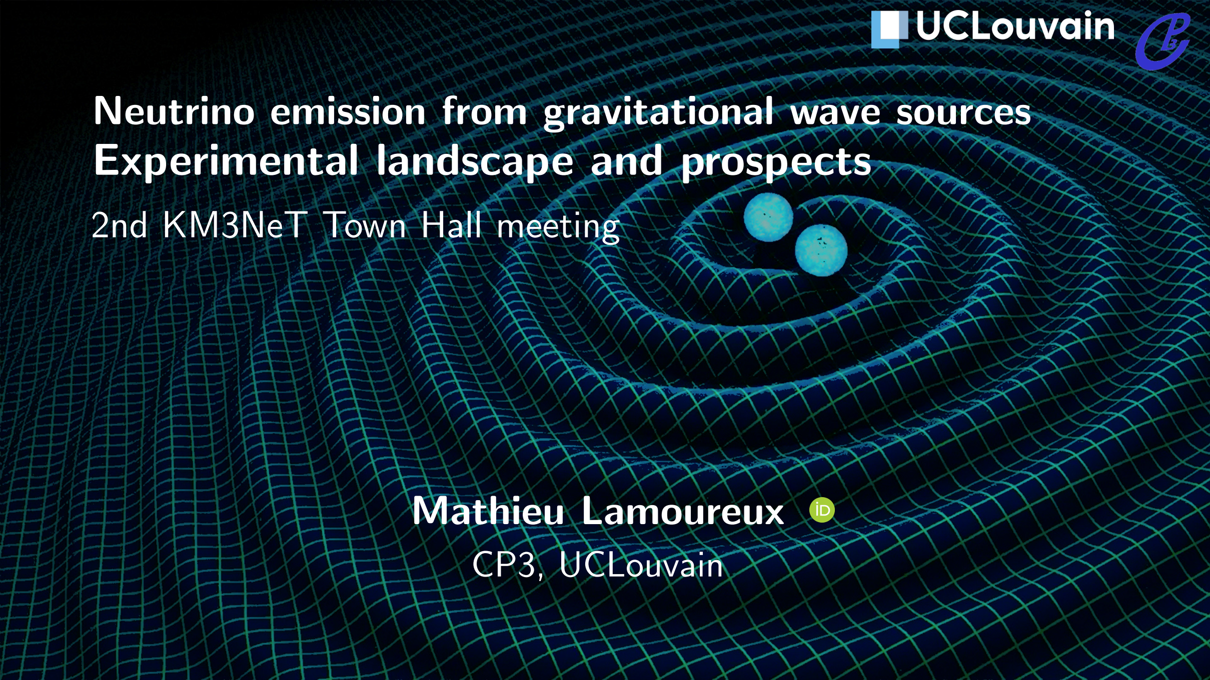
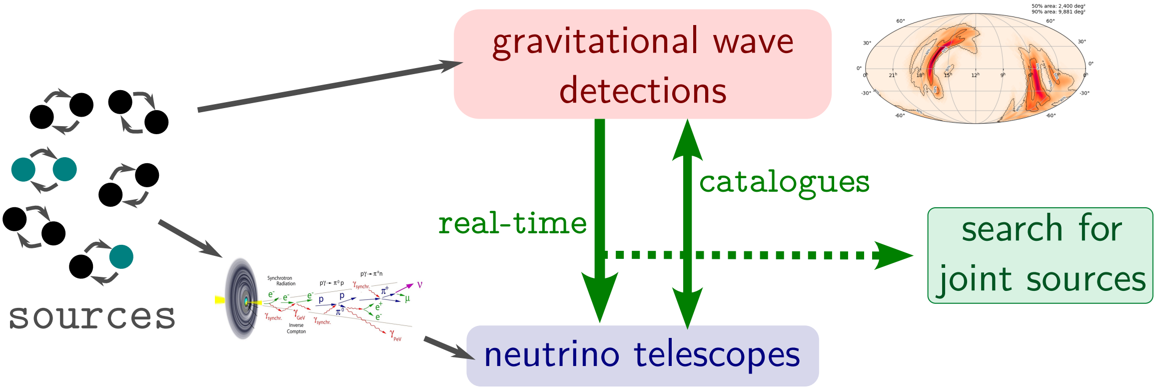


