



SNvD 2023@LNGS: International Conference on
Supernova Neutrino Detection

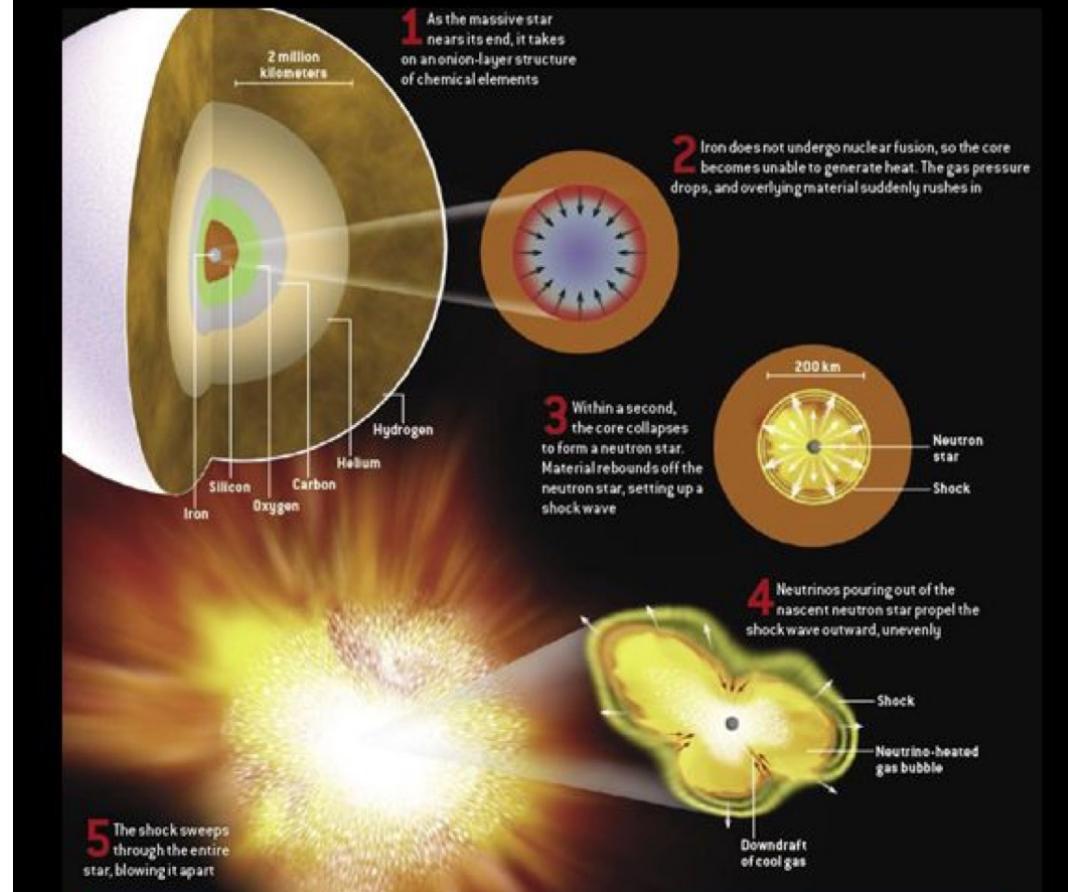
Core-Collapse Supernovae detection with Gravitational Waves and Neutrinos

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Core Collapse Supernovae



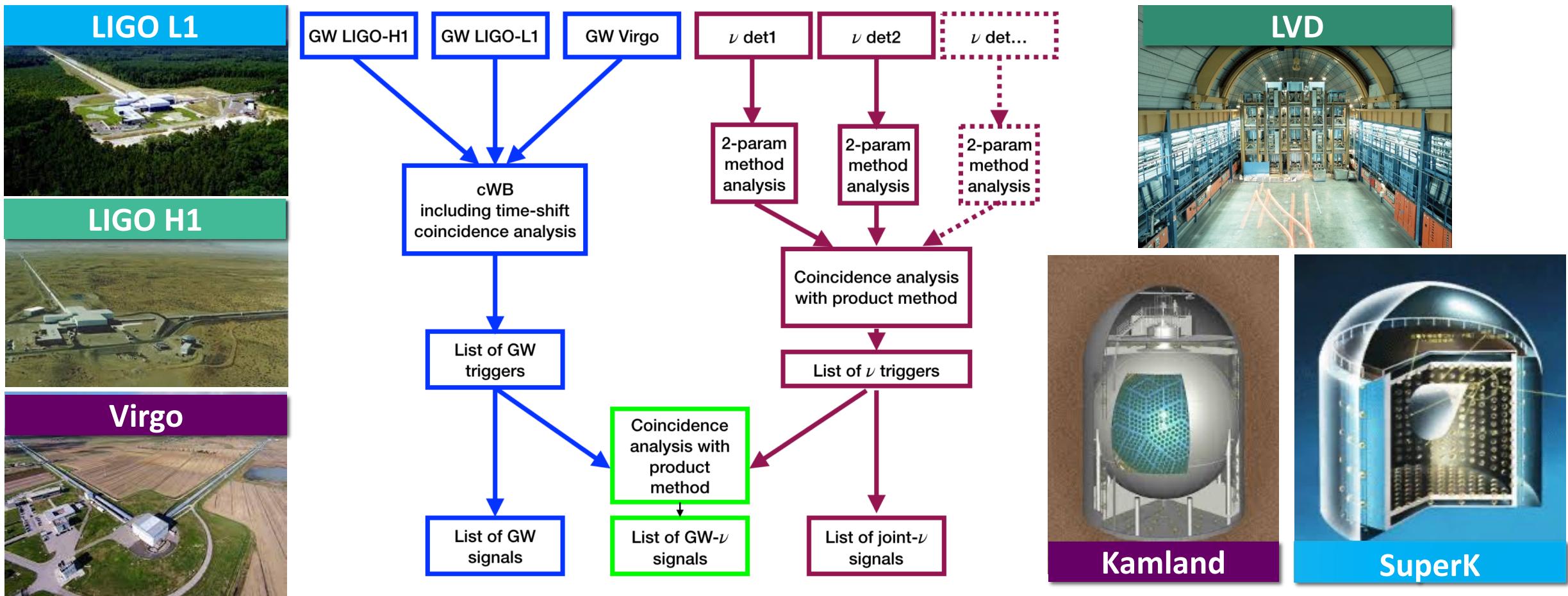
Outline

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

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

Multimessenger analysis with GW-LEN



Joint GW-v Search

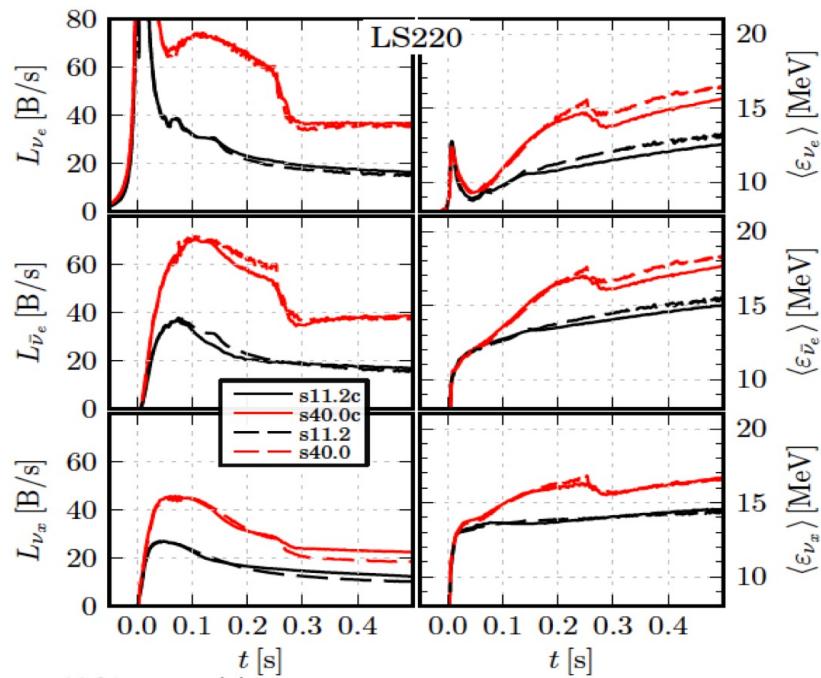
Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

| | | | |
|---|---------------|---------------------|-------------------------|
| Global False Alarm Rate | GW back. Rate | Neutrino back. Rate | Time coincidence window |
| | | | |
| $\text{FAR} = R_{GW}(\eta) \cdot R_\nu(\xi) \cdot 2w$ | | | |

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

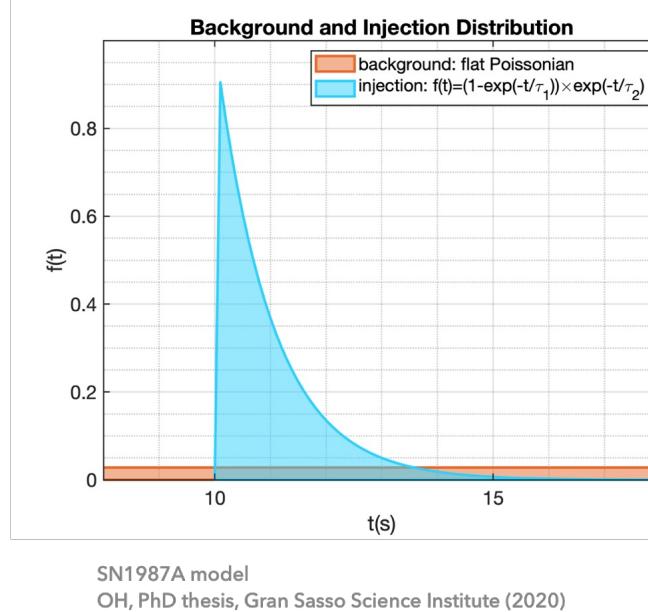
Neutrino signals

NUMERICAL SIMULATIONS



L. Hudepohl, Ph.D. thesis, Technische Universität München
(2014).

PHENOMENOLOGY+ DATA



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

SN1987A

$$\begin{aligned} E_b &= 3 * 10^{53} \text{ erg} \\ \langle E_{\nu_e} \rangle &= 9 \text{ MeV} \\ \langle E_{\bar{\nu}_e} \rangle &= 12 \text{ MeV} \\ \langle E_{\nu_x} \rangle &= 16 \text{ MeV} \\ \tau_2 &= 1 \text{ s} \\ \tau_1 &= 0.1 \text{ s} \end{aligned}$$

LEN analysis efficiency

| Model (identifier) | Progenitor Mass | Super-K ($E_{\text{thr}} = 6.5 \text{ MeV}$) | LVD ($E_{\text{thr}} = 7 \text{ MeV}$) | KamLAND ($E_{\text{thr}} = 1 \text{ MeV}$) |
|------------------------------|--------------------|---|---|---|
| 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}).

