Solar and atmospheric ν's

Masato SHIOZAWA

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (WPI), U of Tokyo

ICFA2014 Seminar at Beijing
October 27, 2014

Solar and atmospheric ν's

Masato SHIOZAWA

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (WPI), U of Tokyo

ICFA2014 Seminar at Beijing
October 27, 2014

3-flavor oscillation scheme

Flavor eigenstate Mass eigenstate

$$^{t}(\nu_e,\nu_\mu,\nu_\tau) = U_{\alpha i}^{MNS\ t}(\nu_1,\nu_2,\nu_3)$$

U^{MNS}: Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\vartheta_{12} & \sin\vartheta_{12} & 0\\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\vartheta_{13} & 0 & \sin\vartheta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\vartheta_{13}e^{i\delta} & 0 & \cos\vartheta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23}\\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Parameterized by 4 (mixing matrix) and 2 (difference of squared masses)

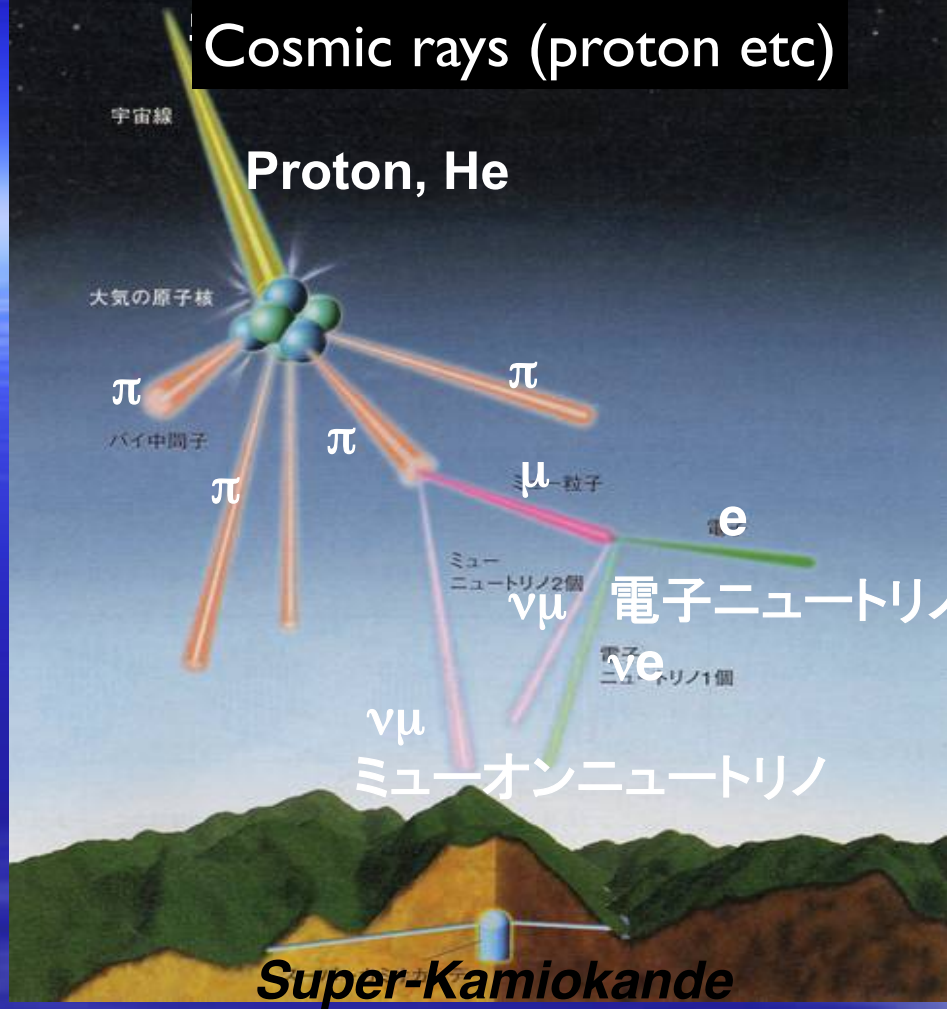
$\theta_{23}\sim45\pm5°$ $\lvert\Delta m^2_{32}\rvert=2.4\times10^{-3}eV^2$	$\theta_{12}\sim34\pm3°$ $\Delta m^2_{21}=+7.6\times10^{-5}eV^2$	$\theta_{13}\sim9°$	δ=unknown
Atmospheric ν, Accelerator ν	**Solar ν**, Reactor ν	Accelerator ν, Reactor ν, **Atm & Solar ν**	Accelerator ν, **Atmospheric ν**

Mass hierarchy ($\Delta m^2_{32}=m^2_3-m^2_2>0$ or $\Delta m^2_{32}<0$) is also unknown:
Accelerator ν, **Atmospheric ν**, reactor ν

Solar&Atmospheric ν's played pioneering roles in the past ν oscillation studies and would also play important roles in future.

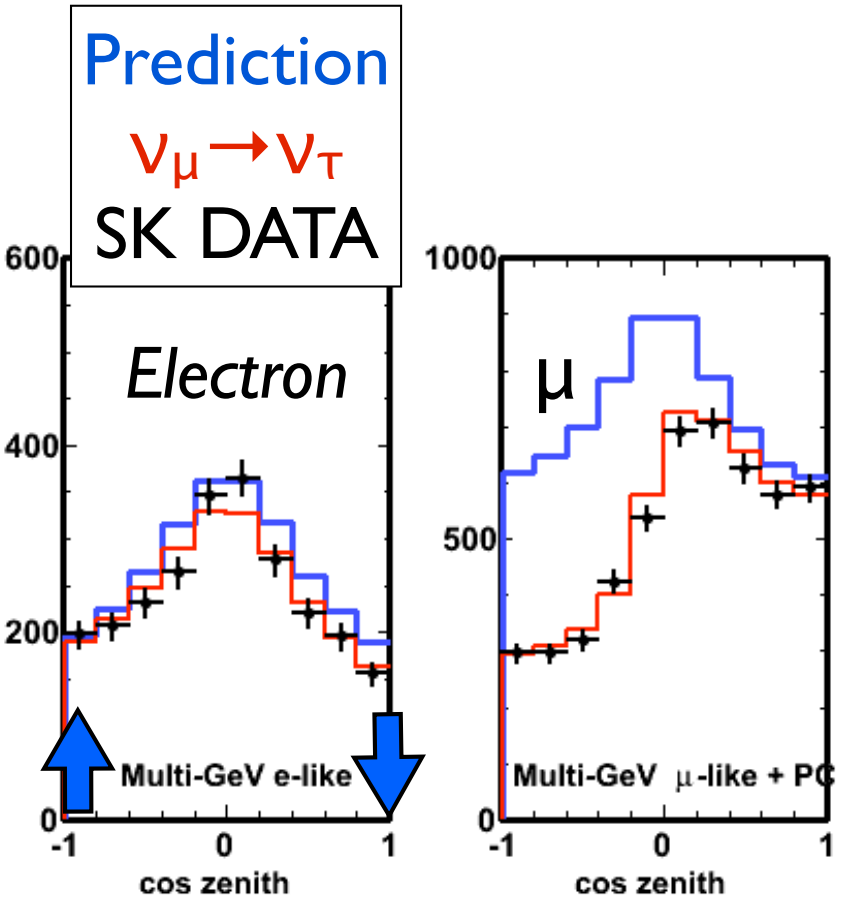
Atmospheric ν's

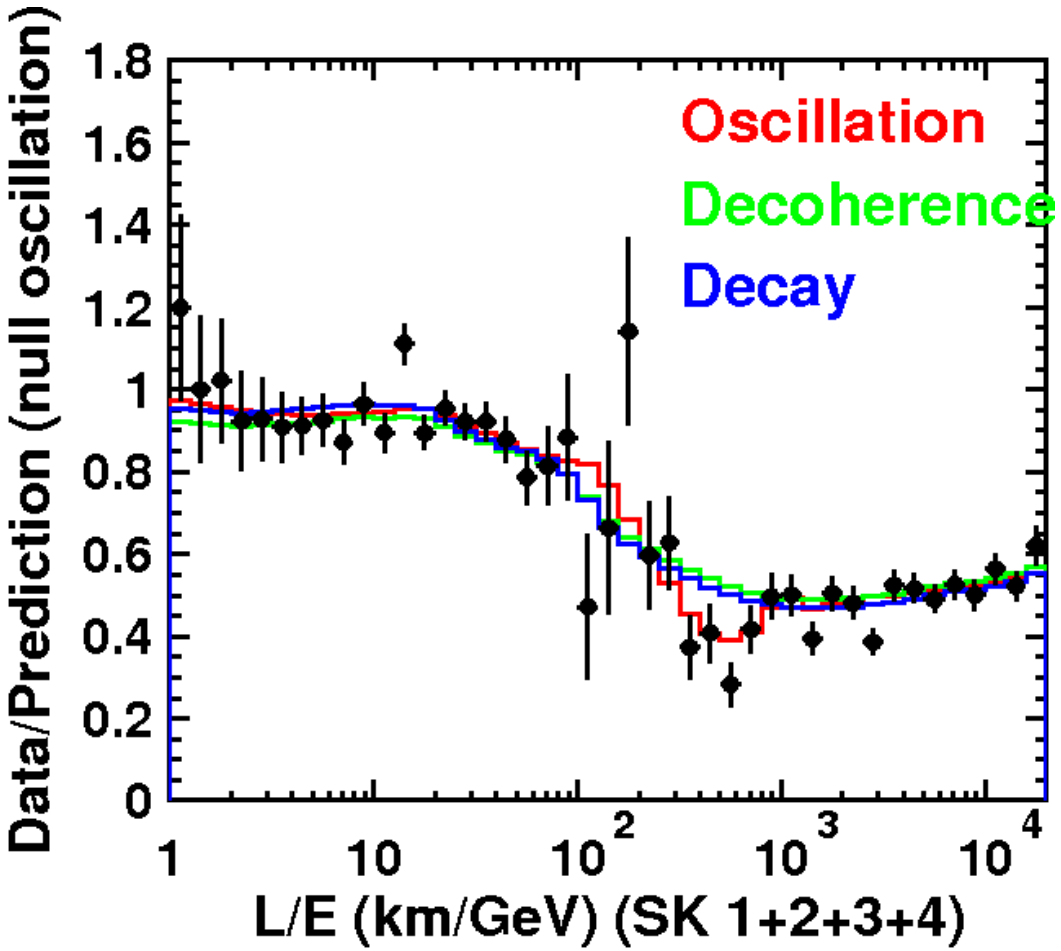
Earth's atmosphere



- Wide range of ν energy (0.1 GeV ~ 10^4 GeV and beyond)
- Wide range of ν baseline (10km downward ~ 13,000km upward)
- ν_μ:ν_e ~ 2:1 at production
- ν oscillation study by high statistical data (>40,000 events in Super-K) and all three flavors (ν_e, ν_μ, ν_τ)
- Unique tests of ν's exotic property (4th ν, Lorentz violation, etc)

