Water Cherenkov detector and Neutrino Physics

✓Neutrino detection
✓Neutrino experiment
- Solar neutrinos
- Supernova neutrinos
- Atmospheric neutrinos

✓Future

Yusuke Koshio
Okayama University

NuSTEC school, 9th Nov., 2015

Happy news

The nobel prize in Physics 2015

T.Kajita and A.McDonald

The Breakthrough Prize in Fundamental Physics 2016

5 experiments (Super-K, SNO, KamLAND, K2K/T2K, Daya Bay)

7 leaders (T.Kajita (SK, atmospheric ν), Y.Suzuki (SK, solar ν), A.McDonald (SNO), A.Suzuki (KamLAND), K.Nishikawa (K2K/T2K), Y.Wang and Kam-Biu Luk (Daya Bay))

Neutrino detection

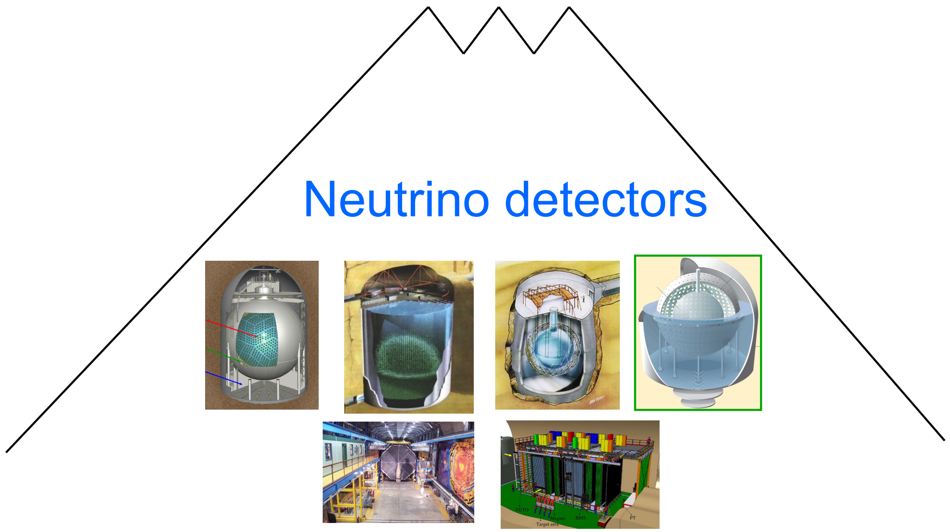
Neutrino experiment

Large size of detector is required, because of very small cross section

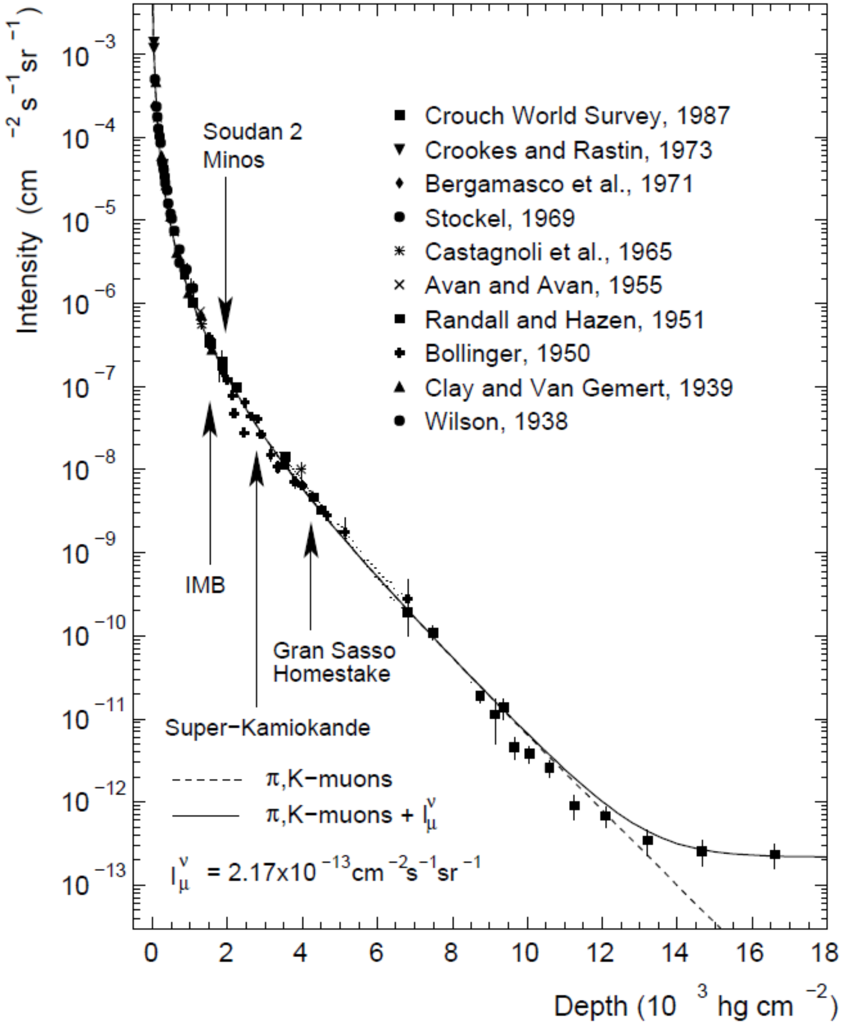
$$\sigma = \frac{G_F^2 s}{\pi}$$

$\sim(E_\nu[\text{GeV}])\text{x}10^{-41}\text{cm}^2$

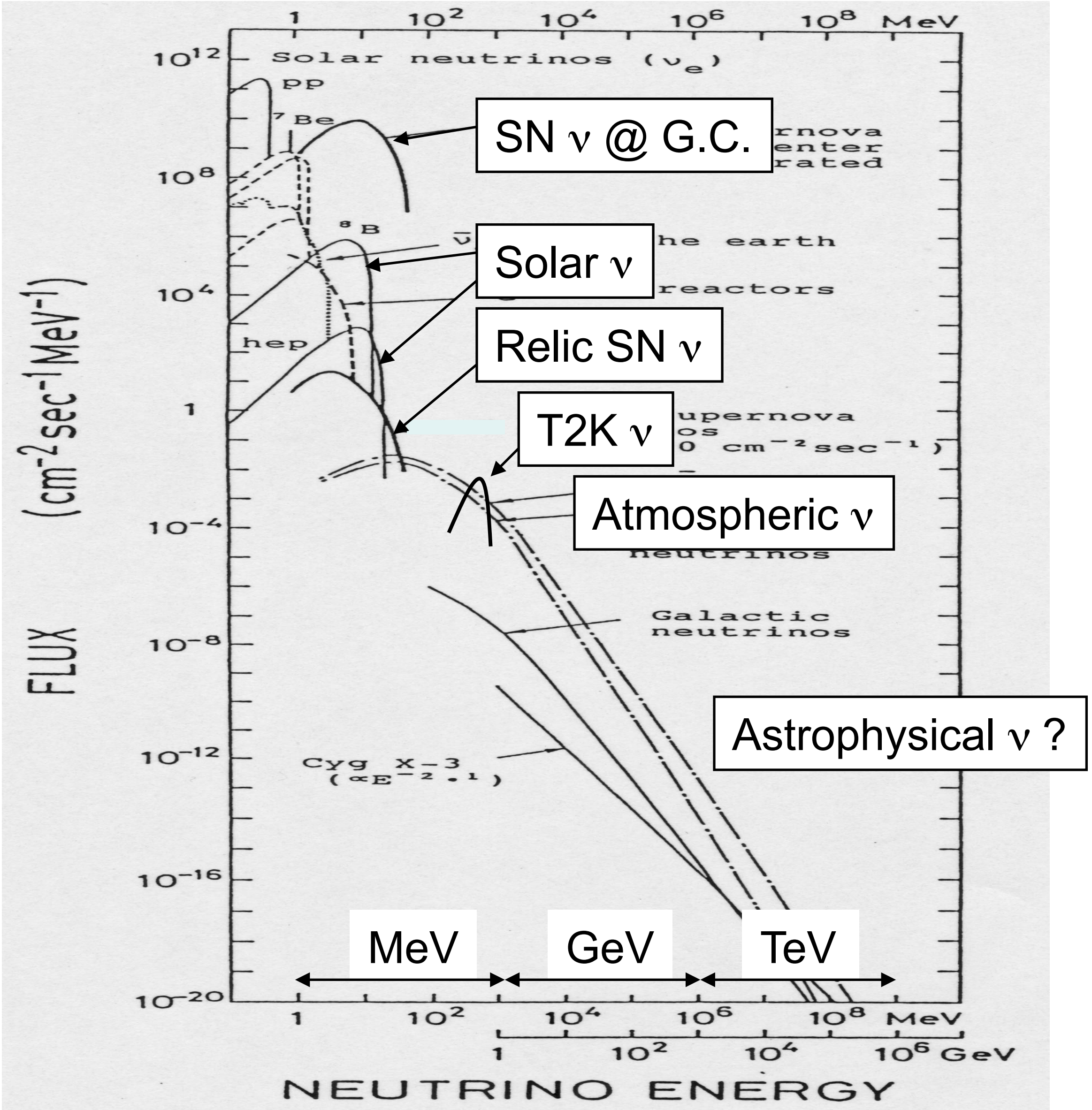
quite small cross section,
e.g. a neutrino with 10MeV interacts after transverse $3\text{x}10^{21}$ cm in the water.
(ref. 1 light year ~ $9.5\text{x}10^{17}$ cm)



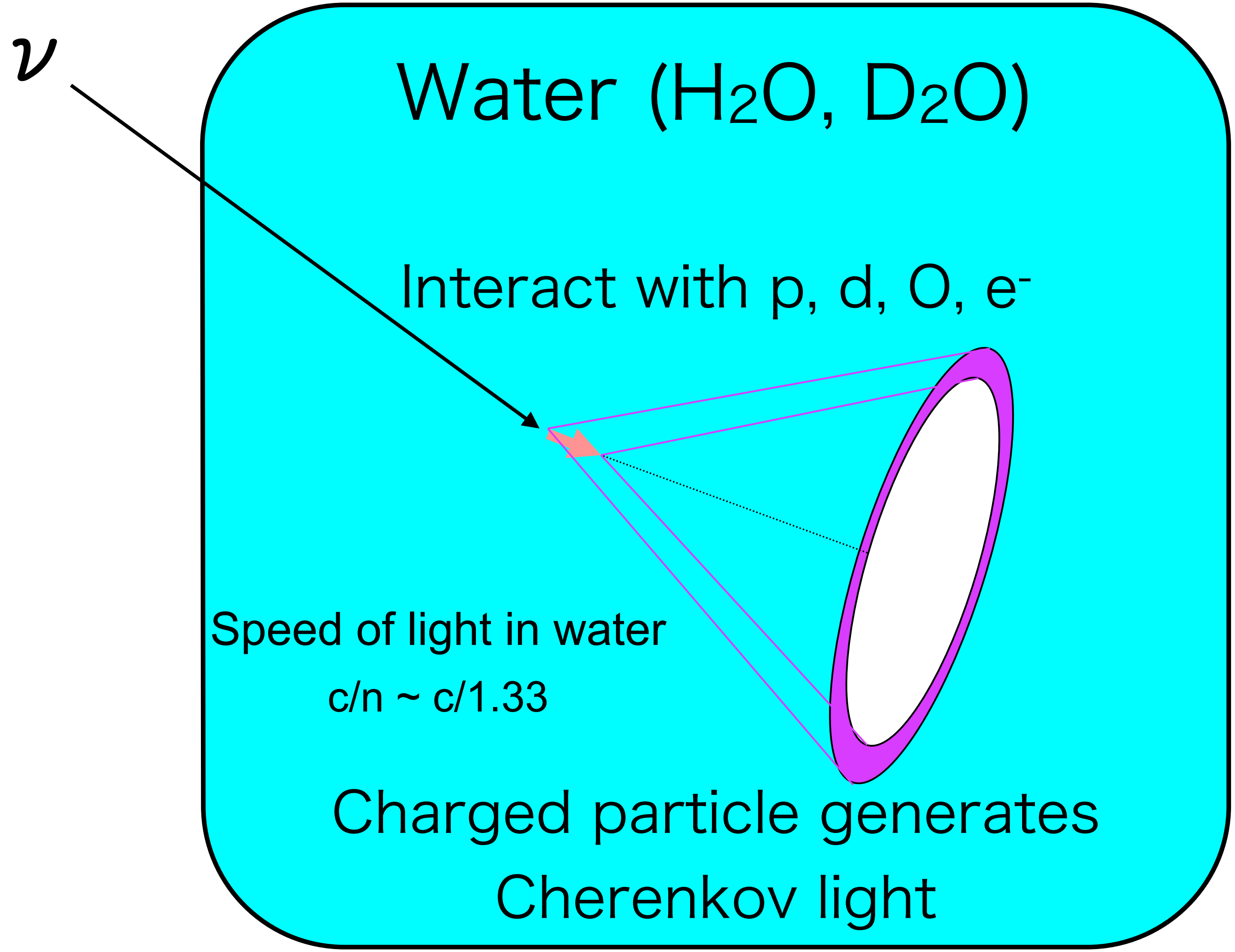
Deep underground in order to remove cosmic ray.



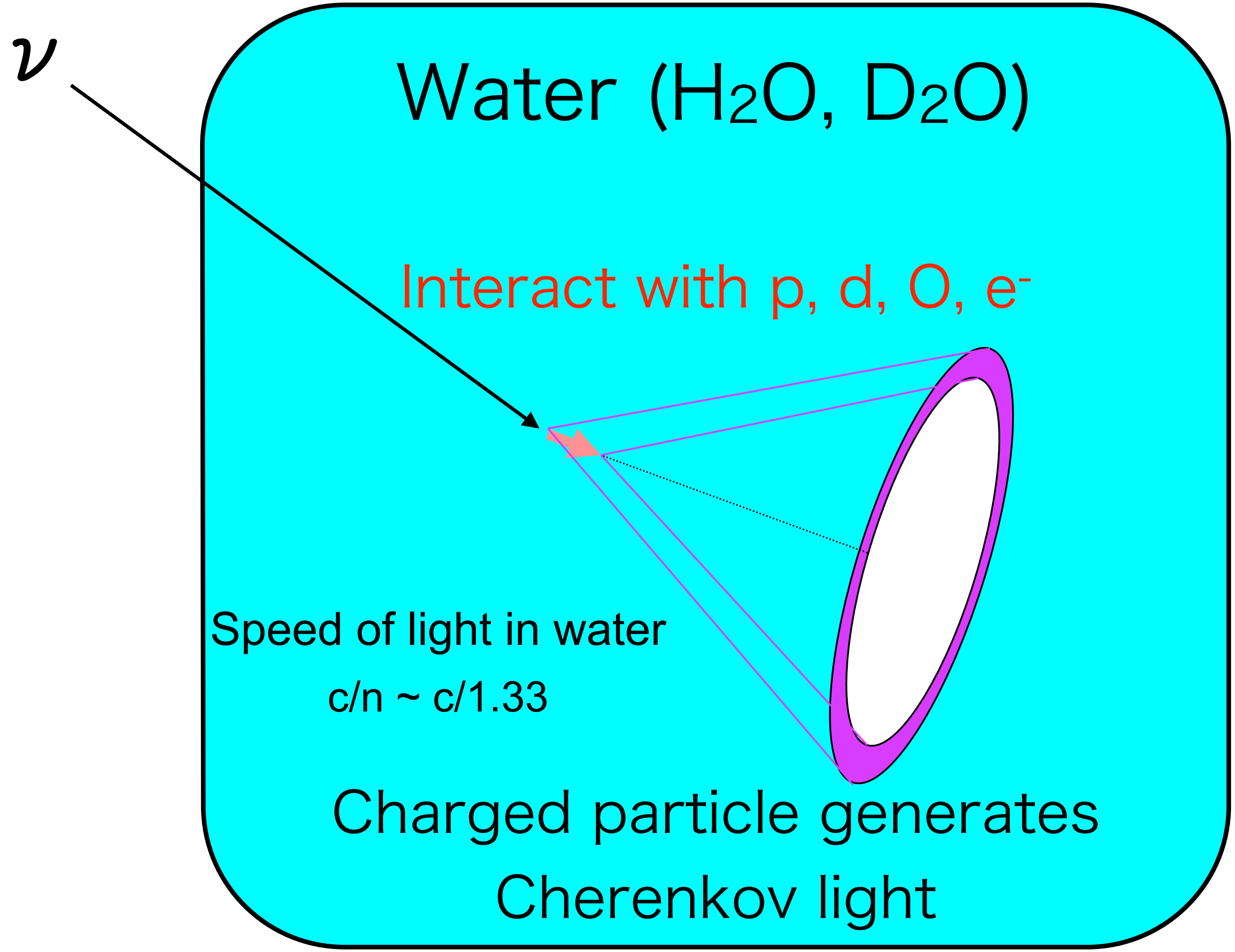
Neutrino spectrum



Water Cherenkov detector



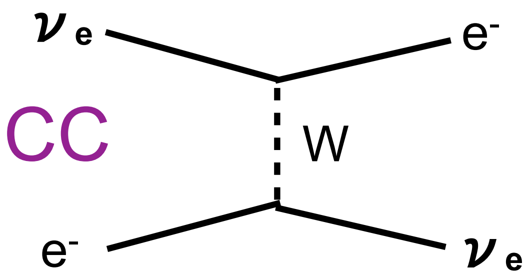
Water Cherenkov detector



Interaction with electron

$$\boxed{\nu + e^- \rightarrow \nu + e^-}$$

(Both Charged Current and Neutral Current interaction)



$$\sigma = \frac{G_F^2 s}{\pi}$$

$\sim(E_\nu[\mathrm{GeV}])\times 10^{-41}\mathrm{cm}^2$

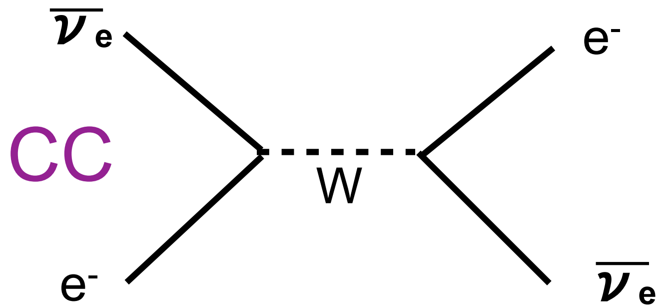
quite small cross section,
e.g. a neutrino with 10MeV interacts after transverse 3×10^{21} cm in the water.
(ref. 1 light year ~ 9.5×10^{17} cm)

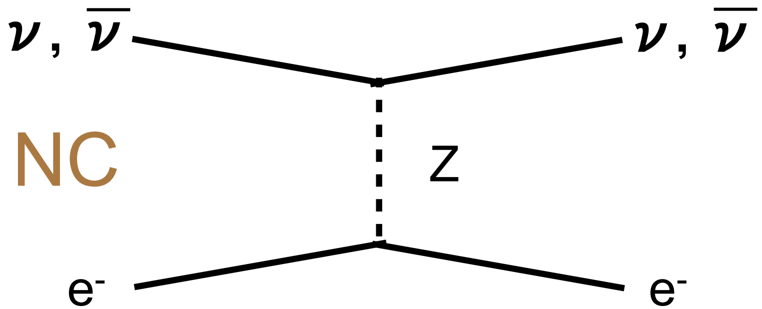
✓ All neutrinos are sensitive

✓ The cross section for ν_e is larger than others because of CC effect.

✓ Well known cross section.

