LES RENCONTRES DE PHYSIQUE
DE LA VALLEE D'AOSTE
Results and Perspectives in Particle Physics

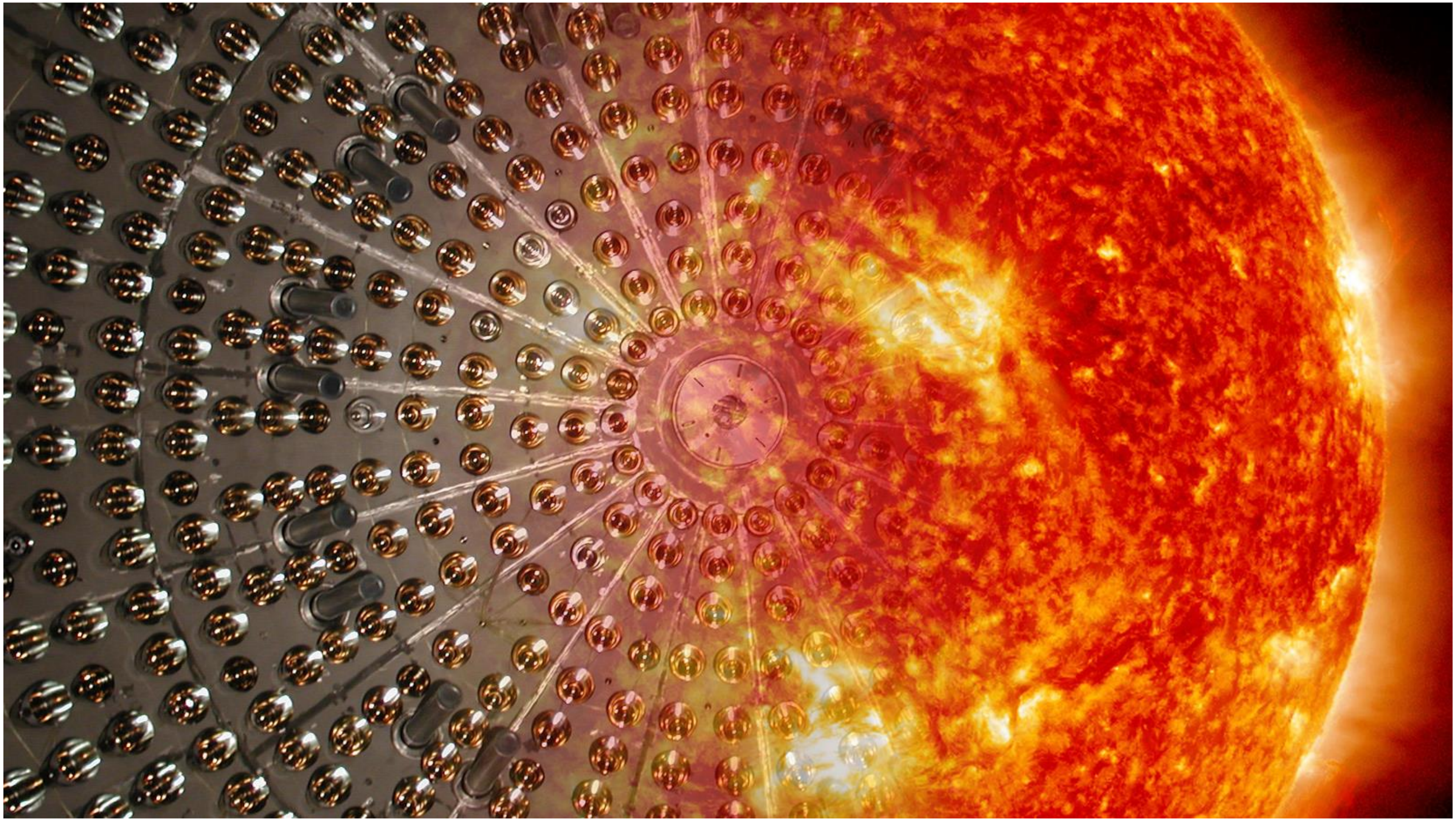
La Thuile, Aosta Valley (Italy)
March 1-7, 2015

New Results from Borexino

Stefano Davini, Gran Sasso Science Institute
on behalf of the Borexino Collaboration

Les Rencontres de Physique de La Valee D'Aoste
La Thuile, March 2, 2015

pp - ν measurement in Borexino



Observation of the neutrinos from
Primary proton-proton fusion in the Sun

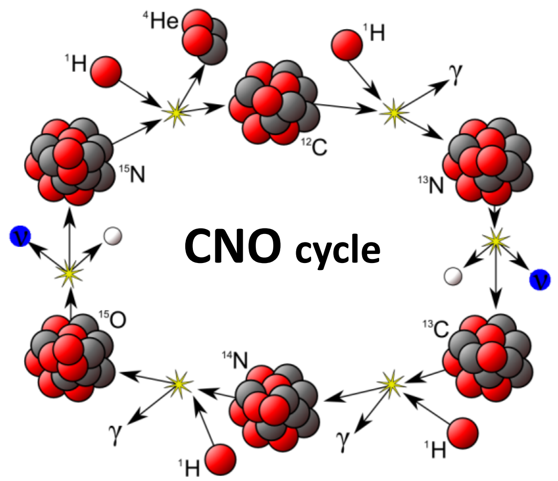
Nature **512**, 383-386 (28 August 2014)

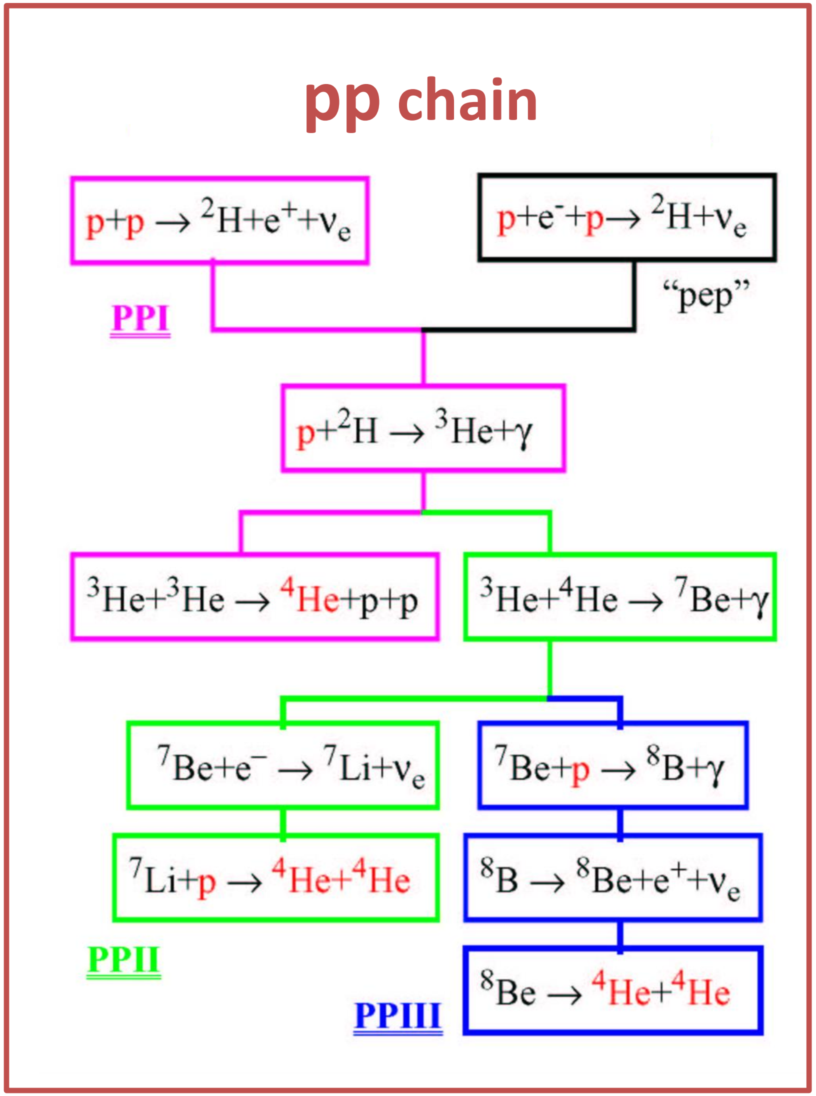
Nuclear reactions in the Sun

Energy production in the **Sun**:

pp chain→ 99% of energy production

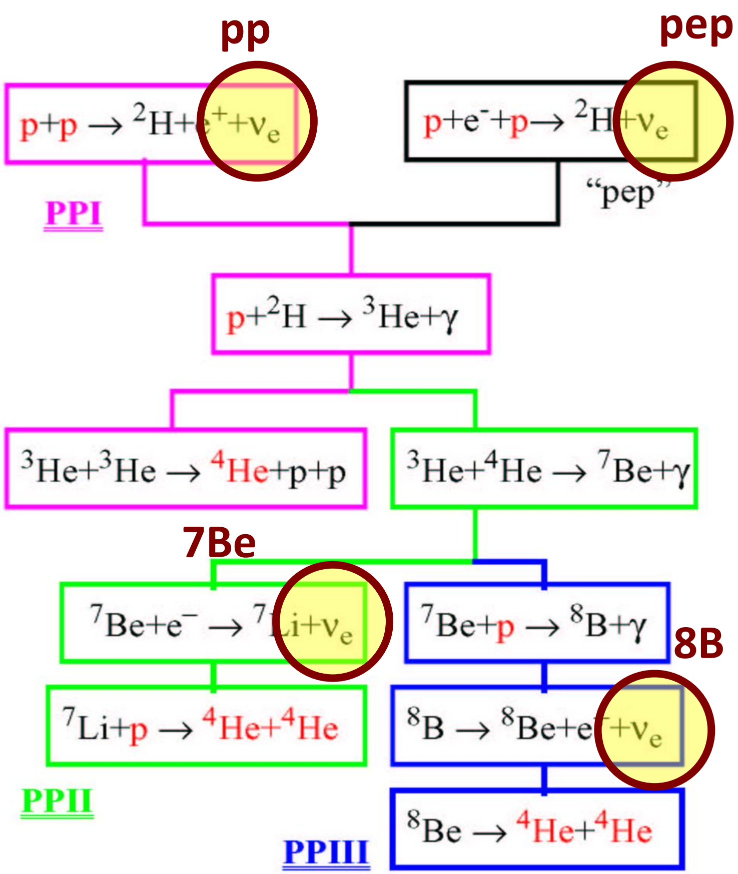
CNO cycle→ minor contribution

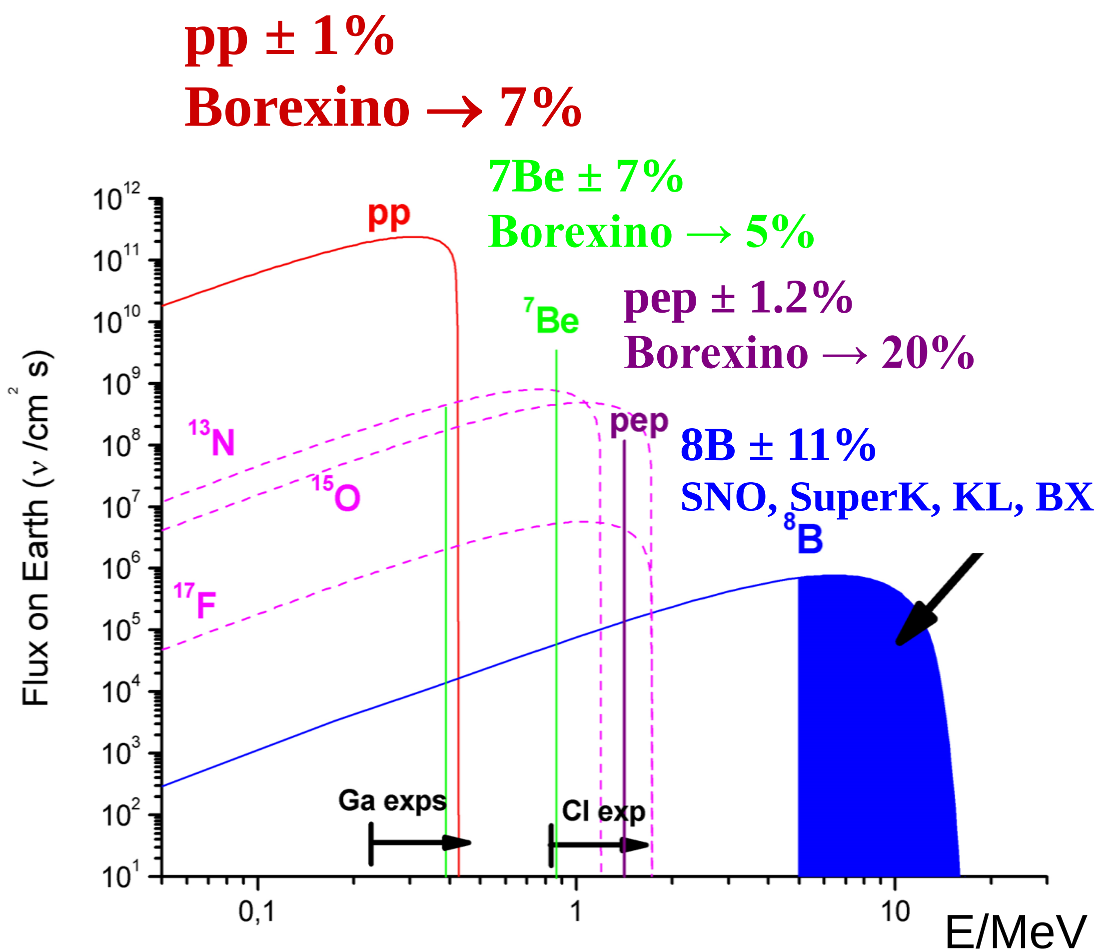




Solar neutrinos

Solar-ν flux and spectrum computed by Standard Solar Model

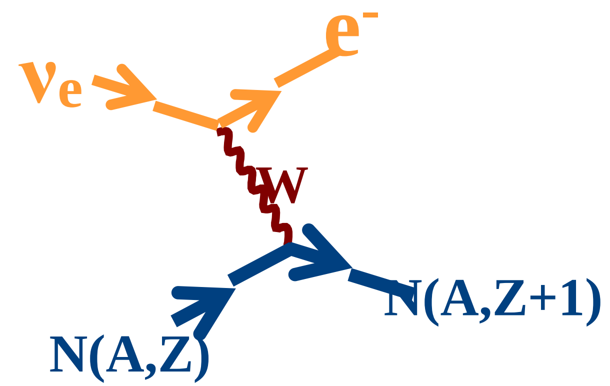




Detection of Solar neutrinos

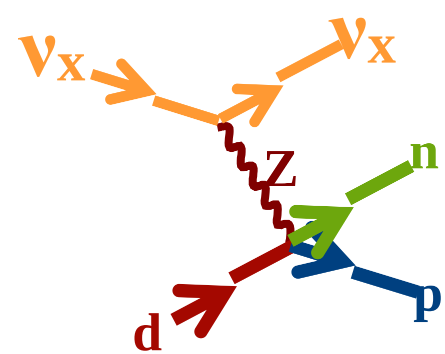
The sun produces **only ν_e**

Detection possible via **3 fundamental processes**



Inverse β decay on proton or nucleus

- **Charged Current** (CC) interaction
- E ~ MeV → **ν_e only**



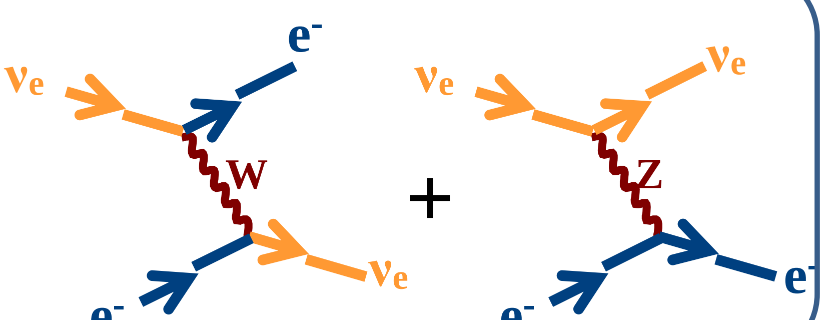
Elastic scattering on nucleus

- **Neutral Current** (NC) interaction
- neutrino not assorbed
- **same** cross section for **ν_e, $\nu_{\mu,\tau}$**

Elastic scattering on electron

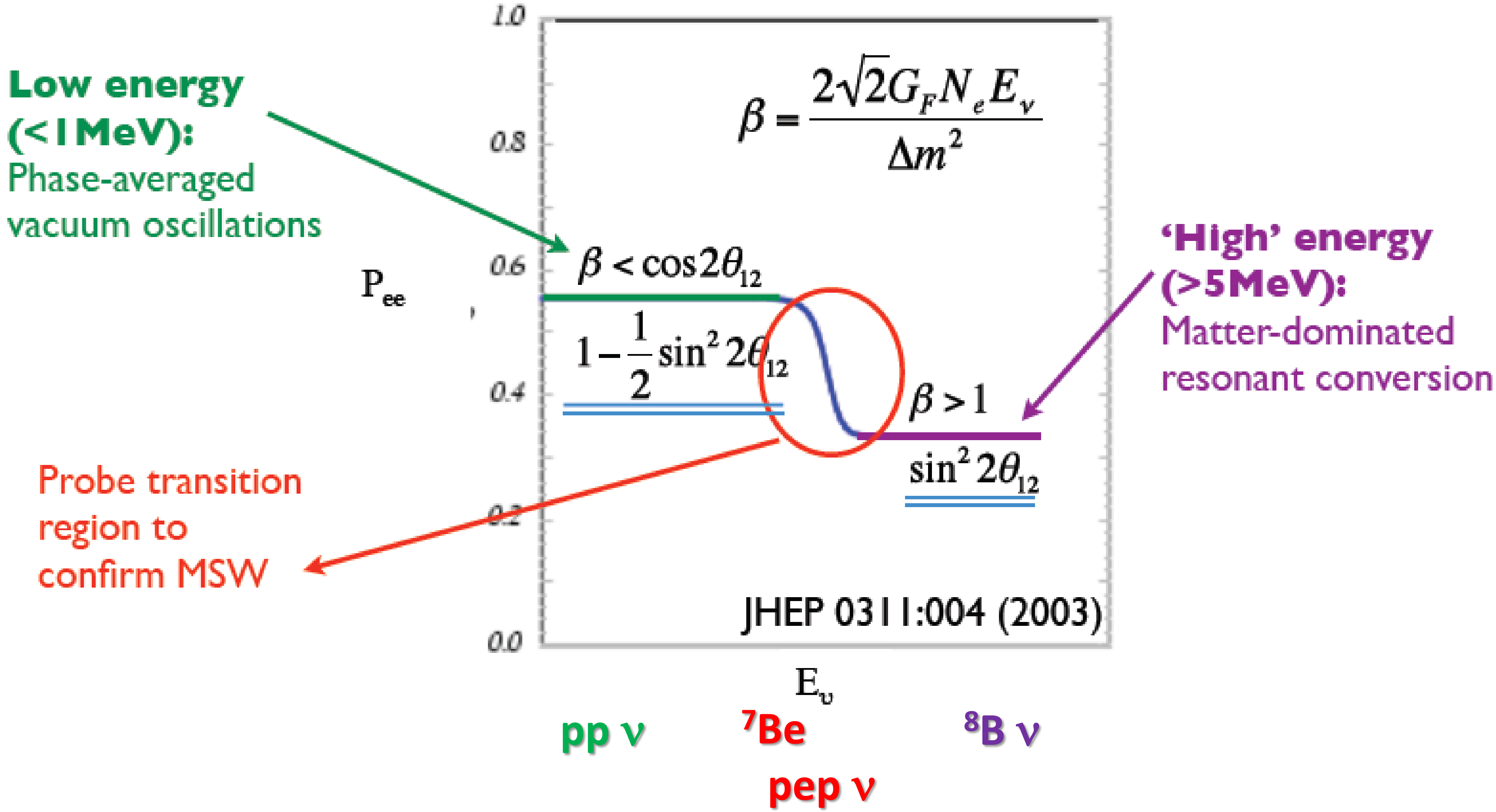
- Charged Current + Neutral Current
- **different** cross section for **ν_e** e **$\nu_{\mu,\tau}$**

$\sigma \sim 10^{-44}\ cm^2$



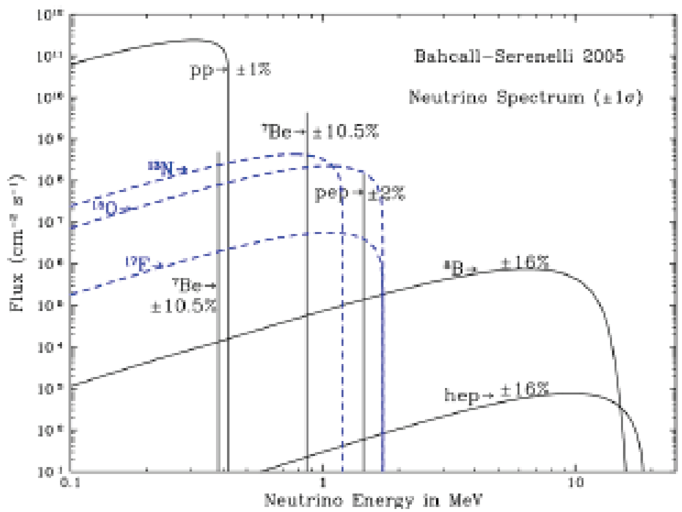
Solar-ν oscillation – MSW effect

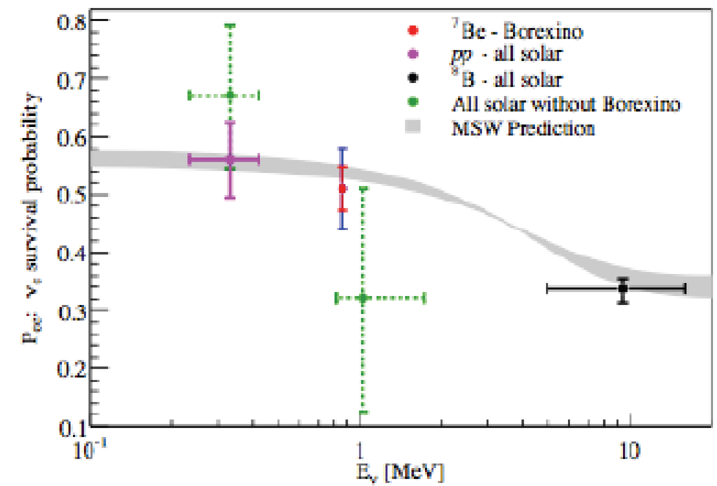
Pee becomes **energy dependent** because of **MSW** effect



Solar-ν searches: motivations

Test of neutrino oscillations and solar models





SCIENCE IDEAS

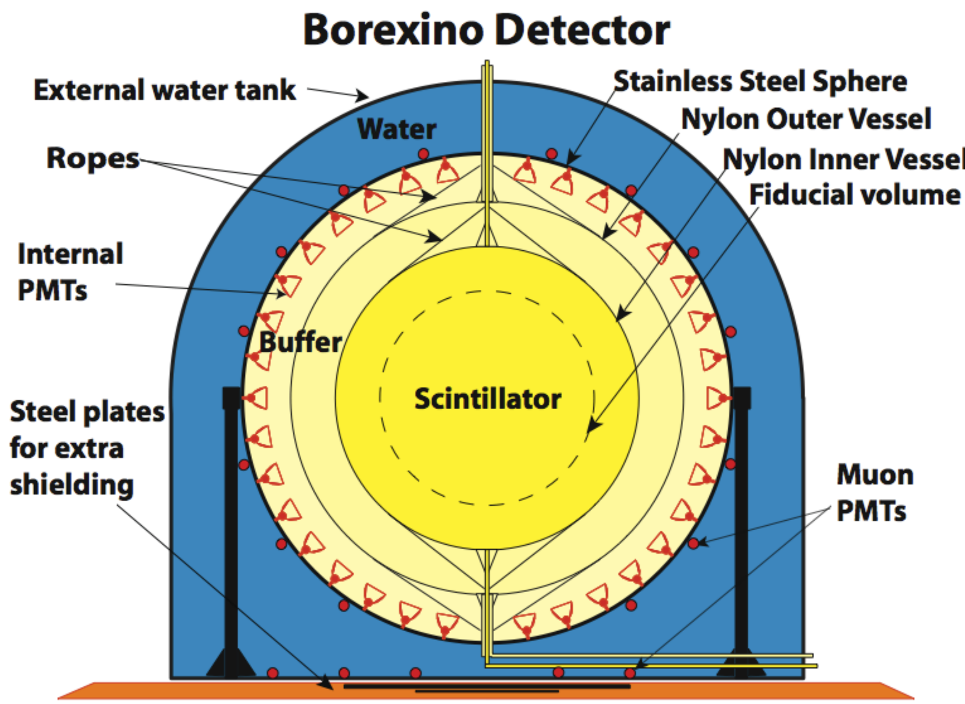
Solar Variability

Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

[Los Alamos Science, 1982]

