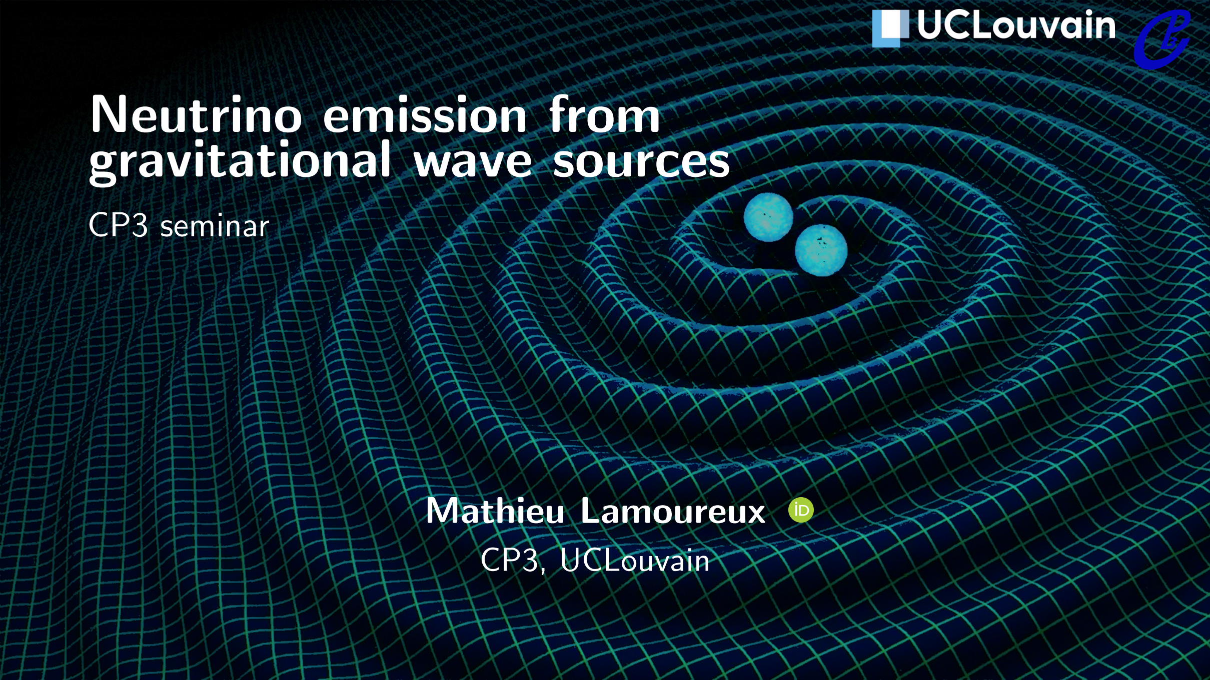
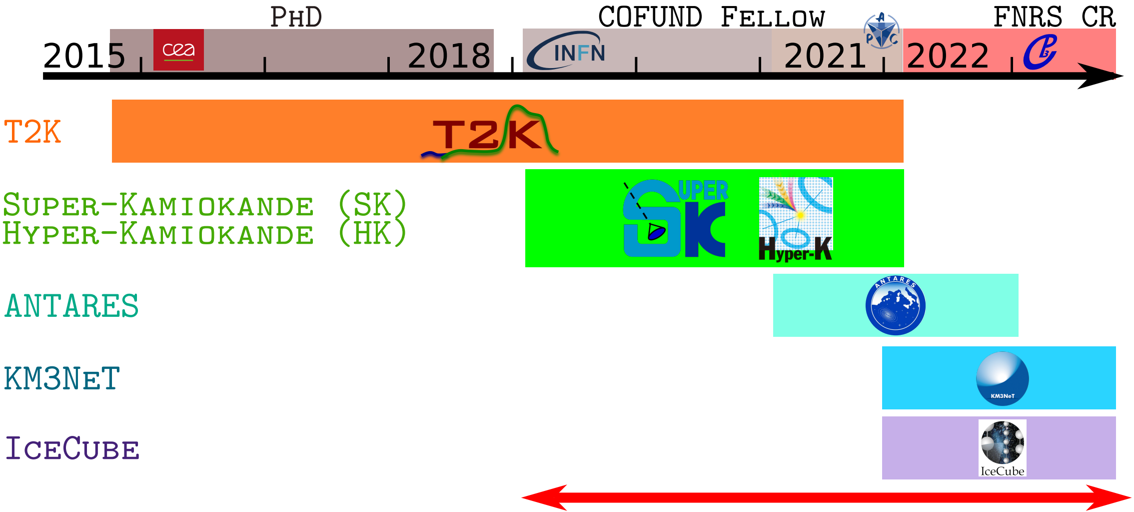


Neutrino emission from gravitational wave sources

CP3 seminar

Mathieu Lamoureux
CP3, UCLouvain

Overview of my path



PhD

COFUND Fellow

FNRS CR

2015

2018

2021

2022

T2K

Super-Kamiokande (SK)
Hyper-Kamiokande (HK)

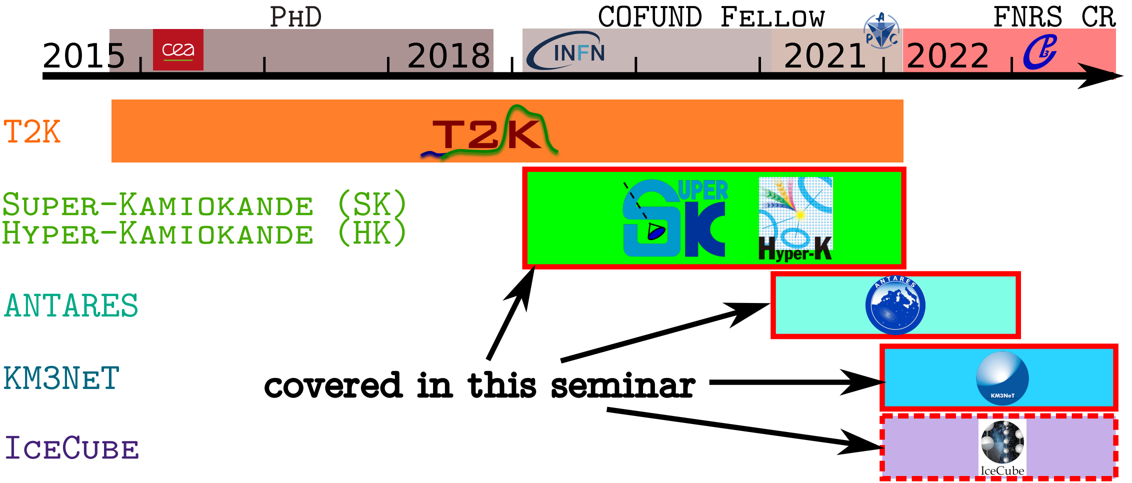
ANTARES

KM3NeT

IceCube

Central theme: multimessenger astronomy with neutrinos and especially neutrinos from gravitational wave sources

Overview of my path



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ANTARES

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IceCube

covered in this seminar

Central theme: multimessenger astronomy with neutrinos and especially neutrinos from gravitational wave sources

Introduction

Binary mergers

Phys. Rev. D 93, 044019
Phys. Rev. D 93, 123015

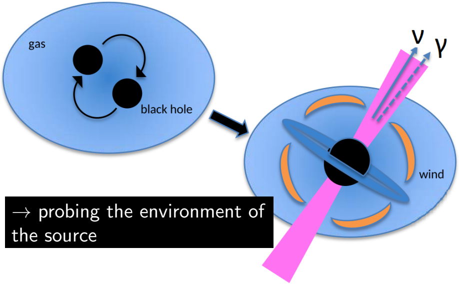
Mergers of compact objects (Neutron Stars -NS-, Black Holes -BH-) are established gravitational wave (GW) emitters.

- **BNS** (NS+NS) or **NSBH** (NS+BH): may produce short Gamma-Ray Bursts with neutrino production
- **BBH** (BH+BH): neutrinos may be produced in the accretion disks of the BHs

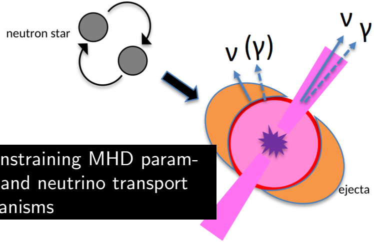
Spectrum	$E^{-\gamma}$ often considered in searches and MeV/GeV emission?
Shape	isotropic (not realistic at high energy) or presence of directional jet?
Timing	GW170817 + GRB170817A observation hints to prompt signal for BNS

Total energy emitted in neutrinos?

Not well estimated, 10^{50}-10^{53} erg? (1 erg ≈ 624 GeV)

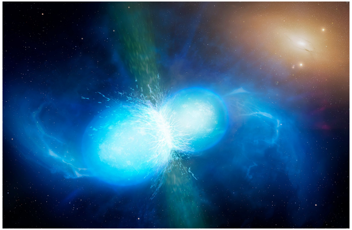


→ probing the environment of the source



→ constraining MHD parameters and neutrino transport mechanisms

Reference for how energetic are these events



$$=$$

Belgium electricity production for $10^{25} - 10^{28}$ years!

