

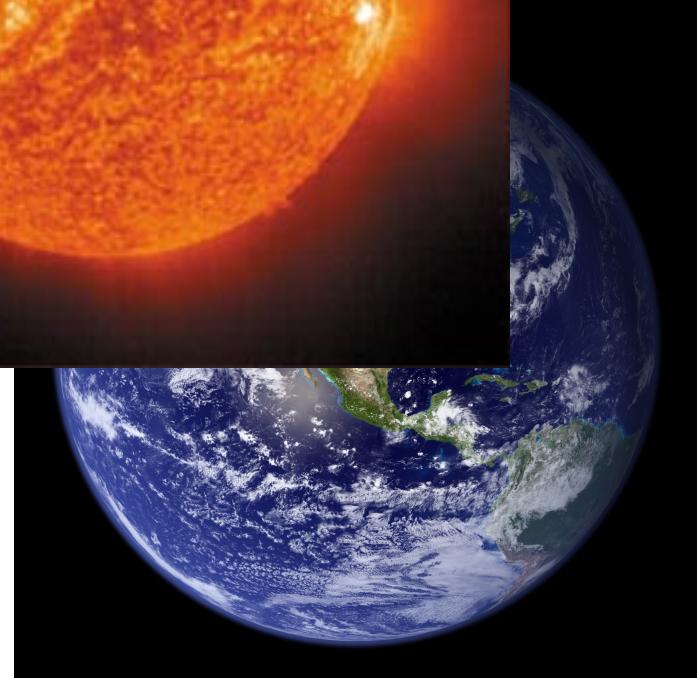
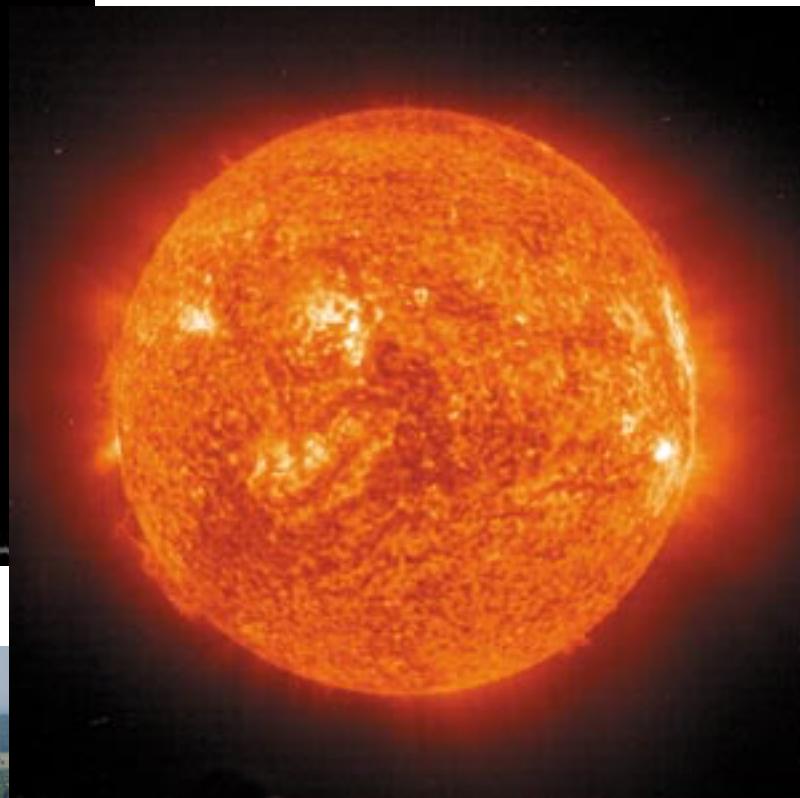
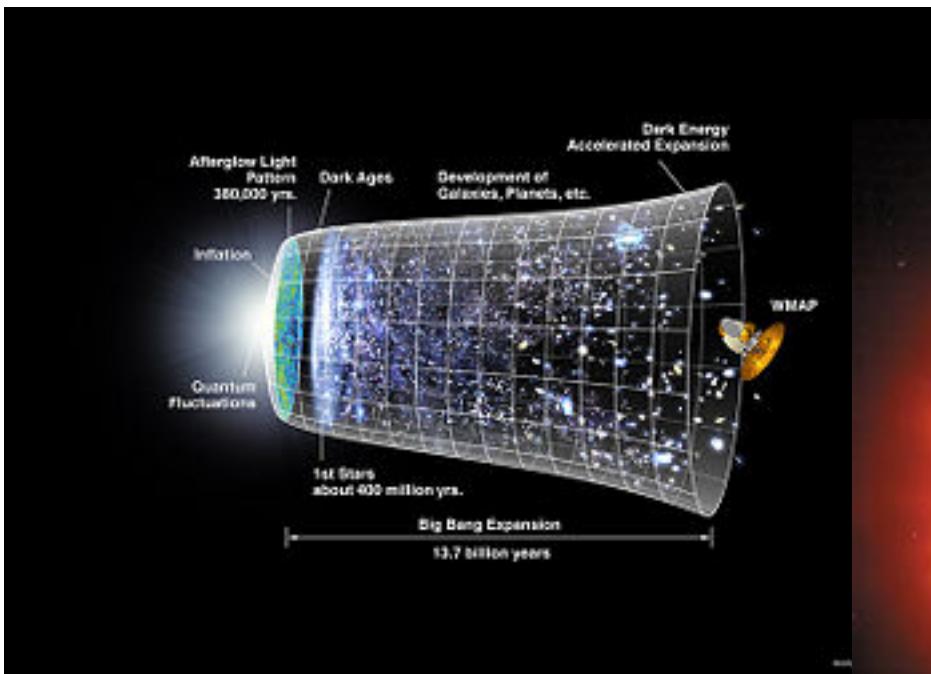
Low energy neutrinos (a talk mainly on solar neutrinos)

