The joint search for Gravitational Wave and Low Energy Neutrino signals from Core-Collapse Supernovae

Methodology and Status report

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on behalf of
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Motivation

0) The discovery of gravitational waves (GW) by the LIGO project
1) The registration of GW is a new method for the study of astrophysical objects/phenomena
2) Investigation of processes with different types of radiation
   - Complementarity in the study of a particular object/phenomenon
   - Clarifying the GW properties and mechanisms of their generation
   - Increase confidence in detection and reliability of data
   - Usage of any kind of radiation as a marker pointing to a specific astrophysical phenomenon
3) Neutrinos and gravitational waves have a few similar properties
   - ν and GW aren't virtually distorted with interstellar matter
   - Propagate with almost the same speed ($v = c$)

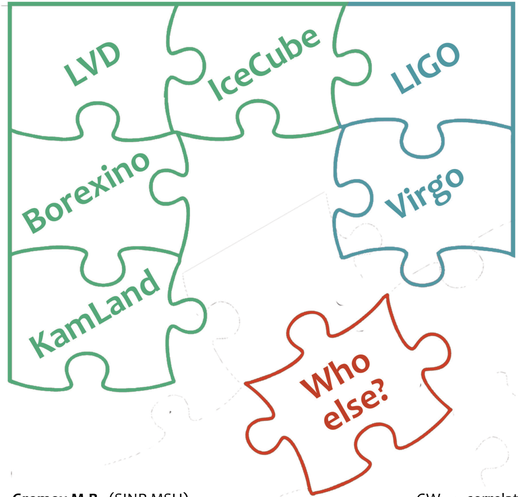
The possibility to investigate processes in very compact and massive objects

Main goal:

Search and investigation of supernova explosions in the Local Group

Participants

GWNU is a working group (not a collaboration)
to search for correlations in the data of the GW and ν experiments



The end of 2014
The beginning of data exchange and development of the methodology

April 2016
KamLAND has officially joint to the group

General requirements

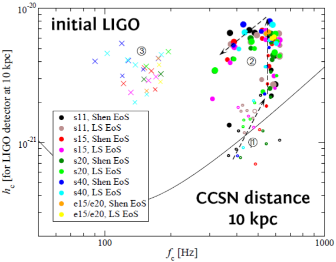
It's obvious that more detectors in the network means more reliable results and higher the chance to register a supernova. But there are some requirements which increase the probability of success:

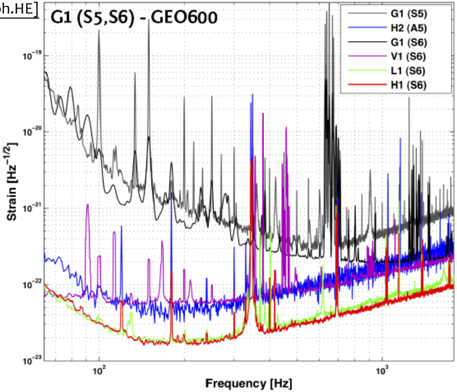
1) The GW and ν detectors must work **simultaneously**
   The duty cycles are not 100% and the low level of accidental coincidence is needed
2) More detectors means softer cuts, more information
3) It requires at least 3 GW detectors to determine the sky position [1] of the **Silent supernova** because the latter isn't observed with electromagnetic radiation (such SNe are behind the centres of galaxies for observers).

[1] Living Rev. Relativity 19 (2016), 1; arXiv:1304.0670v3 [gr-qc]

General requirements

Left: Class.Quant.Grav.26:063001,2009; arXiv:0809.0695v2 [astro-ph]
Right: Phys. Rev. D 89, 122004 (2014); arXiv:1405.1053v2 [astro-ph.HE]





4) Wideband GW telescopes

Candidates (they are not included in the current network):

- **GEO600** Its sensitivity should be enough for GW observations from supernovae
- **KAGRA** Probably it will begin operations in 2018
- **aLIGO-H2 (LIGO-India)** Probably it will begin operations in 2022

First step

The first step of joint analysis is to account for the single detector **its duty cycle** and hence calculate **the common observation time** of the network of involved detectors or any of the resulting subnetworks.

Two types of the joint analysis

1

Model-independent search for correlations between possible ν bursts* and gravitational waves

*any flavours and reaction channels

Status: ongoing

2

Search for correlations between Inverse β -decay events and gravitational waves

The first attempt has been made by KamLAND [2]

Status: under discussion

[2] A. Gando et al. (KamLAND collaboration), 2016, arXiv:1606.07155v1

False Alarm Rate and Joint False Alarm Rate

- The **F**alse **A**larm **R**ate (**FAR** or the Imitation Frequency) is a number of accidental background fluctuation above the SN detection threshold per year.
- The **joint** FAR is a number of accidental coincidence of detector signals in the network

$$FAR_{joint} = \prod_{i=1}^{N} FAR_i \times (2t_{coin})^{N-1}, \quad (1)$$

where t_{coin} is a coincidence window between GW and ν signals in which the correlation is looked for.
Conservative approach: $t_{coin} = 10$ s, whereas in some paper it's in order of tens ms [3].
The factor "2" is due to unknown time order of signals.

