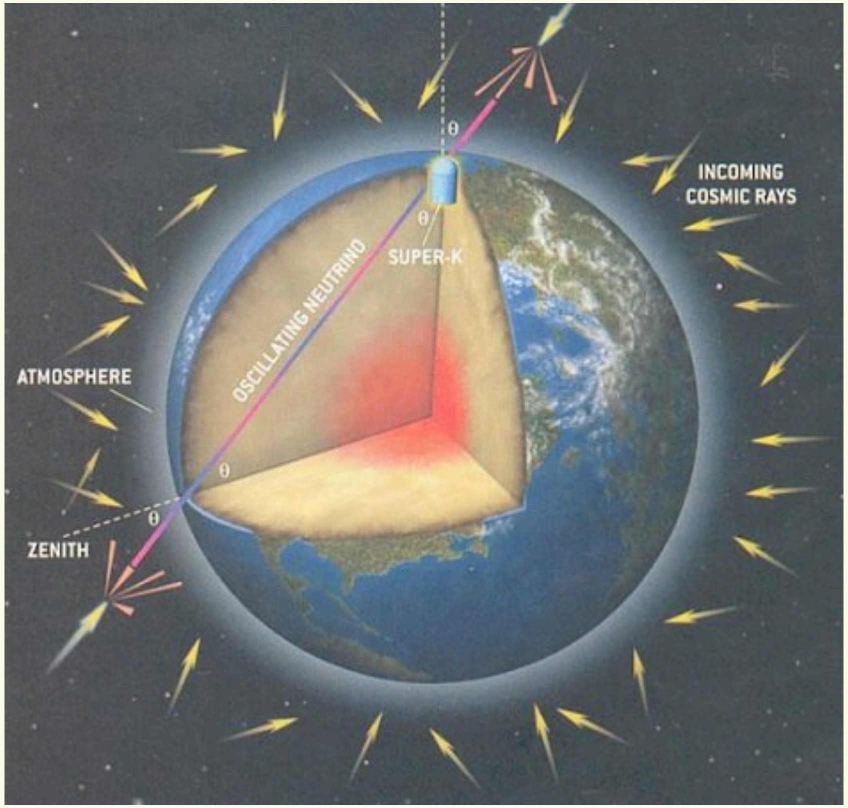
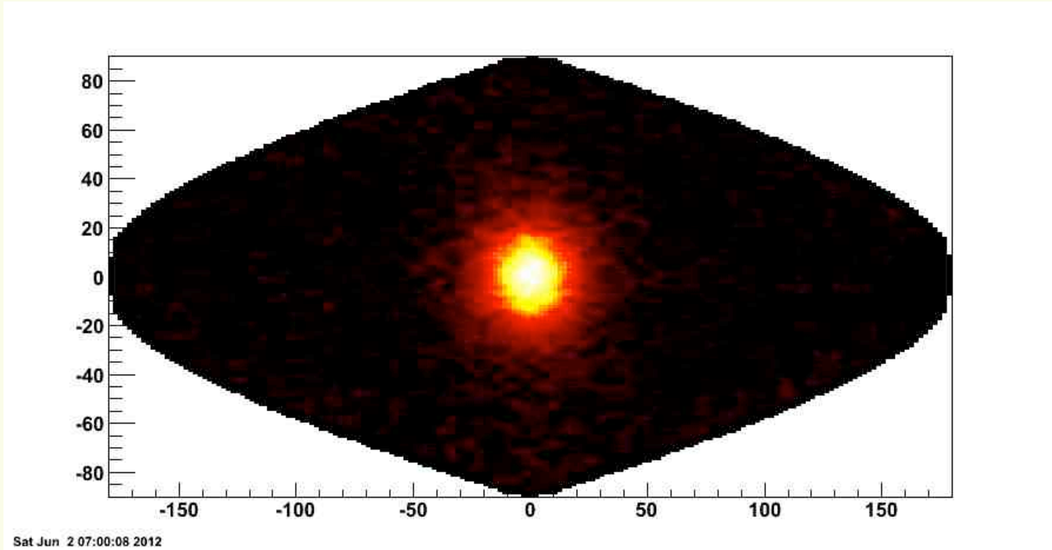
Results and Prospects from Atmospheric and Solar Neutrinos





Yusuke Koshio
Okayama University

19th International Workshop on Neutrinos from Accelerators (NuFact2017)
Uppsala university, 25-30 September, 2017

Request from committee

This overview talk should cover
all large neutrino detectors projects
both for atmospheric and solar neutrino..

Atmospheric and solar neutrinos in neutrino oscillation

Mixing angle : Maki-Nakagawa-Sakata Matrix

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

Atm. and Acc.	Reactor and Acc.	Solar and KamLAND
$\theta_{23} \sim 45 \pm 5^\circ$	$\theta_{13} \sim 9^\circ$	$\theta_{12} \sim 34 \pm 3^\circ$
$\lvert\Delta m^2_{32}\rvert = 2.4 \times 10^{-3}\mathrm{eV}^2$		$\Delta m^2_{21} = +7.6 \times 10^{-5}\mathrm{eV}^2$

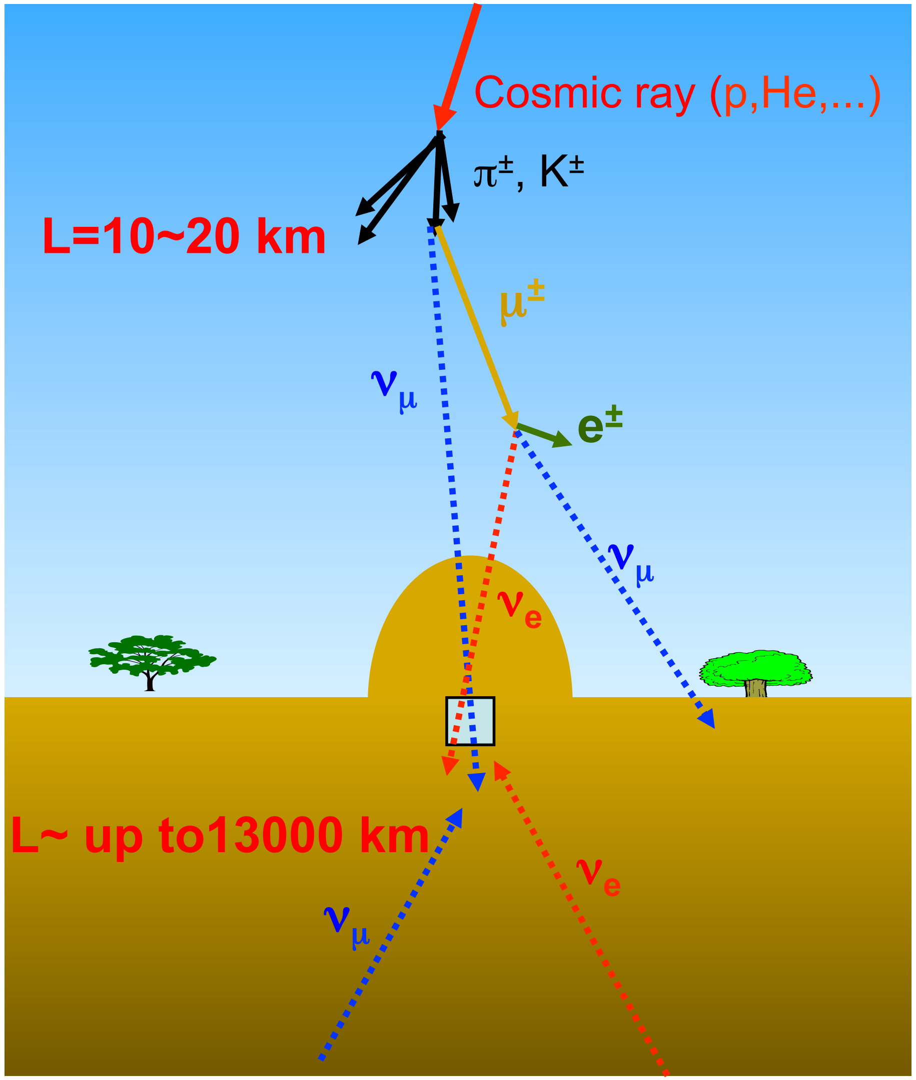
δ cp and Mass hierarchy of 2-3 are unknown

Atmospheric, Accelerator, Reactor

Atmospheric and solar neutrinos play crucial role for determining the neutrino oscillation parameters

Atmospheric neutrino

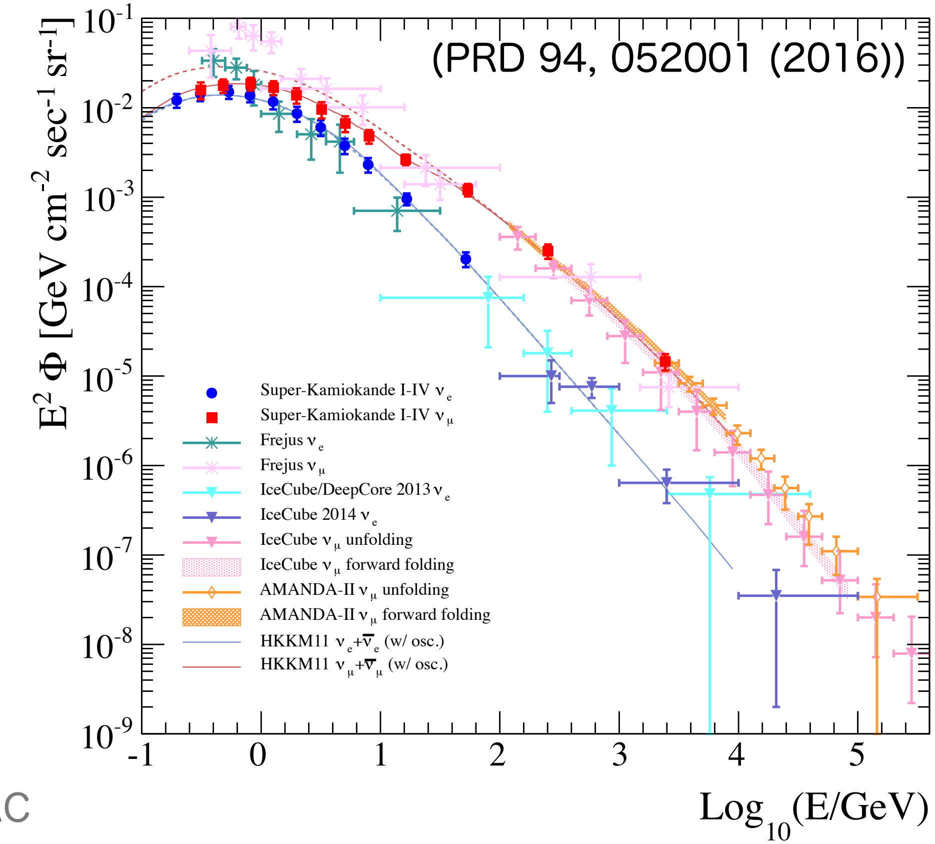
Atmospheric neutrinos



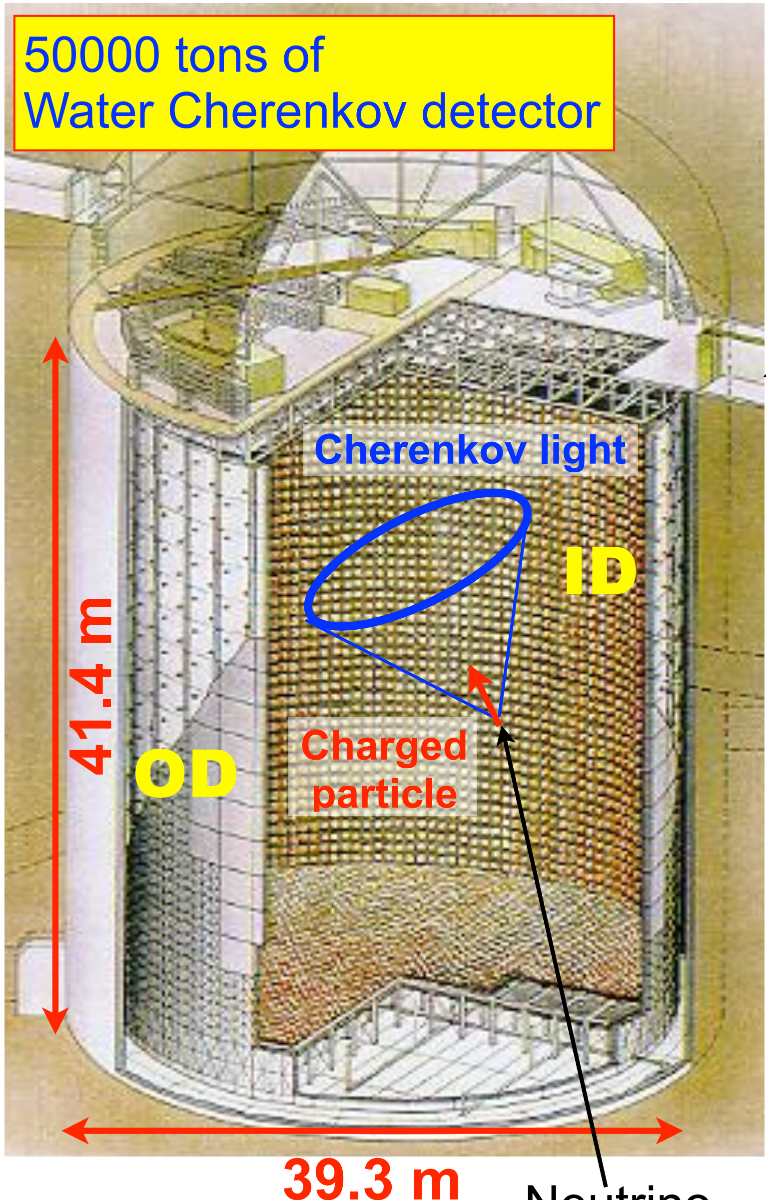
Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

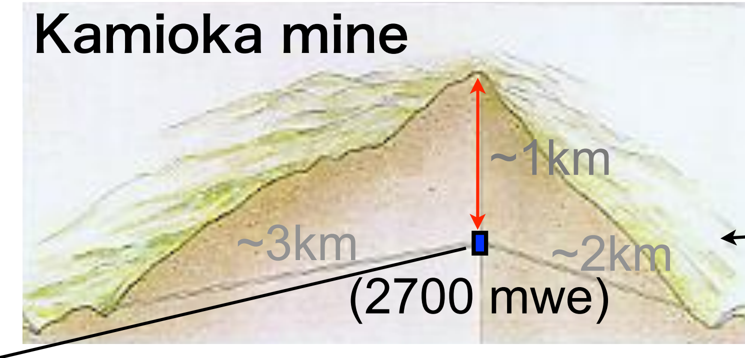
✓ Flux measurement by SK

✓ Model calculation is consistent with data.



Super-Kamiokande





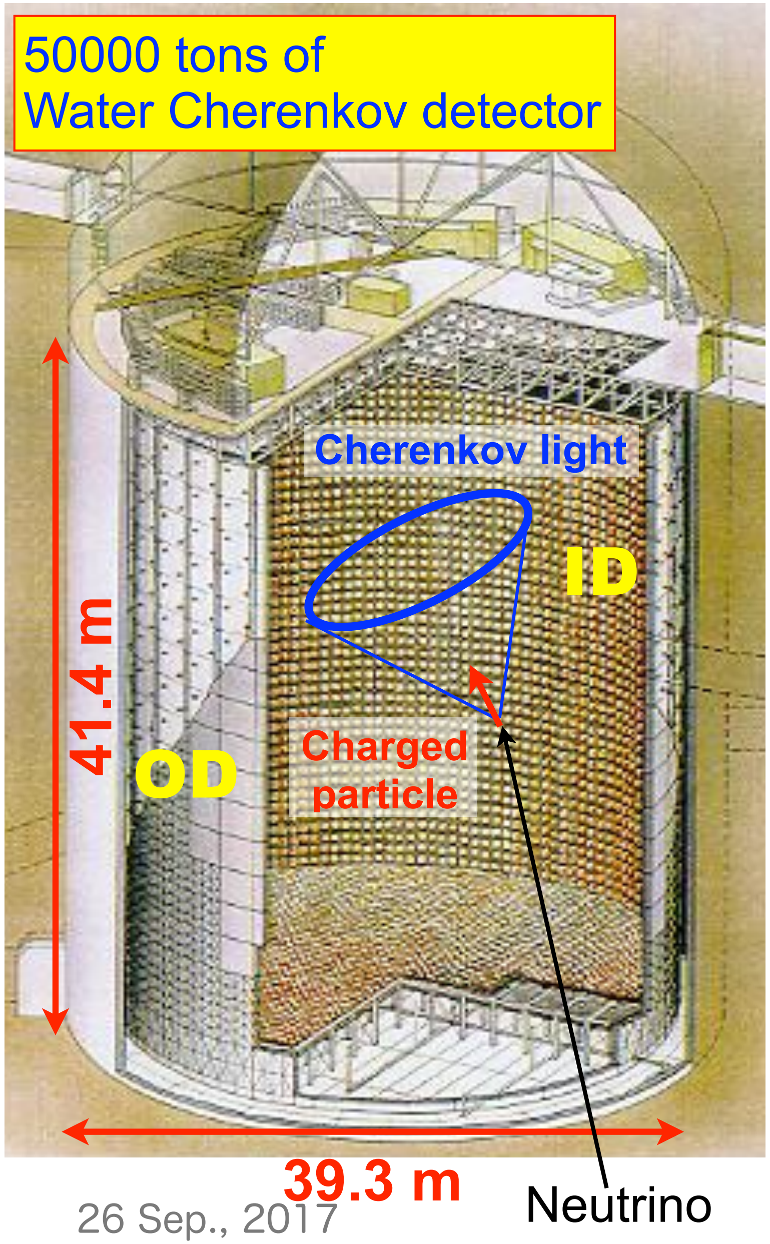
Phase	Period	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)		3.5

(coverage) (Kin. energy)

