GRAN SASSO
SCIENCE INSTITUTE

Searching for Core-Collapse Supernovae in the Multimessenger Era: Low Energy Neutrinos and Gravitational Waves

PhD Thesis Defense - 23 April 2020; 9:00am CET

Odysse Halim - Astroparticle Physics (AP) 32

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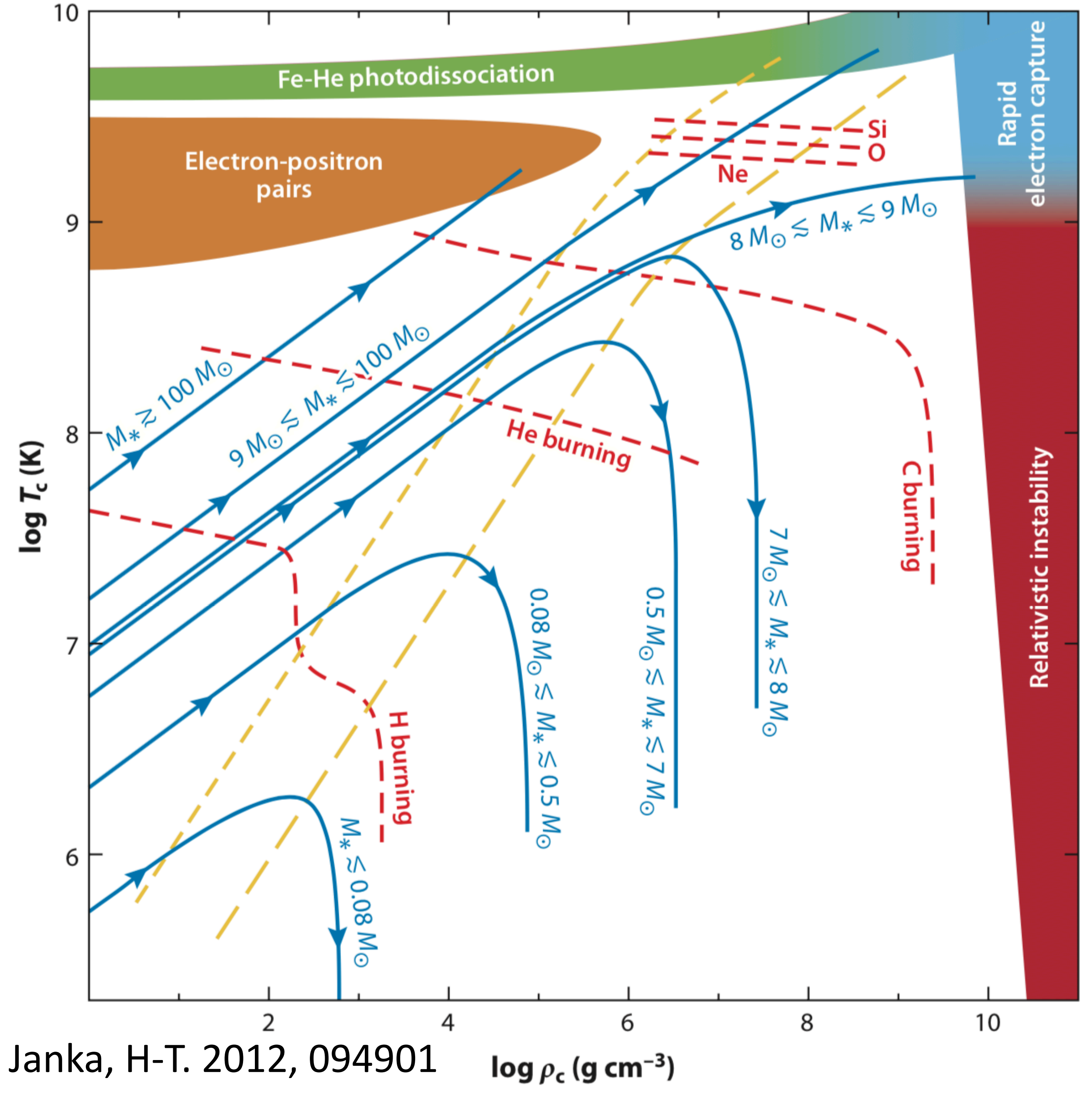
www.gssi.it

SN1987A. Credit: ESO

Outline

1. Core-Collapse Supernovae
2. Coincidence Analysis
3. Increasing Sensitivity of ν-Detectors
4. The GW-ν Joint Search
5. Conclusion

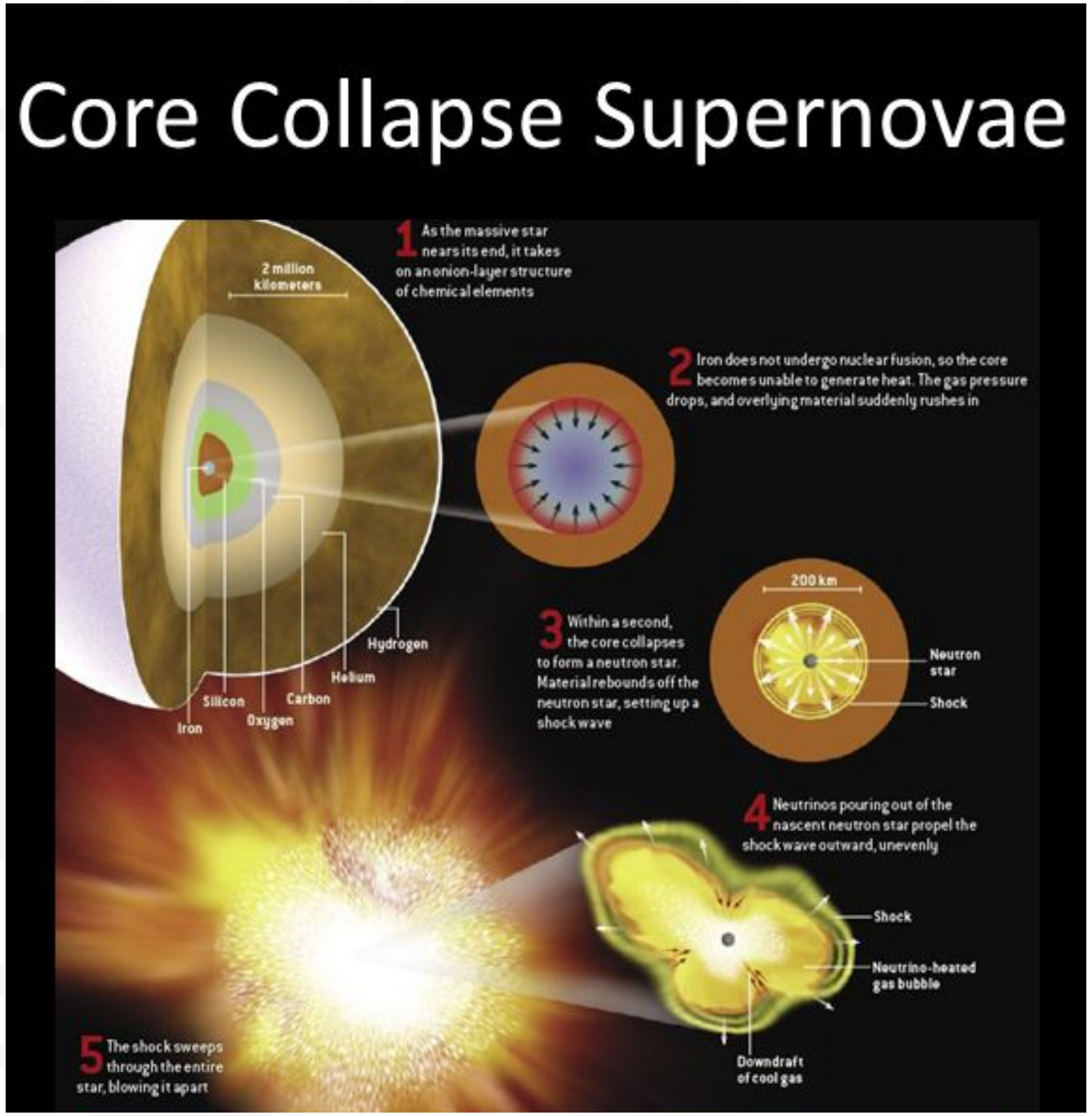
1. Core-Collapse Supernovae (CCSNe)



Janka, H-T. 2012, 094901

- $M_{\rm prog} \gtrsim 8 M_\odot$
- Final phase: the gravitational collapse of the inner core.
- The collapse *may* terminate and the final explosion happens ==> CCSNe
- Remnant: neutron star (NS) or blackhole
- Total energy: $\Delta E_{\rm grav} = E_{\rm NS} - E_{\rm prog} \approx 2 \times 10^{53}\,{\rm erg}$
  - $\sim 99\,\%$ as neutrinos,
  - $\sim 1\,\%$ as kinetic,
  - $\sim 0.01\,\%$ EM,
  - $\lesssim 0.0001\,\%$ GW

1. CCSNe: Astrophysical Mechanism



Core Collapse Supernovae

1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

- Mechanism of core collapse?
- How the energy carried away by neutrinos?
- Standard picture: Neutrino-heating mechanism / Bethe-Wilson delayed scenario.
    - ➡ The basic understanding in core-collapse
- Pure scenario cannot produce explosion in simulations
- + other mechanisms can produce explosion.

Bethe, HA and JR Wilson, 1985. 163343

Bethe, HA. 1990. 62.801

1. CCSNe: Collapse

Pagliaroli, G. 2009. Thesis

- Fe fusion is endothermic

  ==> no iron fusion

  ==> no energy production

- BUT, no runaway collapse *yet*: degenerate electrons

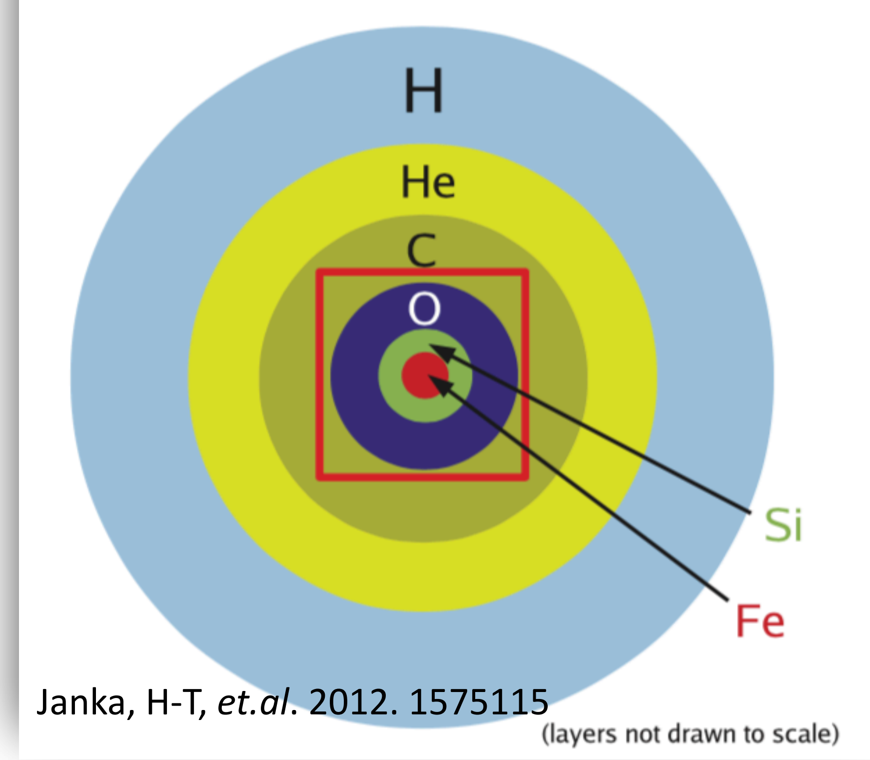
  ==> pressure.