✓ Good directionality
- useful for Solar/SN neutrino



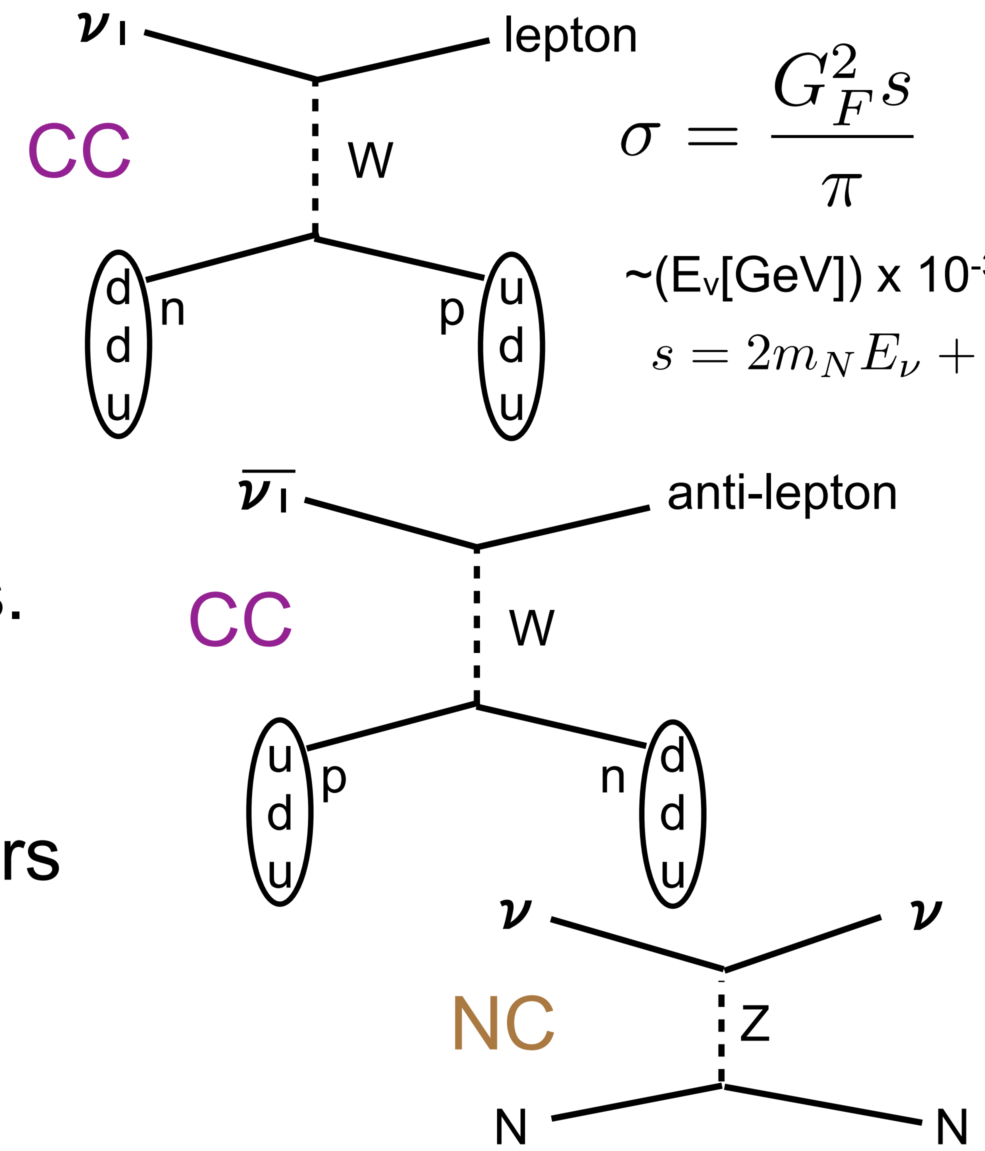


Interaction with nucleon

$$\nu + N \rightarrow l + N'$$
$$\rightarrow \nu + N$$

(Both Charged Current and Neutral Current interaction)

✓ Actually, nucleons are strongly binding in nucleus.
✓ Only free nucleon, such as proton in H_2O, CH, deuteron in D_2O, etc, occurs
✓ Consider nuclear effect for these interaction.



$$\sigma = \frac{G_F^2 s}{\pi}$$

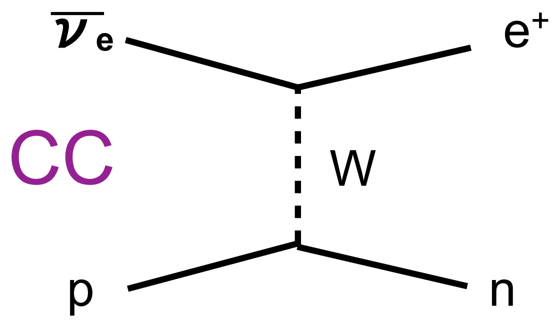
~(E_ν[GeV]) x 10^{-38}cm^2

$$s = 2m_N E_\nu + m_N^2$$

Inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

(Charged Current interaction)



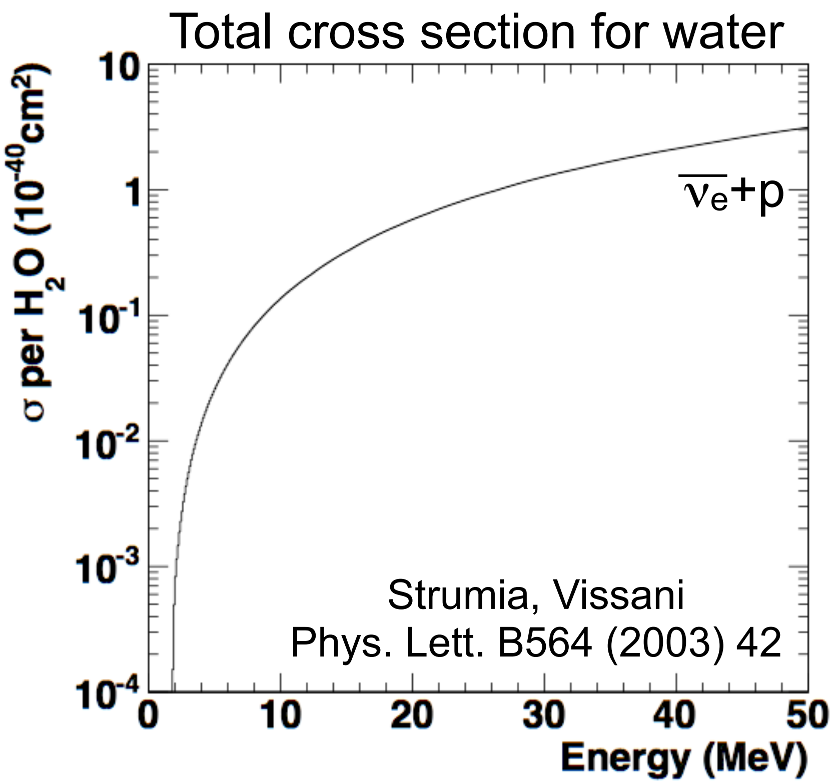
✓ Dominates for detectors with lots of free proton

- Detect positron signal in water, scintillator, etc.

✓ Well known cross section

✓ Good energy resolution

- $E_e \sim E_\nu - (m_n - m_p)$

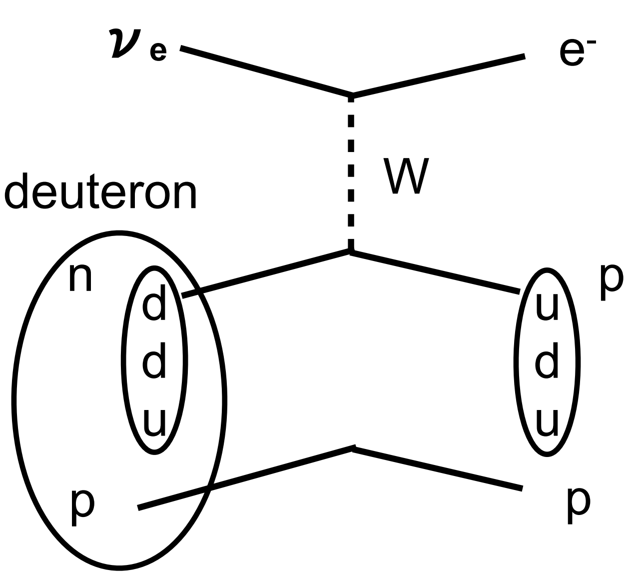


Interaction with deuteron

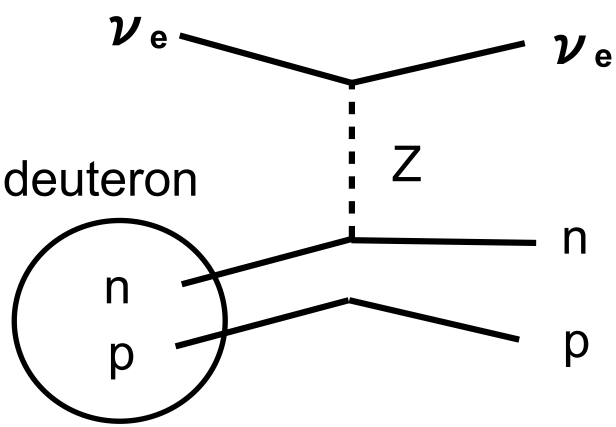
Deuteron is a nucleus which consists on proton and neutron

Both Charged Current and Neutral Current interaction occur.

CC



NC



- ✓ ν_e only
- ✓ Gives ν_e energy spectrum well
- ✓ Weak direction sensitive

- ✓ Equal cross section for all ν type
- ✓ this diagram is resulting in neutron since it is detectable in SNO

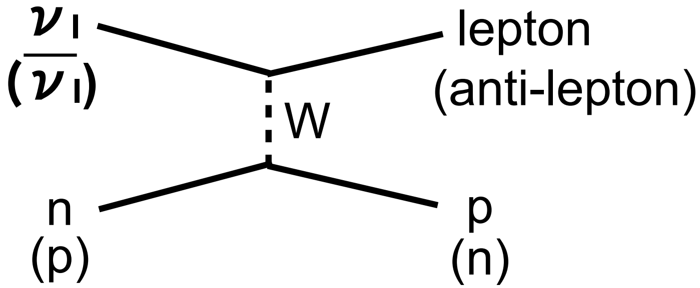
Important for SNO experiment

Interaction with nucleus

Atmospheric, accelerator neutrinos (E_ν > 100MeV)

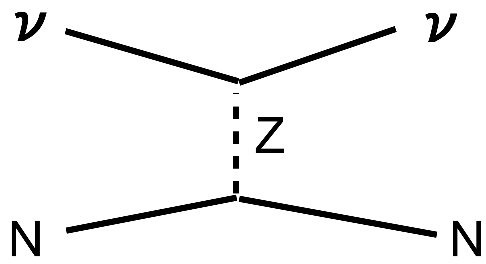
✓Charged Current Quasi-Elastic scattering

$\nu + N \rightarrow l^- + N'$



✓Neutral Current elastic scattering

$\nu + N \rightarrow \nu + N$

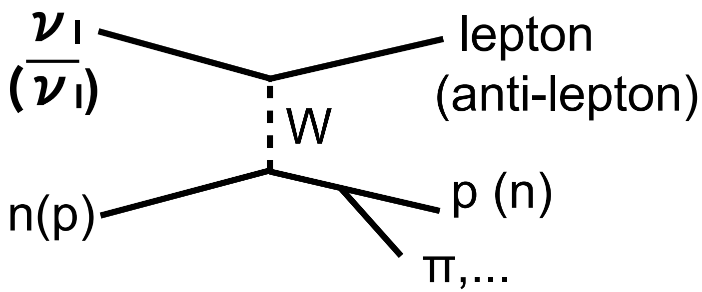


✓Charged Current single meson production

$\nu + N \rightarrow l^- + N' + \pi\,(\eta, K, ..)$

✓Charged Current deep inelastic scattering

$\nu + N \rightarrow l^- + N' + m\pi\,(\eta, K, ..)$

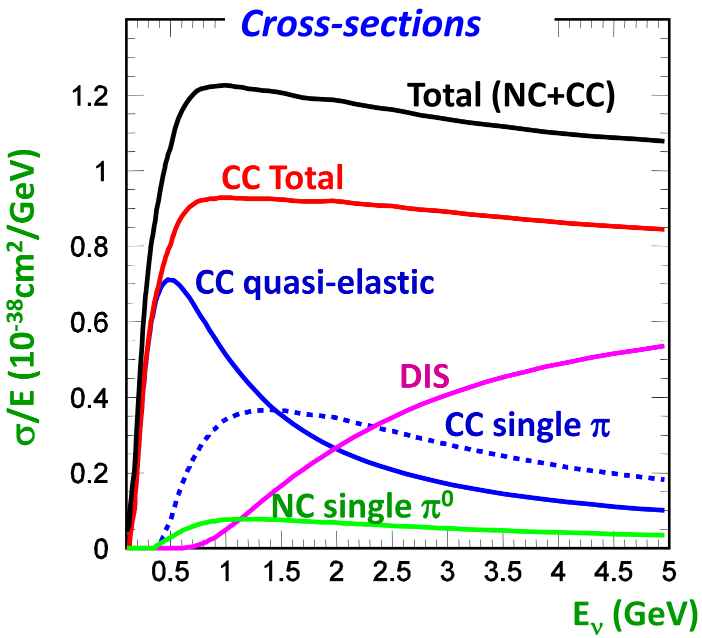


Interaction with nucleus

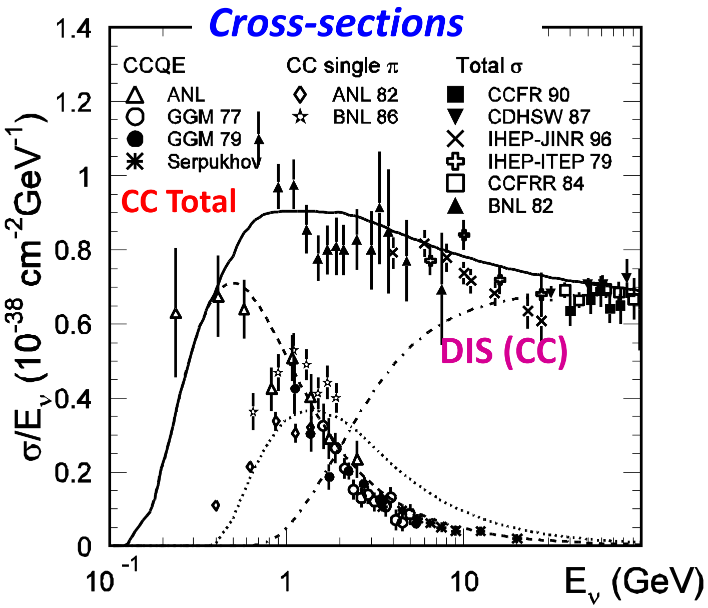
Atmospheric, accelerator neutrinos (E_ν > 100MeV)

✓Charged Current Quasi-Elastic scattering
✓Neutral Current elastic scattering
✓Charged Current single meson production
✓Charged Current deep inelastic scattering

Simulation code



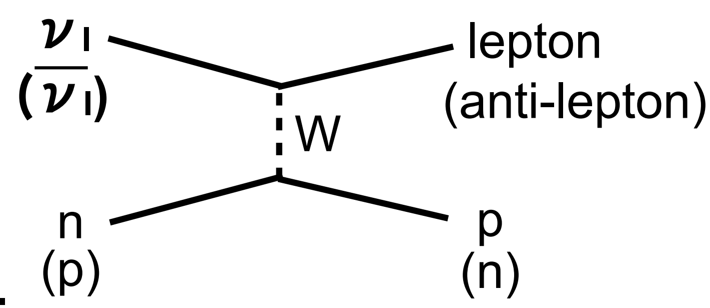
Measurements



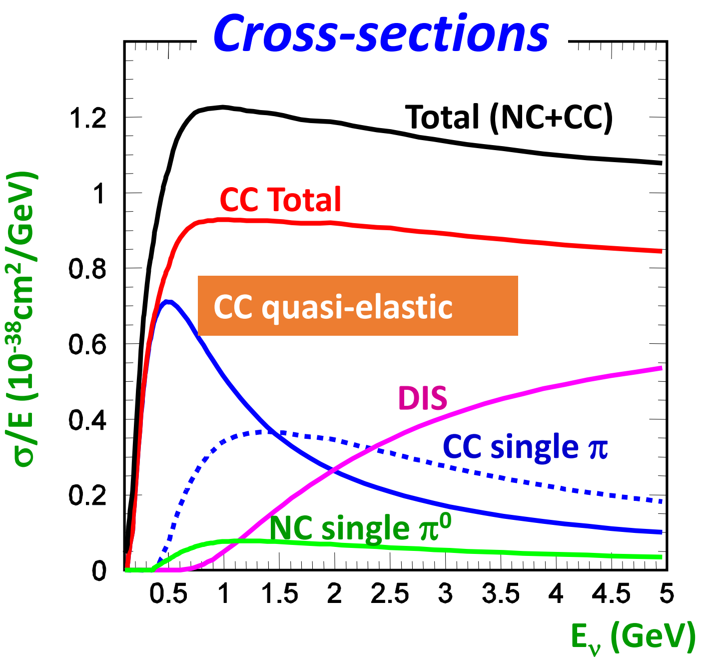
Interaction with nucleus

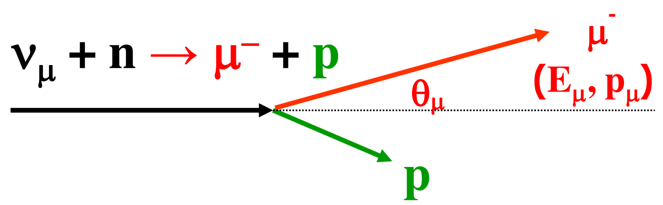
Atmospheric, accelerator neutrinos (E_ν > 100MeV)

✓ Charged Current Quasi-Elastic scattering



- Dominant interaction around a few 100 MeV.
- Two bodies decay → Possible to reconstruct the neutrino energy from the kinematics of charged lepton.





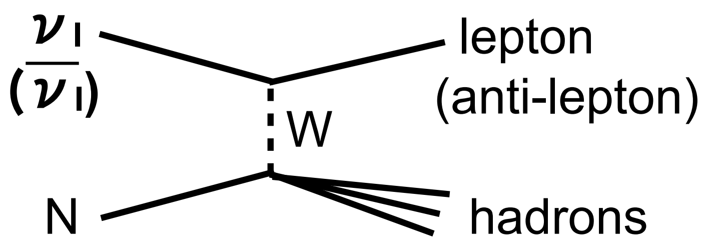
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

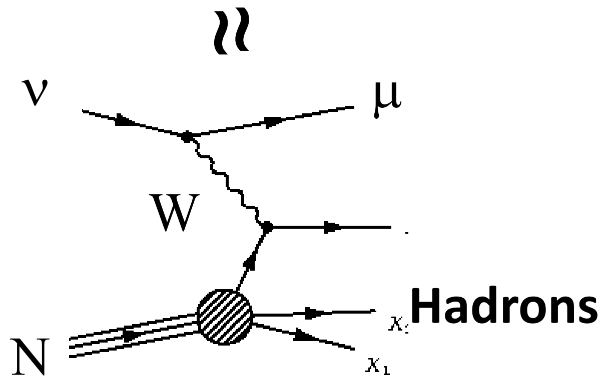
(In the case of rest nucleon)

Interaction with nucleus

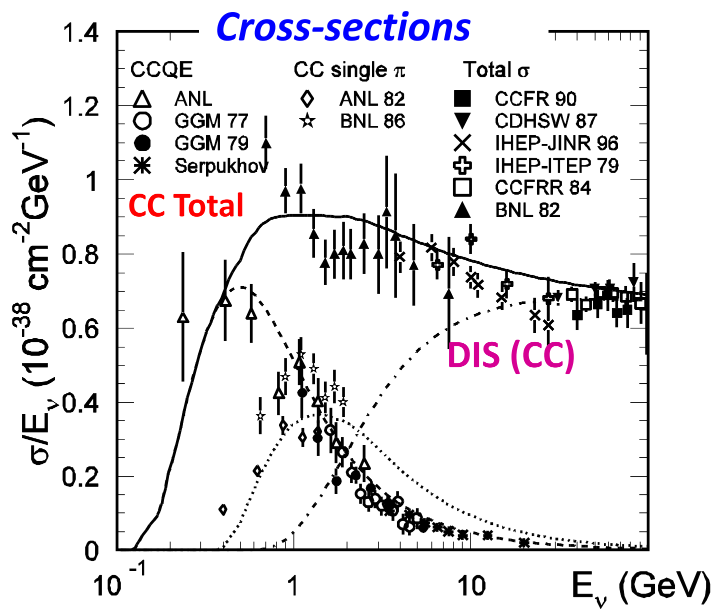
Atmospheric, accelerator neutrinos (E_ν > 100MeV)

✓Charged Current deep inelastic scattering





- Dominant interaction around a few 10 GeV.
- Scattering off quark.
- Cross section is comparably precise obtained.