Running and improvements over 20 years

Super-Kamiokande

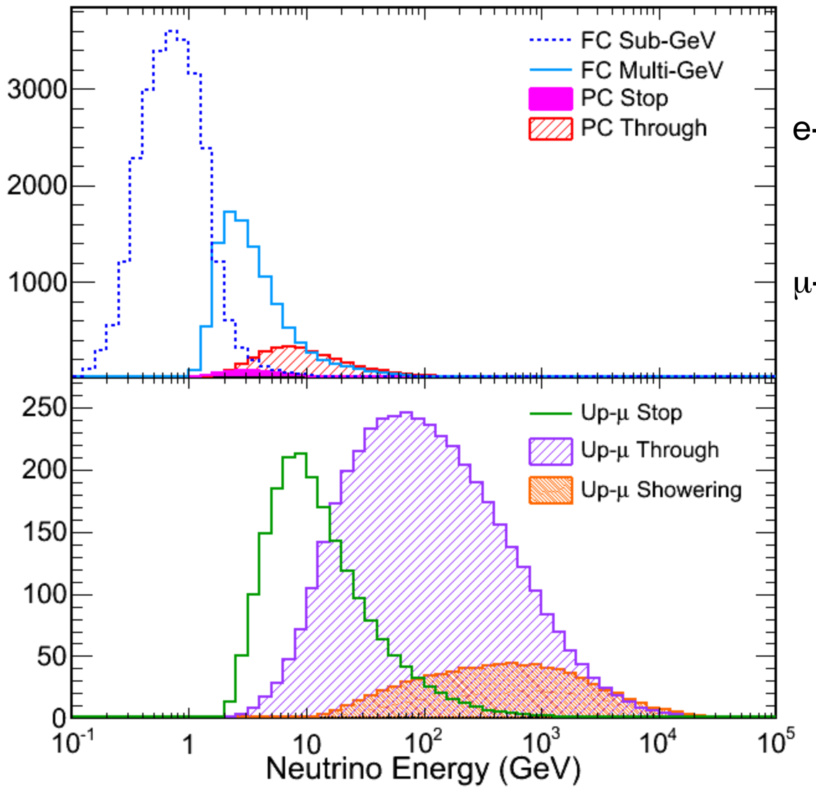
as an atmospheric neutrino detector



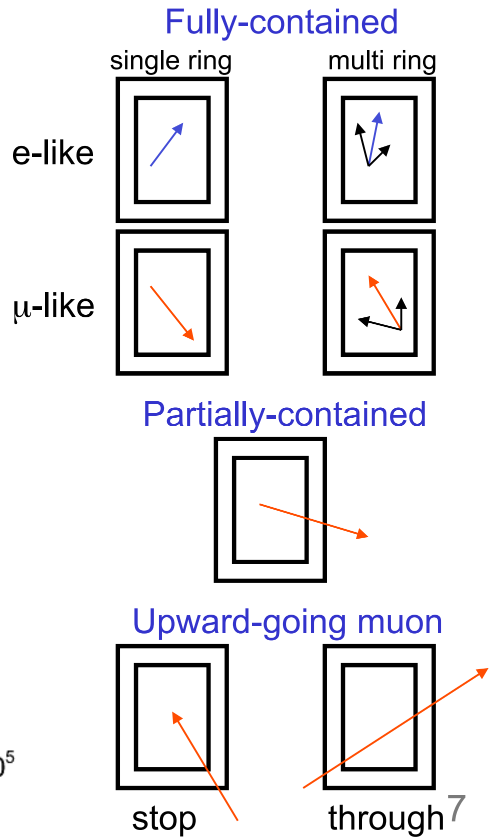
Neutrino interactions in SK

- (quasi-)elastic scattering : ν + N → l + N'
- single meson production : ν + N → l + N' + meson
- deep inelastic interaction : ν + N → l + N' + hadrons
- coherent pion production : ν + ^{16}O → l + ^{16}O + π

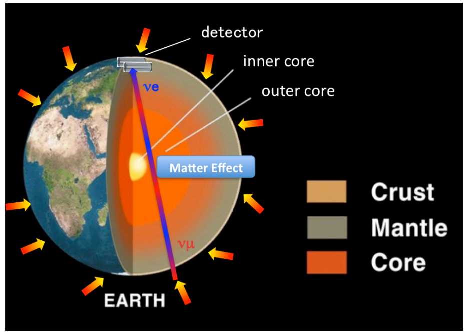
parent neutrino spectra



Event topology



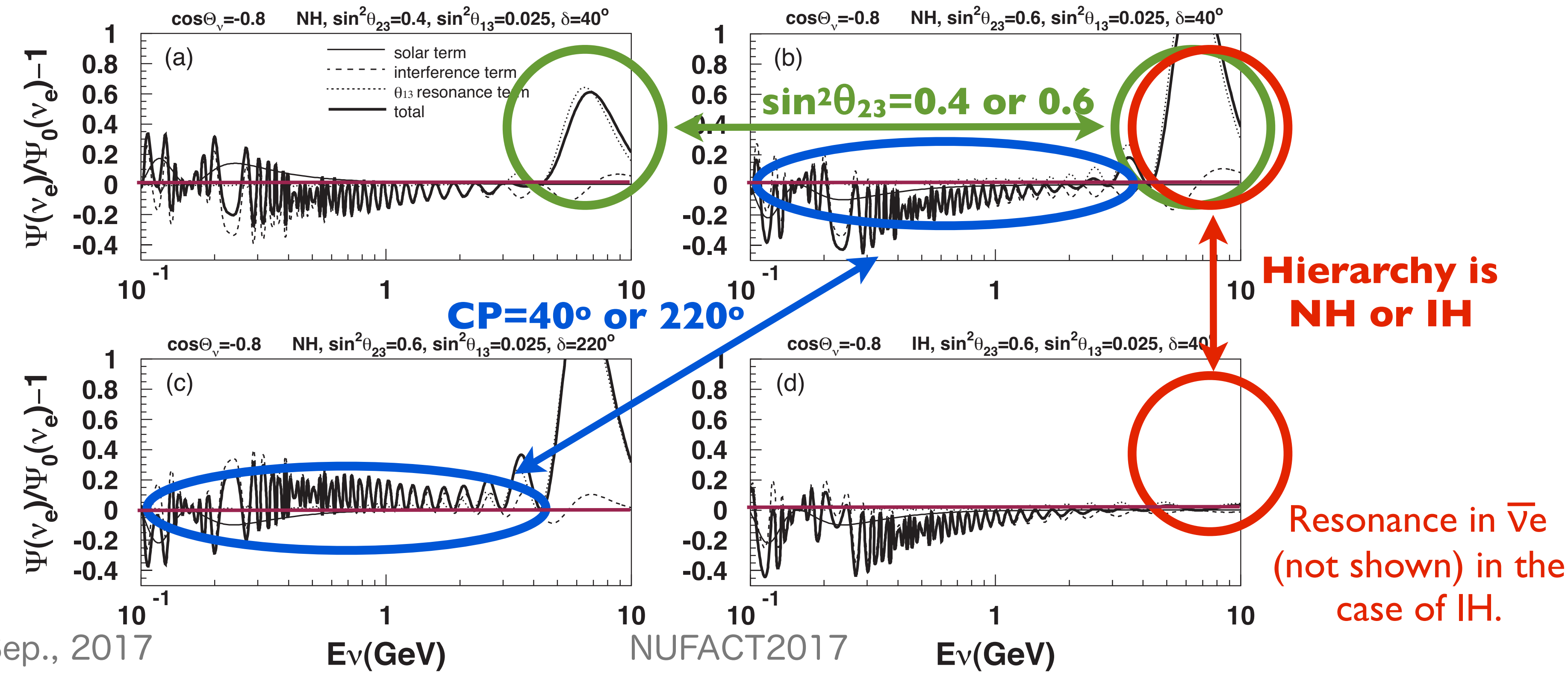
3 flavor neutrino oscillation analysis



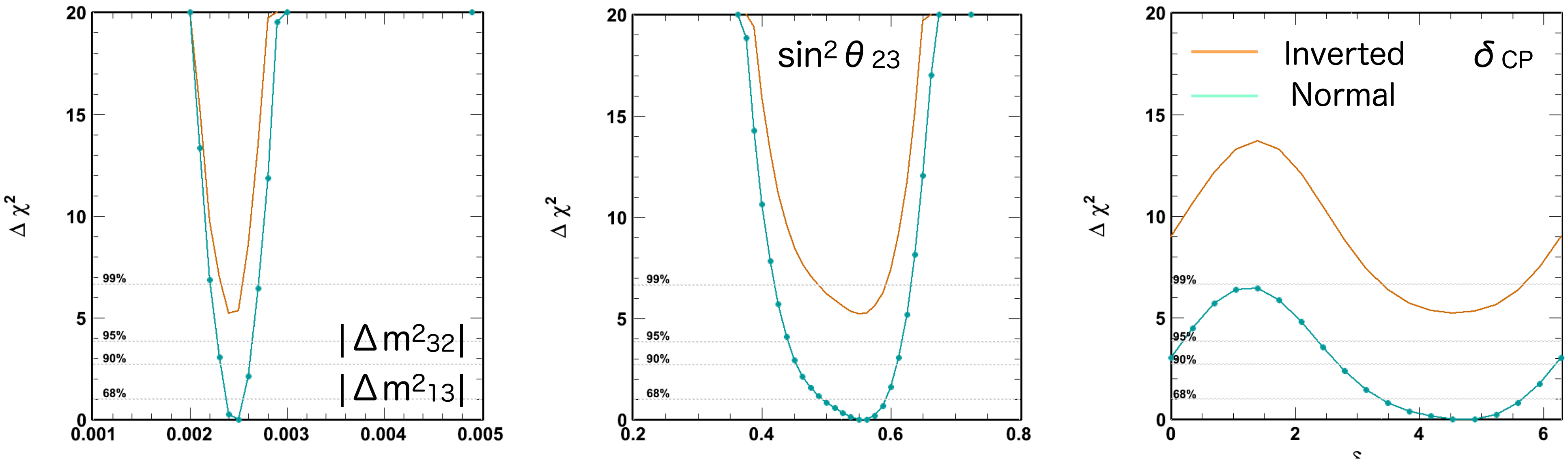
Consider all the sub-leading effects (Δm^2_{21}, matter)

- Mass hierarchy : resonance in multi-GeV ν_e or $\bar{\nu}_e$
- Octant θ_{23} : magnitude of the resonance
- δ_{CP} : interference btw two Δm^2 driven oscillation

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



Parameter determination (SK+T2K)



Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

✓ $\Delta\chi^2=\chi^2_{NH}-\chi^2_{IH}=-5.2$

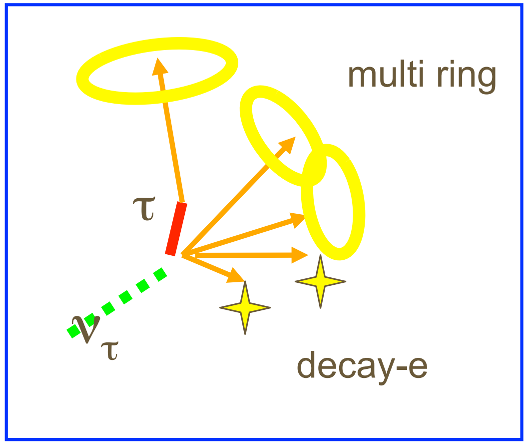
✓ Probability for IH is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4), while for NH is 0.43 ($\sin^2\theta_{23}$=0.6)

Friday afternoon: F.d.M.Blaszczyk

Preliminary

τ neutrino appearance

Hard to identify event by event
but can be statistically seen

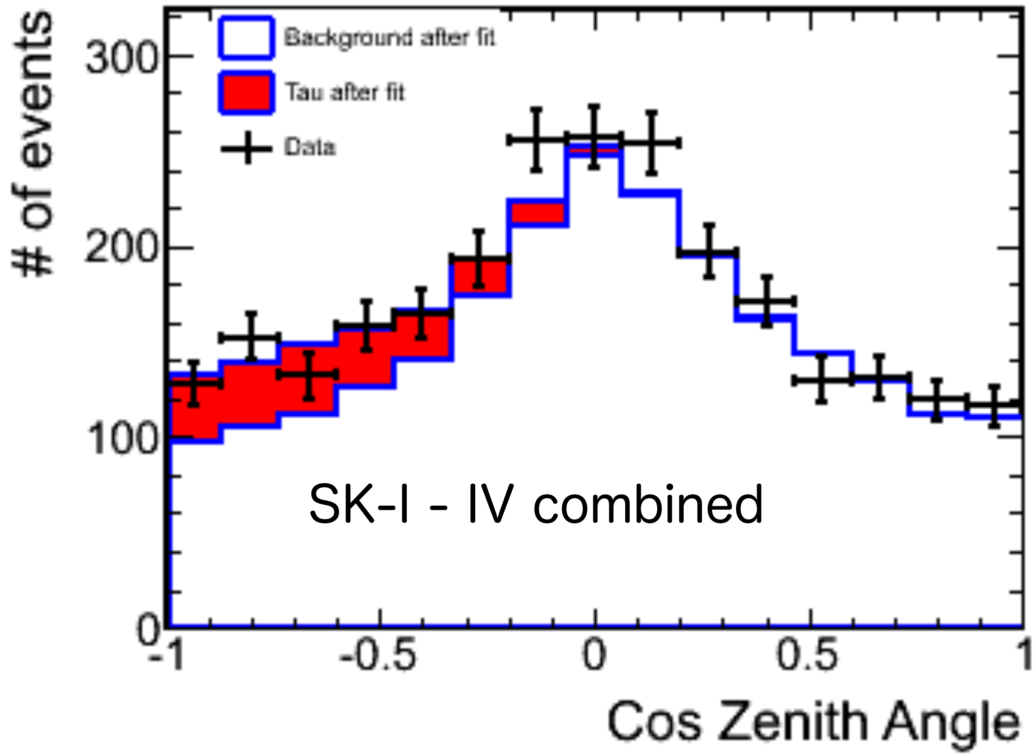


Search for events consistent with hadronic decays of tau lepton using neural network method

data=PDF(BG)+α x PDF(τ)+Σ ε_i x $\underline{PDF_i}$

PDF of i-th sys. error shifting by 1σ

Multi-ring e-like sample

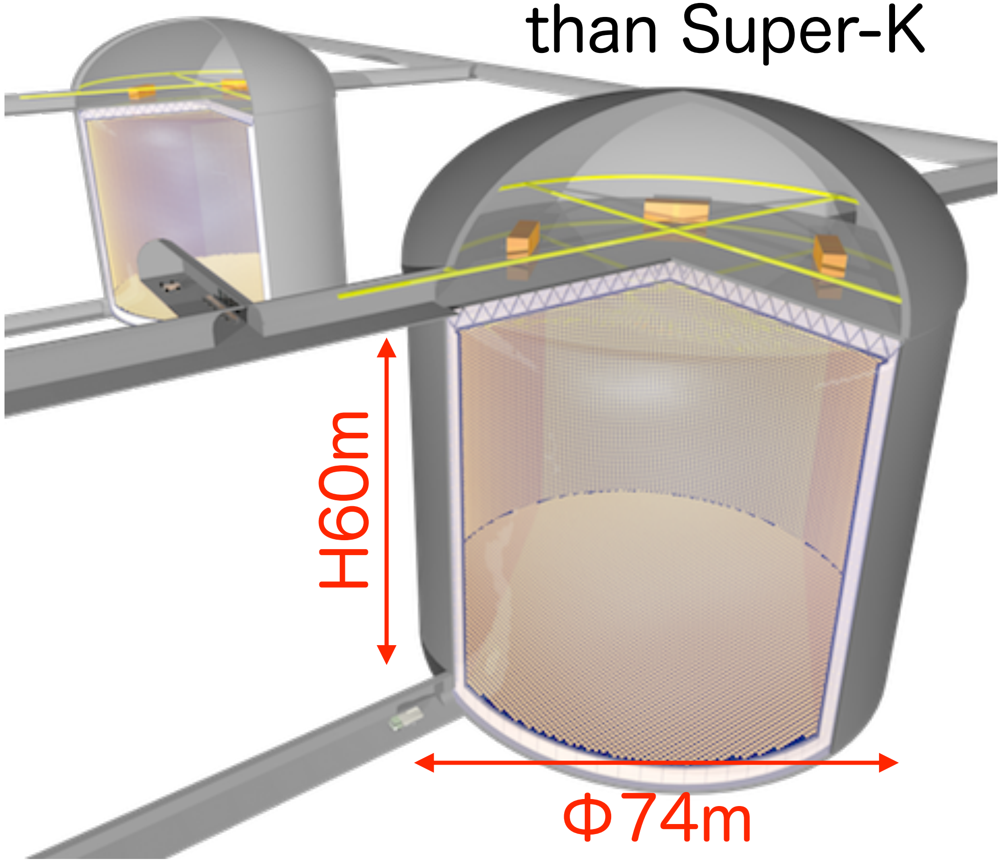


τ fraction is found to be 1.47±0.32, which is 4.6σ from 0.