Stefano Davini

Science Fair @GSSI

GSSI, November 3, 2015

Low energy neutrinos

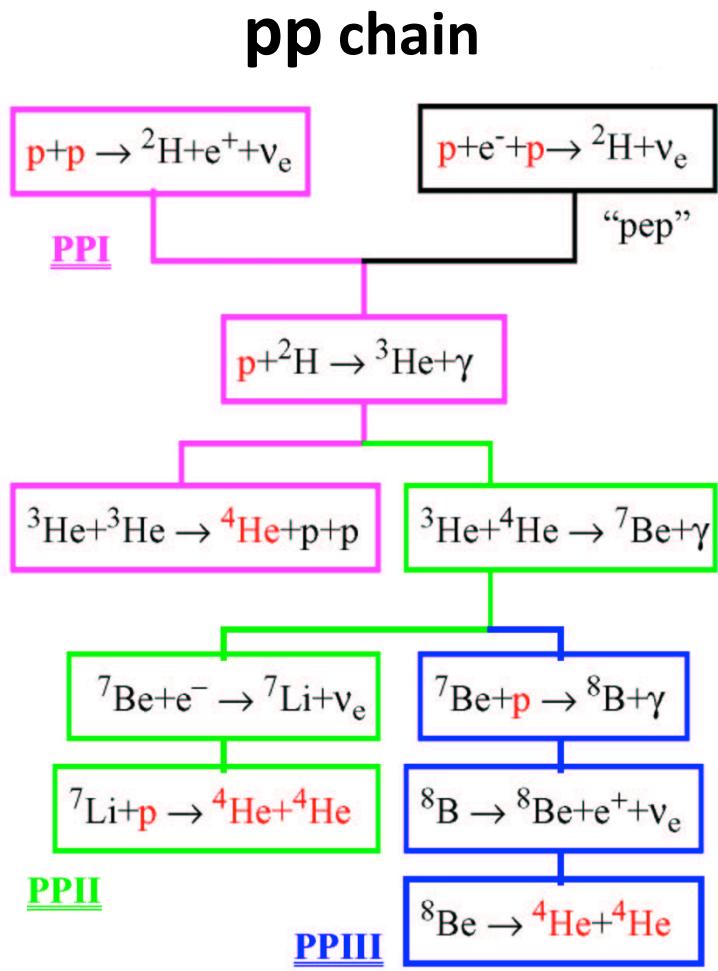
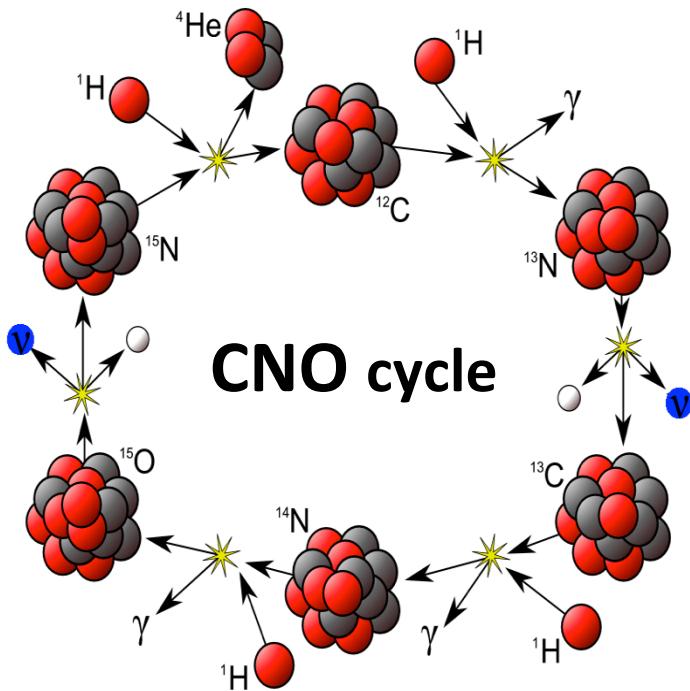


Nuclear reactions in the Sun

Energy production in the Sun:

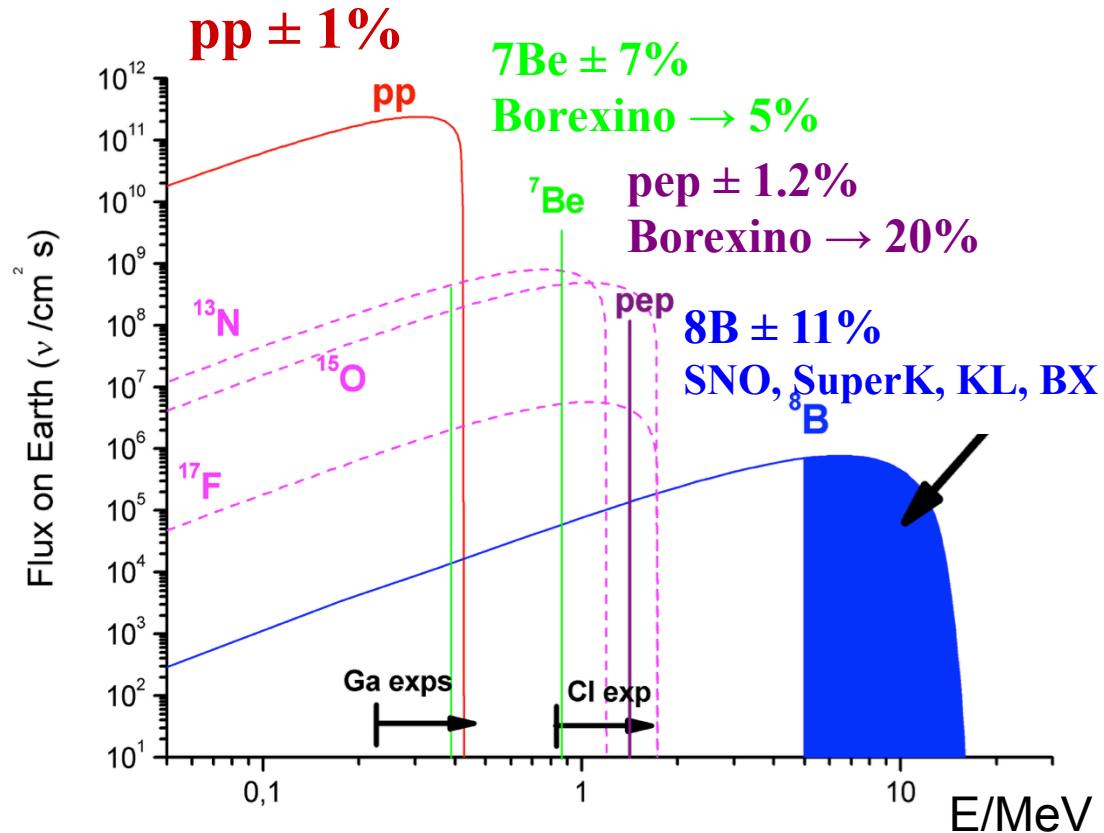
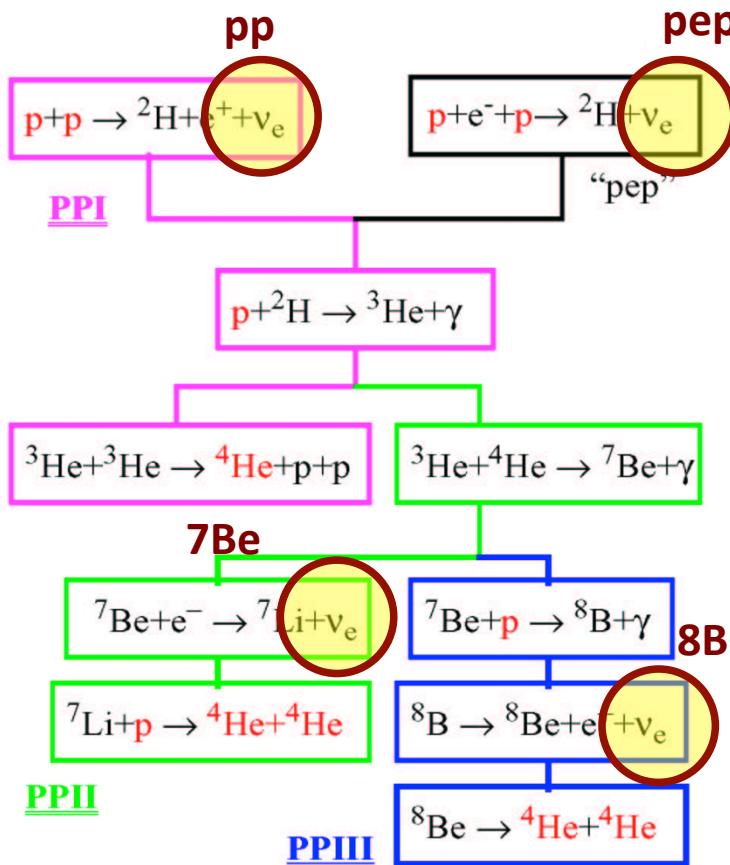
pp chain \rightarrow 99% of energy production

