Joint Analysis Method on Gravitational Waves and Low-Energy Neutrinos to Detect Core-Collapse Supernovae

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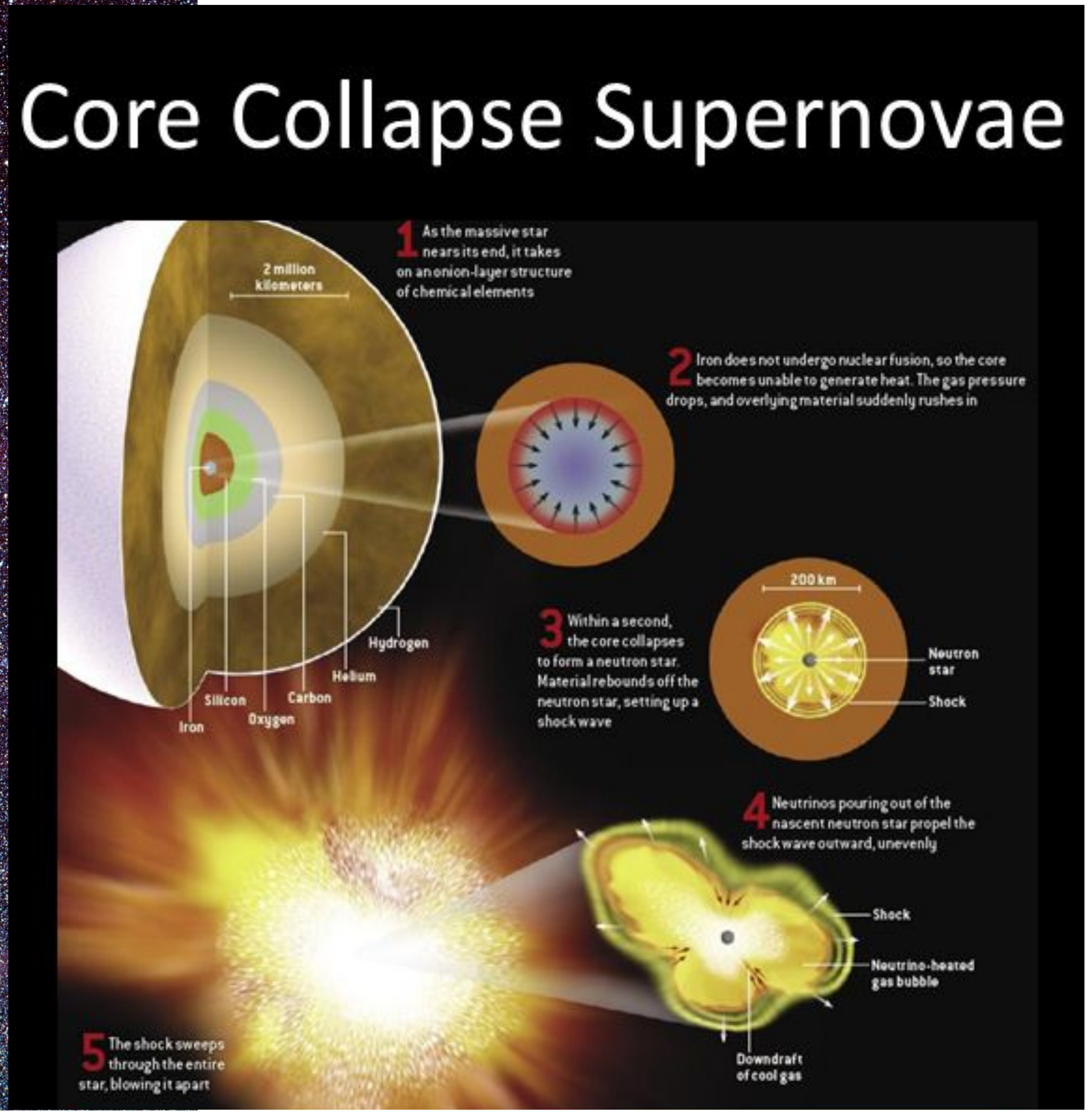
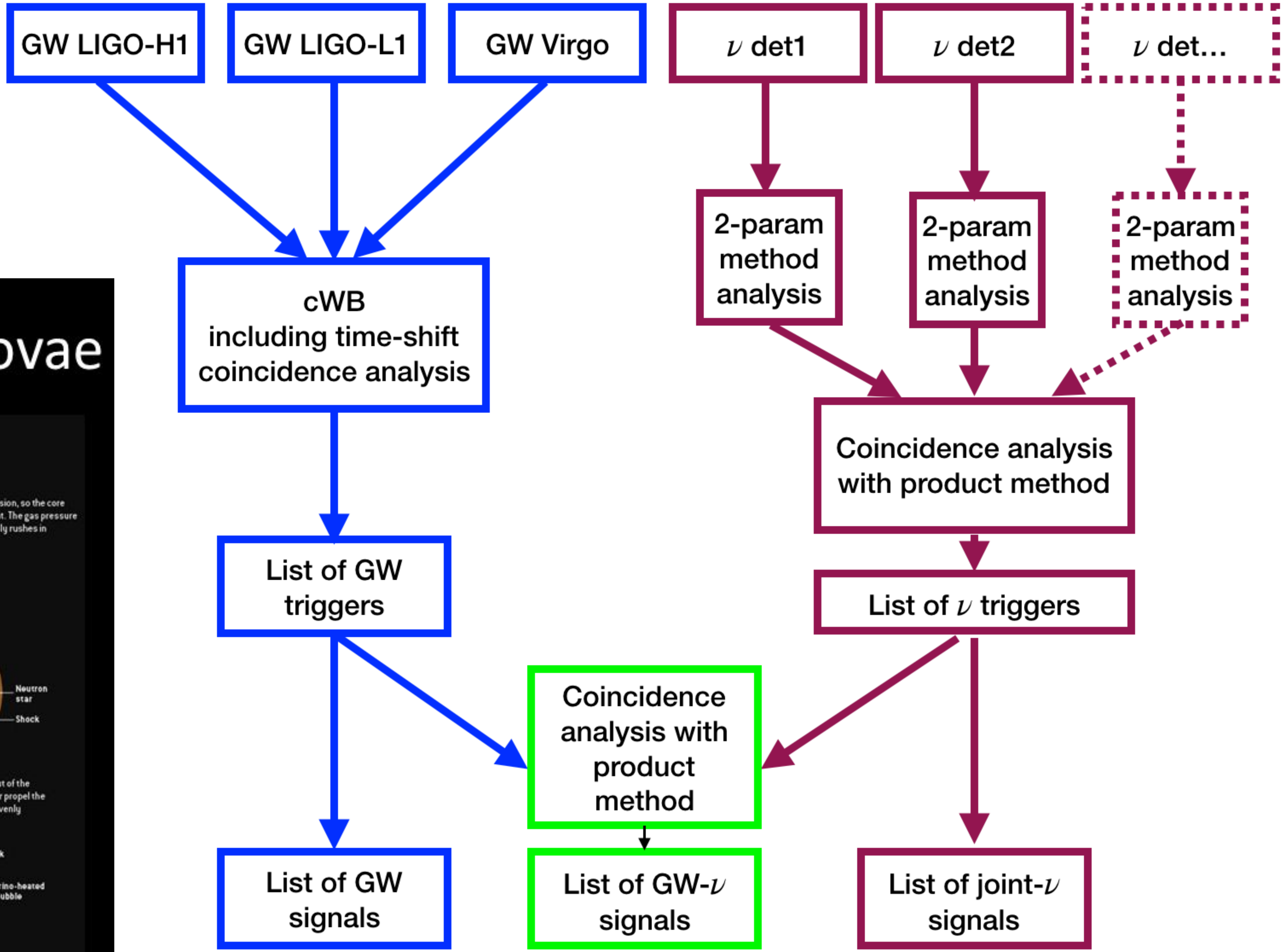
LAYOUT

- Goal and scheme
- Messengers and waveform models
- Data and analysis:
  - Gravitational waves
  - Low-energy neutrinos
  - Multimessenger analysis
- Results:
  - 1-detector neutrino
  - Sub-network of neutrino detectors
  - Global-network of multimessengers
- Conclusions

