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Ultralow background LS and related technologies

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Outline

- Ultra-pure LS: BOREXINO
- Internal and external background: mitigation techniques
- LS purification
- Conclusions

BOREXINO at LNGS

- BOREXINO
- Bcg mitigation
- LS purification
- Conclusions

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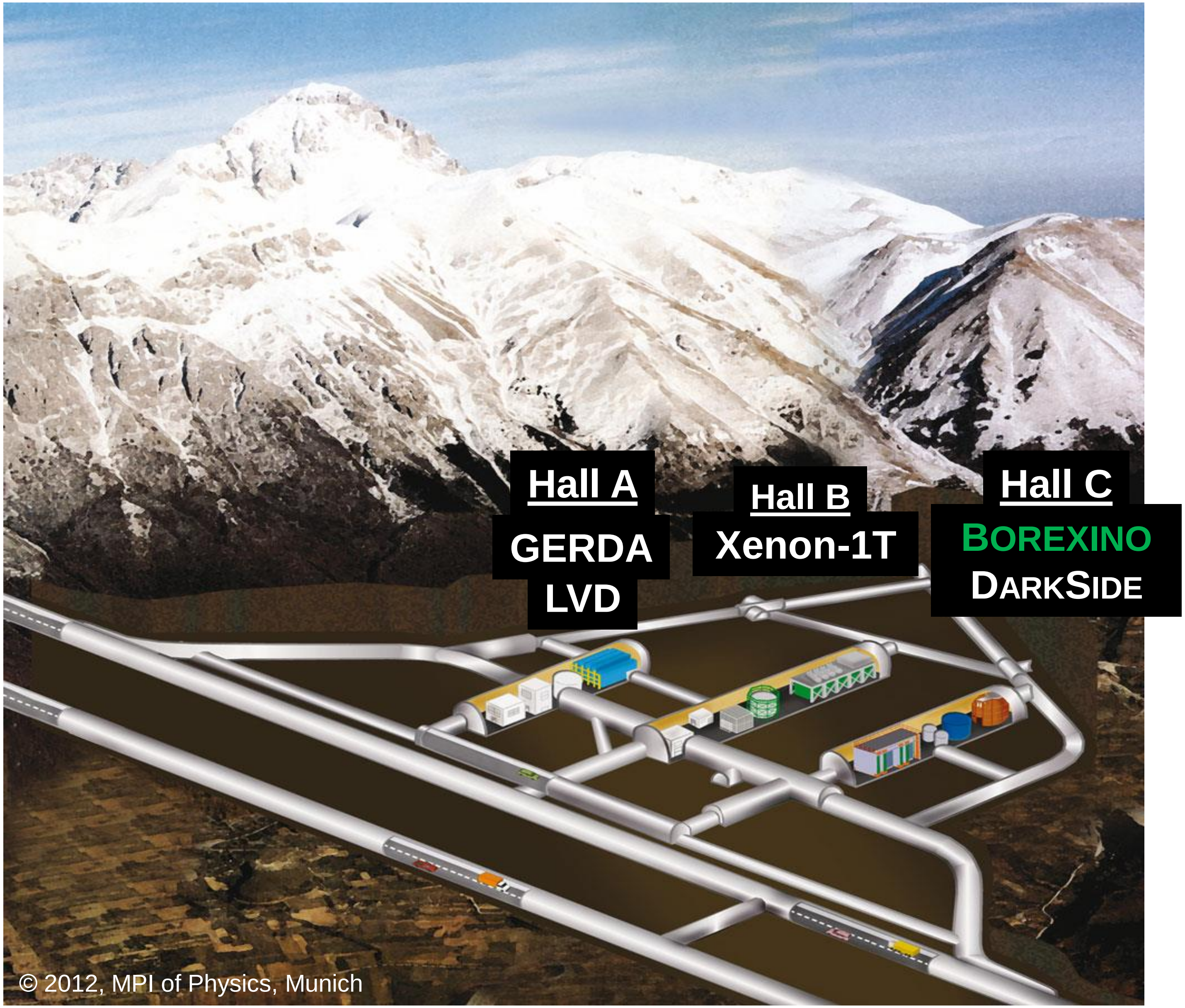
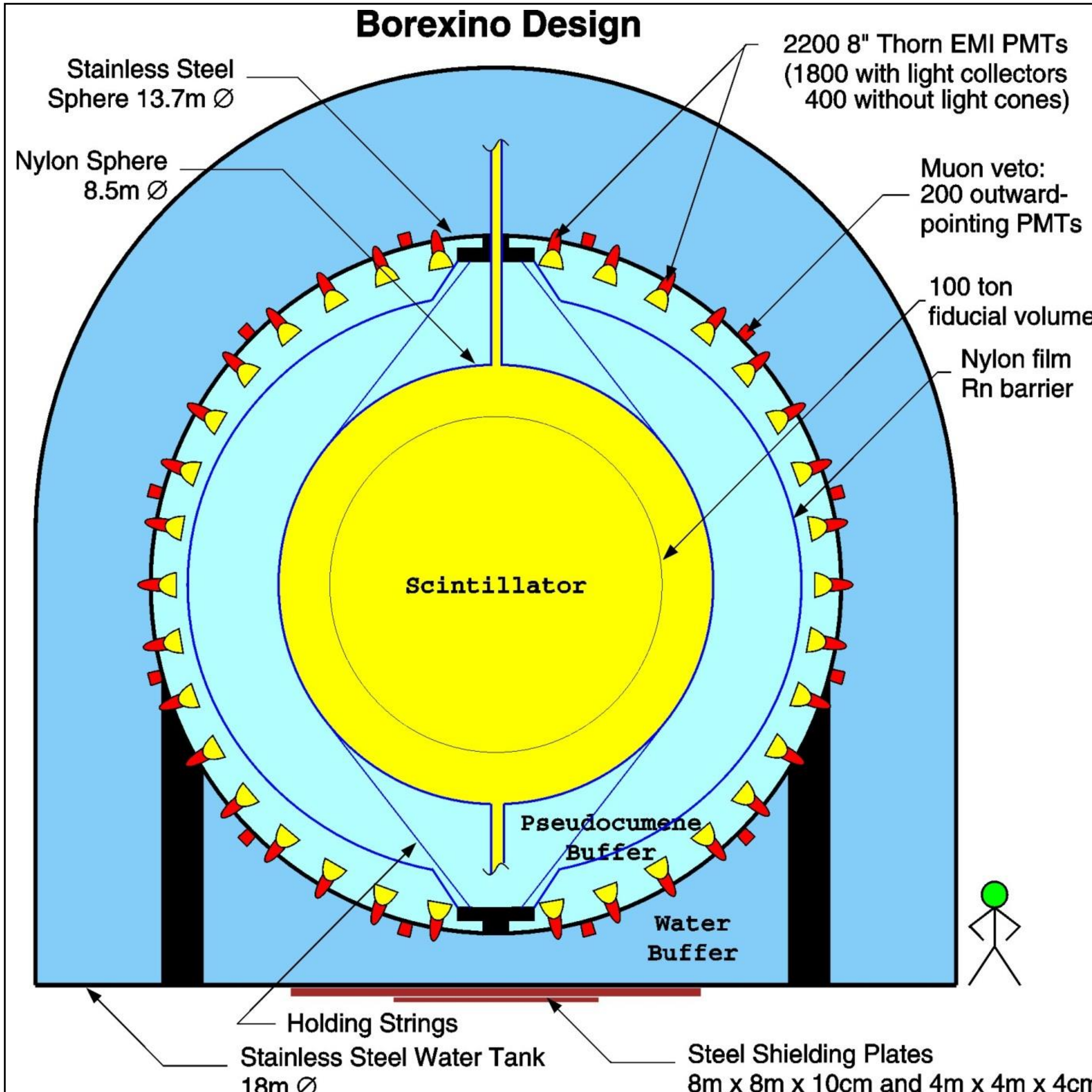


