Joint search for Gravitational Wave and Low Energy Neutrino signals from Core Collapse Supernovae

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Outline

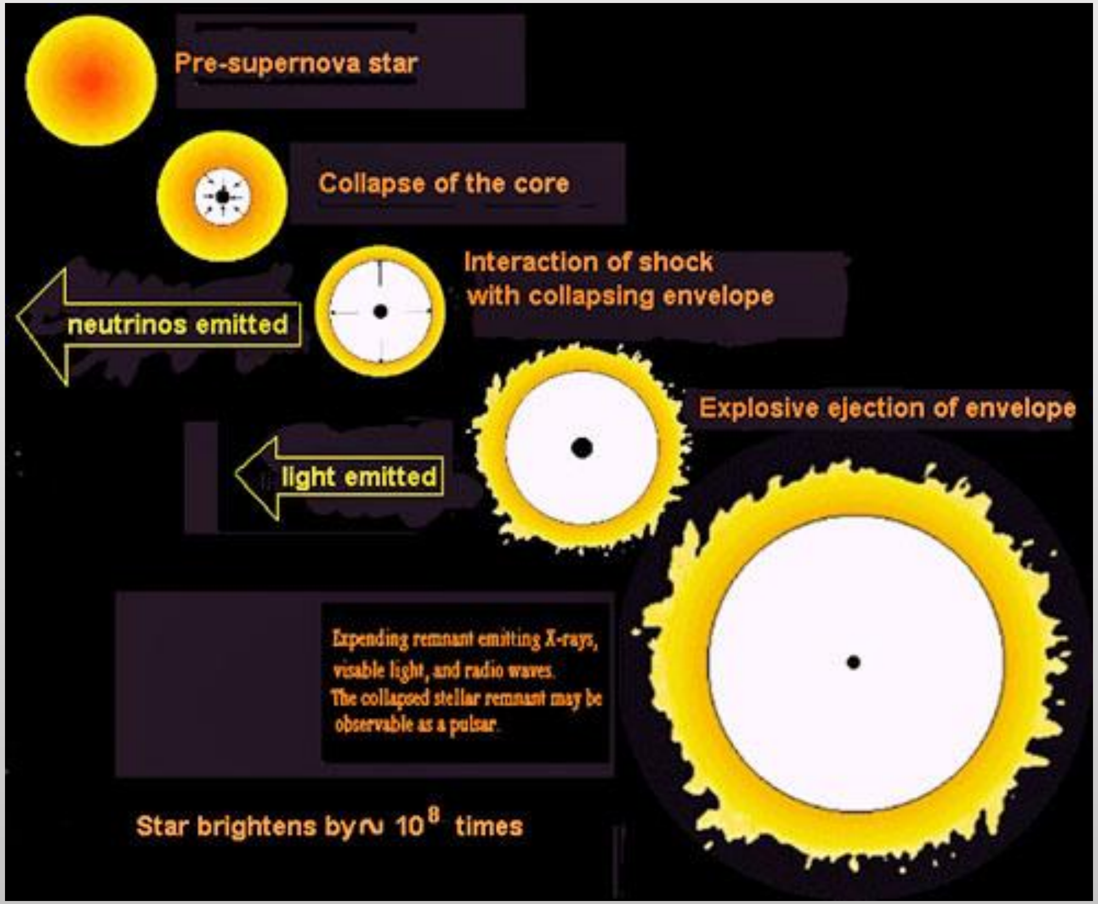
- Scientific motivation and physical scenario;
- The joint analysis: method and benefits;
- The gravitational wave interferometers involved;
- The neutrino detectors involved;
- General framework of the joint analysis;
- Simulations;
- Conclusions.

Scientific motivations

- Core collapse Supernovae (CCSNe) are potential sources of gravitational waves (GWs), neutrinos (ν) and electromagnetic (EM) radiation;
- EM radiation can bring information about the external layers of the star because the mean free path of photons inside the star is very small;
- ν and GWs can leave the stellar structure without interaction with the stellar medium;
- Coincident neutrino and GW signals would bring valuable information from the inner core of the collapsing star, such as the explosion mechanism.

