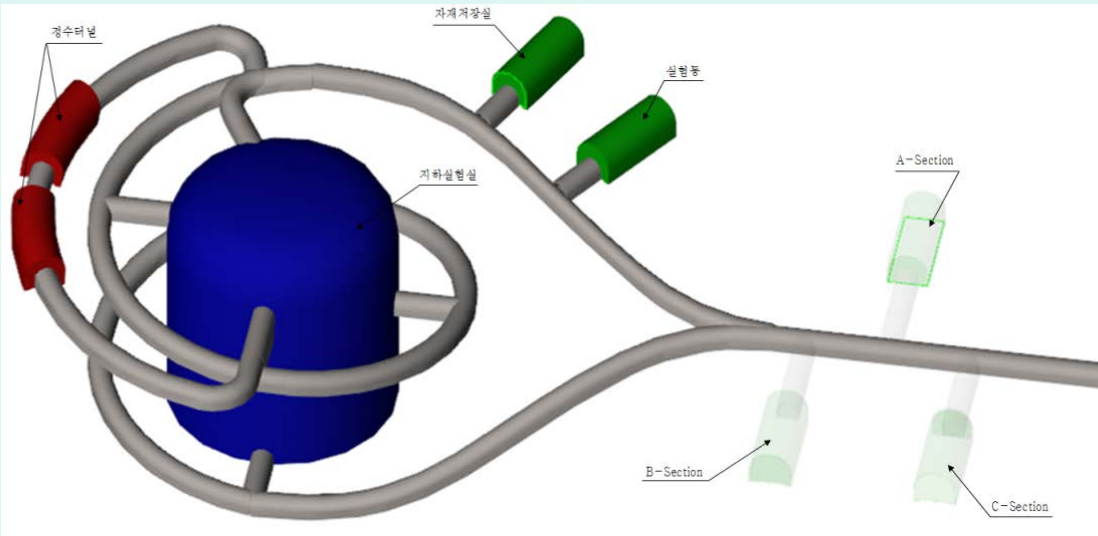
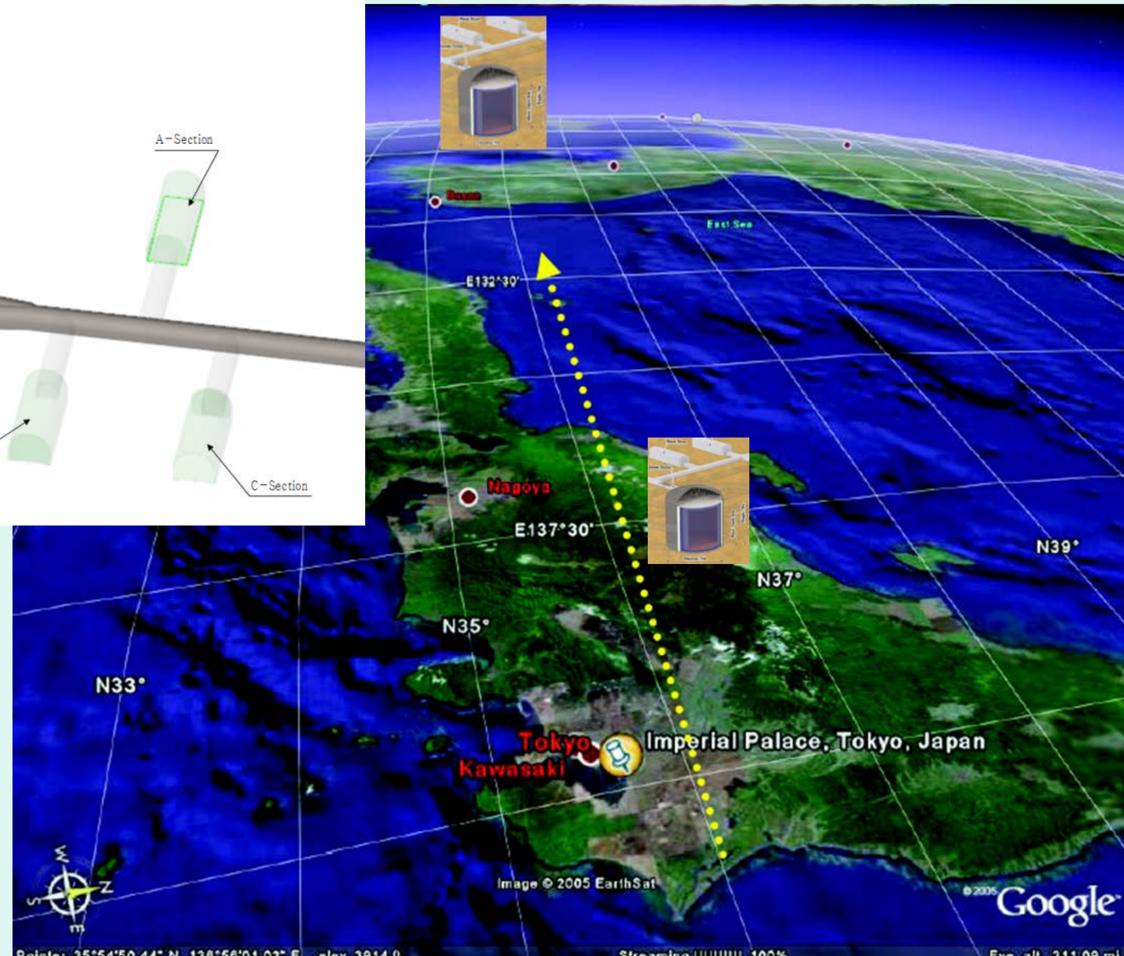
# Solar Neutrinos
# at Korean Neutrino Telescope

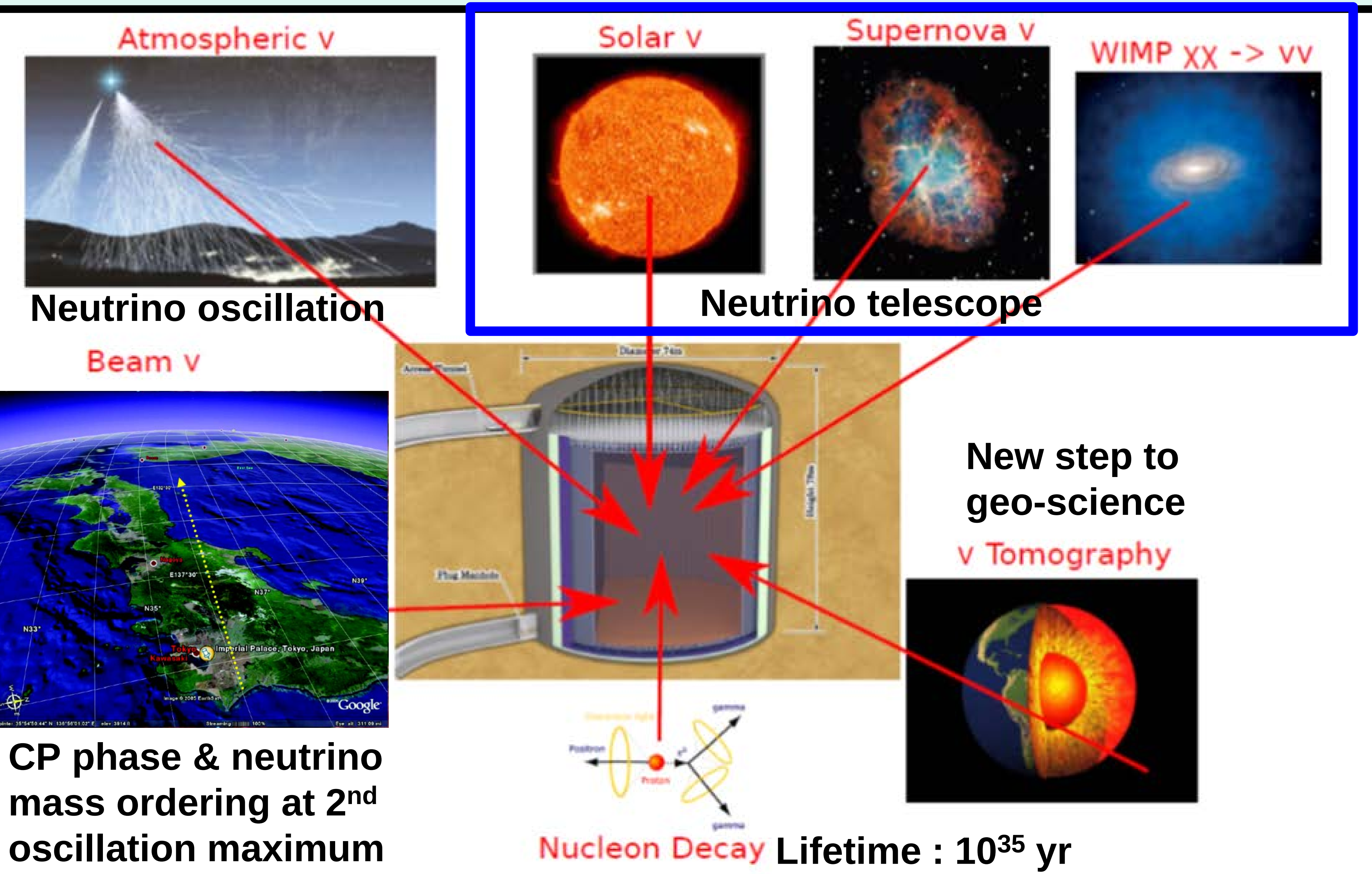


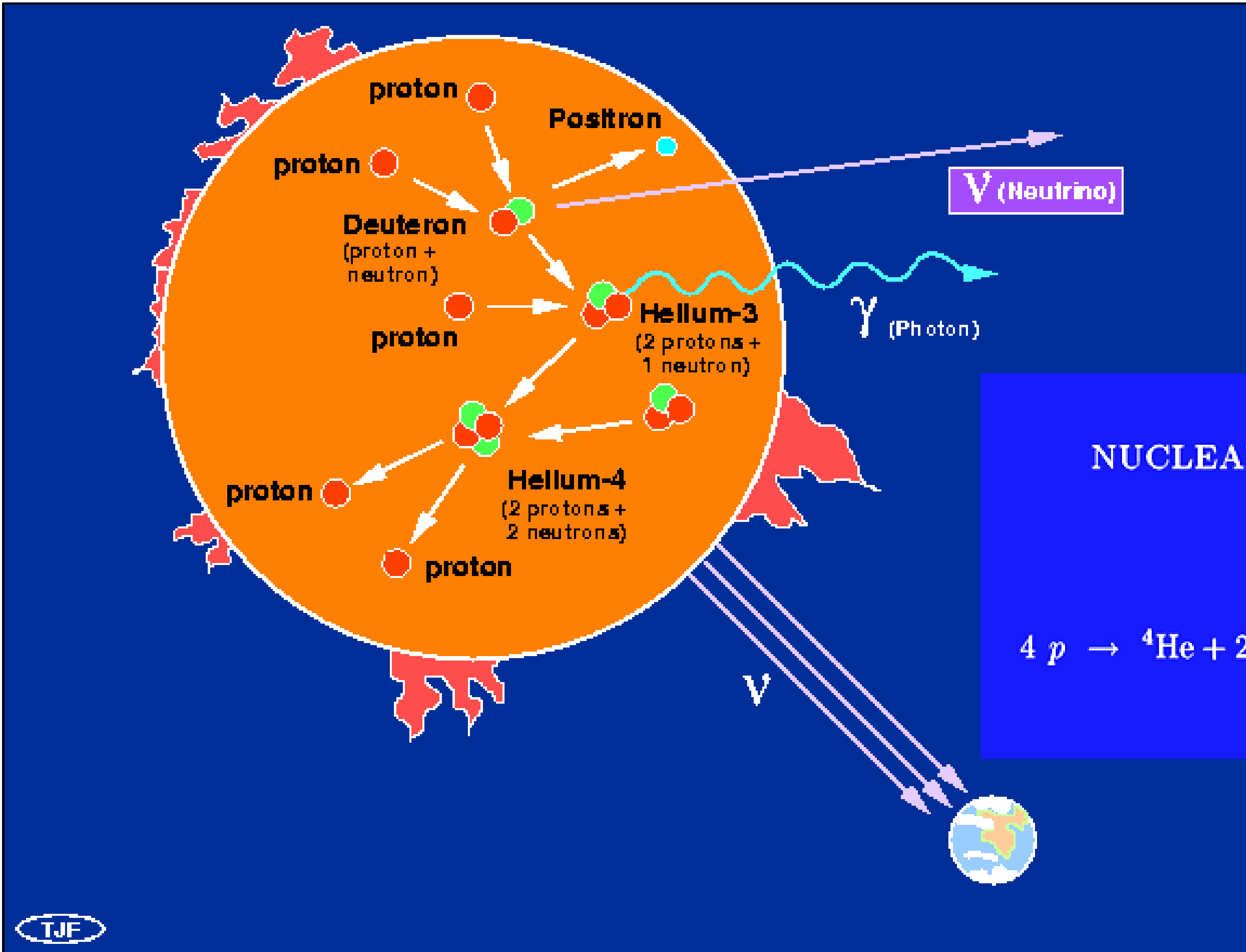

Nov. 2, 2018

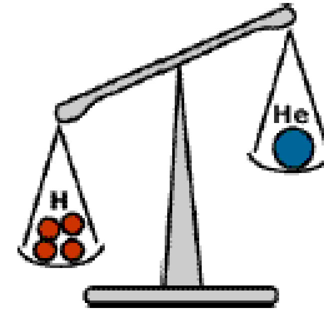
Soo-Bong Kim, Seoul National University

# Korean Neutrino Observatory (KNO)



# Solar Neutrino




NUCLEAR BURNING

$$4\ p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 25\ \mathrm{MeV}$$

# Hydrogen Burning in Star

- pp-1 chain

**86%**

(4 protons $\rightarrow$ 1 $^4$He + pp neutrinos + 26.72 MeV)

