School and Workshop "Physics of the Standard Model and Beyond"

Neutrino Oscillations and Probing the Neutrino Mass Hierarchy

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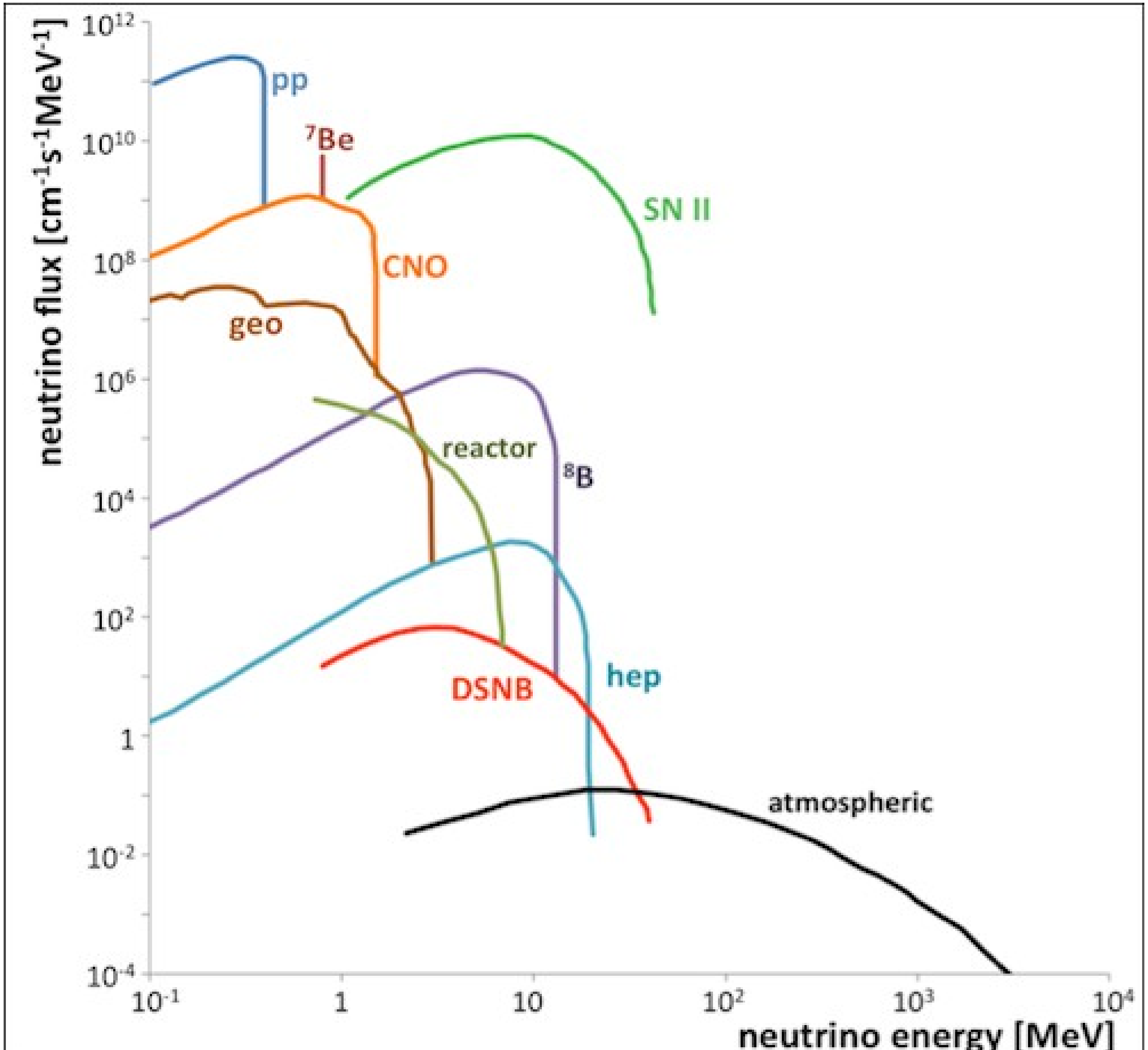
Content

- Neutrino fluxes and the evidence for the neutrino oscillations
- Oscillation phenomenology: PNMS mixing matrix
- Current status of ν-oscillation measurements and NMH
- Probing NHM with the atmospheric neutrinos: KM3NeT/ORCA
- Summary and Outlook

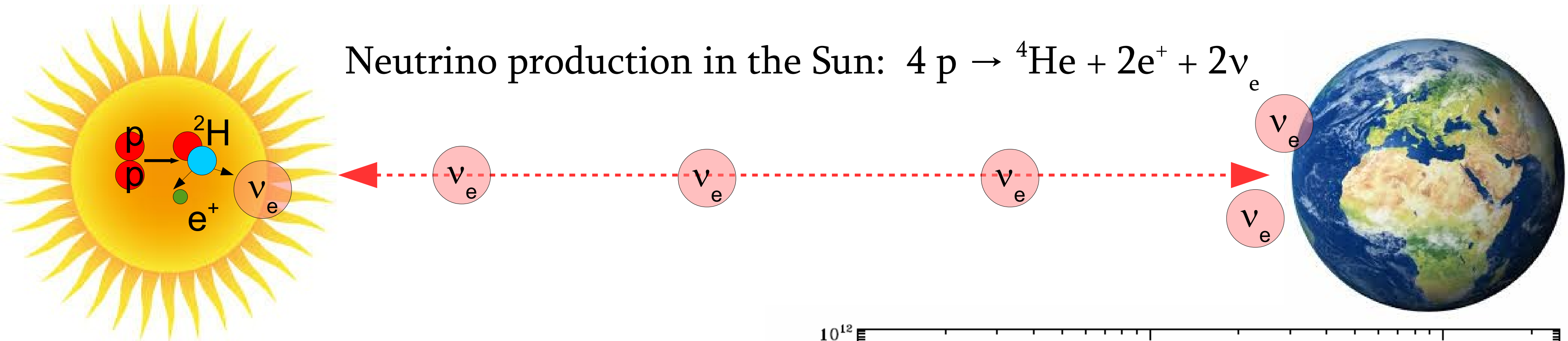
Neutrino Fluxes



- **Solar neutrinos** (ν_e) :
  pp, ^{7}Be, CNO, ^{8}B, hep
- Geo-neutrinos ($\bar{\nu}_e$):
  β^-: ^{40}K, ^{232}Th, ^{238}U (99%)
- **Reactor neutrinos** ($\bar{\nu}_e$):
- Supernova neutrinos :
  SN II : $e^- p \rightarrow n\nu_e$
  $e^+e^- \rightarrow \nu_\alpha \bar{\nu}_\alpha$ $\alpha=e,\mu,\tau$
- DNSB: Diffise Supernova Neutrino Background
- **Atmospheric neutrinos:**
  $\pi \rightarrow \mu\nu_\mu$
  $\mu \rightarrow e\, \nu_\mu \nu_e$
- Accelerator neutrino beams

Solar Neutrino Fluxes

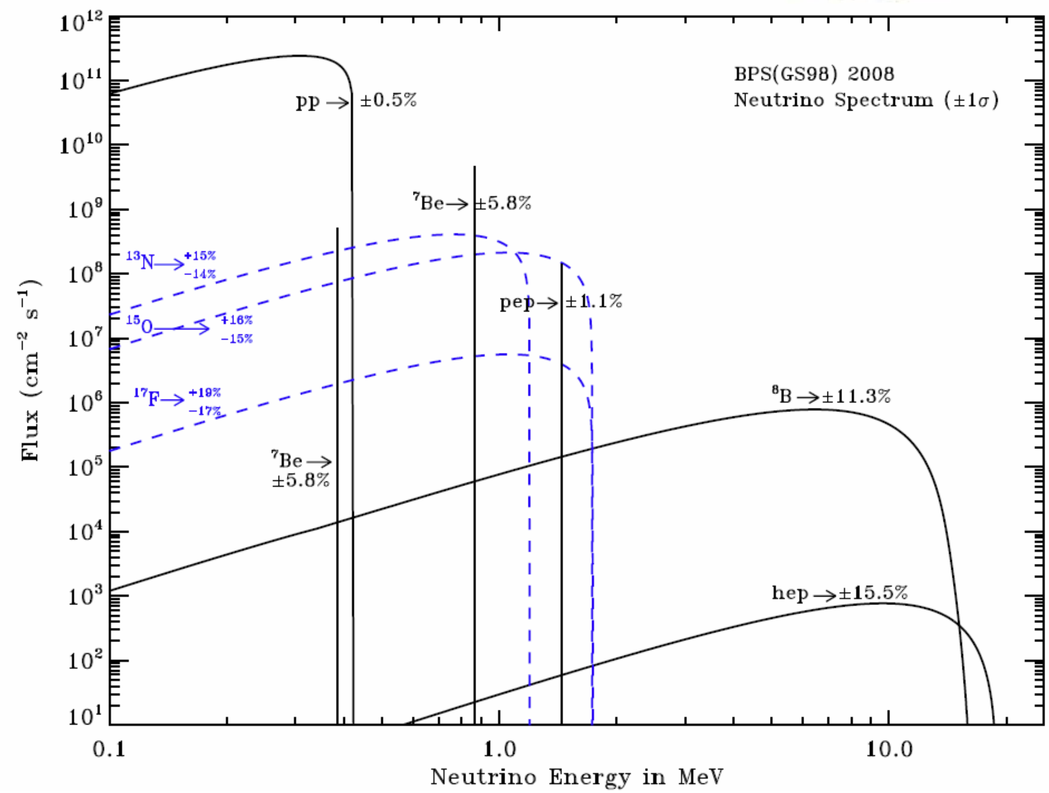
Neutrino production in the Sun: $4\,p \rightarrow {}^4He + 2e^+ + 2\nu_e$



Reaction	type	Fluxes ($cm^{-2}\,s^{-1}$)
$pp \rightarrow {}^2H + e^+ + \nu_e$	*pp*	$5.97(1\pm0.006) \times 10^{10}$
$pe^-p \rightarrow {}^2H + \nu_e$	*pep*	$1.41(1\pm0.011) \times 10^8$
${}^3He\,p \rightarrow {}^4He + e^+ + \nu_e$	*hep*	$7.90(1\pm0.015) \times 10^3$
${}^7Be\,e^- \rightarrow {}^7Li + \nu_e$	^{7}Be	$5.07(1\pm0.006) \times 10^9$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	^{8}B	$5.94(1\pm0.011) \times 10^6$
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	^{13}N	$2.88(1\pm0.015) \times 10^8$
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	^{15}O	$2.15(1{+0.17}{-0.16}) \times 10^8$
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$	^{17}F	$5.82(1{+0.19}{-0.17}) \times 10^6$

