# Neutrino emission from gravitational wave sources
## Experimental landscape and prospects

12th CosPa meeting

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# Outline



1. What are we looking for? Why is it interesting?
2. What GW catalogs are we using? What do we expect in near-future?
3. Which neutrino telescopes are contributing? What are the results?
4. What are the prospects?

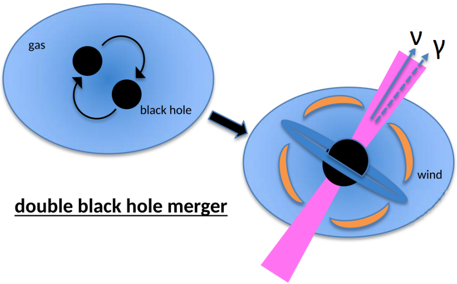
Phys. Rev. D 93, 044019
Phys. Rev. D 93, 123015



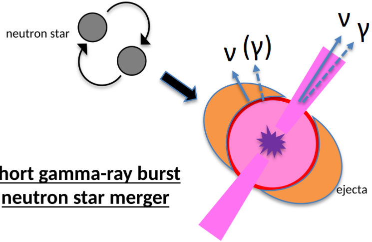
Mergers of compact objects (Neutron Stars -NS-, Black Holes -BH-) are established gravitational wave (GW) emitters.

- **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 |




double black hole merger




short gamma-ray burst
neutron star merger

Phys. Rev. D 93, 044019
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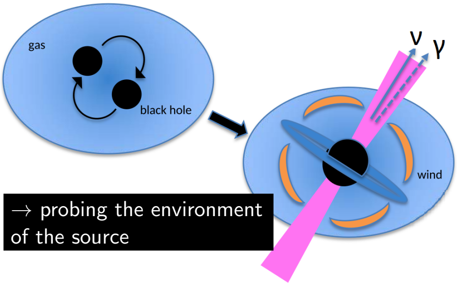
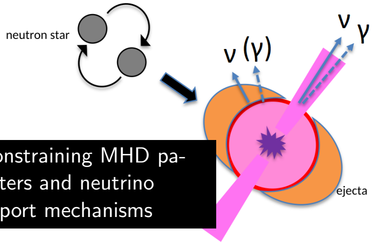


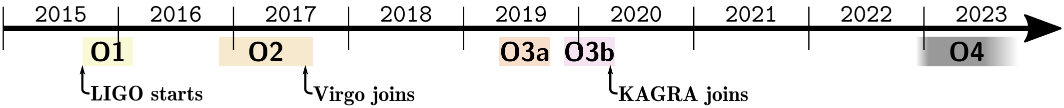

→ probing the environment of the source




→ constraining MHD parameters and neutrino transport mechanisms

# Existing GW catalogs

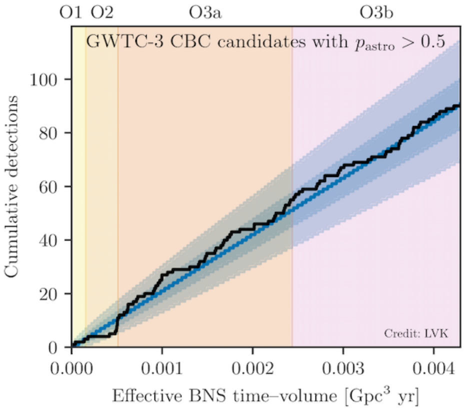
Phys.Rev.X 11 (2021) 021053
arXiv:2111.03606




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

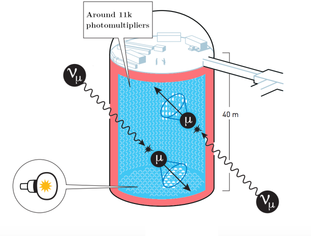
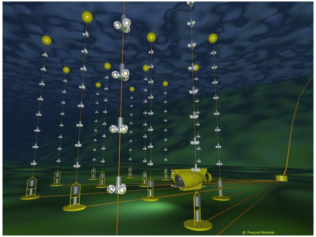
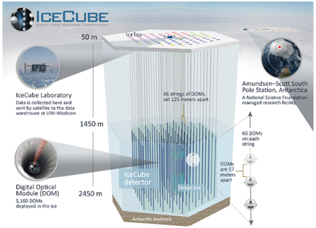
- **GWTC-1:** 11 events from O1 and O2
- **GWTC-2:** 39 events from O3a
- **GWTC-2.1:** low-significance events from O3a
- **GWTC-3:** 35 events from O3b