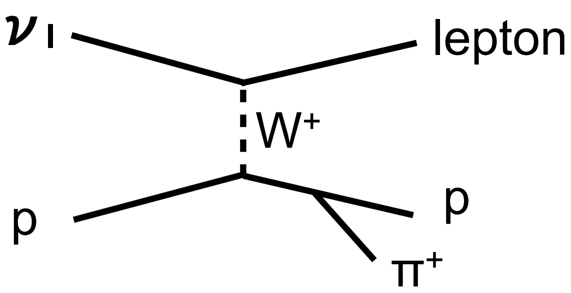


Interaction with nucleus

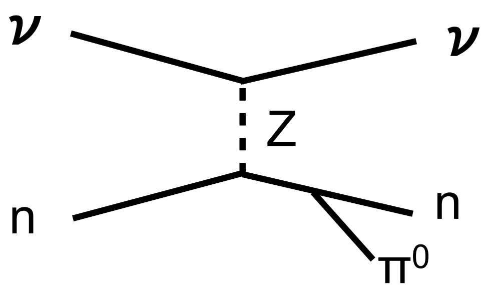
Atmospheric, accelerator neutrinos ($E_\nu > 100$MeV)

✓Single pion production

Charged Current

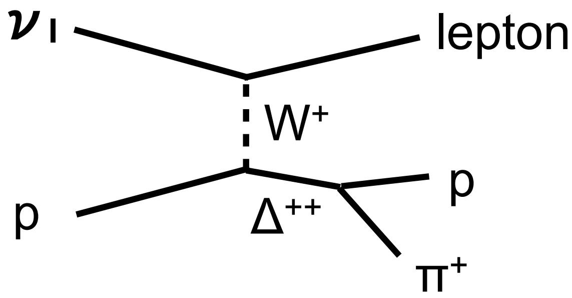


Neutral Current

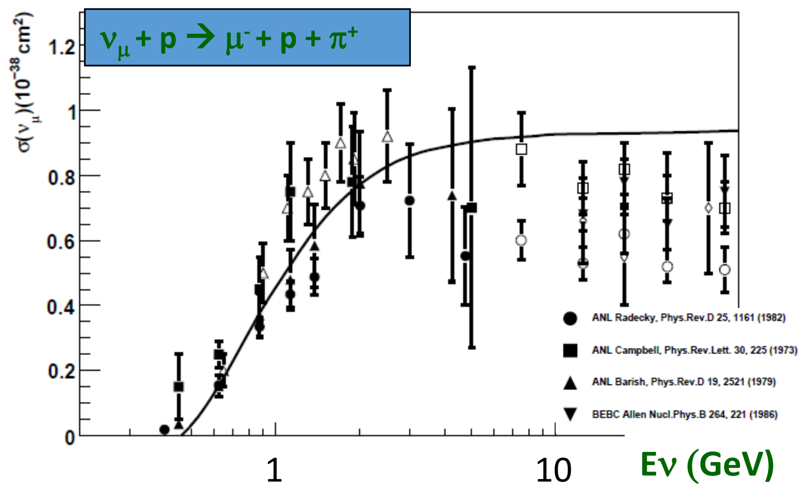


Second dominant interaction
Sometimes B.G. for others if miss pion

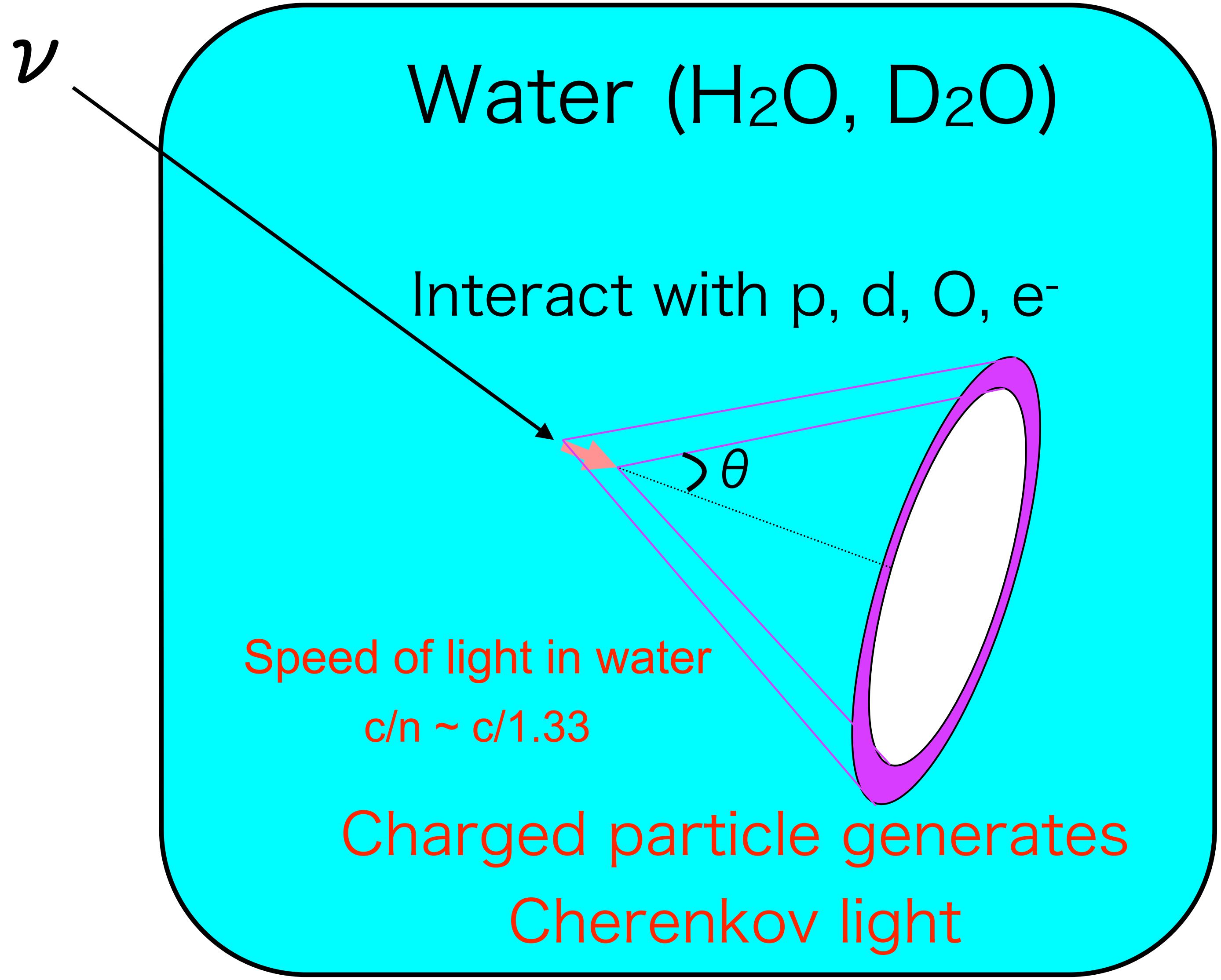
✓Single meson production via resonances



Possible to calculate the cross section for known nucleon resonance including the coherence



Water Cherenkov detector



Water Cherenkov detector

Cherenkov angle

$$\cos\theta = \frac{1}{n\beta},$$

How much is the angle in the case of n=1.33, β~1?

Cherenkov spectrum

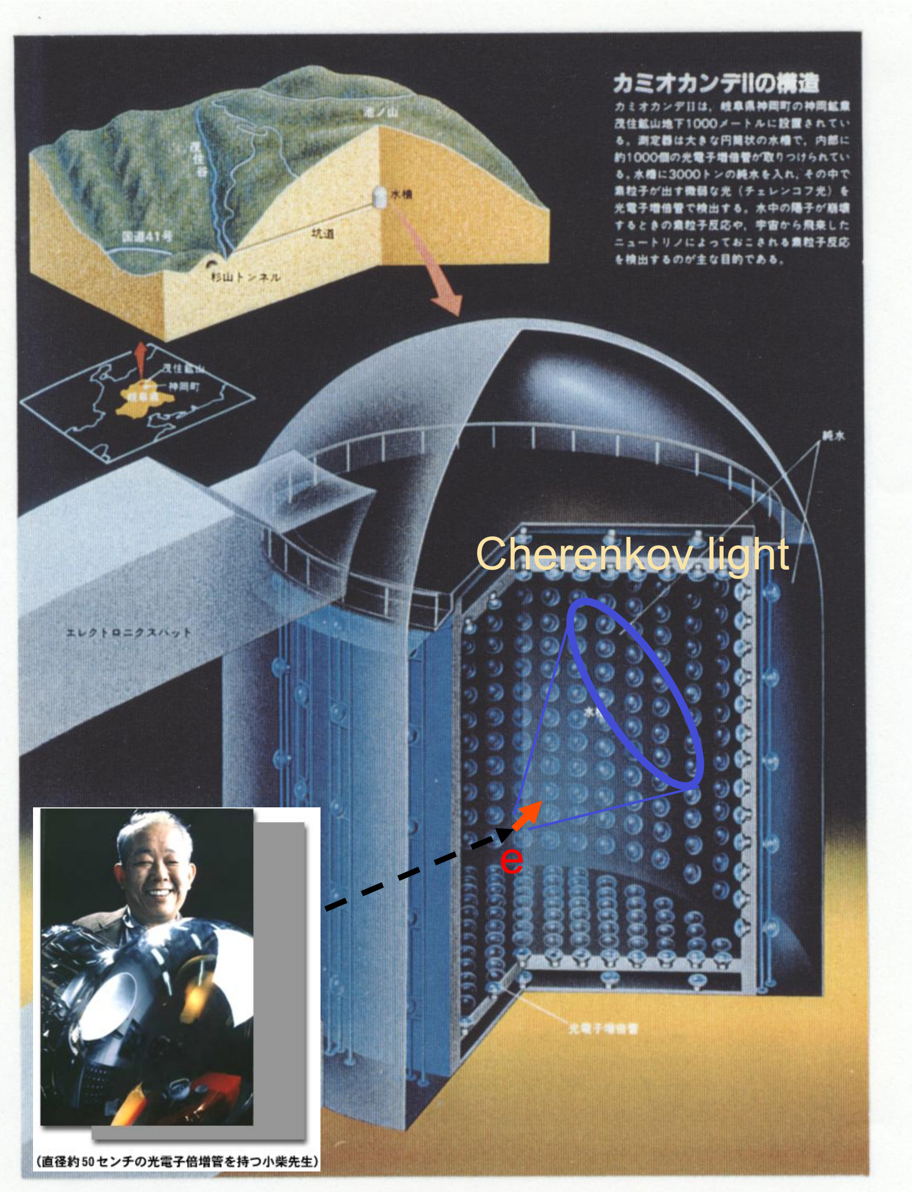
$$\frac{dN}{d\lambda} = \frac{2\pi\alpha x}{c}\left(1 - \frac{1}{n^2\beta^2}\right)\frac{1}{\lambda^2},$$

PMT sensitive region

How many photons are emitted per 1cm in the wave length (300~600nm)?

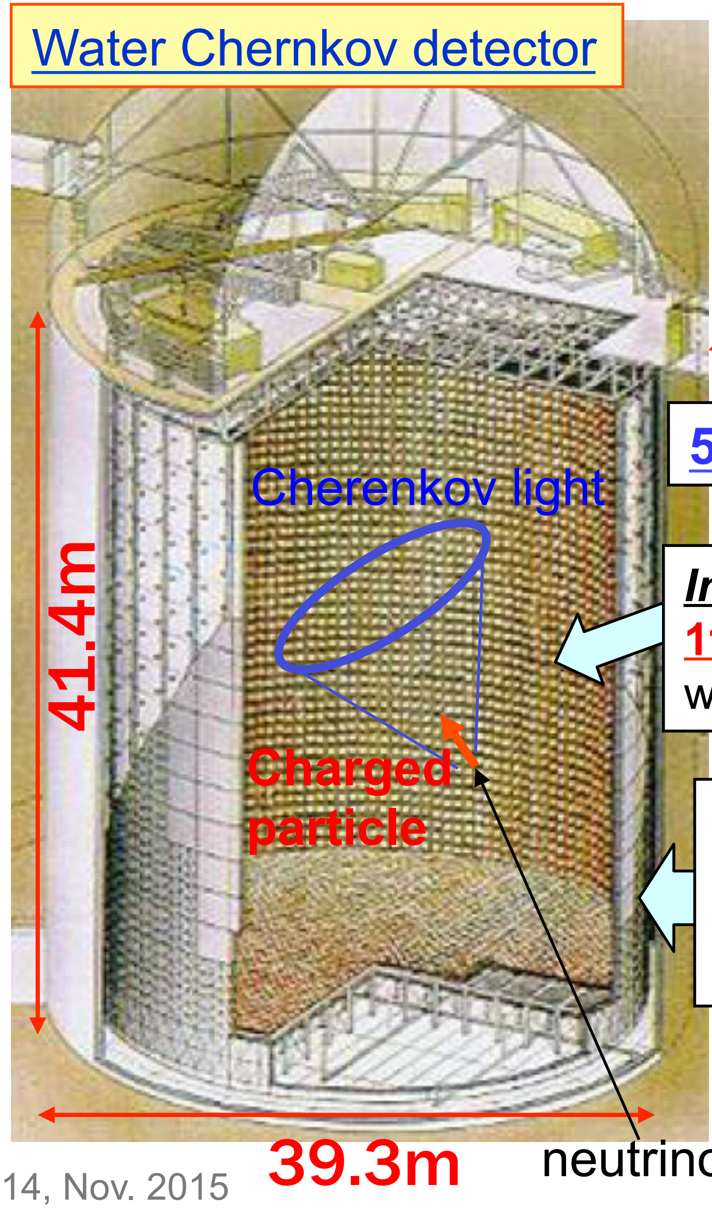
How many photons are detected for 10MeV electrons in the PMTs?
Assuming 2MeV/cm, 20m diameter detector, water transparency 100m,
photo coverage 40%

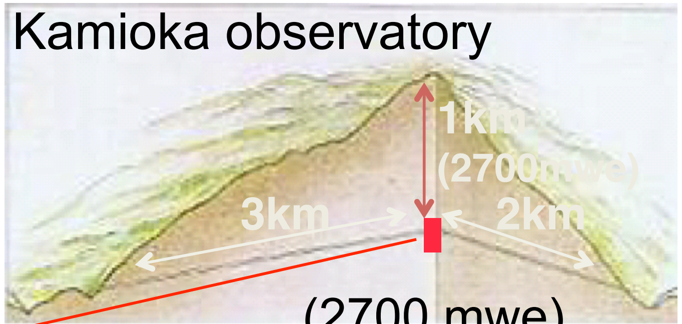
Kamiokande (1983~1996)



Kamioka mine, Japan, 1000m underground (2700m.w.e.), 3000 tons of water tank, with 1000 of 20' PMT

Super-Kamiokande (1996~)





(2700 mwe)

50,000 tons of pure water

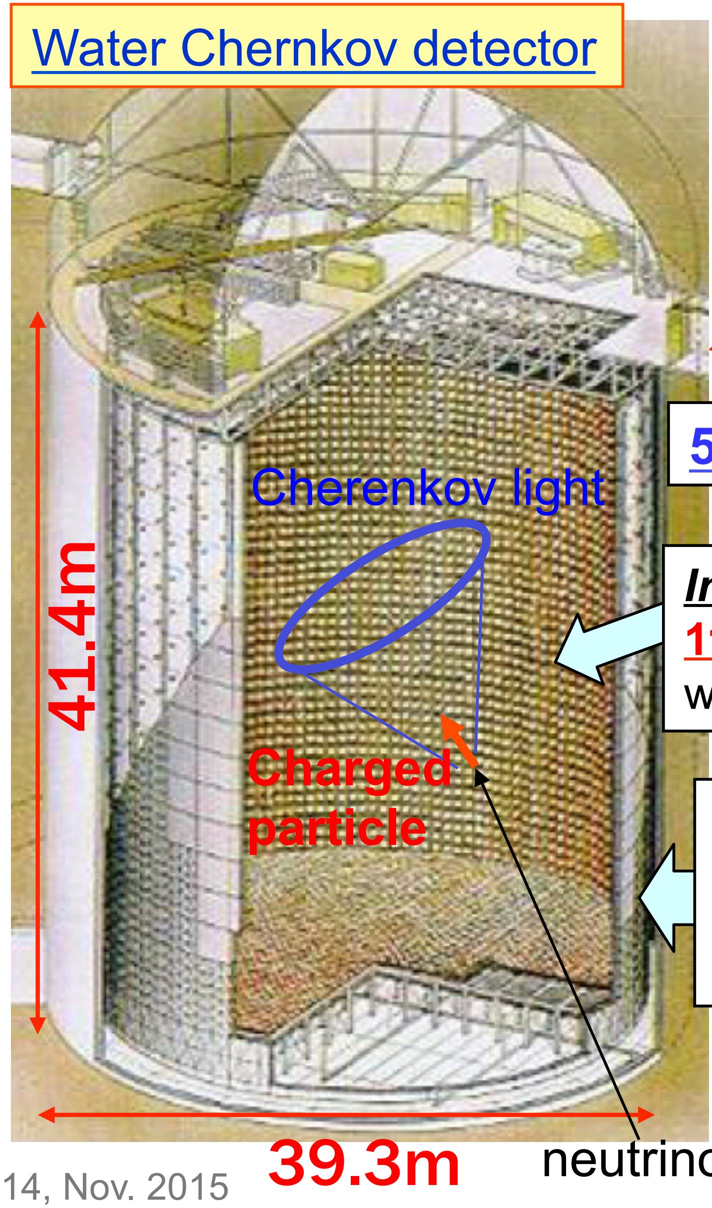
Inner detector:
11129 of 20" PMT
with acrylic cover

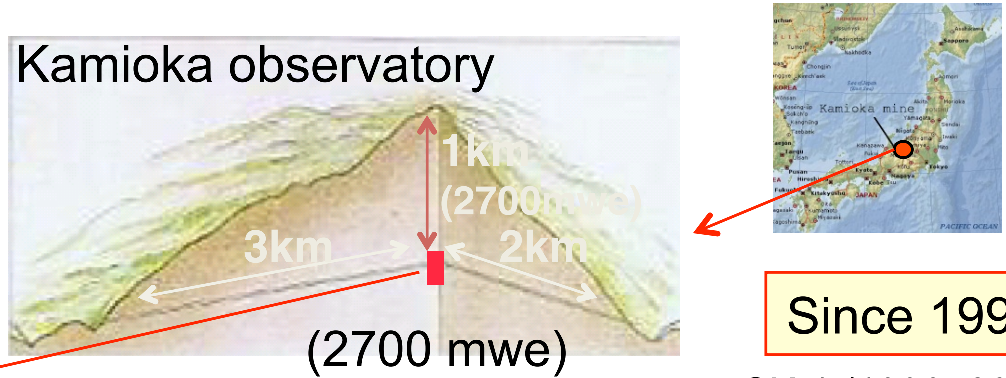
Outer detector:
1885 of 8" PMT
remove cosmic ray μ
γ and n shield from rock