Physical scenario

- A CCSN is formed after the rapid collapse and violent explosion of a massive star;
- The engine of the entire mechanism is the inert iron core formed at the end of the different nuclear fusion processes;
- During the collapsing phase, neutronization take place: $p + e^- \rightarrow n + \nu$.
- Almost simoultaneously, the physics of the collapse can lead to the emission of GW: various models exists.
- Duration of the collapse ≈ msec ⟶ GW burst;

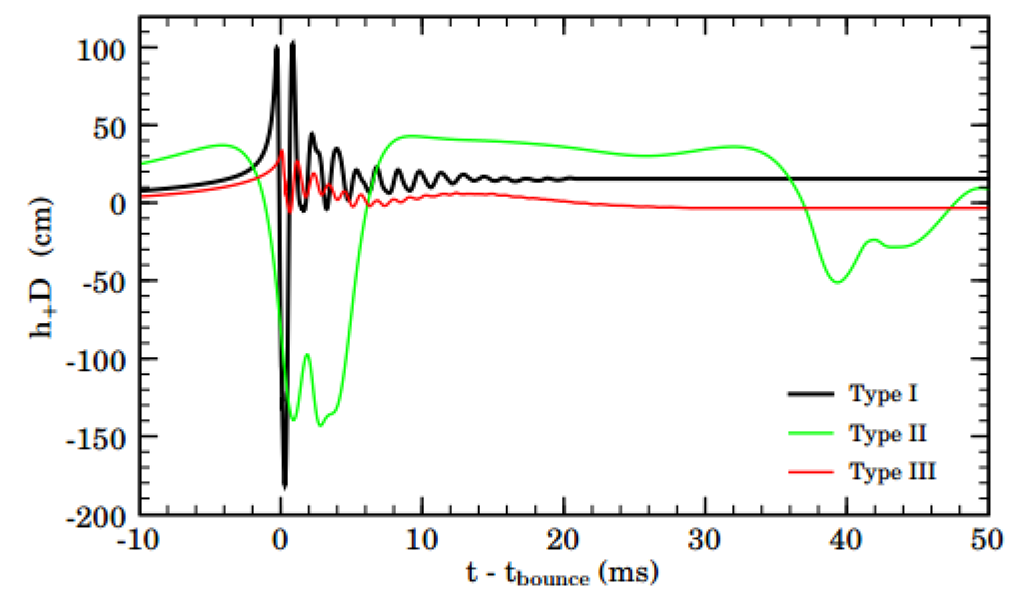


Physical scenario (2)

- Several mechanisms may give rise to GW emission from CCSNe [Ott, Class.Quant.Grav.26:063001,2009], [Ott, arXiv:1501.06951v2 [astro-ph.HE] 29 Apr 2015]:
  - Rotating collapse and bounce;
  - Rotational instability;
  - Turbolent convection;
  - Non-radial PNS Pulsations;
  - …
- It is expected a release of energy in between:

$$10^{-9} M_{\odot} c^2 \leq E \leq 10^{-5} M_{\odot} c^2.$$

- Huge variations in predictions exist: observation is needed.



[Ott, Class.Quant.Grav.26:063001,2009]

Type I – Core bounce not affected significatively by rotation;

Type II - Core bounce affected significatively by rotation and governed by centrifugal forces;

Type III – Fast collapse and extremely small inner core.

Coincident search between GW and CCSNe ν (1)

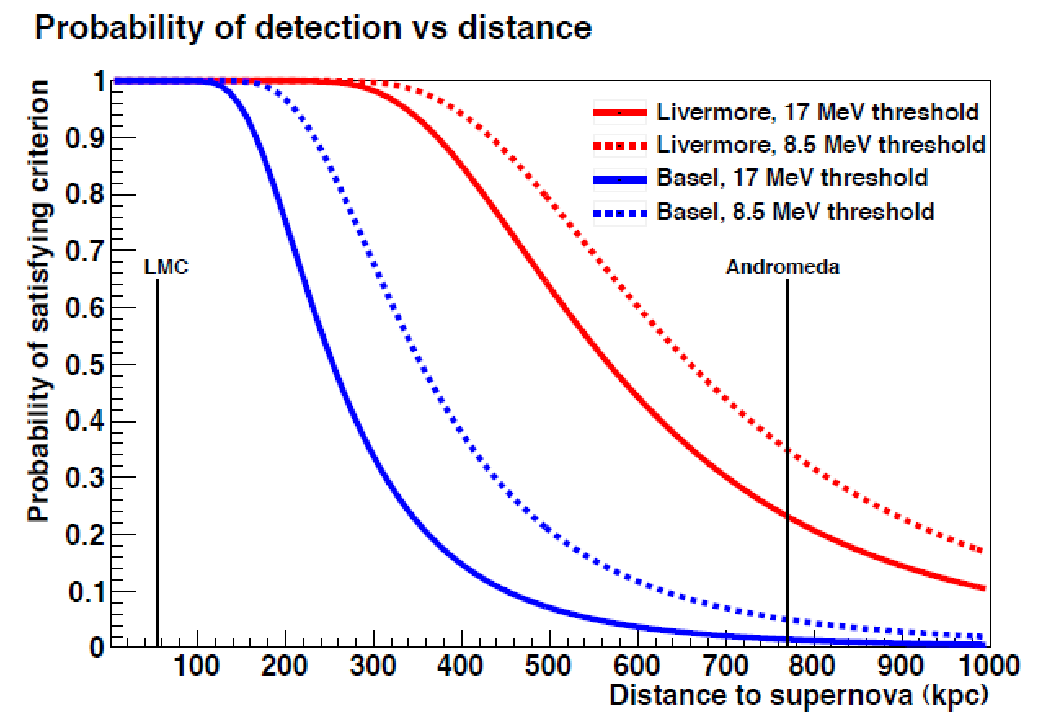
Searching for GWs in coincidence with neutrinos will lead to:

- A deeper understanding of the physics inside the core of the source;

A distant event with low statistical significance in GW could achieve higher confidence from joint search requirments:

- Higher detection confidence;

For galactic CCSNe, a coincidence with GW would help constraining the physical models governing the dynamics inside the core.



Low False Alarm Rate (FAR_{joint}) for the joint search:

- This would allow single detectors to operate at lower thresholds, relaxing criteria for detection.

E.g. with $FAR_{GW} = {}^{1}/_{month}$, $FAR_{\nu} = {}^{1}/_{day}$ and $w_{coin} \sim sec$

$$\boldsymbol{FAR_{joint} = FAR_{GW} \cdot FAR_{\nu} \cdot w_{coin} \sim o\left({}^{1event}/_{kyear}\right)}$$

This choice would correspondingly lead to a 10-20% gain in GW sensitivity

Coincident search between GW and CCSNe ν (2)

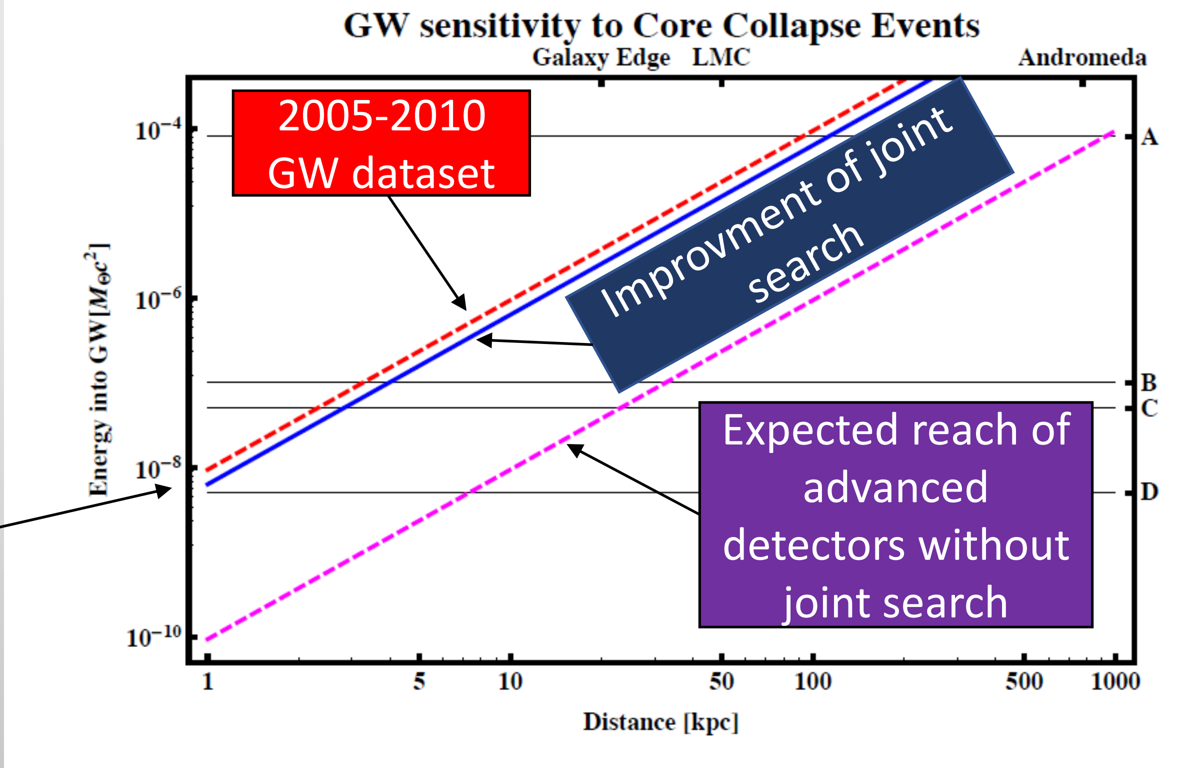
To quantify the potential improvement in sensitivity offered by the joint analysis:

$$E_{GW} = \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{rss}^2$$

[B. P. Abbott et al. Class. Quantum Grav., 24, 5343, 2007]

Here D is the distance in kpc, f_0 the signal frequency and h_{rss} the signal amplitude at the detector.

Improvement in the distance range for GW detectors for a threshold rescaling of 10-20%.



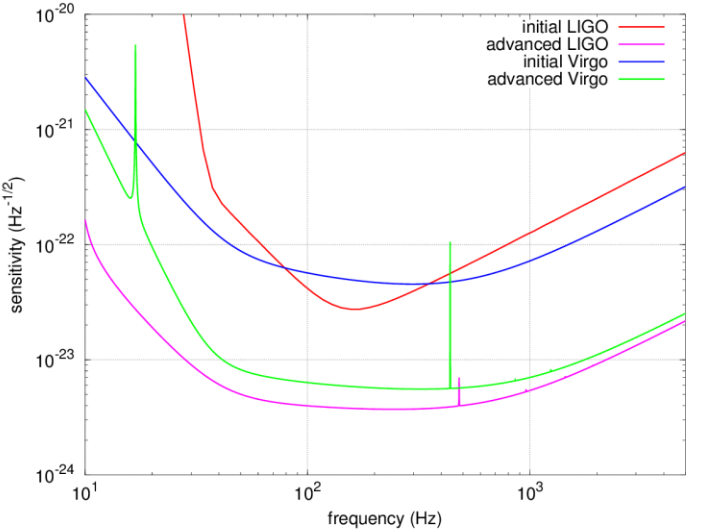
2005-2010 GW dataset

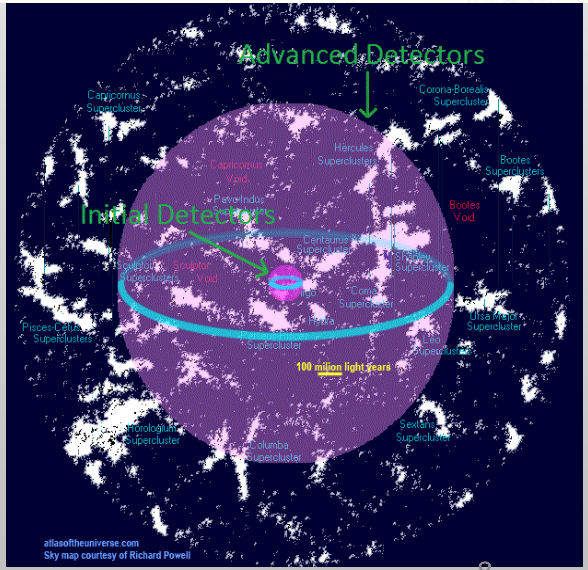
Improvment of joint search

Expected reach of advanced detectors without joint search

GW detectors

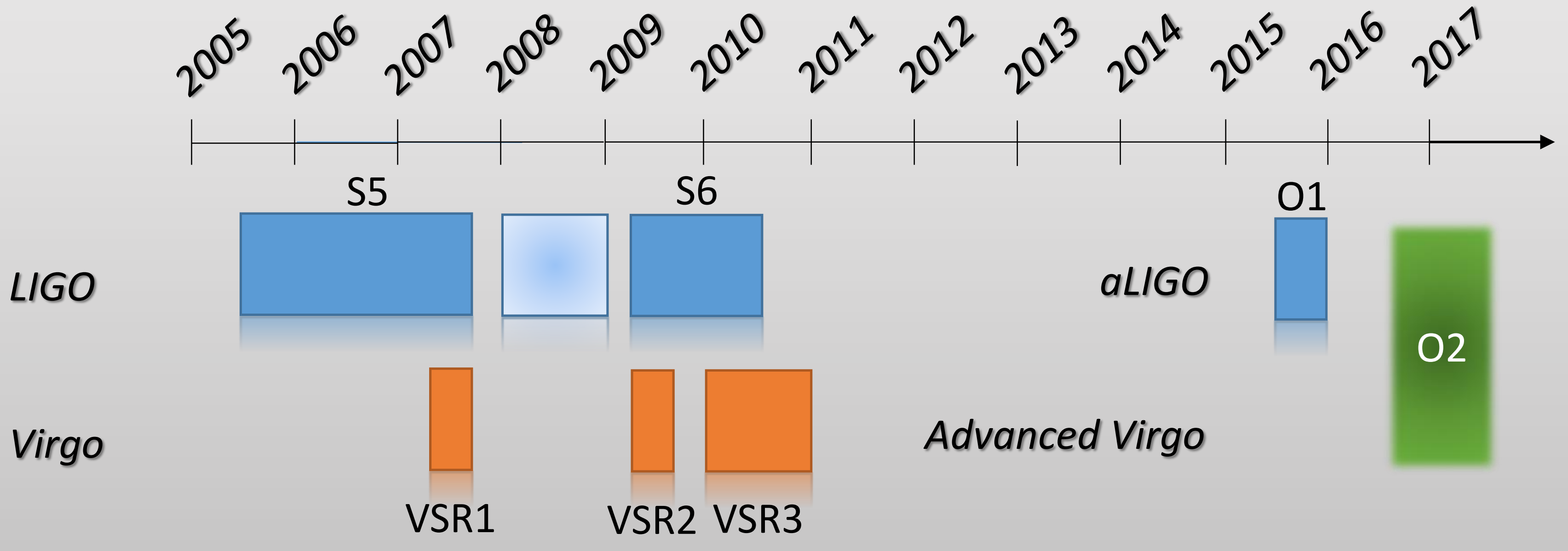
- *LIGO Livingston* and *LIGO Hanford* 4 km detectors located in Livingston and Hanford (USA);
- *Virgo* 3 km detector located in Cascina, near Pisa (Italy);
- They are sensitive to GWs in a wide frequency range, from 10 to 10000 Hz;
