Core-Collapse Supernovae: Gravitational Waves and Neutrinos

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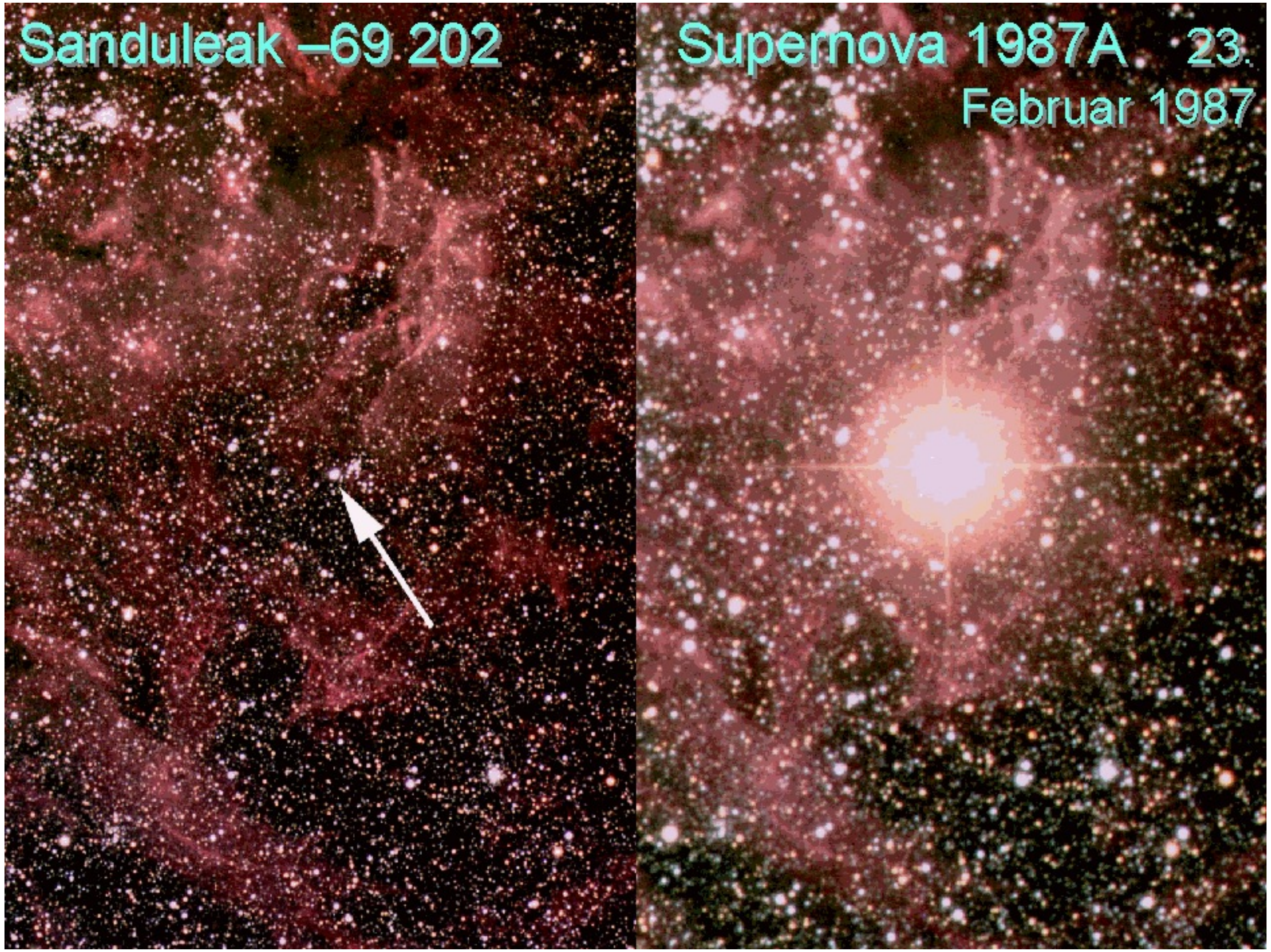
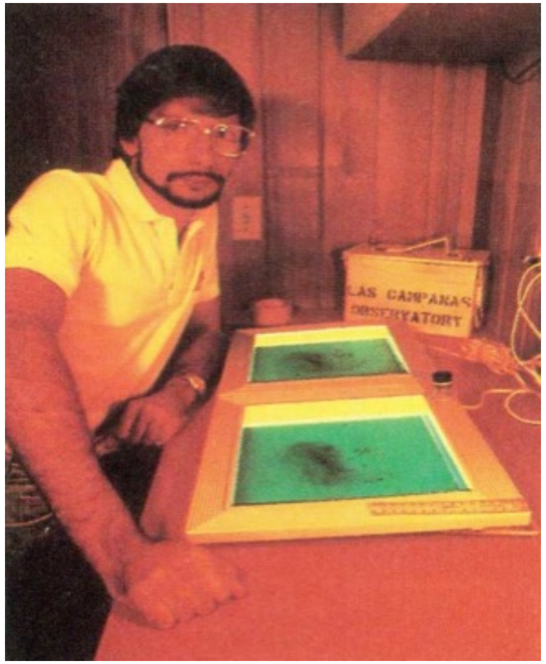
Conference in memory of Veniamin Sergeyevich Berezinsky, GSSI, L'Aquila, October 1-3, 2024

The Event changing paradigms





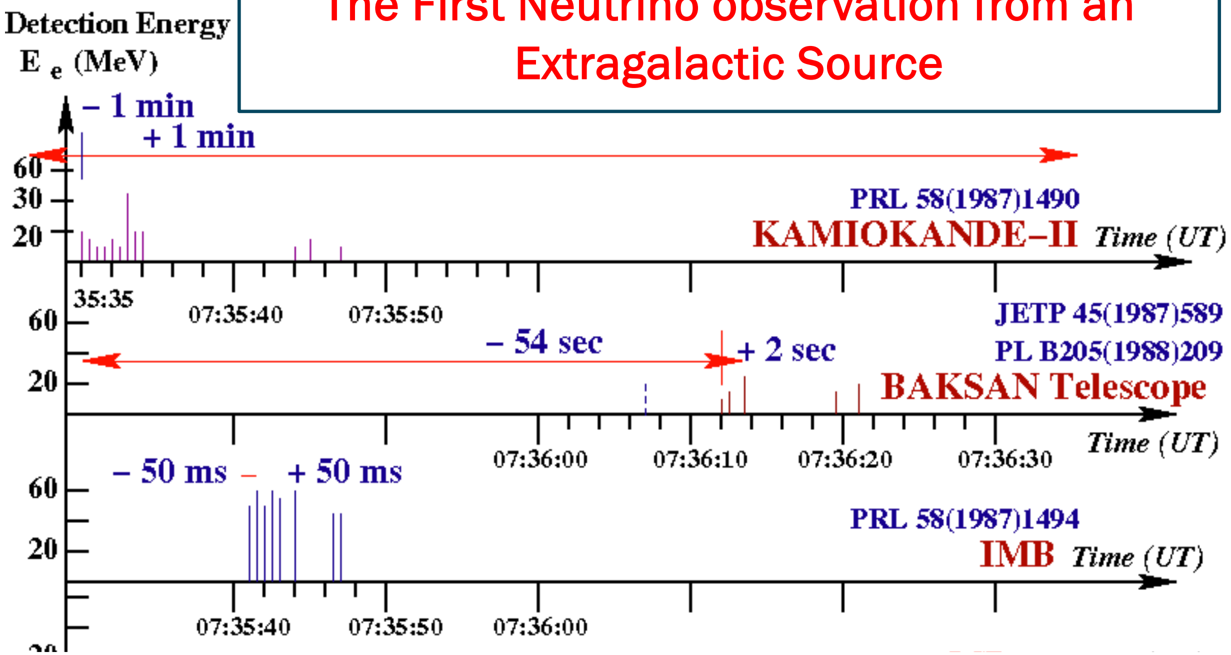
SN1987A

Observed by Ian Shelton at Las Campanas Observatory on February 24.23 UT
Progenitor: A 20 $M_{\odot}$ **Blue Supergiant**

The EM emission provides the first evidence of **Aspherical explosion**

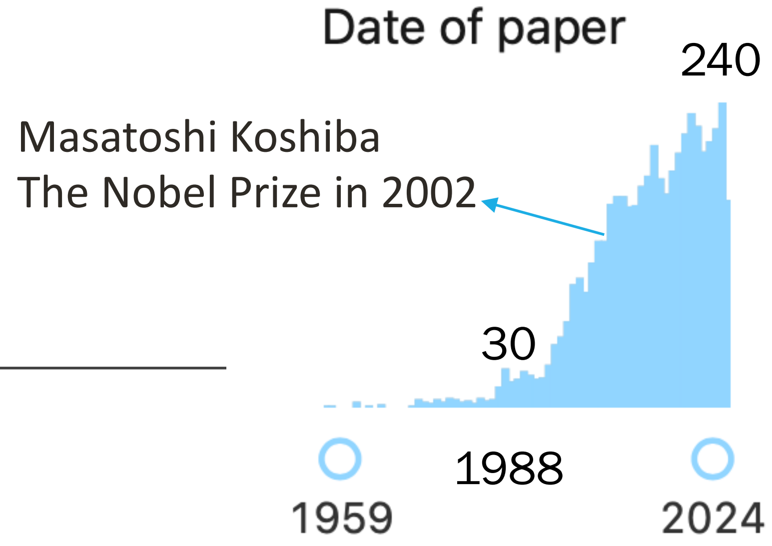
Neutrinos from SN1987A

The First Neutrino observation from an Extragalactic Source



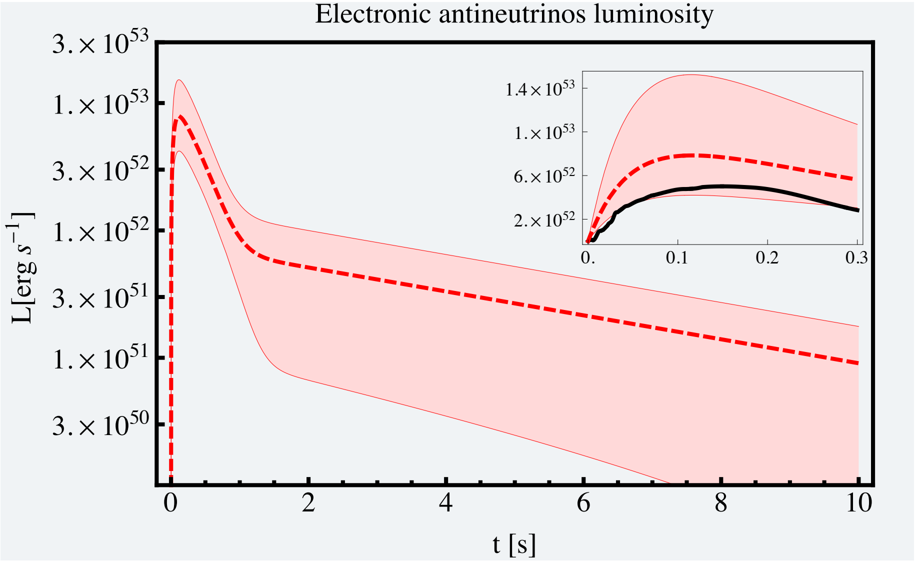
Arnett et al., Ann.Rev.Astron.Astrophys. 27 (1989) 629-700

GP et al. Astroparticle Physics 31 (2009) 163–176



Masatoshi Koshiba
The Nobel Prize in 2002

The KII, IMB and Baksan data helped us in understanding CCSNe and neutrino physics

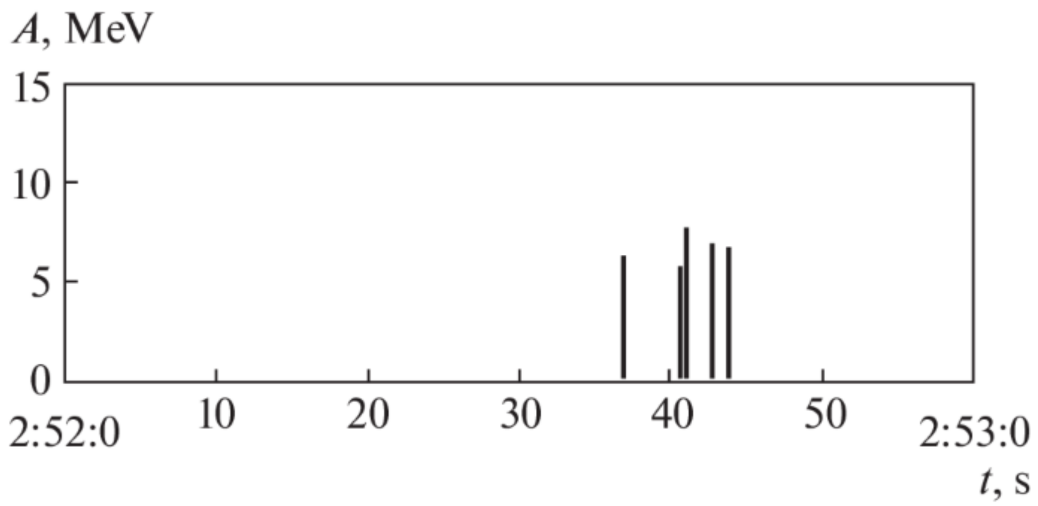


Evidence of Two emission phases!

The PUZZLE of LSD signal

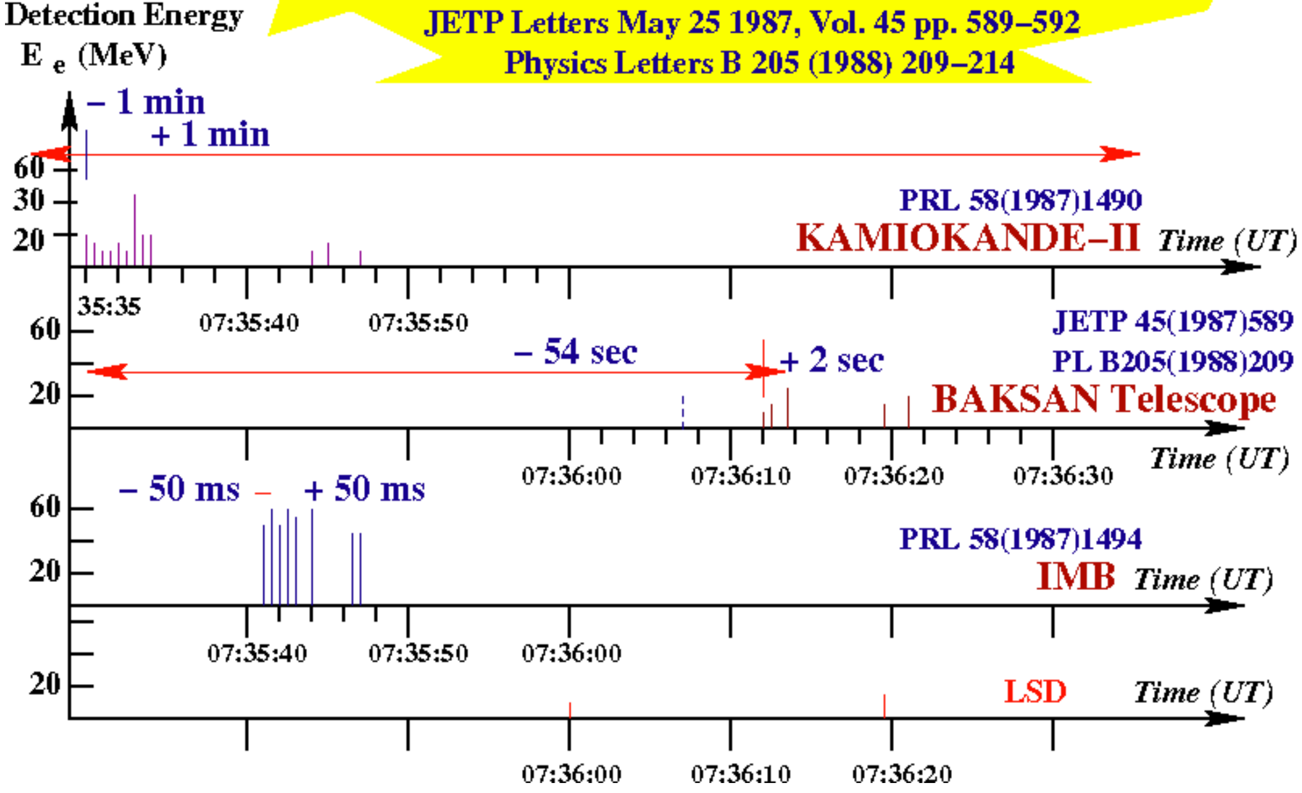
On the possibility of a two-Bang supernova collapse, **V.S. Berezinsky**, C. Castagnoli, V. I. Dokuchaev, P Galeotti
Nuovo Cimento, 11, 287–303, (1988)

Fragmentation of the progenitor due to fast rotation
Prompt BH formation + destruction of the small inside BH

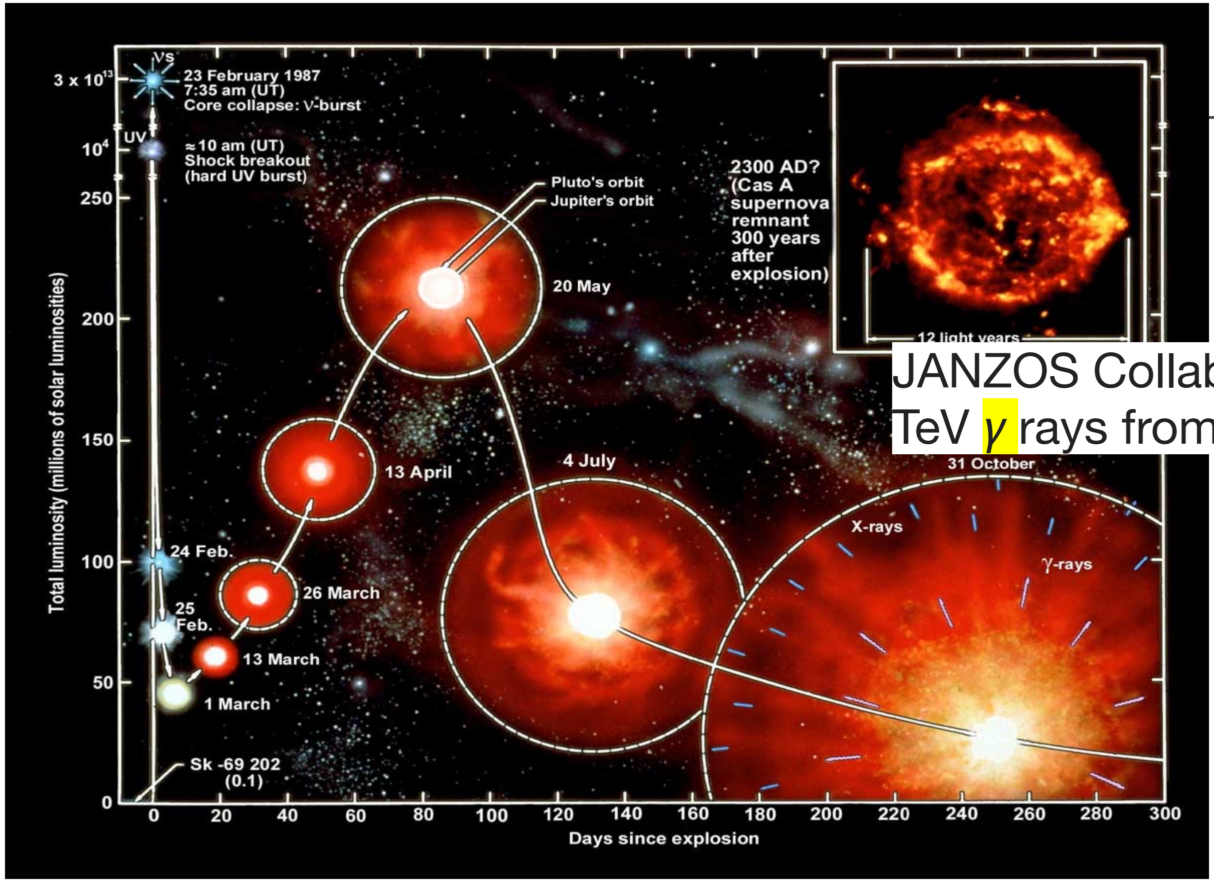


The time sequences of events detected by
KAMIOKANDE–II, Baksan telescope, IMB and LSD detectors
at 07:35 UT on February 23, 1987.

