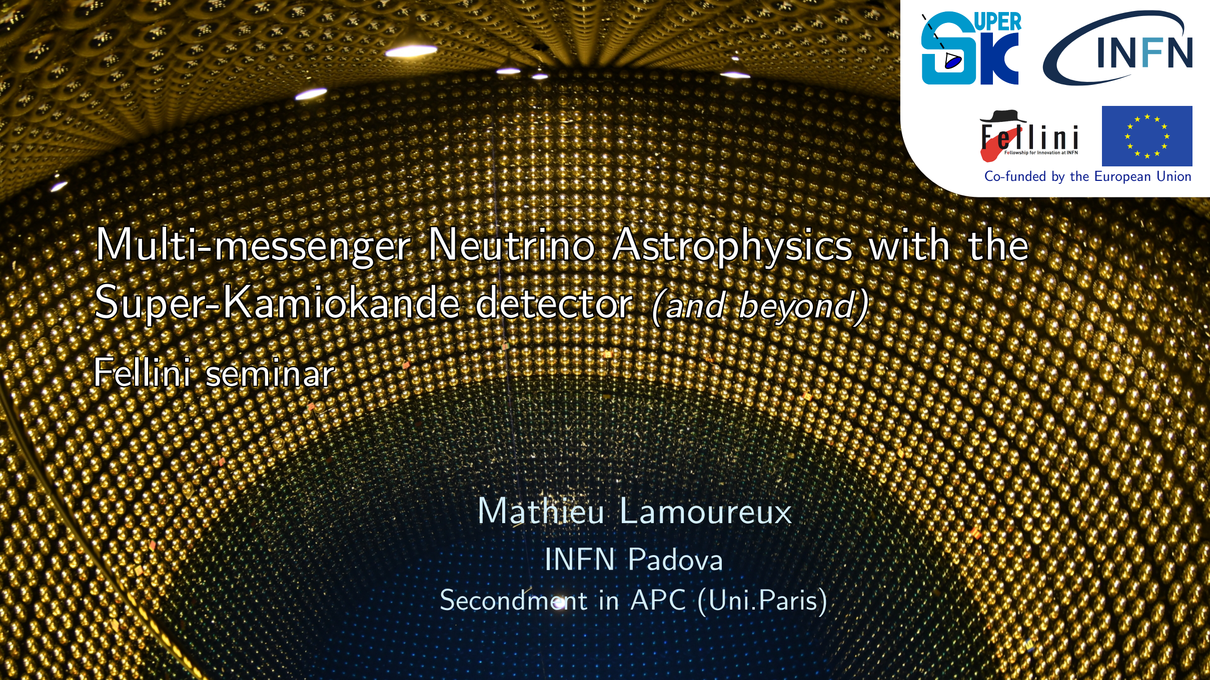


Co-funded by the European Union

Multi-messenger Neutrino Astrophysics with the Super-Kamiokande detector *(and beyond)*

Fellini seminar

Mathieu Lamoureux

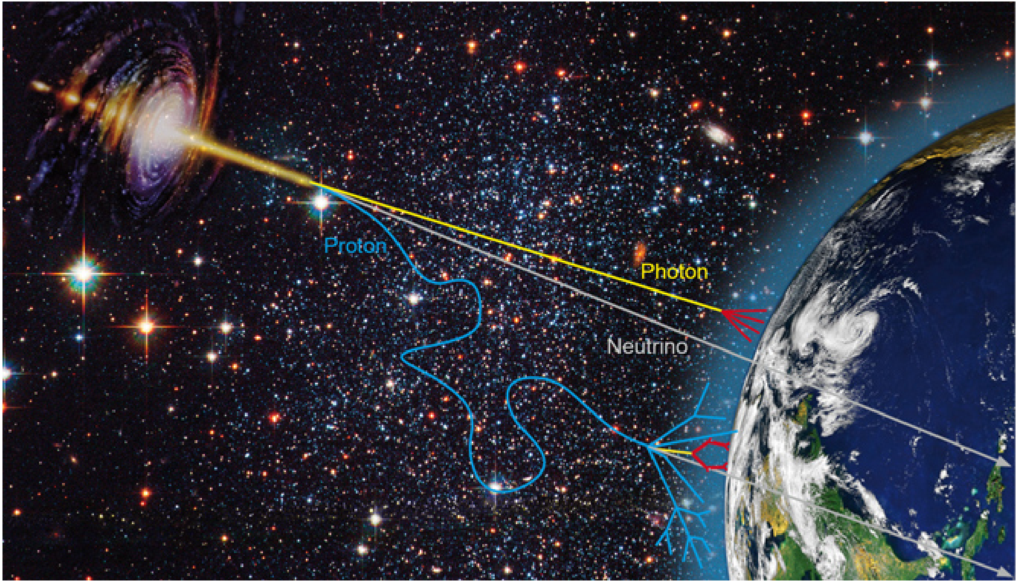
INFN Padova

Secondment in APC (Uni.Paris)

Overview of the presentation

Neutrino astrophysics

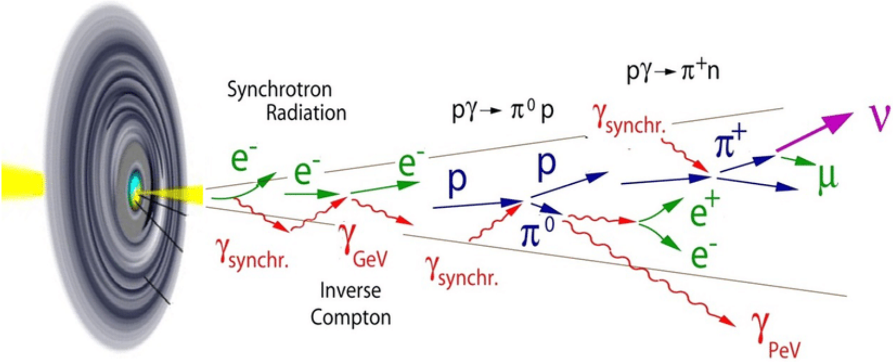
Neutrino astrophysics



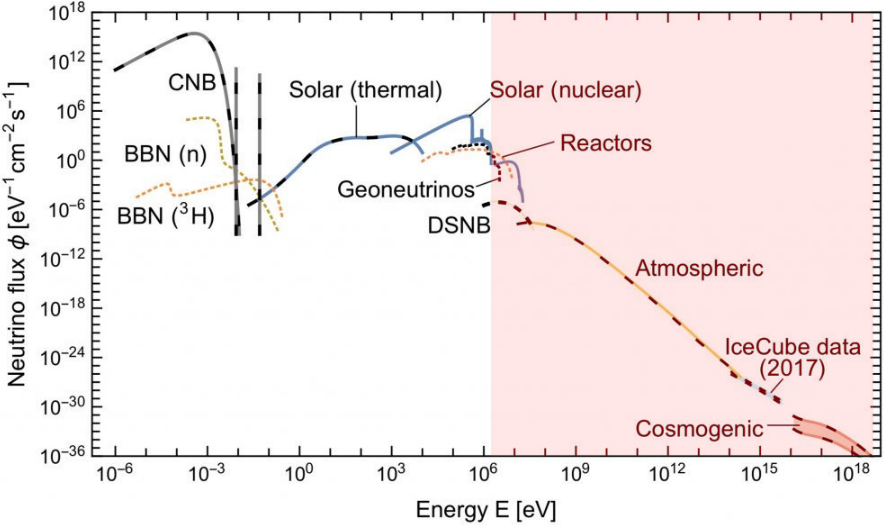
Production of high-energy astrophysical neutrinos

Cosmic ray interactions at acceleration sites or during their propagation are producing pions:

- Charged pion decays are emitting neutrinos
- Neutral pion decays are emitting high-energy gammas.