- *LIGO* and *Virgo* have been upgraded to advanced configuration. *aLIGO* is currently in its 8th engineering run (ER8);
- First *aLIGO* observational run planned to start at mid September 2015.





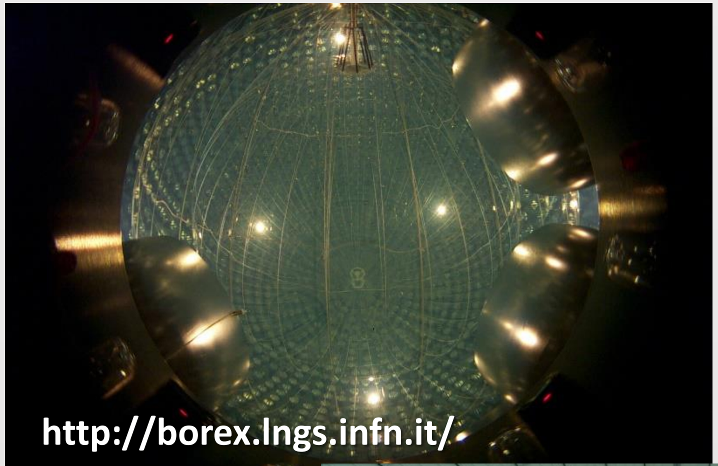
GW scientific runs

- A series of runs have been performed by the GW network;



Neutrino detectors

- *Actually three ν detectors are involved:*
    - ***Borexino***, located in the *LNGS* laboratory near L'Aquila (*Italy), that could observe hundreds of interactions;*
    - ***LVD***, located in the *LNGS* laboratory near L'Aquila (*Italy), that could observe hundreds of interactions;*
    - ***Icecube***, located near the *Amundsen-Scott South Pole Station* in Antarctica, that could observe galactic SNe;
- *Collaboration is open to any interested ν detector;*
    - ***KamLand***, located at the *Kamioka Observatory* near Toyoma (Japan);
    - …