GOAL AND SCHEME

SN1987A. Credit: ESO





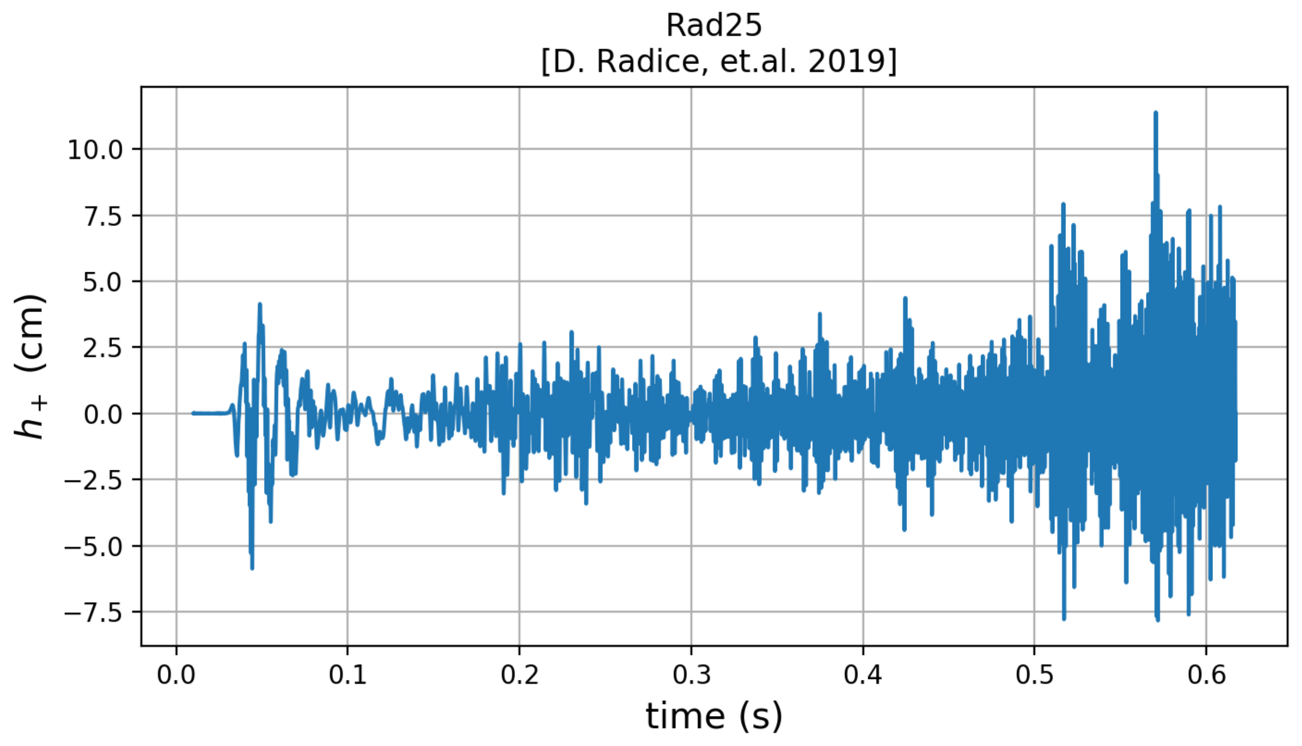
OH, et.al. arXiv:2107.02050

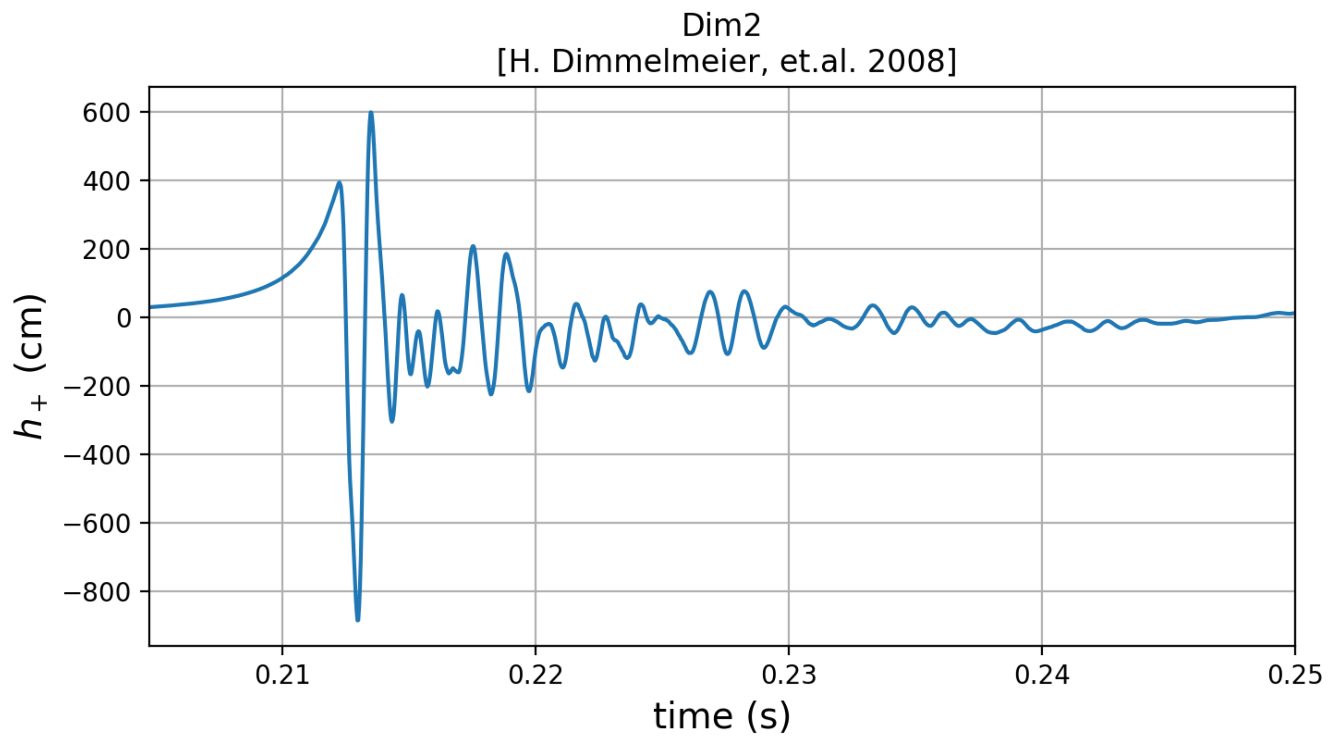
MESSENGERS AND WAVEFORM MODELS: GRAVITATIONAL WAVES

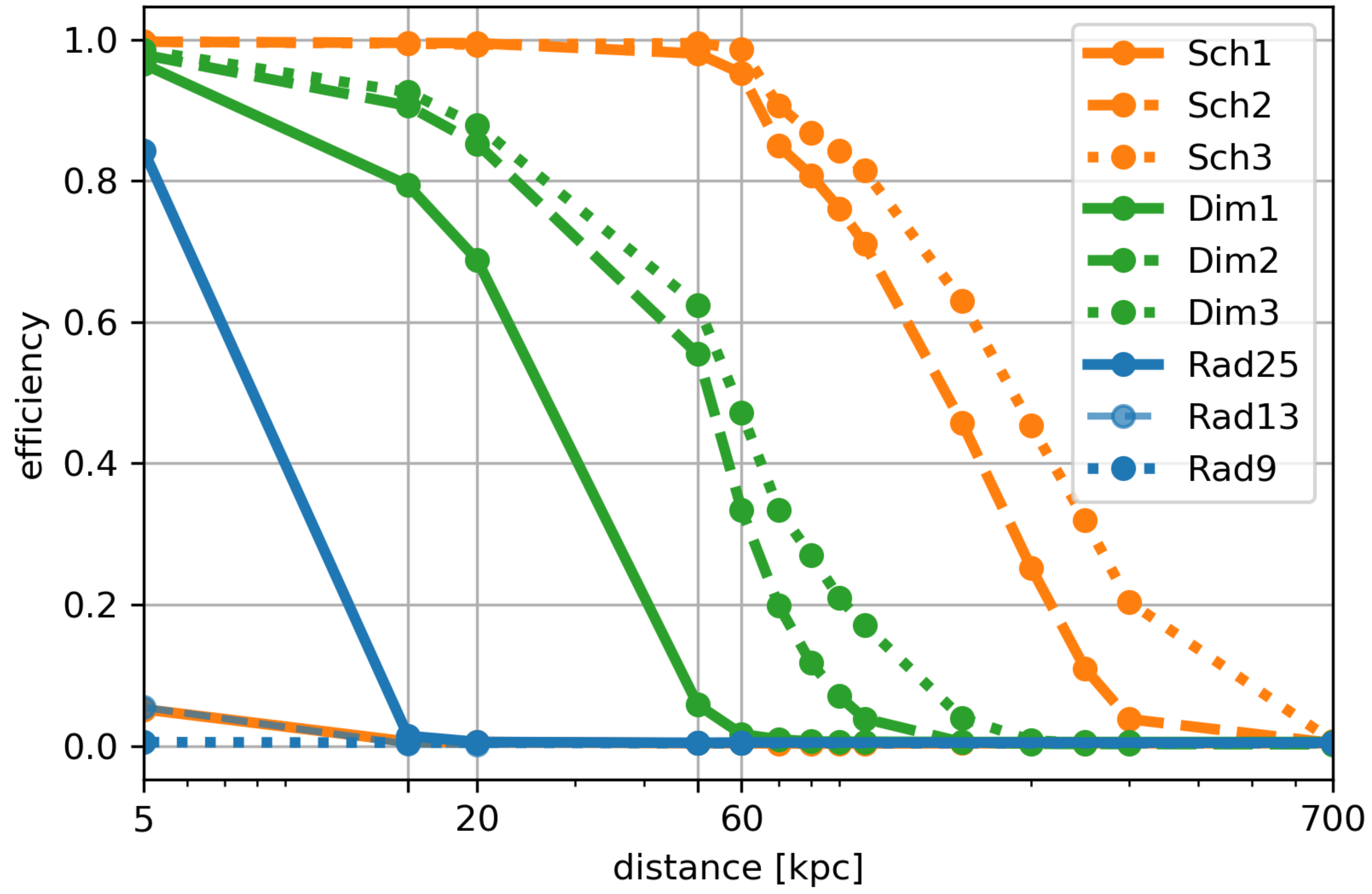
- Neutrino-radiation hydrodynamics (Rad) versus rapid rotation + magnetic field (Dim & Sch)

TABLE I: 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	Abbreviation	Mass $M_\odot$	h_{rss} @10 kpc $(10^{-22}\,1/\sqrt{\text{Hz}})$	f_{peak} [Hz]	E_{GW} $[10^{-9}\,M_\odot c^2]$
Radice [34] 3D simulation; h_+ and $h_\times$ (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 [35] 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 [36] 3D simulation; h_+ and $h_\times$ (Sch)	sch1-R1E1CA$_L$	Sch1	15	0.129	1155	0.1509
	sch2-R3E1AC$_L$	Sch2	15	5.144	466	0.02249
	sch3-R4E1FC$_L$	Sch3	15	5.796	698	0.04023





