Search for neutrinos in coincidence with gravitational wave events from the LIGO-Virgo O3a Observing Run with the Super-Kamiokande

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Photo Credit: Asahi Shimbun/Getty, taken from NATURE article: https://www.nature.com/articles/d41586-019-00598-9

Outline

- Introduction
- Super-Kamiokande experiment, detection technique, used samples
- GW follow-up results
- SK-Gd project and its possible impact on physics results
- Summary and conclusions

Introduction

Since 2015 the LIGO/Virgo Collaboration (LVC) is detecting and sending alerts from gravitational waves from the merger of binary objects:

- Binary Neutron Star (BNS): may produce short Gamma-Ray Bursts (GRB) with neutrino production*
- Binary Black Hole (BBH): neutrino production in the accretion disks of the black holes **
- Neutron Star-Black Hole (NSBH)

Detecting coincident neutrinos from these objects would allow better understanding of the mechanism behind them.

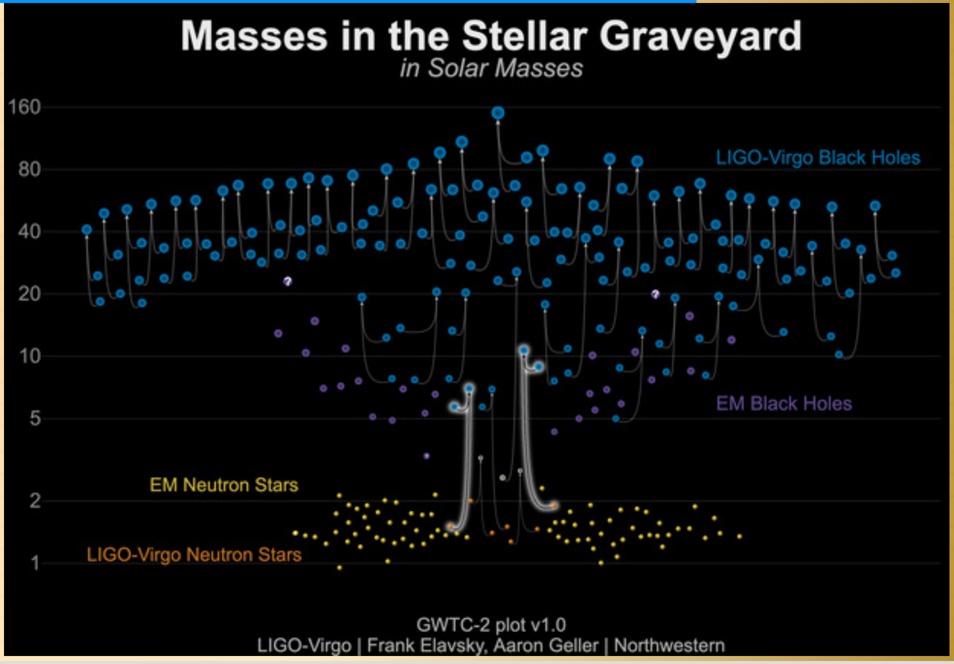
* Foucart, F., et al (2016) Low mass binary neutron star mergers: Gravitational waves and neutrino emission. Physical Review D 93 (4)
* * Caballero, O., et al (2016) Black hole spin influence on accretion disk neutrino detection, Phys.Rev. D 93 123015

* Based on the slides from Mathieu Lamoureux from ICRC 2021 Berlin

GWTC-2 catalogue

- Ligo-Virgo Third Observing Run (O3) is covering data from April 2019 to March 2020: 56 alerts provided in realtime through the Gamma-ray Coordinates Network (GCN)
- GWTC-2 covers the first half of O3 (April 2019- September 2019) -> 39 confirmed detections

For each GW, we have:
- time of the event
- sky localisation
- estimated distance
- estimated mass of the two objects
- can be roughly classified based on masses (m<3Msun=NS, M>3Msun=BH

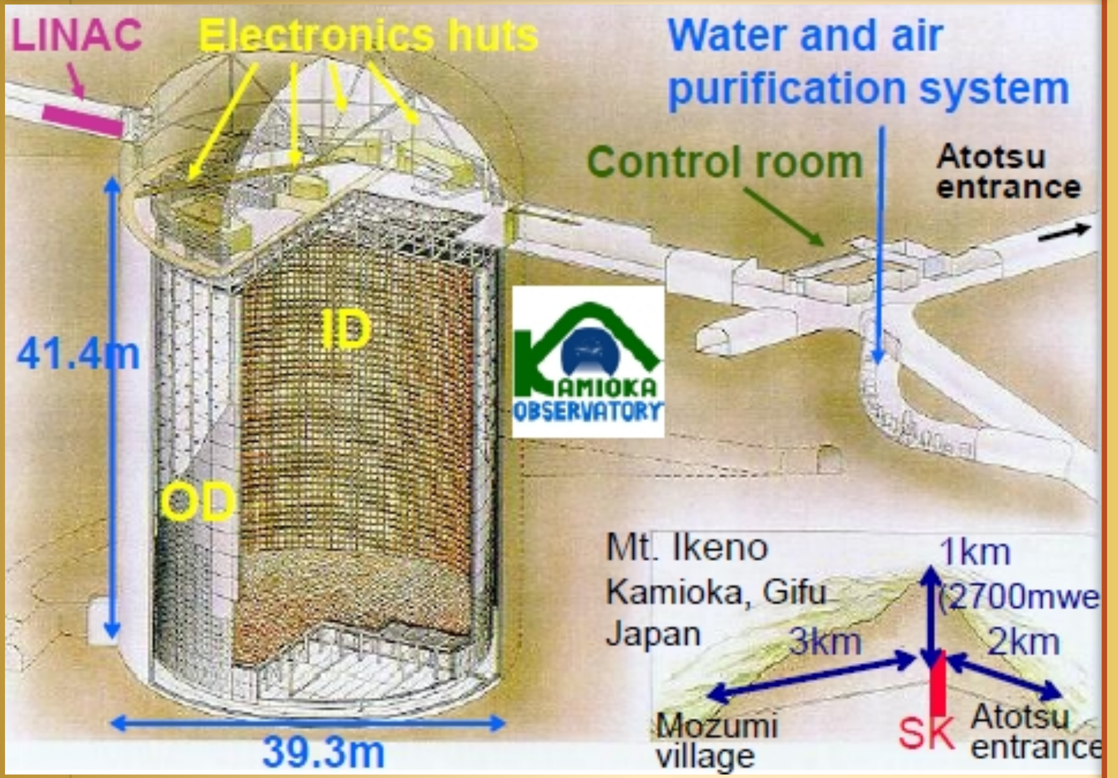


Credits: LIGO-Virgo / Frank Elavsky, Aaron Geller / Northwestern University.

* Based on the slides from Mathieu Lamoureux from ICRC 2021 Berlin

Super-Kamiokande detector

Super-Kamiokande is a neutrino water Cherenkov Detector located 1km under Mount Ikeno near the city of Hida, Japan.



- The detector is filled with 50 ktons of pure water (* until 2020, when Gd was loaded).
- Six run periods:
  1. SK-I (1996-2001)
  2. SK-II (2003-2005) after accident, 1/2 PMT coverage
  3. SK-III (2006-2008) restored PMT coverage
  4. SK-IV (2008-2018) upgraded electronics
  5. SK-V (2019-2020)after refurbishment work
  6. SK-VI (2020- now) Gd loaded into water

- Discovered neutrino oscillations (1998) - Noble Prize in 2015

Super-K PMT's

- The **photo-multiplier-tubes** (PMTs) support structure divides the tank into two distinct, optically isolated volumes, the **inner detector (ID)** and the **outer detector (OD)**.
- Inner detector:
  - **~11,100 50 cm PMTs**
  - ~ 2ns timing resolution
  - ~ 4.5MeV threshold
- Outer detector:
  - layer ~ 2m thick,
  - **1,885 20 cm PMTs**

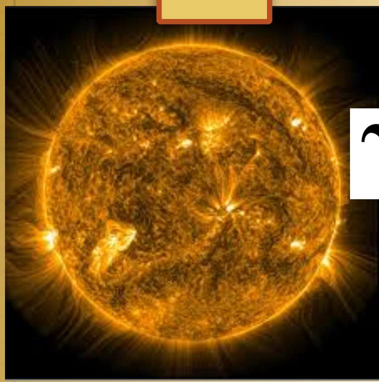
Super-Kamiokande collaboration

~120 collaborators, 31 institutions

2019 Collaboration Meeting in Toyama

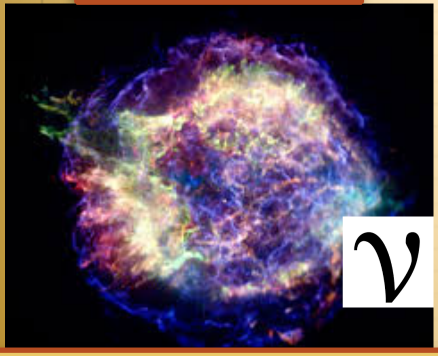
Super-Kamiokande experiment
Main physics programme

Sun



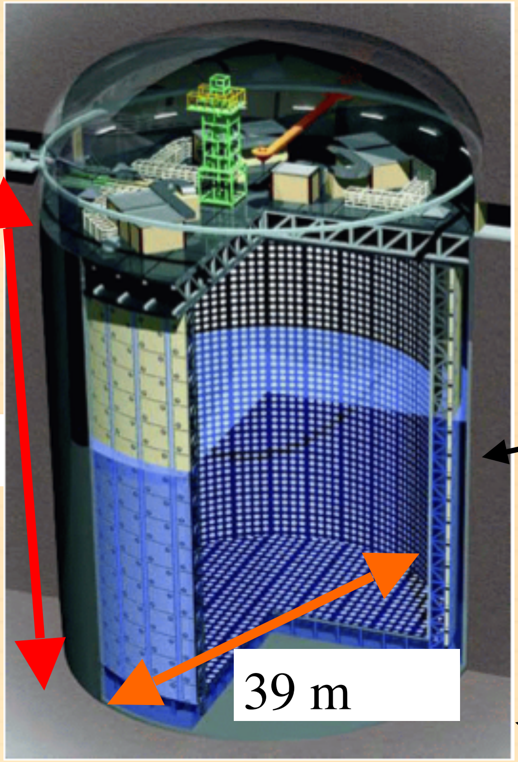
ν

Supernovae



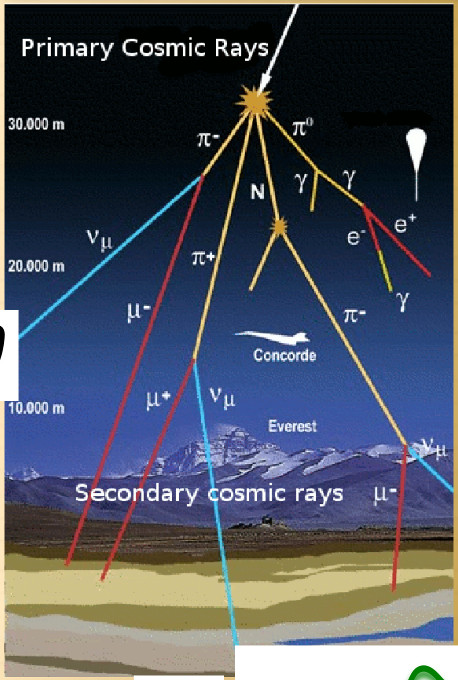
ν

42 m



39 m

Atmospheric neutrinos



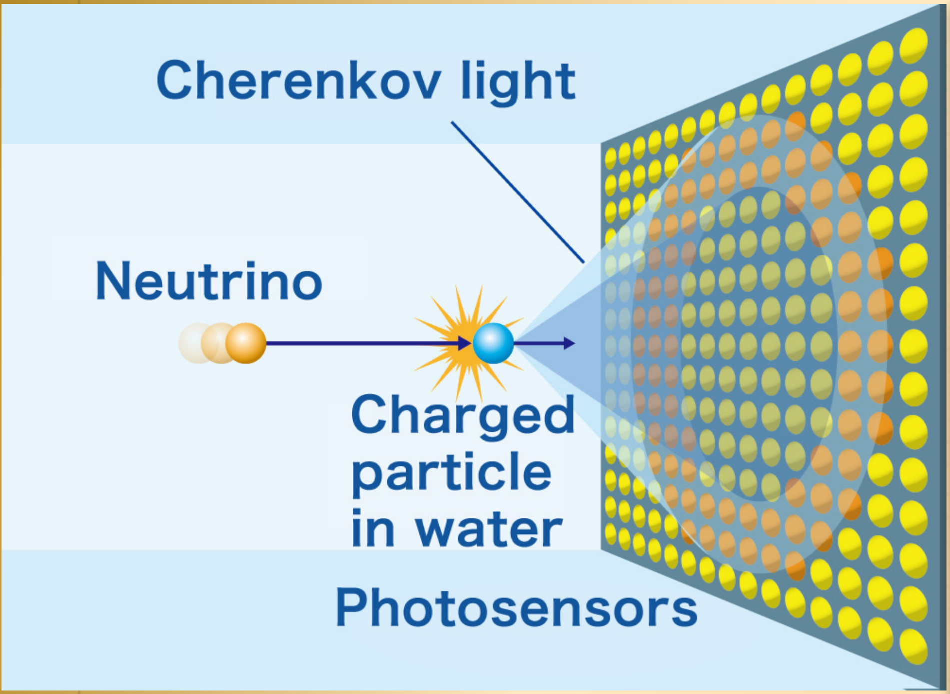
ν

ν

Proton decay searches, Indirect dark matter searches, Astrophysical neutrino searches etc.