Since 1996

SK-1 (1996~2001)
SK-2 (2002~2005)
SK-3 (2006~2008)
SK-4 (2008~present)

Super-Kamiokande (1996~)





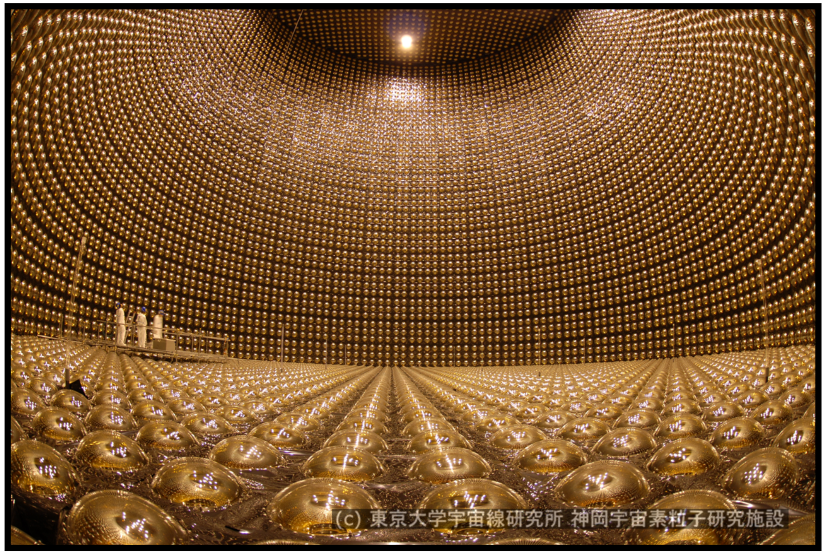
50,000 tons of pure water

Inner detector:
11129 of 20” PMT
with acrylic cover

Outer detector:
1885 of 8” PMT
remove cosmic ray μ
γ and n shield from rock

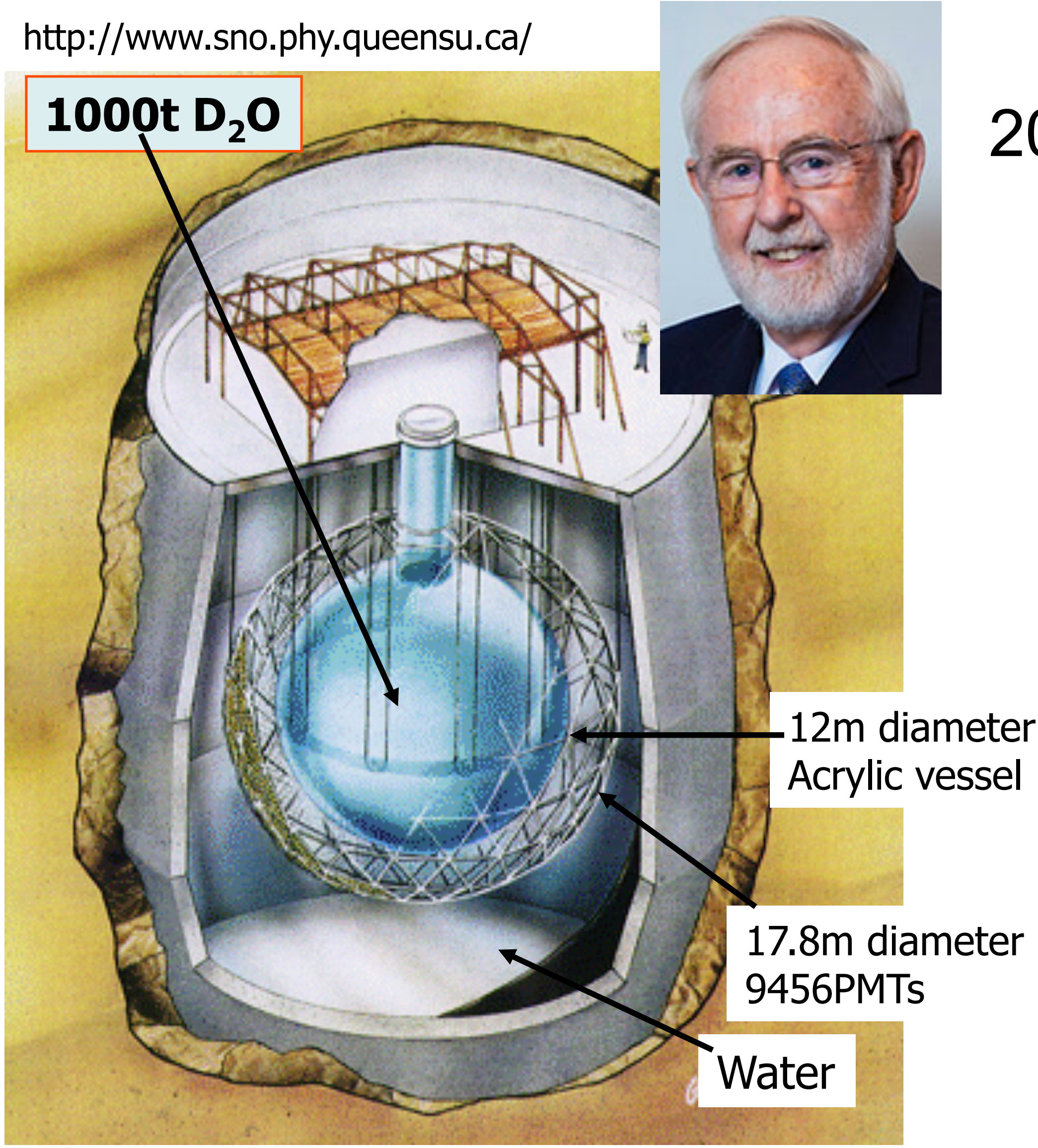
Since 1996

SK-1 (1996~2001)
SK-2 (2002~2005)
SK-3 (2006~2008)
SK-4 (2008~present)



SNO experiment (1999~2008)

http://www.sno.phy.queensu.ca/



Sudbury Neutrino Observatory
2092m underground (5900m w.e.)

<u>The following interactions can be separately observed</u>

✓Charged Current (CC)

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

Only ν_e

✓Neutral Current (NC)

$\nu + d \rightarrow \nu + p + n$

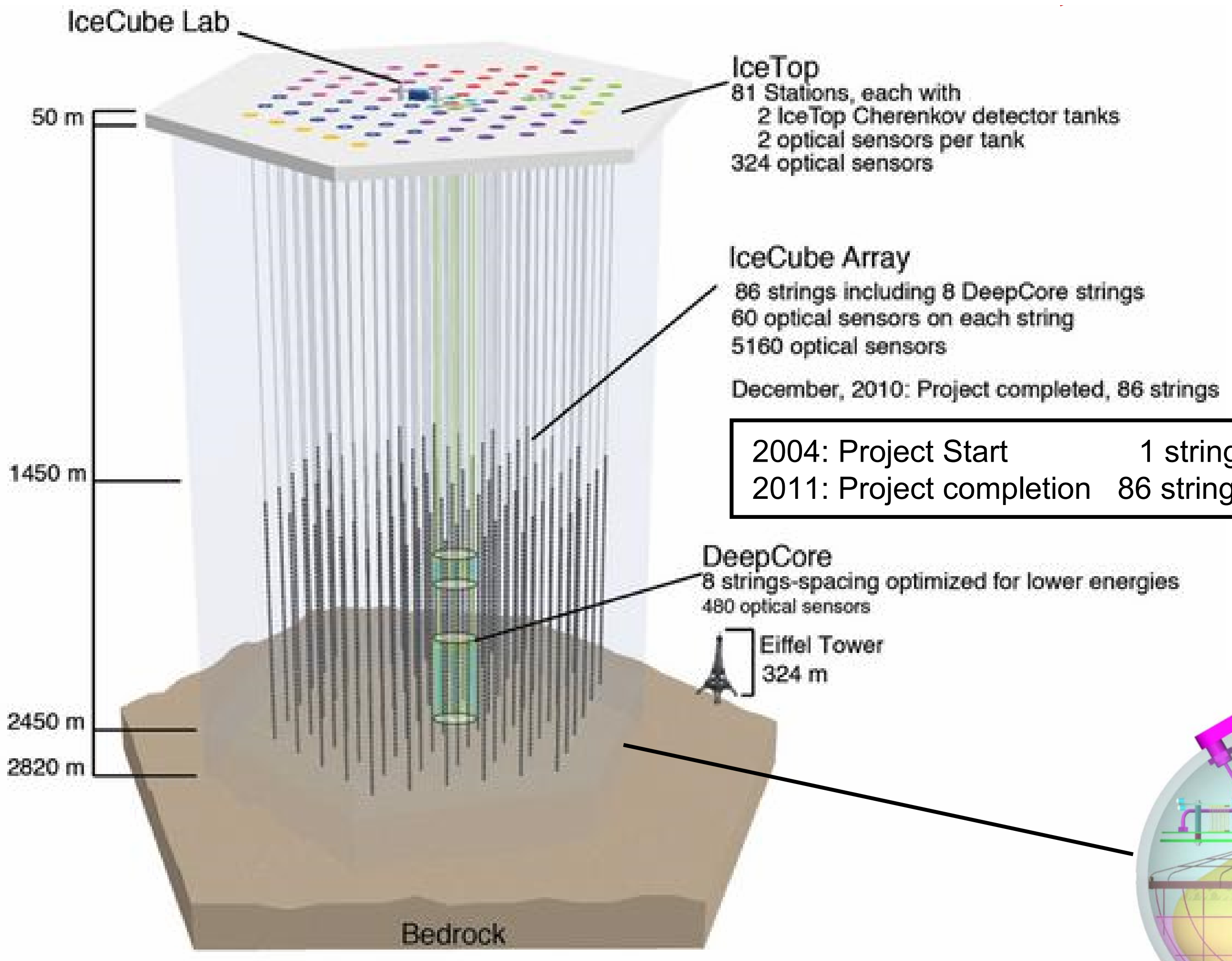
All ν types

✓Elastic scattering (ES)

$\nu + e^- \rightarrow \nu + e^-$

$\nu_e + 0.154(\nu_\mu + \nu_\tau)$

IceCube experiment (2006~)

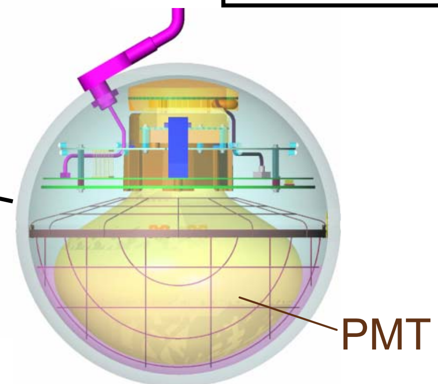


2004: Project Start	1 string
2011: Project completion	86 strings

Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

Shigeru Yoshida

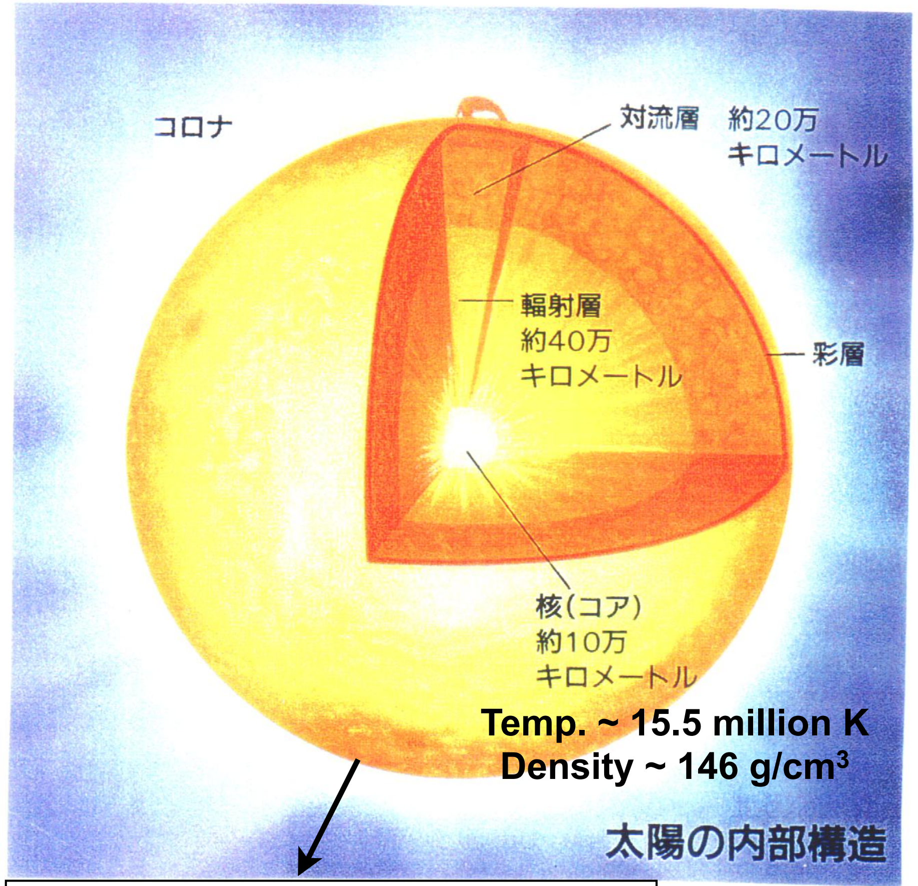


Digital Optical Module (DOM)

Solar neutrinos

Solar neutrino

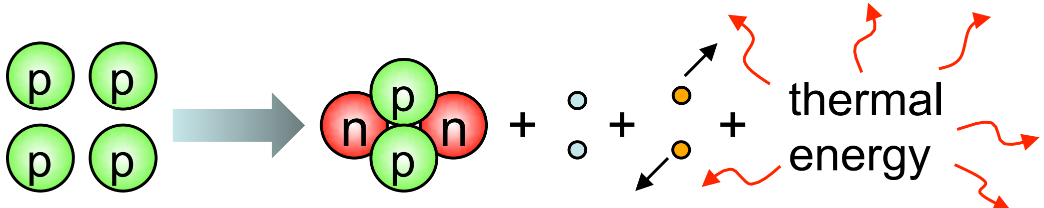
How does the Sun shine?



Photon-measured luminosity

→ ~10^7years radiated from the center to the surface.

Nuclear fusion reactions can occur deep inside the Sun.



$$4p \rightarrow {}^4He + 2\,e^+ + 2\nu_e + 26.7MeV$$

(~6.6×10^{10} neutrinos /sec/cm^2)

Go through the sun immediately (~2sec), since neutrinos only interact with matter via weak force. After ~8min, arrival at the earth → Solar neutrinos can derive the current status in the center of the sun.

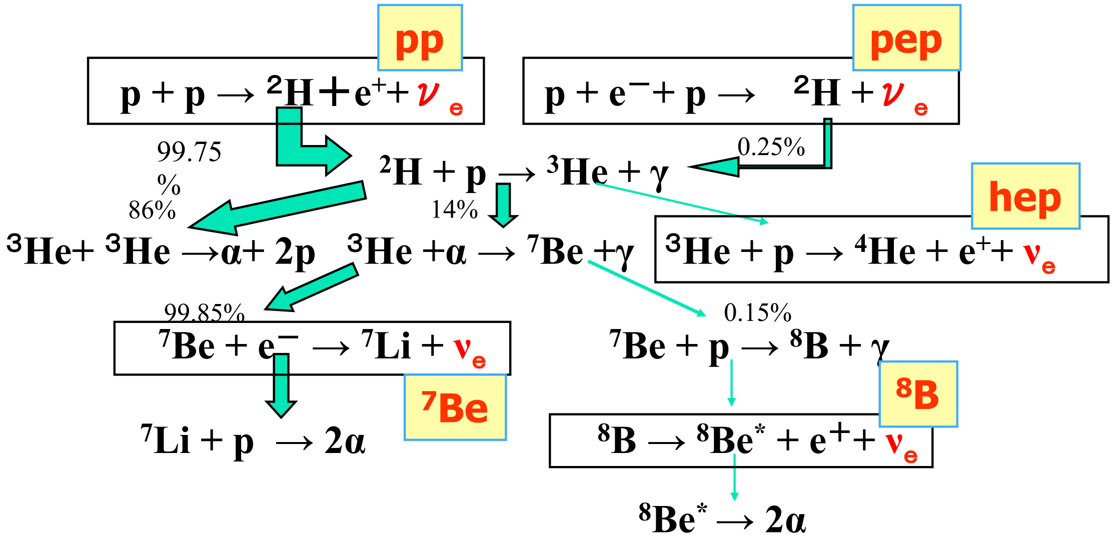
This reaction is actually realized via pp-chain and CNO cycle.

Solar neutrino

pp-chain

W.Fowler

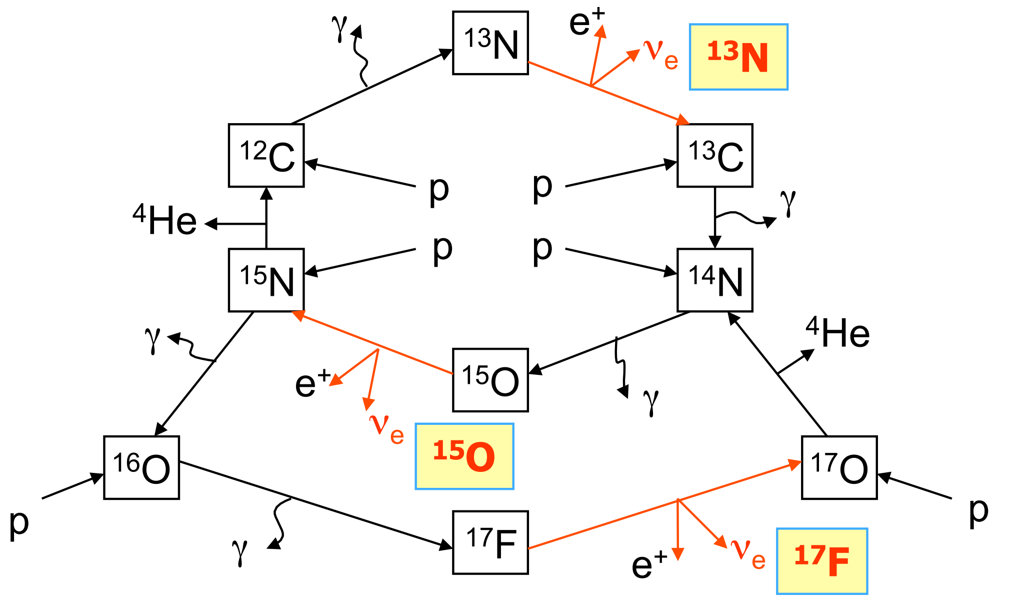
Dominant process in the Sun (~99% of the energy)