Friday afternoon: F.d.M.Blaszczyk

Hyper-Kamiokande (future)

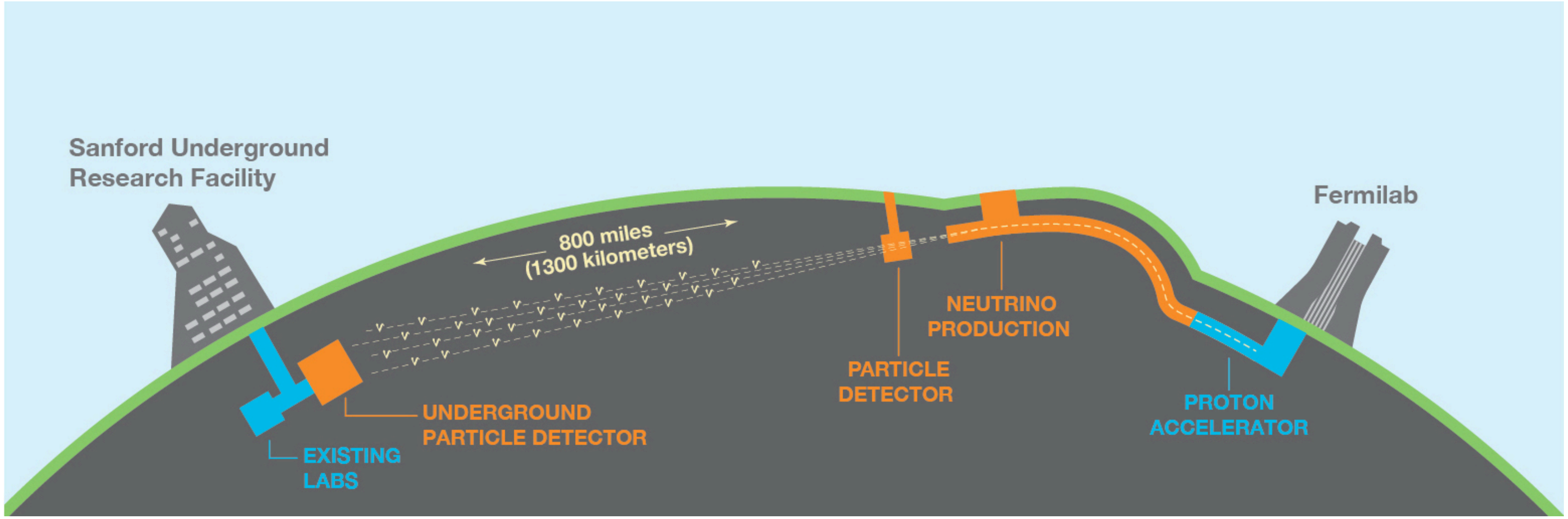
2 tanks x
with staging ~10 times larger volume than Super-K



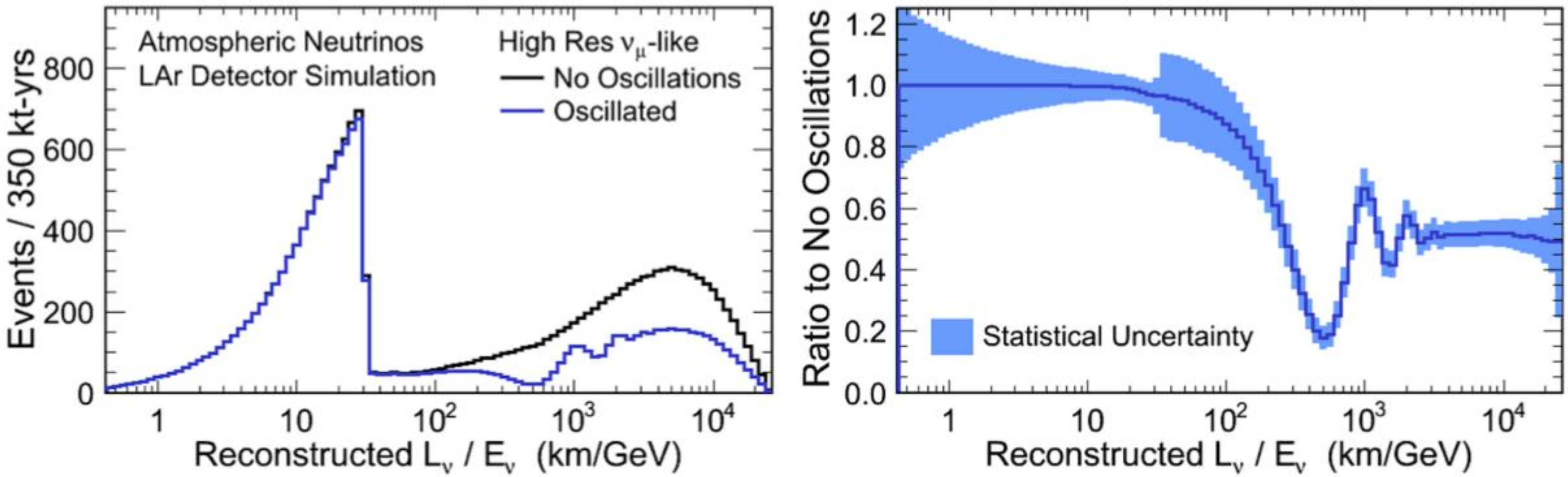
Atm. and acc. ν measurements in Hyper-K will make much more precise determination for
mass hierarchy,
octant θ_{23},
δ_{CP}
be available.

See E. O'Sullivan and C. Bronner's presentation in more detail

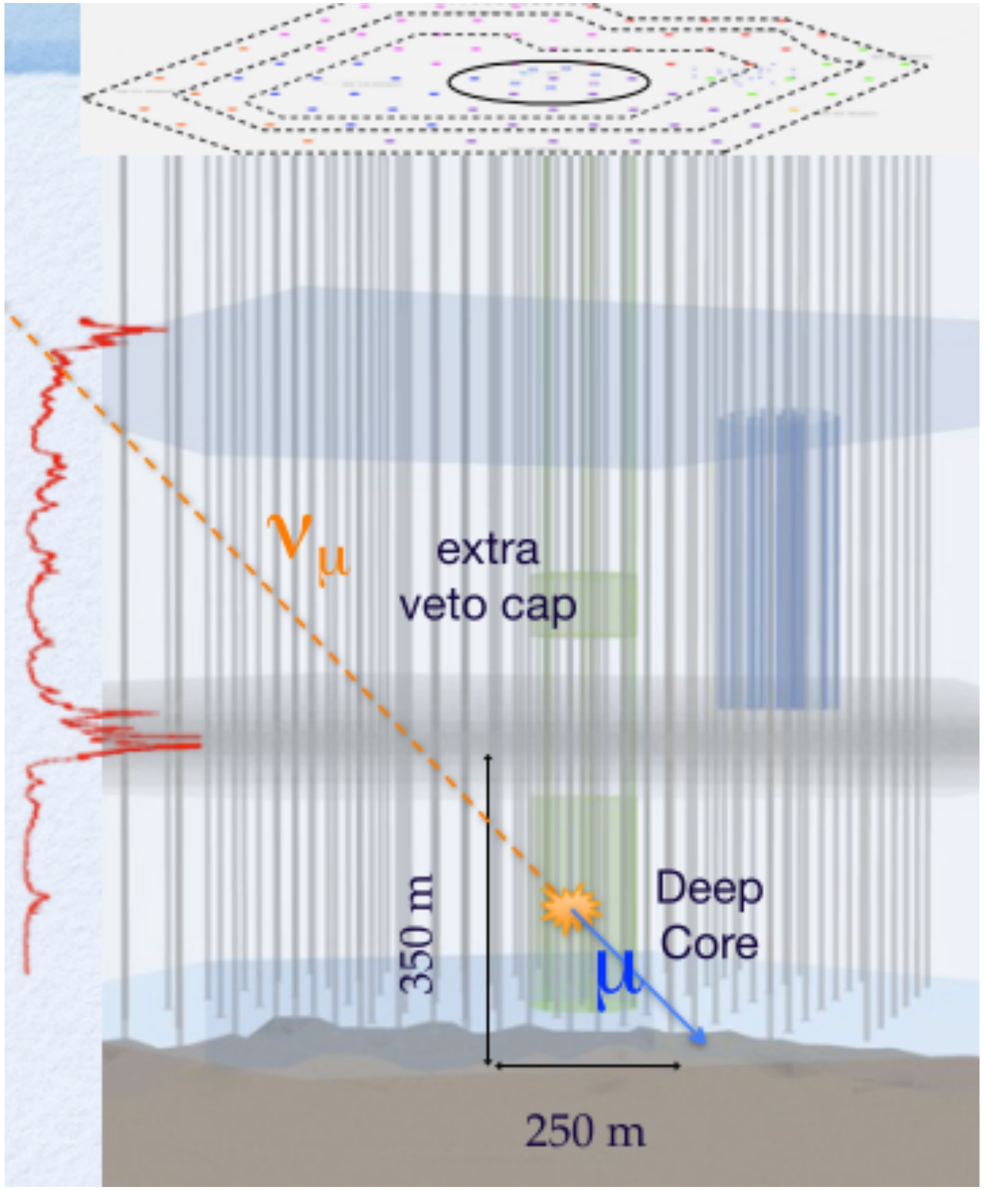
DUNE (future)



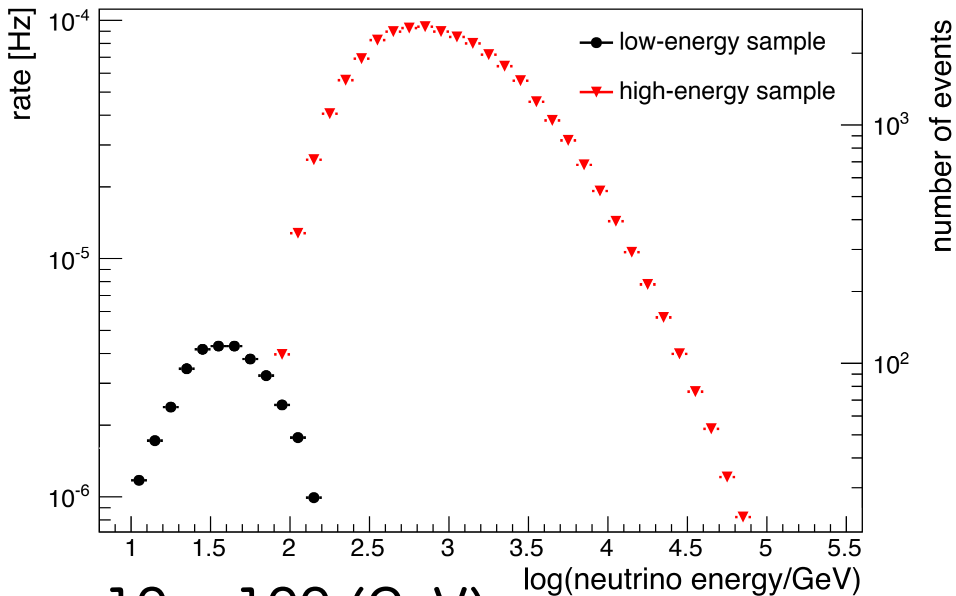
Event rate: 14k e-like, 20k μ-like fully contained for 350kt-year exposure



IceCube DeepCore

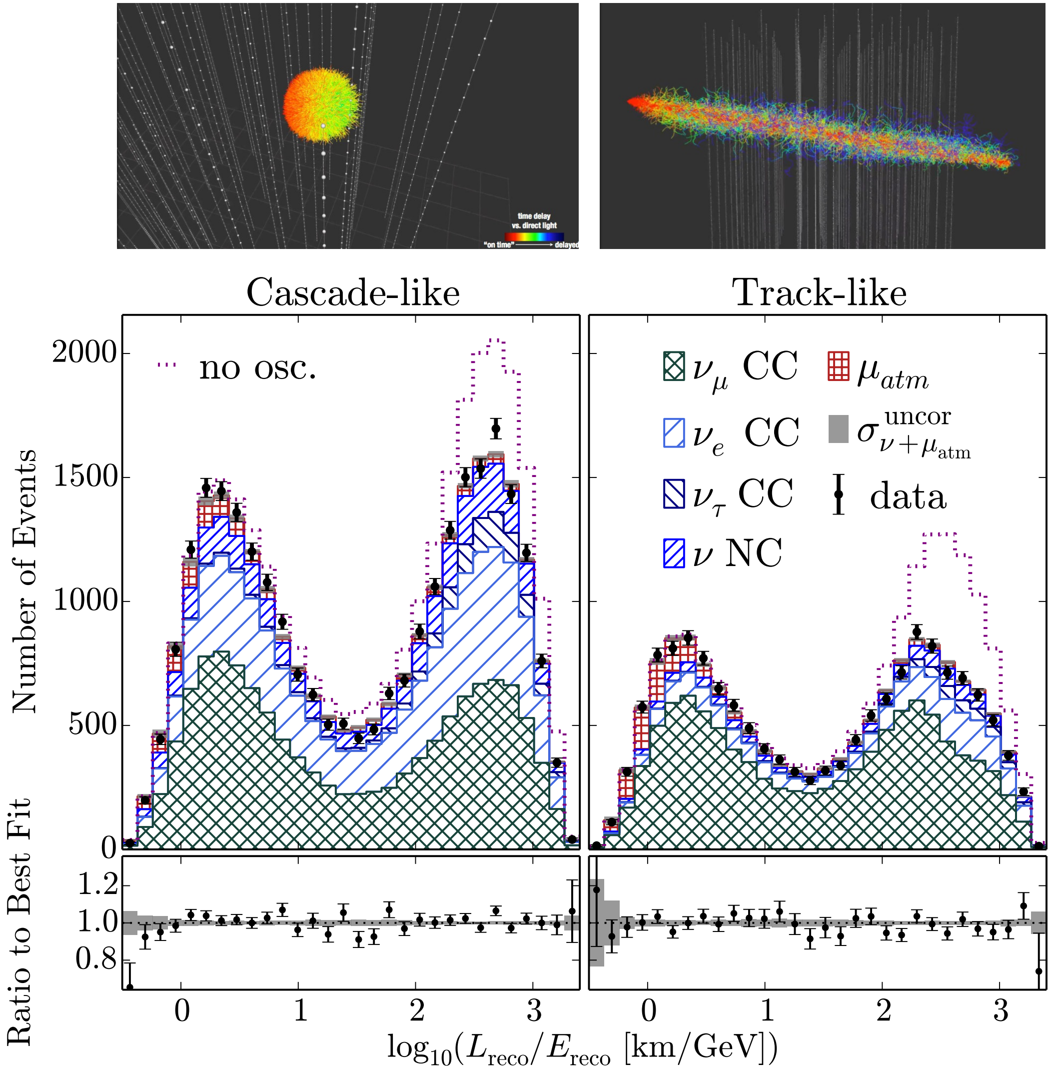


- 8 dedicated string fill ~10^7 m^3 of ice with a typical spacing of 70m.
- Sensors are concentrated in the clearest deep ice, with a denser 7m vertical spacing.
- Energy range is 5.6 to 56 GeV, in which Deep Inelastic Scattering is dominant.



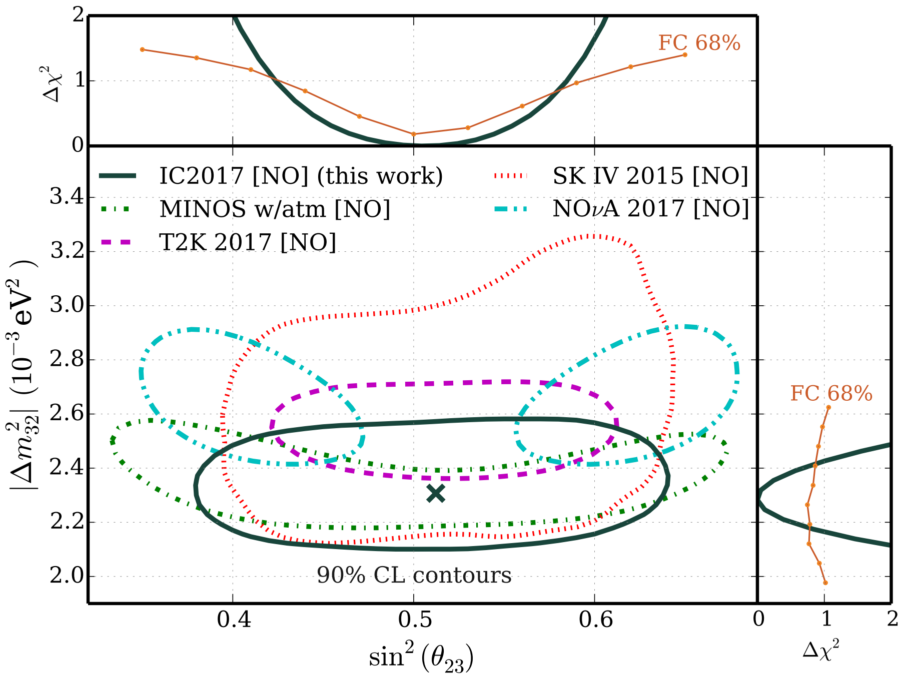
10 100 (GeV)

IceCube DeepCore



arXiv: 1707.07081

Friday afternoon: T.Ehrhardt, P.Eller



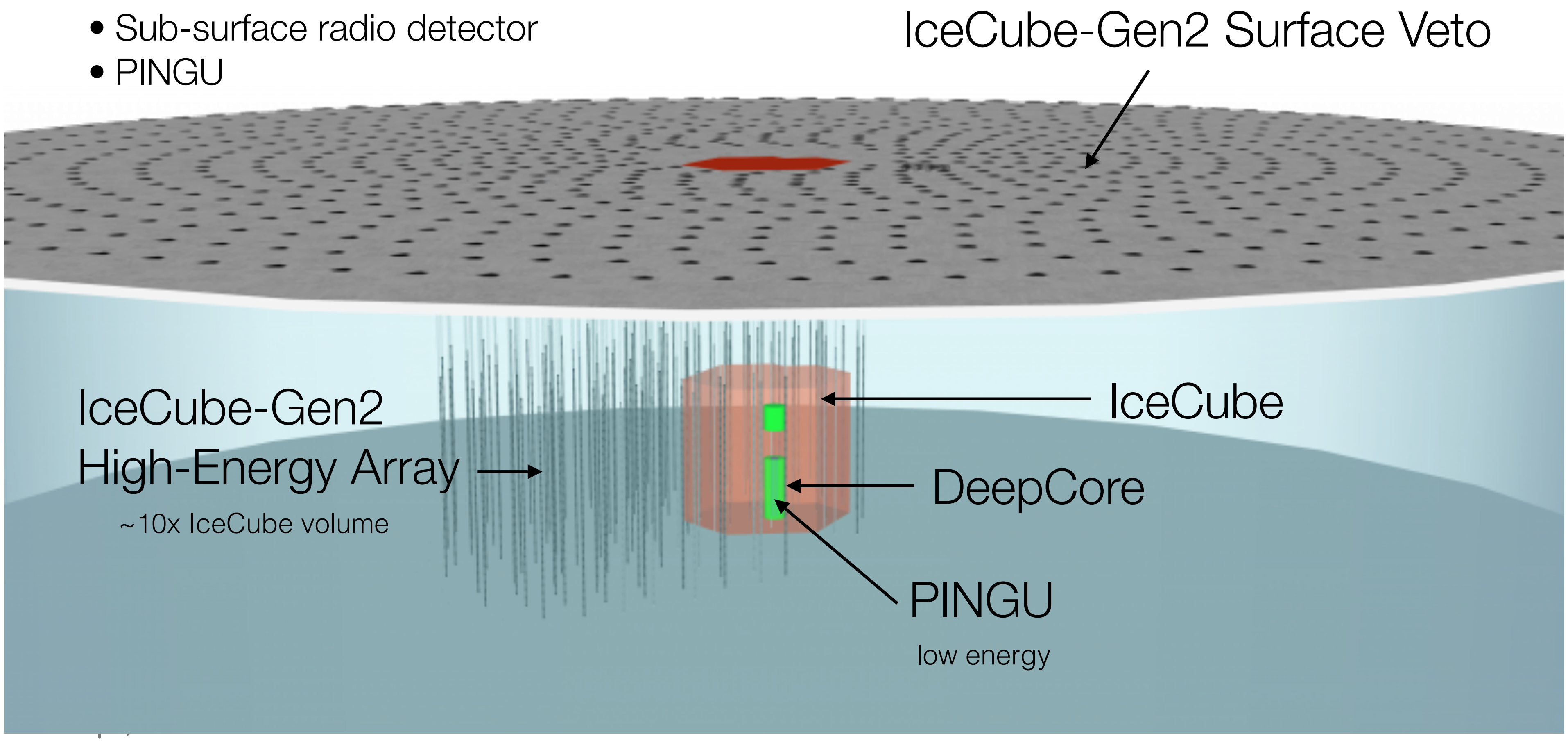
IceCube-Gen2 (future)

