GRAVITATIONAL WAVE FOLLOW-UP WITH THE SUPER-KAMIOKANDE DETECTOR

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Gravitational Wave Follow-up

- Still no evidence of common astrophysical source of Gravitational Waves (GW) and neutrinos (IceCube-170922A).
- Such detection would also significantly improve the localization of the source , making EM follow-up observations easier.
- Advanced LIGO and Virgo are sending realtime public alerts since April 2019 (O3 run) with a rate of 1/week.
- They have recently published GWTC-2 catalog covering first half of O3.

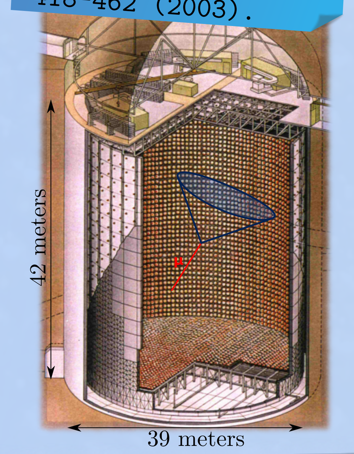
Super-Kamiokande

- 50 kton water Cherenkov detector
- Located in Mozumi mine, Gifu-ken, Japan
- Sensitive to MeV-TeV neutrinos
- Running since 1996, with six different periods
- In Summer 2020, Gadolinium was dissolved into the water (allow better neutron tagging)

Different phases

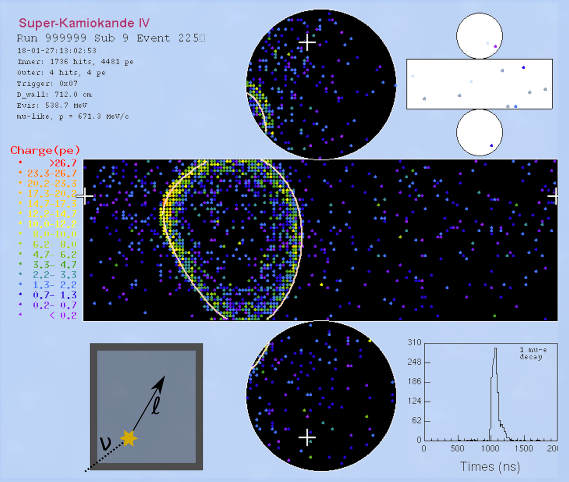
	Start	End
SK-I	04/1996	07/2001
SK-II	10/2002	10/2005
SK-III	07/2006	09/2008
SK-IV	09/2008	06/2018
SK-V	01/2019	07/2020
SK-VI	07/2020	ongoing

NIM Phys. Res. 501, 418-462 (2003)



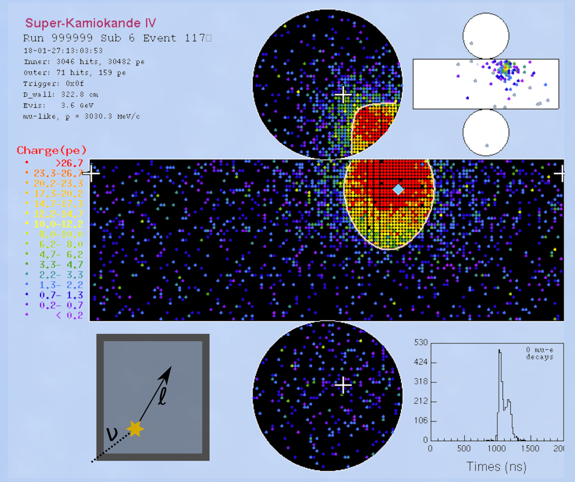
Samples

Fully-Contained (FC)



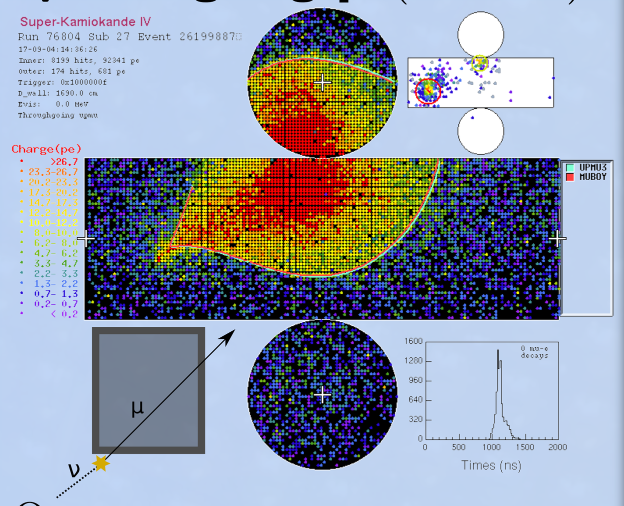
FULL-SKY COVERAGE
Energy range: 0.1-10 GeV
Background in 1000 s: 0.112