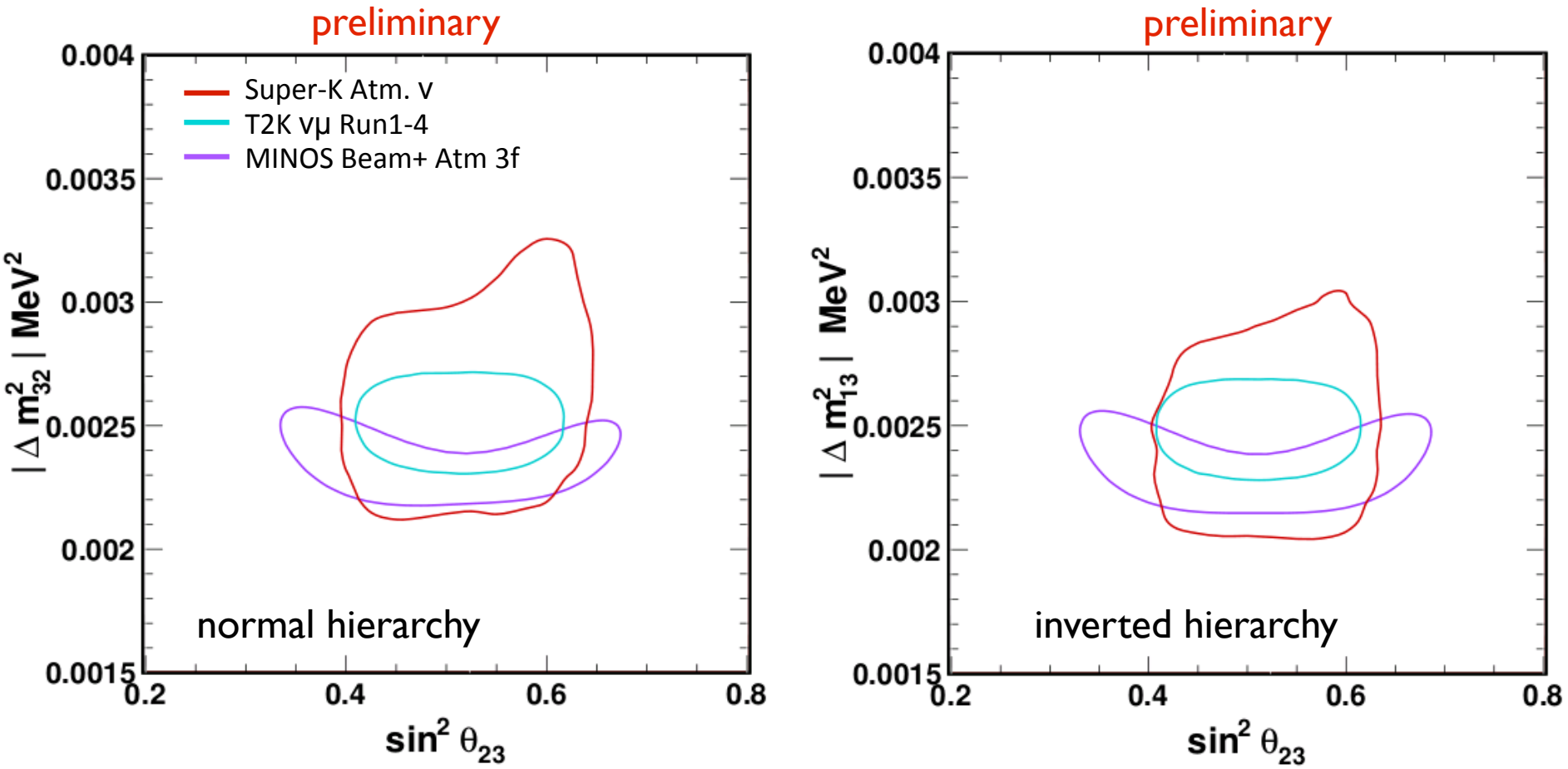
Early history of atmν's oscillations





- Dominant effect is ν_μ disappearance **(discovered in 1998)**
- Oscillatory signature **(evidence in 2004)**

Dominant effect: ν_μ disappearance



Though consistent with accelerator ν experiments atmν allows more parameter space.

$\sin^2\theta_{23}$ =0.5 (maximal mixing) or <0.5 or >0.5 is still a open question (θ_{23} octant problem).

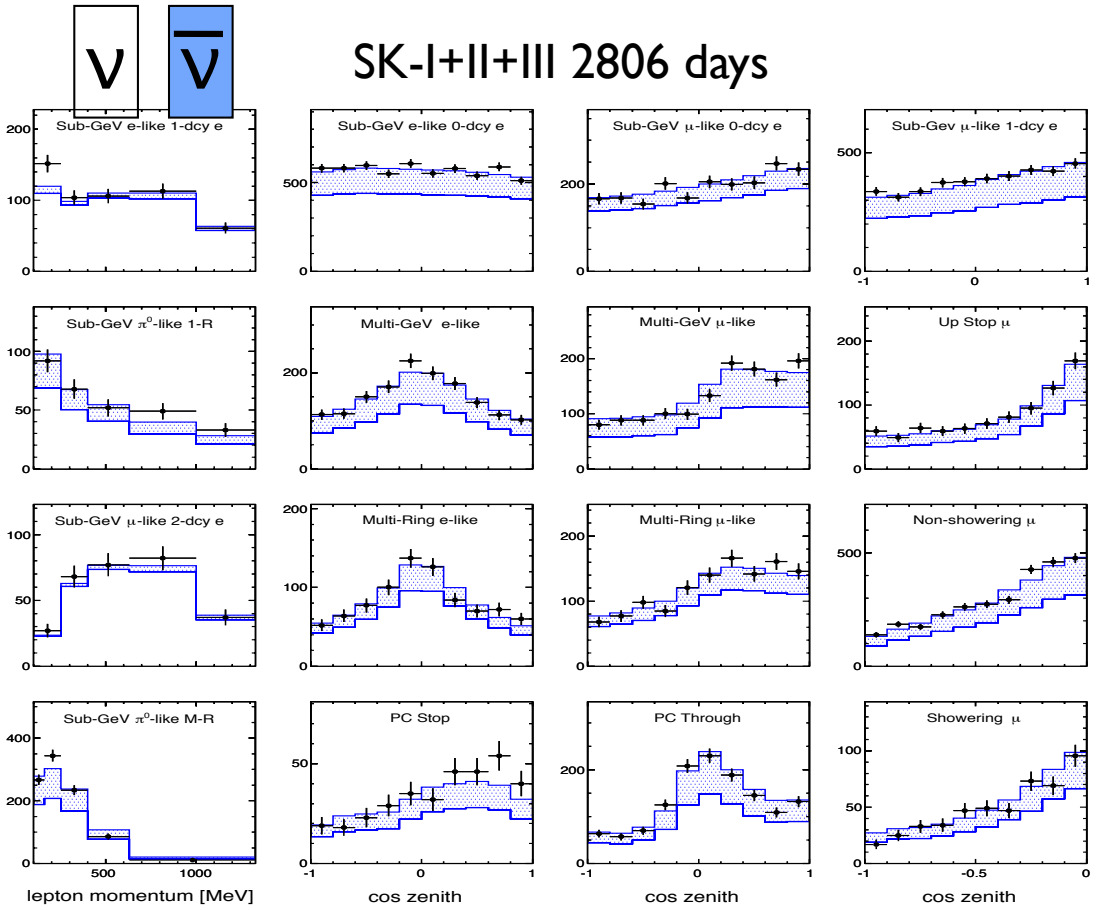
$\bar{\nu}_\mu$ oscillation study

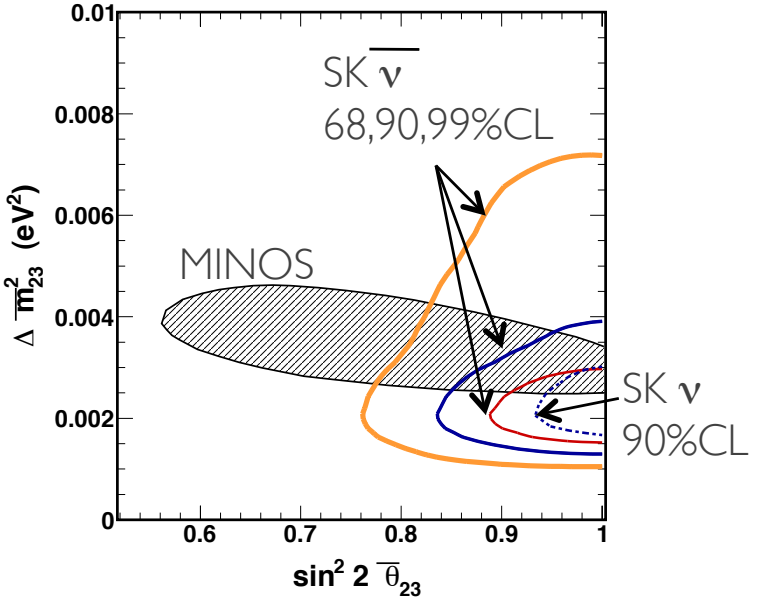
PRL 107, 241801 (2011)

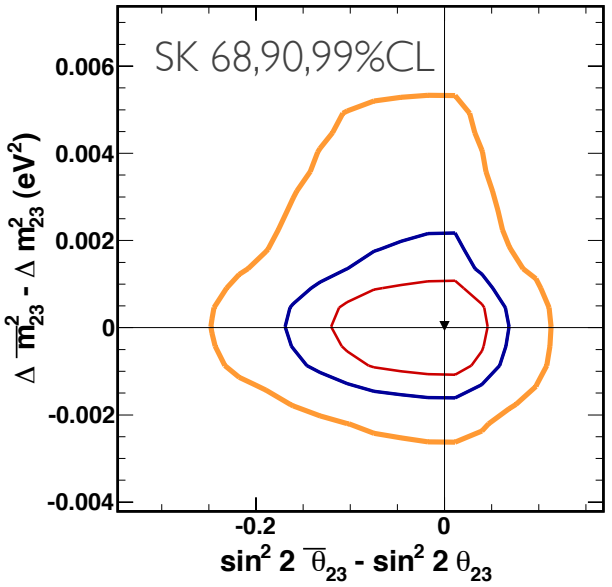
$$P(\nu_\mu \to \nu_\tau) = 1 - \sin^2 2\vartheta \sin\left(\frac{\Delta m^2 L}{E}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\tau) = 1 - \sin^2 2\bar{\vartheta} \sin\left(\frac{\Delta \bar{m}^2 L}{E}\right)$$

