Follow-up of GWTC-2 gravitational wave events with neutrinos from the Super-Kamiokande detector

ICRC

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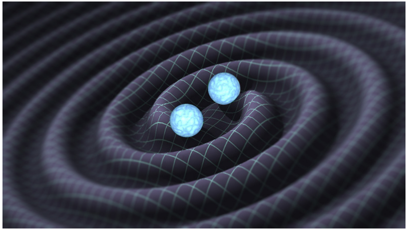
Since 2015, the LIGO/Virgo Collaboration (LVC) is detecting and sending alerts for gravitational waves from the merger of binary objects.

- 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 mechanisms behind them.

* Foucart, F., et al (2016). *Low mass binary neutron star mergers: Gravitational waves and neutrino emission.* Physical Review D, 93(4). 10.1103/PhysRevD.93.044019

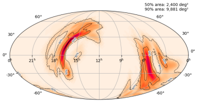
† Caballero, O. L., et al (2016). *Black hole spin influence on accretion disk neutrino detection.* 10.1103/PhysRevD.93.123015

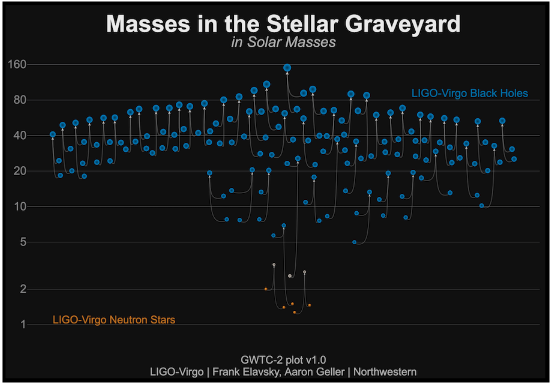
GWTC-2 catalogue

- LIGO-Virgo Third Observing Run (O3) covered April 2019 to March 2020
  $\Rightarrow$ 56 alerts provided in realtime through GCN $\Leftarrow$ **see 10.5281/zenodo.4073262**
- GWTC-2 covers the first half of O3 (April 2019 - September 2019)
  $\Rightarrow$ 39 confirmed detections $\Leftarrow$ **focus of this talk**

For each GW, we have:

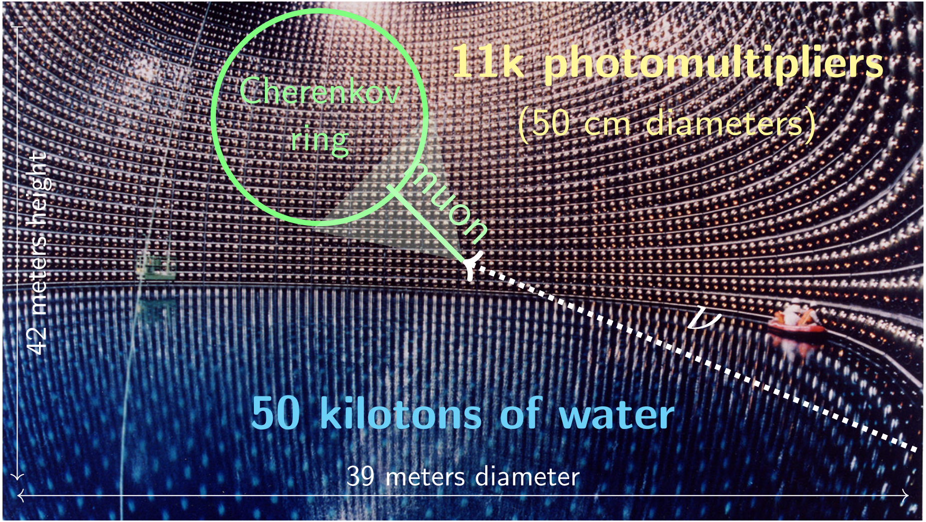
- time of the event
- sky localisation
- estimated distance
- estimated masses of the two objects
- can be roughly classified based on masses ($m < 3\,M_\odot$=NS, $m > 3\,M_\odot$=BH)





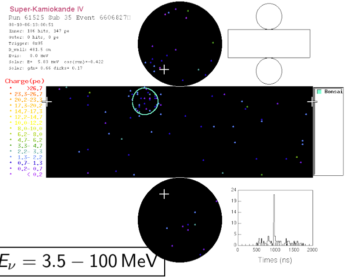
The Super-Kamiokande (SK) experiment

Experiment running since 1998, located in the Mozumi mine in Japan.



