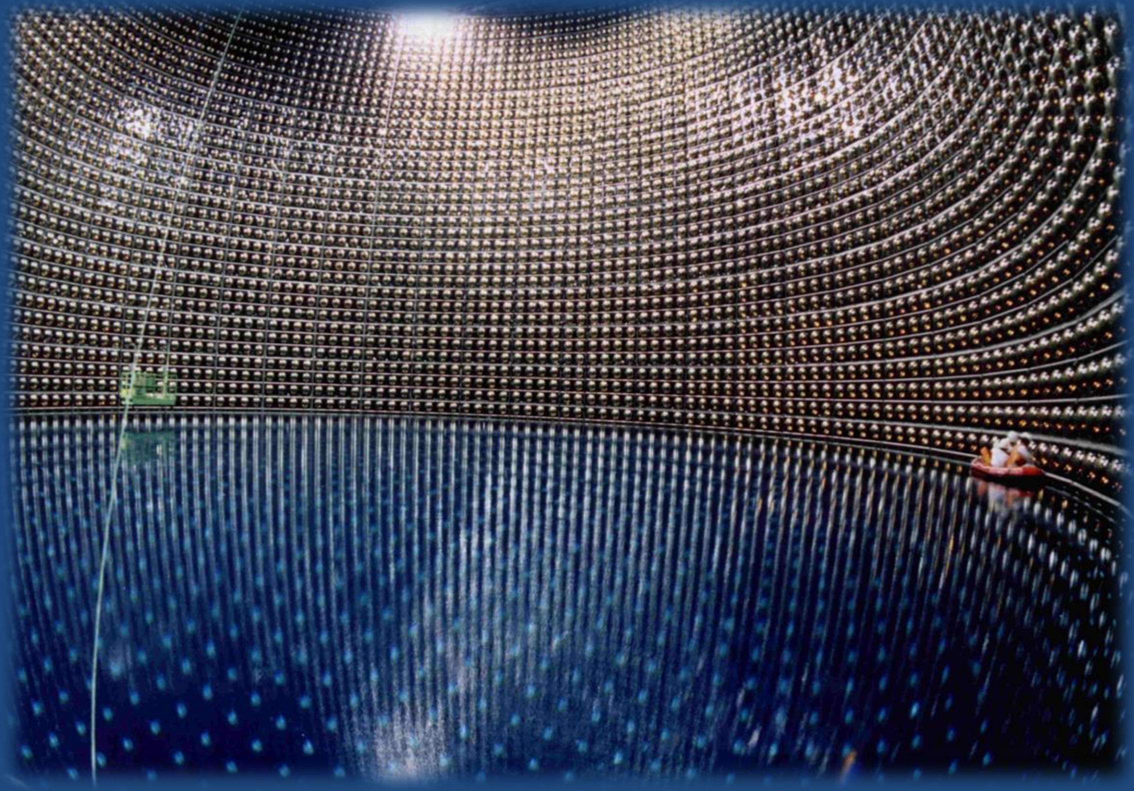
ICHEP 2016, Chicago, Aug. 8, 2016

Discovery of Neutrino Oscillations



Takaaki Kajita

Institute for Cosmic Ray Research, The Univ. of Tokyo

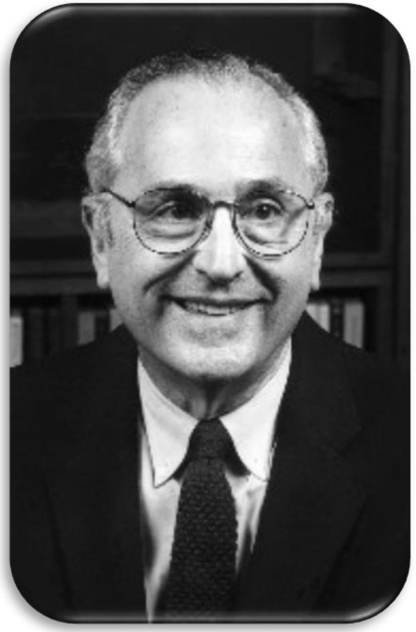
Outline

- Early days
  - Solar neutrinos
  - Atmospheric neutrinos
- Discovery of neutrino oscillations
  - Atmospheric neutrino oscillations
  - Solar neutrino oscillations
- Status and future
- Summary

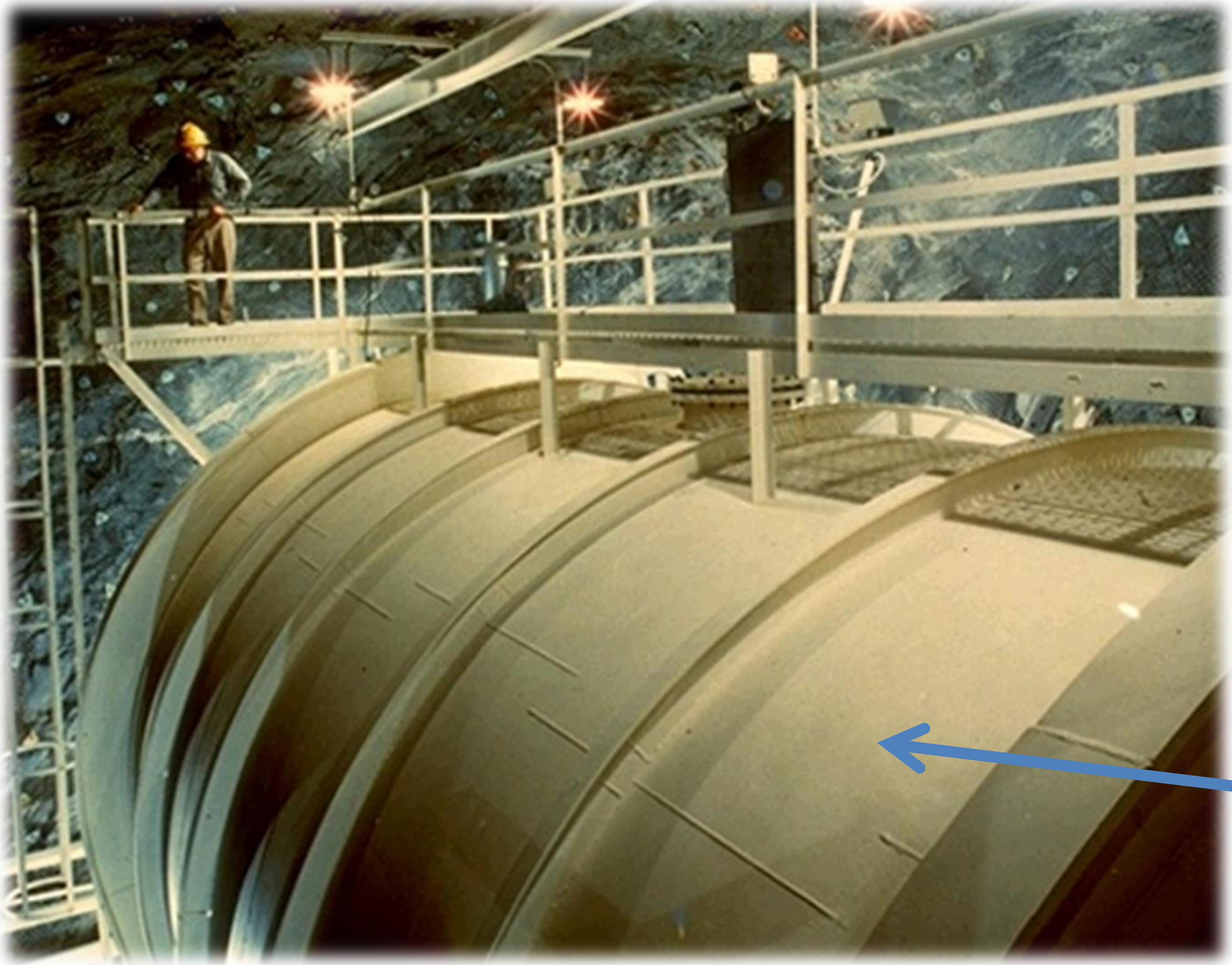
Many thanks to Art McDonald for various information related to SNO