Borexino at LNGS

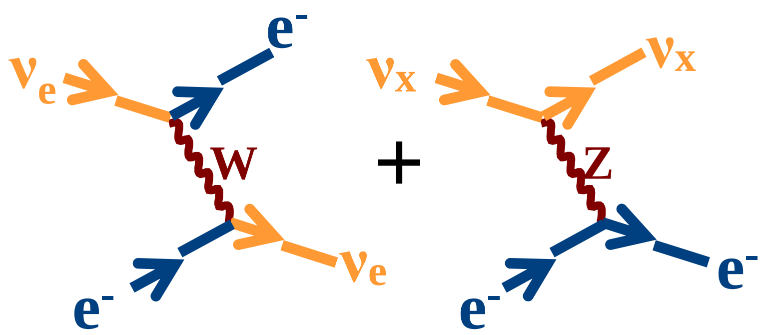


Ultra-pure Liquid scintillator calorimeter

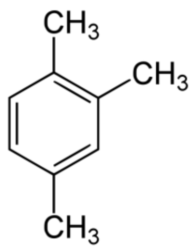
Low energy **threshold**

No directionality, superbe purity required to reject radioactivity

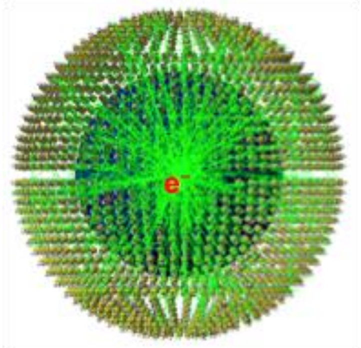
Principles of solar-ν detection



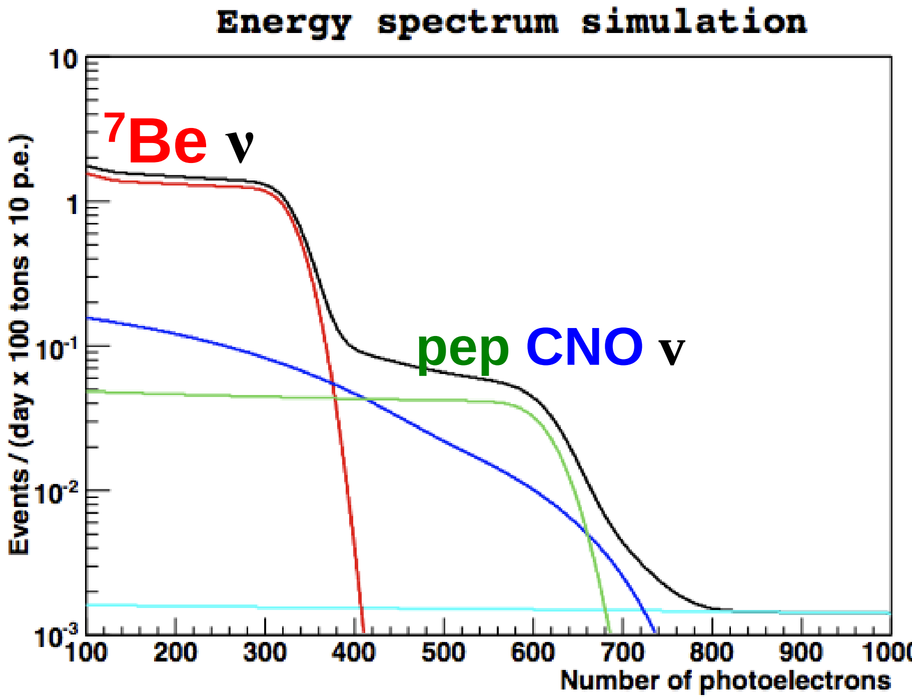
Neutrinos detected via **elastic scattering** on **electrons**



Recoil **electron** produces **Scintillation** light

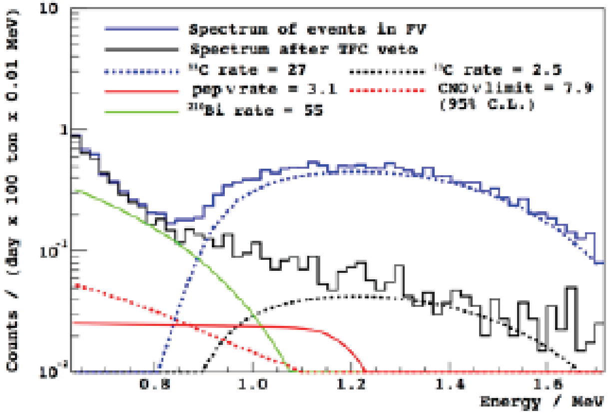


Light seen by **PMTs**

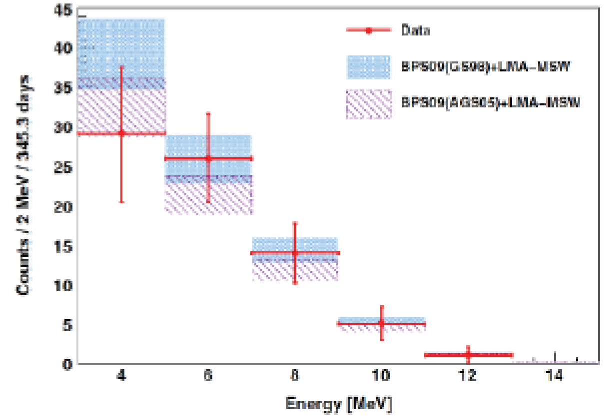


Other Borexino results (phase I)

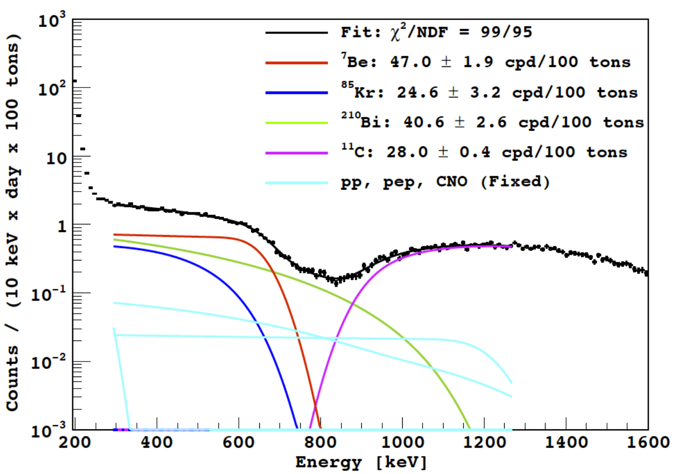
pep PRL 108 051302 (2012)



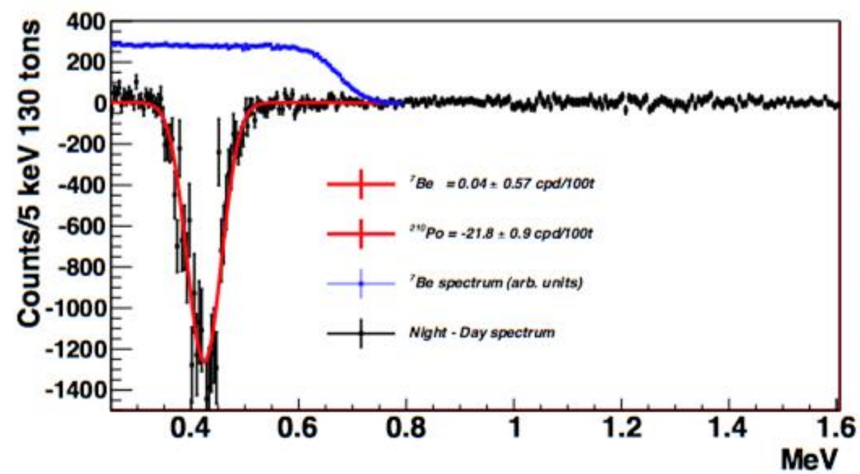
^{8}B PRD 82 033006 (2010)



^{7}Be PRL 107 141302 (2011)



^{7}Be Adn PLB 707 22-26 (2012)



PRD 89, 112007 (2014)

Borexino Phase-II Radiopurity

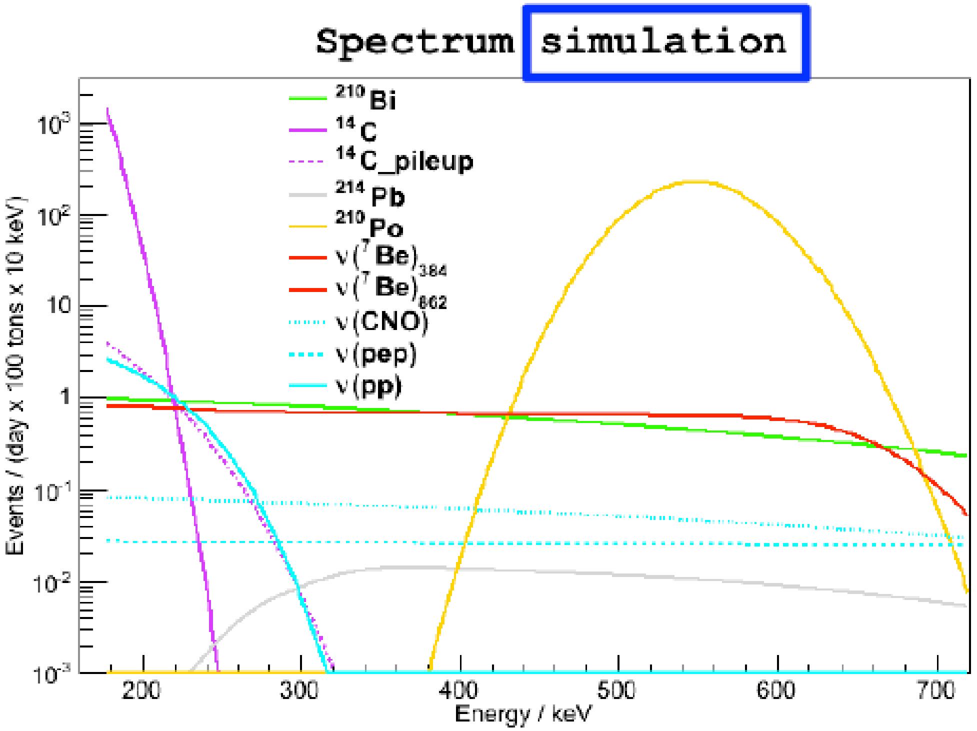
Isotope	Typical abundance (source)	Borexino goals	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	10^{-12} (cosmogenic)	~10^{-18}	$2.7 \cdot 10^{-18}$	$2.7 \cdot 10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	10^{-6}-10^{-5} (dust)	~10^{-16} (1 μБк /т)	$(1.6 \pm 0.1) \cdot 10^{-17}$	<$9.7 \cdot 10^{-19}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	10^{-6}-10^{-5} (dust)	~10^{-16}	$(6.8 \pm 1.5) \cdot 10^{-18}$	<$1.2 \cdot 10^{-18}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	100 atoms/cm^3 (air)	10	1	0.1
^{40}K, g[K_{nat}]/g	$2 \cdot 10^{-6}$ (dust)	~10^{-15}	<$1.7 \cdot 10^{-15}$ (95%)	---
^{210}Po, ev//d/t	Surface contamination	~10^{-2}	80 (initial), $T_{1/2}$=134 days;	2
^{210}Bi, ev/d/100 t	Inequilibrium with ^{222}Rn or ^{210}Pb	Not specified	20-70	~20
^{85}Kr ev/d/100 t	1 Бк/м^3 (technogenic, air)	~1	30.4±5 cpd/100t	< compatble with 0
^{39}Ar ev/d/100 t	17 mБк/м^3 (cosmogenic in air)	~1	<<^{85}Kr	

pp-ν detection challenges

pp **endpoint** 420 keV
(recoil energy < 261 keV)