Analysis Efficiency = N_recovered/N_injected

| Detector | Background |
|----------|------------|
| LVD | 0.028 Hz |
| KAM | 0.015 Hz |
| SK | 0.012 Hz |

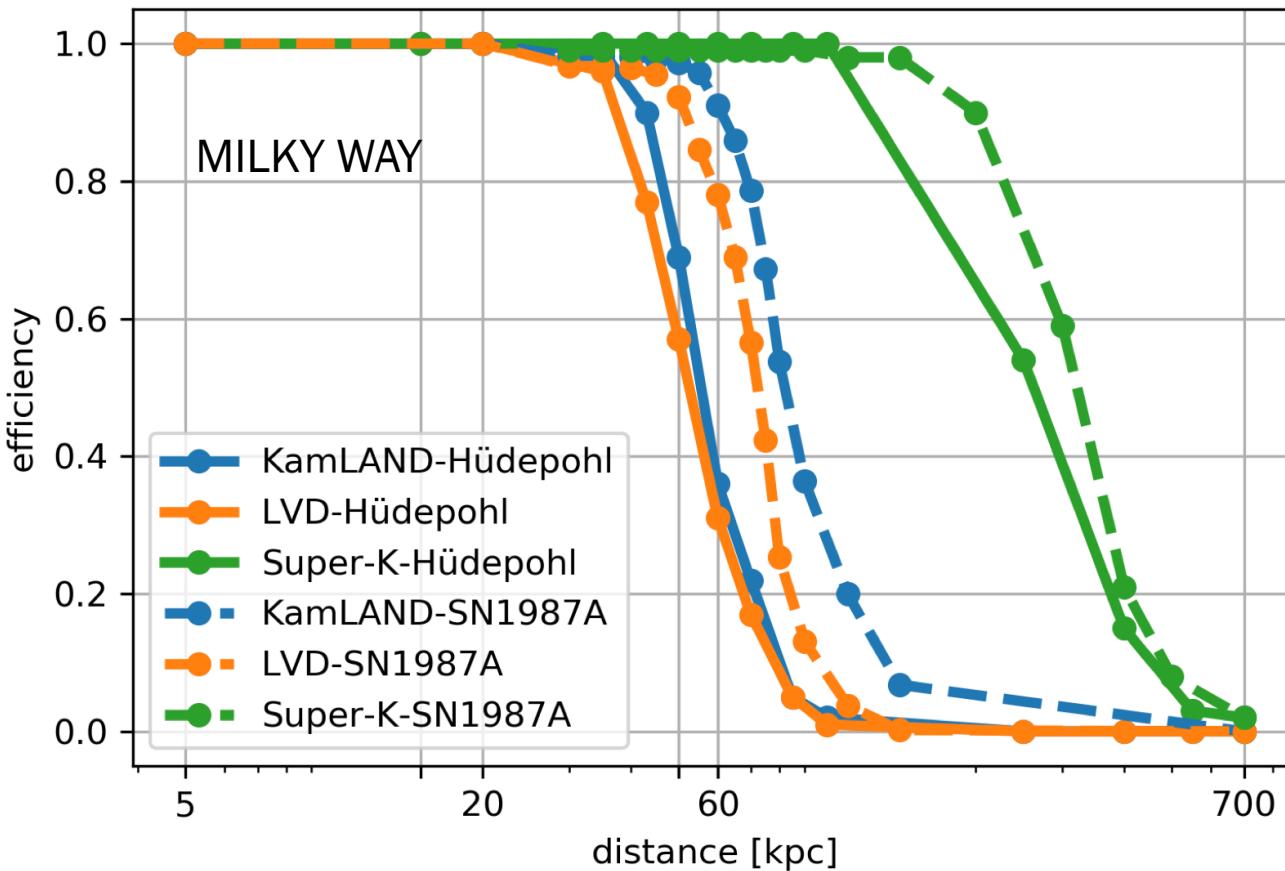
Not requirements on Statistical significance

LEN analysis efficiency

| Model (identifier) | Progenitor Mass | 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 considered parenthesis we report the assumed energy ϵ

$$\text{Efficiency} = \frac{\text{N_recovered}}{\text{N_injected}}$$

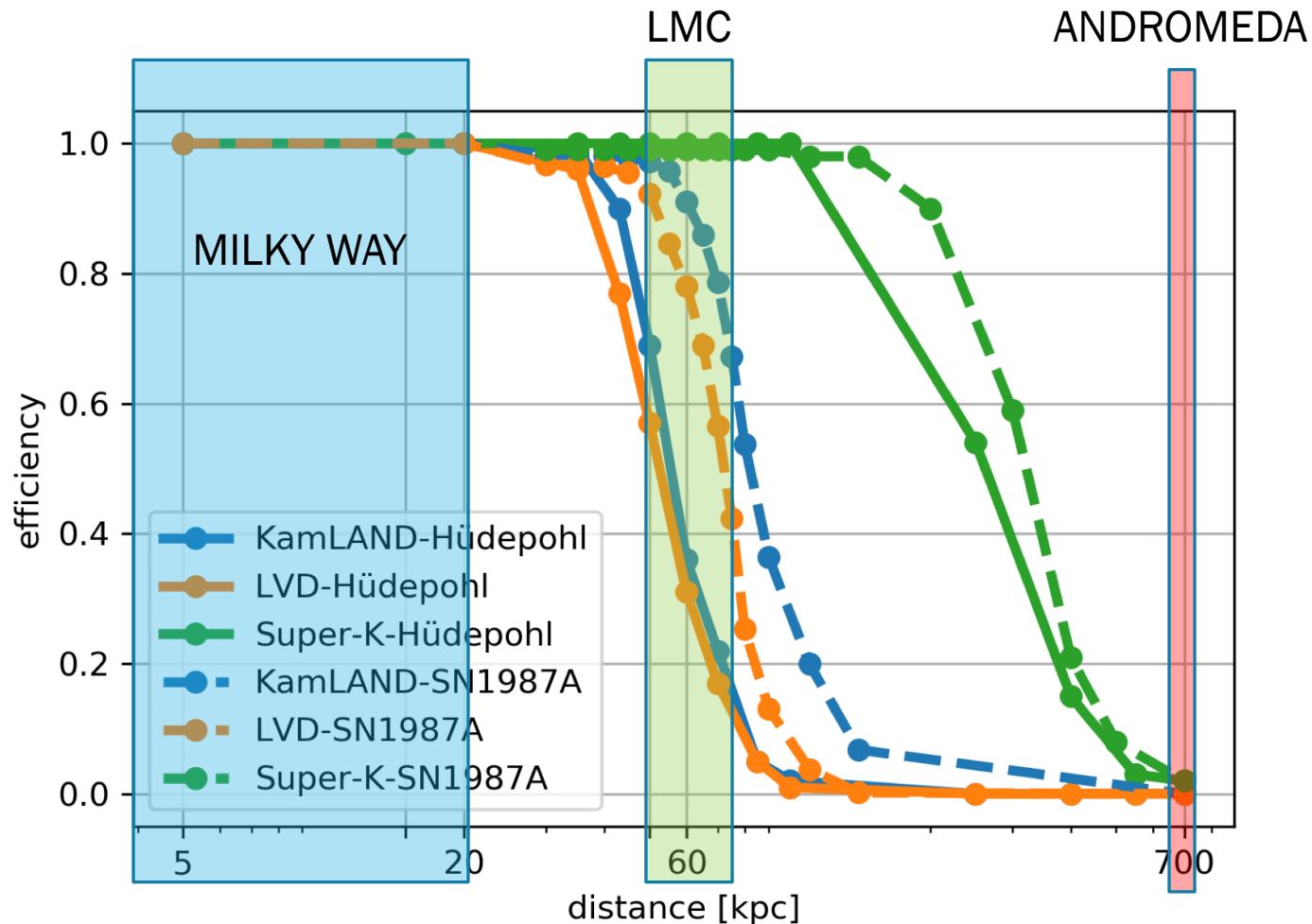


LEN analysis efficiency

MILKY WAY ~100% efficiency

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

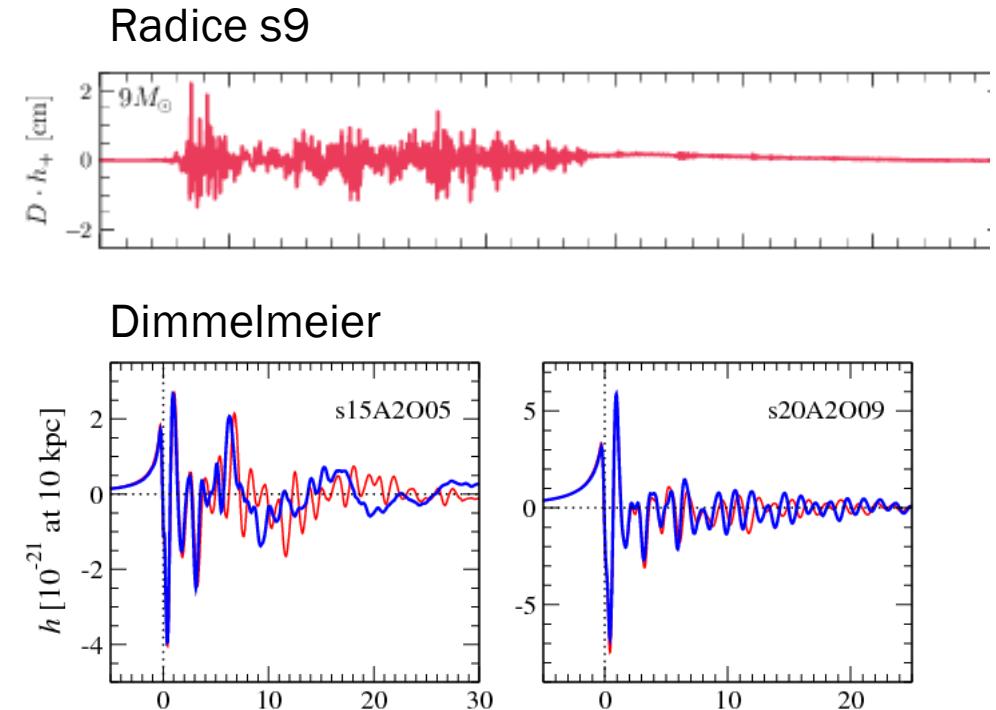
Andromeda
SK ~0-1% efficiency
LVD & KAM 0%



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_{rss} , frequency at which the GW energy spectrum peaks, and emitted GW energy.