$$p + p \rightarrow {}^2_1H + e^+ + \nu_e + 0.42\ \text{MeV}$$

**E(ν) < 0.42 MeV**

- pp-2 chain

**14%**

(4 protons $\rightarrow$ 1 $^4$He + $^7$Be neutrinos + 19.80 MeV)

$$^7_4Be + e^- \rightarrow {}^7_3Li + \nu_e + 0.86\ \text{MeV}$$

**E(ν) = 0.86 MeV (90%)**
**0.39 MeV (10%)**

- pp-3 chain

**0.02%**

(4 protons $\rightarrow$ 1 $^4$He + $^8$B neutrinos + 17.19 MeV)

$$^8_5B \rightarrow {}^8_4Be^* + e^+ + \nu_e + 14.02\ \text{MeV}$$

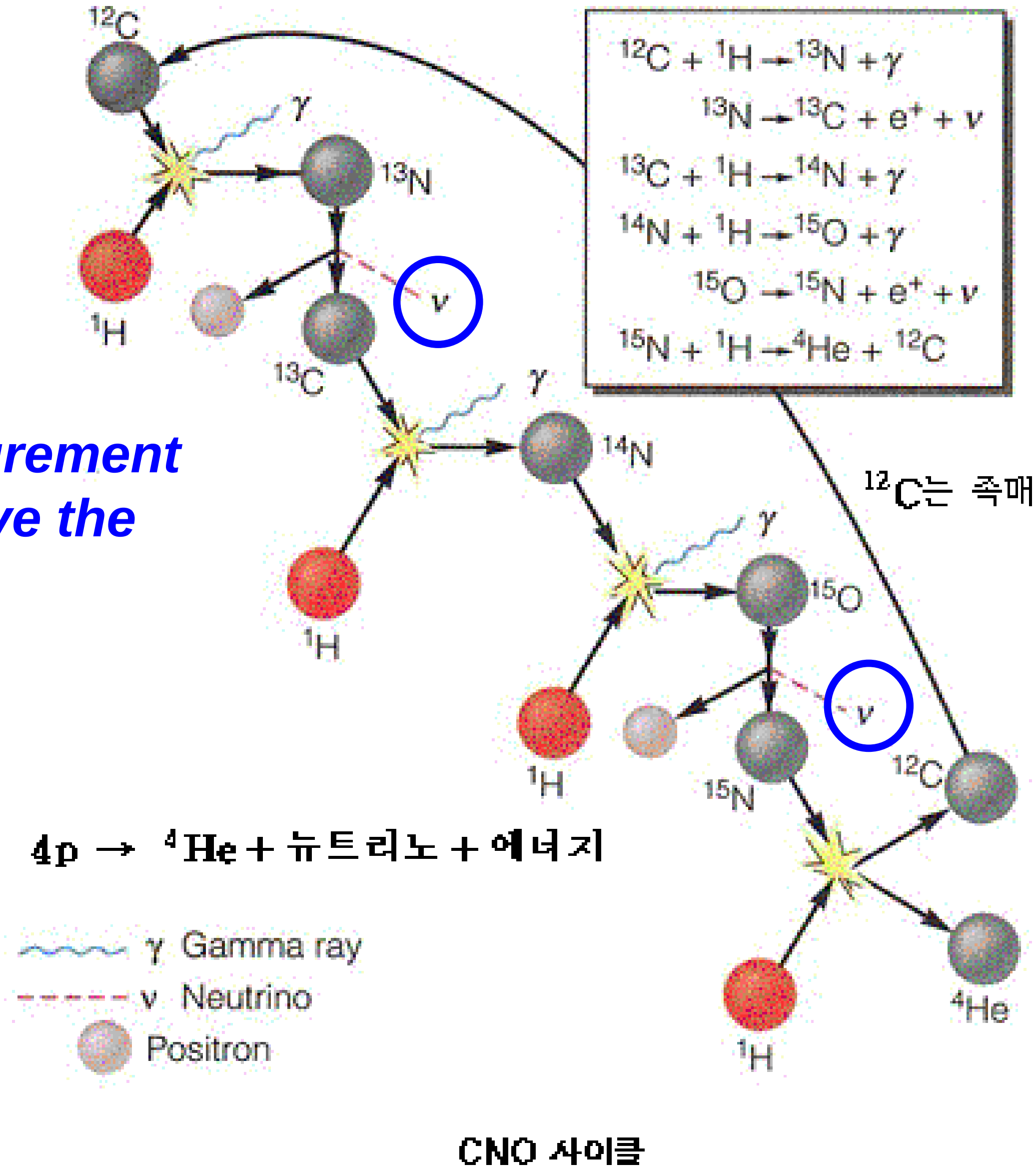
**E(ν) < 14.02 MeV**

- CNO cycle : Hydrogen burning catalyzed by C/N/O nuclei under high temperature, 1~3% in the Sun

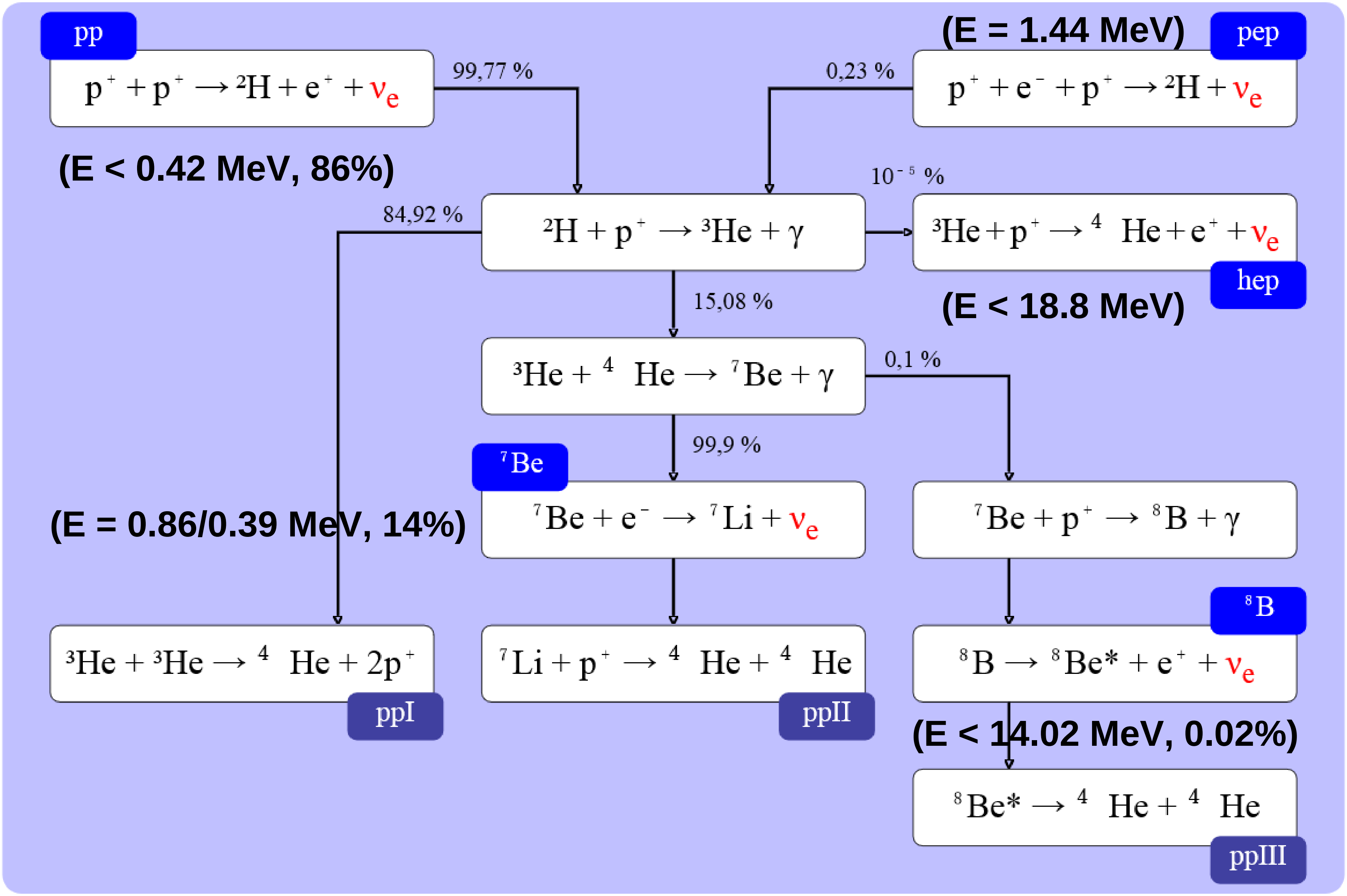
(4 protons $\rightarrow$ 1 $^4$He + $^{13}$C/$^{15}$O neutrinos + energy)

