Neutrino physics in SuperK-Gd

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Introduction

Neutrinos are abundant and elusive, which makes them both difficult to detect and very interesting as probes of new physics.

Super Kamiokande is a water Cherenkov experiment which has already made breakthroughs in the field, notably the discovery of neutrino masses. It can do:

- Real time measurements of ν interactions
- Good angle, energy and flavour (e/μ) reconstruction capabilities
- Some ability to distinguishing neutrinos from antineutrinos
- Proton decay searches and much more!

Dissolving a gadolinium salt in a water Cherenkov detector enables good (>90%) neutron tagging, which in turn allows for recognizing inverse β interactions of antineutrinos!

SuperK-Gd consists on dissolving 100 tons of ultrapure Gd sulphate into SK.

In this presentation we will show its physics potential and our contributions.

Neutrino masses and oscillations

Deficits in flux were observed for solar & atmospheric neutrinos. The anomalies could be explained with neutrino oscillations → 2015 Physics Nobel Prize!
(To Takaaki Kajita from SK and Arthur McDonald from SNO)

Neutrino mass & interaction eigenstates needn't coincide. Their rotation matrix is (PMNS):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Majorana phases α_1 α_2 don't contribute to neutrino oscillations!

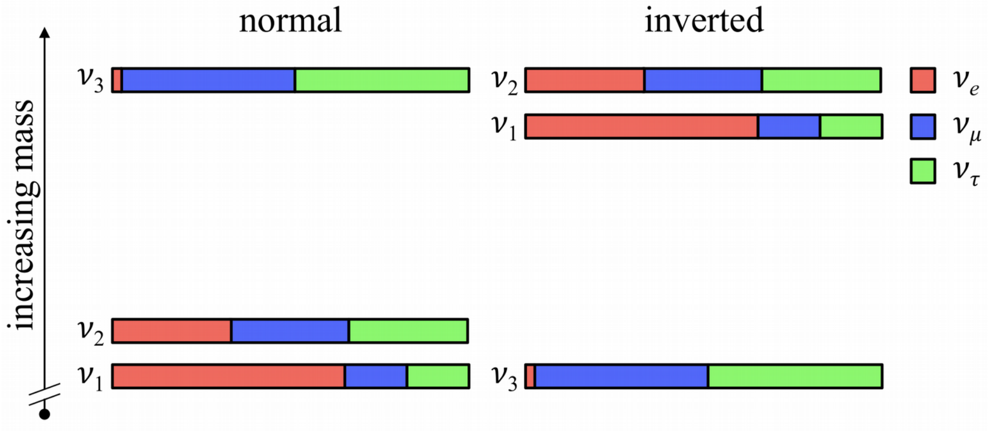
When computing the oscillation probability we obtain:

$$P_{\nu_\alpha \to \nu_\beta}(L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\{U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\} \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\{U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\} \sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

This term has a different sign for neutrinos and antineutrinos

Things to note:

- $\Delta m^2 L/E$ is an important quantity for oscillation experiments.
- Neutrinos and antineutrinos oscillate in different ways if CP isn't conserved.
- In matter (MSW effect) – Forward scattering of ν_e is favoured (high density of electrons in matter)



- **Mass hierarchy**

Oscillations depend on Δm^2, but that leaves two possible mass orderings.

Experimentally, there is a hierarchy and normal seems to be favoured (92% for SK I-IV + T2K)

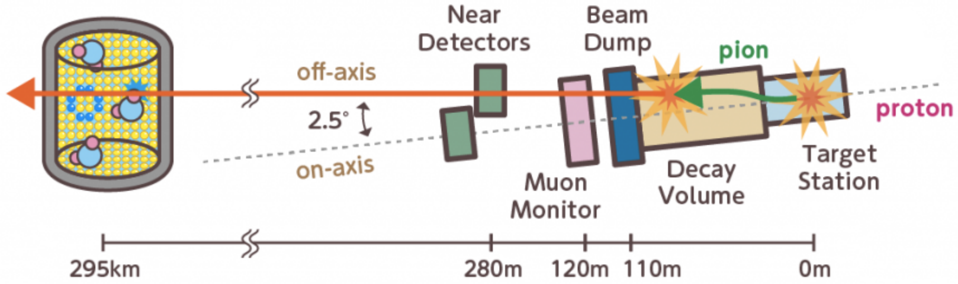
Hierarchy determination in SK: Enhancement of ν_e increases the effective masses of ν_e-dominated states → compresses/expands splittings in NO/IO

- **CP violation**

CPT must be conserved, but CP doesn't need to.

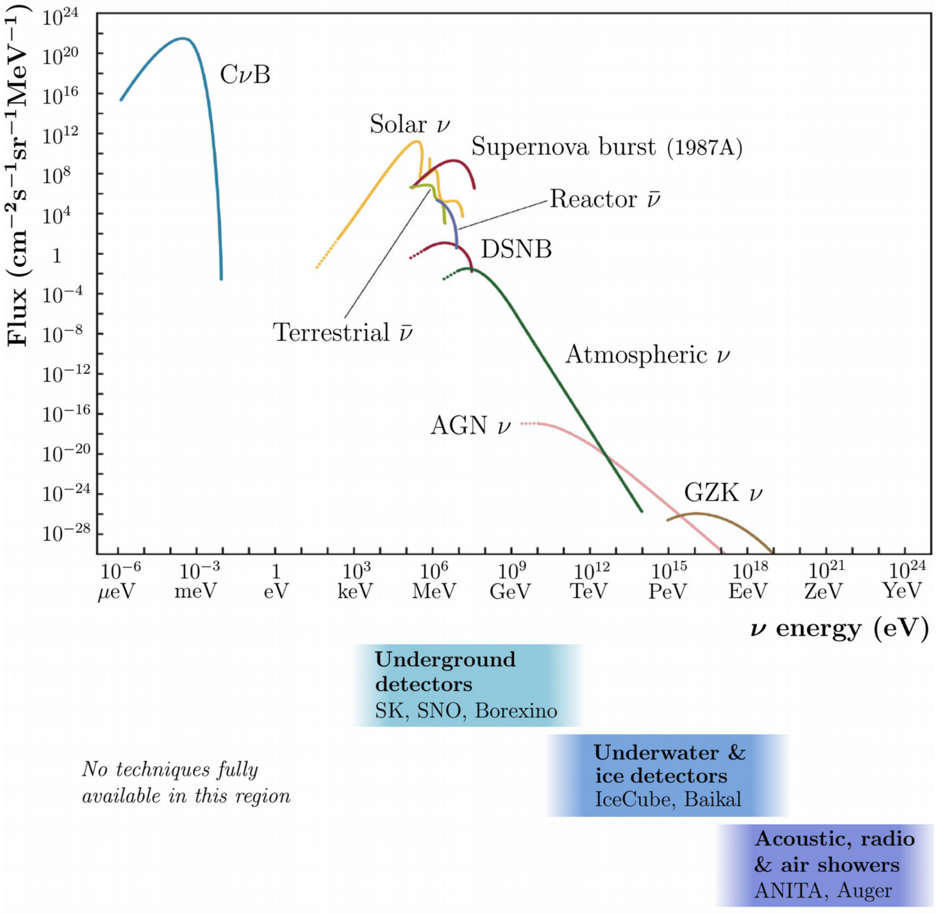
Its breaking in the neutrino sector could be 10^3 times larger than in quarks → explanation for the observed matter-antimatter asymmetry.

