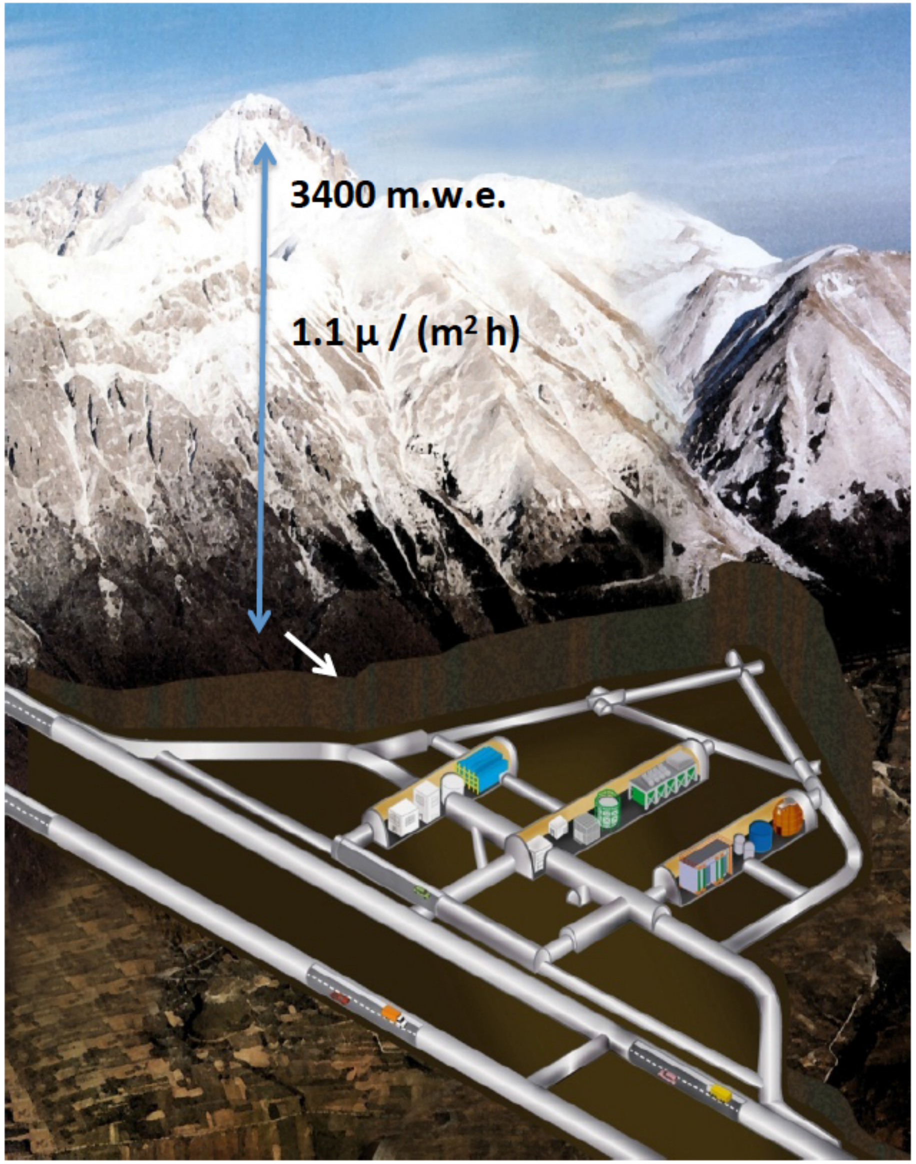
Borexino

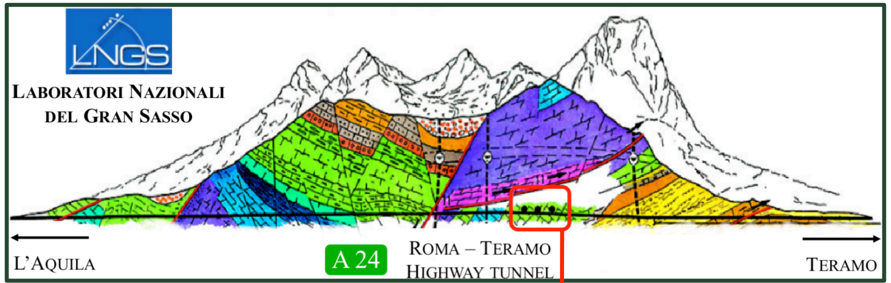
Presented by Livia Ludhova (RWTH Aachen and IKP-2 Forschungzentrum Jülich, Germany)

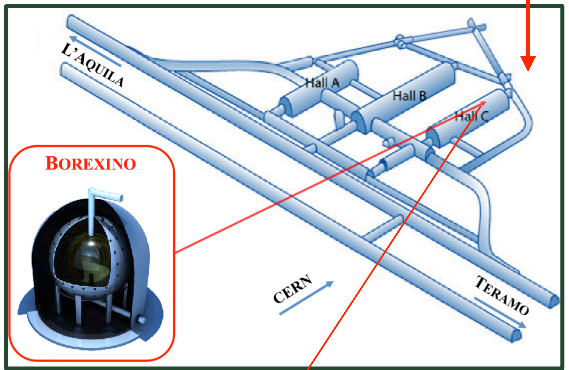
Laboratori Nazionali del Gran Sasso

- Muon flux: 3.0 10^{-4} $m^{-2}s^{-1}$
- Neutron flux:
  2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV)
  0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV)
- Rn in air: 20-80 Bq m^{-3}
- **Surface: 17 800 m^2**
- **Volume: 180 000 m^3**
- Ventilation: 1 vol / 3.5 hours
- **Mechanical Design and Workshop**
- **Electronics Lab & Service**
- **Chemistry Lab & Service**
- **ULB Lab & Service**
- > 900 users from 29 countries
- ~ 100 Staff
- 225 avg. daily presence in 2014
- ~ 8000 visitors/y
- Virtual tour via Street View



Laboratori Nazionali Gran Sasso / LNGS (ITALY)



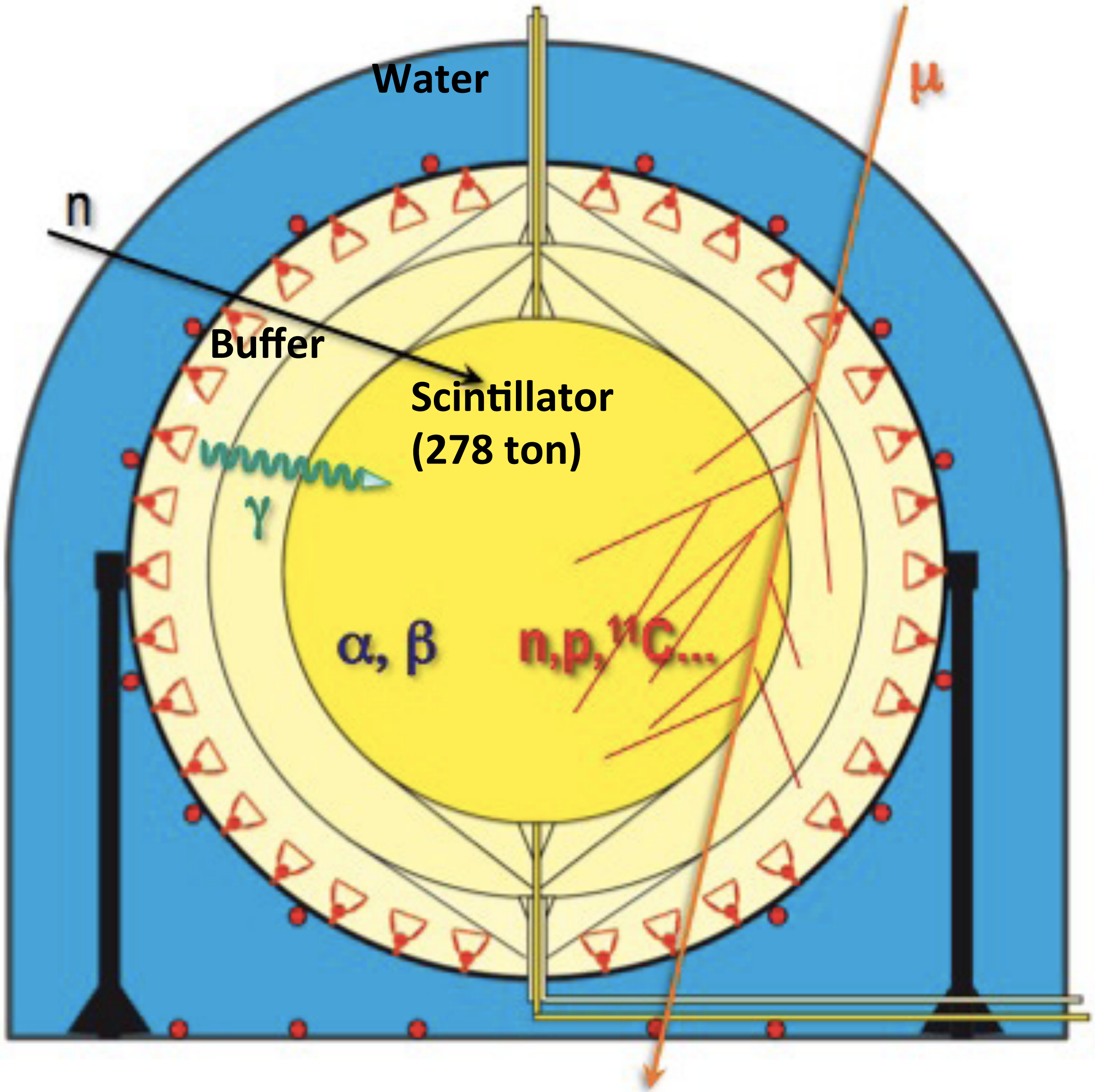


The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

$$\Phi(\mu) \sim 1\,\mu/\mathrm{m}^2/\mathrm{h}$$

Borexino detector

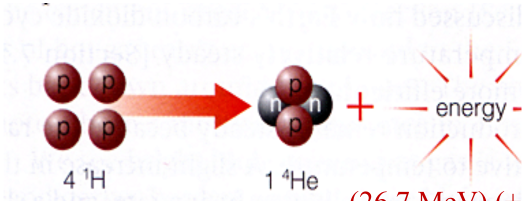


- **Materials** **more and more** **pure** as they get closer to the "core", the Fiducial Volume

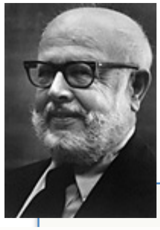
- Ultimate background depending on material purity and, mainly, **radioactive traces** in the scintillator at extremely low levels

15 years of work to reach required radio-purity

Nuclear reactions in the Sun

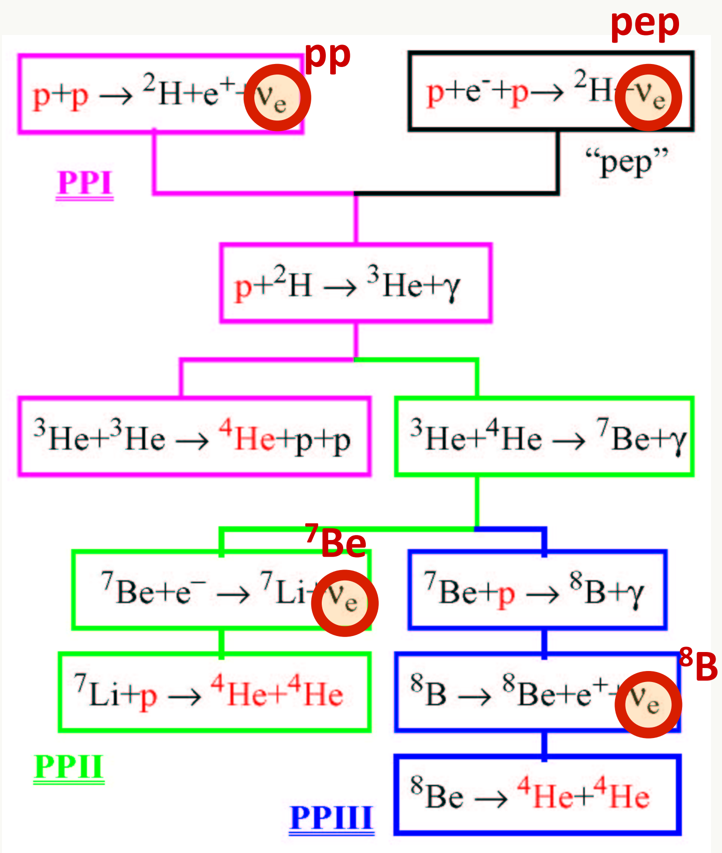


(26.7 MeV) (+ 2ν)

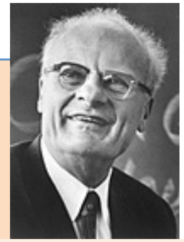


W. Fowler

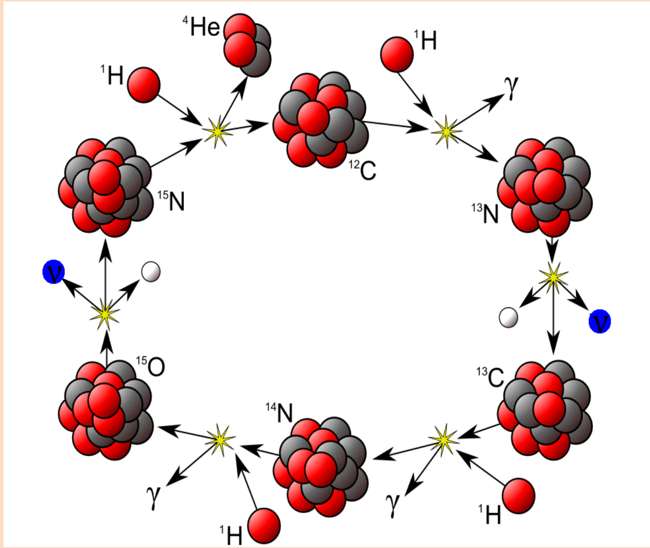
pp-cycle



CNO-cycle

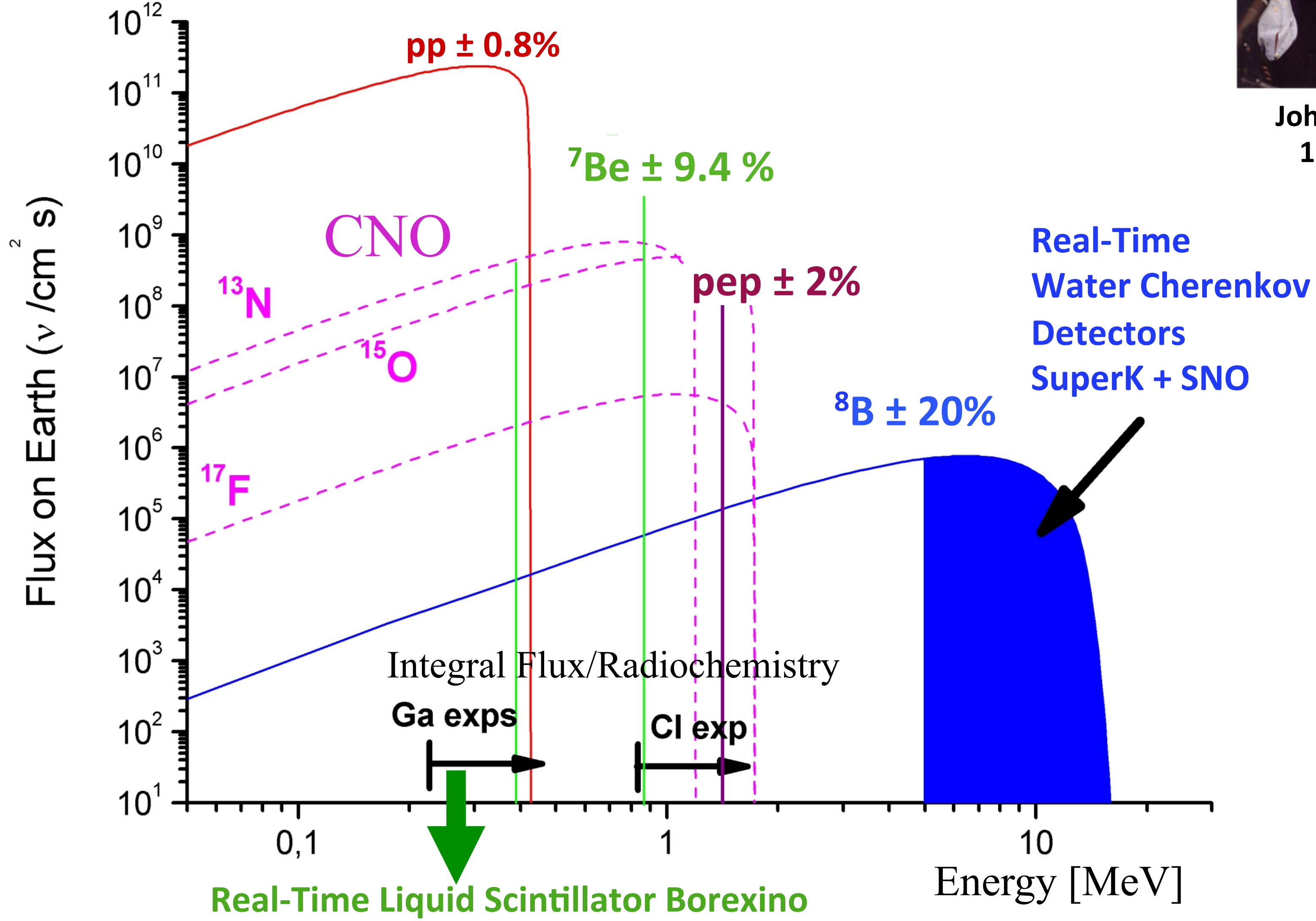


H. Bethe (1938)



- Sun: should contribute <1%
- Heavy stars: should be dominant!
- Never observed until now