Manmade neutrino beams
T2K experiment

Detection technique



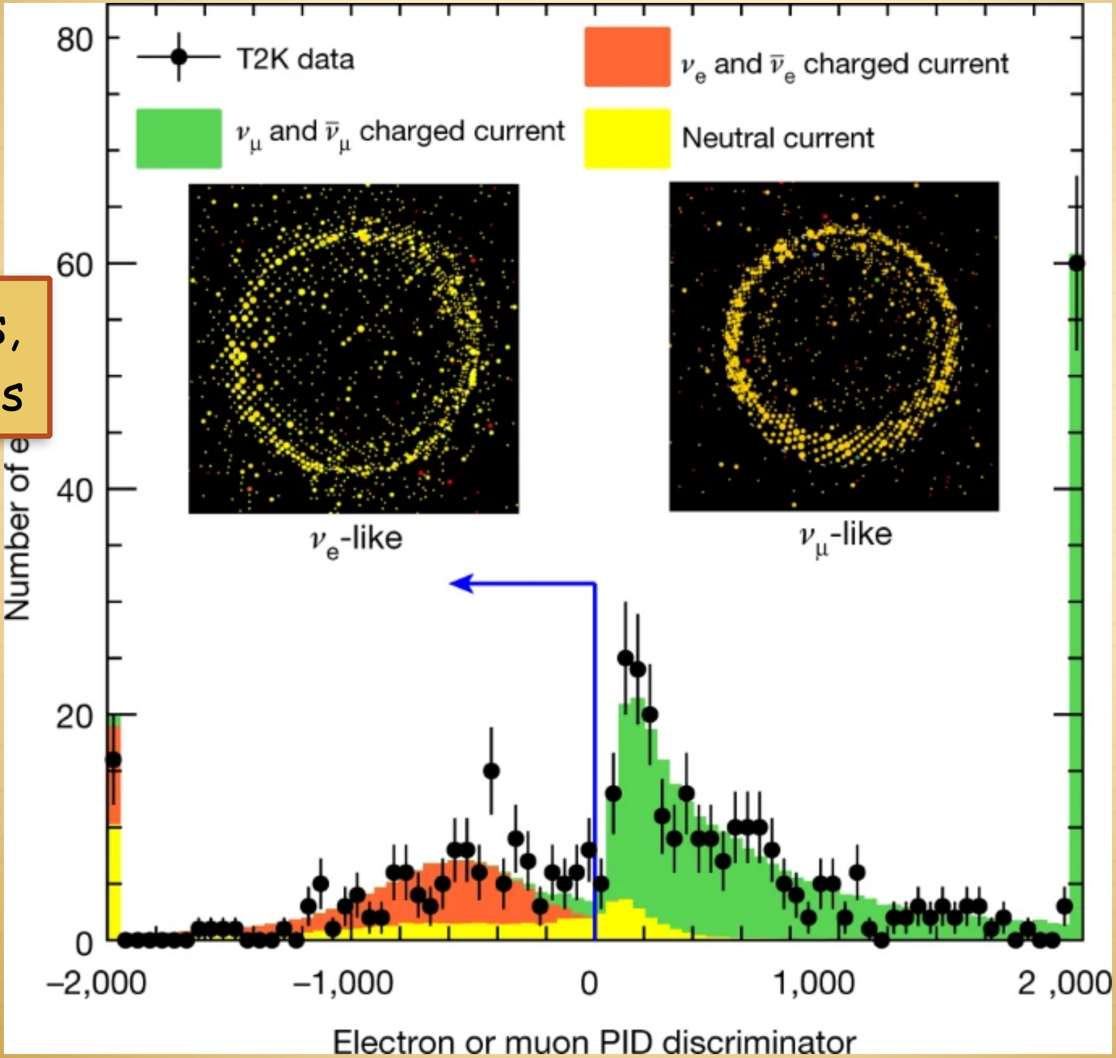
- **In water, light travels about 25% slower** than it does in a vacuum and it is possible for an energetic particle to travel faster than light.
- A **blue light** called **Cherenkov light** is emitted by charged particle.
- This light is detected by an array of light sensitive PMT's
- By measuring **the brightness, shape, and direction of the ring** we can figure out how much energy the particle had, whether it is a muon or electron, and which way it was going.

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\nu_e + n \rightarrow e^- + p$$

Separation between μ and e in Cherenkov detectors

Fuzzy edges, blurred rings



Sharp edges of the ring

Search Method at SK

- The main input to the SK analysis is the trigger time t_G
- It is used to define $\pm$**500* s time window centred on** t_G**,**
- The SK data in this window were collected and divided into four samples (three HE—ν and one LOWE)
- Downtime periods, due to calibration and preparation for Gd-loading in early 2020, prevented the follow up for three of the GW triggers.
- Out of the 39 confirmed events from 03a, SK was able to perform the analysis of 36, and one of them from LOWE was not used since there were large fluctuations in SK near GW time due to high-voltage problems in the PMTs.

*This is consistent with the time window chosen by the authors of Adrian-Martınez, S., Albert, A., Andre, M., et al. 2016, PhRvD, 93, 122010)

Event Samples

- **High Energy-ν** (ATMPD) (HE—ν) which corresponds to the neutrinos with $E_\nu > 100$ MeV. Usually used for **atmospheric neutrino oscillation** analysis.
- The neutrino is detected thanks to the outgoing lepton produced in the neutrino charged -current interaction.
  $\nu_\mu(\nu_e) + n \to \mu^-(e^-) + p$
- $\bar{\nu}_\mu(\bar{\nu}_e) + p \to \mu^+(e^+) + n$
- Note: tau neutrinos are not seen on event by event basis at SK

- **Low Energy-ν** (LOWE) corresponds to the events with energy between 7 and 100 MeV - used for **solar and supernova analyses**.
- The largest cross section is for the inverse beta decay (IBD):
  $\bar{\nu}_e + p \to e^+ + n$
- The second most dominant is neutrino elastic scattering :
  $\nu + e^- \to \nu + e^-$

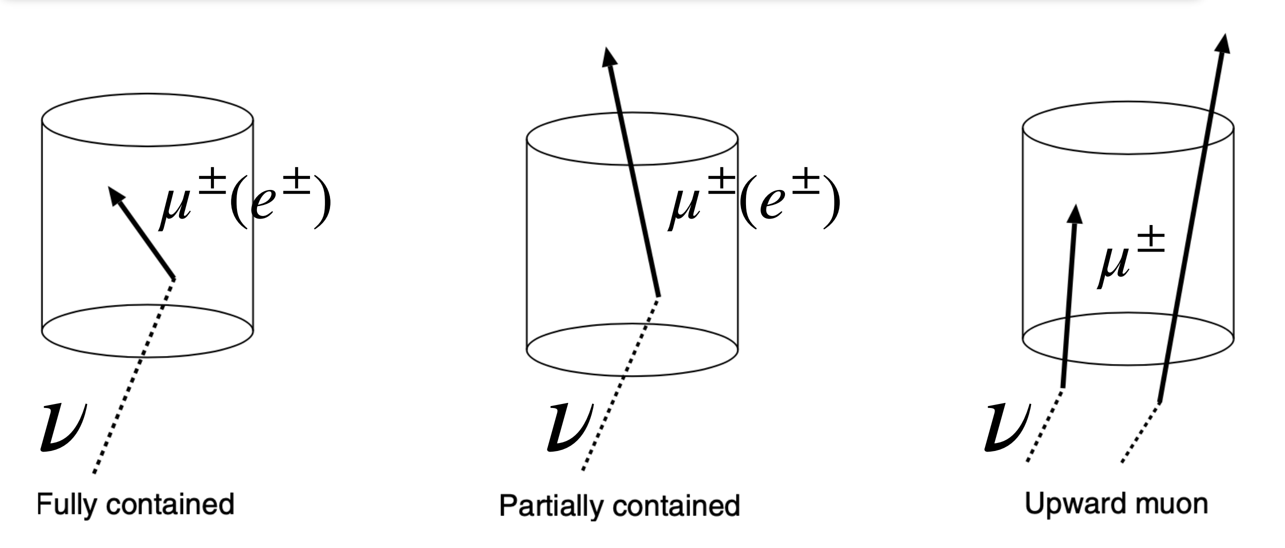
HE−ν samples

Fully contained (FC):
- Reconstructed vertex in ID
- OD hits<16

Partially contained (PC):
- Reconstructed vertex in ID
- OD hits>=16

Upward-going muons (UPMU):
- Through-going with requirement of track length >7 m
- Stopping in the detector

- For events classified as FC and PC, the neutrino interacts within the fiducial volume, defined as the region located more than 200 cm from the ID wall

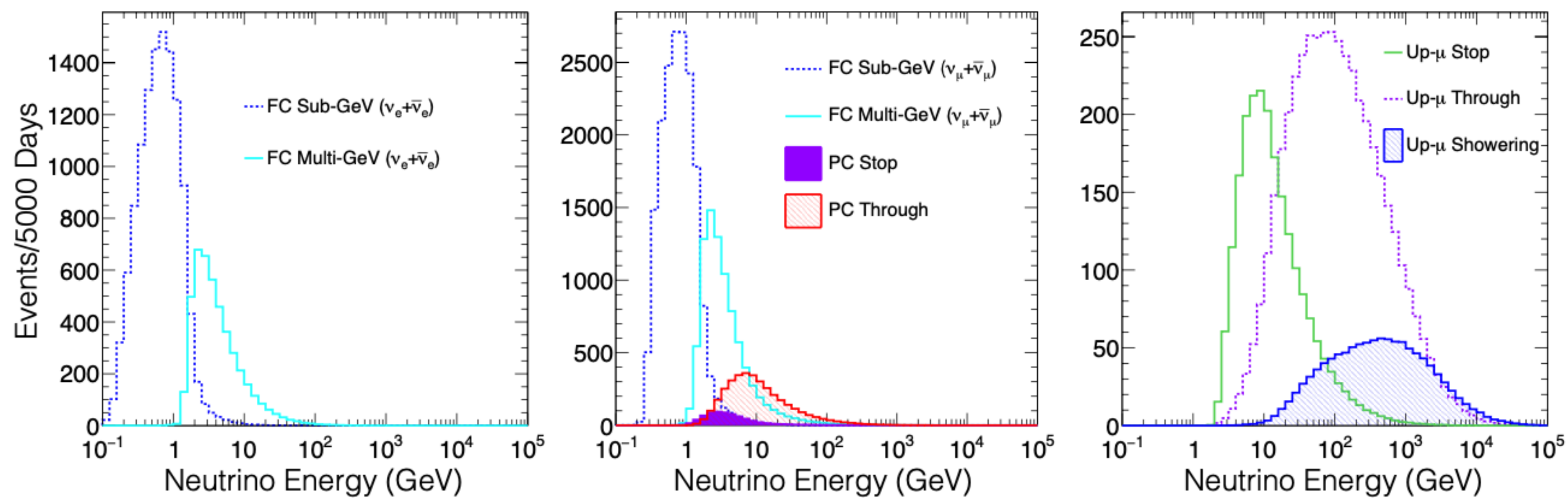


HE−ν samples

Fully contained (FC)

Partially contained (PC)

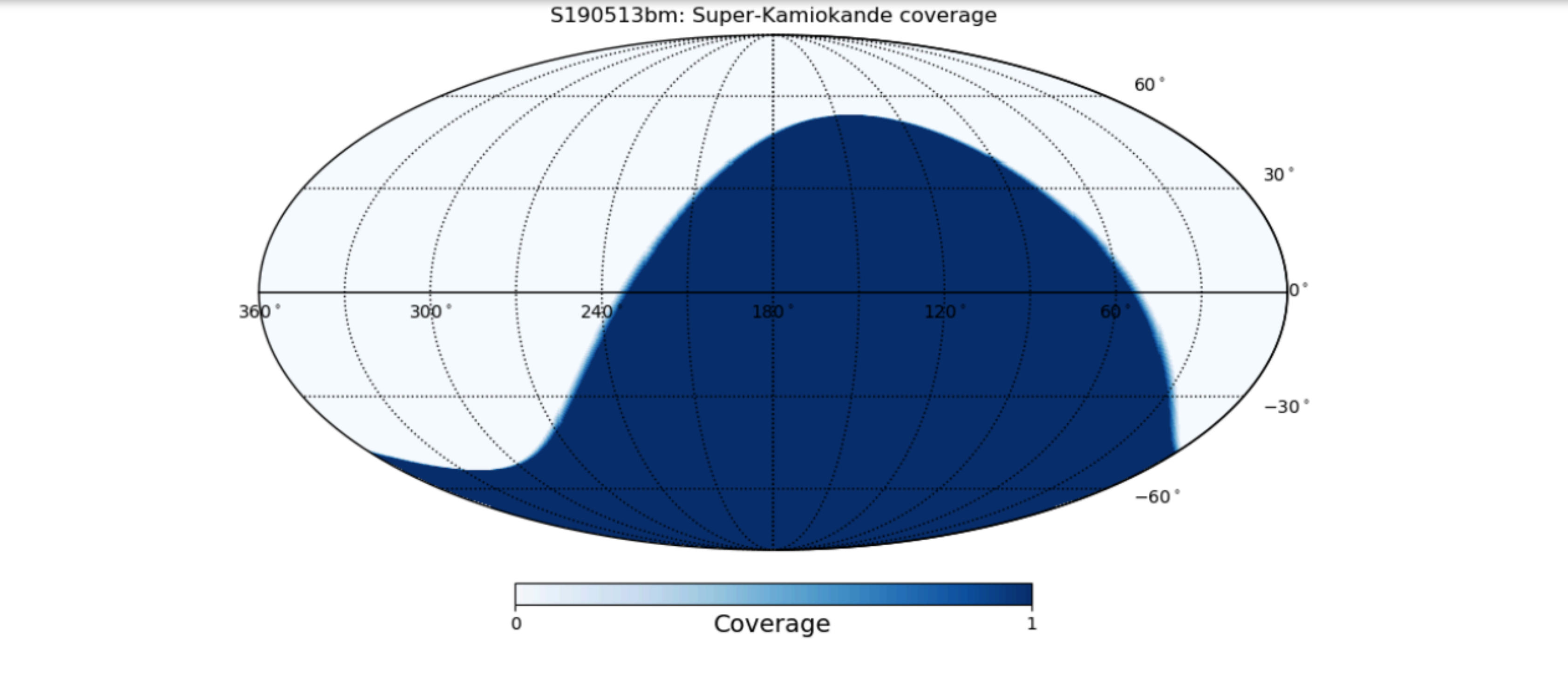
Upward-going muons (UPMU):



Expected neutrino energy spectra of different event categories

UPMU sample

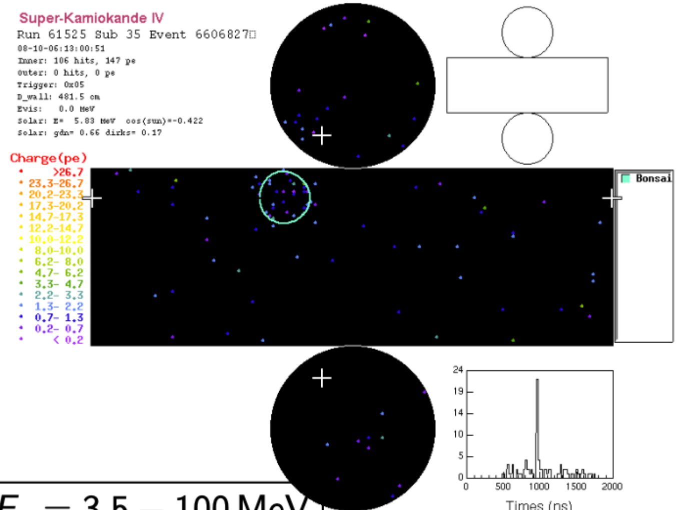
The up-going muon sample can only be used to detect neutrinos coming from below the SK horizon.