Neutrino emission from gravitational wave sources
Experimental landscape and prospects

2nd KM3NeT Town Hall meeting

Mathieu Lamoureux
CP3, UCLouvain

Outline



sources

gravitational wave detections

real-time

catalogues

neutrino telescopes

search for joint sources

What? **Why?** **Where?** **How?**

Introduction

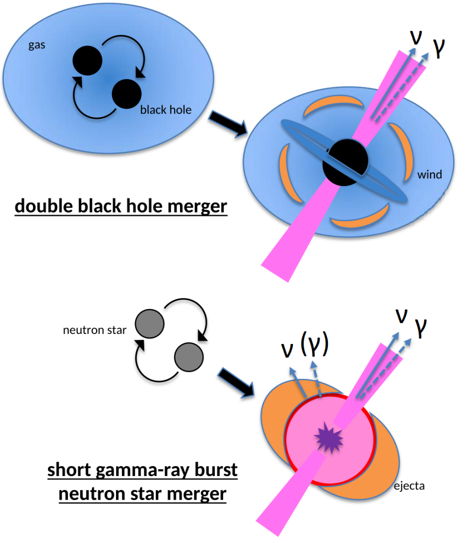
Binary mergers

📖 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



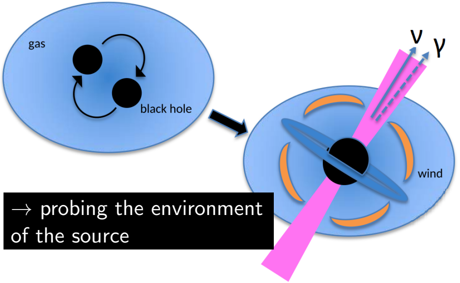
Binary mergers

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

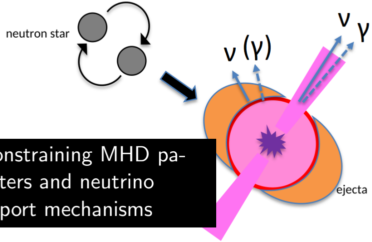
Mergers of compact objects (Neutron Stars -NS-, Black Holes -BH-) are established gravitational wave (GW) emitters.

- **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



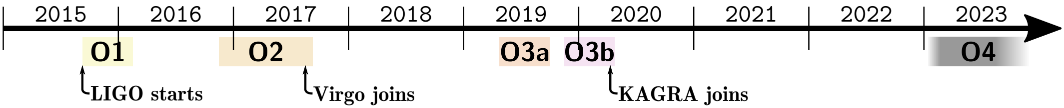
→ probing the environment of the source



→ constraining MHD parameters and neutrino transport mechanisms

Existing GW catalogs

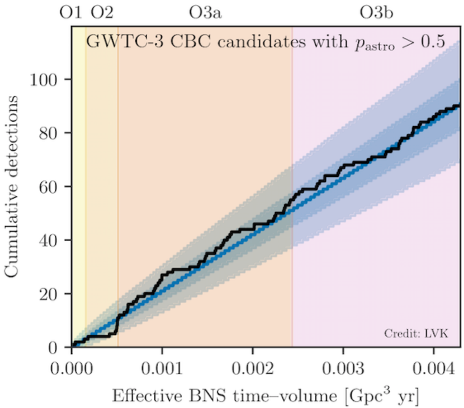
Phys.Rev.X 11 (2021) 021053
arXiv:2111.03606



Since 2015, almost 100 confirmed detections distributed through 4 catalogs:

- **GWTC-1:** 11 events from O1 and O2
- **GWTC-2:** 39 events from O3a
- **GWTC-2.1:** low-significance events from O3a
- **GWTC-3:** 35 events from O3b

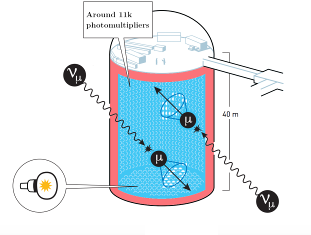
From O4, we expect $\sim$ 100 new detections per year.



