Virtual Iberian Gravitational Wave Meeting
October 2020

Gravitational waves and neutrino astronomy with ANTARES and KM3NeT

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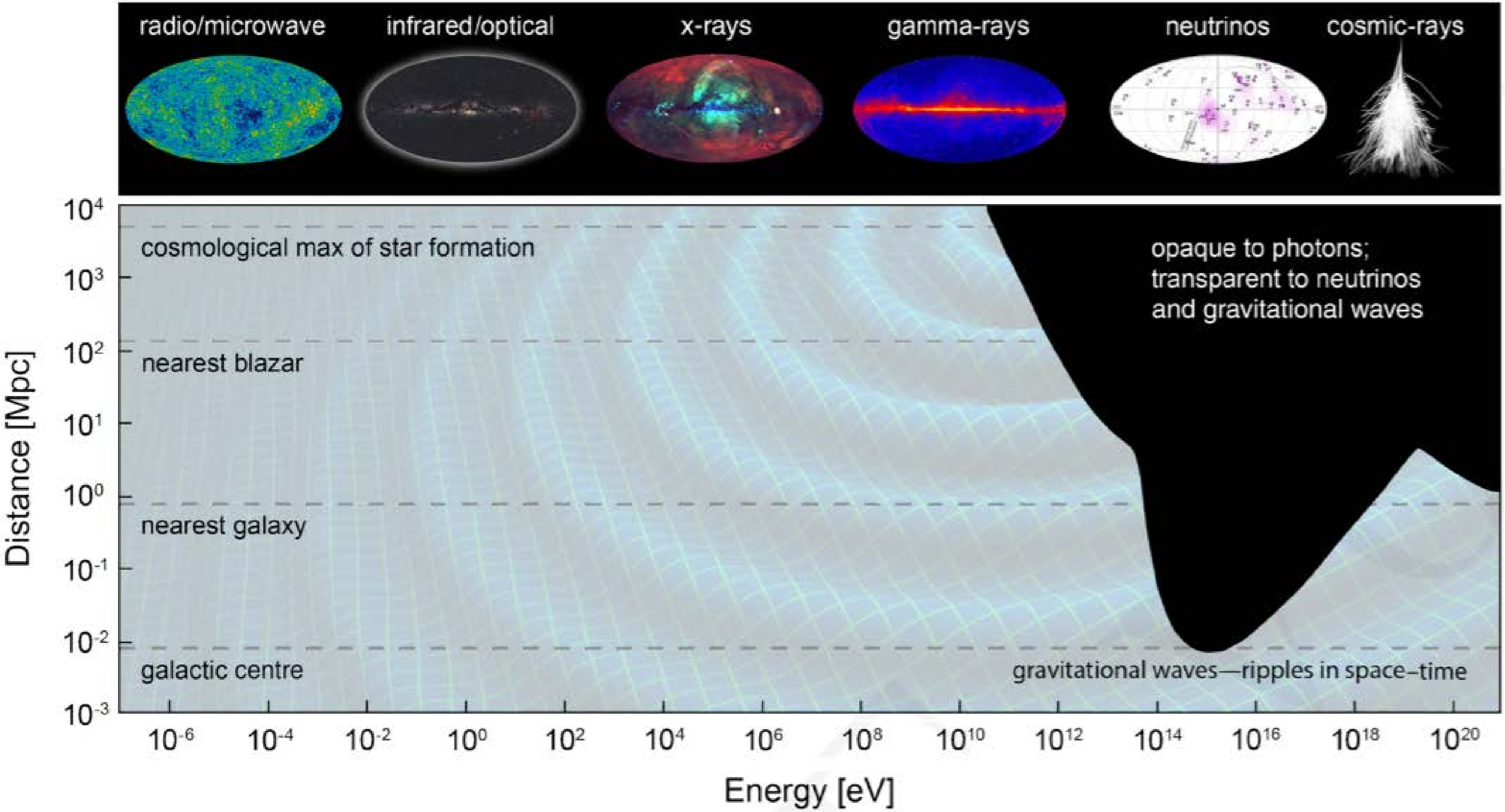
Outline

- Introduction
- ANTARES detector
  - Results from ANTARES[1]
- KM3NeT detector
  - First results from KM3NeT
  - Prospects for KM3NeT
- Conclusions

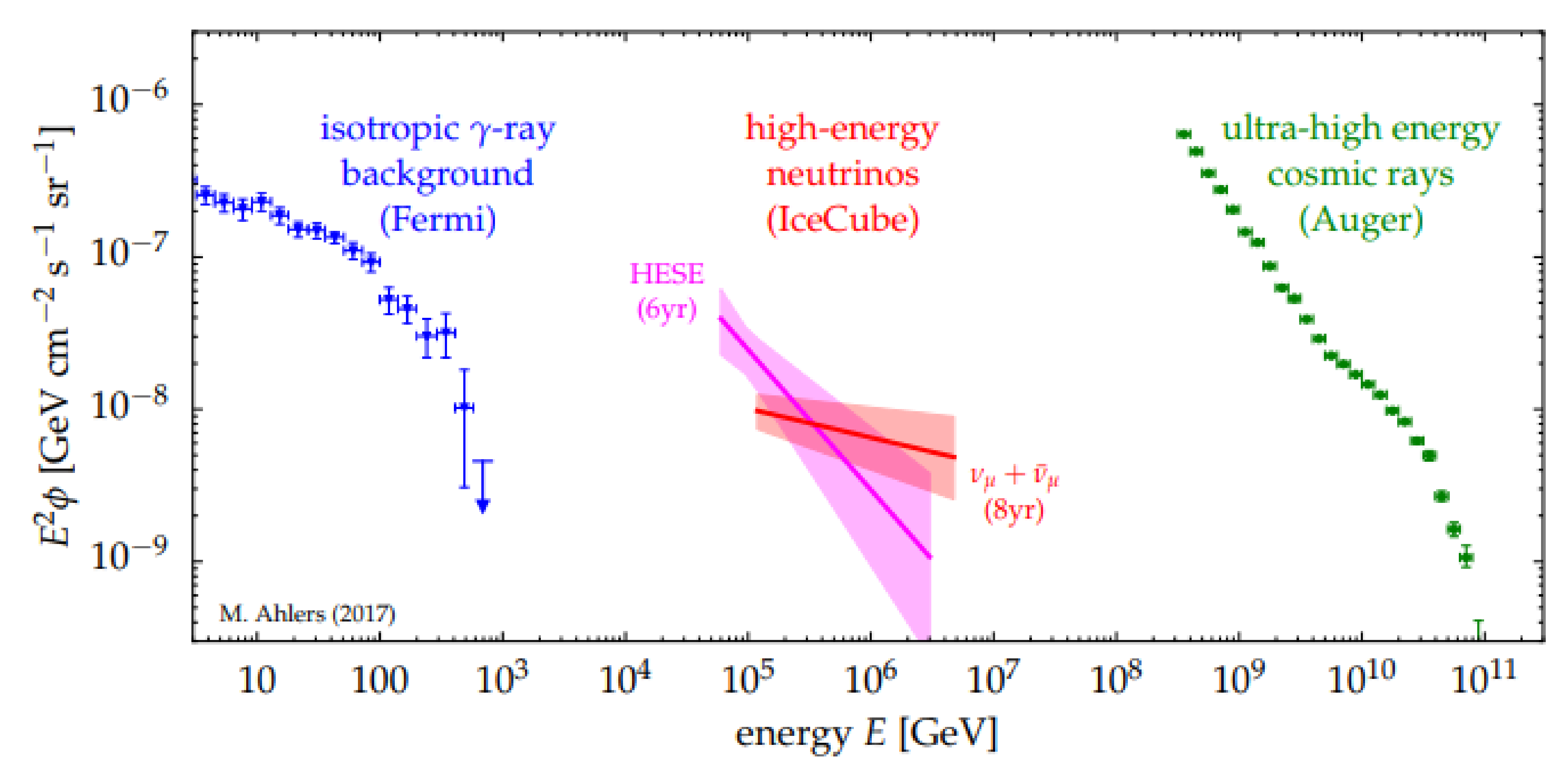
[1]in reverse time order

Introduction

The Universe: how to look at it?



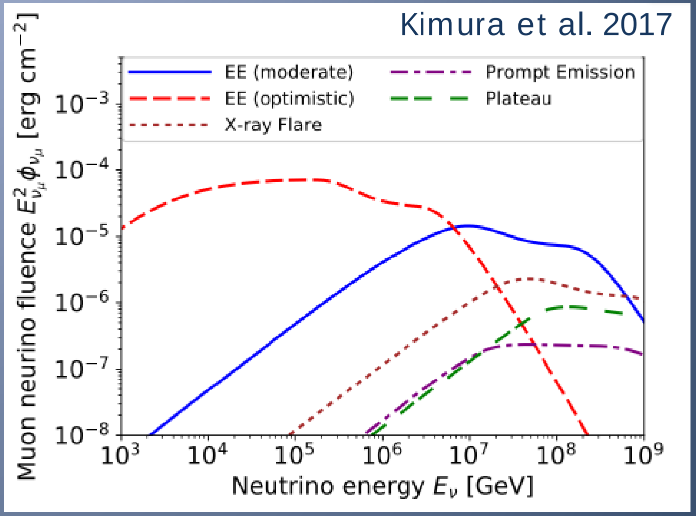
Cosmic fluxes



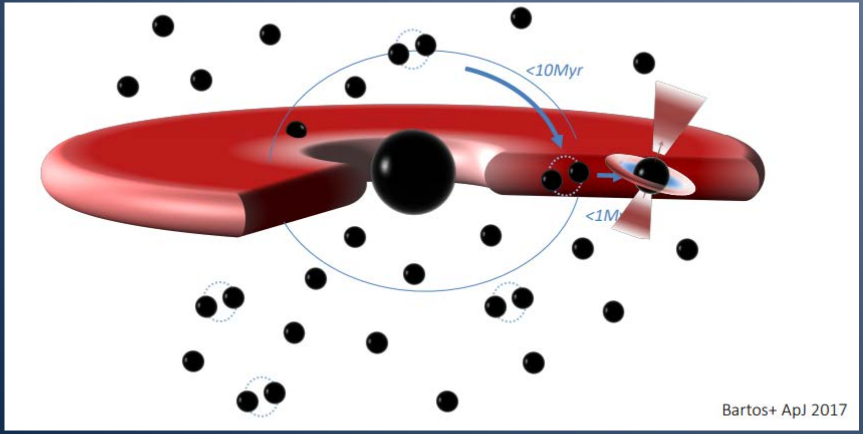
Neutrinos and GWs

Binary neutron star merging

- BNS mergers are the most promising multi-messenger sources
- Moreover they are the only case observed in coincidence of GWs AND electromagnetic signal (GW170817)
- Neutrino flux and energy depend on production site and other conditions