RPP-2016, Neutrino mass, mixing and oscillations

http://pdg.lbl.gov/2017/reviews/rpp2016-rev-neutrino-mixing.pdf

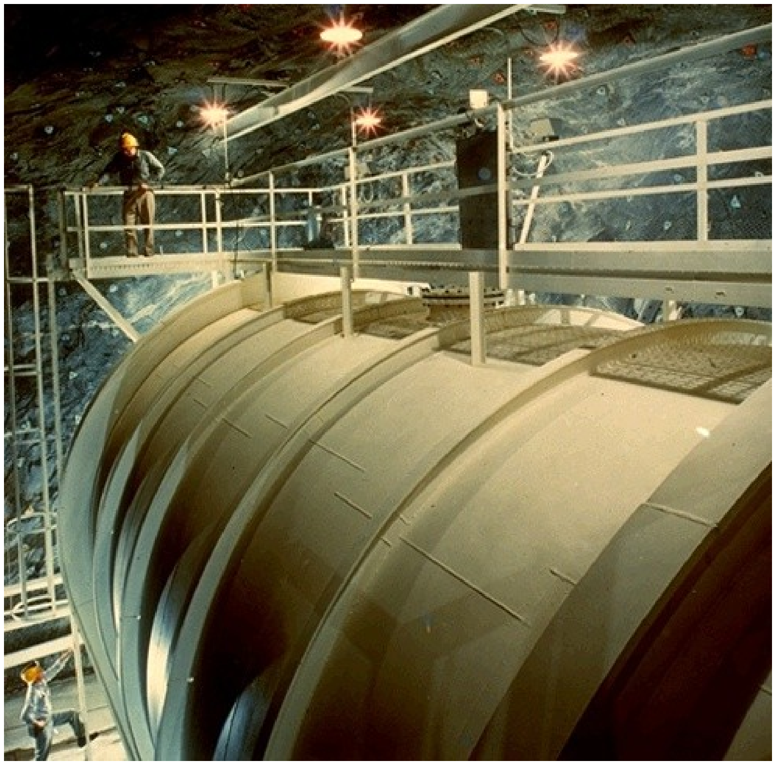


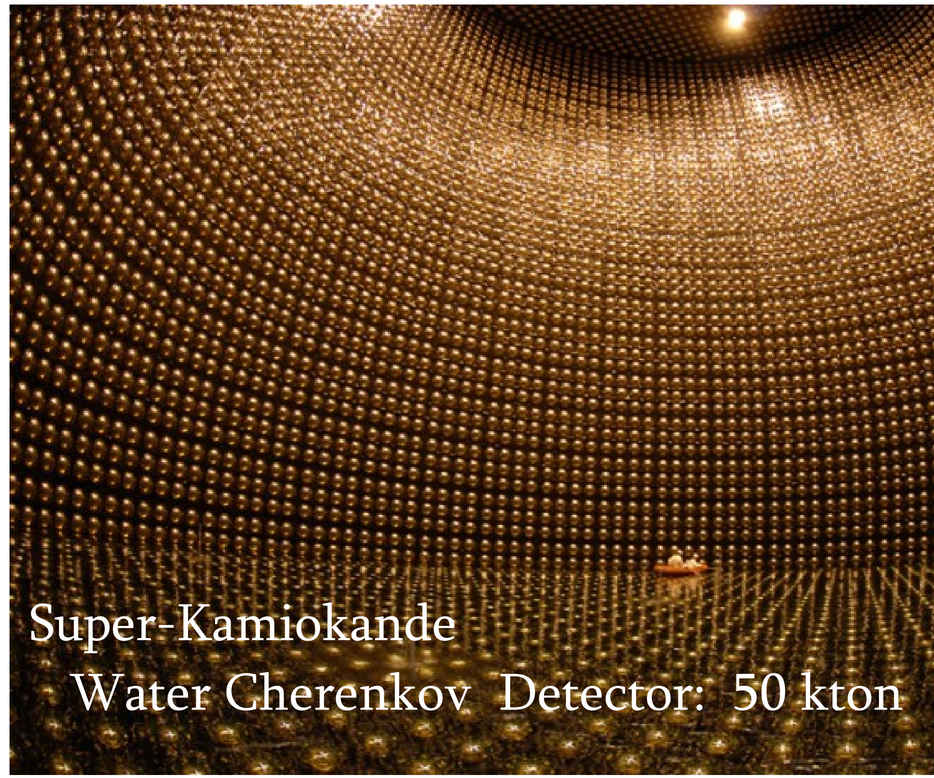
Standard Solar Mo0del (SSM): BPS 2008

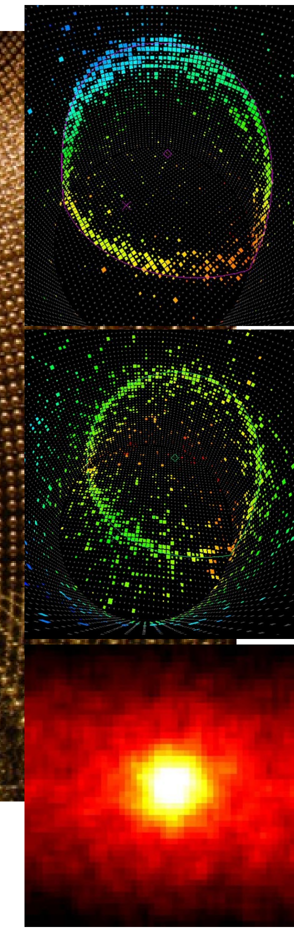
C. Pena-Garay and A.M. Serenelli, arXiv:0811.2424

Solar Neutrino Experiments

- Radio-chemical detection: Homestake(Cl-Ar), Gallex, GNO, SAGE (Ga-Ge)
- Water Cherenkov detectors: Kamiokande(K), Super-K, SNO
- Scintilator detectors: KamLAND, Borexino





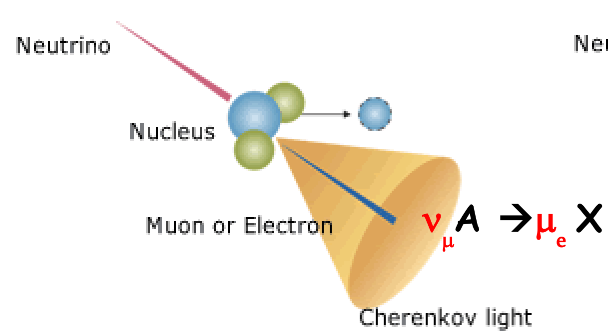


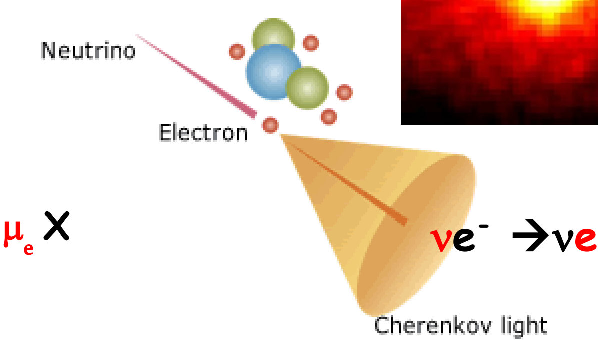
Homestake expriment:

100 000 galons (380 m^3) of C_2Cl_4

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (814 keV)

${}^{71}Ga \rightarrow {}^{71}Ge$ (233 keV)

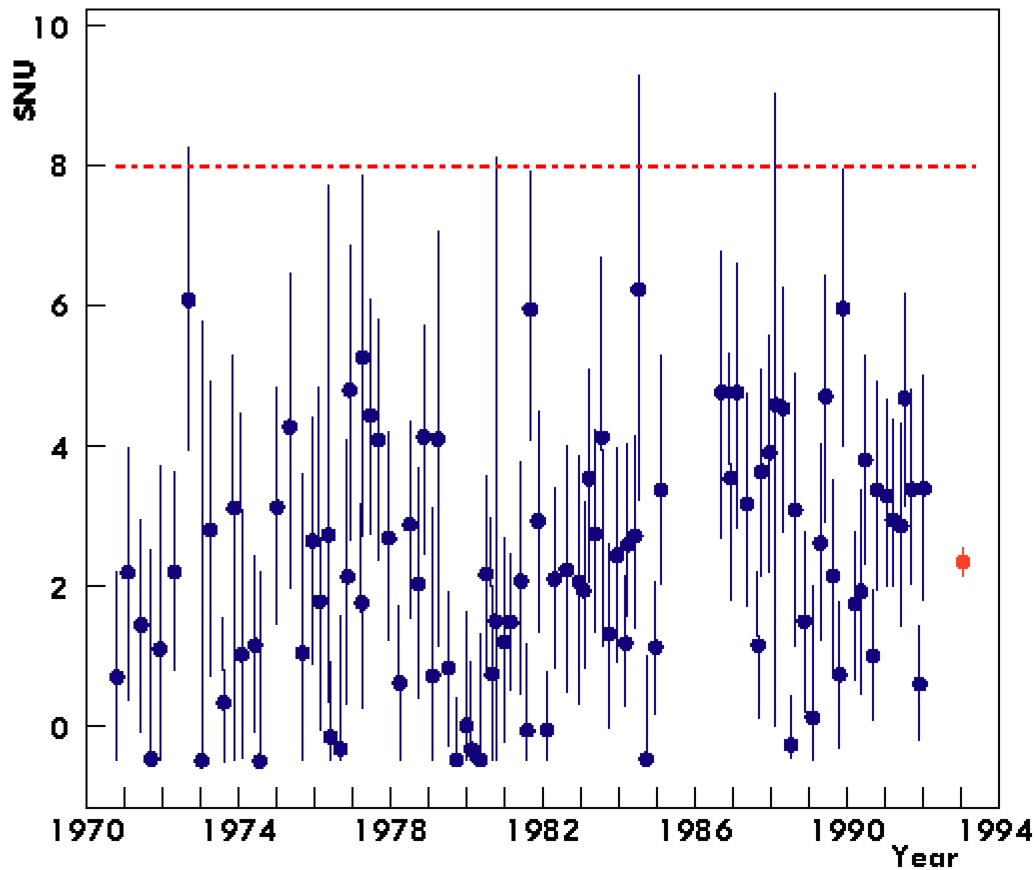




Solar Neutrino Problem

Radio-chemical experiments (Homestake, Gallex, GNO, SAGE):

Deficit of solar-ν_e with respect to SSM predictions.



