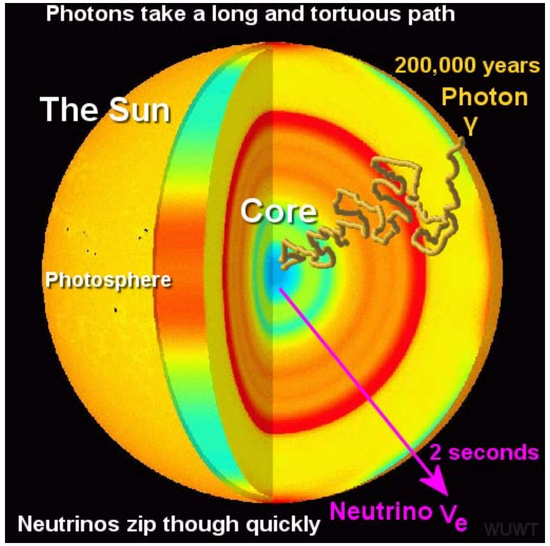
Low-Energy Neutrino Experiments (solar neutrinos)

LEPTON PHOTON 2017



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Lepton Photon Guangzhou
10-8-2017

One of the basic mankind's question: why does the Sun shine?

Ancient Greek's "chariot of the Sun" example of first developed "theories"

La *Sala del Tiepolo* in «palazzo Clerici» Milano

Turning point at the passage between 19th and 20th centuries

- In the 19th century hot controversy between Lord Kelvin and Darwin: age of he Earth and the Sun to account for the evolution of the life on our planet, incompatibility with the sources of energy known at that time

- Clue $\rightarrow$ Aston experiment in 1920: m(He)<4 m(H)

- Eddington: argued in his 1920 presidential address to the British Association for the Advancement of Science that Aston's measurement meant that the Sun could shine by converting hydrogen atoms to helium....

Formulation of the nuclear hypothesis

"If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race---or for its suicide"   A. Eddington

1938 Von Weizsacker $\rightarrow$ Identification of potential CNO cycle

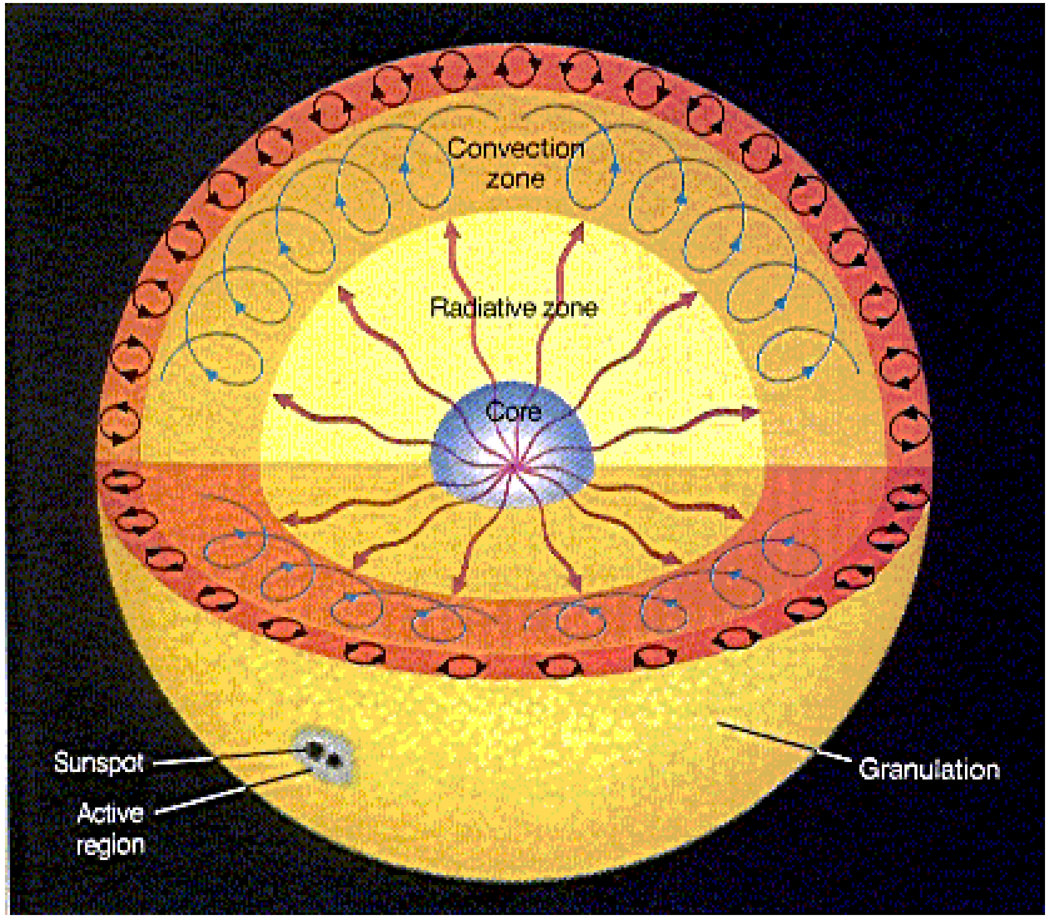
1938 Bethe $\rightarrow$ Identification of potential *p-p* chain and full definition of the nuclear hypothesis

How to prove it ?

Hypothesis : there are nuclear reactions occurring in the core summarized as

$$4\,{}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + \text{energy}$$

Can it be proved?



Yes, neutrinos coming from the reactions are the smoking gun! They pass undisturbed through the solar matter and if detected at Earth they would prove unambiguously the nuclear hypothesis; possibility debated in the context of the discussions about neutrino detection just after the world war II (Pontecorvo '47)

From this trigger the Solar Neutrino Saga: the experimental players taking part to an almost five decades long successful plot

Common ingredient in this challenging rare events search→ ultra-low background

Radiochemical experiments:

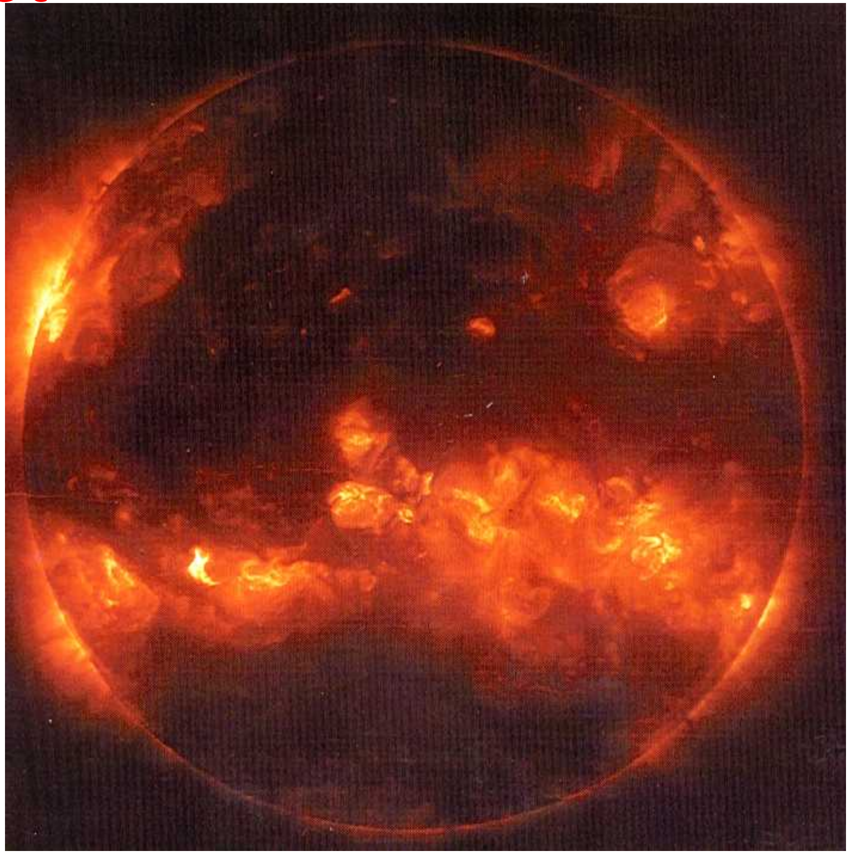
- **Homestake** (Cl)
- **Gallex/GNO** (Ga)
- **Sage** (Ga)

Real time Cherenkov experiments

- **Kamiokande/Super-Kamiokande**
- **SNO** (Heavy water)

Scintillator experiment

- **Borexino**



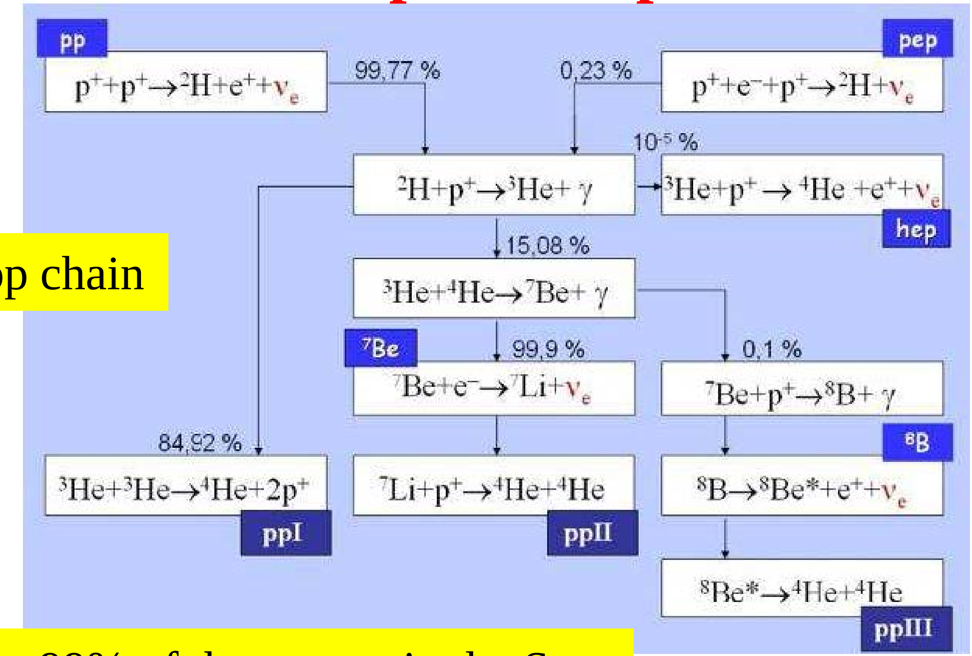
Overall two major accomplishments:

- proof of the Nuclear hypothesis
- Through the identification and solution of the "solar neutrino problem" → contribution to the proof of neutrino oscillations - MSW effect: resonant neutrino flavor conversion in matter

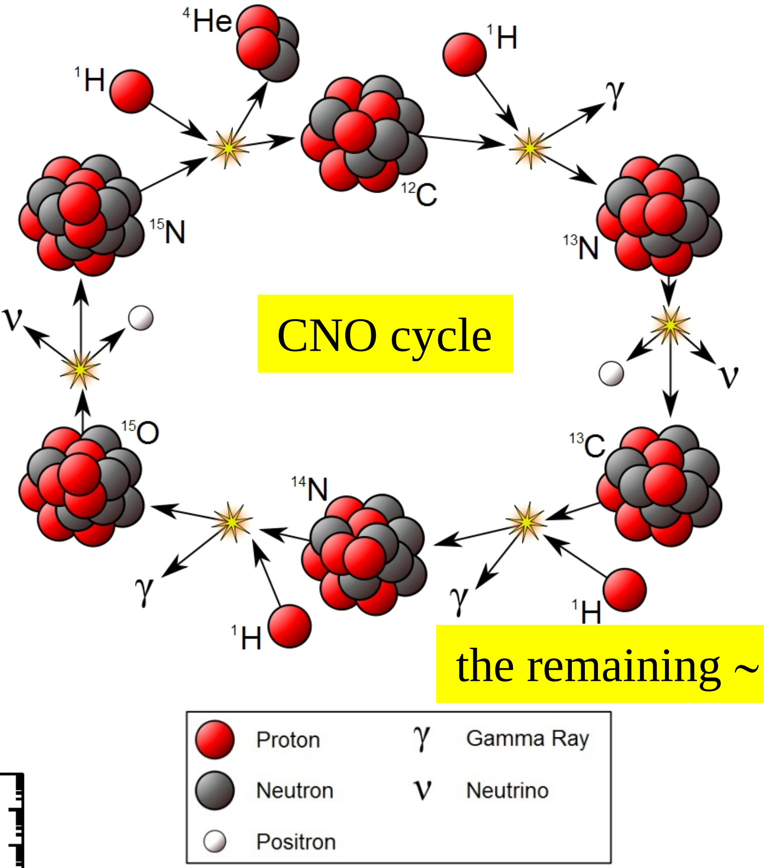
Where we are today theoretically: SSM Solar neutrinos production and spectrum predictions

Achieved with persistent dedication and devotion by John Bahcall over more than 40 years of enduring efforts

pp chain



~99% of the energy in the Sun



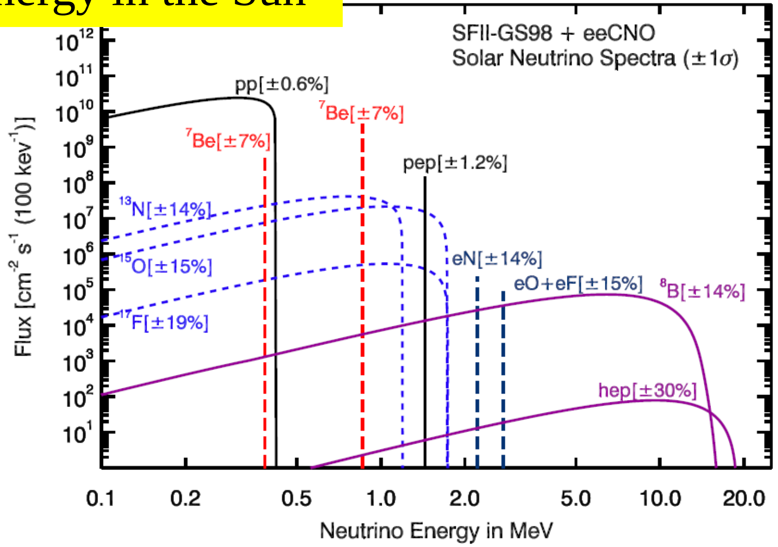
CNO cycle

Dominant in massive stars

the remaining ~1% ?

SSM spectral prediction

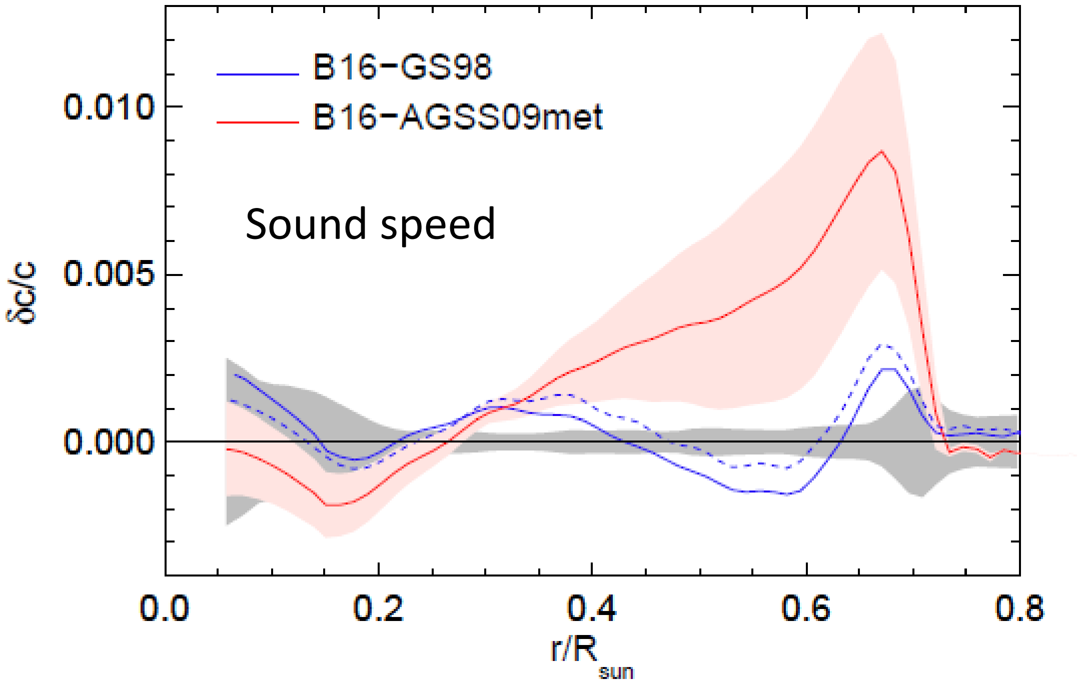
A. Serenelli arXiv:1601.07179



MeV

Not yet the end of the “story”: Controversy about the surface metallicity composition of the Sun still open: High Z vs Low Z models

Standard Solar Model vs Helioseismology



GS 98 high metallicity

AGSS09 low metallicity

N. Vinyoles et al.
arXiv:1611.09867v4

Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0^a

Helioseismology --> high-Z

But more sophisticated Sun's surface modeling→low-Z

The prediction of solar ν flux is sensitive to the Sun metallicity

Units:
pp: 10^{10} cm^{-2} s^{-1};
Be: 10^{9} cm^{-2} s^{-1};
pep, N, O: 10^{8} cm^{-2} s^{-1};
B, F: 10^{6} cm^{-2} s^{-1};
hep: 10^{3} cm^{-2} s^{-1}

Flux	B16-GS98 HZ	B16-AGSS09met LZ
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
CNO $\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
CNO $\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
CNO $\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

^{7}Be: 8.7% diff
^{8}B: 17.6% diff
CNO: 40% diff

N. Vinyoles et al.
arXiv:1611.09867v4

The experimental measurement of the CNO flux is the clue towards the resolution of the metallicity puzzle

The ultimate frontier of the **solar neutrino saga** to understand the SUN

Other intriguing detected and potential effects make the field very vital and of persistent attraction also for the continued study of neutrino properties

Radiochemical methods

The radiochemical technique exploits a detection target which, upon absorption of a neutrino, is converted into a radioactive element whose decay is afterwards counted.

