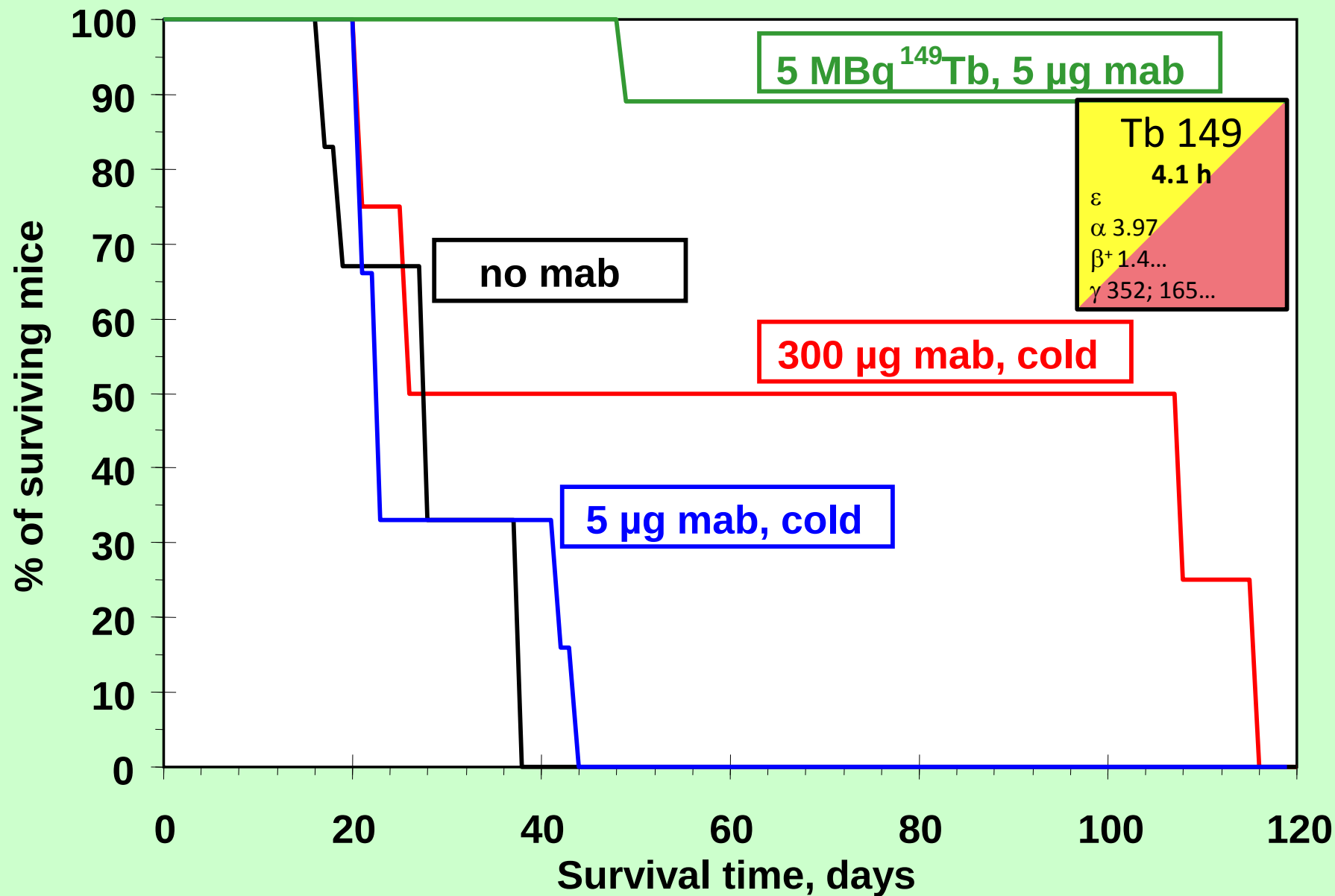
$u^b$

UNIVERSITÄT  
BERN

ENSAR

C. Müller et al. EJNMMI Radiopharm Chem 2016;1:5.

# $^{149}\text{Tb}$ -rituximab in leukemia mouse model



# Terbium: the Swiss knife for nuclear medicine

**Tb 155**

**5.3 d**

$\varepsilon$

$\gamma$  87; 105; 180...

$e^-$

**Tb 152**

**17.5 h**

$\varepsilon$

$\beta^+$  3.0; 2.6; 2.0...

$\gamma$  344; 271; 586...

**Tb 161**

**6.9 d**

$\beta^-$  0.5; 0.6

$\gamma$  26; 49; 75...

$e^-$

**Tb 149**

**4.1 h**

$\varepsilon$

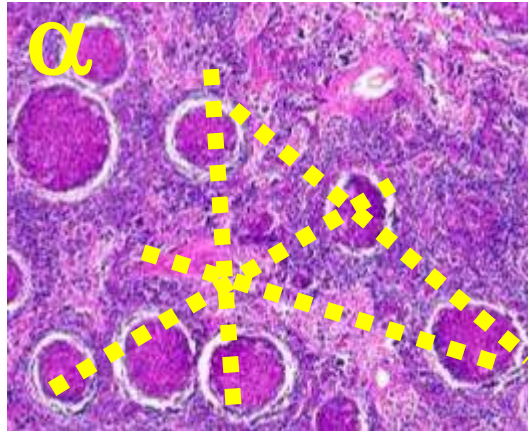
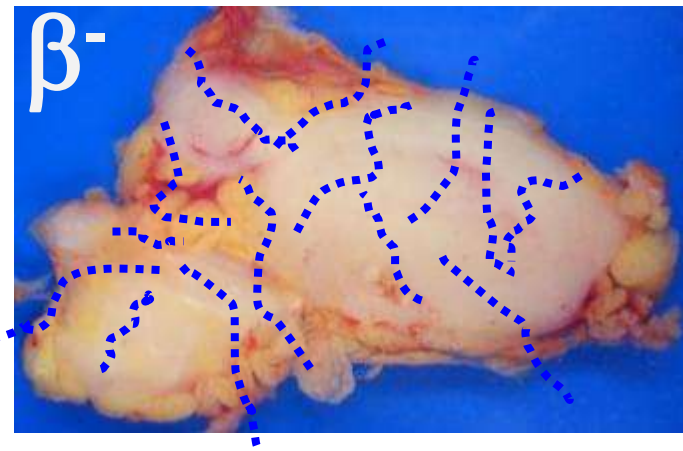
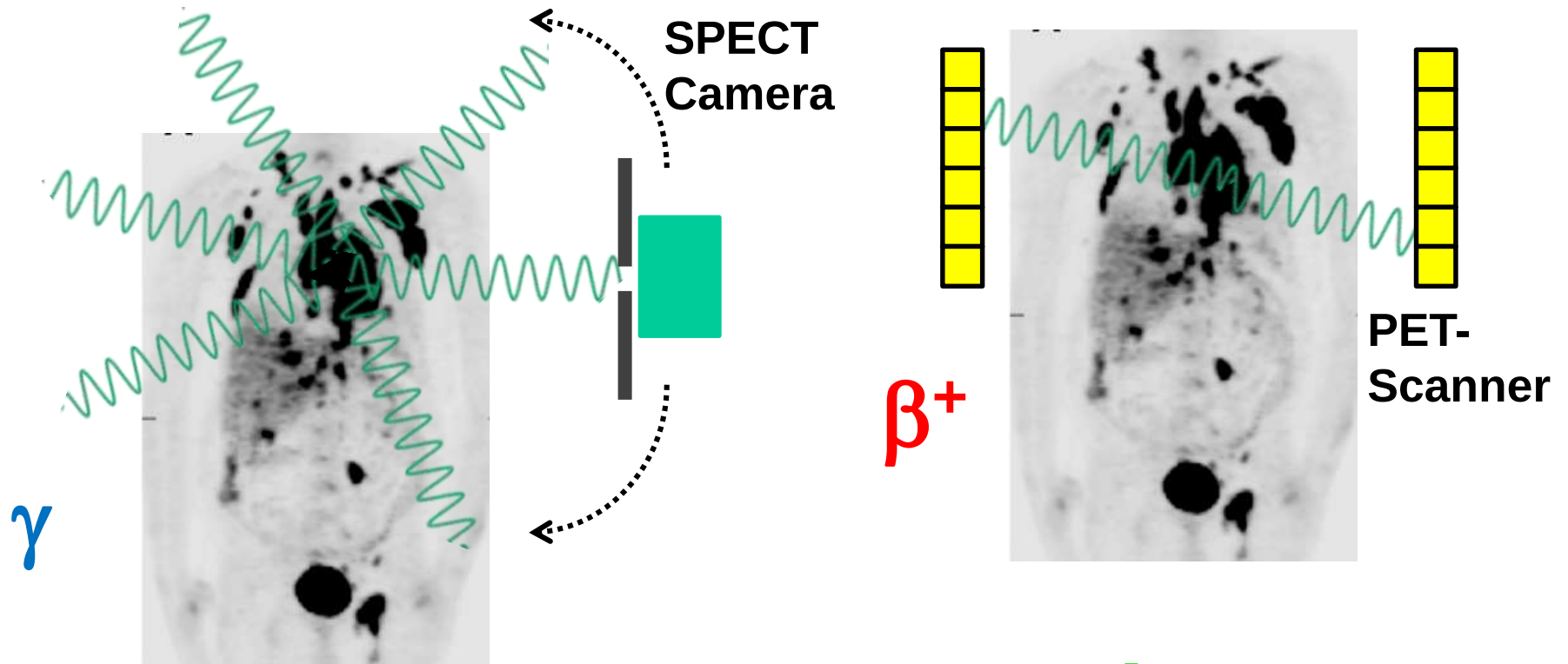
$\alpha$  3.97

$\beta^+$  1.4...

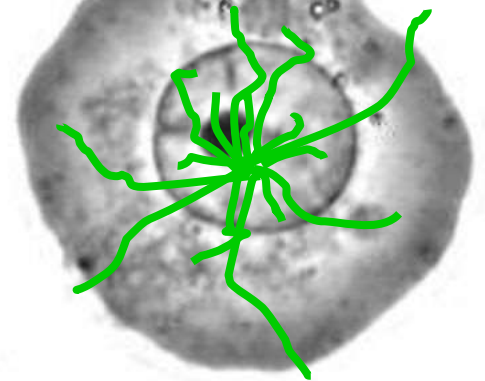
$\gamma$  352; 165...



# The Nuclear Medicine Alphabet

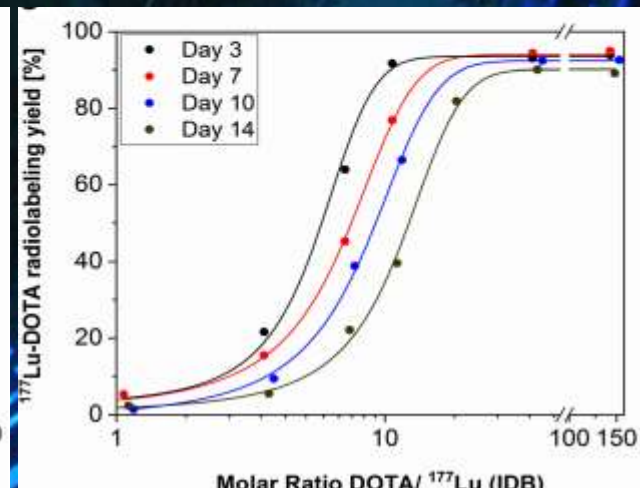
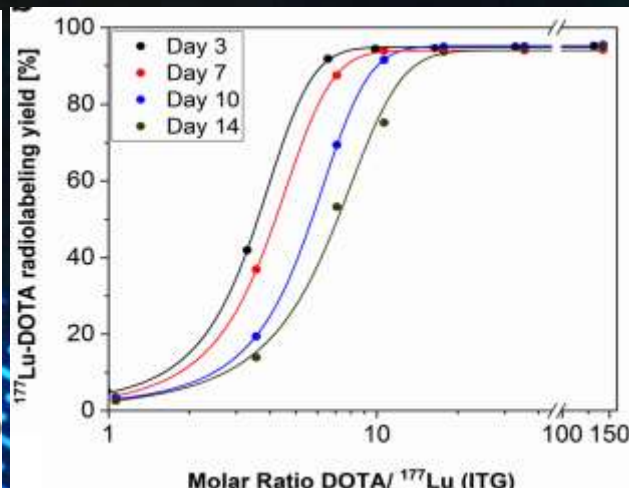
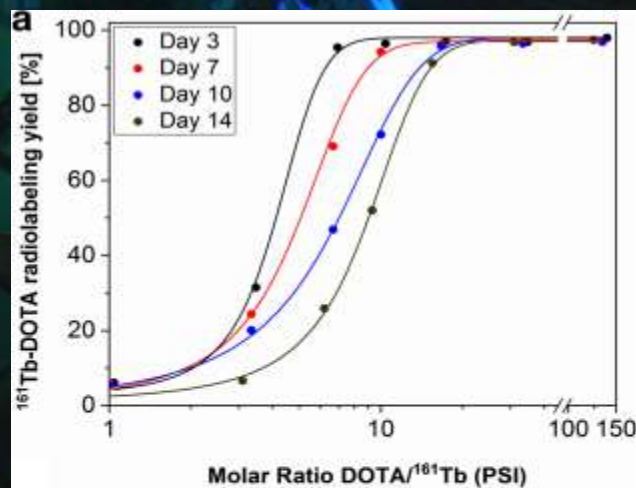
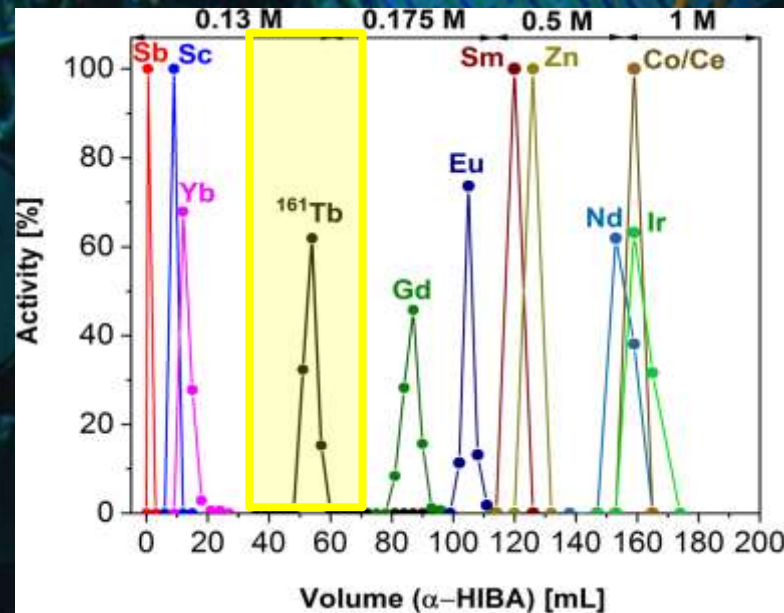


