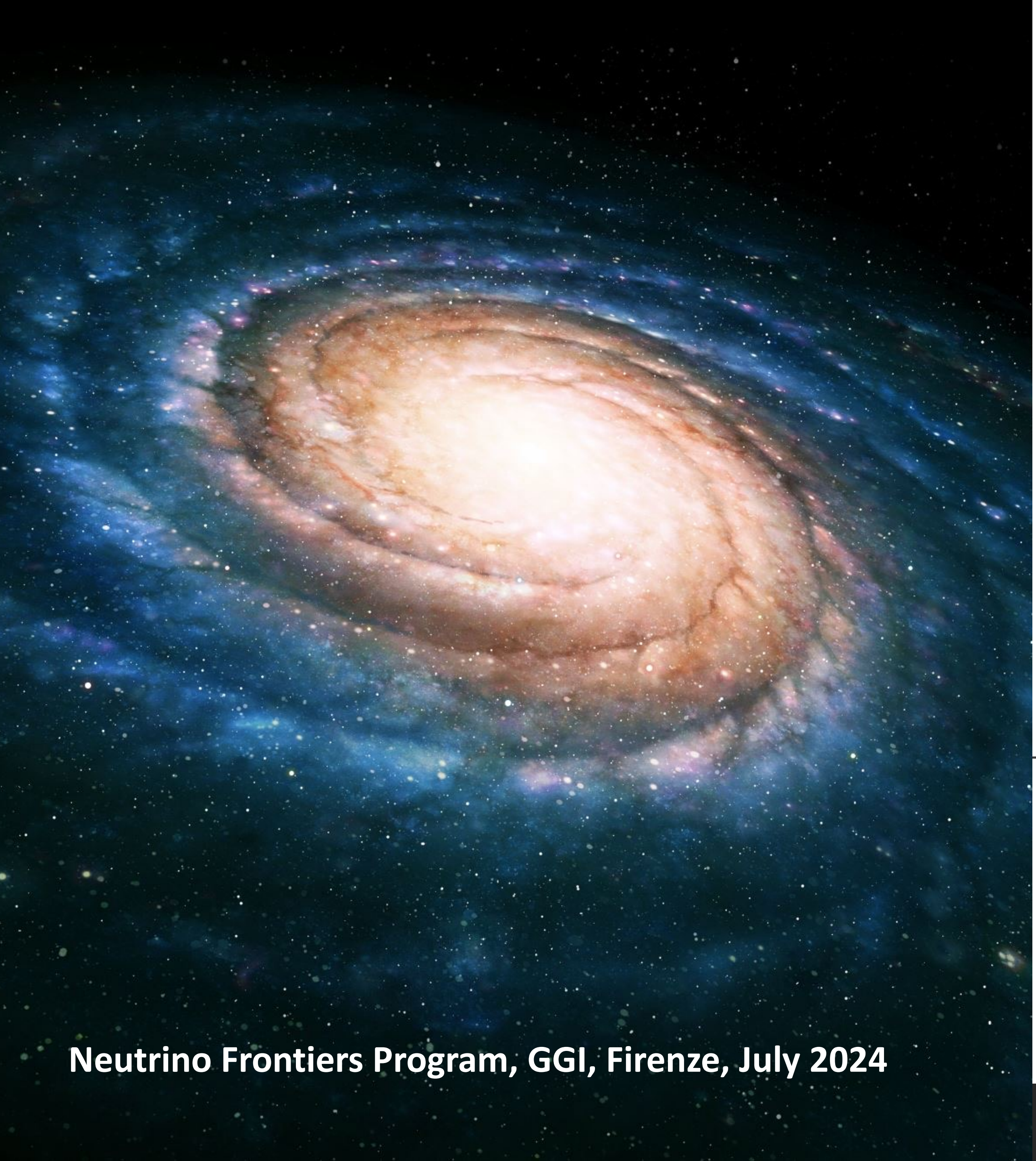


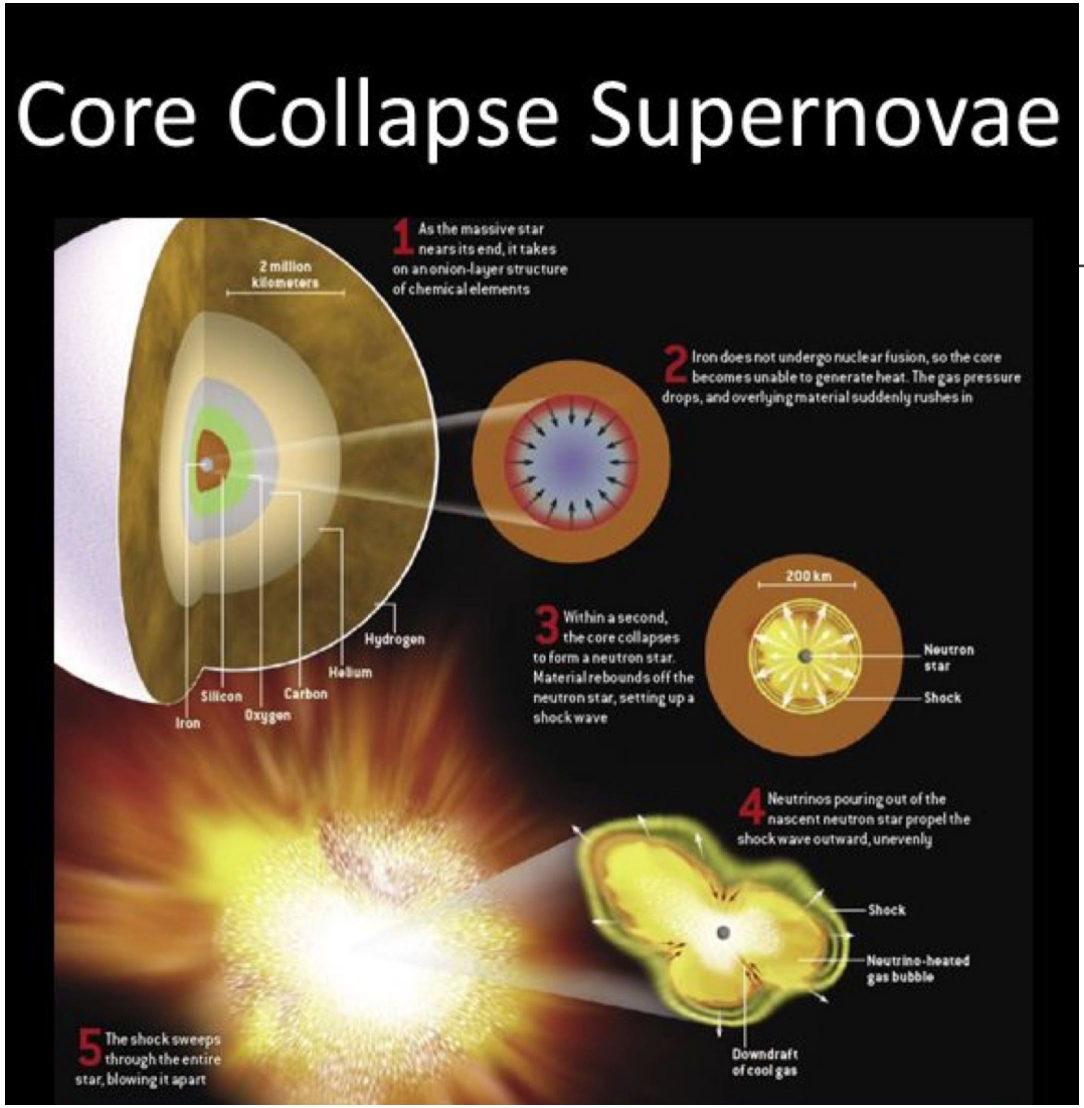
Neutrino Frontiers Program, GGI, Firenze, July 2024

Core-Collapse Supernovae detection with Gravitational Waves and Neutrinos

GIULIA PAGLIAROLI

INFN-LNGS, ITALY

giulia.pagliaroli@lngs.infn.it



Outline

Quantify the CCSNe detection efficiency of a global network of Neutrinos and GW detectors

- ❖Neutrinos and gravitational waves (GW)
  - ❖Emission models and analysis methods
- ❖Data analysis improvement in Neutrino sector
  - ❖Results for LEN detectors
- ❖Multi-messengers analysis
  - ❖Results for a global-network of GW+LEN detectors

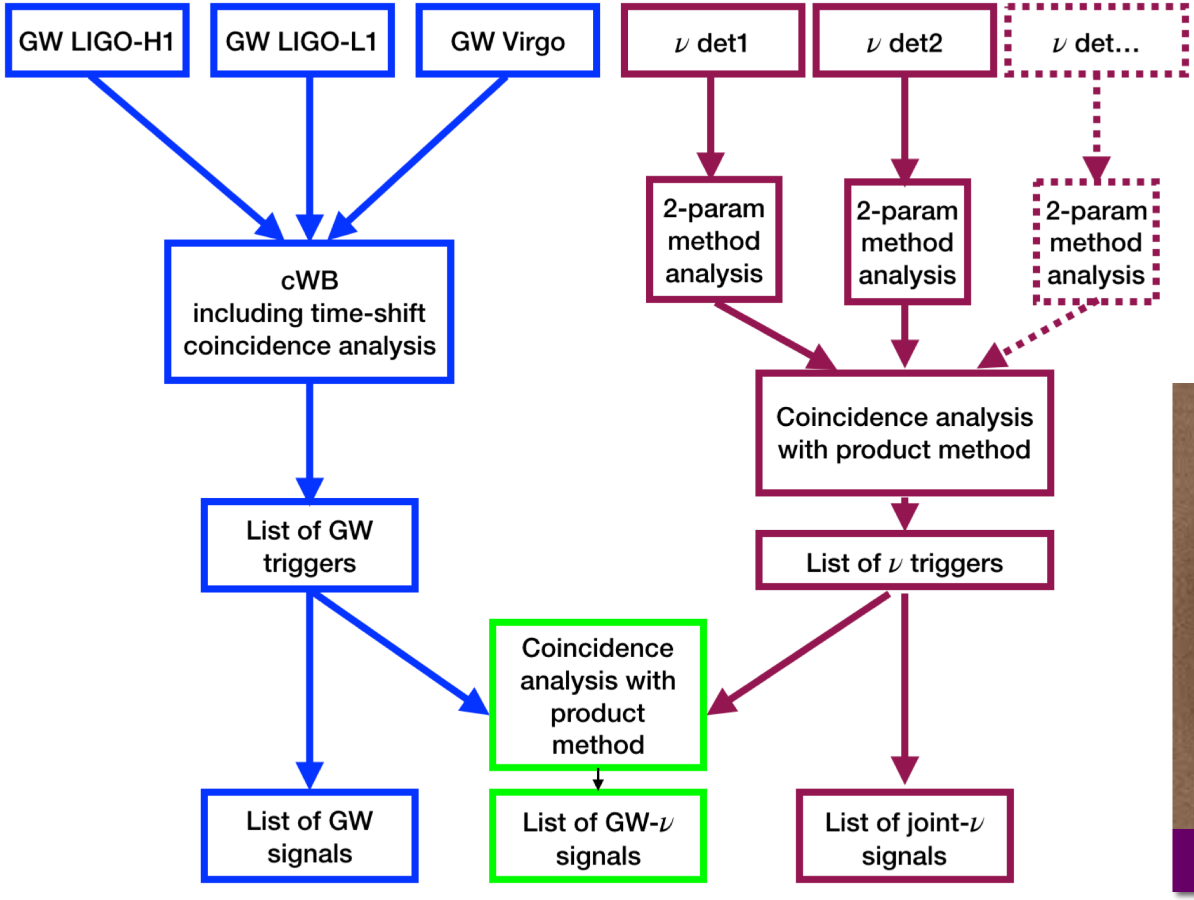
Multimessenger analysis with GW-LEN

O. Halim *et al. JCAP* 11 (2021) 021

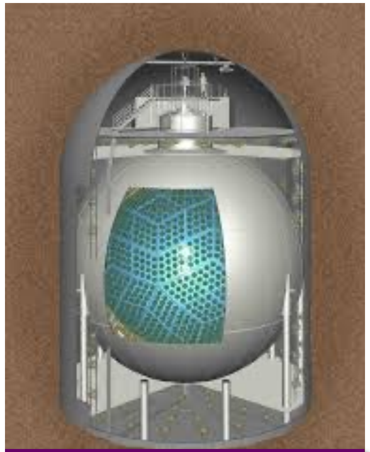
LIGO L1

LIGO H1

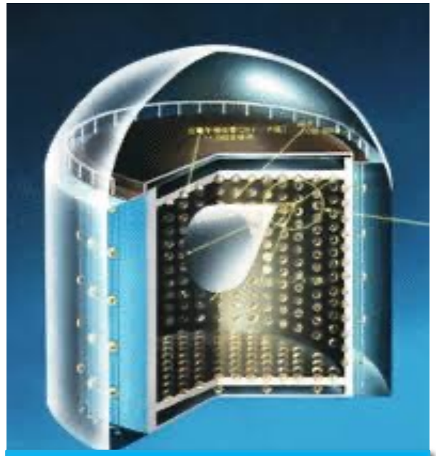
Virgo



LVD



Kamland



SuperK

Joint GW-ν Search

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

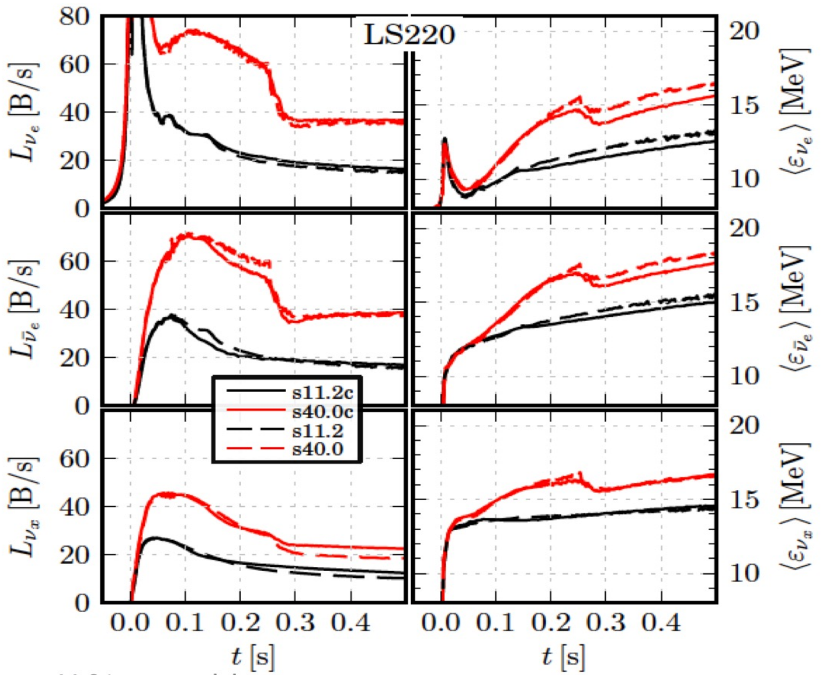
Global False Alarm Rate — GW back. Rate — Neutrino back. Rate — Time coincidence window

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

- FAR=1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.
- w=10 sec to accomodate most emission models
- R_{ν} =1/100 years as in SNEWS

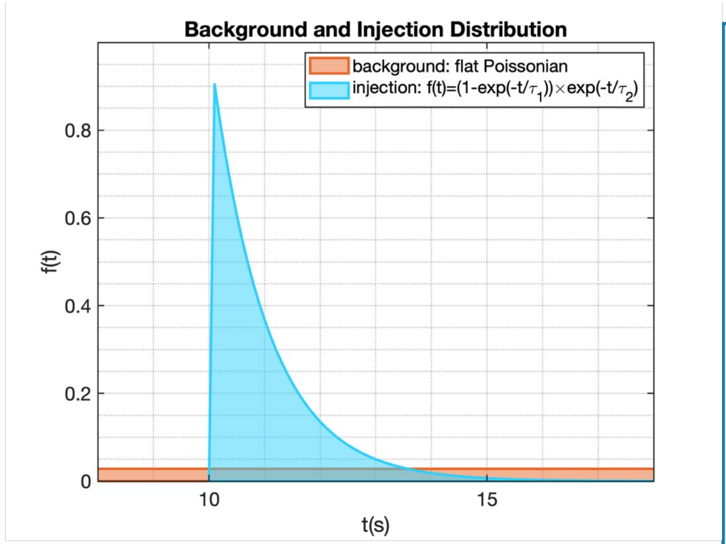
Neutrino signals

NUMERICAL SIMULATIONS



s11.2 is our model
L. Hudepohl, Ph.D. thesis, Technische Universitat Munchen (2014).