ν and ν-bar differ
- cross sections
- flux
- event topology

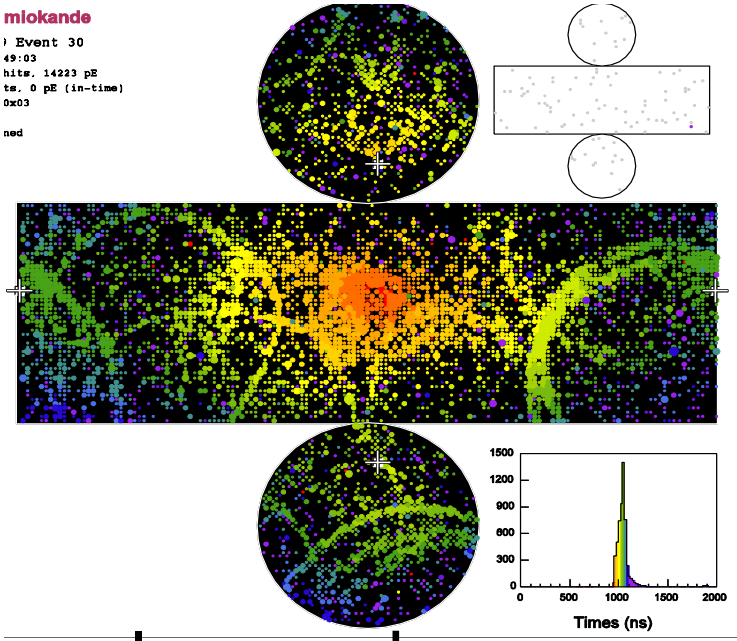






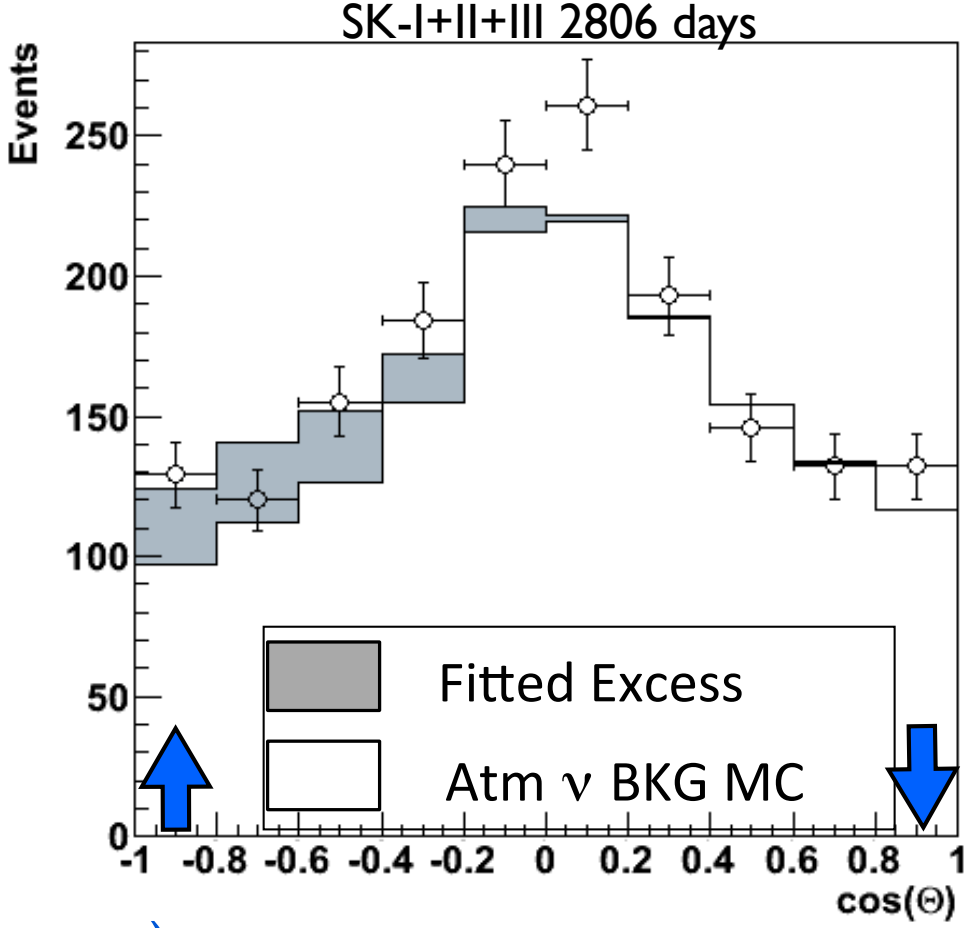
Good constraints on anti-neutrino parameters.
Data is consistent with CPT conservation.

Evidence for τ neutrino appearance



PRL 110, 181802 (2013)

Zenith Distribution of τ-like events



Neural network to enhance events consistent with hadronic decays of τ

$$N_\tau^{DATA}/N_\tau^{exp} = 1.42 \pm 0.35(stat) {}^{+0.14}_{-0.12}(syst)$$

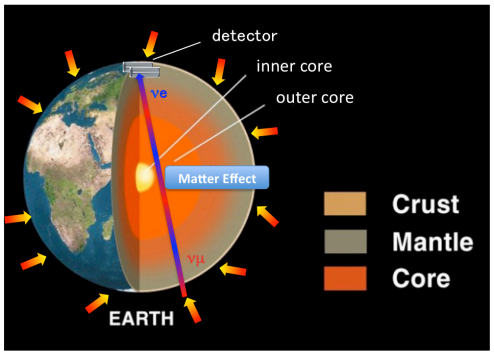
3.8σ significance for null τ

3 τ observation @ OPERA (PRD89, 051102(R) (2014))

$\nu_\mu \rightarrow \nu_\tau$ channel has been established.

Atmospheric ν anomaly (problem) is finally concluded.

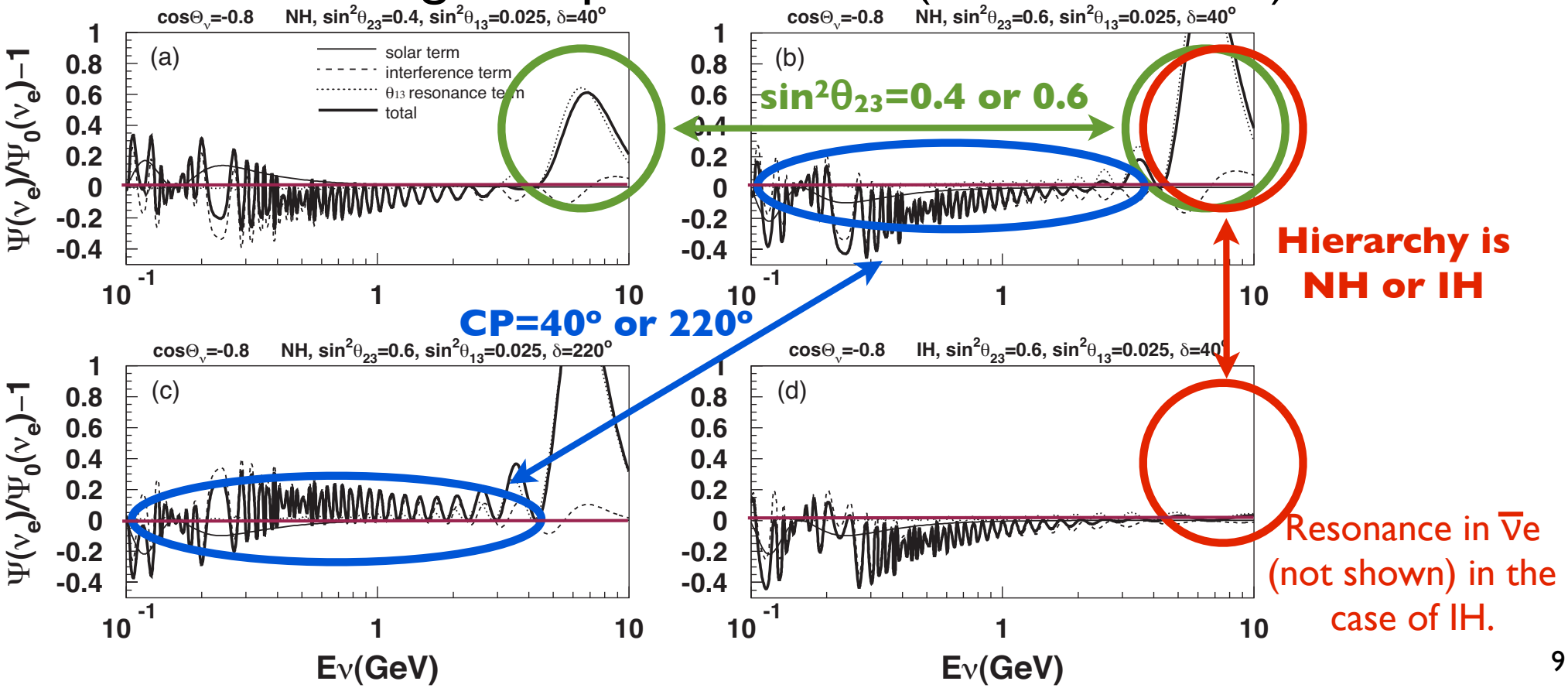
Atmospheric ν_e oscillation



Through the matter effect in the Earth, we study on

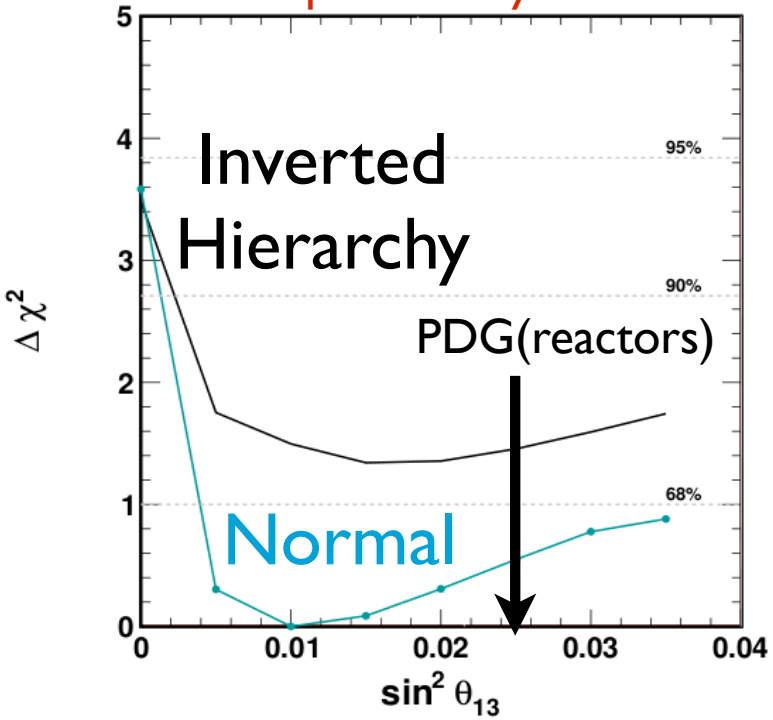
- Mass hierarchy : resonance in multi-GeV $\bar{\nu}e$ or νe
- CP δ : interference btw two Δm^2 driven oscill.
- θ_{23} octant : magnitude of the resonance

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"

