Neutrino Experiments and Armenia

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Yerevan, Armenia

CPHI, September 25, 2018

- our theoretical research
- current long baseline neutrino experiments
- JUNO - Jiangmen Underground Neutrino Observatory, China
- DUNE- Deep Underground Neutrino Experiment, USA (FNAL-CERN)
- Hyper-Kamiokannde, Japan (+possible Korea)
- our participation/contribution

$$i\frac{d}{dx}\nu = \mathcal{H}(x)\nu$$

$$\begin{aligned}
\mathcal{H}(x) &= U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_\odot}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_a}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(x) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
&= U^m \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^{m\dagger}
\end{aligned}$$

$\Delta m^2_\odot \equiv m_2^2 - m_1^2$ $(\approx 7.5\ 10^{-5} eV^2)$
$\Delta m^2_a \equiv m_3^2 - m_1^2$ $(\approx \pm 2.5\ 10^{-3} eV^2,$

$$U = \mathcal{O}_{23} U^\delta \mathcal{O}_{13} U^{\delta *} \mathcal{O}_{12}$$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Solution of cubic equation $\to$ eigenvalues of the Hamiltonian,
than solution of the system of 3 linier equations $\to$ mixing matrix

modification of oscillation parameters in matter

2ν

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_m \;\; \sin^2 \frac{\Delta m_m^2}{4E} L$$

$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - \epsilon)^2 + \sin^2 2\theta}$$

$$\cos 2\theta_m = \frac{\cos 2\theta - \epsilon}{\sqrt{(\cos 2\theta - \epsilon)^2 + \sin^2 2\theta}}$$

$$\epsilon = \frac{2EV}{\Delta m^2} \qquad V = \sqrt{2} G_F N_e$$

$$\sin 2\theta_{13}^m = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - \epsilon_a)^2 + \sin^2 2\theta_{13}}}$$

$$\sin 2\theta_{12}^m = \frac{\cos\theta'_{13} \sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - \epsilon_\odot)^2 + \cos^2\theta'_{13} \sin^2 2\theta_{12}}},$$

$$\frac{\Delta m_{21}^2}{2E} = \frac{\Delta m_\odot^2}{2E}\sqrt{(\cos 2\theta_{12} - \epsilon_\odot)^2 + \cos^2\theta'_{13}\sin^2 2\theta_{12}},$$

$$\frac{\Delta m_{31}^2}{2E} = \frac{\Delta m_{ee}^2}{2E}\sqrt{(\cos 2\theta_{13} - \epsilon_a)^2 + \sin^2 2\theta_{13}} - \frac{1}{4}\frac{\Delta m_{ee}^2}{2E}\sqrt{(\cos 2\theta_{13} - \epsilon_a)^2 + \sin^2 2\theta_{13}} + \frac{1}{4}(\frac{\Delta m_{ee}^2}{2E} + V) + \frac{1}{4E}(\Delta m_{21}^2 - \Delta m_\odot^2 \cos 2\theta_{12})$$

$$\theta_{13}^m = \theta_{13} + \theta'_{13}$$

$$\epsilon_\odot = \frac{2EV}{\Delta m_\odot^2}(\cos^2\theta_{13}^m + \frac{\sin^2\theta'_{13}}{\epsilon_a}), \qquad \epsilon_a = \frac{2EV}{\Delta m_{ee}^2}$$

$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_a^2 + s_{12}^2(\Delta m_a^2 - \Delta m_\odot^2) = \Delta m_a^2 - s_{12}^2 \Delta m_\odot^2$$

The oscillation probabilities $P_{\nu_\alpha \to \nu_\beta}$ $(\alpha, \beta = e, \mu, \tau)$ have the same forms as for the vacuum oscillations with following replacements

$$
\begin{aligned}
&\Delta m^2_\odot \to \Delta m^2_{21} \\
&\Delta m^2_a \to \Delta m^2_{31} \\
&\theta_{12} \to \theta^m_{12} \\
&\theta_{13} \to \theta^m_{13} \\
&\theta^m_{23} \equiv \theta_{23} \\
&\delta^m \equiv \delta
\end{aligned}
$$

This semi-analytic approximate solution is valid for all energies. For anti-neutrino oscillations $P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$, V$\to$ -V and $\delta \to -\delta$. For normal mass hierarchy Δm^2_a is positive and for inverted mass hierarchy it is negative.

