Co-funded by the European Union

Follow-up of gravitational wave events with Super-Kamiokande

Fellini meeting

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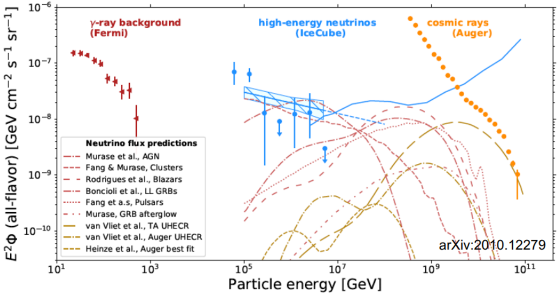
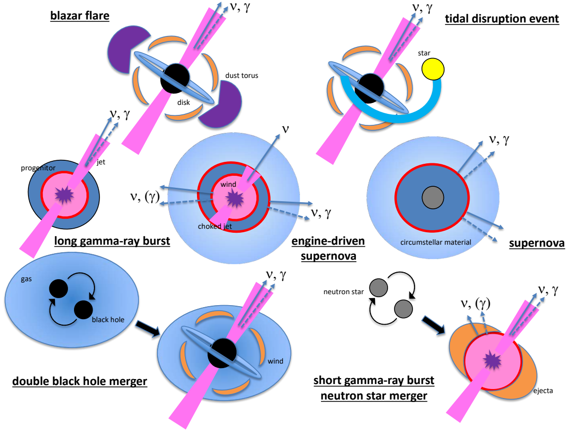
Neutrino multimessenger astrophysics

- Astrophysical sources in the Universe are complex objects with many unknown mechanisms:
  - origin of bright light emission
  - origin of ultra-high-energy cosmic rays
  - how does a supernova explodes?
  - . . .
- Coincident detection with different messengers (photons, gravitational waves, neutrinos) would greatly help.



arXiv:2010.12279



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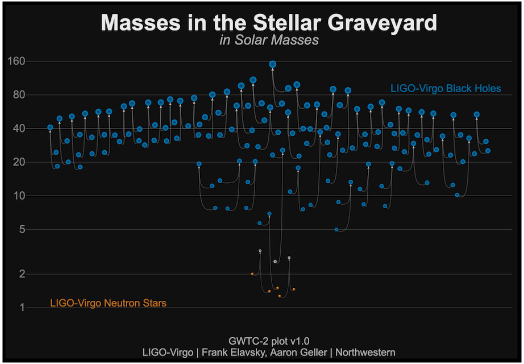
Gravitational waves emitters

Since 2015, LIGO/Virgo interferometers are detecting gravitational waves from the merging of: two black holes (BBH), two neutron stars (BNS) or NS+BH (NSBH).

- All these objects may be associated to a short Gamma-Ray Bursts (GRB) with neutrino production [1,2].
- Detecting these neutrinos would allow better understanding of the mechanisms behind them.
- New GW catalogue was released in October 2020 with 39 confirmed sources detected between April and September 2019 (GWTC-2).
- Worth taking a look...



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[1] 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

