# Supernova Neutrinos Detection @ LNGS

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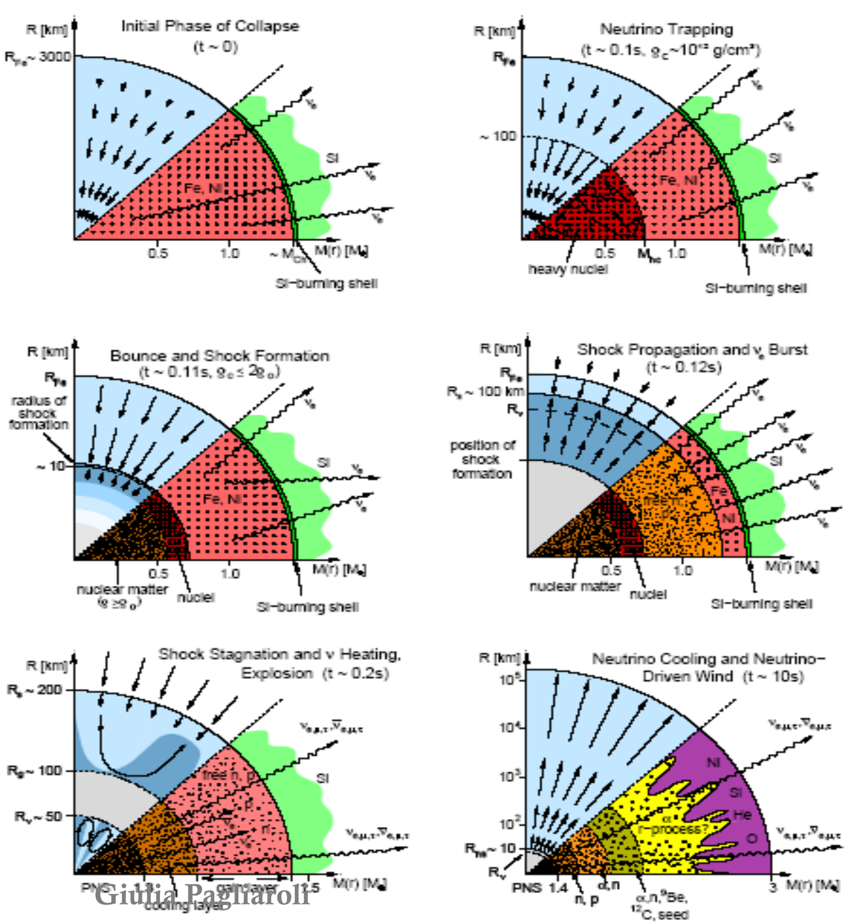
# Outline

- Core Collapse SNe Neutrinos
- LVD detector
- Borexino detector
- Halo 2 @ LNGS?
- The GW-Nu Network

**SN1987A**

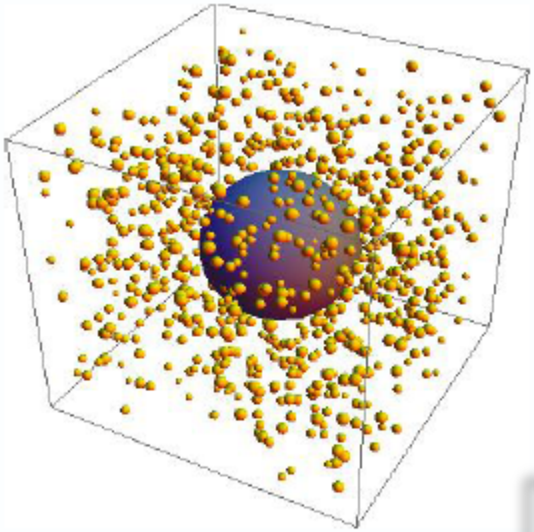
# Core-Collapse SNe




1. Collapse
2. Bounce
3. Shock Propagation
4. Shock Stagnation
5. Accretion
6. Cooling PNS

From JANKA et al. Phys.Rev. 442 (2007)

