Low background techniques

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Deep Underground Laboratory Integrating
Activity in Biology
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Assergi (AQ), Italy

Introduction

- Many fundamental experiments aim to detect very weak signals. They have to fight against background of different origin.
  - cosmic radiation
  - particles of nuclear decays
  - intrinsic natural radioactivity

  $\Rightarrow$ low background α and γ spectrometry @ L.N.G.S.

Rock properties

radioactivity (in Bq kg^{-1}):

	Gran Sasso	M^t Blanc
^{232}Th	0.25-0.5	≈90
^{238}U	5	80-500
^{226}Ra	4.5	30-300
^{40}K	5-50	100-2000

Rock properties

- composition:

  Ca 26 %, Si 1 %, Mg 9 %, O 51.5 %, C 12.5 %

$\langle\rho\rangle = (2.71 \pm 0.05)$ g cm^{-3}

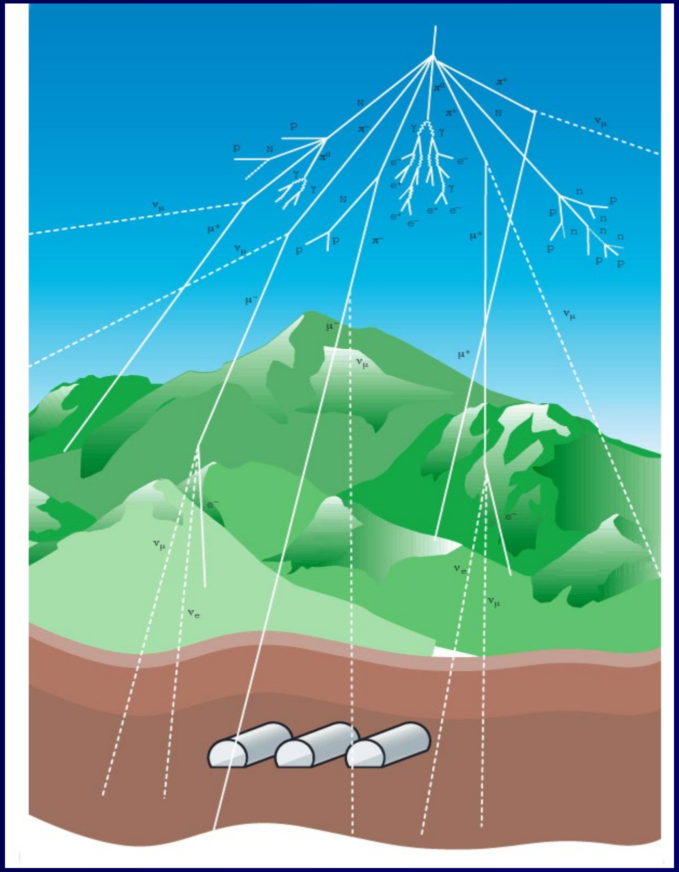
$\langle Z\rangle = 11.4$

$\langle Z^2/A\rangle = 5.7$

Characteristics

lat. 42° 27′ N
long. 13° 34′ E

mean depth:
3800 m.w.e.
min. depth:
3000 m.w.e.

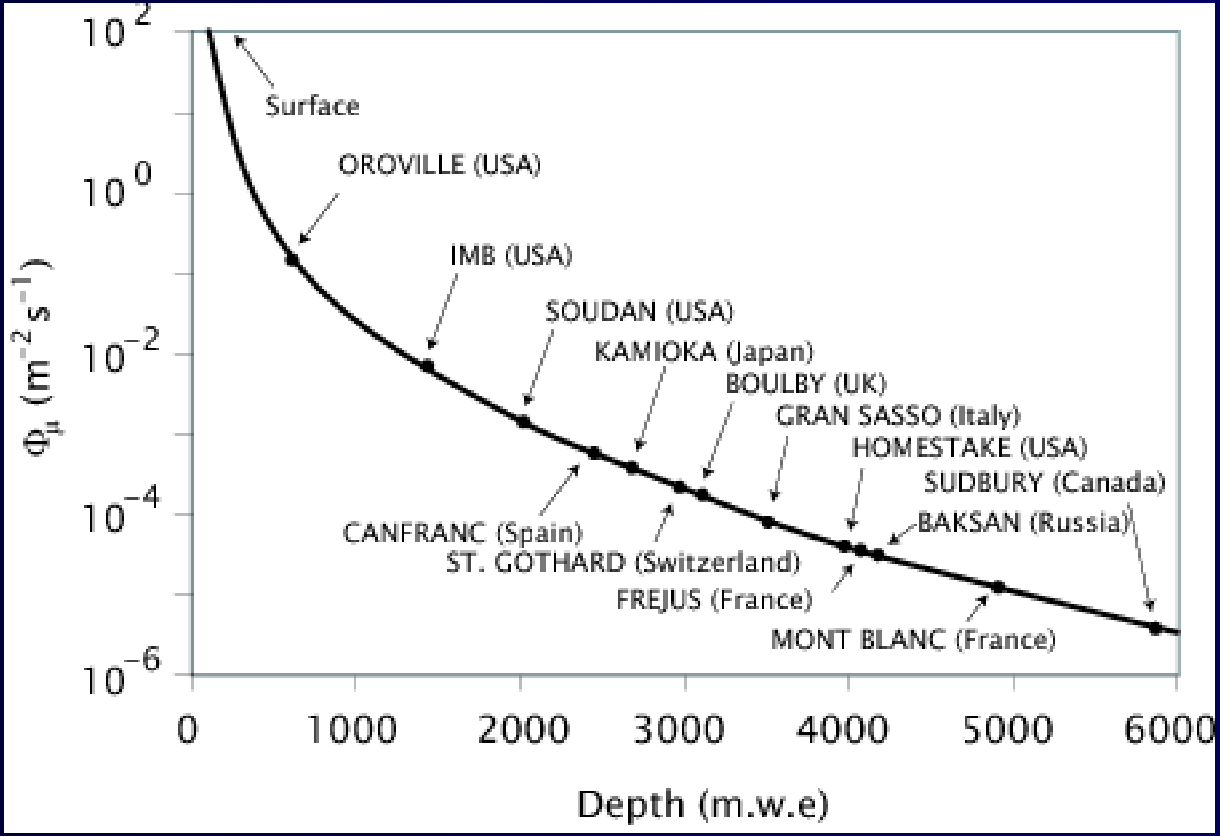


Muons

muon fluence:

$\approx 1\ \mu\ m^{-2}\ h^{-1}$, $E_\mu > 1$ TeV

(10^6 reduction with respect to surface)



by courtesy of Dr. J. Carmona

Neutrons

neutron flux:

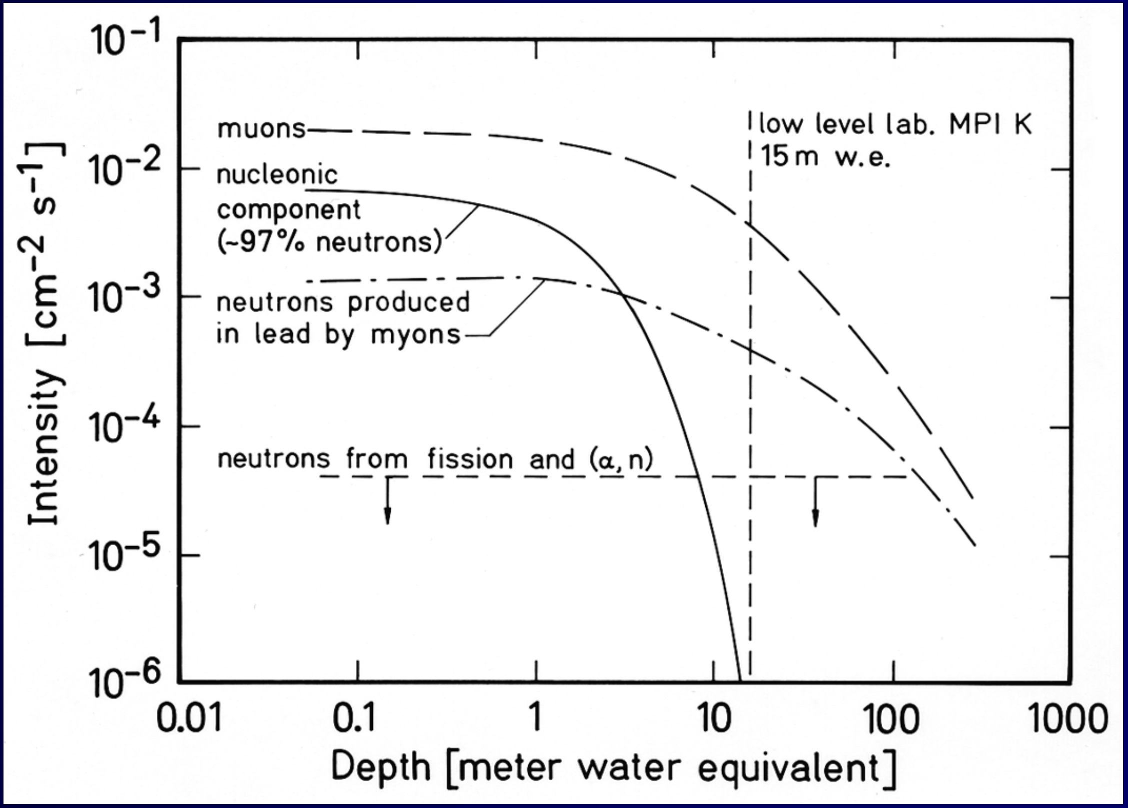
e.g. @ L.N.G.S.

fission and (α,n)

$\Phi_{th} \approx 3\times10^{-6}$ cm^{-2} s^{-1}

$\Phi_{fc} < 0.3\times10^{-6}$ cm^{-2} s^{-1}

(10^3 reduction)



by courtesy of Dr. G. Heusser

Comparison of Radio-assay techniques
for primordial U/Th decay chains and K

	suited for
Ge-spectrometry	γ emitting nuclides
Rn emanation assay	^{226}Ra, ^{228}Th
neutron activation	primordial parents
liquid scintillation counting	α,β emitting nuclides
mass spectrometry (ICP-MS; AMS)	primordial parents
graphite furnace AAS	primordial parents
Röntgen Excitation Analysis	primordial parents
α spectrometry	^{210}Po, α emitting nuclides

difficult to compare because each method has its special application

method	suited for	sensitivity for U/Th
Ge-spectrometry*	γ emitting nuclides	10-100 μBq/kg
Rn emanation assay	^{226}Ra, ^{228}Th	0.1-10 μBq/kg
neutron activation	primordial parents	0. 01 μBq/kg
liquid scintillation counting	α,β emitting nuclides	1 mBq/kg
mass spectrometry (ICP-MS; AMS)	primordial parents	1-100 μBq/kg
graphite furnace AAS	primordial parents	1-1000 μBq/kg
Röntgen Excitation Analysis	primordial parents	10 mBq/kg
α spectrometry	^{210}Po, α emitting nuclides	1 mBq/kg

* Needs counting times from several weeks to several months

see e.g. Borexino Collaboration, Arpesella, C. et al., Measurements of extremely low radioactivity levels in Borexino, Astrop. Phys. 18 (2002) 1-25

What is ULGS?

Ultra Low-level Gamma Spectrometry

i.e. low-level γ-spectrometry with additional background reduction by using active shields, material selection and/or underground laboratories

Sensitivity

Method	Detection limit for U and Th [Bq/kg]
ULGS (non-destructive) γ emitters	10^{-5} - 10^{-4}
ICP-MS (destructive) primordial parents	10^{-6} - 10^{-5}
ULGS + NAA primordial parents	10^{-7}

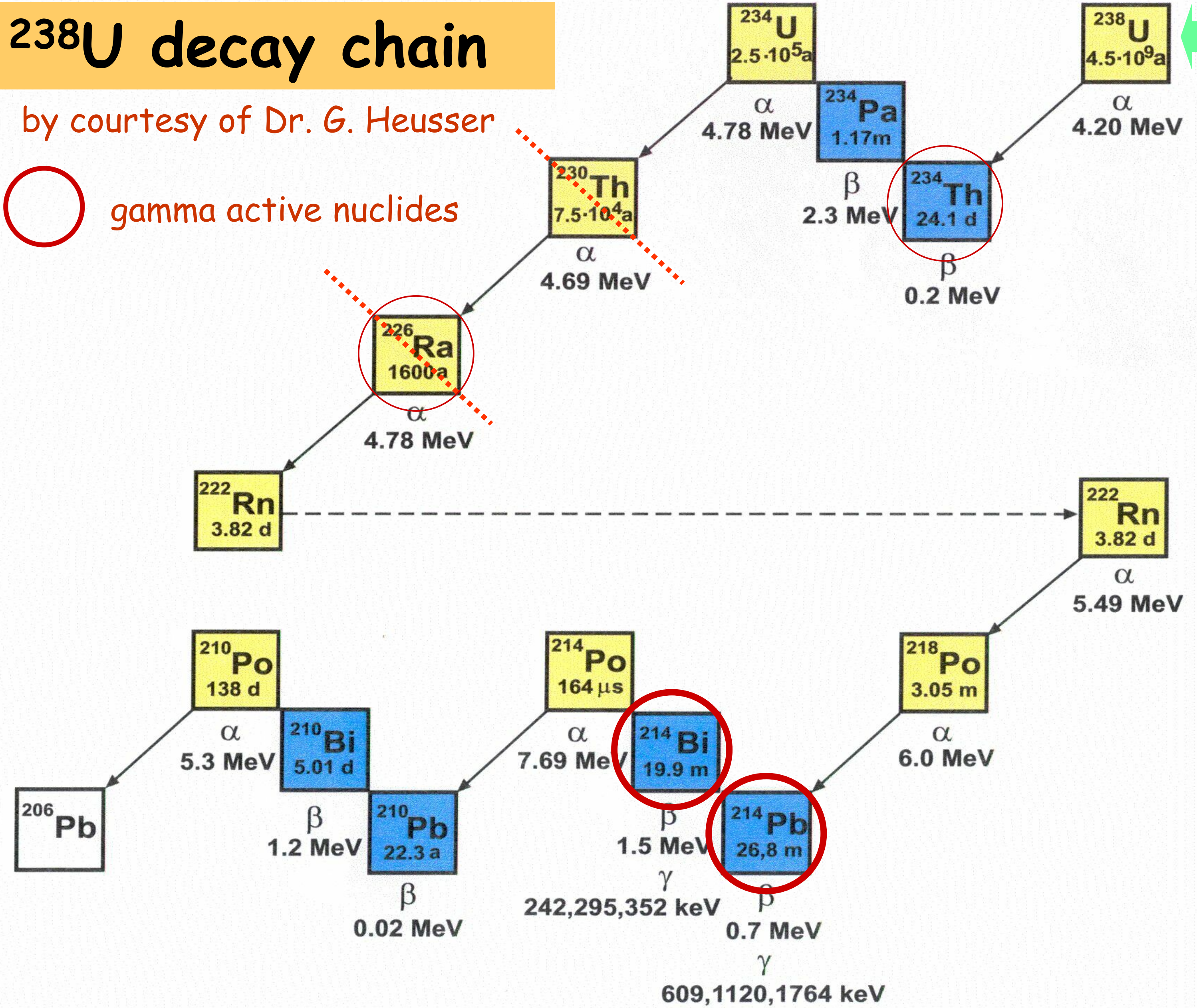
1 Bq ^{238}U/kg ≅ 81 × 10^{-9} g/g
1 Bq ^{232}Th/kg ≅ 246 × 10^{-9} g/g
1 Bq ^{40}K/kg ≅ 32 × 10^{-6} g/g