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

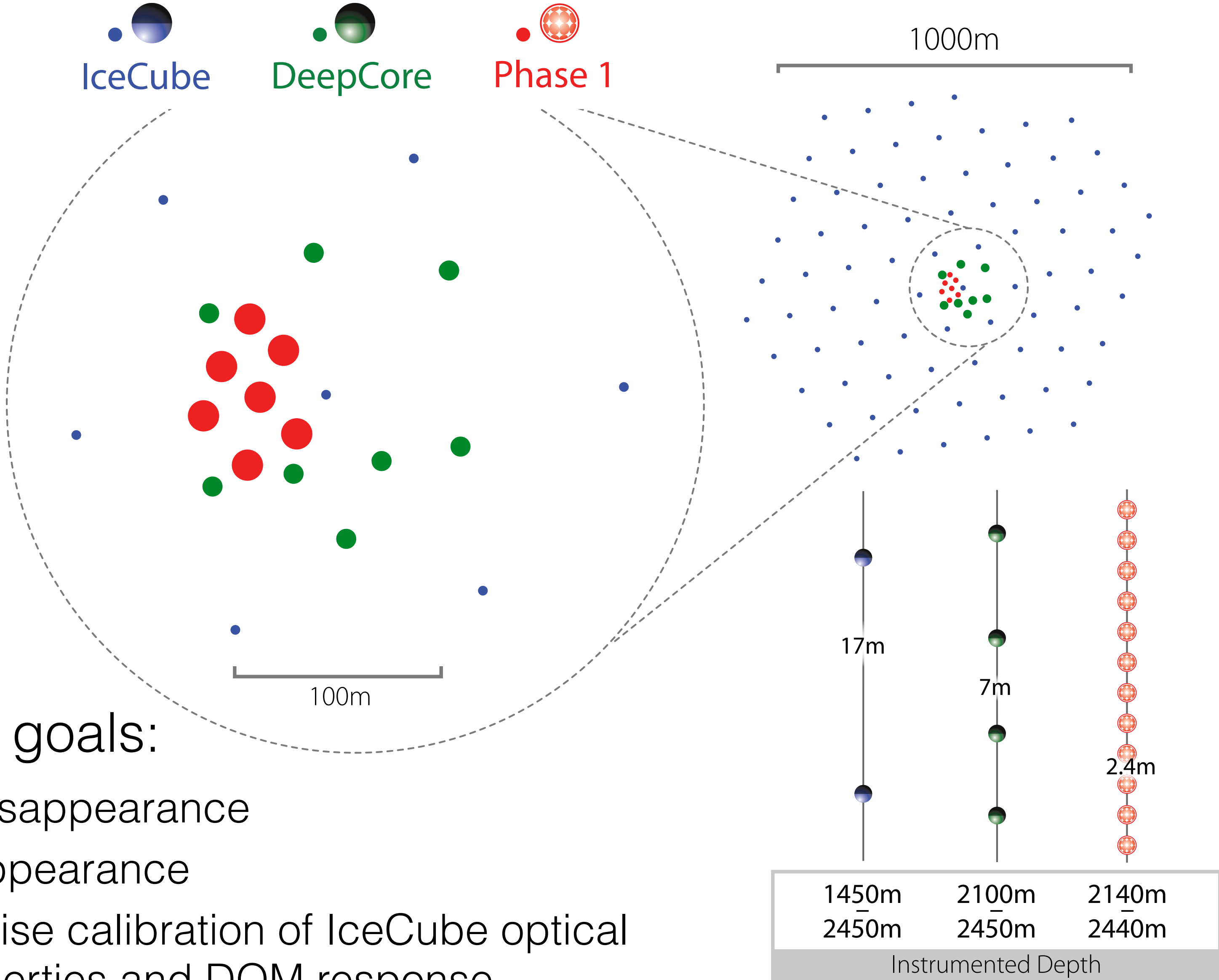
Multi-component observatory:

- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU

Friday afternoon: T.Ehrhardt, P.Eller



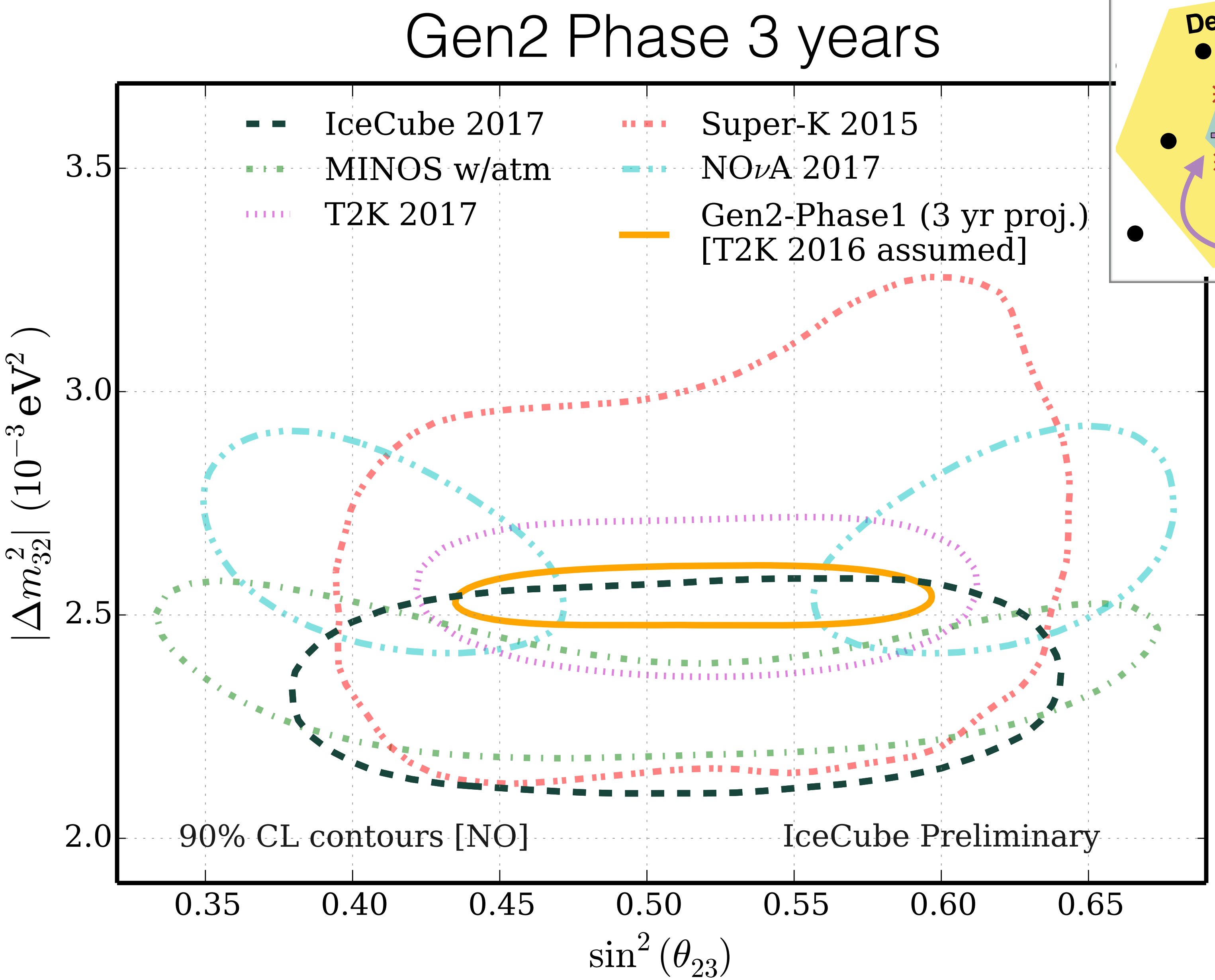
IceCube-Gen2 (future)

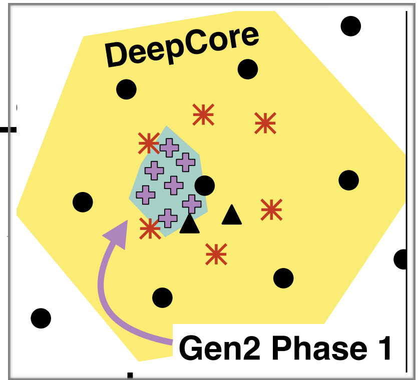


Science goals:

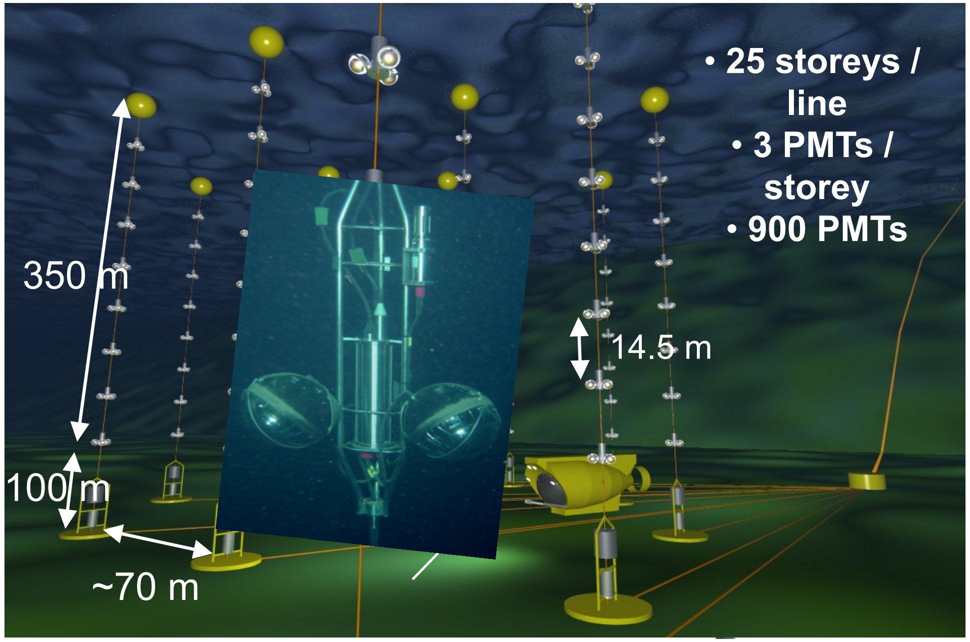
- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response

IceCube-Gen2 (future)



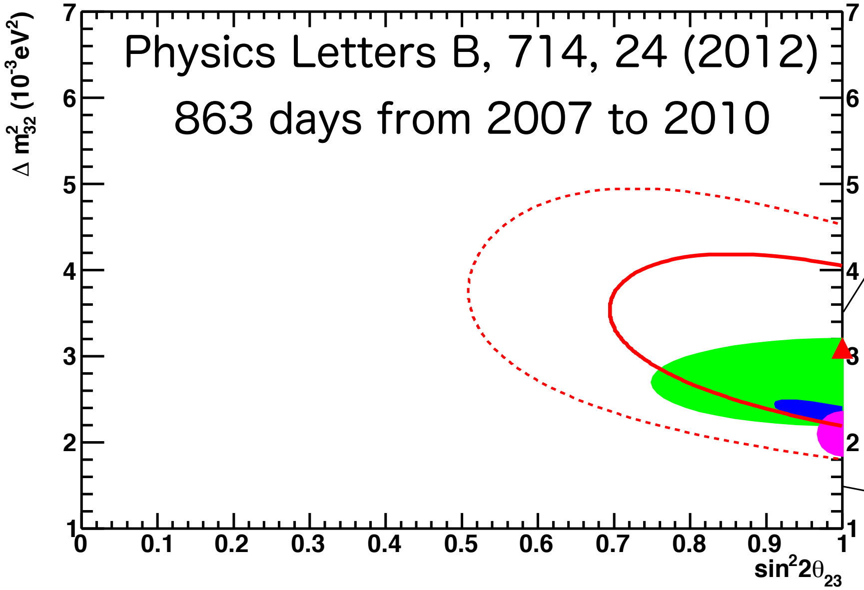


ANTARES

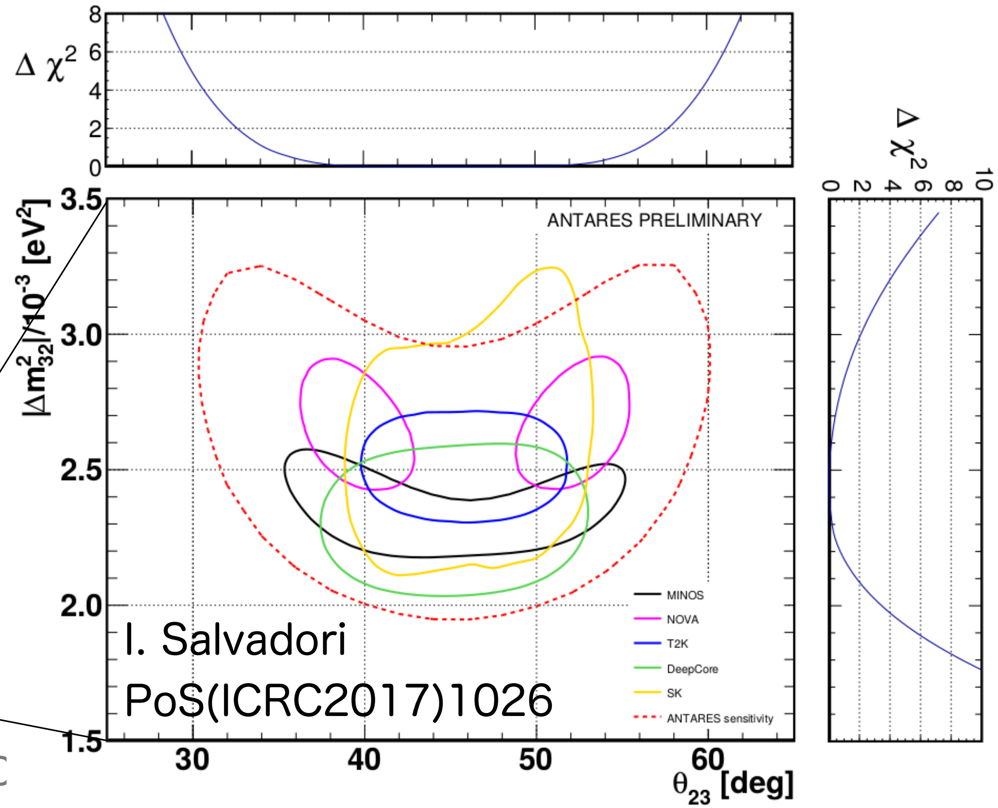


Mediterranean detector since 2008

- Studying the upgoing muon rate as a function of reconstructed muon energy
- Energy is above 20GeV

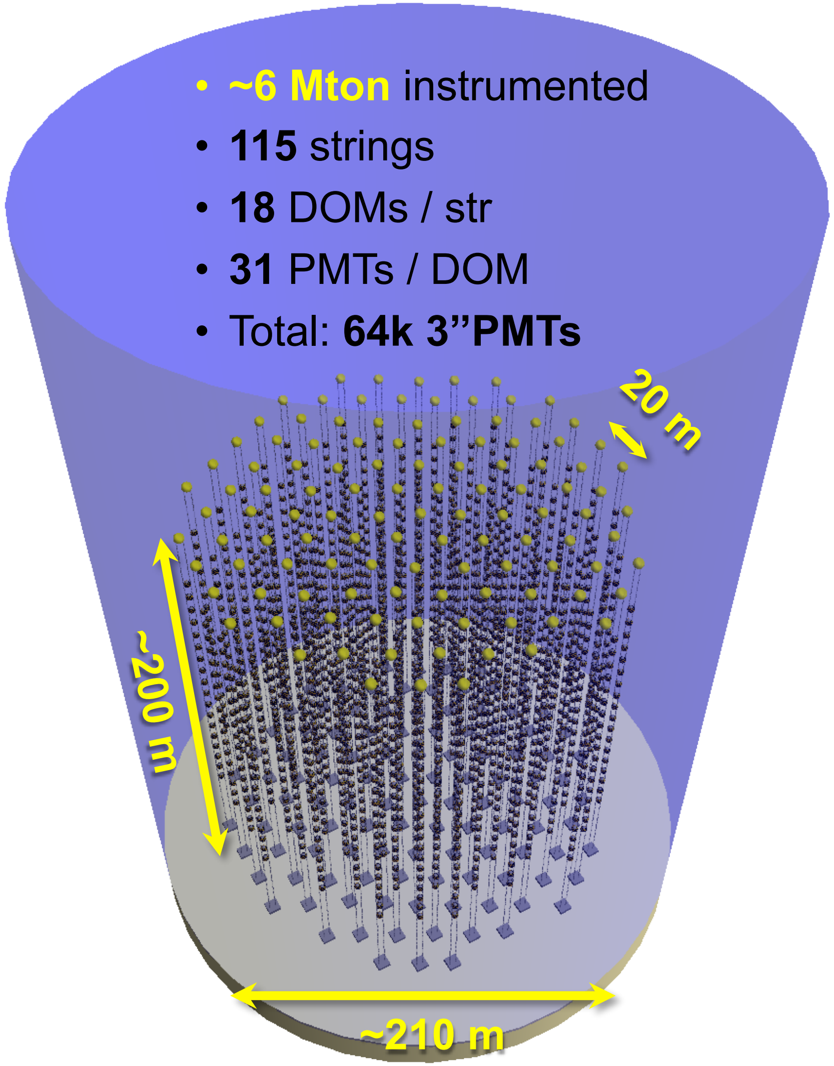


Sensitivity for 2236 days

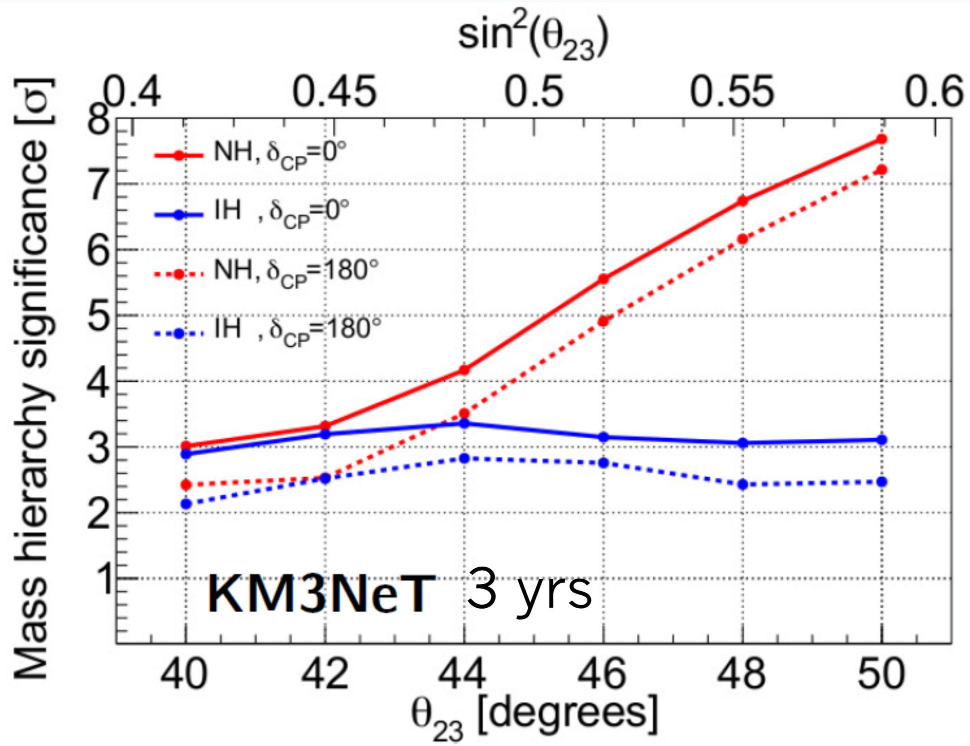


KM3NeT-ORCA (future)

