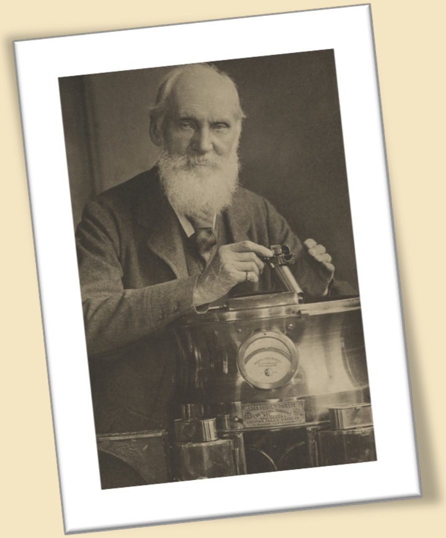
SOLAR NEUTRINO PHYSICS at LNGS
Concluding Remarks

- The sun is the source of the energy that allowed the birth of life on the earth
- At the top of the atmosphere 174000TW
- Life on the earth depends on the balance between the power received and that absorbed, reflected and re-emitted

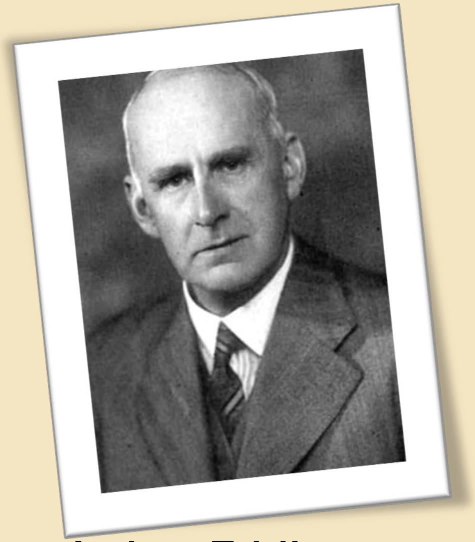
Concluding remarks highlights

- A brief history of solar neutrino physics
- Gran Sasso INFN Laboratory
- Gallex/GNO
- Borexino
- Open problems and future prospects
- Conclusions

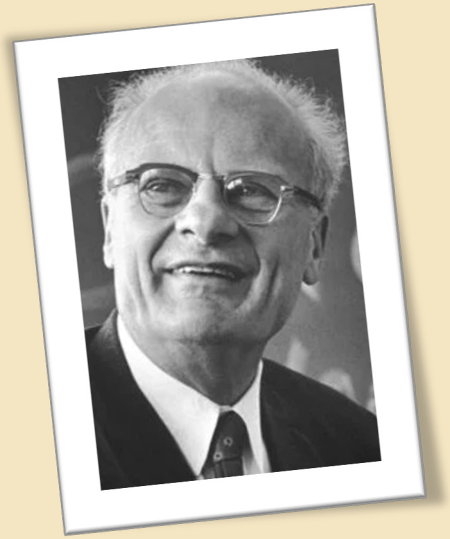
How does the Sun shine?
A long journey…



Lord Kelvin

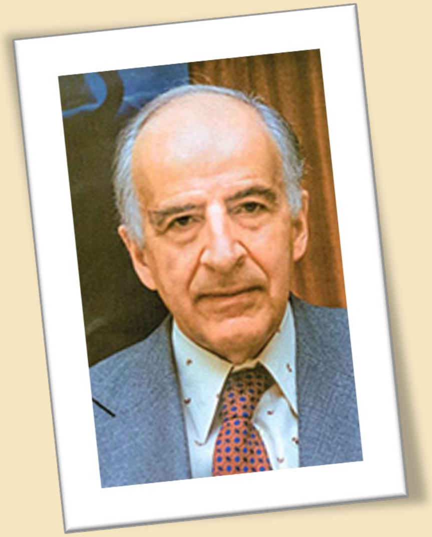


Arthur Eddington



Hans Bethe

John Bachall



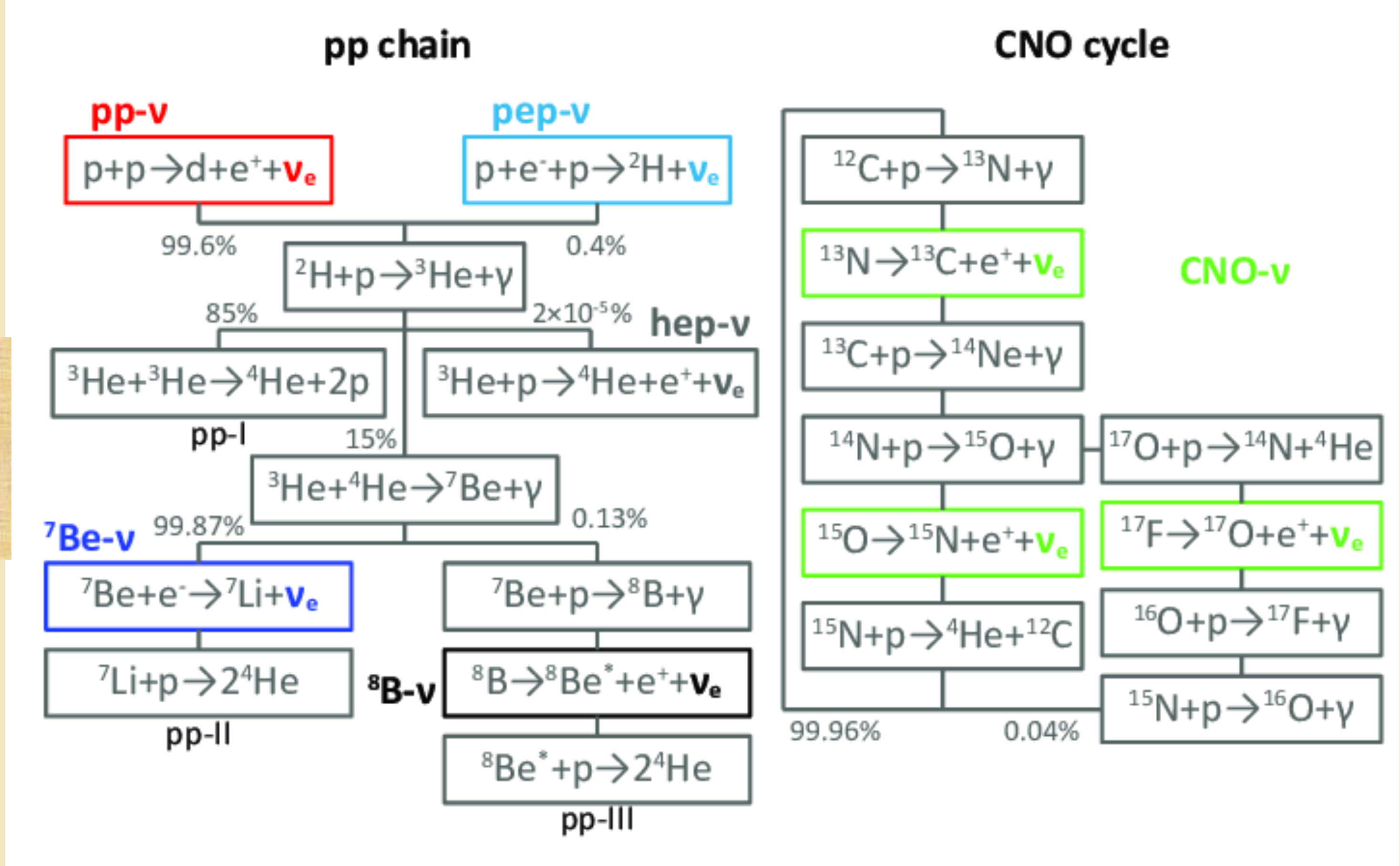
Bruno Pontecorvo

Ray Davis

The Standard Solar Model

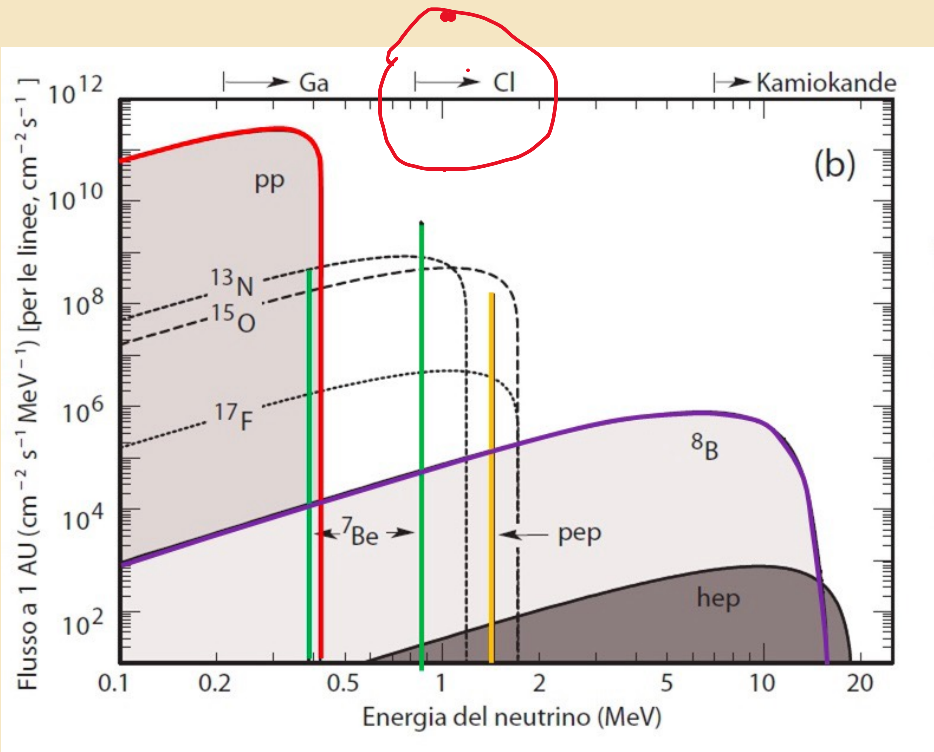
John Bachall: the detection of solar neutrinos is the key to understanding how the sun, and stars in general, shine

99% of solar energy from pp chain



The Ray Davis pioneering experiment
@ Homestake (1970 – 1994)

- Radiochemical experiment using a 380m^3 tank filled with perchloroethylene
- Neutrino detection via the inverse β decay
  $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  $\downarrow$
  $e^- + {}^{37}Ar \rightarrow {}^{37}Cl + \nu_e$
- First demonstration that a few atoms can be detect out of hundreds of tons of target material
- Threshold=0.814 MeV
  sensible to ^{8}B and ^{7}Be
- No use of a calibration source



The Ray Davis pioneering experiment @ Homestake (1970 – 1994)

- Radiochemical experiment using a 380m^3 tank filled with perchloroethylene
- Neutrino detection via the inverse β decay

  $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

  $\downarrow$

  $e^- + {}^{37}Ar \rightarrow {}^{37}Cl + \nu_e$
- First demonstration that a few atoms can be detect out of hundreds of tons of target material
- Threshold=0.814 MeV sensible to ^8B and ^7Be
- No use of a calibration source

- Big Surprise

Measured only $\sim\frac{1}{3}$ of the expected solar neutrino flux, confirmed in many years of data taking.

At that time possible reasons for the deficit could have been that the experiment (no calibration source was used) or solar model was incorrect.

- ***The Beginning of the Solar Neutrino Problem:***

  a puzzle whose design only revealed itself completely when many tiles were inserted

A further tile on the solar neutrino puzzle

- 1987: solar neutrinos detected by Kamiokande water Cherenkov detector, followed by SuperKamiokande
- First real time detection of the upper part of ^8B neutrinos spectrum based on neutrino electron scattering $\nu_x + e^- \rightarrow \nu_x + e^-$ (ν_e scatterng six times more sensitive)
- Correlation between the direction of neutrinos and that of electrons critical in confirming that the observed neutrinos came from the sun
- Confirmation of the ^8B deficit observed in the Homestake experiment
- The deficit stimulated a variety of theoretical efforts in astrophysics, nuclear physics and particle physics fields, including νe disappearance along the path from the sun to the earth
- The Pontecorvo neutrino oscillation theory was already on the table and obtained the largest attention; furthermore the MSW effect of neutrino oscillation in matter had been postulated

A decisive step forward

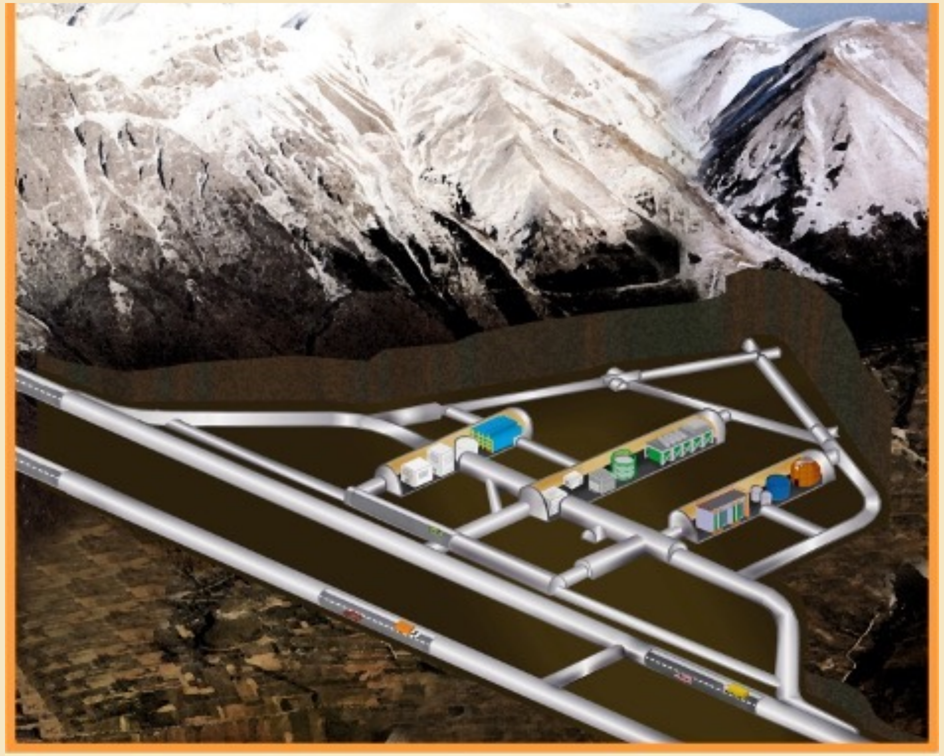
- In the early 90s It became clear that in order to solve the puzzle, ruling out the astrophysical solution, it was necessary to measure the most abundant solar neutrinos: the pp-neutrinos directly connected to the well-known solar luminosity.
- This demanded a detection reaction with very low threshold (<420 KeV) and very low-background experiments
- The only possible option was the $^{71}Ga(\nu_e,e^-)^{71}Ge$ reaction

⬇

SAGE and Gallex/GNO experiments

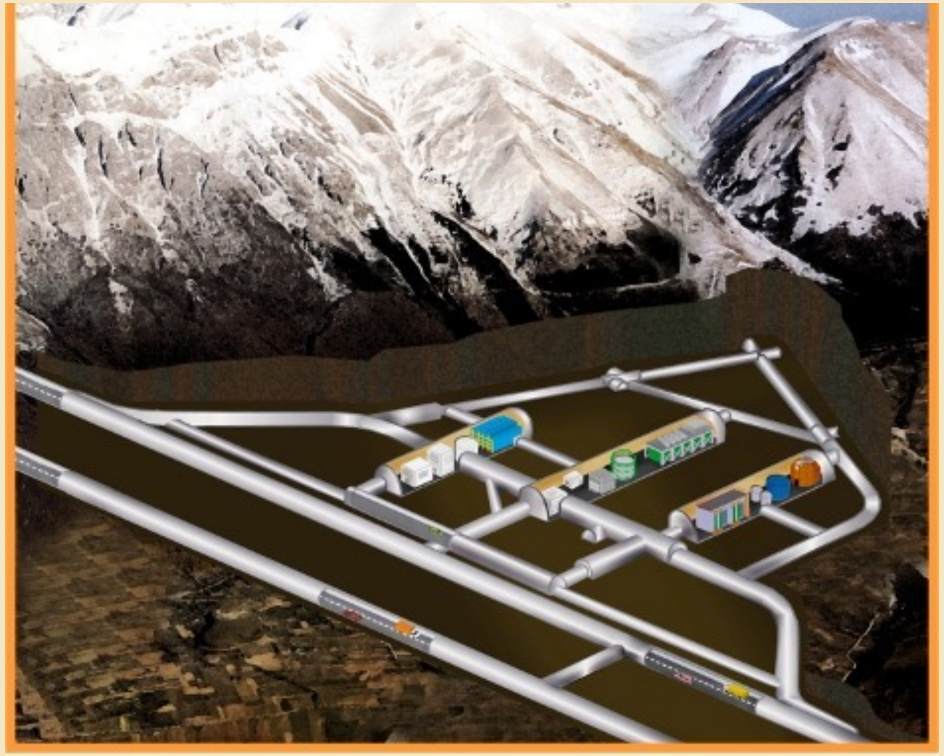
The Gran Sasso Laboratory begins to enter the game

The Gran Sasso INFN Laboratory



- Research activities:
  - Neutrino Physics
  - Dark Matter
  - Nuclear Astrophysics
  - Associate Sciences

The Gran Sasso INFN Laboratory



- Neutrino Physics:
  - Solar neutrinos
  - Disappearance and appearance ν oscillations
  - ν_s from COLLAPSING STARS
  - 0νDBD

Gallex/GNO @LNGS

- Solar neutrinos detected between May 1991 and April 2003 (more than a full solar cycle) via the inverse $^{71}Ga(\nu_e,e^-)^{71}Ge$ reaction in a 100-ton gallium chloride target (30,3 tons of gallium)
- Threshold 233 KeV: pp-neutrinos ($p + p \rightarrow d + e^+ + \nu_e$) included and in total 92% of total solar neutrinos flux
- Very demanding experiment: target radiopurity, separation Ge-Ga at 10^{30} level, low-level proportional counting detector for ^{71}Ge
- Reliability of the radiochemical detector provided via the ^{51}Cr source measurements and with the ^{71}As tests

Gallex/GNO (cont)

- First results of Gallex announced in “Neutrino 92”
- Till 1997, Gallex confirmed the precence of pp-neutrinos and a significant deficit ($\approx$40%} of the sub-MeV solar neutrinos
- First experimental demonstration of the nuclear fusion processes in the sun core and the strongest indication at that time of neutrino oscillations between electron neutrinos in muon-tauon neutrinos on the path from the sun to the earth
- The following GNO measurements improved the quality of the data, added restrictions on possible time variations, reduced the total error on charged current reaction rate for pp neutrinos.
- More recent re-analysis of data: extracted P_{ee} survival probability for pp-neutrinos (0,52 $\pm$ 0,12) after subtraction of ^{8}B (SNO/SK) and ^{7}Be (Borexino) contributions
- **“The first Gallex results marked a cornerstone in neutrino history” (Morales)**

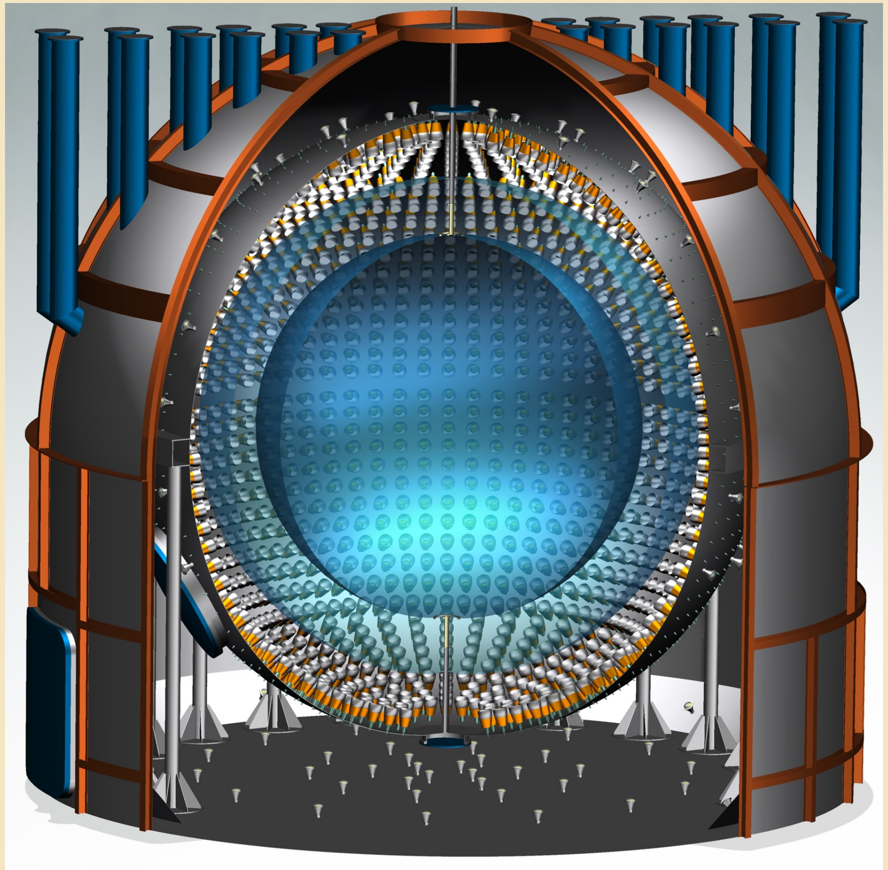
The final proof

- Decisive proofs that the source of the neutrino solar deficit, as confirmed by many experiments, lay in the ν_e oscillation in (ν_μ - $\nu\tau$) were given by SNO (1999-2006) experiment in Canada.
- Real time Cherenkov detector filled with 1000 tons of D_2O surrounded by 1500 tons of normal water as a shield, eventually with improved neutrino capture capability
- Total flux of solar neutrinos on the earth (ν_e ν_μ, $\nu\tau$) detected through NC neutrino interactions and pure ν_e flux through CC interactions on deuteron, and ν_x Elastic Electron Scattering
- **Total flux in agreement with SSM,**
- Ratio between ν_e flux and total flux= 0,32
- The only model-independet measurements of the total solar neutrino flux
- Only ^{8}B neutrinos and 1% of the total neutrino flux detected

Borexino @LNGS

- Despite the great achievements on the solution of the solar neutrino problem, at the beginning of the new millennium a complete and precise spectroscopy of the different processes of the pp chain was still missing
- The Borexino experiment @ LNGS had been designed for this purpose since the early 90s
- The experiment finally took data from 2007 to 2021 @LNGS

Borexino @LNGS



- Onion-like 280 ton liquid scintillator detector
- The key for the success: unprencented levels of radiopurity and extensive thermal stabilization ($\sim 10^{-19}$ g/g of both ^{232}Th and ^{238}U and a rate of ^{210}Bi events $\leq$11,5 counts/d/100t
- Neutrinos of all flavors detected via elastic scattering
- Antineutrinos detected via the Inverse β decay

Borexino @LNGS Main Results

- The only experiment that has performed a full spectroscopy of the pp chain solar neutrinos: pp, ^{7}Be, pep, ^{8}B (ony excepion hep contributing to total flux at 10^{-5} level)
- First ever measurement of the CNO solar neutrinos (absence hypothesis rejected at 5σ level)
- The only experiment that tested simultaneusly flavor conversion both in vacuum and in the matter-dominated regime. (The transition region is sensitive to different models of non-standard neutrino interactions pointing to physics beyond SM)
- Hints in favor of the high metallicity SSM from fluxes of different species (^{7}Be and ^{8}B and mainly from CNO measurement), assuming known neutrino interactions and oscillation parameters
- Expected seasonal modulation of ^{7}Be ν as evidence of its solar origin
- Demonstration of the “Correlated and Integrated Directionality Technique” based on combined Cherenkov and scintillation signals, in the ^{7}Be and CNO measuments, thus paving the way to future hybrid experiments
- Limit on neutrino magnetic moment
- Geoneutrinos also detected

The future of solar neutrino physics

- Solar neutrino physics has given fundamental contributions both to astrophysics, testing the solar model, and to particle physics with the discovery of ν_e oscillations and neutrino mass.
- Combining results from solar neutrino experiments with terrestrial reactor experiment (**KamLAND**), the Large Mixing angle (LMA) MSW solution was established as the correct set of neutrino mixing parameters in this sector.
  Furthermore the order of one of the pairs of neutrinos of defined mass ($m1 < m2$) has been established
- There are still several key aspects of solar neutrino that require further clarification

↓

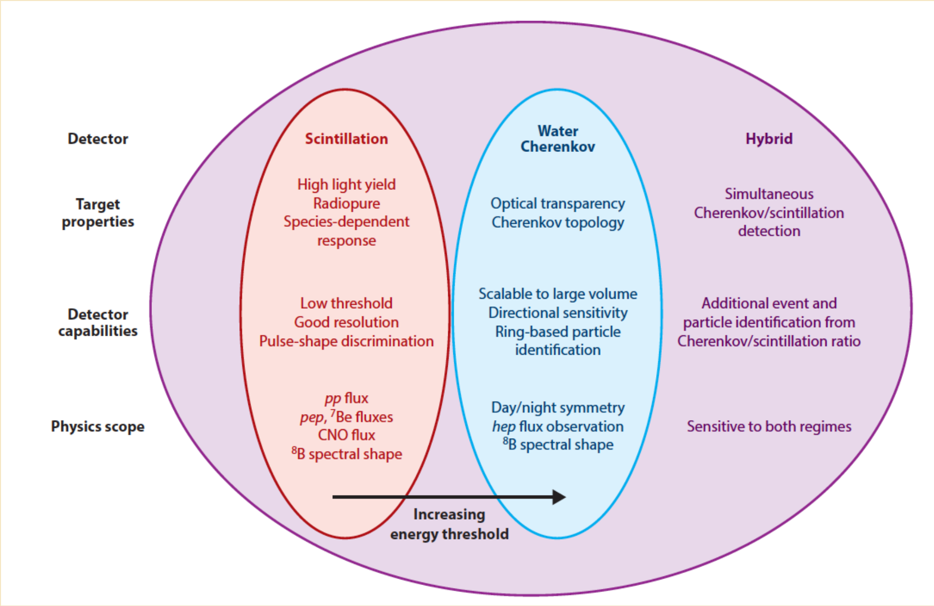
- Next generation experiments (larger scale, cleanliness, depth) are already in construction or planned or proposed

Open problems on solar neutrino physics

- The need for improved determination of neutrino oscillation parameters
  (e.g.: a more precise measurement of Δm^2_{12} could resolve the small tension between reactor and solar data)
- Addressing the solar abundance problem
  (CNO neutrinos are a unique opportunity in this regard)
- Nonstardard interactions (transition region, day-night asymmetry, antineutrinos)
- Detailed analysis of the energy dependence in the low-energy region
  (tight limits on the origin of the solar energy and limits on non-standard energy channels)
- The missing measurement of hep neutrinos
- Search for axions or more general Axion-Like particles

Experimental prospects on solar neutrino

- No single-purpose detectors planned, only multipurpose detectors
- Water Cherenkov detectors: SK, HyperK
- Liquid Scintillator detectors: Juno, SNO+
- Hybrid detectors Jinping, Yemilab, Theia
- Noble Liquid detectors (including those for the search for dark matter: DUNELAr, XENONnT, DARWIN



courtey G. Orebi Gann et al. ,*The future of solar neutrinos*

Conclusions

- Despite the great progress, some of the neutrino's characteristic remain unknown: these include neutrino mass and hierarchy and whether the neutrino is its own antiparticle
- There is space for improvements both in the solar knowledge and particle physics via solar neutrino studies.
- Solar neutrino physics still remains a frontier research topic

Gallex/GNO and Borexino experiments have marked the hystory of the neutrino physics and of the Gran Sasso Laboratory.