Combined search of MeV ν and GWs from astrophysical sources

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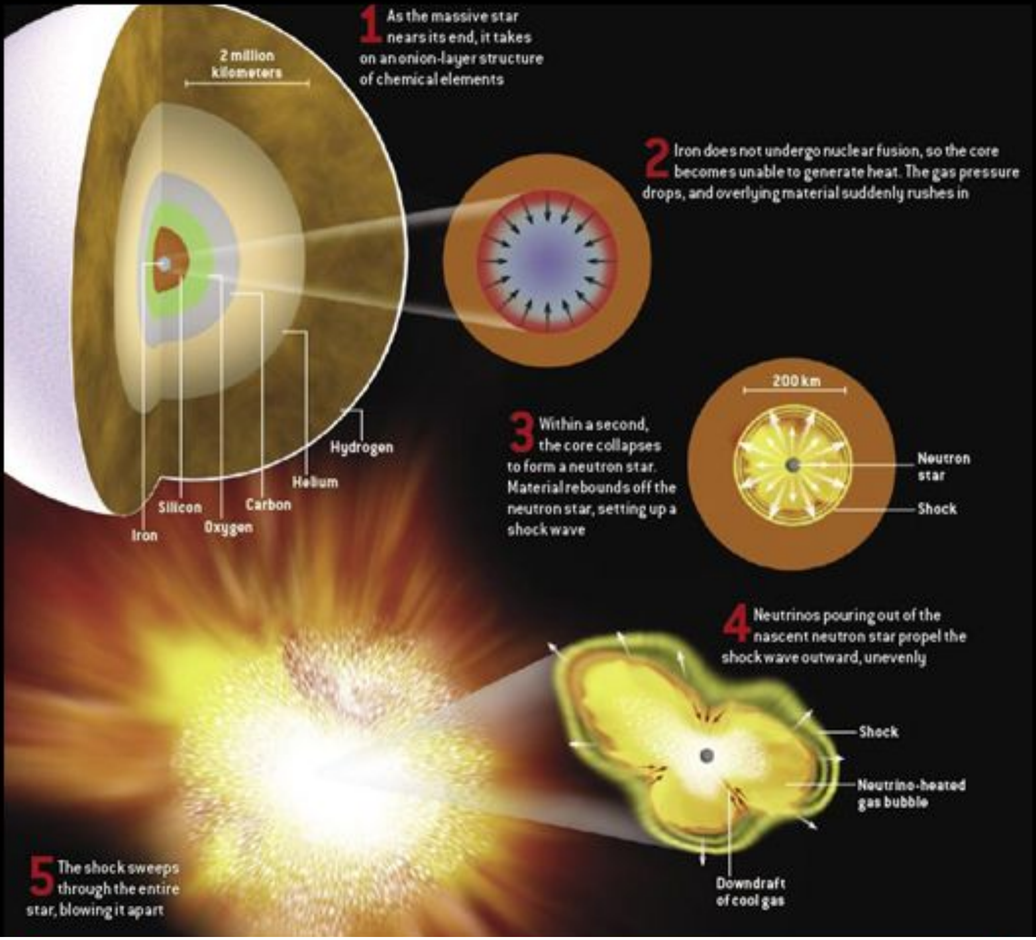
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Outline

- Sources of low-energy neutrinos bursts and GWs
- Combined search of GWs and neutrinos
  - **Novel Search Method for ν bursts**
- Results