^{238}U decay chain

by courtesy of Dr. G. Heusser

gamma active nuclides

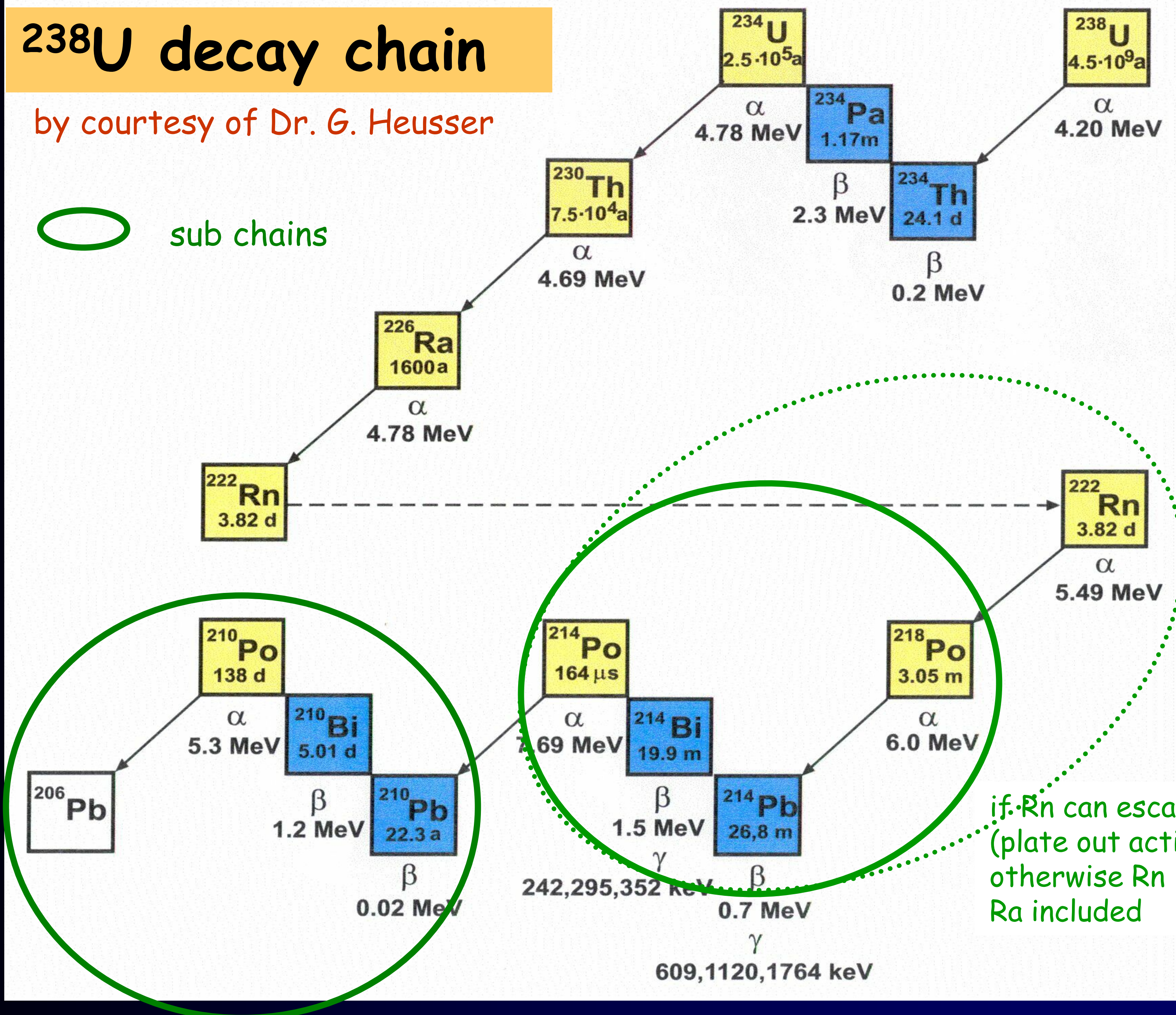
mass spectro-metry



^{238}U decay chain

by courtesy of Dr. G. Heusser

sub chains



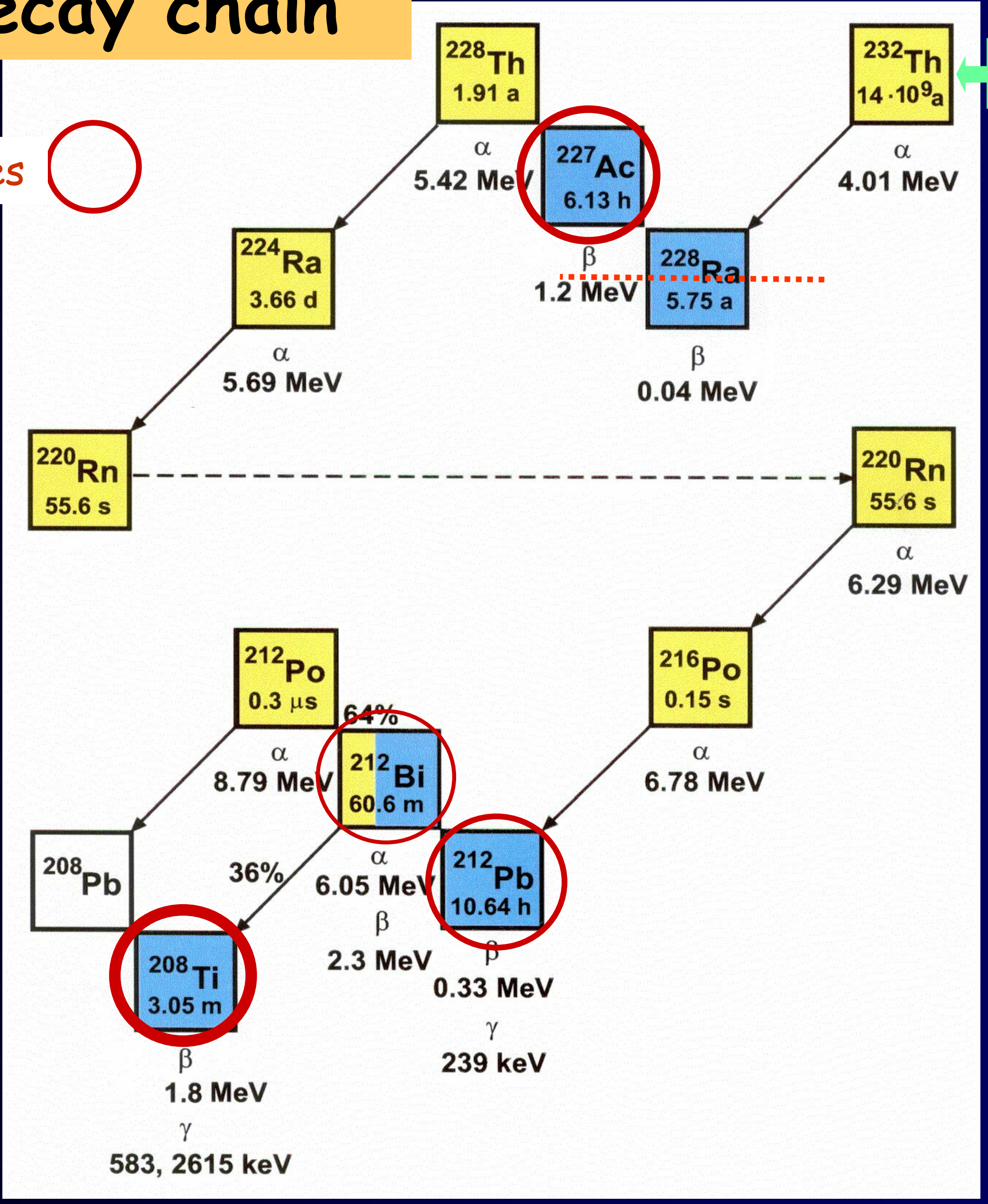
if Rn can escape, (plate out activity) otherwise Rn and Ra included

