Searching for high-energy neutrinos in coincidence with gravitational waves with the ANTARES and VIRGO/LIGO detectors

Véronique Van Elewyck (APC & Université Paris 7 Denis Diderot)

for the ANTARES Collaboration

& the GWHED working group

(also including members of IceCube, VIRGO and LSC)
**Motivations for GW+HEN astronomy**

- **Long-range messengers:** no interactions (or weak ones) with ambient matter
  no deflection by magnetic fields

- **Deep-source messengers:** carry information on the internal processes of the
  astrophysical engines, unaccessible through photons or hadrons

- **Plausible common sources:** galactic (SGRs) & extragalactic (GRBs: short, long,
  low-luminosity, choked,...)

- **Discovery potential for hidden/unknown sources**
  (difficult to detect through conventional photon/cosmic ray astronomy)

**Main requirements for joint GW/HEN detection:**

- massive, compact & relativistic objects
- sudden (< 1s)
- baryon loaded
- close & frequent enough
Usual suspects: long & short GRBs

The fireball model

Short-Hard GRBs: coalescing binaries involving BH and/or neutron stars. → GW associated to coalescence process (inspiral)

GW

Δt ~ few minutes?

HEN

The fireball model

GW

GW

HEN

Chirp

Long-Soft GRBs: associated to core-collapse supernovae (collapsars)

→ GW burst during collapse (unmodelled)

Faint ? (cosmologically distributed)

\[ p\gamma/\text{pp} \rightarrow \pi^\pm/K^\pm \rightarrow \mu^\pm, \nu_\mu \rightarrow e^\pm, \nu_\mu, \nu_e \]

HEN emitted in baryon-loaded jets during prompt (TeV-PeV) & afterglow (PeV - EeV) phases

Expected neutrino spectrum ~ \( E^{-2} \)
More (speculative) suspects among GRBs

Low-luminosity GRBs (llGRBs)
- γ-ray luminosity few orders of magnitude smaller
- Observational evidence for llGRB/SN connection
  → produced by a particularly energetic population of core-collapse SNe?
- larger event rate predicted in local universe

BUT mechanism debated, presence of jets is uncertain (Bromberg, Nakar & Piran, 2011)

Failed GRBs:
from mildly relativistic, baryon-rich and optically thick jets?
→ missing link between (long) GRBs and SNe?
(Ando & Beacom, 2005)

Choked GRBs:
successful jets unable to break through the stellar envelope?
(Eichler & Levinson, 1999; Mészáros & Waxman, 2001)

→ potentially strong HEN/GW emitters;
→ not (or difficultly) observable in photons
→ models poorly constrained and still debated
Bounding the GW-HEN time window

A case study: long GRBs

B. Baret et al., AstroPart. Phys. 35 (2011), 1-7

Observational benchmarks:
* γ-ray emission: $\Delta t \sim 150$ s based on the $t_{90}$ distribution in BATSE bursts (consistent with Fermi HE γ-ray emission)
* 10-20% of GRBs have precursors: $\Delta t_{\text{precursor}} \sim 250$ s from BATSE GRBs

**HEN emission** from internal shocks in relativistic outflow (also BEFORE it emerges from the stellar envelope, $\Delta t \sim 100$ s)

**GW emission** associated to the activity of central engine (BH ringdown + gravitational instabilities in accretion disk + ... )

connected to γ-ray emission
Bounding the GW-HEN time window

A case study: long GRBs

\[ \Delta t_{GW-HEN} \approx \pm 500 \text{ s} \]

Observational benchmarks:
- \( \gamma \)-ray emission: \( \Delta t \approx 150 \text{ s} \) based on the \( t_{90} \) distribution in BATSE bursts (consistent with Fermi HE \( \gamma \)-ray emission)
- 10-20% of GRBs have precursors: \( \Delta t_{\text{precursor}} \approx 250 \text{ s} \) from BATSE GRBs

\( \gamma \)-ray emission from internal shocks in relativistic outflow (also BEFORE it emerges from the stellar envelope, \( \Delta t \approx 100 \text{ s} \))

\( GW \) emission associated to the activity of central engine (BH ringdown + gravitational instabilities in accretion disk + ... )

\( HEN \) emission from internal shocks in relativistic outflow

\( \gamma \)-ray emission

Connected to \( \gamma \)-ray emission
Michelson interferometers:
suspended mirrors act as free test masses

- LIGO Hanford: 4 km (+ 2 km) arms
- LIGO Livingston: 4 km arms
- VIRGO (Pisa, Italy): 3 km arms

current sensitivity to GW amplitude

\[ h = \frac{\delta L}{L} \sim 10^{-21} \]
The detectors

Periods of concomitant data taking:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTARES KM3NeT</td>
<td>5L</td>
<td>10L</td>
<td>12L</td>
<td>KM3NeT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIRGO</td>
<td>VSR1</td>
<td>VS R2</td>
<td>VS R3</td>
<td>Advanced VIRGO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIGO</td>
<td>S5</td>
<td>S6</td>
<td>Advanced LIGO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