# Hydrogen Burning by CNO cycle

***Needs a 10% precision measurement of CNO solar neutrinos to solve the solar metallicity problem***

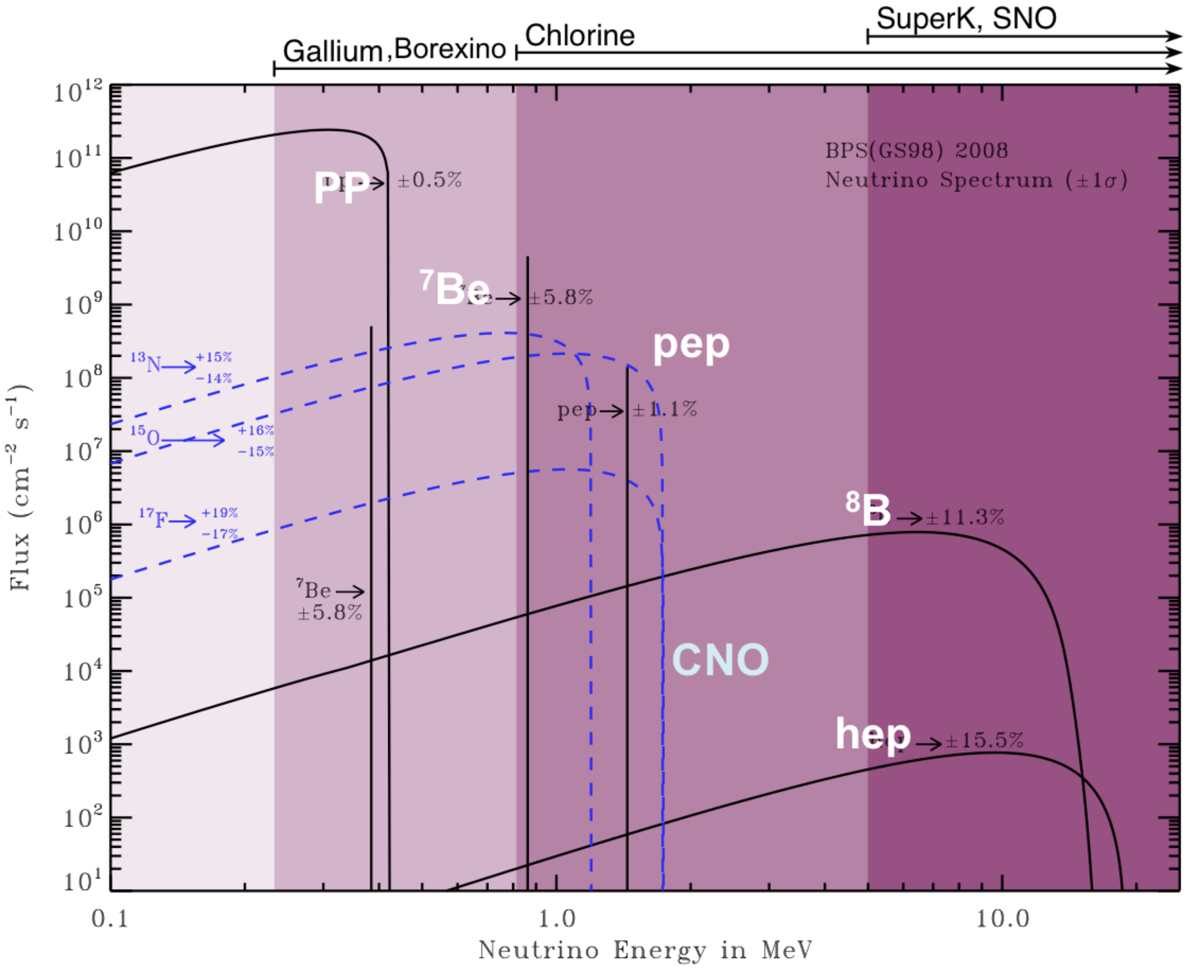


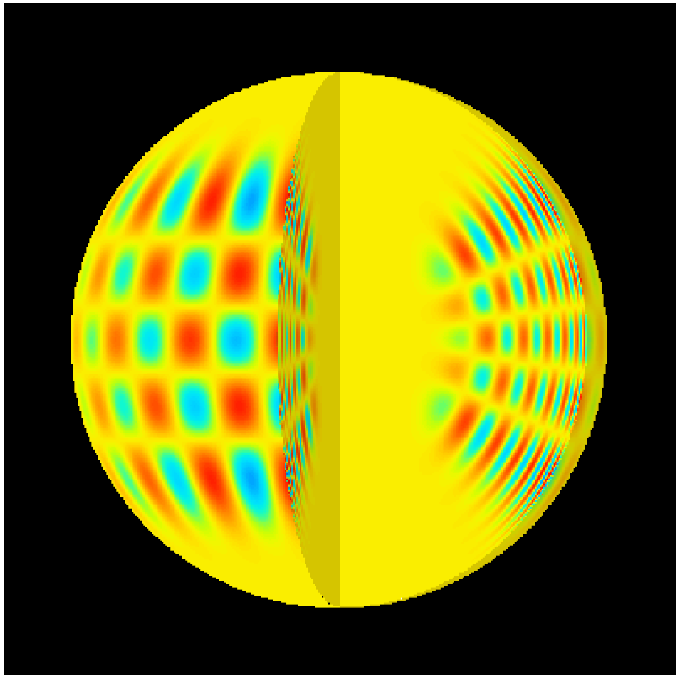
# Solar Neutrinos from Hydrogen Burning



# Standard Solar Model

## ( John. N. Bahcall)

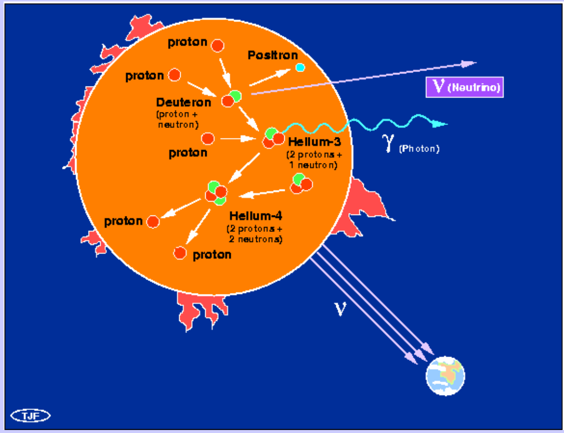


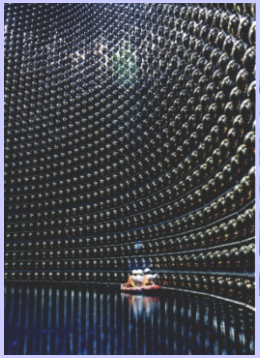
Helioseismology

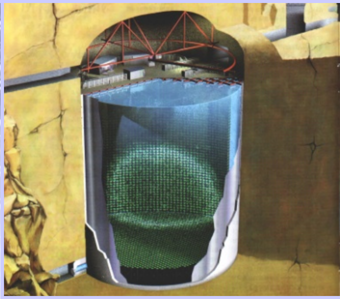
# Solar Neutrino ($\nu_e$) Oscillation ($\theta_{12}$ )

Nuclear fusion : $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ + thermal energy

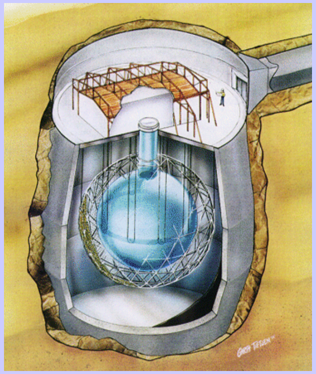



- Deficit of solar neutrinos → Evidence for oscillations
  - Homestake (Cℓ, 1968~1993): first measurement
  - Kamiokande ($H_2O$, 1986~1993): energy/directionality
  - SAGE & GALLEX/GNO (Ga, 1990~2001)
  - Super-Kamiokande ($H_2O$, 1996~ ): precision exp.
  - Borexino (LS, 2007~ ): ultra-low radioactivity.

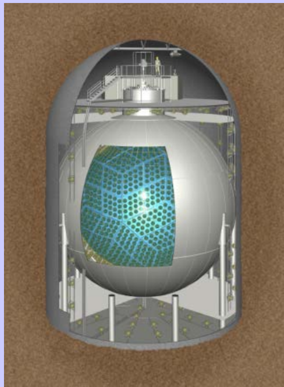




- Discovery of Solar Neutrino Oscillations
  - SNO ($D_2O$, 2002): detect $\nu_\mu / \nu_\tau$ ($\nu_e \rightarrow \nu_\mu$ & $\nu_\tau$ )

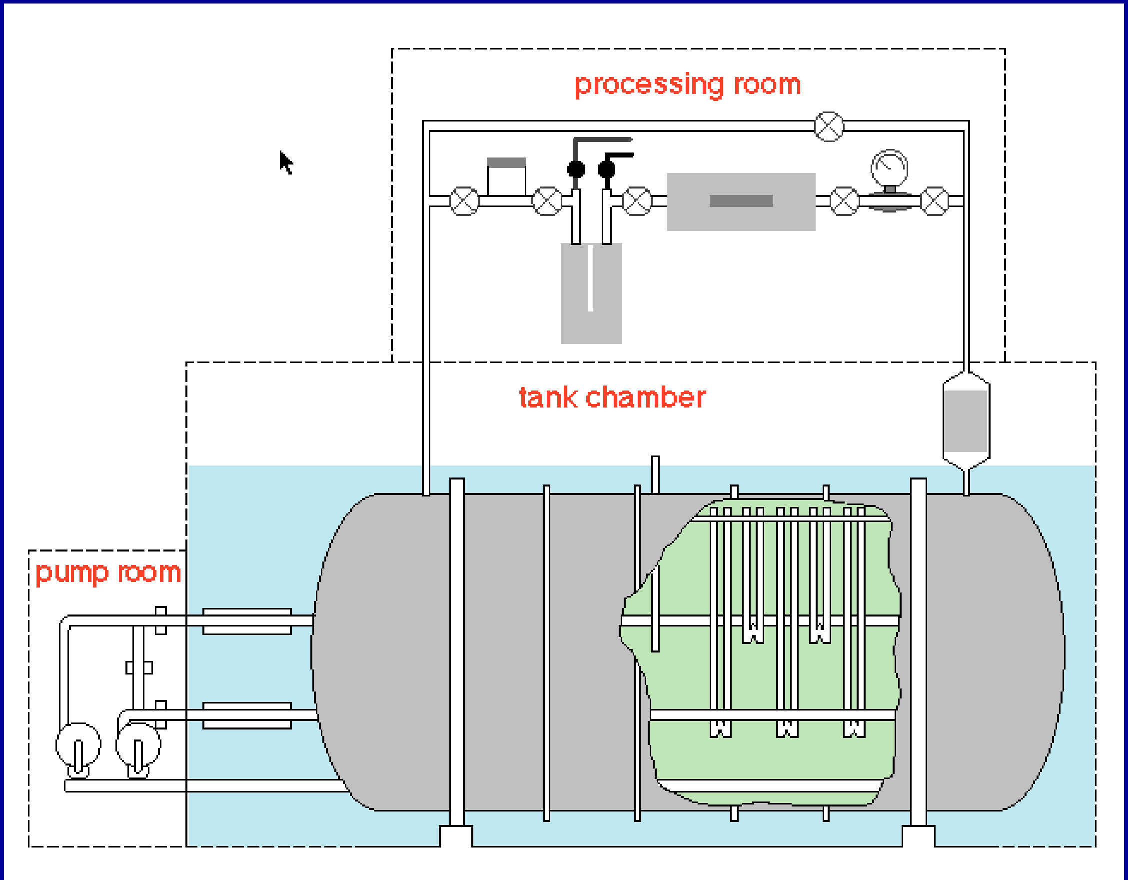


- Confirmation of Solar Neutrino Oscillations
  - KamLAND (2002): reactor neutrino oscillation



# 최초의 태양중성미자 관측 (1968-1993)

**(Raymond Davis Jr.)**




600톤 염소용액 탱크, 중성미자+Cl → Ar+전자

# 태양에서 날아온 중성미자 측정
# 초신성 폭발의 중성미자 최초 관측

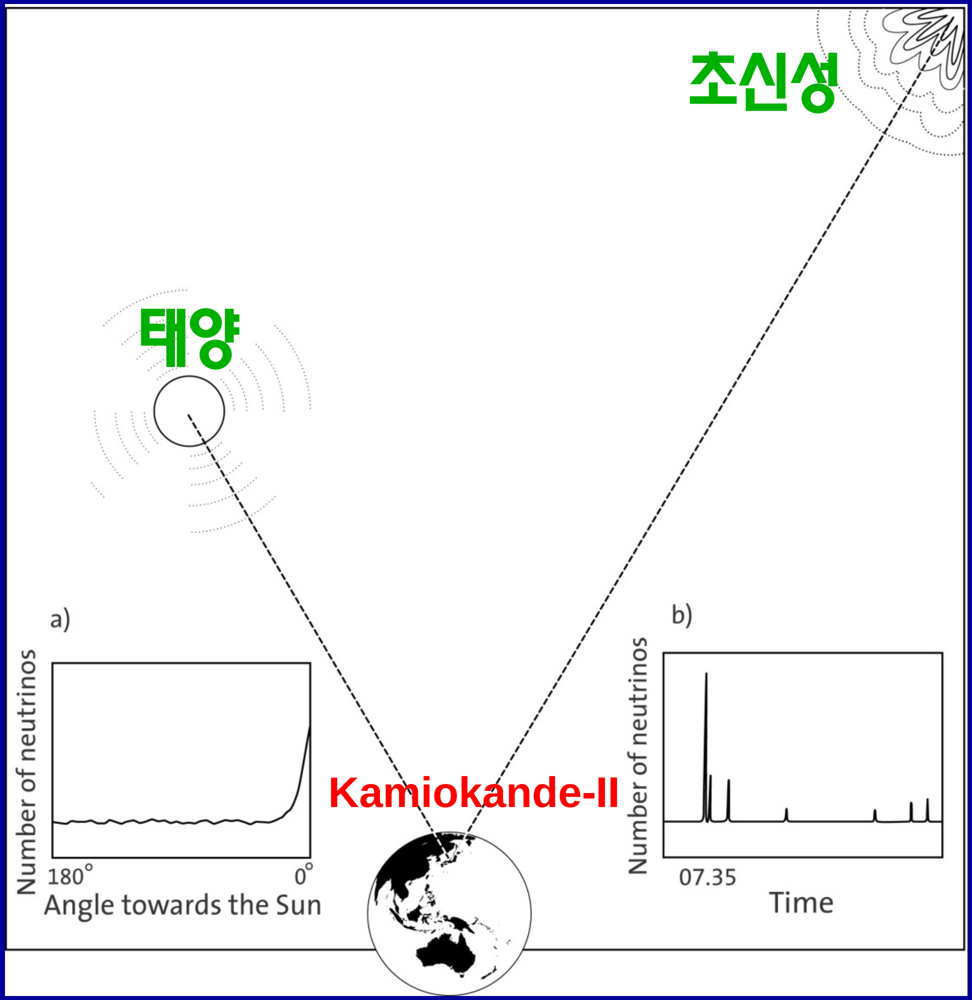
## (Masatoshi Koshiba)

(1) 태양의 핵융합에 의해 생성된 B8의 붕괴에서 나오는 중성미자의 방향, 시간, 에너지를 최초 관측

(별 속의 핵융합 반응 확인!)

(2) 초신성 폭발에서 나오는 중성미자 최초 관측

→ 중성미자 망원경 탄생!




