Disclaimer: Impossible to summarize all wonderful talks in short time given to me. Apologies for skipping many brilliant talks.
This year is the 20th Anniversary of Neutrino Oscillations

NEUTRINO 1998
June 5, 1998@Takayama
Kajita-san
## Discoveries in last 20 years

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Evidence for atmospheric ν osc. (SK)</td>
</tr>
<tr>
<td>1999</td>
<td>Evidence for solar ν osc. (SK vs. SNO CC)</td>
</tr>
<tr>
<td>2000</td>
<td>Evidence for solar ν osc. (SNO CC vs. NC)</td>
</tr>
<tr>
<td>2001</td>
<td>Evidence for reactor ν osc. (KamLAND)</td>
</tr>
<tr>
<td>2002</td>
<td>Evidence for νµ disappearance by artificial ν</td>
</tr>
<tr>
<td>2003</td>
<td>(K2K) Evidence for ντ appearance</td>
</tr>
<tr>
<td>2004</td>
<td>(MINOS)</td>
</tr>
<tr>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>Indication of νe appearance (T2K)</td>
</tr>
<tr>
<td>2009</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td></td>
</tr>
</tbody>
</table>

### Examples of Discovery Plots
- **Evidence for atmospheric ν osc. (SK)**: 
  - Number of Events: 139 vs. 256
  - Significance: 6.2σ !!
- **Evidence for solar ν osc. (SK vs. SNO CC)**
- **Evidence for solar ν osc. (SNO CC vs. NC)**
- **Evidence for reactor ν osc. (KamLAND)**
- **Evidence for νµ disappearance by artificial ν**
- **Evidence for ντ appearance**
- **Indication of νe appearance (T2K)**
- **Observation of νe disappearance in reactor**
- **(Daya Bay)**
- **(RENO)**
- **(Double Chooz)**
- **(SK, 3.8σ)**
- **(OPERA, 5.1σ)**
Workshop for the
Next Generation Nucleon Decay and Neutrino Detector (NNN99)

September 23 - 25, 1999
SUNY at Stony Brook, NY, USA

Listening Groups:
Nucleon Decay
Neutrino Oscillations
Neutrino Astrophysics

NNN99 International Advisory Committee
J. Bahcall, IAS
K. Cowen, IPP
L. DiLella, CERN
S. Feldman, Harvard
I. Gaisser, Darmstadt
M. Goldhaber, BNL
F. Halzen, Wisconsin
W. Hartson, Washington
P. Langacker, Penn
W. Marciano, BNL
D. Moskowitz, CLAS/Savoye
K. Nakamura, KFK
J. Popple, Fermilab
F. Schmidt, Columbia
H. Sohle, UC (Chair, MC)
C. Stirling, DESY/Zeehoven
F. Souto, HEP/PPN
Y. Totuka, JCR
T. Wiegardt, GSI
S. Myokei, Stanford
C. M. Yung, Stony Brook

NNN99 Organizing Committee
B. Giant, GSI
M. Diwan, BNL (Chair)
K. E. Ahn, BNL
K. Choo, Stony Brook (Co-chair)
T. Kayano, JCR
D. McCarty, Stony Brook
D. M. Page, Stony Brook
K. K. Ng, Stony Brook
A. Rubbia, ETH/Zurich
D. Schramm, Stony Brook
R. Shrock, Stony Brook
H. Sohle, Chair, Interational Advisory Committee
K. S. S. Sibstedt, LSI (Chair, Program Committee)
C. Yanagisawa, Stony Brook

For more information, please contact:
Jean Napolitano, Conference Secretary
HEP Group, Dept. of Physics and Astronomy
SUNY at Stony Brook, NY 11794-3800, USA
PHONE: 516-632-8955
FAX: 516-632-8101
EMAIL: nnn99@superk.physics.sunysb.edu

Further information and registration
http://superk.physics.sunysb.edu/NNN99/
What we know now after the 20 years

Note: differences between global fit groups should be resolved.
Next Questions in Neutrino Physics

- Which mass ordering? Normal or Inverted?
- Is CP violated?
- $\theta_{23}$ octant or full mixing?
- What is the absolute mass of neutrinos?
- Is neutrino mass Dirac or Majorana?
- Is there sterile neutrinos?
Mass ordering at present