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



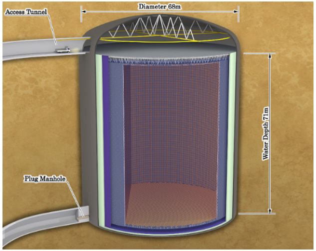
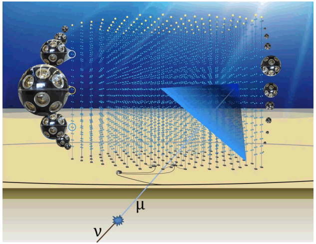
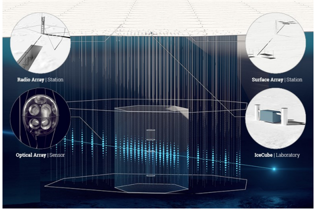
# Neutrino telescopes: current

**Golden technique:** detection of Cherenkov light produced after neutrino interactions
**Golden technology:** large water volume instrumented with photomultipliers

| | **Super-Kamiokande** | **ANTARES** | **IceCube** |
|---|---|---|---|
| |  |  |  |
| Where? | mine in Japan | deep in Mediterranean | deep at South Pole |
| When? | 1996 – running | 2006 – 2022 | 2010 – running |
| How? | 11k PMTs on the walls | 12 lines | 86 strings |
| | 50 kt | 10 Mt | 1 Gt |

# Neutrino telescopes: current & future

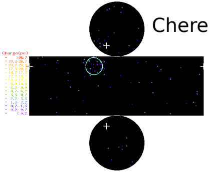
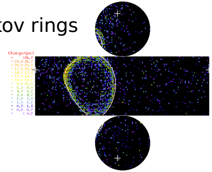
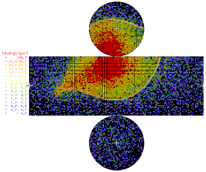
**Golden technique:** detection of Cherenkov light produced after neutrino interactions
**Golden technology:** large water volume instrumented with photomultipliers

| | **Hyper-Kamiokande** | **KM3NeT** | **IceCube-Gen2** |
|---|---|---|---|
| |  |  |  |
| Where? | mine in Japan | deep in Mediterranean | deep at South Pole |
| When? | by 2028 | under construction (2026) | by 2032 |
| How? | 20k+ PMTs | $3 \times 115$ lines | +120 strings |
| | 50 kt | $10\,\mathrm{Mt} + 2 \times 0.5\,\mathrm{Gt}$ | 10 Gt |

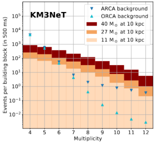
# Neutrino telescopes: energy ranges

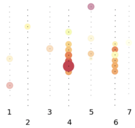
Super-K
Hyper-K

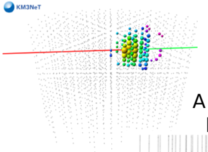
Cherenkov rings

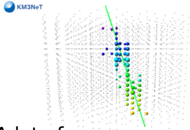




ANTARES
KM3NeT



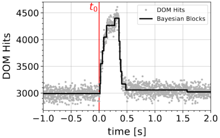



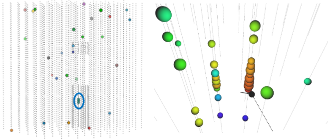

A lot of light

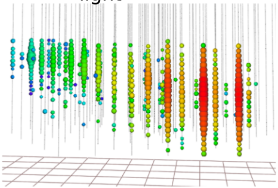
IceCube

Increase of PMT rate




Signal on few DOMs





MeV GeV TeV PeV

# Follow-up strategies and datasets



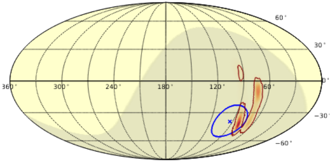
| **Type** | Super-Kamiokande | ANTARES & KM3NeT | IceCube (+DeepCore) | Others |
|---|---|---|---|---|
| Energy range | $7-100$ MeV & $0.1$ GeV $-$ TeV | GeV $-$ TeV & TeV $-$ PeV | $0.5-5$ GeV & $5$ GeV $-$ TeV & TeV $-$ PeV | KamLAND: $\bar{\nu}_e$ 1.8-111 MeV, 1000 s<br>NOvA: MeV $-$ TeV, 1000 s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

