Joint Search between a Gravitational-wave Detector Network and High-Energy Neutrino Detectors

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Possible Sources - Examples

GRBs - Collapsars

Gamma-Ray bursts (GRBs) are thought to be produced by the dissipation of the kinetic energy of relativistic expanding fireballs from energetic cosmic explosions [1]. Fireballs [2] - the relativistic outflows or jets of magnetized plasma, are created when the central engine releases a large amount of energy over a short time and small volume [3]. These jets are powered by the gravitational energy released during mass accretion onto the central black hole.

In the collapsar model, the iron core of a massive star slowly grows until it reaches its effective Chandrasekhar mass, when it becomes gravitationally unstable, resulting in core-collapse. Upon compression to nuclear densities, the equation of state stiffens and the core bounces back, starting a hydrodynamic shock wave. A relativistic jet is emitted along the rotational axis of the star due to the accretion disk formed after the iron core of the massive star progenitor collapsed [5]. This relativistic outflow breaks through the stellar envelope to produce a GRB [6]. Core-collapse that takes only a few milliseconds liberates a large amount of gravitational energy, a part of which is emitted in the form of a short gravitational wave transient.

Artist's impression of a gamma-ray burst. Credit: ESO/A. Roquette (http://www.scitech.ac.uk/resources/image/jpg/GammaRayBurst.jpg)

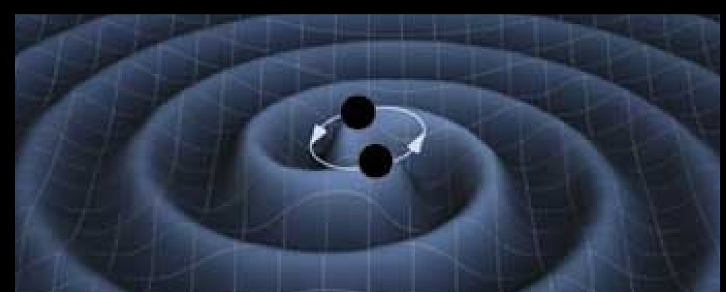
Core-collapse that takes only a few milliseconds liberates a large amount of gravitational energy, a part of which is emitted in the form of a short gravitational wave transient. Gravitational wave transients can originate from core collapse and bounce, or other mechanisms including rotational non-axisymmetric instabilities, post-bounce convection, standing-accretion-shock instability (SASI), or non-radial PNS pulsation.

High energy neutrino production - Variability in the central engine's output results in fluctuations of the plasma outflow, creating internal shocks in the relativistic ejecta, that results in the dissipation of kinetic energy. Dissipation in internal shocks reconvert a substantial part of the kinetic energy into internal energy. This internal energy accelerates electrons and protons in the outflow through the process of Fermi acceleration. Shock-accelerated electrons radiate their energy away through synchrotron and inverse-Compton radiation [17], emitting γ-rays. These photons, being what we detect as a GRB, interact with the shock-accelerated protons of the fireball outflow's shock region. These pγ interactions produce pions [1] and high energy neutrinos (HENs) through leptonic decay $(\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu)$. Theoretical models of HEN production estimate that more than about 10% of the energy of fireballs is converted to ~10^{14} eV neutrinos [1]. In a km^3 detector, such as IceCube, 10-100 detections is expected every year from GRB high energy neutrinos, while a nearby GRB would produce a burst several neutrino events [1].

Upon the initial stage of the collision of the fireball with the surrounding medium, a reverse shock occurs, accelerating electrons backward into the ejecta. These electrons will emit lower energy (UV/optical) photons [20]. If protons are accelerated in the GRB's to 10^{20}eV energies [20], they will interact with the UV/optical photons, creating ultra high energy neutrinos of 10^{18}eV. Neutrinos with such energies are also detectable with HEN detectors, and can provide important information on the engines GRBs.

