Low-background techniques applied in the BOREXINO experiment

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Outline

- BOREXINO
- BOREXINO radio-purity
- Background mitigation techniques
- Summary

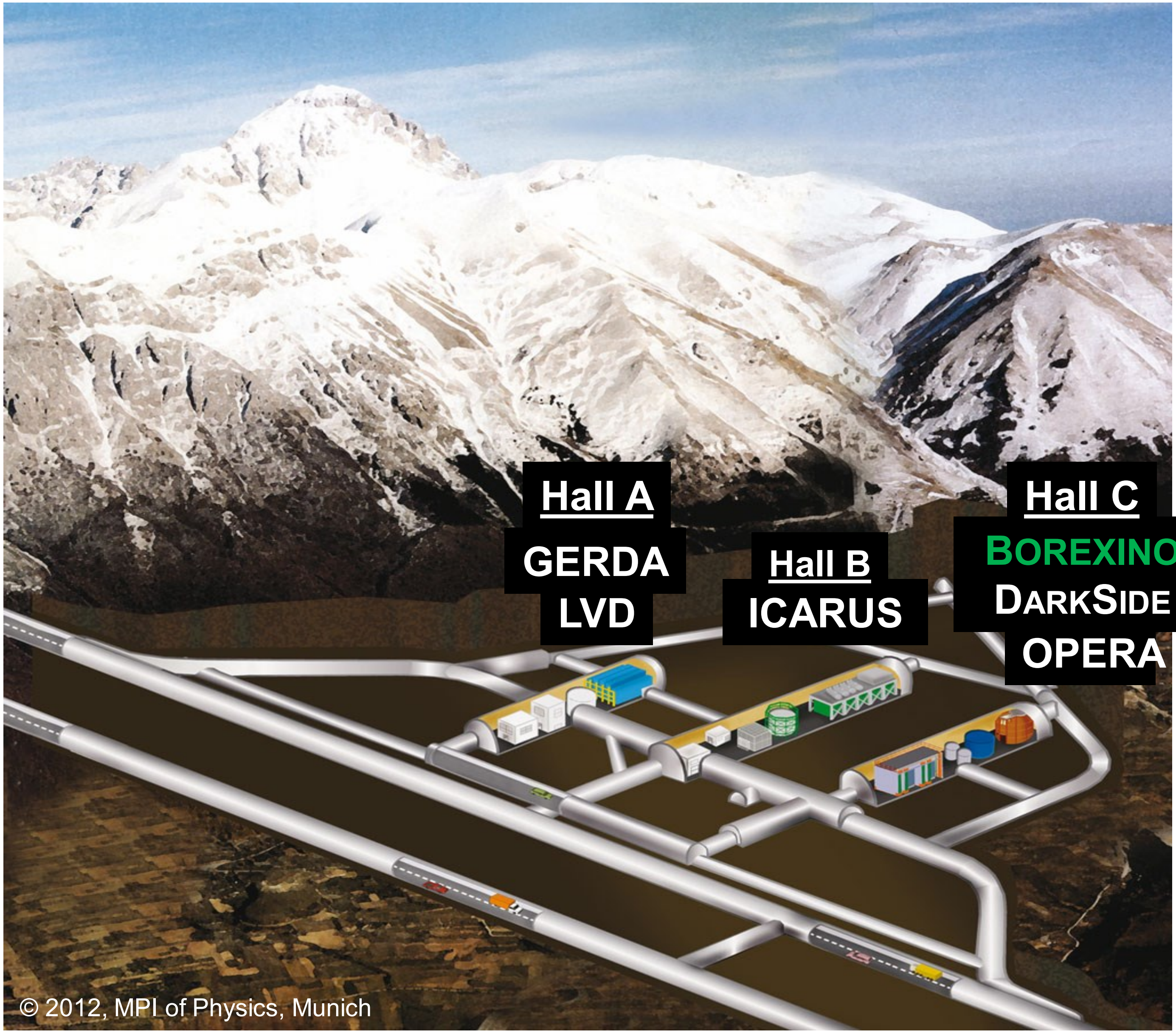
BOREXINO at LNGS

BOREXINO

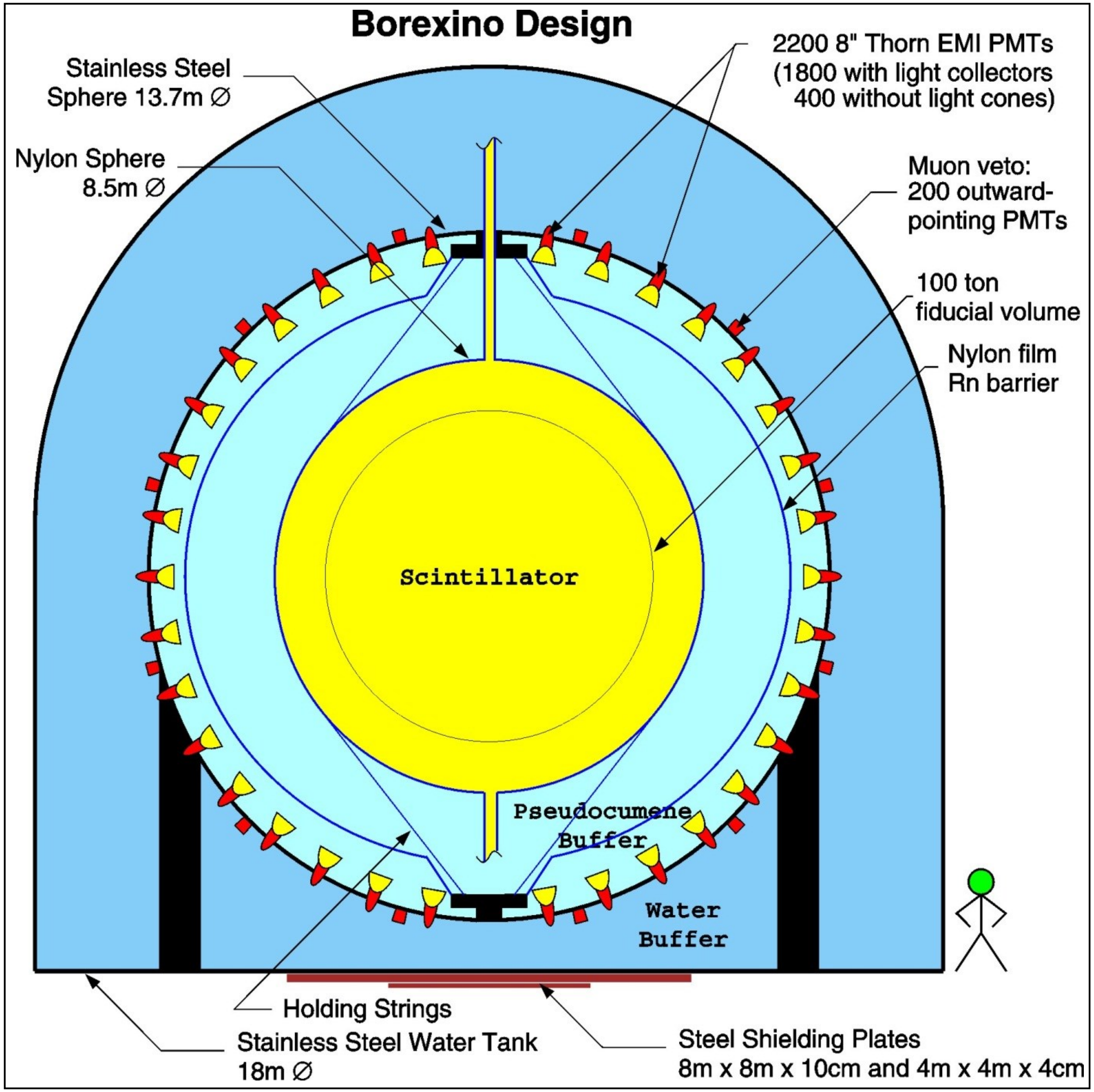
Bx radio-purity

Bcg mitigation

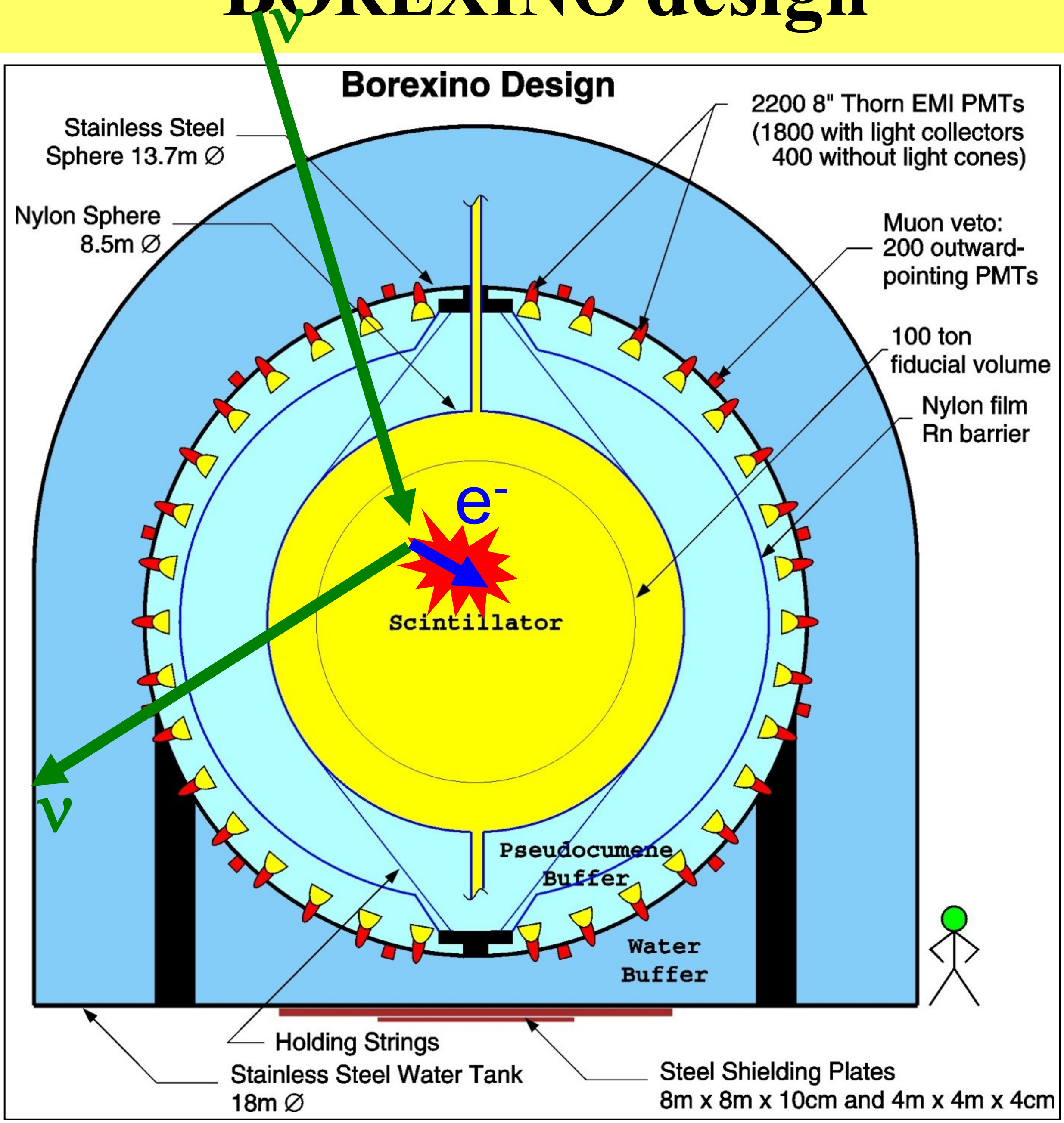
Summary



BOREXINO design



BOREXINO design



BOREXINO radio-purity

In a nutshell: the cleanest detector ever built

Isotope	Specification for LS	Before purification	After purification
^{238}U	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5)\cdot 10^{-18}$ g/g	**< $0.8\cdot 10^{-19}$ g/g**