2475m depth



- Study atmospheric neutrinos in 5-50GeV region which is unique for determination of the mass hierarchy.
- Sensitivity is 3σ in 4 years, or better



Friday afternoon: M.Circella

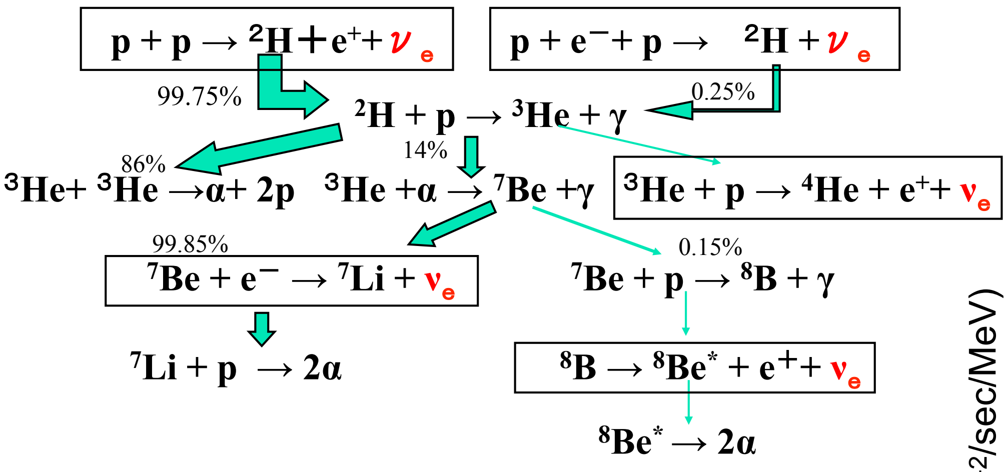
Summary of atmospheric ν

- Full 3 flavor oscillation analysis is performed to extract mass hierarchy, Octant θ_{23}, δ_{CP}.
- Tests of various non-standard scenarios are possible.
- Several large detector experiments are proposed, and determine those parameters in near future.

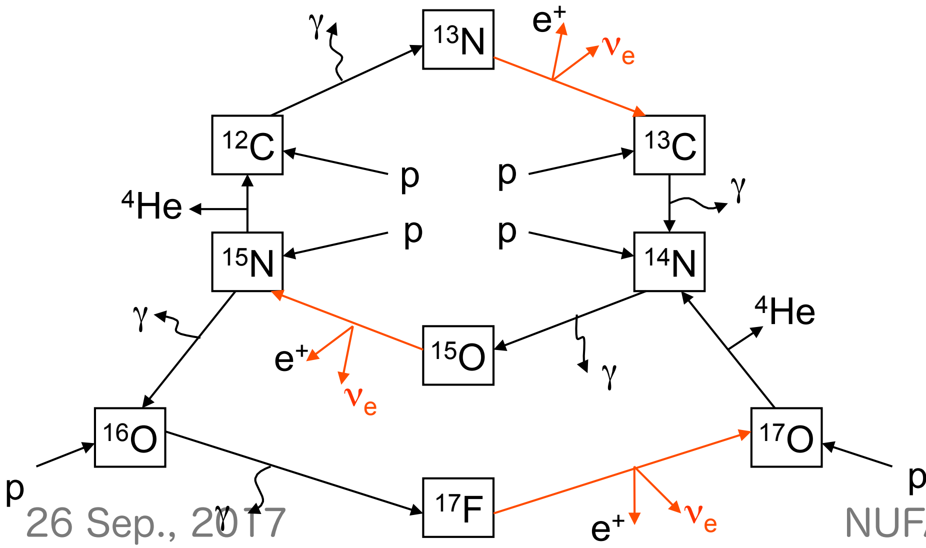
Solar neutrino

Solar neutrinos

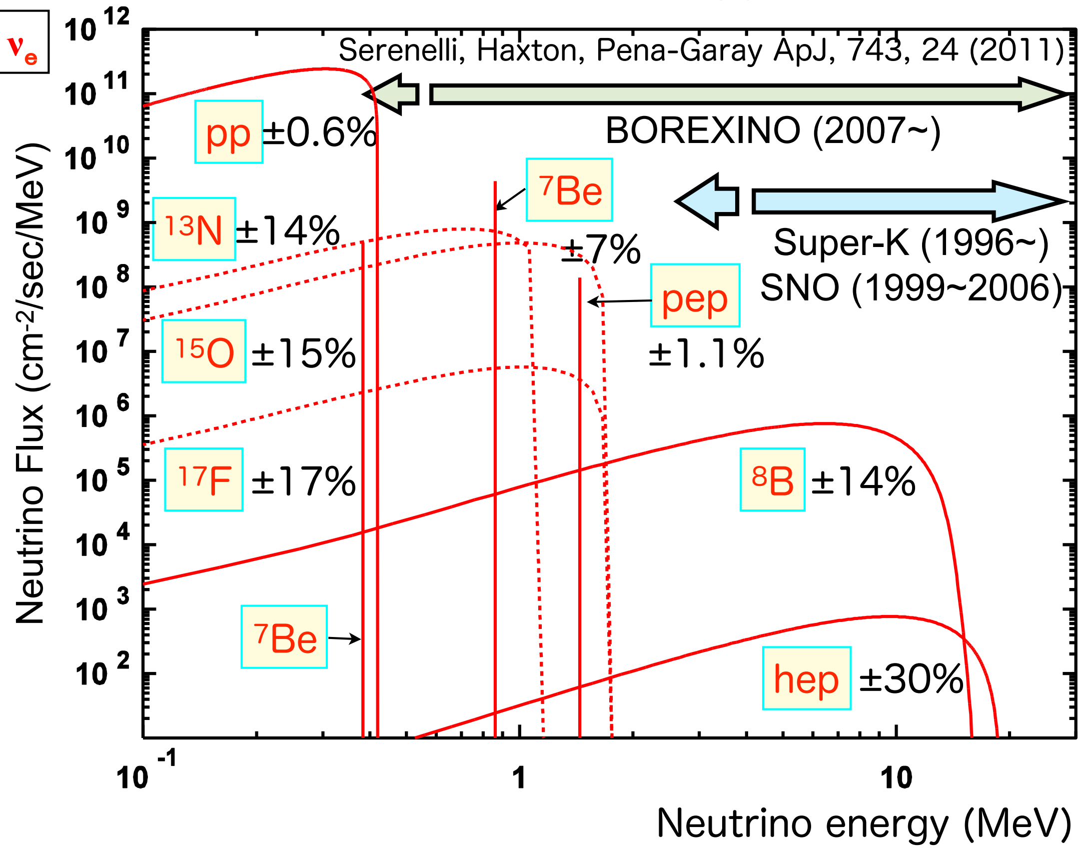
pp-chain



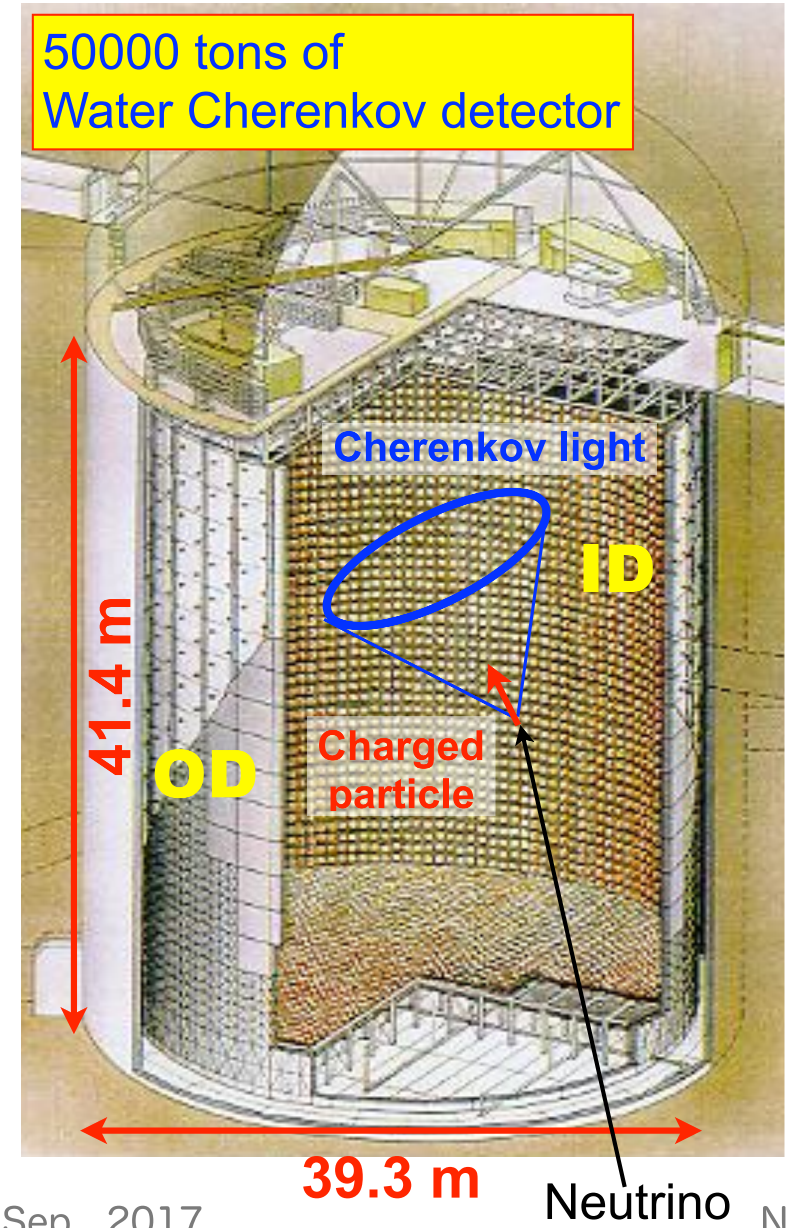
CNO cycle



Solar neutrino energy spectrum



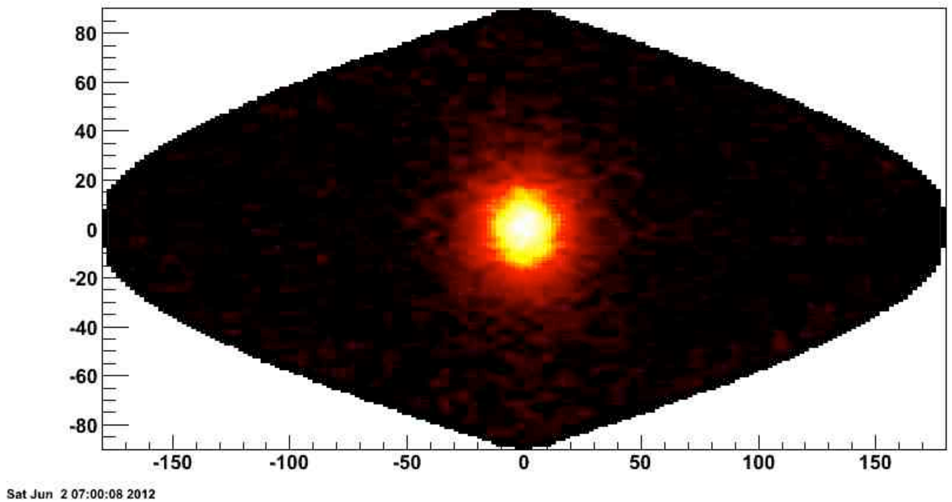
Super-Kamiokande
as a solar neutrino detector



neutrino-electron elastic scattering

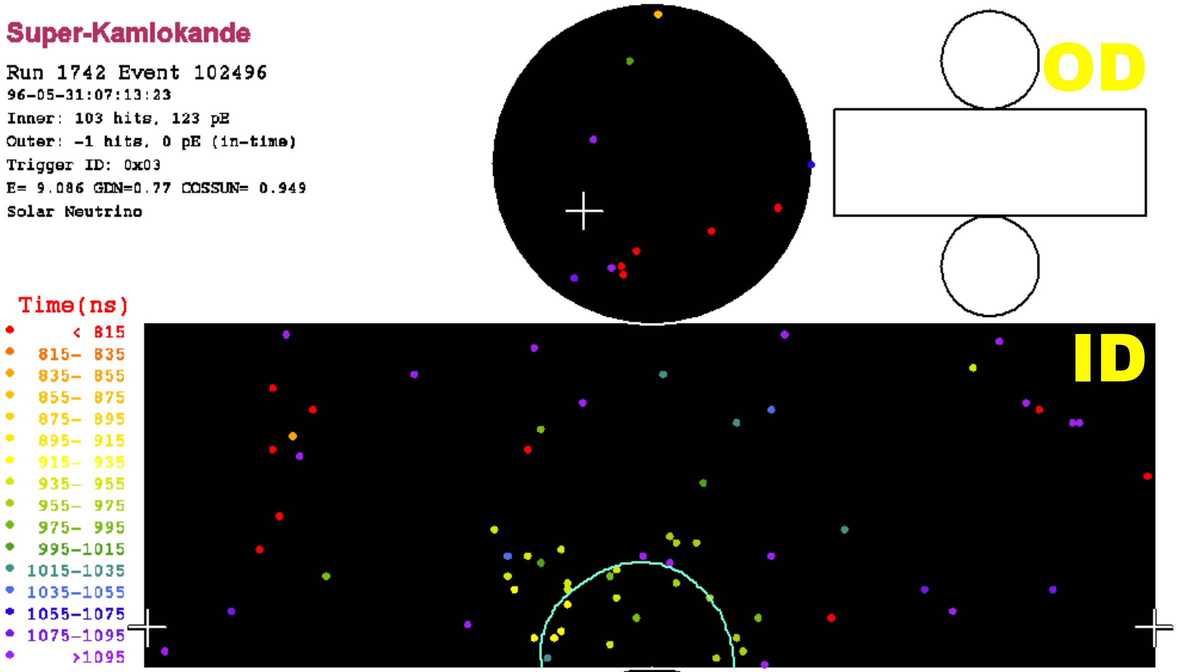
$$\nu + e^- \rightarrow \nu + e^-$$

- ✓Find solar direction
- ✓Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓Energy spectrum

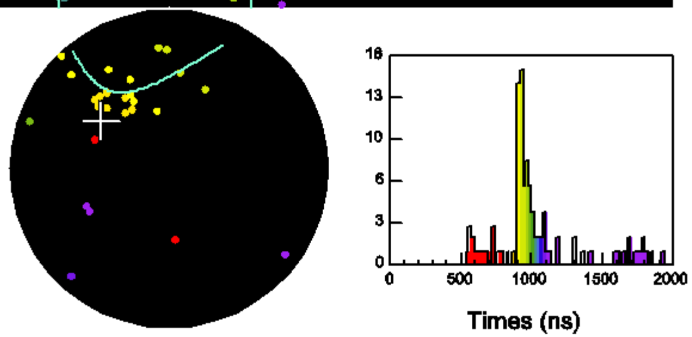


Super-Kamiokande
as a solar neutrino detector

Typical event



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95



neutrino-electron elastic scattering

$$\nu + e^- \rightarrow \nu + e^-$$

- ✓Find solar direction
- ✓Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓Energy spectrum

Detector performance

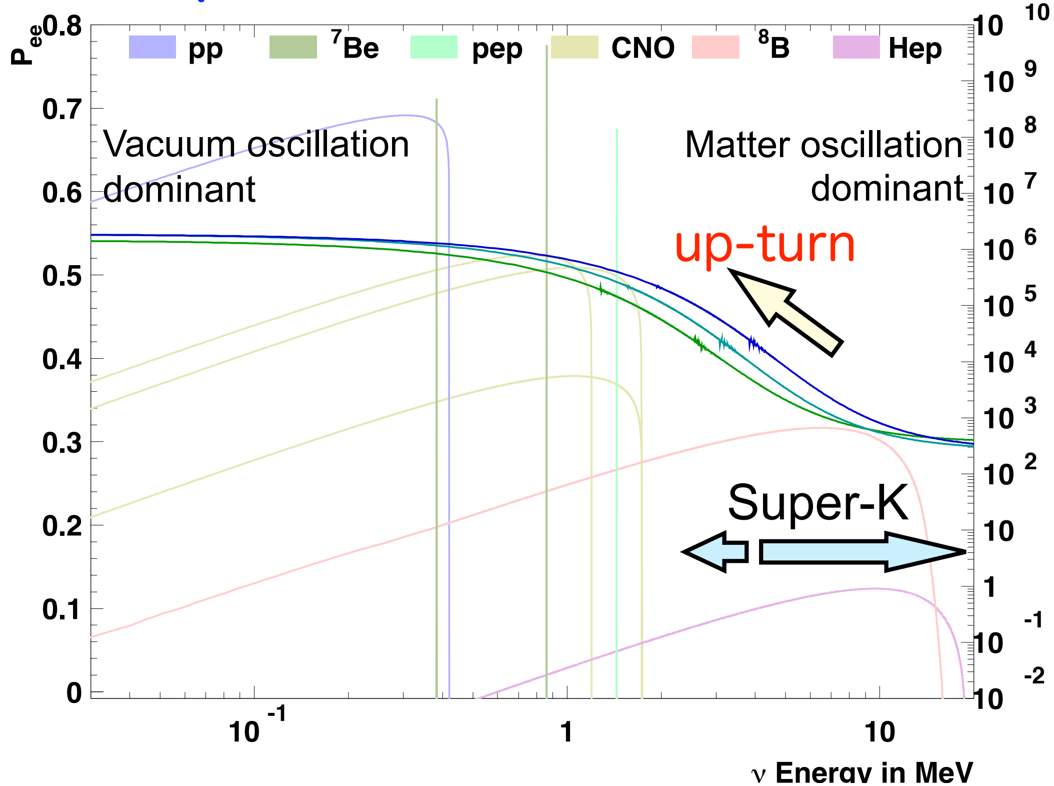
	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC and DT within 0.5% precision

