# Solar neutrinos: present and future

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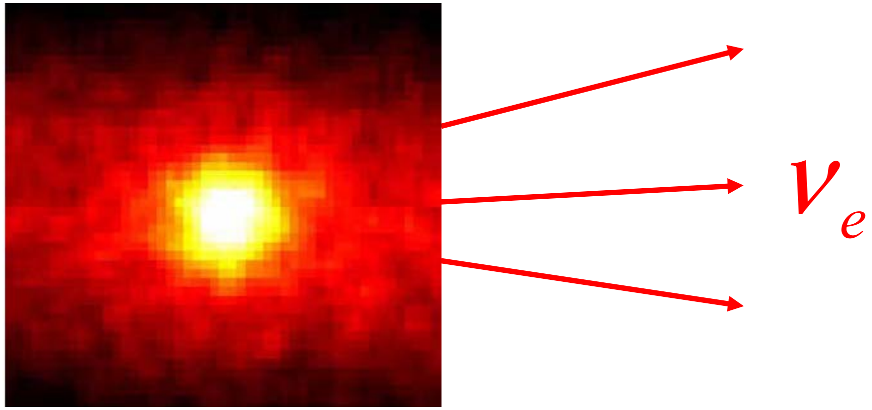
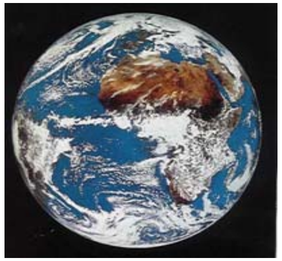
# Outline of the talk

- Solar neutrinos
- Present status
- Upcoming new measurements
- Ideas for the future
- Outlook

# The Sun: a huge close by source of neutrinos and a UNIQUE opportunities for neutrino physics and astrophysics



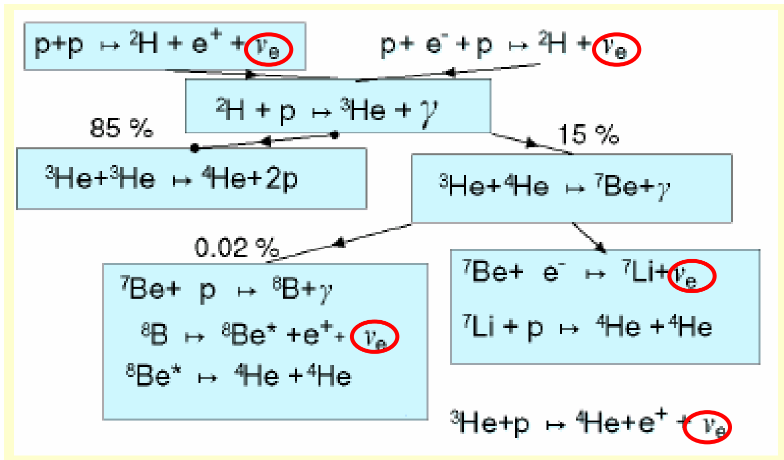



**$4p + 2e^- \rightarrow \alpha + 2\nu_e + Q$**

**(Q=26.7 MeV)**

**$I_\nu = 2L/Q$ ($L=2.4\ 10^{39}$ MeV/s)**

**$\phi_\nu = 6.4\ 10^{10}\ cm^{-2}\ s^{-1}$ (on Earth)**

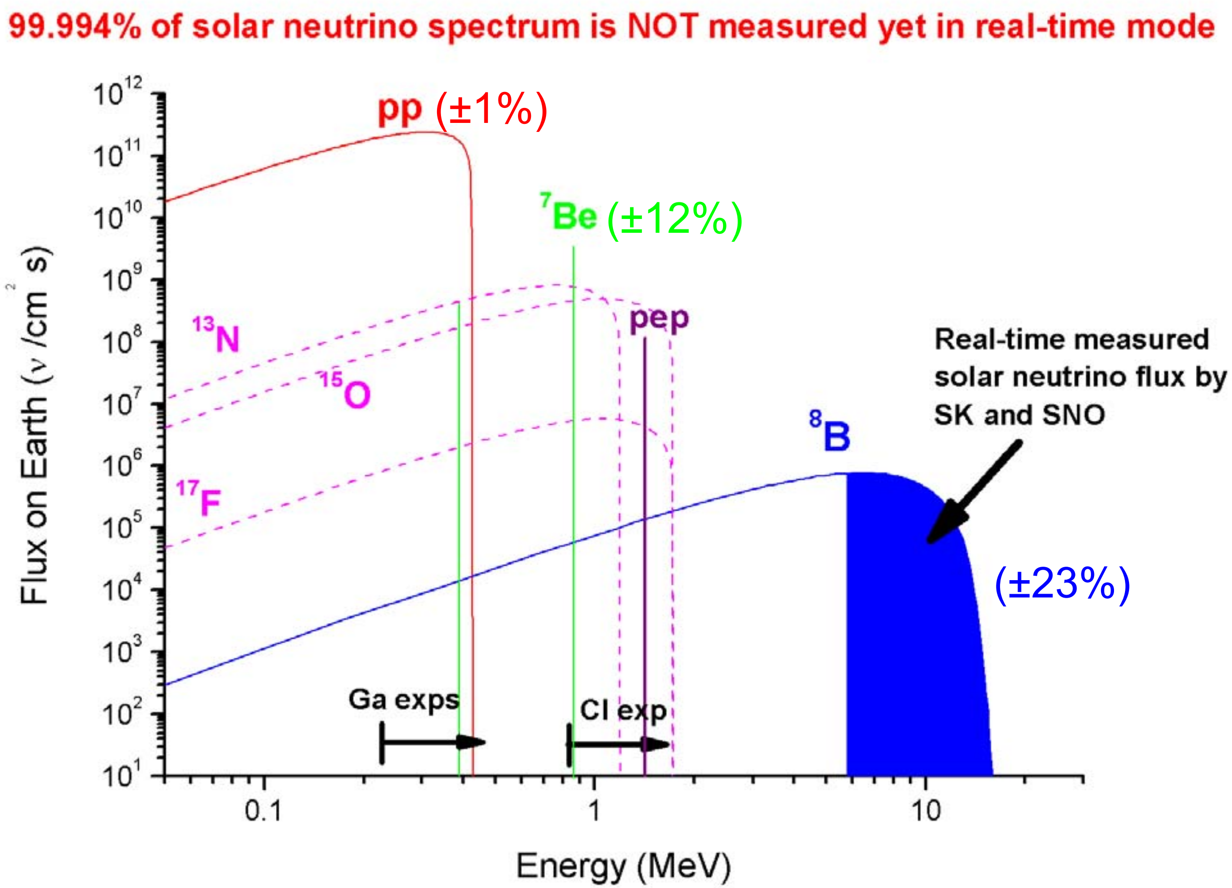


# Observations of solar neutrinos

| Experiment | Type | Thres. (MeV) | | | Started | Status |
|---|---|---|---|---|---|---|
| | | ES | CC | NC | | |
| Homestake(Cl-Ar) | Radioch. | | 0.814 | | 1968 | stopped |
| Kamiokande | Cherenk. | 7.0 | | | 1985 | stopped |
| SAGE | Radioch. | | 0.233 | | 1990 | running |
| GALLEX | Radioch. | | 0.233 | | 1991 | stopped |
| Super-Kamiokande | Cherenk. | 5.0 | | | 1996 | running* |
| GNO | Radioch. | | 0.233 | | 1999 | stopped |
| SNO | Cherenk. | 5.0 | 5.0 | 5.0 | 1999 | running |