CNO cycle \rightarrow minor contribution



Solar neutrinos

Solar- ν flux and spectrum computed by Standard Solar Model



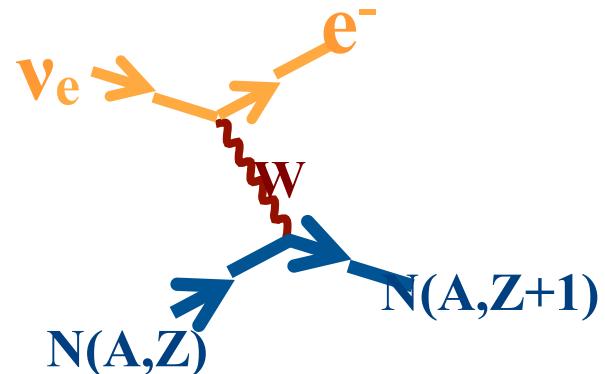
Detection of Solar neutrinos

The sun produces **only ν_e**

Detection possible via **3 fundamental processes**

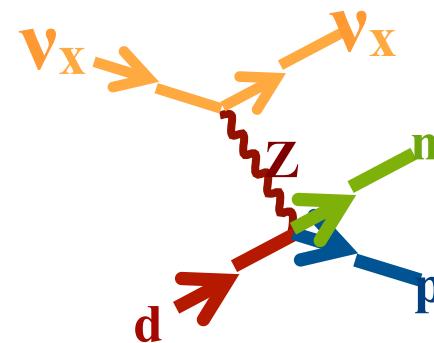
Inverse β decay on proton or nucleus

- **Charged Current (CC) interaction**
- $E \sim \text{MeV} \rightarrow \nu_e$ **only**



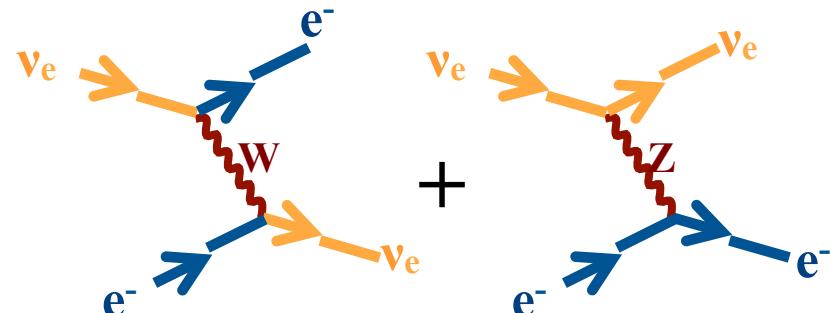
Elastic scattering on nucleus

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



Elastic scattering on electron

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



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

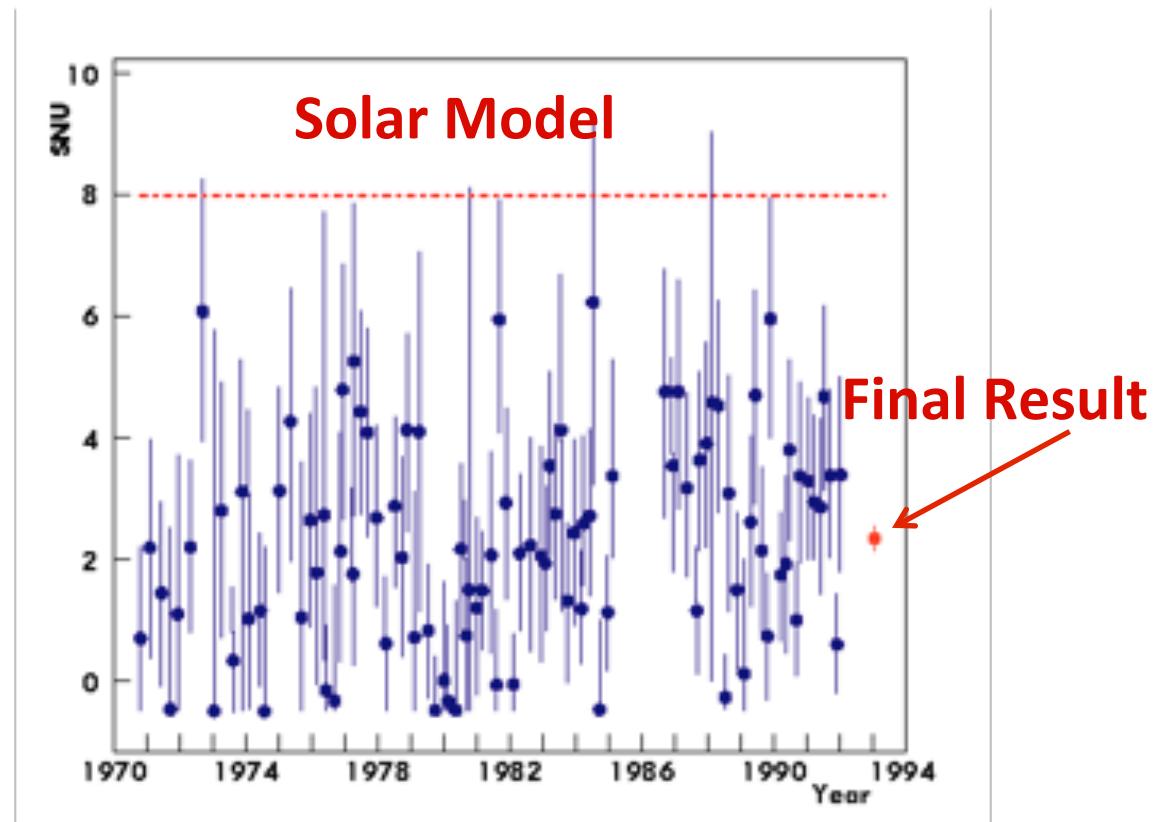
Short history of solar- ν (I)

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

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

Deficit in ν rate \rightarrow new physics or Solar Model inaccurate?