Existing GW catalogs

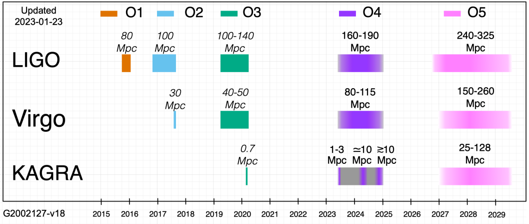
📖 Phys.Rev.X 11 (2021) 021053
📖 arXiv:2111.03606

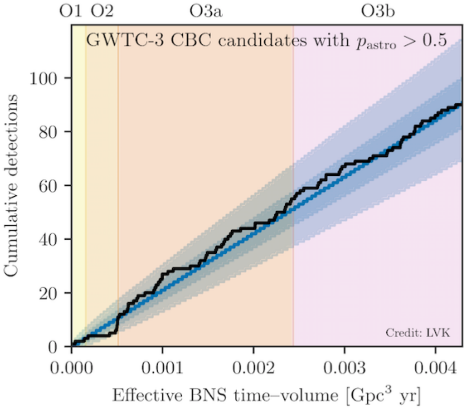
Since 2015, $\sim$ 100 detections distributed in 4 catalogs:

- **GWTC-1:** 11 events from O1 and O2
- **GWTC-2:** 39 events from O3a
- **GWTC-2.1:** 8 add. events from O3a
- **GWTC-3:** 35 events from O3b

Next observation period O4:

- expected to start **end of May 2023**
- **hundreds** of new detections per year





Content of GW catalogs

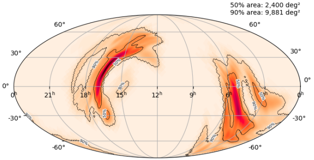
For each GW, we have:

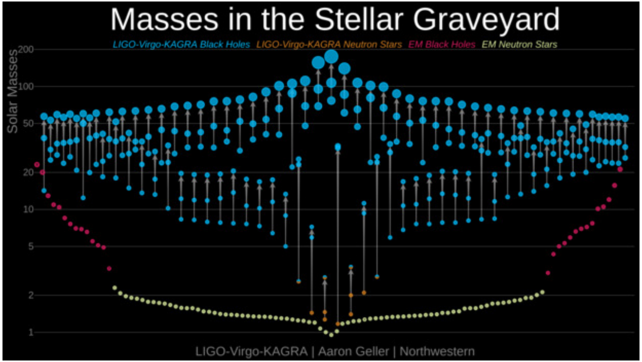
- time of the event
- sky localisation
- estimated distance
- estimated masses

Classification:

Events can be classified based on object masses:

- $m < 3\,\mathrm{M}_\odot$=NS
- $m > 3\,\mathrm{M}_\odot$=BH





In total:

- 2 BNS (GW170817, GW190425)
- 5 NSBH
- the rest are BBH

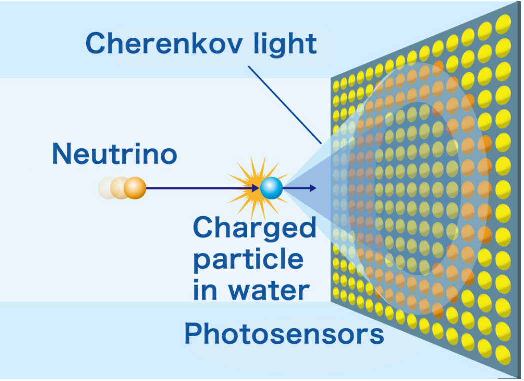
Neutrino detection with large volumes

Golden technique detection of Cherenkov light emitted by charged particles produced during neutrino interaction

Golden technology large water volume instrumented with photomultipliers (PMTs)

Three main strategies:

- *Super-Kamiokande/Hyper-Kamiokande:* water tank with PMTs on the walls of the tank
- *ANTARES/KM3NeT/Baikal-GVD. . . :* PMTs deployed on vertical lines in sea/ocean/lake
- *IceCube:* same as above, but in ice



Follow-up with Super-Kamiokande

The Super-Kamiokande experiment (1)

📖 NIM.A 501 (2003) 418-462

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

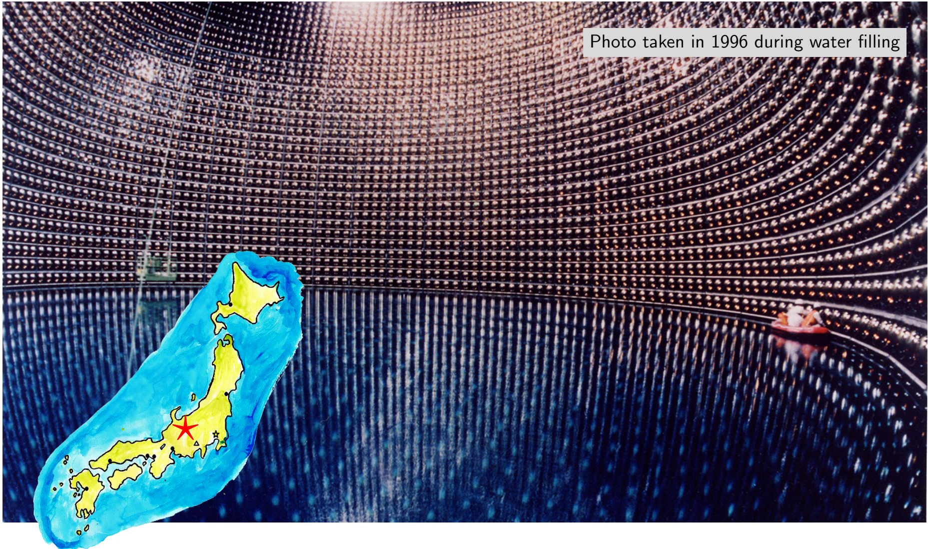
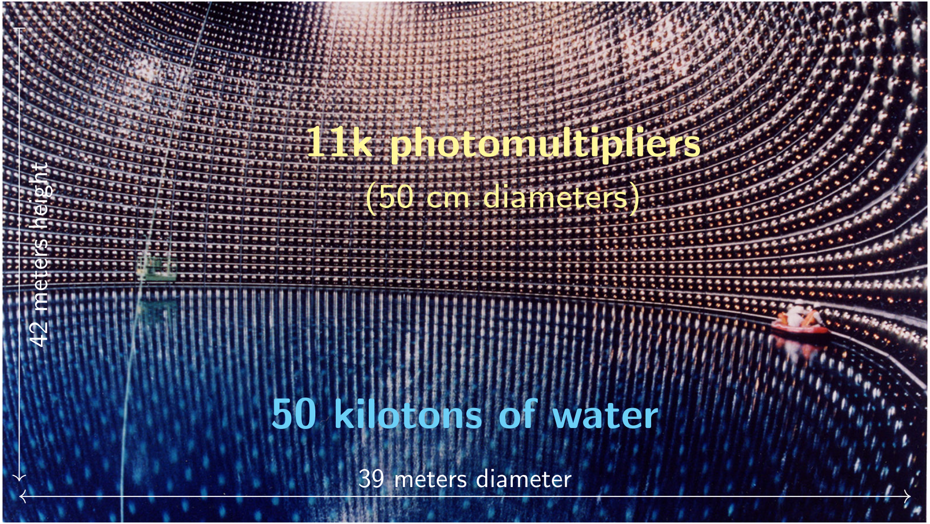


Photo taken in 1996 during water filling

The Super-Kamiokande experiment (1)