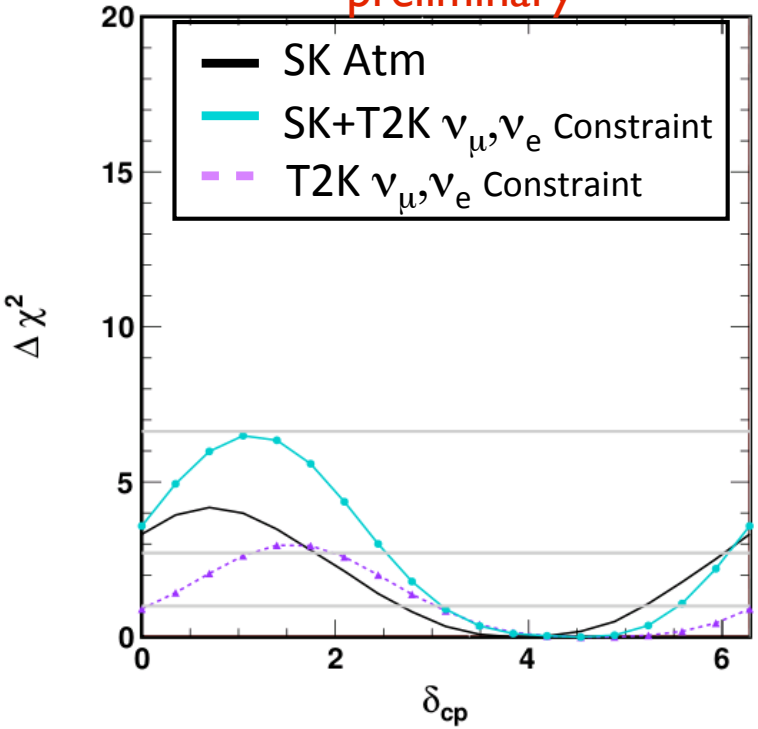


MH and δ_{CP} study

preliminary



preliminary



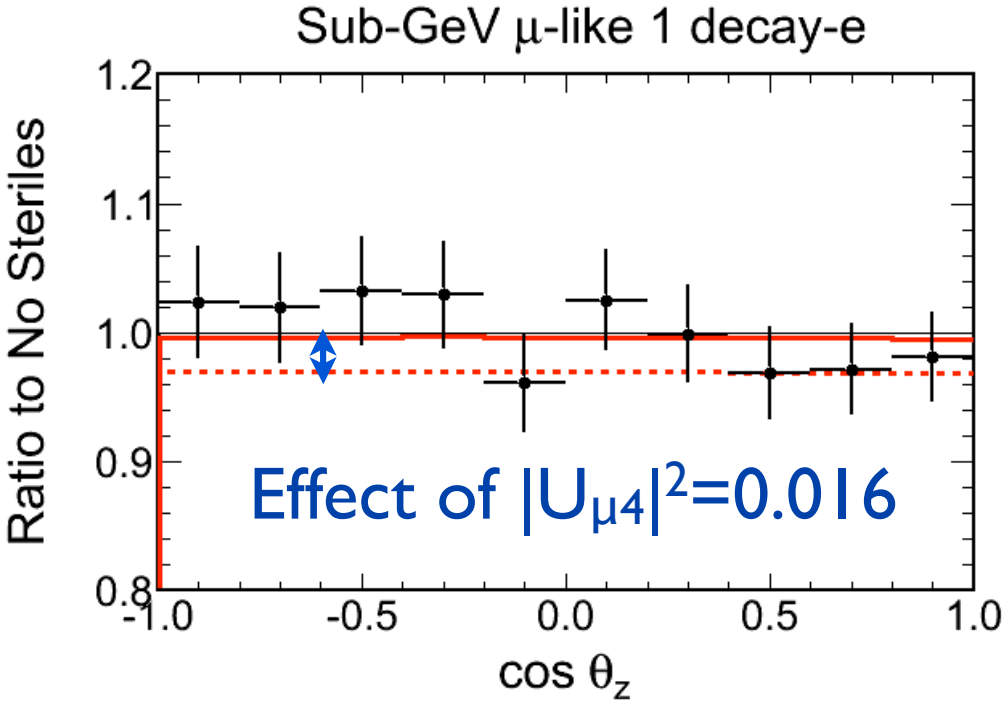
- Preference of normal hierarchy:
  $\chi^2_{IH}-\chi^2_{NH}$=0.9 (SK only)
  1.2 (T2K combined).
- Preference of δ_{CP} near $3\pi/2$ is also strengthened by T2K
  - CP conservation ($\sin\delta_{CP}=0$) is still allowed at 90% CL
- Need more data

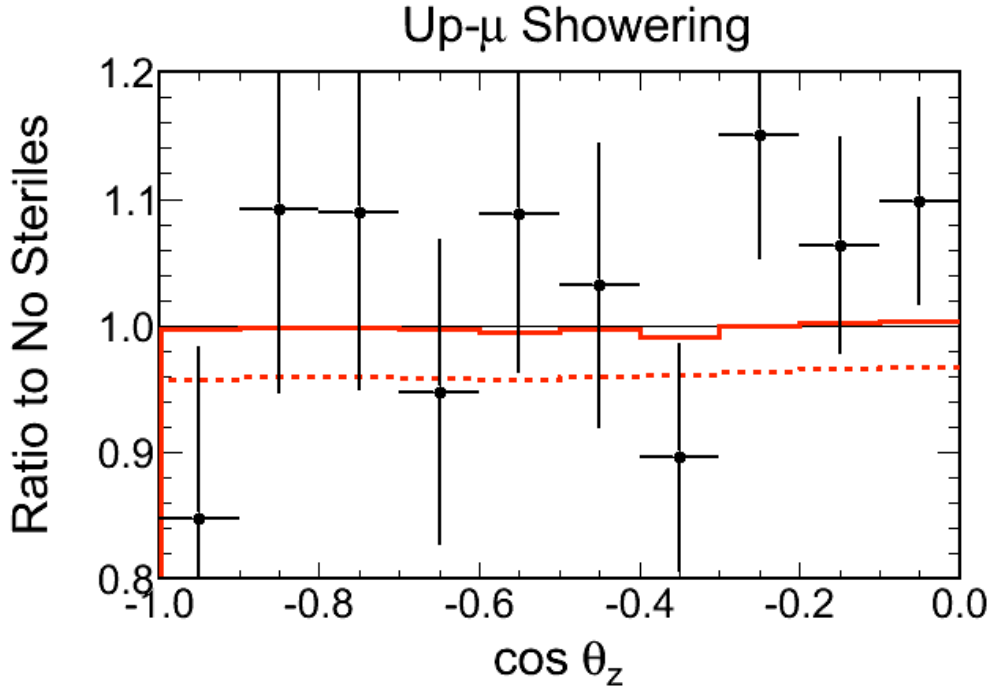
Sterile neutrino oscillations

4th ν(Sterile ν) is indicated by LSND, MiniBooNE, reactor, solar ν exp's

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- independent on the number of sterile νs and $\Delta m^2_{sterile}$
  - constraints for 3+1 framework can be extended to 3+N
  - constant constraints as long as $\Delta m^2_{sterile} > 0.01 eV^2$
- $U_{\mu 4} \rightarrow$ uniform μ deficit in angle/ energy
- $U_{\tau 4} \rightarrow$ shape distortion in angular distributions of high energy μ