[3] G. Pagliaroli et al., Phys.Rev.Lett.103:031102,2009; arXiv:0903.1191v1

Some estimations

Let's choose the joint FAR of **1 cluster/1000 yr** and the GW subnetwork FAR of **1 cl/1 month**. Applying the formula 1:

$$FAR_{joint} = \frac{1 \text{ CL}}{1000 \text{ YR}} = \tag{2}$$

$$= FAR_{GW} \times FAR_{LVD} \times FAR_{IceCube} \times FAR_{BX} \times (2t_{coin})^3 \tag{3}$$

Assuming the same FAR per each ν detector:

$$FAR_{\nu} \sim 2 \times 10^{-3} \text{ Hz} \sim \frac{1 \text{ CL}}{10 \text{ MIN}} \tag{4}$$

If there is only one detector it's nesessary to stay at very low value of FAR_i in order to be statistically significant.

▶ The value equals **1 cl/100 yr** in the LVD paper [4].

[4] N.Y. Agafonova et al. (LVD Collaboration), The Astrophysical Journal, 802:47, 2015; arXiv:1411.1709v2

Strategy of unbiased search. Variant 1

DATA OF THE GW AND ν DETECTORS +
THE TOTAL TIME OF OBSERVATION
WITH THE DIFFERENT CONFIGURATIONS
OF NETWORK

⇩

SELECTING SUBNETS OF CONCURRENT DETECTORS

> GUIDELINE:
> THERE ARE **at least** TWO GW DETECTORS
> AND ONE NEUTRINO OBSERVATORY
> IN A SUBNET

⇩

SET AND FIX
THE JOINT FALSE ALARM RATE
THAT IS THE SAME FOR ALL SUBNETS

> GUIDELINE:
> FAR(JOINT) ~ 1 EVENT / 1000 YEARS
> I.E. AN ACCIDENTAL COINCEDENCE
> MUST BE **no more than**
> ONCE PER 1000 YEARS

⇩

USING ***FAR(joint)***, ESTIMATE ***FAR(I)***
IN EACH DETECTOR FOR EACH SUBNETS

⇩

CHOOSE THE SET OF CUTS
IN EACH DETECTOR FOR EACH SUBNETS

⇩

CANDIDATE SELECTION IN EACH DETECTOR FOR EACH SUBNETS

⇩

SEARCH FOR THE CORRELATIONS IN EACH SUBNETS

⇩

RESULT

Benefits:
- simple
- fast

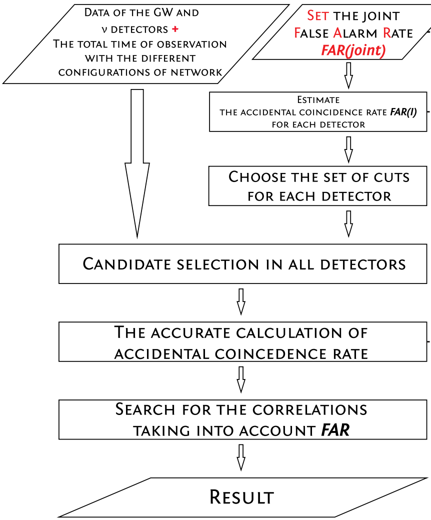
(computer resources, labour time)

Blemish:
- fixed precision
- no confidence level calculation
- low sensitivity

(rough, relatively strict selection criteria)

Guaranteed accuracy:
~ FAR(joint) / Average Rate(SNe)

Strategy of unbiased search. Variant 2



1) Guideline:
FAR(joint) ~ 1 event / 1000 years
I.e. an accidental coincedence must be no more than once per 1000 years
2) There are at least two GW detectors and one neutrino observatory in the network

Guideline:
1) For the GW subnetwork
FAR(GW) ~ 1 event / month
2) For the neutrino subnetwork
FAR( ) ~ 1 event / day

Benefits:
- precision
- confidence level calculation
- high sensitivity
(very soft selection criteria)

1) It is necessary to calculate the reliability of observation
2) It is performed by multiple mutual shifts of the data in time

Blemish:
Relatively time-consuming process of the accidental coincedence background calculatoin

Example of the FAR calculation (for Borexino)

According the LVD paper [4]:

- search for clusters of ν-candidate events
- each event could be the first of a possible ν burst
- the duration Δt of clusters is unknown a priori, so let's consider all possible $\Delta t < \Delta t_{max}$
- let $\Delta t_{max} = 100$ s - the same one as in LVD ()
- ν-candidate event selection
  - This set is really soft in case of Borexino due to its purity.