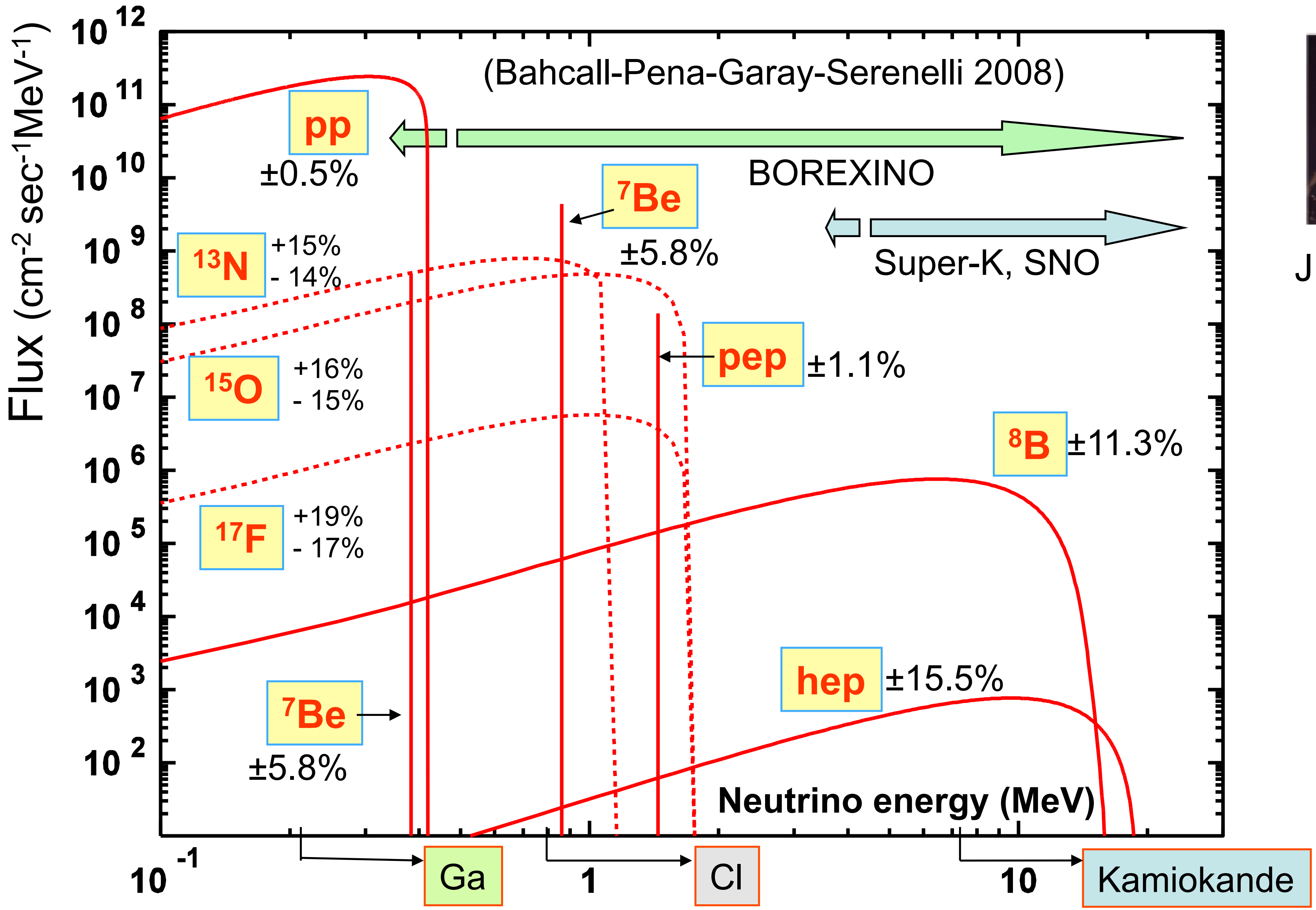
CNO cycle

H.A.Bethe

Small ratio (<1%) in the Sun, poorly know yet



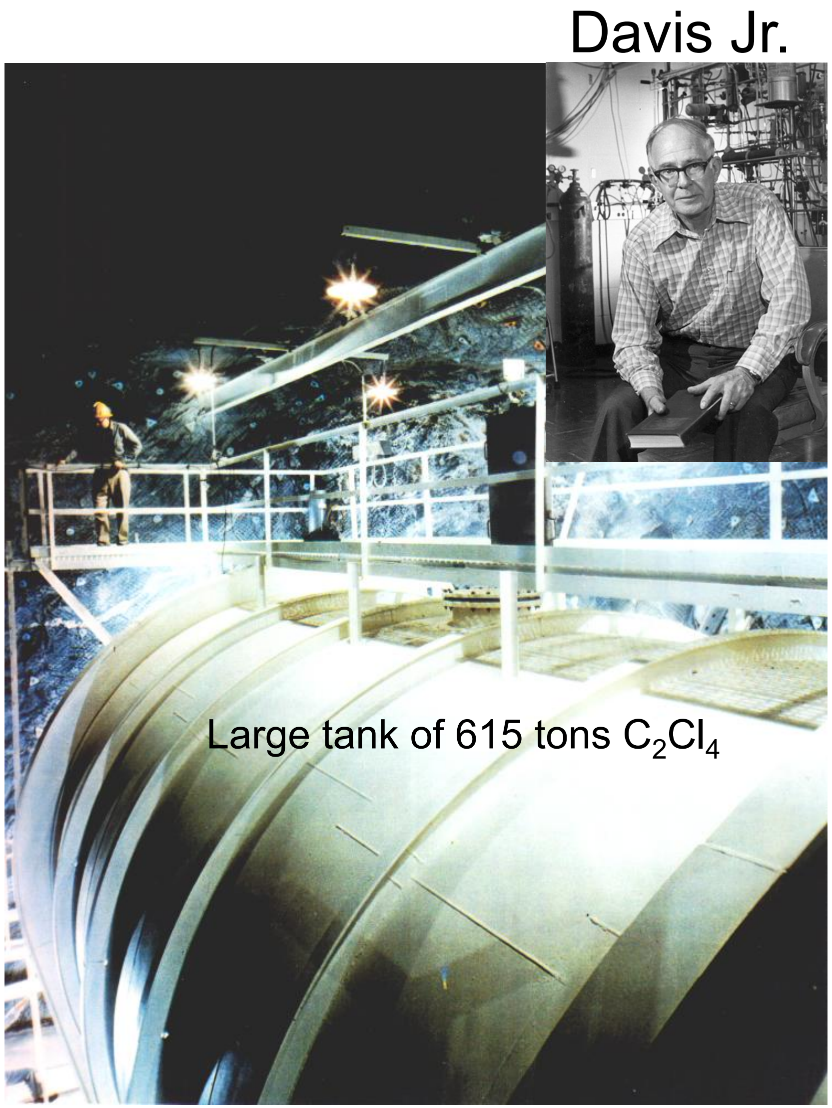
Standard Solar Model (SSM)



J.N.Bahcall

First generation detectors (70's~)

Homestake experiment



Homestake gold mine, South Dakota, USA
1620m underground (4400m.w.e.) since 1970.

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} \quad (\mathrm{CC})$$

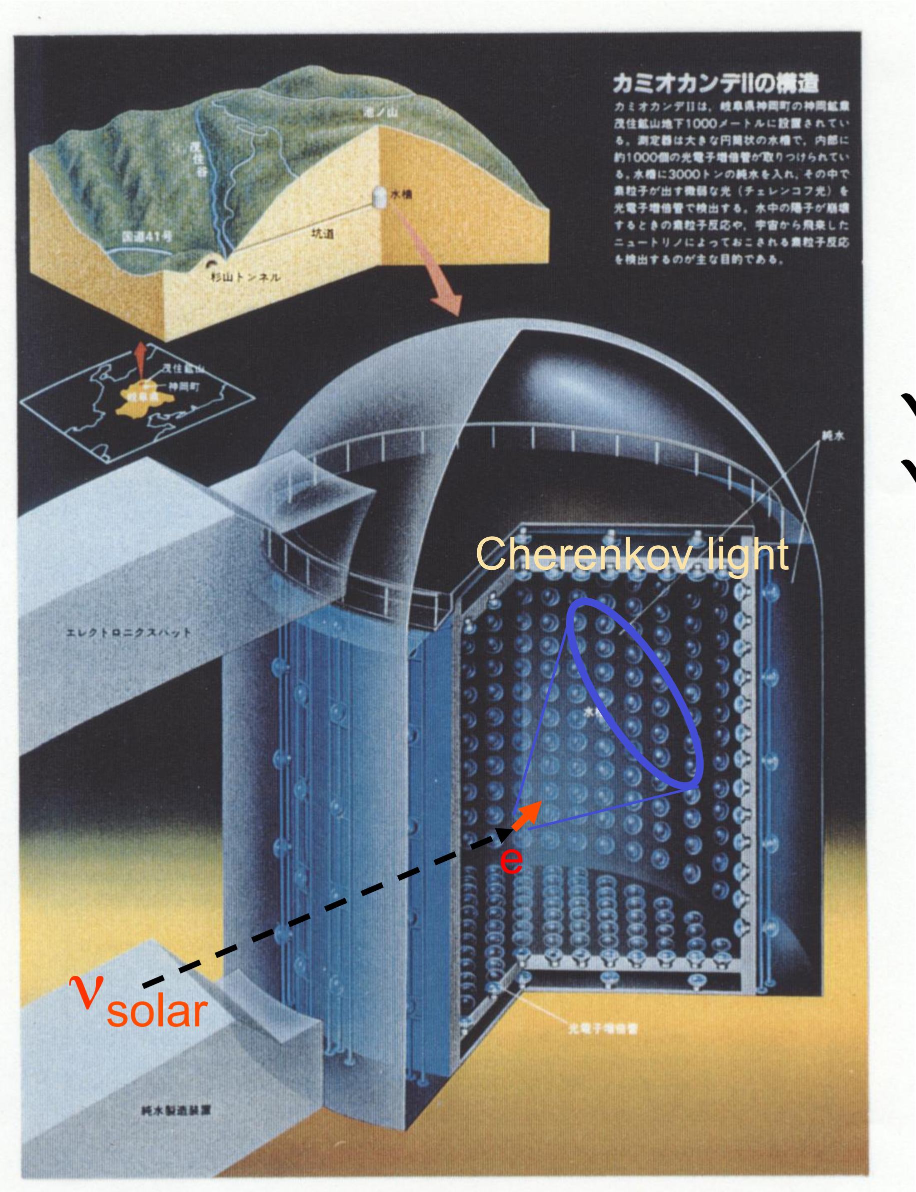
(E_{th}=0.814MeV) $t_{1/2}$=35days

Flux ratio (meas./SSM)=0.31±0.03

Observed solar neutrino flux is significantly less than prediction by SSM

Solar Neutrino Problem

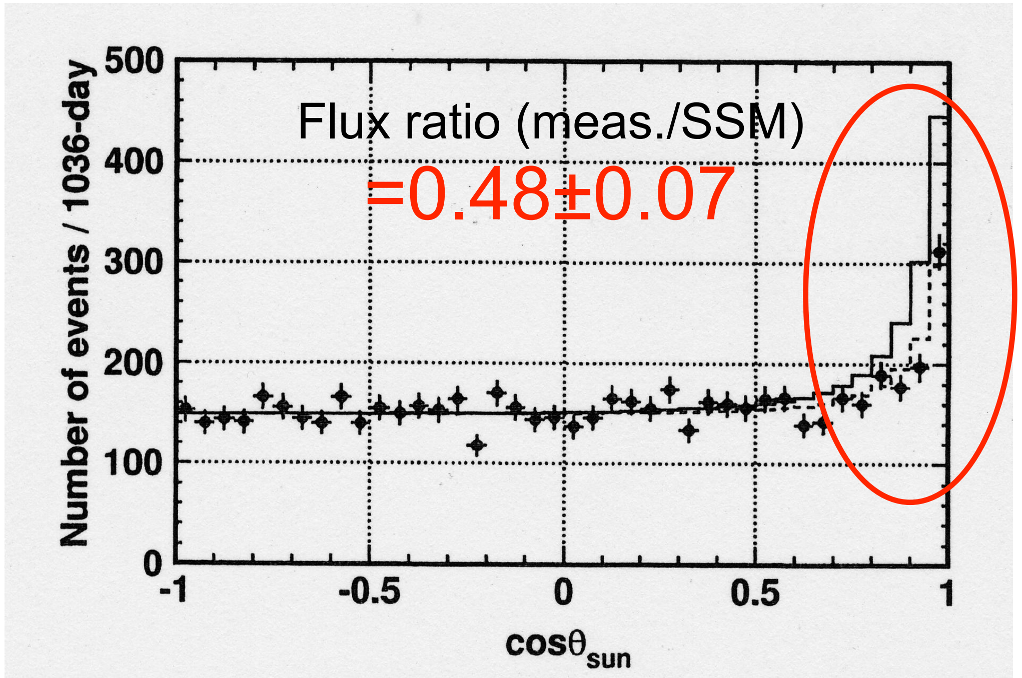
Kamiokande (1983~1996)



Kamioka mine, Japan, 1000m underground (2700m.w.e.), 3000 tons of water tank, with 1000 of 20' PMT

$\nu + e^- \rightarrow \nu + e^-$ (ES) (E_{th}=7.5MeV)

✓First realtime solar neutrino measurement.
✓Strong peak to the solar direction.



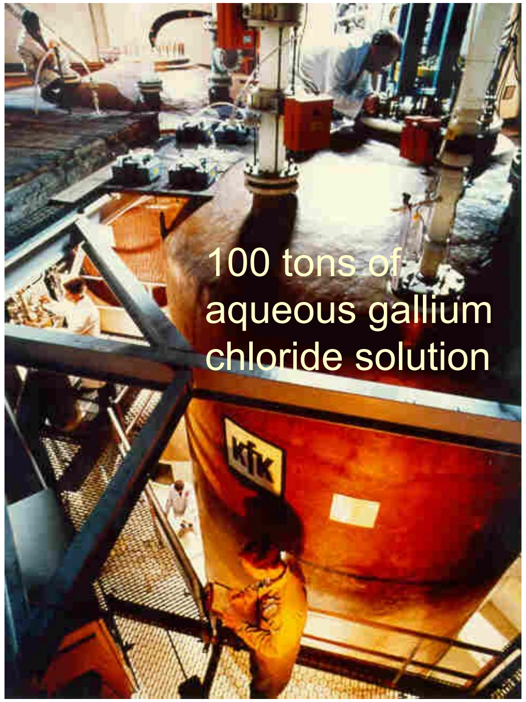
Gallium experiments

SAGE

BAKSAN in Russia, 1800m underground (4700m w.e.) , since 1990. 50 tons of metallic gallium.

GALLEX/GNO

Gran Sasso in Italy, 1300m underground (3500m w.e.), since 1991. 30 tons of natural gallium.



$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (CC)

(E_{th}=0.233MeV) $t_{1/2}$=11days

Measurable pp neutrinos

less solar model depended

Flux ratio (meas./SSM) :

0.53 ± 0.04 (SAGE)

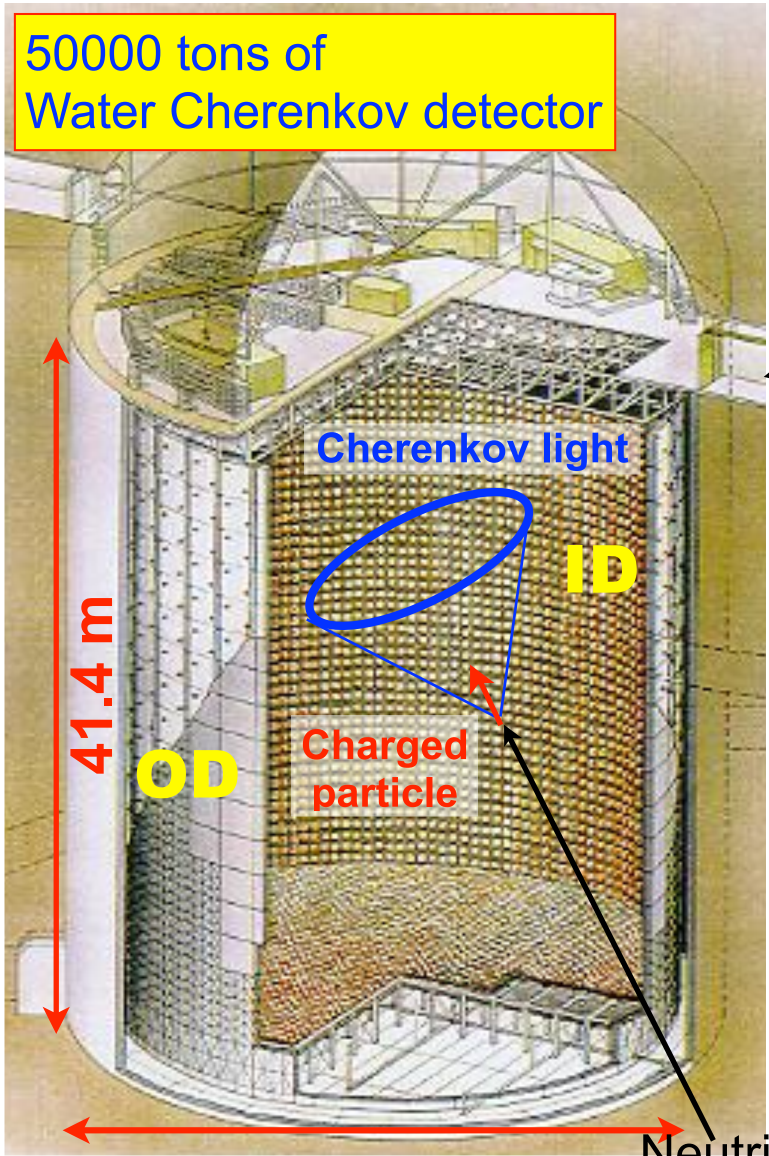
0.55 ± 0.04 (GALLEX+GNO)

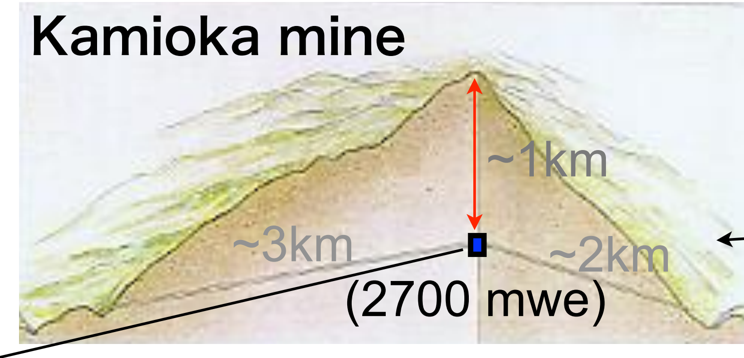
0.54 ± 0.03 (combined)

Flux deficit was observed

Second generation detectors (90's~)