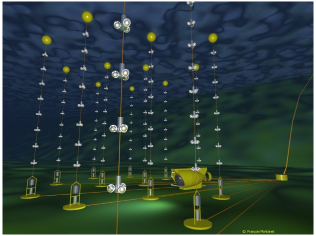
Neutrino telescopes: current

Need detectors covering the whole energy range from MeV to PeV.
Golden technique: detection of Cherenkov light produced after neutrino interactions
Golden technology: large water volume instrumented with photomultipliers

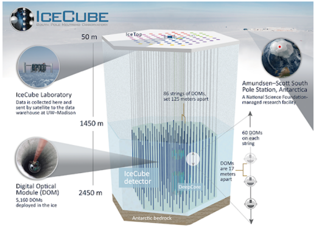
Super-Kamiokande



ANTARES



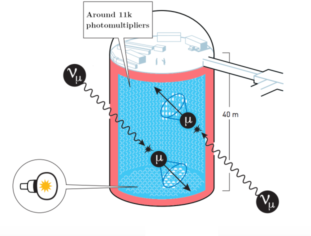
IceCube

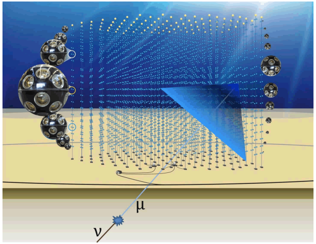


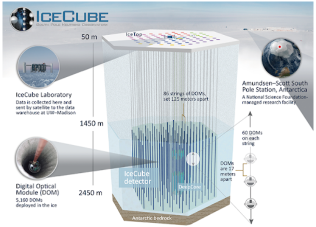
	Super-Kamiokande	ANTARES	IceCube
Where?	mine in Japan	deep in Mediterranean sea	deep in South Pole ice
When?	1996 – running	2006 – 2022	2011 – running
How?	11k PMTs on the walls	12 lines	86 strings
	50 kt	10 Mt	1 Gt

Neutrino telescopes: current

Need detectors covering the whole energy range from MeV to PeV.
Golden technique: detection of Cherenkov light produced after neutrino interactions
Golden technology: large water volume instrumented with photomultipliers





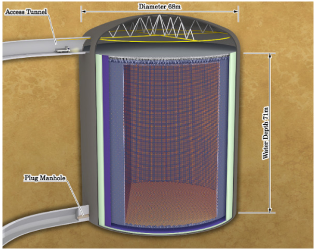


	Super-Kamiokande	**KM3NeT**	**IceCube**
Where?	mine in Japan	deep in Mediterranean sea	deep in South Pole ice
When?	1996 – running	2019 –	2011 – running
How?	11k PMTs on the walls 50 kt	now: 11 lines (ORCA) now: 21 lines (ARCA)	86 strings 1 Gt

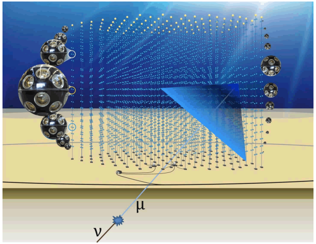
Neutrino telescopes: current & future

Need detectors covering the whole energy range from MeV to PeV.
Golden technique: detection of Cherenkov light produced after neutrino interactions
Golden technology: large water volume instrumented with photomultipliers

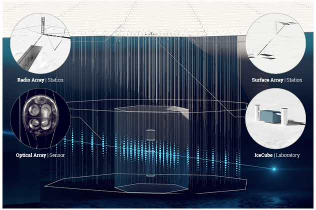
Hyper-Kamiokande



KM3NeT



IceCube-Gen2

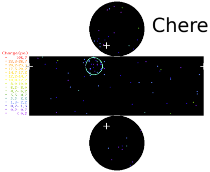


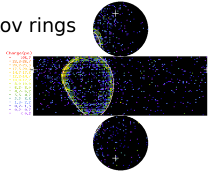
	Hyper-Kamiokande	KM3NeT	IceCube-Gen2
Where?	mine in Japan	deep in Mediterranean sea	deep in South Pole ice
When?	end of 2020s	under construction	2030s
How?	20k+ PMTs 50 kt	3×115 lines $10\,\text{Mt} + 2 \times 0.5\,\text{Gt}$	+120 strings 10 Gt