Experiments of this kind: Homestake, Gallium Detectors (Gallex/GNO, SAGE)

The pioneering Homestake experiment was based on the inverse beta reaction

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \quad \text{(threshold 0.814 MeV)}$$

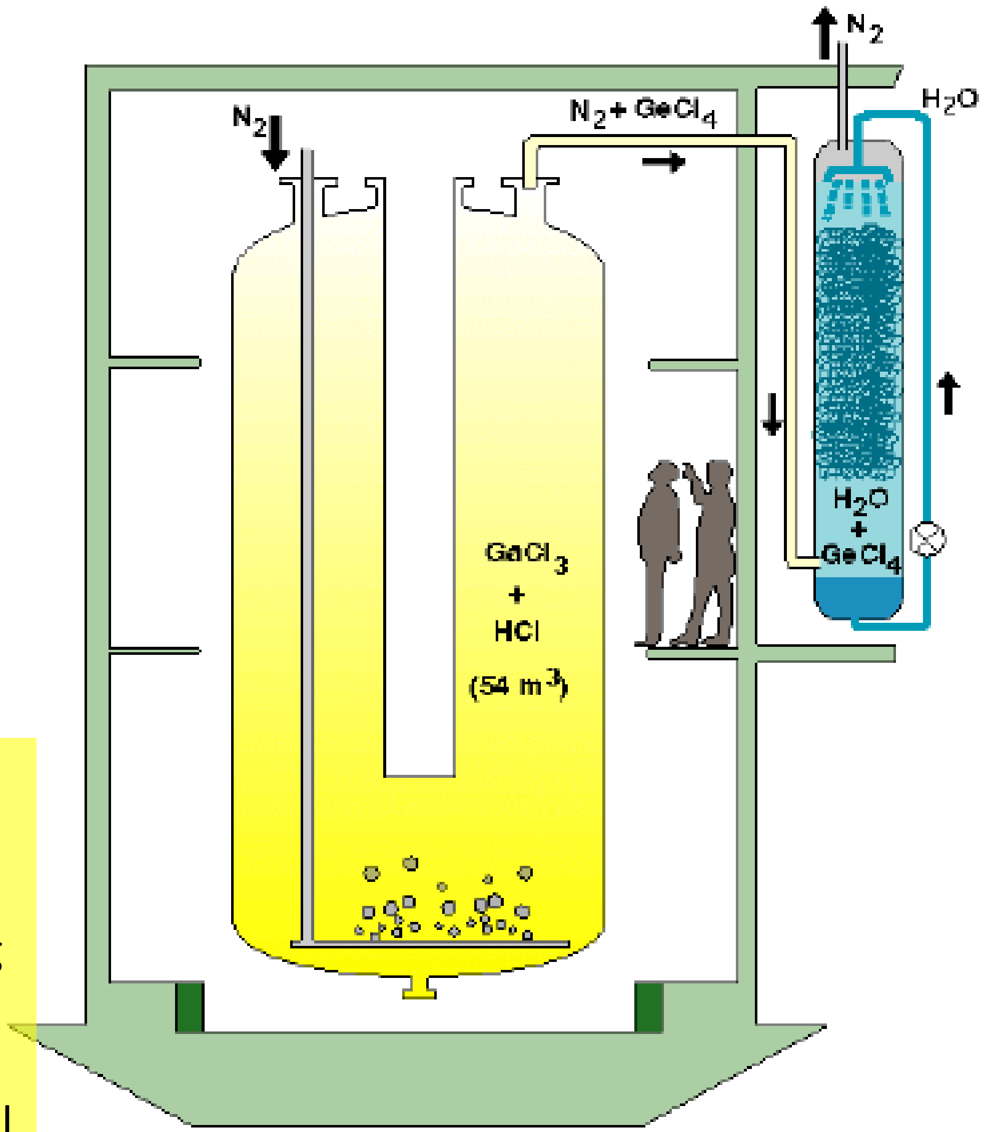
(method proposed by Pontecorvo (1946) and later independently by Alvarez (1949))

The Gallium experiments are based on the reaction:

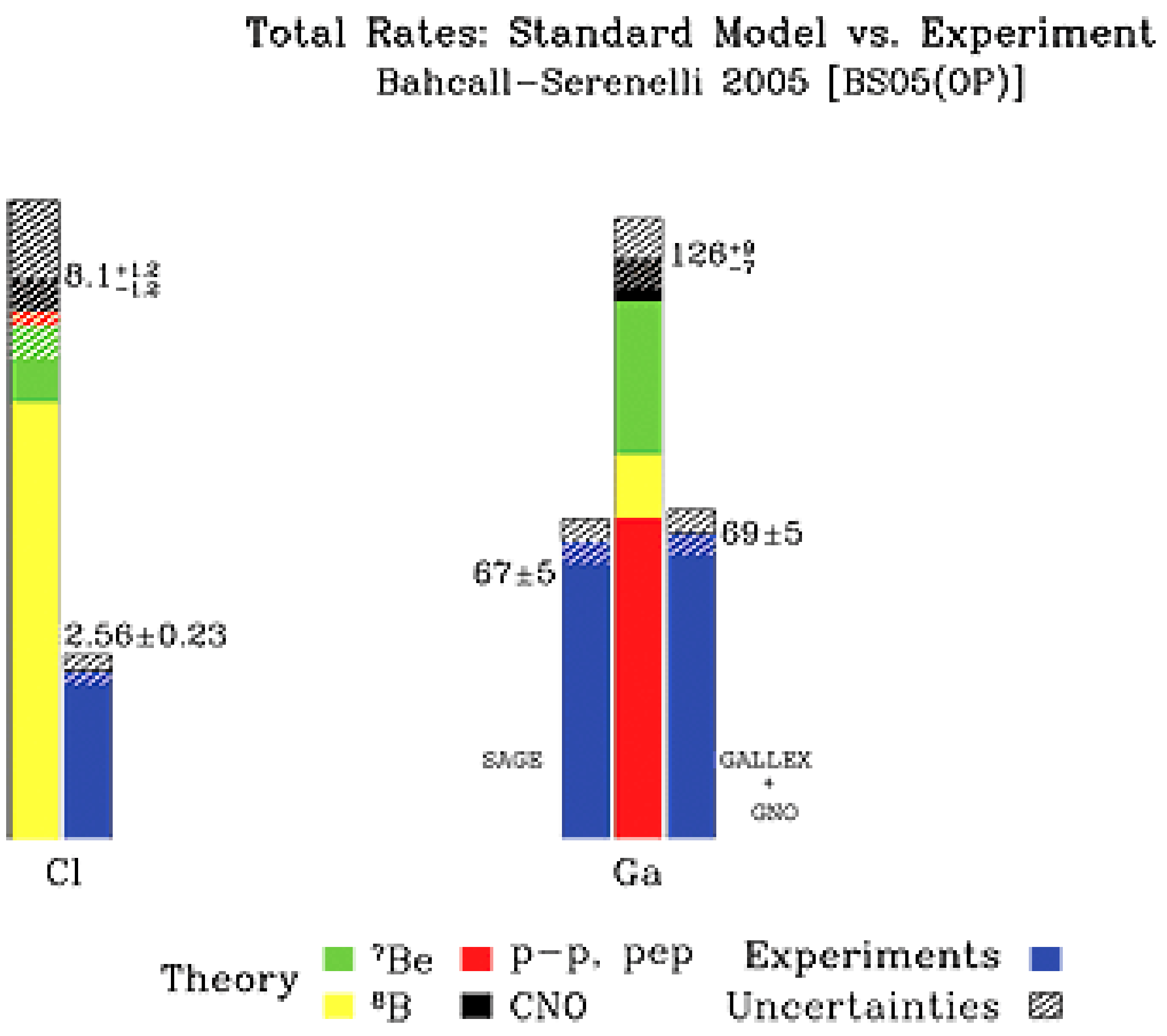
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^- \quad \text{(threshold 0.233 MeV)}$$

(proposed by Kuzmin in 1965)

GNO/Gallex Tank



After 4 weeks about 10 ^{71}Ge nuclei present in solution - extracted through nitrogen purging converted into Germane gas and counted in miniaturized proportional counters



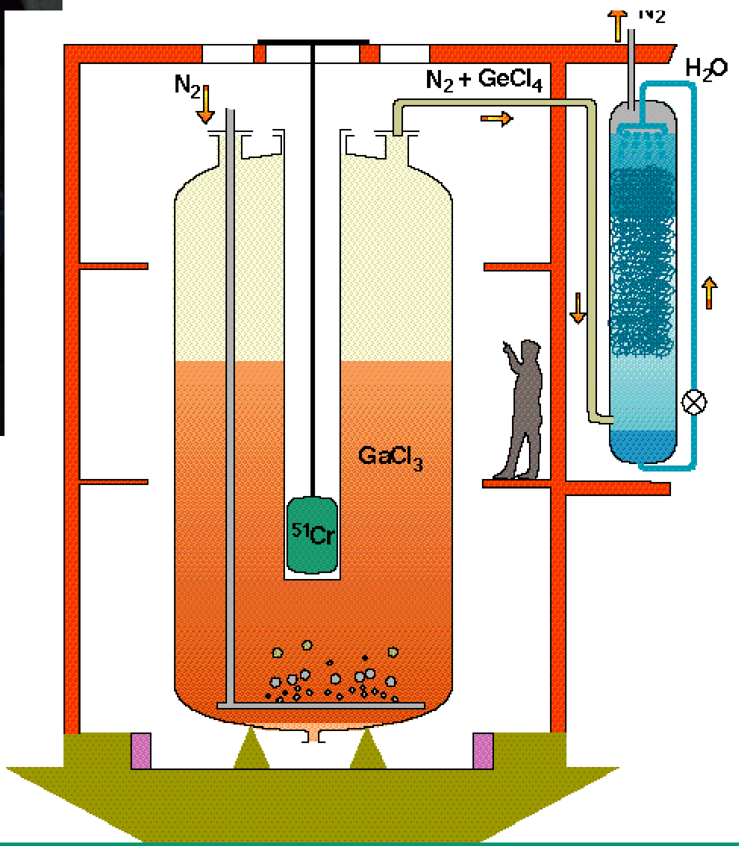
First Homestake data release 1968
Gallex data release in 1992 Grenada Neutrino Conference

From the historic transparencies of John the birth and the evolution of the SNP (Solar Neutrino Problem)

a) Homestake identified first the problem

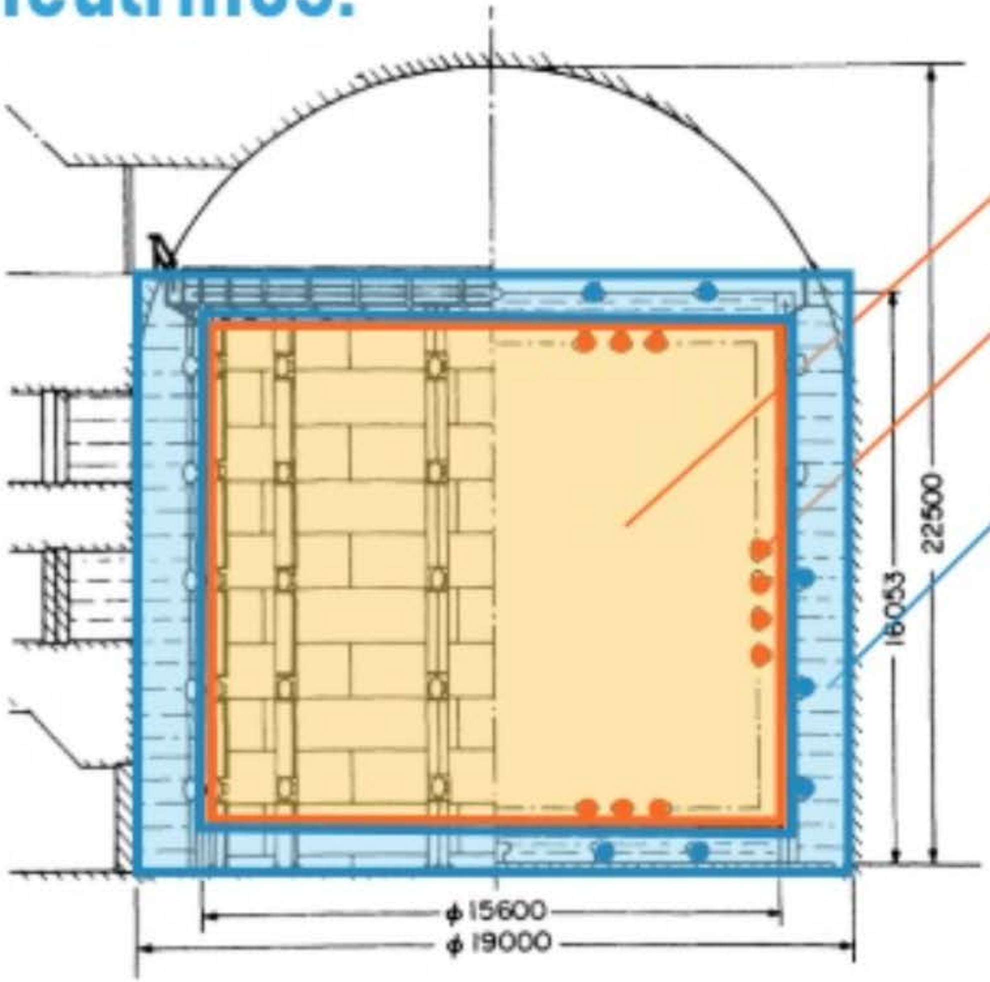
b) The Gallium experiments confirmed it and provided the first initial proof of the pp mechanism fueling the Sun by detecting very low energy neutrinos which were identified as the pp neutrinos

Important part of the overall methodology: global demonstration of the method with a ^{51}Cr neutrino source



Reproduced also in Sage

Upgraded Kamiokande II aimed to detect solar neutrinos.



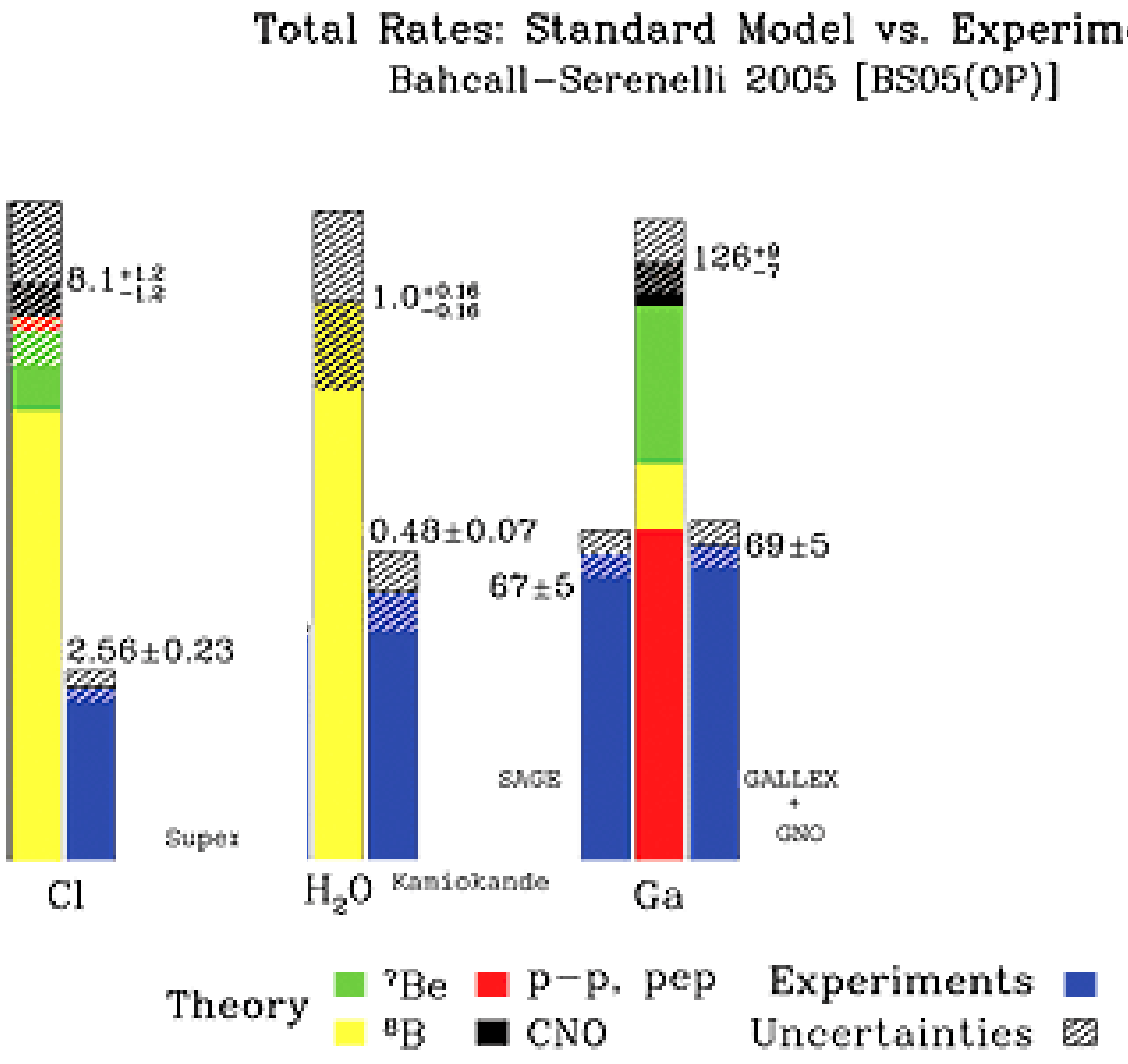
- Real-time detection
- Directional sensitive
- Energy threshold of 8.8 MeV

In Between Cl and Ga
→ Kamiokande II

Confirmation of the SNP with a totally different technique

Water based Cherenkov detector

Elastic scattering of neutrinos off electrons



The situation in the middle of the 90's

SNP firmly established by the data of four experiments and their comparison with the SSM (very similar to that reported here with the 2005 version)

