Current Status and Upgrade of the Super-Kamiokande experiment

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OUTLINE

1 - Super-Kamiokande

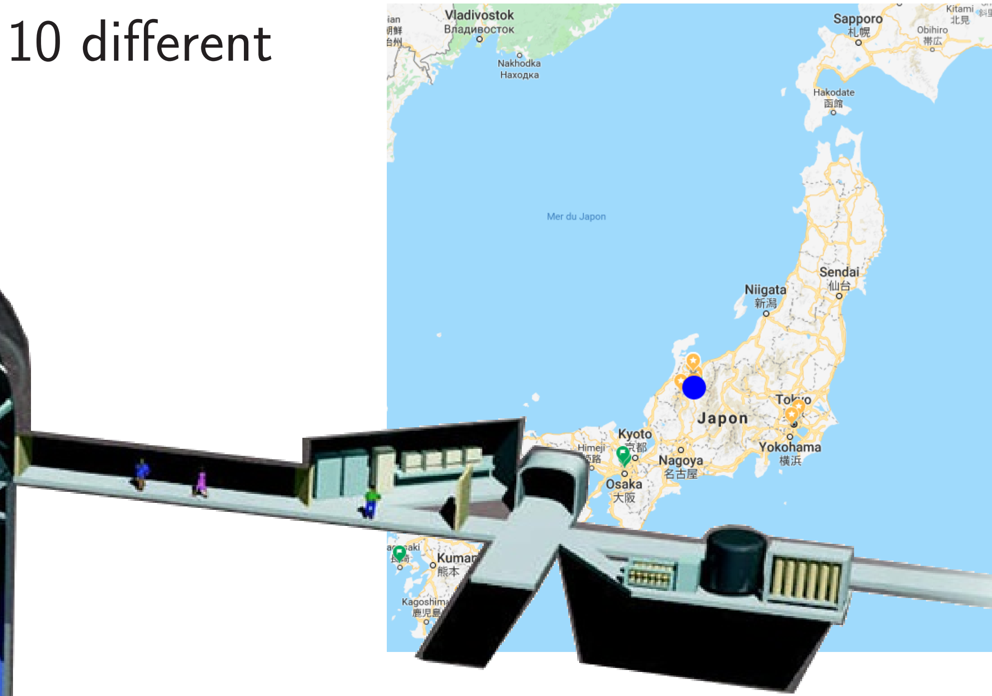
2 - Current status of Super-Kamiokande

3 - Supernova Relic Neutrino

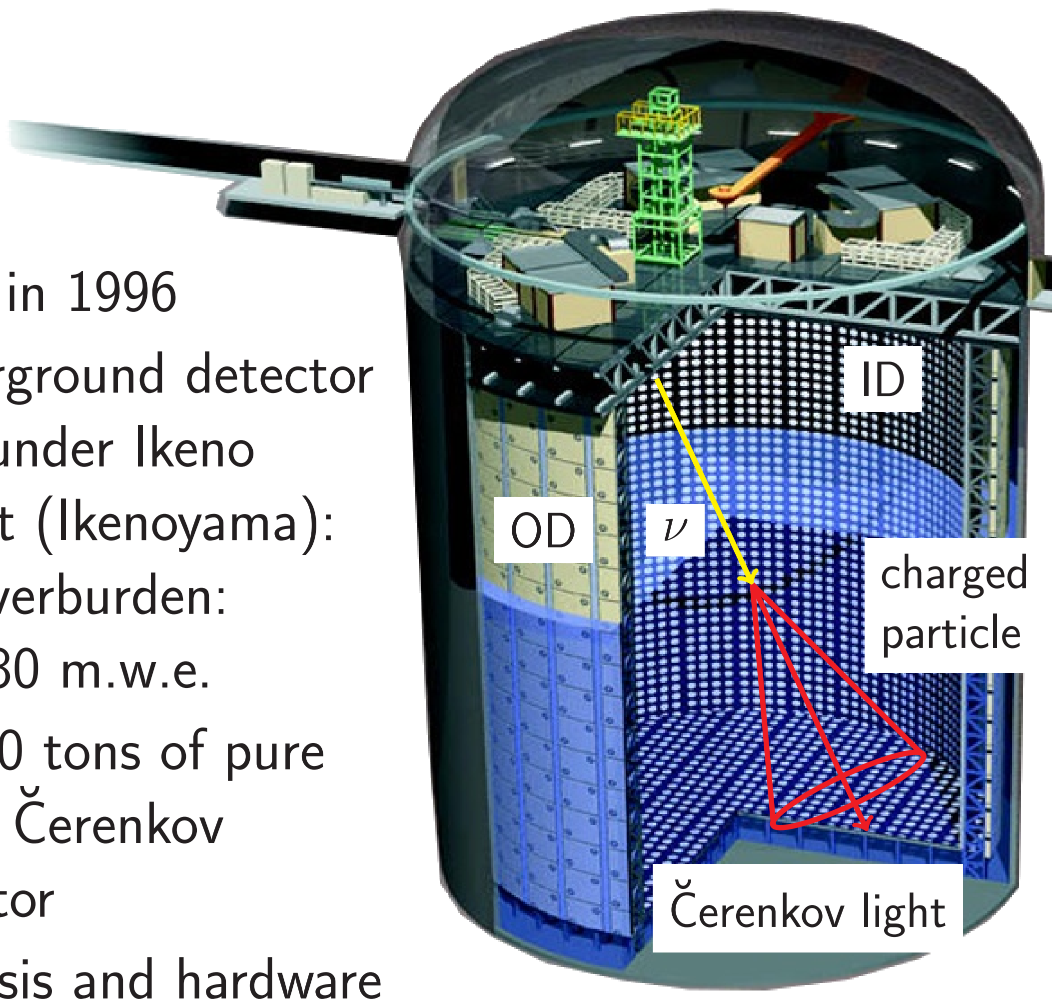
4 - Super-Kamiokande Gd project

Super-Kamiokande

- International collaboration ∼120 collaborators in 10 different countries



- Build in 1996
- Underground detector 1km under Ikeno mount (Ikenoyama): → Overburden: ∼ 2780 m.w.e.
- 50 000 tons of pure water Čerenkov detector
- Analysis and hardware regularly improved since the construction



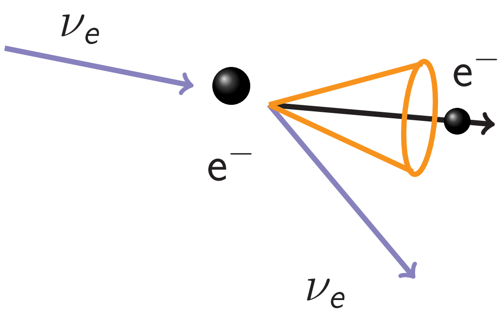
For Solar neutrino analysis

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 16.5 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	2860	22.5 (>5.5MeV) 16.5(4.5<E<5.5) 8.9 (<4.5MeV)		3.5

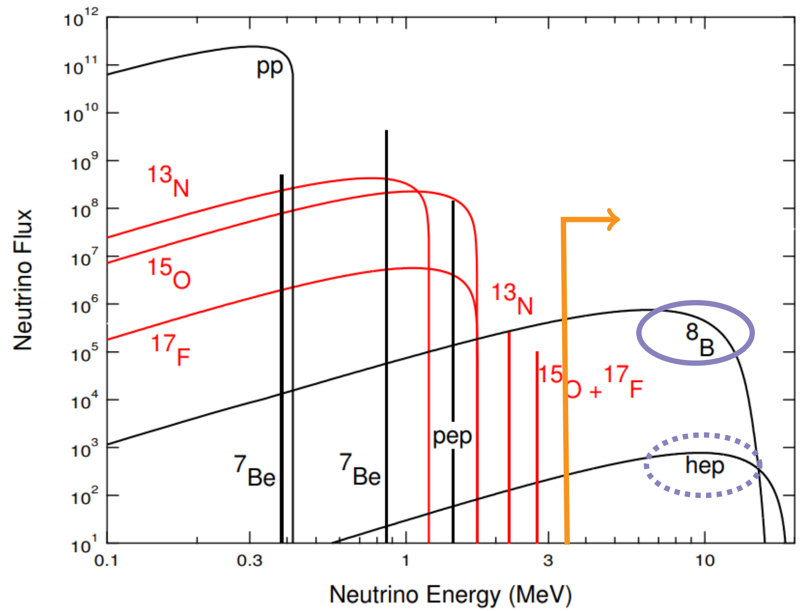
total 5695 days (coverage) (Kinetic energy)

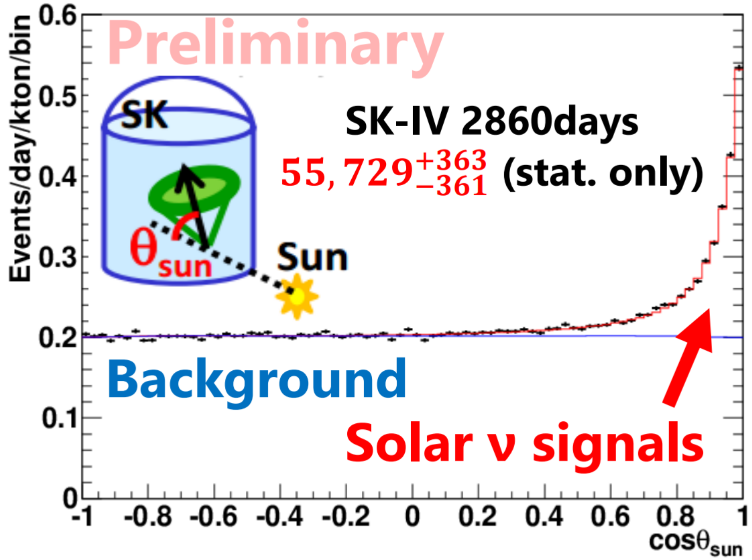
Solar ν in Super-Kamiokande

- Super-Kamiokande is looking at ν_e from Sun
  E_{thr} (SK-IV): 3.5 MeV $\rightarrow$ ^{8}B ν (and hep?)
- Detection channel: ν-e^- elastic scattering



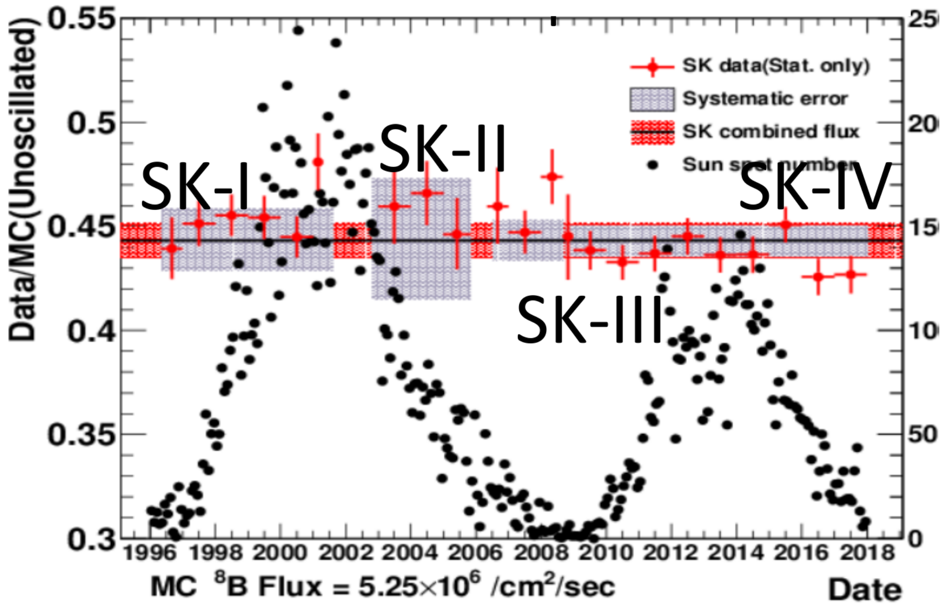
- Direction information used to select solar ν
- Analysis goals:
  - Probe the inside of the Sun
  - Earth matter effect (day/night asymmetry)
  - Observation of the transition region between vacuum and matter oscillations (up-turn?)