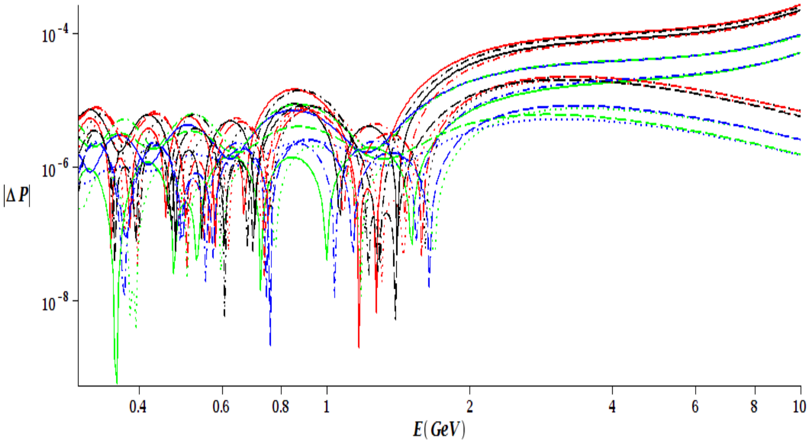

Figure: $|\Delta P| \equiv |P^{num}_{\nu_\mu\to\nu_e} - P^{anl}_{\nu_\mu\to\nu_e}|$.The absolutee error of our analytic result to the exact (numeric) $\nu_\mu \to \nu_e$ oscillation probability for normal/inverted mass hierarchy for neutrinos/antineutrinos, $\delta_{cp} = 0$, $\delta_{cp} = \frac{\pi}{2}$, $\delta_{cp} = \pi$, $\delta_{cp} = -\frac{\pi}{2}$

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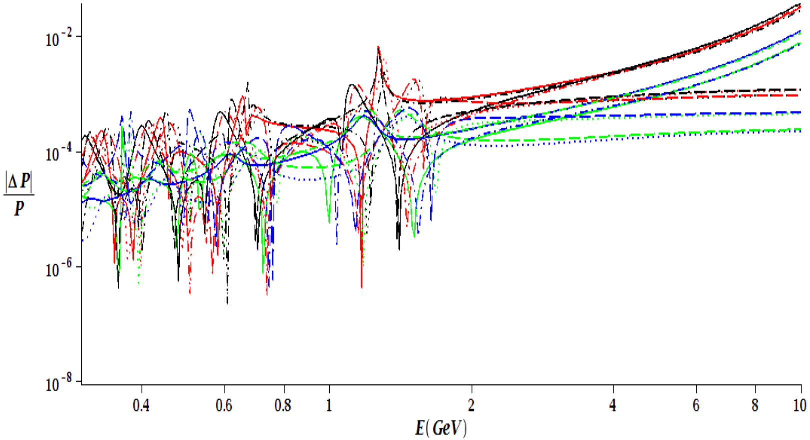
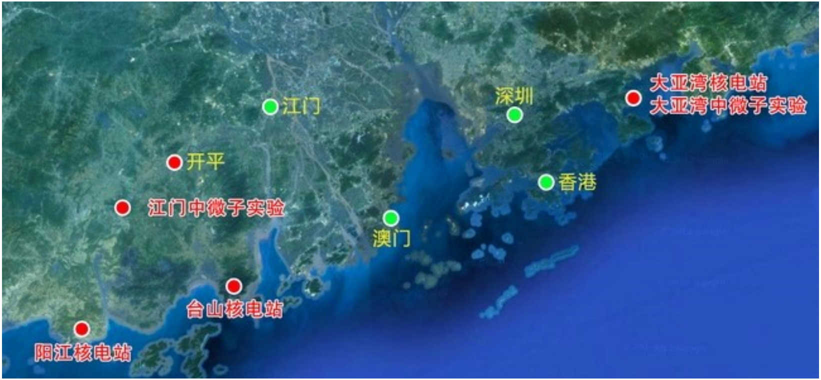
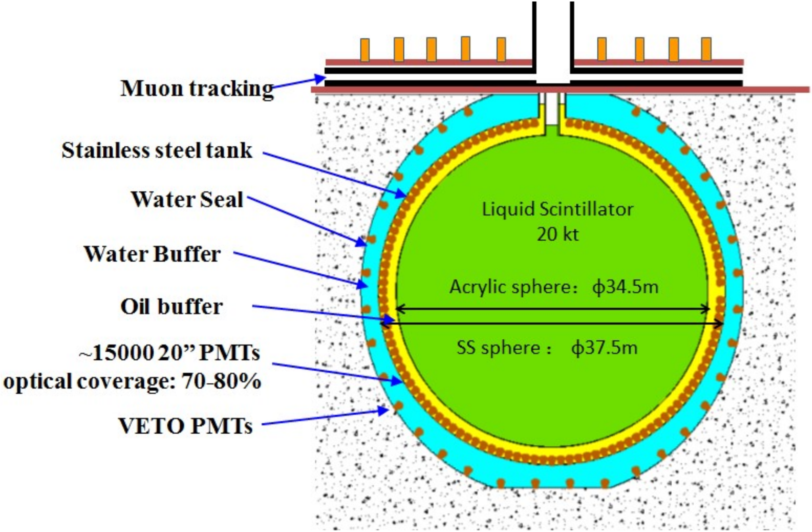