The contemporary era: towards the SNP solution and beyond

SNO -> passing the baton to SNO+

Borexino -> running

Super-Kamiokande -> running

The Sudbury Neutrino Observatory: SNO

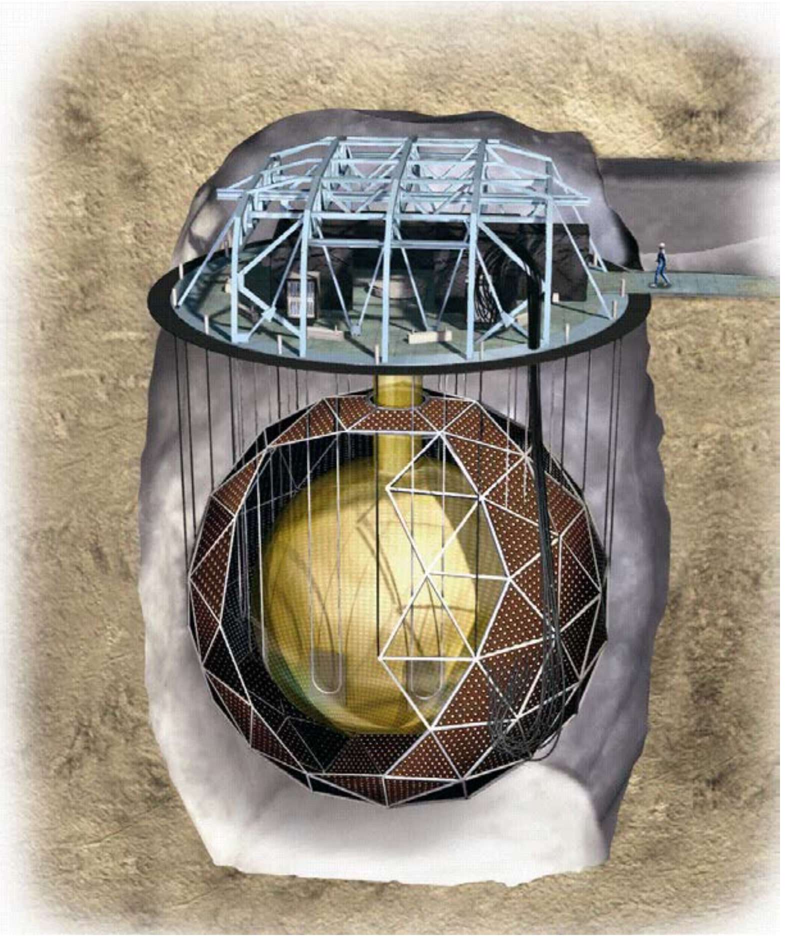
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
($300 million)

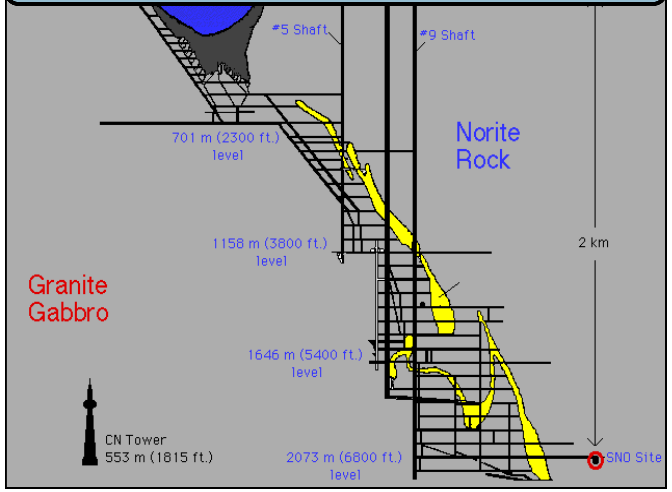
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMT's



6800 feet (~2km) underground

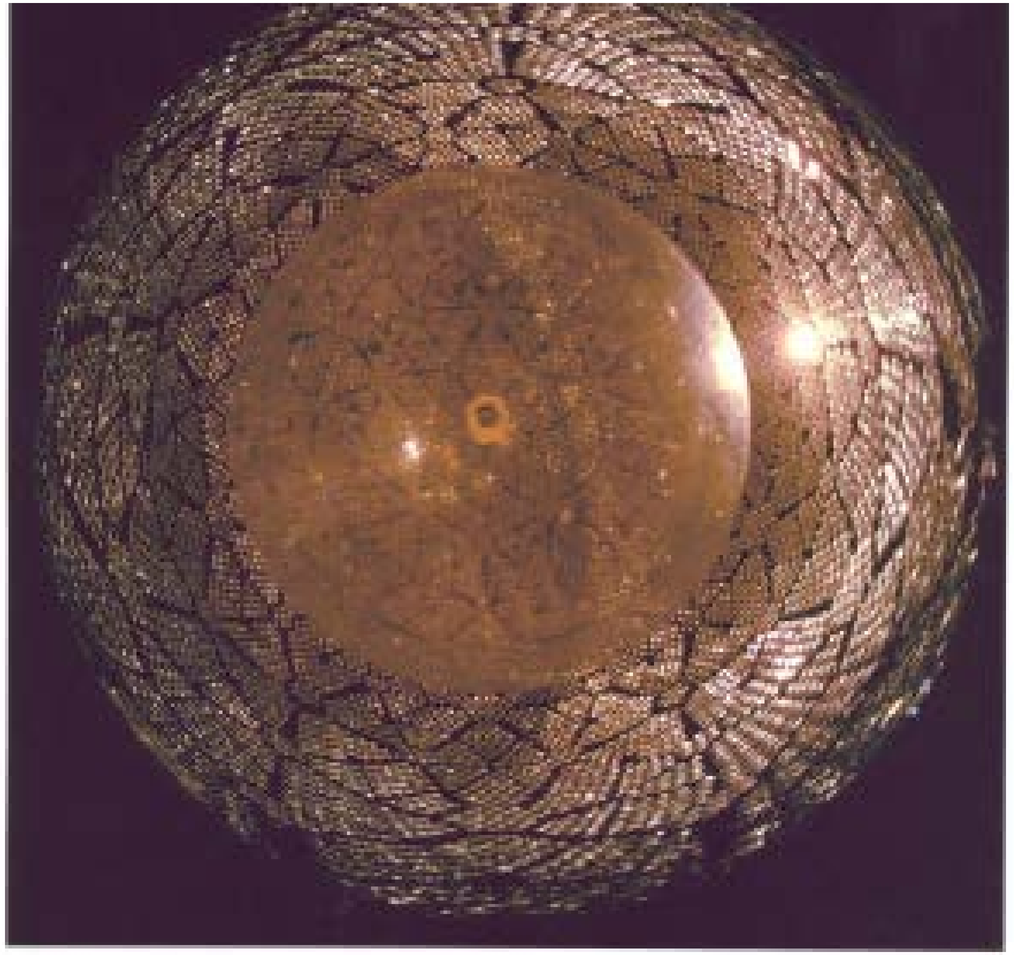


Creighton mine
Sudbury, CA

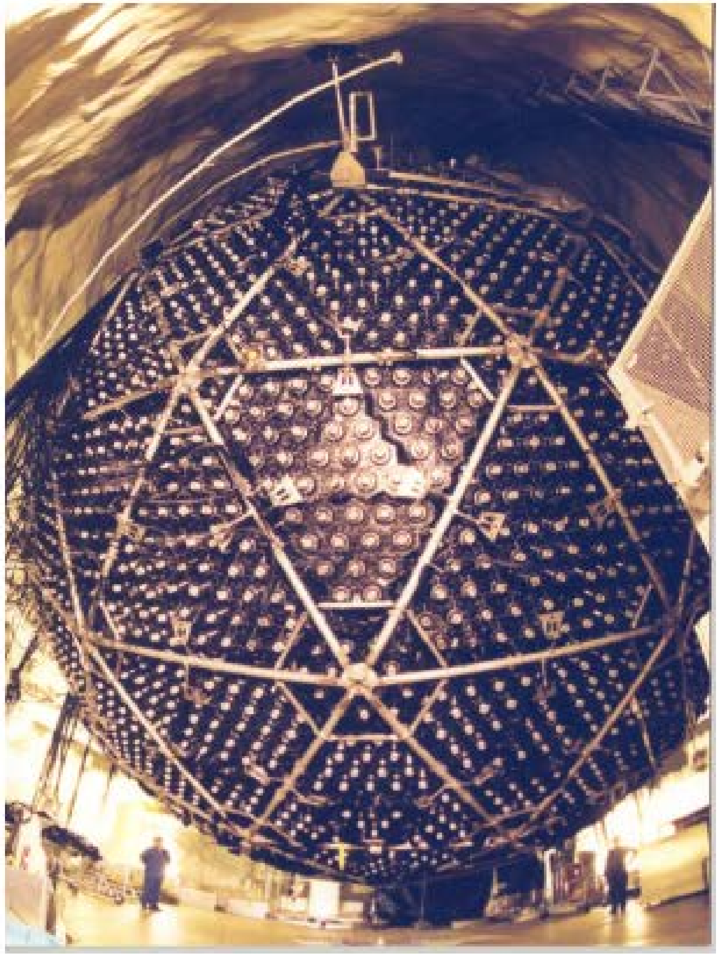
- Entire detector Built as a Class 2000 Clean room
- Low Radioactivity Detector materials

The heavy water has been returned and development work is in progress on SNO+ with liquid scintillator and ^{130}Te additive.

The acrylic vessel surrounded by the lattice of PMTs



PMT's sphere (external view)



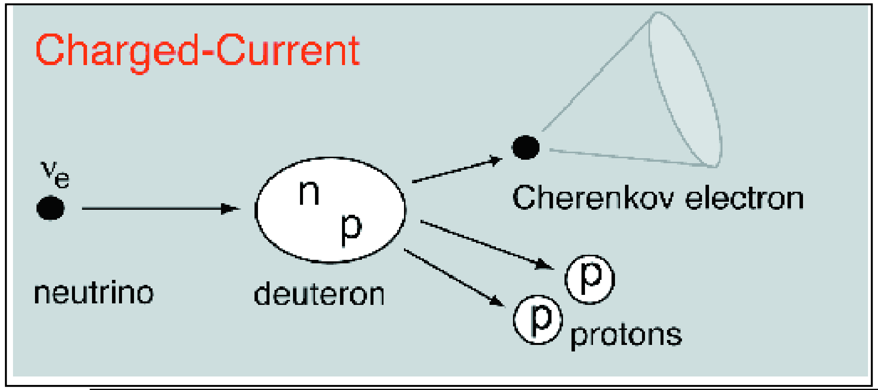
Summary of Signatures in SNO (D_2O)

Charged-Current (CC)

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

$E_{thresh} = 1.4$ MeV

ν_e only

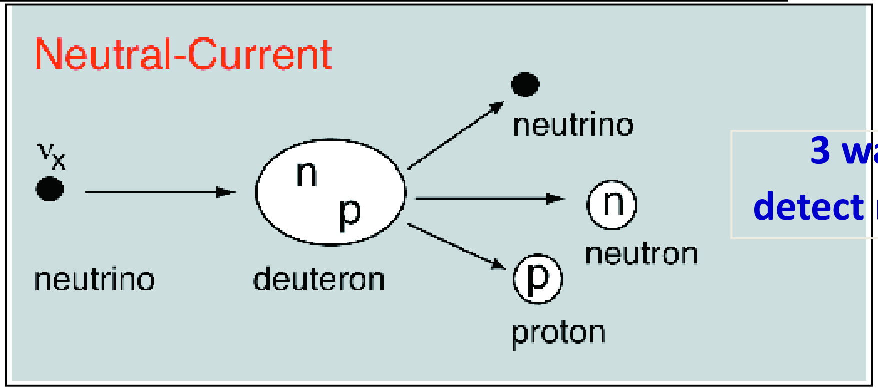


Neutral-Current (NC)

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

$E_{thresh} = 2.2$ MeV

Equally sensitive to $\nu_e\ \nu_\mu\ \nu_\tau$



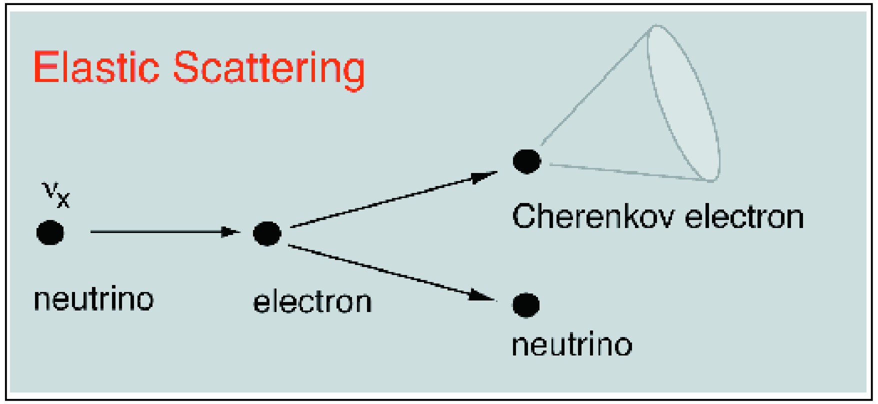
3 ways to detect neutrons

Elastic Scattering (ES) **(D_2O & H_2O)**

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

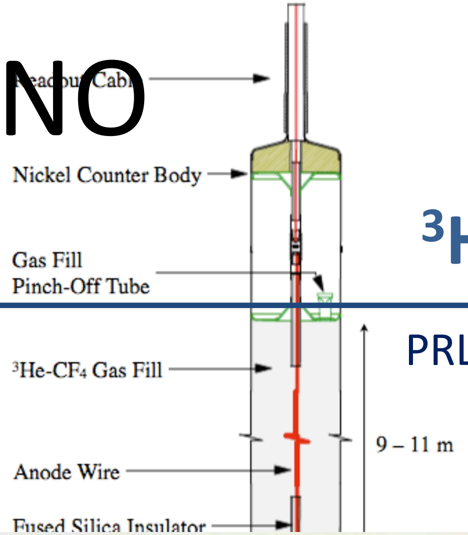
ν_x, but enhanced for ν_e

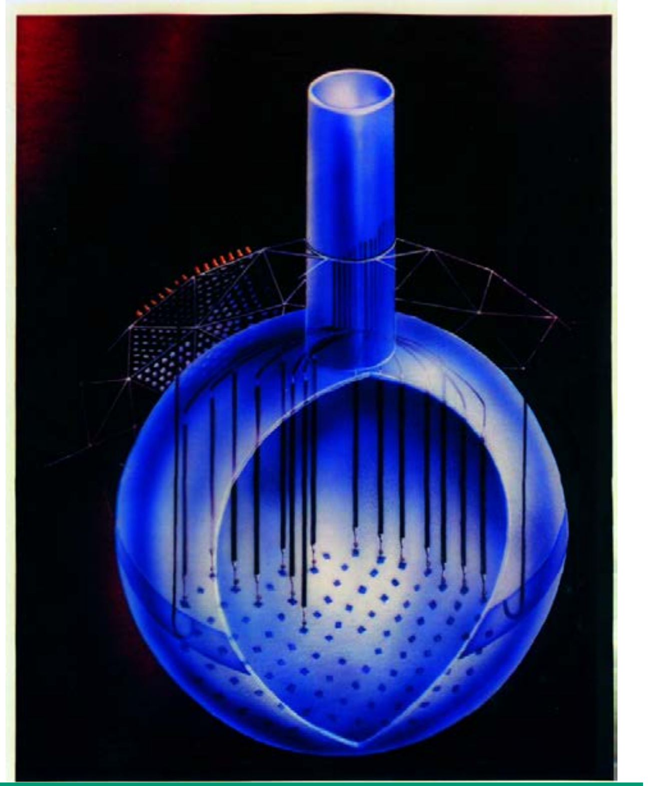
Events point away from the sun.



Three Phases of SNO

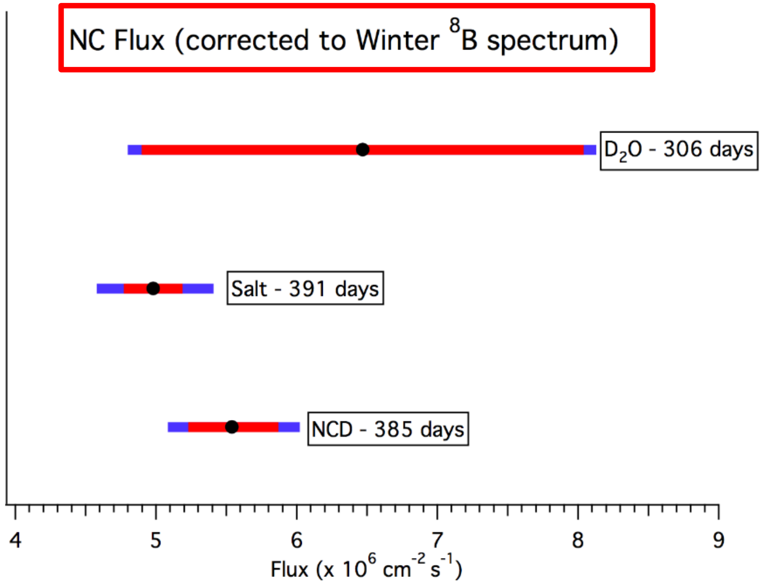
Pure D_2O	**Salt**	**^{3}He counters**
Nov 99 – May 01	**Jul 01 – Sep 03**	PRL 101, 111301 (2008)
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	
$(E_\gamma = 6.25\ MeV)$	$(E_{\Sigma\gamma} = 8.6\ MeV)$	
	enhanced NC rate and separation	
PRL **87**, 071301 (2001)		
PRL **89**, 011301 (2002)		
PRL **89**, 011302 (2002)	PRL **92**, 181301 (2004)	
PRC **75**, 045502 (2007)	PRC **72**, 055502 (2005)	