Global analyses

Super-K atmospheric $\nu$

![Graph showing mass ordering at present](image1)

S. Mine

T2K

![Graph showing mass ordering at present](image2)

L. Kormos

NOvA

![Graph showing mass ordering at present](image3)

G. Pawloski

<table>
<thead>
<tr>
<th>Source</th>
<th>$\chi^2_{IO} - \chi^2_{NO}$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bari</td>
<td>9.5</td>
<td>$\approx 3.1\sigma$</td>
</tr>
<tr>
<td>NuFit</td>
<td>9.1</td>
<td>$\approx 3.0\sigma$</td>
</tr>
<tr>
<td>Valencia</td>
<td>11.7</td>
<td>$\approx 3.4\sigma$</td>
</tr>
</tbody>
</table>

NO is favored over IO at $\sim 3\sigma$ level.
Mass Ordering in near future

JUNO

$\Delta \chi^2 \sim 10$ JUNO only

$\Delta \chi^2 \sim 14$
(if accuracy of $\Delta m^2_{\mu\mu}$ is constraint to be 1% by long baseline exp.)

Data taking will start in 2021.

KM3NeT(ORCA)/PING

~4$\sigma$ level for full mixing.
Mass Ordering, eventually

DUNE

A. Sousa

Mass Ordering

\[
\Delta \chi^2
\]

\[
\sqrt{\Delta \chi^2}
\]

DUNE Sensitivity
Normal Ordering
\[\sin^2 \theta_{13} = 0.085 \pm 0.003\]
\[\theta_{23}: \text{NuFit 2016 (90\% C.L. range)}\]

\[\sin^2 \theta_{23} = 0.441 \pm 0.042\]
CP violation now

**T2K** L. Kormos

**NOvA** G. Pawloski

CP conserving values of $\delta_{\text{CP}}$ lie outside 2$\sigma$ region.

Excludes $\delta_{\text{CP}}=\pi/2$ of IO at >3$\sigma$ but CP conserving values still allowed.
CP violation now

With same horizontal axis

Similar shape for IO. More statistics are necessary to discuss further.
### Future $\delta$CP measurement

#### DUNE vs. Hyper-Kamiokande

<table>
<thead>
<tr>
<th></th>
<th>DUNE</th>
<th>Hyper-K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>1300 km</td>
<td>295 km</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>Several GeV</td>
<td>~0.6 GeV</td>
</tr>
<tr>
<td><strong>Earth Matter effect</strong></td>
<td>Large (sensitive to mass ordering)</td>
<td>Small (less effect from mass ordering)</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>40 kton Liquid Ar TPC</td>
<td>190 kton water Cherenkov</td>
</tr>
</tbody>
</table>

Complementary measurements.
Hot news from DUNE and Hyper-K

A. Pritchard
A. Sousa

The protoDUNE SP at CERN taking beam and cosmic-ray data.

Hyper-K construction will begin in April 2020.

Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.
Future $\delta$CP measurement

DUNE

Hyper-Kamiokande

A. Pritchard

A. Sousa

Precision of $\delta$CP measurement (10 years)

$\sim 16^\circ$ ($\sim 7^\circ$) for $\delta$CP$=\pm 90^\circ$ ($0^\circ$ )

$\sim 22^\circ$ ($\sim 7^\circ$) for $\delta$CP$=\pm 90^\circ$ ($0^\circ$ )
Exploring the Origin of Neutrino Masses

- Majorana Neutrinos
  - Observations of $0\nu\beta\beta$ decays/CvB

- Dirac Neutrinos
  - We are here
  - Discovery of proton decays

- Radiative models
  - Collider Searches
    - Dark Matter
  - Collider Searches
    - New Physics

- New strong dynamics
  - GUT-scale
    - Matter-antimatter Asymmetry
  - TeV-scale
    - Collider Searches for LNV Signals

- A long way to go before we understand the origin of neutrino masses

- A decisive signal will be the discovery of B and L number violation (e.g., nucleon decays & $0\nu\beta\beta$ decays)

- Try different ideas, such as the detection of CvB and atomic/molecular systems
Sign doors at Kamioka
The first door at Kamiokande

Sheldon Lee Glashow
Aug. 30, 1984

I shall decay when the proton returns!