^{232}Th decay chain

by courtesy of Dr. G. Heusser

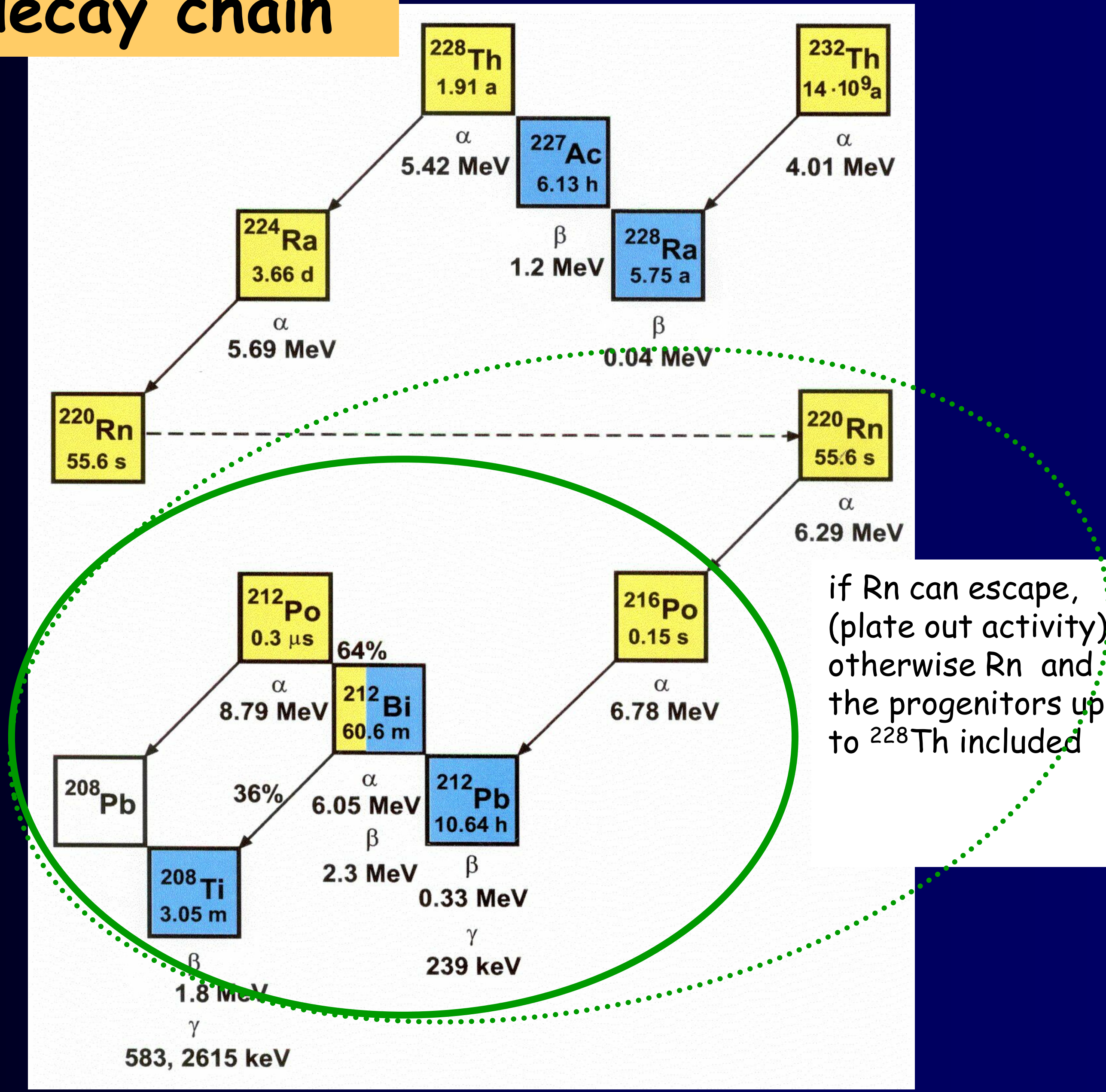
gamma active nuclides

mass spectrometry



^{232}Th decay chain

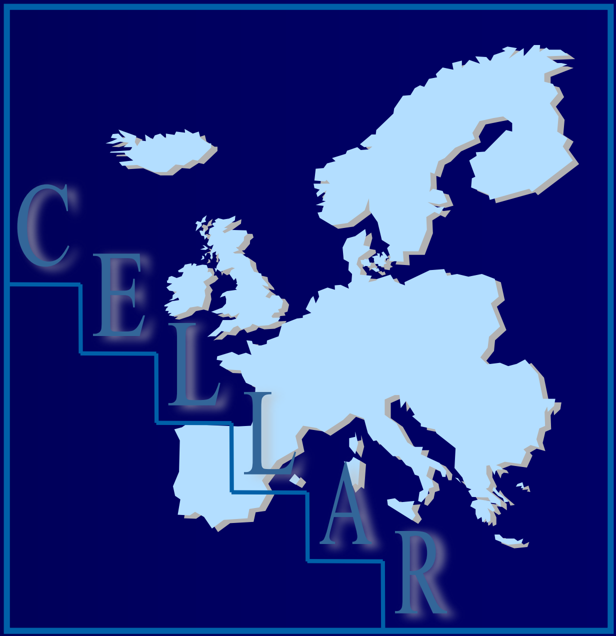
by courtesy of Dr. G. Heusser

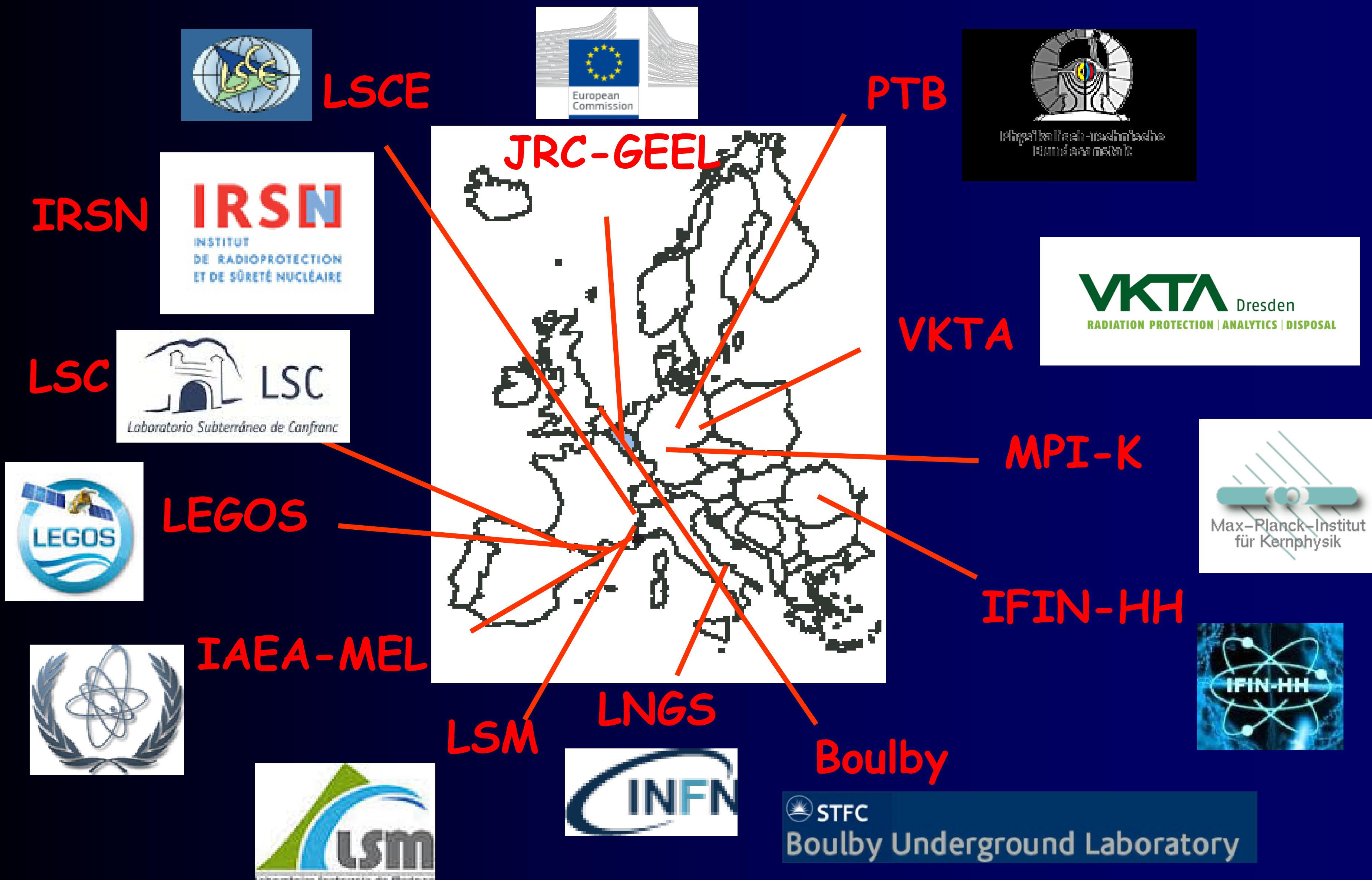


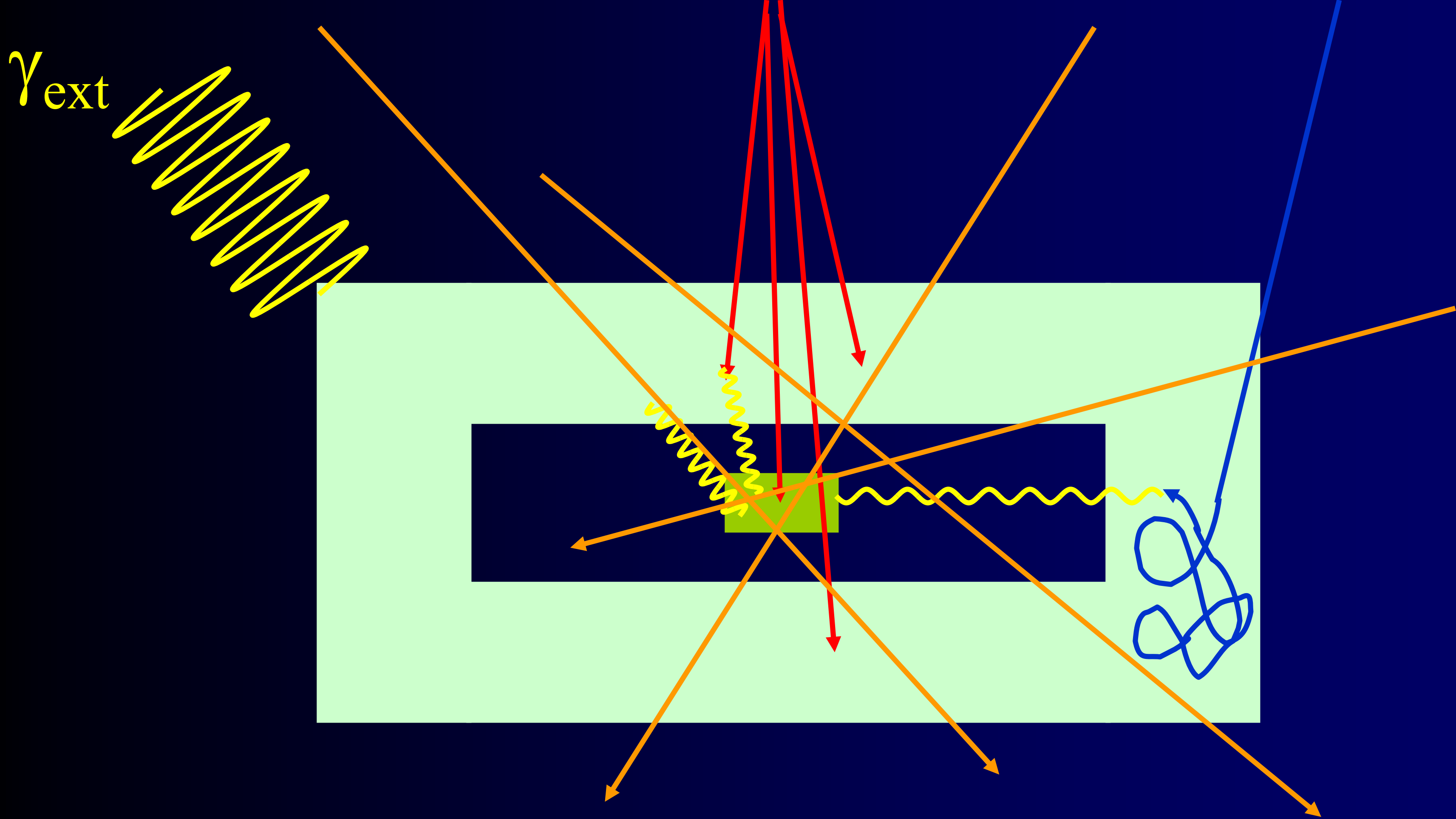
if Rn can escape, (plate out activity) otherwise Rn and the progenitors up to ^{228}Th included

CELLAR

Collaboration of European Low-level underground LAboRatories




LSCE
European Commission
PTB
JRC-GEEL
IRSN
IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
VKTA
VKTA Dresden
RADIATION PROTECTION | ANALYTICS | DISPOSAL
LSC
LSC
Laboratorio Subterráneo de Canfranc
MPI-K
Max-Planck-Institut für Kernphysik
LEGOS
LEGOS
IFIN-HH
IFIN-HH
IAEA-MEL
LNGS
LSM
lsm
INFN
Boulby
STFC
Boulby Underground Laboratory

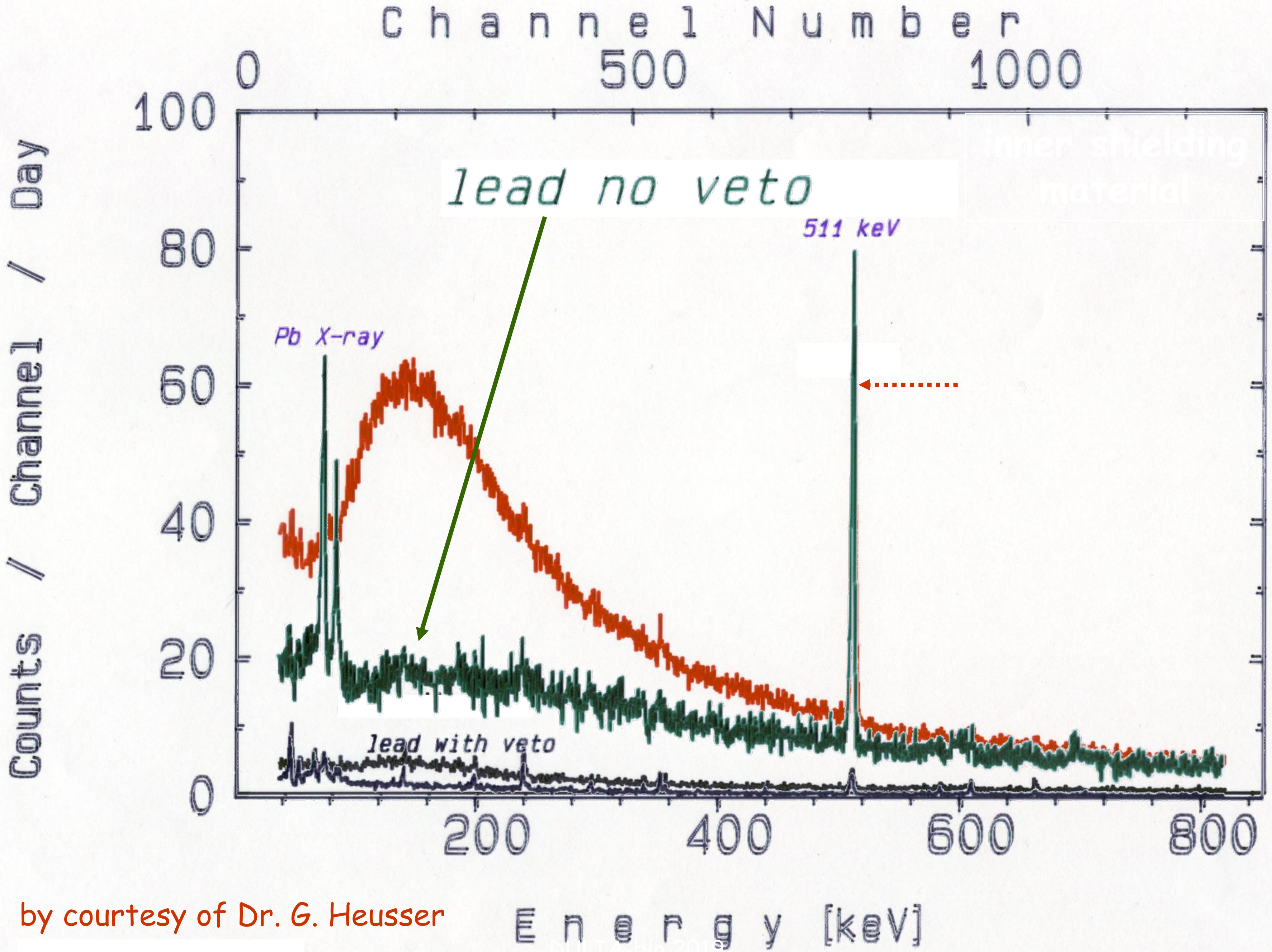


High energy muons are not stopped

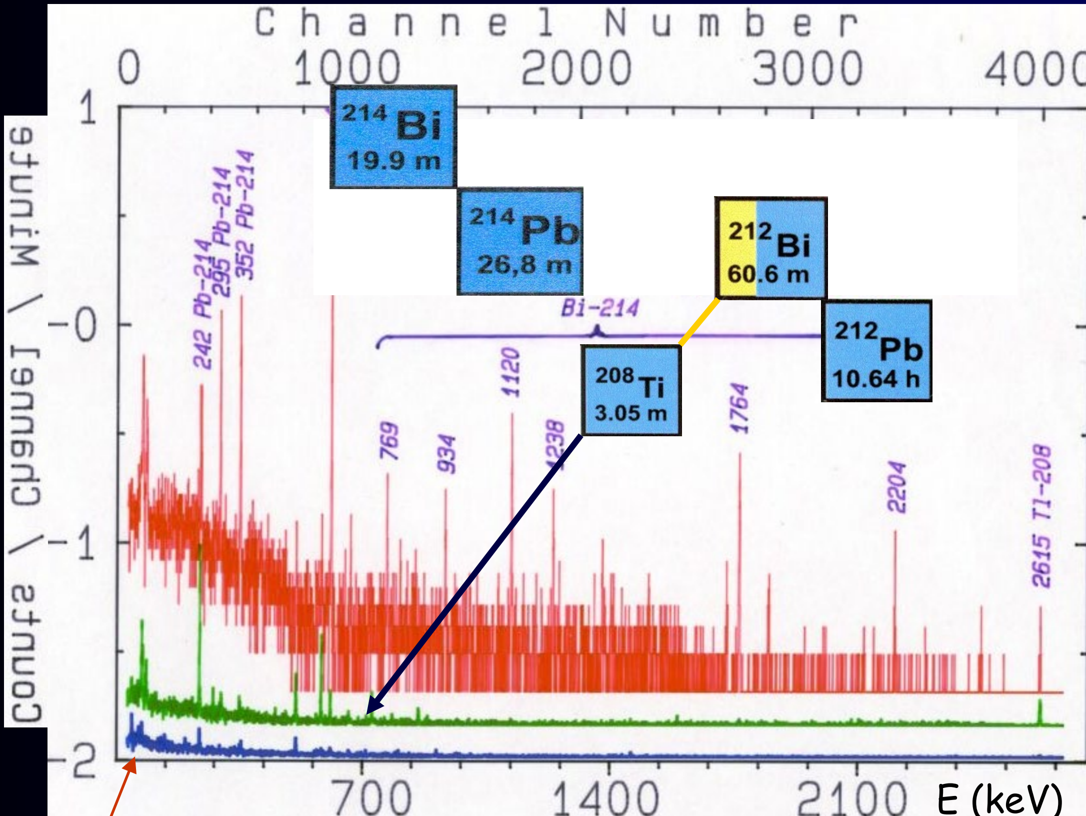
e.m. showers are only partially attenuated