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8)\cdot 10^{-18}$ g/g	**< $1.2\cdot 10^{-18}$ g/g**
$^{14}C/^{12}C$	$\leq 10^{-18}$	$(2.69 \pm 0.06)\cdot 10^{-18}$ g/g	unchanged
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4\cdot 10^{-18}$ g/g	Unchanged
^{85}Kr	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{39}Ar	$\leq$ 1 cpd/100 t	$\ll$ ^{85}Kr	$\ll$ ^{85}Kr
^{210}Po	not specified	~ (70) 1 dpd/100 t	unchanged
^{210}Bi	not specified	(20) 70 dpd/100 t	**(20 ± 5) cpd/100 t**

$$A_{Bx} = \sum (bcg\ ev.) \sim 30 \frac{cpd}{100\ t} \sim \mathbf{10^{-9}} \frac{\mathbf{Bq}}{\mathbf{kg}}$$

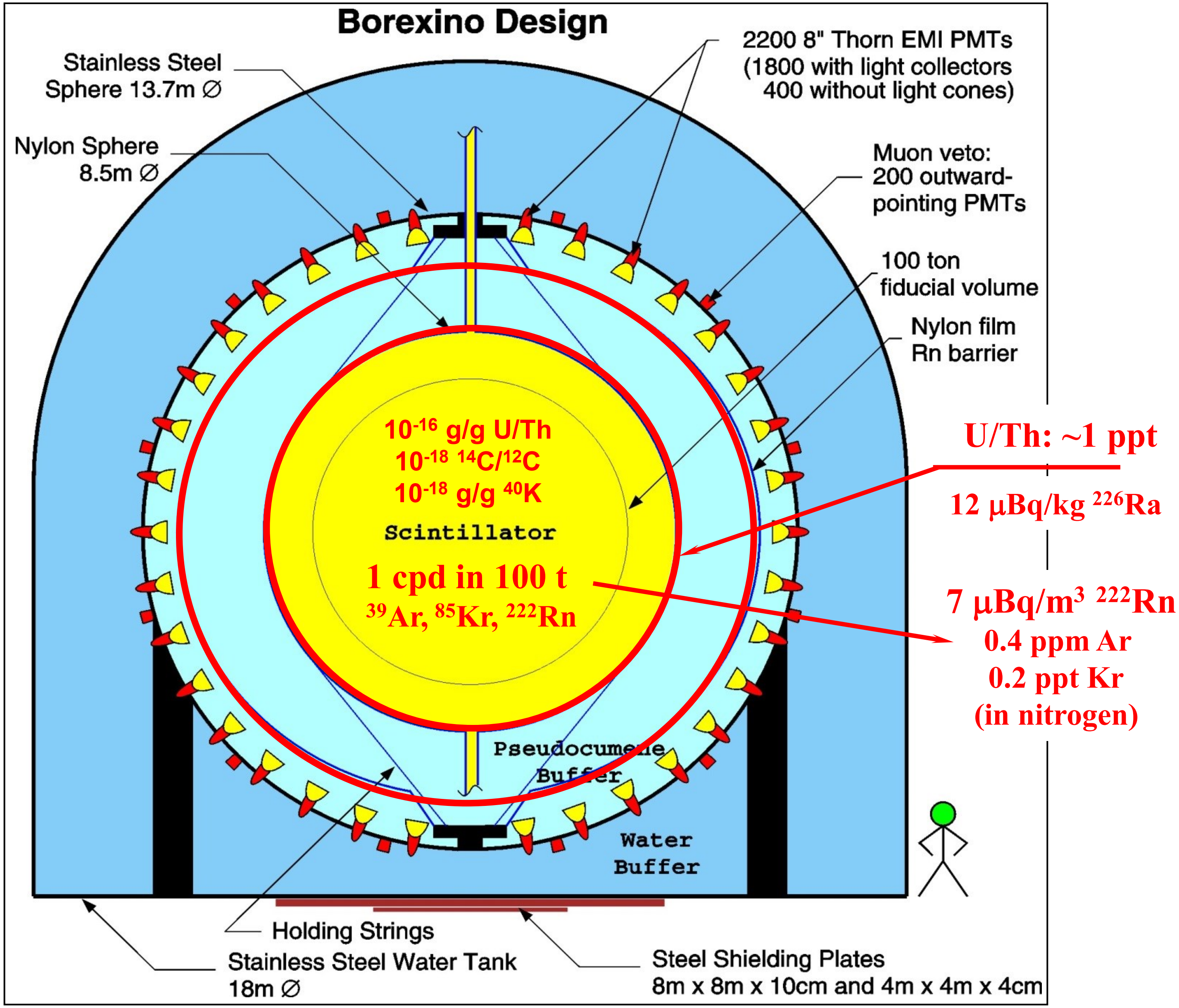
$$A_{water} \sim \mathbf{10} \frac{\mathbf{Bq}}{\mathbf{kg}}$$