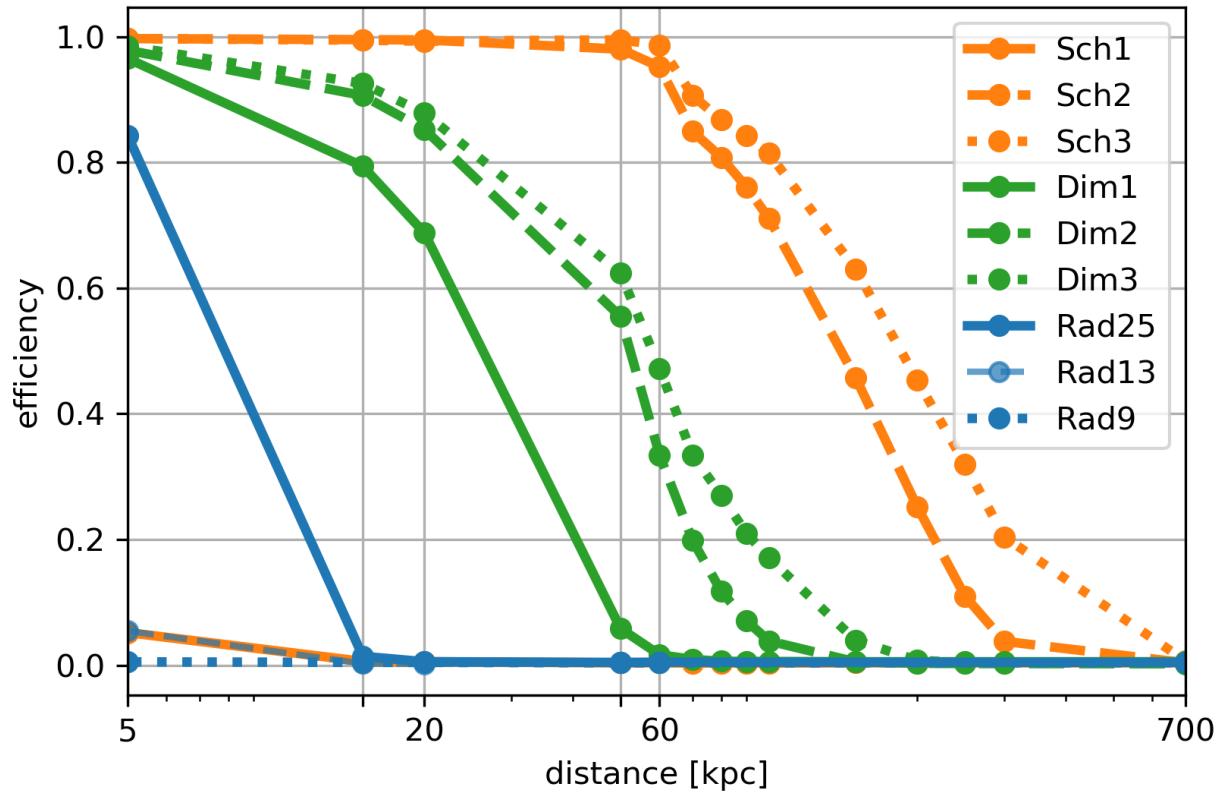
| Waveform Family | Waveform Identifier | Abbr. | Mass M_{\odot} | h_{rss} @10 kpc ($10^{-22} \text{ 1}/\sqrt{\text{Hz}}$) | f_{peak} [Hz] | E_{GW} $[10^{-9} M_{\odot} c^2]$ |
|---|--------------------------|-------|------------------|---|---------------------------|--|
| Radice [36] 3D simulation; h_+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



GW analysis efficiency

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

| Waveform Family | Waveform Identifier | Abbr. | Mass M_{\odot} | h_{rss} (10^{-22}) |
|---|--------------------------|-------|------------------|---------------------------------|
| Radice [36] 3D simulation; h_+ and h_x ; (Rad) | s25 | Rad25 | 25 | 0. |
| | s13 | Rad13 | 13 | 0. |
| | s9 | Rad9 | 9 | 0. |
| Dimmelmeyer [37] 2D simulation; h_+ only; (Dim) | dim1-s15A2O05ls | Dim1 | 15 | 1. |
| | dim2-s15A2O09ls | Dim2 | 15 | 1. |
| | dim3-s15A3O15ls | Dim3 | 15 | 2. |
| Scheidegger [38] 3D simulation; h_+ and h_x ; (Sch) | sch1-R1E1CA _L | Sch1 | 15 | 0. |
| | sch2-R3E1AC _L | Sch2 | 15 | 5. |
| | sch3-R4E1FC _L | Sch3 | 15 | 5. |

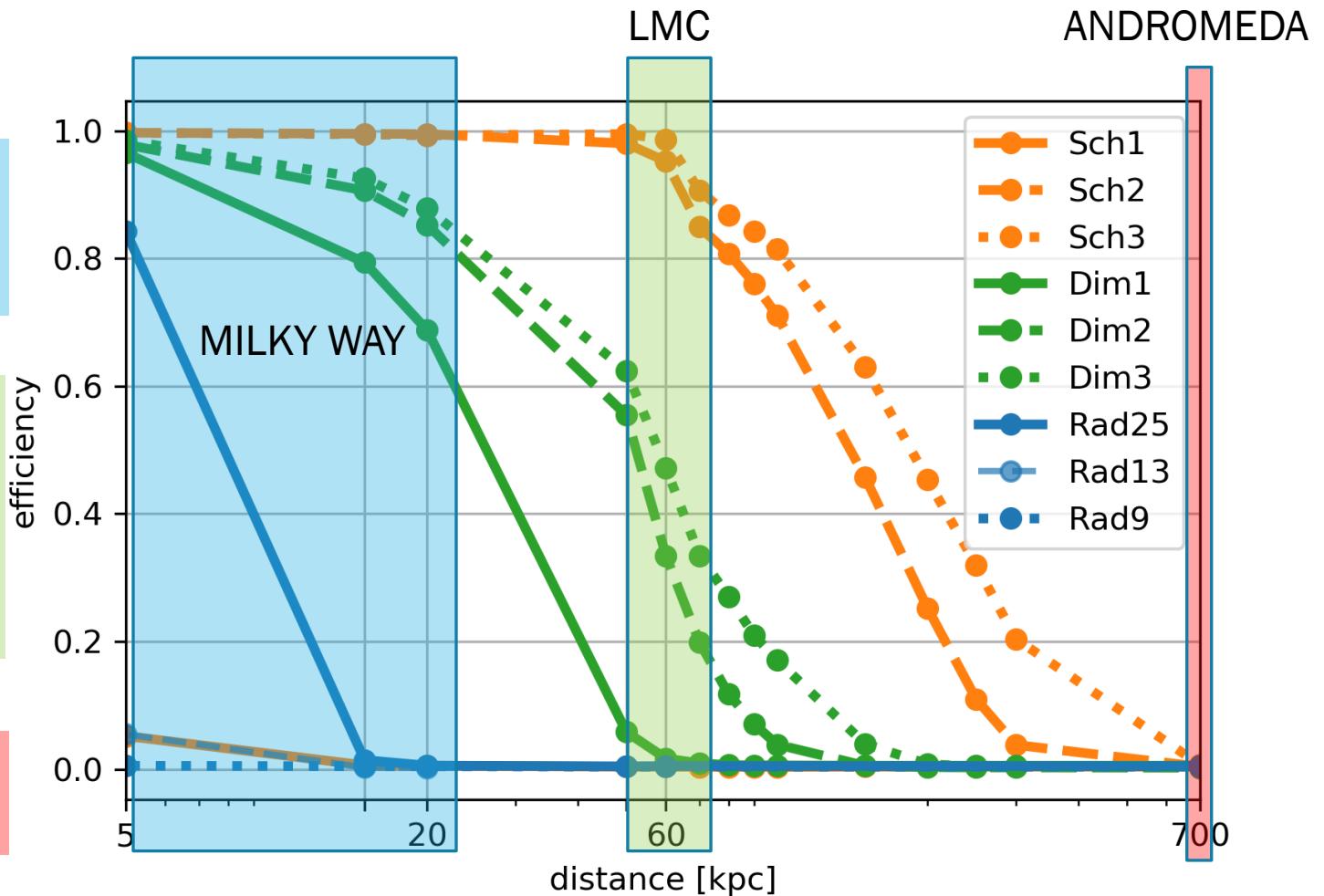


GW analysis efficiency

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

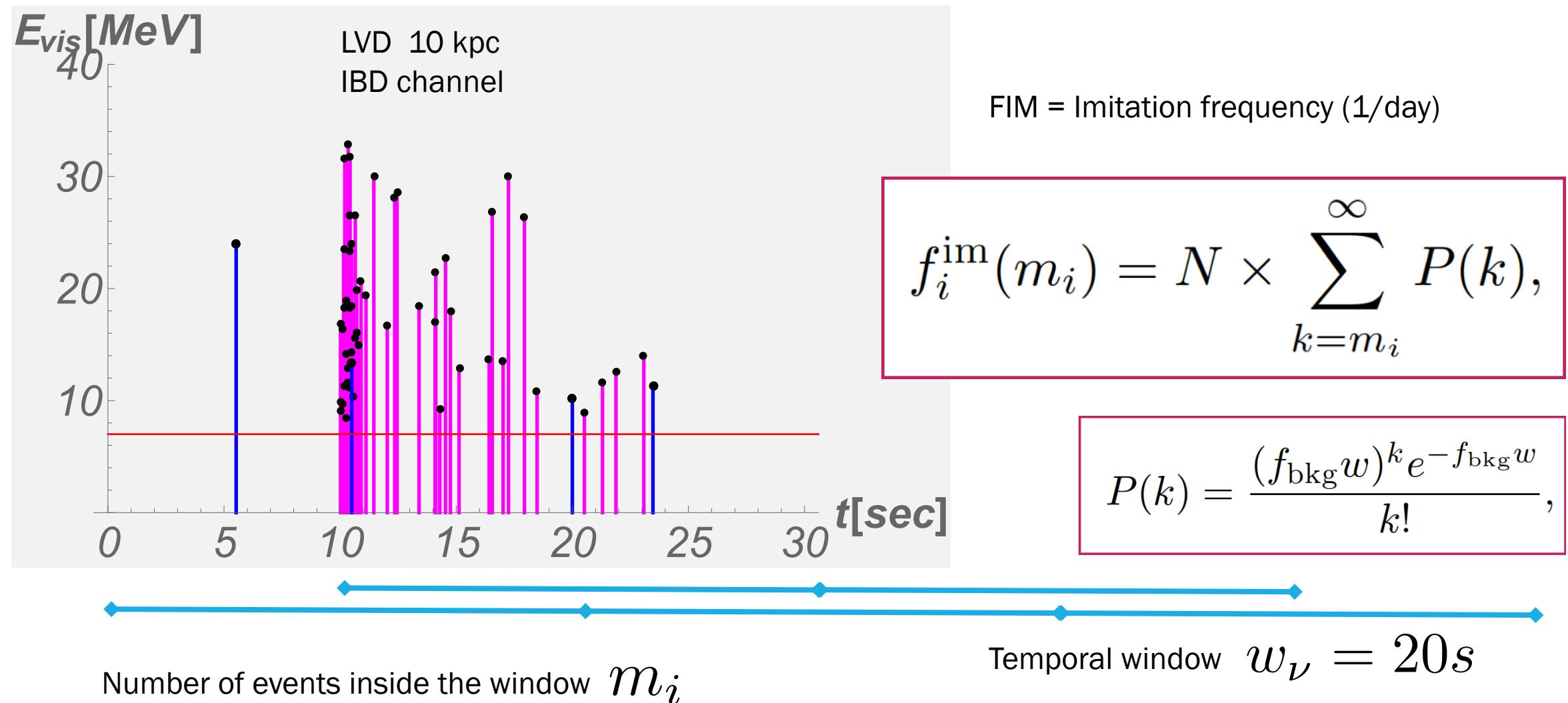
Large Magellanic Cloud
~100% efficiency only for extreme
models
-60%-20% for rotating CCSNe
-0% Non Rotating