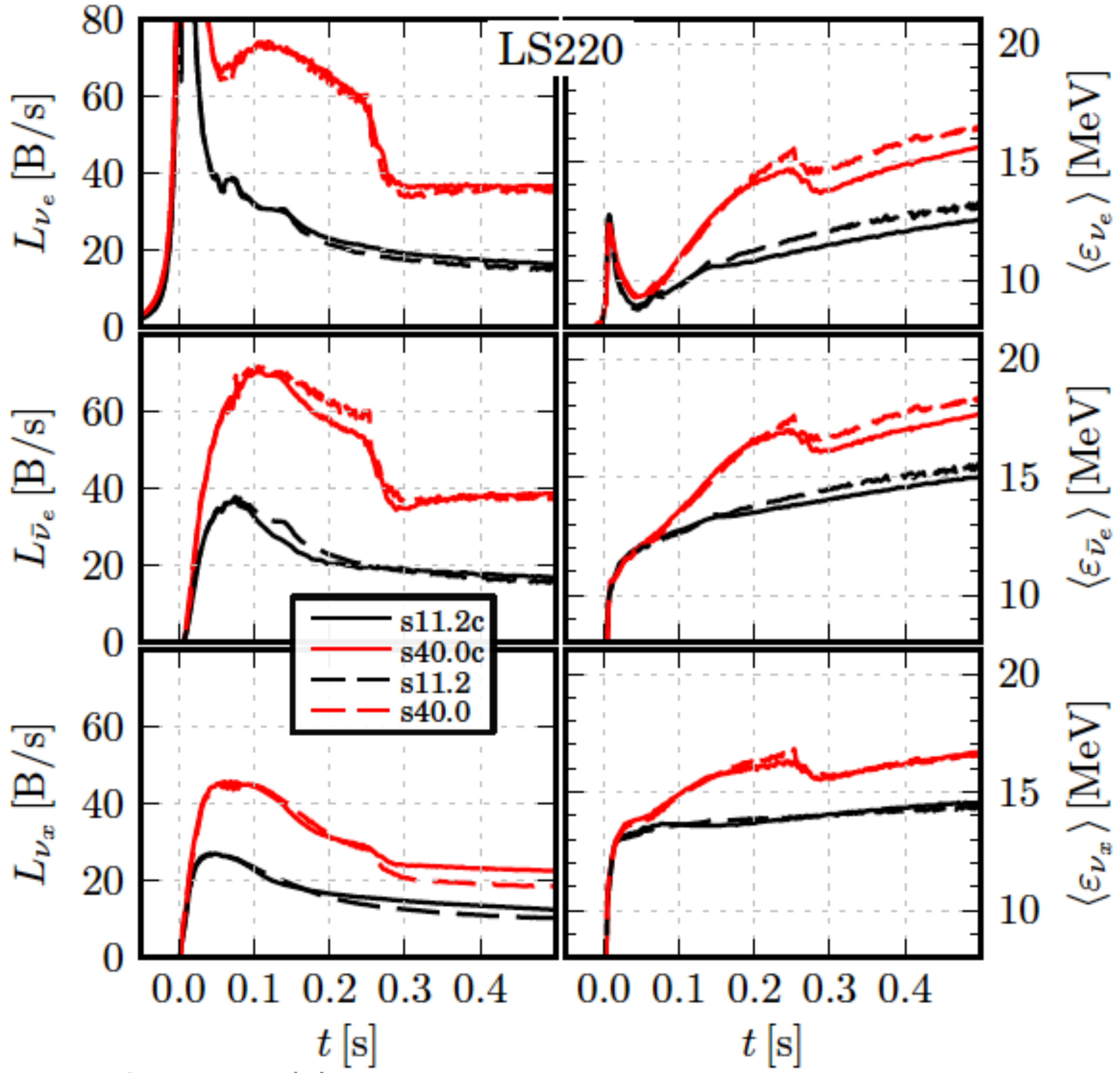


OH, et.al. arXiv:2107.02050

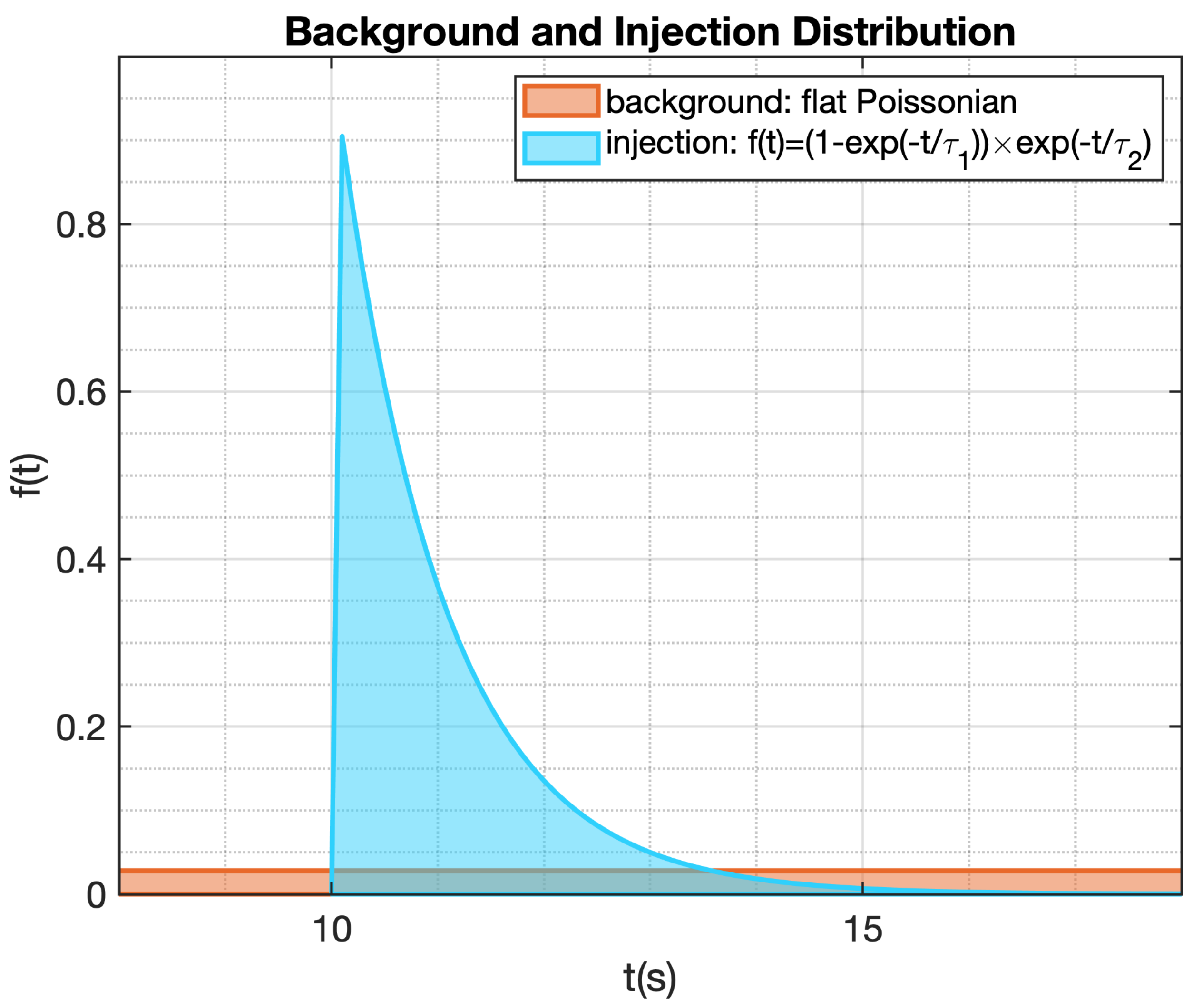
MESSENGERS AND WAVEFORM MODELS: LOW-ENERGY NEUTRINOS

TABLE II: Neutrino models and the expected number of events in the considered detectors (Super-K [4], LVD [5], and KamLAND [6]) with the assumed energy threshold ($E_{\rm thr}$).

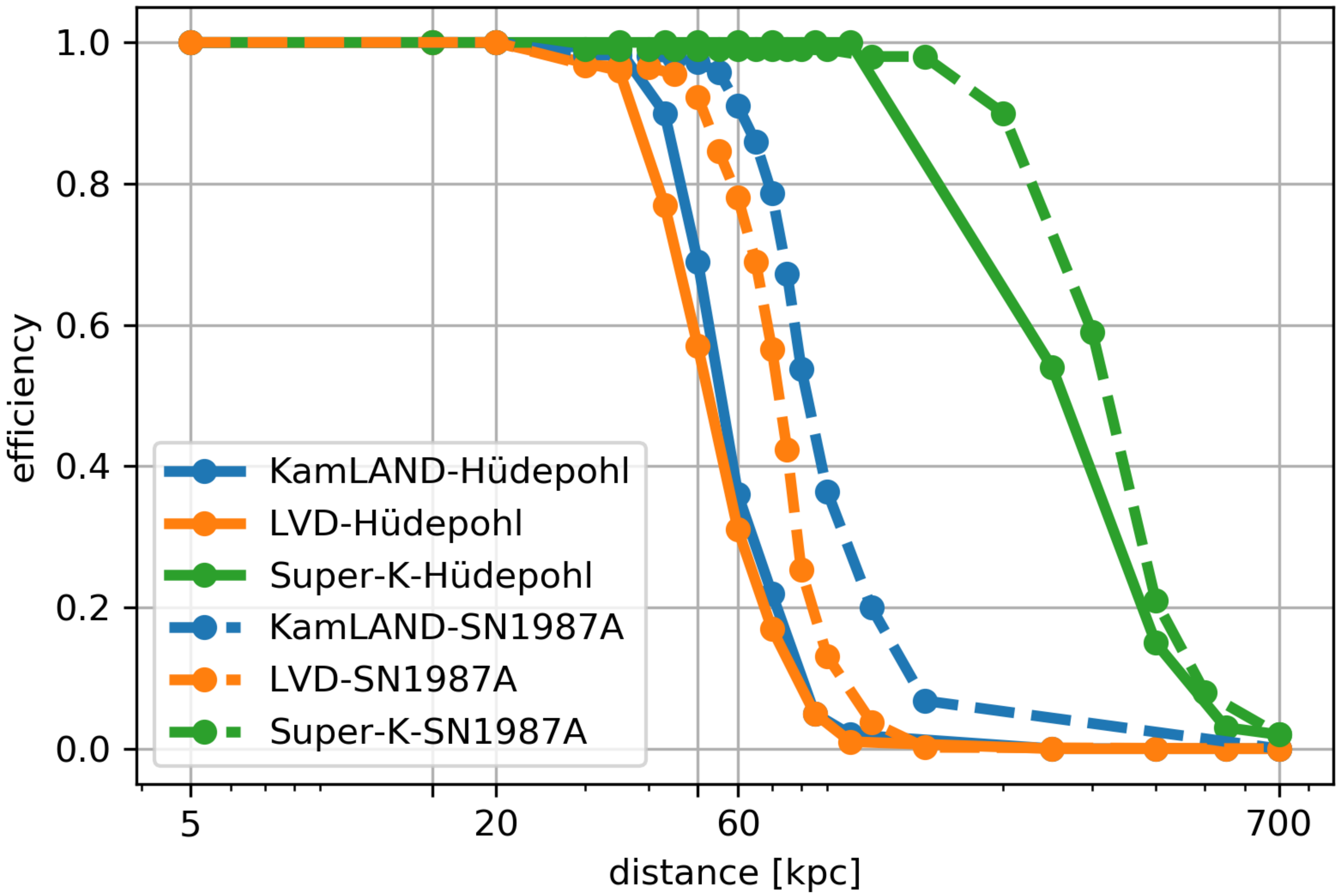
Model (identifier)	Progenitor Mass	Super-K ($E_{\rm thr}$ = 6.5 MeV)	LVD($E_{\rm thr}$ = 7 MeV)	Kamland($E_{\rm thr}$ = 1 MeV)
Pagliaroli [39] (SN1987A)	25 $M_\odot$	4120	224	255
Hüdepohl [38] (Hud)	11.2 $M_\odot$	2620	142	154



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



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



OH, et.al. arXiv:2107.02050

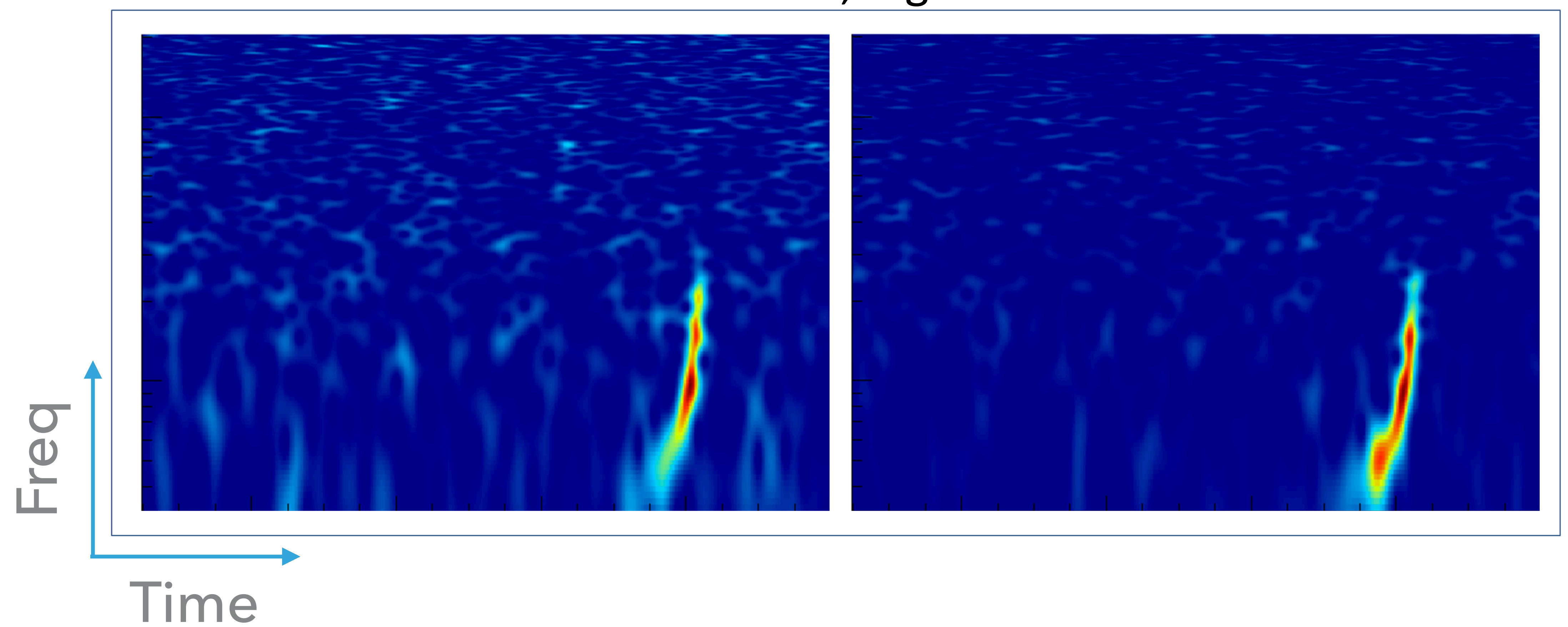
DATA AND ANALYSIS: GRAVITATIONAL WAVES

- cWB pipeline: burst unmodelled search, no need to have any templates
- Finding coherent excess energy among detectors (Virgo, LIGO Hanford, LIGO Livingston)
- Maximum likelihood to identify GW candidates and their parameters (time, freq, amplitude, etc)
- First GW event (GW150914) **online detection by cWB**.
- Time-frequency analysis: time series data to time-frequency map.
- Using fast Wilson-Daubechies time-frequency transform combined with the Meyer wavelet (**WDM**)