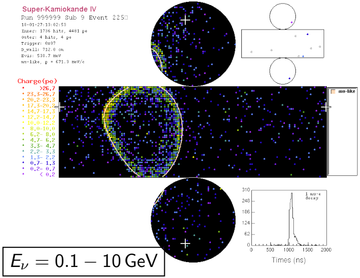
The different samples

Low-energy events



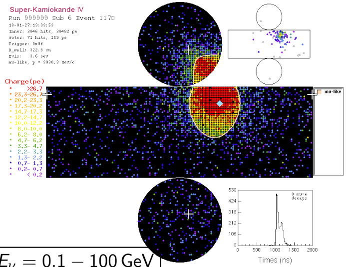
$E_\nu = 3.5 - 100$ MeV

Fully-Contained



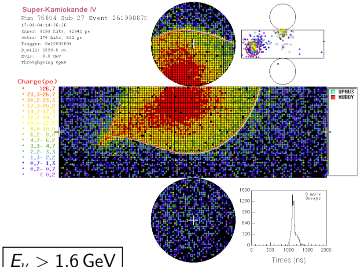
$E_\nu = 0.1 - 10$ GeV

Partially-Contained



$E_\nu = 0.1 - 100$ GeV

Upgoing muons



$E_\nu > 1.6$ GeV

Four samples covering the neutrino energy range from few MeV to $\mathcal{O}$(TeV):

- low-energy (LOWE)
- fully-contained events (FC)
- partially-contained events (PC)
- upgoing muons (UPMU)

LOWE is usually used for solar/supernova analyses.

The other samples are mainly used for atmospheric analysis.

Follow-up strategy with Super-Kamiokande

- Define a $\pm 500\,\mathrm{s}$ centered on GW time
- Search for events within this time window, in the four SK samples
- Compare observation with expected background and extract neutrino flux upper limits

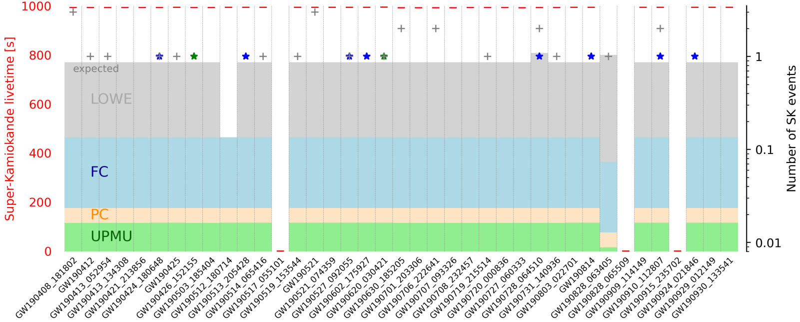
and compute eventual signal significance by comparing neutrino directions and GW localisation (only for high-energy SK samples)

Low-energy sample	**High-energy samples** FC	PC	UPMU
Standard solar/SRN selection + 7 MeV energy threshold to ensure stable bkg rate	Standard atmospheric selection		
expected background in 1000 seconds $= 0.729$	0.112	0.007	0.016

Results of the follow-up

Performed the analysis for the 39 GW in GWTC-2. Three of them were associated to SK downtime (due to calibration) (one less for low-energy due to HV issues).

PRELIMINARY



In total:

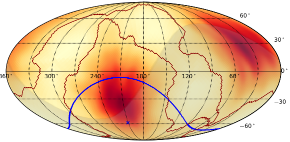
Sample	N_{obs}	N_{exp}
LOWE+	24	24.97
FC⋆	8	3.95
PC⋆	0	0.26
UPMU⋆	2	0.58

PRELIMINARY

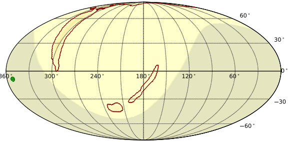
No significant excess was observed in the follow-up analysis.

