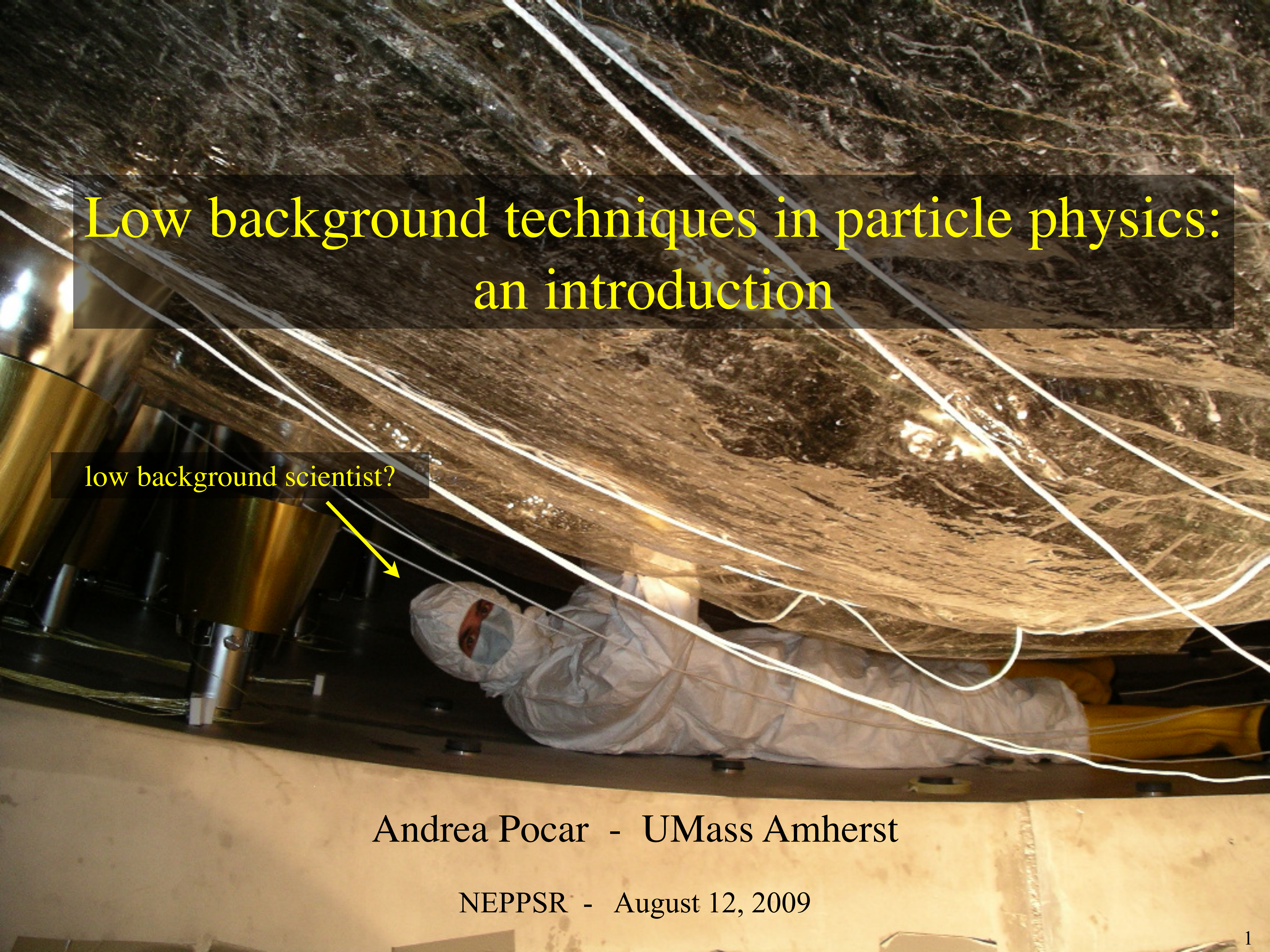
Low background techniques in particle physics: an introduction



low background scientist?

Andrea Pocar - UMass Amherst

NEPPSR - August 12, 2009

Outline

- what is low background particle physics?
  (some definitions)

- low energy neutrinos, double beta decay, proton decay, direct cold dark matter (WIMPs) detection

- some history and milestones; the field today

- experimental techniques (how to detect very rare events with massive underground detectors)

Disclaimers

i. this is inevitably a slanted view of the subject (based on my personal experience with the Borexino and EXO experiments)

ii. the content listed above is presented in mixed order

iii. I do not always thoroughly present the physics of the experiments I use for examples - please ask if you need more details

what do we mean with
‘low background’ and ‘low energy’ ?

low-background particle physics

- all measurements require low (enough) background (in one way or the other)

- typically, large accelerator experiments record an enormous quantity of data through which to sift to find the interesting signals (resonance peaks, vertices, etc)

- the filtering is performed by applying a series of non-trivial cuts to the data (energy, multiplicity, vertex separation, ...) to complicated events, rich of information

- in low energy experiments, the signal events are feeble and usually have pretty uninteresting topologies => need to have ‘quiet’ detectors to begin with

‘quiet’ detector

a detector is ‘quiet’ if (my personal definition):

- it is possible to extract the interesting signals applying relatively few, simple selection rules to the data set

- the trigger rate is low enough that no arbitrary choice has to be performed in the data acquisition at the trigger level
(collect “all” data)

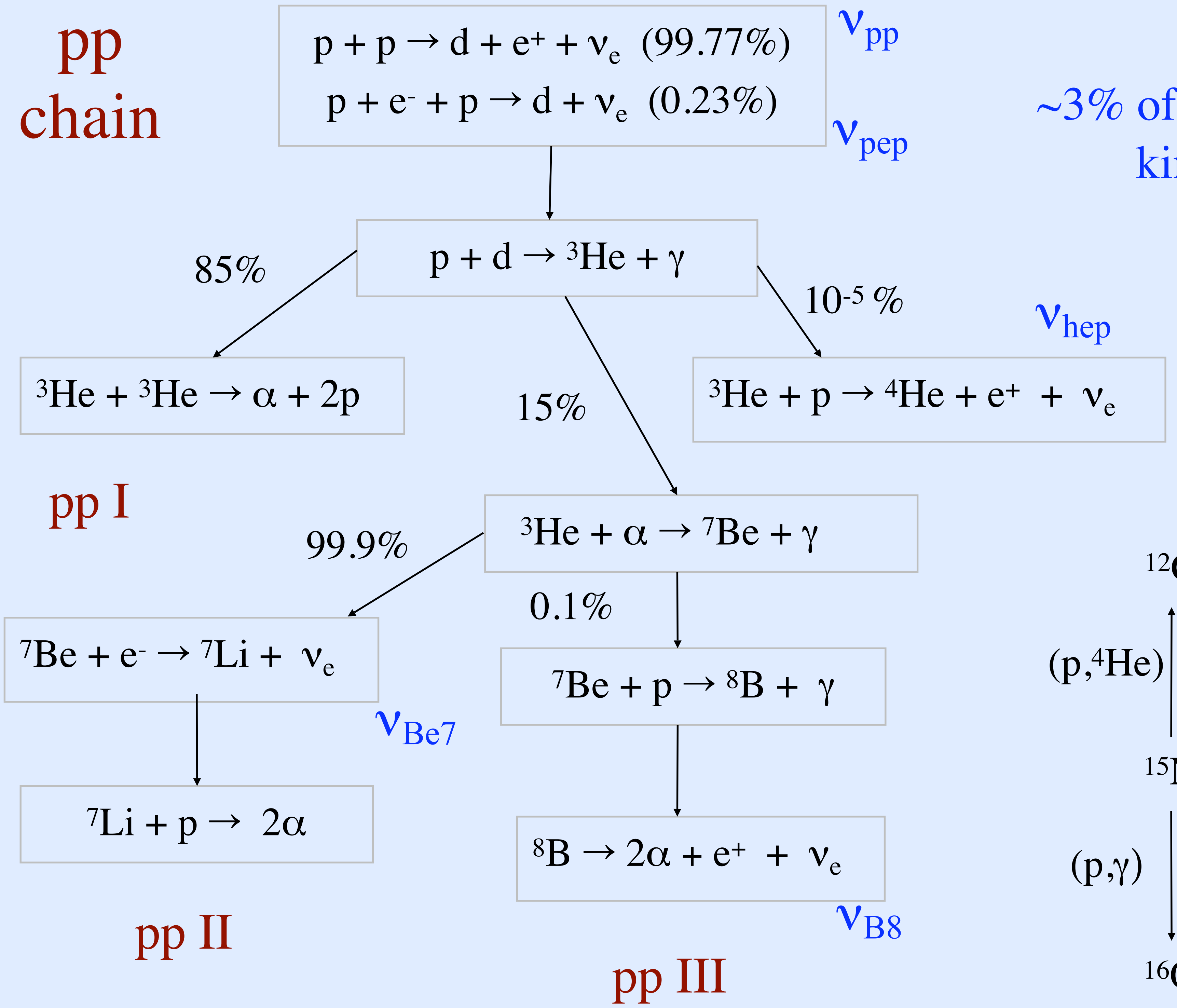
some examples

Neutrino production in the sun

Fundamental fusion reaction:

$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73$ MeV

pp chain



$p + p \rightarrow d + e^+ + \nu_e$ (99.77%) ν_{pp}

$p + e^- + p \rightarrow d + \nu_e$ (0.23%) ν_{pep}

$p + d \rightarrow {}^3He + \gamma$

85%

${}^3He + {}^3He \rightarrow \alpha + 2p$

pp I

15%

$^3He + \alpha \rightarrow {}^7Be + \gamma$

99.9%

$^7Be + e^- \rightarrow {}^7Li + \nu_e$ ν_{Be7}

$^7Li + p \rightarrow 2\alpha$

pp II

0.1%

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow 2\alpha + e^+ + \nu_e$ ν_{B8}

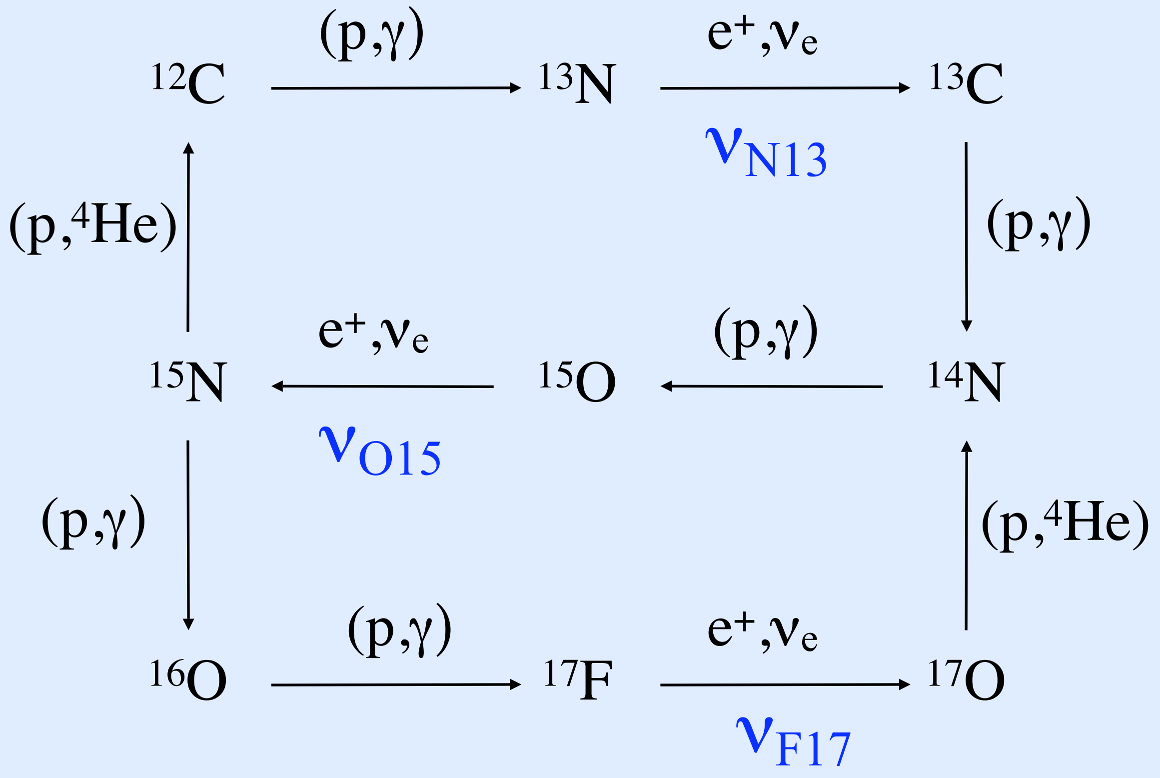
pp III

10^{-5} %

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$ ν_{hep}

~3% of the energy is carried away by kinetic energy of neutrinos

CNO cycle



$^{12}C \xrightarrow{(p,\gamma)} {}^{13}N \xrightarrow[\nu_{N13}]{e^+,\nu_e} {}^{13}C$

$^{13}C \xrightarrow{(p,\gamma)} {}^{14}N$

$^{14}N \xrightarrow{(p,\gamma)} {}^{15}O \xrightarrow[\nu_{O15}]{e^+,\nu_e} {}^{15}N$

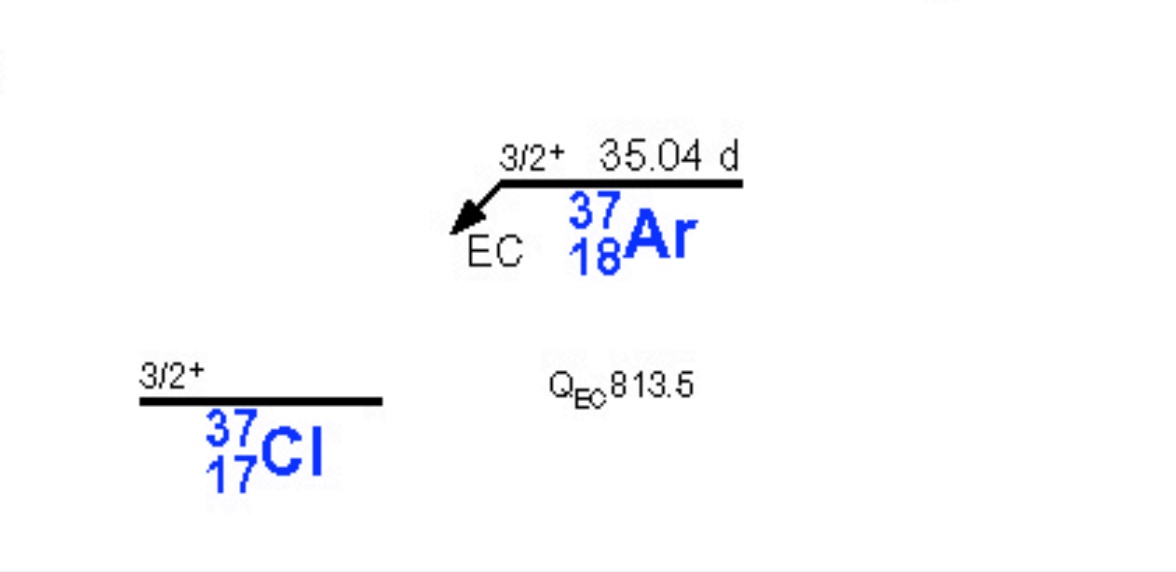
$^{15}N \xrightarrow{(p,{}^4He)} {}^{12}C$

$^{15}N \xrightarrow{(p,\gamma)} {}^{16}O$

$^{16}O \xrightarrow{(p,\gamma)} {}^{17}F \xrightarrow[\nu_{F17}]{e^+,\nu_e} {}^{17}O$