GRBs - Binary Mergers

Compact star mergers are systems of black hole and neutron star binaries with decaying orbits from loss of energy and angular momentum due to the radiation of gravitational waves [11]. They are expected to emit most of their gravitational wave output at the very last stage of their merger when the two objects are close to each other. This last stage is typically order of seconds long, and it is likely to be responsible for the prompt creation of fireballs, and therefore the GRB. The creation of high energy neutrinos is similar to the mechanism for collapsar GRBs.



An artist's representation of the burst of gravitational waves resulting from a merging pair of black holes. Credit: LIGO Scientific Collaboration (LSC) / NASA.

Failed GRBs

For very extended or slowly rotating stars, or if the outflow is extremely baryon-rich, the jet may be unable to break through the envelope, resulting in a so-called failed (or choked) GRB [21]. Failed GRBs emit high-energy neutrinos similarly to regular GRBs [21]. Baryon-rich jets might have HEN emission rates even higher than jets with lower baryon density. Failed GRBs might be far more abundant in the Universe than regular GRBs [21], making them a specifically exciting source in GW-HEN search.

Giant Flares from Soft Gamma Repeaters

According to the magnetar model, Soft Gamma Repeaters (SGRs) are strongly magnetized neutron stars with magnetic fields of up to 10^{15}G [13]. Occasionally, SGRs enter an "active" γ-ray transient period when they emit repeated, short (~0.1s) transients [14]. Active periods are followed by longer, quiet periods that can last for several years [15]. Rarely, SGRs emit a giant flare of intensity about a thousand times higher than typical transients [16]. Crusts inside the magnetar are subjected to strong, evolving magnetic stresses that result in starquakes when magnetic stresses cannot be further balanced by hydrostatic forces and elastic stresses in the crust. Starquakes might excite the neutron star's non-radial modes, resulting in GW emission [18]. Common bursts, as well as giant flares of SGRs are powered by decaying magnetic fields [19]. The spin-down power of the star accelerates protons to high energies, resulting in the production of high energy neutrinos, while the magnetic power produces photons seen in the transients.

An artist's rendering of a magnetar, a type of neutron star. (Image Credit: NASA, CXC, M. Weiss)

Coincidence Time Window

GRB Duration

In collapsars the lifetime of fireballs, and therefore the production of high energy neutrinos (HENs), is limited by the fall-back time of gas onto the black hole. This is thought to be comparable to the lifetime of the GRB [4]. While other HEN sources might exist, for the purposes of GW-HEN analysis we can define a practical upper limit for GRB duration (and HEN production) to be greater or equal than 95% of individual GRB durations. We obtain this using data from the fourth BATSE GRB catalog [12] (using the other BATSE catalogs gives similar results), that includes 1234 GRBs with duration information. As the measure of GRB durations, we use T90, the time interval in which the integrated counts from a GRB in the BATSE detector increased from 5% to 95% [12]. The obtained duration which is greater or equal than 95% of GRB durations as defined above is

$$t_{GRB} \sim 150 \text{ s}$$

Precursor Timing

Gamma ray bursts are sometimes preceded by fainter, softer electromagnetic emissions, so-called precursors. The origin, as well as the underlying mechanism of these precursors are yet unknown. They have been already detected for about 10-20% of GRBs [7, 8, 9], with some GRBs having multiple precursors. It is expected, however, that a higher percentage of GRBs are preceded by precursors, as many of these might be missed due to, e.g., beaming, low signal to noise ratio, the proximity of the precursor and the main event, or the definition of what is considered a precursor [7].