Nobel prize 2002



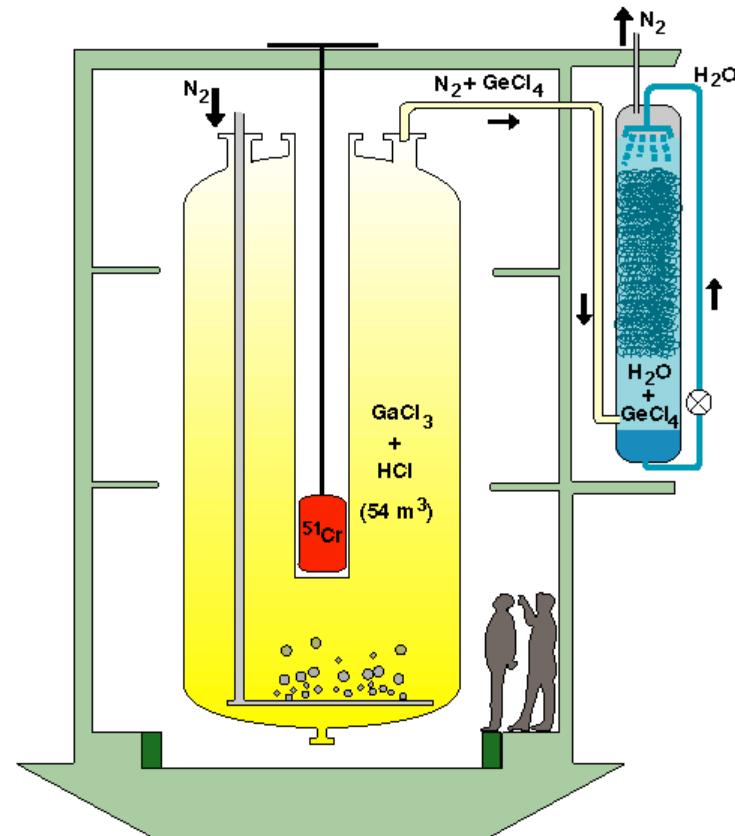
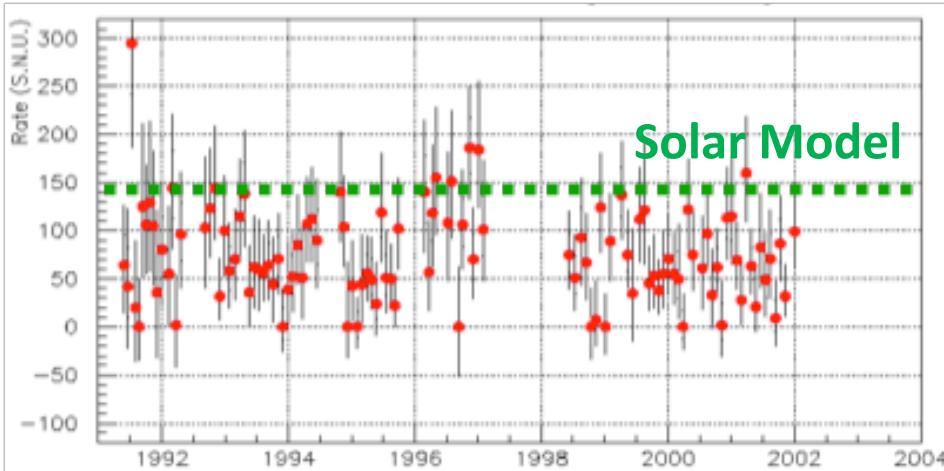
Short history of solar- ν (II)

90's: Gallex (GNO), Sage

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

Observed deficit on pp ν (low energy)

Calibration with neutrino source → real effect

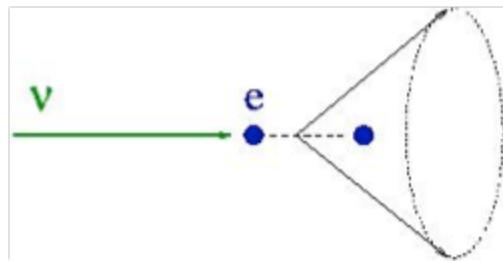


Short history of solar-ν (III)

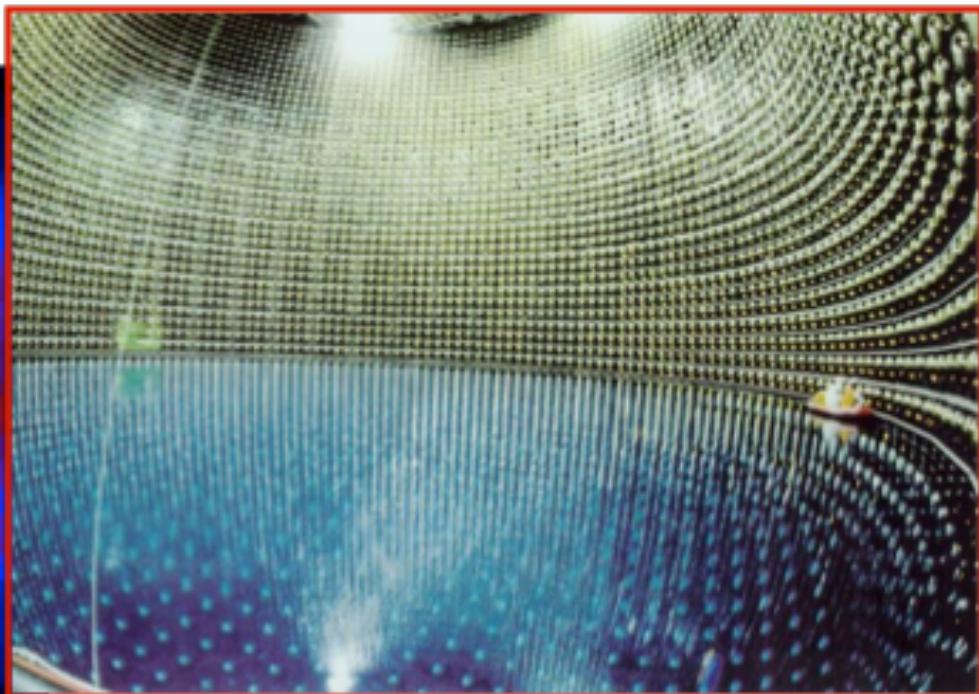
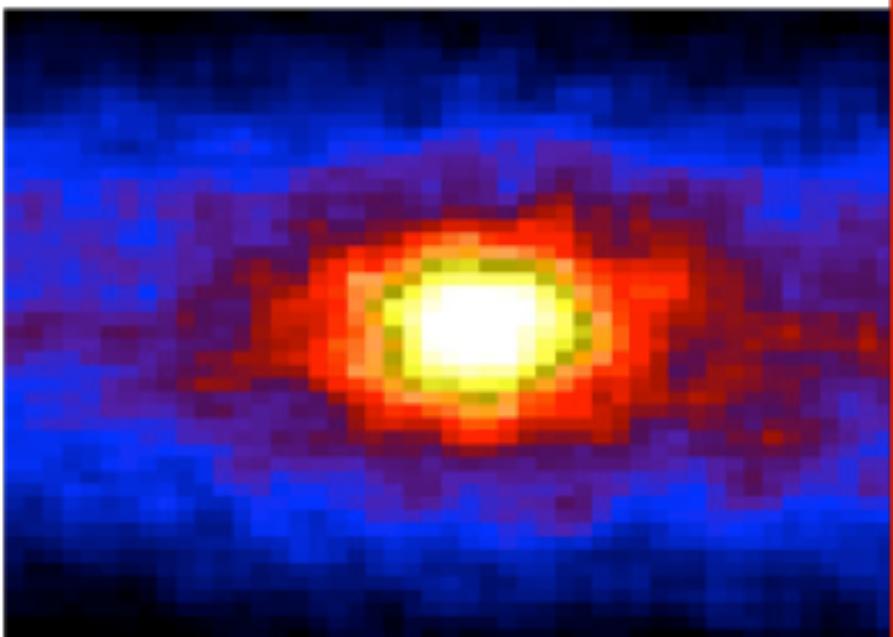
80's-90's: (Super) KamioKande