δ_{CP} has some modulation effects but most importantly it shows in the imaginary term of the neutrino oscillation formula.



In both cases, neutron tagging is very helpful for their determination!

Experiments and parameter values



There are many neutrino sources.

Their flavour composition, energy and oscillation lengths vary, so different experiments are more precise at determining different parameters.

SK is an underground detector mostly focused on solar, reactor, atmospheric and long baseline neutrinos (the ones from the T2K beam).

Solar & reactor	θ_{13}, Δm_{12}^2, θ_{12}
Atmospheric & LBL	θ_{23}, $\lvert\Delta m_{31,32}^2\rvert$, θ_{13}, δ_{CP}, *hierarchy*

Things to note about the neutrino parameters:

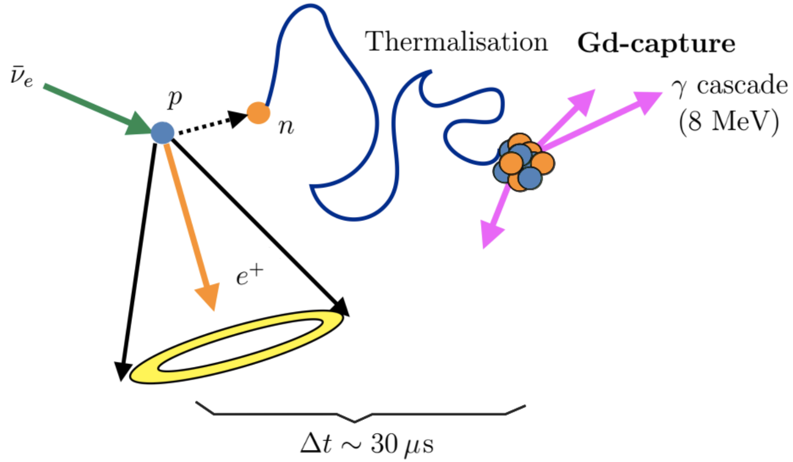
- The mixing angle θ_{13} is small
- $\Delta m_{12}^2 << \Delta m_{31,32}^2$
- $\delta_{CP} \neq 0$ at 3σ confidence level

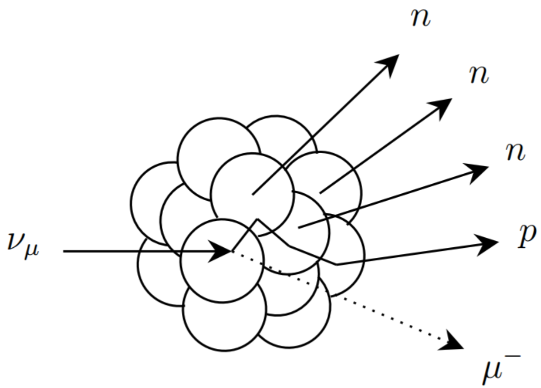
The physics of Gd-doping

- **Neutron tagging**

Without Gd – Neutrons thermalize and are captured by hydrogen in ~200 µs, emitting a single 2.2 MeV photon which is difficult to detect (many backgrounds).

With Gd – Neutrons thermalize and are captured by Gd in ~30 µs, emitting 3 to 5 photons of ~8 MeV in total. This signal is very clean → ease for neutron tagging!





- **How are neutrons produced in SK?**

At low neutrino energies (1-100 MeV), mostly inverse β interactions of electron antineutrinos, makes them easily identifiable in coincidence with Cherenkov radiation.

At higher energies there are more processes. It isn't as good, but Gd doping still improves the neutrino-antineutrino resolution of SK.

Radioactive processes usually involve free neutrons (background).

The Super Kamiokande experiment

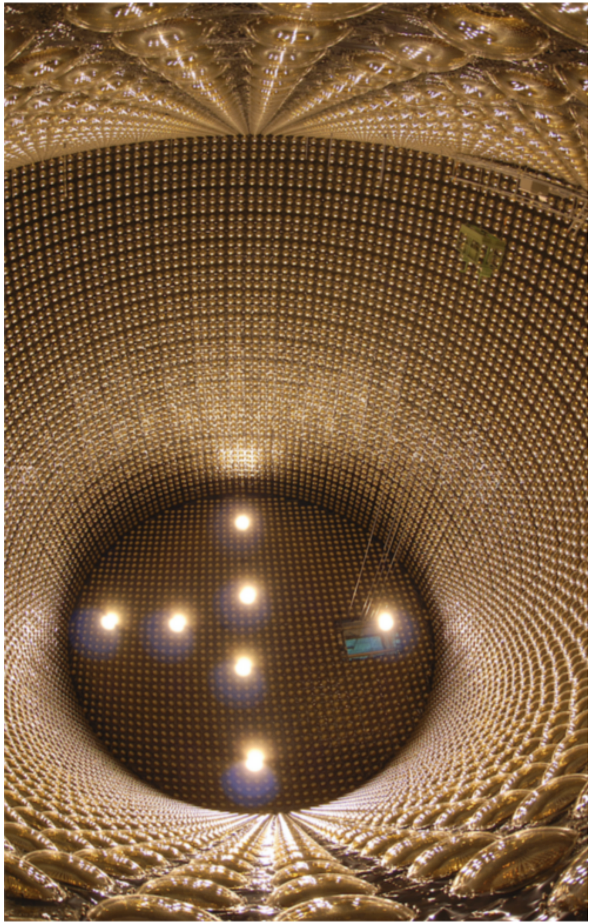
SK is a 50 kton water tank located 1000 m underground.

It is surounded by PMTs (photomultiplier tubes), which are able to detect tiny amounts of light.

When a neutrino interacts via CC inside the tank, a charged lepton with a speed close to the speed of light in the vacuum is produced. It then radiates energy as either Cherenkov or bremsstrahlung.