Binary black hole merging



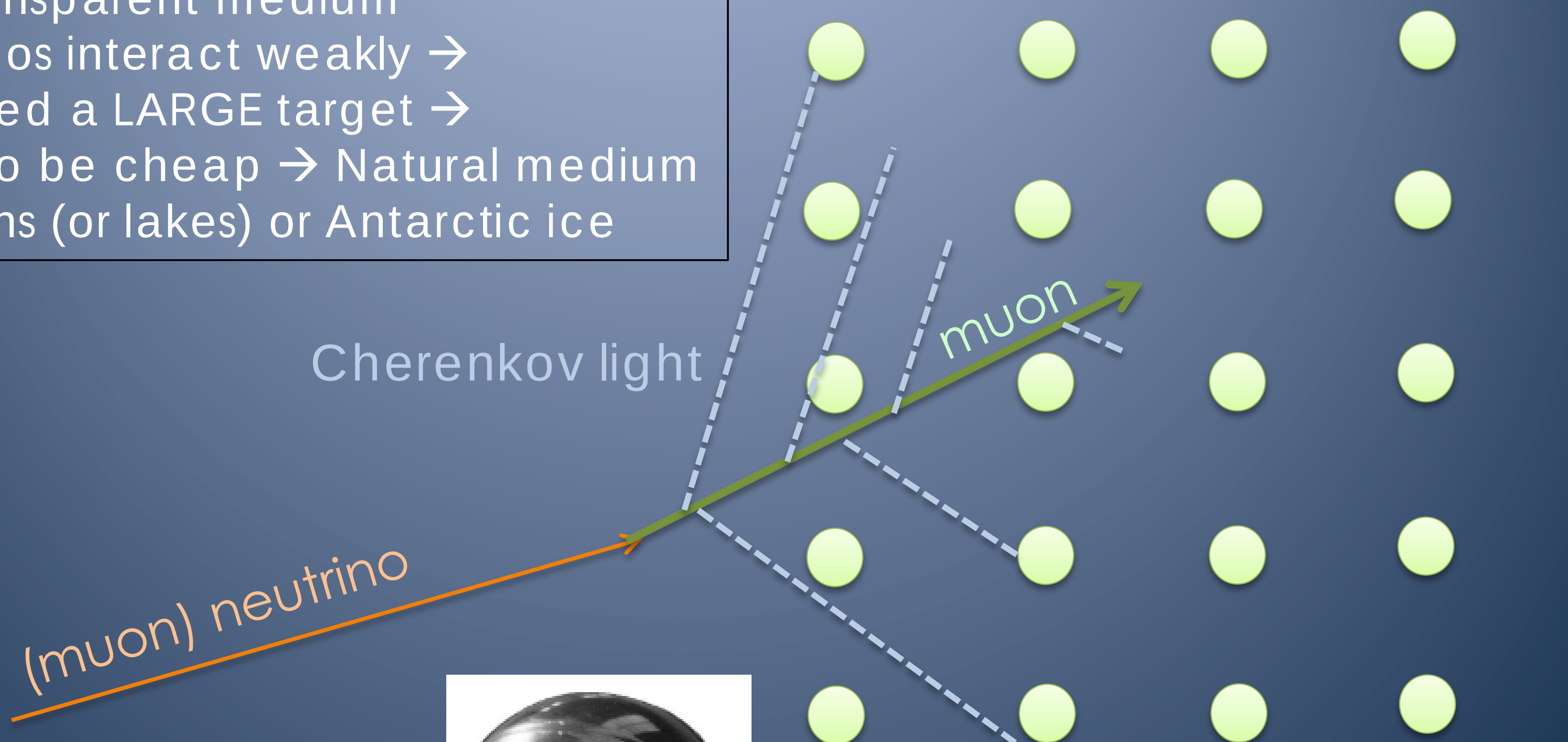
In general, no EM/neutrino emission is expected in BBH merging, but neutrino emission is possible if there is an hadronic environment / strong magnetic field:

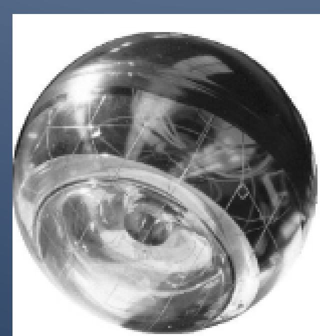
-acretion disk
-relativistic jet
-mergers in AGNs

Kotera 16
Perna 16
Bafrtos 17

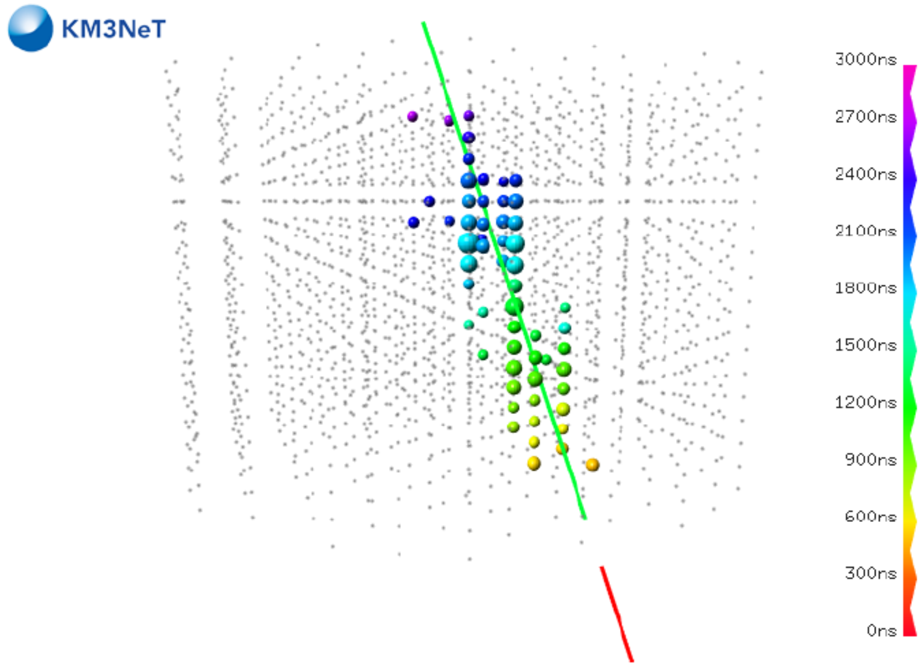
Detection Principle

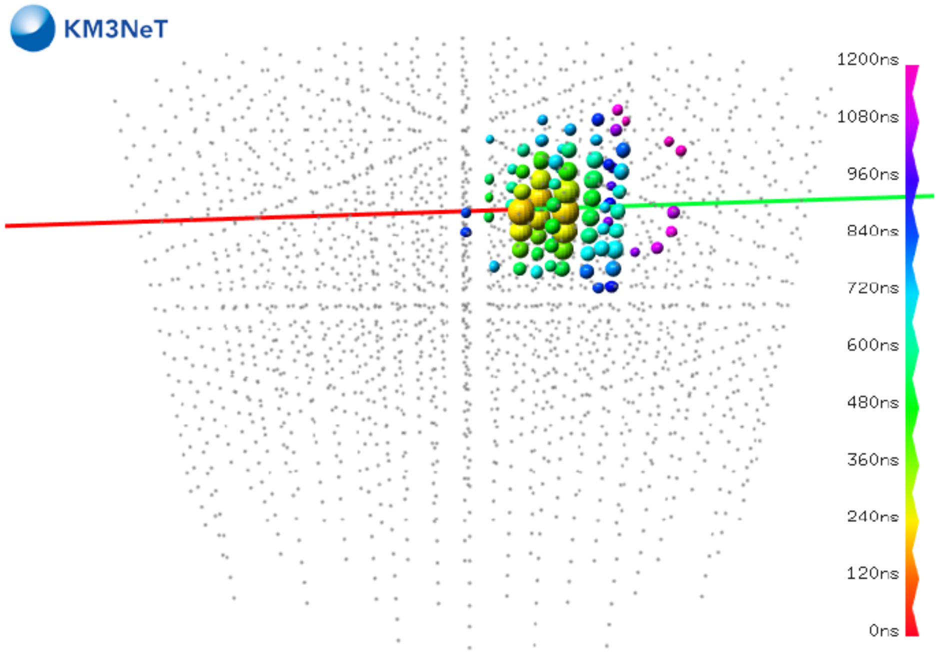
Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice





Tracks vs showers





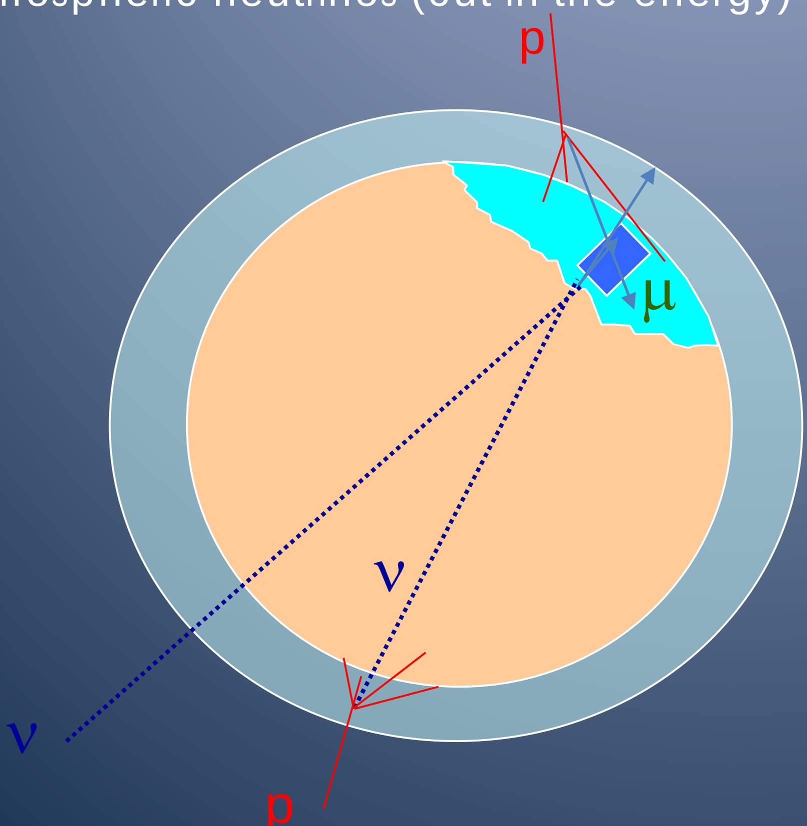
Tracks: CC ν_μ

Showers: CC ν_e, ν_τ and NC

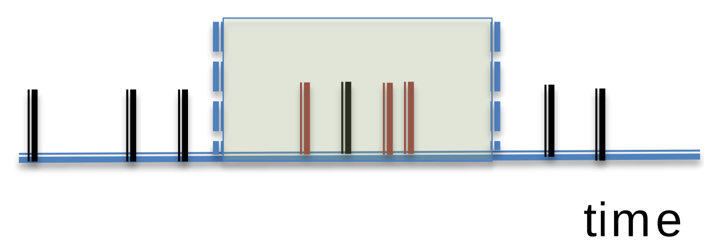
Physical Background

- There are two kinds of background:
  - Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events)
  - Atmospheric neutrinos (cut in the energy)

$$p \to \pi^+(+K^+ \ldots) \to \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \overline{\nu}_\mu + \nu_e$$



time information of the signal (for transient sources



Scientific Scope

- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass ordering
- Dark matter

Detector size

Limitation at high energies:
Fast decreasing fluxes E^{-2}, E^{-3}

Limitation at low energies:
-Short muon range
-Low light yield
-^{40}K (in water)