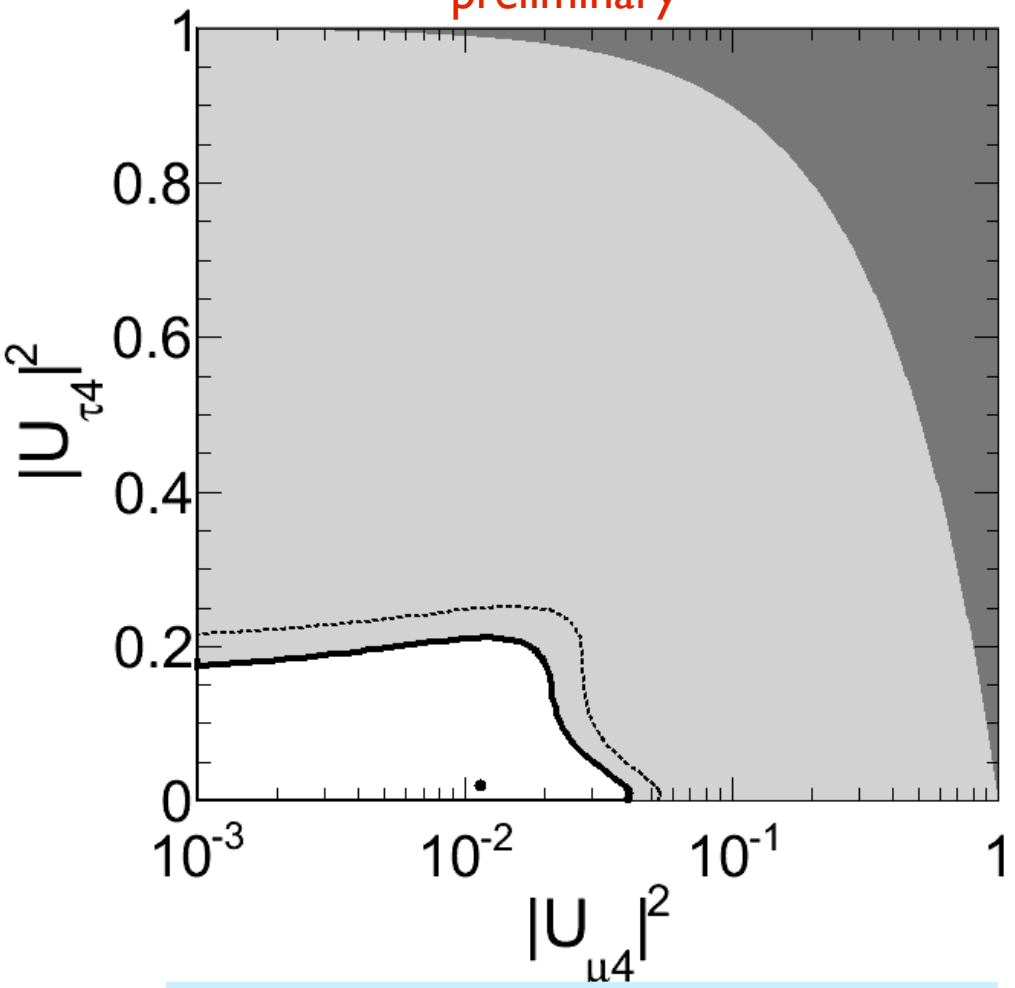




Limits on sterile ν contribution

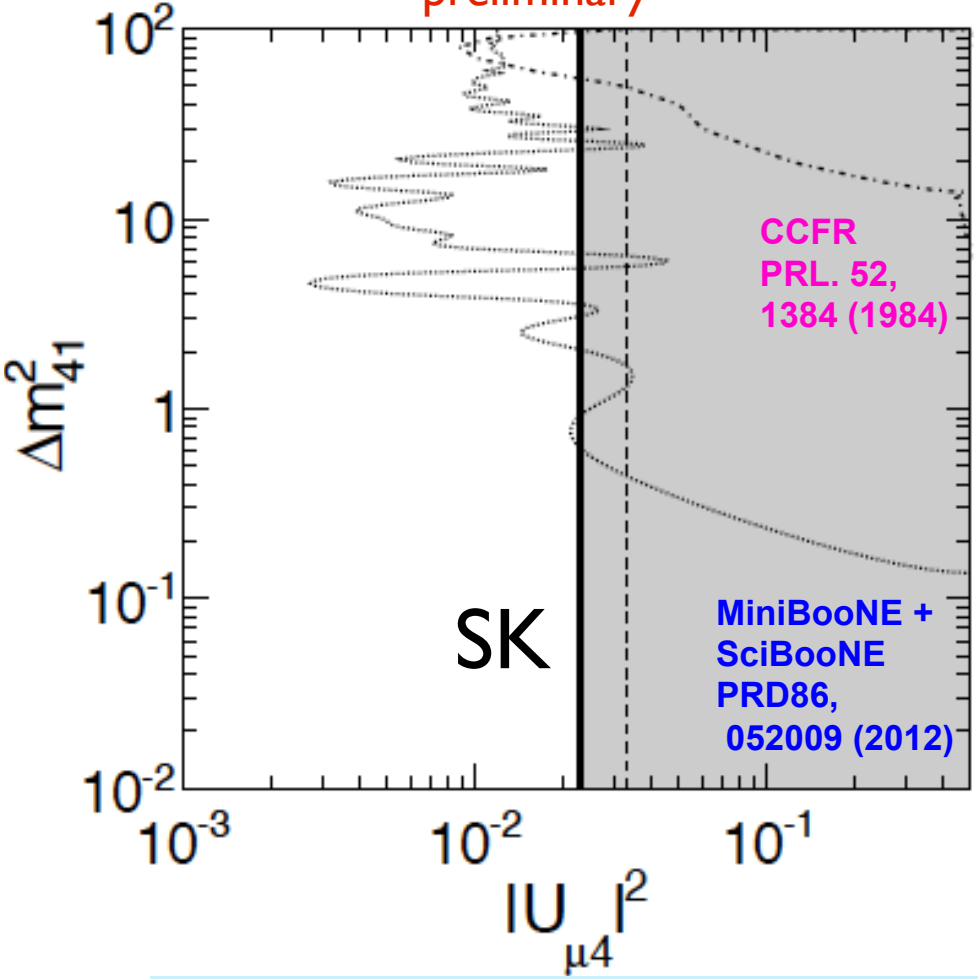
arXiv:1410.2008, submitted to PRD

preliminary



$|U_{\tau 4}|^2 < 0.2$ @ 90% CL

preliminary

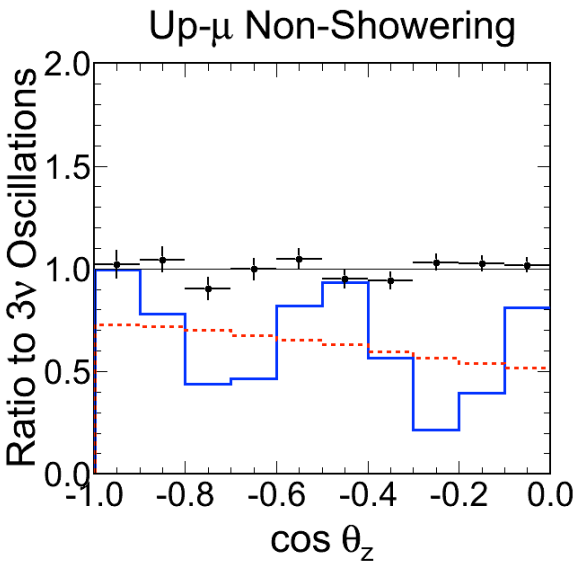


$|U_{\mu 4}|^2 < 0.022$ @ 90% CL

Atmospheric ν data is consistent with 3-active ν framework (no sterileν contribution), and provides limits on mixings.

Lorentz invariance violating oscillations

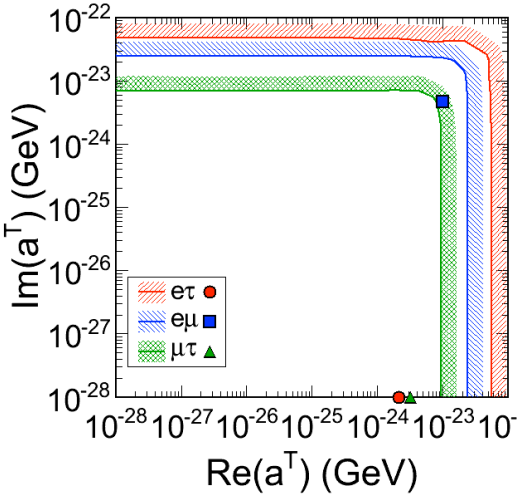
arXiv:1410.4267, submitted to PRD

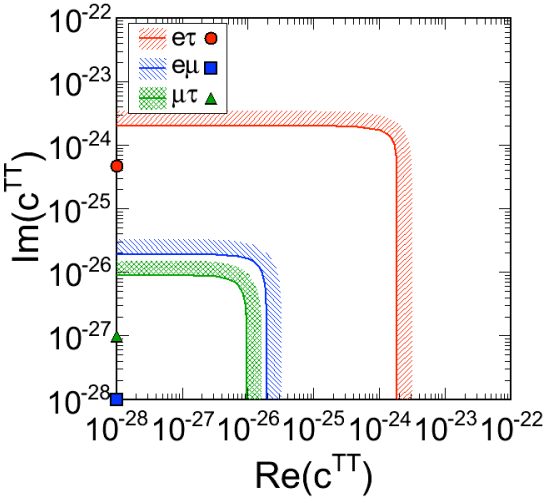


—— No LV

$\overline{a^{T}_{\mu\tau}=10^{-22}\text{GeV}}$

$\overline{c^{TT}_{\mu\tau}=10^{-22}}$





Consistent with null LIV

	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-	$\Im(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-
	2×10^{-23}	4×10^{-23}	8×10^{-24}		2×10^{-23}	2×10^{-23}	4×10^{-24}
	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-	$\Im(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-
	4×10^{-26}	2×10^{-24}	2×10^{-26}		4×10^{-26}	2×10^{-24}	2×10^{-26}

New limits

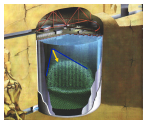
Provided 3~7 orders of magnitude better constraints than past

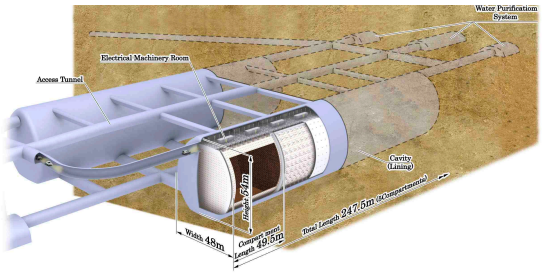
Future prospect of atmν studies: mass hierarchy determination

Super-K
1996-present
50,000 ton

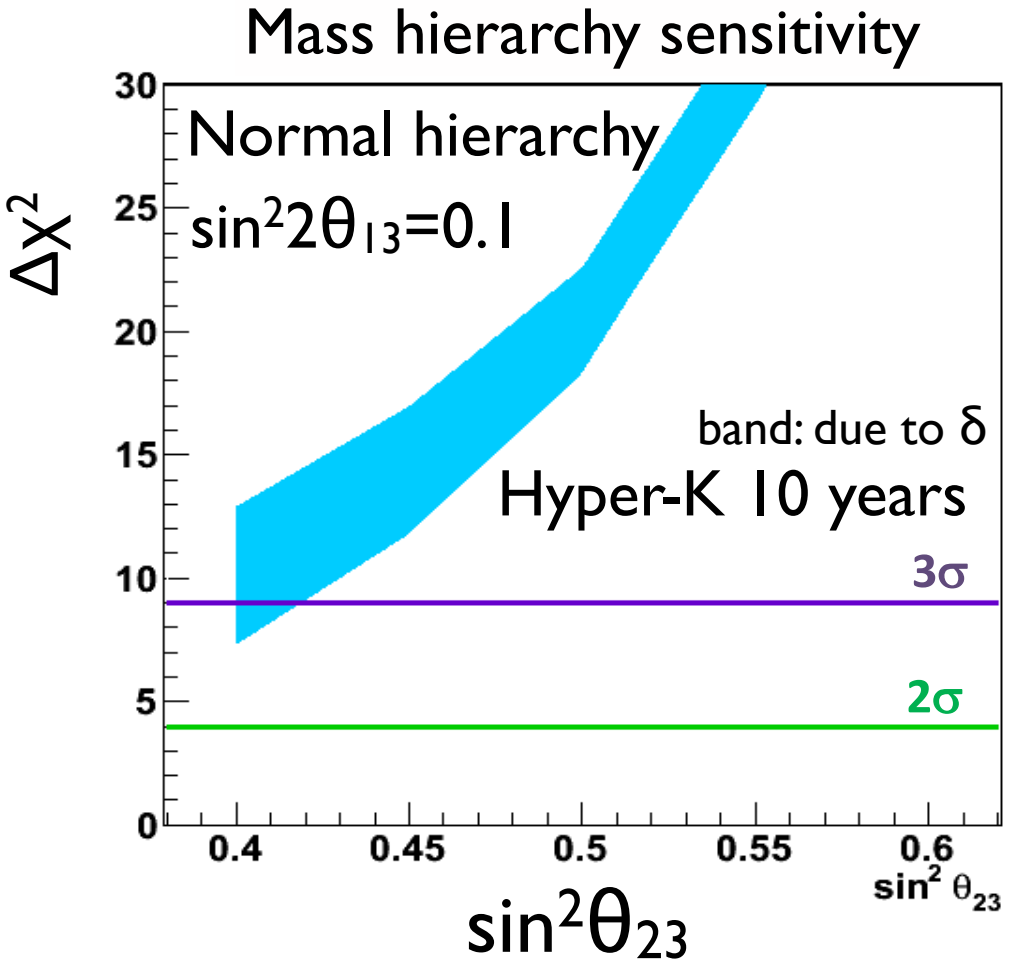
×25

Hyper-K
2025-
1,000,000 ton





- Proton decay searches extends to discovery region
- Studies toward understanding full picture of neutrino oscillations
  - CPV
  - MH determination for any δ
  - θ_{23} octant determination
- Astrophysical neutrino observatory
  - Supernova ν
  - Solar neutrino (~200ν ev/day)