BOREXINO design



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Bcg mitigation

LS purification

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BOREXINO radio-purity

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In a nutshell: the cleanest detector ever built

Isotope	Specification for LS	Achieved after filling (2007 - 2010)
^{238}U	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g
^{14}C/^{12}C	$\leq 10^{-18}$	$(2.69 \pm 0.06) \cdot 10^{-18}$ g/g
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4 \cdot 10^{-18}$ g/g
^{85}Kr	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t
^{39}Ar	$\leq$ 1 cpd/100 t	$\ll$ ^{85}Kr
^{210}Po	not specified	~ (70) 1 dpd/100 t
^{210}Bi	not specified	(20) 70 dpd/100 t

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

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

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

Background mitigation techniques

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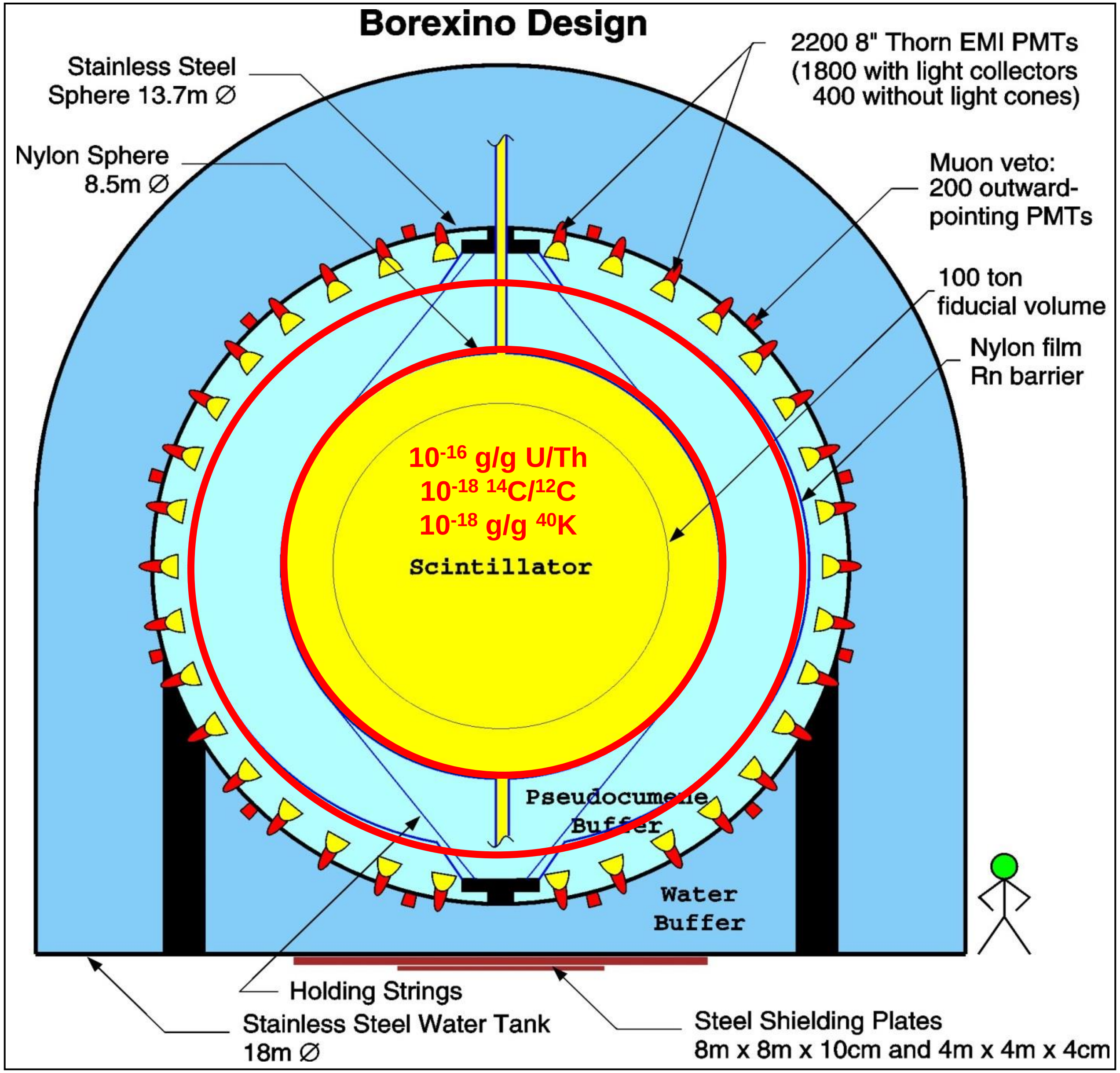
- Graded shielding: traveling inward to the center, each component is protected from external radiation by the preceding one
- The radio-purity level is increasing towards the center
- Active (definition of FV, Čerenkov veto) and passive (PC buffer, water) suppression of external radiation
- Careful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

BOREXINO design



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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)

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

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HPGe spectroscopy

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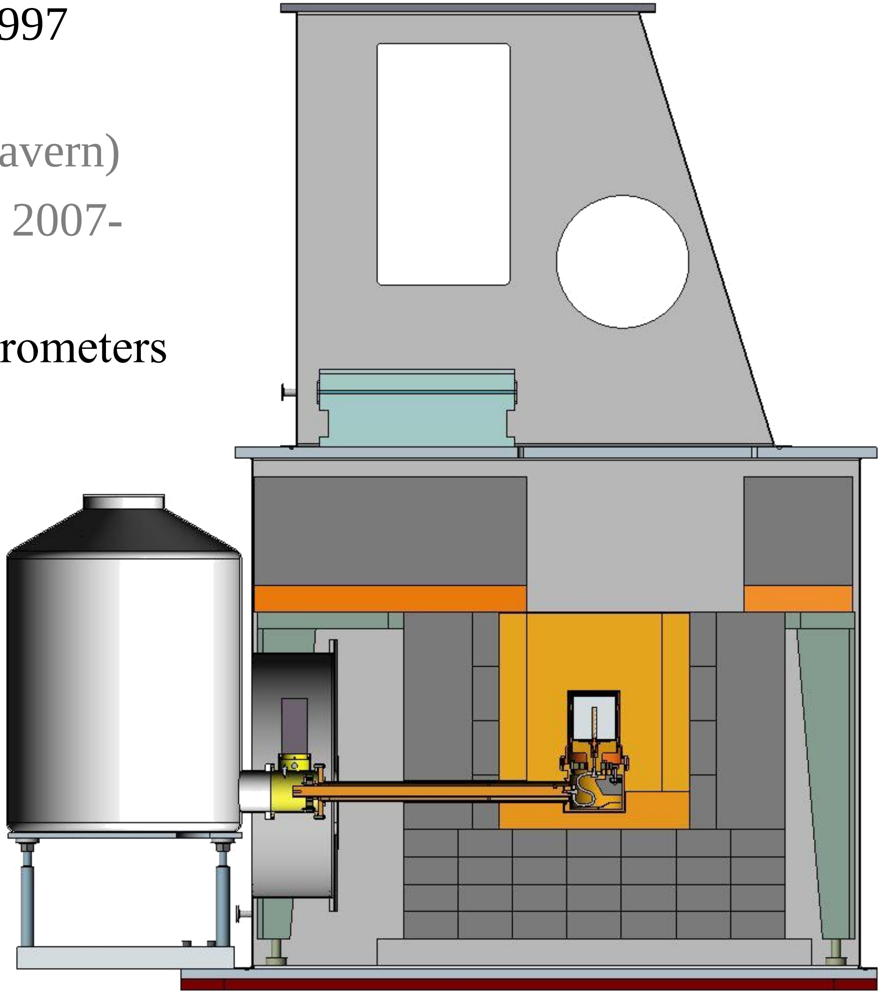
GeMPIs at GS (3800 m w.e.)

