# Pinpointing astrophysical bursts of low-energy $\nu$ embedded into the noise

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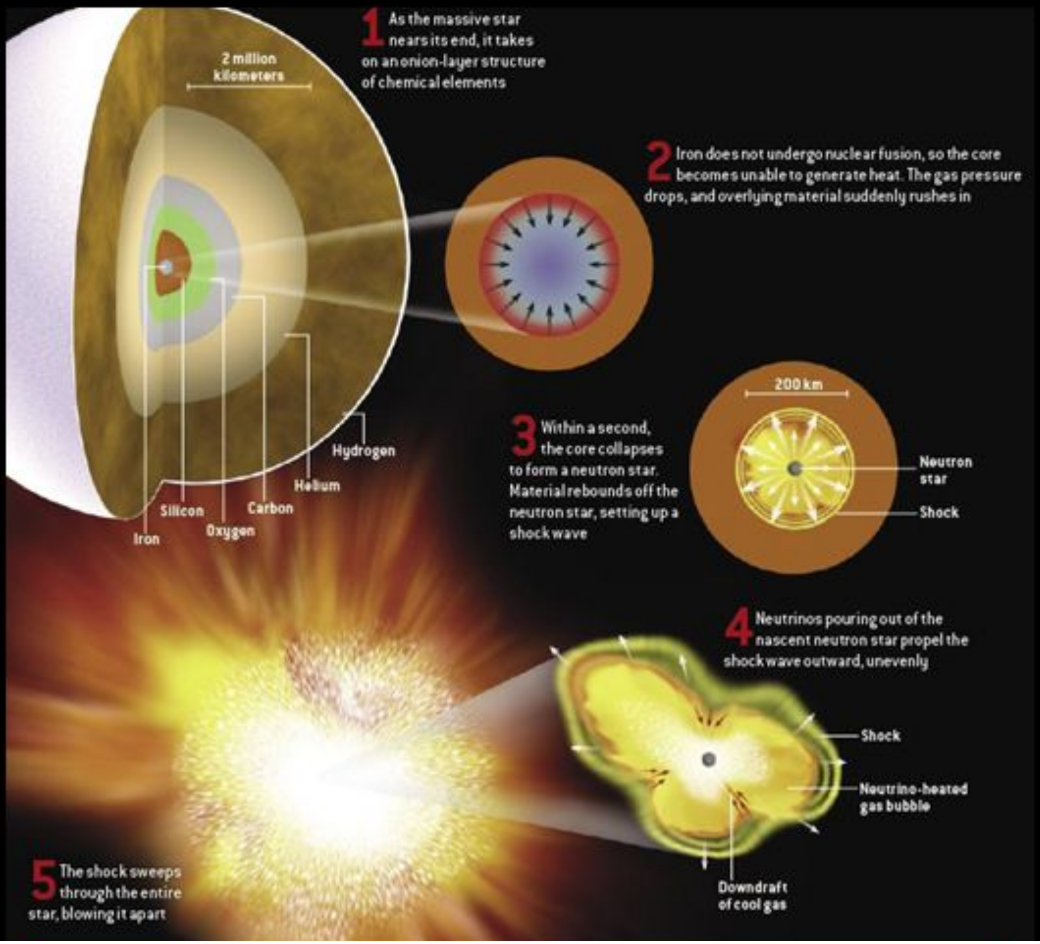
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

# Outline

- Sources of low-energy neutrinos bursts
- Common Signal features
- **<u>Novel Search Method for bursts</u>**
- Results