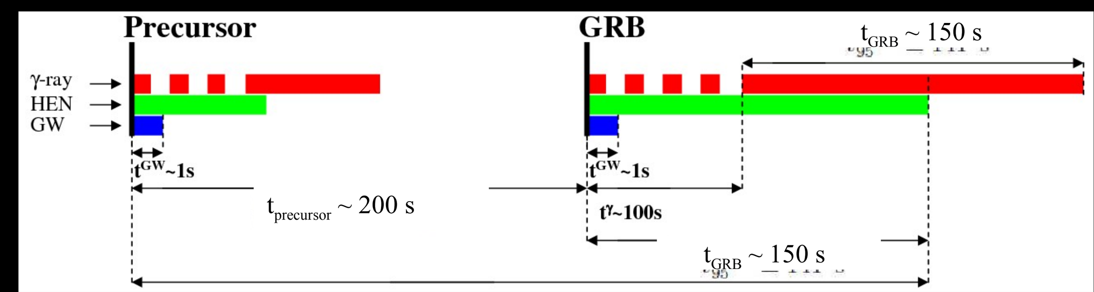
Burlon et al., using data from the SWIFT telescope [8] and BATSE [9], finds that precursors, on average, emit ~30% (for SWIFT) and ~10-20% (for BATSE) of the energy of the main burst. Burlon et al. find that precursors and main events have very similar spectral properties, concluding that precursors and main GRBs are likely to be produced by the same underlying mechanism.

For the purposes of GW-HEN analysis, we define a practical upper limit for the time difference between a precursor and the main GRB to be greater or equal than 95% of individual precursor-GRB time differences. We estimate this time delay using the results of Lazzati [10] of 31 precursors to be

$$t_{precursor} \sim 200 \text{ s}$$

Time Window between GW and HEN

The picture on the right shows the different components of the time delay between gravitational wave and high energy neutrino signals. Based on the available results, we cannot exclude the possibility of being able to detect GW, as well as HEN signals both from the precursor and the main GRB event. Therefore the time delay window $\Delta T_{GW\text{-}HEN}$ that one needs to consider for coincident data analysis, i.e. the maximum time delay of the GW signal compared to the HEN trigger is:



Estimated maximum time delays and durations of different processes within a GRB (with 95% confidence level).