$\rightarrow$ *activity reduction factor* $\boldsymbol{f \sim 10^{10}}$

Background mitigation techniques

- Graded shielding: traveling inward to the center, each component is protected from external radiation by the preceding one
- The radio-purity level is increasing towards the center
- Active (definition of FV, Čerenkov veto) and passive (PC buffer, water) suppression of external radiation
- Careful selection of construction materials and detector components with respect to content of radioactive isotopes, ^{222}Rn emanation and permeability
- Application of appropriate purification (liquids, gases) and cleaning techniques
- Preventing surface contamination

BOREXINO design



CTF – testing the scintillator

CFT – 1: 1995
CTF – 2: 2000
CTF – 3: 2001-2003

- Phys. Lett. B, 422, 349 (1998)
- Astrop. Phys. 8(3), 141 (1998)
- NIM A406, 411 (1998)
- Physics Letters B 525, 29 (2002)
- Physics Letters B 563, 23 (2003)
- Physics Letters B 563, 37 (2003)
- JETP Lett. 78 No 5, 261 (2003)
- Eur. Phys. J. C 37, 421 (2004)
- Eur. Phys. J. C 47, 21 (2006)
- Phys. Rev. C 74, 045805 (2006)

$\frac{^{14}C}{^{12}C} \sim 10^{-18}$ $\quad$ $C_{U/Th} \sim 4 \times 10^{-16}\ g/g$

HPGe spectroscopy

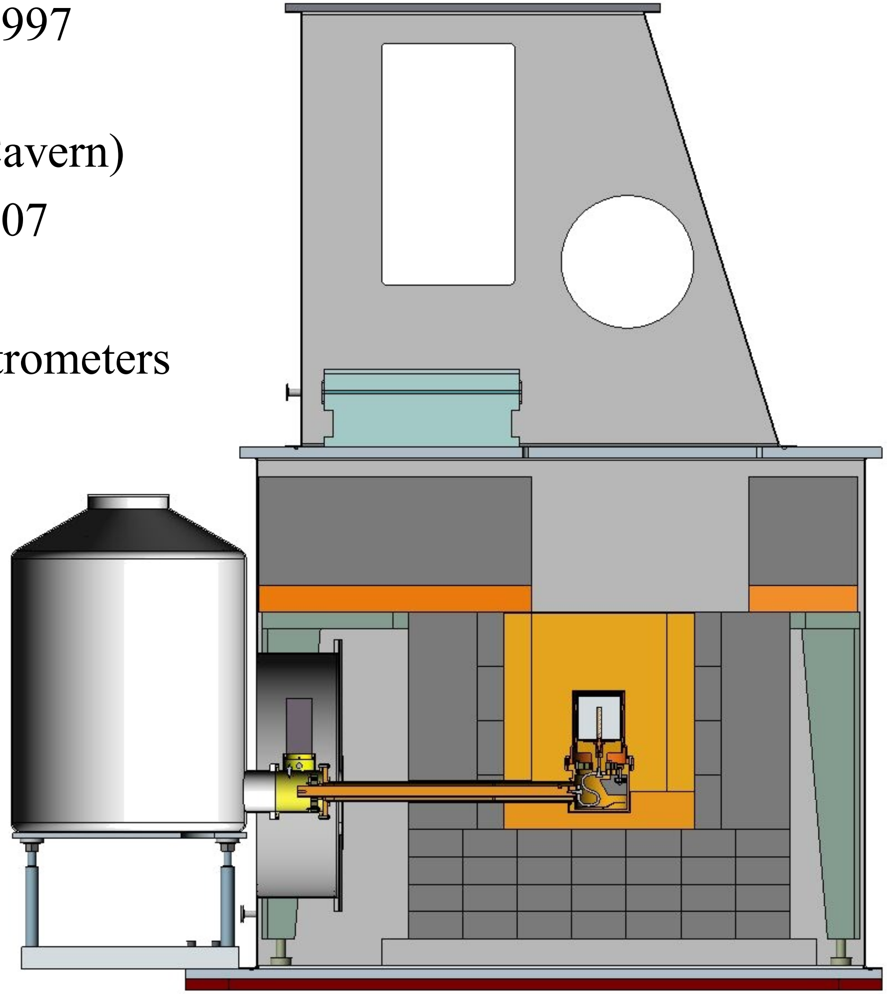
GeMPIs at GS (3800 m w.e.)

- GeMPI I operational since 1997 (MPIK)
- GeMPI II built in 2004 (MCavern)
- GeMPI III constructed in 2007 (MPIK/LNGS)
- World's most sensitive spectrometers

GeMPI I:

- Crystal: 2.2 kg, ε_r = 102 %
- Bcg. Index (0.1-2.7 MeV): 6840 cts/kg/year
- Sample chamber: 15 l