Detector density

Supernovae

Oscillations-Mass ordering-Neutrino properties

Dark matter

Astrophysical neutrinos

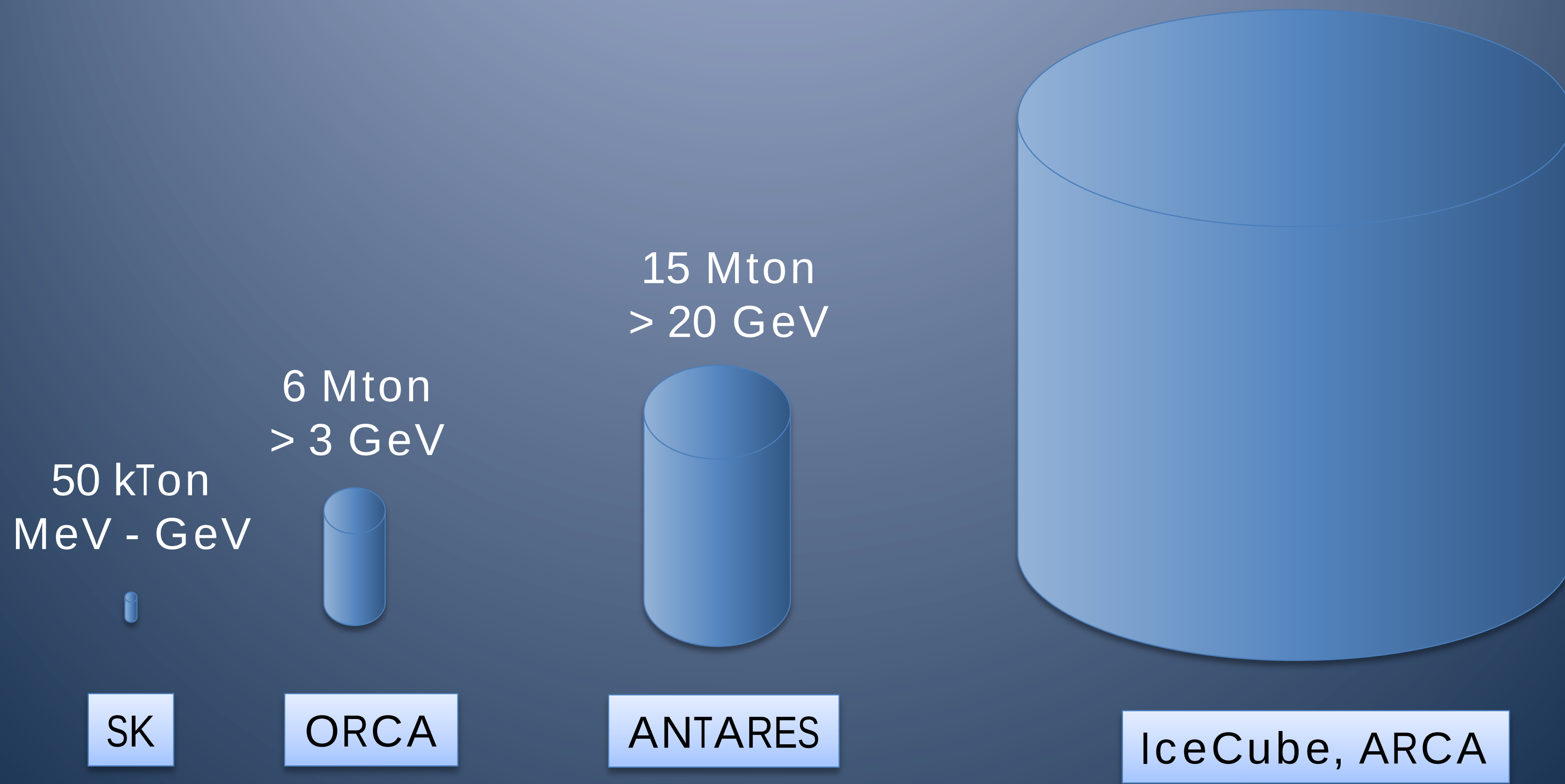
GZK

MeV GeV TeV PeV EeV

Other physics: monopoles, nuclearites, Lorentz invariance, etc...

Detector size

Denser detector → Lower energy threshold
Larger detector → More efficient of low fluxes



Role of NTs with in the context of GW astronomy

- Neutrino telescopes observe:
  - the full sky (or half sky if only upgoing events are considered)
  - continous monitoring
  - good angular resolution

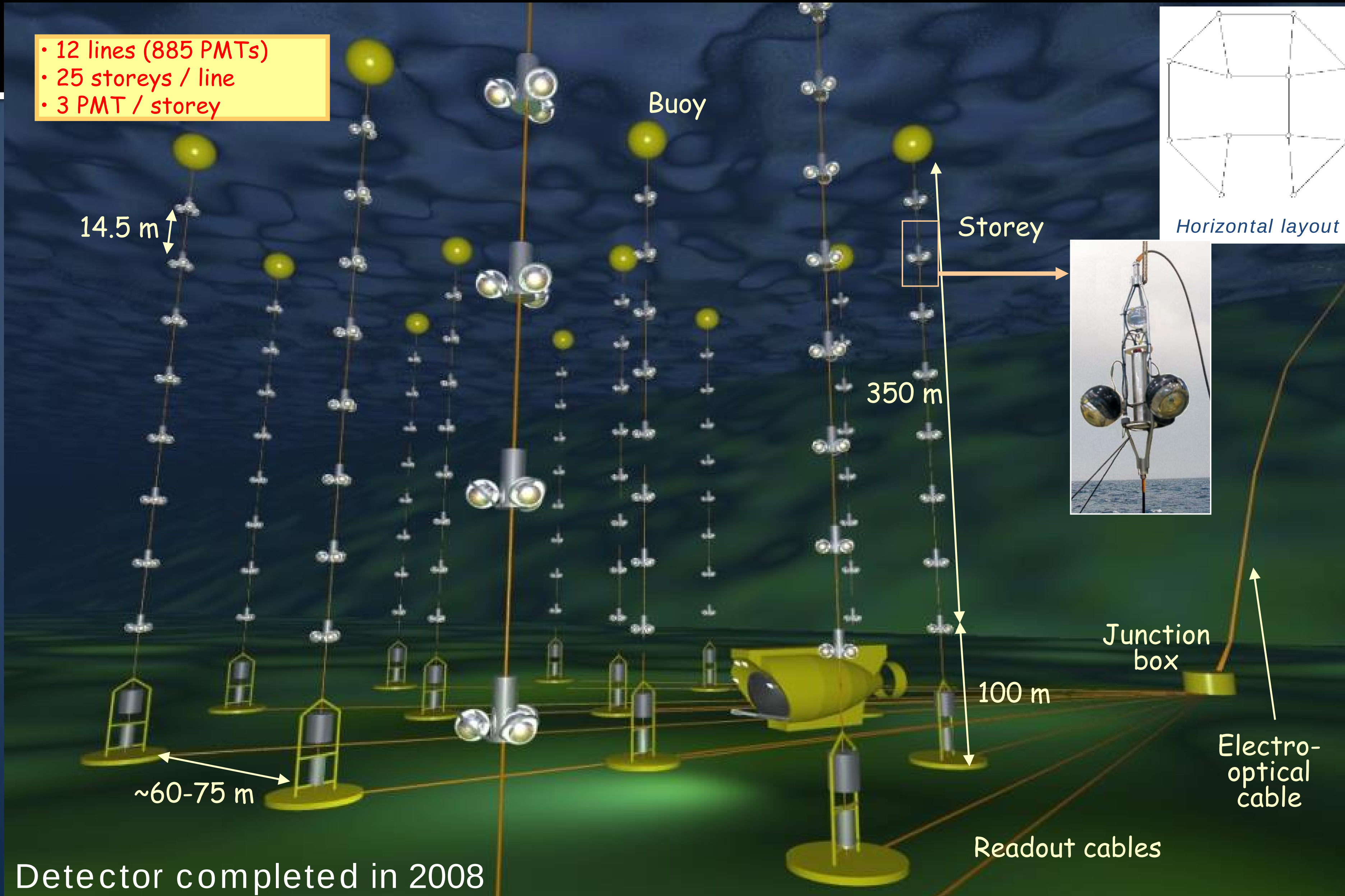
Very helpful for transient events

online: better identification of source position → critical for EM follow up

- Subthreshold events: not enough significance by themselves, but enough with extra messenger
- Multi-messenger astronomy: info from the neutrino channel useful to support/reject models