$^{17}O \xrightarrow{(p,{}^4He)} {}^{14}N$

solar neutrino detection

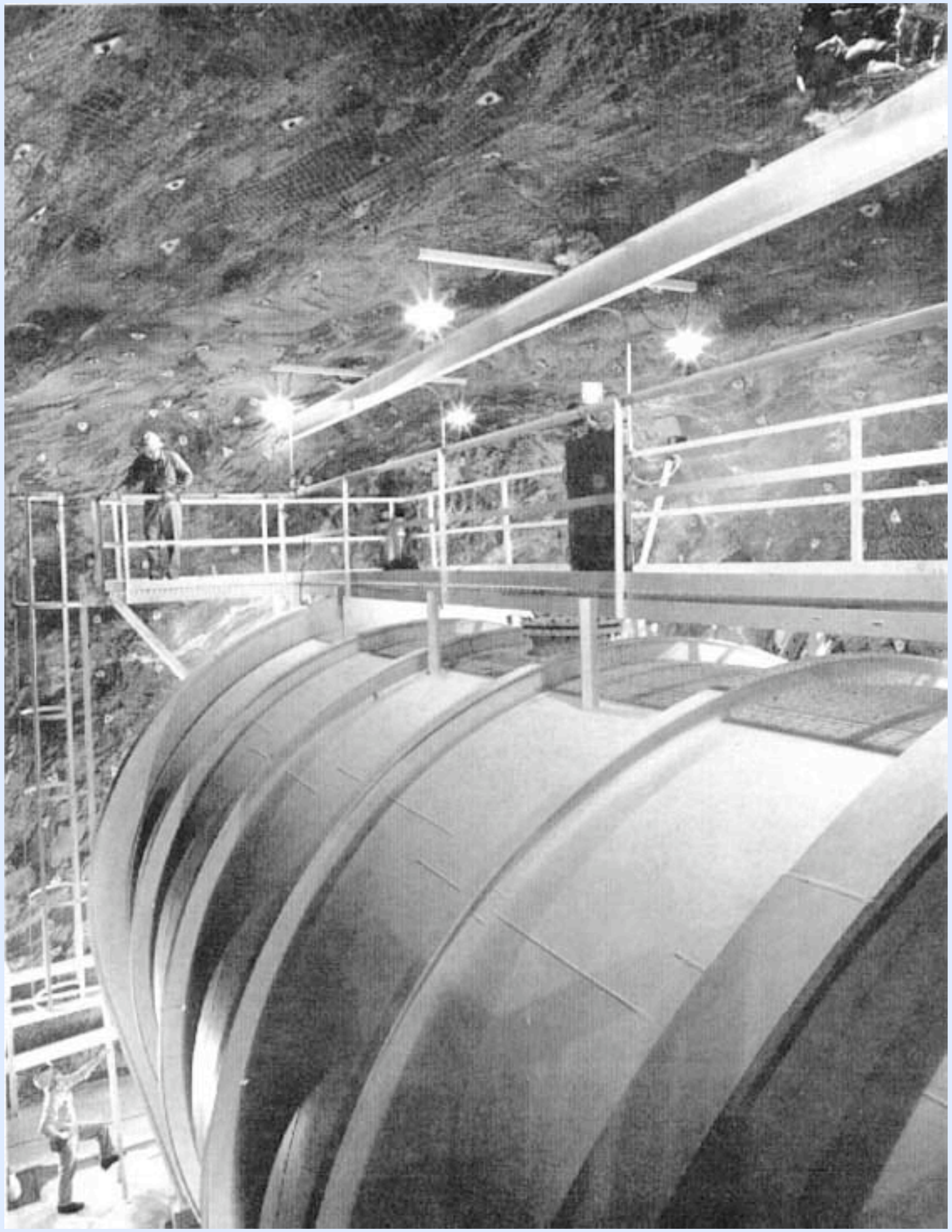


- Homestake Mine, Lead SD, 1400 m underground
- 615 tons of perchloroethylene (C_2Cl_4)
- 2.2*10^{30} atoms of ^{37}Cl
- ^{36}Ar or ^{38}Ar added to the fluid as carrier gas
- data taken continuously: 1967 – 2002
- **~ one ^{37}Ar atom produced every 2 days !**

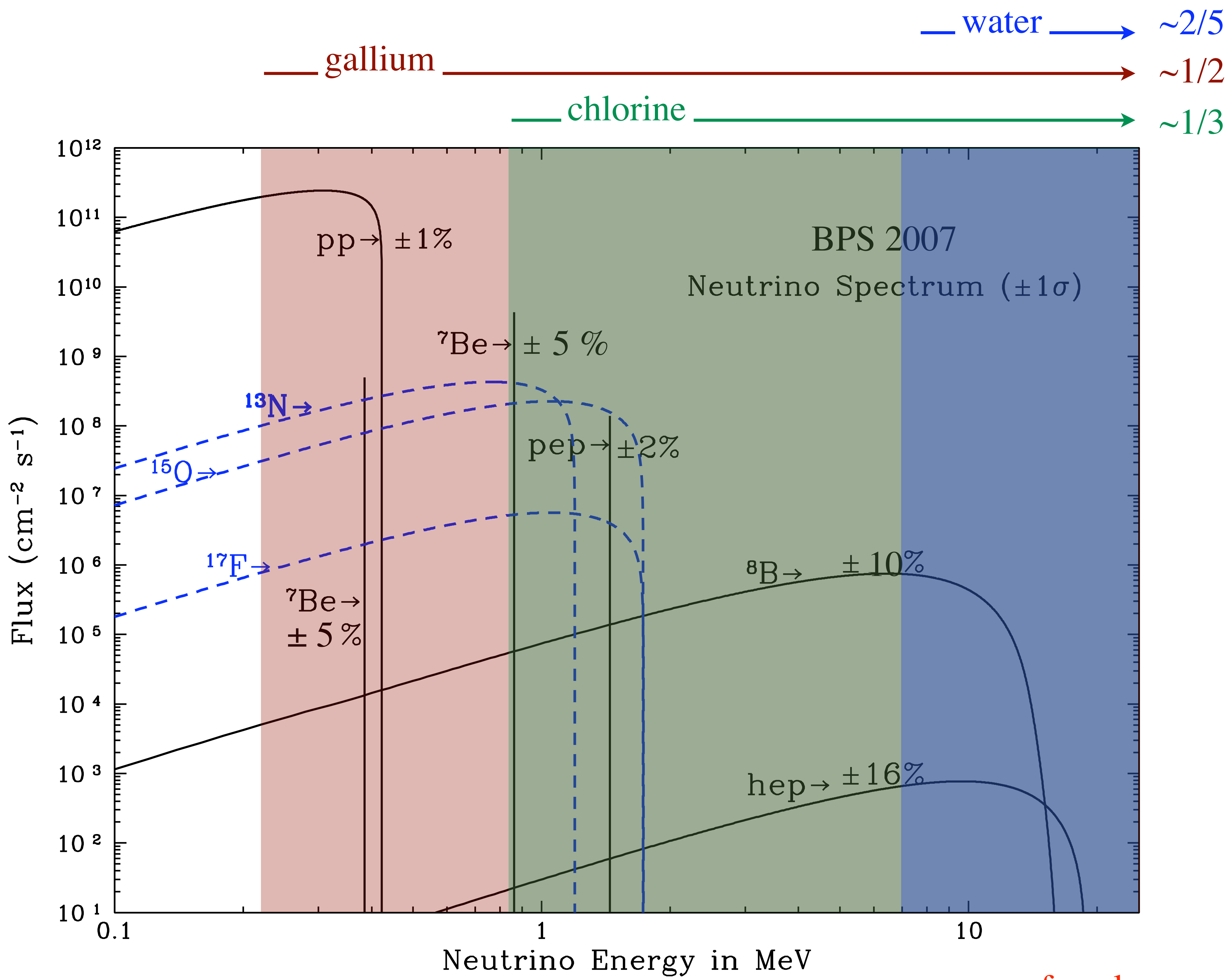
solar neutrino detection proves that there are fusion reactions in the sun (Bethe, 1939)

problem (lesson):

observed only ~1/3 of the expected flux ... of course, neutrinos oscillate!



Solar neutrino spectrum



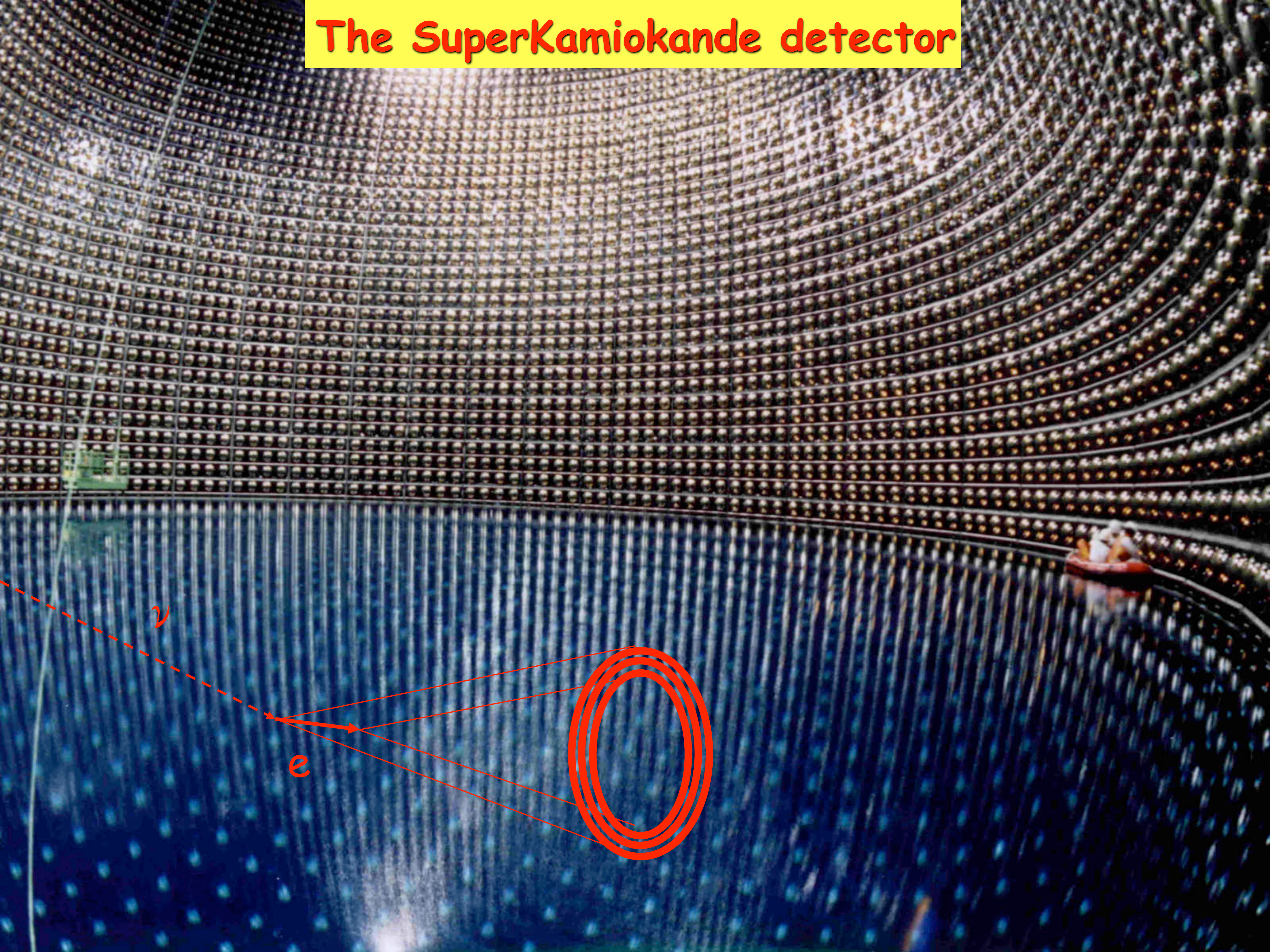
water → ~2/5

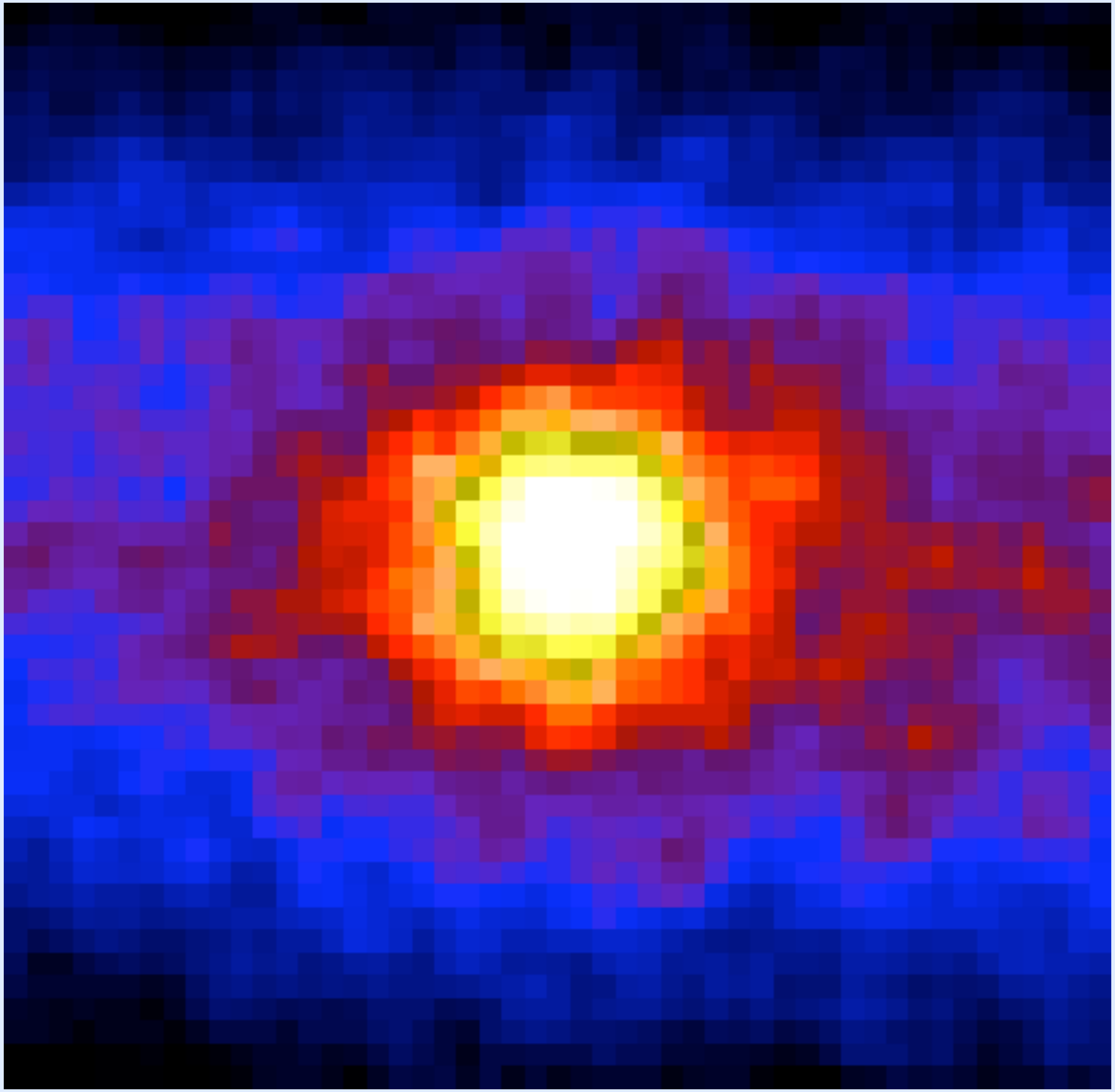
gallium → ~1/2

chlorine → ~1/3

energy range of nuclear reactions

The SuperKamiokande detector





The sun imaged with neutrinos
(courtesy R.Svoboda and the SK collab.)