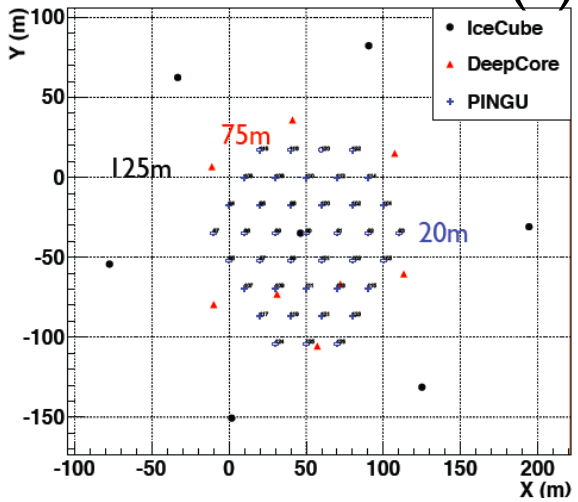


Whole allowed parameter space is covered by atmν only study

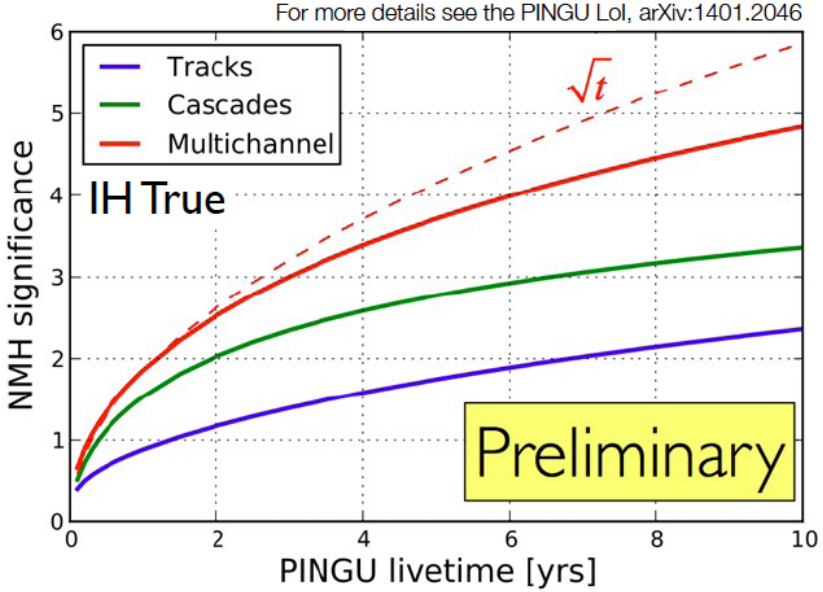
More for hierarchy study

IceCube+DeepCore+PINGU ~2020-

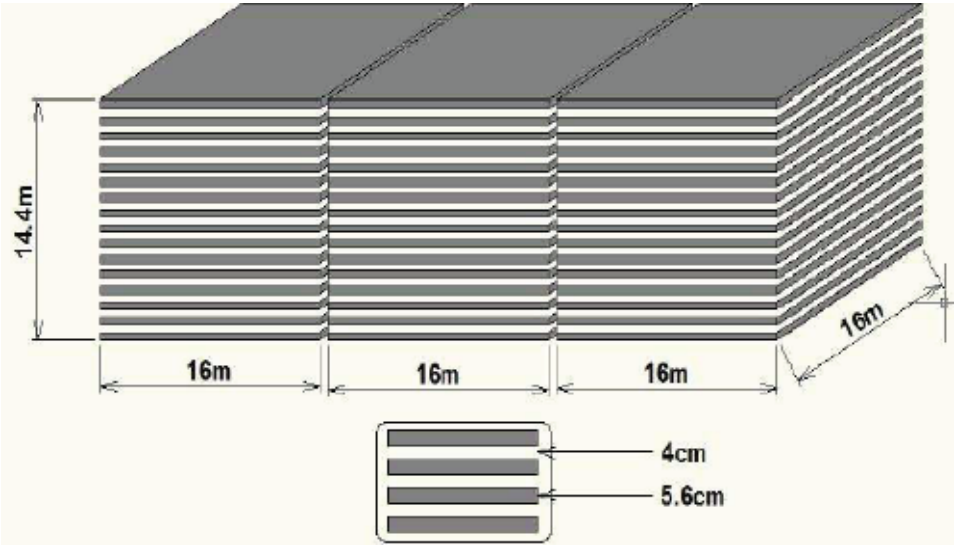
E threshold down to O(1) GeV

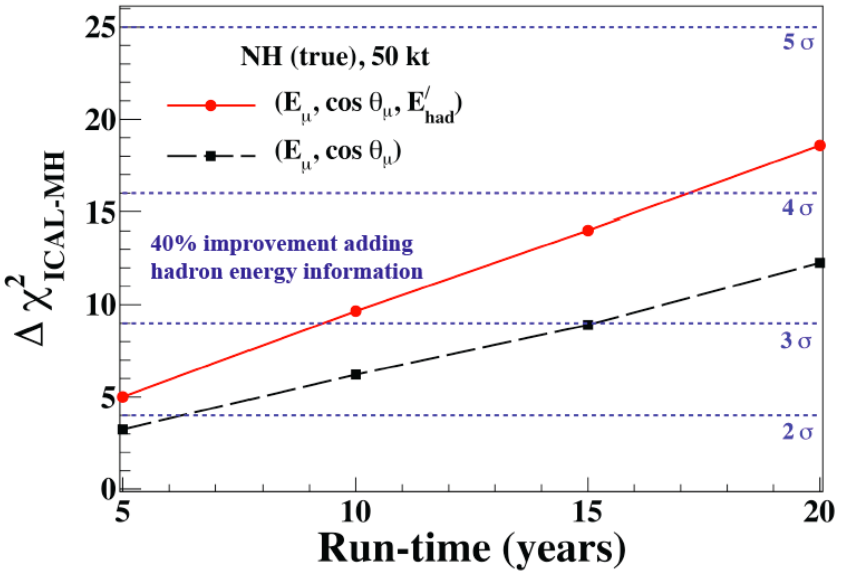


For more details see the PINGU LoI, arXiv:1401.2046



INO ~2020-
50kton Iron Calorimeter





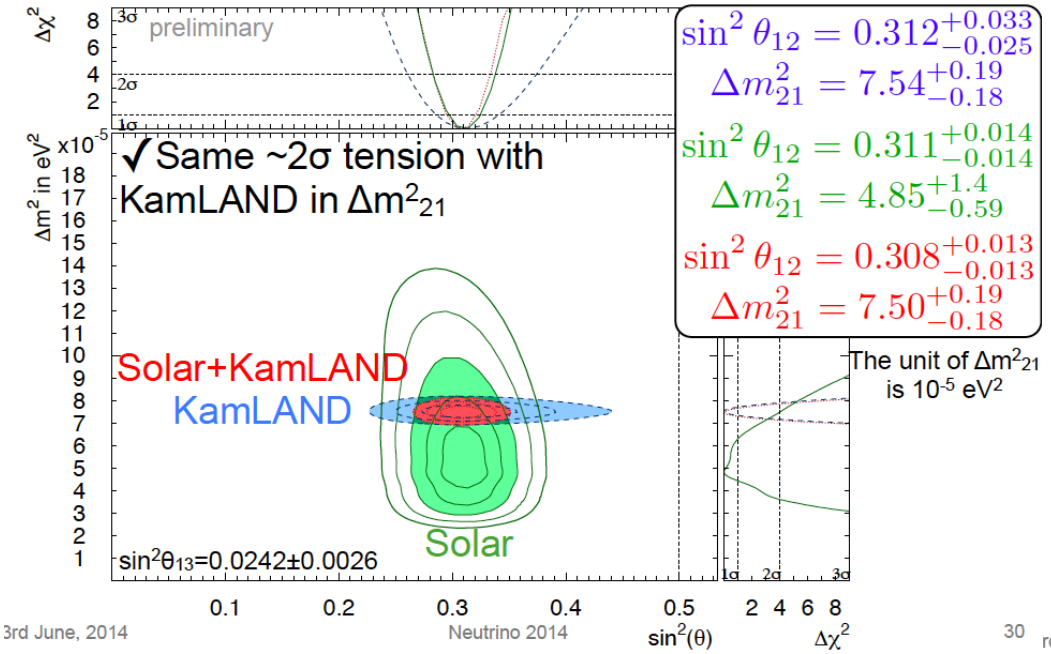
More than 3 σ sensitivities in both programs

Solar neutrino studies

- Pure ν_e source from pp-chain reactions and CNO cycle
- High statistical data available (>70,000 events in Super-K)
- Study on neutrino properties
- Search for new physics beyond the standard model
- Unique probe of solar structure & solar system formation

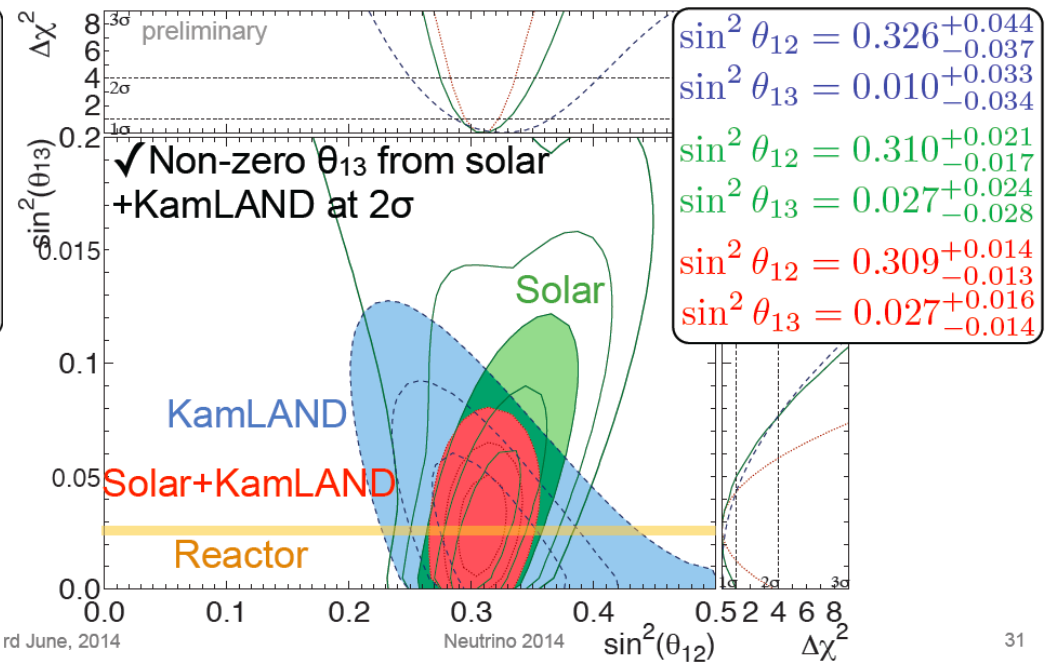
Latest oscillation results (global fit)