Confirm deficit on ${}^8\text{B} \nu$ ($E > \sim 5\text{MeV}$)

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 \rightarrow deficit

2 ν approximation

$$P_{e \rightarrow \mu} = \sin^2(2\theta) \sin^2 \left[\frac{1.27 \Delta m^2 L}{E_\nu} \right] \rightarrow \text{Averaged out for solar-}\nu$$

Δm in eV
L in m
 E_ν in MeV

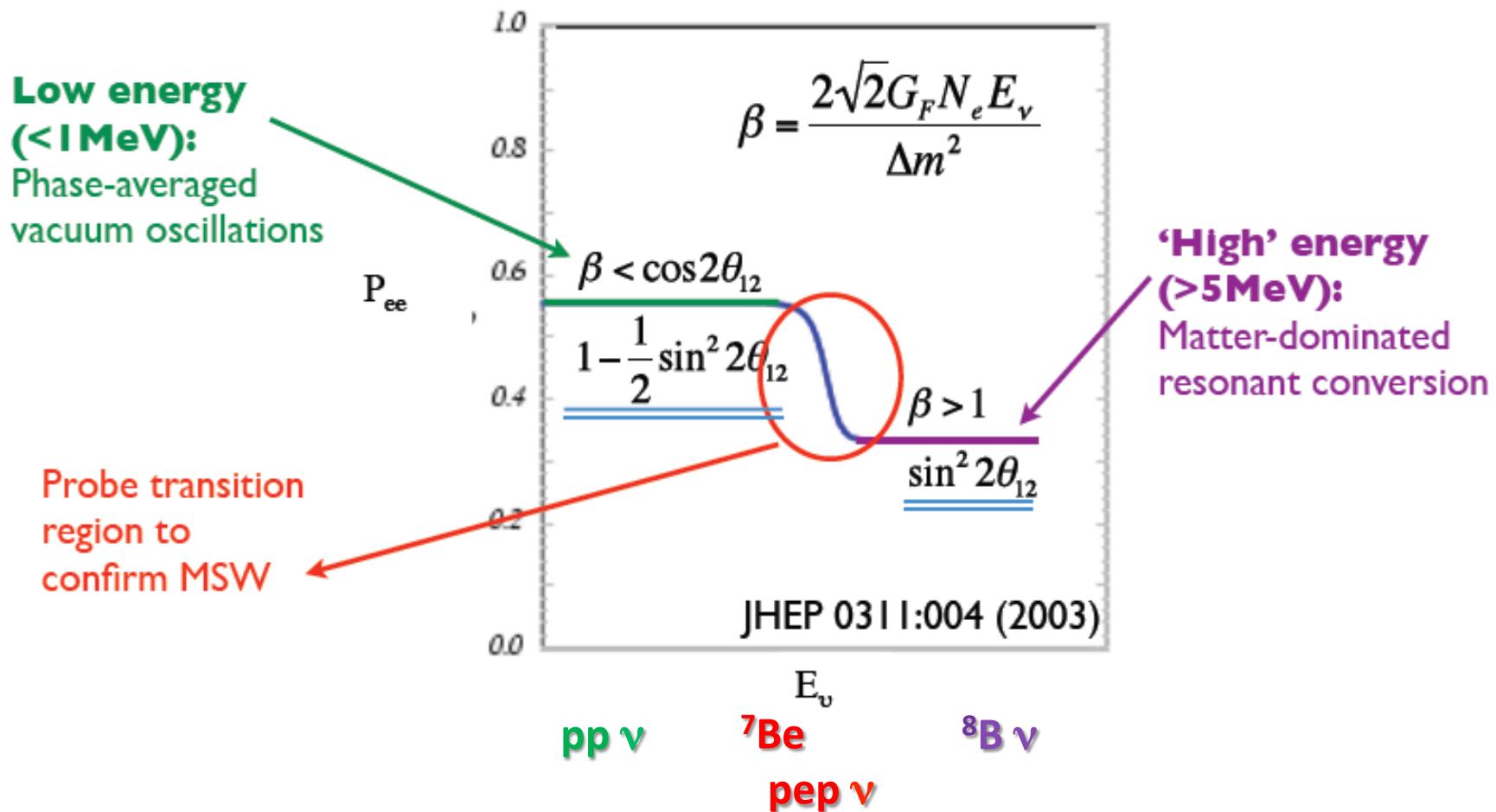
Solar- ν oscillation
in vacuum

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

But propagation
NOT in vacuum:
Sun matter

Solar- ν oscillation in matter - MSW

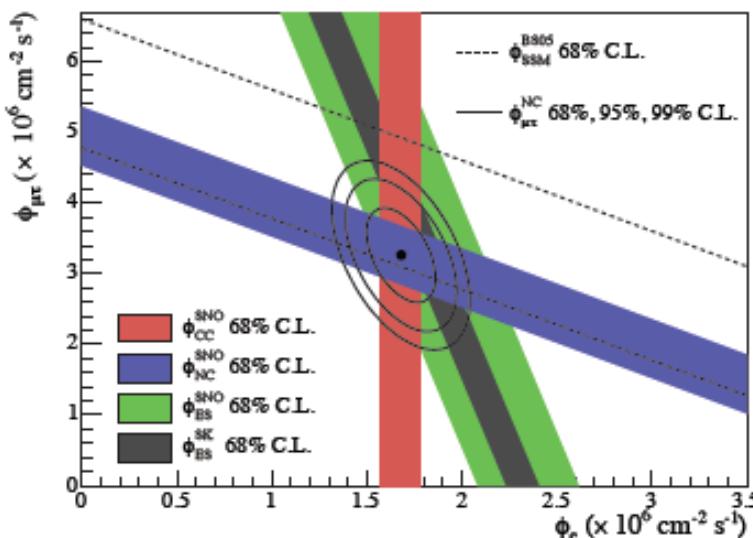
Pee becomes **energy dependent** because of **MSW effect**



Discovery of solar- ν oscillations

Inclusive appearance at the
Sudbury Neutrino Observatory

$$\text{ES: } \nu_x + e^- \rightarrow e^- + \nu_x$$

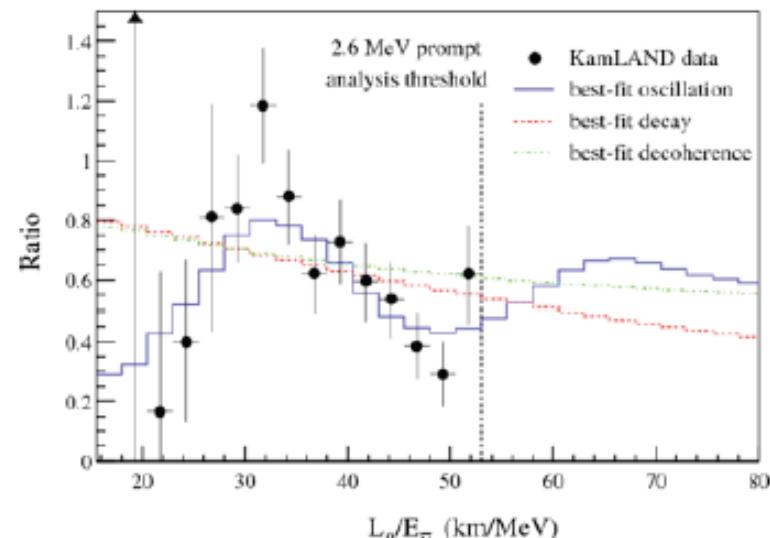


PRL 87 (2001) 071301, PRL 89 (2002) 011301

Oscillations at
KamLAND



Disappearance at >99.99%
Clear oscillation pattern



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



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. MacFarlane.
Queen's University
/SNOLAB