The boundary between the two regions are intermediary values, because they correspond to sky positions that are below the horizon only for a fraction of the time window ; as the time window is short with respect to one day (1000 s over 86 400 s), this effect is relatively small

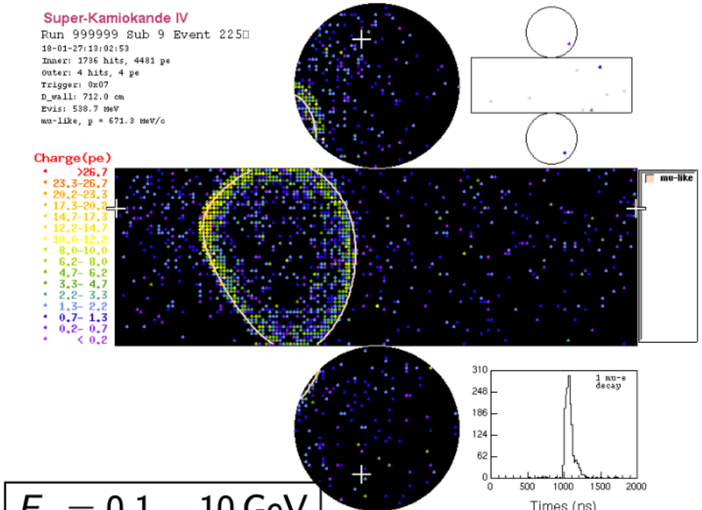
Examples of SK events

Low-energy events



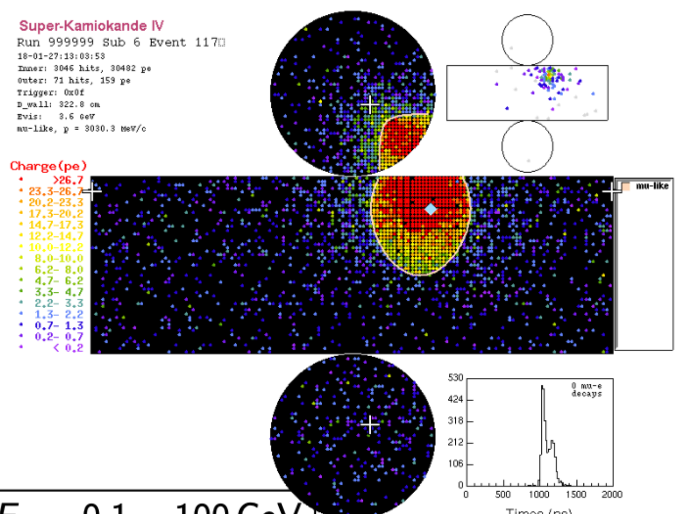
$E_\nu = 3.5 - 100$ MeV

Fully-Contained



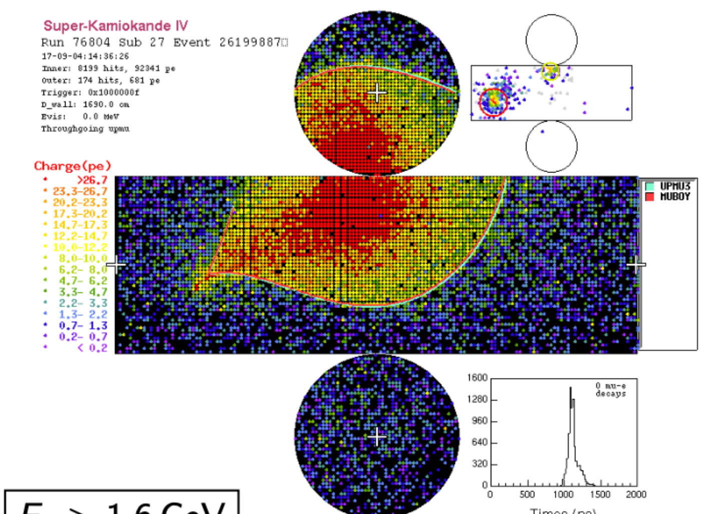
$E_\nu = 0.1 - 10$ GeV

Partially-Contained



$E_\nu = 0.1 - 100$ GeV

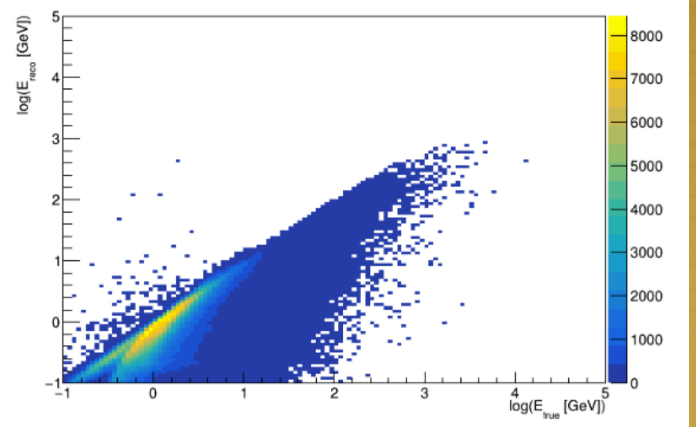
Upgoing muons



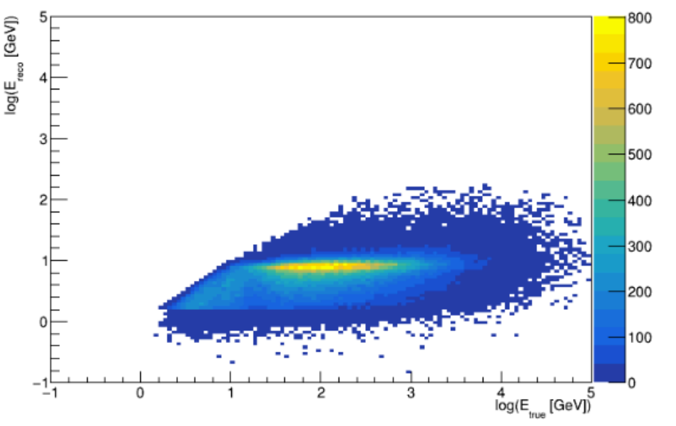
$E_\nu > 1.6$ GeV

Energy estimation

- Knowledge of energy of incoming neutrino is vital for separation of signal and background, computation of flux limits etc:
  - **For FC and PC samples**, we simply use the total visible energy that is an estimator of the total energy deposited in the detector.
  - **For UPMU sample**, we use the momentum obtained by the UPMU fitter, this will give a lower limit for the true momentum of the muon as it is not possible to know its total length (how much it has travelled before and after crossing the SK detector).
  - **For the LOWE**, the energy fitted by Bonsai (SK reconstruction algorithm) is used (based on total deposited energy).



(a) FC



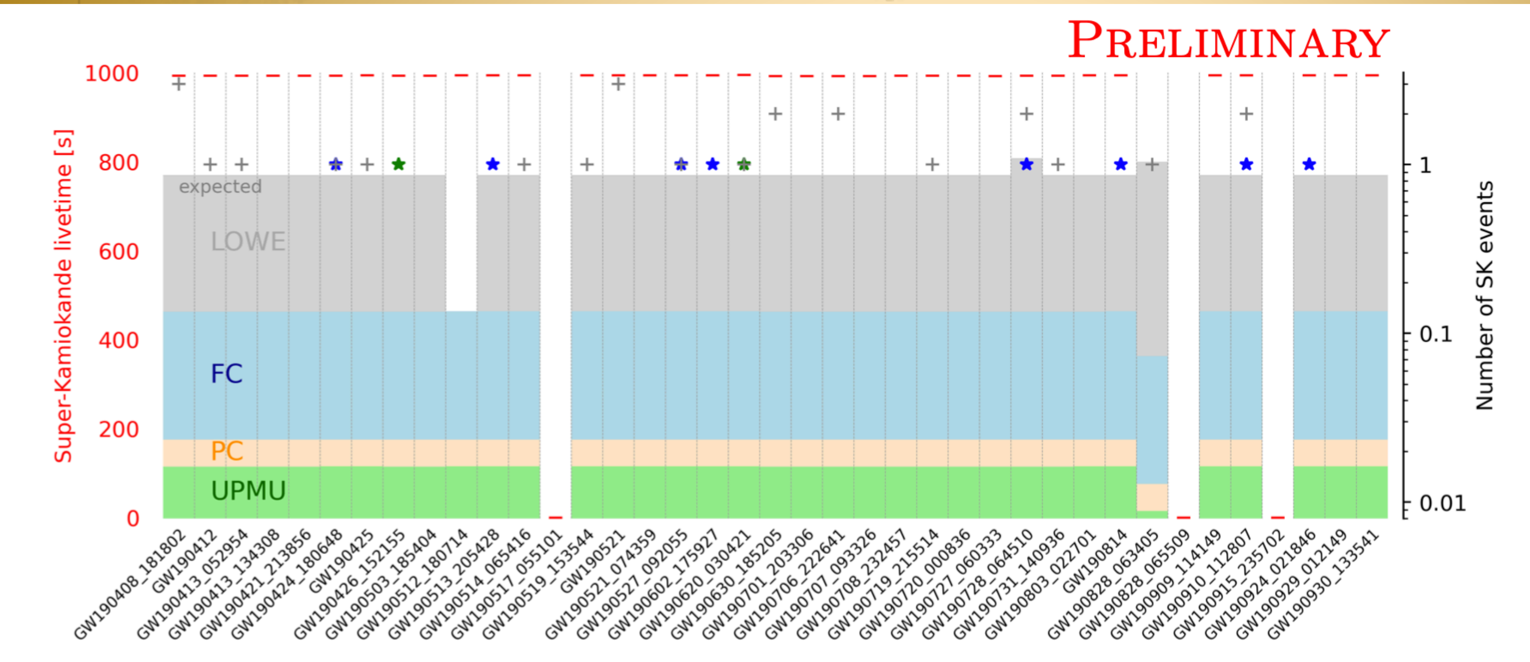
(c) UPMU

Background estimation and characteristics

- **The three ATMPD samples** are dominated by **atmospheric neutrinos**, that will therefore be the **dominant background for the analysis.**
- Fortunately the rate of such events is quite stable with time and their angular distribution only depends on zenith angle θ.
- Background will have one behaviour (atmospheric-like spectrum, isotropic angular distribution) while signal will behave differently (different spectrum, pointing to the source).
- **For LOWE sample** the main bkg under 20 MeV is the spallation products from cosmic ray muons (when muons travel through matter, their energy losses lead to nuclear breakup ("spallation") processes), and above 20 MeV the dominant bkg is from atmospheric neutrino interactions (decay electrons from invisible muons, NC interactions and low energy pions and muons)

Samples	FC	PC	UPMU	LOWE
Expected bkg 1000s window	0.112	0.007	0.016	0.729

Results on follow up



In total:

Sample	N_{obs}	N_{exp}
LOWE+	24	24.97
FC★	8	3.95
PC★	0	0.26
UPMU★	2	0.58

- LOWE: No significant excess was observed with respect to the expected Poisson statistics.
- HE−ν events: we have found 10 events which were associated with GW triggers.
  - For each selected neutrino event the timing $\Delta t = (t_\nu - t_{GW})$, energy, direction and its angular uncertainty are provided.