Auger- $e^-$



# Production of non-carrier-added $^{161}\text{Tb}$

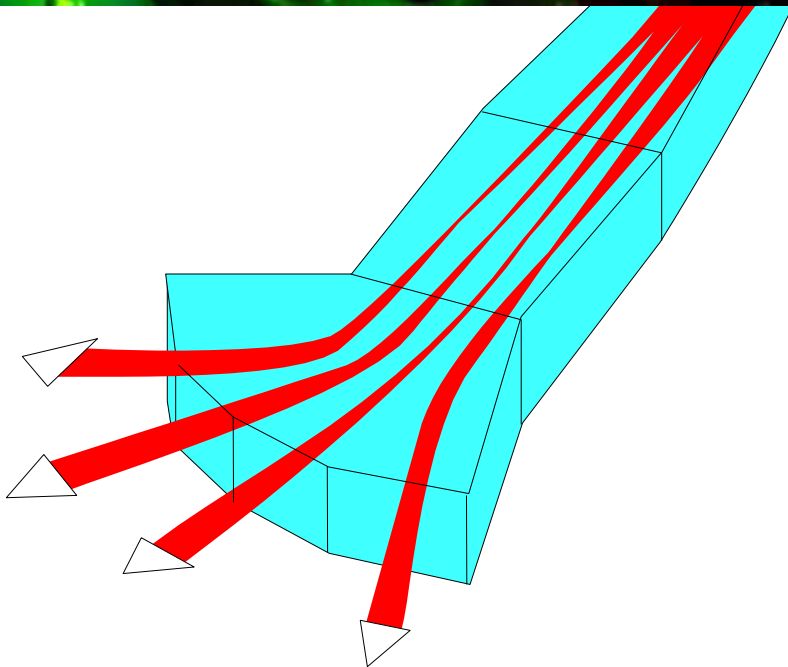
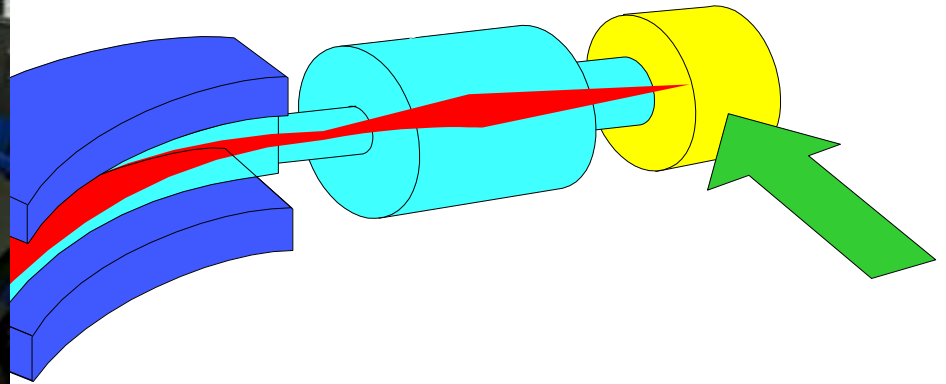
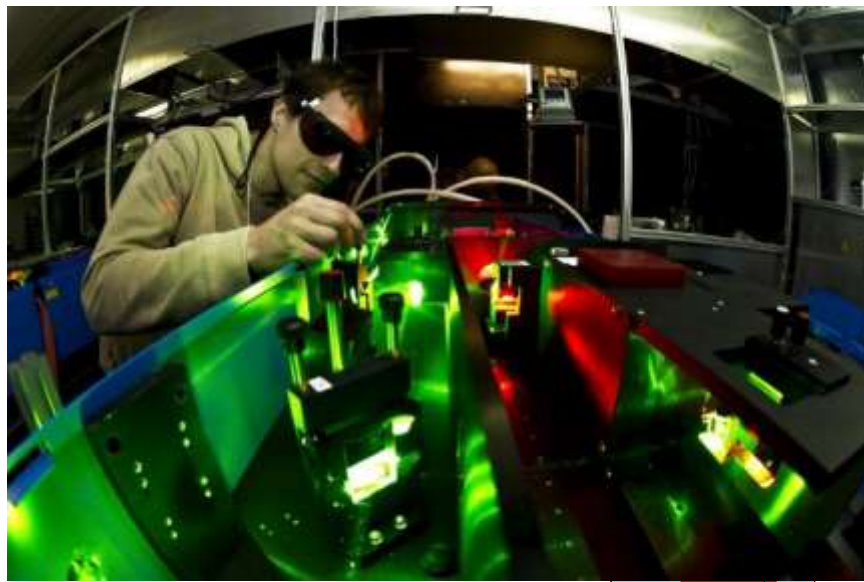
|                                                               |                                                                                           |                                                                                   |                                                                                             |                                                                           |
|---------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Dy 160<br>2.329<br>$\sigma$ 60<br>$\sigma_n, \alpha < 0.0003$ | Dy 161<br>18.889<br>$\sigma$ 600<br>$\sigma_n, \alpha < 1\text{E-}6$                      | Dy 162<br>25.475<br>$\sigma$ 170                                                  | Dy 163<br>24.896<br>$\sigma$ 120<br>$\sigma_n, \alpha < 2\text{E-}5$                        | Dy 164<br>28.260<br>$\sigma$ 1610 + 1040                                  |
| Tb 159<br>100<br>$\sigma$ 23.2                                | Tb 160<br>72.3 d<br>$\beta^-$ 0.6; 1.7...<br>$\gamma$ 879; 299;<br>966...<br>$\sigma$ 570 | <b>Tb 161<br/>6.90 d</b><br>$\beta^-$ 0.5; 0...<br>$\gamma$ 26; 49; 5...<br>$e^-$ | Tb 162<br>7.76 m<br>$\beta^-$ 1.4; 2.4...<br>$\gamma$ 260; 808;<br>888...                   | Tb 163<br>19.5 m<br>$\beta^-$ 0.8; 1.3...<br>$\gamma$ 351; 390;<br>494... |
| Gd 158<br>24.84<br>$\sigma$ 2.3                               | Gd 159<br>18.48 h<br>$\beta^-$ 1.0...<br>$\gamma$ 364; 58...                              | <b>Gd 160<br/>21.86</b><br>$\sigma$ 1.5                                           | Gd 161<br>3.66 m<br>$\beta^-$ 1.6; 1.7...<br>$\gamma$ 361; 315;<br>102...<br>$\sigma$ 20000 | Gd 162<br>8.2 m<br>$\beta^-$ 1.0...<br>$\gamma$ 442; 403...               |



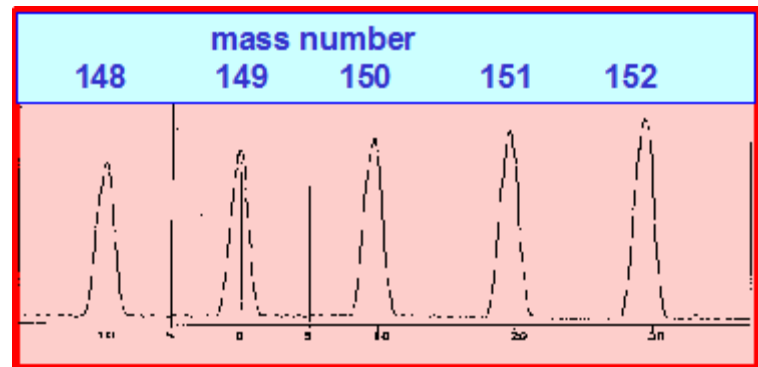
Irradiation at ILL & Necs, chemical separation at PSI

*N. Gracheva et al., EJNMMI Radiopharm Chem 2019;4:12.*

# Production of $^{149}\text{Tb}$ , $^{152}\text{Tb}$ and $^{155}\text{Tb}$ at ISOLDE



radioactive ion beams



# Efficient parallel operation

HRS MAIN GPS MAIN  
HRS USER CENTRAL MASS  
LOW MASS  
HIGH MASS

ISOLTRAP

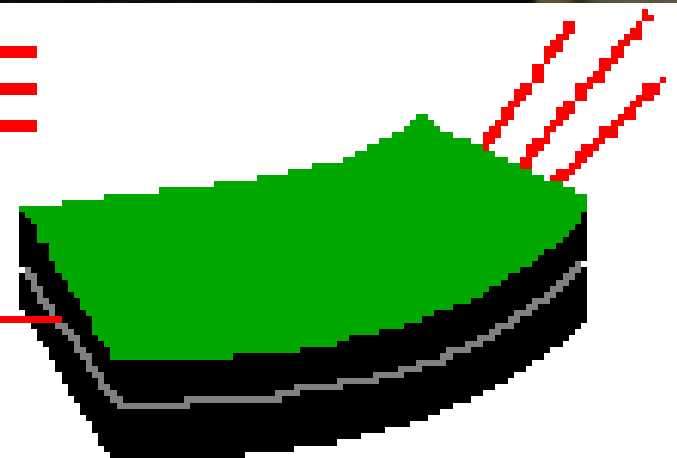
$^{152}\text{Tb}$

$^{149}\text{Tb}$

$^{155}\text{Tb}$

HRS setup

ISOLDE  
CERN



# Transport limitations (ADR, IATA)

## BASIC RADIONUCLIDE VALUES FOR UNKNOWN RADIONUCLIDES OR MIXTURES

| Radioactive contents                                                          | A <sub>1</sub><br>TBq | A <sub>2</sub><br>TBq                       | Activity<br>concentration for<br>exempt material<br>Bq/g |
|-------------------------------------------------------------------------------|-----------------------|---------------------------------------------|----------------------------------------------------------|
| Only beta or gamma<br>emitting nuclides are<br>known to be present            | 0.1<br><br>20 GBq     | 0.02<br><br><sup>161</sup> Tb               | $1 \times 10^1$                                          |
| Alpha emitting nuclides<br>but no neutron emitters<br>are known to be present | 0.2<br><br>90 MBq     | $9 \times 10^{-5}$<br><br><sup>149</sup> Tb | $1 \times 10^{-1}$                                       |



| Terbium (65) |                    | A <sub>2</sub> (TBq) |
|--------------|--------------------|----------------------|
| Tb-149       | $8 \times 10^{-1}$ | $8 \times 10^{-1}$   |
| Tb-157       | $4 \times 10^1$    | $4 \times 10^1$      |
| Tb-158       | $1 \times 10^0$    | $1 \times 10^0$      |
| Tb-160       | $1 \times 10^0$    | $6 \times 10^{-1}$   |
| Tb-161       | $3 \times 10^1$    | $7 \times 10^{-1}$   |

2018 Edition

Specific Safety Requirements

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No. SSR-6 (Rev. 1)