Motivation of the measurement

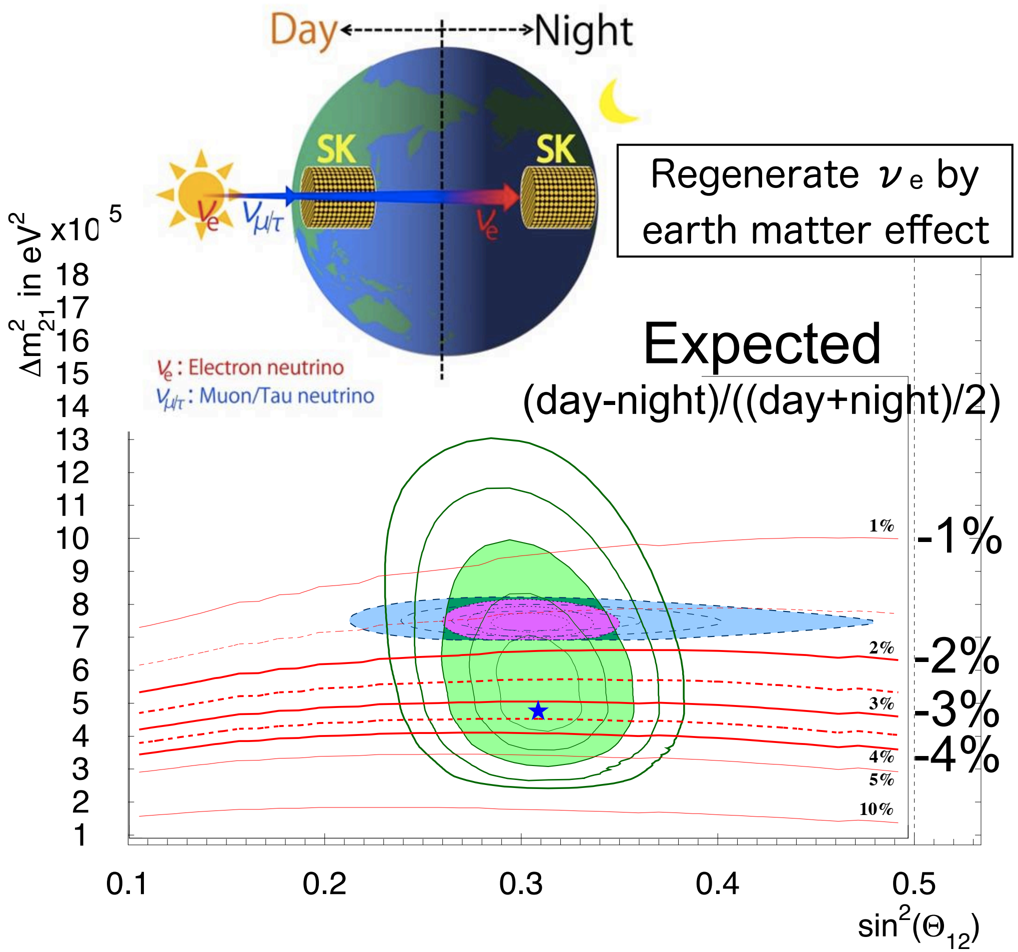
See the neutrino oscillation MSW effect directly

Spectrum distortion

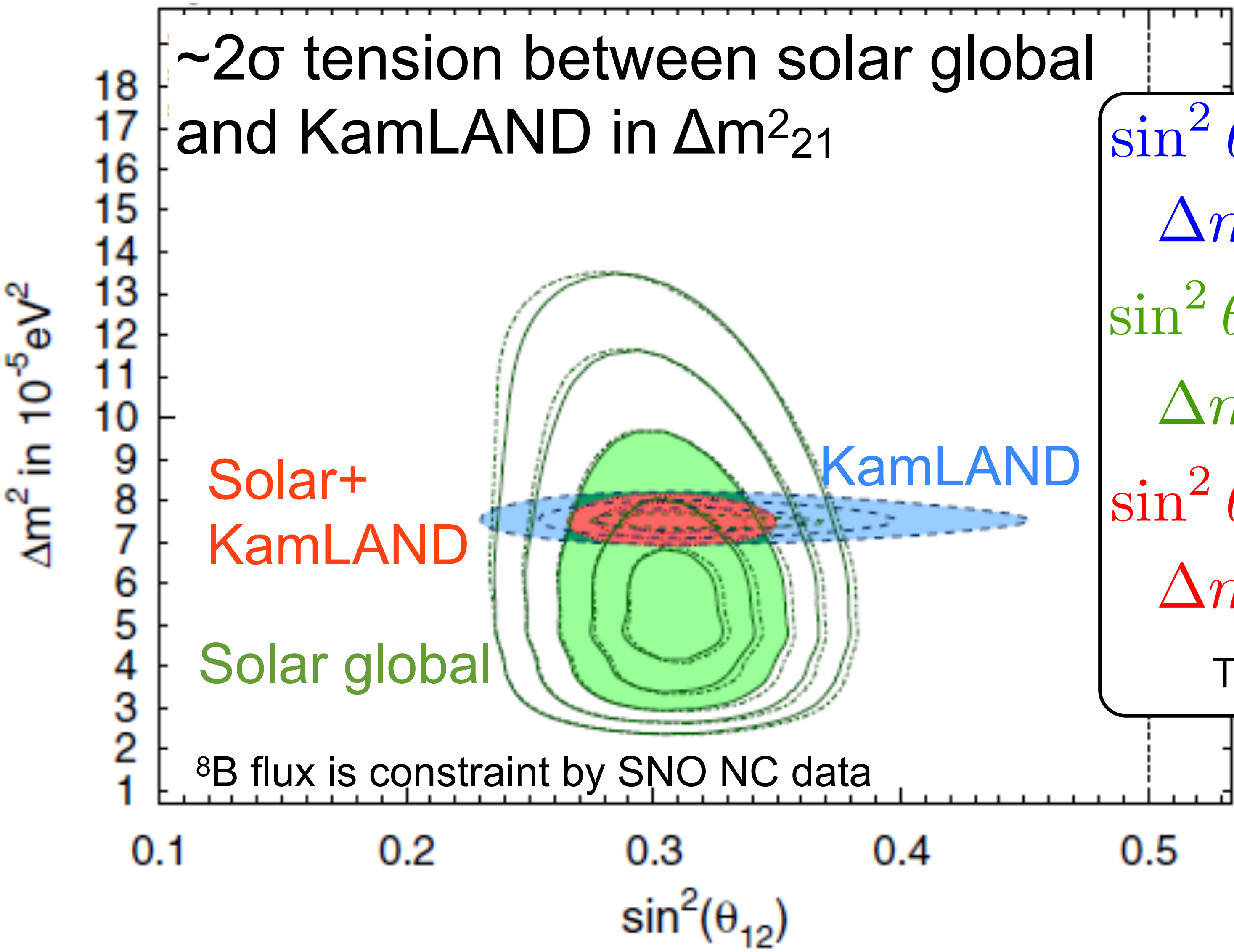


Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



Neutrino oscillation



PRD94, 052010 (2016)

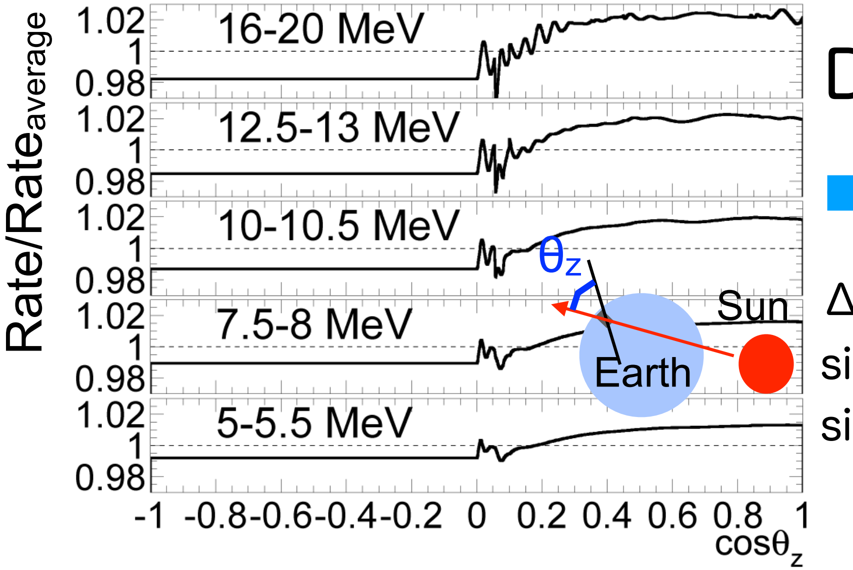
$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.308 \pm 0.014$$
$$\Delta m^2_{21} = 4.85^{+1.33}_{-0.59}$$
$$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

$\sin^2\theta_{13}$=0.0219±0.0014

Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$



PRD94, 052010 (2016)

Day/Night Amplitude was fitted to

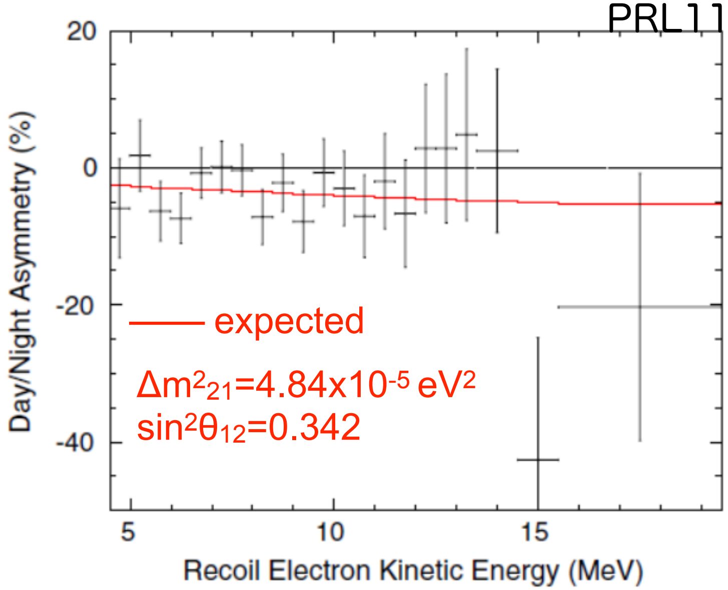
-3.3±1.0±0.5%

$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2
$\sin^2\theta_{12}=0.311$
$\sin^2\theta_{13}=0.025$

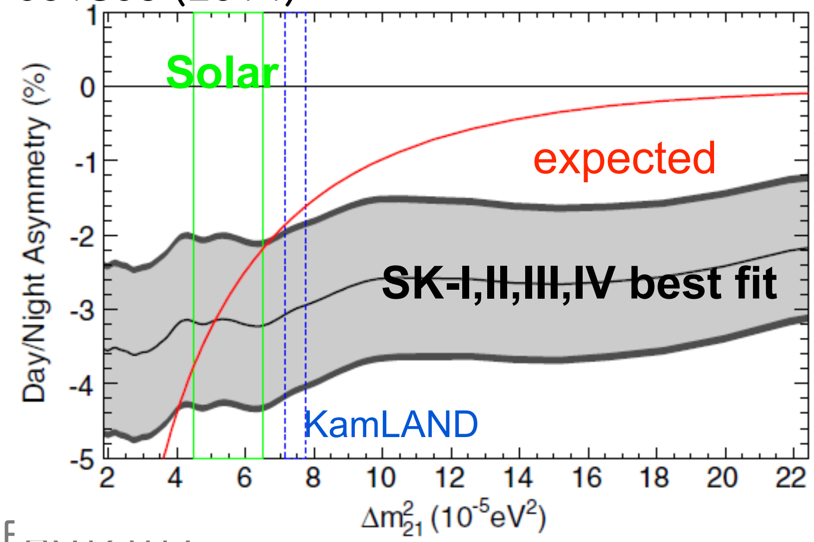
Non-zero significance was

2.9 σ

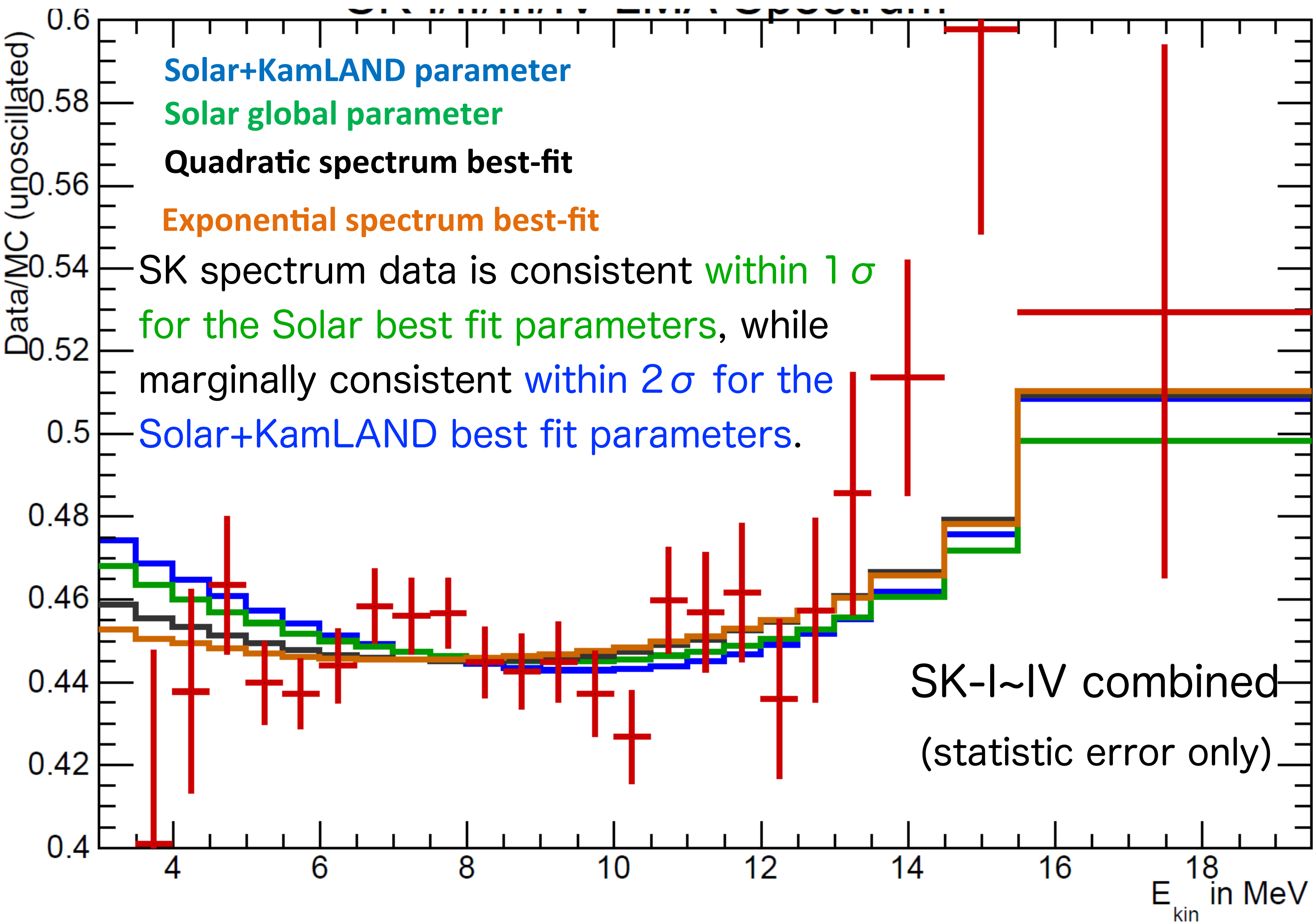
in SK-I to IV (4499 days)



PRL112, 091805 (2014)