The tank is divided in various zones:

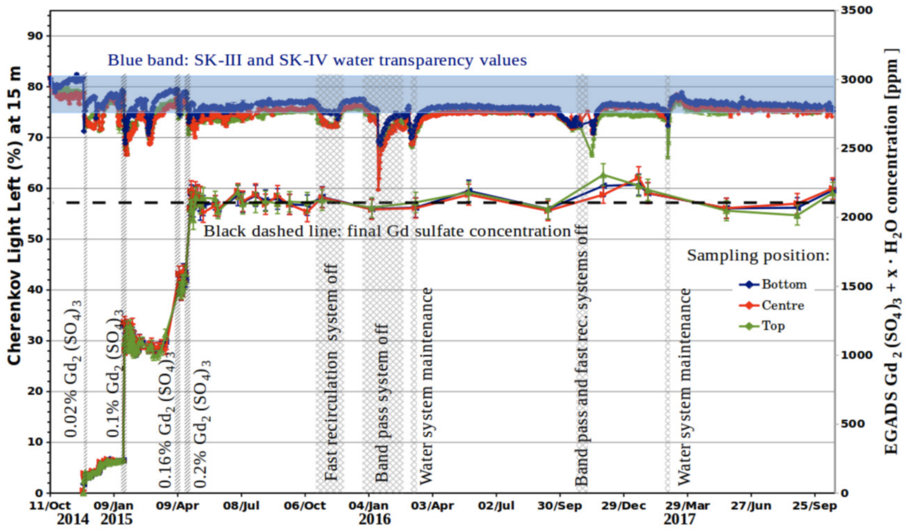
- Outer Detector (OD) – To veto cosmic muons, low photocoverage.
- Inner Detector (ID) – With higher photocoverage (40%).
  - → Events happening at ~2 m from the ID wall are excluded to reduce radioactive background: SK fiducial volume is 22.5 kton.

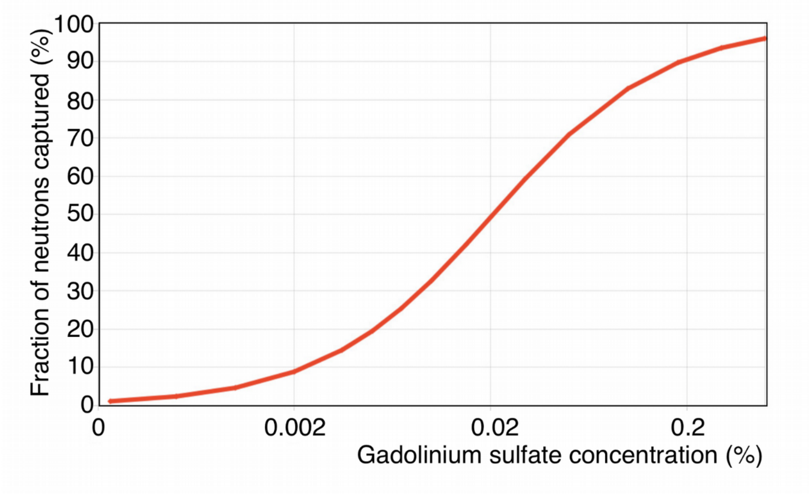


- EGADS

Built to evaluate the feasibility of dissolving Gd in SK.
Similar to SK, but 250 times smaller. It showed that:

- Gd salt doesn't degrade the SK components.
- New water system maintains both good transparency and Gd concentration (see figure).
- Adding/removing Gd is easy and economical.
- Studied the new backgrounds.





- SuperK-Gd

EGADS was a success, so SuperK-Gd was approved.

Final objective: 0.2% of Gd salt concentration (100 ton)
~90% of neutrons tagged.

First phase: 0.028% of Gd salt concentration (14 ton)
~60% of neutrons tagged.
Ongoing, to be finished in 1 month.

Solar and reactor neutrinos

Thermonuclear processes in the Sun are classified under the pp chain and CNO cycle. Most of its energy comes from the former. Both emit neutrinos.

Neutrino flux from all of the pp processes have been measured individually except for the most energetic ones (hep). CNO flux was just measured by Borexino.

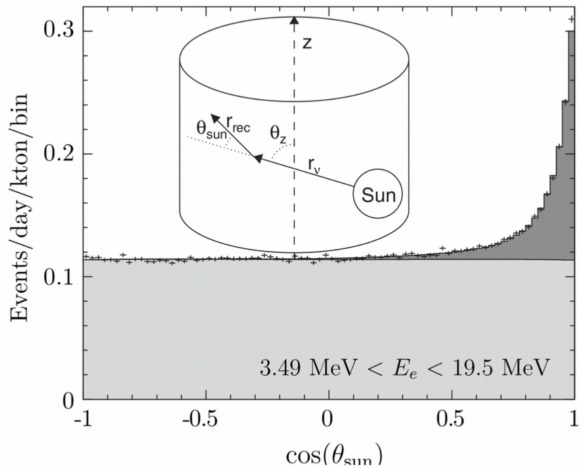
Nuclear reactors emit antineutrinos in a similar energy range.

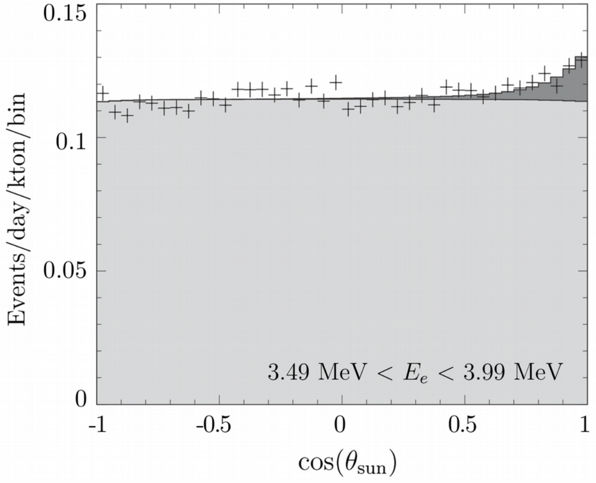
SK was able to measure an angular dependence in the neutrinos at those energies. Reactor neutrinos can't be distinguished in SK, as they're homogeneous in solar angle.

Gd salt allows us to separate the reactor antineutrinos from the solar neutrinos, but introduces new backgrounds:

Solar neutrino flux in SK	200 events/day
Estimated radioactive bkg after T1	~50 events/day

This background is problematic at low energies.





Atmospheric and LBL neutrinos

Atmospheric neutrinos are generated after the decay of charged pions in the atmosphere, caused by cosmic ray impacting with air nuclei.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

The expected ratio of muon to electron neutrinos is 2, but it was seen to be lower! $\mu \leftrightarrow \tau$ oscillations.