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

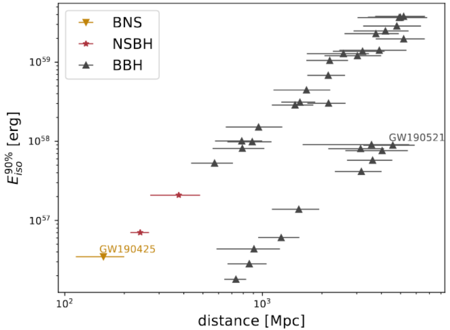
Using low- (MeV $\bar{\nu}_e$) and high-energy (GeV-TeV) samples

*Bkg:* $\sim$ 0.1 event /1000 s

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



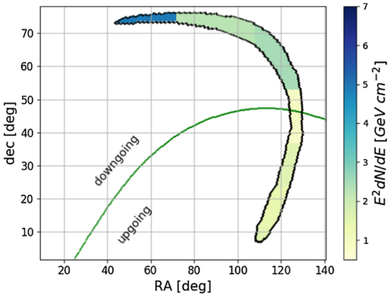
Likelihood analysis to quantify signalness of observation [$P_{\rm pre} = 0.2\%$, $P_{\rm post} = 7.8\%$]




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

To be updated with O3b (GWTC-3) results

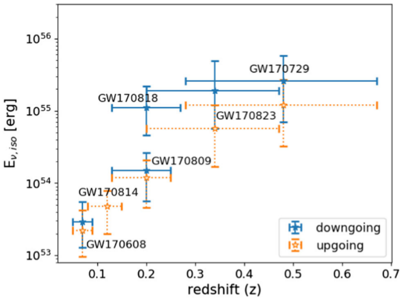
**Papers:** GW150914 (PRD 93, 122010), GW151226 (PRD 96, 022005), GW170104 (Eur.Phys.J.C 77 (2017) 12, 911), GW170817 (ApJ.Lett. 850 (2017) 2, L35), 6 O2 events (Eur.Phys.J.C 80 (2020) 5, 487)




Using both track and shower events

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

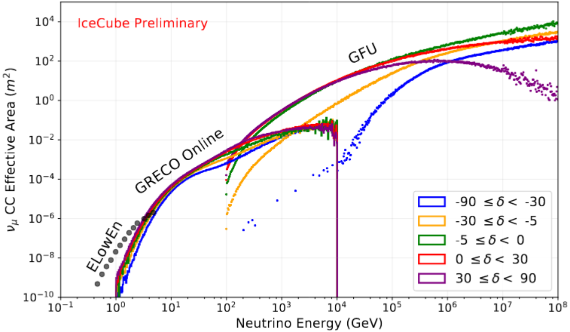
*Limits ($E^{-2}$, per flavour):*
$1 - 9\,\mathrm{GeV\,cm^{-2}}$
$2 \times 10^{53} - 3 \times 10^{55}$ erg

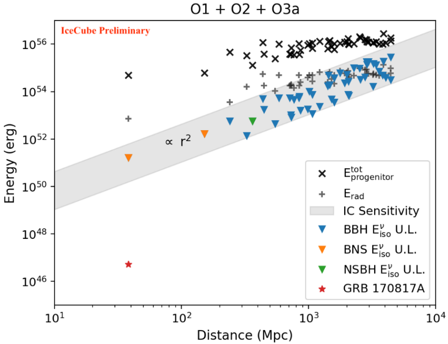



## Ongoing study

- follow-up of O3 events
- all-flavour constraints
- considering isotropic / jetted emission
- studies w/ KM3NeT first data (ORCA4/6)