Sensitivity for U/Th: ~10 μBq/kg



Appl. Rad. Isot., 53 (2000) 191
Astrop. Phys. 18 (2002) 1

Survey of charcoals

BOREXINO

Bx radio-purity

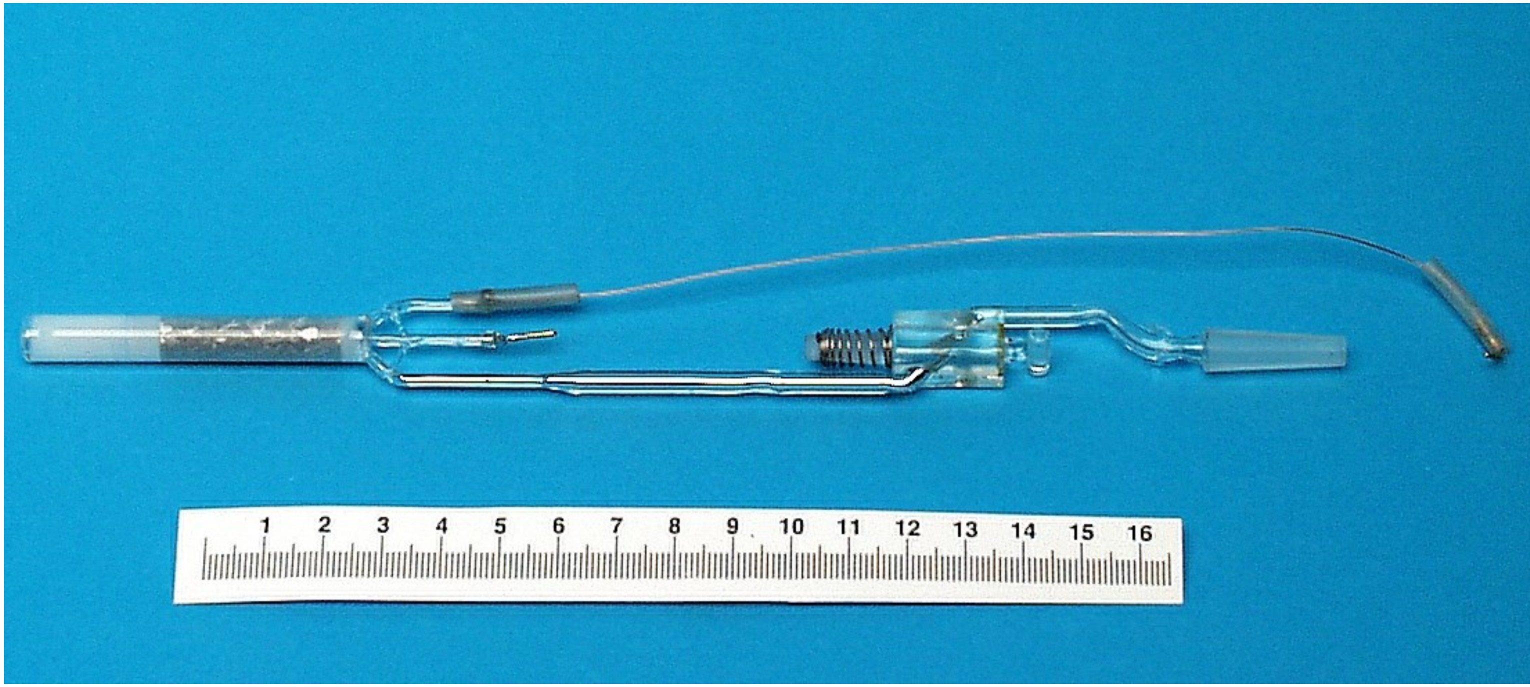
Bcg mitigation

Summary

charcoal sample	*specific activity [Bq/kg]*				
	^{137}Cs	^{228}Th	^{40}K	^{226}Ra	^{222}Rn
Silcarbon Sil40	≤ 1	28 ± 2	80 ± 3	28 ± 2	
Silcarbon C46	1.2 ± 0.2	1.0 ± 0.2	380 ± 15	1.0 ± 0.2	
Silcarbon K48	≤ 1	0.5 ± 0.3	10 ± 0.7	0.4 ± 0.3	0.28 ± 0.05[a]
Hydraffin CC8x30	1.3 ± 0.2	1.2 ± 0.3	275 ± 14	1.0 ± 0.3	0.33 ± 0.02[a]
Hydraffin UV43	3.4 ± 0.2	0.7 ± 0.3	1130 ± 44	0.5 ± 0.3	
Model PCB616	5.3 ± 0.3	0.18 ± 0.12	120 ± 7	0.37 ± 0.09	
Model 1193	0.6 ± 0.1	≤ 0.3	360 ± 20	0.20 ± 0.11	
Alcarbon 12x20	0.1 ± 0.06	≤ 0.3	590 ± 24	≤ 0.3	0.17 ± 0.02[a]
Alcarbon 7x16	1.5 ± 0.2	≤ 0.4	690 ± 28	≤ 0.3	0.10 ± 0.02[a]
Activated Carbon	≤ 0.5	≤ 0.5	≤ 2	≤ 0.3	0.0003 ± 0.0001

[a] Wetterauer, (1994)

^{222}Rn detection



- Developed for the GALLEX/GNO experiment
- Hand-made at MPI-K (~ 1 cm^3 active volume)
- In case of ^{222}Rn only α-decays are detected
- 50 keV threshold
  - bcg: 0.1 – 2 cpd
  - total detection efficiency of ~ 1.5
- Absolute detection limit ~ 30 μBq (15 atoms)

^{222}Rn emanation

- BOREXINO
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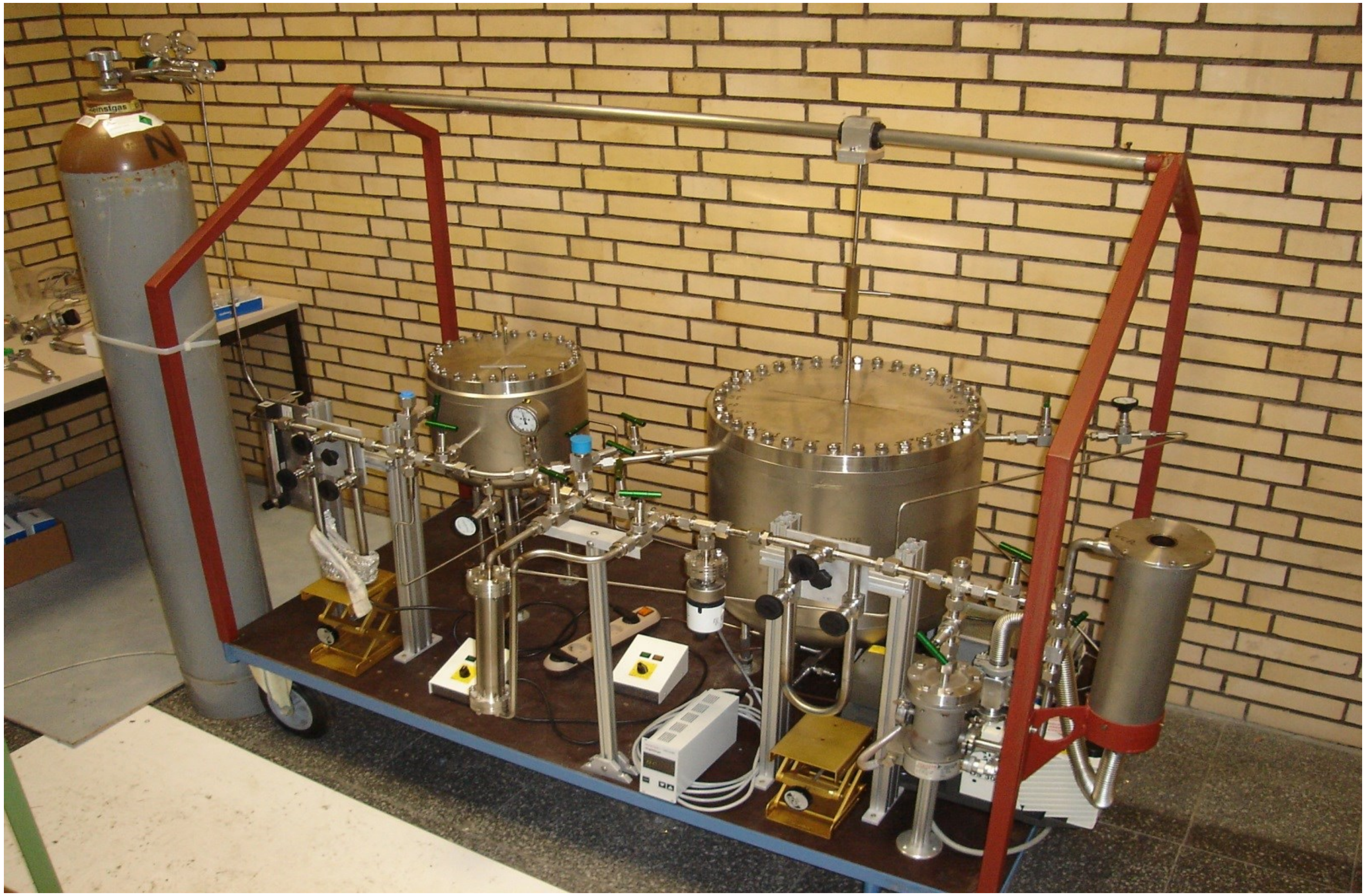


Blanks:

20 l → 50 μBq

80 l → 80 μBq

Absolute sensitivity
~100 μBq [50 atoms]

Appl. Rad. Isot. 53 (2000) 371

Subsystem	Sample	Description	^{222}Rn emanation rate in saturation
Pseudocumene storage area	Stainless steel (SS) vessel TK1	~ 114 m^3, ~ 140 m^2	< 60 mBq
	SS vessel TK2	~ 114 m^3, ~ 140 m^2	(45 ± 8) mBq
	SS vessel TK4	~ 114 m^3, ~ 140 m^2	(24 ± 5) mBq
N_2 distribution system	Electrical heater		(0.92 ± 0.29) mBq
	Pall Supercheminert particle filter	Code: AB1F0023EH11	(0.34 ± 0.13) mBq
	1.5 inch nitrogen distribution line	~ 100 m long with several ports	(0.47 ± 0.13) mBq
Scintillator purification plant	SS package for H_2O extraction column	25 m^2 surface	< 0.12 mBq
(All components are made	H_2O extraction column containing 24 SS packages	Volume: 0.6 m^3, Surface: 608 m^2	(4.83 ± 0.70) mBq
from electro-polished SS)	N_2 sparging column containing 26 SS packages*	Volume: 0.2 m^3, Surface: 280 m^2	(1.78 ± 0.21) mBq
	Tank for H_2O extraction of master solution (HT2)	Volume: 2.1 m^3	(1.22 ± 0.37) mBq
	Tank for storage of master solution (D330)	Volume: 1.58 m^3	(7.13 ± 1.15) mBq
	Buffer tank		< 0.34 mBq
	Body of heat exchanger	measured before reassembly	(2.42 ± 0.17) mBq
	Head of heat exchanger	measured before reassembly	(37.9 ± 2.1) mBq
	Heat exchanger (body plus head)	measured after reassembly	(0.3 ± 0.1) mBq
Nylon inner vessel	Bulk of sniamid nylon film extruded by *MF-Folien*	thickness: 125 μm, cleaned by *CleanFilm*	< 21 μBq/kg
	Surface of sniamid nylon film extruded by *MF-Folien*	thickness: 125 μm, cleaned by *CleanFilm*	< 0.8 μBq/m^2

* Note that a SS package for the N_2 sparging column is significantly smaller than a SS package for the H_2O extraction column.

Over 1000 entries in the DB!