  ☑ $T_{\mathrm{c}} \approx 10^9\,\mathrm{K}$ ==> relativistic e

  ☑ $\rho_c \approx 10^9\,\mathrm{gr/cm^3}$ ==> degenerate e

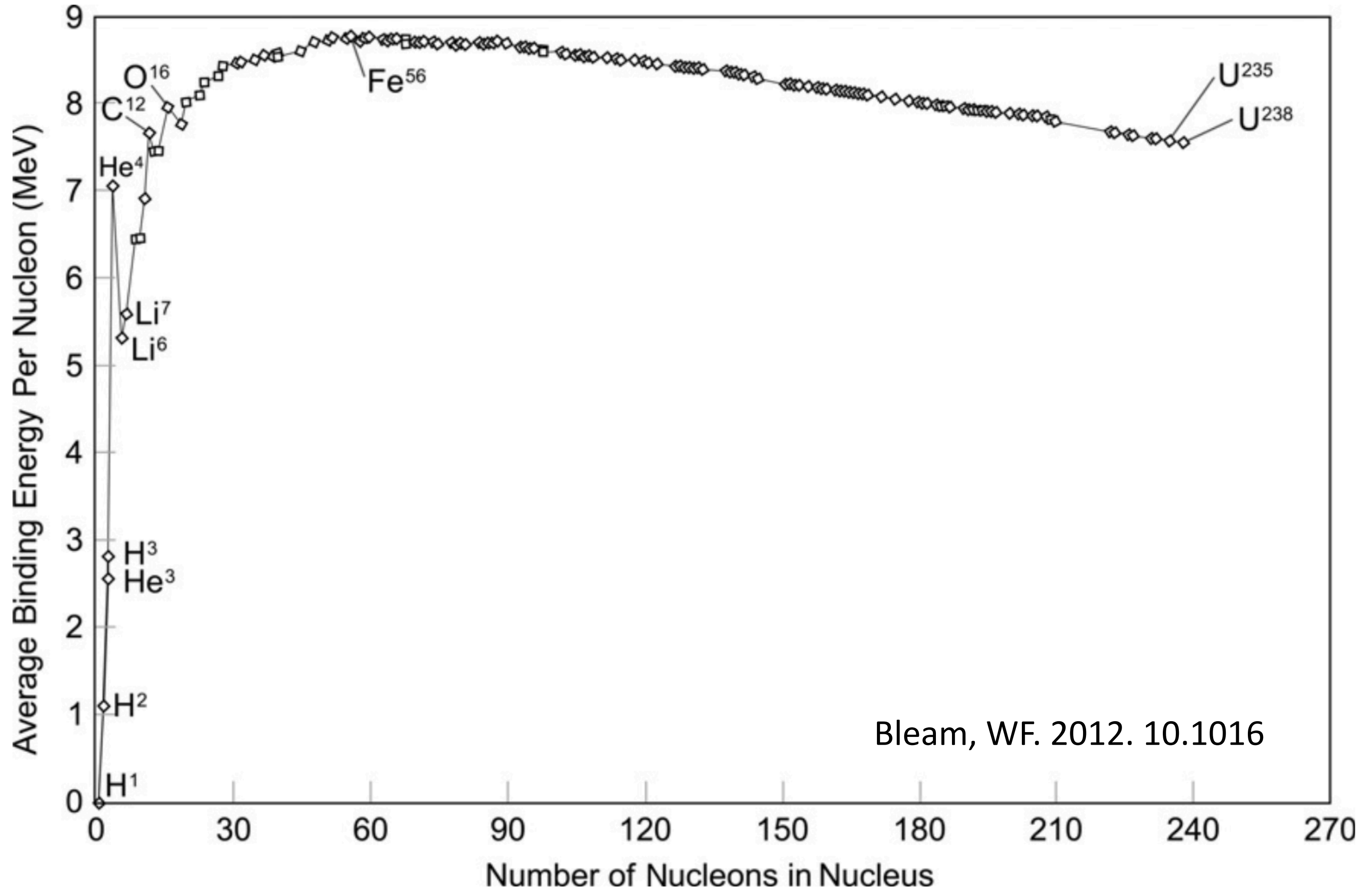
- However, only up to $M_{\mathrm{c,Fe}} \simeq M_{\mathrm{Ch}}$
- $M_{\mathrm{Ch}} \simeq 5.8 Y_e^2 M_\odot \approx 1.4 M_\odot$

Onion-shell structure of pre-collapse star



Janka, H-T, *et.al*. 2012. 1575115

(layers not drawn to scale)



Bleam, WF. 2012. 10.1016

1. CCSNe: Neutrino Trapping

Pagliaroli, G. 2009. Thesis

- $M_{\mathrm{c,Fe}} > M_{\mathrm{Ch}}$ ==> instability due to photodissociation:

  $$\gamma[\mathrm{MeV}] + {}^{56}\mathrm{Fe} \rightarrow 13\,{}^{4}\mathrm{He} + 4n$$

  Endothermic; absorbing $\sim 124.4\,\mathrm{MeV}$ from e-degenerate pressure.

  ==> Less pressure ==> collapse & neutronization: $e^- + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Mn} + \nu_e$

- Y_e reduces, P reduces, collapse accelerates but neutronization not forever:

  ==> Neutrino trapping

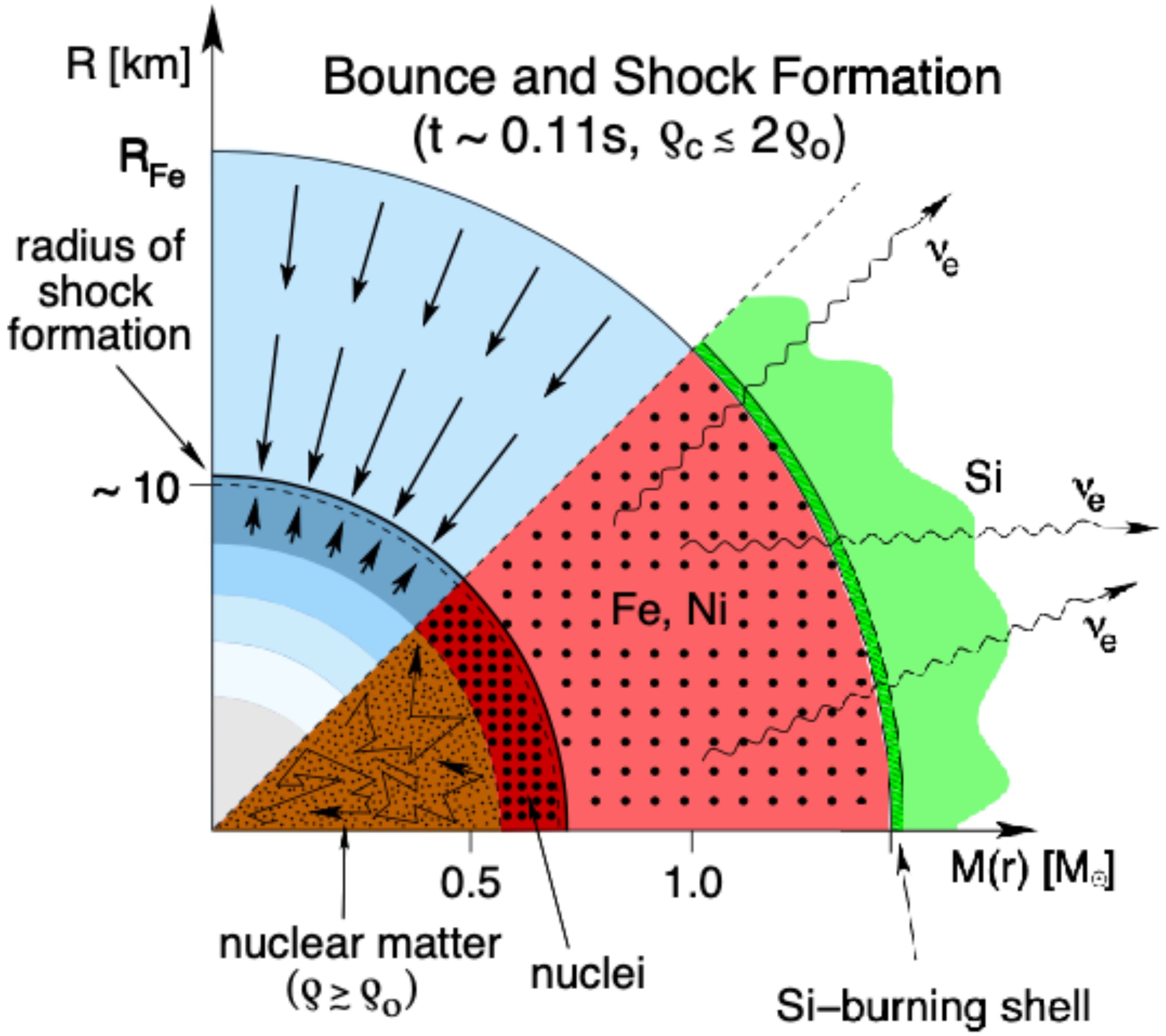
  $$\nu_e + (Z, A) \rightarrow \nu_e + (Z, A); \quad \rho_c \simeq 10^{12}\,\mathrm{erg/cm^3}$$

- Neutronization stops since ν_e degenerate with high fermi energy.