Solar neutrino measurement in SK



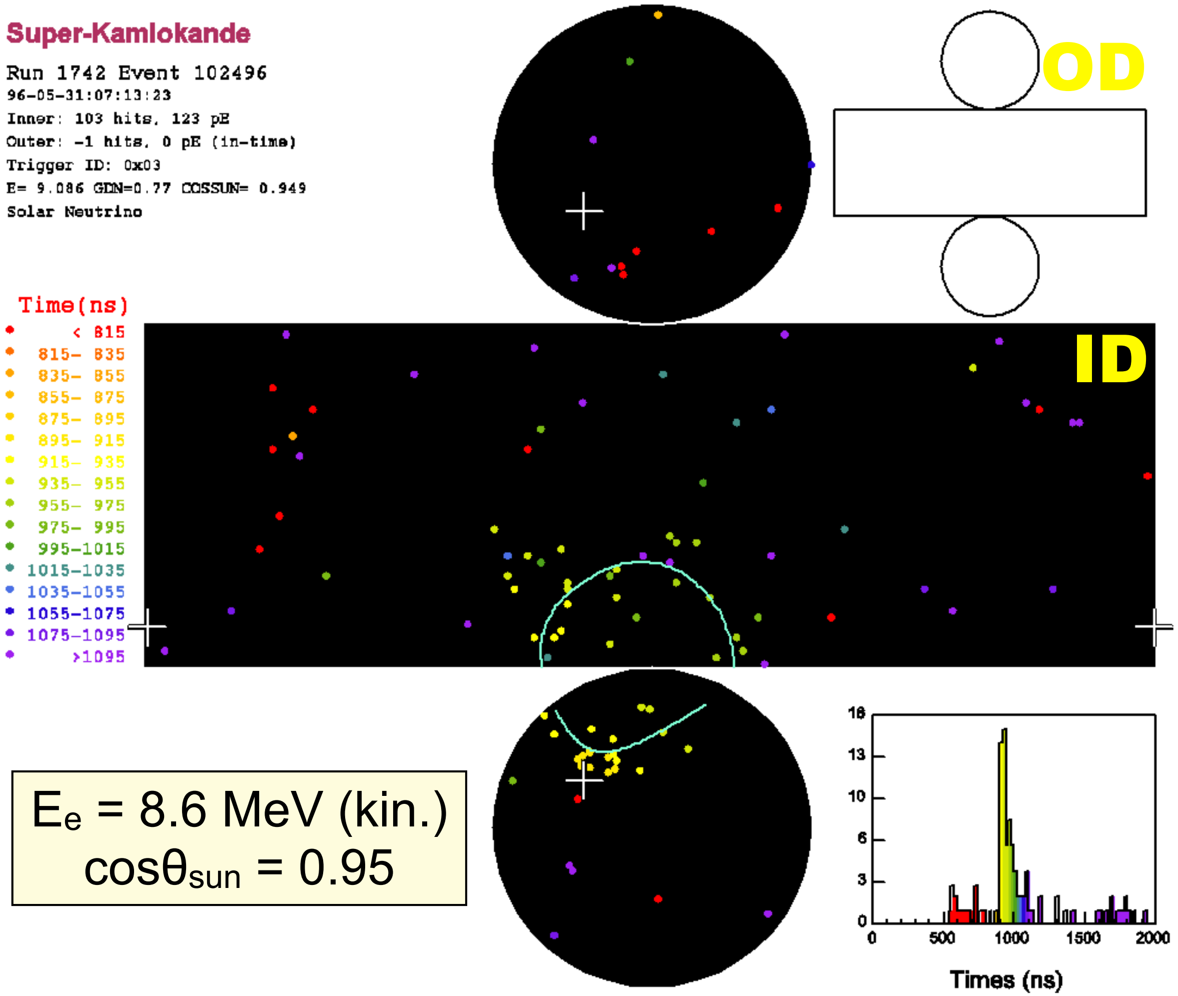


(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		**3.5**
		total **4504** days		(coverage)	(Kinetic energy)

Solar neutrino measurement in SK

Typical event



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

electron elastic scattering (ES)

$$\nu + e^- \rightarrow \nu + e^-$$

- ✓Find solar direction
- ✓Realtime measurement
  - day/night flux differences
  - seasonal variation
- ✓Energy spectrum

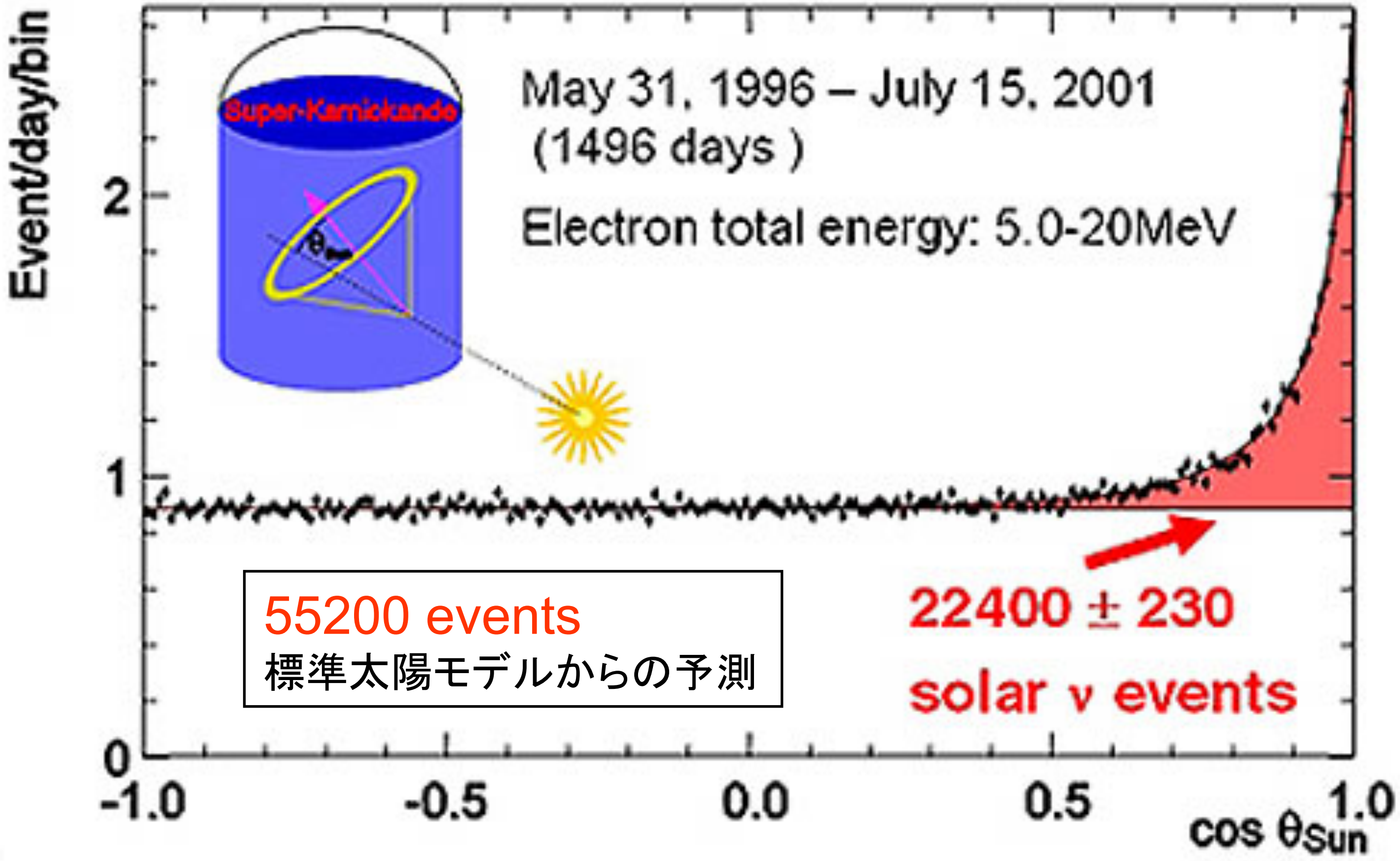
Interaction with all flavors of neutrino

$$\nu_e + 0.154(\nu_\mu + \nu_\tau)$$

Solar neutrino measurement in SK

(~2001)

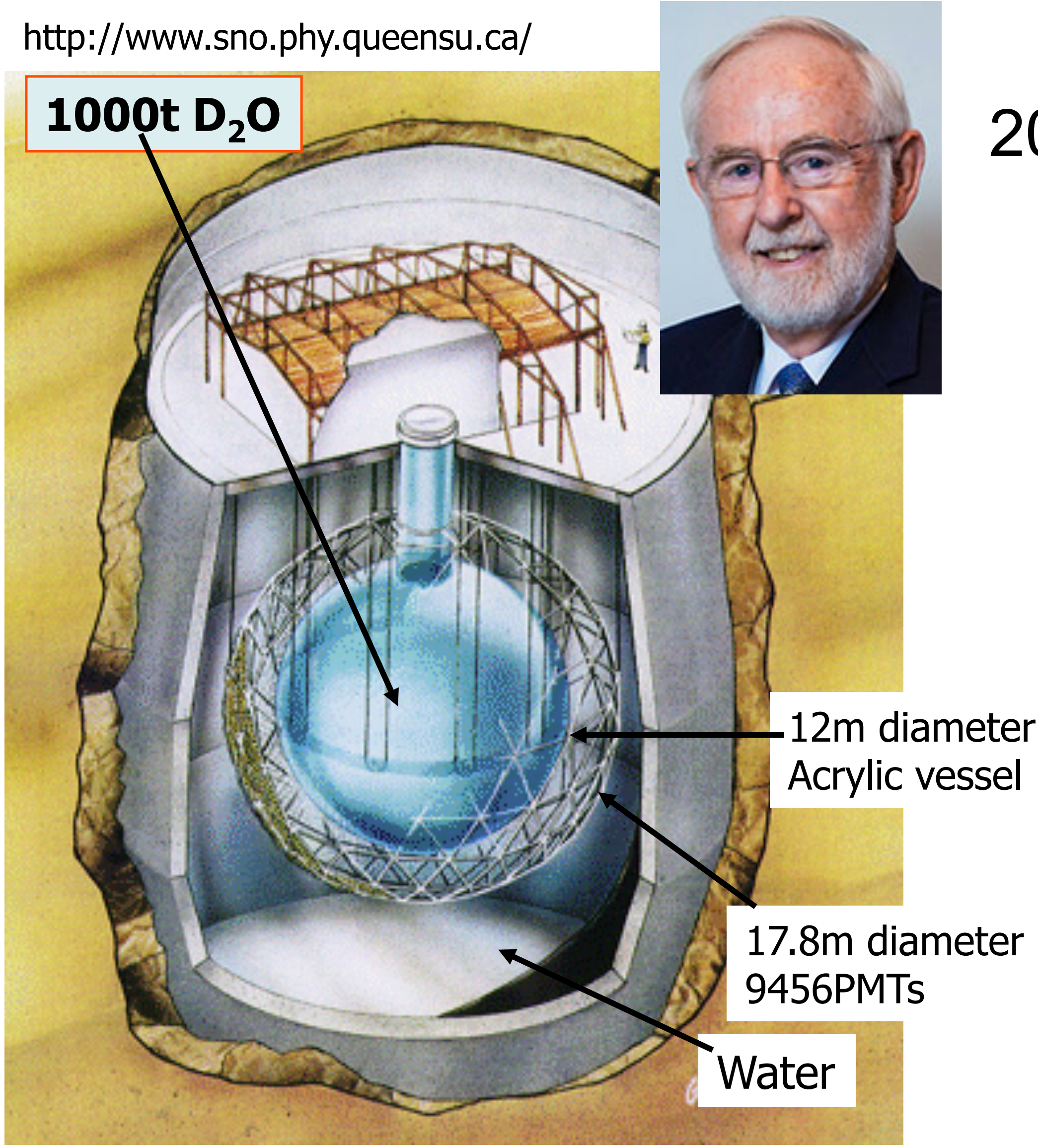
The observed signal direction with the Sun



The deficit from the prediction (40.6%) was observed with high precision (~3%)

SNO experiment (1999~2008)

http://www.sno.phy.queensu.ca/



Sudbury Neutrino Observatory
2092m underground (5900m w.e.)

<u>The following interactions can be separately observed</u>

✓Charged Current (CC)

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

Only ν_e

✓Neutral Current (NC)

$\nu + d \rightarrow \nu + p + n$

All ν types

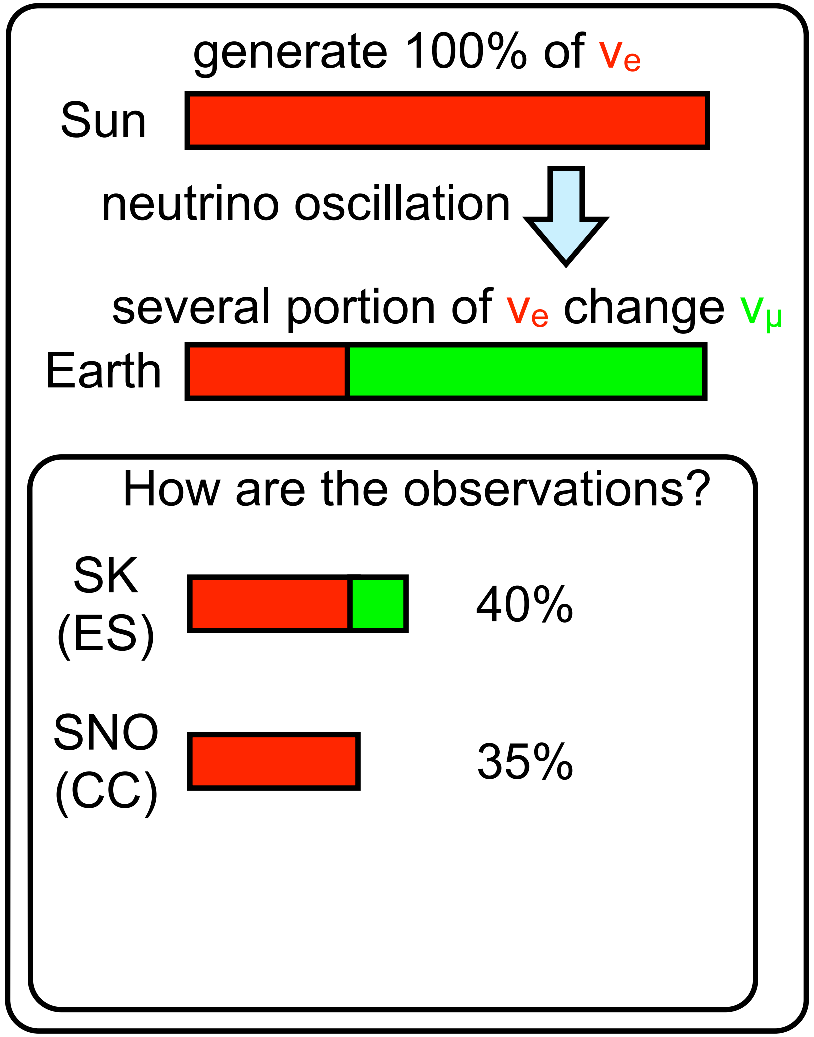
✓Elastic scattering (ES)

$\nu + e^- \rightarrow \nu + e^-$

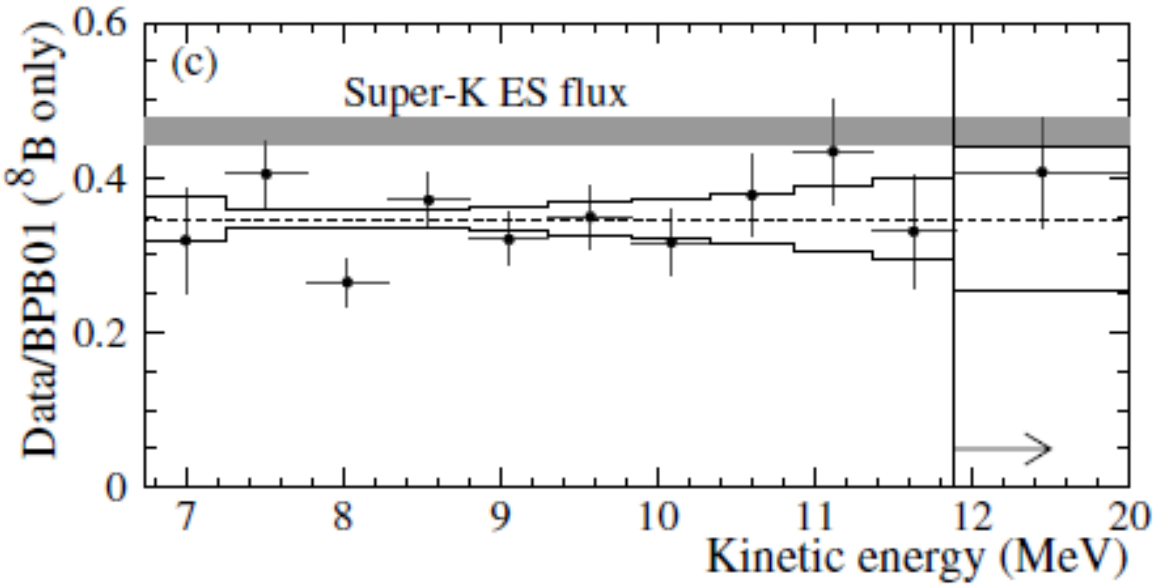
$\nu_e + 0.154(\nu_\mu + \nu_\tau)$

Combined with SK and SNO

First results in SNO (2001)



Phys. Rev. Lett. 87 (2001) 071301



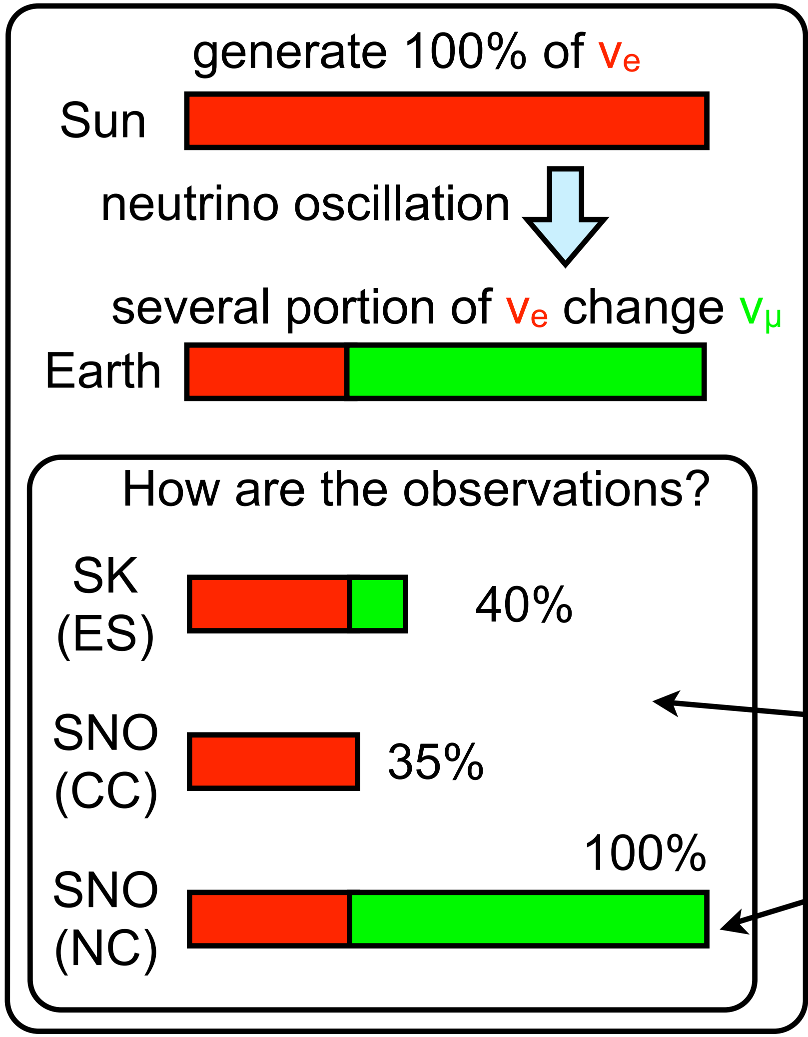
CC in SNO was significantly smaller than ES in SK

"Providing evidence of an active non-ν_e component in the solar neutrino flux"

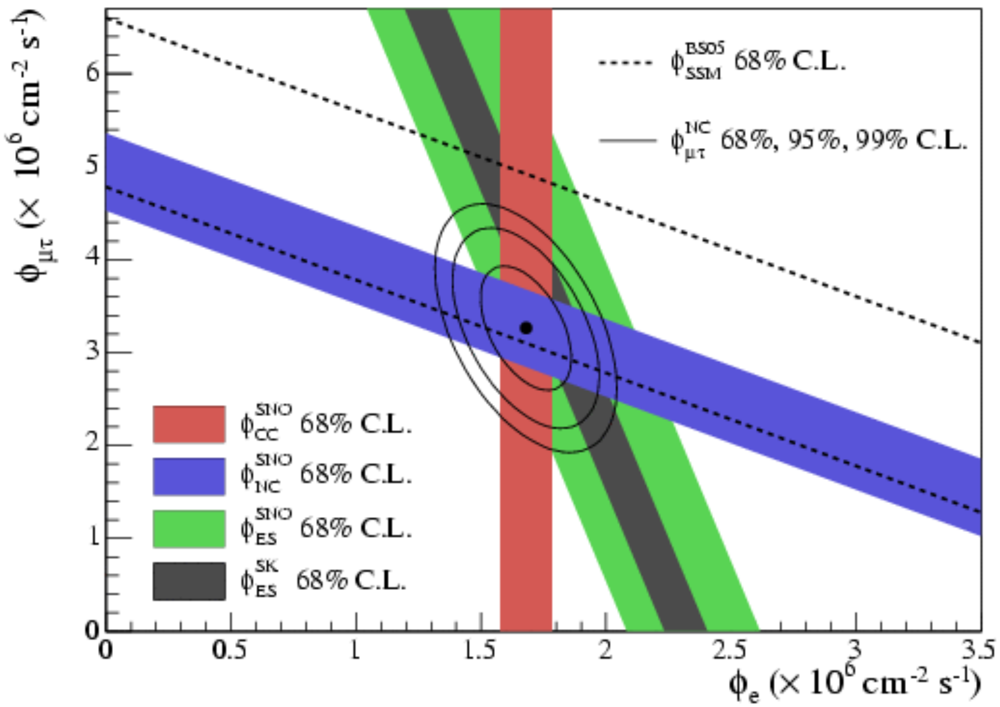
Solar neutrino oscillation

Combined with SK and SNO

SNO results in 2002



Phys. Rev. Lett. 89 (2002) 011301



"Providing strong evidence for solar ν_e flavor transformation"
"Flux measured with the NC reaction is consistent with solar models."