# Neutrinos Expectations



**ENERGY**

$$\varepsilon_B = (1-5)\cdot 10^{53}\, erg$$

$$\varepsilon_\nu = 99\% \cdot \varepsilon_B$$

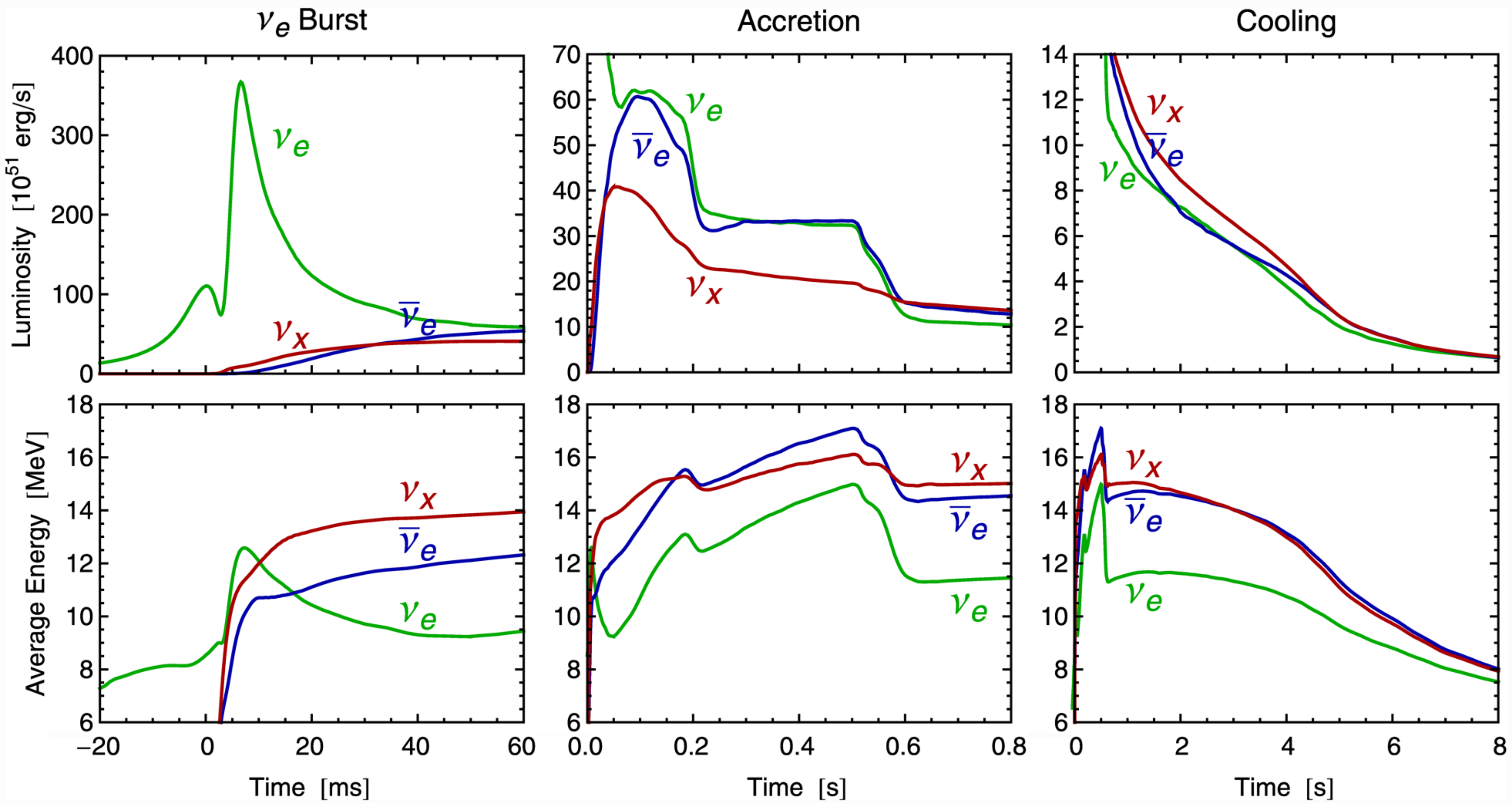
**FLUENCE**

$$F_{\nu_x} \cong \frac{\varepsilon_B}{6\langle E_{\nu_x}\rangle}\frac{1}{4\pi D^2} \approx 5\cdot 10^{10}\left(\frac{20\text{ kpc}}{D}\right)^2 \frac{10\text{MeV}}{\langle E_{\nu_x}\rangle}\frac{\nu_x}{cm^2}$$

**DURATION**

$$\Delta t = 10\sec$$

# Spherically symmetric Garching model (25 $M_\odot$)




- Neutronization burst
- Standard Candle

- Not thermal spectra
- 10% of the total energy
- Explosion Mechanism??