- GeMPI I operational since 1997 (MPIK)
- GeMPI II built in 2004 (MCavern)
- GeMPI III/IV constructed in 2007-2012 (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 different materials

Sample	Description	^{226}Ra [mBq/kg]	^{228}Th [mBq/kg]	^{40}K [mBq/kg]
Stainless Steel	AISI304L: SSS	4.6 ± 0.9	11.4 ± 1.1	< 14
	SS for pipes	< 14	< 10	< 34
	SS for flanges	6.2 ± 1.2	6.5 ± 1.6	< 13
PMTs inner parts	Dynodes	< 280	450 ± 163	< 240
	Ceramic plates	170 ± 50	310 ± 60	960 ± 450
	Al for dynodes	1190 ± 100	980 ± 80	2800 ± 600
PMTs ancillary parts	Mu metal	57 ± 20	< 27	< 180
	Volt. div. board	170 ± 60	80 ± 40	770 ± 360
	Voltage divider	680 ± 30	320 ± 20	3200 ± 320
Glass	Sand for glass	40 ± 3	< 3.1	< 25
	ETL LB glass	820 ± 230	130 ± 12	500 ± 120
	Base glass	520 ± 90	410 ± 90	$(2.2 \pm 0.6) \cdot 10^5$

Astroparticle Physics 18 (2002) 1

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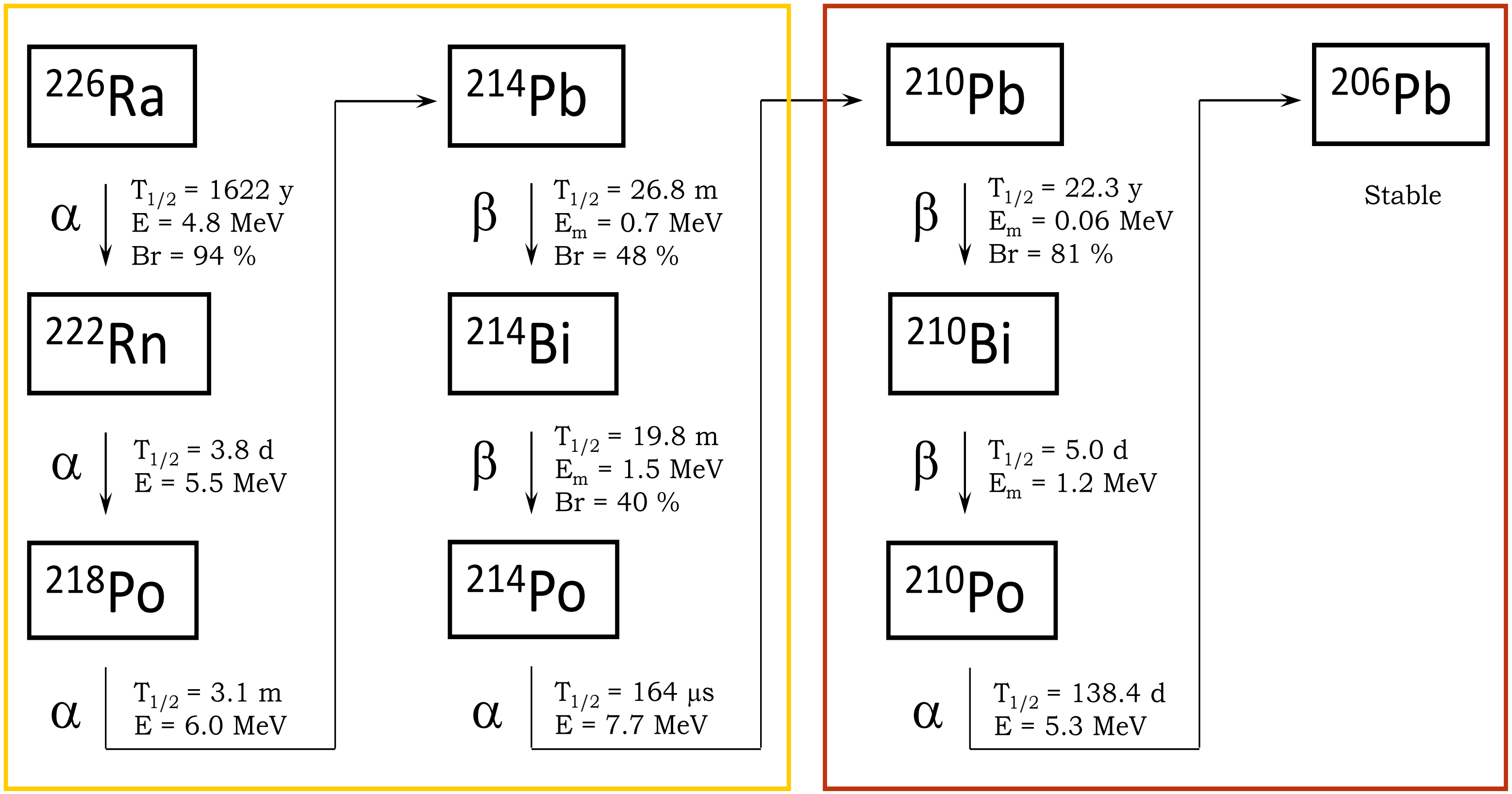
^{222}Rn emanation