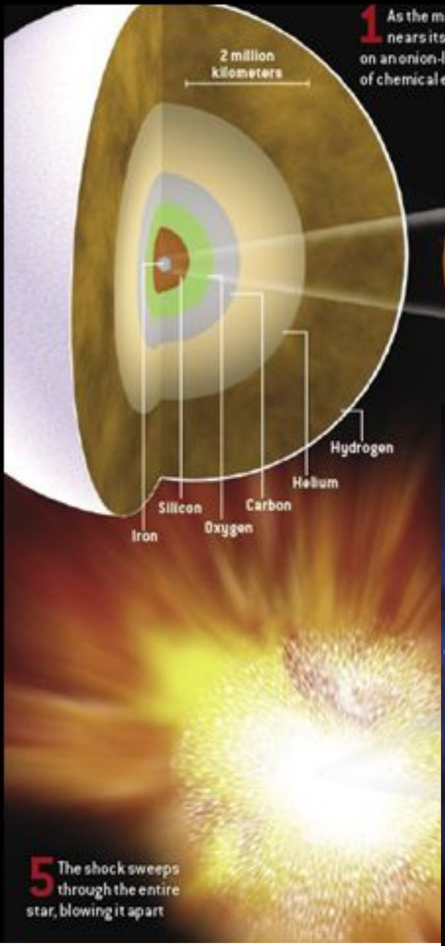
# Core Collapse Supernovae




SOURCES

# SOURCES

## Core Collapse Supernovae



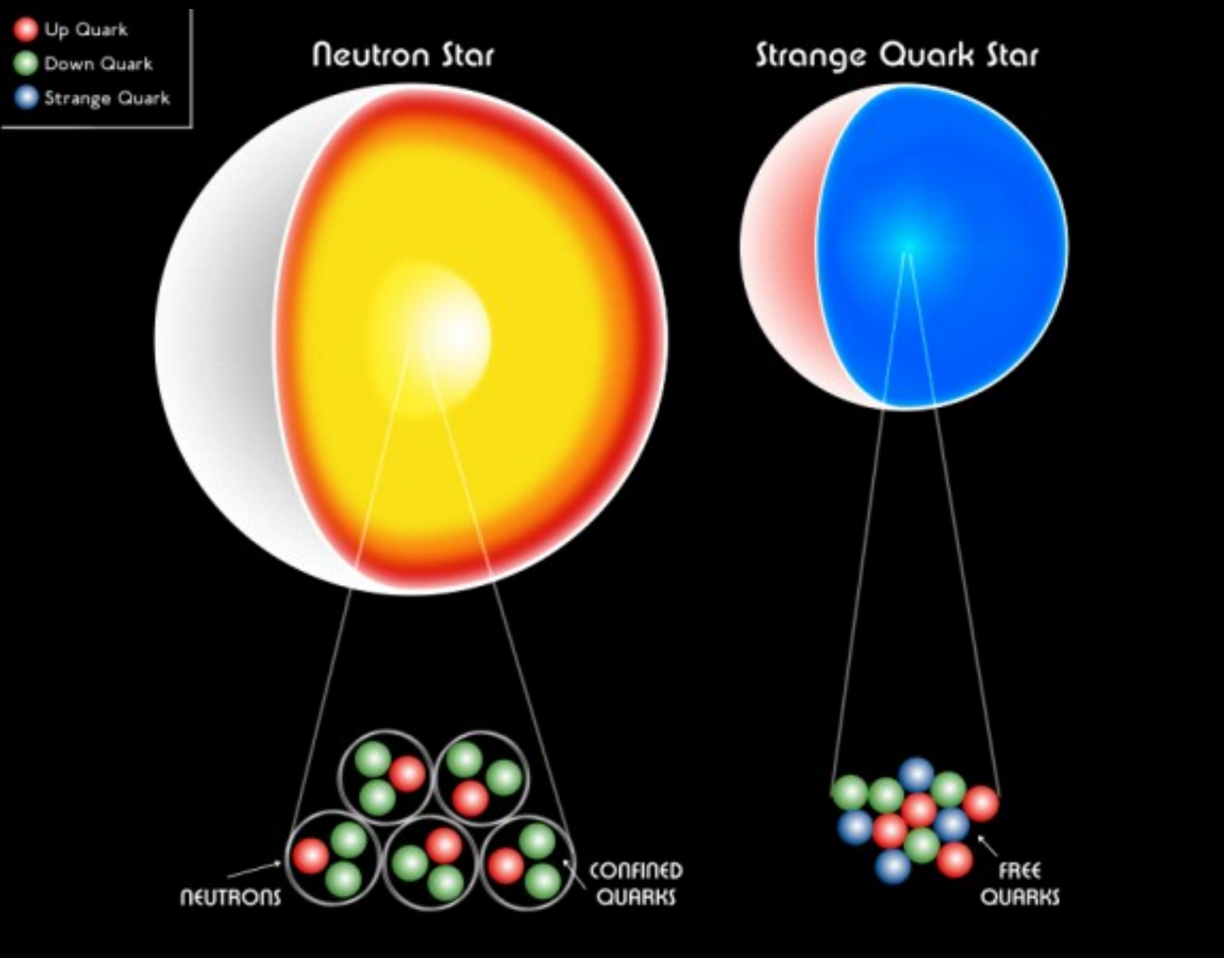

## "Failed" Supernovae

# SOURCES

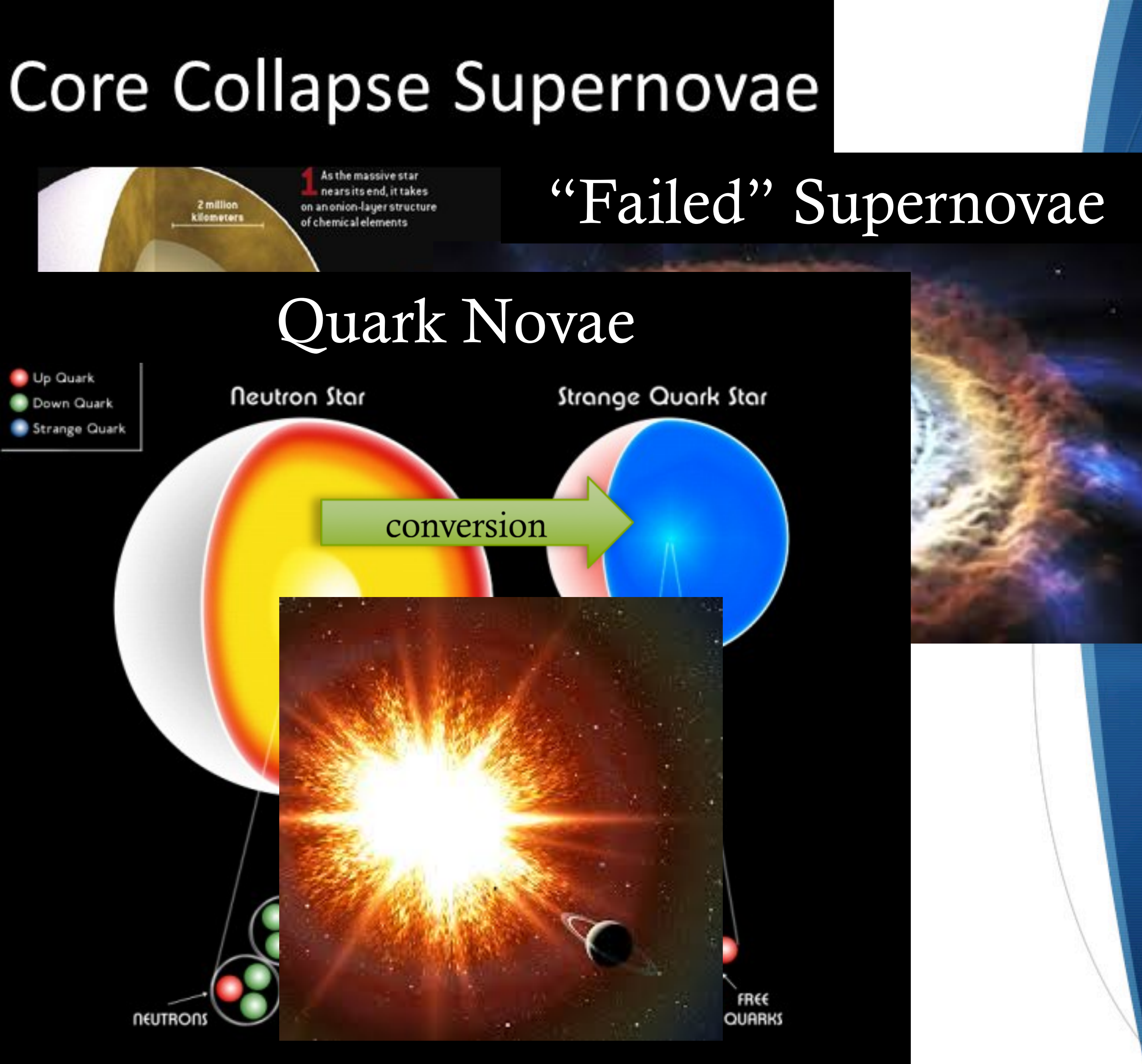
## Core Collapse Supernovae


## "Failed" Supernovae

## Quark Novae



# SOURCES


Core Collapse Supernovae
2 million kilometers
1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements
"Failed" Supernovae
Quark Novae
Up Quark
Down Quark
Strange Quark
Neutron Star
Strange Quark Star
conversion
NEUTRONS
FREE QUARKS

# 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**

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

**DURATION**

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

SOURCES

# Neutrinos Experiments

## 10 years of background data

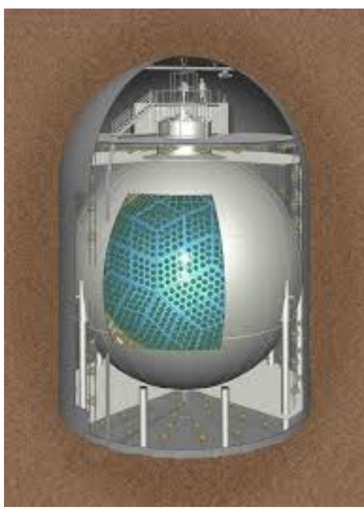
## 3650 injected signals

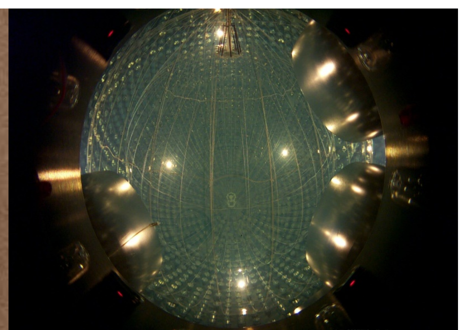
**Kamland**
- Liquid Scintillator
- Energy & NC
- M= 1 kton

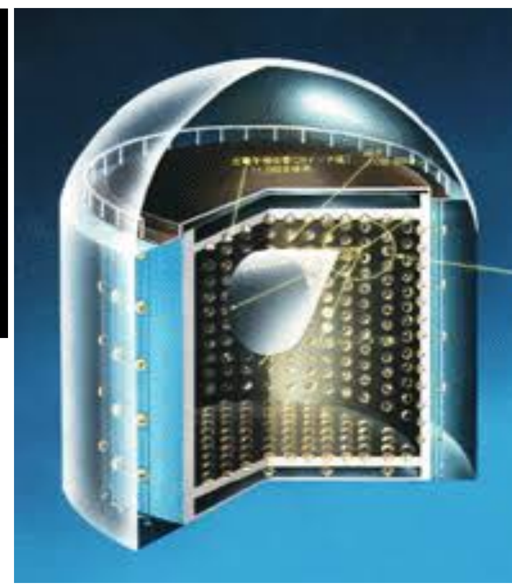
**Borexino**
- Liquid Scintillator
- Energy & NC
- M= 0.3 kton