**Papers:** GW150914 (PRD 93, 122010), GW151226 (PRD 96, 022005), GW170817 (ApJ.Lett. 850 (2017) 2, L35), O1+O2 (ApJ.Lett. 898 (2020) 1, L10), O3a (PoS ICRC (2021) 950)

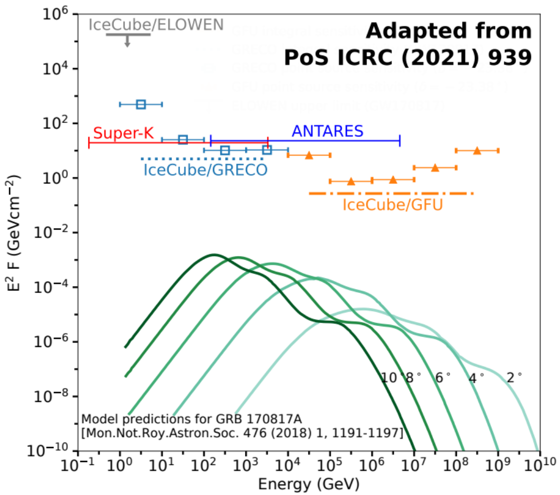



*Different analyses:*
GFU, $> 100\,\text{GeV}$ ($\nu_\mu$), $b = 6.7\,\text{mHz}$
GRECO, $5 - 100\,\text{GeV}$ ($\nu_\mu$), $b = 4.5\,\text{mHz}$
ELOWEN, $0.5 - 5\,\text{GeV}$ (all), $b = 20\,\text{mHz}$

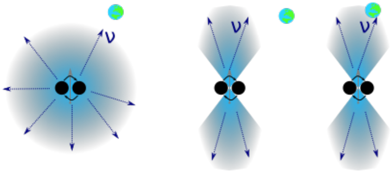
*Limits ($E^{-2}$, per flavour):*
$0.03 - 1\,\text{GeV}\,\text{cm}^{-2}$
$10^{51} - 10^{55}$ erg

New publication with O3b (GWTC-3) results soon




Be aware that this is a specific neutrino emission model, others may be more optimistic (or not)

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?

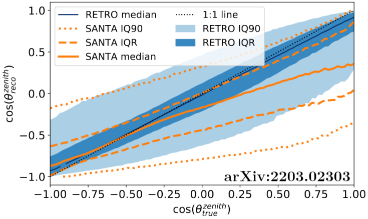
- Very well suited for Super-K/Hyper-K but detector is relatively small
- Light in only few DOMs for KM3NeT/IceCube but huge instrumented volumes
- Pointing strongly limited by neutrino-muon scattering angle

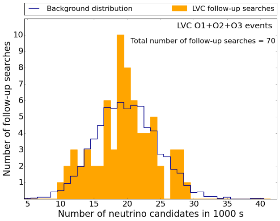
### Recover some directionality

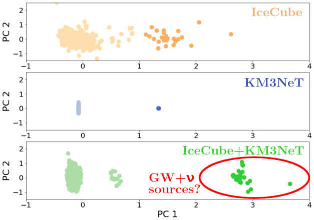
- efforts @ UCLouvain in IceCube (K. Kruiswijk) and KM3NeT (using mPMT structure)
- helps reducing background

### Separating from noise (IceCube=20 mHz)

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



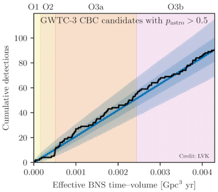
# Summary

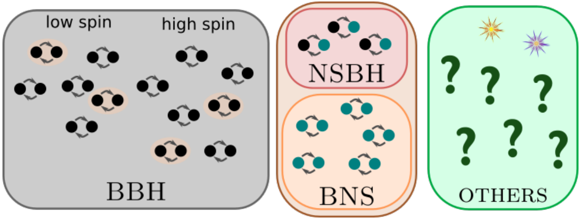
**Take-home message:**

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

*Involvements at UCLouvain:*

- interfacing between KM3NeT and IceCube efforts
- GeV neutrino reconstruction
- development of tools (for instance PyJANG) for combination of available limits