Accelerator neutrinos are generated by a similar mechanism, but by focusing the intermediate charged particles the neutrinos are collimated into a beam. Long baseline experiments (e.g. T2K) can be used to study the same parameters as atmospheric neutrinos, while aiming for the oscillation maximum.

These neutrinos are more energetic than solar & reactor, but they also benefit from Gd doping:

- Neutrino-antineutrino separation helps in δ_{CP} and mass ordering determination.
- Neutron multiplicity depends on the initial neutrino energy.
  - → Neutron tagging improves the energy reconstruction precision.
- Radioactive backgrounds aren't very problematic for these sources.

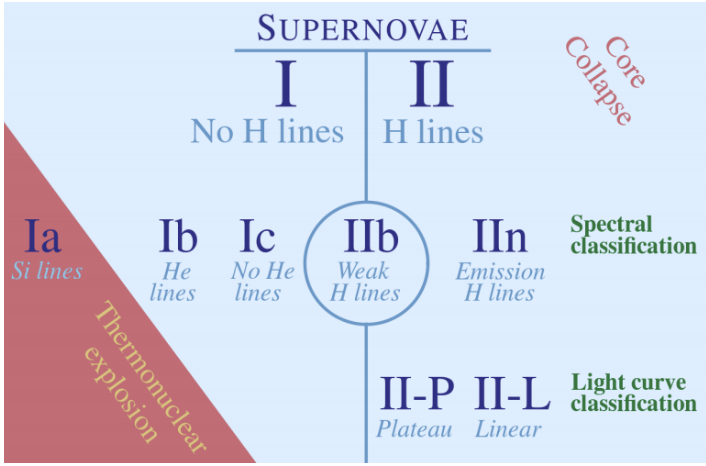
Supernova neutrinos

There are many types of supernovae, the ones which occur due to thermonuclear explosion (Ia) don't emit many neutrinos, so we are interested in the ones due to core collapse.

There are two types of supernova neutrinos:

- **Si-burning phase ν**
  - → A few hours to days prior to the core collapse.
  - → Not very abundant, only seen if SN is close enough.
  - → Can be used in SN early alert systems.
  - → For a SN 0.2 kpc away: ~16 events/day
- **Thermal emission ν**
  - → During the core collapse, emitted in all flavours.
  - → Very abundant, in a short burst.
  - → Useful to determine parameters in SN models!
  - → For a SN in our galaxy: O(1000) events! in SK

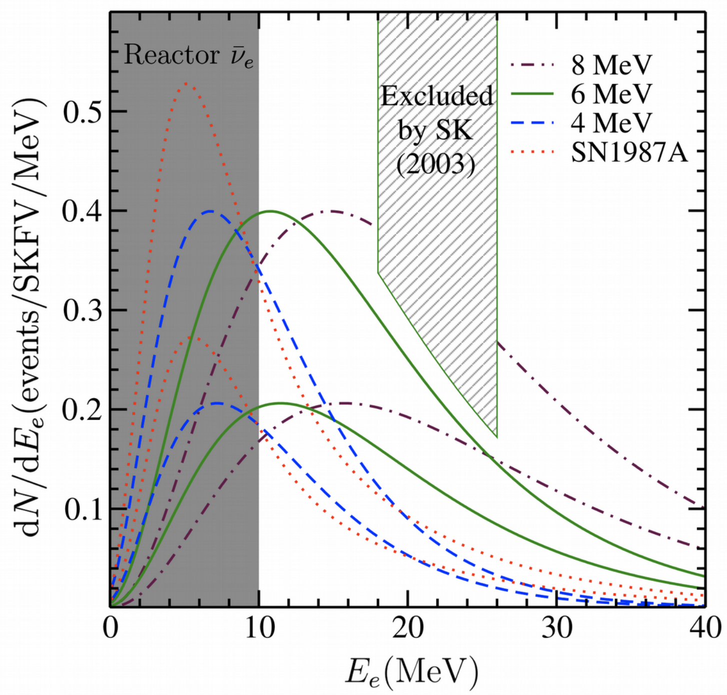
Radioactive backgrounds are negligible here since both are extremely bright sources.



SN 1987A

It was a type II SN, 50 kpc from the Milky Way. **Kamiokande** measured 12 ν, which arived 3 hours before the corresponding photons. No other SN has ever been detected with ν since.

Diffuse supernova neutrino background



Supernova bursts further from our galaxy can't be measured with current detectors, but their integrated flux we can.

Not measured yet, but we are very close to theoretical estimations → important objective of SuperK-Gd.

- → For E_e < 10 MeV – Reactor ν background dominates
- → For E_e > 10 MeV – Spallation background dominates (Cosmic μ impacting oxygen)

In SK the measurement is background dominated at all energies. In SuperK-Gd we can eliminate the spallation bkg!

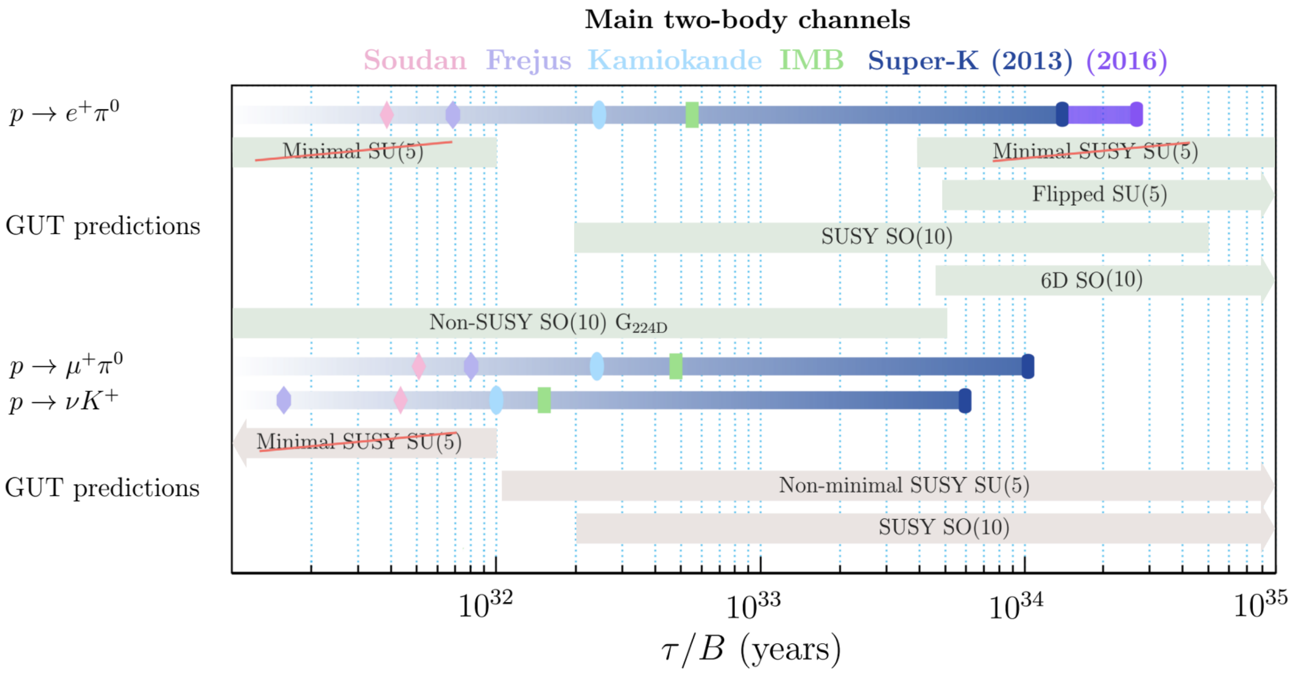
Measuring DSNB flux lets us compare the SN model parameters with the ones from optical measurements.