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

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



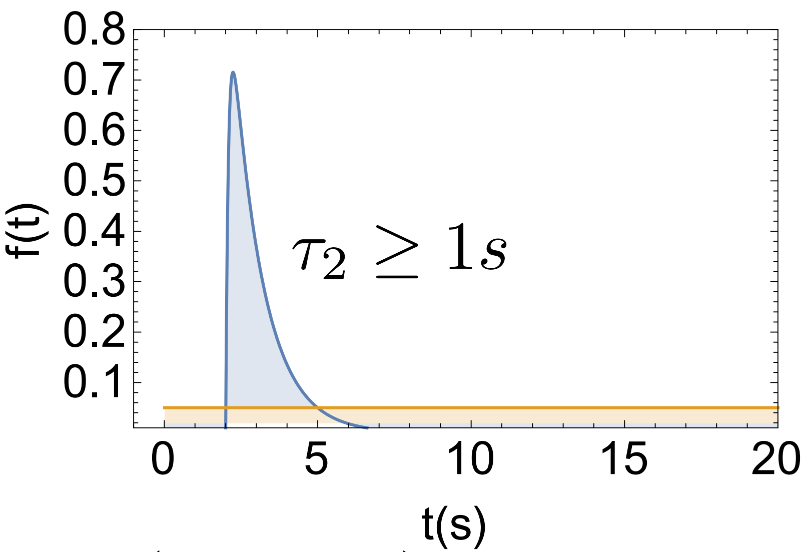


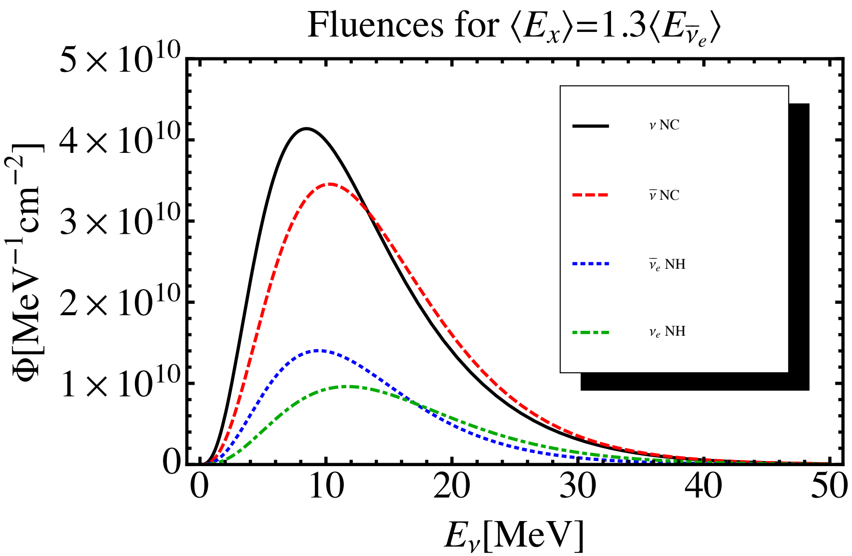


# Neutrinos Burst

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

Normal Hierarchy



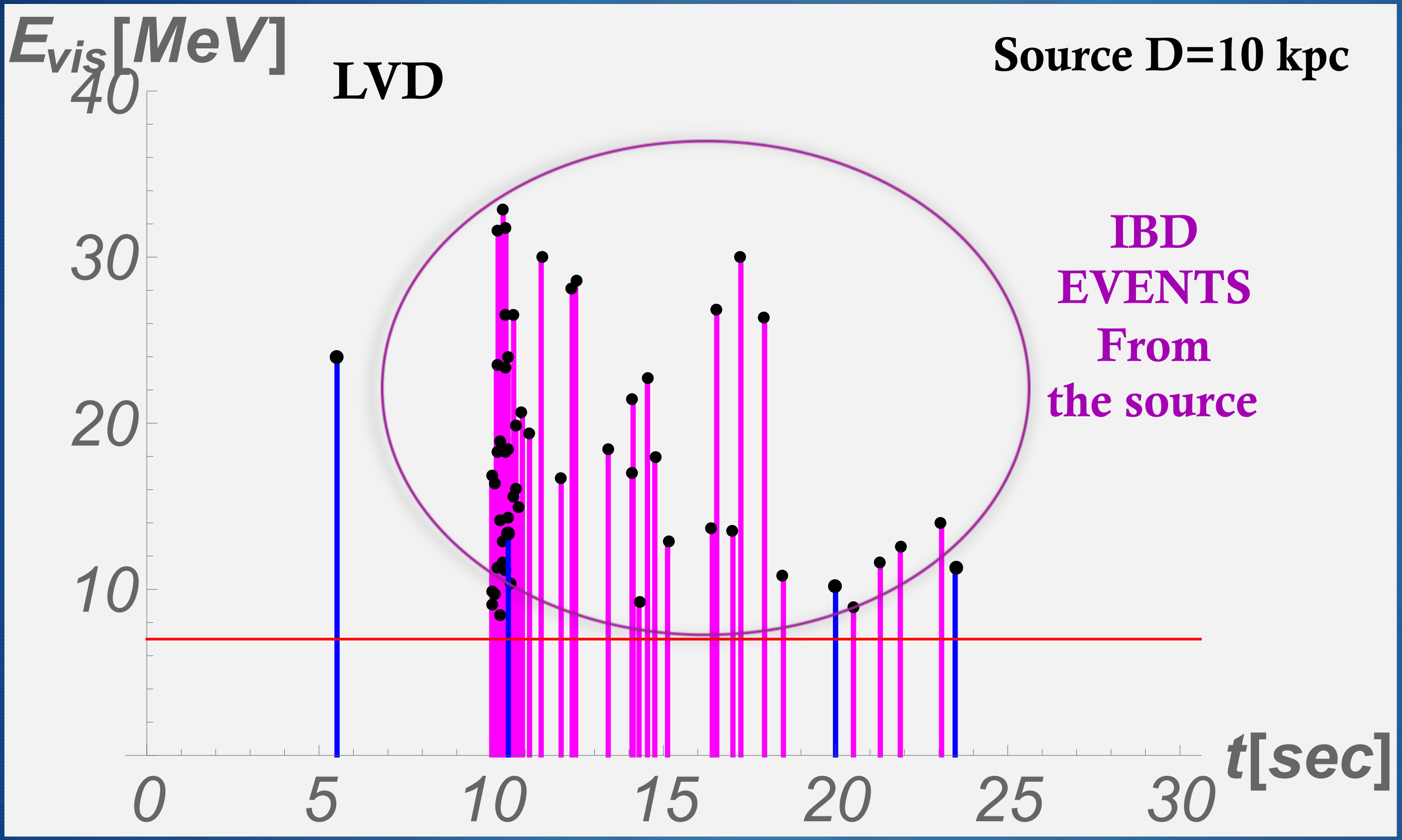




$$\tau_1 = (10 - 100)ms$$

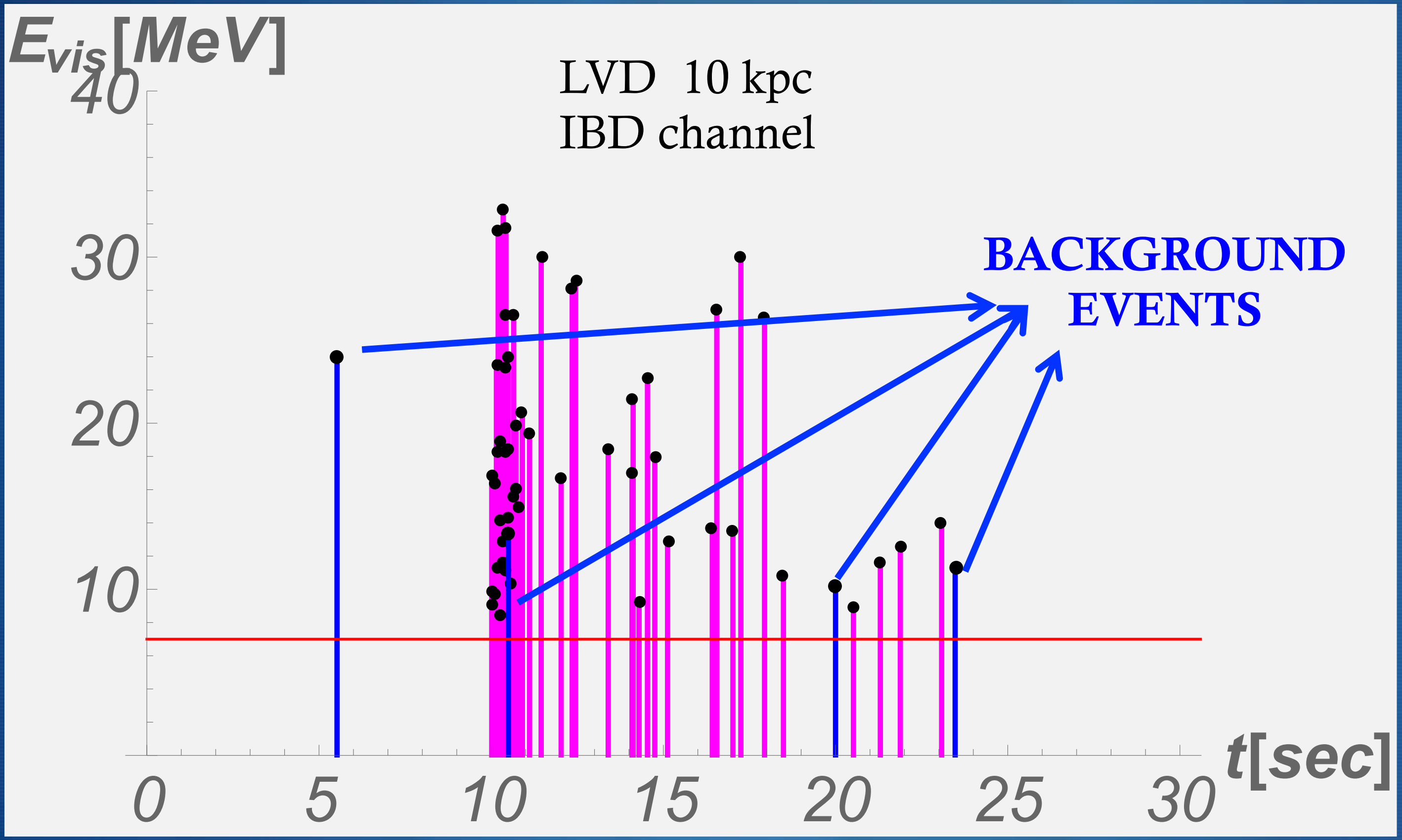
$$\langle E_{\nu_e} \rangle = 9 \text{ MeV} \quad \langle E_{\bar{\nu}_x} \rangle = 15.6 \text{ MeV}$$

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

# The observation of an astrophysical burst



# The observation of an astrophysical burst



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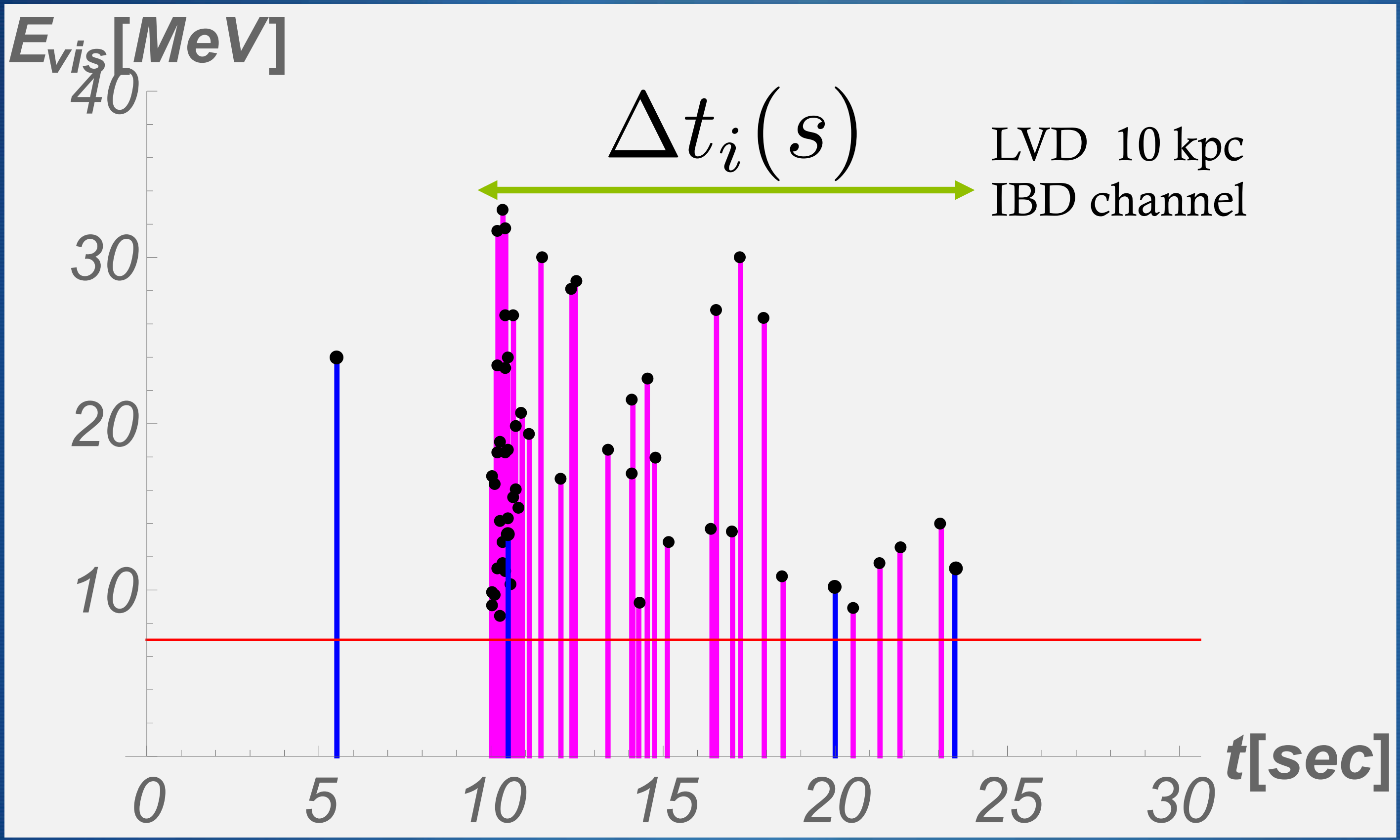