Andromeda
~0% efficiency

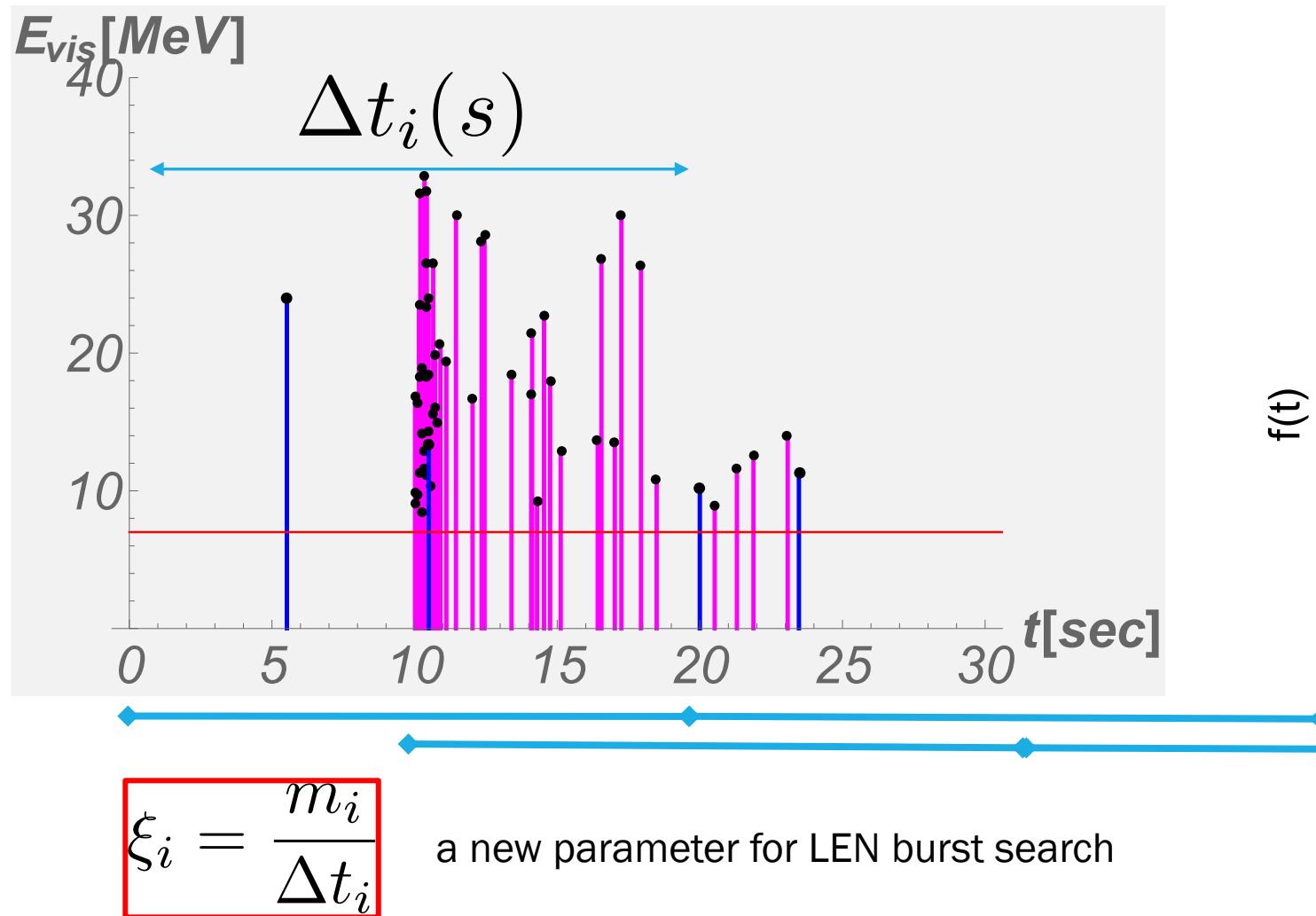


Data analysis improvement in LEN sector

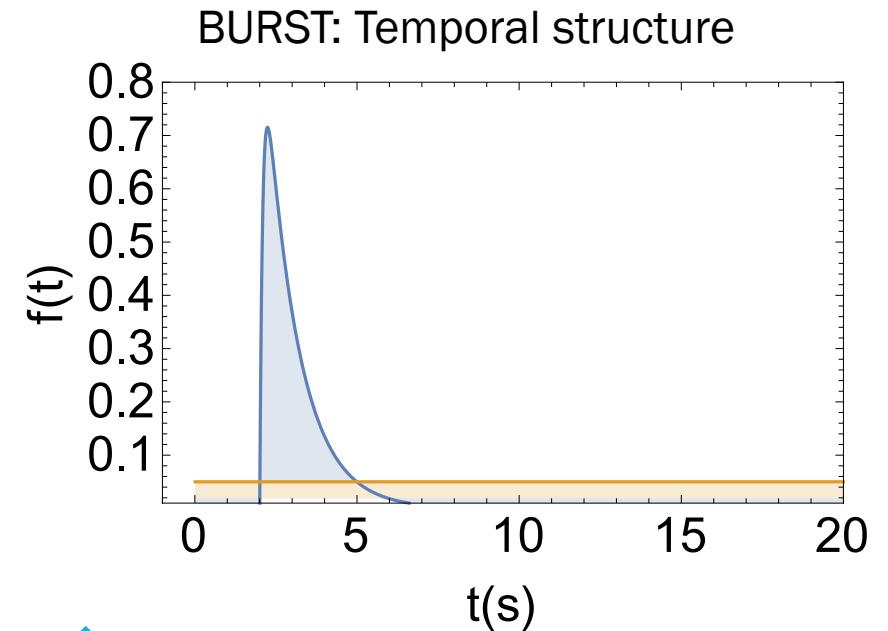
The statistical significance of a LEN events burst: Standard procedure



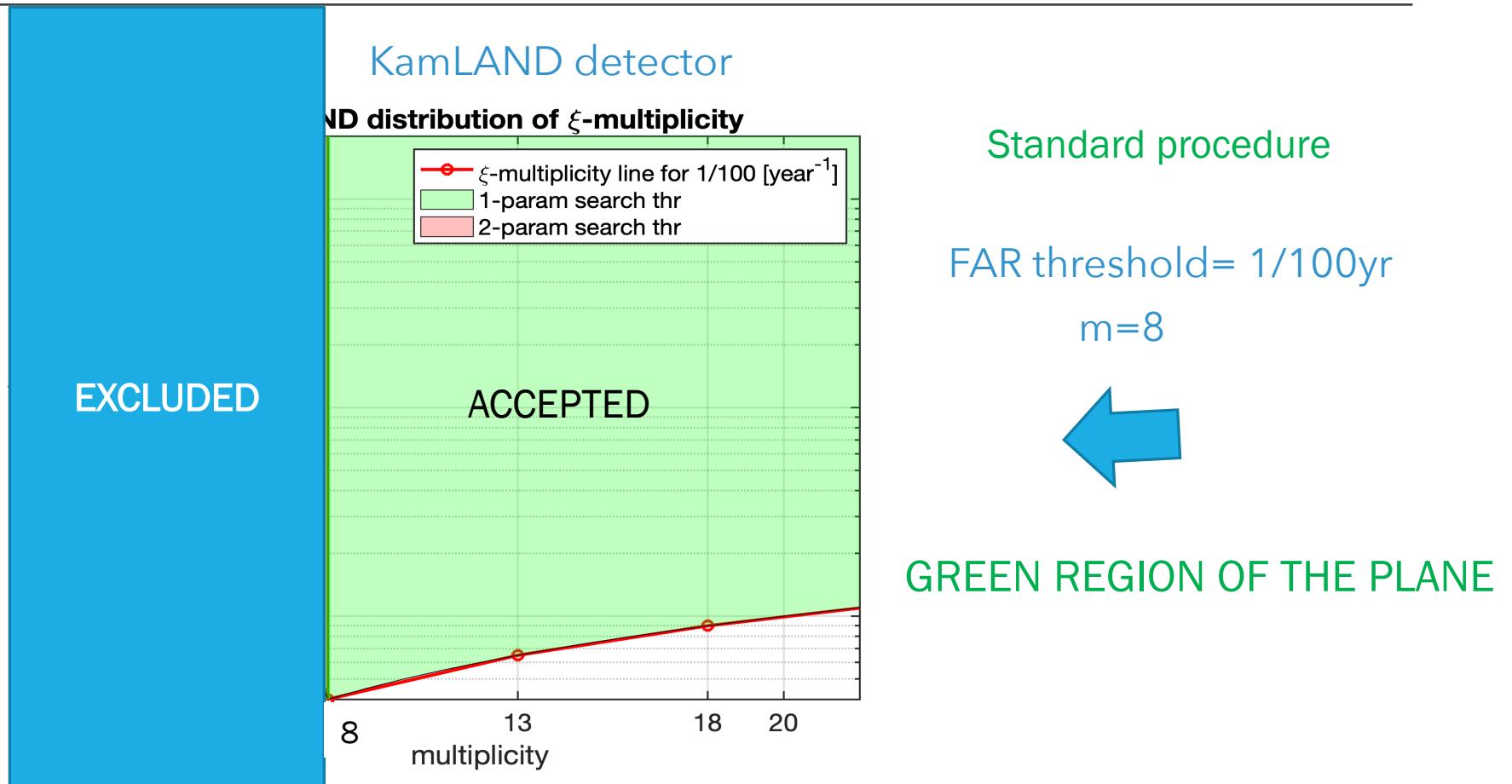
The statistical significance of a LEN events burst: New procedure