  1. Central region collapses homologously: $v(r) \propto r$
  2. Outer (Fe) region collapses in free-fall

1. CCSNe: Bounce

Pagliaroli, G. 2009. Thesis



Janka, HT, *et.al.* 2007. 0612072

- Collapse stops when $\rho_{\rm c} \approx 10^{14}\,{\rm erg/cm^3}$ due to **nuclear** degeneracy pressure.
- Outer region bounces on the core. Acoustic wave is generated and propagates outward until “sonic point” ($v_{\rm sound} = v_{\rm homolog}$)

  ==> discontinuity

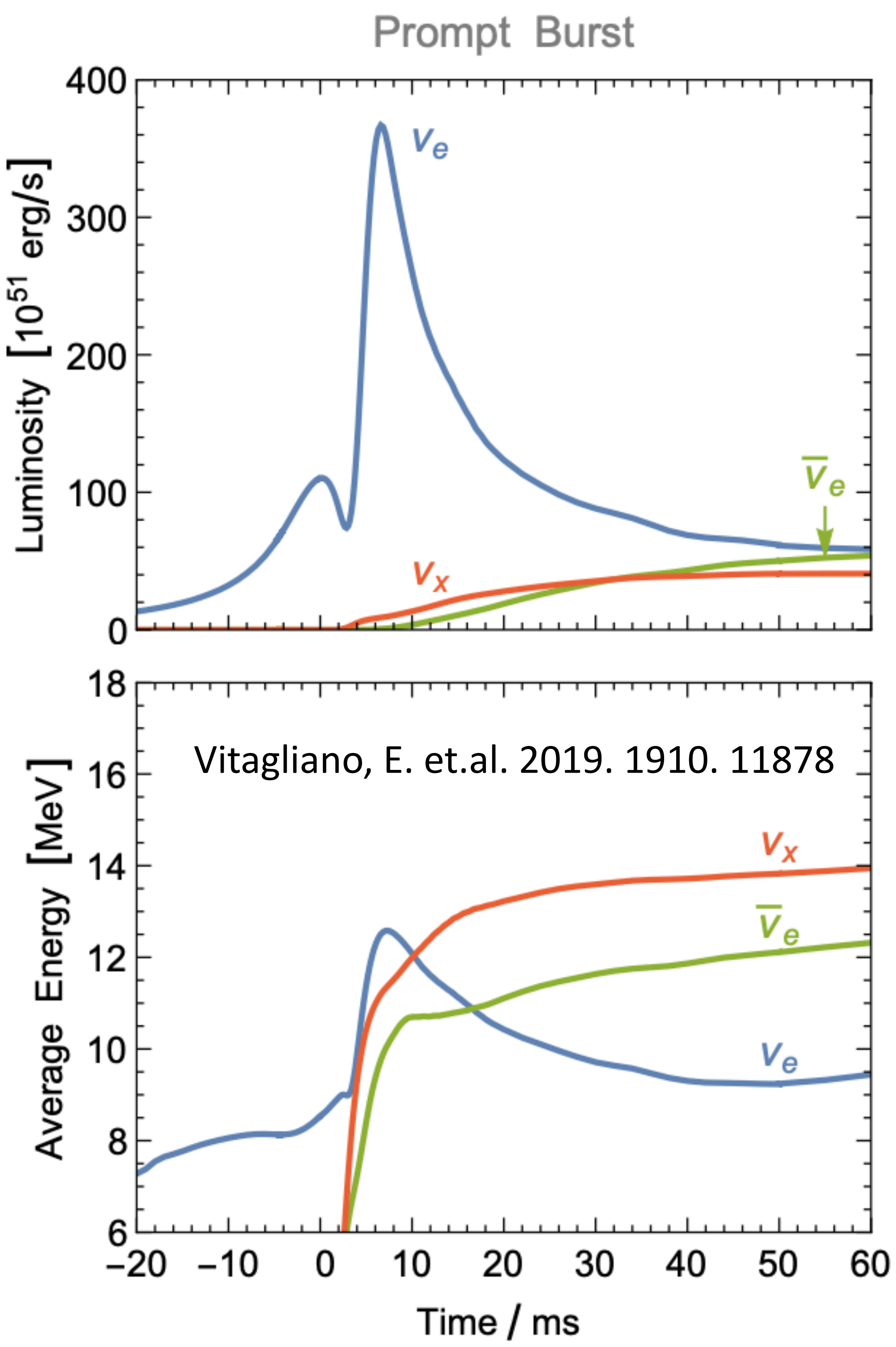
  ==> shock wave. Strength depends on ρ_c, and ρ_c depends on EoS.
- When nuclear density reached in the core ==> EoS stiffer.

  ==> Compression like spring with max $\rho_c = 9.7 \times 10^{14}\,{\rm gr/cm^3}$
- Shock propagates outward and if explosion happens: Prompt mechanism.
- BUT failed in simulations ==> Shock loses energy:

  ☑ Heavy nuclei dissociation (8.8 MeV per nucleon => 2×10^{51} erg per $0.1 M_\odot$; $\quad E_{\rm shock} = 10^{52}\,{\rm erg}$.

  ☑ Neutrino emission ($e^- + p \rightarrow n + \nu_e$)

1. CCSNe: Accretion and Cooling



Vitagliano, E. et.al. 2019. 1910. 11878

- When shock propagates, ρ lower until the neutrino sphere: neutrino prompt emission with a peak luminosity
- Happening at 2 ms after bounce, $R_{\nu_e} = 100\,\mathrm{km}$,

$$E_{\nu_e,\mathrm{prompt}} = 10^{51}\,\mathrm{erg}$$

- Accretion:

  1. Neutrino cooled region (emission > absorption)

  2. neutrino heated region

Pagliaroli, G. 2009. Thesis

1. CCSNe: Shock Revival Mechanisms

Janka, H-T. 2012, 094901

- low mass electron-capture supernovae. neutrino-energy transfer, ex: Crab $(\varepsilon_{\rm tot} = 10^{50}\,{\rm erg})$

- For Fe core, we need SASI ==> nonradial instability of stalled accretion shocks, leading to a large-scale shock deformation

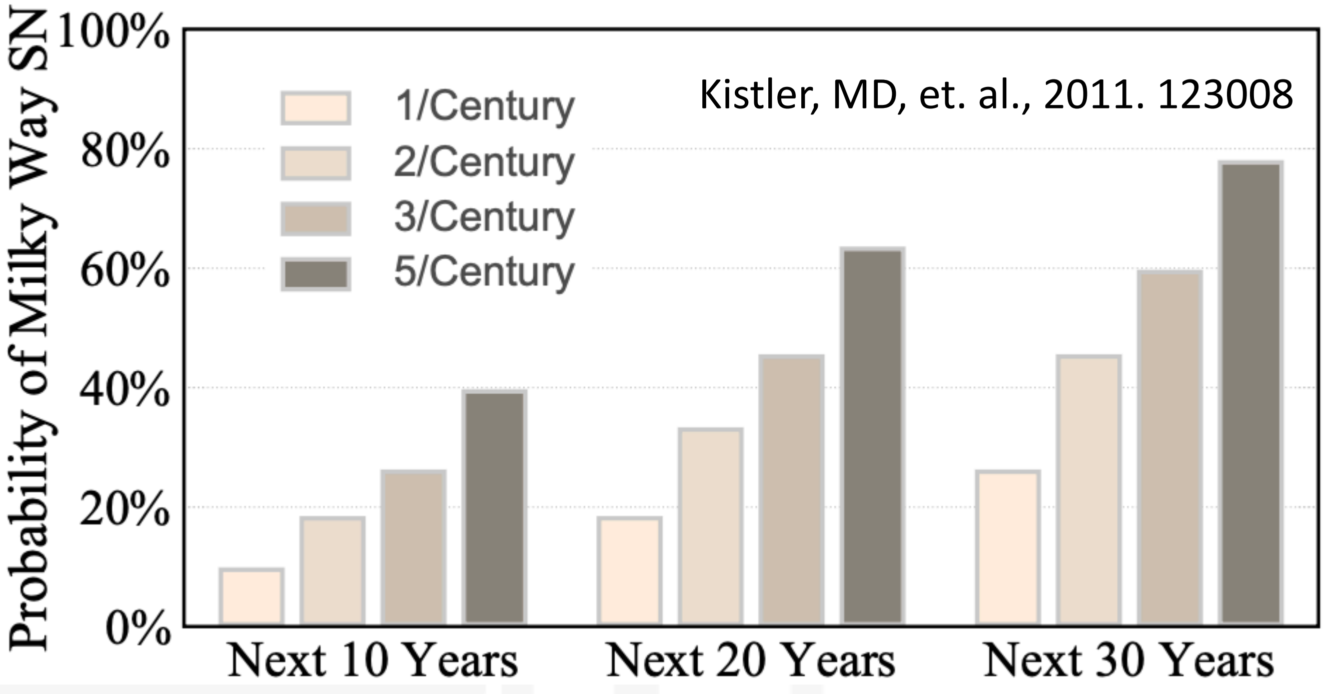
- Magnetorotational mechanism. Core rotation ~ 1ms, but typically 100s (observation of WD & pulsars).

- Large-amplitude dipole gravity-mode oscillations of the proto neutron star core. The amplitude of oscillation can be O(km). The shock can heat up.

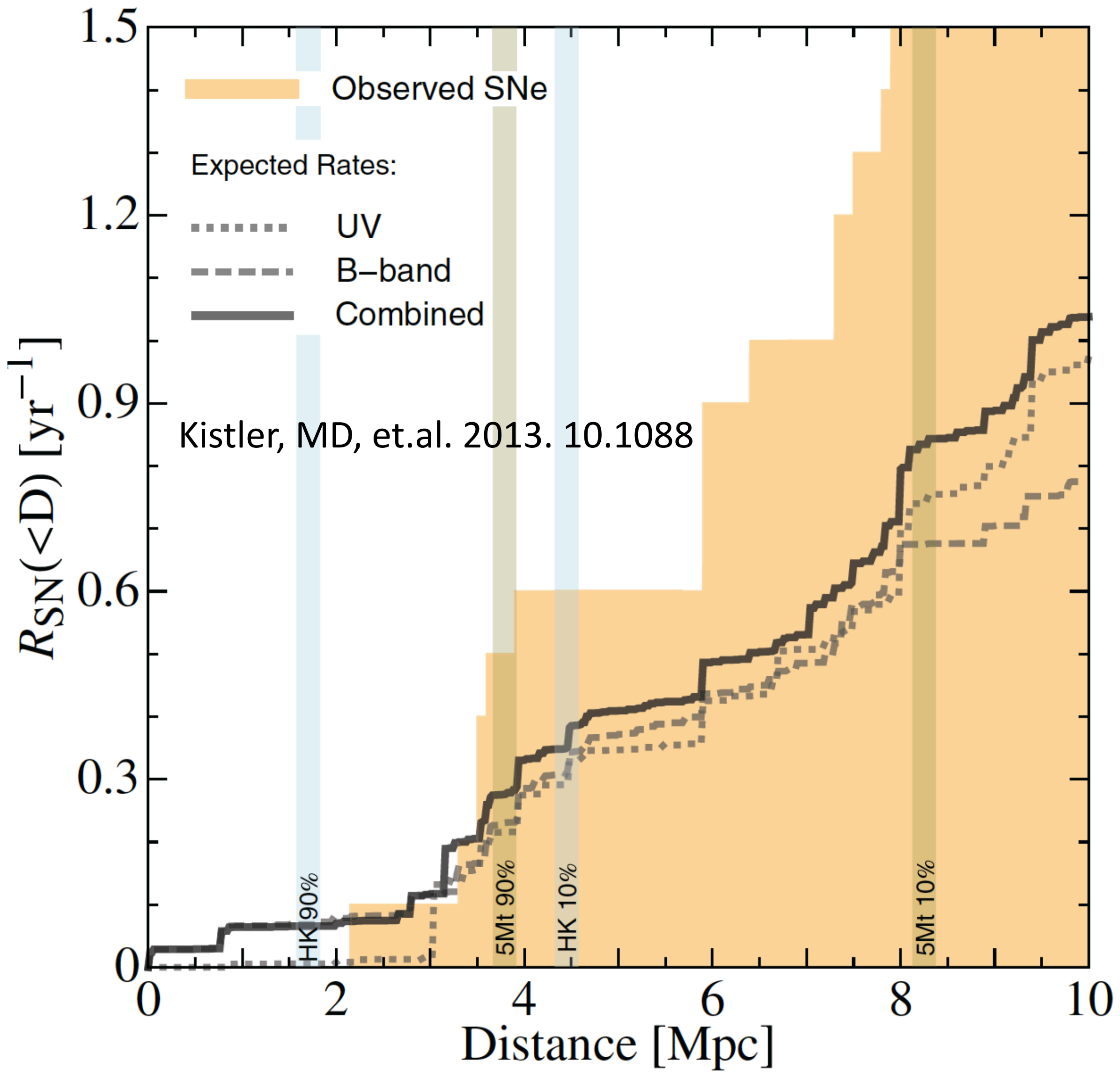
- The first-order hadron-to-quark matter phase transition