Partially-Contained (PC)

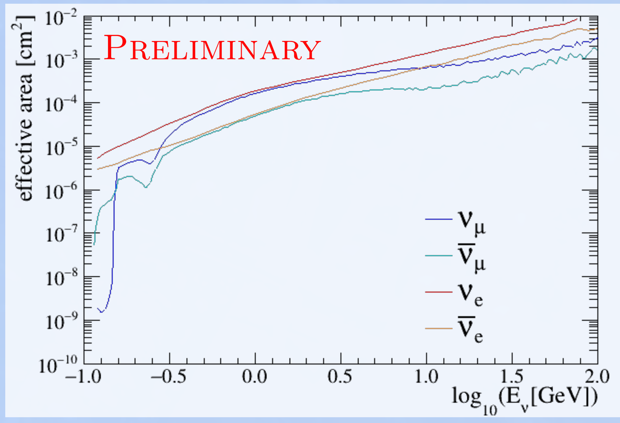


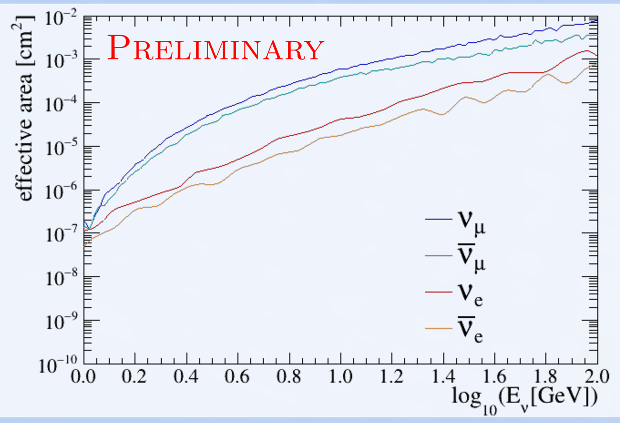
FULL-SKY COVERAGE
Energy range: 0.1-100 GeV
Background in 1000 s: 0.007

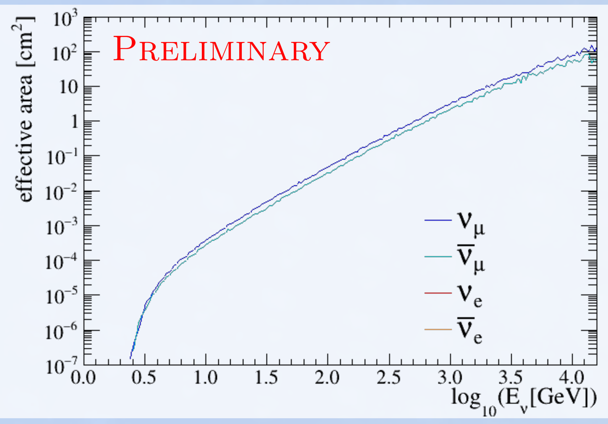
Upward-going μ (UPMU)



ONLY BELOW THE HORIZON
Energy range: few GeV - TeV
Background in 1000 s: 0.016







For each sample: $N_{\rm signal} = \int A_{\rm eff}(E,\Omega) \times \frac{dn(E)}{dE} \times dE$ & $N_{\rm background} = T \times {\rm rate}$