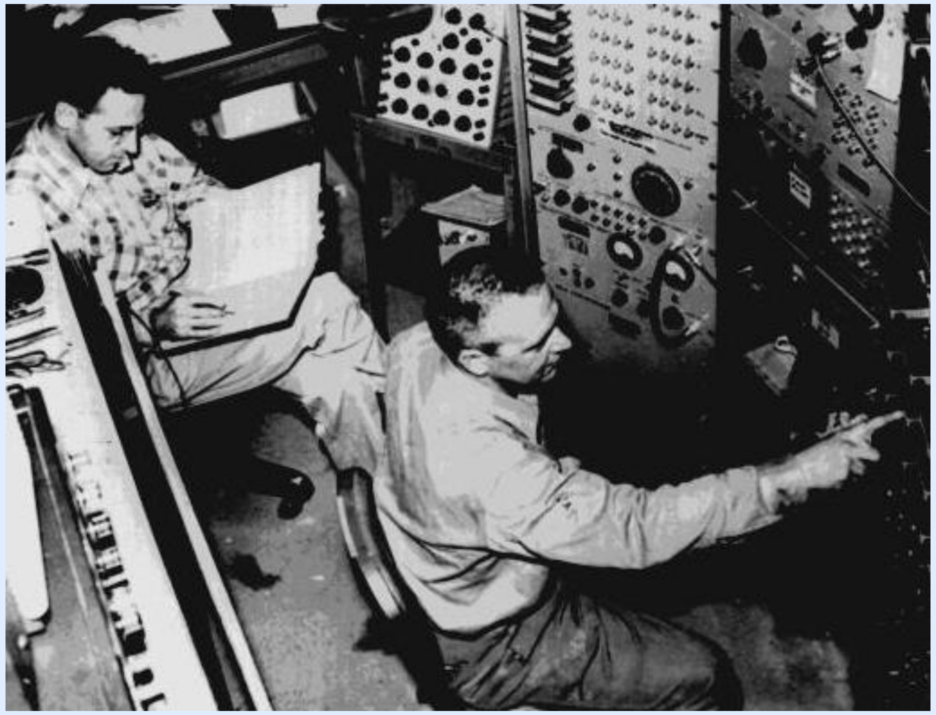
solar neutrino experiments

solar neutrino experiments have pioneered:

- large (hundreds of tons), low radioactivity detectors
- single atom counting at these massive scales

first neutrino detection

1956: first direct (anti)neutrino detection via inverse β-decay of the proton (Reines and Cowan, Savannah River nuclear reactor)



Coincidence event:

prompt

$$\bar{\nu}_e + p \rightarrow n + e^+$$

E_{th} = 1.8 MeV

delayed neutron capture with 2.2 MeV photon emission

the use of coincidences allowed to greatly enhance the signal over the 'singles rate' of the detector

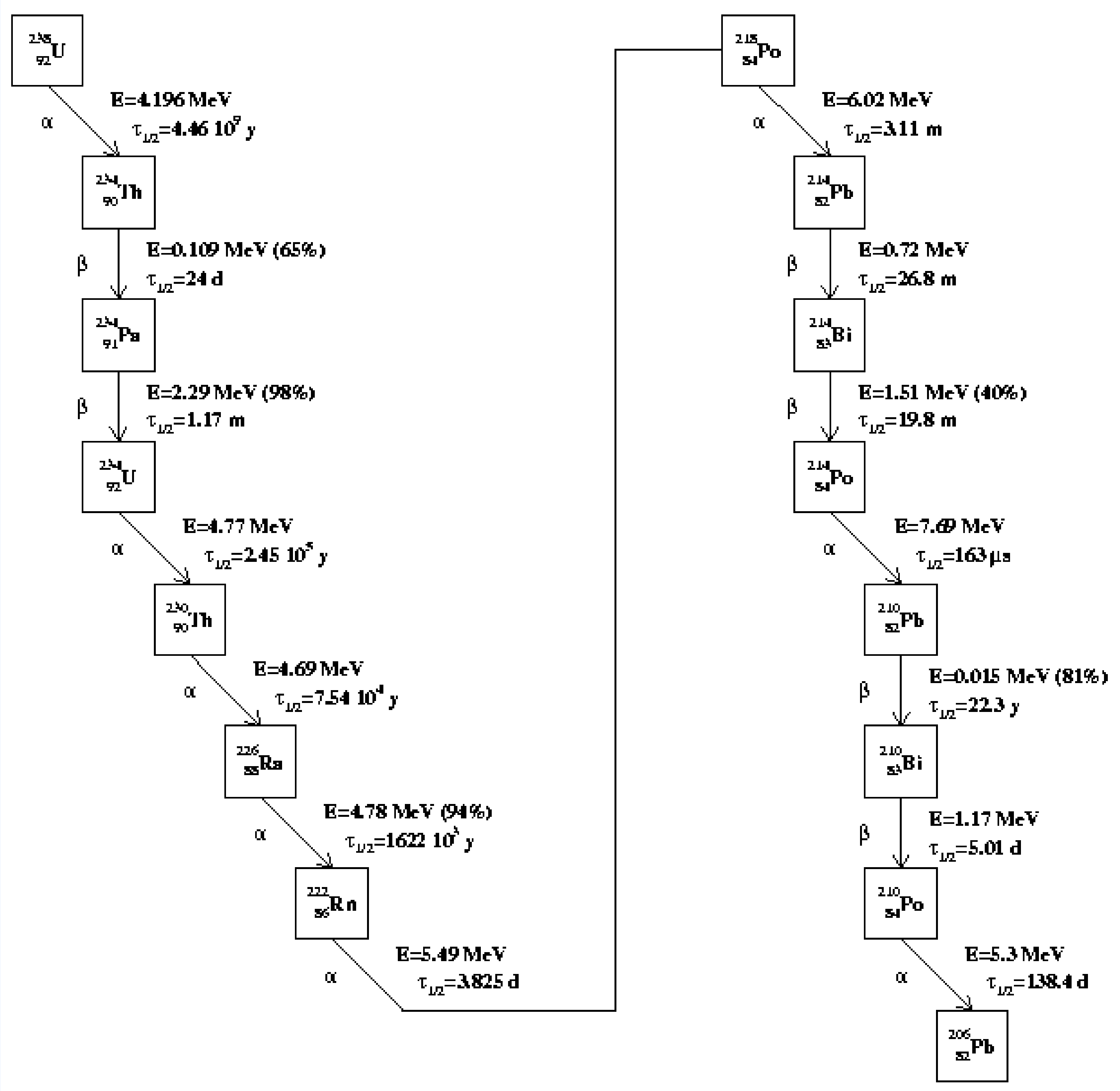
natural radioactivity

primordial (ie with lifetimes in the millions of years) radioactivity:

- ^{238}U, ^{232}Th chains and ^{40}K

- alpha, beta, gamma backgrounds affect experiments differently

E < 10 MeV



muon-related backgrounds

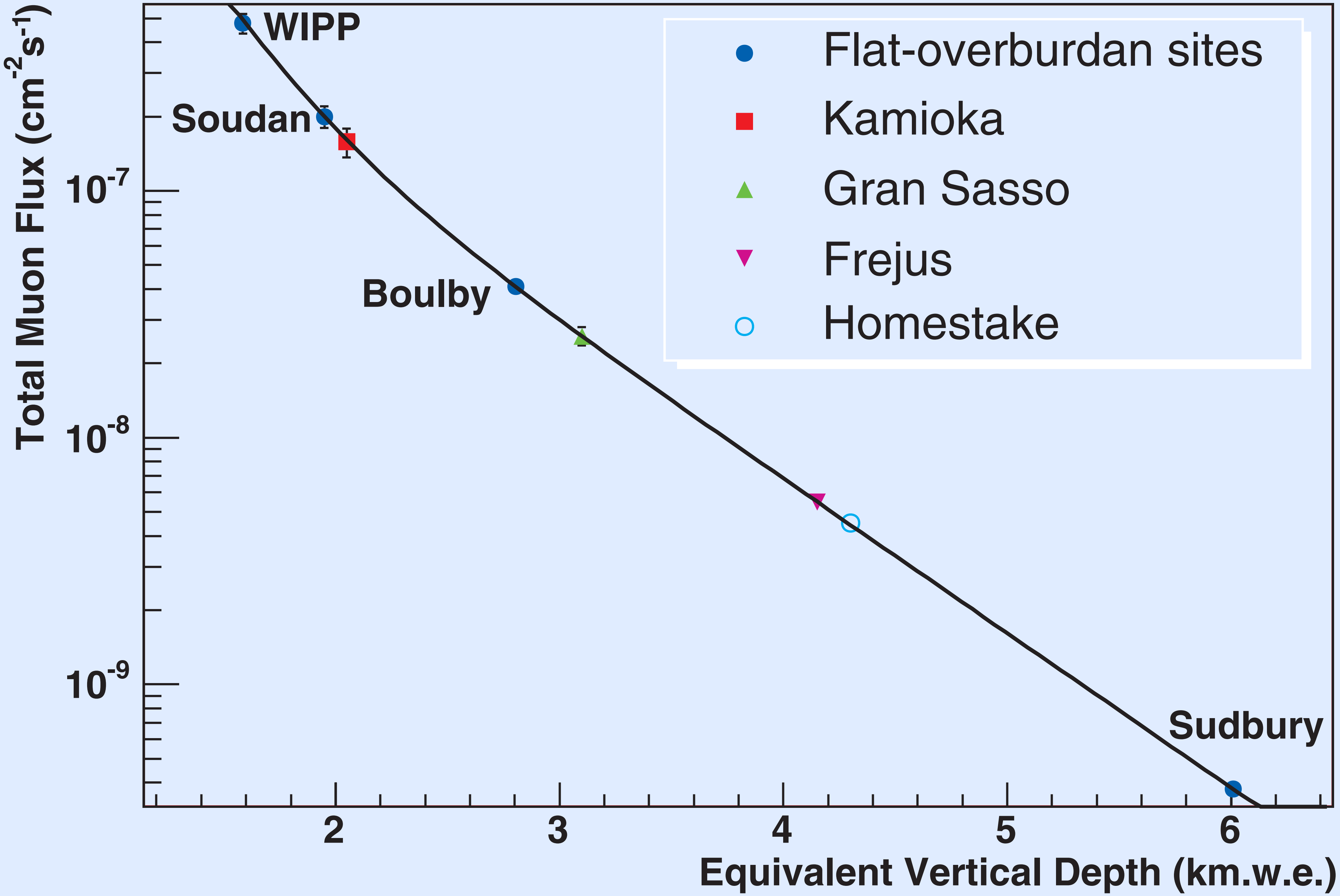
energetic muons are very penetrating and some survive the trip through several km of rock

- secondaries associated with muon showers react with nuclei in and around the detector: the product could be radioactive!

Three issues:

1. cosmic rays muons would blind a detector run on the surface
2. long-lived isotope activation (requires underground storage)
3. in-situ activation of fast decaying isotopes that could be a background

muon flux versus depth

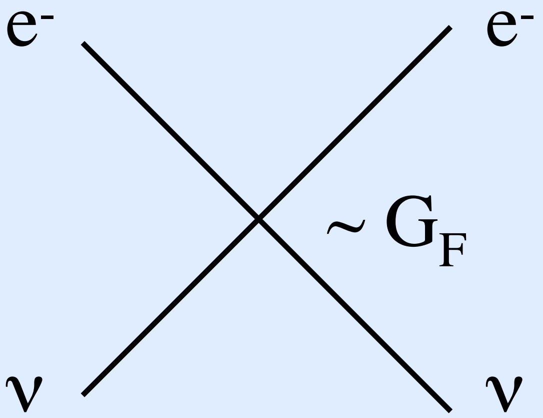


[Mei and Hime, *Phys. Rev. D* **73** (2006) 053004]

Neutrinos don’t interact much ....

- 1930: introduced/postulated by Pauli, as carriers of the apparent missing energy in β-decay

- 1934: Fermi develops the first theory of weak interactions (four-fermion interactions)

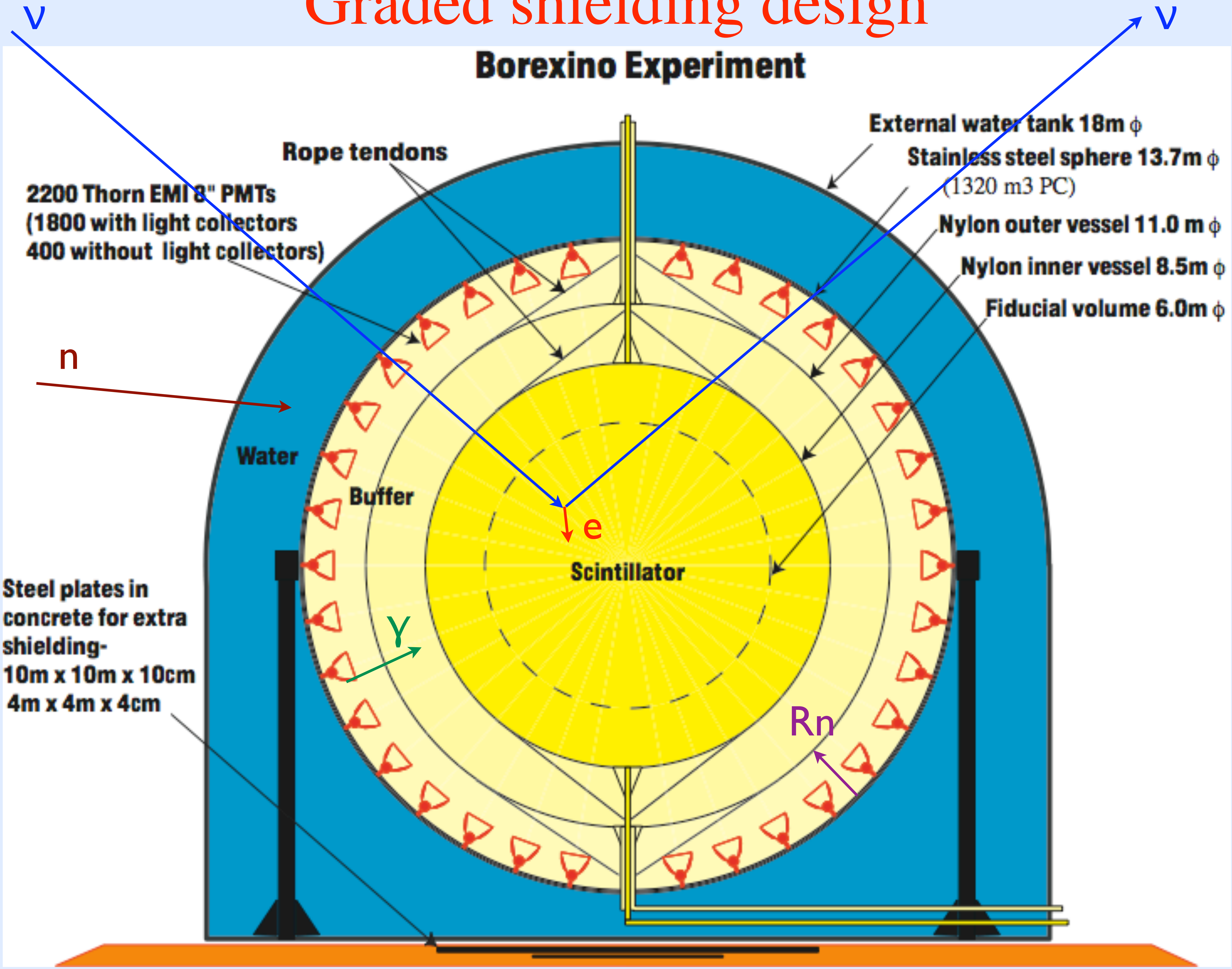


- at typical β-decay energies (1-10 MeV), the elastic scattering cross section of neutrinos on electrons is:

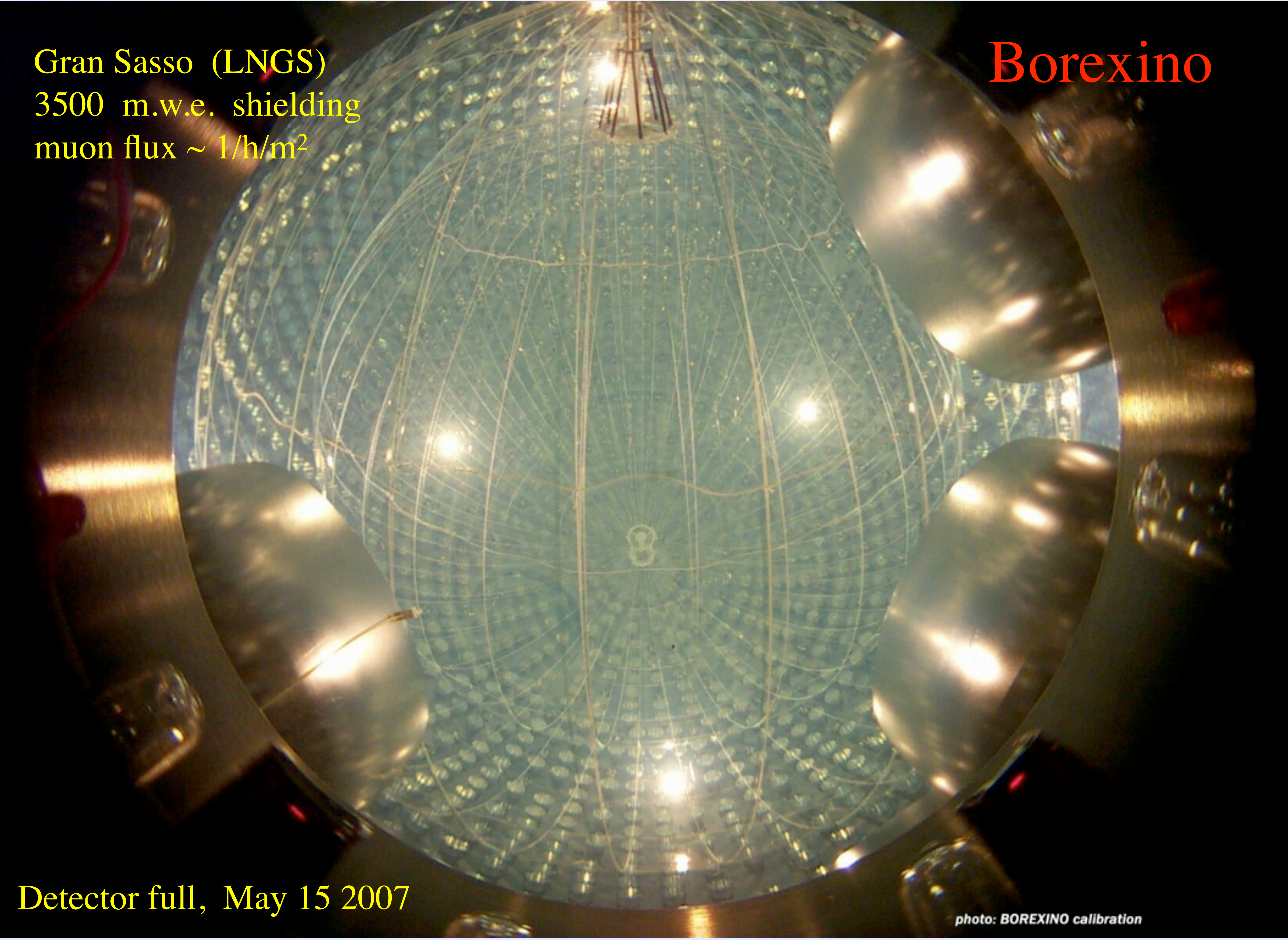
$$\sigma \sim G_F^2 s(\hbar c)^2 \sim 1.7 \text{ x } 10^{-44} E_\nu \text{ [MeV] cm}^2$$