^{14}C beta-decay spectral **shape**
(end point 156 keV)
and **rate** (40 Bq)

^{14}C **pile up**

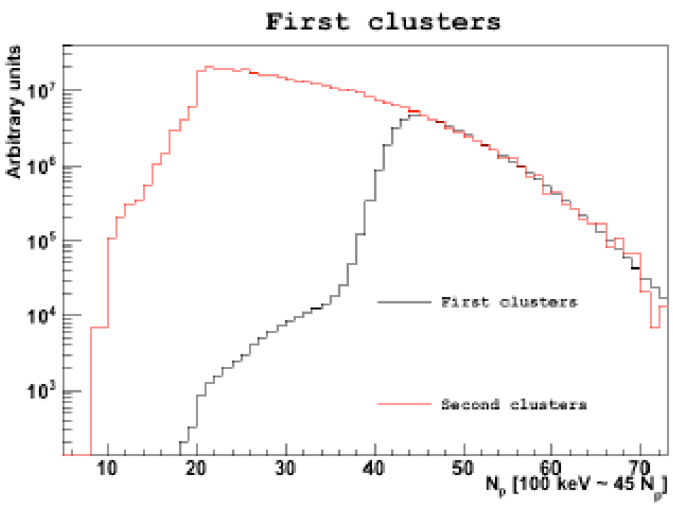


^{14}C decay: rate and shape

^{14}C activity is 5 orders of magnitude bigger than pp rate in BX

Needs to be **constrained**

Spectral shape needed



^{14}C activity estimated **independently** from the main analysis

Look at samples of data where event causing the trigger is followed by a **second event** within same acquisition window

These second events **not subject** to **trigger threshold** in energy

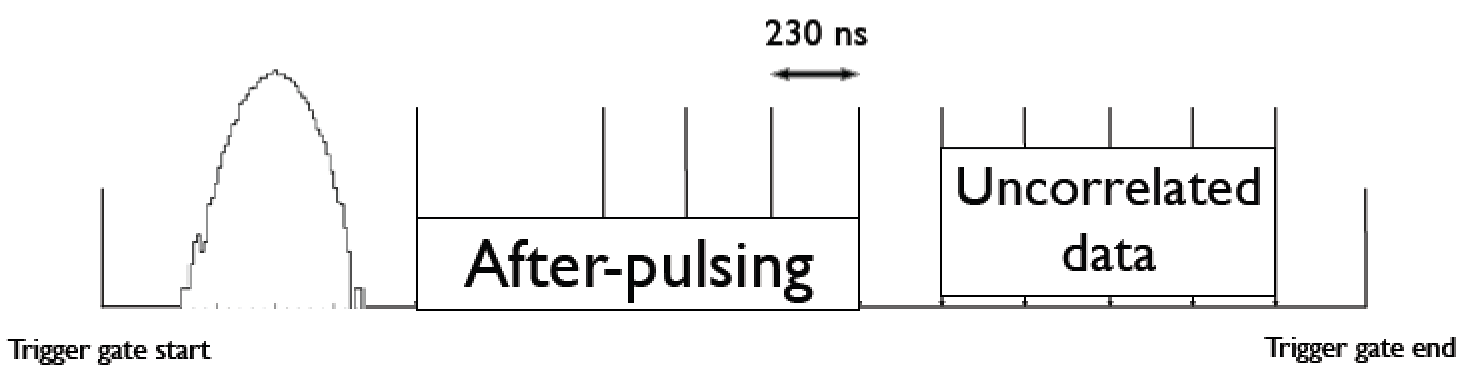
^{14}C activity in BX: 40 ± 1 Bq / 100 ton

^{14}C pileup

Two scintillation events so close in time
that is impossible to resolve them.
^{14}C pileup comparable to pp-ν rate
Spectral shape similar to pp-ν recoil spectrum.

Pile-up may come from ^{14}C but also from other detector events

Synthetic pile-up: overlap uncorrelated data with regular events



Result used to constrain rate of pile-up in final fit

pp-ν analysis recipe

Calculate energy estimator, position, *etc*, for all events

Apply muon, consmogenic, noise, radon, cuts

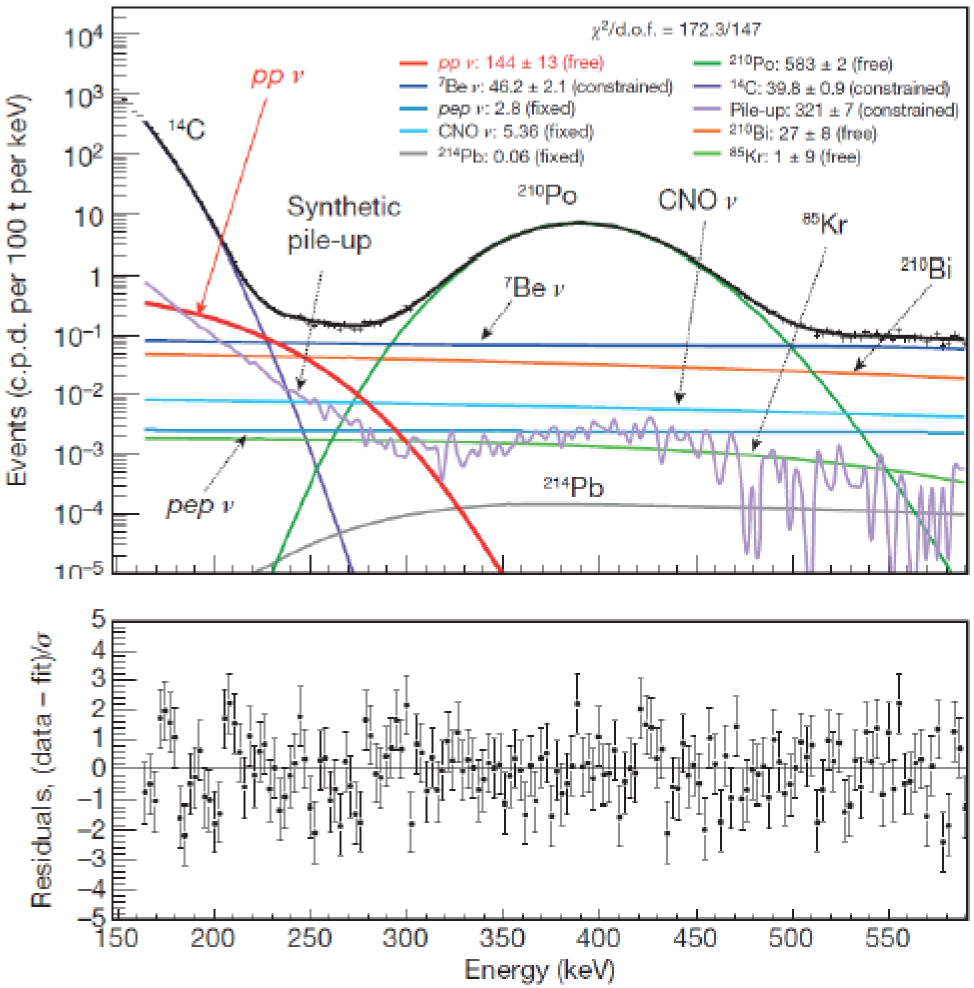
Introduce dark noise

Constrain ^{14}C

Constrain pile-up

Fit the energy spectrum

pp-ν analysis: fit

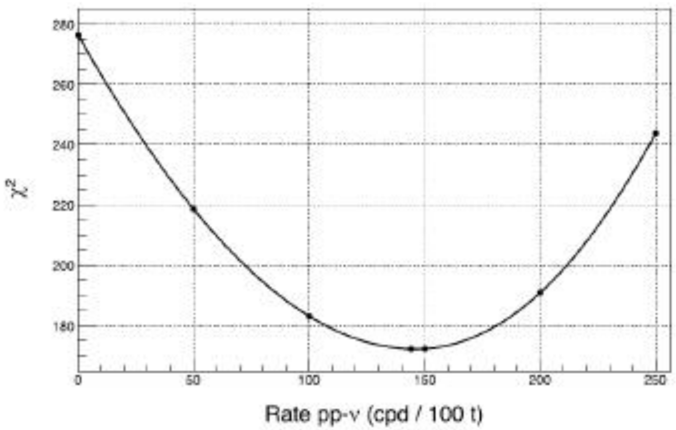


Nature **512**, 383-386 (28 August 2014)

pp neutrino measurement

pp = 144 ± 13 (stat) ± 10 (syst) cpd/100 t
compared to expected (MSW/LMA,HM)
131±2 cpd/100 t

physicsworld
TOP 10
BREAKTHROUGH
2014



pp neutrino flux:

$(6.6 \pm 0.7) \cdot 10^{10}\ cm^{-2}s^{-1}$

vs

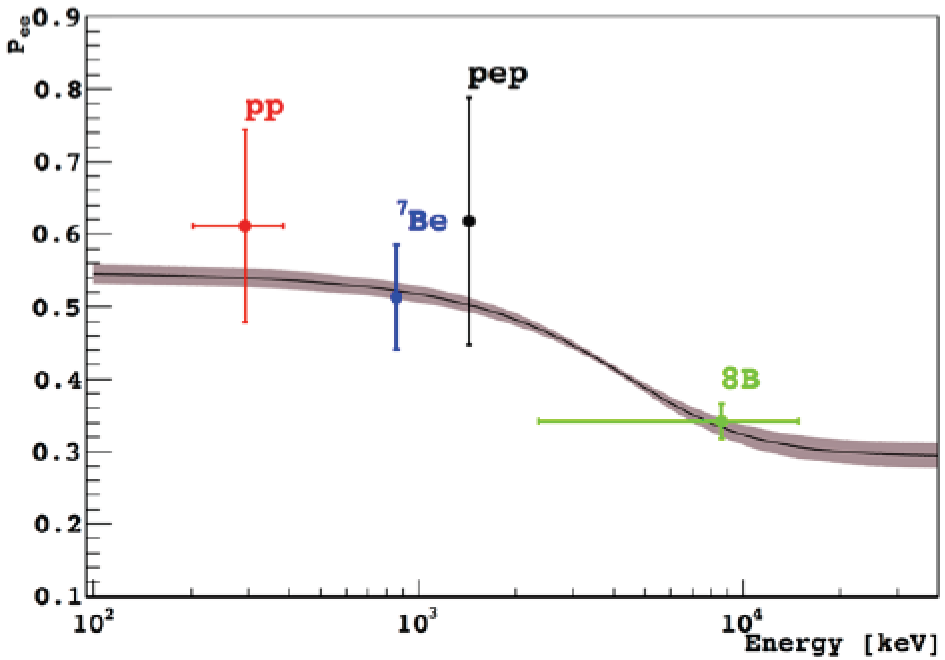
$(5.98 \pm 0.04) \cdot 10^{10}\ cm^{-2}s^{-1}$

Zero pp count is excluded at 10σ level

"Neutrinos from the primary proton–proton fusion process in the Sun"
Nature, Vol. 512 (2014) pp.383-386