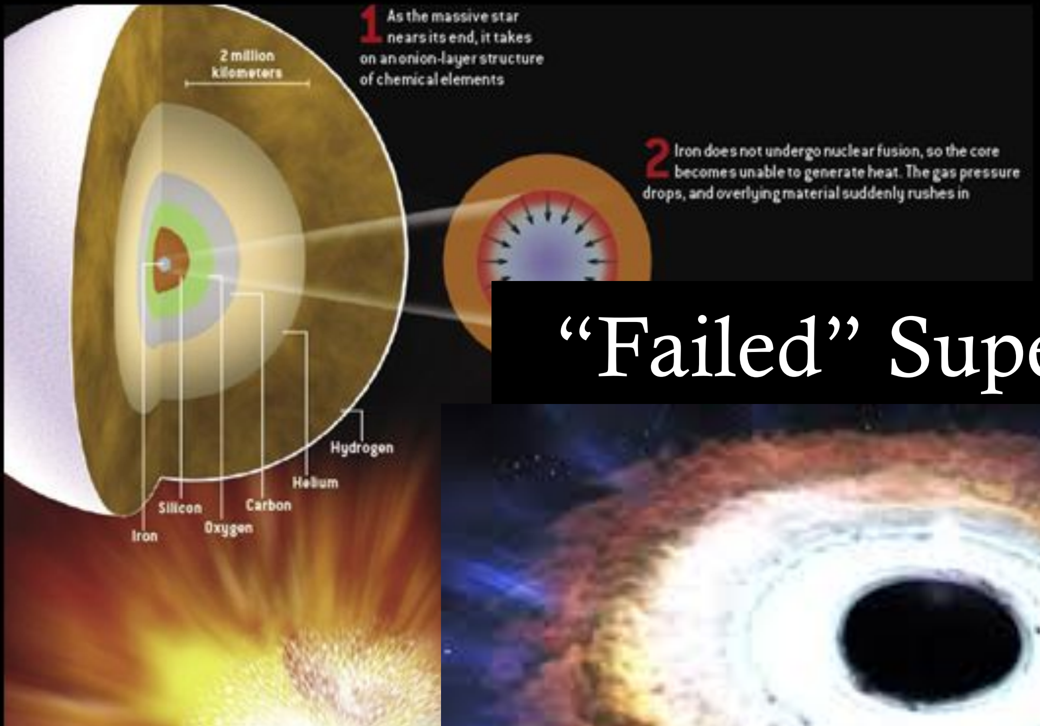
Core Collapse Supernovae



SOURCES

SOURCES

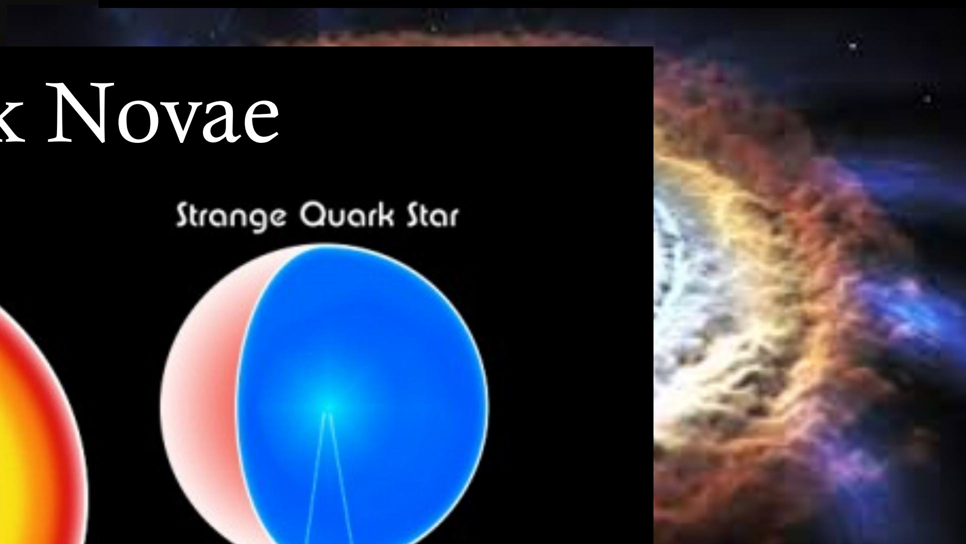
Core Collapse Supernovae



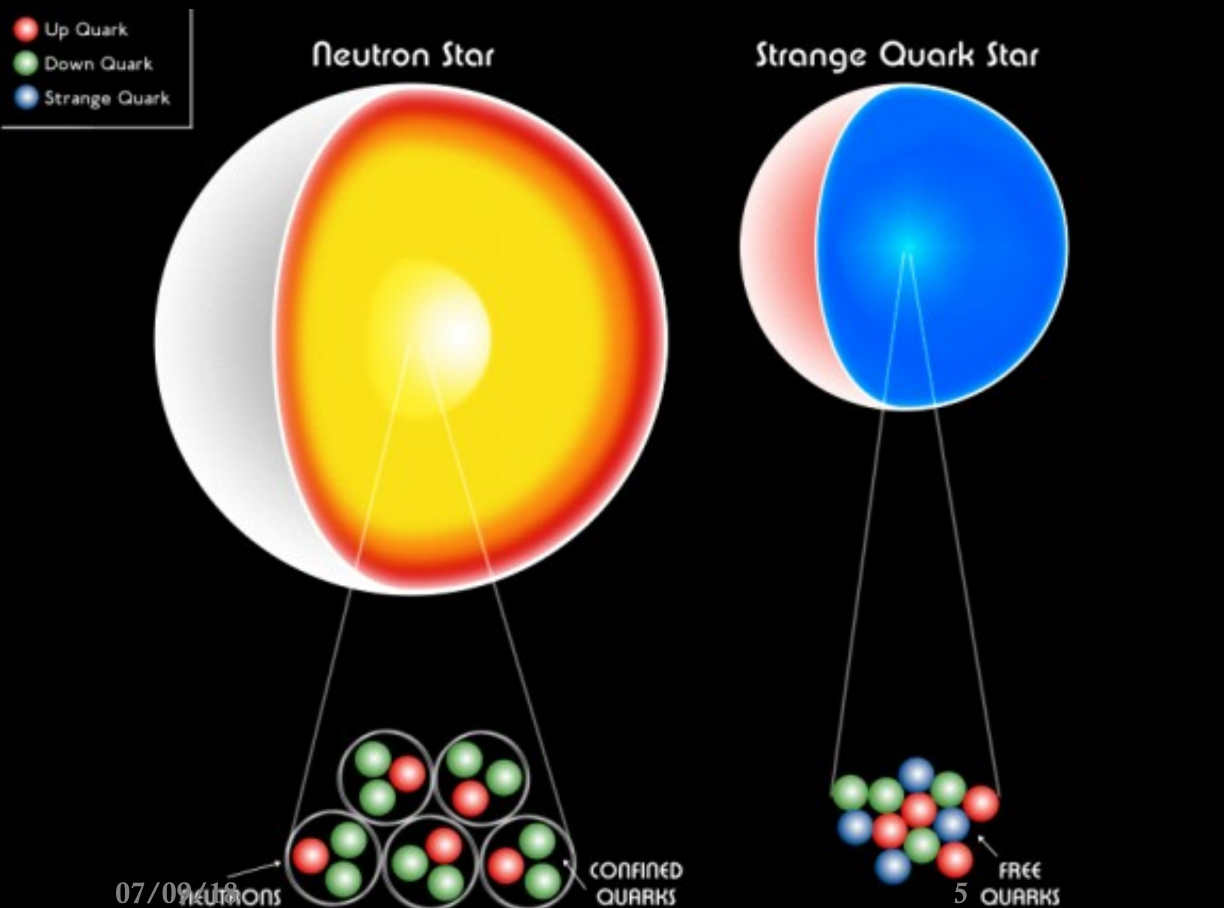
“Failed” Supernovae

Core Collapse Supernovae

"Failed" Supernovae



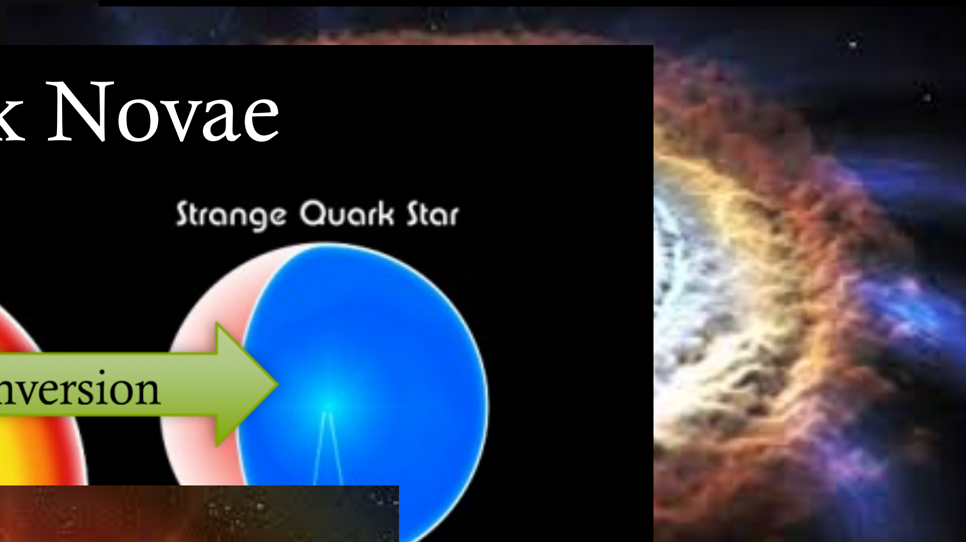
Quark Novae



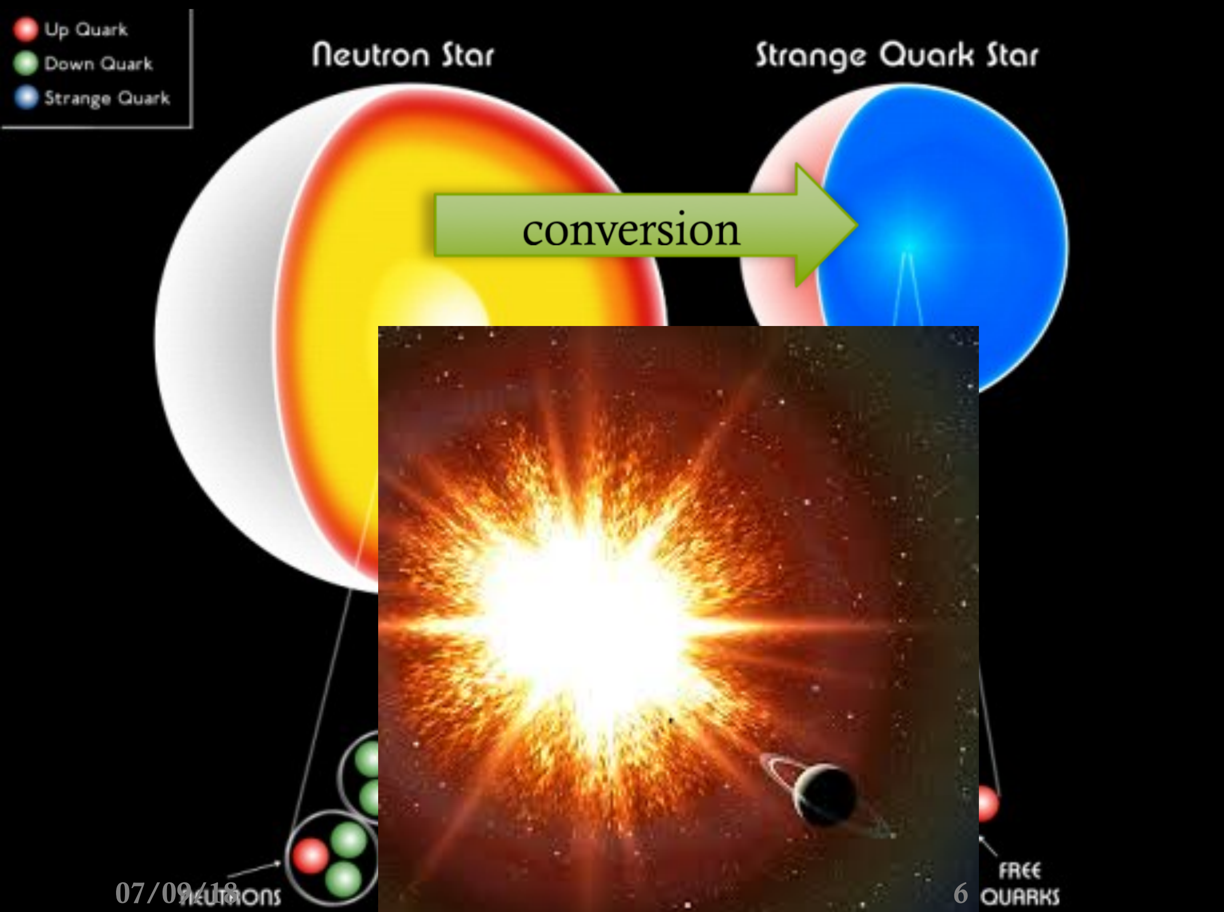
SOURCES

Core Collapse Supernovae

"Failed" Supernovae



Quark Novae



SOURCES

Core Collapse Supernovae

"Failed" Supernovae

Quark Novae

Common Signature:
Impulsive Neutrinos Emission

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

$$\Delta t \cong 10\,\text{sec}$$

SOURCES

Core Collapse Supernovae

"Failed" Supernovae

Quark Novae

Common Signature:
Impulsive GWs Emission

ENERGY

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

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

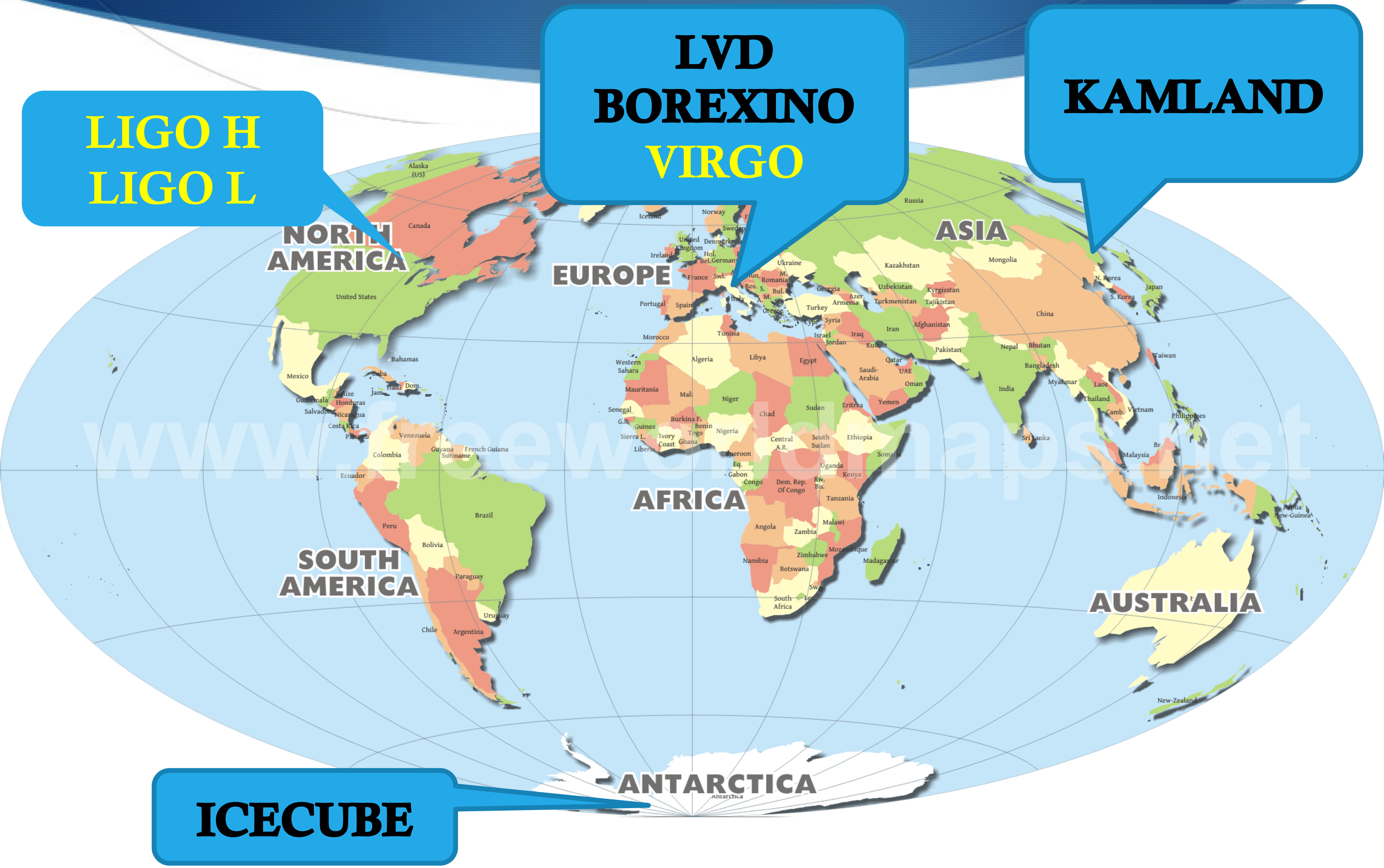
AMPLITUDE

$$10^{-23} < h_{\max}(10\,\mathrm{kpc}) < 10^{-20}$$

DURATION

$$\Delta t = 10 - 1000\, ms$$

SOURCES


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

GWNU *overview*

ν network:
- Trigger definition;
- Detection efficiency.

GW network:
- Trigger definition;
- Detection efficiency.