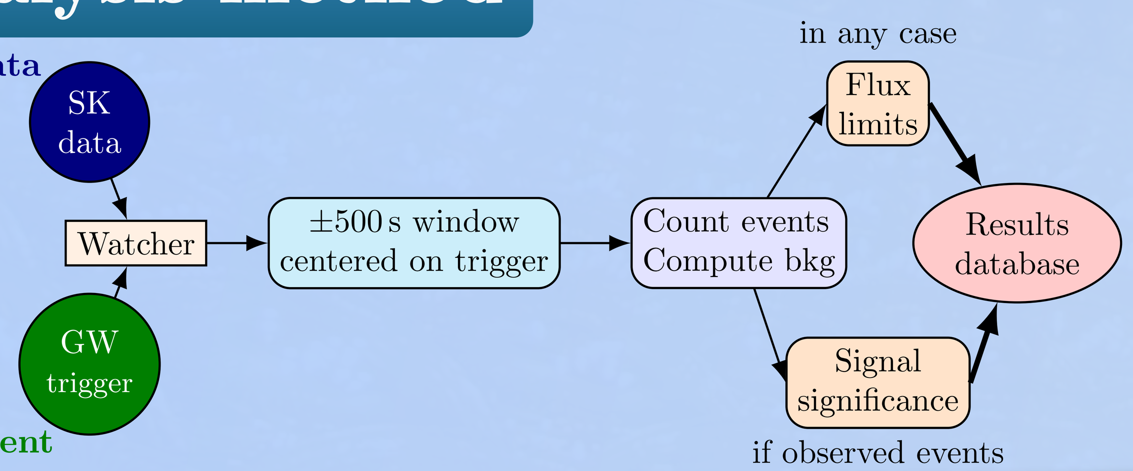
(effective area; incoming neutrino flux; size of time window; atmospheric background rate)

Analysis method

Choice of time window size

The ±500 s time window was derived for GW and ν emission from GRBs. This is now widely used as a conservative coincidence time window in many GW+ν sources searches.

Baret et al. Astropart. Phys. 35, 1-7 (2011)



Sample-by-sample statistics

The neutrino flux from a point-source is:

$$\frac{dn}{dE_\nu} = \phi_0 E_\nu^{-2} \quad \text{assuming } E^{-2} \text{ spectrum}$$

For a given sample s (FC, PC or UPMU):
- expected background $B_{\rm exp}$ is known
- observed number of event $N_{\rm obs}$ is known

→ compute Poisson upper limit on signal

If source position Ω is perfectly known:

$$\phi_{0,\rm up}^{s,f}(\Omega) = \frac{N_{90}}{\int_{E_{\rm min}}^{E_{\rm max}} dE_\nu A_{\rm eff}^{s,f}(E_\nu,\Omega) E_\nu^{-2}} \quad c(\Omega)$$

To take into account wide localisation, we define:

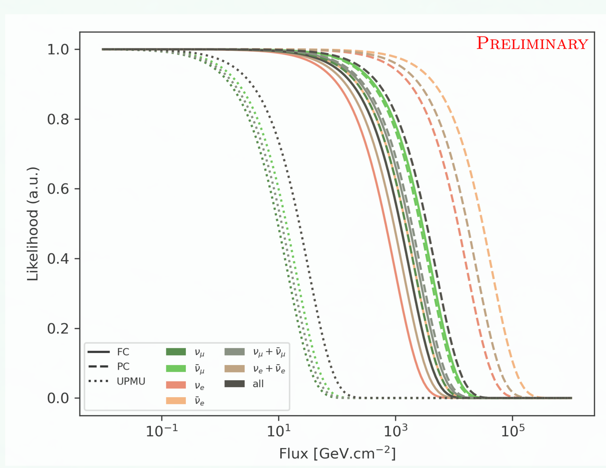
$$\mathcal{L}(\phi_0) = \int \frac{(c(\Omega)\phi_0 + N_{\rm exp})^{N_{\rm obs}}}{N_{\rm obs}!} e^{-(c(\Omega)\phi_0 + N_{\rm exp})} \mathcal{P}_{\rm GW}(\Omega) d\Omega$$

(GW probability distribution)

and find Bayesian upper limit (flat prior on flux):

$$\int_0^{\phi_{0,\rm up}} \mathcal{L}(\phi_0) d\phi_0 = 0.90$$

Example of S190412m (realtime alert)