Figure: $\frac{|\Delta P|}{P} \equiv \frac{|P^{num}_{\nu_\mu \to \nu_e} - P^{anl}_{\nu_\mu \to \nu_e}|}{P^{num}_{\nu_\mu \to \nu_e}}$. The relative error of our analytic result to the exact (numeric) $\nu_\mu \to \nu_e$ oscillation probability for normal/inverted mass hierarchy for neutrinos/antineutrinos, $\delta_{cp} = 0$, $\delta_{cp} = \frac{\pi}{2}$, $\delta_{cp} = \pi$, $\delta_{cp} = -\frac{\pi}{2}$

JUNO

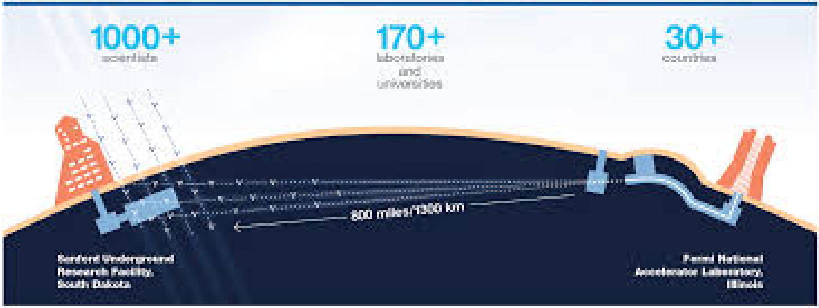



Muon tracking
Stainless steel tank
Water Seal
Water Buffer
Oil buffer
~15000 20” PMTs
optical coverage: 70-80%
VETO PMTs
Liquid Scintillator
20 kt
Acrylic sphere: ϕ34.5m
SS sphere : ϕ37.5m

	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

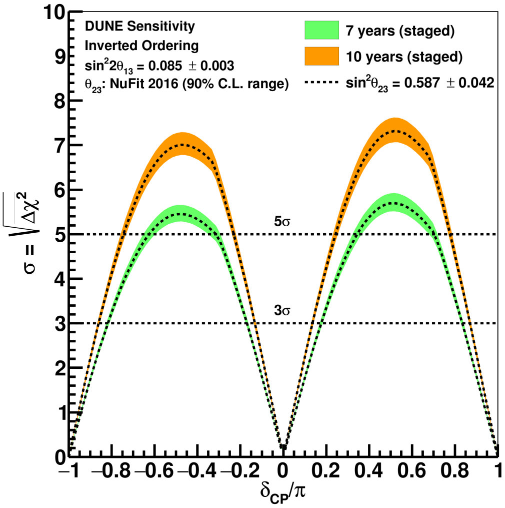
Oscillations of the ^{7}Be solar neutrinos inside the Earth
A.N. Ioannisian , A. Yu. Smirnov , D. Wyler
Phys.Rev. D92 (2015) no.1, 013014