Global network

Joint GW- ν Search

Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate | GW back. Rate | Neutrino back. Rate | Time coincidence window

$$\mathrm{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w$$

- **FAR=1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.**
- w=10 sec to accomodate most emission models

Joint GW-ν Search

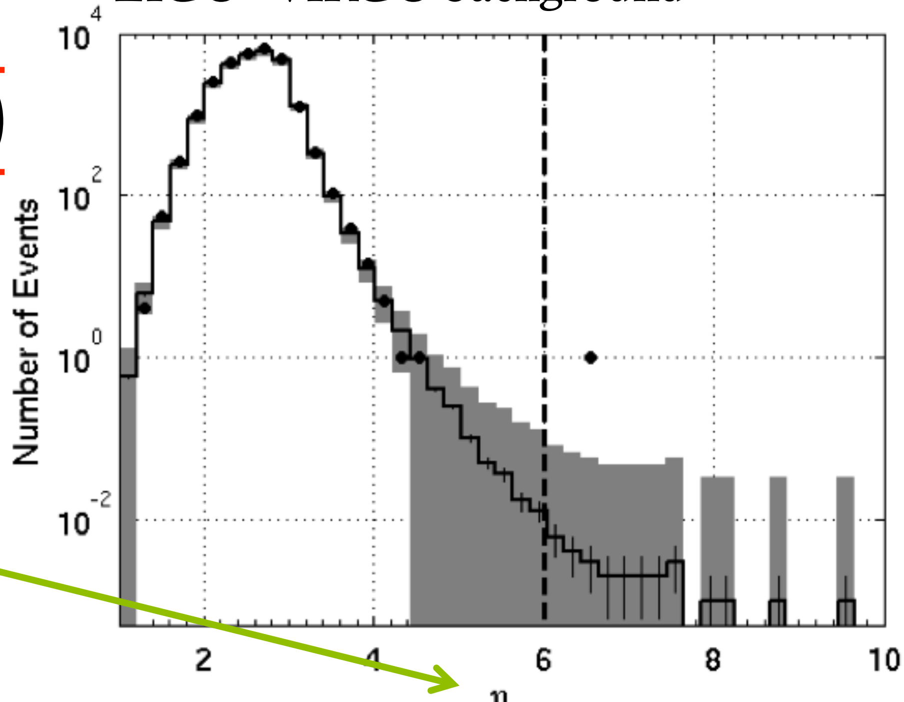
Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate GW back. Rate Neutrino back. Rate Time coincidence window

$$FAR = R_{GW}(\eta)$$

GW detectors work in a combined way and η is the **"Joint coherent statistics"** for the search of GWs

LIGO+VIRGO background



Ababie *et al.* **Phys.Rev. D81 (2010) 102001**

Joint GW- ν Search

Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate | GW back. Rate | Neutrino back. Rate | Time coincidence window

$$\mathrm{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w$$

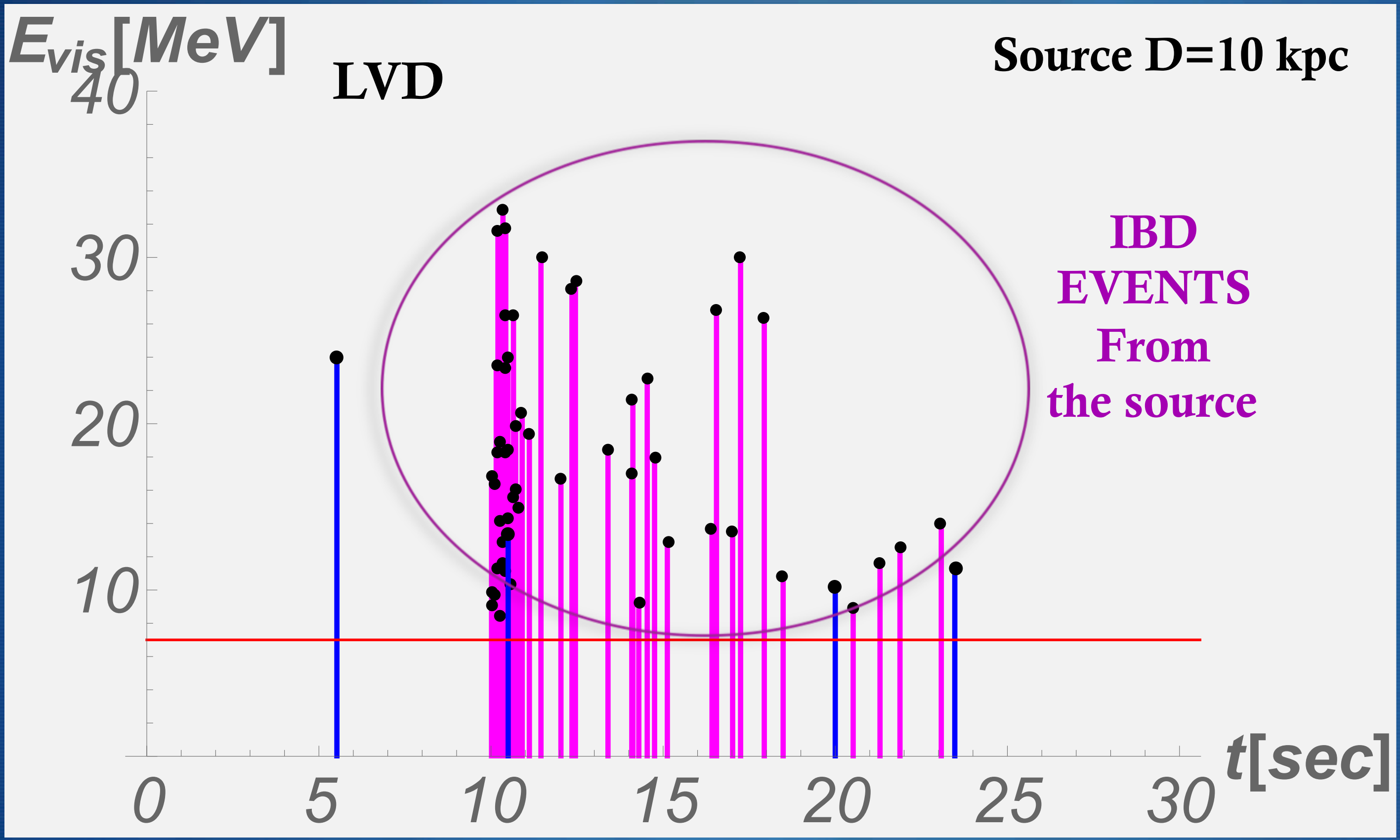
Neutrino detectors should work in a more combined way.

GOAL: Identify the **"Joint coherent statistics"** for the search of neutrino bursts

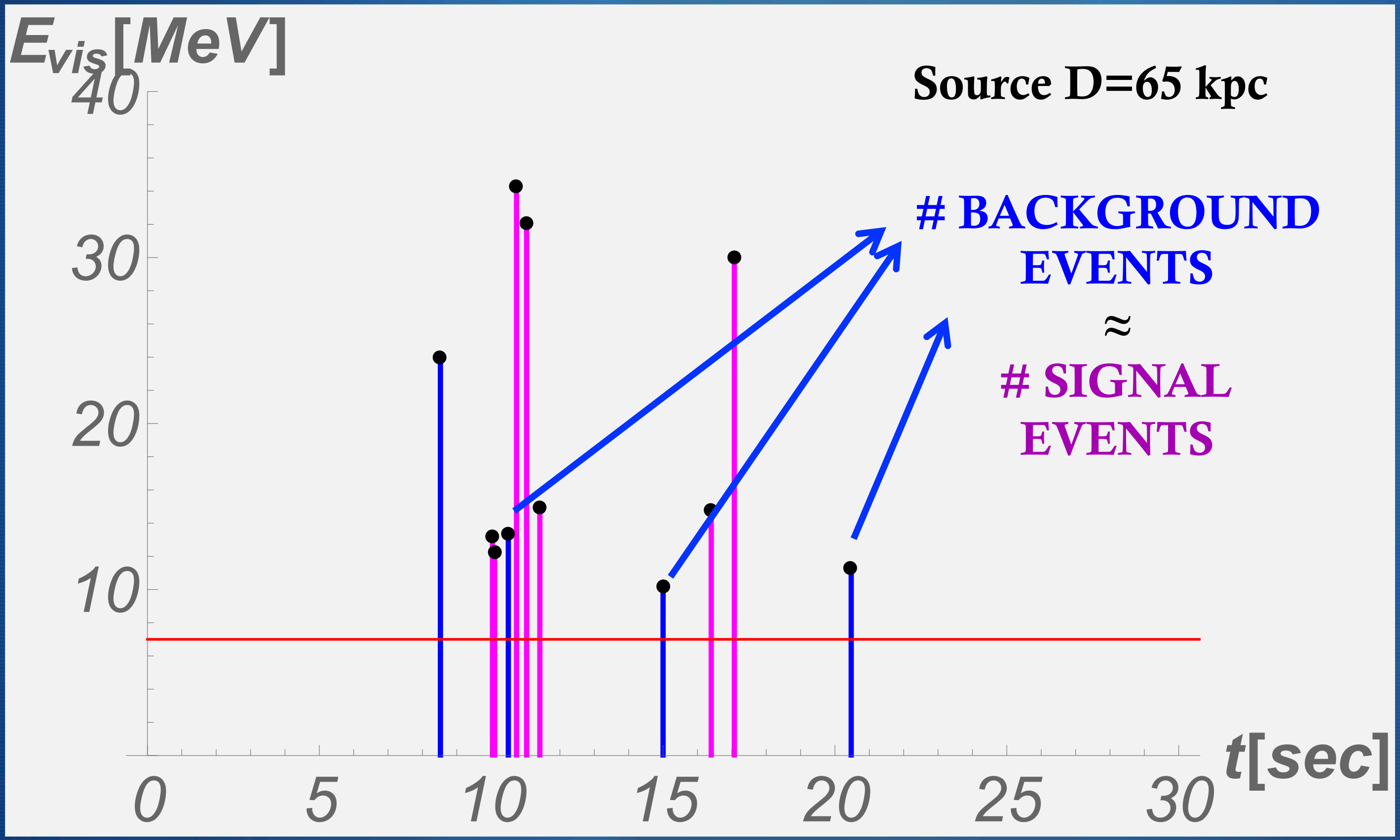
Novel Search Method for ν bursts

Casentini, Pagliaroli, Vigorito, Fafone,
JCAP 1808 (2018) n.08,010

The observation of an astrophysical burst



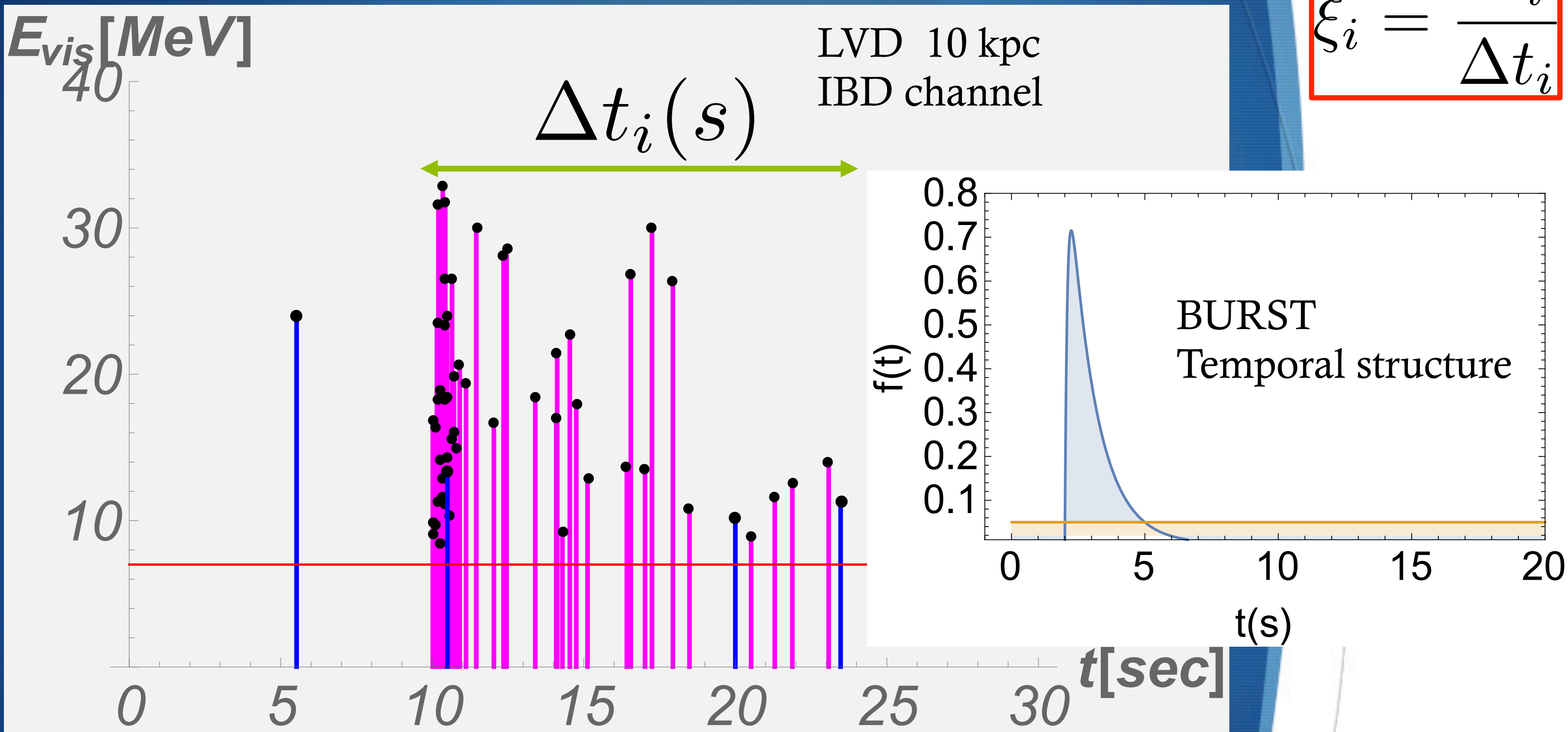
The identification of a small statistics signal



SIGNAL OR BACKGROUND FLUCTUATION?