Combined solar fit w/ KamLAND



3rd June, 2014 Neutrino 2014 30

Without reactor θ_{13} constraint



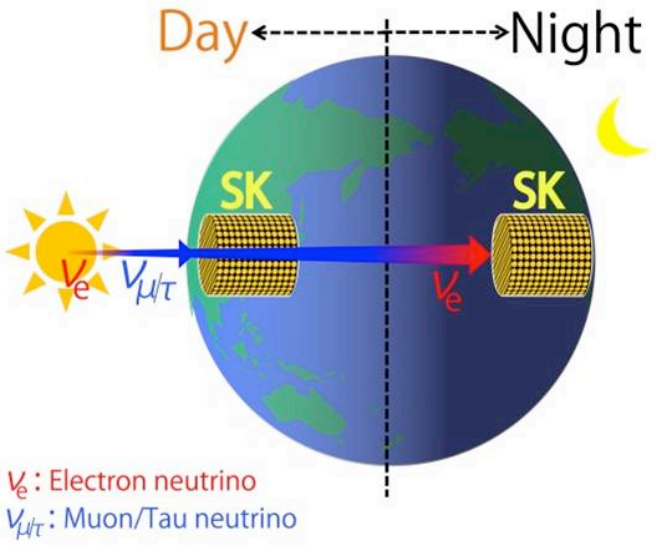
rd June, 2014 Neutrino 2014 31

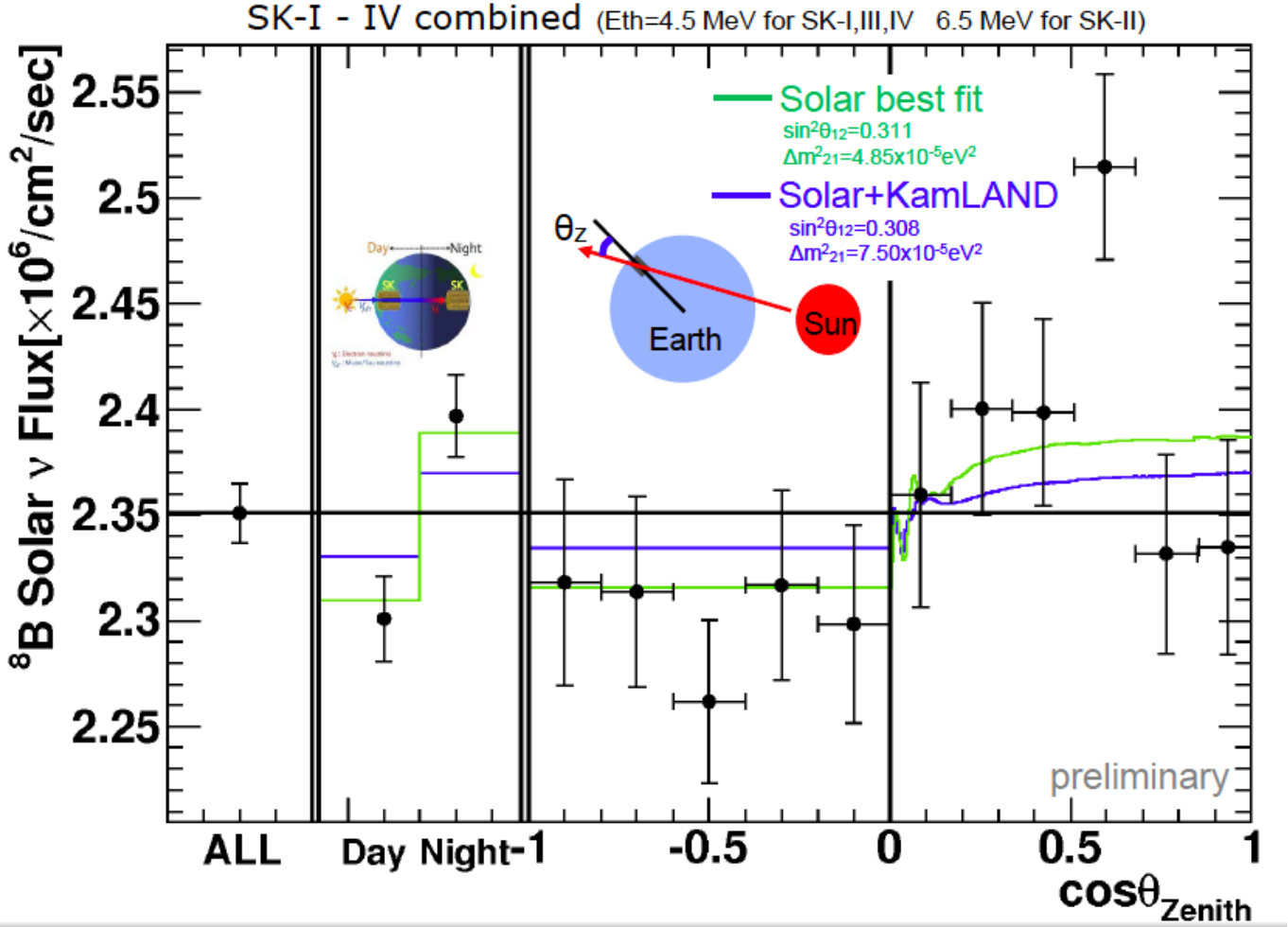
~2σ tension in Δm^2_{21} between solar and KamLAND

- Non-zero θ_{13} at ~2σ by solar and KamLAND only
- Good agreement with $\sin^2\theta_{13}=0.0221\pm0.0012$ by Daya Bay, RENO, and DC

Day/night asymmetry
-- direct test of MSW effect --

PRL112,091805(2014)

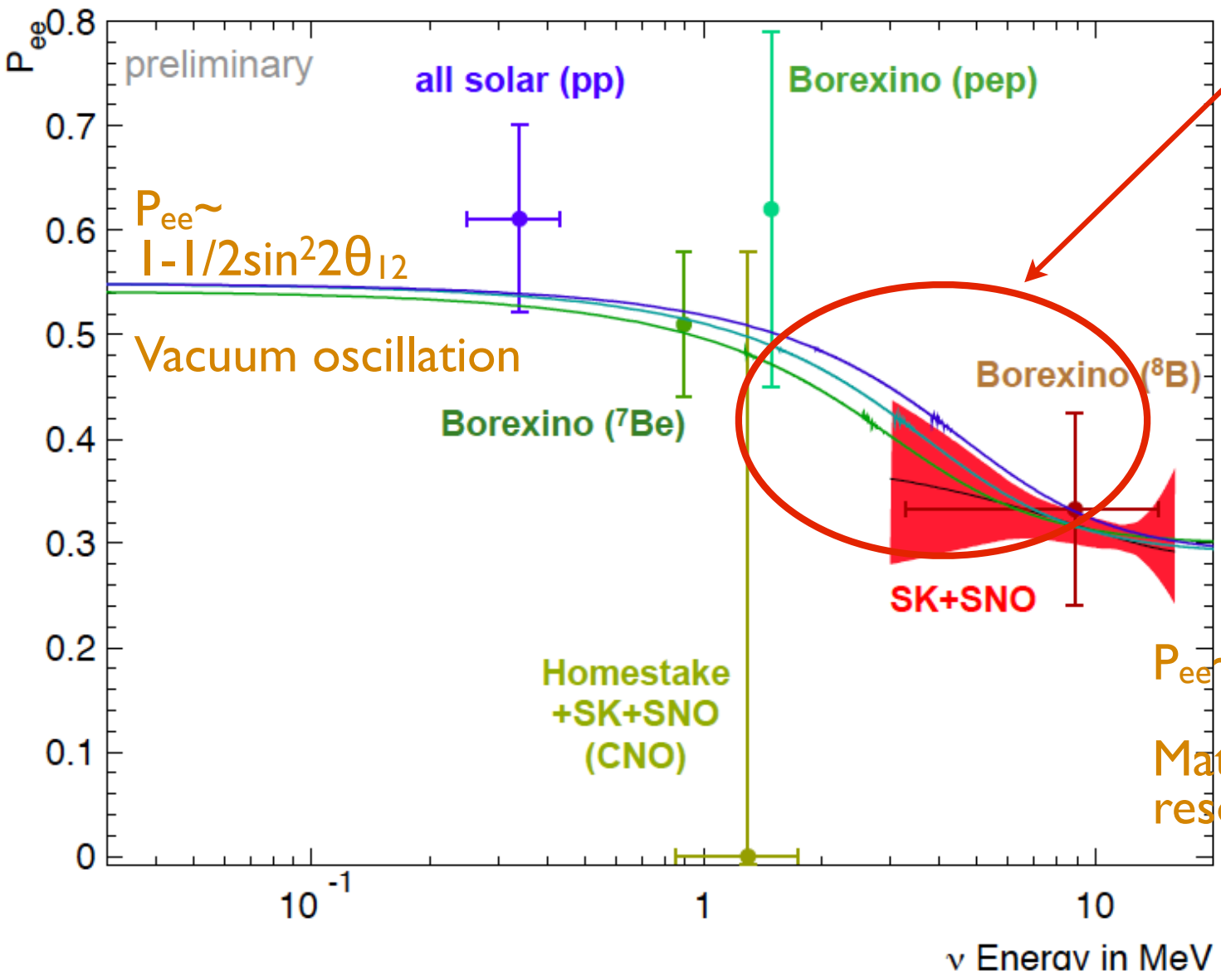




First indication (at 2.8~3.0 σ) of terrestrial matter effects

could be important achievement for future LBL and atmospheric ν studies in which the matter effect is relevant

Survival probability (spectrum)



Transition region
- Test of MSW effect
- non-standard physics

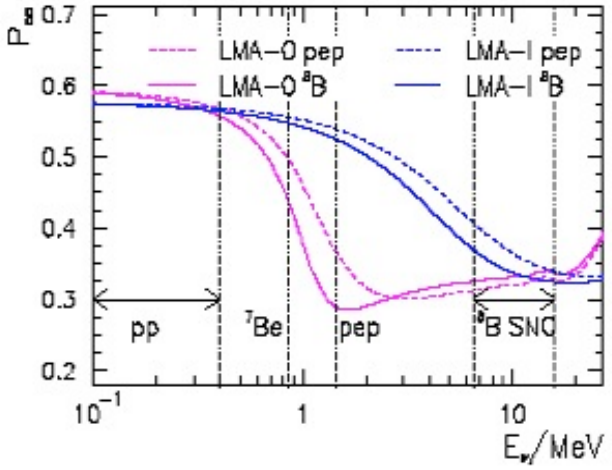
P_{ee}~sin^{2}2θ_{12}

Matter-dominated
resonant conversion

Probing the Unknown

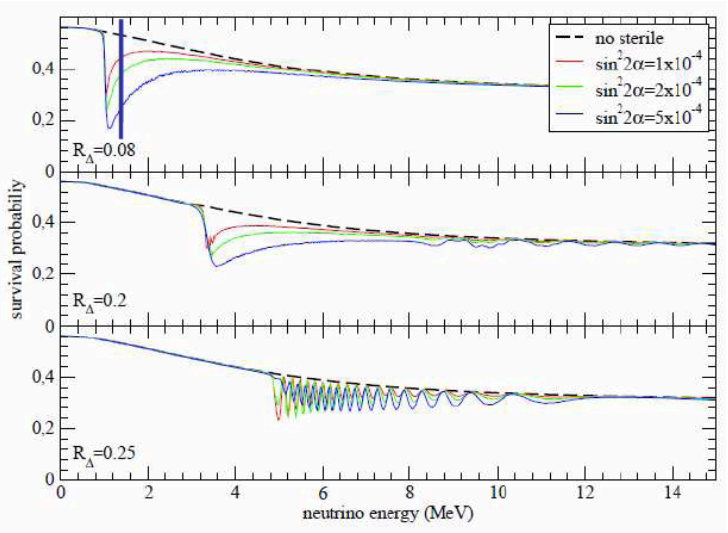
Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions (flavour changing NC)



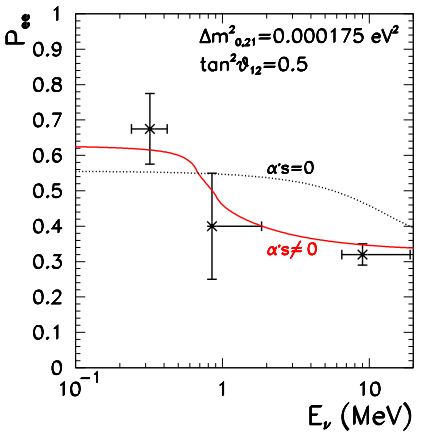
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



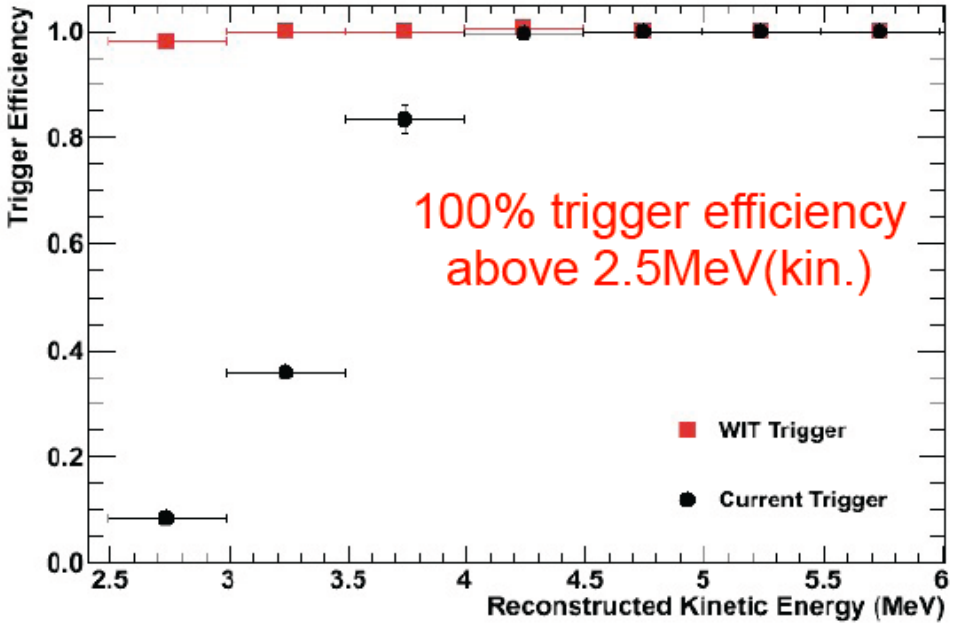
M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