Astroparticle Physics 18 (2002) 1
LRT 2004 proceedings, p. 141 – 149
Int. J. Mod. Phys. A29 (2014) 1442009

^{222}Rn emanation from charcoals

CarboAct for LTA II

Sample No.	Description	Sample mass [kg]	Extraction temp.* [°C]	Emanation rate [mBq/kg]
1	First shipment (few kilograms), April 2001, big glass vial used for test	0.15	200 22	< 0.6 not tested
2	Second shipment (≅ 200 g), May 2001, big glass vial used for test	0.17	220 22	1.5 ± 0.5 < 0.3
3	Third shipment, July 2001 (1 Liter ≅ 170 g), small glass vial used for test	0.06	200 22	1.7 ± 0.8 < 0.6
4	Feb. 2002 (58 g), small glass vial used for test	0.058	200 22	2.6 ± 0.9 0.6 ± 0.4

*) During the Rn growth-in time samples were kept under normal conditions (room temp. ≈ 22 °C) and only short time before and during the extractions charcoal was heated up to the given temperature.

Carbosieve SIII (Kr removal from N_2)

Sample No.	Description	Sample mass [kg]	Extraction temp.* [°C]	Emanation rate [mBq/kg]
1		-	20	0.7 ± 0.1

$^{222}Rn/^{226}Ra$ in water

BOREXINO
Bx radio-purity
Bcg mitigation
Summary

STRAW: System for the ^{222}Rn and ^{226}Ra Assay of Water

- Placed at the BOREXINO water plant
- ^{222}Rn extraction from 350 liters
- ^{222}Rn and ^{226}Ra measurements possible

^{222}Rn detection limit: ~0.1 mBq/m^3
^{226}Ra detection limit: ~0.8 mBq/m^3

Nucl. Instr. Meth. A 497 (2003) 407

H_2O flow [m^3/h]	HPN_2 flow [kg/h]	C_{Rn} [mBq/m^3]	C_{Ra} [mBq/m^3]
2	30	704 ± 7	1.2 ± 0.5
1	20	247 ± 6	3.8 ± 0.7
1	30	186 ± 5	2.0 ± 0.6
Loop mode		3.0 ± 0.4	1.3 ± 0.9

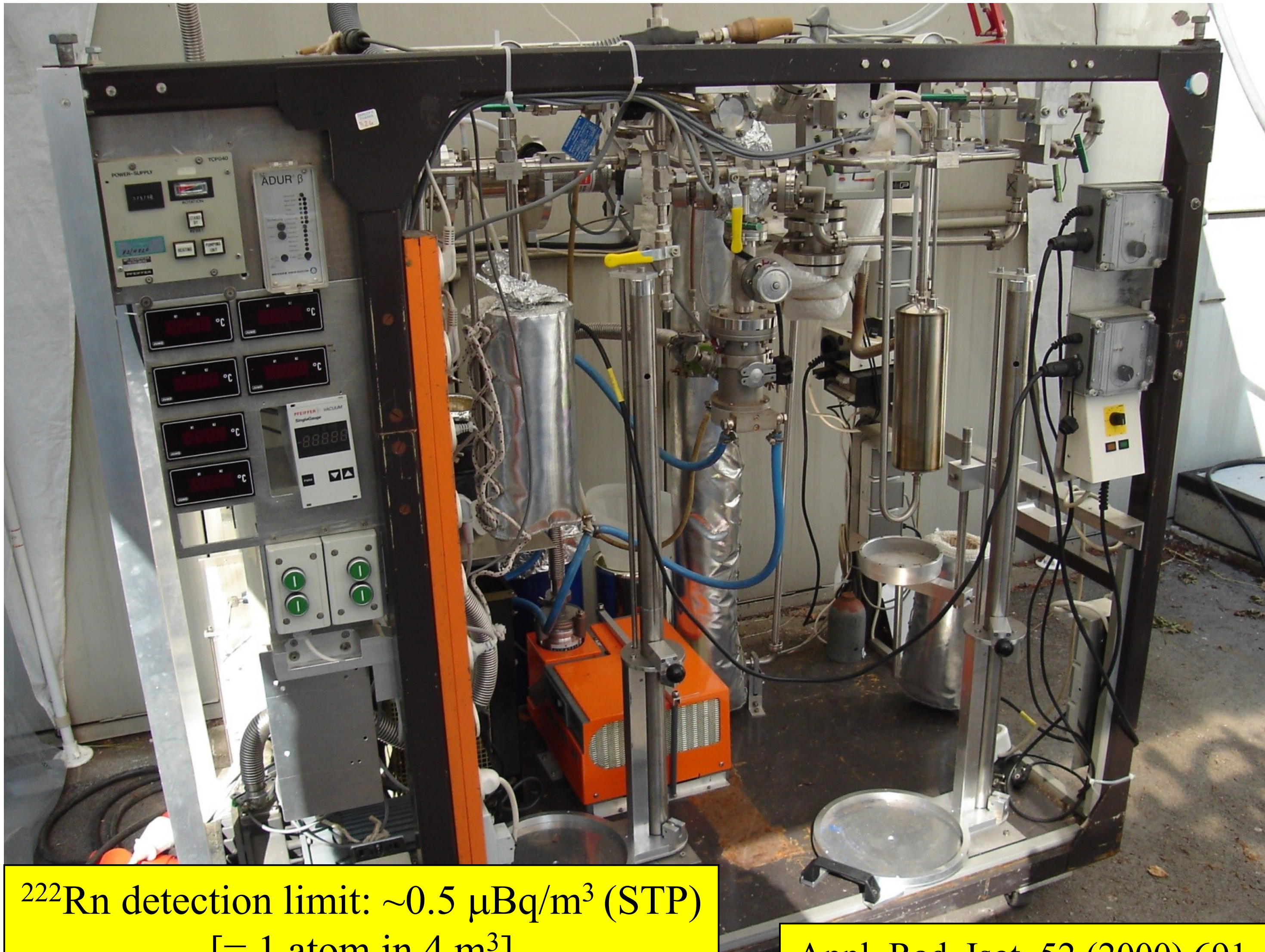
^{222}Rn in gases: MoREx

BOREXINO

Bx radio-purity

Bcg mitigation

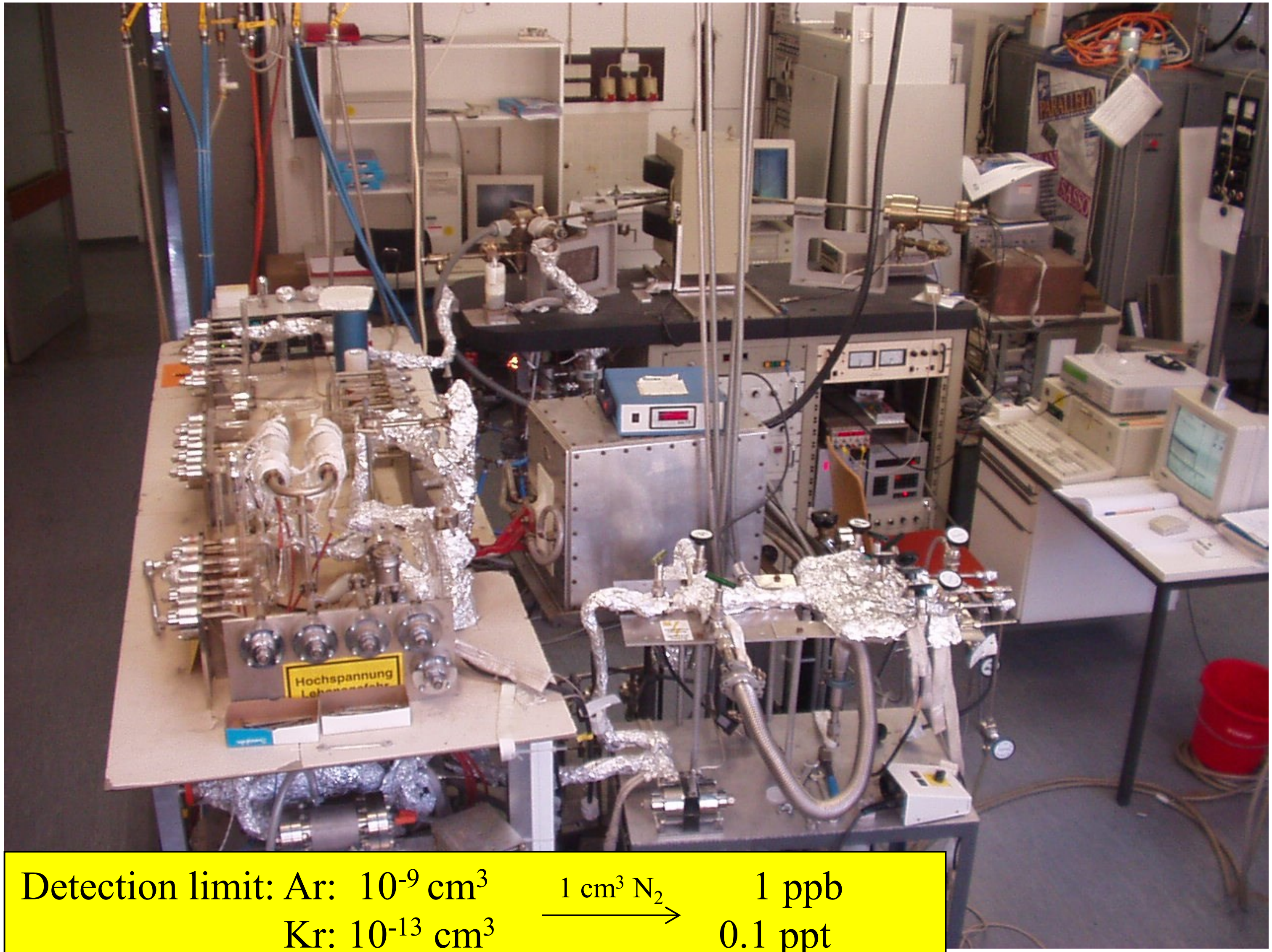
Summary



^{222}Rn detection limit: ~0.5 µBq/m^3 (STP)
[= 1 atom in 4 m^3]

