Solar Experiments

European Strategy for Future Neutrino Physics

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CERN □ October, 1, 2009

1-Solar neutrinos summary
2-Perspectives for further oscillation parameter constraints
3-R&D challenges for the future

Neutrino production in the Sun

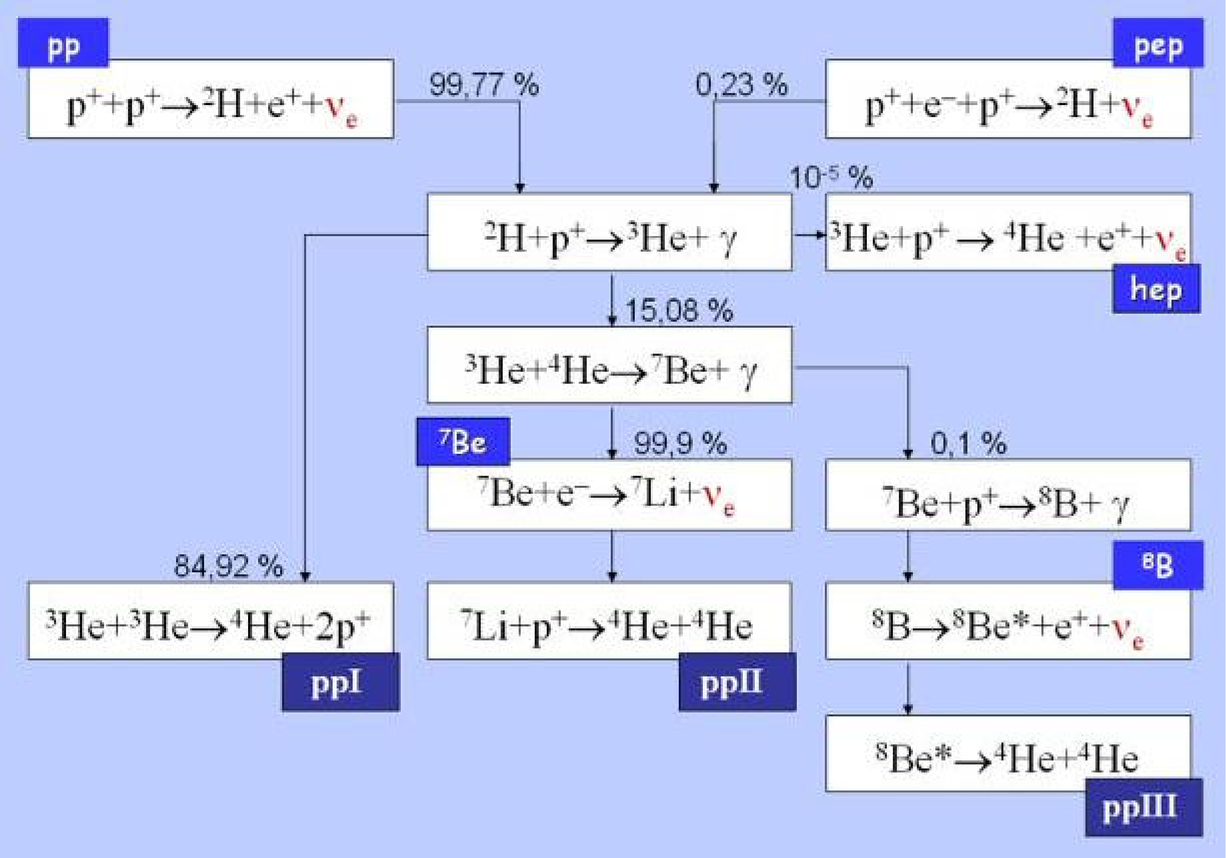
The pp chain reaction

The CNO cycle

In our star > 99% of the energy is created in this reaction

In the Sun < 1% More important in heavier stars

There are different steps in which energy (and neutrinos) are produced



$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

${}^2H + p^+ \rightarrow {}^3He + \gamma$

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

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

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

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

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

pp

ν **from:**

pp

pep

^{7}Be

^{8}B

hep

Monochromatic ν's

(2 bodies in the final state)

CNO

ν **from:**

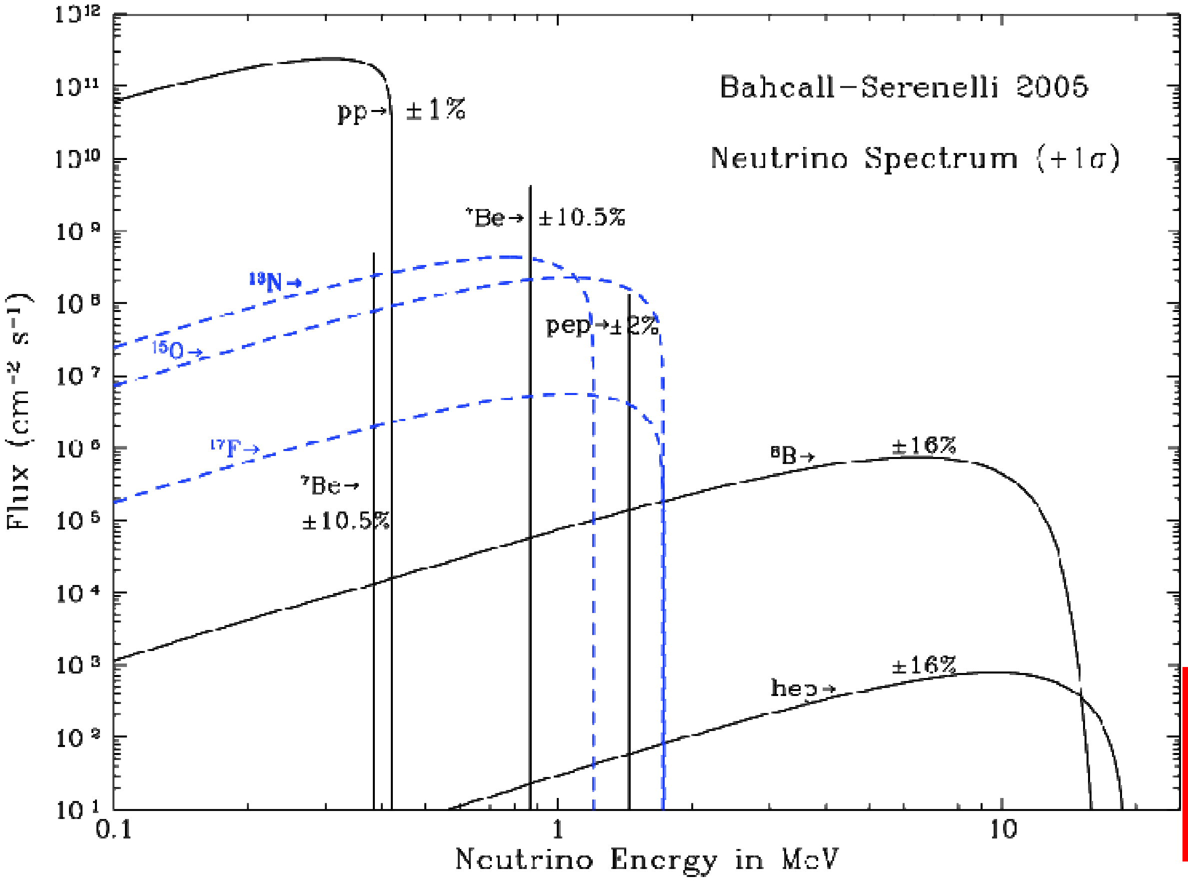
^{13}N

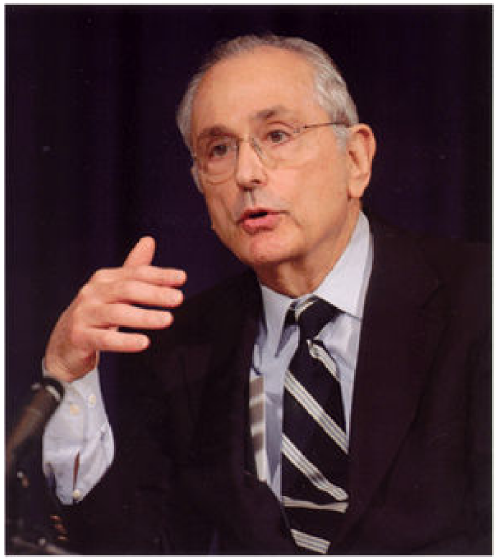
^{15}O

^{17}F

Neutrino production in the Sun

Neutrino energy spectrum as predicted by the **Solar Standard Model (SSM)**





John Norris Bahcall

(Dec. 30, 1934 – Aug. 17, 2005)

^{7}Be: 384 keV (10%)

862 keV (90%)

Pep: 1.44 MeV

Surface metallicity composition controversy still open: High Z vs Low Z

Solar neutrino experiments: a more than four decades long saga

Radiochemical experiments:

- Homestake (Cl)
- Gallex/GNO (Ga)
- Sage (Ga)

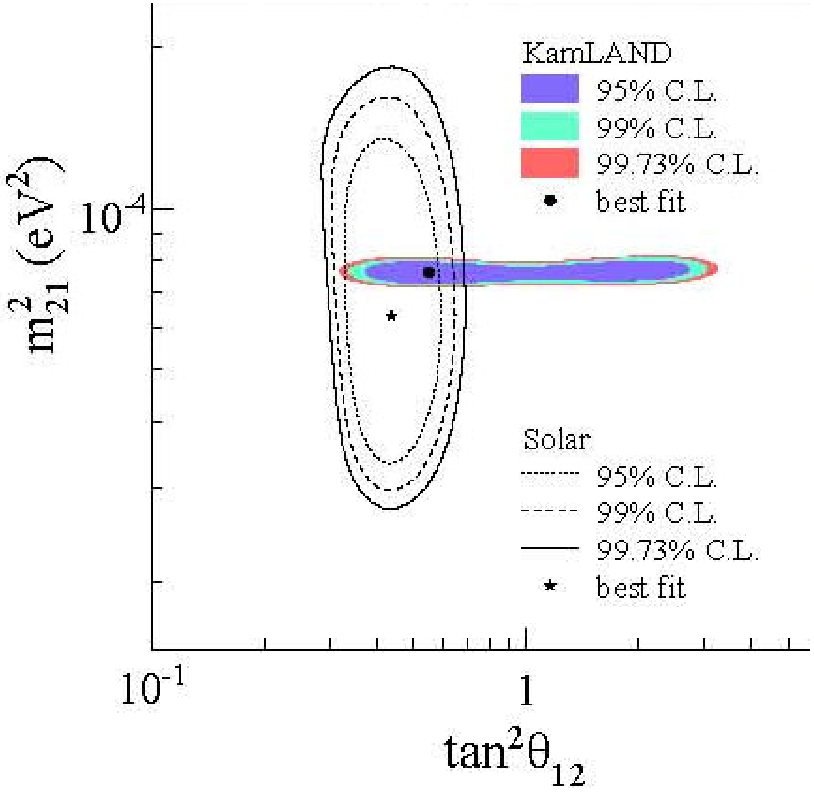
Real time Cherenkov experiments

- Kamiokande/Super-Kamiokande
- SNO

Scintillator experiments

- Borexino

Long standing discrepancy between measured and predicted fluxes: SNP Culminated with a crystal clear proof that neutrino oscillates



SOLAR PLUS

KAMLAND (Reactor ν's)

Neutrino oscillations !

$$\Delta m^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5}$$

$$\theta_{12} = 34.4^{+1.3}_{-1.2}$$

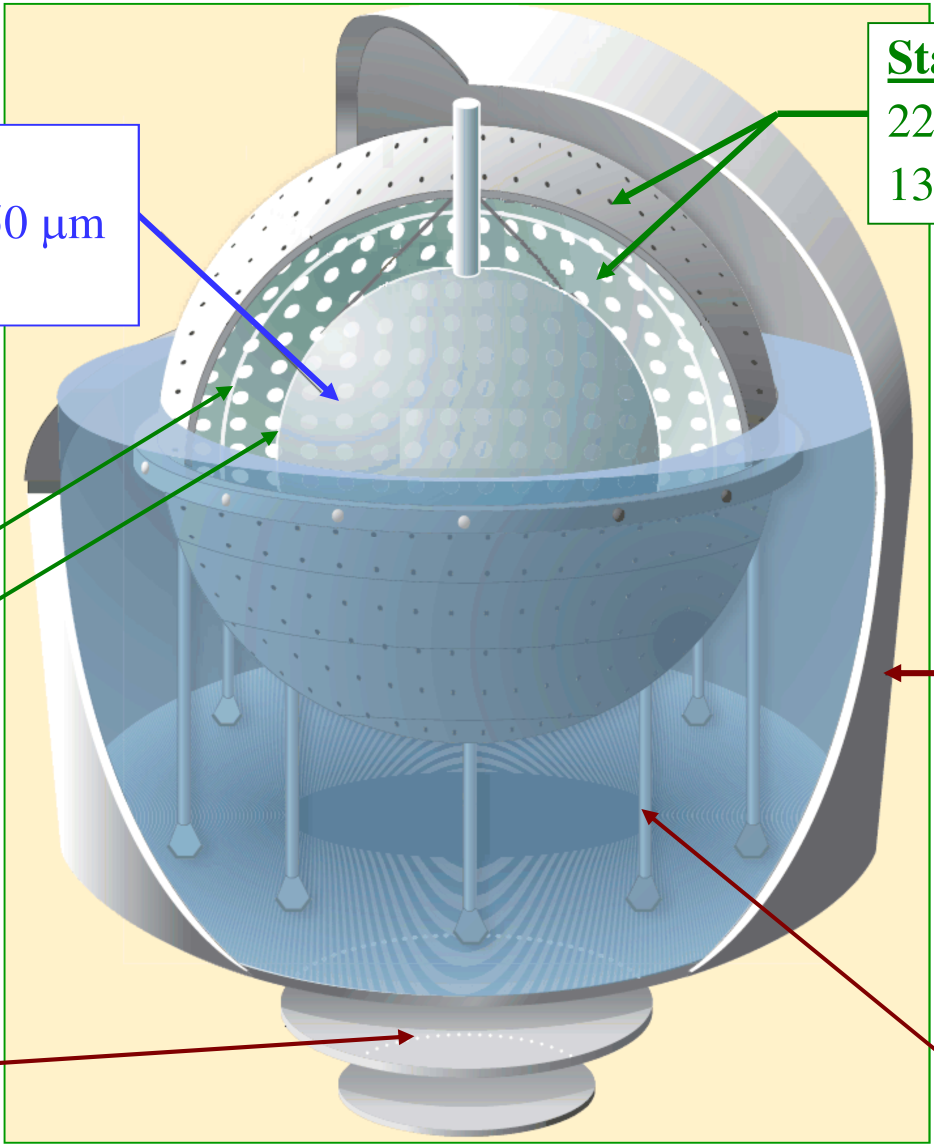
Phys.Rev.Lett.101:111301,2008

MSW matter enhanced flavor conversion
LMA solution

Given these fundamental achievements what’s next?