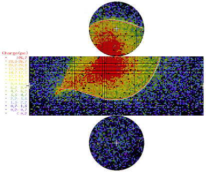
Neutrino telescopes: energy ranges

Super-K
Hyper-K

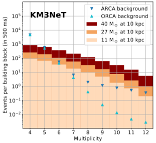
Cherenkov rings

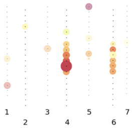


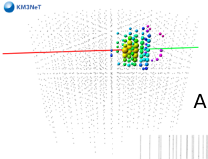


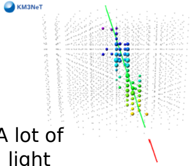


ANTARES
KM3NeT





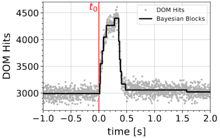




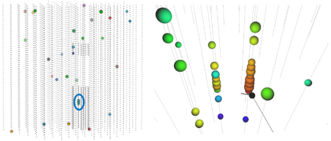
A lot of light

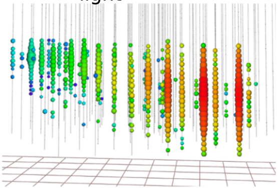
IceCube

Increase of PMT rate



Signal on few DOMs





MeV GeV TeV PeV

Follow-up strategies and datasets

Type	Super-Kamiokande	ANTARES & KM3NeT	IceCube (+DeepCore)	Others
Energy range	$7 - 100$ MeV 0.1 GeV – TeV	$5 - 30$ MeV GeV – TeV TeV – PeV	$0.5 - 5$ GeV 5 GeV – TeV TeV – PeV	KamLAND: $\bar{\nu}_e$ 1.8-111 MeV, 1000 s NOvA: MeV – TeV, 1000 s and 0-45 s AUGER: $>$ 0.1 EeV, 24 h Baikal-GVD: TeV-PeV
Time window	1000 s	1000 s	1000 s + 3 s	
Flavours	$\bar{\nu}_e$/all	all	all/ν_μ	
Online	Under study	Yes	Yes	
Published	O1+O2, O3a	O1, O2, O3	O1, O2, O3	
Ready soon	O3b	O3b (ANTARES)	-	

Latest results

Super-Kamiokande

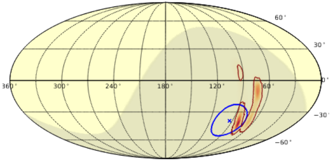
ApJ. 918 (2021) 2, 78

Papers: GW150914/GW151226 (ApJ.Lett. 830 (2016) 1), GW170817 (ApJ.Lett. 857 (2018) 1, L4), all O3 events (ApJ. 918 (2021) 2, 78)

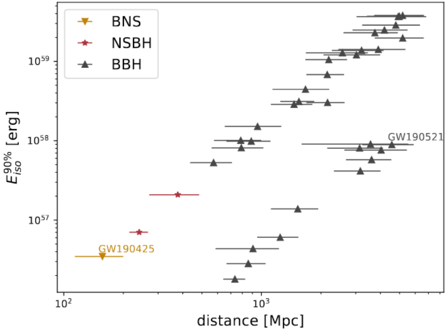
Using low- (MeV $\bar{\nu}_e$) and high-energy (GeV-TeV) samples

Bkg: ~ 0.1 event $/1000\,\mathrm{s}$

Limits (E^{-2}, all-flavour):
$30 - 2000\,\mathrm{GeV\,cm^{-2}}$
$2 \times 10^{56} - 4 \times 10^{59}\,\mathrm{erg}$



Likelihood analysis to quantify signalness of observation $[P_{\rm pre} = 0.2\%, P_{\rm post} = 7.8\%]$



BBH stacking: assuming $E_{\rm iso}^{\nu} = f_\nu \times \mathcal{M}_{\rm tot}$, $\boxed{f_\nu < 1.1 \times 10^{54}\,\mathrm{erg}\,\mathrm{M_\odot}^{-1} = 0.61}$