First generation:
GW horizon for standard binary sources
~ 15 Mpc (~1 binary merger/ 100 years...)
ANTARES 5 active lines

Recent upgrades (VIRGO+/eLIGO):
GW sensitivity ~ x 2 (expected)
Full ANTARES 12 lines, ~0.04 km$^3$ instrumented

Advanced detectors ~2015:
GW sensitivity x 10 → probed volume x 1000
(~ 1 Gpc$^3$ for BH mergers, ~ 40 mergers/yr)
KM3NeT: (few) km$^3$ instrumented volume
### The detectors

#### Periods of concomitant data taking:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTARES KM3NeT</td>
<td>5L</td>
<td>OL</td>
<td>12L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>KM3NeT</td>
</tr>
<tr>
<td>VIRGO</td>
<td>VSR1</td>
<td>VS R2</td>
<td>VS R3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Advanced VIRGO</td>
<td></td>
</tr>
<tr>
<td>LIGO</td>
<td>S5</td>
<td></td>
<td></td>
<td>S6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Advanced LIGO</td>
<td></td>
</tr>
</tbody>
</table>

**First joint analysis:**

104 days of concomitant data taking (Feb - Sept 2007)

**VIRGO + LIGO + ANTARES**
instantaneous sky coverage ~ 30%

(equatorial coordinates)
Joint search strategy

- **GW/HEN common challenge:** faint & rare signals on top of abundant noise or background events.
  
  general search methodology: combination of GW/HEN event lists + search for coincidences in predefined time windows (independent detectors → low combined False Alarm Rate)

- « HEN-triggered » search: HEN event list as an external input for GW burst search

- **on-source coincidence time window:** ± 500 s around HEN arrival time

- **GW spatial search box** defined by (event-by-event) HEN angular accuracy

- Closed-box analysis: parameters tuned on off-source, time-shifted GW data
Hit selection and reconstruction using **Bbfit: fast online algorithm**

- simplified detector geometry (straight lines, 1 OM at the center of each storey)
- reconstruction algorithm based on $\chi^2$ minimization (time residuals + charge distribution)

- ~20% contamination of misreconstructed upgoing atmospheric $\mu$'s in final sample
- degeneracy of events reconstructed with 2 lines:
  2 mirror tracks with same zenith, different azimuths
ANTARES HEN events

Skymap of HEN events:
(equatorial coordinates)

198 events (x2)
18 events

Among them:
59 events with 1 or 0 IFO
29 events with 2 IFOs
65 events with 3 IFOs
63 events with 4 IFOs

157 exploitable events for a GW coherent search
HEN event information

- time
- direction
- angular accuracy
- energy estimators ($N_{\text{lines}}, N_{\text{hits}}$)

HEN-triggered GW search using X-pipeline:
analysis chain looking for unmodelled GW bursts from external triggers (e.g. GRB alerts)

- closed-box (blind) analysis: background estimation & parameter tuning on off-source region

- gain in efficiency w.r.t. all-sky untriggered searches: factor 2.5 (4) at 50% (90%) C.L.

...heavy computational cost: 1 month for $O(100)$ neutrinos
Triggered GW search

- Hanford + Livingston + Virgo data streams coherently combined → time-frequency maps
- Frequency cutoff for GW signal: 500 Hz
+ Additional HF search (500 Hz – 2 kHz) for HEN events with $N_{\text{lines}} = 3$
- Assume known direction of signals → known delay between IFOs
- Define event-by-event angular search window → weighted scan using log-normal parameterization of HEN PSF (in bins of declination & $N_{\text{hits}}$)

Size = 90% quantile of reconstructed space angle
(mirror tracks are processed together)
Triggered GW search

Analysis of time-frequency maps obtained from combining IFOs data streams:
- optimize thresholds using off-source background + injected template GW signals

Inspiral (binary merger)
NS(1.35 \, M_\odot) - NS(1.35 \, M_\odot)
or NS(1.35 \, M_\odot) - BH (5 \, M_\odot)

Sine-gaussian
(generic, possibly core-collapse ?)
100 Hz → 1000 Hz

- estimate significance of on-source events by comparing to expected off-source distribution
  - amplitude upper limits
  - exclusion distances
Coincident search results

Search for a cumulative excess: binomial test

accounts for trial factor due to the large sample of tested HEN triggers:

1) compute GW false alarm probability (p-value) for each HEN trigger
2) sort by loudest event (→ by smallest p-value)
3) for the loudest 5% of events: compute binomial cumulative probability 
   \[ P_{\geq i}(p_i) \]: that i or more events have a p-value smaller than \( p_i \)
4) compare to null hypothesis (uniform distribution of p-values)