Lower threshold in Super-K

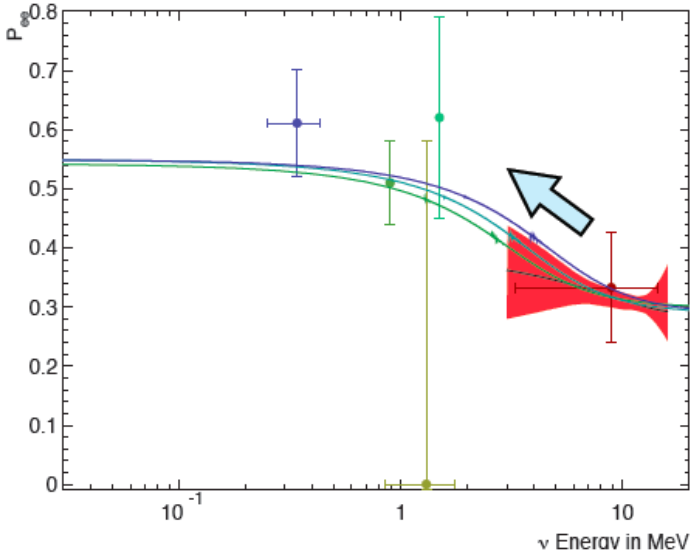
High-speed front-end electronics
"record every hits"

+

Realtime reconst.+reduction
"software trigger"

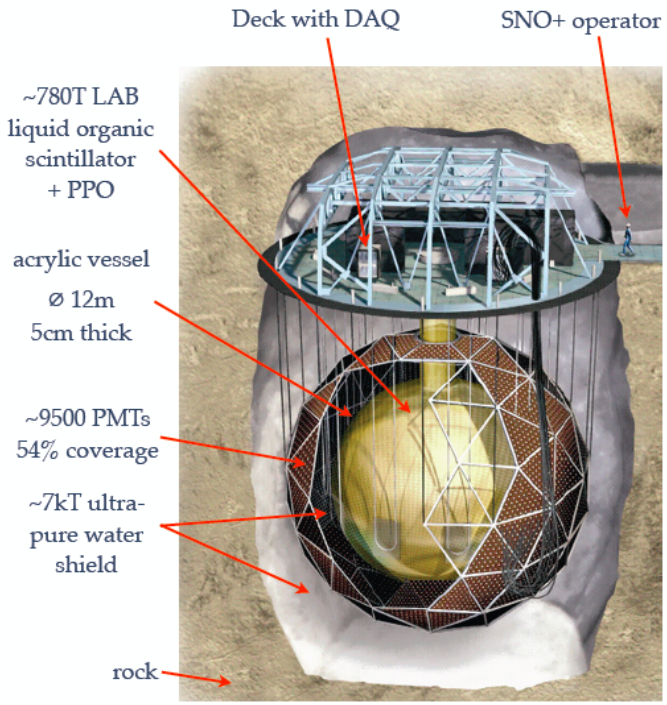


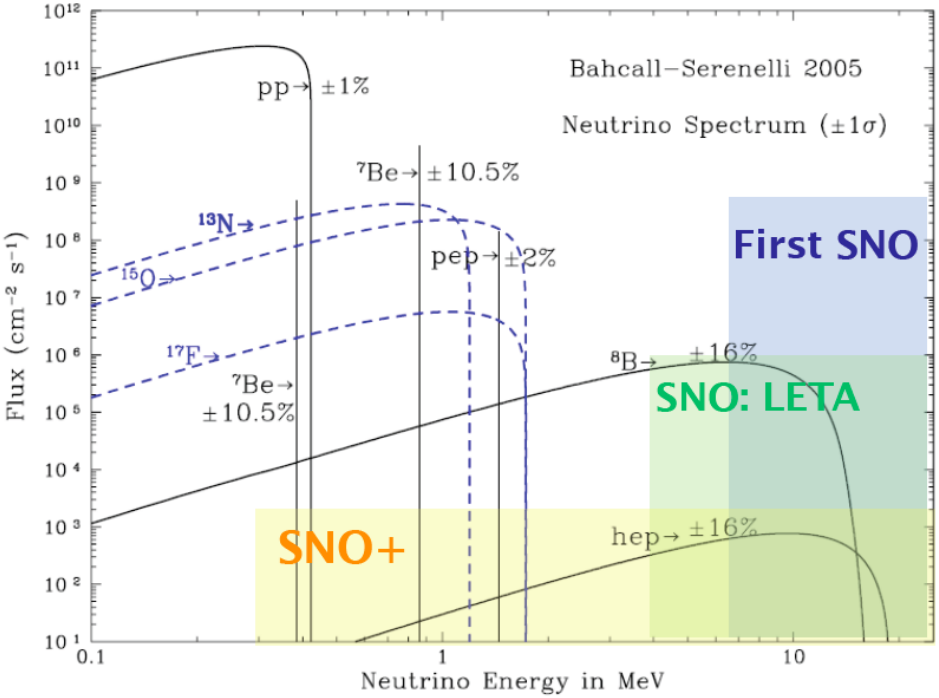
Trigger efficiency is
100%@2.5MeV from 2014

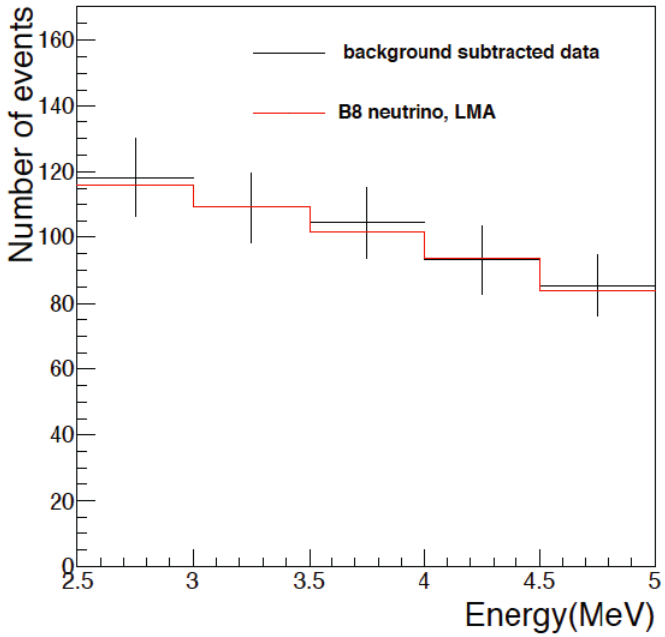


More data at the transition region is coming soon.

SNO+





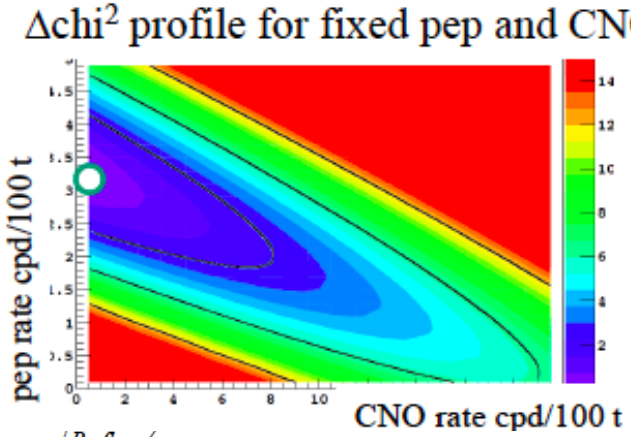


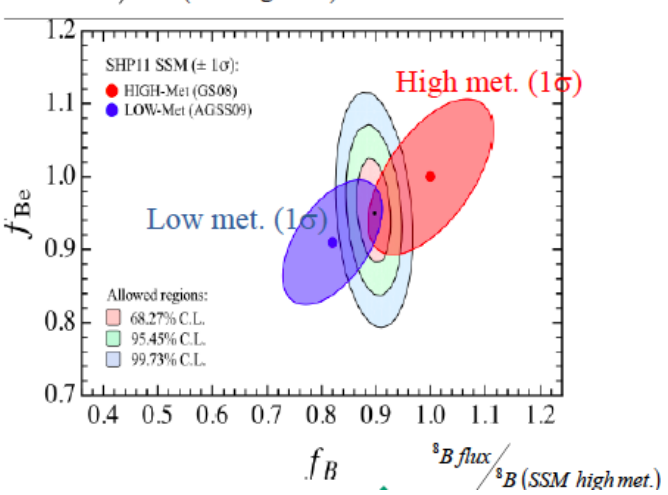
measurement errors

	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

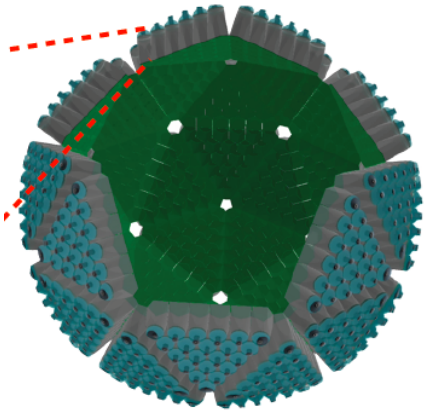
Also to cover ββ decay search, geo-ν, SNν, proton decays...

More on future prospect

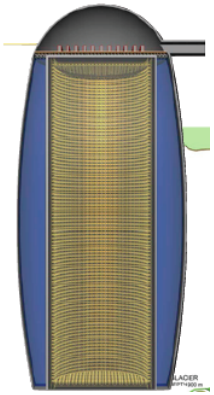




- Borexino (phase-II) continues the hunt for CNO cycle ν aiming to solve metallicity problem of the Sun.



- Clean (liquid Neon), XMASS (liquid Xenon) to measure pp-neutrino with 1%-level precision



- LENA for CNO and low energy ^{8}B
- JUNO, RENO precision measurements of parameters

Summary of atm & solar ν studies

- **Oscillation studies toward full understanding of ν properties**
  - Solar θ_{12}, Δm^2_{21} measurements consistent with reactor results
  - Indication of terrestrial matter effect
  - Atmospheric ν provides complemental measurements of θ_{23}, Δm^2_{32}
  - $\overline{\nu}_\mu$ disappearance consistent with ν_μ (CPT conservation)
  - Need more data for **mass hierarchy** determination, **θ_{23} octant**, and **δ_{CP}**

- **$\nu_\mu \rightarrow \nu_\tau$ channel as a solution of "atmospheric ν anomaly"**
  - No indication of exotic effects such as neutrino decays, sterile ν, Lorentz invariance violation, etc.

- **More solar neutrino experiments and data for oscillation studies, tests of exotic scenarios, and astrophysical studies**