Neutron thermalization produces photons through (n,γ) capture

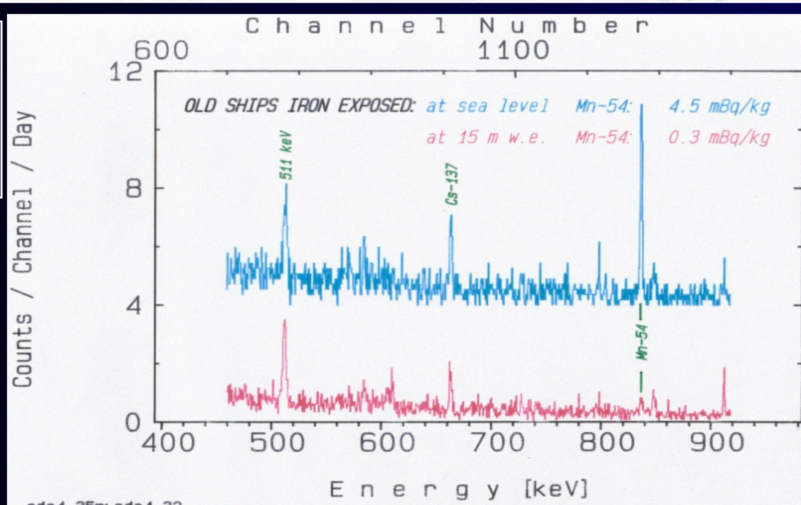
Interaction of high energy particles with shielding induces secondary background



by courtesy of Dr. G. Heusser



background or ^{222}Rn 3.82 d

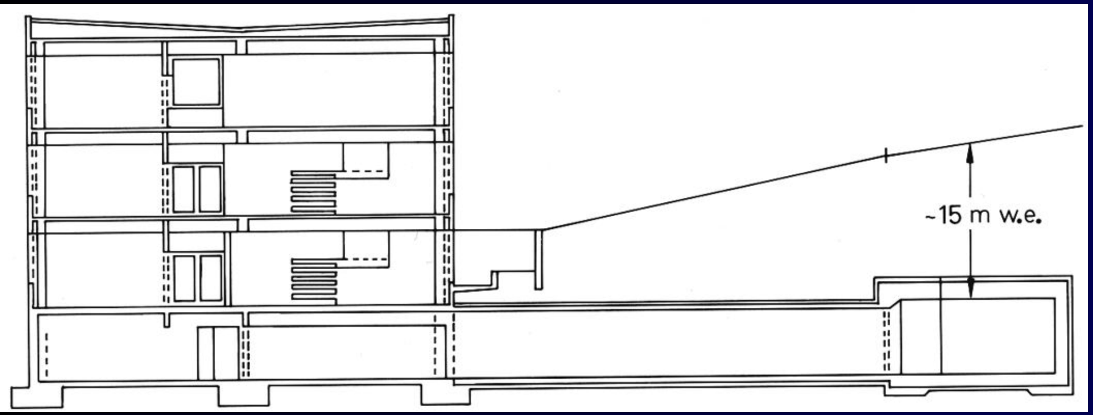


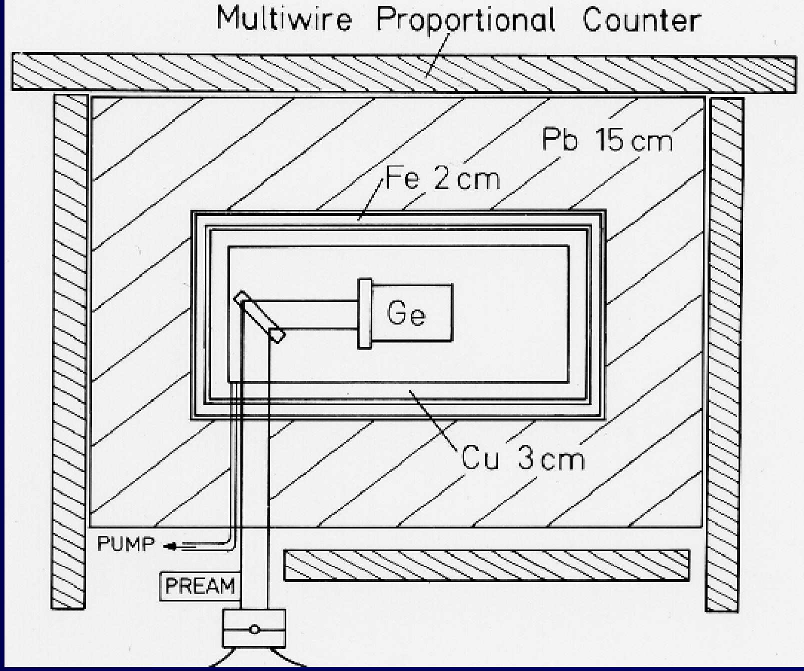
Cosmogenic production

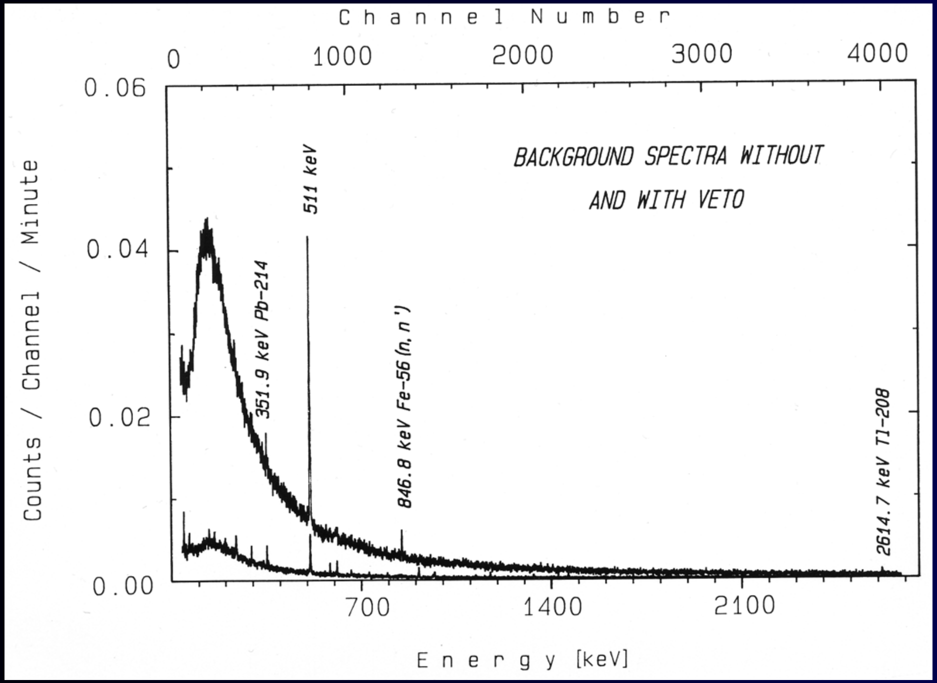
Energy [keV]	Isotope (source)	Reaction
10.37	^{68,71}Ge	^{70}Ge(n,γ)^{71}Ge, ^{70}Ge(n,3n)^{68}Ge
13.3	^{73m}Ge	^{72}Ge(n,γ),^{74}Ge(n,2n)
23.5	^{71m}Ge	^{70}Ge(n,γ), ^{72}Ge(n,2n)
53.4	^{73m}Ge	^{72}Ge(n,γ), ^{74}Ge(n,2n)
66.7	^{73m}Ge	^{72}Ge(n,γ), ^{74}Ge(n,2n)
68.7 [a]	^{73*}Ge	^{73}Ge(n,n′)
109.9	^{19*}F	^{19}F(n,n′)
122.1	^{57*}Fe, ^{57}Co	^{57}Fe(n,n′), activation of Cu/Ni
136.5	^{57}Co	activation of Cu/Ni
139.5	^{75m}Ge	^{74}Ge(n,γ), ^{76}Ge(n,2n)
143.6	^{57}Co	activation of Ge
159.5	^{77m}Ge	^{76}Ge(n,γ)
174.9	^{71m}Ge	^{70}Ge(n,γ), ^{72}Ge(n,2n)
186.0	^{66}Cu	^{65}Cu(n,γ)
198.3	^{71m}Ge	^{70}Ge(n,γ), ^{72}Ge(n,2n)
278.3	^{64*}Cu	^{63}Cu(n,γ), ^{65}Cu(n,2n)
368	^{200*}Hg	^{199}Hg(n,γ)
511	$β^+$	muon-induced pair production
558.4	^{114*}Cd	^{113}Cd(n,γ)
562.8 [a]	^{76*}Ge	^{76}Ge(n,n′)
579.2	^{207*}Pb	^{207}Pb(n,n′)
595.8 [a]	^{74*}Ge	^{74}Ge(n,n′)
651.1	^{114}Cd	^{113}Cd(n,γ)
669.6	^{63*}Cu	^{63}Cu(n,n′)
691.0 [a]	^{72*}Ge	^{72}Ge(n,n′)
803.3	^{206*}Pb	^{206}Pb(n,n′)
805.9	^{114*}Cd	^{113}Cd(n,γ)
810.8	^{58}Co	activation of Cu/Ni
817.9	^{58}Co	activation of Ge
834.0 [a]	^{72*}Ge	^{72}Ge(n,n′)
834.8	^{54}Mn	activation of Fe/Co/Ni
840.8	^{54}Mn	activation of Ge
846.8	^{56*}Fe	^{56}Fe(n,n′)
962.1	^{63*}Cu	^{63}Cu(n,n′)
1063.6	^{207*}Pb	^{207}Pb(n,n′)
1097.3	^{116}In	^{115}In(n,γ)
1115.5	^{65*}Cu	^{65}Cu(n,n′)
1125.2	^{65}Zn	activation of Ge
1173.2	^{60}Co	activation of Cu/Ni
1293.5	^{116}In	^{115}In(n,γ)
1327.0	^{63*}Cu	^{63}Cu(n,n′)
1332.5	^{60}Co	activation of Cu/Ni
1412.1	^{63*}Cu	^{63}Cu(n,n′)
1481.7	^{65*}Cu	^{65}Cu(n,n′)
1547	^{63*}Cu	^{63}Cu(n,n′)
2223	^{2*}H	^{1}H(n,γ)

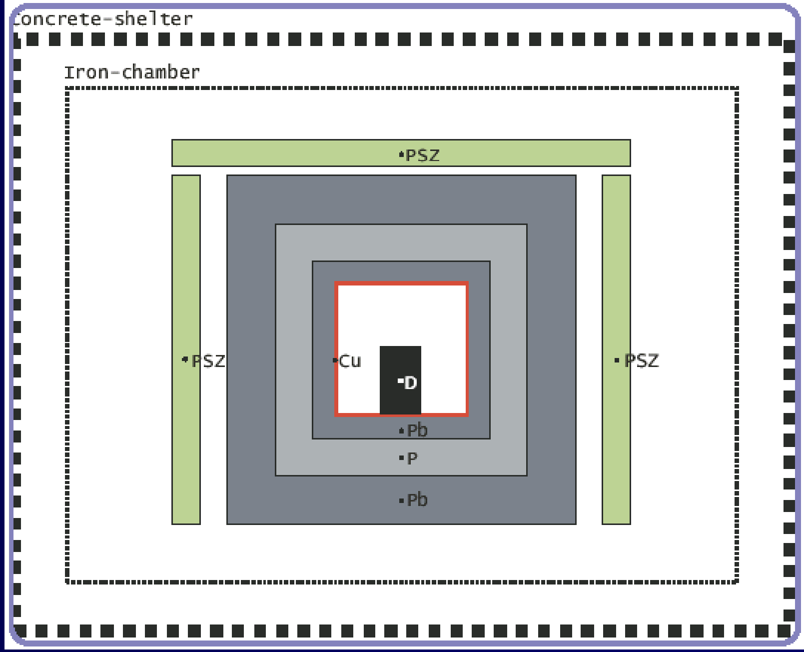
[a] Broadened asymmetric peaks due to recoil.

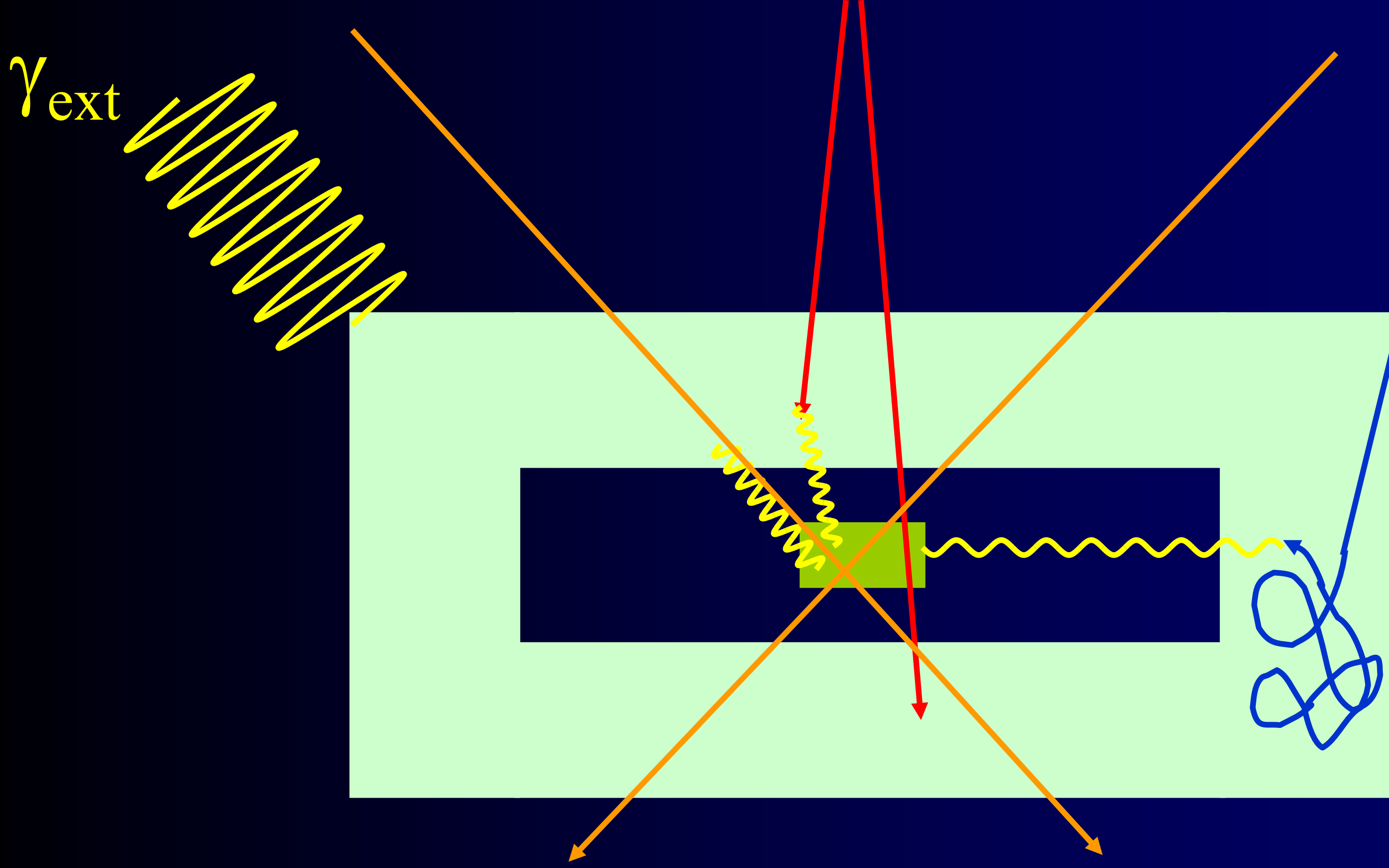
by courtesy of Dr. G. Heusser


~15 m w.e.