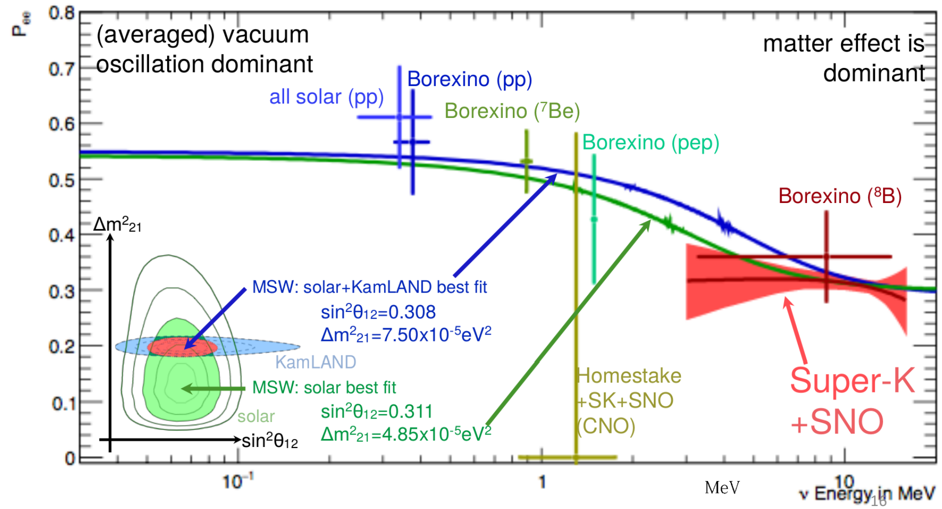




Recent results in solar ν analysis

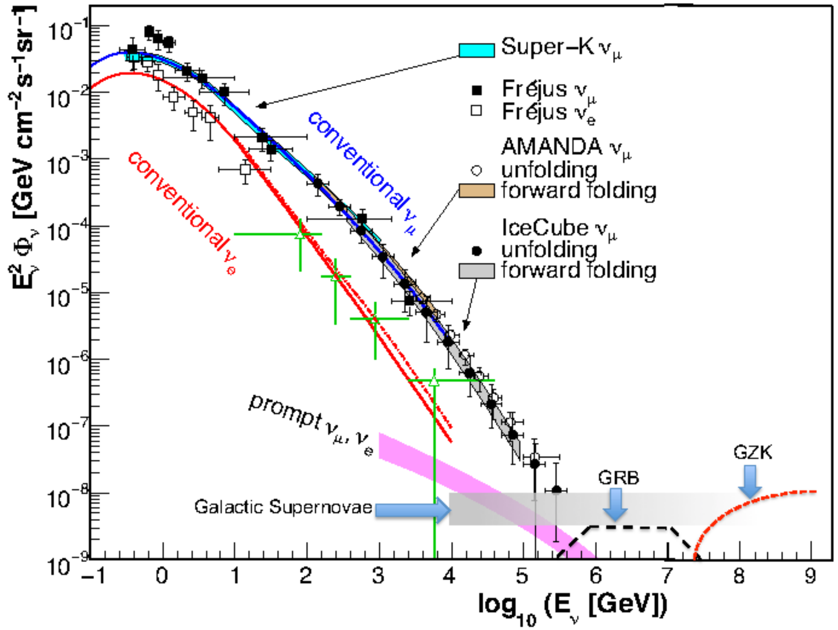
- Finalizing SK-IV analysis (Analyzed period Oct 2008 - Jan 2018)
- ^{8}B ν flux measured for 22 years:
  - No correlation observed with the 11-years solar activity (represented by number of Sun spots)
- The up-turn in the transition region between vacuum and matter oscillations predicted by standard MSW is not yet seen
  - Work on analysis improvement (E_{thr} reduction, BG reduction, etc.)
  - On-going investigations on possible NSI to explain the absence of up-turn

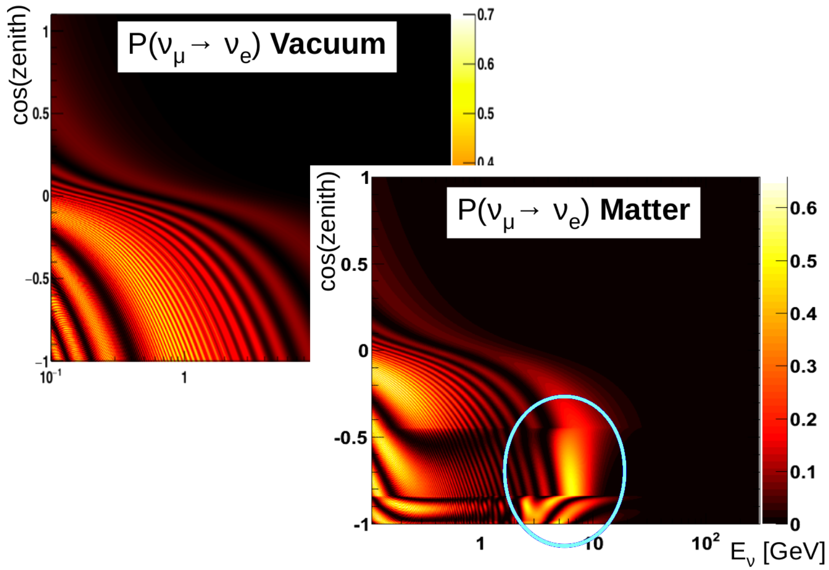




Atmospheric ν in Super-Kamiokande

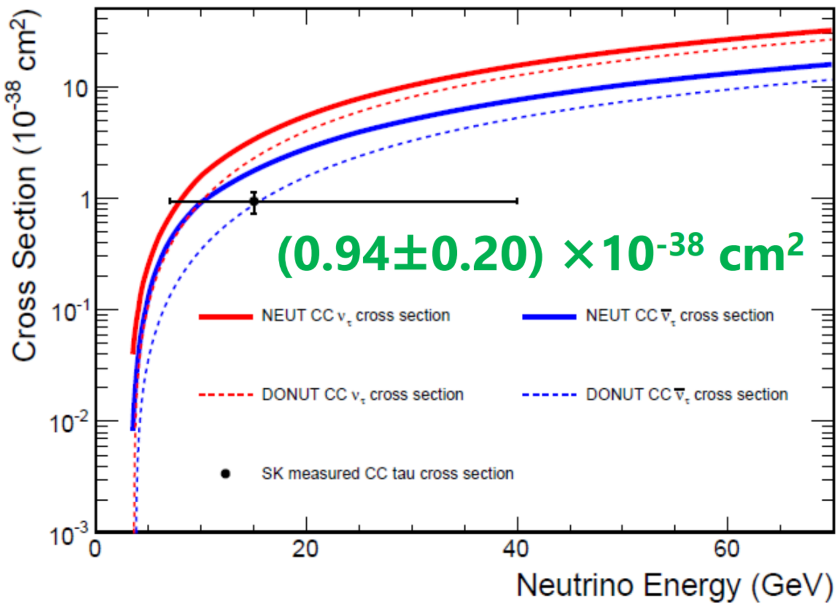
- Super-Kamiokande is also looking at ν from cosmic-rays interactions in the atmosphere
- Broad energy spectrum and range of propagation distances (zenithal angle) $\rightarrow$ large range of L/E for atmospheric ν oscillations study
- Analysis goals:
  - $\nu_\mu \rightarrow \nu_\tau$ oscillations: dominant atmospheric ν oscillation $\rightarrow (\Delta m^2_{23}, \theta_{23})$, test of 3-flavor mixing scheme (appearance)
  - $\nu_\mu \rightarrow \nu_e$ oscillations: resonance due to matter effect in Earth $\rightarrow$ Sensible to mass hierarchy (NH: resonance with ν, IH: resonance with $\overline{\nu}$) $\rightarrow$ Sensible to θ_{23} octant (amplitude driven by θ_{23})
  - δ_{CP} change the oscillation pattern at sub-GeV

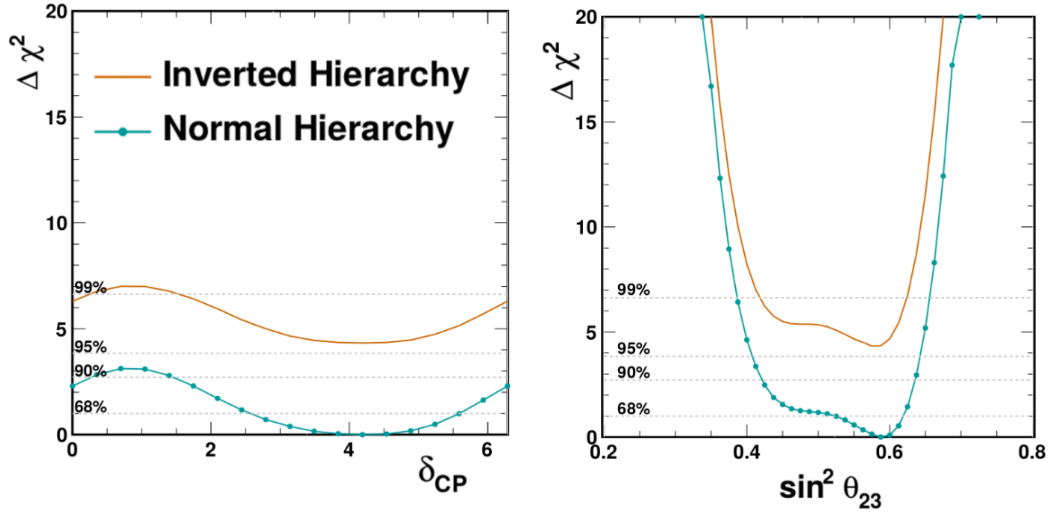




Recent results in Atmospheric ν analysis

- Atmospheric ν dataset: 5326 days (SK-I,II,III,IV)
- 27505 muon-like and 20949 electron-like events
- Tau appearance: 338.1 ± 72.7 events
  - BG discrimination with neural network (efficiency 76%)
  - Reject no-tau-appearance at 4.6σ
  - CC ν_τ cross-section estimated
- $\nu_\mu \to \nu_e$ oscillations study:
  - $\Delta\chi^2 = \chi^2(\text{NH}) - \chi^2(\text{IH}) = -4.33 \to$ Preference for the NH hypothesis
  - With T2K model constraints: stronger exclusion of IH $\Delta\chi^2 = -5.27$
  - Second octant of θ_{23} is favored