(dimensional arguments, $s = 2m_eE_\nu+m_e^2$ invariant of the problem)

Graded shielding design



Borexino



Gran Sasso (LNGS)
3500 m.w.e. shielding
muon flux ~ $1/\mathrm{h}/\mathrm{m}^2$

Detector full, May 15 2007

photo: BOREXINO calibration

an estimation of required purity

- Borexino's fiducial scintillator volume is m = 100 tons (3 meter sphere), in which a few tens of neutrino events per day are expected

- ^{238}U has a mean life $\tau = 7 \times 10^{9}$ years; if its concentration (by mass) is C, the number of its decays/day R in the fiducial volume is:

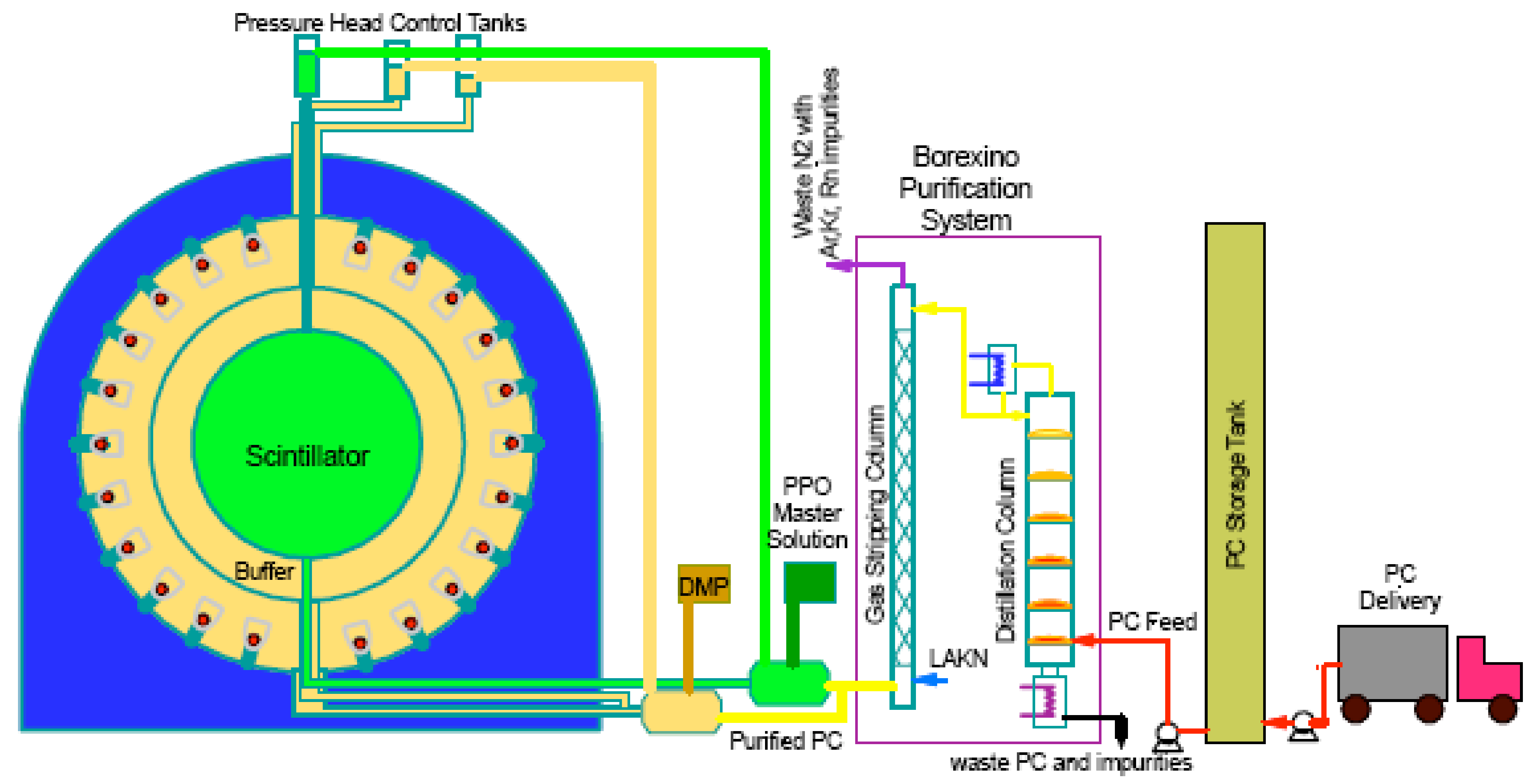
$$R = C[g/g]\ m[g]\ 6\text{x}10^{23}\ /\ 238[g/mol]\ \tau[d]$$

In order to have one decay/day, C has to be: $C \sim 10^{-17}$ g/g !!!

if you were wondering, we actually reached it :)

BX: scintillator purification

- petroleum derivative with $^{12}C/^{14}C \sim 10^{-18}$ ($\times 10^6$ lower than surface carbon)
- fast shipment underground to minimize 7Be activation (EC, $t_{1/2}$=53 d, 478 keV γ-ray)
- 6-stage distillation + low Ar/Kr N_2 gas stripping for PC solvent
- separate filtration, distillation + stripping for concentrated PPO fluor solution
- all plants, tanks and lines precision cleaned (detergent + acid etching)



BX data: an example of simple cuts

- 4136 days × tons exposure (note: events with z > 1.8 m were also excluded due to Rn contamination during detector top-off operations)

Main features:

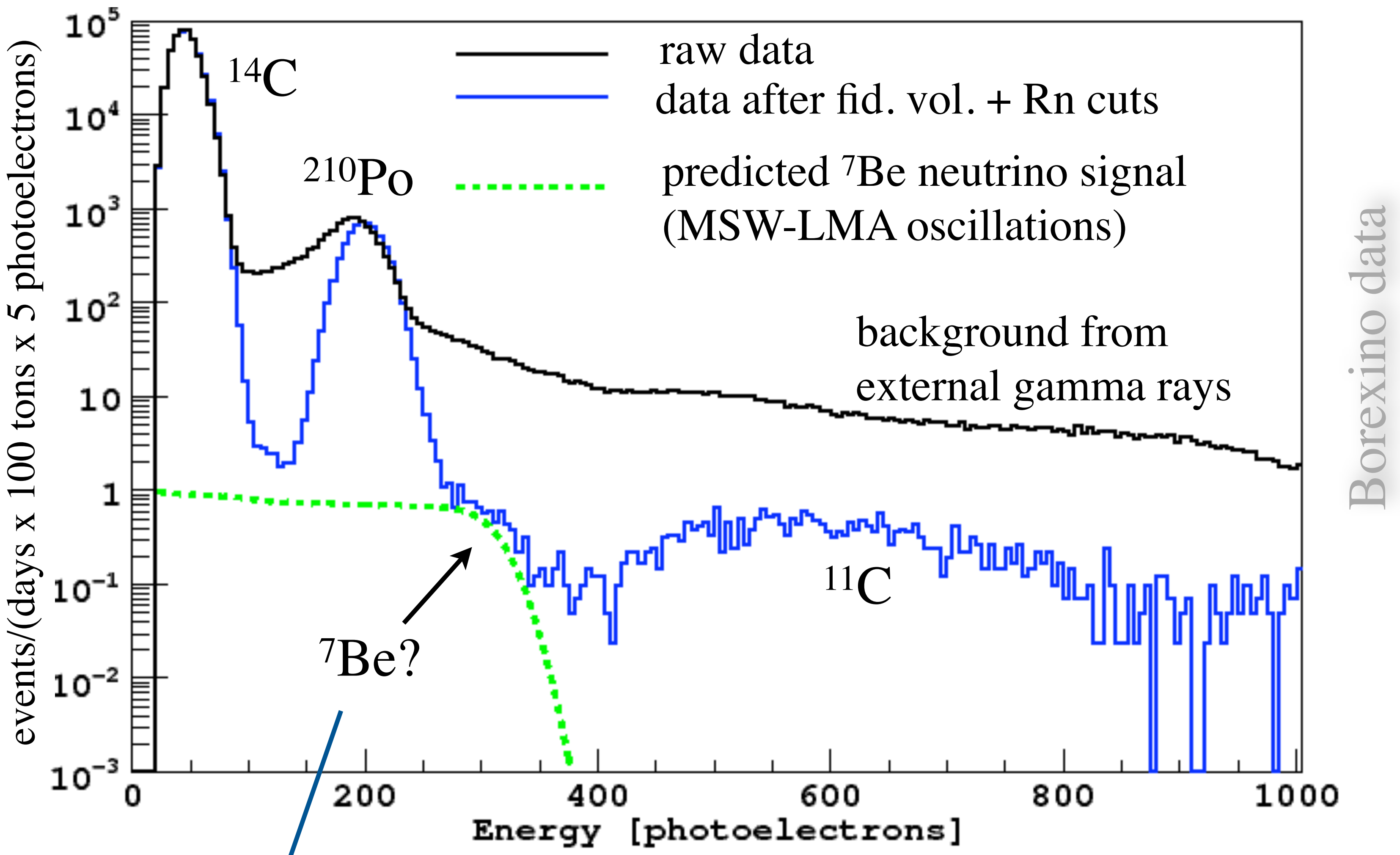
^{14}C: unaltered

^{210}Po: - sharper peak
- same amplitude

gamma background substantially reduced

^{11}C: muon produced positron emitter

Energy spectrum (fid. vol. + Rn cuts)



possible ^{7}Be Compton shoulder already visible after these very simply cuts!

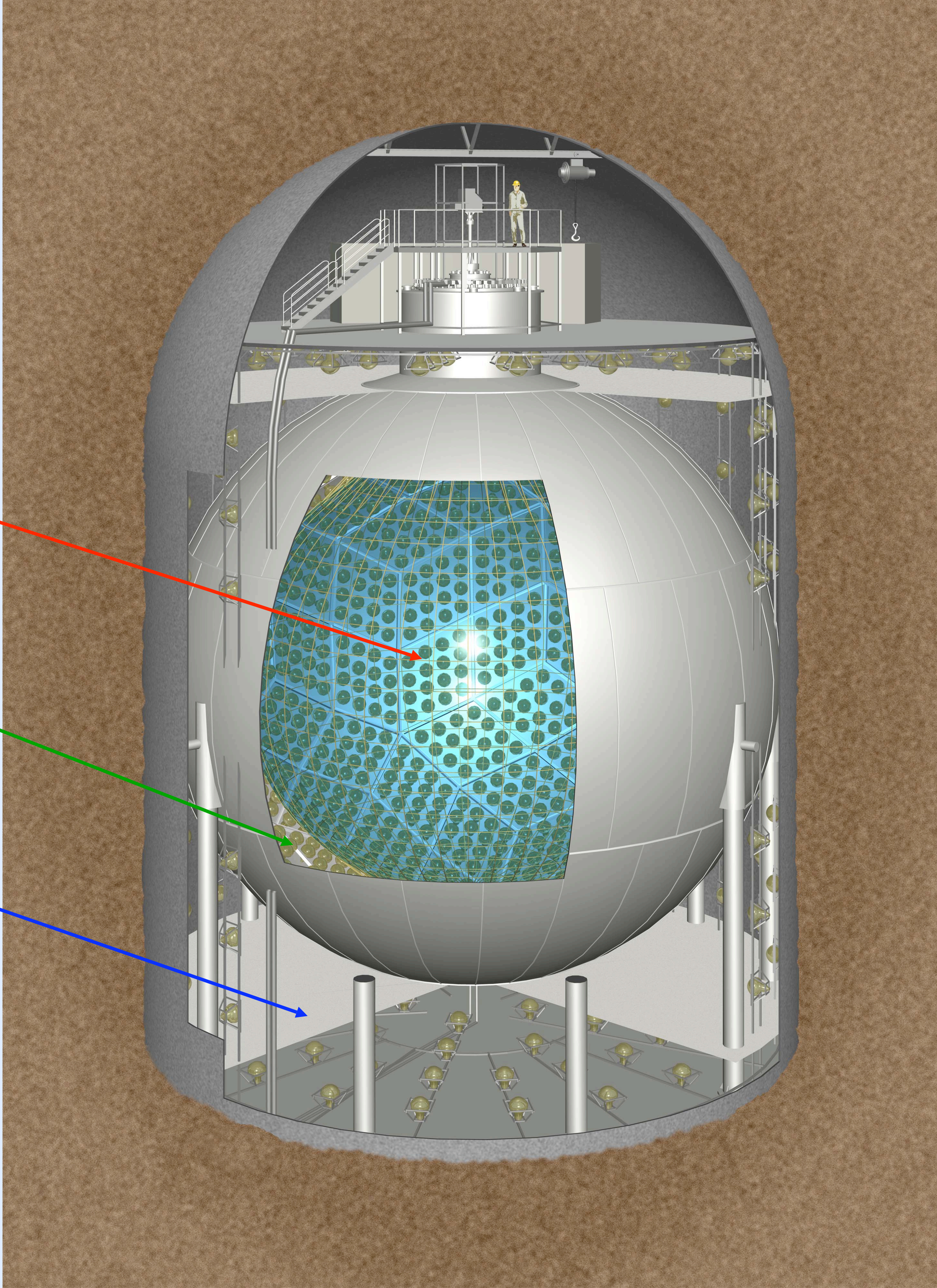
^{14}C: an unavoidable cosmogenic

half life ~ 5000 years

in BX it is present at a few parts in 10^{18}, but it anyhow determines the trigger rate of the experiment (~ 10 Hz, 50 keV threshold)

its presence determines the low energy threshold for neutrino physics of the experiment

KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector



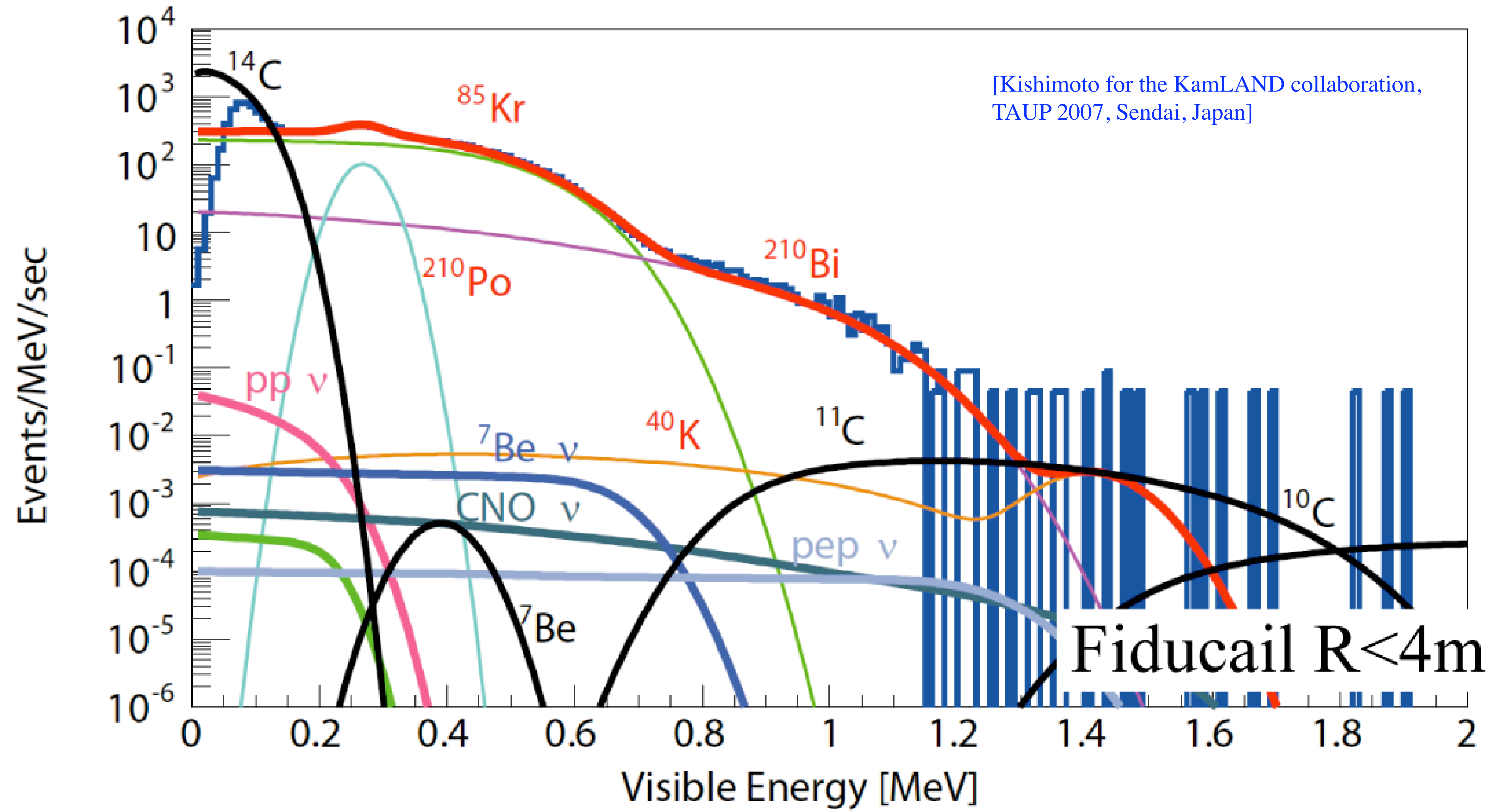
- 1 kton liq. Scint. Detector

  in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter

$$\bar{\nu}_e + p \rightarrow n + e^+$$

the KamLAND example - modest air contamination

In KamLAND, where little specific measures were taken to maximize radio-purity at low energy, the background was 5 orders of magnitude above the ^{7}Be expected signal