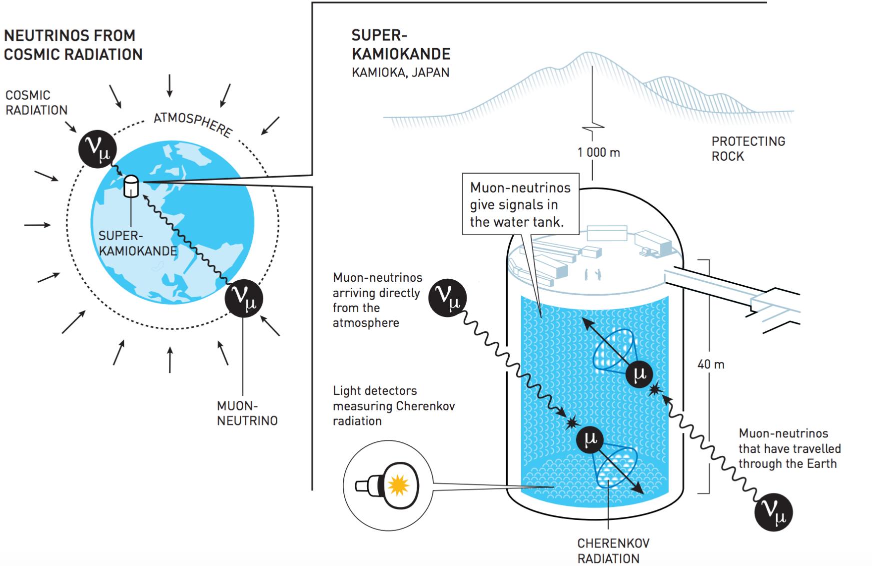
📖 NIM.A 501 (2003) 418-462

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



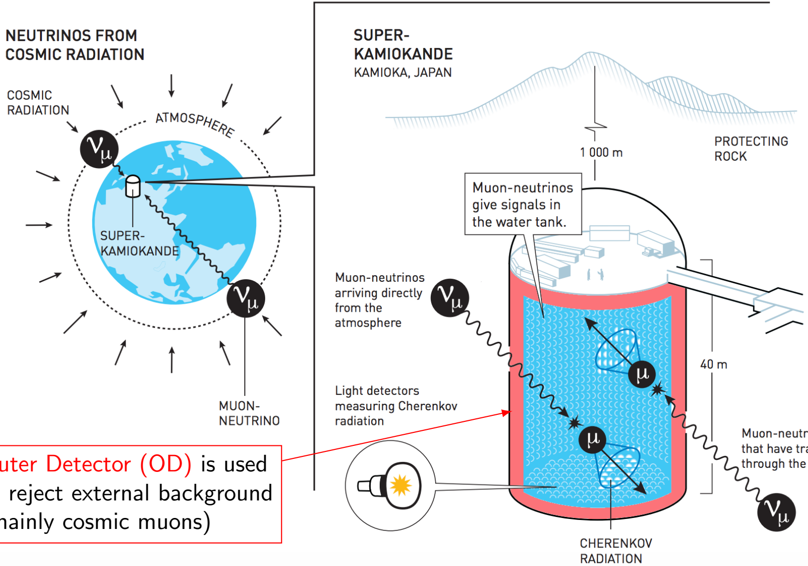
The Super-Kamiokande experiment (2)

📖 NIM.A 501 (2003) 418-462



The Super-Kamiokande experiment (2)

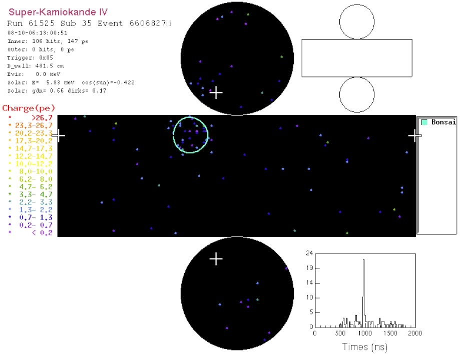
📖 NIM.A 501 (2003) 418-462



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

The different samples

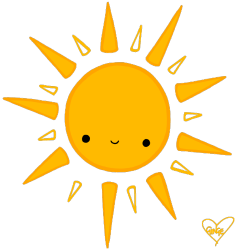
Low-energy events

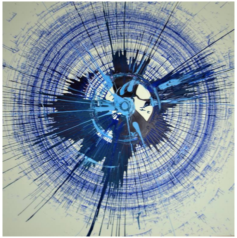


```
Super-Kamiokande IV
Run 61525 Sub 35 Event 6606827
08-10-06:13:00:51
Inner: 106 hits, 147 pe
Outer: 0 hits, 0 pe
Trigger: 0x05
D_wall: 481.5 cm
Evis:   0.0 MeV
Solar: E=  5.83 MeV  cos(sun)=-0.422
Solar: gdn= 0.66 dirks= 0.17
```

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

sparse PMT hits, faint ring

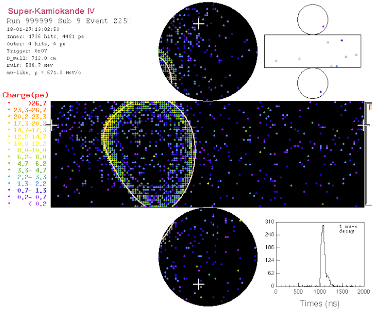


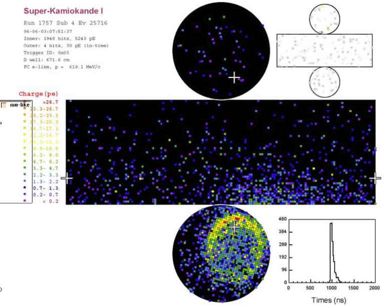


INCREASING ENERGY

The different samples

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 (LOWE)

$E_\nu \sim 3.5 - 100$ MeV

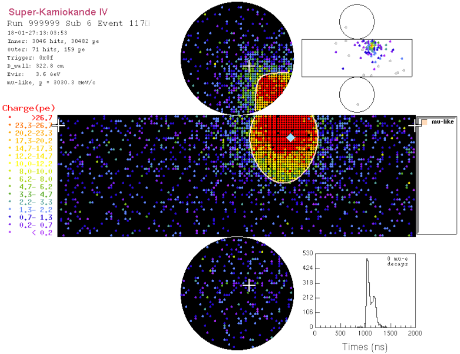
INCREASING ENERGY

The different samples

LOW-ENERGY EVENTS (LOWE)
$E_\nu \sim 3.5 - 100$ MeV

FULLY-CONTAINED EVENTS (FC)
$E_\nu \sim 0.1 - 10$ GeV

Partially-Contained (PC) events



```
Run 999999 Sub 6 Event 117
18-01-27:13:03:53
Inner: 3046 hits, 30482 pe
Outer: 71 hits, 159 pe
Trigger: 0x0f
D_wall: 322.8 cm
Evis:   3.6 GeV
mu-like, p = 3030.3 MeV/c
```

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

exit activity in OD

INCREASING ENERGY

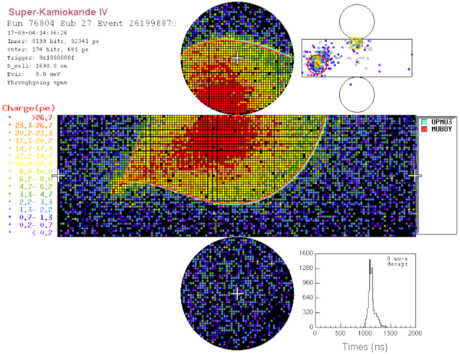
The different samples

LOW-ENERGY EVENTS (LOWE)
$E_\nu \sim 3.5 - 100$ MeV

FULLY-CONTAINED EVENTS (FC)
$E_\nu \sim 0.1 - 10$ GeV

PARTIALLY-CONTAINED EVENTS (PC)
$E_\nu \sim 0.1 - 100$ GeV

Upward-going muons (UPMU)



Upgoing only to reject atmospheric muons

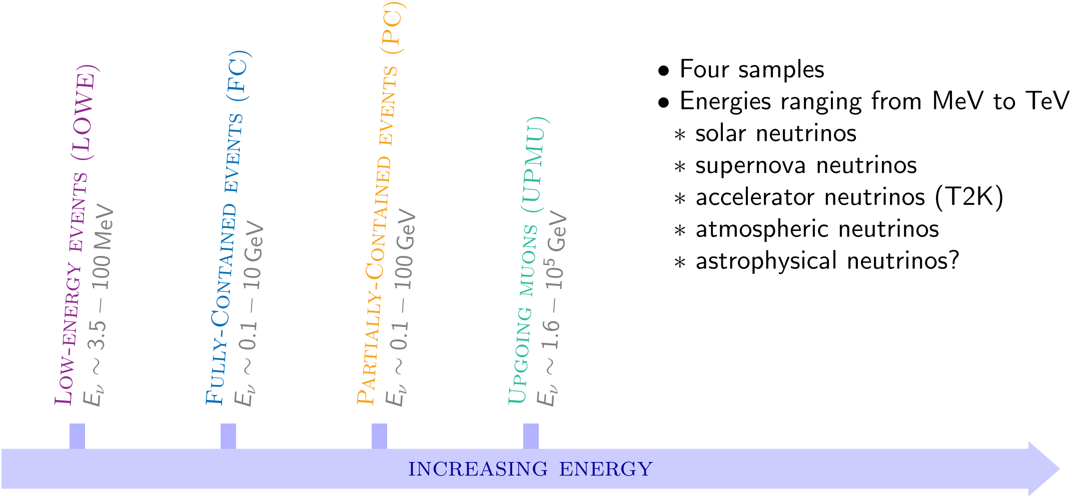
$$\boxed{E_\nu = 1.6\text{ GeV} - 10\text{ TeV}}$$

entering activity in OD

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

INCREASING ENERGY

The different samples



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

INCREASING ENERGY

- Four samples
- Energies ranging from MeV to TeV
  - ∗ solar neutrinos
  - ∗ supernova neutrinos
  - ∗ accelerator neutrinos (T2K)
  - ∗ atmospheric neutrinos
  - ∗ astrophysical neutrinos?