Energy spectrum



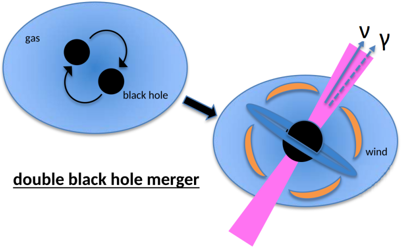
Physics case of binary mergers

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

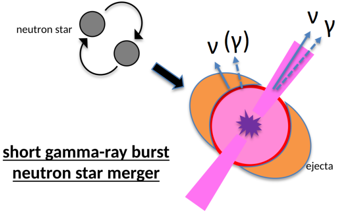
Since 2015, LIGO/Virgo interferometers are detecting gravitational waves from mergers of binary objects.

- Binary Neutrino Star (BNS): may produce short Gamma-Ray Bursts (GRB) with neutrino production
- Binary Black Hole (BBH): neutrino production in the accretion disks of the black holes
- Neutron Star - Black Hole (NSBH)

Detecting neutrinos from these objects would allow a better understanding of the mechanisms behind them.



double black hole merger



short gamma-ray burst
neutron star merger

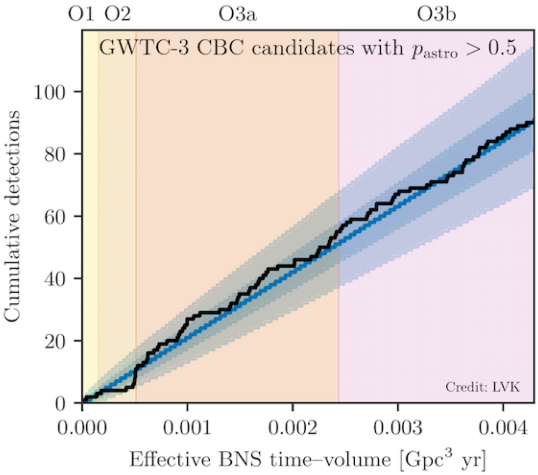
LIGO-Virgo catalogues (1)

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

- First detection in 2015
- **GWTC-1:** 11 events from 2015 to 2017 (O1 and O2)
- **GWTC-2:** 39 events from the first half of the third observing run (O3a)
- **GWTC-2.1:** update of GWTC-2, containing events with higher FAR
- **GWTC-3:** 35 events from the second half of the third observing run (O3b)

$\sim$ 100 events in total

We expect $>$ 100 events/year starting from O4.



Credit: LVK

LIGO-Virgo catalogues (2)

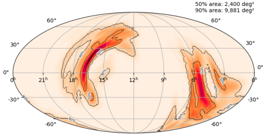
For each GW, we have:

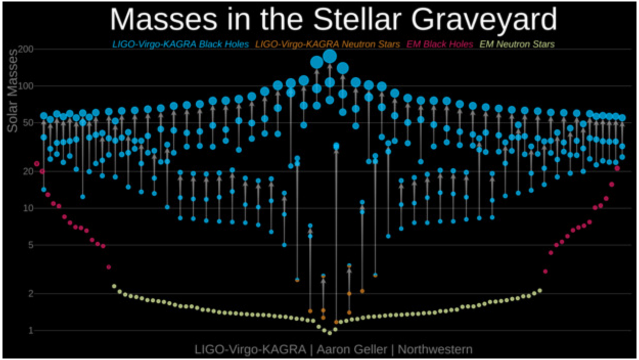
- time of the event
- sky localisation
- estimated distance
- estimated masses

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
- 5 NSBH
- the rest are BBH

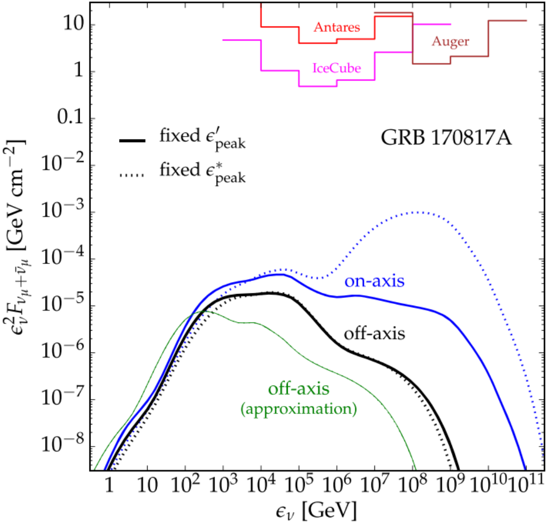
Neutrino emission expectation

MNRAS 490 (2019) 4, 4935-4943
Astropart.Phys. 35 (2011) 1-7

- Very few models available on the market.
- What is the jetting of the neutrino emission?
  - isotropic: easy to constrain but unrealistic, especially for high-energy emission
  - structured jet: in absence of any (EM) counterpart, it is difficult to constrain
- What is the timescale of the neutrino emission? Prompt, precursor, delayed?

Usual time window

Neutrino signal is usually searched in a 1000 s time window centered on GW.

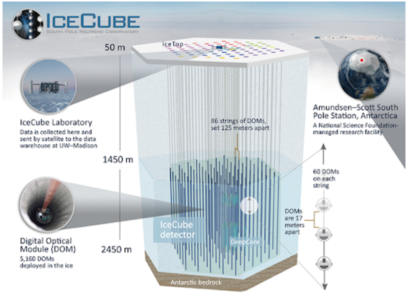


Neutrino telescopes

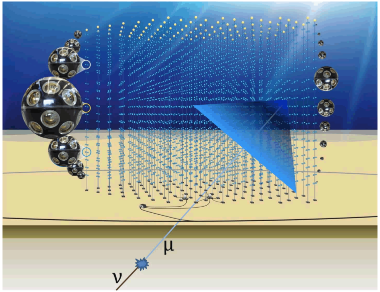
📖 J.Phys.G 43 (2016) 8, 084001
📖 JINST 12 (2017) 03, P03012

Need very large detectors to detect such low fluxes...

Two big players



IceCube



KM3NeT

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

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

Neutrino telescopes

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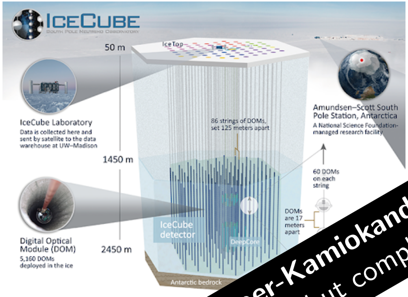
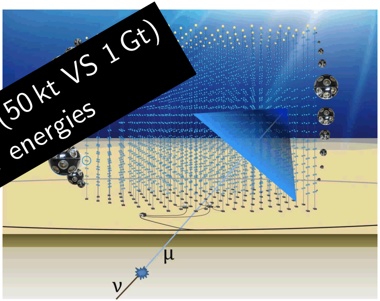


Ice



KM3NeT

Super-Kamiokande is much smaller (50 kt VS 1 Gt)
but complementary for lower energies

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

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

Super-Kamiokande

The Super-Kamiokande experiment (1)