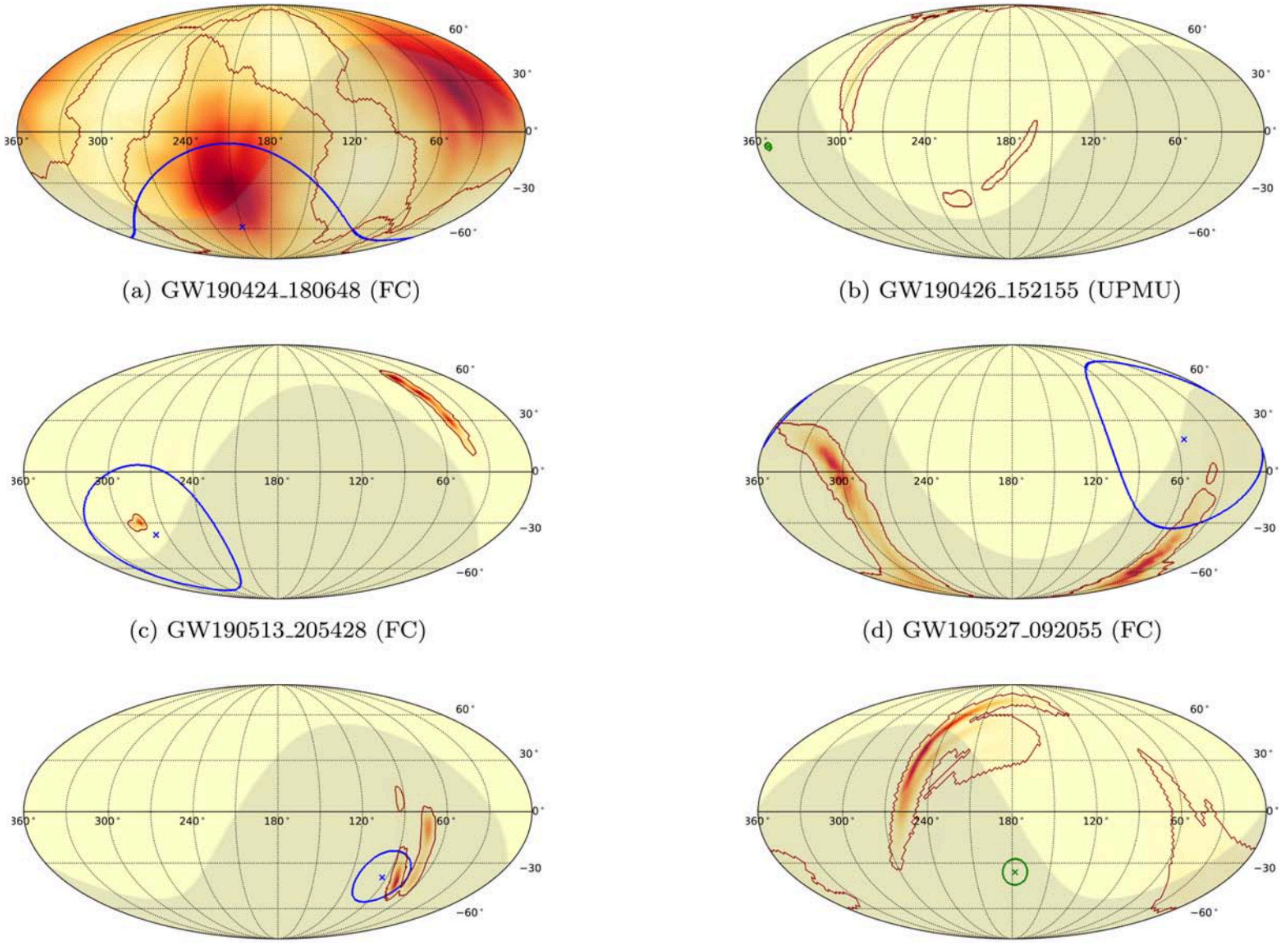
List of selected HE—ν events

In total 10 HE—ν events were selected

Trigger Name	SK Sample	ΔT (s)	E_{reco} (GeV)	R.A. (deg)	Decl. (deg)
GW190424_180648	FC	104.03	0.57	210.82	−58.74
GW190426_152155	UPMU	278.99	9.52	352.37	−8.46
GW190513_205428	FC	−183.27	0.68	279.34	−37.27
GW190527_092055	FC	248.41	0.48	54.09	18.80
GW190602_175927	FC	−286.52	2.75	93.67	−38.90
GW190620_030421	UPMU	−327.70	2.33	177.69	−35.59
GW190728_064510	FC	102.99	0.19	300.45	29.71
GW190814	FC	250.36	1.21	157.59	−9.47
GW190910_112807	FC	301.42	1.08	160.13	−22.70
GW190924_021846	FC	411.87	0.30	281.38	−54.52

- For FC and PC, the direction of each event was estimated by reconstructing the Cherenkov rings in the ID, while the direction of UPMU event is determined using the OD hit information.
- This local direction was converted to equatorial coordinates, R. A. and decl., so that it can easily be compared with GW localisation.

Ten SK high-energy events in time coincidence(1)



(a) GW190424_180648 (FC)

(b) GW190426_152155 (UPMU)

(c) GW190513_205428 (FC)

(d) GW190527_092055 (FC)

(e) GW190602_175927 (FC)

The spatial distribution is superimposed with the skymap provided by the LIGO/Virgo collaboration, allowing direct comparison of sky positions.

Skymaps in equatorial coordinates

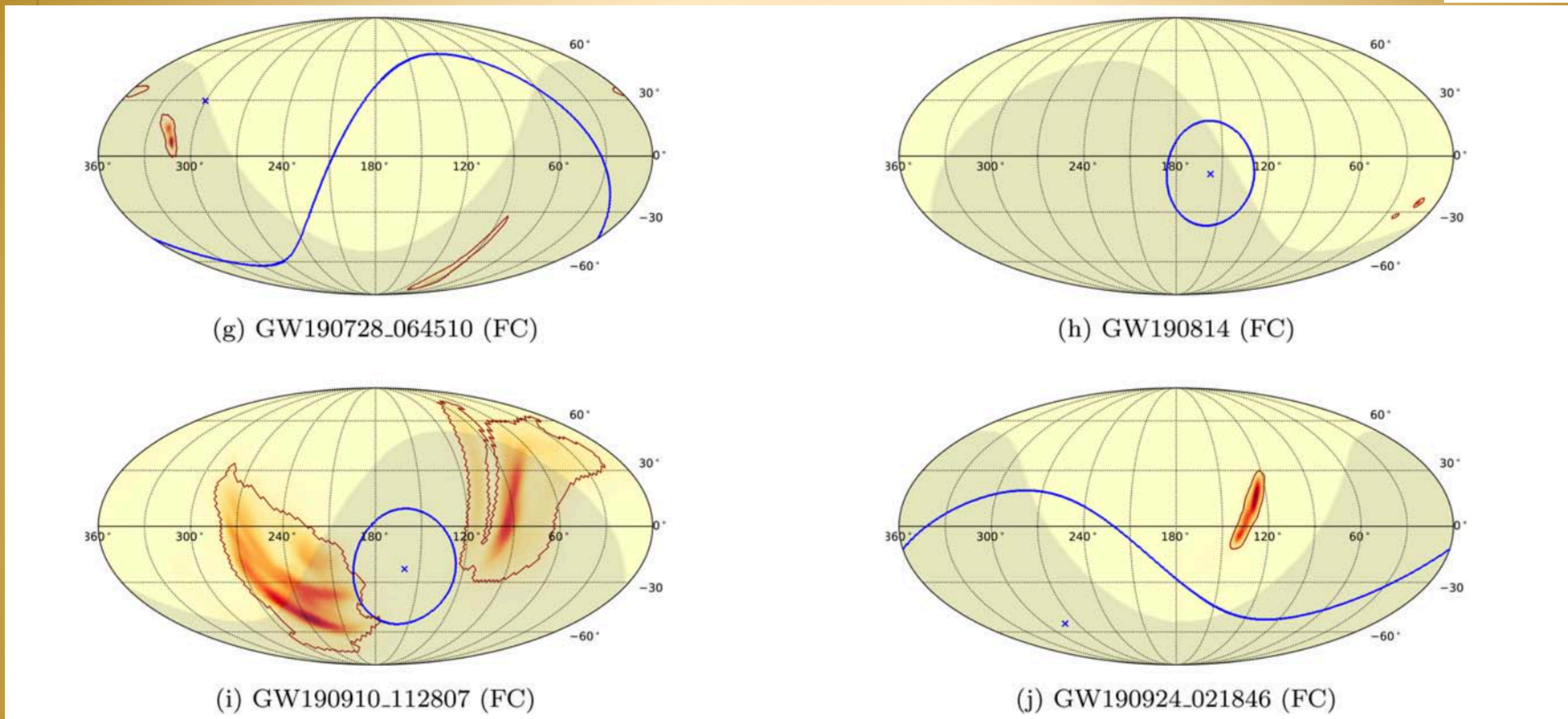
Red: GW localisation and 90% contour

Blue: SK FC events with 1σ angular uncertainty

Green: SK UPMU events.

Shaded area: SK upgoing sky.

Ten SK high-energy events in time coincidence(2)



(g) GW190728_064510 (FC)

(h) GW190814 (FC)

(i) GW190910_112807 (FC)

(j) GW190924_021846 (FC)

Skymaps in equatorial coordinates

Red: GW localisation and 90% contour

Blue: SK FC events with 1σ angular uncertainty

Green: SK UPMU events.

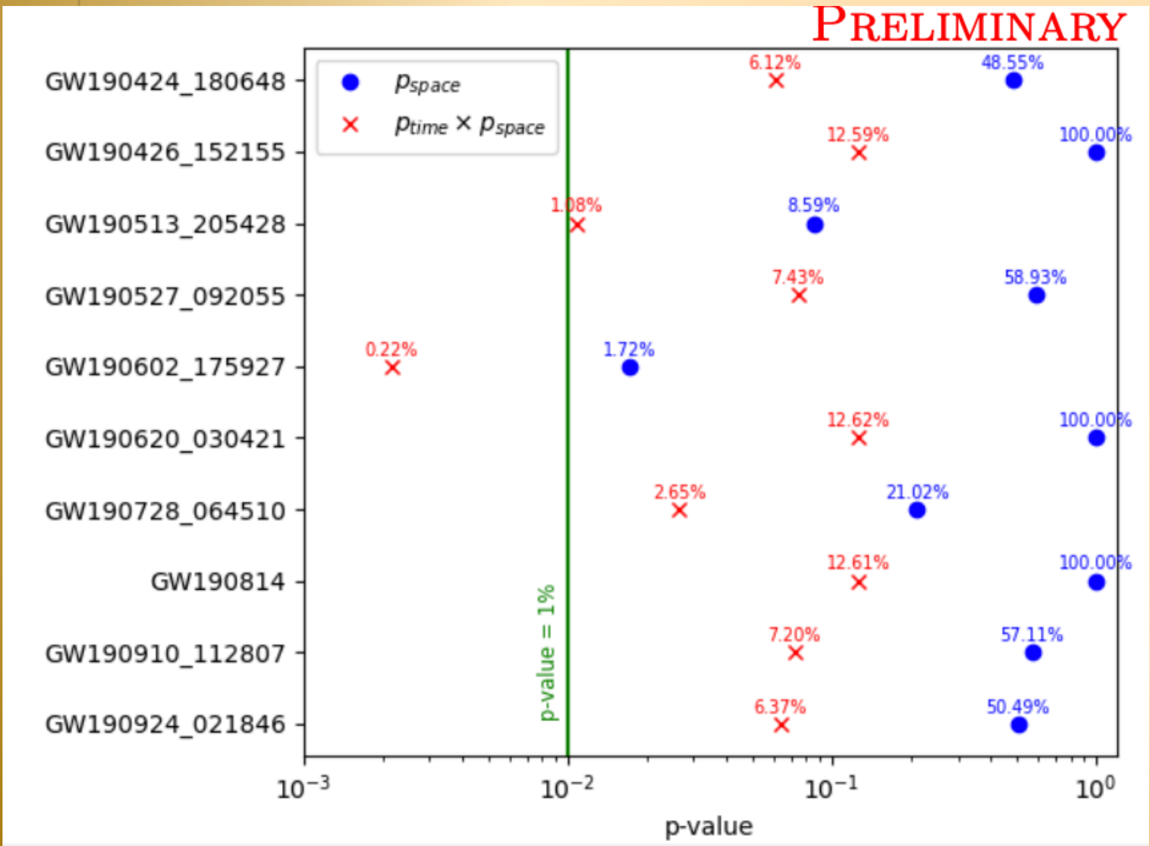
Shaded area: SK upgoing sky.

Observation significance (1)

- Test statistics (TS) has been built to separate signal (point source consistent with GW localization, $E^{-\gamma}$ spectrum)from background (full sky). It compares p-values (compared observed TS to BKG distributions)
- P-value was divided into:
  - **temporal component** p_{time} that is evaluating the probability to observe at least one SK event in time coincidence with GW -> this is the Poisson probability to observe at least one event in selected time window $p_{time} = p(N \geq 1) = 1 - \exp^{(-n_B)}, p_{time} = 12.6\,\%$ for $n_B = 0.13$(total number of events - total background (FC+PC+UPMU) expected in 1000s window)
  - **spatial component** p_{space}comparing the direction of reconstructed neutrinos with the GW localisation. This is obtained using a maximum likelihood method with the GW localisation used as spatial prior.
  - $p = p_{time} * p_{space}$
  - Method presented by IceCube collaboration. IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog. Astrophys.J.Lett. 898 (2020) 1, L10

Observation significance (2)

Test statistics (TS) has been built to separate signal (point source) from background (full sky). It compares p-values (compared observed TS to Bkg distributions)



The most significant GW+ν coincidence is for GW190602_175927 p=0.22%

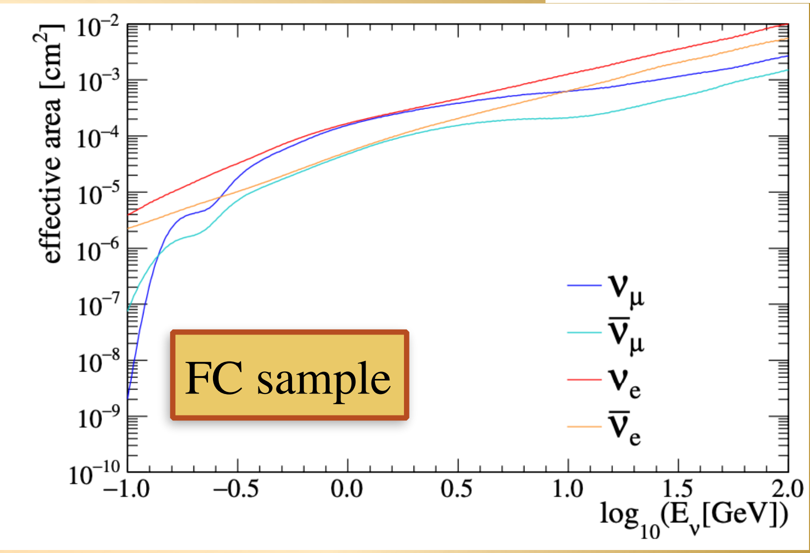
Considering the number of trials (N=36 follow-ups) we get post-trial value P=7.8% (1.4σ) which is fully consistent with the background only hypothesis.