Results from Homestake ($^{37}Cl \rightarrow {}^{37}Ar$) experiments

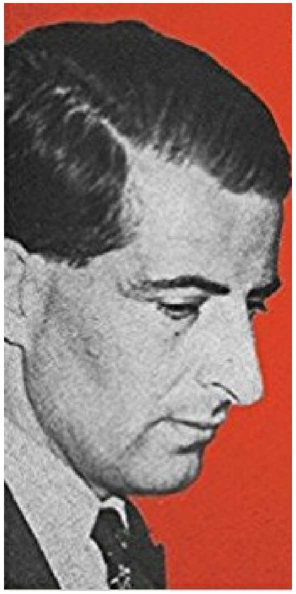
	$^{71}Ga \rightarrow {}^{71}Ge$ (SNU)
GALLEX	$77.5 \pm 6.2^{+4.3}_{-4.7}$
GNO	$62.9^{+5.5}_{-5.3} \pm 2.5$
GNO+GALLEX	$69.3 \pm 4.1 \pm 3.6$
SAGE	$65.4^{+3.1\ +2.6}_{-3.0\ -2.8}$
SSM [PPS08(GS)]	$127.9^{+8.1}_{-8.2}$

Results from $^{71}Ga \rightarrow {}^{71}Ge$ experiments and the prediction of the SSM [BPS08(GS)]

SNU (Solar Neutrino Unit):

10^{-36} ν-captures per atom per second.

Neutrino Oscillations



Bruno Pontekorvo

2ν – mixing:

Mixing of flavor neutrinos (ν_α, ν_β) with massive neutrino states (ν_1, ν_2)

$$\nu_\alpha = u_{\alpha i} \nu_i \qquad \alpha = e, \mu \qquad i = 1,2$$

$$u_{\alpha i} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \nu_\alpha(x) = \cos\Theta\, \nu_1(x) + \sin\Theta\, \nu_2(x)$$

Neutrino propagation: $P_{\alpha\alpha} + P_{\alpha\beta} = 1$

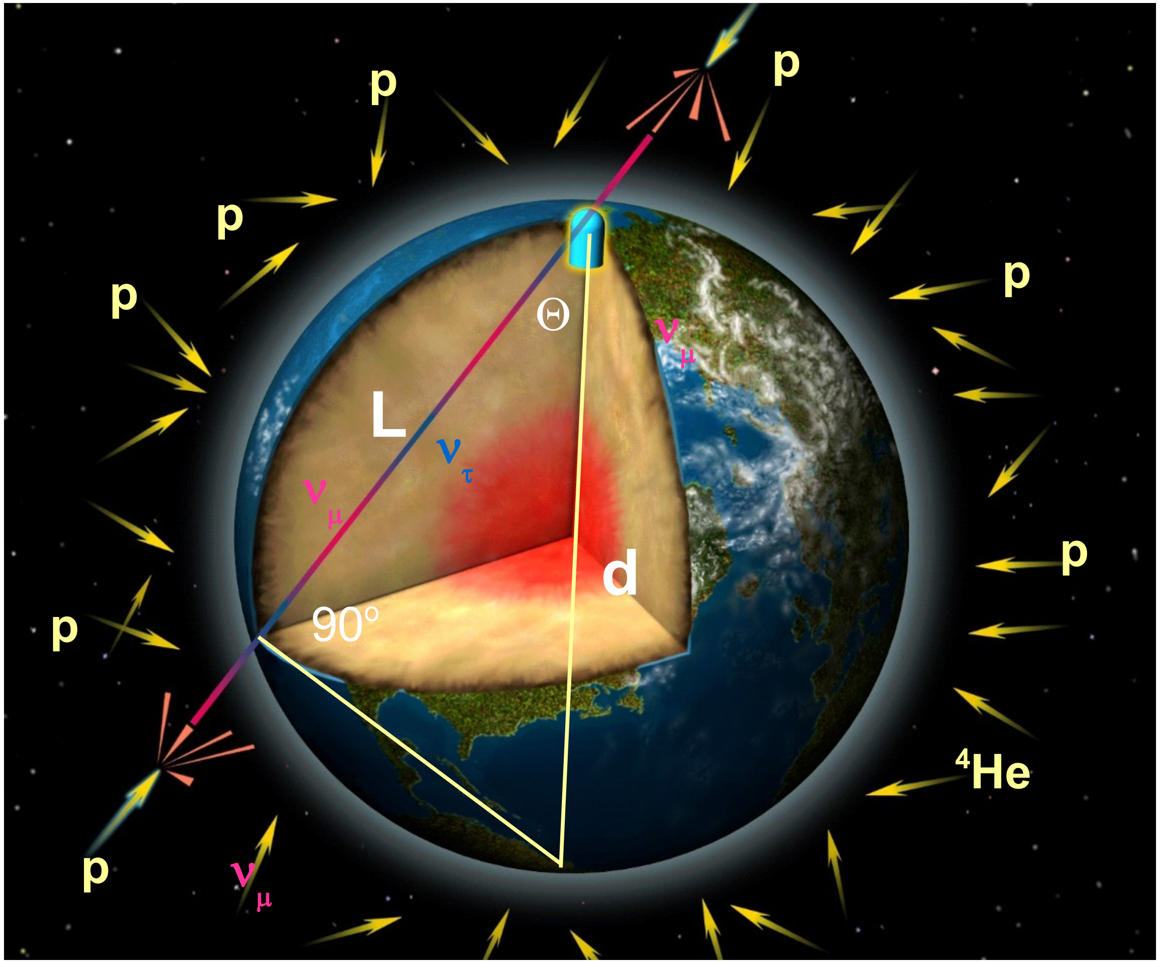
$P_{\alpha\alpha}$ - survival(disappearance) probability

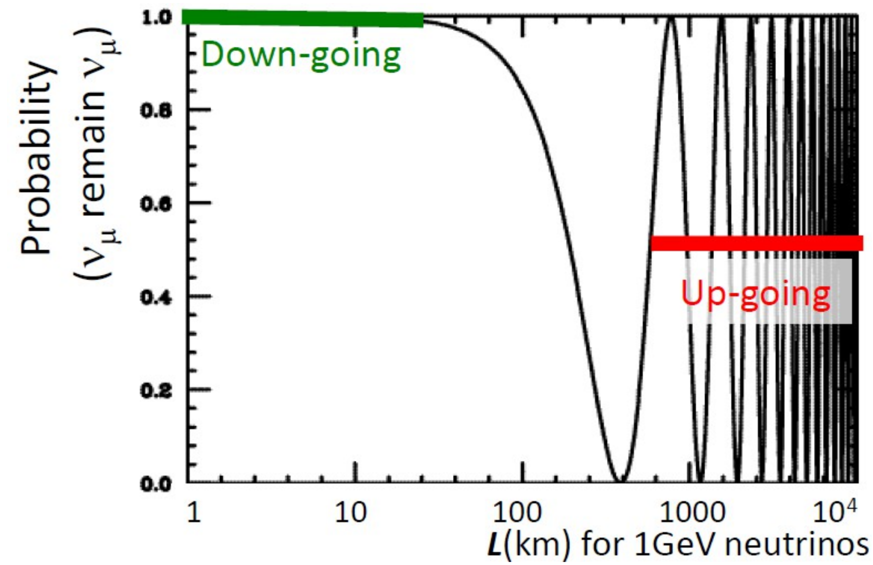
$P_{\alpha\beta}$ - appearance probability

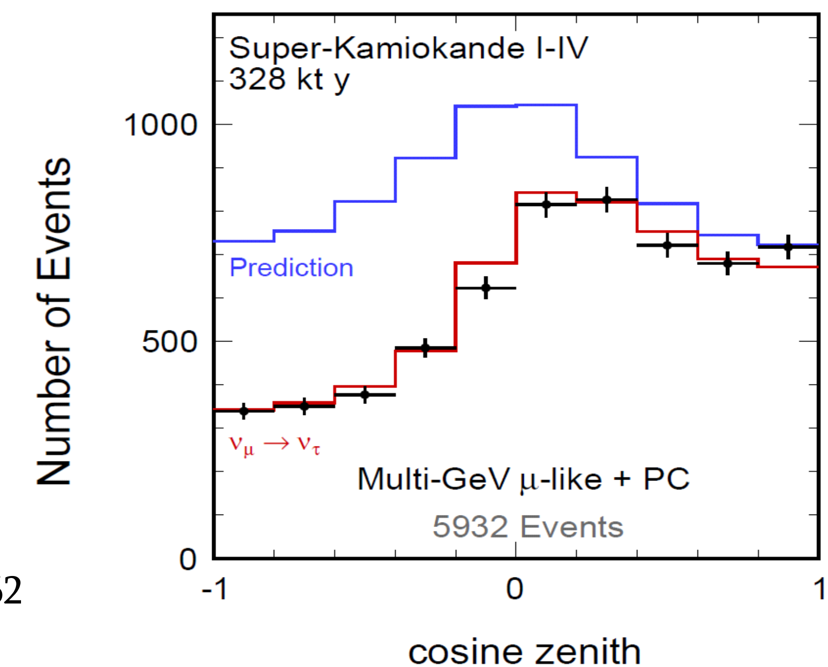
$$P_{\alpha\beta}(\theta, \Delta m^2_{21}, L, E_\nu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{12} L}{4 E_\nu}\right)$$

Oscillation parameters: $\theta, \Delta m^2_{21}$

Conditions: $\begin{cases} \theta \neq 0 \\ \Delta m^2_{21} = m^2_2 - m^2_1 \neq 0 \end{cases}$







$$10\ km < L_\nu\ (d\ cos\Theta) < d_{earth} = 1.27 \times 10^4\ km$$

Super-K Collaboration (Y. Fukuda et al), Phys.Rev.Lett. 81 (1998) 1562
Evidence for oscillation of atmospheric neutrinos

Neutrino Oscillations: 3ν Flavors

3 neutrino case:

$$\nu_\alpha = u_{\alpha i} \nu_i \qquad u_{\alpha i} = U_{PMNS}$$

$$\alpha = e, \mu, \tau \quad i = 1,2,3$$

PMNS matrix
(Pontecorvo–Maki–Nakagawa Sakata)

$$U_{PMNS} = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} \\ u_{\mu 1} & u_{\mu 2} & u_{\mu 3} \\ u_{\tau 1} & u_{\tau 2} & u_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\Theta_{ij} \qquad s_{ij} = \sin\Theta_{ij}$$

Oscillation parameters: $\begin{cases} \Theta_{23}, \ \Theta_{13}, \ \Theta_{12}, \ \delta_{CP} \\ \Delta m^2_{32}, \ \Delta m^2_{31}, \ \Delta m^2_{21} \end{cases}$

$$\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$$

$$\pm \Delta m^2_{32} = m^2_3 - m^2_2$$

(Neutrino Mass Hierarchy, NMH)

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2(\Delta m^2_{32} L_\nu / 4 E_\nu)$$