E.N. Alexeyev, L.N. Alexeyeva, I.V. Krivosheina and V.I. Volchenko
JETP Letters May 25 1987, Vol. 45 pp. 589–592
Physics Letters B 205 (1988) 209–214



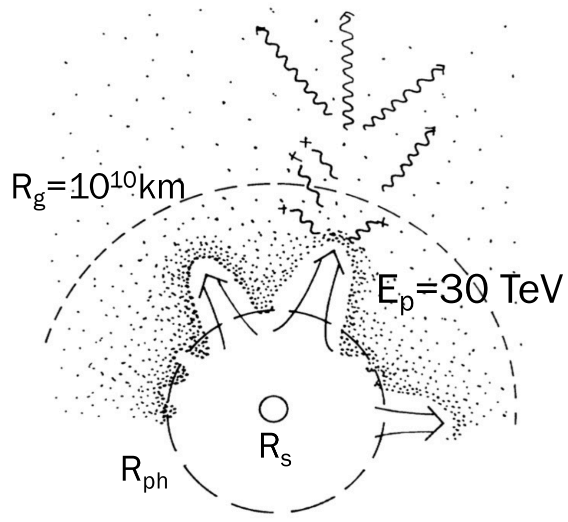
The PUZZLE of the TeV emission



The Burst of TeV gamma-rays from SN1987A
V.S. Berezinsky and T. Stanev
Phys.Rev.Lett. 63 (1989) 1035-1037

JANZOS Collaboration has reported a 2-day burst of TeV γ rays from SN 1987A 11 months after the explosion!

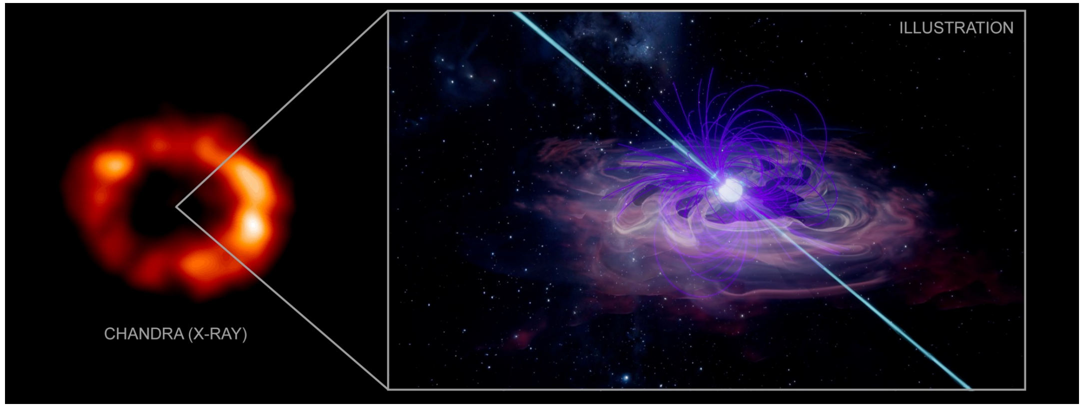
Hadronic emission lasting few days due to cumulated protons beam outside the photosphere



Cosmic rays and gamma radiation from the shell of SN1987A
V. S. Berezinsky and V. L. Ginzburg ,*Nature* **volume 329**, pages 807–809 (1987)

37 years later…

1. JWST finally observed the compact Remnant: a Neutron Star (Science 22 Feb 2024 Vol 383, Issue 6685 pp. 898-903)…..**NO BH FORMATION**
2. The LSD signal is still a mystery
3. No other observations of HE gammas from CCSNe (UL from CANGAROO)
4. No other CCSN exploded since 1987 inside a horizon of 60 Kpc



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Progress & Open Questions

Bruenn et al. 2016. *Ap.J.* **818**, 123.

Neutrinos Mechanism and Turbulence crucial to most explosions, necessitating multi-D Treatment

- Computational methods (sped and resolution)
- Neutrino oscillations
- Progenitors dependence
- Systematics and explodability

NEXT GALACTIC SUPERNOVA

Burrows and Vartanyan, *Nature* 589 (2021) 7840, 29-39

Janka *et al., Ann.Rev.Nucl.Part.Sci.* 66 (2016) 341-375

The Power of Multi-Messengers

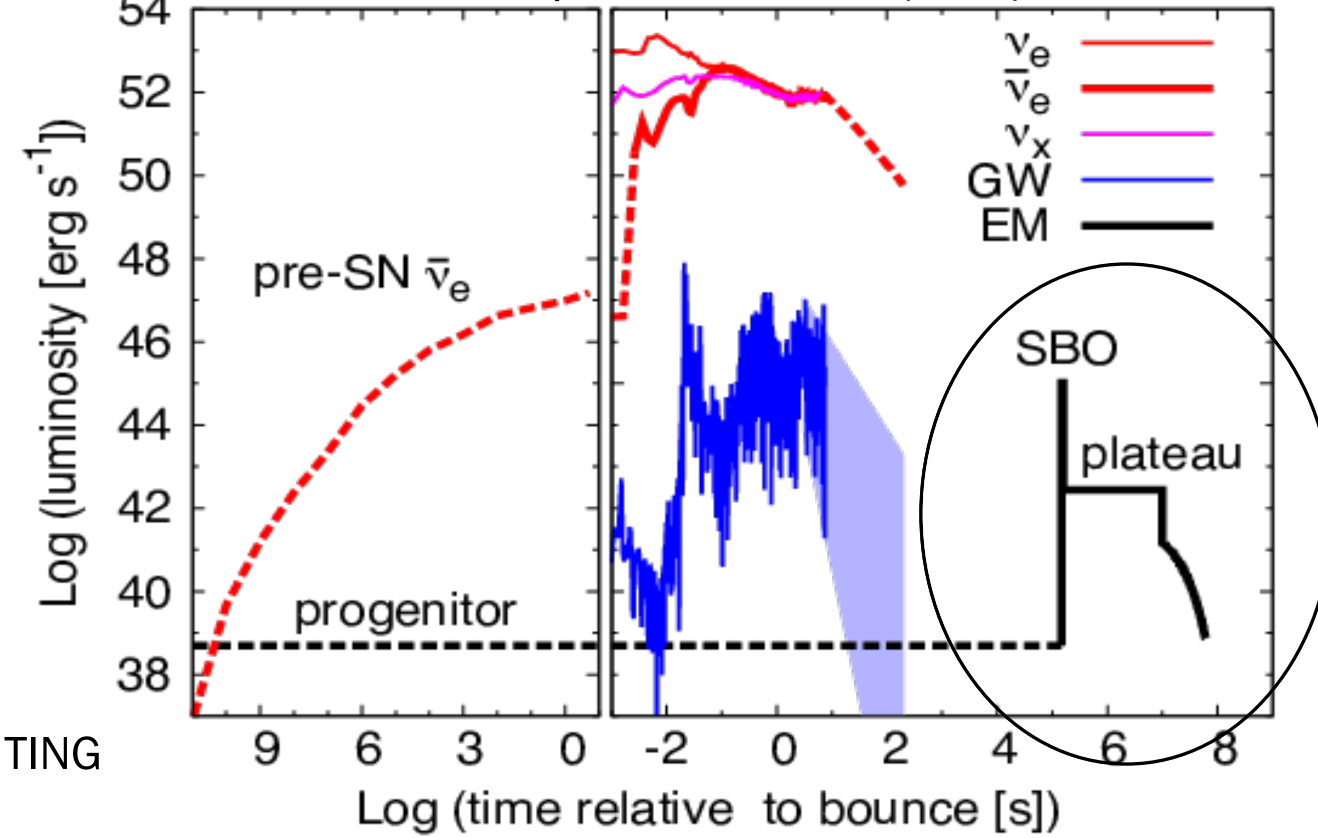
EM signal determines hosting Galaxy and Progenitor Mass, nucleosynthesis of heavy elements. $E_\gamma \sim 0.01\% E_b$

Wongwathanarat et al., *Astron.Astrophys.* 577 (2015) A48
Sandoval et al., *Astrophys.J.* 921 (2021) 2, 113

A few hours to days after the core collapse, the supernova shock breaks out of the progenitor surface, suddenly releasing the photons behind the shock in a flash bright in UV and x-rays

CHALLENGING TO SEE-> FAST ALERT AND GOOD POINTING

Nakamura *et al.,Mon.Not.Roy.Astron.Soc.* 461 (2016) 3, 3296-3313



The Power of Multi-Messengers

Neutrino signal characterizes the total emitted energy, pointing, timing, neutrino properties (absolute neutrino mass, mass hierarchy)

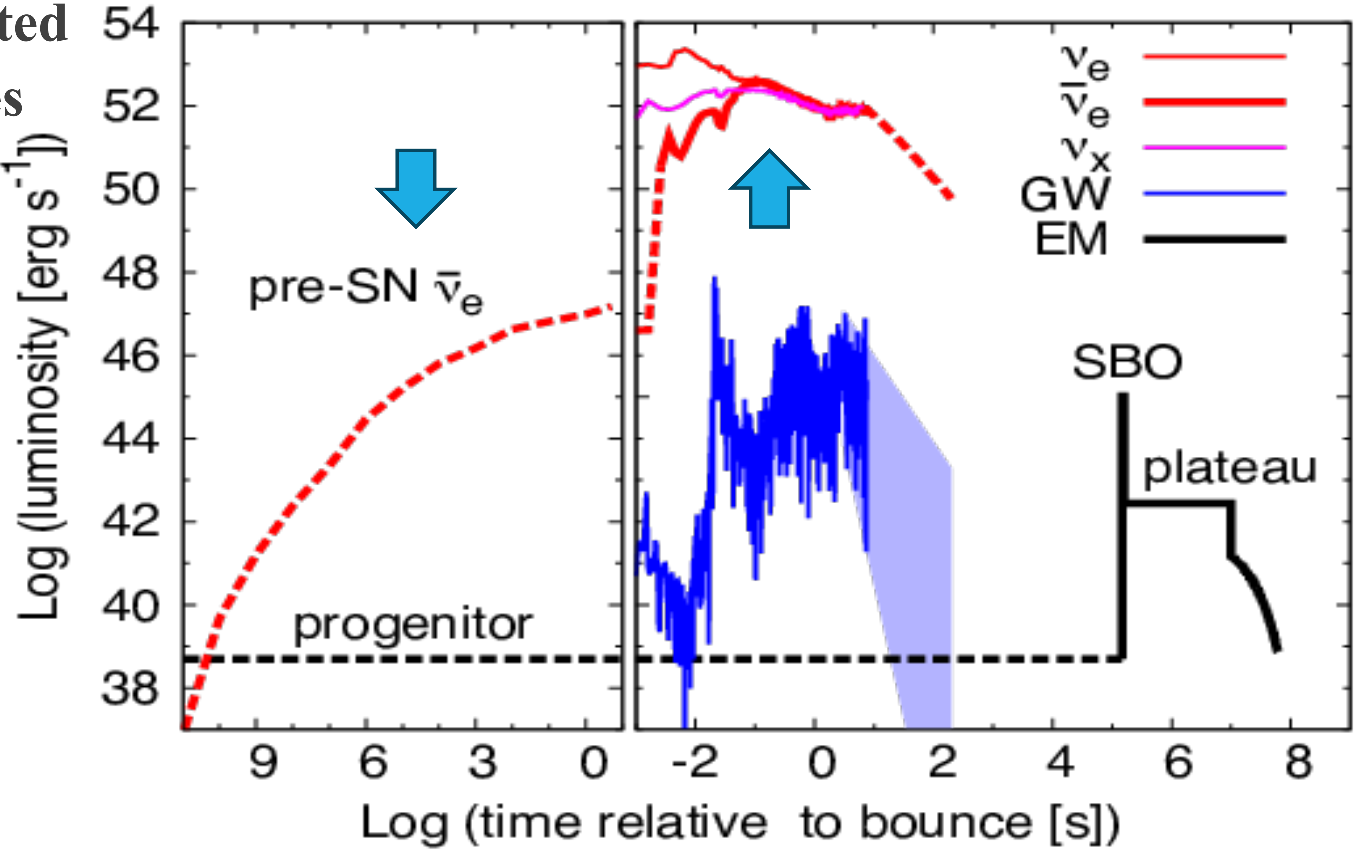
Mirizzi et al. Riv.Nuovo Cim. 39 (2016) 1-2, 1-112

https://snews2.org

ALERT TO EM and GW detectors

$E_\nu = 99\% E_b$

Nakamura *et al.,Mon.Not.Roy.Astron.Soc.* 461 (2016) 3, 3296-3313



The Power of Multi-Messengers

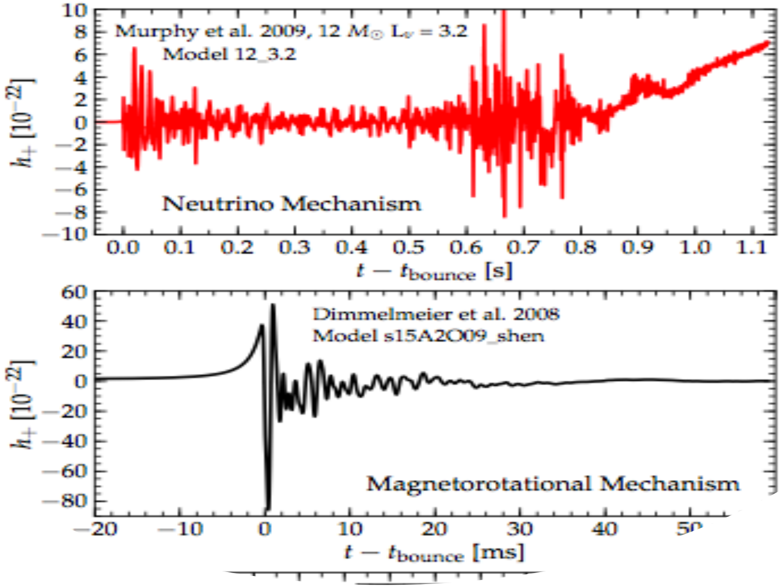
GW signal one-to-one connected with the explosion mechanism, EOS of dense matter

Mitra *et al., Mon.Not.Roy.Astron.Soc.* 529 (2024)3582
Abdikamalov, GP *et al* 2020

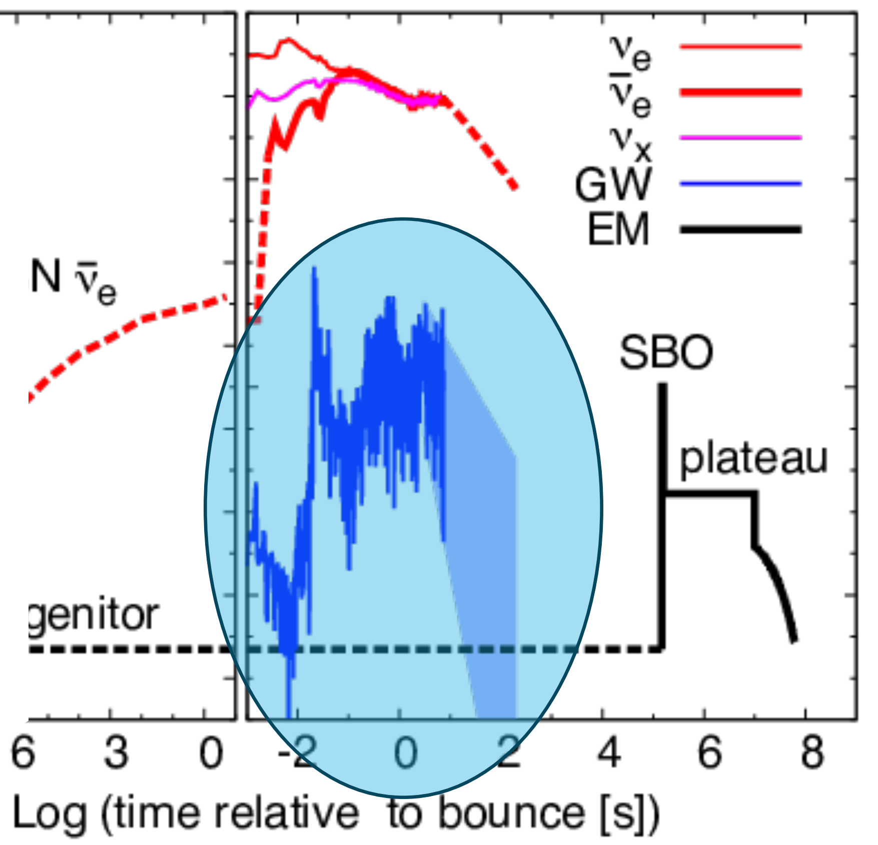
$E_{GW} < 0.0001\% E_b$

Already first-generation LIGOs should be able to see same of such signals throughout the Milky Way. However, they are **unmodeled burst** like the spikes of the noise

NEUTRINOS CAN HELP!



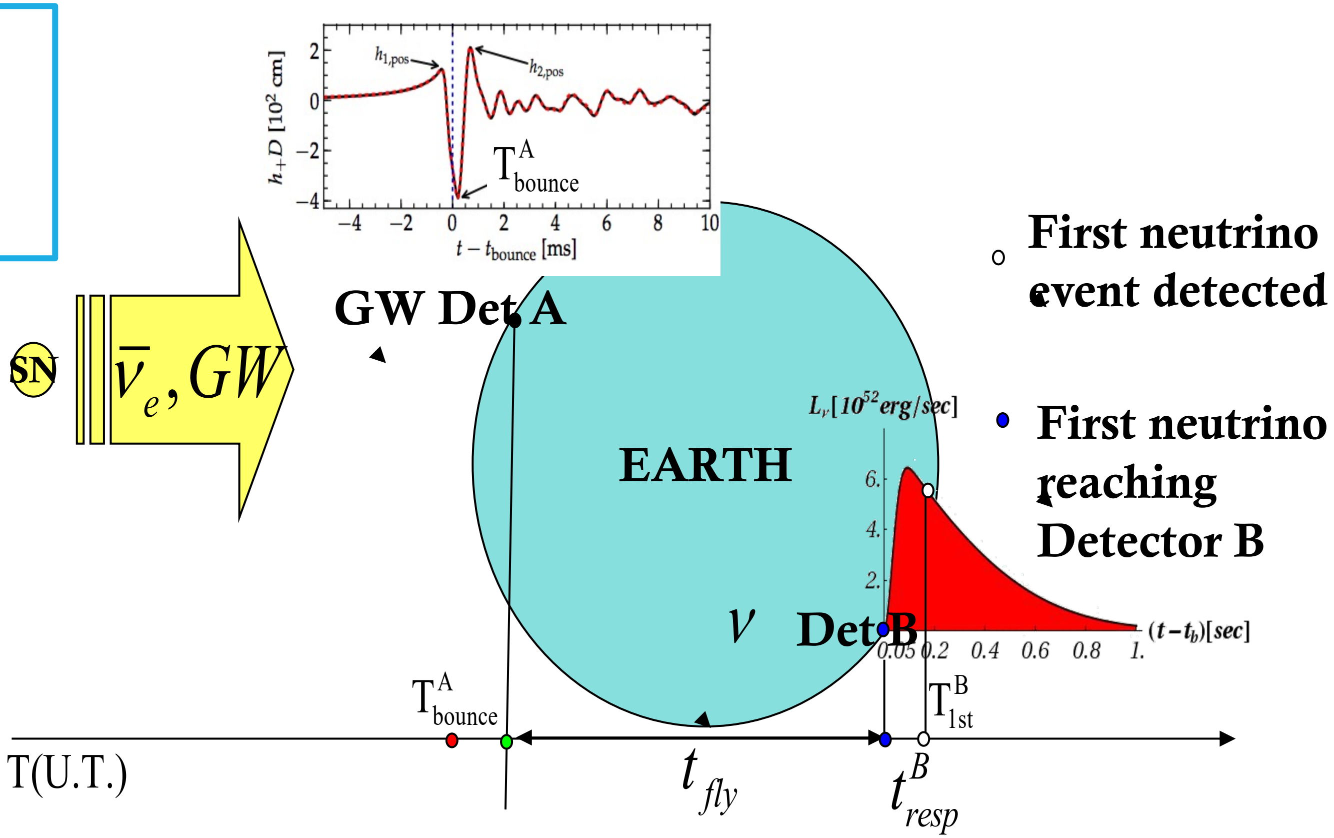
Nakamura *et al.,Mon.Not.Roy.Astron.Soc.* 461 (2016) 3, 3296-3313



GW and Neutrino Signals

The starting times of both signal at the source are always concident within few ms

Has been demonstrated that the analysis of Neutrino data can provide this starting time At GW detector with an average error of few ms depending on the emission model