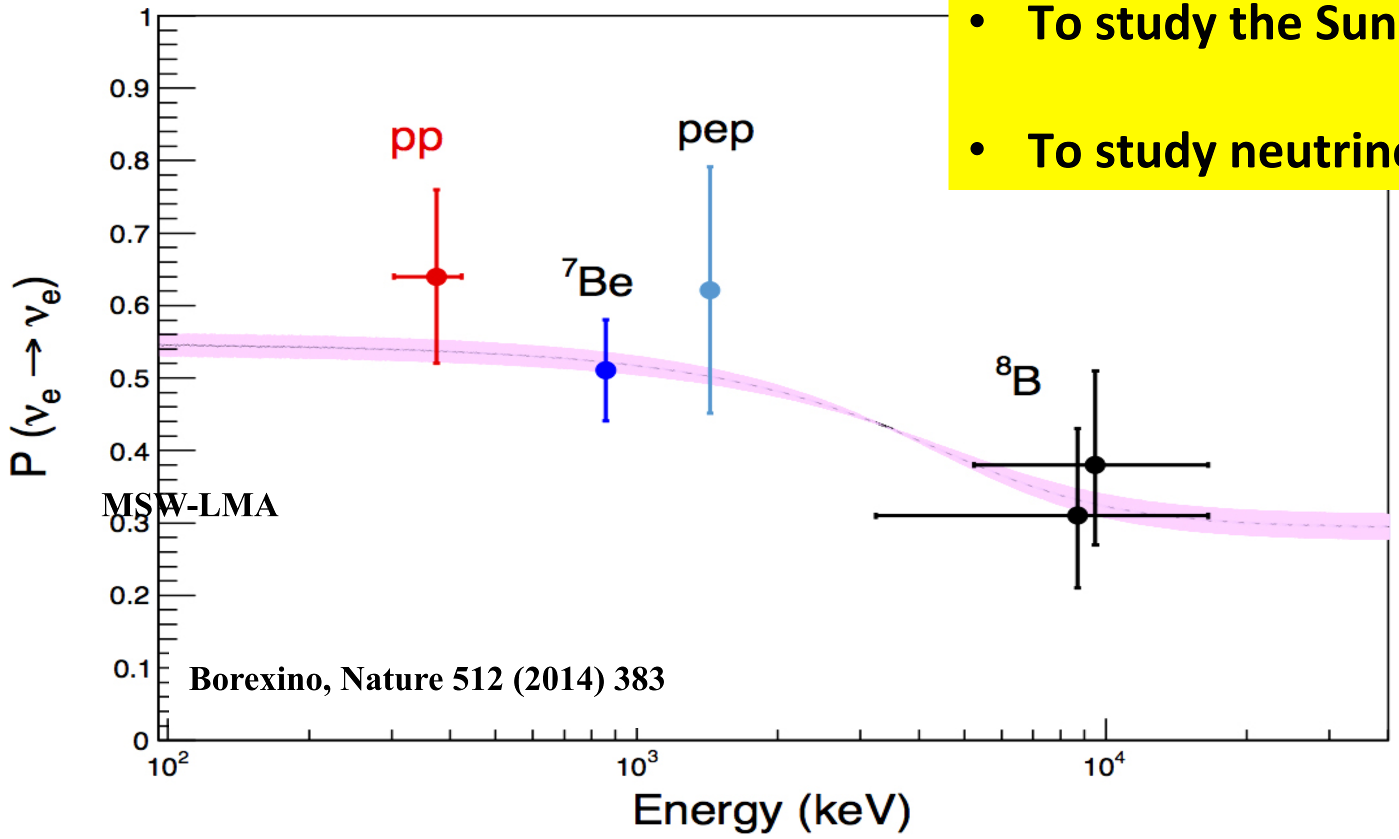
Energy spectrum of solar neutrinos



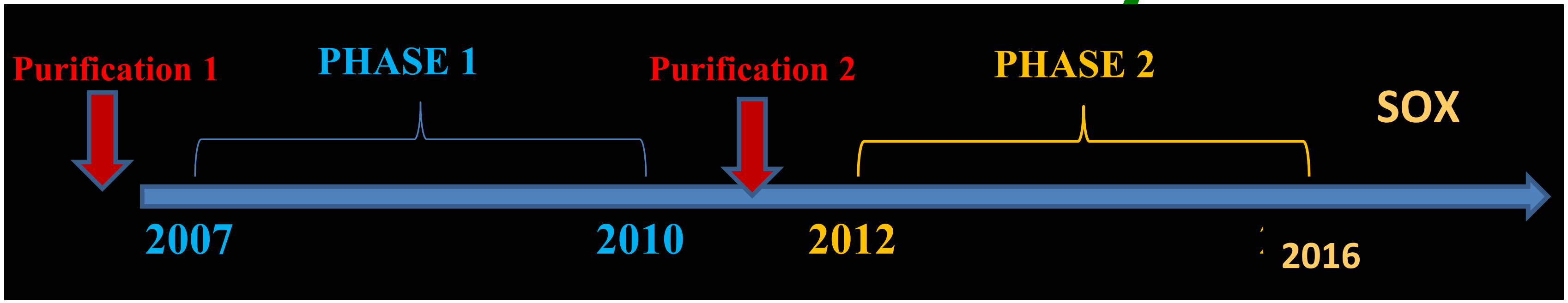
John N. Bahcall
1934 - 2005

Borexino solar neutrino results

- To study the Sun
- To study neutrino oscillations



Borexino history



PHASE 1 (2007-2010)

Solar neutrinos

- ^{7}Be ν : 1st observation+ precise measurement (5%); √
- Day/Night asymmetry; √
- pep ν: 1st observation; √
- ^{8}B ν; √
- CNO n: best limit √

Geo-neutrinos

- Evidence > 4.5σ √

- Limit on rare processes √
- Study on cosmogenics √

PHASE 2 (2012 – end 2016)

Improved radiopurity

- ^{85}Kr compatible with 0
- ^{210}Bi reduced (factor ~3)
- ^{232}Th and ^{238}U negligible

Solar neutrinos:

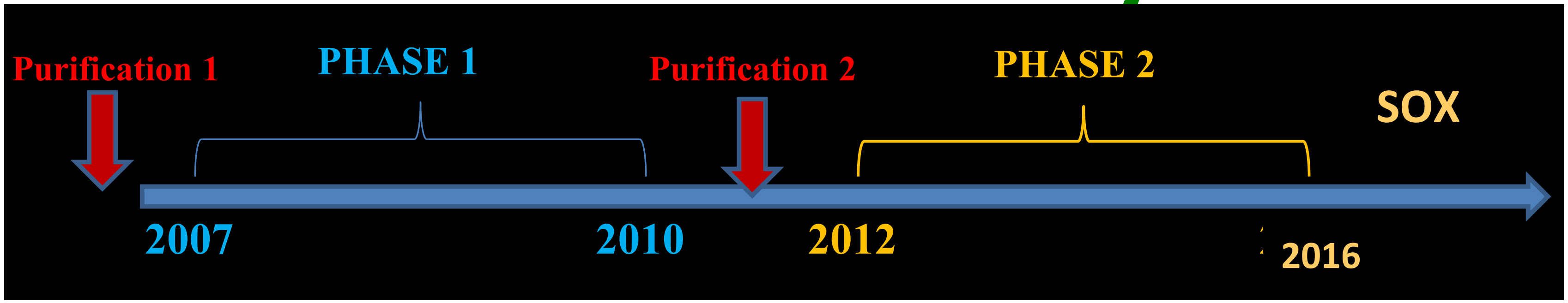
- pp-ν: first real time detection

Geo-neutrinos: 5.9 sigma C.L.

Rare processes:

- e^- decay/charge conservation

Borexino history



<u>What is going on now:</u>

- update of **all solar neutrino** measurements (^{7}Be, pep, pp, ^{8}B)
- effort to measure **CNO neutrinos** (not easy…)
- Final update of **geoneutrino** measurements
- 3-4 months long calibration campaign ahead

<u>SOX project:</u>

- ✓ Short distance neutrino oscillations with Borexino
- ✓ insertion of a strong ^{144}Ce/^{144}Pr antineutrino generator at the end of 2016
- ✓ Search for a **sterile neutrino**

Why it took so long….

Low background and radiopurity of the construction materials

- In **100 ton** of scintillator: ~**50 events/day** from ^{7}Be solar ν expected
  (50 / 86400 / 100 t = **~ 6 10^{-9} Bq/kg)**

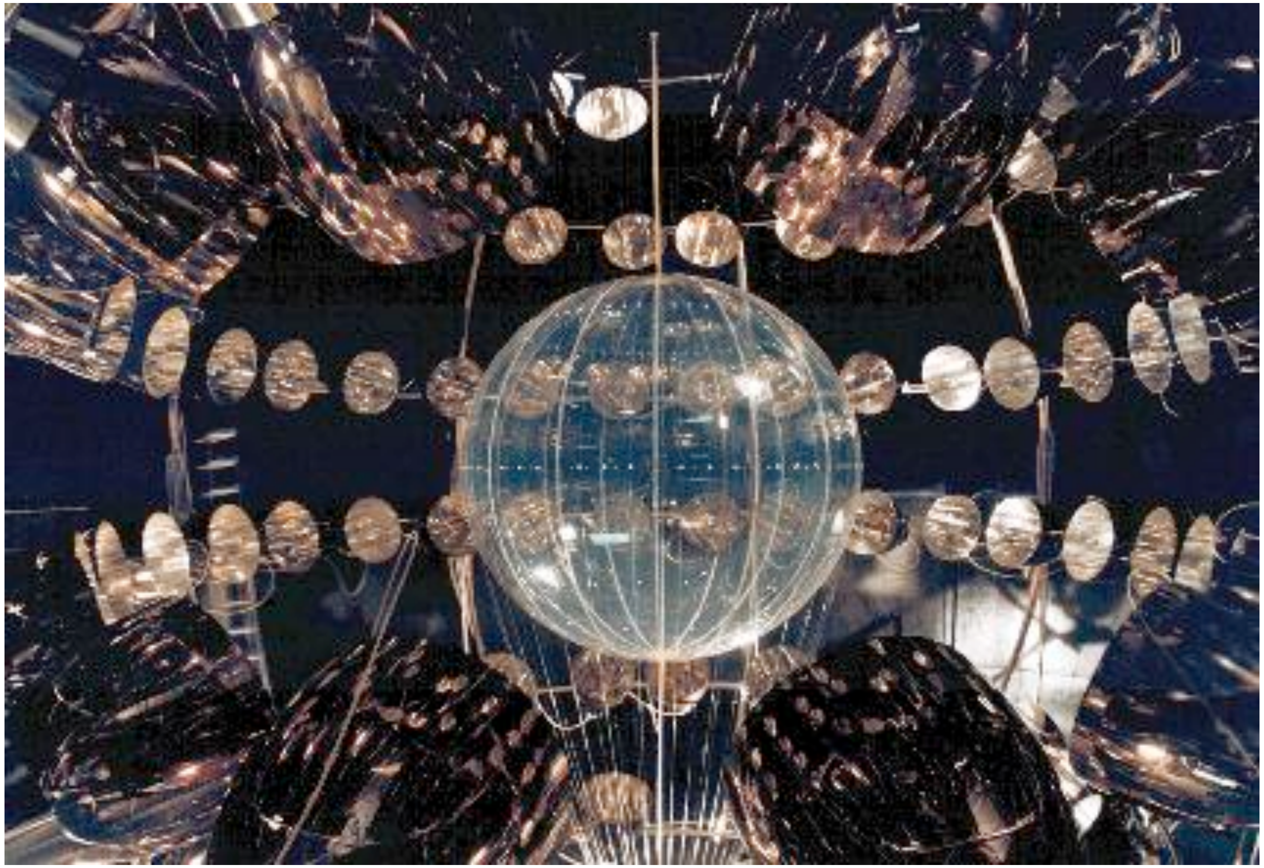
- The scattering of a neutrino on an electron is **intrinsically not distinguishable** from a **β radioactivity** event or from Compton scattering from **γ radioactivity**

- ***Typical natural radioactivity:***
  - ✓ *Good mineral water:* *~10 Bq/kg* *^{40}K, ^{238}U, ^{232}Th*
  - ✓ *Air:* *~10 Bq/m^3* *^{222}Rn, ^{39}Ar, ^{85}Kr*
  - ✓ *Typical rock* *~100-1000 Bq/kg* *^{40}K, ^{238}U, ^{232}Th, + many others*

- If you want to detect solar neutrinos with liquid scintillator, you must be **9-10 orders of magnitude more pure than anything on Earth**

Backgrounds now : ^{238}U< 8 10^{-20} g/g at 95% C.L., ^{232}Th < 9 10^{-19} g/g at 95% C.L.