$w = 20s$

$m_i$

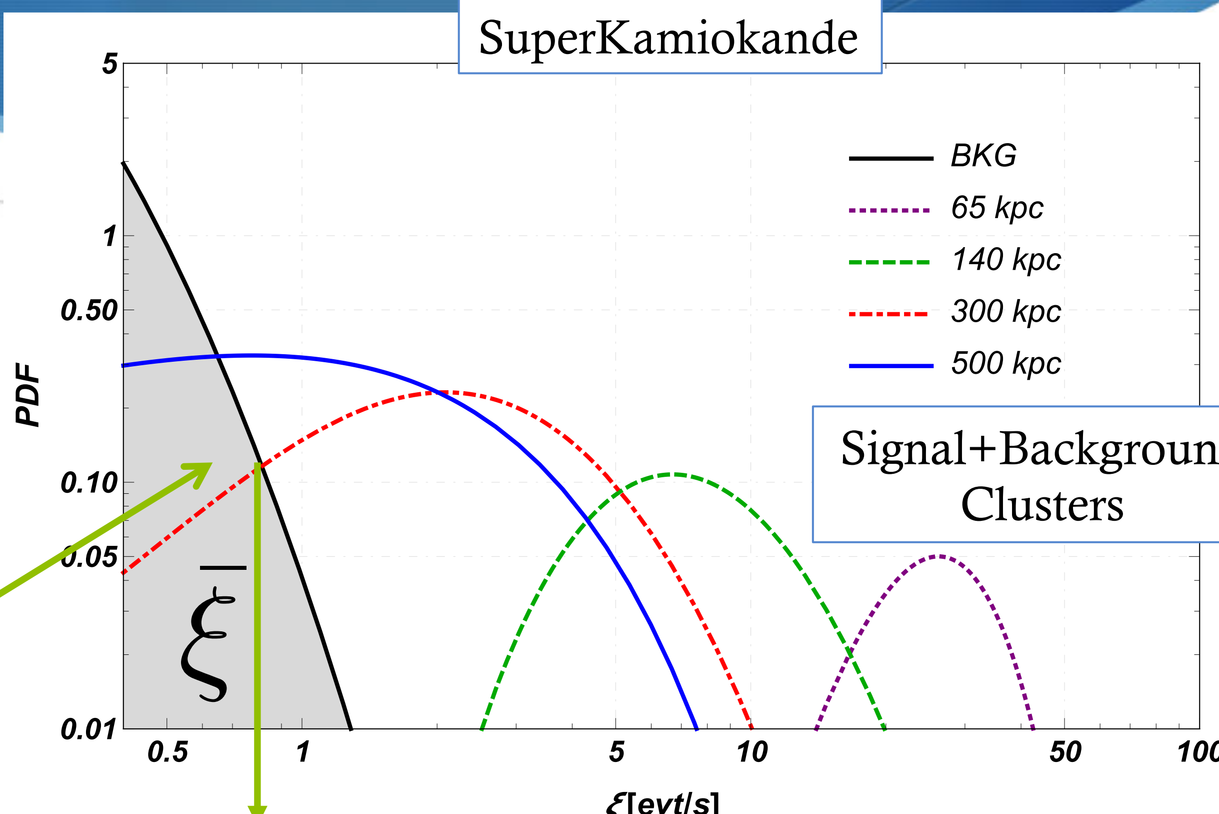
Number of events inside the window

# Background-Signal separation

Probability density Distributions

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

Pure Background Clusters

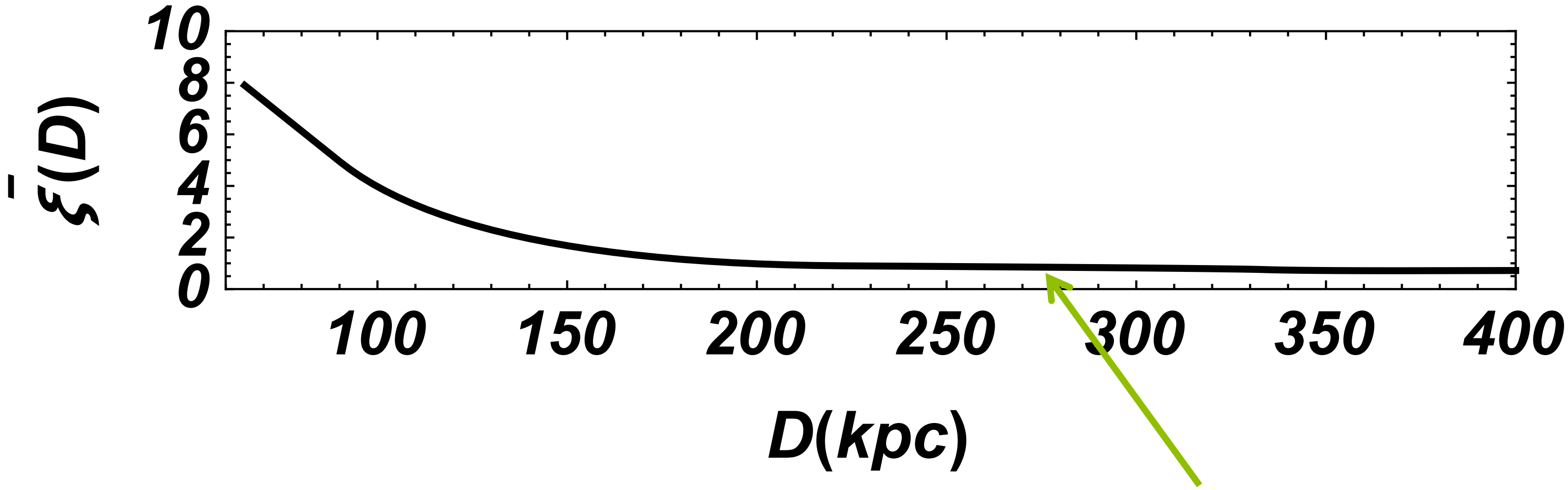



Signal+Background Clusters

Cutting value for the $\xi$ parameter providing

Maximum of the signal to noise ratio

# Optimal cut value for blind search



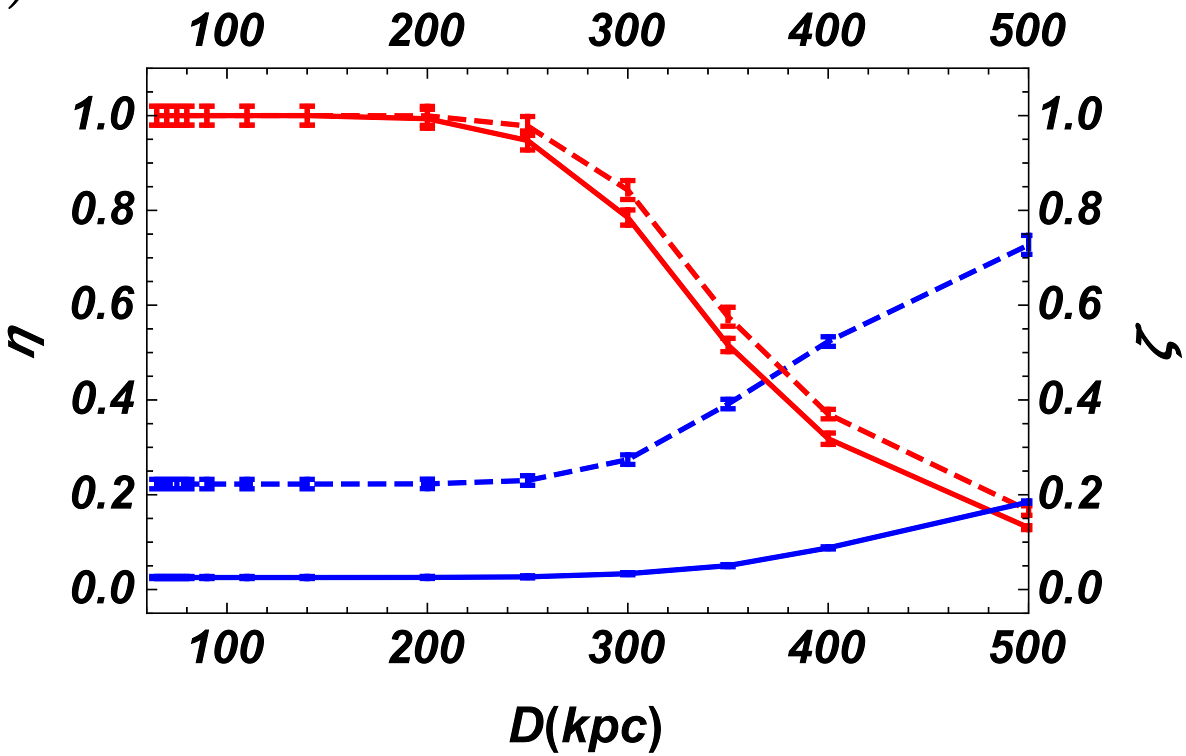

The distance of the source is unknown and the search is optimized to the larger distance allowed by the proposed method