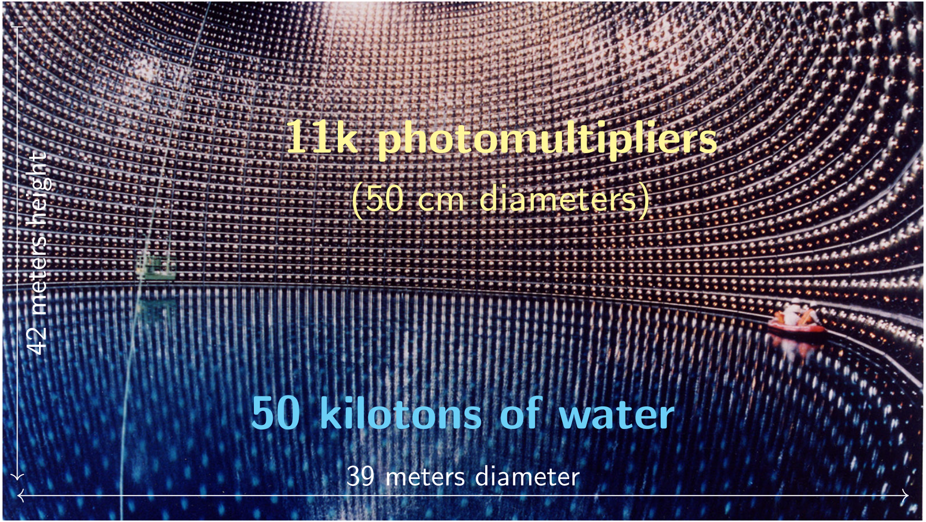

*Topics not covered:* other neutrino detectors and results, sub-threshold GW+$\nu$ analyses

# Backups

NIM.A 501 (2003) 418-462



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



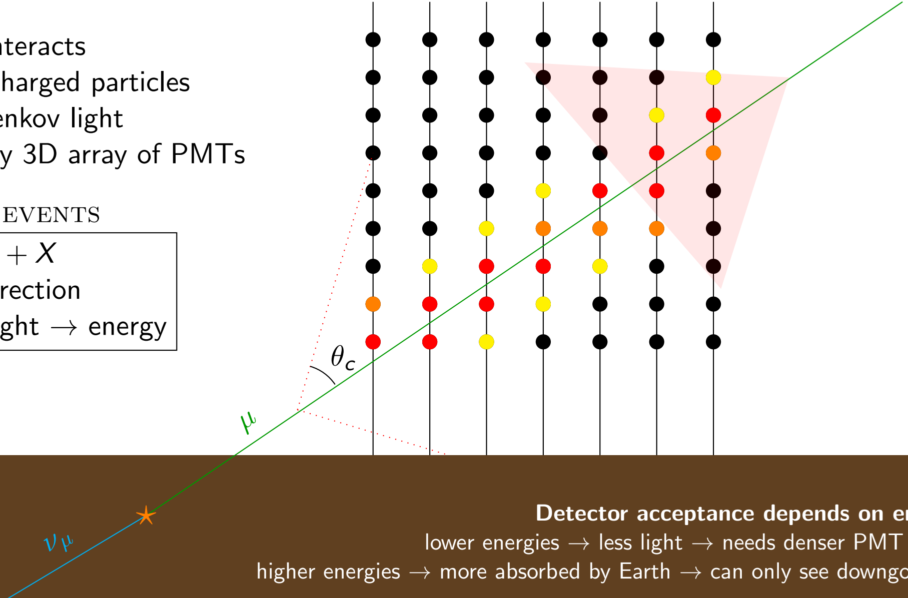
# Cherenkov detection principle



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 $\rightarrow$ direction
- amount of light $\rightarrow$ energy




**Detector acceptance depends on energy:**
lower energies $\rightarrow$ less light $\rightarrow$ needs denser PMT layout
higher energies $\rightarrow$ more absorbed by Earth $\rightarrow$ can only see downgoing $\nu$s