To be updated with O3b (GWTC-3) results

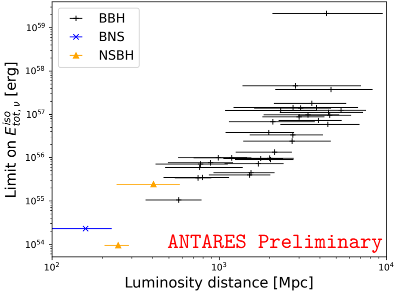
ANTARES

Papers: GW150914 (PRD 93, 122010), GW151226 (PRD 96, 022005), GW170104 (Eur.Phys.J.C 77 (2017) 12, 911), GW170817 (ApJ.Lett. 850 (2017) 2, L35), 6 O2 events (Eur.Phys.J.C 80 (2020) 5, 487)

All-flavour search, using tracks and showers

Bkg: $2.7 \times 10^{-3}/1000\,\mathrm{s}$

Limits (E^{-2}, all-flavour):
$4 - 600\,\mathrm{GeV\,cm^{-2}}$
$10^{54} - 10^{59}$ erg



BBH stacking:

$\boxed{E^{\nu}_{\mathrm{iso}} < 1.3 \times 10^{54}\ \mathrm{erg}}$ and

$\boxed{E^{\nu}_{\mathrm{iso}}/E_{\mathrm{rad}} < 0.4}$

+ some non-isotropic jet emission models can also be constrained

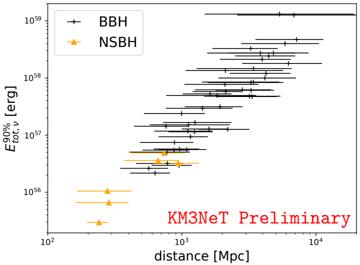
Results for GWTC-2 presented at Neutrino 2022. Publication including as well GWTC-2.1 and GWTC-3 under preparation.

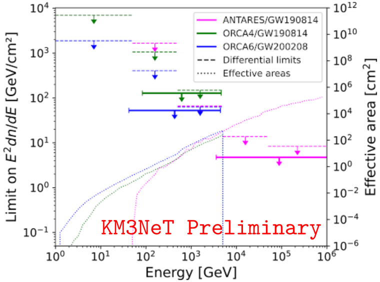
First GW analysis with data from the first ORCA lines (4 in 2019, 6 in 2020).

Using solely upgoing tracks (< 5 TeV)

Bkg estimated using OFF regions: $0.1 - 0.5/1000\,\mathrm{s}$

Limits (E^{-2}, all-flavour):
$50 - 500\,\mathrm{GeV\,cm^{-2}}$
$3 \times 10^{56} - 10^{59}$ erg





Current effective area is comparable with the one of ANTARES

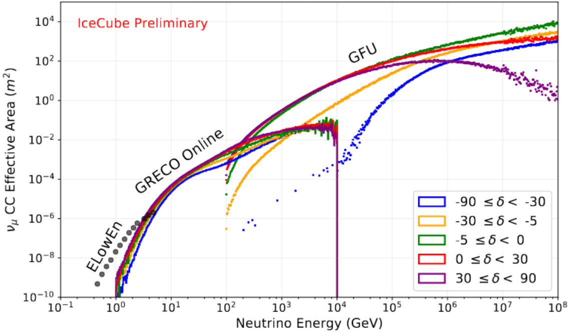
BBH stacking: $E^{\nu}_{\mathrm{iso}} < 3.1 \times 10^{55}$ erg and $E^{\nu}_{\mathrm{iso}}/E_{\mathrm{rad}} < 12$

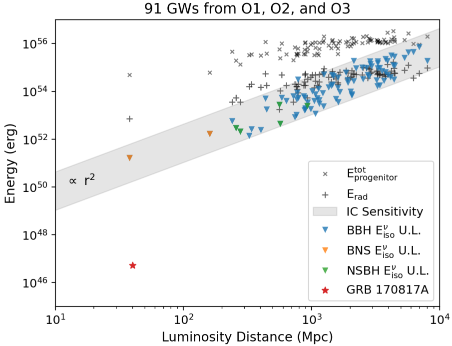
NSBH stacking: $E^{\nu}_{\mathrm{iso}} < 1.9 \times 10^{55}$ erg and $E^{\nu}_{\mathrm{iso}}/E_{\mathrm{rad}} < 46$

Promising prospects for O4 (≥ 11 lines for ORCA, ≥ 21 lines for ARCA).