Casentini et al. JCAP 08(2018)010



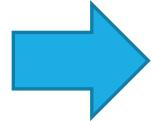
Results for single-LEN detector



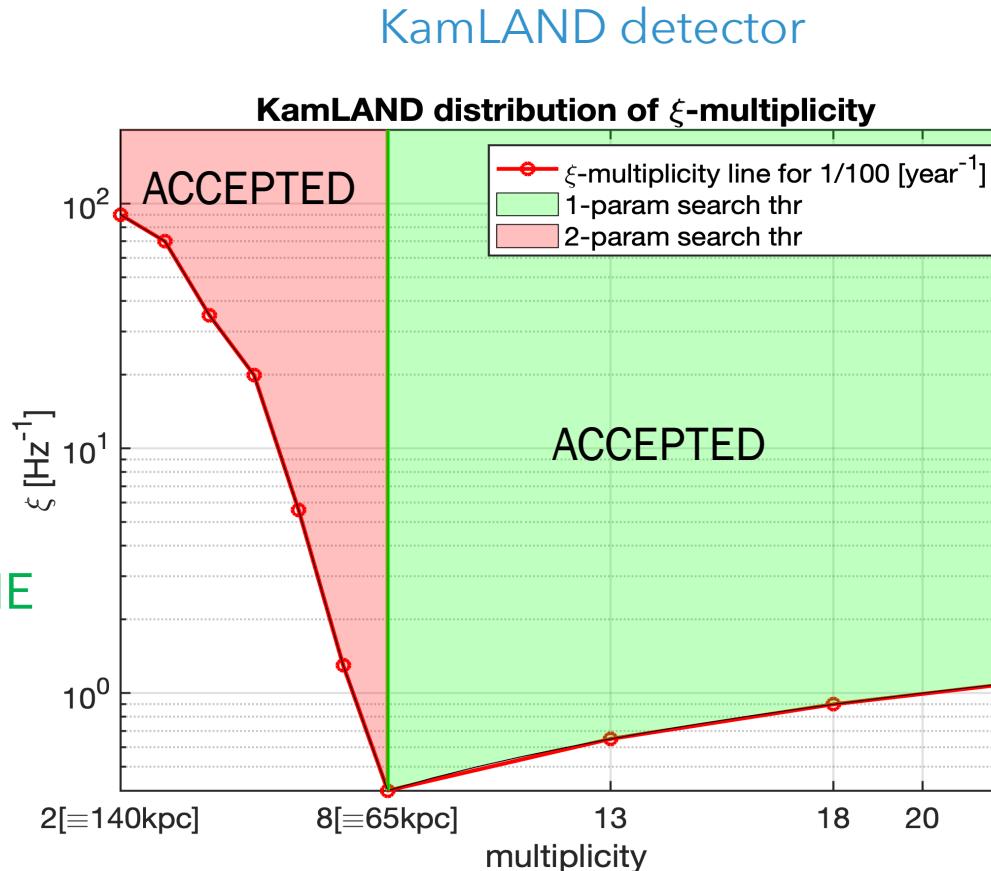
Results for single-LEN detector

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

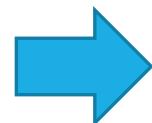
KamLAND detector

New procedure

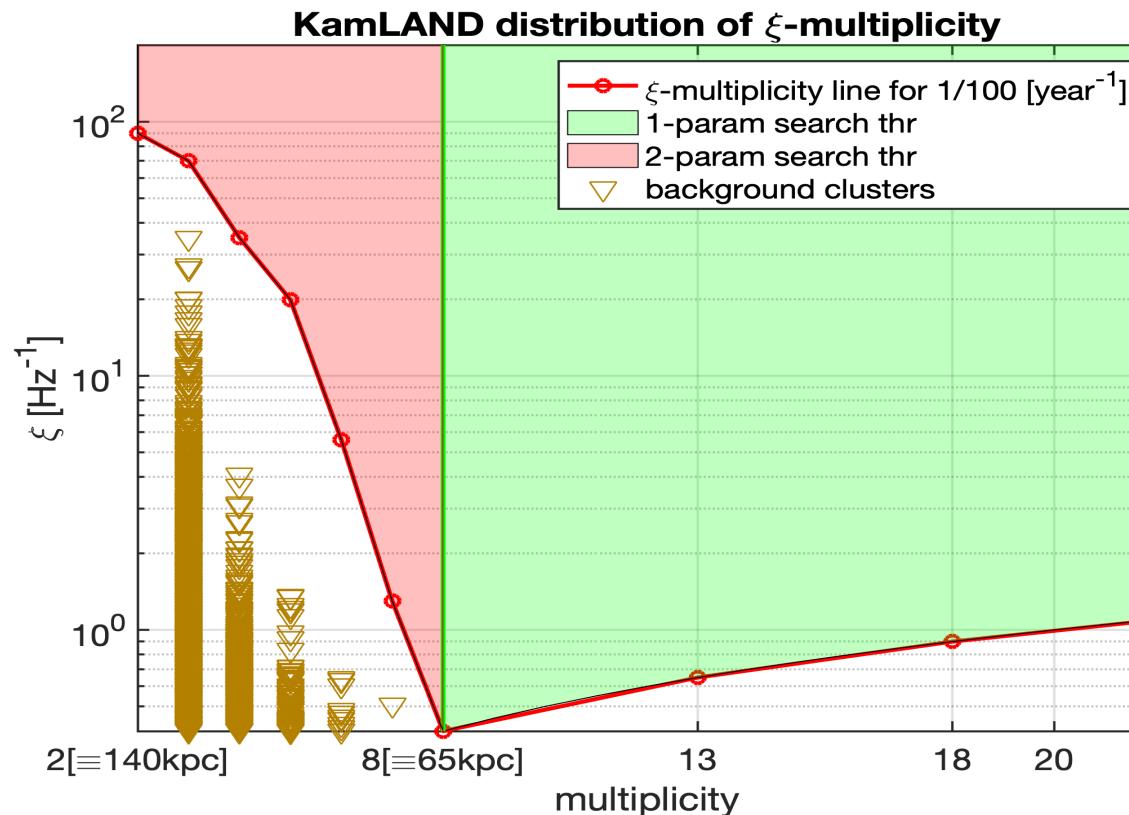
BACKGROUND CLUSTERS

> 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

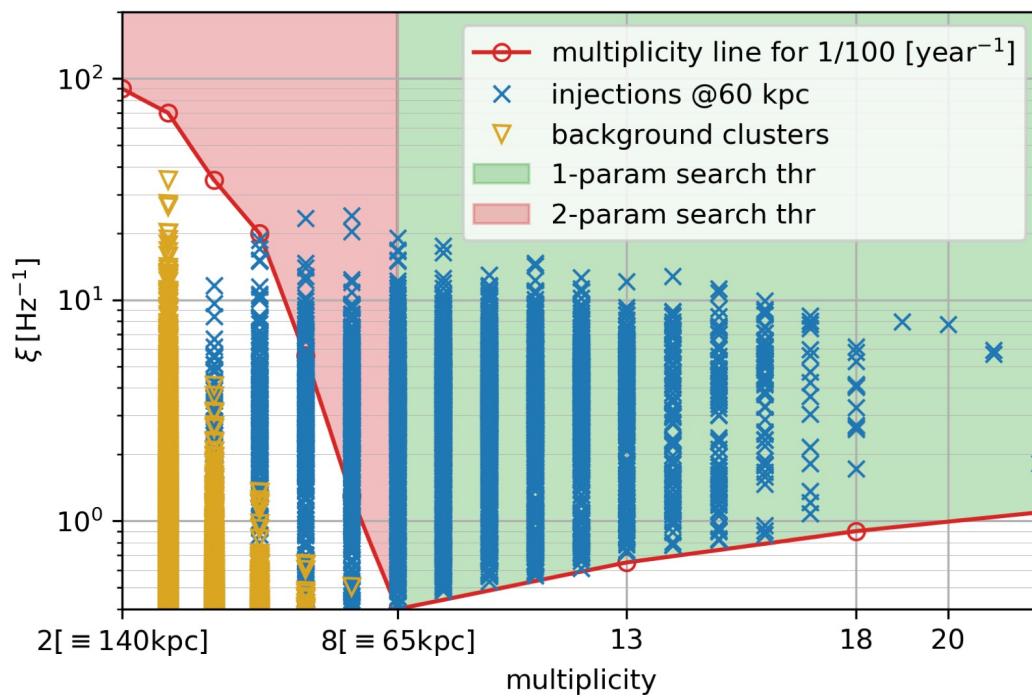


TABLE III: Efficiency (η) comparison between 1-parameter and 2-parameter method of single detector KamLAND 60-kpc for $\text{FAR}_\nu < 1/100 [\text{year}^{-1}]$ with SN1987A model.

| 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

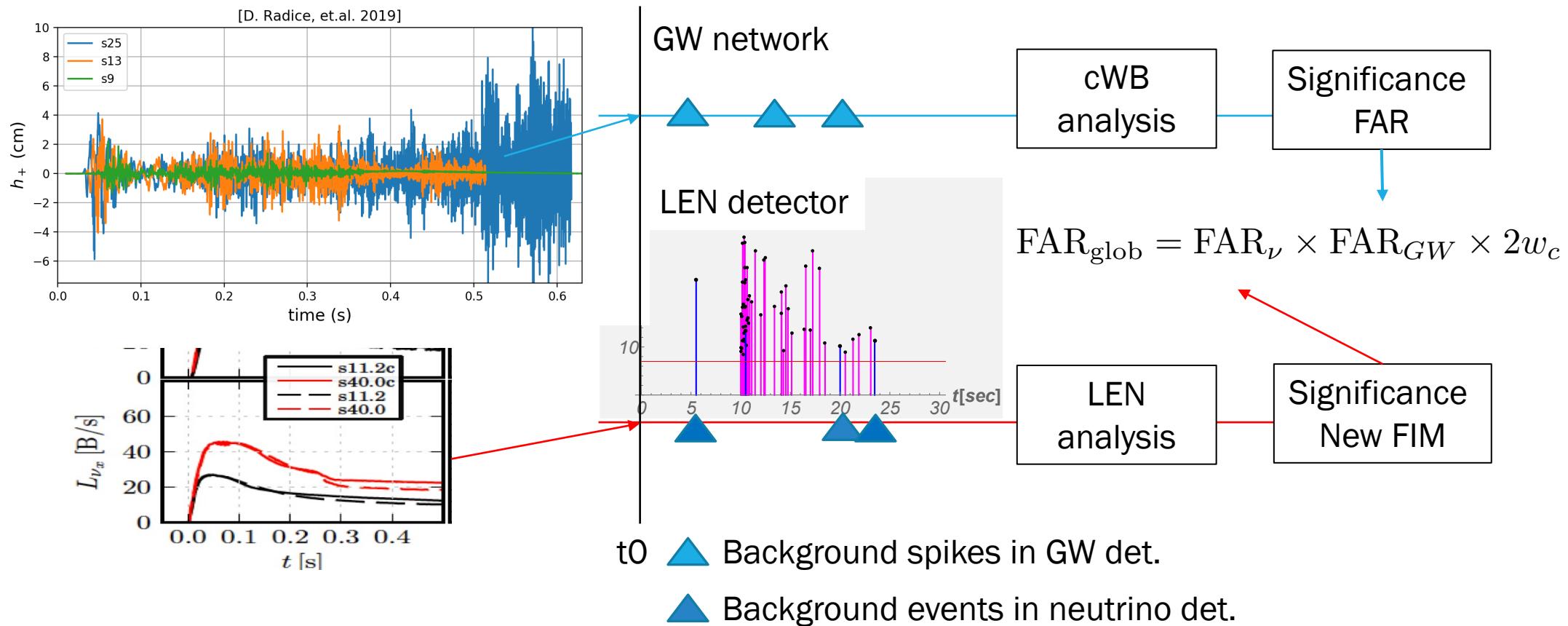
The use of the new parameter for LEN burst search increases the detection efficiency of 10% @ horizon

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

Data analysis for combining GW-LEN

Data analysis procedure

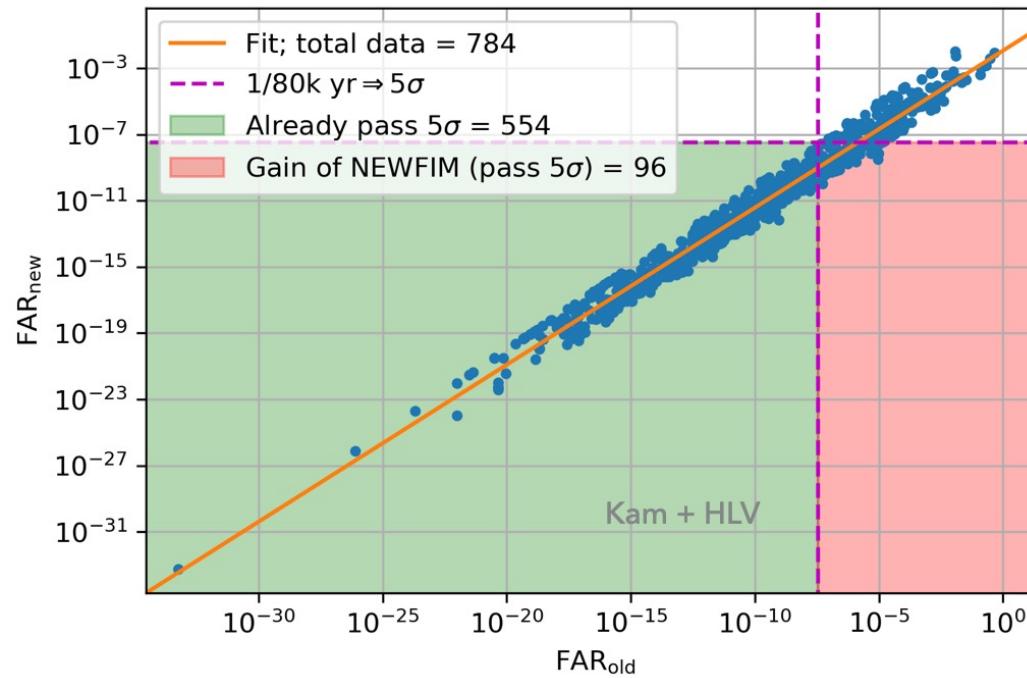
For each specific CCSN Distance and location