Interpretation: Neutrino Oscillations

Solar neutrino (ν_e) survival probability vs energy

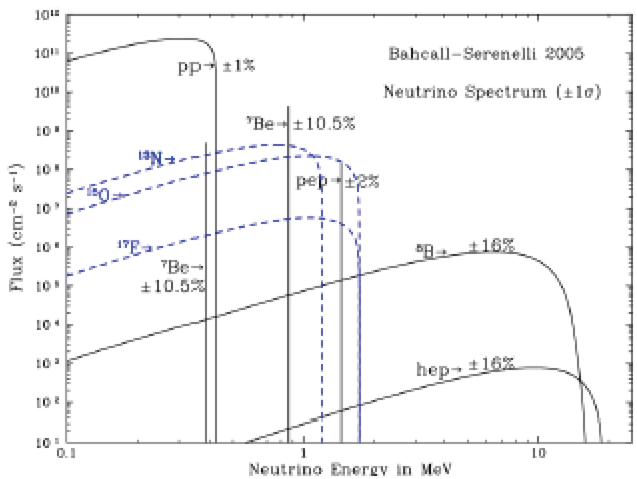


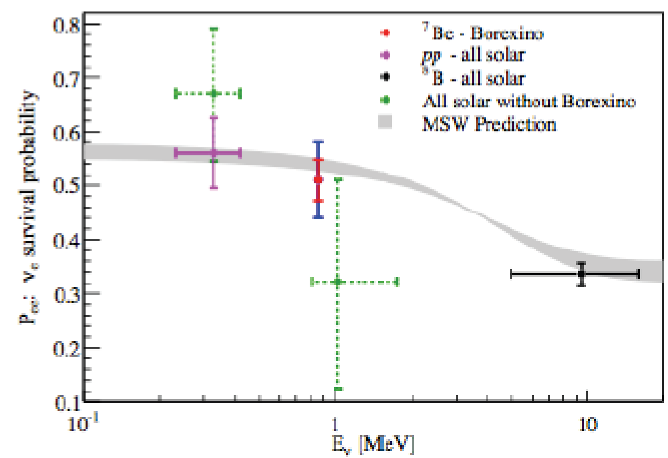
$$P_{ee} = \begin{cases} 0.612 \pm 0.133 & \text{measured} \\ 0.543 \pm 0.013 & \text{expected} \end{cases}$$

Nature **512**, 383-386 (28 August 2014)

Interpretation: Solar Neutrino Flux

From neutrino interaction rate to Solar Neutrino Flux





$$\phi = \begin{cases} (6.42 \pm 0.85) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{measured} \\ (5.98 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (high}-Z) \\ (6.03 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (low}-Z) \end{cases}$$

Nature **512**, 383-386 (28 August 2014)

Combining Borexino with Gallex/GNO and SAGE

Radiochemical + ^{7}Be Borexino:

$\Phi(pp) = (6.14 \pm 0.61)10^{10}\ cm^{-2}s^{-1}$

Borexino only:

$\Phi(pp) = (6.6 \pm 0.7)10^{10}\ cm^{-2}s^{-1}$

Combined

$\Phi(pp) = (6.37 \pm 0.46)10^{10}\ cm^{-2}s\text{-}^{1}$ **(7%)**

Nature **512**, 383-386 (28 August 2014)

Conclusions and Outlook

Borexino set new records in radiopurity of liquid organic scintillator, these allowed to challenge the measurements beyond the original physical program

Completed first set of solar neutrino measurments related to the pp cycle
Direct measurement of **pp neutrinos:** test Sun luminosity

Borexino is continuing to take data, update of results on the Solar neutrino flux are envisaged in Phase II: **^{7}Be, pep, ^{8}B**

New detector calibrations in late 2015

the **CNO** neutrino flux measurement (or setting the stronger limits) is another challenging task

Data taking ongoing also for non-solar physics: **geoneutrinos**, …

Borexino will become the **sterile ν** hunter **SOX** in 2016

the Borexino Collaboration

INFN

Milano

München

Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

JINR Dubna

Virginia Tech

Houston

Paris

Moscow

Princeton

UMass Amherst

Los Angeles

St. Petersburg

Kurchatov Moscow

Backups

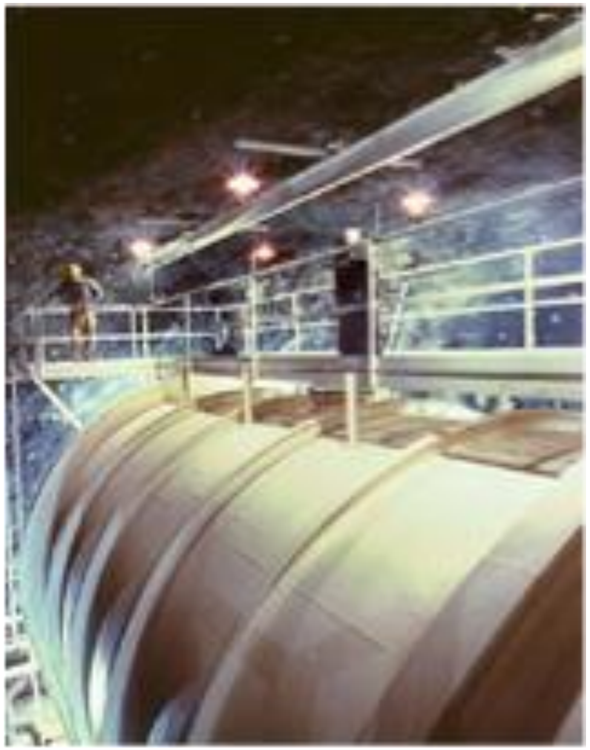
Short history of solar-ν (I)

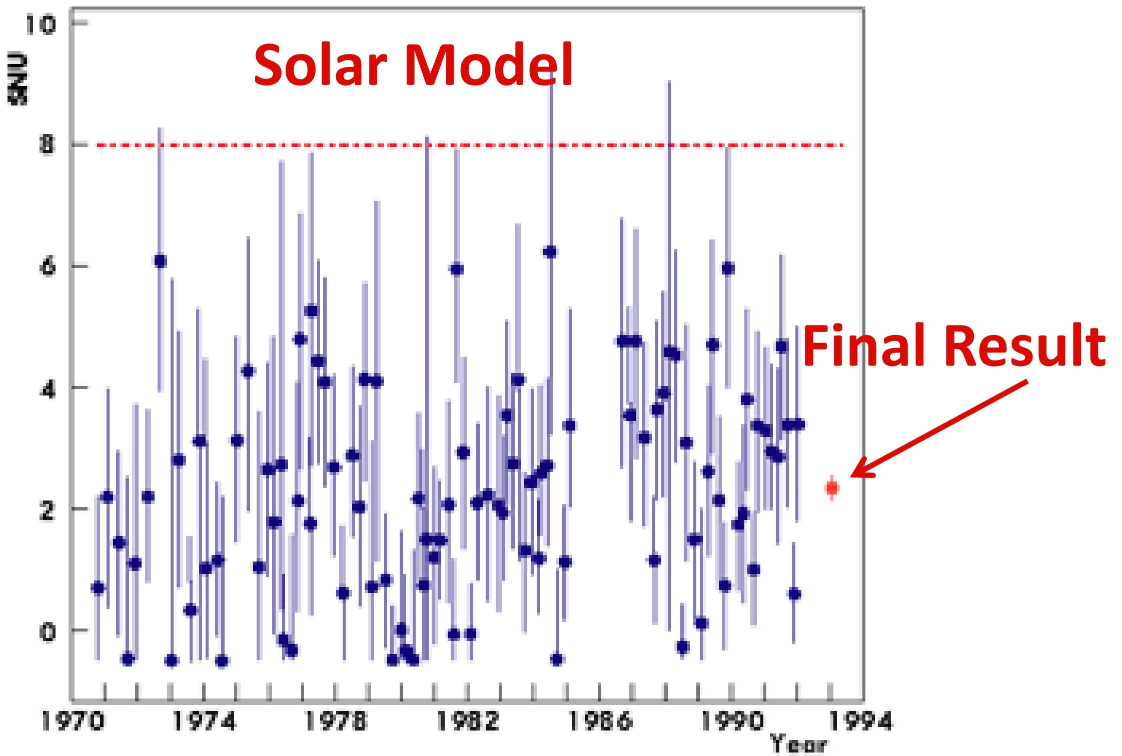
70's-80's: Homestake (R. Davies)

radiochemical experiment: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ **(E_ν >1.4 MeV)**

Deficit in ν rate → new physics or Solar Model unaccurate?

Nobel prize 2002





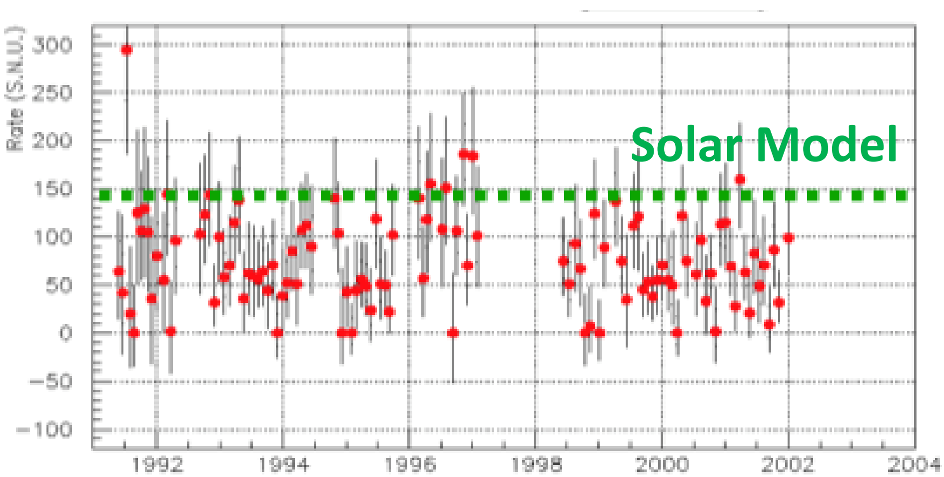
Short history of solar-ν (II)

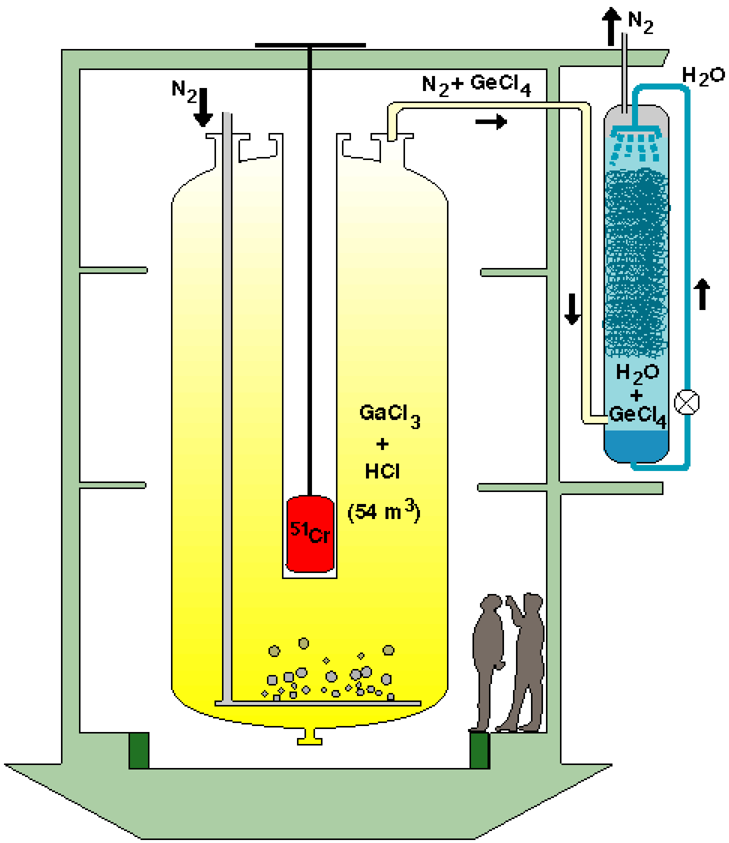
90's: Gallex (GNO), Sage

Radiochemical experiment: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ **(E_ν > 200 keV)**

Observed deficit on pp ν **(low energy)**

Calibration with neutrino source → real effect



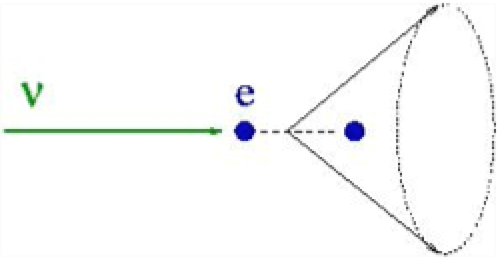


Short history of solar-ν (III)