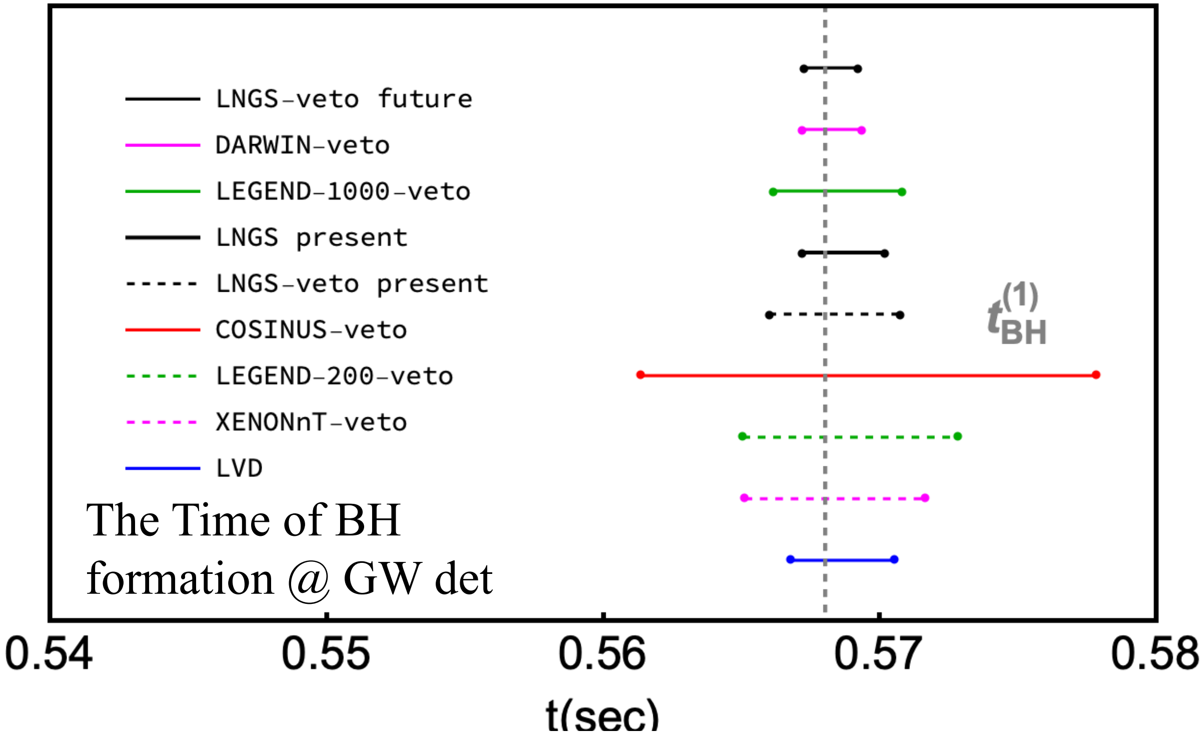
GP *et al. PRL 103, 031102 (2009)*

Halzen and Raffelt, *Phys.Rev.D* 80 (2009) 087301

GW and Neutrino Signals

In case of Failed SNe also the ending time of both signals at the source are always concident with the time of BH formation

Also in this case the analysis of Neutrino data can provides the time of BH formation within a window of few ms



The Time of BH formation @ GW det

LNGS – VIRGO $\delta T^{\mathrm{GW}}_{\mathrm{BH}} = \delta T^{\mathrm{LNGS}}_{\mathrm{BH}} + \delta t_{\mathrm{fly}} = 4\,\mathrm{ms}$

Beacom et al. *Phys.Rev.D* 63 (2001) 073011
GP and Ternes, *JCAP* 06 (2024) 022

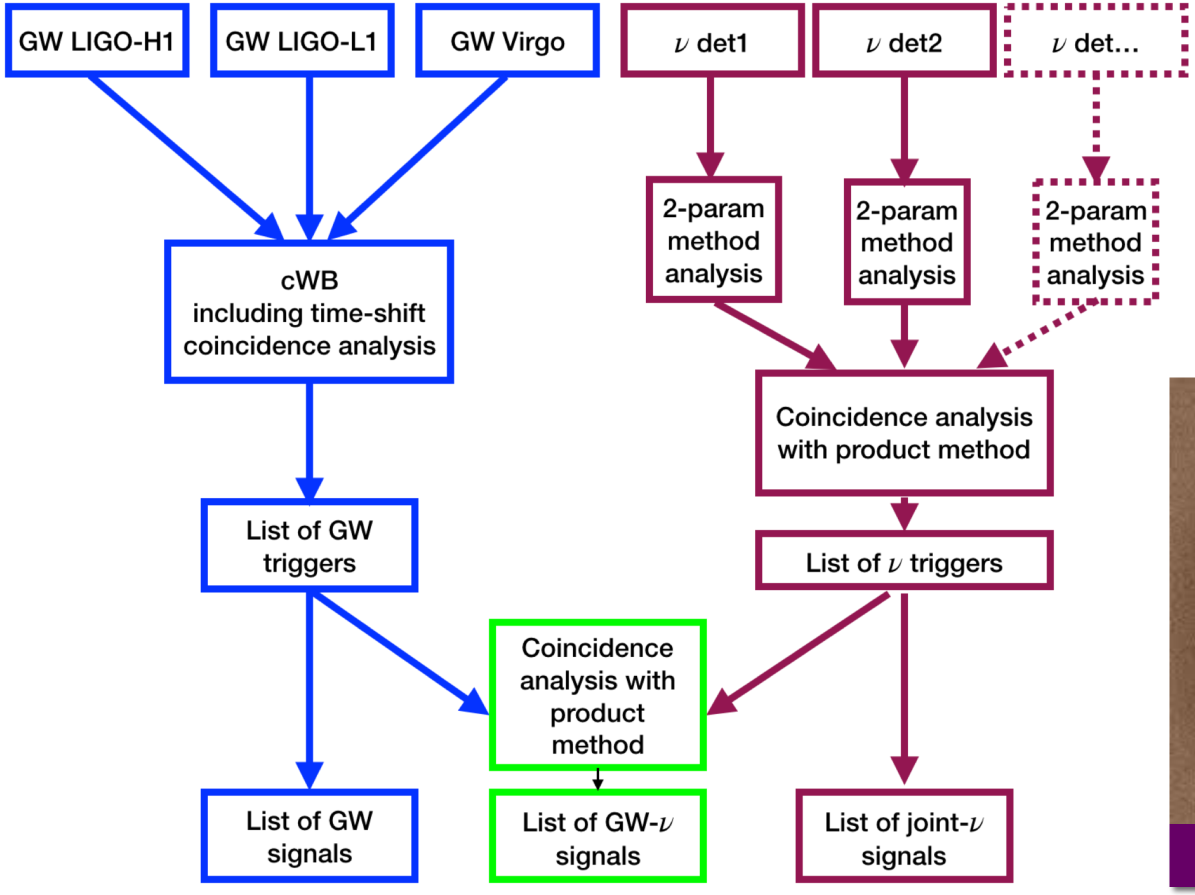
Multimessenger analysis with GW-ν

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

LIGO L1

LIGO H1

Virgo



GW LIGO-H1

GW LIGO-L1

GW Virgo

cWB including time-shift coincidence analysis

List of GW triggers

List of GW signals

ν det1

ν det2

ν det…

2-param method analysis

2-param method analysis

2-param method analysis

Coincidence analysis with product method

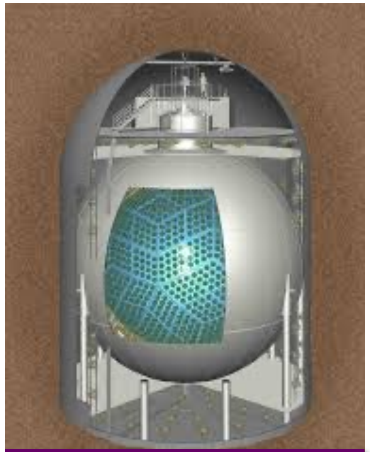
List of ν triggers

List of joint-ν signals

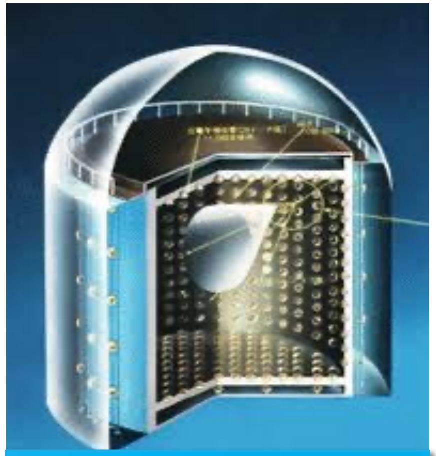
Coincidence analysis with product method

List of GW-ν signals

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

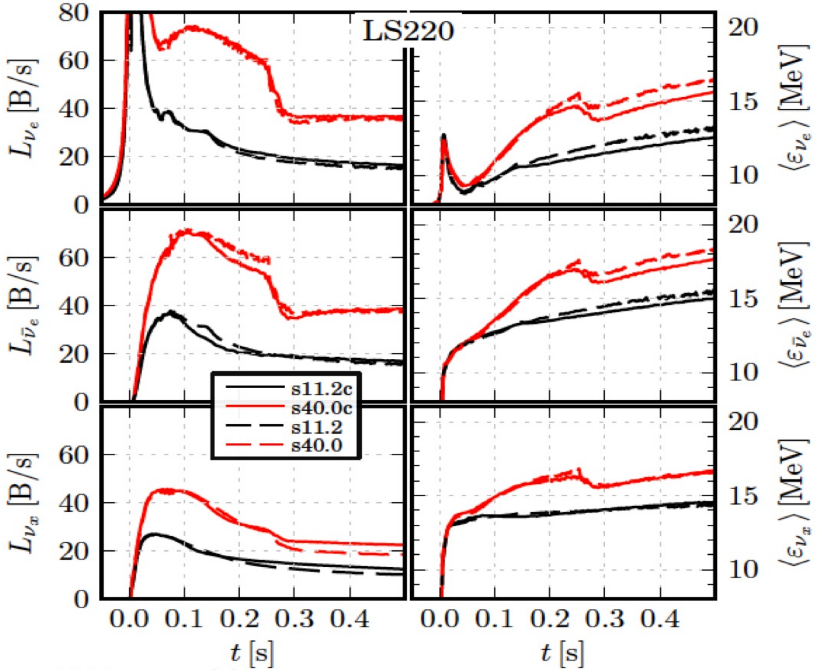
Time coincidence window

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

- 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_{υ} =1/100 years as in SNEWS

Neutrino signals

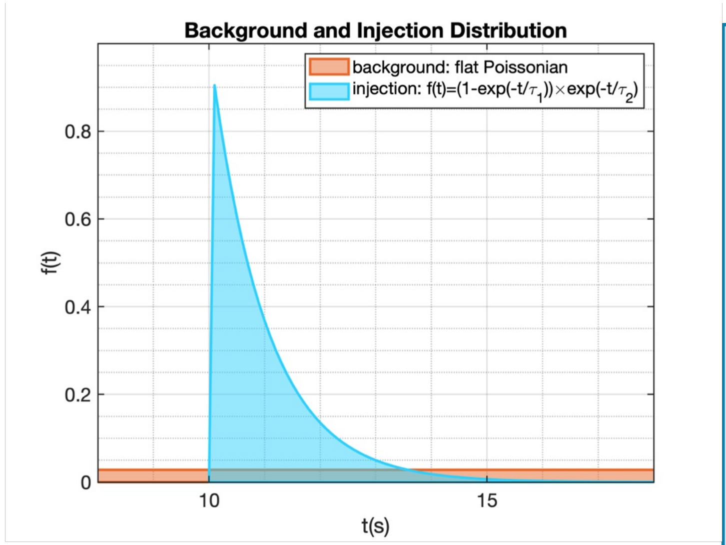
NUMERICAL SIMULATIONS



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

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

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

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

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

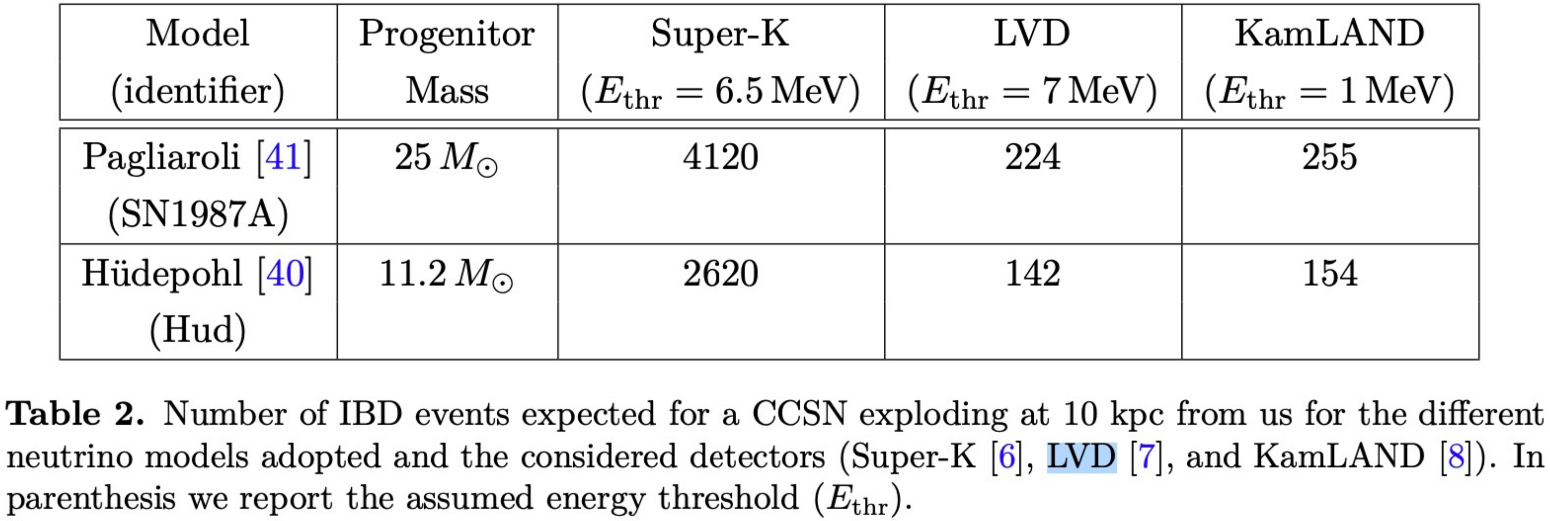
$\tau_2 = 1\, s$

$\tau_1 = 0.1\, s$

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

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

Neutrino analysis efficiency



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

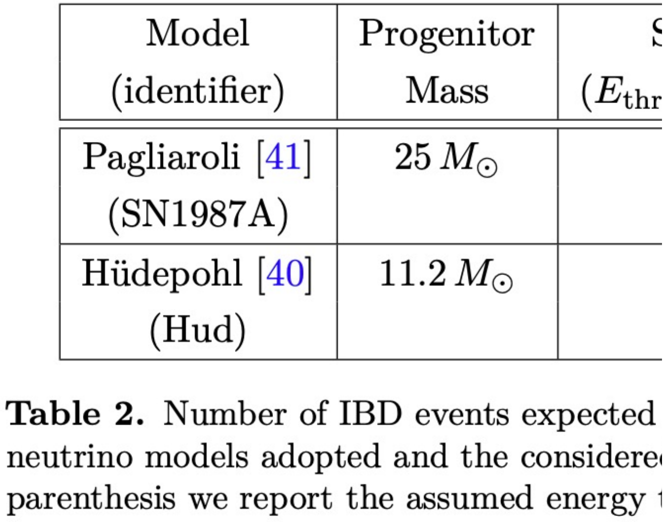
Table 2. Number of IBD events expected for a CCSN exploding at 10 kpc from us for the different neutrino models adopted and the considered detectors (Super-K [6], LVD [7], and KamLAND [8]). In parenthesis we report the assumed energy threshold ($E_{\rm thr}$).

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

Neutrino analysis efficiency



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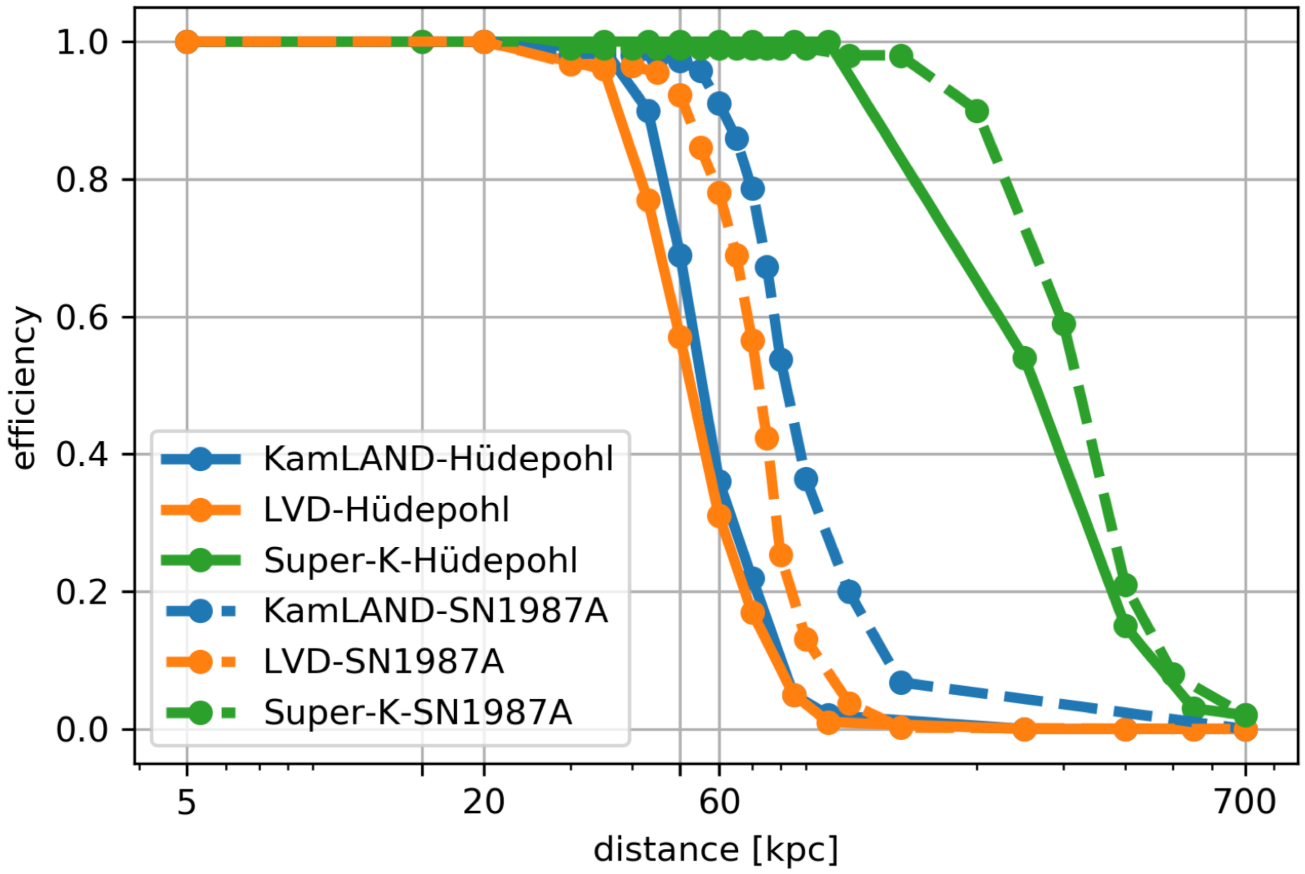
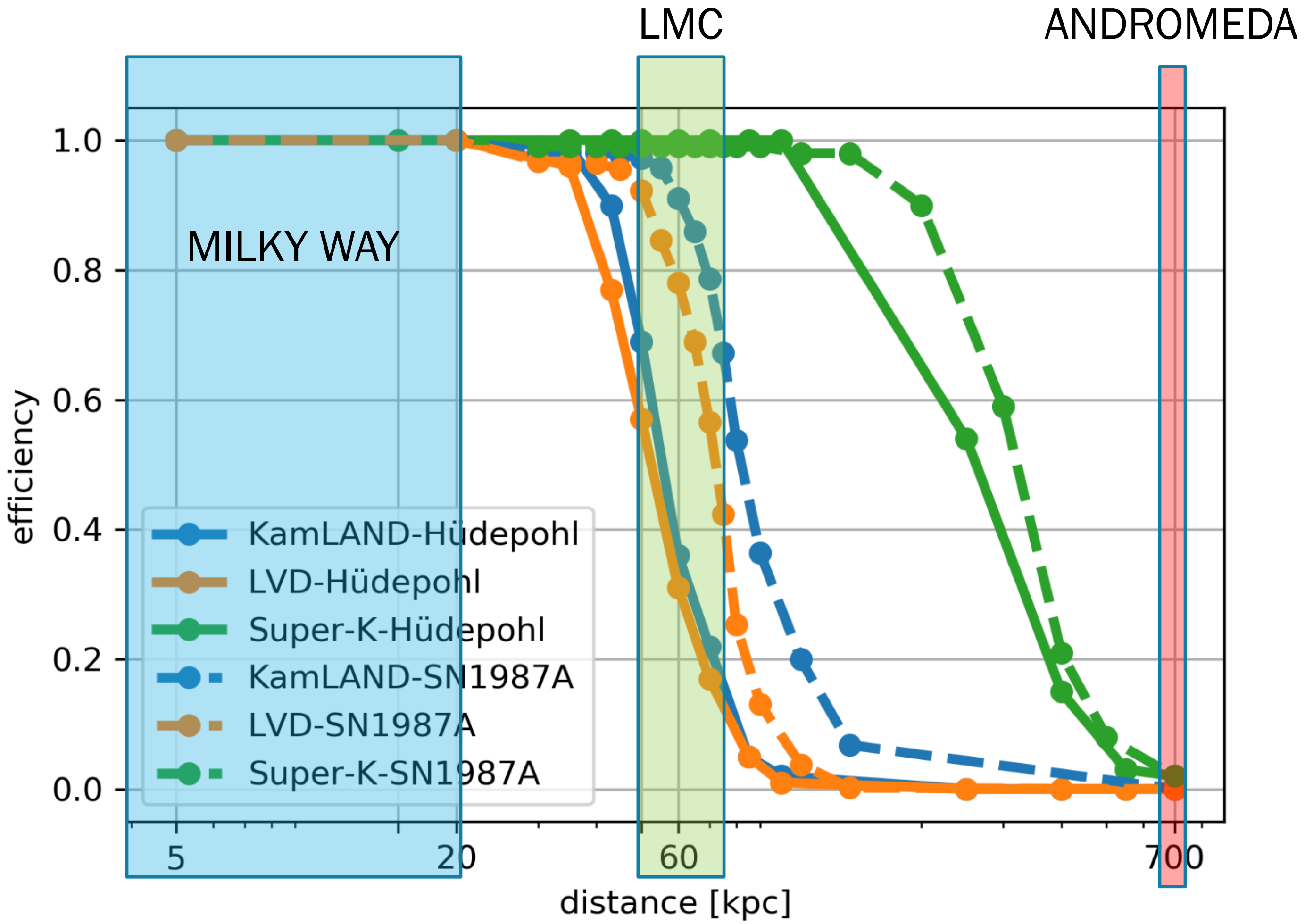