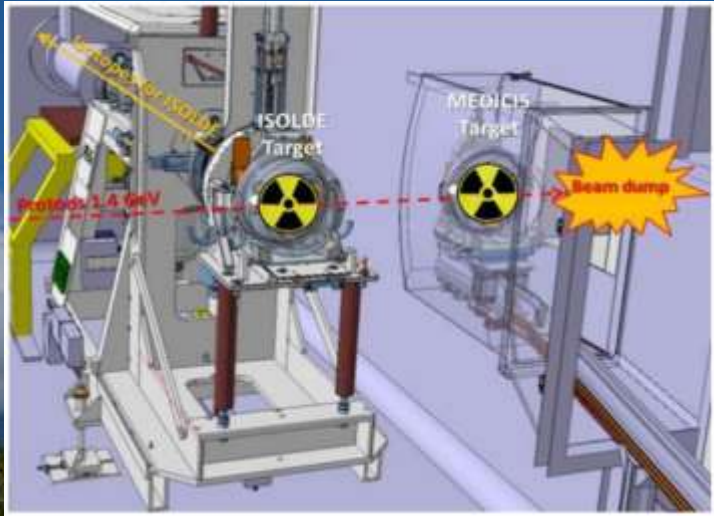


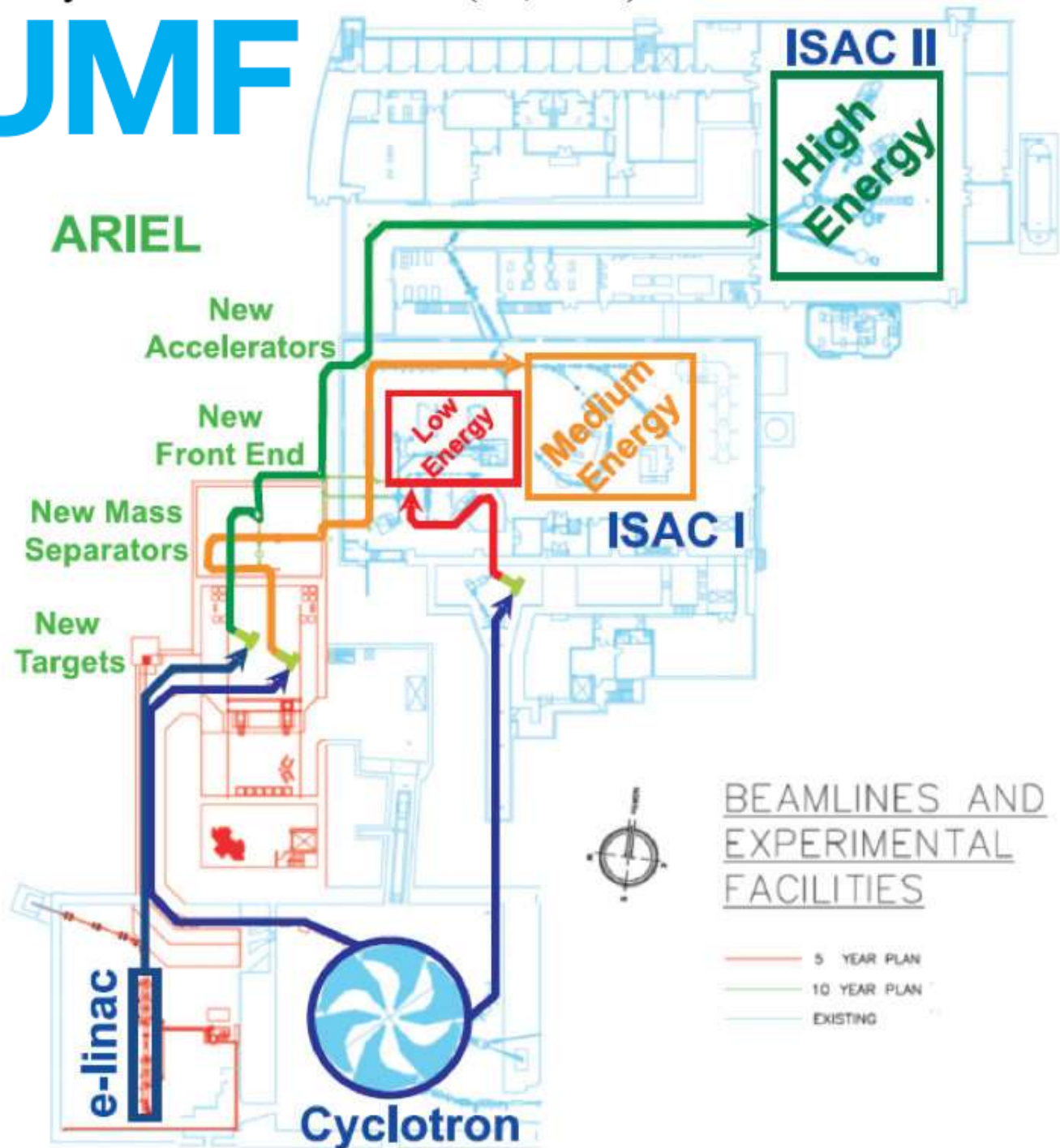
**IAEA**

International Atomic Energy Agency

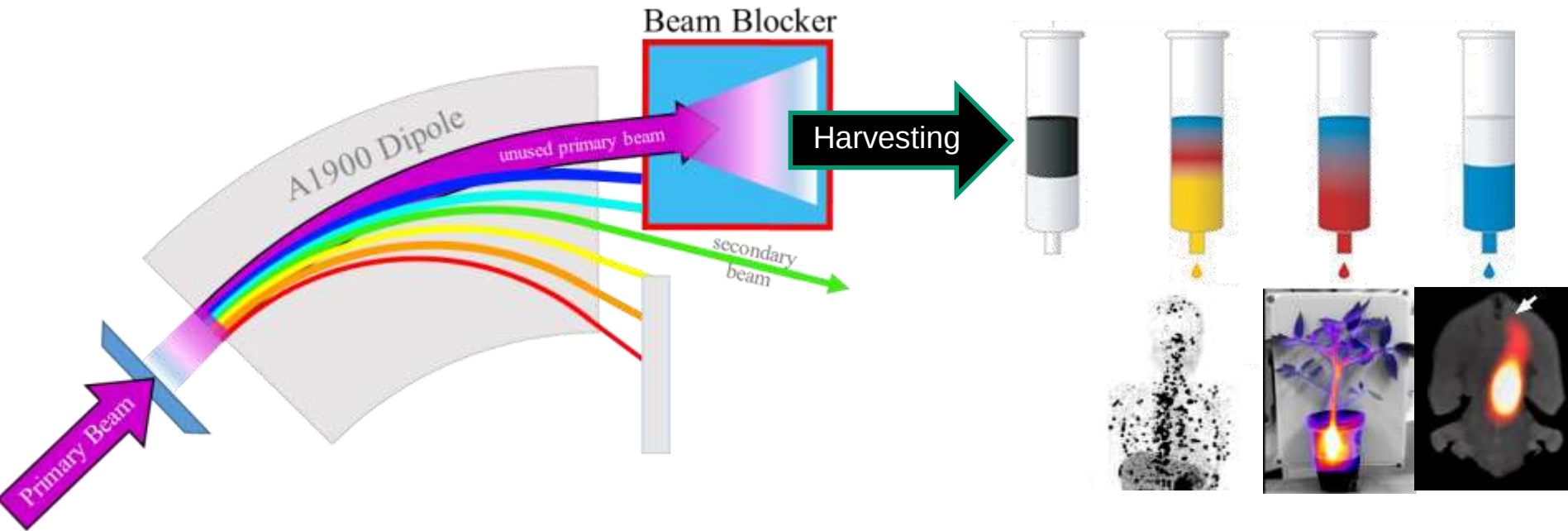


a very useful beam dump !



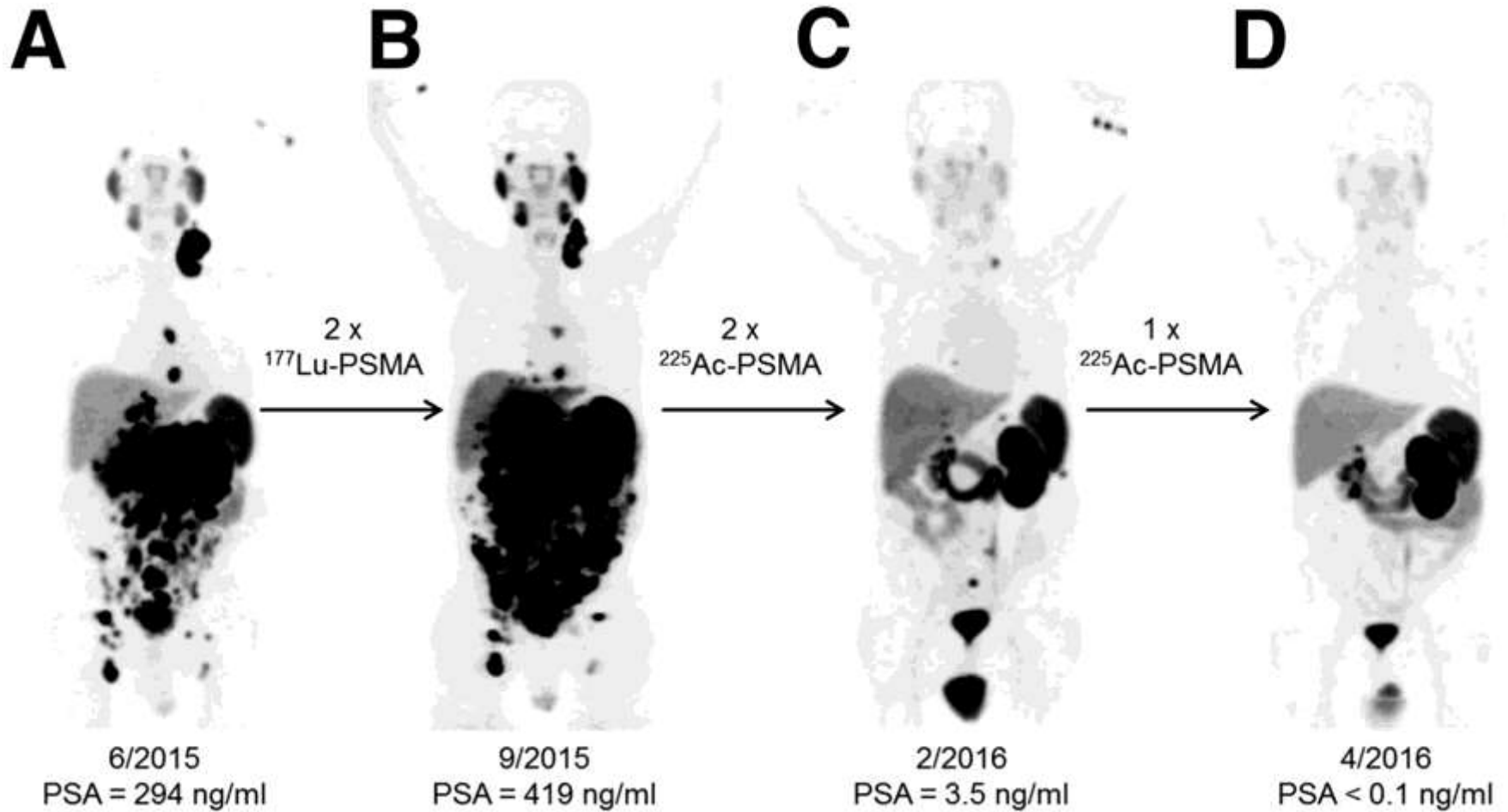


# Harvesting isotopes at FRIB



*courtesy: Greg Severin (MSU)*

# Targeted therapy with $^{225}\text{Ac}$



*Clemens Kratochwil et al. J Nucl Med 2016;57:1941.*

# Isotopes for targeted alpha therapy

|      |                   |                               |                          |                   |                        |                        |                           |                   |                   |                  |                         |                   |                          |                  |
|------|-------------------|-------------------------------|--------------------------|-------------------|------------------------|------------------------|---------------------------|-------------------|-------------------|------------------|-------------------------|-------------------|--------------------------|------------------|
| 12 s | Ac 213<br>0.80 s  | Ac 214<br>8.2 s               | Ac 215<br>0.17 s         | Ac 216<br>0.44 ms | Ac 217<br>0.74 $\mu$ s | Ac 218<br>1.1 $\mu$ s  | Ac 219<br>11.8 $\mu$ s    | Ac 220<br>26 ms   | Ac 221<br>52 ms   | Ac 222<br>5.0 s  | Ac 223<br>2.10 m        | Ac 224<br>2.9 h   | <b>Ac 225<br/>10.0 d</b> | Ac 226<br>29 h   |
| 11 s | Ra 212<br>13.0 s  | Ra 213<br>2.1 ms              | Ra 214<br>2.46 s         | Ra 215<br>1.67 ms | Ra 216<br>2.0 ns       | Ra 217<br>0.18 $\mu$ s | Ra 218<br>1.6 $\mu$ s     | Ra 219<br>10 ms   | Ra 220<br>23 ms   | Ra 221<br>28 s   | Ra 222<br>38 s          | Ra 223<br>11.4 d  | Ra 224<br>3.66 d         | Ra 225<br>14.8 d |
| 10 m | Fr 211<br>3.10 m  | Fr 212<br>20.0 m              | Fr 213<br>34.6 s         | Fr 214<br>3.35 ms | Fr 215<br>0.09 $\mu$ s | Fr 216<br>0.70 $\mu$ s | Fr 217<br>16 $\mu$ s      | Fr 218<br>1.0 ms  | Fr 219<br>21 ms   | Fr 220<br>27.4 s | <b>Fr 221<br/>4.9 m</b> | Fr 222<br>14.2 m  | Fr 223<br>21.8 m         | Fr 224<br>3.3 m  |
| 09 m | Rn 210<br>2.4 h   | Rn 211<br>14.6 h              | Rn 212<br>24 m           | Rn 213<br>19.5 ms | Rn 214<br>6.3 ns       | Rn 215<br>2.3 $\mu$ s  | Rn 216<br>45 $\mu$ s      | Rn 217<br>0.54 ms | Rn 218<br>35 ms   | Rn 219<br>3.9 s  | Rn 220<br>55.6 s        | Rn 221<br>25 m    | Rn 222<br>3.825 d        | Rn 223<br>23.2 m |
| 08 h | At 209<br>5.4 h   | At 210<br>8.3 h               | <b>At 211<br/>7.22 h</b> | At 212<br>119 ms  | At 213<br>0.11 $\mu$ s | At 214<br>0.76 $\mu$ s | At 215<br>0.1 ms          | At 216<br>0.3 ms  | At 217<br>32.3 ms | At 218<br>~2 s   | At 219<br>0.9 m         | At 220<br>3.71 m  | At 221<br>2.3 m          | At 222<br>54 s   |
| 07 h | Po 208<br>2.898 a | Po 209<br>102 a               | Po 210<br>138.38 d       | Po 211<br>0.316 s | Po 212<br>45.1 s       | Po 213<br>4.2 $\mu$ s  | Po 214<br>164 $\mu$ s     | Po 215<br>1.78 s  | Po 216<br>0.15 s  | Po 217<br>1.53 s | Po 218<br>3.05 m        | Po 219<br>>300 ns | Po 220<br>>300 ns        |                  |
| 06 d | Bi 207<br>31.55 a | Bi 208<br>3.68 $\cdot 10^8$ a | Bi 209<br>100            | Bi 210<br>5.013 d | Bi 211<br>2.17 a       | Bi 212<br>60.60 min    | <b>Bi 213<br/>45.59 m</b> | Bi 214<br>19.9 m  | Bi 215<br>38.9 s  | Bi 216<br>3.6 m  | Bi 217<br>98.5 s        | Bi 218<br>33 s    |                          |                  |
| 05 d | Pb 206<br>24.1    | Pb 207<br>22.1                | Pb 208<br>52.4           | Pb 209<br>3.253 h | Pb 210<br>22.3 a       | Pb 211<br>36.1 m       | Pb 212<br>10.64 h         | Pb 213<br>10.2 m  | Pb 214<br>26.8 m  |                  |                         |                   |                          |                  |
| 04 a | Tl 205<br>70.48   | Tl 206<br>3.7 m               | Tl 207<br>1.33 s         | Tl 208<br>3.053 m | Tl 209<br>2.16 m       | Tl 210<br>1.30 m       | Tl 211<br>>300 ns         | Tl 212<br>>300 ns |                   |                  |                         |                   |                          |                  |

