Solar neutrinos: an update

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on behalf of the Borexino Collaboration

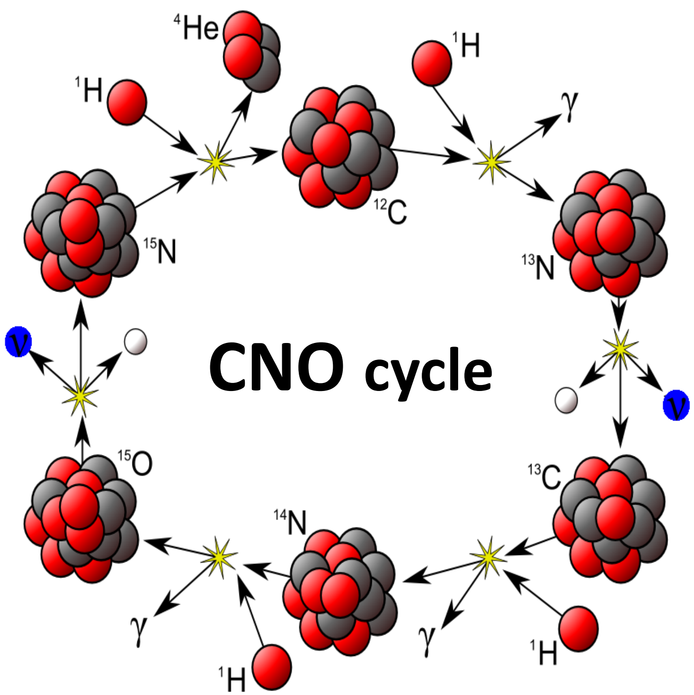
Heavy Quarks and Leptons 2014
Mainz, August 26, 2014

Nuclear reactions in the Sun

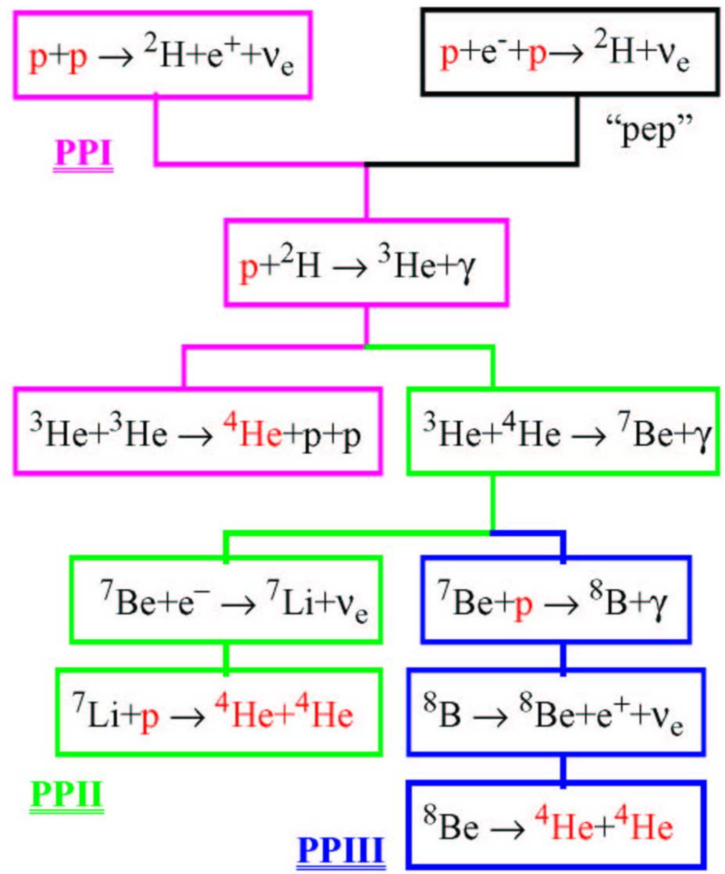
Energy production in the **Sun**:

pp chain→ 99% of energy production

CNO cycle→ minor contribution

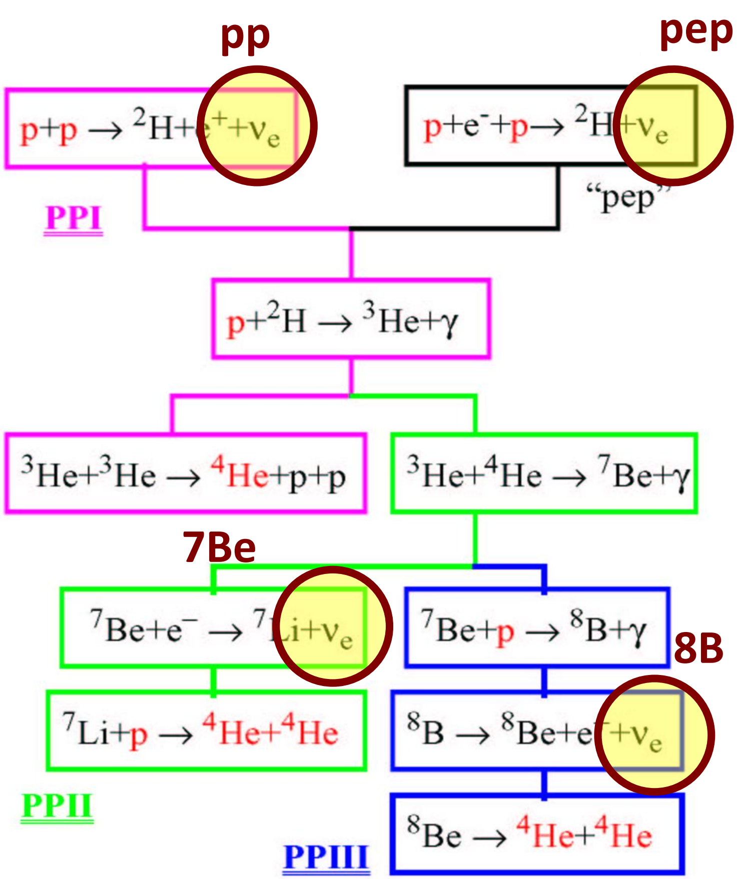


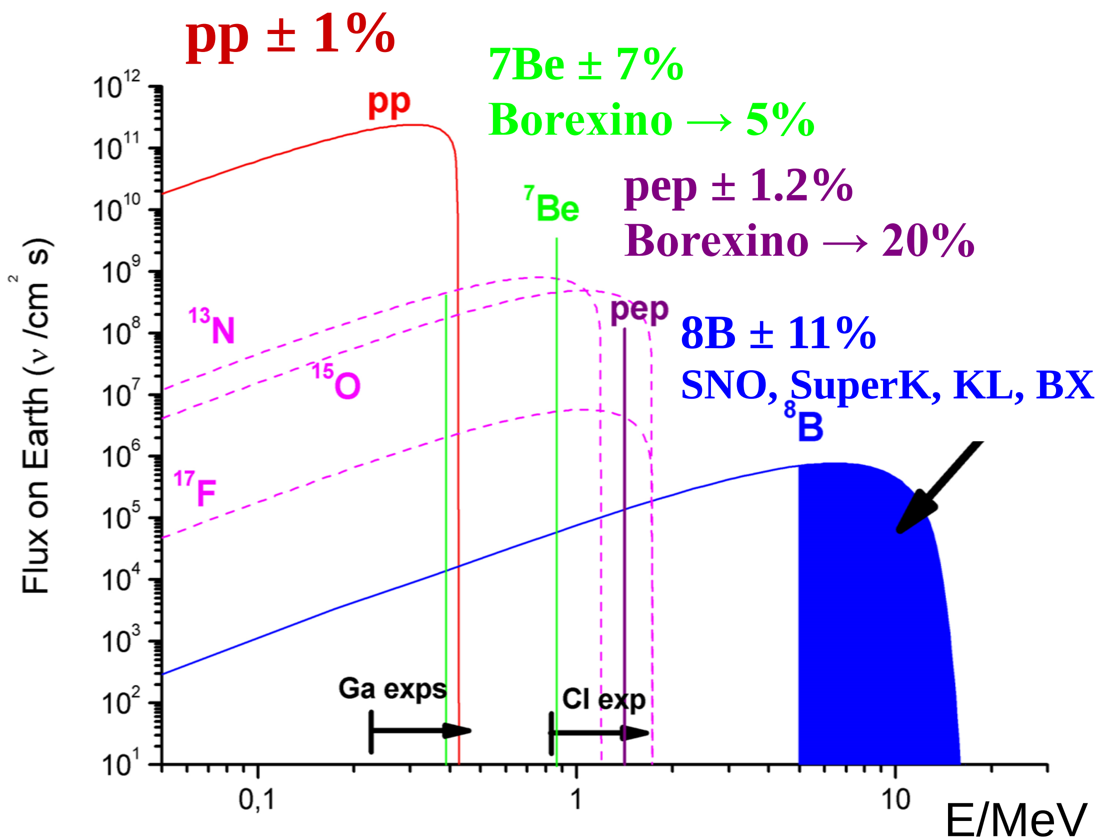
pp chain



Solar neutrinos

Solar-ν flux and spectrum computed by Standard Solar Model

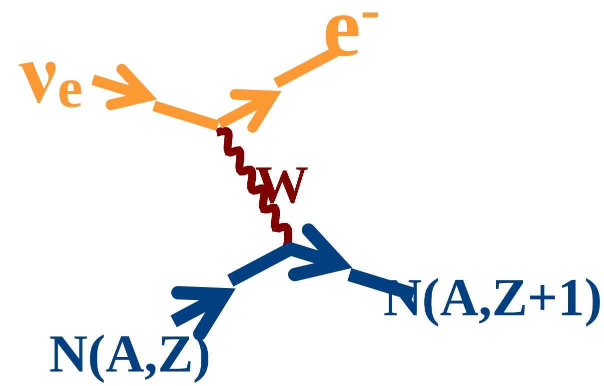




Detection of Solar neutrinos

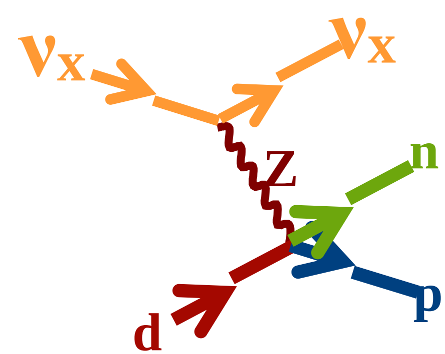
The sun produces **only ν_e**

Detection possible via **3 fundamental processes**



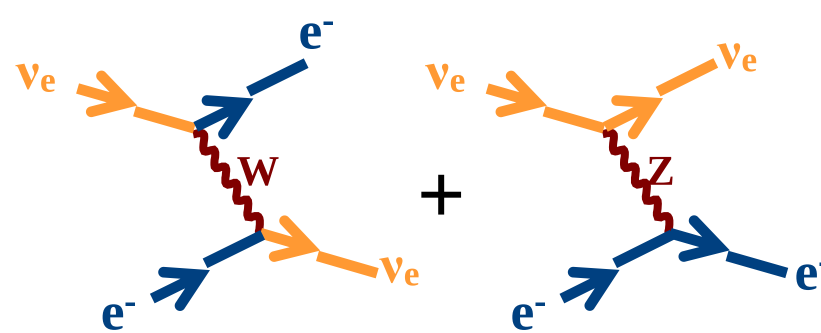
Inverse β decay on proton or nucleus

- **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

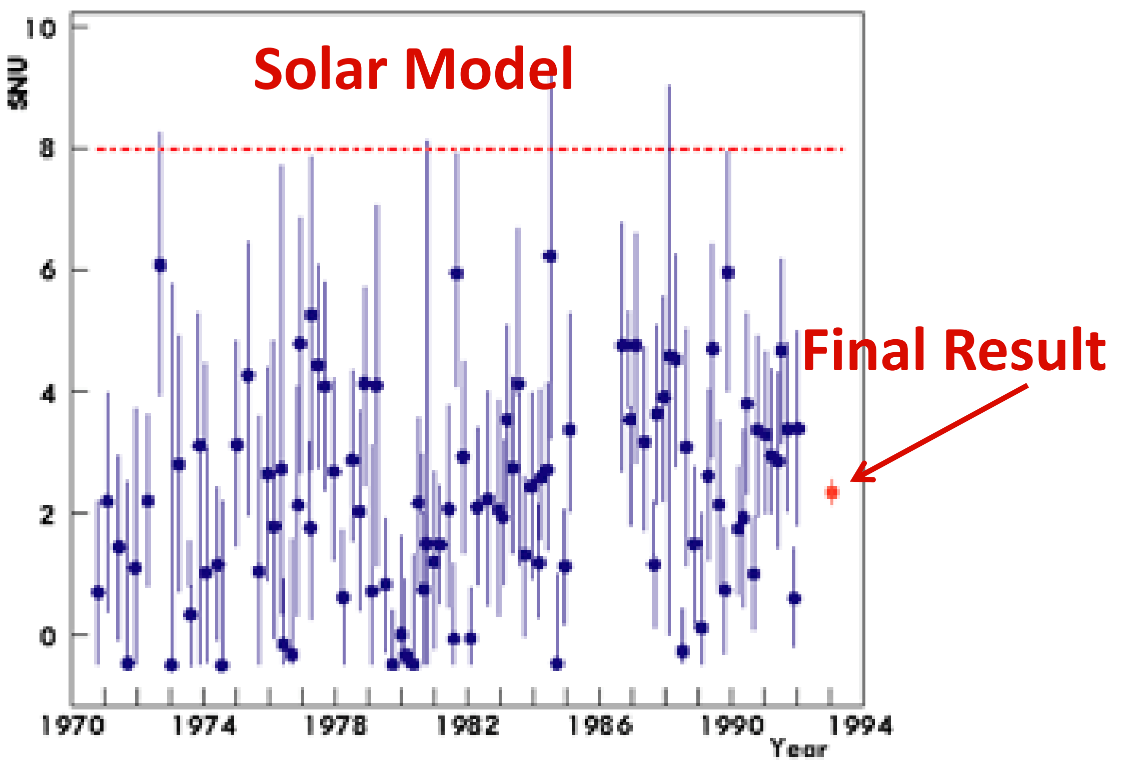
Short history of solar-ν (I)

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



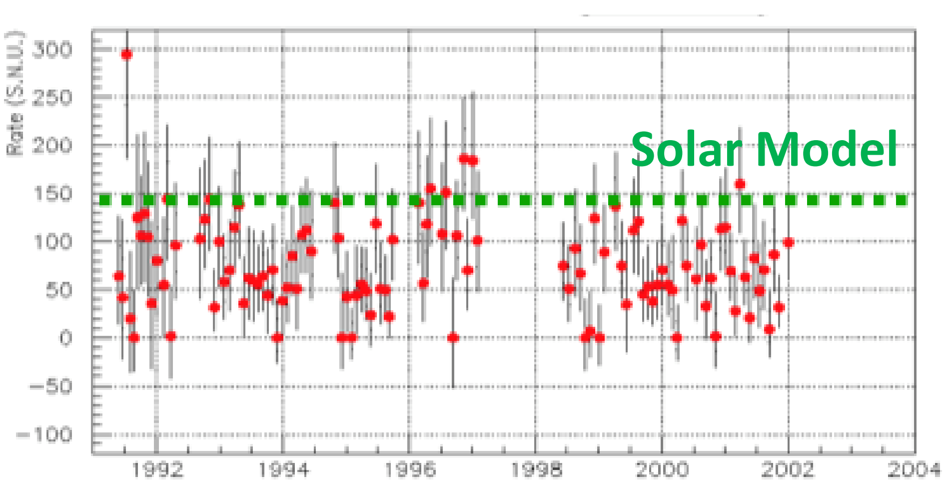
Short history of solar-ν (II)

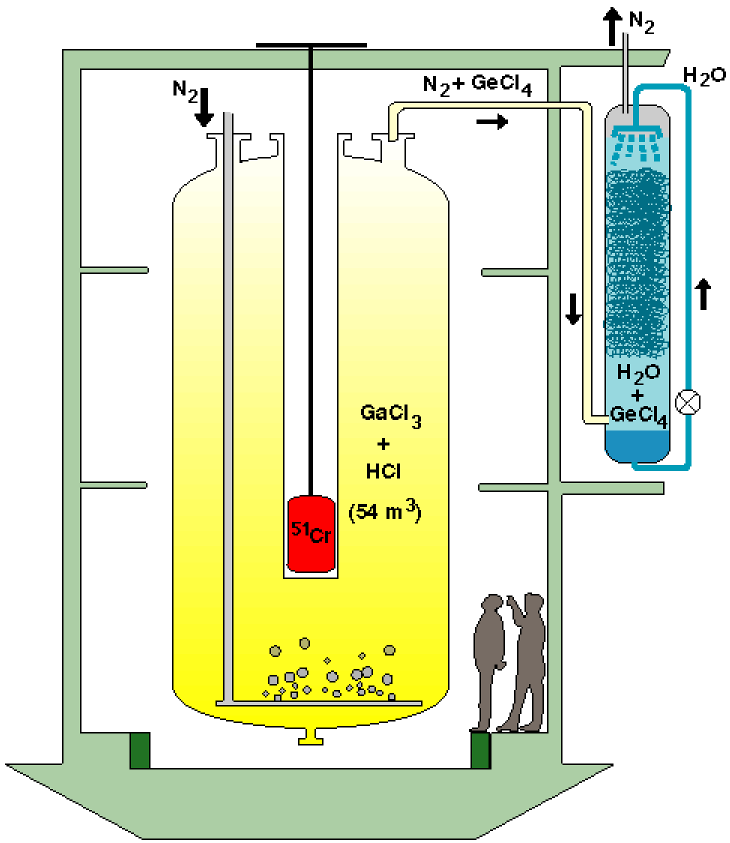
90's: Gallex (GNO), Sage

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



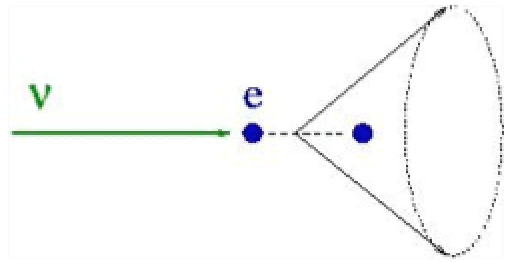


Short history of solar-ν (III)

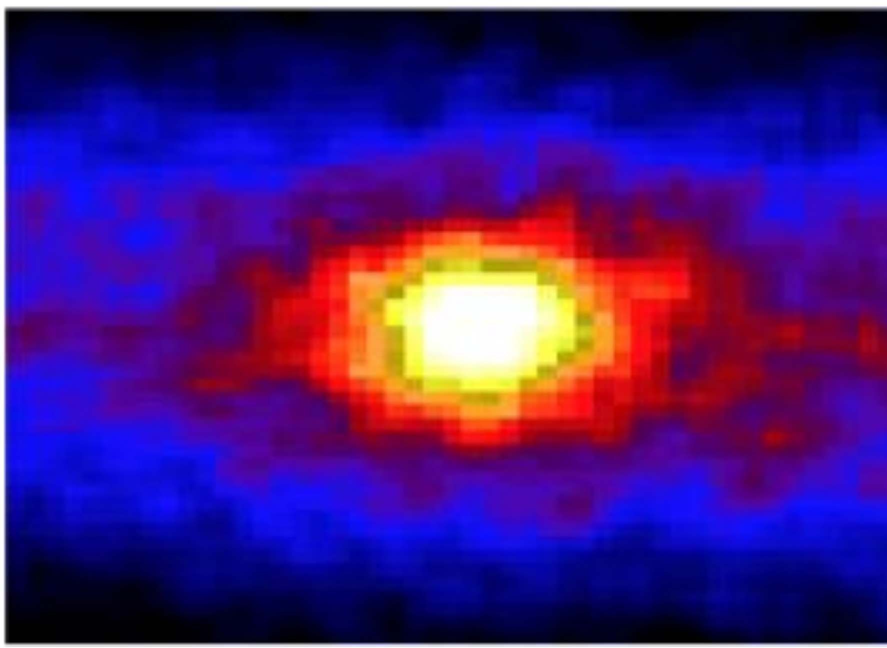
80's-90's: (Super) KamioKande

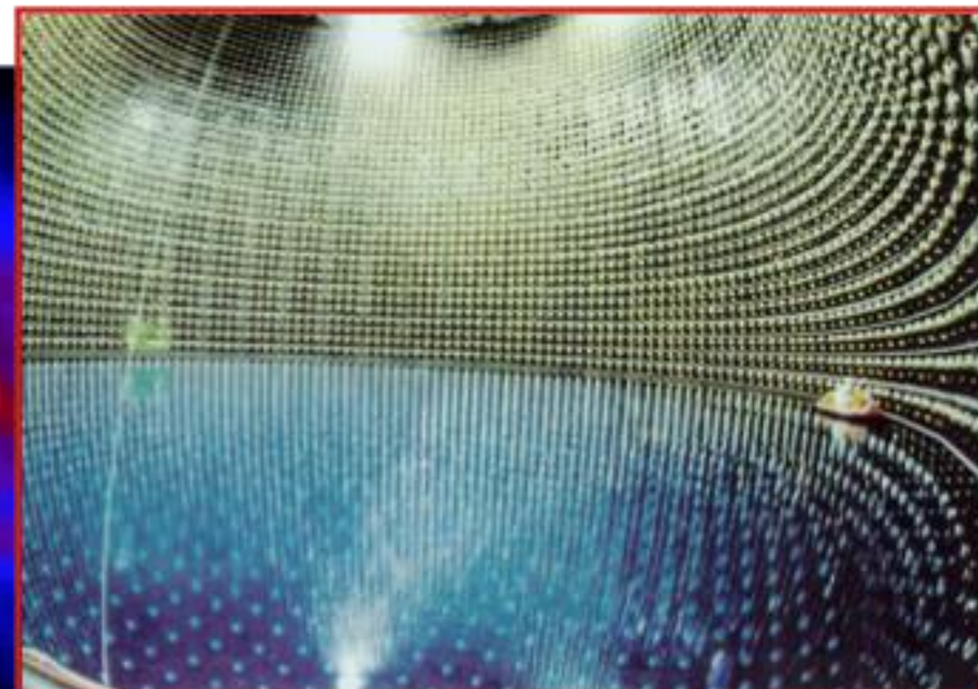
Confirm deficit on ^{8}B ν **(E> ~5MeV)**