# ❑ The Nobel Prize in Physics

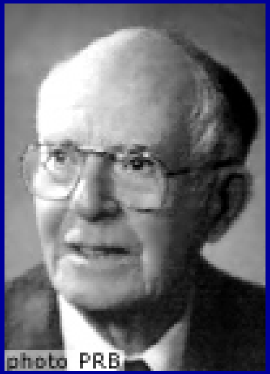
**"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos“**

**Raymond Davis Jr.** **USA**

(University of Pennsylvania)

**Masatoshi Koshiba** **Japan**

(University of Tokyo)



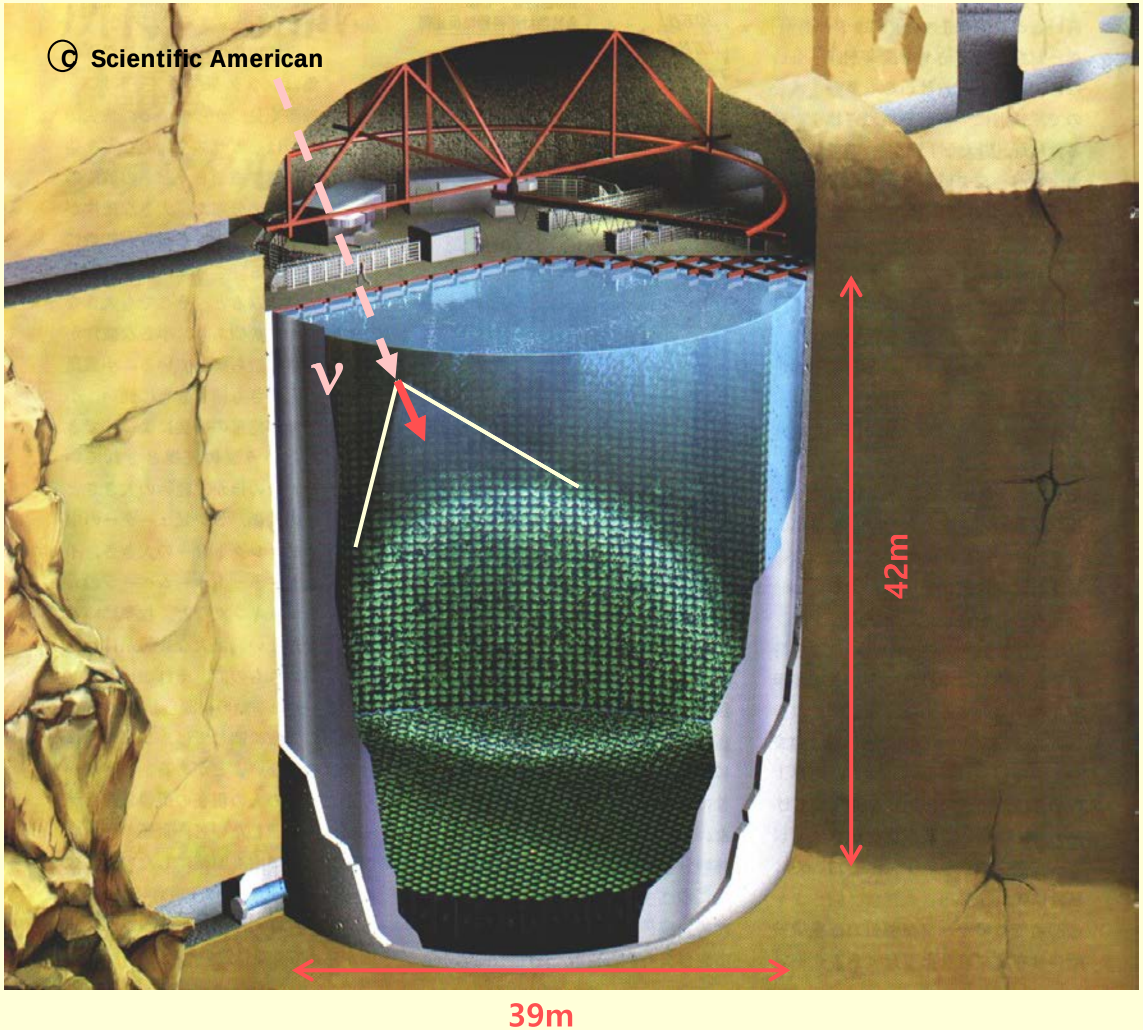


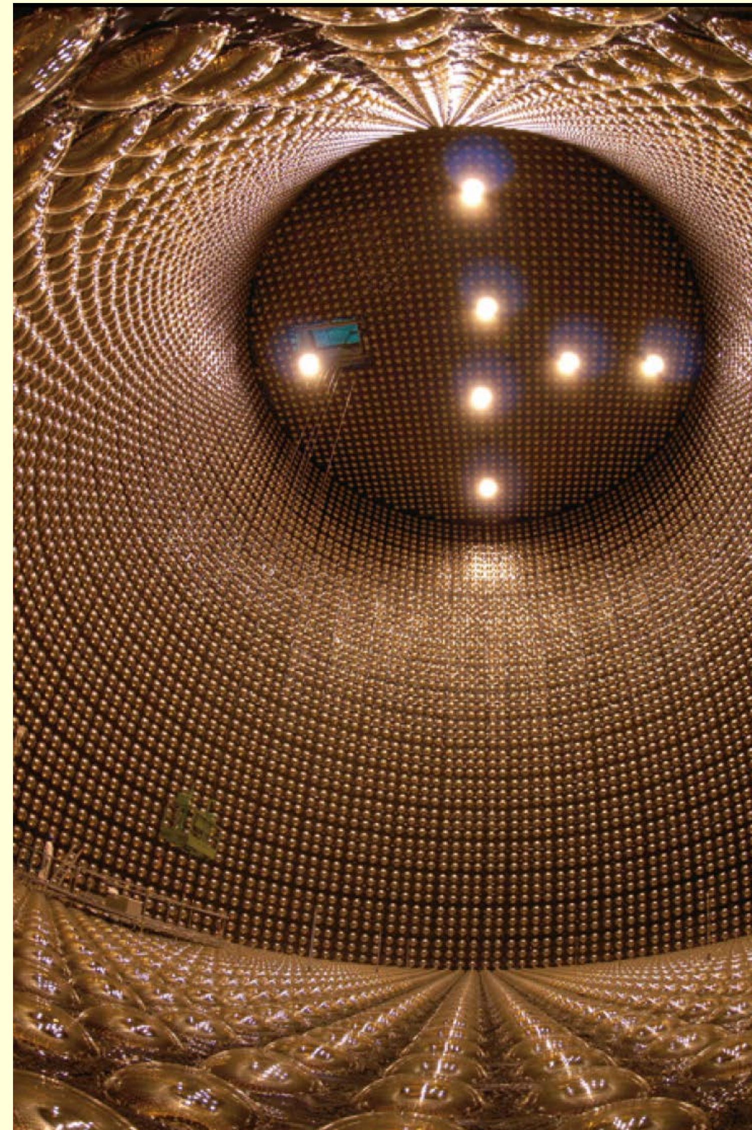
**"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources“**

**Riccardo Giacconi** **USA**

(Associated Universities Inc.)

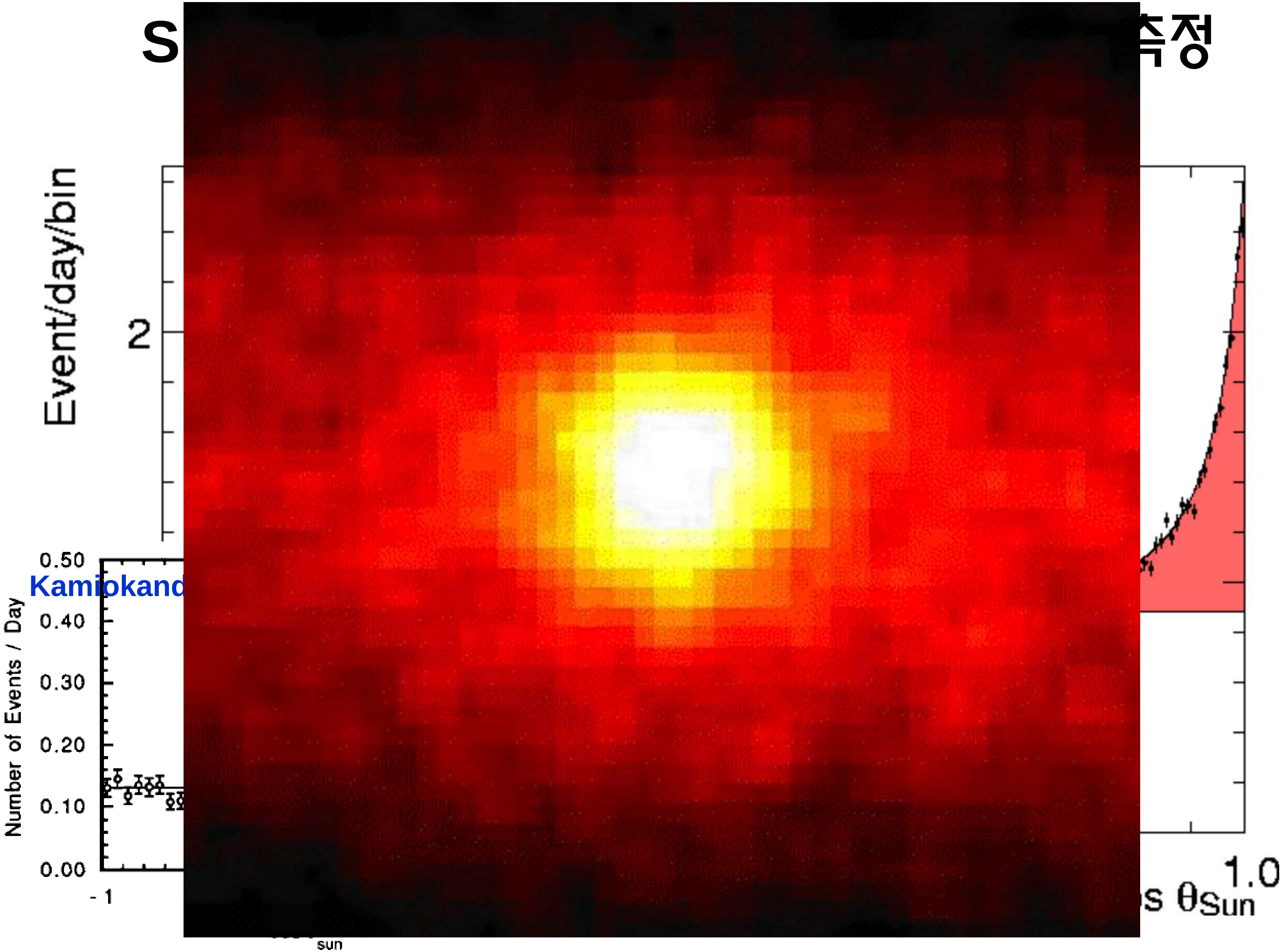
# 수퍼카미오칸데 (Super- Kamiokande)