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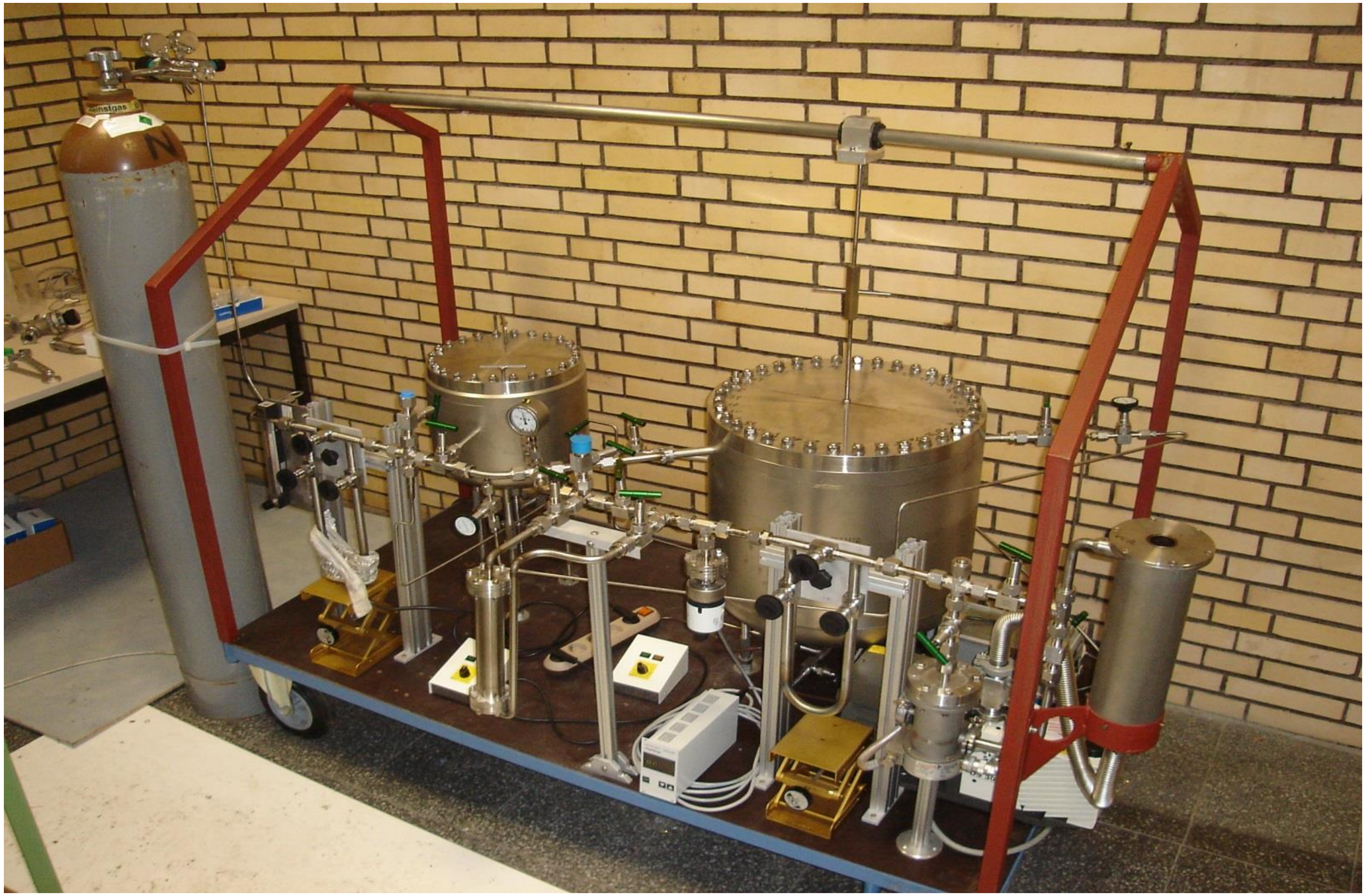

Blanks:

20 l → 50 μBq

80 l → 80 μBq

Absolute sensitivity
~100 μBq [50 atoms]

Appl. Rad. Isot. 53 (2000) 371

^{222}Rn emanation: examples

System	Sample	Description	^{222}Rn em. rate
PC storage area	SS vessel TK1	114 m^3	< 60 mBq
	SS vessel TK2	114 m^3	(45 ± 8) mBq
	SS vessel TK3	114 m^3	(24 ± 5) mBq
N_2 distribution line	Electrical heater		(0.92 ± 0.29) mBq
	Particle Filter		(0.34 ± 0.13) mBq
	1.5" distrib. line	~ 100 m long	(0.47 ± 0.13) mBq
LS purification plant	SS package	25 m^2	< 0.12 mBq
	H_2O extraction column + 24 SS packages	0.6 m^3 / 608 m^2	(4.83 ± 0.70) mBq
	N_2 sparging column + 26 SS packages	0.2 m^3 / 280 m^2	(1.78 ± 0.21) mBq

Over 1000 entries in the DB!

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

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

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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

BOREXINO design

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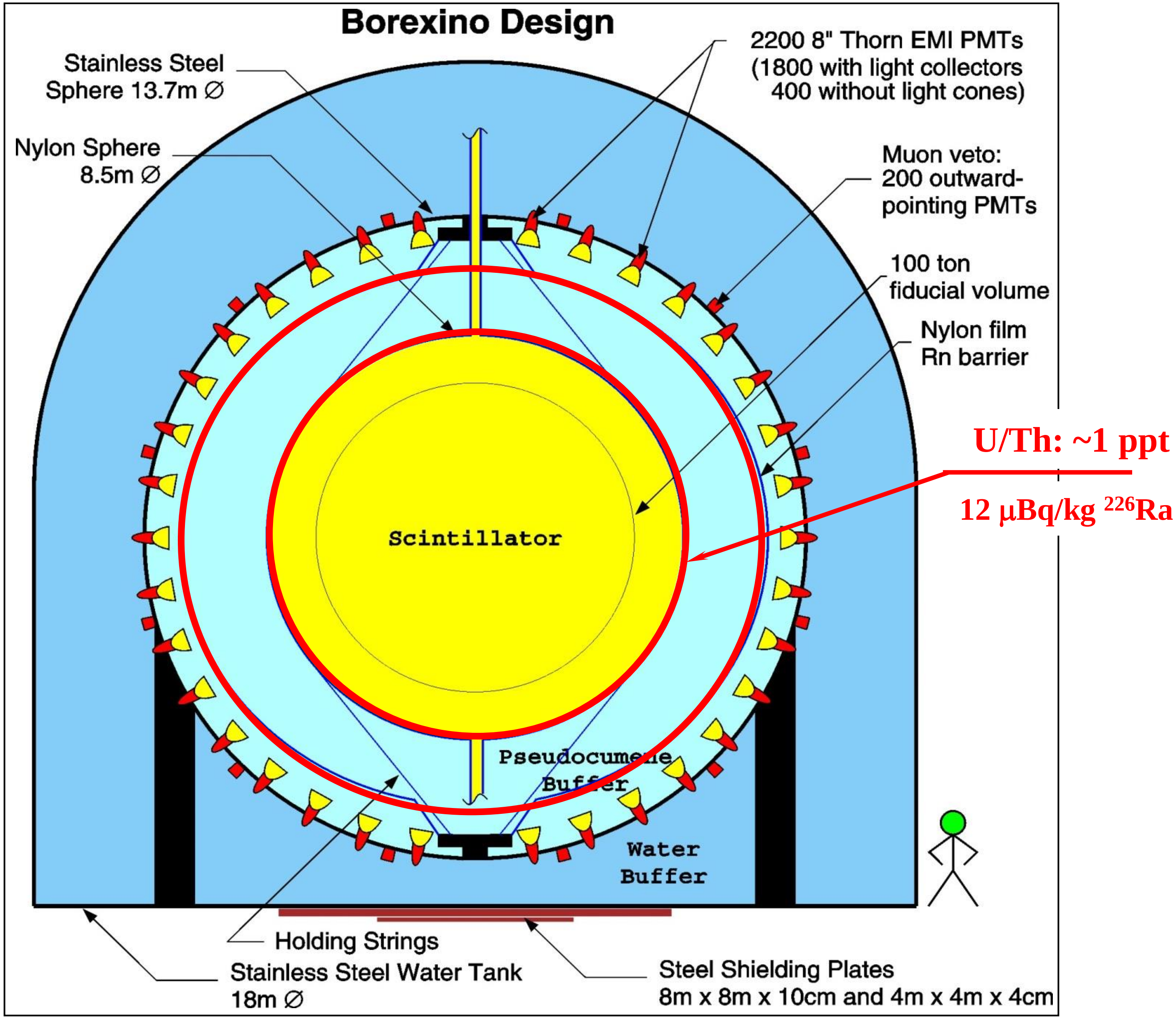