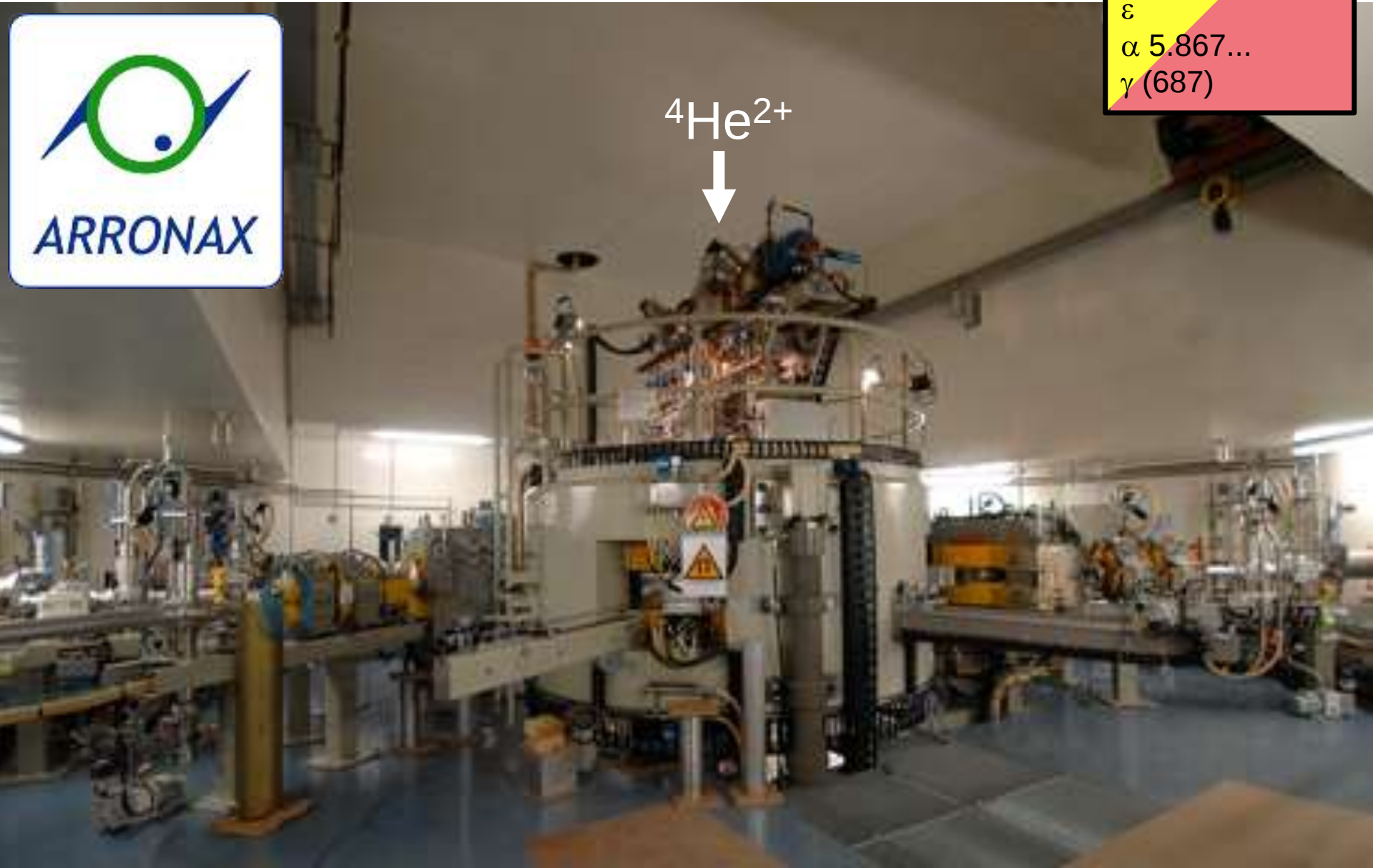
# $^{211}\text{At}$ production at ARRONAX

$^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$  with 28-29 MeV  $\alpha$  beams

At 211  
7.2 h

$\varepsilon$   
 $\alpha$  5.867...  
 $\gamma$  (687)

$^4\text{He}^{2+}$   
↓



# $^{211}\text{At}$ production at SPIRAL2

$^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$  with 28-29 MeV  $\alpha$  beams

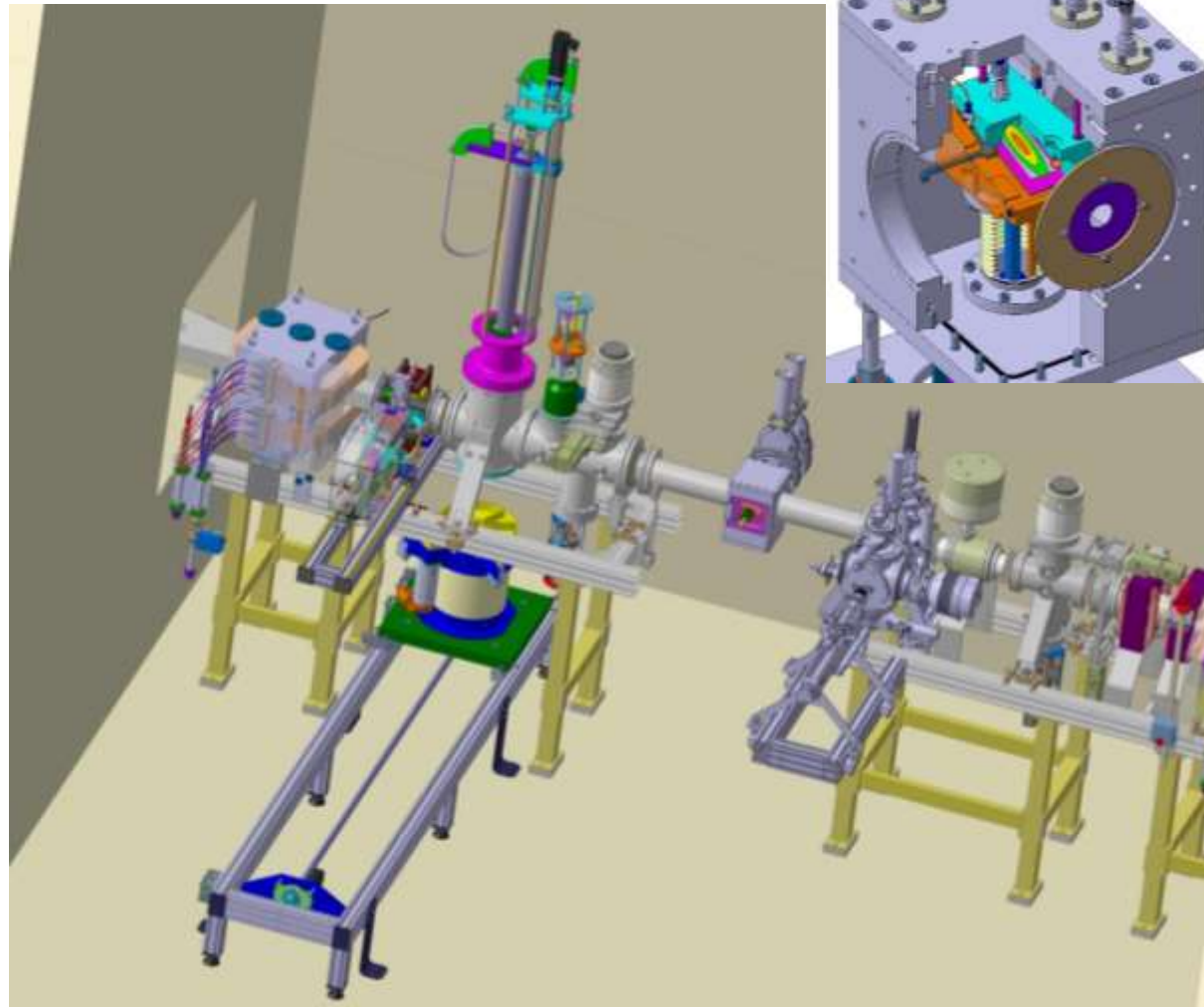
At 211  
7.2 h

$\varepsilon$   
 $\alpha$  5.867...  
 $\gamma$  (687)

1. Use of 1 kW station ( $\approx 10$  doses in 4 h) in 2020 once alpha beams are available at SPIRAL2.

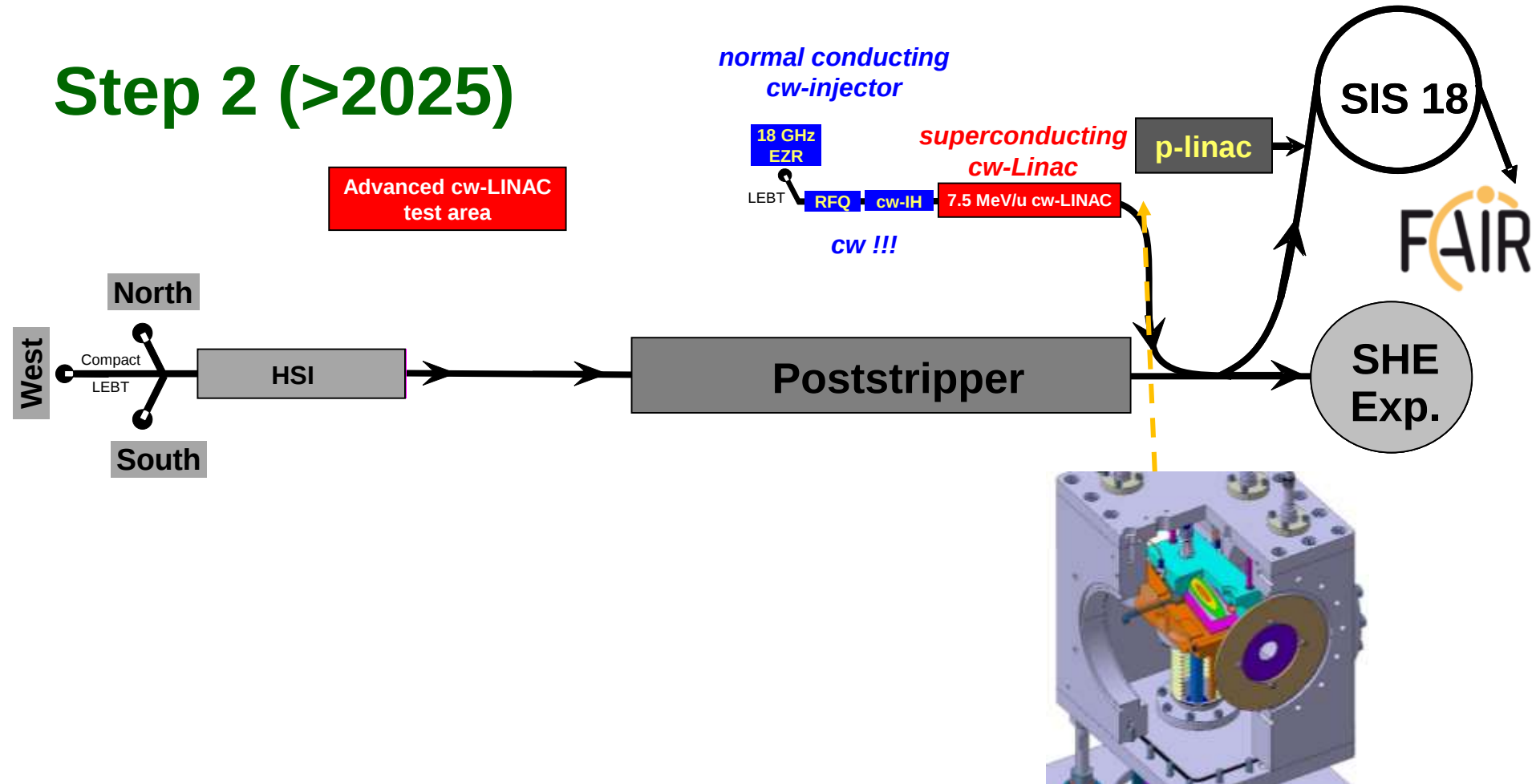
2. Design of a 10 kW rotating solid target ( $\approx 100$  doses in 4 h).