CTF: Counting Test Facility

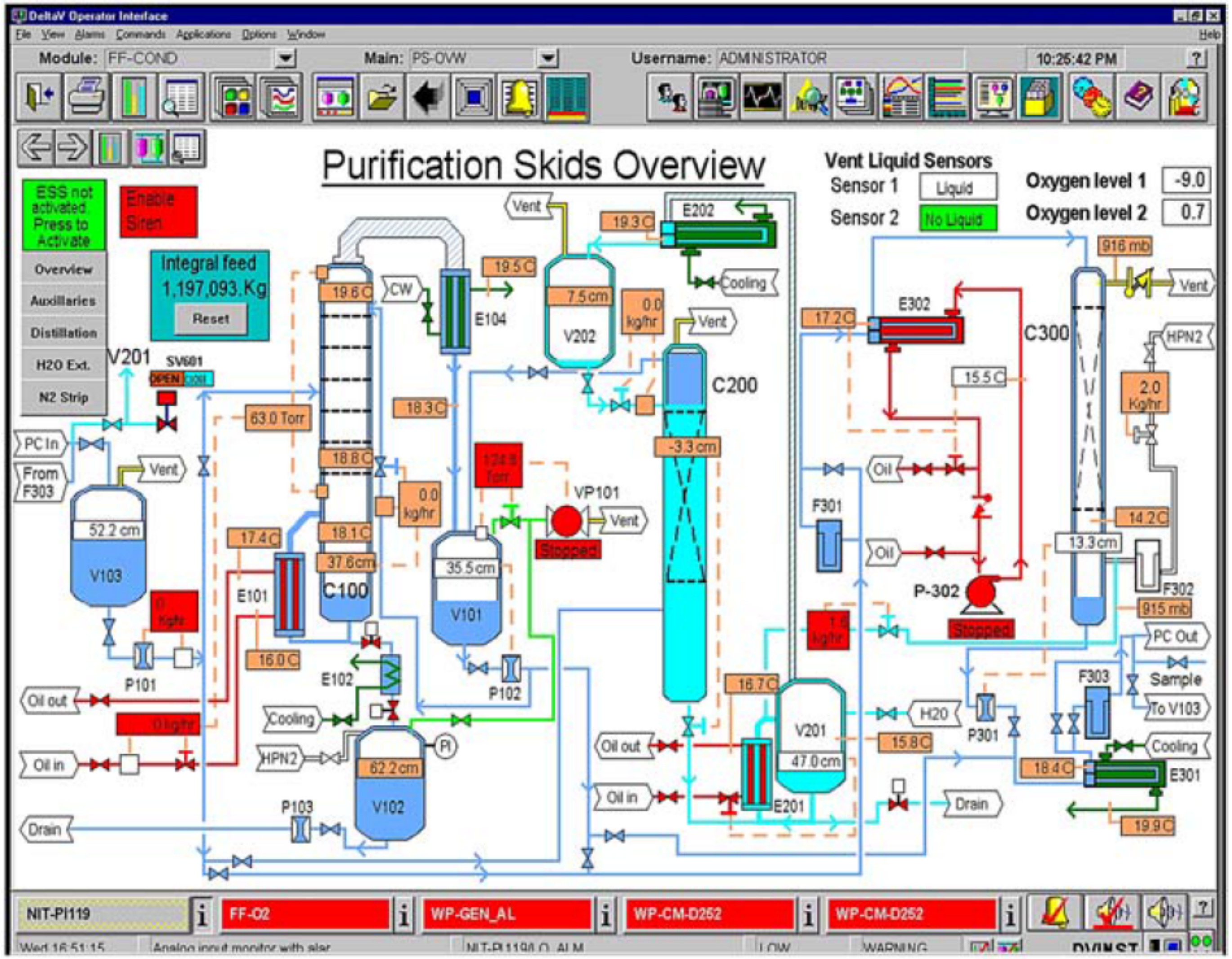


5 m^3 of scintillator and 100 PMTs

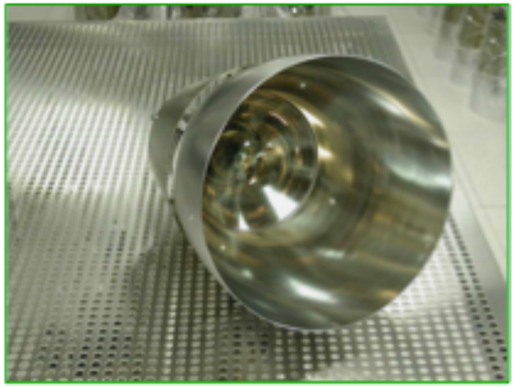
Was built to test the radiopurity of the scintillator, since all other detectors were just too radioactive for the required precision!

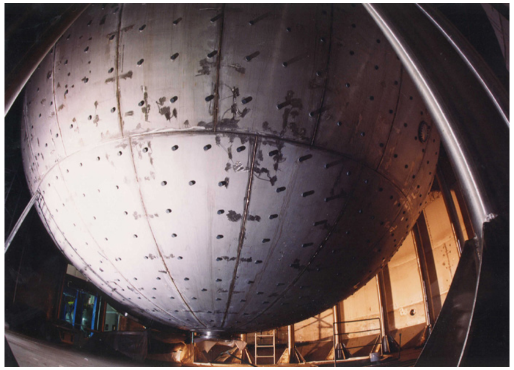
Just for illustration

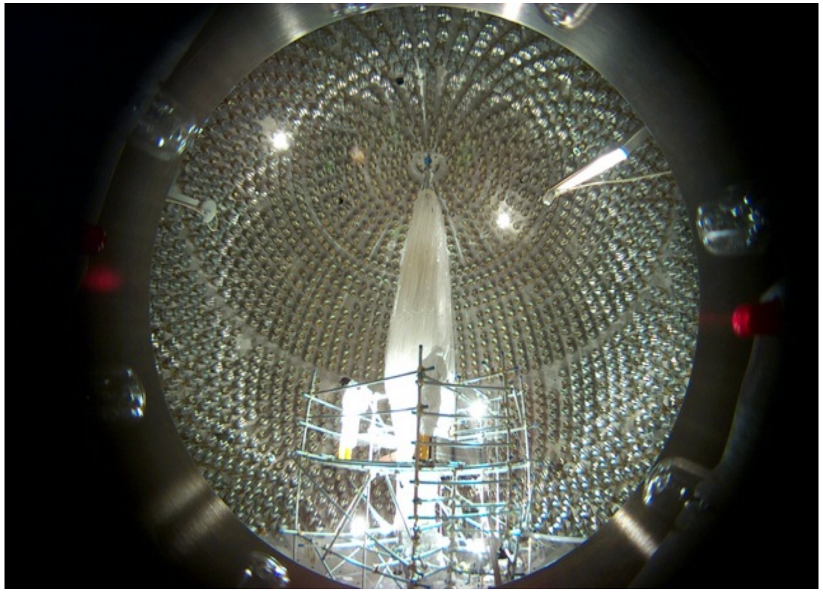
Complexity of the plants for scintillator purification by distillation, water extraction and nitrogen stripping

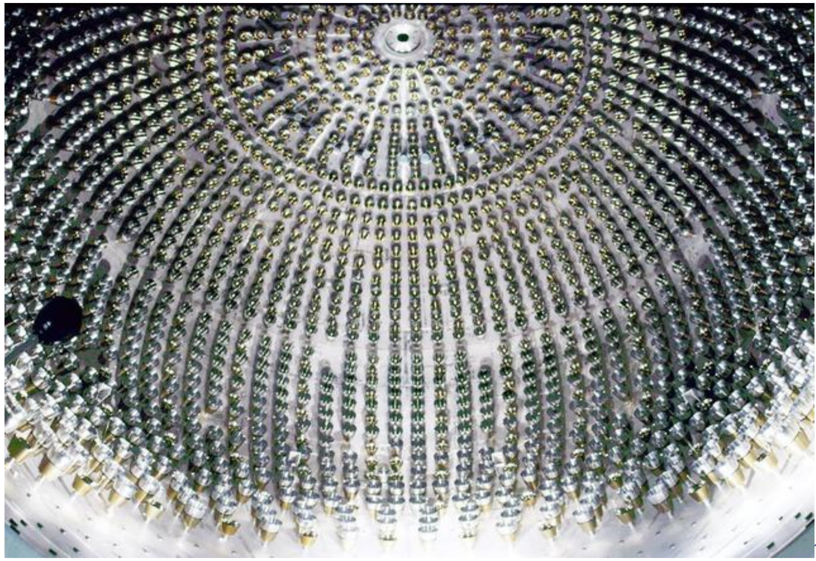


Detector picture gallery

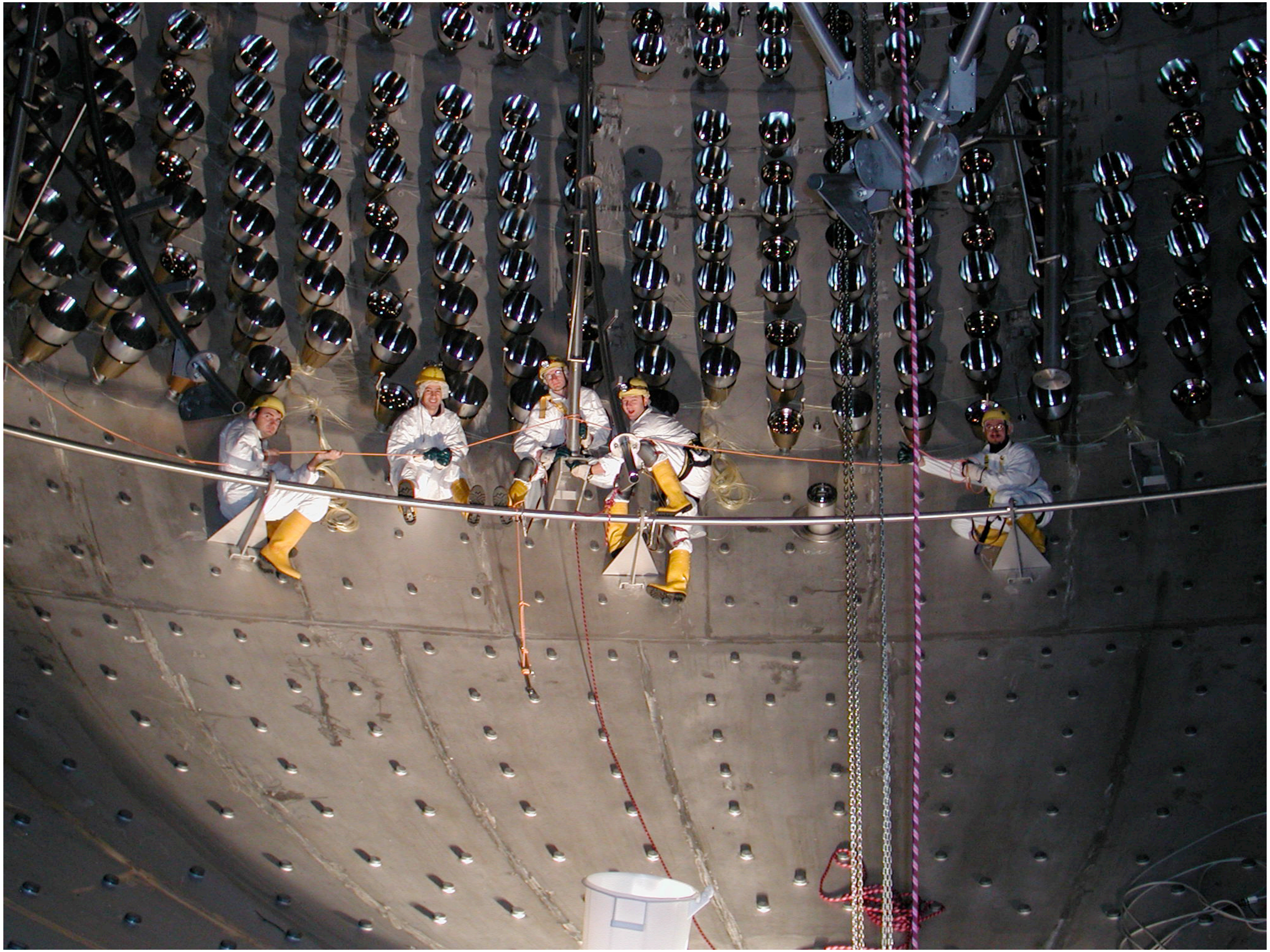


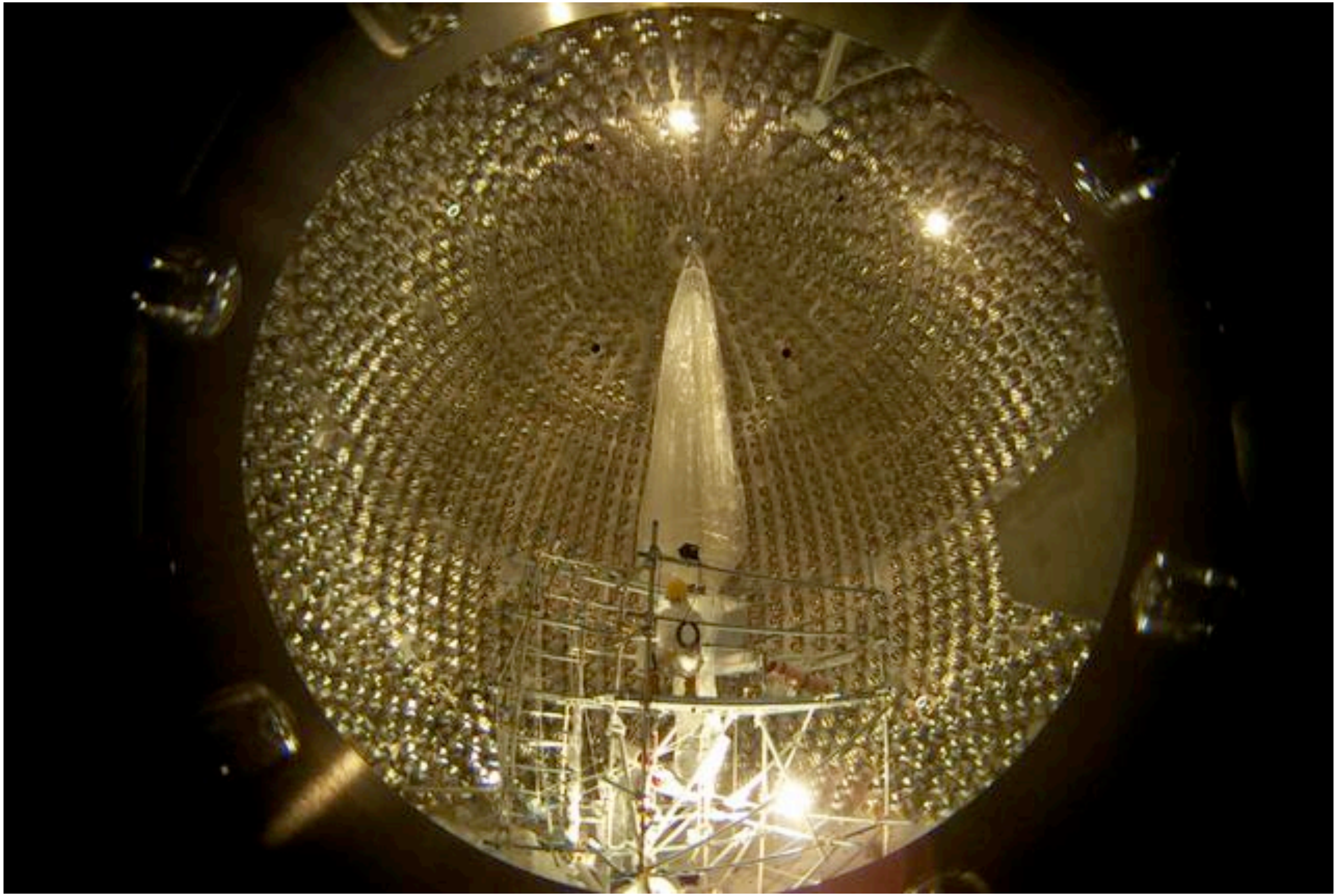







SCIENCE PHOTO LIBRARY





Detector filling

End October 2006

LAKN –
Low Argon and
Krypton Nitrogen

Ultra-pure water

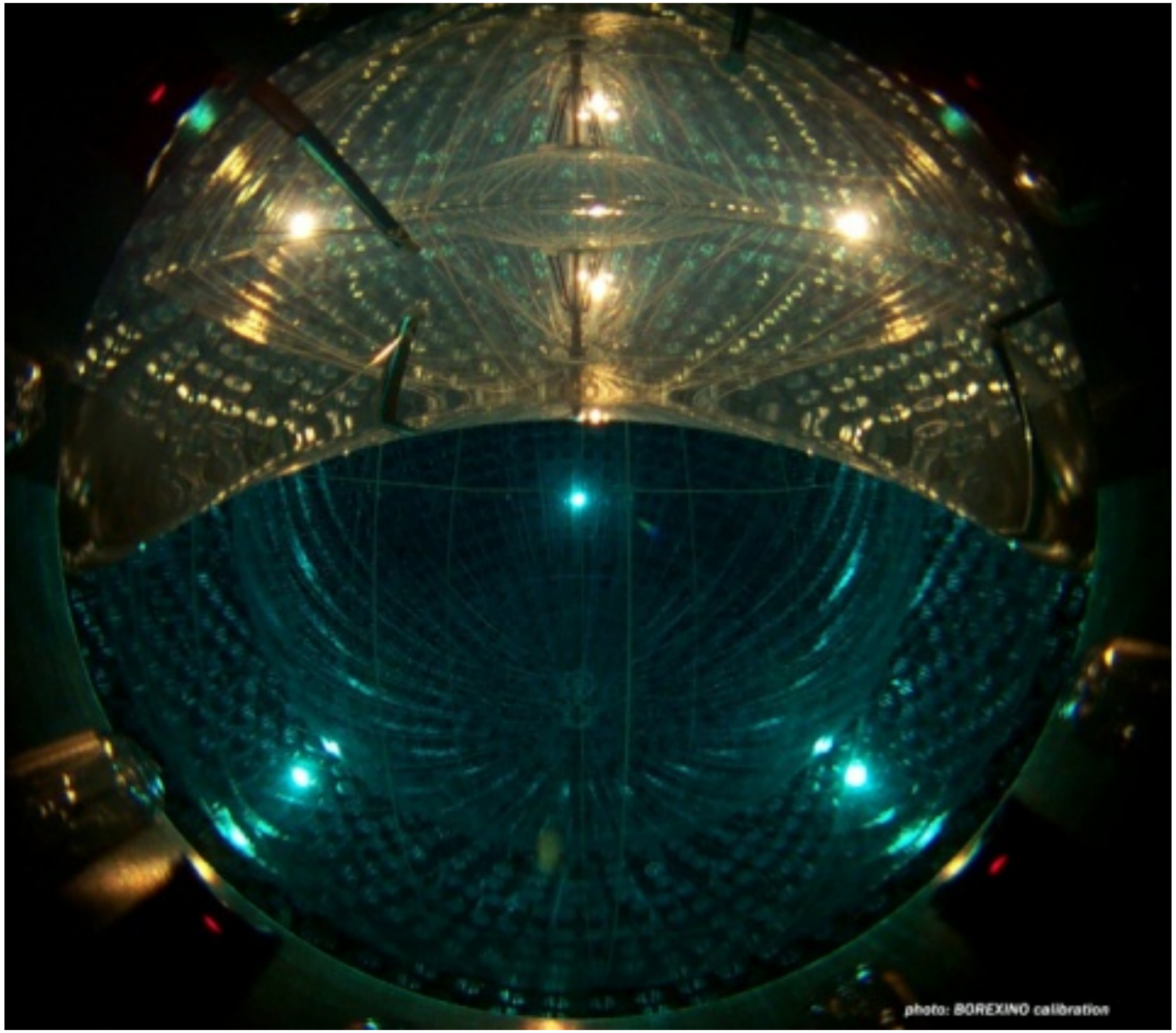
Fotos taken with one of 7 CCD cameras placed inside the detector