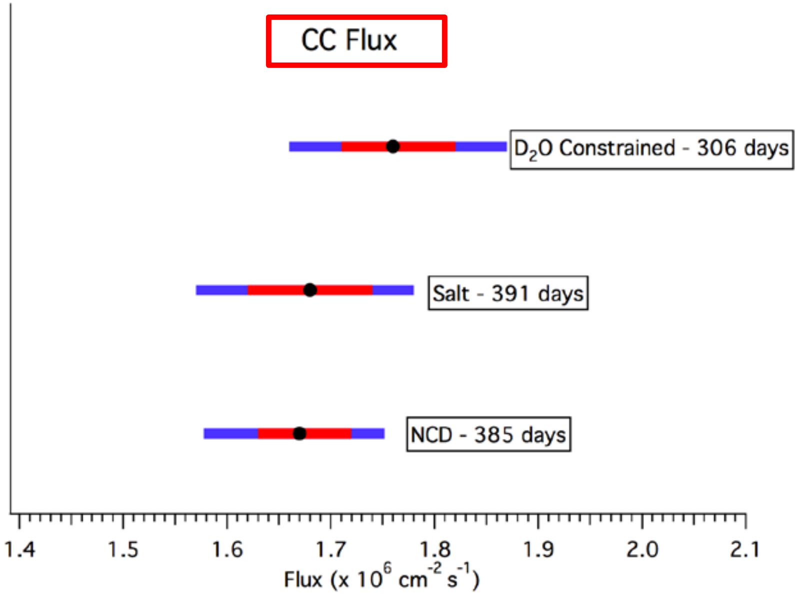




SNO Fluxes: 3 Phases

stat   stat + syst



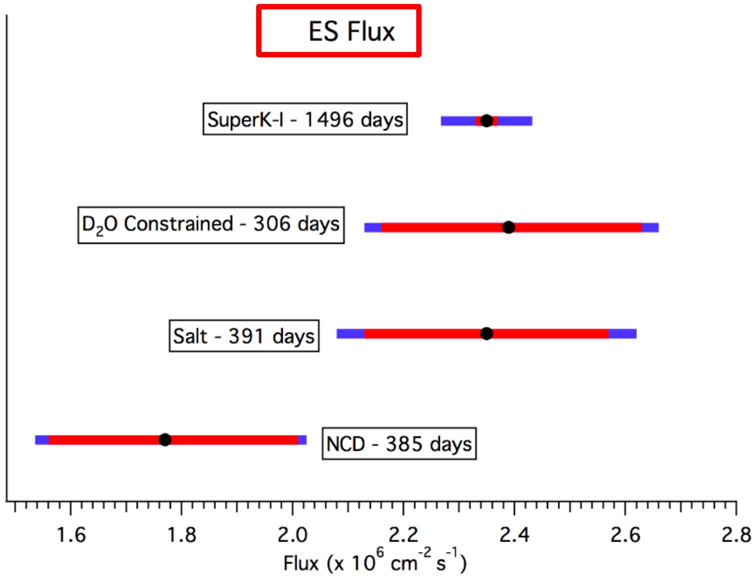


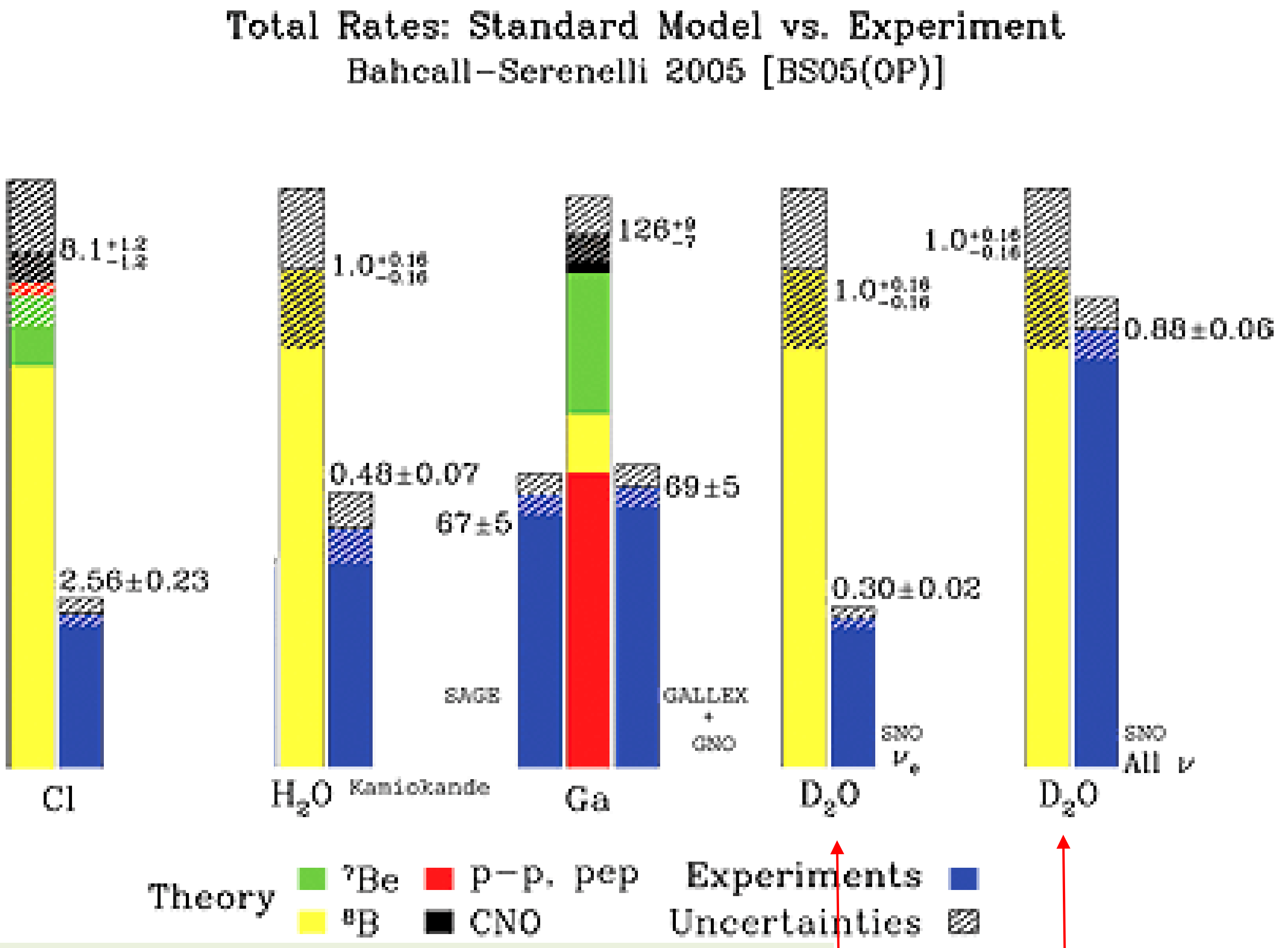
The SNO program culminated in the determination of this ratio

$$P_{SNO} \equiv \frac{\Phi_e}{\Phi_{NC}} = 0.340 \pm 0.023 \,{}^{+0.029}_{-0.031},$$

Rev. Mod. Phys. **88** (2016) no.3, 030502

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





SNO with its flavor specific and flavor independent measurements proved unambiguously that the SNP was due to the neutrino flavor conversion effect

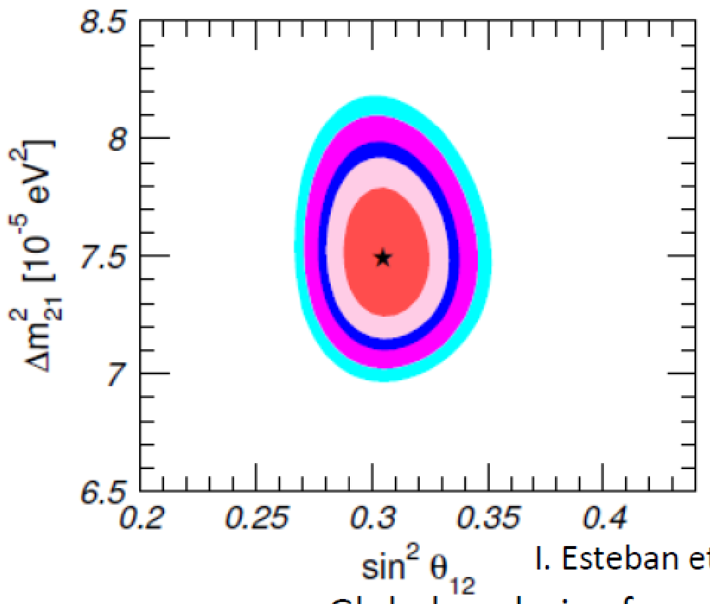
2002 & 2015 Nobel prizes

Together with KamLAND proof of neutrino oscillation with MSW effect: resonant neutrino flavor conversion in matter and LMA large mixing angle solution

The solution of the SNP

- Evidence of ν oscillations
- Interaction of ν with matter MSW

Kamland reactor results + solar : LMA-MSW (year 2002)



I. Esteban et al, JHEP 01 (2017).

Global analysis of oscillation data

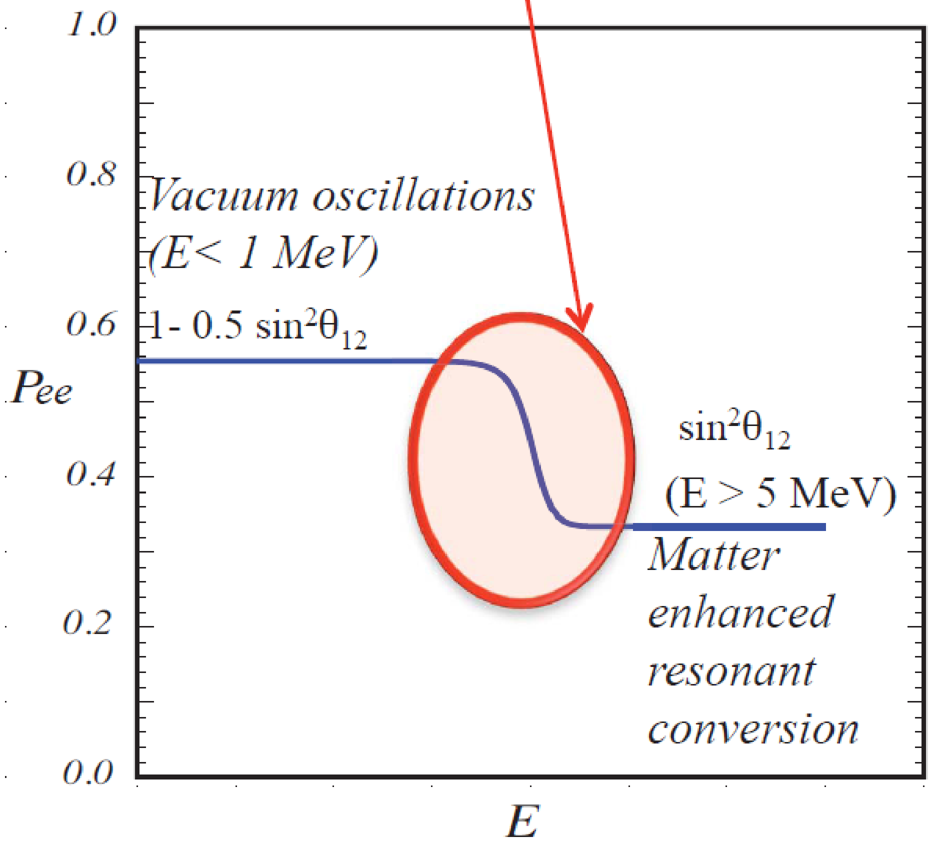
relative precision about 4.7% both for θ_{12} and Δm^2_{21}

MSW Mikheyev-Smirnov-Wolfenstein effect

The transformation of the electron neutrinos is governed by the interplay between the vacuum oscillation phenomenon and the different from the others propagation of the electron neutrinos in matter, since they are the only species to undergo charged-current interactions with the electrons of the medium as argued by Wolfenstein. The physics is very well understood and described by the analysis of Mikheyev and Smirnov.

The electron neutrino survival probability confirmation of the MSW-LMA scenario and probe of new physics

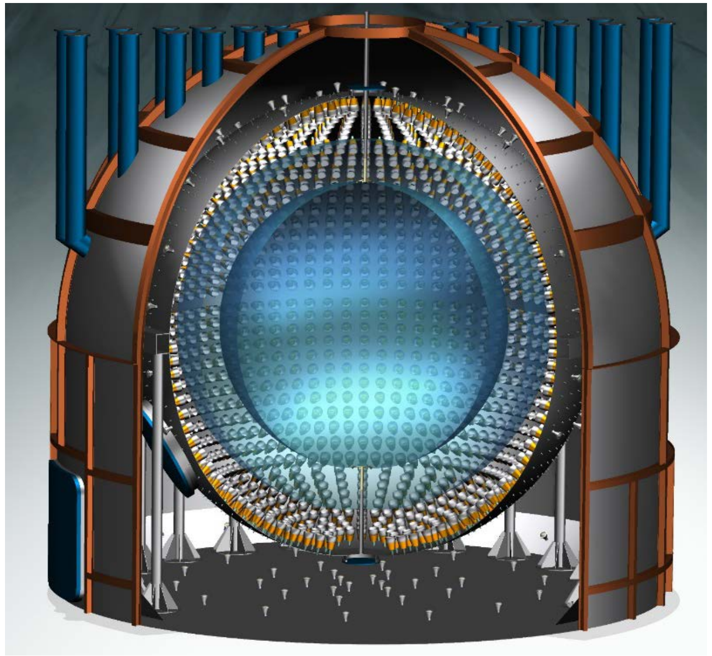
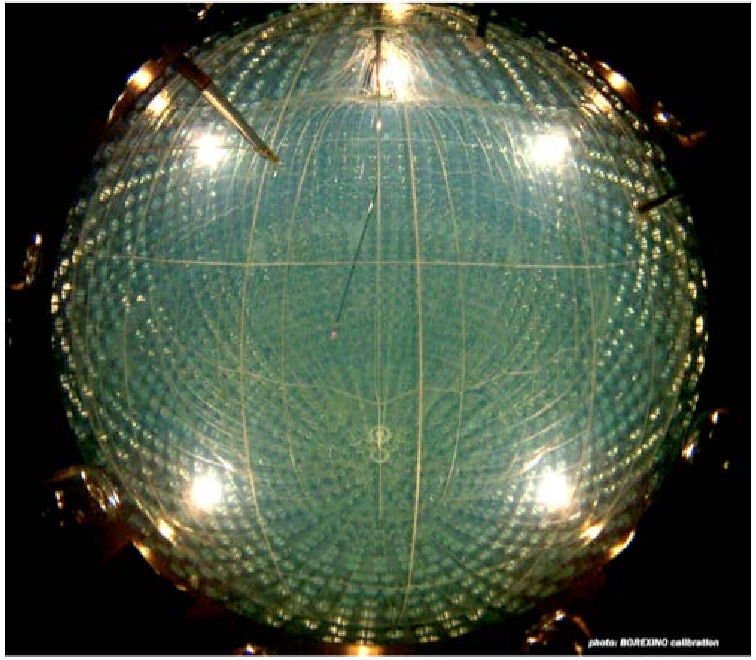
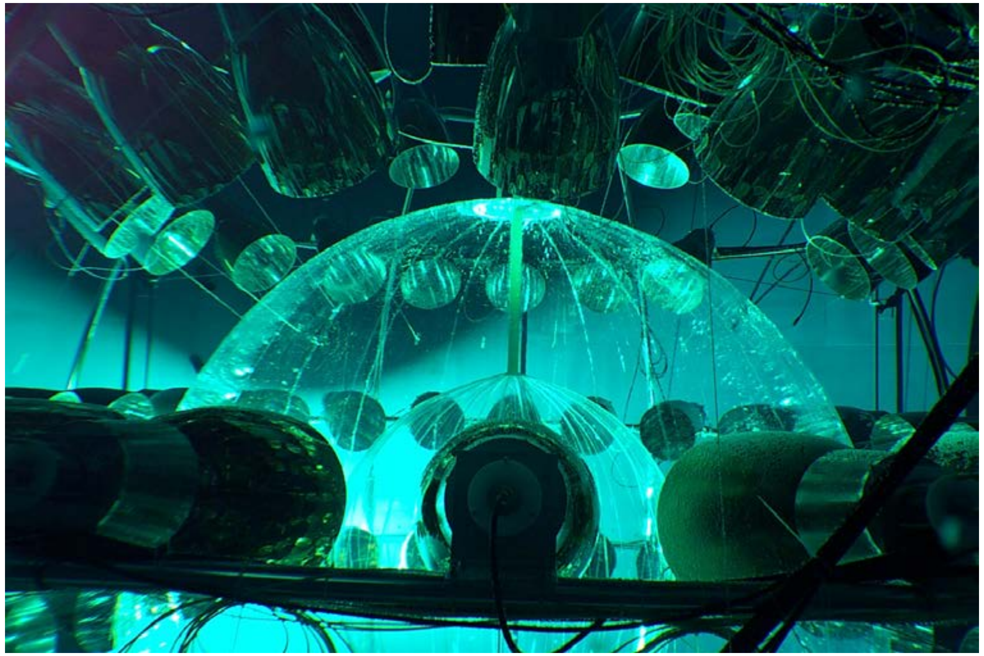
searching for deviations from MSW-LMA scenario of solar ν oscillations, especially in the **transition region of P_{ee}** (e.g. mass-varying neutrinos or non-standard interactions models)



Bahcall & Pena-Garay:JHEP 0311:004 (2003)

Examples of suggested new-physics models:

- Mass varying neutrinos (Gonzales-Garcia & Maltoni 2008)
- Non-Standard Interactions/flavour changing NC (Friedland, Lunardini, Pena-Garay, 2008)
- Sterile Neutrinos (Holanda & Smirnov 2011)

Borexino

- ✓ Approaching the full solar neutrino spectroscopy in a single experiment through the individual real time detection of each spectral component - 4 out of 5 so far

- ✓ Unique Validation in the low energy regime of the LMA-MSW ν oscillation paradigm through the experimental determination of the Pee