Neutrino analysis efficiency

MILKY WAY ~100% efficiency

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

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



GW signals

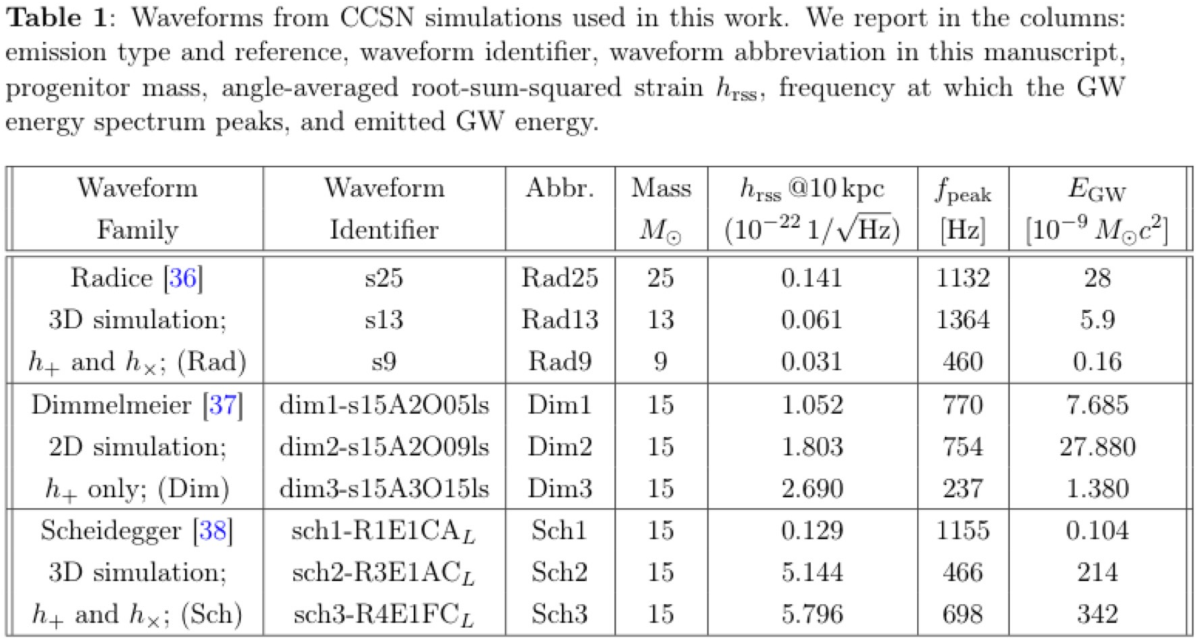
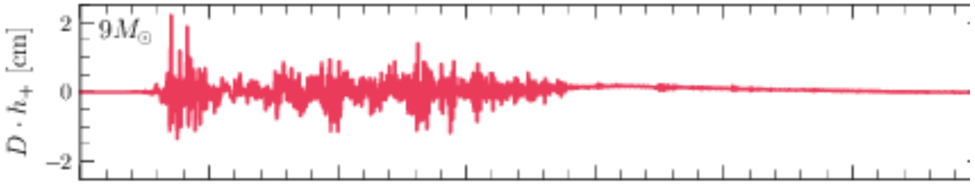


Table 1: Waveforms from CCSN simulations used in this work. We report in the columns: emission type and reference, waveform identifier, waveform abbreviation in this manuscript, progenitor mass, angle-averaged root-sum-squared strain $h_{\rm rss}$, frequency at which the GW energy spectrum peaks, and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

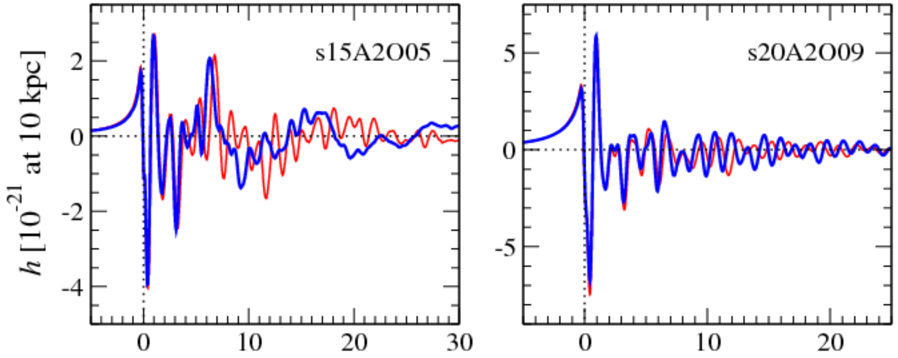
Waveform Family	Waveform Identifier	Abbr.	Mass $M_\odot$	$h_{\rm rss}$ @10 kpc $(10^{-22}\,1/\sqrt{\rm Hz})$	$f_{\rm peak}$ [Hz]	$E_{\rm GW}$ $[10^{-9}\,M_\odot c^2]$
Radice [36]	s25	Rad25	25	0.141	1132	28
3D simulation;	s13	Rad13	13	0.061	1364	5.9
h_+ and $h_\times$; (Rad)	s9	Rad9	9	0.031	460	0.16
Dimmelmeier [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

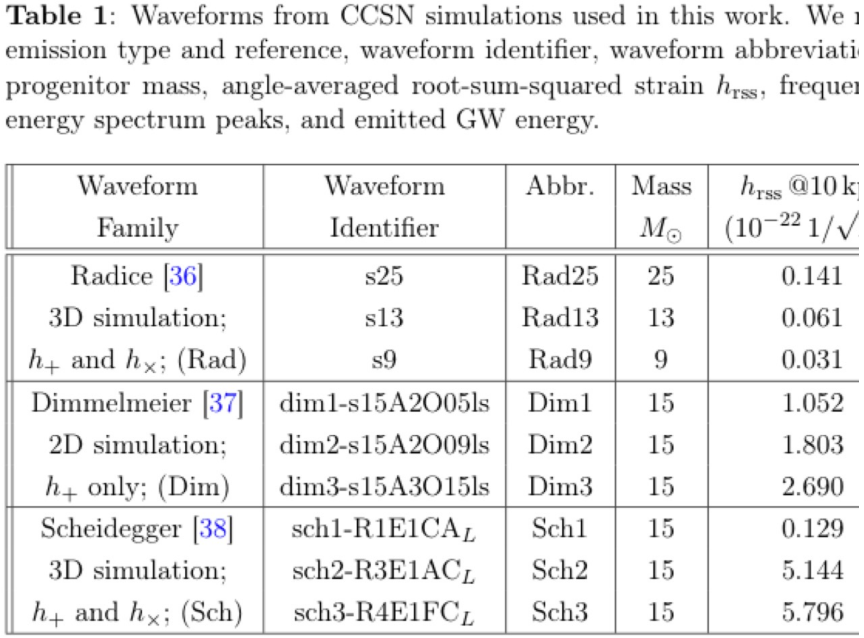
Radice *et al.*, Astrophys. J. Lett., 876(1):L9, 2019



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



GW analysis efficiency



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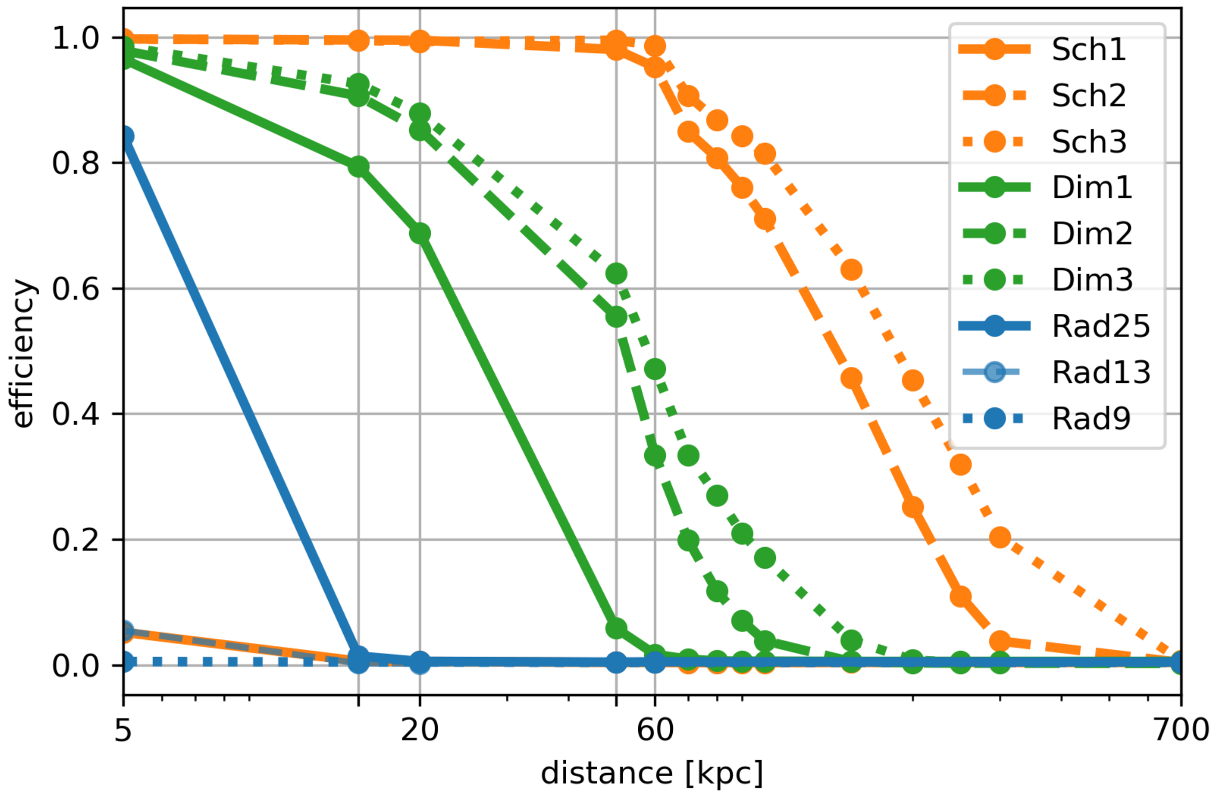
3D simulation;	s13	Rad13	13	0.061
h_+ and $h_\times$; (Rad)	s9	Rad9	9	0.031
Dimmelmeier [37]	dim1-s15A2O05ls	Dim1	15	1.052
2D simulation;	dim2-s15A2O09ls	Dim2	15	1.803
h_+ only; (Dim)	dim3-s15A3O15ls	Dim3	15	2.690
Scheidegger [38]	sch1-R1E1CA$_L$	Sch1	15	0.129
3D simulation;	sch2-R3E1AC$_L$	Sch2	15	5.144
h_+ and $h_\times$; (Sch)	sch3-R4E1FC$_L$	Sch3	15	5.796

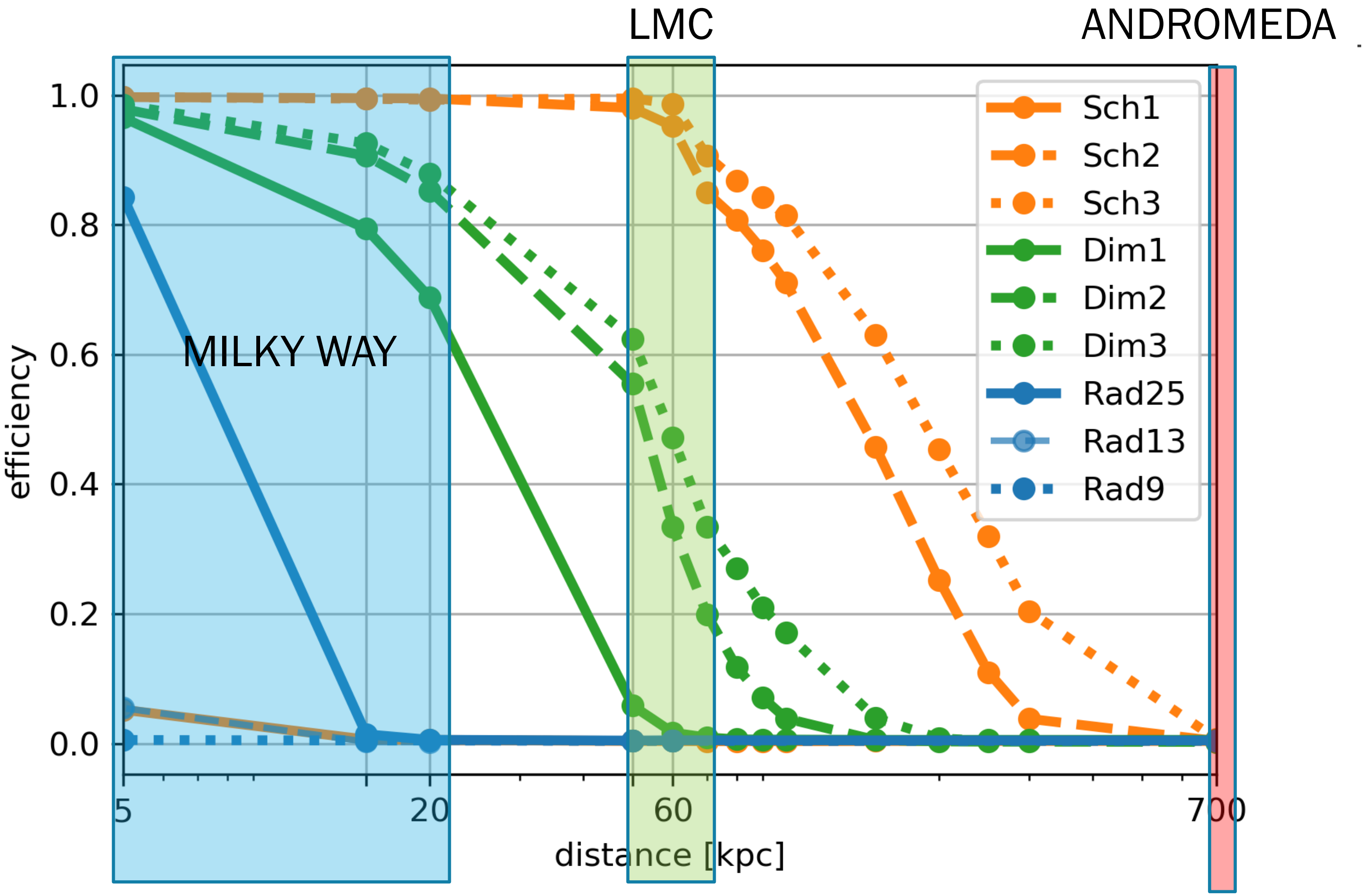


GW analysis efficiency

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

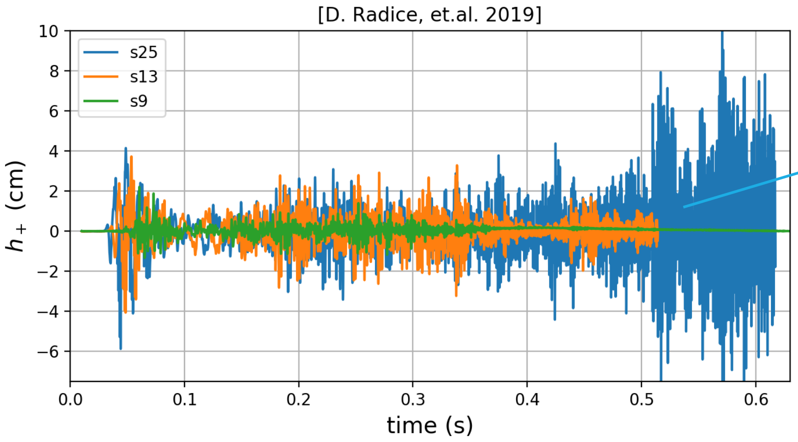
Andromeda
~0% efficiency

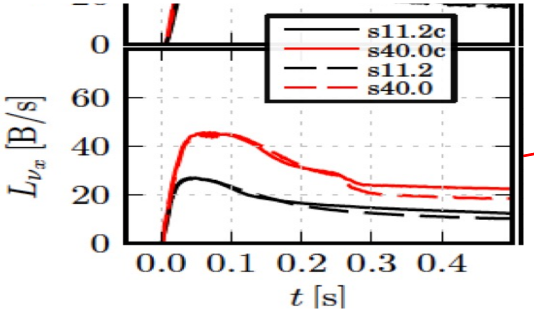


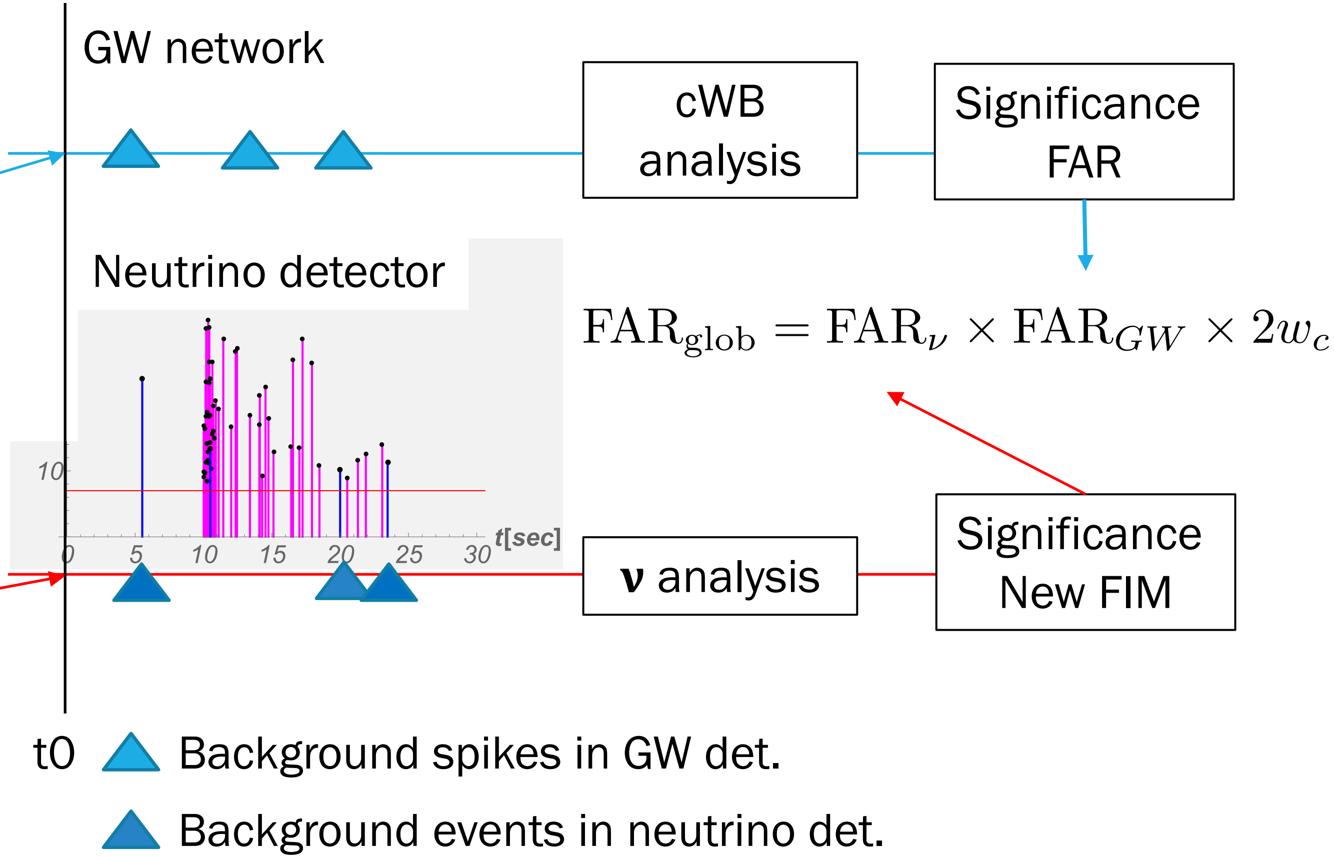
Data analysis combining GW-**ν**

Data analysis procedure

For each specific CCSN Distance and location


[D. Radice, et.al. 2019]





GW network

cWB analysis

Significance FAR

Neutrino detector

ν analysis

Significance New FIM

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

t0

△ Background spikes in GW det.