$$\Delta T_{GW\text{-}HEN} \sim [-350\text{s}, 200\text{s}]$$

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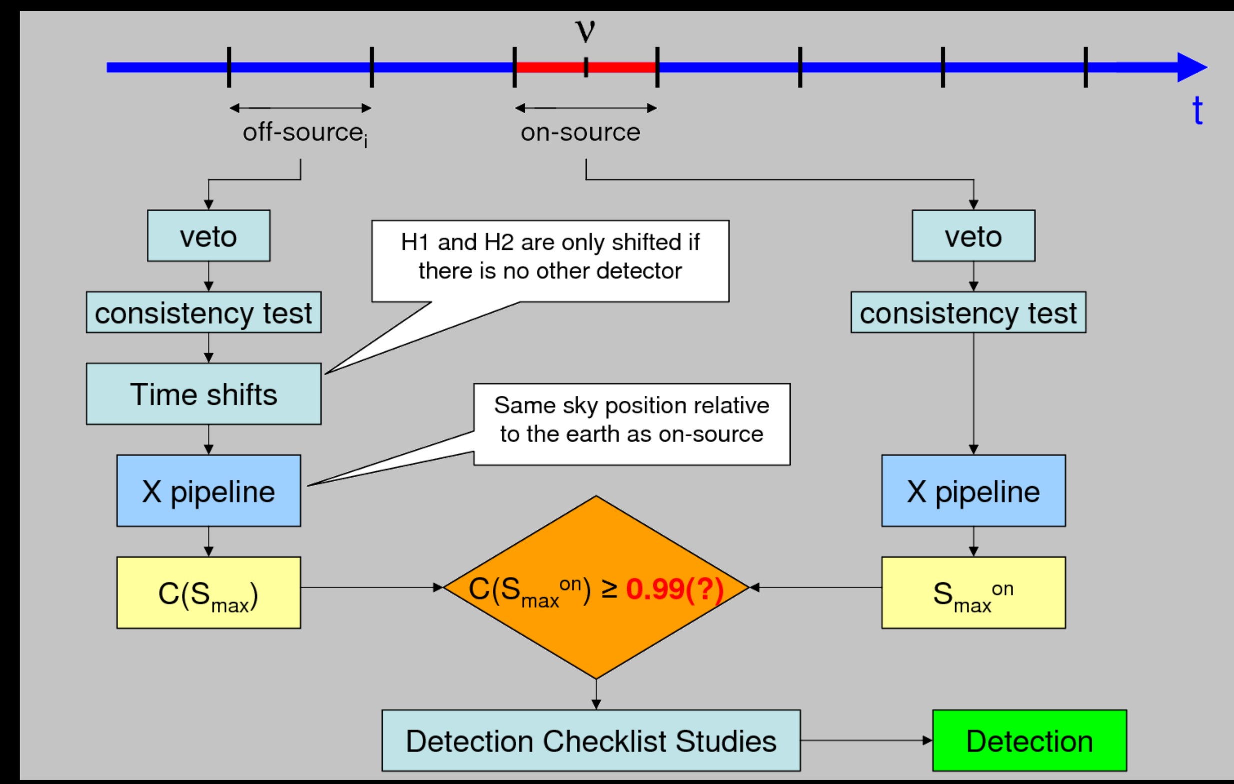
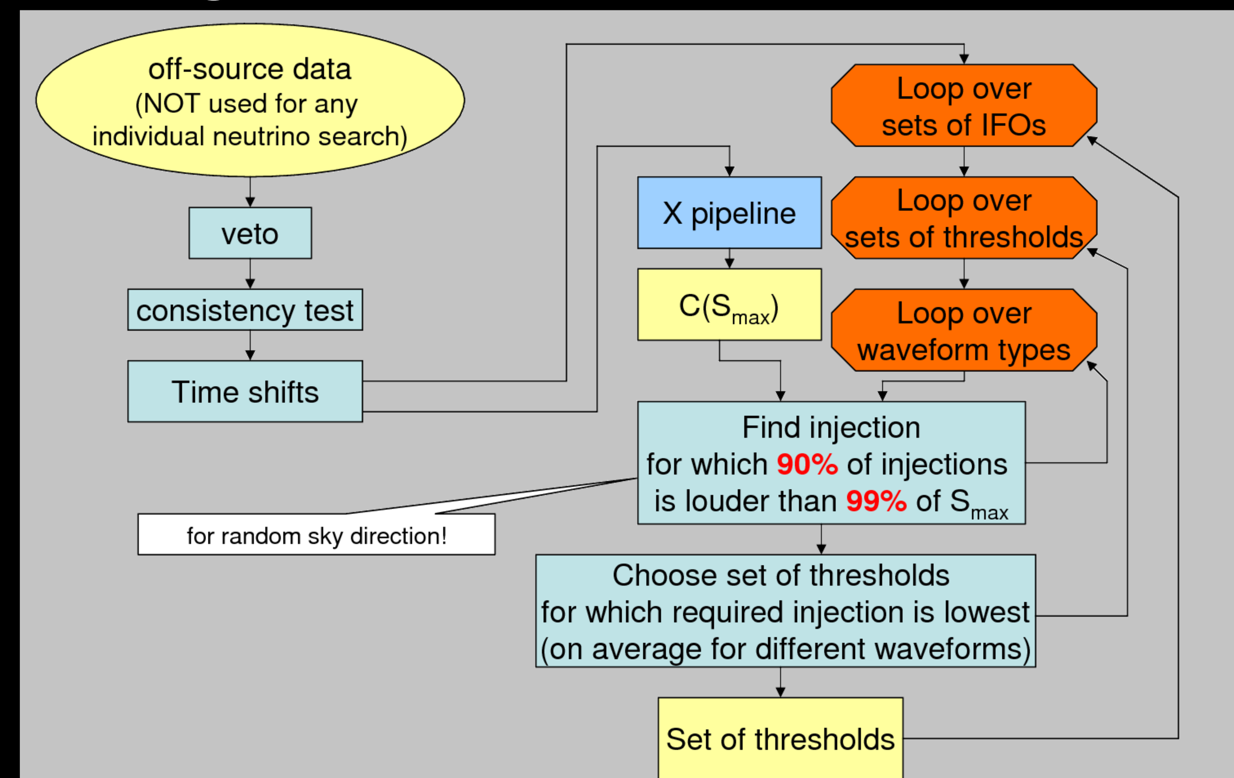
Possible Data Analysis