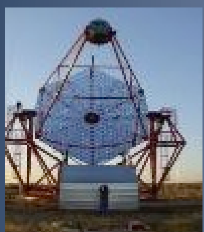
ANTARES

The ANTARES Detector



ANTARES: Astronomy

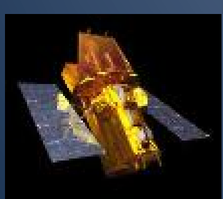
Multimessenger




GeV-TeV γ-rays
Fermi / HESS,
HAWC…

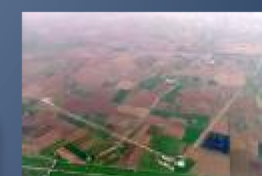
UHECR
Auger

High energy
neutrinos

Optical / X-rays
TAROT/ Swift,
ZADKO,
MASTER…

Gravitational
Waves
Virgo / LIGO

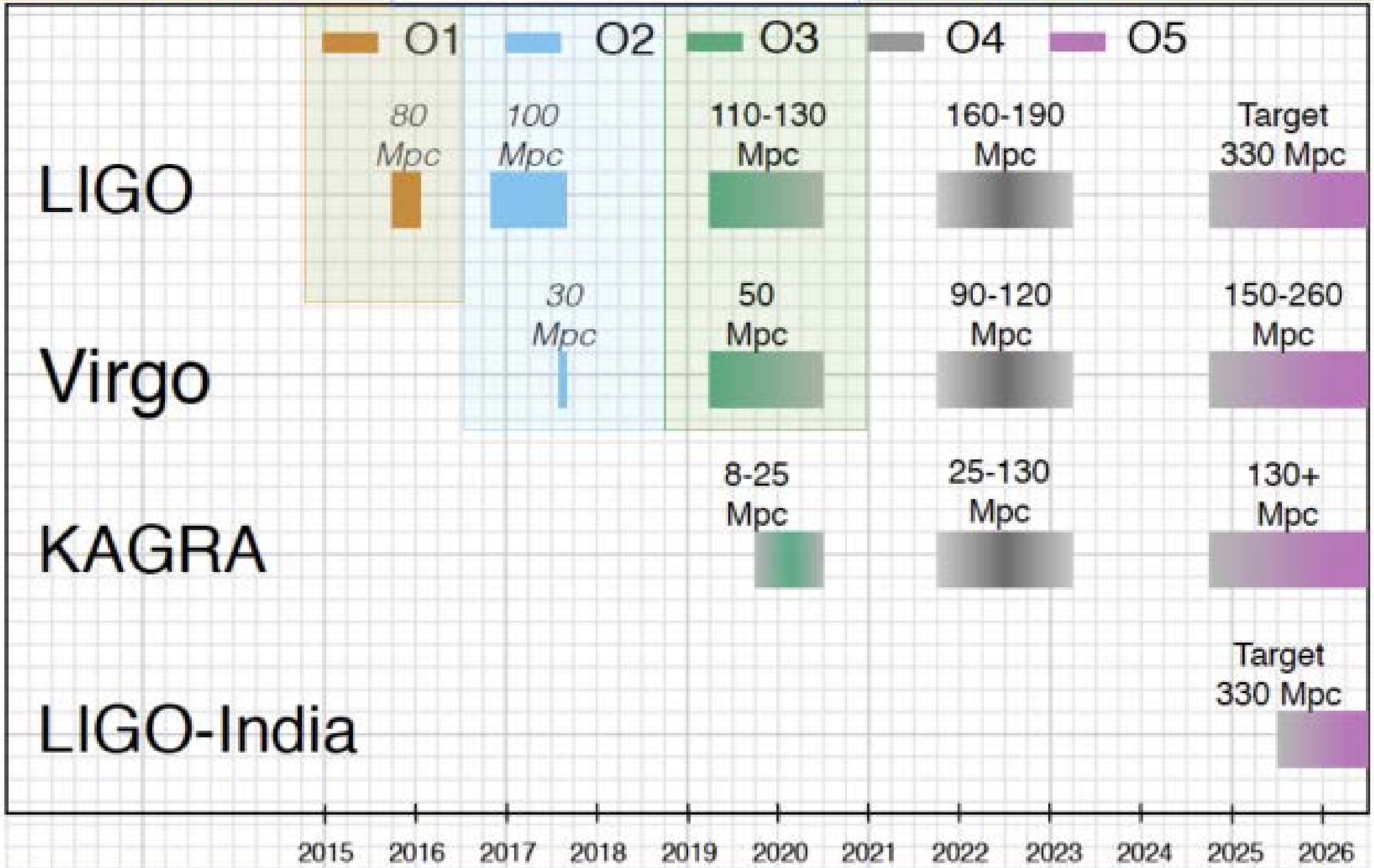



- It increases the chances of detection
  - Common sources for different messengers
  - Backgrounds and systematics non correlated
  - ANTARES is able to get the hits and send a trigger alert of the reconstructed direction of the event in ~5s

ANTARES alerts:
- Doublet of neutrinos: ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 ev/yr
- Single VHE neutrinos: ~30 TeV, ~3-4 ev/yr

GWs with ANTARES

O1 : 12/09/2015 → 19/01/2016 BBH GW150914 Individual BBH (3 papers) Subthreshold (1 paper)	O2 : 30/11/2016 → 25/08/2017 BNS GW170817 (2 papers) Catalog BBH → 11 events, 1 paper	O3a : 01/04 → 30/09/2019 O3b : 01/11/2019 → 27/03/2020 56 online GW events 4 GW papers (1 BNS, 1 NSBH) Catalog BBH O3a soon



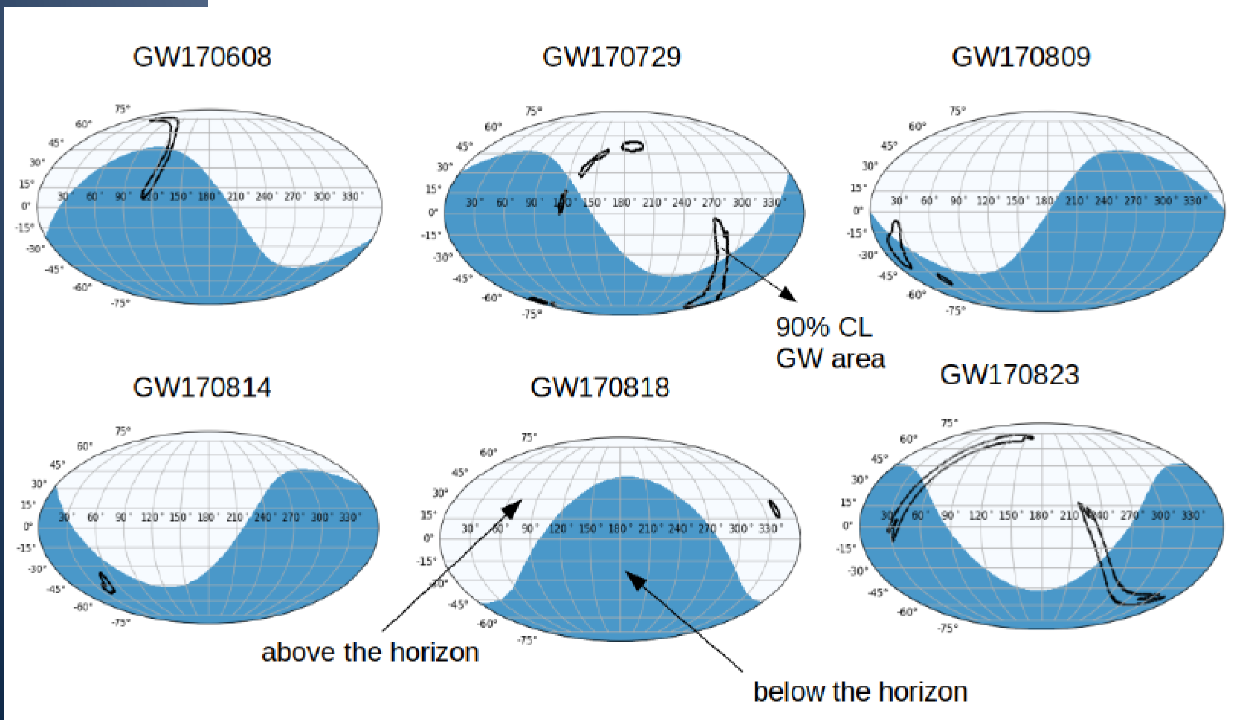
ANTARES publications on GWs

1. **Search for neutrino counterparts of catalogued gravitational-wave events detected by Advanced-LIGO and Virgo during run O2 with ANTARES,** A. Albert et al., Eur. Phys. J. C 80, 487 (2020)
2. **Search for Multi-messenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during its first Observing Run, ANTARES and IceCube**A. Albert et al. (ANTARES and IceCube and LIGO and Virgo Collaborations), Astrophys.J. 870 (2019) no.2, 134
3. **All-sky search for high-energy neutrinos from gravitational wave event GW170104 with the ANTARES neutrino telescope,** A. Albert et al., Eur. Phys. J. C 77, 911 (2017)
4. **Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory, A. Albert et al., ApJL 850 L35 (2017).**
5. **Search for High-energy Neutrinos from Gravitational Wave Event GW151226 and Candidate LVT151012 with ANTARES and IceCube,** A. Albert et al., Phys. Rev. D 96 (2017) 022005
6. **High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube,** Adrián-Martínez et al., Phys. Rev. D 93, 122010
7. **A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007,** S. Adrian-Martinez et al., JCAP 06 (2013) 00

Eur. Phys. J. C (2020) 80:487

New: O2 LIGO and VIRGO

Event	$A_{up}^{90\%}$ $(°)^2$	$A_{down}^{90\%}$ $(°)^2$	#GCN GW/ANTARES	D_L [Mpc]	M_{chirp} [$M_\odot$]
GW170608	226	170	21221/21223	320^{+120}_{-110}	$7.9^{+0.2}_{-0.2}$
GW170729	553	475	No GCN sent	2750^{+1350}_{-1320}	$35.7^{+6.5}_{-4.7}$
GW170809	245	95	21431/21433	990^{+320}_{-380}	$25.0^{+2.1}_{-1.6}$
GW170814	87	0	21474/21479	580^{+160}_{-210}	$24.2^{+1.4}_{-1.1}$
GW170818	0	39	No GCN sent	1020^{+430}_{-360}	$26.7^{+2.1}_{-1.7}$
GW170823	878	771	21656/21659	1850^{+840}_{-840}	$29.3^{+4.2}_{-3.2}$



- -Six **BBH merging** events
- -Search for prompt neutrino emmision (**±500 s**)
- -First **online** (only upgoing track events)
- -Then **offline** (upgoing and downgoing and all-flavor) + better calibration

Eur. Phys. J. C (2020) 80:487

Analysis method

Tracks

-**Cuts** optimized for having 3σ excess with just one event

-Background is estimated from data outside the search window

-Upgoing events: analysis cuts based on the reconstruction quality parameter Λ(likelihood, numer of degrees of freedom)

-Downgoing events: cuts based on Λ and number of hits used in reconstruction (proxy for energy). A spectrum E^{-2} is assumed for the neutrino signal.

Showers

-Events not passing the track selection and passing the shower criteria. Only contained events are considered.

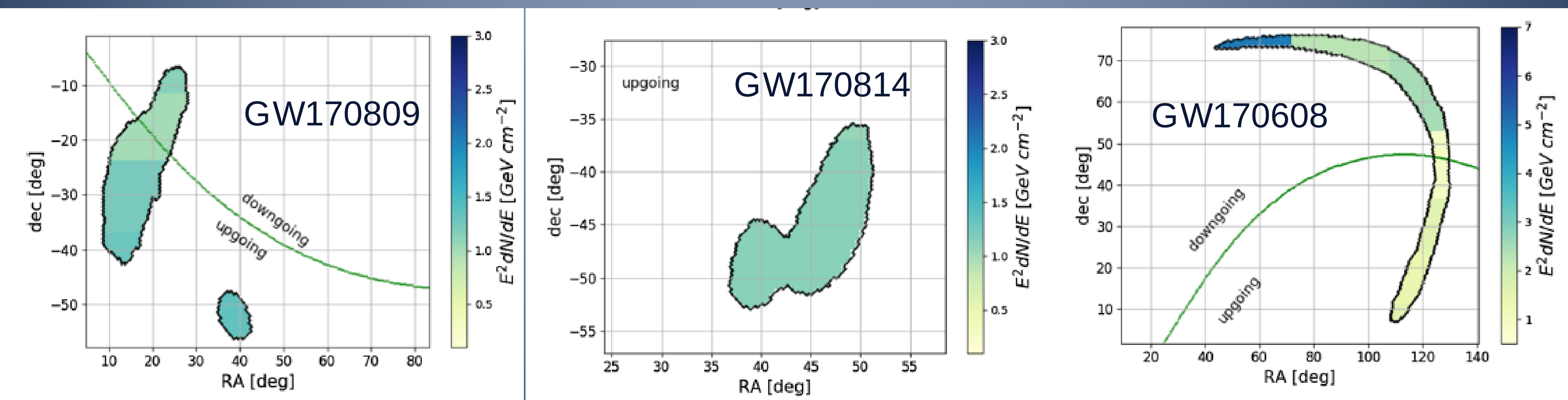
-After preselection based on a reconstruction parameter, selection based on RDF classifier and an extended likelihood ratio

Eur. Phys. J. C (2020) 80:487

O2 LIGO and VIRGO: results

No coincident events found → upper limits on spectral fluence and isotropic energy radiated in neutrinos

Limits on the spectral fluence:



Marta Colomer's PhD thesis,
U. Paris – U. Valencia, 2020

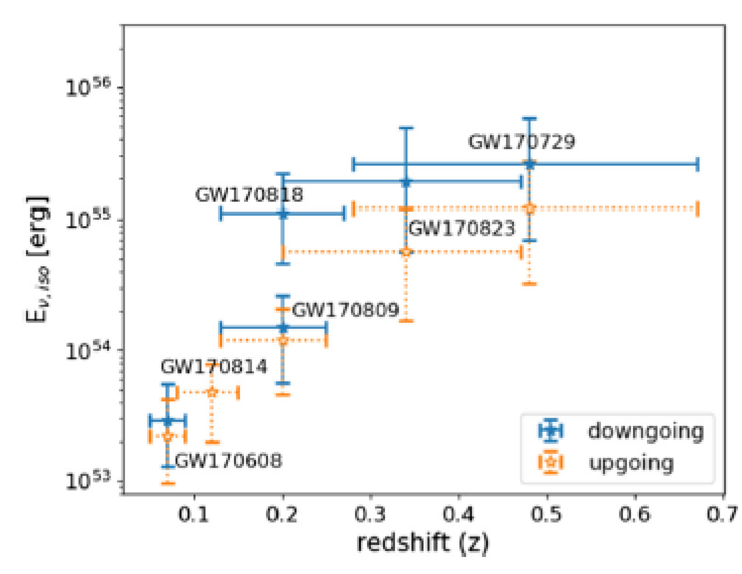
GW event	$\phi_0^{90\%}$ (GeV cm^{-2}) Upgoing	Downgoing
GW170608	1.6±0.5	2.2±0.9
GW170729	1.7±0.5	4.0±1.0
GW170809	1.1±0.3	1.2±0.5
GW170814	1.1±0.3	–
GW170818	–	9.0±4.0
GW170823	1.7±0.5	6.0±2.0

O2 LIGO and VIRGO: results

Constraints on the total equivalent isotropic energy emitted by the source in high-energy neutrinos (TeV-PeV) are derived from the fluence limits and the luminosity distance provided by LIGO-Virgo:

$$E_{\nu,\mathrm{iso}} = \frac{4\pi D_L(z)^2}{1+z}\int_{E^{5\%}}^{E^{95\%}} E_\nu^{-2}\phi_0^{90\%} E_\nu \, dE_\nu$$

GW event	Redshift (z)	$E^{\mathrm{up}}_{5-95\%}$	$E^{\mathrm{down}}_{5-95\%}$	$E^{\mathrm{up}}_{\nu,\mathrm{iso}}$ [erg]	$E^{\mathrm{down}}_{\nu,\mathrm{iso}}$ [erg]
GW170608	$0.07^{+0.02}_{-0.02}$	2.5 TeV–4.0 PeV	20 TeV–25 PeV	2.2×10^{53}	2.9×10^{53}
GW170729	$0.48^{+0.19}_{-0.20}$	3.2 TeV–4.0 PeV	32 TeV–25 PeV	1.2×10^{55}	2.6×10^{55}
GW170809	$0.20^{+0.05}_{-0.07}$	3.2 TeV–4.0 PeV	8 TeV–20 PeV	1.2×10^{54}	1.5×10^{54}
GW170814	$0.12^{+0.03}_{-0.04}$	2.5 TeV–5.0 PeV	–	4.8×10^{53}	–
GW170818	$0.20^{+0.07}_{-0.07}$	–	20 TeV–32 PeV	–	1.1×10^{55}
GW170823	$0.34^{+0.13}_{-0.14}$	4.0 TeV–4.0 PeV	20 TeV–25 PeV	5.7×10^{54}	1.9×10^{55}



The Astrophysical Journal, 870:134, 2019

O1: ANTARES+IceCube

- LIGO O1: September 2015 – January 2016
- 23 C1 events, 23 C2/C3 events (these have higher chance of astrophysical origin). FAR ~ 0.5/day for each group
- Focus on candidate events whose astrophysical origins could not be determined from a single messenger
- IceCube: muon tracks
- ANTARES: up-going muon track (cuts for 3σ with one event)
- Time window: ± 500 s

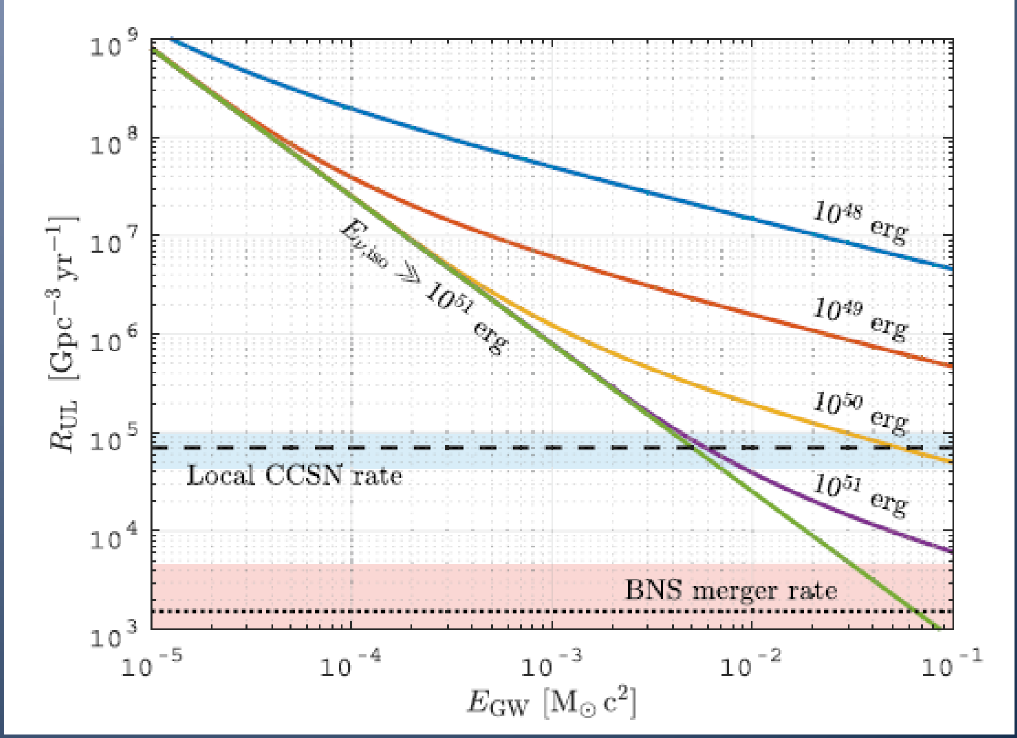
The Astrophysical Journal, 870:134, 2019

O1: ANTARES+IceCube

- 42 of the 46 GW event candidates had temporally coincident neutrino candidates for IceCube (195 coincident neutrinos). No coincidence for ANTARES → All consistent with background expectations
- Constraints on the rate density of astrophysical sources emitting GW + neutrinos

$$R_{\mathrm{UL}} = \frac{3.9 f_{\mathrm{b}}}{T_{\mathrm{obs}}} \left[\int_0^\infty 4\pi r^2 p_{\mathrm{det}}\, dr \right]^{-1}$$

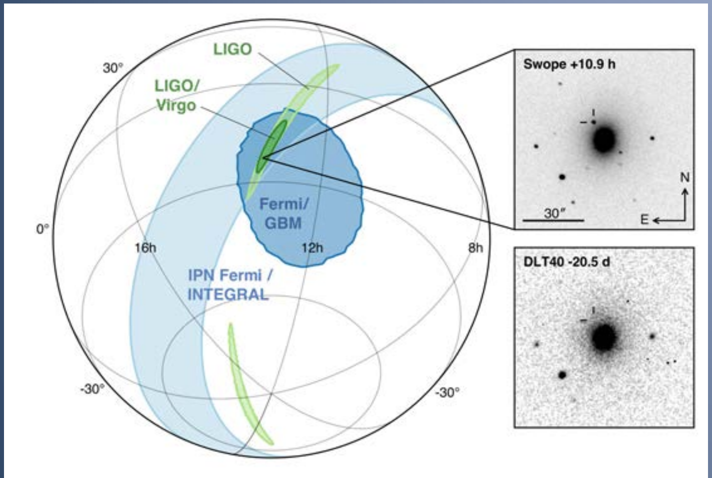
where $f_b(1 - \cos q_j)^{-1}$ is the neutrino emission's beaming factor for jet-opening half-angle θ_j, and p_{det} is related to the probability to be detected in coincidence by the detectors (see original reference)



ApJL 848 L12 (2017)

ApJL 850 L35 (2017)

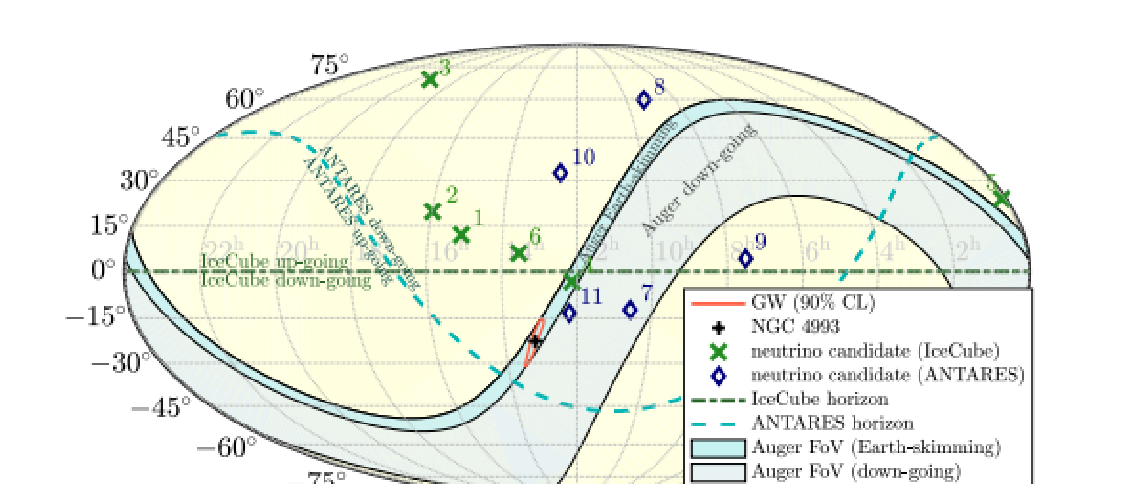
GW170817 (NS-NS)



GW170817 (neutron star merging at 40 Mpc): Correlation with electromagnetic counterparts observed (GRB)

Search for neutrinos time window of ±500 s:

- ANTARES: 5 events, NO time+space coincidences.
- IceCube: 6 events, NO time+space coincidences.
- Auger: 0 events