^{222}Rn diffusion

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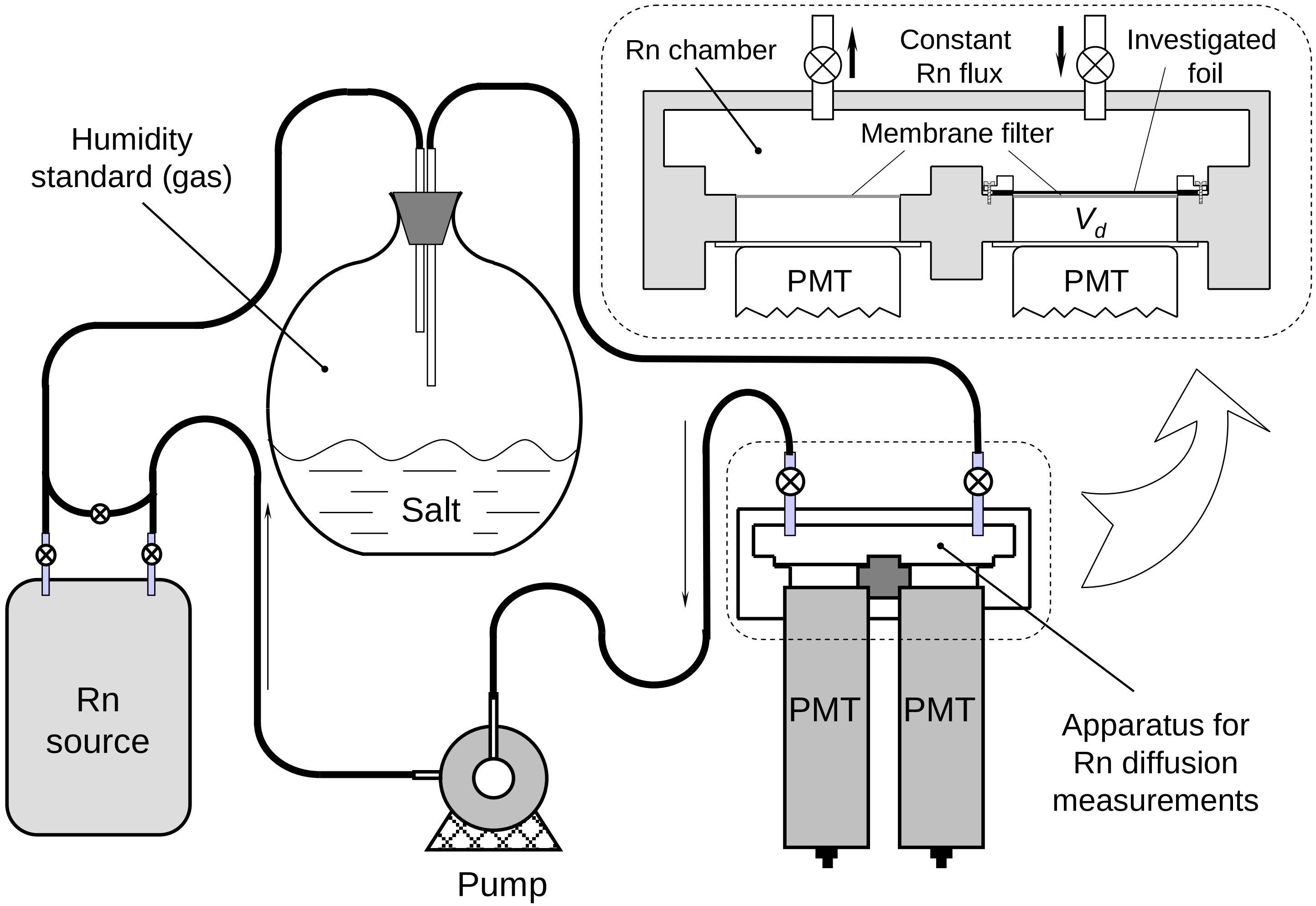

Sensitivity: D ~ 10^{-13} cm^2/s
d_e ~ 2 μm

^{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	$(2.1 \pm 0.4) \times 10^{-12}$	4.5 ± 0.7
$H_3PO_4 \cdot \frac{1}{2}H_2O$	9 ± 1	0.72 ± 0.04	$(2.3 \pm 0.3) \times 10^{-12}$	2.5 ± 0.3
$LiCl_2 \cdot H_2O$	12 ± 1	0.87 ± 0.04	$(2.2 \pm 0.3) \times 10^{-12}$	2.2 ± 0.3
$CaCl_2 \cdot 6H_2O$	32 ± 2	2.09 ± 0.04	$(4.3 \pm 0.5) \times 10^{-12}$	1.8 ± 0.2
$Na_2Cr_2O_7 \cdot 2H_2O$	52 ± 2	3.74 ± 0.05	$(1.9 \pm 0.3) \times 10^{-11}$	1.4 ± 0.2
$Na_2S_2O_3 \cdot 5H_2O$	76 ± 2	6.35 ± 0.05	$(6.5 \pm 0.9) \times 10^{-11}$	1.5 ± 0.2
K_2CrO_4	88 ± 3	7.60 ± 0.05	$(1.3 \pm 0.2) \times 10^{-10}$	1.5 ± 0.2
$Na_2SO_4 \cdot 10H_2O$	93 ± 3	9.12 ± 0.07	$(3.3 \pm 0.4) \times 10^{-10}$	1.0 ± 0.1
H_2O vapors	100 ± 3	10.14 ± 0.09	$(1.3 \pm 0.2) \times 10^{-9}$	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

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

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^{226}Ra in/on BOREXINO nylon

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

D_{dry} = 2x10^{-12} cm^2/s (d_{dry}= 7 μm)
D_{wet} = 1x10^{-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