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 $FAR_{GW} < 864/d$ | $\eta_{1\text{param}} [> 5\sigma]$ | $\eta_{2\text{param}} [> 5\sigma]$ |
|------------------------------|------------------------------|------------------------------------|------------------------------------|
| HLV-KAM (Dim2-SN1987A) | 784/2346 = 33.4% | 554/784 = 70.7% | 650/784 = 82.9% |

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

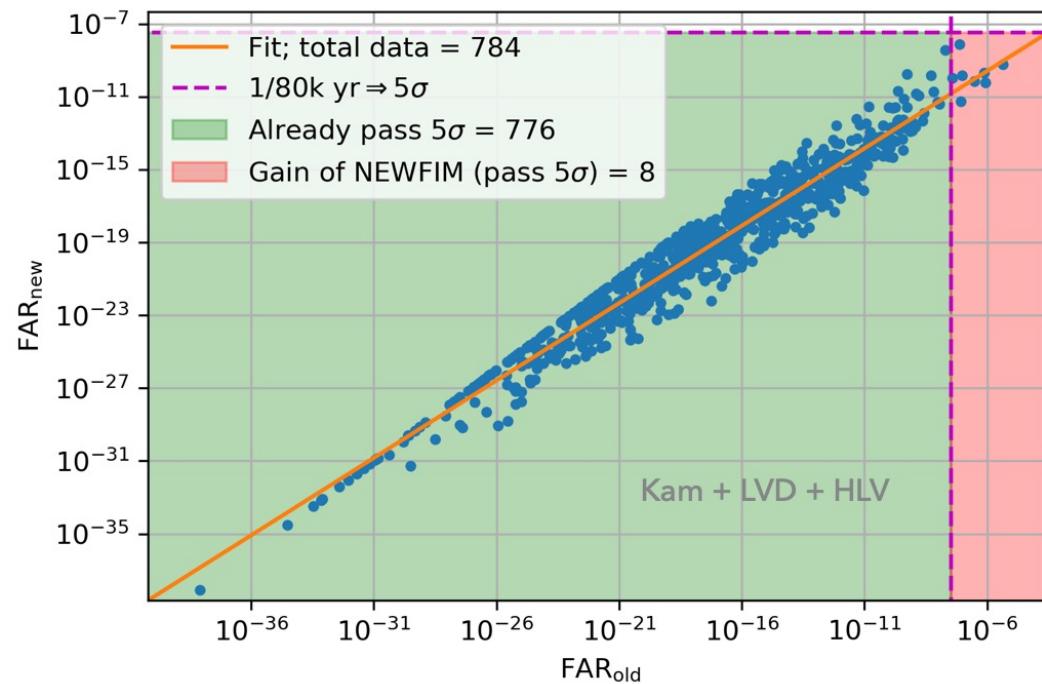
Take home message #2

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 | $\eta_{1\text{param}} > 5\sigma$ | $\eta_{2\text{param}} > 5\sigma$ |
|-------------------------------|-------------------------------------|----------------------------------|----------------------------------|
| 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

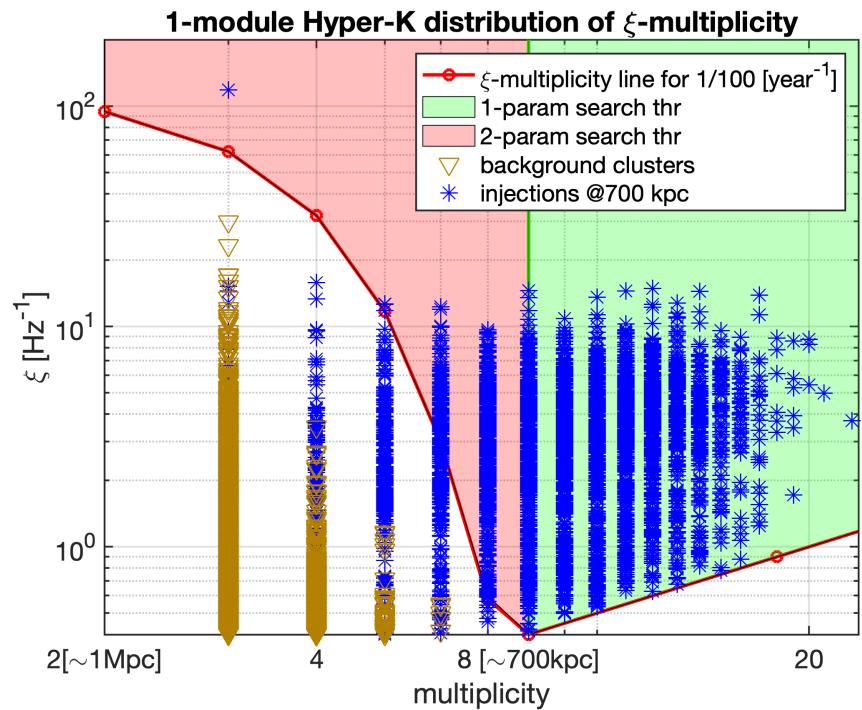


TABLE 7.5: One-module Hyper-K with 700-kpc injections.

| Total | Background | 1-parameter | 2-parameter (this work) |
|------------|-----------------|--------------------------|--------------------------|
| Background | [< 1/100 years] | [< 1/100 years] | [< 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.

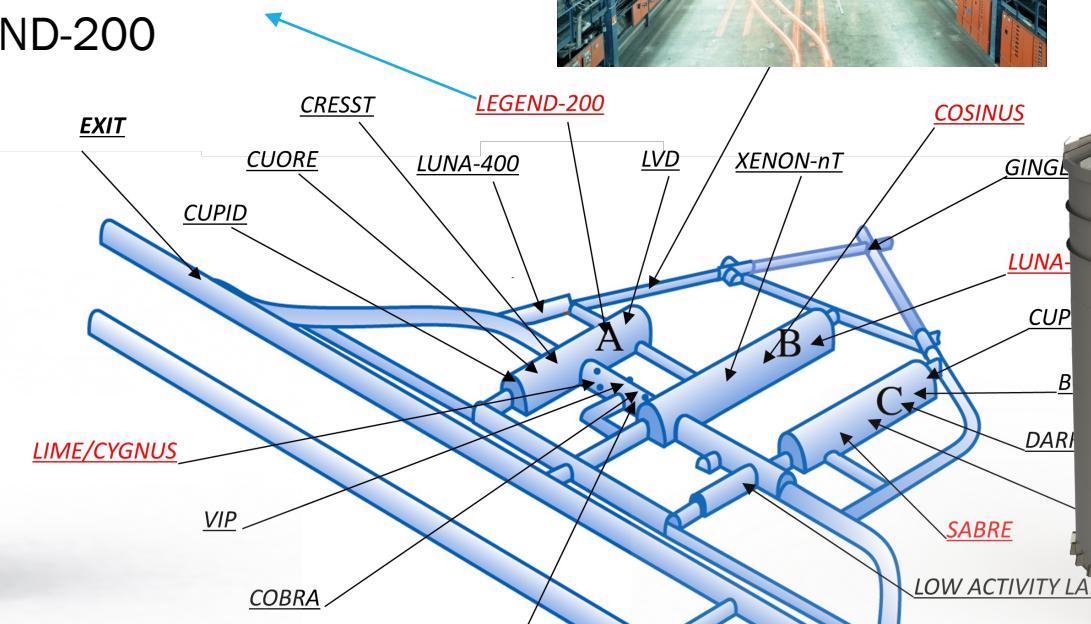
Before questions....

PRELIMINARY

SN@LNGS



LEGEND-200

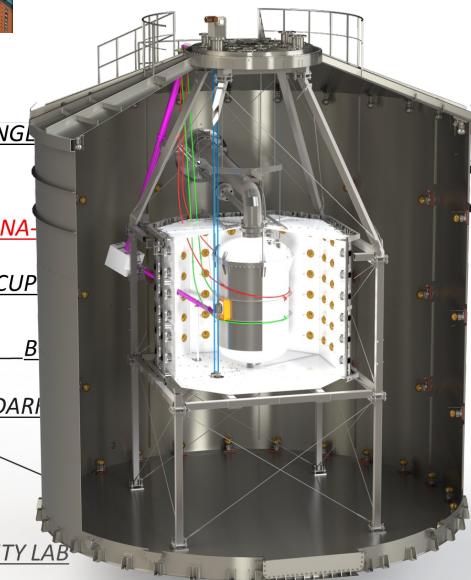


LVD (220 events)

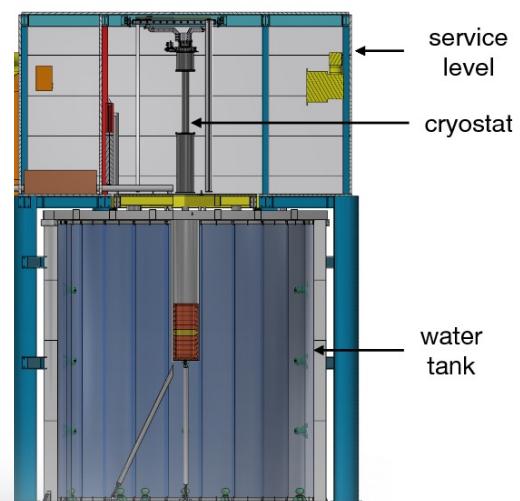


SN@10 kpc → H₂O IBD and NO
XENONnT (700 ton) = 120
LEGEND 200 (590 ton) = 100
COSINUS (270 ton) = 50

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.