DUNE

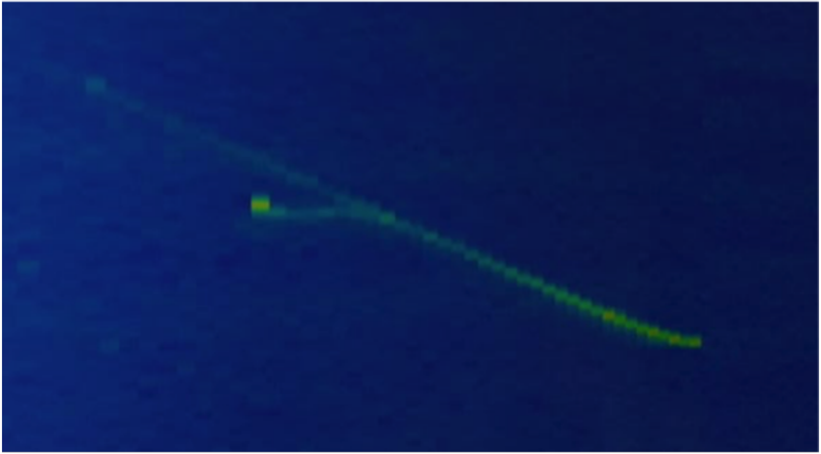


1000+
scientists
170+
laboratories
and
universities
30+
countries
800 miles/1300 km

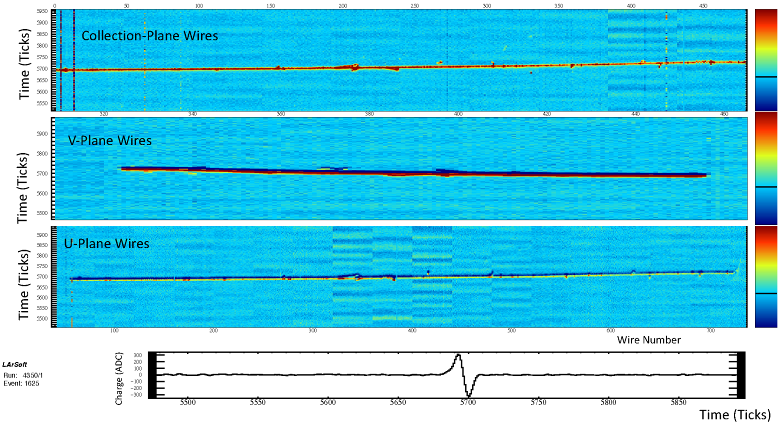
CP Violation Sensitivity



protoDUNE (CERN)

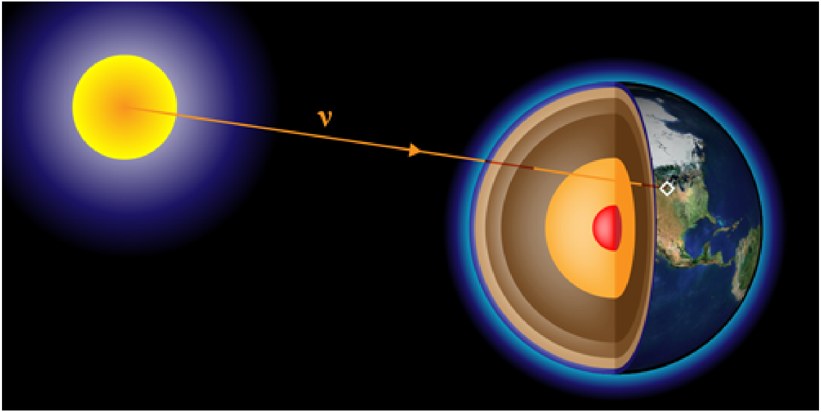


protoDUNE (CERN)



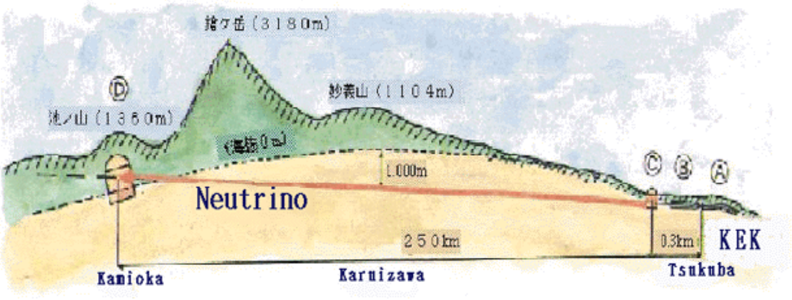
Scanning the Earth with solar neutrinos and DUNE
Ara Ioannisian , Alexei Smirnov , Daniel Wyler
Phys.Rev. D96 (2017) no.3, 036005