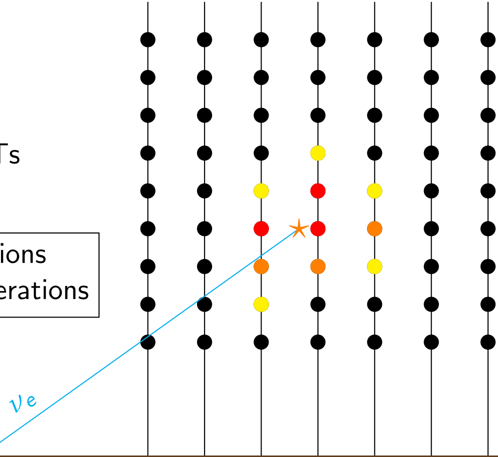
# Cherenkov detection principle



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 |

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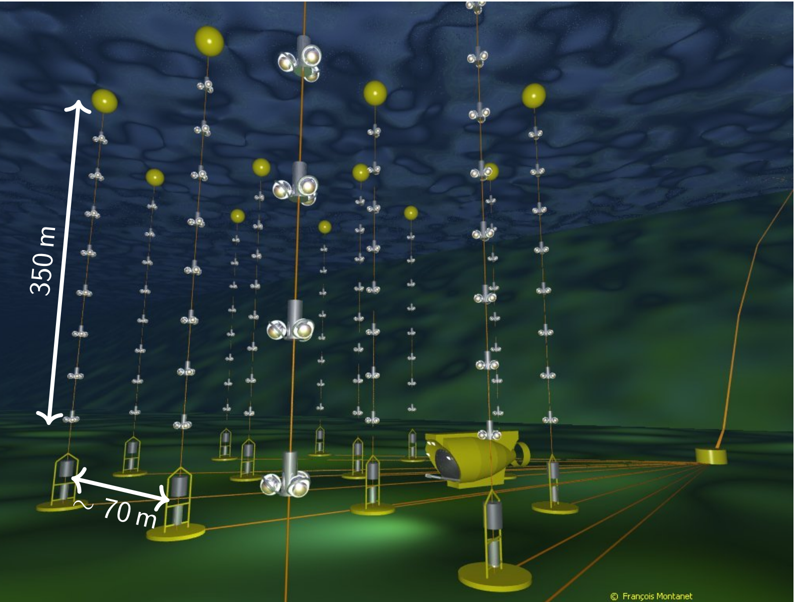
# The ANTARES experiment