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

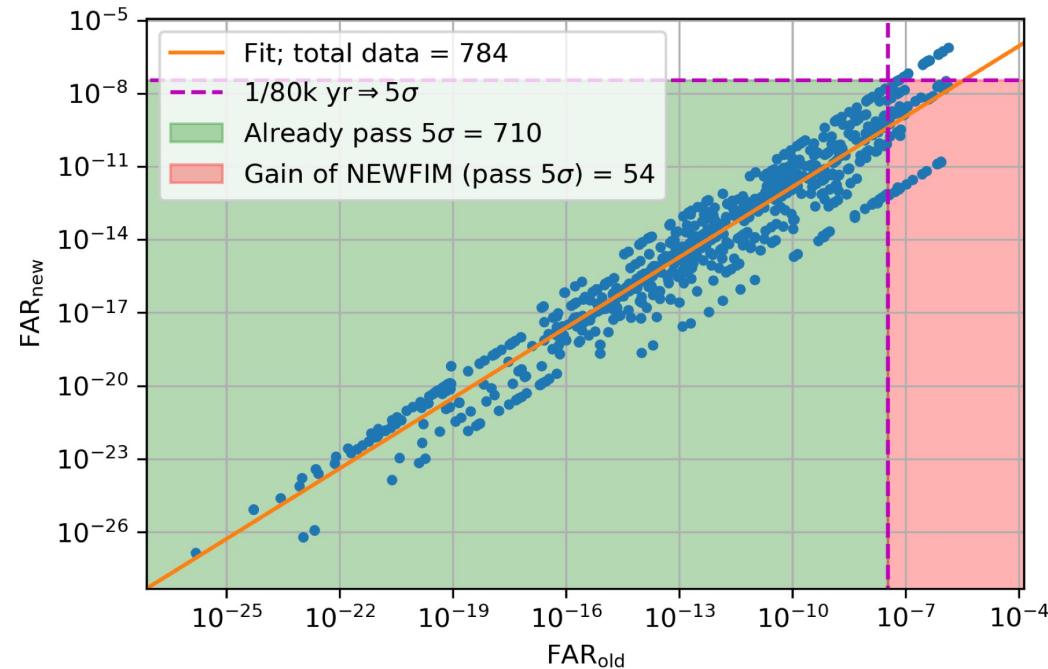


TABLE VI: Efficiency (η) comparison of 1-parameter and our 2-parameter method for Figure 9. The columns are analogous to Table V.

| Network & Type of Injections | Recovered $FAR_{\text{GW}} < 864/d$ | $\eta_{1\text{param}} [> 5\sigma]$ | $\eta_{2\text{param}} [> 5\sigma]$ |
|------------------------------|-------------------------------------|------------------------------------|------------------------------------|
| 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: | $33.4\% * 97.5\% = 32.6\%$ |

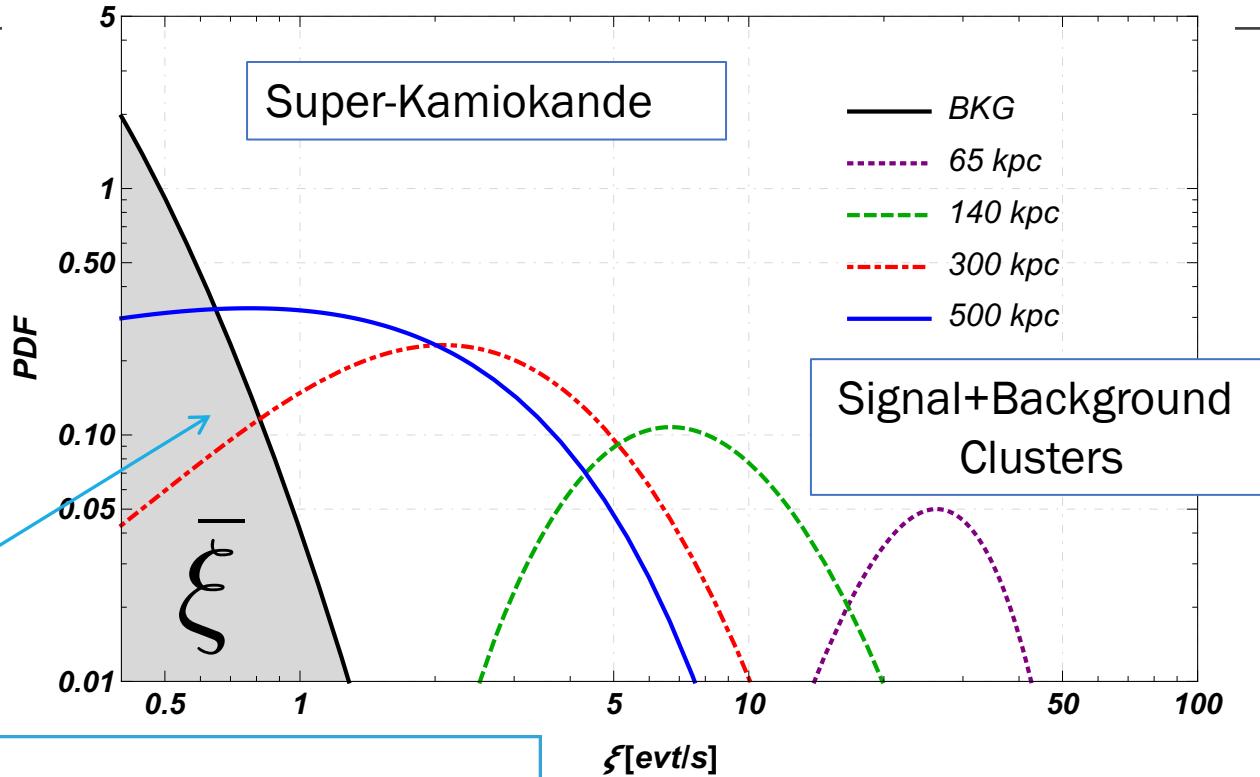
Background-Signal separation

Probability Density Functions (PDF)

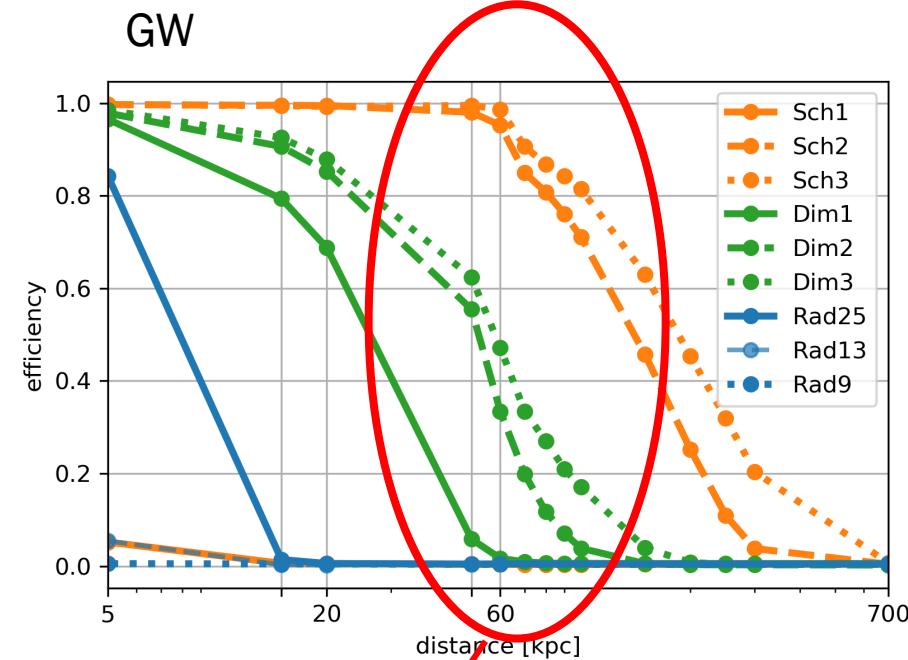
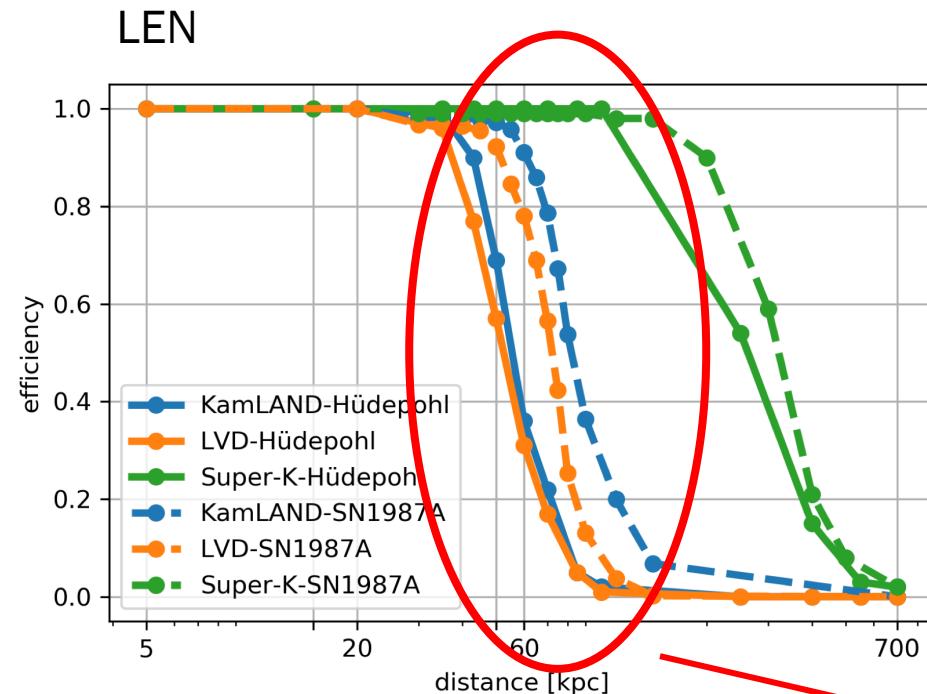
$$\xi_i = \frac{m_i}{\Delta t_i}$$

Pure Background Clusters

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



Combined analysis LEN+GW



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

D=60 kpc

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

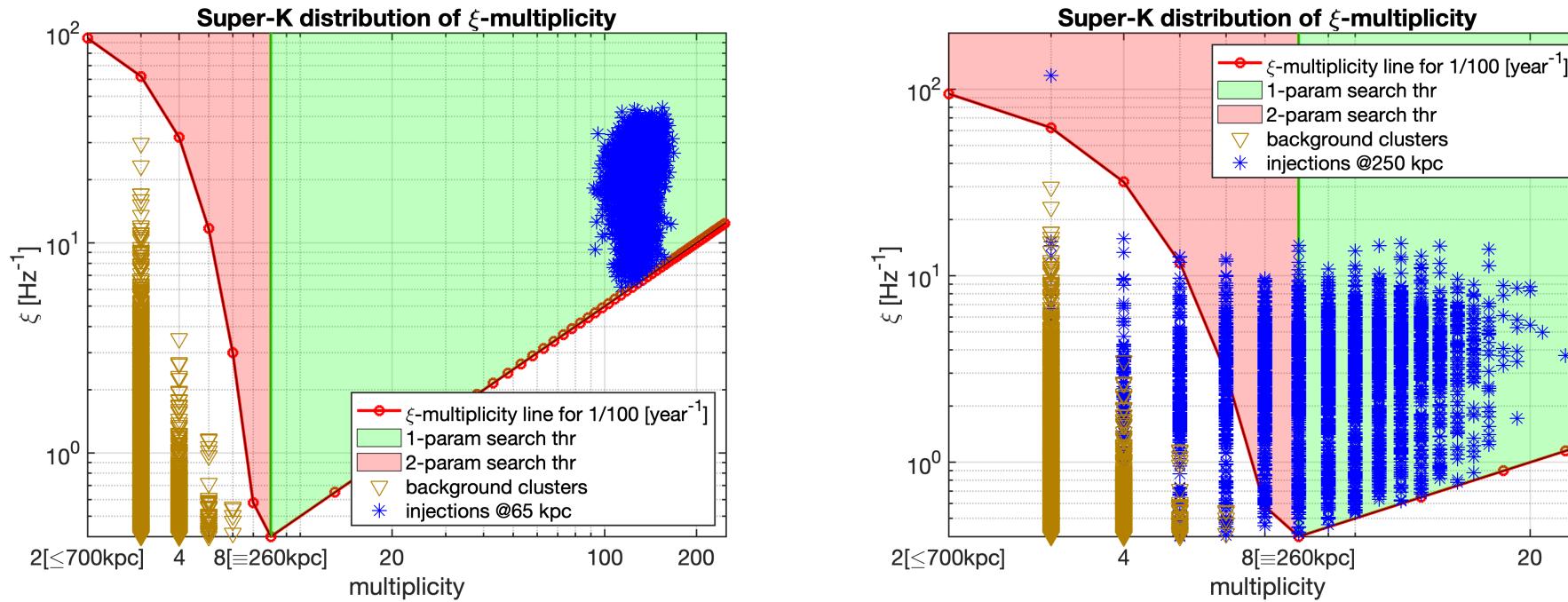


TABLE 7.3: Single detector SuperK analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