gwburst.gitlab.io

Left: LL; Right: LH

Necula, V, et.al. 2012. 10.1088

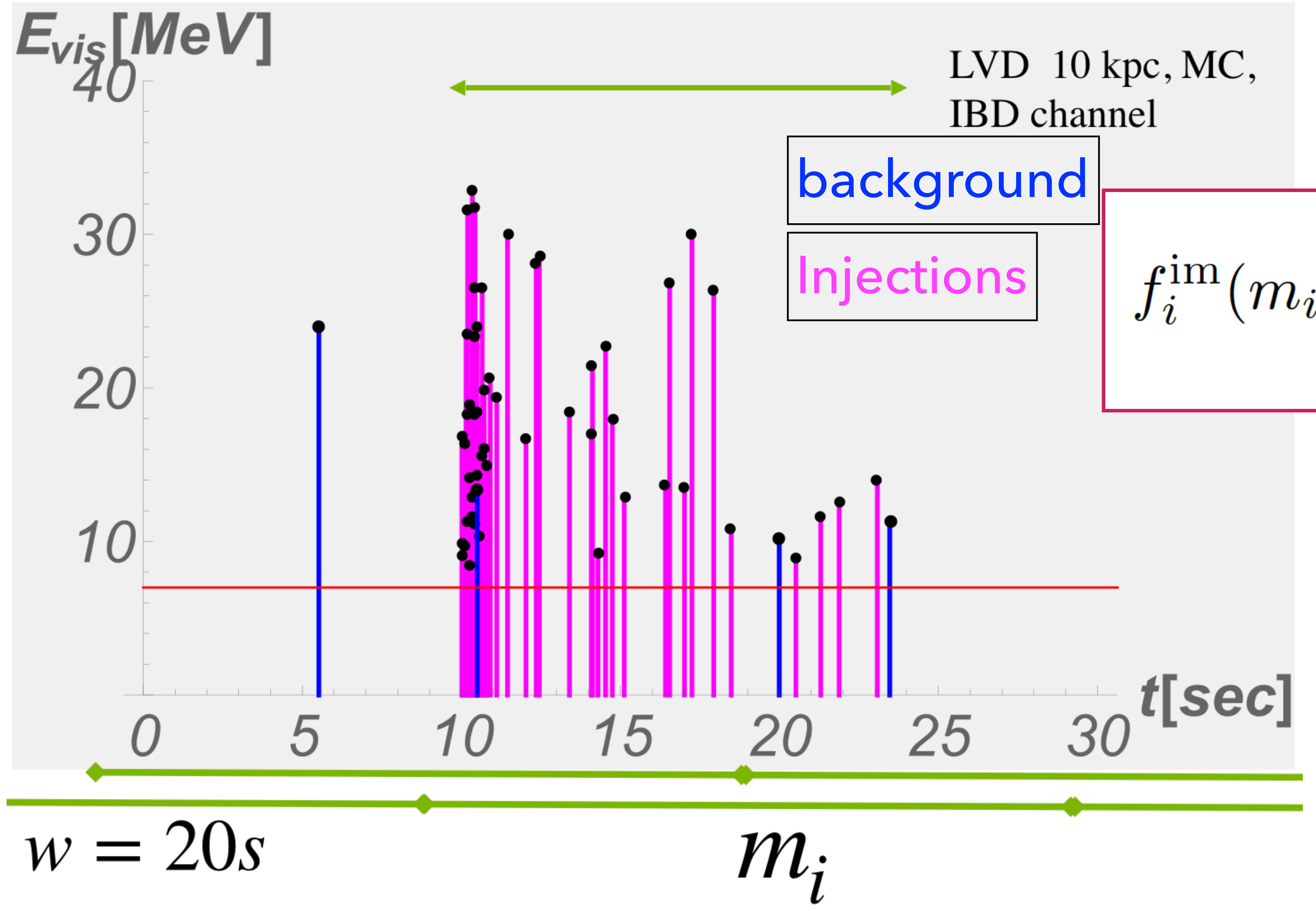


DATA AND ANALYSIS: LOW-ENERGY NEUTRINOS (STANDARD METHOD)

- Standard parameter: the **number** of events in a bin, ***multiplicity*** $\equiv m_i$

Poisson PDF:

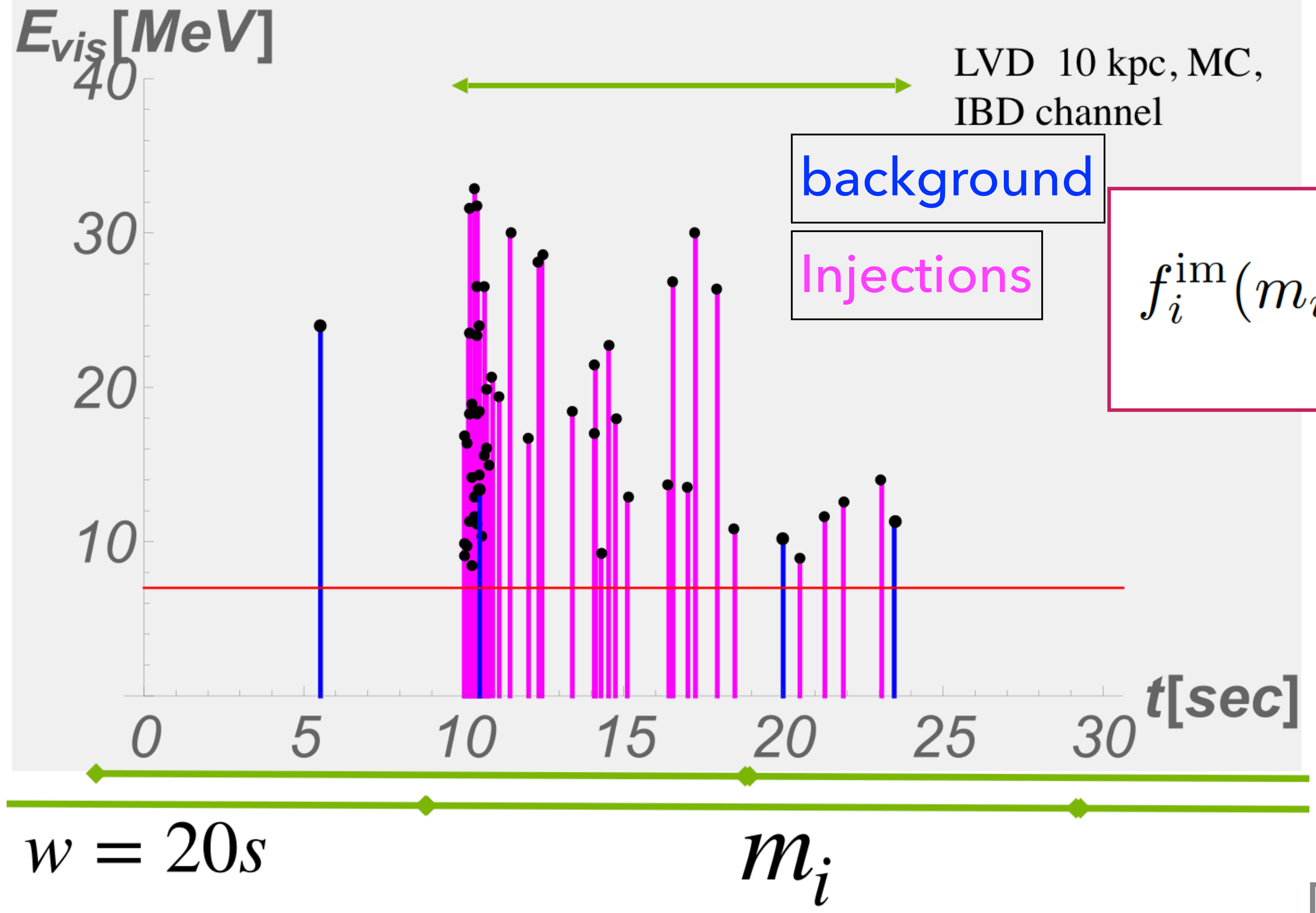
$$P(k) = \frac{(f_{\rm bkg} w)^k e^{-f_{\rm bkg} w}}{k!},$$



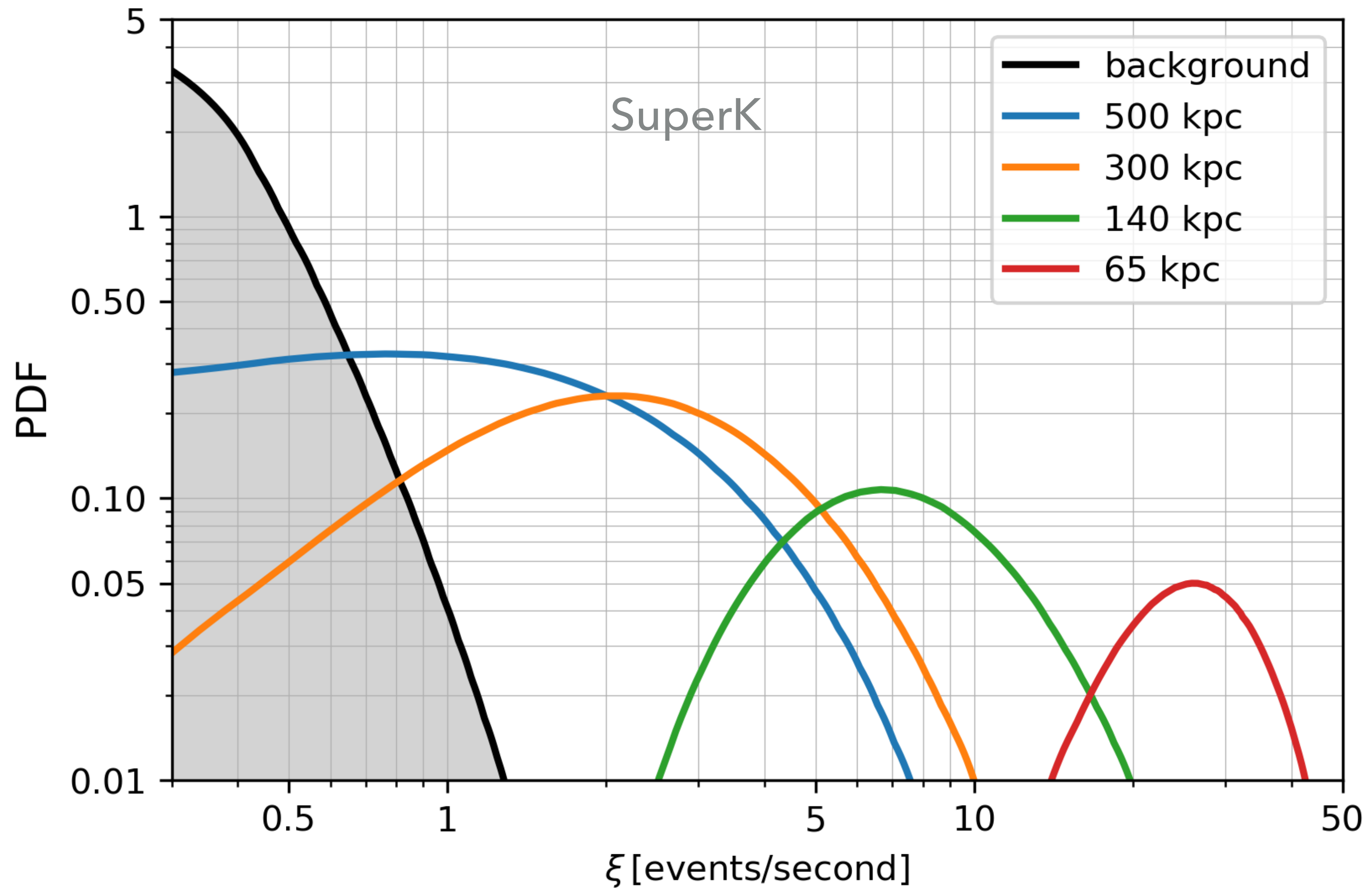
$$f_i^{\rm im}(m_i) = N \times \sum_{k=m_i}^{\infty} P(k),$$

DATA AND ANALYSIS: LOW-ENERGY NEUTRINOS (OUR METHOD)

- Standard parameter: the **number** of events in a bin, ***multiplicity*** $\equiv m_i$
- A new parameter: behaviour of events (how close or well separated) in a bin, $\xi_i \equiv m_i/\Delta t_i$
  - Δt_i is the **duration**



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



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

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

Detailed formula: OH, PhD thesis, Gran Sasso Science Institute (2020)

DATA AND ANALYSIS: MULTIMESSENGER

- Single-detector neutrino threshold: 1/100 year in FAR
- Coincidence analysis threshold: 5σ (5.7×10^{-7}) in FAP

$$\mathrm{FAR}_{\nu} = \mathrm{Nd} \times w_{\nu}^{\mathrm{Nd}-1} \prod_{i=1}^{\mathrm{Nd}} F_i^{\mathrm{im}},$$

↓

$$\mathrm{FAR}_{\mathrm{glob}} = \mathrm{Net} \times w_c^{\mathrm{Net}-1} \prod_{X=1}^{\mathrm{Net}} \mathrm{FAR}_X,$$

↓

$$\mathrm{FAP} = 1 - e^{-\mathrm{FAR} \times \mathrm{livetime}},$$

OH, et.al. [arXiv:2107.02050]