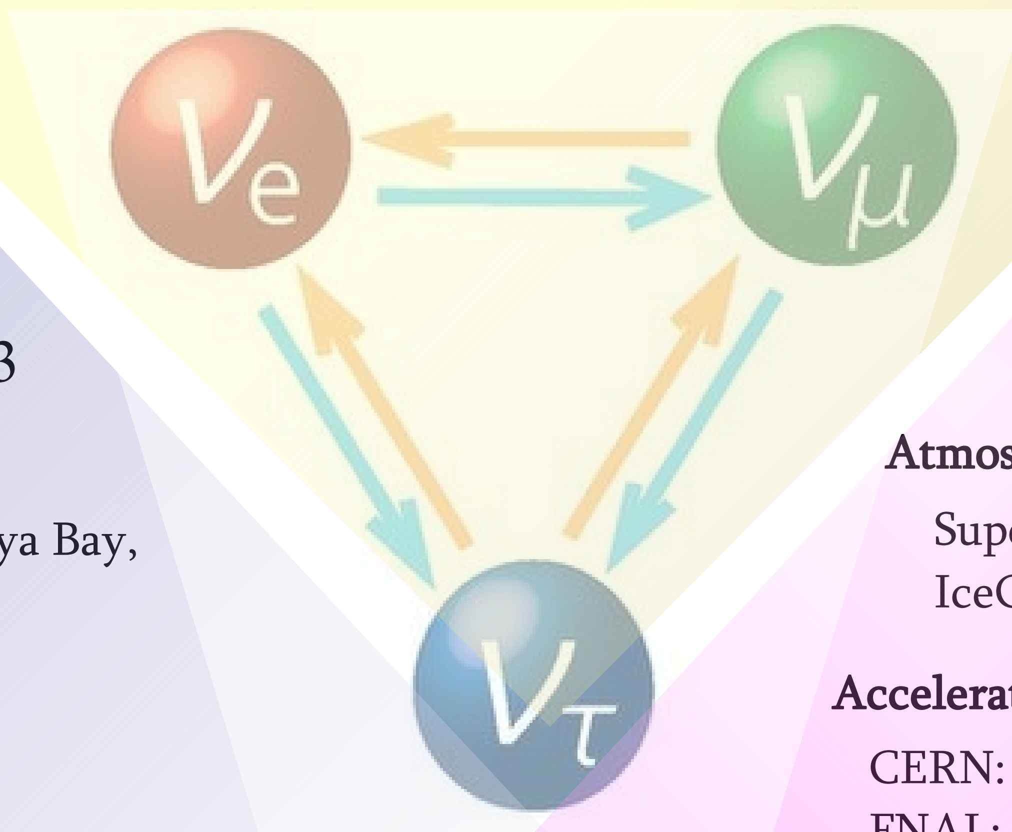
(ignoring Δm^2_{21}, δ and matter effects)

Oscillation Experiments

$$\Delta m^2_{21}, \Theta_{12}$$

Solar(ν_e) and reactor($\bar{\nu}_e$):

Homestake, Gallex, GNO, SAGE
Super-K, SNO
KamLAND, Borexino



$$\Delta m^2_{31}, \Theta_{13}$$

Reactor($\bar{\nu}_e$):

Double Chooz, Daya Bay,
RENO

$$\Delta m^2_{32}, \Theta_{23}$$

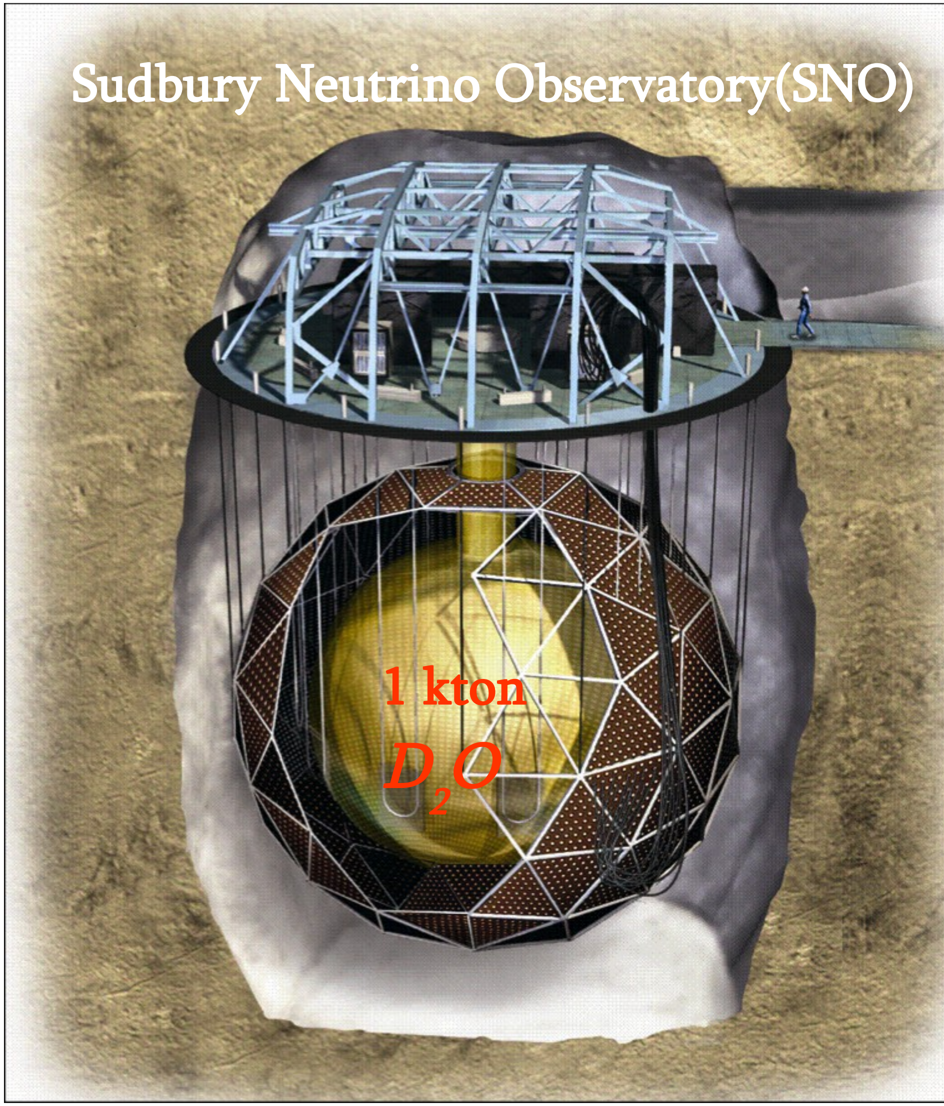
Atmospheric neutrinos(ν_μ, ν_e):

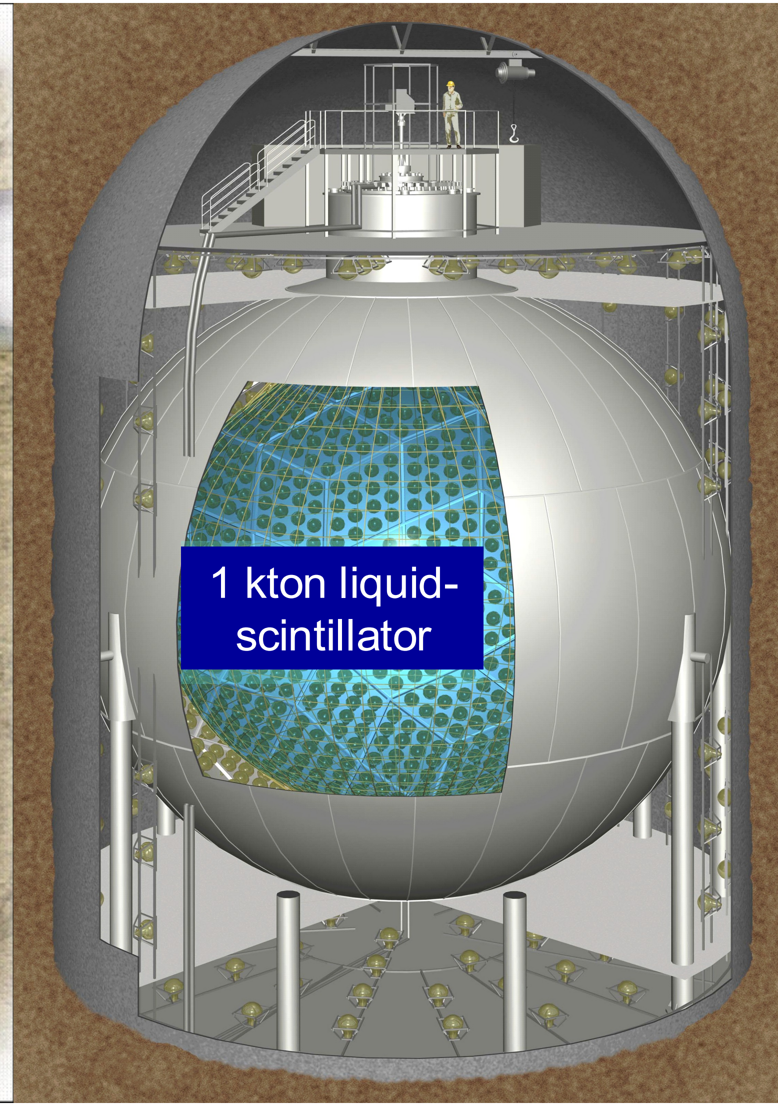
Super-K, MACRO, ANTARES,
IceCube/DeepCore

Accelerator beams (ν_μ):

CERN:	CNGS(Opera, ICARUS)
FNAL:	MINOS, NOνA
KEK:	K2K, T2K

Solar Neutrino Oscillations: SNO and KamLAND





SNO:
Solar-ν flux: Good agreement with SSM.