Early days

Solar neutrinos



J. N. Bahcall

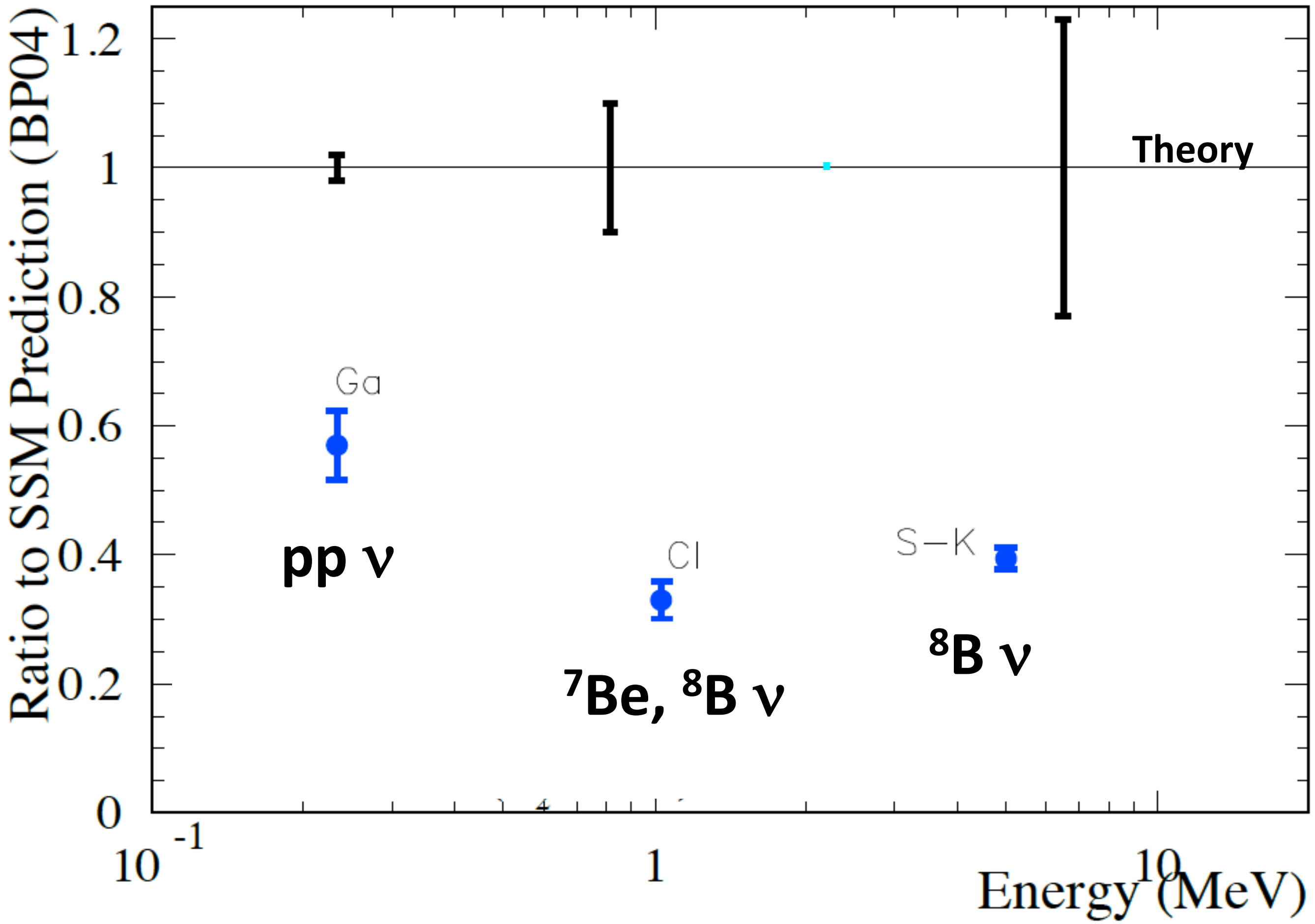


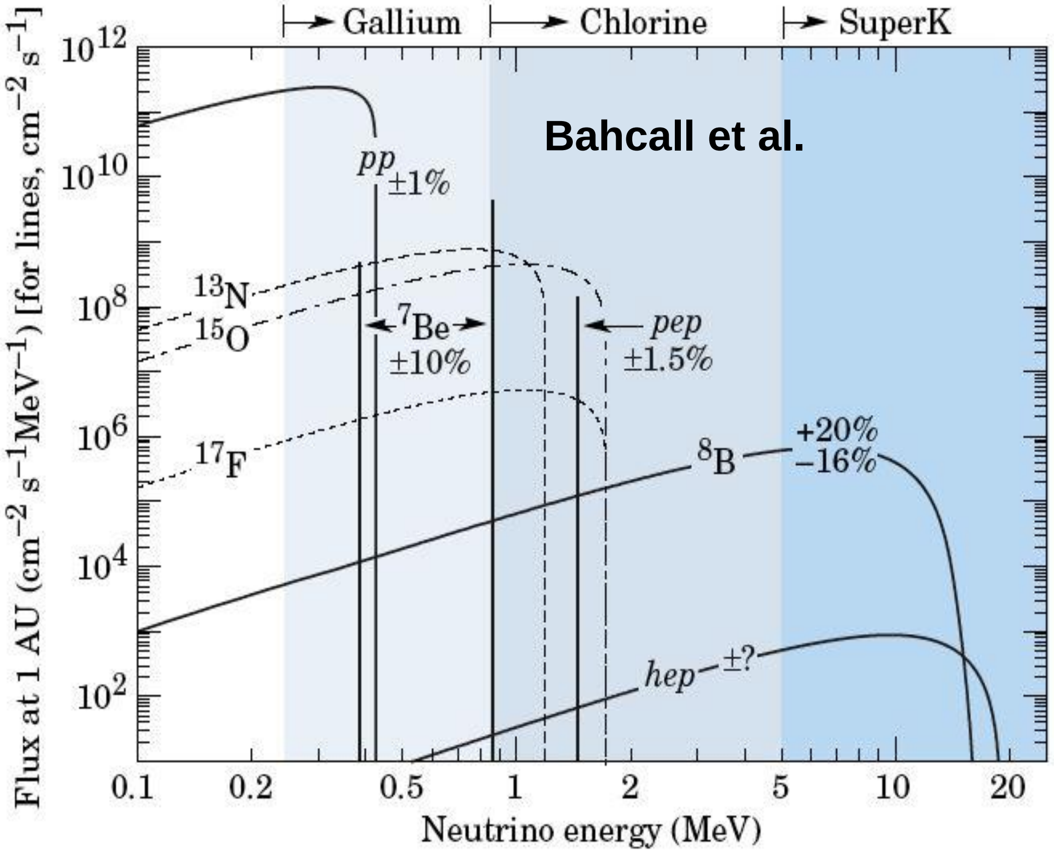
R. Davis Jr.
Noble Laureate 2002

600ton
C_2Cl_4

Pioneering Homestake solar neutrino experiment observed only about 1/3 of the predicted solar neutrinos (1960’s).

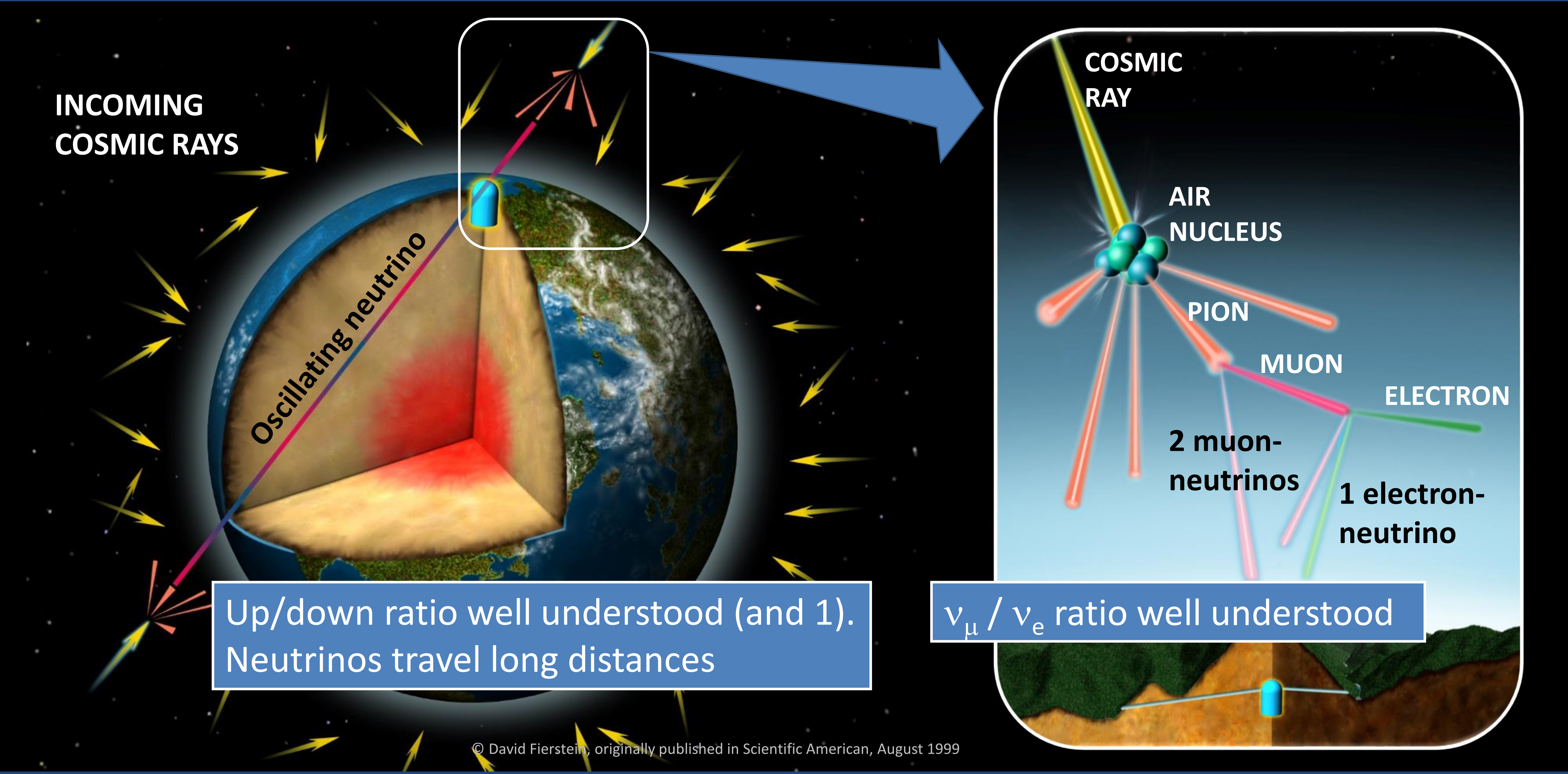
Results from solar neutrino experiments (before ~2000)





Subsequent solar neutrino experiments in the 80's and 90's confirmed the deficit of solar neutrinos.

Atmospheric neutrinos

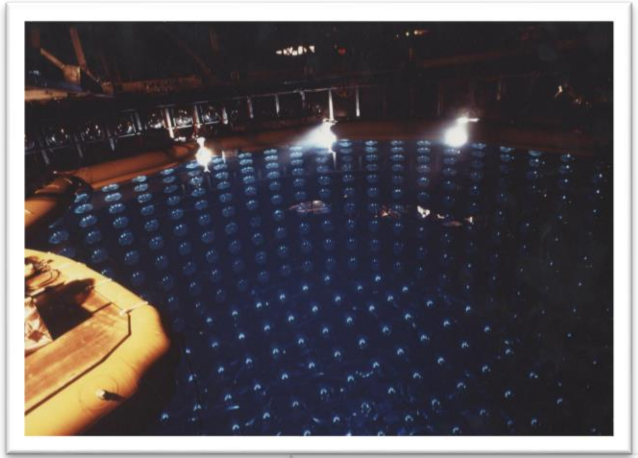


Up/down ratio well understood (and 1).
Neutrinos travel long distances

ν_μ / ν_e ratio well understood

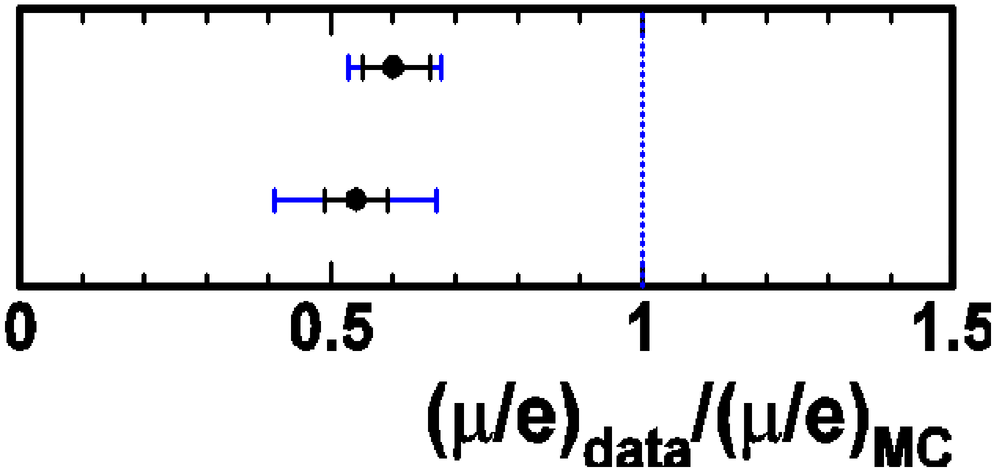
Atmospheric ν_μ deficit (1980's to 90's)

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric ν_μ events was observed.



Kamiokande (1988, 92, 94)

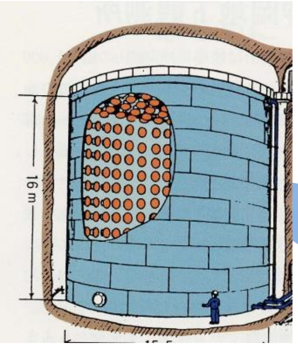
IMB (1991, 92)



Discovery of neutrino oscillations:

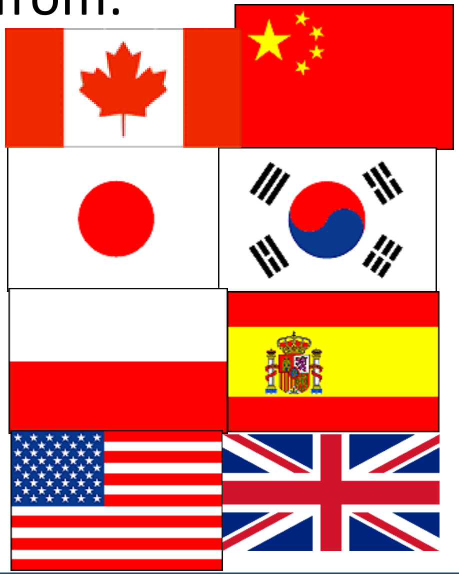
- Atmospheric neutrino oscillations

Super-Kamiokande detector

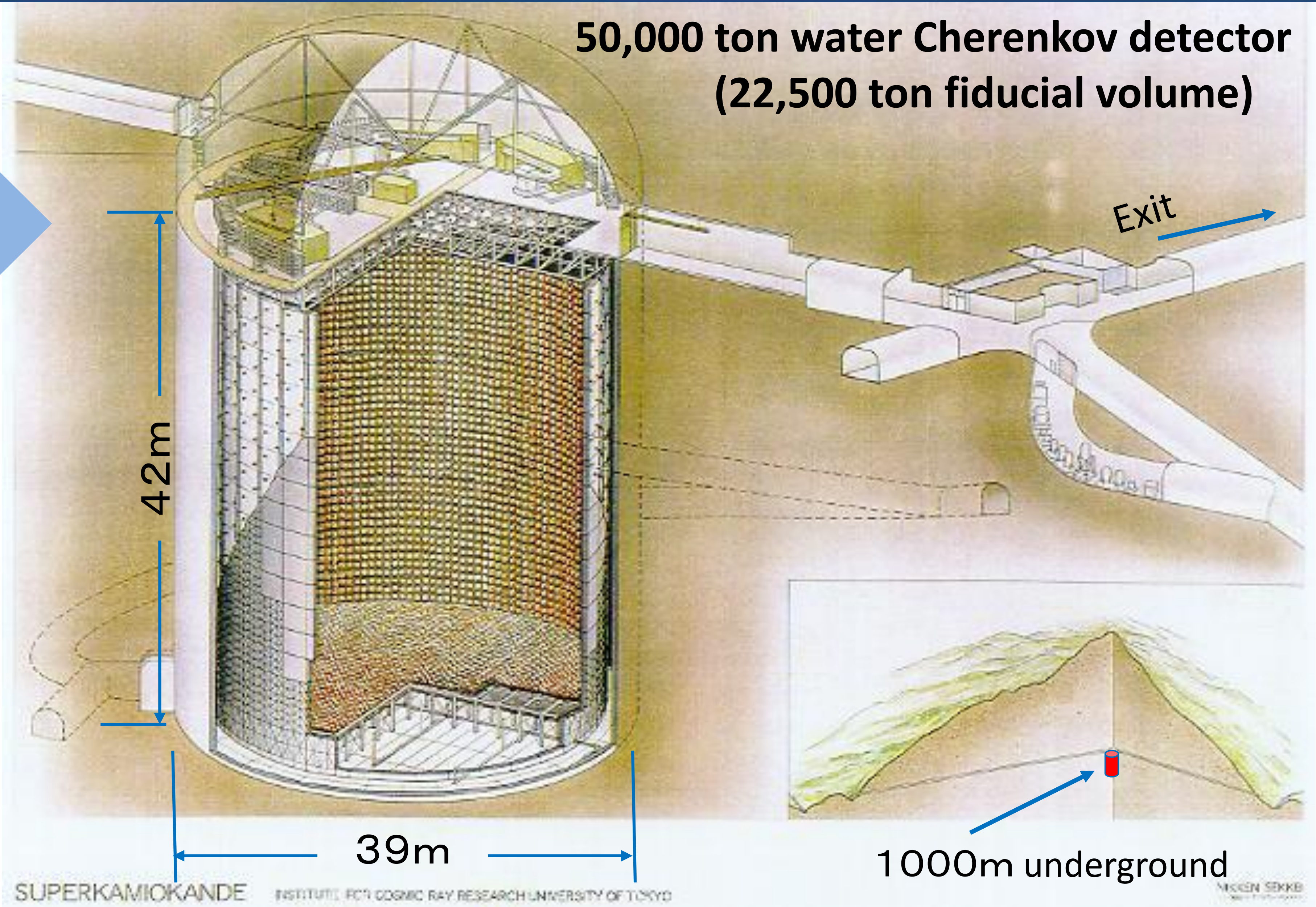


More than 20
times larger mass

~130 collaborators
from:



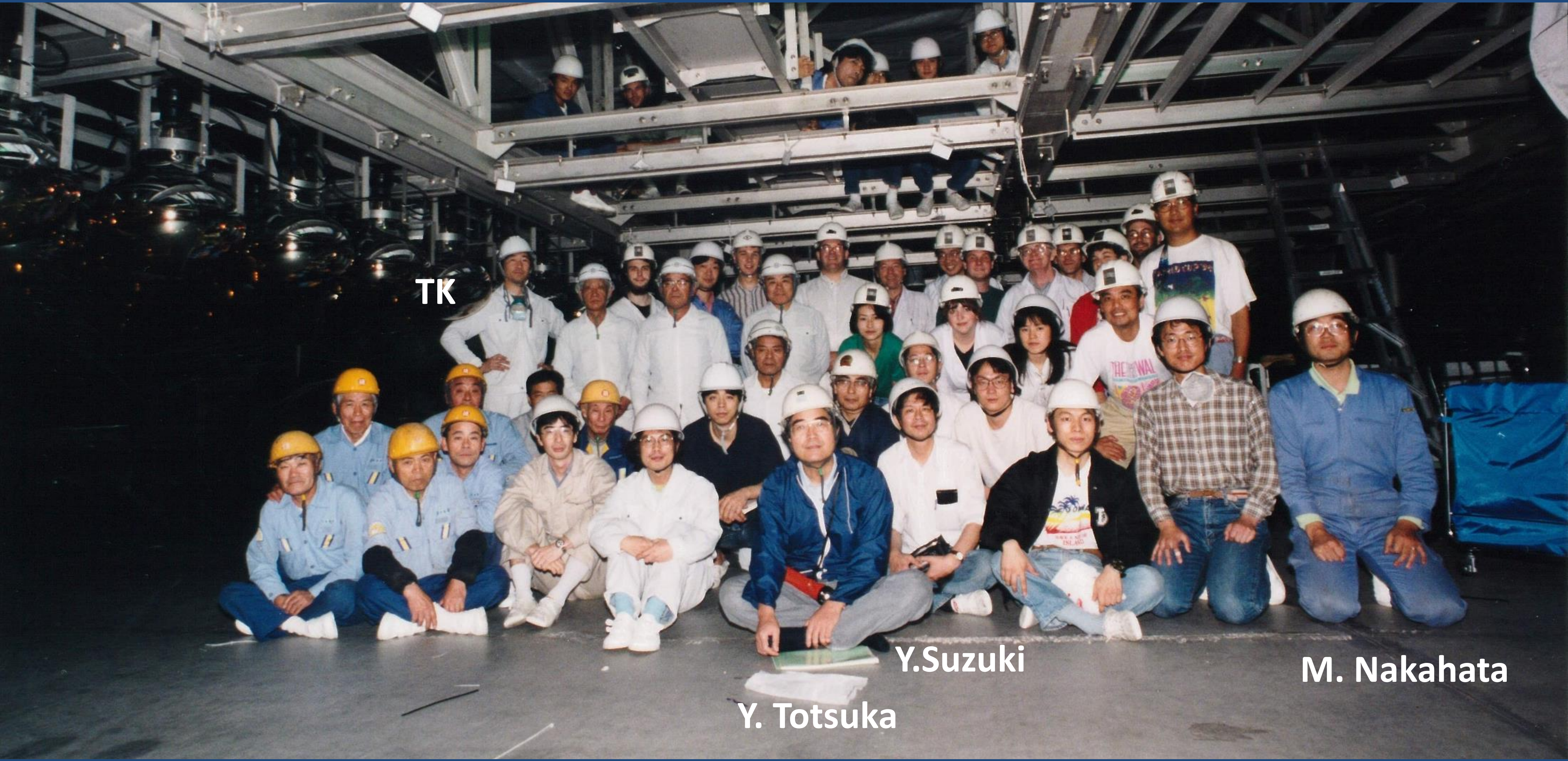
50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)



Beginning of the Super-Kamiokande collaboration between Japan and USA

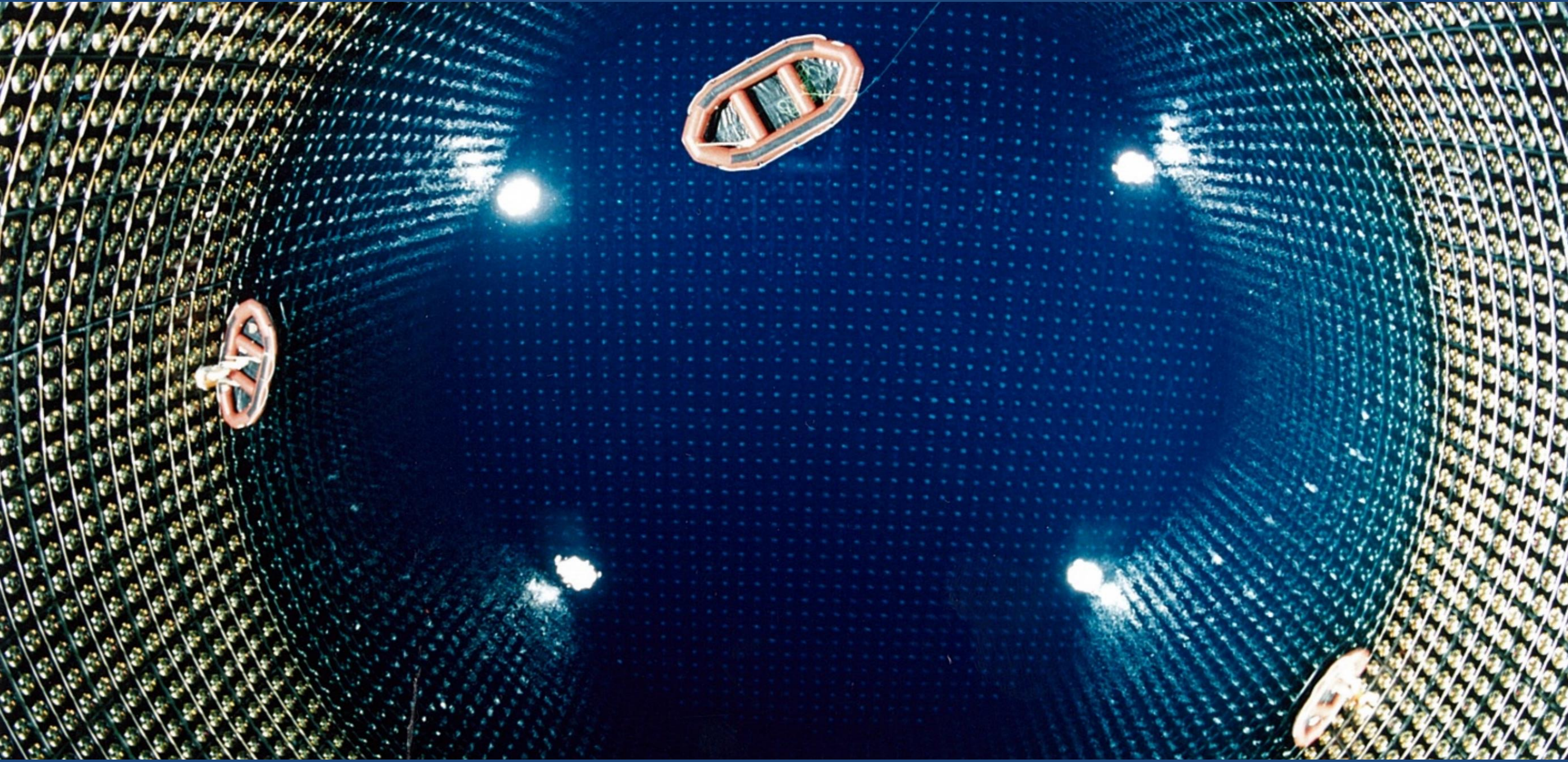
@ Institute for Cosmic Ray Research, 1992

Constructing the Super-Kamiokande detector (spring 1995)