- Trapped Neutrinos
- Thermal spectra
- 90% of the total energy

# Standard MSW oscillations

**Normal Hierarchy**

$$P_{ee}^{MSW} = 0 \quad P_{\overline{ee}}^{MSW} \cong 0.7$$

$$F_e = F_x^0$$

$$F_{\overline{e}} = 0.7 \cdot F_{\overline{e}}^0 + 0.3 \cdot F_x^0$$

**Inverted Hierarchy**

$$P_{ee}^{MSW} \cong 0.3 \quad P_{\overline{ee}}^{MSW} \cong 0$$

$$F_e = 0.3 \cdot F_e^0 + 0.7 \cdot F_x^0$$

$$F_{\overline{e}} = F_x^0$$

# Time Integrated Features

Total energy budget

$$E_b = 3 \cdot 10^{53} erg$$

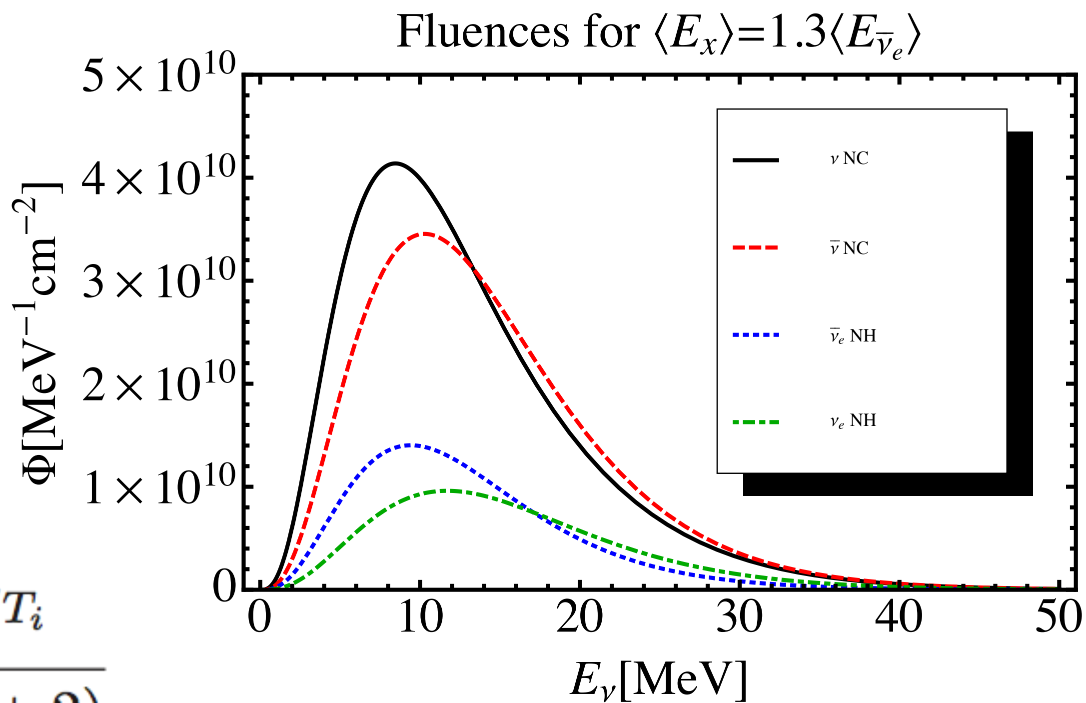
Equipartition Hypothesis

$$\varepsilon_i = E_b \cdot f_i$$

$$f_i = 1/6$$

Fluence at the Earth

$$\Phi_i = \frac{\mathcal{E}_i}{4\pi D^2} \times \frac{E^{\alpha} e^{-E/T_i}}{T_i^{\alpha+2}\Gamma(\alpha+2)}$$




Pinched spectra with $\alpha = 3 \quad T_i = \langle E_i \rangle / (\alpha + 1)$

# Supernova Neutrinos Detection

EMISSION

$$\langle E_{\nu_e} \rangle = 9.5\,\mathrm{MeV}$$

$$\langle E_{\bar{\nu}_e} \rangle = 12\,\mathrm{MeV}$$

$$\langle E_{\nu_x} \rangle = 15.6\,\mathrm{MeV}$$

DETECTION

$$\langle E_{\nu_e} \rangle = 15.6\ \mathrm{MeV}$$

$$\langle E_{\bar{\nu}_e} \rangle = 13\ \mathrm{MeV}$$

$$\langle E_{\nu_x} \rangle = 13\ \mathrm{MeV}$$

$$\langle E_{\bar{\nu}_x} \rangle = 14\ \mathrm{MeV}$$

Neutrinos Fluences

$$\mathrm{N}_{ev} \propto \mathrm{N}_t \int_{\mathrm{E}_{thr}}^{\infty} \mathrm{dE}_{vis}\, \sigma_{Int}(\mathrm{E}_\nu)\mathrm{F}_\nu(\mathrm{E}_\nu)$$

Number of targets

Detector Energy Threshold

Cross Section
Kinematic threshold

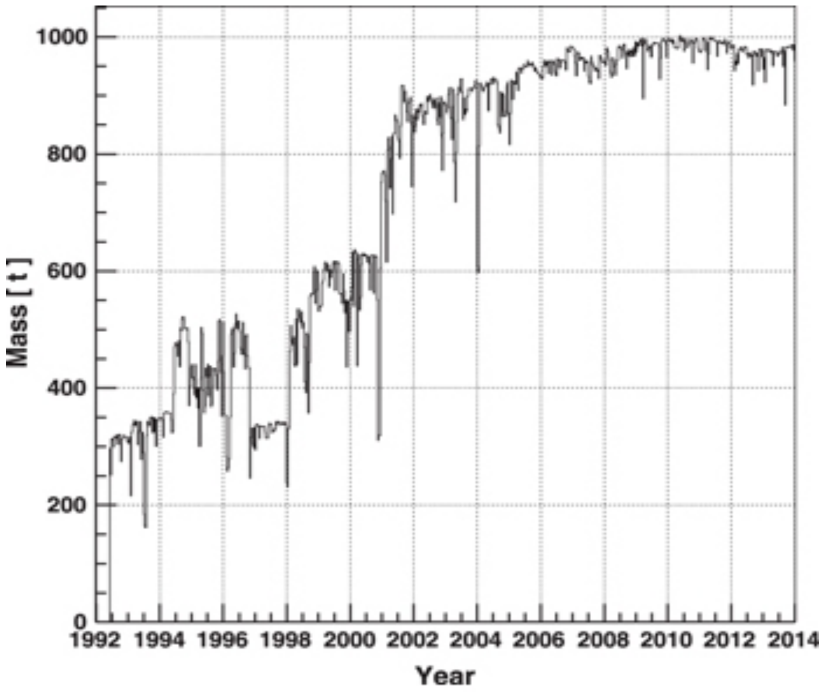
# LVD: Large Volume Detector

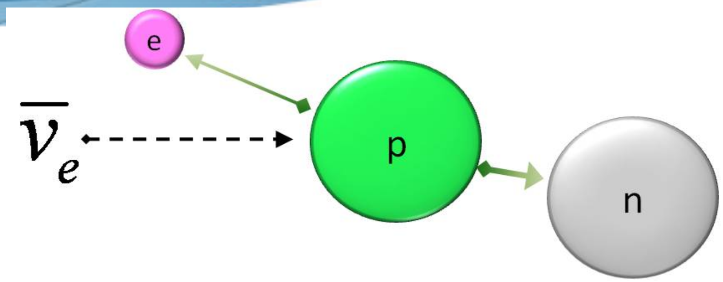
LVD consists of an array of 840 scintillator counters, interleaved by streamer tubes, and arranged in a compact and modular geometry.

| | |
|---|---|
| Mass ($ktons$) | 1.0 |
| Energy threshold ($MeV$) | 4.0 |
| Scintillator composition | $C_{10}H_{20}$ |
| Protons ($10^{31}$) | 9.34 |
| Carbon nuclei ($10^{31}$) | 4.23 |
| Electrons ($10^{31}$) | 34.7 |
| Iron nuclei ($10^{30}$) | 9.71 |

# A 21 years Neutrinos Observatory

LVD active mass as a function of time in the period from 1992 June to 2013 December.