The observation of an astrophysical burst

$$\xi_i = \frac{m_i}{\Delta t_i}$$



$w = 20s$

m_i

Number of events inside the window

Neutrinos Experiments

10 years of background data

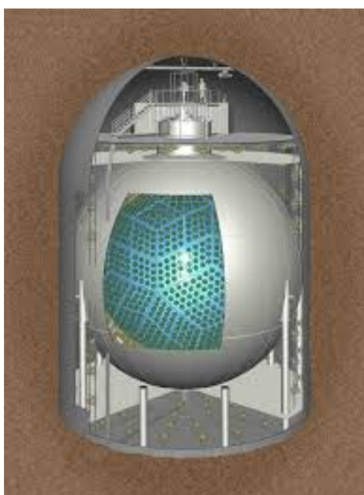
3650 injected signals

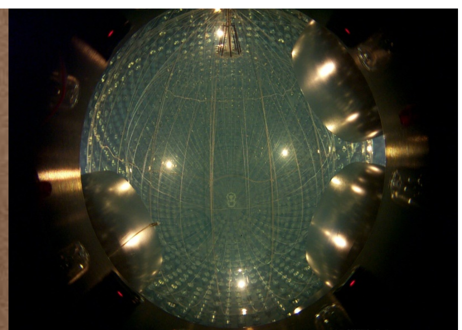
Kamland
- Liquid Scintillator
- Energy & NC
- M= 1 kton

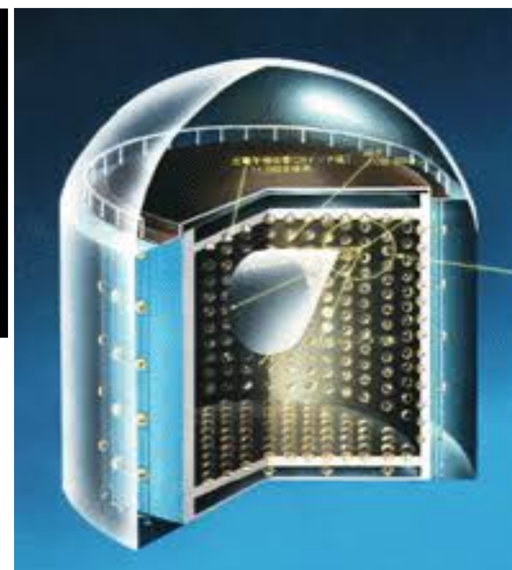
Borexino
- Liquid Scintillator
- Energy & NC
- M= 0.3 kton

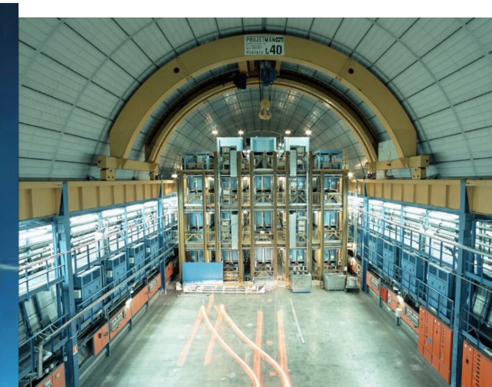
SuperK
- Water Cerenkov
- Energy & NC
- M≈ 22 kton

LVD
- Liquid Scintillator
- Energy & NC
- M= 1 kton







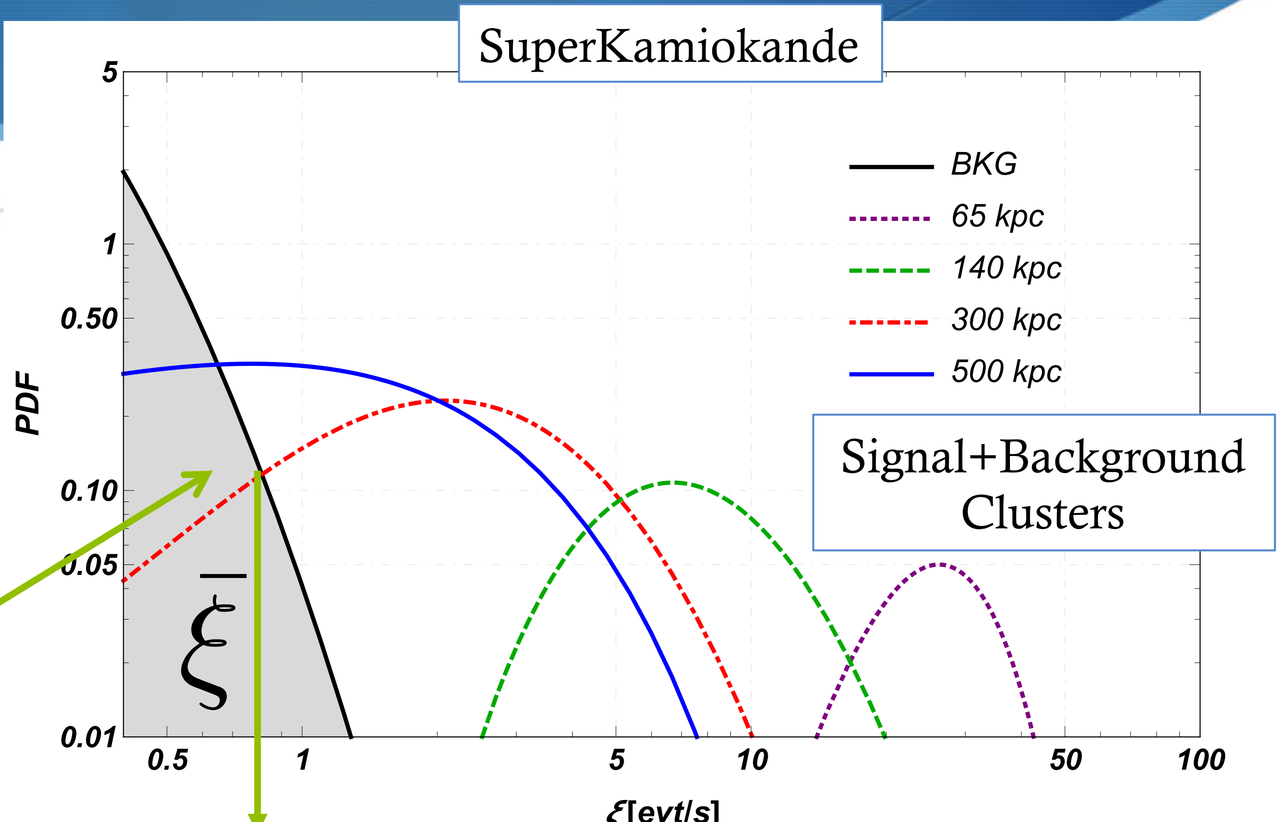


Background-Signal separation

Probability density Distributions

$$\xi_i = \frac{m_i}{\Delta t_i}$$

Pure Background Clusters



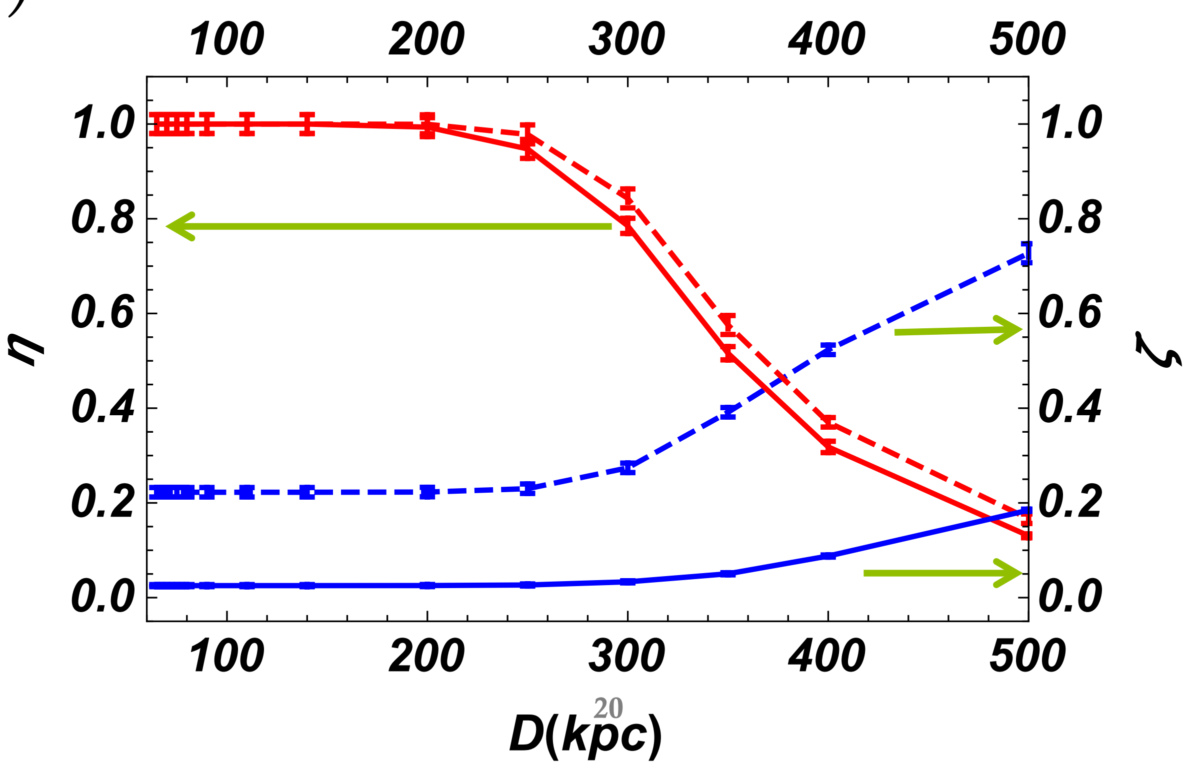
Cutting value for the ξ parameter providing Maximum of the signal to noise ratio