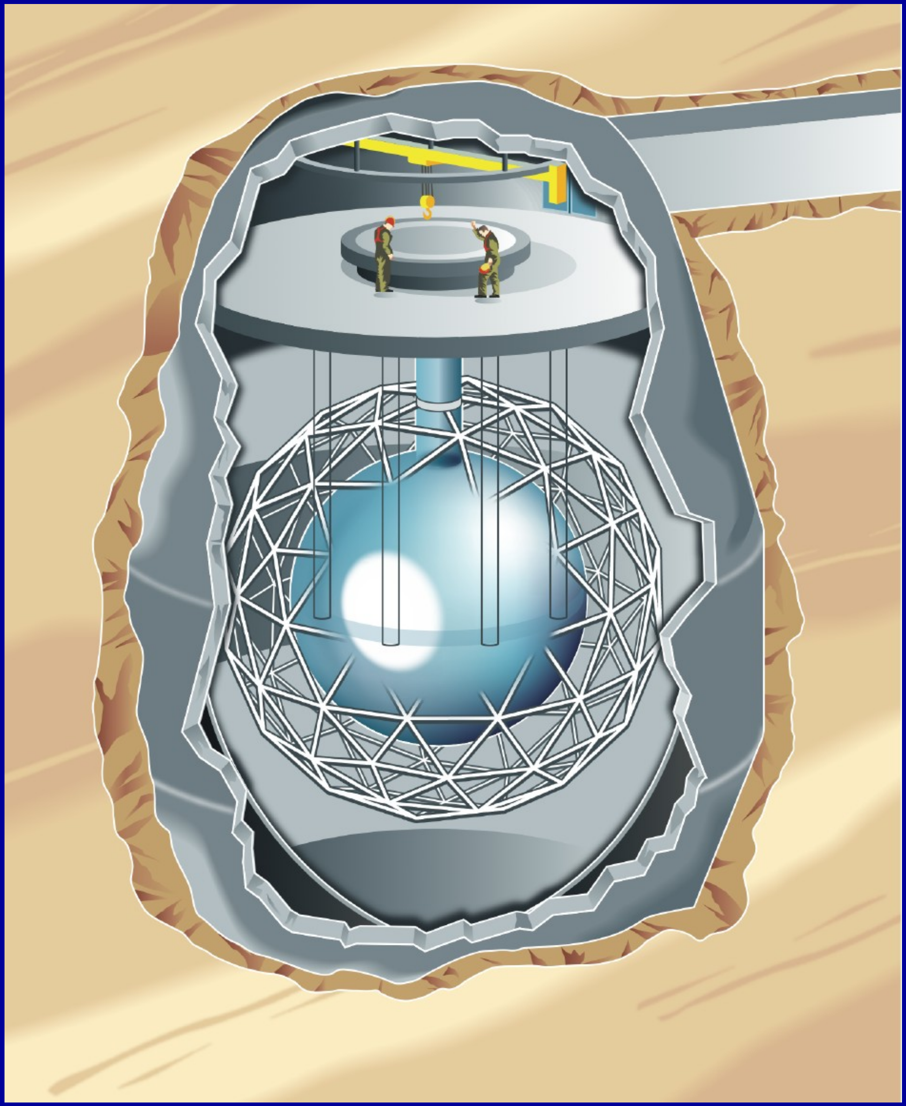



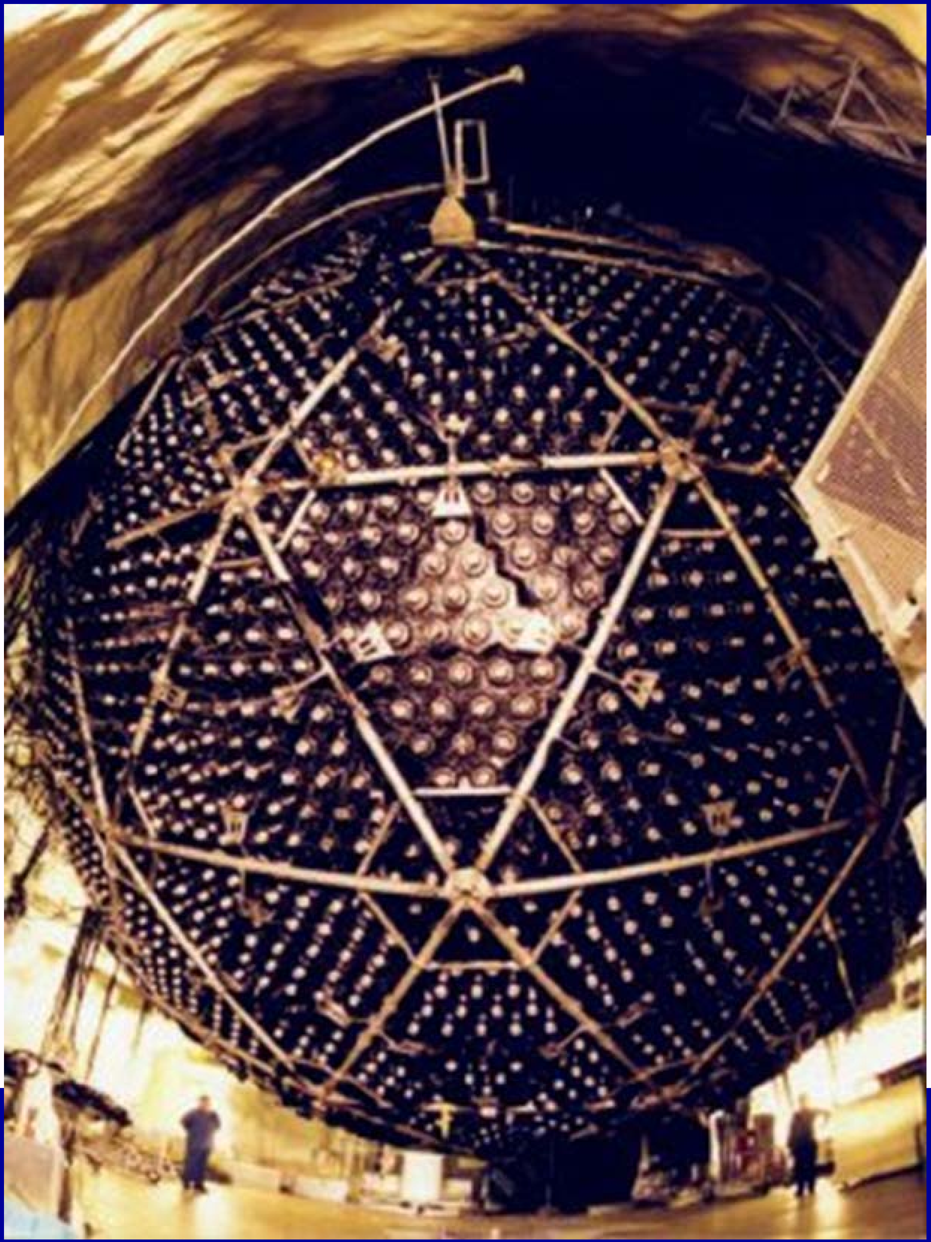
**Water Cherenkov detector**

- 1000 m underground
- 50,000 ton
- 11,146  20 inch PMTs

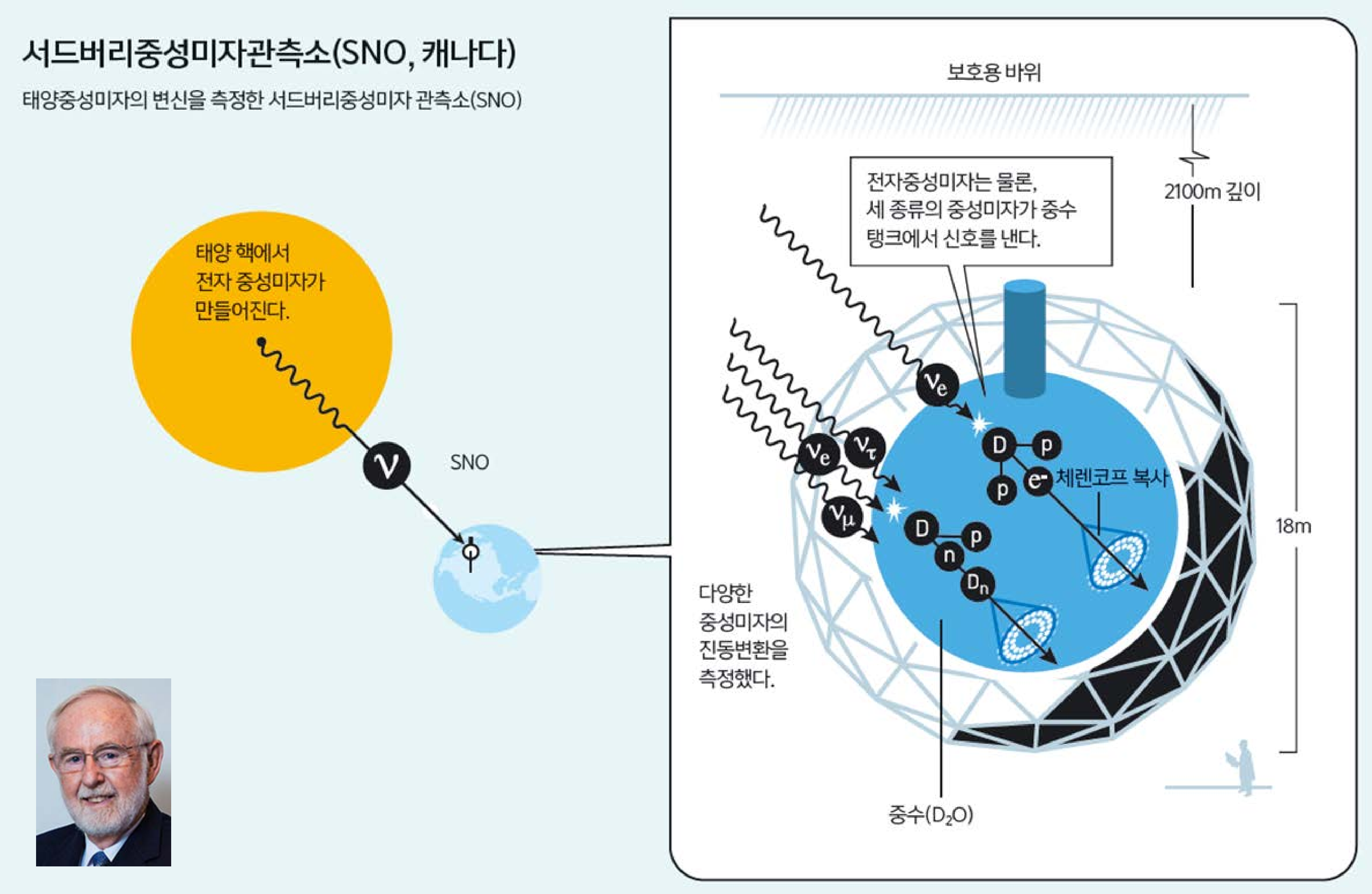

S
측정
Event/day/bin
2
1.0
s θSun
Kamiokand
Number of Events / Day
0.50
0.40
0.30
0.20
0.10
0.00
- 1
sun

# SNO (Sudbury Neutrino Observatory)





# SNO의 태양 중성미자 진동변환 발견

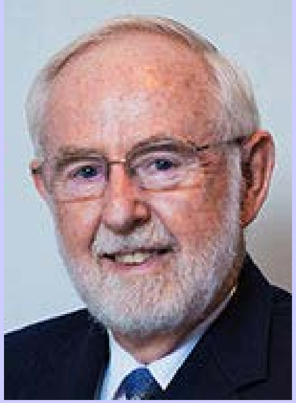


## ❑ The Nobel Prize in Physics, 2015

***"for the discovery of neutrino oscillations, which shows that neutrinos have mass"***

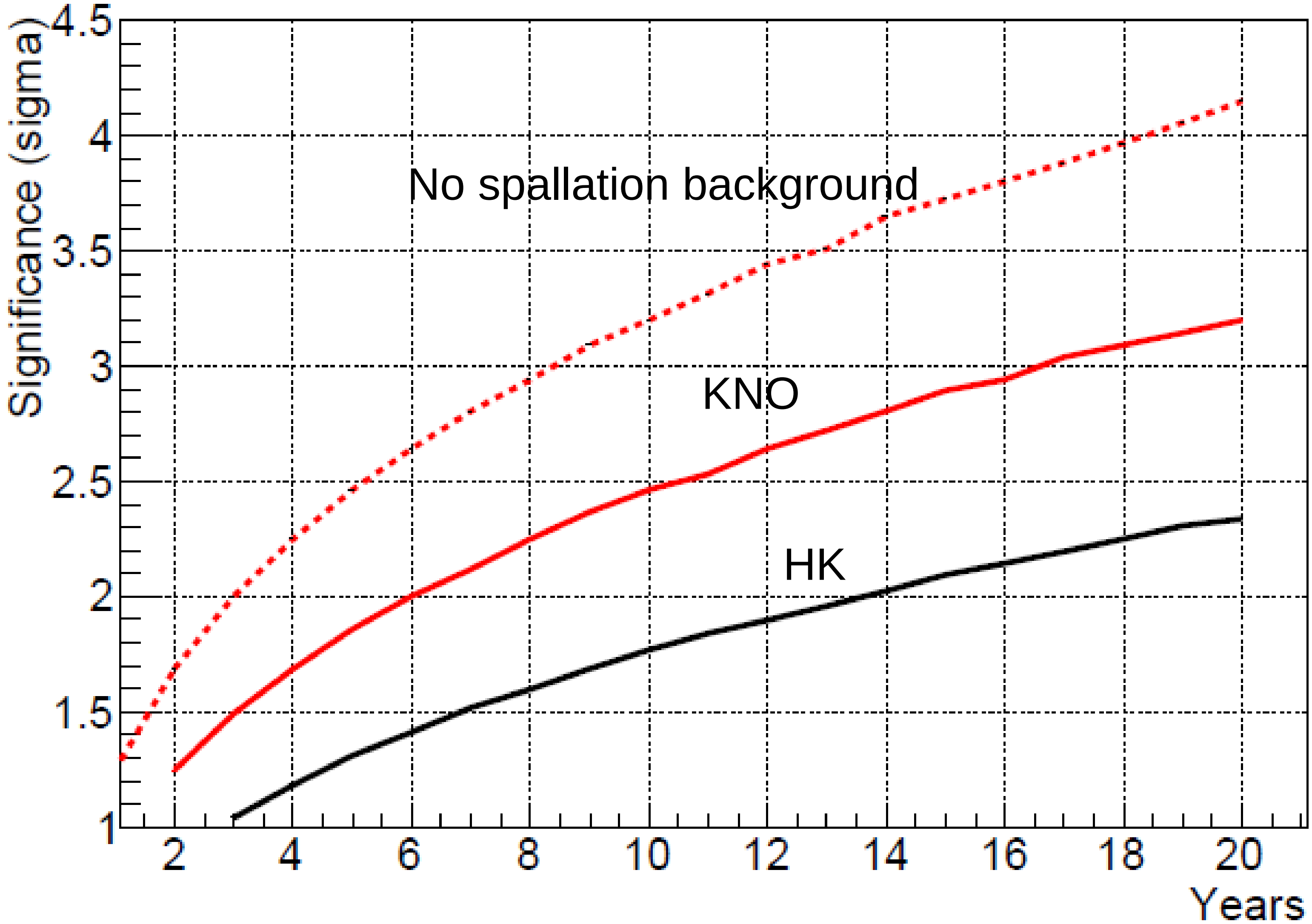
**Takaaki Kajita**
**Super-Kamiokande Collaboration**
(University of Tokyo, Japan)

**Arthur B. McDonald**
**Sudbury Neutrino Observatory Collaboration**
(Queen's University, Canada)



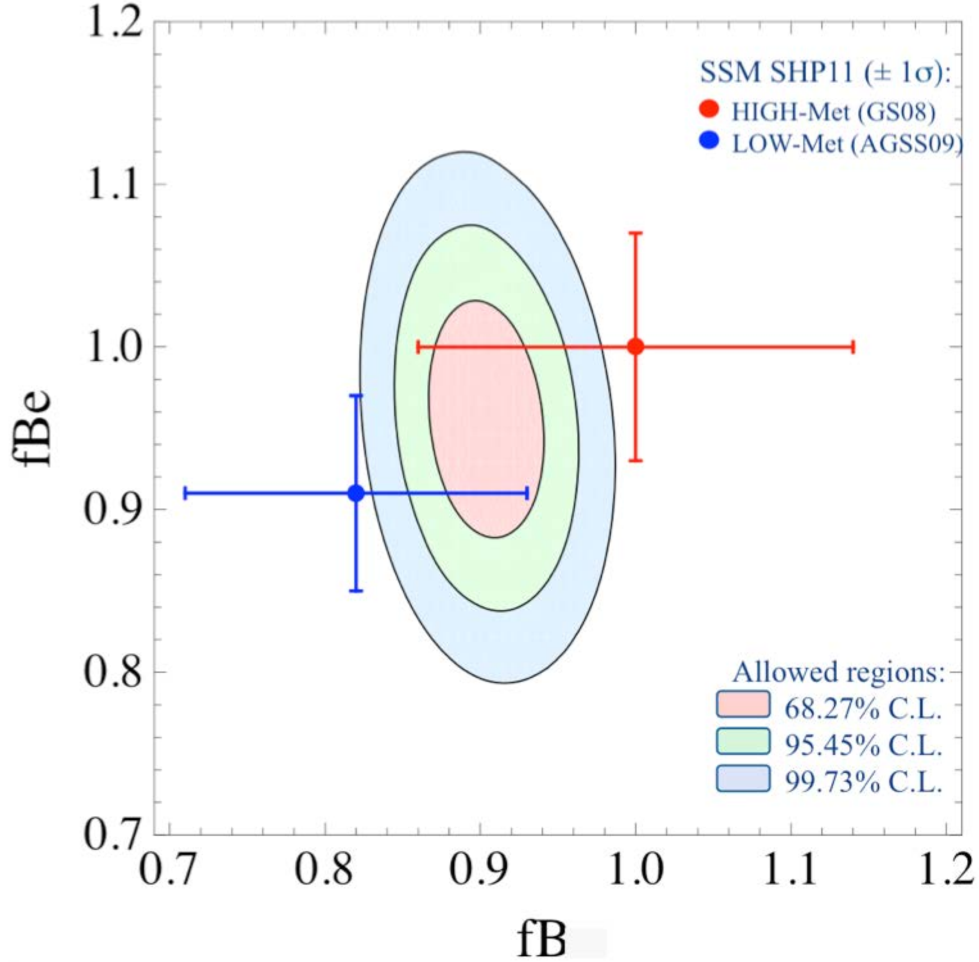
# Solar hep neutrinos

**Expected solar hep neutrino sensitivity at HK and KNO**



# Solar Metallicity

**Measured values of 7Be and 8B neutrino fluxes as a fraction of High-Z SSM prediction with two metallicity expectation**