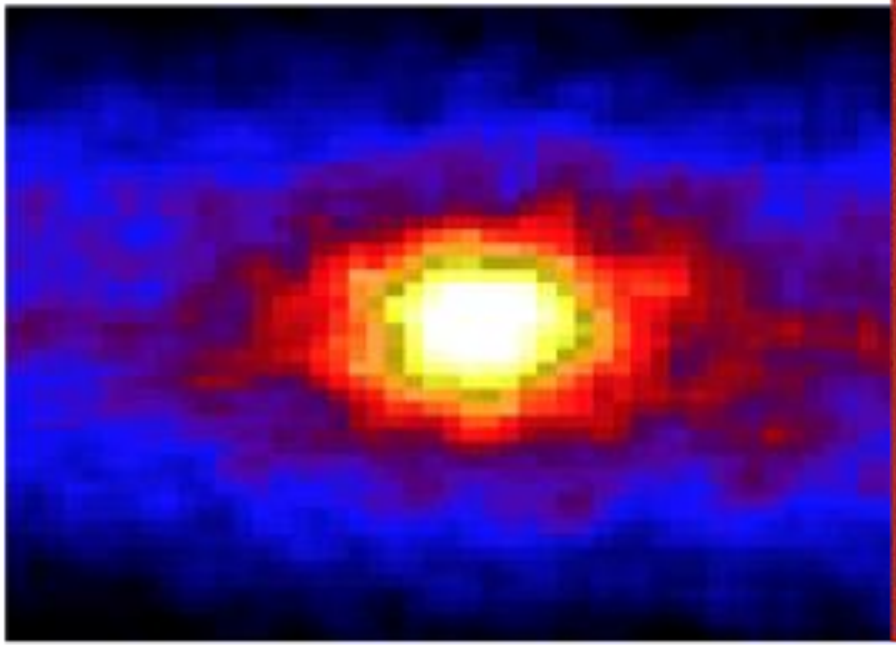
80's-90's: (Super) KamioKande

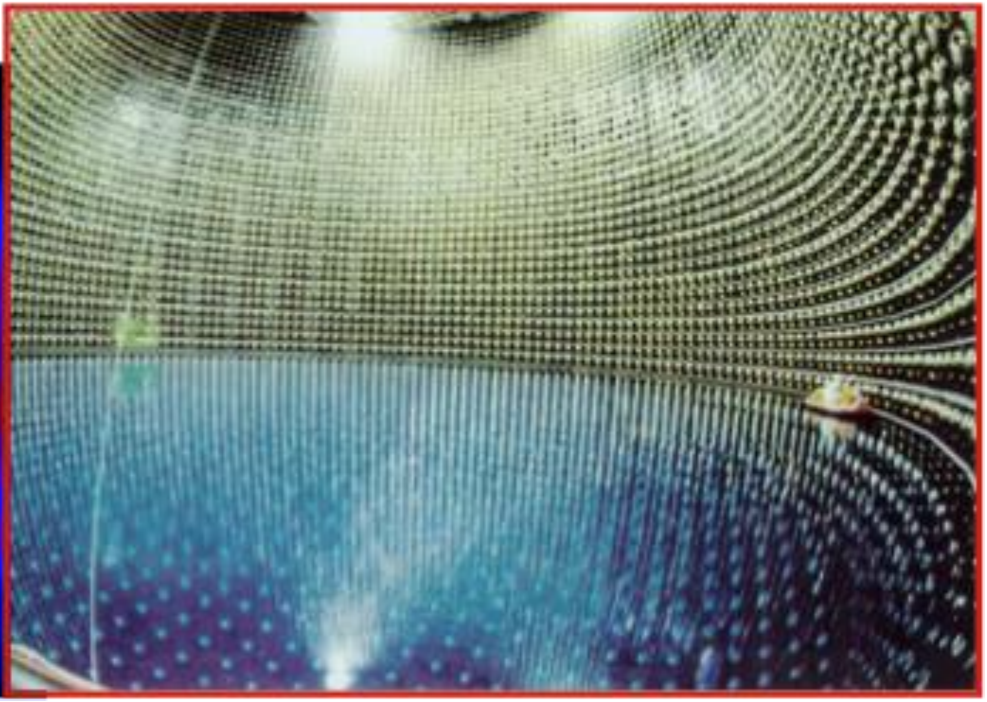
Confirm deficit on ^{8}B ν **(E> ~5MeV)**

Direction of solar neutrinos



A beautiful image of the Sun in neutrinos





Solar-ν oscillation in vacuum

flavor transition in flight

if only ν_e detected → **deficit**

2ν approximation

$$P_{e\to\mu} = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$

→ **Averaged out for solar-ν**

Δm in eV
L in m
E_ν in MeV

Solar-ν oscillation in vacuum

$$P_{e\to\mu} = \frac{1}{2}\sin^2(2\theta)$$

But propagation NOT in vacuum: Sun matter

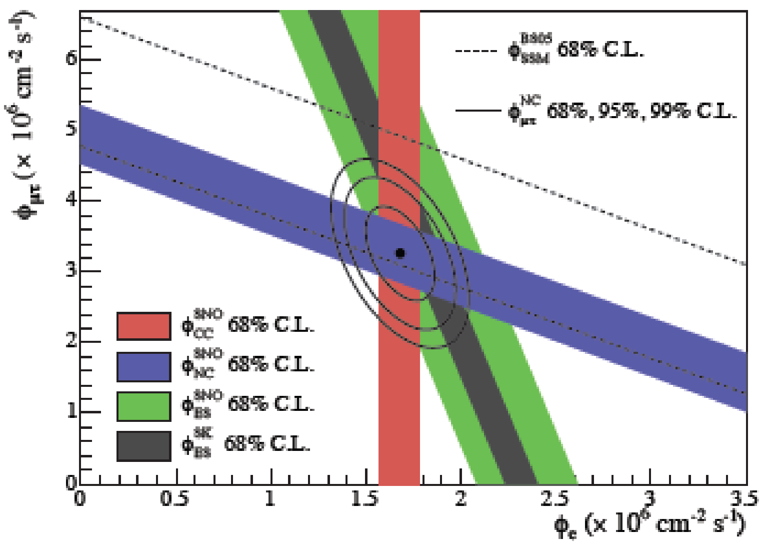
Discovery of solar- ν oscillations

Inclusive appearance at the Sudbury Neutrino Observatory

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

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

NC: $\nu_x + {}^2H \rightarrow n + p + \nu_x$

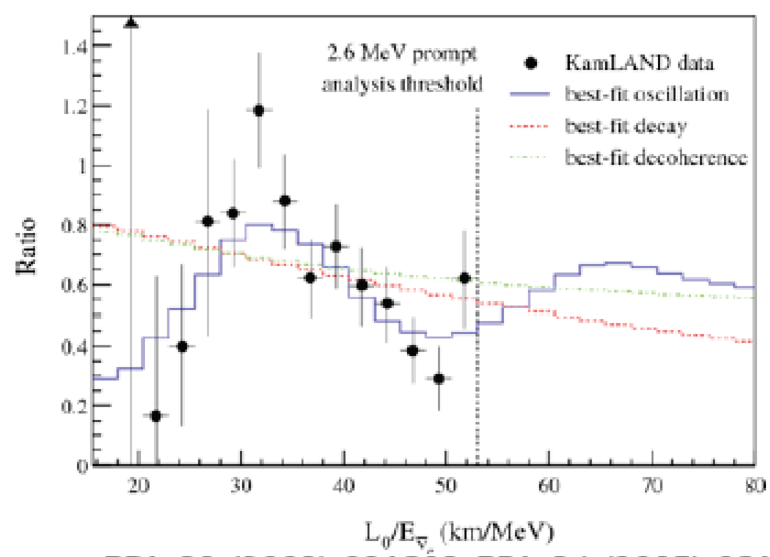


PRL 87 (2001) 071301, PRL 89 (2002) 011301

Oscillations at KamLAND

Disappearance at >99.99%

Clear oscillation pattern

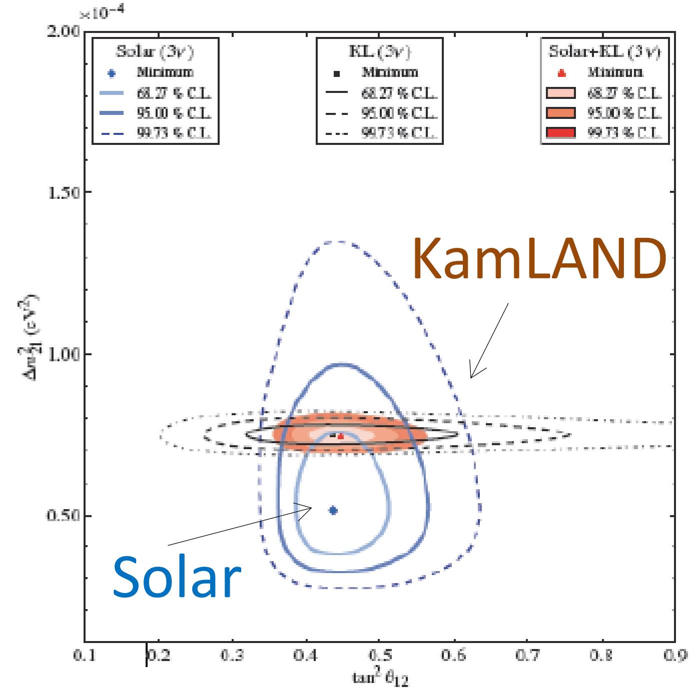


PRL 90 (2003) 021802, PRL 94 (2005) 081801

MSW-LMA

Global Fit
Solar exp + KamLAND
evidence
Large **M**ixing **A**ngle

Solar neutrino oscillations
described by
MSW-LMA scenario



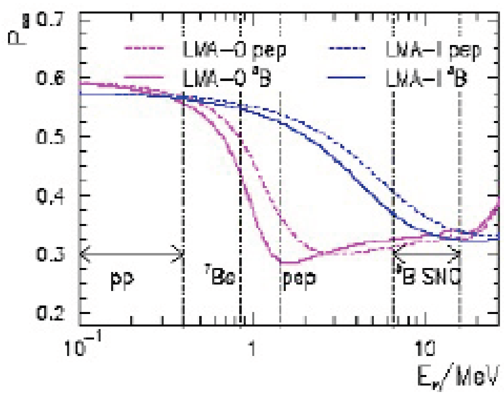
What may we still learn from solar-ν?

Non standard physics can alter Pee shape – position of MSW rise

Precision measurements to probe Pee

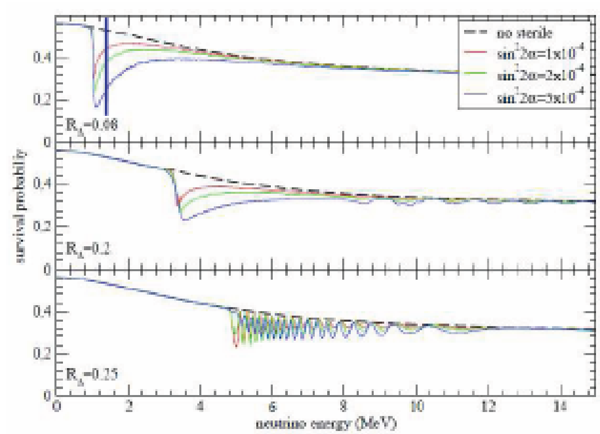
Constrain non-standard neutrino and solar physics

Non-standard interactions (flavour changing NC)



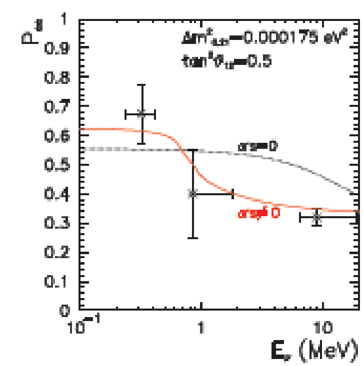
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