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

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

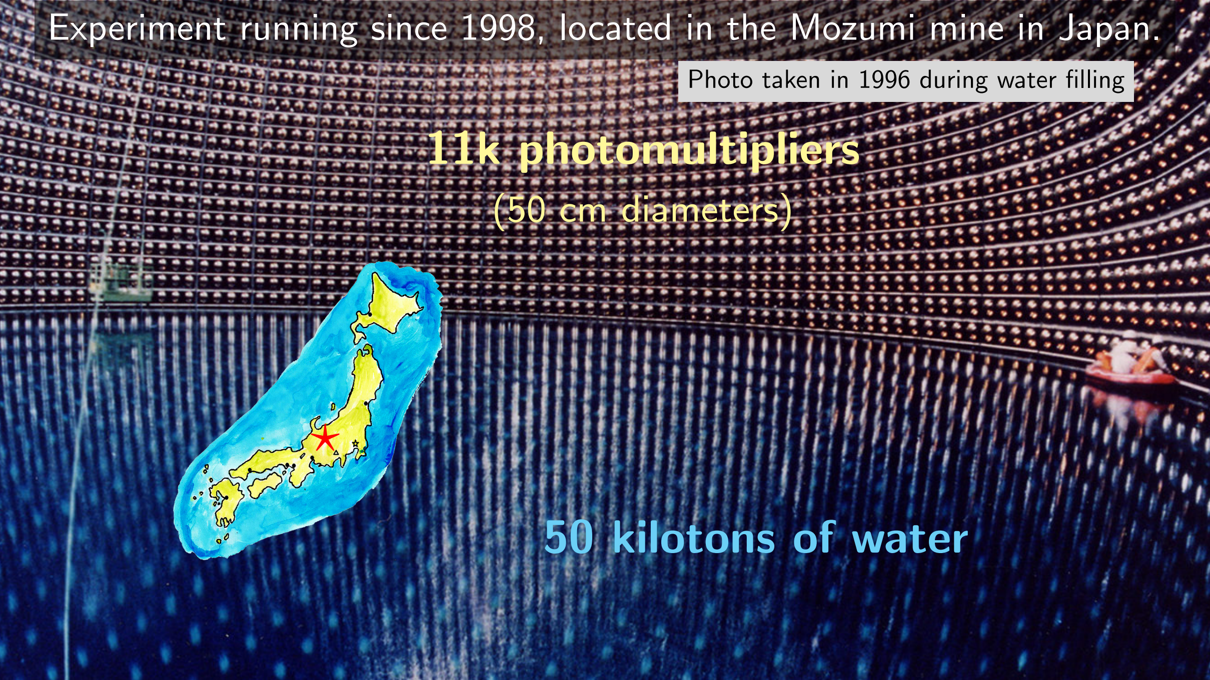


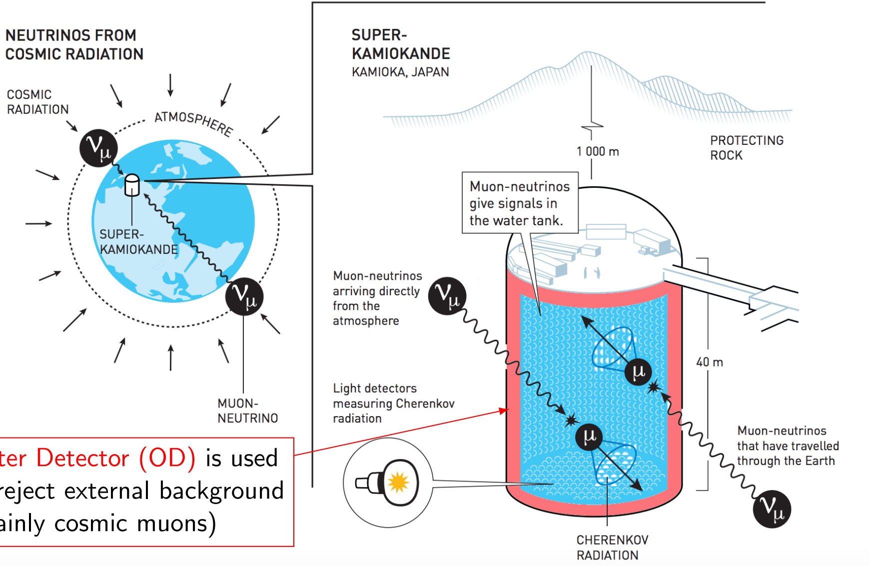
Photo taken in 1996 during water filling

11k photomultipliers

(50 cm diameters)

50 kilotons of water

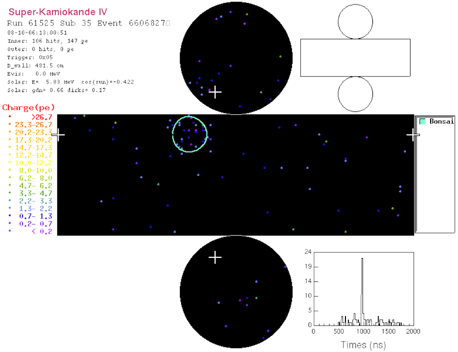
The Super-Kamiokande experiment



Outer Detector (OD) is used to reject external background (mainly cosmic muons)