PHENOMENOLOGY+ DATA



SN1987A model
OH, PhD thesis, Gran Sasso Science Institute (2020)

SN1987A

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

$\langle E_{\nu_e} \rangle = 9MeV$

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

$\langle E_{\nu_x} \rangle = 16MeV$

$\tau_2 = 1\, s$

$\tau_1 = 0.1\, s$

$$F(t) = (1 - e^{-t/\tau_1})e^{-t/\tau_2}$$

GP et al. Astropart.Phys. 31 (2009) 163-176

LEN analysis efficiency

Model (identifier)	Progenitor Mass	Super-K ($E_{thr} = 6.5$ MeV)	LVD ($E_{thr} = 7$ MeV)	KamLAND ($E_{thr} = 1$ MeV)
Pagliaroli [41] (SN1987A)	$25\,M_\odot$	4120	224	255
Hüdepohl [40] (Hud)	$11.2\,M_\odot$	2620	142	154

Table 2. Number of IBD events expected for a CCSN exploding at 10 kpc from us for the different neutrino models adopted and the considered detectors (Super-K [6], LVD [7], and KamLAND [8]). In parenthesis we report the assumed energy threshold (E_{thr}).

Detector	Background
LVD	0.028 Hz
KAM	0.015 Hz
SK	0.012 Hz

Analysis Efficiency = N_recovered/N_injected

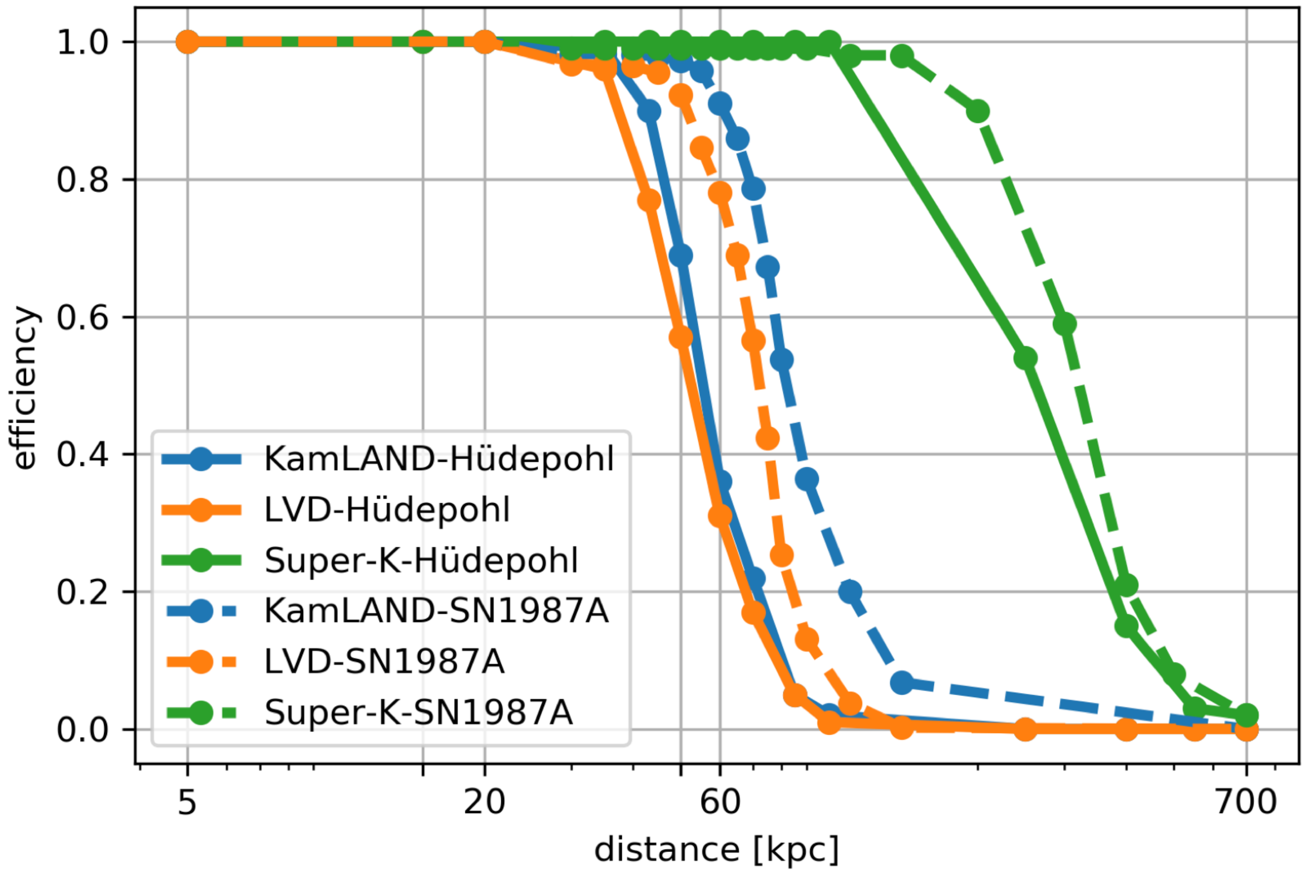
Not requirements on Statistical significance

LEN analysis efficiency

Model (identifier)	Progenitor Mass	S (E$_{thr}$
Pagliaroli [41] (SN1987A)	25 $M_\odot$	
Hüdepohl [40] (Hud)	11.2 $M_\odot$	

Table 2. Number of IBD events expected
neutrino models adopted and the considere
parenthesis we report the assumed energy t

Efficiency = N_recovered/N_injected

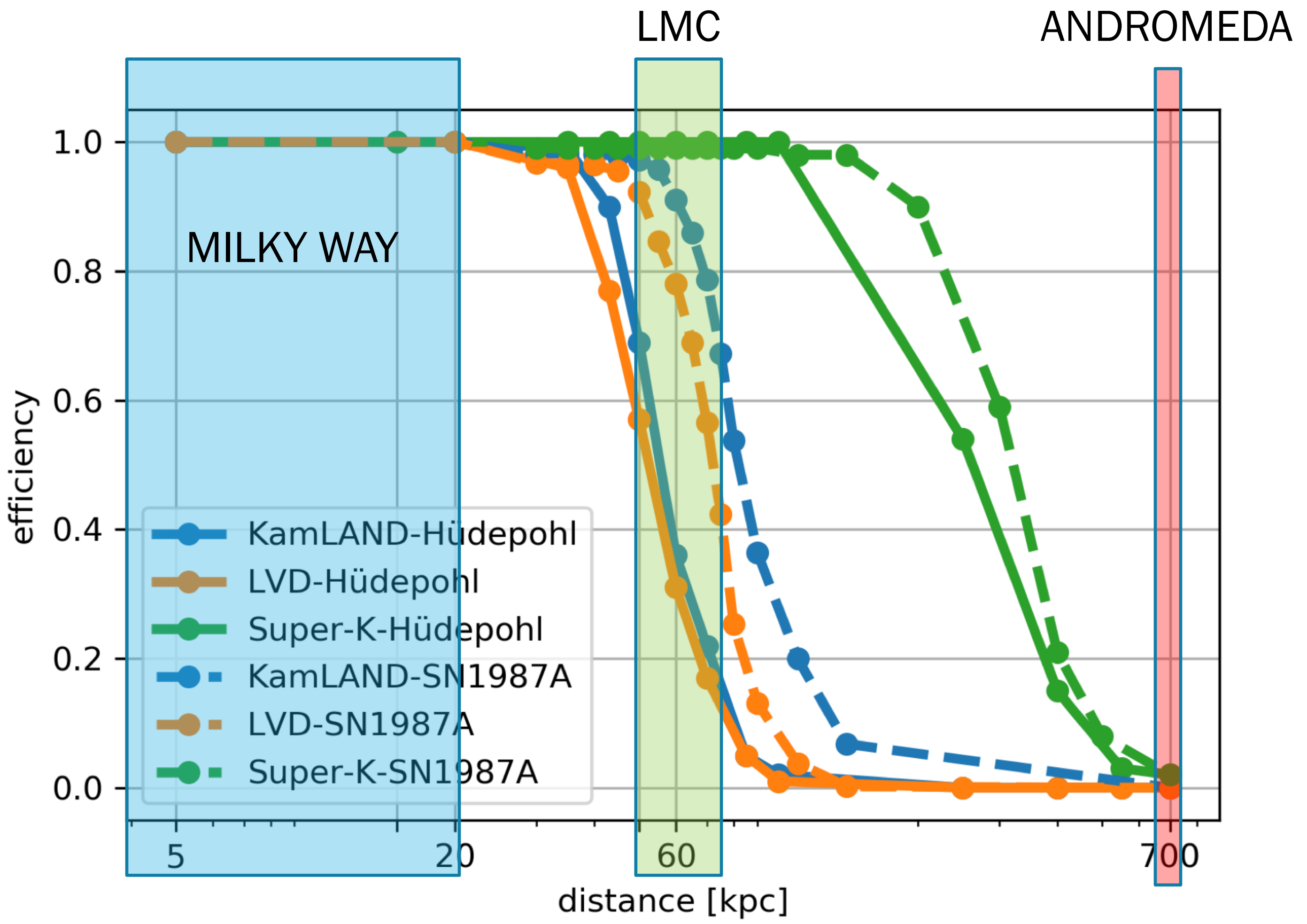


LEN analysis efficiency

MILKY WAY ~100% efficiency

Large Magellanic Cloud
SK ~100% efficiency
LVD & KAM (98%-20%)

Andromeda
SK ~0-1% efficiency
LVD & KAM 0%



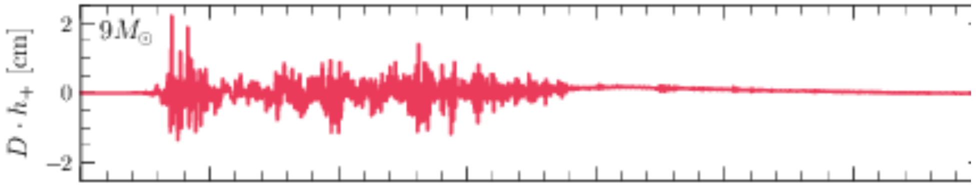
GW signals

Table 1: Waveforms from CCSN simulations used in this work. We report in the columns: emission type and reference, waveform identifier, waveform abbreviation in this manuscript, progenitor mass, angle-averaged root-sum-squared strain $h_{\rm rss}$, frequency at which the GW energy spectrum peaks, and emitted GW energy.

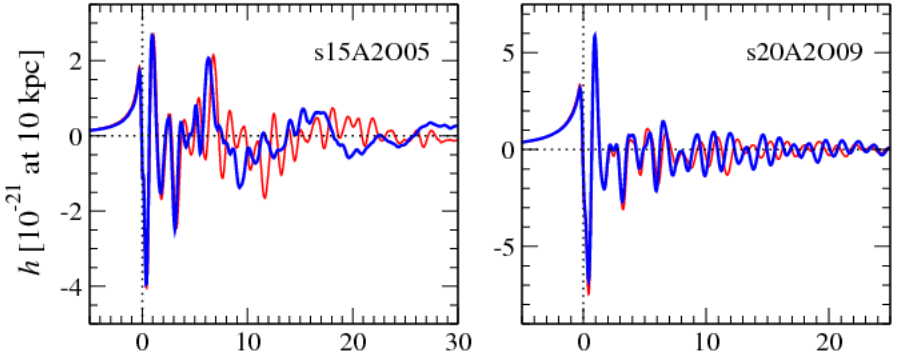
Waveform Family	Waveform Identifier	Abbr.	Mass $M_\odot$	$h_{\rm rss}$ @10 kpc $(10^{-22}\,1/\sqrt{\rm Hz})$	$f_{\rm peak}$ [Hz]	$E_{\rm GW}$ $[10^{-9}\,M_\odot c^2]$
Radice [36]	s25	Rad25	25	0.141	1132	28
3D simulation;	s13	Rad13	13	0.061	1364	5.9
h_+ and $h_\times$; (Rad)	s9	Rad9	9	0.031	460	0.16
Dimmelmeier [37]	dim1-s15A2O05ls	Dim1	15	1.052	770	7.685
2D simulation;	dim2-s15A2O09ls	Dim2	15	1.803	754	27.880
h_+ only; (Dim)	dim3-s15A3O15ls	Dim3	15	2.690	237	1.380
Scheidegger [38]	sch1-R1E1CA$_L$	Sch1	15	0.129	1155	0.104
3D simulation;	sch2-R3E1AC$_L$	Sch2	15	5.144	466	214
h_+ and $h_\times$; (Sch)	sch3-R4E1FC$_L$	Sch3	15	5.796	698	342