CLUSTERS WITH $\xi_i < \bar{\xi}$ ARE ELIMINATED

Results for SuperKamiokande

$\eta(D)$ Detection efficiency = Survived signals/Injected signals

$\zeta(D)$ Misidentification probability = Background clusters/Survived clusters



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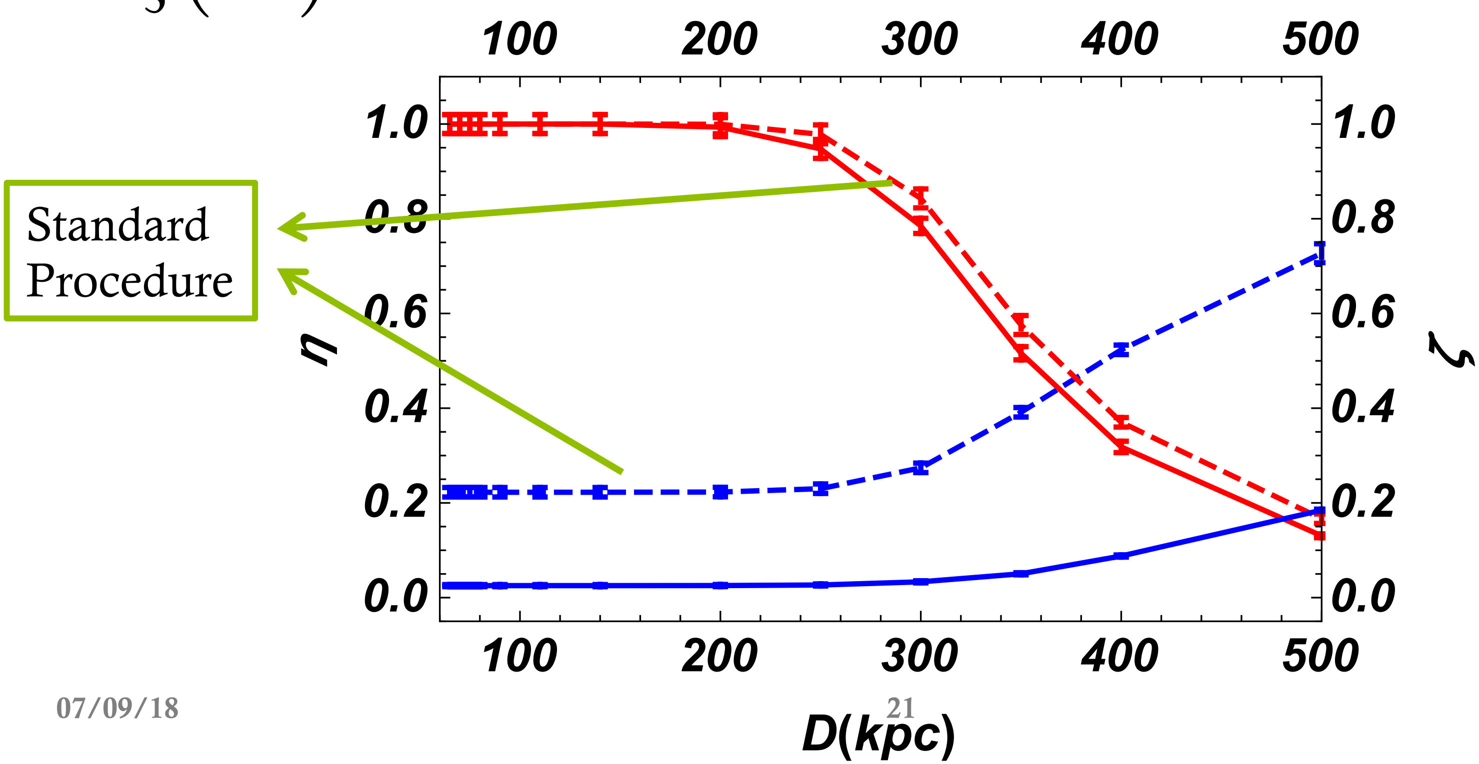

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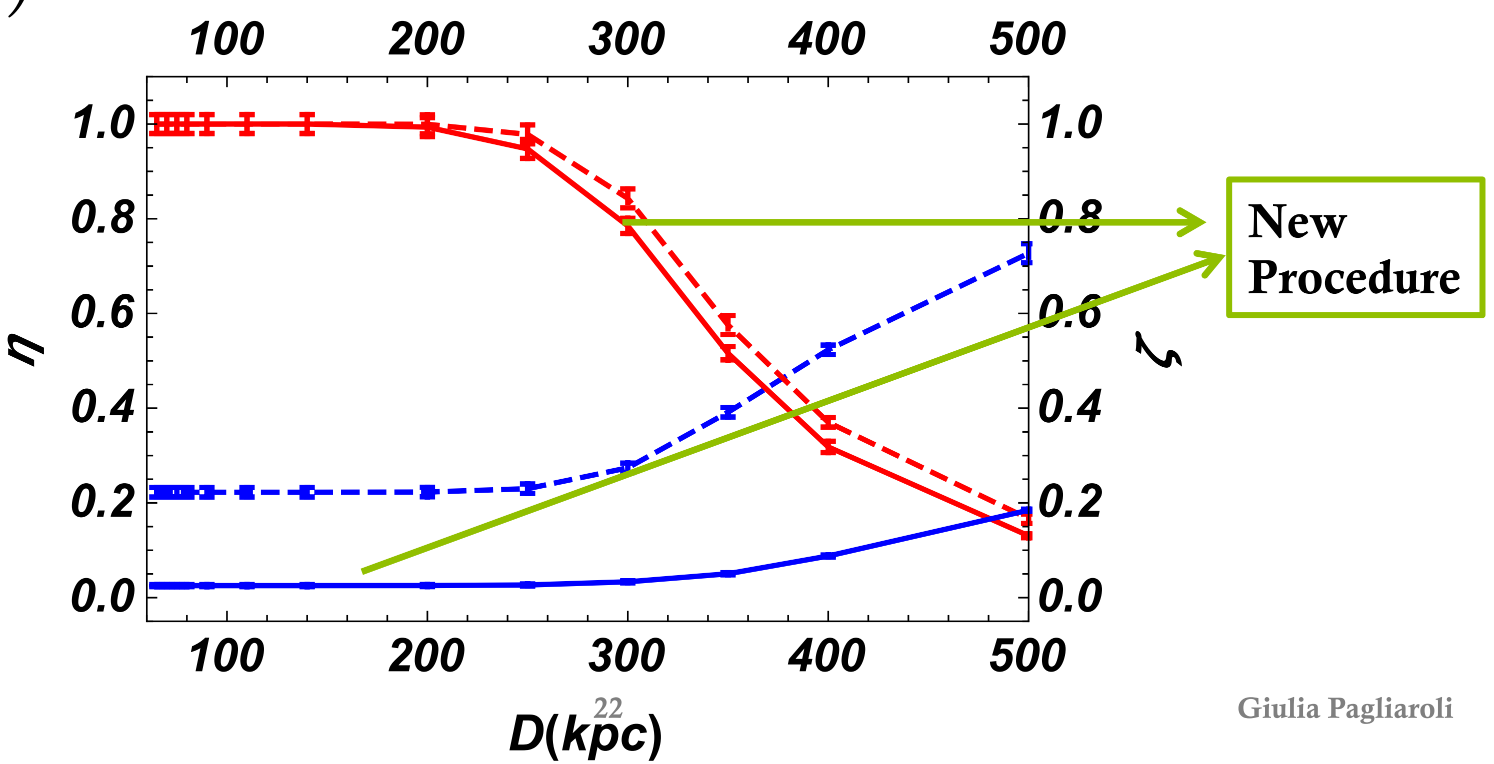