▲ Background events in neutrino det.

Results for global-network of Neutrino-GW

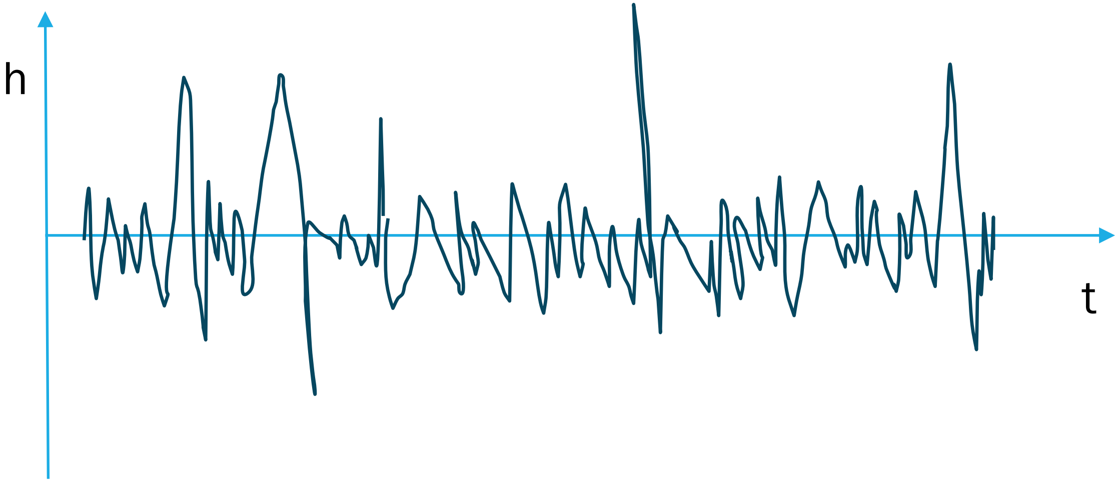
CCSN exploding in the SMC @60kpc with a neutrino signal as SN1987A and a GW emission as in rotating SN

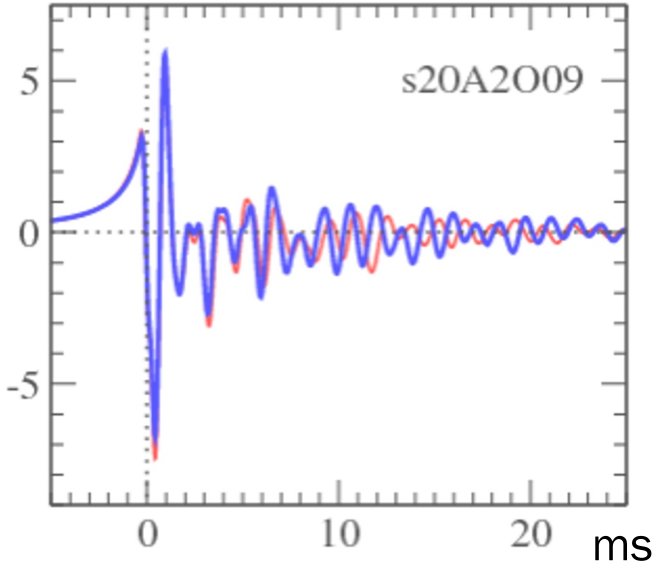
LIGO L1

LIGO H1

Virgo

GW Det Noise





GW CCSN signal

Results for global-network of Neutrino-GW

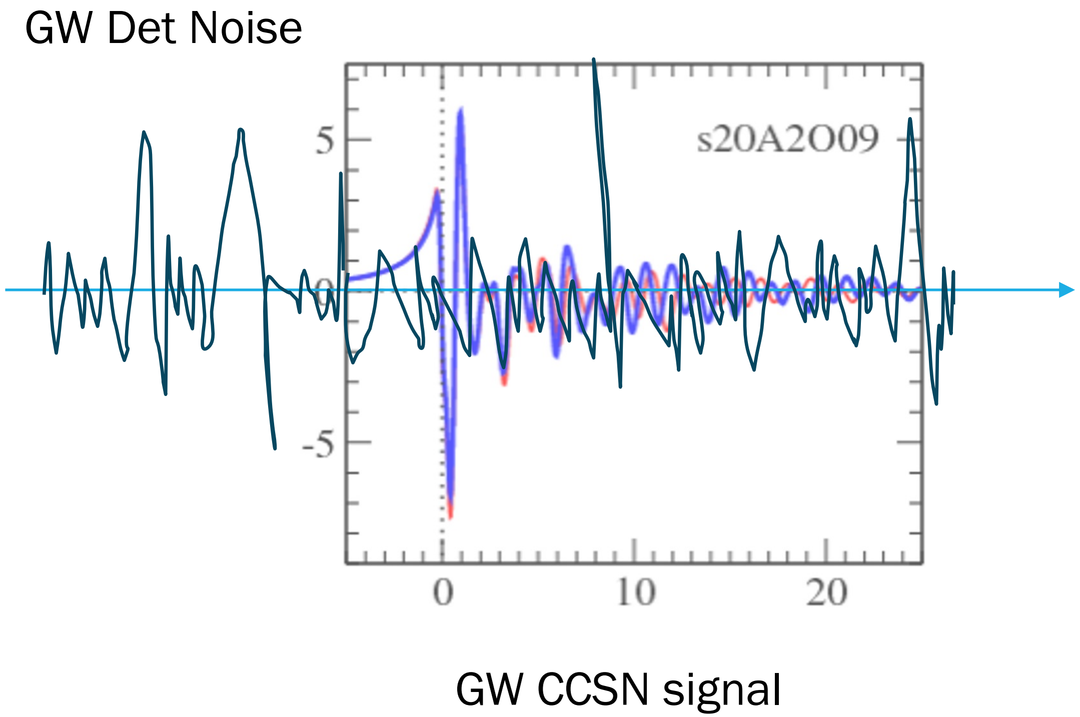
CCSN exploding in the SMC @60kpc with a neutrino signal as SN1987A and a GW emission as in rotating SN

LIGO L1

LIGO H1

Virgo

Only ~33% of GW-signals are recovered and all of them are far to be statistically significant: the 5σ GW detection efficiency is **0%**



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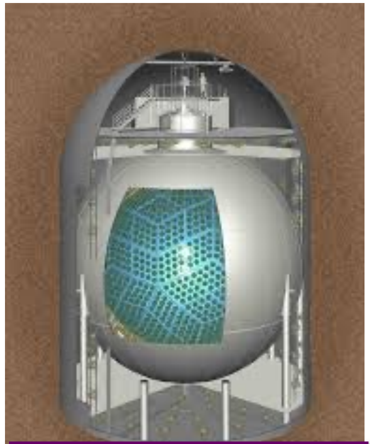


Kamland

By adding the Kamland detector 83% of the GW signal go in coincidence with the neutrino bursts and the 5σ GW detection efficiency becomes:

33.4%*82.9% = 27.7%

Results for global-network of Neutrino-GW

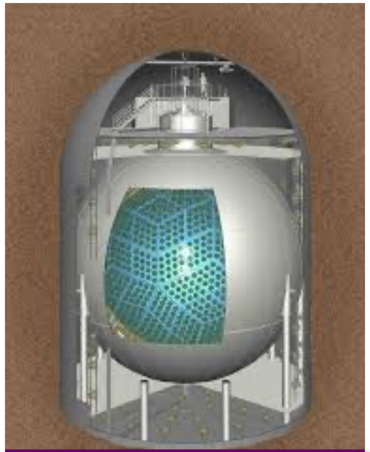
CCSN exploding in the SMC @60kpc with a neutrino signal as SN1987A and a GW emission as in rotating SN

LIGO L1

LIGO H1

Virgo

Only ~33% of GW-signals are recovered and all of them are far to be statistically significant: the 5σ GW detection efficiency is **0%**



Kamland

LVD

By adding both Kamland and LVD detectors all the recovered GW signals go in coincidence with the neutrino bursts and the 5σ GW detection efficiency becomes:

33.4%*100% = 33.4%

Take home message

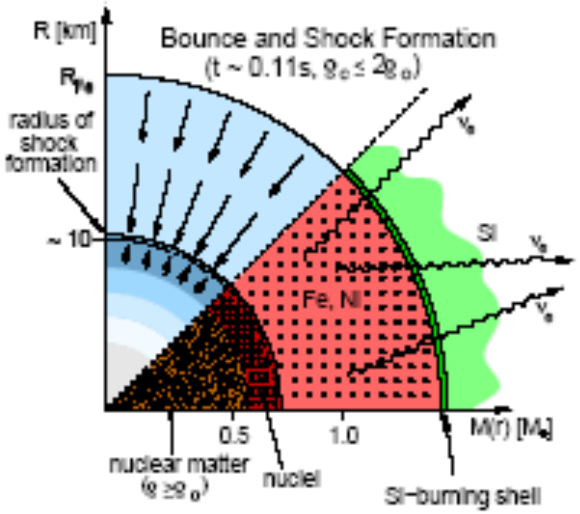
Combining the neutrino search method with the GW one the GW detection efficiency grows from 0% to ~33%

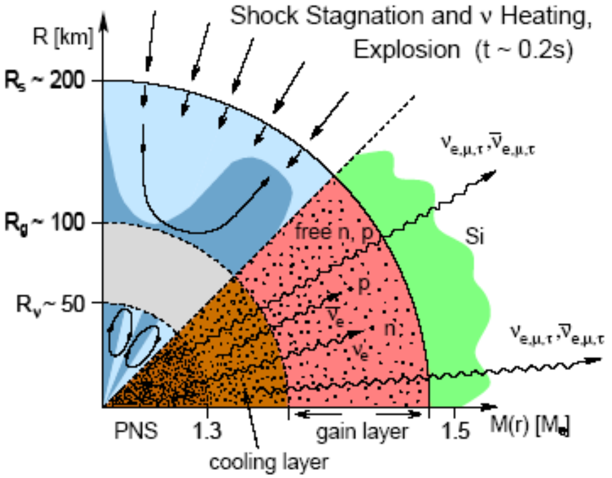
Summary

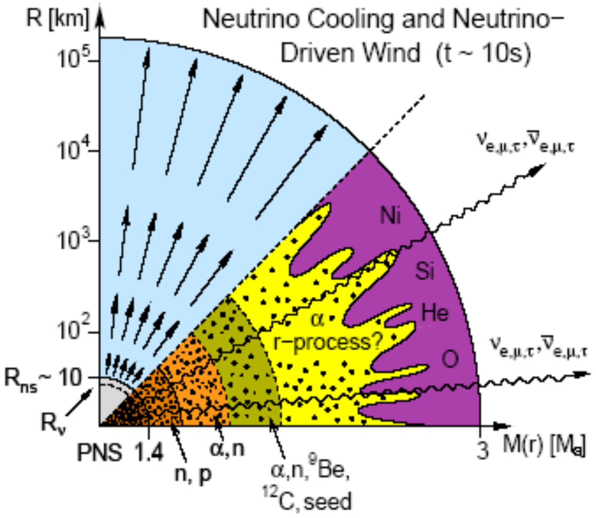
- SN1987A allowed us an unexpected leap in knowledge of Core-Collapse Supernovae.
- After 37 years we have made a lot of progress, but there are still many blind spots.
- We need another galactic supernova and above all we need to see the Multi-Messenger emission.
- The detection of neutrinos can help that of gravitational waves but the GW analysis for this source still needs to be improved.

NEW IDEAS AND METHODS ARE NEEDED BEFORE NEXT GALACTIC CCSN
... it could be Tomorrow!


Thank You







$$\varepsilon^b_{NS} \cong \frac{3}{5}\frac{GM^2}{R} = (1-5)\cdot 10^{53}\,erg$$

Neutrinos → $\varepsilon_\nu \approx 99\% \cdot \varepsilon^b$

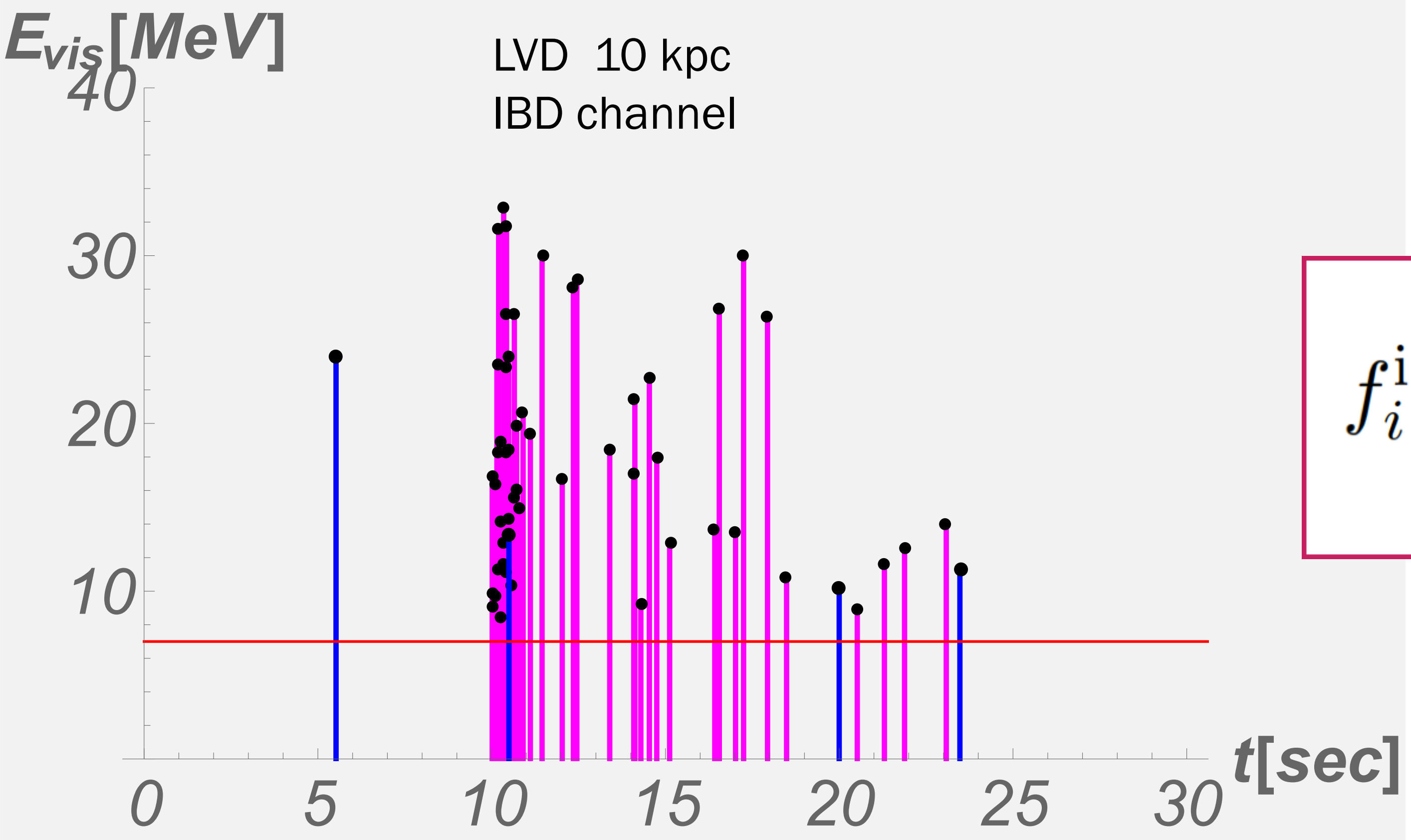
Kinetic energy of the gas → $\varepsilon_{kin} \approx 1\% \cdot \varepsilon^b$

Photons → $\varepsilon_\gamma \sim 0.01\% \cdot \varepsilon^b$

Gravitational Waves → $\varepsilon_{GW} \leq 0.0001\% \cdot \varepsilon^b$

Data analysis improvement in LEN sector

The statistical significance of a LEN events burst: Standard procedure



FIM = Imitation frequency (1/day)

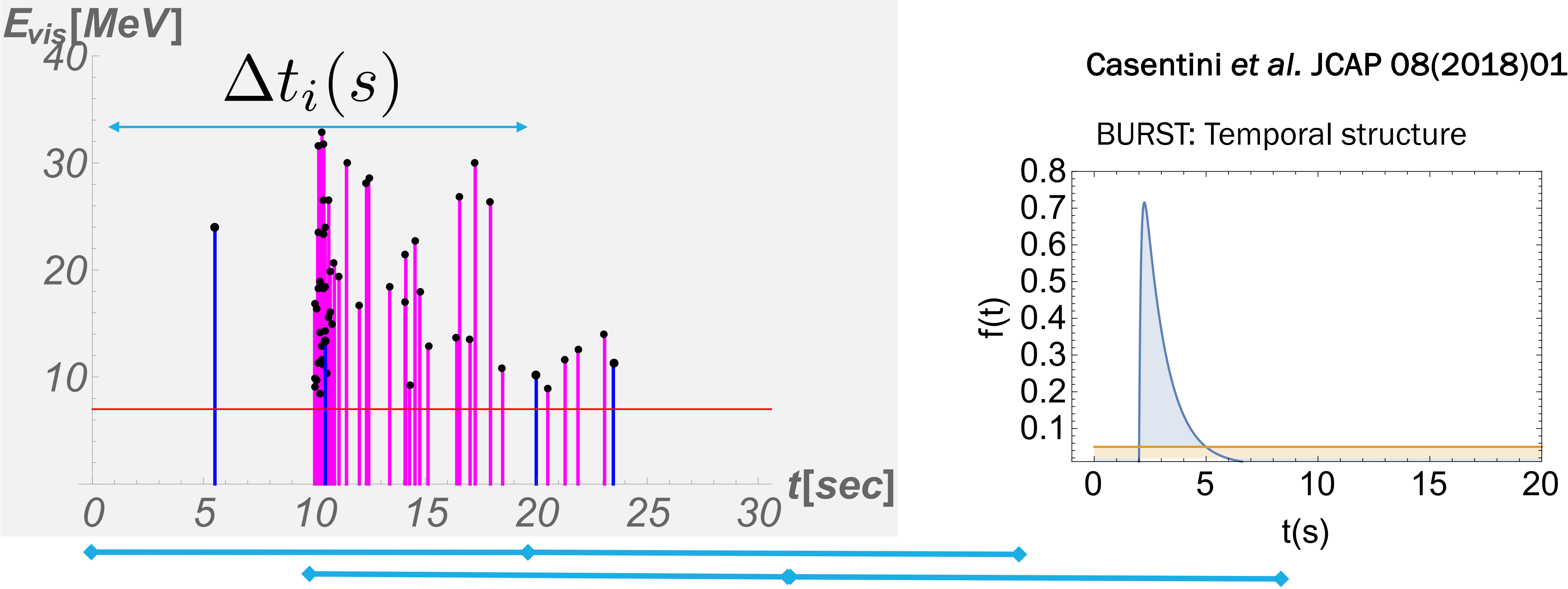
$$f_i^{\rm im}(m_i) = N \times \sum_{k=m_i}^{\infty} P(k),$$