Scheidgger *et al*., Astron. Astrophys., 514:A51, 2010

Radice *et al*., Astrophys. J. Lett., 876(1):L9, 2019



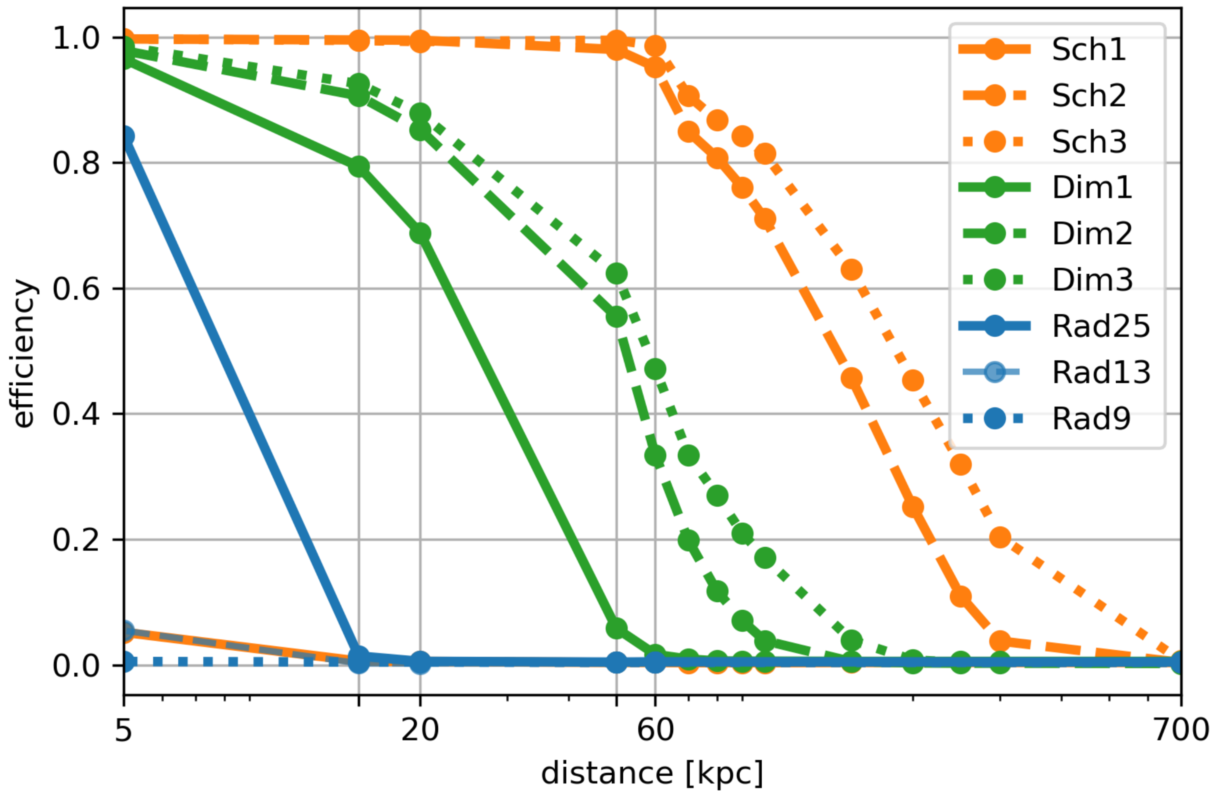
Dimmelmeier *et al*., Phys. Rev. D, 78:064056, Sep 2008



GW analysis efficiency

Table 1: Waveforms from CCSN simulations used in this work. We r
emission type and reference, waveform identifier, waveform abbreviati
progenitor mass, angle-averaged root-sum-squared strain $h_{\rm rss}$, freque
energy spectrum peaks, and emitted GW energy.

Waveform Family	Waveform Identifier	Abbr.	Mass $M_\odot$	$h_{\rm rss}$ @10 k (10^{-22} 1/√
Radice [36]	s25	Rad25	25	0.141
3D simulation;	s13	Rad13	13	0.061
h_+ and $h_\times$; (Rad)	s9	Rad9	9	0.031
Dimmelmeier [37]	dim1-s15A2O05ls	Dim1	15	1.052
2D simulation;	dim2-s15A2O09ls	Dim2	15	1.803
h_+ only; (Dim)	dim3-s15A3O15ls	Dim3	15	2.690
Scheidegger [38]	sch1-R1E1CA$_L$	Sch1	15	0.129
3D simulation;	sch2-R3E1AC$_L$	Sch2	15	5.144
h_+ and $h_\times$; (Sch)	sch3-R4E1FC$_L$	Sch3	15	5.796

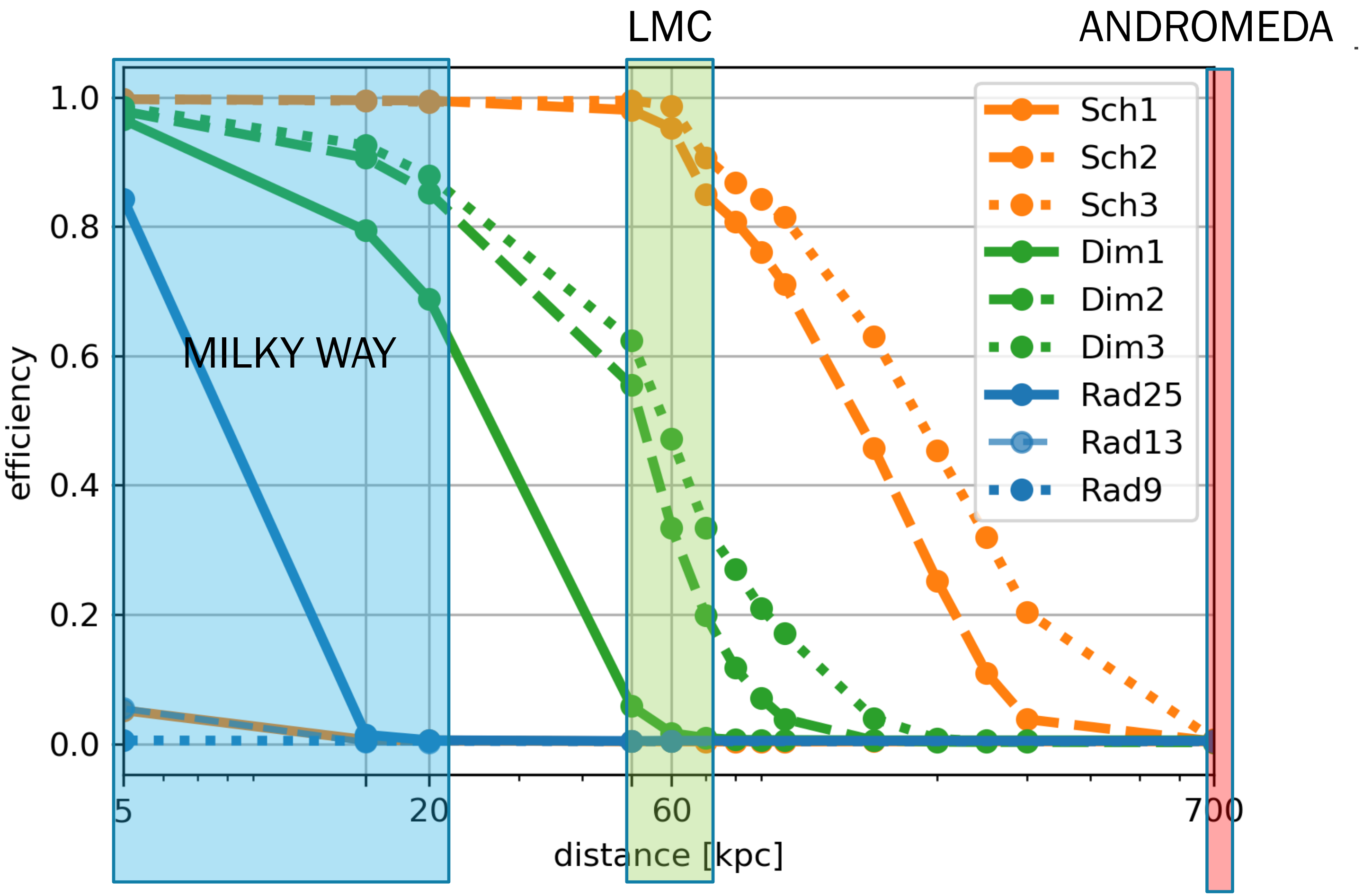


GW analysis efficiency

MILKY WAY ~100%-Extreme models
-80%-90% Rotating
<10% Non Rotating

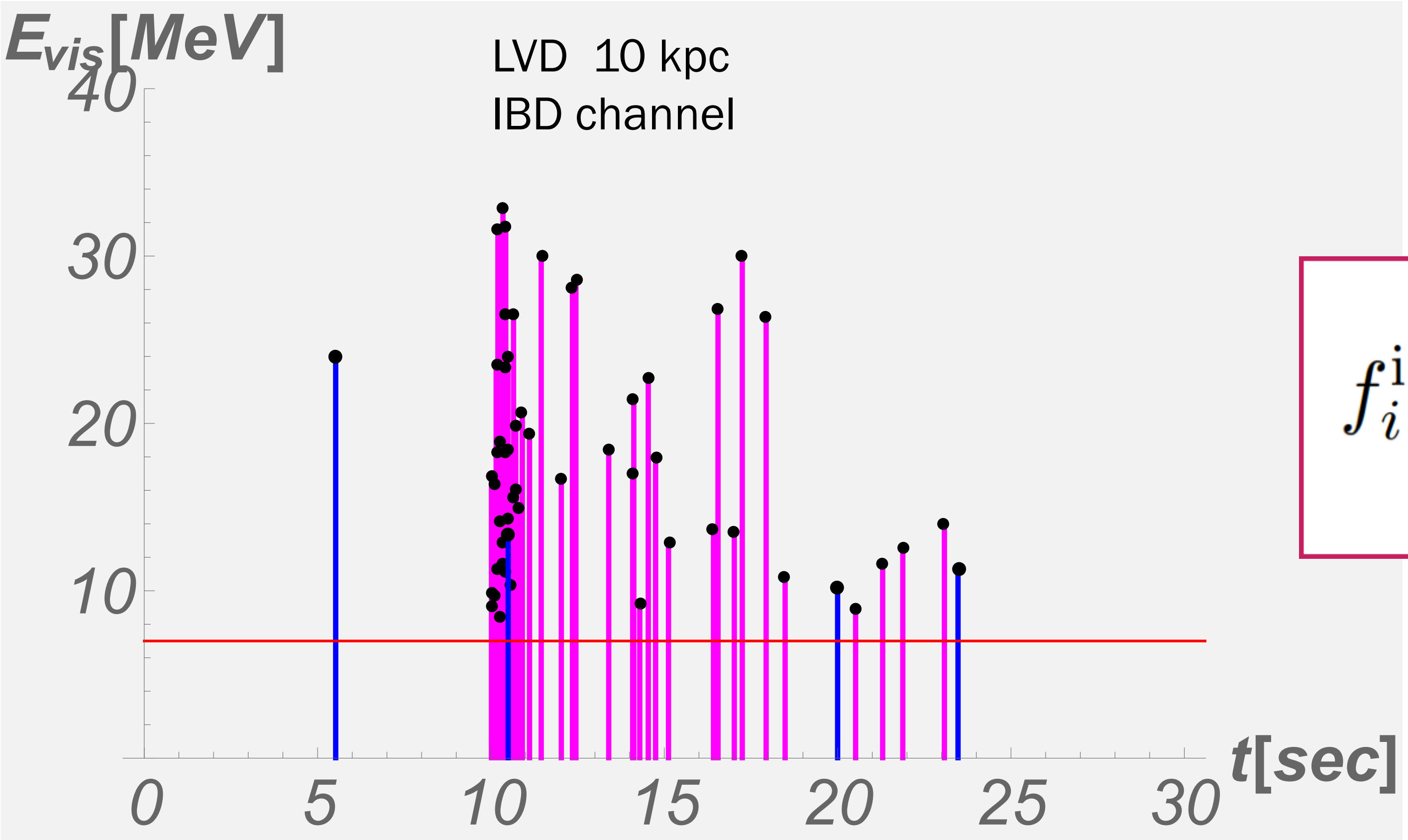
Large Magellanic Cloud
~100% efficiency only for extreme models
-60%-20% for rotating CCSNe
-0% Non Rotating

Andromeda
~0% efficiency



Data analysis improvement in LEN sector

The statistical significance of a LEN events burst: Standard procedure



FIM = Imitation frequency (1/day)

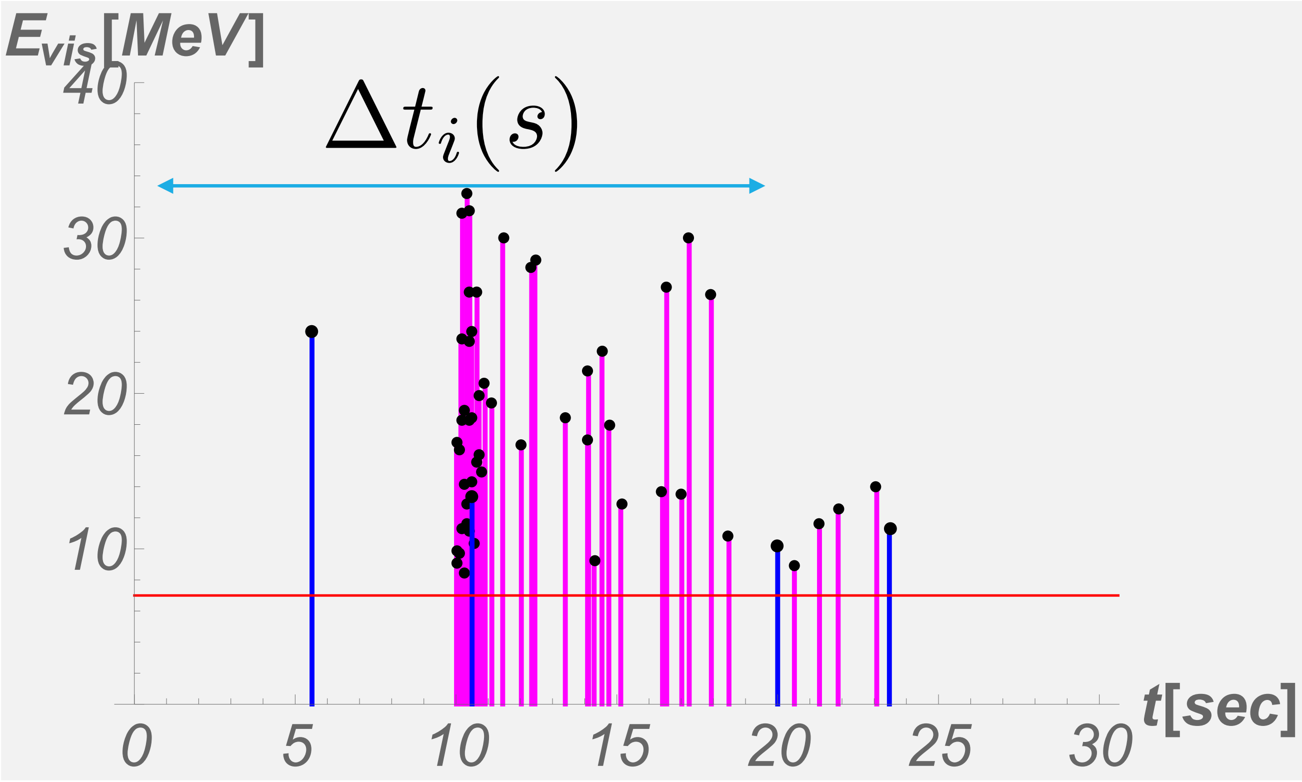
$$f_i^{\mathrm{im}}(m_i) = N \times \sum_{k=m_i}^{\infty} P(k),$$