Follow-up strategy with Super-Kamiokande

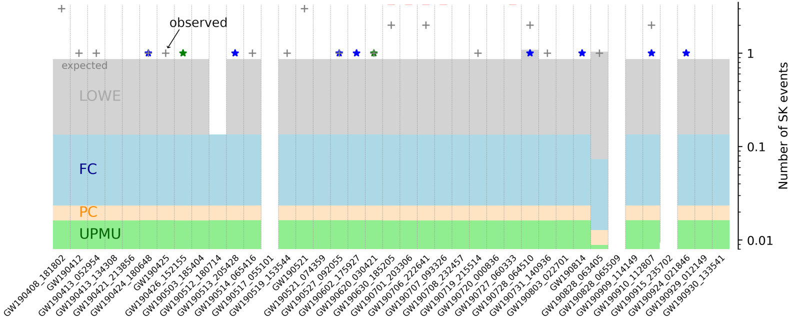
ApJ 918 (2021) 2, 78

- Focus on **GWTC-2** catalog
- 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 **constraints** on neutrino emission
- Compute signal significance by comparing neutrino directions and GW localisation

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



In total:

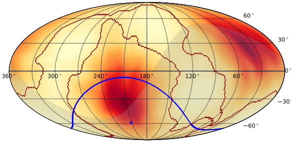
Sample	N_{obs}	N_{exp}
LOWE +	24	24.97
FC ★	8	3.95
PC ★	0	0.26
UPMU ★	2	0.58

No significant excess was observed in any of the samples.

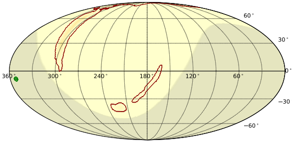
Ten SK high-energy events in time coincidence

📖 ApJ 918 (2021) 2, 78

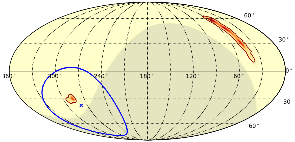
GW190424_180648



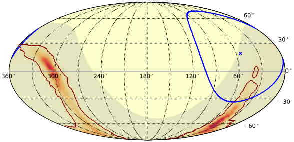
GW190426_152155



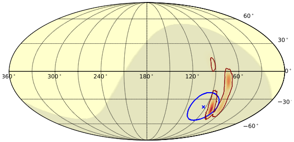
GW190513_205428



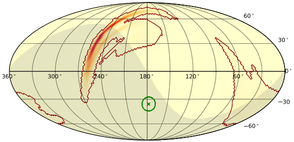
GW190527_092055



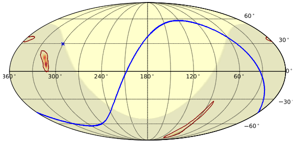
GW190602_175927



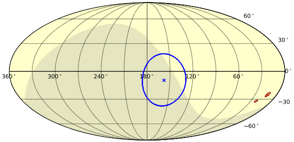
GW190620_030421



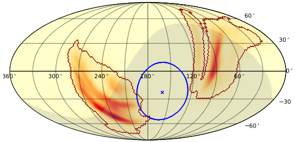
GW190728_064510



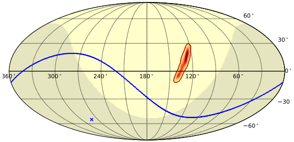
GW190814



GW190910_112807



GW190924_021846



Skymaps in equatorial coordinates

Red: GW localisation and 90% contour

Blue: SK FC events with 1σ angular uncertainty

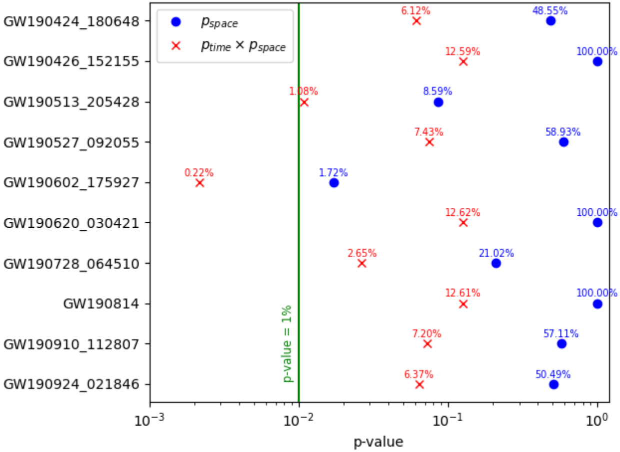
Green: SK UPMU events.

Shaded area: SK upgoing sky.

Observation significance

ApJ 918 (2021) 2, 78

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:

$$\boxed{p = 0.22\%}$$

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

$$\boxed{P = 7.8\%}$$

High-Energy Flux limits (1)

ApJ 918 (2021) 2, 78

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

Sample-by-sample flux limits

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

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

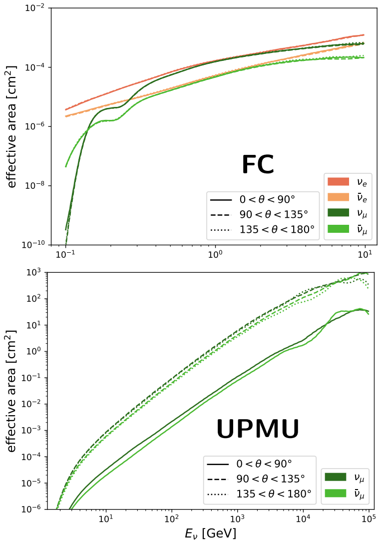
where $a(\Omega) = \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\nu A_{\text{eff}}(E_\nu, \theta) E_\nu^{-2}$ is the **acceptance**.

90% limit on flux 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 used for significance computation.

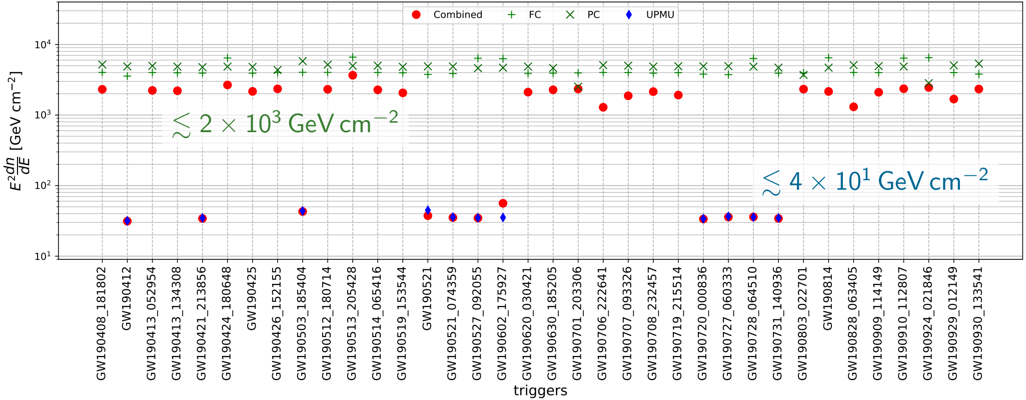
Effective area A_{eff}



High-Energy Flux limits (2)

📖 ApJ 918 (2021) 2, 78

Example of limits for ν_μ flavour:



$\lesssim 2 \times 10^3$ GeV cm^{-2}

$\lesssim 4 \times 10^1$ GeV cm^{-2}

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

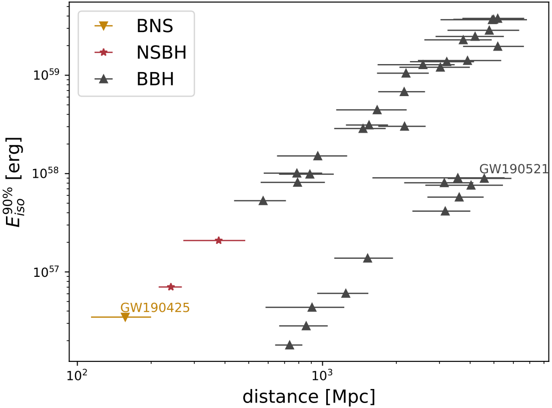
Limits on the total energy emitted in neutrinos

ApJ 918 (2021) 2, 78

- We assume isotropic emission of high-energy neutrinos around the source.
- The distance to the GW source is estimated by LIGO/Virgo from GW observations.
- The total energy emitted in neutrinos from the source is related to the flux at Earth:

$$E_{\mathrm{iso}} = 4\pi d^2 \int \frac{\mathrm{d}N}{\mathrm{d}E} \times E \, \mathrm{d}E$$

- Limits on E_{iso} are computed in the same way as the ones on the flux.
- They range between 2×10^{56} erg and 4×10^{59} erg.

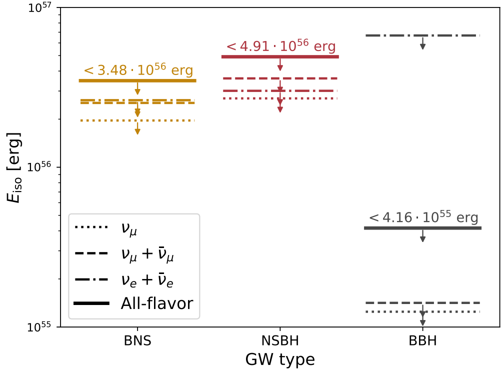


Population study

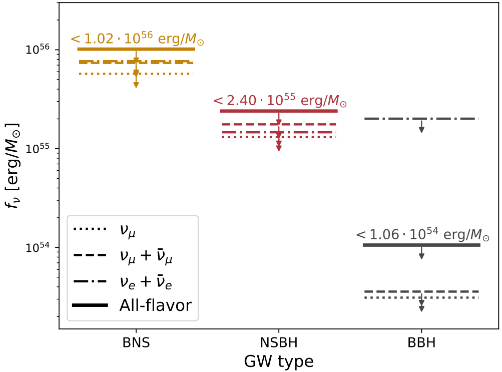
📖 ApJ 918 (2021) 2, 78

- We may expect all BBH mergers will have similar behaviour (same for NSBH and BNS).
- *Hypothesis 1:* they all the same neutrino emission and we want to constrain $E_{\rm iso}$
- *Hypothesis 2:* the emissilon scales with the "size" of the binary system e.g., $E_{\rm iso} = f \times M_{\rm initial}$.