3. Design of a liquid Bi target for continuous  $^{211}\text{At}$  or  $^{211}\text{Rn}$  extraction.



# Future superconducting cw-Linac at GSI

## Step 2 (>2025)



W. Barth, "Acceleration of Heavy Ion Beams with a Superconducting cw-Linac at GSI",  
GSI-Acc. Seminar, 11 April 2019

# Radionuclides for Radioligand Therapy

| Radio-nuclide | Half-life | E mean (keV)                      | E $\gamma$ (B.R.) (keV) | Range                                        |
|---------------|-----------|-----------------------------------|-------------------------|----------------------------------------------|
| <b>Y-90</b>   | 2.67 d    | 934 $\beta$                       | -                       | <b>12 mm</b>                                 |
| <b>I-131</b>  | 8.02 d    | 182 $\beta$                       | 364 (82%)               | <b>3 mm</b>                                  |
| <b>Lu-177</b> | 6.65 d    | 134 $\beta$                       | 208 (10%)<br>113 (6%)   | <b>2 mm</b>                                  |
| <b>Tb-161</b> | 6.96 d    | 154 $\beta$<br>5, 17, 40 e $^{-}$ | 75 (10%)                | <b>2 mm</b><br><b>1-30 <math>\mu</math>m</b> |
| <b>Tb-149</b> | 4.12 h    | 3967 $\alpha$                     | 165,...                 | <b>25 <math>\mu</math>m</b>                  |
| <b>Ge-71</b>  | 11.4 d    | 8 e $^{-}$                        | -                       | <b>1.7 <math>\mu</math>m</b>                 |
| <b>Er-165</b> | 10.3 h    | 5.3 e $^{-}$                      | -                       | <b>0.6 <math>\mu</math>m</b>                 |

**cross-fire**

**Estab-  
lished  
isotopes**

**Emerging  
isotopes**

**future  
isotopes:  
supply-  
limited!**

**localized**

**Better targeted ligands require shorter-range radiation  
⇒ need for **adequate (R&D) radioisotope supply.****

## M E M O R A N D U M

DATE: December 4, 1958

Today 30 million clinical applications per year !

TO: Addressees Below

FROM: Daniel M. Schaeffer, Head   
BNL Patent Office

SUBJECT: P-701 and P-702 - PREPARATION OF  
CARRIER-FREE MOLYBDENUM AND OF  
TECHNETIUM FROM FISSION PRODUCTS

The New York Patent Group has carefully studied the information available relative to the above-identified item. The AEC does not at present desire to prepare a patent application on this item for the following reason:

"The method of producing carrier-free molybdenum-99 from fission products is disclosed in U. S. Patent Application S.N. 732,108, Green, Powell, Samos & Tucker (BNL Pat No. 58-17). It is noted that molybdenum-99 may be separated from its radioactive daughter, technetium-99, by absorption of a solution of molybdenum-99 on alumina and subsequent elution of its daughter with .1 nitric acid. While this method is probably novel, it appears that the product will probably be used mostly for experimental purposes in the laboratory. On this basis, no further patent action is believed warranted."

believe that this attitude is significant. We are not aware of a potential market for technetium-99 great enough to encourage one to undertake the risk of patenting in hopes of successful and rewarding licensing. We would recommend against filing on the Tucker, Greene and Murrenhoff separation process."

# A great model: the US DOE Isotope Program



## Welcome to the NIDC!

The **National Isotope Development Center (NIDC)** interfaces with the isotope user community and manages the coordination of isotope production across the facilities and business operations involved in the production, sale, and distribution of isotopes. A virtual center, the NIDC is funded by the [U.S. Department of Energy Isotope Program](#) within the [Office of Nuclear Physics](#) in the [Office of Science](#).

# PRISMAS-MAP: improved access to emerging medical radioisotopes

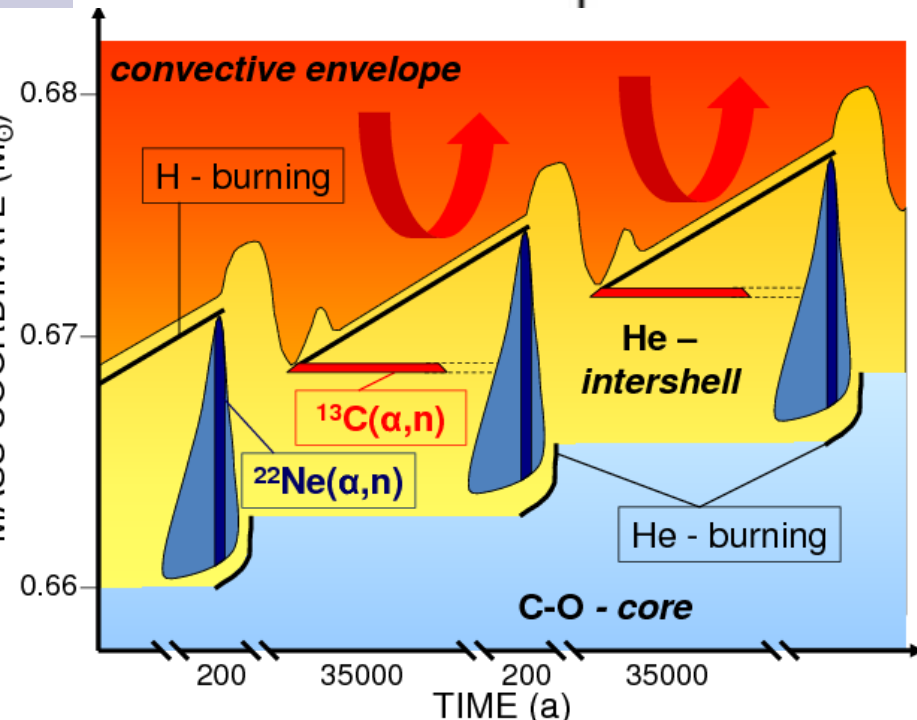
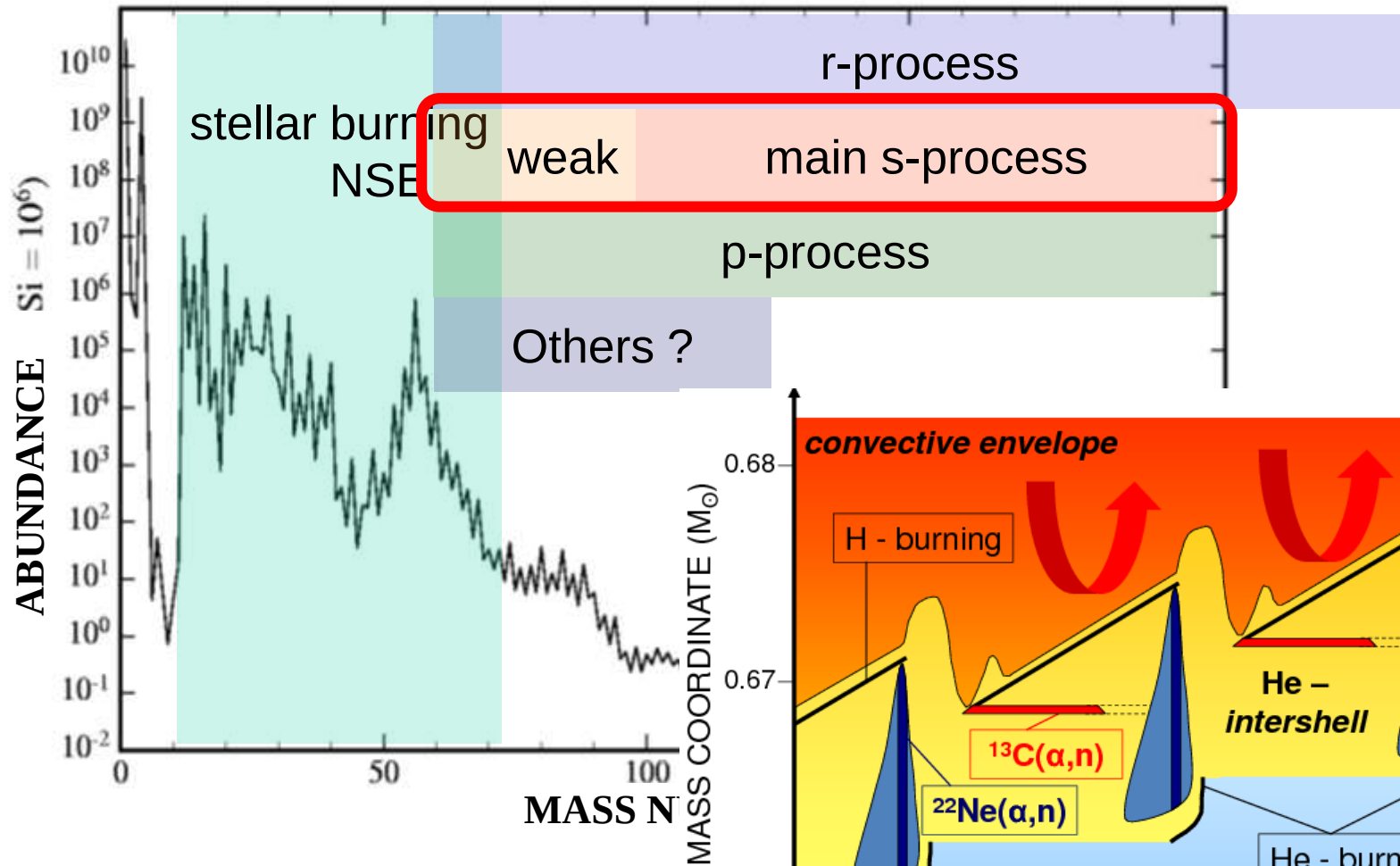