Multiwire Proportional Counter
Pb 15 cm
Fe 2 cm
Ge
Cu 3 cm
PUMP
PREAM


Channel Number
0
1000
2000
3000
4000
0.06
0.04
0.02
0.00
Counts / Channel / Minute
BACKGROUND SPECTRA WITHOUT
AND WITH VETO
511 keV
351.9 keV Pb-214
846.8 keV Fe-56 (n,n')
2614.7 keV Tl-208
700
1400
2100
Energy [keV]


concrete-shelter
Iron-chamber
PSZ
PSZ
PSZ
Cu
D
Pb
P
Pb

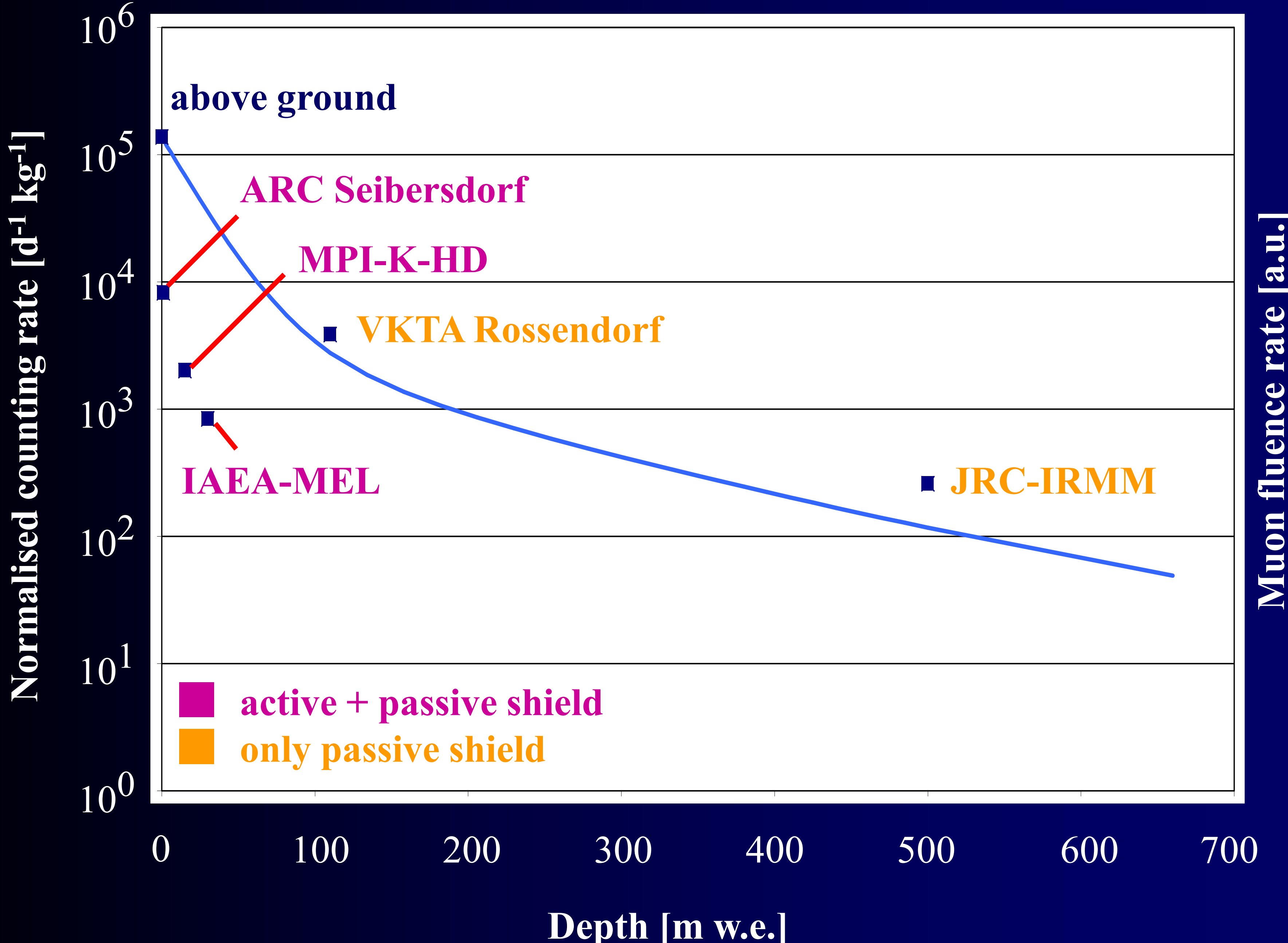


high energy muons are reduced by overburden and/or active shield

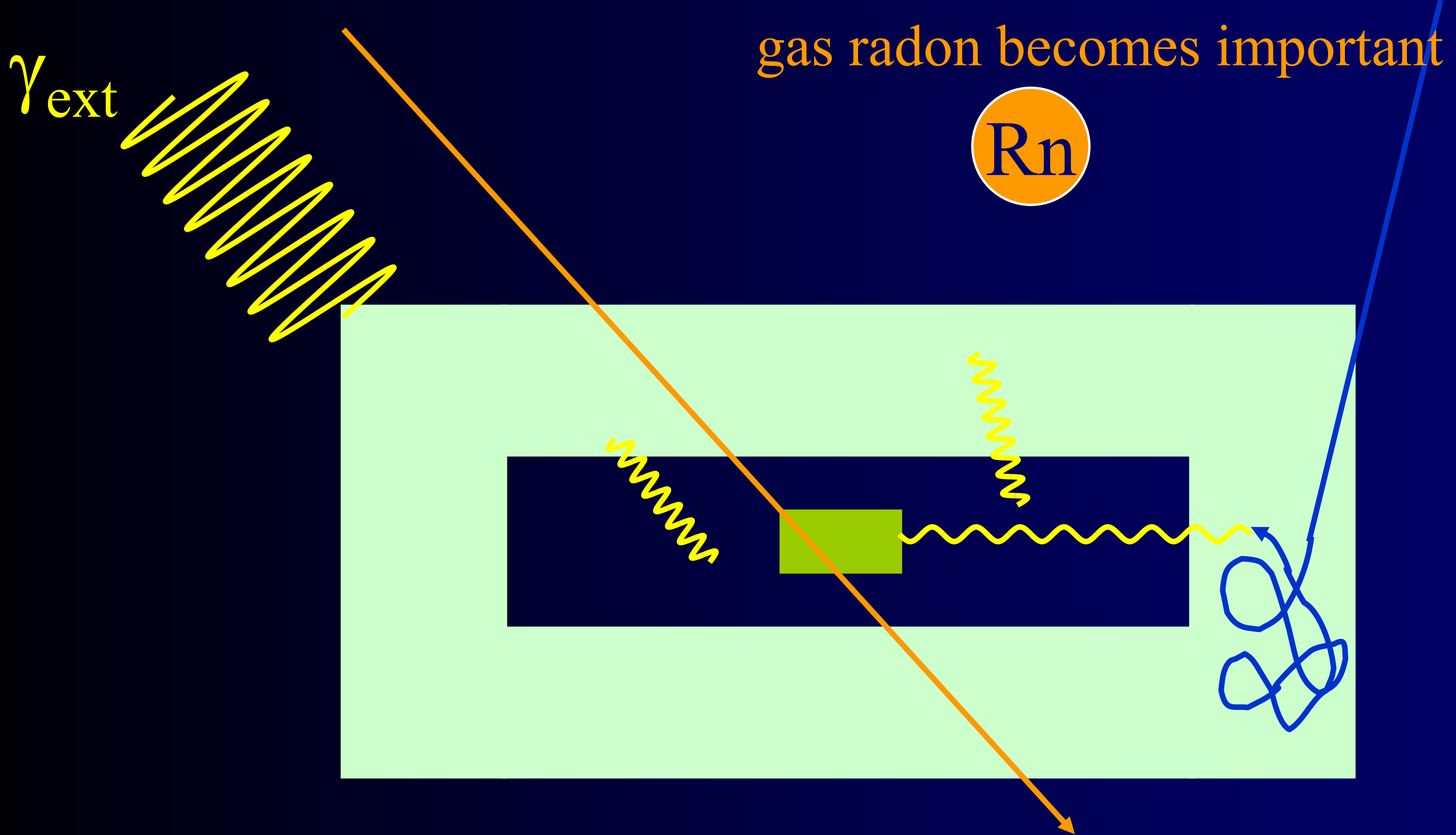
e.m. showers are attenuated

Neutron thermalization produces photons through (n,γ) capture

Interaction of high energy particles with shielding induces secondary background



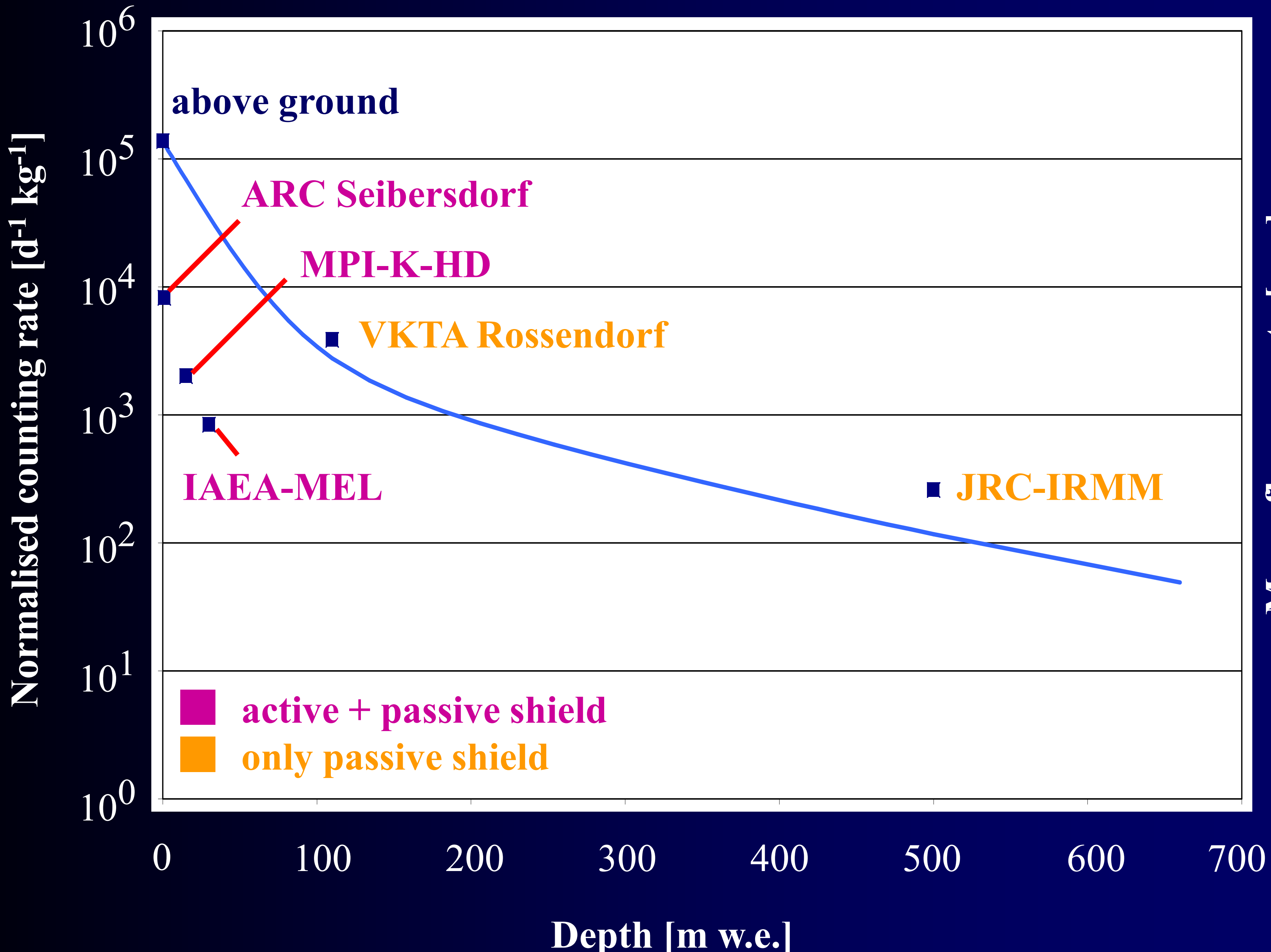
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Normalised counting rate [d-1 kg-1]
above ground
ARC Seibersdorf
MPI-K-HD
VKTA Rossendorf
IAEA-MEL
JRC-IRMM
active + passive shield
only passive shield
Muon fluence rate [a.u.]
0
100
200
300
400
500
600
700
Depth [m w.e.]