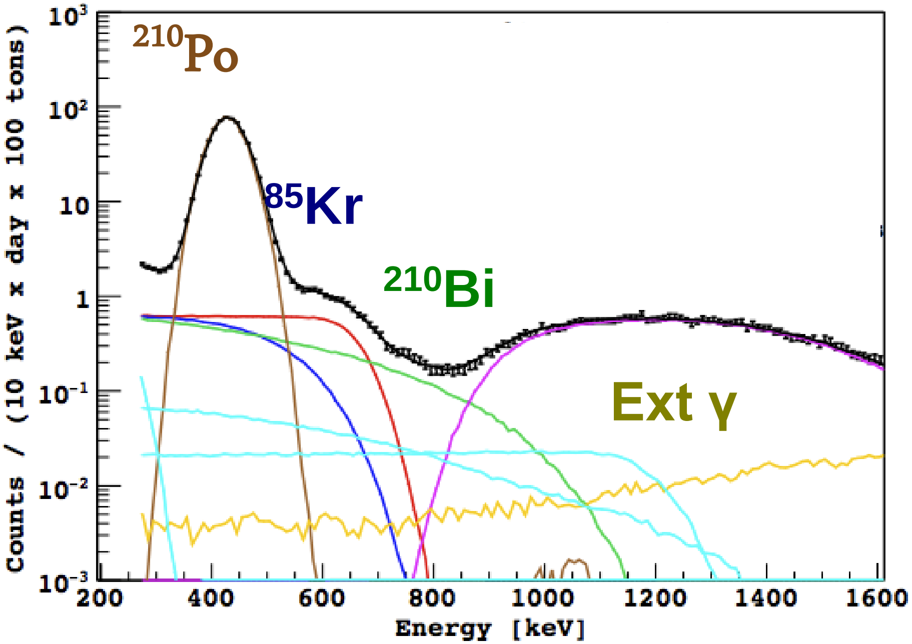
Holanda & Smirnov PRD 83 (2011) 113011

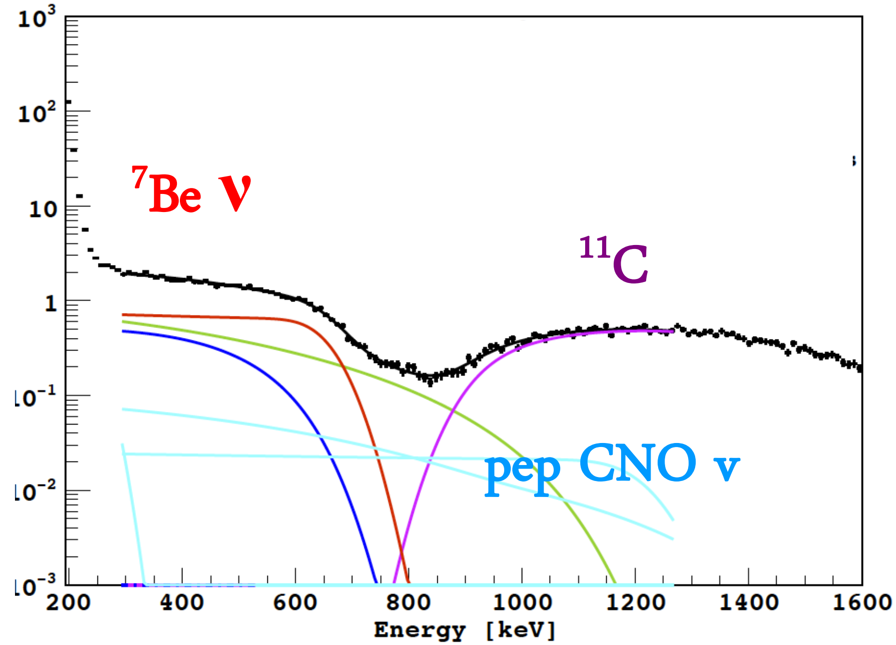
Mass varying neutrinos (MaVaNs)



M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

^{7}Be-ν precise flux measurement (BX)





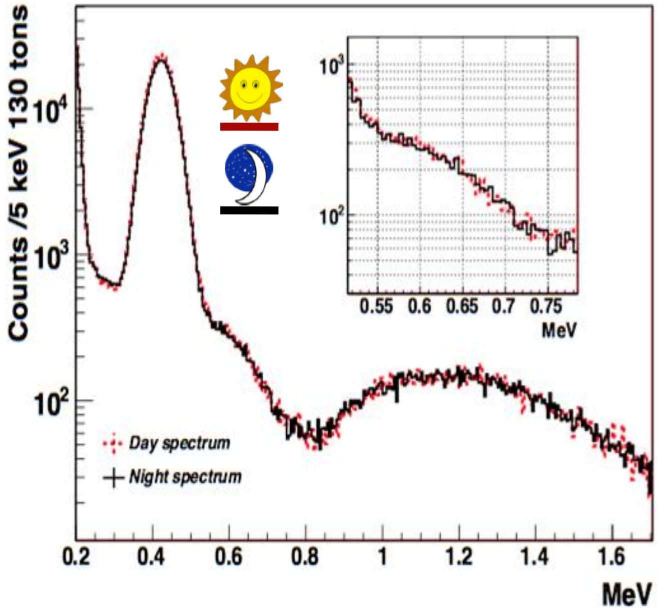
Rate ^{7}Be = 46.0 $\pm$ 1.5$_{stat}$ $^{+1.6}_{-1.5 syst}$ counts/day/100tons

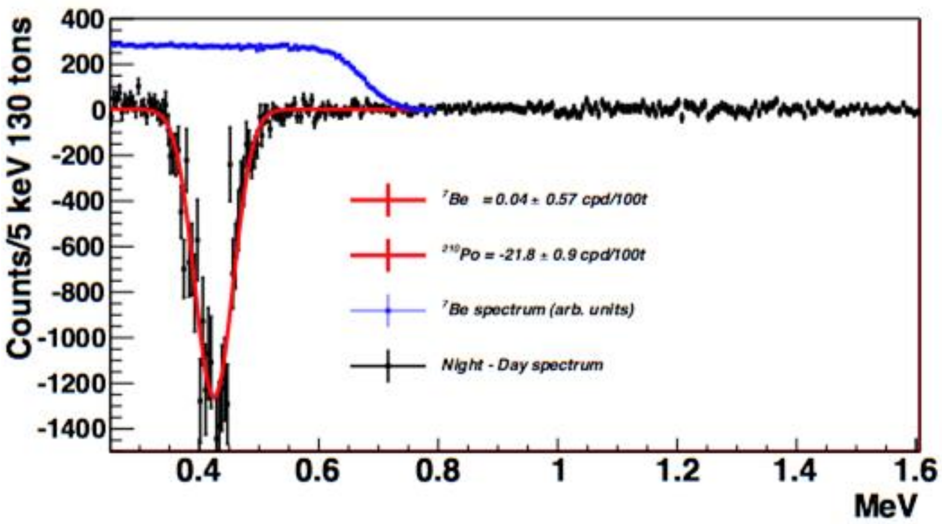
$$\Phi_{7Be} = 3.10 \pm 0.15 \cdot 10^{9}\ cm^{-2}\ s^{-1}$$

No oscillation excluded at 5σ

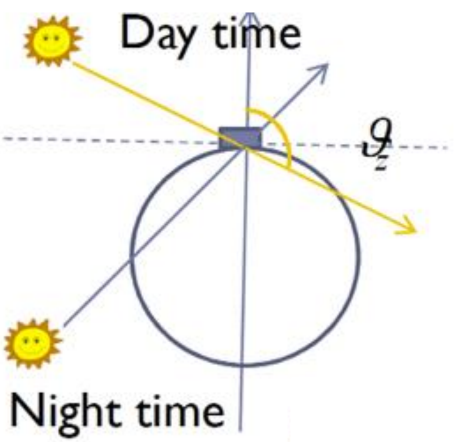
PRL 107, 141302 (2011)
PRD 89, 112007 (2014)

^{7}Be-ν day night asymmetry (BX)

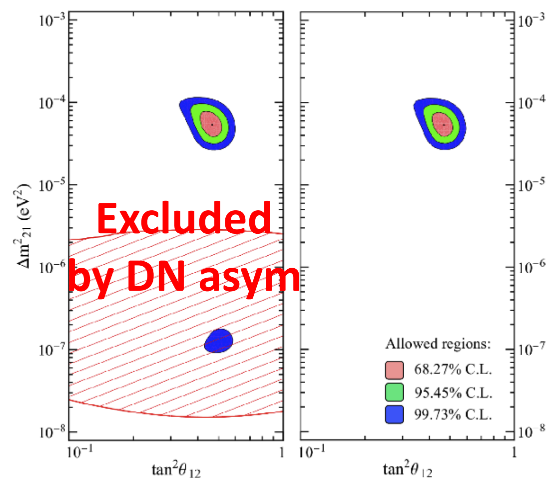




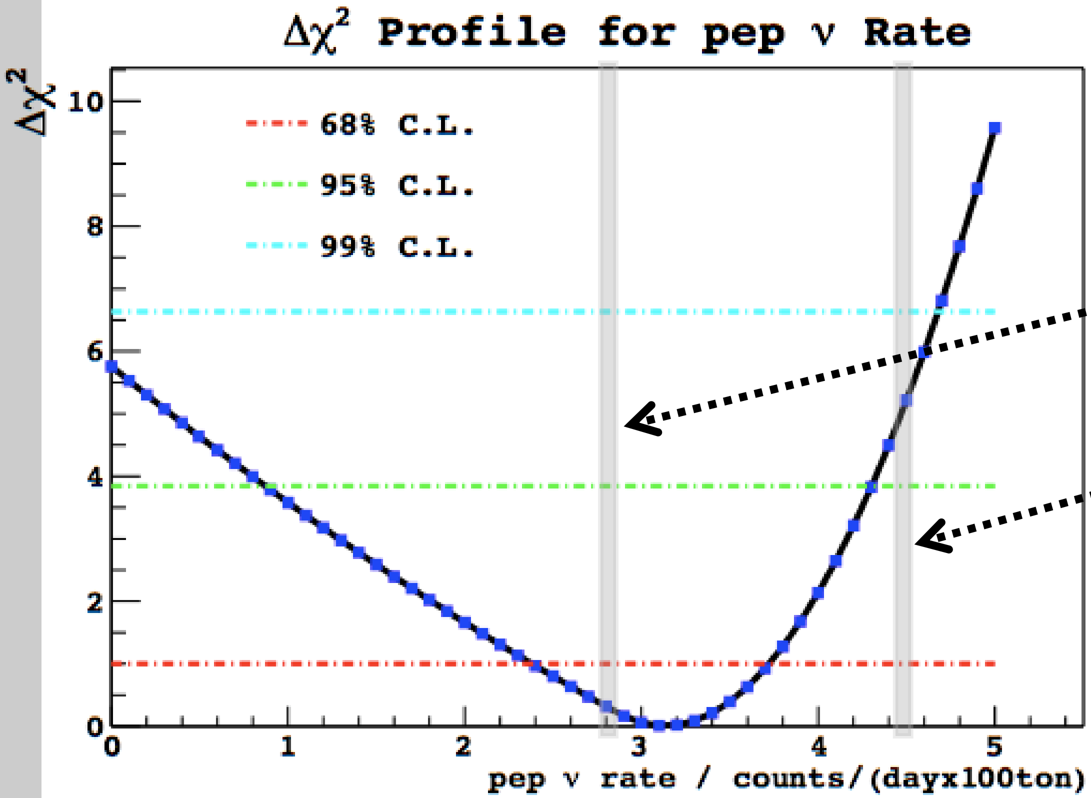
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = 0.001 \pm 0.012 \pm 0.007$$



PLB 707, 22-26 (2012)
PRD 89, 112007 (2014)

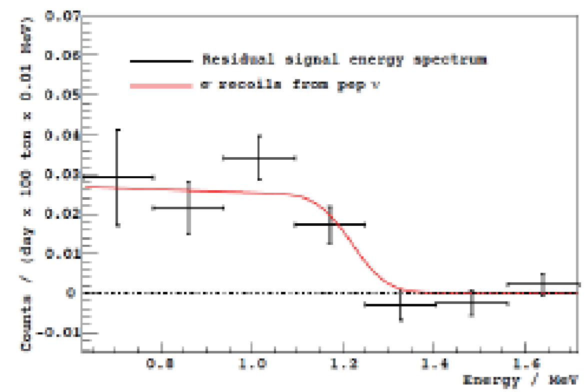


pep- ν detection (Borexino)