Appl. Rad. Isot. 52 (2000) 691

Ar and Kr in nitrogen



Detection limit: Ar: 10^{-9} cm^3 $\xrightarrow{1\ \mathrm{cm}^3\ N_2}$ 1 ppb

Kr: 10^{-13} cm^3 0.1 ppt

BOREXINO nitrogen

BOREXINO

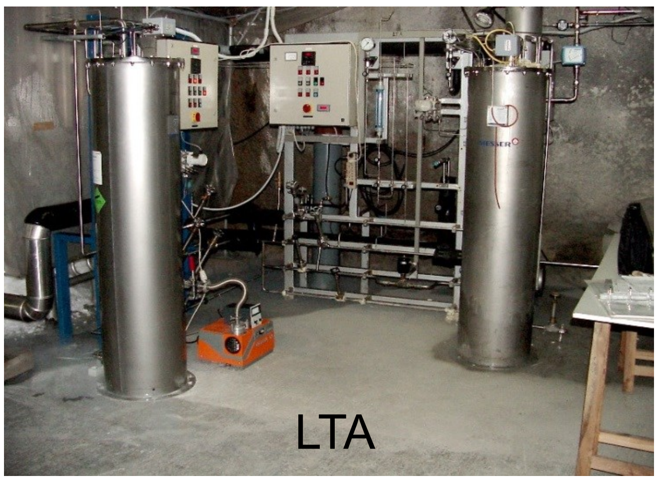
Bx radio-purity

Bcg mitigation

Summary

Regular Purity Nitrogen:
- Technical 4.0 quality, not purified
- Production rate up to 100 m3/h (STP)
- **^{222}Rn (30 – 70) µBq/m^3**
  Ar ~ 10ppm, Kr ~ 30 ppt

High Purity Nitrogen:
- ^{222}Rn adsorption on charcoal (LTA)
- Achieved concentration **(0.30 ± 0.09) µBq/m^3**
- Production rate up to 100 m^3/h (STP)
- Ar and Kr not removed



LAK (Low Ar and Kr) Nitrogen:
- Spec. Ar < 0.4 ppm, Kr < 0.2 ppt
  ^{222}Rn < 7 µBq/m^3
- Purification by adsorption on different materials extensively studied (successfully!)
- Cooperation with companies on the nitrogen survey
- Tests of the nitrogen delivery chain

Nitrogen survey

Nitrogen sample	C_{Ar} [ppm]	C_{Kr} [ppt]
MESSER (4.0)	200 ± 30	1680 ± 240
Air Liquide (4.0)	11.0 ± 1.3	40 ± 5
Linde AG, (7.0)	0.031 ± 0.004	2.9 ± 0.4
SOL (6.0)	0.0063 ± 0.0006	0.04 ± 0.01
Westfalen AG (6.0)	0.00050 ± 0.00008	0.06 ± 0.02
Goal (BOREXINO)	< 0.4	< 0.2

Tests of the delivery chains

Supplier/setup	C_{Rn} [µBq/m^3]	C_{Ar} [ppm]	C_{Kr} [ppt]
Linde AG, 3-m^3 movable tank	1.2	0.018	0.06
SOL, 16-m^3 tank	8	0.012	0.02

BOREXINO LAK nitrogen

- BOREXINO
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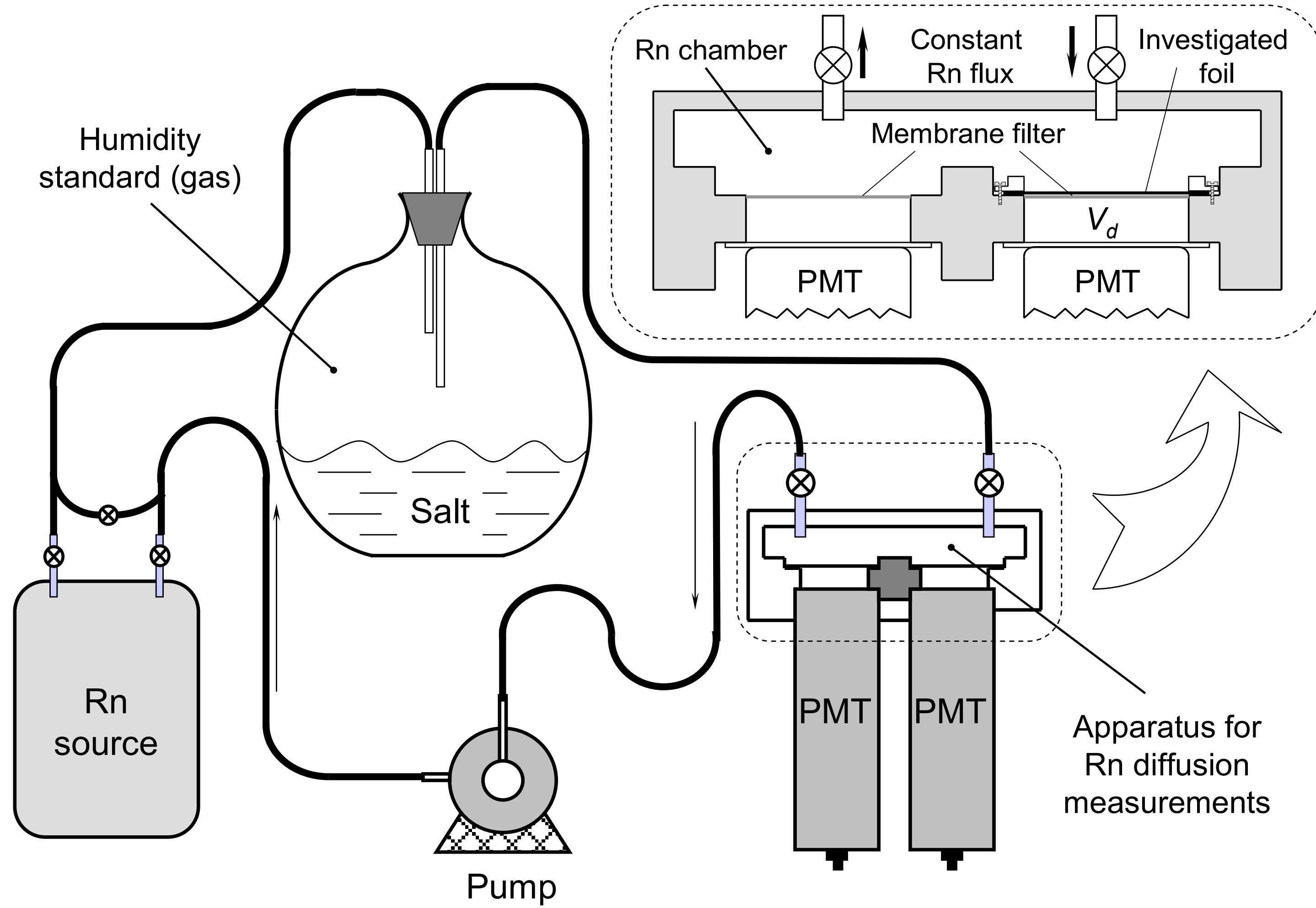
LAK Nitrogen tank installed at Gran Sasso

^{222}Rn ~ 8 μBq/m^3
Ar ~ 15 ppb
Kr ~ 0.1 ppt

Appl. Rad. Isot. 61 (2004) 197
AIP Conf. Proc. 897 (2007) 45
Int. J. Mod. Phys. A29 (2014) 1442009