$$P(k) = \frac{(f_{\mathrm{bkg}} w)^k e^{-f_{\mathrm{bkg}} w}}{k!},$$

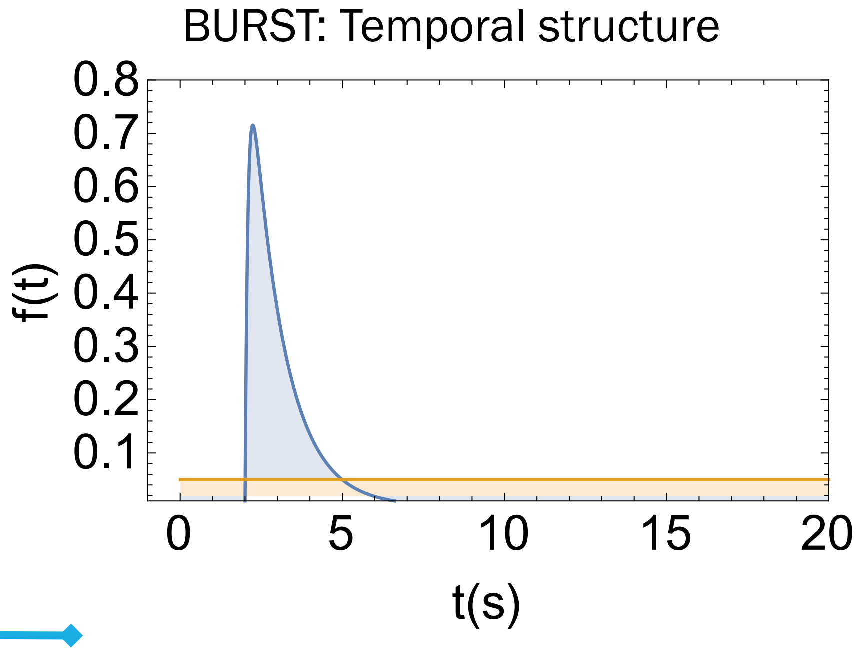
Temporal window $w_\nu = 20s$

Number of events inside the window m_i

The statistical significance of a LEN events burst: New procedure



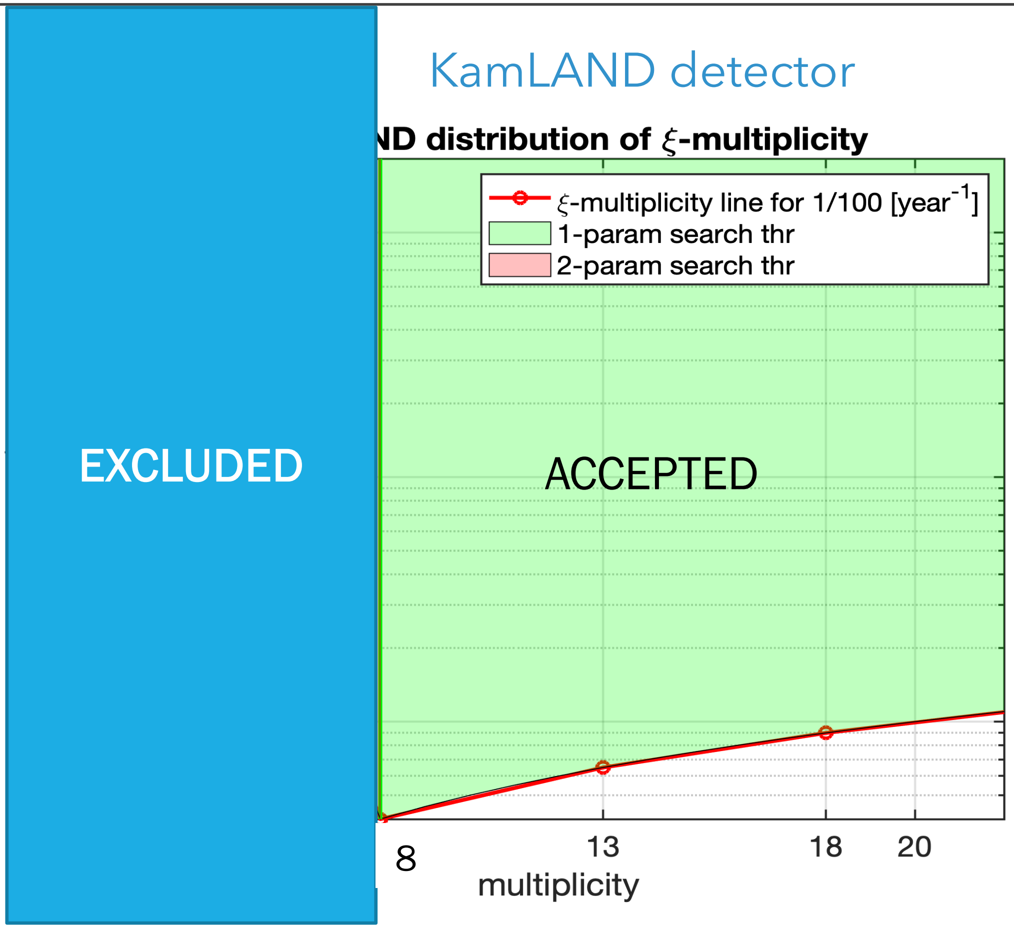
Casentini *et al.* JCAP 08(2018)010



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

a new parameter for LEN burst search

Results for single-LEN detector



Standard procedure

FAR threshold= 1/100yr

m=8

GREEN REGION OF THE PLANE

Results for single-LEN detector

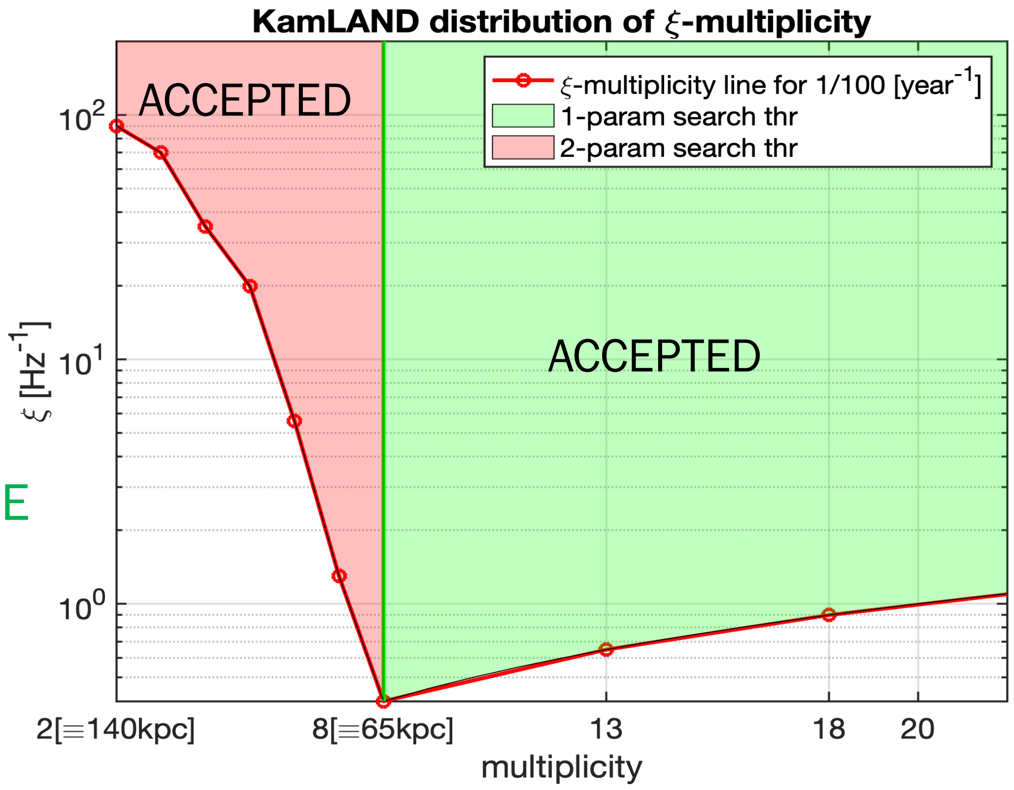
KamLAND detector

New procedure

FAR threshold= 1/100yr

FAR(m,ξ) = red line

GREEN REGION OF THE PLANE
+
RED REGION OF THE PLANE



Standard procedure

FAR threshold= 1/100yr

m=8

GREEN REGION OF THE PLANE

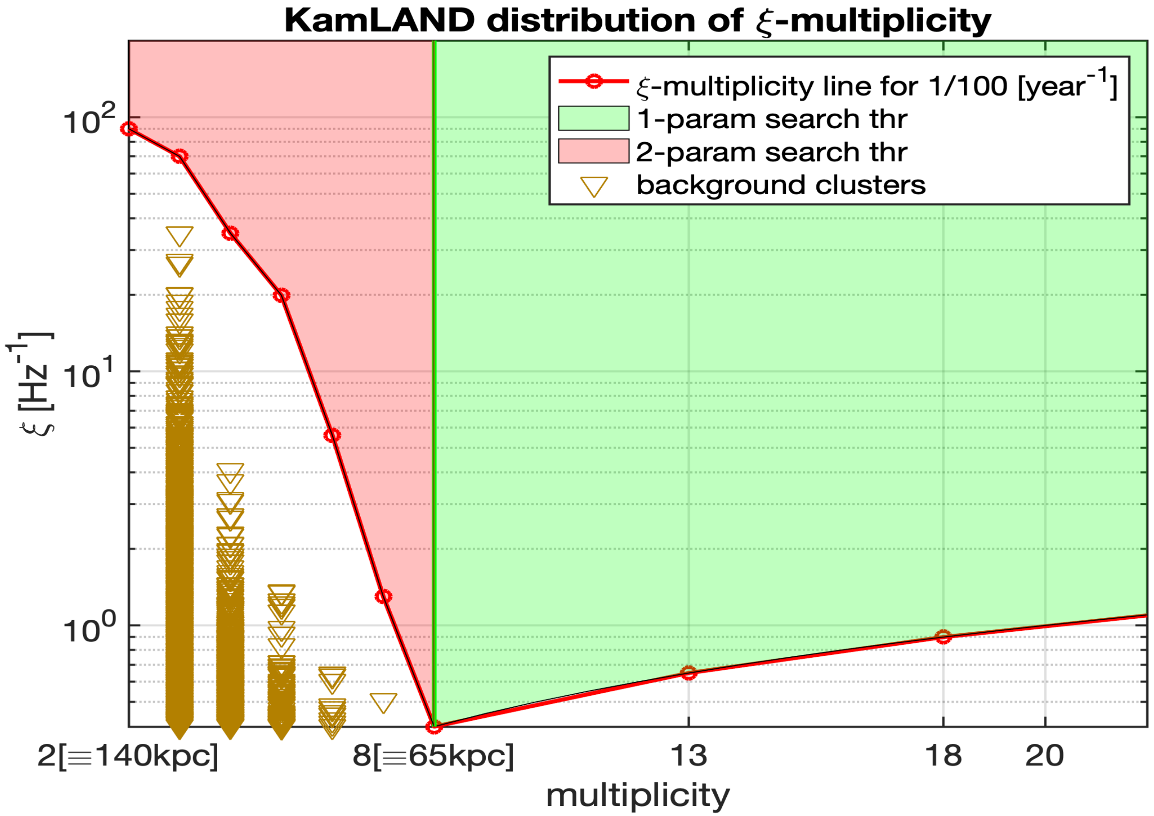
Results for single-LEN detector

KamLAND detector

New procedure

BACKGROUND CLUSTERS
> 70000
In 10 years of data

All below the
FAR threshold= 1/100yr



Results for single-LEN detector

SN1987A-model @60kpc injections, KamLAND detector, 1/100yr FAR threshold

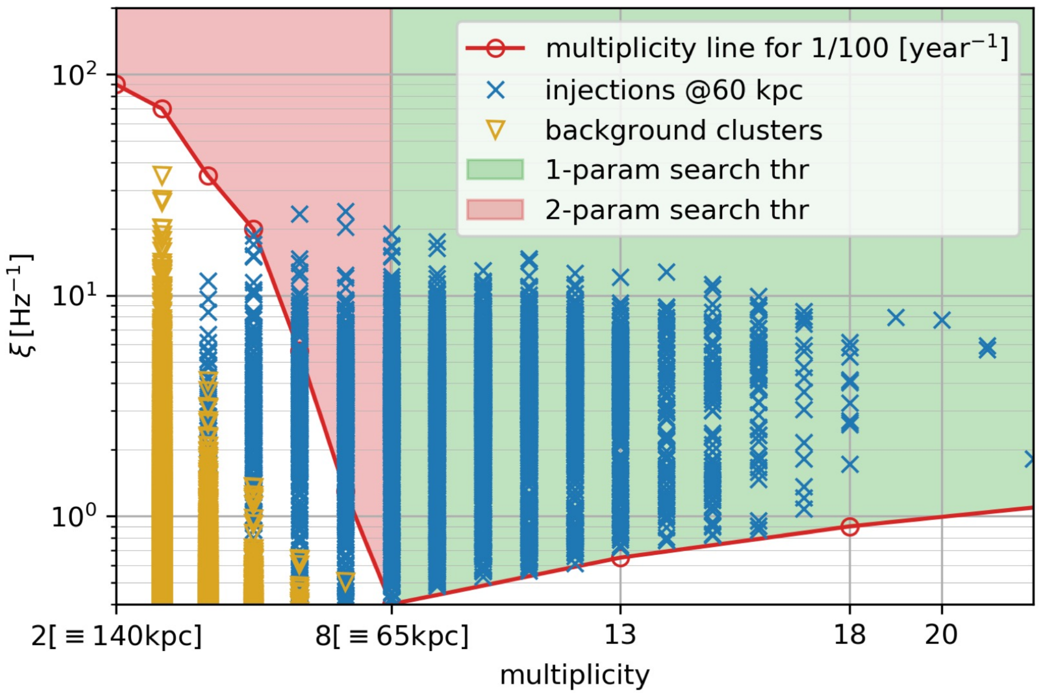


TABLE III: Efficiency (η) comparison between 1-parameter and 2-parameter method of single detector KamLAND 60-kpc for FAR$_\nu$ < 1/100 [year^{-1}] with SN1987A model.