📖 NIM.A 501 (2003) 418-462

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

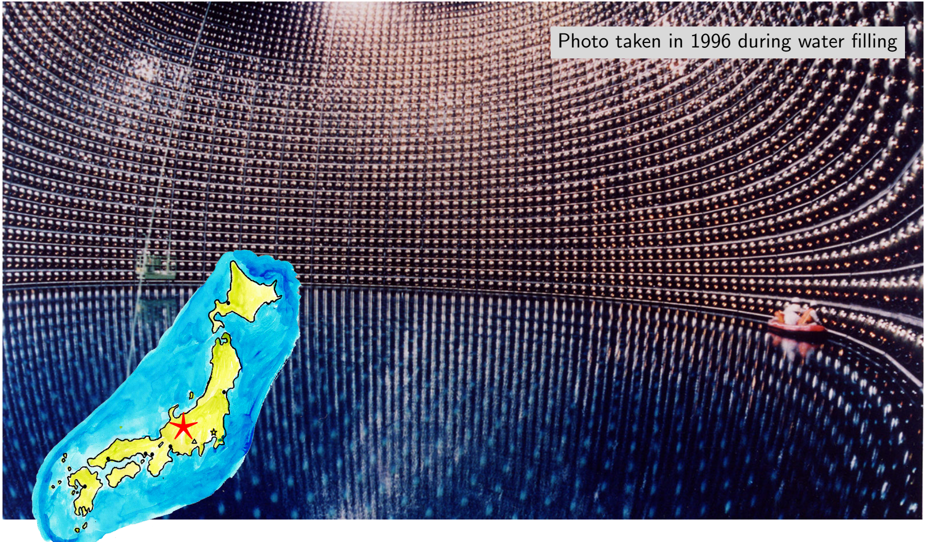
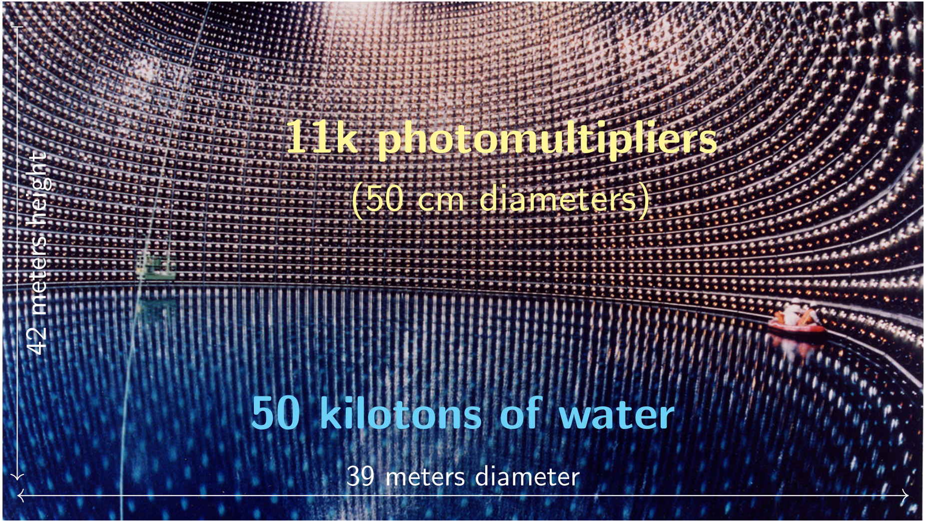


Photo taken in 1996 during water filling

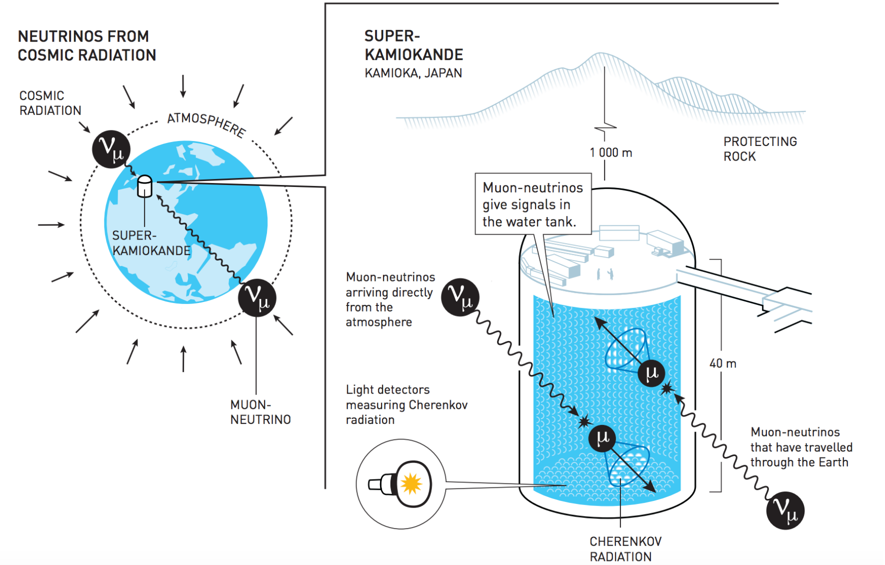
The Super-Kamiokande experiment (1)

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



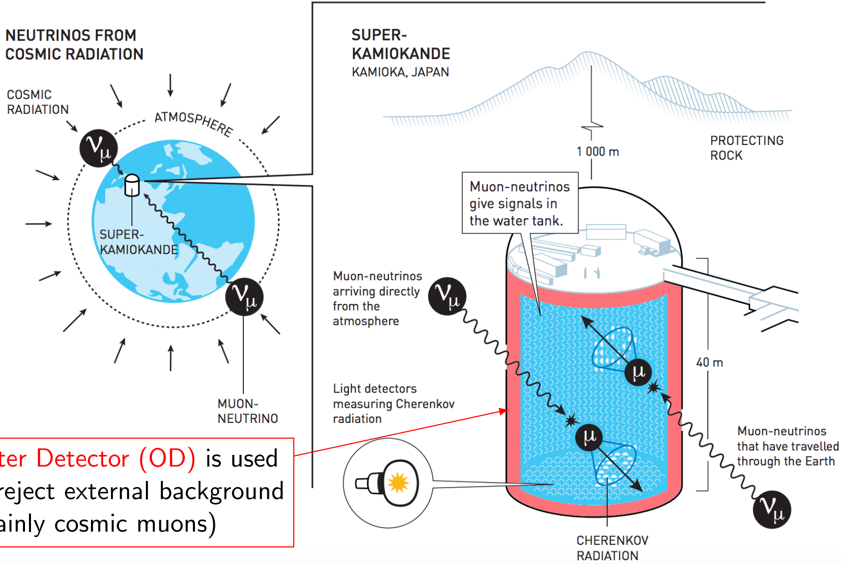
The Super-Kamiokande experiment (2)

📖 NIM.A 501 (2003) 418-462



The Super-Kamiokande experiment (2)

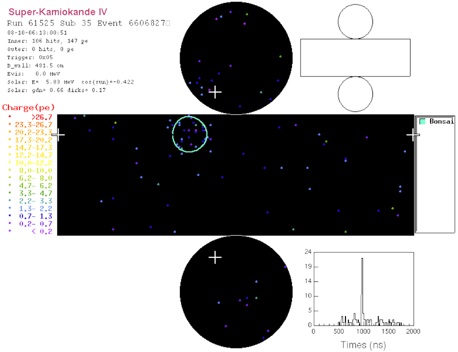
NIM.A 501 (2003) 418-462



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
```

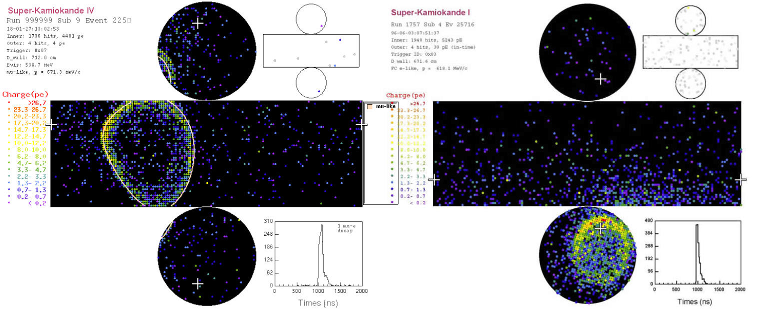
$$\boxed{E_\nu = 3.5 - 100\,\text{MeV}}$$

sparse PMT hits, faint ring

INCREASING ENERGY

The different samples

Fully-Contaned (FC) events