*stop for full reconstruction work after 2001 incident in Nov. 2005, resume activity in Jun. 2006

# Solar neutrinos: spectrum on Earth



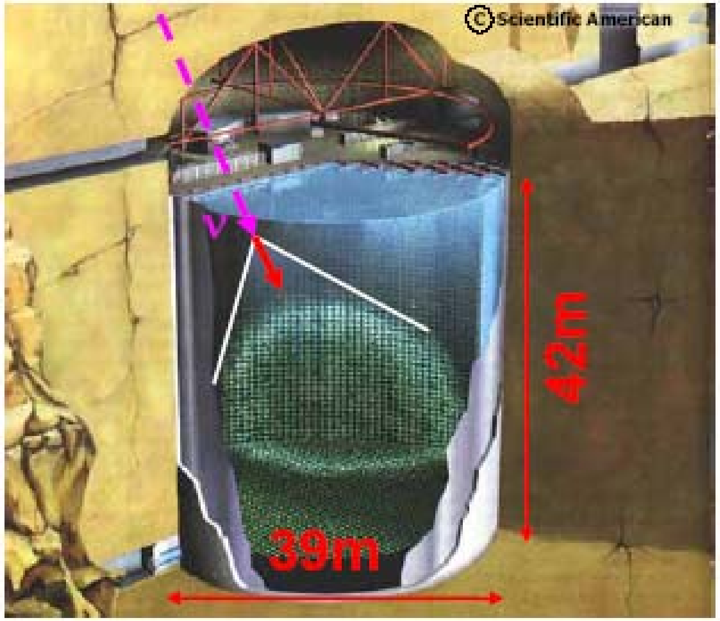
# Solar neutrinos in real time at present

- **SuperKamiokande**

- **SNO**

# SuperKamiokande

- 50kton of $H_2O$ [22.5kton FV]
- 1000 underground
- Inner Detector: 11,146 PMTs 50cm with 40% coverage
- Outer Detector: 1,885 PMTs 20cm



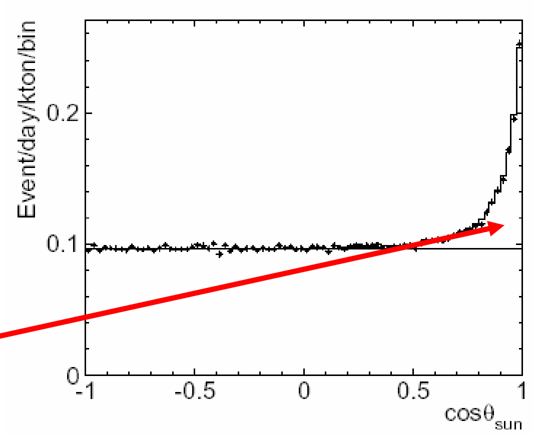

•$^8$B solar neutrino measurement by ($E_e$>5 MeV)

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

•directionality

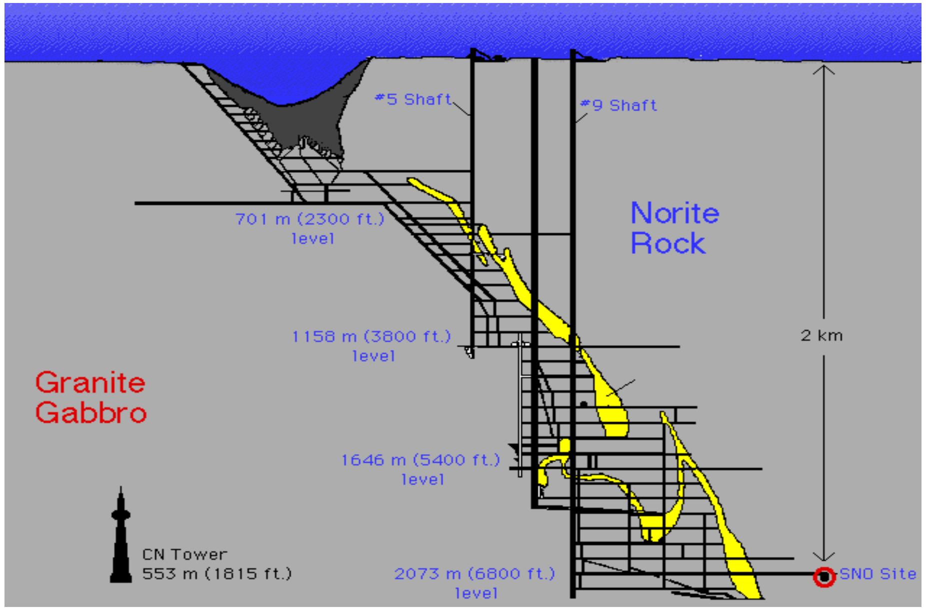
•Real time meas. 15 events/day

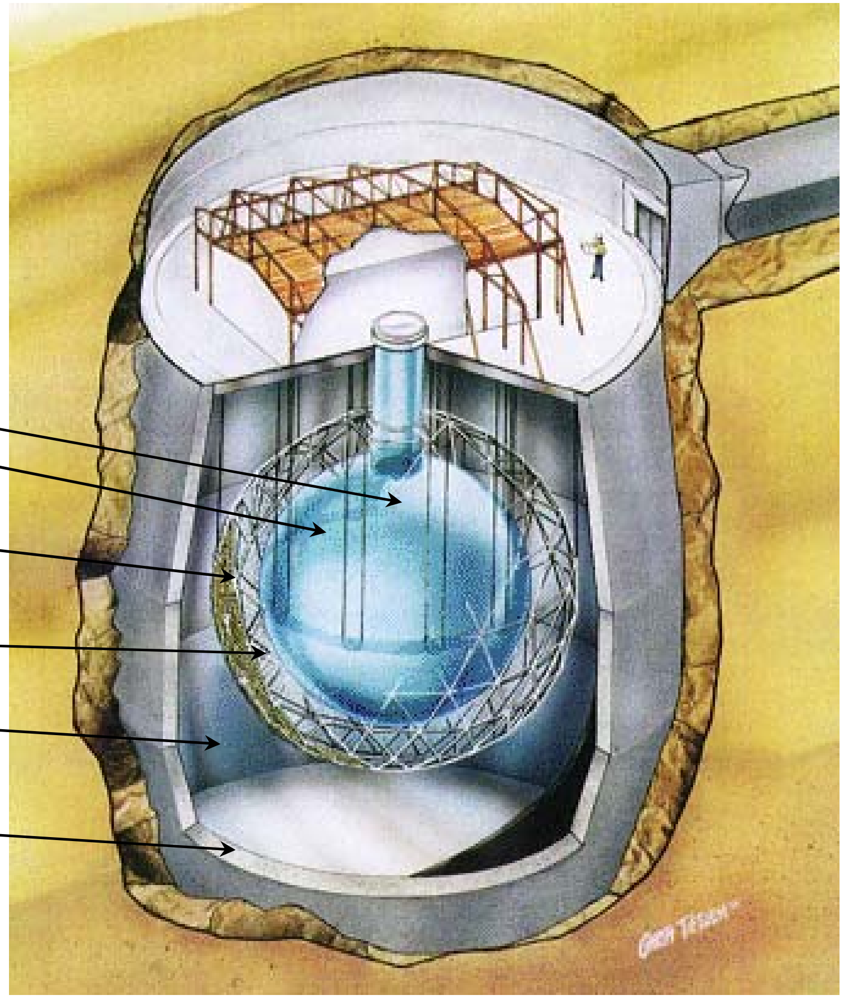
•sensitivity to all flavours: $\sigma(\nu_{\mu(\tau)} + e^-) \sim 0.15\ \sigma_{\nu e}$