Expected DSNB flux in SK	~5 events/year
Radioactive bkg with current bounds	<1 events/year

Proton decay

The Kamiokande detector was originally designed as a proton decay experiment!

Now they're mainly neutrino detectors, but they can still look for this rare decay, predicted by GUTs.



Super Kamiokande is the current leader in proton decay bounds and it has already excluded two unified theories.

In SuperK-Gd, we can further reduce the background for these processes by doing a neutron veto, as proton decay channels don't usually have neutrons.

Why is Gd radiopurity important?

Radioactive processes in PMTs and electronics are removed after restricting events to the fiducial volume, but Gd salt is dissolved among all the tank water. This creates irreducible backgrounds:

- **High energy β decays**

  Elements from transuranic decay chains may beta decay emitting MeV γ and e^-.

- **(α,n)** $^{18}\mathrm{O} + \alpha \rightarrow {}^{22}\mathrm{Ne} \rightarrow {}^{20}\mathrm{Ne} + 2n$

  An α may be captured by oxygen nuclei in the water, emitting two neutrons.

- **Spontaneous fission**

  Heavy isotopes may split, emitting a few n and sometimes an energetic photon (>10 MeV).

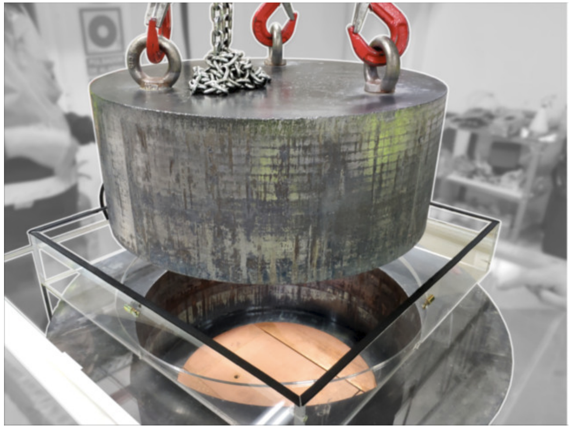
- **Fluorescence**

  Cerium can absorb γ and re emit with lower energy, difficulting energy reconstruction.

The salt is already incredibly pure after purchased, but additional measures are taken.

→ HPGe at the Canfranc Underground Laboratory were used to screen the activities of 15 Gd samples.

→ ICPMS was also employed to measure element concentrations.

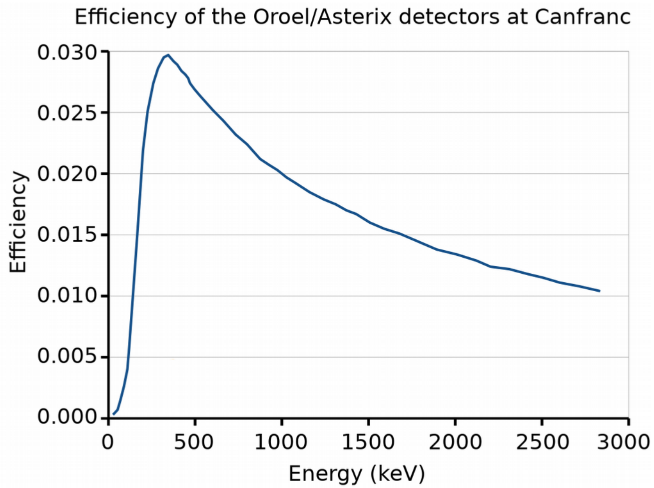


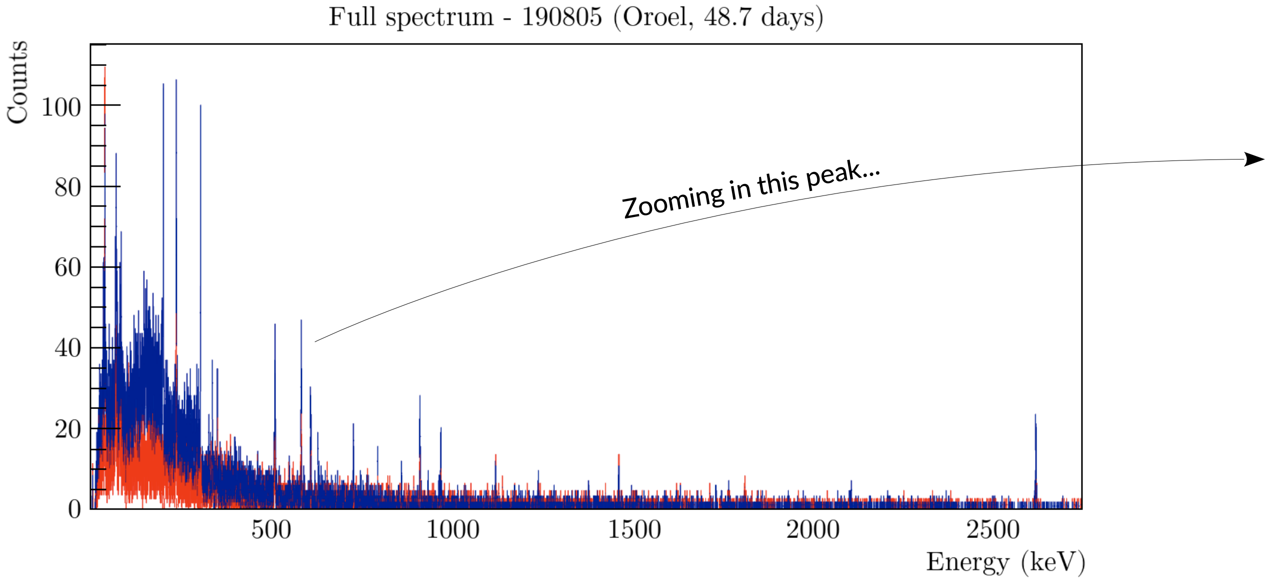
- **Signal and bound calculation from HPGe spectra**