Arthur B. McDonald

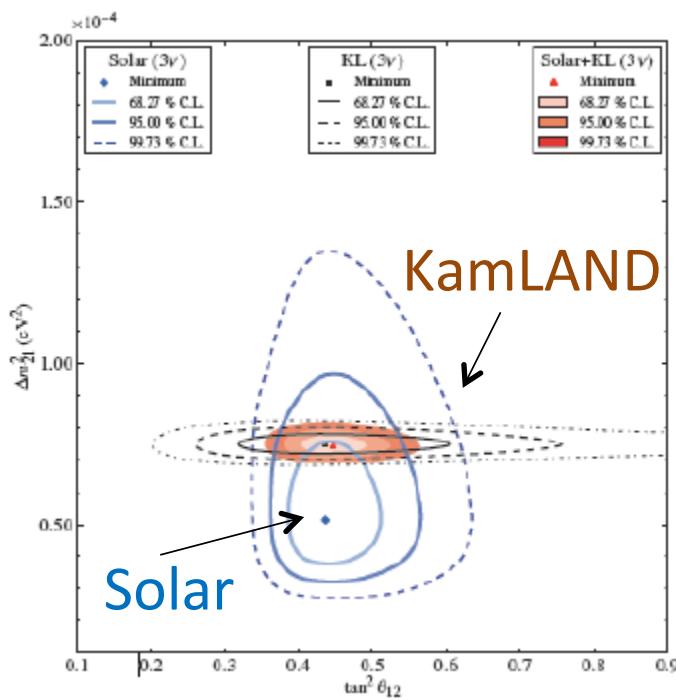
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

MSW-LMA

Global Fit
Solar exp + KamLAND
evidence
Large **Mixing Angle**

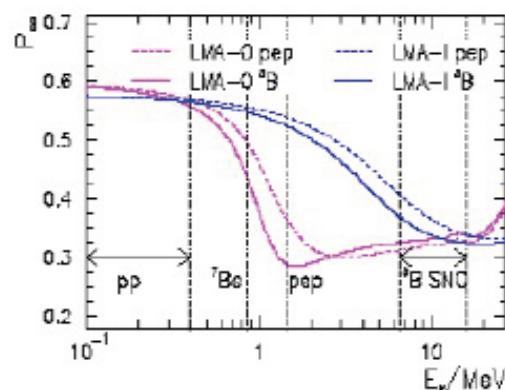
Solar neutrino oscillations
described by
MSW-LMA scenario



What may we still learn from solar- ν ?

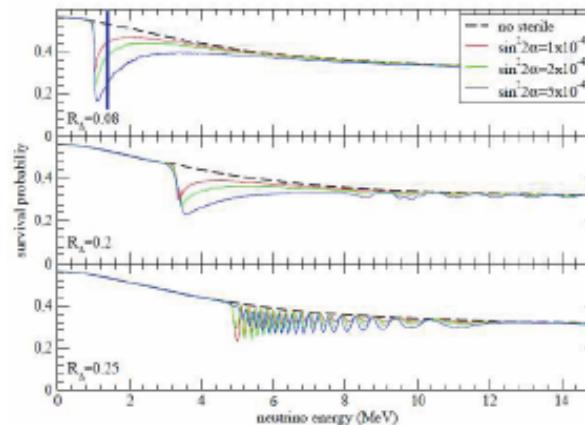
Non standard physics can alter Pee shape – position of MSW rise
Precision measurements to probe Pee
Constrain non-standard neutrino and solar physics

Non-standard interactions (flavour changing NC)



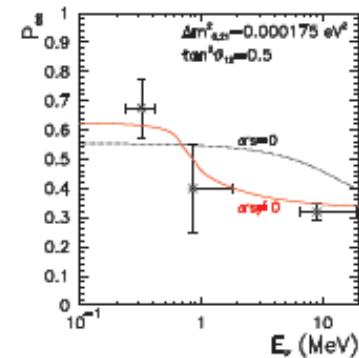
Friedland, Lunardini, Peña-Garay,
PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



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

What may we still learn from solar- ν ?

Proof of CNO cycle in Sun

Abundances of heavy elements in Sun have great **impact** on **CNO neutrino flux magnitude**

Test of Solar Models (HighZ vs LowZ)

Serenelli, Haxton, Pena-Garay
arXiv 1104.1639

CNO Flux ($10^8 \text{ cm}^{-2} \text{ s}^{-1}$)

HIGH Z SSM

5.24 ± 0.84

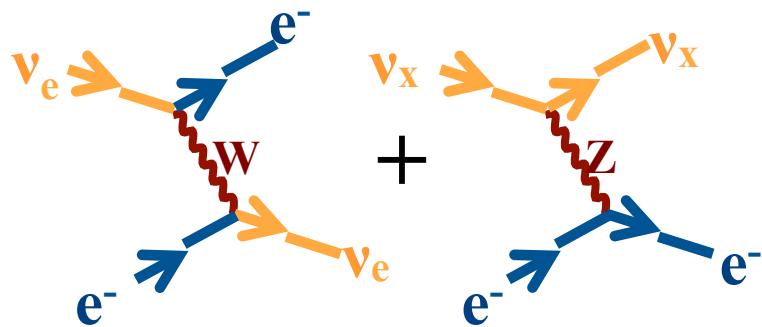
LOW Z SSM

3.76 ± 0.60

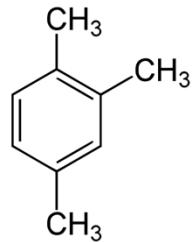
$\Delta \Phi$

28%

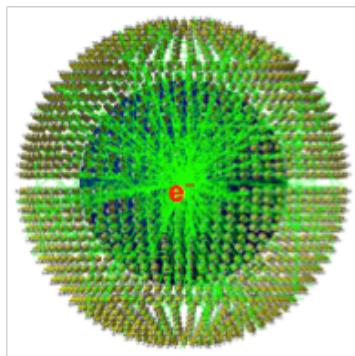
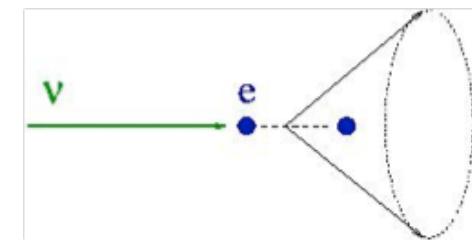
Principles of solar- ν detection