```
Super-Kamiokande IV
Run 999999 Sub 9 Event 225
18-01-27:13:02:53
Inner: 1736 hits, 4481 pe
Outer: 4 hits, 4 pe
Trigger: 0x07
D_wall: 712.0 cm
Evis: 538.7 MeV
mu-like, p = 671.3 MeV/c
```

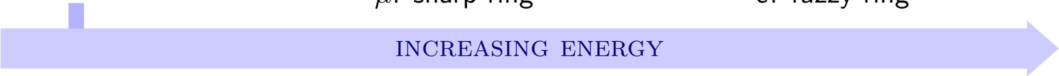
```
Super-Kamiokande I
Run 1757 Sub 4 Ev 25716
96-06-03:07:51:37
Inner: 1948 hits, 5243 pE
Outer: 4 hits, 30 pE (in-time)
Trigger ID: 0x03
D wall: 671.6 cm
PC e-like, p =  618.1 MeV/c
```

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

no activity in OD

μ: sharp ring

e: fuzzy ring



The different samples

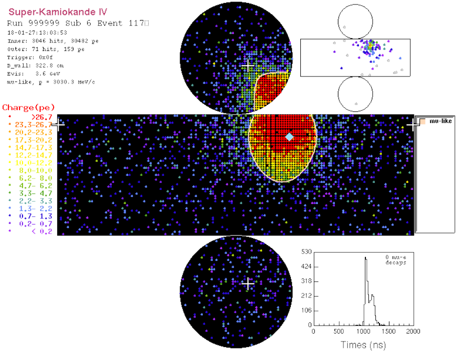
LOW-ENERGY EVENTS (LE)

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

FULLY-CONTAINED EVENTS (FC)

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

Partially-Contained (PC) events



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

exit activity in OD

INCREASING ENERGY

The different samples

Low-energy events (LE)

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

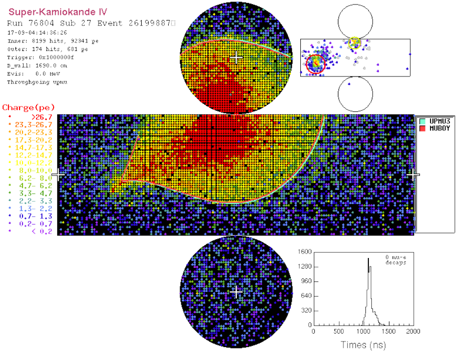
Fully-Contained events (FC)

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

Partially-Contained events (PC)

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

Upward-going muons (UPMU)



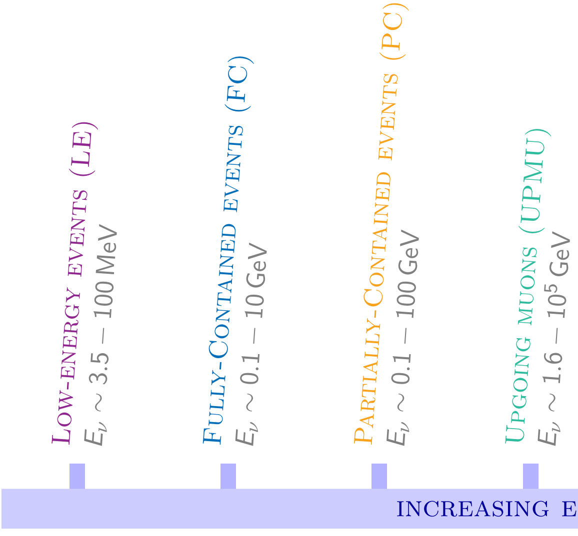
$$\boxed{E_\nu = 1.6\,\text{GeV} - 10\,\text{TeV}}$$

entering activity in OD

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

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

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

INCREASING ENERGY

- 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 of GWTC-2 events

Follow-up strategy with Super-Kamiokande

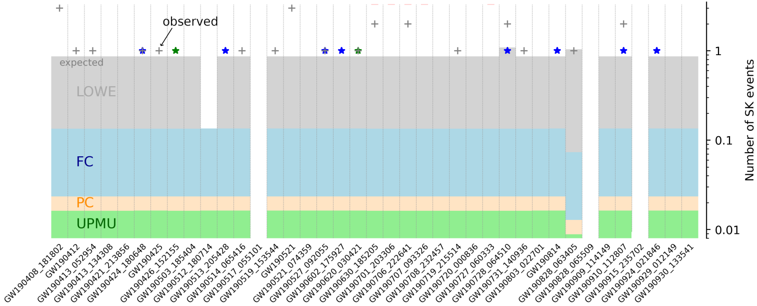
📖 ApJ 918 (2021) 2, 78

- Focus on GWTC-2 catalogue
- 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)

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

Results of the follow-up

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



In total:

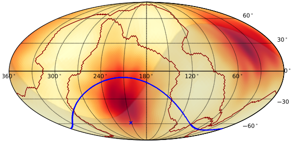
Sample	N_{obs}	N_{exp}
LOWE +	24	24.97
FC ★	8	3.95
PC ★	0	0.26
UPMU ★	2	0.58

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

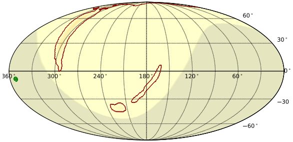
Ten SK high-energy events in time coincidence

📖 ApJ 918 (2021) 2, 78

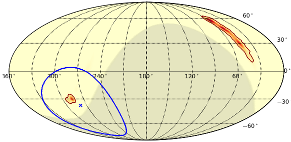
GW190424_180648



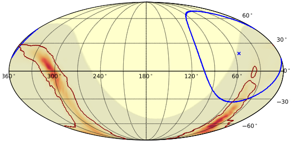
GW190426_152155



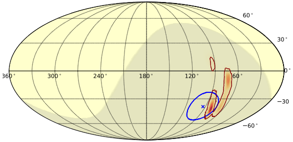
GW190513_205428



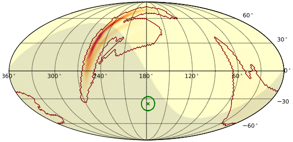
GW190527_092055



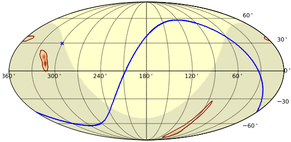
GW190602_175927



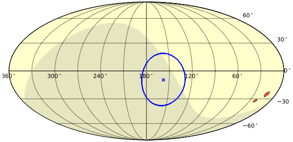
GW190620_030421



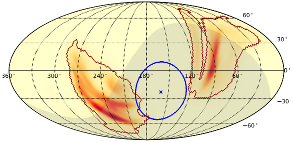