**Needs 10% accuracy of solar CNO neutrino flux to solve solar metallicity problem**

**Solar heavy element mass fraction (Z/X)**

**- Solar neutrino flux:**

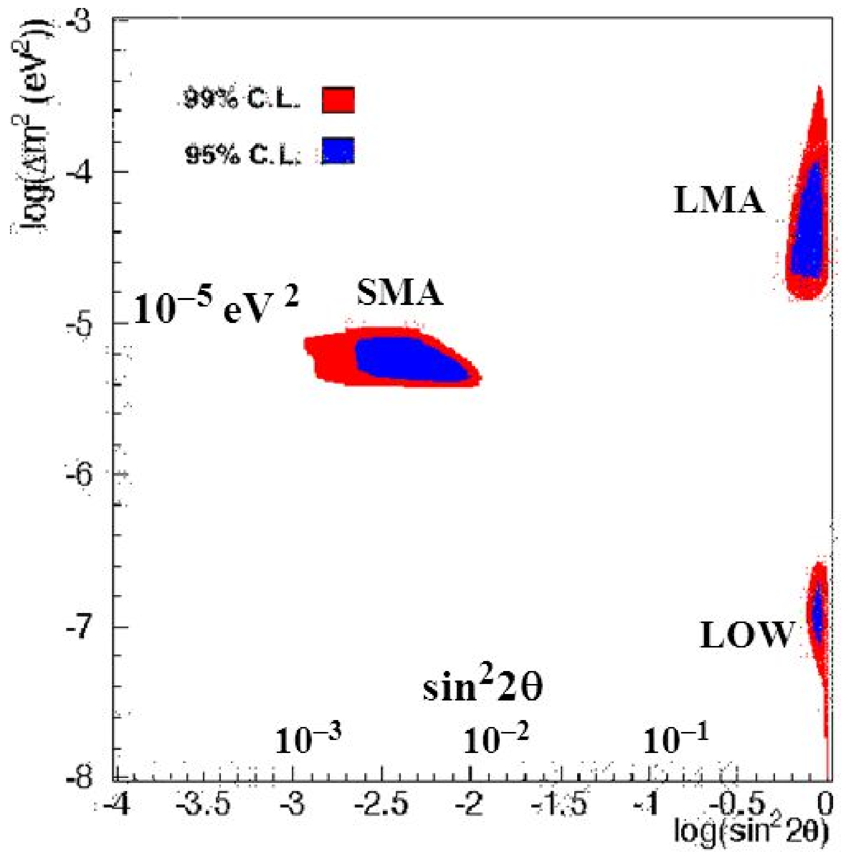
**0.0229 → 0.0165**

**- Discrepancy between SSM and helioseismology results**

**Solve solar metallicity problem by precisely measured 8B neutrino flux**

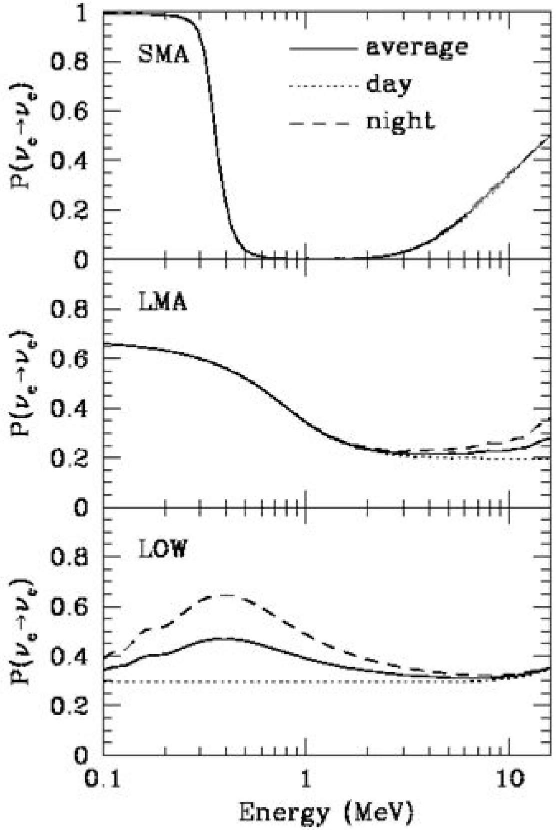
# LMA Solution of MSW Effect

Matter-enhanced solar neutrino oscillations ("MSW solutions")
(using only data available before the end of the year 2000)