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

# Results for SuperKamiokande

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

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



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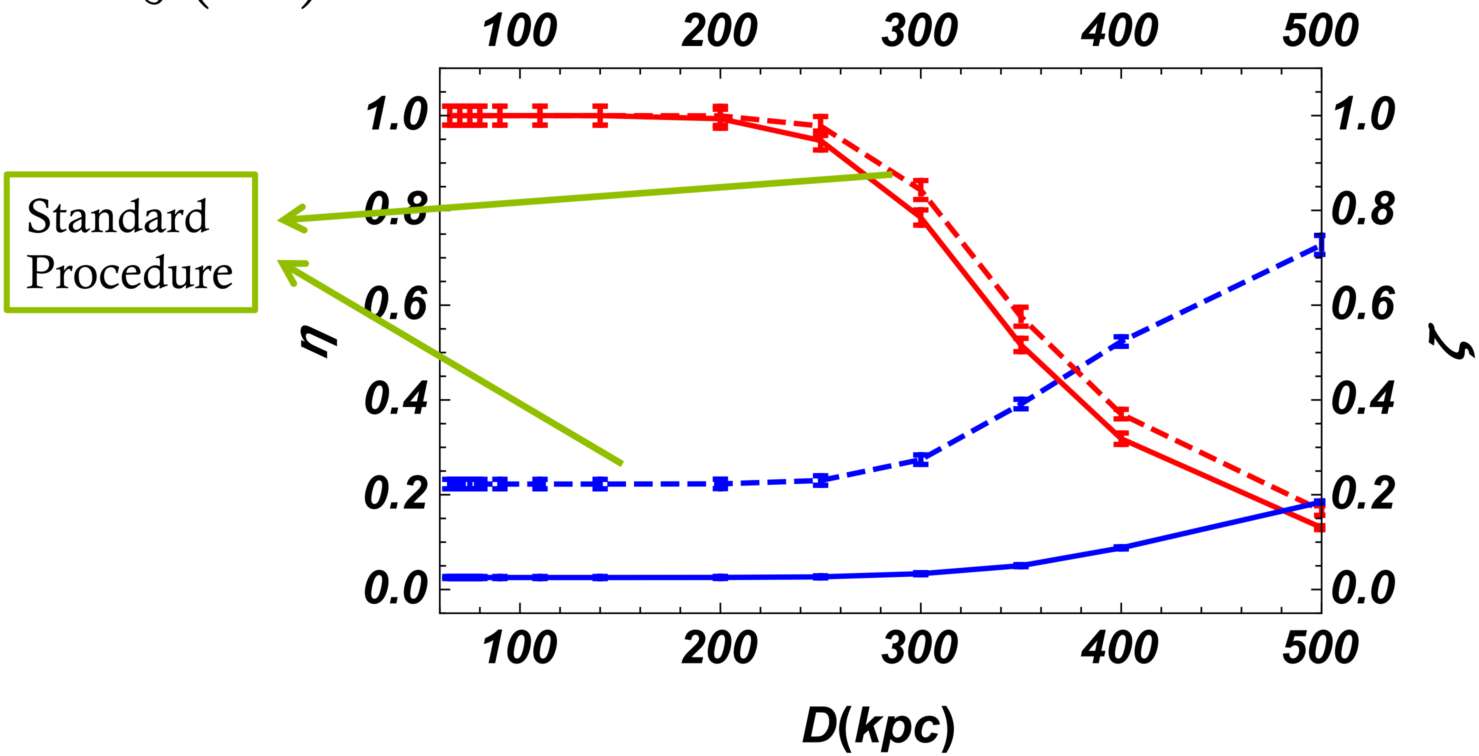

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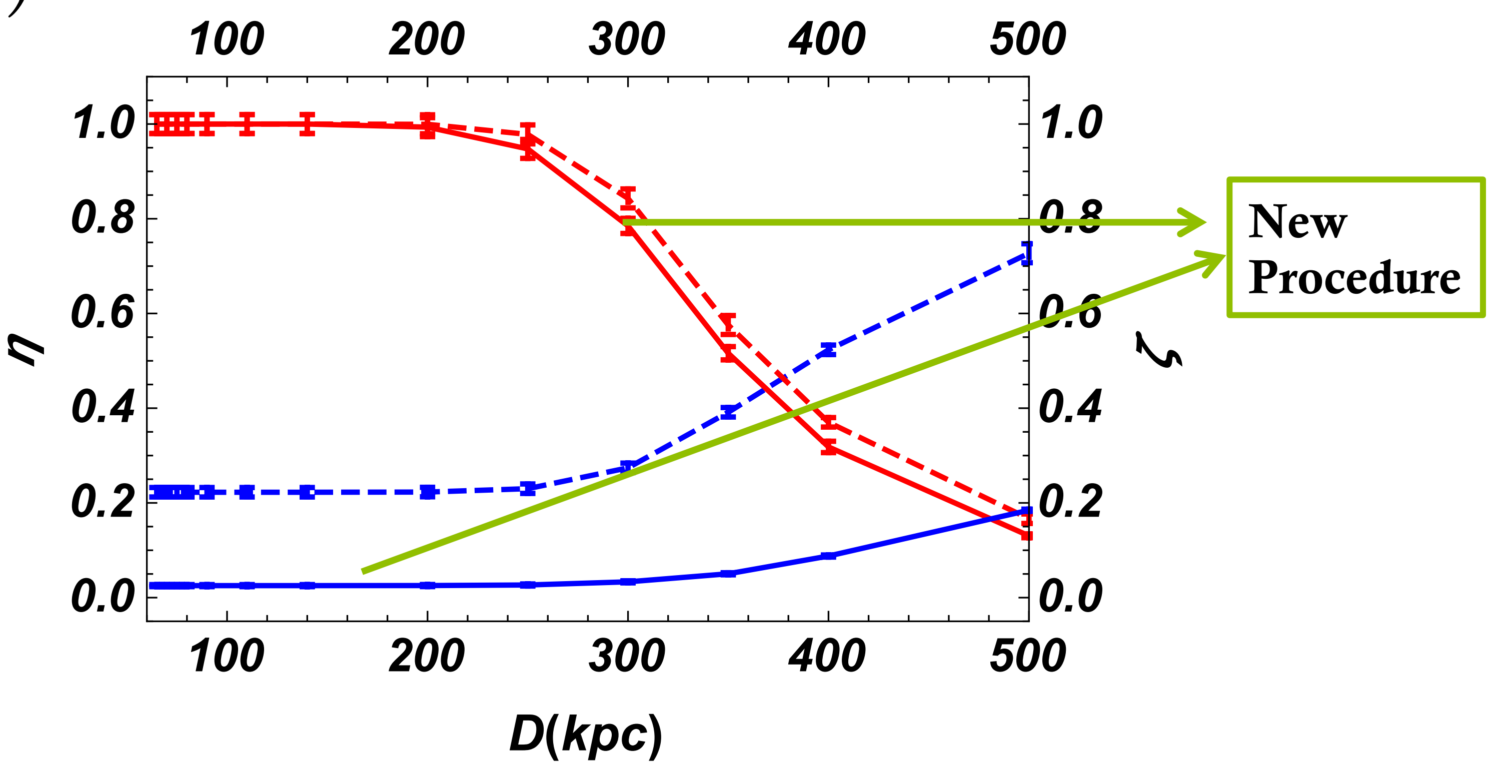