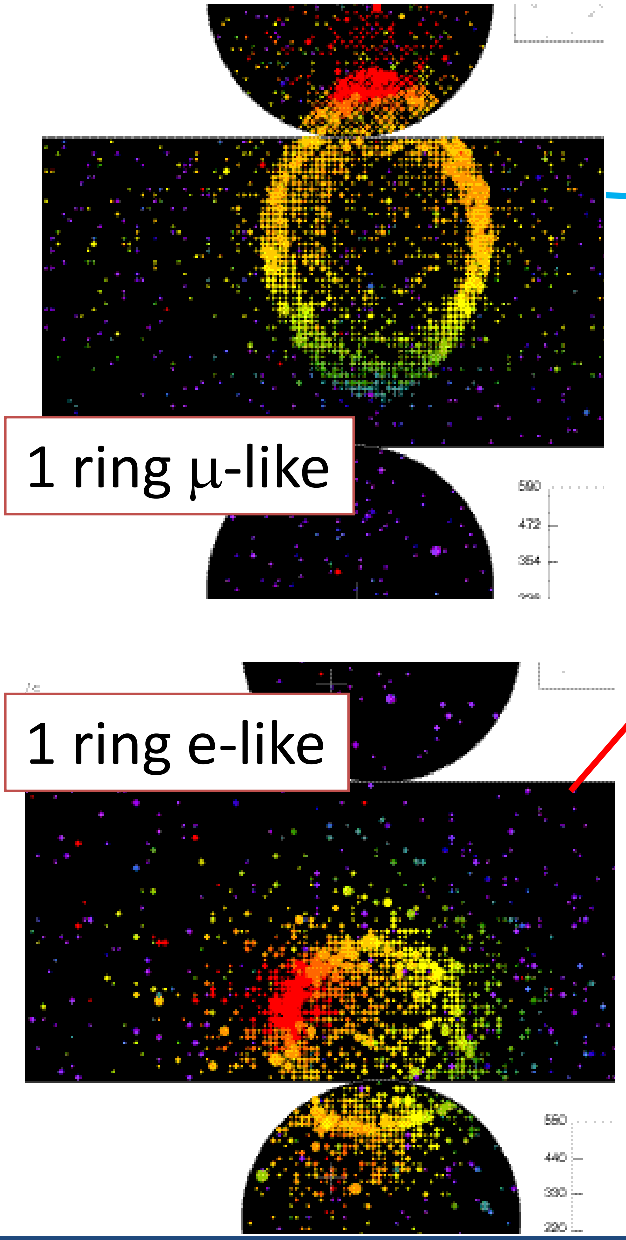


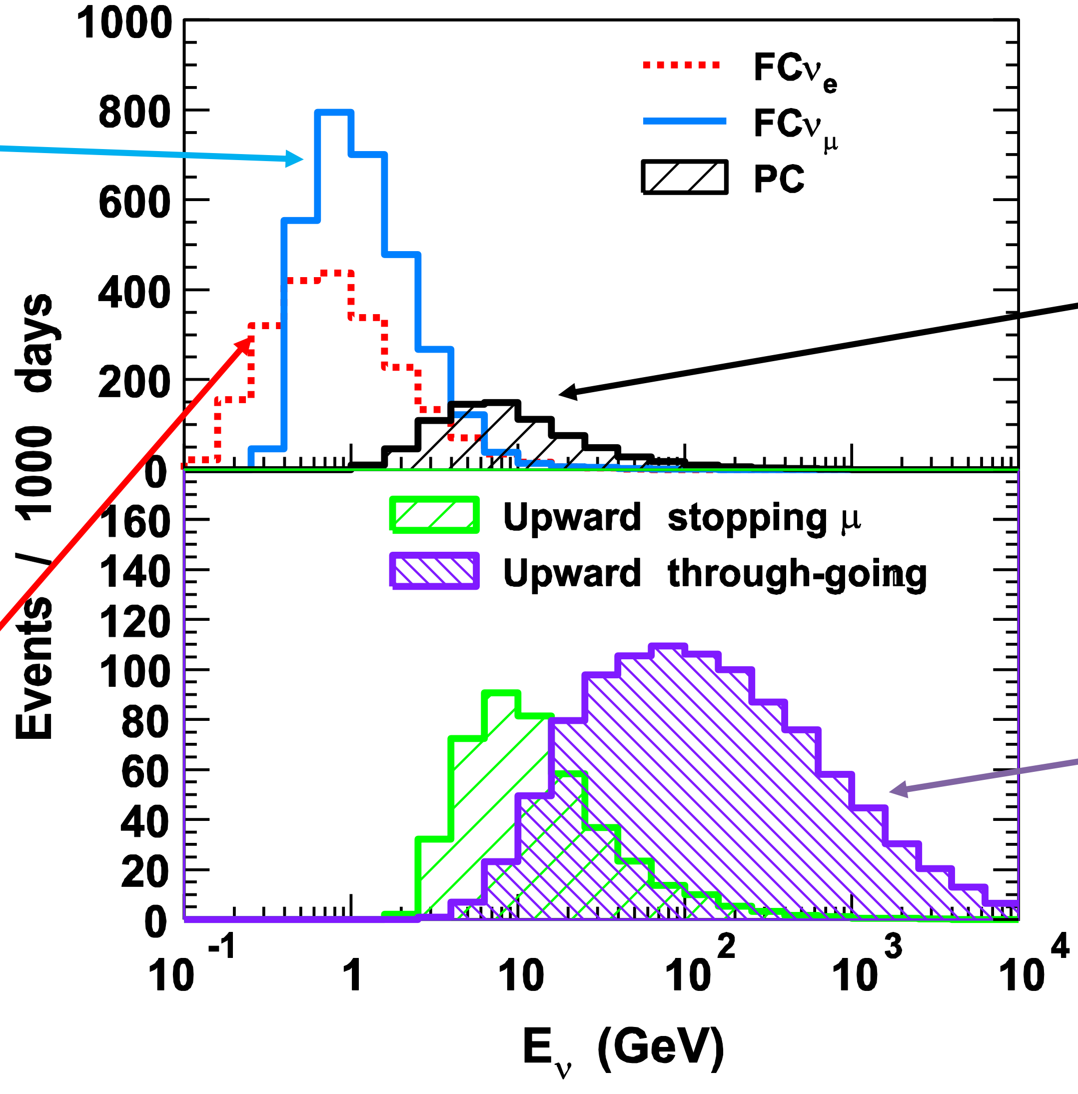
Filling water in Super-Kamiokande

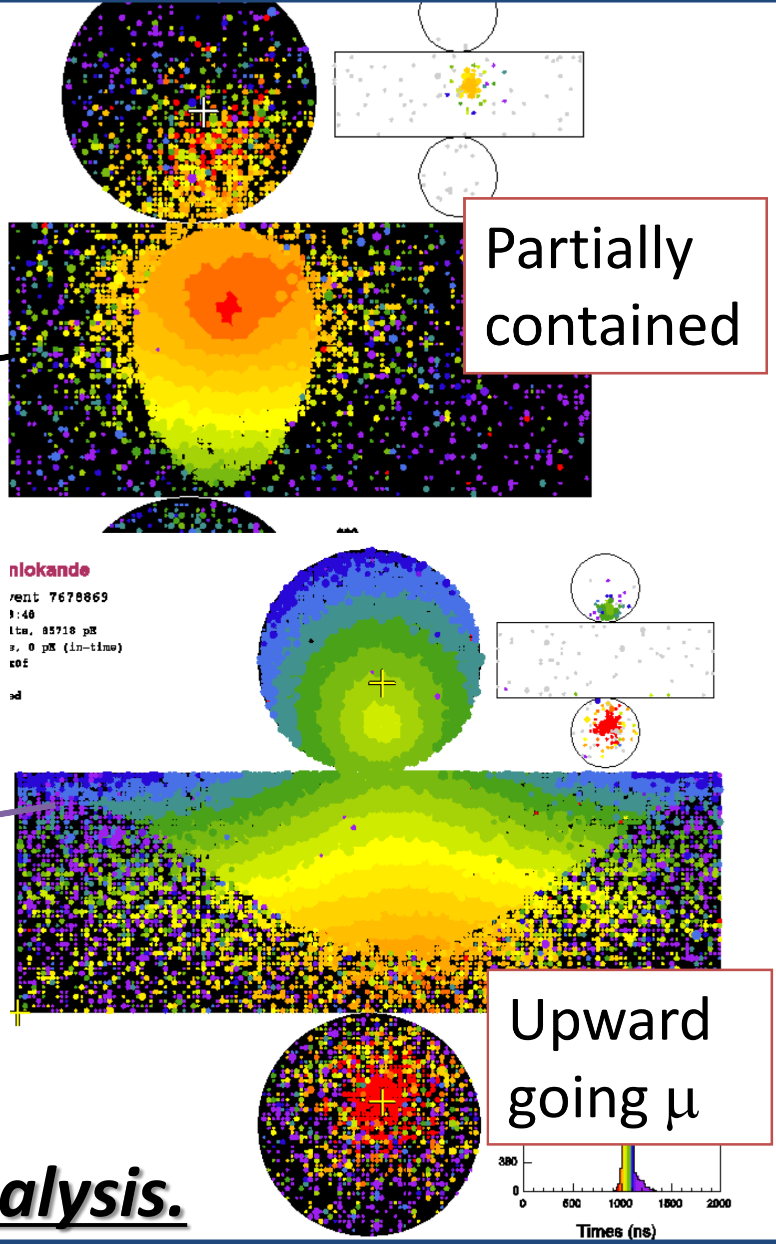
Jan. 1996



Event type and neutrino energy

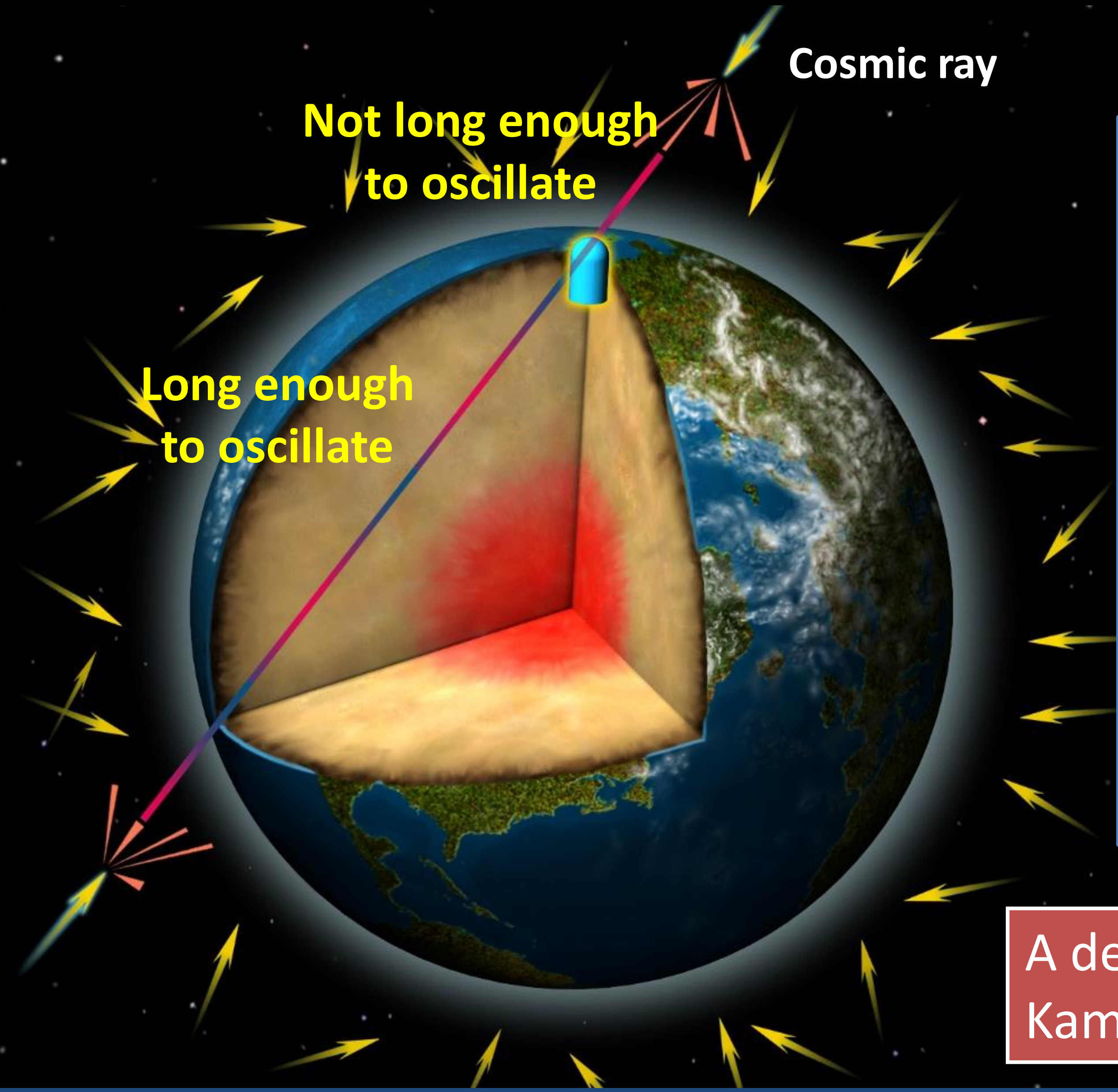


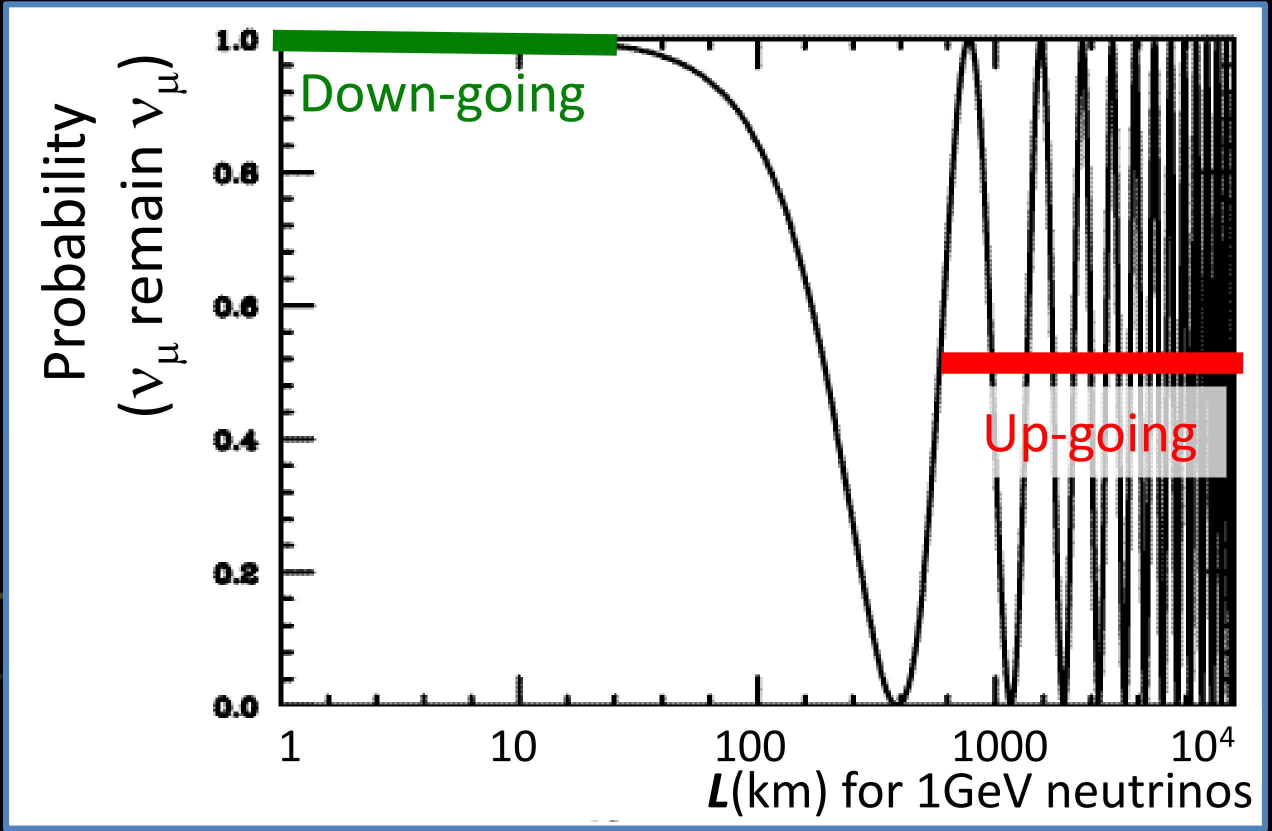