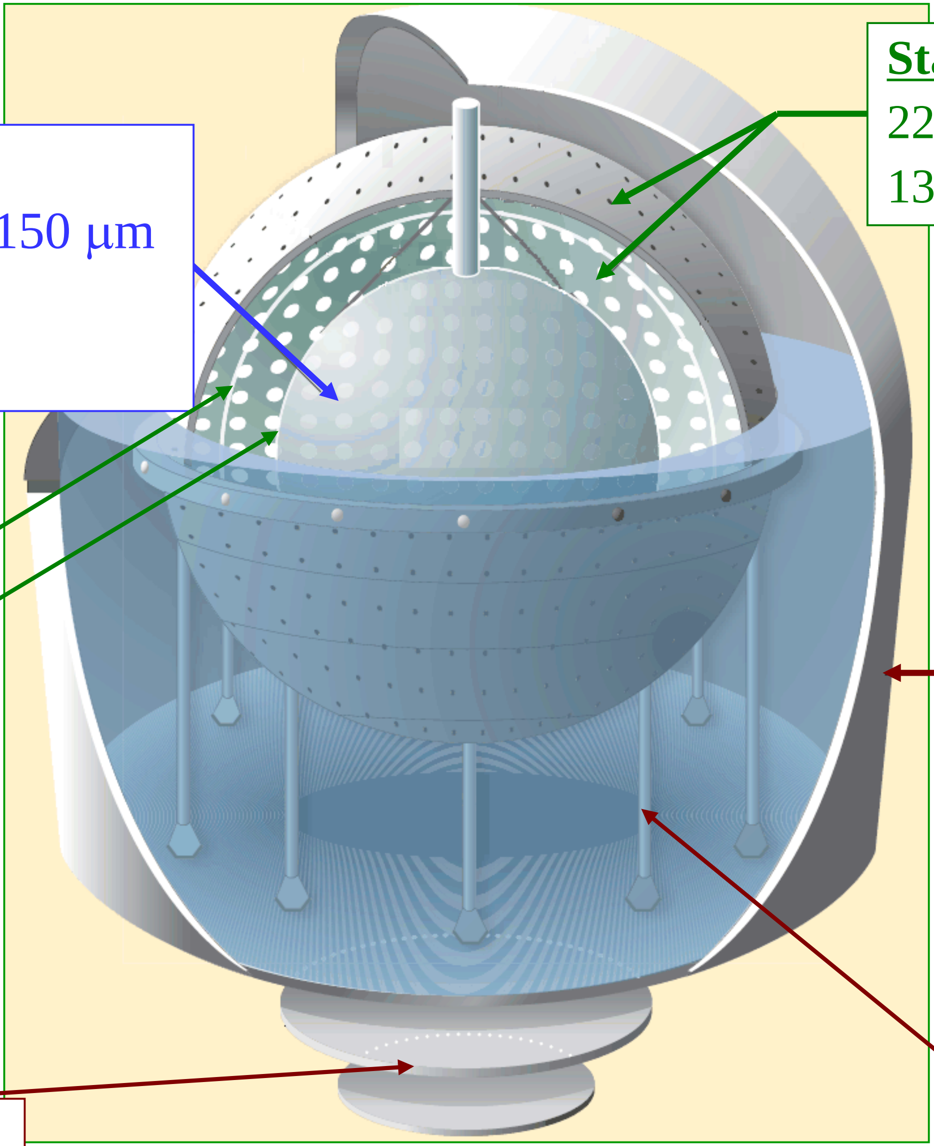
Borexino at Gran Sasso: low energy real time detection

Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel
Nominal FV 100 t

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Neutrino electron scattering

$\nu e \rightarrow \nu e$



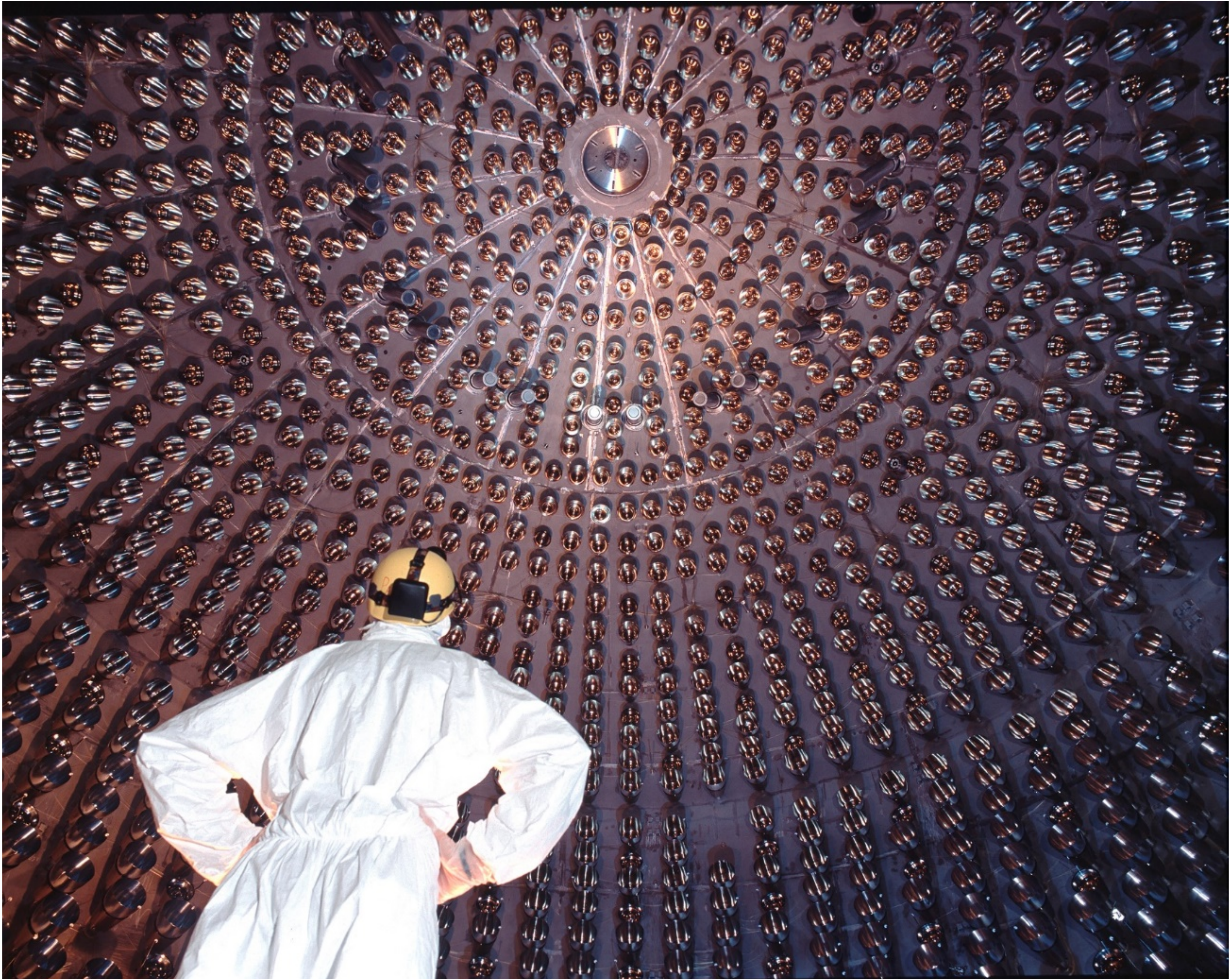
Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shielding

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

20 legs

Carbon steel plates



Detection principle

$$\nu_x + e \rightarrow \nu_x + e$$

Elastic scattering off the electrons of the scintillator
threshold at ~ 60 keV (electron energy)

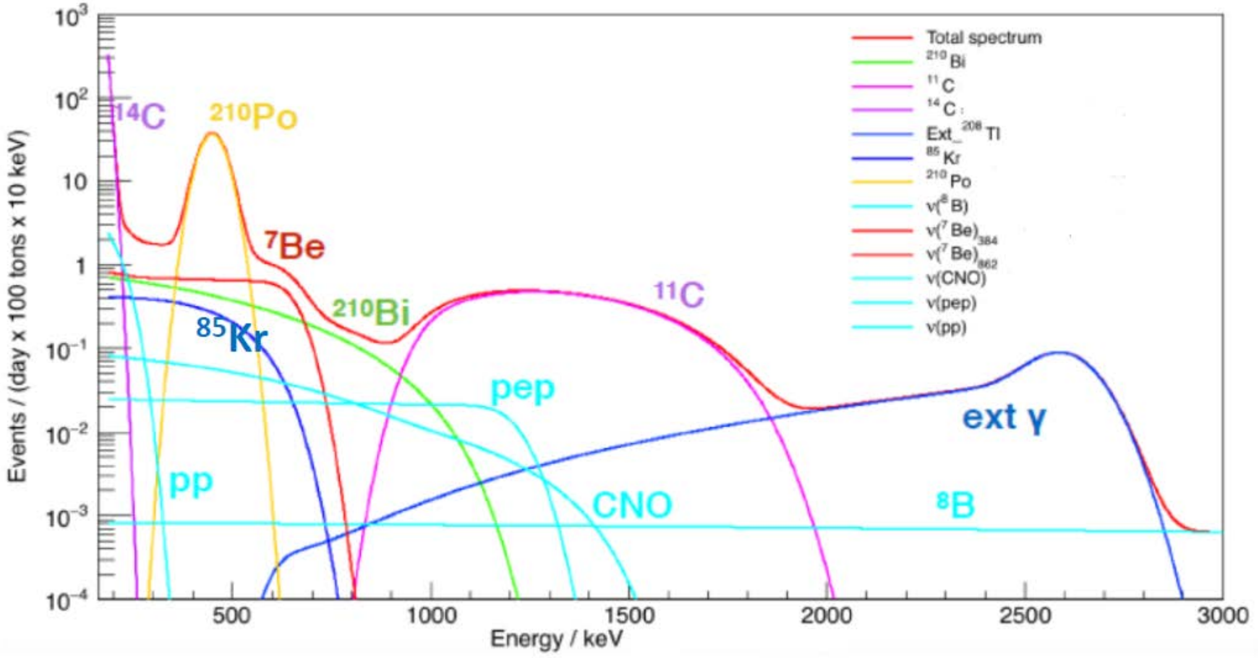
Capabilities of the experiment : (in read tasks already accomplished)

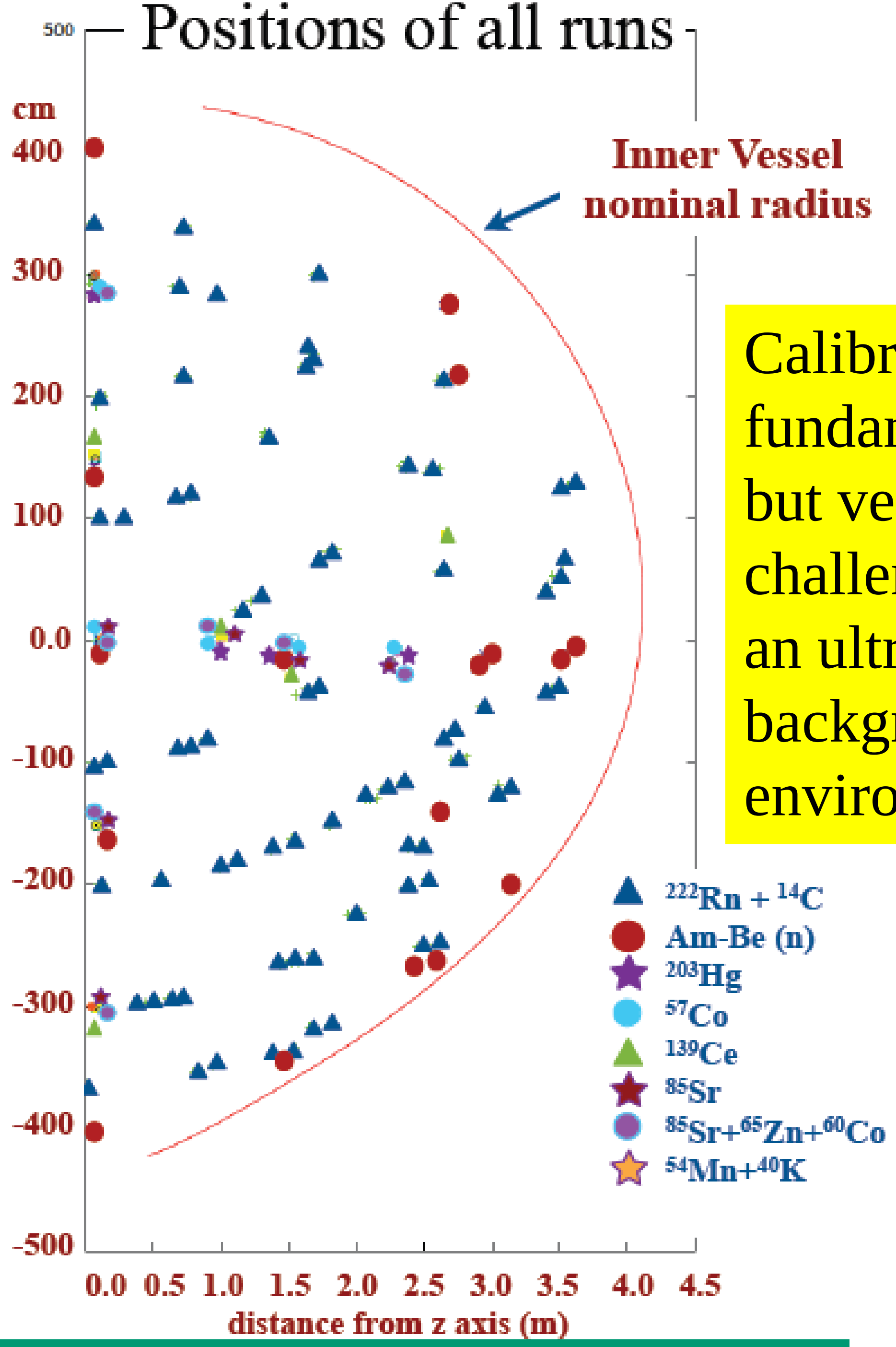
^{7}Be flux
^{8}B with a lower threshold down to about 3 MeV
pep (1.44 MeV)
tight upper limit on CNO
pp neutrinos
Geo-antineutrinos
Supernovae neutrinos
and possibly actual CNO measure in the future ?

Achieved almost full solar ν-spectroscopy in a single experiment

All goals requiring ultra-low background - very low even in the context of the solar neutrino studies due to the absence of other signatures

MC prediction of signal + intrinsic Background





Calibrations fundamental but very challenging in an ultra low background environment

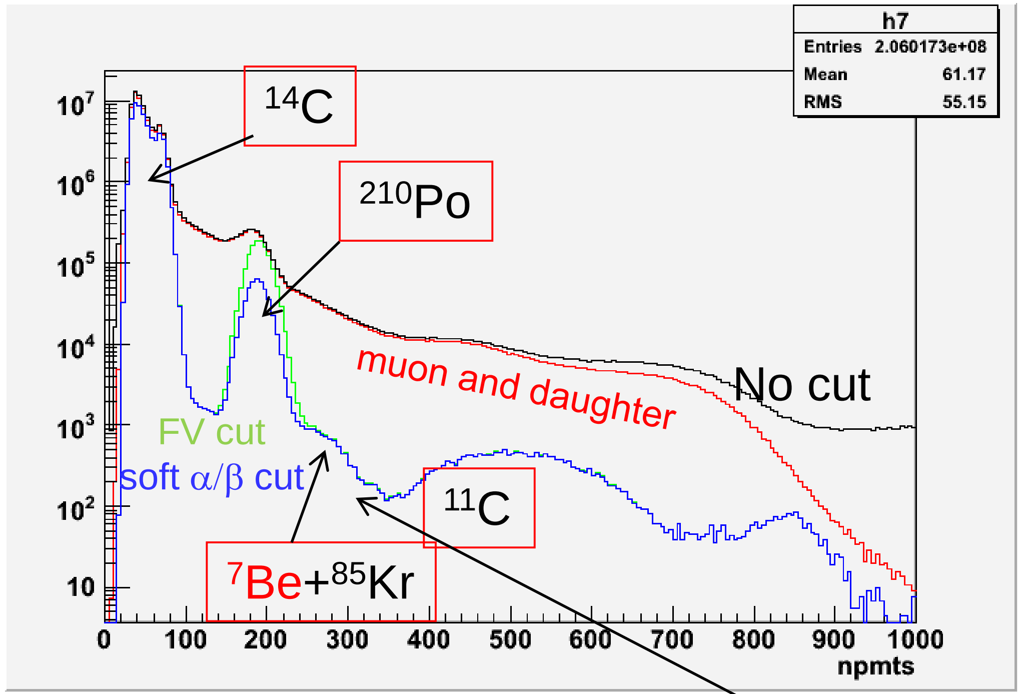
In addition also a careful analytical modeling of the detector response

Phys. Rev. D 89, 112007 (2014) and arXiv:1704.02291

An old slide:

Borexino at the beginning of data taking 10 years ago

^{7}Be scattering edge detected with 3 months of data taking



The spectrum after the cuts witnesses the unprecedented ultra-low background achieved in Borexino

^{14}C-β emitter-156 keV end point

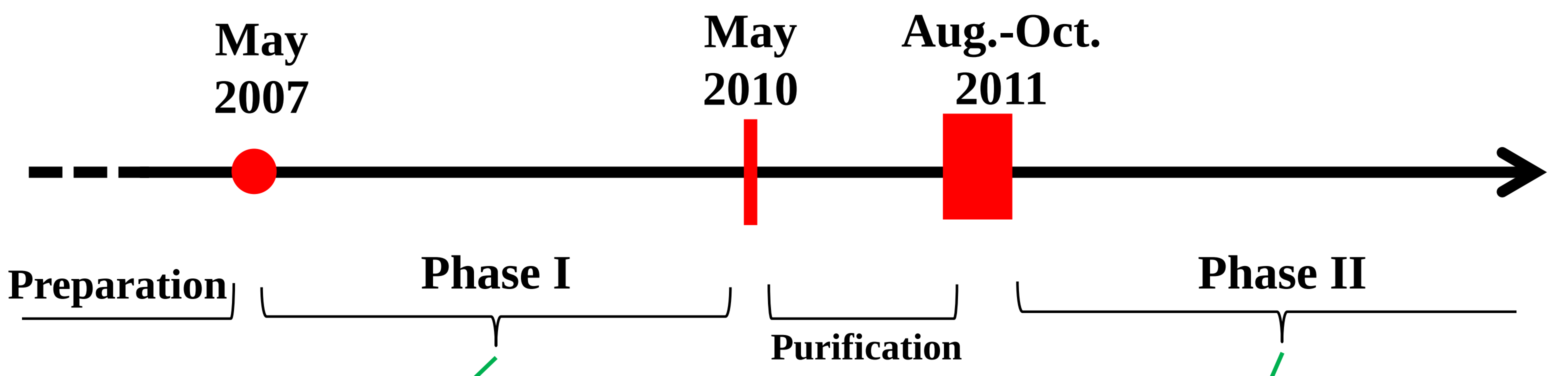
^{210}Po– α emitter- likely from the surfaces of the plumbing lines

^{11}C- β^{+} emitter -cosmogenic- 1.2 μ/ m^2 h

Effect of the application of the selection cuts on the raw spectrum including muon removal and restriction to the Fiducial Volume

The scattering edge is the unambiguous signature of the ^{7}Be solar neutrino detection.

Borexino timeline



More than 10 years of successful data taking Phase I and II before and after the 2011 purification campaign → U 10^{-20} g/g   Th 10^{-19} g/g

3 to 4 orders of magnitude better than the design value!