Detector filling

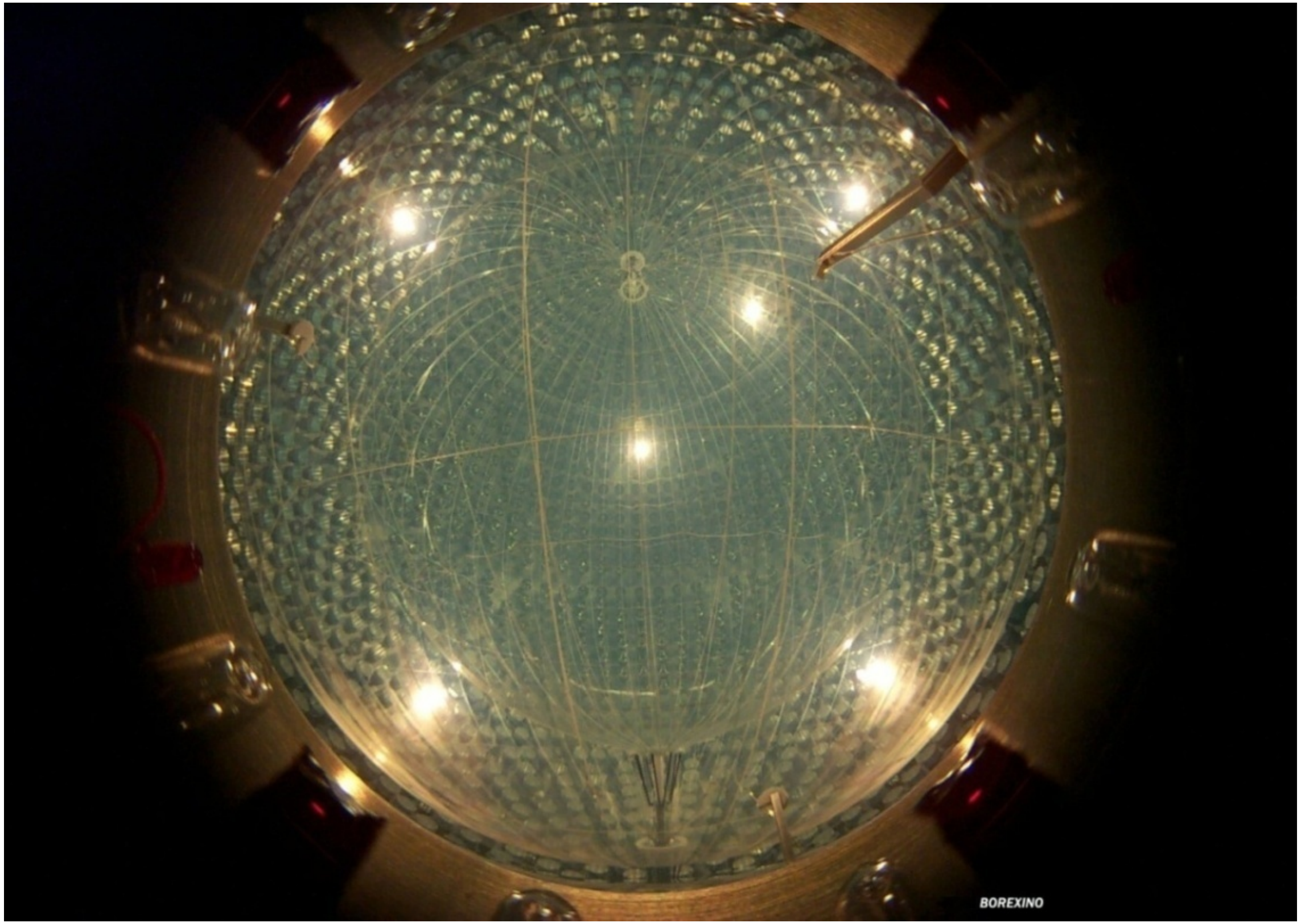
March 2007

Liquid scintillator

Ultra-pure water

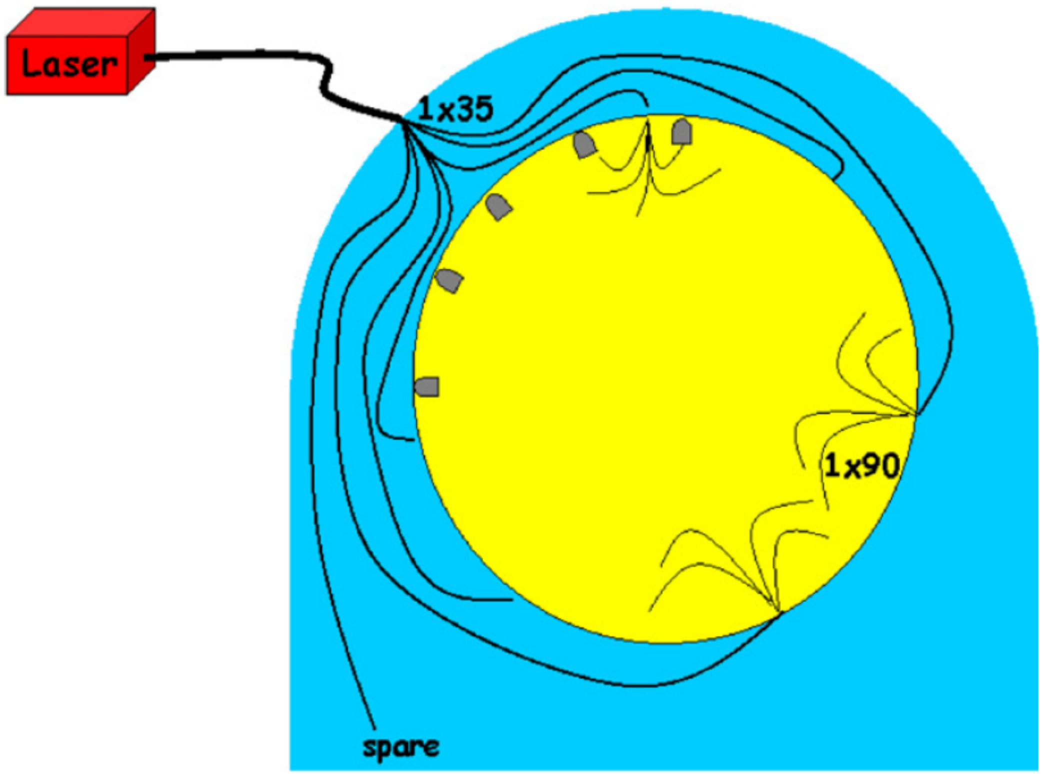


Detector fully filled on May 15th, 2007: DAQ starts



PMT calibration

G. Alimonti et al. / Nuclear Instruments and Met

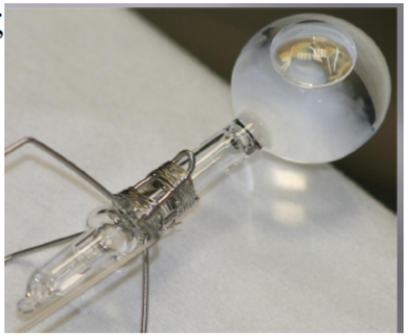


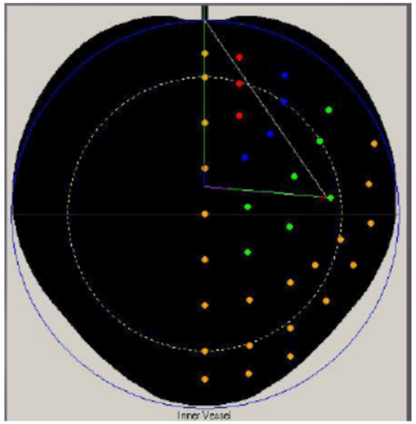
- Time alignment among PMTs
- Shape of the single photoelectron peak for every PMT

Borexino calibration with radioactive sources

	γ								β		α	n (AmBe)		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n+^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

- Absolute source position: LED and CCD cameras (± 2cm);
- cca. 300 points through the whole scintillator volume;

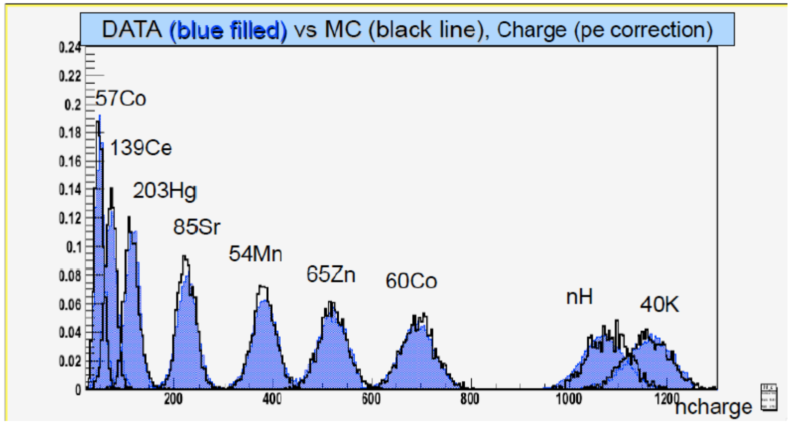




- **Detector response as a function of position;**
- **Fiducial volume definition and tuning of the spatial reconstruction algorithm;**
- **Energy scale definition**

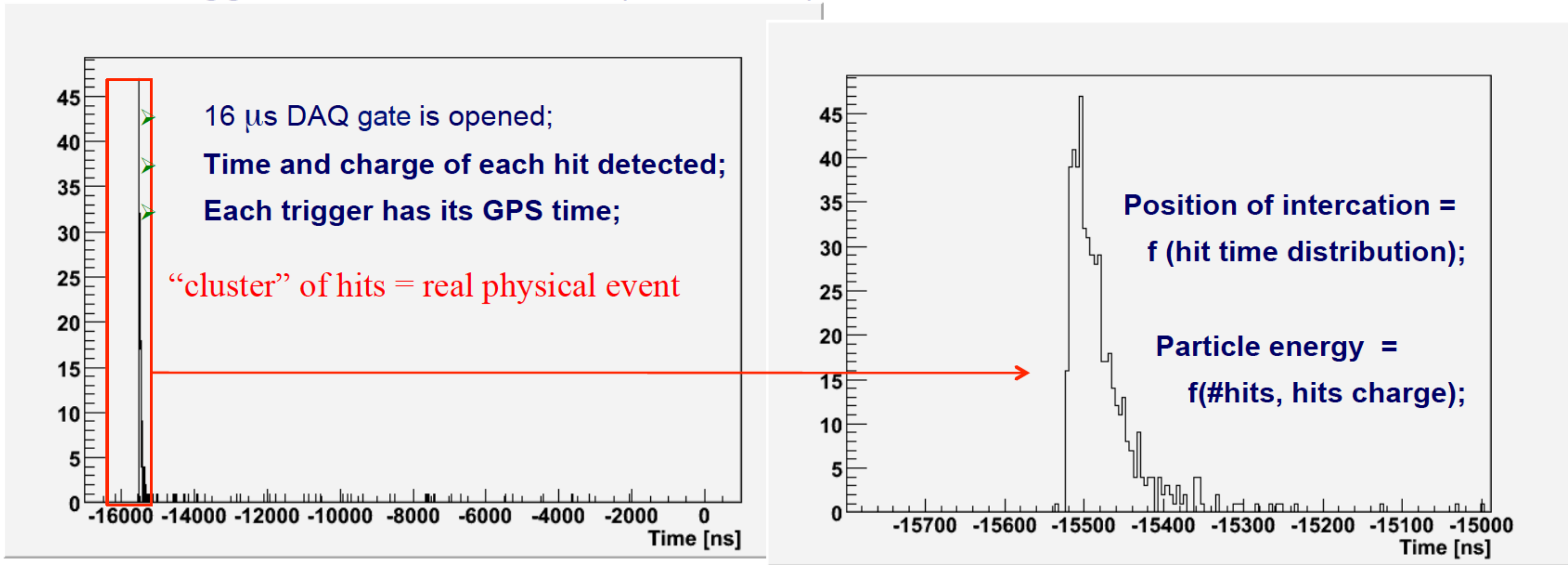
  precise calibration in the 0-7 MeV range.
- **Tuning of the full Monte Carlo simulation**

SYSTEMATIC ERROR REDUCTION
For ALL SOLAR NEUTRINO RESULTS



Borexino data structure

- Charged particles and γ produce scintillation light: photons hit inner PMTs;
- DAQ trigger: > 25 inner PMTs (from 2212) are hit within 60-95 ns:



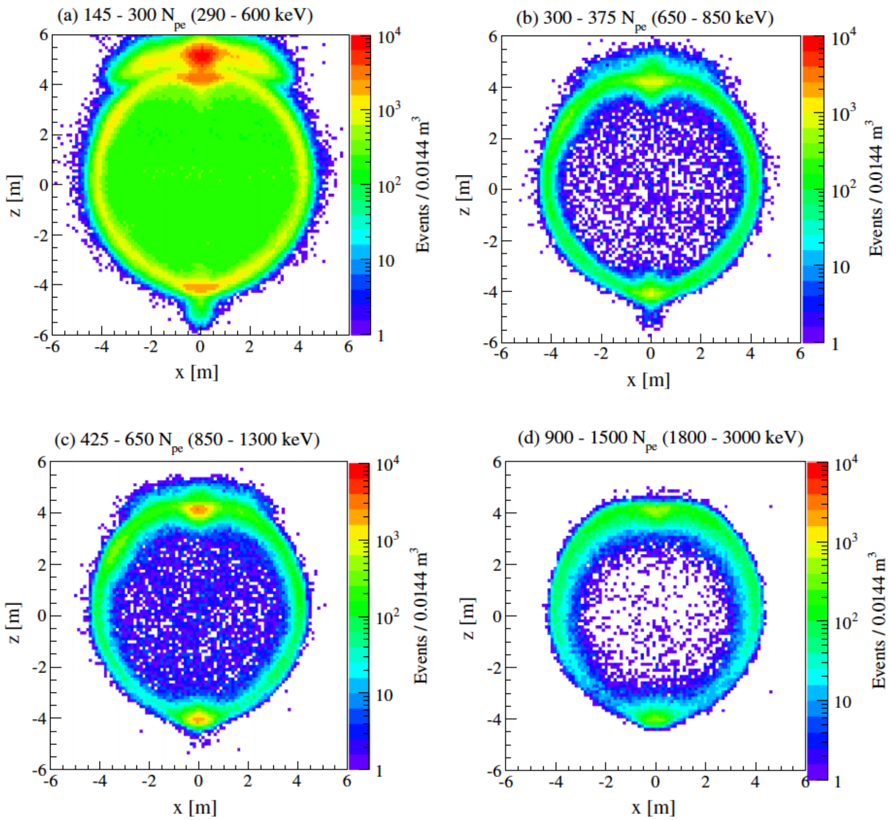
- Outer detector gives a muon veto if at least 6 outer PMTs (from 208) fire;