22385±230 solar neutrino events in 1496 days

# Sudbury Neutrino Observatory



1000 tonnes $D_2O$

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding $H_2O$

5300 tonnes outer shielding $H_2O$

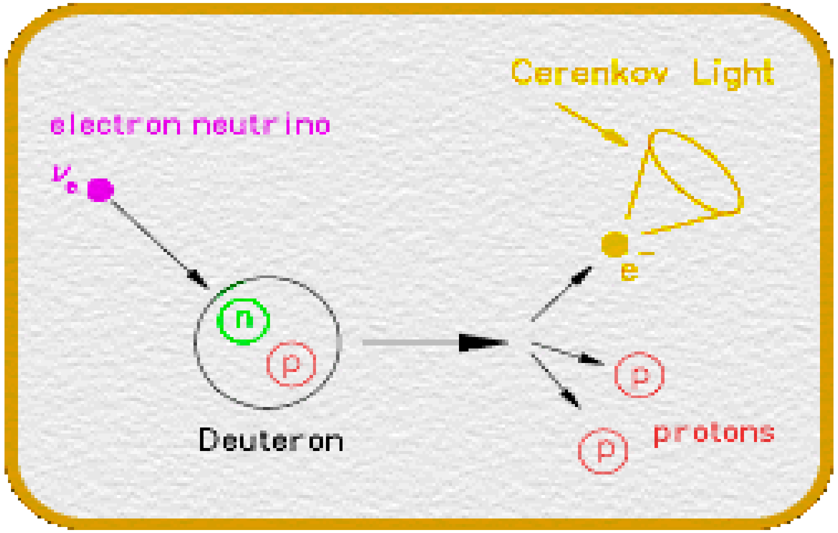
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 μ/day

# Neutrino Reactions in SNO

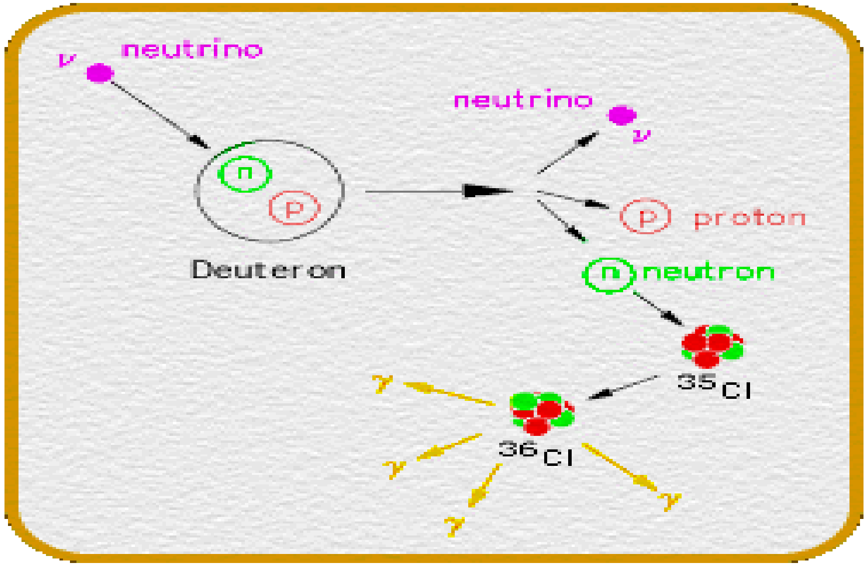
**CC** $\nu_e + d \rightarrow p + e^- + p$

- Q = 1.445 MeV
- good measurement of $\nu_e$ energy spectrum
- some directional sensitivity ∝ ( – 1/3 cosθ)
- $\nu_e$ only




**NC** $\nu_x + d \rightarrow p + n + \nu_x$

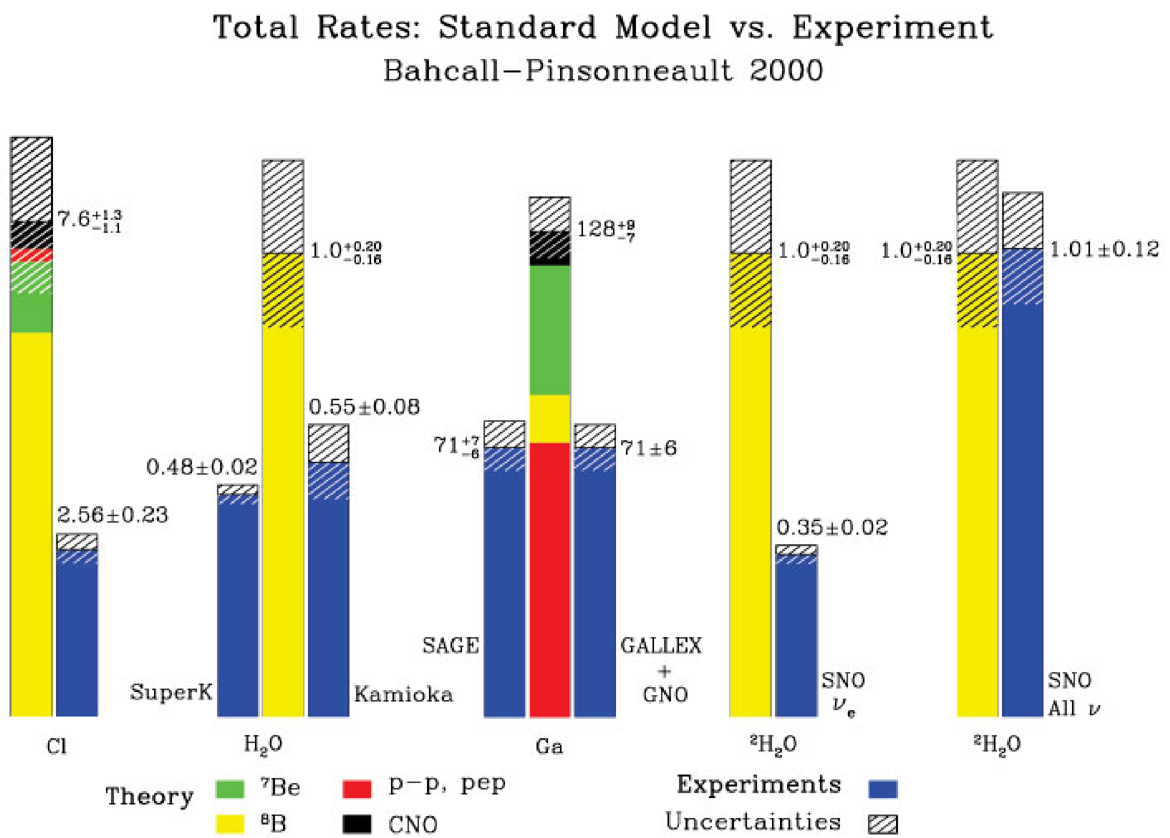
- Q = 2.22 MeV
- measures total $^8$B ν flux from the Sun
- equal cross section for all ν types