| 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 |

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

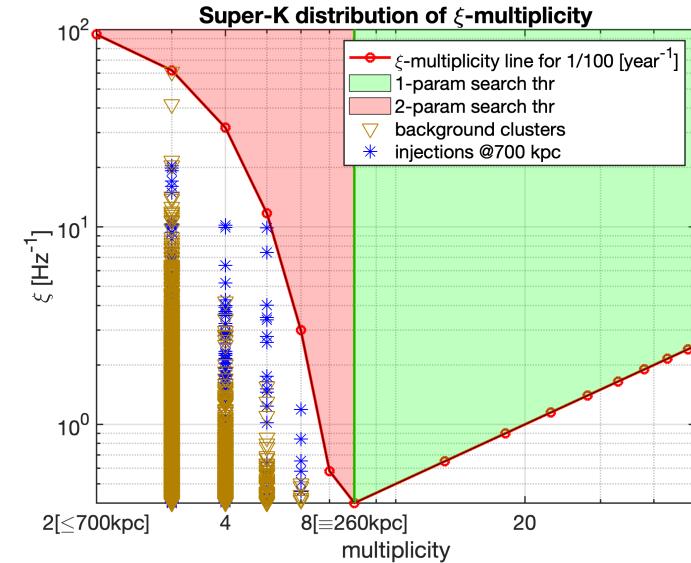
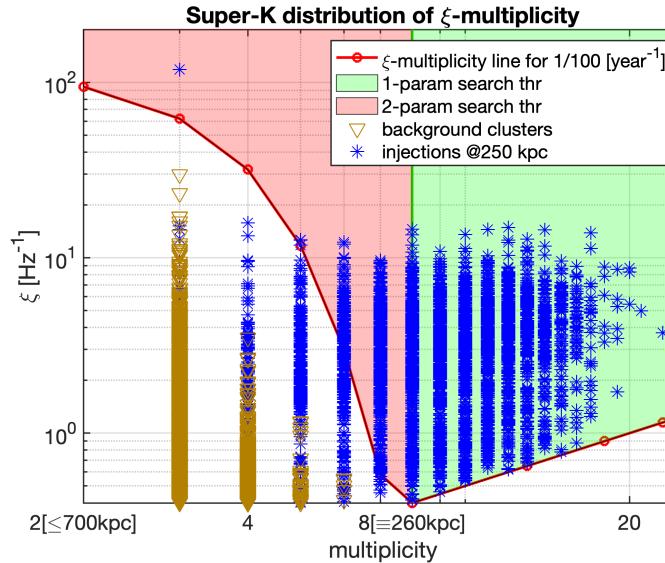
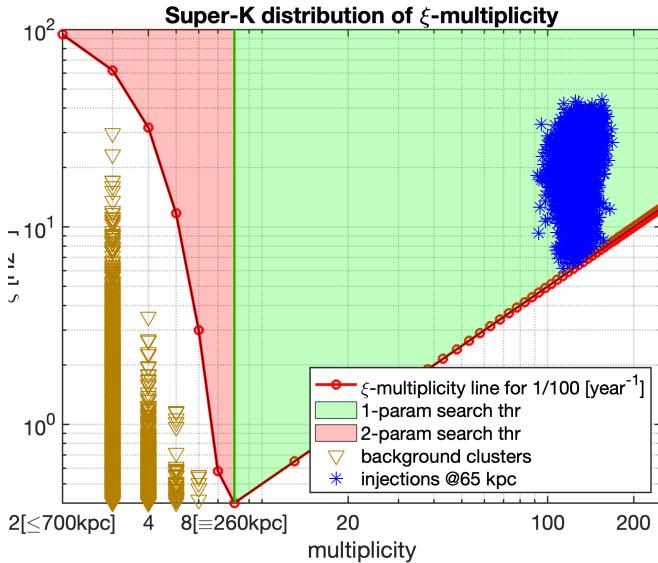


TABLE 7.3: Single detector Super-K analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

| Total Background | Background $[< 1/100 \text{ years}]$ | 1-parameter $[< 1/100 \text{ years}]$ | 2-parameter (this work) $[< 1/100 \text{ years}]$ |
|---------------------|---|--|--|
| 49200 | 0% = 0 / 49200 | 70.6% = 2575 / 3645 | 85.5% = 3117 / 3645 |

LVD-KamLAND joint-detector analysis.

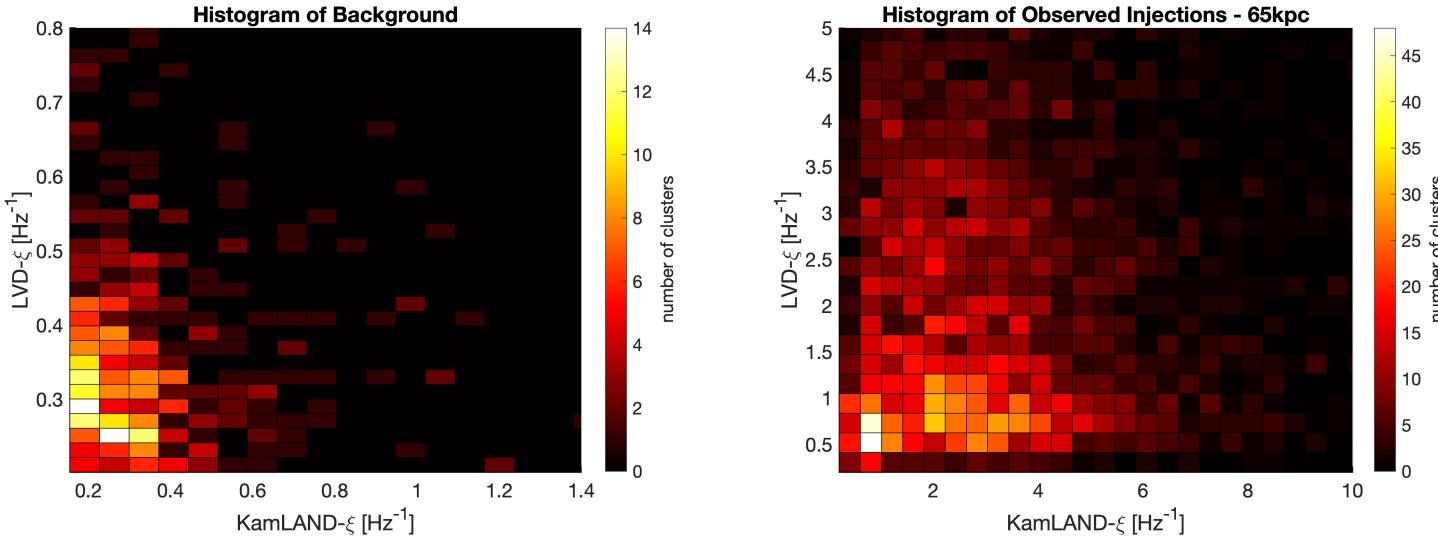


TABLE 7.4: Efficiency η and misidentification probability ζ for KamLAND-LVD 10 year - 65 kpc.

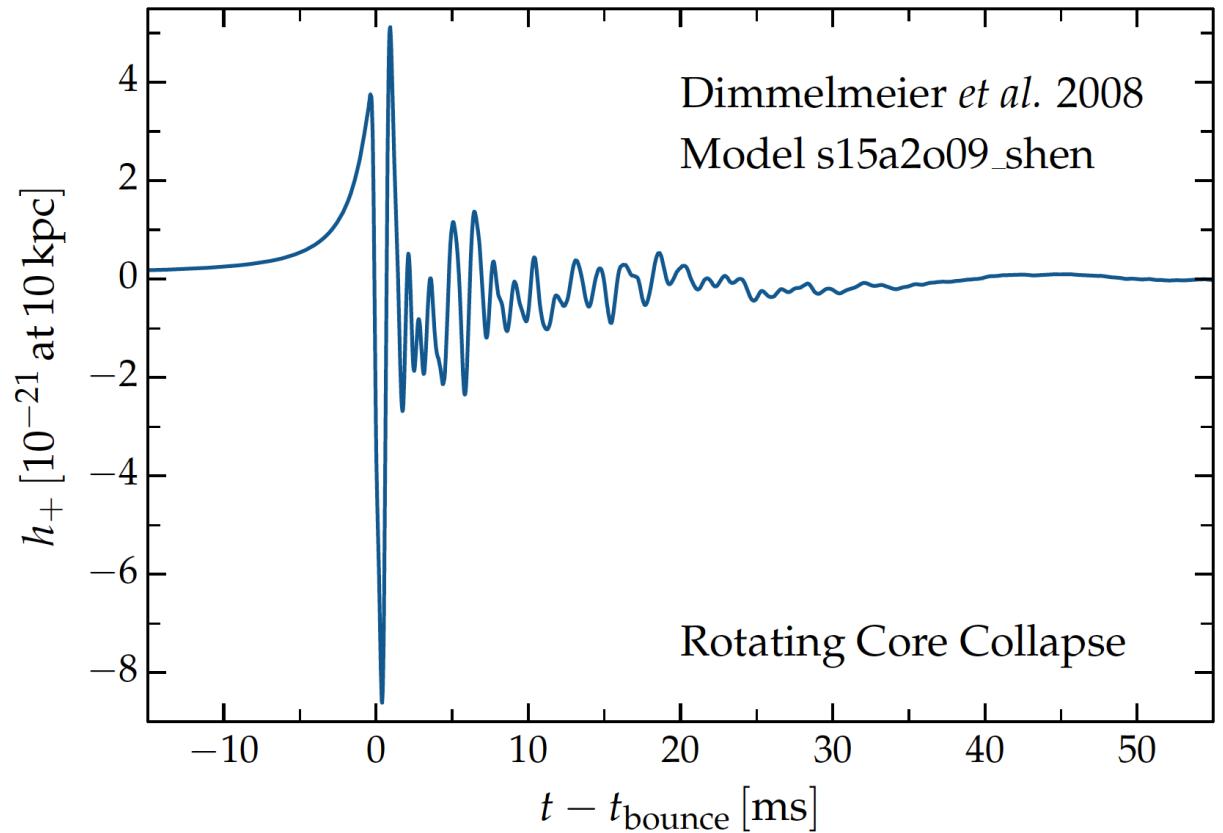
| 2-detector: LVD - KamLAND | 10 year - 65 kpc | |
|------------------------------|--------------------------|--------------------------|
| | Old Method | New Method |
| Raw η | 93.7% = 3425/3654 | |
| Raw ζ | 11.5% = 447/3872 | |
| $5\sigma \eta$ | 62.9% = 2298/3654 | 80.8% = 2951/3654 |
| $5\sigma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

GW signal

Magnetorotational Hydrodynamics,

Source: Strong centrifugal deformation of inner core (\sim 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 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)