- recent and future implications
  - from Borexino ,SNO ,Super-Kamiokande
    - note: SNO no more operating
- future prospects
  - KamLAND
  - SNO+
  - LENS
  - CLEAN, MOON, XMASS (multidisciplinary projects)

Borexino@LNGS: real time detection



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shilding

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

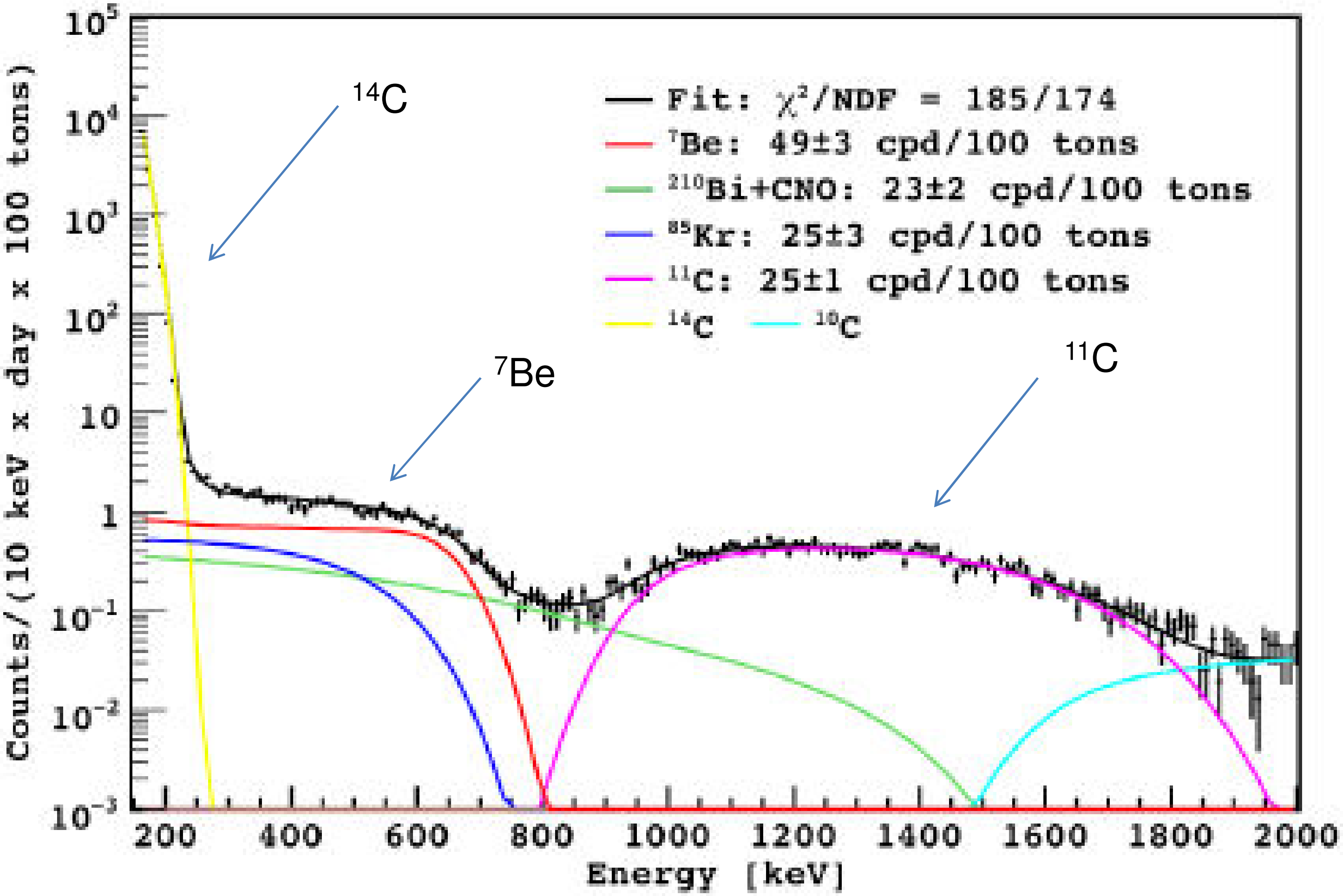
Neutrino electron scattering

$\nu e \to \nu e$

Carbon steel plates

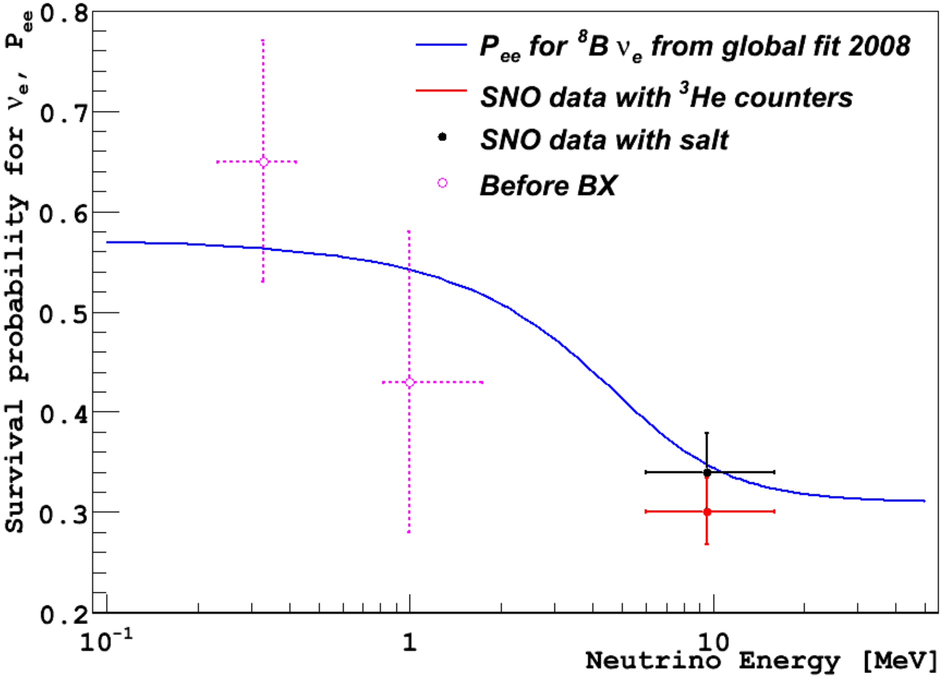
20 legs

Unprecedented intrinsic ultra low background levels allow the ^{7}Be spectroscopy measure



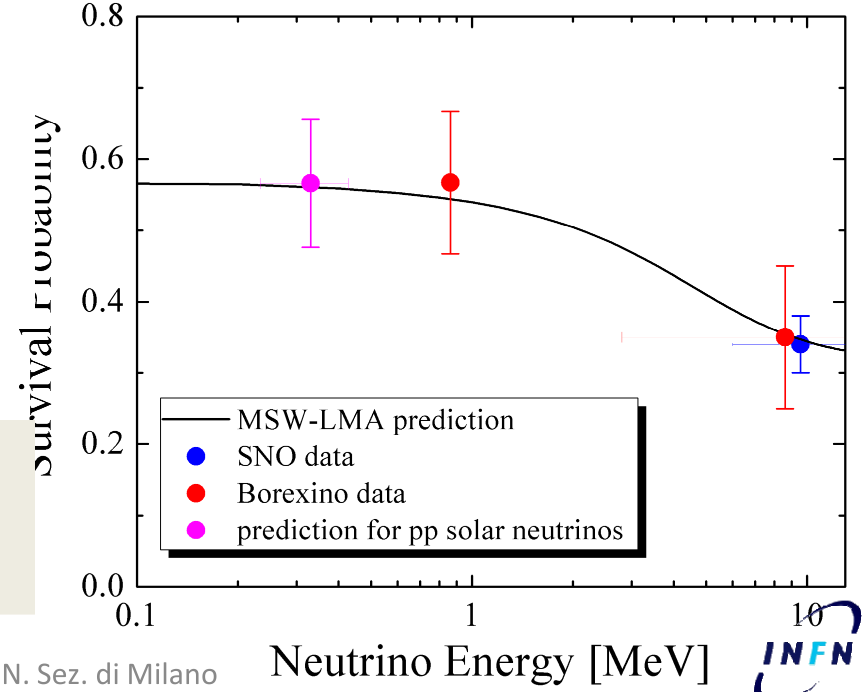
$49\pm 3_{stat} \pm 4_{syst}$ cpd/100tons for 862 keV ^{7}Be solar ν

$\Phi(^7Be)=(5.12 \pm 0.51)\mathrm{x}10^9 cm^{-2}s^{-1}$ SSM; H.M.(5.08 ± 0.56) x$10^9 cm^{-2}s^{-1}$
L.M.(4.55 ± 0.5) x$10^9 cm^{-2}s^{-1}$



Before Borexino

After Borexino



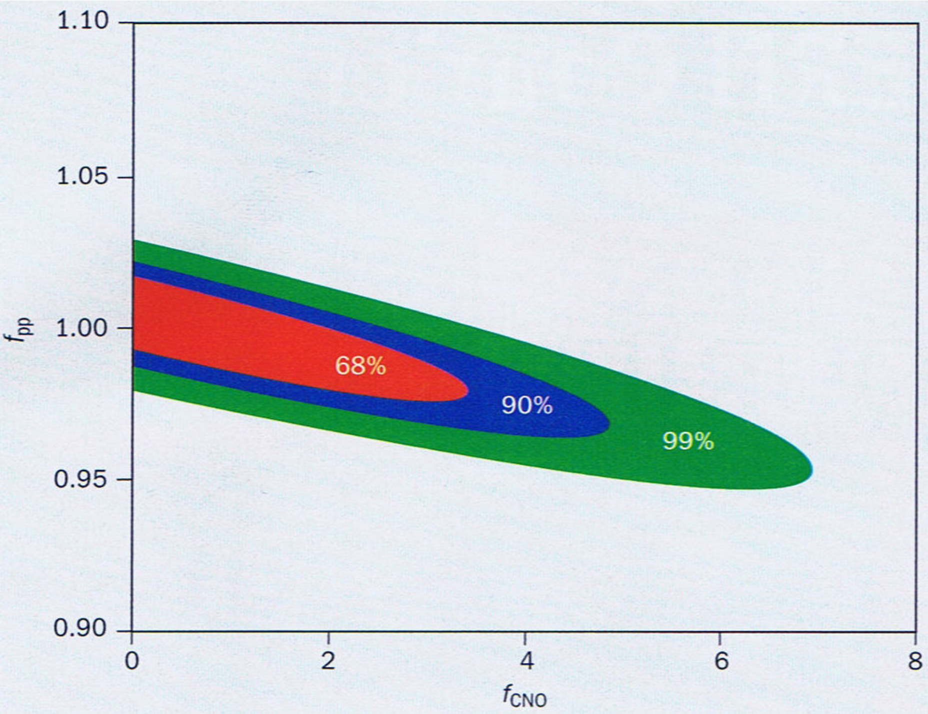
Striking first confirmation of the predicted MSW transition between vacuum and matter regimes to be improved with a future 5% measure

Other limits obtained by Borexino after 192 days of data taking - the best in the literature

1- Limits on pp e CNO solar fluxes; with the Luminosity constraint:

$$\Phi_{pp}(Borexino\ data)/\Phi_{pp}(SSM) = 1.004^{+0.008}_{-0.020}$$

$$\Phi_{CNO}(Borexino\ data)/\Phi_{CNO}(SSM) < 3.8\ (90\%C.L.)$$



2- upper limit on the neutrino magnetic moment: $5.4 \cdot 10^{-11} \mu_B\ \ (90\%C.L.)$