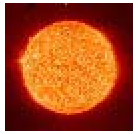

**ES** $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to $\nu_e$, some $\nu_\mu$ and $\nu_\tau$
- strong directional sensitivity

# Reults on solar neutrino rates



# Neutrino oscillations framework



source

$\nu_e$

$P_{ee}\nu_e, (1-P_{ee})(\nu_\mu + \nu_\tau)$

detector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

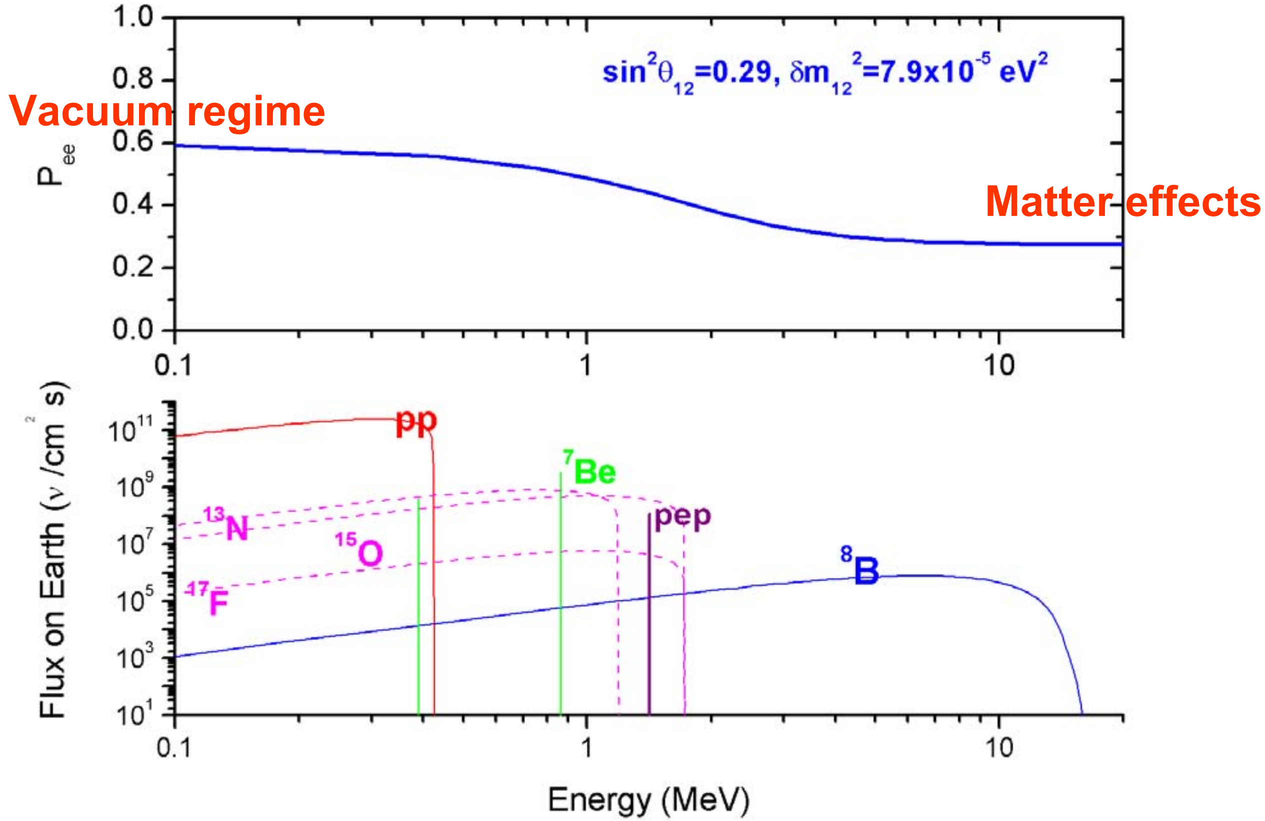
$|U_{e1}| = \cos\theta_{12}\cos\theta_{13}$
$|U_{e2}| = \sin\theta_{12}\cos\theta_{13}$

$|U_{e3}| = \sin\theta_{13}$

$|U_{\mu 3}| = \sin\theta_{23}\cos\theta_{13}$
$|U_{\tau 3}| = \cos\theta_{23}\cos\theta_{13}$

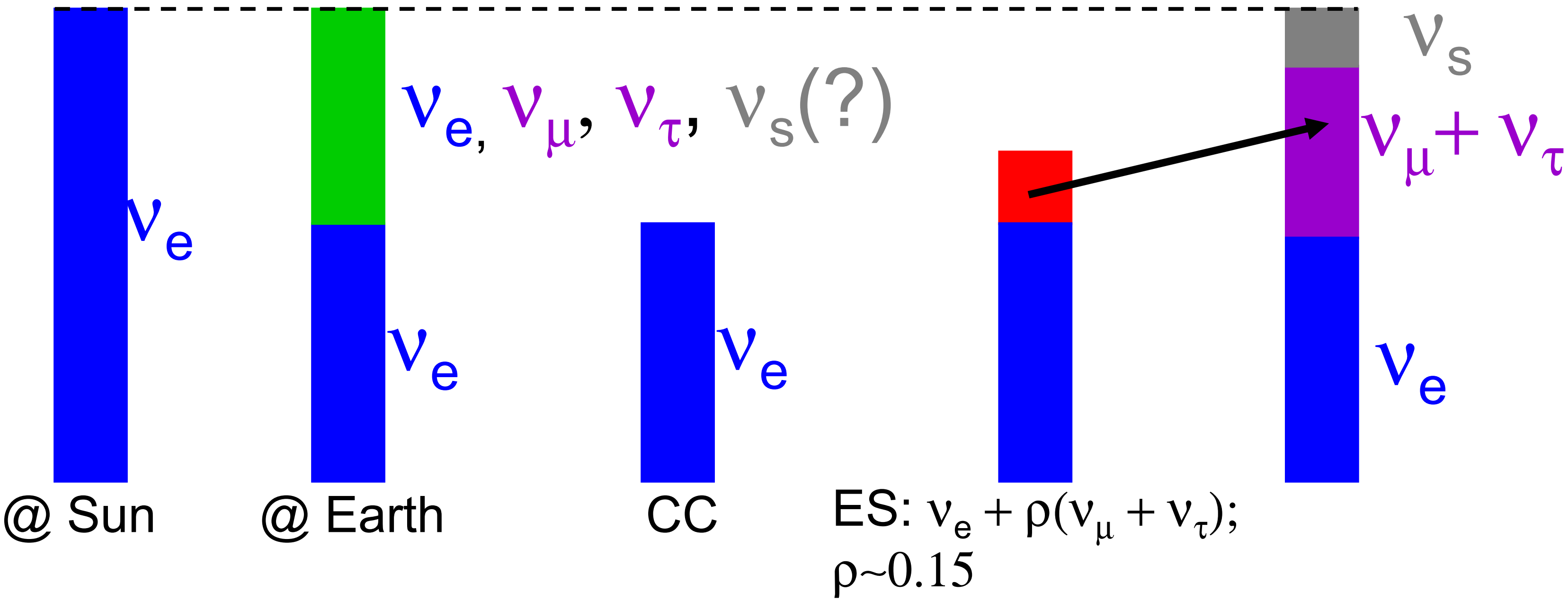
Oscillations in terms of three angles and two mass related parameters:
$(\theta_{12}, \theta_{13}, \theta_{23}, \delta m^2 = m^2_2 - m^2_1, \Delta m^2 = m_2{}^2 - m_1{}^2)$