Paul Langacker
August 5, 1985

Decay or not decay?
That is the question.
Yoichiro Nambu’s sign

Like the Sleeping Beauty
I shall wake up after a hundred years to see the Kamioka results on proton decay.

16 Nov 1984

My interpretation
It would take a hundred years to discover proton decay, if you keep taking data with Kamiokande. You must make a much bigger detector.

A hundred years at Kamiokande = a few years at Hyper-Kamiokande
Proton decay current results

\[ p \to e^+ \pi^0 \] search result

- Total expected \#BKG (SK I-IV) < 1:
  - confirmed with K2K \( \nu \) beam data; PRD 77, 032003 (2008)
- No data candidate (SK I-IV 0.37 Mt·yrs)
  - \( \tau/B_{p \to e\pi} > 2.0 \times 10^{34} \) years (90% CL)

\[ p \to \nu K^+ \] search result

- No data candidate (SK I-IV 0.37 Mt·yrs)
  - \( \tau/B_{p \to \nu K^+} > 8.2 \times 10^{33} \) years (90% CL)

SNO+ limit on 3\( \nu \) decay mode

- Total expected \#BKG (SK I-IV) < 1:
  - confirmed with K2K \( \nu \) beam data; PRD 77, 032003 (2008)
- No data candidate (SK I-IV 0.37 Mt·yrs)
  - \( \tau/B_{p \to e\pi} > 2.0 \times 10^{34} \) years (90% CL)
Proton decay sensitivity of HK

\[ p \rightarrow e^+ \pi^0 \]

3\(\sigma\) discovery sensitivity:
\[ \frac{\tau}{BR} = 10^{35} \text{ years} \]

\[ p \rightarrow \nu K^+ \]

3\(\sigma\) discovery sensitivity:
\[ \frac{\tau}{BR} = 3 \times 10^{34} \text{ years} \]
Double beta decay

Unique method to investigate Majorana feature of neutrino mass.

<table>
<thead>
<tr>
<th>Past &amp; present</th>
<th>Half life</th>
<th>Mass of isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sim 100\text{meV} )</td>
<td>( 10^{25}\sim10^{26}\text{y} )</td>
<td>( 10\sim10^2\text{kg} )</td>
</tr>
<tr>
<td>Near future</td>
<td>( 10^{26}\sim10^{27}\text{y} )</td>
<td>( 10^2\sim10^3\text{kg} )</td>
</tr>
<tr>
<td>Future</td>
<td>( 10^{27}\sim10^{28}\text{y} )</td>
<td>( 10^3\text{kg} )</td>
</tr>
</tbody>
</table>
Summary of “multi-messenger signals” from exploding 17 $M_{\odot}$ star


Energetics: $E_{\text{neutrino}} \sim 10^{53}$ erg, $E_{\text{kinetic}} \sim 10^{51}$ erg, $E_{\text{photon}} \sim 10^{49}$ erg, $E_{\text{GW}} \sim 10^{46}$ erg

K. Kotake
High frequency variation by SASI might be observed.
Supernova burst detectors in the world now

- Super-Kamiokande
- KamLAND
- Baksan
- LVD
- Borexino
- SNO+
- IceCube
- HALO
- NOvA
- Daya Bay
- MicroBooNE

Target mass:
- Super-Kamiokande: 32 kt
- KamLAND: 1 kt
- Baksan: 0.3 kt
- LVD: 1 kt
- Borexino: 0.3 kt
- SNO+: 1 kt
- IceCube: 0.16 kt
- HALO: 76 t
- NOvA: 14 kt
- MicroBooNE: 90 t
- Daya Bay: 1 gt

Liquid scintillator, Water, Ice, Other
Precise measurement of average energy and luminosity for all neutrino flavors.

\(~1\% \text{ for } \langle E \rangle \text{ for } \bar{\nu}_e\)

\(~10\% \text{ for } \langle E \rangle \text{ for } \nu_e\)

\(~5\% \text{ for } \langle E \rangle \text{ for } \nu_x\)

\(\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*\)
is the dominant interaction.