- A thermonuclear mechanism for $M > 100 M_\odot$

1. CCSNe: Rate and Distribution



Kistler, MD, et. al., 2011. 123008



Kistler, MD, et.al. 2013. 10.1088

Maggiore, M. 2018. ISBN:9780198570899

- Observations of SNe in other galaxy and then normalised the *B*-band luminosity (~ stellar mass) of the galaxy to our Galaxy:

Cappellaro & Turatto. 2001. 0012455

==> 1-3 events / century

- SN1987A. Up to now, no new ν-detection of CCSNe. Upper bound:

Maggiore, M. 2018. ISBN:9780198570899

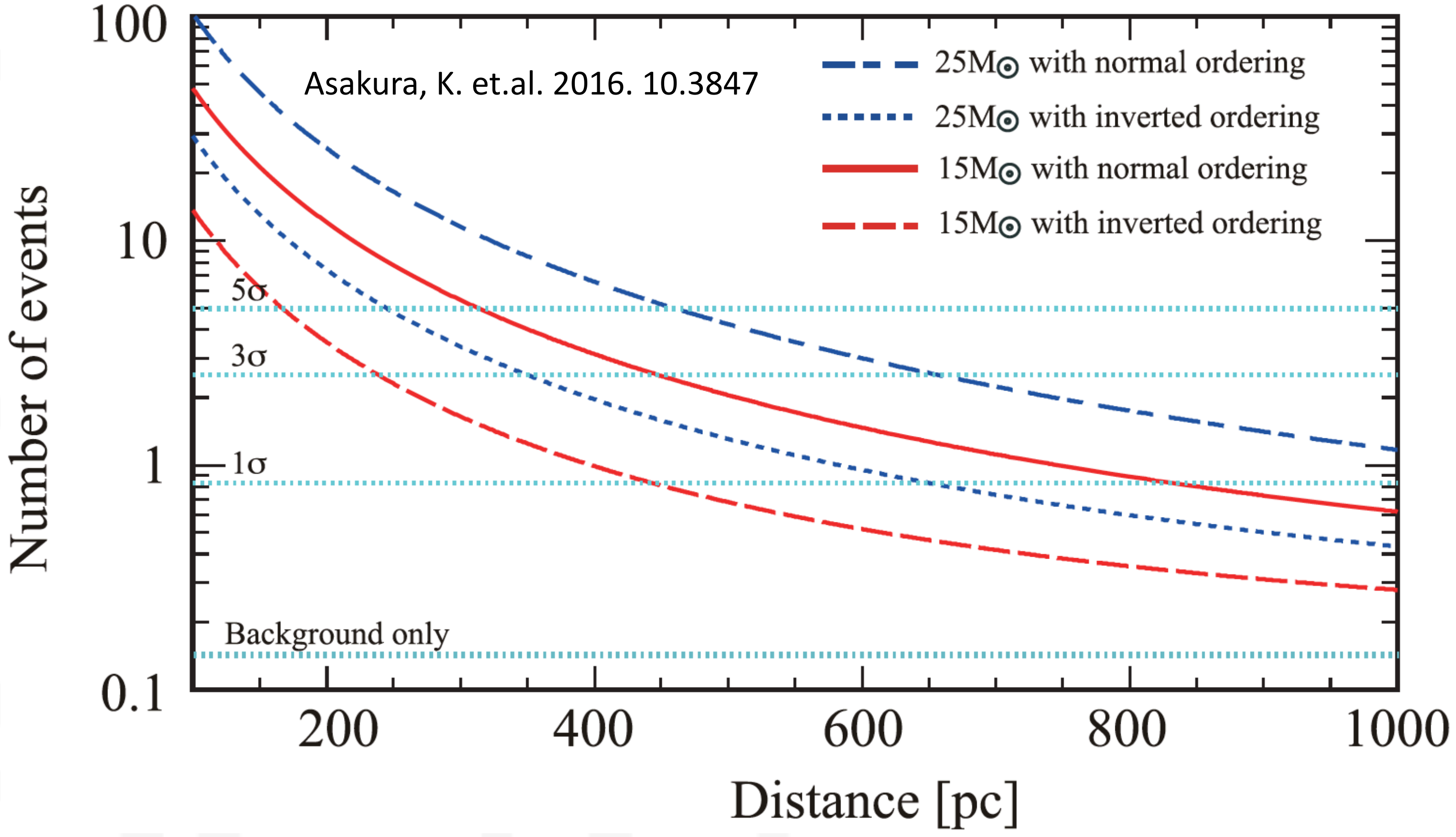
==> 7.7 events / century

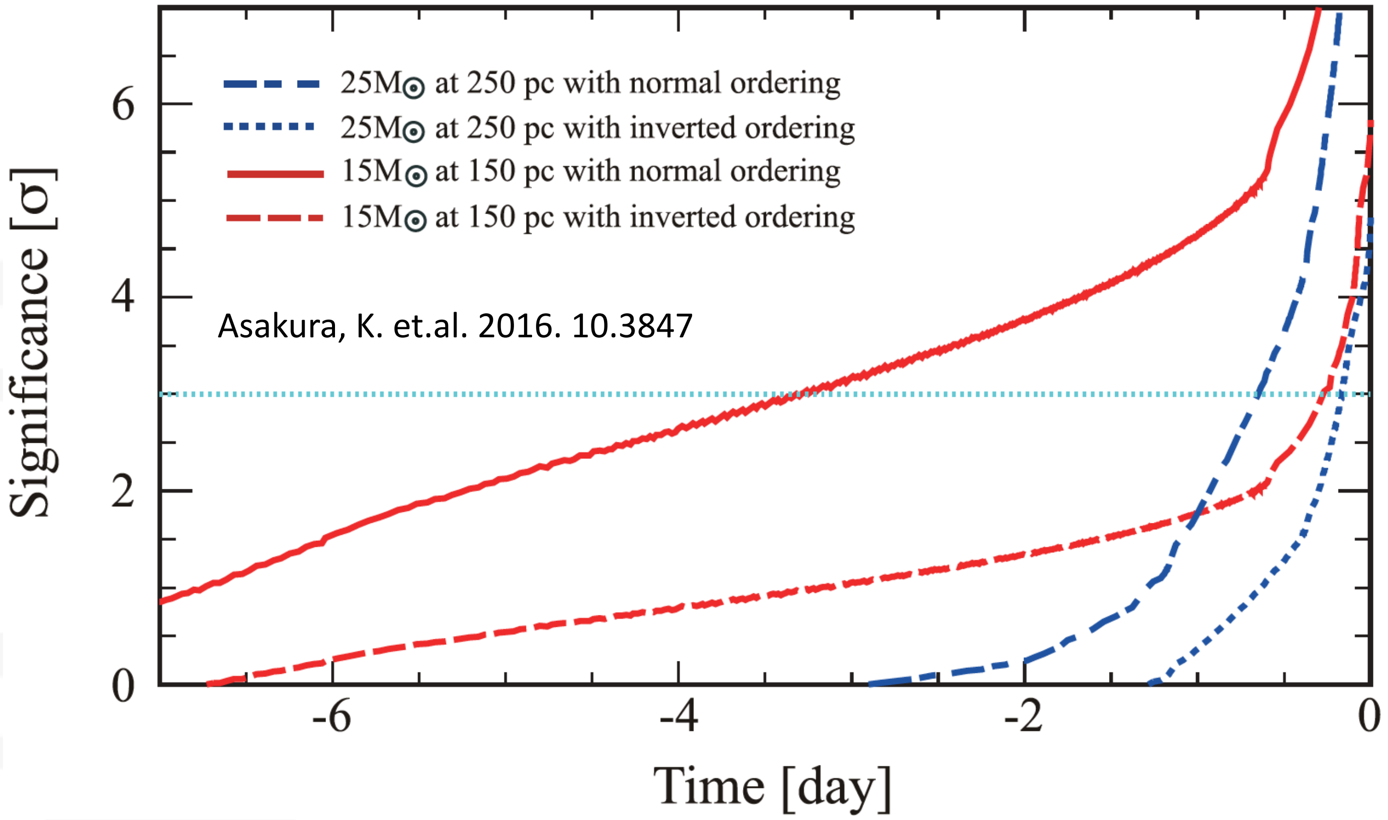
- γ-rays produced by the radioactive decay of $^{26}\mathrm{Al}$ (from massive stars):

Diehl, R., et.al. 2006. 0601015

==> ~ 2 events / century

1. CCSNe: Neutrino Signals





Significance if Betelgeuse star has a mass of 15M⊙ and with the distance at 150 pc, the 3σ detection by KamLAND

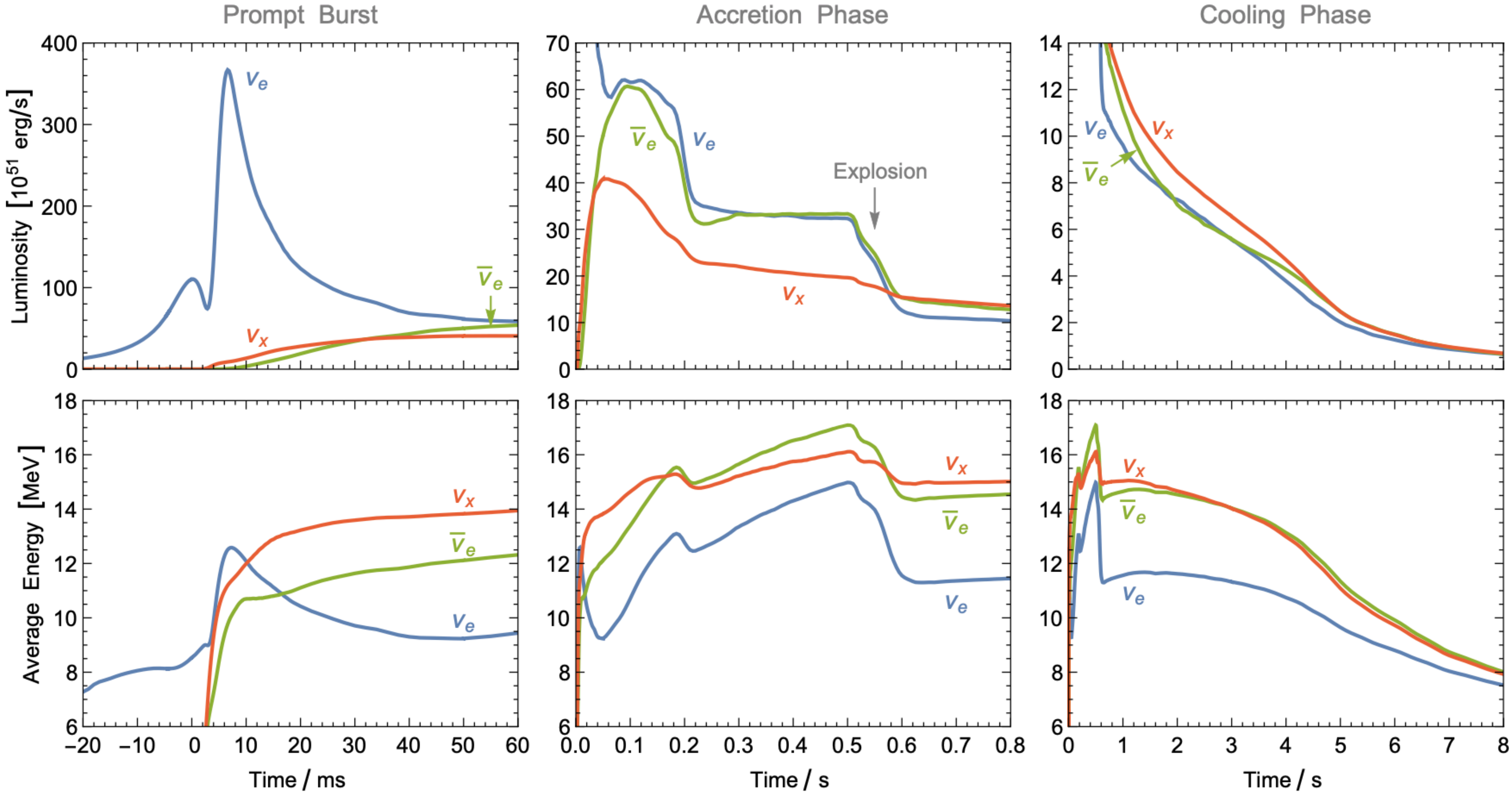
- pre-SN: MeV-neutrinos from thermal emission of advanced burning phases, ex: the Si burning.
- Could be detected by Borexino, KamLand, JUNO, DUNE, Super-K (+ ^{64}Gd)
- Main detection channel, IBD;