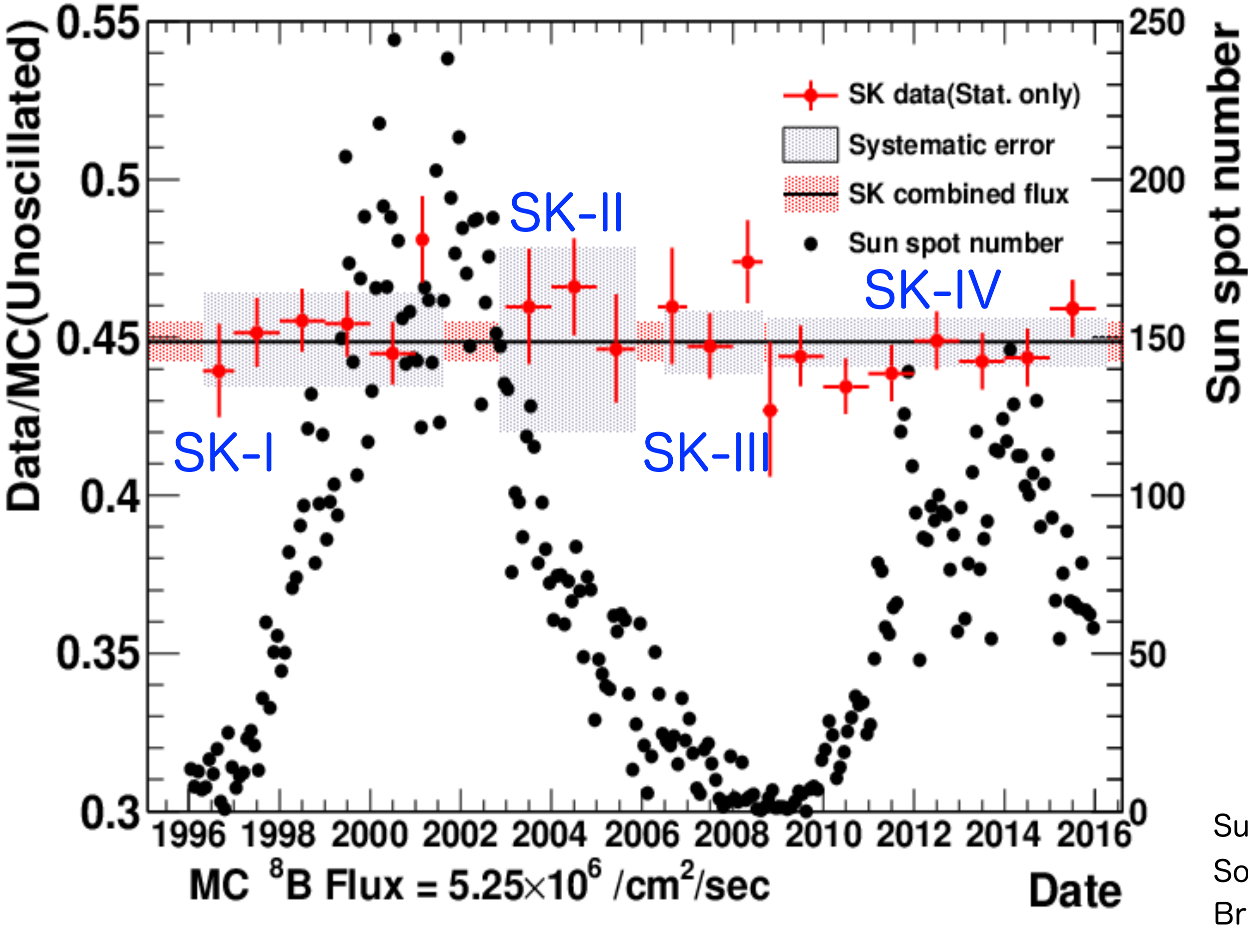


Recoil electron spectrum



Preliminary

Yearly solar neutrino flux



^{8}B flux vs sun spot

No correlation with 11 years solar activity is observed

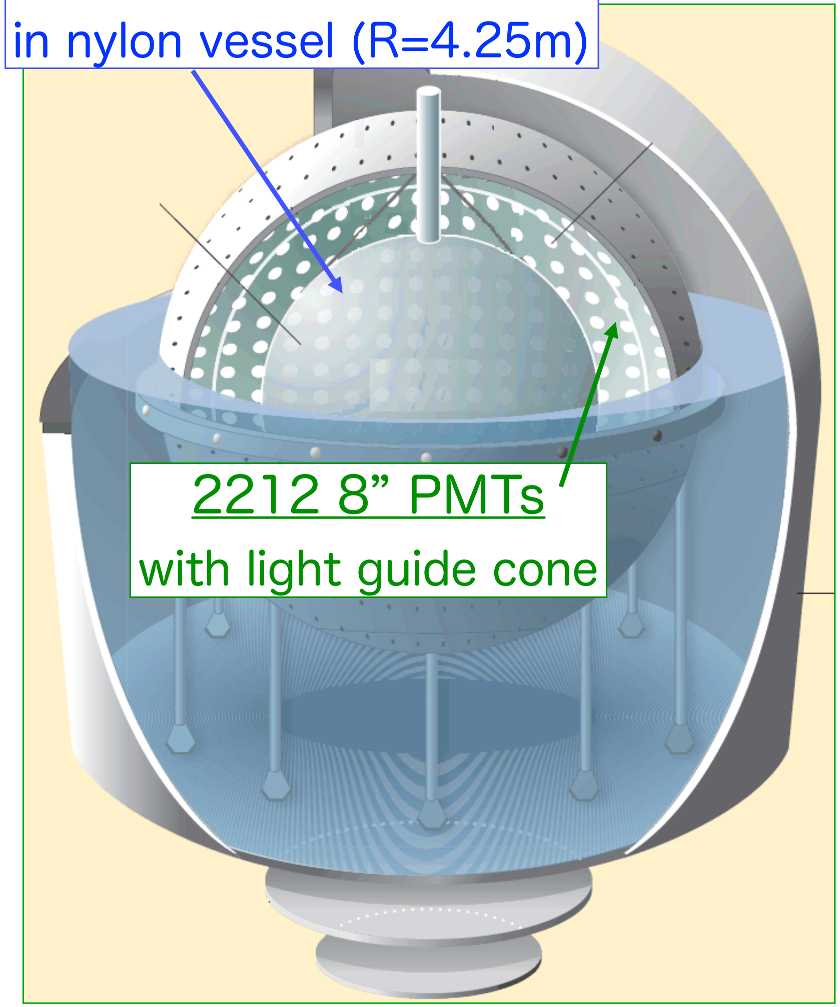
χ^2=15.52/19 (dof)

Prob. = 68.9%

Sun spot number : http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Solar neutrino rate measurement in SK is fully consistent with a constant solar neutrino flux emitted by the Sun

Borexino



Gran Sasso in Italy since 2007
(10th years anniversary)

https://agenda.infn.it/conferenceDisplay.py?confId=12485

neutrino-electron elastic scattering

$$\nu + e^- \longrightarrow \nu + e^-$$

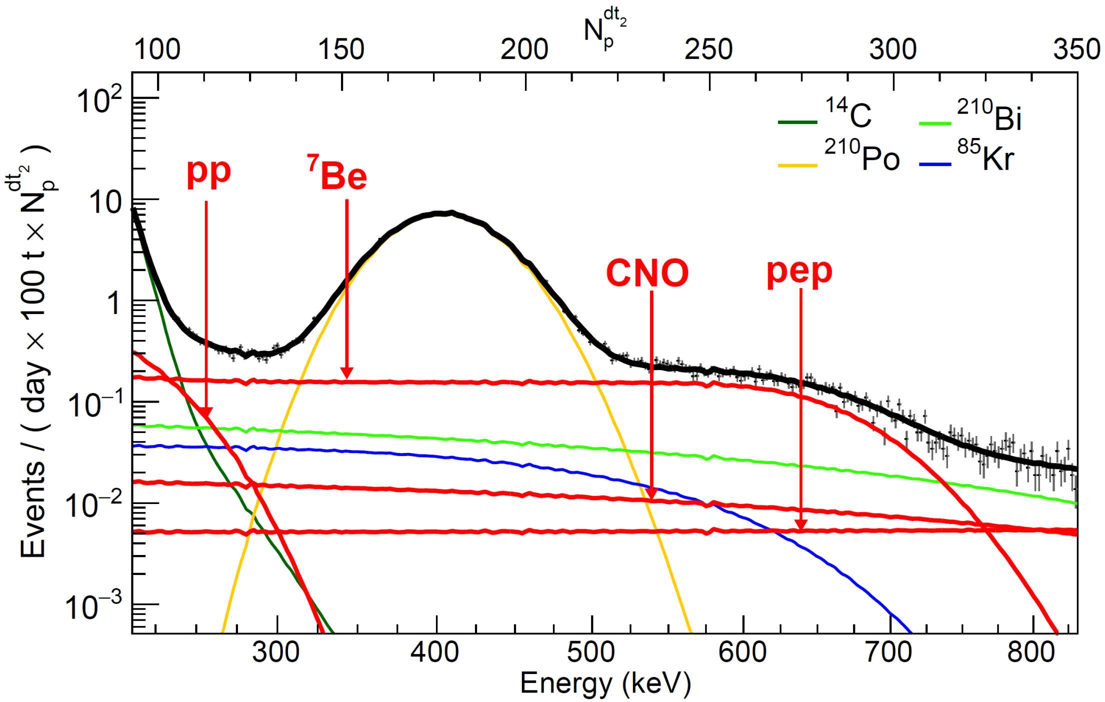
✓High light yield
- lowering energy threshold
- good energy resolution

✓Realtime measurements

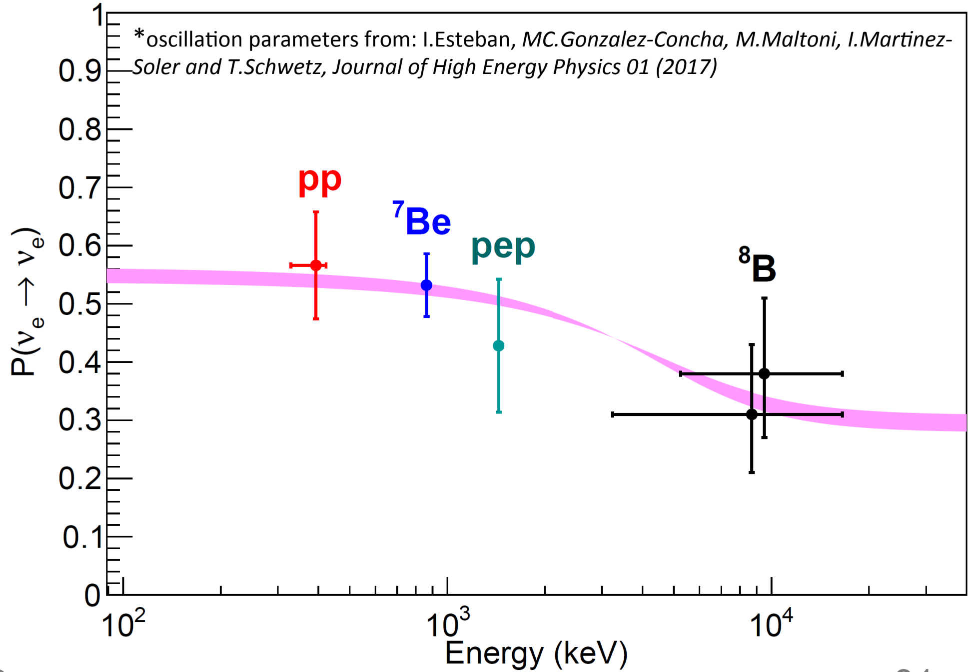
✓No neutrino directional information
- background reduction and understanding are critical

Borexino

Extract the each solar neutrino rate and the BG contribution from the spectrum



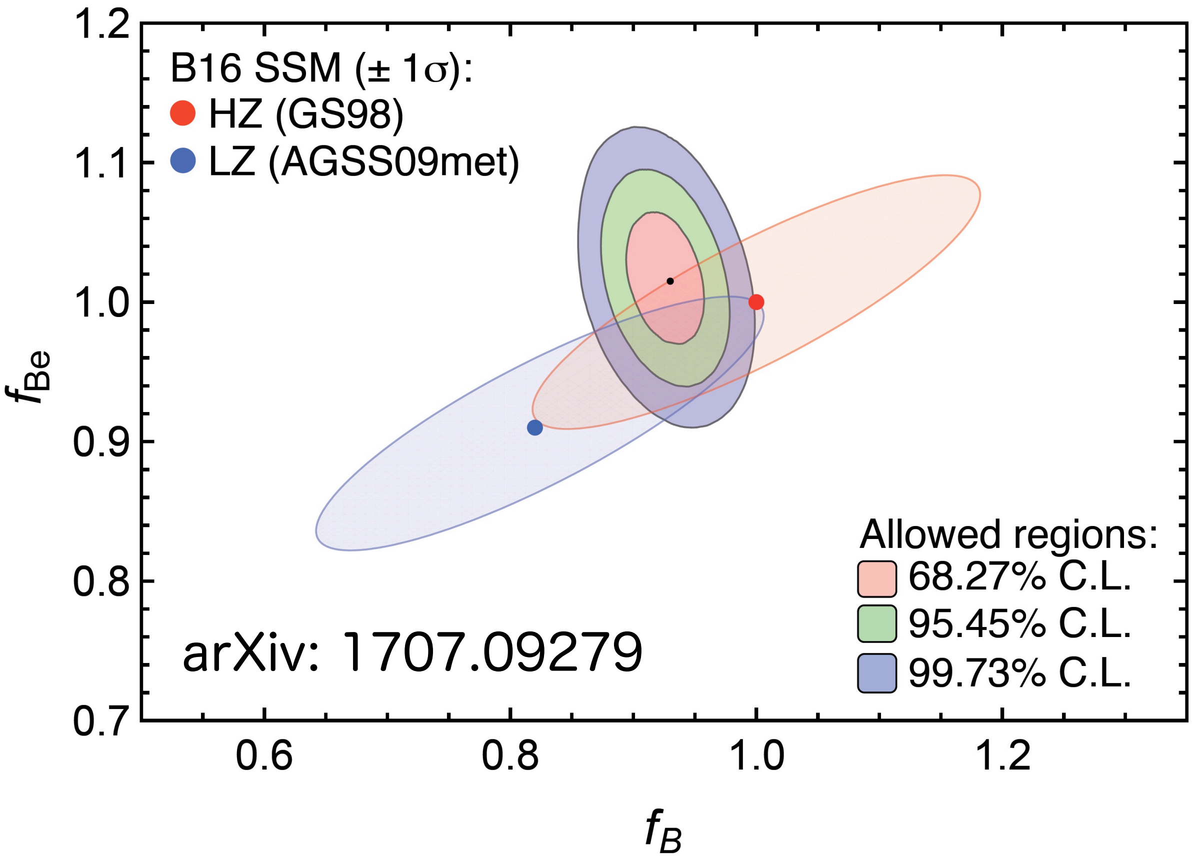
- P_{ee}(pp) = 0.57 ± 0.10
- P_{ee}(^{7}Be, 862keV) = 0.53 ± 0.05
- P_{ee}(pep) = 0.43 ± 0.11



arXiv: 1707.09279

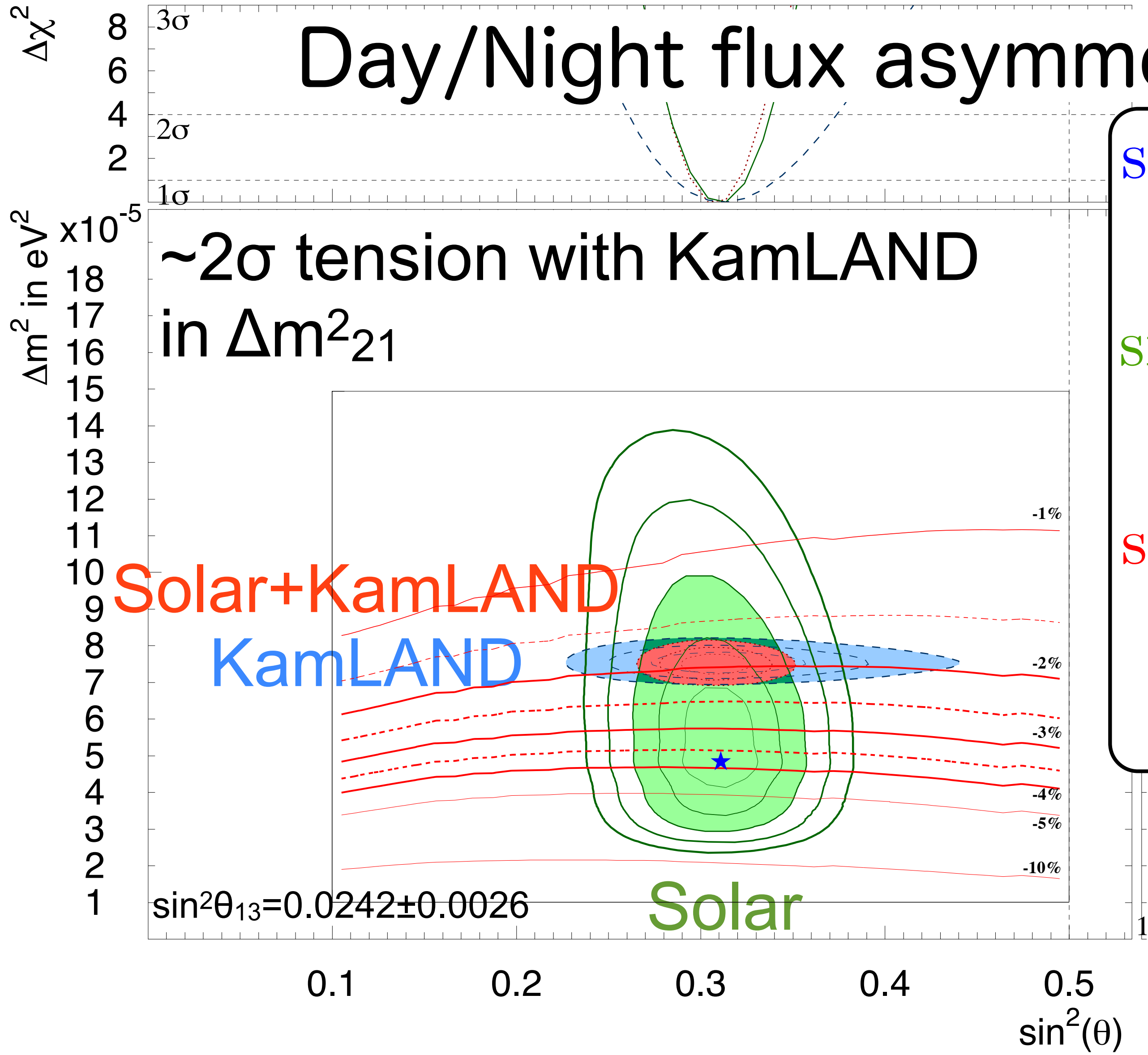
Borexino

Astrophysical point of view



BX results seem to give a hint towards the High Metallicity hypothesis in spite of the large theoretical error

Solar neutrinos in Hyper-K



$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.308 \pm 0.014$$
$$\Delta m^2_{21} = 4.85^{+1.33}_{-0.59}$$
$$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