The different samples

Low-energy events



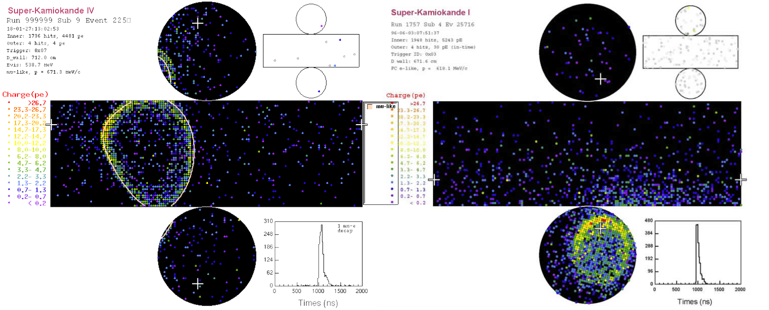
```
Super-Kamiokande IV
Run 61525 Sub 35 Event 6606827
08-10-06:13:00:51
Inner: 106 hits, 147 pe
Outer: 0 hits, 0 pe
Trigger: 0x05
D_wall: 481.5 cm
Evis:   0.0 MeV
Solar: E=  5.83 MeV  cos(sun)=-0.422
Solar: gdn= 0.66 dirks= 0.17
```

$$\boxed{E_\nu = 3.5 - 100\,\mathrm{MeV}}$$

sparse PMT hits, faint ring

INCREASING ENERGY

Fully-Contained (FC) events



$$\boxed{E_\nu = 0.1 - 10\ \text{GeV}}$$

no activity in OD

μ: sharp ring

e: fuzzy ring

Low-energy events (LE)

$E_\nu \sim 3.5 - 100$ MeV

INCREASING ENERGY

The different samples

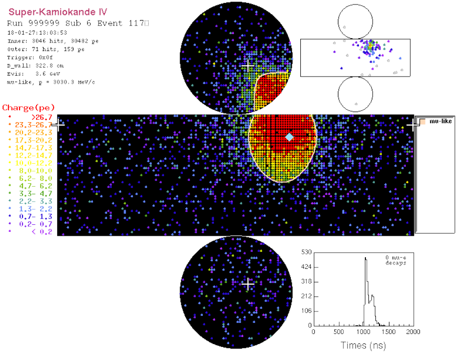
LOW-ENERGY EVENTS (LE)

$E_\nu \sim 3.5 - 100$ MeV

FULLY-CONTAINED EVENTS (FC)

$E_\nu \sim 0.1 - 10$ GeV

Partially-Contained (PC) events



$$\boxed{E_\nu = 0.1 - 100\,\text{GeV}}$$

exit activity in OD

INCREASING ENERGY

The different samples

LOW-ENERGY EVENTS (LE)

$E_\nu \sim 3.5 - 100\,\text{MeV}$

FULLY-CONTAINED EVENTS (FC)

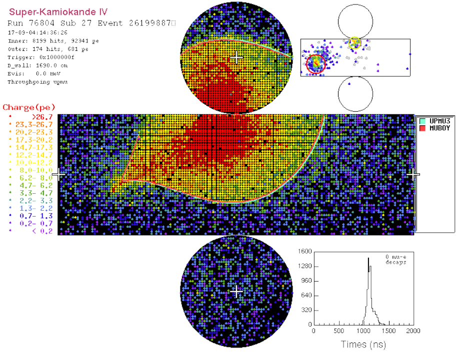
$E_\nu \sim 0.1 - 10\,\text{GeV}$

PARTIALLY-CONTAINED EVENTS (PC)

$E_\nu \sim 0.1 - 100\,\text{GeV}$

INCREASING ENERGY

Upward-going muons (UPMU)