Gemma : $3.2 \cdot 10^{-11} \mu_B\ (90\%C.L.)$

3- day-night asymmetry: $ADN^{\upsilon} = 0.02 \pm 0.04_{stat}$

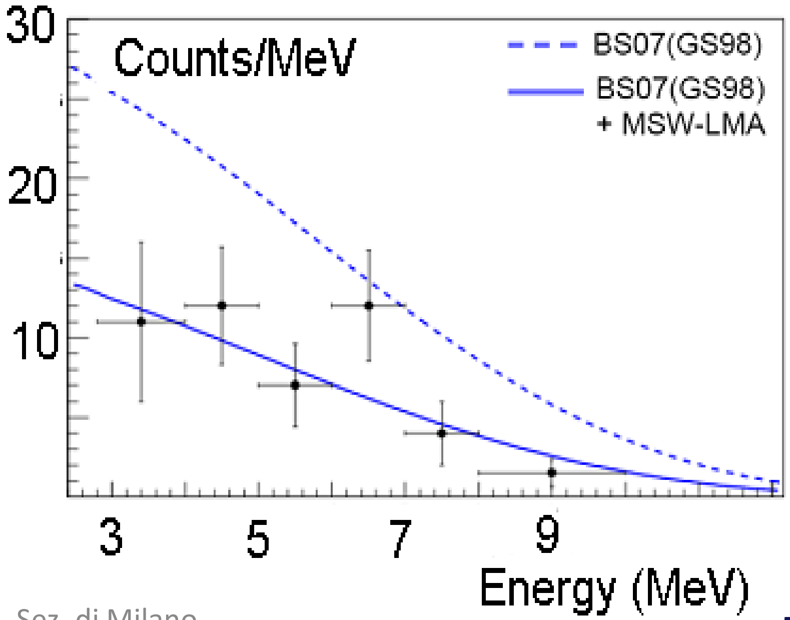
The low threshold measurement of the ^{8}B solar neutrinos

Major background sources:
1) Muons;
2) Gammas from neutron capture;
3) Radon emanation from the nylon vessel;
4) Short lived (t < 2 s) cosmogenic isotopes;
5) Long lived (t > 2 s) cosmogenic isotopes (^{10}C);
6) Bulk ^{232}Th contamination (^{208}Tl);

$$Rate_{>2.8\,MeV} = (0.26 \pm 0.04_{\text{stat}} \pm 0.02_{\text{sys}})\ \text{counts/day /100 tons}$$

- ^{7}Be and ^{8}B flux measured with the same detector
- Borexino ^{8}B flux above 5 MeV agrees with existing data
- Neutrino oscillation is confirmed by the ^{8}B of Borexino at 4.2 sigma

The Borexino ^{8}B spectrum



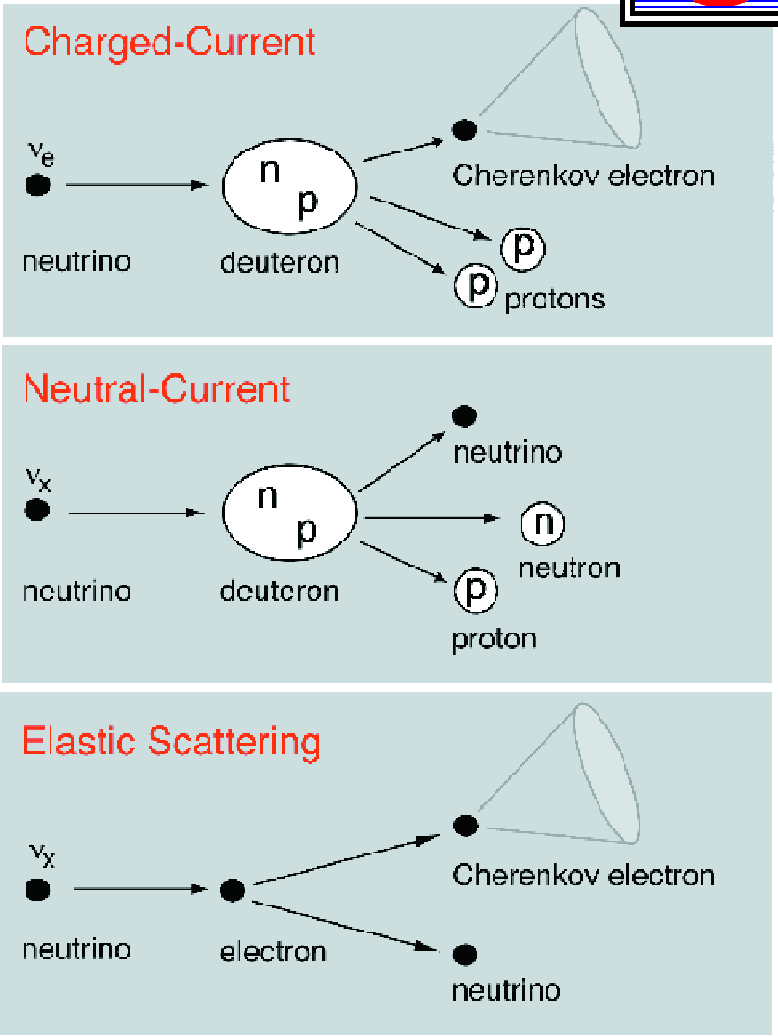
Sudbury Neutrino Observatory

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

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

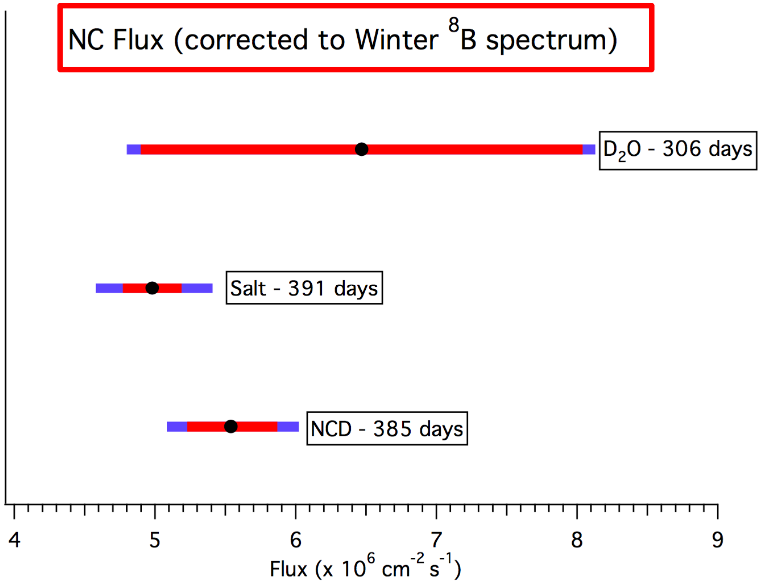
- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors

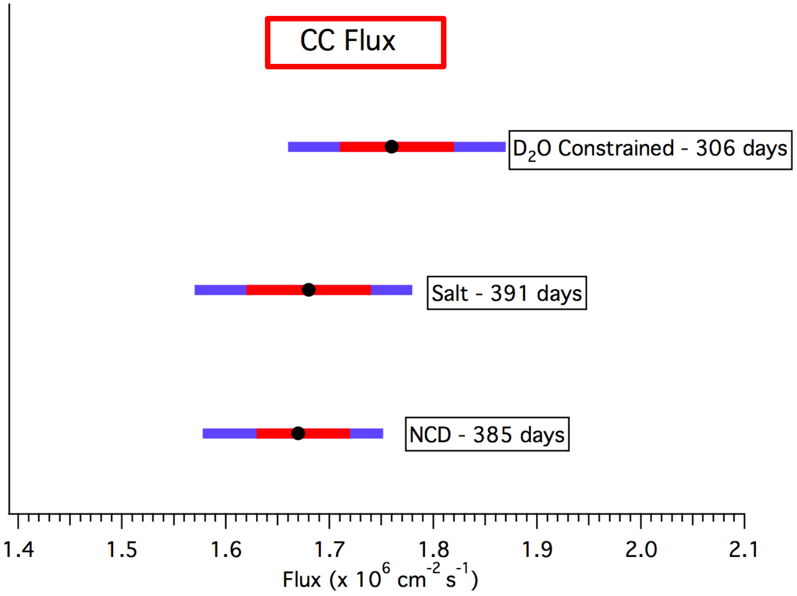
ES $\nu_x + e^- \rightarrow \nu_x + e^-$



SNO Fluxes: 3 Phases

🟥 stat 🟦 stat + syst

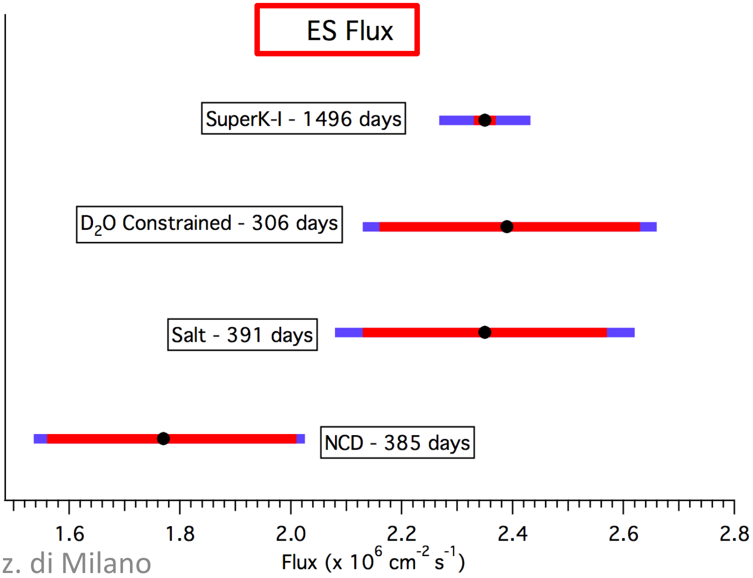




Art MacDonald@Neutel 2009

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033 \text{ (total).}$$

p-value for consistency of NC/CC/ES in the salt & NCD phases + D2O NC(unconstr) is 32.8%



Solar + KamLAND fit results

$$\Delta m^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5}$$ eV²

$$\phi_{8B} = 4.91 \times 10^6 cm^2 s^{-1} (\pm \sim 7\%)$$

$\theta_{12} = 34.4^{+1.3}_{-1.2}$ degrees

$\theta_{12} = 33.9^{+2.4}_{-2.2}$ deg (previous)

Art MacDonald@Neutel 2009

The accuracy on θ_{12} and ϕ_{8B} will improve with new data analysis: SNO LETA

Recent results:

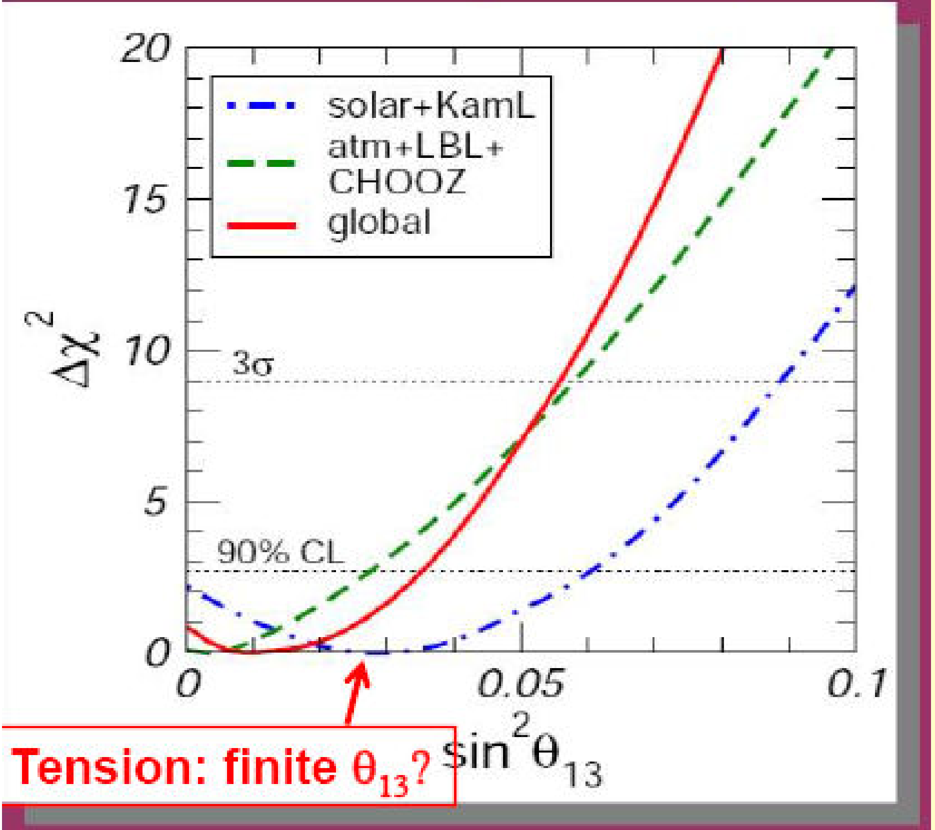
- SNO NCD results agree well with previous SNO phases. Minimal correlation with CC. Different systematics.
- New precision on θ

Future solar analysis:

- **LETA (Low Energy Threshold Analysis)**
- 3-neutrino analysis
- *hep* flux
- Day-night, other variations

STATUS OF THETA13

Schwetz et al **NJPhys.10:113011,2008**

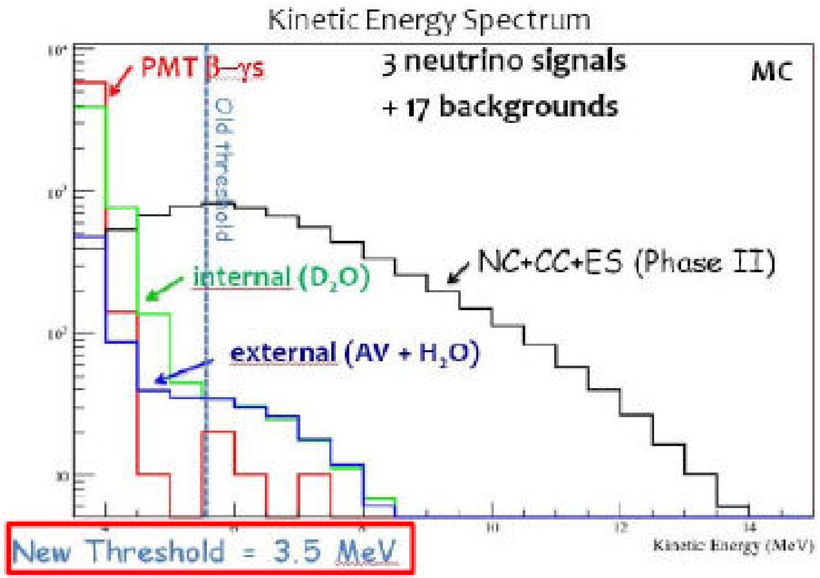


Tension: finite θ_{13}?