All these events are used in the analysis.

What will happen if the ν_μ deficit is due to neutrino oscillations

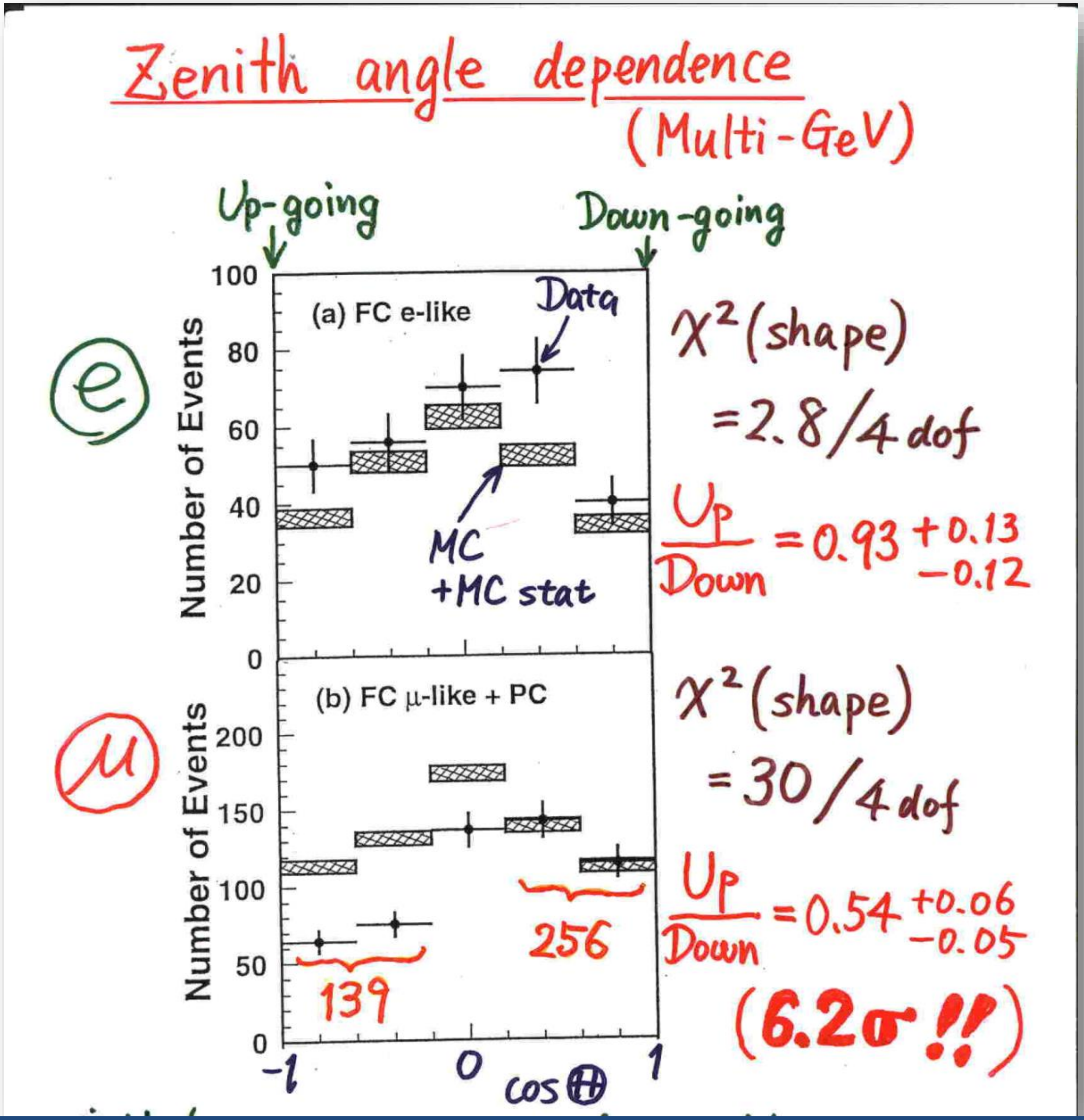


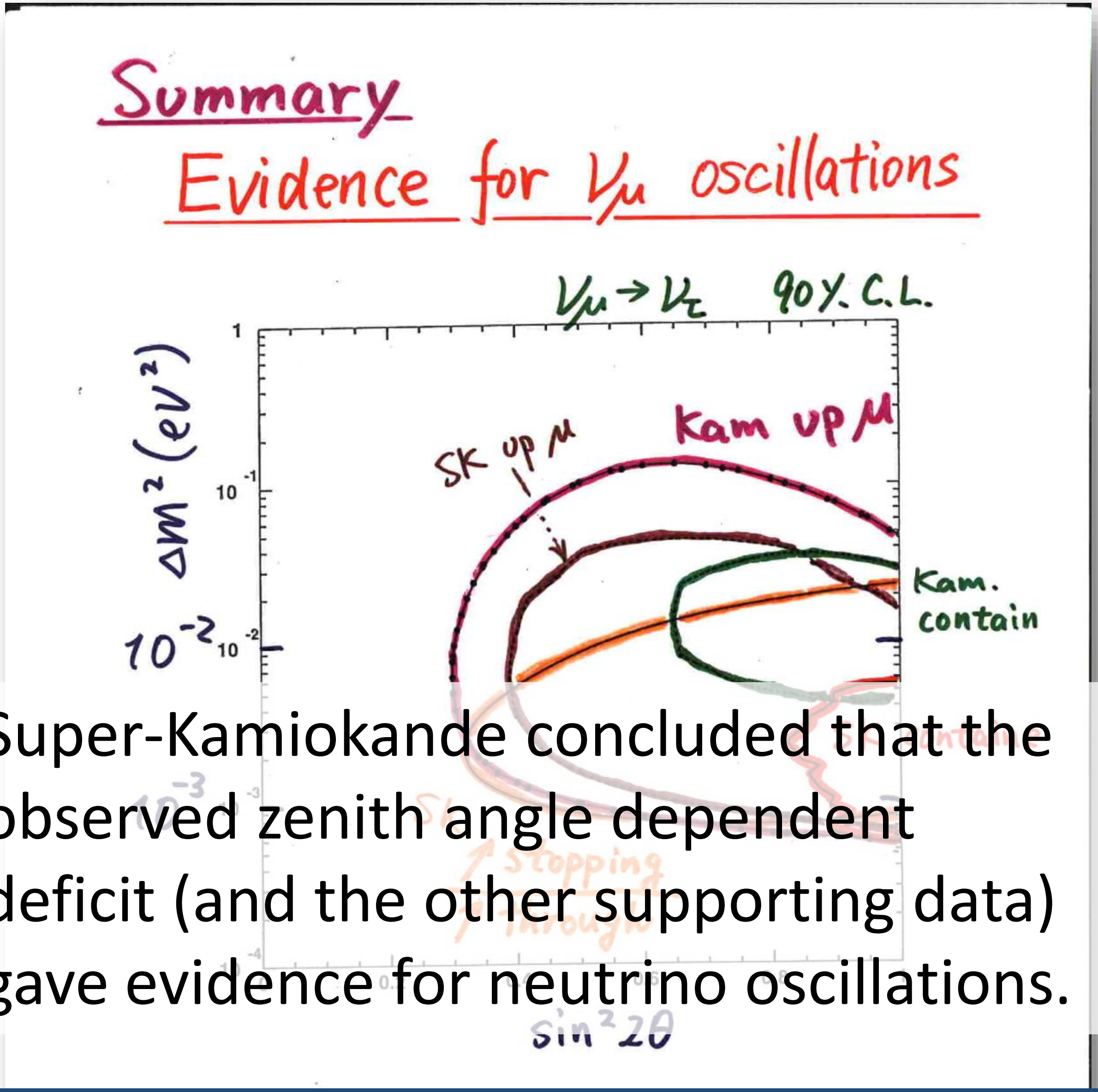


A deficit of upward going ν_μ's should be observed!
Kamiokande was too small. ➔ Super-Kamiokande