Results for SuperKamiokande

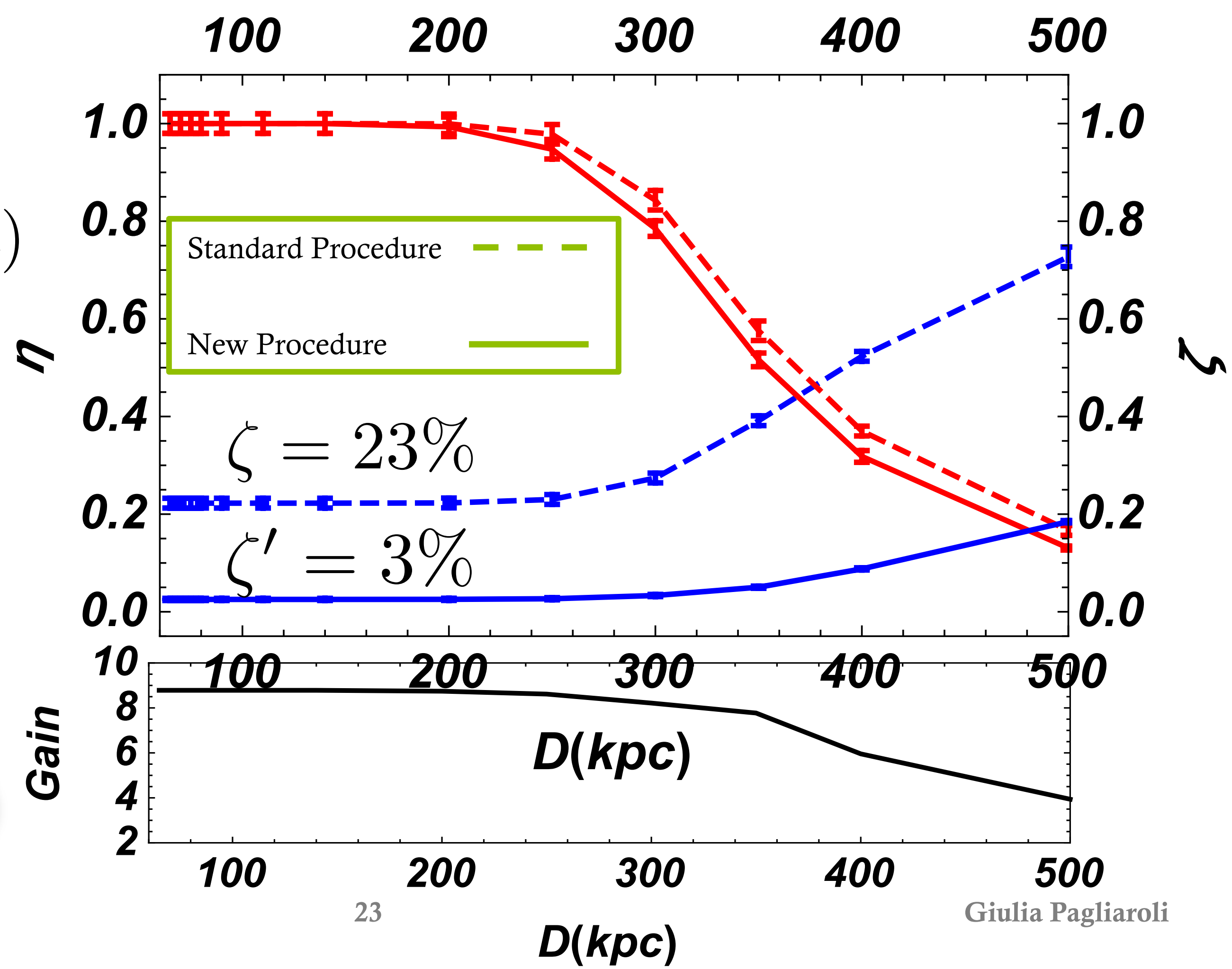
No Efficiency loss for

$$D \leq \bar{D} = 200(kpc)$$

Gain factor on the misidentification probability

$$\text{Gain} = \zeta/\zeta'$$

$$\text{Gain} = 8.9$$

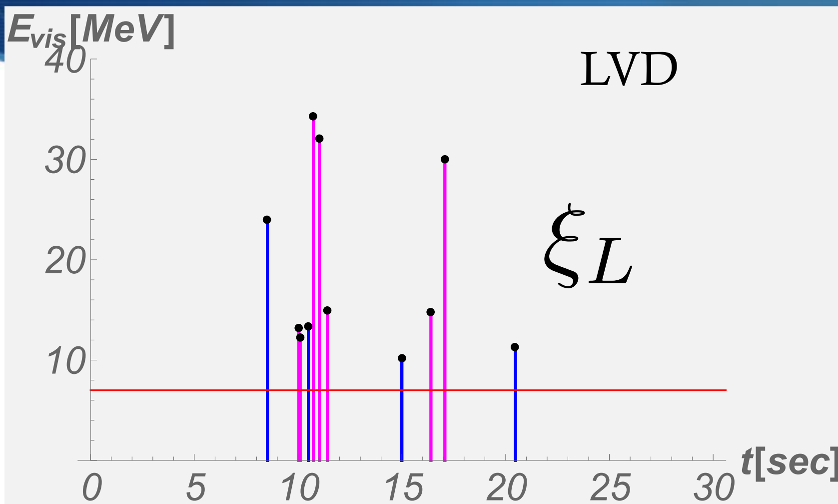


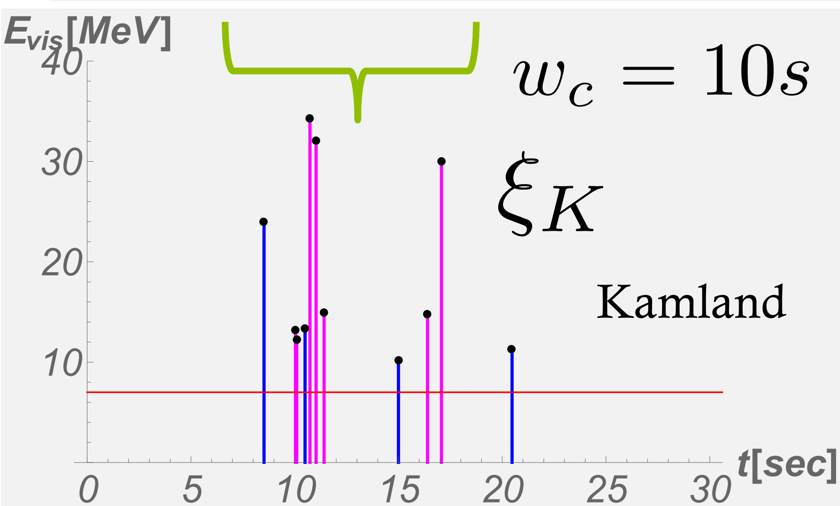
Gain Factors

Detector	M(kton)	E_{thr}(MeV)	f_{bkg} (Hz)	$\bar{\xi}$(Hz)	$\bar{D}$(kpc)	G
Borexino	0.3	1	0.048	0.65	20	6.9
SuperK	22.5	7	0.012	0.72	200	8.9
KamLAND	1	1	0.015	0.77	50	13.4
LVD	1	10	0.028	0.72	40	14.0

Table 1: Columns in order show: sensitive detector mass in kton; energy threshold considered for the anlisys in MeV; average background frequency in Hz; value for the $\bar{\xi}$ parameter that maximize the signal to noise ratio, as described in the text; maximal distance $\bar{D}$ without efficiency loss after the new cut; gain factor obtained by using the new proposed method.

Clusters Selection for Networks





$$\sqrt{\xi_L * \xi_K} > \sqrt{\bar{\xi_L} * \bar{\xi_K}}$$

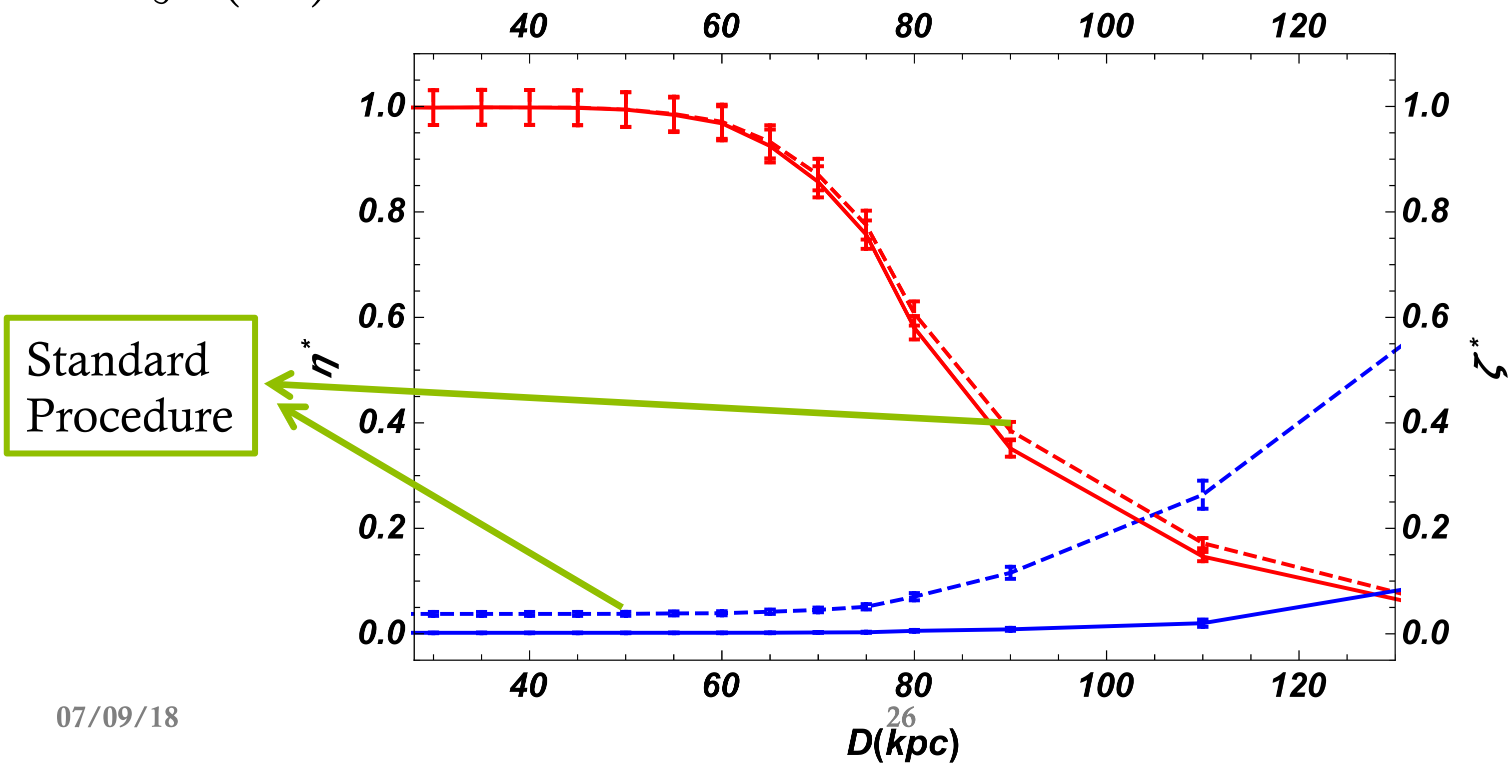
The product of the ξ values bigger than:

$$\bar{\xi}^* = \sqrt[Net]{\prod_i^{Net} \bar{\xi_i}}$$

The network LVD+Kamland

$\eta^*(D)$ Detection efficiency = Survived coincidences/Injected signals

$\zeta^*(D)$ Misidentification probability = Background coincidences/Total



The network LVD+Kamland

$\eta^*(D)$ Detection efficiency = Survived coincidences/Injected signals

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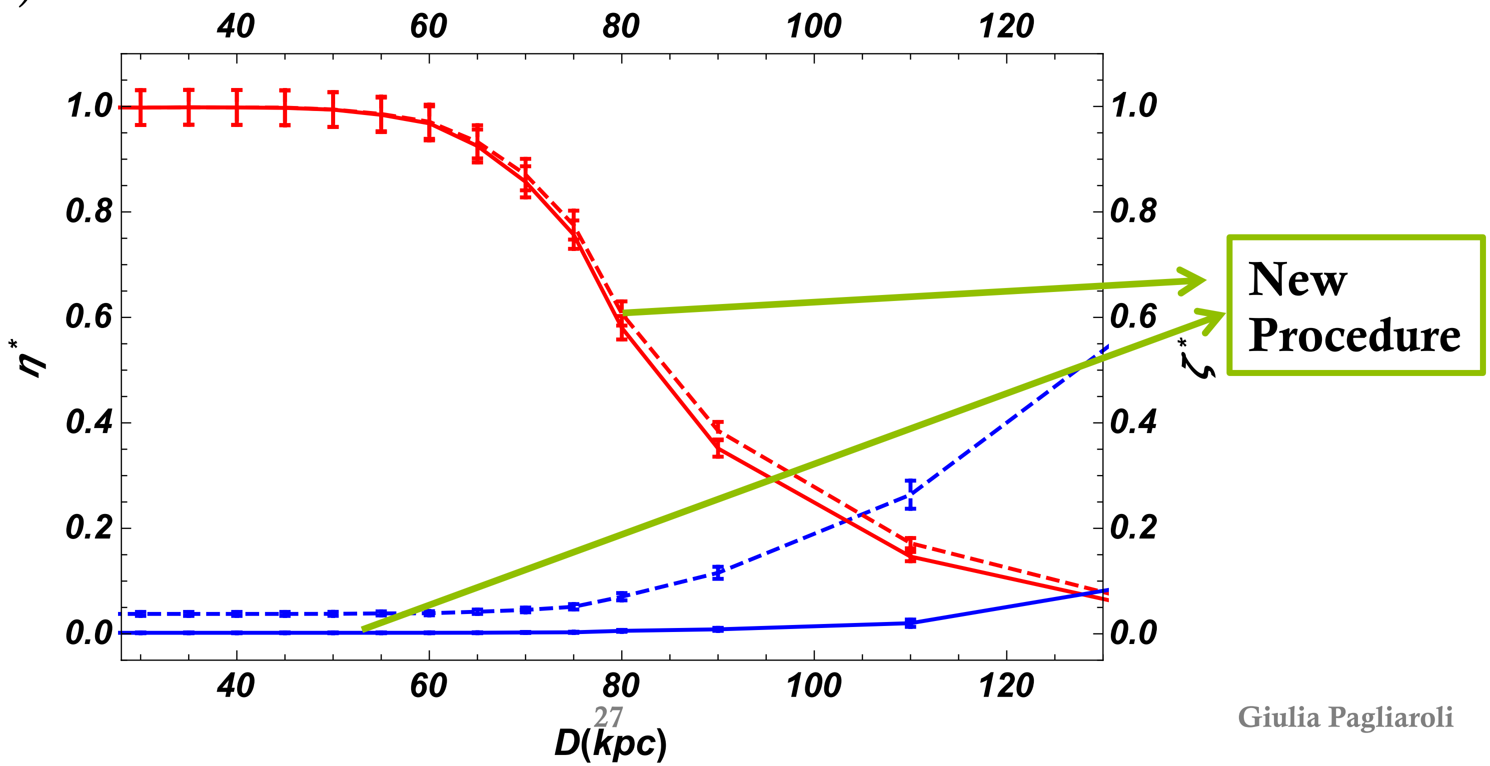