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

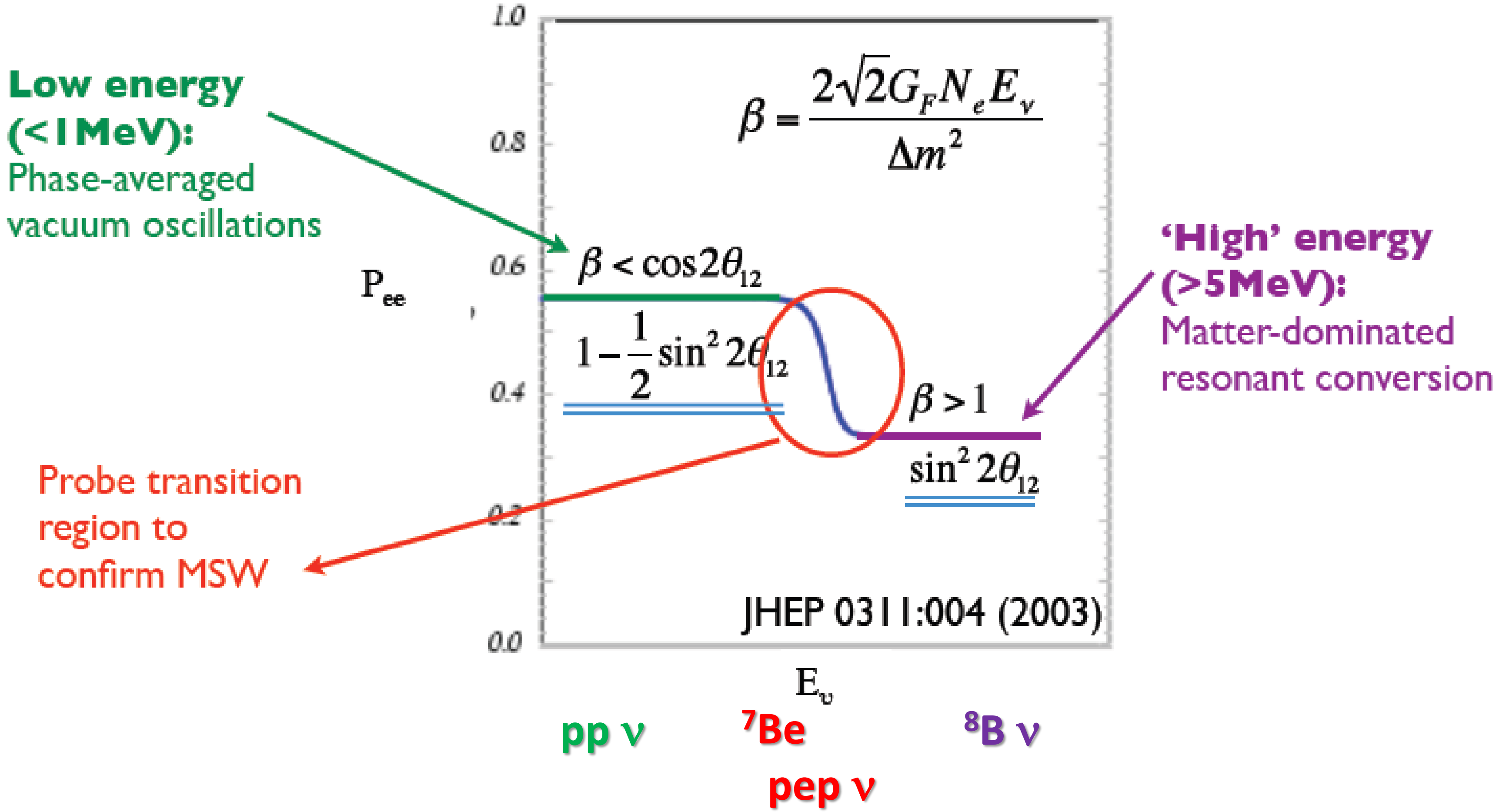
Solar-ν oscillation in vacuum

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

But propagation NOT in vacuum: Sun matter

Solar-ν oscillation in matter - MSW

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



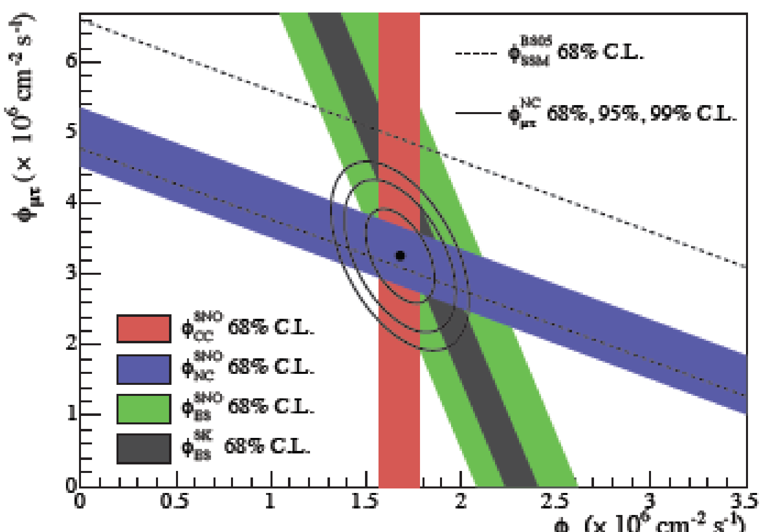
Discovery of solar- ν oscillations

Inclusive appearance at the Sudbury Neutrino Observatory

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

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

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

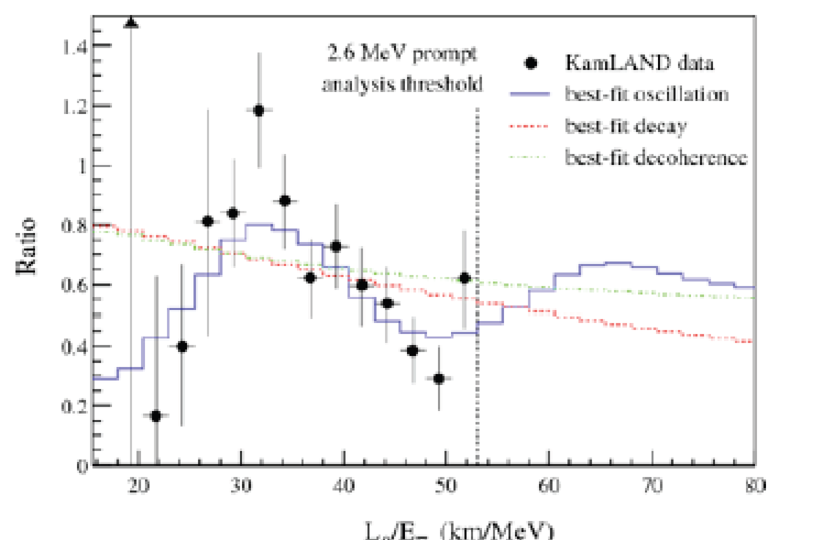


PRL 87 (2001) 071301, PRL 89 (2002) 011301

Oscillations at KamLAND

Disappearance at >99.99%

Clear oscillation pattern

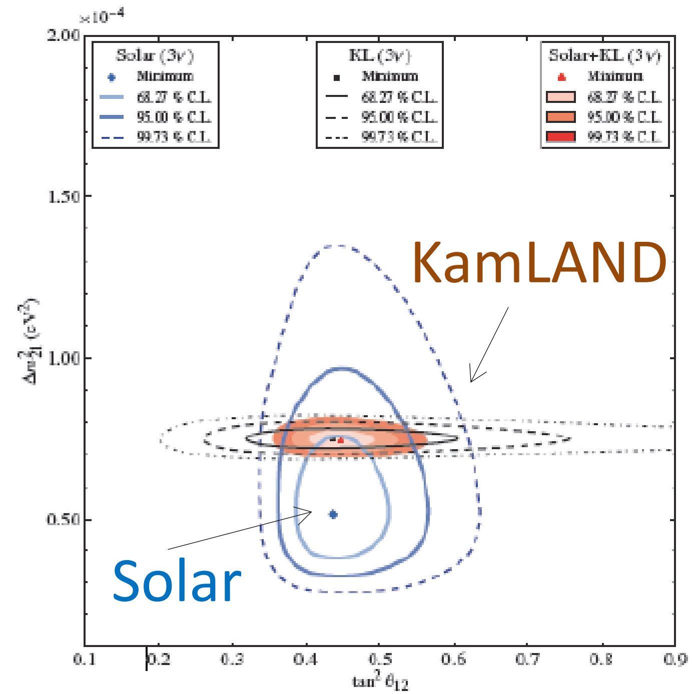


PRL 90 (2003) 021802, PRL 94 (2005) 081801

MSW-LMA

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

Solar neutrino oscillations
described by
MSW-LMA scenario



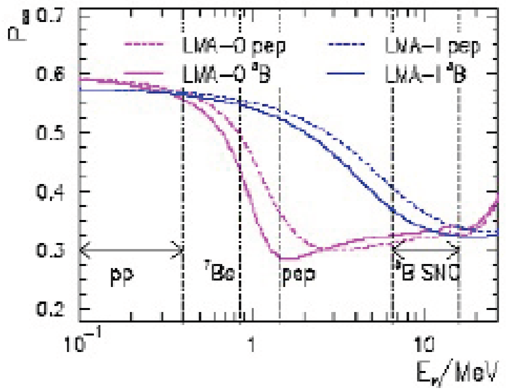
What may we still learn from solar-ν?