  For the moment: **not a muon**, **not a noise**, **$0.85 < E < 60$ MeV**.
- calculation of average background f_{bk} for each period of measurements under constant conditions (trigger levels, purity,...)
  - Every ν-candidate event is considered as a background event

[4] N.Y. Agafonova et al. (LVD Collaboration), The Astrophysical Journal, 802:47, 2015; arXiv:1411.1709v2

Example of the FAR calculation (for Borexino, continuation)

According the LVD paper [4] (continuation):

- each cluster is characterized by duration Δt_i and multiplicity m_i
- each cluster is associated with FAR_i^{cl} as it's shown in [5]:

$$FAR_i^{cl} = {f_{bk}}^2 \Delta t_{max} \sum_{k \geqslant m_i - 2} P(k, f_{bk} \Delta t_i), \qquad (5)$$

where $P(k, f_{bk}\Delta t_i)$ is the Poisson probability to have k events in the time window Δt_i, i -- the detector index

- choose those clusters that have $FAR_i^{cl} < FAR_i^{th}$, where FAR_i^{th} is the FAR estimation for the detector i.
$FAR_{LVDonly}^{th}$ = **1 cl/100 yr**; FAR_{BXnet}^{th} = **1 cl/10 min**

[4] N.Y. Agafonova et al. (LVD Collaboration), The Astrophysical Journal, 802:47, 2015; arXiv:1411.1709v2
[5] W. Fulgione, N. Mengotti-Silva and L. Panaro, NIMPA, 368, 2, 512--516 (1996)

What's next?

To test the technique on archived data - ongoing

For the moment the analysis uses data 2005-2014

Simulation. For what?

- Verification techniques and tools
- The efficiency of the search for correlations depending on the distance to the supernova and the number of detectors in the network - **ongoing**

How?

By inserting the generated signals to real data

Penalty: model-dependent efficiency

Difficulties and limitations

Difficulties:

- Measurement techniques for different neutrino detectors are different.
  As a result, the FAR_i is calculated differently, and depends on different physical quantities
- Some tools are not ready
- What models can be considered as the references?

Physical limitation:

- **It's expected that the collapse must be asymmetrical**

What models can be considered as the references?

Neutrino radiation

The first approach:

reproduce SN1987A signal, taking, for example, the main parameters from the analysis G. Pagliaroli, F. Vissani, M.L. Costantini, A. Ianni "Improved analysis of SN1987A antineutrino events", 2009 [6]

Other suggestions:

1) This is the so-called Lawrence Livermore model, with characteristics similar to SN1987A. It is clearly outdated, but often used for a comparison between experiments.

T. Totani, K. Sato, H.E. Dalhed, J.R. Wilson "Future Detection of Supernova Neutrino Burst and Explosion Mechanism", 1998 [7]

2) This is sort of the most conservative assumption producing the lowest flux.

L. Huedepohl, B. Mueller, H.-Th. Janka, A. Marek, G.G Raffelt "Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling", 2010 [8]

3) This is clearly an „optimistic assumption“ of a rare supernova, that produces lots of neutrinos with rising energy.

K. Sumiyoshi, S. Yamada, H. Suzuki "Dynamics and neutrino signal of black hole formation in non-rotating failed supernovae. I. EOS dependence", 2007 [9]

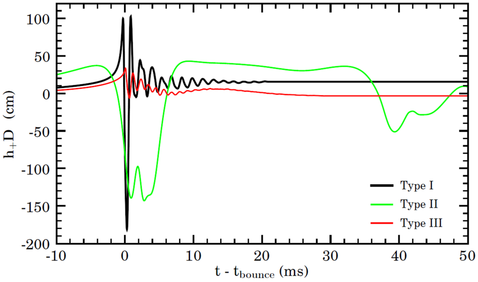
[6] Astroparticle Physics 31 (2009) 163–176; arXiv:0810.0466v1 [astro-ph]
[7] Astrophys.J. 496 (1998) 216-225; arXiv:astro-ph/9710203v1
[8] Phys.Rev.Lett.104:251101,2010; Erratum-ibid.105:249901,2010; arXiv:0912.0260v3 [astro-ph.SR]
[9] Astrophys.J.667:382-394,2007; arXiv:0706.3762v1 [astro-ph]

What models can be considered as the references?

GW radiation

[10] Class.Quant.Grav.26:063001,2009; arXiv:0809.0695v2 [astro-ph]
[11] Astron.Astrophys. 388 (2002) 917-935; arXiv:astro-ph/0204288v1

The "last" simulations indicate that the GW signal form is likely the first type. See details in [10,11]



$$\Delta E_{GW} = 10^{-10} - 10^{-4} M_{\odot}; \quad (6)$$

$$h_c \sim 2.7 \times 10^{-20} \left(\frac{\Delta E_{GW}}{M_{\odot} c^2}\right)^{1/2} \left(\frac{1\ \mathbf{kHz}}{f_c}\right)^{1/2} \left(\frac{10\ \mathbf{Mpc}}{r_0}\right). \quad (7)$$

As a conclusion:

The concentration ~~of production~~ of scientific research
gives us once again a possibility
to glimpse into the depths of the universe.
Let us not miss this opportunity!

Join the GWNU community!