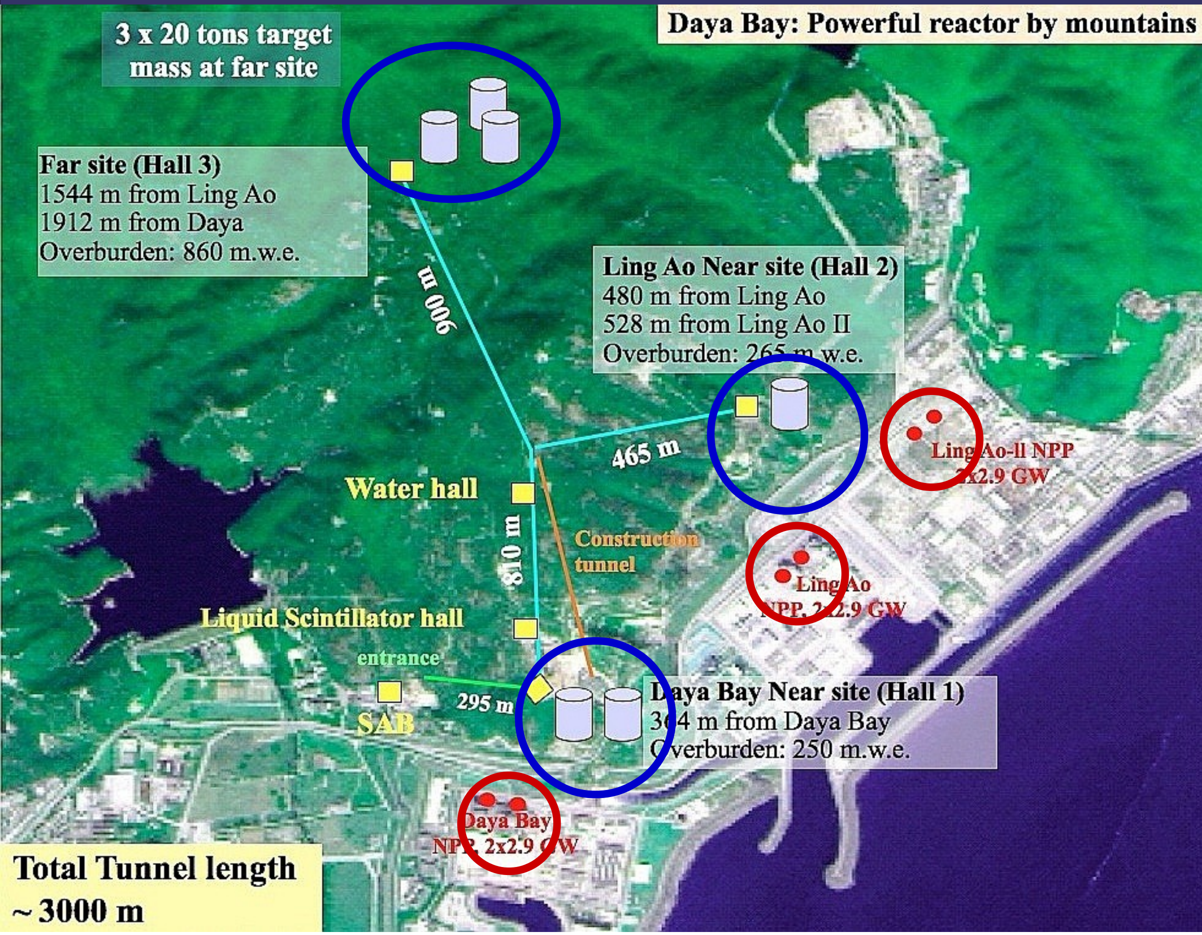
KamLAND:
Measurement of: Θ_{12} Δm_{12}^2

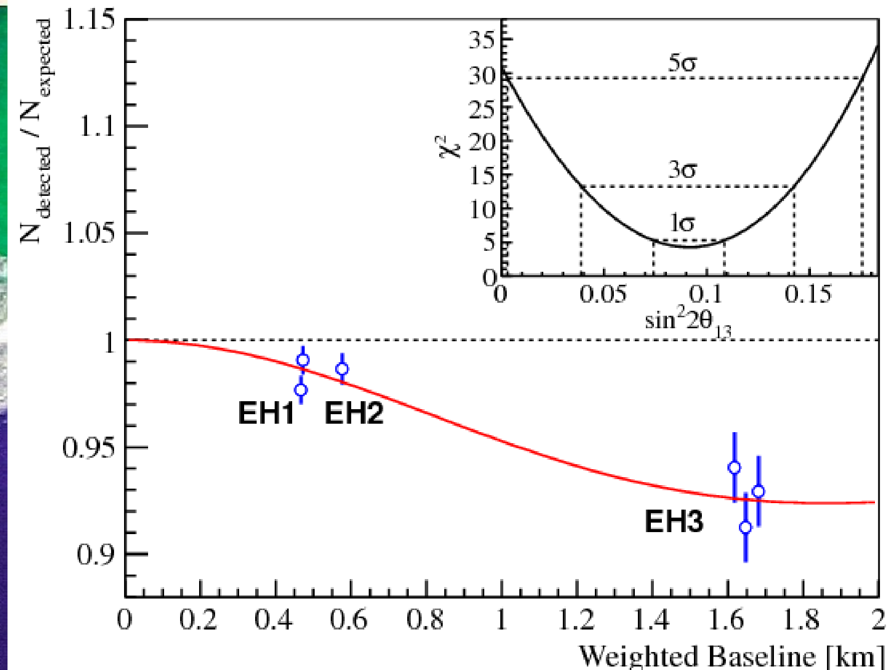
- $\nu_x + e^- \rightarrow e^- + \nu_x$ (ES)
- $\nu_e + {}^2H\,(D) \rightarrow p + p + e^-$ (CC)
- $\nu_x + {}^2H\,(D) \rightarrow p + n + \nu_x$ (NC)

- IBD: $\nu_e + p \rightarrow n + e^+$

$e^+ e^- \rightarrow 2\gamma \qquad np \rightarrow {}^2H + \gamma$

Measurement of Θ_{13}





R=Observed/Expected(no osc) curve measured In the Daya Bay experiment*

The Daya Bay experiment.

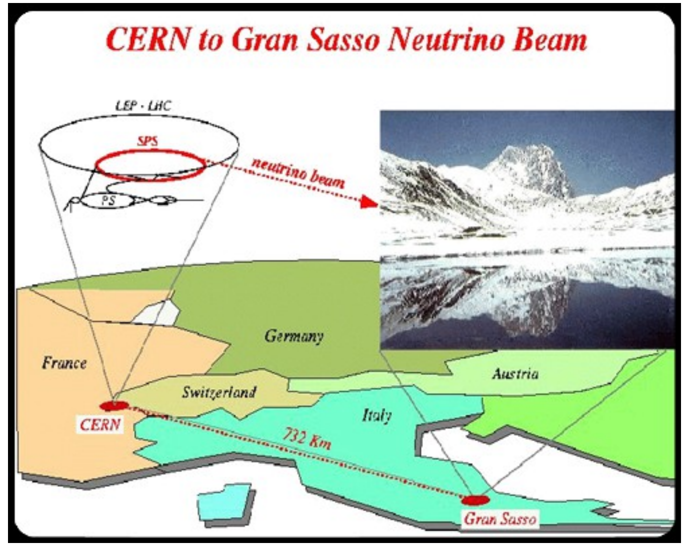
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})^*$$

RENO: $0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$

Double Chooz: $0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

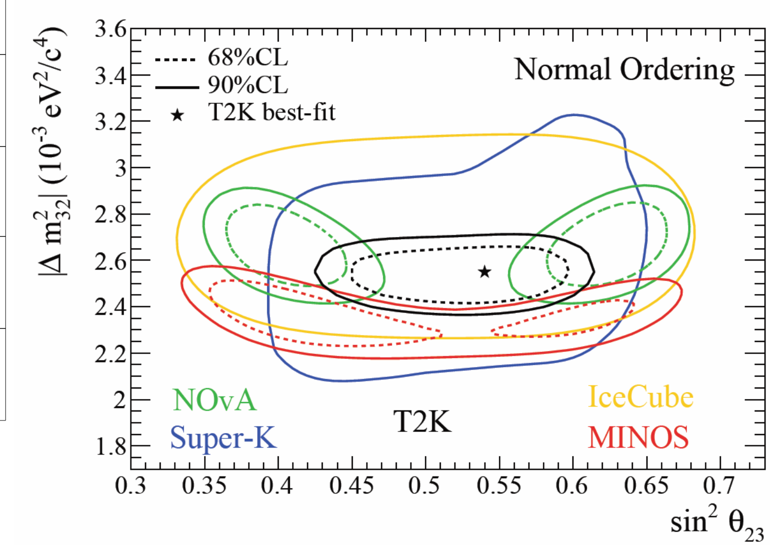
* Daya Bay Collaboration (F.P. An et al.), Phys.Rev.Lett. 108 (2012), 171803
Observation of electron-antineutrino disappearance at Daya Bay