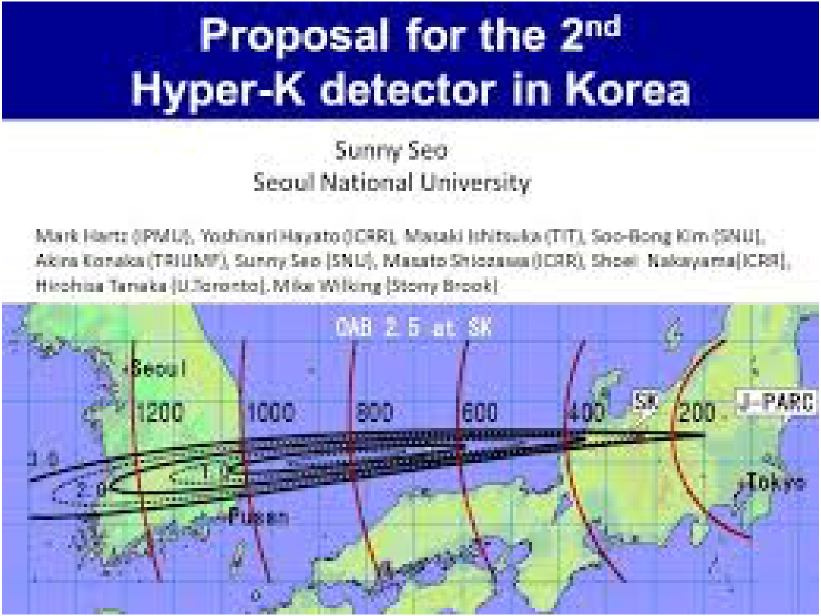
PRD Synopsis: Scanning Earths Interior with Neutrinos