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

Precision measurements to probe Pee

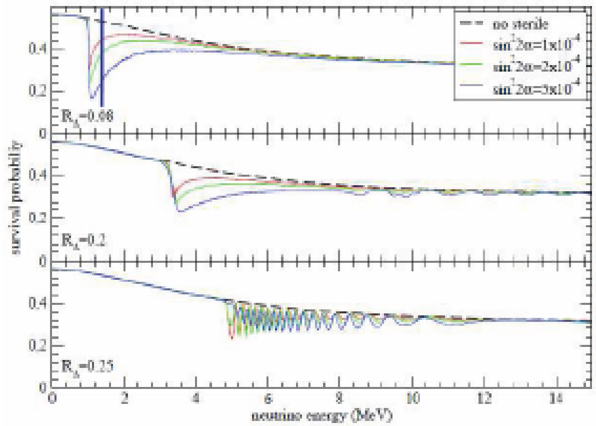
Constrain non-standard neutrino and solar physics

Non-standard interactions (flavour changing NC)



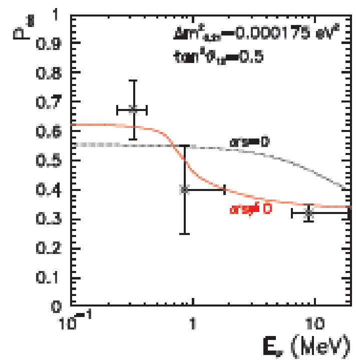
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov PRD 83 (2011) 113011

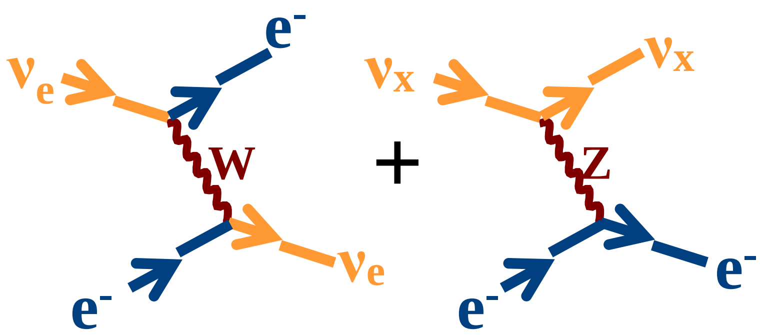
Mass varying neutrinos (MaVaNs)



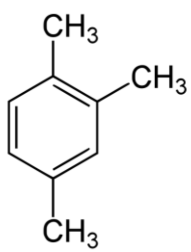
M.C. Gonzalez-Garcia, M. Maltoni

Phys Rept 460:1-129 (2008)

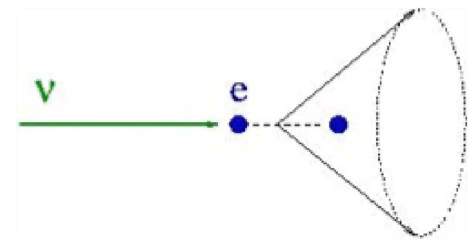
Principles of solar-ν detection

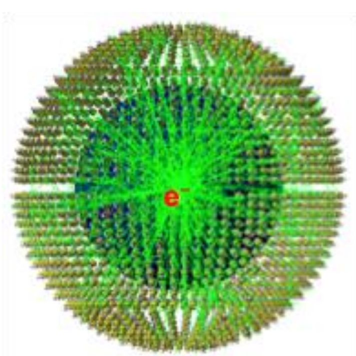


Neutrinos detected via **elastic scattering** on **electrons**

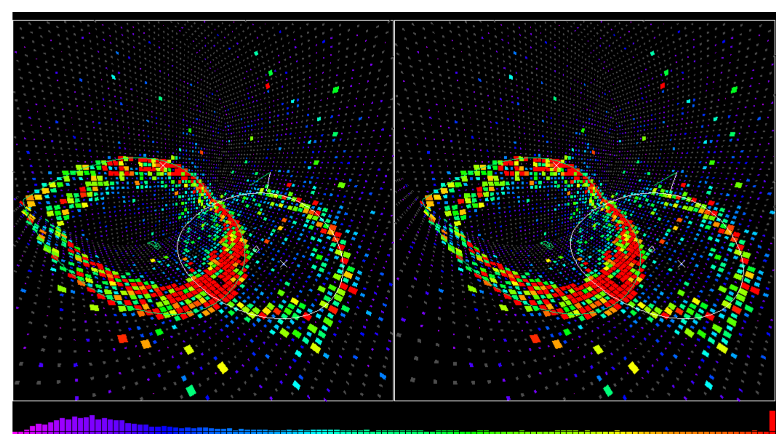


Recoil **electron** produces **Scintillation** or **Cherenkov** light

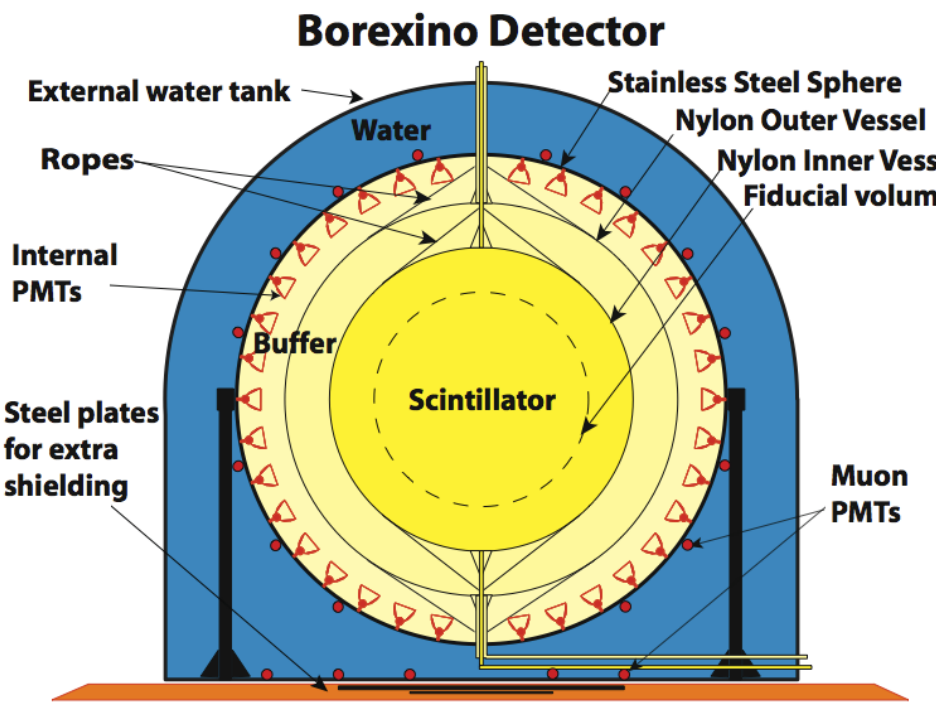


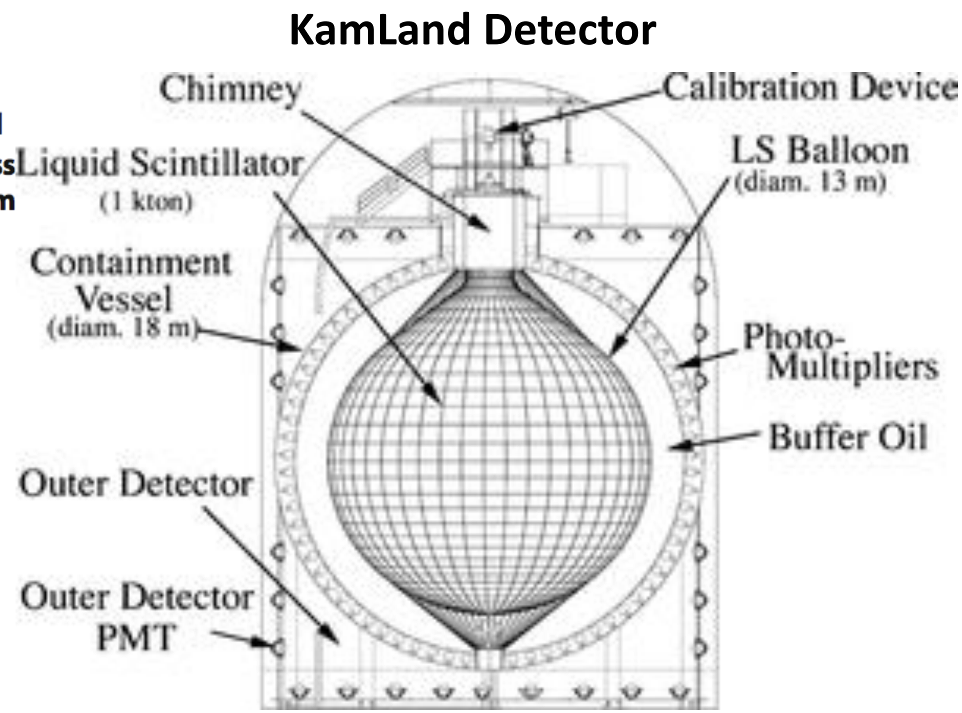


Light seen by **PMTs**



Borexino and KamLAND



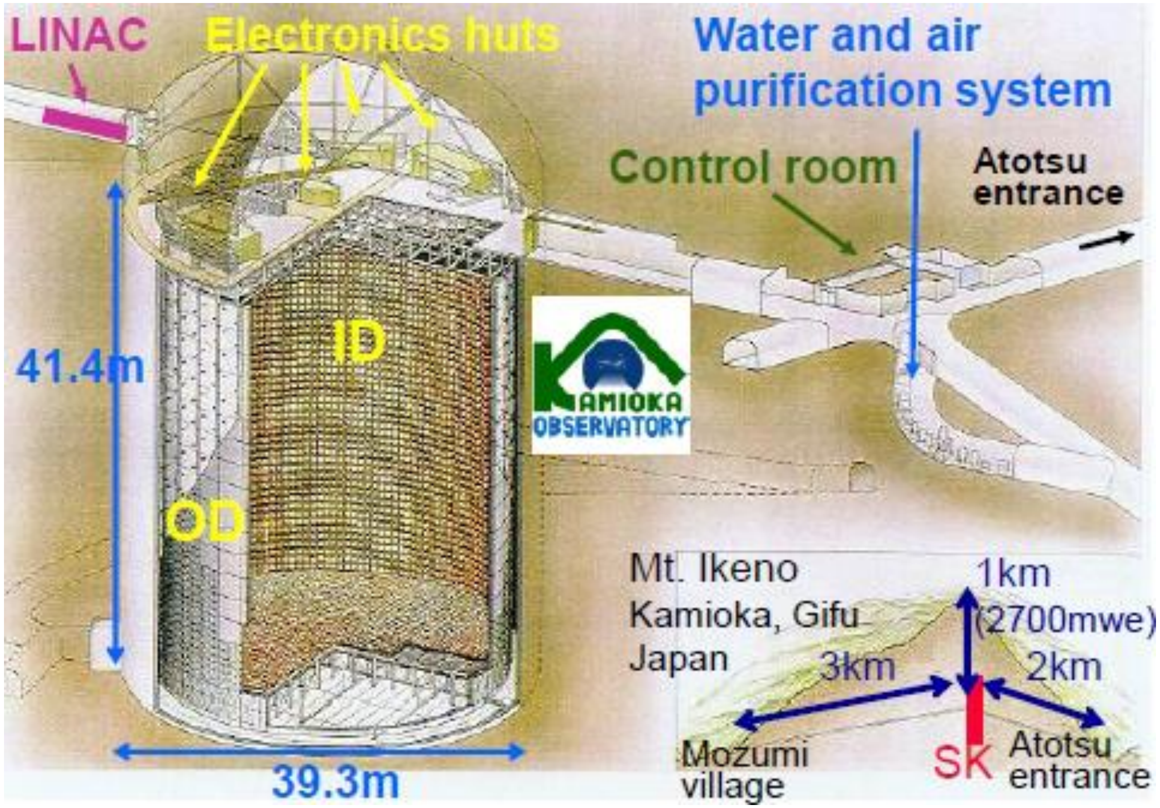


Liquid scintillator detectors

Low energy **threshold** (200 keV, limited by ^{14}C, not by signal)