IceCube

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:2208.09532)





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), $b = 20\,\mathrm{mHz}$

Limits (E^{-2}, per flavour):
$0.03 - 1\,\mathrm{GeV\,cm^{-2}}$
$10^{51} - 10^{55}\,\mathrm{erg}$

Outlooks

Prospects for real-time follow-ups

Quick neutrino follow-up of GW alerts
→ Better pointing to the source direction ($10 - 1000\,\mathrm{deg}^2 \rightarrow \lesssim 1\,\mathrm{deg}^2$)
→ Higher chance to detect EM counterpart (easier to cover for pointing telescopes)

Currently in IceCube:

- real-time pipeline run in 5-20 minutes
- GCN circular sent within 1 hour
- done for all events (except retracted in the meanwhile)

KM3NeT:

- plan to build in on the experience in ANTARES
- see Sébastien's & Godefroy's talks on Thursday for details

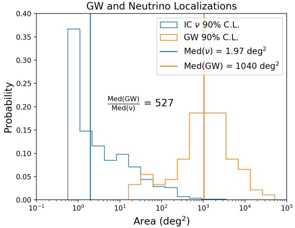


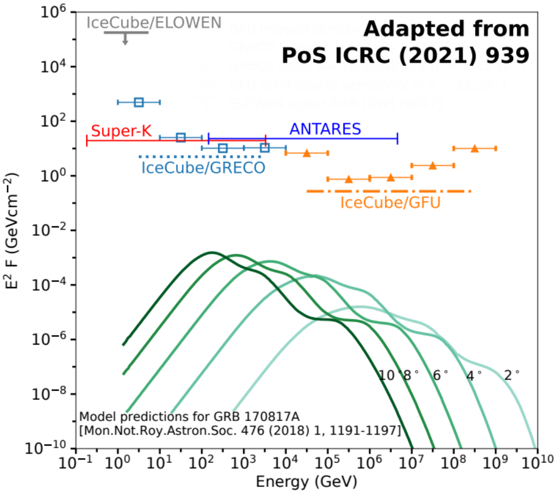
Fig: comparison of 90% containment areas for GW and IceCube events (arXiv:2208.09532)

Open questions: In the future, we expect more and more GW alerts:

- Should some filtering be applied to real-time follow-ups?
- Are all results relevant to be reported as GCNs? (as random coincidence rates get higher)

How far we are & what we can do

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

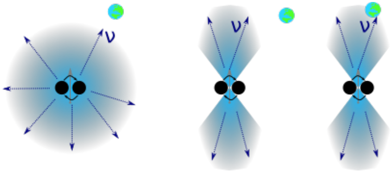


Adapted from PoS ICRC (2021) 939

Model predictions for GRB 170817A
[Mon.Not.Roy.Astron.Soc. 476 (2018) 1, 1191-1197]

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

① Waiting to get lucky for high-energy 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.

To lowest energies and beyond

arXiv:2105.13160
JINST 16 (2021) 12, C12012

How to better exploit the 0.5-5 GeV energy range?

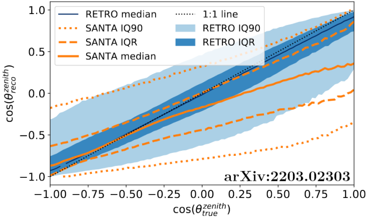
- Very well suited for Super-K/Hyper-K but detector is relatively small
- Light in only few DOMs for KM3NeT/IceCube but huge instrumented volumes
- Pointing strongly limited by neutrino-muon scattering angle

Recover some directionality

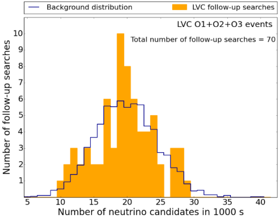
- efforts @ UCLouvain in IceCube (K. Kruiswijk) and KM3NeT (using mPMT structure)
- helps reducing background

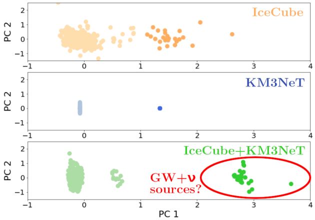
Separating from noise (IceCube=20 mHz)