- **First solar ^{7}Be-ν measurement**
- **^{7}Be-ν day-night asymmetry**
- **Low-threshold ^{8}B-ν**
- **First pep-ν detection**
- **Best upper limit on CNO-ν**
- **^{7}Be-ν seasonal modulation**

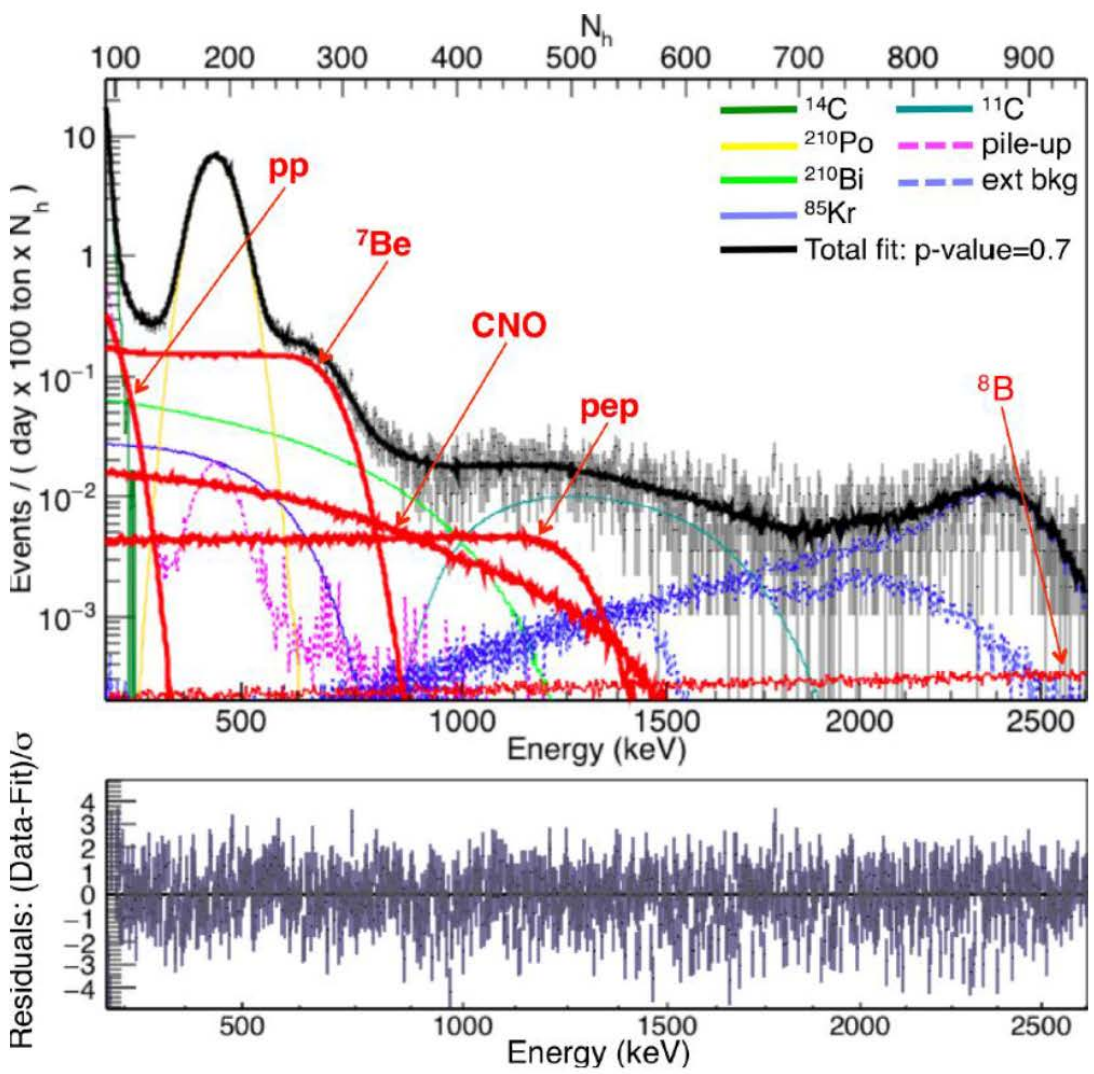
- **Geo-ν observation at > 5σ (phase I + part of phase II data)**

- **Muon seasonal variations**
- **Limits on rare processes**
- **Neutrons and other cosmogenics**

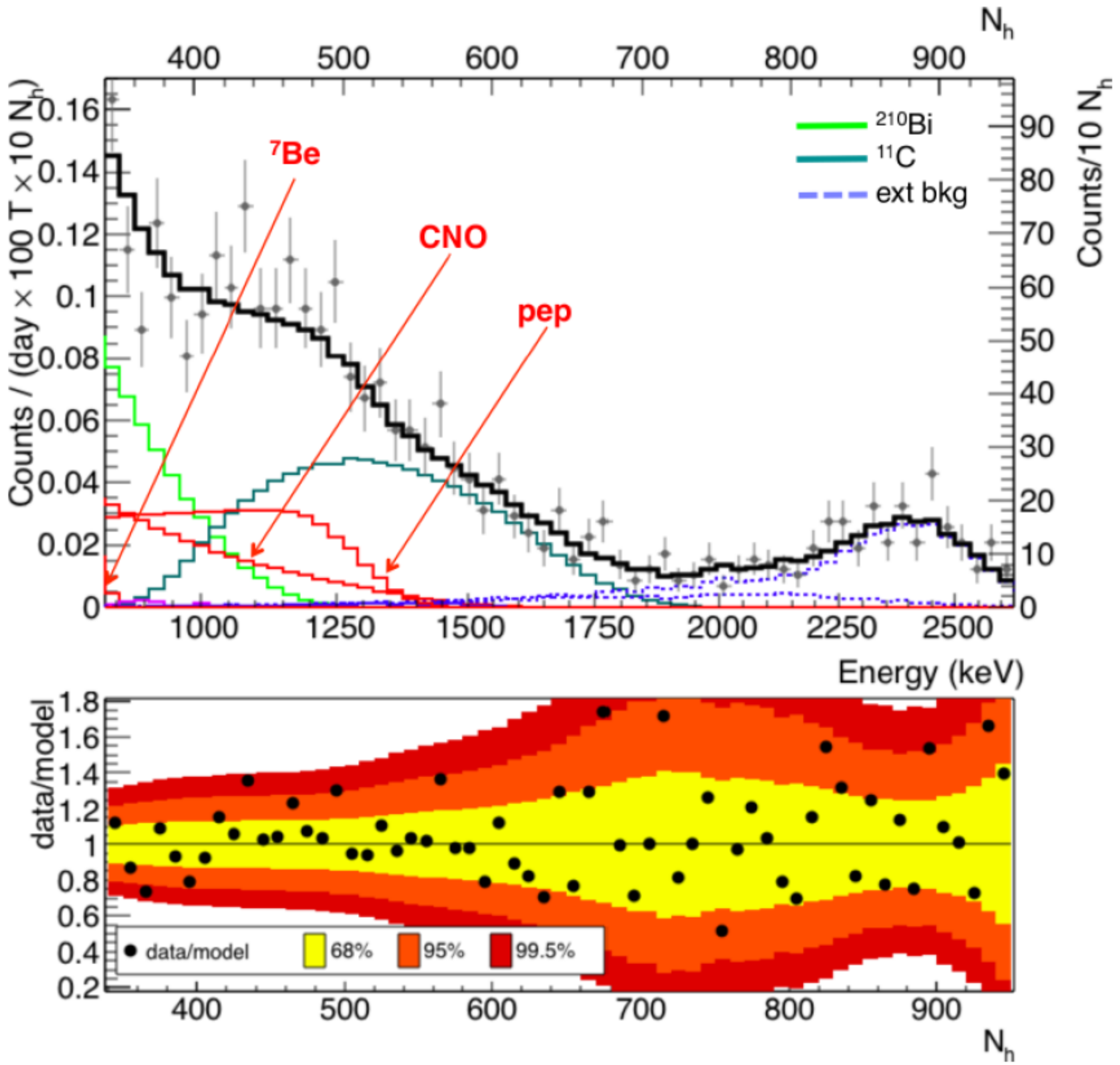
- Measurement of pp-ν flux crucial milestone towards the full solar-ν spectroscopy (Nature 2014) and strong evidence of the pp mechanism
- Improved ^{7}Be-ν seasonal modulation 2017
- New round of the previous measurements with improved precision just released at TAUP updated pp ^{7}Be and pep fluxes, ^{8}B to be updated → almost full solar-ν precision spectroscopy!
- Short-baseline ν oscillation: SOX from April 2018 up to Fall 2019 with ^{144}Ce source
- Continued quest for possible determination of CNO-ν flux (ultimate goal for solar neutrinos)

Full spectroscopy and evidence of the pep scattering edge

Released at TAUP@SNOLAB **arXiv:1707.09279**



More than 5σ evidence for the pep signal



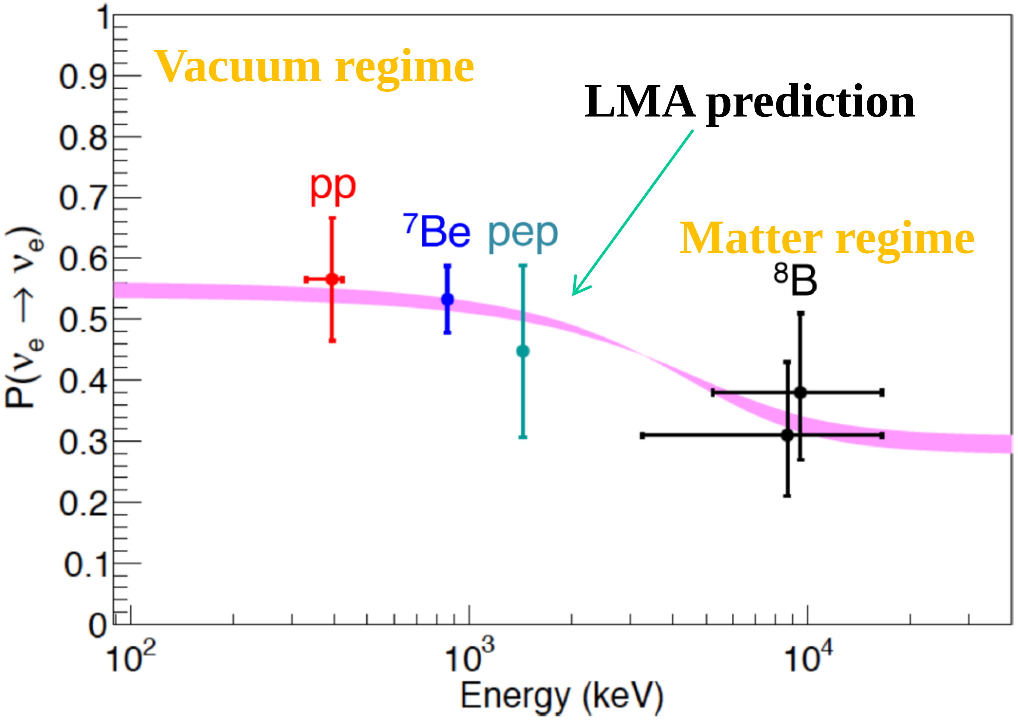
Comparison between Phase I and Phase II results

	Phase I	Phase II	Uncertainty reduction $\frac{Phase\ II}{Phase\ I}$
pp	144 ± 13±10	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be(862KeV)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	0.57
pep	3.1 ± 0.6 ± 0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61

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

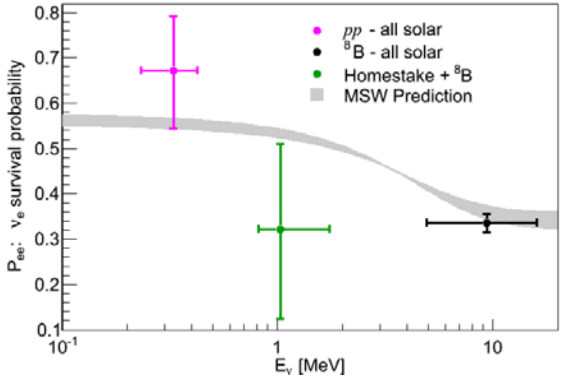
The global oscillation picture: survival probability of the electron neutrinos contrasted with the Borexino data points

arXiv:1707.09279



FROM BOREXINO VALIDATION AT LOW ENERGY OF THE LMA-MSW OSCILLATION PARADIGM

Open issues : ^{8}B upturn at low energy? Sub-leading effects?



Before the Borexino results

"Although historically by measuring Δm^2_{21} KamLAND has uniquely selected the LMA solution, now the solar neutrino experiments alone can do this due to new measurements by Borexino, which validated the solution at low energies, and due to higher accuracy of other results." M. Maltoni and A.Yu. Smirnov EPJA 52 , 87 2016

P_{ee} curve (magenta band) as expected from ν oscillation+Matter effect (LMA-MSW)

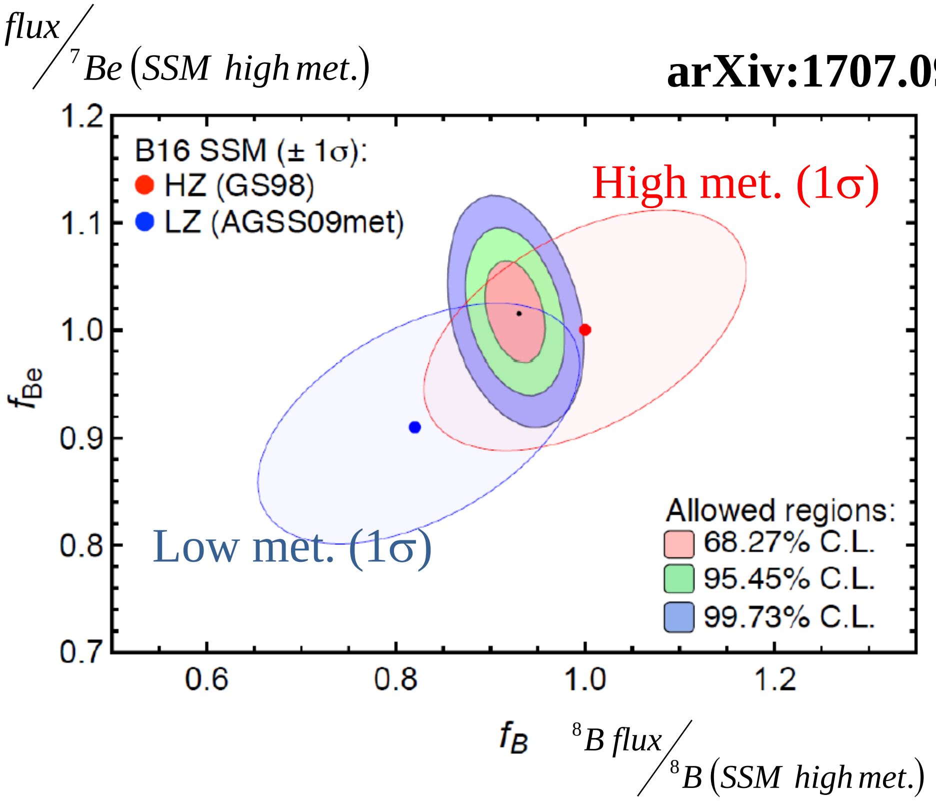
$$A^{^7Be}_{DN} = \frac{D-N}{(N+D)/2} = (-0.1 \pm 1.2 \pm 0.7)\%$$

Borexino Coll., Phys. Lett. B707 (2012) 22

Day-Night asymmetry of ^{7}Be neutrinos consistent with 0 in agreement with the LMA-MSW expectation

Can the current data discriminate between high and low metallicity ?

arXiv:1707.09279



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

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

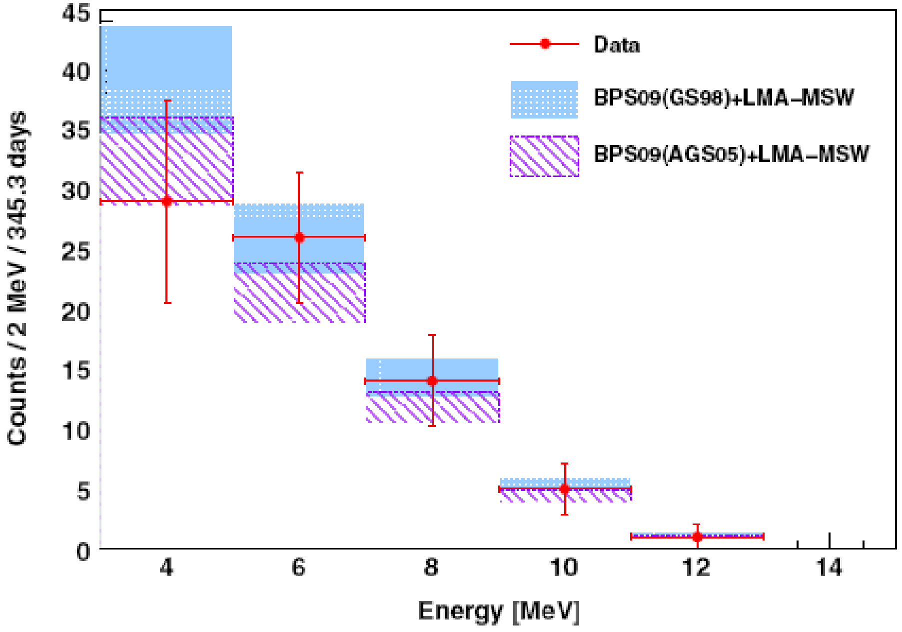
	Borexino results Flux ($cm^{-2}s^{-1}$)	expected HZ Flux ($cm^{-2}s^{-1}$)	expected LZ Flux ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$	$5.98\ (1 \pm 0.006)\ 10^{10}$	$6.03\ (1 \pm 0.005)\ 10^{10}$
^{7}Be(862+384 KeV)	$(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$	$4.93\ (1 \pm 0.06)\ 10^{9}$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

The latest Borexino data though cannot disentangle between the two models point to a slight preference for the HZ

p-value for HZ-SSM 0.87
p-value for the LZ-SSM 0.11
weak hint towards the HZ hypothesis not statistically significant

Other achievements of Borexino

^{8}B with low threshold



	Threshold [MeV]	$\Phi^{ES}_{^8B}$ $[10^6\ cm^{-2}\ s^{-1}]$
SuperKamiokaNDE I [7]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$

Phys. Rev. D, 82 (2010) 033006

The complete spectroscopy from **pp to ^{8}B** (to be further updated) represents the first and unique determination of the pp cycle $\rightarrow$ **final crowing of the experimental quest for the burning mechanism fueling the Sun!**