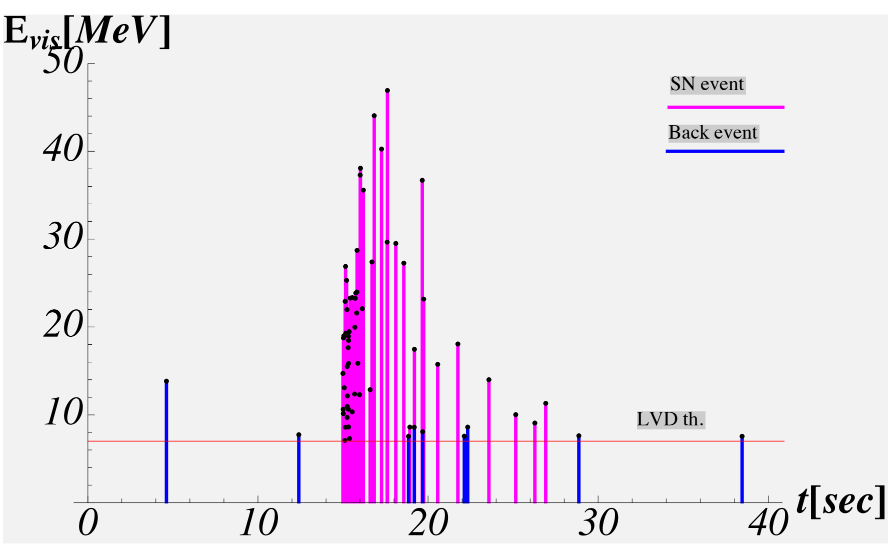


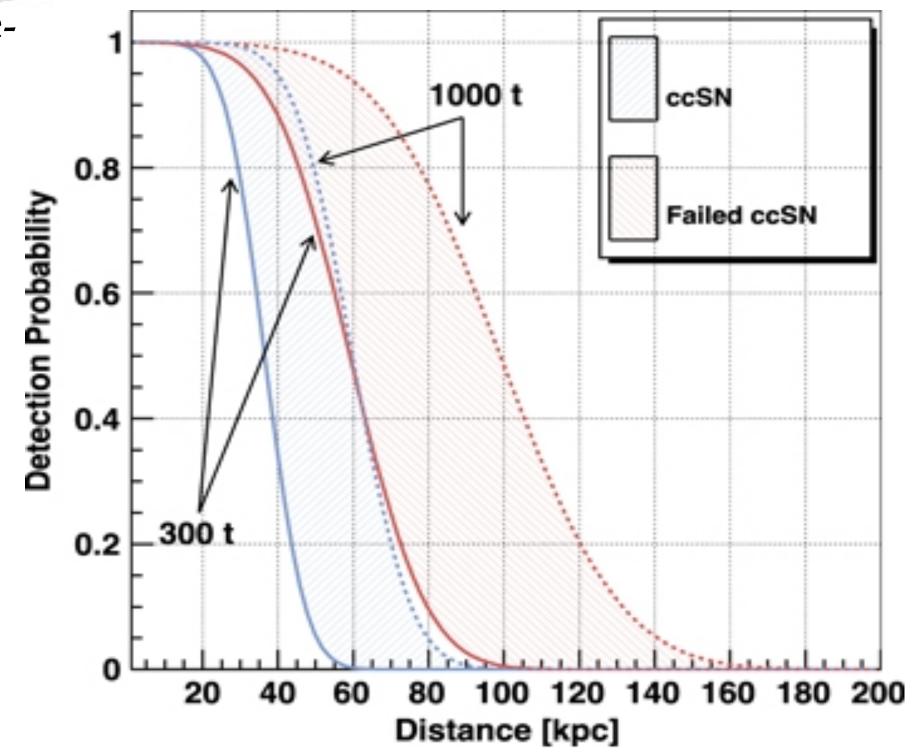




| | LVD |
|---|---|
| Total number @ 10 kpc | 335 |
| $\bar{\nu}_e + p \rightarrow n + e^+$ | 87.1% |
| $\nu_x + e^- \rightarrow \nu_x + e^-$ | 3.2% |
| $\nu_e +^{12} C \rightarrow {}^{12}N + e^-$ | 1.1% |
| $\bar{\nu}_e +^{12} C \rightarrow {}^{12}B + e^+$ | 1.0% |
| $\nu_x +^{12} C \rightarrow \nu_x +^{12} C + \gamma_{15.1MeV}$ | 2.1% |
| $\nu_e +^{56} Fe \rightarrow^{56} Co^* + e^-$ | 3.0% |
| $\bar{\nu}_e +^{56} Fe \rightarrow^{56} Mn + e^+$ | 0.6% |
| $\nu_x + {}^{56}Fe \rightarrow \nu_x + {}^{56}Fe^*$ | 1.9% |

# Detection Probability

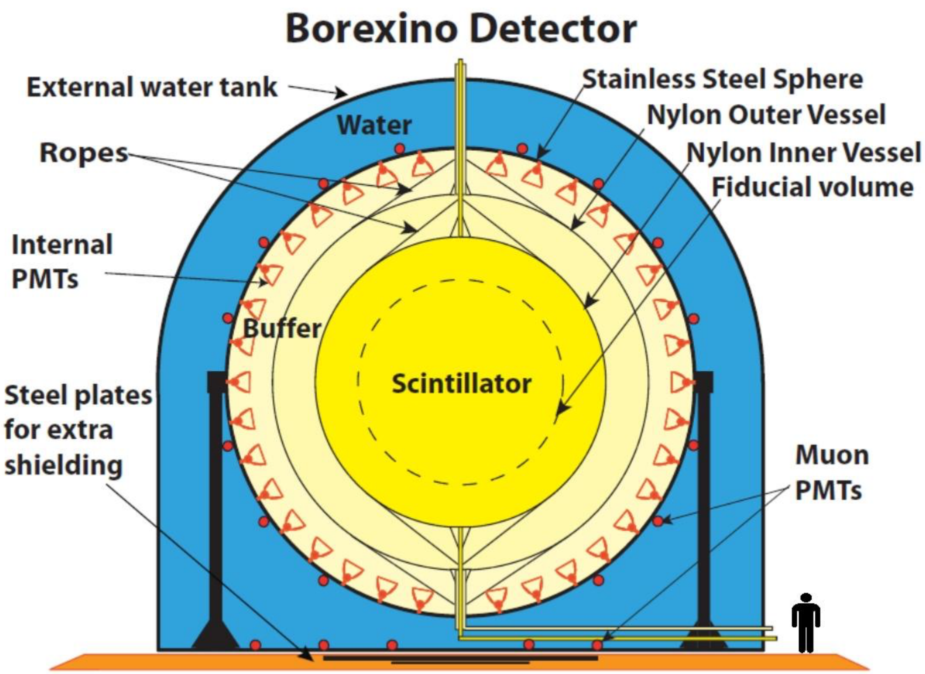
The 90% C.L. upper limit on the rate of core-collapse and failed supernova explosions out to distances of 25 kpc is found to be 0.114 y−1 .