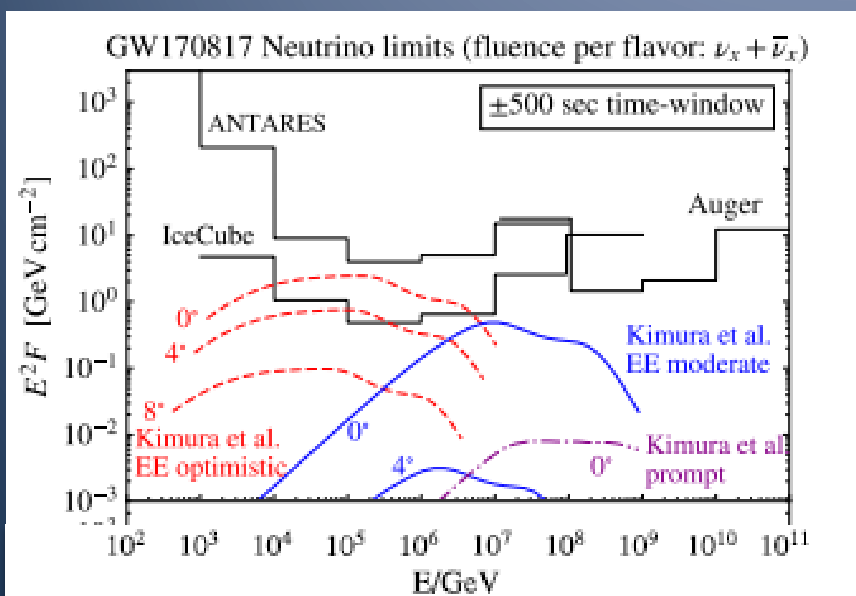
Event skymap

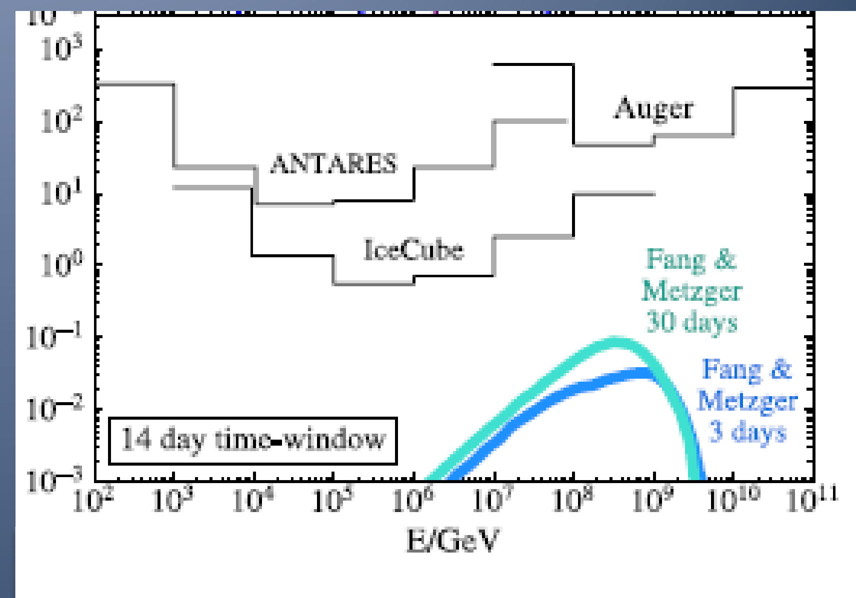
ApJL 848 L12 (2017)

ApJL 850 L35 (2017)

GW170817

- Limits on the fluence set for two time windows
- Constraints set on the viewing angle of the jet axis for prompt emission (optimistic) models



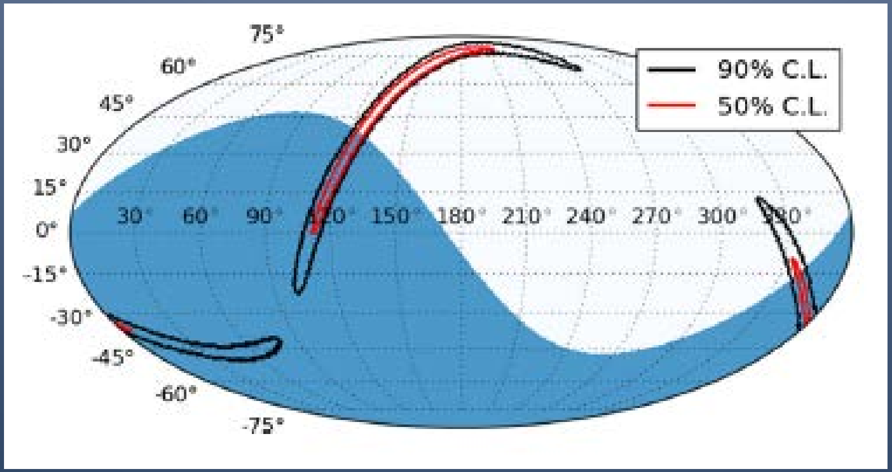


Eur. Phys. J. C (2017) 77:911

GW170104 (BH-BH)

- Originated by coalescence of two black holes (O2 run)
- Presence of accretion disk to excluded, so neutrino production is possible if there is hadronic particle acceleration in the jets
- GCN#20370 sent in less than 24 hours (only realtime neutrino follow-up related to this event)
- All sky search performed
- Two time windows used:
  - ±500 s
  - ± 3 months

No correlation was found

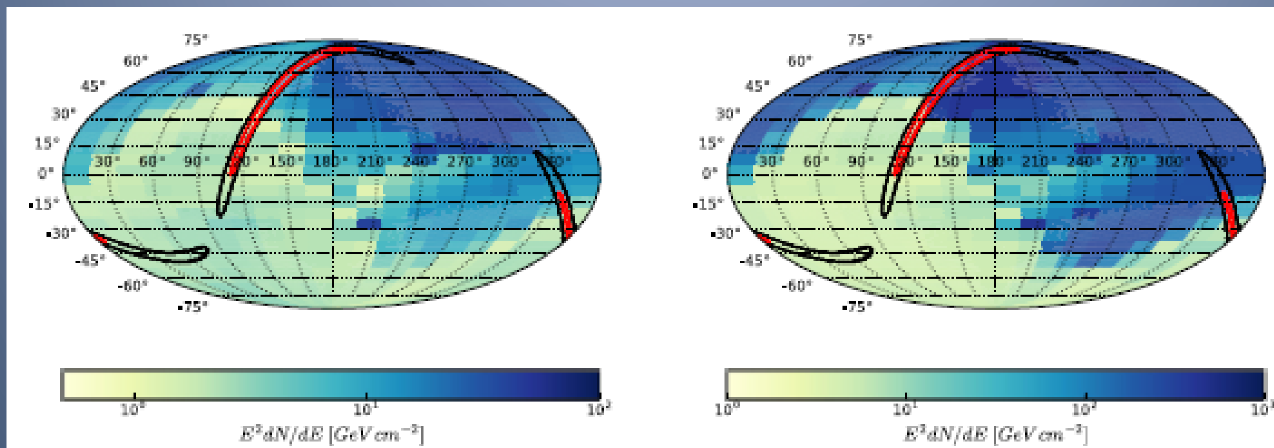


Eur. Phys. J. C (2017) 77:911

GW170104 (BH-BH)

All-sky upper limits on spectral fluence and energy radiated in ν for two spectra:

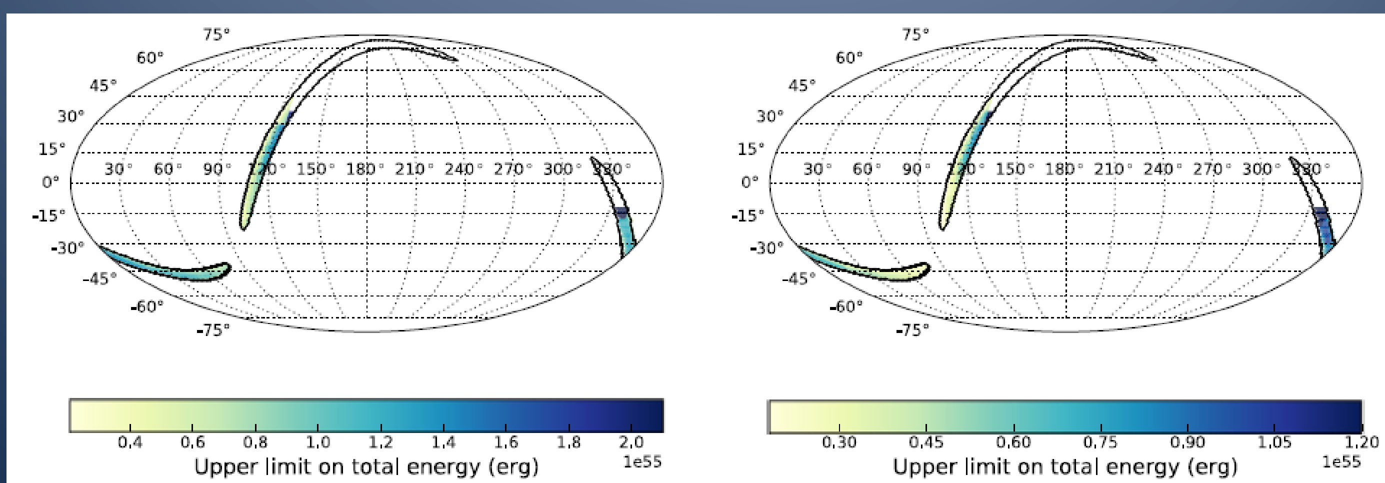
fluence



$$dN/dE = \phi_0 E^{-2}$$

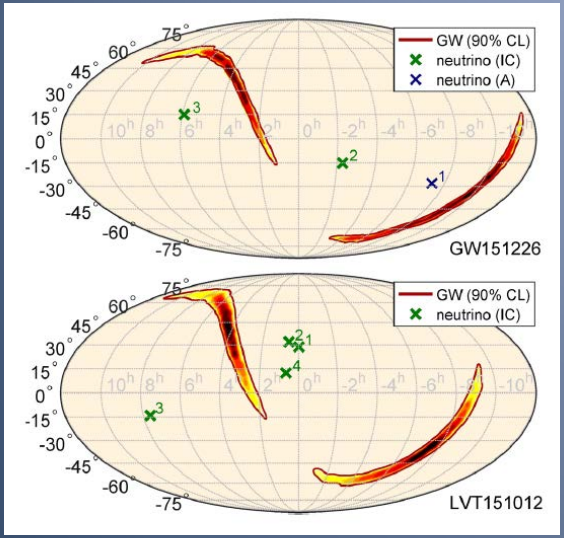
$$dN/dE = \phi_0 E^{-2} \exp\left[-\sqrt{(E/100\mathrm{TeV})}\right].$$

energy emitted in neutrinos



Phys. Rev. D 96, 022005 (2017)

GW151226 and LTV151012



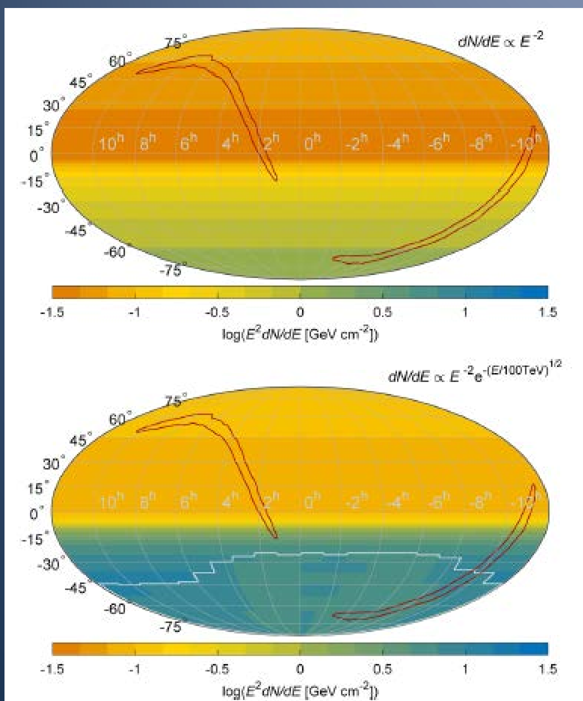
- Two more BBH mergers after discovery of GW150914
- Follow up searches increase sensitivity for subthreshold events
- Joint search for correlations with ANTARES and IceCube
- Serch in ±500 s window