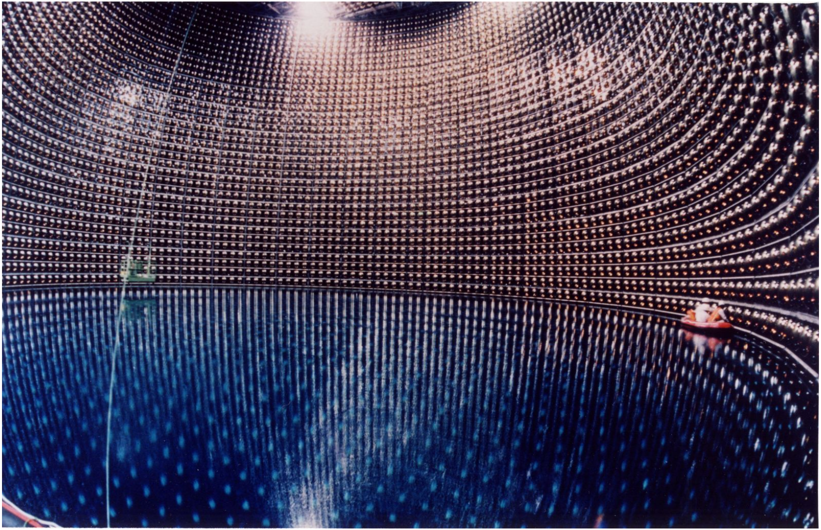


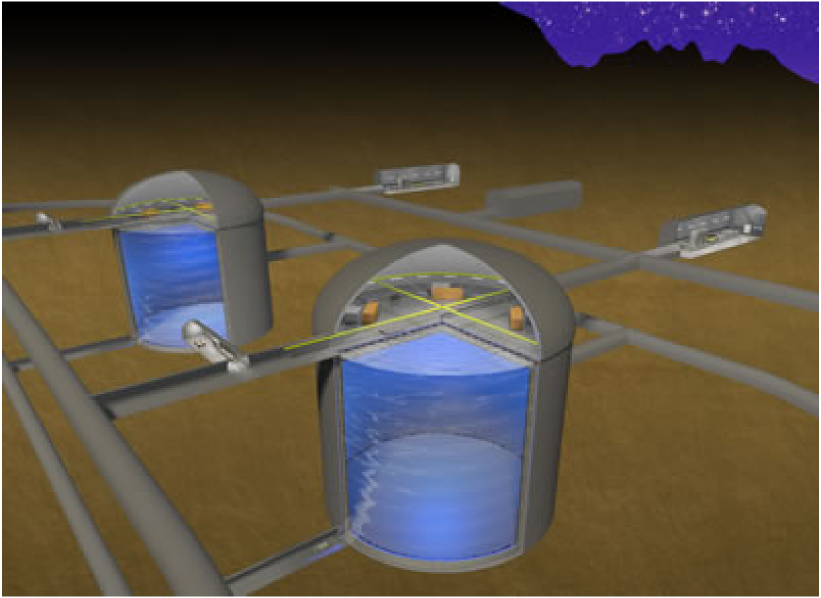
also highlighted at FNAL and CERN COURIER

Hyper-Kamiokande

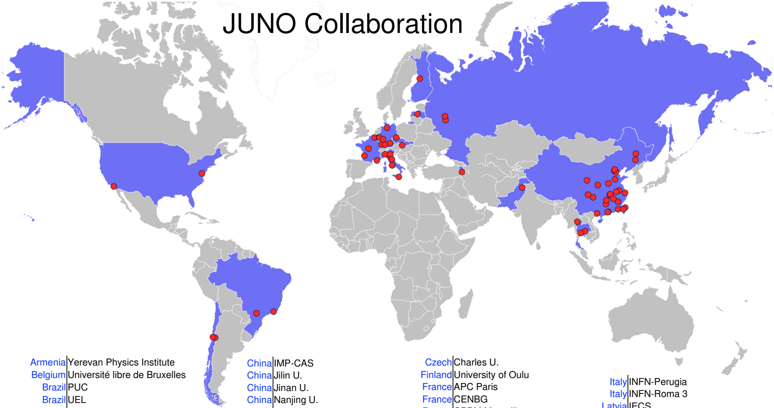



Proposal for the 2nd
Hyper-K detector in Korea
Sunny Seo
Seoul National University
Mark Hartz (IPMU), Yoshinari Hayato (ICRR), Masaki Ishitsuka (TIT), Soo-Bong Kim (SNU),
Akira Konaka (TRIUMF), Sunny Seo (SNU), Masato Shiozawa (ICRR), Shoei Nakayama (ICRR),
Hirohisa Tanaka (U.Toronto), Mike Wilking (Stony Brook)
OAB 2.5 at SK
Seoul
1200
1000
800
600
400
SK
200
J-PARC
Tokyo
Pusan





JUNO Collaboration



Armenia	Yerevan Physics Institute
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Brazil	PUC
Brazil	UEL
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Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of Technology
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	NUDT
China	Peking U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
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China	Wuhan U.
China	Xi'an JT U.
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France	IPHC Strasbourg
France	Subatech Nantes
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Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ Jülich
Germany	U. Mainz
Germany	U. Tuebingen
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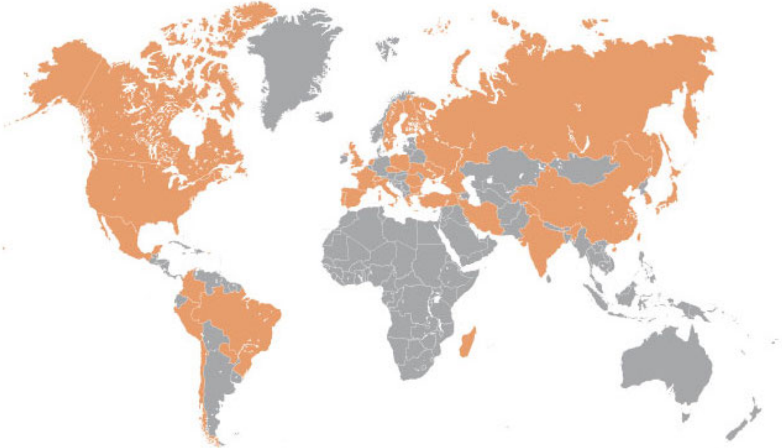
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

DUNE collaboration



Hyper-Kamiokande proto collaboration

THANK YOU