Construction of nylon vessels

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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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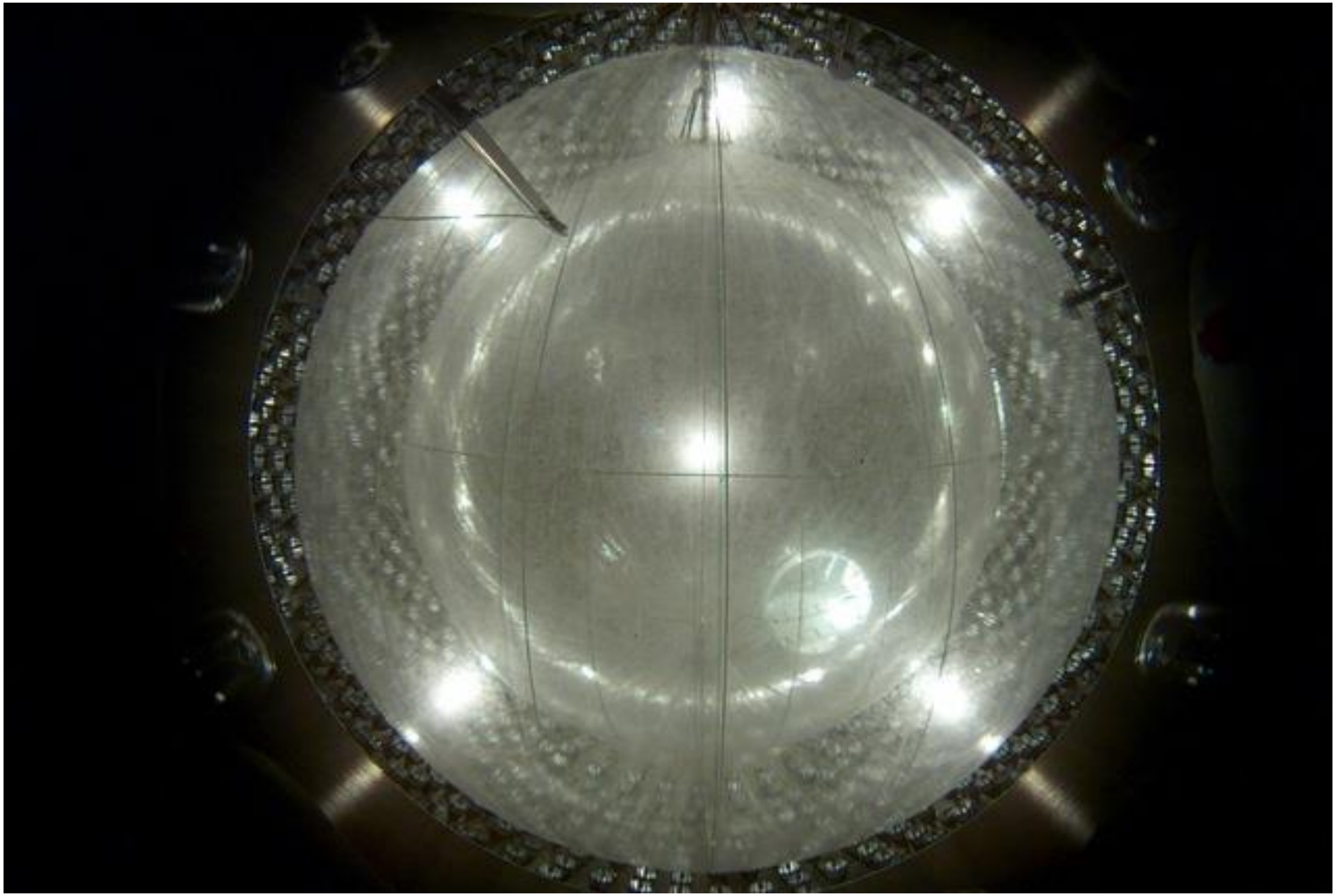

The nylon vessels were inflated in the sphere with synthetic air: $C_{Rn} < 100\ \mu Bq/m^3$

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

LS purification

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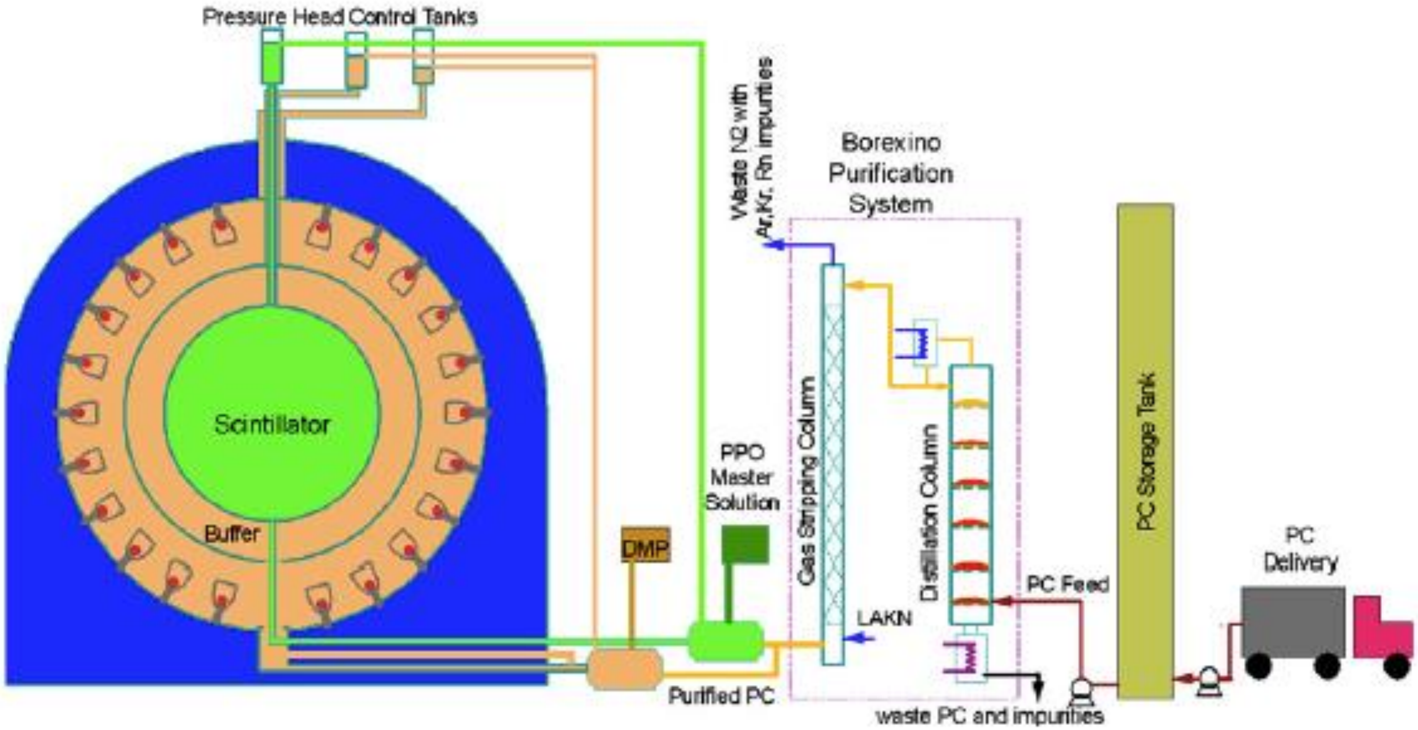
Effective scintillator purification processes

- Efficient removal of radioactive elements
  - distillation
  - water extraction
  - nitrogen stripping
- Development of cleaning methods to remove radioactivity from equipment surfaces
- Purification of scintillator before and after filling detector