# Life, the Universe and Everything

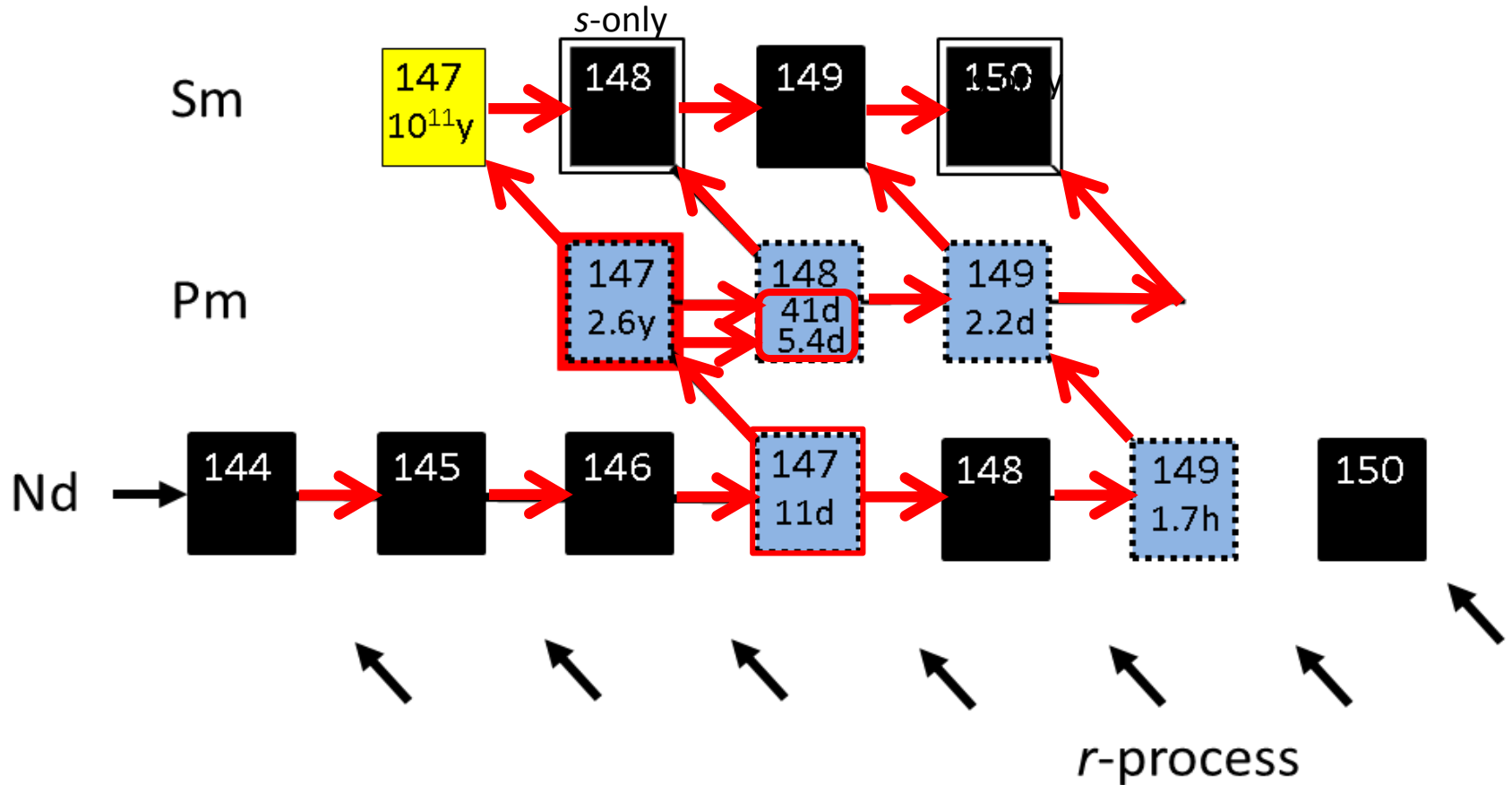


# the Universe: nucleosynthesis

solar abundance distribution

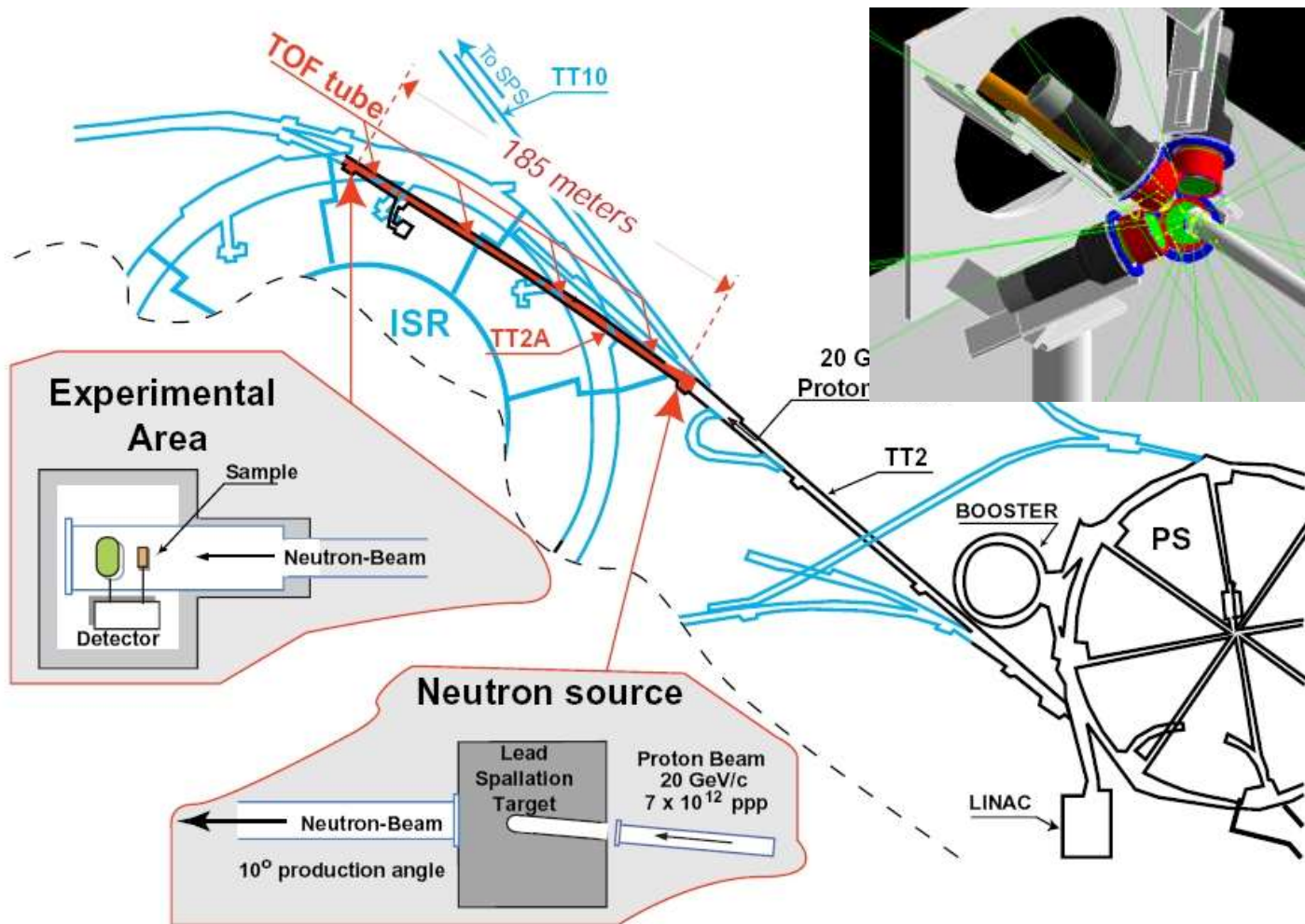


# Branching points: example at A=147/148



# Neutron capture at s-process branching points

|                                                                                                     |                                                                            |                                                                                                                |                                                                                |
|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Sm 147<br>14.99<br>$1.06 \cdot 10^{-11}$ a<br>$\alpha$ 2.235<br>$\sigma_{nuc}$ 56, $\sigma_{nuc}$ 4 | Sm 148<br>11.24<br>$7 \cdot 10^{-12}$ a<br>$\alpha$ 1.96<br>$\sigma$ 2.4   | Sm 149<br>13.82<br>$\alpha$ 40100<br>$\sigma_{nuc}$ 0.031                                                      | Sm 150<br>7.38<br>$\alpha$ 102                                                 |
| Pm 146<br>5.53 a<br>$\alpha$ 5, $\sigma$ 0.8<br>454, 747<br>$\sigma$ 6400                           | Pm 147<br>2.62 a<br>$\beta^-$ 0.2<br>$\gamma$ (121...)<br>$\sigma$ 84 + 36 | Pm 148<br>5.37 a<br>$\beta^-$ 2.3<br>$\gamma$ 980, 1489<br>$\sigma$ 178, 147<br>$\sigma$ 1990<br>$\alpha$ 1000 | Pm 149<br>53.1 h<br>$\beta^-$ 1.1<br>$\gamma$ 286<br>$\sigma$ 1400             |
| Nd 145<br>8.293<br>$\alpha$ 47<br>$\sigma_{nuc}$ 12E-5                                              | Nd 146<br>17.189<br>$\alpha$ 1.5                                           | Nd 147<br>10.98 d<br>$\beta^-$ 0.9<br>$\sigma$ 2.4                                                             | Nd 148<br>5.756<br>$\alpha$ 2.4                                                |
| Yb 170<br>2.982<br>$\alpha$ 12<br>$\sigma_{nuc}$ < 1.0E-5                                           | Yb 171<br>14.09<br>$\alpha$ 53<br>$\sigma_{nuc}$ < 1.5E-5                  | Yb 172<br>21.68<br>$\alpha$ 1.3<br>$\sigma_{nuc}$ < 1E-6                                                       | Yb 173<br>16.103<br>$\alpha$ 16<br>$\sigma_{nuc}$ < 1E-6                       |
| Tm 169<br>100<br>$\alpha$ 108                                                                       | Tm 170<br>127.8 d<br>$\beta^-$ 1.0<br>$\gamma$ 84...<br>$\sigma$ 92        | Tm 171<br>1.92 a<br>$\beta^-$ 0.1<br>$\gamma$ (107...)<br>$\sigma$ 15                                          | Tm 172<br>63.6 h<br>$\beta^-$ 0.9<br>$\gamma$ 71, 1094, 1367, 1530, 1466, 1809 |
| Er 168<br>26.978<br>$\alpha$ 2.3<br>$\sigma_{nuc}$ 9E-5                                             | Er 169<br>9.40 d<br>$\beta^-$ 0.3...<br>$\gamma$ (110...)<br>$\sigma$ 7    | Er 170<br>14.910<br>$\alpha$ 8                                                                                 | Er 171<br>7.52 h<br>$\beta^-$ 1.5<br>$\gamma$ 206, 112                         |
| Pb 204<br>57.2 m<br>$\alpha$ 0.99, 912<br>379<br>$\sigma$ 0.04                                      | Pb 205<br>1.5 $\cdot 10^{-10}$ a<br>$\alpha$ 5                             | Pb 206<br>24.1<br>$\alpha$ 0.027                                                                               |                                                                                |
| Tl 203<br>29.52<br>$\alpha$ 11<br>$\sigma_{nuc}$ < 0                                                | Tl 204<br>3.78 a<br>$\beta^-$ 0.2<br>$\gamma$ 279                          | Tl 205<br>70.48<br>$\alpha$ 0.11                                                                               |                                                                                |
| Hg 203<br>29.60<br>$\alpha$ 4.9                                                                     | Hg 204<br>6.87<br>$\alpha$ 0.4                                             |                                                                                                                |                                                                                |