# Survival probability and matter-vacuum transition



# CC and ES experiments at low energy

In order to measure the total flux of active neutrinos both ES and CC Channels need to be explored.
Room for sterile neutrino search with precise pp measurement.



# Low energy solar neutrinos … why?

**Physics and astrophysics point of view:**

- **Test how the Sun shines. Input parameters (Z/X, opacity, …) of SSM are correct?**
- **How much energy from CNO (1.5% from SSM)? Any other energy source?**
- **Photon luminosity versus Neutrino luminosity**
- **High precision neutrino flux and annual modulation determination. High precision mixing angle ($\theta_{12}$ ) determination [mainly by meas. pp].**
- **Test of vacuum-matter transition (energy dependence of $\nu$ oscillations).**
- **New physics (neutrino magnetic moment, NSI, new vacuum osc. [Vissani,03])**
- **CPT test by comparison with terrestrial anti-neutrino experiments**

# Solar neutrinos … what next?

- Low energy solar neutrinos … a MUST!
- Further step asks for BIG experimental effort (see coming slides)
- Multi-purpose detector would be a good choice
- A megaton water Cerenkov for high energies and precise measurements with B8 neutrinos … hep search
- Low energy (<1MeV) asks for scintillation techniques (upcoming experiments)
- For low energy on the road liquid noble gases and metal loaded organic scintillators

# Low energy solar neutrinos … how?

Organic liquid scintillators:

1. $\rho$~1g/cm$^3$ (efficient self shielding), ~10$^4$photons/MeV, 5% energy resolution @ 1MeV, sigma ~ 10cm @ 1 MeV for vertex reconstruction
2. Expected 1.3 ev/day/ton for pp and 0.5 for $^7$Be in full energy range
3. 10tons target mass for pp gives about 10 counts/day
4. ONLY ES channel (rely on detection of single electron)
5. $^{14}$C ($\beta$ w/ 156keV) limits low energy sensitivity to only $^7$Be with achieved $^{14}$C/$^{12}$C~10$^{-18}$ (~0.2 Bq/ton background below end-point)
6. $^{238}$U, $^{232}$Th, $^{40}$K, $^{85}$Kr, $^{39}$Ar, $^{210}$Pb sources of important background
7. Needed U,Th < 1$\mu$Bq/ton to get S/B>1 … possible!
8. Needed ~0.5 $\mu$Bq(Kr,Ar)/m$^3$ of $N_2$ … possible!
9. Needed $^{210}$Pb < 1$\mu$Bq/ton … rely on distillation of scintillator!
10. Deep location to measure pep and avoid cosmogenic $^{11}$C background: expected 0.03 pep/day/ton vs 0.15 $^{11}$C/day/ton @ Gran Sasso depth; a factor 100 less @ SNO!

# Low energy solar neutrinos … how?

Metal loaded organic liquid scintillators:

1. Goal: CC real time detection
2. Method: electron-capture reaction
3. Needed either a transition to an isomeric excited state or a transition to an unstable final state in order to have a good tagging
4. Needed a low (<0.4MeV) threshold energy to measure pp and Be neutrinos
5. Possible isotopes (there are only a few!): $^{115}$In, $^{100}$Mo, $^{160}$Gd
6. Needed a stable loaded scintillator with large scattering length of scintillation light
7. Due to strong tagging less stringet requirements on radiopurity
8. With $^{115}$In expected 0.07 counts/ton/day for Be and 0.3 for pp

# Low energy solar neutrinos … how?

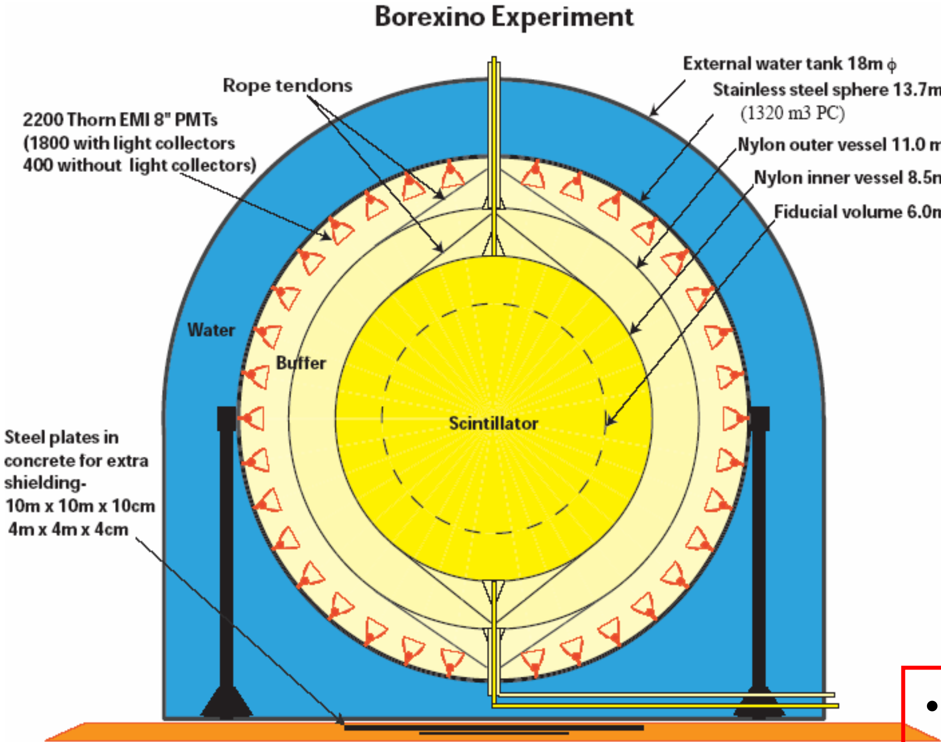
Noble gases liquid scintillators:

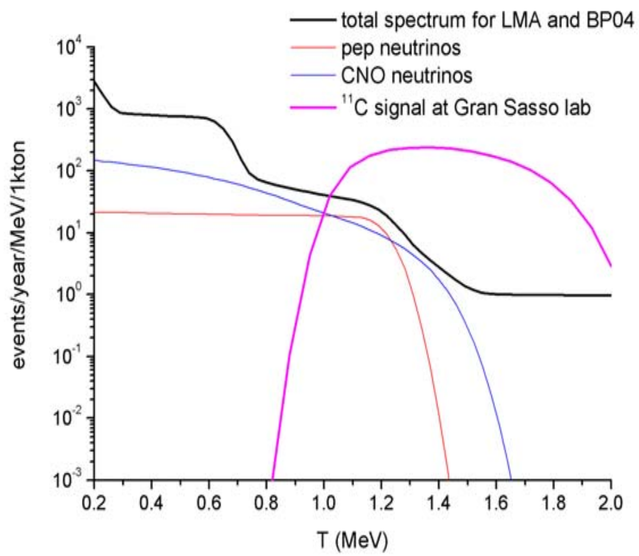
1. $\rho$~1-3g/cm$^3$ (efficient self shielding), ~1-4 x10$^4$photons/MeV
2. Under study Xe(boiling point @ 165K) and Ne (@ 27K)
3. Expected 1 ev/day/ton for pp and 0.4 for $^7$Be in full energy range with Xe
4. 10tons target mass for pp gives about 10 counts/day
5. ONLY ES channel
6. No problem with $^{14}$C!
7. $^{85}$Kr, $^{39}$Ar important background
8. 1ppb Kr in Xe achieved with distillation!
9. Needed R&D for PMTs working at low temperatures
10. Problems with $\beta\beta$ decays using Xe

# Upcoming next generation experiments

- Borexino
- KamLAND
- SNO+(?)

# Borexino at Gran Sasso Laboratory



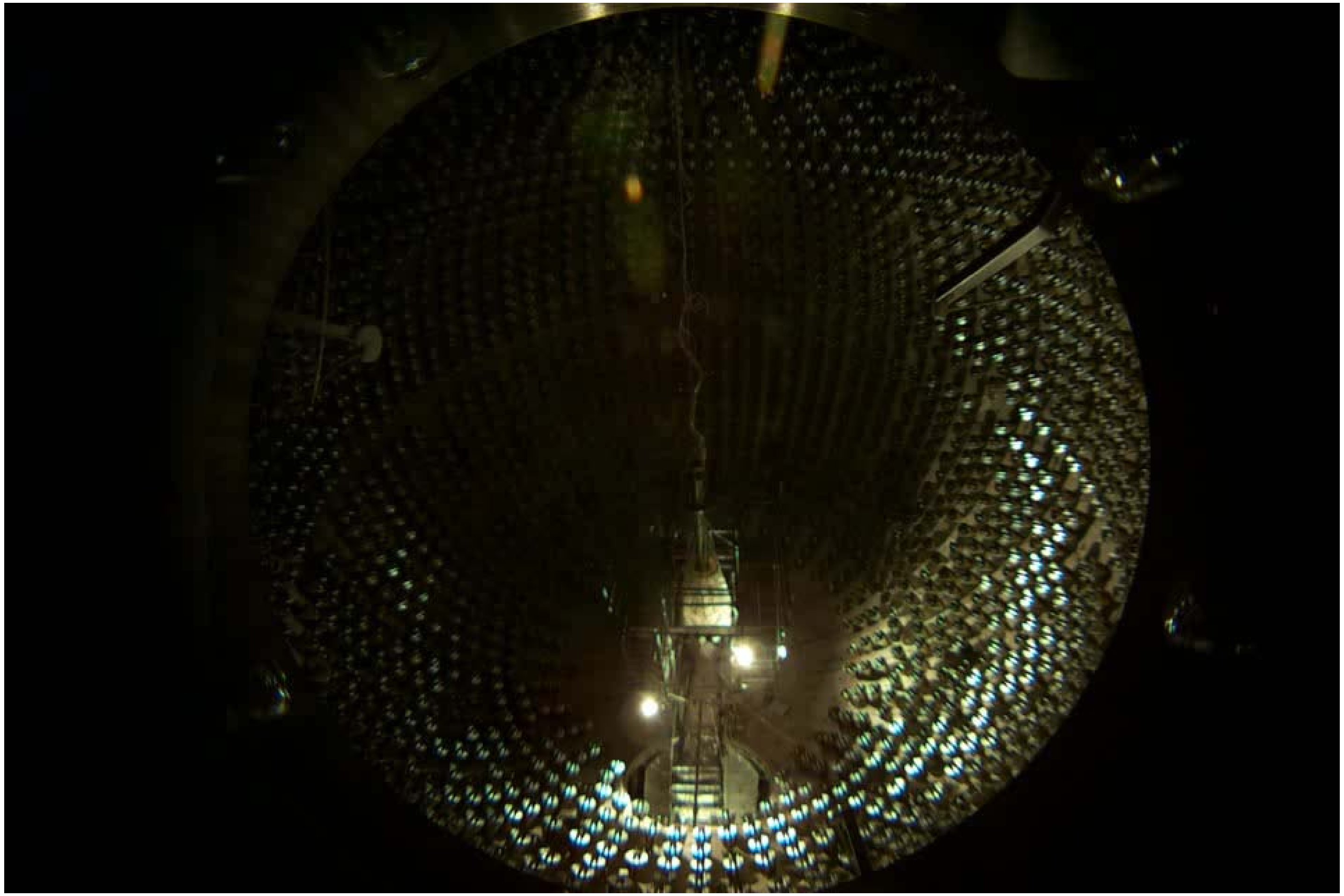




- 100tons target mass of $C_9H_{12}$ scintillator (pseudocumene) + 1.5g/l PPO
- ~10,000 photons/MeV (400phe$^-$/MeV)
- Energy resolution= 5%@1MeV
- Background studies carried out with a 4ton Prototype, the Counting Test Facility
- Main background issues: $^{210}$Pb,$^{39}$Ar,$^{85}$Kr

- Elastic scattering
- $1/R^2$ signature due to Earth's eccentricity: in 2yr 3σ measurement
- Compton like threshold signature for $^7$Be neutrinos
- spectroscopy
- Expected ~30 events/day in [0.25,0.8]keV
- Expected sensitivity for pep neutrinos

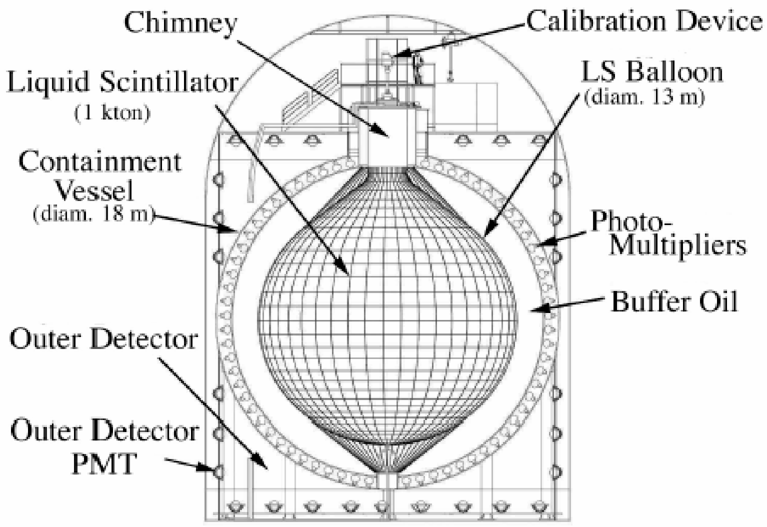
Data taking in 2007

# Nylon Vessels installation



# KamLAND at Kamioka

- 18m in diameter Kamiokande $H_2O$ tank
- 3000m$^3$ stainless steel containment vessel
- 13m in diameter nylon vessel
  (1000ton of liquid scintillator)
- Liquid scintillator =
  80%PC + 20%dodecane + 1.52 g/l PPO
- 1325 17” + 554 20” PMTs, 34% coverage
- Energy resolution: 6.3% @ 1MeV




Outstanding physics results achieved with reactors neutrinos! To move to solar neutrinos major upgrade of fluid handling and purification systems required. Works in progress! New phase foreseen in 2007!

# SNO+: a liquid scintillator for the SNO detector

- after physics with heavy water completed (>2006)
- main goals: solar pep + geo-neutrinos
- with pep observe rise in survival probability + test solar model

- foreseen target mass of about 600tons
- expected ~3000 pep events/year/600ton (>0.8MeV)
- low cosmogenic $^{11}C$ background due to deep site
- U, Th not a problem if KamLAND purity achieved
- Ar, Kr and Pb at lower energies are not a problem

# Future low energy solar neutrino experiments*

| Experiment | Detection channel | target | Expected signal counts/year for pp(Be) |
|---|---|---|---|
| LENS | CC channel $^{115}In+\nu_e \text{->} e^- + ^{115}Sn,\gamma$ | 20ton In-loaded scintillator cells | 2190(511) |
| MOON | CC channel $^{100}Mo+\nu_e \text{->} e^- + ^{100}Tc(\beta)$ | 3.3ton Mo foils + plastic scintillator | 240(77) |
| XMASS | Elastic Scattering | 10ton liquid Xe | 2373(1241) with 50keV thres. |
| CLEAN | Elastic Scattering | 10ton liquid Ne | 2869(1518) with 50keV thres. |

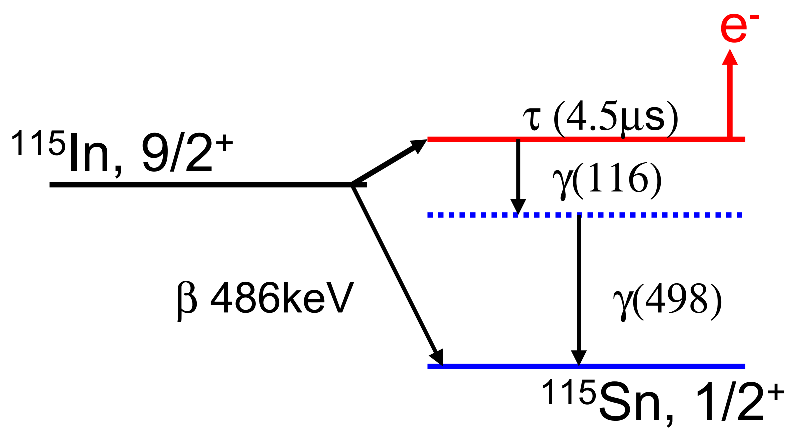
*only mentioned those which have a stronger R&D in progress!

# LENS(Low Energy Neutrino Spectroscopy)

- Scintillator loaded(8%) with $^{115}$In (96% natural); 20tons In mass and 400-600tons scintillator mass
- CC measurement of pp and Be solar neutrinos
- Strong tagging

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$$

$$(A,Z+1)^* \rightarrow (A,Z) + \gamma$$

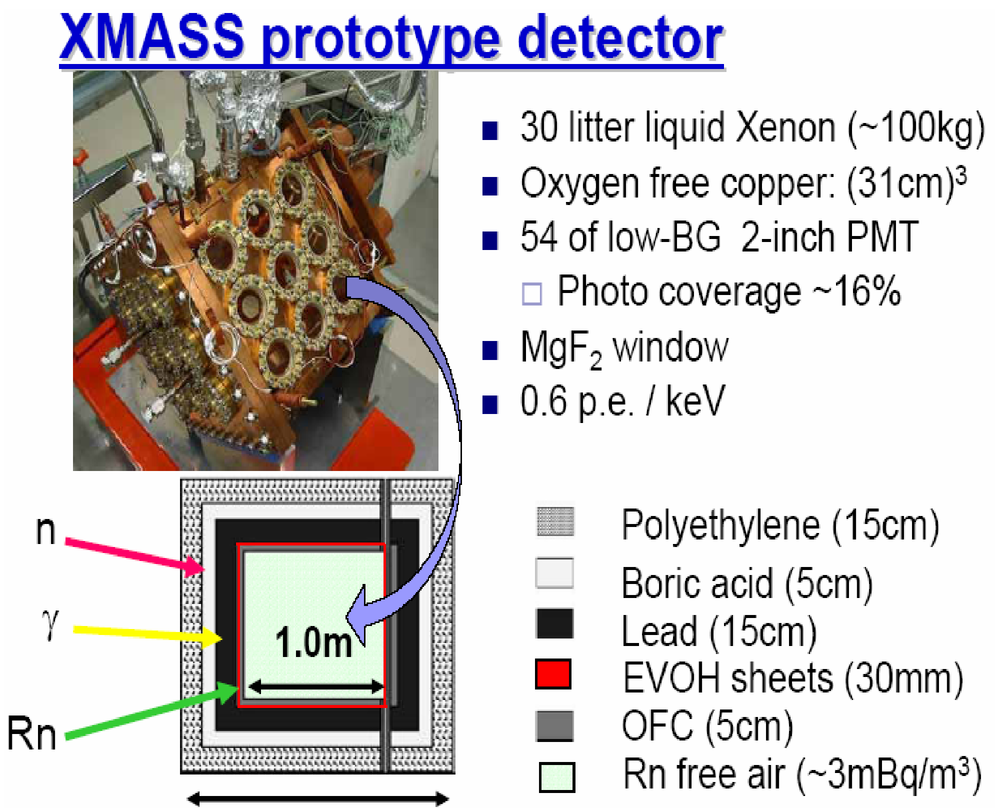



•Background from beta decay + bremssstrahlung can mimic neutrino signal; removed by a modular structure with In-free cells around In-loaded cells

# XMASS

Main experimental idea is based on self shielding and distillation.
Plan: from 100kg prototype to 1ton

and eventually to 10tons




- •42,000 photons/MeV (@173nm)
- •360 p.e. @50 keV
- •Longest isotope $^{127}$Xe(36.4days)
- •Problem of $^{85}$Kr solved by distillation thanks to difference of boiling points (Xe:165K; Kr:120K)@1atm
From 300ppb Kr/Xe to <5ppt Kr/Xe
- •U and Th to be reduced by a factor of 30

# Outlook

Soon (~2yr) Borexino & KamLAND will perform the first low energy (<1MeV) measurement of solar neutrinos.

This measurement can open new opportunities:

- Precision test of solar model
- Test matter-vacuum transition
- Test sub-leading effects
- Test CPT

New projects underway (multi-purpose detectors) will further improve opportunities with pp measurement:

- best way to search for sterile neutrinos (needed CC+ES meas!)
- Precise oscillation parameters determination

Yet, hard experimental work needed to move the new projects from being nice ideas to real experiments

# Experimental approach for detecting low energy solar neutrinos [first generation]

- From Cerenkov to scintillator detectors
- Elastic Scattering or Absorption

- High level of intrinsic radiopurity:

- In organic scintillators $^{238}U$ and $^{232}Th$ @ $10^{-16}$ g/g
(~2 events/day/ton in [0.25,0.8]MeV detection window for recoil electrons for ES; with PSD and subtraction of correlated events 0.2events/day/ton)
- Low $^{14}C$ content ($^{14}C/^{12}C \sim 10^{-18}$): it allows to set a threshold at about 0.2MeV

- Deep underground to avoid cosmogenic background

# MOON

- Detector consists of modules of Mo films and fiber/plate Scintillators

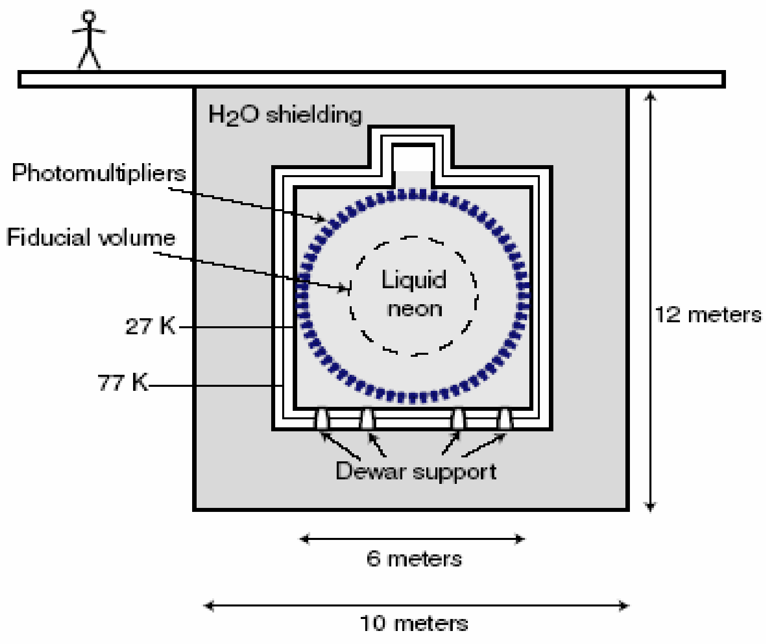
- Low threshold at 0.17MeV
- $^{100}$Tc decays with $\tau$=15.8 s
- Tracking freseen to reduce background ($\beta\beta$)

- Position read-out by fibers (2.2m x 2.2m x 0.4mm)
- Energy read-out by scintillators (sigma = 5.5%)
- Total 4 units ofr 3.3tons target mass
- One unit is 2.2m x 2.2m x 2m for 260 modules

# CLEAN

• Goal: perform neutrino ES+neutrino nucleus scattering with low threshold
•Expected ~3000 pp events/year/10ton (>50keV)

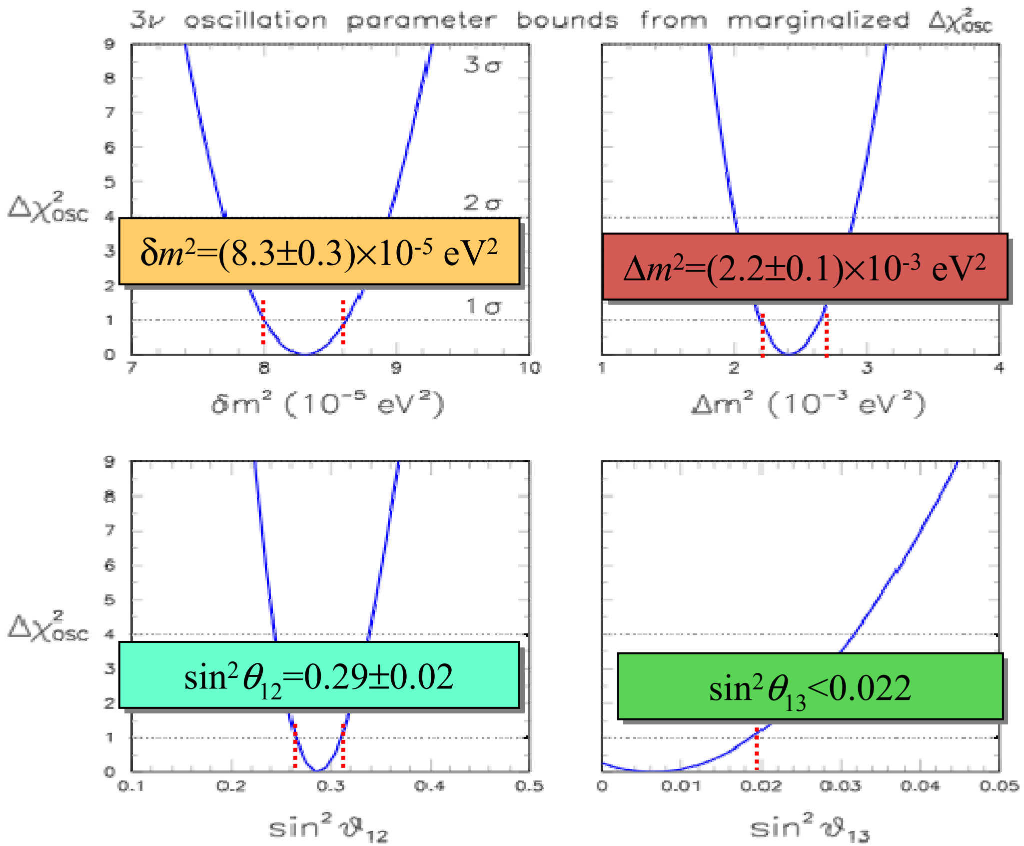
•PMTs equipped with a quartz/acrylic window
•Each window coated with a layer of organic material to convert 80nm scint. Ne light to the visible
•Use Ne outer layer to shield against gamma rays an neutrons
•Ne has no long-lived radioactive isotopes
•Ne has low binding energy to variety of surfaces
•Density = 1.3 g/cm$^3$




PMTs tested in LNe
Purification R&D in progress

Pulse shape analysis for different radiation types in progress

# Solar neutrinos in the framework of neutrino oscillations




Courtesy of D. Montanino, hep-ph/0408045