# Results for SuperKamiokande

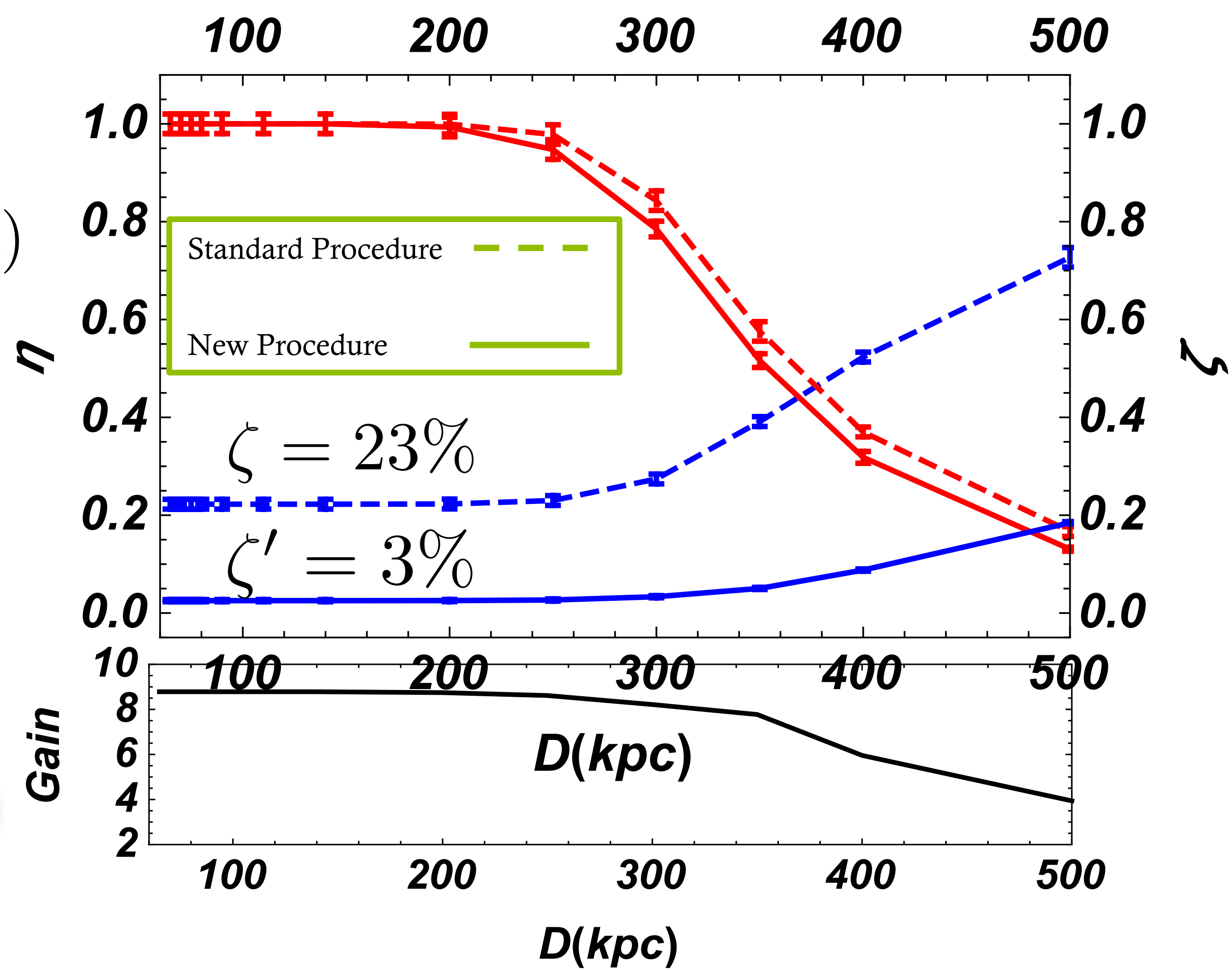
No Efficiency loss for

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

Gain factor on the misidentification probability

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

$$\text{Gain} = 8.9$$

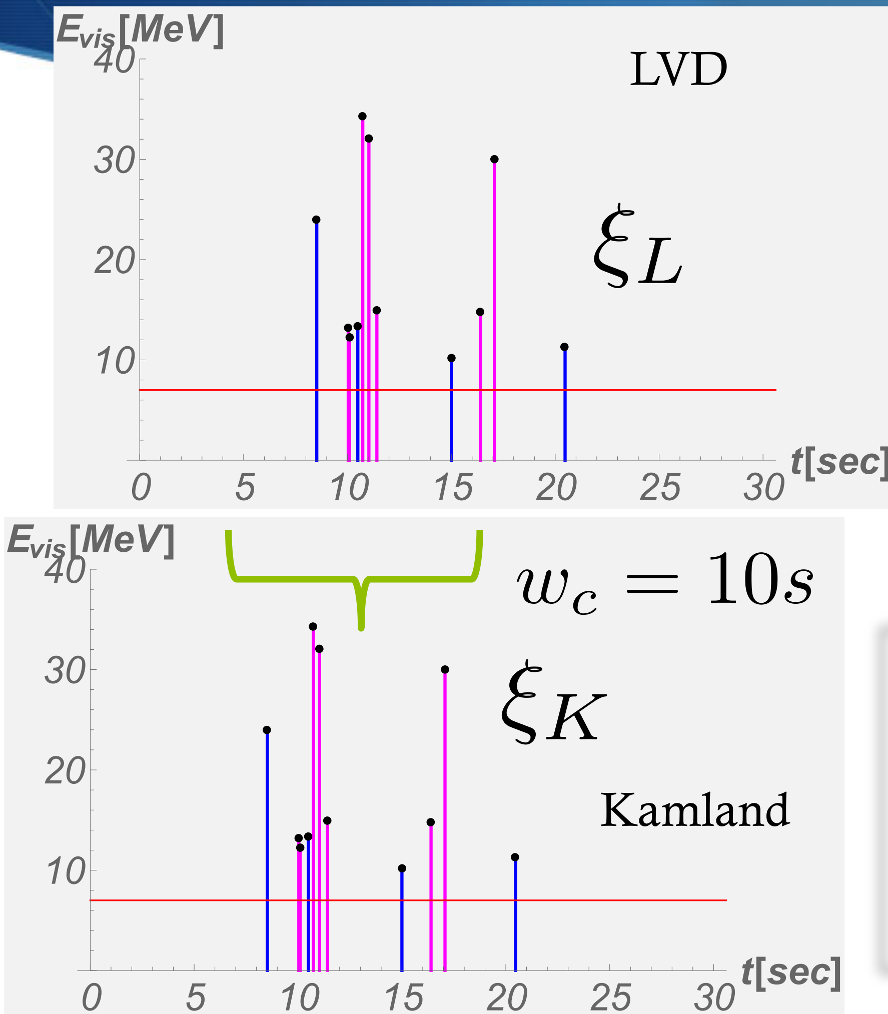


# Gain Factors

| **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




$$\xi_K * \xi_L \geq \bar{\xi}_L * \bar{\xi}_K$$

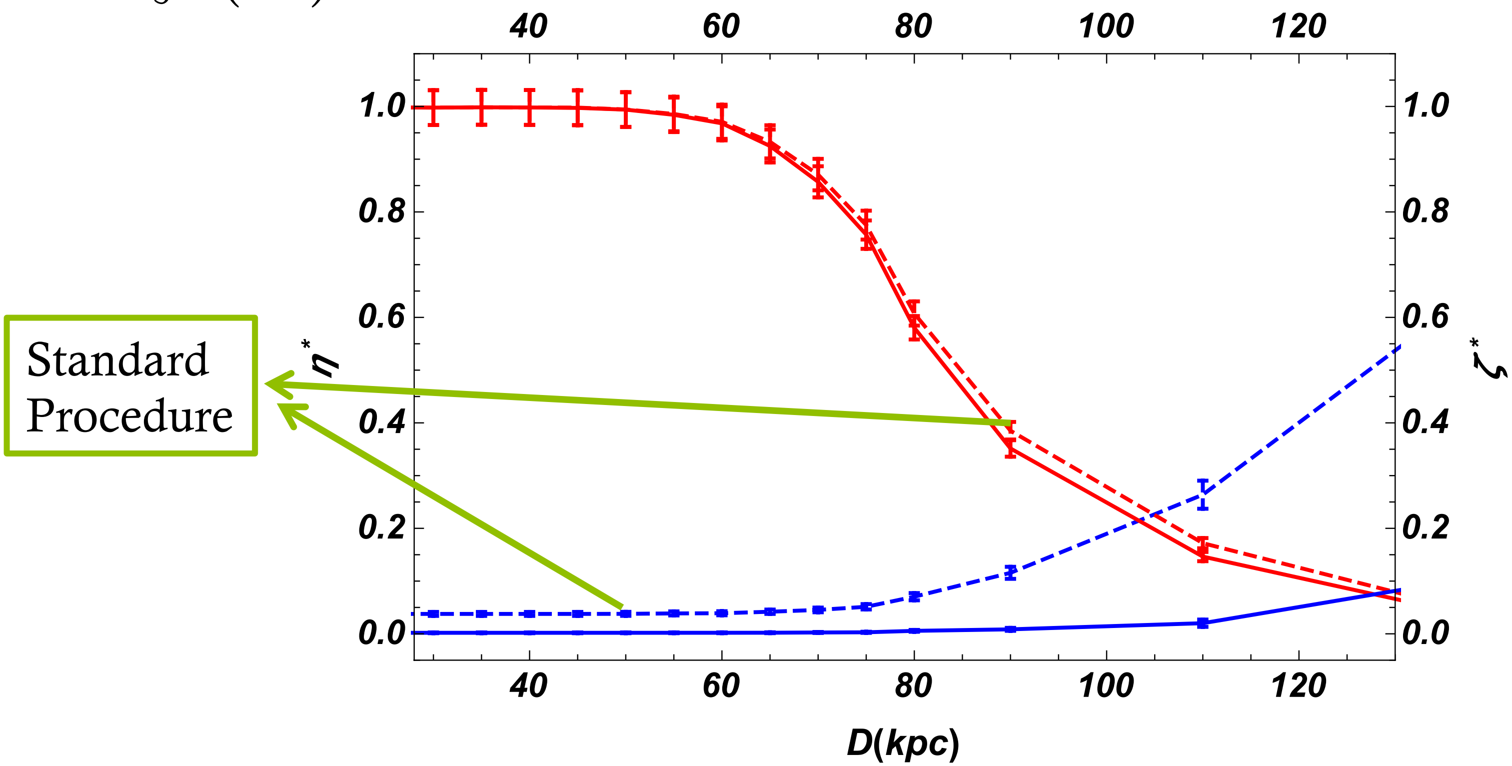
The product of the $\xi$ values bigger than:

$$\bar{\xi}^* = \prod_{X=1}^{N} \bar{\xi}_X$$

# The network LVD+Kamland

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

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



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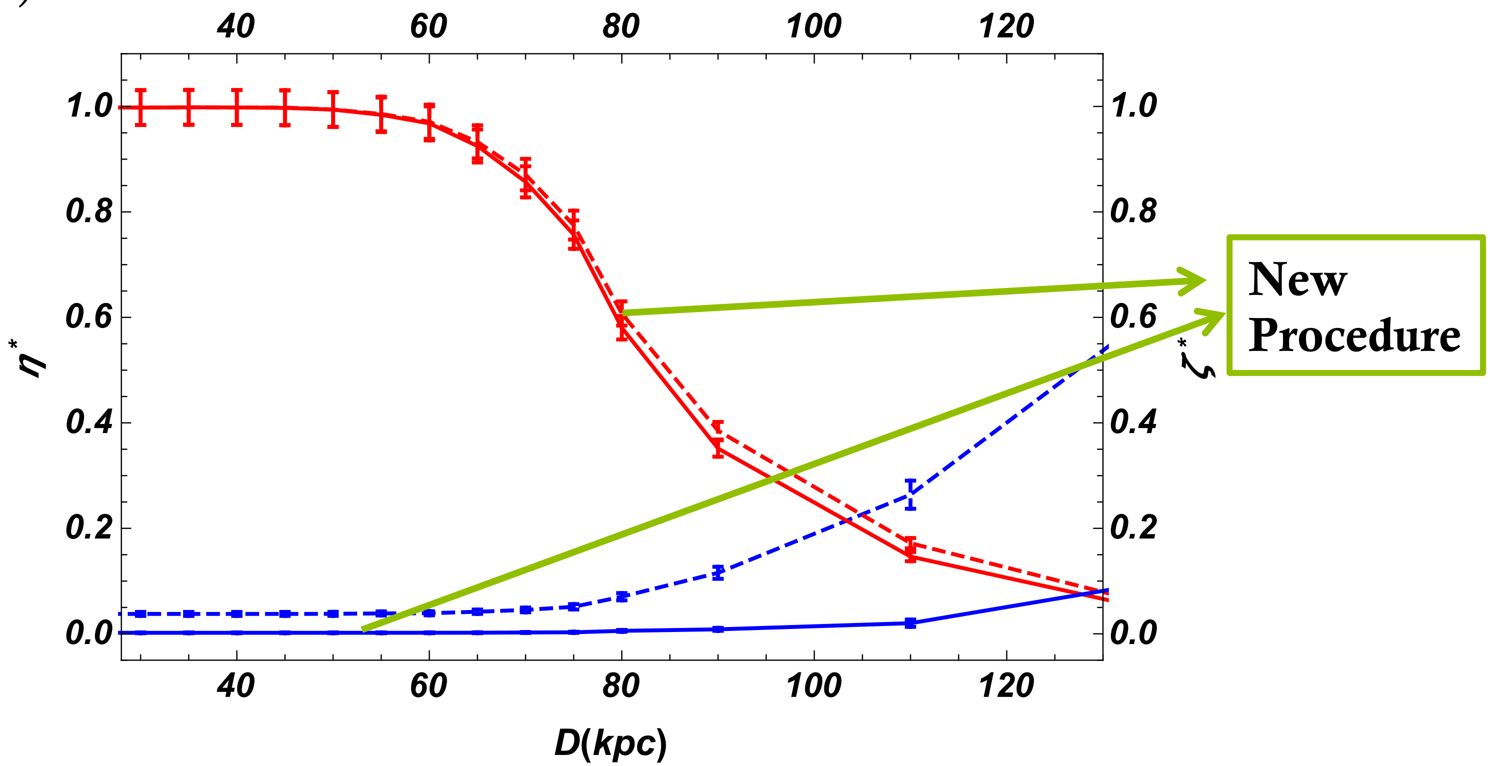


# Results for a network LVD+Kamland

No Efficiency loss for

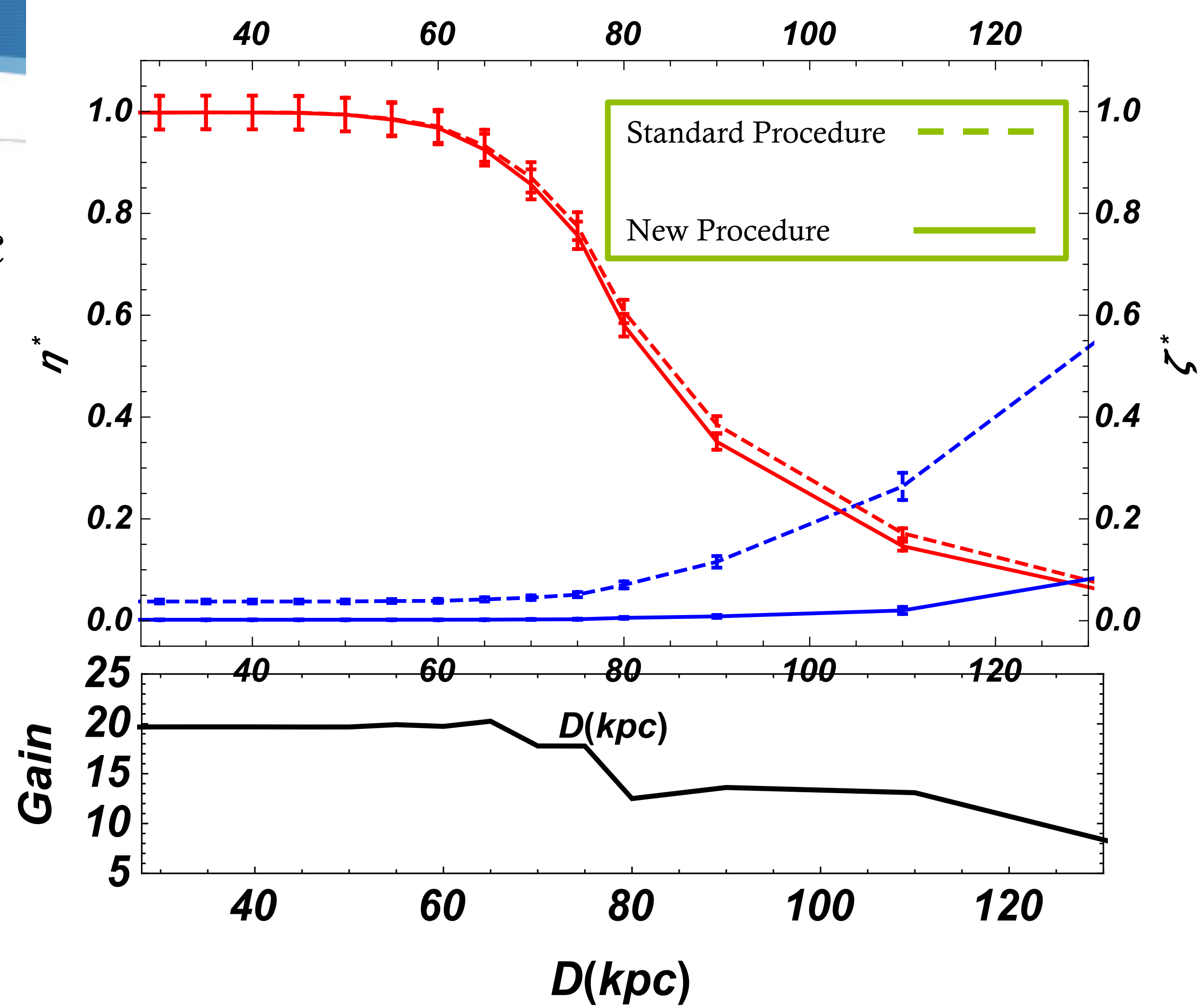
$$D < \bar{D} = 75kpc$$

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
- Holds for all the impulsive sources of low-energy neutrinos
- Applies to different detectors or networks of detectors
- Allows to decrease the misidentification probability between a factor 10-20 without loosing on detection efficiency