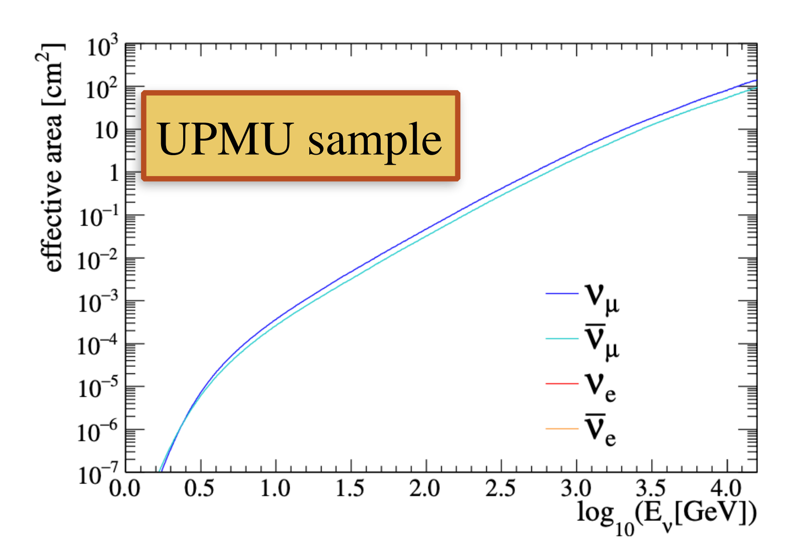
High energy flux limits (1)

- The neutrino flux is assumed as $\frac{dn}{dE_\nu} = \phi_0 E_\nu^\gamma, \quad \gamma = -2$ and $N_{\text{expected signal}} = \int_{E_{min}}^{E_{max}} dE_\nu A_{eff}^{s,f}(E_\nu,0) x \frac{dn}{dE_\nu}$
- **Sample-by-sample flux limits:**
  - For each sample "s" and flavour "f" $(\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e)$ and source position Ω, the neutrino flux ϕ_0 is related to the number of events $N_{sig} = \phi_0^{s,f} * \int A_{eff}^{(s,f)}(E_\nu, \Omega) * E_\nu^{-2} dE_\nu = \phi_0^{s,f} * c^{(s,f)}(\Omega)$,
  - where $A_{eff}^{(s,f)}$ **is the SK detector effective area** for selected sample and neutrino flavour and integration range is (0.1 - 10^5)GeV.
  - $c^{(s,f)}(\Omega)$ is the detector acceptance that takes into account the source direction
  - The effective areas have been computed as a function of neutrino energy and zenith angle using 500 -years-equivalent of atmospheric MC simulations

SK detector effective area

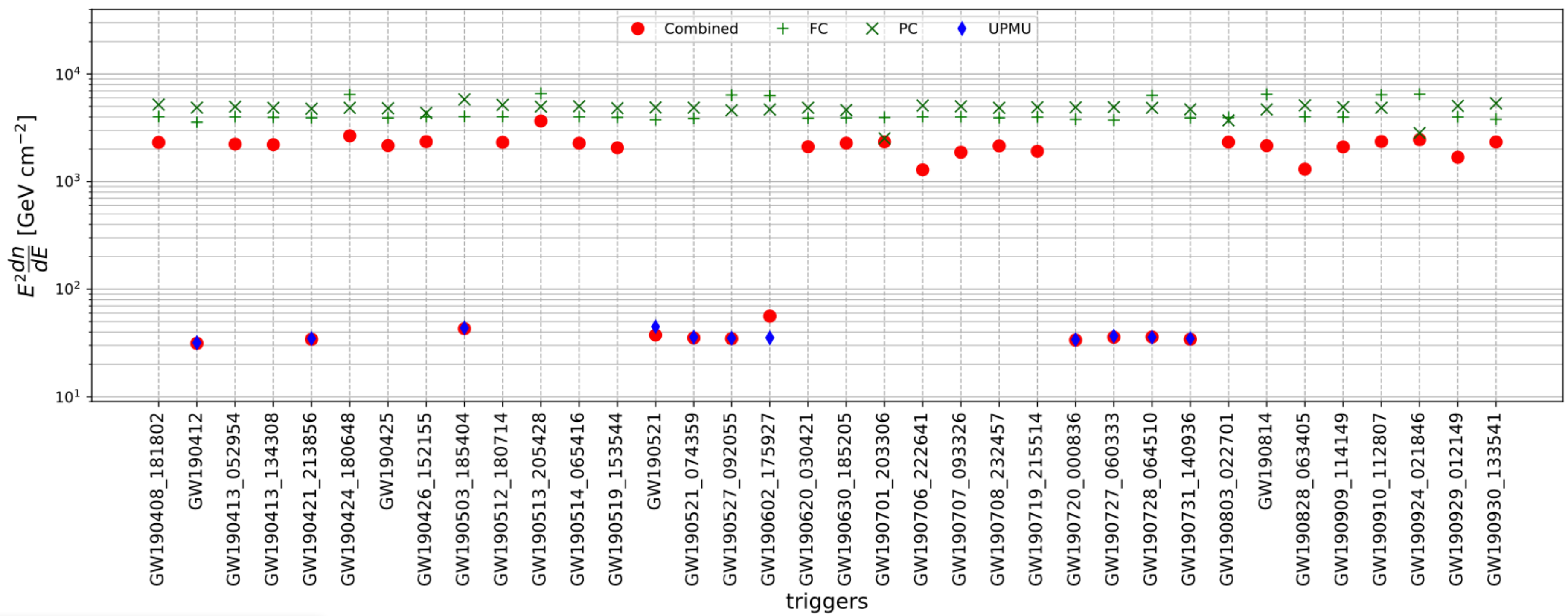
- For a given neutrino flavour, we know the atmospheric neutrino flux $\Phi_{atm}(E,\theta)[GeV^{-1}cm^{-2}s^{-1}sr^{-1}]$
- For a given bin $[E, E+dE],[\theta,\theta+d\theta]$ (integrating over azimuth angle) in terms of truth information, for given lifetime T (e.q 500 years) we define $M^{bin}_{true}[cm^{-2}]$:
  $M^{bin}_{true} = \Phi_{atm}(E,dE) * dE * \sin\theta d\theta * 2\pi * T$
- For given sample and neutrino flavour, we look at the number of events after simulation+reconstruction+selection $N^{bin}_{selected}$
- The effective area is: $A^{f,s}_{eff}(E,\theta) = \frac{N^{bin}_{selected}}{M^{bin}_{true}}$





High energy flux limits(2)

Because no statistically significant event excess was observed within the 1000s time window in the HE-ν samples, the observation can be converted to an upper limit on the incoming neutrino flux.

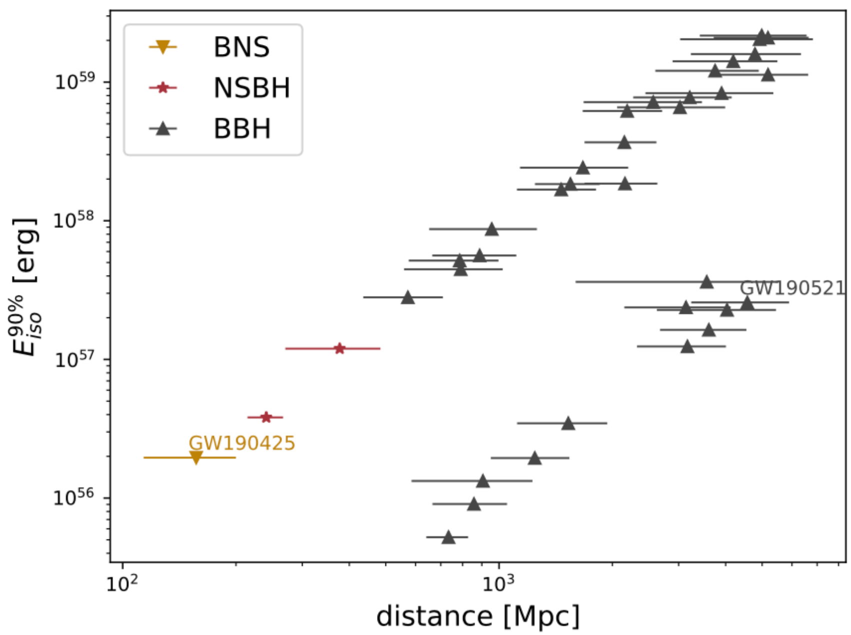


The full results for ν_μ

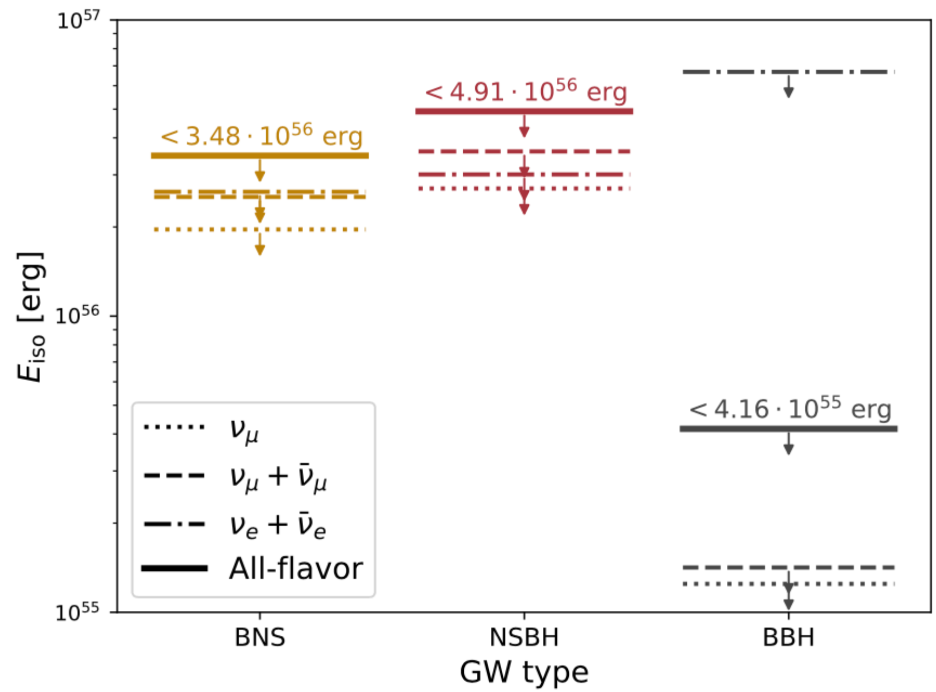
Note: UPMU upper limits are only reported if the GW localisation is mainly below the horizon, where this sample has sensitivity. Combined are close to the individual ones.

The total energy of neutrinos from the source

- The total energy of neutrinos from the source (assuming isotropic) is $E_{iso} = 4\pi d^2 \int \frac{dn}{dE} * EdE$



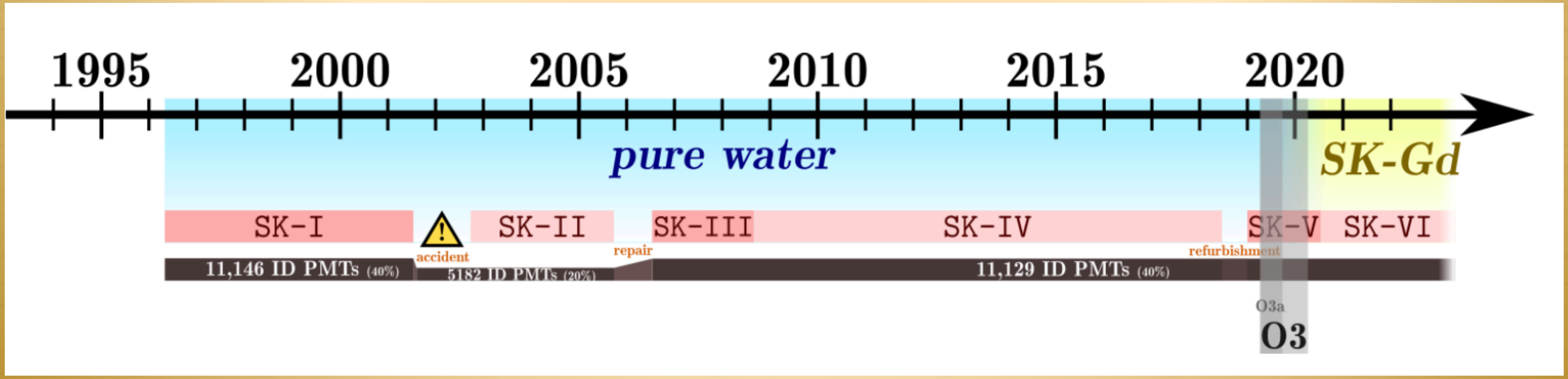
(a) Limits on $E_{\rm iso}^{\nu_\mu}$



The 90% C.L. upper limits on the isotropic energy emitted in neutrinos for the 36 GW triggers followed up by SK, as a function of source distance. The distance and its error, as well as the source type (indicated by the different colors and markers), are provided using the data from Abbott et al. (2021) (m < 3 M = NS, m > 3 M = BH).

SK-Gd era

Gadolinium project at Super-K: SK-Gd



SK detector refurbishment work in 2018

Fix water leak from the tank

About 1 ton per day of pure water leaked from the SK detector until 2018. We have sealed all welding joints of the stainless steel panels that make up the tank.

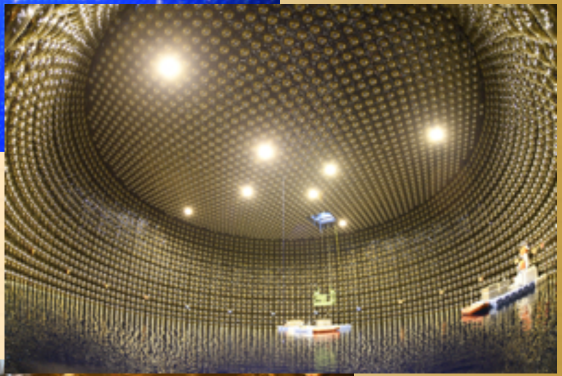
Improvement of tank piping

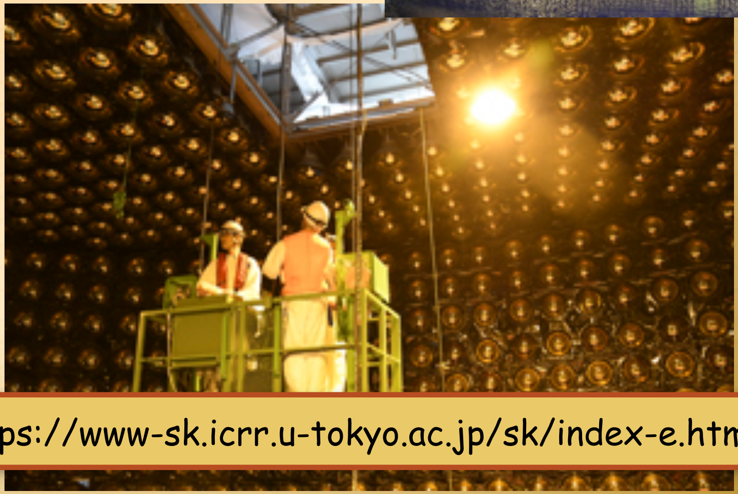
Ultra-pure water in the tank was circulated at a flow rate of 60 tons per hour before. We improved the water piping and water systems so that they can process and circulate water at 120 tons per hour. (17days per one circulation).