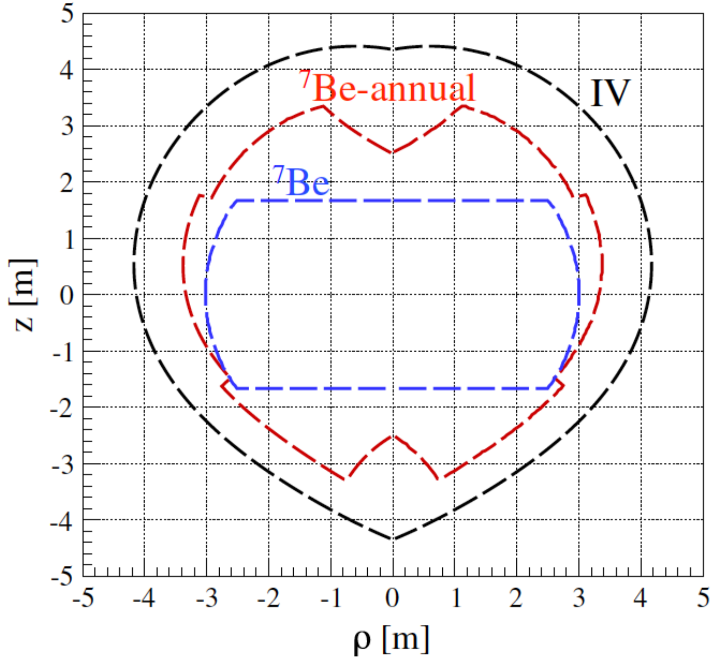
Light yield: (500 ± 12) p.e./MeV
taking into account quenching factor

Energy resolution (s): 10% @ 200 keV
8% @ 400 keV
6% @ 1000 keV

Spatial resolution: 35 cm @ 200 keV
16 cm @ 500 keV

Fiducial Volume

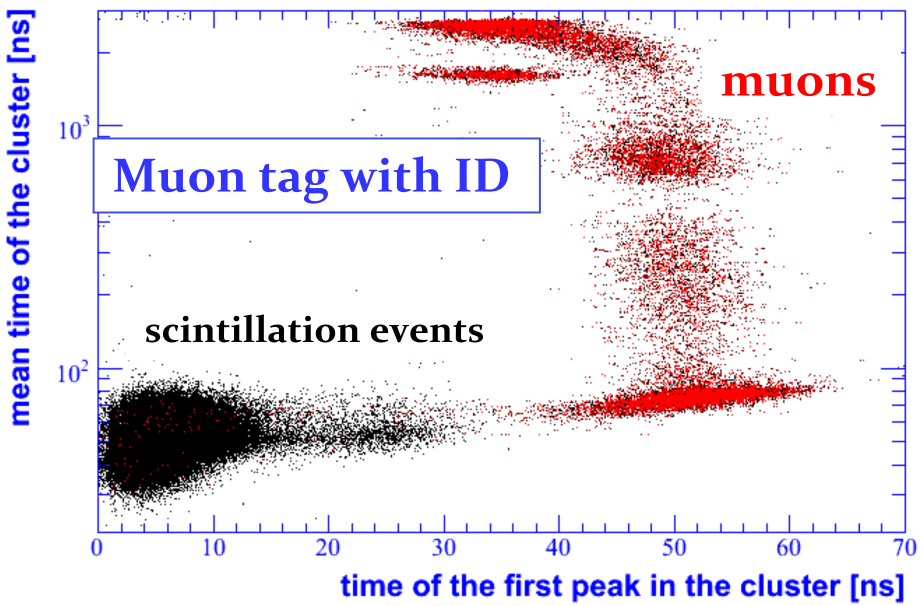




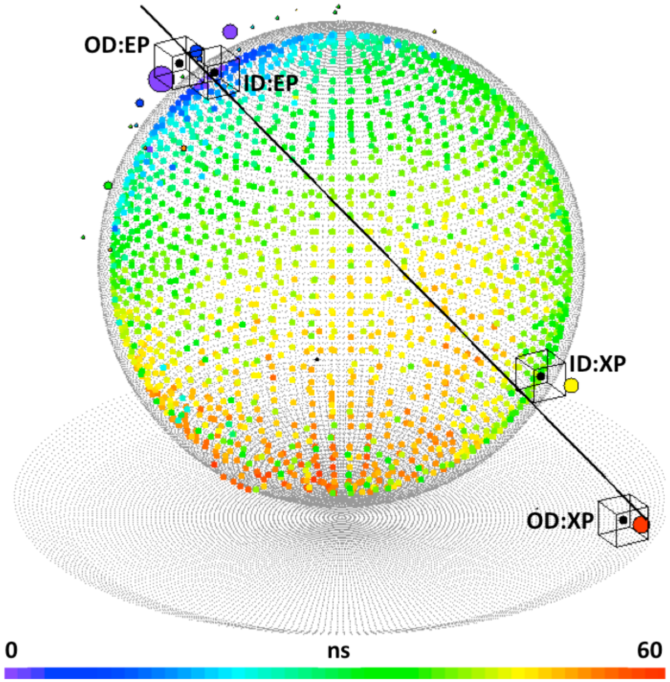
For geoneutrinos only 25-30 cm cut along the vessel!

Muon and neutron detection

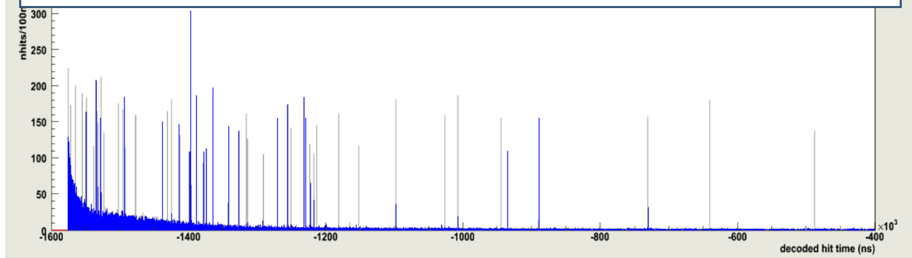
- μ are identified by the OD and by the ID
  - OD eff: > 99.28%
  - ID analysis based on pulse shape variables
    - Cluster mean time, peak position in time
  - **Combined overall efficiency > 99.992%**
  - **After cuts, μ not a relevant background for ^{7}Be**
  - **Residual background: < 1 count /day/ 1 00 t**



Muon track reconstruction



After each μ, 1.6 ms gate opened to detect neutrons: example with several tens of neutrons.



Position reconstruction

- Measured hit time pattern corrected for the time-of-flight

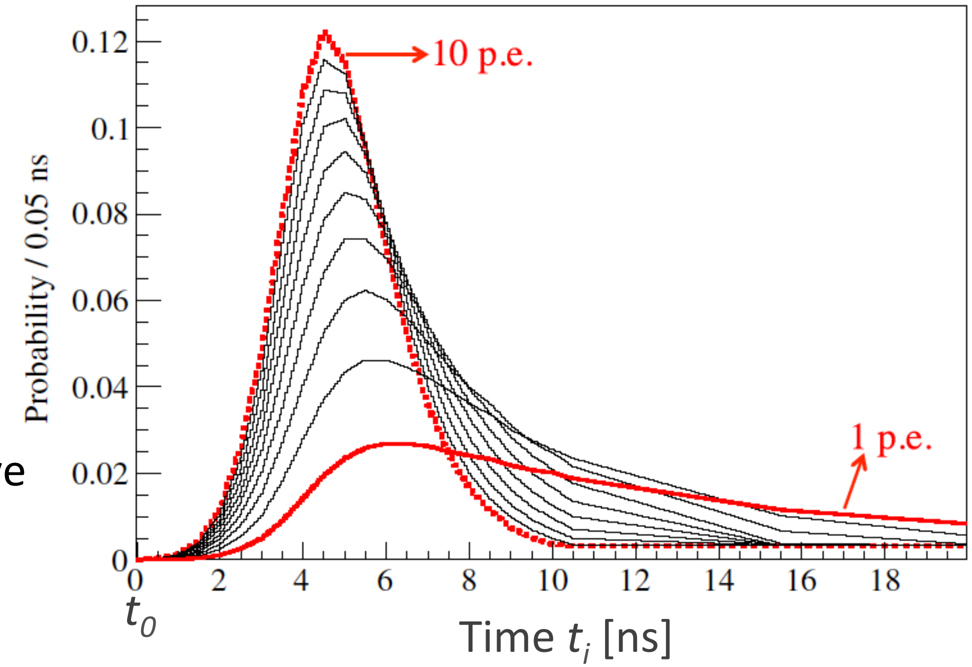
$$T^j_{\text{flight}}(\vec{r}_0, \vec{r}^j) = |\vec{r}_0 - \vec{r}^j|\,\frac{n_{\text{eff}}}{c}$$

Position of interaction

Position of PMT j

Effective refractive index 1.68

Probability density function of measuring the hit, as a function of total charge on each PMT



and then it maximizes the likelihood $L_E(\vec{r}_0, t_0|(\vec{r}^j, t_i^j))$ that the event occurs at the time t_0 in the position $\vec{r}_0$ given the measured hit space-time pattern $(\vec{r}^j, t_i^j)$.'

KamLAND

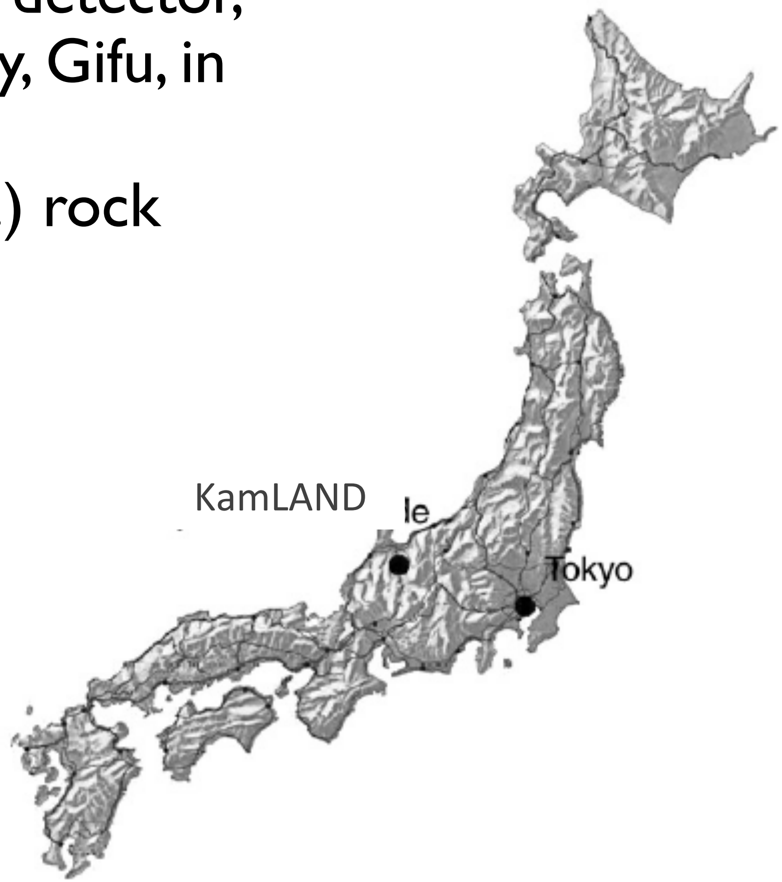
KamLAND

Kamioka Liquid Scintillator Antineutrino Detector

The world largest liquid scintillator detector, located in Kamioka mine, Hida-city, Gifu, in Japan,
under 1km (2.7 km-water-equiv.) rock overburden

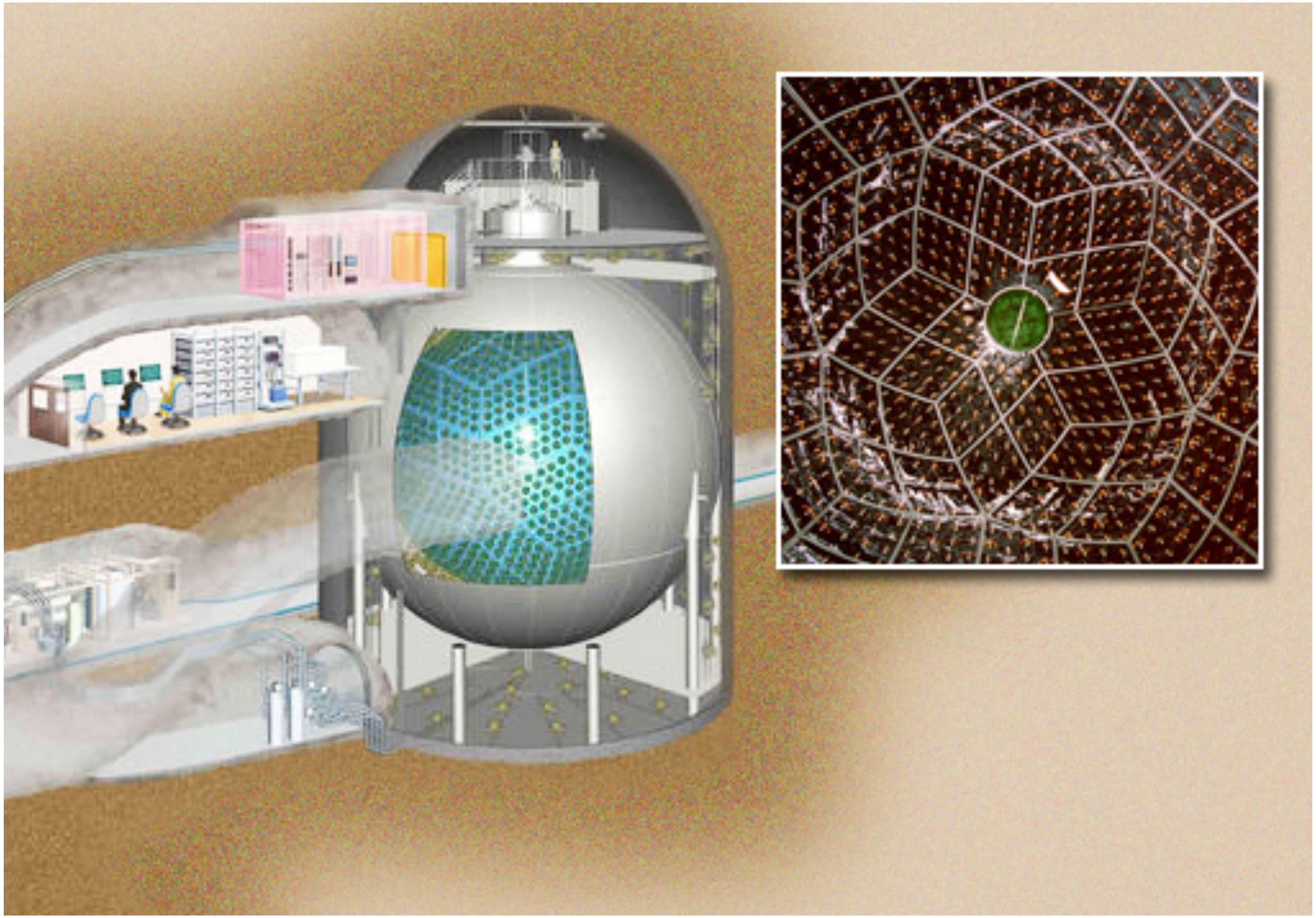
DAQ started in 2002

130 people and about 35 institutes from Japan, the United States, Korea, China, Poland, Spain, Canada and UK.