Neutrino Oscillation with Accelerator ν-Beams

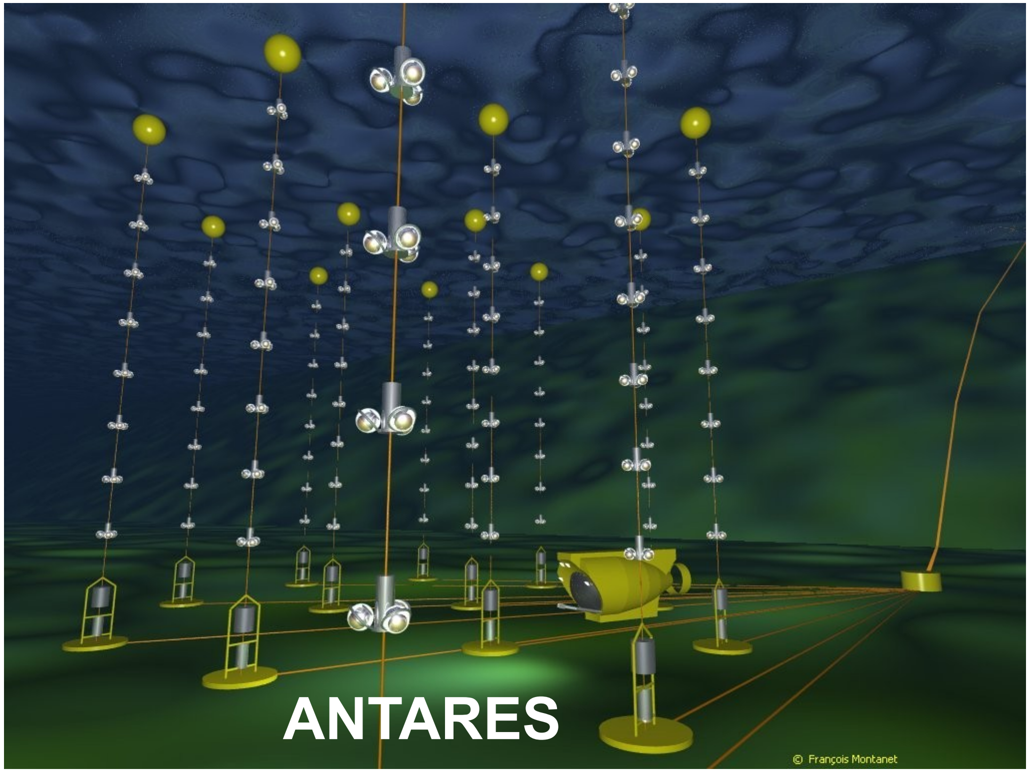


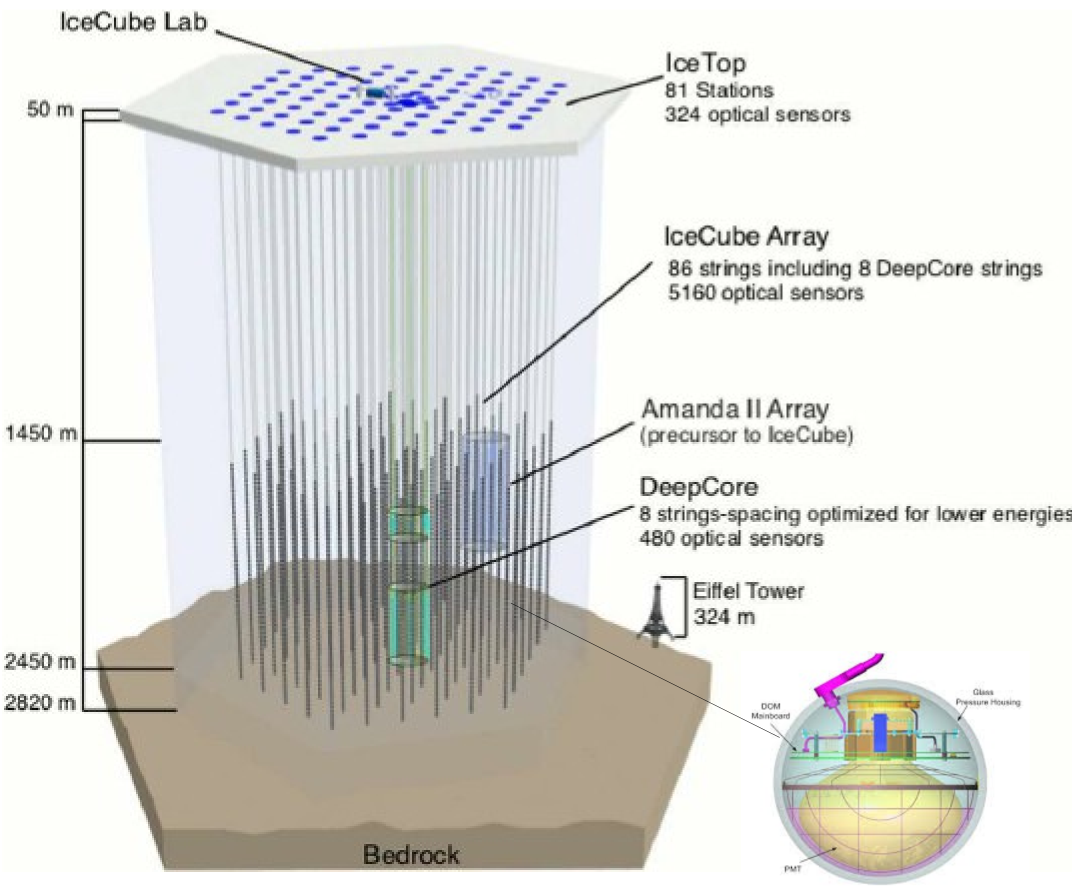
Accelerator Long Baseline Neutrino Experiments (LBNE)

LBNE	L[km]	E_p[GeV]	Detector	
K2K	250	12	Super-K(WC)	$\nu_\mu \rightarrow \nu_\mu$
T2K	295	30	Super-K	$\nu_\mu \rightarrow \nu_\mu / \nu_e$
OPERA	732	450	OPERA	$\nu_\mu \rightarrow \nu_\tau$
MINOS	735	120	5.4 kton M-Cal.	$\nu_\mu \rightarrow \nu_\mu / \nu_e$
NOvA	810	120	15 kton LS-Det.	$\nu_\mu \rightarrow \nu_\mu / \nu_e$



Neutrino Telescopes: ANTARES and IceCube





IceCube DOM

- ANTARES Collaboration, Phys. Lett. , B714 (2012) 224-230
  Measurement of Atmospheric Neutrino Oscillations with the ANTARES Neutrino Telescope

- IceCube Collaboration, Phys. Rev. D91 (2015) , 072004
  Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data

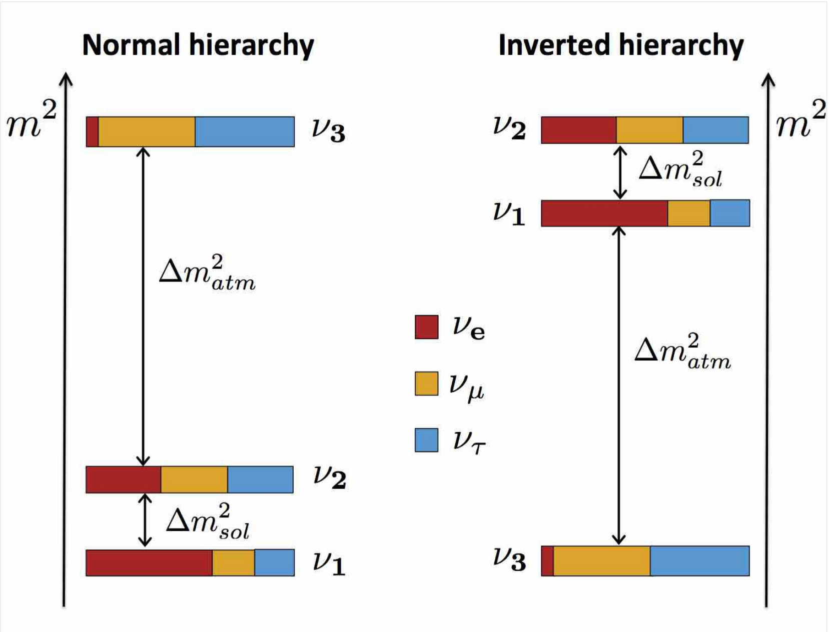
Neutrino Oscillation Parameters

Parameter	NMH	Best fit[1]	1σ range[1]	RPP-2016	Unit
δm^2		7.37	7.21 – 7.54	7.53 ± 0.18	10^{-5} eV^2
$\sin^2\Theta_{12}$		2.97	2.81 – 3.14	$3.07^{+0.13}_{-0.12}$	10^{-1}
Δm^2	NH	2.50	2.46 – 2.54	2.45 ± 0.05	10^{-3} eV^2
	IH	2.46	2.42 – 2.51	2.52 ± 0.05	
$\sin^2\Theta_{23}$	NH	4.37	4.17 – 4.70	5.1 ± 0.4	10^{-1}
	IH	5.69	4.28 – 4.91 ⊕ 5.18 – 5.97	5.0 ± 0.4	
$\sin^2\Theta_{13}$	NH	2.14	2.05 – 2.25	2.10 ± 0.11	10^{-2}
	IH	2.18	2.06 – 2.27		

$$\delta m^2 = \Delta m^2_{21} \qquad \Delta m^2 = \Delta m^2_{32}$$

[1] F. Capozzi, E. Lisic, A. Marrone, D. Montaninoe, A. Palazzod, l.Phys. B908 (2016) 218
Neutrino masses and mixings: Status of known and unknown 3ν parameters

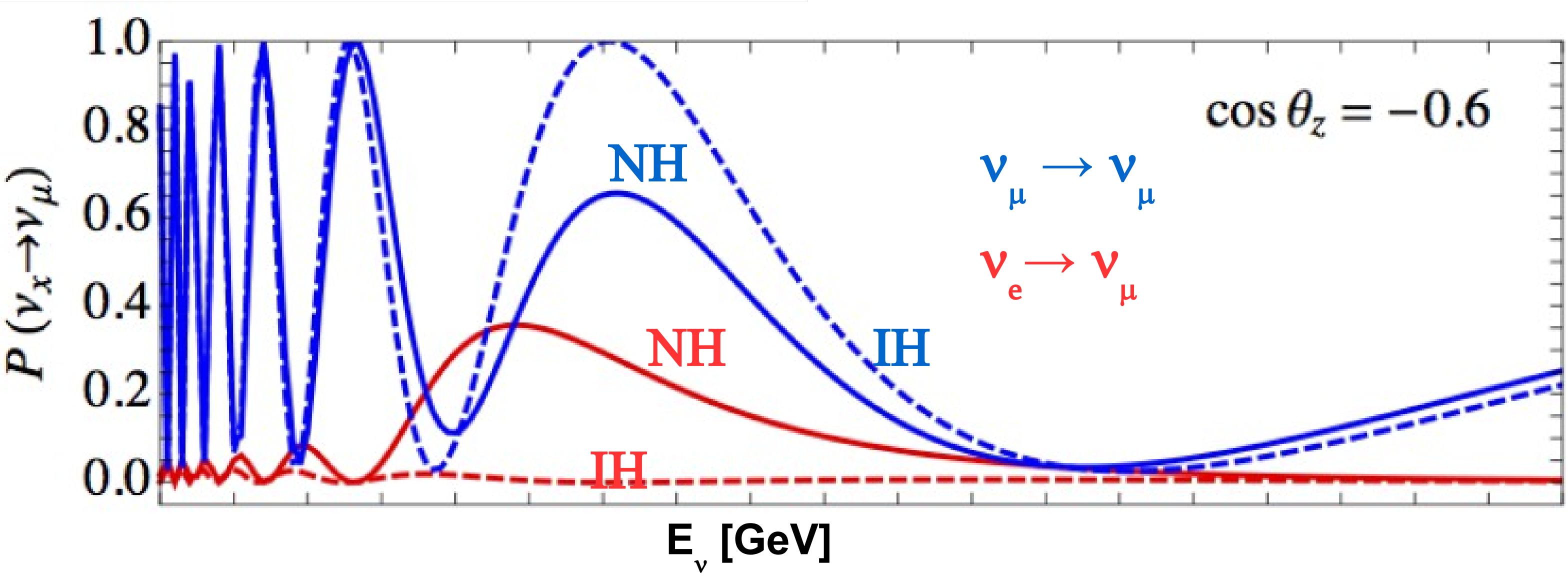
Neutrino Mass Hierarchy



Unknown ν-oscillation parameters:
Neutrino mass hierarchy, CP-phase, Octant of Θ_{23}

NMH 1) Normal Hierarchy (NH): $m_3 > m_2$
2) Inverted Hierarchy (IH): $m_3 < m_2$

Neutrino oscillations in matter:
MSW effect and parametric enhancement.