Results for a network LVD+Kamland

No Efficiency loss for

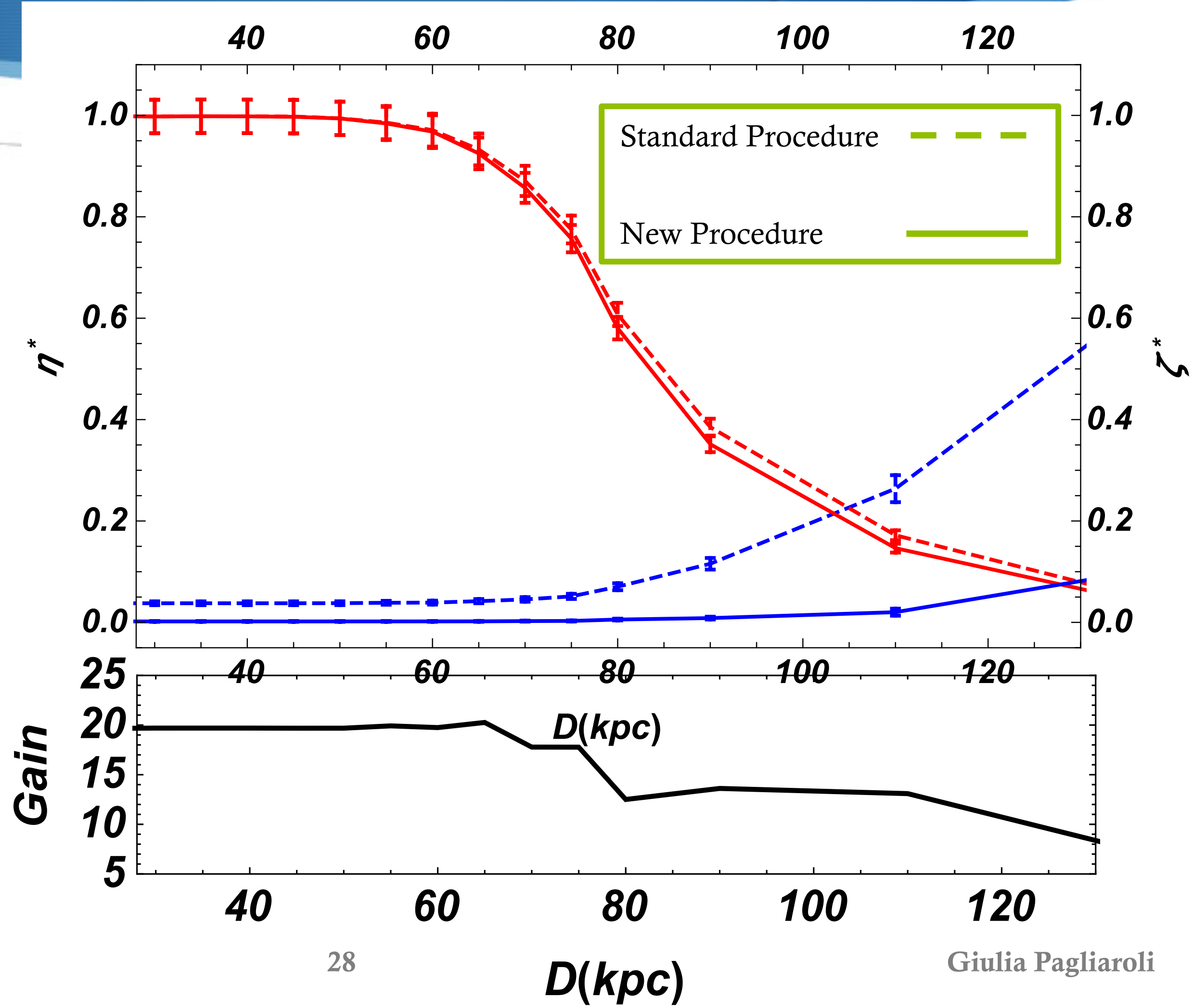
$$D < \bar{D} = 75kpc$$

Gain factor on the misidentification probability

$$\zeta^* = 4\%$$

$$\zeta^{*'} = 0.2\%$$

$$\text{Gain} = 20$$



Conclusions

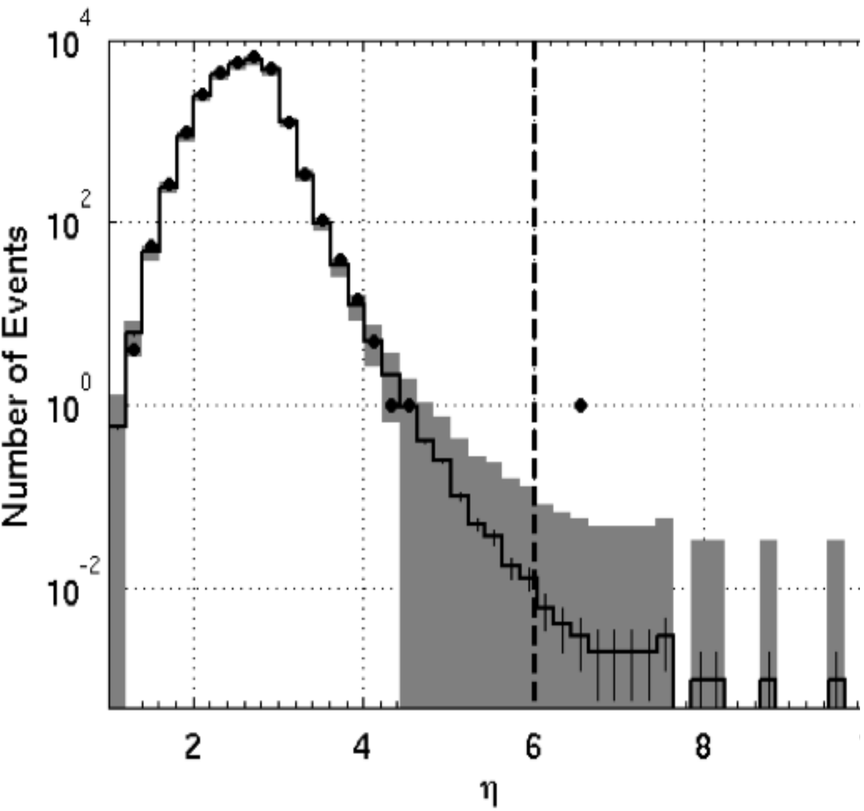
The novel proposed method:

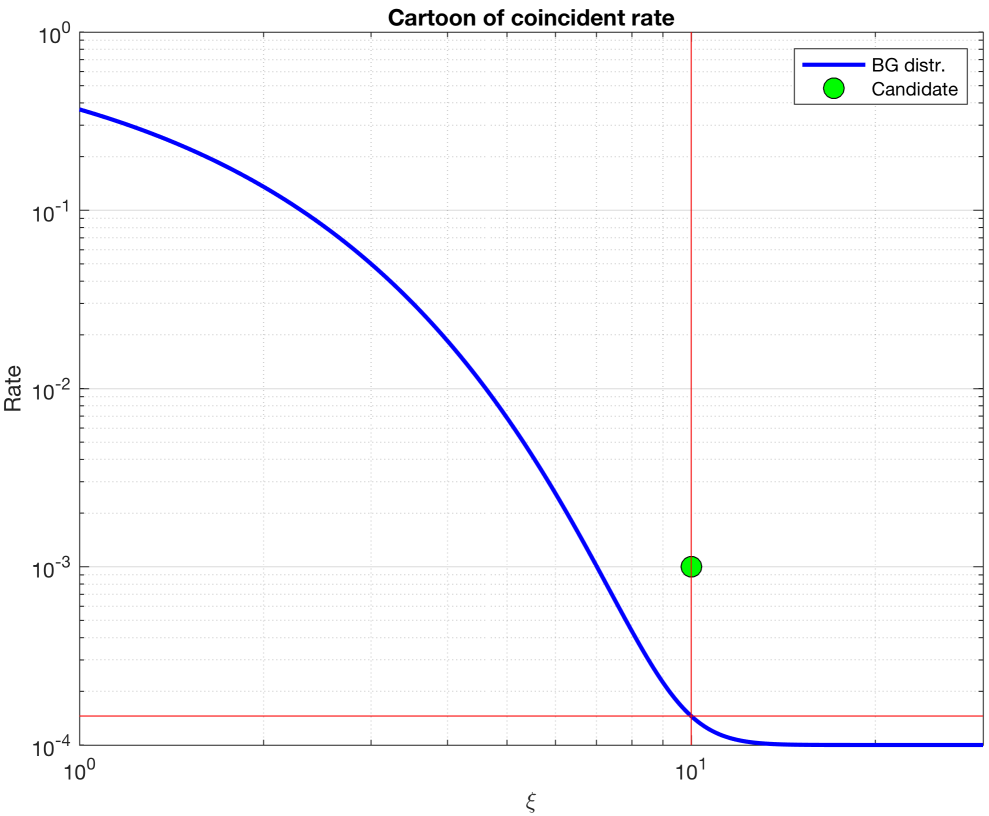
- Exploits the temporal structure of a burst emission
- Applies to different detectors or networks of detectors
- Allows to decrease the misidentification probability between a factor 10-20 without loosing on detection efficiency
- Can be considered as the "joint statistic" for the neutrino network

$$\mathrm{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w$$

ON GOING

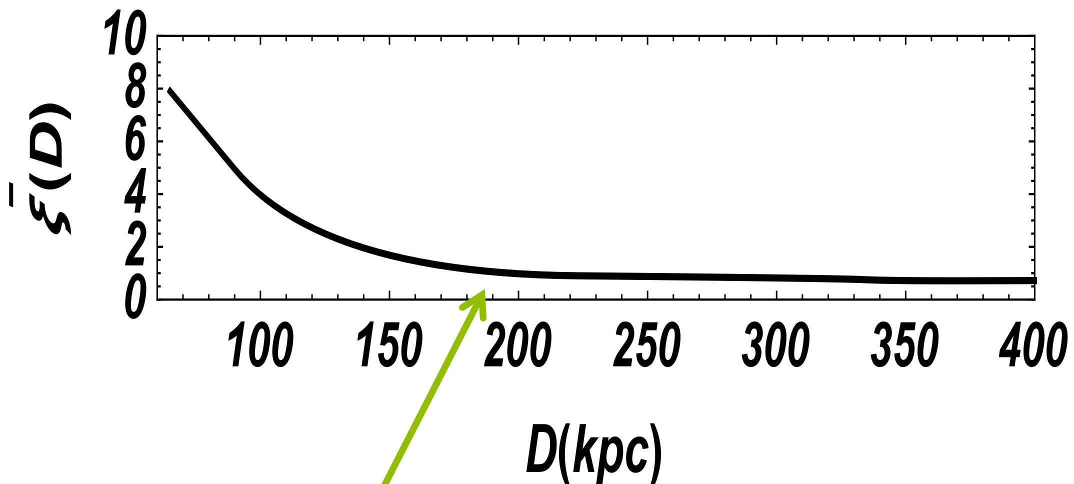
$$\text{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w$$