GW190728_064510



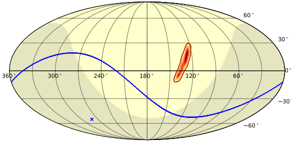
GW190814



GW190910_112807



GW190924_021846



Skymaps in equatorial coordinates

Red: GW localisation and 90% contour

Blue: SK FC events with 1σ angular uncertainty

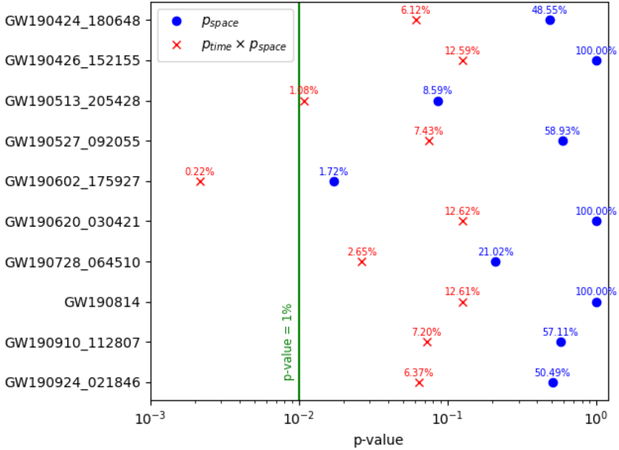
Green: SK UPMU events.

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 $N_{\text{expected signal}} = \int_{E_{\text{min}}}^{E_{\text{max}}} \mathrm{d}E_\nu A_{\text{eff}}^{s,f}(E_\nu, \theta) \times \frac{dn}{dE_\nu}$.

Sample-by-sample flux limits

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

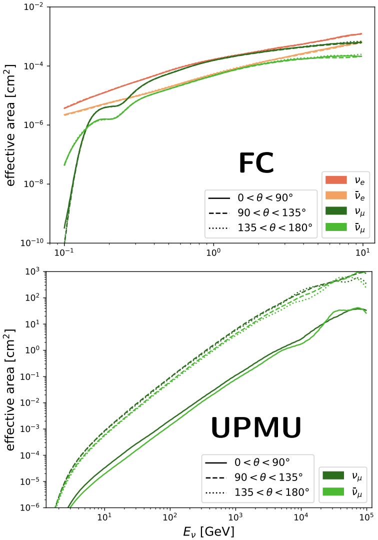
$$\boxed{\mathcal{L}(\phi_0; n_B, N) = \int \frac{(c(\Omega)\phi_0 + n_B)^N}{N!} e^{-(c(\Omega)\phi_0 + n_B)} \mathcal{P}_{\text{GW}}(\Omega) d\Omega}$$

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

Combined flux limits

Limits combining FC, PC and UPMU are obtained by using the combined TS defined before.

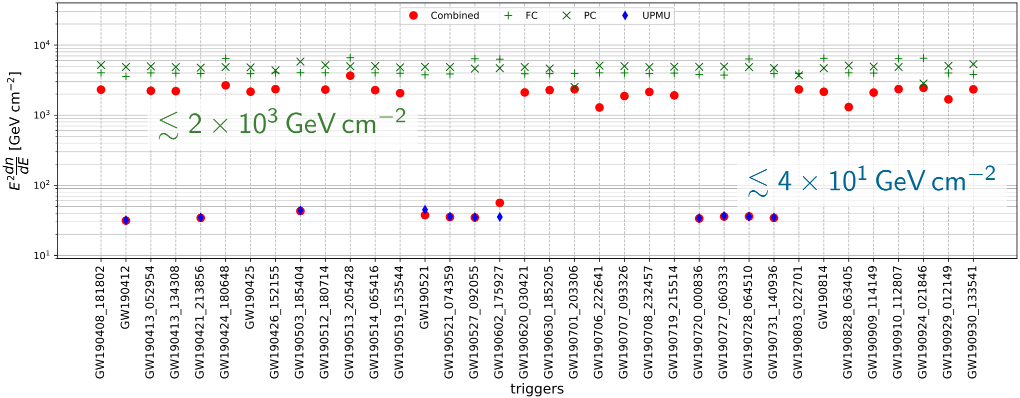
Effective area A_{eff}



High-Energy Flux limits (2)

📖 ApJ 918 (2021) 2, 78

Example of limits for ν_μ flavour:



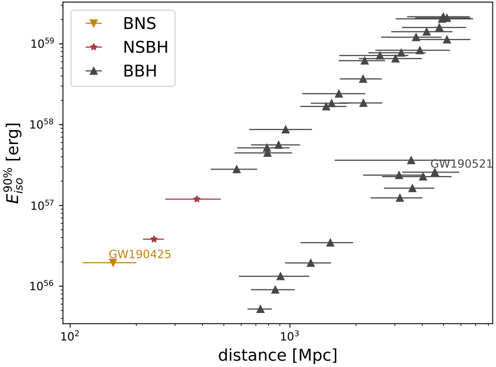
Better limits with the UPMU sample when the GW is below the local horizon. Combined limits are close to the best individual one.

Limits on $E_{\rm iso}$

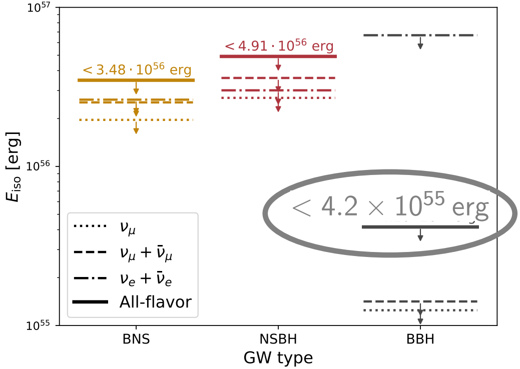
ApJ 918 (2021) 2, 78

- The total energy in ν from the source (assuming **isotropy**) is $E_{\rm iso} = 4\pi d^2 \int \frac{\mathrm{d}n}{\mathrm{d}E} \times E\,\mathrm{d}E$
  $\Rightarrow$ $E_{\rm iso}$ limits obtained by using the 3D localisation skymap from the LVC data release[1].
- We can stack events by nature, assuming same emission (or $E_{\rm iso} \propto M_{\rm source}$).

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



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



---

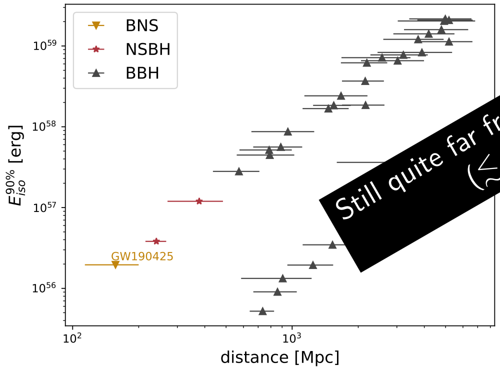
[1] This is done assuming the flux at Earth is equally distributed between the flavours ($\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$)

Limits on E_{iso}

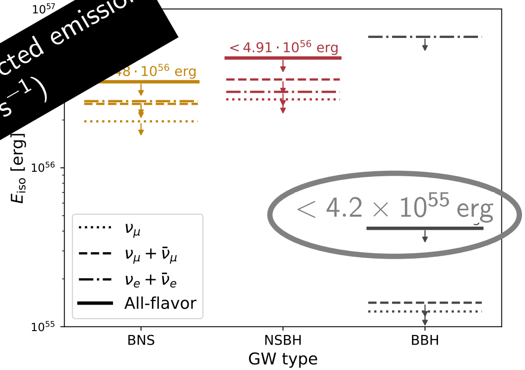
ApJ 918 (2021) 2, 78

- The total energy in ν from the source (assuming **isotropy**) is $E_{\text{iso}} = 4\pi d^2 \int \frac{\mathrm{d}n}{\mathrm{d}E} \times E\,\mathrm{d}E$
  $\Rightarrow$ E_{iso} limits obtained by using the 3D localisation skymap from the LVC data release[1].
- We can stack events by nature, assuming same emission (or $E_{\text{iso}} \propto M_{\text{source}}$).

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



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



Still quite far from expected emission
