Gd-doping and the impact on Super-K and T2K

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for the Super Kamiokande Collaboration

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- The SuperK-Gd Project
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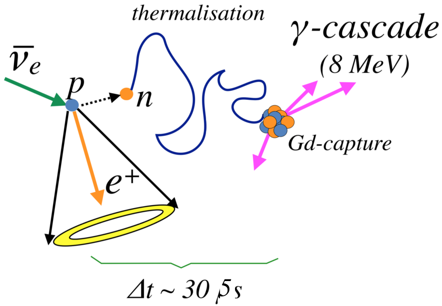
Conclusions

Gadolinium in Water-Cerenkov Detectors

Gadolinium Neutron Tagging

★ Gadolinium has the largest neutron capture cross-section of all stable nuclei in nature,around 48800 barn on average given the natural abundances of its isotopes

★ The **$Gd_2(SO_4)_3$** salt was finally decided to be the best option in terms of transparency and corrosion



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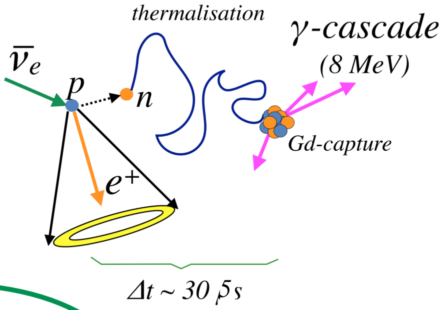
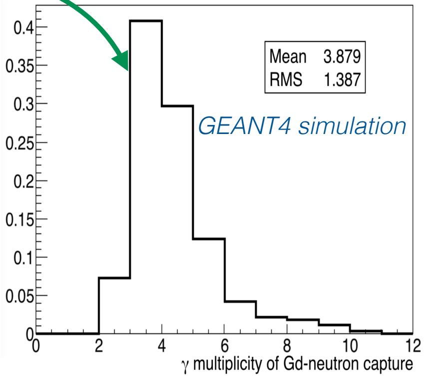
★ After the neutrino interaction neutrons may be emitted and thermalised (~15μs mean time). Once the neutron is thermal, it is captured by a Gd nucleus (~20μs mean lifetime), resulting in an excited Gd nucleus, then this nucleus de-excites emitting a γ-ray cascade of **~8 MeV** of **3 to 5 photons**

$$n + {}^{X}Gd \rightarrow {}^{X+1}Gd^{*} \rightarrow {}^{X+1}Gd + \gamma s\ (8\ MeV)$$





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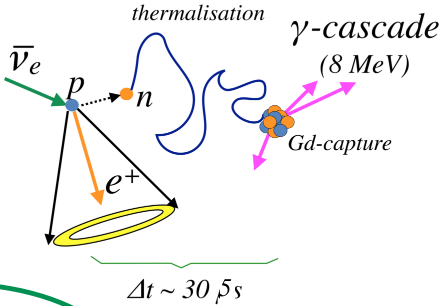
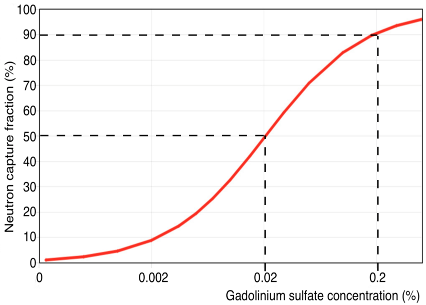
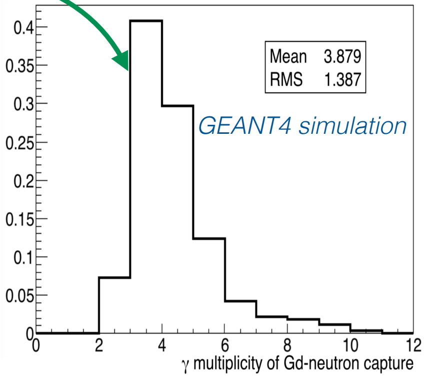


$$n + {}^{X}Gd \rightarrow {}^{X+1}Gd^{*} \rightarrow {}^{X+1}Gd + \gamma s\ (8\ MeV)$$

- ★ For **0.2%** $Gd_2(SO_4)_3$ concentration by mass dissolved in water, **90%** of neutrons produced will be captured by Gd and **50%** with **0.02%** concentration

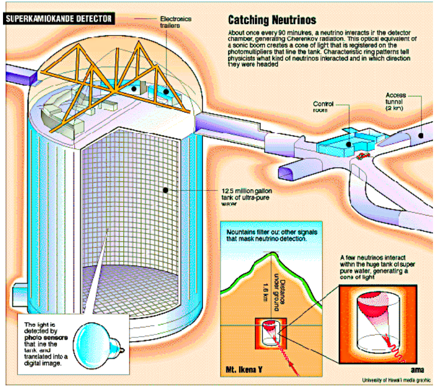




The SuperK-Gd Project

★ **Super-Kamiokande** (**SK**) is a 50,000 ton water Cherenkov detector located in the Kamioka mine under 1000 m of rock

★ SK celebrates this year its 20th anniversary since the start of its measurements



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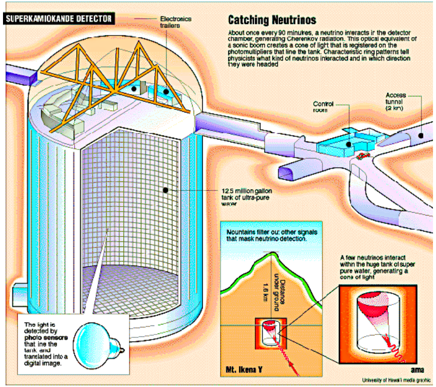
- ★ By adding this **0.2% by mass** of the Gd salt, 90% of the produced neutrons in the detector will be captured by Gd after they thermalise
- ★ **SuperK-Gd** will be able to detect **~80%** of all the neutrons produced in the detector, providing a much more complete information of the final state of the interaction



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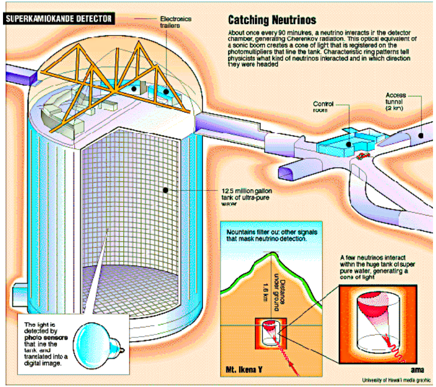

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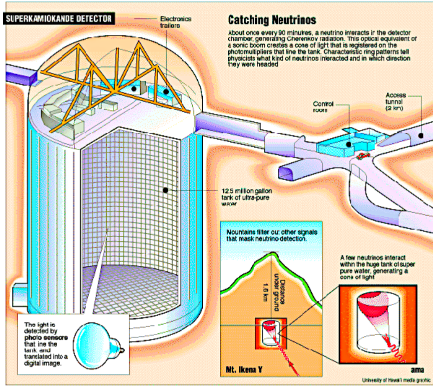


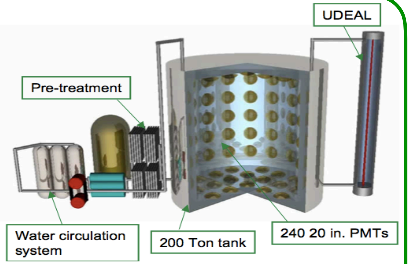
On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.

Gadolinium Addition to SuperK (I): EGADS

★ **EGADS** (Evaluating Gadolinium's Action on Detector Systems) was a R&D project for testing the feasibility of adding Gd in water Cherenkov detectors, specifically focused in the realisation of SuperK-Gd

★ **EGADS** detector is a scaled down Super Kamiokande, containing 200 ton of ultrapure water and instrumented with 240 PMTs (40% photocoverage), 227 of them are similar to those in the SK and the other 13 are developing photosensors for HyperK



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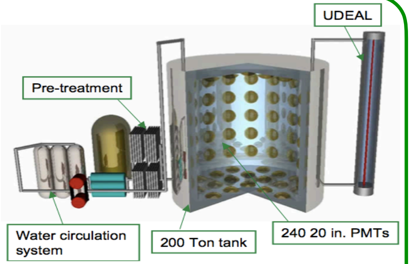
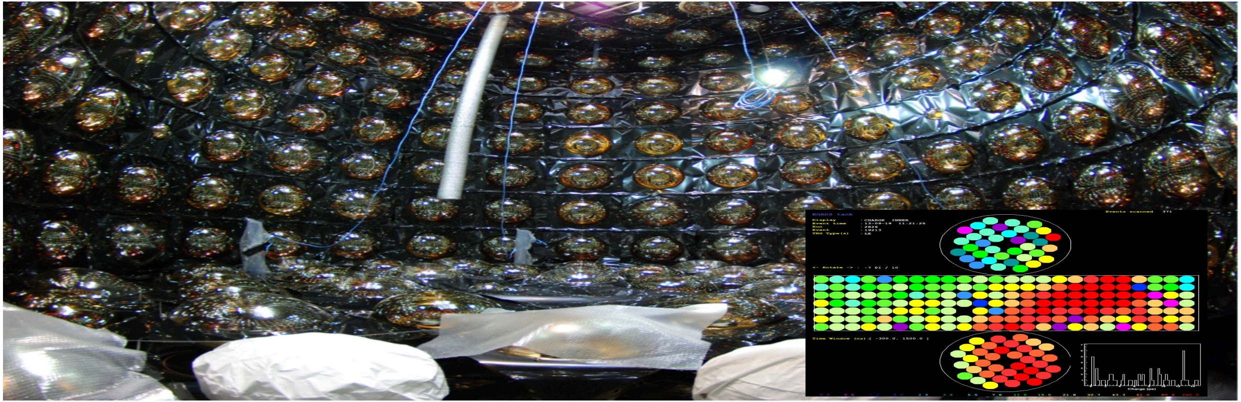
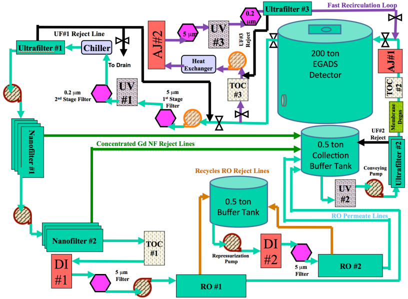




Gadolinium Addition to SuperK (I): EGADS

★ In this context, **EGADS** has proven that 4 key characteristics can be achieved for the realisation of SuperK-Gd

➡ New water systems for dissolving Gd into water (**pre-treatment**) and purifying the Gd-doped water (**selective filtration system**). These are specifically design to match the ultrapurity requirements like the SK water and to keep all the Gd and sulphate ions dissolved



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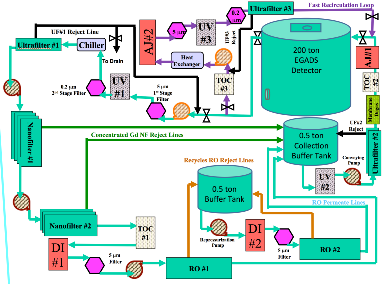

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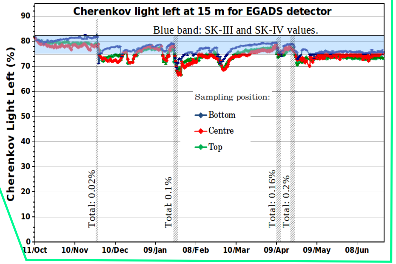
➡ The sophisticated Gd water system makes the **water transparency** of Gd-doped water very similar to that of SK



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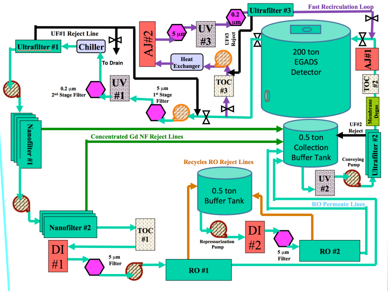

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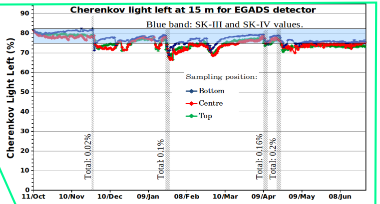
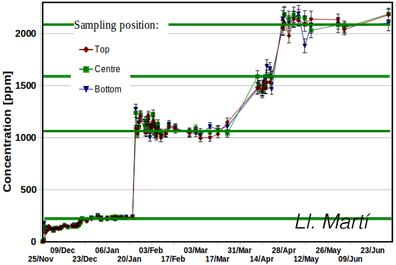


➡ The concentration of Gd is measured by **AAS**, showing its uniformity and agreement with the expected



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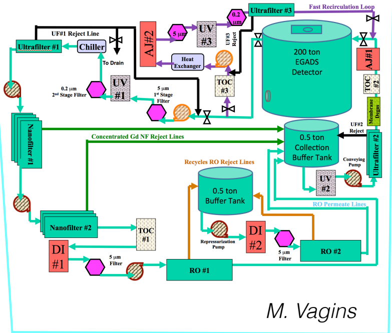

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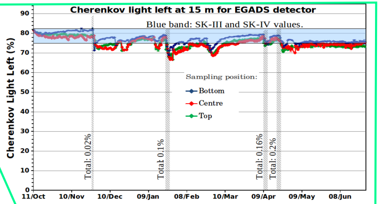

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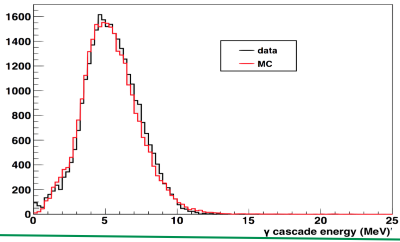
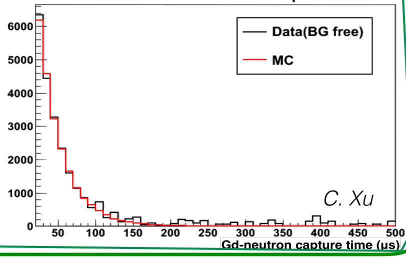
➡ Data and Monte Carlo simulations agreement of the Gd-neutron capture

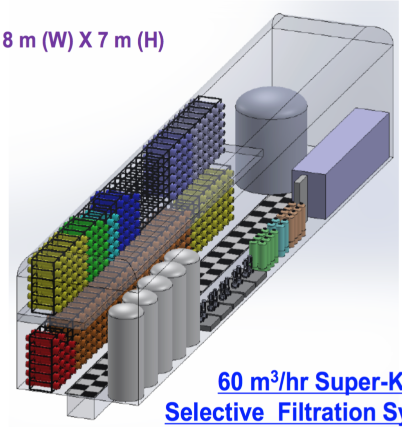




Gadolinium Addition to SuperK (II): SuperK-Gd water system

★ The works for scaling the **EGADS** water system to SK dimensions have alredy began designing the SuperK-Gd selective filtration system and the excavation of the new hall which will host it

31 m (L) X 8 m (W) X 7 m (H)



60 m^3/hr Super-K Selective Filtration System

Gadolinium Neutron Tagging Reconstruction

★ Algorithm for detecting the Gd-neutron capture: a two-step process

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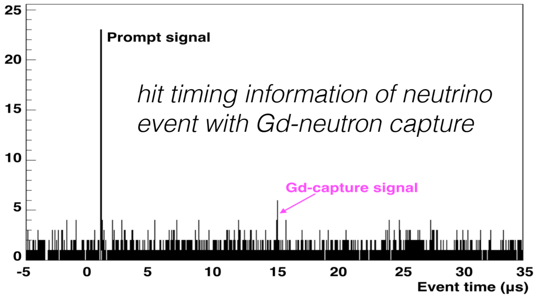
➡ Candidates are selected by scanning the number of hits clustered in the hit timing distribution after the prompt signal is triggered



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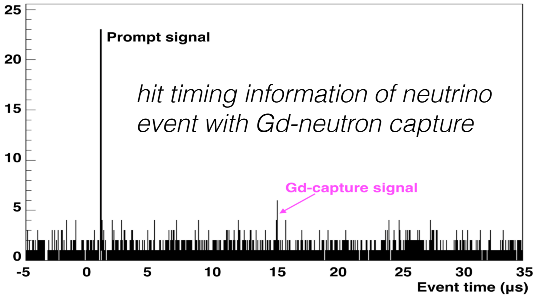
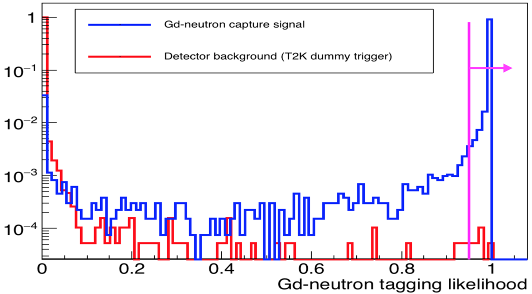


➡ In order to discern Gd-neutron captures from the background candidates, a likelihood method is used



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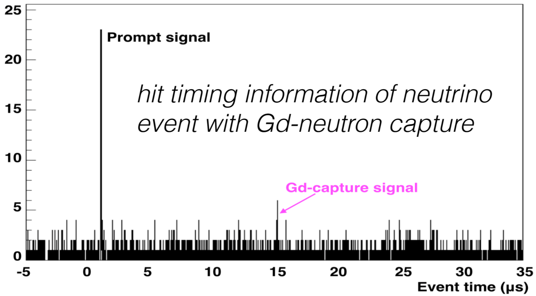

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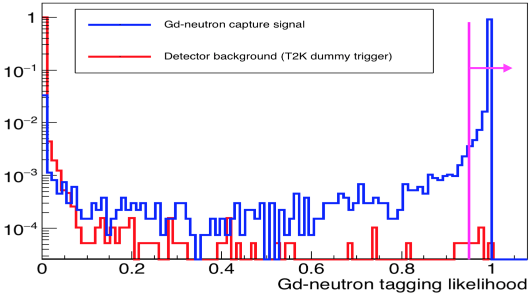


	Gd-neutron capture	Background
Candidate selection	99.3%	2.72 event^{-1}
Likelihood selection	93.3%	0.009%
Total efficiency	92.7%	$2.4 \cdot 10^{-4}\ \text{event}^{-1}$

★ As **~90%** of neutrons are captured by Gd —> total Gd-neutron tagging efficiency: **~80%**

Gadolinium Impact on Physics

Low Energy Neutrinos in SuperK-Gd (I): Supernovae

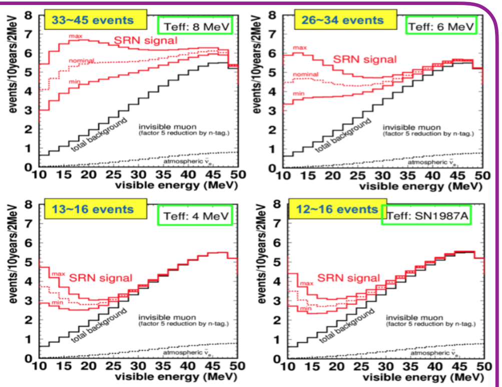
★ **Diffuse Supernova Neutrino Background (DSNB)**

➡ SuperK-Gd will be able to first measure the antineutrinos coming from all the past supernovae explossions through their inverse β interaction in the detector, largely supressing the current spallation background

Signal: ~5 events/year/SK

➡ The main remaining background is due to **^{238}U SF** that might get into the detector as contaminant of the Gd salt

Background: ~0.11 events/year/SK per mBq/kg of $Gd_2(SO_4)_3$



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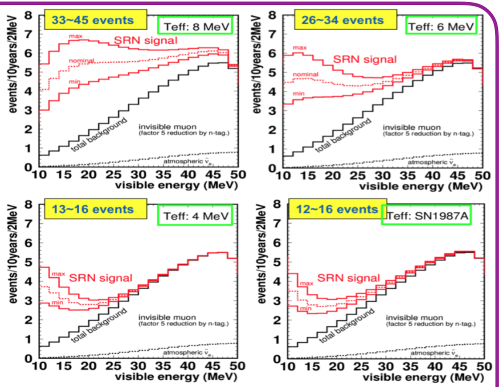


★ **Supernova Early Warning**

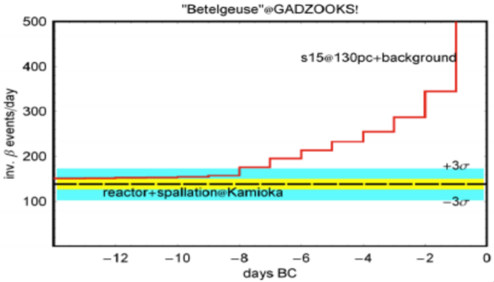
➡ This refers to th <u>Si burning</u> phase previous to the core-collapse where ~1% of the total enegy is released in the form of low energy neutrinos

➡ the number of events above 3 MeV assuming a very close supernova such as Betelgeuse (0.2 kpc away) in the 24h before the explossion is

Signal: 16.4 events/24h/SK

➡ The main remaining background is due to reactor neutrinos, assuming all Japanese reactors

Background: ~30 events/day/SK ⟶ ***Significance: 3.4σ***



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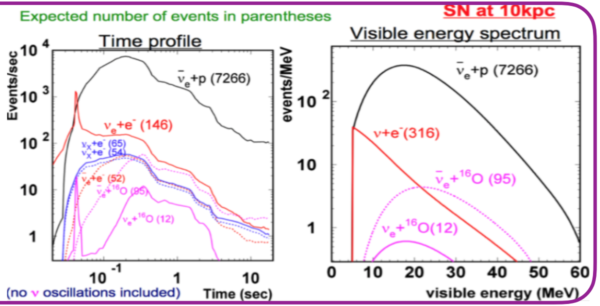
★ **Supernova Burst**

- ➡ Supernova electron antineutrinos will be much better distinguished from neutrinos due to the Gd-neutron tagging
- ➡ This measurement, will provide much information about early stages of the core-collapse process, its spectrum and time profile, yielding to more detailed picture of the whole core-collapse
- ➡ SuperK-Gd will detect ***thousends of events*** with ***negligible background*** where ν and ν fluxes independently will be extracted independently



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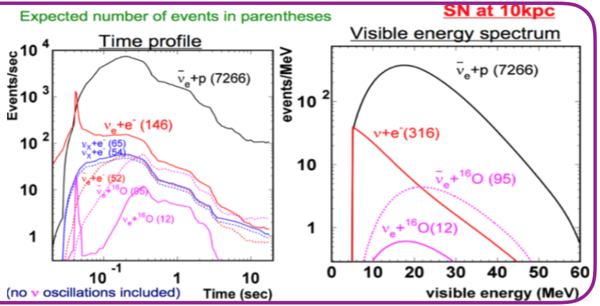
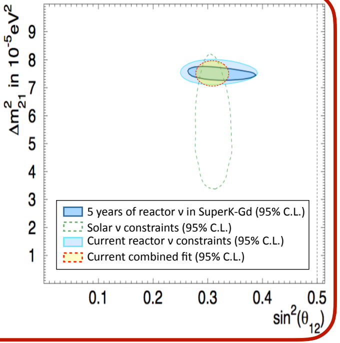


Low Energy Neutrinos in SuperK-Gd (II): Reactor

★ The expected reactor antineutrinos in SuperK-Gd is around ***2800 events/year*** *in SK* , with all Japanese reactors are on with small background due to ^{238}U SF

65.7 events/year/SK per mBq/kg of $Gd_2(SO_4)_3$

★ The sensitivity to the solar oscillation parameters will be significantly enhanced



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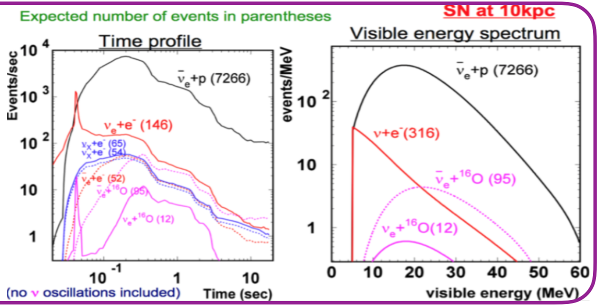

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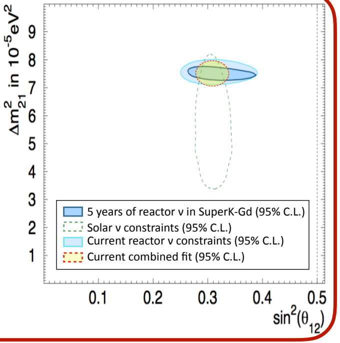

Low Energy Neutrinos in SuperK-Gd (III): Solar

★ With the addition of Gd to SK water solar neutrinos may be affected due to the radioactive β decays from the contamination in the Gd salt

★ Low energy (from 3 MeV) events in SK after solar cuts are

~200 events/day/SK

★ The radiopurity requirements for low energy solar neutrino analysis are

- ➡ ***^{228}Th: <0.03 mBq/kg of $Gd_2(SO_4)_3$***
- ➡ ***^{226}Ra: <0.51 mBq/kg of $Gd_2(SO_4)_3$***

Low Energy Neutrinos in SuperK-Gd (IV): Radioactive contamination

★ The Gd salt will be dissolved uniformly along the whole volume of SK and, therefore, special attention has to paid to its induced radioactive contamination as seen previously

★ Exhaustive radioactive maesuring capaings are being carried out at Canfranc Underground Lab. (Spain), Kamioka Observatory (Japan) and Boulby mine (UK)

Measured radioactivity in mBq/kg for all the $Gd_2(SO_4)_3$ batches

Chain	^{238}U		^{232}Th		^{235}U		Others		
Sub-Chain (Supplying Companies)	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{227}Ac	^{40}K	^{138}La	^{176}Lu
Company A (09/04)	51 ± 21	8 ± 1	11 ± 2	28 ± 3	< 32	214 ± 10	29 ± 5	8 ± 1	80 ± 8
Company A (10/08)	< 33	2.8 ± 0.6	270 ± 16	86 ± 5	< 32	1700 ± 20	12 ± 3	$<$	21 ± 2
Company B (12/08)	292 ± 6	74 ± 2	1099 ± 12	504 ± 6	< 112	2956 ± 30	101 ± 10	683 ± 15	566 ± 6
Company C (13/02)	74 ± 28	13 ± 1	205 ± 6	127 ± 3	< 25	1423 ± 21	60 ± 7	3 ± 1	12 ± 1
Company B (13/03)	242 ± 6	13 ± 2	21 ± 3	374 ± 6	< 25	175 ± 42	18 ± 8	42 ± 3	8 ± 2
Company A (13/08)	71 ± 20	8 ± 1	6 ± 1	159 ± 3	< 32	295 ± 10	3 ± 2	5 ± 1	30 ± 1
Company D (13/07a)	47 ± 26	5 ± 1	14 ± 2	13 ± 1	< 12	< 6	2 ± 2	< 1	1.6 ± 0.3
Company D (13/07b)	73 ± 27	6 ± 1	3 ± 1	411 ± 5	< 30	< 18	8 ± 4	< 2	< 2
Company A (14/12)	< 76	< 1.4	2 ± 1	29 ± 2	< 1.8	190 ± 6	< 5	23 ± 1	2.5 ± 0.6
Company E	< 34	< 0.8	< 1.1	2.0 ± 0.5	< 0.6	11 ± 4	< 3	< 0.6	2.9 ± 0.2
Company F (15/12)	< 139	< 2.1	2.8 ± 1.9	1.8 ± 0.9	< 2.4	< 10	< 14	< 1.9	< 1.6
Company F (16/04)	< 20	< 0.64	< 0.67	0.5 ± 0.2	< 0.7	< 2.3	< 1.6	< 0.3	< 0.4

L. Labarga, J. Pérez

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★ Exhaustive radioactive maesuring capaings are being carried out at Canfranc Underground Lab. (Spain), Kamioka Observatory (Japan) and Boulby mine (UK)

★ Current gadolinium sulphates batches have lower radioactive contamination due to cooperation with suplying companies

★ At EGADS, big efforts are being done to remove the remaining most relevant contaminants for these measurements

➡ AmberJet removes **U** more than a factor 100

➡ Resin AJ1020Gd is being developed for removing **Ra**

➡ Several methods, such pH shock, are being studied for **Th removal**

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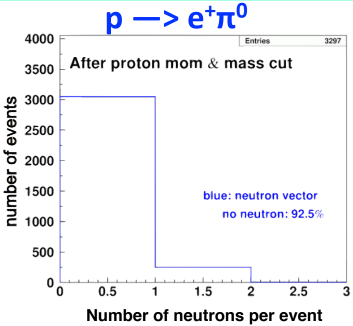
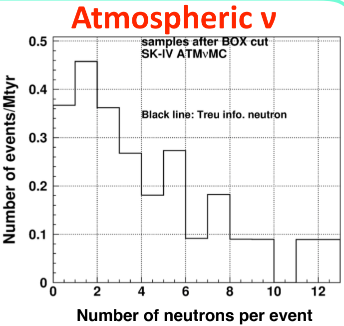
High Energy Physics in SuperK-Gd (I): Proton decay

★ Neutron tagging provides an improvement on the sensitivity of proton decay searches

★ As illustration, in the p —> $e^+\pi^0$ decay mode the neutron multiplicity of proton decay is significantly different from the neutron multiplicity distribution of atmopsheric neutrinos after the proton decay cuts are applied





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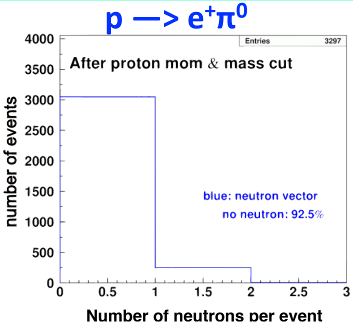
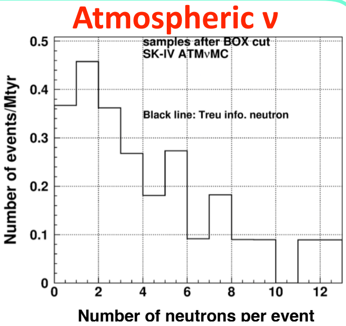
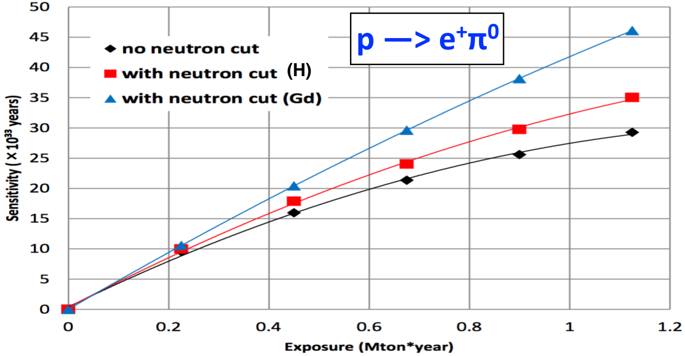


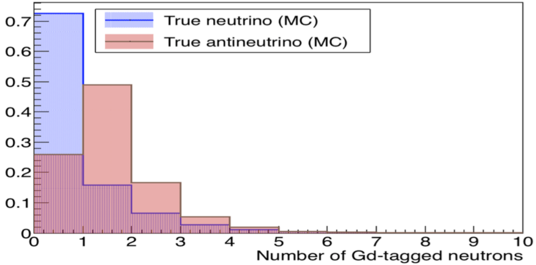


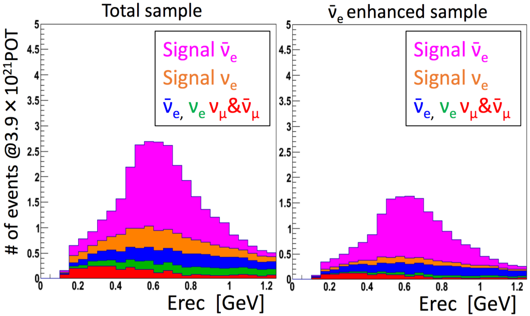
- ★ For the sensitivity study, **80%** neutron tagging efficiency is assumed as discussed previously
  - ➡ For this case, <u>92.5%</u> of proton decays produce no neutrons in their final state
  - ➡ The remaining background for 10 years of observation in SK is 0.58, whereas for SuperK-Gd is only 0.098 events



High Energy Physics in SuperK-Gd (II): T2K Long baseline neutrinos

- ★ Long baseline neutrinos can also benefit from the **ν-ν̄ separation** induced by the **80%** Gd-neutron tagging
  - ➡ For the separation a likelihood distribution is built using the number of neutrons and the scattering angle
  - ➡ This way, neutrino and antineutrino purity of samples is enhanced





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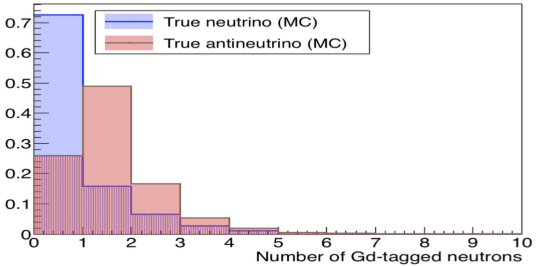
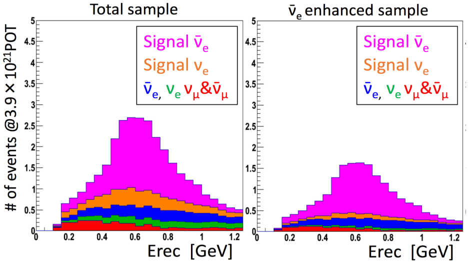
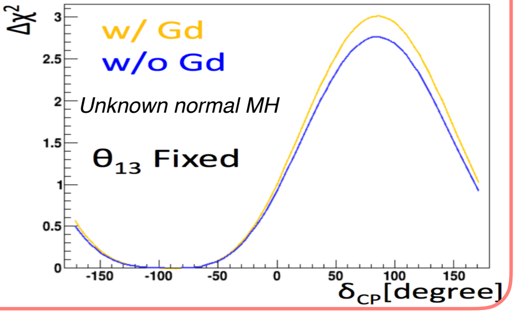




- ➡ With the **T2K** analysis tools the official sensitivity to the CP phase is compared with that using the neutrino-antineutrino separation from Gd-neutron tagging
- ➡ The sensitivity curves are done assuming the PDG values, $\sin^2\theta_{23}=0.5$ and $3.9 \cdot 10^{21}$POT

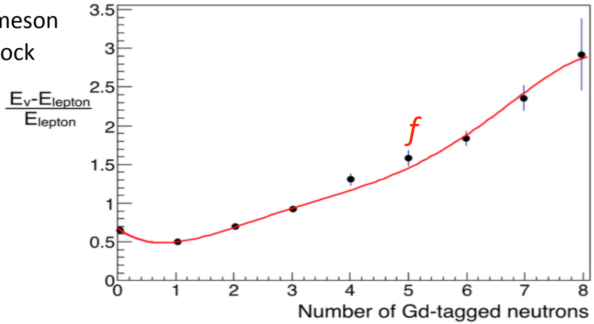


High Energy Physics in SuperK-Gd (II): T2K Long baseline neutrinos

★ Neutron multiplicity of a given neutrino event can also be used to improve the **reconstruction of its energy**

➡ Neutrons contain information of the energy lost due to neutral meson production interacting inside the nuclear media being able to knock out a neutron from the nucleus

$$E_{rec}^{Gd} = E_{vis}(1 + f(\text{Gd-neutrons}))$$



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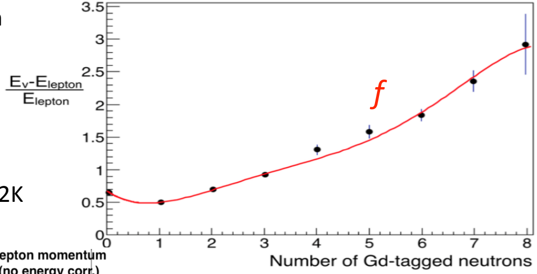
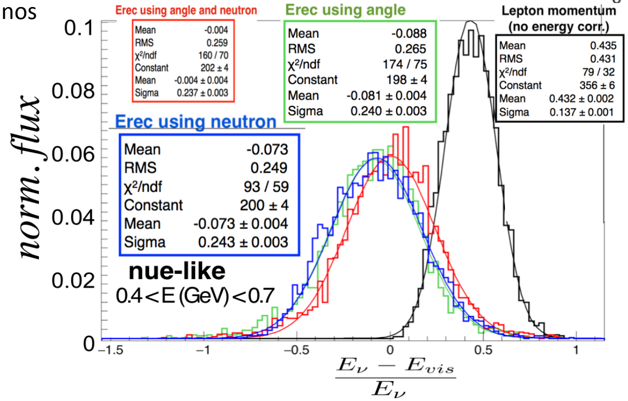


➡ Neutron corrected energy shows a similar performance to the usual T2K angle corrected energy, providing a good motivation for the case of atmospheric neutrinos



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★ Neutrons produced in neutrino interactions provide three advantages in the atmospheric neutrino oscillation analysis

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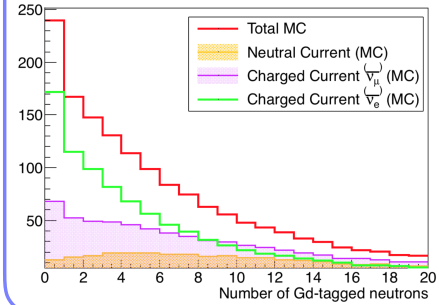
➡ **NC-DIS-CC separation**

Thay are used to distinguish between Neutral Current (NC), Charged Current Deep Inelastic Scattering (CCDIS) and the rest of Charged Current (CC) neutrino interactions. This applies to the MultiRing MultiGeV e-like sample, very sensitive energy region to the MH, and largely contaminated with NC and ν_μ (from DIS) events



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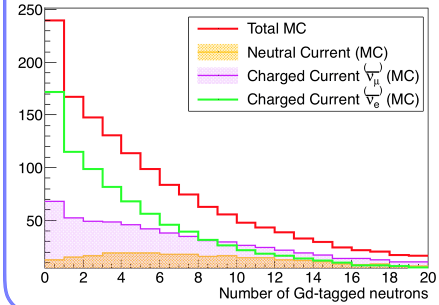
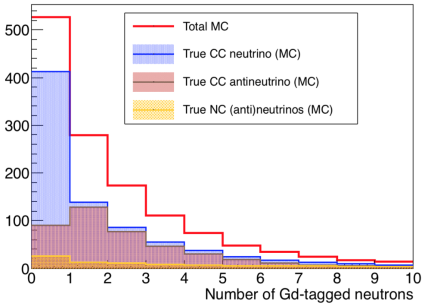


➡ **ν–ν̄ separation**

This is done for all the atmospheric neutrino samples.

Here, the fact that antineutrinos tend to produce more neutrons in the final state than neutrinos in charged current interactions



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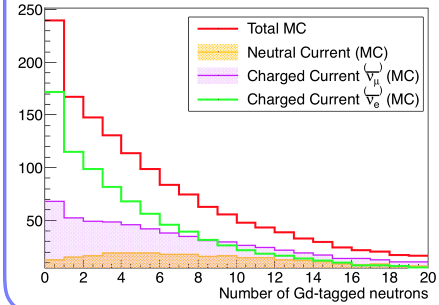

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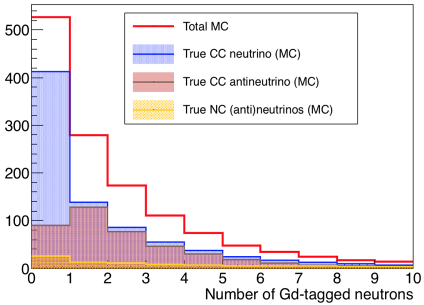
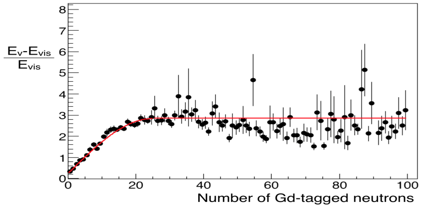
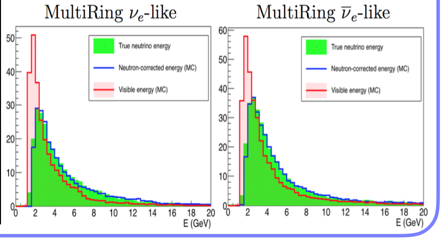


➡ Neutron energy corrections

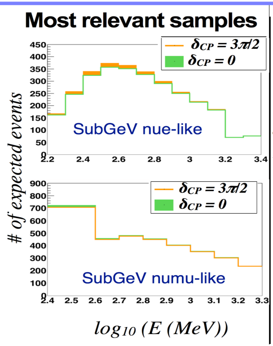
It is observed that neutron multiplicity provides information about the fraction of the neutrino energy invisible to the detector, due to its relation with the neutral hadron production (π, η, κ...). inside the nuclear media

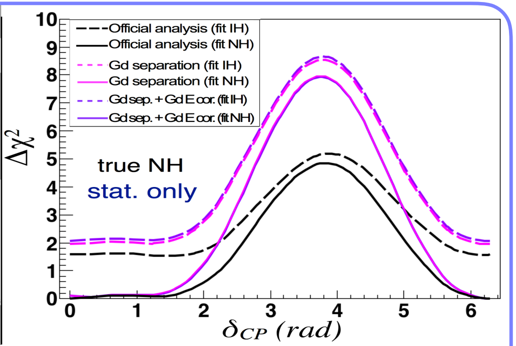




High Energy Physics in SuperK-Gd (III): Atmospheric neutrinos

- ★ The sensitivity to the <u>CP violation phase</u> is largely improved due to the high efficiency of the ν-ν̄ separation in the SubGeV samples Adjacent plots show the spectra of two of the most sensitive samples to the δ_{CP} and its χ2 distribution for rejecting δ_{CP}=0





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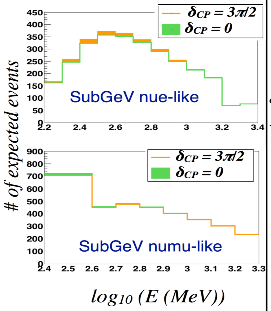
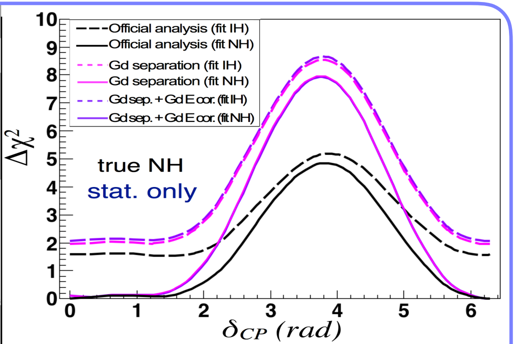
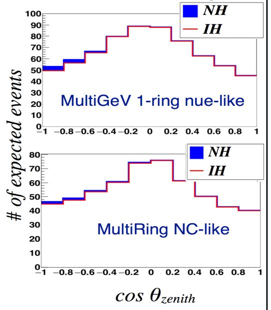
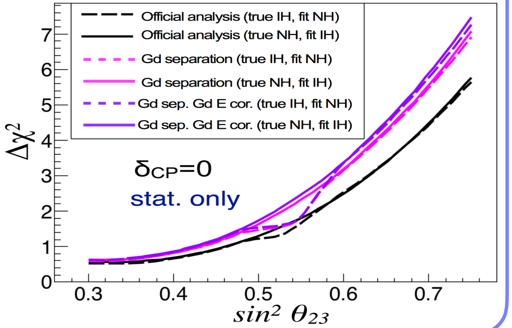




★ The sensitivity to the <u>neutrino mass hierarchy</u> is improved due to the NC-DIS-CC and ν-ν̄ separation in the MultiGeV and MultiRing e-like samples
Adjacent plots show the zentih angle distribution of two of the most sensitive samples to the MH and its χ2 distribution as function of θ_{23}

Most relevant samples





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