The solar neutrino problem was solved

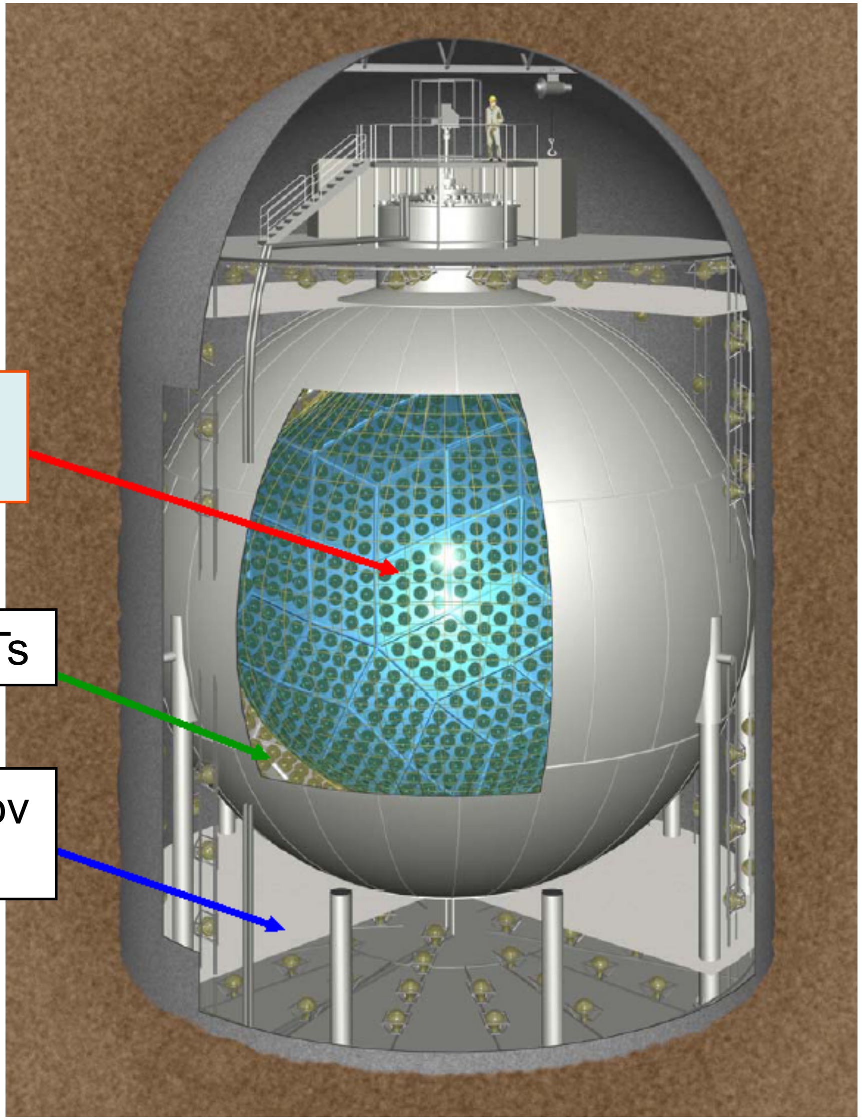
KamLAND

http://www.awa.tohoku.ac.jp/KamLAND/index.html

1000t liquid scintillator

1879 17” PMTs

H_2O Cherenkov veto counter



Re-use the Kamiokande cavern since 2001

- Reactor neutrinos (L~160km from the main reactor)
- Geo neutrinos
- Solar neutrinos

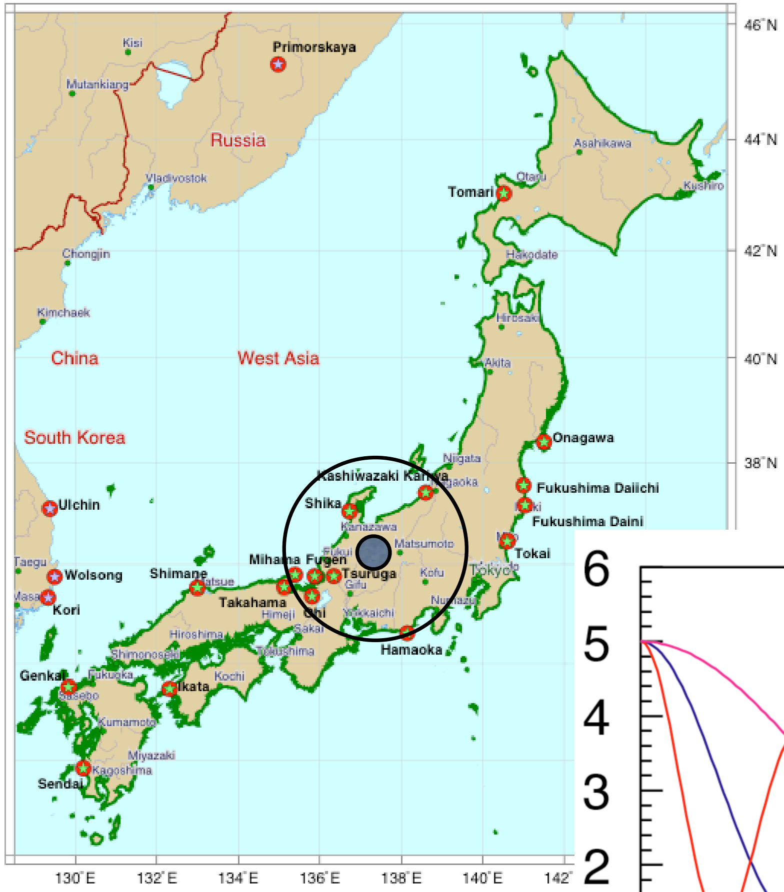
Delayed coincidence

$$\boxed{\nu_e + p \rightarrow e^+ + n}$$

~200μsec

$$\boxed{n + p \rightarrow d + \gamma}$$

Neutrino oscillation with reactors



70 GW (7% of world total) is generated at 130-220 km distance from Kamioka.

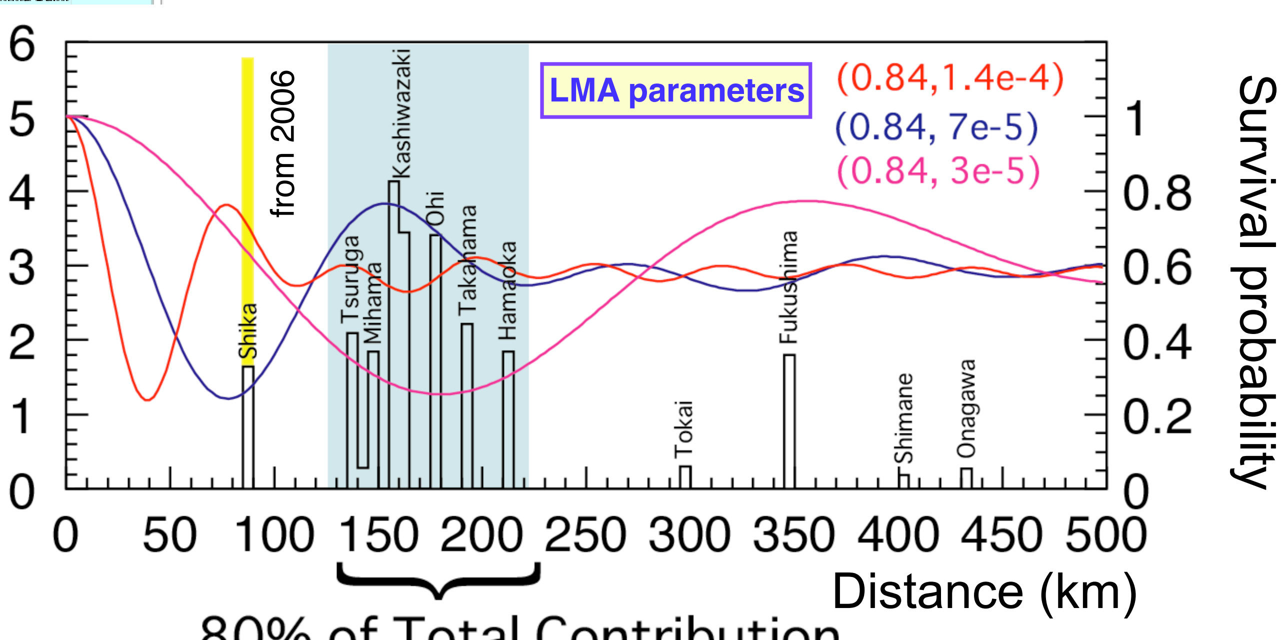
Reactor neutrino flux,

~95.5% from Japan
~3.5% from Korea

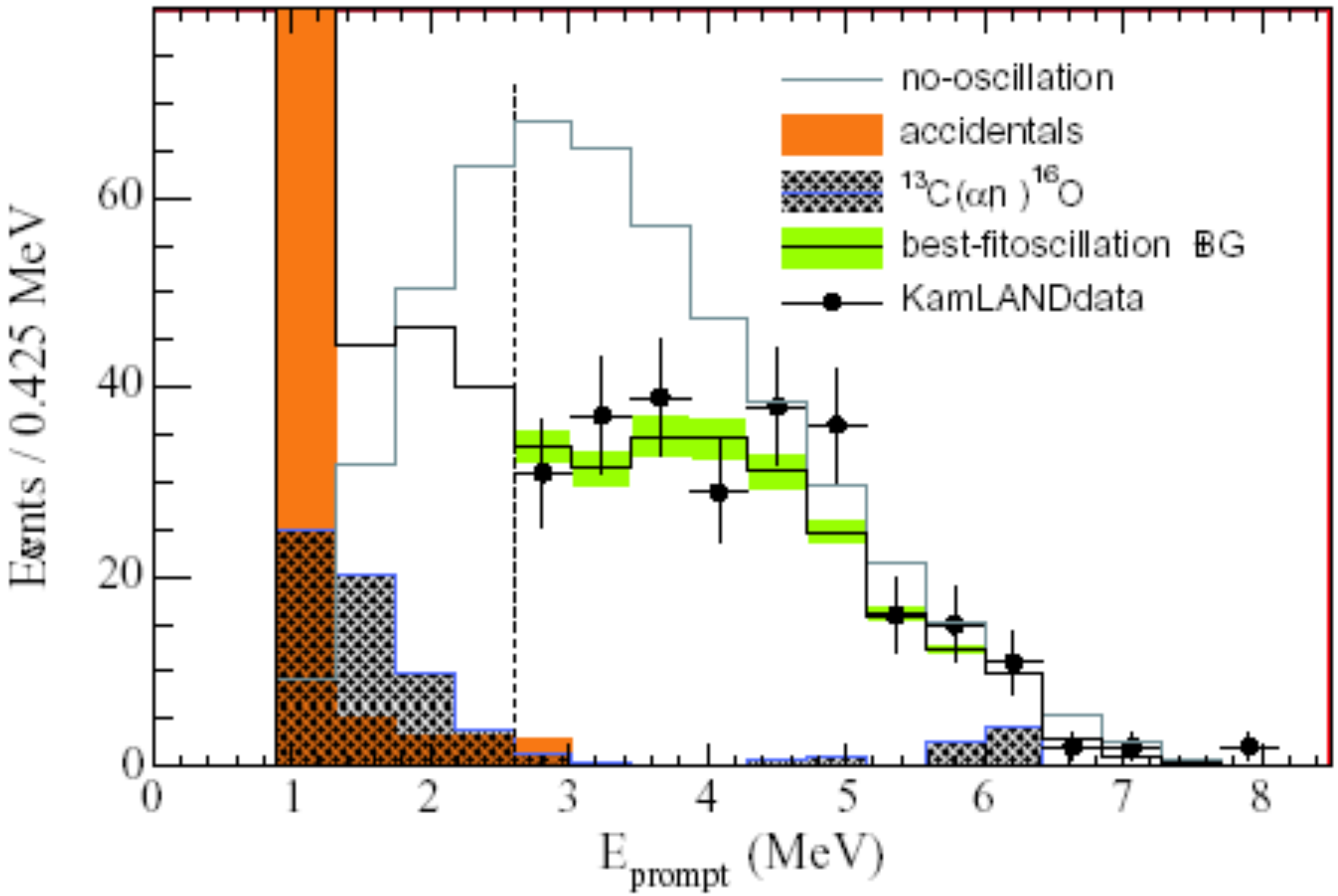
(2nd result period)

effective distance ~180km

(weighted average by event rate up to 400 km)

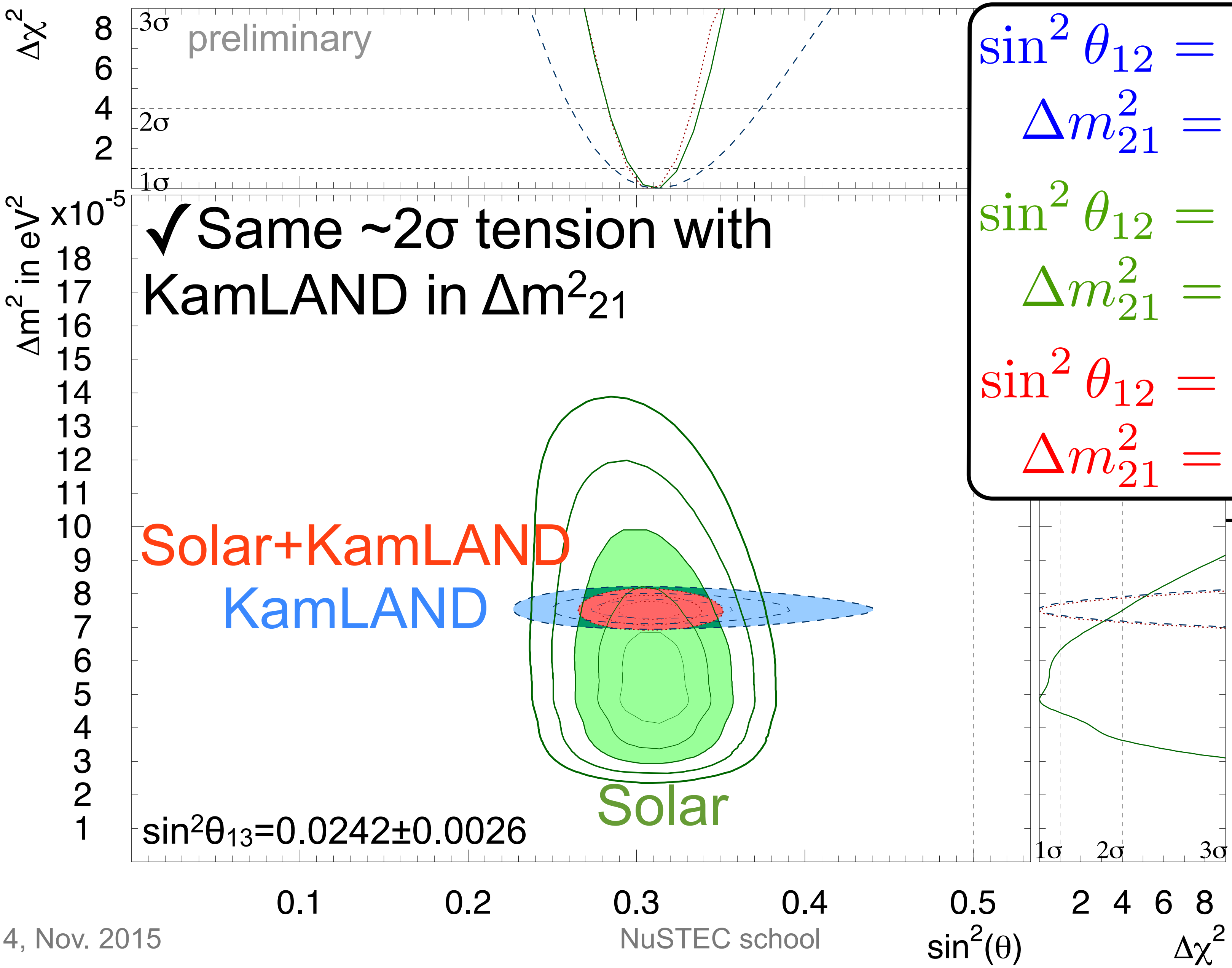


KamLAND (reactor neutrino)



Discovery of neutrino oscillation for $\overline{\nu_e}$

Neutrino oscillation of Solar+KamL



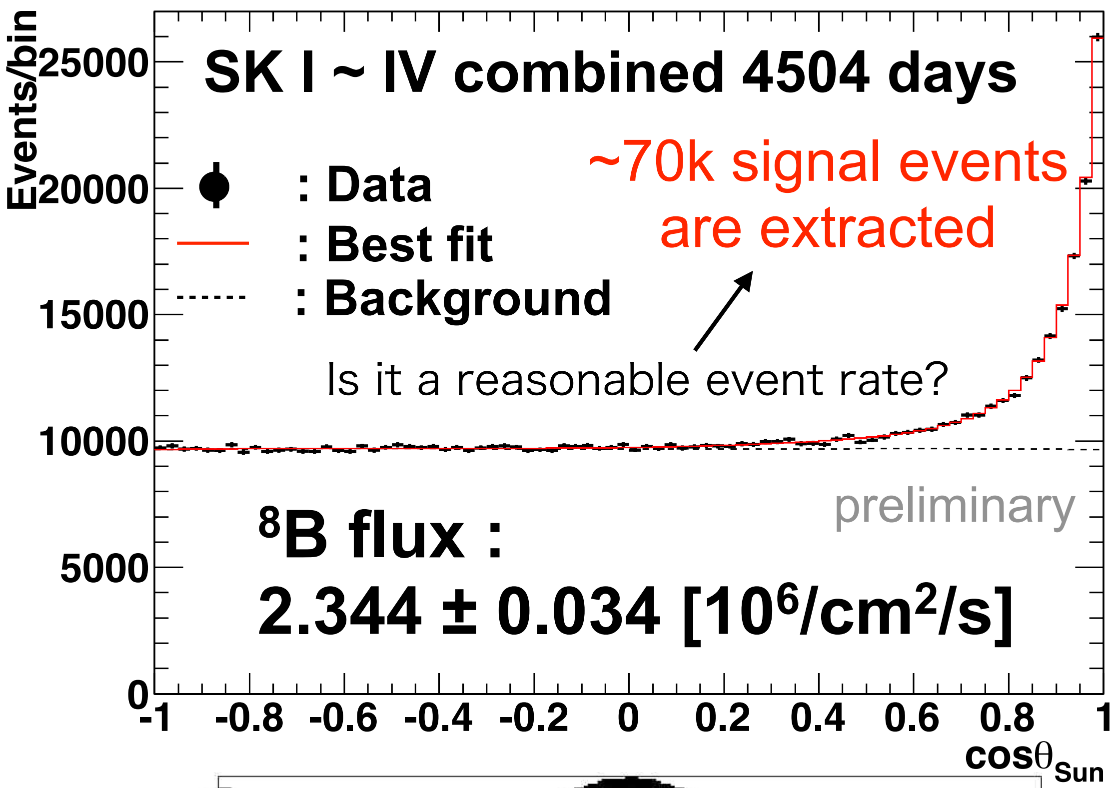
$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$