NIM.A 656 (2011) 11-38



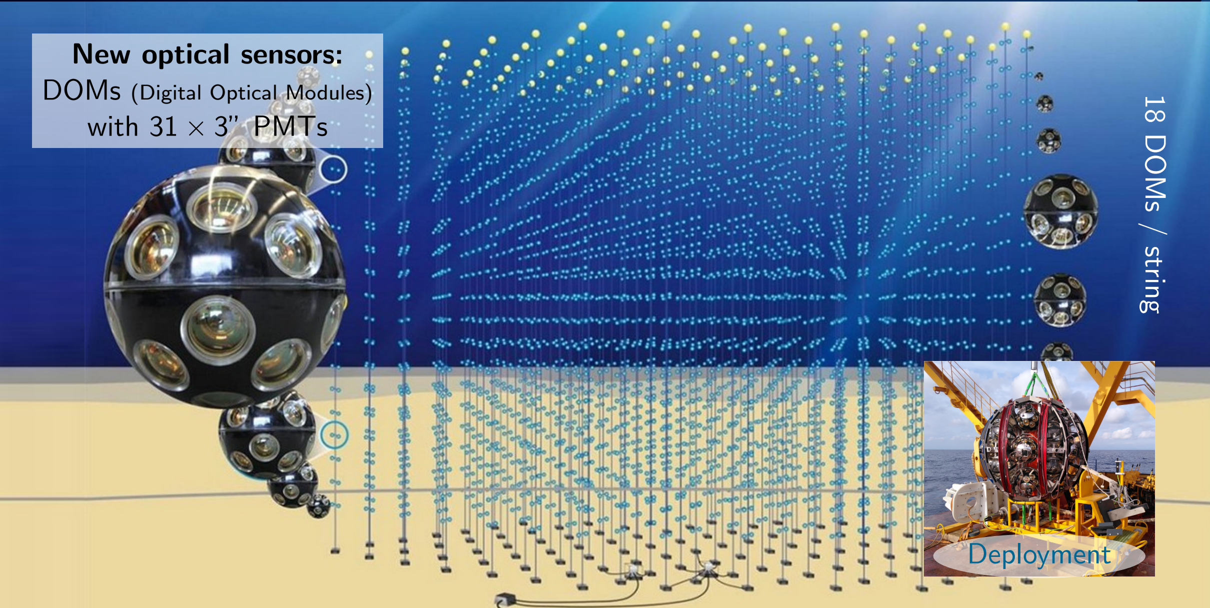

- In operation since 2006 (completed in 2008)
- Off the coast of Toulon
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

*Total instrumented volume:*
10 Mt

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



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



# The KM3NeT project

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

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

1 building block = 115 strings (DUs)

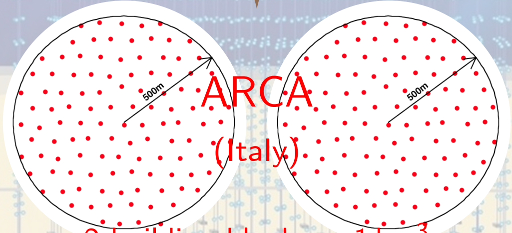
**ORCA** (France)

$E_\nu = 1 - 100$ GeV

complementary

$E_\nu > 100$ GeV

**ARCA** (Italy)

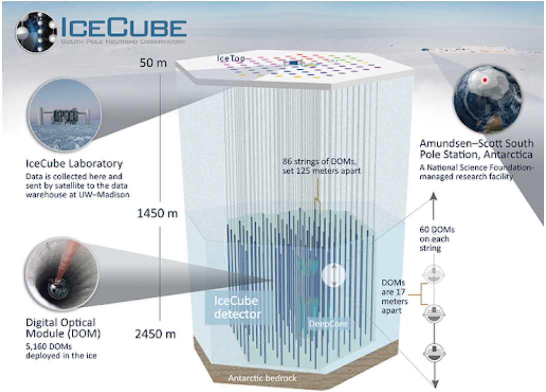


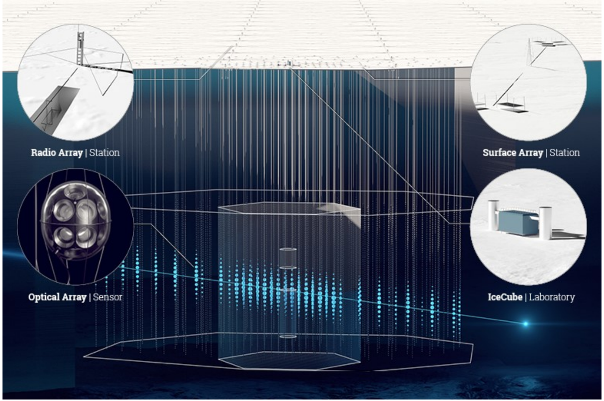

2 building blocks $\sim 1\,\text{km}^3$

18 DOMs / string

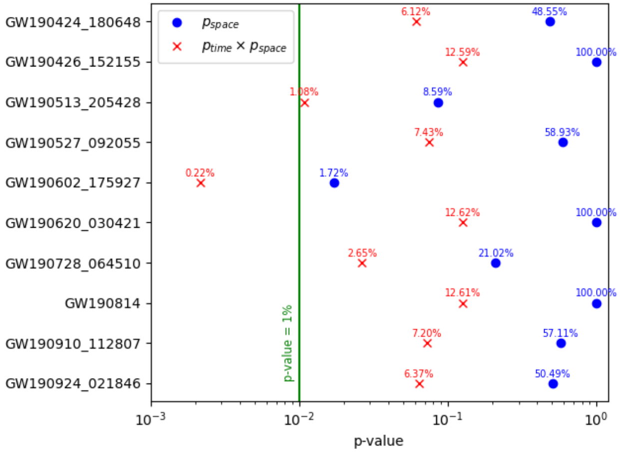
# The IceCube experiment and Gen-2





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).