Event	No.	Detector	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\mathrm{rec}}$ [°]	E_μ^{rec} [TeV]
GW151226	1	ANTARES	−387.3	16.7	−28.0	0.7	9
GW151226	2	IceCube	−290.9	21.7	−15.1	0.1	158
GW151226	3	IceCube	−22.5	5.9	14.9	0.7	6.3
LVT151012	1	IceCube	−423.3	24.0	28.7	3.5	0.38
LVT151012	2	IceCube	−410.0	0.5	32.0	1.1	0.45
LVT151012	3	IceCube	−89.8	7.7	−14.0	0.6	13.7
LVT151012	4	IceCube	147.0	0.6	12.3	0.3	0.35

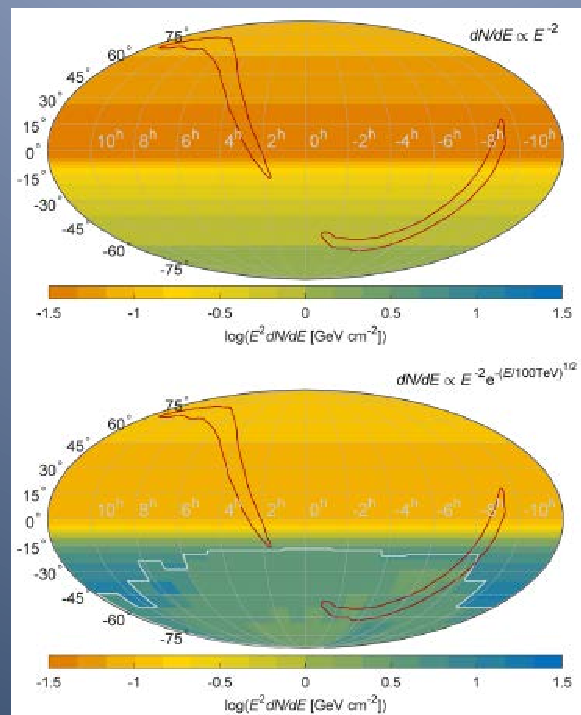
Phys. Rev. D 96, 022005 (2017)

GW151226 and LTV151012

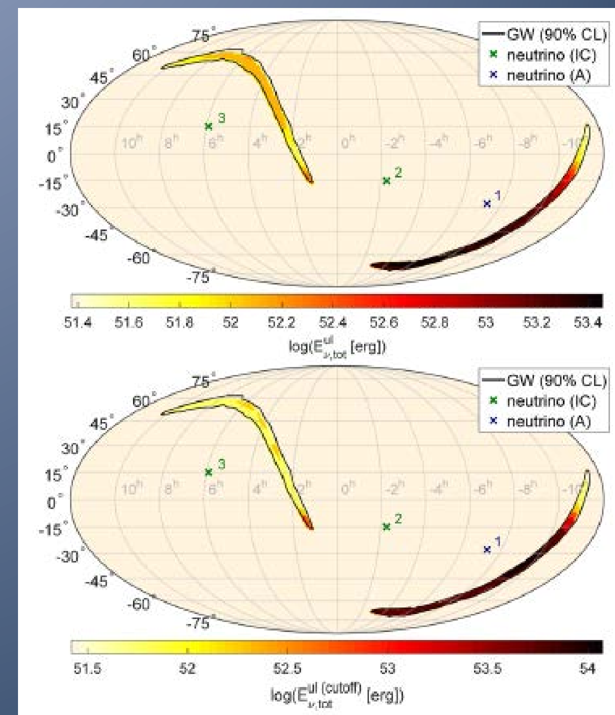
- No time-space coincidence found → upper limits
- Limits on GW151226 ~2x10^{51} – 2x10^{54} erg in total neutrino emission



Upper limits on spectral neutrino fluence for GW151226



Upper limits on spectral neutrino fluence for LVT151226



Upper limits in total energy radiated in neutrinos for GW151226 for both spectra

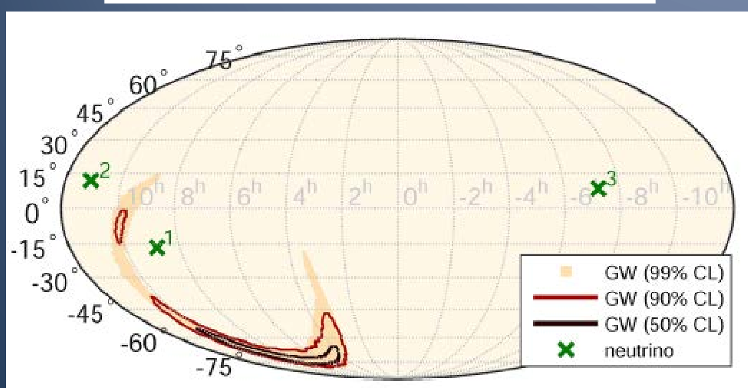
Phys. Rev. D 93, 122010 (2016)

GW150914

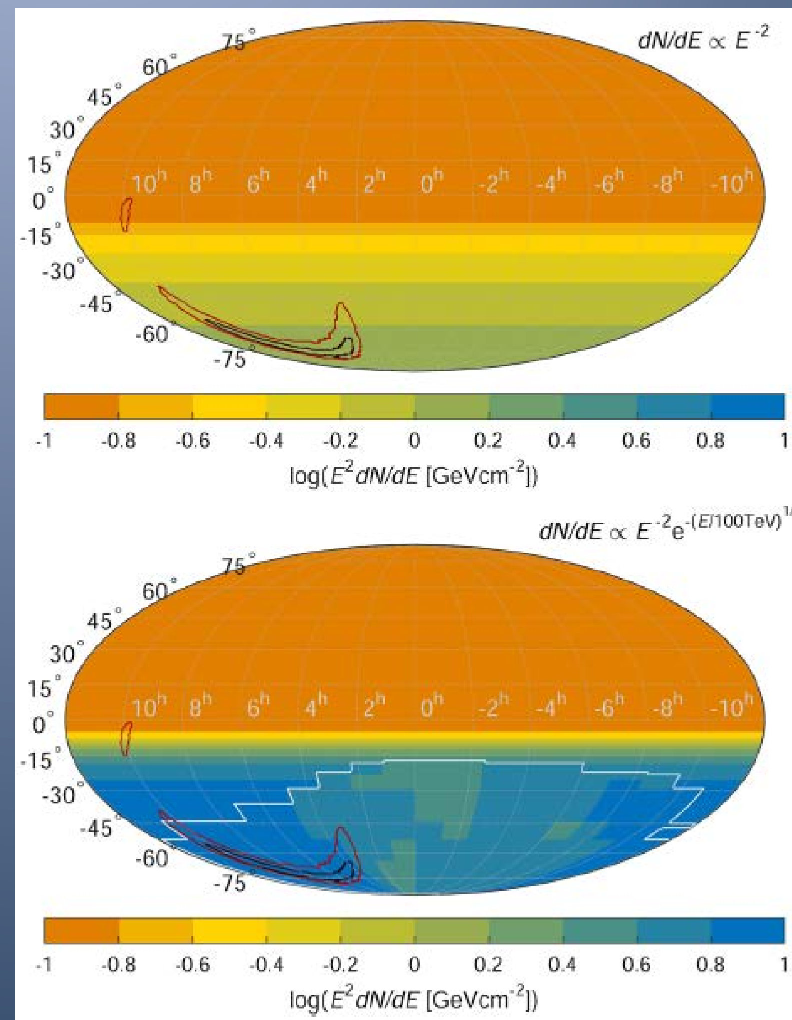
- First GW detected
- Reconstructed mass ~ 30 M_o
- 90% CL area 610 deg^2

$$E^{ul}_{\nu,tot} = 5.4 \times 10^{51} – 1.3 \times 10^{54} \text{ erg}$$

$$E^{ul(cutoff)}_{\nu,tot} = 6.6 \times 10^{51} – 3.7 \times 10^{54} \text{ erg}$$



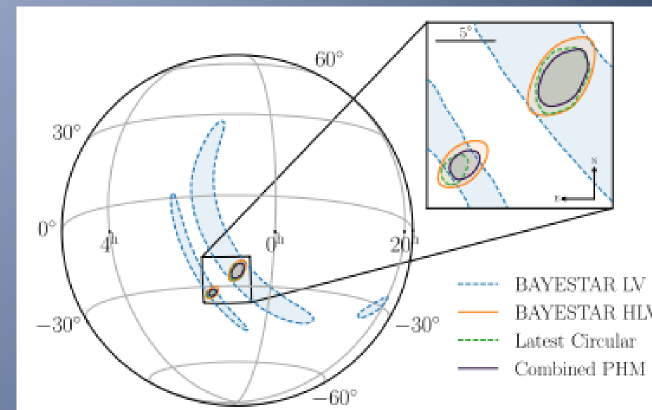
No.	ΔT [s]	RA [h]	Dec [°]	σ^{rec}_{μ} [°]	E^{rec}_{μ} [TeV]	Fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%



News from O3

The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20
https://doi.org/10.3847/2041-8213/ab960f

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

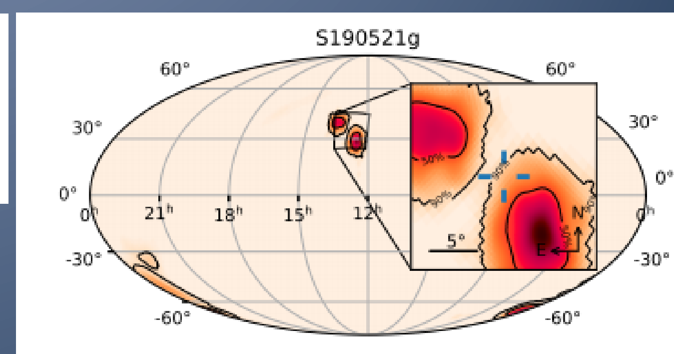


BH + object in mass gap
Distance: ~200 Mpc
Below the ANTARES horizon: upgoing!
Well localized (no counterpart observed)

PHYSICAL REVIEW LETTERS 124, 251102 (2020)

Editors' Suggestion   Featured in Physics

Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*

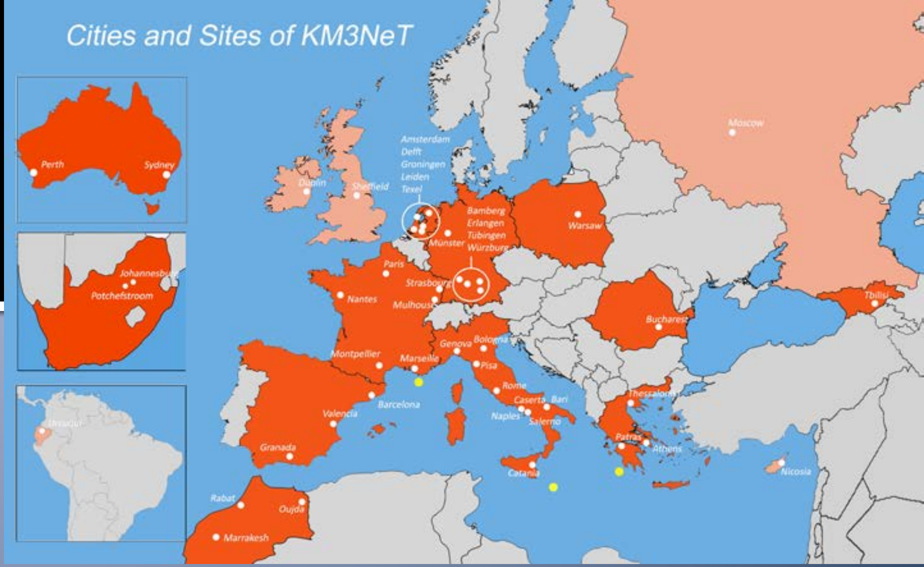


BBH merger
It could be located close to an AGN
Potential EM counterpart (26 days after GW)
Downgoing for ANTARES