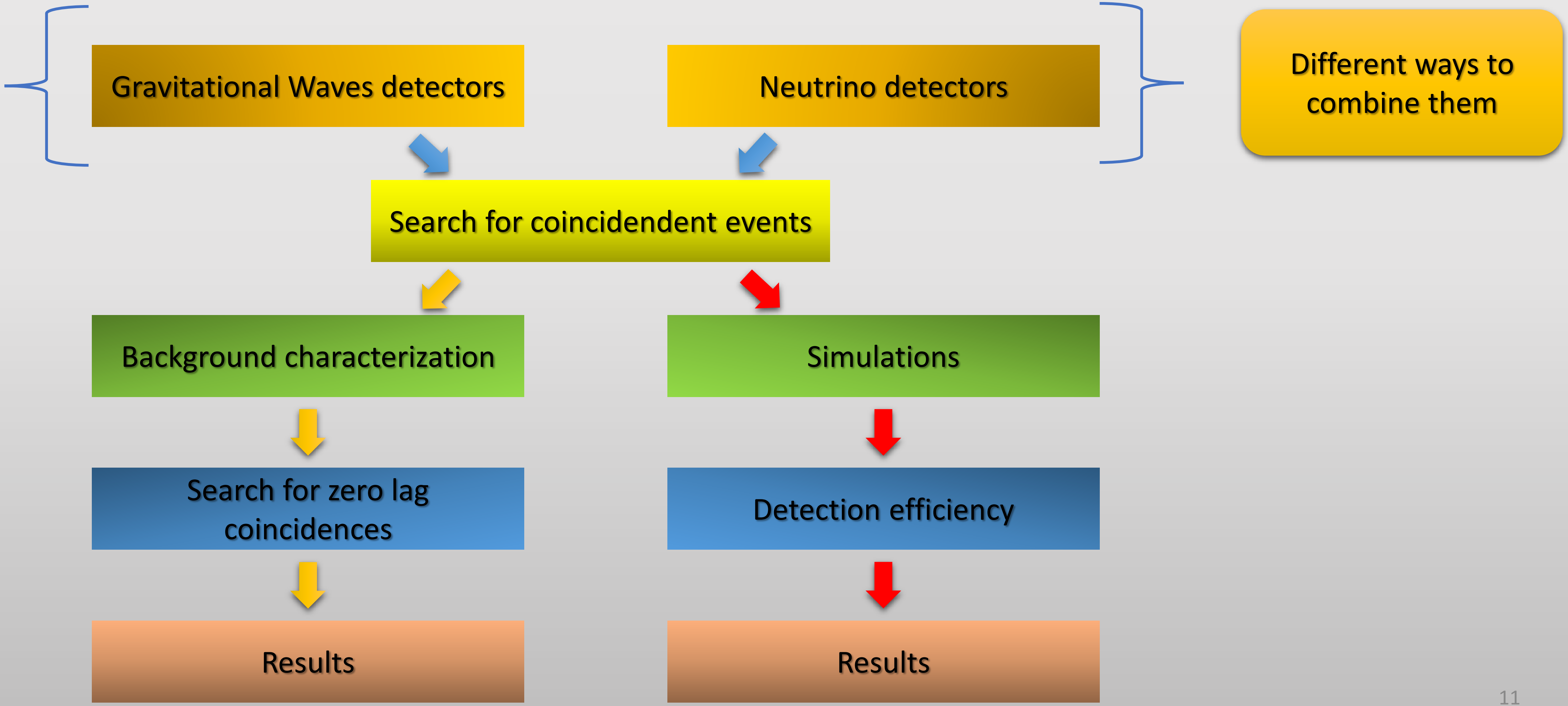


http://borex.lngs.infn.it/

www.nu.to.infn.it/exp/all/lvd/

https://icecube.wisc.edu/

The general framework of the analysis (1)