Replacement of faulty photomultiplier tubes

Since the last in-tank SK maintenance during 2005-2006, some photomultipliers became faulty. We have replaced a few hundred PMTs.

The refurbish started from May 2018 and completed by January 2019.

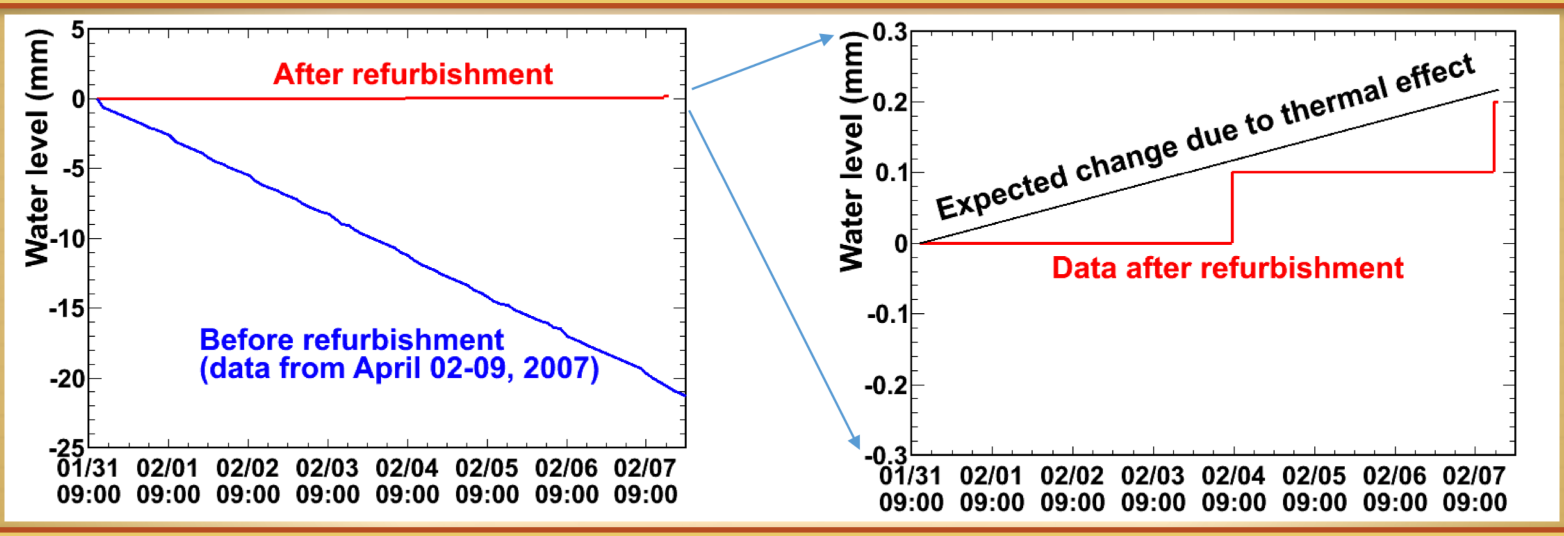




Photocredit: ICRR, Kamioka Observatory check https://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

Water Leakage check after refurbishment

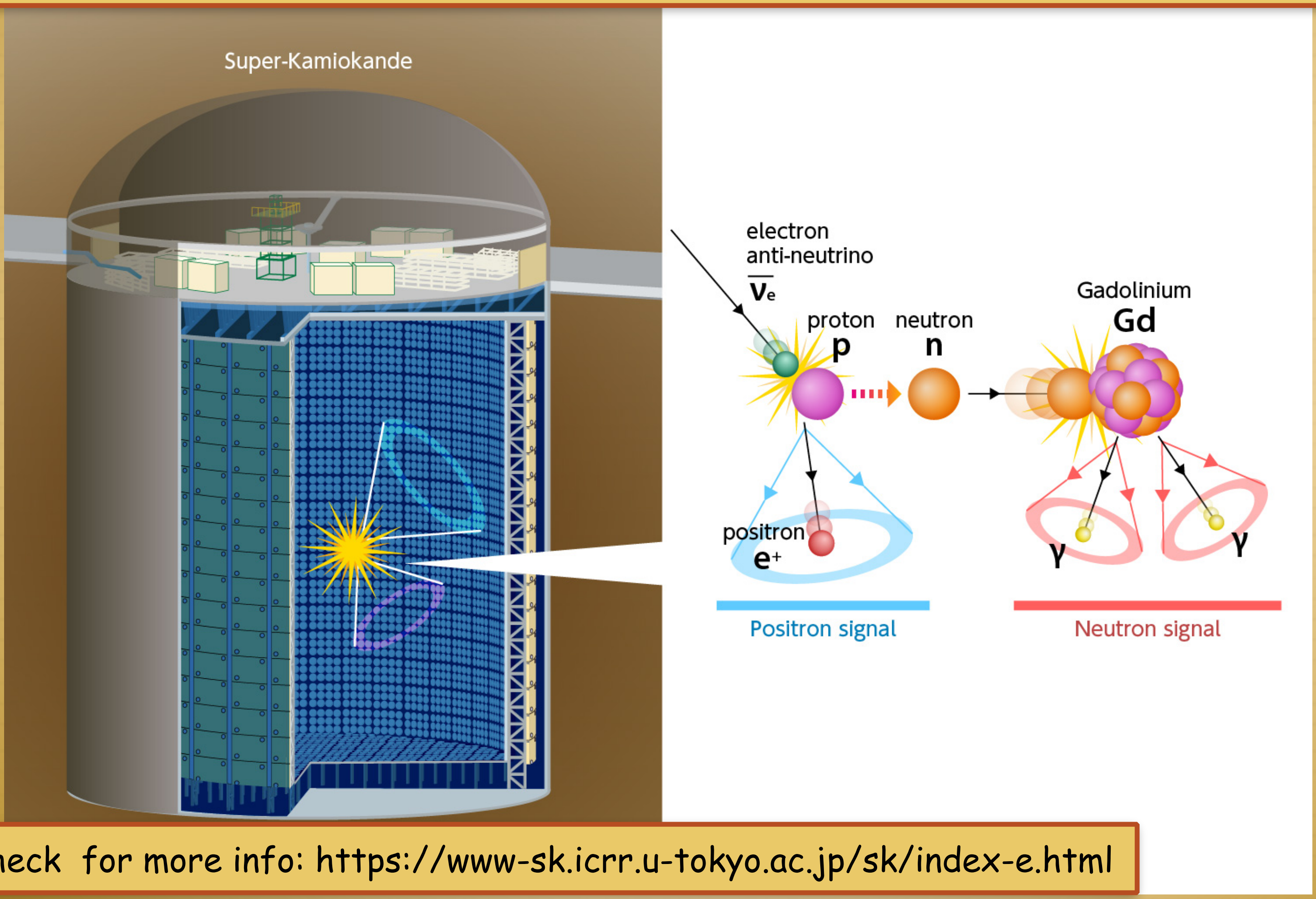
After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)



Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.

SK-Gd era

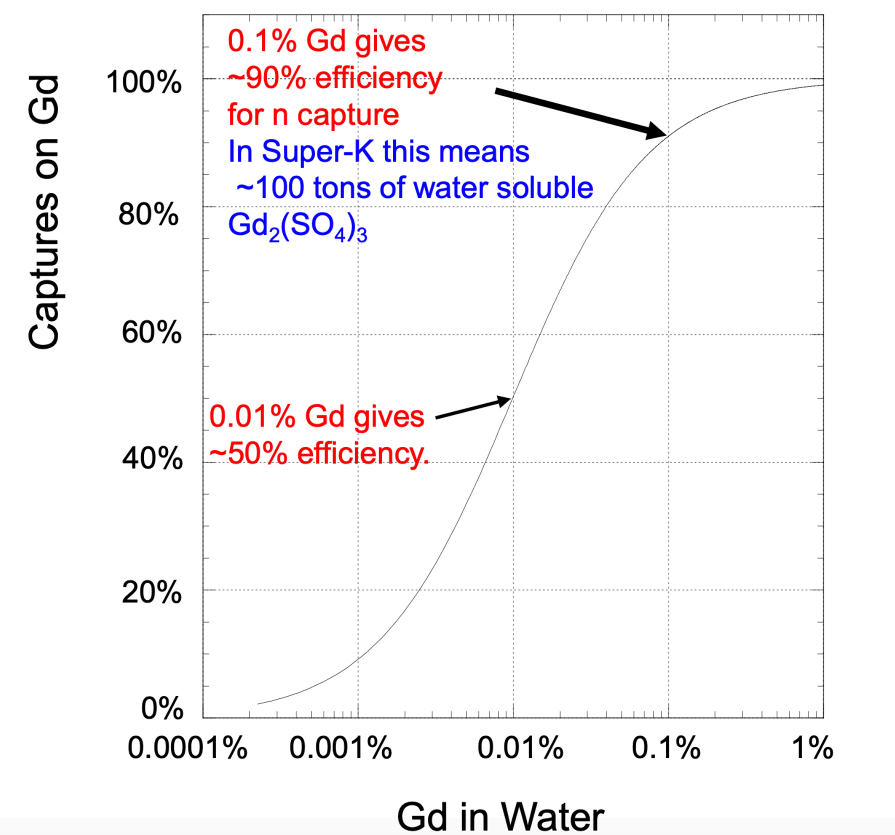
- Identify $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse Beta Decay- IBD) events by neutron tagging with Gadolinium.
- Gadolinium has large neutron capture cross section and emits 8MeV gamma cascade.



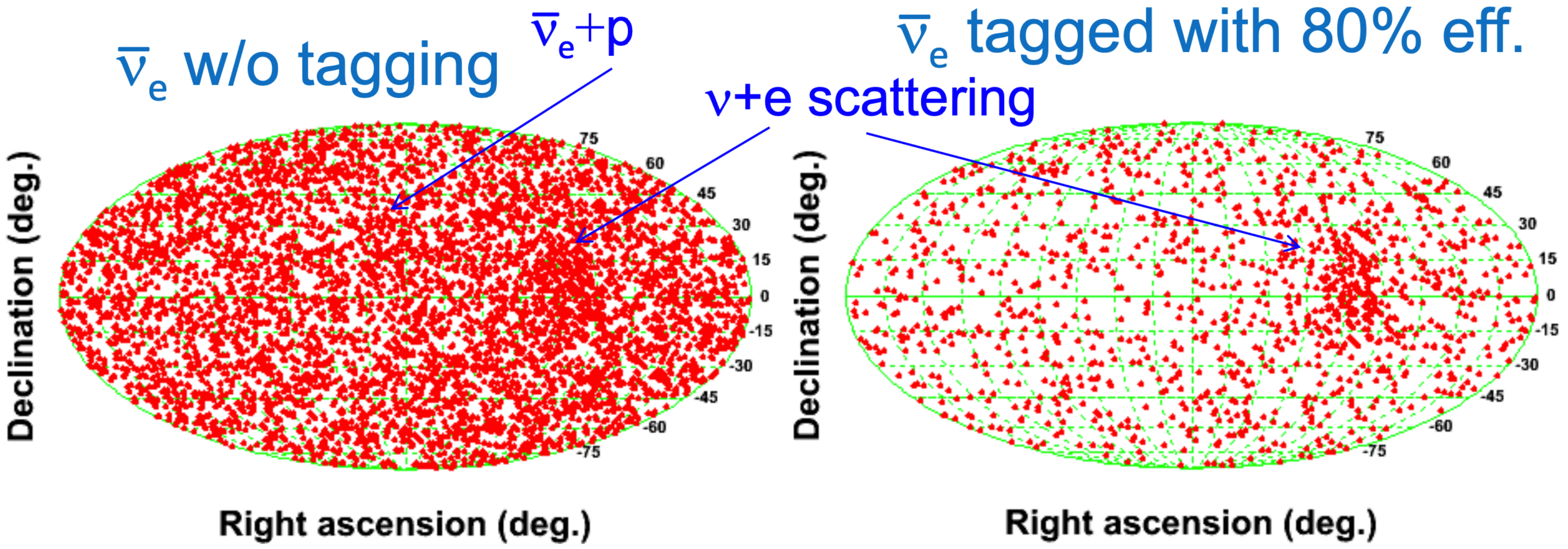
Check for more info: https://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

SK-Gd era

- The addition of gadolinium improves SK's ability to:
  - to observe **Supernova Relic Neutrinos** (SRN)(also called Diffuse Supernova Neutrino Background (DSNB)). First observation is expected at SK-Gd
  - **Improve observation of supernova burst neutrinos**
    - Improve pointing accuracy
    - $\nu_e(+\nu_x)$ spectrum measurement
    - Possible detection of neutrinos from Si burning.
  - **Reduce neutrino background for proton decays**
    - Anti-tag neutrons to reduce atmospheric neutrino background
  - **Discriminate neutrino and anti-neutrino events for T2K**



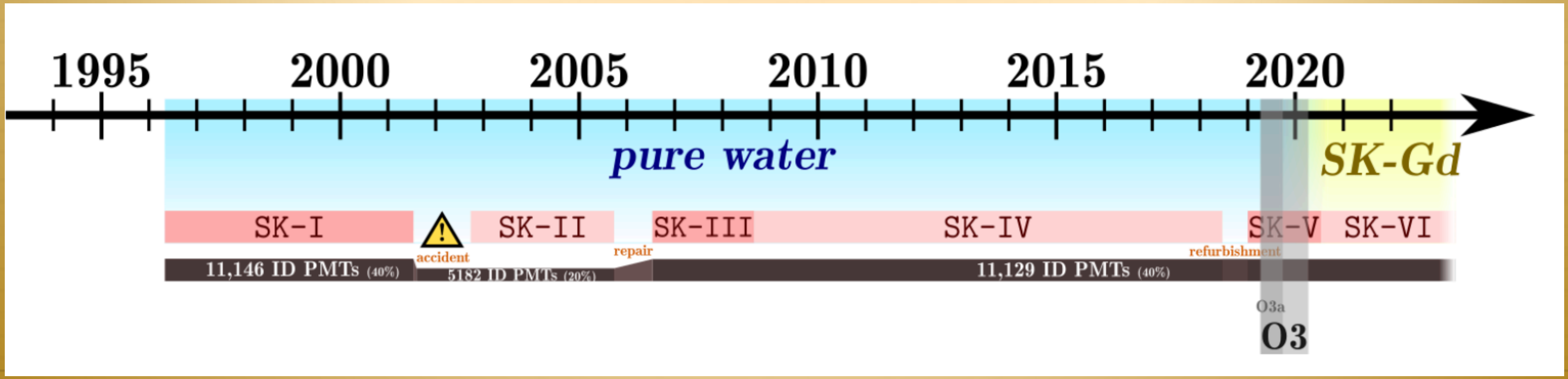
SK-Gd era
Improving pointing accuracy



If $\bar{\nu}_e$ can be tagged and subtracted from the plot, directional events (ν+e scattering events) can be enhanced and pointing accuracy can be improved.