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Vitagliano, E. et.al. 2019. 1910. 11878

1. CCSNe: Neutrino Signals

Garching model, $27M_{\odot}$: https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/



Pagliaroli, G. 2009. Thesis

- After core bounce:
  - ➡ the luminosity of *neutronization burst* $\sim 3.5 \times 10^{53}\,\mathrm{erg/s}$,
  - ➡ ν_e dominant; ~10 ms
  - ➡ $\varepsilon_{\mathrm{bounce}} \sim 1\,\%\,\varepsilon_{\nu}$
  - ➡ A standard candle ==> observation/not ==> mass hierarchy; survival ν_e probability in MSW regions

Muller, B. 2019. 1904.11067

- In accretion:
  - ➡ $\langle E_{\bar{\nu}_e} \rangle \sim O(15)\,\mathrm{MeV}$;
  - ➡ timescale $\sim O(0.5-1)$ s
  - ➡ $\varepsilon_{\mathrm{acc}} \sim 10\,\%\,\varepsilon_{\nu}$
- Cooling phase:
  - ➡ similar luminosity for all, decreases exponentially,
  - ➡ $\langle E_{\nu} \rangle$ towards one value.
  - ➡ The decay time-scale of $\sim O(10)$ seconds.
  - ➡ $\varepsilon_{\mathrm{cool}} \sim 90\,\%\,\varepsilon_{\nu}$

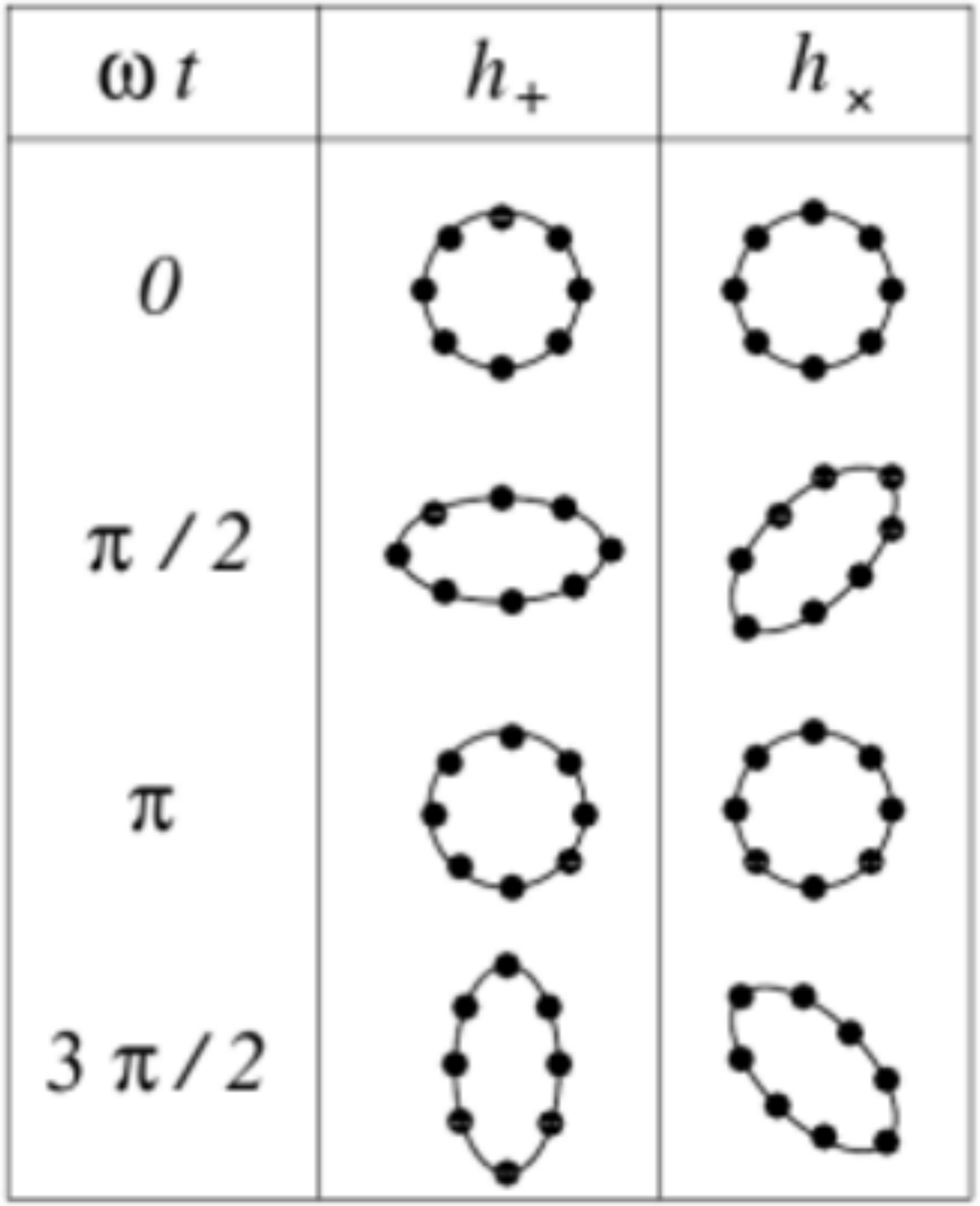
CC

$$e^- + p \to n + \nu_e$$
$$e^+ + n \to p + \bar{\nu}_e.$$

$e^+e^- \to \nu_i\bar{\nu}_i$	pair annihilation
$e^{\pm} + (p,n) \to e^{\pm} + (p,n) + \nu_i + \bar{\nu}_i$	electron – nucleon Bremsstrahlung
$\gamma_p \to \nu_i + \bar{\nu}_i$	plasmon decay
$\gamma + e^{\pm} \to e^{\pm} + \nu_i + \bar{\nu}_i$	photo annihilation,

NC

1. CCSNe: GW Signals



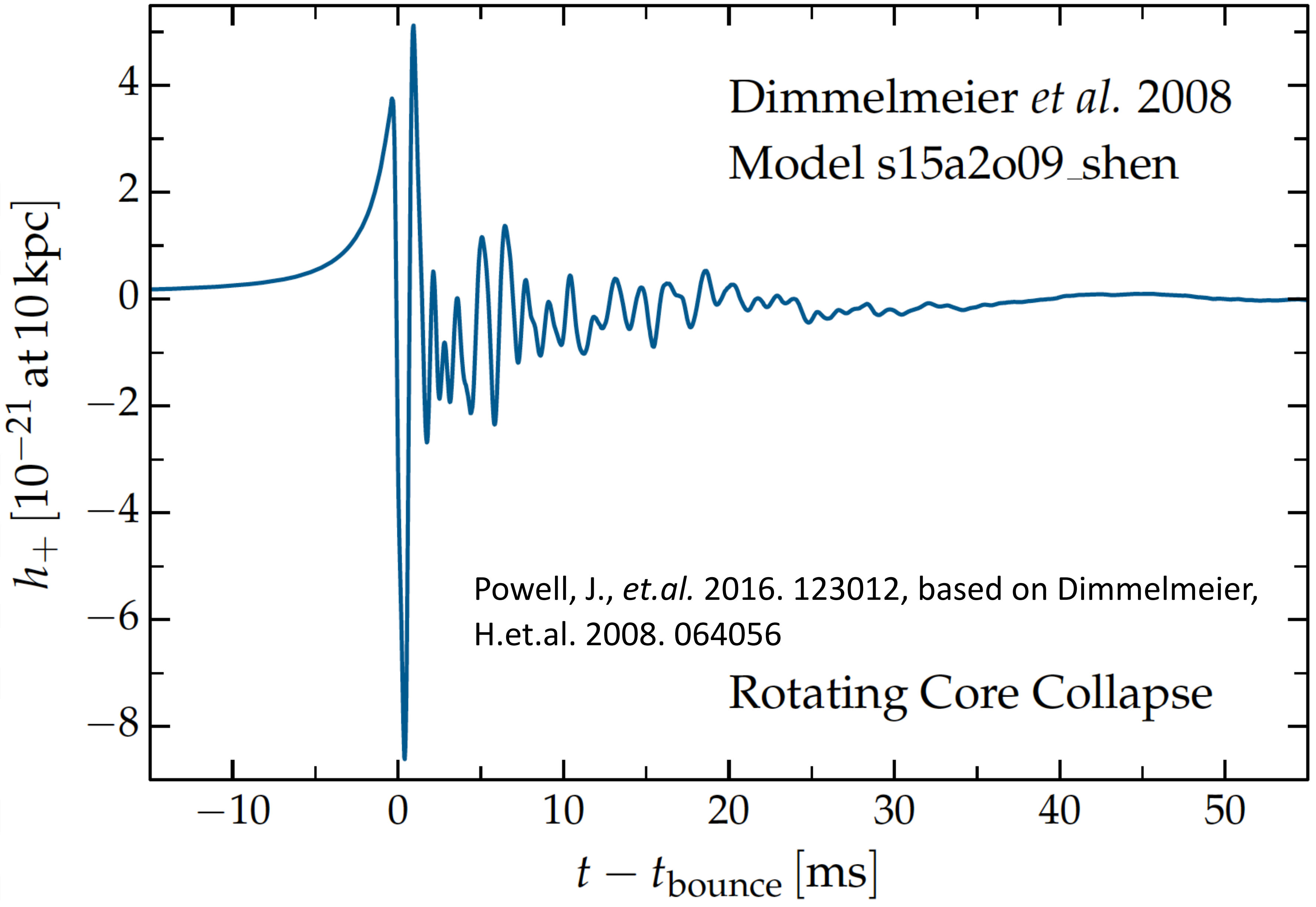
Maggiore, M. 2007. ISBN: 9780198570745.