[Kishimoto for the KamLAND collaboration, TAUP 2007, Sendai, Japan]

Fiducail R<4m

general strategy includes:

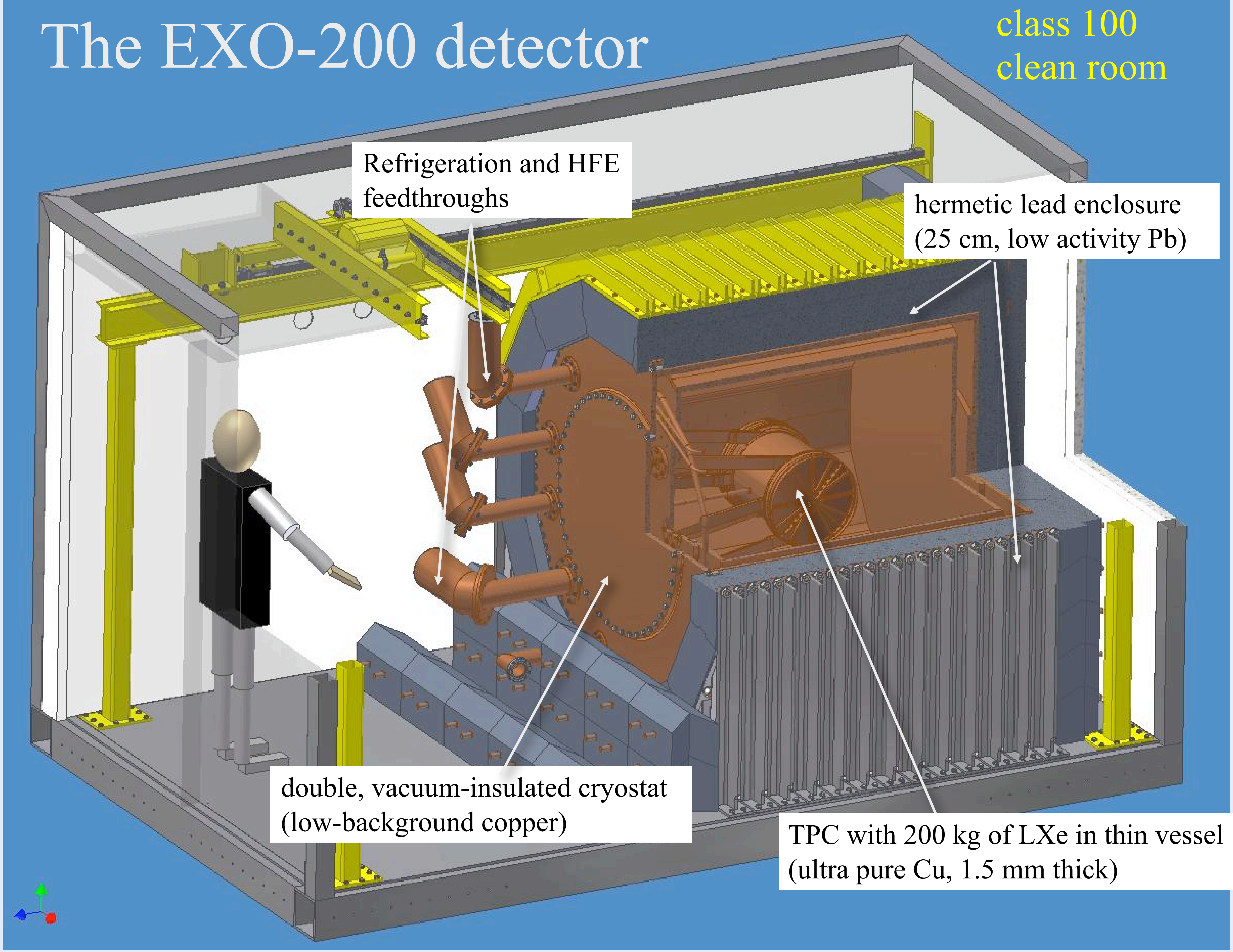
- large target/source

- go deep (enough) underground

- build detectors with ultra-clean techniques (material selection, clean room environment, graded shielding design, low Rn, material purification, ...)

- avoid/minimize (long- and medium-lived) radioactive isotope activation

The EXO-200 detector



class 100
clean room

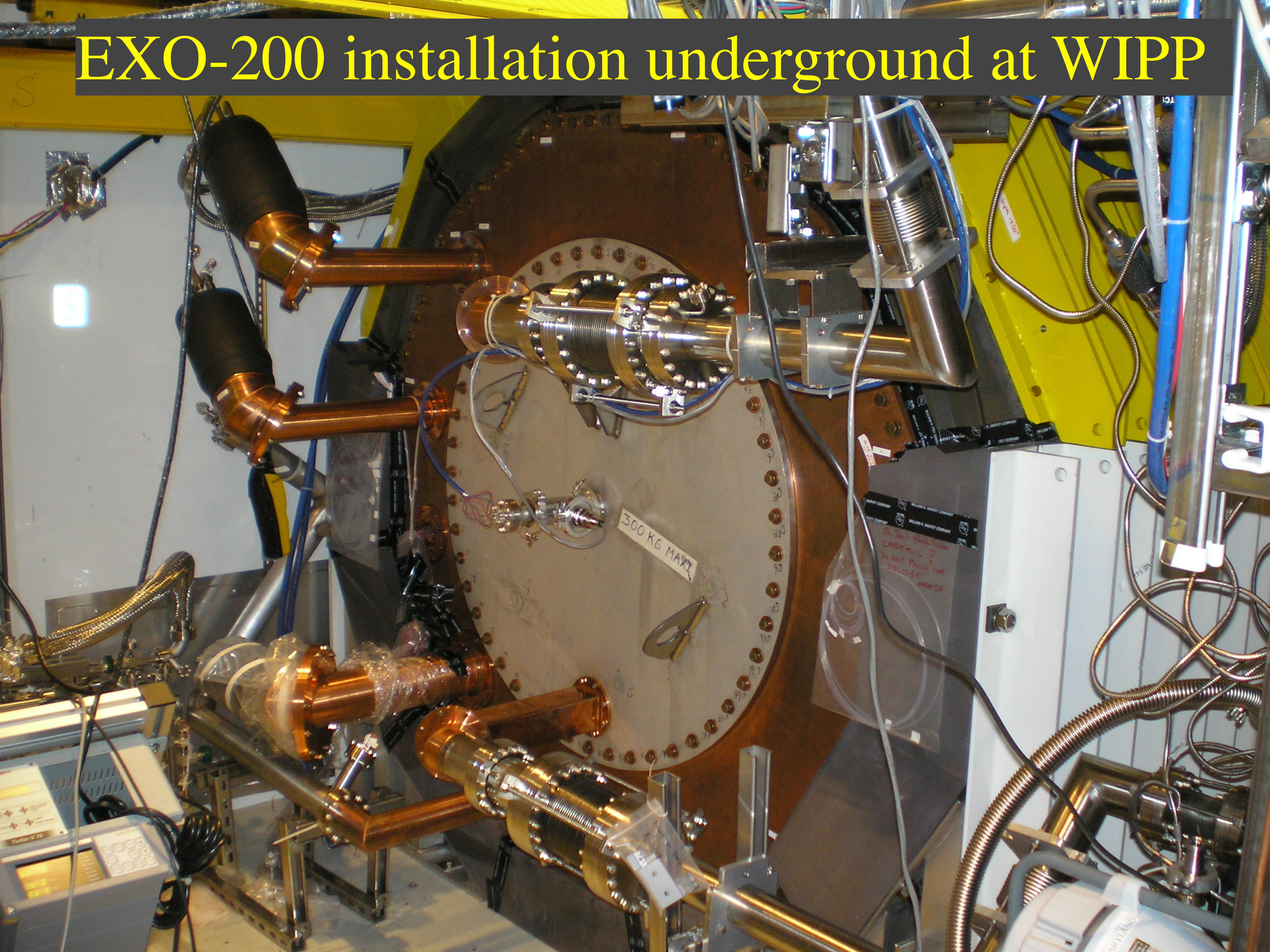
Refrigeration and HFE
feedthroughs

hermetic lead enclosure
(25 cm, low activity Pb)

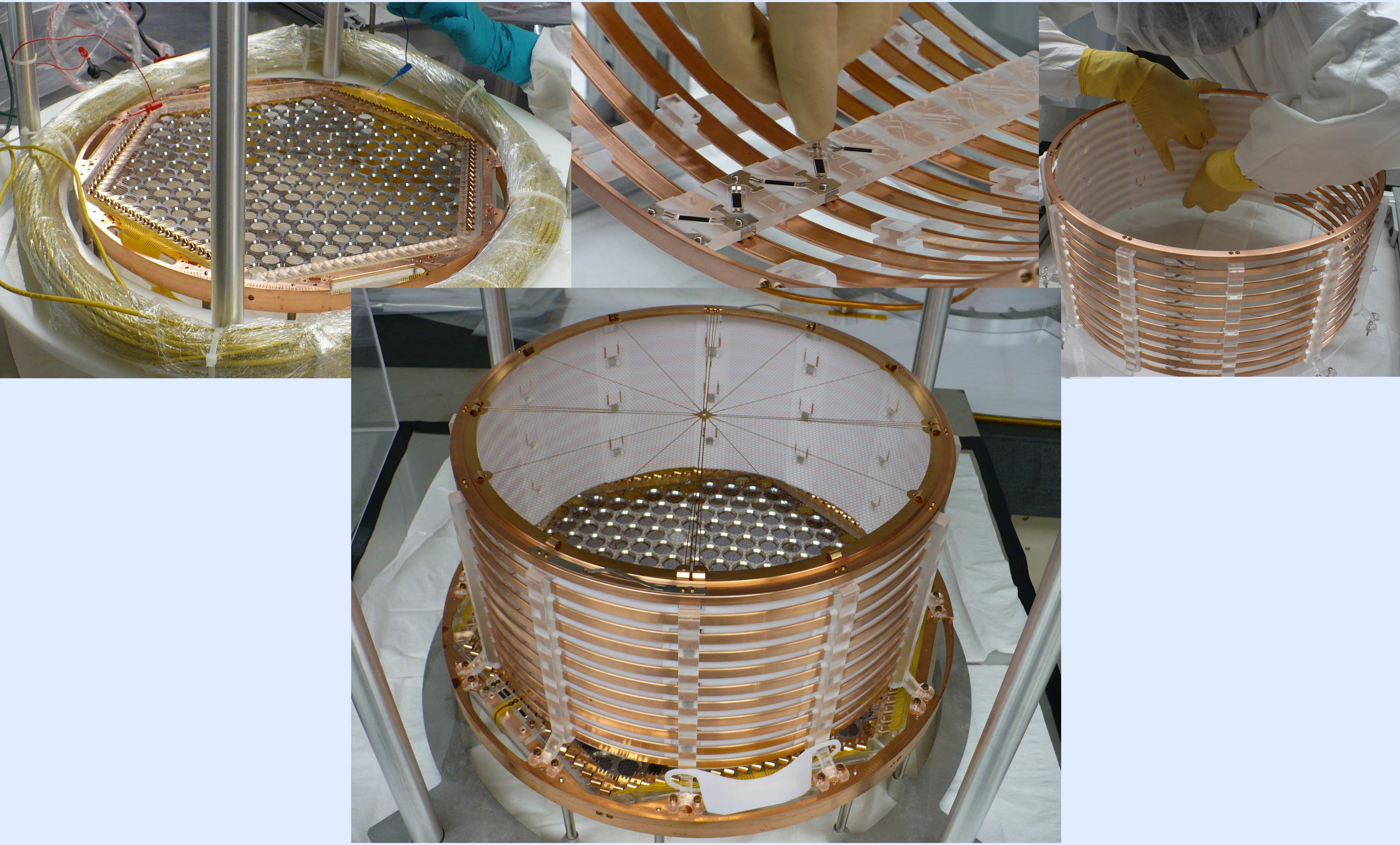
double, vacuum-insulated cryostat
(low-background copper)

TPC with 200 kg of LXe in thin vessel
(ultra pure Cu, 1.5 mm thick)