LF (60-500 Hz) search:

no significant excess found

(largest deviation from null hypothesis: occurs in 64% of pseudo-experiments under same background conditions)
Coincident search results

Search for a cumulative excess: binomial test
accounts for trial factor due to the large sample of tested HEN triggers:

1) compute false alarm probability (p-value) for each HEN trigger
2) sort by loudest event (→ smallest p-value)
3) for the loudest 5% of events: compute binomial cumulative probability
   \[ P_{\geq i}(p_i) \]: that i or more events have a p-value smaller than \( p_i \)
4) compare to null hypothesis (uniform distribution of p-values)

HF (500-2000 Hz) search:

no significant excess found

(largest deviation from null hypothesis:
occurs in 66% of pseudo-experiments under same background conditions)
Exclusion distances

Estimate the detection horizon for each injected GW template signal:

1) vary the amplitude of injected signal
2) determine the threshold amplitude for producing, in 90% of the cases, a louder event than observed in data
3) convert amplitude → distance:

**Typical GW horizon ~ 5-10 Mpc**
*Typical HEN horizon ~ 4 Mpc*

**Typical GW horizon ~ 5-20 Mpc**
*Typical HEN horizon ~ 12 Mpc*
Conclusions and perspectives

First joint search for HEN and GW performed with (sub-optimal) detectors ANTARES 5L + LIGO S5 + VIRGO VSR1:
   No evidence for coincident events found

Common sources of GW and HEN are likely to exist!
combined GW+HEN observations can provide new constraints on astrophysical mechanisms:

\[ N_{\text{GWHEN}} \leq 2.3 \text{ at 90\% C.L. in } T_{\text{obs}} = 104 \text{ days within } d_{\text{GWHEN}} \]

limits on the population density of joint GW+HEN emitters:

\textbf{Short GRB-like:} \quad \rho_{\text{GWHEN}} \leq 10^{-2} \text{ Mpc}^{-3} \text{ yr}^{-1}

...to be compared with estimated density of NS-NS mergers:
\[ \rho_{\text{NS-NS}} \approx 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1} \quad \text{(Kalogera et al. 2004 ; Belczynski et al. 2011)} \]

\textbf{Long GRB-like:} \quad \rho_{\text{GWHEN}} \leq 10^{-3} \text{ Mpc}^{-3} \text{ yr}^{-1}

...to be compared with estimated density of Type II/Ibc core-collapse SN:
\[ \rho_{\text{SNII}} \approx 2 \times 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1} \quad \text{(Bazin et al. 2009)} \]
\[ \rho_{\text{SNIbc}} \approx 2 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1} \quad \text{(Guetta & Valle 2007)} \]
Conclusions and perspectives

First joint search for HEN and GW performed with (sub-optimal) detectors ANTEARES 5L + LIGO S5 + VIRGO VSR1: No evidence for coincident events found

Common sources of GW and HEN are likely to exist! combined GW+HEN observations can provide new constraints on astrophysical mechanisms:

\[ N_{\text{GWHEN}} \leq 2.3 \text{ at } 90\% \text{ C.L. in } T_{\text{obs}} = 104 \text{ days within } d_{\text{GWHEN}} \]

limits on the population density of joint GW+HEN emitters:

Short GRB-like: \( \rho_{\text{GWHEN}} \leq 10^{-2} \text{ Mpc}^{-3} \text{ yr}^{-1} \) requires 10x increase in \( d_{\text{GWHEN}} \)

...to be compared with typical rate of NS-NS mergers:
\[ \rho_{\text{NS-NS}} \approx 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1} \] (Kalogera et al. 2004 ; Belczynski et al. 2011)

Long GRB-like: \( \rho_{\text{GWHEN}} \leq 10^{-3} \text{ Mpc}^{-3} \text{ yr}^{-1} \) requires 2x increase in \( d_{\text{GWHEN}} \)

...to be compared with typical rate of Type II/Ibc core-collapse SN:
\[ \rho_{\text{SNII}} \approx 2 \times 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1} \]
\[ \rho_{\text{SNIbc}} \approx 2 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1} \] (Bazin et al. 2009) (Guetta & Valle 2007)
Conclusions and perspectives

Next step: 2009-2010 concomitant data sample
ANTARES 12L + LIGO S6 + VIRGO VSR2-3

- Larger detectors: ~x2 in nominal sensitivity
- Improved HEN reconstruction strategy (no doublets, sub-degree angular resolution)
- New GW pipeline: cWB: coherent Wave Burst (all-sky coherent search algorithm)
  + time window $\Delta t = \pm 500s$
  + skymask provided by the HEN angular search window:
    - lower computational cost (O(1000) neutrinos)
    - allows to constrain direction for data analyzed with 2 ITF

Joint optimisation of the selection cuts based on a fixed rate of accidental coincidences (or False Alarm Probability)

time to probe astrophysical models of source populations (e.g. long/choked GRBs)?
Stay tuned for the outcome of the analysis!