- GWs: quadruple mass moment rapidly changing in time.

$$\left[h_{ij}^{\mathrm{TT}}(t,\mathbf{x})\right]_{\mathrm{quad}} = \frac{1}{r}\frac{2G}{c^4}\Lambda_{ij,kl}(\hat{n})\ddot{I}_{kl}(t-r/c)$$
$$= \frac{1}{r}\frac{2G}{c^4}\ddot{I}_{ij}^{\mathrm{TT}}(t-r/c),$$

$$\ddot{I}_{kl} = \int \rho\left(x_k x_l - \frac{1}{3}\delta_{jk}r^2\right)d^3x$$

1. CCSNe: GW Signals

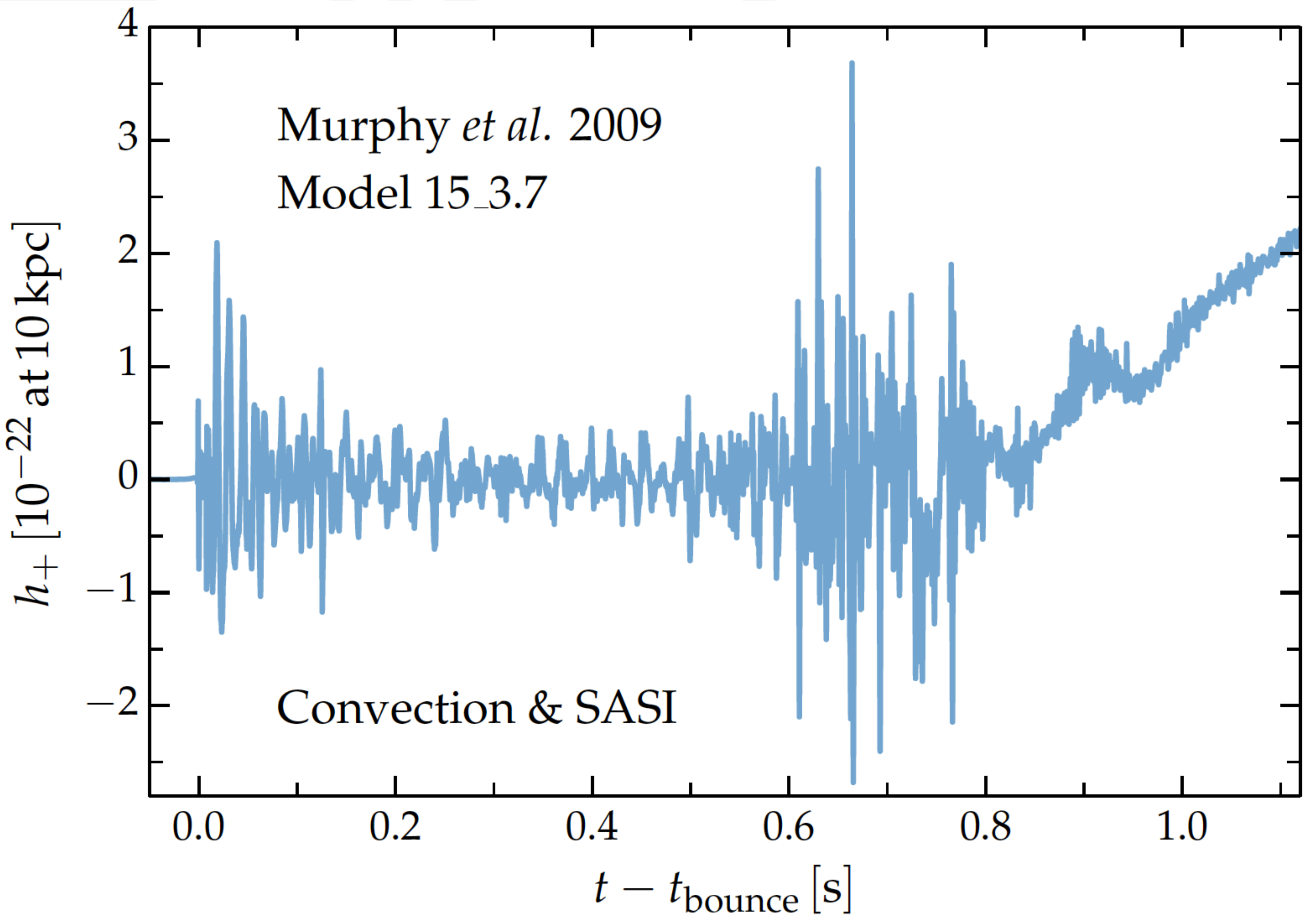


Powell, J., *et.al.* 2016. 123012, based on Dimmelmeier, H.et.al. 2008. 064056

- Magnetorotational Hydrodynamics,
- Source: Strong centrifugal deformation of inner core (~ oblateness), due to rapidly rotating precollapse core.
  - $p_{\mathrm{prog}} \sim 1\,\mathrm{s}; \quad p_{\mathrm{remnant}} \sim 1\,\mathrm{ms}$
  - $E_{\mathrm{rot}} \sim 10^{52}\,\mathrm{erg.}$
  - $h \sim 10^{-21} - 10^{-20}; \quad \mathrm{for}\ D \sim 10\,\mathrm{kpc}$
  - $E_{\mathrm{GW}} \sim 10^{-10} - 10^{-8} M_{\odot} c^2$
  - Narrowband frequency: 500-800Hz
  - Timescale of 10 ms

1. CCSNe: GW Signals

Powell, J., *et.al.* 2016. 123012, based on Murphy, J.W, et.al. 2009. 10.1088

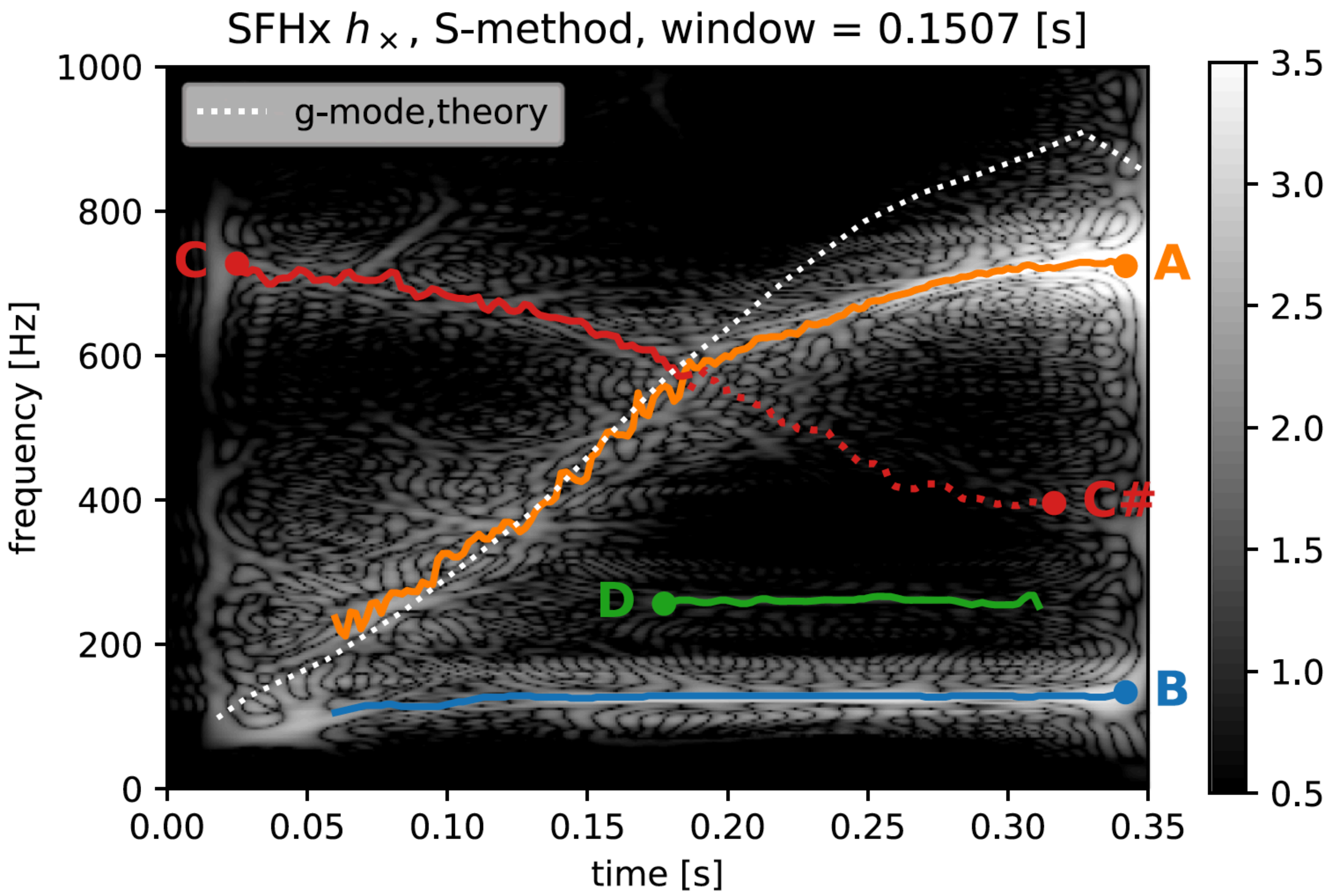


- Convection & SASI

1. prompt convection, immediately after the bounce, GWs lie on $\sim 100 - 300$ Hz,
2. ν-driven convection at later times, produces GWs with significant power on $\sim 300 - 1000$ Hz (frequency increases in time),
3. Proto neutron-star convection causes the time-varying quadruple mass moment happens in the highest frequency 1000 – 1100 Hz.
4. There will be gain in GWs at later times as the shock front becomes unstable
5. Lasting of about $\sim 0.3 - 2$ s
6. An order weaker than magnetorotational hydrodynamics,
    - $h \sim 10^{-22}$ at 10 kpc.
    - $E_{\mathrm{GW}} \sim 10^{-11} - 10^{-9} M_\odot c^2$

1. CCSNe: GW Signals

Kuroda, T. et.al., 2016 based on Steiner, A.W., et.al. 2013



- *g*-mode oscillation from acoustic power generated in the inner core.
- Oscillation period of 3 ms,
- growing ~ 500 ms after bounce