Typical emission per source population



Constraint on scaling factor f (hyp.2)



Improvement of a **factor 5** for BBH with respect to individual limits.

Follow-up with ANTARES

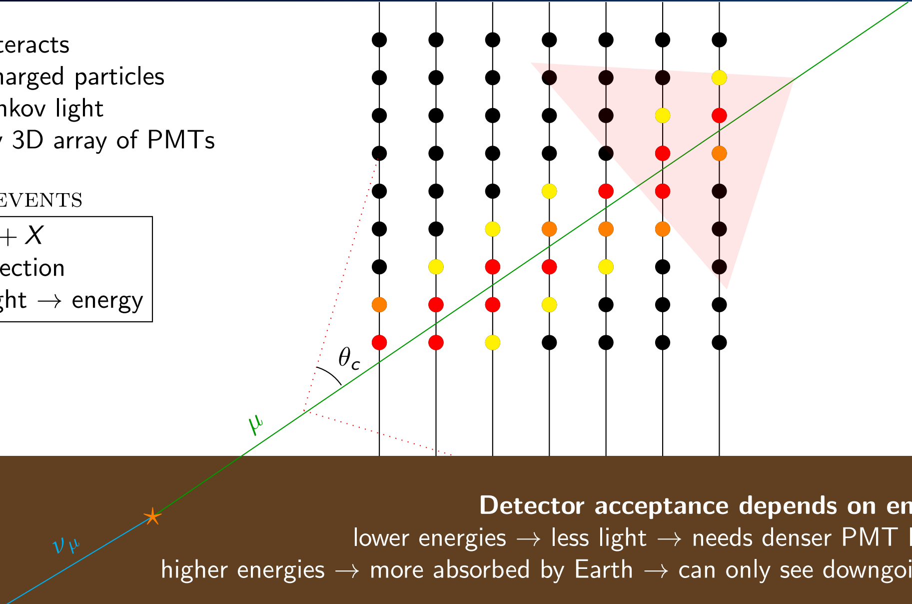
Detection principle

1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

TRACK EVENTS

$\nu_\mu + N \rightarrow \mu + X$

- fit line → direction
- amount of light → energy



Detector acceptance depends on energy:

lower energies → less light → needs denser PMT layout

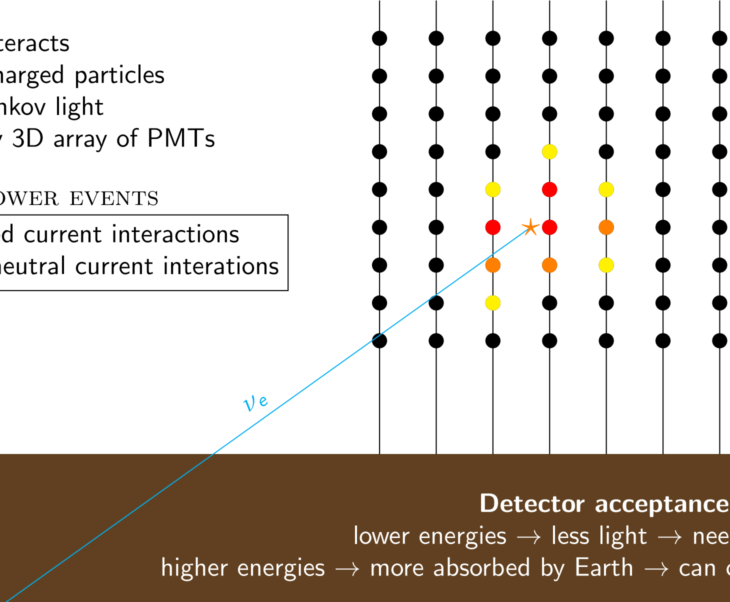
higher energies → more absorbed by Earth → can only see downgoing νs

Detection principle

1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

Shower events

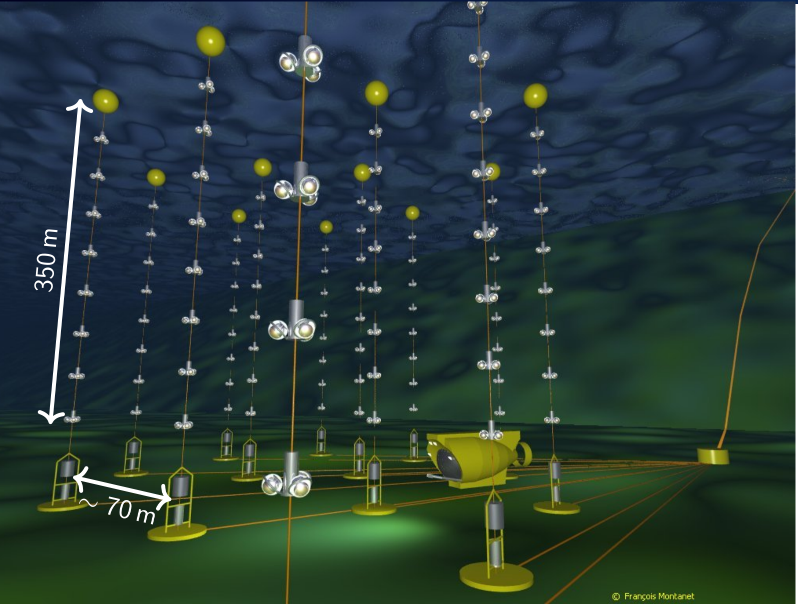
$\nu_e + \nu_\tau$ charged current interactions
$\nu_e + \nu_\mu + \nu_\tau$ neutral current interations



Detector acceptance depends on energy:
lower energies → less light → needs denser PMT layout
higher energies → more absorbed by Earth → can only see downgoing νs

The ANTARES experiment

NIM.A 656 (2011) 11-38



- In operation since 2006 (completed in 2008)
- Off the coast of Toulon
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

Total instrumented volume:
10 Mt

Analysis overview

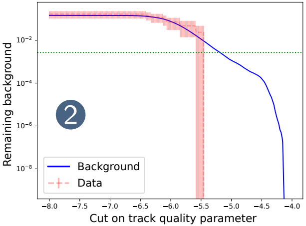
Using both track and shower events

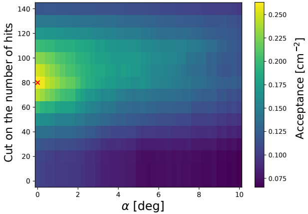
For each GW:

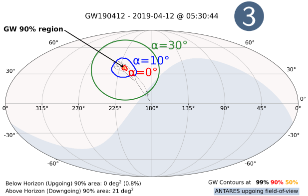
① Find corresponding data period
② **Estimate background**
③ **Optimize search region and cuts** to ensure low background and maximise signal acceptance
④ Compute detector acceptance
⑤ Estimate systematic uncertainties
⑥ Count number of events in data
⑦ **Constrain neutrino emission**

For BBH population (same for NSBH):

- Constrain typical emission







⑦ $$\mathcal{L} = \prod_c \mathrm{Poisson}\left[N_{\mathrm{obs}}^{(c)}; N_{\mathrm{bkg}}^{(c)} + \phi a^{(c)} \mathcal{A}^{\gamma,(c)}(\Omega)/6\right]$$

Constraints on neutrino emission

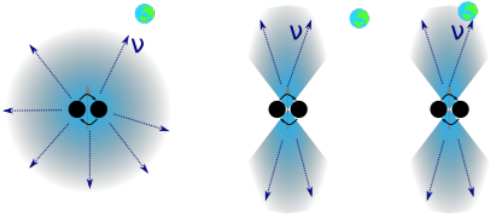
arXiv:2302.07723

Assumption: $\left.\frac{\mathrm{d}N}{\mathrm{d}E}\right|_{\mathrm{all-flavours}} = \phi_0\, E^{-\gamma}$ + equipartition between flavours

- Constraints on the flux normalisation $\phi_0 = E^{\gamma}\mathrm{d}N/\mathrm{d}E$
- Constraints on the total energy emitted in neutrino:
  - assuming **isotropic** emission
  - assuming **jetted** emission [new w.r.t. SK paper]
- Constraints on $f_\nu = E_{\mathrm{tot},\nu}/E_{\mathrm{rad}}$ [different w.r.t. SK paper]
  ($E_{\mathrm{rad}} = \sum M_{\mathrm{init}} - M_{\mathrm{final}}$ is the total energy radiated in GWs)

Method

- Poisson counting in each event category:
  $\mathcal{L} = \prod_{c\in\mathcal{C}} \mathrm{Poisson}\left(N^{(c)}; B^{(c)} + \phi_0 \cdot a_\gamma^{(c)} \cdot f_\gamma^{(c)}(\Omega)\right)$
- Priors on background and signal to cover systematics, flat prior on ϕ_0, $E_{\mathrm{tot}}\ldots$
- Posterior distribution:
  $P(\phi_0) \propto \sum_t \mathcal{L}\left(\{N^{(c)}\}; \{B^{(c)}\}_t, \{a_\gamma^{(c)}\}_t, \Omega_t, \phi_0, \gamma\right)$