Quantitative probe of the pp solar fusion long advocated by John Bahcall

$$R = \frac{Rate(^3He + ^3He)}{Rate(^3He + ^4He)} \qquad R = \frac{2\,\Phi(^7Be)}{\Phi(pp) - \Phi(^7Be)}$$

Expected values: (C. Pena Garay, private comm,)

$R = 0.180 \pm 0.011 \quad HZ$

$R = 0.161 \pm 0.010 \quad LZ$

Measured value:

$R = 0.18 \pm 0.02$

arXiv:1707.09279

Borexino crowns a more than one century long scientific adventure

Further recent accomplishments

Limit of ν magnetic moment from ^{7}Be scattering spectrum

$$\mu^2_{eff} = P^{3\nu}\,\mu^2_e + (1 - P^{3\nu})\,(\cos^2\theta_{23}\,\mu^2_\mu + \sin^2\theta_{23}\,\mu^2_\tau)$$

$$P_{ee} = P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}$$
$$P^{2\nu} = \sin^2\theta_{12}\,\sin^2(\Delta m^2_{12}\,L/4E)$$

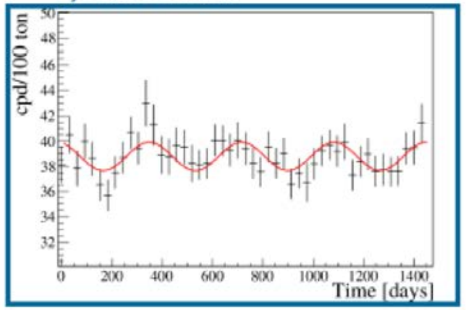
Assuming
LMA-MSW
$P^{2\nu}$ for pp- and ^{7}Be-ν is the same

arXiv:1707.09355

(Dec 2011- May 2016)
1291 days
90% C.L.
from $\mu_{eff} < 2.8 \times 10^{-11}\mu_B$:
$\mu_e < 4.8 \times 10^{-11}\mu_B$
$\mu_\mu < 6.4 \times 10^{-11}\mu_B$
$\mu_\tau < 6.8 \times 10^{-11}\mu_B$

Modulation due to the Earth's orbit eccentricity

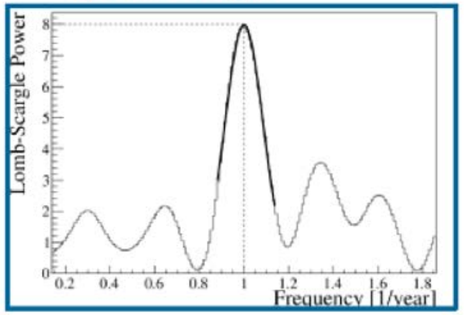
1) Sinusoidal fit



The **period**, **amplitude**, and **phase** of the observed time evolution of the signal are **consistent with its solar origin**, and **the absence of an annual modulation is rejected at 99.99% C.L.**

	Simulated Data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

2) Lomb-Scargle



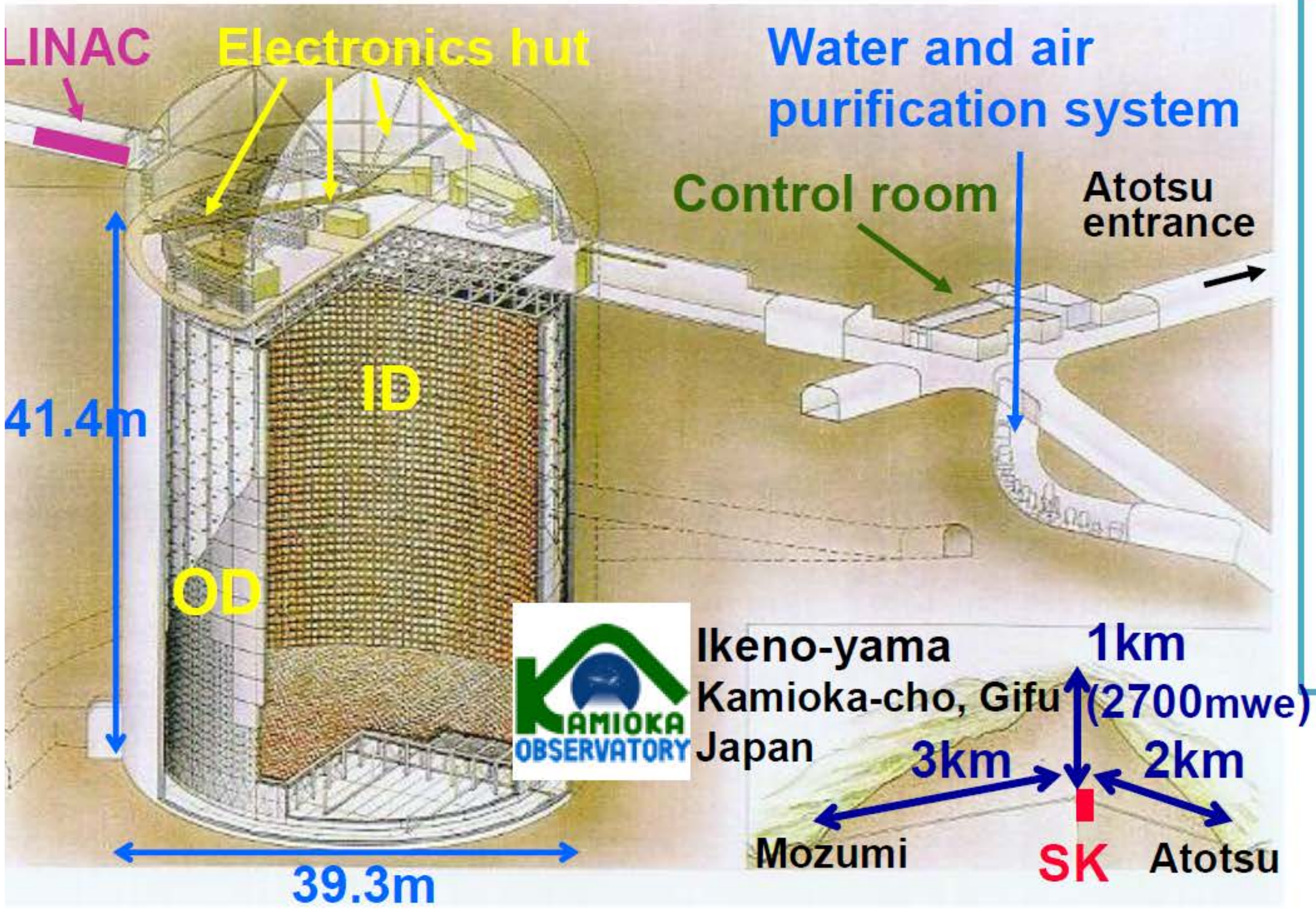
Successful consistency check of the solar origin of the signal and of the stability of the detector

[Astropart.Phys. 92 (2017) 21-29]

	Borexino result	Expected HZ	Expected LZ
CNO ν	< 8.1 95%C.L cpd/100t	4.91 +-0.56 cpd/100t	3.62 +- 0.37 cpd/100t

Previous limit (set by Borexino Phase I):
7.9 cpd/100t
arXiv:1707.09279

Super-Kamiokande



- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-IV is running

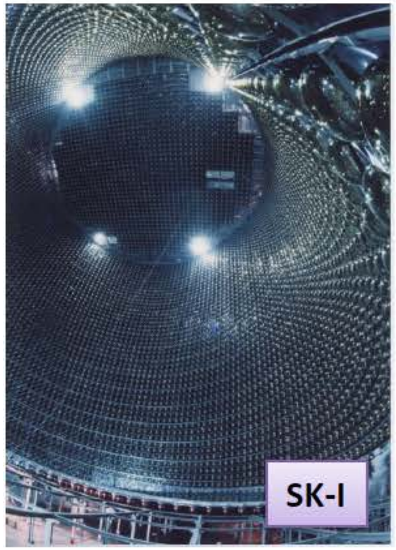
Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

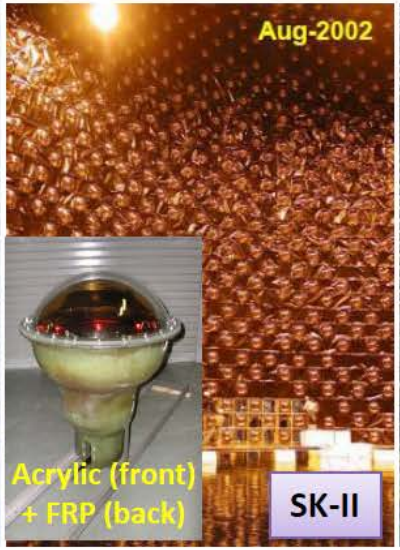
History and plan of Super-Kamiokande

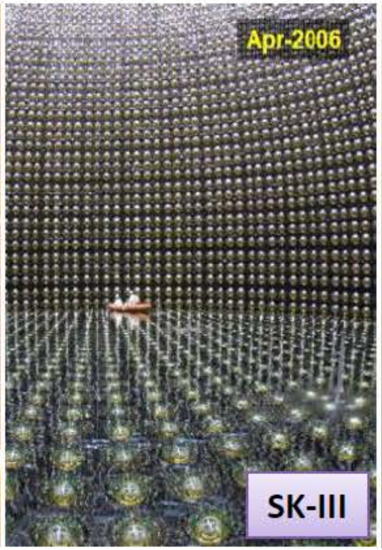
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

SK-I SK-II SK-III SK-IV

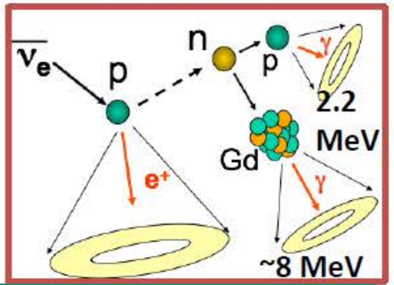
Start upgrade for
SK-Gd
(current plan)







SK-I	SK-II	SK-III	SK-IV	SK-Gd
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	Neutron tagging with Gd
4.5 MeV	6.5 MeV	4.5 MeV	3.5 MeV	
1496 days	791 days	548 days	2645 days (~March 2017)	



- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

Current total: 5480 days

SK signal and ^{8}B results

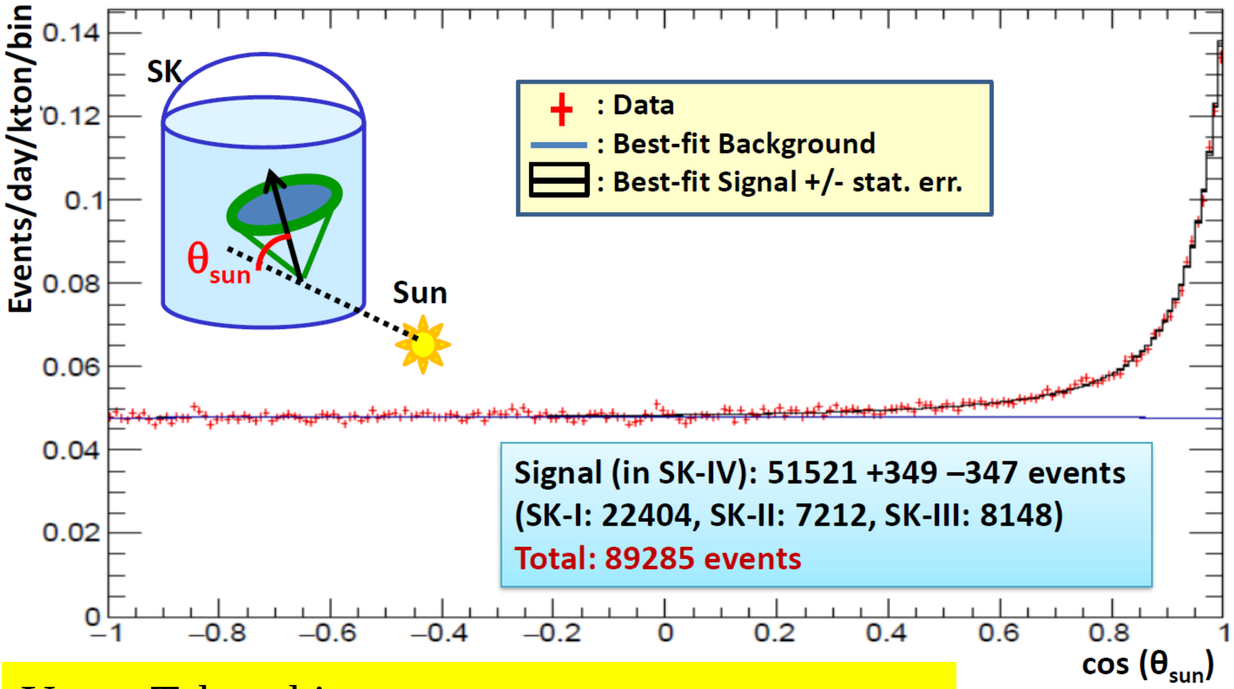
SK-IV solar neutrino signal

SK-IV 3.5-19.5 MeV(kin)

June 2017

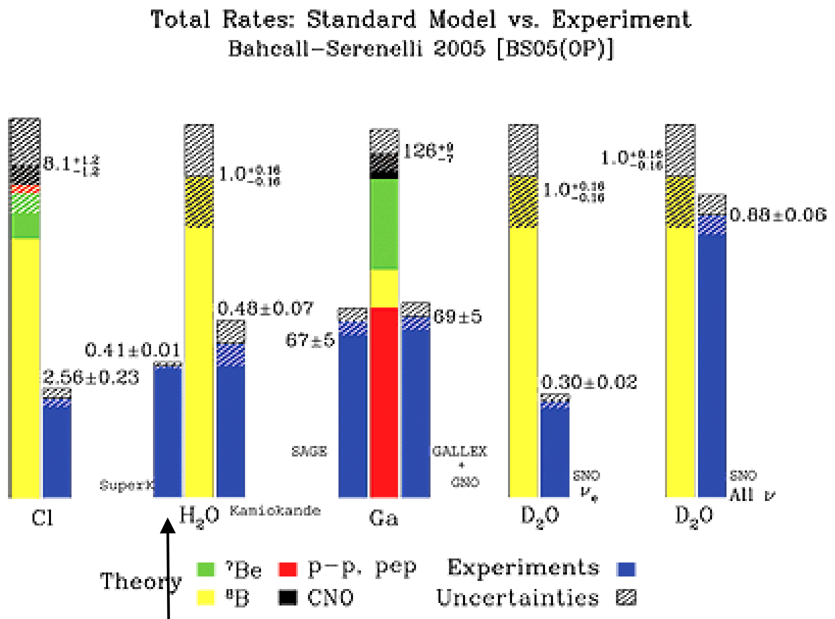
Preliminary

SK-IV 2645 days



Signal (in SK-IV): 51521 +349 –347 events
(SK-I: 22404, SK-II: 7212, SK-III: 8148)
Total: 89285 events

Yasuo Takeuchi
Rencontres du Vietnam July 2017, Quy Nhon



The historic role of SK in the SNP

^{8}B flux = (2.308 ± 0.020(stat.)+0.039 −0.040(syst.)) × 10^6/(cm^{2}sec) assuming no oscillations 1.9%

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

	A_{DN}^{fit} (%)
SK-IV, 1664 days	-3.3+/-1.5+/-0.6
SK-I~IV, 4499 days	-3.3+/-1.0+/-0.5
Non-zero significance	2.9 σ

PRD94, 052010 (2016)

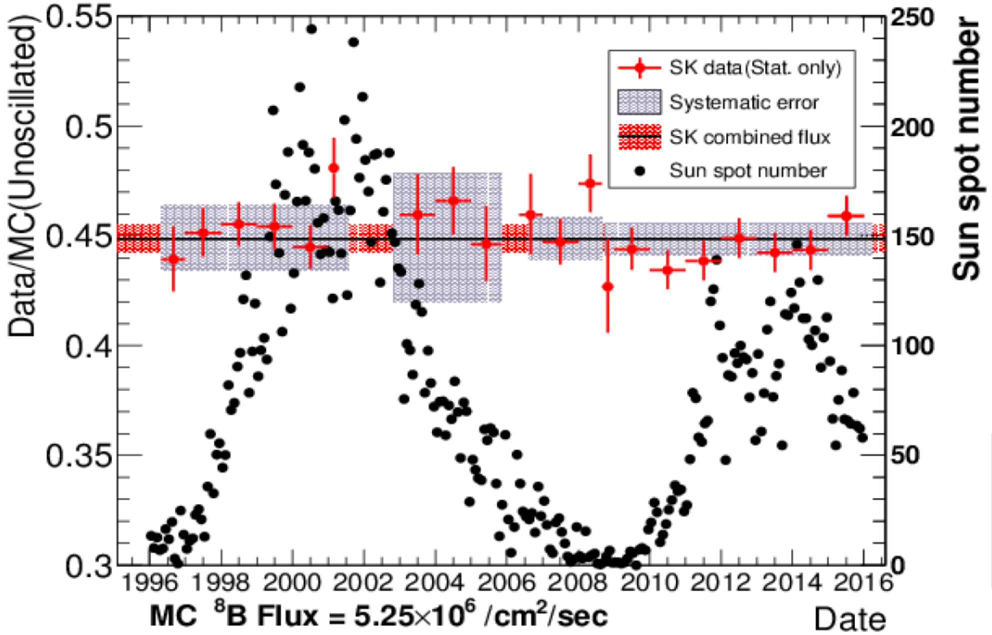
^{8}B day/night asymmetry at 3σ

Time variation analysis of the ^{8}B flux

^{8}B solar neutrino flux: Yearly plot

Preliminary

SK-I~IV 5200 days



Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels

χ^2 = 15.52 / 19 d.o.f. → Confidence level = 69 %

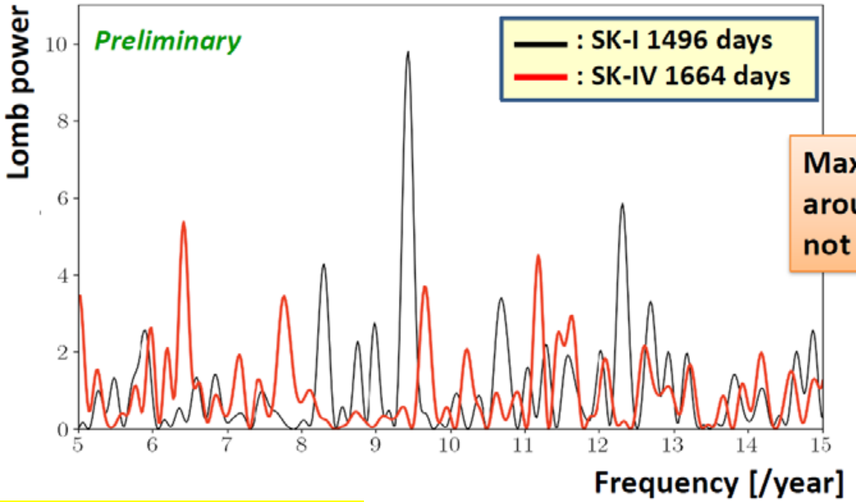
Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

Periodic modulation analysis in SK-IV

June 2017

Preliminary

- Data set:
  - SK-I: 1496days, 5-day long sample, 4.5-19.5 MeV(kin)
  - SK-IV: 1664 days, 5-day long sample, 4.5-19.5 MeV(kin)
  - Generalized LS method (with symmetric error)
  - Search region: 5 – 15 [/year]



Maximum peak at around 9.43 /year is not found in SK-IV.