EXO-200 installation underground at WIPP

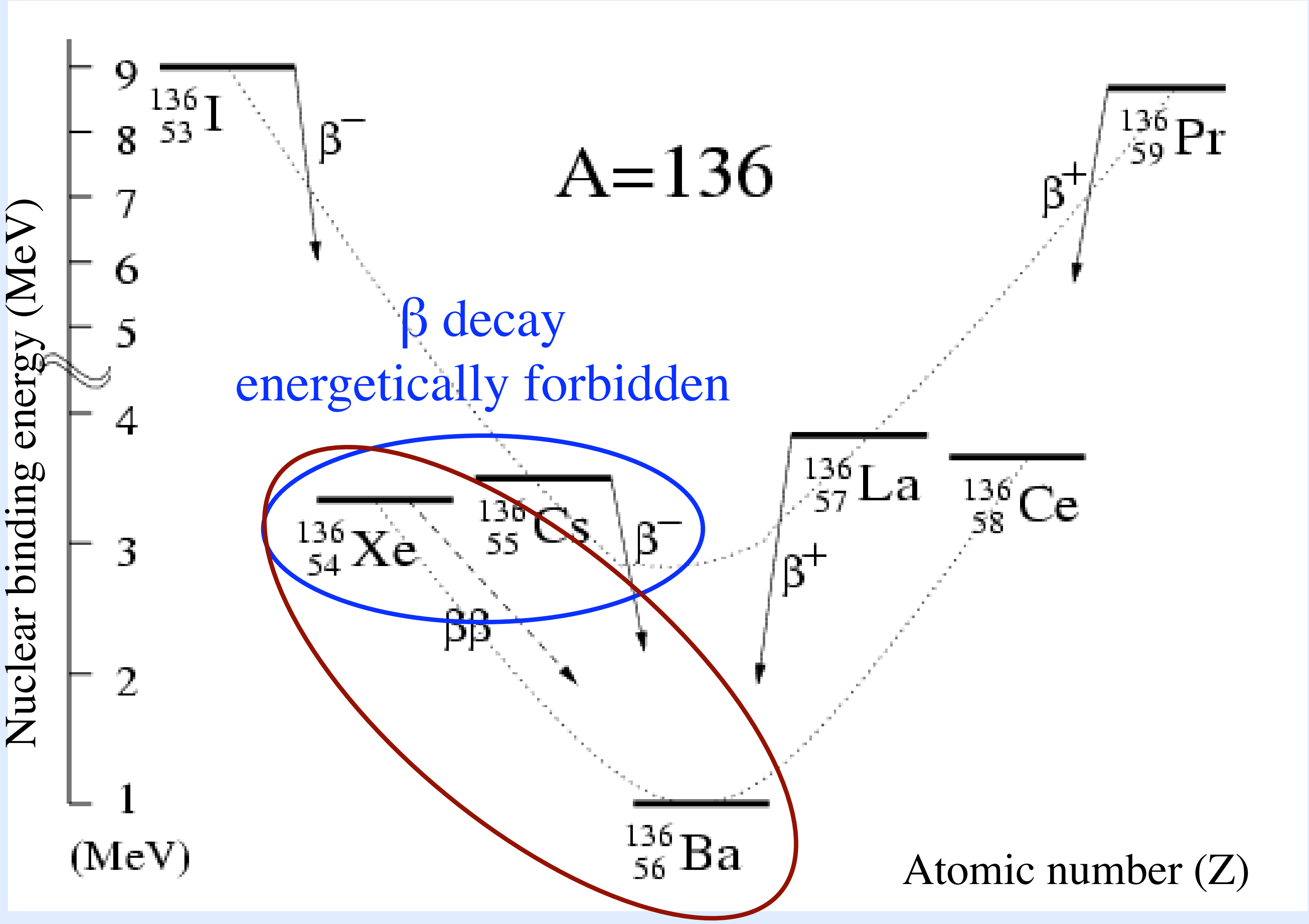


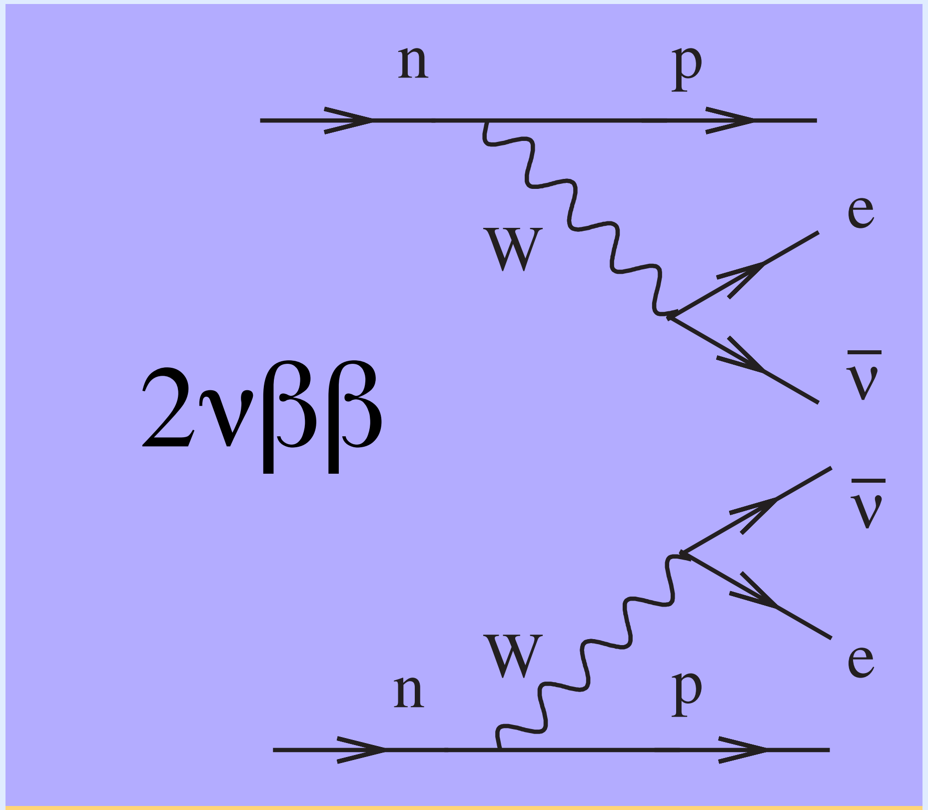
Enriched Xenon Observatory for double beta decay

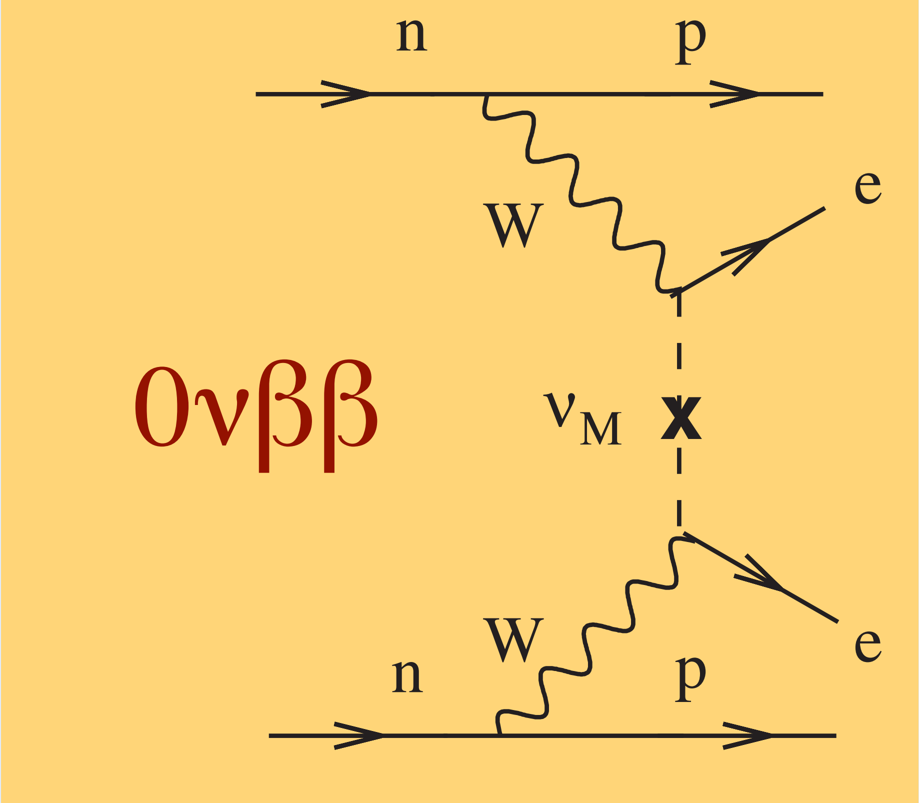


double beta decay

- standard, second order weak process
- predicted in 1935 by Goeppert-Meyer







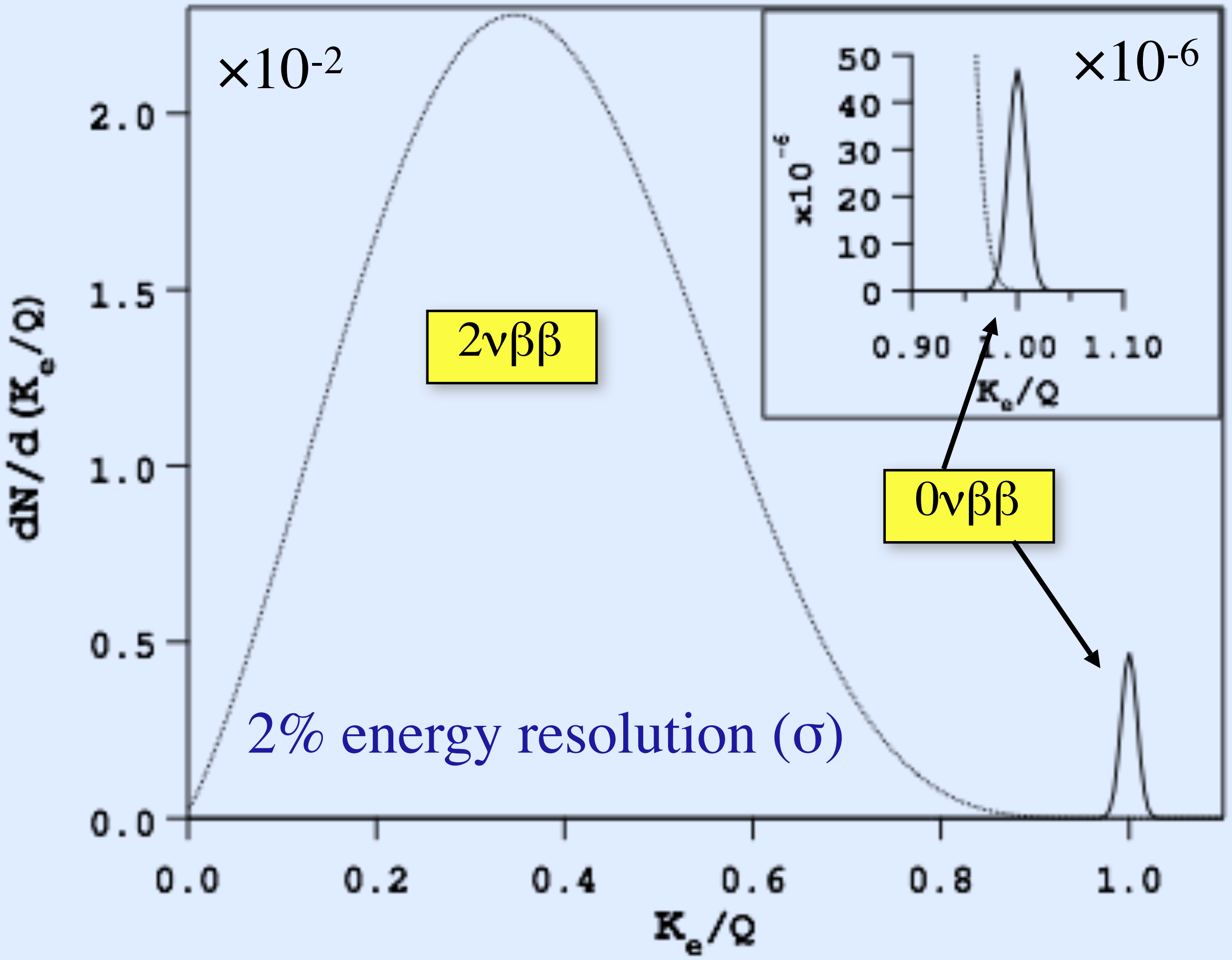
possibility of non-standard 0νββ process

how is 0νββ measured in the laboratory?

- very rare events: need to suppress non-ββ background with low radioactivity detectors and underground

- large mass: large source, isotope enrichment

- energy resolution: separate 0νββ mono-energetic peak from the 2νββ energy spectrum and fewer non-ββ background events in the peak



[P. Vogel, arXiv:hep-ph/0611243]

- tracking: identify individual electron tracks to discriminate between single- and 2-electron events (discrimination of β and γ background radiation)

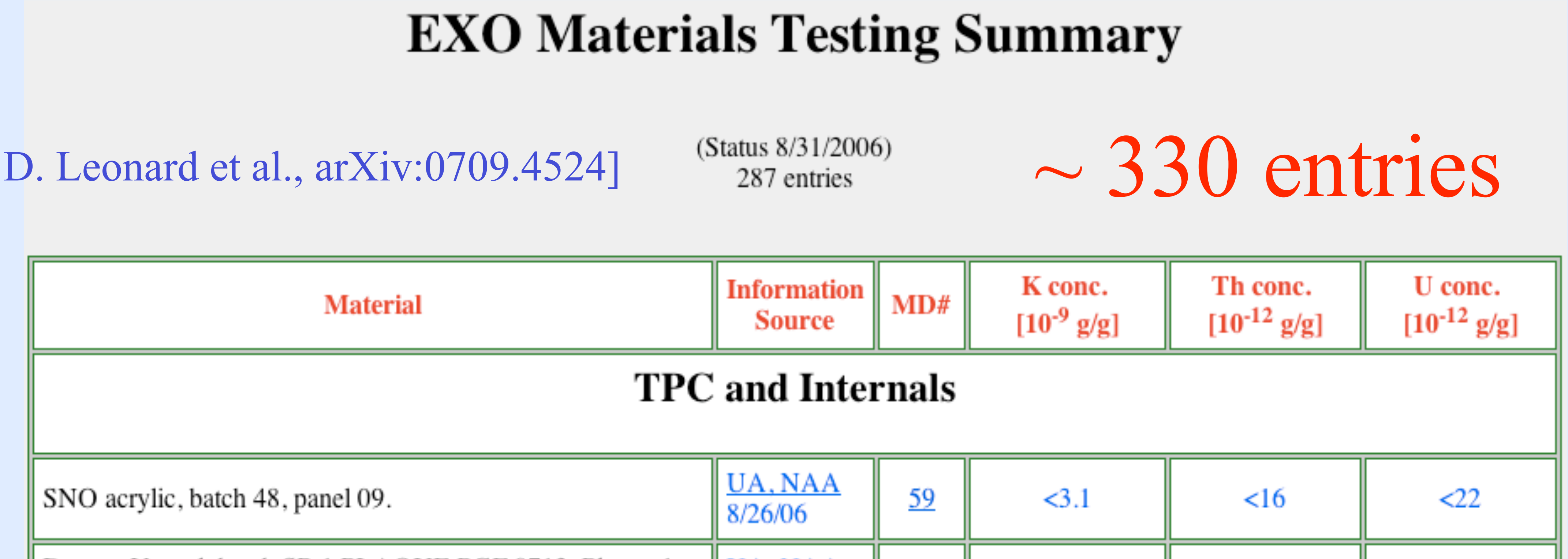
- multi-isotope: measure different isotopes with the same detector to cross-check results and reduce systematic and theoretical uncertainties

- decay product identification: unambiguously from ββ events

Material screening - the EXO example

- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (a concern for the $2\nu\beta\beta$)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- in situ cosmogenics in Xe, neutron capture de-excitations, ...
- ^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)

analytical methods:
ICP-MS, NAA, direct gamma/alpha counting, Rn emanation counting



EXO Materials Testing Summary

(Status 8/31/2006)
287 entries

Material	Information Source	MD#	K conc. [10^{-9} g/g]	Th conc. [10^{-12} g/g]	U conc. [10^{-12} g/g]
TPC and Internals					
SNO acrylic, batch 48, panel 09.	UA, NAA 8/26/06	59	<3.1	<16	<22

[EXO collaboration; D. Leonard et al., arXiv:0709.4524]

~ 330 entries

Radon - ubiquitous enemy

3.8235 d	$^{222}_{86}$**Rn**	α: 5.4895 (99.92)		γ: 511 (0.076)
	100 $\downarrow$ α	α: 4.986 (0.078)		
3.10 m	$^{218}_{84}$**Po**	α: 6.0024 (100)		NO γ-RAYS
	0.020 99.980		β: NO DATA	
	β $\swarrow$ $\searrow$ α			
1.6 s	$^{218}_{85}$**At** $^{214}_{82}$**Pb**	α: 6.694 (90)	β: 0.728 (42.2)	γ: 351.93 (35.1/37.6)
26.8 m	99.9 100		β: 0.670 (48.9)	γ: 295.22 (18.2/19.3)
	α $\searrow$ $\swarrow$ β		β: 1.030 (6.3)	γ: 242.00 (7.12/7.43)
19.9 m	$^{214}_{83}$**Bi**	α: 5.452 (53.9)	β: 3.275 (18.2)	γ: 609.31 (44.6/46.1)
	0.021 99.979	α: 5.516 (39.2)	β: 1.542 (17.8)	γ: 1764.49 (15.1/15.4)
	α $\swarrow$ $\searrow$ β		β: 1.508 (17.02)	γ: 1120.29 (14.7/15.1)
			β: 1.425 (8.18)	γ: 1238.11 (5.78/5.79)
			β: 1.894 (7.43)	γ: 2204.21 (4.98/5.08)
1.3 m	$^{210}_{81}$**Tl** $^{214}_{84}$**Po**	α: 7.6868 (99.99)		γ: 799.7 (0.0104)
164.3 μs	100 100		β: 4.209 (30)	γ: 799.7 (0.021)
	β $\searrow$ $\swarrow$ α		β: 1.863 (24)	
22.3 y	$^{210}_{82}$**Pb**		β: 0.017 (80)	γ: 46.54 (4.25)
	100 $\downarrow$ β		β: 0.063 (20)	
5.013 d	$^{210}_{83}$**Bi**			
	100 $\downarrow$ β		β: 1.162 (99)	NO γ-RAYS
138.376 d	$^{210}_{84}$**Po**	α: 5.3043 (99.99)		γ: 803.10 ($1.22 * 10^{-3}$)
	100 $\downarrow$ α			
stable	$^{206}_{82}$**Pb**			

$^{*}\gamma$-emission: intensity per 100 decays in equilibrium/absolute;