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

Temporal window $w_\nu = 20s$

Number of events inside the window m_i

The statistical significance of a LEN events burst: New procedure



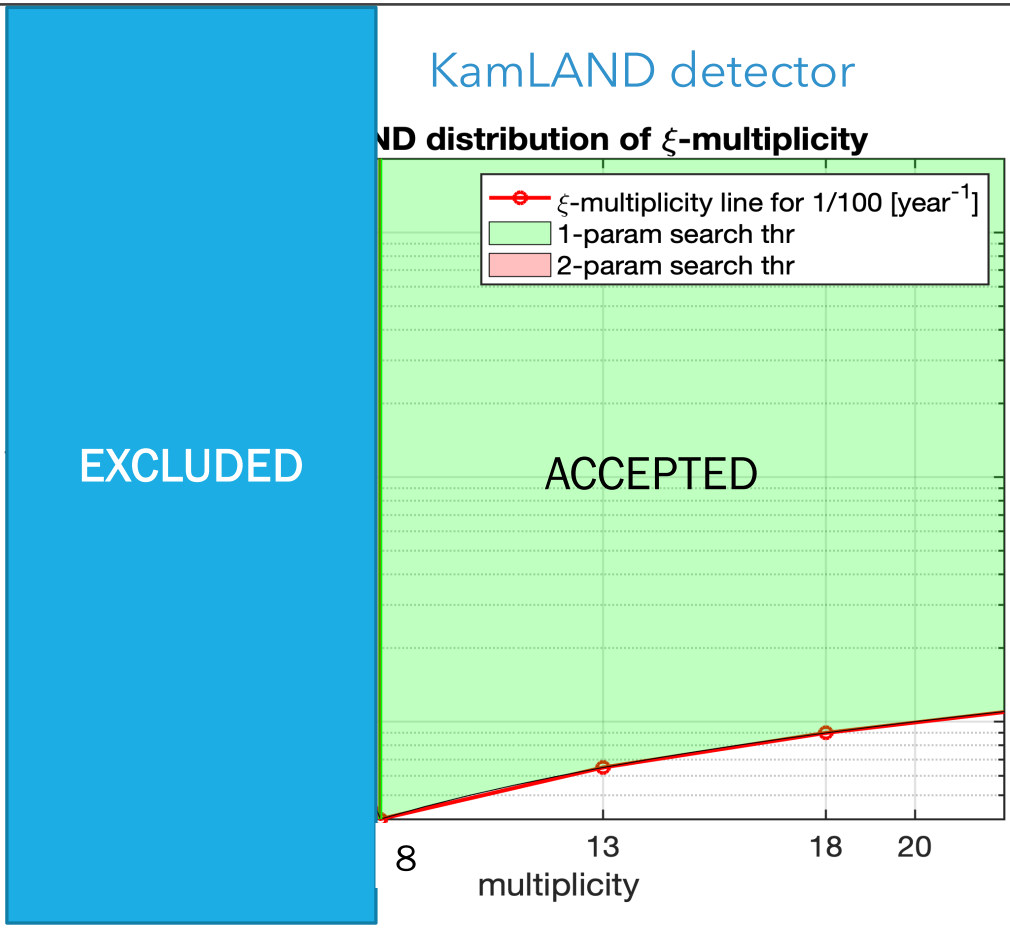
Casentini *et al.* JCAP 08(2018)010

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

a new parameter for LEN burst search

Results for single-LEN detector

KamLAND detector



Standard procedure

FAR threshold= 1/100yr

m=8

GREEN REGION OF THE PLANE

Results for single-LEN detector

KamLAND detector

New procedure

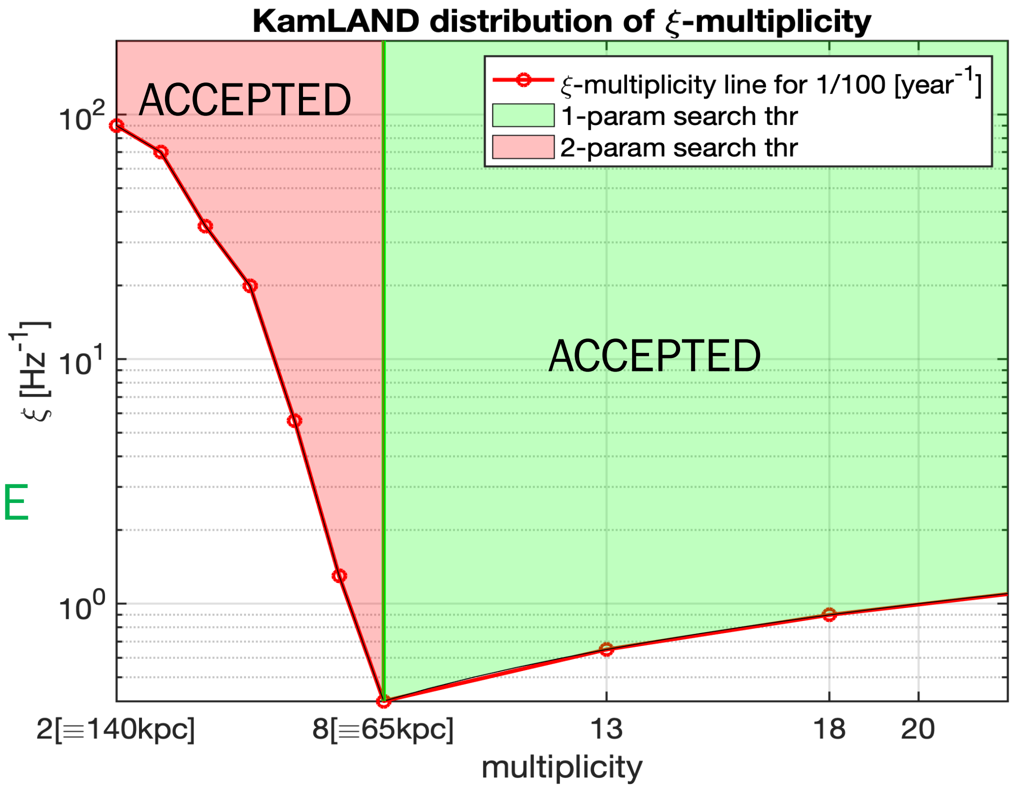
FAR threshold= 1/100yr

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

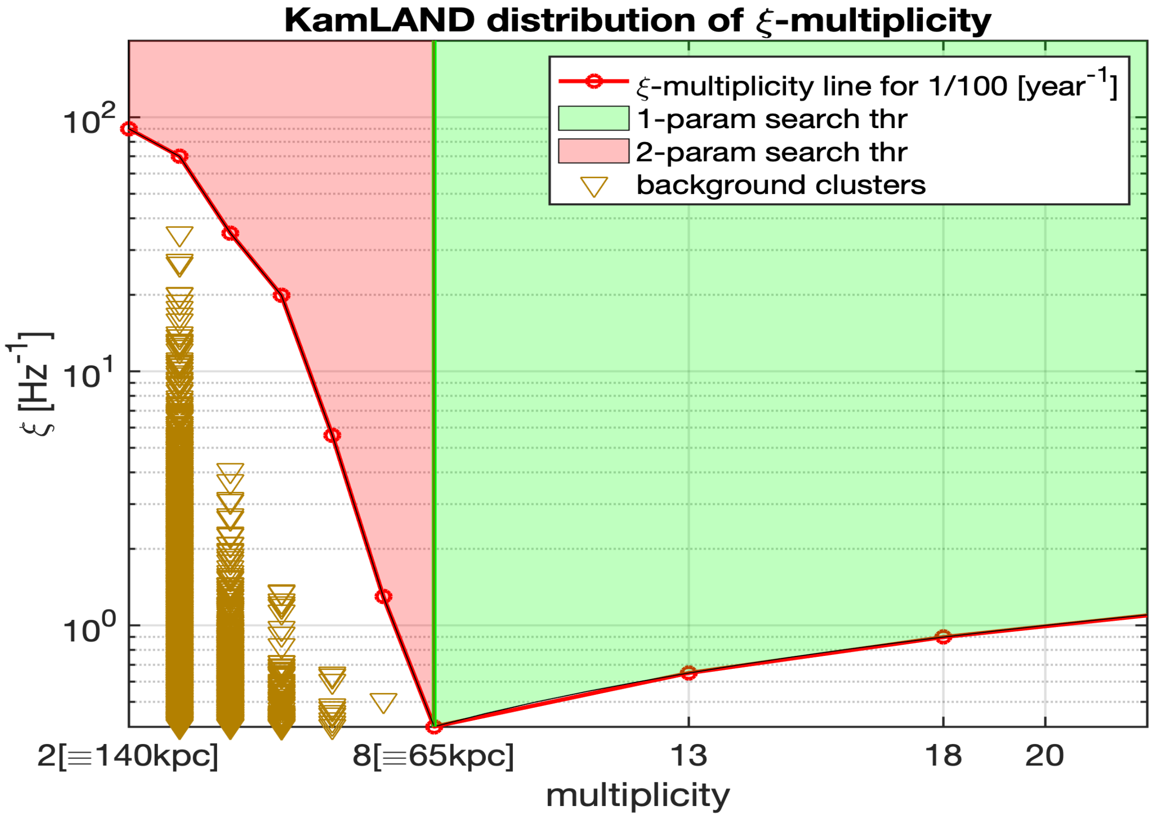
Results for single-LEN detector

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

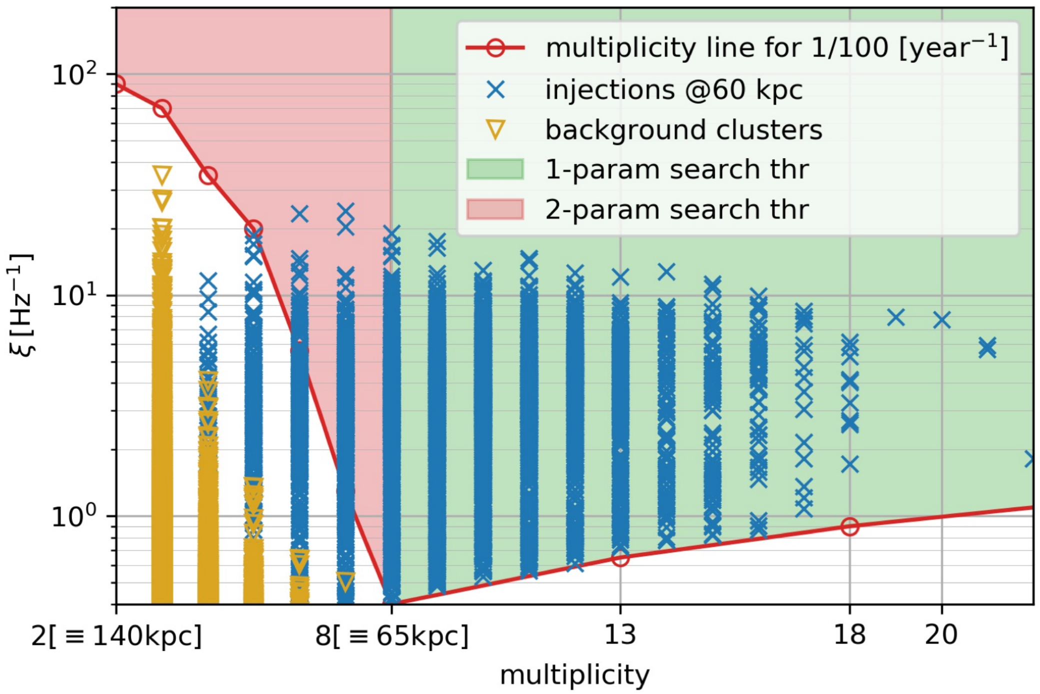


TABLE III: Efficiency (η) comparison between 1-parameter and 2-parameter method of single detector KamLAND 60-kpc for FAR$_\nu$ $< 1/100\,[\text{year}^{-1}]$ with SN1987A model.

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

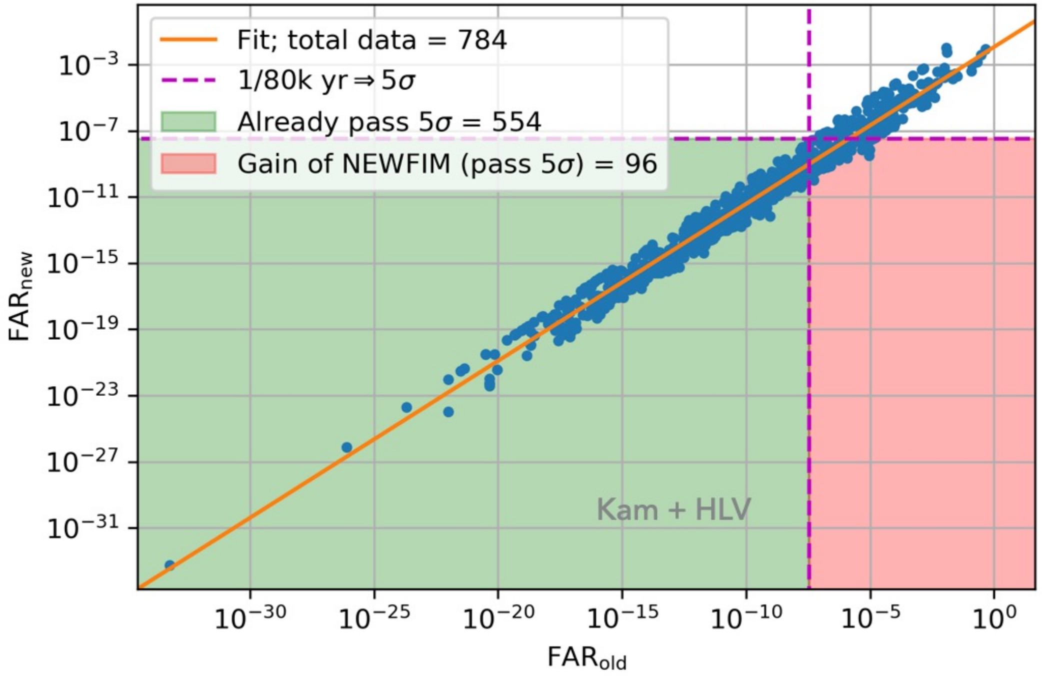
Take Home Message #1

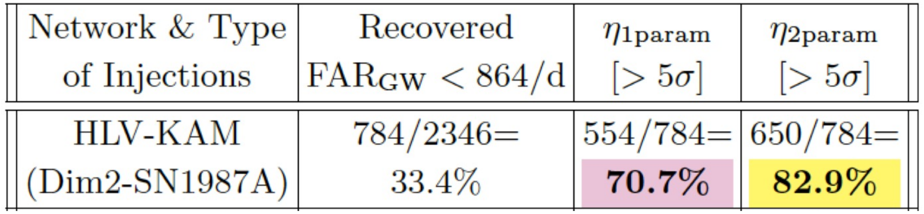
The use of the new parameter for LEN burst search increases the detection efficiency of 10% @ horizon

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

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} [> 5σ]	η_{2param} [> 5σ]
HLV-KAM (Dim2-SN1987A)	784/2346= 33.4%	554/784= **70.7%**	650/784= **82.9%**

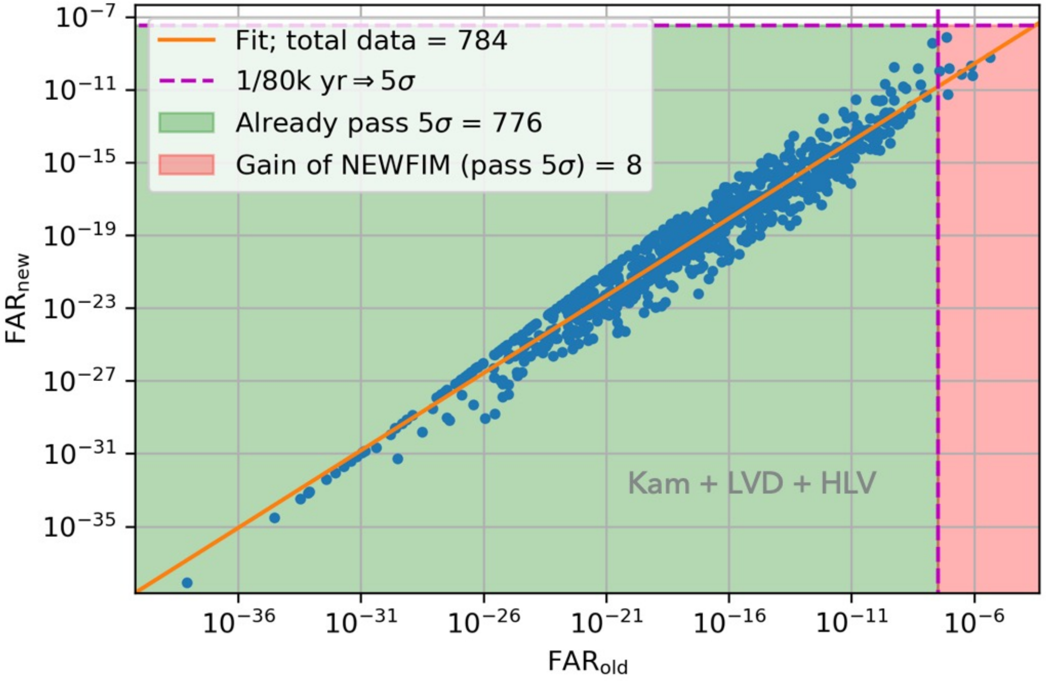
The ~33% GW-signals recovered are far to be statistically significant:
the 5σ detection efficiency is 0%.

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



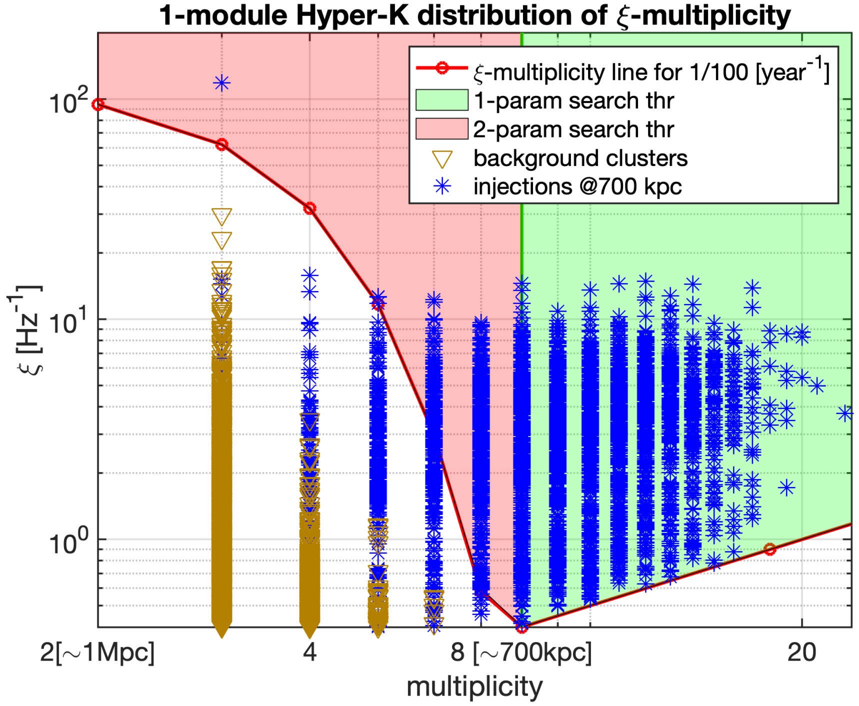
Network & Type of Injections	Recovered $FAR_{GW} < 864/d$	η_{1param} $[> 5\sigma]$	η_{2param} $[> 5\sigma]$
HLV-KAM (Dim2-SN1987A)	784/2346= 33.4%	554/784= **70.7%**	650/784= **82.9%**
HLV-KAM-LVD (Dim2-SN1987A)	784/2346= 33.4%	776/784= **99.0%**	784/784= **100%**

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%

3.3. Hyper-K single-detector analysis



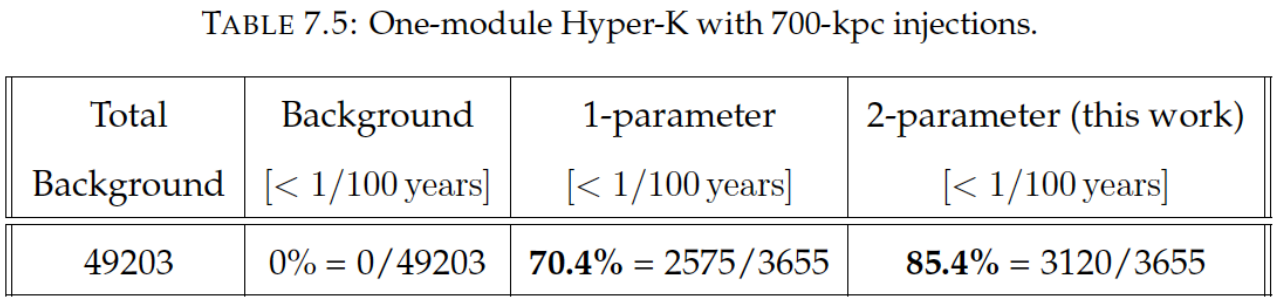


TABLE 7.5: One-module Hyper-K with 700-kpc injections.

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.

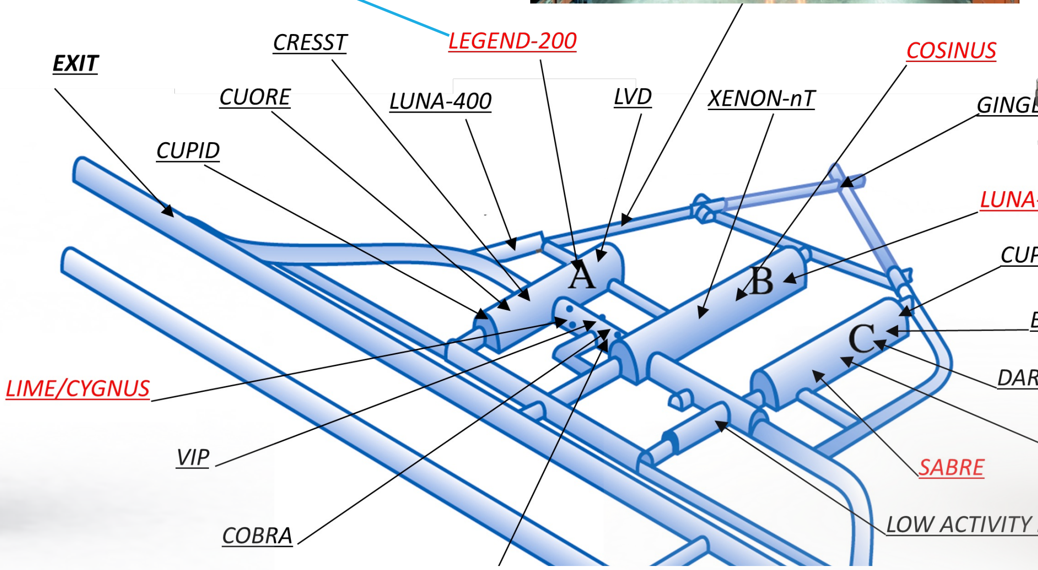
Before questions….