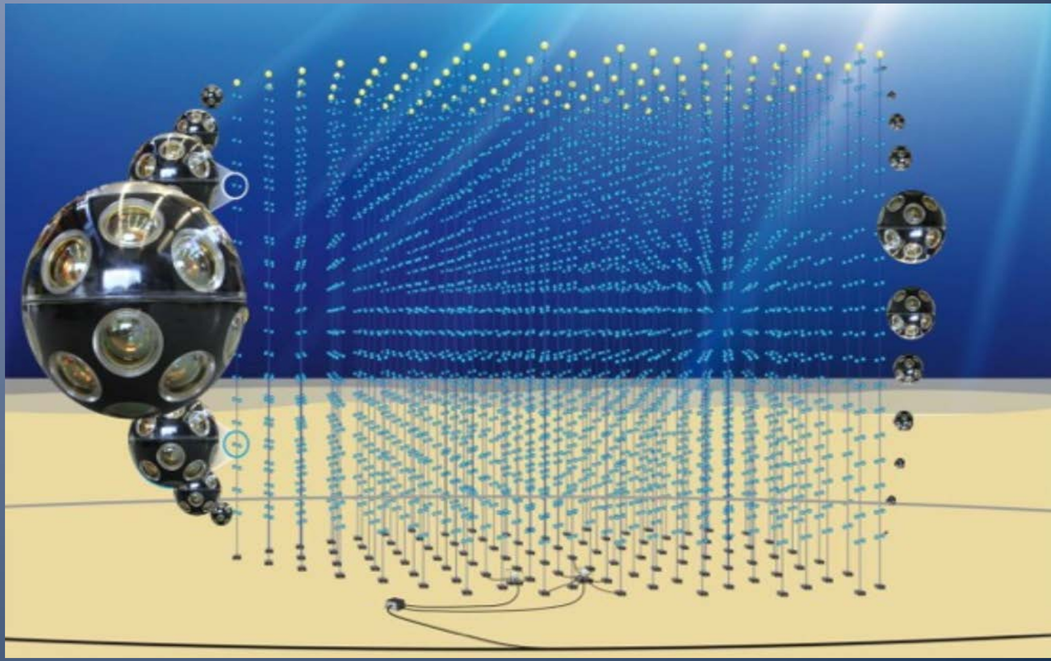
Analysis prepared: waiting for unblinding

KM3NeT

KM3NeT



- KM3NeT is a common project to construct neutrino telescope in the Mediterranean with an instrumented volume of several cubic kilometers
- It will also be a platform for experiments on sea science, oceanography, geophysics, etc.
- ~60 institutes and groups of Astroparticle Physics and Sea Science from 18 countries are involved
- New groups are very welcome!



Letter of Intent: J. Phys. G: Nucl. Part. Phys. 43 084001 (2016), arXiv:1601.07459

Phases, status and plans

PHASE 1:

- 30 lines (24 in Italy, 6 in France)
- Proof of feasibility and first science results

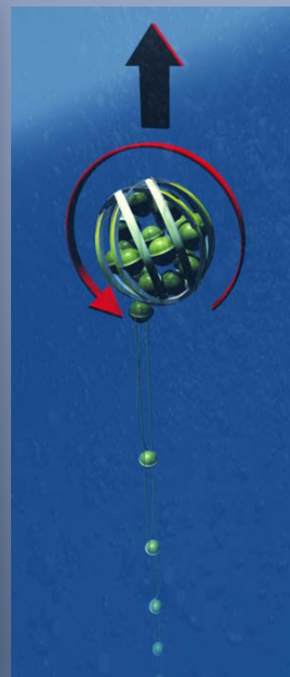
Physics starts as soon as a few lines are deployed…
=NOW!

ORCA: 6 lines installed, taking data; 29L built (most deployed) by end of 2021
ARCA: 2 lines depolyed; 24L deployed by end of 2021





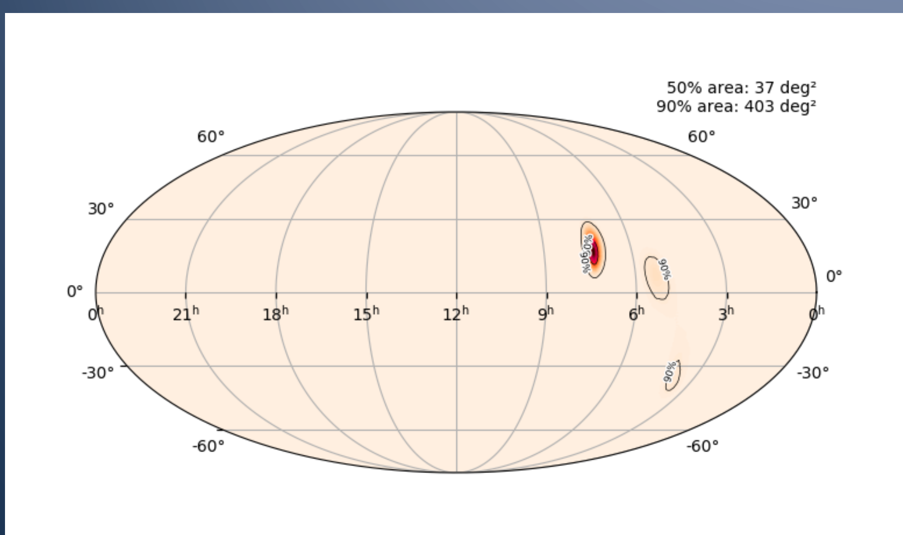
First KM3NeT lines installed and taking data



First results with KM3NeT: S200114f

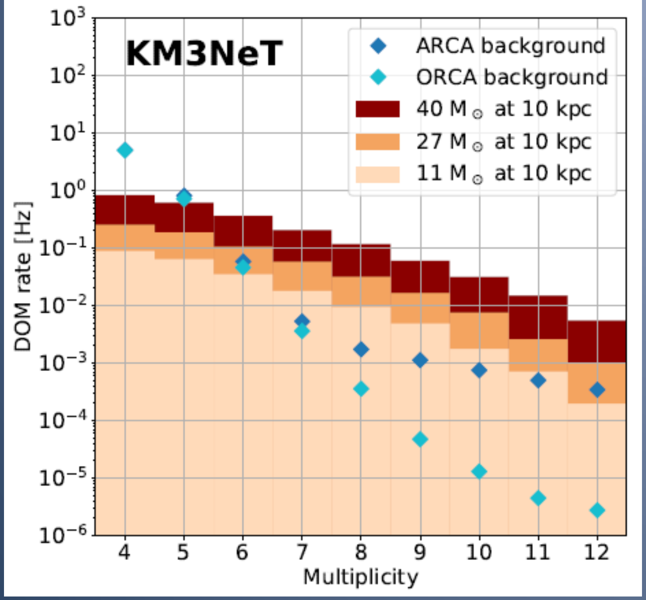
- Event: burst S200114f
- GCN GCN #26734
- Date: November 10th, 2019
- Detector: ORCA4

unmodelled GW trigger
→ CCSN candidate



https://gracedb.ligo.org/superevents/S200114f/view/

Detour: detecting Sne with NTs



Multiplicity = number of PMTs in a DOM detecting a photon in a 10 ns window

Looking for SN neutrinos with neutrino telesopes is <u>challenging</u>, in particular in the sea
Supernova neutrinos are of very low energy (~MeV)

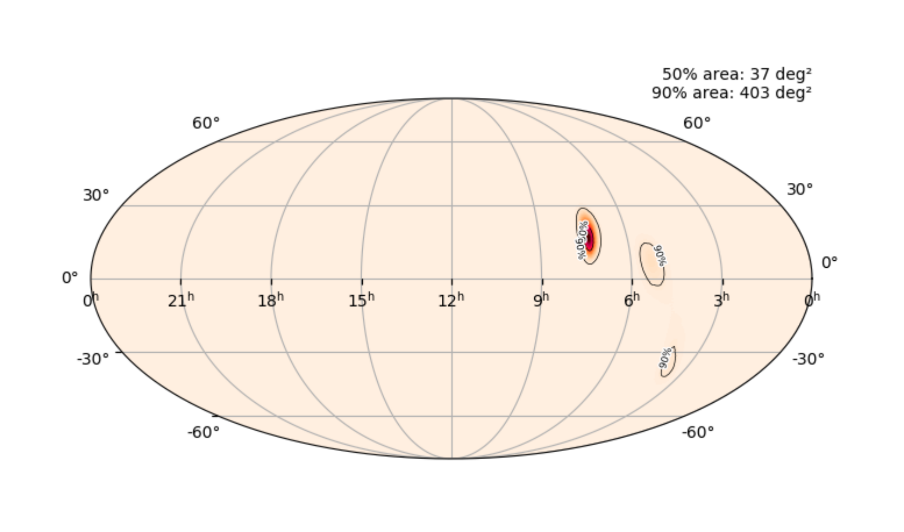
Strategy: look for an overall increase in coincidences in the DOMs

Background: K40, bioluminescence, atmospheric muons

First results with KM3NeT: s20014f

- Event: burst S200114f
- GCN GCN #26734
- Date: November 10th, 2019
- Detector: ORCA4

unmodelled GW trigger
→ CCSN candidate



Strategy: search for correlations of MeV neutrinos in 400 ms window after the trigger:

Two events observed
1.4 expected

→

p-value = 40%
(GCN #26751)

https://gracedb.ligo.org/superevents/S200114f/view/

s20014f

Marta Colomer's PhD thesis,
U. Paris – U. Valencia, 2020

- Assuming CCSN Garching flux models, we can derive the expected signal (S_0) and therefore we can contrain parameters in case of non-observation:

$$D^{90\%} = (10\text{kpc}) \times \sqrt{\frac{S_0}{S_{90\%}}}$$

Progenitor	$d_{90\%}$ [kpc] (lower limit)	Galactic coverage
11 $M_\odot$	6.1	10-15%
27 $M_\odot$	11.5	∼65%
40 $M_\odot$	21	∼98%

- We can also derive limits in the total energy emitted in neutrinos:

$$\boxed{E^{tot}{}_{\nu}(90\%) = 2.9\ 10^{53}\ \text{erg}}$$

(assuming quasi-thermal distribution with $<E\nu>$=15 MeV, α=3, d=10 kpc)

Summary

- Neutrino telescopes and gravitational wave detectors are the new kids on the block in the multi-messenger era
- Several analyses with ANTARES data looking for correlations already published
- Waiting for O3 catalogue, keeping an eye on published alerts
- First lines of KM3NeT are taking data and have joined the team, with first follow ups already done
- Interesting times ahead

Thanks for your attention!