($\lesssim 10^{52}$ erg s^{-1})

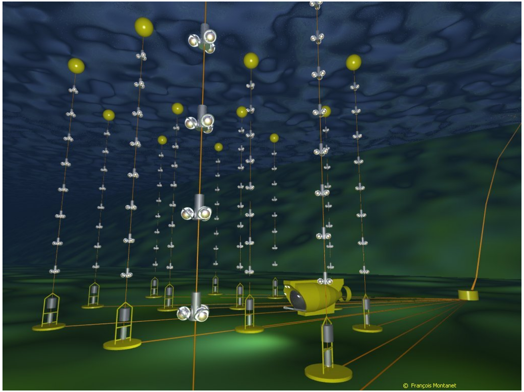
---

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

Outlook

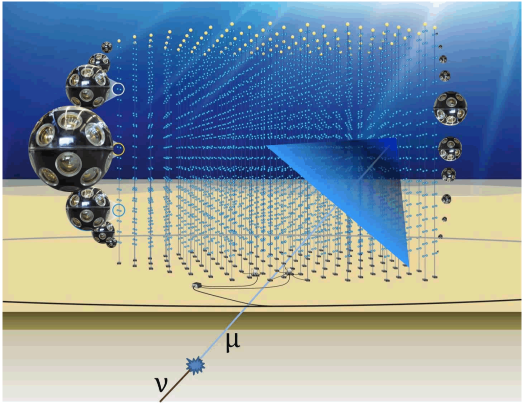
ANTARES and KM3NeT: telescopes in the Mediterranean Sea

ANTARES



- 12 lines instrumenting 10 Mt
- Took data continously from 2007 to 02/2022

KM3NeT

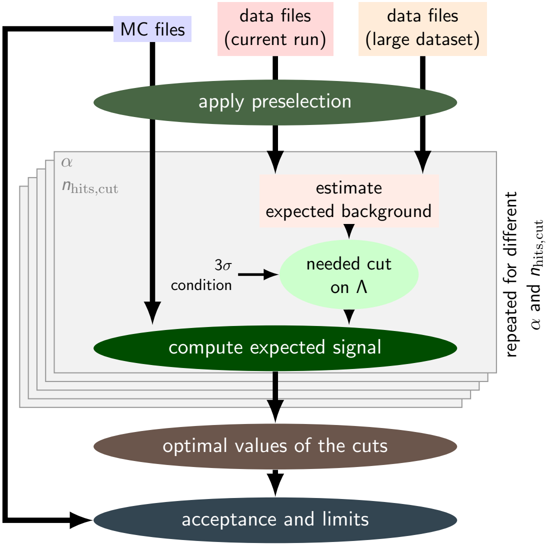


- 3 × 115 lines instrumenting 7 Mt + 2 × 0.5 Mt
- Under construction but already taking data with a limited number of lines

Follow-up of GW events with ANTARES

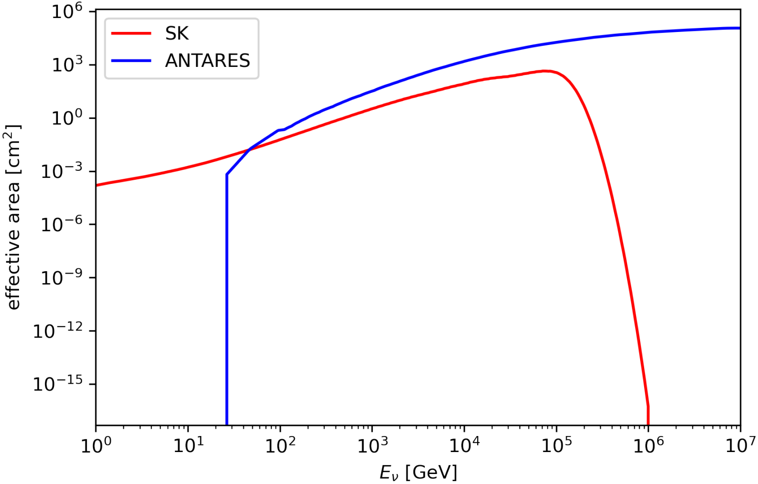
Detector is located in a less stable environment with respect to Super-Kamiokande.
⇒ need **event-by-event treatment**

- Impact of background may fluctuate depending on sea conditions
- Selection cuts need to be optimized to ensure low background
- Detector acceptance will then vary
- Limits are obtained and a stacking analysis can be done as for SK



Complementarity between experiments (1)

Let's consider ANTARES and Super-Kamiokande, and their published effective areas.



Complementarity between experiments (2)

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):

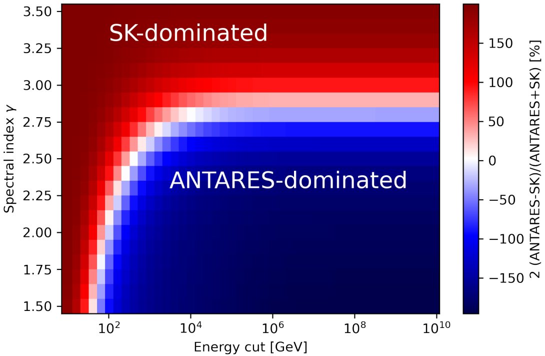


Fig: Relative diff. between ANTARES and SK limits.

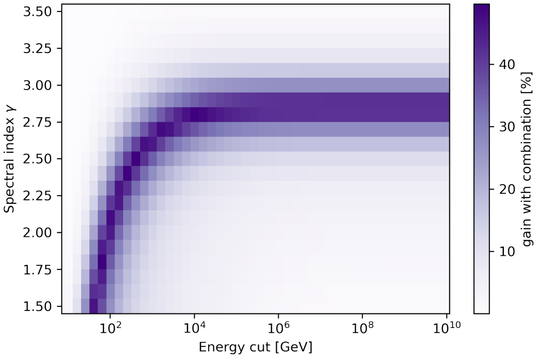
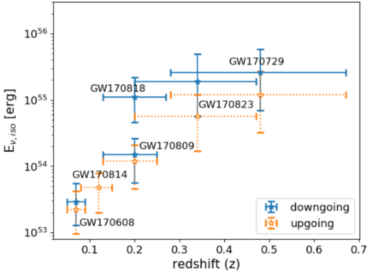


Fig: Relative gain with the combination.

Ongoing efforts

- Currently finalizing follow-up of O3 events with ANTARES (similar strategy to SK's)
- Developing a Python package to handle various detector and allow combinations
  → can be used to investigate further SK+ANTARES
- At the end of Fellini, will start to work within KM3NeT and IceCube, with the aim to expand their low energy selection and make population studies
- Next GW observation run (O4) expected to start in December 2022 / early 2023.

ANTARES O2 results



PyJANG package (under development)

JANG

New contract in Louvain (Belgium)

UCLouvain

Take-away messages

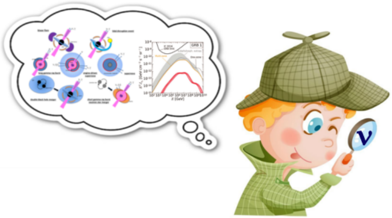
① *Common sources of neutrinos and gravitational waves* are expected (in particular from astrophysical objects involving neutron stars), but have not yet been detected.

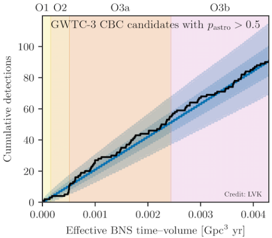
② SK is sensitive to such neutrinos with *energies range from MeV to TeV*.

③ Search was performed using latest GW catalog, but *no significant excess* has been found.

④ There are interesting prospects in existing or under construction experiments:

- **LOWERING** the energy threshold
- **ANALYSING** together the different detectors
- **COMBINING** all sources in catalogs for population studies