\(~4000\text{ events for } 10\text{kpc SN.} \sim 60\text{ events from neutronization burst for IO case} \sim 0\text{ for NO.}\)

\(~50\text{~}80k \bar{\nu}_{e\mu} \text{ for } 10\text{ kpc SN.} \sim 2\text{~}3k\text{ events for LMC,} \sim 10\text{ events for M31.}\)

Precise measurement of time variation (e.g. SASI).

\(3\sim 4k \nu + e \text{ gives } \sim 1\text{ deg. pointing accuracy.}\)
Diffuse supernova $\nu$ in SK-Gd

*Similar sensitivity expected at JUNO too.*
On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction, as reported by Fermi-LAT on September 28, 2017, consistent with the flaring gamma-ray blazar TXS 0506+056.
High energy neutrino astronomy by IceCube

Spectrum index depends on event type.

EHE IceCube spectrum
High Energy Neutrino Astrophysics: Future

KM3NeT/ARCA

- 115 Detection Units (DU)
- 18 DOMs/DU
- 31 PMT/DOM
- 64000 PMTs
- 200 m (ORCA)
- 750 m (ARCA)

~210 m (ORCA)
~1km (ARCA)

ARA

IceCube Upgrade

IceCube
DeepCore
Upgrade

ARA station

Interaction Vertex

ICE array

Radio Array
Surface Array
Main Array
Core (PINGU)

IceCube-Gen2

N. Whitehorn

J. Hignight
Anomalies (problems) are important for future discoveries, e.g. “solar neutrino problem” in the Homestake experiment and atmospheric $\nu$ anomaly in Kamiokande.
Composition of the reactor core change with time.

$^{239}\text{Pu}$ yield is consistent with model.

$^{235}\text{U}$ yield disagree with the model at $\sim3\sigma$ level. This result suggests that this isotope may be the primary source of the anomaly.
New Solar Neutrino Problem?

Tension in $\Delta m_{21}^2$ between reactor and solar neutrinos. In future, spectrum and day/night measurements by Hyper-K and JUNO should solve the issue.

$\Delta m_{21}^2$ is the mass squared difference between two neutrino states.

$\sin^2 \theta_{12}$ is the mixing angle between the two states.

SNO+ and Borexino has potential to measure CNO neutrinos.
Fermilab SBN program

Staged approach to address short baseline anomalies
Phase 1: MicroBooNE – definitive test of the MiniBooNE low energy excess
Phase 2: SBND + MicroBooNE + ICARUS – $\nu_e$ appearance and $\nu_\mu$ disappearance searches

Analysis of MicroBooNE data is on-going. We hope to see phase 1 results in near future.

SBND: Detector construction on-going.
   Plan to begin taking data in 2020
ICARUS: Currently instrumenting and commissioning the detector
   Plan to begin taking data in 2019
New underground sites

- **JUNO**: ~700 m underground
- **Hyper-K**: 650 m underground
- **CJPL**: 2400 m underground
- **LBNF/DUNE**: 1475 m underground
Development for possible future large volume detectors

**Theia**

- Large-scale detector (50-100 kton)
- Water-based LS target
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Li...)
- **Flexible!** Target, loading, configuration
  - Broad physics program!

**Development of water-based LS**

**ANNI**

- **G. D. Orebi Gann**

More interesting plots. See Dr. Gann’s presentation

**V. Fischer**

- **Pure water fill**
  - Spring 2019
  - Commissioning

- **Gadolinium loading**
  - Spring 2019 - Summer 2020
  - Physics data taking
  - Neutron yield measurement
  - CC cross section measurement
  - CC0π cross section measurement

- **Additional LAPPDs**
  - Fall 2020
  - More detailed reconstruction of multi-track final states and pions
  - Possible NC cross section measurement

- **Phase III**
  - ~2021
  - Testbed for new technologies
Conclusion

• Fantastic neutrino physics in last 20 years.
• We expect another interesting ~20 years.
• Let’s continue to enjoy neutrino physics.
• Hope to discover proton decays and double beta decays sometime in future.