$\theta_{13} = 0.0219 \pm 0.0124$ (reactor average)

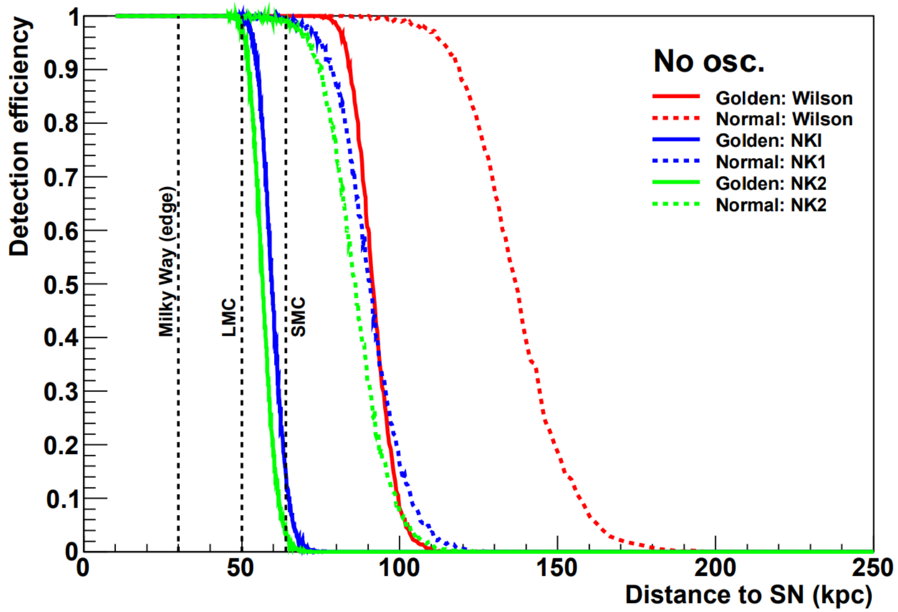
Supernova Neutrino

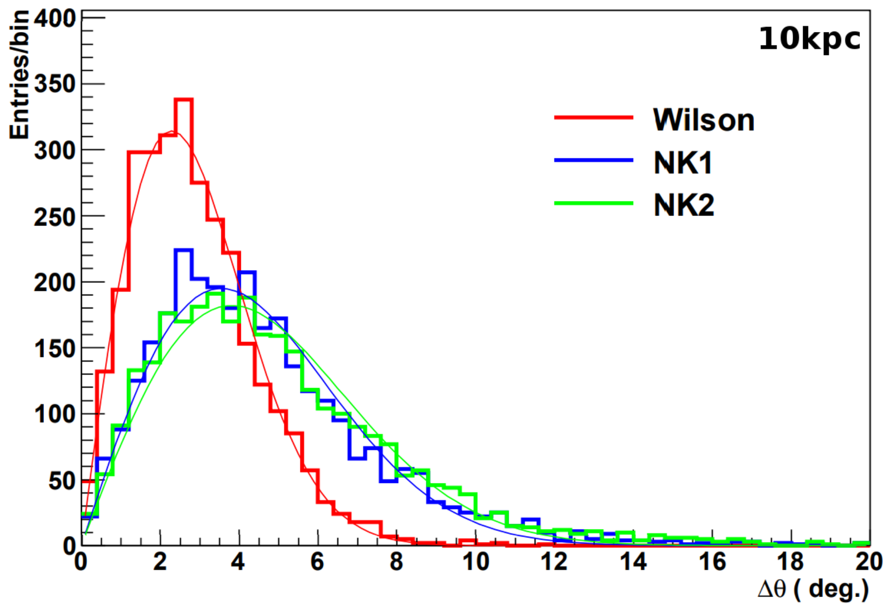
- Super-Kamiokande is also looking for supernova (SN) neutrinos
- Online burst detection system ready

  K. Abe et al., Astropart. Phys. 81 (2016) 39-48
- 100% detection efficiency for SN burst detection up to 50kpc (Wilson, NK1, and NK2 models)
- 3.1 $\sim$ 3.8 deg (Wilson) pointing accuracy for SN occurring at 10kpc
- Such events are expected about once every 30 years $\rightarrow$ Super-K is waiting for the next one
- **However**:

  $\sim 10^{11}$ stars/galaxy $\times 10^{11}$ galaxies $\times 0.3\%$ (chance to become SNe)

  $\rightarrow \sim O(10^{19})$ SNe in the universe past

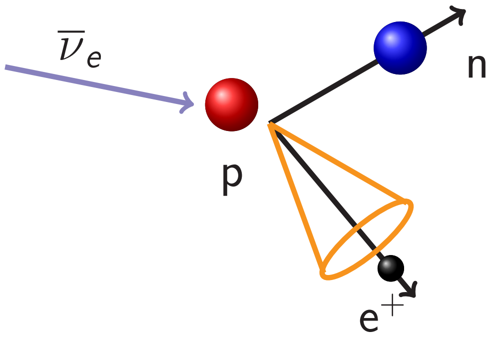


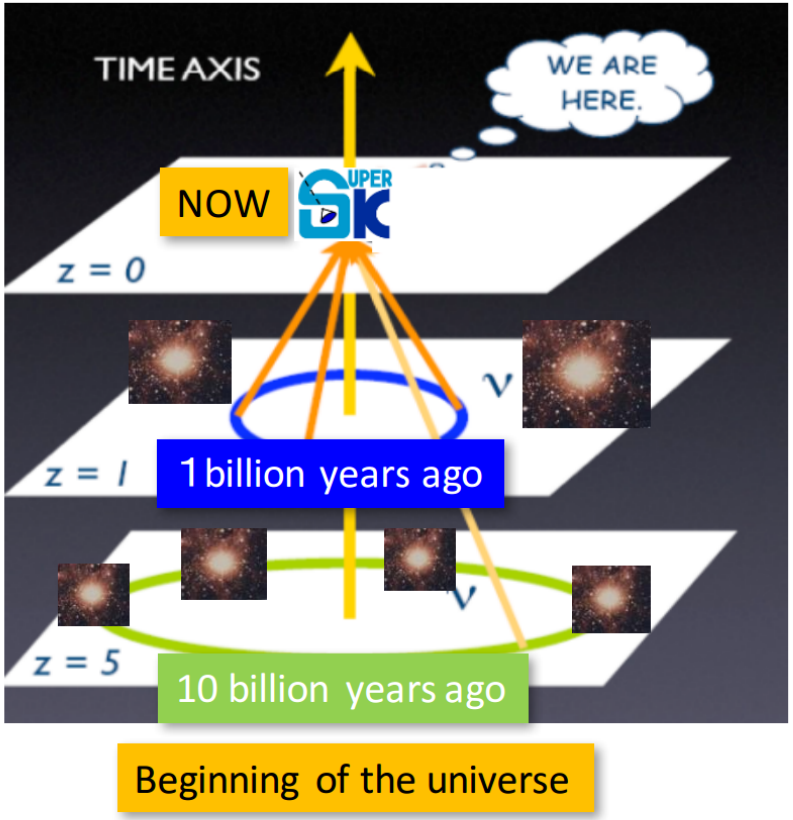


Supernova Relic Neutrino

- All the past SNe should have produce ν burst
- There should be a "Diffuse Supernova Neutrino Background" or **"Supernova Relic Neutrino"** (SRN)

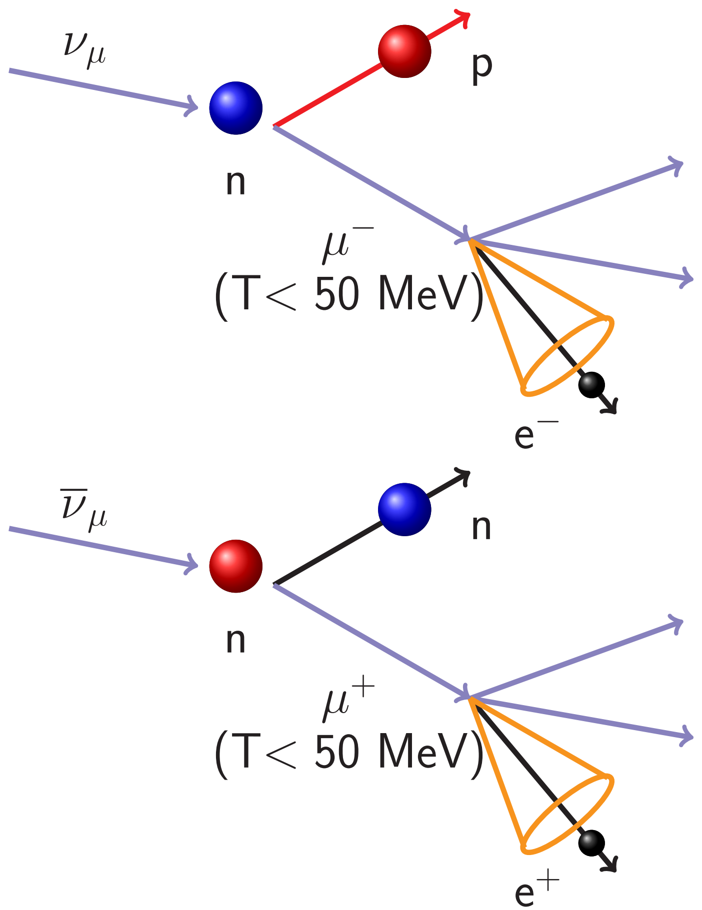
  L. M. Krauss, S. L. Glashow and D. N. Schramm, Nature 310, 191 (1984)
- Theoretical flux prediction : $0.3 \sim 1.5$ /cm^2/s (17.3MeV threshold)
- Signal: Inverse β decay reaction:



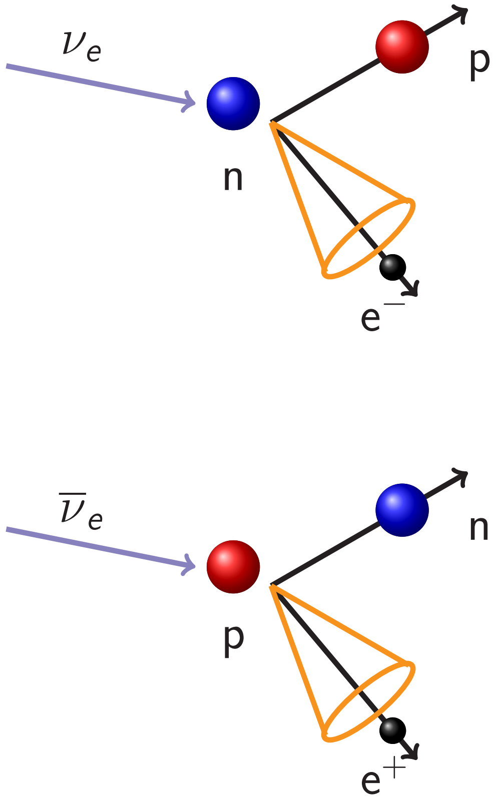


- Difficult analysis due to large backgrounds

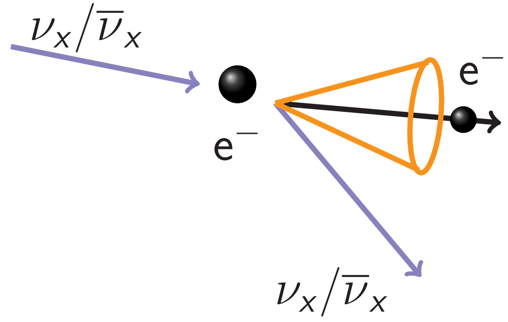
Atmospheric ν_μ CC



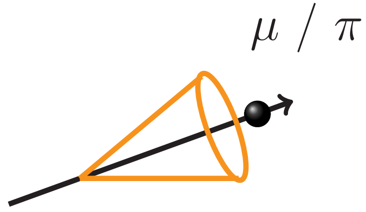
Atmospheric ν_e CC



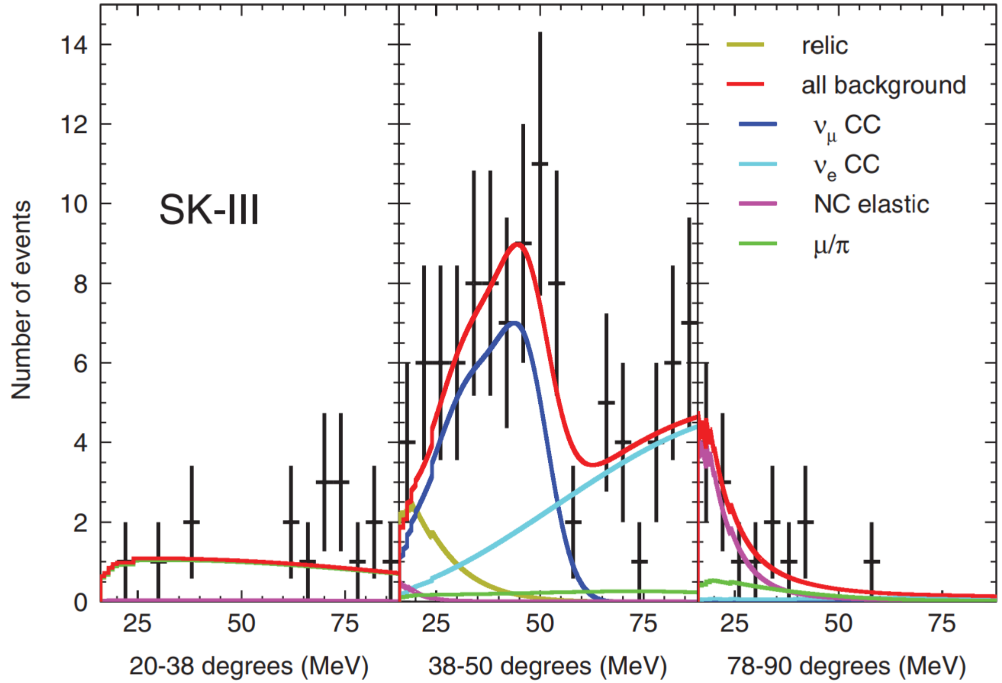
Atmospheric ν NC

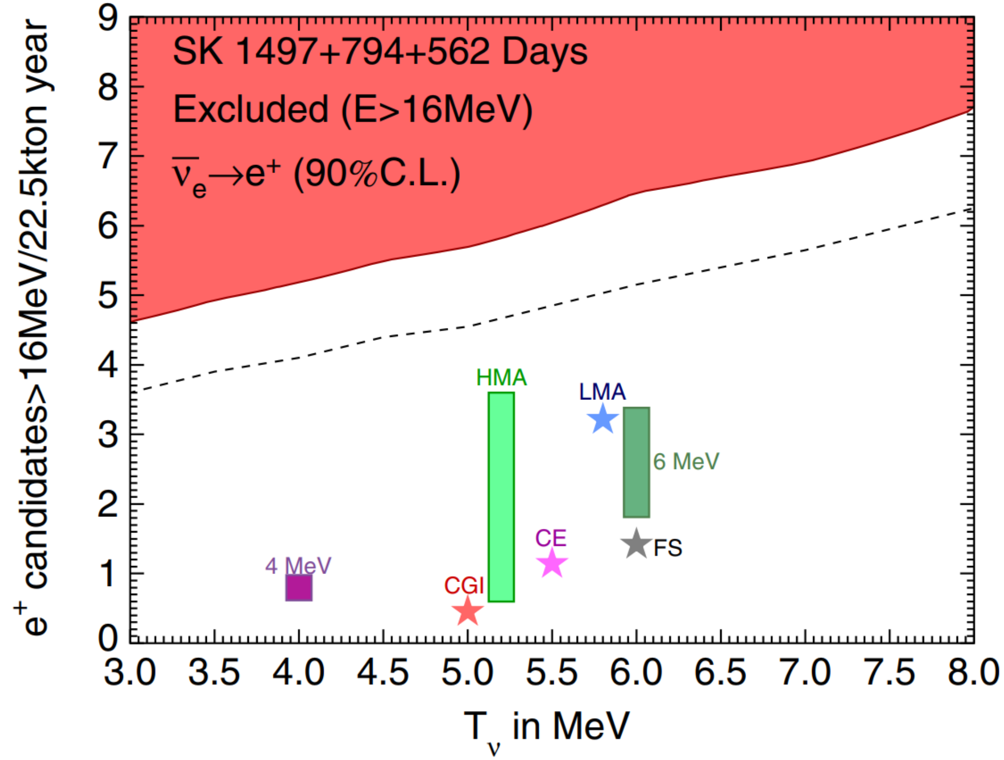


Mis-identified μ / π



Super-Kamiokande results



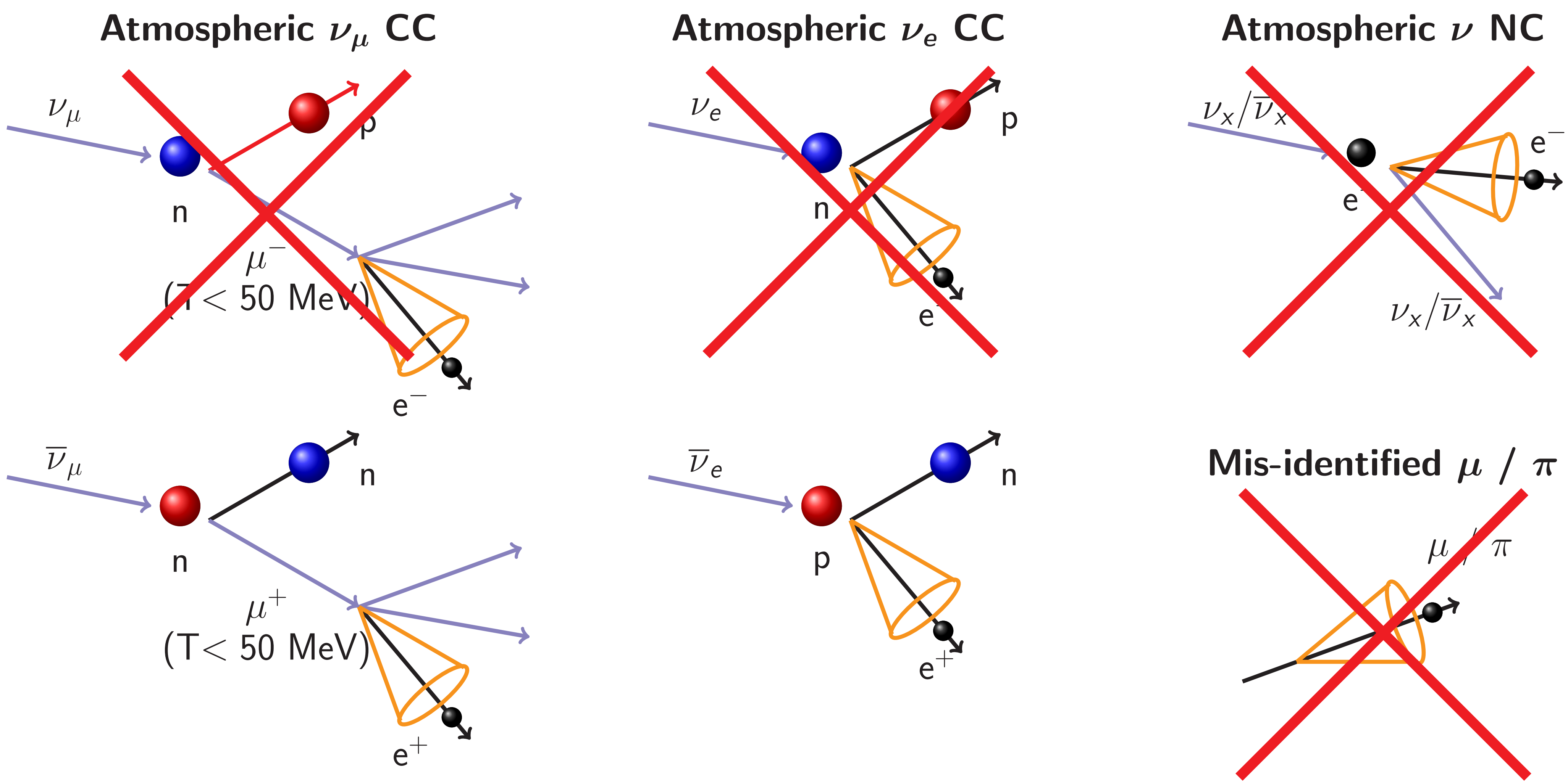


plots from Phys Rev D 85 052007 (2012)

- Super-K currently hold best limits on the SRN flux. No signal so far...
- Can we reduce the backgrounds?