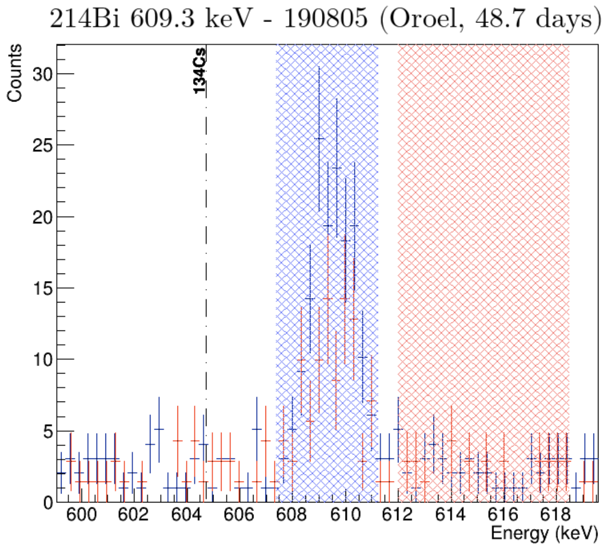
  Samples are measured for 30-50 days. The gamma spectrum is compared to the detector background and then converted into radioactive activities, for which we need to know:

  → Detector efficiencies (from Monte Carlo simulation)

  → Intensity of that gamma line (tabulated in JANIS)







Analysis of our results

Let us analyze a condensed version of the full results table (which is available in a backup slide).

Condensed Canfranc HPGe results (mBq/kg 95% c.l.)

#	Detector	^{238}U$\triangle$	^{238}U∇	^{232}Th$\triangle$	^{232}Th∇	^{235}U$\triangle$	^{235}U∇	^{138}La	^{176}Lu
	γ line (keV) $\rightarrow$	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element $\rightarrow$	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement $\rightarrow$	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
190302	ge-Asterix	< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
190303	ge-Asterix	< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
190305	ge-Asterix	< 9.0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	0.5 ± 0.1	0.14 ± 0.13
190601	ge-Asterix	< 10.2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 0.16	1.25 ± 0.14
190602	ge-Tobazo	< 29	< 0.49	< 1.64	< 0.82	< 0.76	< 1.85	< 0.21	1.64 ± 0.20
190603	ge-Anayet	< 25.95	< 0.45	< 1.03	< 0.76	< 0.58	< 2.02	< 0.18	1.71 ± 0.14
190607	ge-Oroel	< 7.2	< 0.30	< 0.79	< 0.42	< 0.30	< 0.96	< 0.18	< 0.13
190608	ge-Asterix	< 8.8	< 0.53	< 0.43	< 0.35	< 0.40	< 0.88	< 0.14	< 0.25
190702	ge-Oroel	< 11	< 0.45	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
190703	ge-Asterix	< 8.4	< 0.35	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
190803	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 0.09	3.5 ± 0.1
190805	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 0.09	9.38 ± 0.09
190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

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Condensed [illegible] l.)

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We aren't quite there (we would need many months of measurements) but from ICPMS measurements we know that upper 238U **meets the requirements**

Analysis of our results

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These are the requirements for low **solar** backgrounds.

Condensed Canfranc HPGe results (mBq

#	Detector	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	^{235}			
	γ line (keV) →	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element →	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement →	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
190302	ge-Asterix	< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
190303	ge-Asterix	< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
190305	ge-Asterix	< 9.0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	0.5 ± 0.1	0.14 ± 0.13
190601	ge-Asterix	< 10.2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 0.16	1.25 ± 0.14
190602	ge-Tobazo	< 29	< 0.49	< 1.64	< 0.82	< 0.76	< 1.85	< 0.21	1.64 ± 0.20
190603	ge-Anayet	< 25.95	< 0.45	< 1.03	< 0.76	< 0.58	< 2.02	< 0.18	1.71 ± 0.14
190607	ge-Oroel	< 7.2	< 0.30	< 0.79	< 0.42	< 0.30	< 0.96	< 0.18	< 0.13
190608	ge-Asterix	< 8.8	< 0.53	< 0.43	< 0.35	< 0.40	< 0.88	< 0.14	< 0.25
190702	ge-Oroel	< 11	< 0.45	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
190703	ge-Asterix	< 8.4	< 0.35	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
190803	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 0.09	3.5 ± 0.1
190805	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 0.09	9.38 ± 0.09
190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

Analysis of our results

Let us analyze a condensed version of the full results table (which is available in a backup slide).

These are the requirements for low **solar** backgrounds.

These three columns don't have many signals and even then, they're under the experimental requirements

Condensed Canfranc HPGe results (mBq/

#	Detector	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	235			
	γ line (keV) →	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element →	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement →	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
		< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
		< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
		< 9.0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	0.5 ± 0.1	0.14 ± 0.13
		< 10.2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 0.16	1.25 ± 0.14
		< 29	< 0.49	< 1.64	< 0.82	< 0.76	< 1.85	< 0.21	1.64 ± 0.20
		< 25.95	< 0.45	< 1.03	< 0.76	< 0.58	< 2.02	< 0.18	1.71 ± 0.14
		< 7.2	< 0.30	< 0.79	< 0.42	< 0.30	< 0.96	< 0.18	< 0.13
190608	ge-Asterix	< 8.8	< 0.53	< 0.43	< 0.35	< 0.40	< 0.88	< 0.14	< 0.25
190702	ge-Oroel	< 11	< 0.45	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
190703	ge-Asterix	< 8.4	< 0.35	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
190803	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 0.09	3.5 ± 0.1
190805	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 0.09	9.38 ± 0.09
190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

Analysis of our results

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These are the requirements for low **solar** backgrounds.

Condensed Canfranc HPGe results (mBq/

#	Detector	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	^{235}			
	γ line (keV) →	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element →	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement →	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
190302	ge-Asterix	< 0.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
[illegible]	[illegible]	[illegible]4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
[illegible]	[illegible]	[illegible]0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	0.5 ± 0.1	0.14 ± 0.13
[illegible]	[illegible]	[illegible].2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 0.16	1.25 ± 0.14
[illegible]	[illegible]	[illegible]9	< 0.49	< 1.64	< 0.82	< 0.76	< 1.85	< 0.21	1.64 ± 0.20
[illegible]	[illegible]	[illegible]95	< 0.45	< 1.03	< 0.76	< 0.58	< 2.02	< 0.18	1.71 ± 0.14
[illegible]	[illegible]	[illegible]2	< 0.30	< 0.79	< 0.42	< 0.30	< 0.96	< 0.18	< 0.13
190608	ge-Asterix	< 8.8	< 0.53	< 0.43	< 0.35	< 0.40	< 0.88	< 0.14	< 0.25
190702	ge-Oroel	< 11	< 0.45	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
190703	ge-Asterix	< 8.4	< 0.35	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
190803	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 0.09	3.5 ± 0.1
190805	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 0.09	9.38 ± 0.09
190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

These aren't below the requirement, but we don't see a signal (and we don't expect one in most of these samples)

Analysis of our results

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These are the requirements for low **solar** backgrounds.

Condensed Canfranc HPGe results (mBq/[illegible]

#	Detector	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	^{235}[illegible]	[illegible]	[illegible]	[illegible]
	γ line (keV) →	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element →	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement →	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
190302	ge-Asterix	< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
190303	ge-Asterix	< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
190305	ge-Asterix	< 9.0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	0.5 ± 0.1	0.14 ± 0.13
190601	ge-Asterix	< 10.2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 0.16	1.25 ± 0.14
[illegible]	[illegible]	[illegible]	[illegible]	< 1.64	< 0.82	< 0.76	< 1.85	< 0.21	1.64 ± 0.20
[illegible]	[illegible]	[illegible]	[illegible]	< 1.03	< 0.76	< 0.58	< 2.02	< 0.18	1.71 ± 0.14
[illegible]	[illegible]	[illegible]	[illegible]	< 0.79	< 0.42	< 0.30	< 0.96	< 0.18	< 0.13
[illegible]	[illegible]	[illegible]	[illegible]	< 0.43	< 0.35	< 0.40	< 0.88	< 0.14	< 0.25
[illegible]	[illegible]	[illegible]	[illegible]	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
[illegible]	[illegible]	[illegible]	[illegible]	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
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190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

One order of magnitude above the requirement.

→ Problematic for lowE solar ν

Analysis of our results

Let us analyze a condensed version of the full results table (which is available in a backup slide).

Condensed Canfranc HPGe results (mBq/[illegible]

#	Detector	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	^{235}[illegible]	[illegible]	[illegible]	[illegible]
	γ line (keV) →	1001.0	609.3	911.2	583.2	185.7	236.0	1435.8	306.8
	γ line element →	^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{138}La	^{176}Lu
	Exp requirement →	< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-
190302	ge-Asterix	< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	0.26 ± 0.1	< 0.21
190303	ge-Asterix	< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	0.45 ± 0.09	0.16 ± 0.12
190305	ge-Asterix	< 9.0	< 0.34	< 0.36	[illegible]	[illegible]	[illegible]	[illegible]	0.14 ± 0.13
190601	ge-Asterix	< 10.2	< 0.52	< 0.35	[illegible]	[illegible]	[illegible]	[illegible]	1.25 ± 0.14
[illegible]	[illegible]	[illegible]	[illegible]	< 1.64	[illegible]	[illegible]	[illegible]	[illegible]	1.64 ± 0.20
[illegible]	[illegible]	[illegible]	[illegible]	< 1.03	[illegible]	[illegible]	[illegible]	[illegible]	1.71 ± 0.14
[illegible]	[illegible]	[illegible]	[illegible]	< 0.79	[illegible]	[illegible]	[illegible]	[illegible]	< 0.13
[illegible]	[illegible]	[illegible]	[illegible]	< 0.43	[illegible]	[illegible]	[illegible]	[illegible]	< 0.25
[illegible]	[illegible]	[illegible]	[illegible]	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 0.20	0.23 ± 0.13
[illegible]	[illegible]	[illegible]	[illegible]	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 0.20	0.51 ± 0.13
190801	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 0.18	2.7 ± 0.2
190803	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 0.09	3.5 ± 0.1
190805	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 0.09	9.38 ± 0.09
190901	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 0.13	4.87 ± 0.11
190903	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 0.14	4.89 ± 0.13

These are the requirements for low **solar** backgrounds.

One order of magnitude above the requirement.

→ Problematic for lowE solar ν

There is an empyrical correlation with high 176Lu signals, but this doesn't affect the experiment itself.

Implications of our results for the future of SuperK-Gd

The signals found correspond to relatively high ^{228}Ra concentrations. Together with the measurements from Boulby and Kamioka, about half of the T1 samples are ^{228}Ra-contaminated.

When dissolving, resins in the water system can remove ~90% of the ^{228}Ra.
The ^{228}Ra-induced backgrounds halve every two years.

For the first phase (T1) we had two options:

- **Option 1**
  - → Dissolving all clean samples (7 ton)
  - → 6-12 solar bkg events/day in SKFV
  - → ~30% neutron capture efficiency
- **Option 2**
  - → Dissolving all samples (14 ton)
  - → 55-62 solar bkg events/day in SKFV
  - → ~60% neutron capture efficiency

Option 2 has been taken

A R&D program was set to know how to further purify future samples, in case that the problem persists.

Conclusions

- Neutrino discoveries are vital for theoretical physics and Super Kamiokande has proven to be an invaluable experiment in this field.
- Its new phase, SuperK-Gd, has promising prospects like the first measurement of the DSNB and better determination of δ_{CP} and mass hierarchy.
- EGADS was successful at loading Gd salt in a water Cherenkov detector.
- Our work on the radiopurity of SuperK-Gd salt has changed the course of the experiment, as half of the T1 samples were seen to have relatively high ^{228}Ra levels.
- A R&D program was started to know how to further purify Gd sulphate from ^{228}Ra.

Thanks for your attention

(Questions or comments?)

Experiments and parameter values

Experiment type	Notable examples	Dominant	Important
Solar experiments	*SNO, SK, borexino*	θ_{12}	$\Delta m^2_{21}, \theta_{13}$
Reactor LBL	*KamLAND*	Δm^2_{21}	θ_{12}, θ_{13}
Reactor MBL	*Daya-Bay, Reno, D-Chooz*	$\theta_{13}, \lvert\Delta m^2_{31,32}\rvert$	
Atmospheric exp.	*SK, IC-DC*	$\theta_{23}, \lvert\Delta m^2_{31,32}\rvert$	θ_{13}, δ_{CP}
Accel. LBL ν_μ, $\bar{\nu}_\mu$ disapp.	*K2K, MINOS, T2K, NOνA*	$\lvert\Delta m^2_{31,32}\rvert, \theta_{23}$	
Accel. LBL ν_e, $\bar{\nu}_e$ app.	*MINOS, T2K, NOνA*	δ_{CP}, θ_{13}	θ_{23}

	Normal Ordering		Inverted Ordering	
	$\pm1\sigma$ range	$\pm3\sigma$ range	$\pm1\sigma$ range	$\pm3\sigma$ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
δ_{CP}/rad	$-1.89^{+0.70}_{-0.58}$	$-3.41 \to -0.03$	$-1.38^{+0.48}_{-0.54}$	$-2.54 \to -0.32$
$\Delta m^2_{21}/10^{-5}\mathrm{eV}^2$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\Delta m^2_{3l}/10^{-3}\mathrm{eV}^2$	$2.528^{+0.029}_{-0.031}$	$2.436 \to 2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

Canfranc T1 results

#	Lab.	Detector / technique	^{238}U△	^{238}U▽	^{232}Th△	^{232}Th▽	^{235}U△	^{235}U▽	^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
			Ge, main chains (mBq/kg 95% c.l.)						Ge, other (mBq/kg 95% c.l.)				
	Chosen γ line (keV) →		1001.0	609.3	911.2	583.2	185.7	236.0	1460.8	1435.8	306.8	795.9	661.6
	γ line element →		^{234*}Pa	^{214}Bi	^{228}Ac	^{208}Tl	^{235}U	^{227}Th	^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
	Experimental requirement →		< 5	< 0.5	< 0.05	< 0.05	< 30	< 30	-	-	-	-	-
190302	Canfranc	ge-Asterix	< 9.8	< 0.32	< 0.35	< 0.29	< 0.42	< 0.92	< 1.6	0.26 ± 0.1	< 0.21	< 0.09	< 0.09
	HADES	Ge10+Ge11	< 105	< 8.6	< 3.3	< 3.6	< 5.6	< 10.4	< 8.8	< 1.66	< 2.47	-	< 0.93
190303	Canfranc	ge-Asterix	< 8.4	< 0.3	< 0.44	< 0.29	< 0.39	< 0.81	< 1.5	0.45 ± 0.09	0.16 ± 0.12	< 0.08	< 0.09
190304	Canfranc	*(t.b.m.)*	-	-	-	-	-	-	-	-	-	-	-
	HADES	Ge10+Ge11	< 88	< 7.7	< 2.6	< 3.3	< 5.0	< 9.5	< 10	1.34 ± 0.96	< 1.28	-	< 1.26
190305	Canfranc	ge-Asterix	< 9.0	< 0.34	< 0.36	< 0.30	< 0.41	< 0.90	< 1.6	0.5 ± 0.1	0.14 ± 0.13	< 0.09	< 0.12
190601	Canfranc	ge-Asterix	< 10.2	< 0.52	< 0.35	< 0.41	< 0.50	< 1.36	< 1.90	< 0.16	1.25 ± 0.14	< 0.10	< 0.11
	Kamioka	*RaEmporeDisk*	-	< 0.32	< 0.39	< 0.34	-	-	-	-	-	-	-
190602	Canfranc	ge-Tobazo	< 29	< 0.49	< 1.64	< 0.82	< 0.76	< 1.85	< 2.10	< 0.21	1.64 ± 0.20	< 0.17	< 0.14
	Kamioka	*RaEmporeDisk*	-	< 0.28	< 1.01	< 0.28	-	-	-	-	-	-	-
190603	Canfranc	ge-Anayet	< 25.95	< 0.45	< 1.03	< 0.76	< 0.58	< 2.02	< 1.58	< 0.18	1.71 ± 0.14	< 0.15	< 0.12
190607	Canfranc	ge-Oroel	< 7.2	< 0.30	< 0.79	< 0.42	< 0.30	< 0.96	< 1.59	< 0.18	< 0.13	< 0.12	< 0.09
190608	Canfranc	ge-Asterix	< 8.8	< 0.53	< 0.43	< 0.35	< 0.40	< 0.88	< 1.50	< 0.14	< 0.25	< 0.08	< 0.09
	Kamioka	-	< 20.4	-	< 1.22	< 0.71	< 3.4	< 1.6	-	-	< 0.45	-	-
	Kamioka	*RaEmporeDisk*	-	< 0.49	< 0.43	< 0.55	-	-	-	-	-	-	-
190702	Canfranc	ge-Oroel	< 11	< 0.45	< 1.11	< 0.50	< 0.37	2.4 ± 0.9	< 1.50	< 0.20	0.23 ± 0.13	< 0.12	< 0.11
	Kamioka	-	< 9.4	< 0.57	< 0.97	< 0.26	< 2.6	< 1.4	-	-	< 0.44	-	-
190703	Canfranc	ge-Asterix	< 8.4	< 0.35	< 0.51	< 0.50	< 0.45	1.8 ± 1.0	< 1.70	< 0.20	0.51 ± 0.13	< 0.10	< 0.10
190801	Canfranc	ge-Anayet	< 28	0.39 ± 0.32	< 1.5	< 0.77	< 0.80	< 1.17	< 1.44	< 0.18	2.7 ± 0.2	< 0.23	< 0.18
190803	Canfranc	ge-Asterix	< 7.0	< 0.31	0.39 ± 0.21	0.55 ± 0.22	< 0.36	< 0.71	< 1.4	< 0.09	3.5 ± 0.1	< 0.08	< 0.07
190805	Canfranc	ge-Oroel	< 8.39	0.25 ± 0.23	0.53 ± 0.39	0.60 ± 0.36	< 0.40	< 0.89	< 1.12	< 0.09	9.38 ± 0.09	< 0.10	< 0.08
	Kamioka	IPMU-P	< 103	< 1.6	< 3.2	< 4.9	< 16	< 7.0	< 18	-	8.83 ± 0.82	-	< 1.2
190901	Canfranc	ge-Asterix	< 6.85	< 0.27	0.48 ± 0.23	0.34 ± 0.24	< 0.42	< 1.09	< 1.31	< 0.13	4.87 ± 0.11	< 0.09	< 0.12
	Kamioka	-	< 110	< 2.3	< 2.9	< 2.1	< 14.9	< 12.2	< 27	-	5.6 ± 0.7	-	< 1.1
190903	Canfranc	ge-Asterix	< 8.88	< 0.37	0.59 ± 0.28	0.35 ± 0.28	< 0.54	< 1.72	< 1.50	< 0.14	4.89 ± 0.13	< 0.10	< 0.09
	Kamioka	-	< 69	< 6.3	< 4.0	< 2.4	< 17.6	< 5.3	< 32	-	5.4 ± 0.8	-	< 1.0