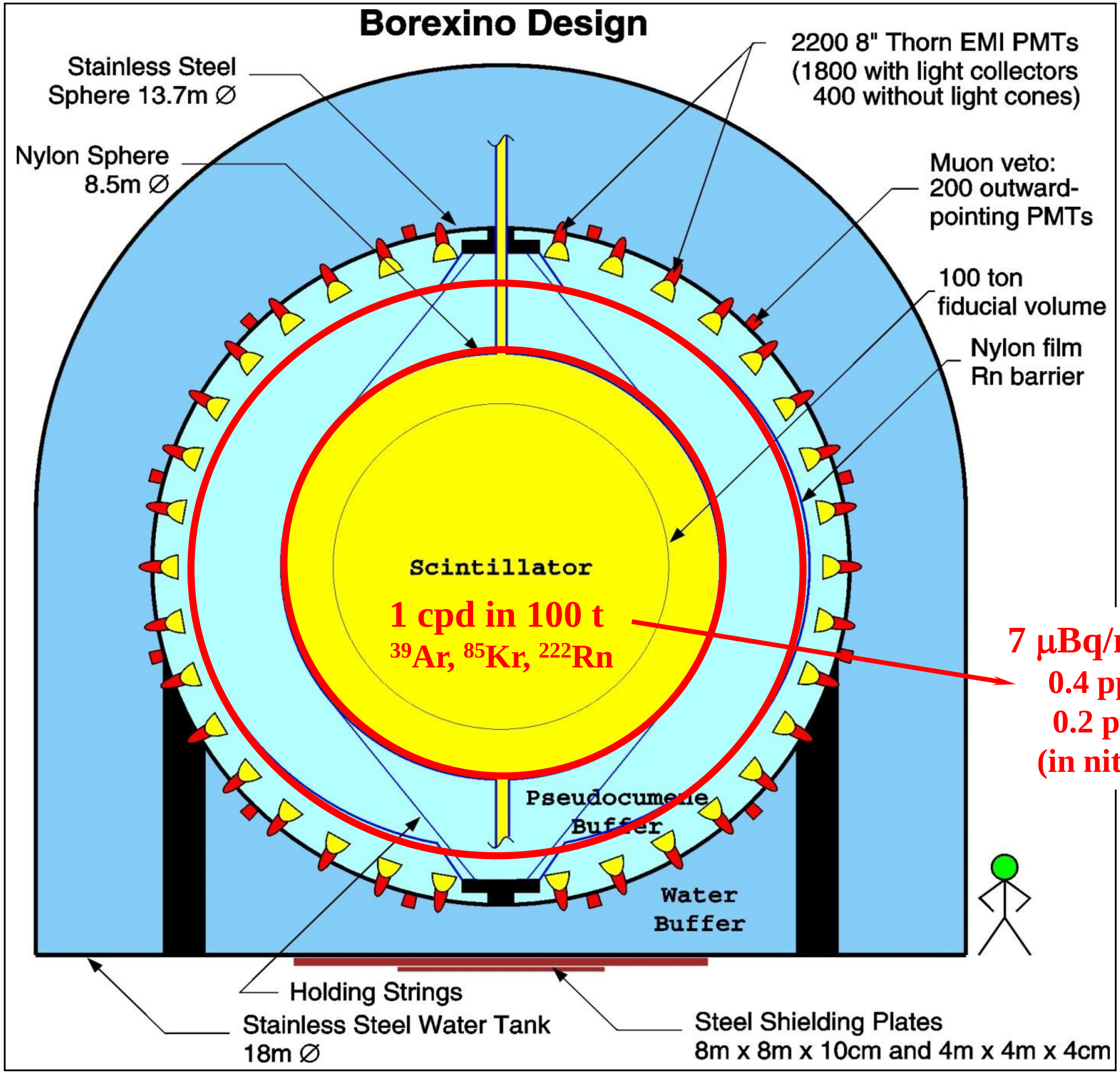
LS purification during filling

- Vessels inflated with synthetic air
- Vessels filled with high-purity deionized water
- Scintillator distilled and stripped with LAK nitrogen during filling
- Detector filled with scintillator from top, while draining water from bottom

J. Benziger et al. / Nuclear Instruments and Methods in Physics Research A 587 (2008) 277–291



BOREXINO design



7 μBq/m^3 ^{222}Rn
0.4 ppm Ar
0.2 ppt Kr
(in nitrogen)

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^{222}Rn in gases: MoREx

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LS purification

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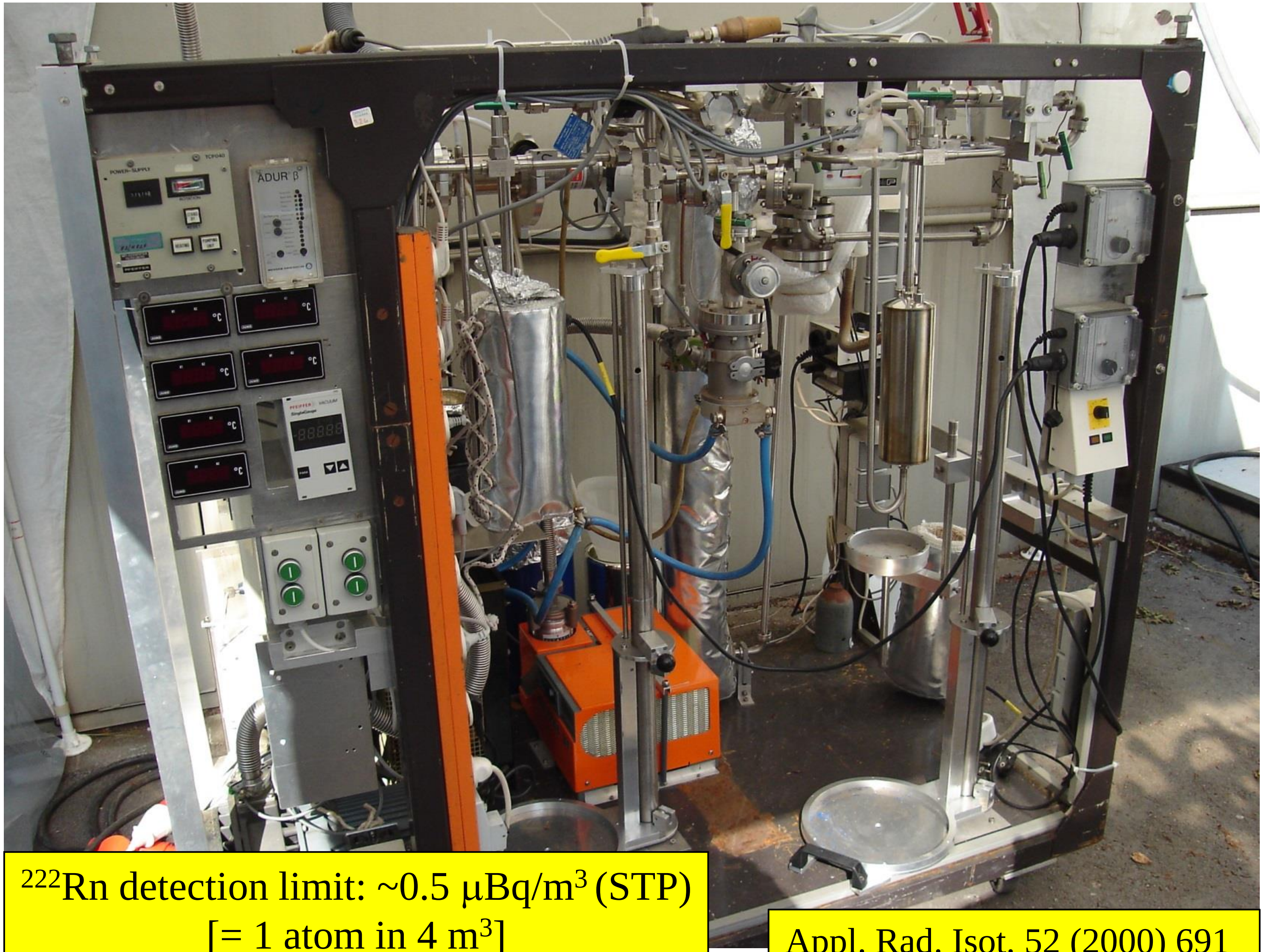