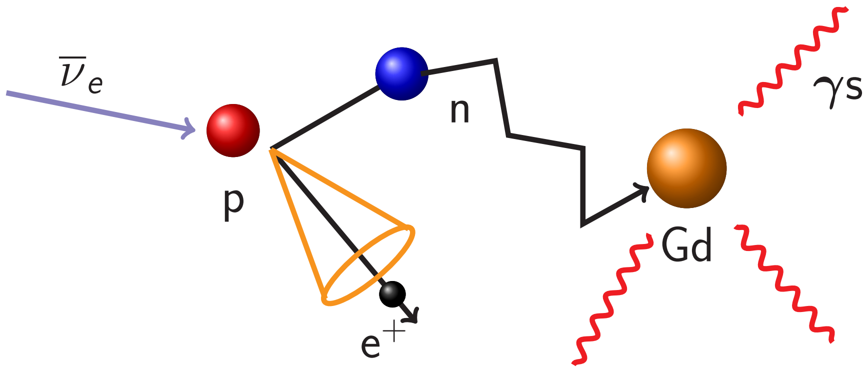
Backgrounds

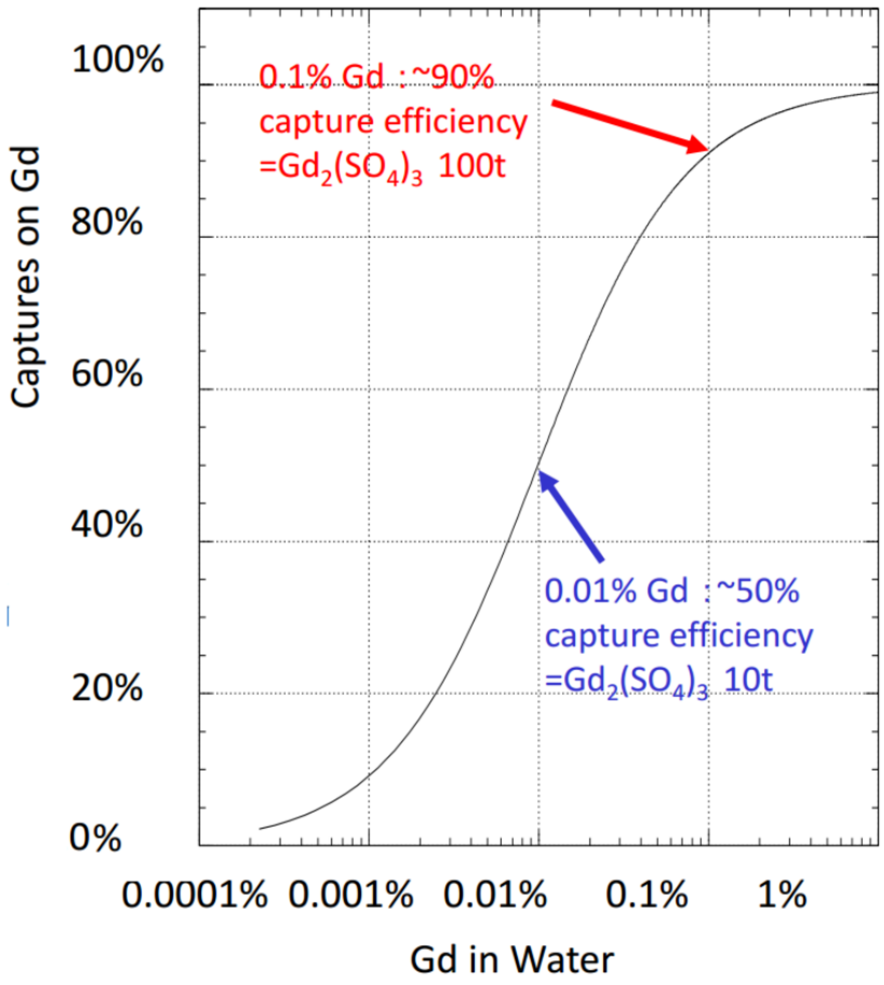
- Signal produce one neutron, and most background interactions do not
- Neutron detection $\rightarrow$ BG reduction



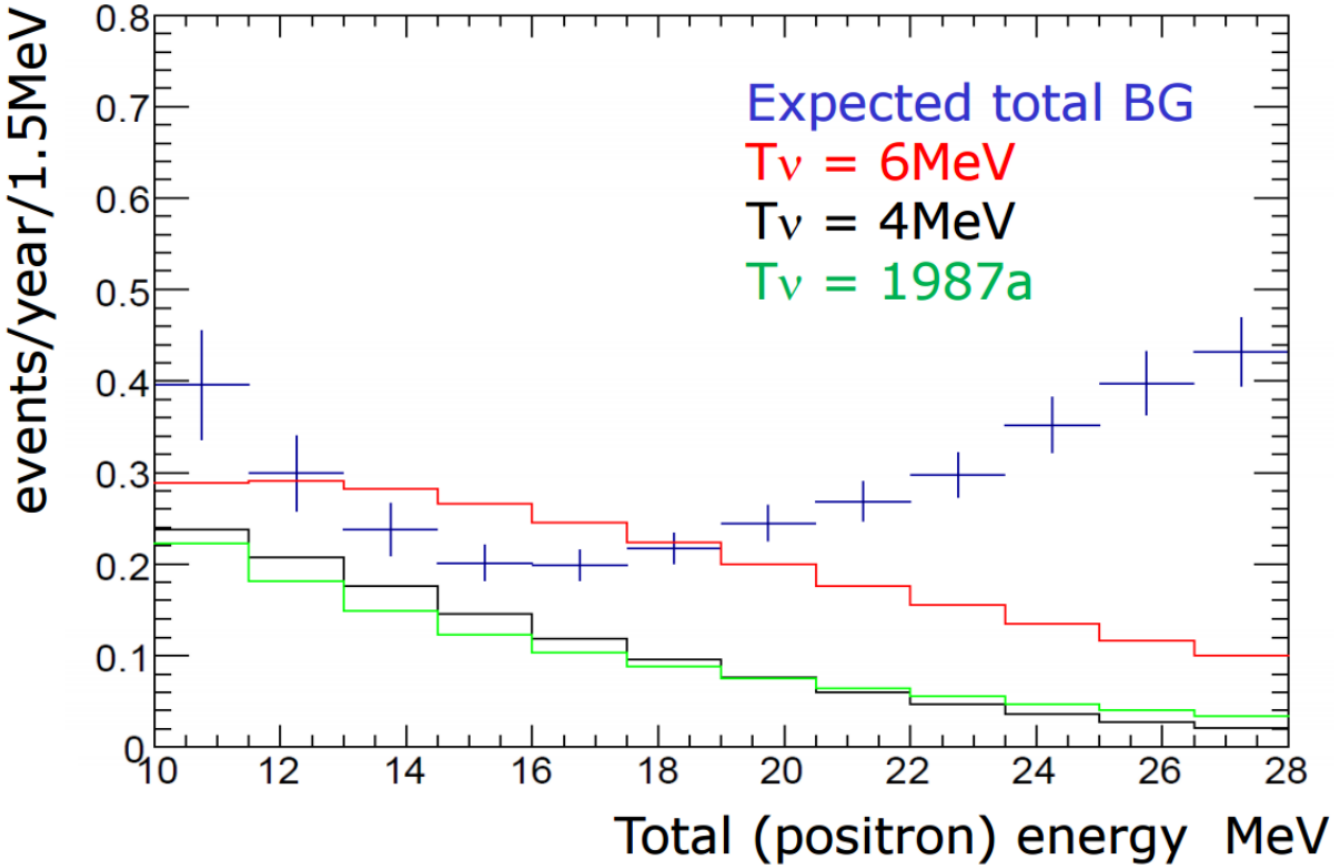
Super-Kamiokande Gd project

- Super-Kamiokande-Gd project (SK-Gd): load Gd in SK in order to detect neutrons from $\overline{\nu}$ interactions.
  - Gd: largest neutron capture cross-section among stable elements, and clear signal (γ cascade).
  - $\sim$ 80% of neutron tagging efficiency with 0.1% of Gd ($\sim$ 90% of Gd-n capture)
- Expect Supernova Relic Neutrino detection!





Supernova Relic Neutrino in SK-Gd



Dependence on the typical SN emission spectrum

HDB*	10-16 MeV	16-28 MeV	Total	significance
T_{eff} 8 MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6 MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4 MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987A	5.1	6.8	11.9	2.1 σ
BG	10	24	34	–

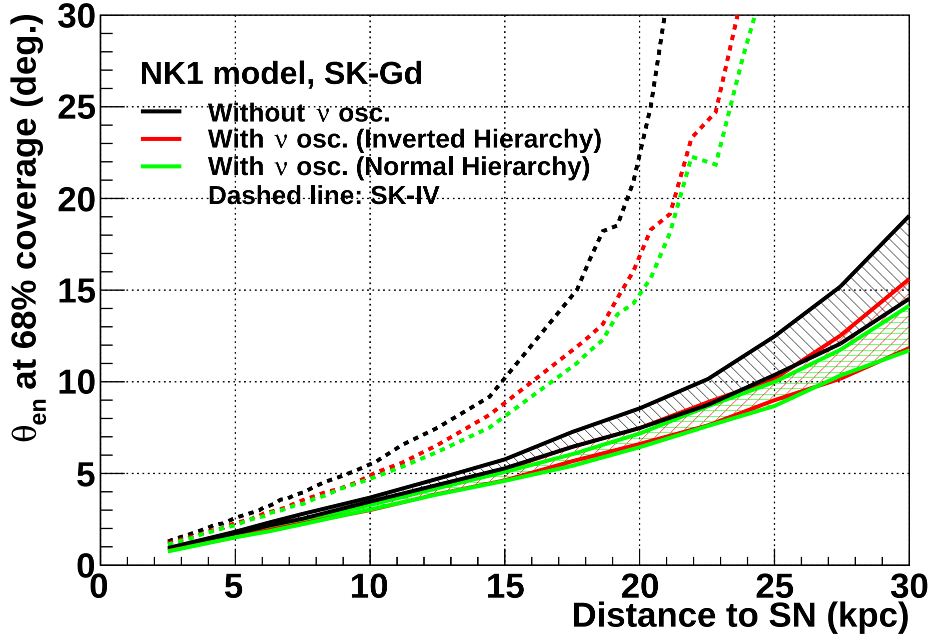
In events/10years

Significance is determined with 2 energy bins

* Horiuchi, Beacom and Dwek, Phys Rev D 79 083013 (2009)