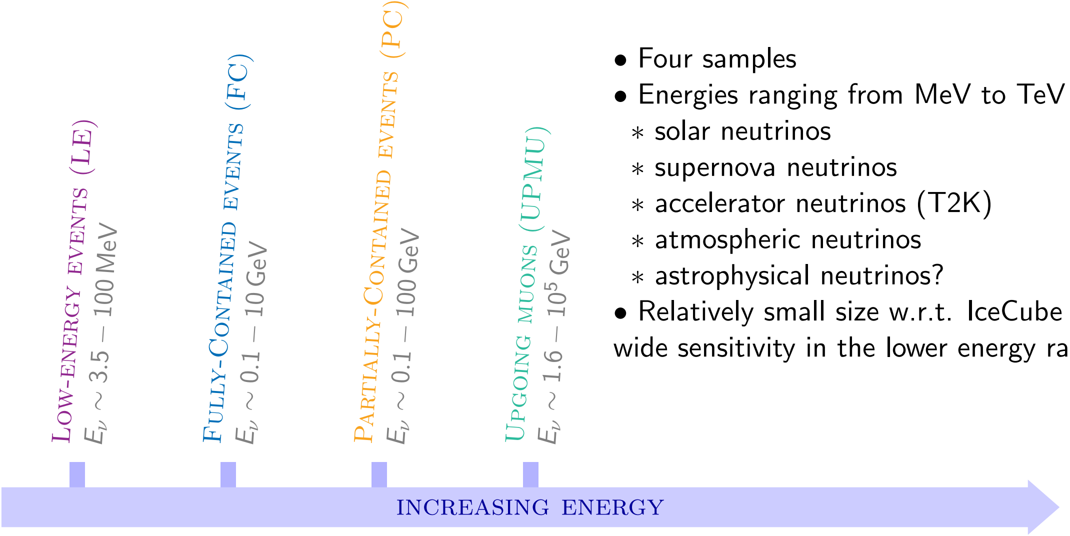


$$\boxed{E_\nu = 1.6\,\text{GeV} - 10\,\text{TeV}}$$

entering activity in OD

stopping ($p_\mu > 1.6\,\text{GeV}$) or through-going ($L > 7\,\text{m}$)

The different samples



Low-energy events (LE)
$E_\nu \sim 3.5 - 100$ MeV

Fully-Contained events (FC)
$E_\nu \sim 0.1 - 10$ GeV

Partially-Contained events (PC)
$E_\nu \sim 0.1 - 100$ GeV

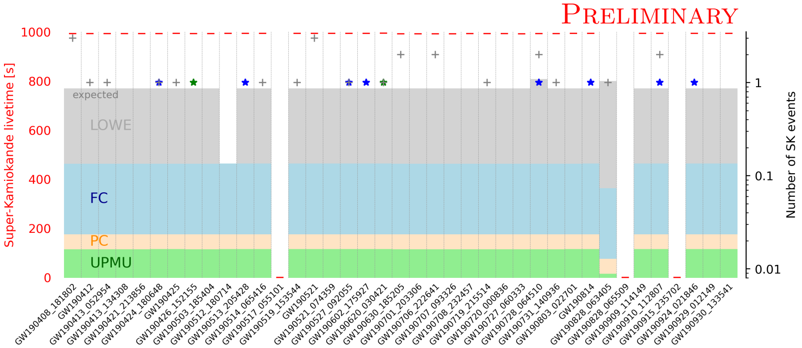
Upgoing muons (UPMU)
$E_\nu \sim 1.6 - 10^5$ GeV

- Four samples
- Energies ranging from MeV to TeV
  - solar neutrinos
  - supernova neutrinos
  - accelerator neutrinos (T2K)
  - atmospheric neutrinos
  - astrophysical neutrinos?
- Relatively small size w.r.t. IceCube but wide sensitivity in the lower energy range

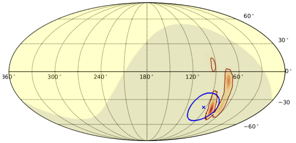
Follow-up results

- Define a ±500 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

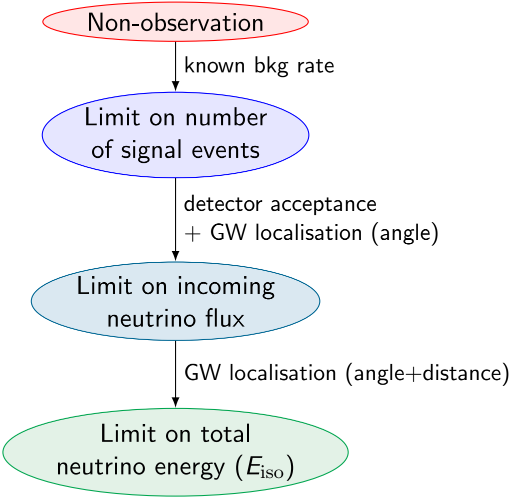
and compute eventual signal significance by comparing neutrino directions and GW localisation (only for high-energy SK samples)