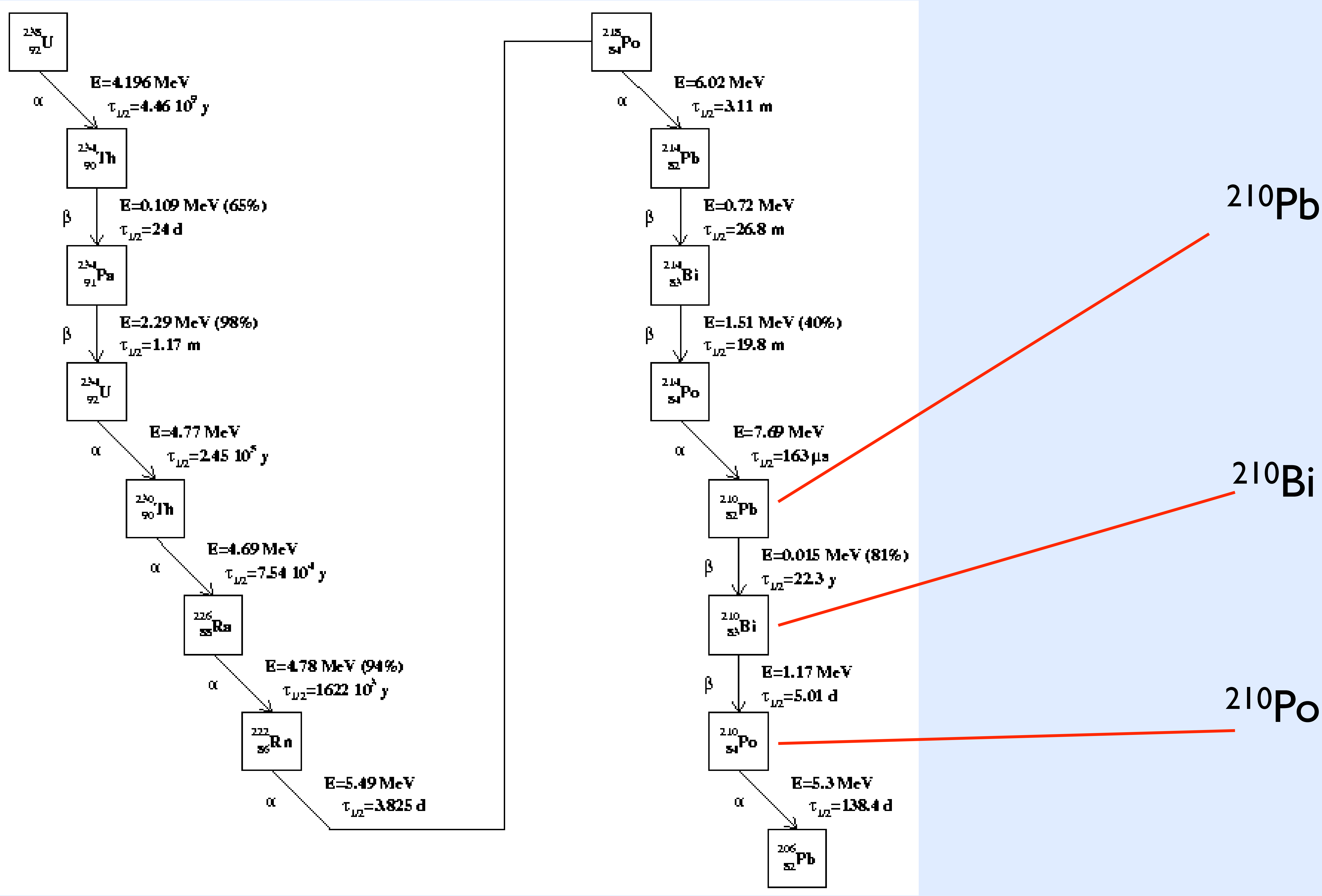
$^{**}\alpha$-, β-decay: absolute intensity $\Sigma \approx$100%; for intensity per 100 decays multiply by branch

Radon - ubiquitous enemy

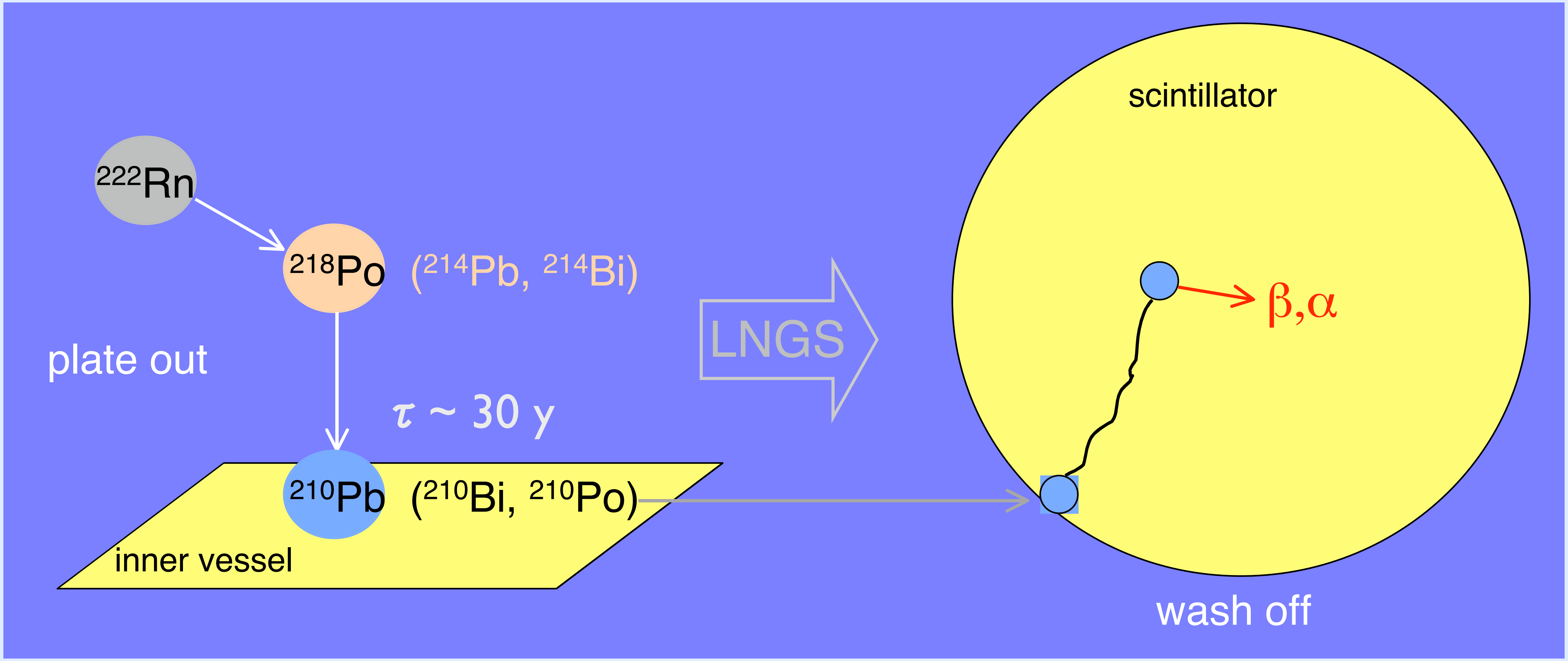
different decays in the Rn chain affect different experiments:

- Kamland: ^{13}C (alpha,n) ^{16}O
- CDMS: ^{210}Pb decays, low energy surface electrons
- COUPP: alpha decays
- EXO (and other double beta decay experiments): gamma rays

Radon daughters



Radon daughter surface contamination



➙ only direct measurement available (data are the ultimate test!)

➙ a naïve model is to say that all radon daughters decaying in the air column above the surface stick to it:

~1300 ev/d/(hr of exposure)   (in 100 tons)

(assumptions: 3m air column, air at 20 Bq/m3, 100% plate out, 100% wash off)

BX nylon vessels

- nylon pellets with 10^{-12} Th, U concentration in weight (ppt) [C. Arpesella et al., Astropart. Phys. **18**, 1 (2002)]

- clean extrusion and post-extrusion surface cleaning to level 25 Mil. Std. 1246C (^{226}Ra contamination of final film < 21 μBq/kg) [M. Wójcik et al., NIM A **498**, 240 (2003)]

- nylon vessels (inner for scintillator containment, outer Rn barrier) made in a class 100 clean room

- surfaces kept covered as much as possible during assembly, shipping and installation

- each vessels assembled as a self-covering stack and assembled into a nested set

- radon-scrubbed clean room make up air, via a room temperature vacuum swing adsorption (VSA) on activated charcoal device (first of its kind)

- clean room air humidified with aged water

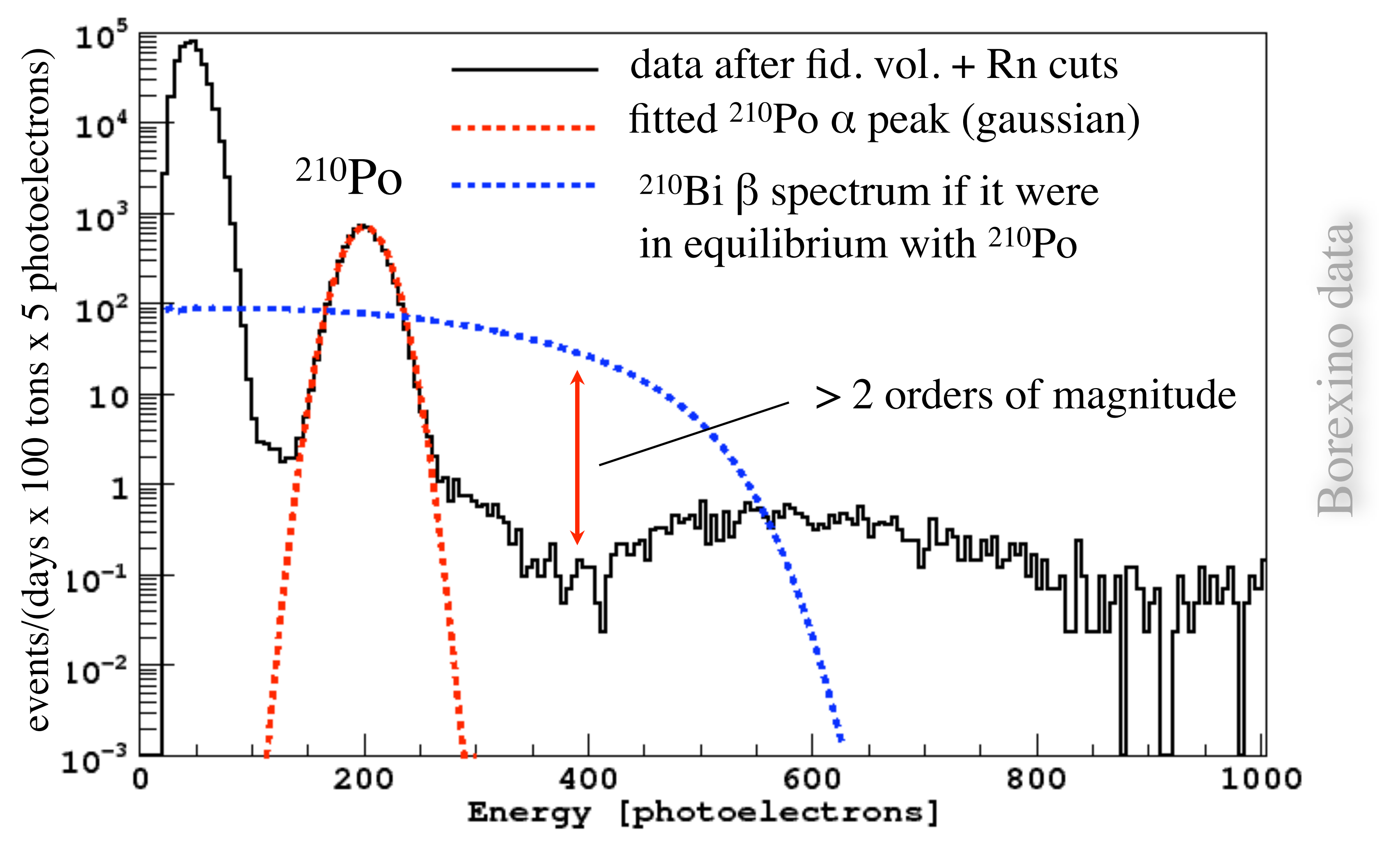
- detector turned into a class 10,000 clean room

[J. Benziger et al., Nucl. Instr. Meth. A **582**, 509 (2007)]

^{210}Po background - learn some chemistry

- ^{210}Po (τ = 200 d) activity is ~ 60 events/d/ton (> 100× the predicted ^{7}Be solar neutrino rate!)

- ^{210}Po is out of equilibrium with ^{210}Pb and ^{210}Bi, since the decay rate of the latter is >100 times smaller (β and γ decays of ^{210}Pb are < 100 keV and buried under ^{14}C)



Borexino data

^{210}Po has a very complicated chemistry, certainly different than that of ^{210}Pb:

- confirms tests performed with the latest CTF runs
- also seen during recent KamLAND scintillator purification [Kishimoto, TAUP 2007, Sendai, Japan]
- contamination and wash-off patterns studied in the lab
- needs dedicated purification strategy

tiny Rn contamination is sometimes handy ...

Certain isotopes can be readily identified as they produce coincident decays in rapid succession at the same location in the detector

$${}^{214}\mathrm{Bi} \xrightarrow[3.3\ \mathrm{MeV}]{\beta+\gamma} {}^{214}\mathrm{Po} \xrightarrow[7.7\ \mathrm{MeV}]{\alpha} {}^{210}\mathrm{Pb} \quad (\tau = 237\ \mu\mathrm{s},\ {}^{238}\mathrm{U}\ \text{chain},\ {}^{222}\mathrm{Rn}\ \text{daughter})$$

$${}^{212}\mathrm{Bi} \xrightarrow[3.3\ \mathrm{MeV}]{\beta+\gamma} {}^{212}\mathrm{Po} \xrightarrow[8.8\ \mathrm{MeV}]{\alpha} {}^{208}\mathrm{Pb} \quad (\tau = 431\ \mathrm{ns},\ \mathrm{BR} = 64\%,\ {}^{232}\mathrm{Th}\ \text{chain})$$

$${}^{85}\mathrm{Kr} \xrightarrow[687\ \mathrm{keV}]{\beta} {}^{85\mathrm{m}}\mathrm{Rb} \xrightarrow[514\ \mathrm{keV}]{\gamma} {}^{85}\mathrm{Rb} \quad (\tau = 1.46\ \mu\mathrm{s},\ \mathrm{BR} = 0.43\%)$$

free calibration tool!

event topology is poor, but some discrimination is possible ....

- alpha/beta separation in organic scintillators (discriminate on the decay time of the scintillation light)

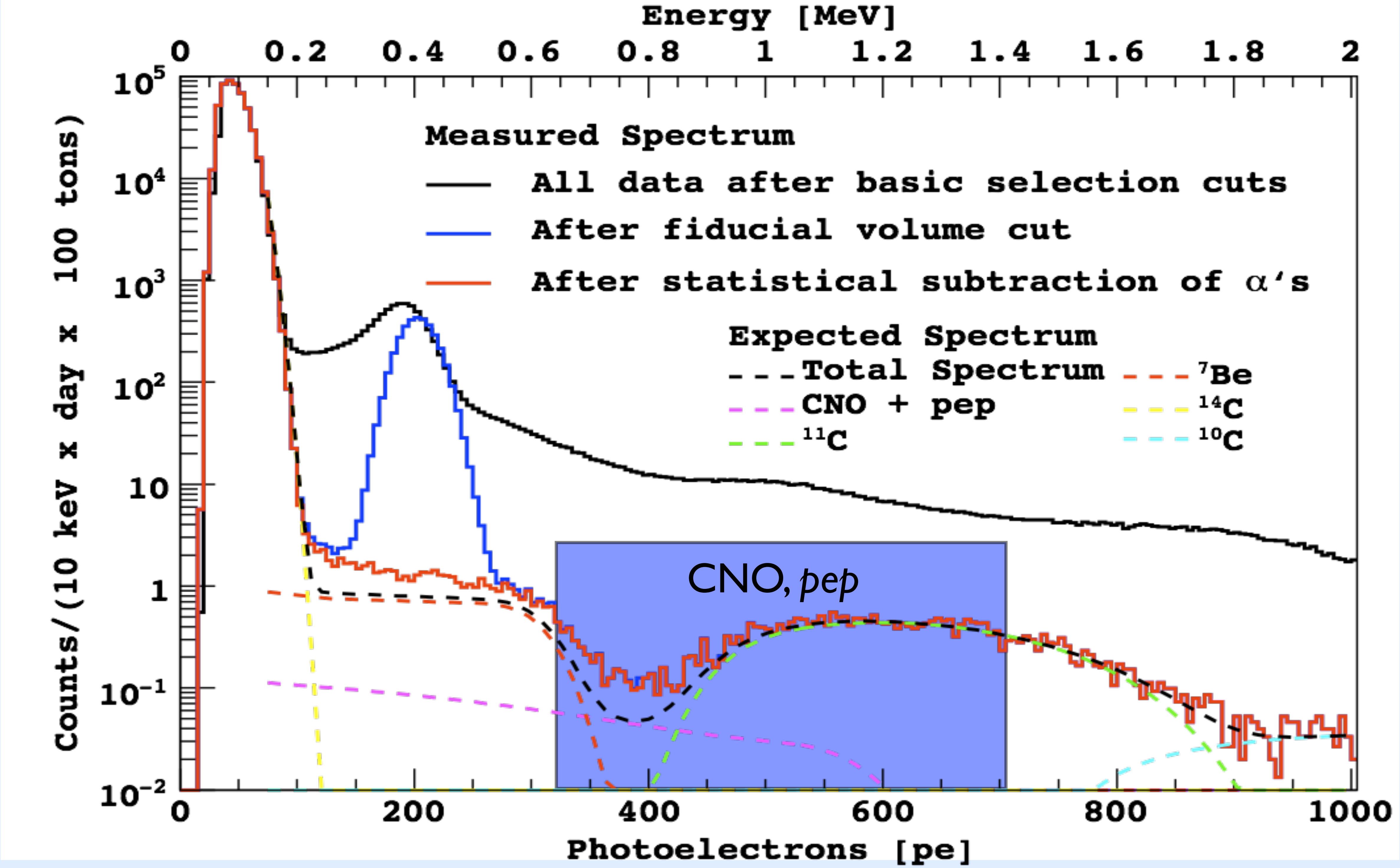
- electron + gamma vs nuclear recoils in noble liquids (different primary scintillation pulse shape as well as different partition between primary scintillation and ionization)