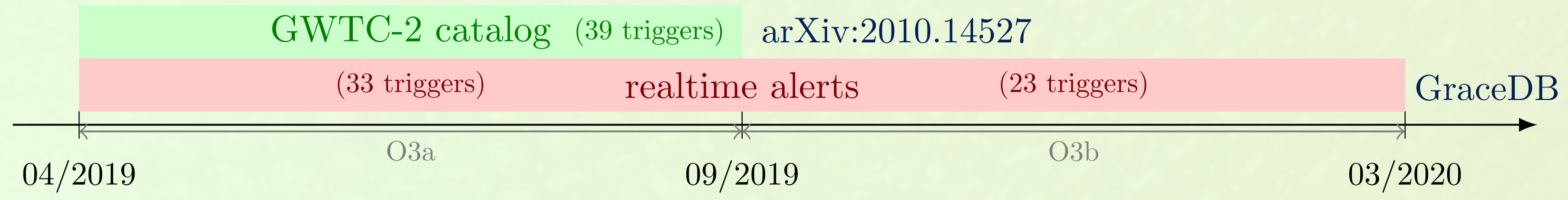
One limit per flavour and per sample

Sample	ν_μ	$\bar\nu_\mu$	ν_e	$\bar\nu_e$
FC	✔	✔	✔	✔
PC	✔	✔	✔	✔
UPMU	✔	✖	✔	✖

ν_μ limit dominated by UPMU: $\phi_0 < 31$ GeV.cm^{-2}

ν_e limit dominated by FC: $\phi_0 < 2.1 \cdot 10^3$ GeV.cm^{-2}

O3 results



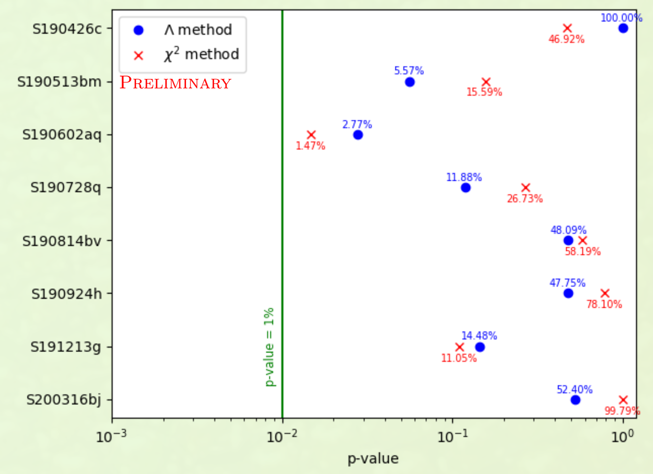
Results of SK GW follow-up of O3 realtime alerts presented at Neutrino 2020

- 46 GWs with SK running
- 8 coincident neutrinos

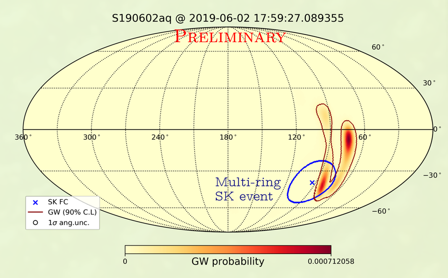
PRELIMINARY

Sample	Total observed	Total expected)
FC	6	5.06
PC	0	0.33
UPMU	2	0.74

NO SIGNIFICANT OBSERVATION



MOST SIGNIFICANT:
S190602aq
p=1.5%



Ongoing analysis of GWTC-2 events (publication soon...)

- Catalog events: more precise sky localisation, distance estimation and properties (masses...) of the source objects.
- This could be used to constrain precisely neutrino emission from the source.
- Distance uncertainties and correlations covered by using this likelihood:

Veske et al. arXiv:2001.00566

$$\mathcal{L}(E_{\rm iso}; TS_m, \mathcal{V}_{GW}) = \int \sum_{k=0}^{2} \left[\frac{(c'(r,\Omega)E_{\rm iso})^k}{k!} e^{-c'(r,\Omega)E_{\rm iso}} \times P_k(TS_m) \right] \mathcal{V}_{\rm GW}(r,\Omega) r^2 dr d\Omega$$

(conversion from $E_{\rm iso}$ to number of events; GW 3D localisation)

- It may also be used to combine different GW of the same type to get a stronger constrain:

$$\mathcal{L}(E_{\rm iso}) = \prod_i \mathcal{L}^{(i)}(E_{\rm iso}) \quad \text{or} \quad \mathcal{L}(k_\nu) = \prod_i \mathcal{L}^{(i)}(k_\nu C_i)$$

(product over a selection of GW)
assuming all objects have exact same emission; assuming emission ∝ source characteristic C_i (e.g. total mass)