Noise	Noise [< 1/100 yr]	$\eta_{1\text{param}}$ [< 1/100 yr]	$\eta_{2\text{param}}$ [< 1/100 yr]
75198	0/75198	2665/3654=**72.9%**	3026/3654=**82.8%**

Take Home Message #1

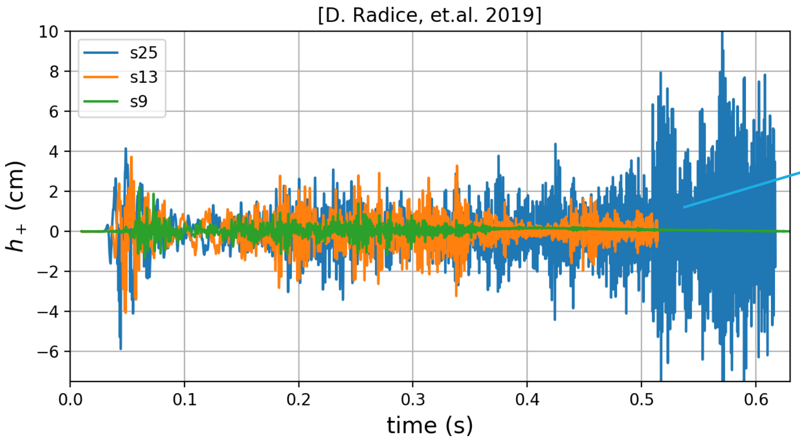
The use of the new parameter for LEN burst search increases the detection efficiency of 10% @ horizon

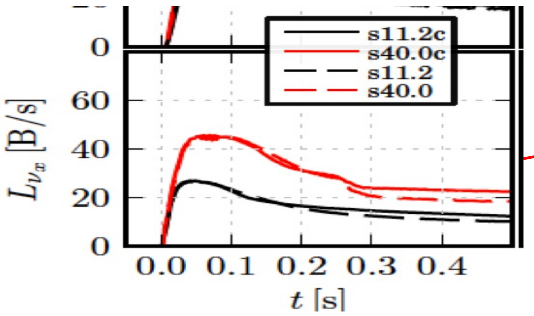
Gain for SNEWS alerts for the e.m. community!

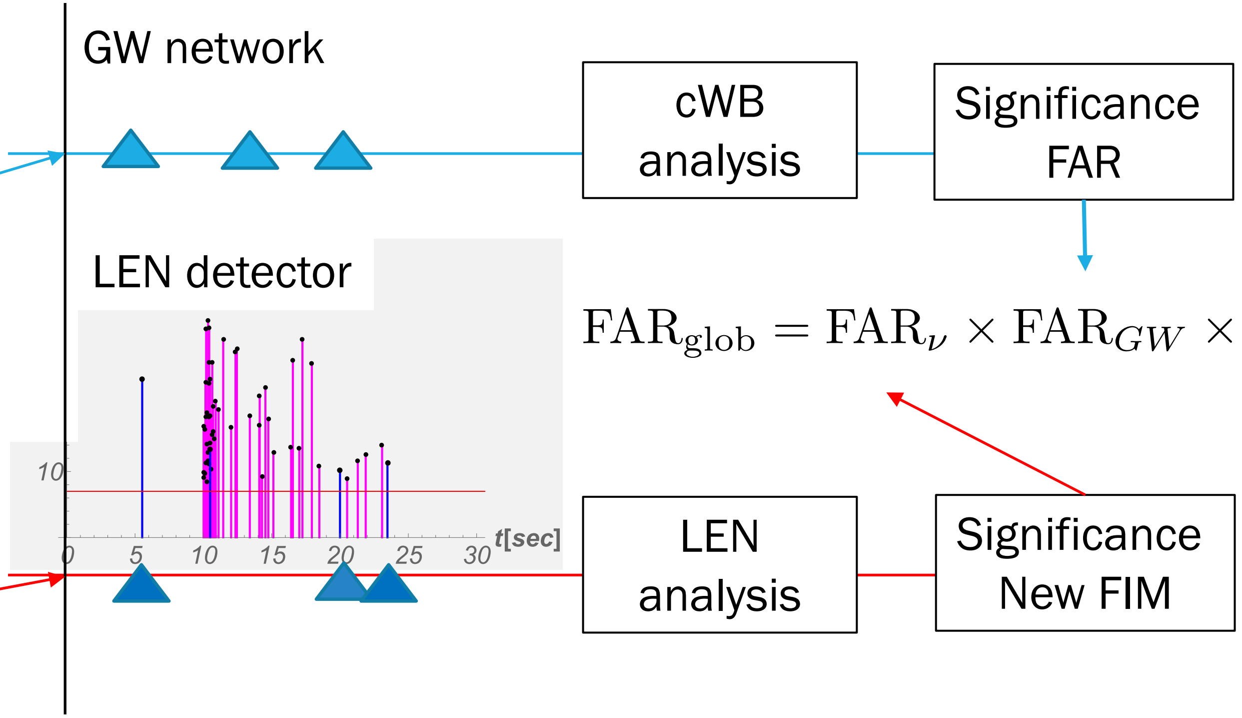
Data analysis for combining GW-LEN

Data analysis procedure

For each specific CCSN Distance and location







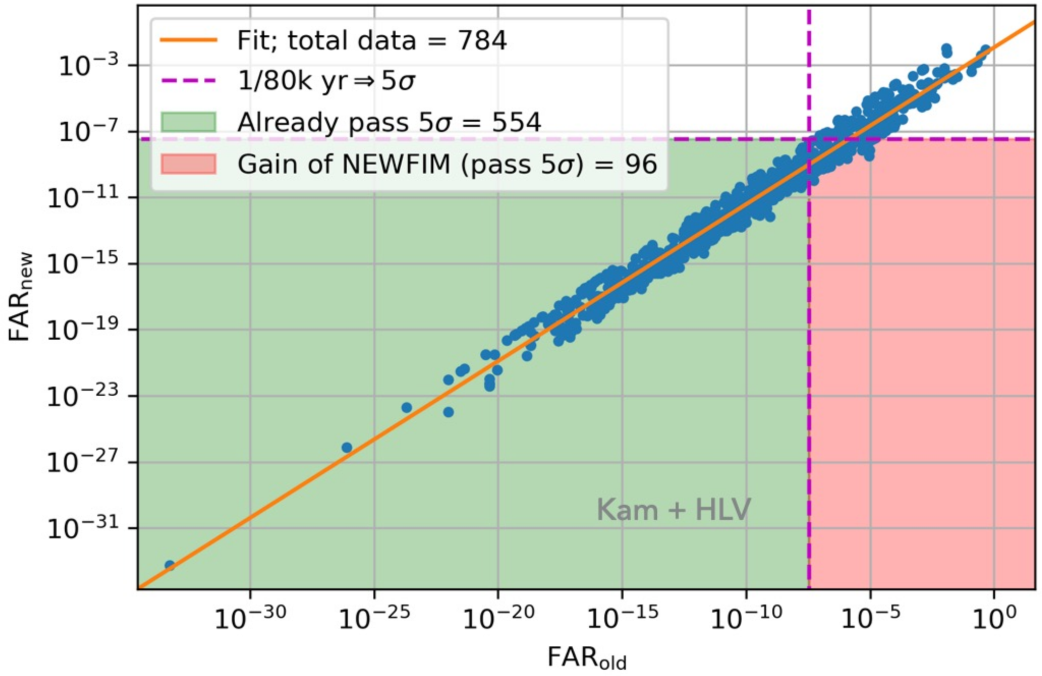
$$\mathrm{FAR_{glob}} = \mathrm{FAR}_{\nu} \times \mathrm{FAR}_{GW} \times 2w_c$$

Background spikes in GW det.

Background events in neutrino det.

Results for global-network of LEN-GW

SN1987A-LEN signal model @60kpc injections, KamLAND detector, 5 sigma-FAP threshold
Dimmelmeier2-GW model @60kpc injections, LIGO-H, LIGO-L, Virgo detectors



Network & Type of Injections	Recovered $FAR_{GW} < 864/d$	η_{1param} $[> 5\sigma]$	η_{2param} $[> 5\sigma]$
HLV-KAM (Dim2-SN1987A)	784/2346= 33.4%	554/784= **70.7%**	650/784= **82.9%**

The ~33% GW-signals recovered are far to be statistically significant:
the 5σ detection efficiency is 0%.

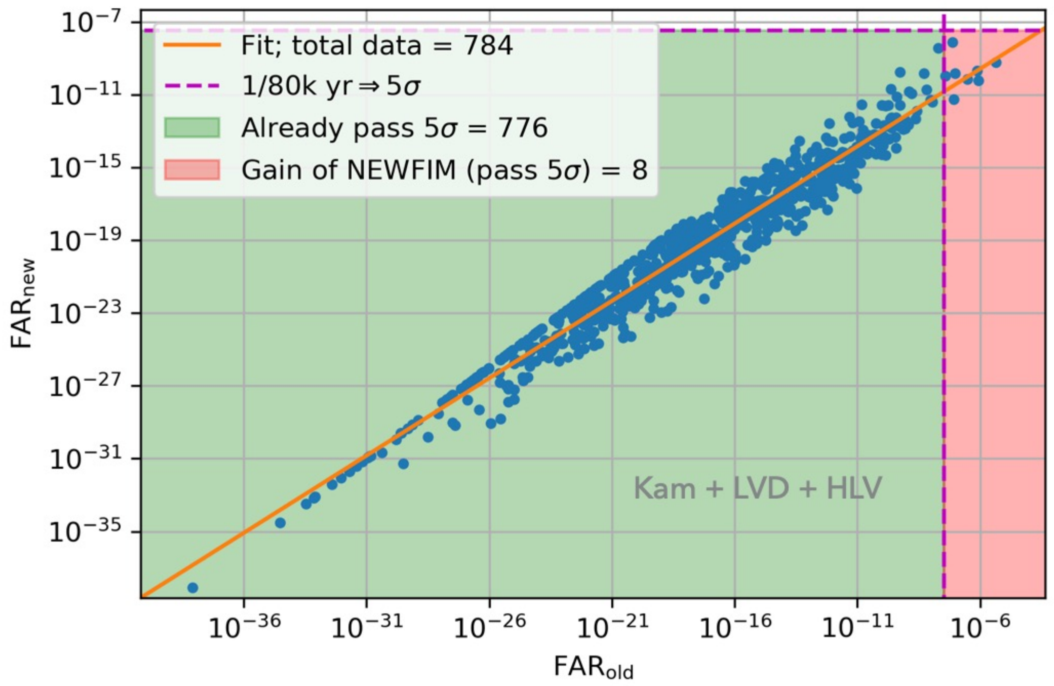
Take home message #2

By adding the KAM det. the 5σ detection efficiency becomes:

33.4%*82.9% = 27.7%

Results for global-network of LEN-GW

SN1987A-LEN signal model @60kpc injections, KamLAND and LVD detectors, 5 sigma-FAP threshold
Dimmelmeier2-GW model @60kpc injections, LIGO-H, LIGO-L, Virgo detectors



Network & Type of Injections	Recovered $FAR_{GW} < 864/d$	η_{1param} $[> 5\sigma]$	η_{2param} $[> 5\sigma]$
HLV-KAM (Dim2-SN1987A)	784/2346= 33.4%	554/784= **70.7%**	650/784= **82.9%**
HLV-KAM-LVD (Dim2-SN1987A)	784/2346= 33.4%	776/784= **99.0%**	784/784= **100%**

GW-LEN Det. efficiency with 2-param method: 33.4%*100% = 33.4%

Take home message #3

Combining the LEN 2-param search method with the GW one the detection efficiency grows from 0% to ~33%

Summary

- We quantify the CCSNe analysis efficiency of a global network of LEN and GW detectors.
- We improve the LEN data-analysis increasing the detection efficiency of LEN detectors of 10% @ horizon.
- The new method is sensitive to low statistics signals (far/weak), is fast and adaptive.
- Useful to expand the detection horizon of future detector (Hyper-K) to reach Andromeda.

3.3. Hyper-K single-detector analysis

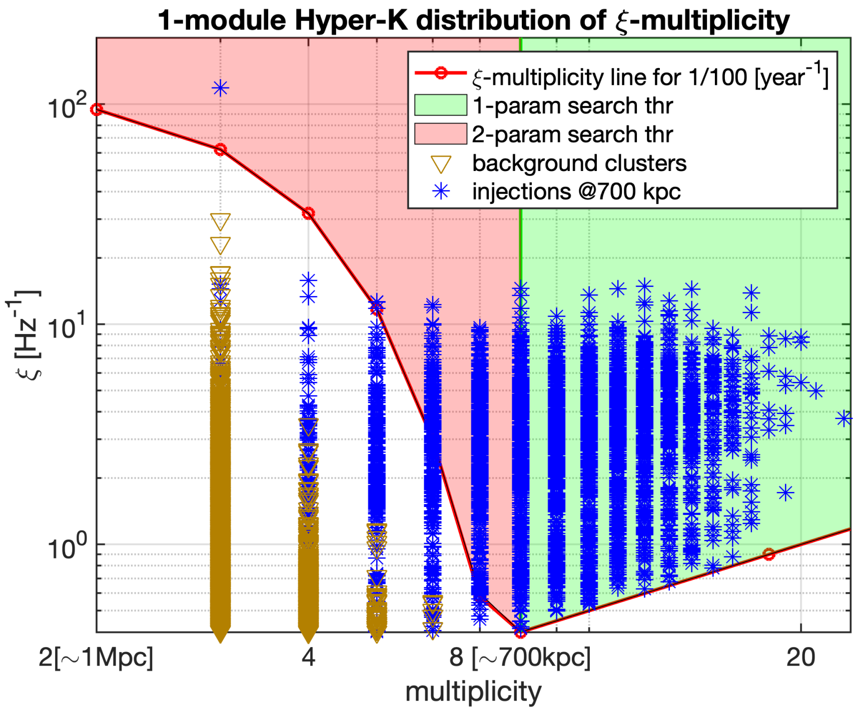


TABLE 7.5: One-module Hyper-K with 700-kpc injections.

Total Background	Background [< 1/100 years]	1-parameter [< 1/100 years]	2-parameter (this work) [< 1/100 years]
49203	0% = 0/49203	**70.4%** = 2575/3655	**85.4%** = 3120/3655

Summary

- We quantify the CCSNe analysis efficiency of a global network of LEN and GW detectors.
- We improve the LEN data-analysis increasing the detection efficiency of LEN detectors of 10% @ horizon.
- The new method is sensitive to low statistics signals (far/weak), is fast and adaptive.
- Useful to expand the detection horizon of future detector (Hyper-K) to reach Andromeda.
- We show that the GW CCSNe detection efficiency greatly increases when GWs and LEN data are combined.

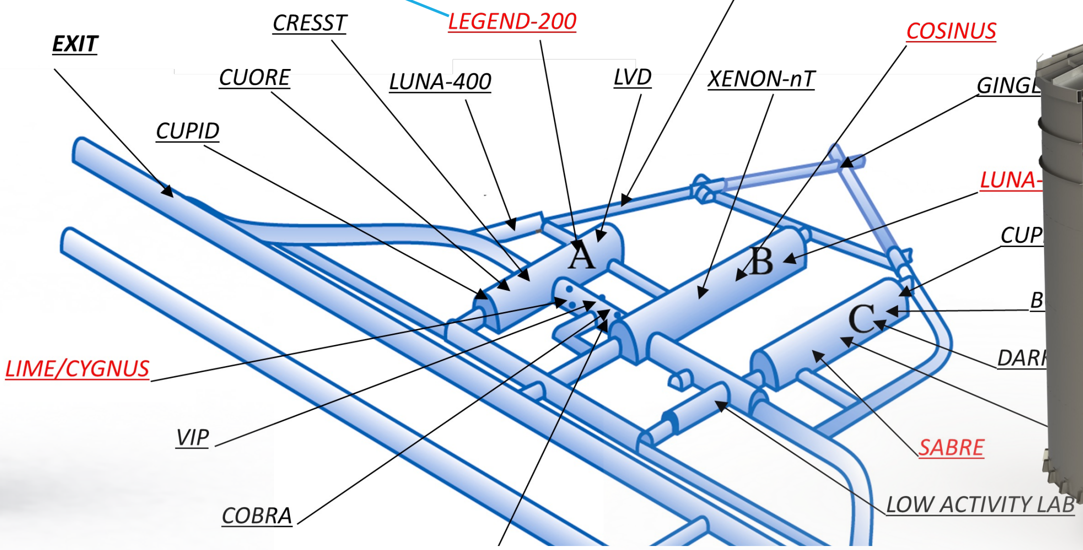
Before questions....