No directionality, superbe purity required to reject radioactivity

Super-Kamiokande



Water Cherenkov detector

Directionality

High energy threshold: ^{8}B neutrinos only (E>4 MeV)

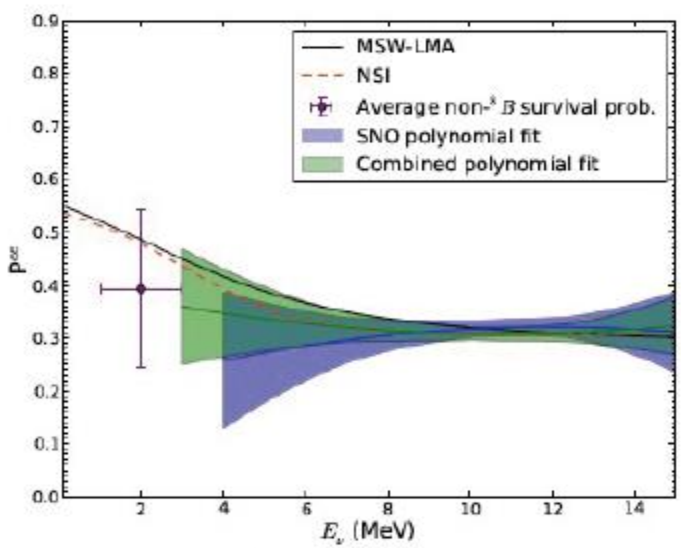
^8B solar neutrino measurements

Super Kamiokande
Energy analysis down to 3.5-4.5 MeV
Day-night asymmetry

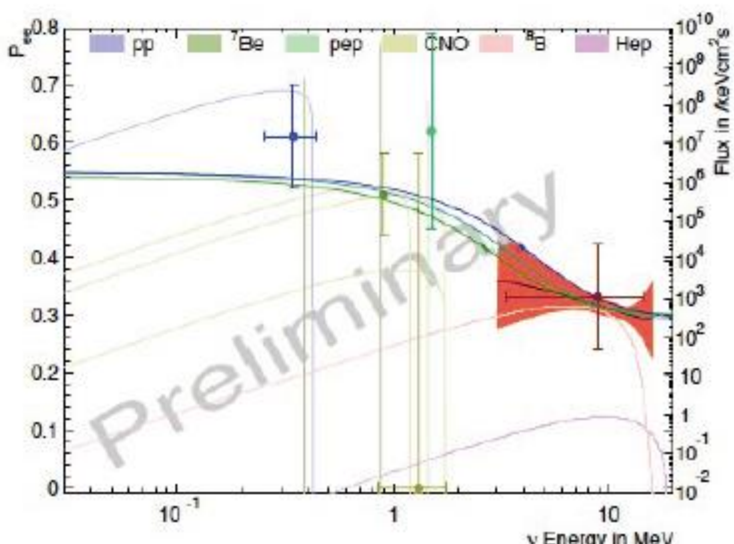
SNO Leta energy analysis down to 3.5 MeV

KamLAND E > 5 MeV

Borexino E > 3 MeV but smaller statistics w.r.t. SK and SNO



R. Bonventre et al.
arXiv 1305.5835 (May 2013)
Phys. Rev. D 88 (2013) 053010



Super-K collab
arXiv 1403.4575 (Mar 2014)

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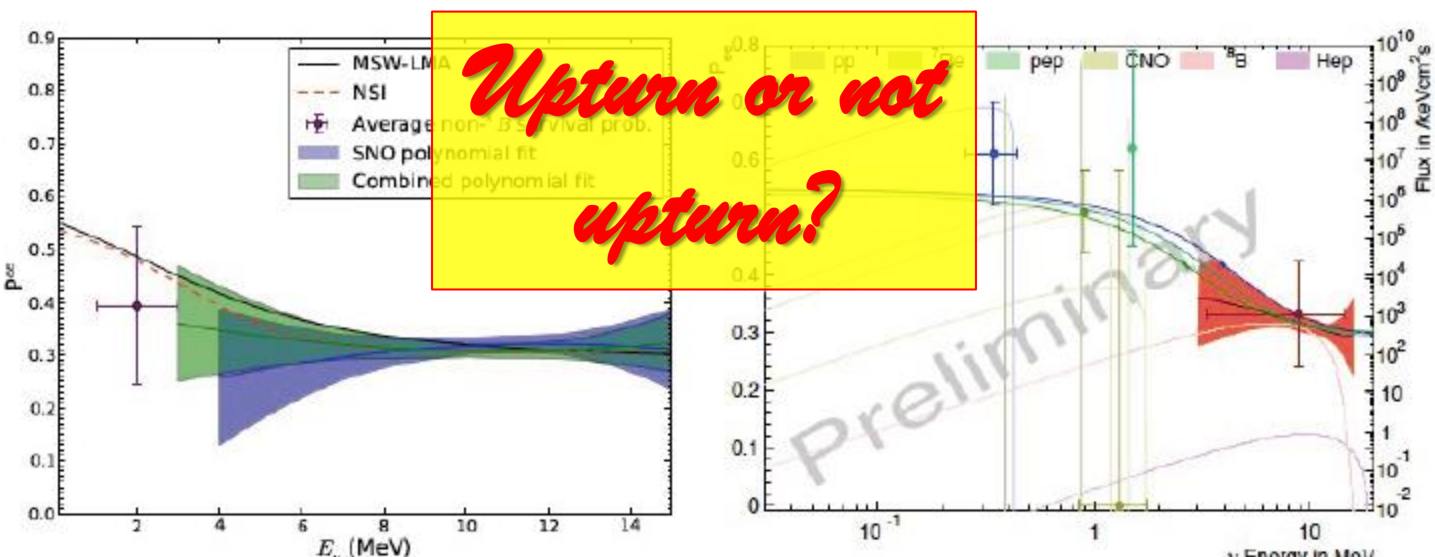

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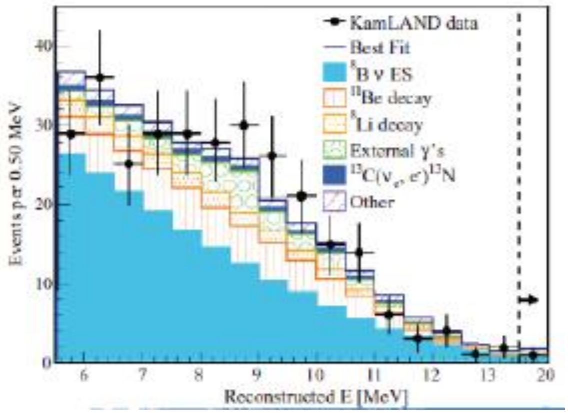
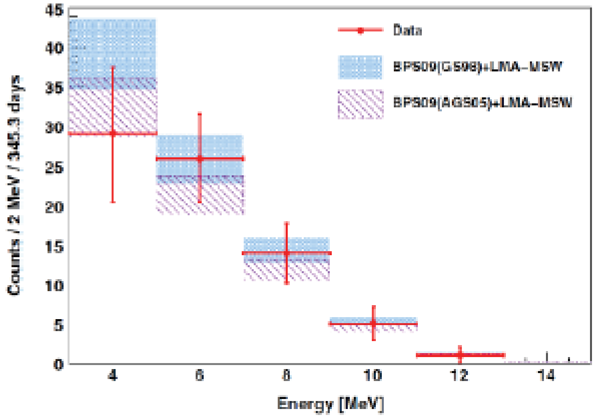
Super-K collab
arXiv 1403.4575 (Mar 2014)

^{8}B-ν recoil spectra

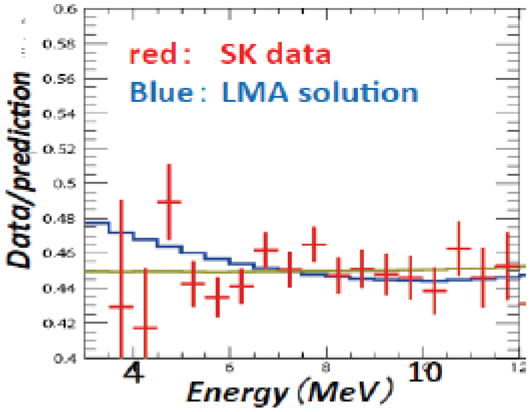
KamLAND PRC 84, 035804 (2011)



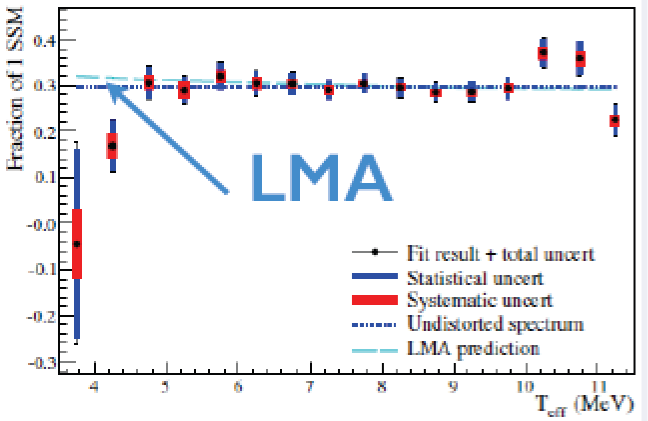
Borexino PRD 82 033006 (2010)