Gravitational Waves detectors

Neutrino detectors

Different ways to combine them

Search for coincidendent events

Background characterization

Simulations

Search for zero lag coincidences

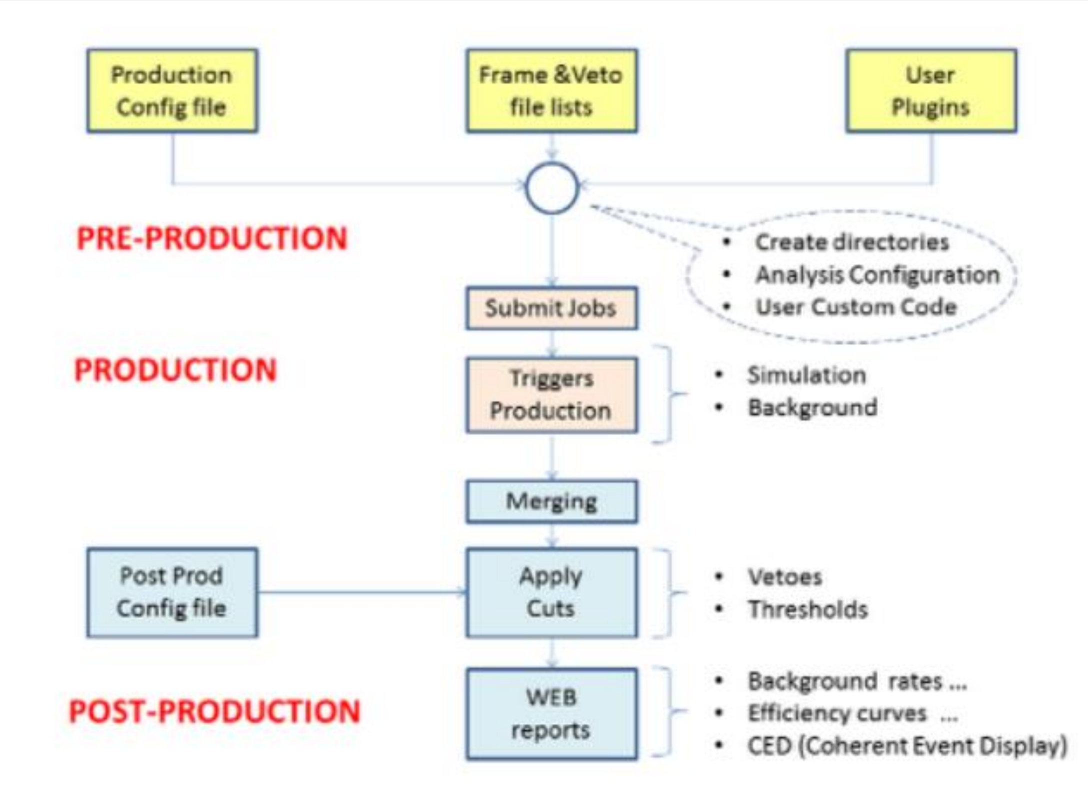
Detection efficiency

Results

Results

The general framework of the analysis (2)

- The analysis will be performed using the coherent waveburst pipeline (cWB) [Klimenko et al, Class.Quant.Grav.25:114029,2008];
- cWB is a wavelet-based data analysis pipeline designed to search for unmodelled GW burst signals;
- cWB has been adapted to search for gravitational wave burst signals in coincidence with an external astrophysical event. For example, a GW-optically triggered SN search is in progress.

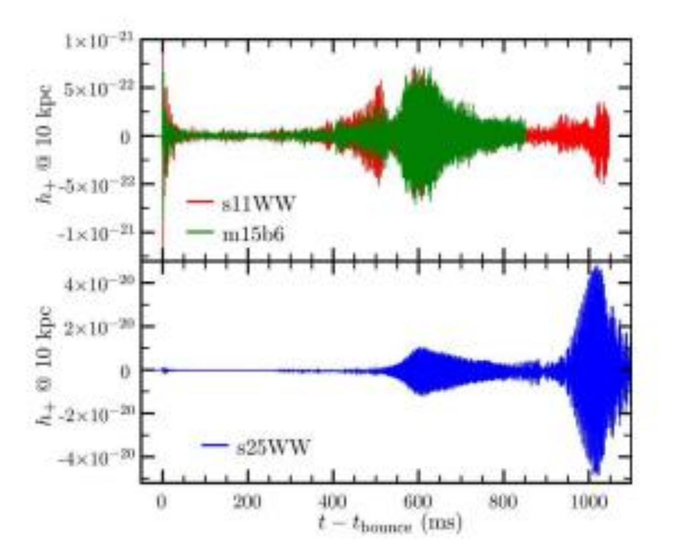


https://atlas3.atlas.aei.uni-hannover.de/~waveburst/doc/cwb/man/

Simulations – testing the methods through software injection

GW simulations

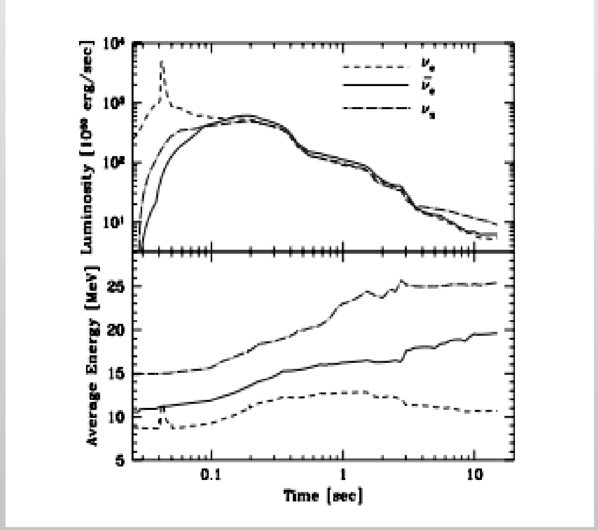
- Consider possible waveforms representing the GW emission process:



Ott et *al.,* Phys. Rev. Lett., 96:201102

Neutrino simulations

- Accounting for the theoretical distribution of the neutrino emission process associated with GW emission;
- For any theoretical model, CCSN distance and detector:
  - Average number of observed events;
  - Average responde time;
  - Average duration of the signal;
  - Average energy of the events.



Totani et *al.* 1998, ApJ **496** 216

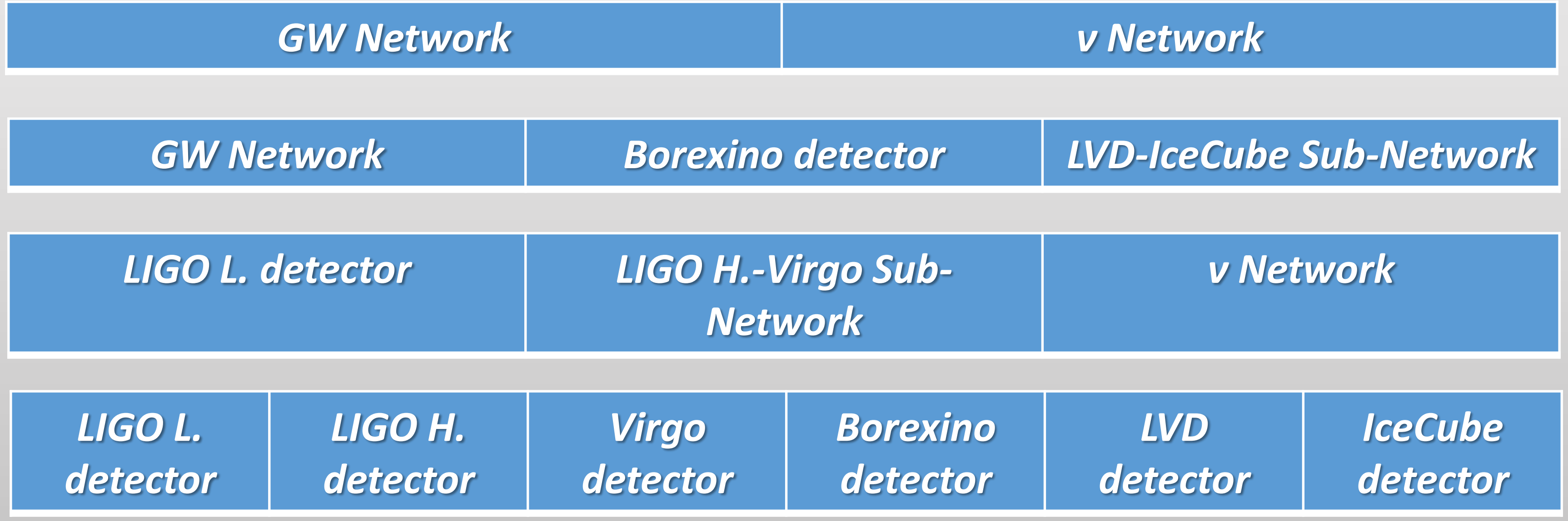
Conclusions and future steps

- The joint search is in progress;
- Both GW and ν search would benefit from the joint search;
- Collaboration already involving GW and ν detectors. It is open to any interested neutrino detectors;
- Future steps:
  - Testing the analysis method on real data;
  - Being ready for upcoming data from advanced gravitational interferometers and neutrino detectors;

EXTRA SLIDES

How to combine different detectors – extra 1

- Find temporal coincidences between different datasets;
- Various possible solution to combine these datasets. A few examples:



GW Network	*ν Network*

GW Network	*Borexino detector*	*LVD-IceCube Sub-Network*

LIGO L. detector	*LIGO H.-Virgo Sub-Network*	*ν Network*

LIGO L. detector	*LIGO H. detector*	*Virgo detector*	*Borexino detector*	*LVD detector*	*IceCube detector*