RESULTS: 1-DETECTOR NEUTRINO

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

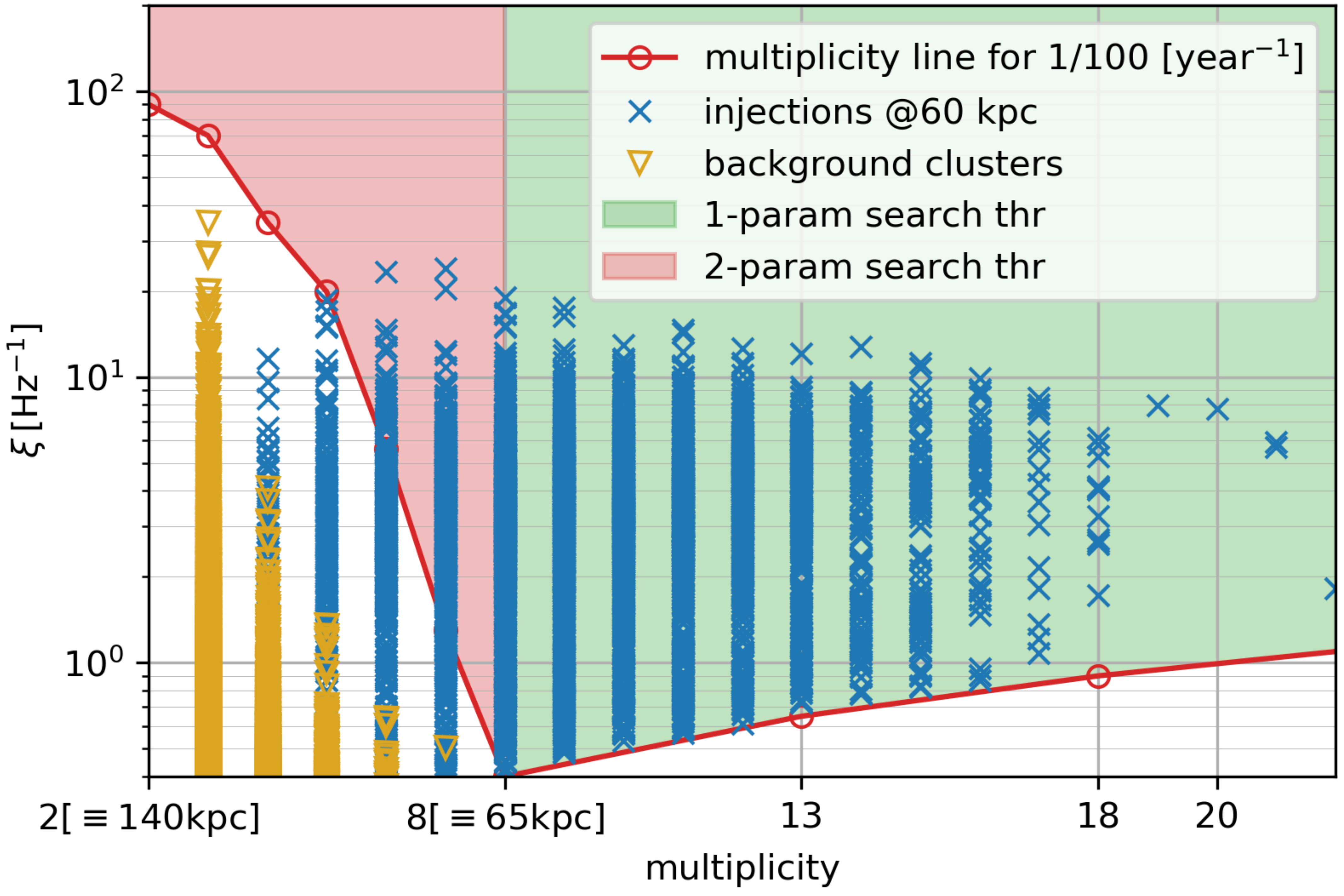


TABLE III: Efficiency (η) comparison between 1-parameter and 2-parameter method of single detector KamLAND 60-kpc for FAR$_\nu$ < 1/100 [year^{-1}] with SN1987A model.

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

OH, et.al. arXiv:2107.02050

RESULTS: SUB-NETWORK OF NEUTRINO DETECTORS

- Hüdepohl-signal model [5, 15, 20, 50, 60]-kpc injections, KamLAND+LVD detector model, 5σ-FAP threshold

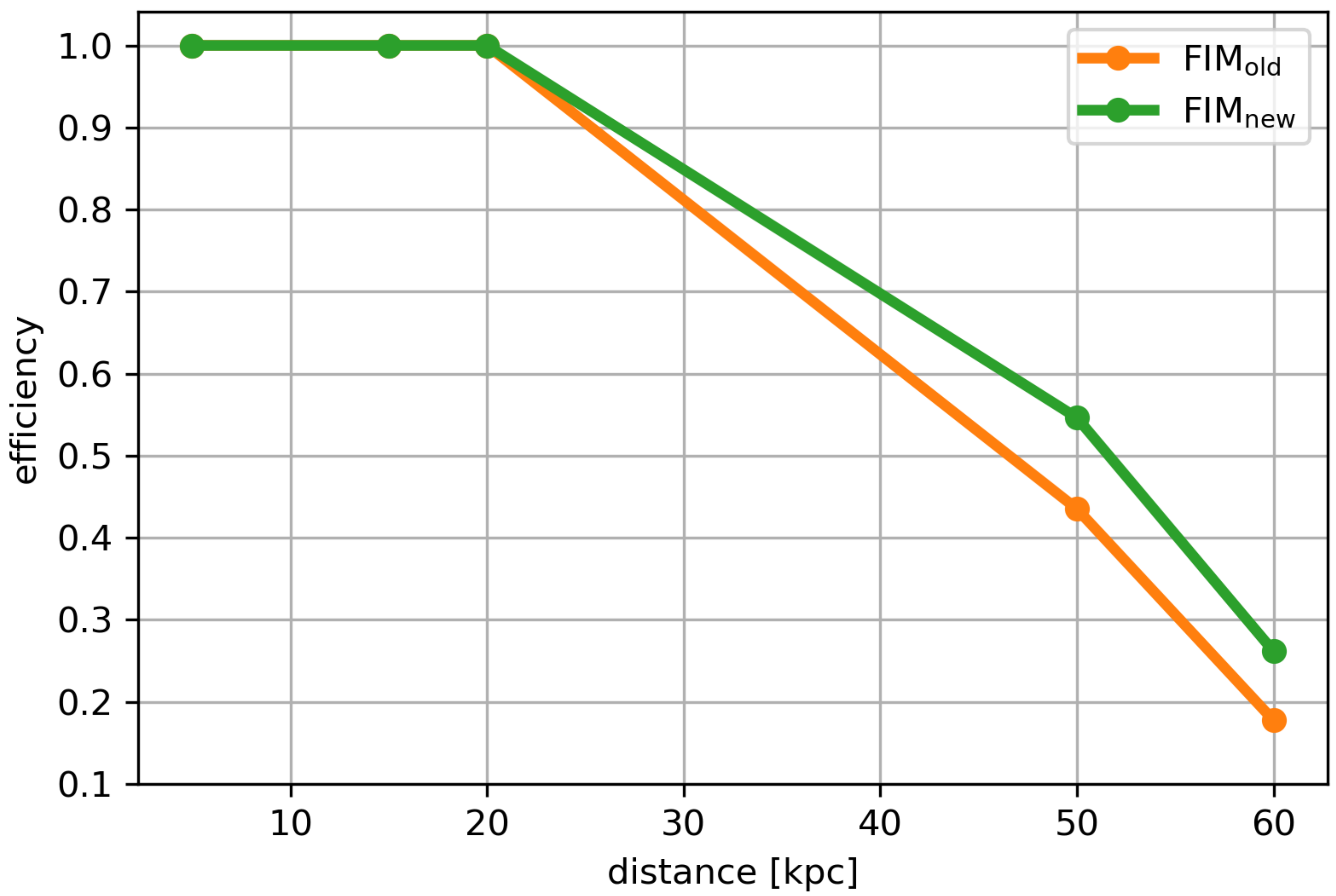


TABLE IV: Efficiency (η) comparison between 1-parameter and 2-parameter method for analysis of KamLAND-LVD with neutrino Hud model and for $\text{FAP}_\nu > 5\sigma$.

Distance [kpc]	$\eta_{1\text{param}}$ [$> 5\sigma$]	$\eta_{2\text{param}}$ [$> 5\sigma$]
50	**47/108=43.5%**	**59/108=54.6%**
60	**19/107=17.8%**	**28/107=26.2%**

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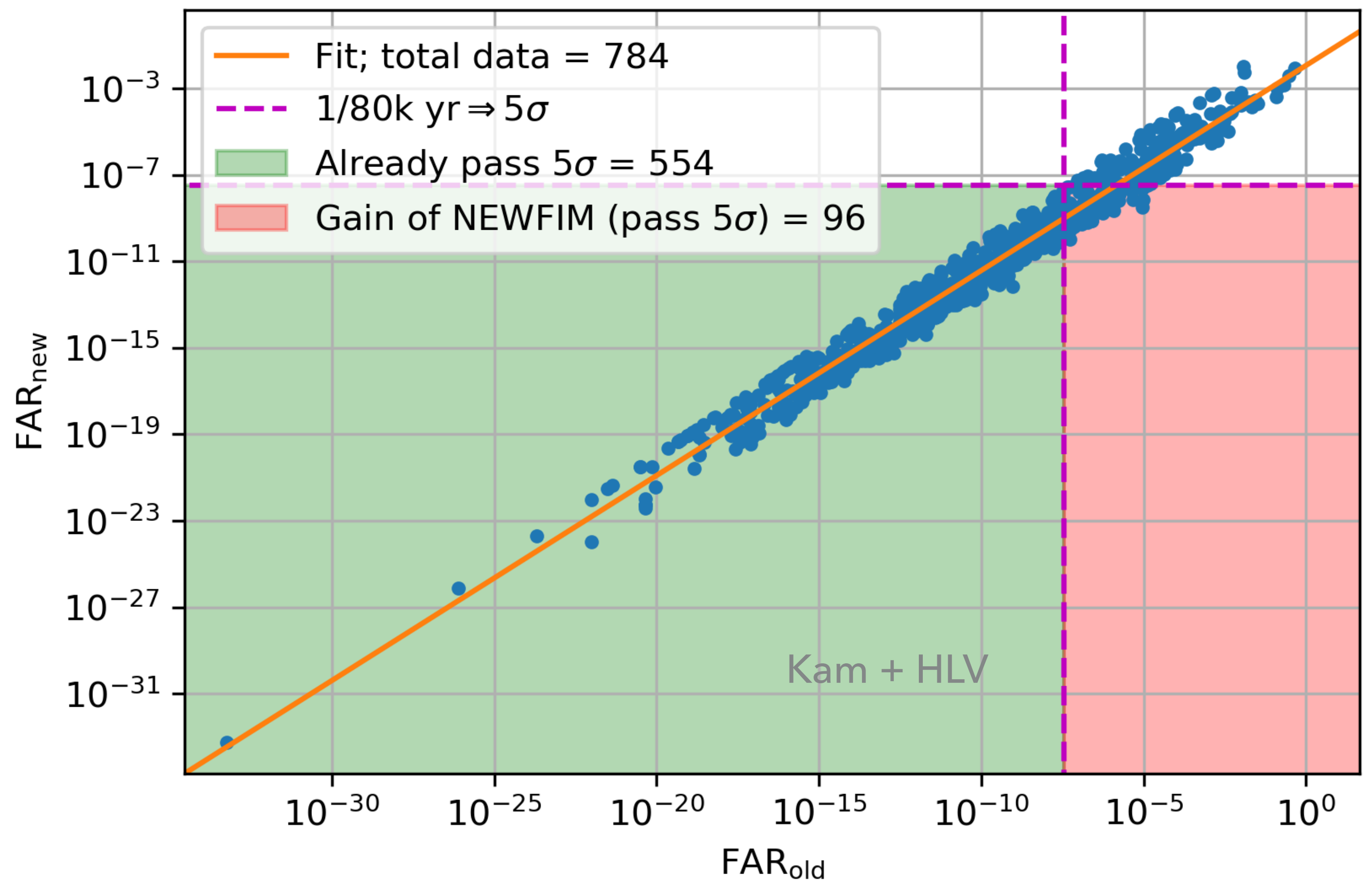
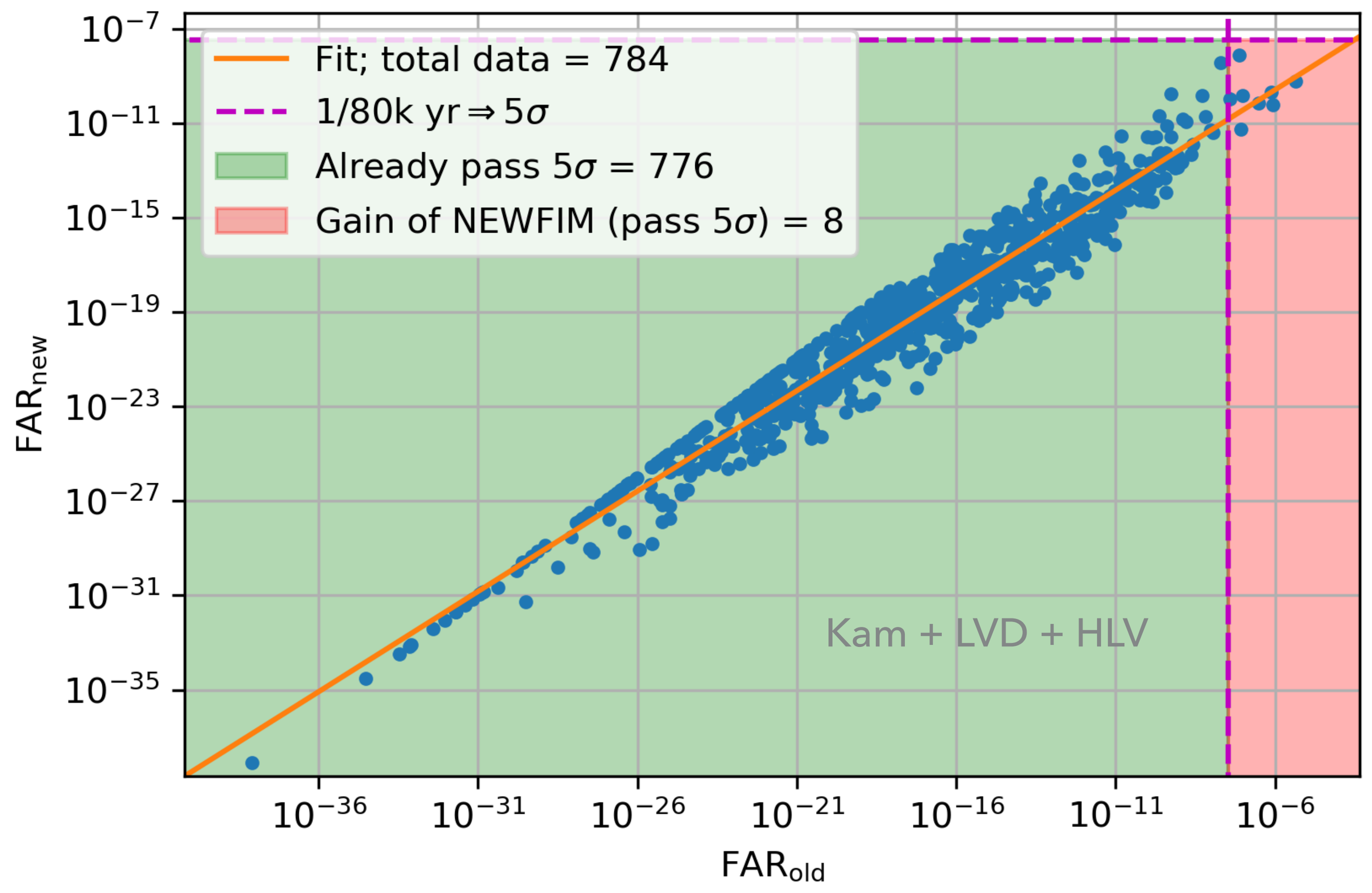
RESULTS: GLOBAL-NETWORK OF MULTIMESSENGERS