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Y. Fukuda et al., PRL 81 (1998) 1562



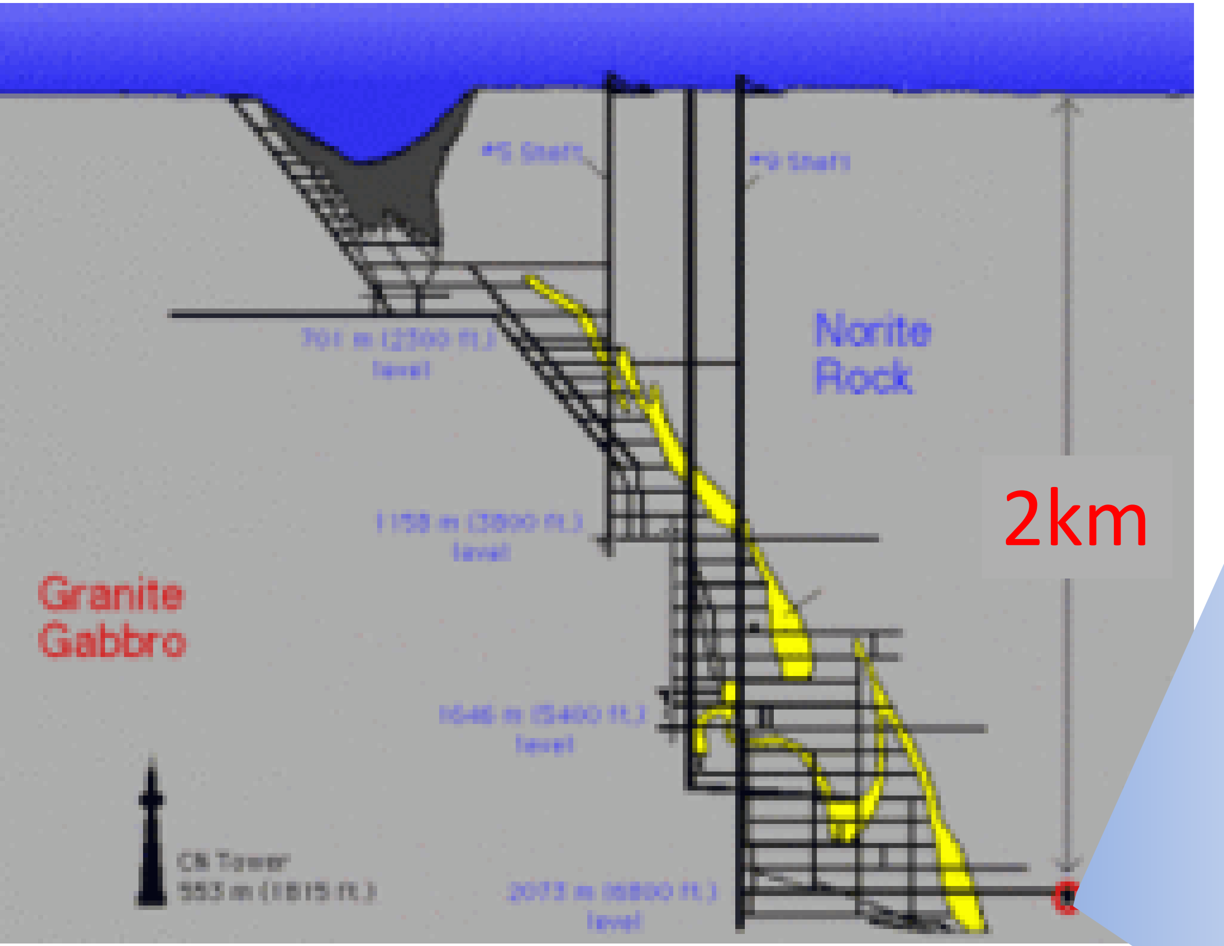


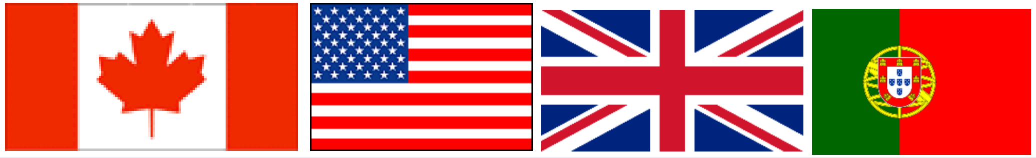
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

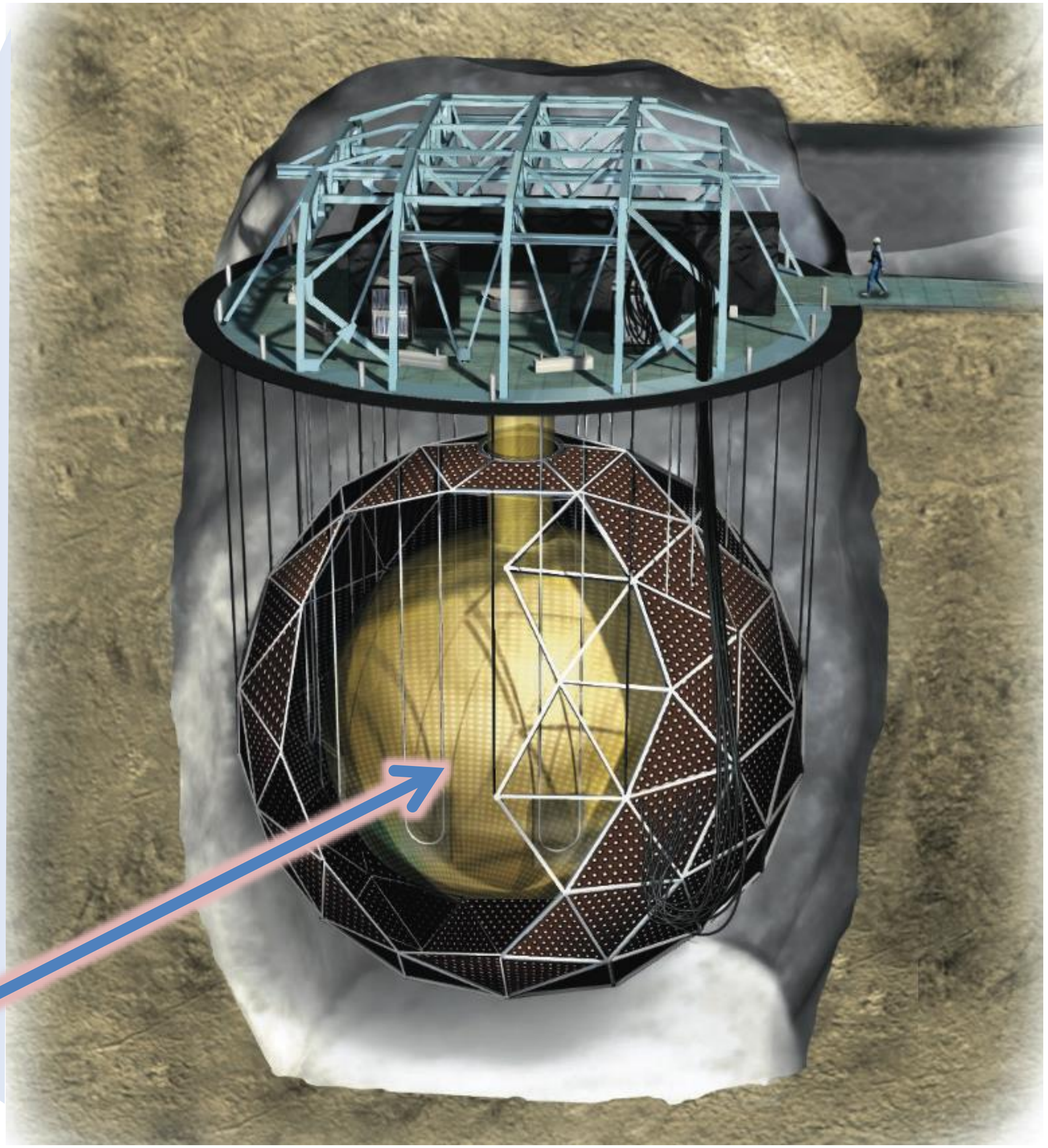
Discovery of neutrino oscillations:

- Solar neutrino oscillations

SNO detector





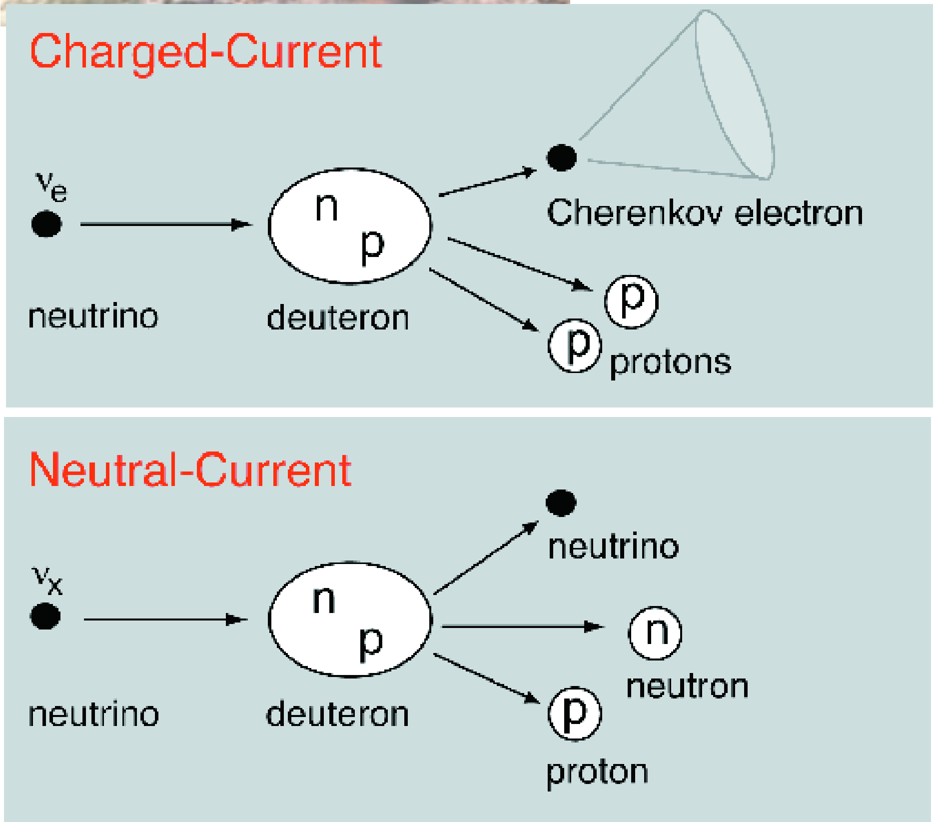


1000 ton of heavy water

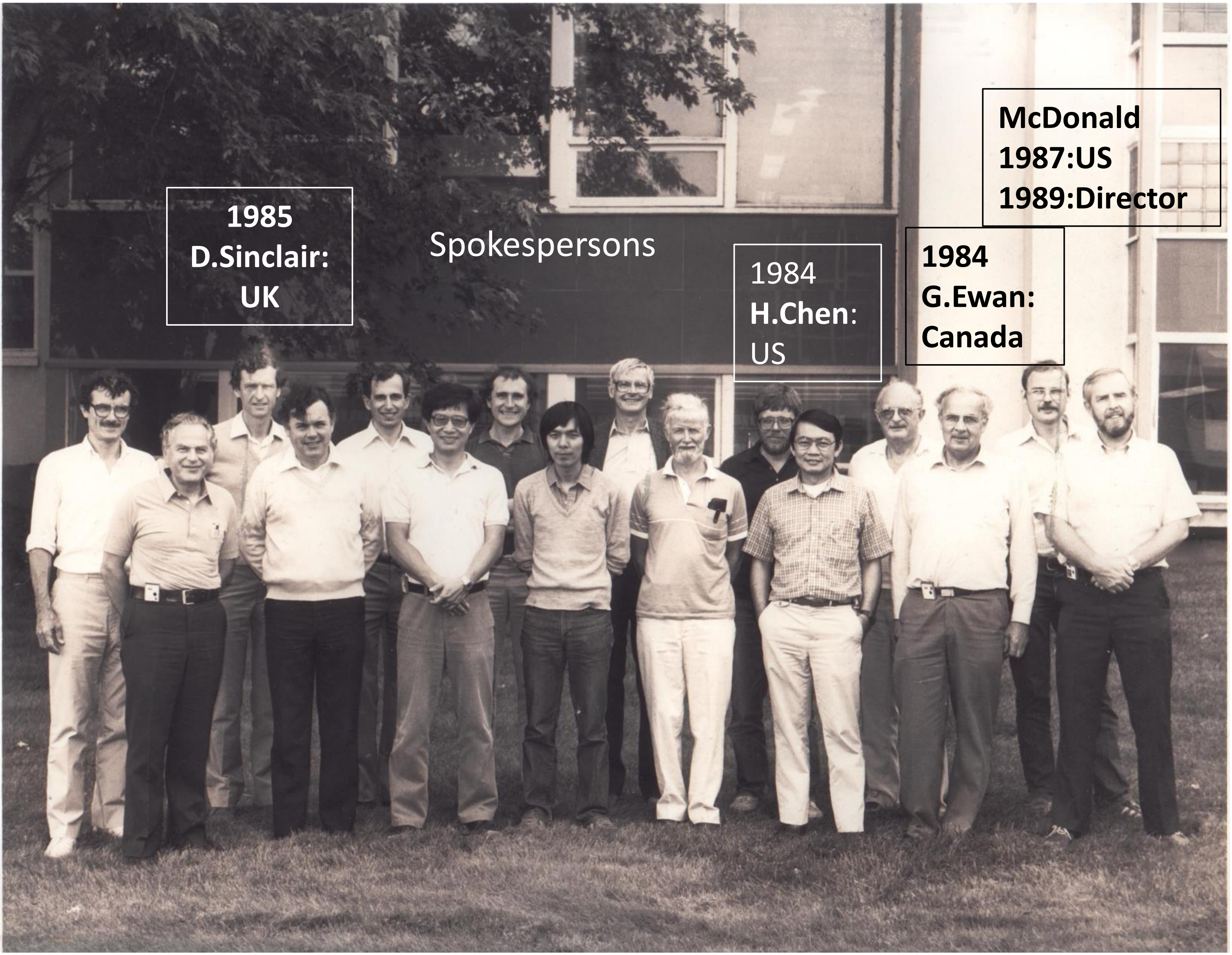
Unique signatures of heavy water (D_2O) experiments

Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu+d \rightarrow \nu+p+n$ and the charged-current reaction $\nu_e+d \rightarrow e^-+p+p$, is suggested for this purpose.



SNO Collaboration Meeting, Chalk River, 1986

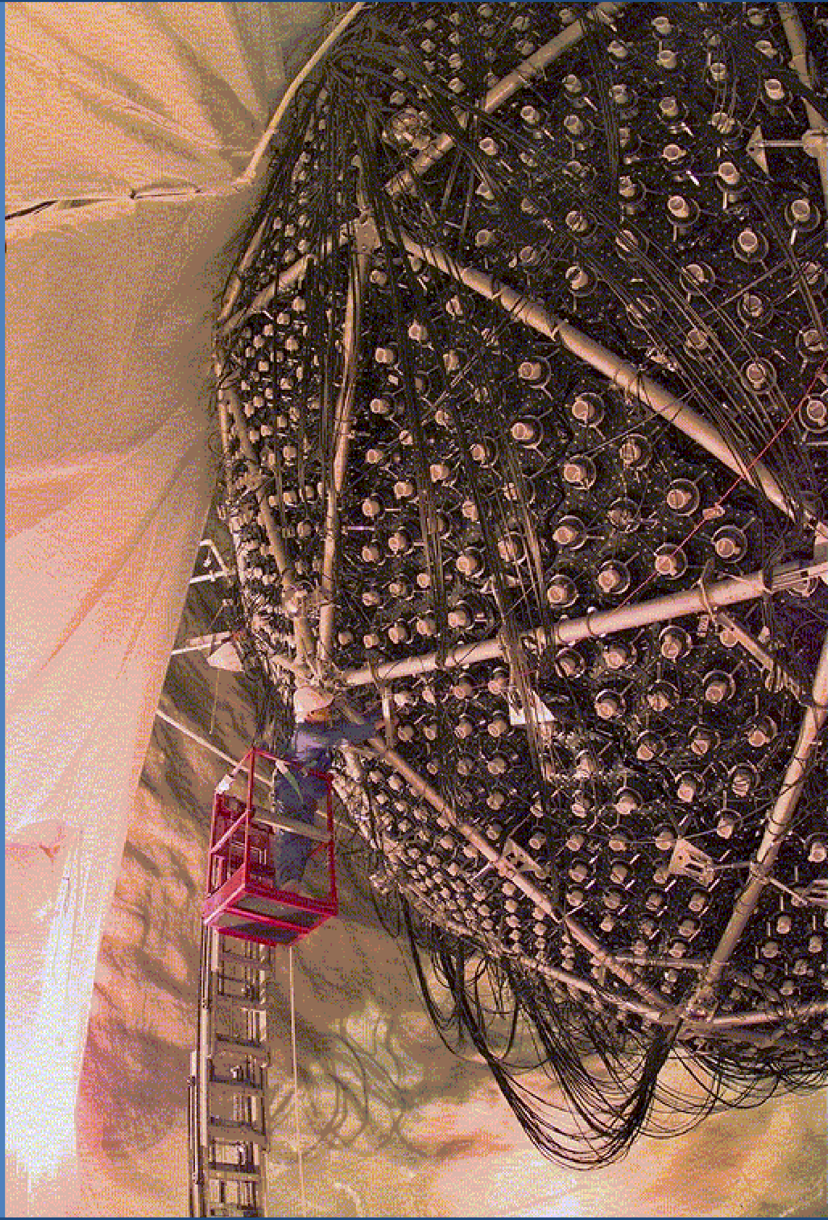


PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA

D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il Nuovo Cimento C9, 308 (1986)

Constructing the SNO detector

One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions.

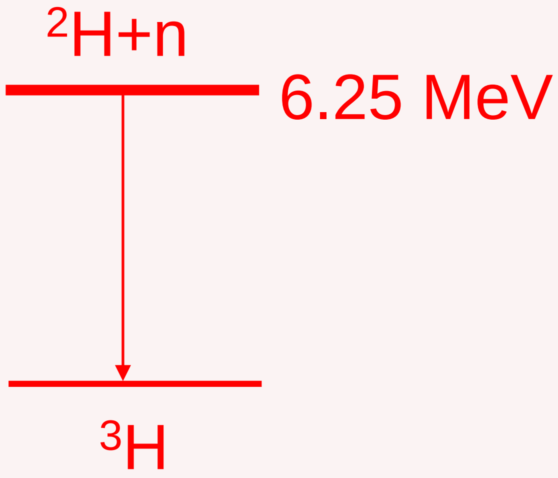


Filled with pure and heavy water in April 1999.

3 neutron detection methods (for $\nu d \rightarrow \nu p n$ measurement)

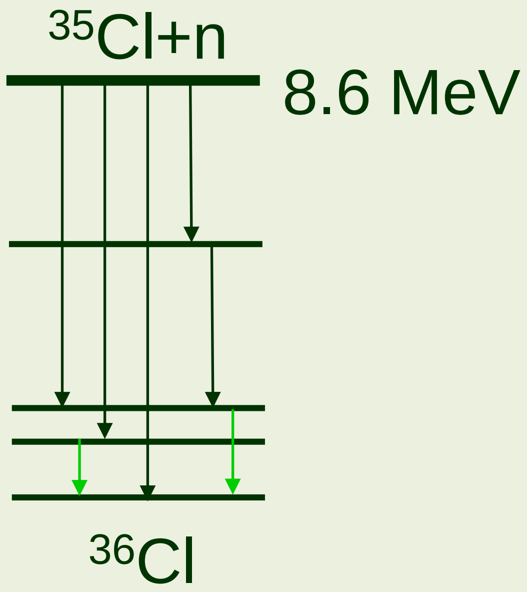
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Eff. ~14.4%



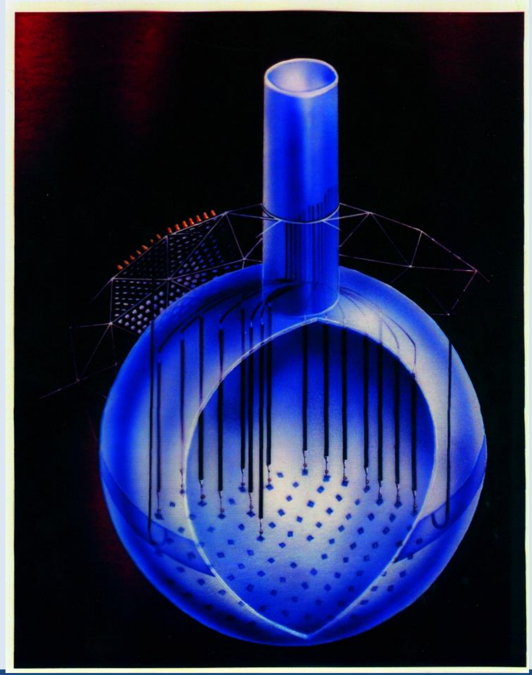
Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Eff. ~40%



Phase III (^3He)
Nov. 04-Dec. 06

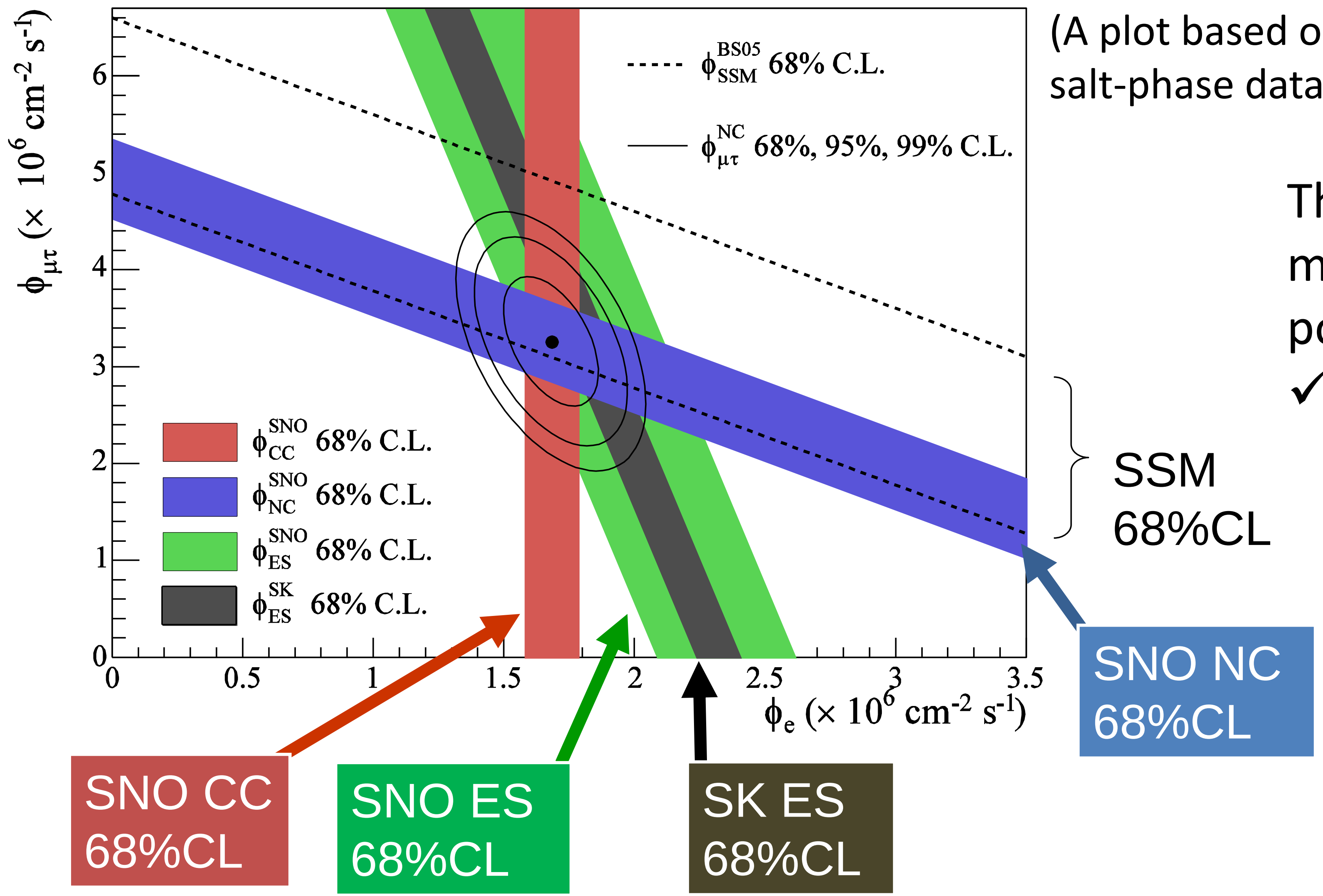
400 m of proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture



Evidence for solar neutrino oscillations

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

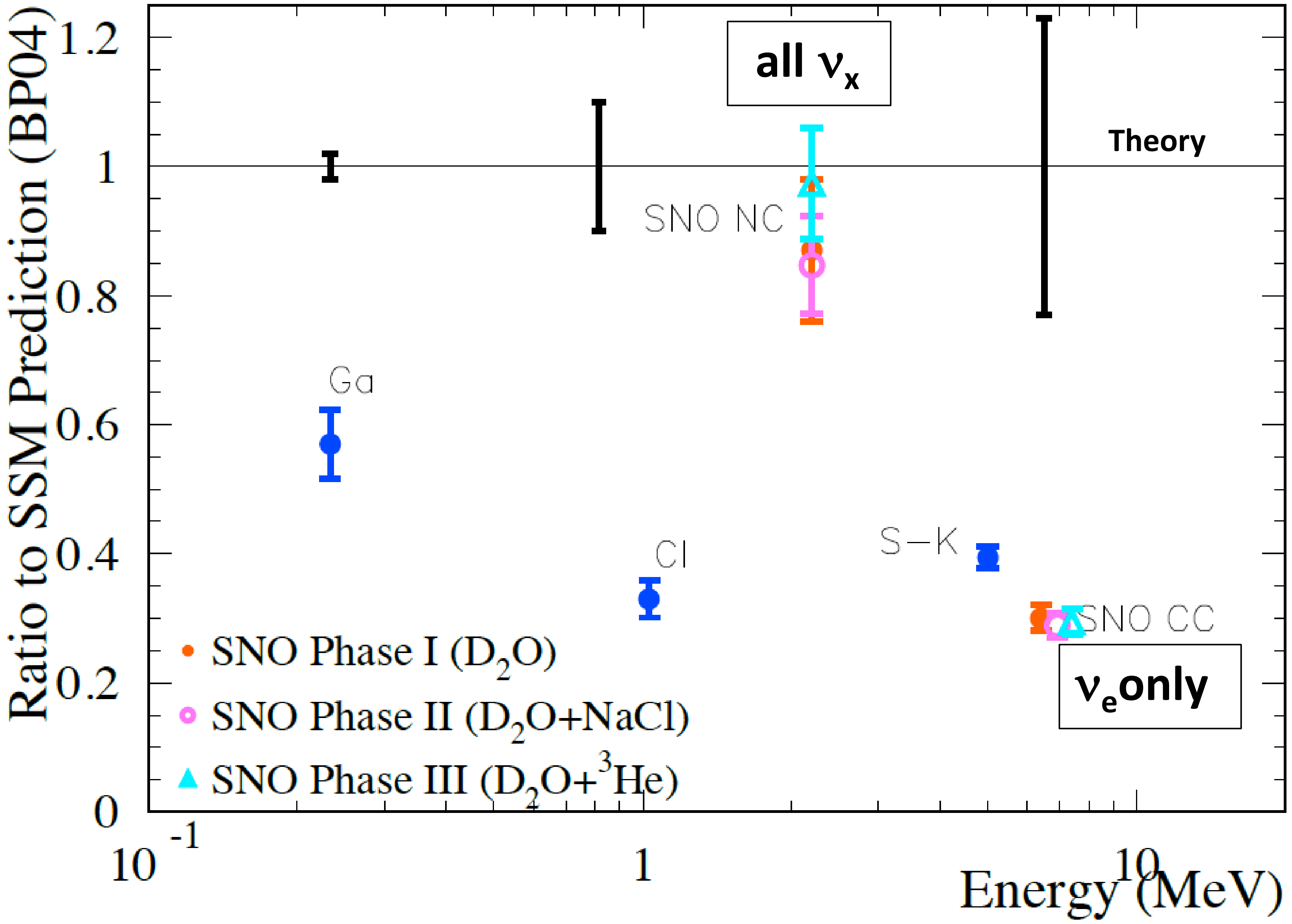
(A plot based on the salt-phase data)

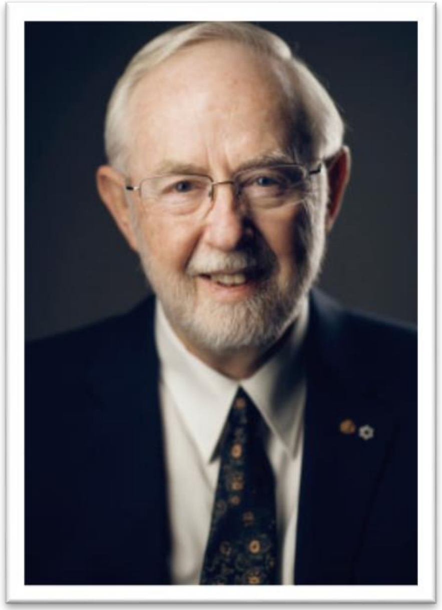


Three (or four) different measurements intersect at a point.

✓ *Evidence for (ν_μ+ν_τ) flux*

SNO results from 3 phases





Art McDonald

Status and future

Neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)

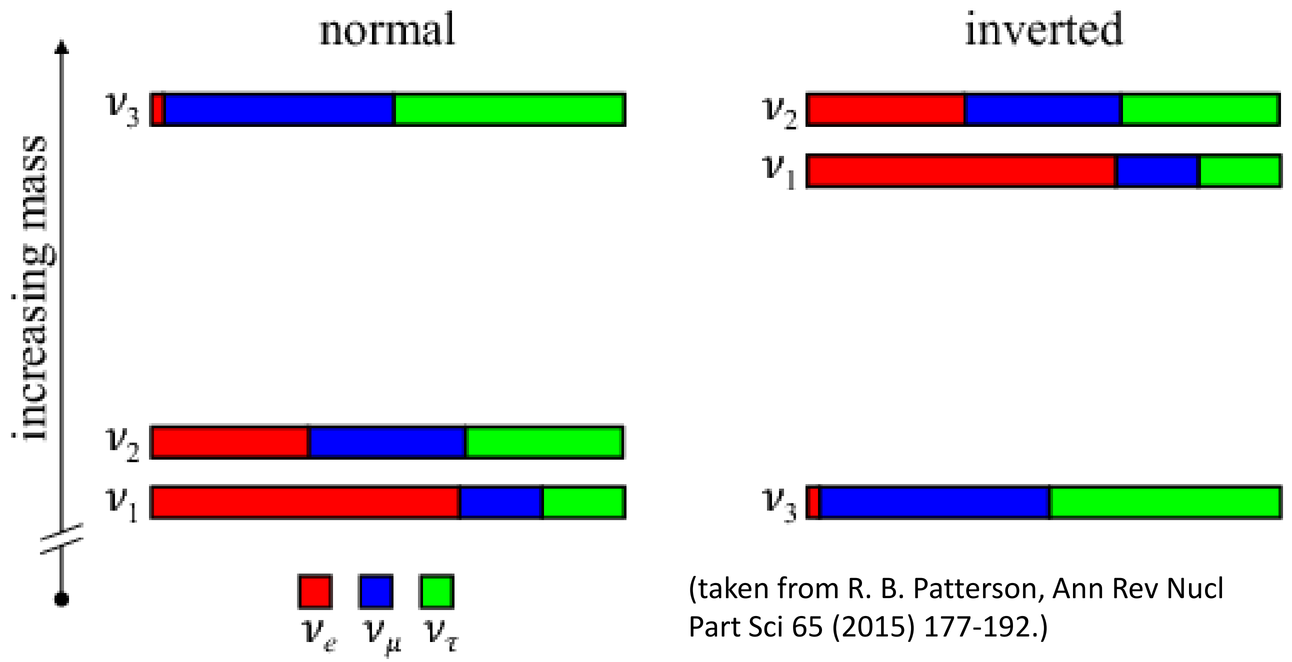
Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\|\Delta m^2\|$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$

K. Nakamura and S.T. Petcov, "14. Neutrino mass, mixing and oscillations"

Basic structure for 3 flavor oscillations has been understood!

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

Absolute neutrino mass?

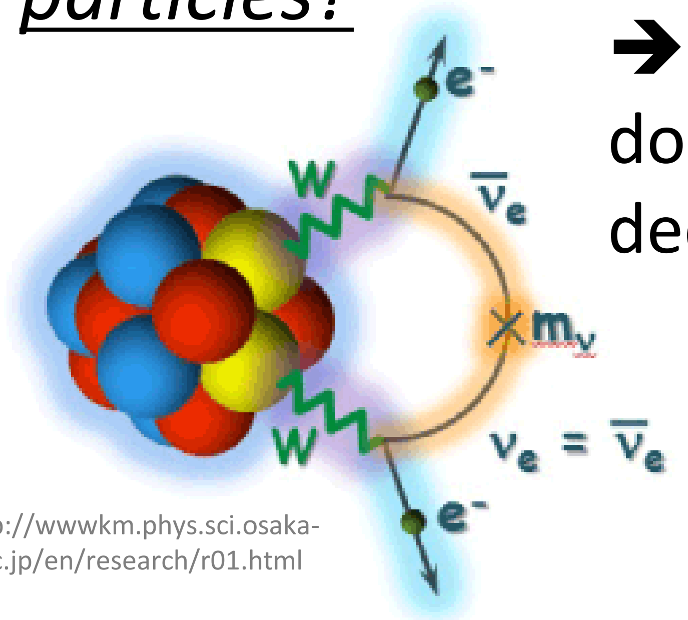
Beyond the 3 flavor framework? (Sterile neutrinos?)

CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?



http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

➔ Neutrinoless double beta decay

Summary

- "Proton decay experiments" in the 1980's observed many contained atmospheric neutrino events, and discovered the atmospheric ν_μ deficit. Subsequently, in 1998, Super-Kamiokande discovered neutrino oscillations.
- Solar neutrino experiments began in the 1960's. Various solar neutrino experiments before 2000 observed the deficit of solar neutrinos. Then the SNO experiment discovered solar neutrino oscillations by the measurements of CC and NC reactions of solar neutrinos.
- Since then, various experiments have studied neutrino oscillations.
- The discovery of non-zero neutrino masses opened a window to study physics beyond the Standard Model of particle physics. Neutrinos might also be the key to understand the baryon asymmetry of the Universe.

It is very important to learn the most from neutrinos!