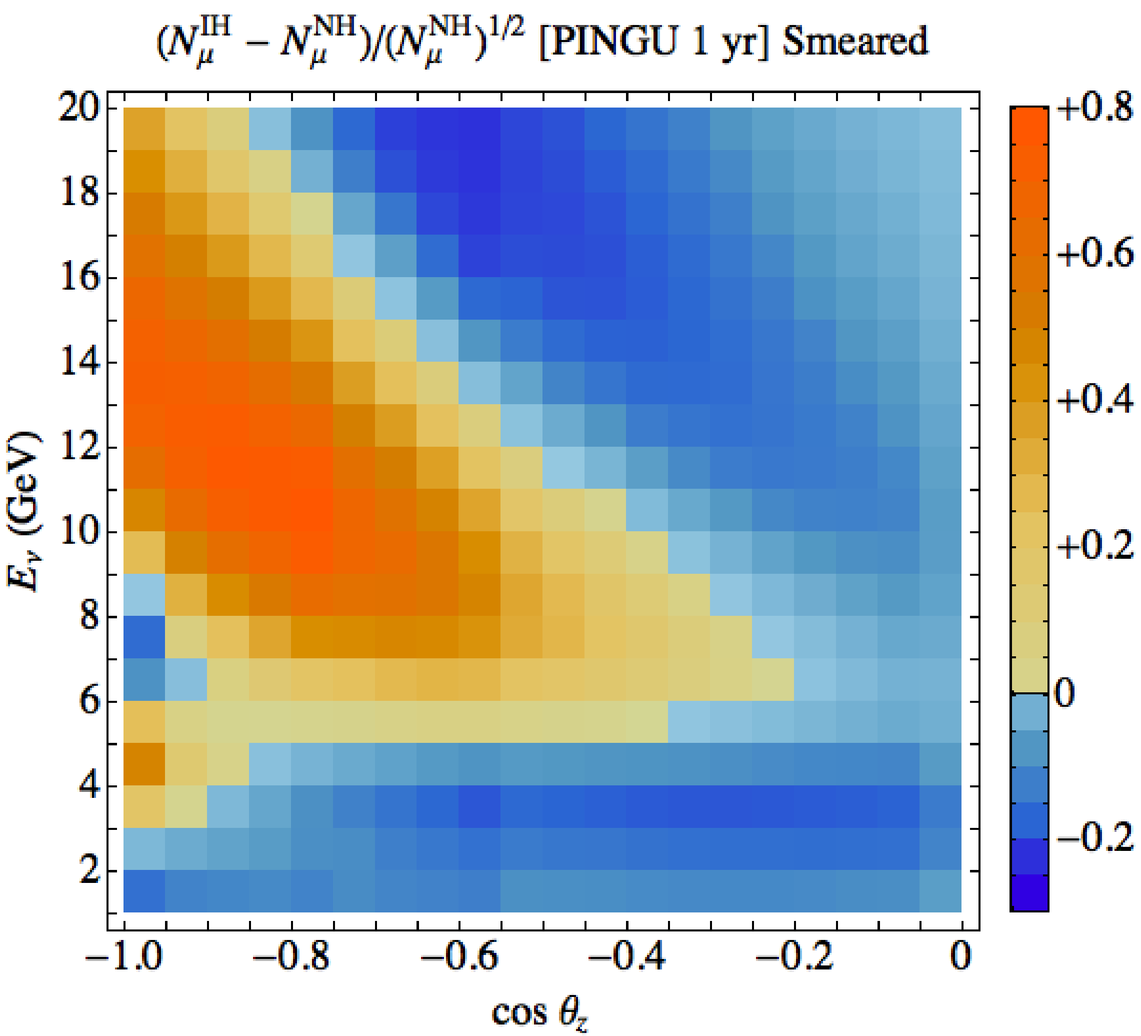


Neutrino oscillations probabilities with the matter effects (MSW) for $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$.

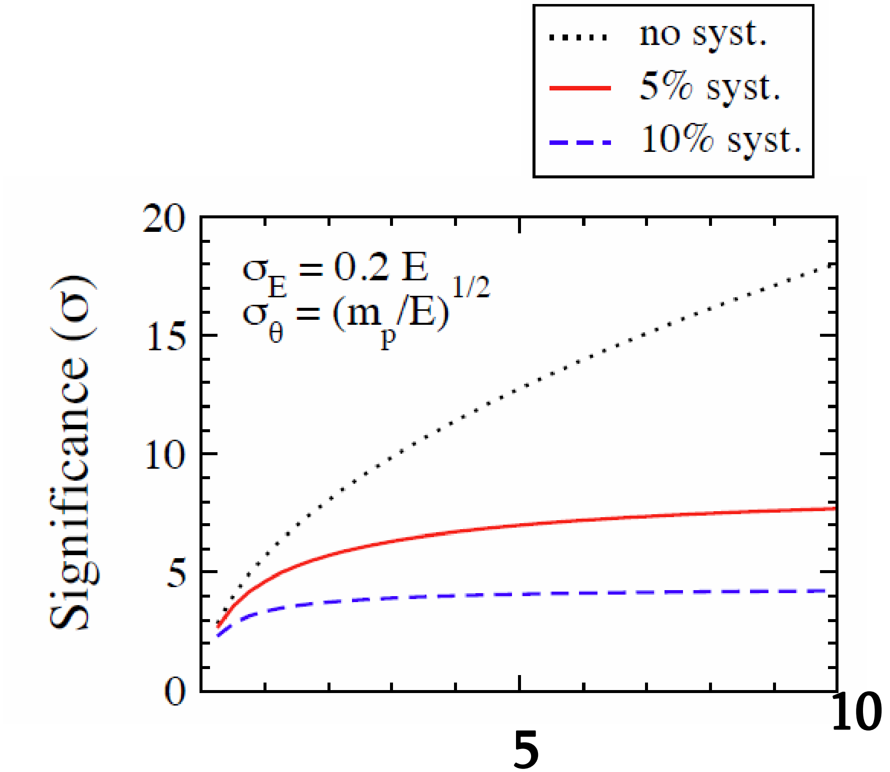
Solid lines: NH
Dashed lines: IH

E. Akhmedov, S. Razzaque and A. Yu. Smirnov, JHEP 1302 (2013) 082
Mass hierarchy, 2-3 mixing and CP-phase with Huge Atmospheric Neutrino Detectors

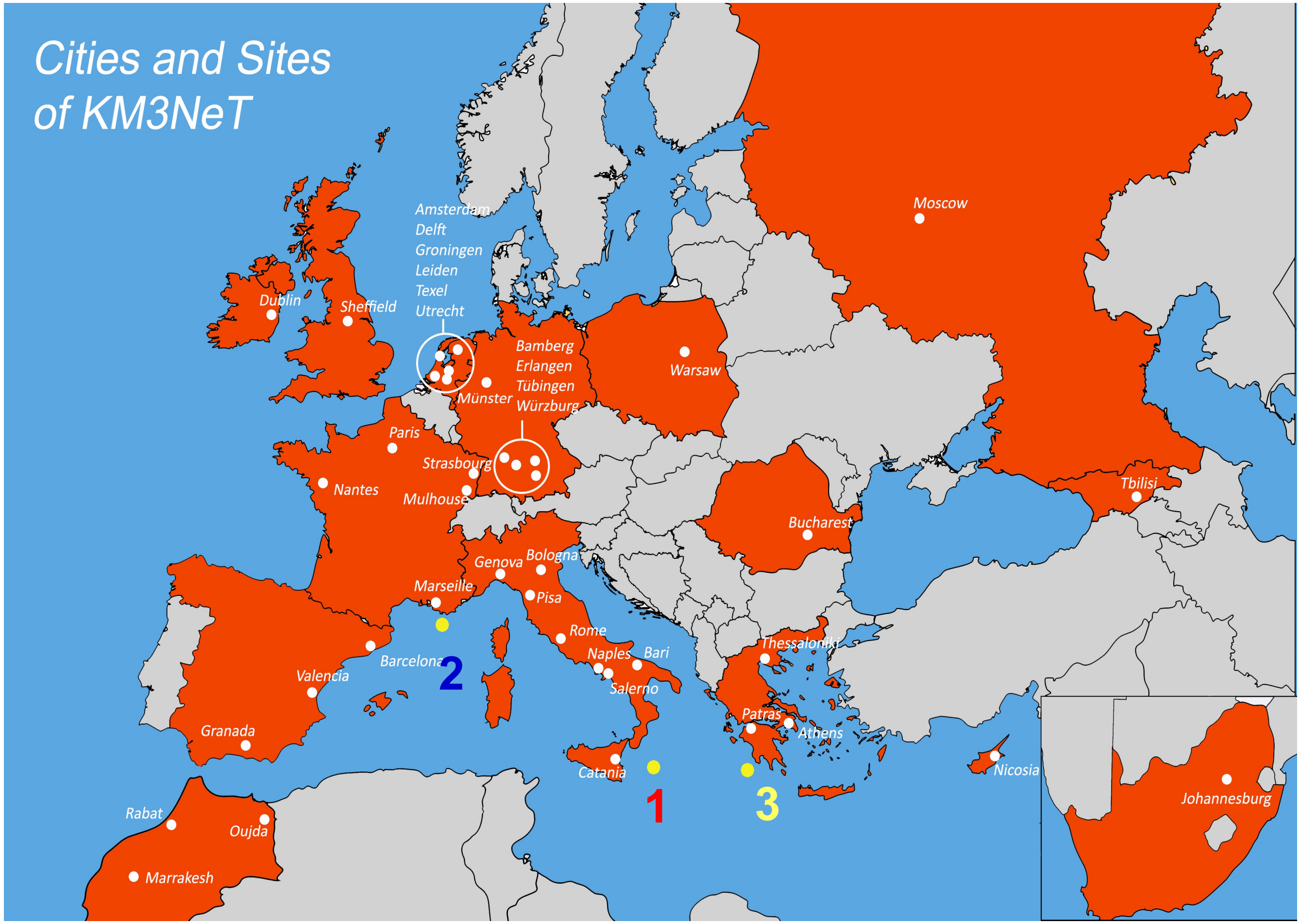
Probing the Neutrino Mass Hierarchy



Neutrino oscillogram obtained after smearing $\mu(\nu_\mu)$ events in the (E_ν-cosθ_z) plane with σ_E=0.2E and σ_θ= $(m_p/E_\nu)^{1/2}$



Significance of NMH determination vs. exposure time. Different curves correspond to different systematic uncertainties



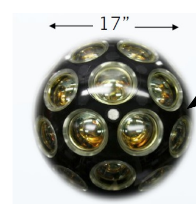
KM3NeT/**ORCA**
Oscillation **R**eseach in with **C**osmics in **A**byss