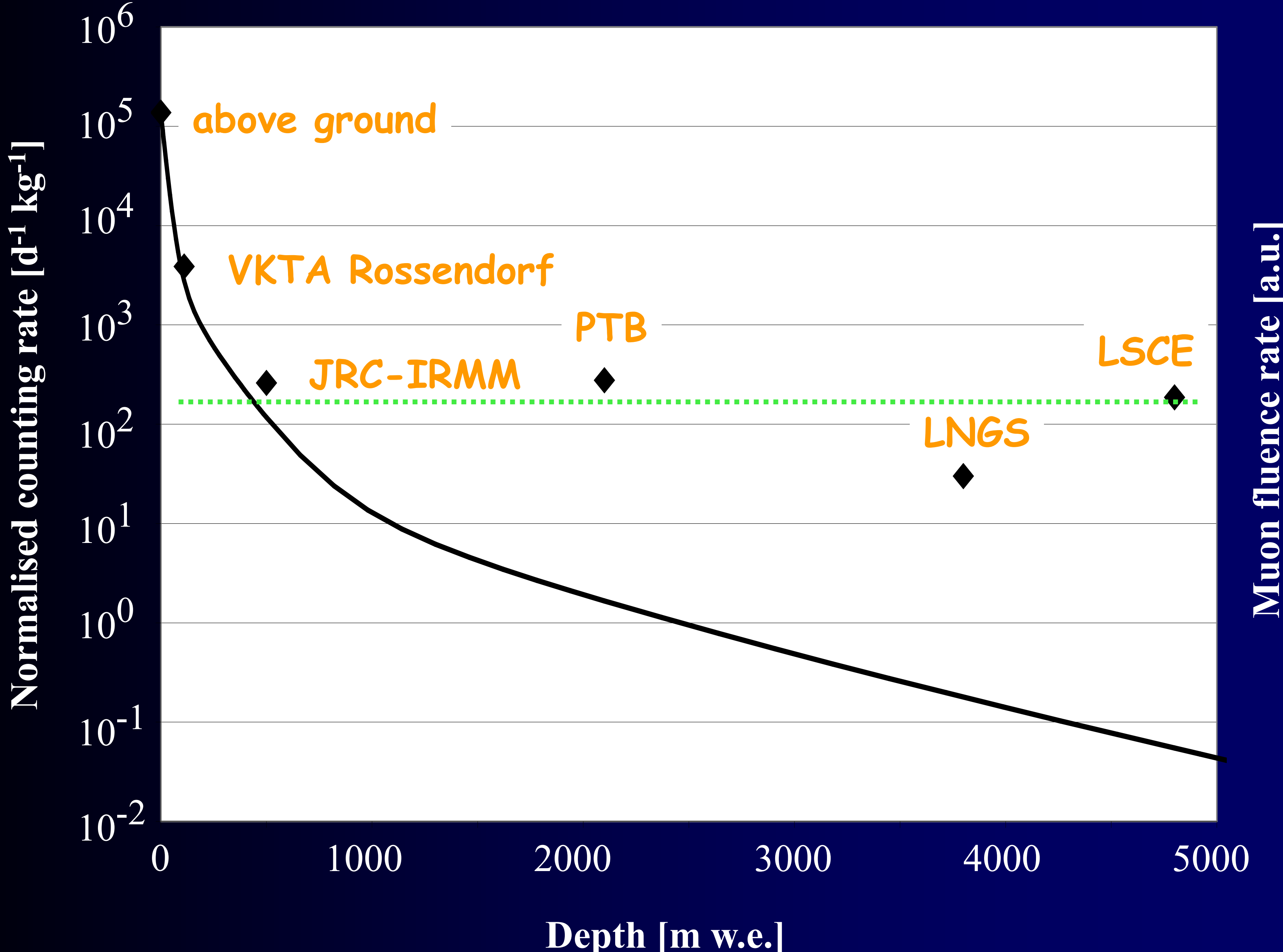


high energy muons are reduced further deep underground
(factor >10^{-6} reduction @ LSCE & LNGS)

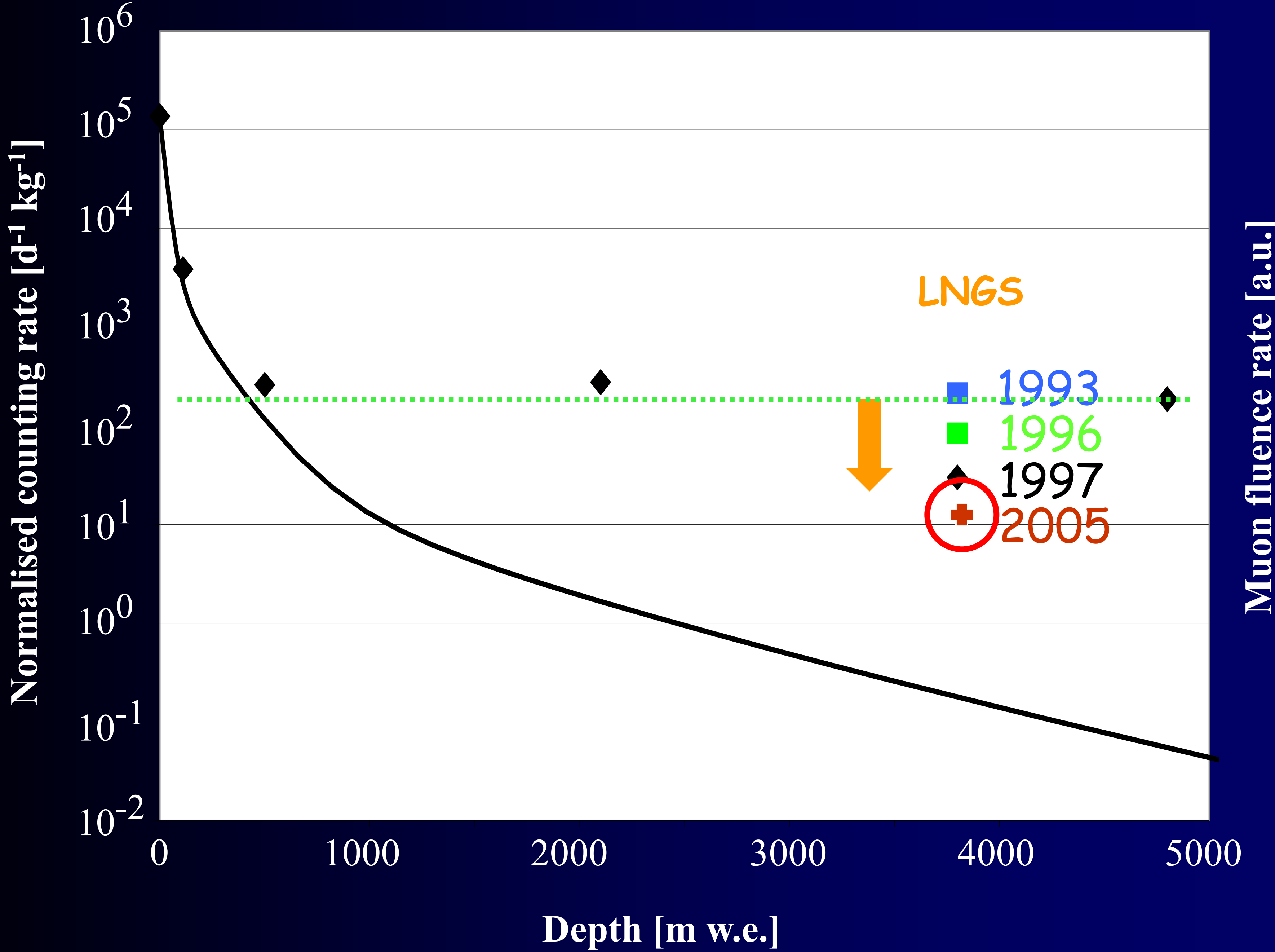
Neutrons now induced from natural radioactivity ((α,n) & fission)
(factor 10^{-3} reduction @ LNGS)

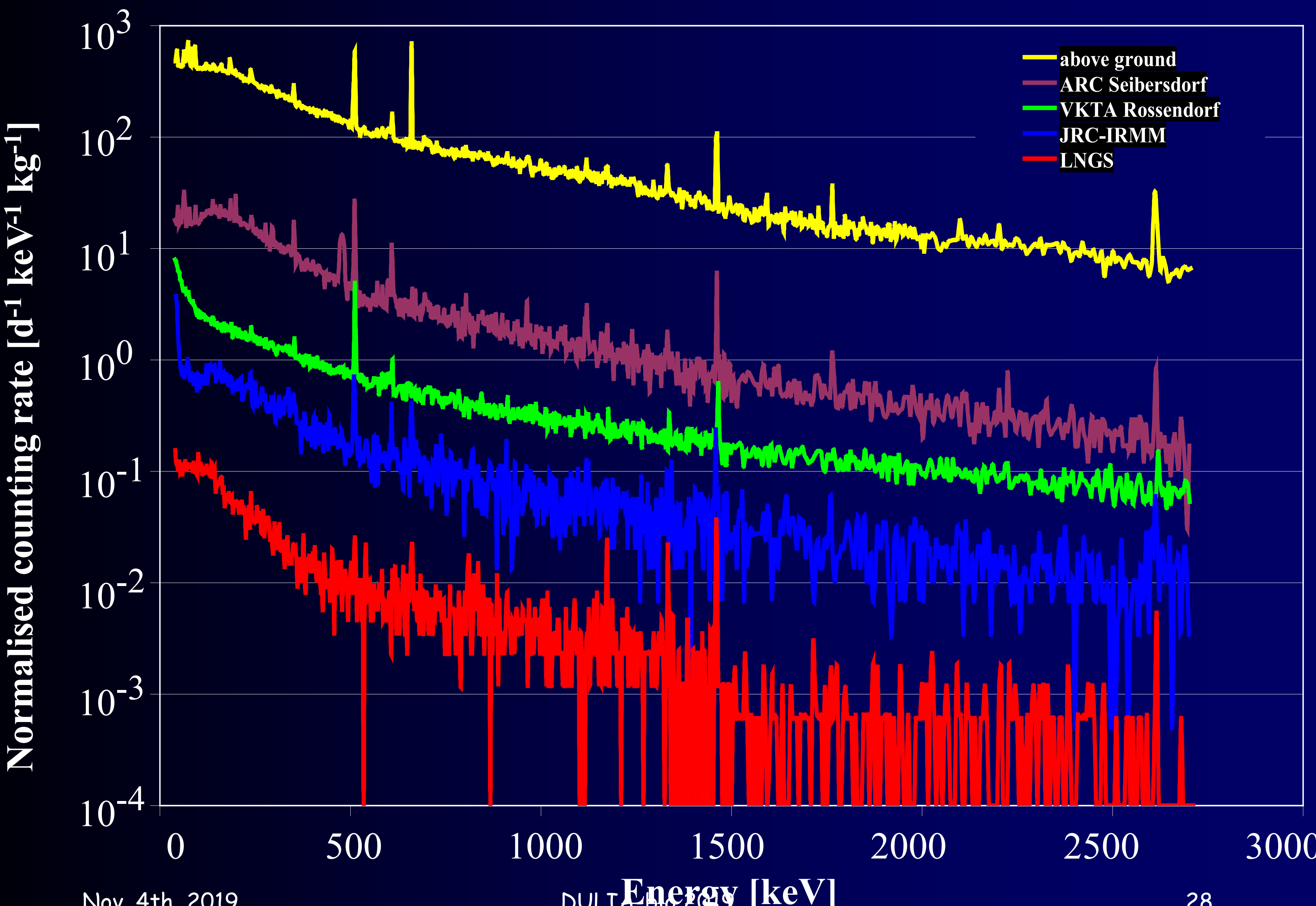
γ's now from natural radioactivity inside shielding and detector components


10^6
10^5
10^4
10^3
10^2
10^1
10^0
Normalised counting rate [d-1 kg-1]
above ground
ARC Seibersdorf
MPI-K-HD
VKTA Rossendorf
IAEA-MEL
JRC-IRMM
active + passive shield
only passive shield
Muon fluence rate [a.u.]
0
100
200
300
400
500
600
700
Depth [m w.e.]



above ground
VKTA Rossendorf
PTB
JRC-IRMM
LSCE
LNGS
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
1000
2000
3000
4000
5000
Normalised counting rate [d-1 kg-1]
Muon fluence rate [a.u.]
Depth [m w.e.]


10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
Normalised counting rate [d-1 kg-1]
LNGS
1993
1996
1997
2005
Muon fluence rate [a.u.]
0
1000
2000
3000
4000
5000
Depth [m w.e.]



above ground
ARC Seibersdorf
VKTA Rossendorf
JRC-IRMM
LNGS
Normalised counting rate [d^{-1} keV^{-1} kg^{-1}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
500
1000
1500
2000
2500
3000
Energy [keV]

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HPGe detectors

shielding:

20 cm low activity lead (^{210}Pb < 20 Bq kg^{-1})

5 cm OFHC copper

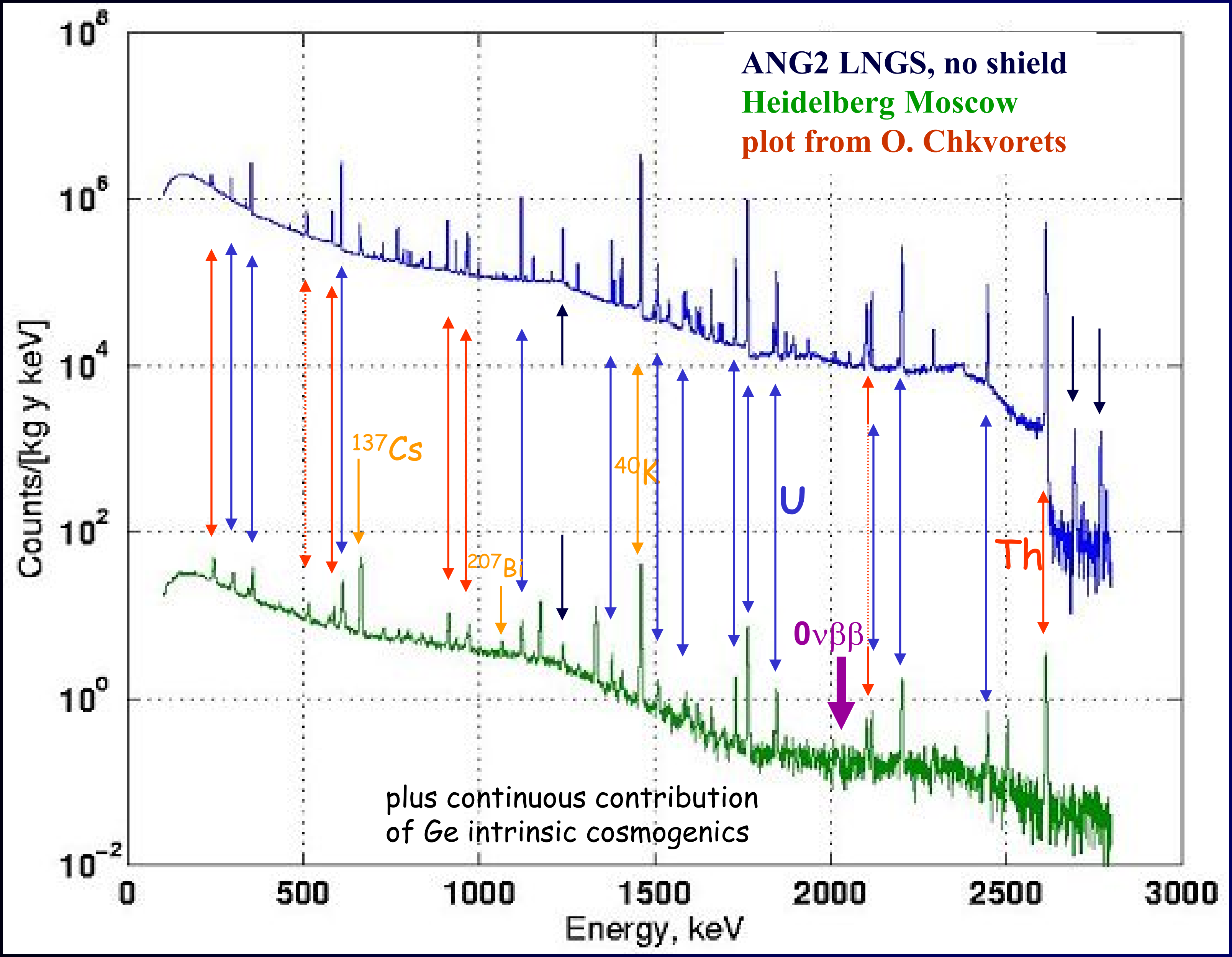
5 cm acrylic on the bottom

Rn-suppression:

1 cm acrylic cover with continuous N_2 flow

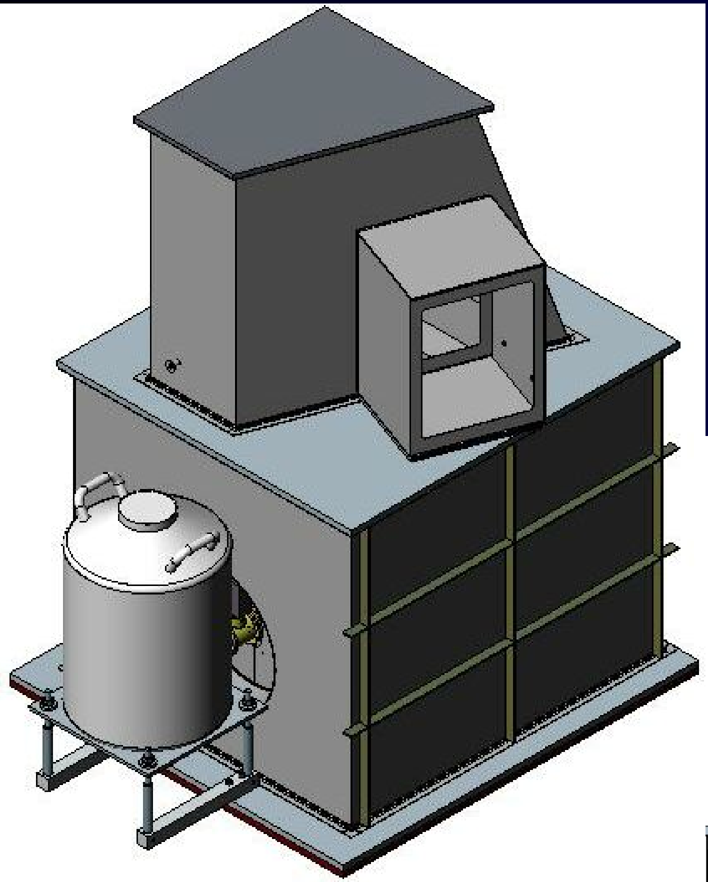
material selection:

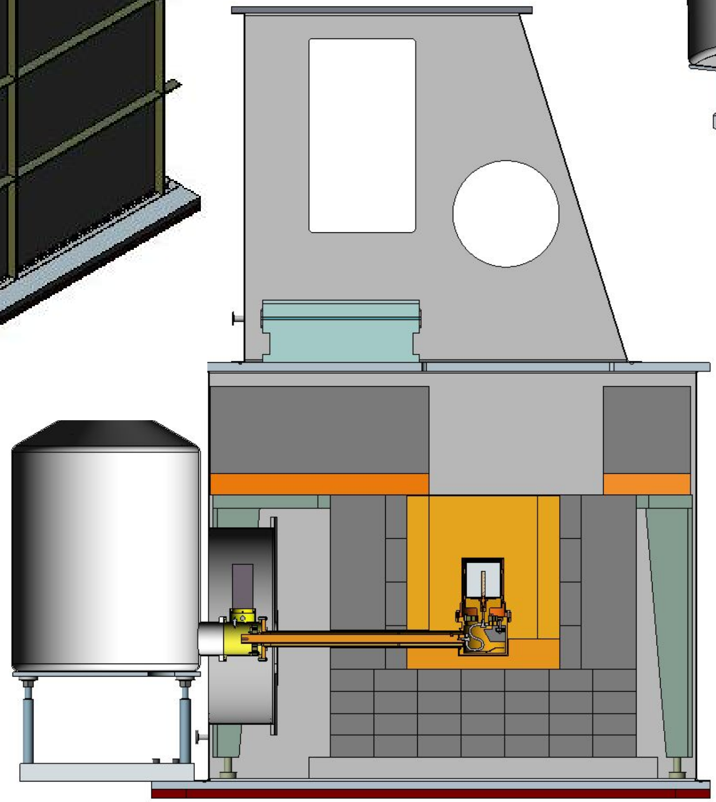
highly radiopure, (almost) no activation

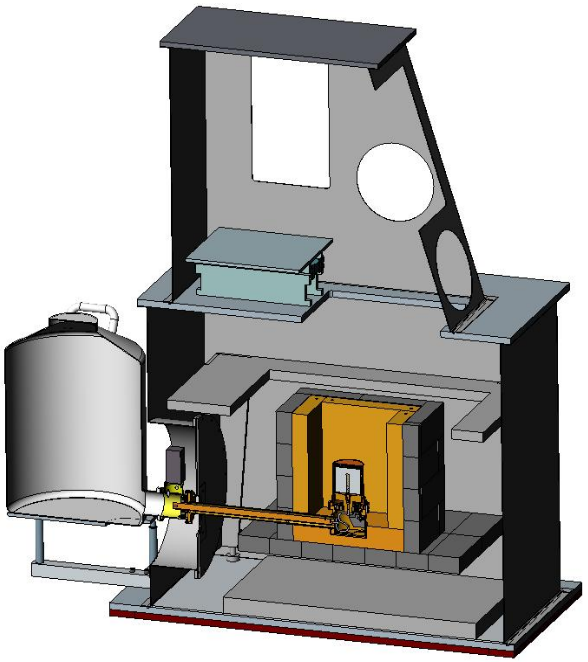

ANG2 LNGS, no shield
Heidelberg Moscow
plot from O. Chkvorets
Counts/[kg y keV]
Energy, keV
137Cs
40K
207Bi
U
Th
0νββ
plus continuous contribution
of Ge intrinsic cosmogenics

GeMPI

Operated at
LNGS
(3800 m w.e.)





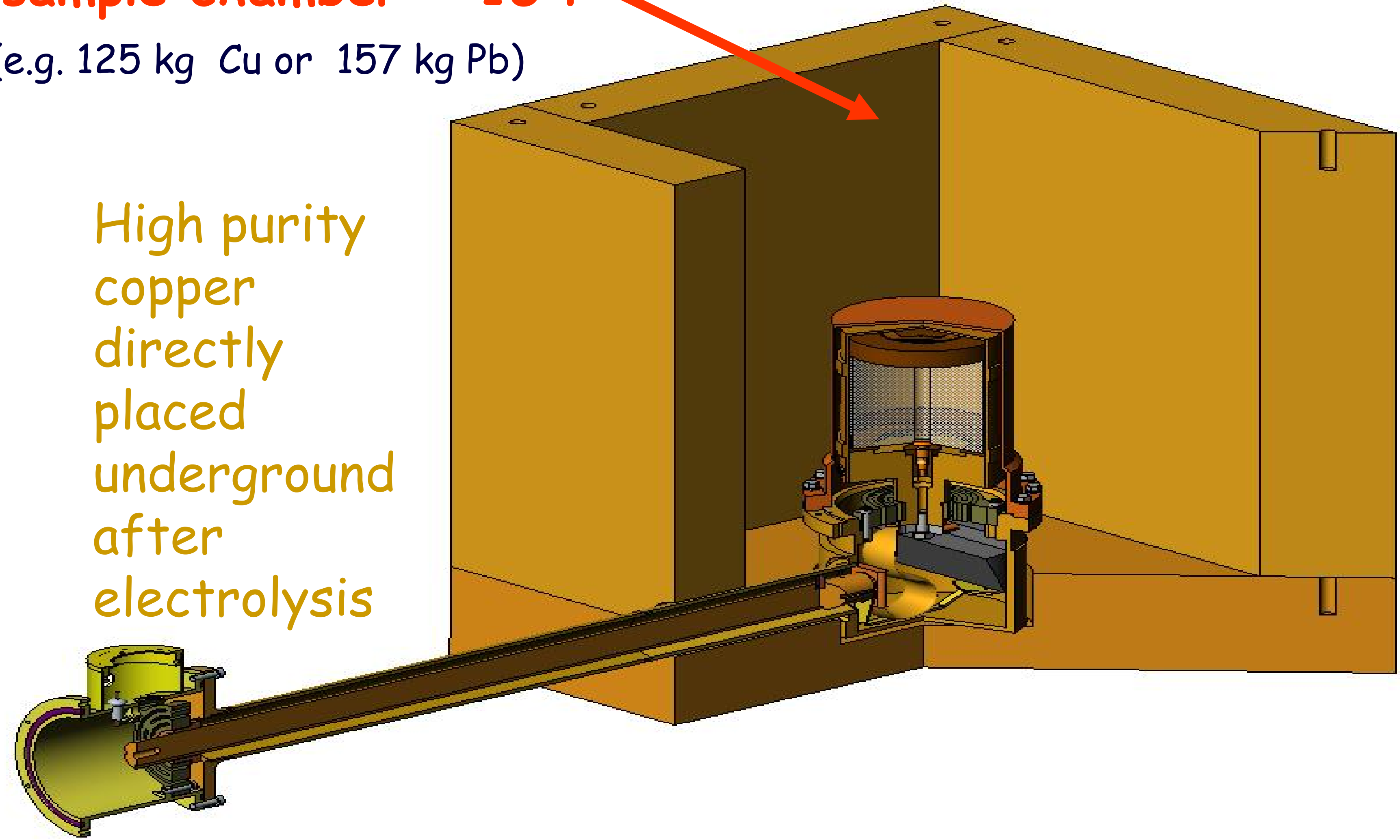


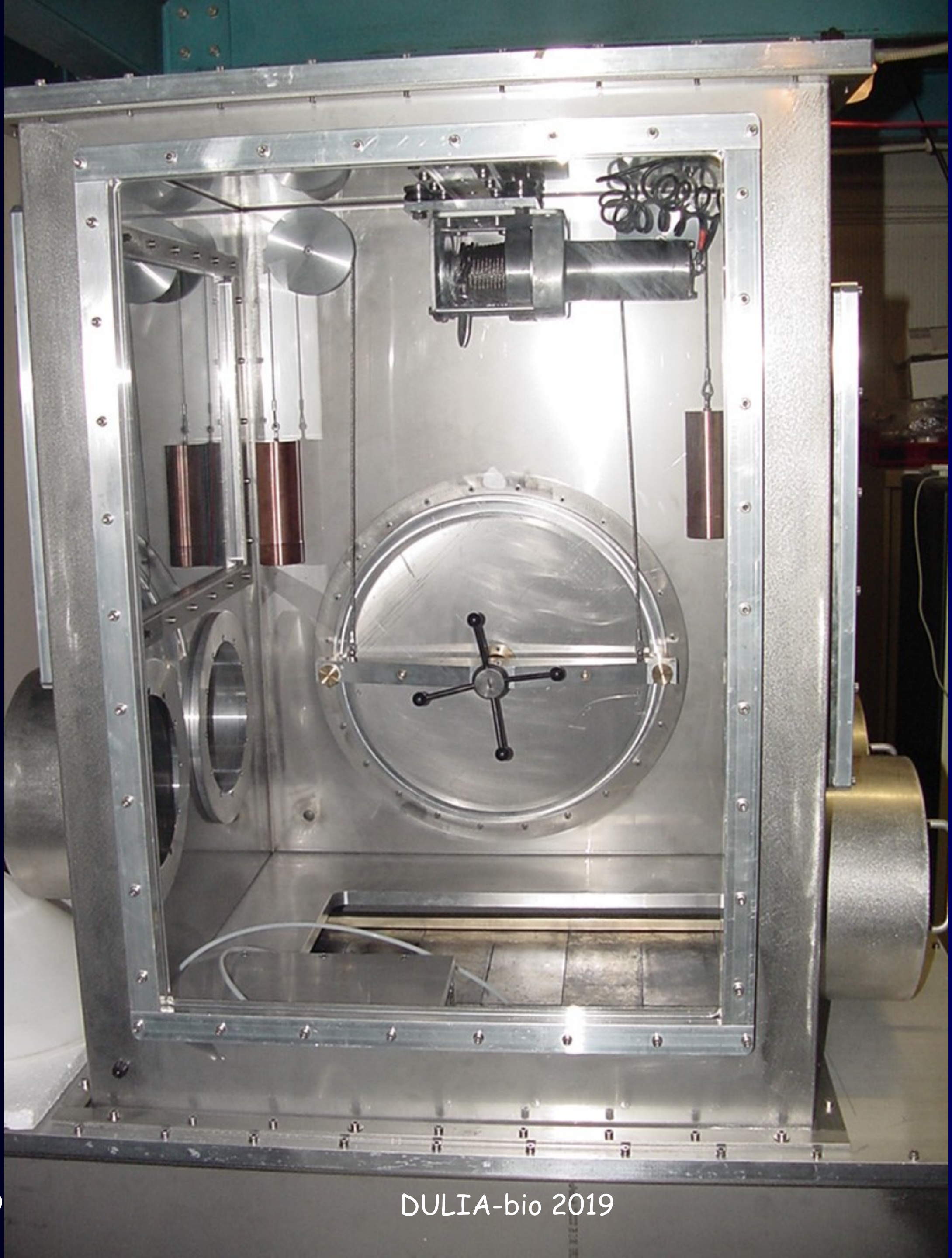
G. Heusser
B. Prokosch
H. Neder
M. Laubenstein

effective volume of sample chamber ~ 15 l

(e.g. 125 kg Cu or 157 kg Pb)