Backup Slides

Optimal cut value for blind search



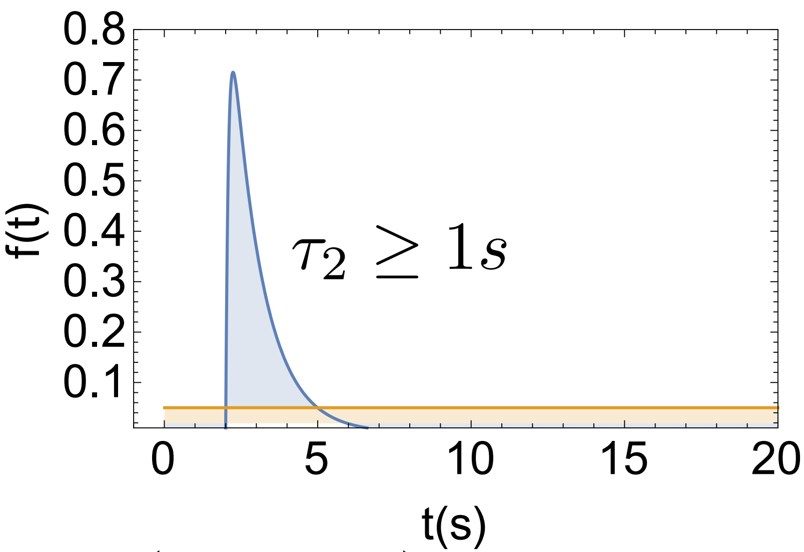
The distance of the source is unknown and the search is optimized to the larger distance allowed by the proposed method

$$\bar{\xi} = 0.72$$

CLUSTERS WITH $\xi_i < \bar{\xi}$ ARE ELIMINATED

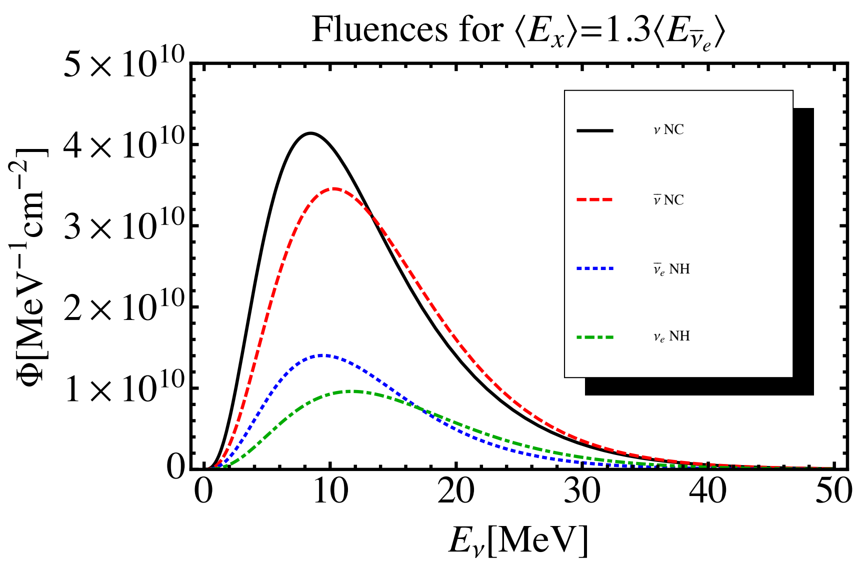
Neutrinos Burst

$$f(t) = (1 - \exp(-t/\tau_1))\exp(-t/\tau_2)$$



$$\tau_1 = (10 - 100)ms$$

Normal Hierarchy



$\langle E_{\nu_e} \rangle = 9$ MeV $\langle E_{\bar{\nu}_x} \rangle$=15.6 MeV

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

SNEWS comparison

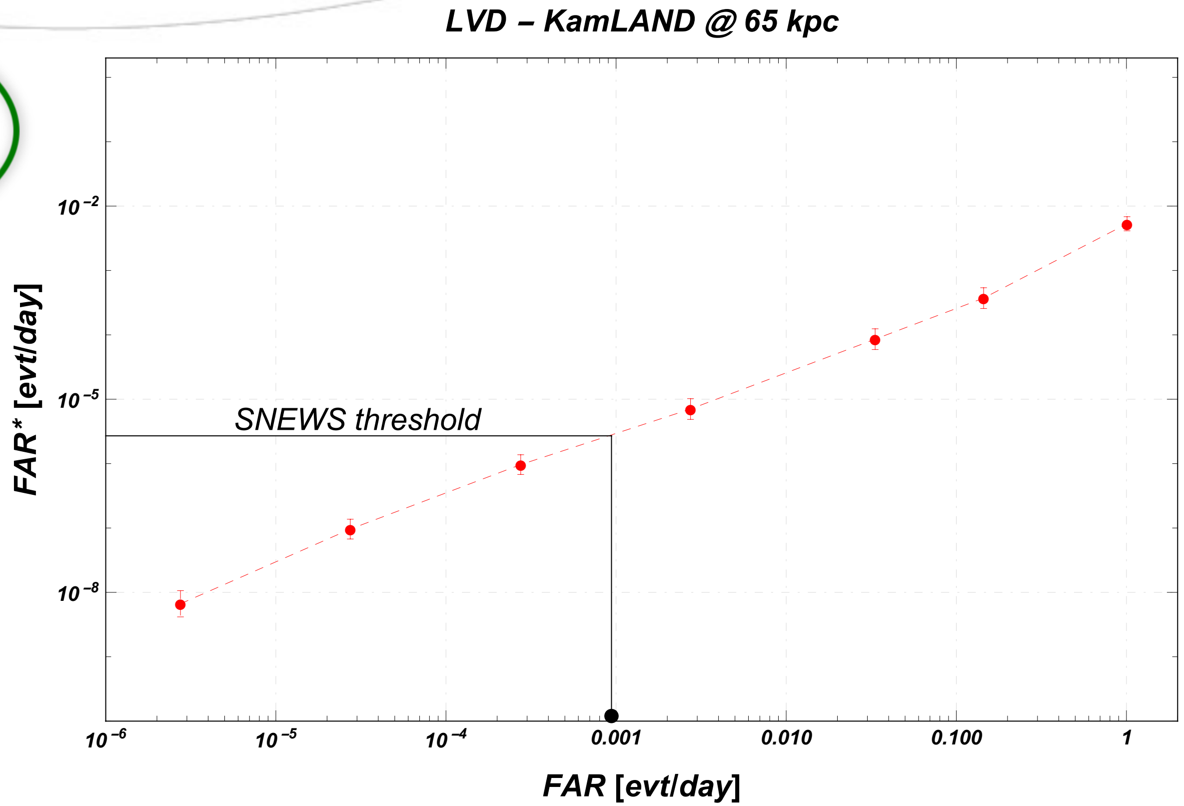
SNEWS threshold
$FAR^* = 1/1000$ years

EQUIVALENT

$FAR = 0.365/year$

+

$\bar{\xi}^*{}_{cut}$



Increasing the detection probability of faint signals 57%->75%

Clusters Selection

- Standard Procedure

$$f_i^{im} = N * \sum_{k=m_i}^{\infty} \frac{(f_{bkg} w)^k e^{-f_{bkg} w}}{k!} day^{-1}$$

Statistical cut on the imitation frequency

$f^{im} \leq 1/\mathrm{day}$ $\quad m_i \geq 4$

- New Procedure
  - Standard cut
  - The new selection criteria

$$\xi_i > \bar{\xi}$$

$\eta(D)$ Detection efficiency = Survived signals/Injected signals

$\zeta(D)$ Misidentification probability = Background clusters/Survived clusters

Clusters Selection for Networks

- Standard Procedure:
  - Coincidences in time

$$w_c = 10s$$

- Statistical cut on the global false alarm rate

$$\mathrm{FAR} = 2w_c^{N-1}\prod_{X=1}^{N} f_X^{im}$$

- New Procedure
  - Standard cuts
  - The new selection criteria: the product of the xi values bigger than:

$$\bar{\xi}^* = \sqrt[Net]{\prod_i^{Net} \bar{\xi}_i}$$

$\eta^*(D)$ Detection efficiency = Survived coincidences/Injected signals

$\zeta^*(D)$ Misidentification probability = Background coincidences/Total

Time Integrated Features

Total energy budget

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

Equipartition Hypothesis

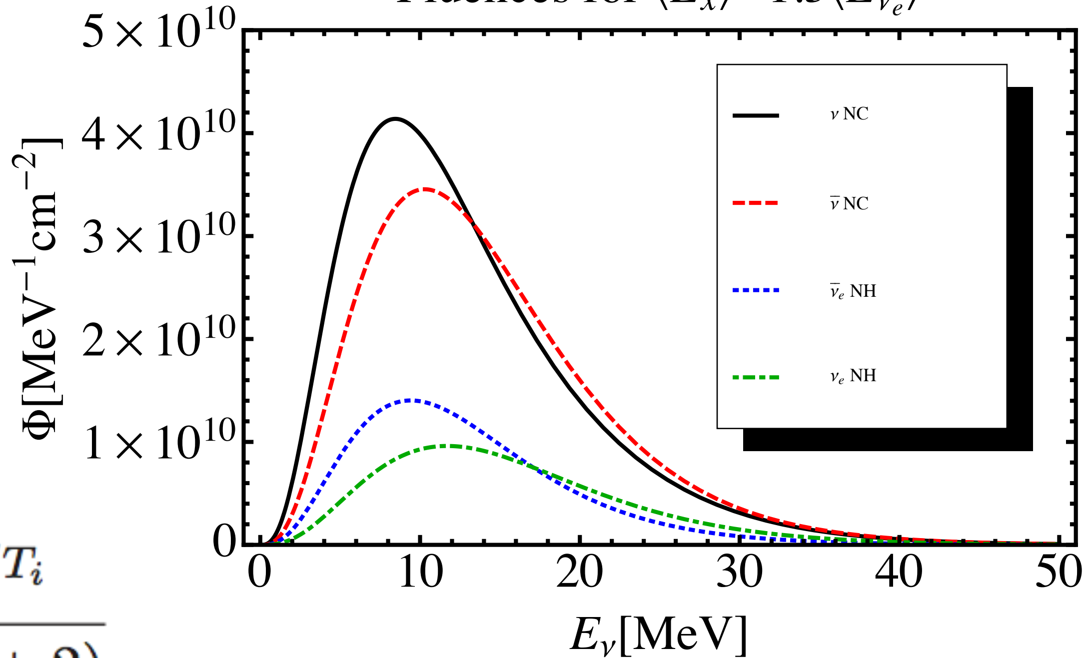
$$\varepsilon_i = E_b \cdot f_i$$

$$f_i = 1/6$$

Fluence at the Earth

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

Fluences for $\langle E_x \rangle = 1.3 \langle E_{\bar{\nu}_e} \rangle$



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