KM3NeT 2.0

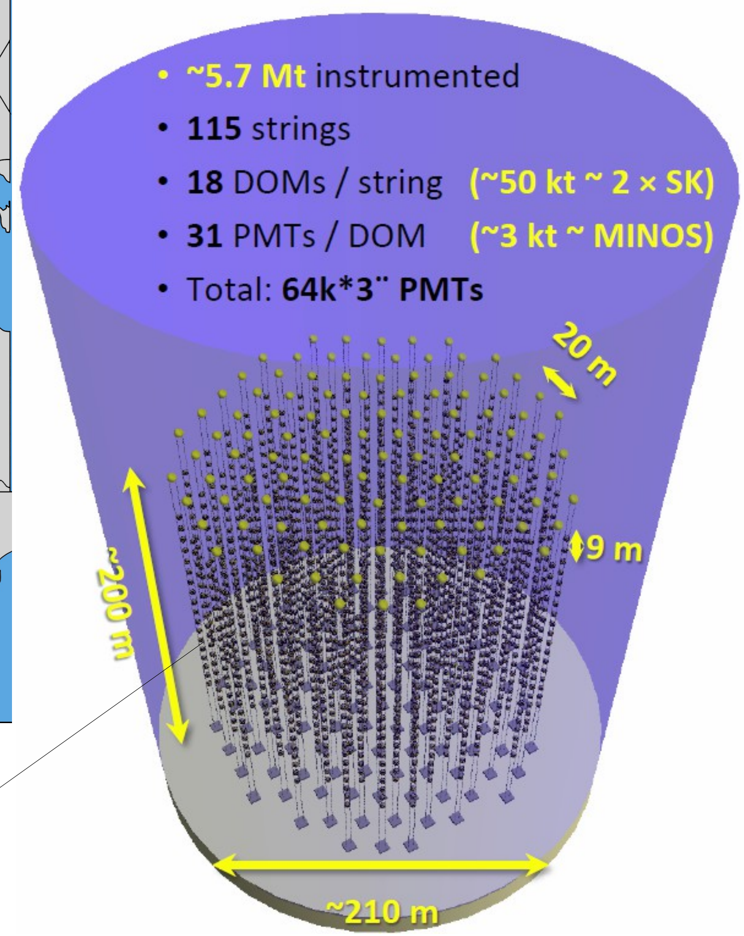
www.km3net.org

1 KM3NeT/ARCA

2 KM3NeT/ORCA



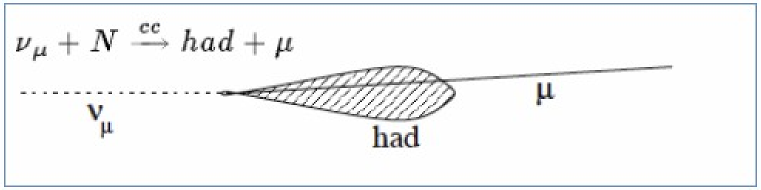
KM3NeT DOM

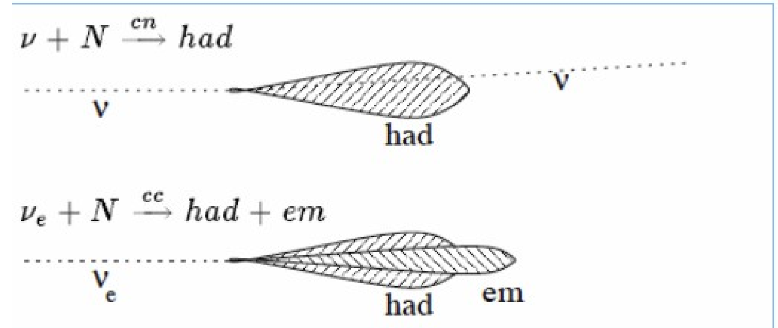


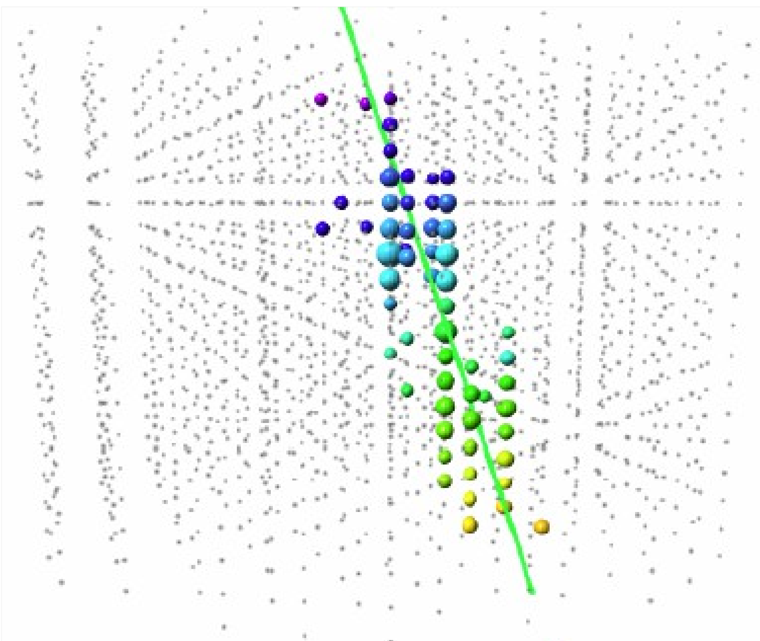
ORCA neutrino detector at a depth of 2575 m

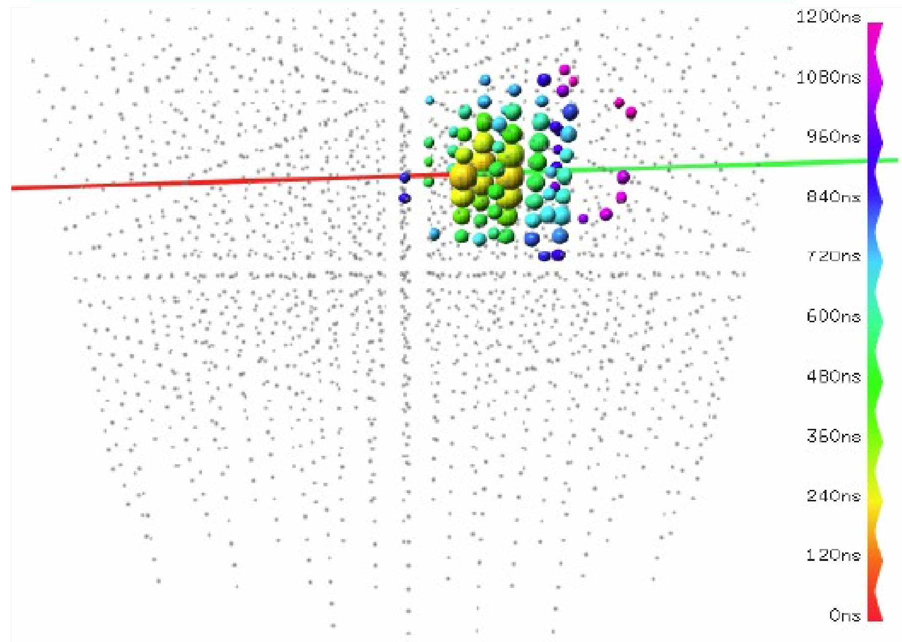
KM3NeT Collaboration (S. Adrián-Martínez, S), J.Phys. G43 (2016) 084001
Letter of intent for KM3NeT 2.0 [arXiv: 1601.07459]

KM3NeT/ORCA Simulations







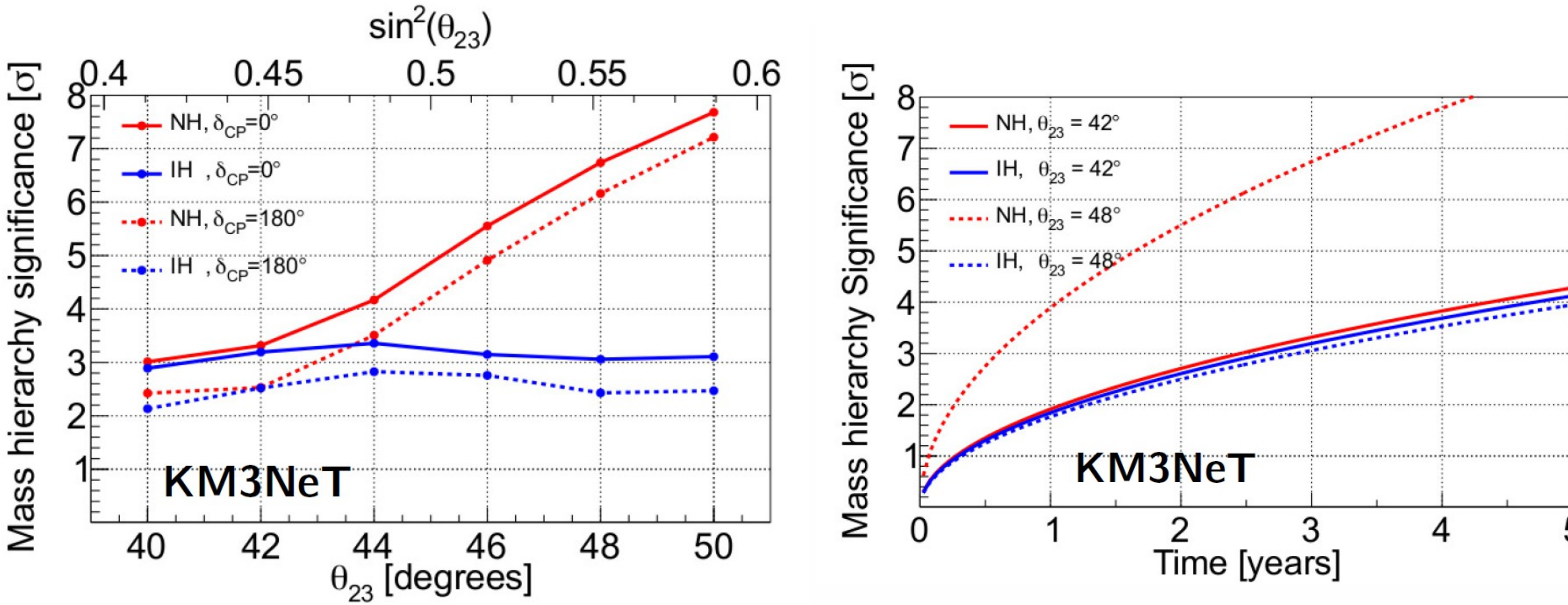


Reconstructed ν_μ and ν_e events.

KM3NeT/ORCA simulation chain includes:
ν-interactions (Genie), simulation of detector response (KM3Sim), simulation of the optical background, trigger simulation.

KM3NeT/ORCA Sensitivity to NMH

KM3NeT/ORCA neutrino mass hierarchy sensitivity for a detector wit 9m vertical spacing.



Left plot: NMH dependency on Θ_{23} for two values δ_{CP} for 3 years of operation time.

Right: NMH significance evolution over time for two selected values of θ_{23} .

Summary and Outlook

- Atmospheric, accelerator, solar and reactor neutrino experiments have provided compelling evidence for the neutrino oscillations.

- Neutrino oscillation parameters: PMNS mixing angles Θ_{12}, Θ_{13}, Θ_{23} and squared mass differences Δm^2_{32} and Δm^2_{21} are measured and defined.

- Neutrino oscillation parameters NMH(neutrino mass hierarchy), δ_{CP} and octant of Θ_{23} are still undefined from the current experiments.

- Neutrino oscillation parameters (including NHM, Θ_{23} octant, δ_{CP}) will be defined with high a precision in the future experimental projects such as JUNO, DUνE, KM3NeT/ORCA, Hyper-K, INO, IceCube/PINGU.