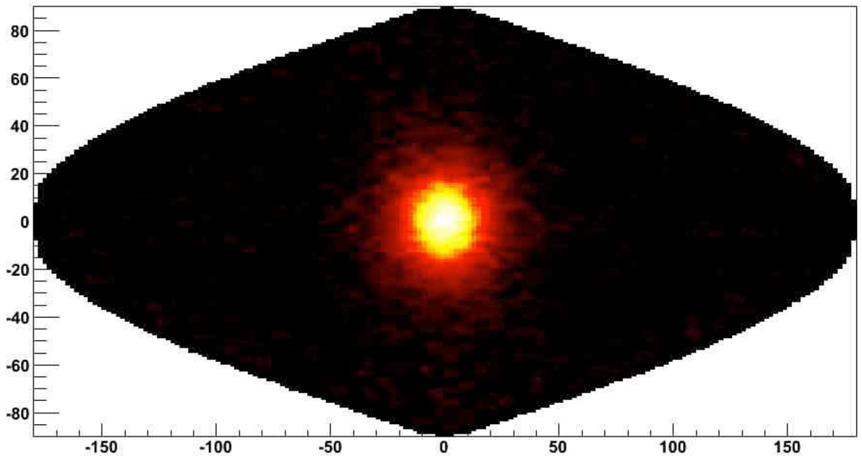
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$

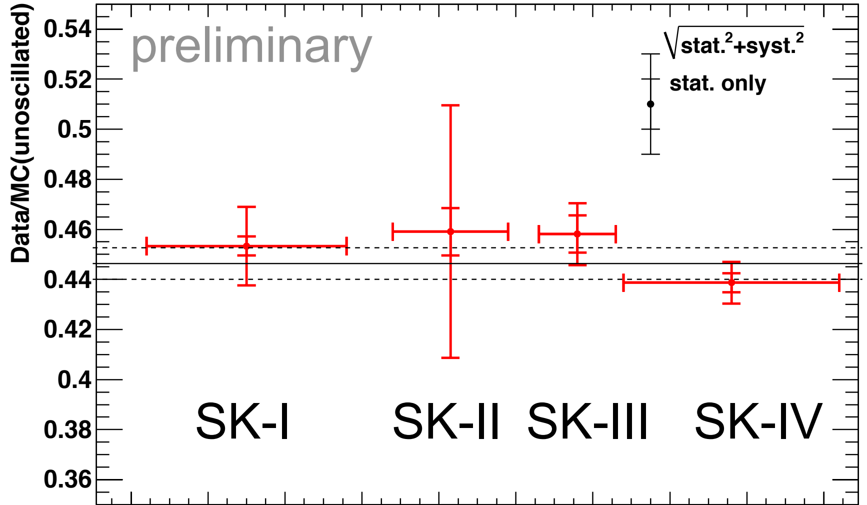
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

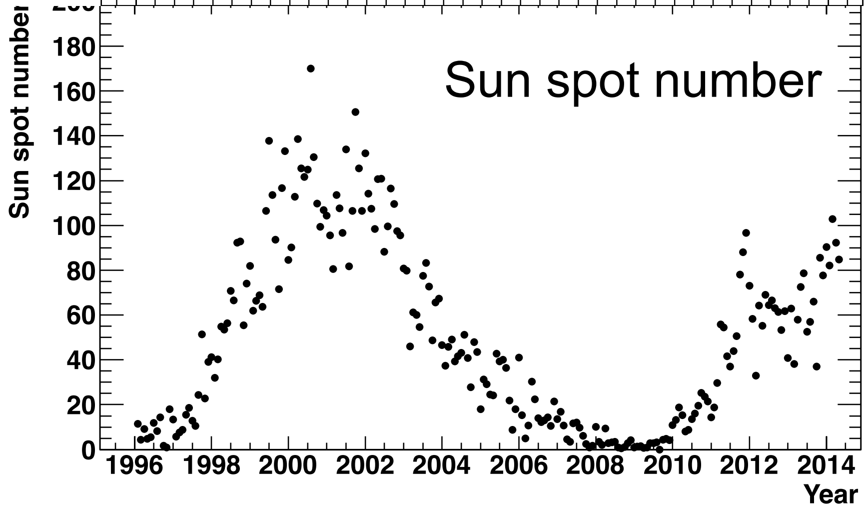
The unit of Δm^2_{21} is 10^{-5} eV^2

Recent results in SK



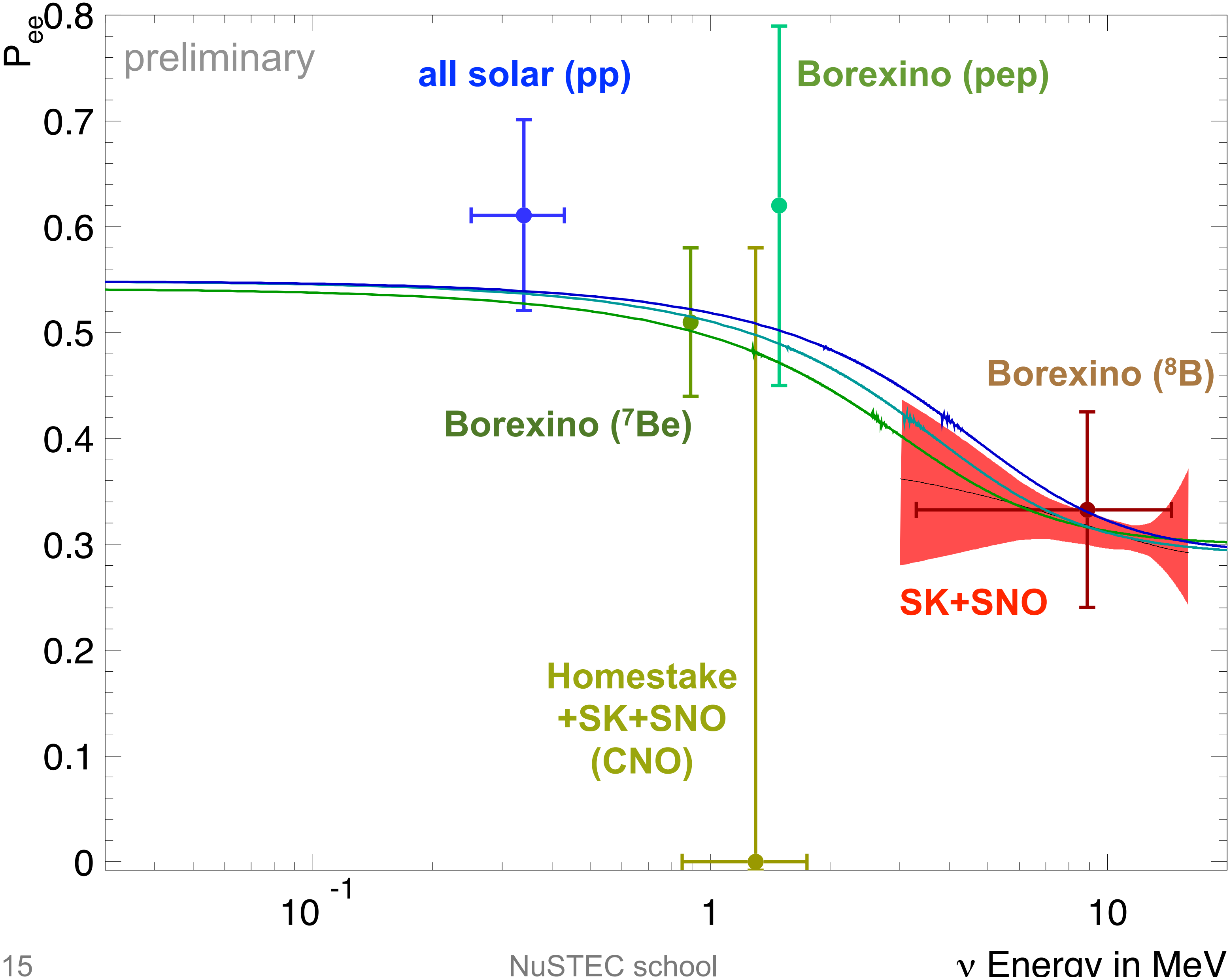






No correlation with solar activity is seen.
More sophisticated analyses such as yearly flux plot are being prepared.

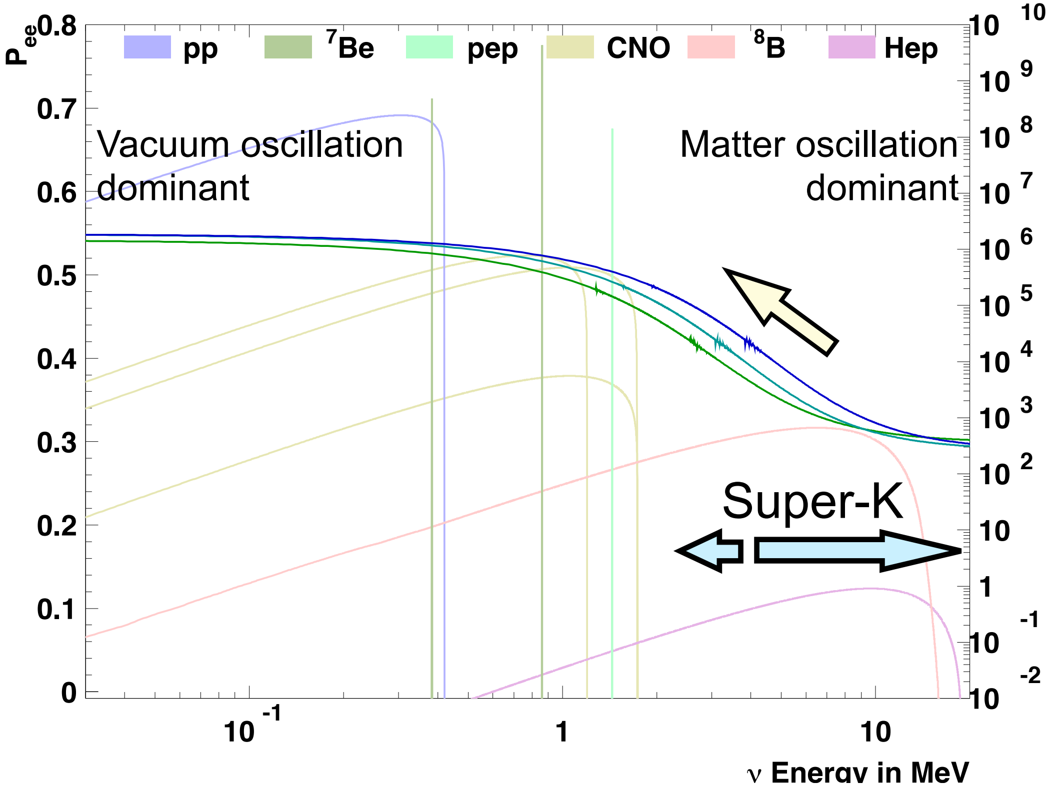
Survival probability of solar ν_e



Another motivation

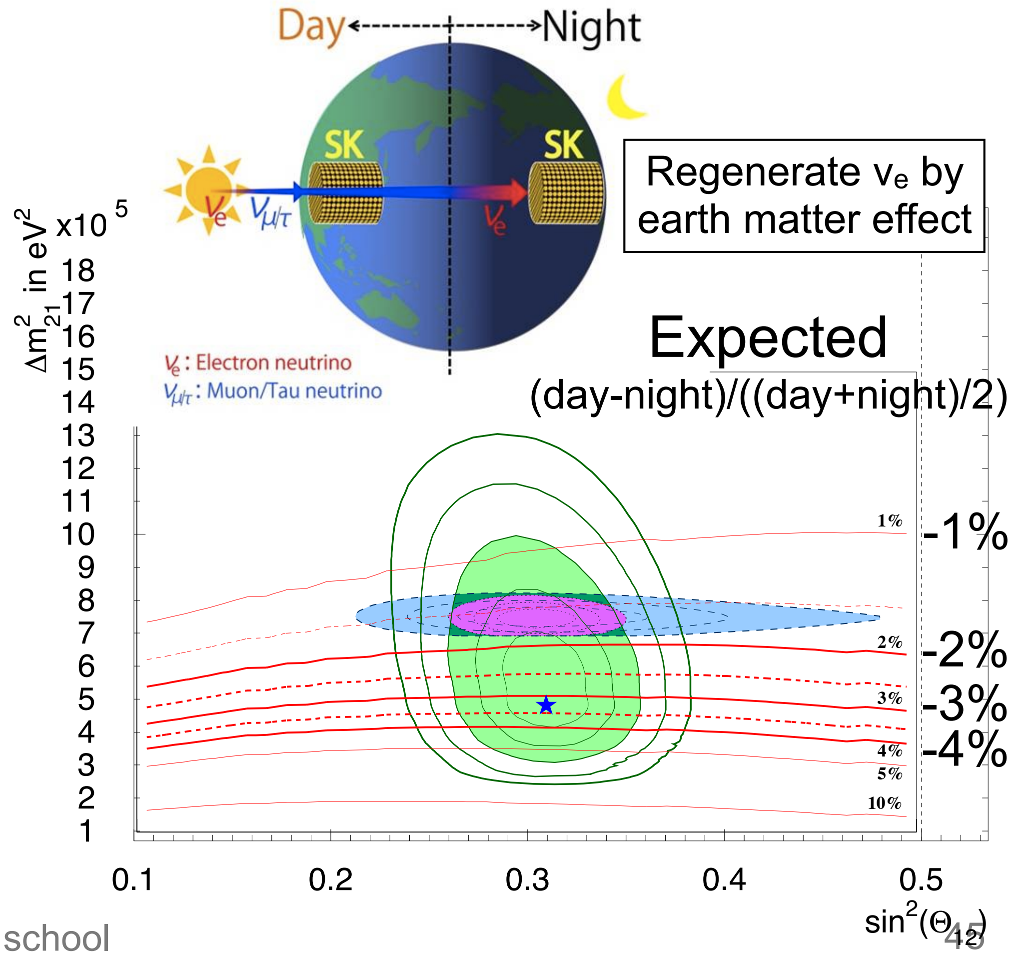
See the neutrino oscillation MSW effect directly

Spectrum distortion



Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect

Day-Night flux asymmetry

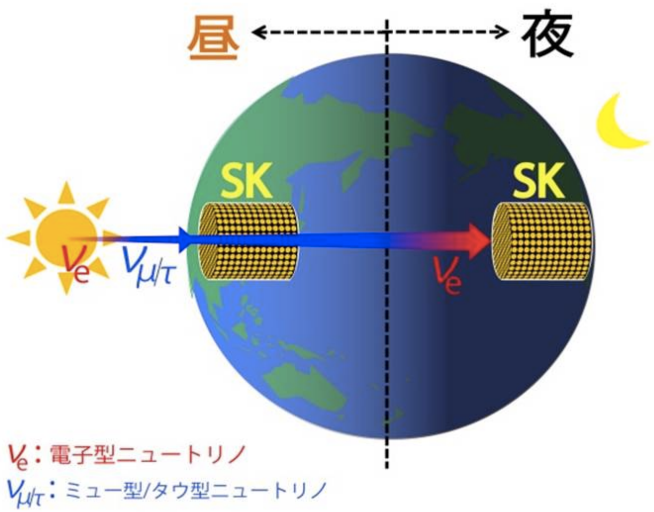


Day/Night differences

	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	3.0σ	2.8σ	2.8σ

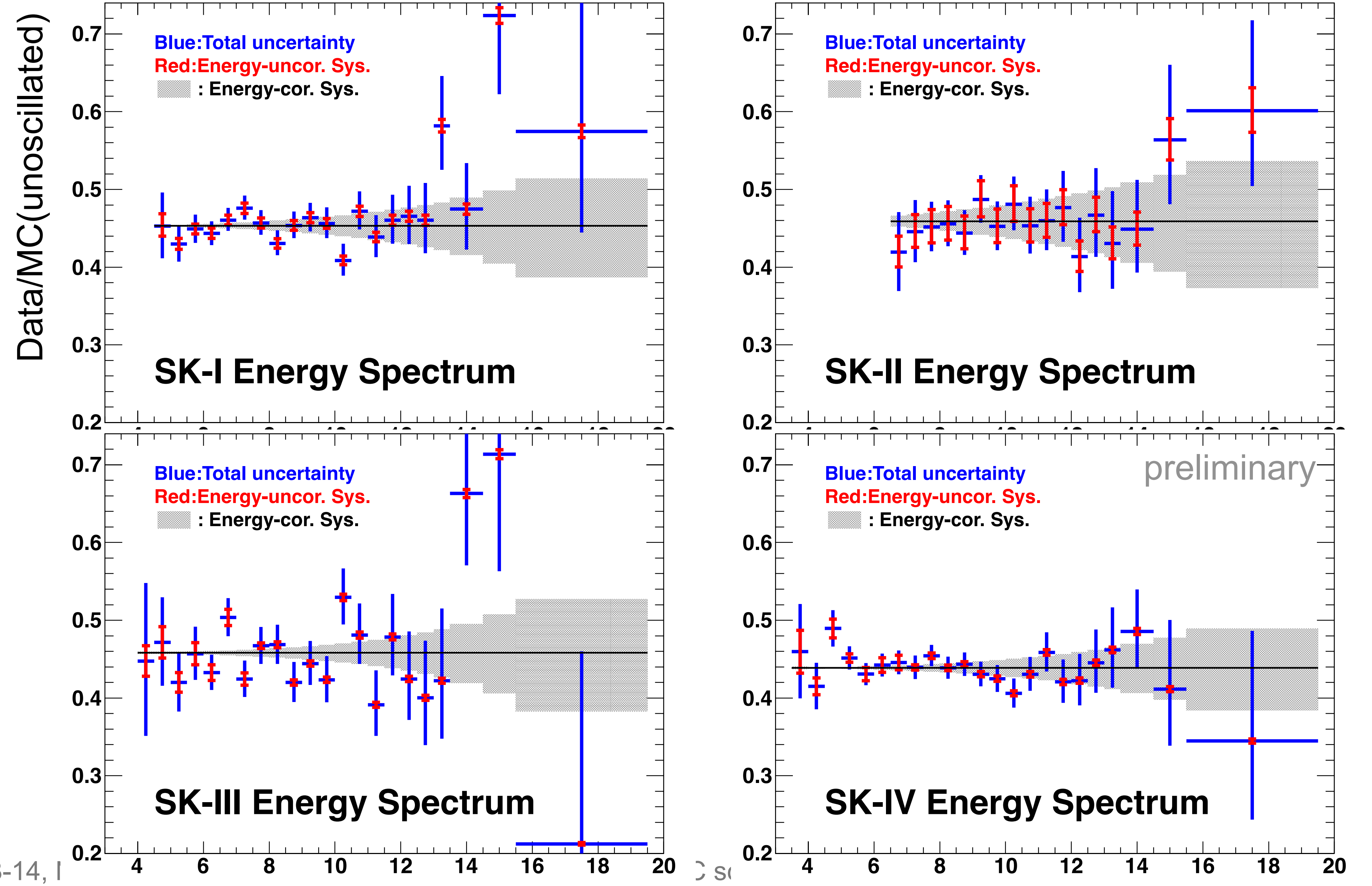
($\sin^2\theta_{12}$=0.311, $\sin^2\theta_{13}$=0.025)

preliminary



First direct observation of matter effect in the neutrino oscillation

Recoil electron spectrum



to be continued…