Final results

arXiv:2302.07723

- Follow-up of **80 GW events** reported during O3 (April 2019 – March 2020).
- **No excess observed** in any channels.
- Upper limits on neutrino emission:
  - typical flux limits:

    $$\boxed{E^2 \mathrm{d}N/\mathrm{d}E < 4 - 60\,\mathrm{GeV\,cm}^{-2}}$$

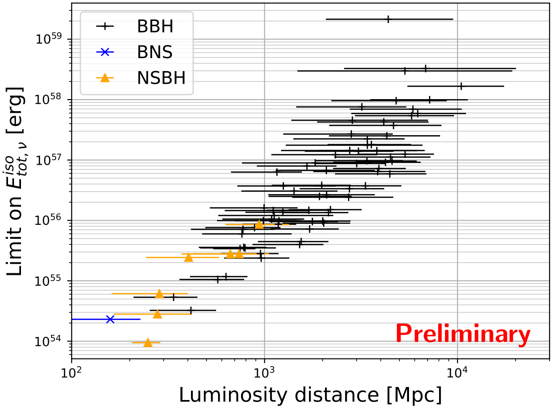
  - limits on total energy emitted in neutrinos (assuming isotropic emission):

    $$\boxed{E^{\mathrm{iso}}_{\mathrm{tot},\nu} < 10^{54} - 2 \times 10^{59}\,\mathrm{erg}}$$

  - limits on $f^{\mathrm{iso}}_{\nu} = E^{\mathrm{iso}}_{\mathrm{tot},\nu} / E_{\mathrm{rad}}$:

    $$\boxed{f^{\mathrm{iso}}_{\nu} < 2 - 50\,000}$$

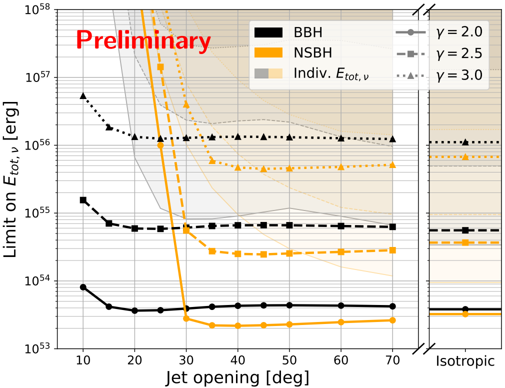
Individual limits on total isotropic energy

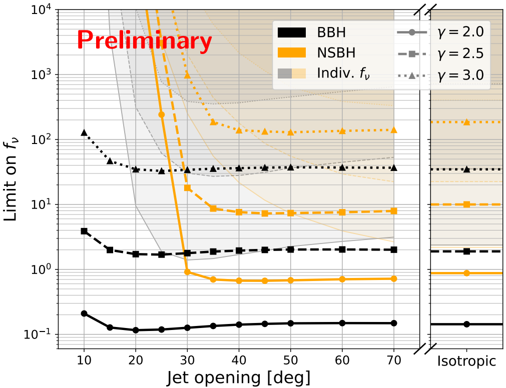


Population study

arXiv:2302.07723

Same strategy as for Super-K, except that we also consider non-isotropic emissions and $E^{-2.5}$, $E^{-3.0}$ spectra.





BBH stacking (72 events)

$E^{\text{iso}}_{\text{tot},\nu} < 4 \times 10^{53}$ erg, $f_\nu < 0.15$

NSBH stacking (7 events)

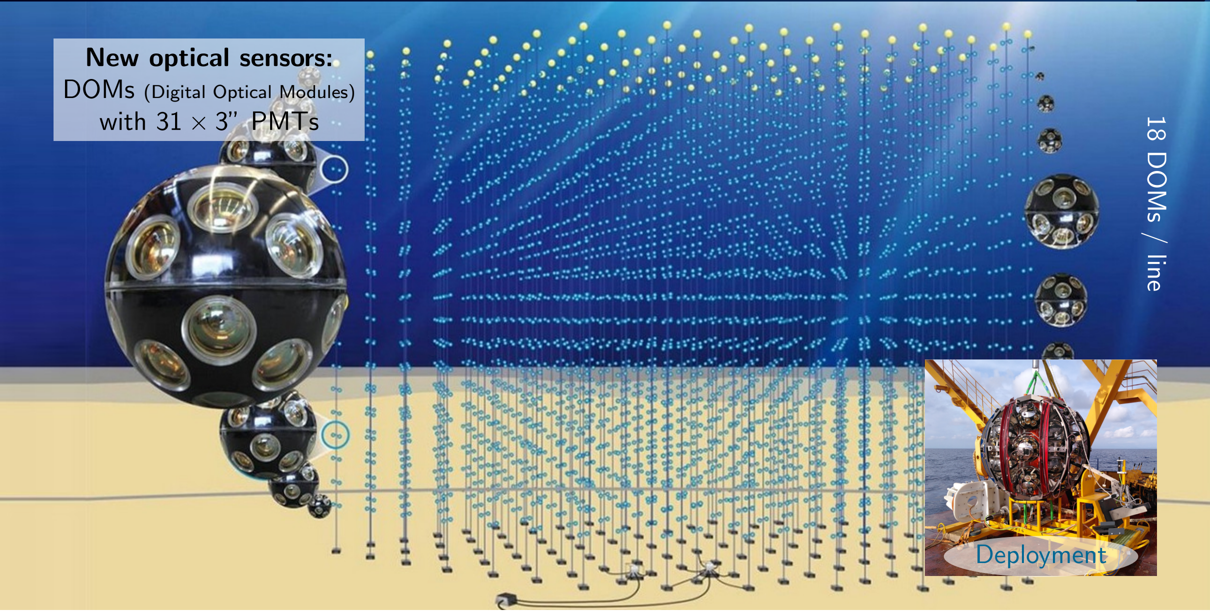
$E^{\text{iso}}_{\text{tot},\nu} < 3.2 \times 10^{53}$ erg, $f_\nu < 0.88$

Follow-up with KM3NeT

The KM3NeT experiment

J.Phys.G 43 (2016) 8, 084001

New optical sensors:
DOMs (Digital Optical Modules)
with 31 × 3" PMTs

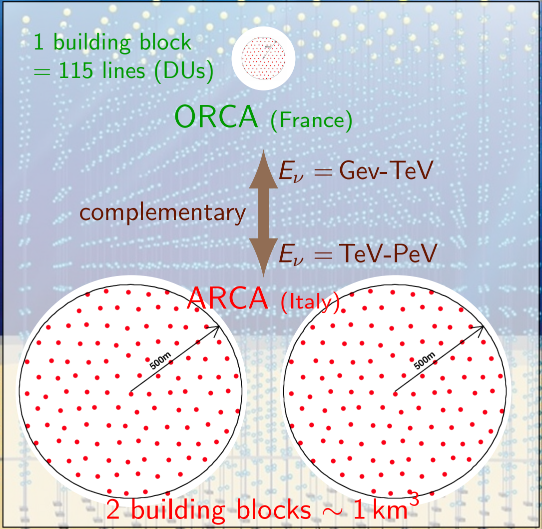


18 DOMs / line

The KM3NeT experiment

J.Phys.G 43 (2016) 8, 084001

New optical sensors:
DOMs (Digital Optical Modules)
with 31 × 3" PMTs



1 building block
= 115 lines (DUs)

ORCA (France)

E_ν = Gev-TeV

complementary

E_ν = TeV-PeV

ARCA (Italy)

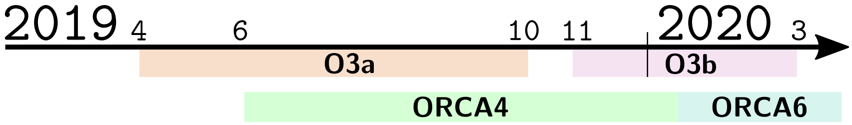
2 building blocks ~ 1 km^3

18 DOMs / line

Deployment

Analysis strategy

During the O3 run, KM3NeT/ORCA was taking data with 4-6 lines (ORCA4 / ORCA6)



Two different selections

Search in the 5-30 MeV **energy range**

- *Search time window:* $[t_{\mathrm{GW}}, t_{\mathrm{GW}} + 2\,\mathrm{s}]$.
- Based on supernova search framework.
- Looking for an **excess of coincidental hits** in sliding 500 ms time windows.
- The maximum number of coincidences is converted to a p-value and limits on neutrino emission (quasi-thermal spectrum).