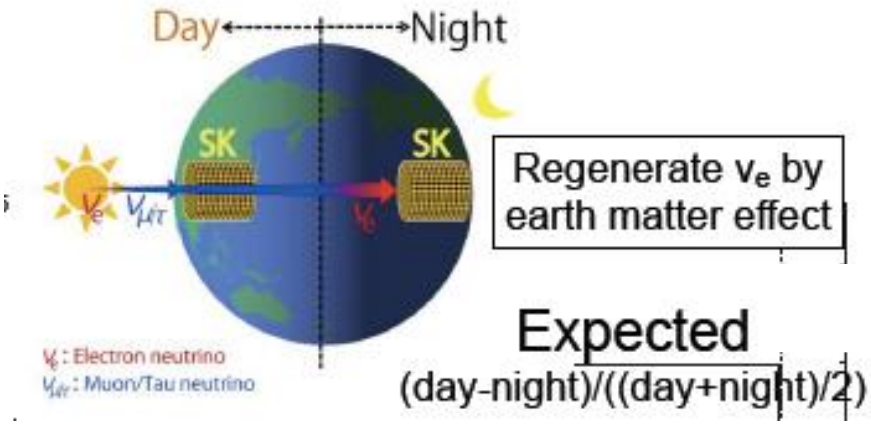
Super-K Y. Koshio@Neutrino 2014

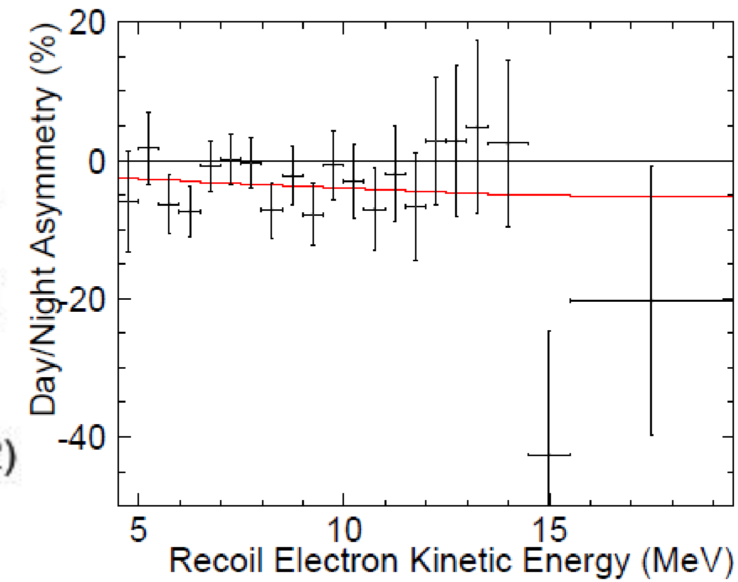


SNO LETA PRC 88 025501 (2013)



^{8}B-ν day-night asymmetry (Super-K)



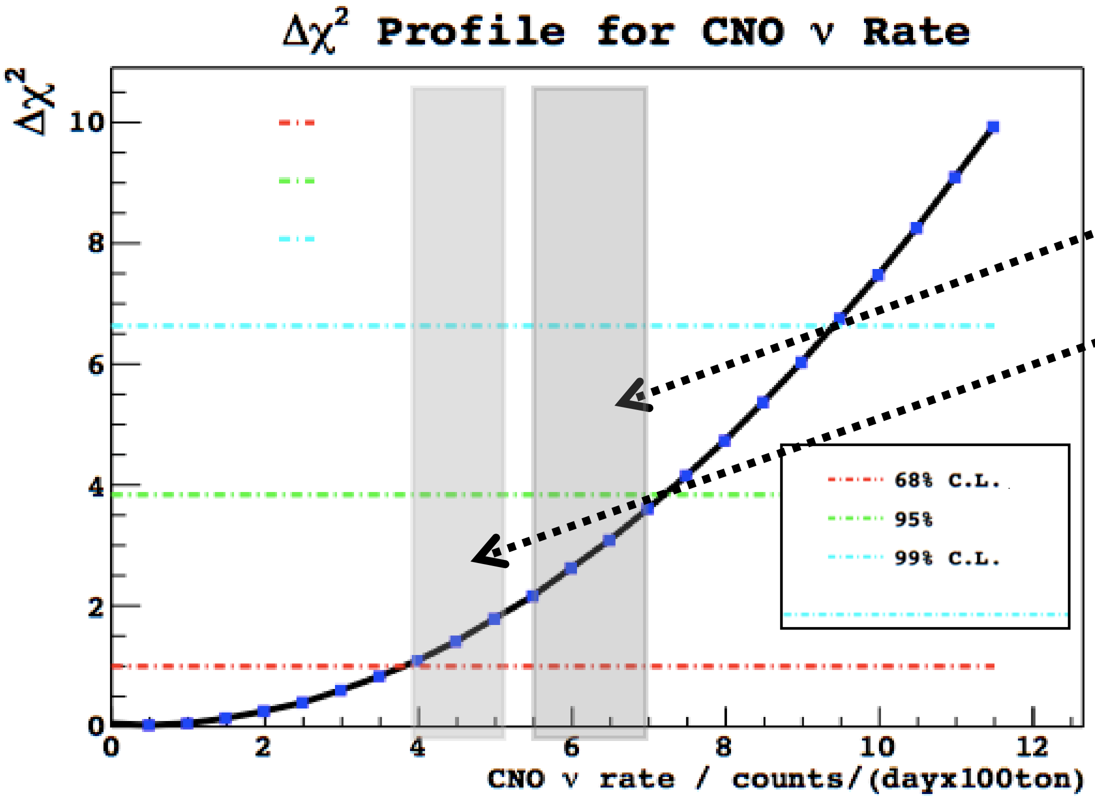


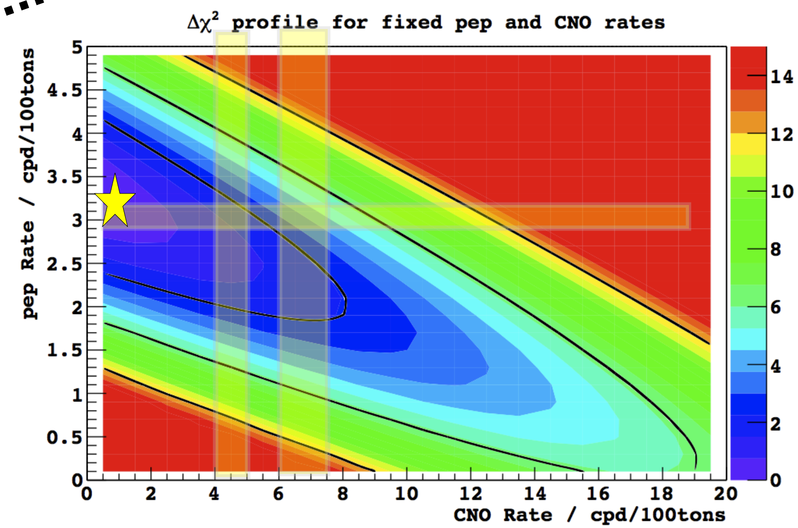
	Amplitude fit		Straight calc.
	Δm^2_{21}=4.84x10^{-5} eV^2	Δm^2_{21}=7.50x10^{-5} eV^2	(D-N)/((D+N)/2)
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero significance	3.0 σ	2.8 σ	2.8 σ

($\sin^2\theta_{12}$=0.311, $\sin^2\theta_{13}$=0.025)

PRL 112, 091805 (2014)

CNO-ν limit (Borexino)

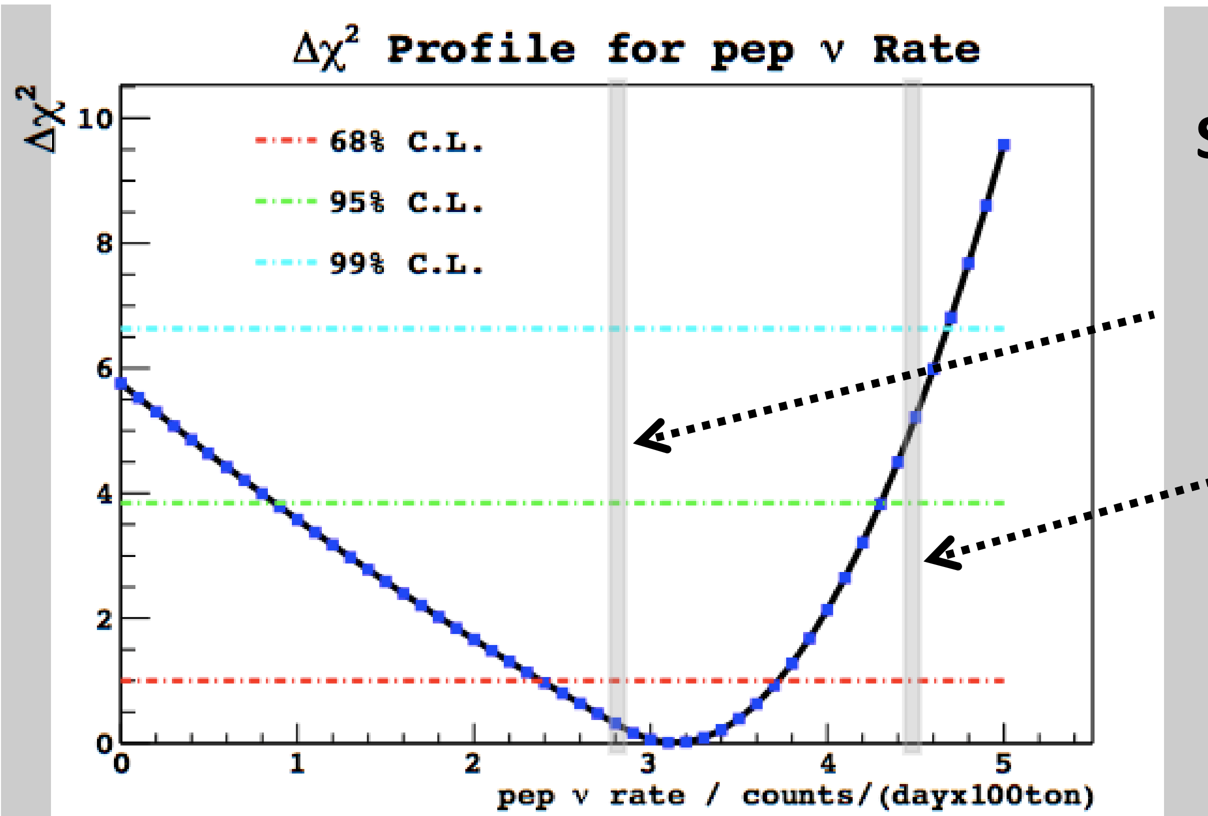




$\Phi_{CNO} < 7.7 \cdot 10^{8}$ cm^{-2} s^{-1} (95% CL)

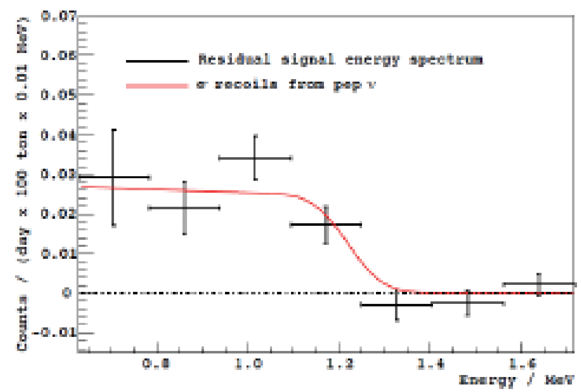
PRL 108, 051302 (2012)
PRD 89, 112007 (2014)

pep- ν detection (Borexino)