SN@LNGS

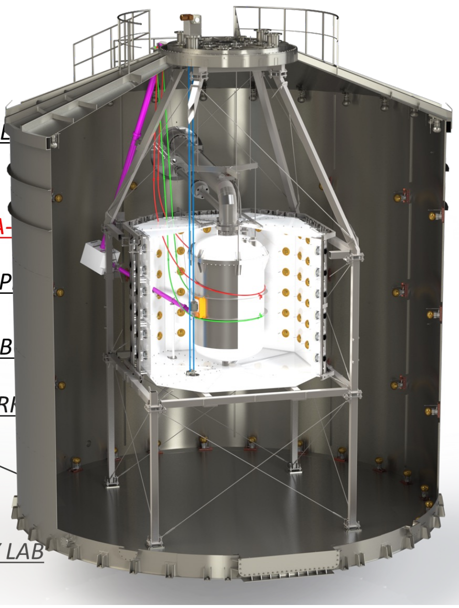
LVD (293 events)

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

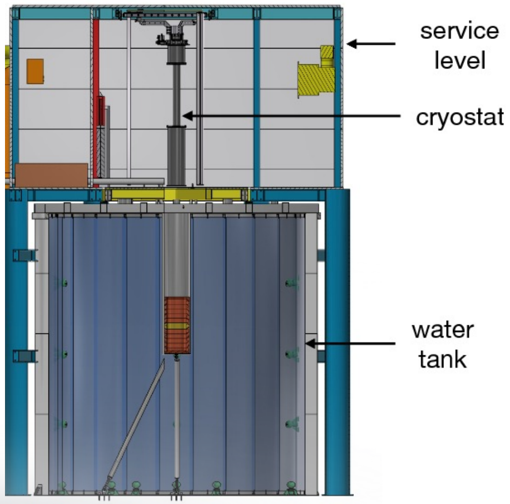
LEGEND-200



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.

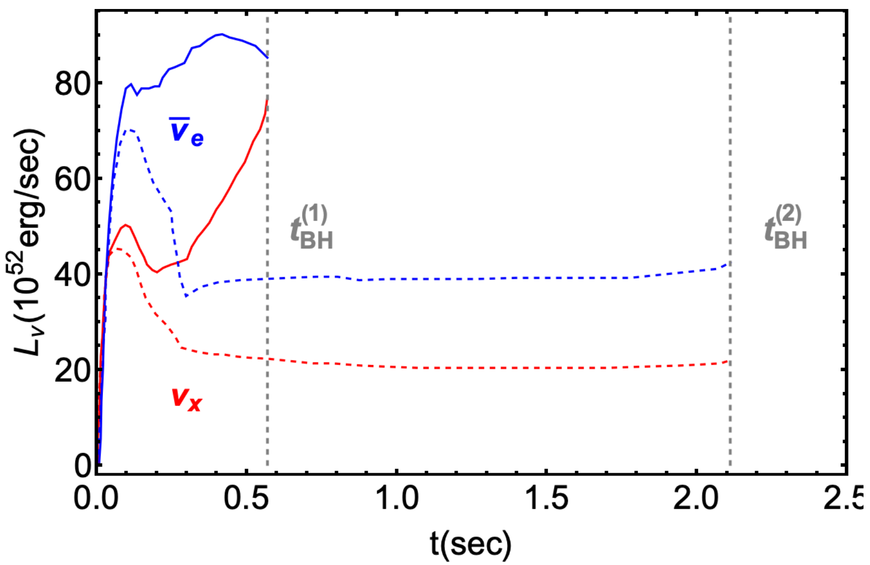
Failed Supernovae @ LNGS

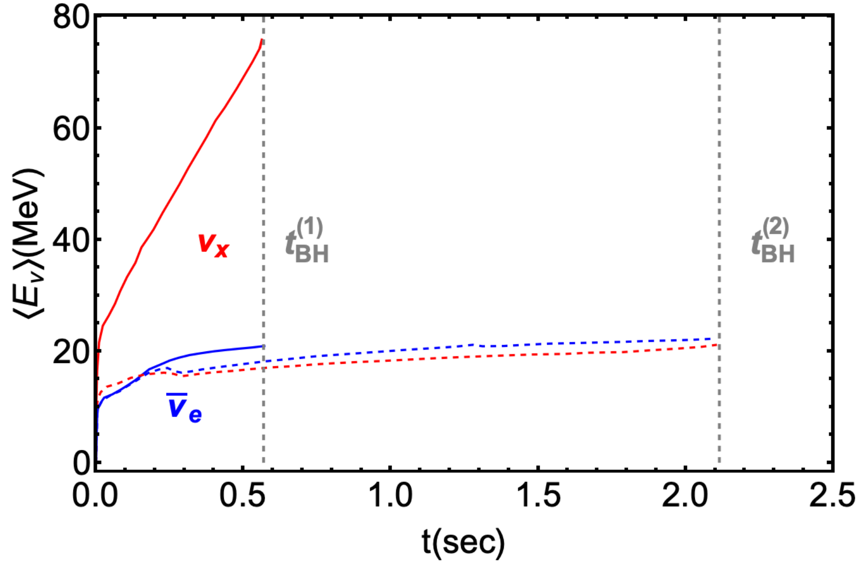
The neutrino and GW emissions end abruptly at the time of the Black Hole formation.

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

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



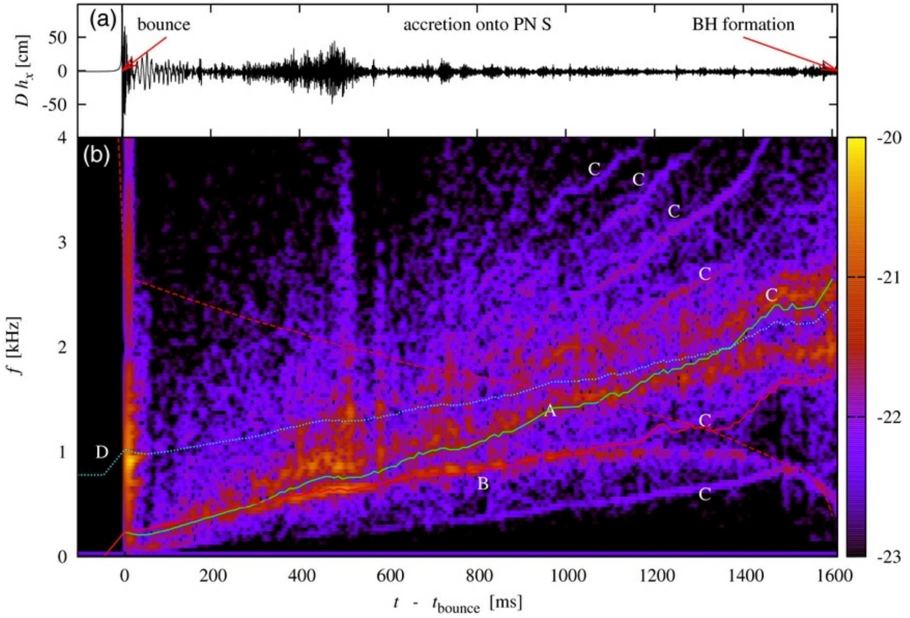


Model 1: Woosley and Weaver, Astrophys. J. Suppl. 101, 181 (1995)

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

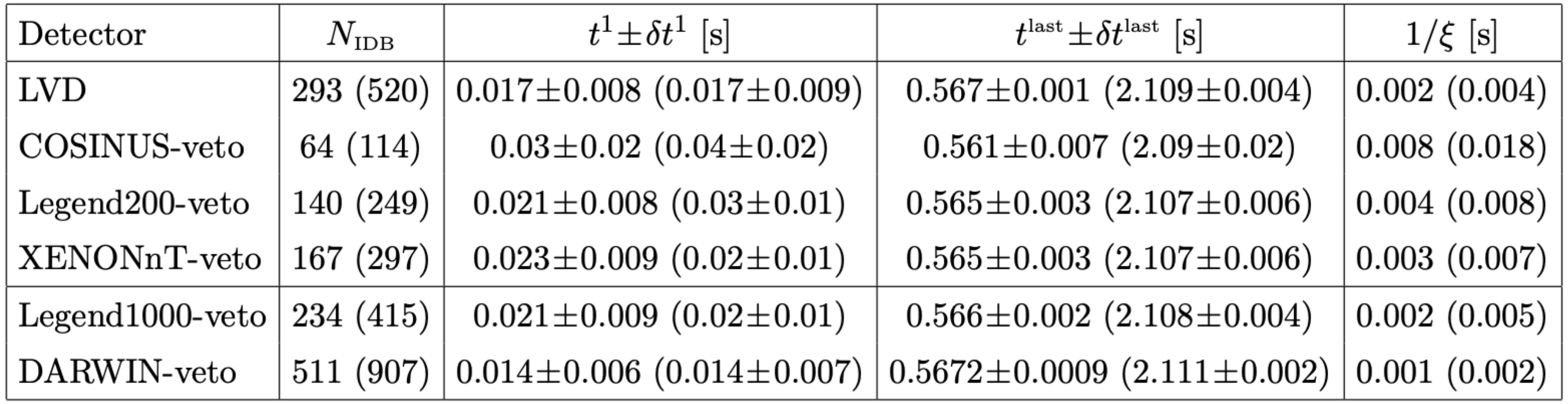


Pablo Cerdá-Durán *et al* 2013 *ApJL* **779** L18

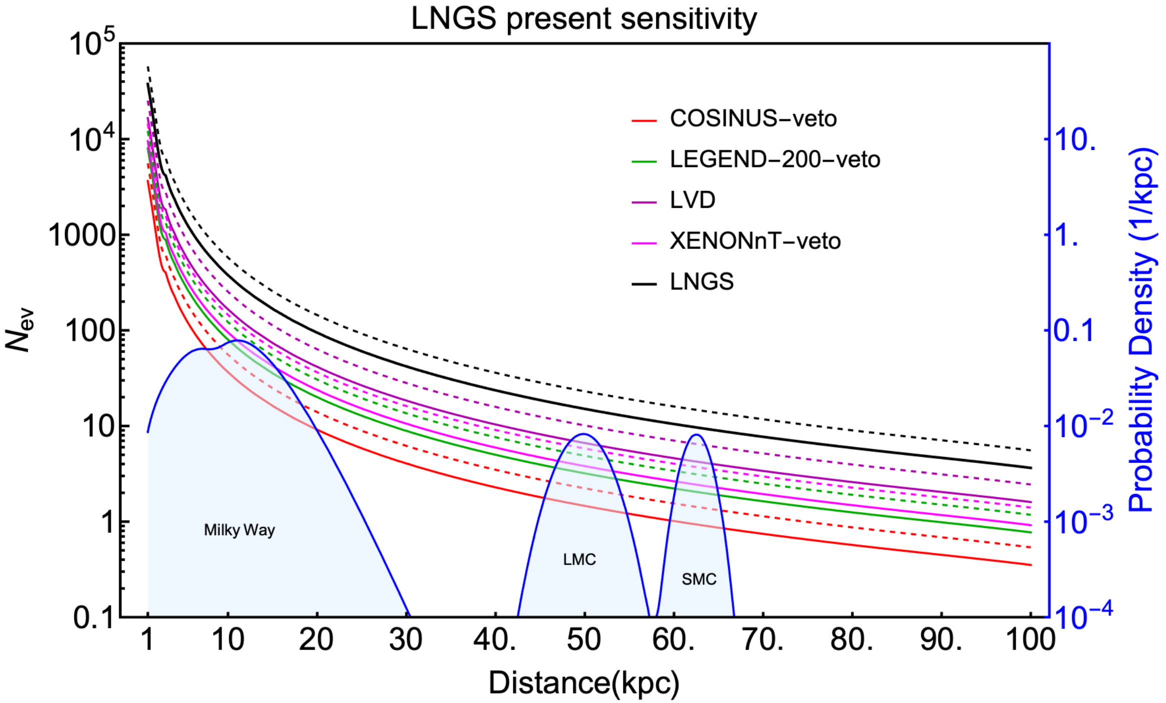
The Time of BH formation @ LNGS

Results for D=10 kpc

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



Detector	N_{IDB}	$t^1 \pm \delta t^1$ [s]	$t^{\text{last}} \pm \delta t^{\text{last}}$ [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)



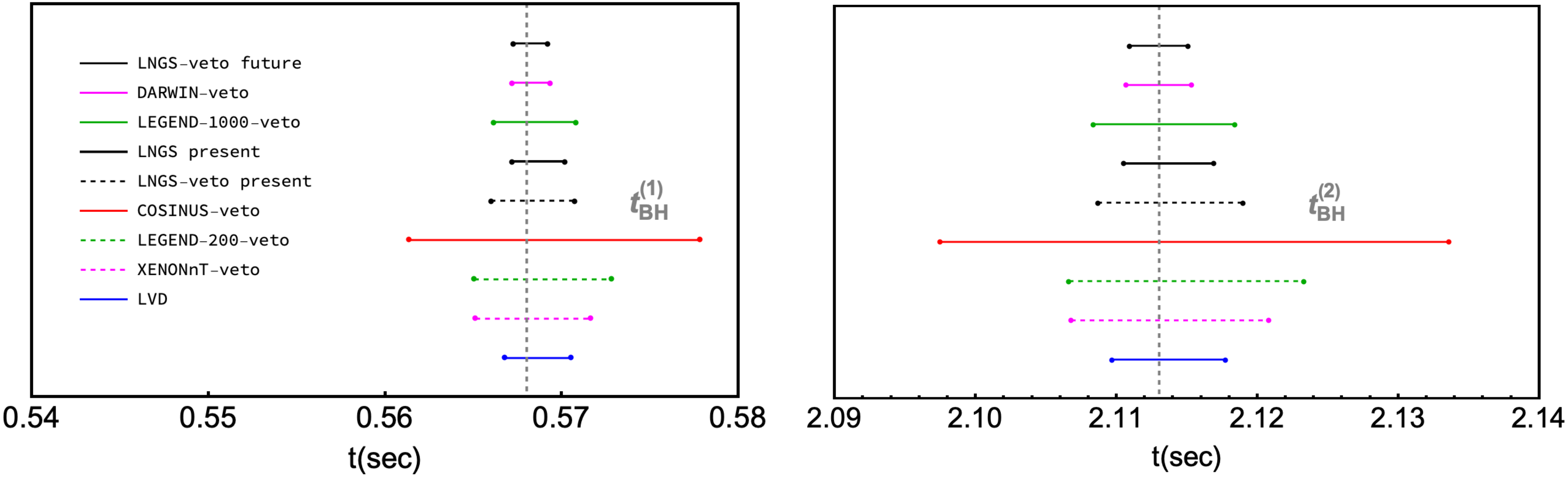
$$\xi = N_{\text{IBD}}/(t^{\text{last}} - t^1).$$

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

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

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

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

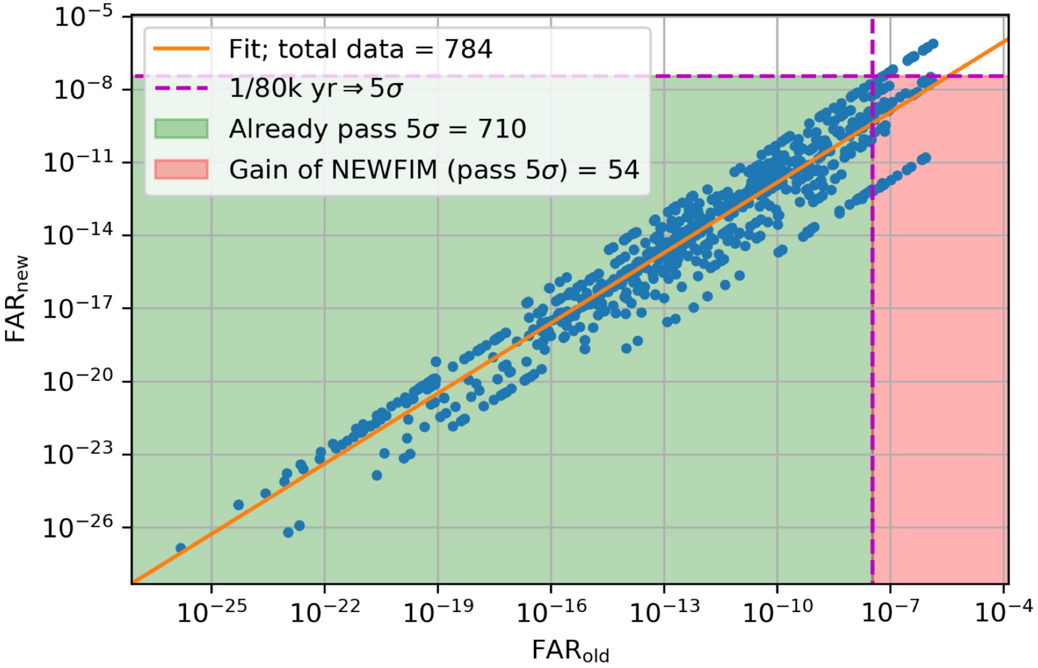
SK– VIRGO

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

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

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



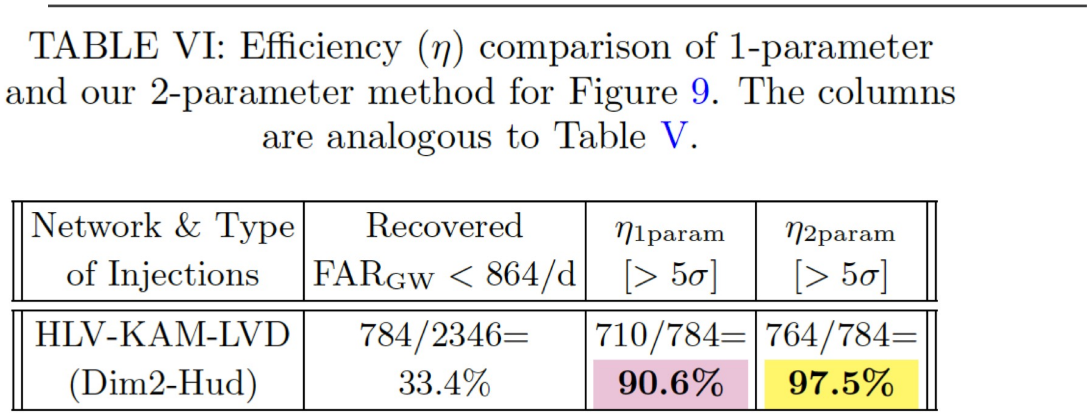


TABLE VI: Efficiency (η) comparison of 1-parameter and our 2-parameter method for Figure 9. The columns are analogous to Table V.