^{222}Rn diffusion



Sensitivity: D ~ 10^{-13} cm^2/s
$d_e \sim 2$ μm

^{222}Rn diffusion

Results obtained for the 0.018 mm thick C38F film (BOREXINO)

RH standard salt	RH in gas phase (%)	Water amount in nylon, M (%)	Diffusion coefficient, D (cm^2/s)	Solubility, S
$Mg(ClO_4)_2$	~ 0	~ 0	$(2.1\pm0.4)\times10^{-12}$	4.5 ± 0.7
$H_3PO_4\cdot\frac{1}{2}H_2O$	9 ± 1	0.72 ± 0.04	$(2.3\pm0.3)\times10^{-12}$	2.5 ± 0.3
$LiCl_2\cdot H_2O$	12 ± 1	0.87 ± 0.04	$(2.2\pm0.3)\times10^{-12}$	2.2 ± 0.3
$CaCl_2\cdot 6H_2O$	32 ± 2	2.09 ± 0.04	$(4.3\pm0.5)\times10^{-12}$	1.8 ± 0.2
$Na_2Cr_2O_7\cdot 2H_2O$	52 ± 2	3.74 ± 0.05	$(1.9\pm0.3)\times10^{-11}$	1.4 ± 0.2
$Na_2S_2O_3\cdot 5H_2O$	76 ± 2	6.35 ± 0.05	$(6.5\pm0.9)\times10^{-11}$	1.5 ± 0.2
K_2CrO_4	88 ± 3	7.60 ± 0.05	$(1.3\pm0.2)\times10^{-10}$	1.5 ± 0.2
$Na_2SO_4\cdot 10H_2O$	93 ± 3	9.12 ± 0.07	$(3.3\pm0.4)\times10^{-10}$	1.0 ± 0.1
H_2O vapors	100 ± 3	10.14 ± 0.09	$(1.3\pm0.2)\times10^{-9}$	0.7 ± 0.1

There is 3 orders of magnitude difference between the diffusion in the dry and in the foil saturated with water!

Nucl. Instr. Meth. A 449 (2000) 158
Nucl. Instr. Meth. A 524 (2004) 355

$$d_e = \sqrt{\frac{D}{\lambda}} \qquad d_e^d = 7\,\mu m \qquad d_e^w = 270\,\mu m$$

^{226}Ra in/on BOREXINO nylon

1 ppt U required
(~12 µBq/kg for ^{226}Ra)

$D_{dry} = 2\text{x}10^{-12}$ cm^2/s ($d_{dry} = 7$ µm)
$D_{wet} = 1\text{x}10^{-9}$ cm^2/s ($d_{wet} = 270$ µm)

$A_{dry} = A_{sf} + 0.14 \cdot A_{bulk}$
$A_{wet} = A_{sf} + A_{bulk}$

Separation of the bulk and surface ^{226}Ra conc. was possible through ^{222}Rn emanation

Very sensitive technique:
(C_{Ra} ~ 10 µBq/kg)

Bx IV foil: bulk ≤ 15 µBq/kg
surface ≤ 0.8 µBq/m^2
total = (16 ± 4) µBq/kg (1.2 ppt U eqiv.)

NIM A 498 (2003) 240

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Construction of nylon vessels

Princeton clean room class 100 with ^{222}Rn-reduced air (VSA filter): $C_{Rn} \sim 1$ Bq/m^3

A. Pocar, PhD Thesis (2003)

Inflation of vessels in SSS

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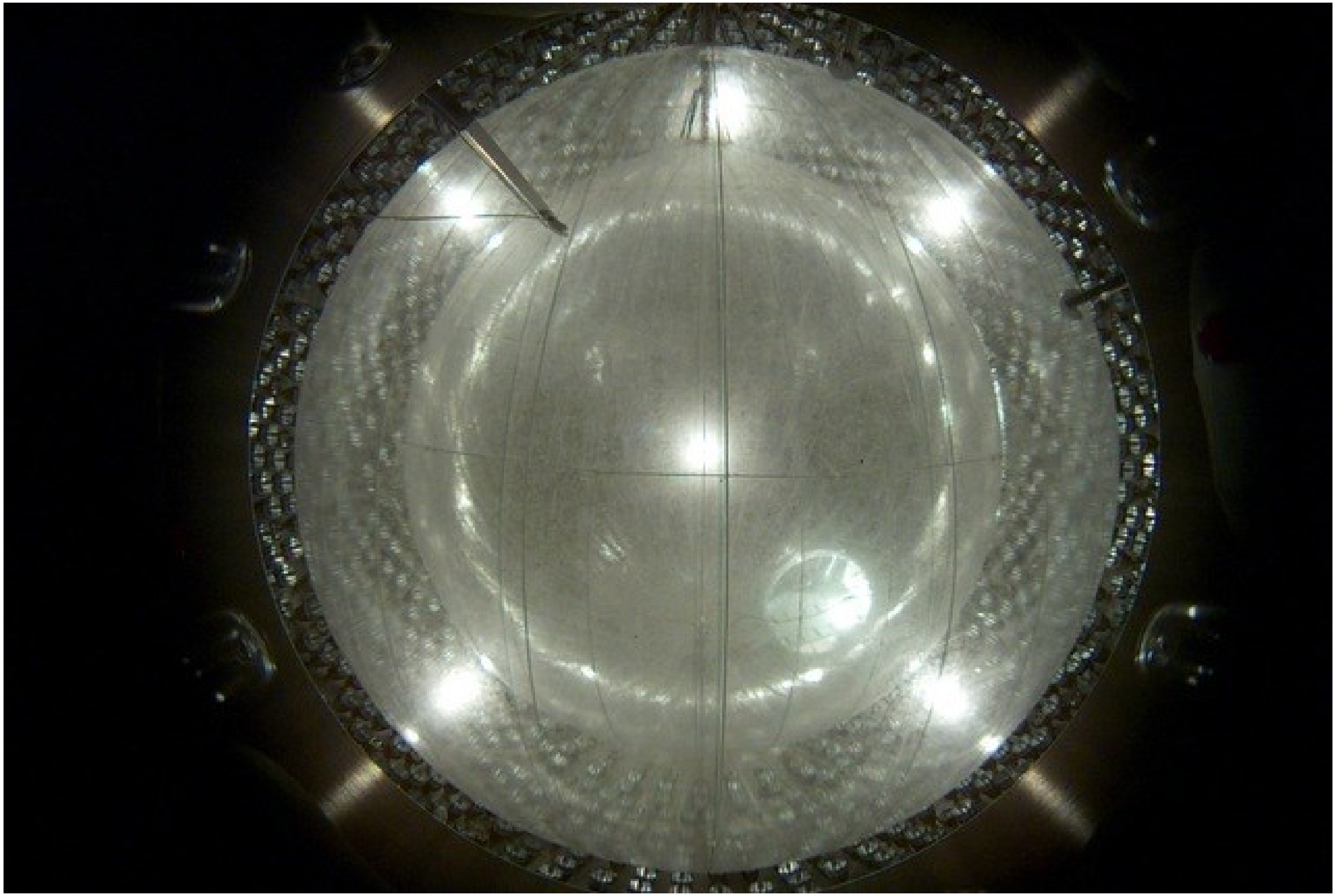


The nylon vessels were inflated in the sphere with synthetic air: $C_{Rn} < 100\ \mu Bq/m^3$

Int. J. Mod. Phys. A29 (2014) 1442009

Topics not discussed

- ^{226}Ra adsorption on the nylon vessel (J. Rad. Nuc. Chem. 296 (2013) 639)
- ^{222}Rn-daughters deposition on the nylon vessel (E. Harding, Princeton)
- Tests of ^{210}Pb removal from PC (J. Rad. Nuc. Chem. 296 (2013) 639)
- Online ^{222}Rn monitoring with an electrostatic detector (NIM A 460 (2001) 272)
- Adsorption of noble gases on various porous materials (B. Freudiger, PhD Thesis (2003))
- NAA and ICP-MS measurements (Astroparticle Physics 18 (2002) 1)