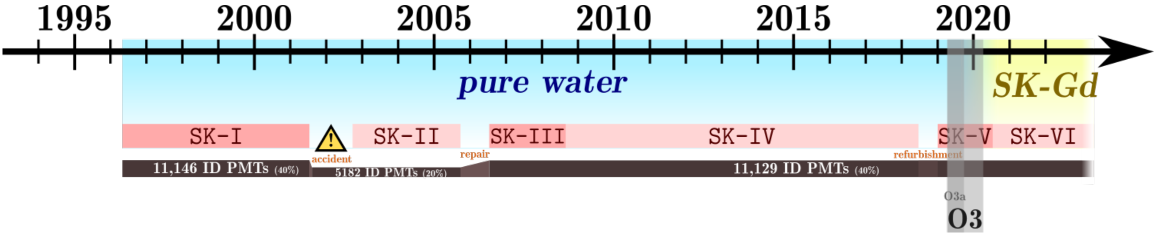
Credit: LVK

THANK YOU

SK collaboration meeting, Toyama, 15/11/2019

Backups

Super-Kamiokande timeline



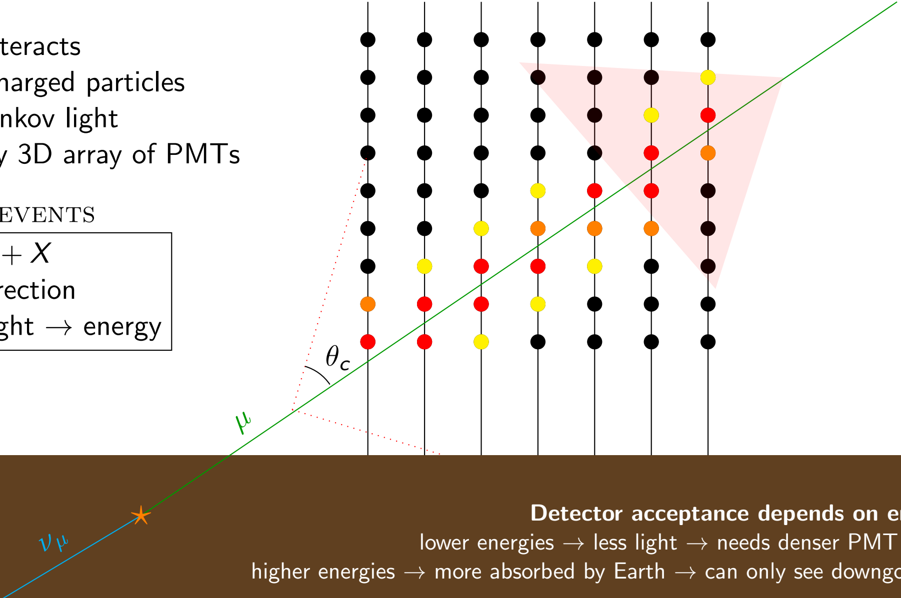
Detection principle

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

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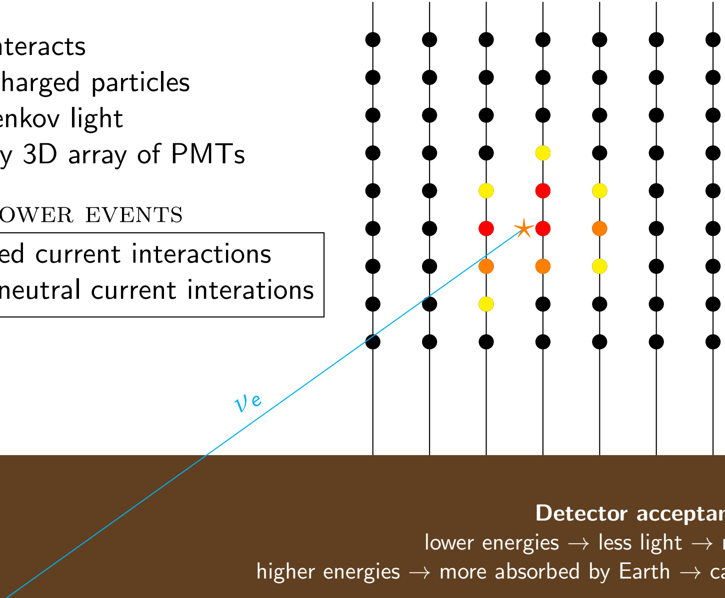
Shower events

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



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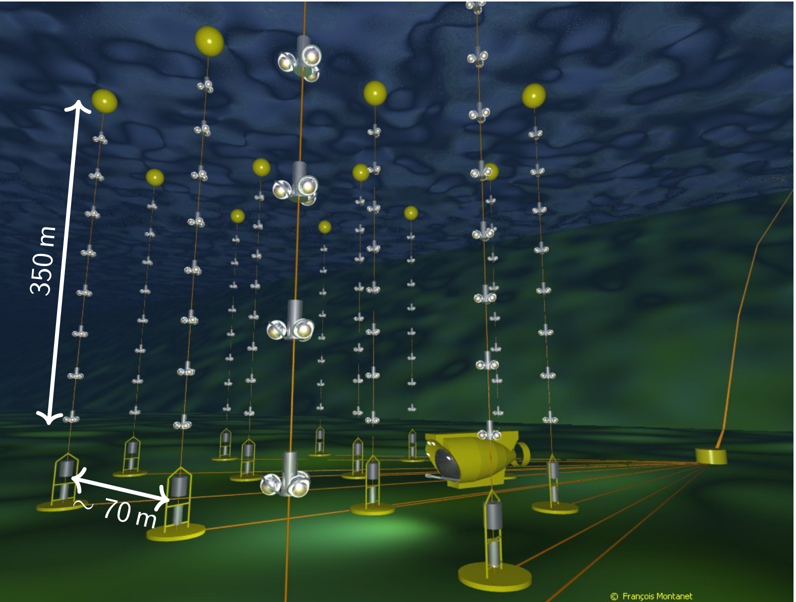
The ANTARES experiment

NIM.A 656 (2011) 11-38



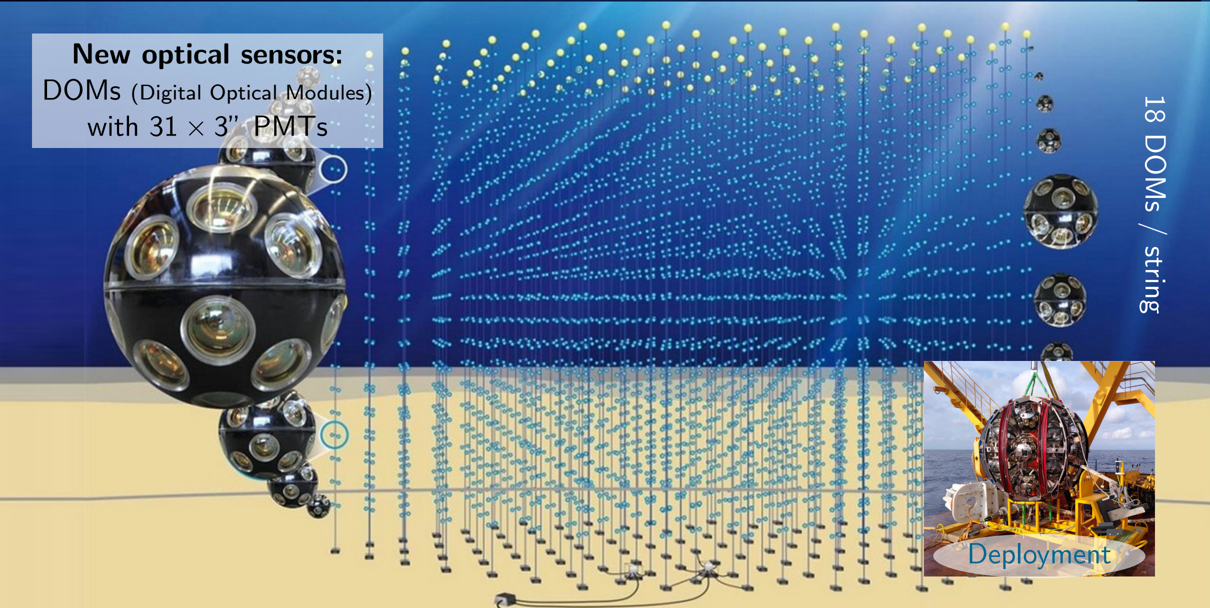
- In operation since 2006 (completed in 2008)
- Off the coast of Toulon
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

Total instrumented volume:
10 Mt

The KM3NeT project

📖 J.Phys.G 43 (2016) 8, 084001

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



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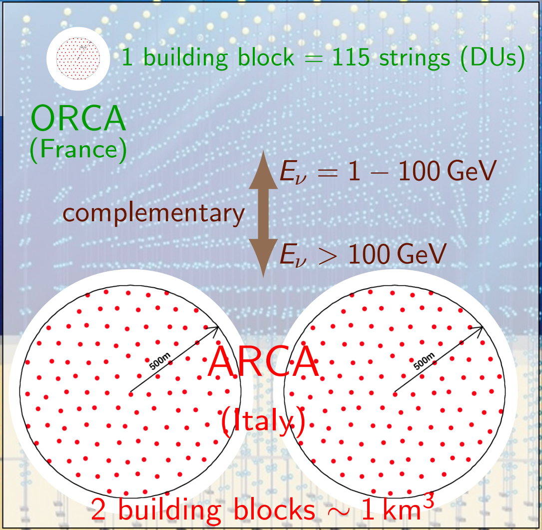

1 building block = 115 strings (DUs)

ORCA
(France)

$E_\nu = 1 - 100$ GeV

complementary

$E_\nu > 100$ GeV

ARCA
(Italy)

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

18 DOMs / string

Deployment

SKGW: Observation significance

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

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

- $p_{\rm time} = {\rm Prob}(N \geq 1) = 1 - e^{-n_B} \sim 12.6\%$ for $n_B =$ total background (FC+PC+UPMU) $= 0.13$
- $p_{\rm space}$ is obtained by comparing neutrino direction and GW localisation[2]
    - For each sample ($k =$ FC, PC or UPMU), define the point-source likelihood $\mathcal{L}_\nu^{(k)}(n_S^{(k)}, \gamma; \Omega_S)$ that separates background from signal ($dn/dE \propto E^{-\gamma}$, direction Ω_S).
    - Compute the maximum log-likelihood ratio Λ (GW localisation $\mathcal{P}_{GW}$ used as prior) and find the source direction Ω_S that maximises it:

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

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

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[2] IceCube collaboration. IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog. Astrophys.J.Lett. 898 (2020) 1, L10

SKGW: Test statistic

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.

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

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

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

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

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

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

SN: introduction