High purity copper directly placed underground after electrolysis






Nov. 4th, 2019
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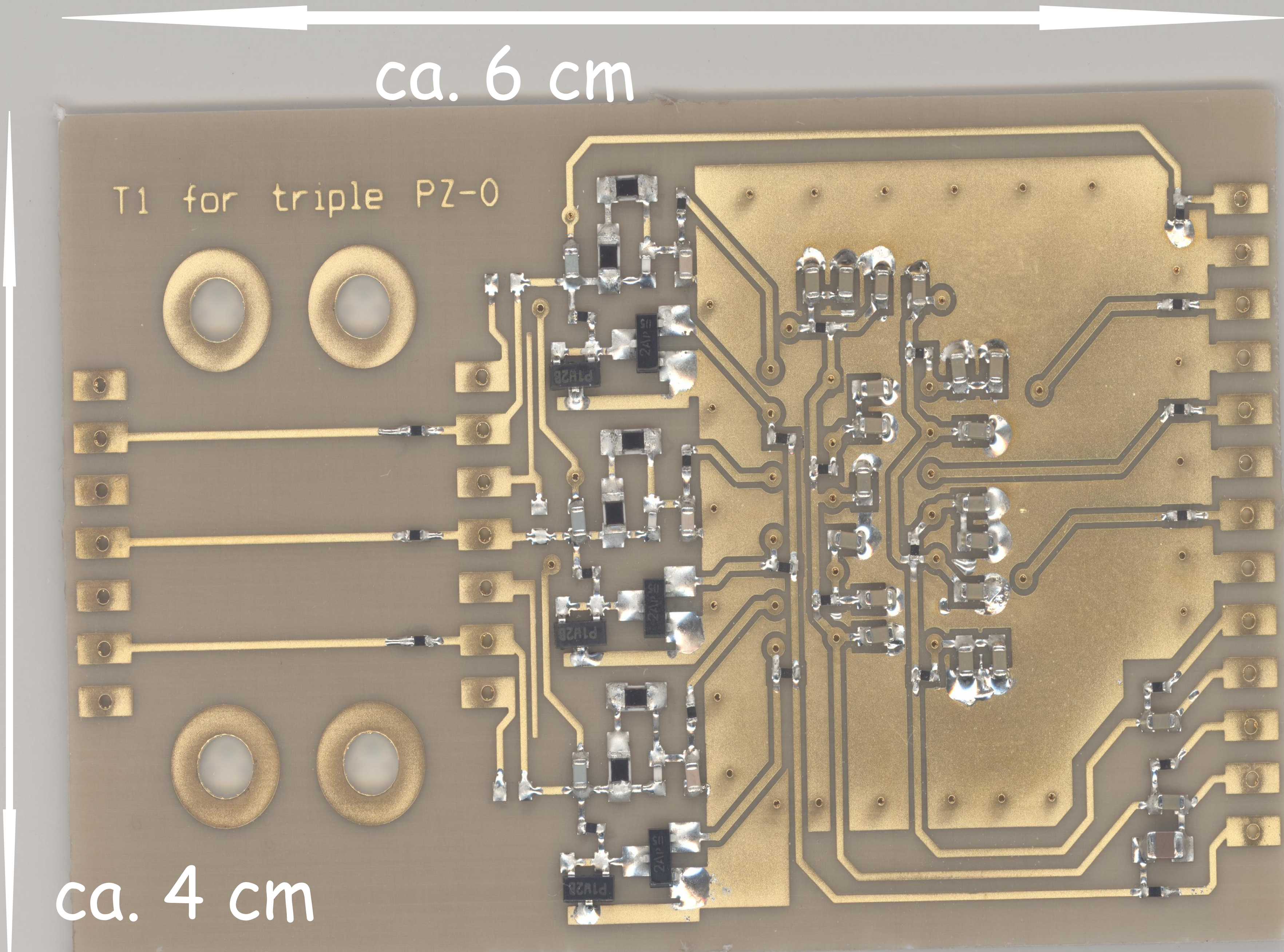
GeDSG



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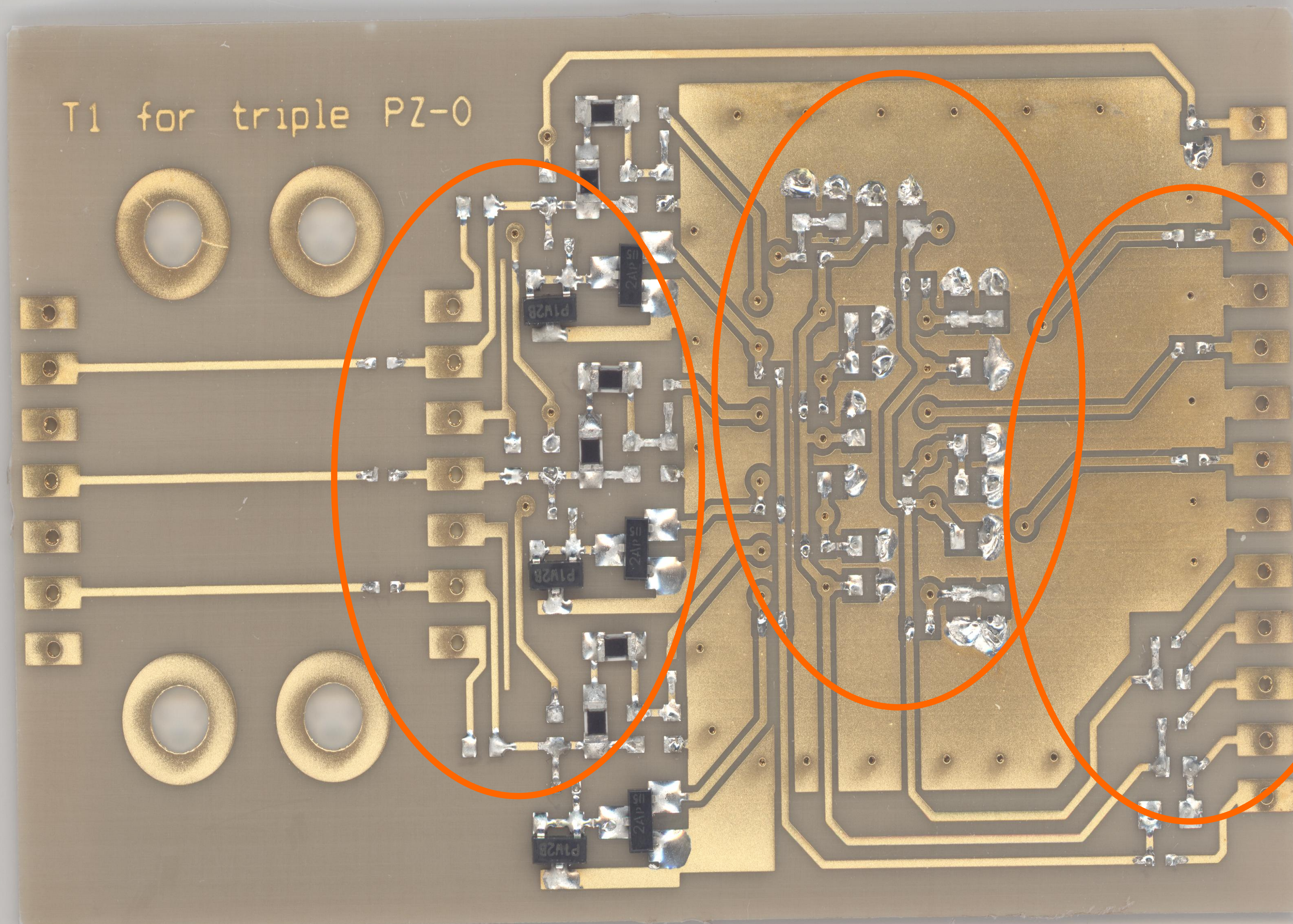

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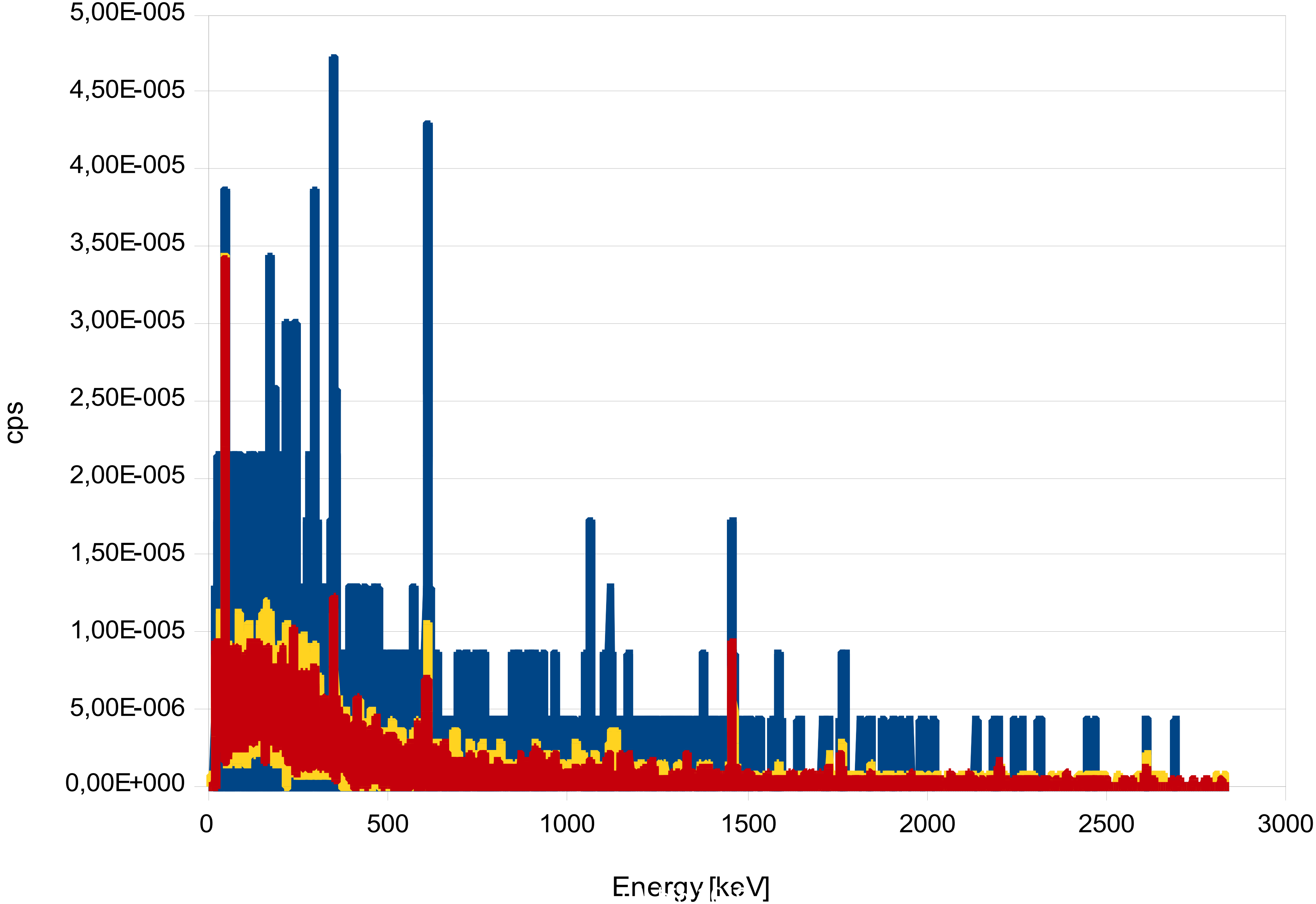
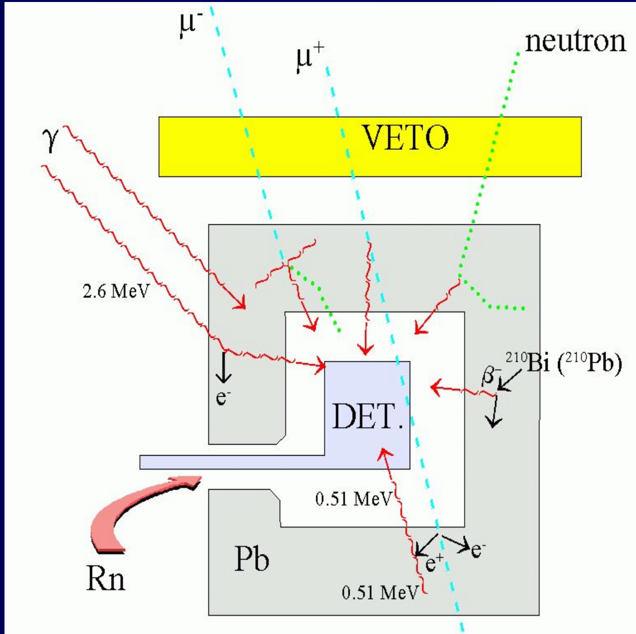
PCB 1 - with and without components & bg



Background components in Ge spectrometry

- external gamma radiation (2.6 MeV ^{208}Tl, {up to 3.2 MeV ^{214}Bi})
- radio-impurities close to crystal (primordial, anthropogenic)
- Rn and its progenies
- cosmic rays (neutrons, muon and activation)
- neutrons from fission and (α,n) reactions

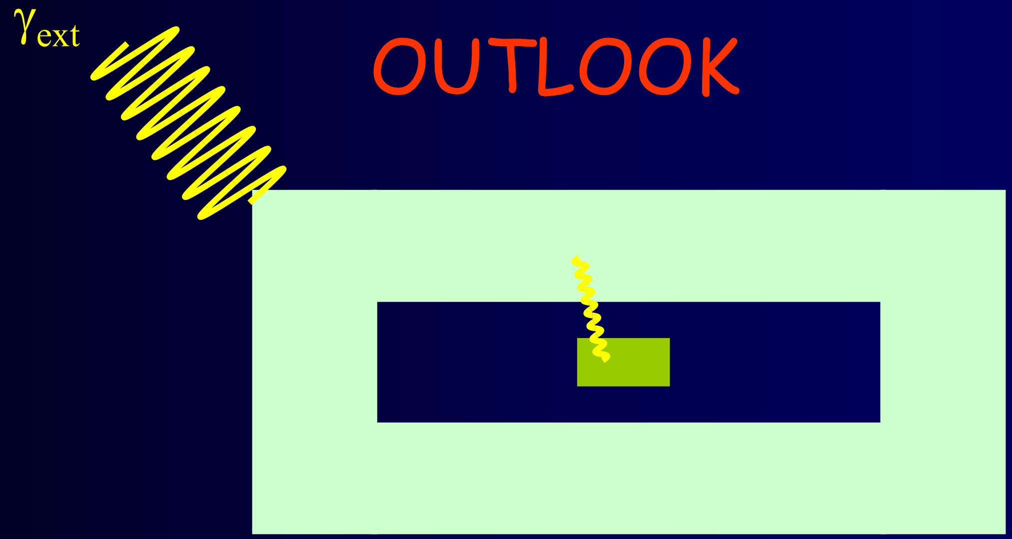


by courtesy of Dr. G. Heusser

most important: material screening

U/Th chains and K dominant from Bq/kg down to μBq/kg only reliably radiopure material - Cu – but mBq/kg cosmogenics besides Si, Ge, Au, Ag, Hg, (Pb – except ^{210}Pb)

improvements in iterative steps



OUTLOOK

further improvements possible:

- neutron shield
- material selection improved
- active shield
- going deeper underground
- storage of construction material underground
- multisegmented crystals or multiple crystals
- collaboration with producers

Conclusions

1.) The exceptional sensitivity and high resolution of high purity germanium detectors in gamma-ray spectrometry and their use in underground laboratories has increasing application.

2.) A growing number of underground measurements is done in fields such as environmental monitoring, surveillance of nuclear activities, benchmarking and material selection for experiments, which require materials with extremely low levels of radioactivity.