Search for upgoing tracks (GeV–TeV neutrinos)

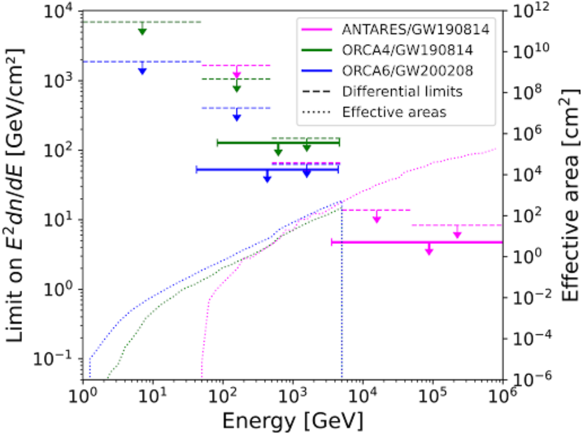
- *Search time window:* $t_{\mathrm{GW}} \pm 500\,\mathrm{s}$.
- Background estimated using off-time events.
- Selection based on a **Boosted Decision Tree**.
- Cut on the score is optimized.
- Limits on neutrino emission (E^{-2} spectrum): $P(\phi) = \int \mathcal{L}(N_{\mathrm{ON}}|b, \phi, a(\Omega)) \times \pi(b)\pi(a)\pi(\Omega)$ assuming the source is in upgoing sky.

Results

- Follow-up of ~ 50 **GW sources**.
- Again, **no significant excess** in both searches.
- Typical high-energy (GeV-TeV) flux limits:
  - **ORCA4:** $E^2 \mathrm{d}N/\mathrm{d}E < 100 - 500\,\mathrm{GeV\,cm^{-2}}$
  - **ORCA6:** $E^2 \mathrm{d}N/\mathrm{d}E < 50 - 200\,\mathrm{GeV\,cm^{-2}}$
- Typical total energy limits:
  - **MeV:** $E^{\mathrm{iso}}_{\mathrm{tot},\nu} < 6 \times 10^{59} - 10^{63}$ erg
  - **GeV-TeV:** $E^{\mathrm{iso}}_{\mathrm{tot},\nu} < 2 \times 10^{56} - 10^{59}$ erg
- Population studies for GeV–TeV analysis:
  - **BBH:** $E^{\mathrm{iso}}_{\mathrm{tot},\nu} < 3.1 \times 10^{55}$ erg
  - **NSBH:** $E^{\mathrm{iso}}_{\mathrm{tot},\nu} < 1.9 \times 10^{55}$ erg

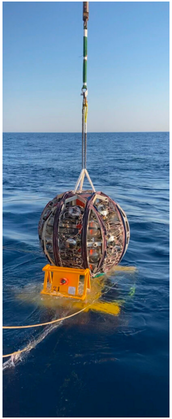
Paper under preparation

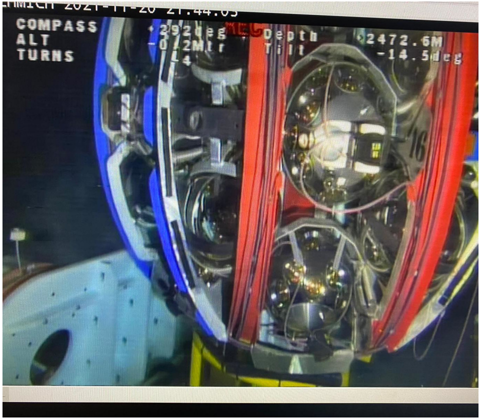
Comparison between ANTARES and KM3NeT/ORCA4-6



Current status and near future

ORCA: 15 lines, **ARCA:** 21 lines. **In 2023:** new lines in spring/autumn (live blog 🐦 ▶, app)





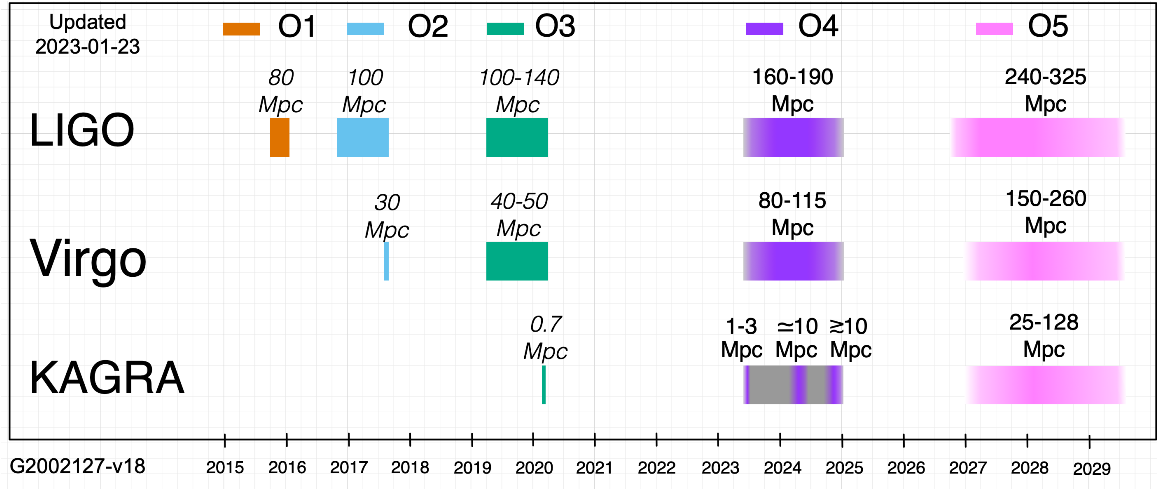
Summary (1)

Type	Super-Kamiokande	ANTARES	KM3NeT
Energy range	7 – 100 MeV 0.1 GeV – TeV	100 GeV – PeV	5 – 30 MeV GeV – TeV
Time window	1000 s	1000 s	2 s and 1000 s
Flavours	$\bar{\nu}_e$/all	all	all and $\nu_\mu + \bar{\nu}_\mu$
Flux limits (E^{-2})	40-2000 GeV cm^{-2}	4-60 GeV cm^{-2}	50-500 GeV cm^{-2}
$E^{\mathrm{iso}}_{\mathrm{tot},\nu}$, BBH stacking	4×10^{55} erg	4×10^{53} erg	3×10^{55} erg
More details. . .	Paper in ApJ	Paper on arXiv	Paper incoming!

- Different selections, but same underlying statistical methods in all these searches.
- All observations are fully compatible with the expected background.

Outlooks

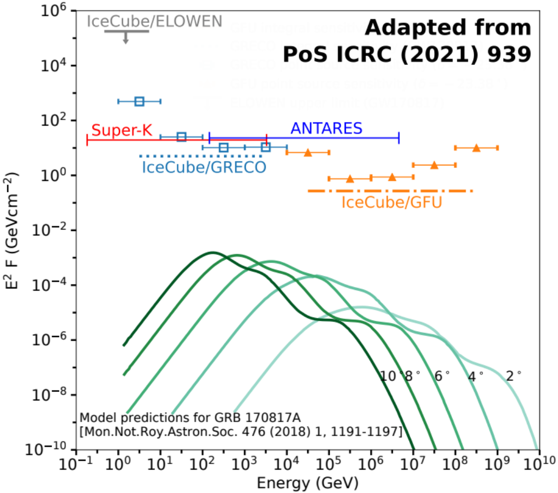
Next GW observation period



O4 expected to start on **May 24th, 2023**. Significant GW alert rate: **1 per day**

How far we are & what we can do

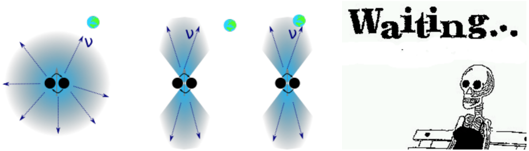
📖 MNRAS 476 (2018) 1, 1191-1197
📖 MNRAS 490 (2019) 4, 4935-4943



Be aware that this is a specific neutrino emission model, others may be more or less optimistic.

Despite many analyses, no excess found yet. . .

1. Waiting to get lucky for any signficant neutrino detection?



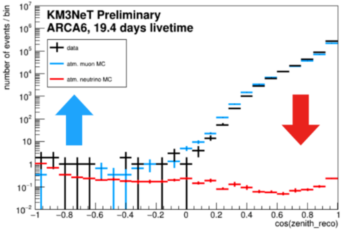
2. Extend the reach of current large telescopes (KM3NeT/IceCube) to the lowest energies.
3. Perform stacking analyses and population studies, taking benefit of the increasing catalog of GW sources.