Coherent and coincident data analysis will be performed to the three gravitational wave (GW) and two high energy neutrino (HEN) detectors. A neutrino event from one of the HEN detectors, after filtered through the detectors quality cuts, can be used as a trigger for GW coherent searches. The GW event will be expected from the direction of the neutrino, while the allowed difference in arrival time is defined based on our theoretical/observational expectations (see section to the left). Coherent GW data analysis will be based on X-pipeline [17]. Below we present a flow diagram of a possible analysis pipeline from the point of receiving a HEN trigger to making a detection or obtaining upper limits. Note that the analysis parameters shown in red are subject to tuning.

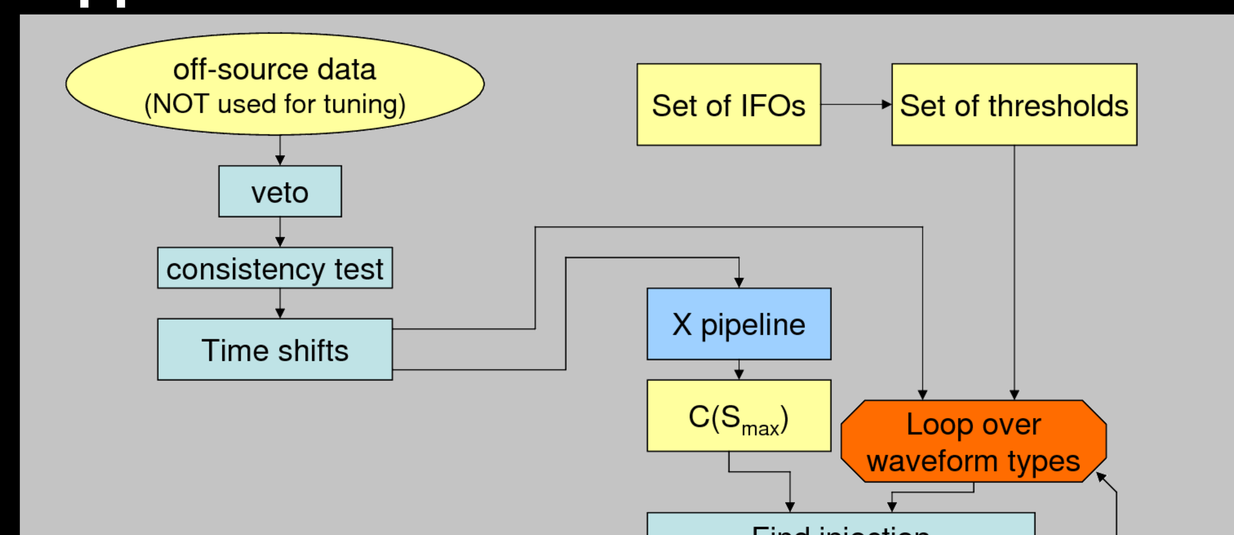
Detection Procedure



Tuning



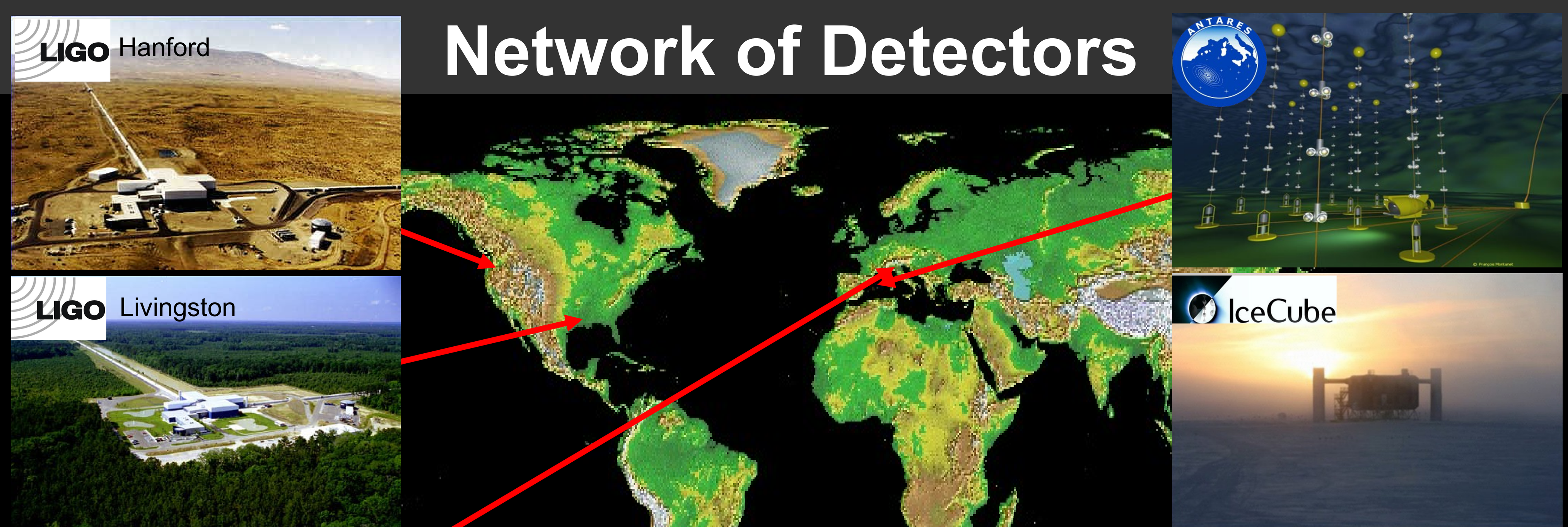
Upper Limit



Notation

X-pipeline - software package for the coherent analysis of data from networks of GW interferometers for detecting bursts
S_{max} – significance of loudest event
S_{max}^{on} – significance of loudest on-source event
$C(S_{max})$ – cumulative distribution function of S_{max}
IFO – interferometer (LIGO or Virgo)
H1 and H2 – LIGO Hanfrod 1 and 2 detectors

Network of Detectors



Gravitational wave observatories: LIGO Hanford and Livingston, and Virgo. High energy neutrino detectors: IceCube and Antares. Multiple GW detectors are important to increase sensitivity, also decreasing its direction dependence. The Antares and IceCube detectors are placed roughly on the opposite side of the globe to have complementary directional sensitivity. A common calendar of the detectors and their future upgrades is shown to the right.