PRELIMINARY

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



Constraining neutrino emission



Non-observation

known bkg rate

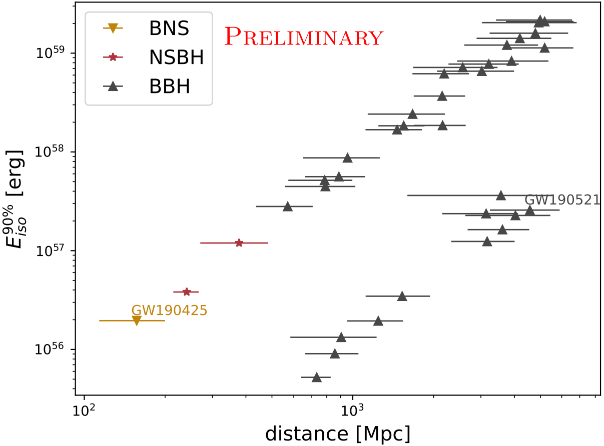
Limit on number of signal events

detector acceptance + GW localisation (angle)

Limit on incoming neutrino flux

GW localisation (angle+distance)

Limit on total neutrino energy (E_{iso})

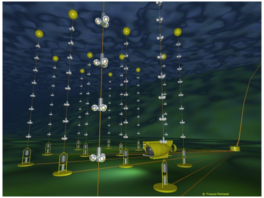


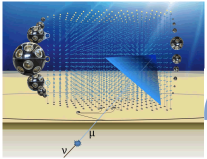
Publication with detailed results is incoming...

What about combining with other measurements?

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

- One cam imagine combining Super-Kamiokande with ANTARES, so that we span a very large energy range.
  → work during the secondment period in *APC (Paris)* from May 2021
- Looking into the future:
  - next-generation detectors will be much bigger: **Hyper-Kamiokande** in Japan, **KM3NeT** in the sea
  - increased sensitivity of GW detectors (more precise localisation, much more events. . .)



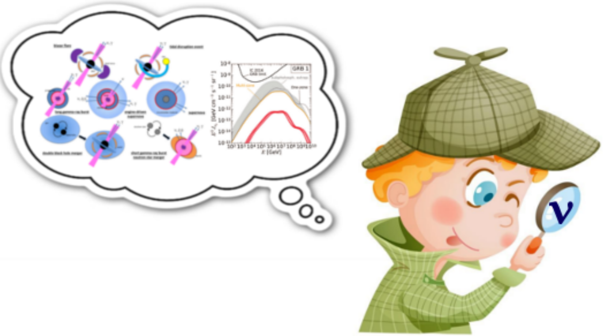


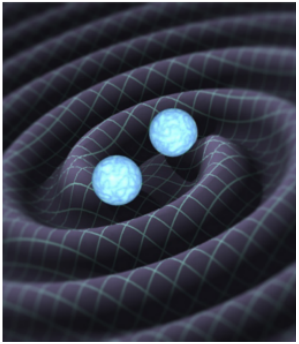
Take-away

- Detecting neutrinos in coincidence with gravitational waves would provide exceptional information on the mechanisms behind the corresponding astrophysical objects

- No detection so far (with Super-Kamiokande or any other experiment). . .

- We have computed upper limits on the total energy emitted in neutrino for these sources (binary neutron stars, binary black holes, NSBH)



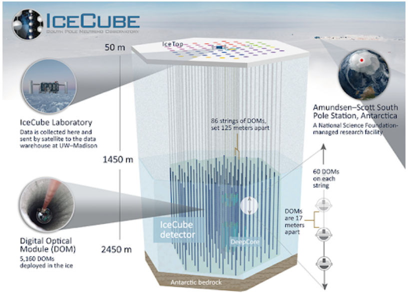


Backups

Neutrino telescopes

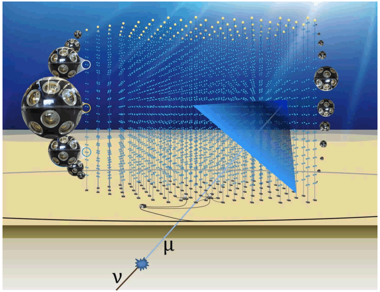
Need very large detectors to detect them...

Two big players



IceCube

One kilometer-cube of Ice at the South Pole, instrumented with $\sim 5k$ optical modules.