KM3NeT @ UCLouvain

EPS-HEP2021 091
KM3NeT Town Hall

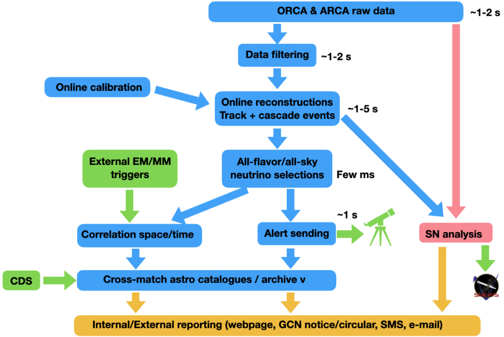
Ongoing development of new selections

- selection of GeV neutrinos using single-DOM events, to be used for transient searches **[Jonathan]**
- selection of downgoing track-like events:
  - needs to separate downgoing neutrinos from the dominant atmospheric muon background
  - development of dedicated boosted decision tree



Getting prepared for O4

- new realtime framework under finalisation
- getting ready to follow O4 alerts quickly, with ORCA and ARCA, with low- and high-energy events



ORCA & ARCA raw data ~1-2 s

Data filtering ~1-2 s

Online calibration

Online reconstructions
Track + cascade events ~1-5 s

External EM/MM triggers

All-flavor/all-sky neutrino selections Few ms

Correlation space/time

Alert sending ~1 s

SN analysis

CDS

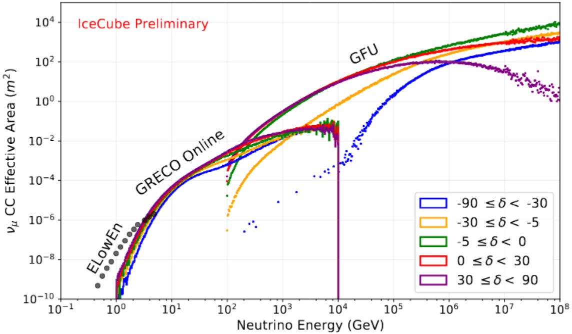
Cross-match astro catalogues / archive v

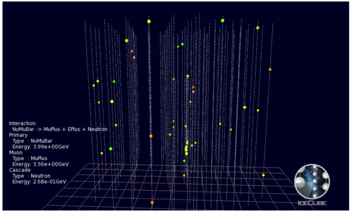
Internal/External reporting (webpage, GCN notice/circular, SMS, e-mail)

IceCube @ UCLouvain

arXiv:2105.13160
Gwen's thesis

Papers: GW150914 (PRD 93, 122010), GW151226 (PRD 96, 022005), GW170817 (ApJ.Lett. 850 (2017) 2, L35), O1+O2 (ApJ.Lett. 898 (2020) 1, L10), O3 (PoS ICRC2021, 939, arXiv:2105.13160, arXiv:2208.09532)





Interaction:
NuMuBar -> MuPlus + EPlus + Neutron
Primary
Type : NuMuBar
Energy: 3.99e+00GeV
Muon
Type : MuPlus
Energy: 3.56e+00GeV
Cascade
Type : Neutron
Energy: 2.68e-01GeV

Example of GeV neutrino event (+noise)

Different analyses:

- GFU, $> 100\,\mathrm{GeV}$ (ν_μ), $b = 6.7\,\mathrm{mHz}$
- GRECO, $5 - 100\,\mathrm{GeV}$ (ν_μ), $b = 4.5\,\mathrm{mHz}$
- ELOWEN, $0.5 - 5\,\mathrm{GeV}$ (all), $b = 20\,\mathrm{mHz}$

Ongoing works with **[Gwen]** *and* **[Karlijn]***:*

- improvement of the ELOWEN selection (0.5-5 GeV)
- studies about adding directionality information to the ELOWEN events
- getting prepared for quick follow-up of O4 real-time alerts!

Prospects for combination

📖 JANG GitHub repository

All experiments publish independent results. How complementary are they?

Joint **A**nalysis of **N**eutrinos and **G**ravitational waves

New Bayesian framework aiming to perform quick analysis for single detector and combination of different samples in different detectors to exploit complementarity.

Inputs:

- **Neutrino:** observation, background, Instrumental Response Functions
- **GW:** posterior samples, skymap

Configuration:

- Neutrino spectrum (E^{-2}, E^{-3}, $E^{-2}e^{-E/E_{\rm cut}}\dots$), emission model
- Priors on nuisance and signal parameters
- Poisson or point-source likelihood

Outputs:

- Limits on the flux, on the total energy...
- Stacked limits for sub-populations

Can be used to investigate synergies between different searches.

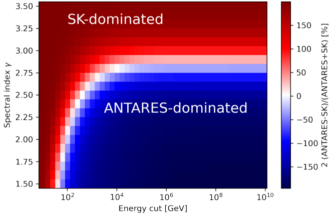
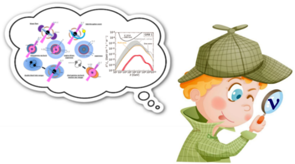


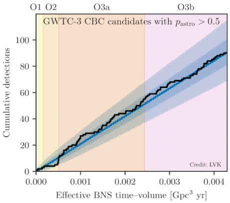
Fig: Example with ANTARES and Super-K, as a function of energy cut (x-axis) and spectral index (y-axis).

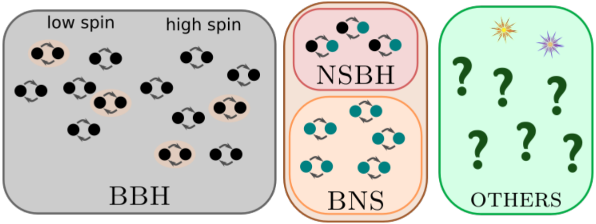
Summary (2)

Take-home message:

- Neutrino emission expected from binary mergers
- Many constraints from existing neutrino telescopes, but **no detection yet**
- Promising prospects with O4 (more events, more BNS. . .)
- ... but we should also benefit from new developments at neutrino telescopes:
  - extension to lower energies [GeV range explored here @ UCLouvain]
  - synergies between experiments
  - more advanced population studies



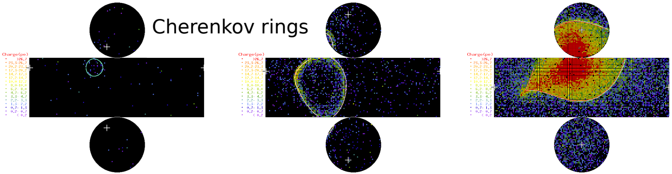




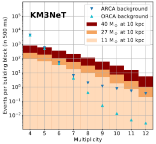
Backups

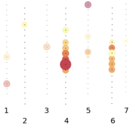
Energy ranges of neutrino telescopes

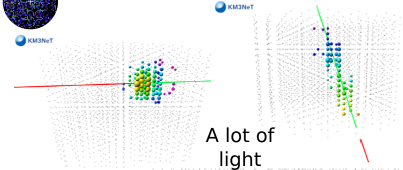
Super-K
Hyper-K


Cherenkov rings

ANTARES
KM3NeT



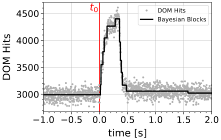




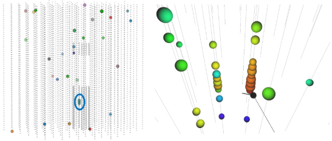
A lot of light

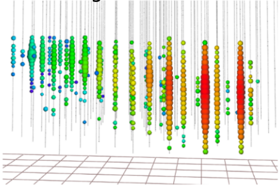
IceCube

Increase of PMT rate



Signal on few DOMs





MeV GeV TeV PeV

Super-Kamiokande: Significance

Astrophys.J.Lett. 898 (2020) 1, L10

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

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

- $p_{\text{time}} = \text{Prob}(N \geq 1) = 1 - e^{-n_B} \sim 12.6\%$ for $n_B =$ total background $_{\text{(FC+PC+UPMU)}} = 0.13$
- p_{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:

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

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

Super-Kamiokande: Test statistic

Astrophys.J.Lett. 898 (2020) 1, L10

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:

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

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

Super-Kamiokande: Combined limits

Astrophys.J.Lett. 898 (2020) 1, L10

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

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

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:

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

ANTARES: Constraints on neutrino emission

📖 arXiv:2302.07723

Inputs

- detector acceptance as a function of direction
- number of observed/expected events in track and shower channels
- GW information (posterior samples, skymap)

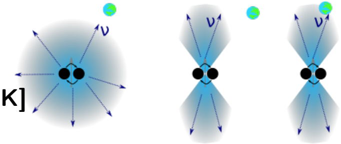
Assumptions

$$\boxed{\left.\frac{\mathrm{d}N}{\mathrm{d}E}\right|_{\mathrm{all-flavours}} = \phi_0\, E^{-\gamma} + \text{equipartition between flavours}}$$

Outputs

- constraints on the flux normalisation $\phi_0 = E^{\gamma}\mathrm{d}N/\mathrm{d}E$
- constraints on the total energy emitted in neutrino:
  - assuming isotropic emission
  - assuming jetted emission **[DIFFERENT w.r.t. Super-K]**
- constraints on $f_\nu = E_{\mathrm{tot},\nu}/E_{\mathrm{rad}}$ **[DIFFERENT]**

  ($E_{\mathrm{rad}} = \sum M_{\mathrm{init}} - M_{\mathrm{final}}$ is the total radiated energy = total energy budget of the merger process)



Method

- Poisson counting in each event category:

  $$\mathcal{L} = \prod_{c\in\mathcal{C}} \mathrm{Poisson}\left(N^{(c)}; B^{(c)} + \phi_0 \cdot a_\gamma^{(c)} \cdot f_\gamma^{(c)}(\Omega)\right)$$
- Priors on background and signal to cover systematics, flat prior on ϕ_0, $E_{\mathrm{tot}}\ldots$
- Posterior distribution: $P(\phi_0) \propto \sum_{t\in\mathrm{toys}} \mathcal{L}\left(\{N^{(c)}\}; \{B^{(c)}\}_t, \{a_\gamma^{(c)}\}_t, \Omega_t, \phi_0, \gamma\right)$