Ten SK high-energy events in time coincidence

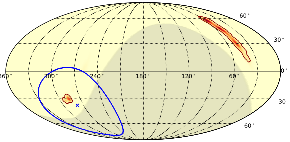
GW190424_180648



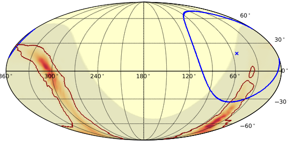
GW190426_152155



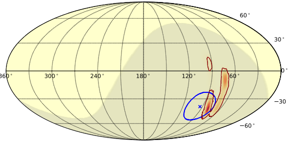
GW190513_205428



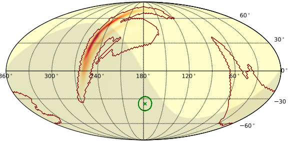
GW190527_092055



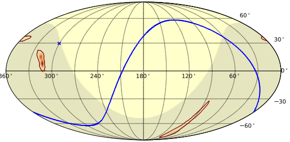
GW190602_175927



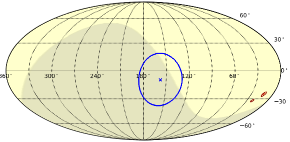
GW190620_030421



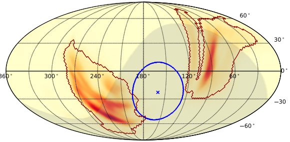
GW190728_064510



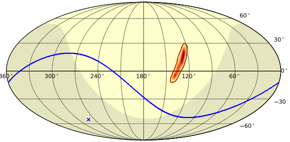
GW190814



GW190910_112807



GW190924_021846



All plots are PRELIMINARY

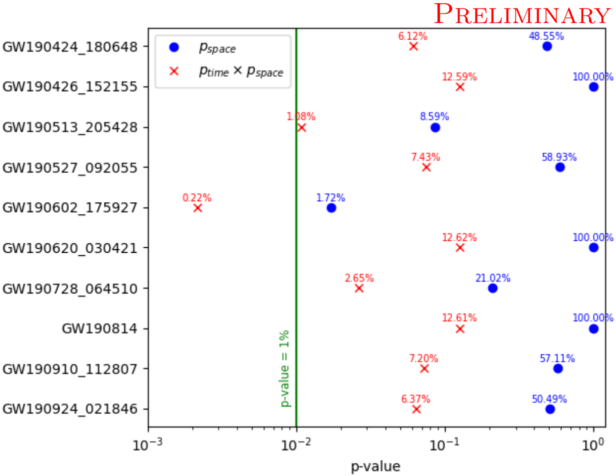
Skymaps in equatorial coordinates

- **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

Test statistic (TS) has been built to separate signal (point-source) from background (full-sky). It is used to compute p-values (compared observed TS to background distribution).



The most significant GW+ν coincidence is for GW190602_175927:

$$p = 0.22\%$$

Considering the number of trials ($N = 36$ follow-ups), we get a **post-trial** p-value:

$$P = 7.8\%$$

(more details in arXiv:2104.09196)

High-Energy Flux limits (1)

The neutrino flux is assumed as $\frac{dn}{dE_\nu} = \phi_0 E_\nu^{-2}$ and $N_{\text{expected signal}} = \int_{E_{\text{min}}}^{E_{\text{max}}} \mathrm{d}E_\nu A_{\text{eff}}^{s,f}(E_\nu, \theta) \times \frac{dn}{dE_\nu}$.

Sample-by-sample flux limits

For each sample and flavour $(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu)$, we define the flux likelihood:

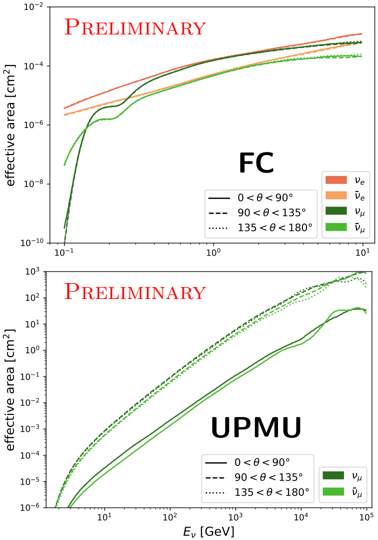
$$\mathcal{L}(\phi_0; n_B, N) = \int \frac{(c(\Omega)\phi_0 + n_B)^N}{N!} e^{-(c(\Omega)\phi_0 + n_B)} \mathcal{P}_{\text{GW}}(\Omega) d\Omega$$

with $c(\Omega) = \int_{E_{\text{min}}}^{E_{\text{max}}} \mathrm{d}E_\nu A_{\text{eff}}(E_\nu, \theta) E_\nu^{-2}$ and the 90% U.L on the flux ϕ^{up} is obtained by solving $\int_0^{\phi^{\text{up}}} \mathcal{L}(\phi) d\phi = 0.9$