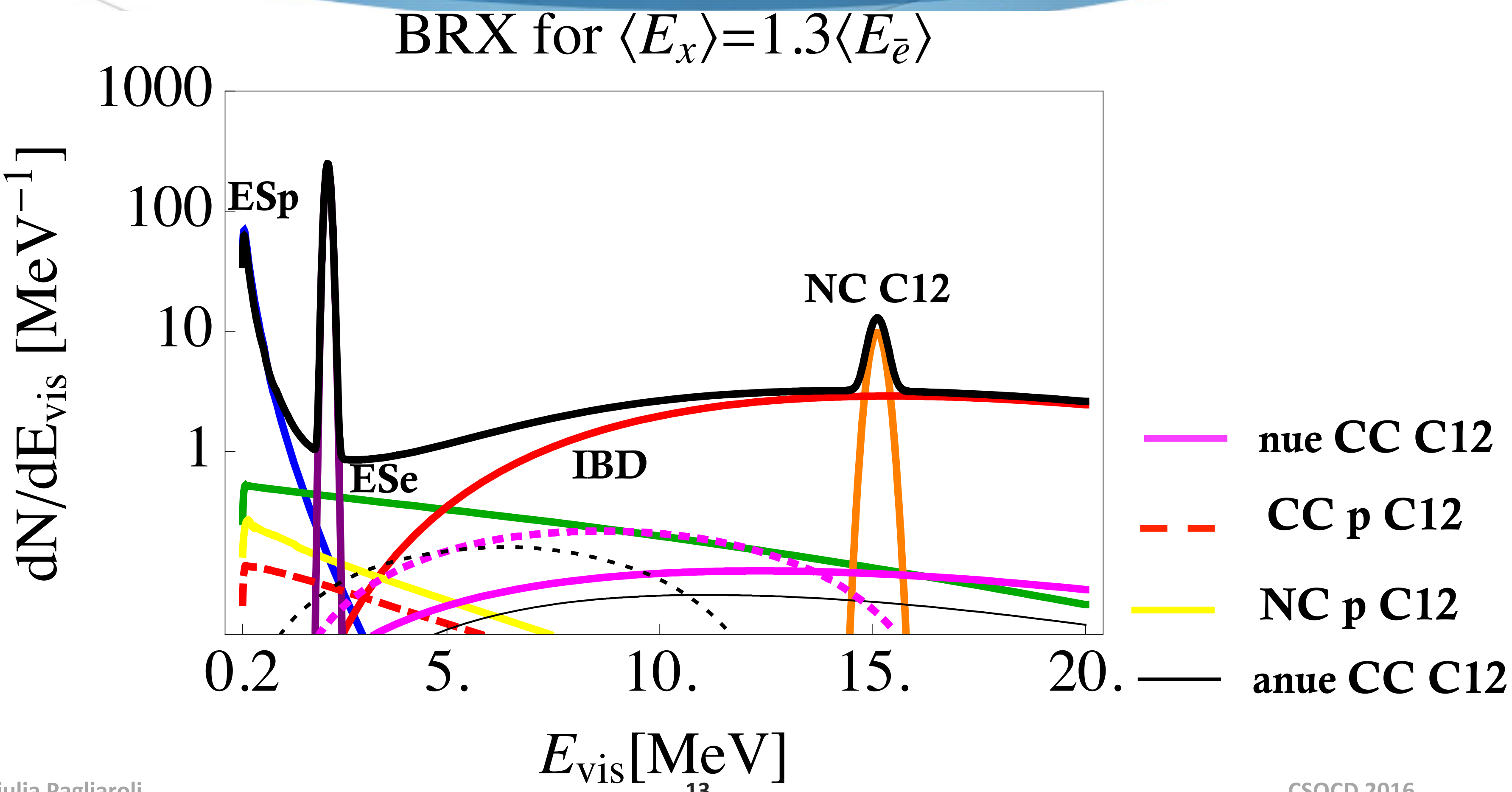

Astrophys.J. 802 (2015) no.1, 47

# BOREXINO Detector




| | BRX |
|---|---|
| Mass ($ktons$) | 0.3 |
| Energy threshold ($MeV$) | 0.25 |
| Scintillator composition | $C_9H_{12}$ |
| Protons ($10^{31}$) | 1.81 |
| Carbon nuclei ($10^{31}$) | 1.36 |
| Electrons ($10^{31}$) | 9.94 |