A. is *g*-mode mechanism

B. is mass accretion by SASI

C. is *p*-mode

D. is overtone of SASI

1. CCSNe: GW Signals

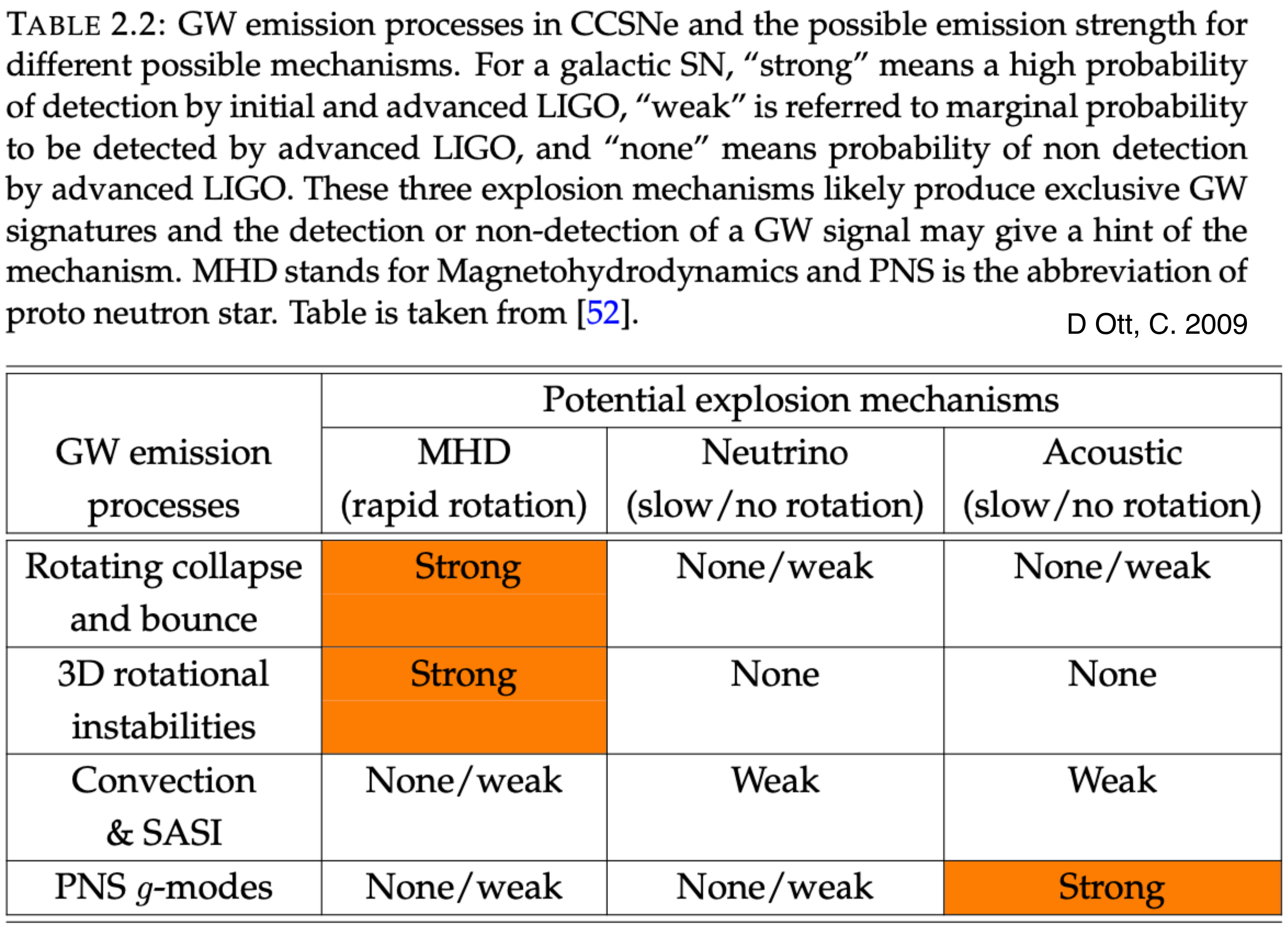


TABLE 2.2: GW emission processes in CCSNe and the possible emission strength for different possible mechanisms. For a galactic SN, "strong" means a high probability of detection by initial and advanced LIGO, "weak" is referred to marginal probability to be detected by advanced LIGO, and "none" means probability of non detection by advanced LIGO. These three explosion mechanisms likely produce exclusive GW signatures and the detection or non-detection of a GW signal may give a hint of the mechanism. MHD stands for Magnetohydrodynamics and PNS is the abbreviation of proto neutron star. Table is taken from [52].

D Ott, C. 2009

GW emission processes	Potential explosion mechanisms		
	MHD (rapid rotation)	Neutrino (slow/no rotation)	Acoustic (slow/no rotation)
Rotating collapse and bounce	Strong	None/weak	None/weak
3D rotational instabilities	Strong	None	None
Convection & SASI	None/weak	Weak	Weak
PNS g-modes	None/weak	None/weak	Strong

1. CCSNE: Detectors

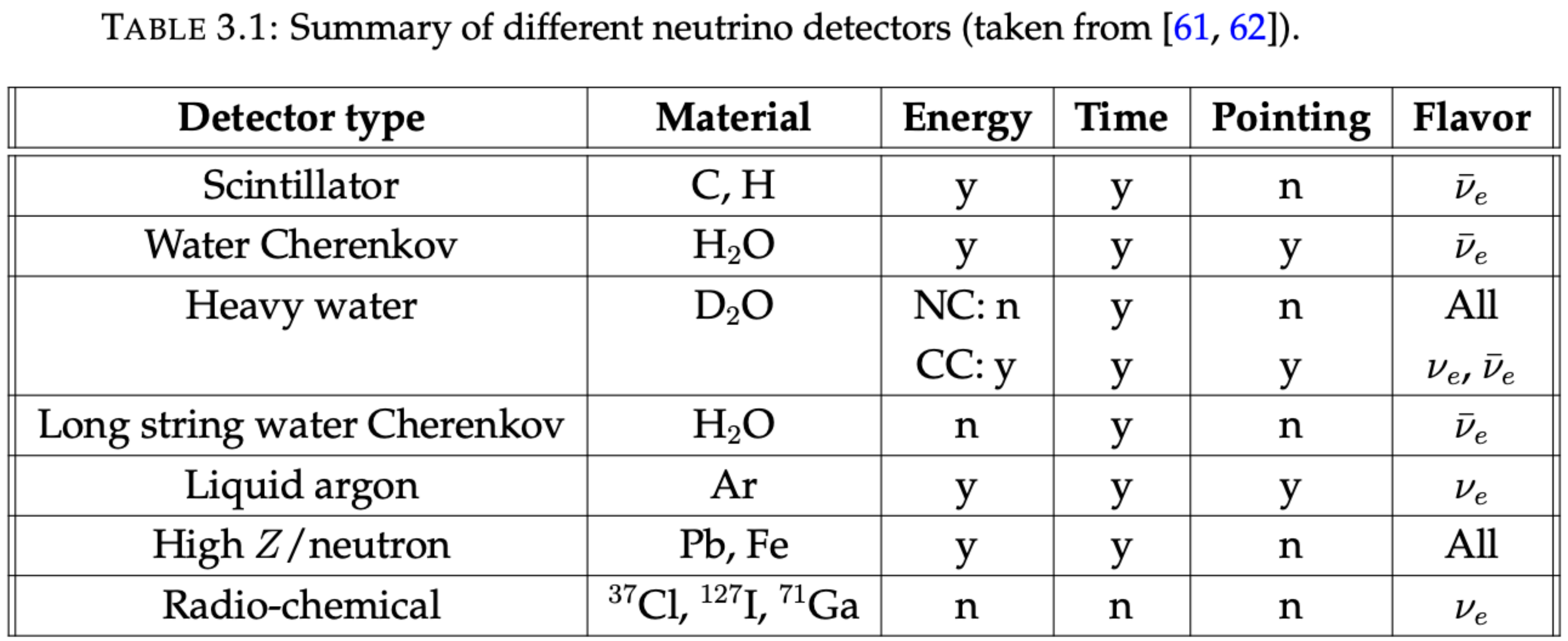


TABLE 3.1: Summary of different neutrino detectors (taken from [61, 62]).

Detector type	**Material**	**Energy**	**Time**	**Pointing**	**Flavor**
Scintillator	C, H	y	y	n	$\bar{\nu}_e$
Water Cherenkov	H_2O	y	y	y	$\bar{\nu}_e$
Heavy water	D_2O	NC: n	y	n	All
		CC: y	y	y	$\nu_e, \bar{\nu}_e$
Long string water Cherenkov	H_2O	n	y	n	$\bar{\nu}_e$
Liquid argon	Ar	y	y	y	ν_e
High Z/neutron	Pb, Fe	y	y	n	All
Radio-chemical	^{37}Cl, ^{127}I, ^{71}Ga	n	n	n	ν_e

Scholberg, K. 2001

Antonioli, P, *et.al.* 2004

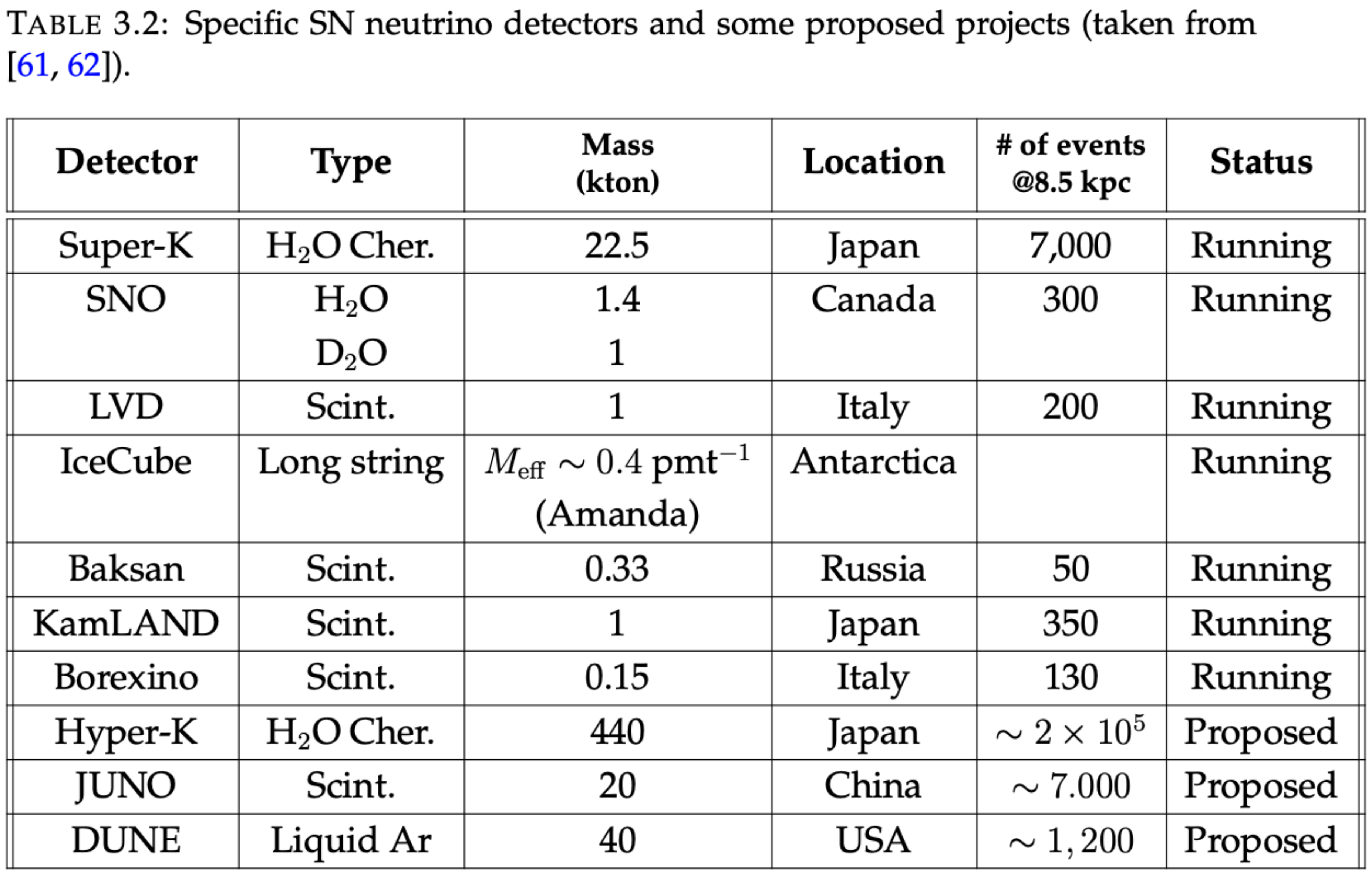
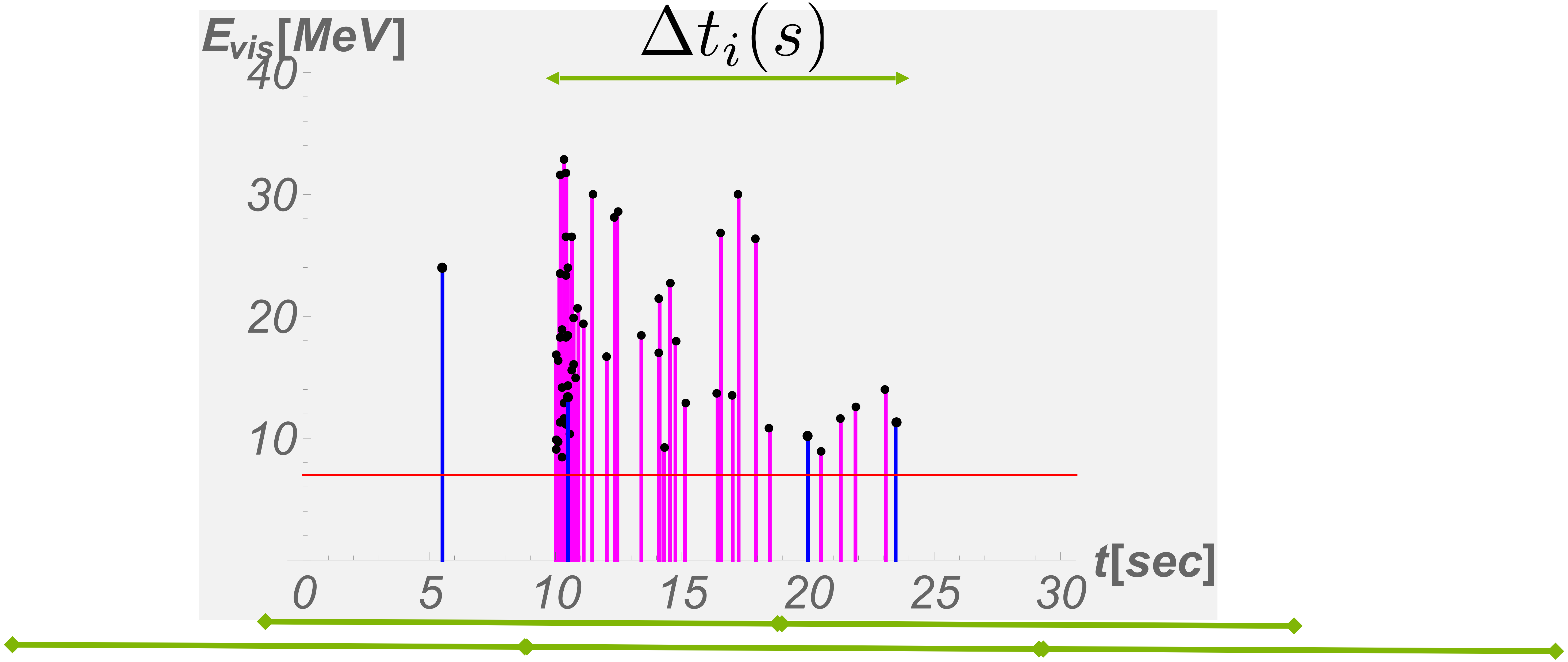