Combined flux limits

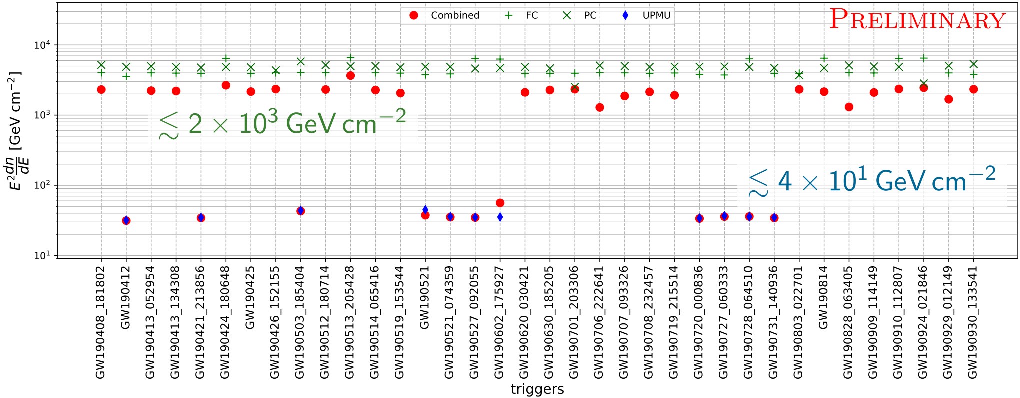
Limits combining FC, PC and UPMU are obtained by using the combined TS defined before (details in backup).

Effective area A_{eff}



High-Energy Flux limits (2)

Example of limits for ν_μ flavour:

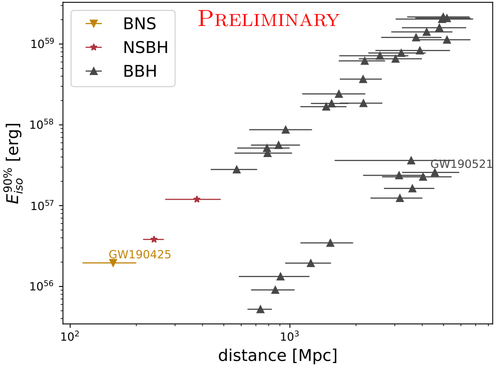


Better limits with the UPMU sample when the GW is below the local horizon. Combined limits are close to the best individual one.

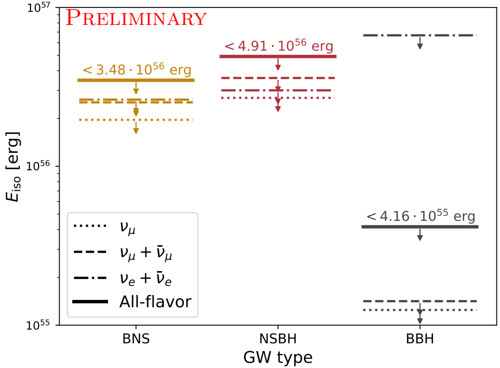
Limits on E_{iso}

- The total energy in ν from the source (assuming isotropic) is $E_{\text{iso}} = 4\pi d^2 \int \frac{\mathrm{d}n}{\mathrm{d}E} \times E\,\mathrm{d}E$
  $\Rightarrow$ E_{iso} limits obtained by using the 3D localisation skymap from the LVC data release.
- We can stack events by nature, assuming same emission (or $E_{\text{iso}} \propto M_{\text{source}}$ in backup).

Individual limits on $E_{\text{iso}}^{\nu_\mu}$



Stacked limits on $E_{\text{iso}}^{\text{all-flavours}*}$



* This is done assuming the flux at Earth is equally distributed between the flavours ($\nu_e : \nu_\mu : \nu_\tau = 1:1:1$)

Results for the low-energy sample

- For low-energy analysis, the case is simpler as SK acceptance does not depend on direction.