Combined analysis

Hussain et al. arXiv:1908.07706
Aartsen et al. arXiv:2004.02910

- Define a likelihood and test statistic to separate between signal (point-source) and background:

$$\mathcal{L}^{(s)}(n_S^{(s)}, \gamma; \vec{x_S}) = \frac{e^{-(n_S^{(s)}+n_B^{(s)})}(n_S^{(s)}+n_B^{(s)})^{N^{(s)}}}{N^{(s)}!} \prod_{i=1}^{N^{(s)}} \frac{n_S^{(s)} S^{(s)}(\vec{x_i}, E_i; \vec{x_S}, \gamma) + n_B^{(s)} \mathcal{B}^{(s)}(\vec{x_i}, E_i)}{n_S^{(s)} + n_B^{(s)}}$$

(sample; direction of source; signal events; expected background; observed events; product on selected events; signal pdf; background pdf; event direction/energy)

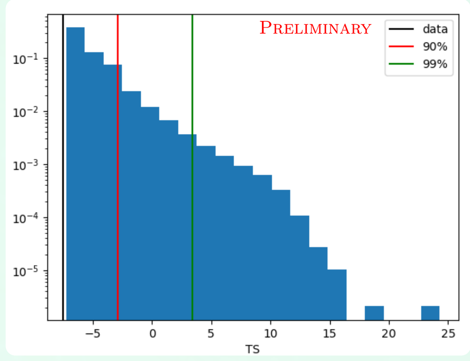
&

$$TS = \max_\Omega [\Lambda(\Omega)] \text{ with } \Lambda(\Omega) = 2\sum_s \ln\left[\frac{\mathcal{L}_\nu^{(s)}(\widehat{n_S^{(s)}}, \widehat{\gamma^{(s)}}; \Omega)}{\mathcal{L}_\nu^{(s)}(n_S^{(s)}=0; \Omega)}\right] + 2\ln \mathcal{P}_{\rm GW}(\Omega)$$

(best-fit position; values maximising the likelihood; GW probability distribution)

Compute signal significance

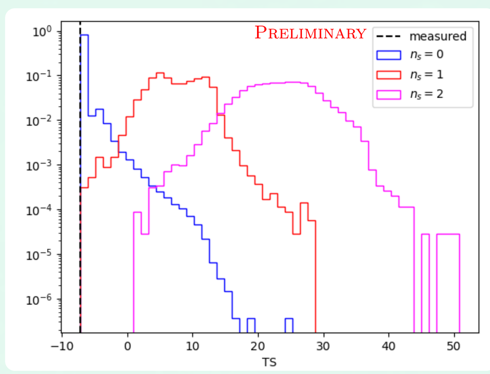
- The background distribution of TS is obtained using time-scrambled neutrinos and expected background rate (FC + PC + UPMU together).
- The test statistical value for real data is computed: $TS_{\rm data}$
- The p-value is: $p_\Lambda = \int_{TS_{\rm data}}^{\infty} P_{\rm bkg}(TS)\, dTS$



Background TS is computed using toys with at least one observed event → p-value is interpreted as the probability for background to raise an observation at least as extreme as the data, given that at least one event was observed.

Compute flux limits

Inspired from arXiv:2001.00566
- Compute TS distribution for signal injections (consistent with GW localisation), with $n_{\rm sig}=0$ (background-only), $n_{\rm sig}=1$, $n_{\rm sig}=2$.
- Compute $P_0(TS_{\rm data})$, $P_1(TS_{\rm data})$ and $P_2(TS_{\rm data})$, the associated "data" probabilities
- Compute likelihood: $\mathcal{L}(\phi_0; TS_m, \mathcal{P}_{GW}) = \int \sum_{k=0}^{2} \left[\frac{(c(\Omega)\phi_0)^k}{k!} e^{-c(\Omega)\phi_0} \times P_k(TS_m)\right] \times \mathcal{P}_{GW}(\Omega) d\Omega$
- Find Bayesian upper limit as in sample-by-sample approach.



$P_k(TS)$ using signal simulations

> This gives the most constraining results for each flavour individually + one can combine flavours (e.g. $\nu_\mu + \bar\nu_\mu$)

Combining flavours require an assumption on distribution of flavours. Used scenario is:
$\nu_e : \nu_\mu : \nu_\tau = (1:2:0)_{\rm source} \to (1:1:1)_{\rm Earth}$, $\phi_\nu = \phi_{\bar\nu}$