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

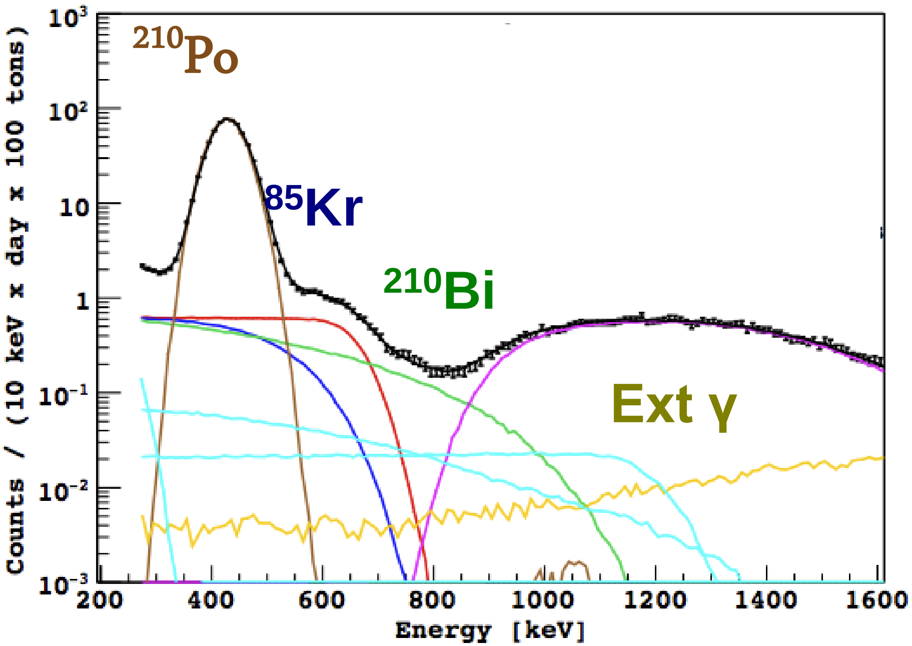
No oscillation disfavoured at 97% CL

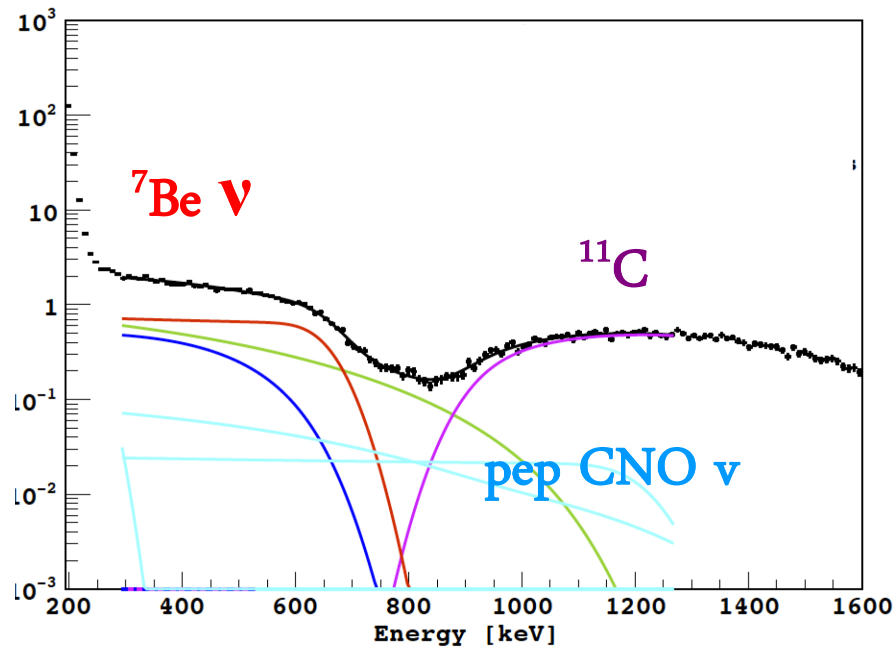


$$\Phi_{pep} = 1.6 \pm 0.3 \cdot 10^{8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

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

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





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

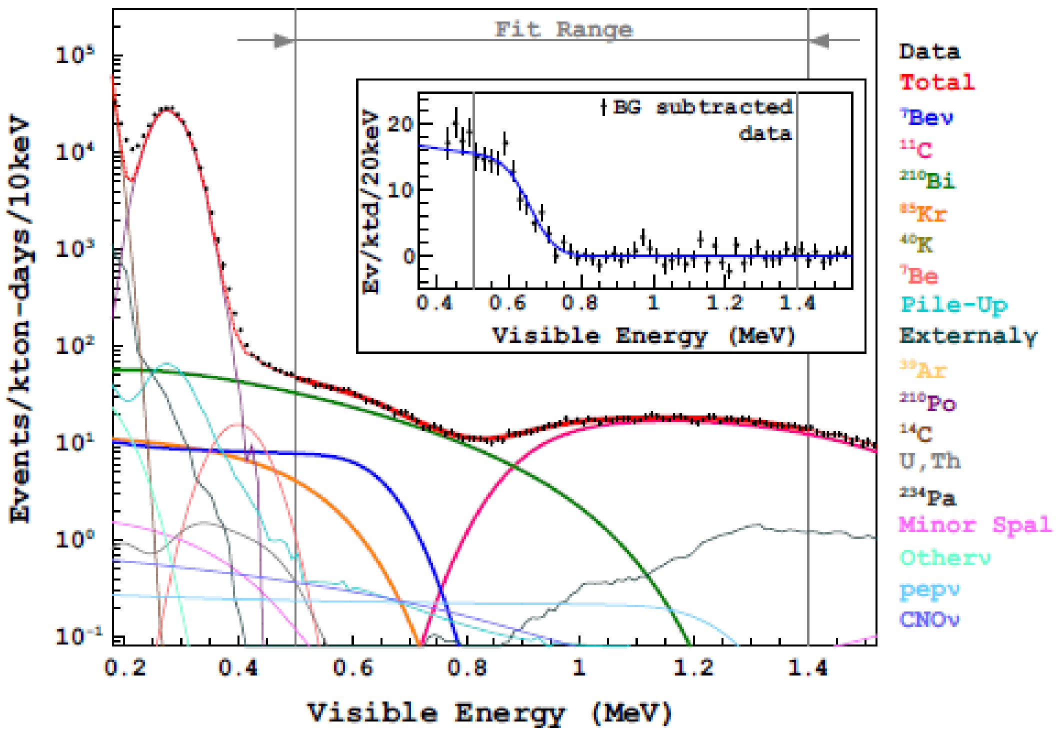
$$\Phi_{7Be} = 3.10 \pm 0.15 \cdot 10^{9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

No oscillation excluded at 5σ

PRL 107, 141302 (2011)

PRD 89, 112007 (2014)

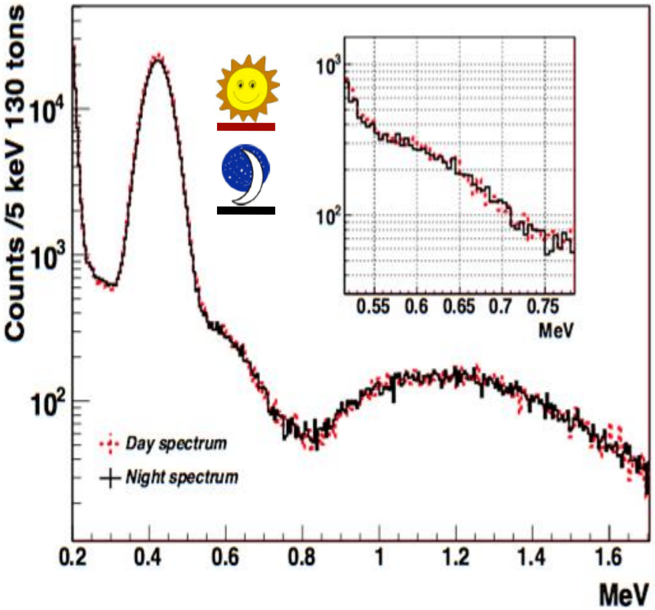
^{7}Be-ν first KamLAND measurement

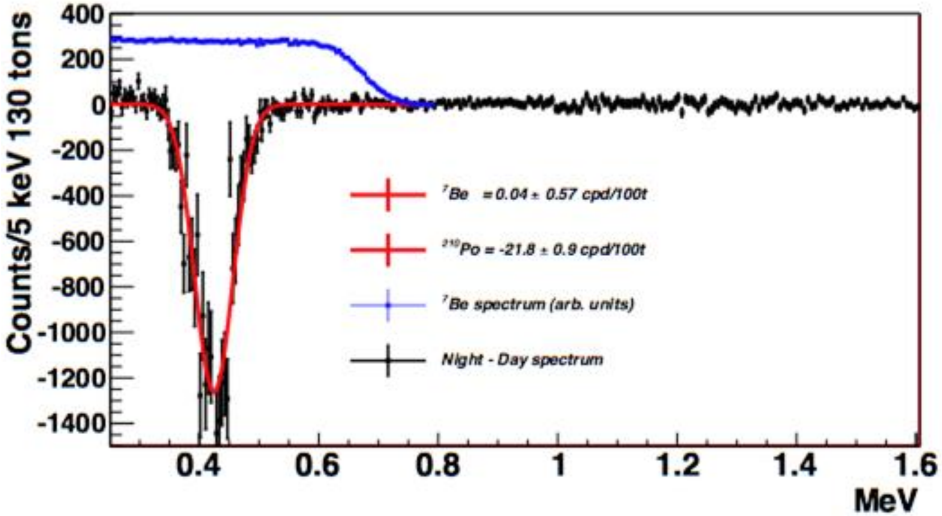


$$\Phi_{7Be} = 3.26 \pm 0.50 \cdot 10^{9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

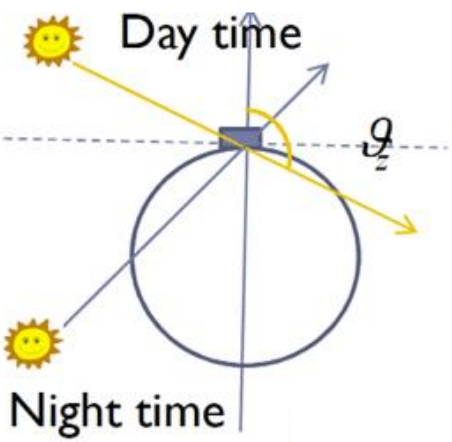
arXiv: 1405.6190

^{7}Be-ν day night asymmetry (BX)