- Upper limits on fluence are obtained assuming Fermi-Dirac ($\langle E \rangle = 20\,\mathrm{MeV}$):

$$\Phi_{90} = \frac{N_{90}}{N_{\mathrm{Target}} \int \lambda(E_\nu)\sigma(E_\nu)R(E_e, E_{\mathrm{vis}})\epsilon(E_{\mathrm{vis}})\,\mathrm{d}E_\nu} \text{ with } \lambda(E_\nu) = \text{F.-D.}$$

- Typical fluence limits: $\begin{cases} \Phi(\nu_e) \lesssim 5 \times 10^{9}\,\mathrm{cm}^{-2}, & \Phi(\bar{\nu}_e) \lesssim 1 \times 10^{8}\,\mathrm{cm}^{-2} \\ \Phi(\nu_x) \lesssim 3 \times 10^{10}\,\mathrm{cm}^{-2}, & \Phi(\bar{\nu}_x) \lesssim 4 \times 10^{10}\,\mathrm{cm}^{-2} \ (\nu_x = \nu_{\mu,\tau}) \end{cases}$

- E_{iso} limits are obtained as in the high-energy case, using the LVC distance estimate:
  $E_{\mathrm{iso}}^{\bar{\nu}_e} < 9.59 \times 10^{57}\,\mathrm{erg}$ for GW190425 ($d \sim 160\,\mathrm{Mpc}$)

It is not very constraining as compared to typical expected emission e.g.,
$L_{\mathrm{iso}}^{\mathrm{model}} \sim 4 - 7 \times 10^{53}\,\mathrm{erg\,s^{-1}}$ in Phys.Rev.D 93 (2016) 4, 044019

Summary

- Follow-up analysis of GWTC-2 events using SK low/high-energy samples
- **No excess** has been observed with respect to expected background.
- Most significant observation is for GW190602_175927 $\Rightarrow$ **post-trial p-value is** 7.8% **(**1.4σ**)**
- Flux limits have been computed:
  - **High-Energy:** $E^2 \frac{dn}{dE}\Big|_{\nu_\mu} \lesssim 4 \times 10^1\,\mathrm{GeV\,cm^{-2}}$ if GW below the horizon (2×10^3 otherwise)
  - **Low-energy:** $\Phi(\bar{\nu}_e) \lesssim 10^8\,\mathrm{cm^{-2}}$
- Limits on $E_{\rm iso}$ were also extracted, independently event-by-event or by stacking events of the same nature, e.g. $\boxed{E_{\rm iso}^{\rm BBH} \lesssim 4 \times 10^{55}\,\mathrm{erg}}$
- **Publication on arXiv** (2104.09196) and **data release** on Zenodo. *Accepted by ApJ.*
- **Future:** possible realtime follow-up (within few days) from O4

Acknowledgements

This presentation was made on behalf of the Super-Kamiokande collaboration

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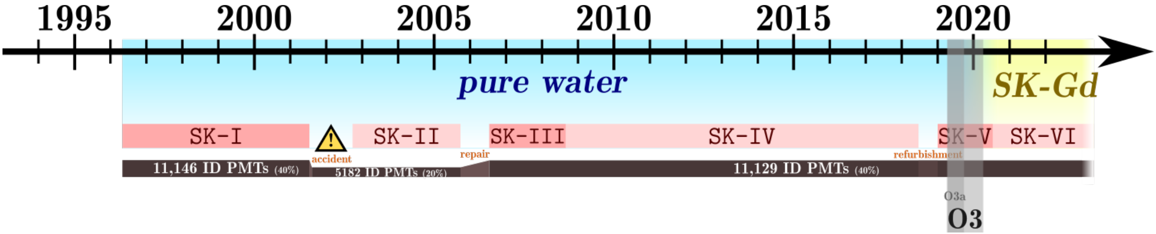
Backups