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BARCELONATECH



PAUL SCHERRER INSTITUT  
PSI

NEUTRONS  
FOR SOCIETY

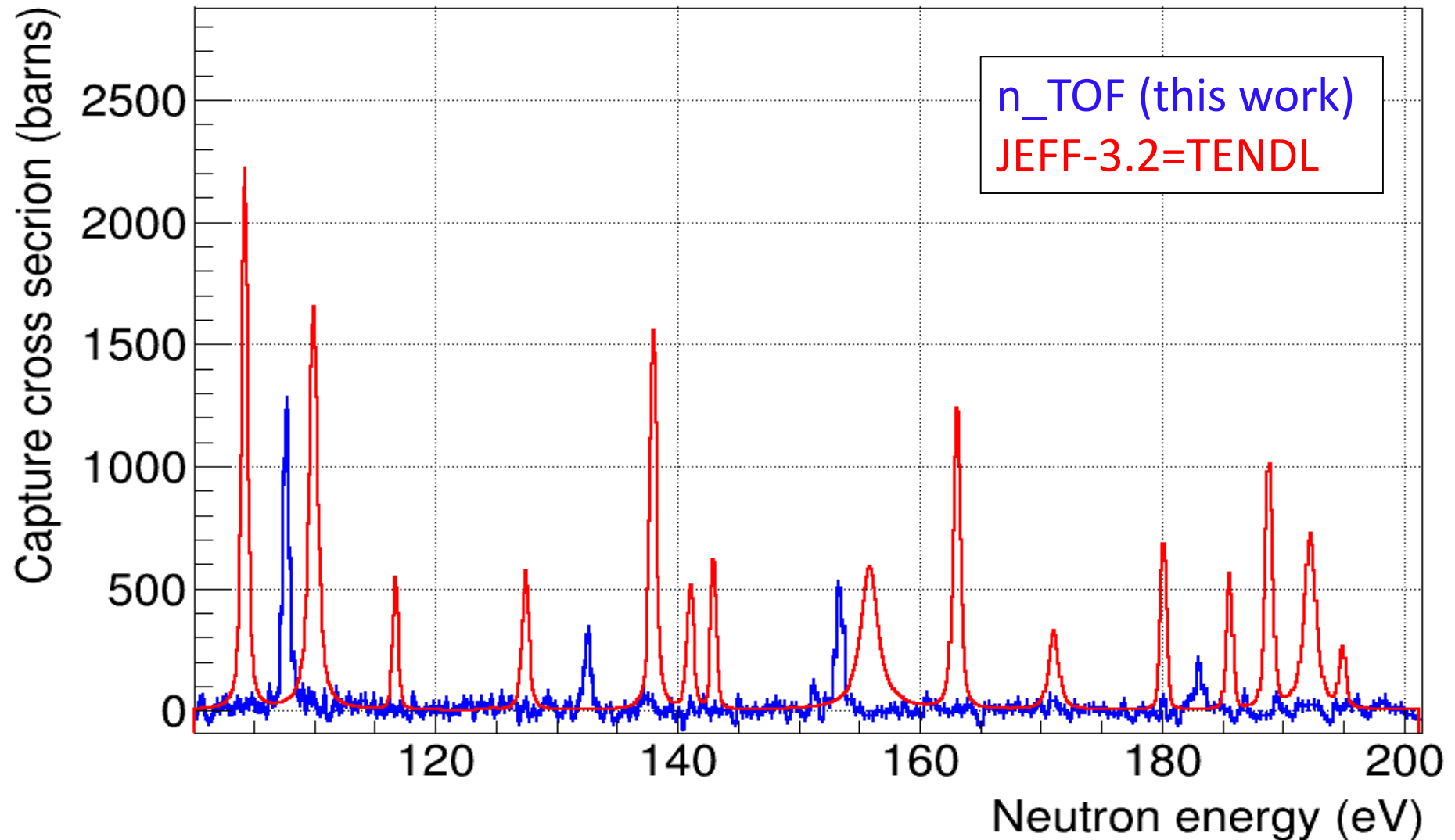


SOREQ  
Soreq Nuclear Research Center

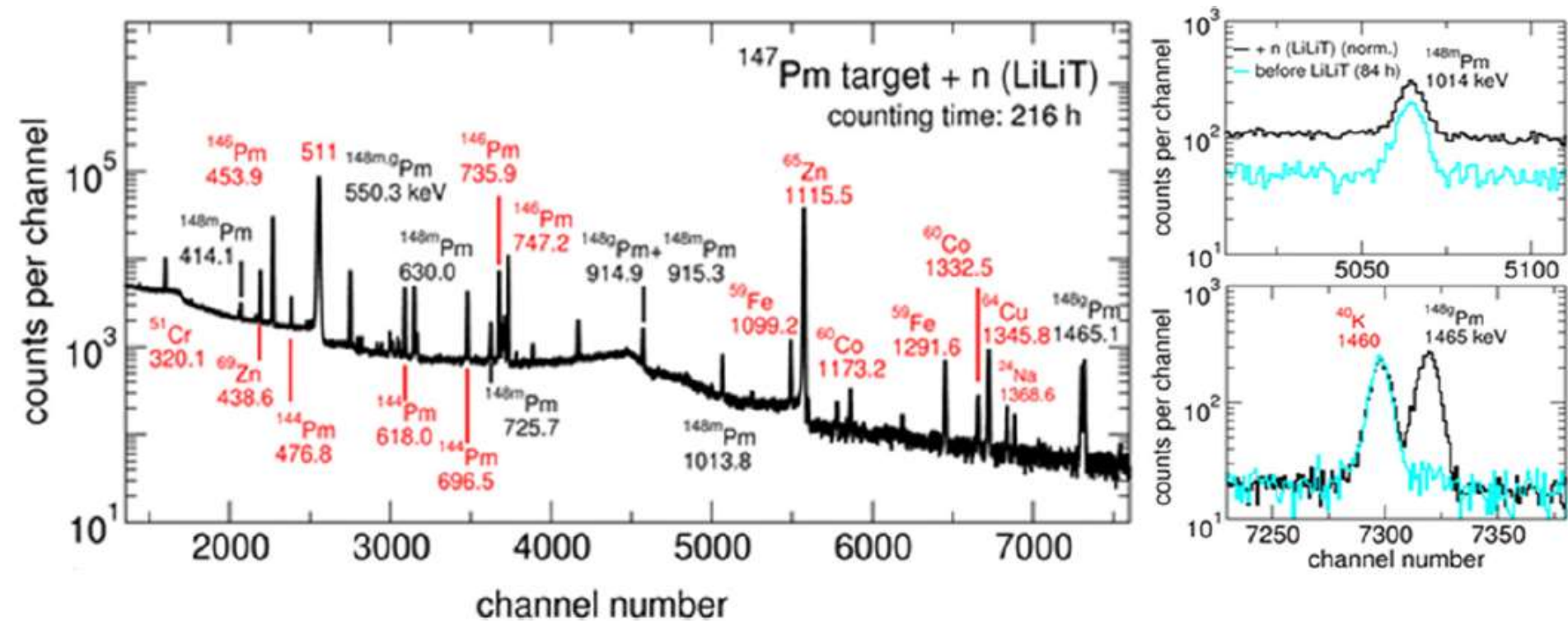


האוניברסיטה העברית בירושלים  
THE HEBREW UNIVERSITY OF JERUSALEM

# Results for $^{171}\text{Tm}(n,\gamma)$ measured at n\_TOF-EAR1



# $^{147}\text{Pm}(n,\gamma)^{148\text{g,m}}\text{Pm}$ MACS at SARAF-LiLiT



$^{147}\text{Pm}(n,\gamma)^{148\text{g}}\text{Pm}$

$^{147}\text{Pm}(n,\gamma)^{148\text{m}}\text{Pm}$

$^{147}\text{Pm}(n,\gamma)^{148\text{g,m}}\text{Pm}$

469(50) mb MACS at 30 keV

357(27) mb MACS at 30 keV

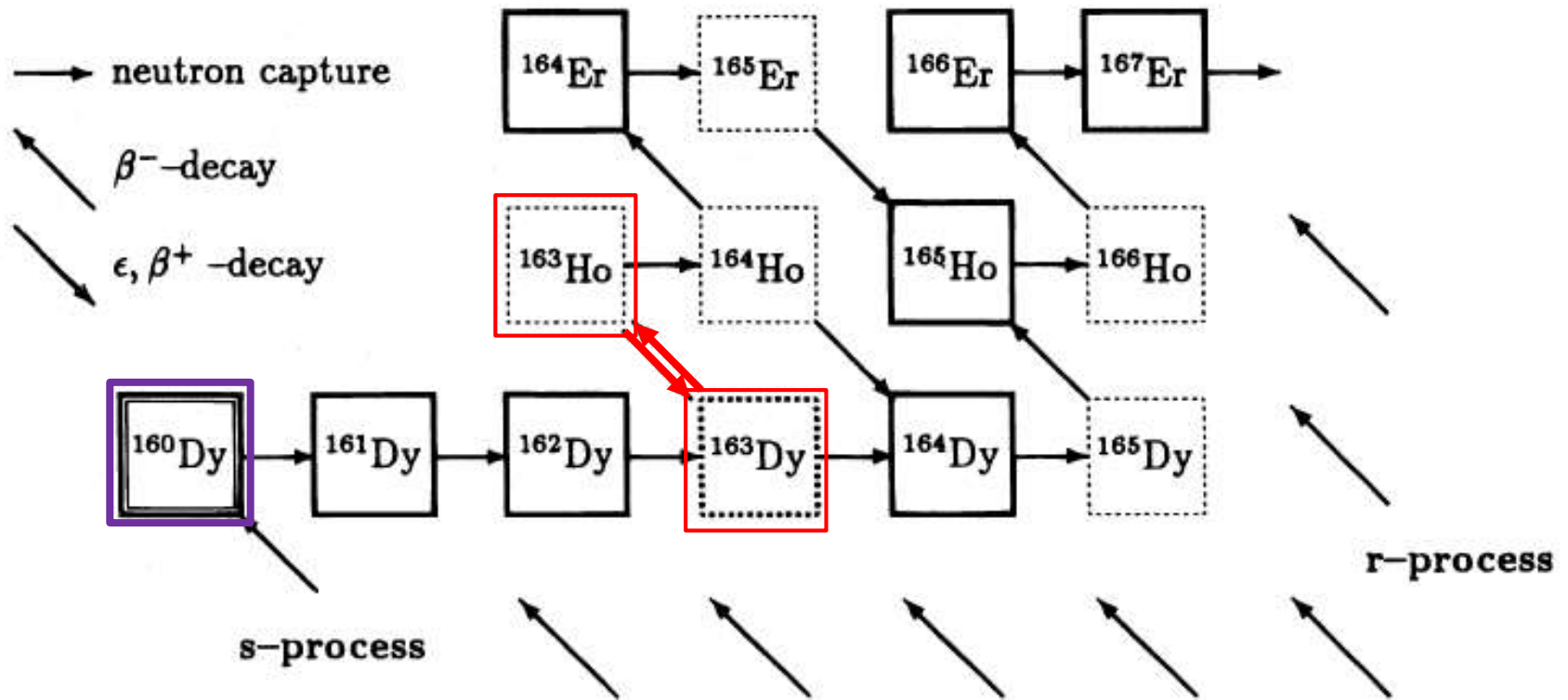
826(57) mb MACS at 30 keV

# $^{163}\text{Ho}$ as part of branching at $A=163$

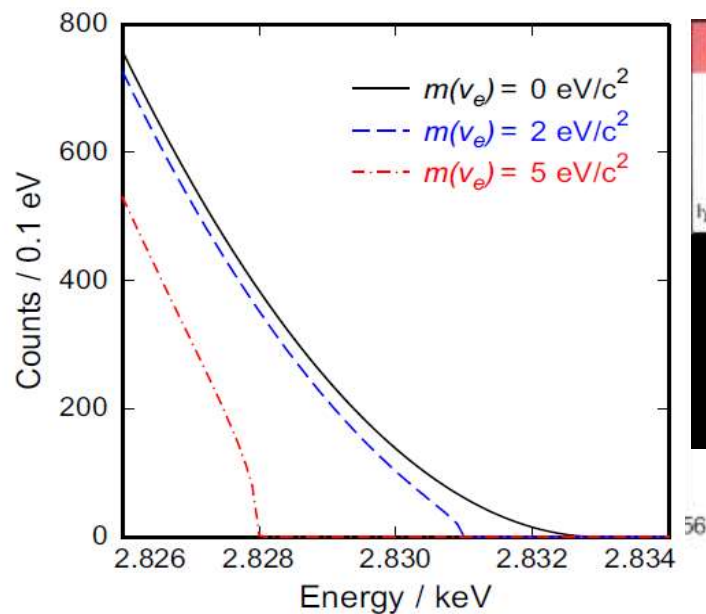
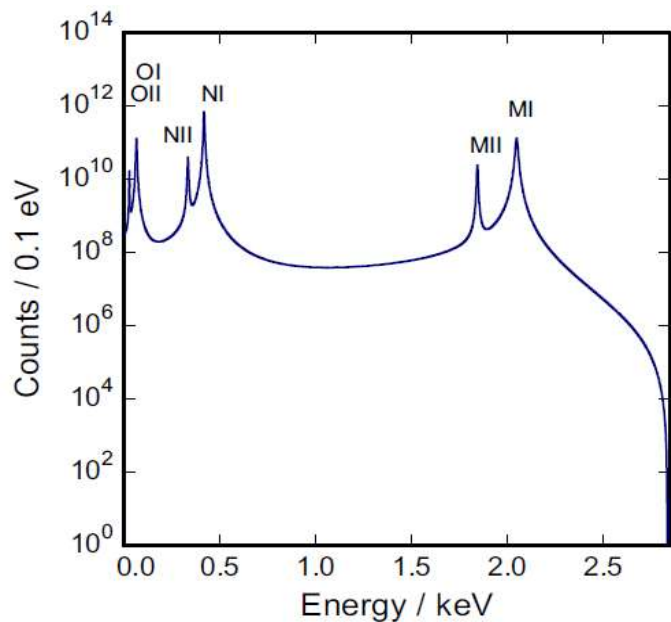
$^{163}\text{Dy}$  stable, but  $\beta^-$  (47 d) to  $^{163}\text{Ho}$  when fully ionized (stellar plasma)

Equilibrium abundance of  $^{163}\text{Ho}$  (from  $^{163}\text{Dy}$ ) produces  $^{164}\text{Ho}$  via  $(n,\gamma)$ .

The equilibrium abundance of  $^{163}\text{Ho}$  is determined by the temperature and electron density in the star.



# $^{163}\text{Ho}$ for Neutrino Mass Measurements



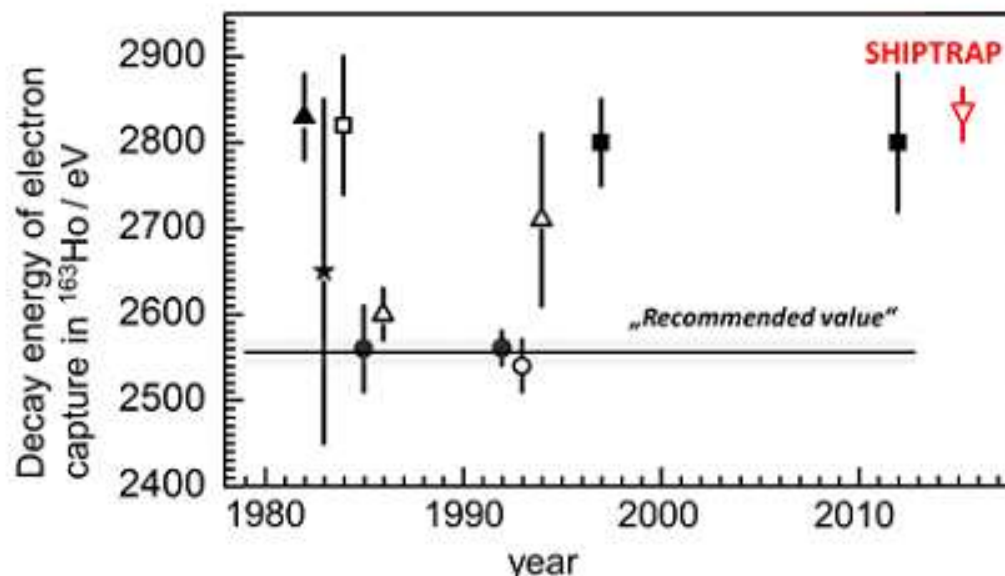
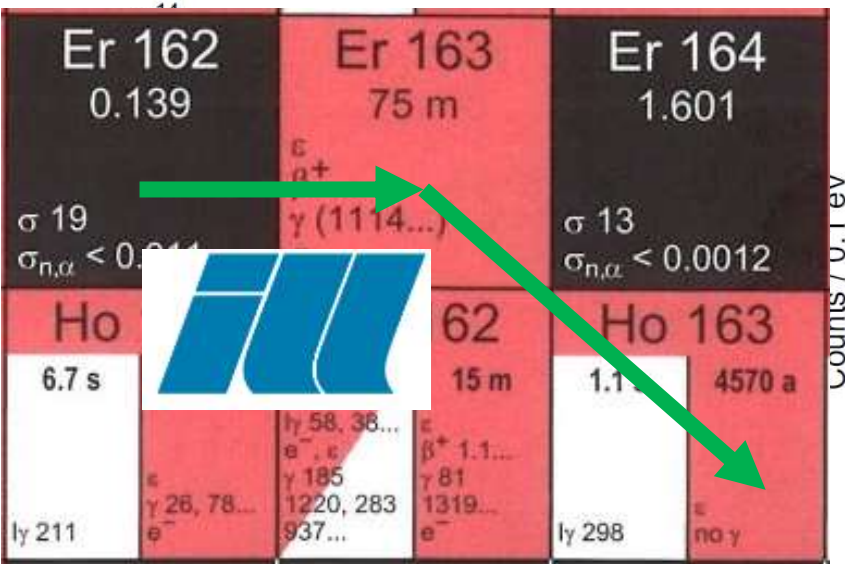
| Ho 163                            |                        |
|-----------------------------------|------------------------|
| 1.1 s                             | 4570 a                 |
| ly 298                            | $\epsilon$ no $\gamma$ |
| Dy 163                            |                        |
| 24.896                            |                        |
| $\sigma$ 120                      |                        |
| $\sigma_{n,\alpha} < 2\text{E-}5$ |                        |

*L. Gastaldo et al. Eur Phys J Spec Top 2017;226:1623.*

# $^{163}\text{Ho}$ for Neutrino Mass Measurements

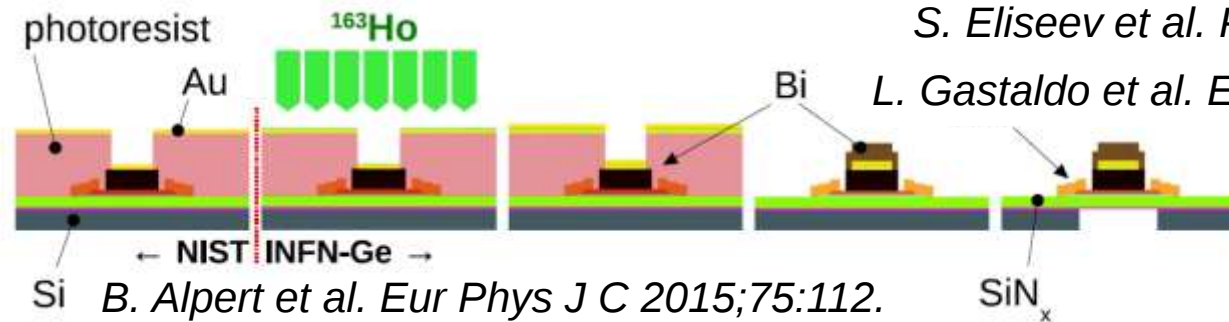


RUPRECHT-KARLS-  
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S. Eliseev et al. Phys Rev Lett 2015;115:062501.