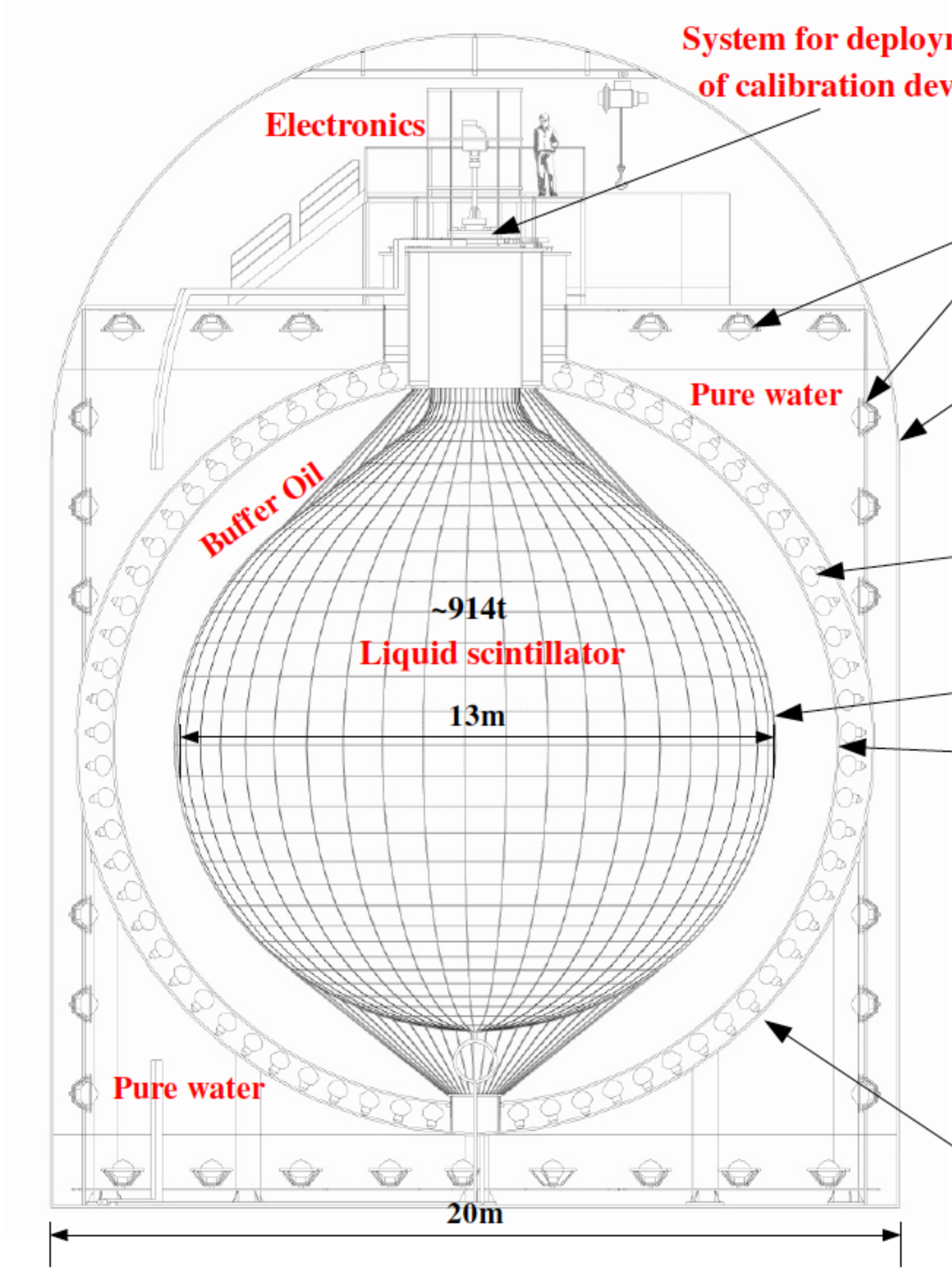


Goals of KamLAND

- Discovery of reactor antineutrino oscillations
- Principal goal: reactor antineutrinos oscillations with L = 260 km, measurement of Δm^2_{12}
- Geoneutrinos
- Antineutrinos from unknown sources



KamLAND detector



225 Muon detector 20''PMTs

Rock walls/
PE sheet/
RN blocking resin/
Tyvek reflector

Inner detector PMTs:
1325 of 17'' type
554 of 20'' type

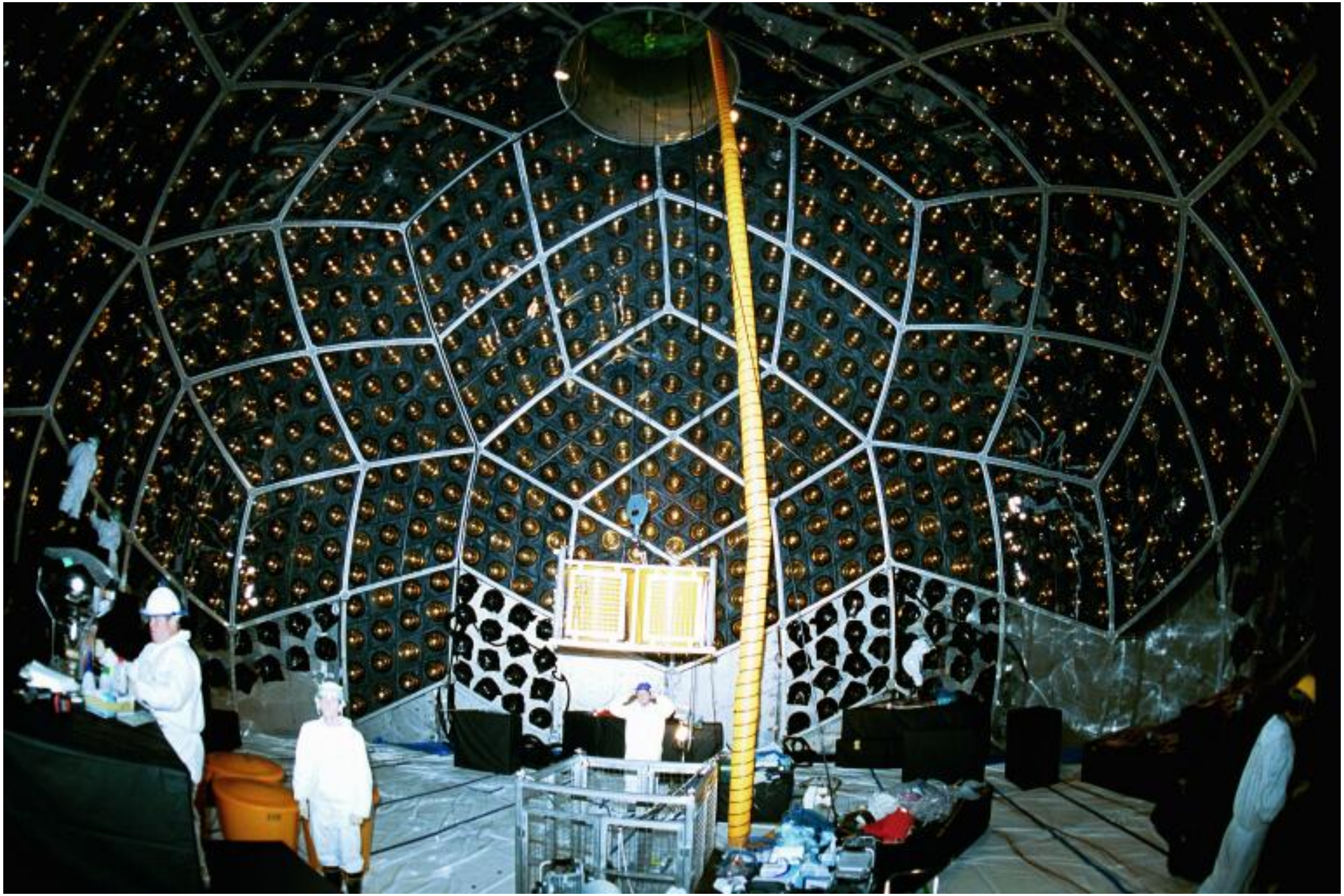
Balloon: EVOH/Nylon/EVOH

Acrylic sphere (3mm)

Liquid scintillator ($1200m^3$):
20% Pseudocumene
80% dodecane
1.52 g/l PPO

Buffer oil ($1800m^3$):
50% dodecane
50% isoparaffin

Stainless steel tank (∅18m)



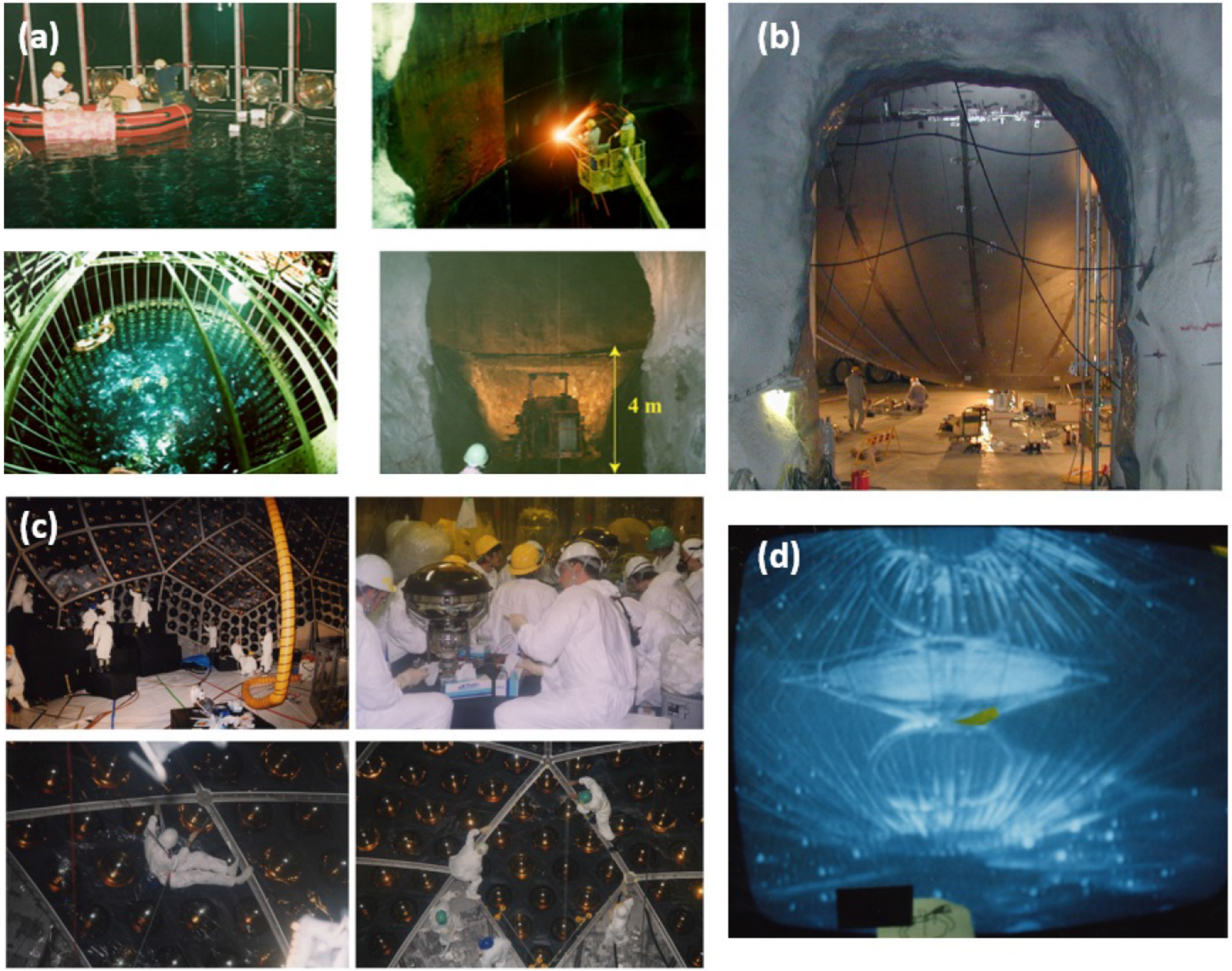


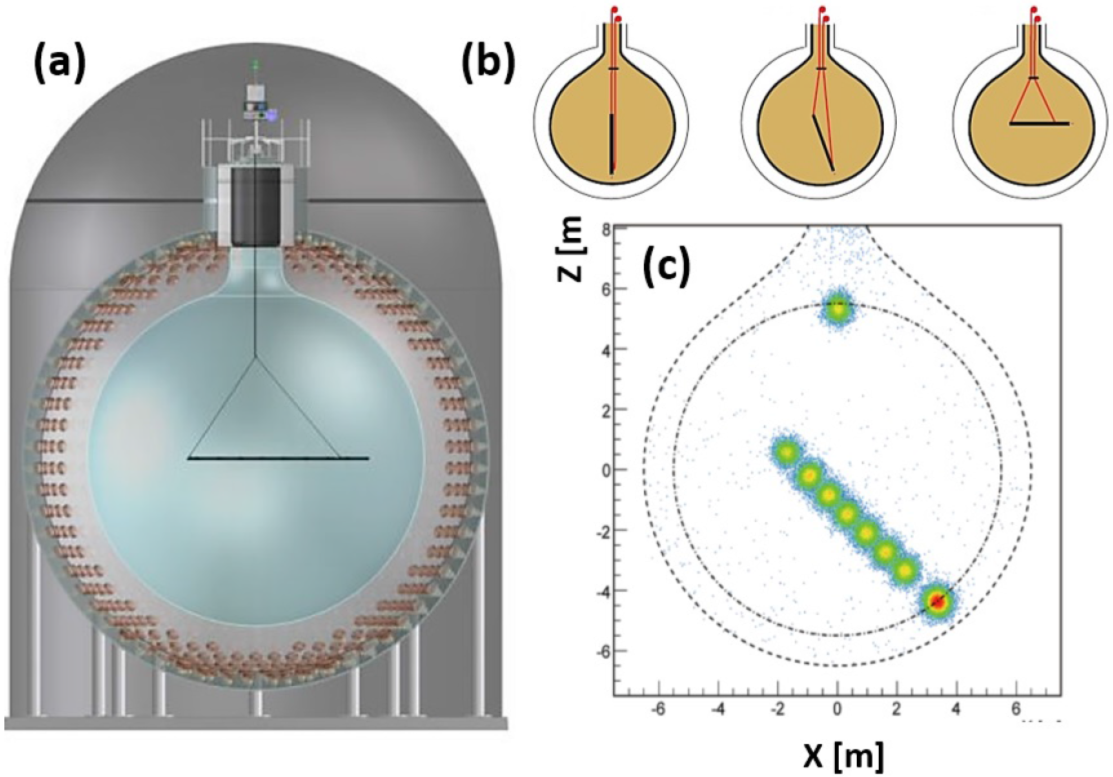
Fig. 5. (a) Kamiokande dismantling in 1998. (b) Stainless steel vessel construction in 1999-2000. (c) PMT installation in 2001 and (d) Oil-fill inside the detector in 2001.