Polish SK group

is member of SK from the beginning



Prof. dr hab. Danuta Kiełczewska 1945-2016

The first and only participant of the Super-Kamiokande experiment from the very beginning (1996)

Thanks to prof. Kieczewska Polish neutrino groups could join T2K in 2006.

Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande Collaboration

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Polish SK group members

Currently there are only two Polish institutions @ SK:

- University of Warsaw, Faculty of Physics
- National Centre for Nuclear Research (NCBJ)

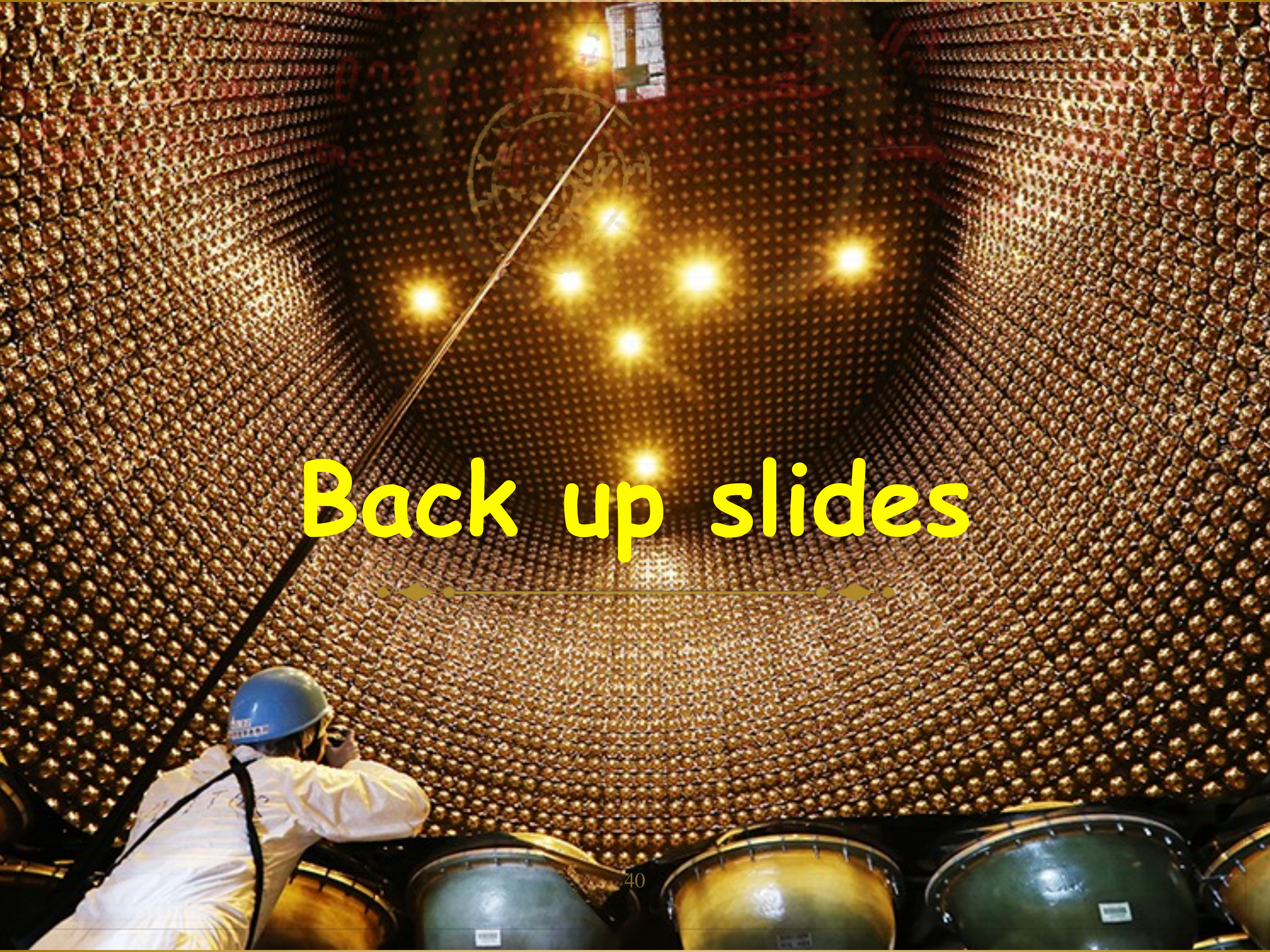
- Physics related topics **(ATMPD group):**
  - **Dark matter searches**: Dr Piotr Mijakowski (NCBJ), dr Katarzyna Frankiewicz (NCBJ)*
  - **Tau appearance analysis**: Ms Maitrayee Mandal (NCBJ), dr hab Justyna Łagoda (NCBJ), dr Magdalena Posiadała-Zezula
  - **Atmospheric neutrino oscillation analysis**: dr Magdalena Posiadala-Zezula
- Calibration part **(Calibration group):**
  - **Tuning of the reflectivity from the PMT's of the Super-Kamiokande inner detector**: Lakshmi Mohan (NCBJ), dr Magdalena Posiadala-Zezula
  - **Study of the reflectivity changes on physics results:** dr Joanna Zalipska (NCBJ), Yashwanth Prabhu (NCBJ)

* left Super-K

Summary

- Search for neutrinos in SK with coincidence with GW events from LIGO-Virgo O3a was performed
- In the ±500s time windows centred on the triggers, **no excess with respect to the background hypothesis was observed** in any of the four considered samples (three for HE-ν, one for LE-ν).
- Most significant observation is for GW 190602_175927 (1.4σ)
- Flux limits have been computed:
  - High energy: $E^2 \frac{dn}{dE}|_{\nu_\mu} \leq 4x10$ GeV/cm2 if GW below horizon ($2x10^3$ otherwise)
- SK-Gd phase is on. Main physics target is the detection of supernova relic neutrinos.
  - SK-Gd will improve pointing accuracy for galactic supernova.
  - Will also improve separation of neutrino from antineutrino interactions at SK

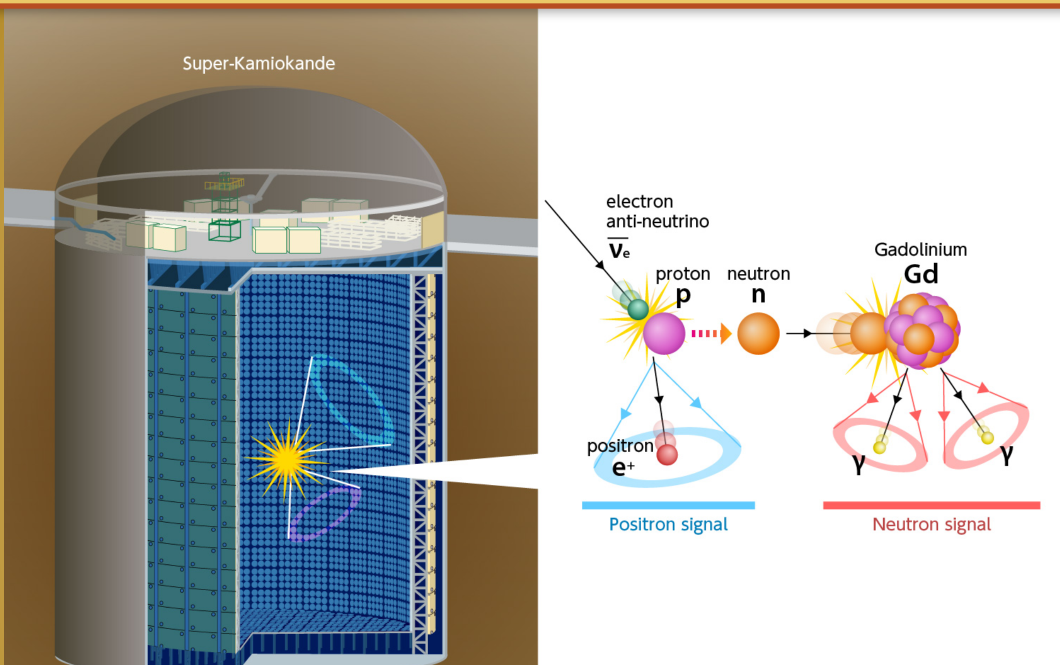

Thank you !

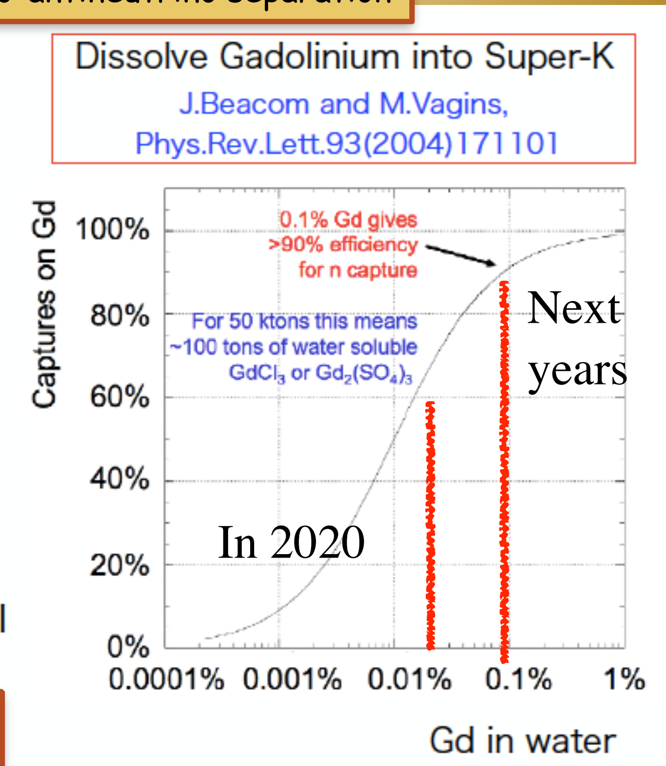


Back up slides

Why Gd salt was added ?

MAIN AIM: improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos"
FOR T2K and SUPER-K ATM. ANALYSES: we may be able to improve neutrino-antineutrino separation





Cross section for neutron capture for Gd is 49000 barns, while for protons is only 0.3 barn.

Problems:

- discrepancy between predictions and data for neutron capture on hydrogen- studies ongoing

Place for new studies on selections

High energy flux limits (2)

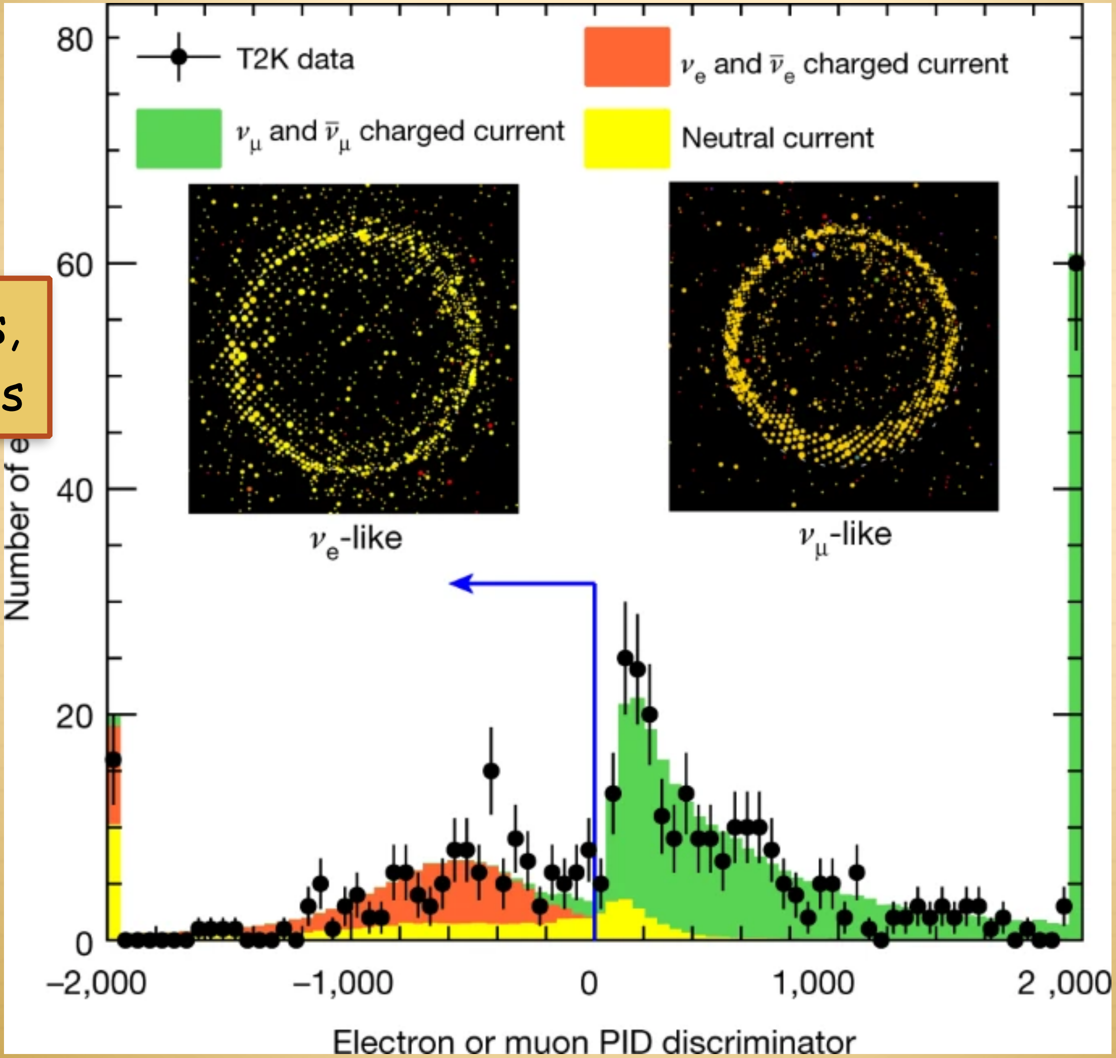
- **Sample-by-sample flux limits:**
  - For each sample "s" and flavour "f" ($\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$) and source position Ω, we marginalize over the source localisation the following Poisson likelihood is defined as:

$$L(\phi_0, n_B, N) = \int \frac{(c(\Omega)\phi_0 + n_B)^N}{N!} * \exp^{-(c^{s,f}(\Omega)*\phi_0 + n_B)} * P_{GW}(\Omega) d\Omega$$

  - And 90% confidence level upper limit on the flux ϕ_0^{up} is obtained by solving $\int_0^{\phi_0^{up}} L(\phi) d\phi = 0.9$
- **Combination of the samples:** Limits obtained combining FC, PC and UPMU and using TS defined before.