KM3NeT

Kilometer-cube scale infrastructured in the Mediterranean Sea. Currently under deployment.

Combined flux/E_{iso} limits

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

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

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 ($\int_0^{\phi_0^{\mathrm{up}}} \mathcal{L}(\phi_0) d\phi_0 = 0.90$).

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

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

Detailed results for GW190425 (BNS, $d = 0.16\,\mathrm{Gpc}$)

Trigger name	Sample		ν_e	$\bar{\nu}_e$	$\nu_\mu\ (\nu_x)$	$\bar{\nu}_\mu\ (\bar{\nu}_x)$
GW190425	HE $E^2\frac{dn}{dE}$	FC	$2.22 \cdot 10^3$	$4.32 \cdot 10^3$	$3.91 \cdot 10^3$	$9.42 \cdot 10^3$
		PC	$3.32 \cdot 10^4$	$1.12 \cdot 10^5$	$4.81 \cdot 10^3$	$8.74 \cdot 10^3$
		UPMU	–	–	–	–
		Combined	$2.09 \cdot 10^3$	$4.28 \cdot 10^3$	$2.16 \cdot 10^3$	$4.20 \cdot 10^3$
	HE E_{iso}	Per-flavour	$1.98 \cdot 10^{56}$	$3.85 \cdot 10^{56}$	$1.96 \cdot 10^{56}$	$3.69 \cdot 10^{56}$
		$\nu + \bar{\nu}$	$2.62 \cdot 10^{56}$		$2.52 \cdot 10^{56}$	
		All	$3.47 \cdot 10^{56}$			
	LE Φ	Flat	$1.49 \cdot 10^9$	$1.83 \cdot 10^7$	$9.35 \cdot 10^9$	$1.11 \cdot 10^{10}$
		Fermi-Dirac	$3.92 \cdot 10^9$	$9.57 \cdot 10^7$	$2.43 \cdot 10^{10}$	$2.87 \cdot 10^{10}$
	LE E_{iso}	Per-flavour	$3.92 \cdot 10^{59}$	$9.59 \cdot 10^{57}$	$2.43 \cdot 10^{60}$	$2.87 \cdot 10^{60}$
		All	$5.54 \cdot 10^{58}$			

PRELIMINARY $E^2\frac{dn}{dE}$ [in GeV cm^{-2}], Φ [in cm^{-2}], E_{iso} [in erg]

Statistical analysis

For each sample k, we define the likelihood:

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

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:

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

The final test statistic and p-value are:

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

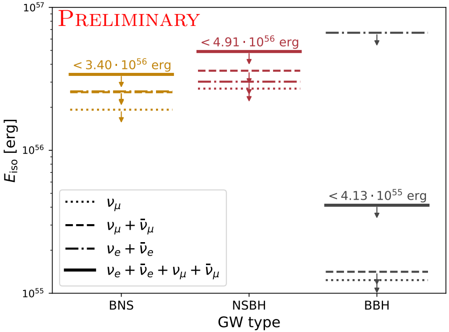
where $\mathcal{P}_{\text{bkg}}(TS)$ is the expected background distribution.

Stacking population analysis

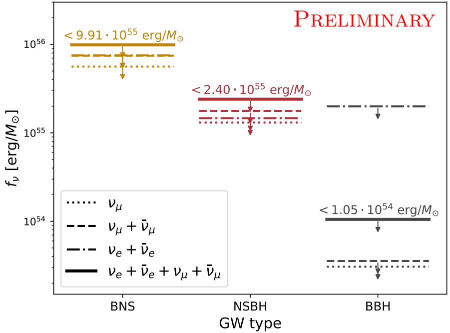
We combine the likelihoods within a given population[3]:

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

assuming same E_{iso}



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



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[3] Veske et al. JCAP 05 (2020) 016

Supernova analysis

- With Super-K (and even Hyper-K), we expect only few events from SNe outside of our galaxy:
  $\Rightarrow$ **if SN happens in Andromeda, we may miss it!**
- It is useful to have a SN burst detection system with a threshold on number of detected neutrinos **as low as possible**.
- New method RTS^2 was proposed to use time structure of the signal in order to separate signal (burst) from background (constant).
- It is performing much better for low multiplicity = further SNe
- It may be implemented in Hyper-K or other detectors in the SNEWS network of neutrino detectors.