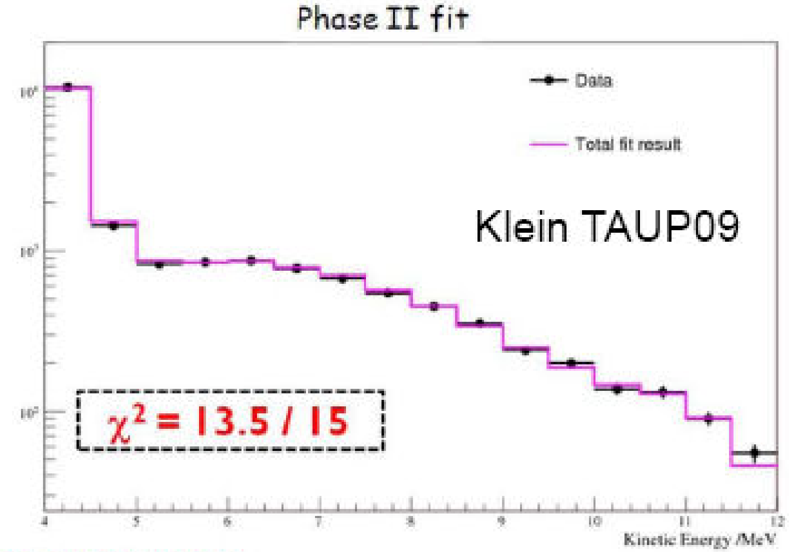
c.f. Fogli et al, 2008 & MINOS

$$\sin^2\theta_{13} \le \begin{cases} 0.060\ (0.089) & \text{(solar+KamLAND)} \\ 0.027\ (0.058) & \text{(CHOOZ+atm+K2K+MINOS)} \\ 0.035\ (0.056) & \text{(global data)} \end{cases}$$

New SNO analysis, soon with lower threshold, smaller uncertainties on CC/NC so $\sin^2\theta_{12}$. Hence also $\sin^2\theta_{13}$



New Threshold = 3.5 MeV



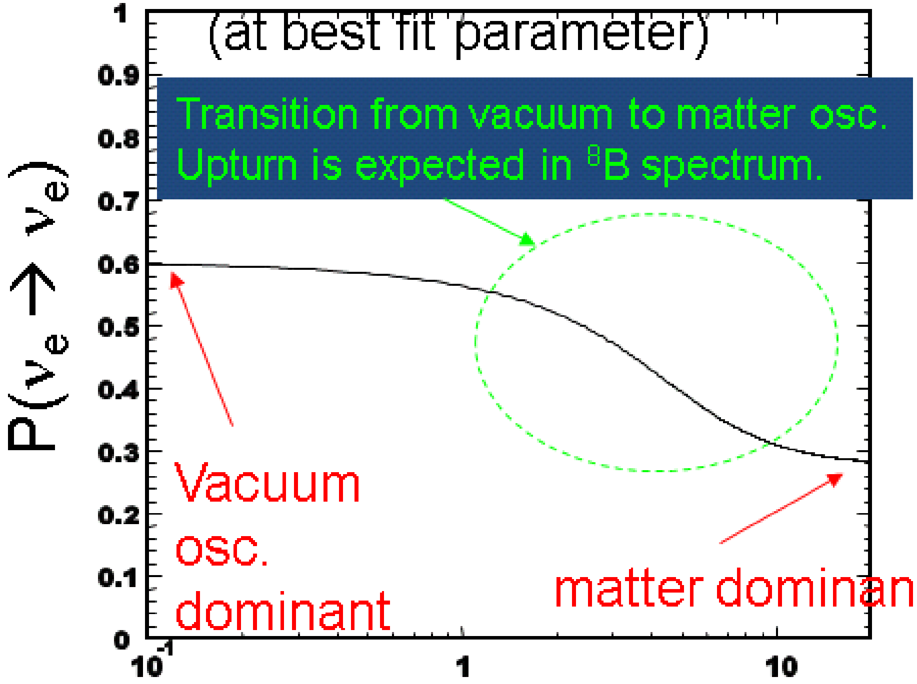
Klein TAUP09

PRELIMINARY

Solar Neutrino future prospects in SK

ν_e survival probability

(at best fit parameter)



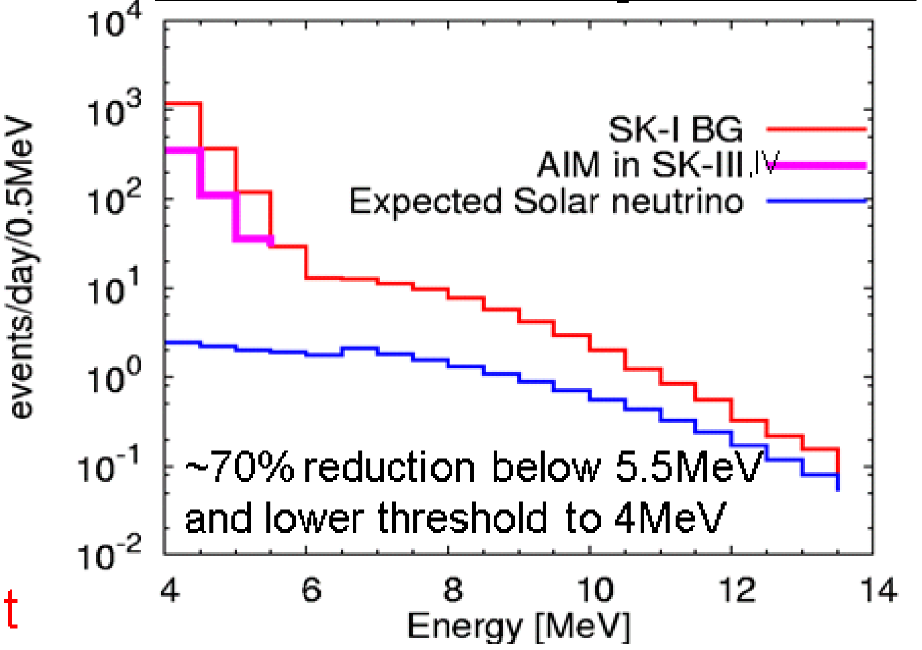
Transition from vacuum to matter osc.

Upturn is expected in ^{8}B spectrum.

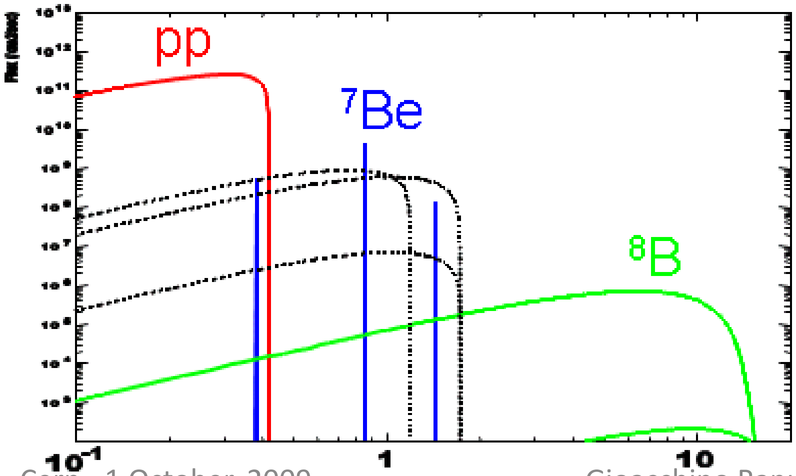
Vacuum osc. dominant

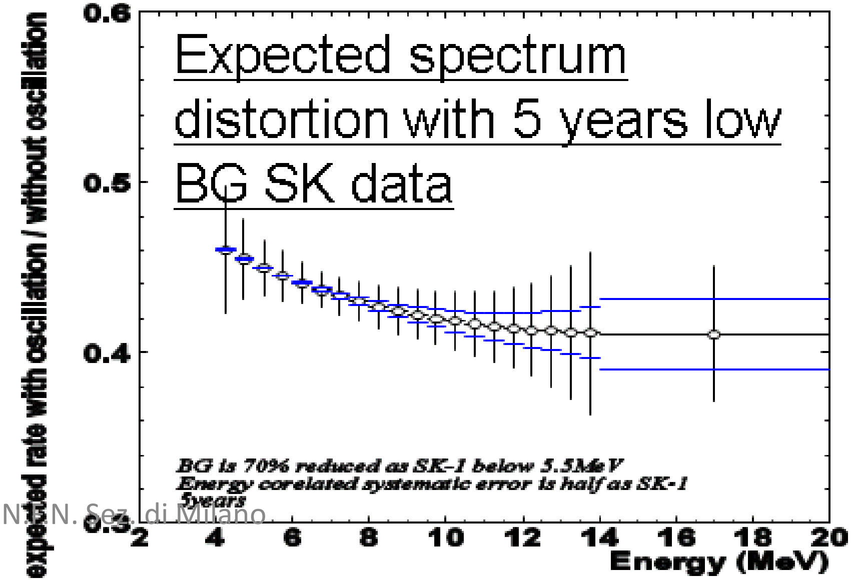
matter dominant

Aim to reduce background in SK



~70% reduction below 5.5MeV and lower threshold to 4MeV



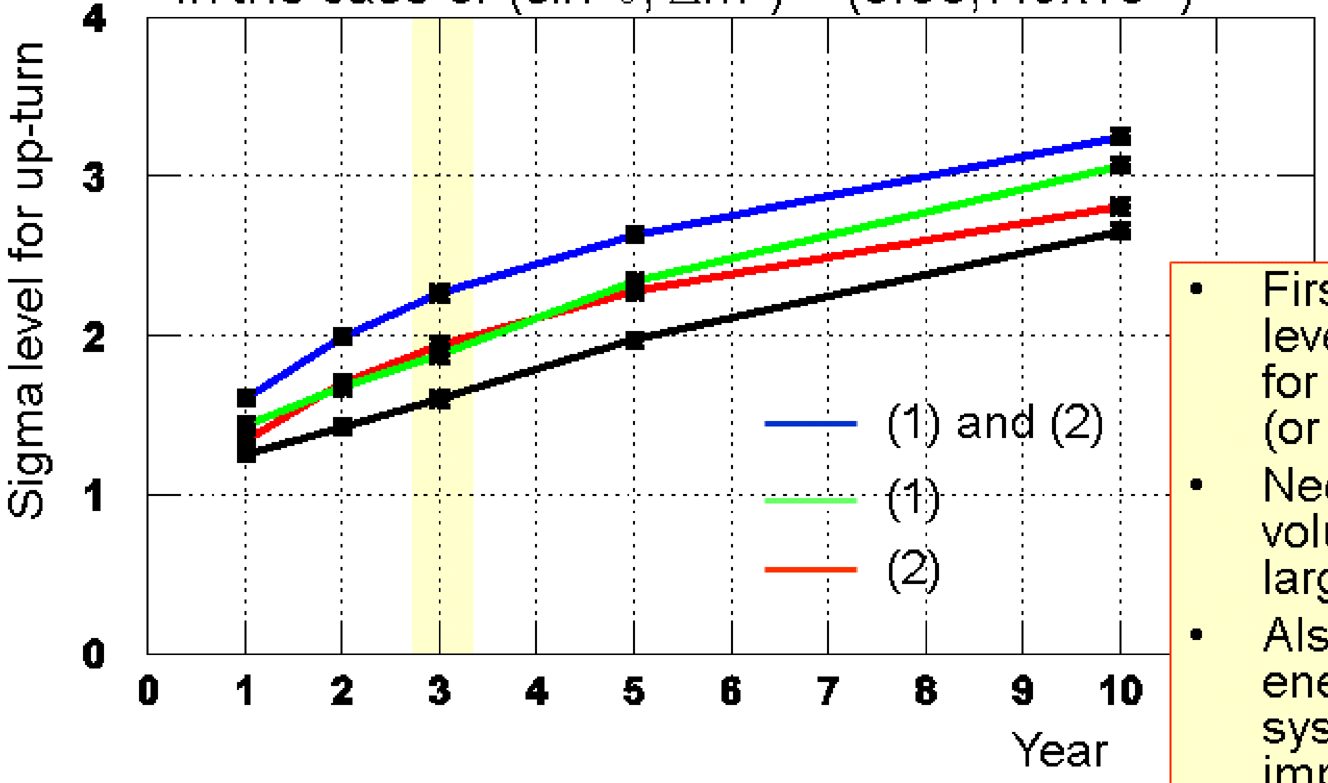


Expected spectrum distortion with 5 years low BG SK data

BG is 70% reduced as SK-1 below 5.5MeV
Energy corelated systematic error is half as SK-1
5years