Separation between μ and e in Cherenkov detectors

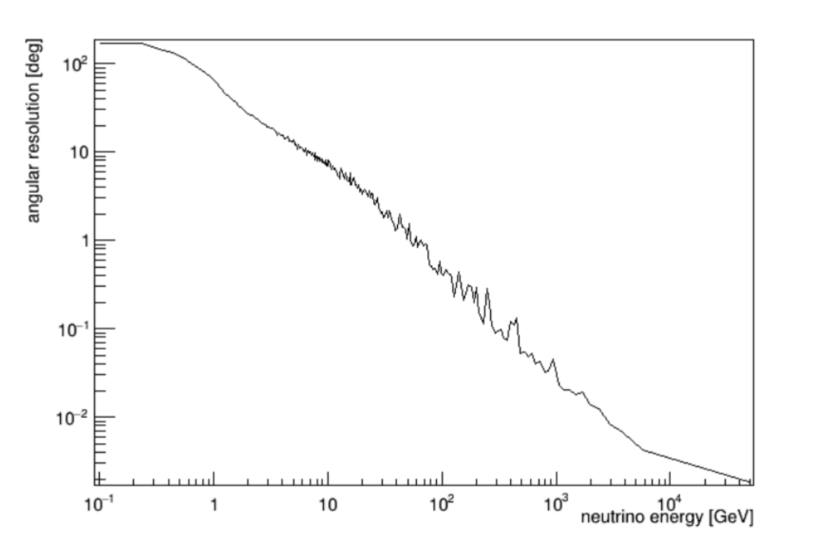
Fuzzy edges, blurred rings



Sharp edges of the ring

Angular resolution

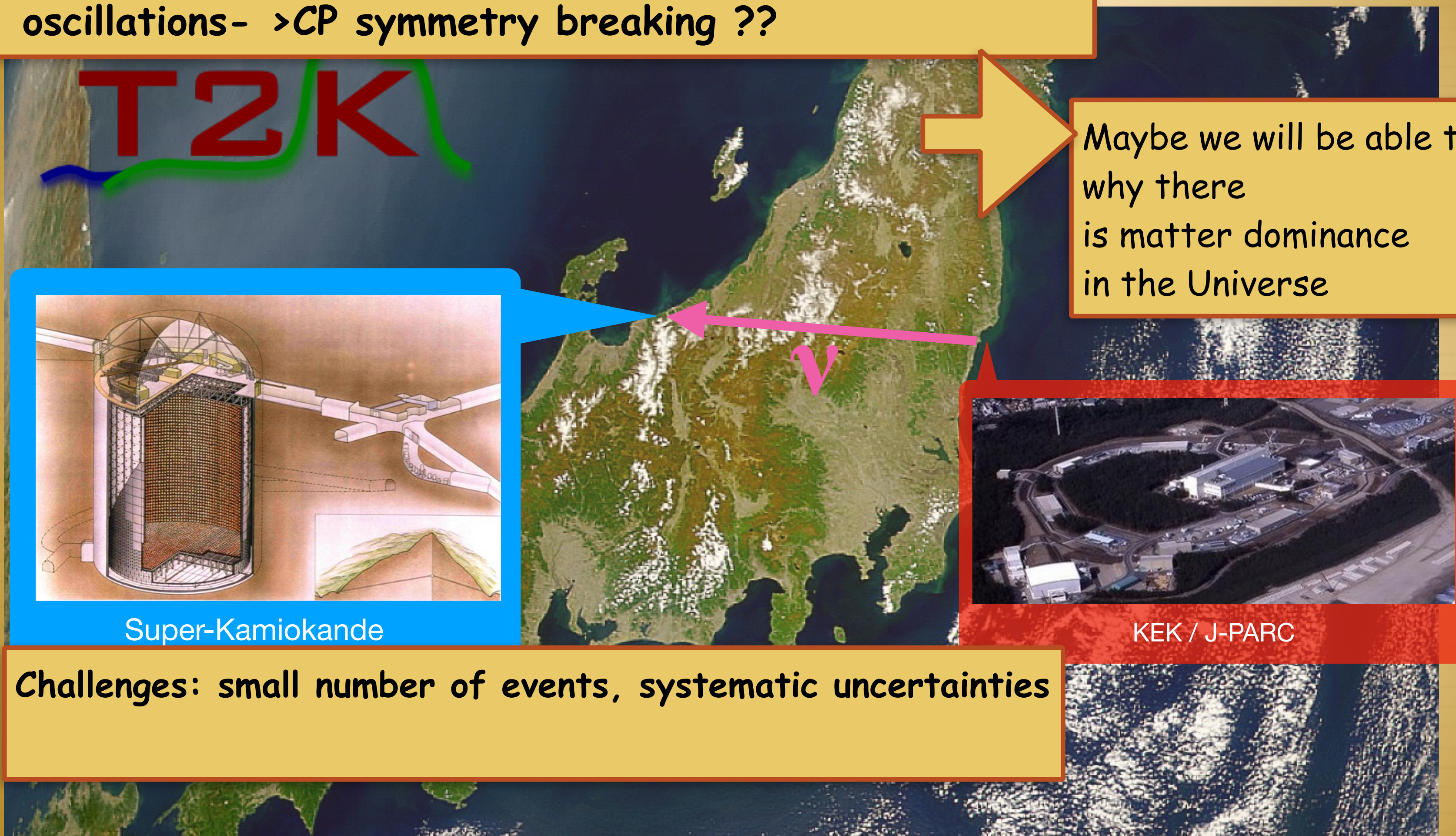
- For a given neutrino detection in SK , the reconstructed direction is not pointing exactly to the neutrino direction.
- There are two reasons for that:
  - During neutrino-nucleus scattering, the outgoing muon is not aligned with the incoming neutrino direction because there is momentum exchange with the nucleus->important for the lower momentum
  - SK reconstruction is simply not perfect
- The goal of this analysis is to reconstruct the position of the source (which is eq to neutrino direction) based on the only information we have -> direction of reconstructed event -> angular resolution is a key!



T2K project

Aim: precise measurements of neutrino and antineutrino oscillations- >CP symmetry breaking ??

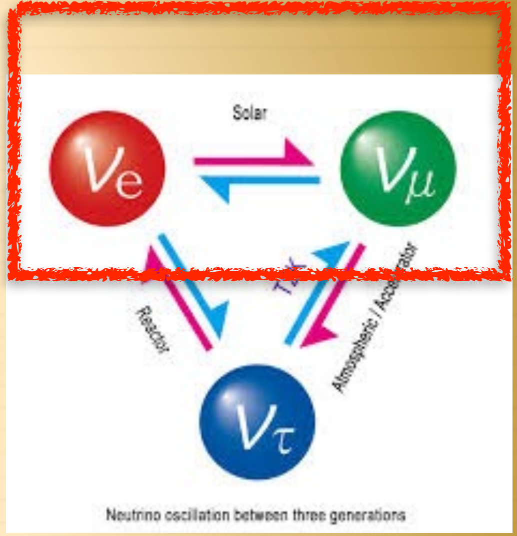
Maybe we will be able to explain why there
is matter dominance
in the Universe



Challenges: small number of events, systematic uncertainties

How can we measure CP violation ?

- CP symmetry measurement needs oscillations of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- We need to:
  - produce neutrino beam mode of ν_μ and antineutrino beam mode of $\bar{\nu}_\mu$
  - separate interactions of $\nu_\mu(\bar{\nu}_\mu)$ from $\nu_e(\bar{\nu}_e)$ in the detector
  - distinguish neutrino from antineutrino would be also very useful

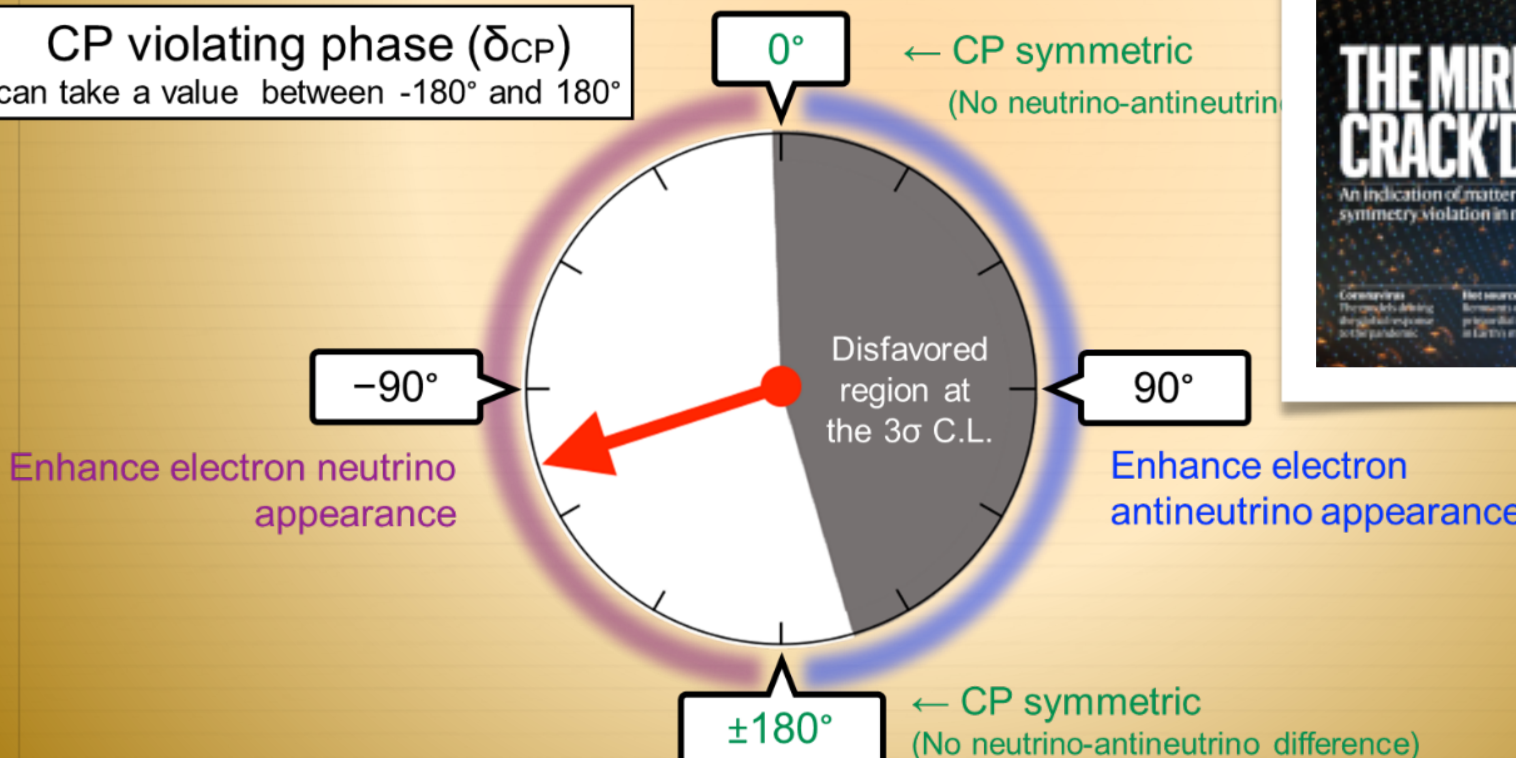


CP symmetry breaking

The charge-conjugation and parity-reversal (CP) symmetry of fundamental particles is a symmetry between matter and antimatter.

Recently Tokai-2-Kamioka (T2K) experiment has published its results in the NATURE magazine (April 2020)

CP violating phase (δ_{CP})
can take a value between -180° and 180°



Neutrino oscillations

Neutrino oscillations are described by the PMNS matrix with :

➢ 3 mixing angles, 1 complex CP phase δ_{CP}

with C_{ij} (S_{ij}) representing $cos\theta_{ij}$ ($sin\theta_{ij}$), where θ_{ij} is the mixing angle between the generations i and j.

flavour eigenstates

mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric and accelerators

$\theta_{23} \cong 45^0$

$\Delta m^2_{32} \cong 2.4 \times 10^{-3}$ eV^2

interference

$\theta_{13} \cong 9^0$

$\delta_{CP} = ?$

solar and reactors

$\theta_{12} \cong 34^0$

$\Delta m^2_{21} \cong 7.6 \times 10^{-5}$ eV^2

Long baseline accelerator experiments are sensitive to:

➢Atmospheric parameters ($\boldsymbol{\theta_{23}}$, Δm^2_{32}) → **mainly ν_μ disappearance**

➢Interference parameters ($\boldsymbol{\theta_{13}}$, $\boldsymbol{\delta_{CP}}$) → **mainly ν_e appearance**

Super-Kamiokande - appearance and disappearance searches

Appearance searches:
Oscillation signal:

$$\nu_\mu \rightarrow \nu_e$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Reactions of interest in Super-K CCQE 1 ring events for:

$$\nu_e + n = e^- + p$$
$$\bar{\nu}_e + p = e^+ + n$$

NEW sample!

and CC1π^+ single ring events:

$$\nu_e + p = e^- + \Delta^{++} = e^- + p + \pi^+$$

Disappearance searches:
Oscillation signal:

$$\nu_\mu \rightarrow \nu_\mu$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

Reactions of interest in Super-K CCQE 1 ring events for:

$$\nu_\mu + n = \mu^- + p$$
$$\bar{\nu}_\mu + p = \mu^+ + n$$