📖 Astron.Astrophys. 654 (2021) A95

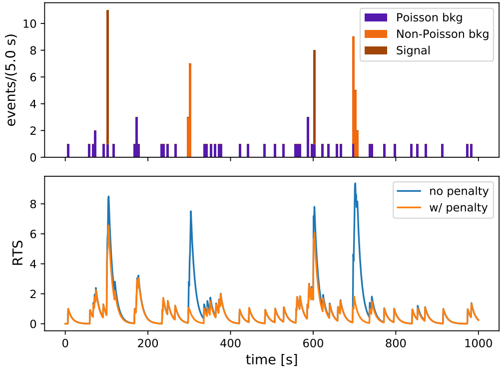
A galactic supernova would create a burst of low-energy neutrinos in any significantly big detector. In the search for such bursts, the usual technique is to:

- define a fixed-width time window (e.g. $w = 20\,\mathrm{s}$)
- compute multiplicity m of selected "cluster"
- send alert if $m >$ threshold ($+$ additional checks)

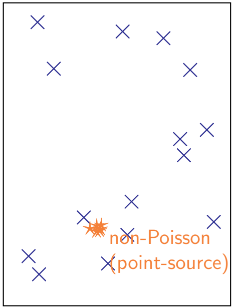
But this does not take benefit of the special time distribution of signal (events very concentrated in time) with respect to background (uniformly distributed in time) and additional checks are needed to remove spatially-correlated background.
$\Rightarrow$ This is critical for small detectors and/or far SNe, where the expected number of signal events is low.

We propose a new approach where the clustering is replaced by a continuous variable that characterises the "signalness" of the data.

SN: illustration of the idea



Generated positions:

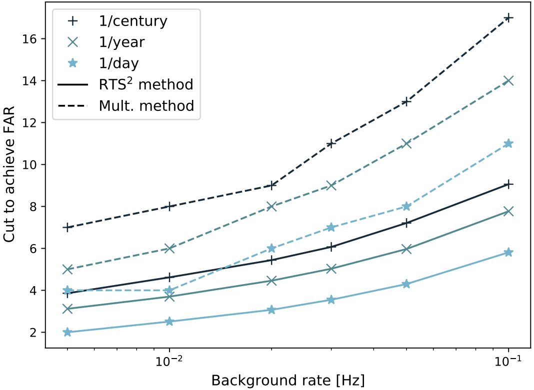


New RTS^2 method

We define $\mathcal{F}(t) = \sum_i f(t;t_i)$ with $f(t;t_i) = e^{-\frac{t-t_i}{T_c}} \times H(t-t_i) \times \prod_{j<i}\left(1 - e^{-\frac{t_i-t_j}{T_{sp}}} e^{-\frac{\|\vec{x}_i-\vec{x}_j\|^2}{2\sigma_{sp}^2}}\right)$ where T_c is a chosen time characteristic (one naive choice would be $T_c = 1/\text{rate}$).

SN: raw performance

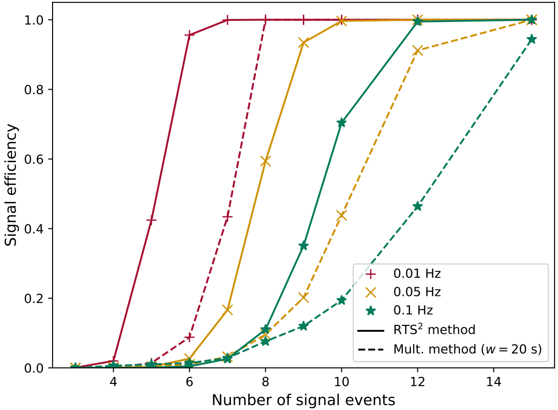
Which cut should be applied on $\mathcal{F}$ to achieve a false alarm rate (FAR) of e.g. one per century or one per day?



We can compare the limits on $\mathcal{F}$ tu achieve a given FAR ($\sim$ minimum number of signal events) to the multiplicity cut from the standard approach.

SN: gain in signal efficiency

In the following, signal is simulation by assuming a simple double-exponential shape:$p(t) = \left(1 - e^{-t/\tau_1}\right) \times e^{-t/\tau_2}$ (in the following, $\tau_1 = 10\,\mathrm{ms}$, $\tau_2 = 1\,\mathrm{s}$).



- Simulated background is Poisson distributed with a fixed rate r.
- $N \gg 1$ centuries are simulated in order to find the cut $\mathcal{C}$ to apply to get a given false alarm rate.
- Inject signal with fixed multiplicity (on top of background).
- The signal efficiency is the ratio of events passing $\mathcal{C}$.

SN: prospects

- The developed tool may be used for the detection of far SNe (in the local cluster) in Hyper-Kamiokande or other large detectors.
- Similar technique may be exploited for the identification of GeV astrophysical neutrinos in KM3NeT and IceCube:
  - Background: time independent and localised (within a detector)
  - Signal: burst