Other physics improvement of SK-Gd

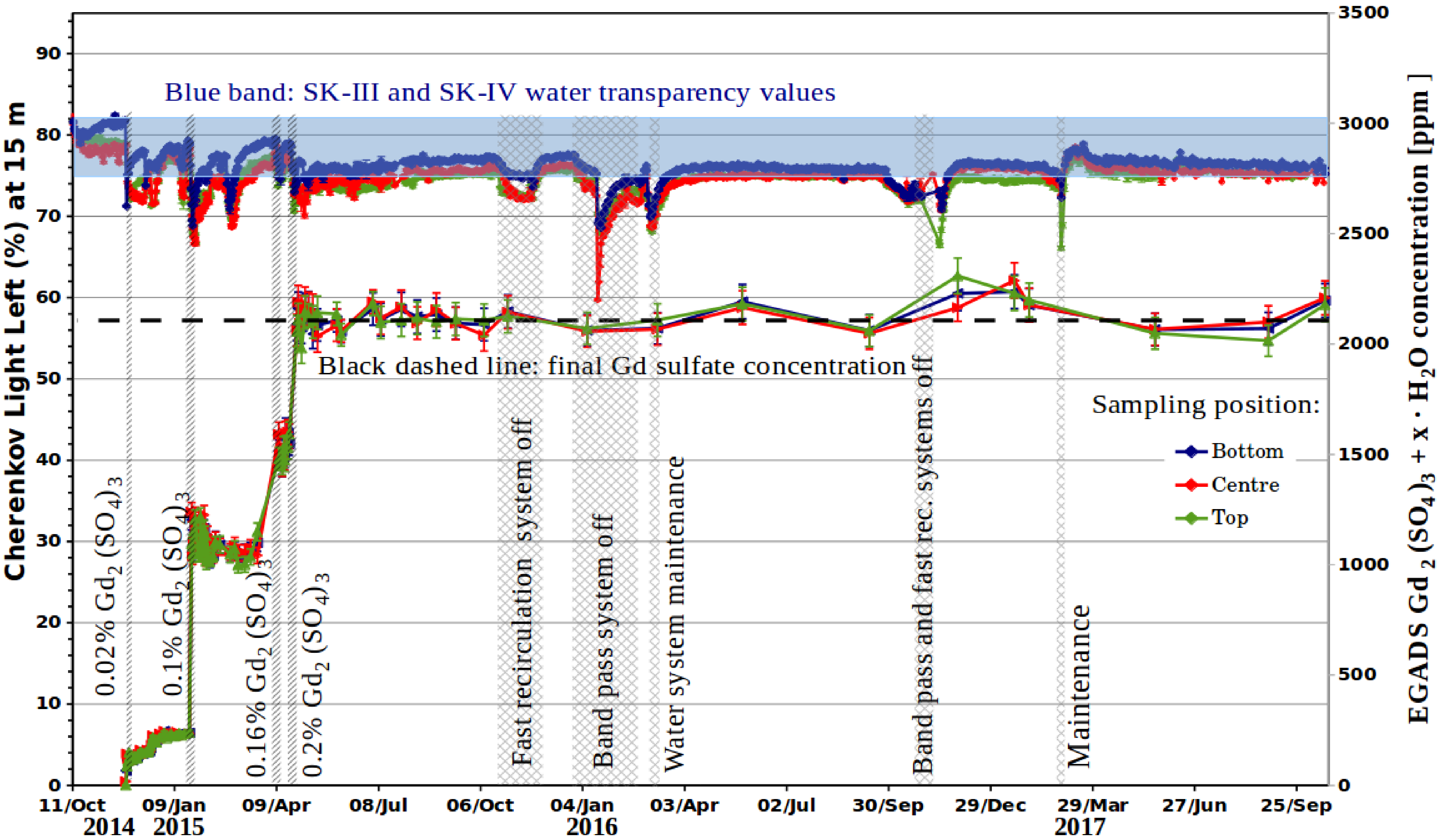
- Gd loading will have other impact on the physics capability of SK:
  - Improvement of the pointing accuracy for galactic supernova:
    By a factor $\sim$ **2** at at 10 kpc
  - Detection of pre-Supernova Si-burning neutrinos
  - Reduction of the proton decay background
  - Neutrino/anti-neutrino discrimination
  - Detection of reactor neutrinos



Status of the Super-Kamiokande Gd project

- Test the impact of Gd on water transparency and on SK detector materials
- Reduce the radioactivity background coming from the Gd powder, which would affect the SRNs and Solar ν analysis
- Prepare dedicated water system for Gd water purification
- Fix the leak of the detector in order to avoid Gd leakage to the environment

EGADS water transparency



Status of the Super-Kamiokande Gd project

- Test the impact of Gd on water transparency and on SK detector materials $\rightarrow$ Done with EGADS prototype
- Reduce the radioactivity background coming from the Gd powder, which would affect the SRNs and Solar ν analysis
- Prepare dedicated water system for Gd water purification
- Fix the leak of the detector in order to avoid Gd leakage to the environment

Gd powder radioactivity reduction

- In order to reduce the background in the SRNs and Solar ν analysis, the radioactivity background from Gd powder needs to be minimized
- New radio-purity measurement method developed in order to obtains more precise values

Chain	Isotope	Goal (mBq/kg)	Company A Ge	Company A ICPMS	Company B Ge	Company B ICPMS	Company C Ge	Company C ICPMS
238U	238U	$<$ **5**	..	$\sim$ **0.04**	$<$ 10	$<$ **0.04**	$<$ 11	$<$ **0.04**
	226Ra	$<$ **0.5**	..	–	$<$ **0.2**	–	$<$ **0.2**	–
232Th	232Th	$<$ **0.05**	–	$\sim$ 0.09	–	$\sim$ 0.06	–	$\sim$ **0.02**
	228Ra	$<$ **0.05**	..	–	$<$ 0.2	–	$<$ 0.3	–
	228Th	$<$ **0.05**	..	–	$<$ 0.3	–	$<$ 0.3	–
235U	235U	$<$ **3**	..	–	$<$ **0.3**	–	$<$ **0.4**	–
	227Ac/Th	$<$ **3**	..	–	$<$ **1.2**	–	$<$ **1.7**	–

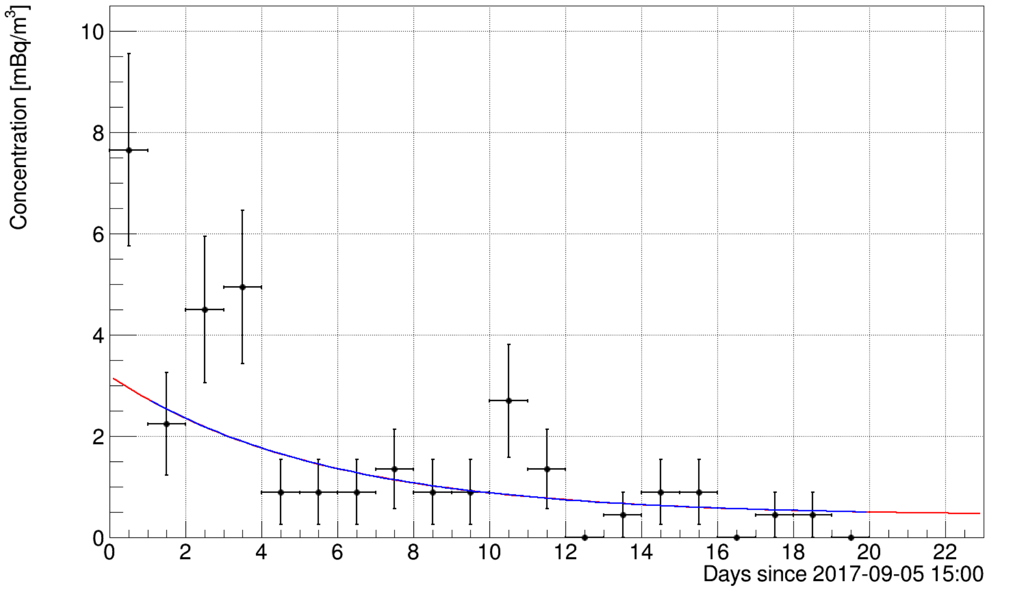
- Thanks to the work with the different companies, we are close to our goal.
- EGADS prototype has been filled with Company C best sample to test it.

Status of the Super-Kamiokande Gd project

- Test the impact of Gd on water transparency and on SK detector materials $\rightarrow$ Done with EGADS prototype
- Reduce the radioactivity background coming from the Gd powder, which would affect the SRNs and Solar ν analysis $\rightarrow$ finalizing
- Prepare dedicated water system for Gd water purification
- Fix the leak of the detector in order to avoid Gd leakage to the environment

Gd Water system

- Dedicated water purification system for Gd-water
- The radon emissions from the different part of the system will be checked:
  - Some parts were tested with Gd water $\rightarrow$ ex: membrane de-gasifier: Rn emission compatible with measurement system BG expectations (0.5 ± 0.3 mBq/m^3)
- After the tank opening, the system will be used in order to improve the water quality early right after the filling (first real test of the system).