# BOREXINO SPECTRUM



# Ultrapure Liquid Scintillator SN at 10 kpc

| Channel | Color code | Signal | BRX |
|---|---|---|---|
| $\bar{\nu}_e + p \rightarrow n + e^+$ | red | $e^+$ | 54.1 (49.6) |
| $n + p \rightarrow D + \gamma_{2.2\ \mathrm{MeV}}$ | purple | $\gamma$ | 46.0 (42.1) |
| $\nu + p \rightarrow \nu + p$ | blue | $p$ | 16.0 (5.7) |
| $\nu +^{12} C \rightarrow \nu +^{12} C^*$ | orange | $\gamma$ | 4.7 (2.1) |
| $\nu + e^- \rightarrow \nu + e^-$ | green | $e^-$ | 4.4 (4.6) |
| $\nu_e +^{12} C \rightarrow e^- +^{12} N$ | magenta | $e^-$ | 2.0 (0.7) |
| $\bar{\nu}_e +^{12} C \rightarrow e^+ +^{12} B$ | black thin | $e^+$ | 1.2 (0.8) |
| $\nu +^{12} C \rightarrow \nu + p +^{11} B$ | yellow | $p$ | 0.8 (0.2) |
| $\nu_e +^{12} C \rightarrow e^- + p +^{11} C$ | red dashed | $p$ | 0.5 (0.1) |

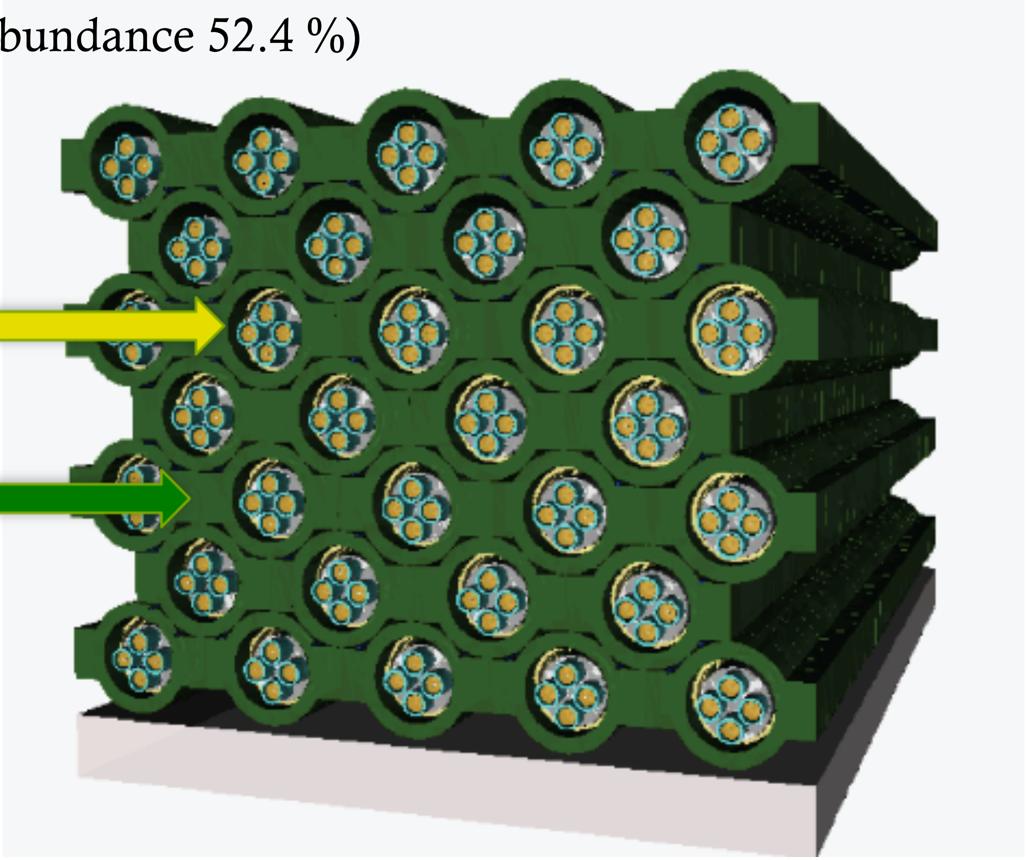
C. Lujan-Peschard, GP and F. Vissani **JCAP 1407 (2014) 051**

# HALO 2 @ LNGS ?

1300 tons of Pb (Opera isotopic abundance 52.4 %)

a Helium and
Lead Observatory

"Helium" – because 3He
neutron detectors
+
"Lead" – because of high
nue-Pb cross sections,
low n-capture cross-section



# Electronic SN Neutrinos

CC interaction processes

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^- \quad E_\nu > 9.26\mathrm{MeV}$$

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^- \quad E_\nu > 24\ \mathrm{MeV}$$

NC interaction processes

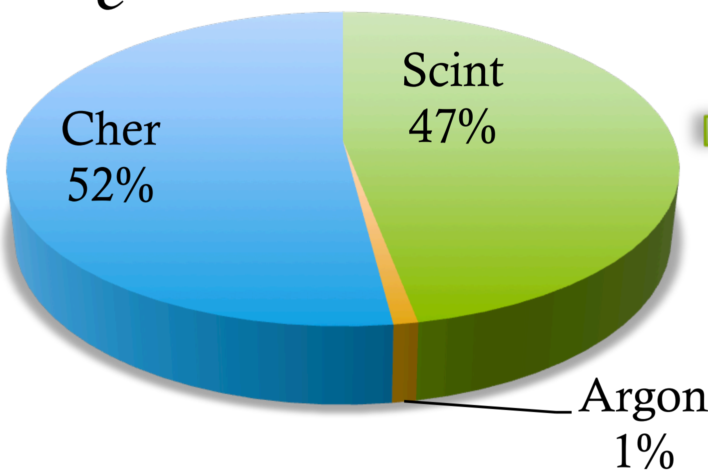
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + \mathrm{n} \quad \mathrm{E}_\nu > 7.37 MeV$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2\mathrm{n} \quad \mathrm{E}_\nu > 17.86 MeV$$