Sensitivity of the upturn measurement

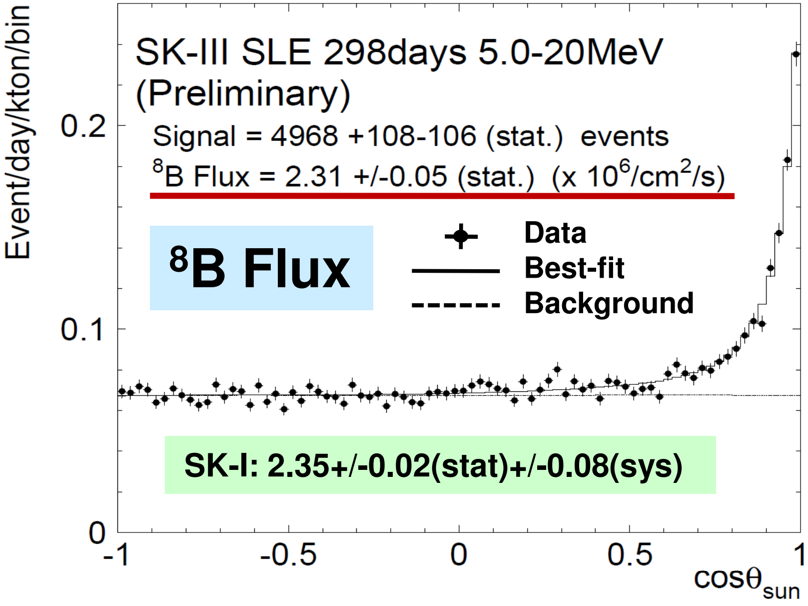
In the case of $(\sin^2\theta, \Delta m^2) = (0.30, 7.9\mathrm{x}10^{-5})$

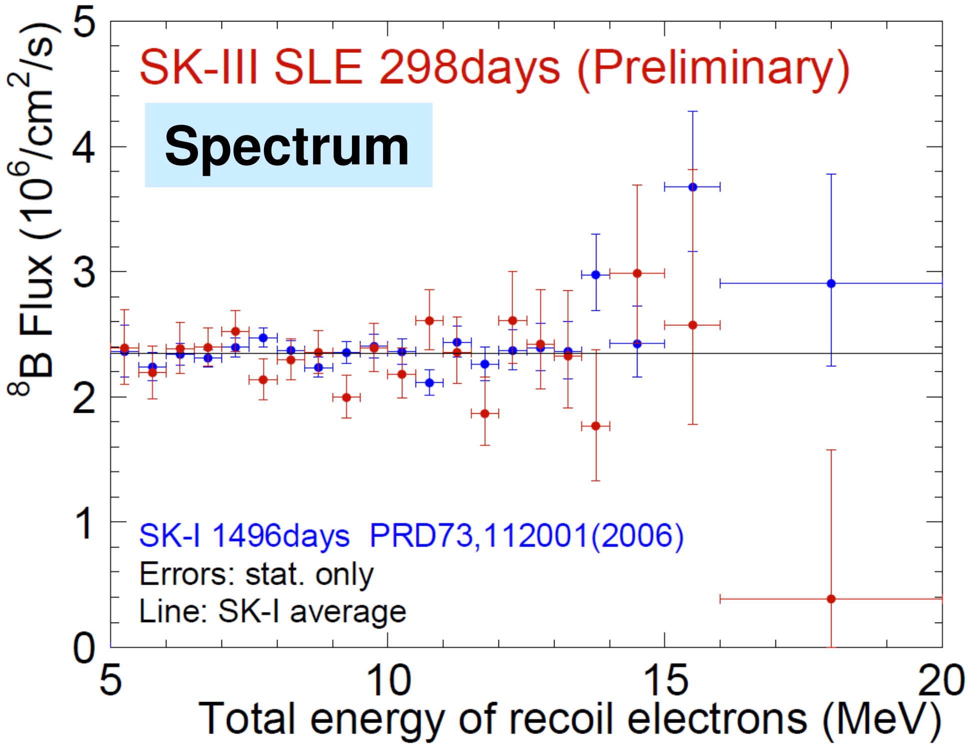


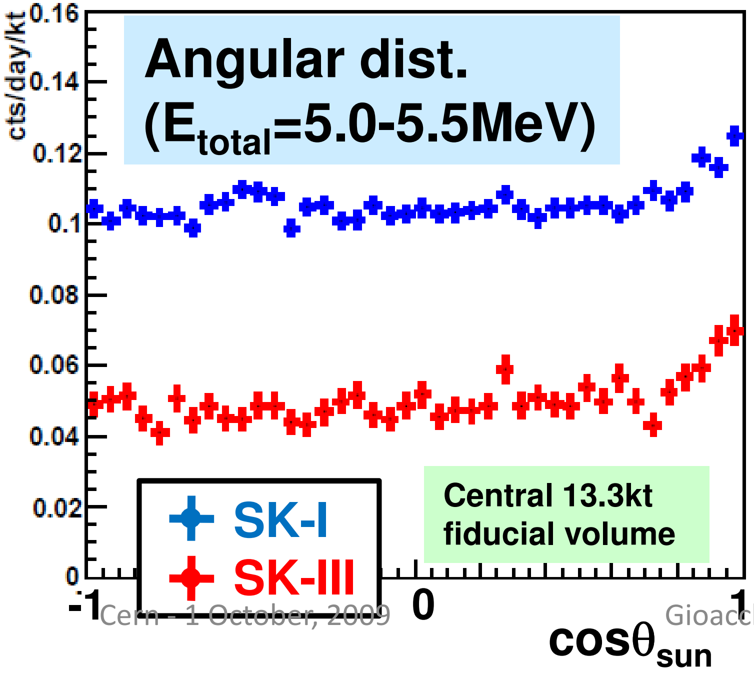
- First target : 2 sigma level up-tern discovery for 3 years observation. (or exclude the up-tern)
- Need to enlarge fiducial volume with low BG as large as possible
- Also the reduction of the energy correlated systematic error is important.

(1) Enlarge fiducial volume to 22.5kton with low B.G.
(2) Half energy correlated systematic error as SK-1.
The black line shows the 13.3kton (<5.5MeV), 22.5kton (>5.5MeV) fiducial volume with the same energy correlated error as SK-1.

Solar ν measurements in SK-III







- **Most of the reconstruction tools & reduction criteria are retuned recently.**
- **The improved reconstruction of event vertex & direction leads to 10% better angular resolution compared to SK-I.**
- **SK-III has lower background level in central area in low-energy region.**

Confusing non-zero teta$_{13}$ with non-standard interactions in the solar neutrino sector

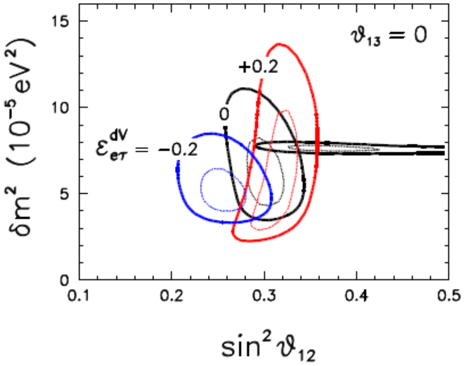
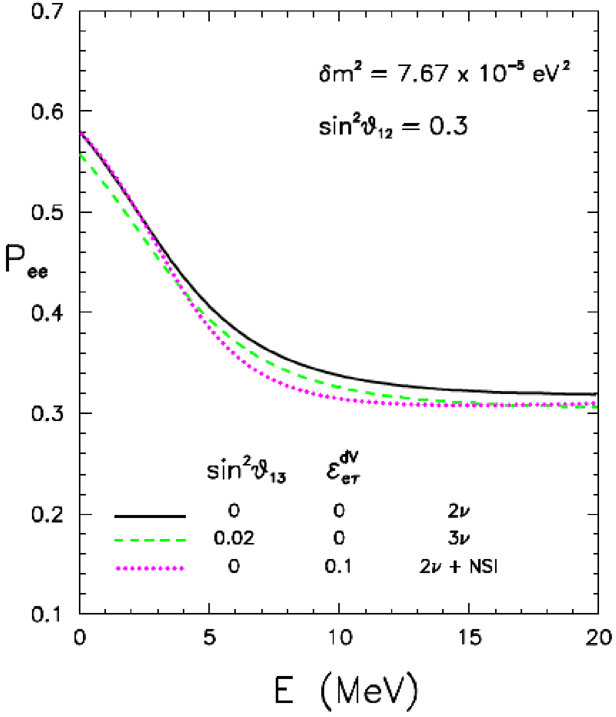


FIG. 1: Region of oscillation parameters allowed ($\Delta\chi^2 = 1, 4$) by KamLAND data (independent of FCI) superimposed to the solar LMA solutions obtained in the standard case $\epsilon^{dV}_{e\tau} = 0$ and for two representative non-standard cases with FCI having equal amplitude and opposite sign ($\epsilon^{dV}_{e\tau} = \pm 0.2$).



A. Palazzo, J. W. F. Valle Arxiv:0909.1535

FIG. 3: Solar ν_e survival probability (averaged over the ^{8}B ν production region) for three representative cases.

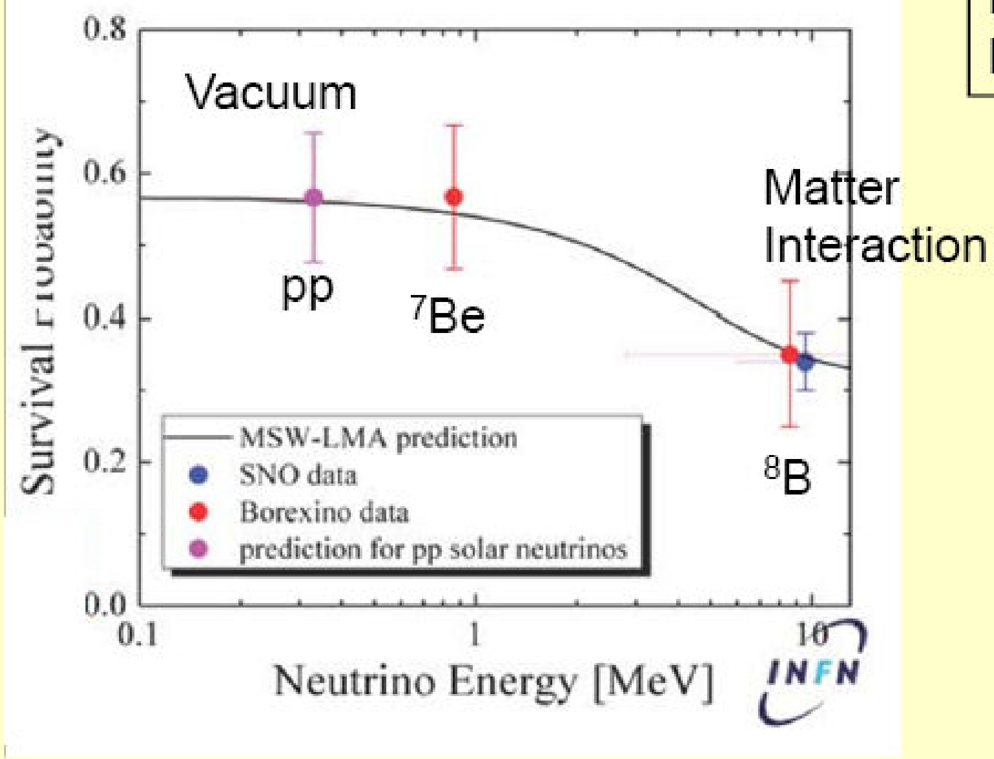
the possibility to disentangle the different behavior at intermediate energies could perhaps become realistic in high-energy experiments with a lowered threshold.