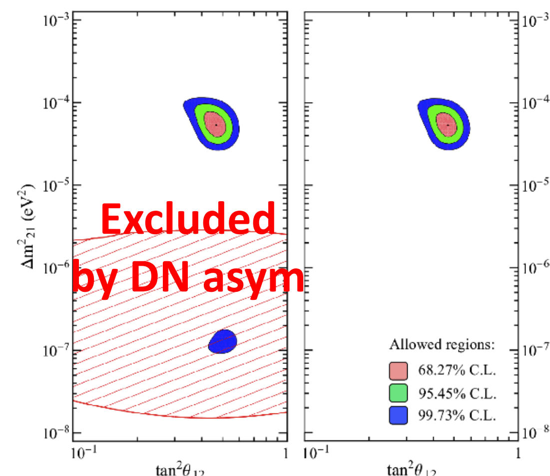




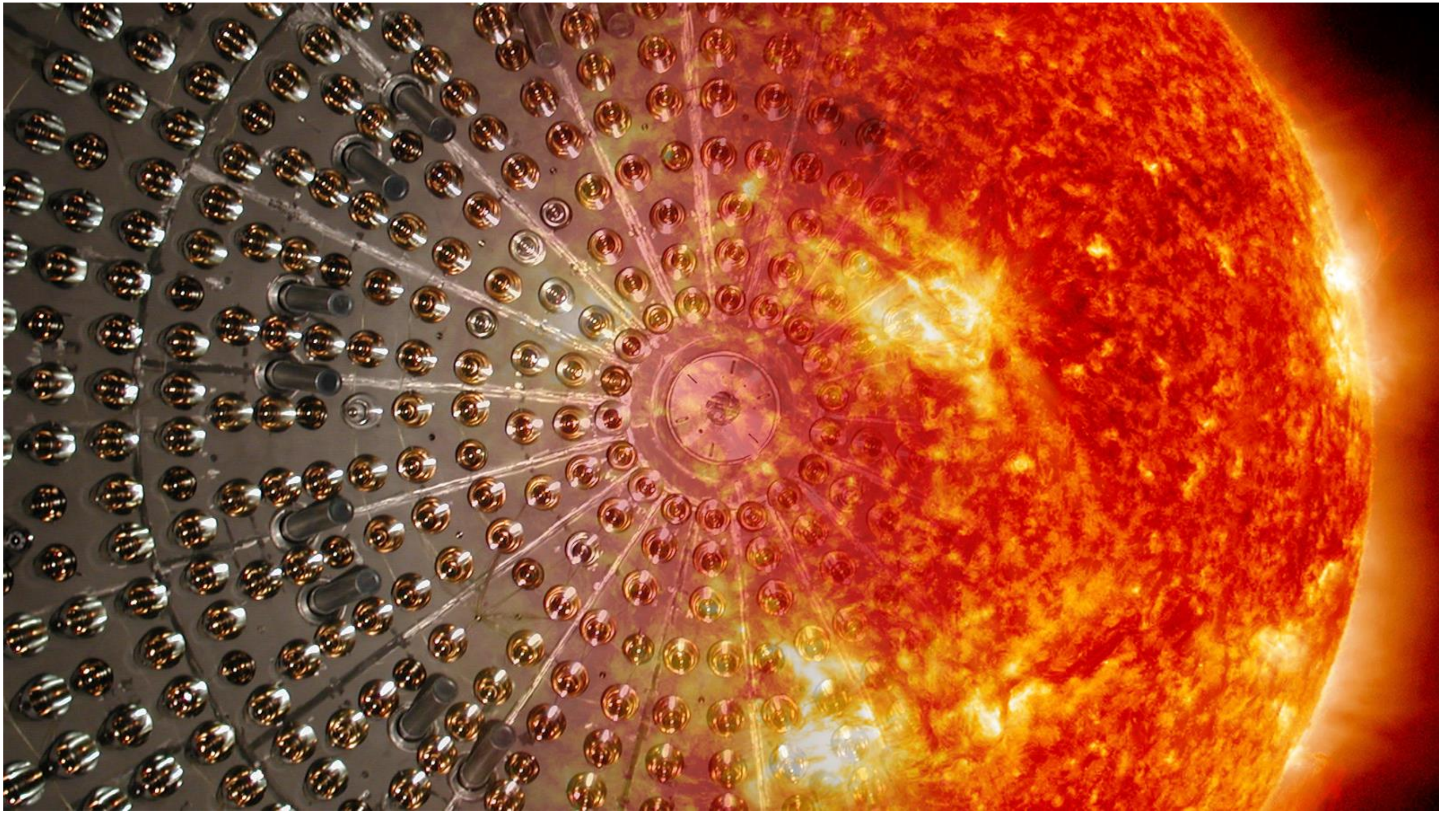
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = 0.001 \pm 0.012 \pm 0.007$$



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



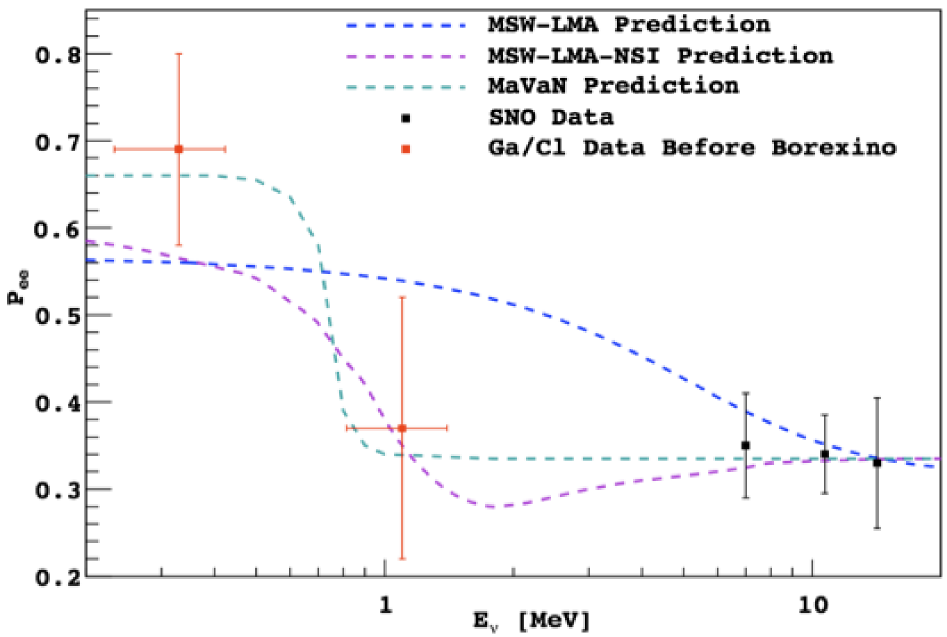
pp - ν observation in Borexino



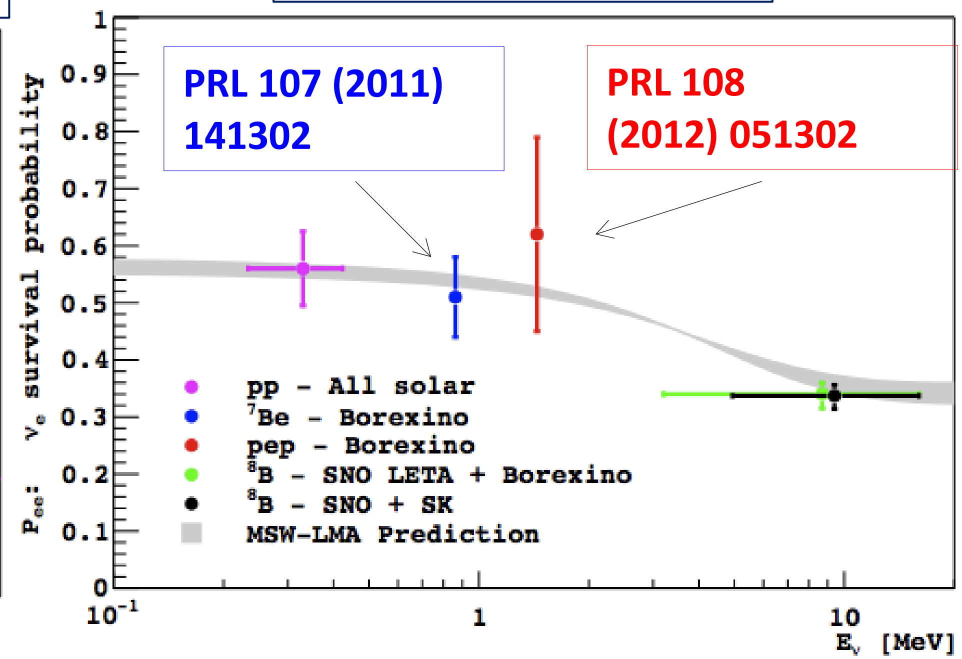
Observation of the neutrinos from
Primary proton-proton fusion in the Sun
Imminent …

Current status of Pee probe

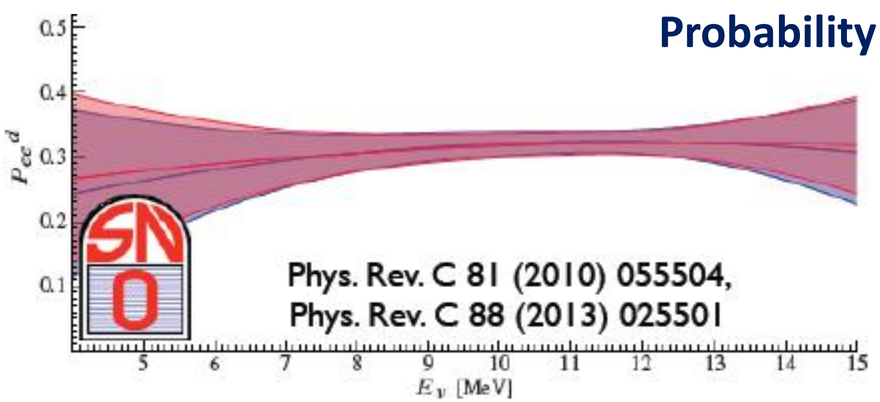
Pee measurment before BOREXINO

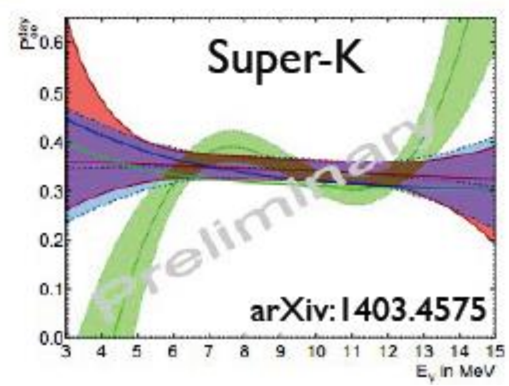


Today



Direct Fit for Energy-Dependent Survival Probability





Conclusions and Outlook

Solar neutrinos have been pivotal to the discovery of ν oscillations
- Now entering the **precision** era

Next goals: precision low energy neutrino physics and stellar physics
- Direct measurement of **pp neutrinos** (*imminent*): test Sun luminosity

- **^{8}B up-turn**: reduce the threshold, search for new physics in solar neutrino interactions by means of high precision measurements (SK, KL, BX)

- High precision **pep ν** : Non Standard Interactions, precision test of Pee transition

- Detection of **CNO ν** : test solar and stellar models

- Improve **^{7}Be** measurement (useful if SSM models and calculations improve as well)

- Solar ν detectors are ideal **sterile ν** hunters (see M. Wurm's talk)