Status of the Super-Kamiokande Gd project

- Test the impact of Gd on water transparency and on SK detector materials → Done with EGADS prototype
- Reduce the radioactivity background coming from the Gd powder, which would affect the SRNs and Solar ν analysis → finalizing
- Prepare dedicated water system for Gd water purification → on-going
- Fix the leak of the detector in order to avoid Gd leakage to the environment

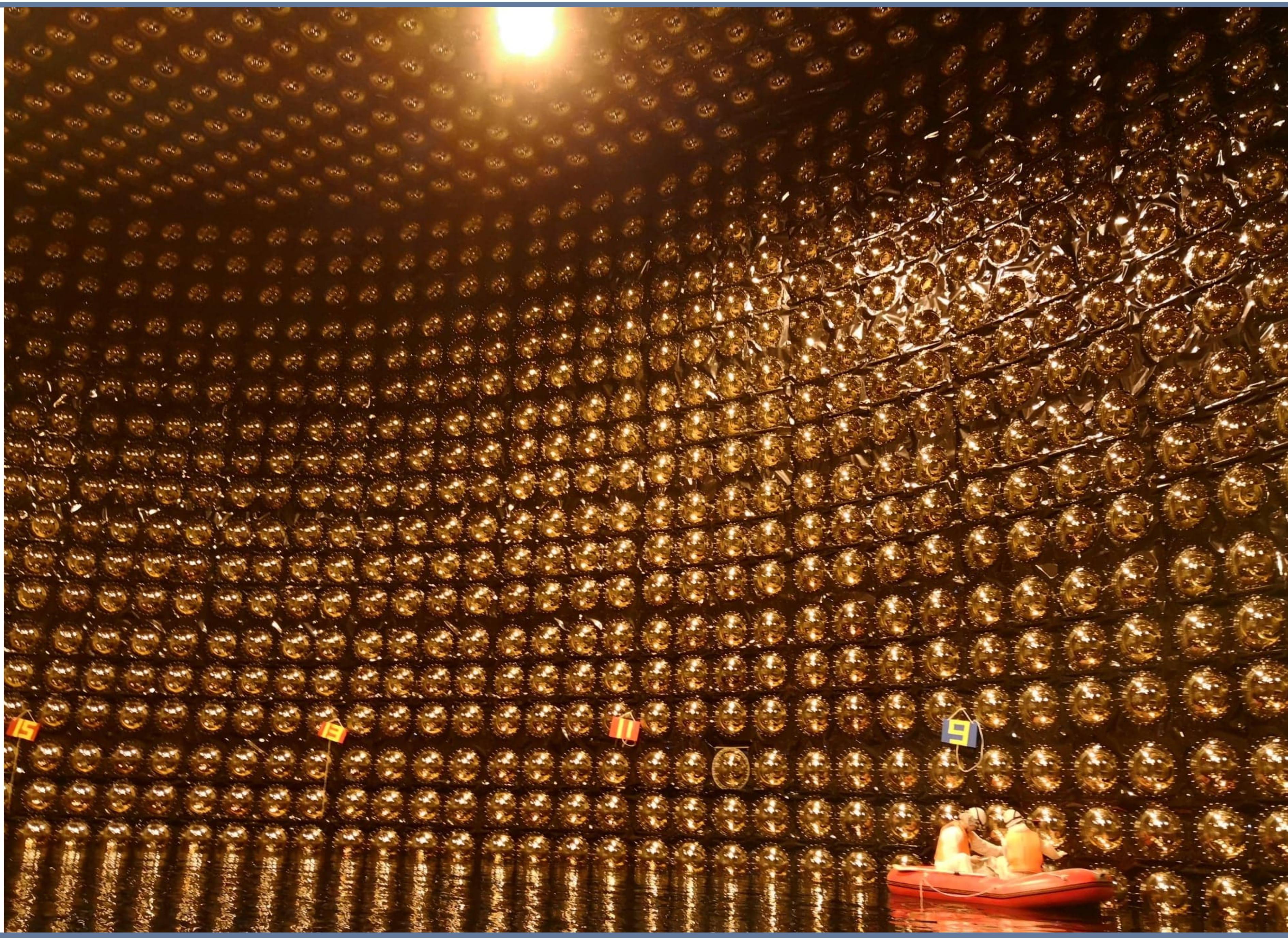
Tank opening

- Since June 1st the tank is drained every 3 days and refurbishing / leak fix is on-going
- Tank operations are expected to be finished in September/October, afterward the tank will be filled again with pure water

Summary

- Solar ν: the up-turn is still not observed
  - Investigation on-going in order to understand the reason why (threshold reduction, NSI, etc.)
- Atmospheric ν:
  - Non-0 ν_τ appearance at 4.6σ
  - Preference for the Normal Hierarchy
- Super-Kamiokande is planning to load 0.1% of Gd into the water tank in order to detect SRN
  - Possible discovery of SRN after 10 years of Gd data taking
- The project is close to the final step, Gd loading can be considered from mid-2019 (to be discussed with T2K collaboration)
- Let's expect that everything will go well and enjoy Gd physics in a few years!

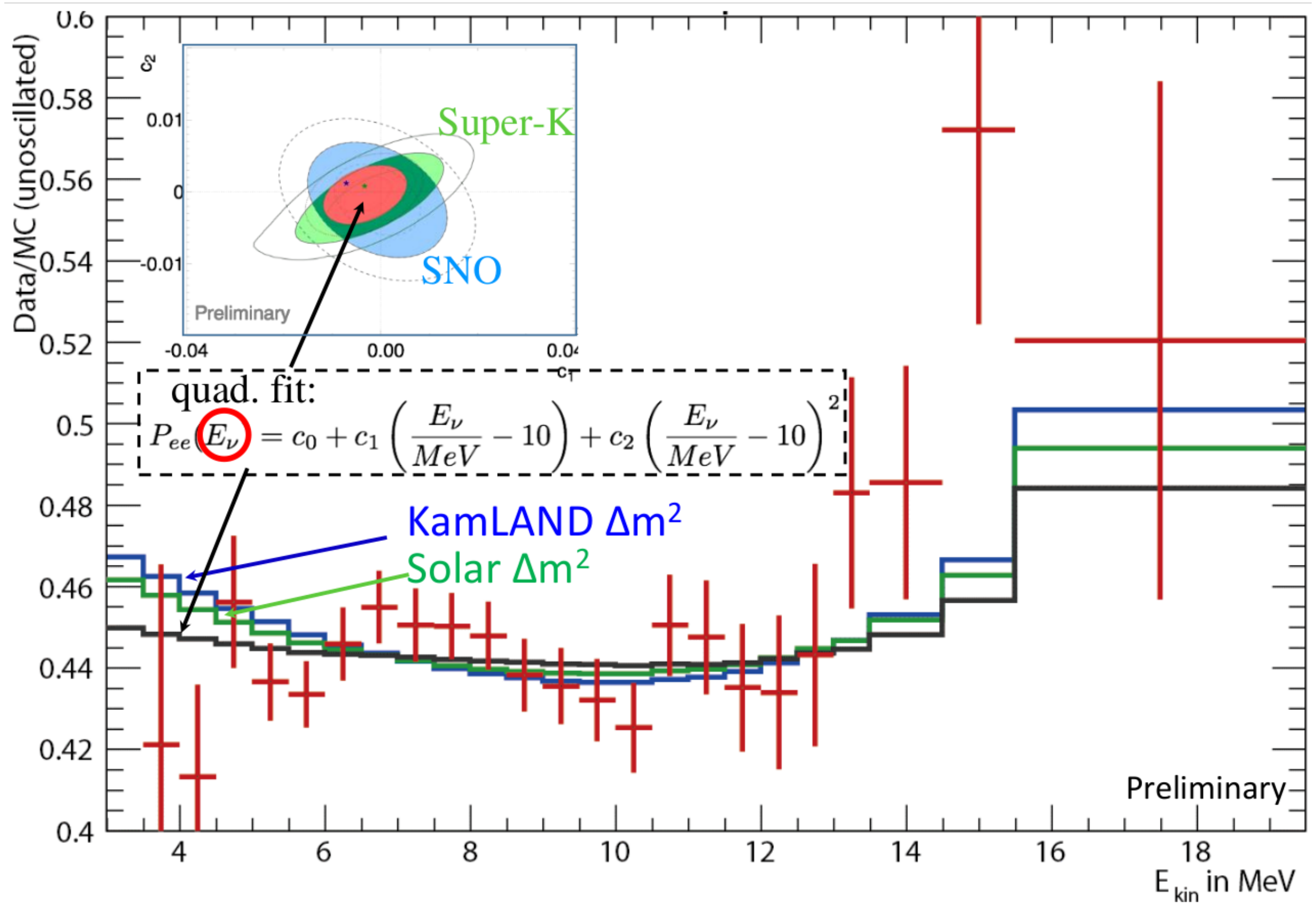
Thank you!



Backup

Recent results in solar ν analysis (II)

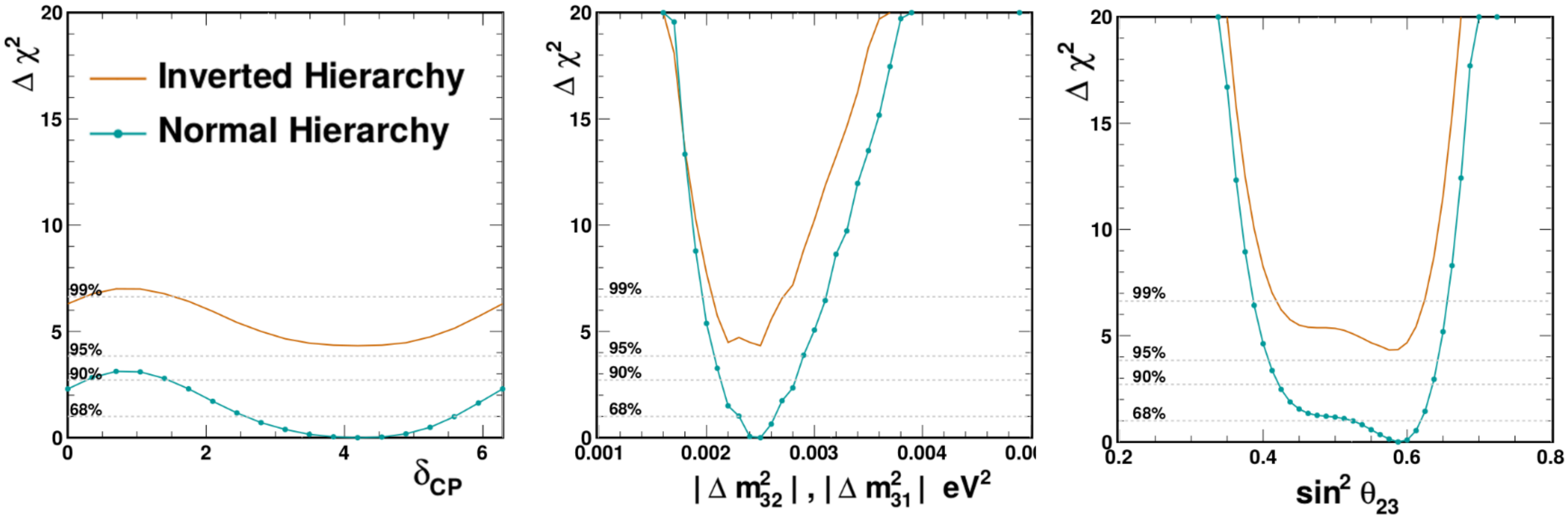
- Spectrum quadratic fit of all SK data:



- SK favors solar exp. over KamLAND

Recent results in atmospheric ν analysis (SK-only)

- Atmospheric ν dataset: 5326 days (SK-I,II,III,IV)
- 27505 muon-like and 20949 electron-like events
- Oscillation analysis results:

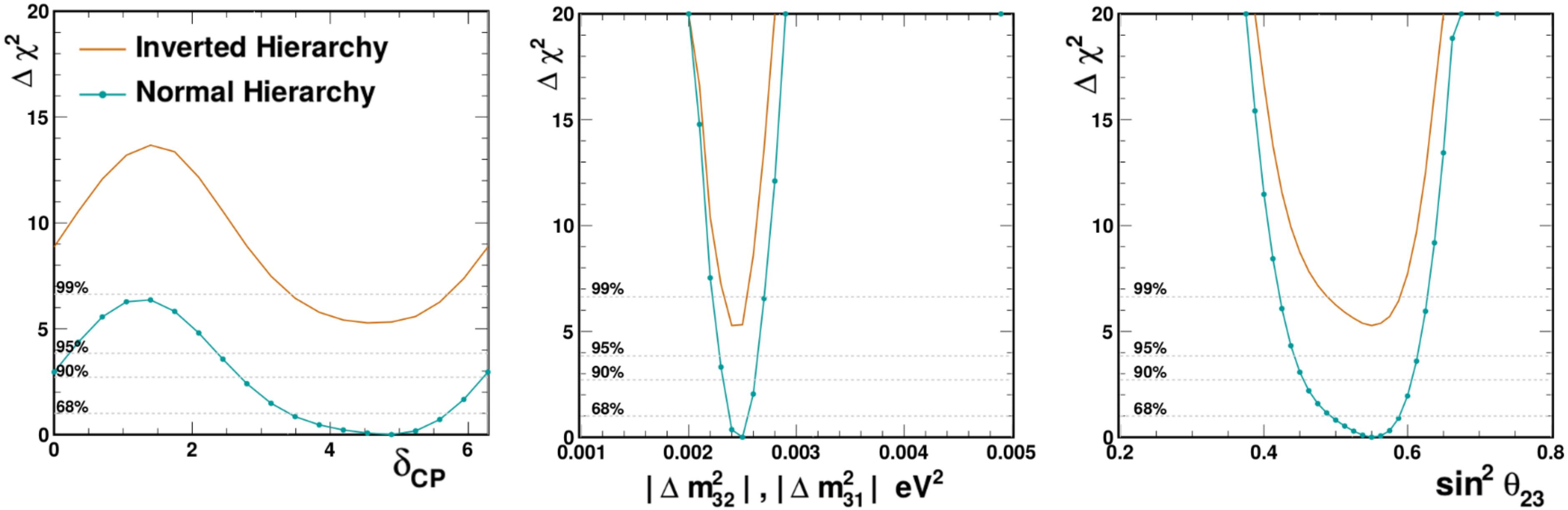


	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal Hierarchy	571.33	2.5×10^{-3}	0.5875	4.18
Inverted Hierarchy	575.66	2.5×10^{-3}	0.575	4.18

- $\Delta\chi^2 = \chi^2(\mathrm{NH}) - \chi^2(\mathrm{IH}) = -4.33 \rightarrow$ Preference for the NH hypothesis

Recent results in atmospheric ν analysis (SK-T2K)

- Add T2K model to constrain SK fit (not joint analysis)

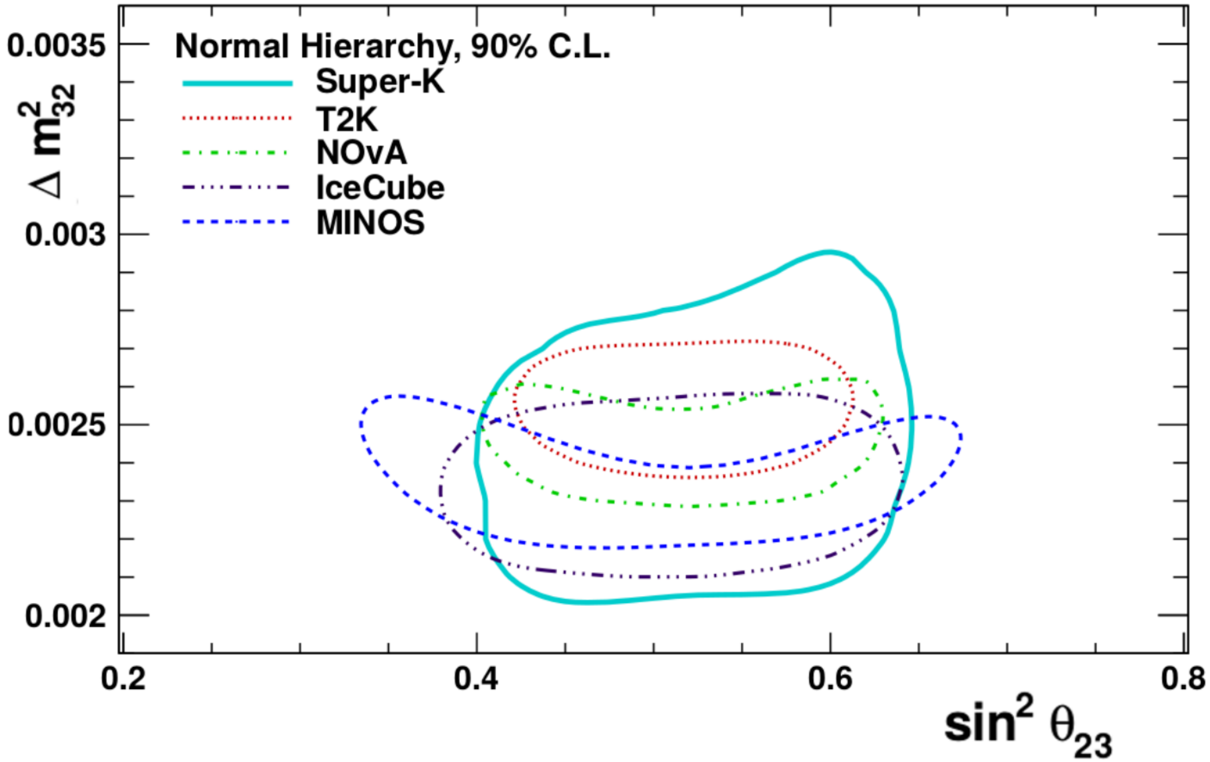


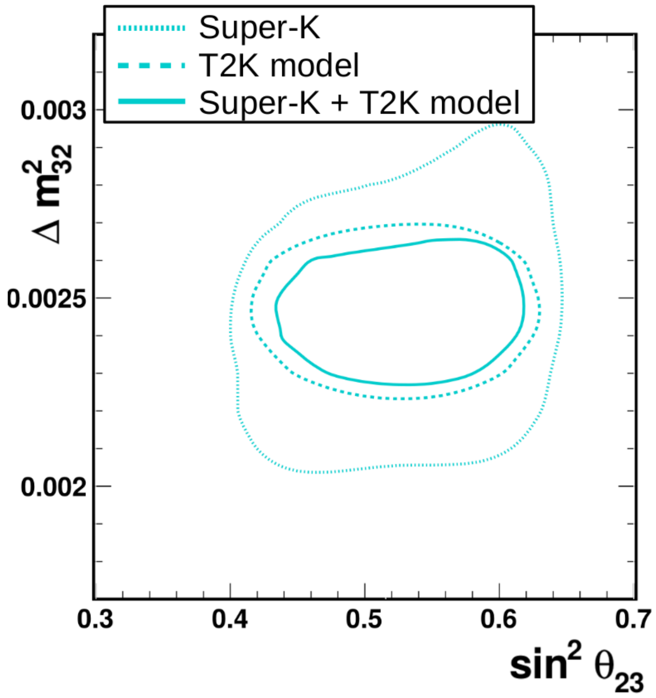
	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal Hierarchy	639.43	2.50×10^{-3}	0.550	4.88
Inverted Hierarchy	644.70	2.40×10^{-3}	0.550	4.54

- $\Delta\chi^2 = \chi^2(\text{NH}) - \chi^2(\text{IH}) = -5.27 \rightarrow$ Preference for the NH hypothesis

Atmospheric parameters

- Here is the current picture of the "Atmospheric" parameters (90% CL contours for the normal hierarchy case)
- SK only: compatible with all experimental results
- SK-T2K: dominated by T2K data

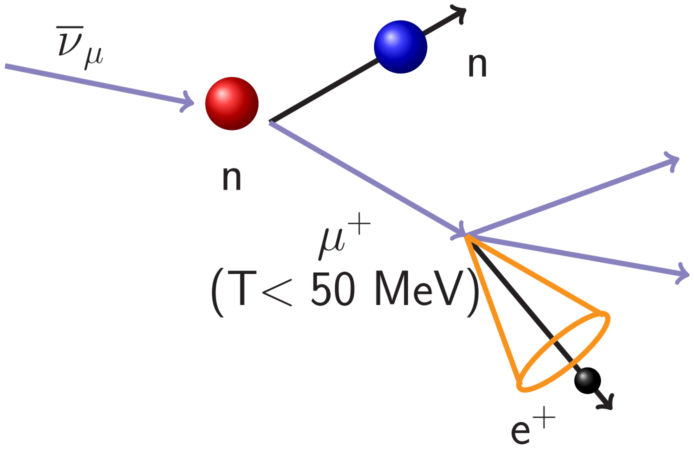




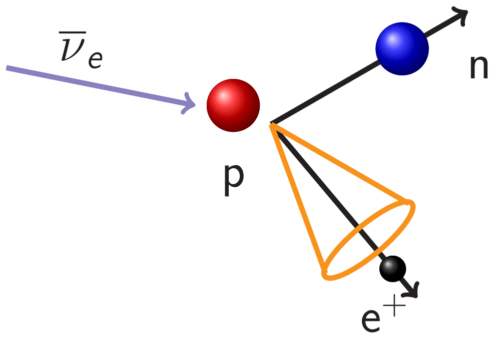
SRN Backgrounds with neutron captures

▶

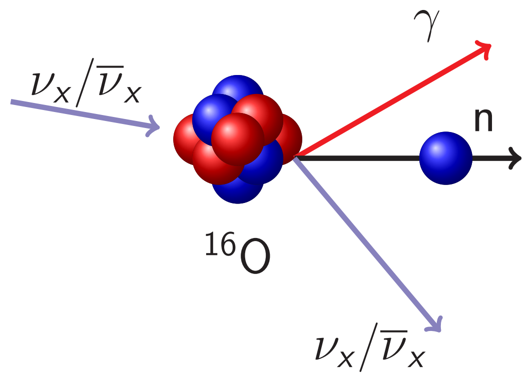
Atmospheric ν_μ CC



Atmospheric ν_e CC



Atmospheric ν NC



Gd water radioactivity removal

- During detector operation, radio-isotope can dissolved in the tank water, leading to a background for the experiment
- Need to use resin to remove radio-isotope (mostly U and Ra)
- Anion removal resin already tested and U removal demonstrated
- Special cation removal resin is needed to keep Gd in the water and remove only Ra $\rightarrow$ test on-going

- Resin test system working
- Gd powder best sample tested without resin to determine upper limit: 0.4 ± 0.6 mBq/m^3 (BG subtracted)
- Resin will be tested with dirty Gd powder after BG measurements finalized