SN@LNGS

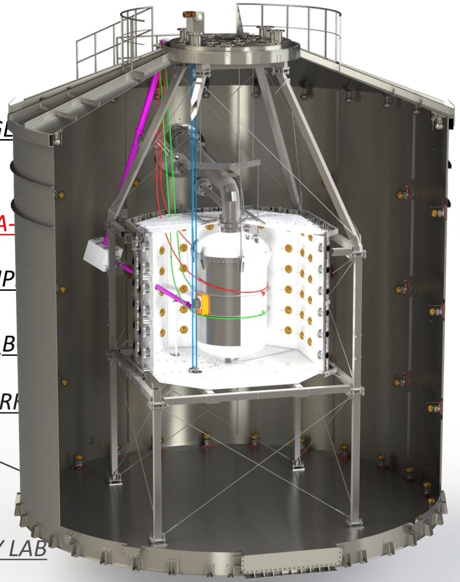
LVD (293 events)

SN@10 kpc -→H20 IBD and NO
XENONnT (700 ton) = 167
LEGEND 200 (590 ton) = 140
COSINUS (270 ton) = 64

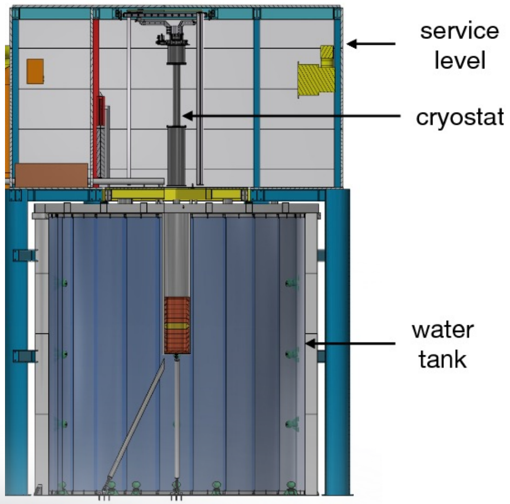
LEGEND-200



XENONnT



COSINUS



An infrastructure with several detectors sensitive to SN neutrinos: an interesting network of different detectors located in the same place. Combined Horizon: LMC. Very high duty cycle and fast coincidences in time (ms).

The Agreement with the Experiments is ongoing.

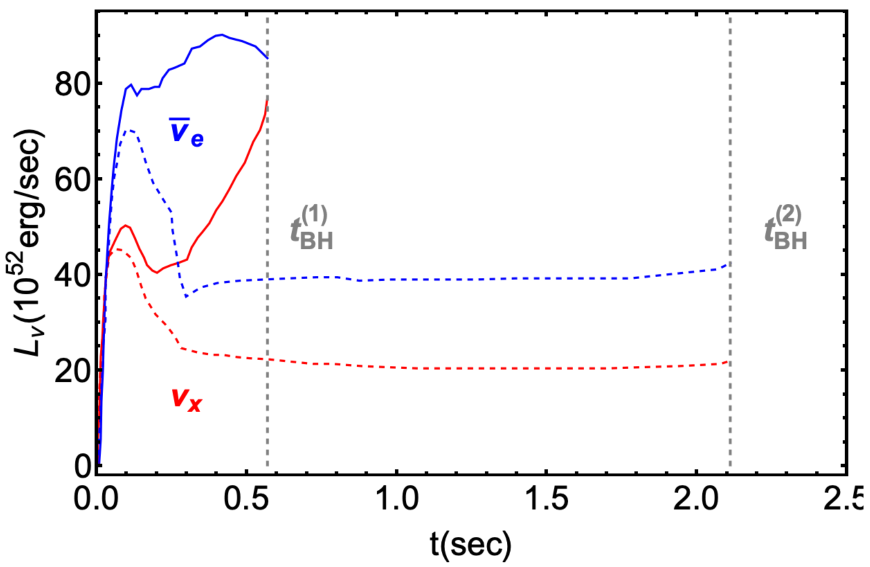
Failed Supernovae @ LNGS

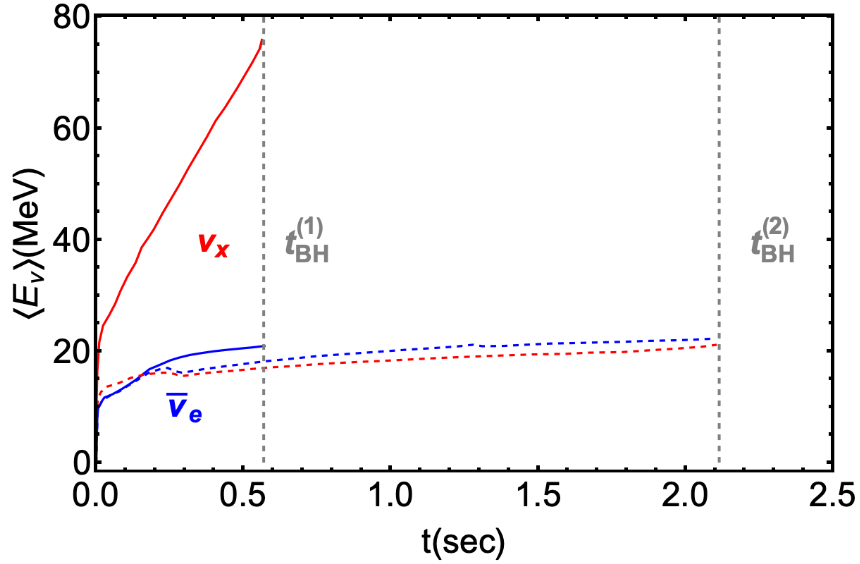
The neutrino and GW emission end abruptly at the time of the Black Hole formation.

The EM counterpart of this event is easily missing.

Let's see the capability of the LNGS infrastructure to identify the time of the BH formation

$$T_{BH}^{GW} = T_{BH}^{\nu} \pm t_{fly}$$
$$\boldsymbol{\delta} T_{BH}^{GW} = \boldsymbol{\delta} T_{BH}^{\nu} + \boldsymbol{\delta} t_{fly}$$



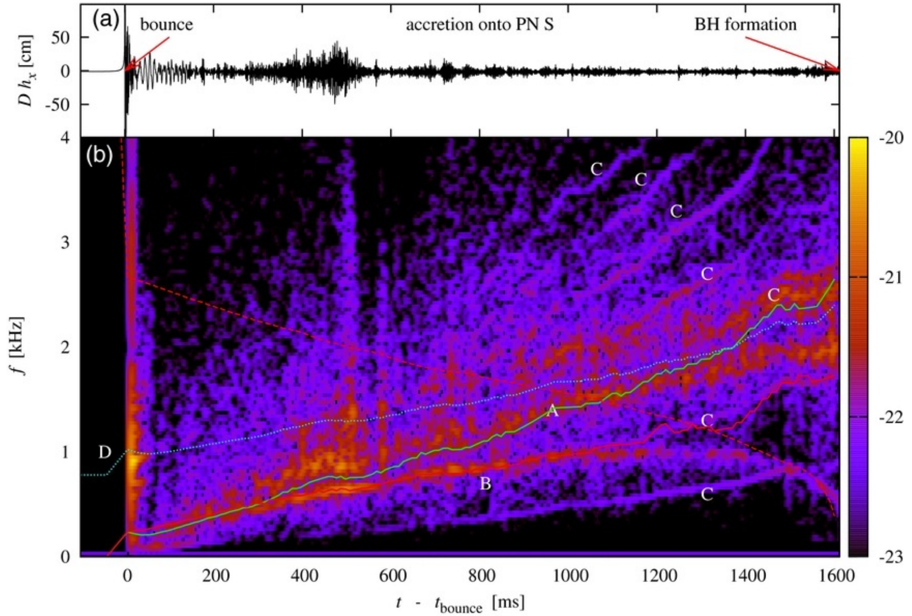


Model 1: Woosley and Weaver, Astrophys. J. Suppl. 101, 181 (1995)

FAST BH formation after 0.568 s

Model 2: Woosley et.al , Rev. Mod. Phys. 74, 1015 (2002)

SLOW BH formation after 2.113 s



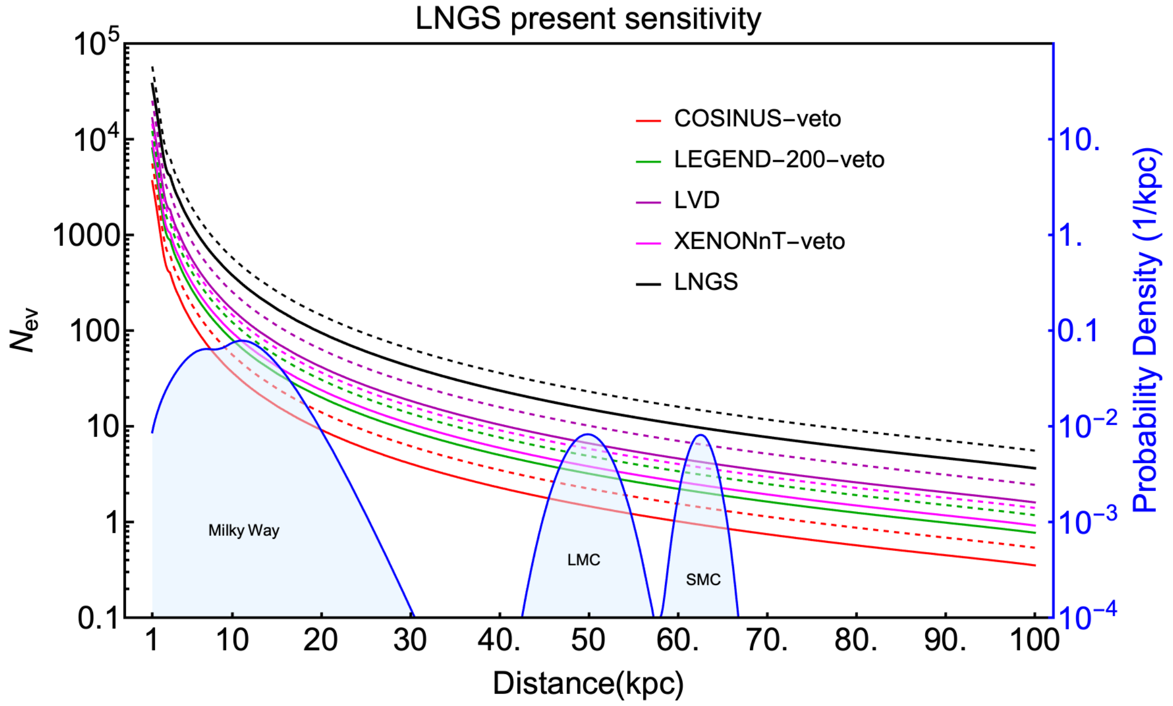
Pablo Cerdá-Durán *et al* 2013 *ApJL* **779** L18

The Time of BH formation @ LNGS

Results for D=10 kpc

Future Exp.
Legend-1000 = 980 ton
Darwin = 1240 ton

Detector	N_{IDB}	$t^1 \pm \delta t^1$ [s]	$t^{\mathrm{last}} \pm \delta t^{\mathrm{last}}$ [s]	$1/\xi$ [s]
LVD	293 (520)	0.017±0.008 (0.017±0.009)	0.567±0.001 (2.109±0.004)	0.002 (0.004)
COSINUS-veto	64 (114)	0.03±0.02 (0.04±0.02)	0.561±0.007 (2.09±0.02)	0.008 (0.018)
Legend200-veto	140 (249)	0.021±0.008 (0.03±0.01)	0.565±0.003 (2.107±0.006)	0.004 (0.008)
XENONnT-veto	167 (297)	0.023±0.009 (0.02±0.01)	0.565±0.003 (2.107±0.006)	0.003 (0.007)
Legend1000-veto	234 (415)	0.021±0.009 (0.02±0.01)	0.566±0.002 (2.108±0.004)	0.002 (0.005)
DARWIN-veto	511 (907)	0.014±0.006 (0.014±0.007)	0.5672±0.0009 (2.111±0.002)	0.001 (0.002)



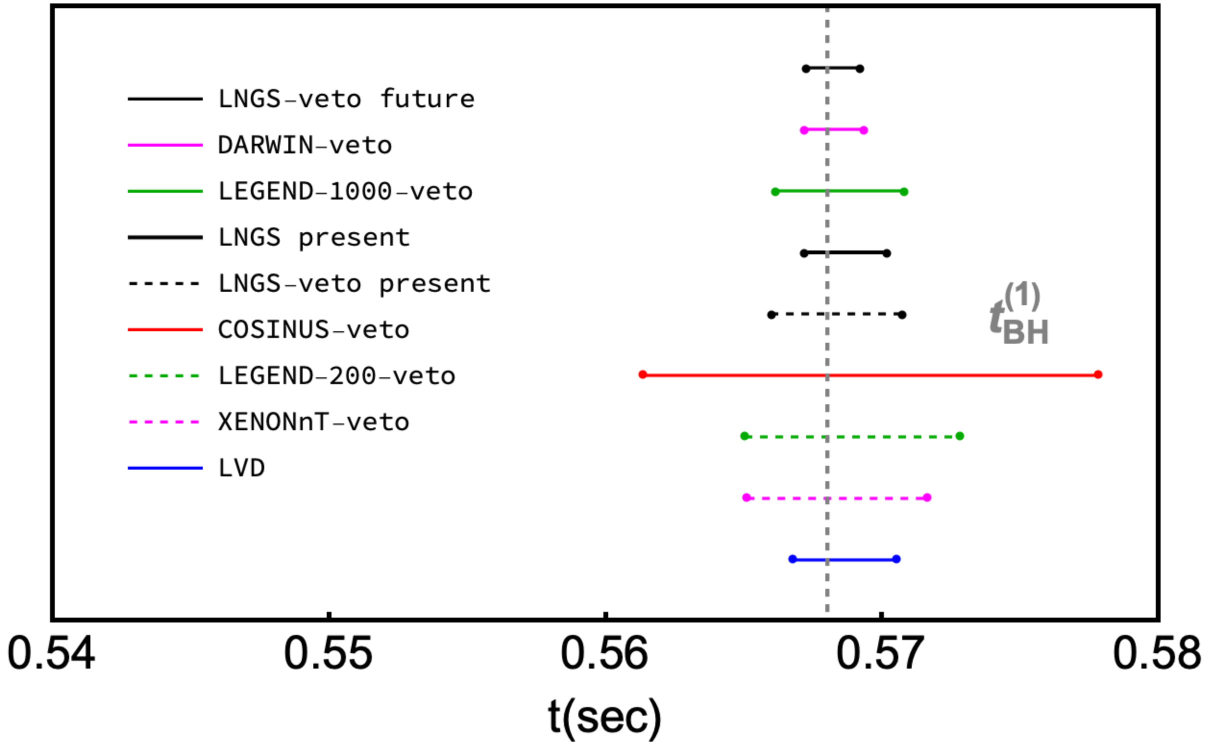
$$\xi = N_{\mathrm{IBD}}/(t^{\mathrm{last}} - t^1).$$