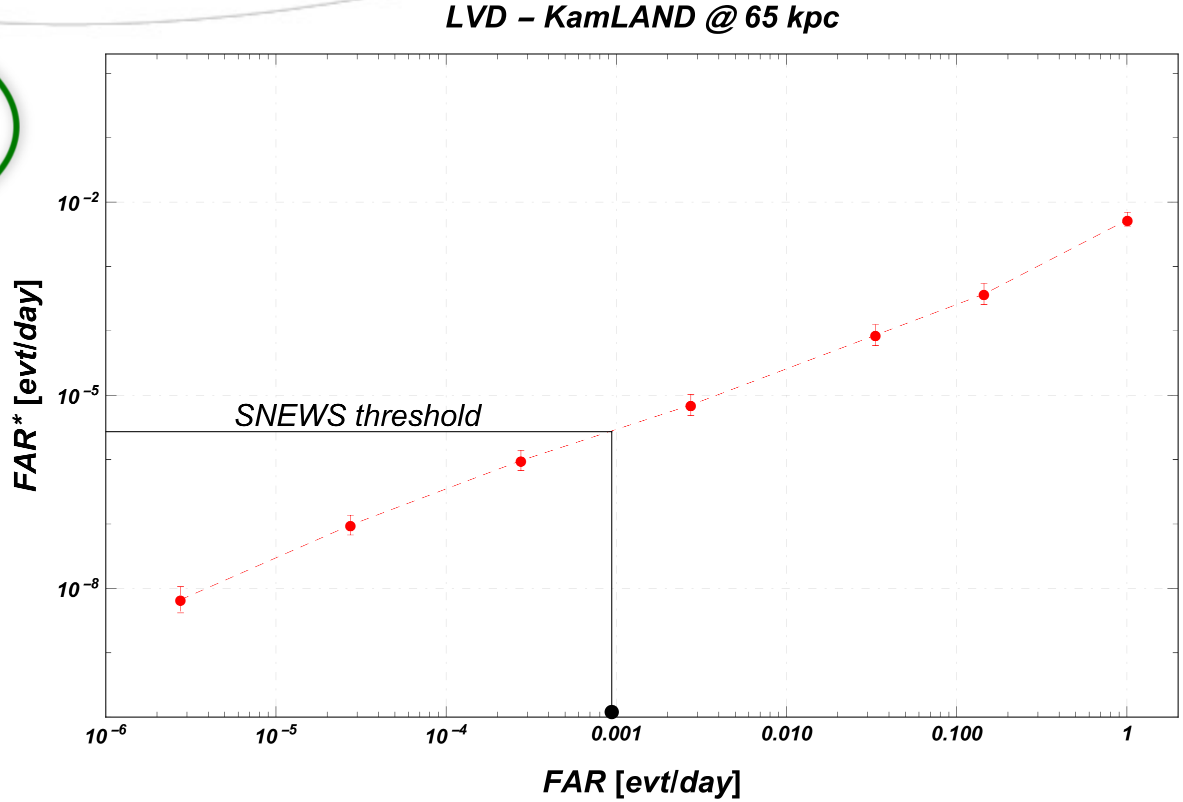
# Backup Slides

# SNEWS comparison

SNEWS threshold
FAR* = 1/1000 years

**EQUIVALENT**

FAR = 0.365/year
+
$\bar{\xi}^*{}_{\mathrm{cut}}$




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

$f^{im} \leq 1/\text{day}$ $\qquad m_i \geq 4$

- 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

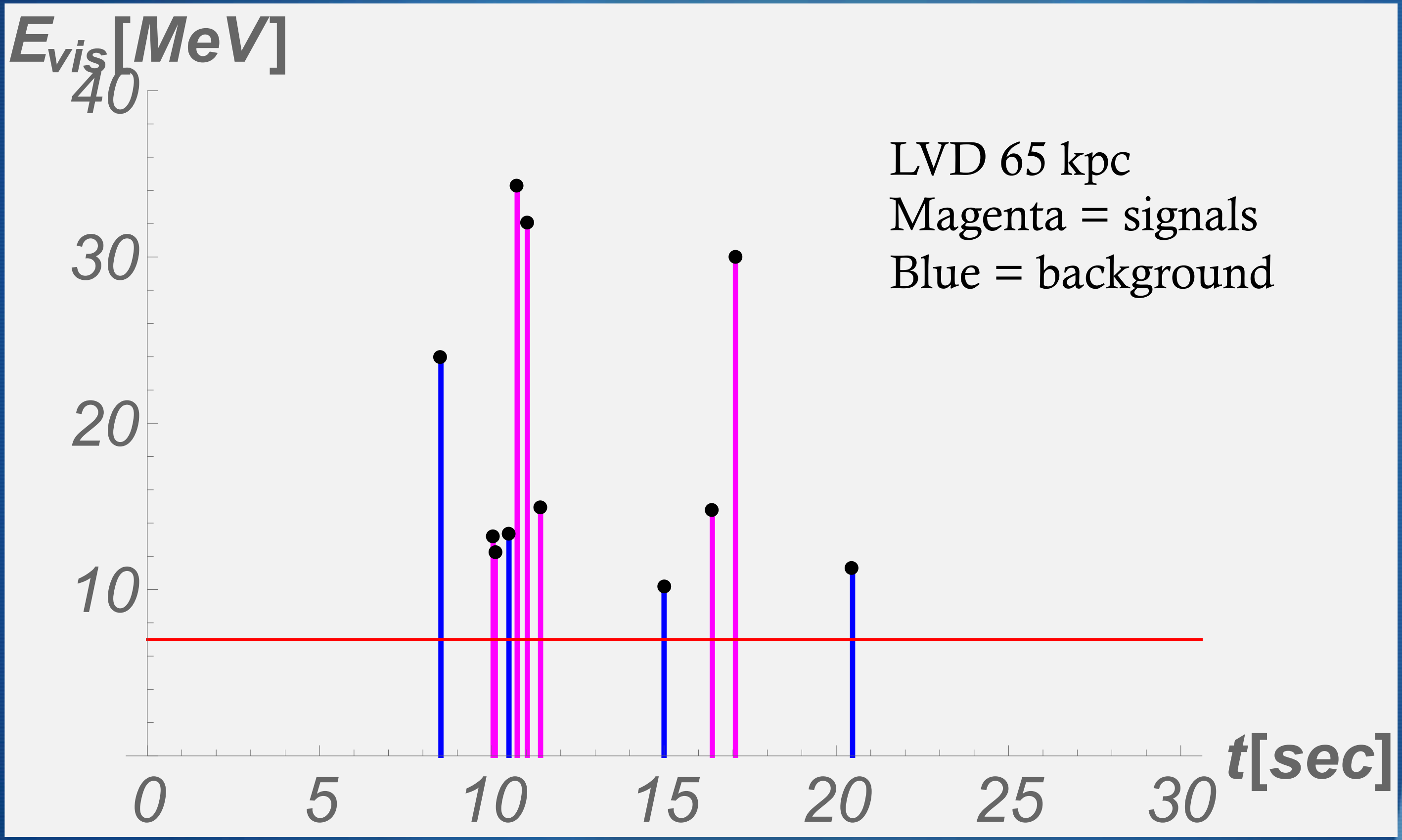
$$\mathrm{FAR} = 2w_c^{N-1} \prod_{X=1}^{N} f_X^{im}$$

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

$$\overline{\xi}^* = \prod_{X=1}^{N} \overline{\xi}_X$$

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

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



$E_{vis}$[MeV]
40
30
20
10
0
5
10
15
20
25
30
t[sec]
LVD 65 kpc
Magenta = signals
Blue = background

# Time Integrated Features

Total energy budget

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

Equipartition Hypothesis

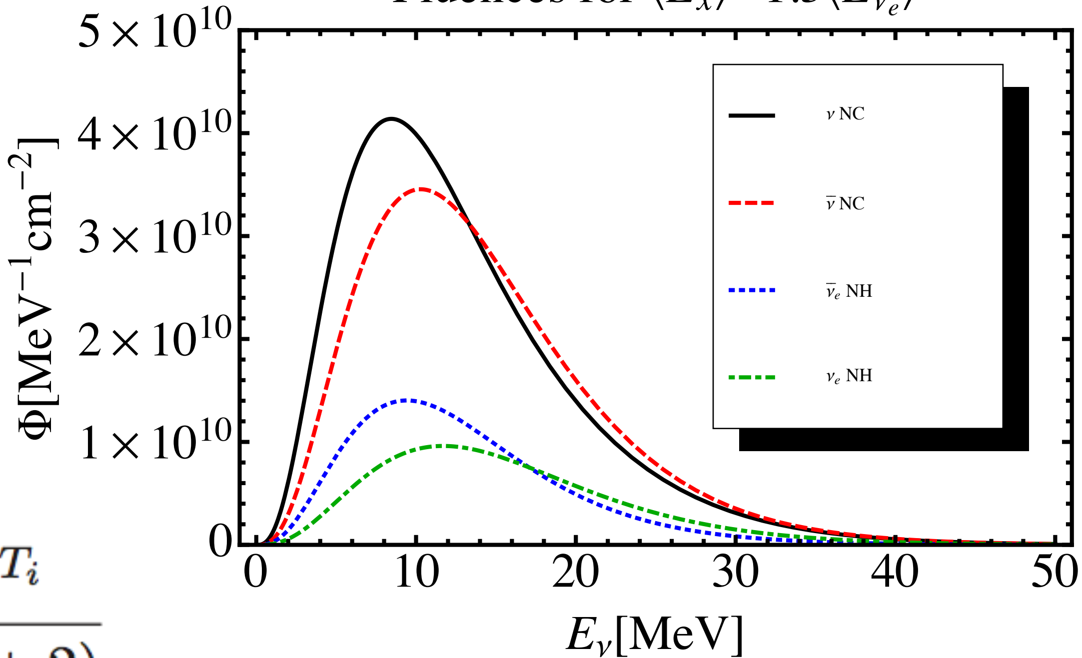
$$\varepsilon_i = E_b \cdot f_i$$

$$f_i = 1/6$$

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

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

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

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

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

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

Neutrinos Fluences

Number of targets

Detector Energy Threshold

Cross Section
Kinematic threshold