Yasuo Takeuchi
Rencontres du Vietnam July 2017, Quy Nhon

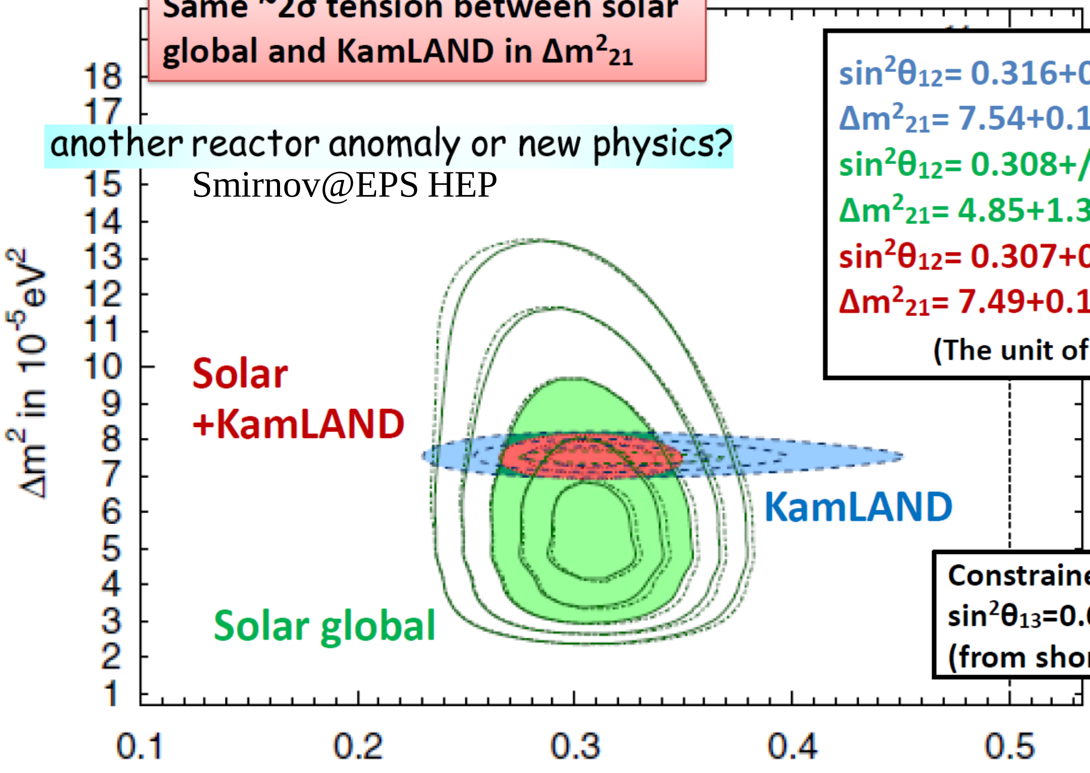
Anomalies?!

Same ~2σ tension between solar global and KamLAND in Δm^2_{21}

another reactor anomaly or new physics?

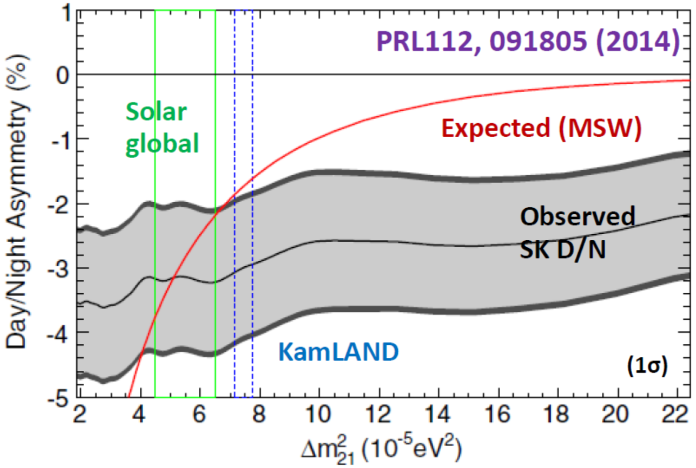
Smirnov@EPS HEP

PRD94, 052010 (2016)



$\sin^2\theta_{12}$= 0.316+0.034/-0.026
Δm^2_{21}= 7.54+0.19/-0.18
$\sin^2\theta_{12}$= 0.308+/-0.014
Δm^2_{21}= 4.85+1.33/-0.59
$\sin^2\theta_{12}$= 0.307+0.013/-0.012
Δm^2_{21}= 7.49+0.19/-0.18
(The unit of Δm^2_{21} is 10^{-5} eV^2)

Constrained with $\sin^2\theta_{13}$=0.0219+/-0.0014 (from short baseline exp.)



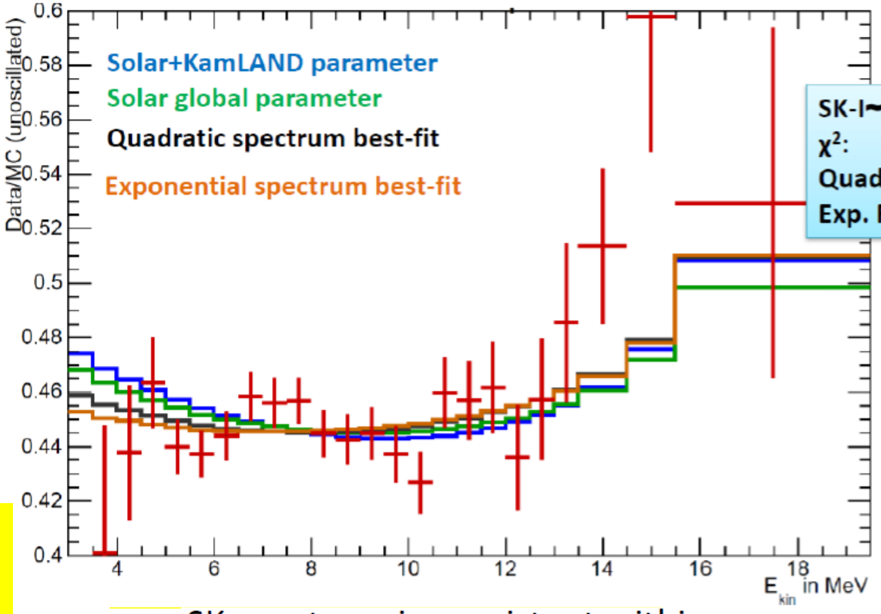
The measured ^{8}B day night asymmetry is fully consistent with the pure solar expectation while only marginally compatible with the KamLAND expectation

Low energy upturn in the ^{8}B spectrum?
Predicted by the LMA-MSW solution

Super-K spectral data

June 2017

Preliminary



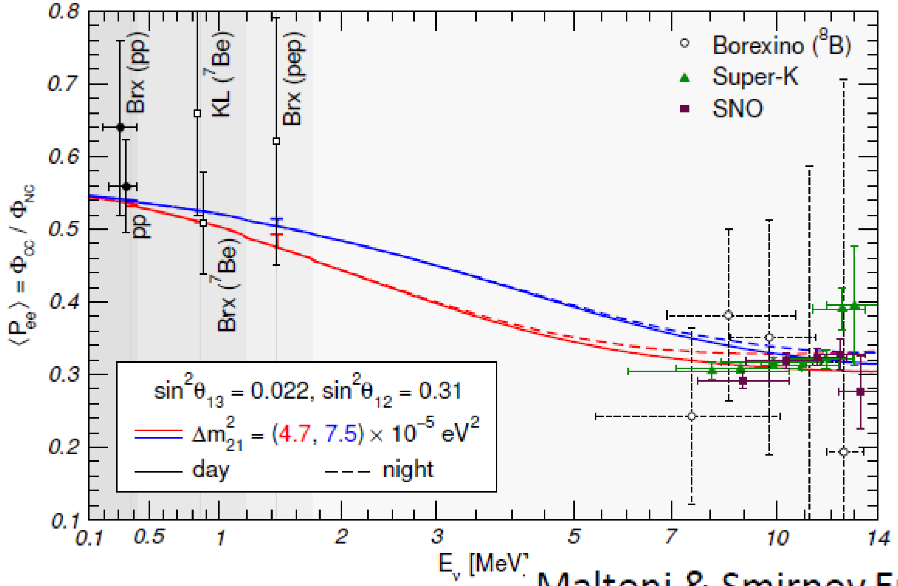
SK-I~IV: 83 bins
χ^2:
Quad. Fit: 75.5 /80 dof
Exp. Fit: 75.5 /80 dof

All SK phases are combined without regards to energy resolution or systematics in this figure

SK spectrum is consistent within
1 σ with the MSW upturn obtained with Osc. Param from solar
2 σ with MSW upturn obtained with Osc Param. from solar+Kamland

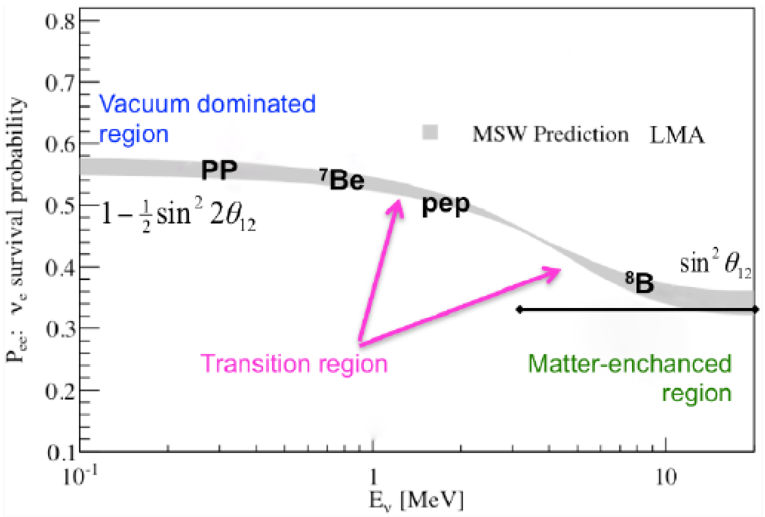
Even going down in the SNO data

The richness of the Pee potential signatures and the importance of the precision spectroscopy

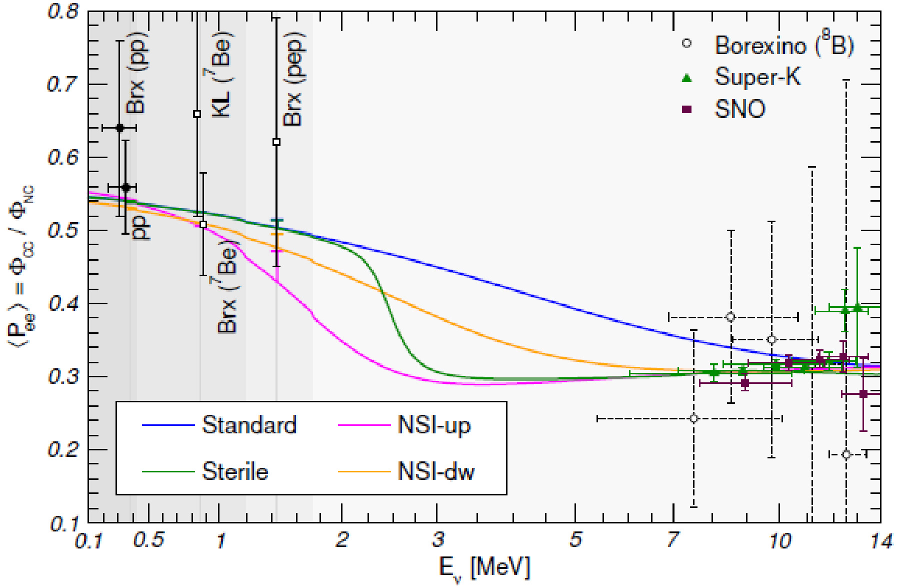


Maltoni & Smirnov,Eur.Phys.J.2016

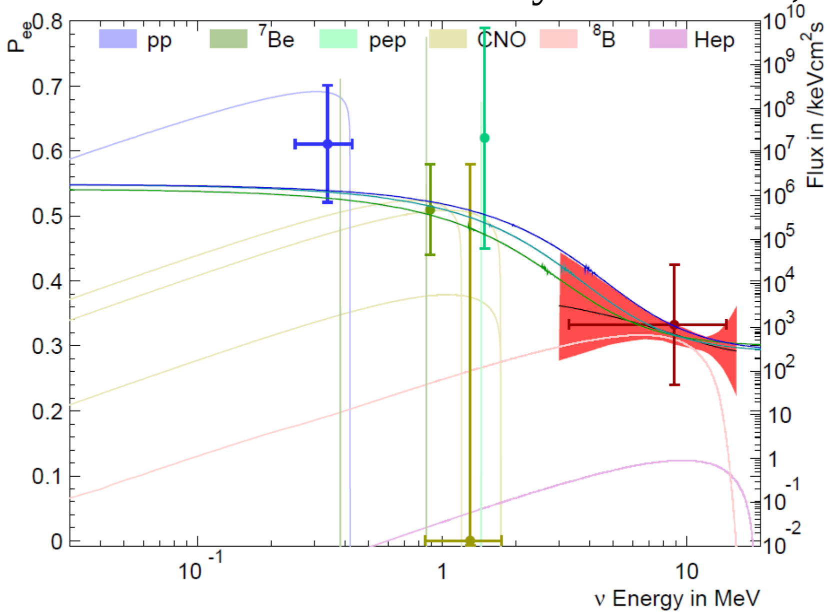
New physics and may be indications for the anomalies may lurk in the still unexplored transition region



Phys. Rev. D 94, 052010 (2016)



More to come and to learn ……



The red region stems from the joint ^{8}B analysis of SNO and SK

Conclusions and outlooks

Solar neutrinos investigation one of the most successful and prolific of results area of experimental particle physics over the past 5 decades triggering and motivating the major developments in neutrino physics in this period

- Fundamental contribution to establish the 3ν oscillation paradigm→ oscillations in vacuum and matter with resonance flavor conversion

- The LMA-MSW scenario firmly established as the true solution of the solar neutrino problem and "solar" oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21} measured with good precision together with KamLAND

- Definite and conclusive quantitative assessment of the pp burning mechanism fueling the Sun

Conclusions and outlooks

Borexino and Super-Kamiokande entered the precision era – open questions

- Which is the nature of the hinted anomalies? Are they flukes or signatures of more profound facts?
- Are there sub-leading effects beyond the LMA MSW solution ?– imprinting of new physics in the transition region?
- Further tests for solar model – metallicity puzzle – CNO open issue

New experiments with solar neutrinos among their capabilities which will enter the field in the near-medium term

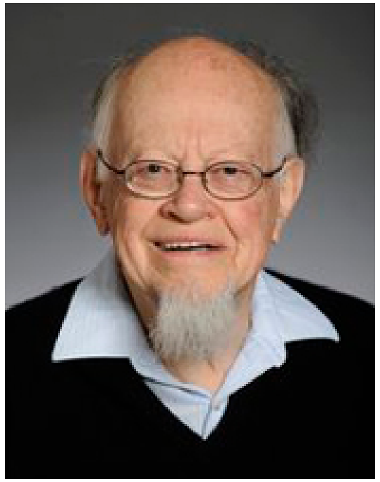
SNO+ JUNO (liquid scintillator) Hyper-Kamiokande (water Cherenkov) DUNE (liquid Argon)

We expect more from the running and future experiments……………

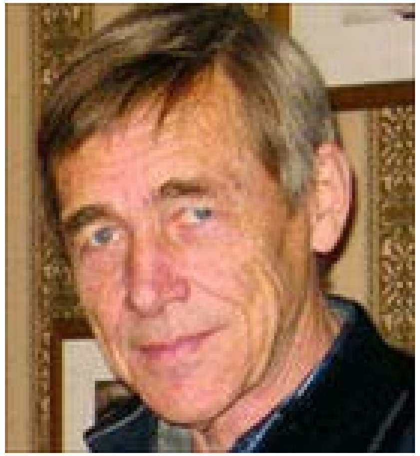
Solar neutrinos proved to be a gold mine of opportunities for physics and astrophysics…

……Talk dedicated to those great physicists no more with us who paved the way towards the unveiling of the secret treasures of this wonderful “mine”

Bruno

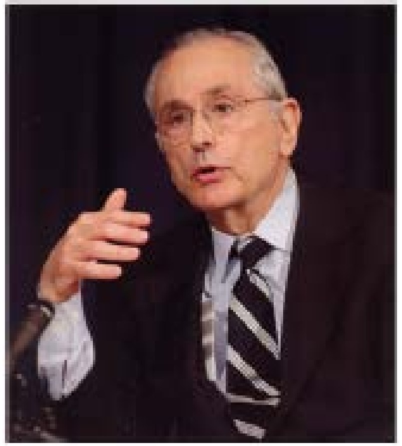


Lincoln



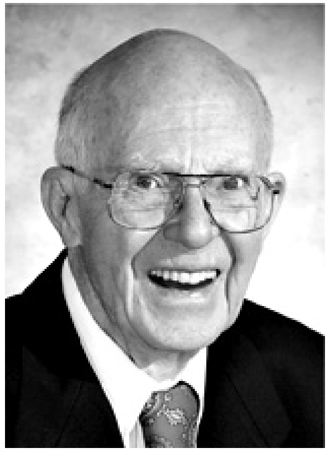
Stanislav

Herb



John

Raju



Ray

Yōji

Thanks