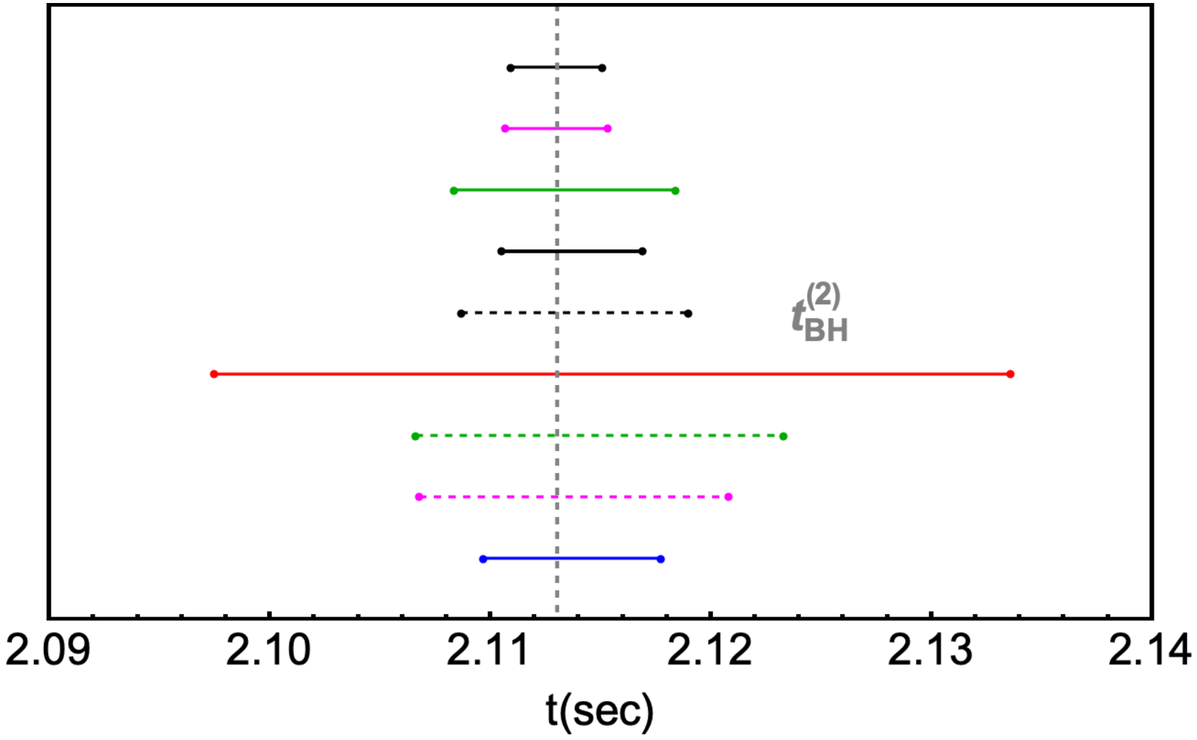
$$T^{\nu}_{\mathrm{BH}} = \mathrm{Max}[T_i^{\mathrm{last}}] + 1/\xi_{\mathrm{Max}}$$

$$\delta T^{\nu}_{\mathrm{BH}} = \sqrt{1/\sum_i (\xi_i^2)}$$

In agreement with
Sarfati et al.Phys.Rev.D 105 (2022) 2, 023011
Brdar et al. JCAP04(2018)025

The Time of BH formation @ GW det





LNGS – VIRGO

$$\delta T_{\rm BH}^{\rm GW} = \delta T_{\rm BH}^{\rm LNGS} + \delta t_{\rm fly} = 4\,{\rm ms}$$

SK– VIRGO

$$\delta T_{\rm BH}^{\rm GW} = \delta T_{\rm BH}^{\rm SK} + \delta t_{\rm fly} = 28.3\,{\rm ms}$$

GP and Ternes, *JCAP* 06 (2024) 022


Thank You

Results for global-network of LEN-GW

Hüdepohl-LEN signal model @60kpc injections, KamLAND and LVD detectors, 5 sigma-FAP threshold
Dimmelmeier2-GW model @60kpc injections, LIGO-H, LIGO-L, Virgo detectors

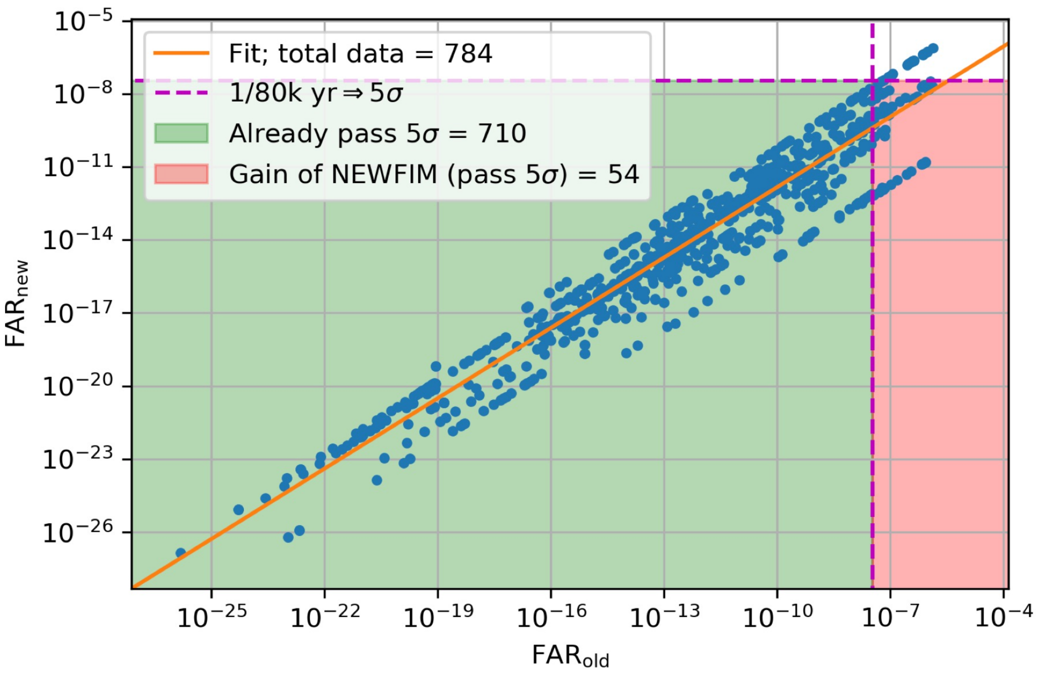


TABLE VI: Efficiency (η) comparison of 1-parameter and our 2-parameter method for Figure 9. The columns are analogous to Table V.

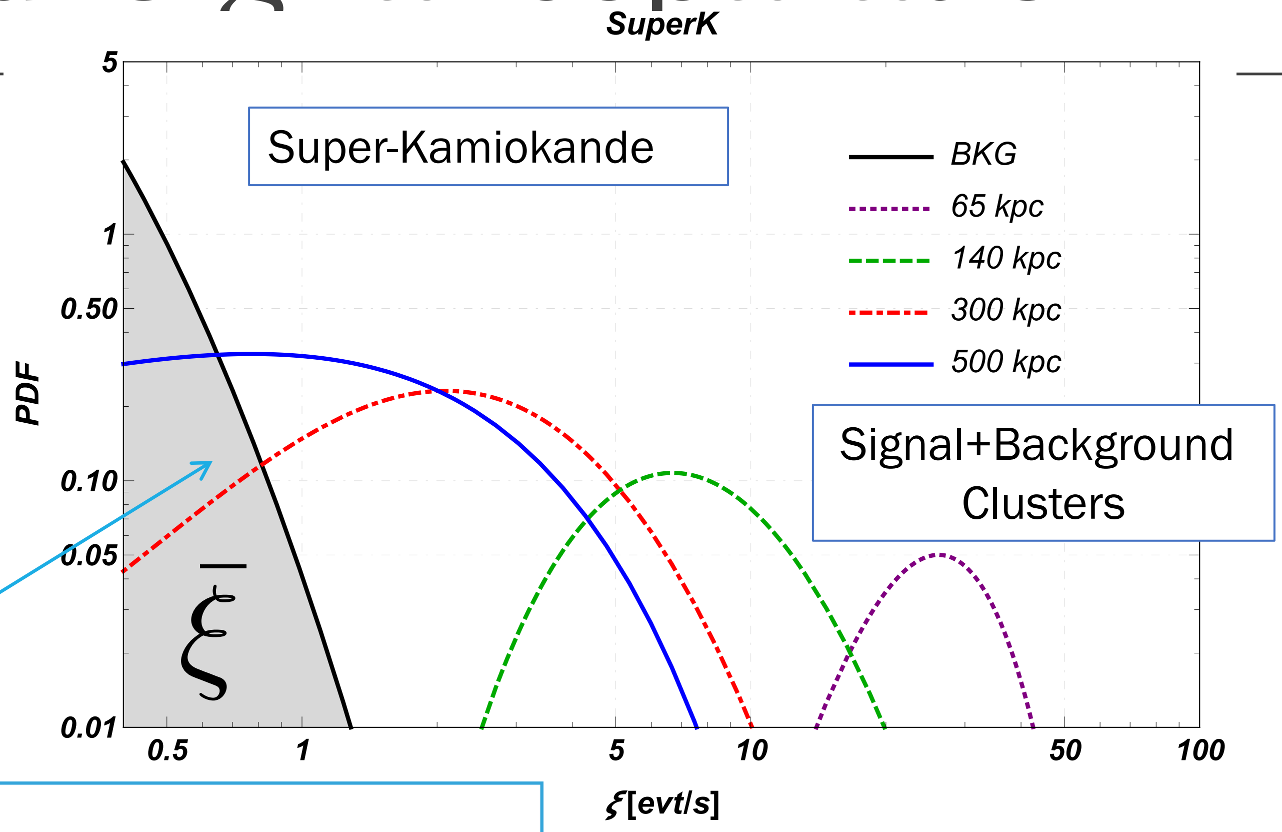
Network & Type of Injections	Recovered $FAR_{GW} < 864/d$	η_{1param} [$> 5\sigma$]	η_{2param} [$> 5\sigma$]
HLV-KAM-LVD (Dim2-Hud)	784/2346= 33.4%	710/784= **90.6%**	764/784= **97.5%**

GW Detection efficiency without LEN network:		0%
GW-LEN Det. efficiency with 1-param method:	33.4%*90.6% =	30.3%
GW-LEN Det. efficiency with 2-param method:	33.4%*97.5% =	32.6%

Background-Signal separation

Probability Density Functions (PDF)

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

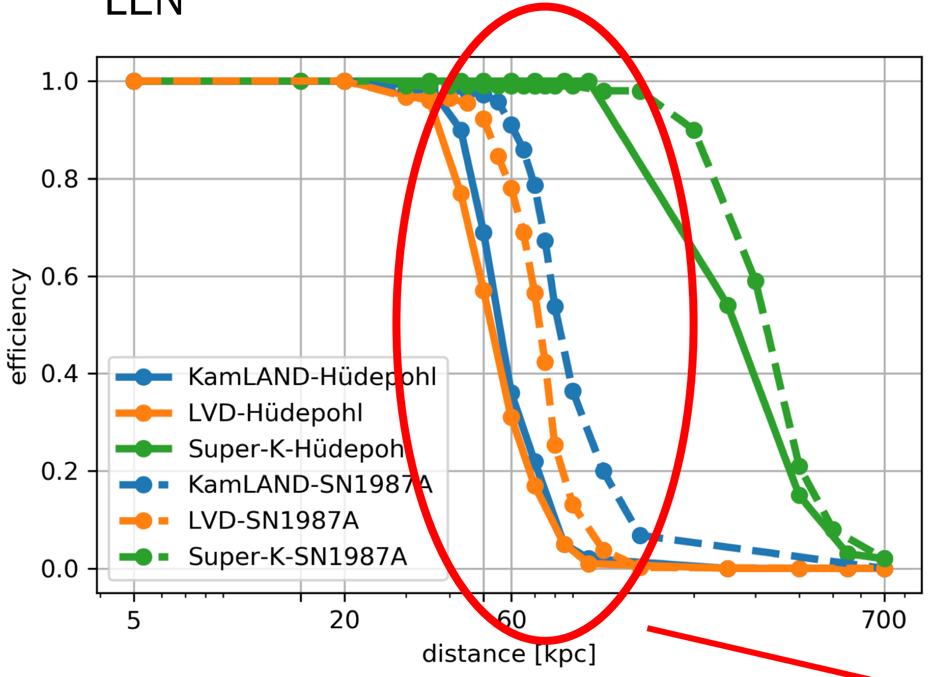


Pure Background Clusters

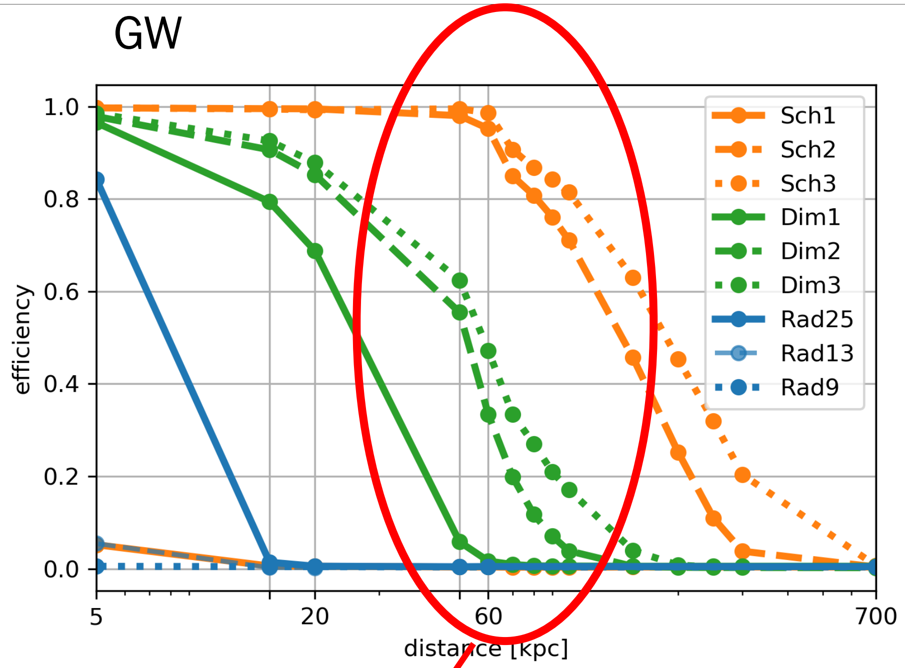
$$F_i^{\mathrm{im}}(m_i, \xi_i) = N \times \sum_{k=m_i}^{\infty} P(k) \int_{\xi=\xi_i}^{\infty} \mathrm{PDF}(\xi \geq \xi_i | k) d\xi.$$