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%**

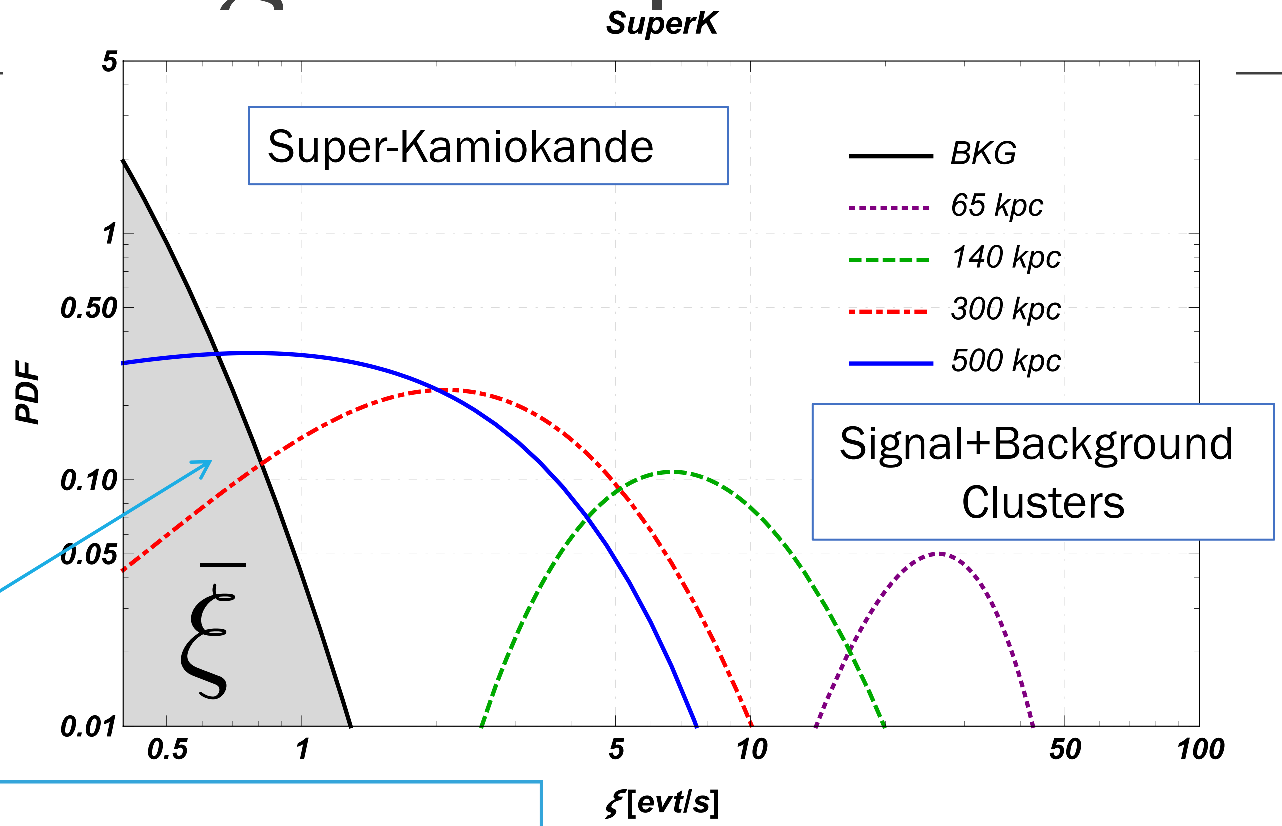
GW-LEN Det. efficiency with 1-param method: 33.4%*90.6% = 30.3%

GW-LEN Det. efficiency with 2-param method: 33.4%*97.5% = 32.6%

Background-Signal separation

Probability Density Functions (PDF)

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



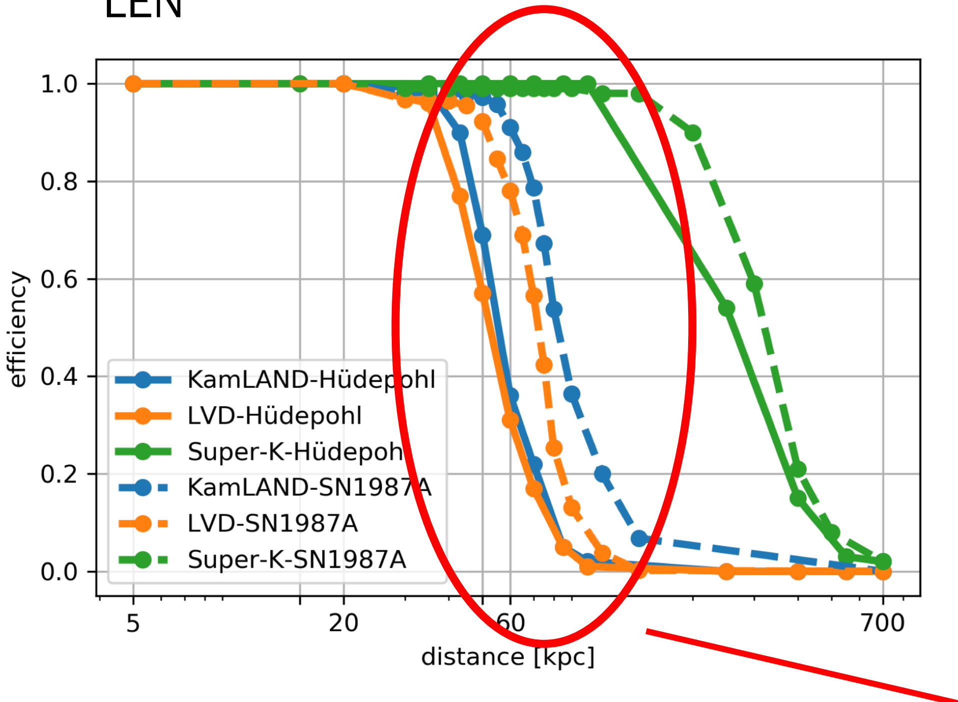
Signal+Background Clusters

Pure Background Clusters

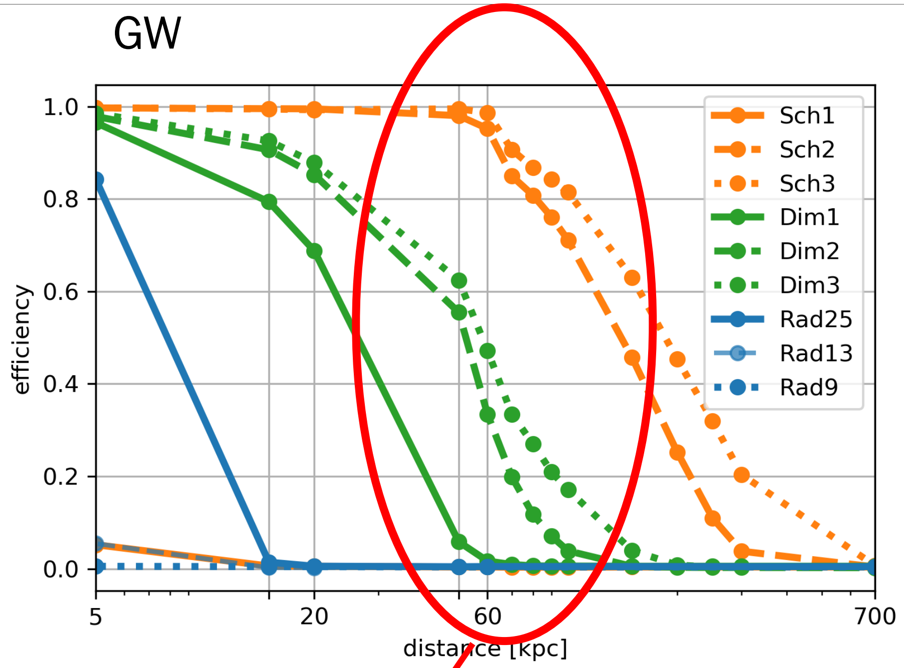
$$F_i^{\text{im}}(m_i, \xi_i) = N \times \sum_{k=m_i}^{\infty} P(k) \int_{\xi=\xi_i}^{\infty} \text{PDF}(\xi \geq \xi_i | k) d\xi.$$

Combined analysis LEN+GW

LEN



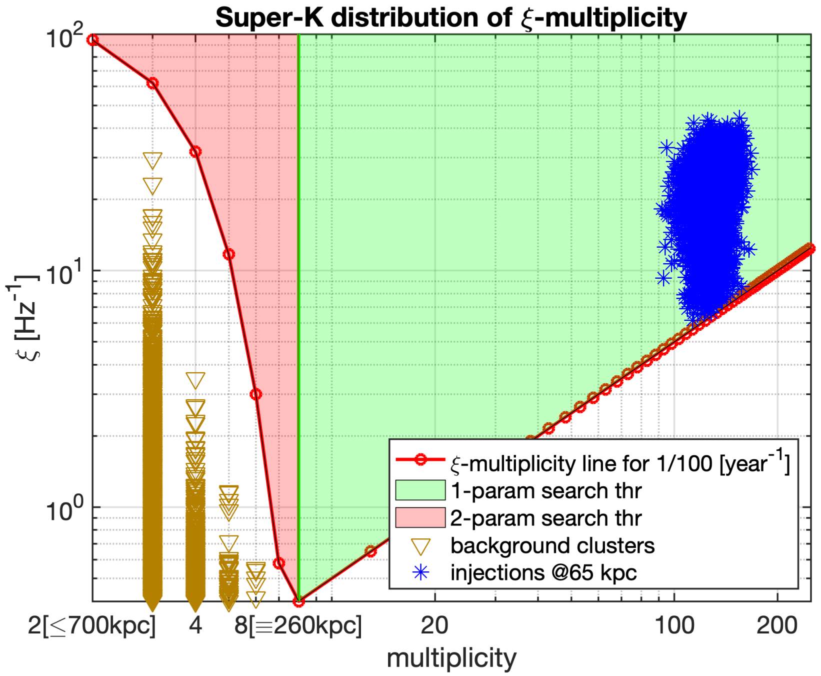
GW



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

D=60 kpc

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



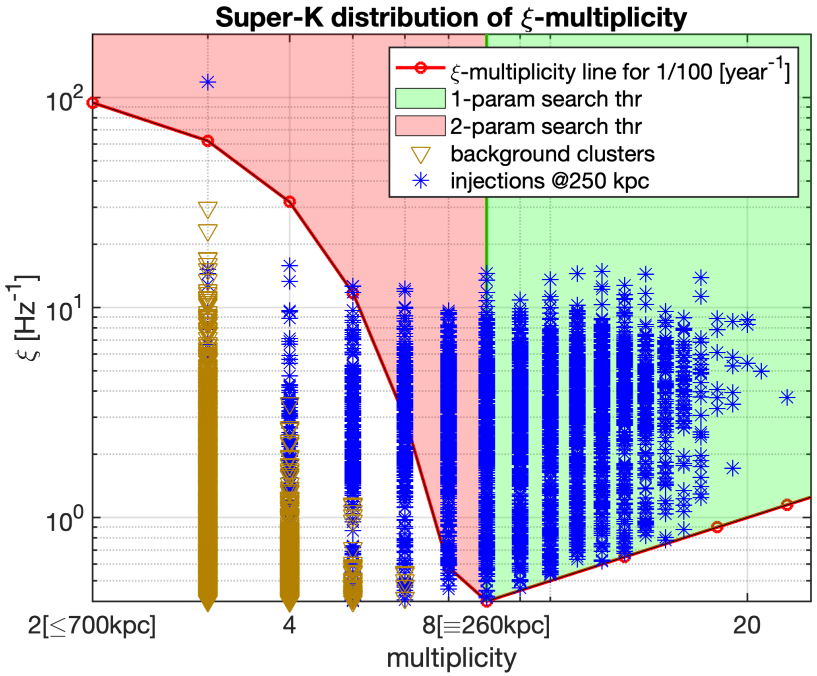
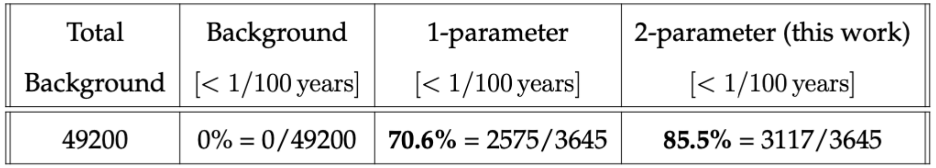


TABLE 7.3: Single detector SuperK analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.



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

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

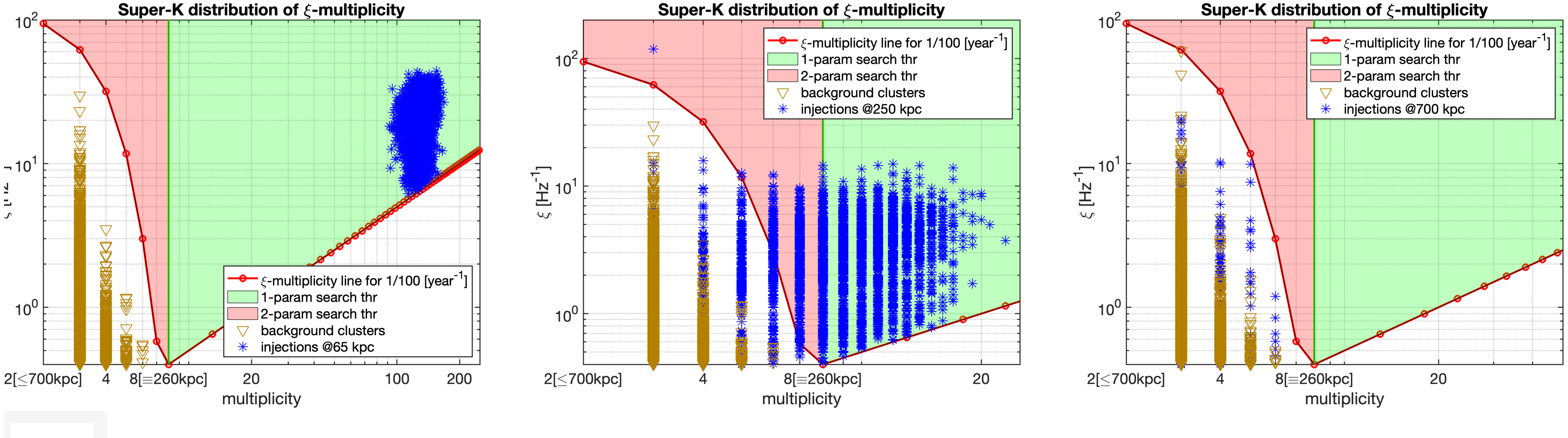
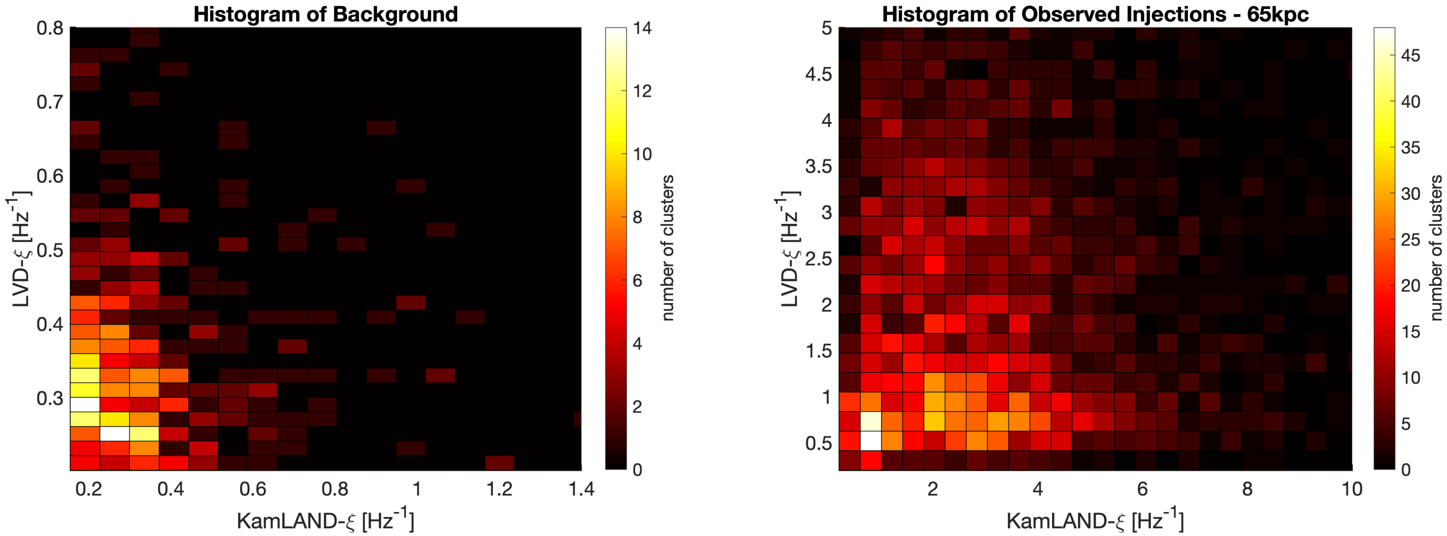


TABLE 7.3: Single detector Super-K analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

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.



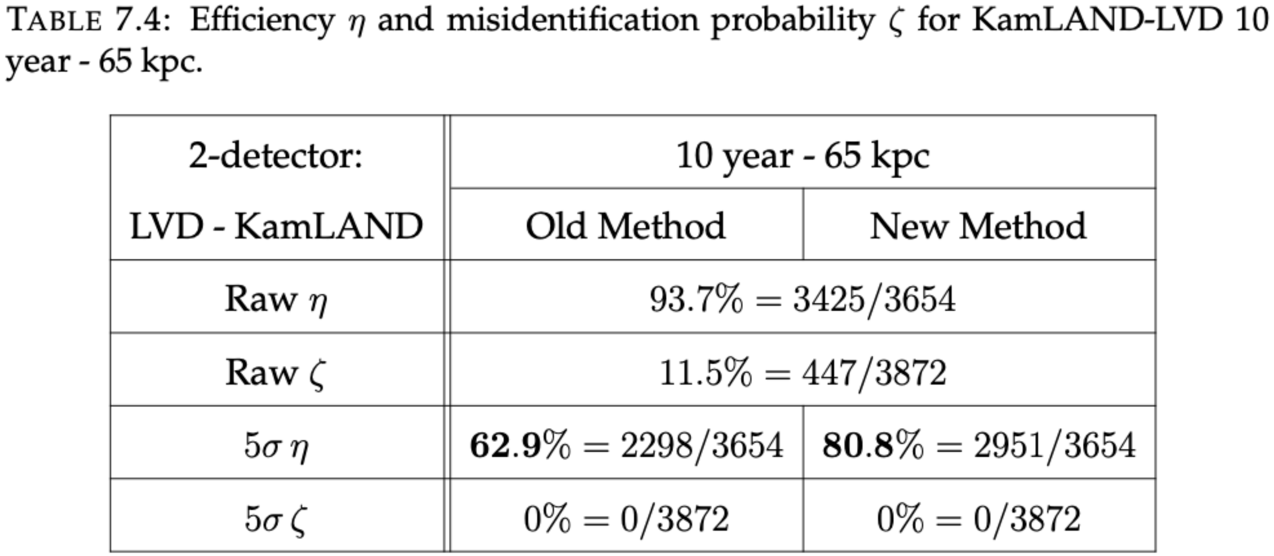


TABLE 7.4: Efficiency η and misidentification probability ζ for KamLAND-LVD 10 year - 65 kpc.

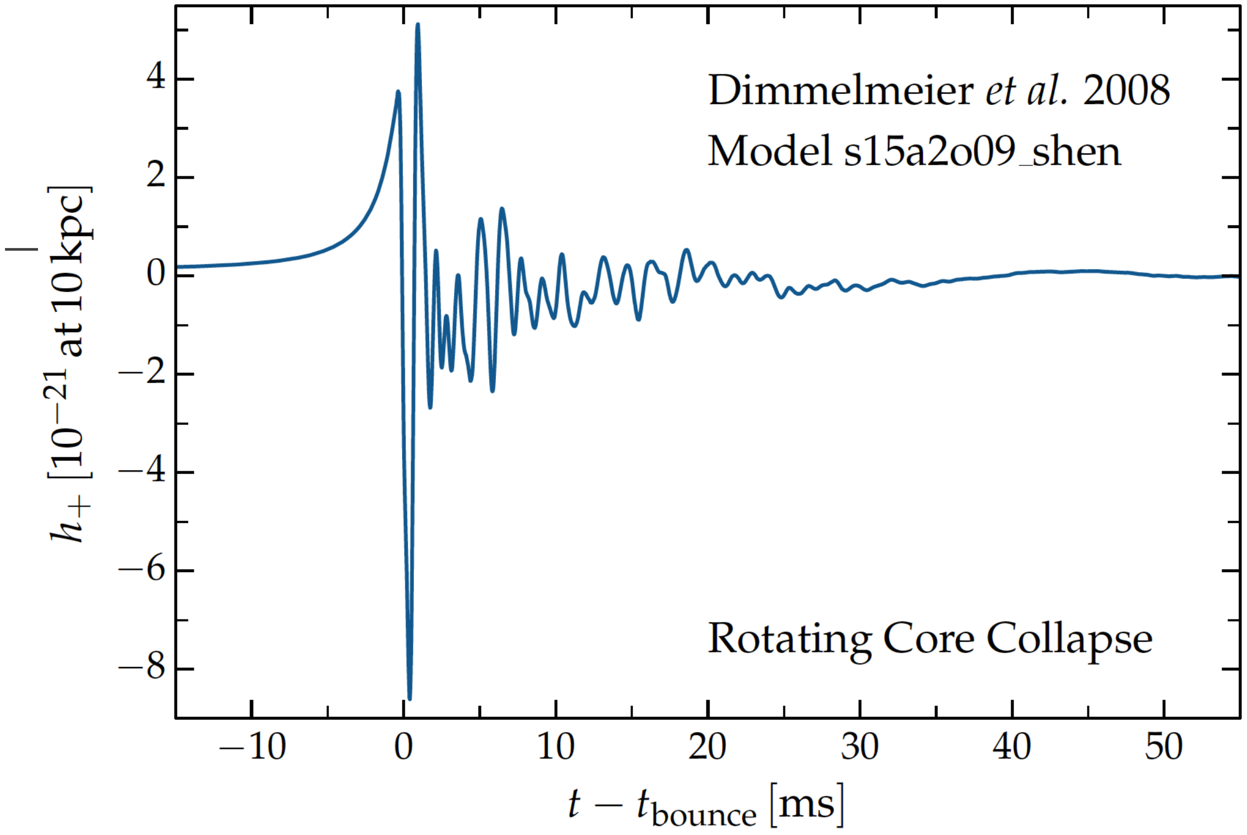
2-detector:	10 year - 65 kpc	
LVD - KamLAND	Old Method	New Method
Raw η	$93.7\% = 3425/3654$	
Raw ζ	$11.5\% = 447/3872$	
$5\sigma\ \eta$	$\mathbf{62.9}\% = 2298/3654$	$\mathbf{80.8}\% = 2951/3654$
$5\sigma\ \zeta$	$0\% = 0/3872$	$0\% = 0/3872$

GW signal

Magnetorotational Hydrodynamics,

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

- $p_{\rm prog} \sim 1\,{\rm s}; \quad p_{\rm remnant} \sim 1\,{\rm ms}$
- $E_{\rm rot} \sim 10^{52}\,{\rm erg}.$
- $h \sim 10^{-21} - 10^{-20}; \quad {\rm for}\, D \sim 10\,{\rm kpc}$
- $E_{\rm GW} \sim 10^{-10} - 10^{-8} M_{\odot} c^2$
- 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 searc 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)