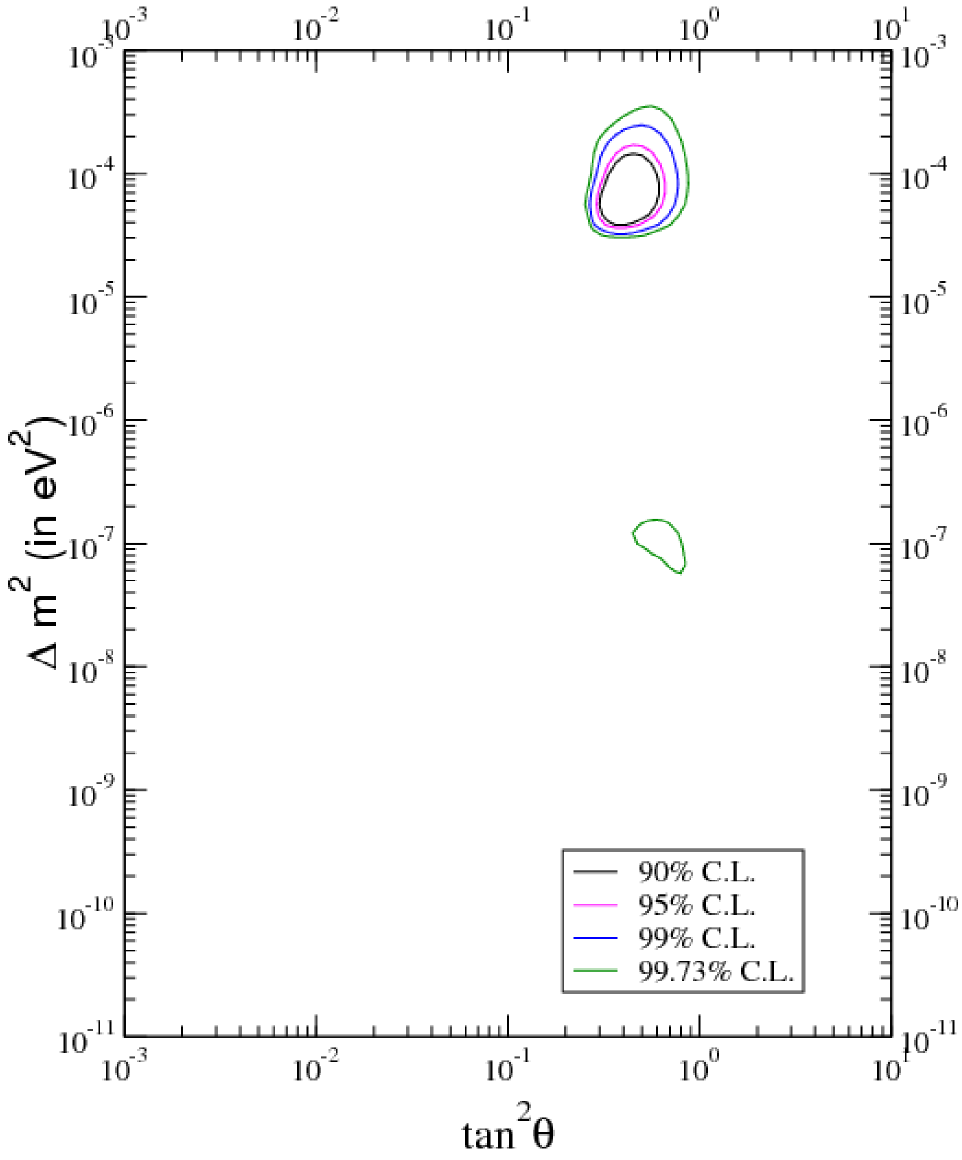


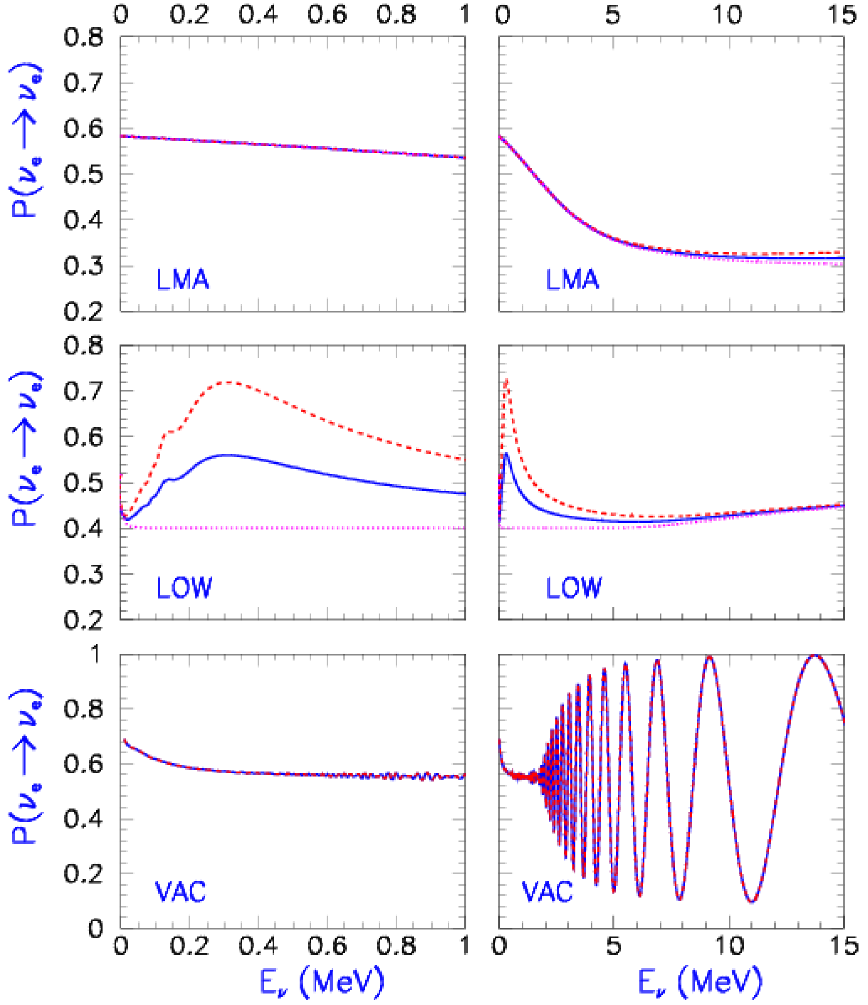

LMA: Large Mixing Angle
SMA: Small Mixing Angle

Survival probability versus neutrino energy



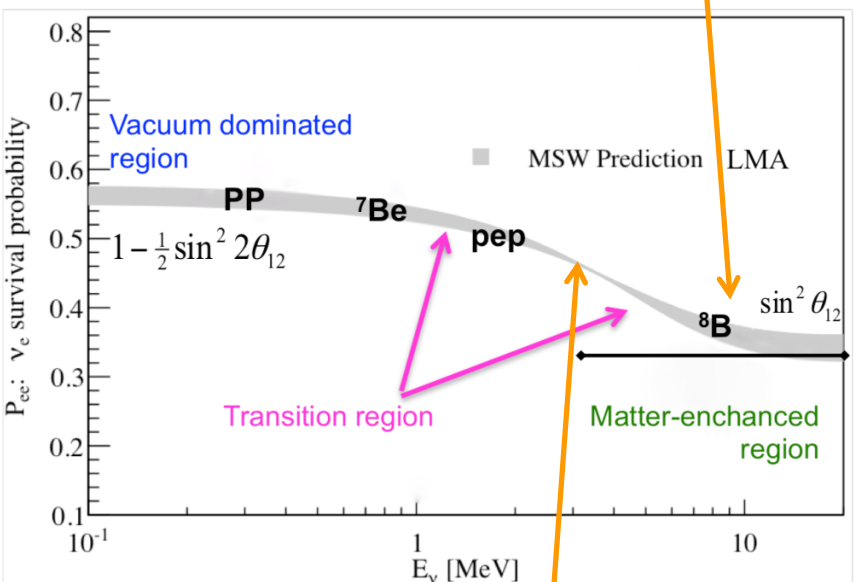
# LMA Solution of MSW Effect

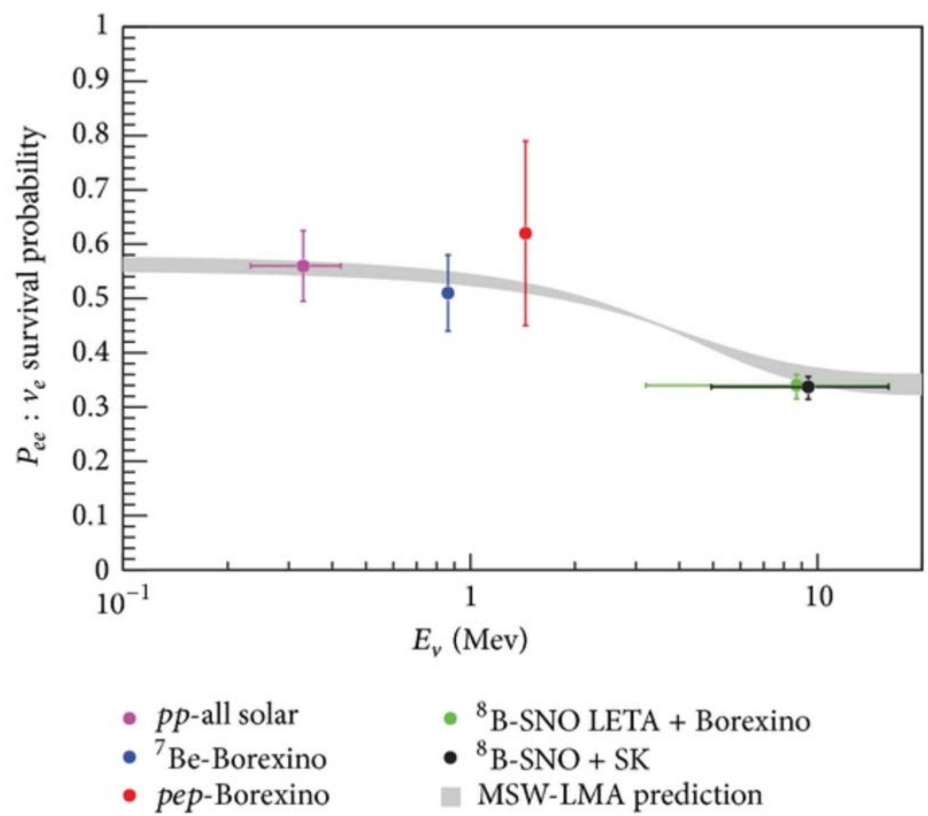


# Vacuum vs. Matter-enhanced Solar Neutrino Oscillation

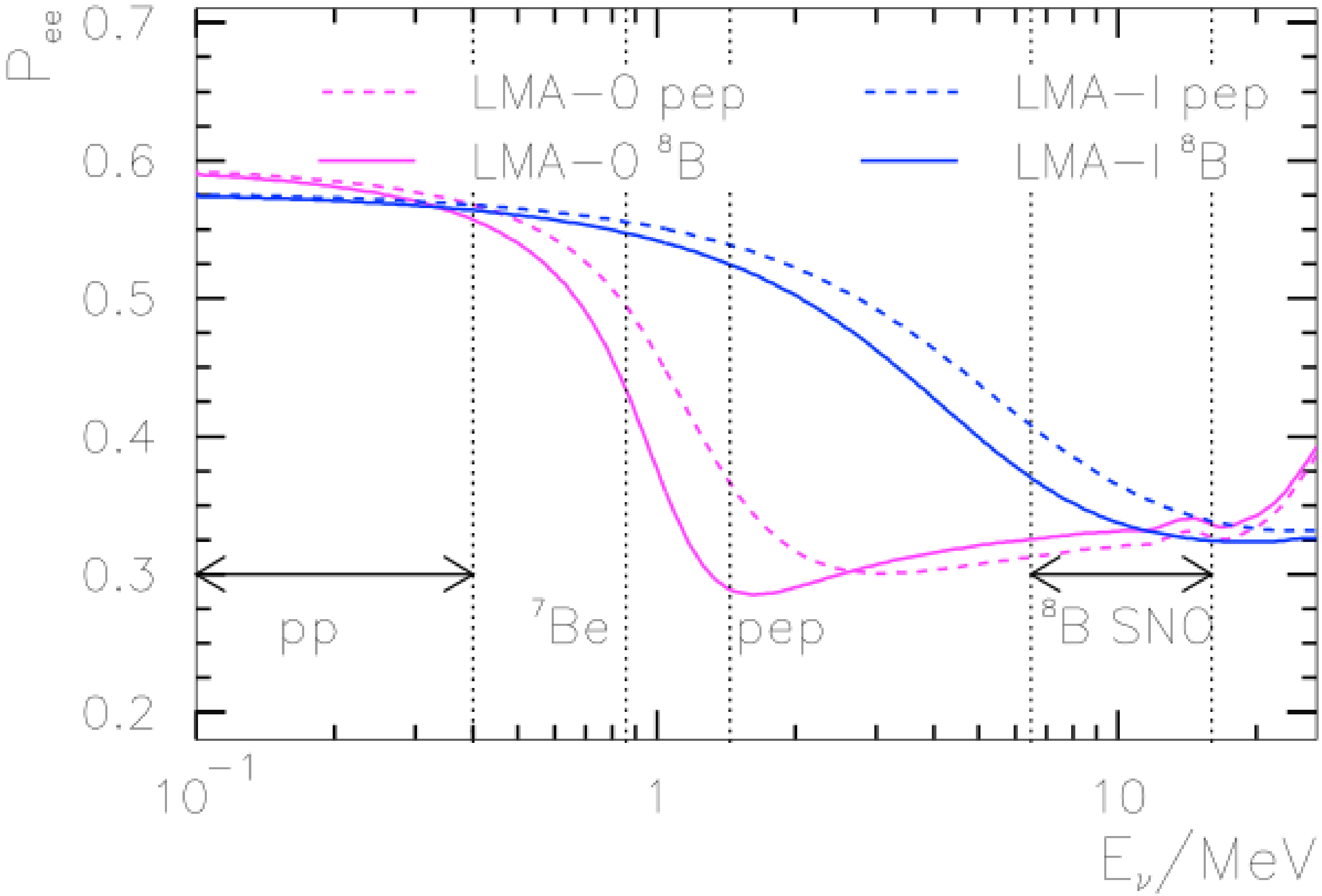
- **Day-night flux asymmetry due to regeneration of solar electron neutrinos through MSW effect in the Earth:**
  - **- SK: observation at 3σ level**
  - **- KNO: conclusive result at 4~5σ level**