- Look for significant excess with...
  - ...short time window, stacking GWs?
  - ...combining IceCube + KM3NeT?



arXiv:2203.02303





Personal advertisement

JANG GitHub repository

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:

- ν**:** observed/expected number of events in each sample, acceptance or effective area, p.d.fs
- **GW:** posterior samples and skymaps from public catalogs

Configuration:

- Assumed neutrino spectrum, emission model (isotropic or jetted)
- Priors on nuisance and signal parameters
- Type of likelihood: Poisson (cut-and-count) or point-source-like

Outputs:

- Limits on the flux, on the total energy $E_{\mathrm{tot},\nu}$, or $E_{\mathrm{tot},\nu}/E_{\mathrm{rad}}$
- Stacked limits for a considered sub-population

Can be used to investigate synergies between different searches/detectors/energy ranges.

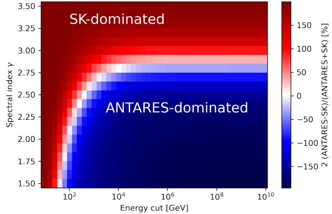
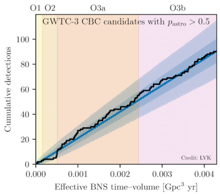


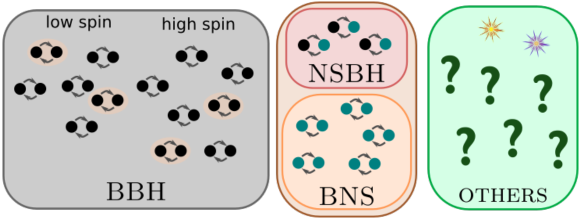
Fig: Example with ANTARES and Super-K, as a function of energy cut (x-axis) and spectral index (y-axis).

Summary

Take-home message:

- Neutrino emission expected from binary mergers
- Many constraints from existing neutrino telescopes
- Promising prospects with O4...
- ... But we should also benefit from new developments @ neutrino telescopes:
  - extension to lower energies
  - synergies between experiments
  - clever stacking





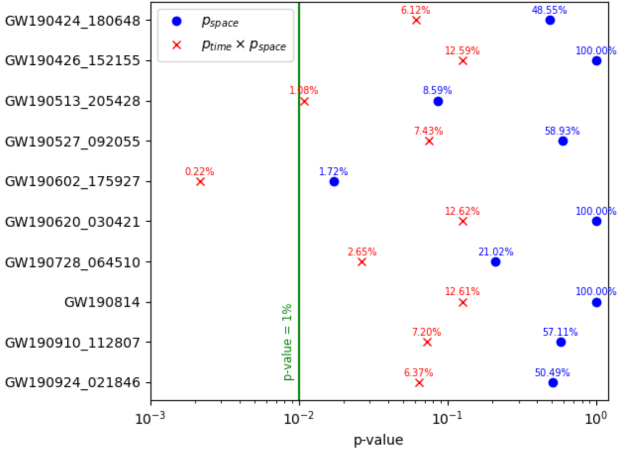
Topics not covered: other neutrino detectors and results, sub-threshold GW+ν analyses

Backups

Super-Kamiokande - 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:

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

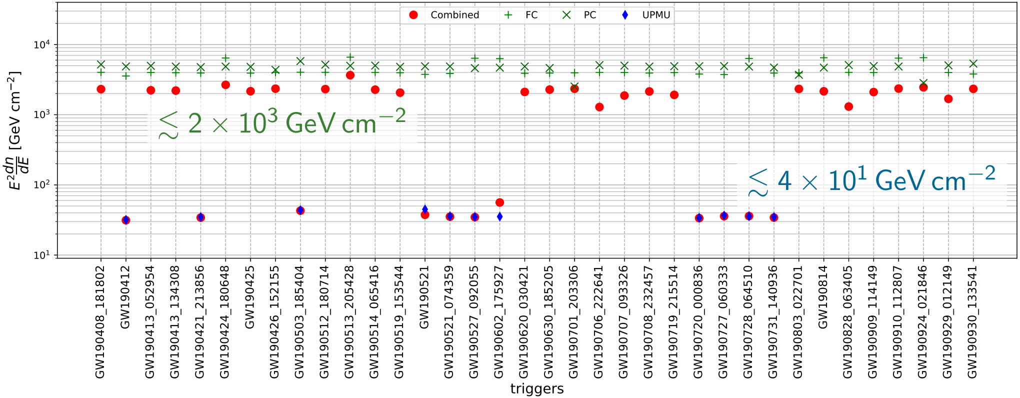
Considering the number of trials ($N = 36$ follow-ups), we get a **post-trial** p-value:

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

Super-Kamiokande - flux limits

ApJ 918 (2021) 2, 78

$$\boxed{\mathcal{L}(\phi_0; n_B, N) = \int \frac{(c(\Omega)\phi_0+n_B)^N}{N!} e^{-(c(\Omega)\phi_0+n_B)} \mathcal{P}_{\mathrm{GW}}(\Omega) d\Omega}$$ with $c(\Omega) = \int_{E_{\min}}^{E_{\max}} \mathrm{d}E_\nu A_{\mathrm{eff}}(E_\nu, \theta) E_\nu^{-2}$



$\lesssim 2 \times 10^3$ 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.

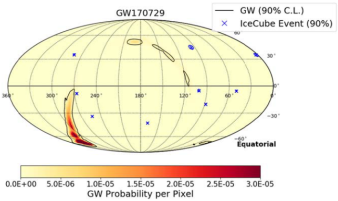
IceCube - method and limits

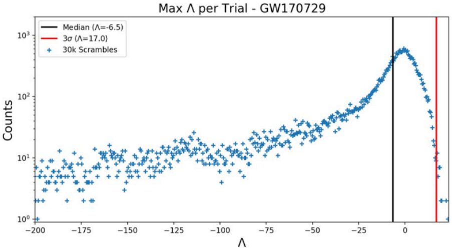
ApJ.Lett. 898 (2020) 1, L10

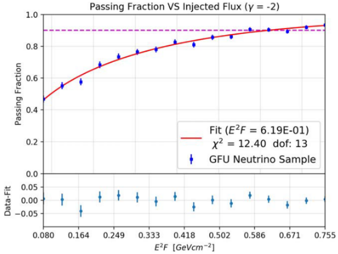
Few **different samples** with background rate 4-20 mHz and sensitivity from GeV to PeV

Different **analysis pipelines** including Maximum-likelihood Analysis where TS is assigned to each observation using GW localization and neutrino directions

Flux limit = minimum flux you need to have a significant excess in terms of TS (done for E^{-2} spectrum)







Complementarity between experiments

What is the expected gain by considering both experiments simultaneously to compute upper limits on $F = \int \frac{dn}{dE} dE$ with $\frac{dn}{dE} \propto E^{-\gamma} e^{-E/E_{\mathrm{cut}}}$?

Simple test with Poisson likelihood (one per experiment and a combined one): PRELIMINARY

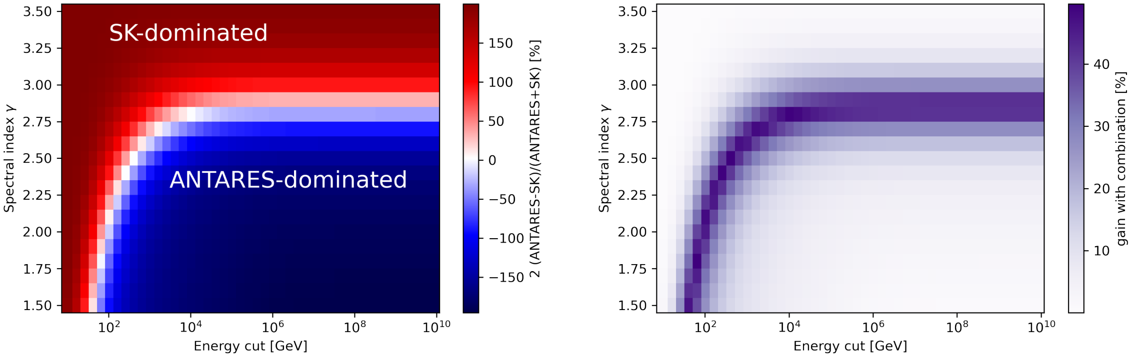


Fig: Relative diff. between ANTARES and SK limits.

Fig: Relative gain with the combination.