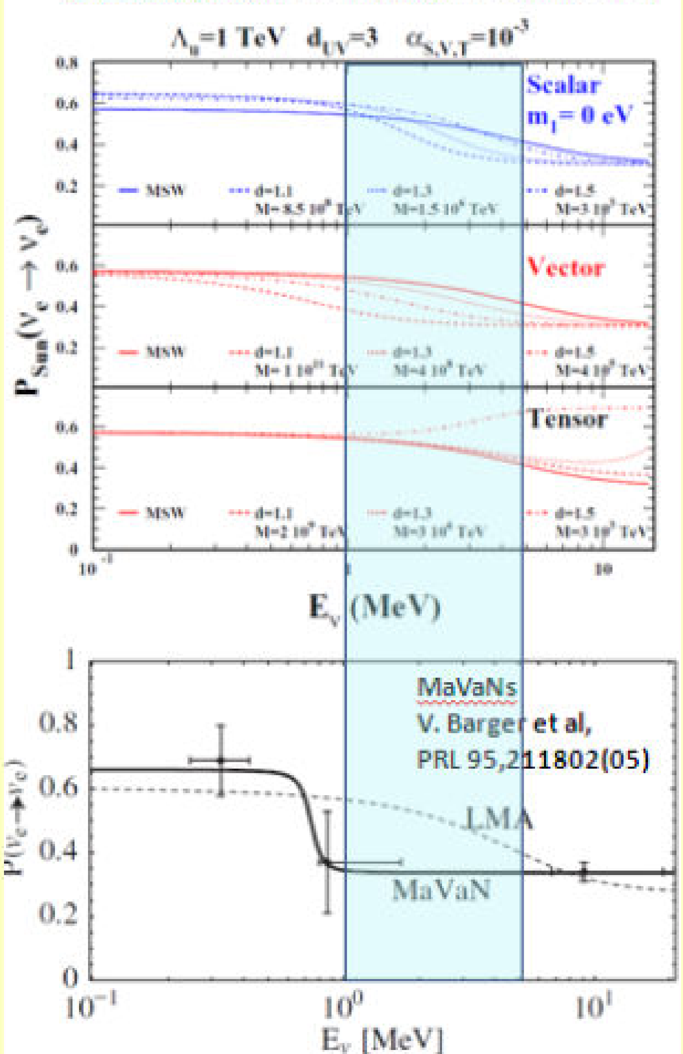
In this respect the new ^{8}B data expected from Borexino, Super-K-III, and from the low energy threshold analysis (LETA) underway in the SNO collaboration, may play an important role.

θ_{12}

The transition region (1 – 5 MeV) is a sensitive place to look for sub-dominant effects: Non-standard Int, Mass Varying ν

Recent BOREXINO





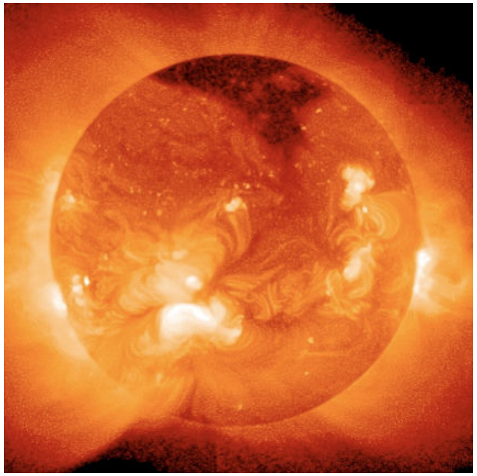
Long range force
M.C.Gonzalez-Garcia et al, hep-ph 0803.1180v2

MaVaNs
V. Barger et al,
PRL 95,211802(05)

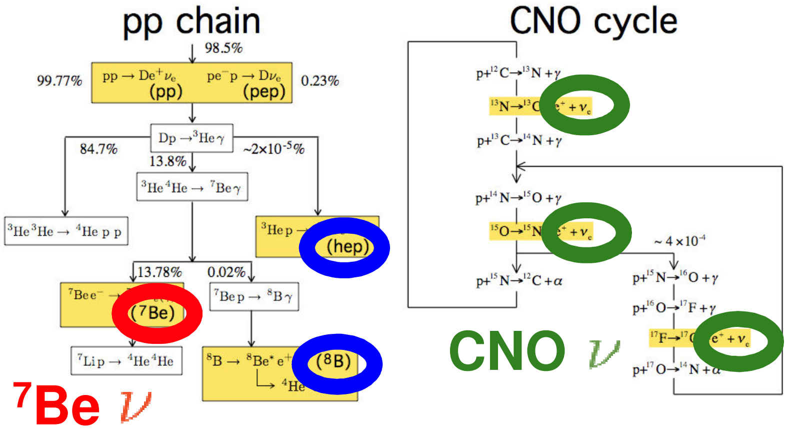
Future running: BOREXINO, KAMLAND, SuperK, SAGE (Source calibration?)
Being Developed: SNO+ (Recently Funded), LENS, MOON, CLEAN, XMASS

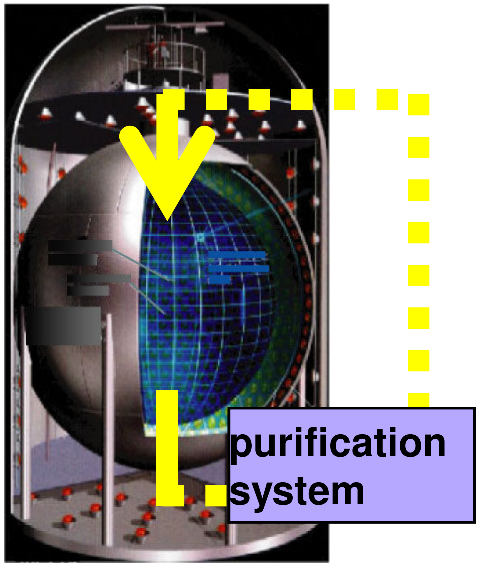
Other Interest:(BOREXINO, SNO+)
Measure pep (transition region),
Solar Models (Metallicity): CNO

Solar Neutrino in KamLAND



nuclear fusion reaction in the sun





Standard Solar Model (SSM)

J.N. Bahcall and A.M. Serenelli, Astro. Phys. J. 621, 85 (2005)

Model	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
BS05(AGS,OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
BS05(AGS,OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

GS98

AGS05

Test low abundance of heavy element (AGS05)

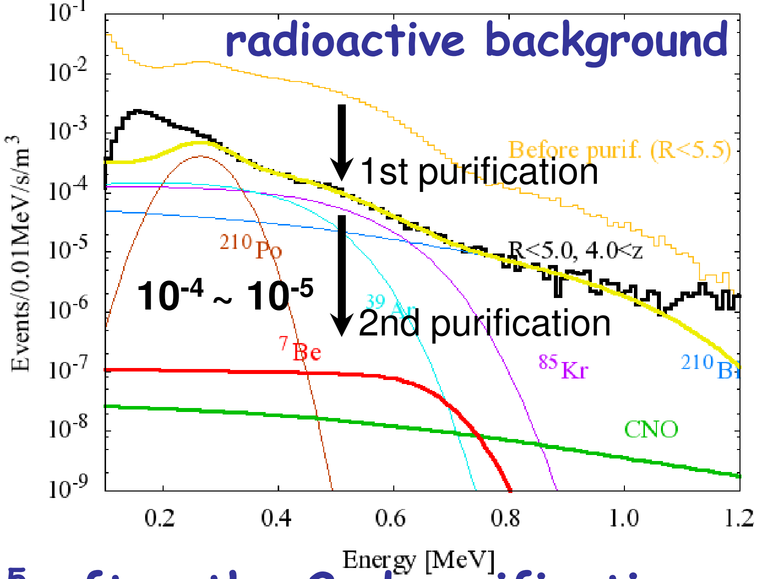
-10%

S_{34} : 2.5%

-38%

$S_{1,14}$: 8.4%

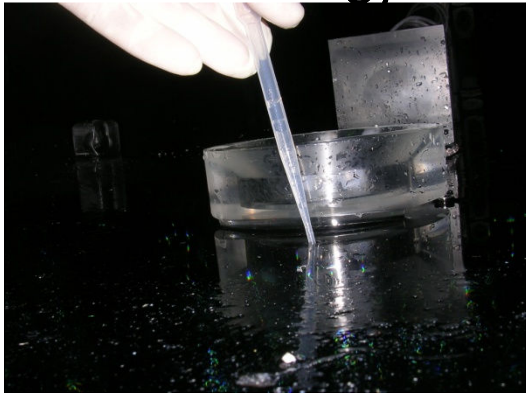
singles spectra after 1st purification

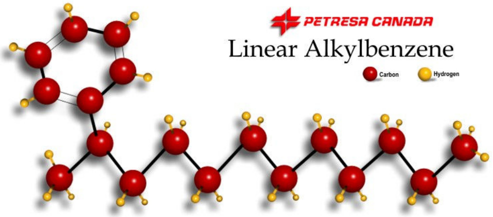


Radioactive BG reduction (^{85}Kr) : 10^{-4}~10^{-5} after the 2nd purification

SNO+

- \$300M of heavy water removed and returned to Atomic Energy of Canada Limited (every last drop)
- SNO detector to be filled with liquid scintillator
  - 50-100 times more light than Čerenkov
- linear alkylbenzene (LAB)
  - compatible with acrylic, undiluted
  - high light yield, long attenuation length
  - safe: high flash point, low toxicity
  - cheaper than other scintillators

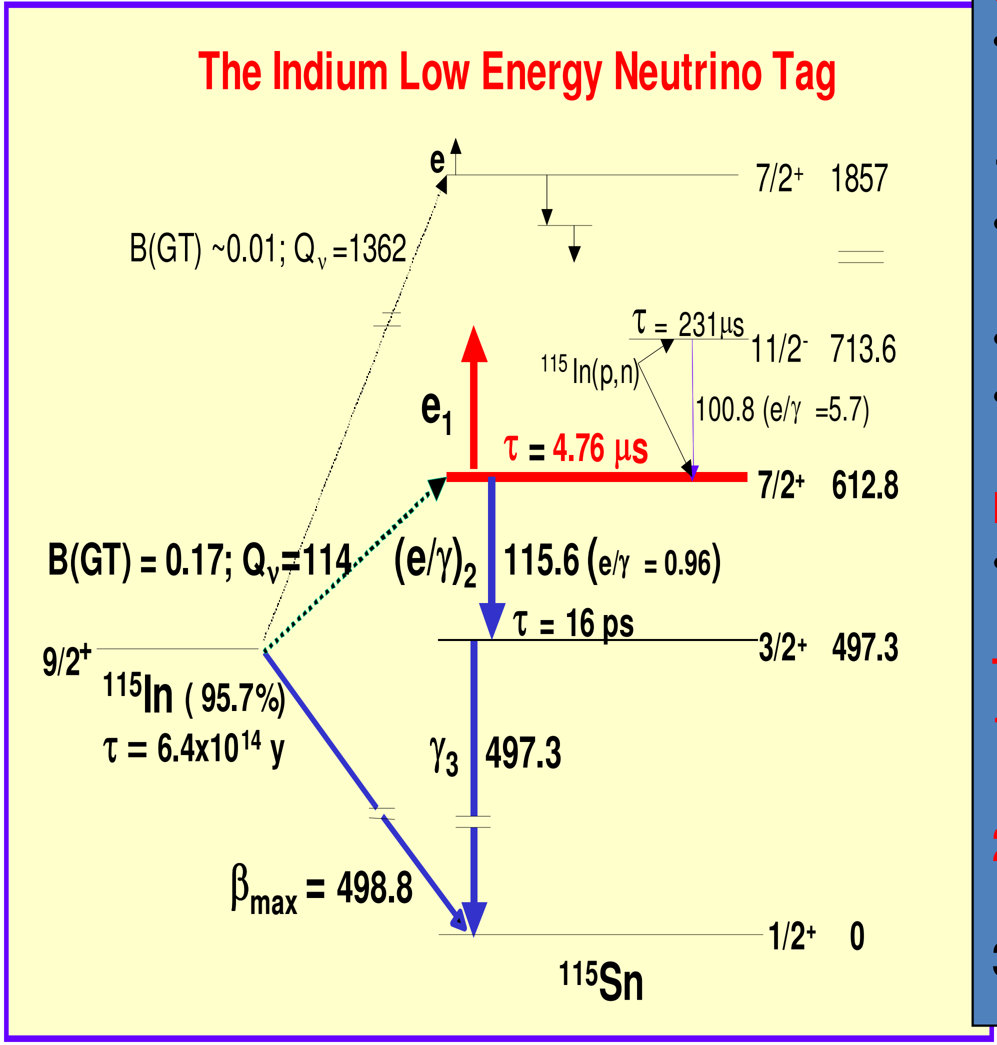




- physics goals: *pep* and *CNO* solar neutrinos, geo neutrinos, reactor neutrino oscillations, supernova neutrinos, double beta decay with Nd
- Approved and funded on June 2009

LENS Detection Scheme

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\mu s)2\gamma + {}^{115}Sn$$



The Indium Low Energy Neutrino Tag

Unique:

- Specifies ν Energy

  $E_\nu = E_e + Q$

→ Complete LE nu spectrum

- Lowest Q known→ 114 keV

  →access to 95.5% pp nu's

- Target isotopic abundance ~96%
- Powerful delayed coinc. Tag

  Can suppress bgd $=10^{11}$ x signal

Downside:

- Bgd from ^{115}In radioactivity to

  (pp nu's only)→ rate= 10^{11} x signal

Tools:

1. Time & Space coinc.→ Granularity

   (10^7 suppression already)