- SN1987A-signal model @60kpc injections, KamLAND and LVD detector model, 5σ-FAP threshold
- Dimmelmeier2-GW model @60kpc injections, [LIGO-H, LIGO-L, Virgo] detectors





The recovered injections (784/2346) from cWB have FAR too low to be considered even as sub-thresholds

TABLE V: Efficiency (η) comparison of 1-parameter and our 2-parameter method for Figure 7 and 8. The first column points the specific network of detectors considered and the adopted emission models. The second column is after we impose the threshold on FAR of GW data (< 864/day). The third and last columns report the fraction of signals with a significance greater than 5σ (efficiency) with 1-parameter and 2-parameter methods.

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%**

GLOBAL EFFICIENCY OF 1-PARAM METHOD:
$33.4\% \times 99.0\,\% = 33.1\,\%$

GLOBAL EFFICIENCY OF 2-PARAM METHOD:
$33.4\% \times 100.0\,\% = 33.4\,\%$

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RESULTS: GLOBAL-NETWORK OF MULTIMESSENGERS

- Hüdepohl-signal model @60kpc injections, KamLAND and LVD detector model, 5σ-FAP threshold
- Dimmelmeier2-GW model @60kpc injections, [LIGO-H, LIGO-L, Virgo] detectors

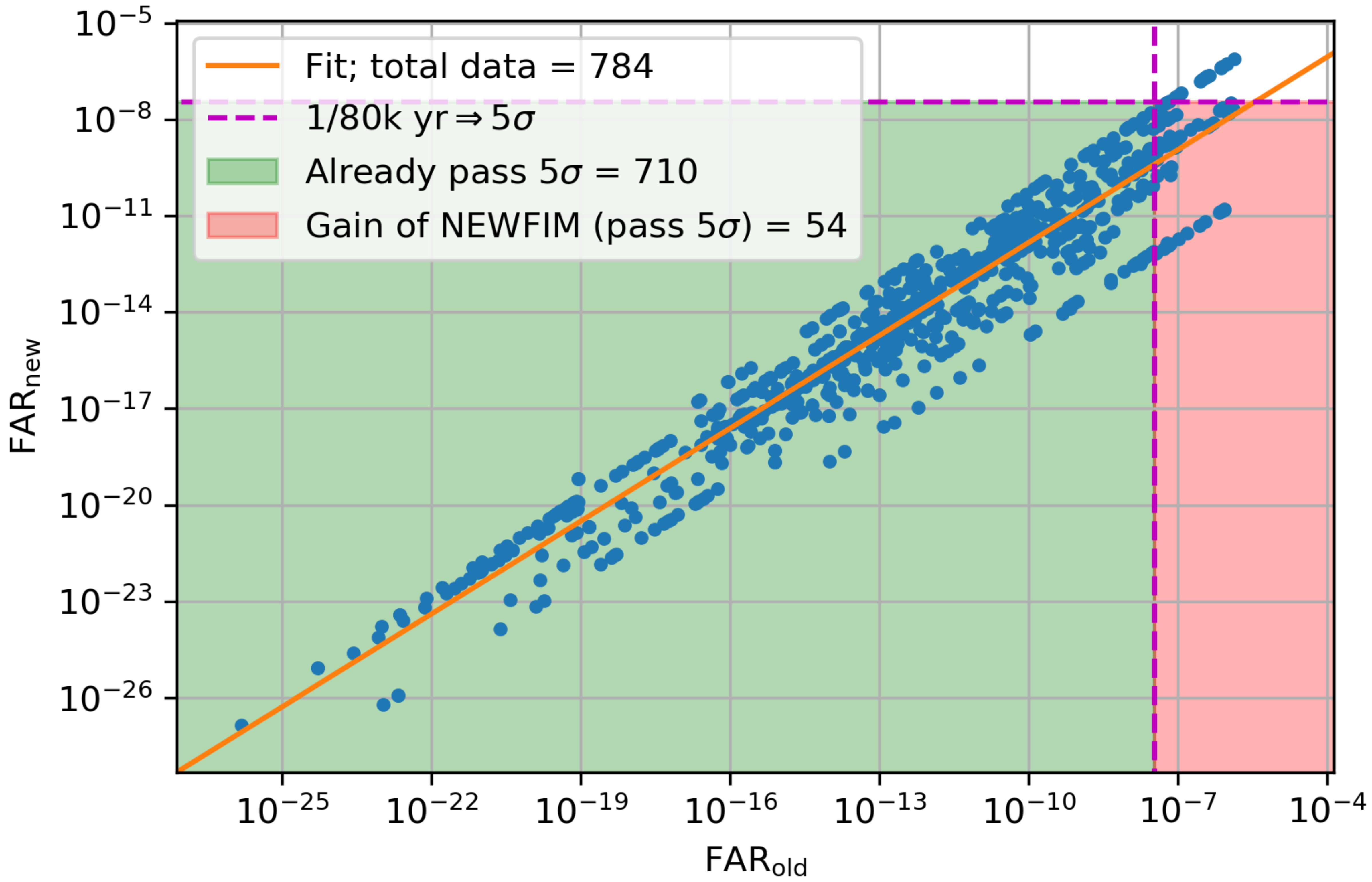


TABLE VI: Efficiency (η) comparison of 1-parameter and our 2-parameter method for Figure 9. The columns are analogous to Table V.

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

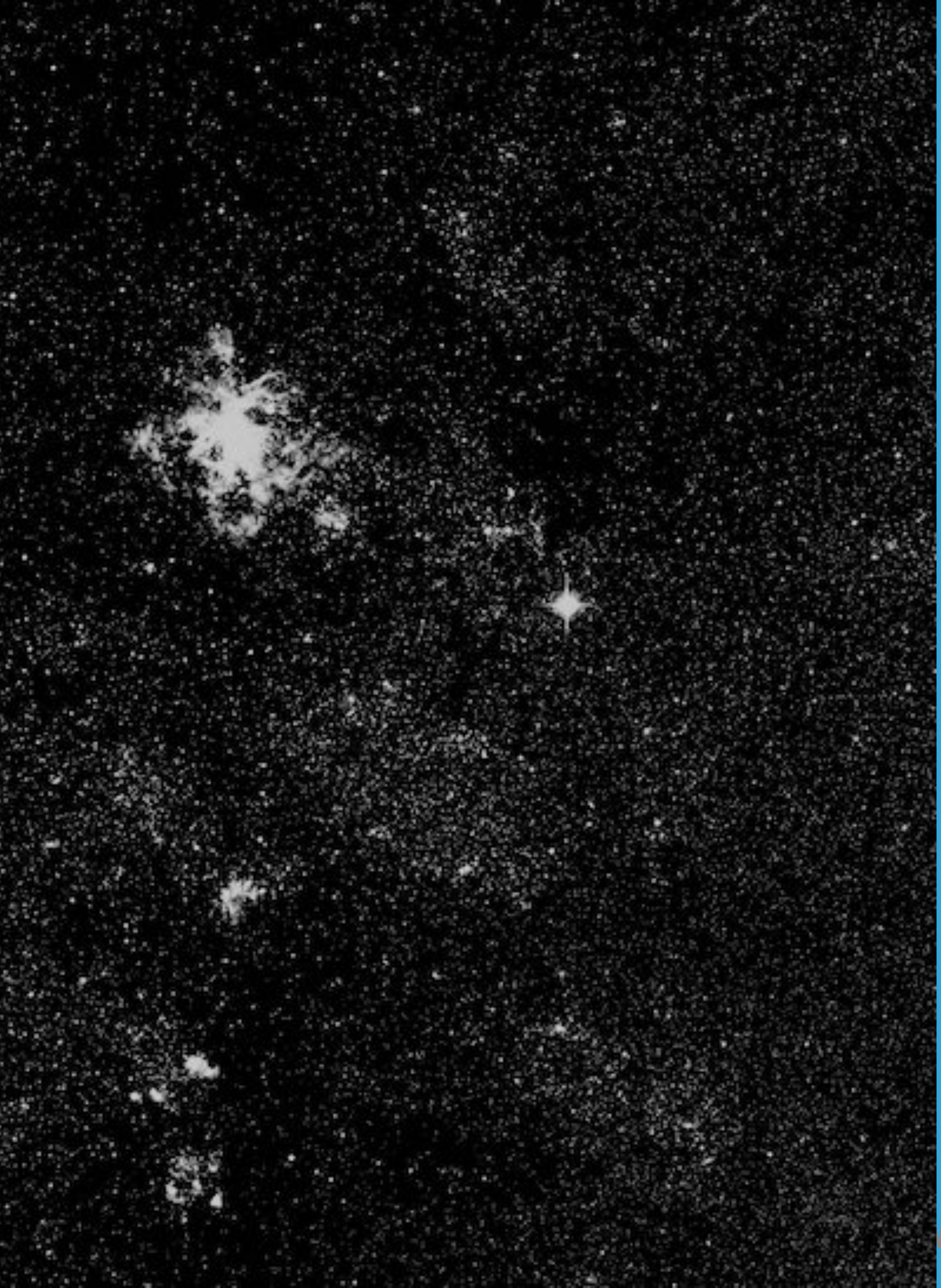
GLOBAL EFFICIENCY OF 1-PARAM METHOD:
$33.4\% \times 90.6\,\% = 30.3\,\%$