L. Gastaldo et al. Eur Phys J Spec Top 2017;226:1623.



B. Alpert et al. Eur Phys J C 2015;75:112.



European  
Research  
Council



# and Everything

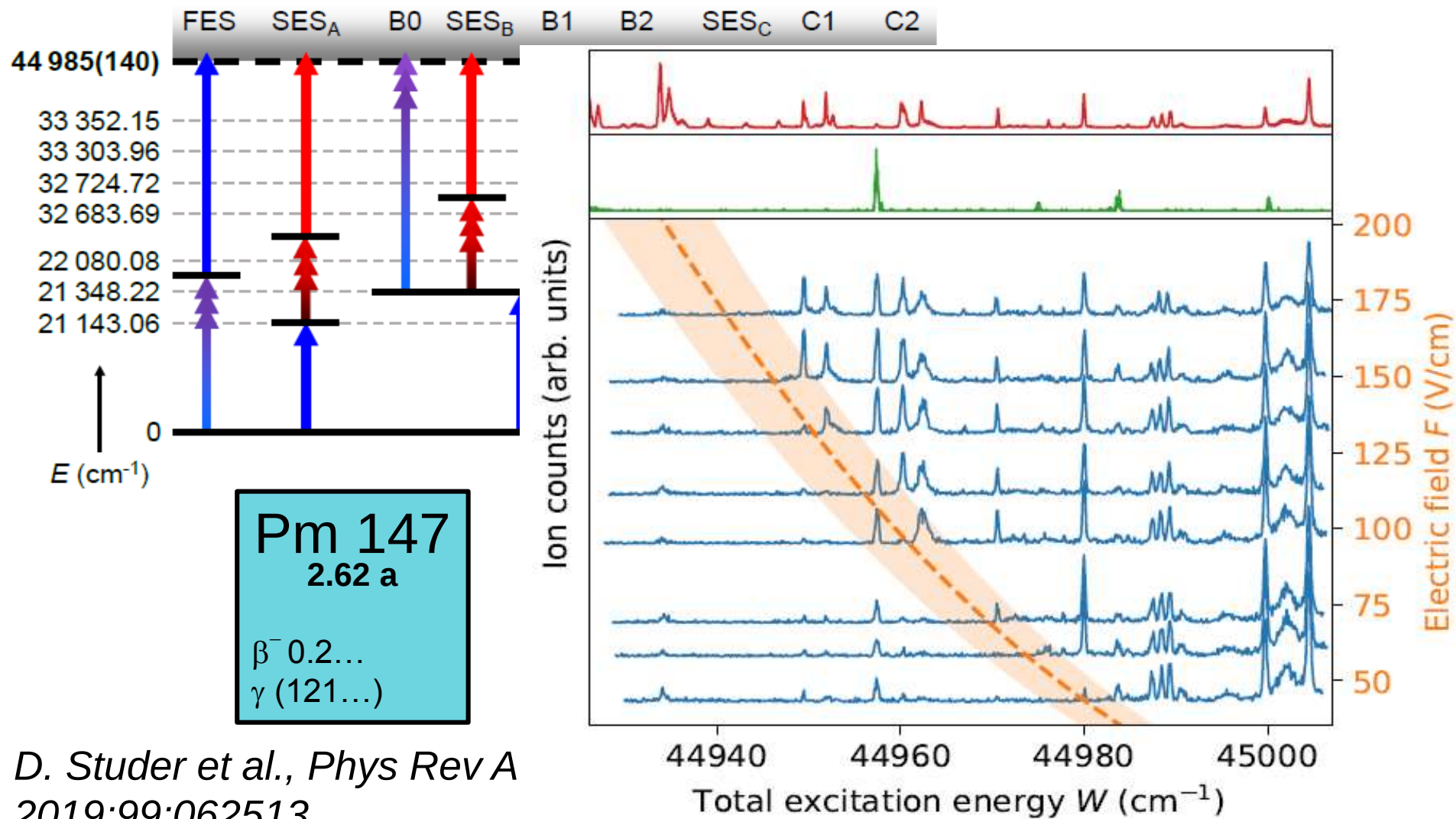




International Year  
of the Periodic Table  
of Chemical Elements

|          |          |          |          |          |          |          |          |          |          |           |           |           |           |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|
| 58<br>Ce | 59<br>Pr | 60<br>Nd | 61<br>Pm | 62<br>Sm | 63<br>Eu | 64<br>Gd | 65<br>Tb | 66<br>Dy | 67<br>Ho | 68<br>Er  | 69<br>Tm  | 70<br>Yb  | 71<br>Lu  |
| 90<br>Th | 91<br>Pa | 92<br>U  | 93<br>Np | 94<br>Pu | 95<br>Am | 96<br>Cm | 97<br>Bk | 98<br>Cf | 99<br>Es | 100<br>Fm | 101<br>Md | 102<br>No | 103<br>Lr |

# Resonance ionisation spectroscopy of Pm I



**Pm 147**  
2.62 a

$\beta^-$  0.2...  
 $\gamma$  (121...)

*D. Studer et al., Phys Rev A  
2019;99:062513.*



|                                                                                   |                                      |
|-----------------------------------------------------------------------------------|--------------------------------------|
|  | Uncertainty < 0.1 $\mu\text{eV}$     |
|  | Uncertainty 0.1 - 1.0 $\mu\text{eV}$ |
|  | Uncertainty 1 - 10 $\mu\text{eV}$    |
|  | Uncertainty 10 - 100 $\mu\text{eV}$  |
|  | Uncertainty 0.1 - 1 meV              |
|  | Uncertainty 10 - 200 meV             |
|  | No experimental value                |

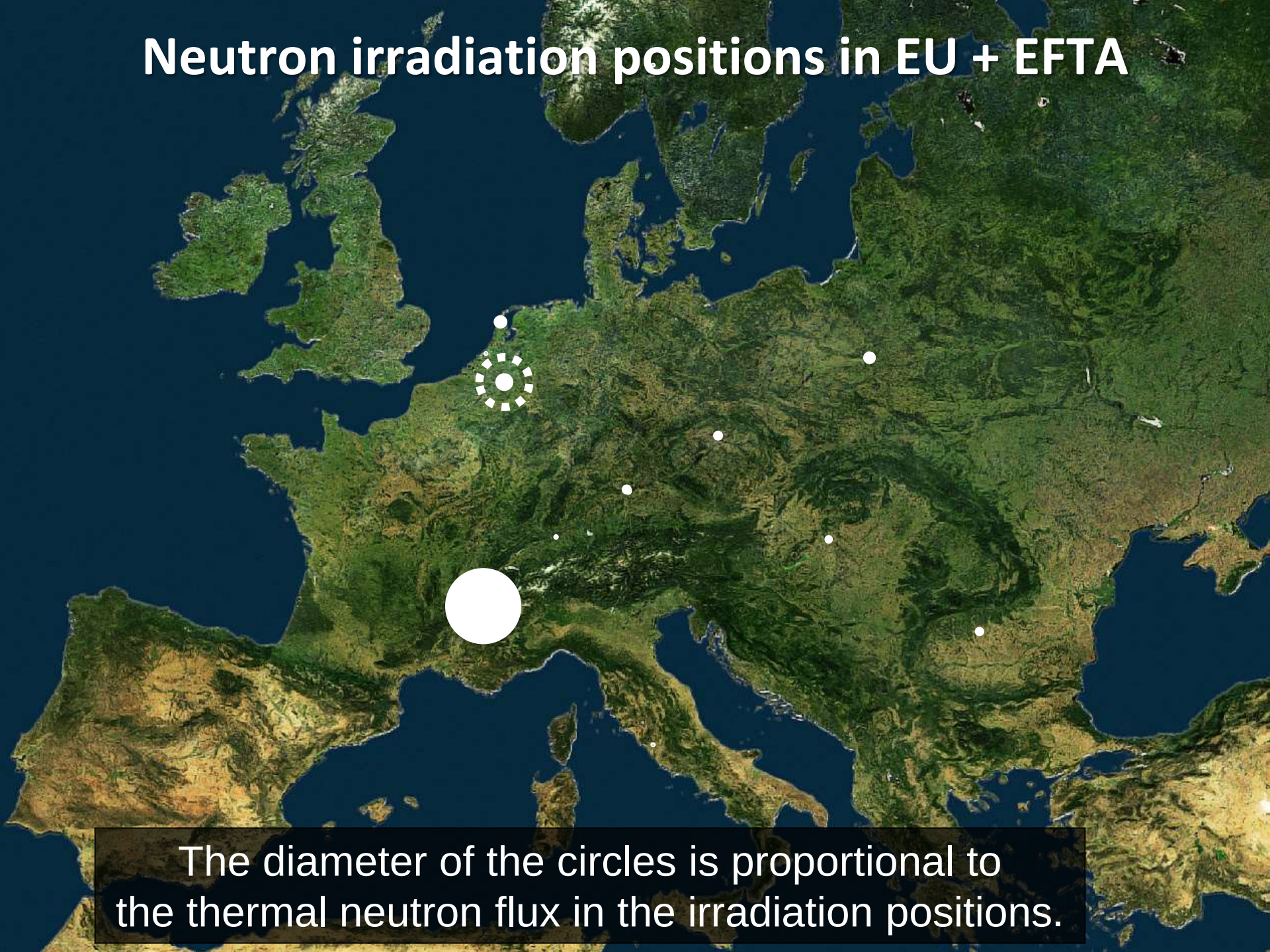
|          |          |          |          |          |          |          |          |          |          |           |           |           |           |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|
| 58<br>Ce | 59<br>Pr | 60<br>Nd | 61<br>Pm | 62<br>Sm | 63<br>Eu | 64<br>Gd | 65<br>Tb | 66<br>Dy | 67<br>Ho | 68<br>Er  | 69<br>Tm  | 70<br>Yb  | 71<br>Lu  |
| 90<br>Th | 91<br>Pa | 92<br>U  | 93<br>Np | 94<br>Pu | 95<br>Am | 96<br>Cm | 97<br>Bk | 98<br>Cf | 99<br>Es | 100<br>Fm | 101<br>Md | 102<br>No | 103<br>Lr |

# The highest neutron flux in the European Union

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

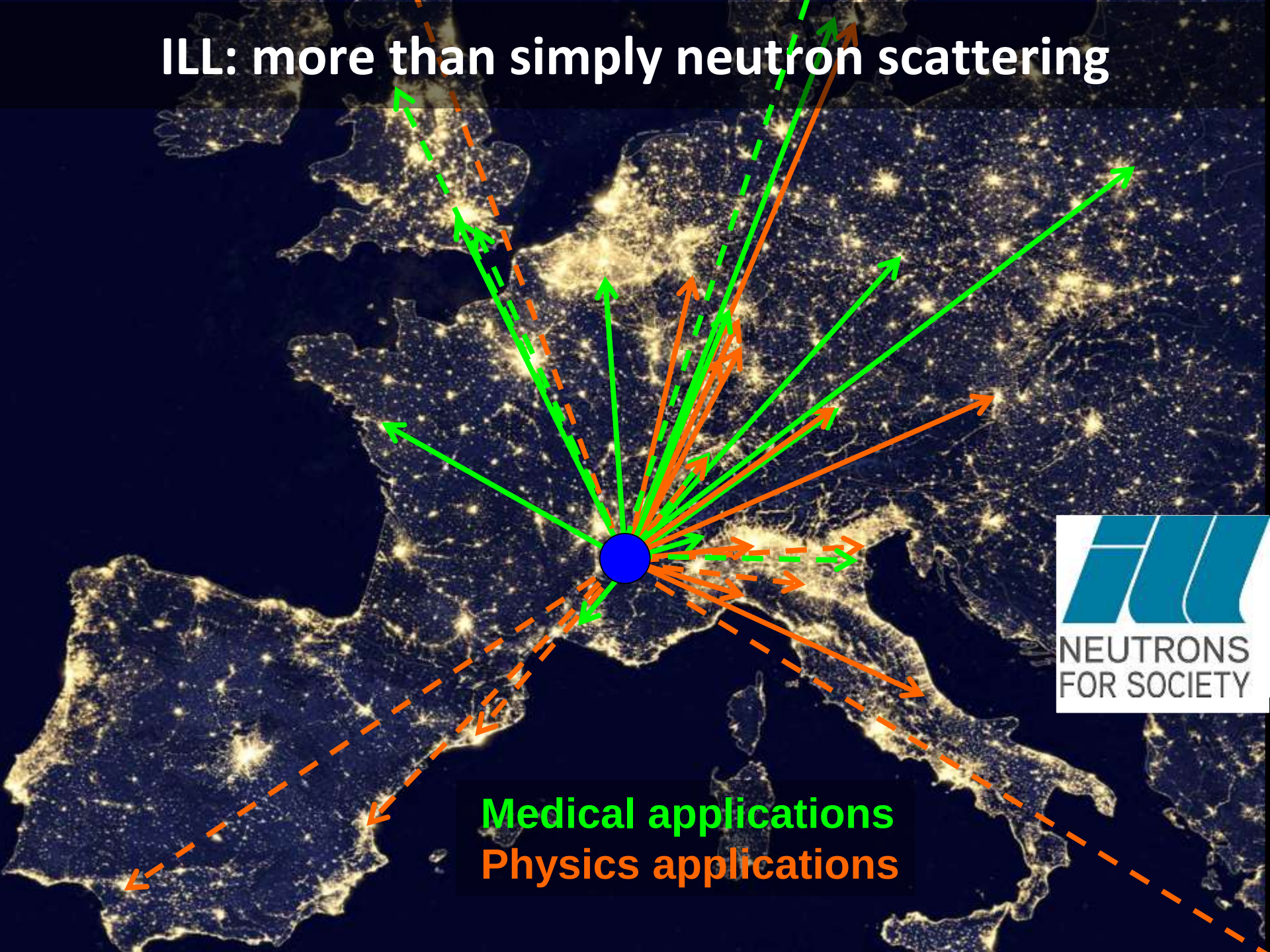


# Neutron irradiation positions in EU + EFTA



The diameter of the circles is proportional to the thermal neutron flux in the irradiation positions.

# ILL: more than simply neutron scattering



Medical applications  
Physics applications