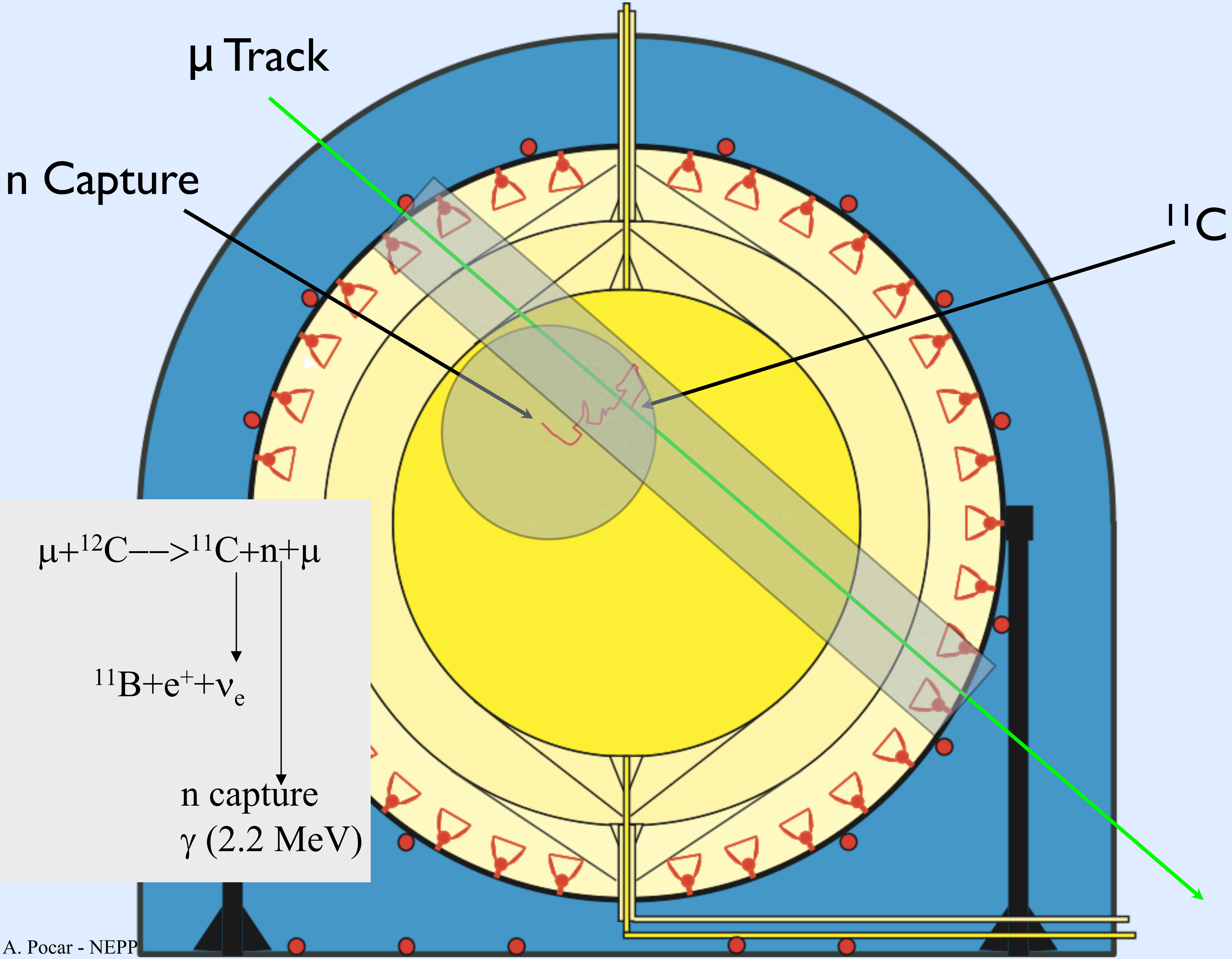
- single/multiple site events

- tracking (modest but non-trivial topology: double beta tracks, directional WIMPs, ...)

- cosmogenic background subtraction

example: ^{11}C subtraction





$\mu + {}^{12}C \rightarrow {}^{11}C + n + \mu$

$^{11}B + e^{+} + \nu_e$

n capture

γ (2.2 MeV)

use discrimination for designing your detector

every experiment tries to exploit some discrimination techniques to improve sensitivity

some examples ....

dark matter: identify nuclear recoils vs electron events
(xenon/argon 1 or 2-phase, cdms, cresst, dama, ...)

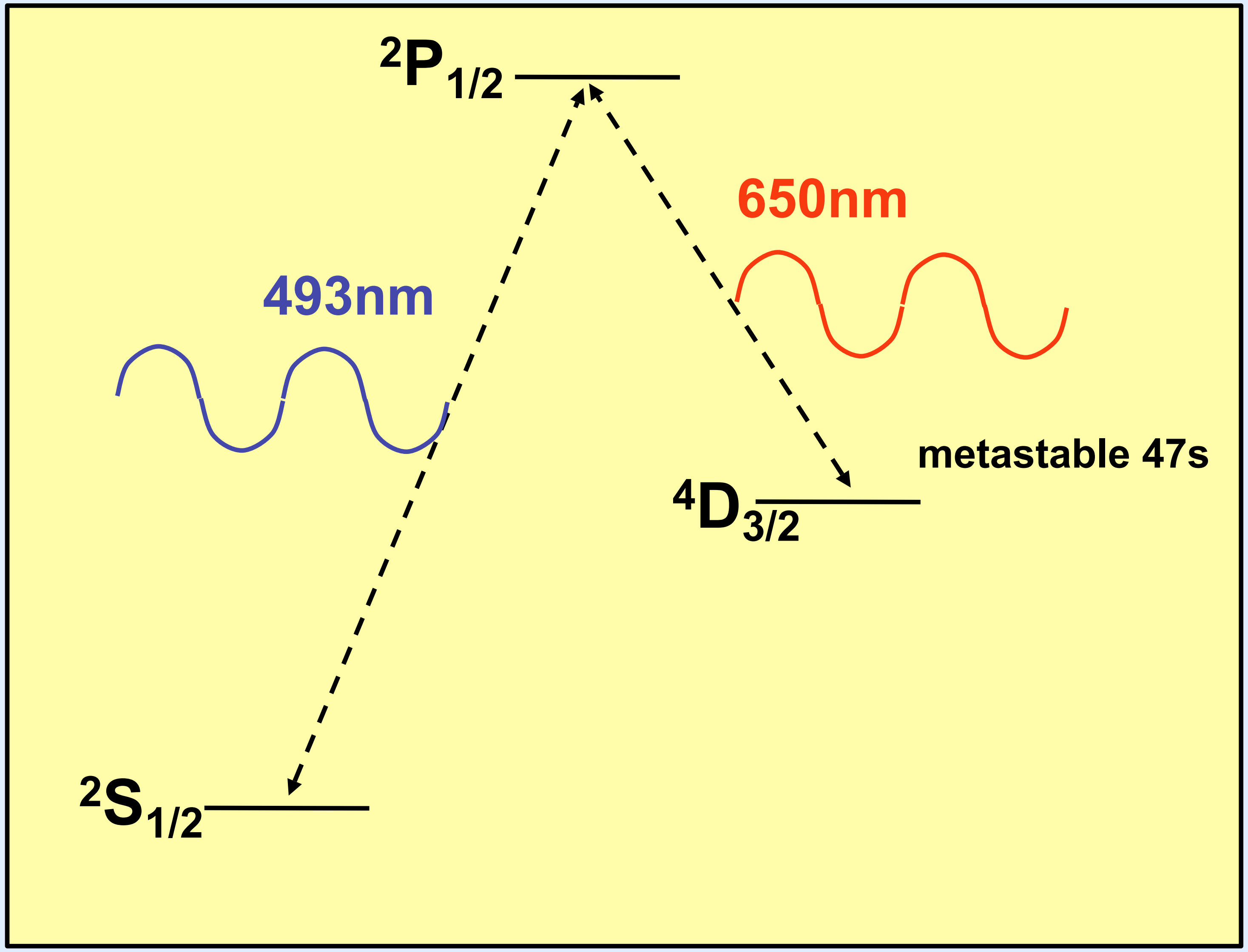
double beta decay: sharp energy resolution, tracking,
(exo, SNO+, cuore, gerda, ...)

solar neutrinos: liquid scintillator, lxe, lens, sno+, ...

a crazy idea: Ba ion tagging

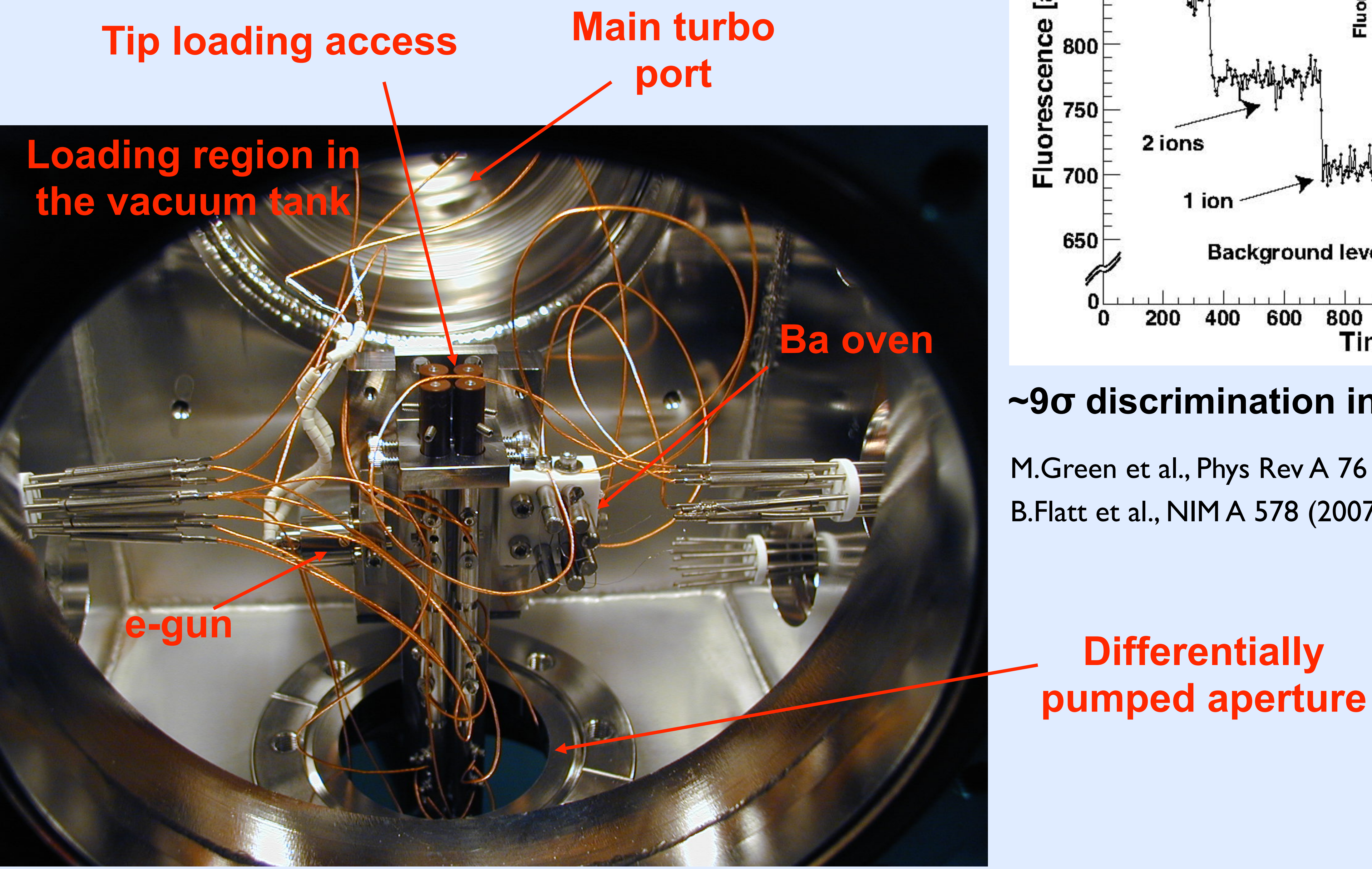
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-}$

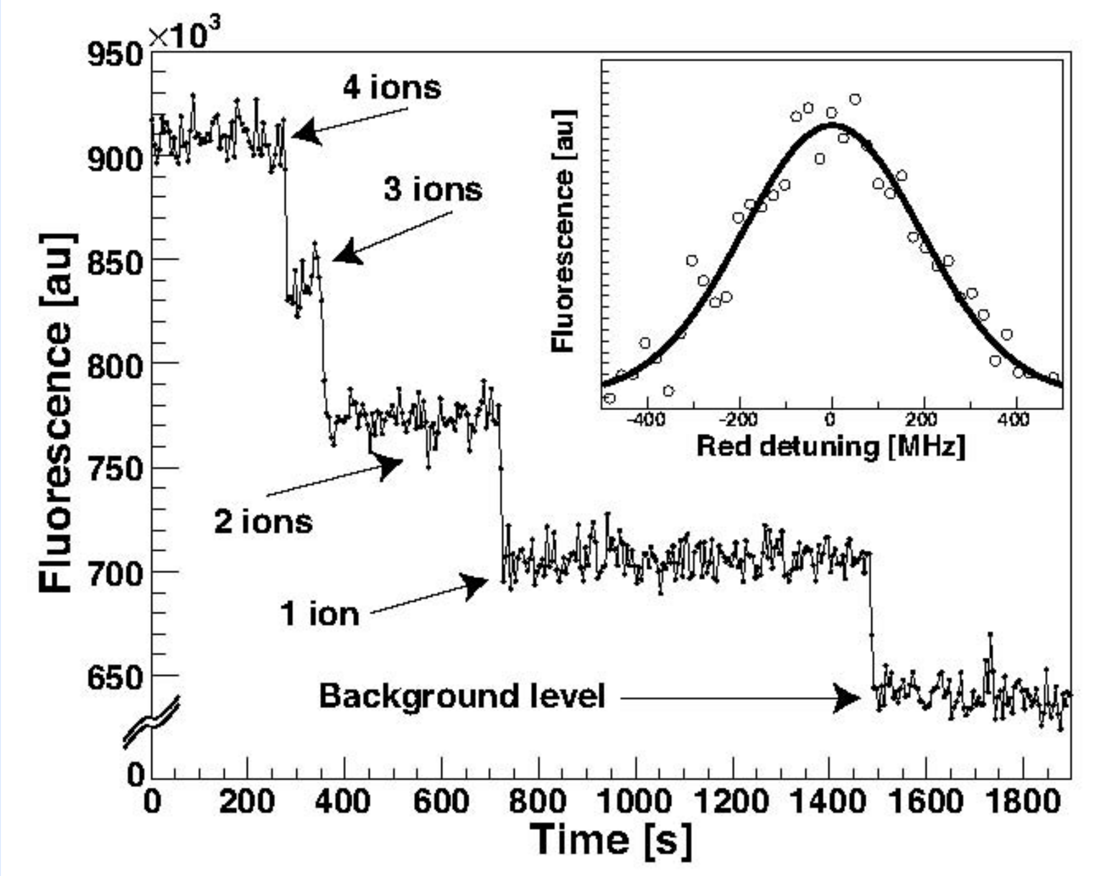
- Ba^{+} system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
- Very specific signature
- Single ions can be detected from a photon rate of 10^7/s



Ba^{+} tagging would allow for the elimination of all backgrounds except the background from $2\nu\beta\beta$.

single ion trapping





~9σ discrimination in 25s integration

M.Green et al., Phys Rev A 76 (2007) 023404
B.Flatt et al., NIM A 578 (2007) 409

low background particle physics achievements

- detection of (anti)neutrinos
  - detection of solar neutrinos and (some of) its various components
    - observation of neutrino oscillations and its mixing parameters

    - stringent limits (detection?) of neutrinoless double beta decay

    - ever tighter limits (detection?) on cold dark matter

    - tight limits on the existence of proton decay (relevant to discard grand unification theories)

    - detection of neutrinos from nuclear reactors and the Earth's radioactivity

    - possible monitoring of nuclear reactors and nuclear fuel

    - and ......

.... now you have all the tools to design the next successful experiment!

choose well and GOOD LUCK!