GLOBAL EFFICIENCY OF 2-PARAM METHOD:
$33.4\% \times 97.5\,\% = 32.6\,\%$

OH, et.al. arXiv:2107.02050

CONCLUSIONS

- Multimessenger analysis strategy has been done by combining gravitational wave and low-energy neutrino data
- Gravitational wave analysis uses cWB pipeline in order to produce low-significant triggers
- The 2-parameter refined analysis on low-energy neutrino data has been introduced and it has been proven to increase neutrino candidates' significance
- Multimessenger analysis will increase sub-threshold GW triggers' significance



THANK YOU

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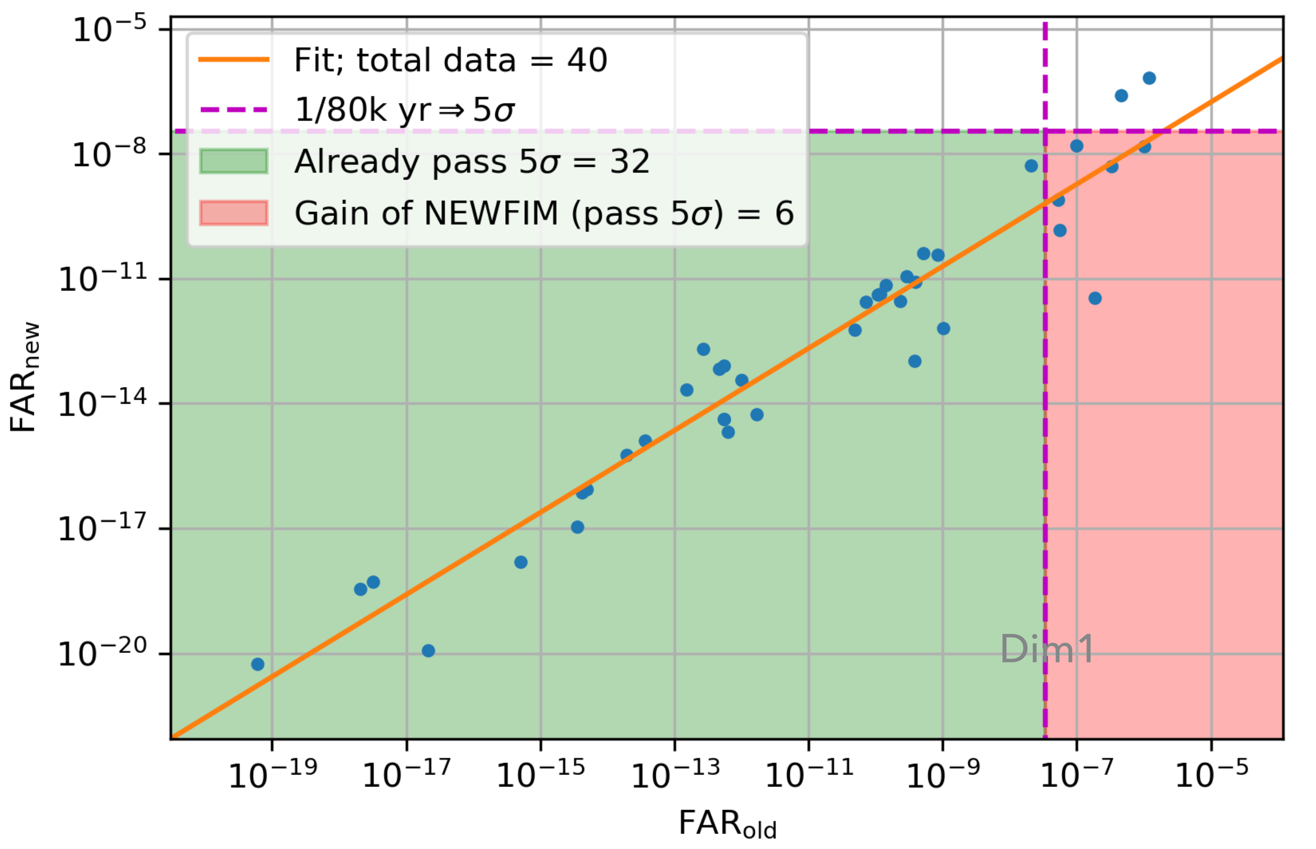
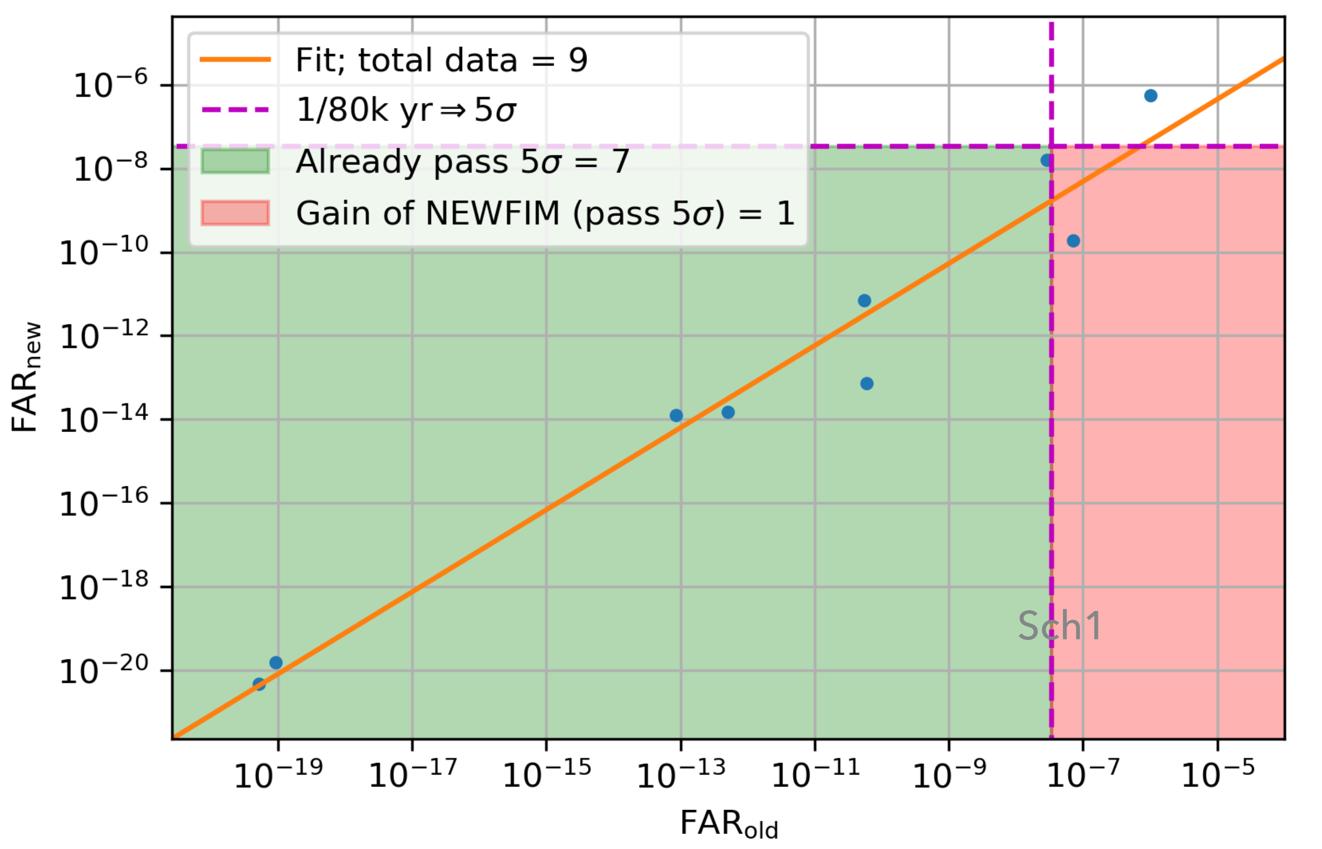
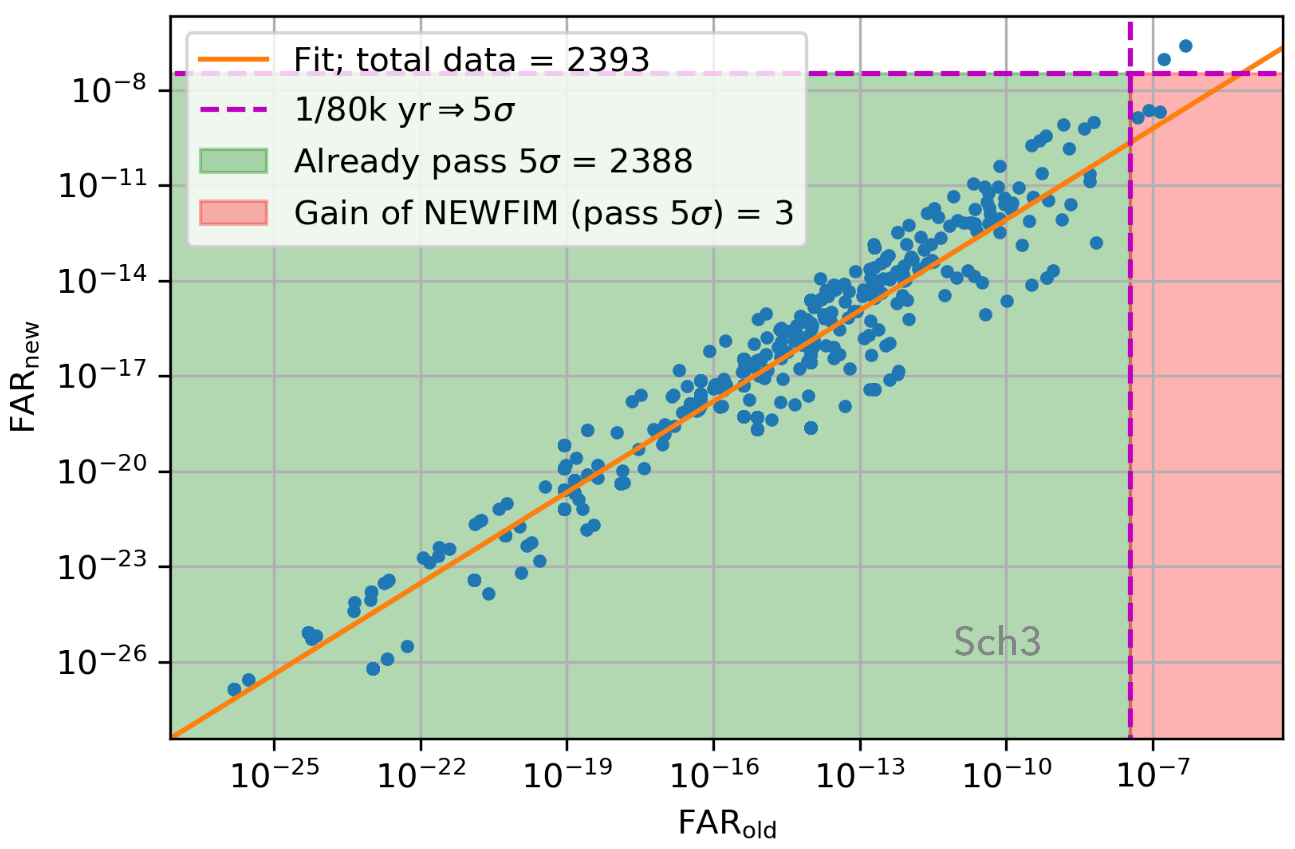
BACKUP SLIDES