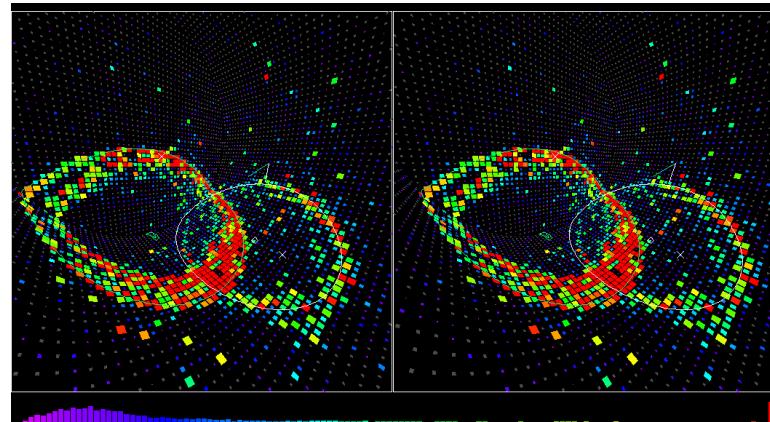
Neutrinos detected via
elastic scattering
on **electrons**



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

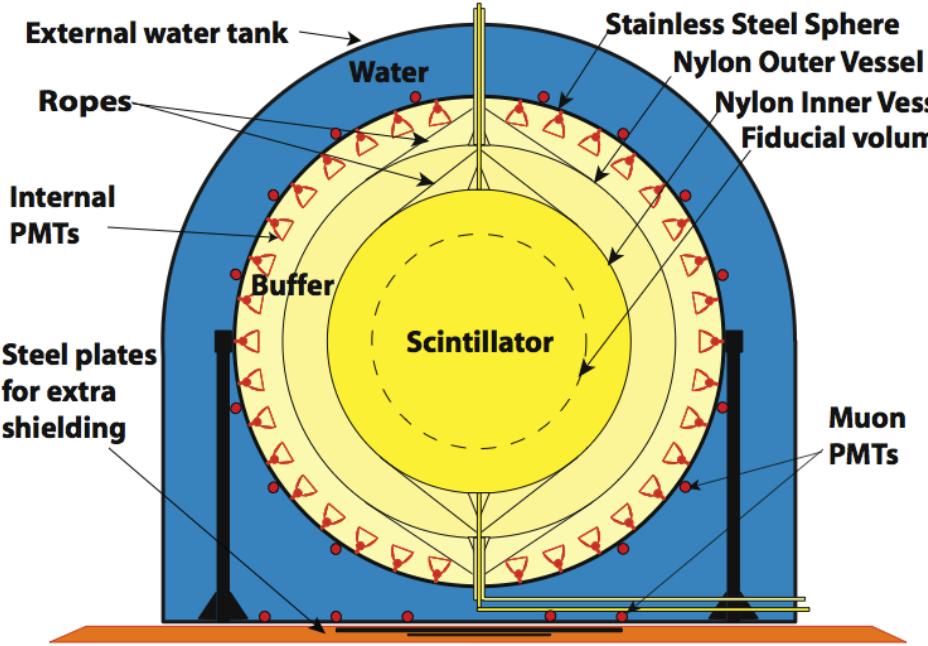


Light seen
by **PMTs**

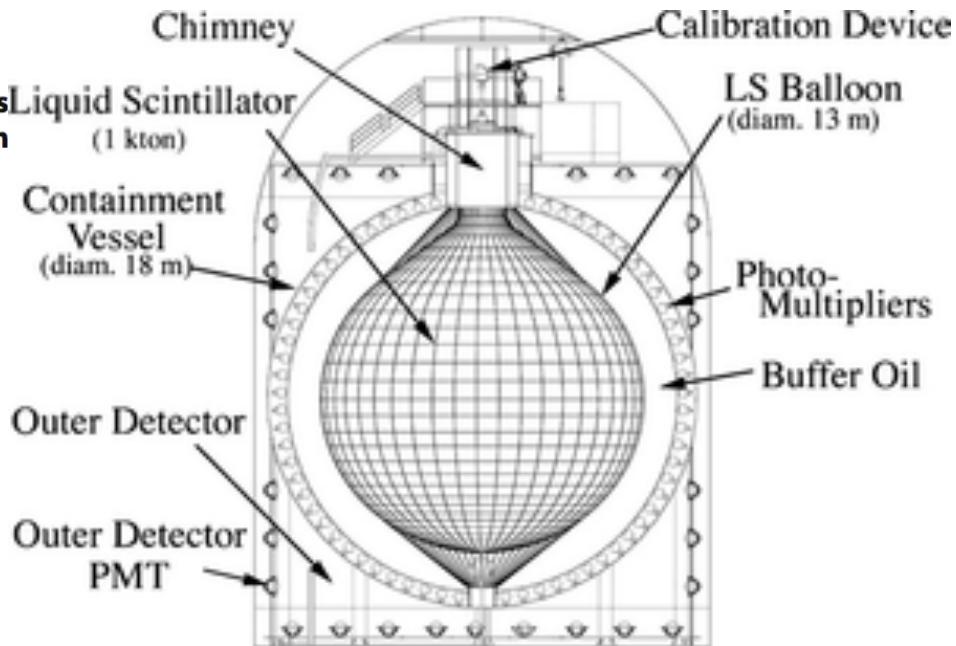


Borexino and KamLAND

Borexino Detector



KamLAND Detector

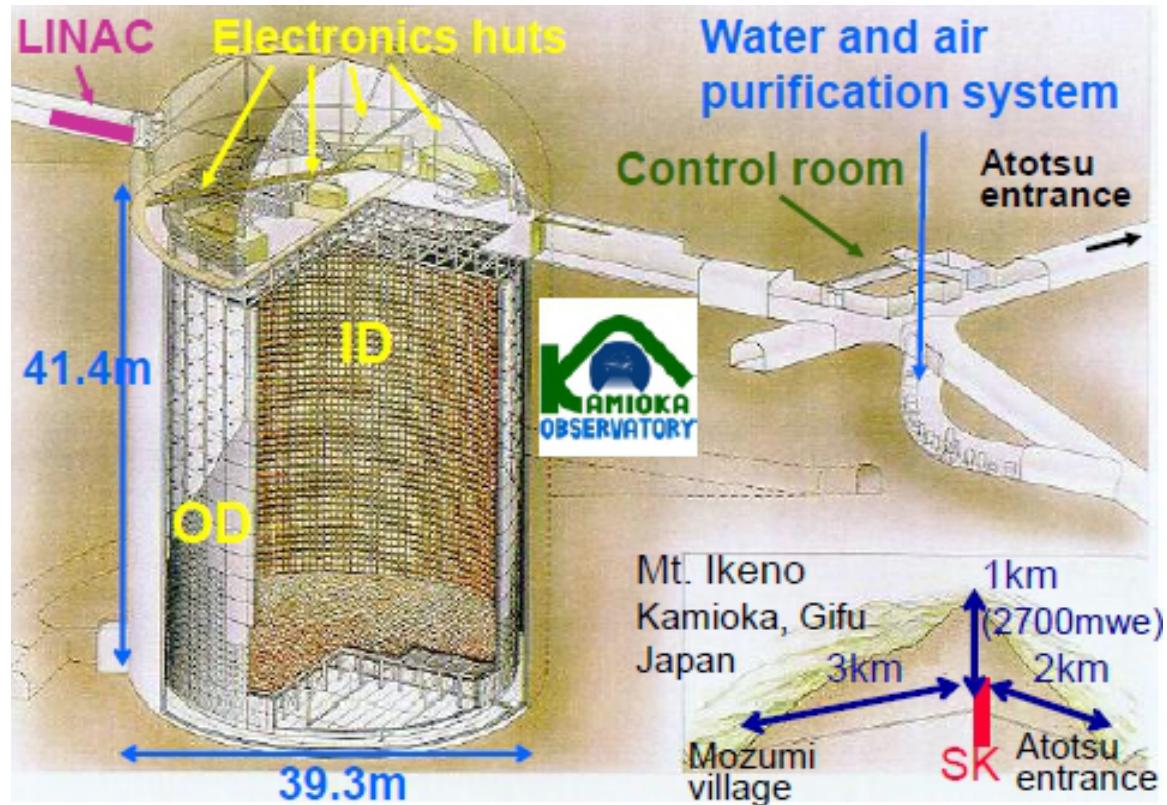


Liquid scintillator detectors

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

No directionality, superb purity required to reject radioactivity