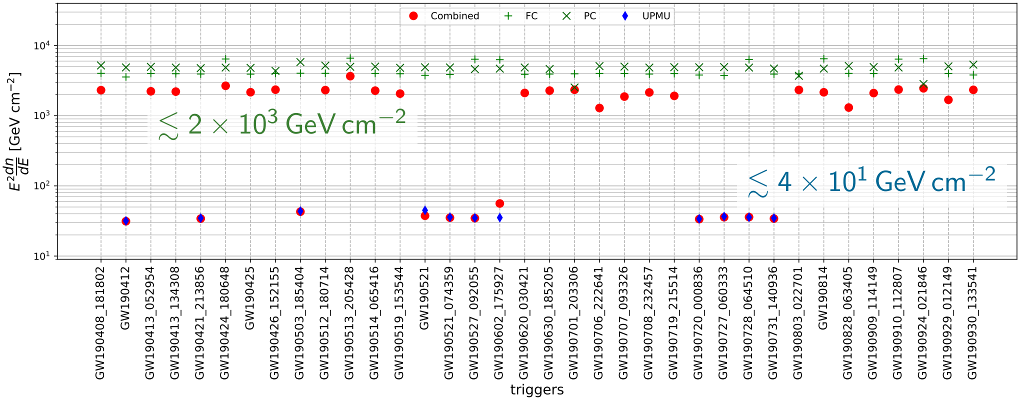

The most significant GW+$\nu$ coincidence is for GW190602_175927:

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

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

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

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




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

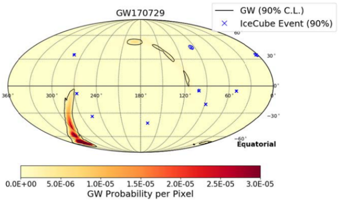
ApJ.Lett. 898 (2020) 1, L10

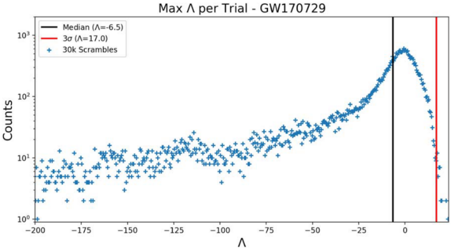


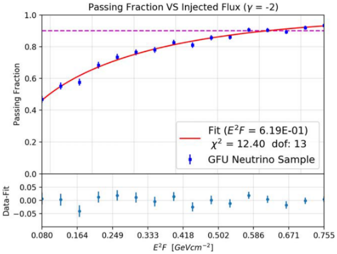
Few **different samples** with background rate 4-20 mHz and sensitivity from GeV to PeV

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)



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

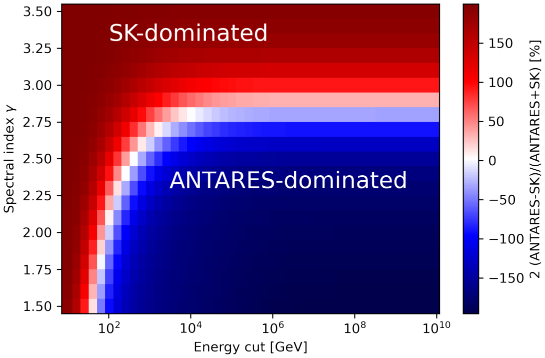



**Fig:** Relative diff. between ANTARES and SK limits.

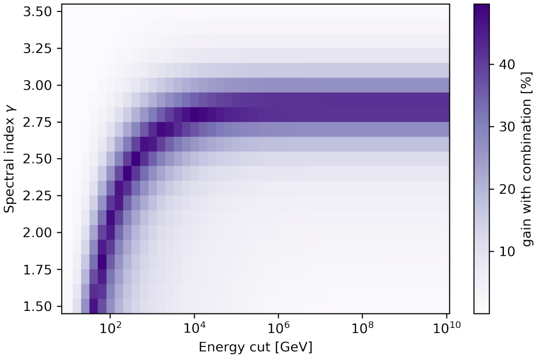



**Fig:** Relative gain with the combination.