| EVENTS NH (IH) | % due to nu_e NH (IH) |
|---|---|
| 212 (169) | 85 (81) |

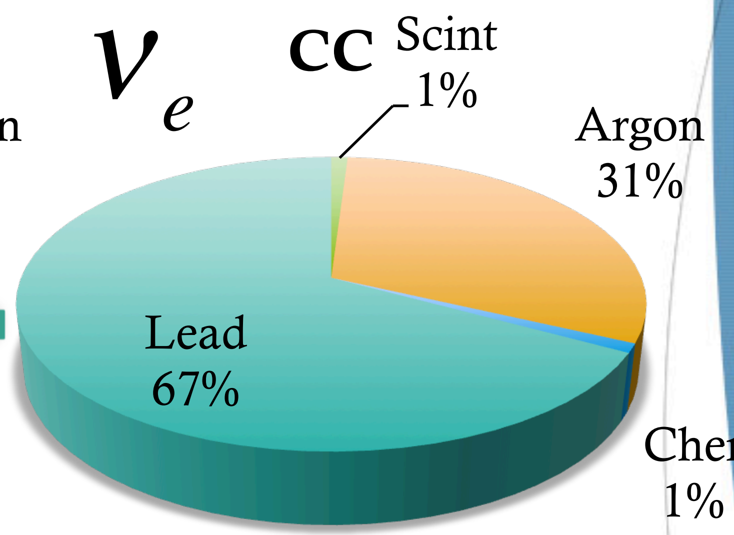
# Flavor Sensitivity @ LNGS

$\bar{\nu}_e$ **CC**



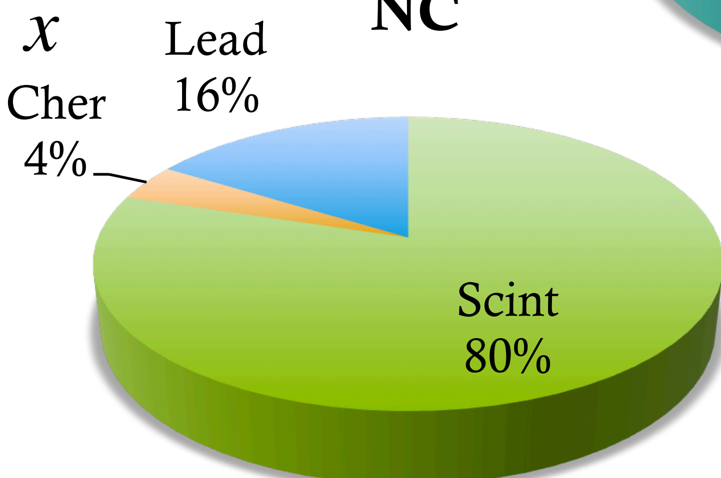

**LVD Detector**

$\nu_e$ **CC**




**HALO 2 Detector**

$\nu_x$ **NC**




**BOREXINO Detector**

# MULTI-MESSENGERS with Gravitational Waves

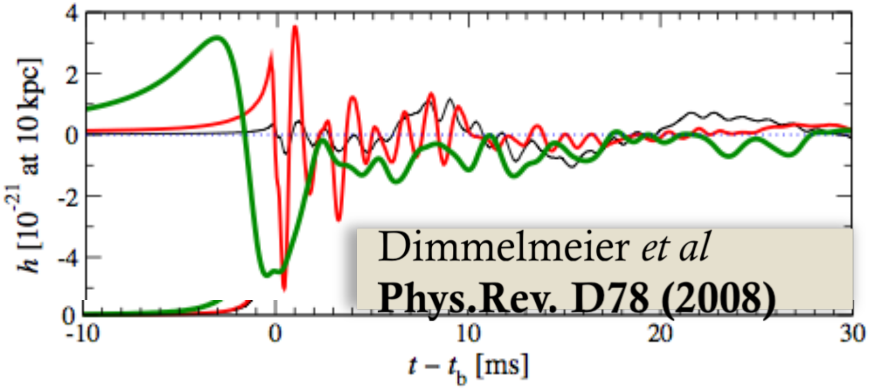
Collaboration:

G.P., E. Katsavounidis, E. Coccia, C. Casentini, V. Fafone, W. Fulgione, F. Vissani, C.Vigorito, G.Testera, C. D. Ott, V. Re, K. Scholberg, M. Gromov, L. Koepke

References:

- Proposal for data exchange among GW detectors: LIGO, Virgo and neutrinos detectors: Borexino, LVD and IceCube
  - I. Leonor *et al.*, **Class.Quant.Grav. 27 (2010)**
  - G.P. *et al.*, **Phys.Rev.Lett. 103 (2009) 031102**

# GW expectations




**ENERGY** $\varepsilon_{GW} \leq 0.0001\% \cdot \varepsilon_B$

**DURATION** $\Delta t = 10 - 1000\ ms$

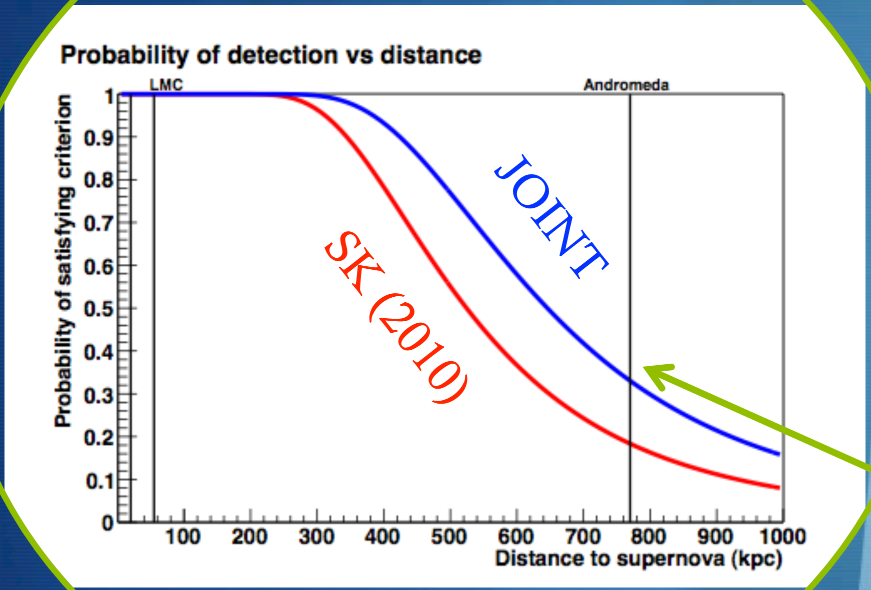
**Amplitude:** $6 \cdot 10^{-23} < h_{max} < 5 \cdot 10^{-20}$