Super-Kamiokande timeline



List of selected SK events in GWTC-2

PRELIMINARY

Trigger	Sample	Δt [s]	E [GeV]	RA [deg]	Dec [deg]	δ [deg]	p-value [%]
GW190424_180648	FC	104.03	0.57	210.82	-58.74	52.08	48.55
GW190426_152155	UPMU	278.99	9.52	352.37	-8.46	2.15	100.00
GW190513_205428	FC	-183.27	0.68	279.34	-37.27	41.19	8.59
GW190527_092055	FC	248.41	0.48	54.09	18.80	52.08	58.93
GW190602_175927	FC	-286.52	2.75	93.67	-38.90	16.22	1.72
GW190620_030421	UPMU	-327.70	2.33	177.69	-35.59	8.04	100.00
GW190728_064510	FC	102.99	0.19	300.45	29.71	92.51	21.02
GW190814	FC	250.36	1.21	157.59	-9.47	28.26	100.00
GW190910_112807	FC	301.42	1.08	160.13	-22.70	32.09	57.11
GW190924_021846	FC	411.87	0.30	281.38	-54.52	73.58	50.49

Observation significance

How likely the SK observation is associated to background, given time+space correlations?

The p-value can be dissociated in $\boxed{p = p_{\rm time} \times p_{\rm space}}$, with:

- $p_{\rm time} = {\rm Prob}(N \geq 1) = 1 - e^{-n_B} \sim 12.6\%$ for $n_B =$ total background $_{\text{(FC+PC+UPMU)}} = 0.13$
- $p_{\rm space}$ is obtained by comparing neutrino direction and GW localisation*
  - For each sample ($k =$ FC, PC or UPMU), define the point-source likelihood $\mathcal{L}_\nu^{(k)}(n_S^{(k)}, \gamma; \Omega_S)$ that separates background from signal ($dn/dE \propto E^{-\gamma}$, direction Ω_S).
  - Compute the maximum log-likelihood ratio Λ (GW localisation $\mathcal{P}_{GW}$ used as prior) and find the source direction Ω_S that maximises it:

$$\Lambda(\Omega_S) = 2\sum_k \ln\left[\frac{\mathcal{L}_\nu(\widehat{n_S^{(k)}}, \widehat{\gamma^{(k)}}; \Omega_S)}{\mathcal{L}_\nu(n_S^{(k)} = 0; \Omega_S)}\right] + 2\ln\mathcal{P}_{GW}(\Omega_S) \text{ and } \boxed{\mathrm{TS} = \max_\Omega [\Lambda(\Omega)]}$$

  - Compare $TS_{\rm data}$ with the expected background distribution (with $N \geq 1$) to obtain $p_{\rm space}$.

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* 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

Test statistic

For each sample k, we define the likelihood:

$$\mathcal{L}_\nu^{(k)}(n_S^{(k)}, \gamma; \Omega_S) = \frac{e^{-(n_S^{(k)}+n_B^{(k)})}(n_S^{(k)}+n_B^{(k)})^{N^{(k)}}}{N^{(k)}!} \prod_{i=1}^{N^{(k)}} \frac{n_S^{(k)}\mathcal{S}^{(k)}(\vec{x}_i, E_i; \Omega_S, \gamma) + n_B^{(k)}\mathcal{B}^{(k)}(\vec{x}_i, E_i)}{n_S^{(k)}+n_B^{(k)}}$$

where $\mathcal{S}^{(k)}$ and $\mathcal{B}^{(k)}$ are the signal/background p.d.f. (characterizing detector response).
Then, we compute the log-likelihood ratio:

$$\Lambda(\Omega_S) = 2\sum_k \ln\left[\frac{\mathcal{L}_\nu(\widehat{n_S^{(k)}}, \widehat{\gamma^{(k)}}; \Omega_S)}{\mathcal{L}_\nu(n_S^{(k)} = 0; \Omega_S)}\right] + 2\ln \mathcal{P}_{GW}(\Omega_S)$$

The final test statistic and p-value are:

$$TS = \max_{\Omega}\,[\Lambda(\Omega)] \text{ and } p_{\text{space}} = \int_{TS_{\text{data}}}^{\infty} \mathcal{P}_{\text{bkg}}(TS)\,\mathrm{d}\,TS$$

where $\mathcal{P}_{\text{bkg}}(TS)$ is the expected background distribution.