^{222}Rn detection limit: ~0.5 μBq/m^3 (STP)
[= 1 atom in 4 m^3]

Appl. Rad. Isot. 52 (2000) 691

Ar and Kr in nitrogen

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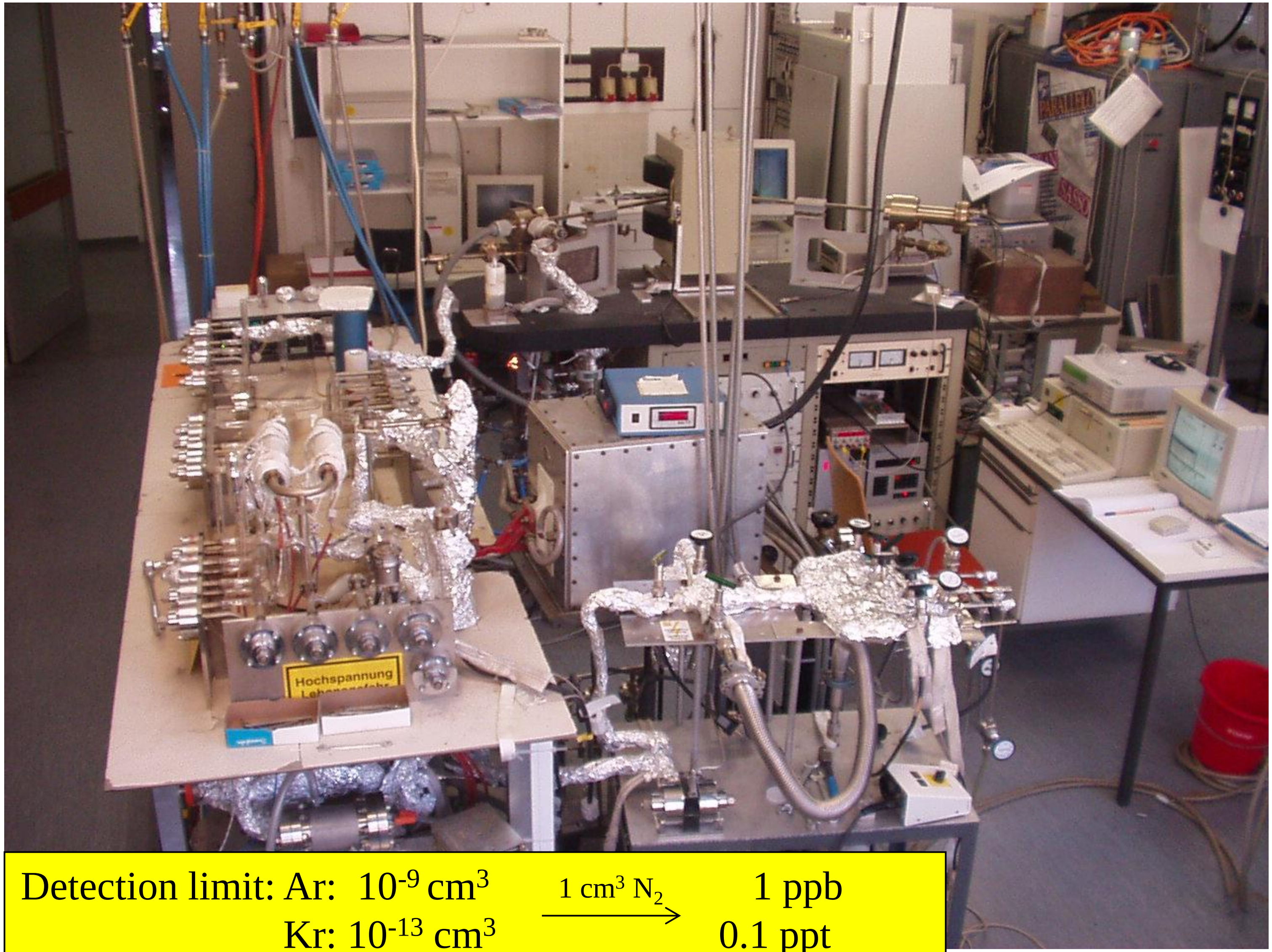


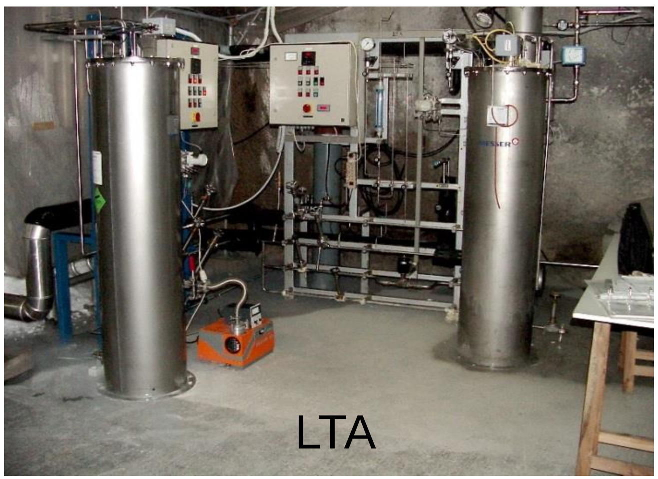
Detection limit: Ar: 10^{-9} cm^3 $\xrightarrow{1\ cm^3\ N_2}$ 1 ppb

Kr: 10^{-13} cm^3 → 0.1 ppt

BOREXINO nitrogen

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

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LAK Nitrogen tank installed at Gran Sasso

$^{222}Rn \sim 8\ \mu Bq/m^3$
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

LS re-purification

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- From 2007 to 2010 the ^{210}Bi background increased
  - Scintillator refills to compensate the vessel leak / others ?
  - ^{210}Bi rate: 20 $\rightarrow$ 70 cpd/100 t
  - ^{85}Kr rate: 30 cpd/100 t (constant)
- To reduce background, scintillator was re-purified using two processes:
  - Water extraction to remove ^{210}Pb (^{210}Bi)
  - Nitrogen stripping to remove ^{85}Kr and other volatiles
- Six purification cycles were performed, each took ~1 month
  - Each operation processed all the scintillator in the detector once (320 m^3).
  - Data were acquired to evaluate backgrounds after each operation.
  - Not all six operations were successful.

BOREXINO radio-purity

Isotope	Specification for LS	Achieved after filling (2007 - 2010)	After aditional 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	<< ^{85}Kr	<< ^{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**

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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)

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Conclusions

- BOREXINO has achieved an unprecedented background level in the liquid scintillator
- Strict quality control program including the assay of all components of the detector during its construction
- **+10 years of R&D, many people/institutions 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,…)

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