Standard **S**olar **M**odel + **MSW-LMA** oscillation Predicted rate

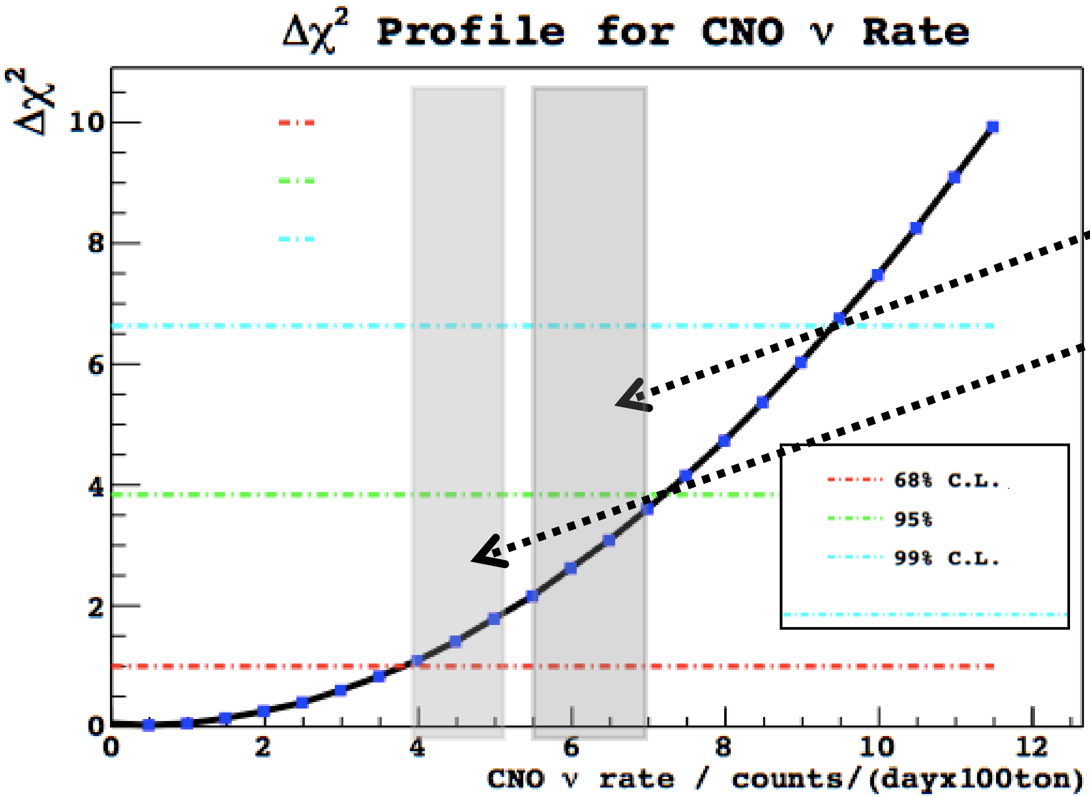
No oscillation disfavoured at 97% CL



$$\Phi_{pep} = 1.6 \pm 0.3 \cdot 10^8\ cm^{-2}\ s^{-1}$$

PRL 108, 051302 (2012)
PRD 89, 112007 (2014)

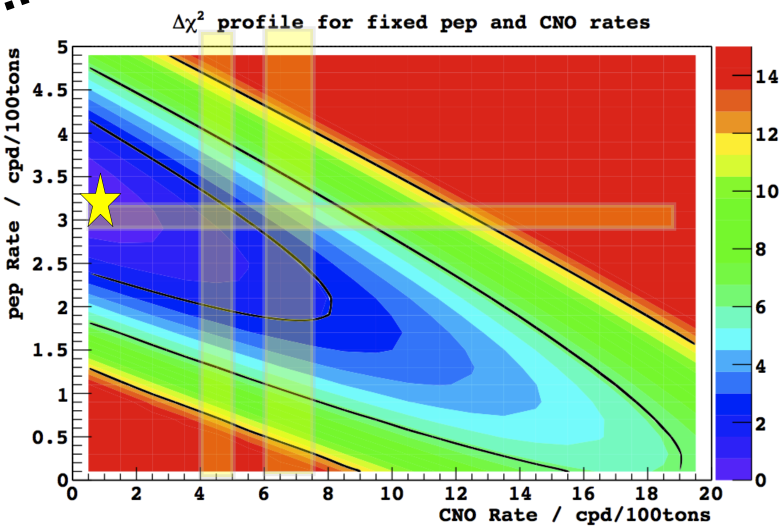
CNO-ν limit (Borexino)



Standard Solar Model

High Z prediction

Low Z prediction

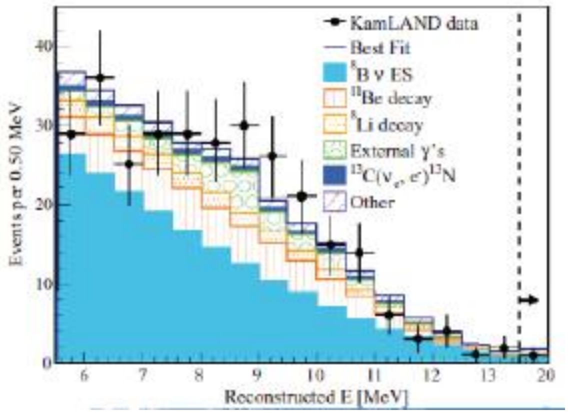


$\Phi_{CNO} < 7.7 \cdot 10^{8}\ cm^{-2}\ s^{-1}$ (95% CL)

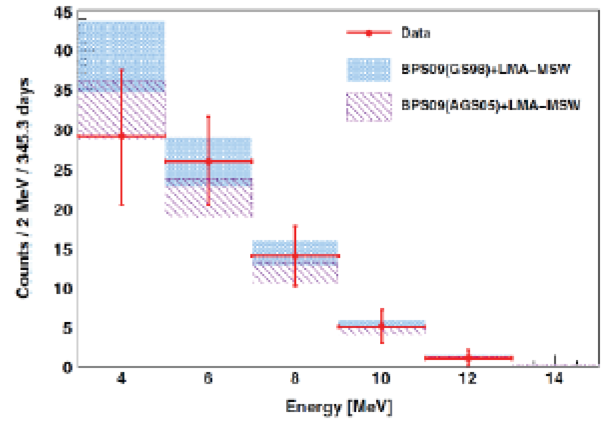
PRL 108, 051302 (2012)
PRD 89, 112007 (2014)

^{8}B-ν recoil spectra

KamLAND PRC 84, 035804 (2011)



Borexino PRD 82 033006 (2010)



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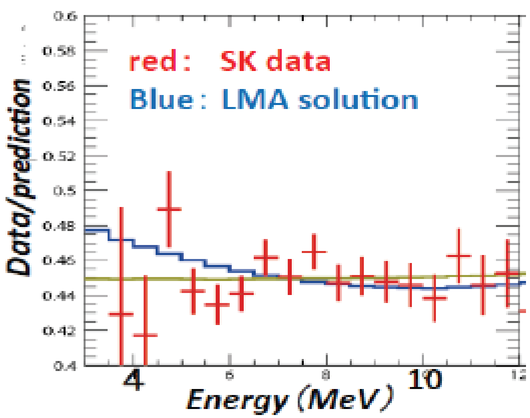
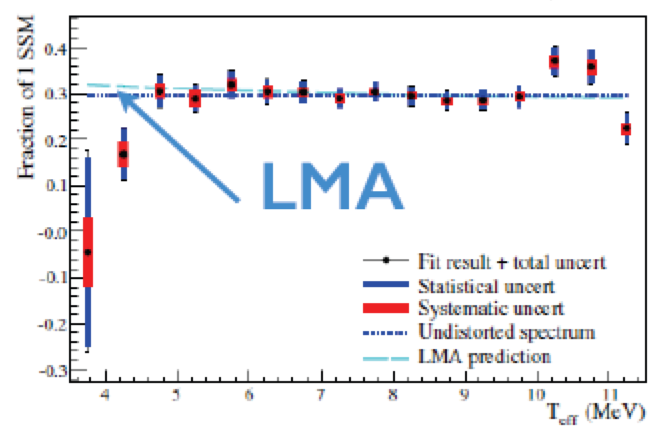
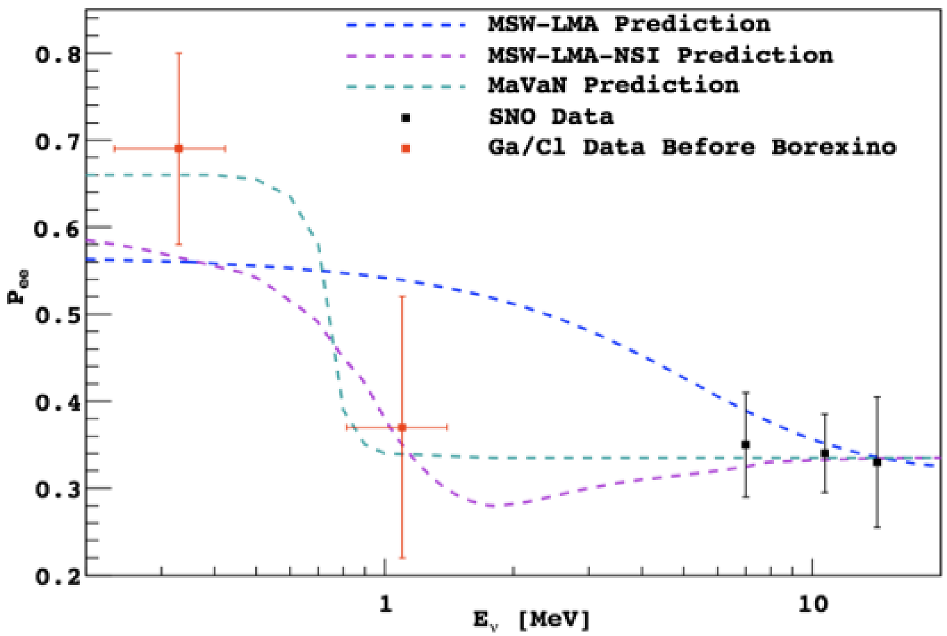


SNO LETA PRC 88 025501 (2013)

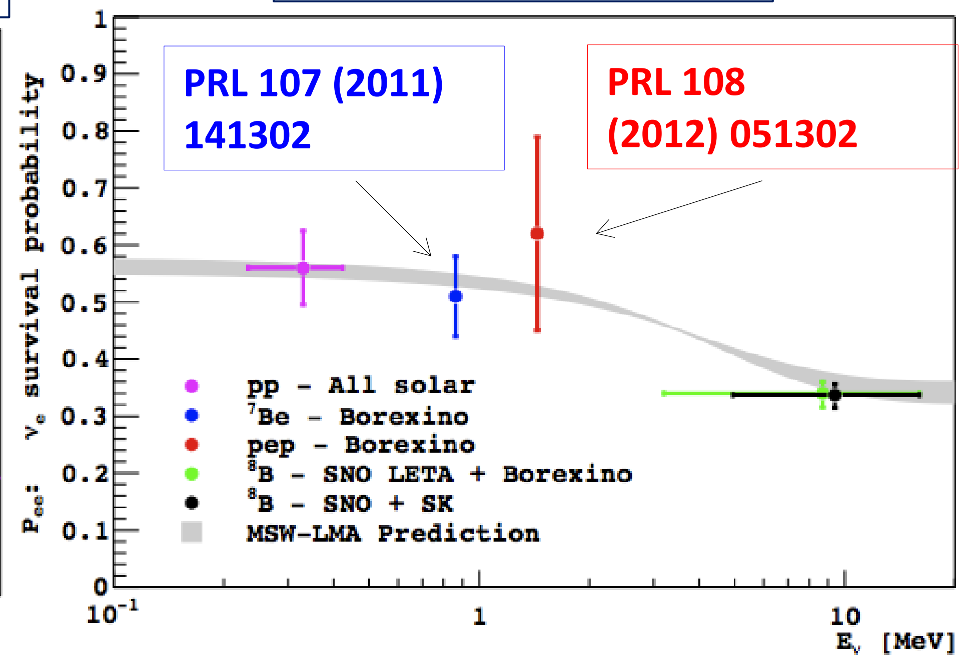


Current status of Pee probe

Pee measurment before BOREXINO



Today



Direct Fit for Energy-Dependent Survival Probability