Summary

BOREXINO

Bx radio-purity

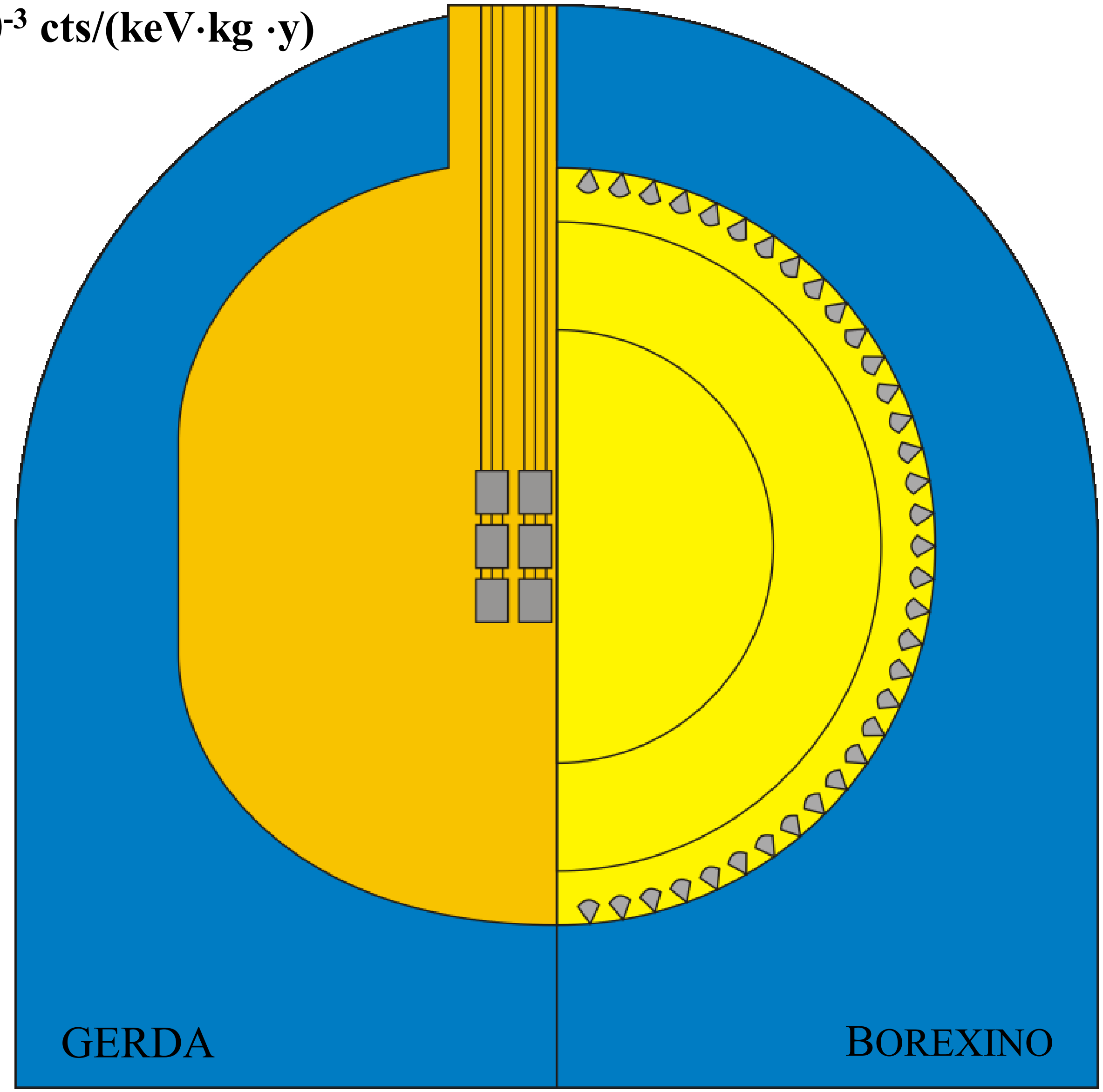
Bcg mitigation

Summary

- BOREXINO achieved an unprecedented background level (still improving)
- Strict quality control program including the assay of all components of the detector during its construction
- ~15 years of R&D, several people involved
- Several detectors and experimental methods were developed allowing measurements even at a single atom level.
- Most of the developed techniques are world-wide most sensitive (Ge spectroscopy, ^{222}Rn detection, ^{222}Rn diffusion) and are applied in next-generation experiments (GERDA, XENON, DARKSIDE,…)

Summary

BI = 10^{-3} cts/(keV·kg ·y)



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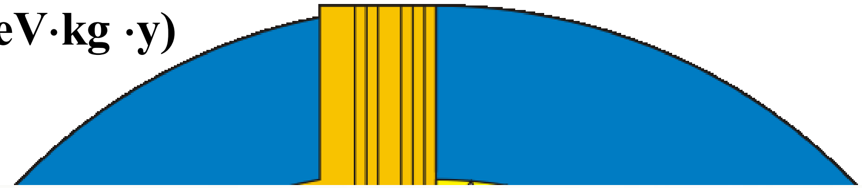

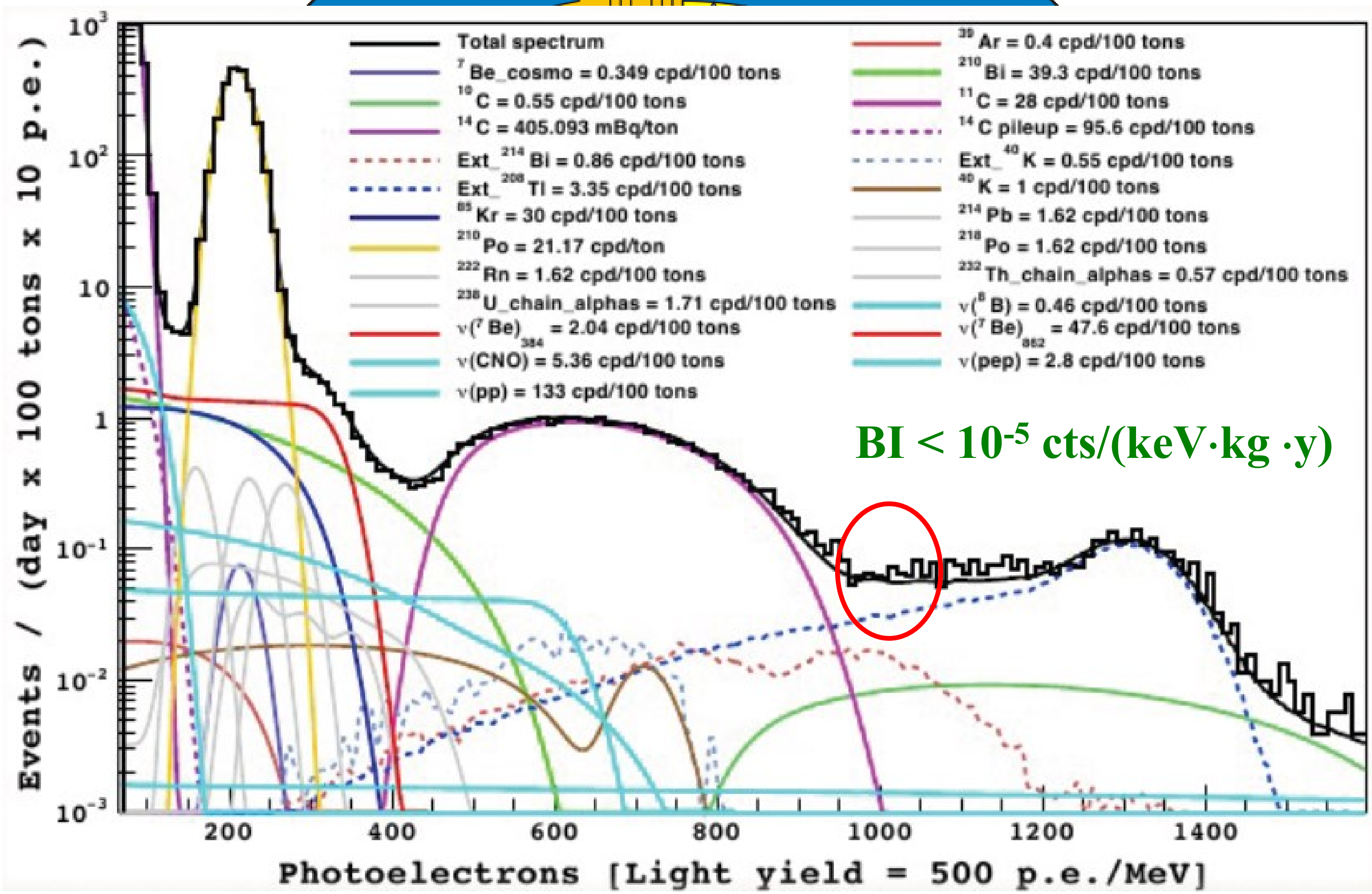

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