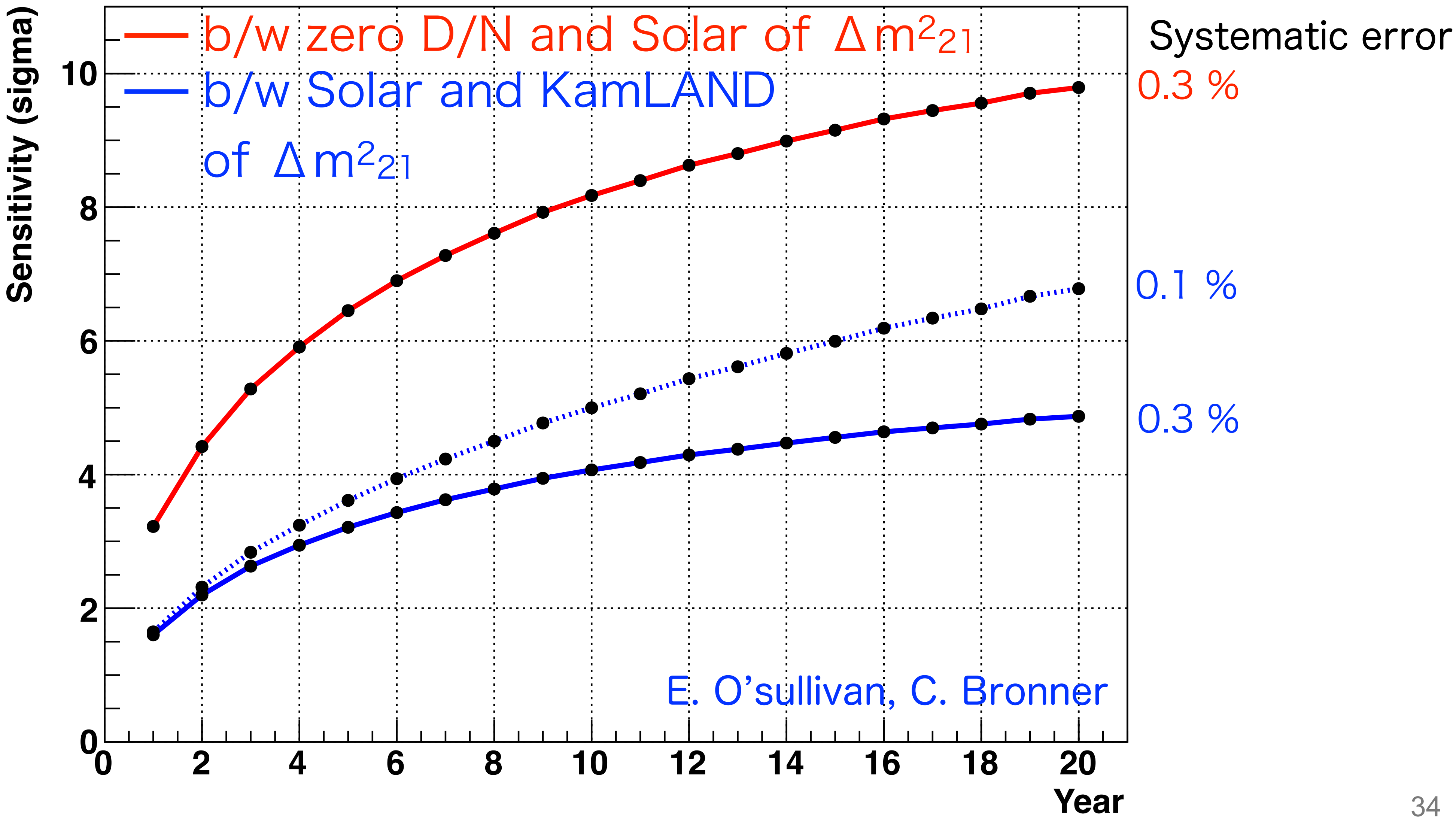
~4% at solar best

~2% at KamLAND

(E_{th} = 6.5MeV)

Solar neutrinos in Hyper-K

Sensitivity of Day/Night flux asymmetry

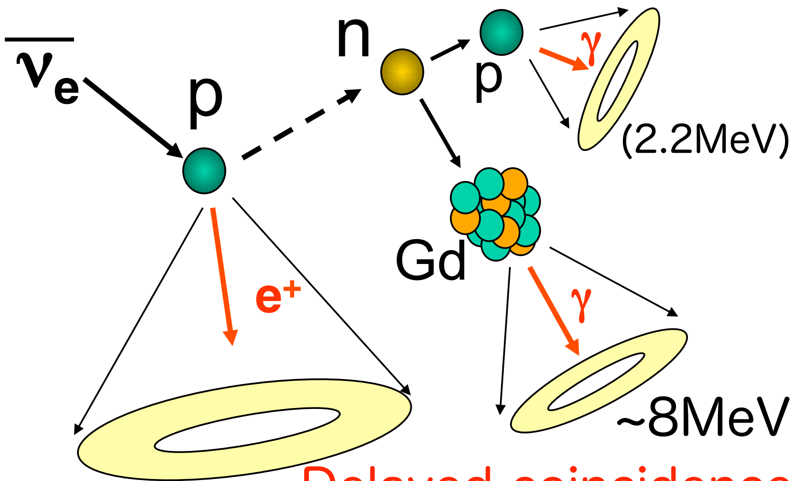


Summary of solar ν

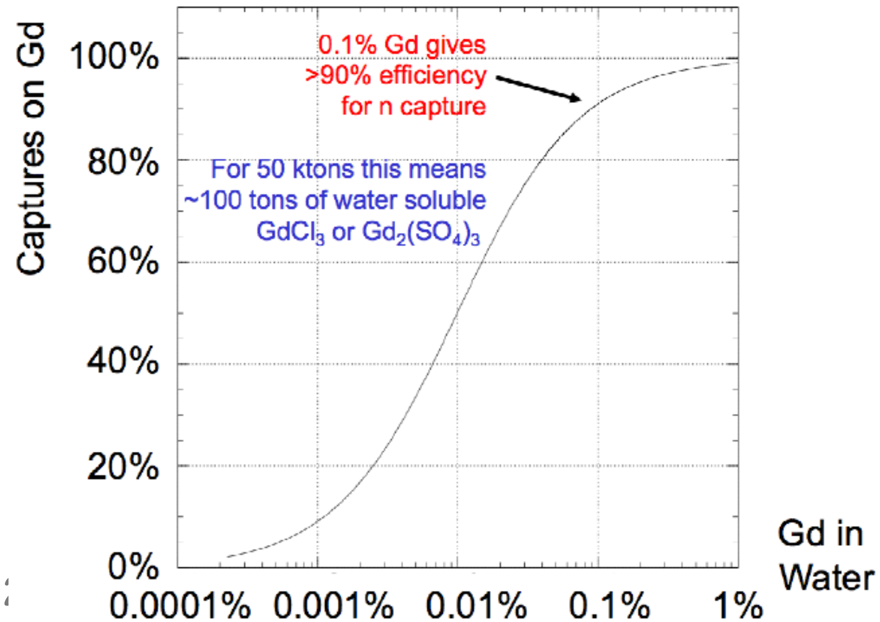
- Current running detectors are Super-Kamiokande and Borexino.
  - Indication of Day-Night asymmetry has been found in Super-K at 3σ level.
  - Precise measurements of pp, ^{7}Be, pep has succeeded in Borexino
- 2σ tension between solar and KamLAND Δm_{21}^2 is seen. Day-night measurement in Hyper-K can determine the parameter.

Super-K Gd

Inverse beta decay

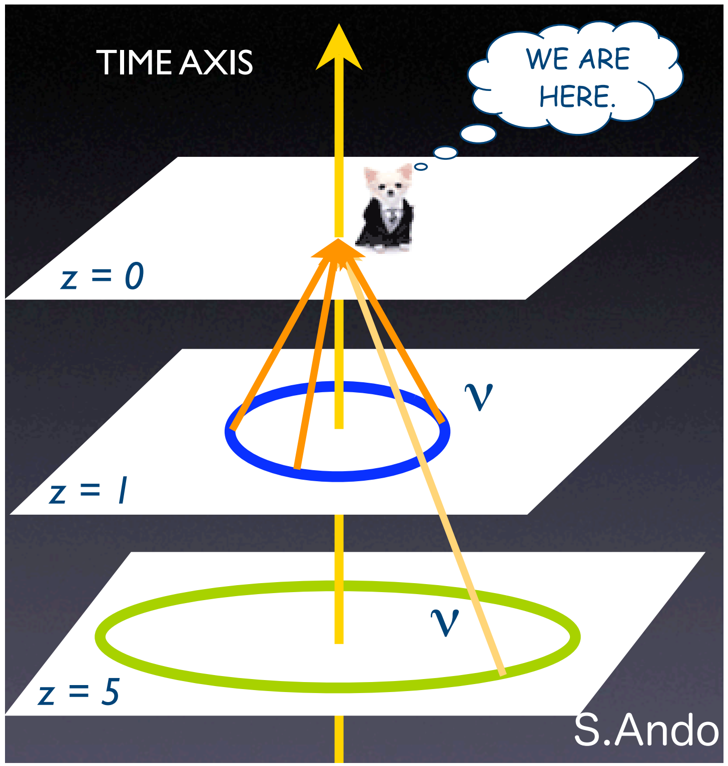


Delayed coincidence



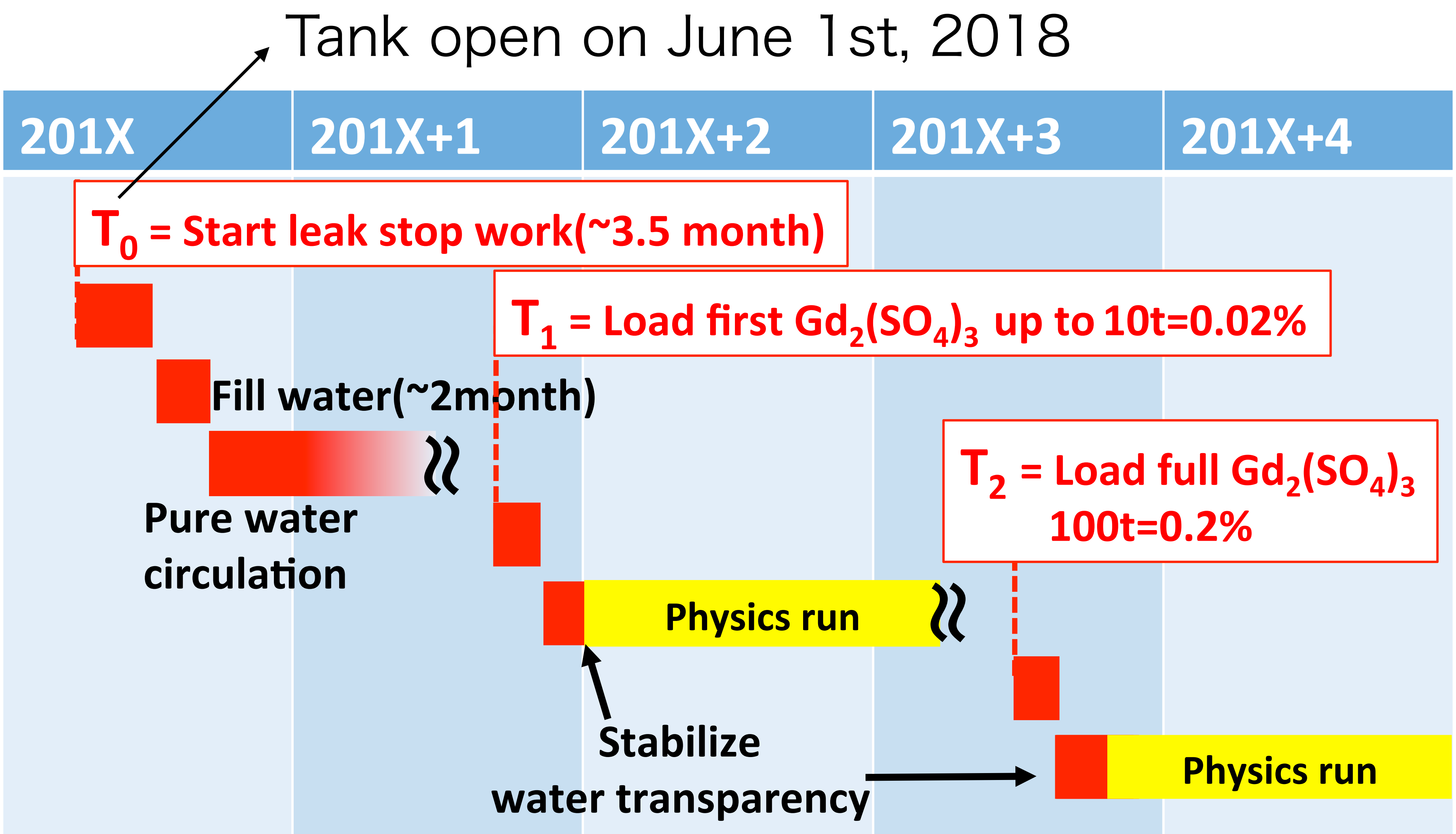
Dissolve Gadolinium into Super-K

J.Beacom and M.Vagins, Phys.Rev.Lett.93(2004)171101



First observation of neutrinos emitted from past supernovae

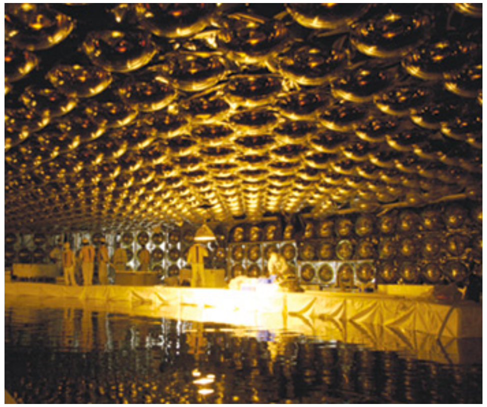
Super-K Gd

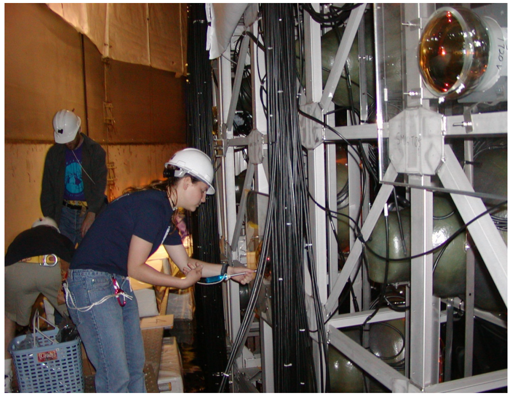


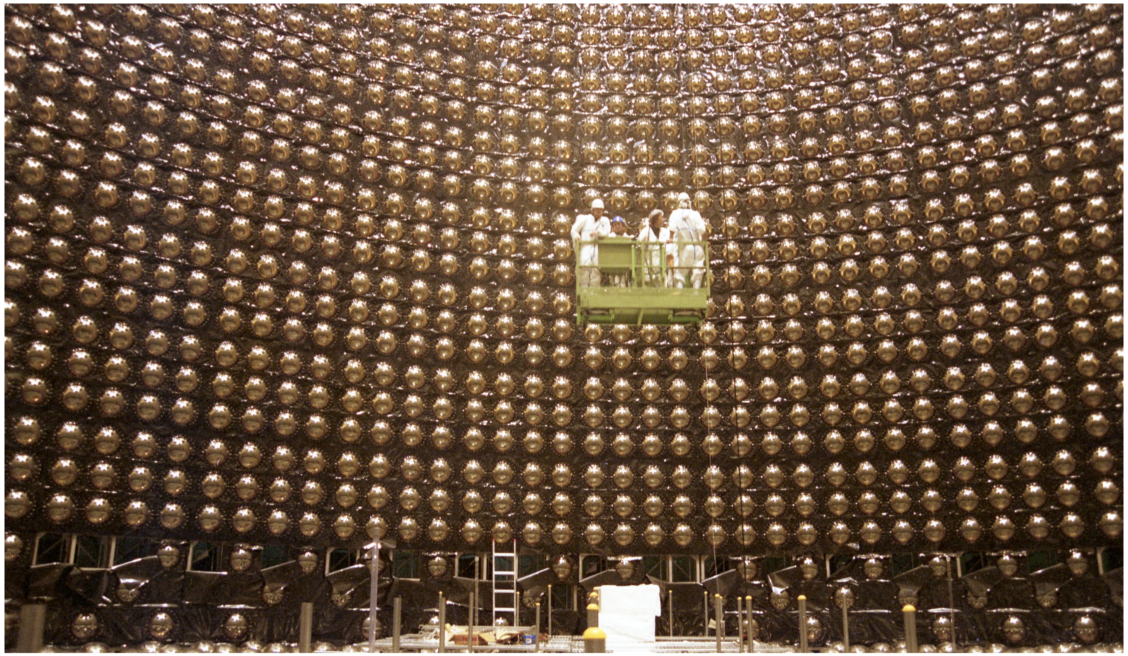
Tank open on June 1st, 2018
201X
201X+1
201X+2
201X+3
201X+4
T_0 = Start leak stop work(~3.5 month)
T_1 = Load first $Gd_2(SO_4)_3$ up to 10t=0.02%
Fill water(~2month)
T_2 = Load full $Gd_2(SO_4)_3$ 100t=0.2%
Pure water circulation
Physics run
Stabilize water transparency
Physics run

Around this time next year

Open the Super-K tank since 2006

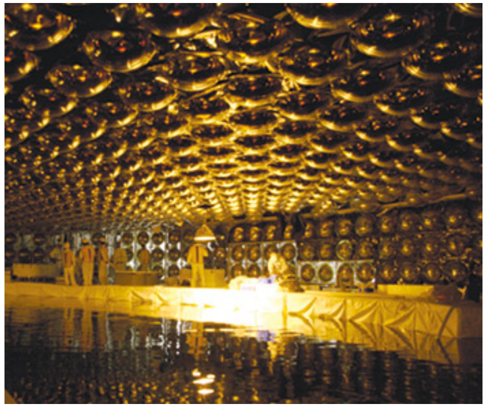


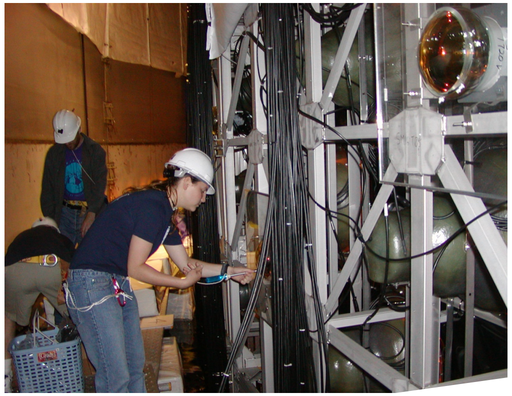




Around this time next year

Open the Super-K tank since 2006





Stay tuned!

Thank you for your attention