Calibration with radioactive sources

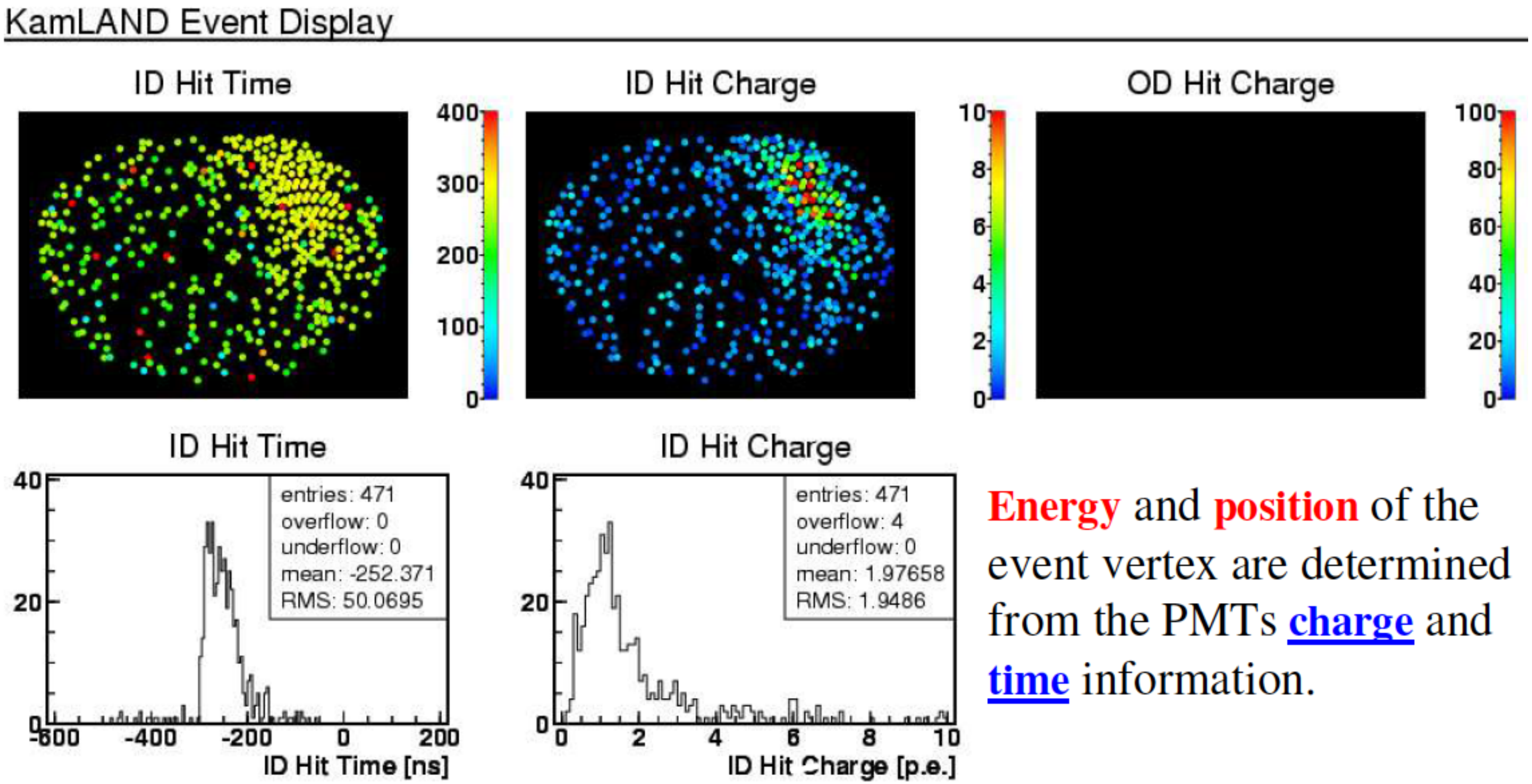
- Light yield of 300 p.e./MeV in the center of the detector

Energy resolution = 6.2% / sqrt(E [MeV])

Position reconstruction resolution = 30 cm/ sqrt(E [MeV])



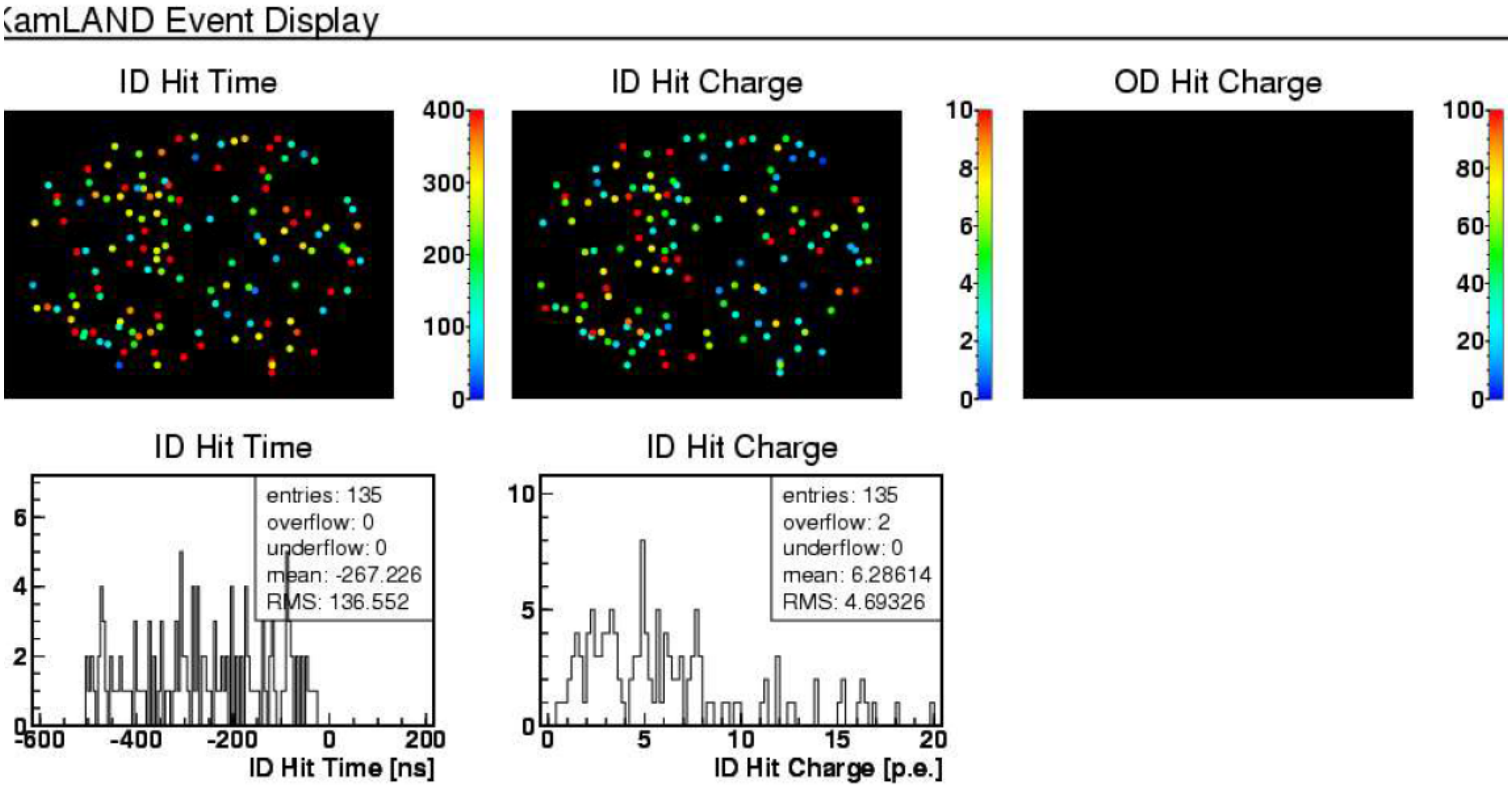
Event display



Energy and **position** of the event vertex are determined from the PMTs **charge** and **time** information.

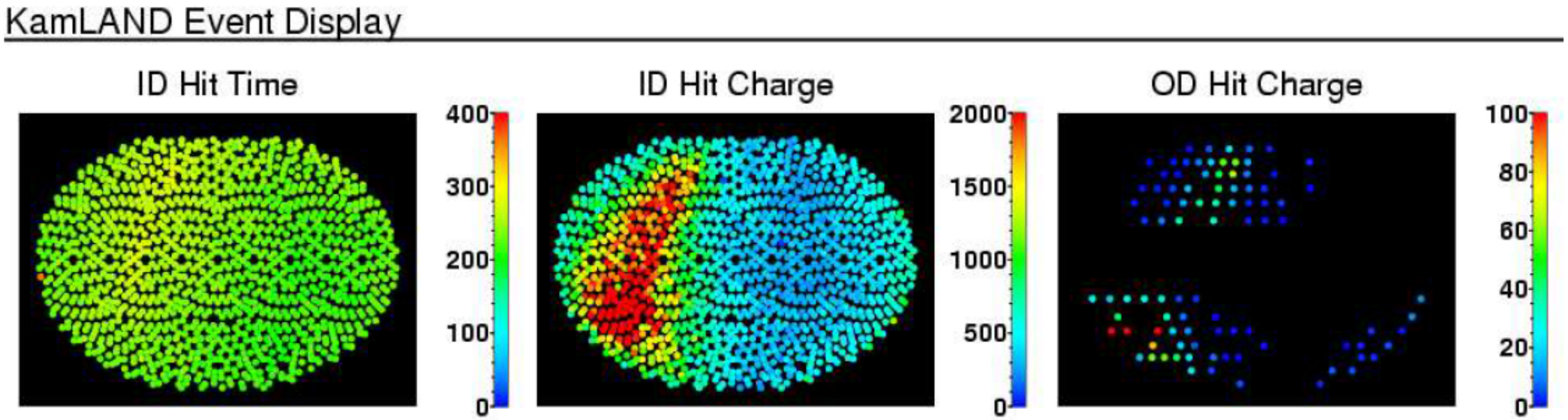
Real **low energy event** forms a cluster of PMTs, and PMT timing distribution has a well defined peak. Muon **O**uter **D**etector sees **no** signal. A PMT signal consists of **several** photo-electrons.

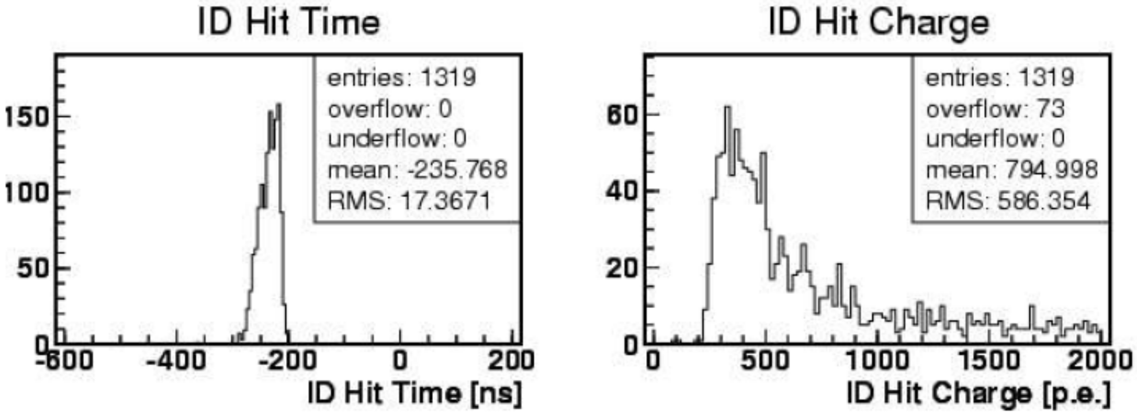
Noise events



Noise events are characterized by a **flat timing distribution** and absence of the event vertex. They are easily recognized and rejected.

Muon events





Number of photo-electrons in the **I**nner **D**etector PMTs can reach **several thousands.**
Muon **track reconstruction** is based on the **PMT's timing.**

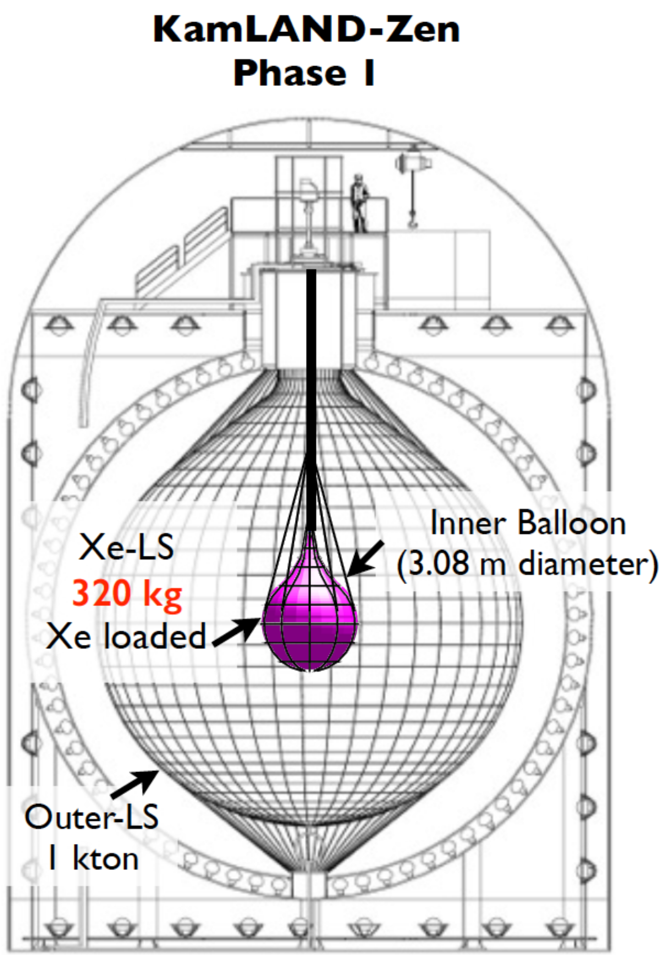
Muons passing through **buffer oil** emit Cherenkov light only:
dQ/dx ~ 31 p.e./cm
Muons passing through **scintillator** produce both scintillation and Cherenkov light:
dQ/dx ~ 630 p.e./cm

Muons in KamLAND

- Muon rate is **~0.34 Hz**, muon mean energy **~250 GeV**
- **2 ms** veto of the entire detector volume after all muons effectively removes background from spallation neutrons
  (**~3000 events/kton/day**)
- **2 s** veto of the entire detector volume after showering muons
  $\Delta E > 3$GeV (~10^6 photo-electrons),
  ΔE = detected μ energy – expected energy for minimum ionizing μ)
- **2 s** veto of the entire detector volume for the muons tracked with poor reliability
- **2 s** veto along **3m radius cylinder** for well-tracked non-showering muons
- The fraction of muon veto is **~10%** of runtime

KamLAND-Zen: 0ν-$\beta\beta$ decay

- ✓the first liquid scintillator based detector entering on the scene of 0ν–$\beta\beta$ decay experiments
- ✓ if this process would be observed: neutrinos Majorana particles
- ✓Start in 2011 (Phase 1): doping of the scintillator with ^{133}Xe
- ✓Problem with ^{110m}Ag contamination
- ✓2012-2013 long purification campaign and Dec 2013 Phase 2 (^{110m}Ag reduced by a factor 10)

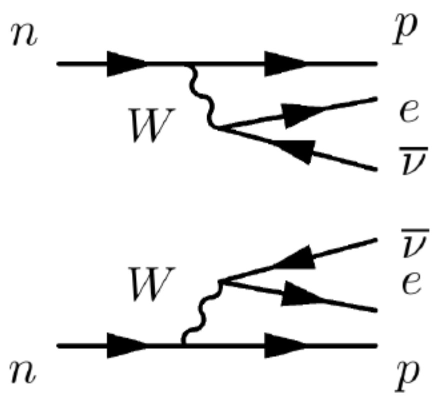


Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

σ_E(2.5MeV) = 4%

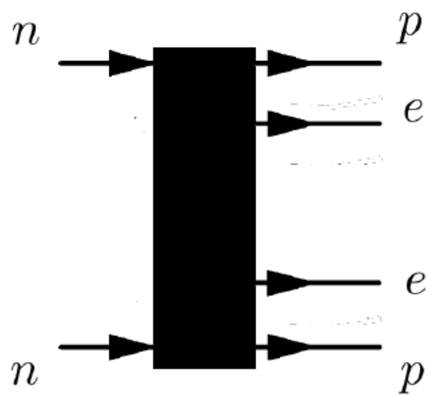
2-neutrino double-β decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



Neutrinoless double-β decay ($0\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- foreseen by many extensions of the Standard Model
- lepton number violation ($\Delta L = 2$)
- $T_{1/2}^{0\nu}$ limits in the range $10^{21} - 10^{26}$ yr