2. Energy Resolution—important for

   In betas <500 keV; ∑Tag = 613 keV

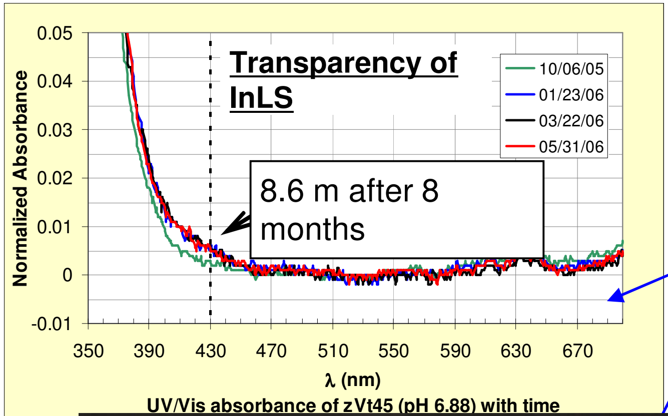
3. Other analysis cuts

Technology and Bgd Control

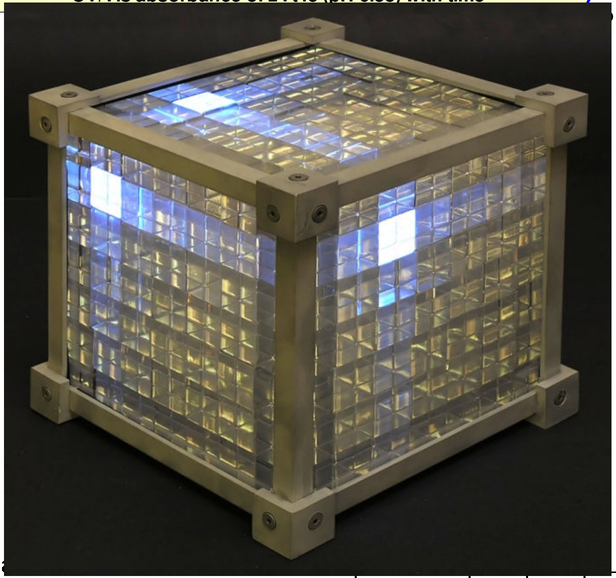
< Towards **Hi Precision** fluxes >

- **Hi Quality InLS**
- **New Detector Design**
- **Background Analysis Insights**

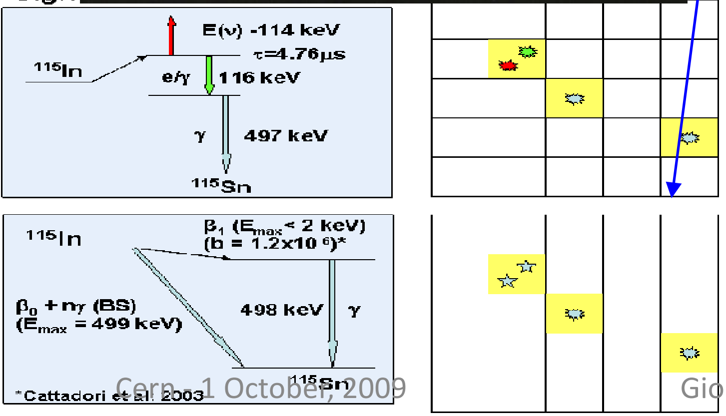
→ In decay bgd suppressed →S/N ~3 for first time



UV/Vis absorbance of zVt45 (pH 6.88) with time



	Status
Design of Detector	Cubic Lattice Chamber
InLS: In content Light attenutation L(1/e) Signal Eff Pe/MeV	>8% >8m 900
Indium Mass(1900 pp/5y)	10 ton
Total Mass	125 ton
PMT's	13,300
Neutrino detection eff.	64%



Raghavan@Physun workshop

Expected Result: Low Energy Solar ν-Spectrum

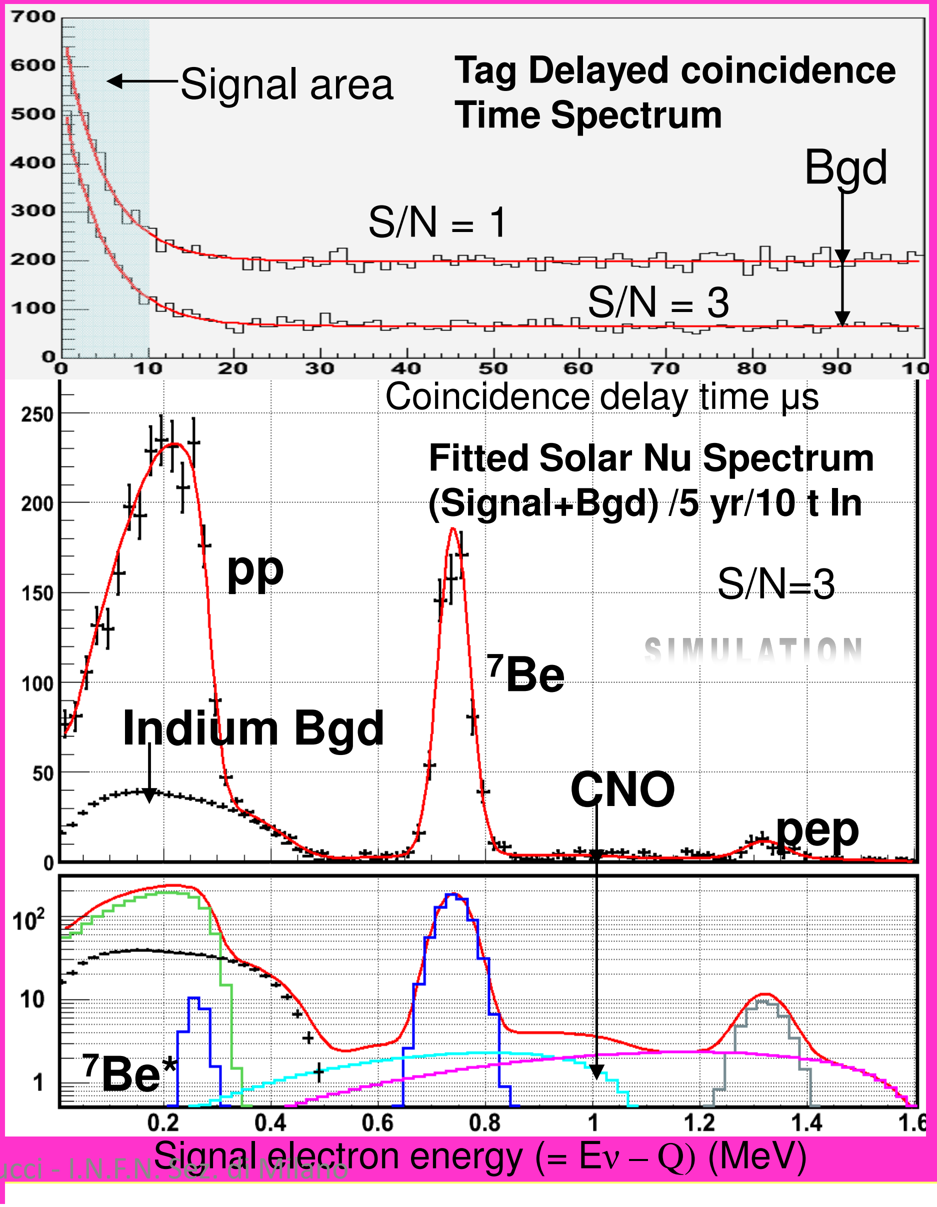
LENS Signal
[SSM(low CNO) + LMA
xDetection Efficiency ε]

pp: ε=64%;^{7}Be ^others: ε >85%

- → **Rate: pp 40 /y /t In**
- → **2000 pp ev. / 5y→ ±2.5%**
- → **Design Goal: S/N ≥ 3**

Access to pp spectral
***Shape* for the first time**

- **Valid Event: Coincidences only Not Singles—**
- **→Radiopurity <10^-13g/g, e.g.C14 OK**
- **ALL Bgd: Only Random Coinc.**
- **MEASURED Live with Signal at long delays—No uncertainty of bgd**
- **Signal extracted by exponential fit with known lifetime and stripped**
- **Bgd only for pp's—In decay <500 keV**

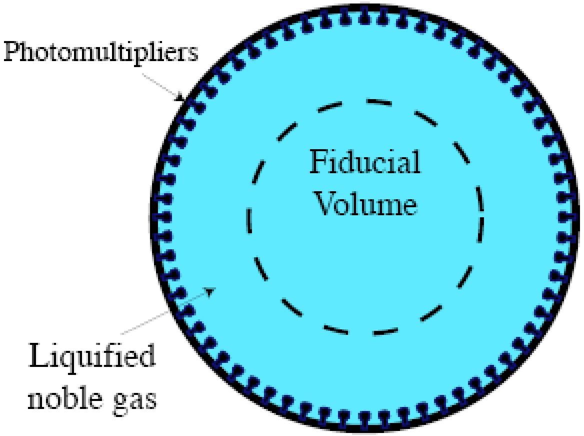


The CLEAN Approach

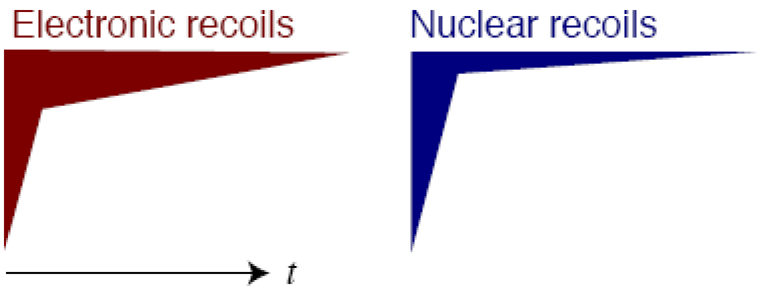
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

Liquid neon and liquid argon are bright scintillators (30,000 - 40,000 photons/MeV).
Do not absorb their own scintillation.
Are inexpensive (Ar: $2k/ton, Ne: $60k/ton).
Are easily purified underground.
Exhibit effective pulse shape discrimination.
Exchange of targets allows better characterization of radioactive backgrounds

Self-shielding



Pulse-shape discrimination



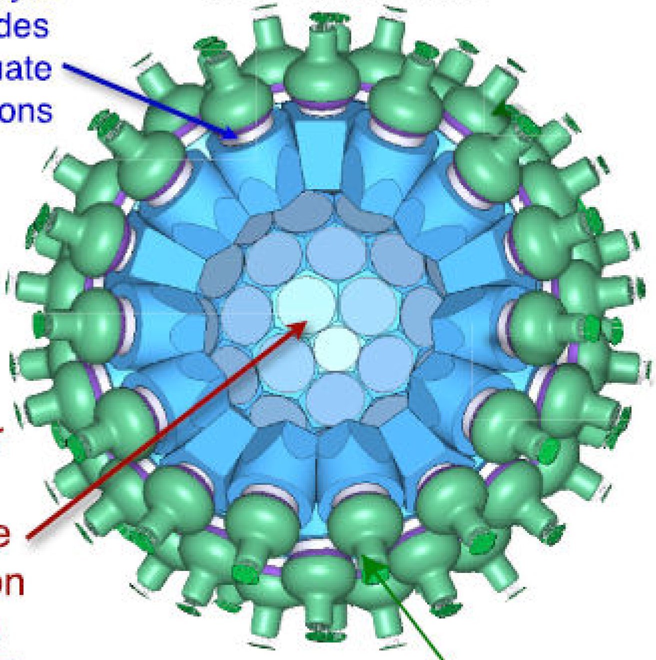
Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

Mini-CLEAN central detector

Single-phase LAr/LNe detector; high light detection and simplicity
Cryostat under construction; to be installed in SNOLAB in 2009