Common Calendar

2007	LIGO Virgo S5/VSR1	ANTARES 5 strings	Ice Cube 22 strings
2009	eLIGO Virgo+ S6/VSR2	ANTARES 12 strings	Ice Cube 59 strings
2015	aLIGO adVirgo	Km3net ?	Ice Ray ?
~2020	Einstein telescope & LISA		

time

Detection Principles

The LIGO and Virgo gravitational wave detectors use suspended mirrors at the ends of kilometer-scale, orthogonal arms to form a power-recycled Michelson interferometer with Fabry-Perot cavities. A gravitational wave induces a time-dependent strain h(t) on the detector. While acquiring scientific data, feedback to the mirror positions and to the laser frequency keeps the optical cavities near resonance, so that interference in the light from the two arms recombining at the beam splitter depends on the difference between the lengths of the two arms.

Antares and IceCube are large area Cherenkov detectors placed deep in the Mediterranean Sea and under the ice at the geographic South Pole, respectively. They aim to detect high energy neutrinos with energies between 100 GeV and 100 TeV. These neutrinos, upon interacting with matter, create high energy muons. These muons emit Cherenkov light, which is detected using photomultipliers placed throughout the detector (see picture to the right). Cherenkov radiation enables the reconstruction of neutrino direction and energy. The effective surface areas of Antares and IceCube are 0.1 km^2 and 1 km^2, respectively. The main background of HEN detectors is atmospheric muons, that is largely filtered out by only detecting particles that came through the Earth.