**Frequency:** $\Delta f_{max} = 50 - 1000\ \text{Hz}$

Uncertainty on the prediction of orders of magnitude!

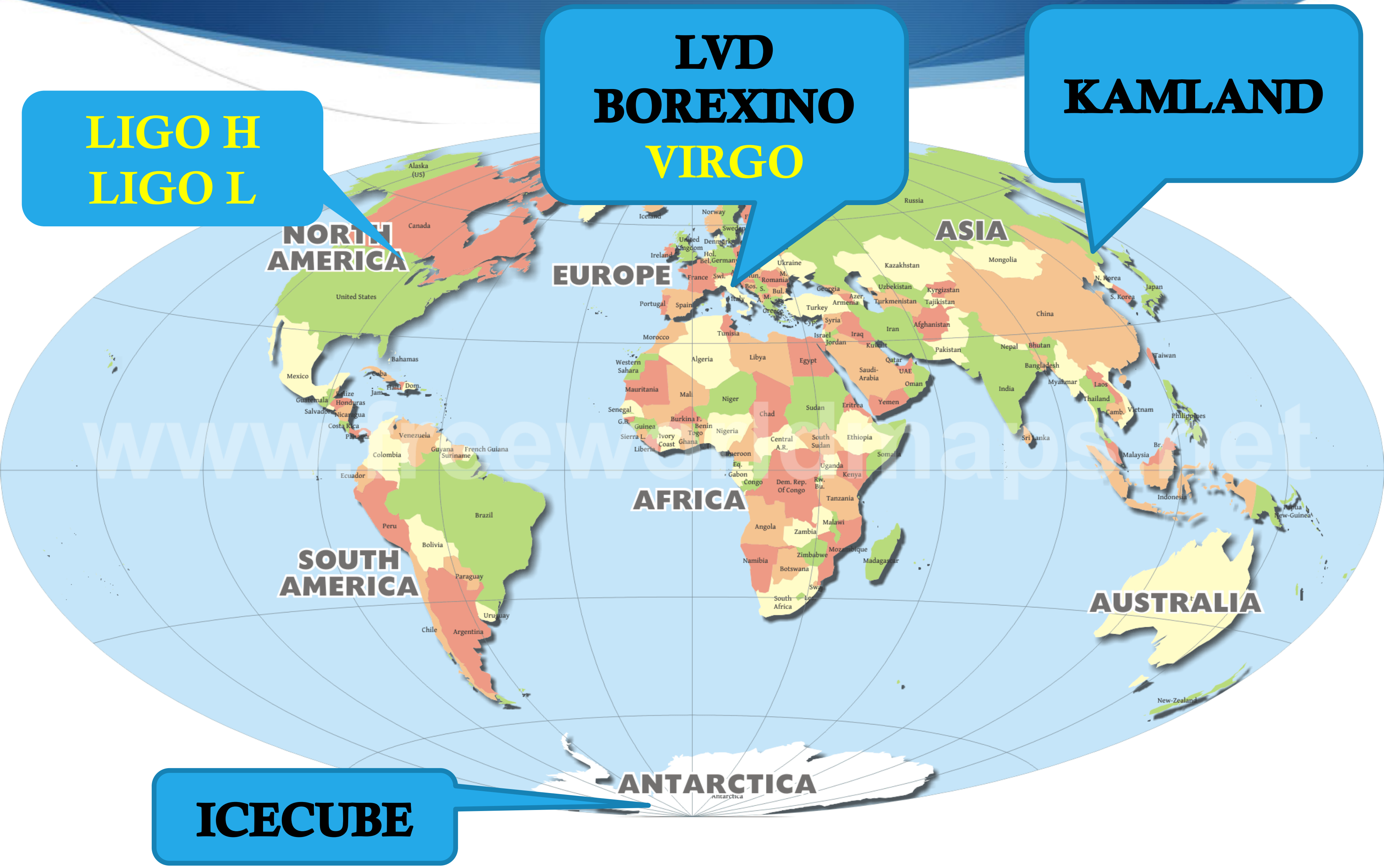
**Signals cannot be modeled.**
**It's very compelling to discriminate**
**These short duration bursts of GWs**
**From the spikes due to the Noise**

# Distance Reach




- Super-Kamiokande 's recent "distant" burst search requiring two neutrino events (with energy threshold 17 MeV) within 20 seconds shows a ~**18%** probability of detecting a SN in M31
- Requiring the coincidence with a GW trigger it is possible to lower the threshold to 8.5 MeV increasing the detection probability to the ~**35%**

Leonor et al. Class.Quant.Grav. 27 (2010) 084019



LIGO H
LIGO L
LVD
BOREXINO
VIRGO
KAMLAND
ICECUBE
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
ASIA
AUSTRALIA
ANTARCTICA
www.freeworldmaps.net

# Conclusions

- Neutrinos emitted from CCSNe can be fundamental probes to infer about the explosion mechanism
- LNGS shows an interesting dedicated program
- A complete picture can be obtained only by combining different detectors techniques