Combined analysis LEN+GW

LEN



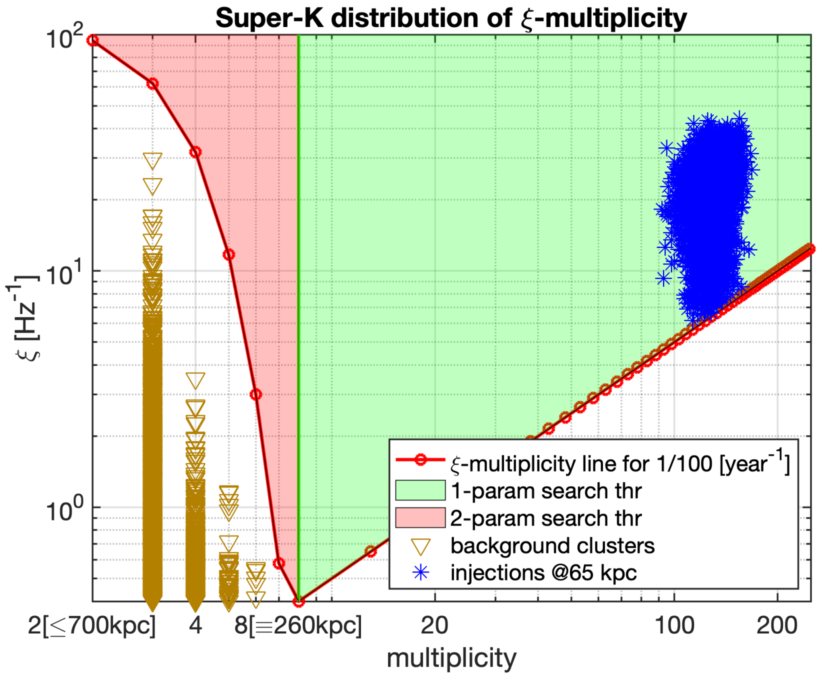
GW



Combined analysis in the LMC with LVD+Kamland+HLV(Rotating CCSNe)

D=60 kpc

- Super-K single-detector analysis. $m = 8 \Rightarrow D = 260\,\mathrm{kpc}$



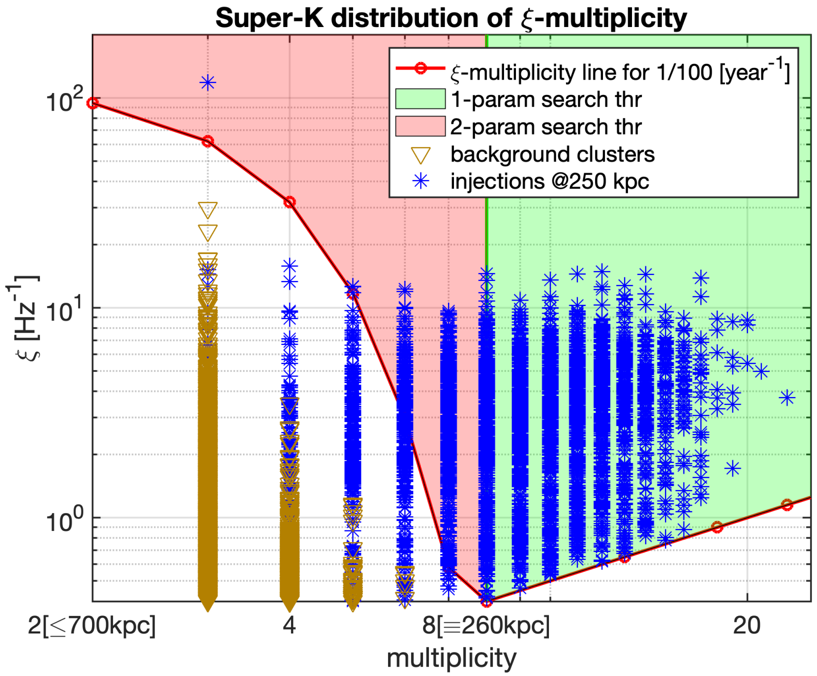


TABLE 7.3: Single detector SuperK analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

Total Background	Background [< 1/100 years]	1-parameter [< 1/100 years]	2-parameter (this work) [< 1/100 years]
49200	0% = 0/49200	**70.6%** = 2575/3645	**85.5%** = 3117/3645

44

Super-K single-detector analysis. $m = 8 \Rightarrow D = 260\,\mathrm{kpc}$

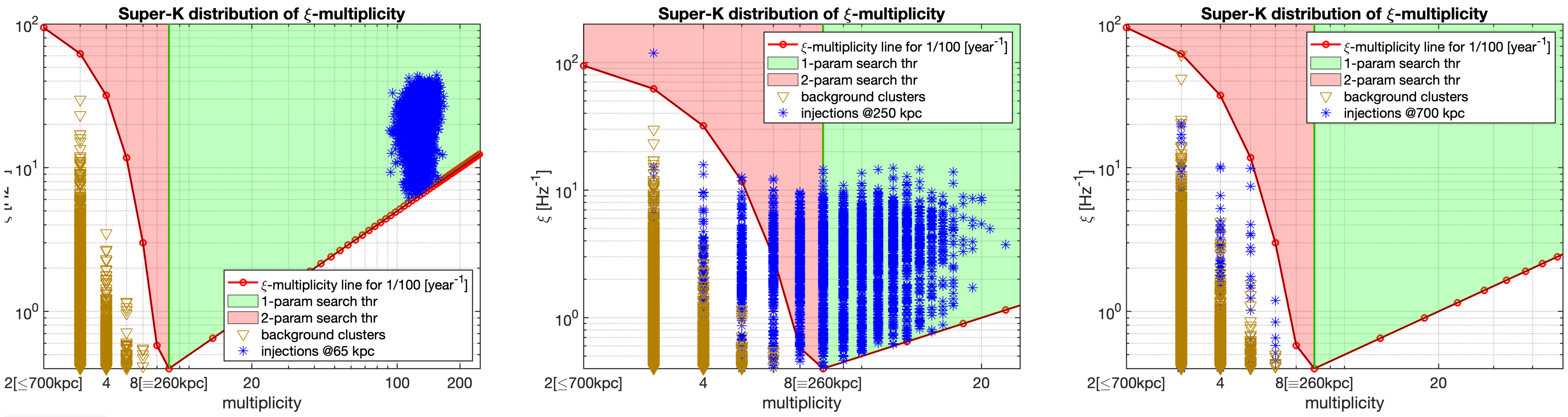
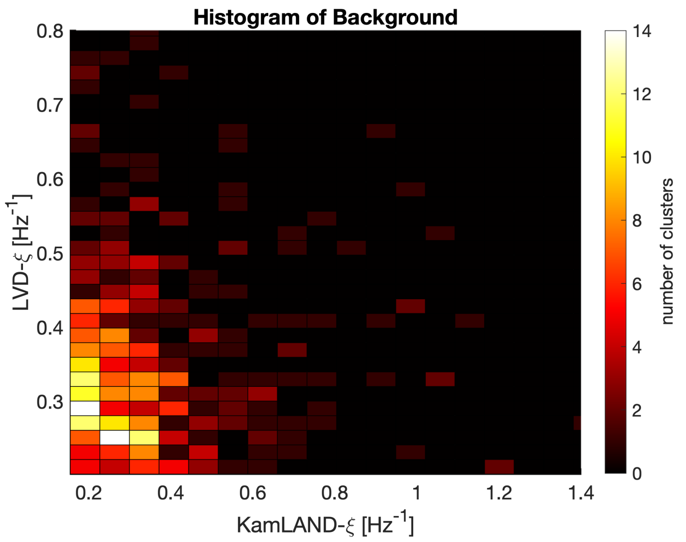


TABLE 7.3: Single detector Super-K analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

Total Background	Background [< 1/100 years]	1-parameter [< 1/100 years]	2-parameter (this work) [< 1/100 years]
49200	0% = 0/49200	**70.6%** = 2575/3645	**85.5%** = 3117/3645

LVD-KamLAND joint-detector analysis.



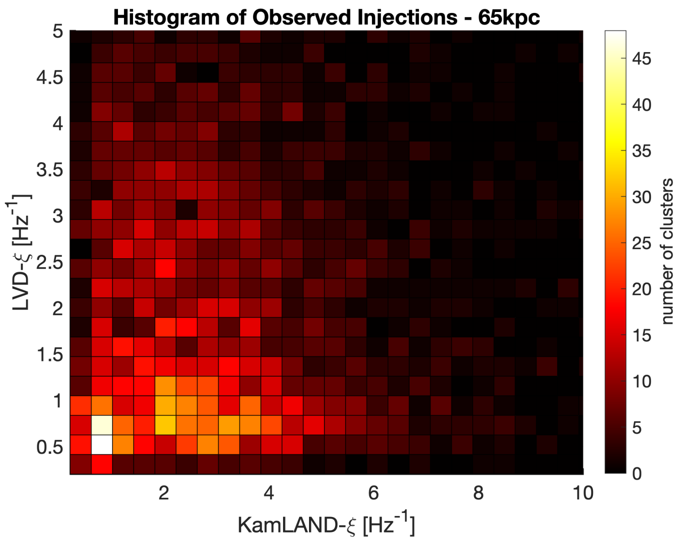


TABLE 7.4: Efficiency η and misidentification probability ζ for KamLAND-LVD 10 year - 65 kpc.

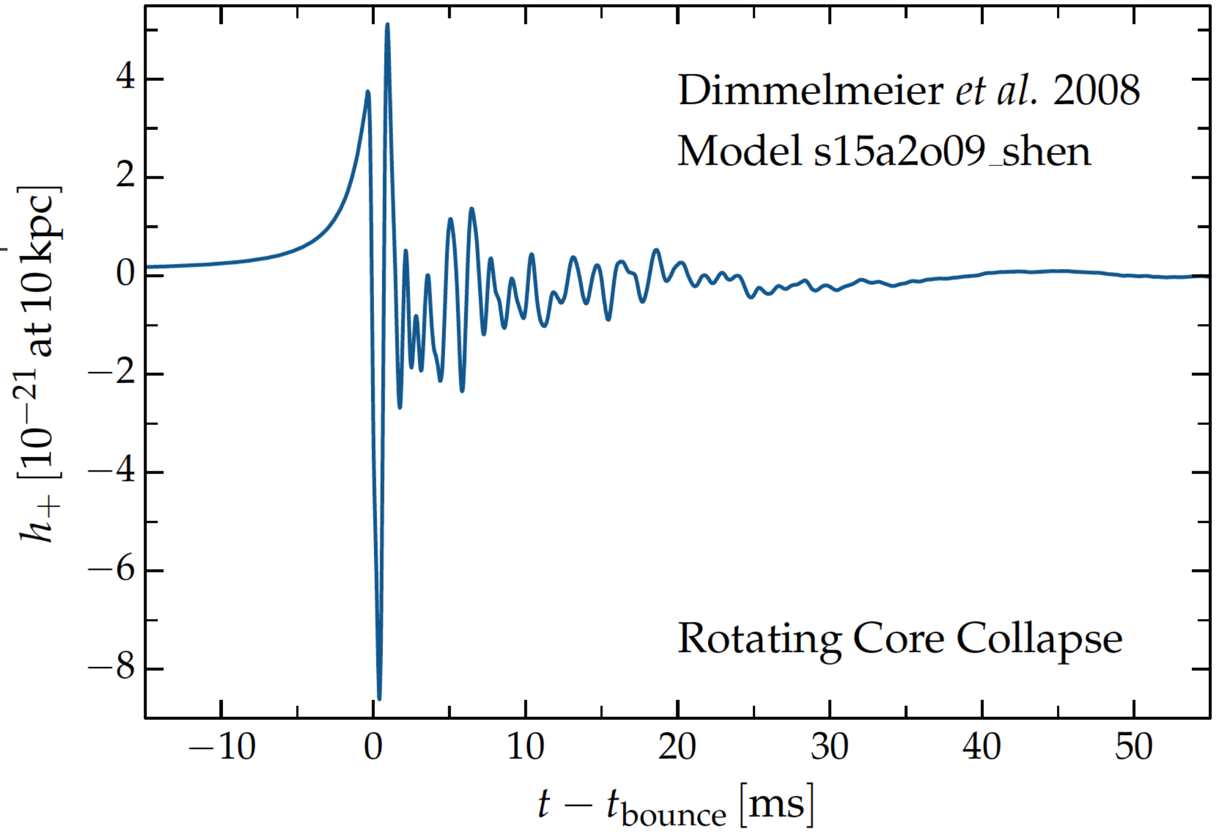
2-detector: LVD - KamLAND	10 year - 65 kpc	
	Old Method	New Method
Raw η	$93.7\% = 3425/3654$	
Raw ζ	$11.5\% = 447/3872$	
$5\sigma\ \eta$	$\mathbf{62.9}\% = 2298/3654$	$\mathbf{80.8}\% = 2951/3654$
$5\sigma\ \zeta$	$0\% = 0/3872$	$0\% = 0/3872$

GW signal

Magnetorotational Hydrodynamics,

Source: Strong centrifugal deformation of inner core (~ oblateness), due to rapidly rotating precollapse core.

- $p_{\text{prog}} \sim 1\,\text{s}; \quad p_{\text{remnant}} \sim 1\,\text{ms}$
- $E_{\text{rot}} \sim 10^{52}\,\text{erg}.$
- $h \sim 10^{-21} - 10^{-20}; \quad \text{for}\, D \sim 10\,\text{kpc}$
- $E_{\text{GW}} \sim 10^{-10} - 10^{-8} M_{\odot} c^2$
- Narrowband frequency: 500-800Hz



3.3. Perspectives

1. Sensitive to low-statistical signals (far/weak),

2. Fast ==> needed for online search with low latency,

3. Adaptive ==> background can be estimated from the real data,

4. Pretty model-independent, the double exponential model for the neutrino from CCSNe is very basic but **enough** for low-statistic signals,

5. Only needs minimal information; no need for a complete data sharing

- This method can disentangle signals vs BG for the single-detector analysis with higher statistical significance for signals. It is a one-step improvement from our previous ξ-cut

   A. The efficiency of the 65-kpc simulated KamLAND increases from 59.0% to 70.6% without adding a noise.

   B. There is also improvement of 5sigma efficiency for 2-detector analysis up to SMC for current detectors, where the efficiency increases from 62.9% to 80.8%.

- JUNO-Super-K network may work like LVD-KamLAND.

- This method could be also useful to enhance the future detectors (Hyper-K) *to expand* the CCSN search horizon in order to reach M31/Andromeda.

- Two-module Hyper-K can work as a network to reach ~1 Mpc.

- **Failed-SN search** by Super-K till L/SMC together with GWs. The duration maybe smaller (0.5s vs 20s)