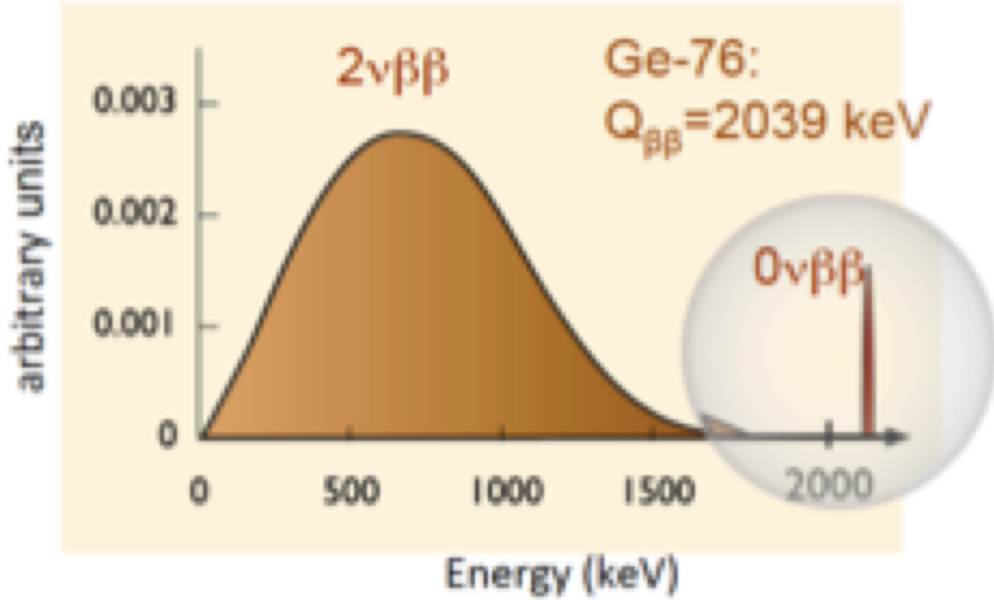


$$\boxed{(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A,Z)|^2|m_{\beta\beta}|^2}$$

- $G_{0\nu}$ phase space factor
- $\mathcal{M}_{0\nu}$ nuclear matrix element
- $|m_{\beta\beta}|$ effective Majorana mass

$$\boxed{\begin{aligned} |m_{\beta\beta}| &\equiv \left|\textstyle\sum_i U_{ei}^2 m_i\right| \\ &= \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right| \end{aligned}}$$

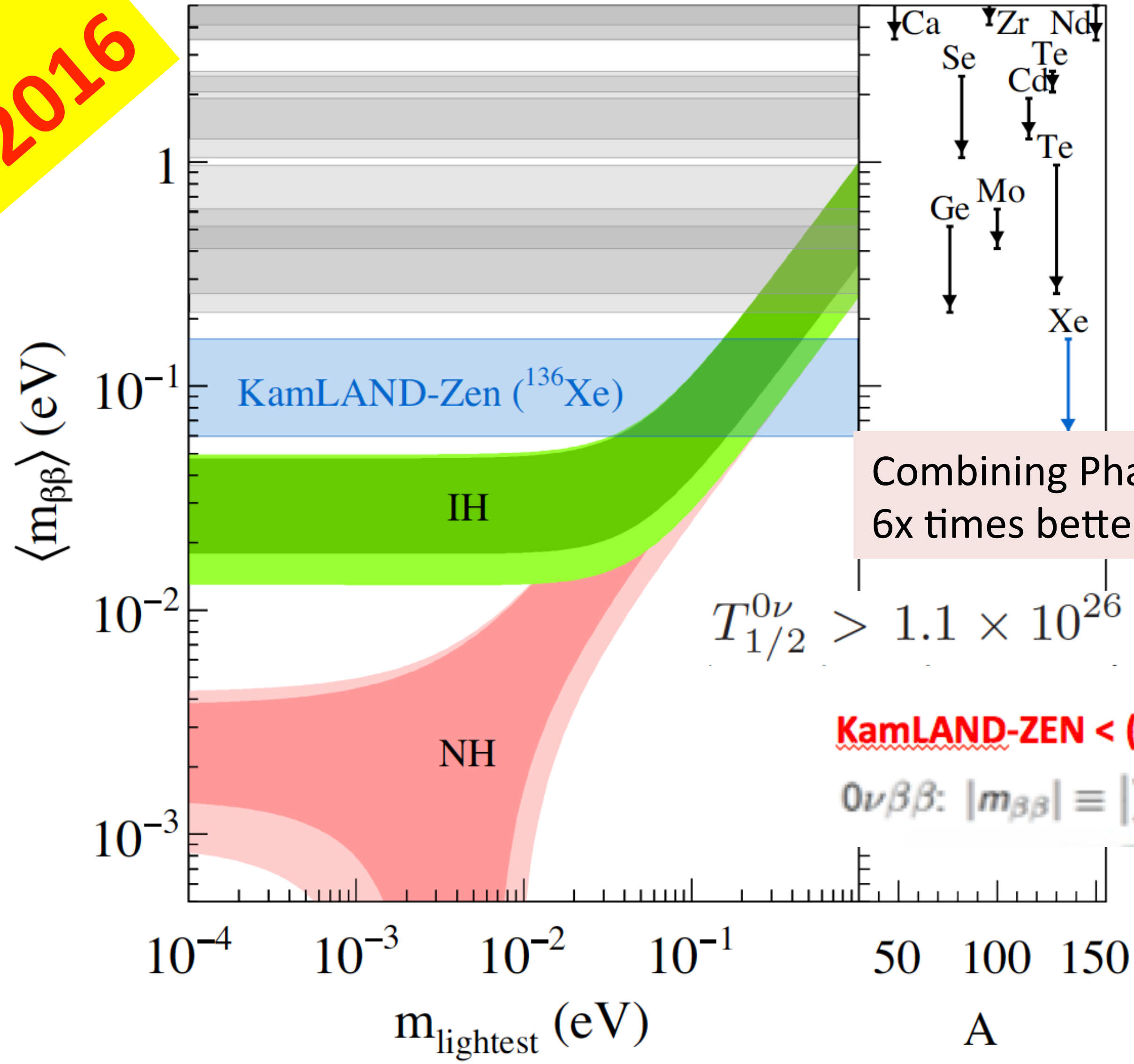
be sm



KamLAND-ZEN Phase-2 results

New
May 2016

December 11, 2013, and October 27, 2015.



Combining Phase 1 + 2:
6x times better than Phase-1

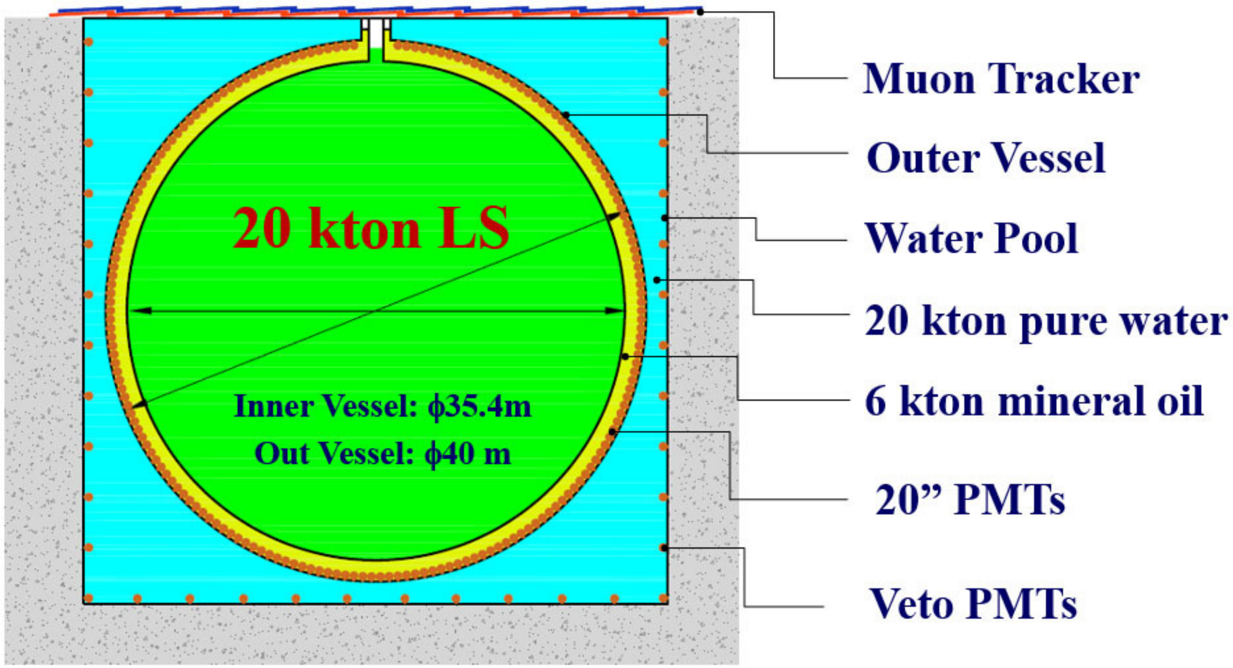
$T^{0\nu}_{1/2} > 1.1 \times 10^{26}$ yr at 90% C.L.,

KamLAND-ZEN < (60 - 160) meV

$0\nu\beta\beta$: $|m_{\beta\beta}| \equiv |\sum_i U^2_{ei} m_i|$

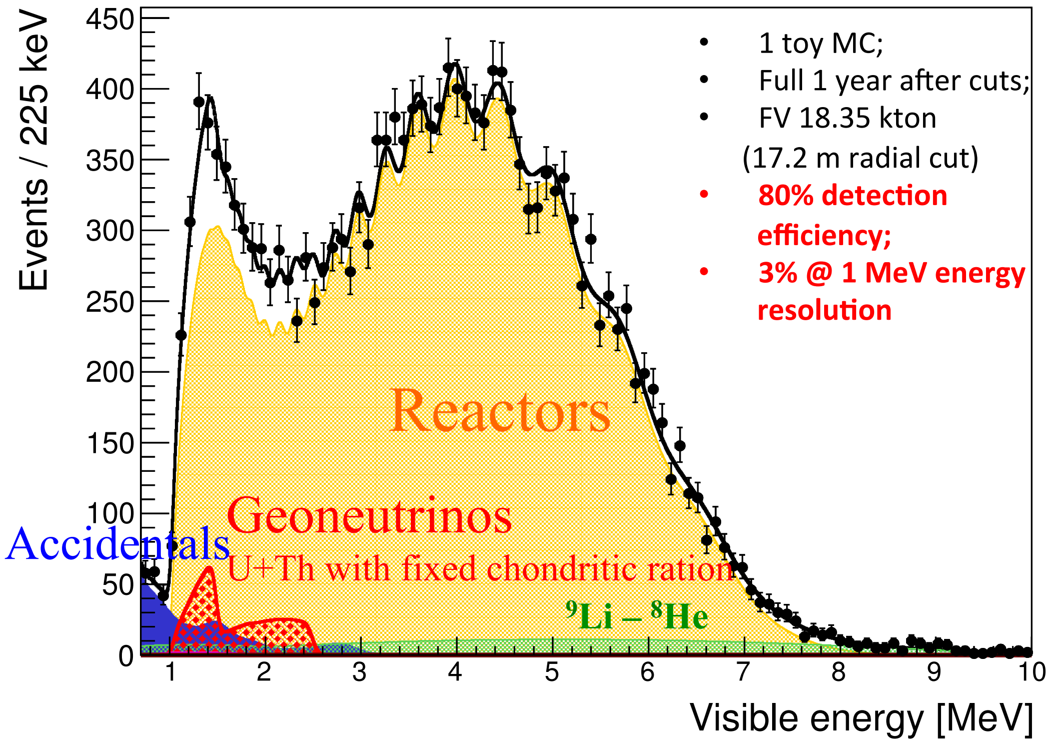
Future projects

JUNO detector



Main goal: Determination of neutrino mass hierarchy based on reactor antineutrinos with L = 53 km at 700 m depth

JUNO potential to measure geoneutrinos



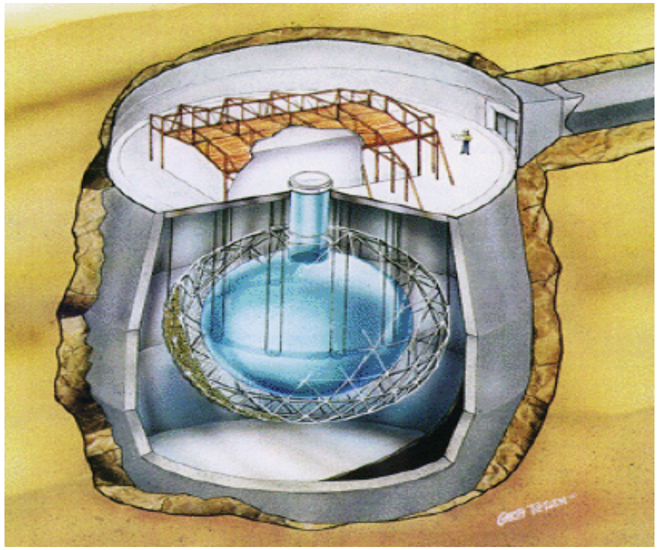
Big advantage:
- ✓ Big volume and thus high statistics (400 geonu / year)!

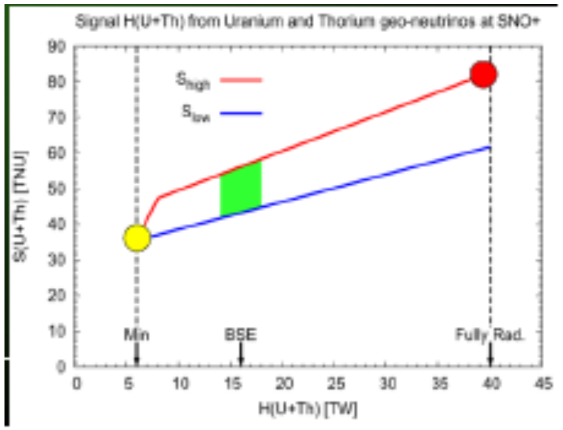
Main limitations:
- ✓ Huge reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:
- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

JUNO can provide another geoneutrino measurement with a comparable or even a better precision than existing results at another location in a completely different geological environment;

SNO+ at Sudbury, Canada





SHOULD BE COMING SOON!

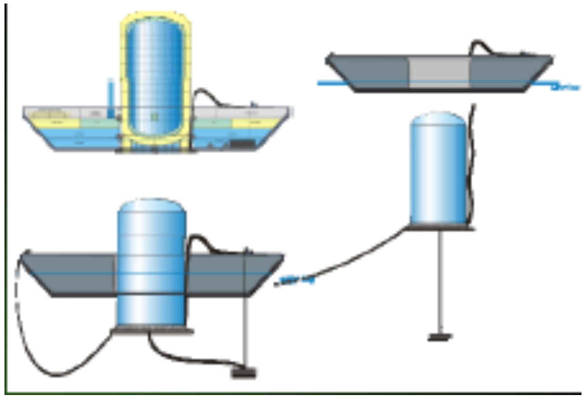
After SNO: D_2O replaced by 1000 tons of liquid scintillator
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

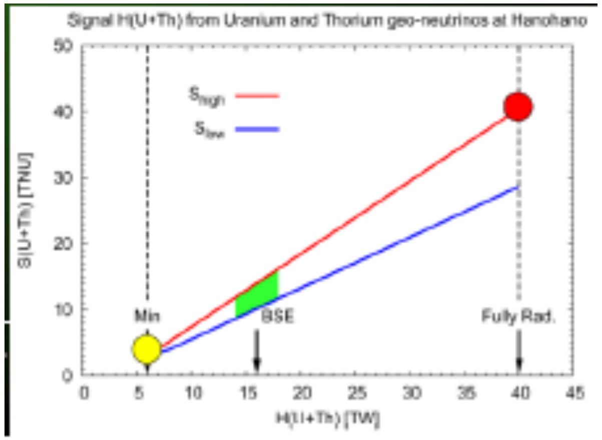
Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent” in Hawaiian





Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

Since Hawai placed on the U-Th depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year

Geoneutrino future

- **Borexino** will switch to SOX (see later) in late 2016 – closure of geoneutrino dataset;
- **KamLAND**: possible next update with low reactor-background data after the end of 2015;
- **SNO+** (Canada): 780 ton & DAQ start in 2017; detector should be able to provide geoneutrino results;
- **JUNO** (China): 20 kton & DAQ start in 2020; If non antineutrino background low and under control, JUNO will soon beat the precision of existing measurements;
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution: "**THE" GEONU DETECTOR: MISSING FUNDING!**

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Power of combined analysis and importance of multi-site measurements at geologically different environments

Geoneutrino summary

- The new interdisciplinary field is born;
- Collaboration among geologists and physicists is a must;
- The current experimental results confirm that geo-neutrinos can be successfully detected;
- Signal prediction and data interpretation: local geology around the experimental site must be studied;
- The first results are in agreement with geological expectations
- New measurements and the new generation experiments are needed for geologically highly significant results: