# Liquid Scintillator and Water Cherenkov Detectors


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LNGS - Italy

# Performances

Two categories

- Background -> residual internal/external radioactivity and muon rejection efficiency

- Measurement capabilities as extended scintillation counter
  - ❖ Light yield i.e. how many photons/MeV per deposit energy – threshold
  - ❖ Position resolution to locate the events within the active volume – definition of a fiducial volume
  - ❖ Energy resolution and linearity for adequate spectroscopy of the signal
  - ❖ $\alpha/\beta$ discrimination capability to suppress the residual alpha background

# Output of the quest for the ultimate purity

| Radio-Isotope | | Concentration or Flux | | Strategy for Reduction | | Final in phase I |
|---|---|---|---|---|---|---|
| Name | Source | Typical | Required | Hardware | Software | |
| μ | cosmic | ~ 200 $s^{-1}$ $m^{-2}$ @ sea level | <$10^{-10}s^{-1}$ $m^{-2}$ | underground water detector | Cerenkov PS analysis | < $10^{-10}$ eff. > 0.99992 |
| γ | rock | | | water | fid. vol. | negligible |
| γ | PMTs, SSS | | | buffer | fid. vol. | negligible |
| $^{14}C$ | intrinsic PC | ~$10^{-12}$ g/g | ~$10^{-18}$ g/g | selection | threshold | 2.7 x$10^{-18}$ $^{14}C/^{12}C$ |
| $^{238}U$ $^{232}Th$ | dust, metallic | $10^{-5}$-$10^{-6}$ g/g | <$10^{-16}$ g/g | distillation, W.E., filtration, mat. selection, cleanliness | tagging, α/β | $5.35 \pm 0.5\times10^{-18}$ $3.8 \pm 0.8 \times 10^{-18}$ g/g |
| $^{7}Be$ | cosmogenic | ~3 $10^{-2}$ Bq/t | <$10^{-6}$ Bq/t | distillation | -- | not seen |
| $^{40}K$ | dust, PPO | ~2. $10^{-6}$ g/g (dust) | <$10^{-18}$ g/g | distillation, W.E. | -- | not seen |
| $^{210}Po$ | surface cont. from $^{222}Rn$ | | <1 c/d/t | distillation, W.E., filtration, cleanliness | fit | May '07: 70 c/d/t Jan '10: ~1 c/d/t |
| $^{222}Rn$ | emanation from materials, rock | 10 Bq/l air, water 100-1000 Bq rock | <10 cpd 100 t | $N_2$ stripping cleanliness | tagging, α/β | <1 cpd 100 t |
| $^{39}Ar$ | air, cosmogenic | 17 mBq/$m^3$ (air) | < 1 cpd 100 t | $N_2$ stripping | fit | << $^{85}Kr$ |
| $^{85}Kr$ | air, nuclear weapons | ~ 1 Bq/$m^3$ (air) | < 1 cpd 100 t | $N_2$ stripping | fit | 30 ± 5 cpd/100 t |

May 2007 to May 2010

Threshold

20 times better than the design value

Bismuth-210 41.0±1.5±2.3 c/d/100t

**U Th and K ok**

Issue -> out of equilibrium $^{210}Bi$ and $^{210}Po$ , plus gaseous $^{85}Kr$

Determined through the observation of the features of the scintillator signals

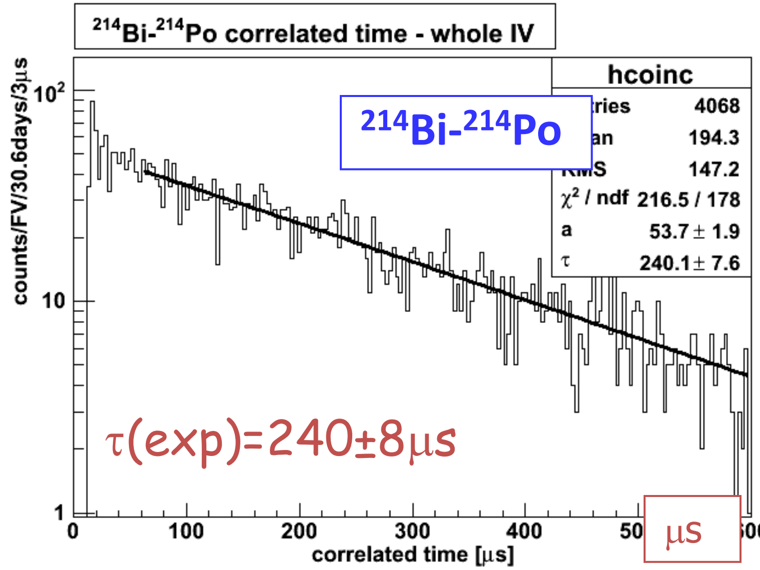
# What it does mean to determine a background through the observation of the features of the scintillator signals

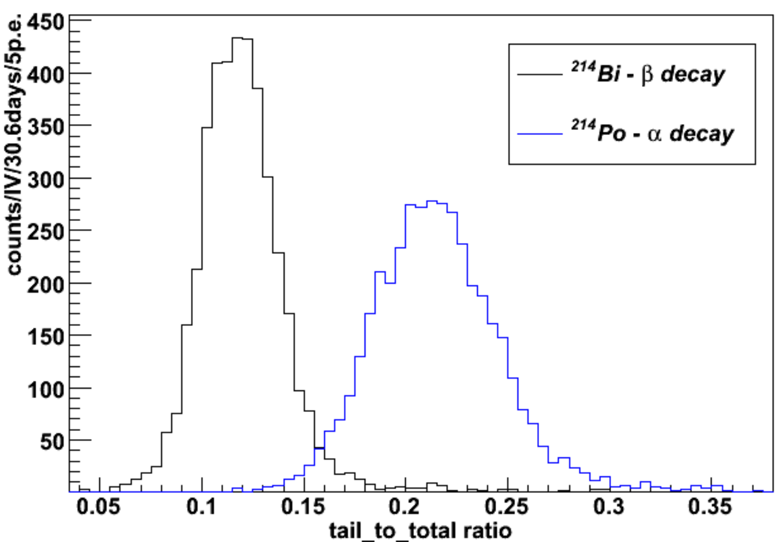
## Example: $^{238}$U content

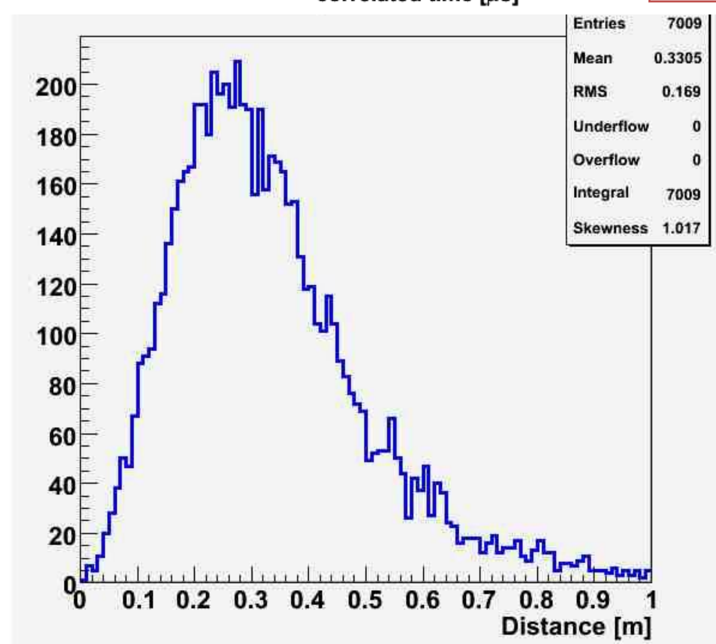
Assuming secular equilibrium, **$^{238}$U** is measured with the delayed concidence:

**$\tau$ = 236 μs**

$$^{214}\text{Bi} \xrightarrow[\text{3.2 MeV}]{\beta} {}^{214}\text{Po} \xrightarrow[\text{\textasciitilde 700 KeV eq.}]{\alpha} {}^{210}\text{Pb}$$



# Purification after phase I – August 2010 to December 2011

Further data taking with improved **backgrounds** after the **online purification**

Th< **5.7 $10^{-19}$** g/g 95% C.L.
U < **9.4 $10^{-20}$** g/g 95% C.L.
Kr< 7.1 cpd/100 tons 95% C.L.

**Purification (water extraction and nitrogen stripping) astonishingly effective in further reducing the already ultralow background Evaluated through the delayed coincidence tag**

Only sizable residual backgrounds:

$^{210}$Po factor 100 less than at the beginning of data taking

$^{210}$Bismuth (**the most relevant)** factor 2 less than in phase I

Just after the purification - later $^{210}$Po further decreased as effect of **decay (200 d τ)** and of the subsequent thermal stabilization which stopped the recontamination from the vessel **surface**

**General validity for these kind of detectors: $^{210}$Bi-$^{210}$Po out of equilibrium always present and may limit the sensitivity in the sub-MeV region**

$^{210}$Po is an alpha emitter -> removable with PSD in a liquid scintillator
Because of its intrinsic high mobility ubiquitous present in rare events set ups especially on the surfaces

# Takeaway from the Borexino experience about radiopurity of large underground liquid scintillator detectors

- U Th and K can be well beyond the specifications and further removed with purification
- Transient out of equilibrium $^{222}$Rn gas a concern, but manageable
- Gaseous $^{85}$Kr removable with nitrogen selection and stripping
- Low energy sub-MeV limit mainly from residual $^{210}$Bi, $^{210}$Po not a real concern because PSD (**important: this may not be true for other techniques**)
- Intrinsic $^{14}$C dictates the low energy limit for physics measurements abut 120 keV
- Surface treatments and cleanliness of the construction environment crucial

All in all, a thorough strategy encompassing

- Selection of materials including nitrogen
- Cleanliness of surfaces
- Purification of the scintillator and of water
- and a fill procedure that does not spoil the key elements above

$\rightarrow$can result in a very ultra pure environment in the inner core of the detector

# Measured quantities

The electronics measures and provides for each triggered event:

•The photomultipliers pulse height

→ energy measurement

•The photoelectrons arrival times (better than 0.5 ns precision)

→ position identification

- The absolute time of the event

Expected detector perfomances

Effective coverage 30% (by design, it depends upon the concentrator)

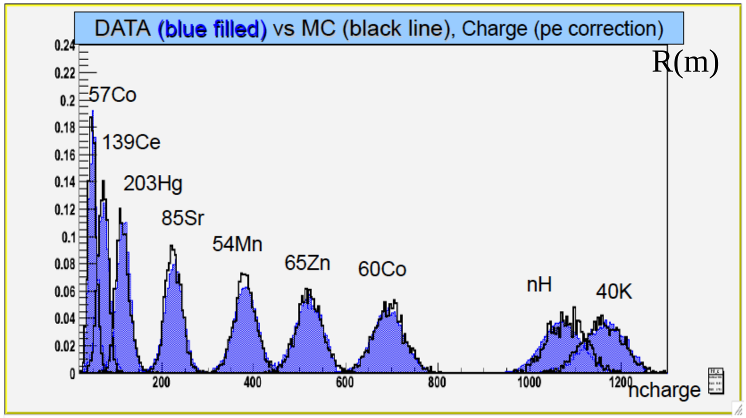
Photoelectron yield 500 pe/MeV

Energy resolution @ 1 MeV 5%

Position resolution @ 1 MeV 10 cm

# How to cross check: calibration

Very convenient and easy to use→ γ sources
Self made radon sources → radon in a scintillator vial
AmBe as neutron source




## Energy scale-Resolution

$\frac{5\%}{\sqrt{E}}$ from 200 keV to 2 MeV

Beyond 2 MeV: γ from n capture on C and H

@ MC tuned on γ source results

@ Determination of Light yield and of the Birks parameter $k_B$

L.Y. → obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**

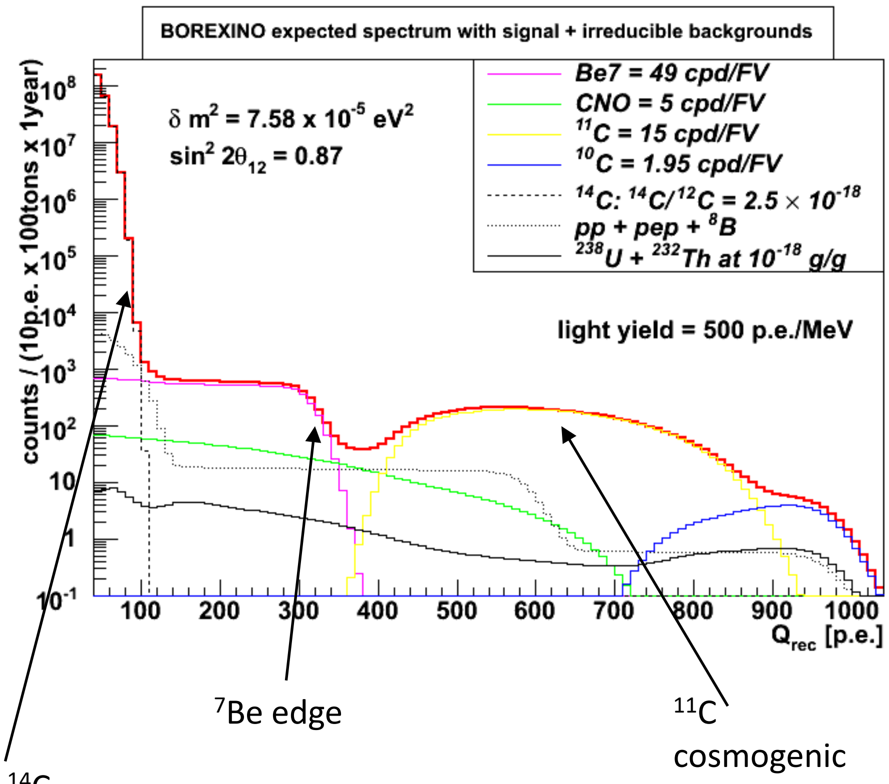
→ left as free parameter in the total fit in the analytical approach

@ Precision of the energy scale global determination: max deviation **1.5%**

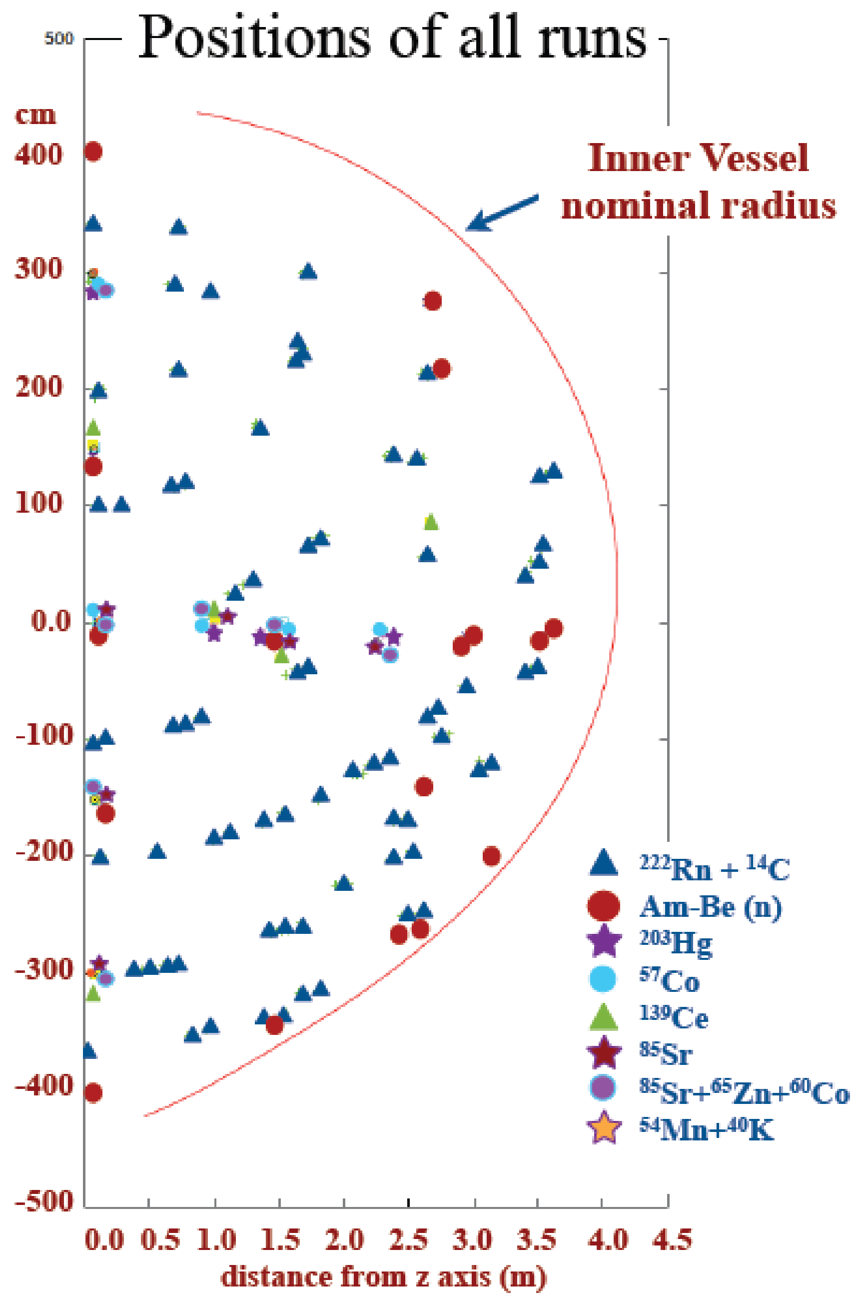
@ Fiducial volume uncertainty: $\boxed{{}^{+0.5}_{-1.3}\,\%}$ ( 1 σ) (radon sources)

Optimum agreement with the expectations

MC prediction of signal + intrinsic Background




Main visible features



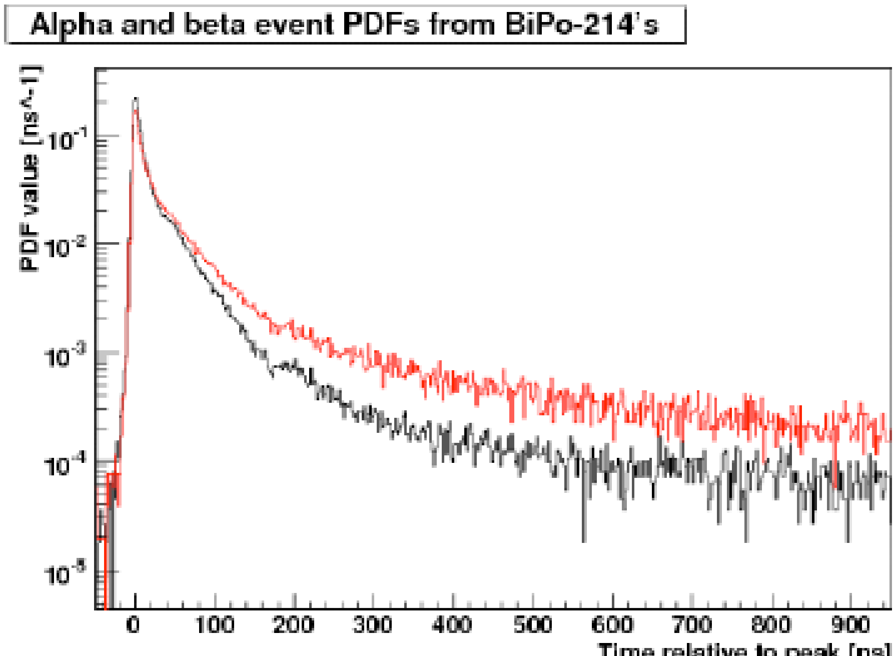
# $\alpha/\beta$ Discrimination Calibration

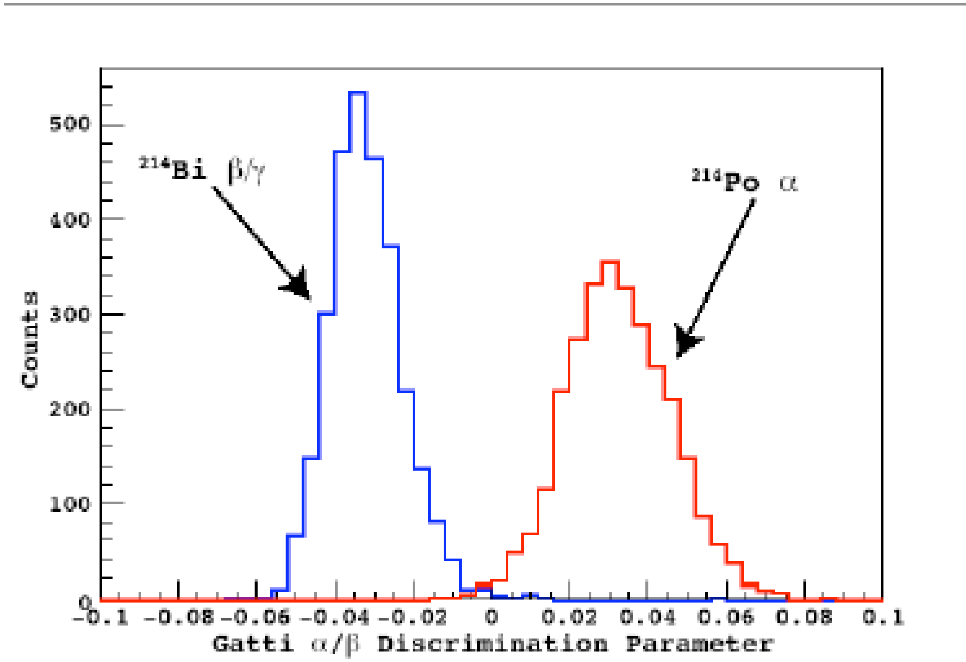
Different discrimination methods

Tail-to-total    linear processing via so called Gatti method    neural network like approach

Calibrated with intrinsic radon and following daughters especially $^{214}$Bi and $^{214}$Po

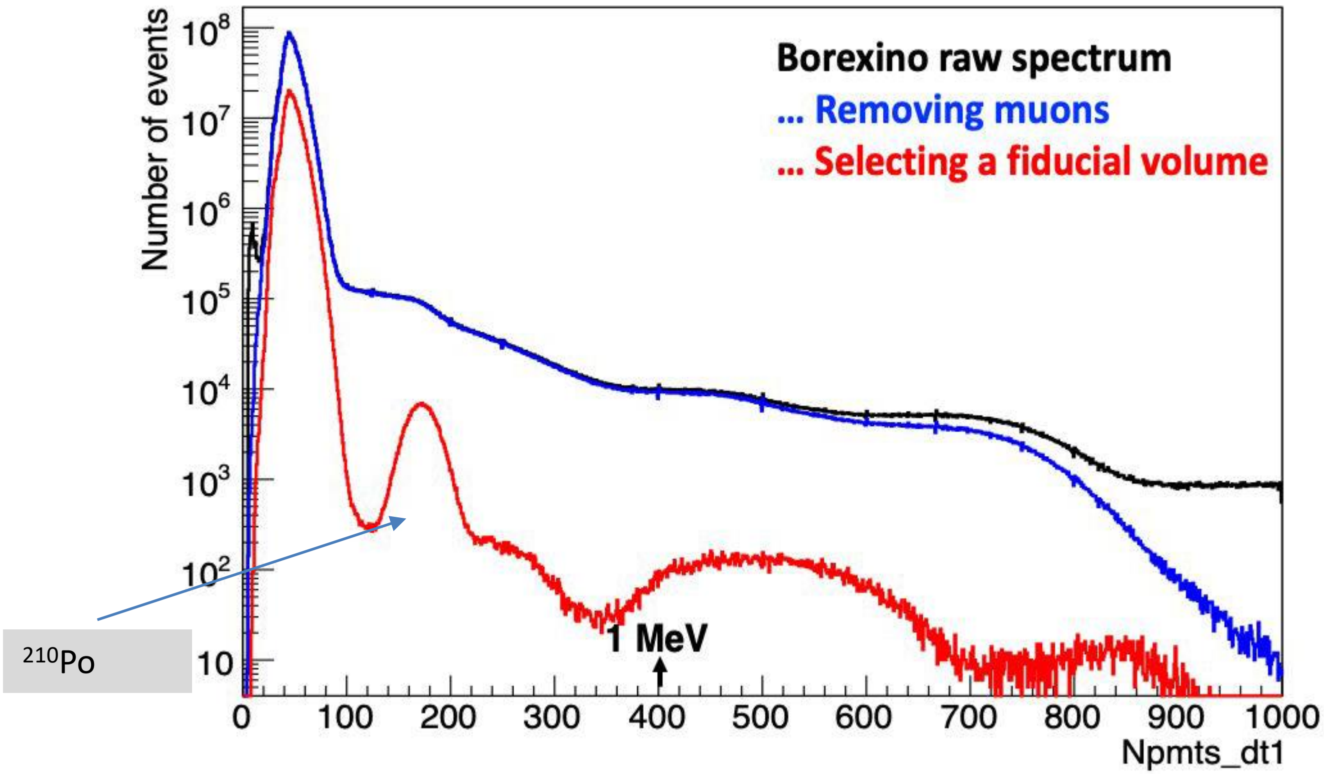
Efficiency energy dependent and MC modeled - about 95% for $^{214}$Po alpha @ 7.8 MeV




This analysis for the reference curves has been done during the filling period, when $^{222}$Rn was present

# Actual data histogram



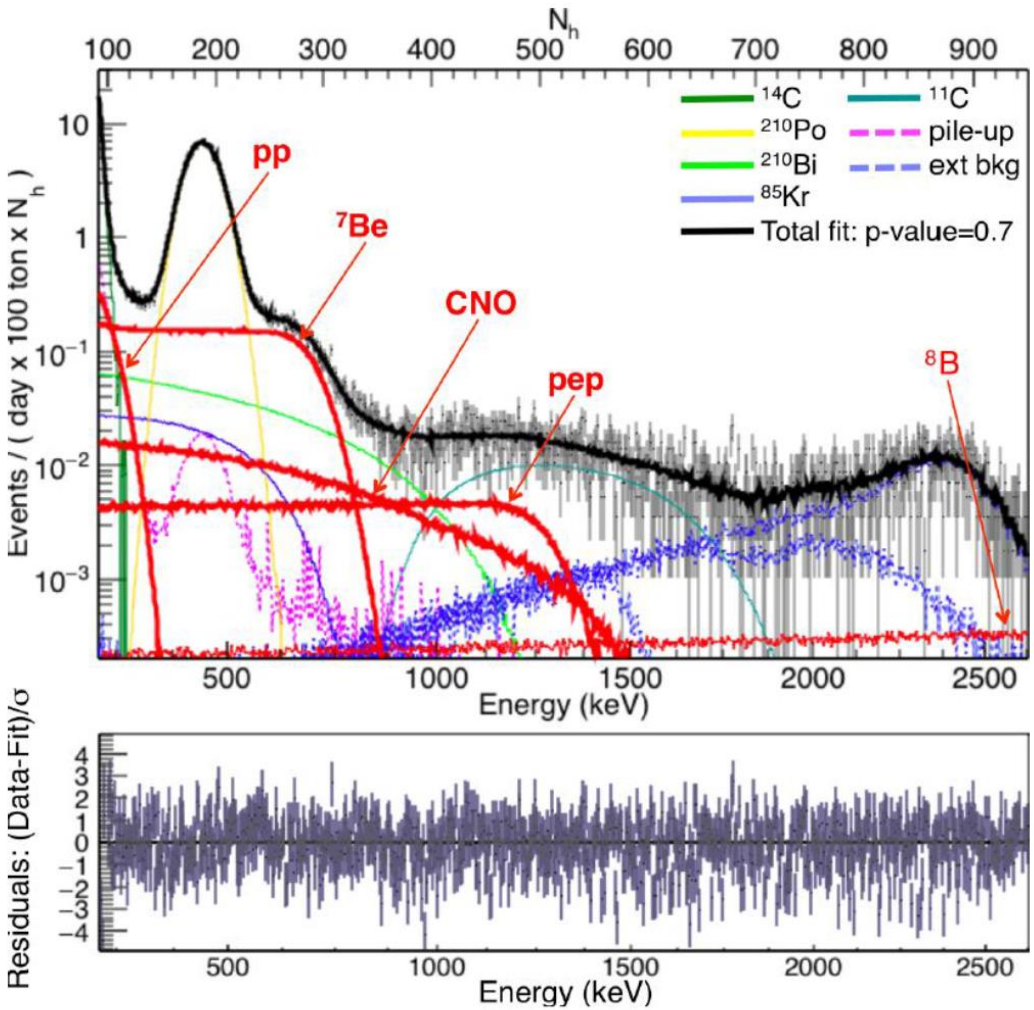

**The same features noted in the MC spectrum** plus the $^{210}$Po out of equilibrium peak

This agreement indicates the very good job done with the Mc modeling and the calibrations

Even at the Borexino very high radiopurity conditions, we still have background events contaminating our solar neutrino signal and we need to apply software cuts to data, in order to remove as much background as possible. Furthermore, we need a powerful tool to separate the signal from the residual background components -> **fit to a signal + background model**

## Phase II data simultaneous low energy spectroscopy data-to-model fit

**Nature, Volume 562, pp. 505-510 (2018) and Physical Review D, Volume 100, Issue 8, id.082004 (2019)**

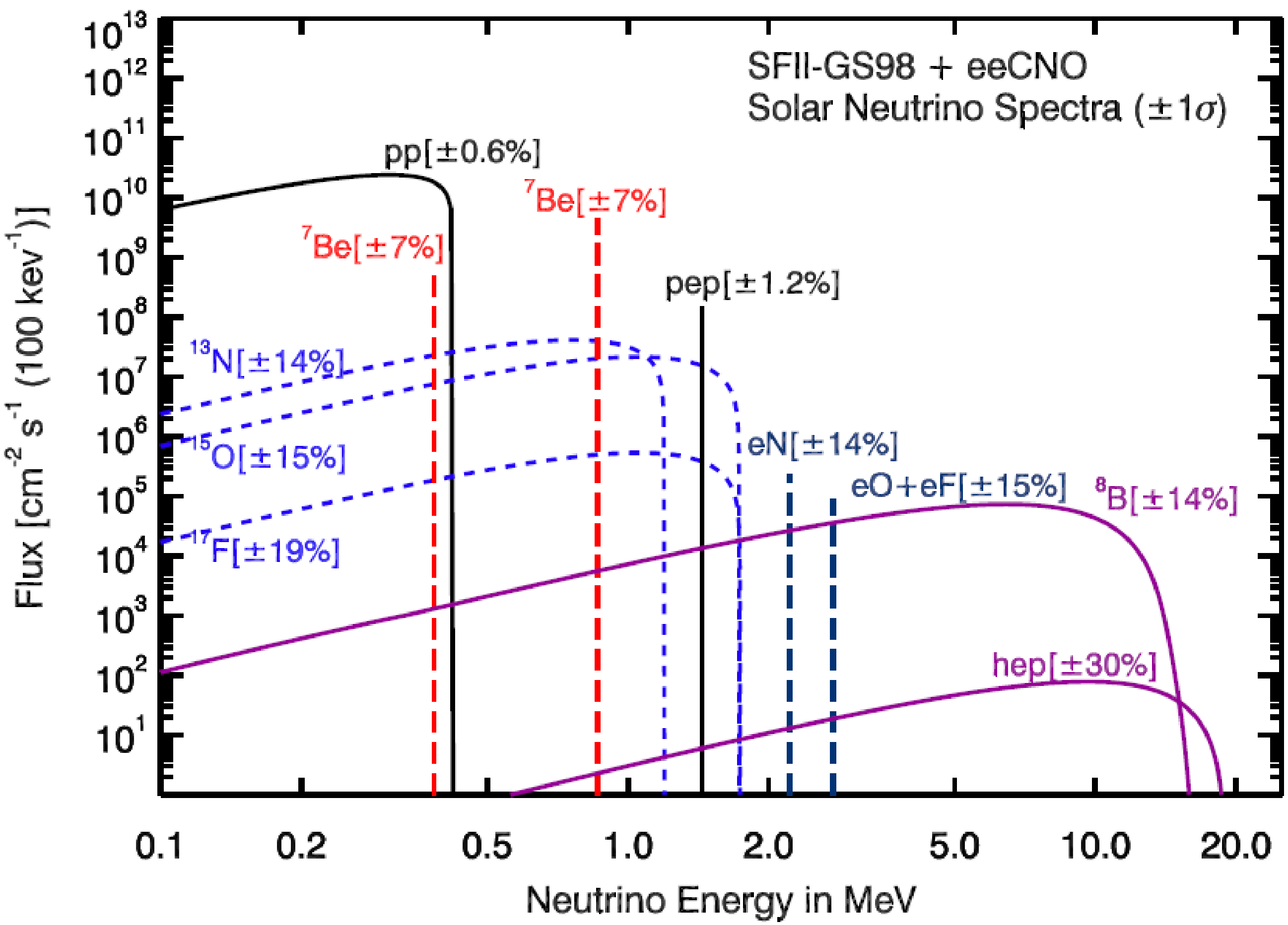



Example of how the amplitude distribution of the scattered electron signals is fit to a signal + background model in Borexino - similar approach in any large scintillator detector – the model can be MC or analytical

From the fit the flux rate of each component is inferred

The background model is obtained through the extensive studies outlined before

# Signal model – theoretical input




Predicted neutrino spectra from a **Standard Solar Model**

Used for the electron signal model in the detector response via the quantification of the scattering process off the electrons of the scintillator

Two sequences of reactions postulated in the Sun

**pp chain**

**CNO cycle**

# Main achievements of Borexino

Astroparticle physics

Full spectroscopy of the neutrinos coming from the two sequences of nuclear reactions occurring in the core of the Sun

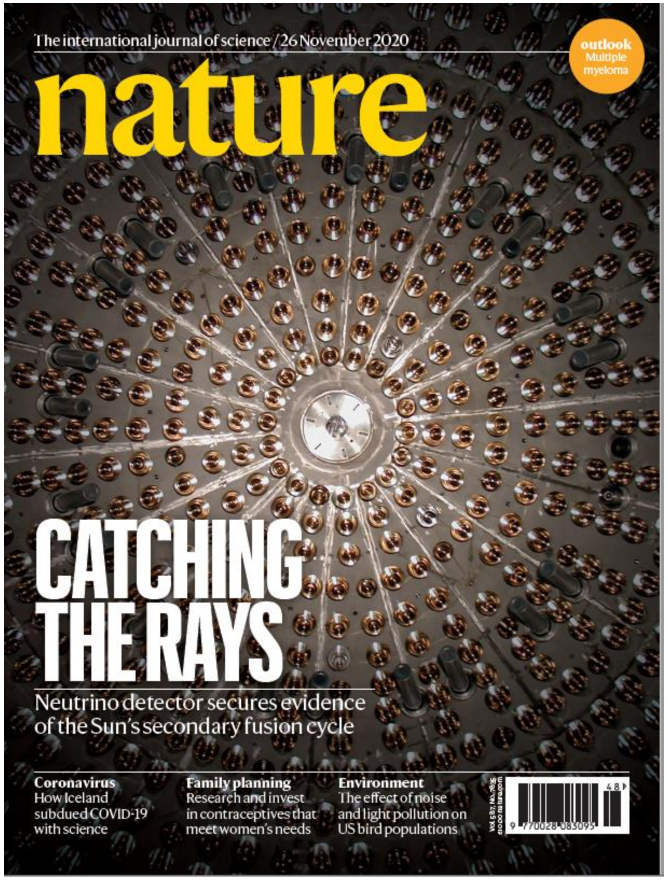
- **pp chain** – first detection ever of the separated low energy components
- **CNO cycle** – first detection ever of this flux

Particle physics – neutrino oscillations

Confirmation of the energy dependent neutrino oscillation phenomenon via the so called MSW (Mikheyev, Smirnov and Wolfenstein) effect - vacuum flavor conversion altered by the interaction of neutrinos with the matter's electrons / Sun and Earth

Moreover

Geoneutrinos – antineutrinos from Earth via IBD reaction (see later and Francesco talk) less demanding for background




**An effective technique leading to outstanding results**

# For reference: Compendium of Borexino results

New pp, $^{7}$Be, pep results of the analysis of Phase II data

Phys. Rev. D **101**, 012009 – 2020
**Geo-neutrinos**

| | Borexino results cpd/100t | expected HZ cpd/100t | expected LZ cpd/100t |
|---|---|---|---|
| pp | $134 \pm 10^{+6}_{-10}$ | $131.0 \pm 2.4$ | $132.1 \pm 2.4$ |
| $^{7}$Be(862+384 KeV) | $48.3 \pm 1.1^{+0.4}_{-0.7}$ | $47.8 \pm 2.9$ | $43.7 \pm 2.6$ |
| pep (HZ) | $2.43 \pm 0.36^{+0.15}_{-0.22}$ | $2.74 \pm 0.05$ | $2.78 \pm 0.05$ |
| pep (LZ) | $2.65 \pm 0.36^{+0.15}_{-0.24}$ | $2.74 \pm 0.05$ | $2.78 \pm 0.05$ |

| | Borexino results Flux ($cm^{-2}s^{-1}$) | expected HZ Flux ($cm^{-2}s^{-1}$) | expected LZ Flux ($cm^{-2}s^{-1}$) |
|---|---|---|---|
| pp | $(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$ | $5.98\ (1 \pm 0.006)\ 10^{10}$ | $6.03\ (1 \pm 0.005)\ 10^{10}$ |
| $^{7}$Be(862+384 KeV) | $(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$ | $4.93\ (1 \pm 0.06)\ 10^{9}$ | $4.50\ (1 \pm 0.06)\ 10^{9}$ |
| pep (HZ) | $(1.27 \pm 0.19^{+0.08}_{-0.12})\ 10^{8}$ | $1.44\ (1 \pm 0.009)\ 10^{8}$ | $1.46\ (1 \pm 0.009)\ 10^{8}$ |
| pep (LZ) | $(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$ | $1.44\ (1 \pm 0.009)\ 10^{8}$ | $1.46\ (1 \pm 0.009)\ 10^{8}$ |

**Nature, Volume 562, pp. 505-510 (2018) and Physical Review D, Volume 100, Issue 8, id.082004 (2019)**

Beginning of the precision era in the study of low energy solar neutrinos
$^{7}$Be precision 2.7%

$^{8}$B $= 0.220^{+0.015}_{-0.016}\,(stat)\ ^{+0.006}_{-0.006}\,(syst)$ cpd/100 t.

Expected 0.211 ±0.025 cpd/100t

$^{8}$B flux $= 2.55 \pm 0.18 \pm 0.07 \times 10^{6}\ cm^{-2}\ sec^{-1}$

PHYSICAL REVIEW D 101, 062001 (2020)

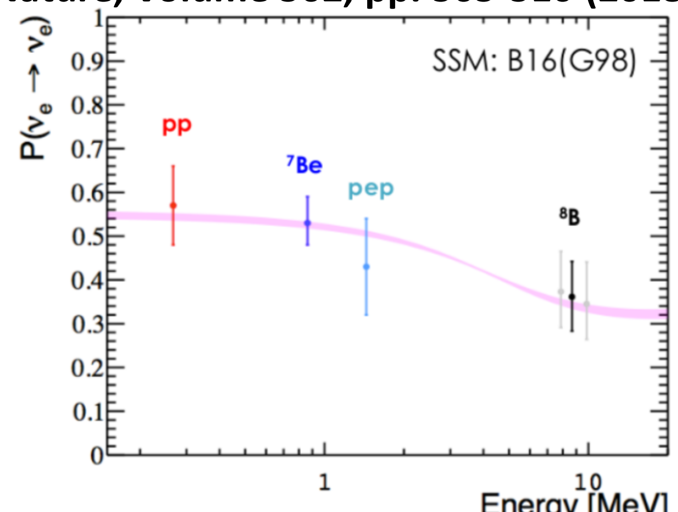
CNO = $6.7\ ^{+2.0}_{-0.8}$ cpd/100t

CNO flux $6.6\ ^{+2.0}_{-0.9} \times 10^{8}\ cm^{-2}\ s^{-1}$

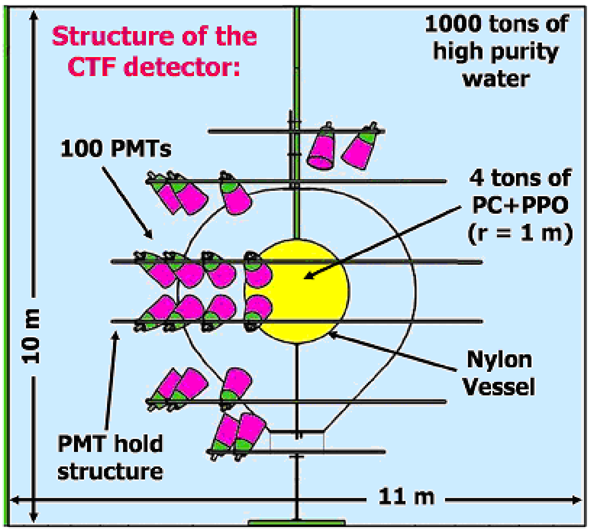
arXiv:2205.15975

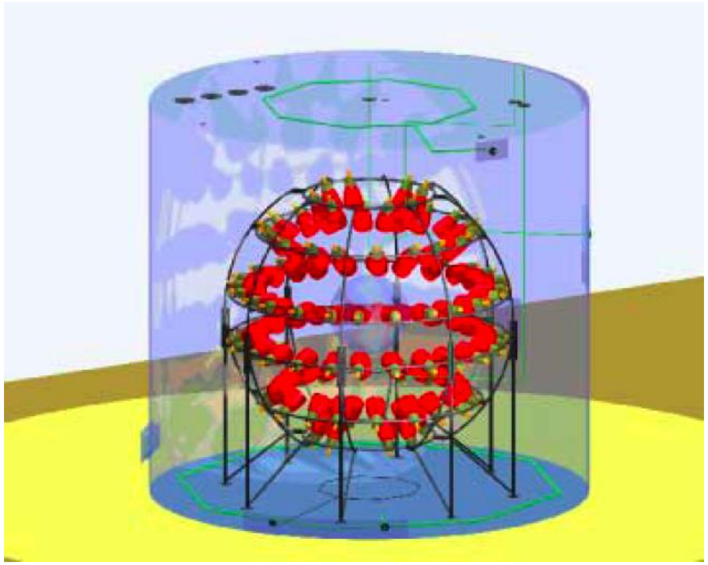
MSW proof

**Nature, Volume 562, pp. 505-510 (2018)**



Sometimes a prototype detector to test the technologies and prove the feasibility – this was the role of CTF for Borexino



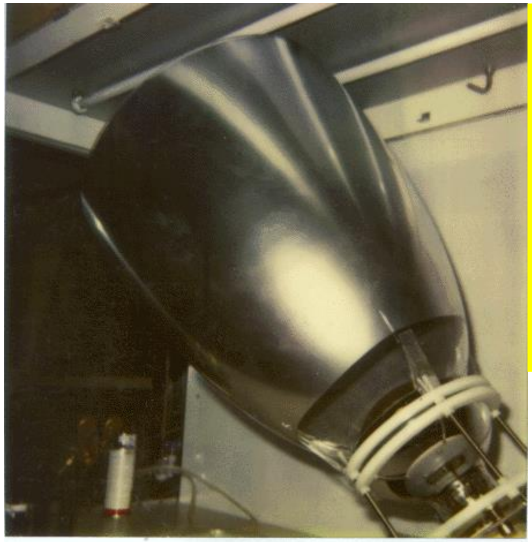
The concept


The implementation

You may recognize the similarity with the SOUP image………

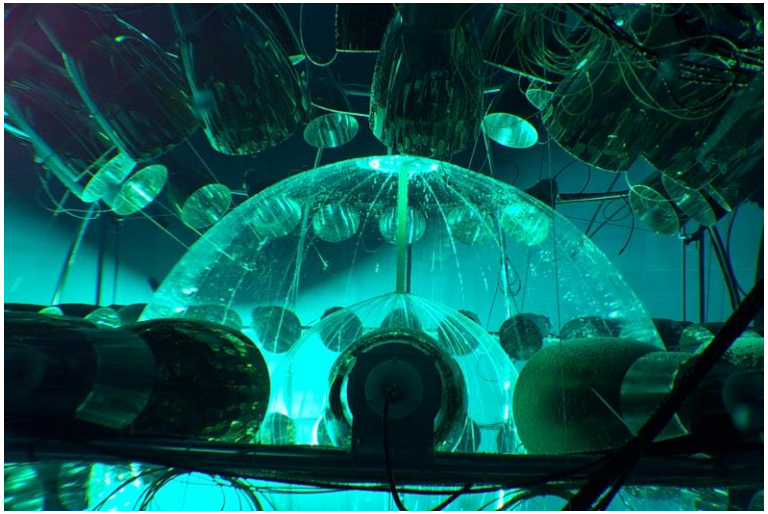
## Other equipment

The tank in Hall C – still there surrounded by the Borexino equipment



A CTF concentrator note the difference with that of Borexino

Second vessel with outer barrier



The steel structure now !

# CTF: most important results and activities

- **First measurement in a liquid scintillator of $^{238}U$, $^{232}Th$ e $^{14}C$ radiopurity level; at that time a real *"breakthrough"* in the field of ultra pure material;**

- **Identification of the specific background issues of $^{85}Kr$ and $^{210}Po$;**

- **Investigation of removal and purification techniques : water extraction, nitrogen stripping, distillation, alpha-beta discrimination;**

- **Large scale quality check of optics and radiopurity of the scintillator to be used for the Borexino fill;**

- **check of the operational properties and of the compliance to the specifications of the filling stations and of the purification set-ups: distillation and water extraction plants.**

**Pilot fish of Borexino!**

# The next frontier of large LS underground detectors - JUNO

- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution 1200 pe/MeV

Both crucial for the physics capabilities

Steel Truss to support the acrylic and hold PMTs

~20000 x 20”

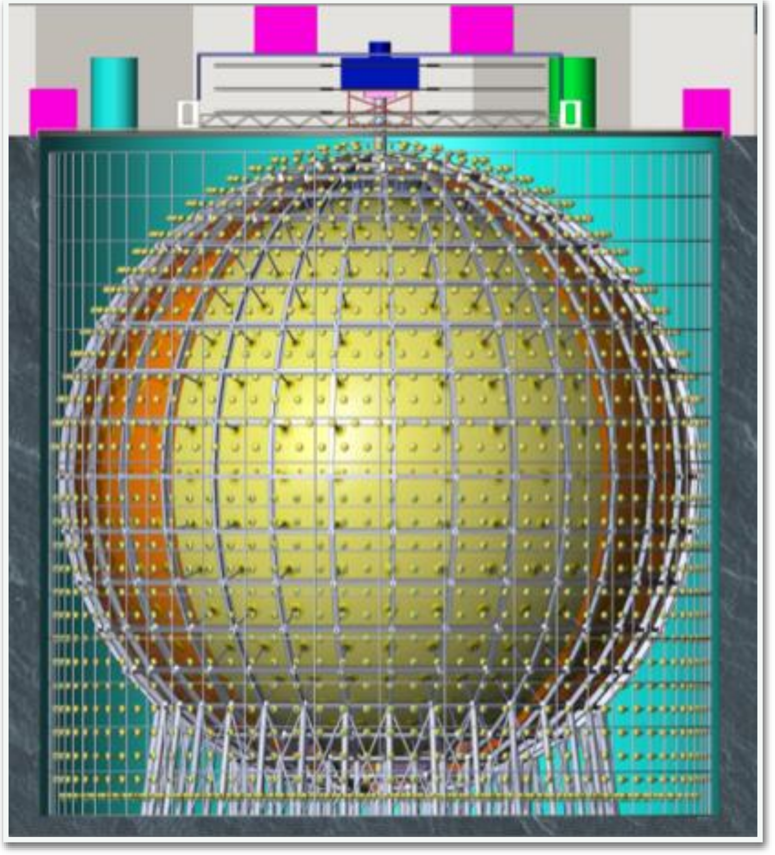
18000 Inner

2000 veto

~25000 x 3”

Acrylic Sphere

filled with 20 kt LS



**JUNO has been approved in China in Feb. 2013 – under construction**

**Participation and contributions from several other countries:**

- **Armenia**
- **Belgium**
- **Brazil**
- **Chile**
- **Czechia**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Latvia**
- **Pakistan**
- **Russia**
- **Slovakia**
- **Taiwan**
- **Thailand**
- **USA**

# Antineutrino beams from reactors at medium distance

| NPP | Daya Bay | Huizhou | Lufeng | Yangjiang | Taishan |
|---|---|---|---|---|---|
| Status | Operational | Planned | Planned | 6 built | 2 built + 2 future |
| Power | 17.4 GW | 17.4 GW | 17.4 GW | 17.4 GW | 18.4 GW |

installed: 26.6 GW

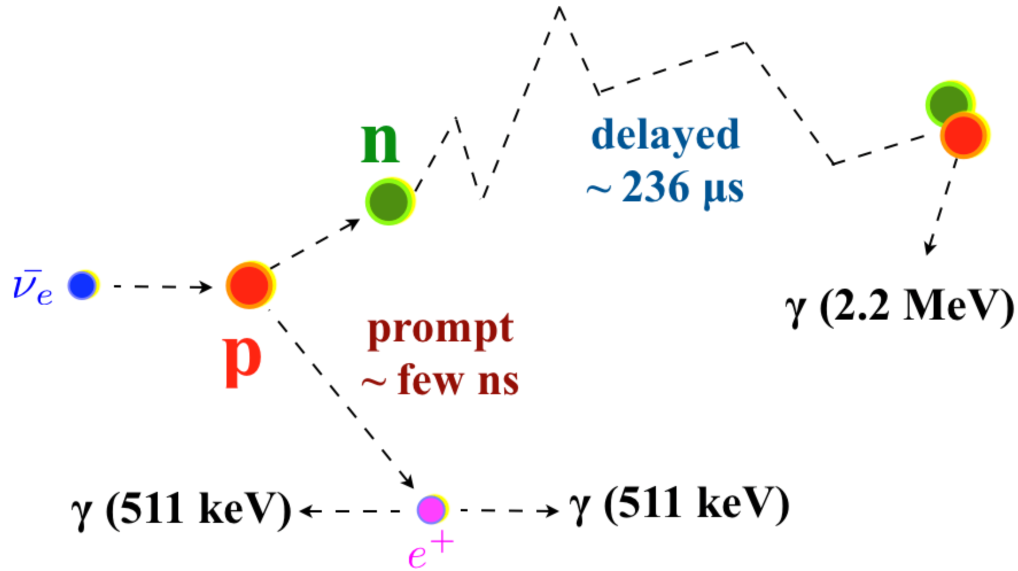

| Cores | YJ-C1 | YJ-C2 | YJ-C3 | YJ-C4 | YJ-C5 | YJ-C6 |
|---|---|---|---|---|---|---|
| Power (GW) | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Baseline (km) | 52.75 | 52.84 | 52.42 | 52.51 | 52.12 | 52.21 |
| Cores | TS-C1 | TS-C2 | TS-C3 | TS-C4 | DYB | HZ |
| Power (GW) | 4.6 | 4.6 | 4.6 | 4.6 | 17.4 | 17.4 |
| Baseline (km) | 52.76 | 52.63 | 52.32 | 52.20 | 215 | 265 |

# Antineutrino detection

Detection through the classical inverse beta decay reaction

Reaction used by Cowan and Reines for the first (anti)neutrino observation at the Savannah River experiment

$$\bar{\nu} + p \rightarrow n + e^{+}$$ $E_{\nu}$>1.8 MeV




The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the antineutrino studies is the positron spectrum

It results that $E_{vis}(e^+)=E(\nu)-0.8$ MeV - same reaction used for antinus from Earth: geoneutrinos

# Physics of JUNO

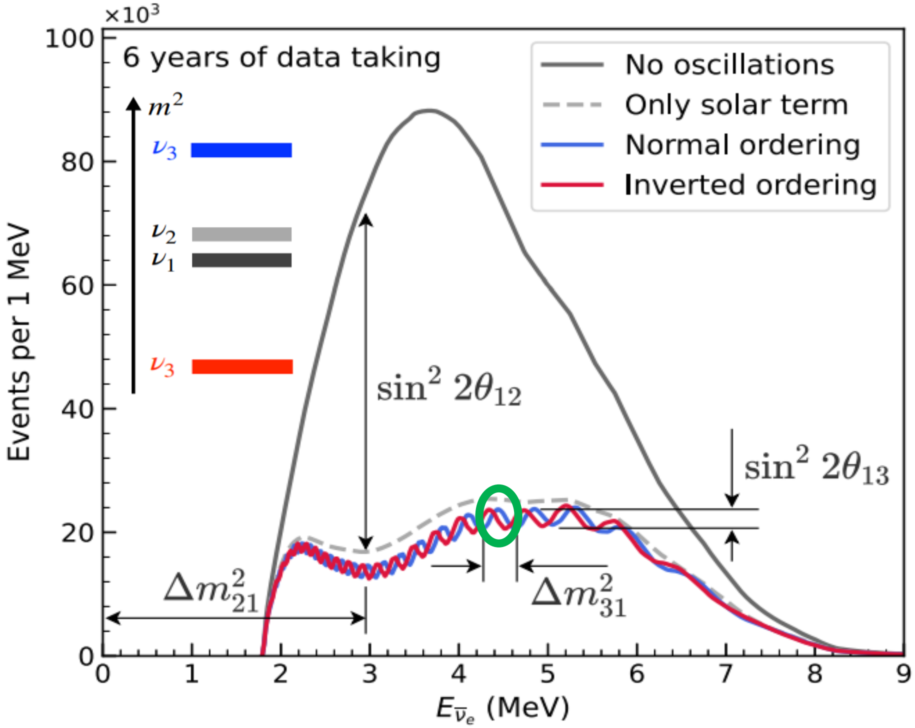
- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – 53 km – from a set of high power nuclear complexes
- Precise measurements of neutrino oscillation parameters

IBD

- Vast astroparticle program
  - Solar neutrinos
  - Atmospheric neutrinos
  - Supernova neutrinos
  - Relic neutrinos from past supernovae
  - geoneutrinos

IBD and
νe
scattering

# Physics from the observed spectrum




The oscillation phenomenon depends upon three mixing angles $\theta_{12}$ , $\theta_{13}$ **and** $\theta_{23}$ and three mass differences (only two independent) $\Delta m^2_{21}$ $\Delta m^2_{31}$ $\Delta m^2_{32}$

Summary of how JUNO will extract the information on neutrino oscillation – mass hierarchy and oscillation parameters – from the features of the observed spectrum

Goals

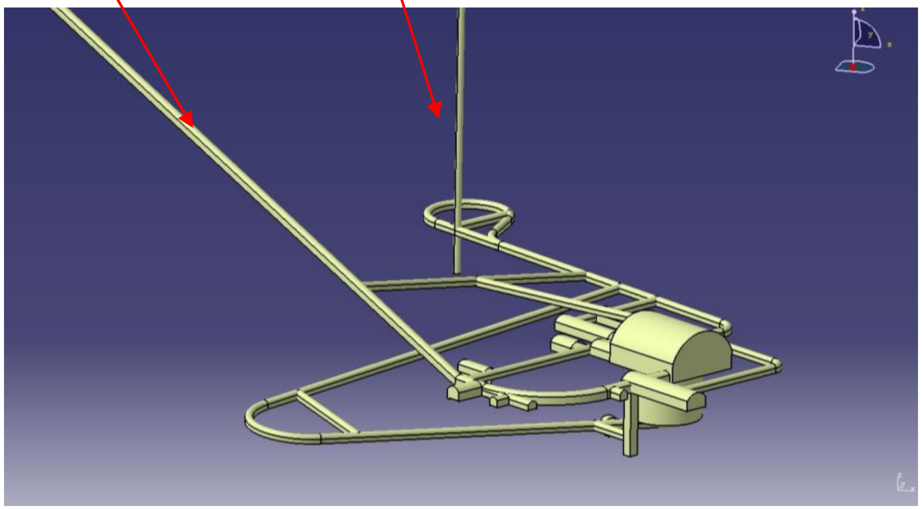
Sub percent precision on the parameters

$3\sigma$ discrimination of hierarchy

# Layout of the site

Slope tunnel

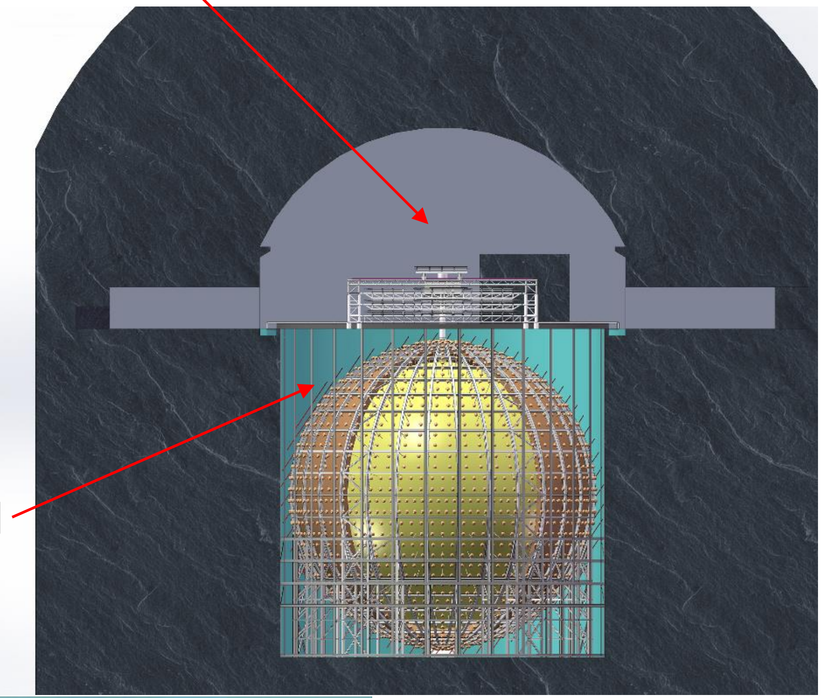
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool



Surface buildings

# Detector's layout

**Central detector**

- Acrylic sphere with 20k t liquid scintillator
- PMTs in water buffer on a stainless steel truss - 18k 20” and 25k 3”
- 78% PMT coverage

**Water Cherenkov muon veto**

- 2000 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 $Bq/m^3$

**Compensation coils**

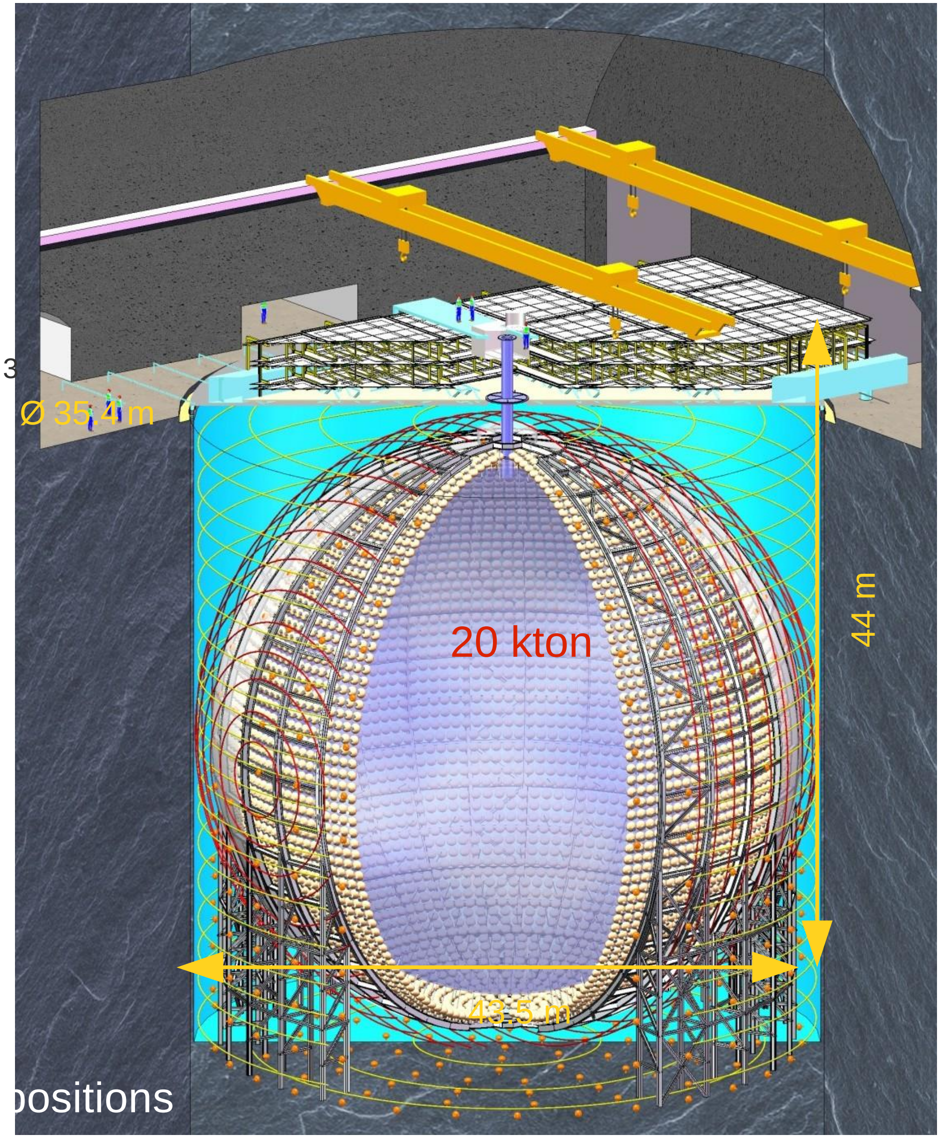
- Earth's magnetic field <10%
- Necessary for 20” PMTs

**Top tracker**

- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

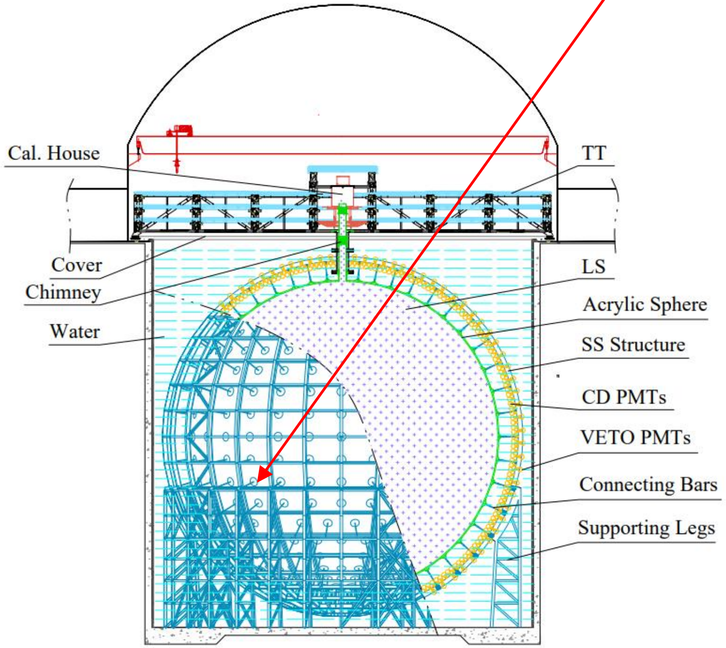
**Calibration System**

- 4 complementary sub-systems
- various particle types, ranges and positions



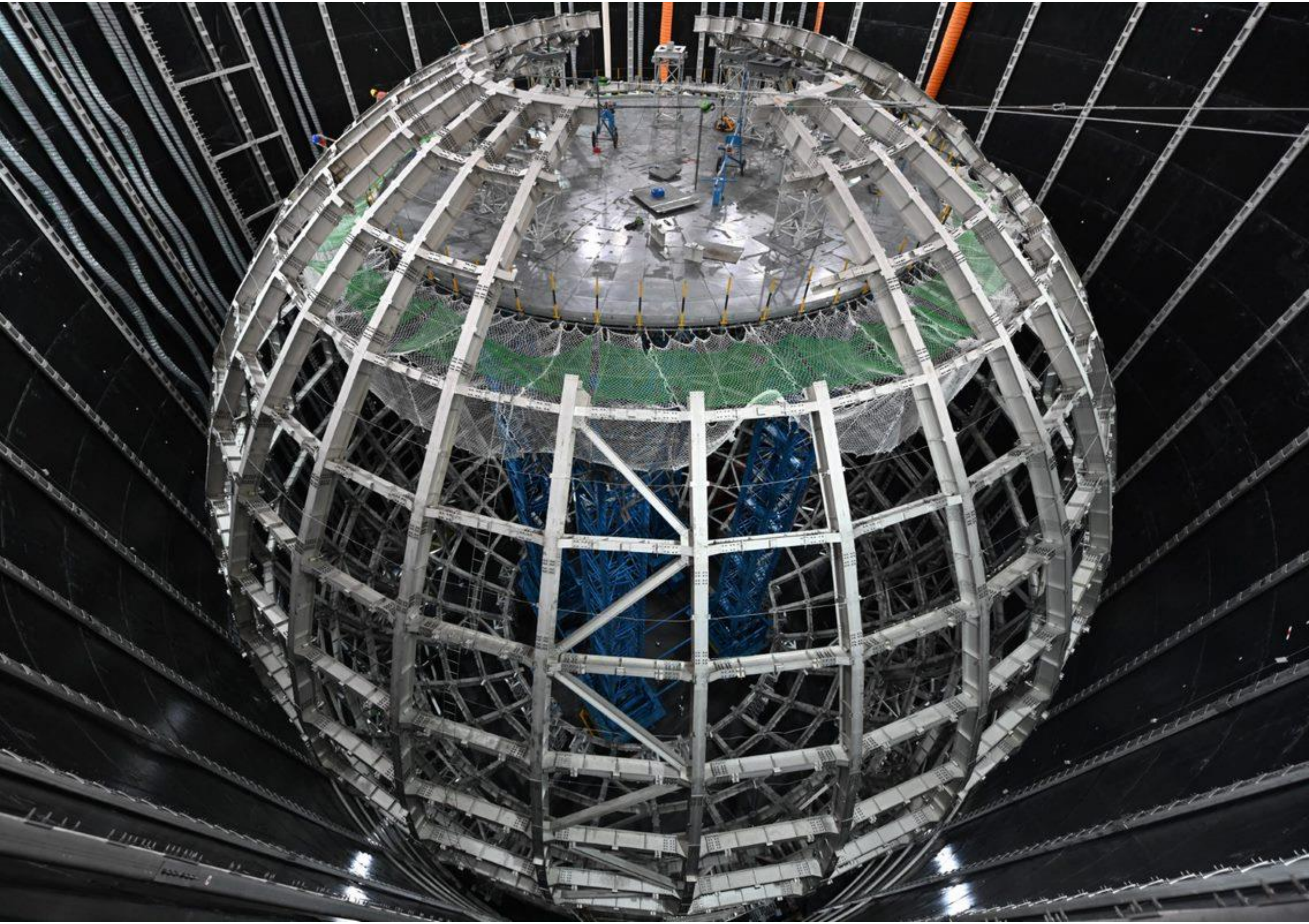
# Status of the installation

Experimental pool with the liner just before the installation startup



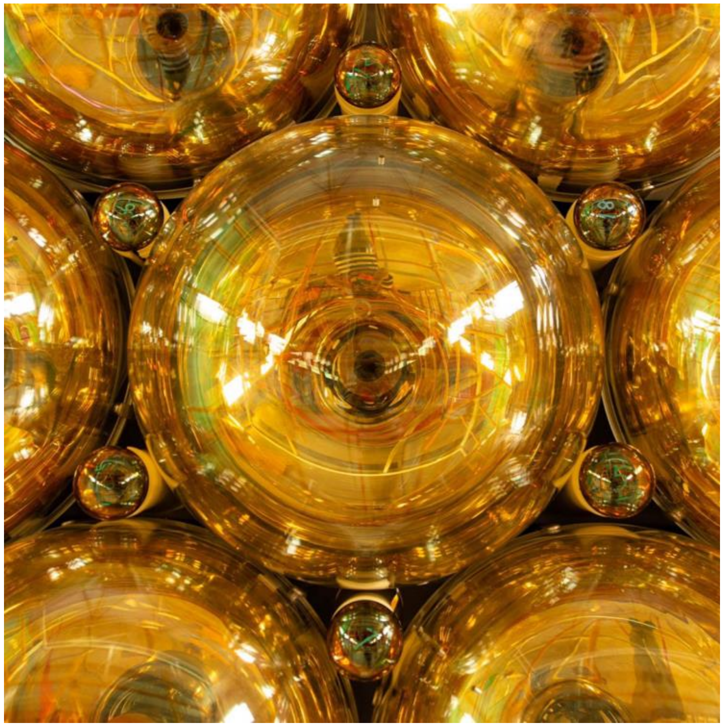

Platform ready for acrylic vessel installation

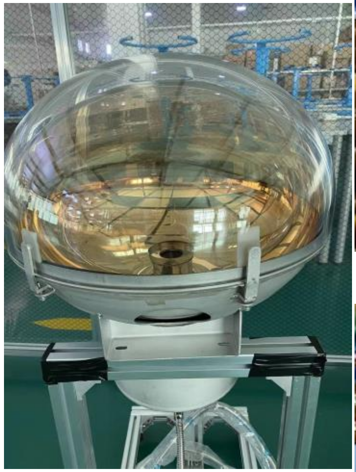
Assembly in clean room environment class 1000-10000



# Photomultipliers

Synergy between large and small PMTs

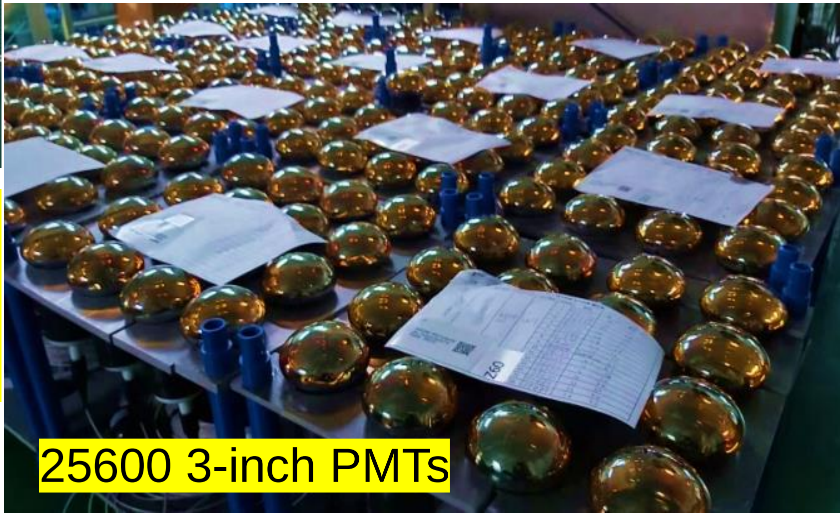




Acrylic cover against implosion

Preparation

17612 (CD) + 2400 (Veto) 20-inch PMTs



25600 3-inch PMTs

# Purification of the scintillator

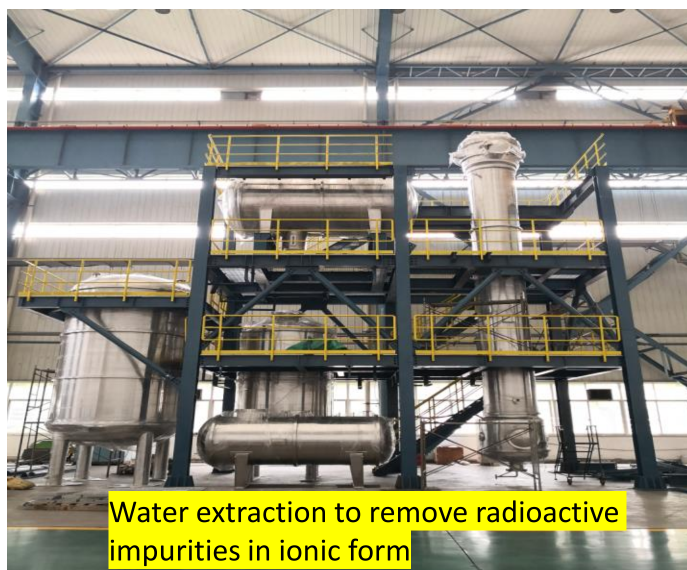
**Methods inherited from the Borexino experience**

Distillation to remove radioactive impurities

Distillation

**JUNO has inherited also the thorough strategy of background control of Borexino: materials, cleanliness, filling strategy**

Water extraction



Water extraction to remove radioactive impurities in ionic form

Gas stripping to remove Rn and $O_2$

Stripping

**Linear alkyl benzene chosen as base of the scintillator**

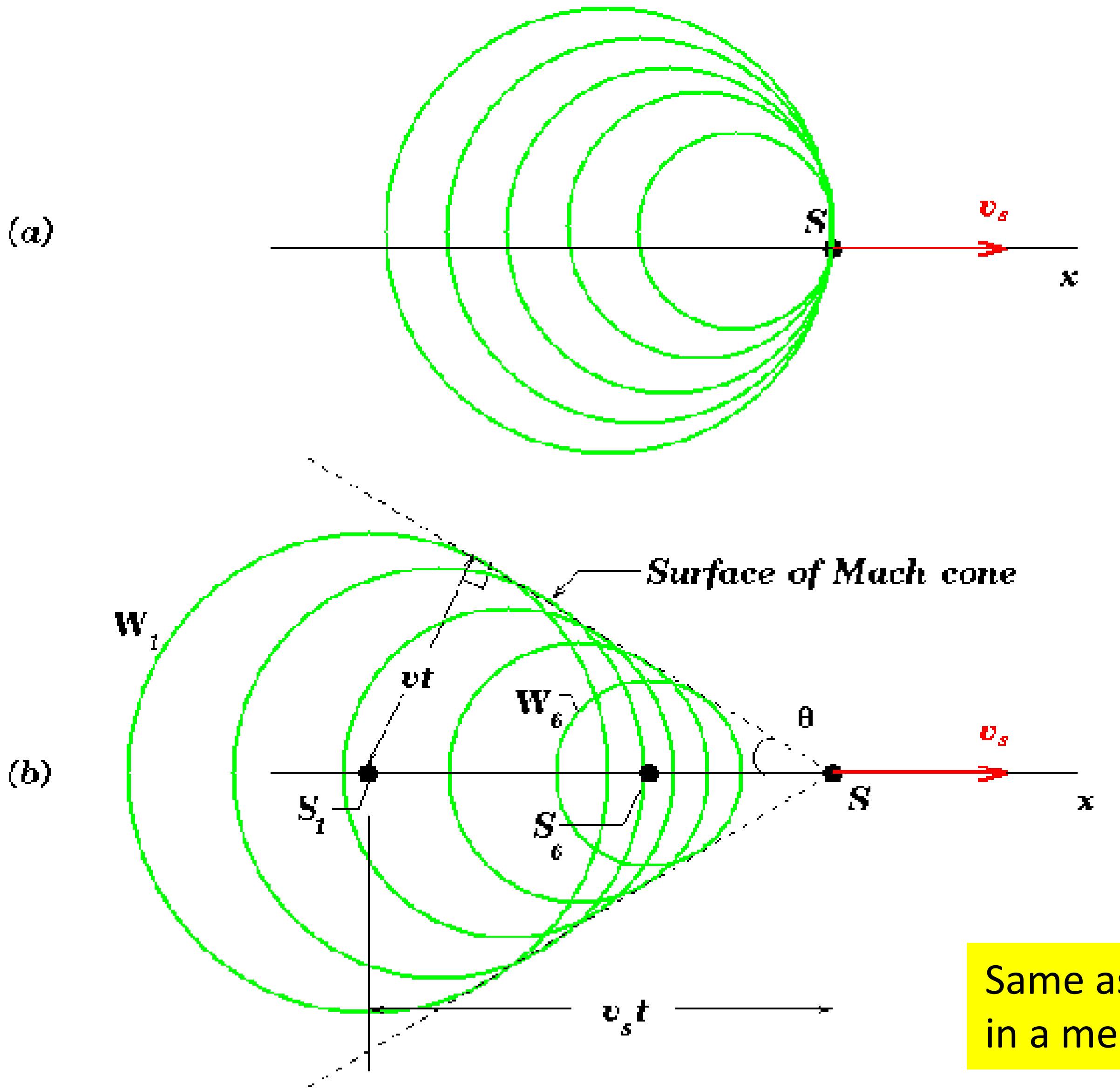
## In conclusions the scintillator technology

- Very mature and reliable
- Well rooted in past experiences
- Crucial for many achievements in neutrino physics
- With a bright future ahead to complete the unveiling of the neutrino properties

# Cherenkov radiation

- ✓ In a material with refractive index n a charged particle emits photons if its velocity is greater than the local phase velocity of light
- ✓ The charged particle polarizes the atoms along its trajectory
- ✓ These time dependent dipoles emit electromagnetic radiations
- ✓ If $v<c/n$ the dipole distribution is symmetric around the particle position and the sum of all dipoles vanishes
- ✓ If $v>c/n$ the distribution is asymmetric and the total time dependent dipole is non null, and thus radiates

# Geometrical Construction of the conical wavefront




Same as sound waves in a medium

# Wavefront animation

The angle is $\cos\theta = \frac{1}{\beta n}$ $\beta$=speed of particle/speed of light

The spectrum has a dependence $\frac{1}{\lambda^2}$ Ultraviolet divergence

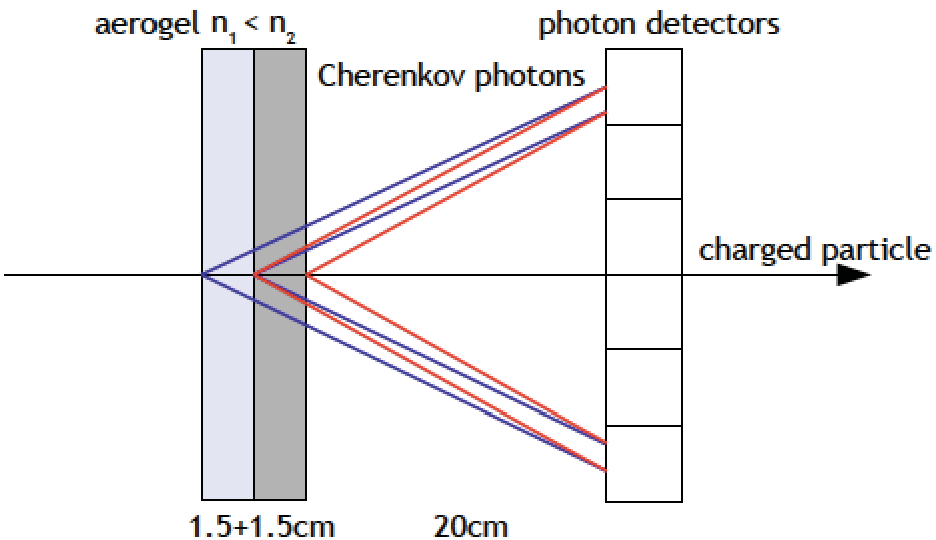
# Practical characteristics

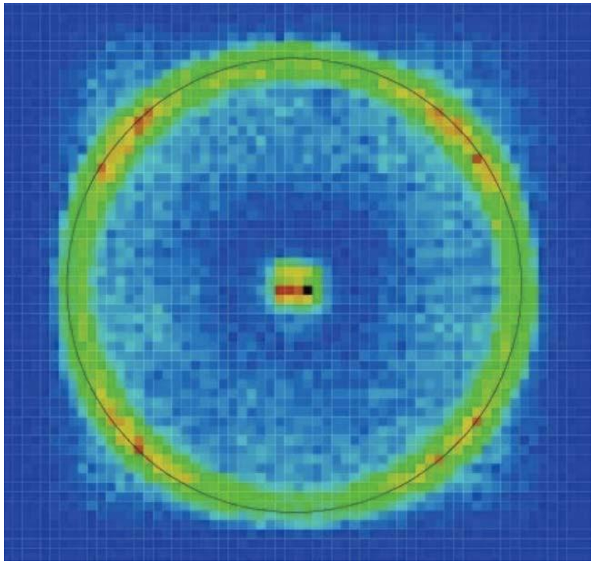
- As in the case of the scintillators the light is observed by photomultipliers, the window performs a low wavelength cut off – bialkali photocatode
- The amount of light is very feeble typically 50-100 time less than that produced by a standard scintillator
- The velocity cut off implies an energy cut off dependent upon the index of refraction, for electrons in water is 0.2 MeV
- The timing of the Cherenkov light is very sharp at picosends level, much shorter than the typical scintillation lifetimes
- The directionality of the Cherenkov light vs the isotropic scintillation light is to kept in mind

# Detection of Cherenkov radiation- **Cherenkov ring**

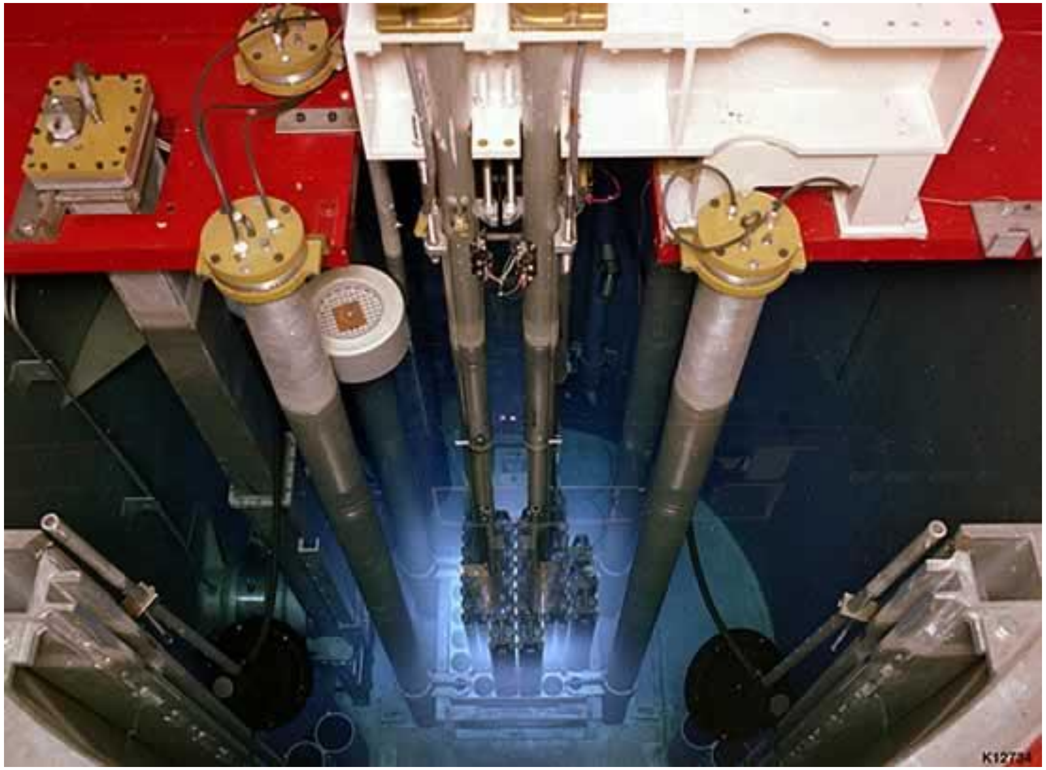
**Parameters of Typical Radiator**

| Medium | n | $\beta_{thr}$ | $\theta_{max}$ [$\beta$=1] | $N_{ph}$ [$eV^{-1}$ $cm^{-1}$] |
|---|---|---|---|---|
| Luft | 1.000283 | 0.9997 | 1.36 | 0.208 |
| Isobutan | 1.00127 | 0.9987 | 2.89 | 0.941 |
| Water | 1.33 | 0.752 | 41.2 | 160.8 |
| Quartz | 1.46 | 0.685 | 46.7 | 196.4 |



# Cerenkov light is produced in a pool reactor where the core is submerged in water



# Class of underground/astroparticle physics detectors based on Cherenkov methodology

Proton decay
IMB
Kamiokande/Super-Kamiokande
IMB and Kamiokande are the detector of the first and so far only detection of Supernova neutrino → share of the 2002 Nobel prize to Kamiokande

Solar Neutrino
Kamiokande/Super-Kamiokande
SNO (Heavy Water)

Accelerator Neutrinos
Kamiokande/Super-Kamiokande as far detectors of the K2K/T2K neutrino beams from the KEK Laboratory (Tokyo)

String underwater/under-ice detectors for UHE astrophysical neutrinos
AMANDA
ANTARES
Icecube
Baikal
KM3NET

SNO @ SNOLAB and Super-Kamiokande @ Kamioka as paradigmatic examples

# The Sudbury Neutrino Observatory: SNO

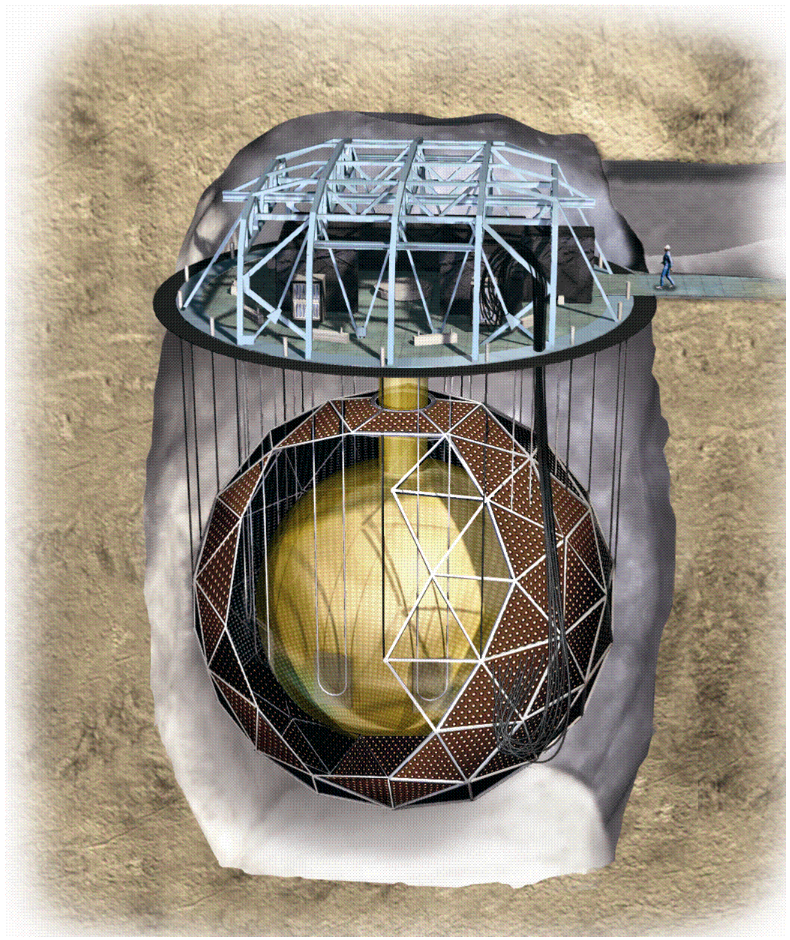
Acrylic vessel (AV)
12 m diameter

1000 tonnes $D_2O$
($300 million)

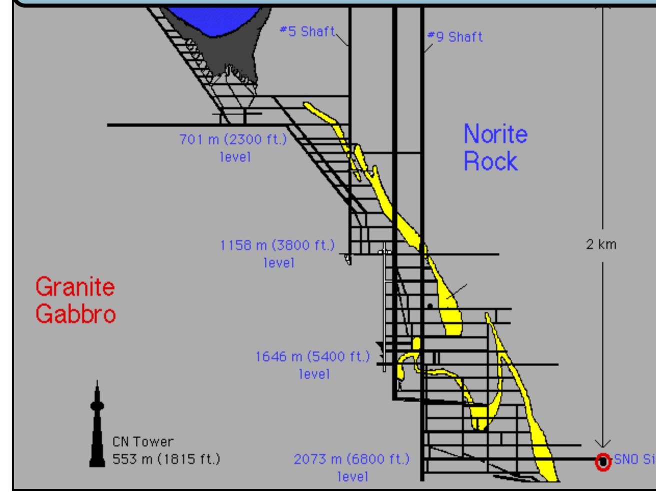
1700 tonnes $H_2O$
inner shielding

5300 tonnes $H_2O$
outer shielding

~9500 PMT's



6800 feet (~2km) underground

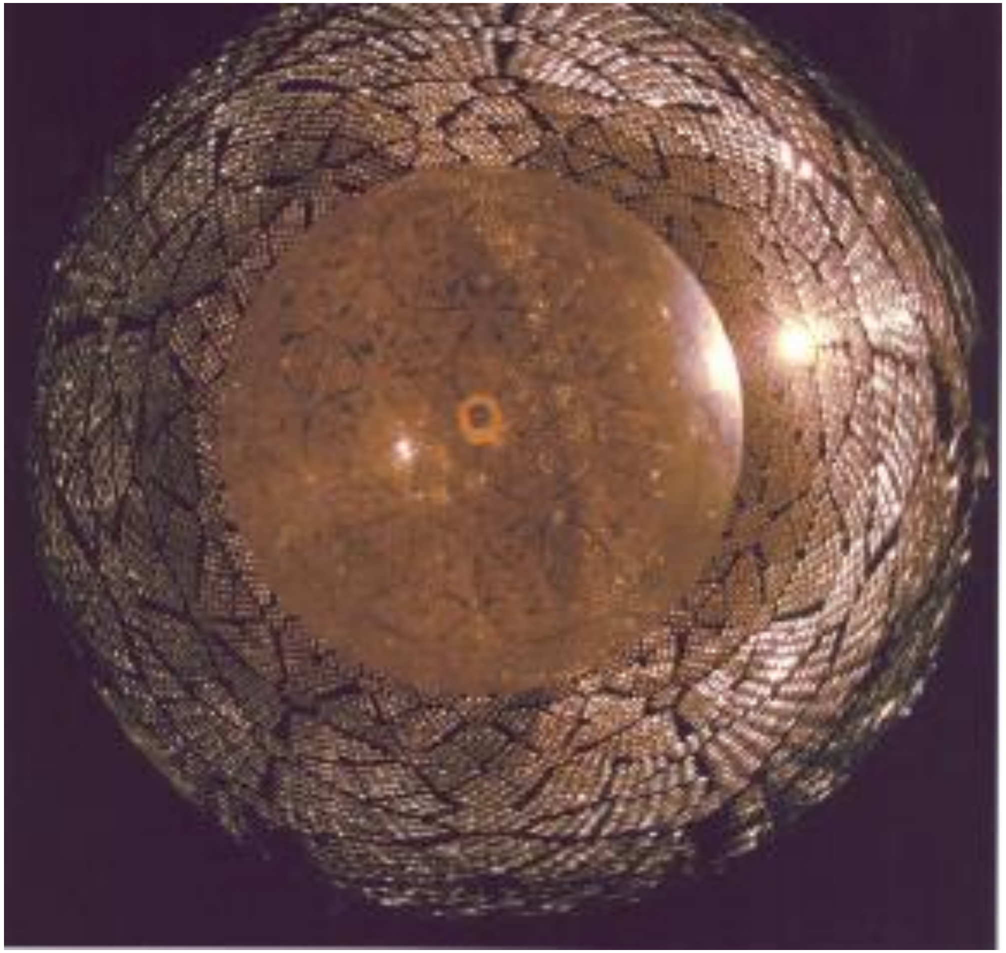



Creighton mine
Sudbury, Ontario, CANADA

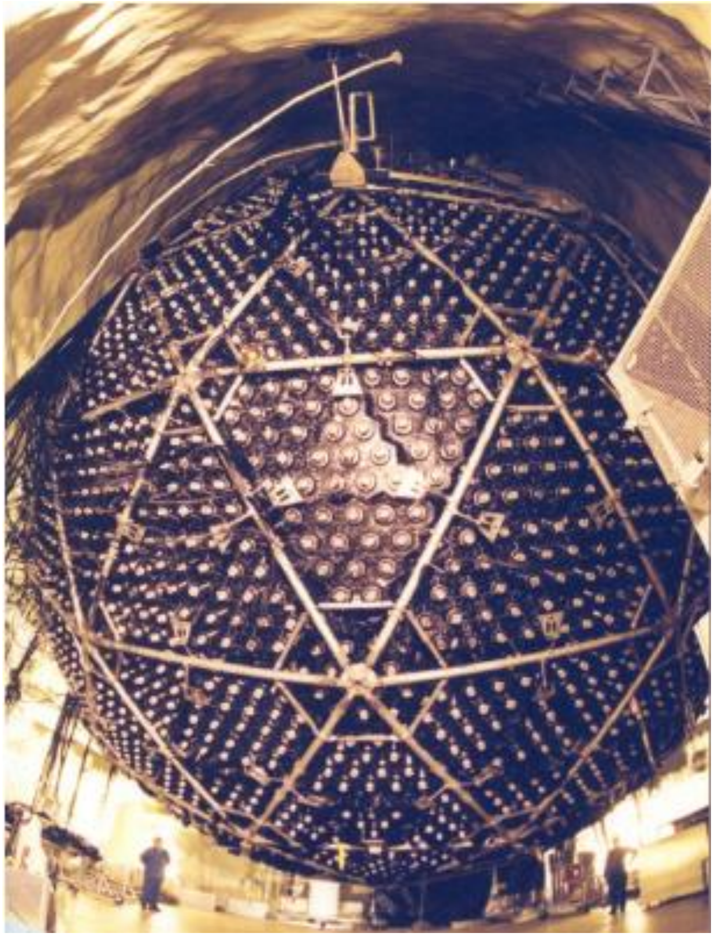
- Entire detector
Built as a Class 2000
Clean room
- Low Radioactivity
Detector materials

Run from 1999 to 2006 - The heavy water has been returned and now replaced with scintillator
→ SNO+ liquid scintillator detector running from few months

# Photomultipliers



Inner view – Acrylic vessel surrounded by the PMT's



Outside view of the PMT's

# Difference and similarity with a liquid scintillator

## Differences

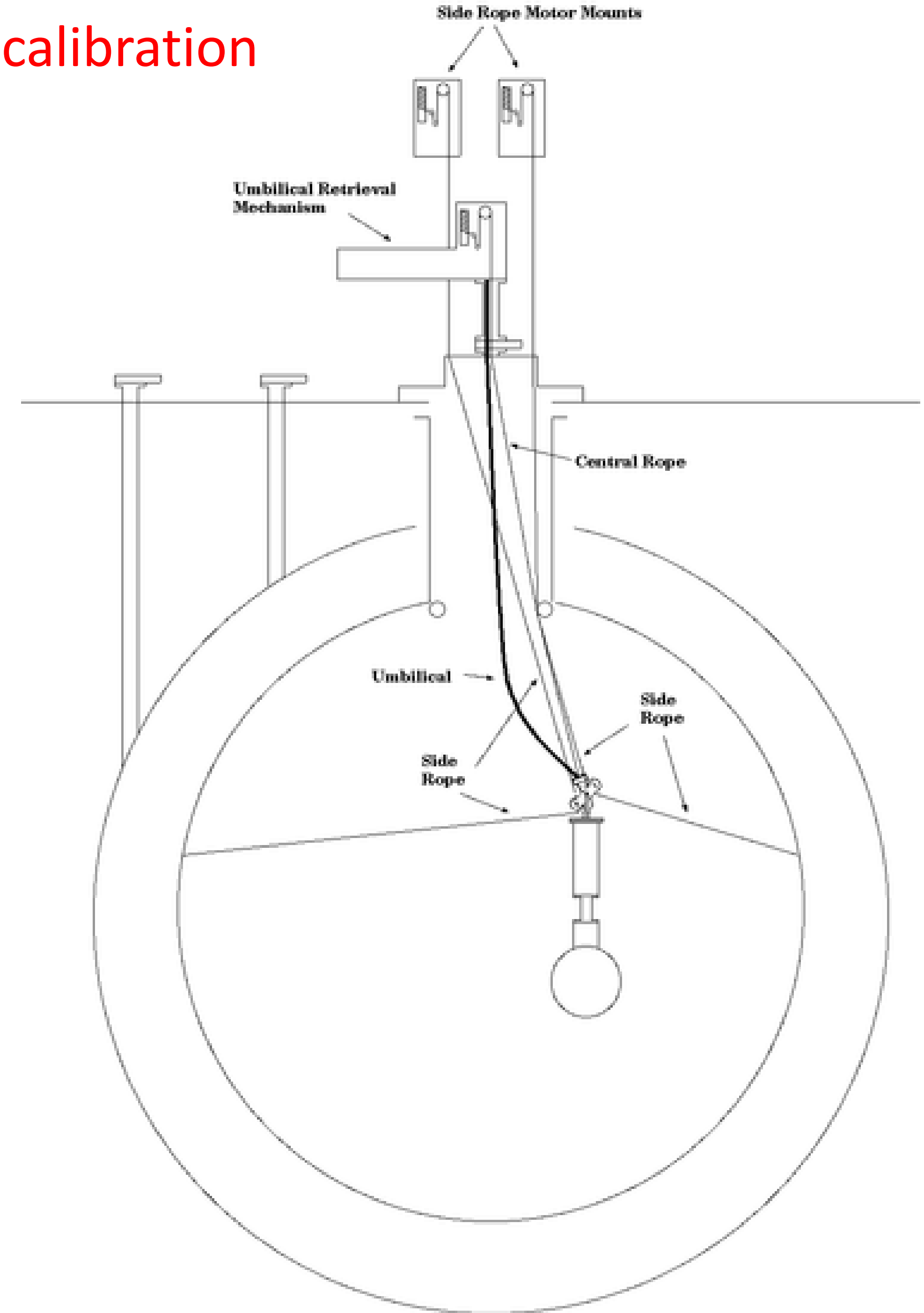
- Lower luminosity and thus higher threshold: the sub-MeV regime is not attainable, practical lower threshold about 3 MeV
- Directionality of the light: the signature is a Cherenkov ring mapped onto the photomultiplier sphere
- Radiopurity: at best water can be purified to the regime of $10^{-14}$ /$10^{-15}$ g/g in terms of $^{238}U$ and $^{232}Th$ and more $^{222}Rn$ at regime
- Attenuation length in water 100 m or even more

## Similarity

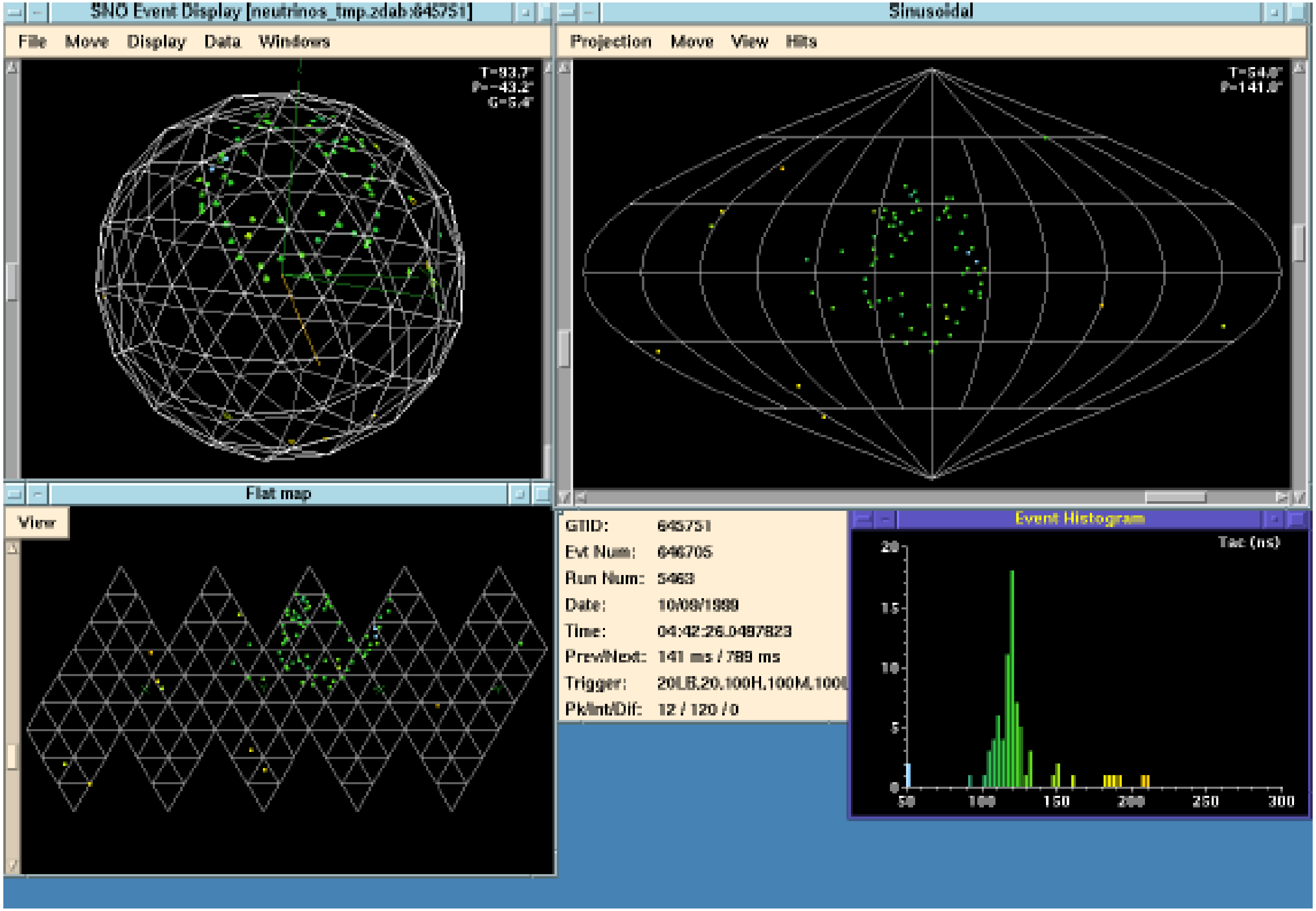
- Same type of phototubes: the bialkali photocathode is matched also to the Cherenkov light
- Same Veto structure: surrounding water instrumented with sparse phototubes to tag the residual muons through the rock overburden
- Electronics measurements: amplitude and timing of the photomultiplier signal or full waveform in modern implementations
- Trigger logic: multiplicity trigger
- Light concentrator: same Winston cone type
- Radiopurity: Rn spikes issue during operations

# Other important similarity: calibration

Accurate measurement of physics processes in the SNO detector requires a chain
of calibrations and calculations to link the
photomultiplier data to a full description of the interaction
in terms of energy, direction, and particle type
Sources deployed everywhere in the detector volume



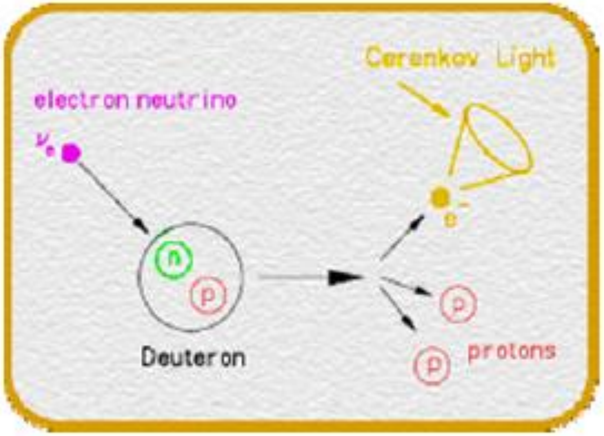
# An example of a Cherenkov event in SNO




Intersection

# Why Cherenkov implementation with heavy water in SNO

Context : solar neutrino problem i.e. less than expected neutrinos detected from the Sun – originally produced as $\nu_e$ in the Sun's core




Idea: independent measurements of

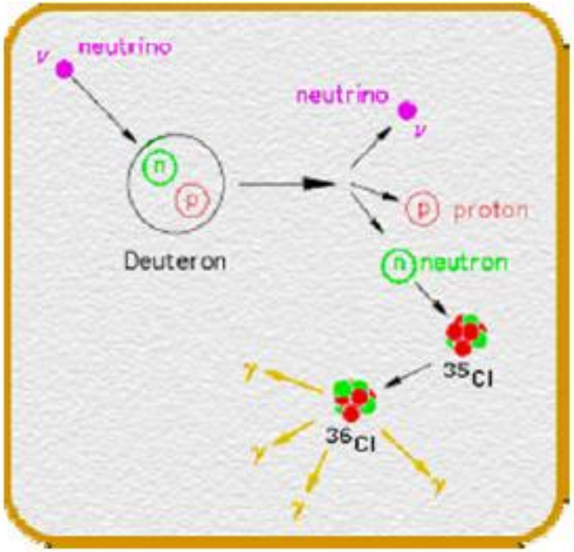
- the flux of electron neutrinos
- the cumulative flux of muon and tau neutrinos

The latter should be zero unless there is flavor conversion en-route from Sun to Earth

Three reactions

Charged current reaction ($e^-$ flavor specific)

$\nu_e + d \rightarrow p + p + e^-$ Cherenkov light from $e^-$




Neutral current reaction (flavor insensitive)

$\nu_x + d \rightarrow p + n + \nu_x$ Cherenkov light from $\gamma$ capture

n capture on

1. deuterium - phase 1
2. on Salt - phase 2
3. with $^3$He counters - phase 3

# What came out for solar neutrinos

By comparing the
The charged current $\rightarrow n_e$ flux
The neutral current $\rightarrow n_e + n_\mu + n_\tau$ flux

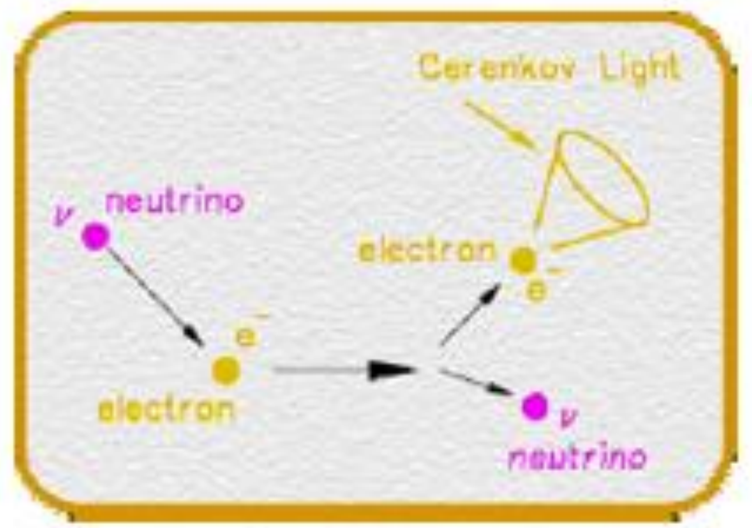
The former resulted about 1/3 of the latter!

Proof of the flavor conversion as solution of the solar neutrino problem

Solution to a puzzle lasted more than 30 years

$\rightarrow$ Share of 2015 Nobel prize

# A third reaction




Electron scattering

$e^- + \nu_x \rightarrow e^- + \nu_x$

All flavors with different cross sections

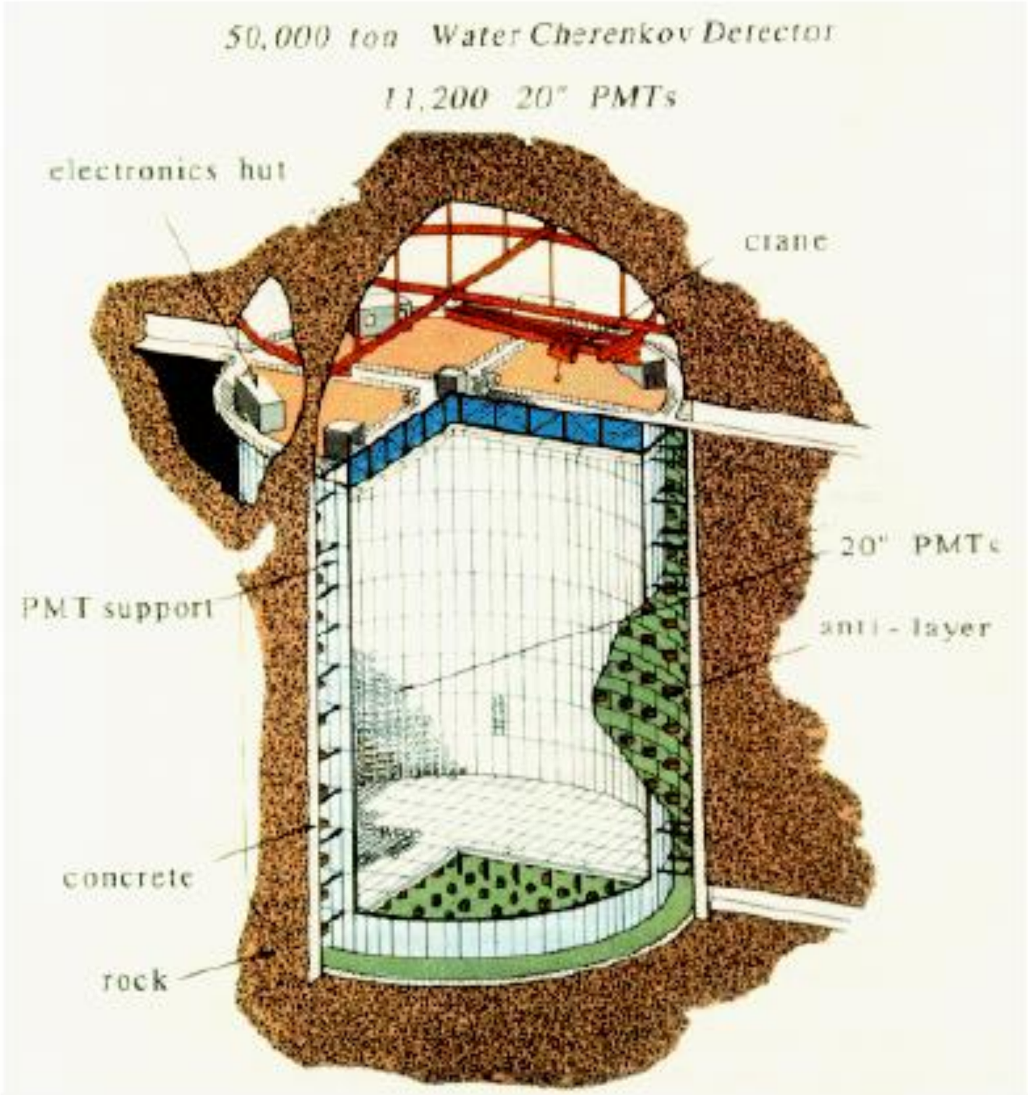
The same as in the liquid scintillator and also in normal water

The only reaction in Kamiokande/Super-Kamiokande

Important feature $\rightarrow$ the scattered electron retains the directionality from the Sun

Superkamiokande artistic view

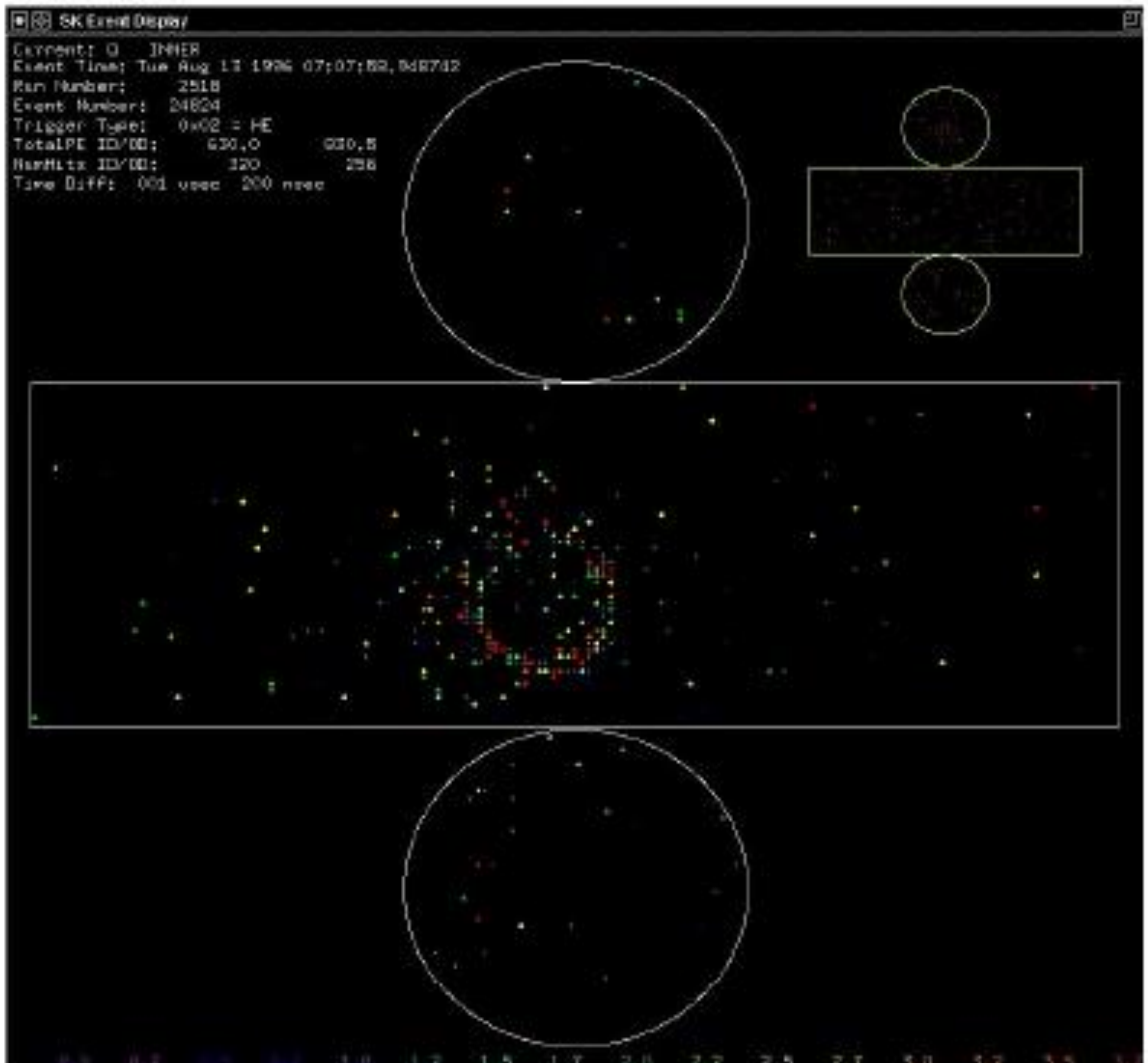
Other example of Cerenkov detector




**Detection via *ve* scattering as third detection method in SNO**

# Example of Cerenkov ring

Solar neutrino – energy around few MeV

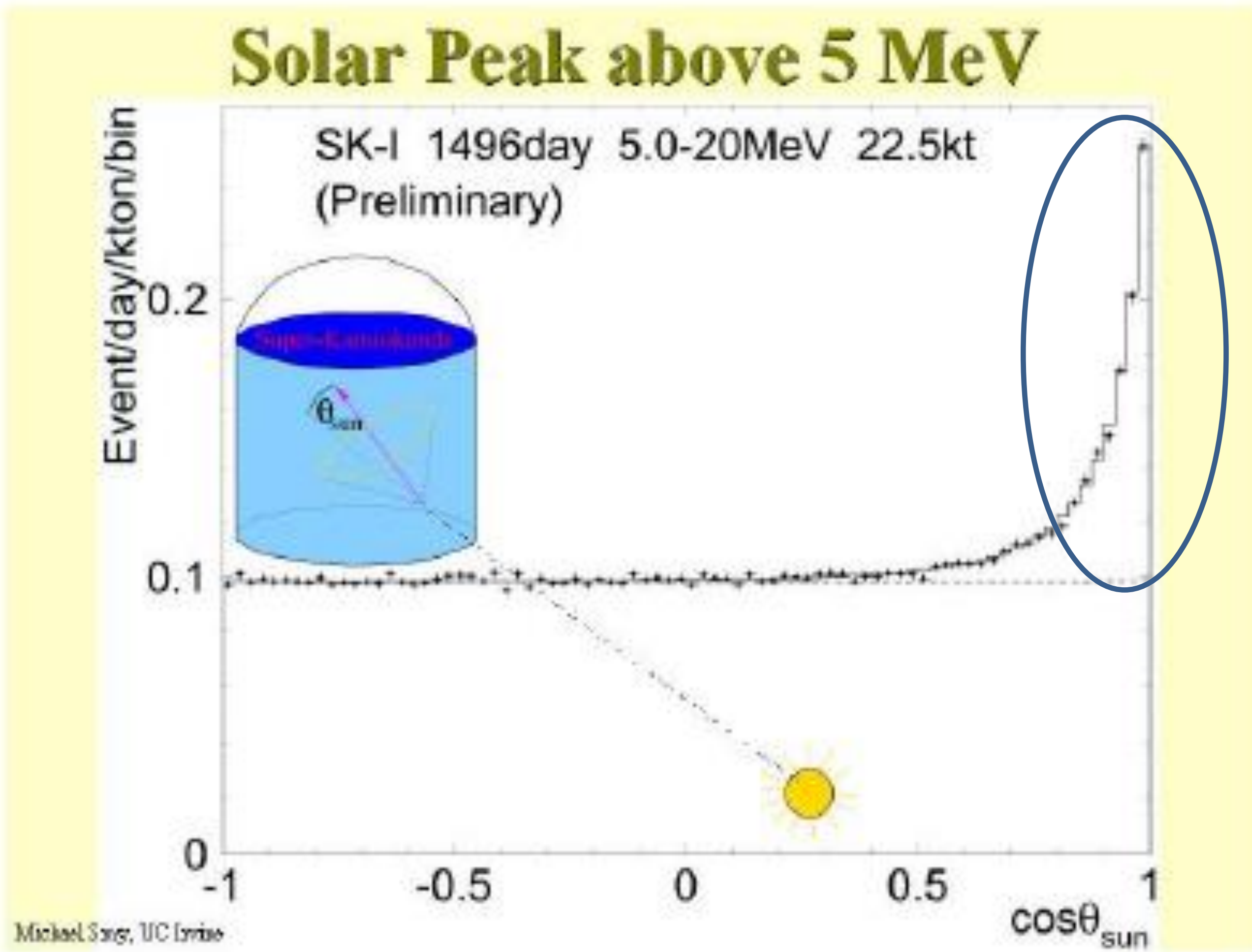


# How to exploit the Cerenkov light directionality

With this capability Kamiokande and Super-Kamiokande contributed to the assessment of the solar neutrino problem

Background level

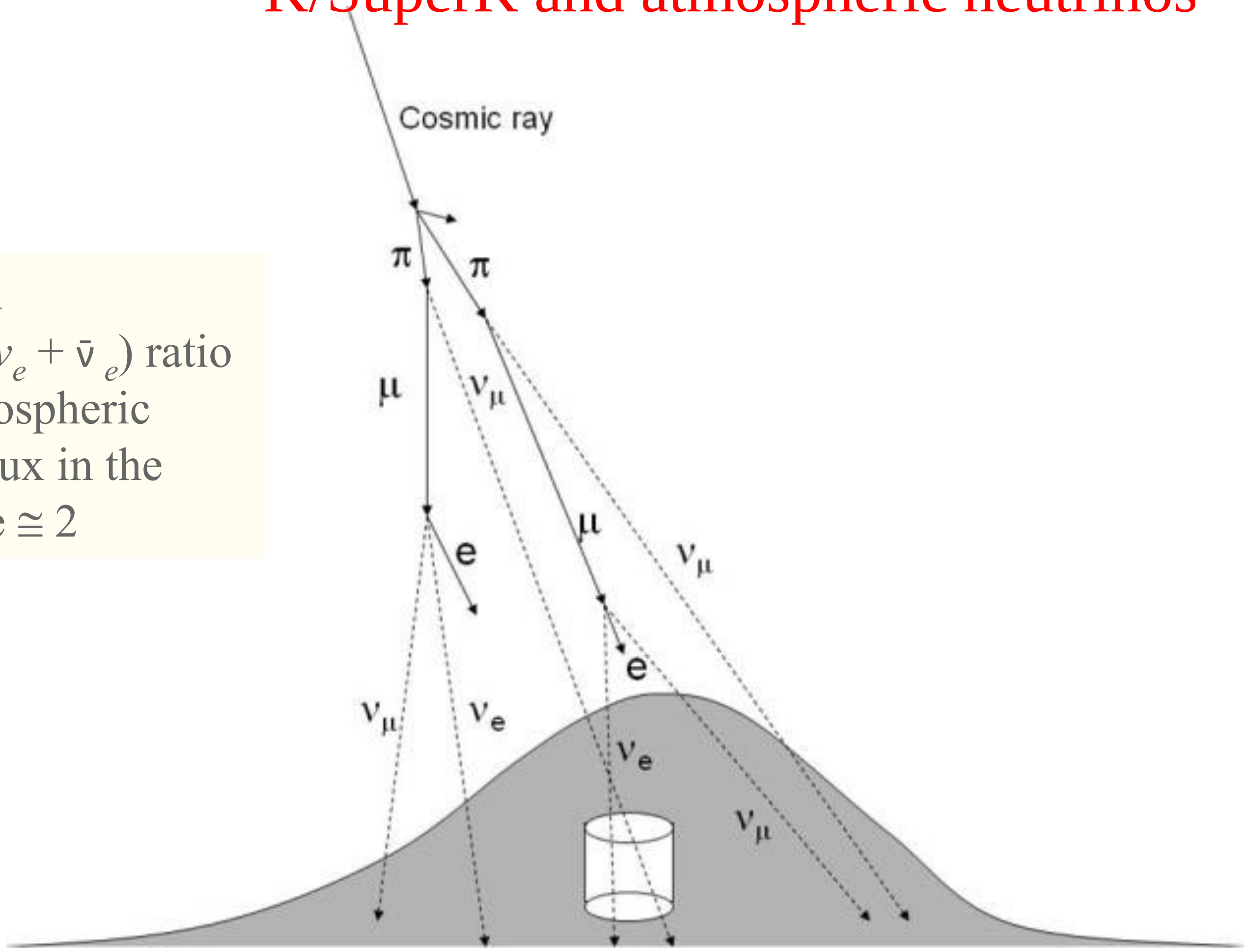
Mainly Radon




Solar signal peak -> less demanding requirement than a scintillator for background

# K/SuperK and atmospheric neutrinos

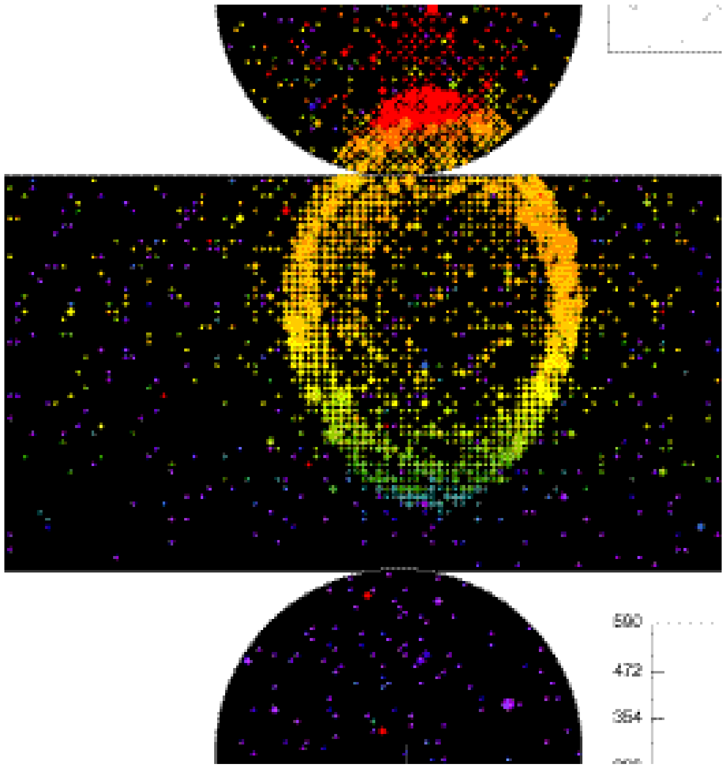
Calculated $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio of the atmospheric neutrino flux in the GeV range $\cong 2$



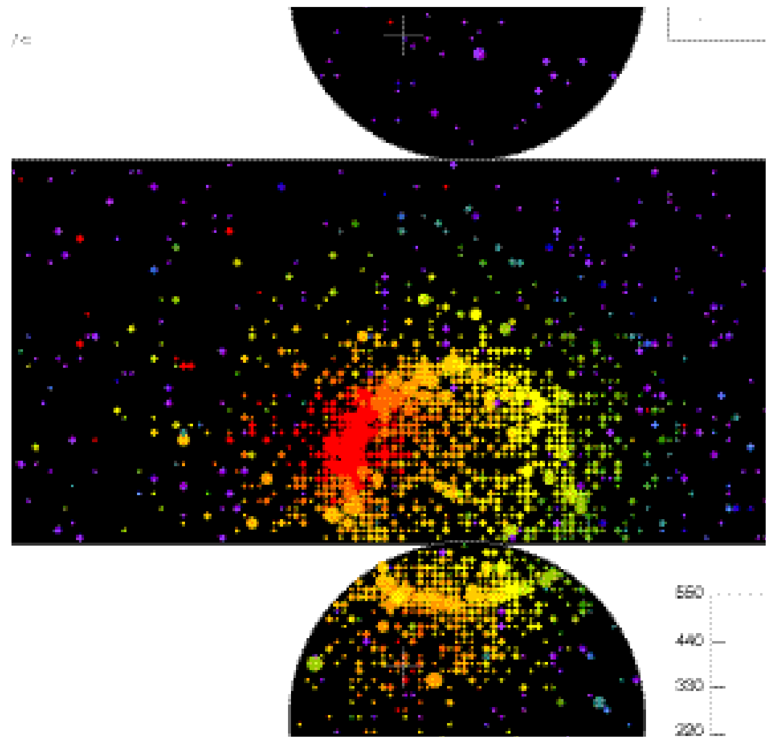

Production of neutrinos by cosmic-ray interactions with the air nuclei in the atmosphere. The typical height of the neutrino production is 15 km above the ground

- $\nu_e$ and $\nu_\mu$ distinguishable - different features of corresponding Cherenkov rings: defined $\rightarrow \nu_\mu$ fuzzy $\rightarrow \nu_e$
- Kamiokande (88) & IMB (92) (also Cherenkov) found the above ratio lower $\rightarrow$ birth of the atmospheric neutrino anomaly
- Actually careful comparison between data and several accurate model predictions

# The rings




1 ring μ-like




1 ring e-like

Tens of GeV energy region

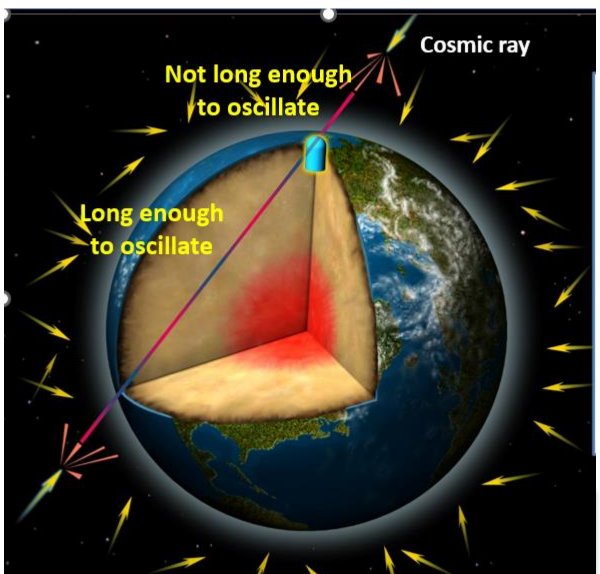
# Discovery of Atmospheric Neutrino Oscillations

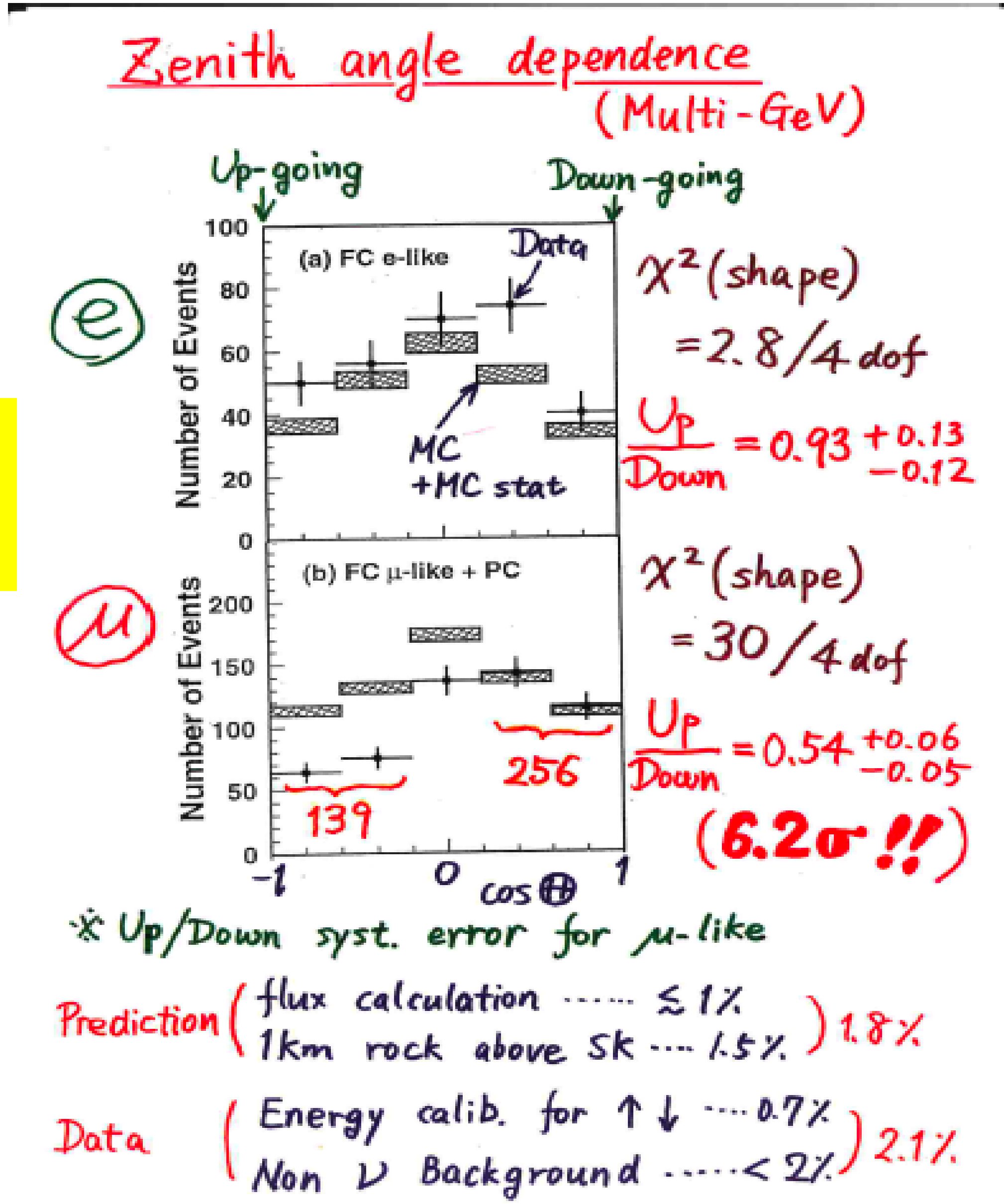
Consistent indications from Macro and Soudan-2

- Neutrino 1998,

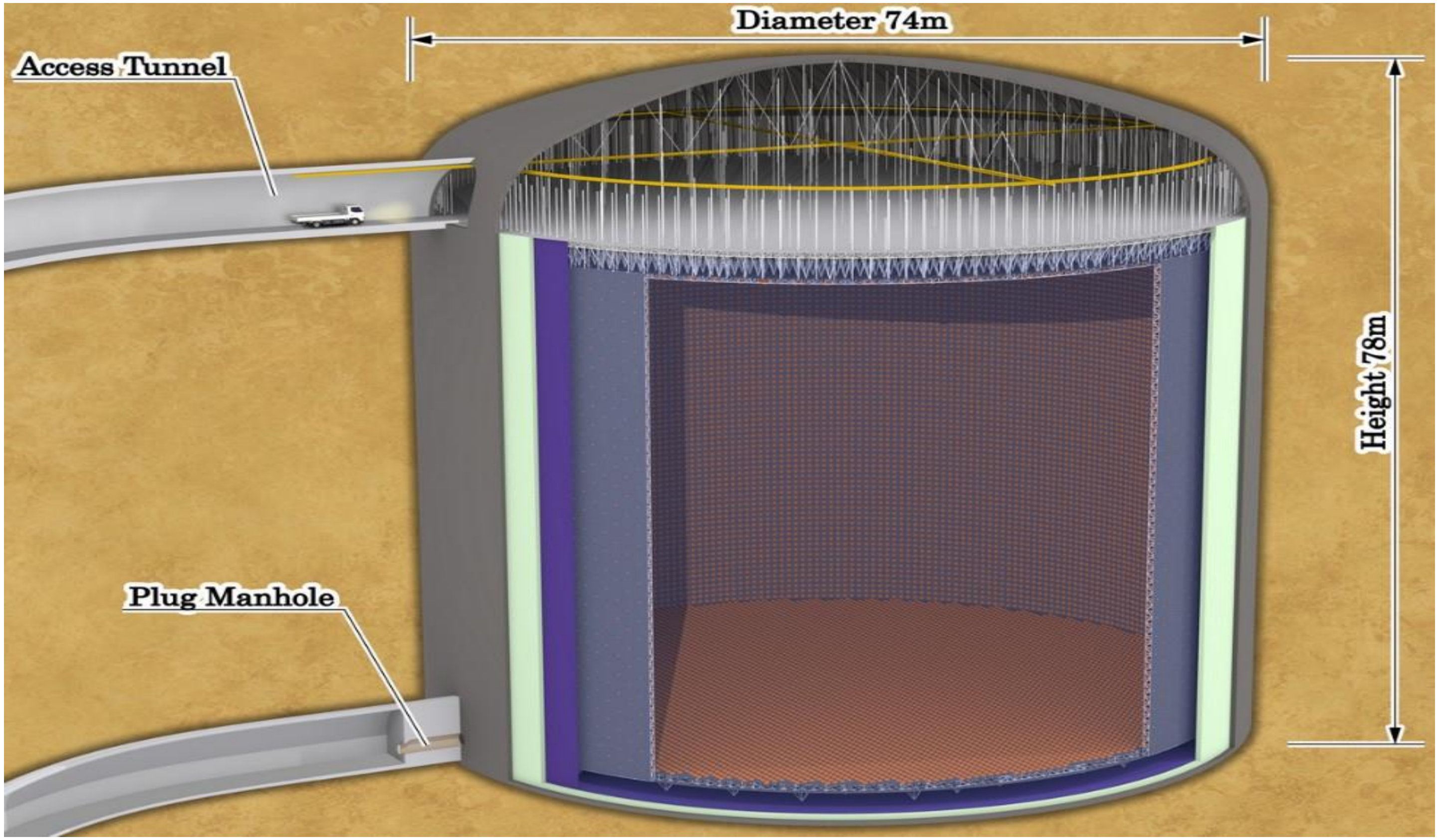
Takayama, Japan

$\nu_\mu$ oscillates along the path in Earth, too short for $\nu_e$ oscillation - they oscillates on a Earth-Sun like distance



# A 4 decades old tradition that will go ahead still for many years

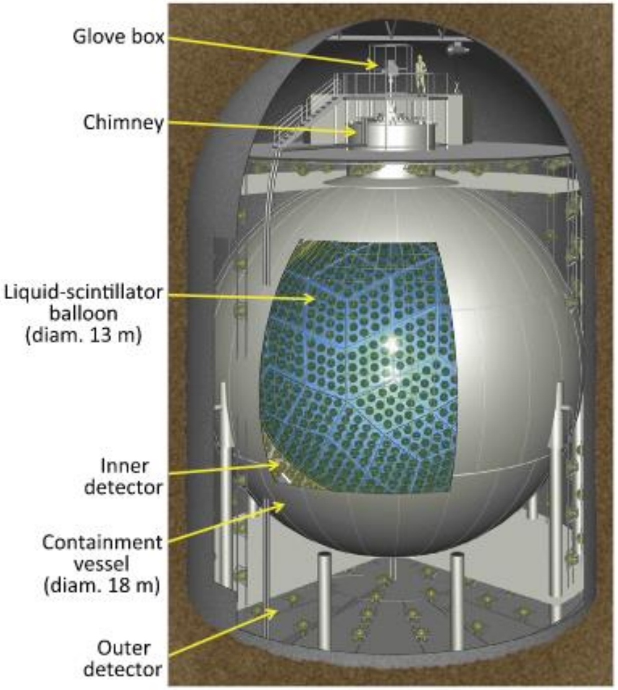



Hyperkamiokande 250 kton of water – start up date planned for 2027

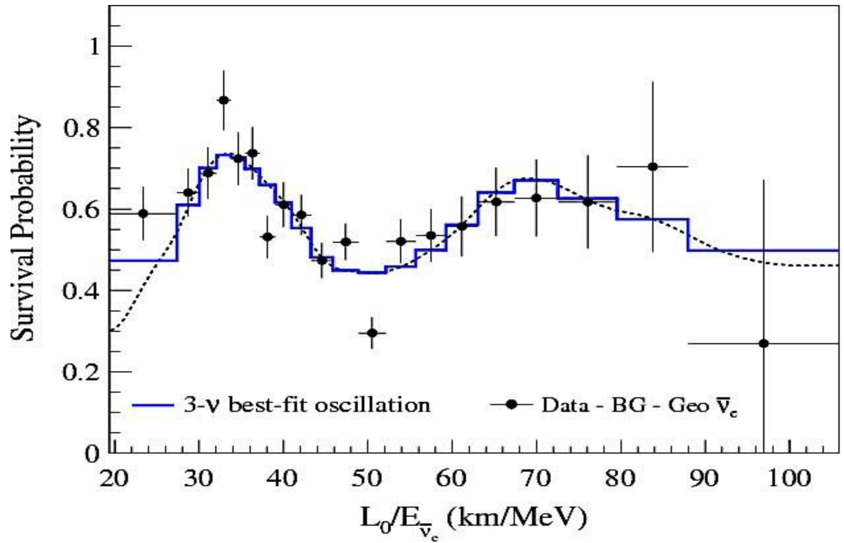
# Synergy for a Noble prize

Super-Kamiokande alone proved the neutrino oscillation in the atmospheric sector

- SNO proved that in the solar neutrino sector the origin of the solar neutrino problem was the flavor conversion effect - but not the mechanism behind it
- Other explanations for the flavor conversion beyond the neutrino oscillation were still viable when SNO presented its results
- It was the liquid scintillator experiment detecting neutrinos from reactor KamLAND that proved definitively the neutrino oscillation origin of the flavor conversion observed by SNO




L/E Oscillatory signature with reactor neutrinos → smoking gun of the oscillation mechanism



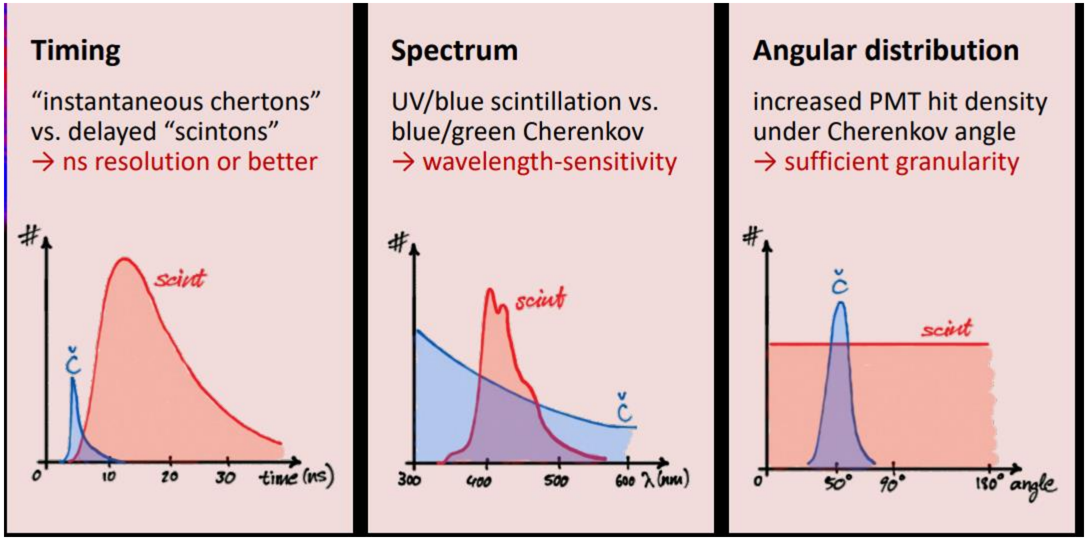
# The next technological frontier Hybrid Cherenkov/Scintillation Detectors

To couple the best features of both

→ The lower threshold of the scintillation detectors
→ The directionality and larger transparency of the Cherenkov detectors

Vigorous R&D push for Water based Liquid scintillators – In a standard LS there is a 5% contribution of Cherenkov light

Purpose is to resolve the concurrent Cherenkov/scintillation signals to exploit them both at best in the overall analysis

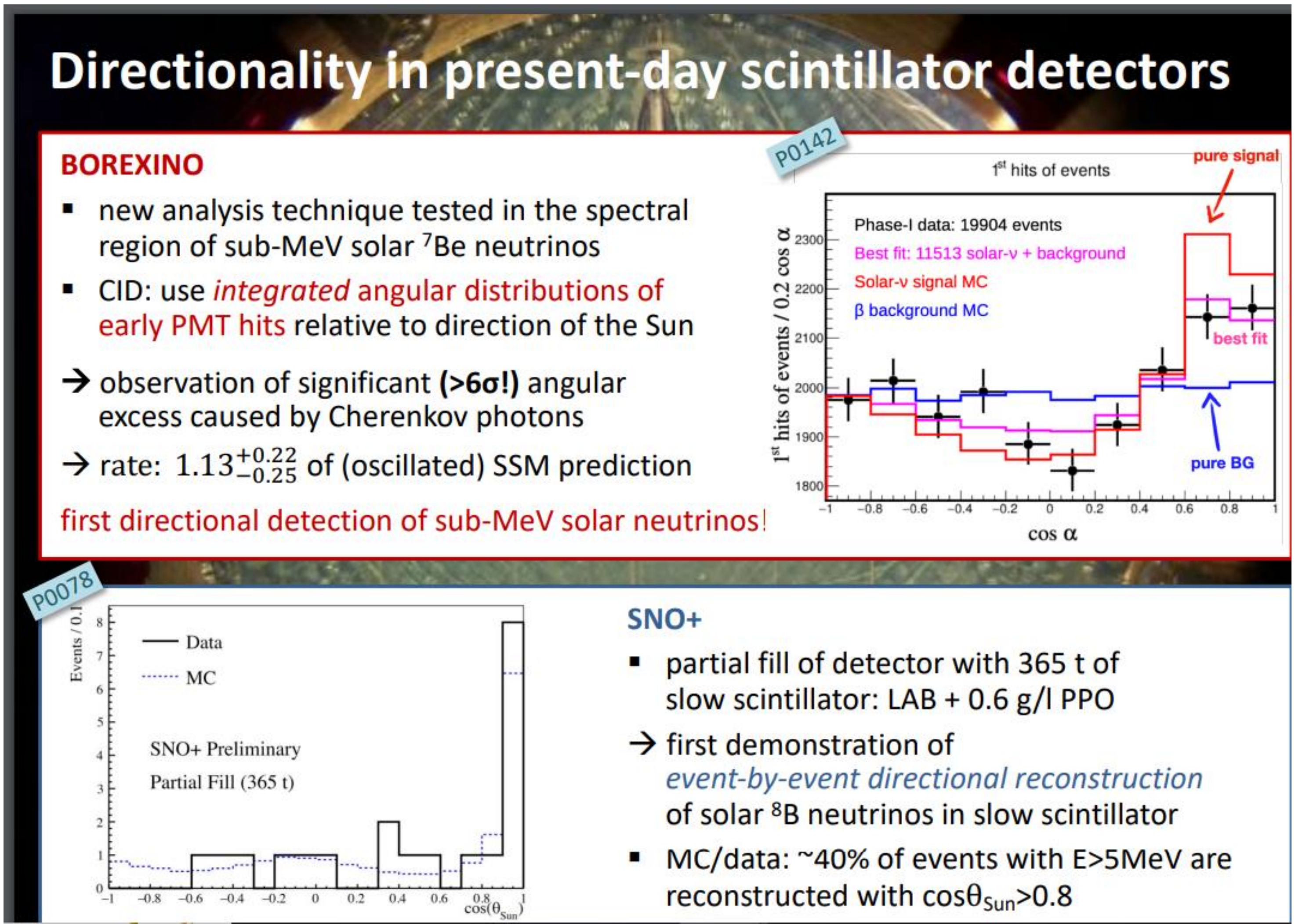


# A very active research field

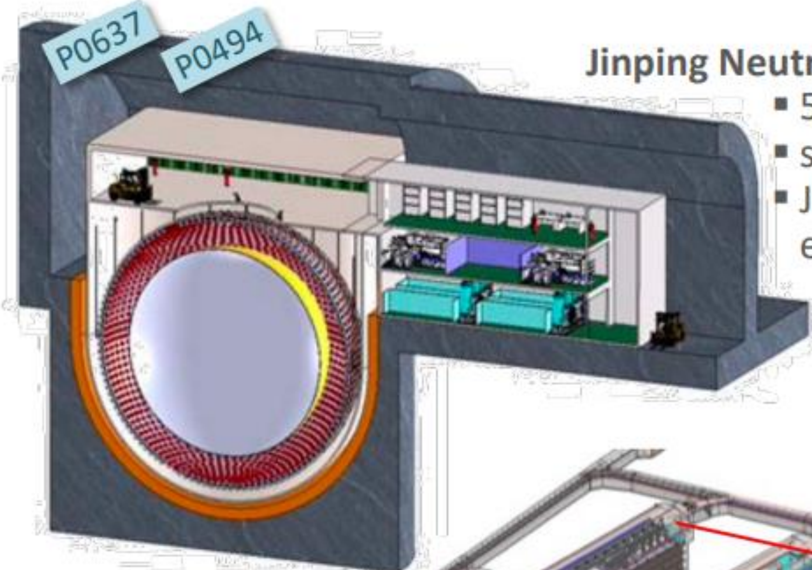
Several R&D table top set-ups

Ton scale demonstrators ANNIE/SANDI @FERMILAB - Jinping 1 ton @Jinping - EOS @ UC Berkeley

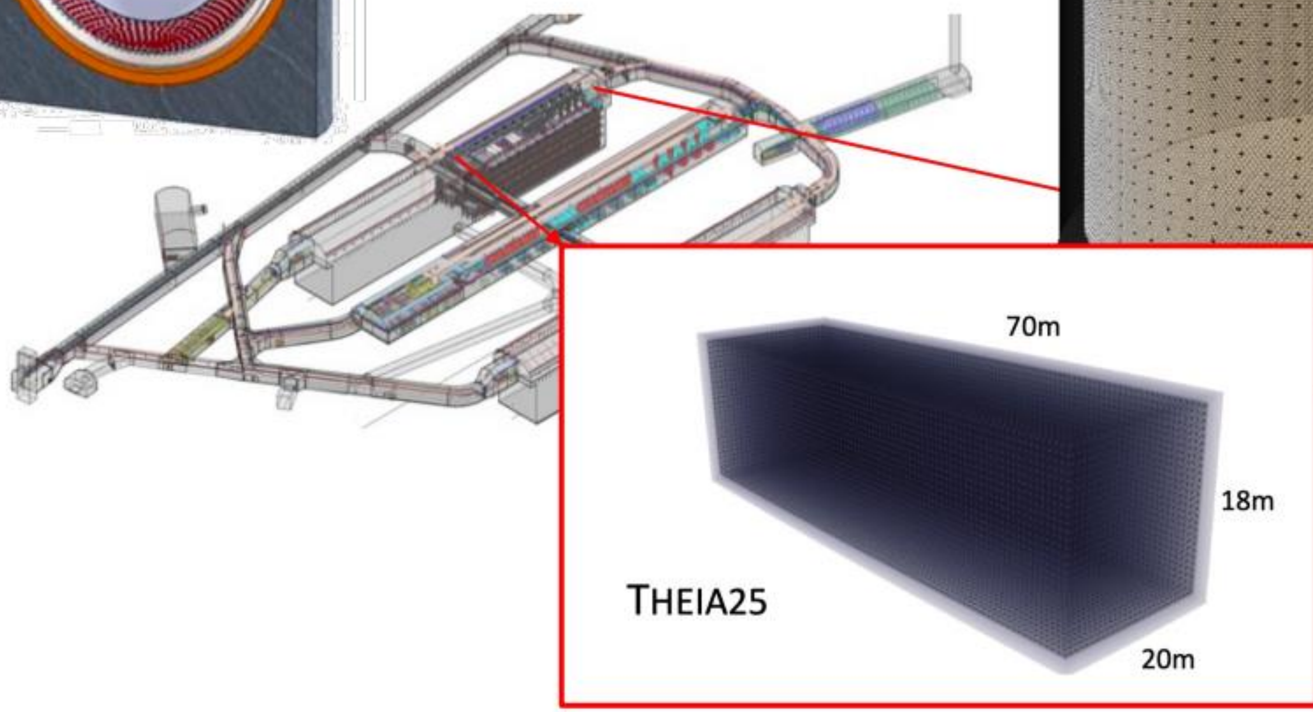
And



# Future Large-Scale Hybrid Detectors




**Jinping Neutrino Experiment**
- 500t → 4kt
- slow scintillator
- Jinping lab >> excellent shielding


**Theia**
- 25kt/100kt
- water-based LS
- SURF >> LBNF
- several stages

# Conclusion

Cherenkov and liquid scintillator techniques since the 50's proved to be essential tools for the realization of powerful, flexible and effective underground experiments in the context of neutrino investigation

From the first antineutrino detection on they have been pivotal to unveiling the properties of this elusive particle, as well as of the natural sources from which they come, in case of non man-made beams

The discovery of the neutrino oscillation phenomenon was their huge breakthrough $\rightarrow$ first indication of BSM physics

And Scintillator and Cerenkov methodologies will continue to play a fundamental role in the next research frontiers with gigantic detectors focused to study a plurality of neutrino sources of natural and artificial origin

Therefore, with a bright perspective ahead, both technique will continue to dominate the field for the foreseeable future