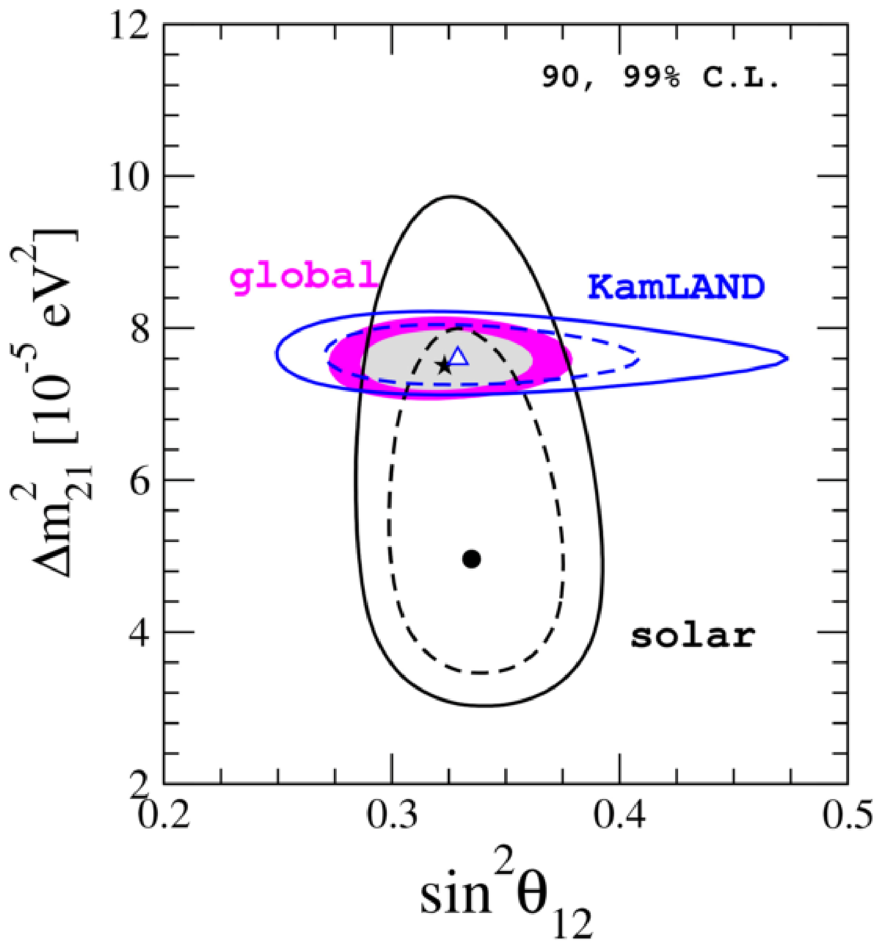

**Upturn sensitivity at KNO: 3~5σ for 10 years**

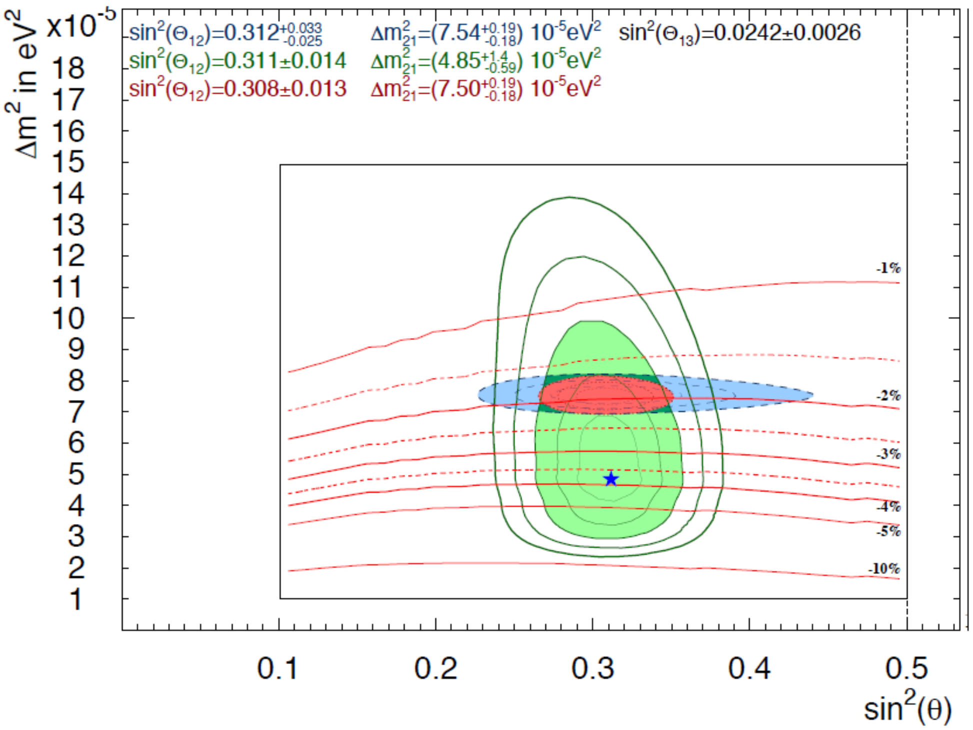
# NSI LMA Solution of MSW Effect



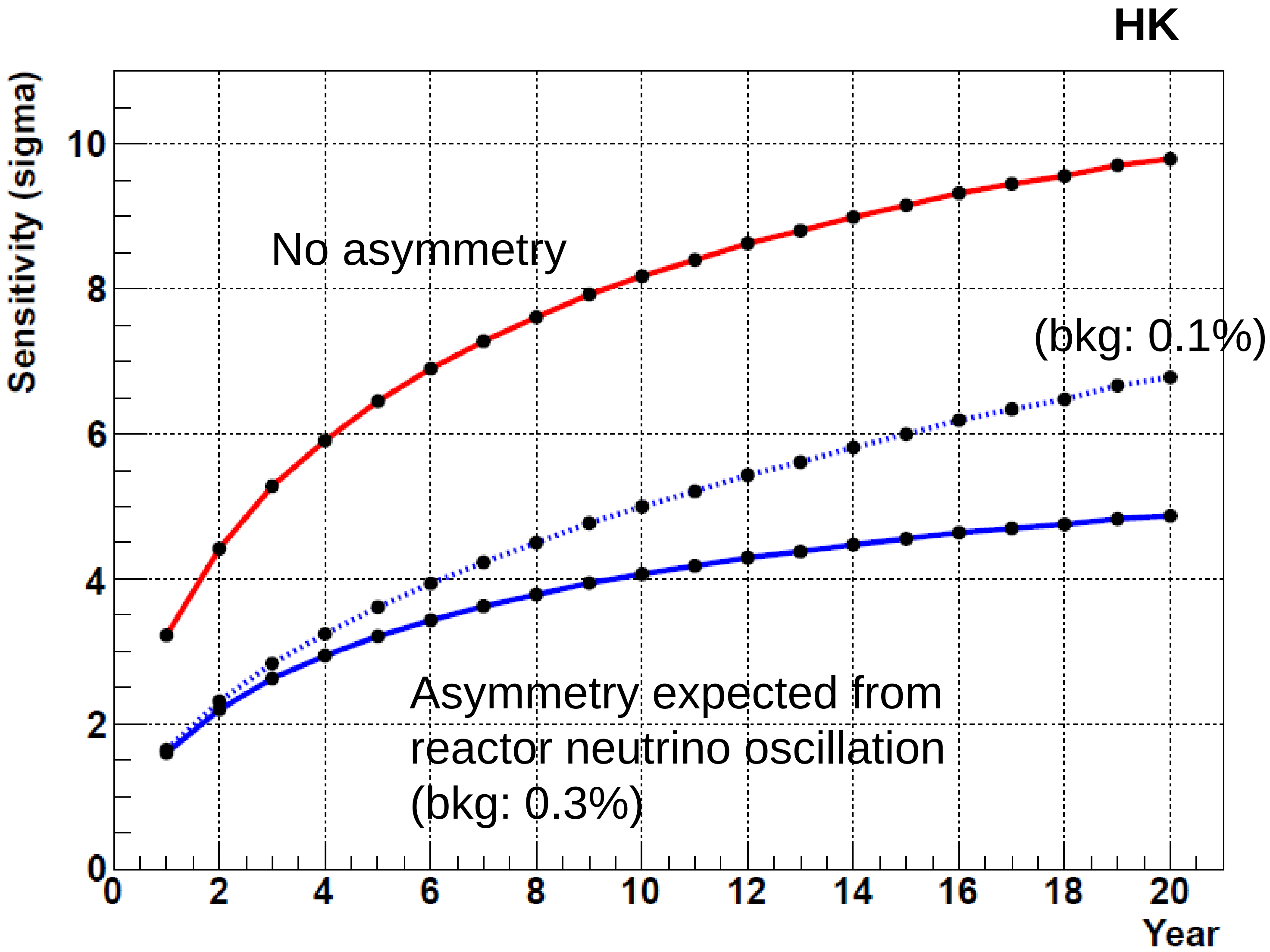
# Precise Solar Oscillation Parameters

- Tension in a measured value of $\Delta m_{21}^2$ between solar neutrino ($\nu_e$) and reactor electron antineutrino experiments → CPT test
- Precision measurement of solar mixing angle $\theta_{21}$ → Unitarity test



# Day-night Asymmetry Sensitivity



# Solar Neutrino Flux Dependence on Core Temperature

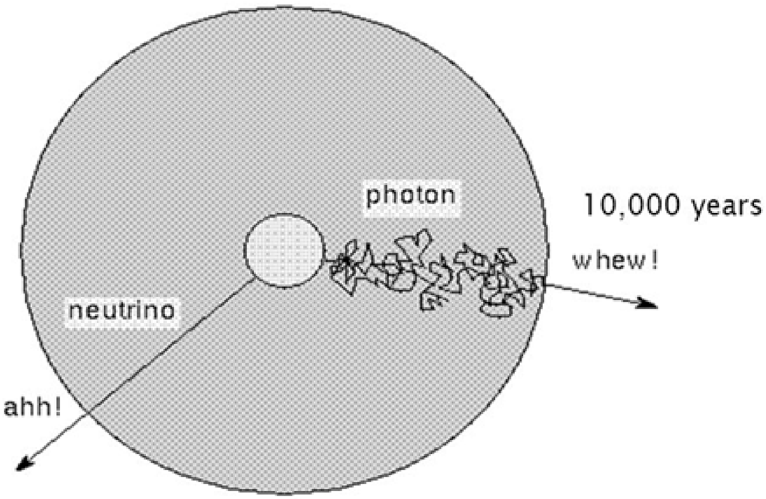
Predicted dependence of the $\nu_e$ fluxes on $T_c$:

From $e^- + Be^7 \rightarrow \nu_e + Li^7$: $\Phi(\nu_e) \propto T_c^{10}$

From $B^8 \rightarrow Be^8 + e^+ + \nu_e$: $\Phi(\nu_e) \propto T_c^{24}$

$\Phi \propto T_c^N$ ⟶ $\Delta\Phi/\Phi = N\,\Delta T_c/T_c$

How precisely do we know the temperature T of the Sun core?

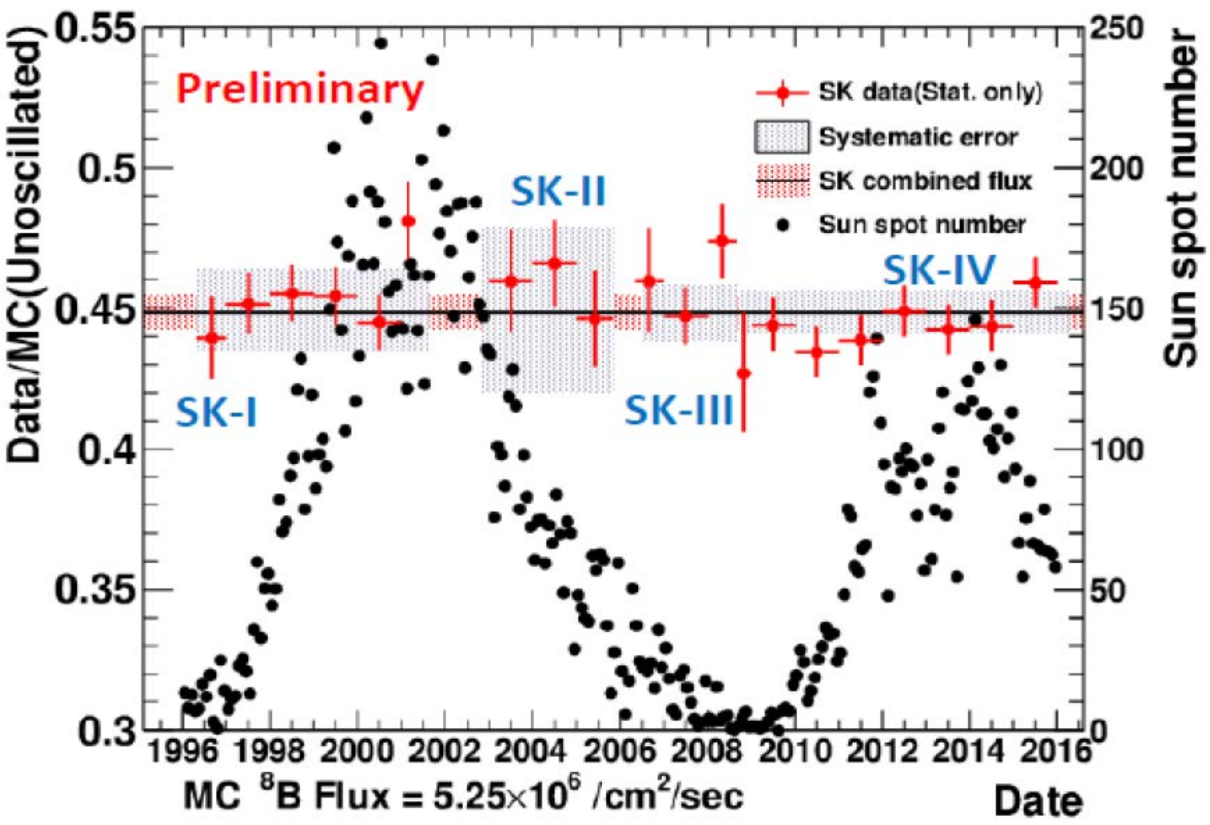



Photons take tortuous paths out of the Sun's interior.
Neutrinos pass right on through in just two seconds.

**Probing solar core temperature with neutrinos that do not interact with the interior of the Sun**

**(in contrast to slow moving photons and solar oscillation wave)**

# Variation of Solar Neutrino Flux



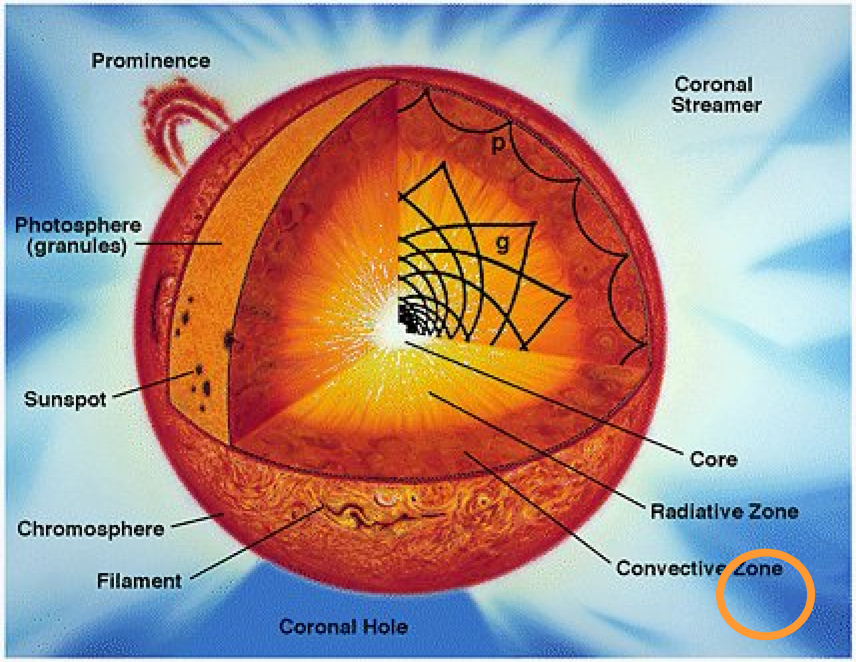

**Davis report on possible anticorrelation of solar neutrino flux against sun spot number of 11-year cycle**

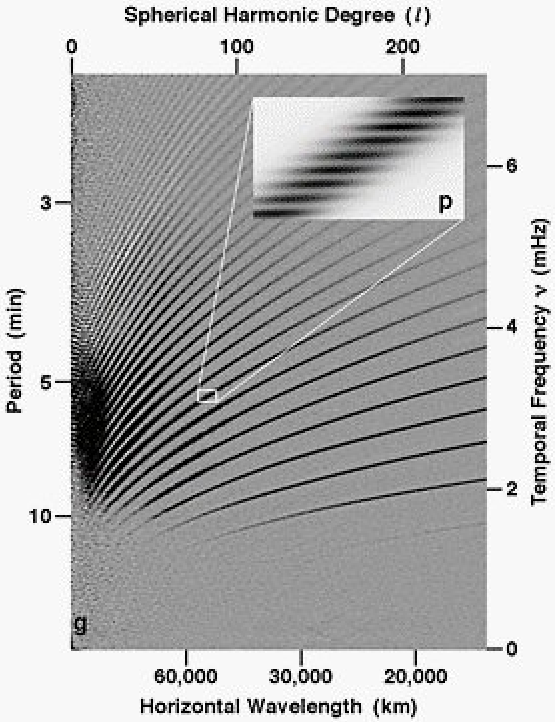
**→ No confirmation**

**A few % variation of B8 solar neutrino flux between day and night due to MSW effect at Super-Kamiokande**

# Variation of B8 Solar Neutrino Flux

**A few hour variation of B8 solar neutrino flux due to g-mode solar oscillation in the interior of the Sun**




**Solar oscillation:**

- **Standing acoustic wave trapped in solar cavity**

*B8 solar neutrino flux could be enhanced by ~170 times.*

*→ may be discovered by KNO*

**g-mode oscillation:**

- **gravitational restoring force**
- **a few hour cycle in the core**

**p-mode oscillation:**

- **pressure in convective layer**
- **~5 min. cycle in solar surface**

# Neutrinos from Solar Flare

**A sudden eruption of power energy accompanied by coronal mass ejection and radio wave emission**

**Solar flares occur in active regions around sunspots, where intense magnetic fields penetrate the photosphere to link the corona to the solar interior.**

**It ejects accelerated particles (electrons, protons and heavy ions) and electromagnetic radiation (radio waves, X-rays and gamma-rays) due to magnetic energy conversion.**

**(can produce $10^{33}$ ergs of energy for tens of minutes and protons with ~10 GeV)**

# Search for Solar Flare Neutrinos

**Observational evidence for pion production due to nuclear reaction of accelerated protons**

**→ prediction of neutrino emission (R. Davis, 1970)**

*- R. Davis, in Proc. 7th Workshop on Grand Unification, Toyama, Japan published by World Scientific, Singapore (1986).*

*- J.N. Bahcall, Phys. Rev. Lett. 61, 2650 (1988).*

**Evidence for pion production during solar flare:**

**- Detection of solar neutrons**

**- Detection of 2,2 MeV gamma-rays from neutron capture on H**

**- Detection of gamma-ray from neutral pion decays**

**Expected number of solar neutrinos by solar flare at KNO: 6~7**

**→ Understanding particle acceleration mechanism by solar flare**

**Thank you for your attention!**