Combined flux/$E_{\rm iso}$ limits

- **Flux:** We define the following likelihood by using the TS defined before:

$$\mathcal{L}(\phi_0; TS_{\rm data}, \mathcal{P}_{GW}) = \int \sum_{k=0}^{2} \left[\frac{(c(\Omega)\phi_0)^k}{k!} e^{-c(\Omega)\phi_0} \times \mathcal{P}_k(TS_{\rm data})\right] \times \mathcal{P}_{GW}(\Omega)\,\mathrm{d}\Omega$$

where $P_i(TS)$ is the distribution of the test statistic assuming the signal consists in i events, assuming E^{-2} spectrum ($dn/dE = \phi_0 E^{-2}$). The 90% upper linit is obtained as above ($\int_0^{\phi_0^{\rm up}} \mathcal{L}(\phi_0) d\phi_0 = 0.90$).

- **Total energy:** Same for $E_{\rm iso}$ limits:

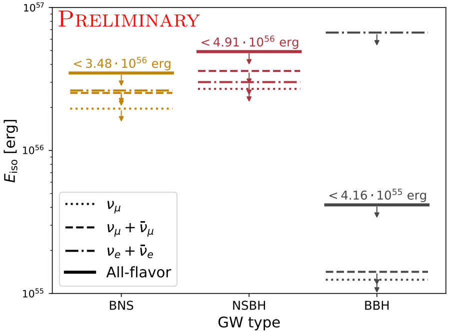
$$\mathcal{L}(E_{\rm iso}; TS^{(i)}_{\rm data}, \mathcal{V}^{(i)}_{GW}) = \int \sum_{k=0}^{2} \left[\frac{(c'(r,\Omega)E_{\rm iso})^k}{k!} e^{-c'(r,\Omega)E_{\rm iso}} \times \mathcal{P}^{(i)}_k(TS^{(i)}_{\rm data})\right] \times \mathcal{V}^{(i)}_{GW}(r,\Omega)\mathrm{d}\Omega$$

Stacking population analysis

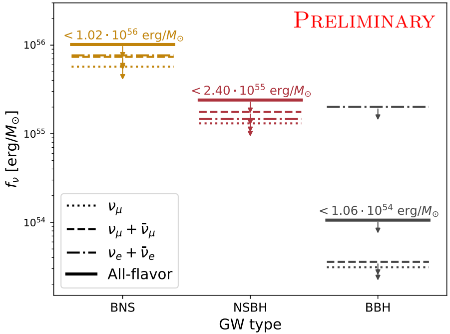
We combine the likelihoods within a given population*:

- Assuming same expected $E_{\rm iso}$ for all events:
  $$\mathcal{L}^{\rm Pop}(E_{\rm iso}; \{TS_{\rm data})^{(i)}\}, \{\mathcal{V}_{GW}^{(i)}\}) = \prod_{i=1}^{N} \mathcal{L}(E_{\rm iso}; TS_{\rm data})^{(i)}, \mathcal{V}_{GW}^{(i)})$$
- Assuming neutrino emission scales with object total mass $\mathcal{M}_{\rm tot}$:
  $$\mathcal{L}^{\rm Pop}(f_\nu; \{TS_{\rm data})^{(i)}\}, \{\mathcal{V}_{GW}^{(i)}\}, \{\mathcal{M}_{\rm tot}^{(i)}\}) = \prod_{i=1}^{N} \int \mathcal{M}_{\rm tot}^{(i)} \mathcal{L}(f_\nu \mathcal{M}_{\rm tot}^{(i)}; TS_{\rm data})^{(i)}, \mathcal{V}_{GW}^{(i)}) p_{\rm GW}(\mathcal{M}_{\rm tot}^{(i)}) {\rm d}\mathcal{M}_{\rm tot}^{(i)}$$

assuming same $E_{\rm iso}$



assuming $E_{\rm iso} \propto \mathcal{M}_{\rm tot}$



*Veske et al. JCAP 05 (2020) 016

Comparison with ANTARES and IceCube

Experiment	Super-Kamiokande	ANTARES	IceCube
Energy range	0.1-10^5 GeV	TeV-PeV	10-$10^{9.5}$ GeV
$E^2 dn/dE$ limits (min)	4×10^1 GeV cm^{-2}	1 GeV cm^{-2}	0.03 GeV cm^{-2}
$E^2 dn/dE$ limits (max)	2×10^3 GeV cm^{-2}	9 GeV cm^{-2}	0.6 GeV cm^{-2}
Reference	this work	Poster @CRνMM	PoS-ICRC2019-918

This is assuming E^{-2}. The situation will be in favour of SK for $\gamma > 2$ (e.g. E^{-3}).