View of internals

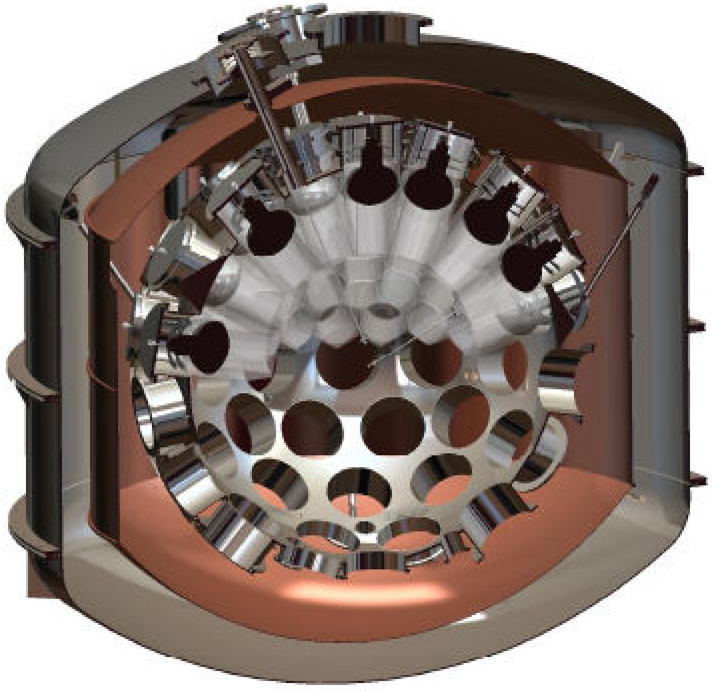


20 cm long acrylic
light guides
to attenuate
fast neutrons

360 kg of LAr
or
310 kg of LNe
in central region
inner surface
coated with TPB

92 Hamamatsu
R5912-02MOD
20 cm PMTs
fully immersed
in liquid

View of cryostat

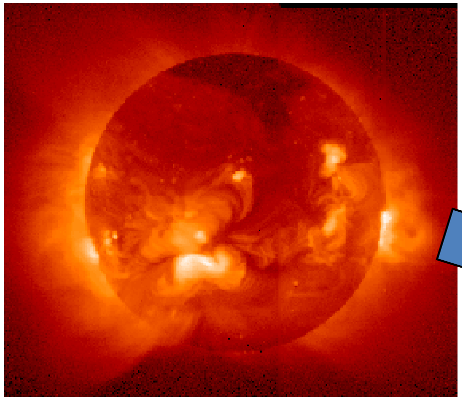


MINI-CLEAN 360 DETECTOR - SECTION VIEW

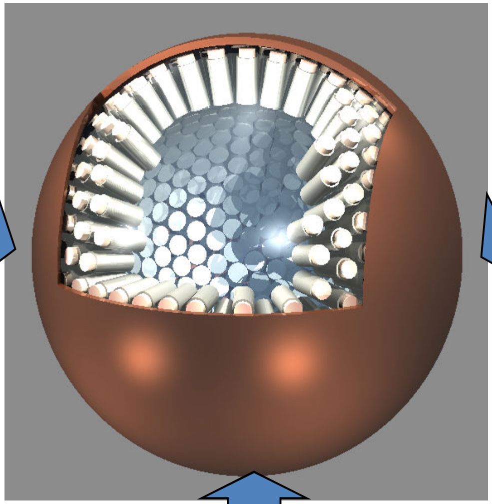
What's XMASS

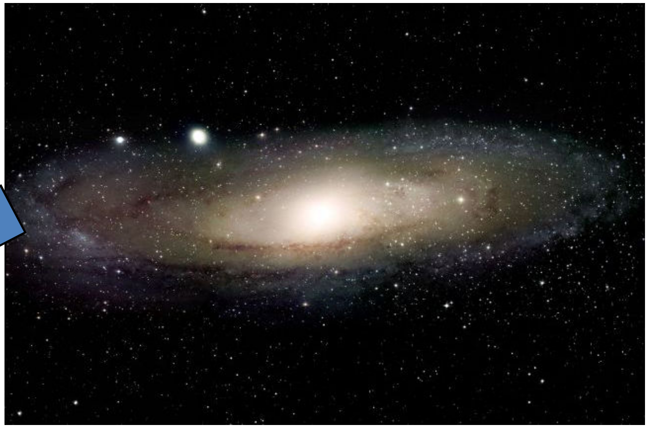
Multi purpose low-background and low-energy threshold experiment with liq. Xe

- **X**enon detector for Weakly Interacting **MASS**ive Particles (**DM search**)
- **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
- **X**enon neutrino **MASS** detector (**ββ decay**)

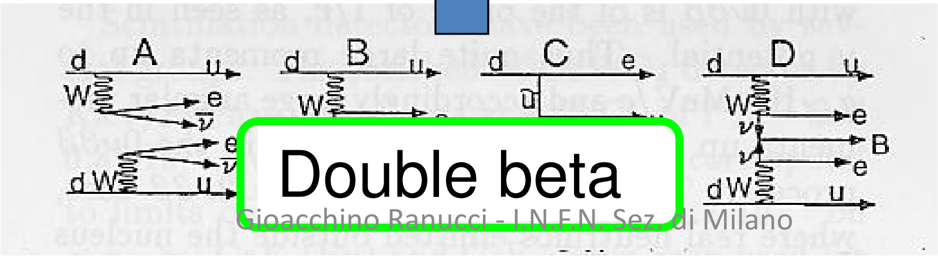


Solar neutrino



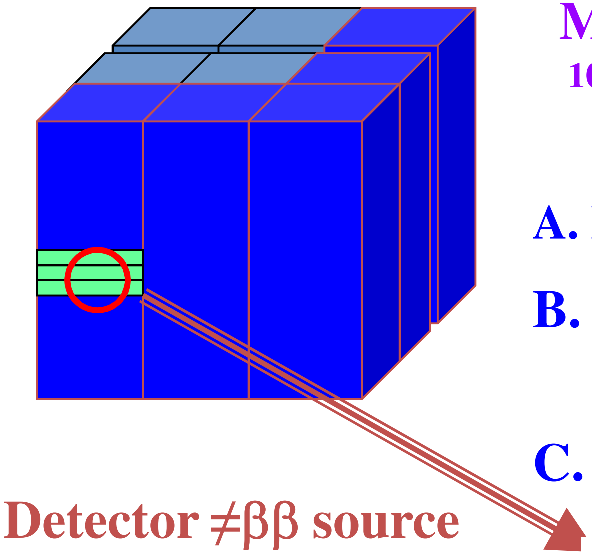


Dark matter



Double beta

MOON OSAKA CTU FNAL HU ICU JINR LANL UNC TU UW VNIIEF



Multilayer PL plates and PL fiber planes with thin ^{100}Mo source film for pp-Be7 solar ν and ββ with 30 meV.

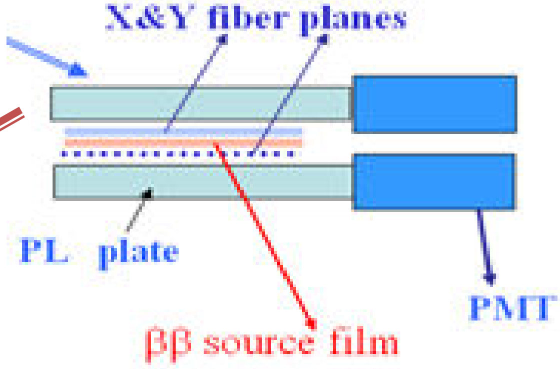
$\nu_e + {}^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Tc} + e^-$

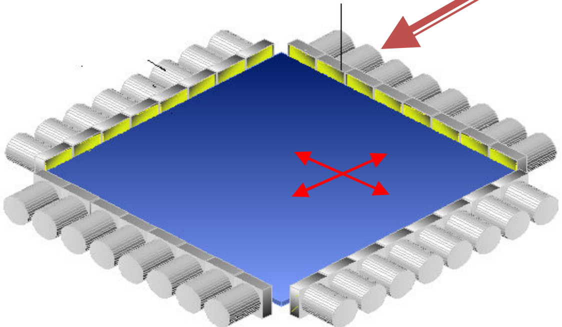
A. Low Q=0.17 MeV, large CC of 680 & 220 SNU for pp & ^{7}Be-ν.

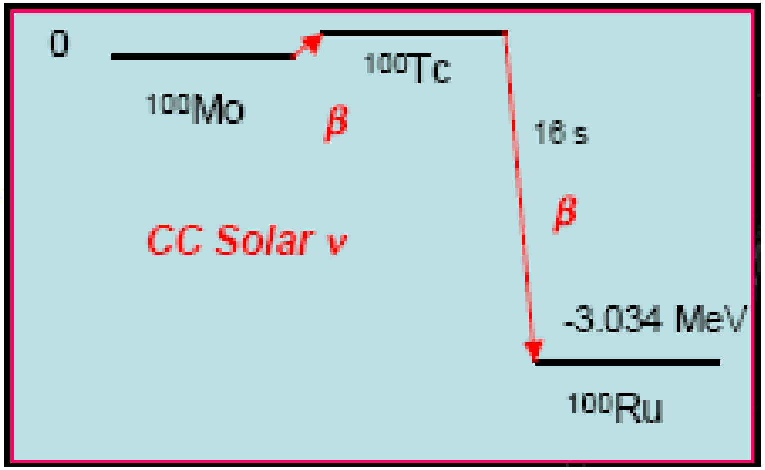
B. Real time studies of inverse β rays in delayed coincidence with the β decays from ^{100}Tc.

C. 9-units 0.27 ton 100m^3 , 32 units, 1 ton 300 m^3

Detector ≠ββ source
Select ββ sources
Solar ν as well

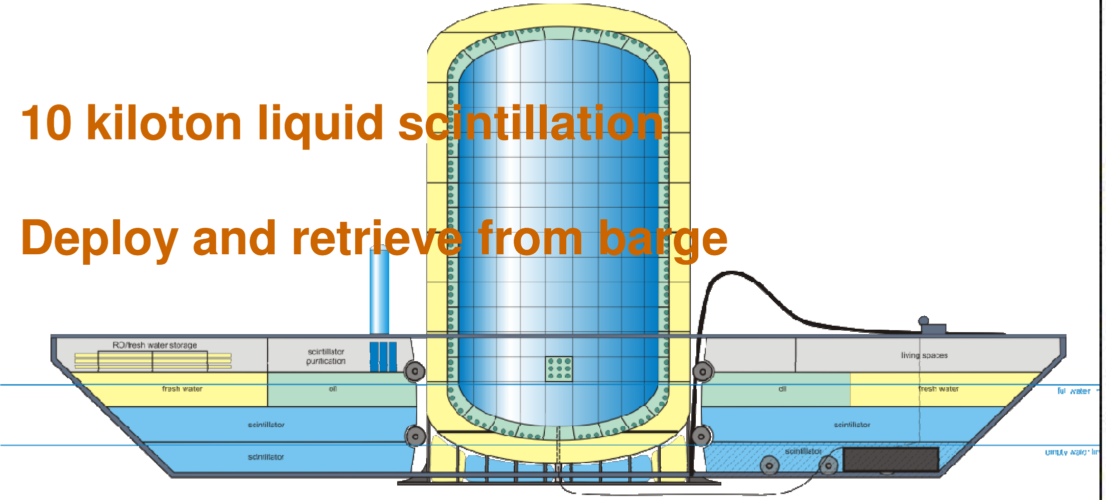






H. Ejiri, et al., PRL, 85, 2000.
H. Ejiri, J. Phys. Soc. Japan 74 2005.
H. Ejiri European Phys. J. 162 2008

Hanohano
a mobile deep ocean detector

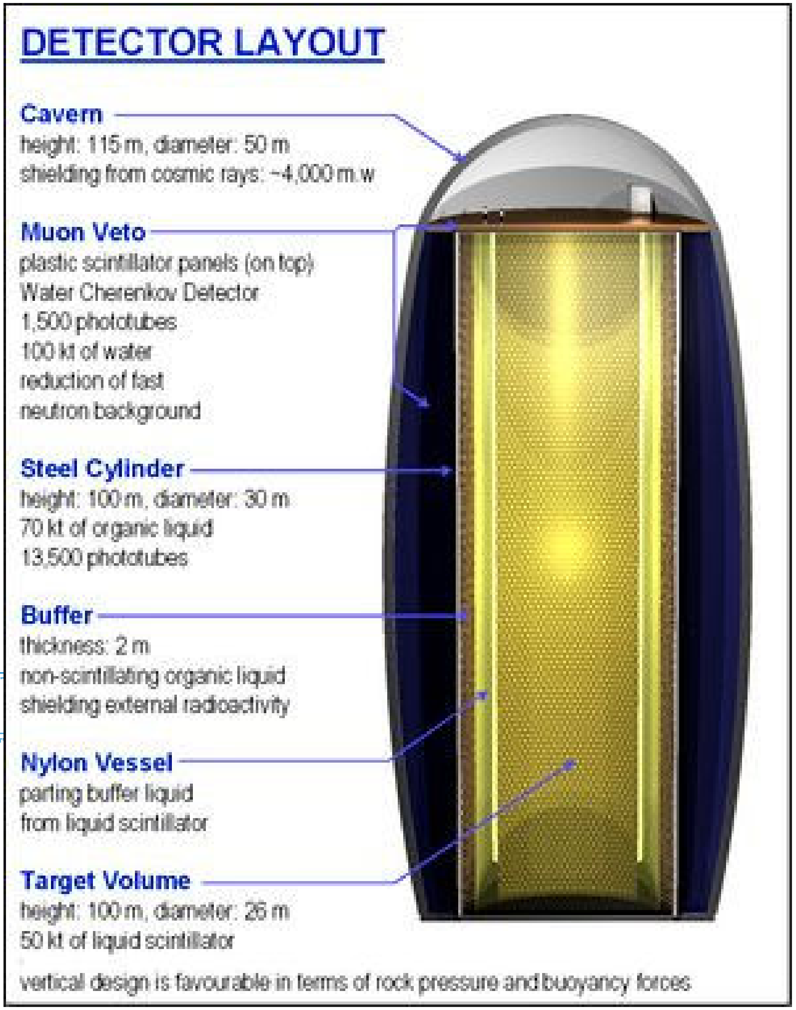


10 kiloton liquid scintillation

Deploy and retrieve from barge

100 kton-scale scintillator detector concepts

LENA,



DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

vertical design is favourable in terms of rock pressure and buoyancy forces

Conclusions

Solar neutrino physics is a field that has accumulated epochal successes, especially over the past decade, which constitute a solid heritage and foundation for the next round of precision experiments aimed to the accurate determination of the oscillation parameters.

Nevertheless , the perspectives of additional insights in the sub-MeV solar spectrum with the current and future solar experiments, as well as the low threshold investigation of the ^{8}B spectrum, pave the way for new interesting outputs especially for the non zero hint of θ_{13} and for further improvement on θ_{12} .

So this mature field still is in condition to express interesting promises for the further deepening of the understanding of the neutrino mass-mixing properties

" **I tell you: one must have chaos within oneself, to give birth to a dancing star.**" ~ Friedrich Nietzsche from *Thus Spoke Zarathustra*