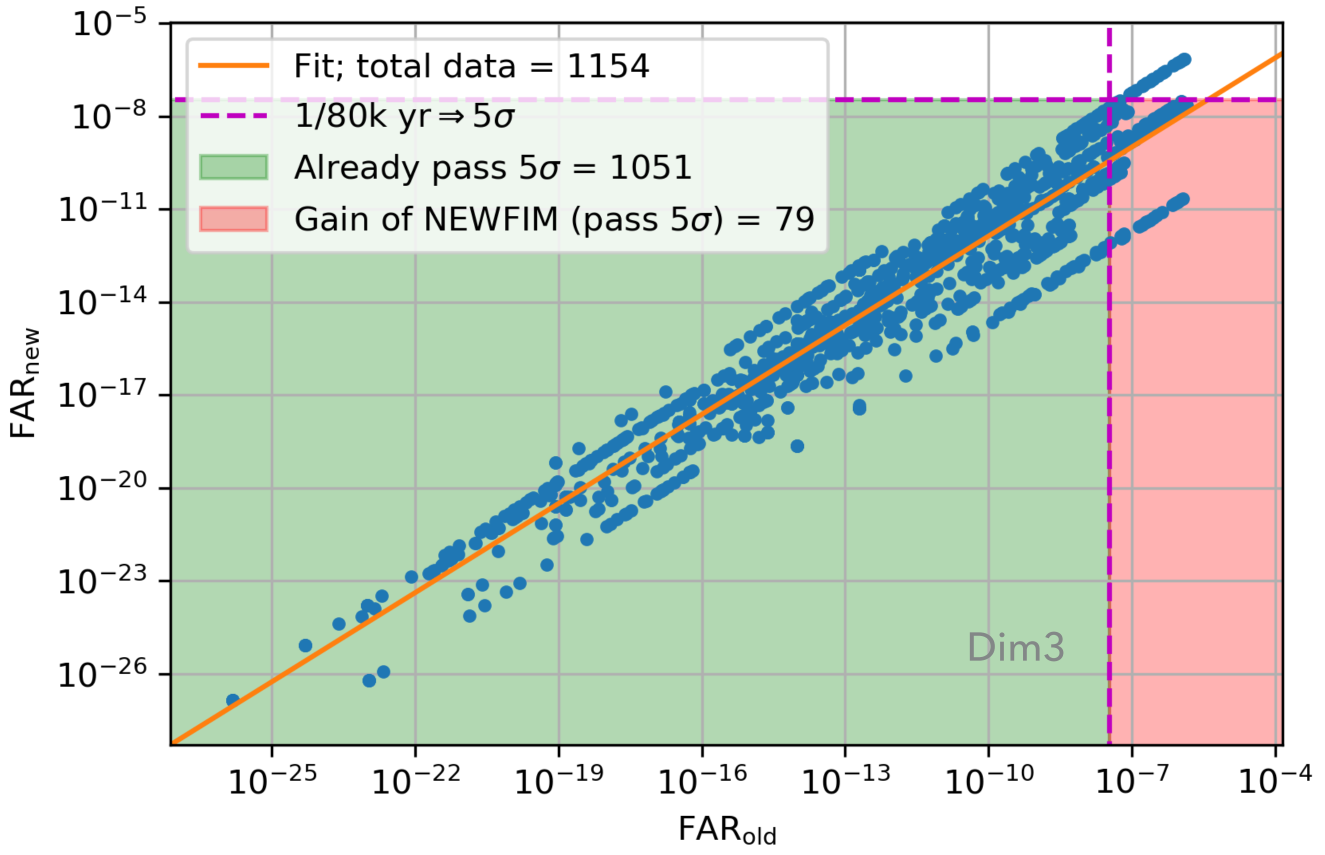
GLOBAL-NETWORK OF MULTIMESSENGERS FROM OTHER GW-MODELS

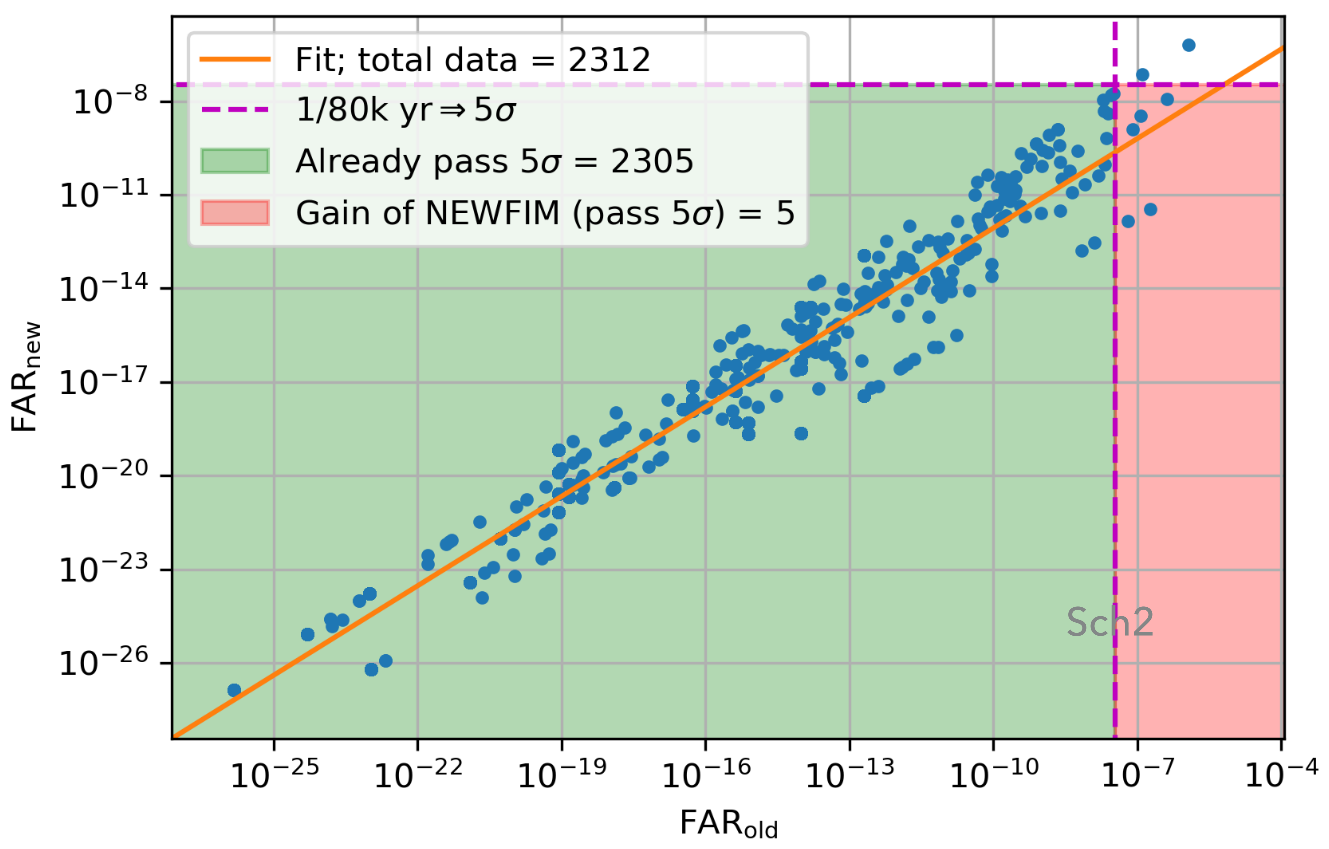
- Hüdepohl-signal model @60kpc injections, KamLAND and LVD detector model, 5σ-FAP threshold
- other-GW model @60kpc injections, [LIGO-H, LIGO-L, Virgo] detectors











Type & Number of Injections	Recovered $FAR_{GW} < 864/d$	η_{1param} $[> 5\sigma]$	η_{2param} $[> 5\sigma]$
Dim1-KAM-LVD = 86	46.5% = 40/86	**37.2%** = 32/86	**44.2%** = 38/86
Dim3-KAM-LVD = 1386	83.3% = 1154/1386	**75.8%** = 1051/1386	**81.5%** = 1130/1386
Sch1-KAM-LVD = 23	39.1% = 9/23	**30.4%** = 7/23	**34.8%** = 8/23
Sch2-KAM-LVD = 2329	99.3% = 2312/2329	**99.0%** = 2305/2329	**99.2%** = 2310/2329
Sch3-KAM-LVD = 2398	99.8% = 2393/2398	**99.6%** = 2388/2398	**99.7%** = 2391/2398

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RESULTS: 1-DETECTOR NEUTRINO

- Super-K @250-kpc, SN1987A model

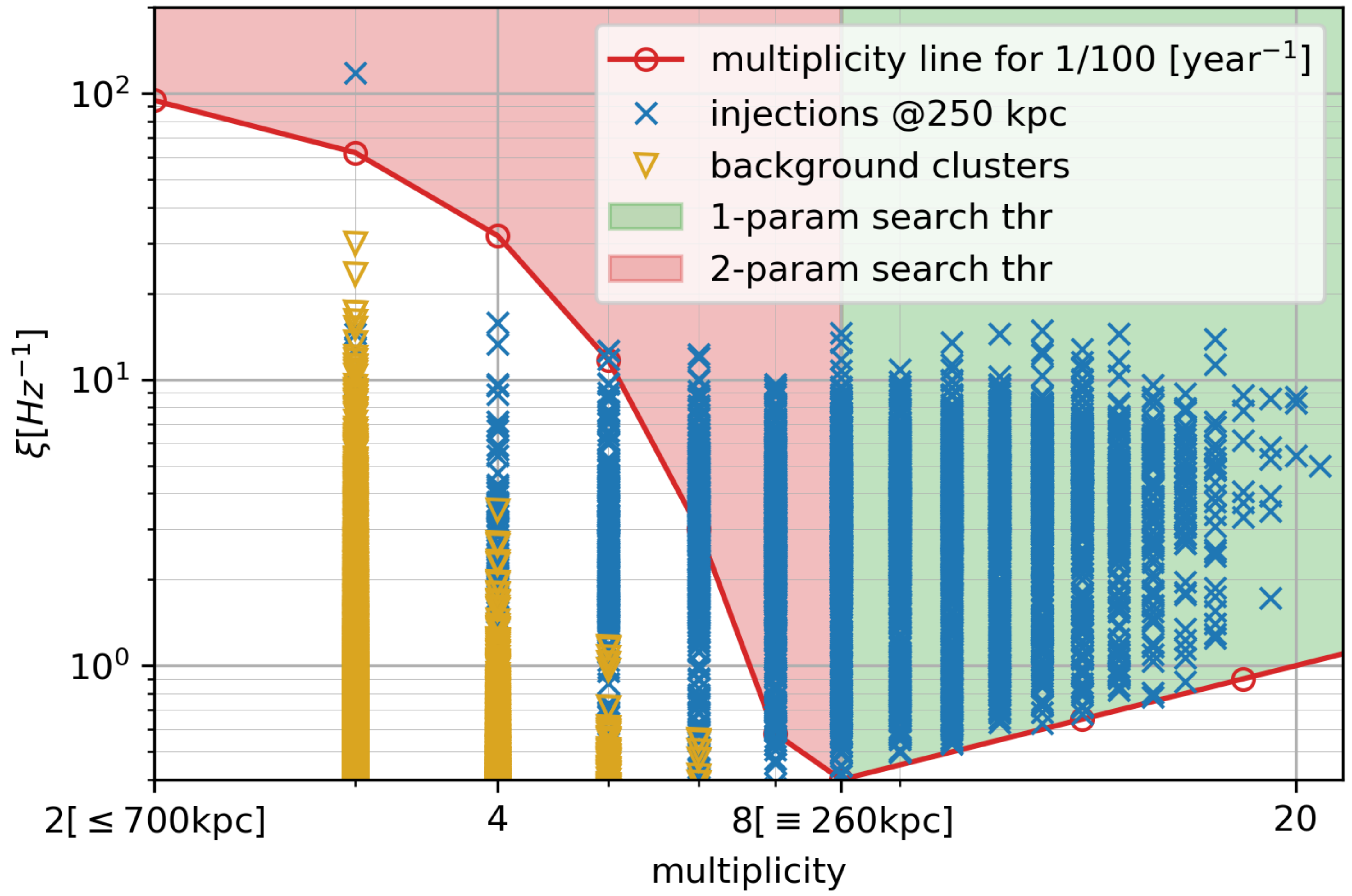

TABLE VIII: Efficiency (η) comparison between 1-parameter and 2-parameter method of single detector Super-K with $D = 250$ kpc for $\mathrm{FAR}_\nu \leq 1/100$ [year^{-1}]

D [kpc]	Noise [< 1/100 yr]	$\eta_{1\mathrm{param}}$ [< 1/100 yr]	$\eta_{2\mathrm{param}}$ [< 1/100 yr]
250	0/49200	2575/3645=**70.6%**	3117/3645=**85.5%**

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