Super-Kamiokande



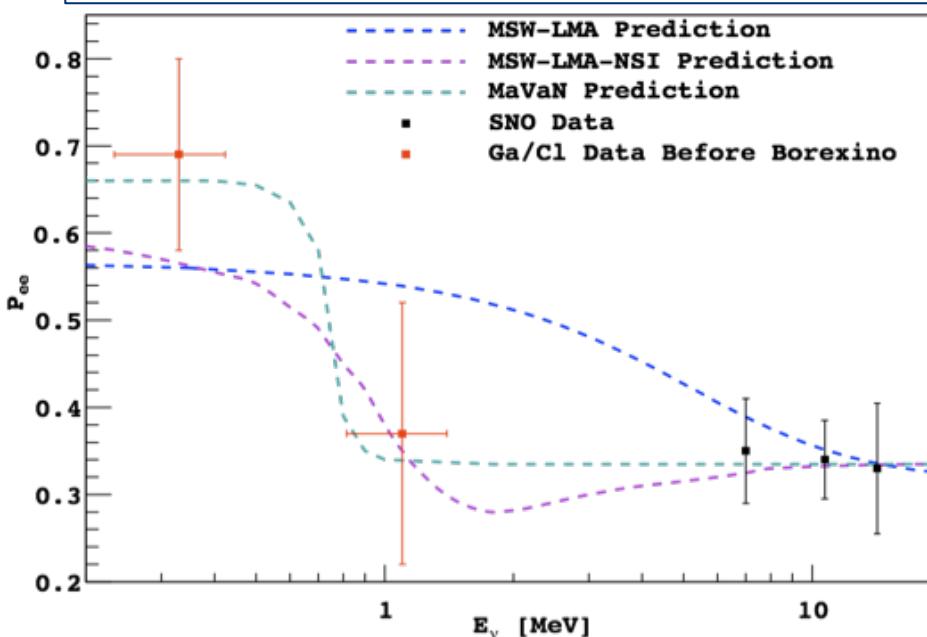
Water Cherenkov detector

Directionality

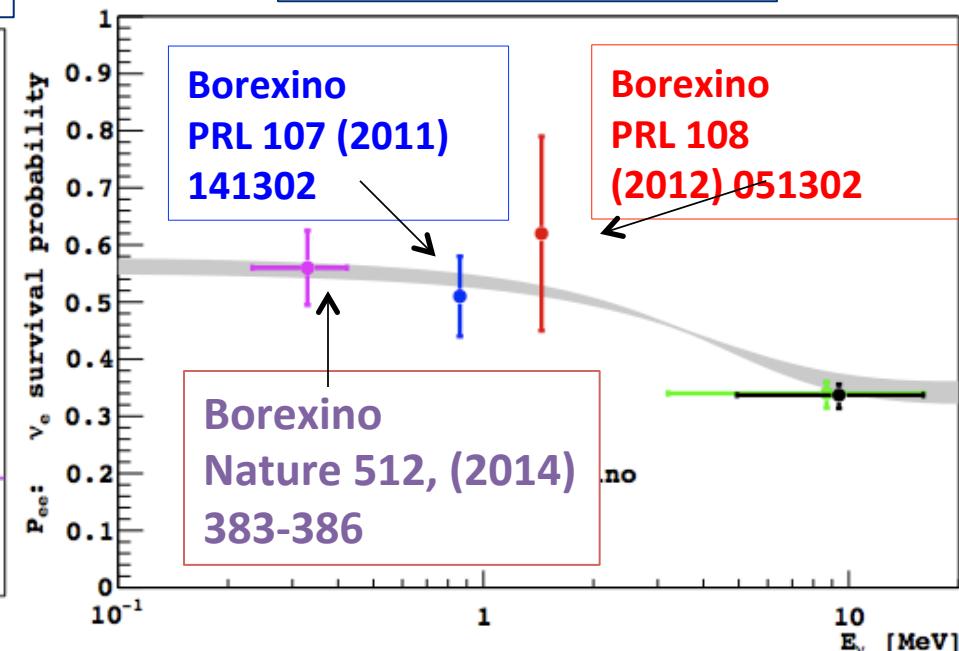
High energy threshold: ^8B neutrinos only ($E > 4 \text{ MeV}$)

Current status of Pee probe

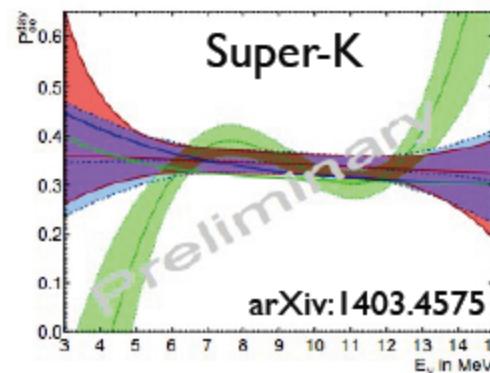
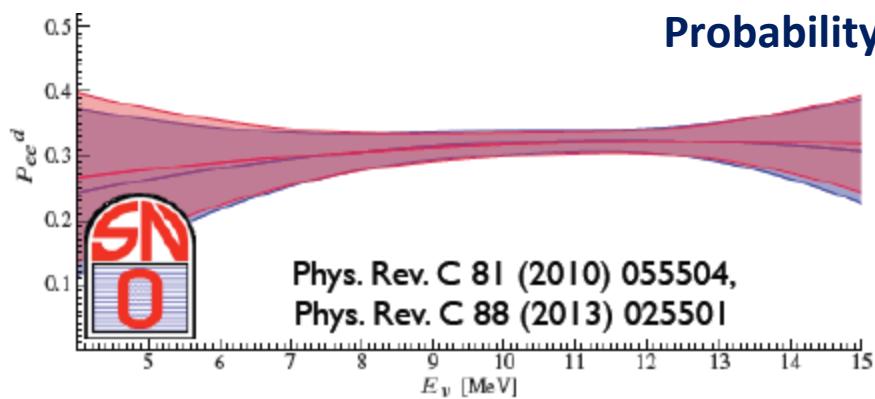
Pee measurement before BOREXINO



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

You will learn more at **GSSI**

Borexino and **LVD** at **LNGS** await you