TABLE 3.2: Specific SN neutrino detectors and some proposed projects (taken from [61, 62]).

Detector	**Type**	**Mass (kton)**	**Location**	**# of events @8.5 kpc**	**Status**
Super-K	H_2O Cher.	22.5	Japan	7,000	Running
SNO	H_2O	1.4	Canada	300	Running
	D_2O	1			
LVD	Scint.	1	Italy	200	Running
IceCube	Long string	$M_{\text{eff}} \sim 0.4$ pmt^{-1} (Amanda)	Antarctica		Running
Baksan	Scint.	0.33	Russia	50	Running
KamLAND	Scint.	1	Japan	350	Running
Borexino	Scint.	0.15	Italy	130	Running
Hyper-K	H_2O Cher.	440	Japan	$\sim 2 \times 10^5$	Proposed
JUNO	Scint.	20	China	~ 7.000	Proposed
DUNE	Liquid Ar	40	USA	$\sim 1,200$	Proposed

1. CCSNe: Counting Analysis

The observation of astrophysical burst clusters



$w \sim O([\text{seconds}])$

m_i

Number of events inside the window = a cluster

1. CCSNe: Analysis by Super-K

Super Kamikande (Super-K): IBD, $\bar{\nu}_e$

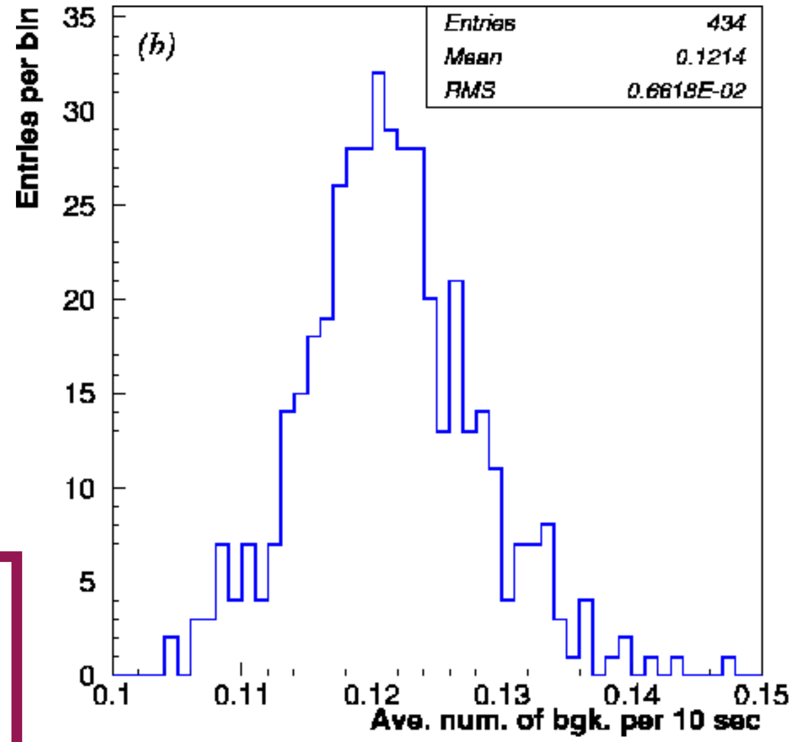
Offline:
Signal tend to spread in detector volume, while background is not—> parameter

1. Distant search -> M31: $m \geq 2;\ E_{\mathrm{thr}} = 17\,\mathrm{MeV}$
2. Low energy threshold; $E_{\mathrm{thr}} = 7\,\mathrm{MeV}$:
   $m \geq 3$ for $w = [0.5\,\mathrm{s}]$;
   $m \geq 4$ for $w = [2\,\mathrm{s}]$;
   $m \geq 8$ for $w = [10\,\mathrm{s}]$;
   if ties, take highest m
3. Neutronization burst search; $E_{\mathrm{thr}} = 7\,\mathrm{MeV}$:
   $w = \{1, 10, 100\}\,[\mathrm{ms}]$

Ikeda, M., *et.al.* 2007

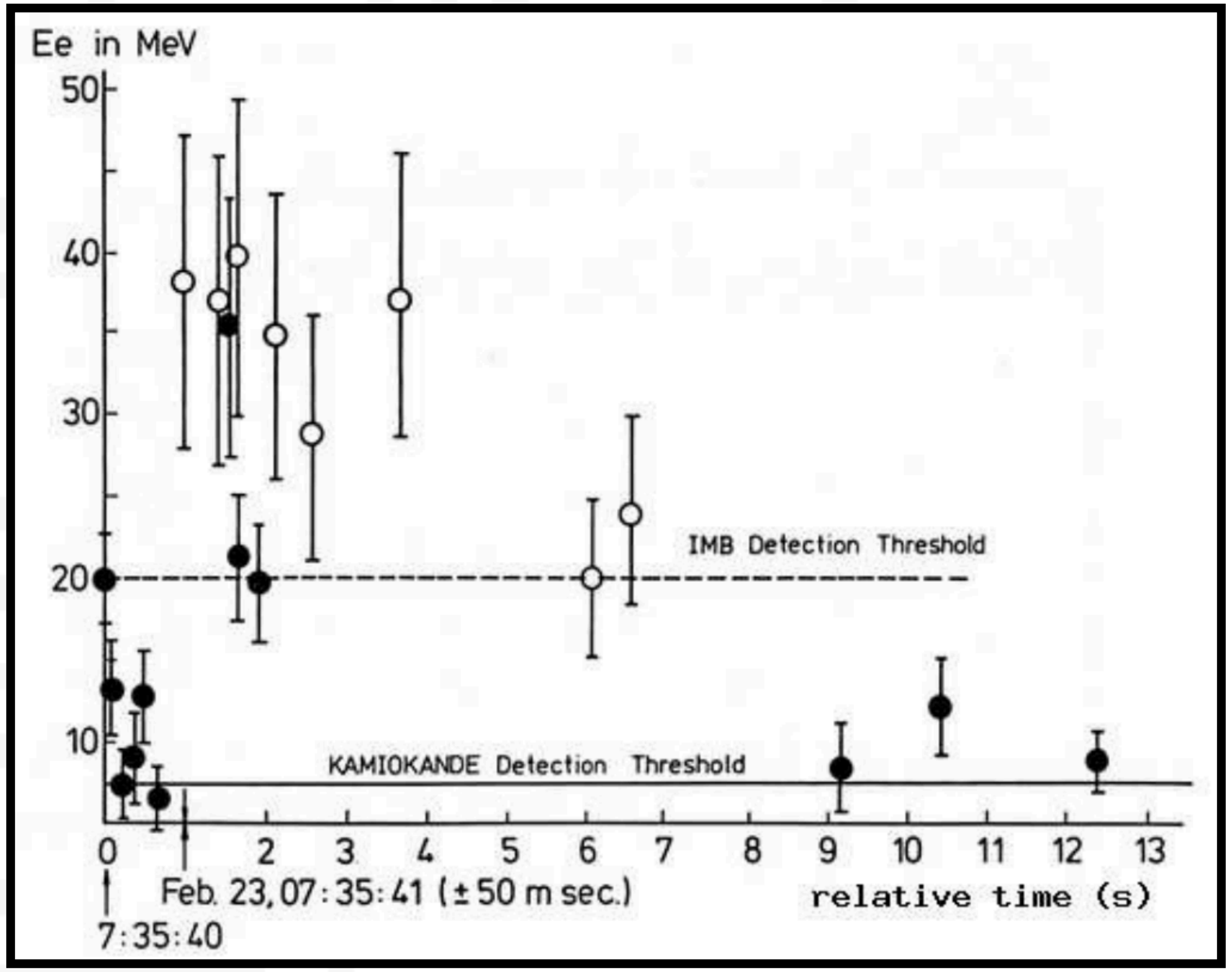
Online:
Spatial distribution parameter cut

1. Golden warning: $m \geq 60;\ w = 20\,\mathrm{s} \Rightarrow$ 1 hour public
2. Silver warning: $m \geq 25\ w = 20\,\mathrm{s} \Rightarrow$ to experts/SNEWS
3. “Silent” warning : $m \geq 13\ w = 10\,\mathrm{s} \Rightarrow$ BG studies



Abe, K. *et.al.* 2016

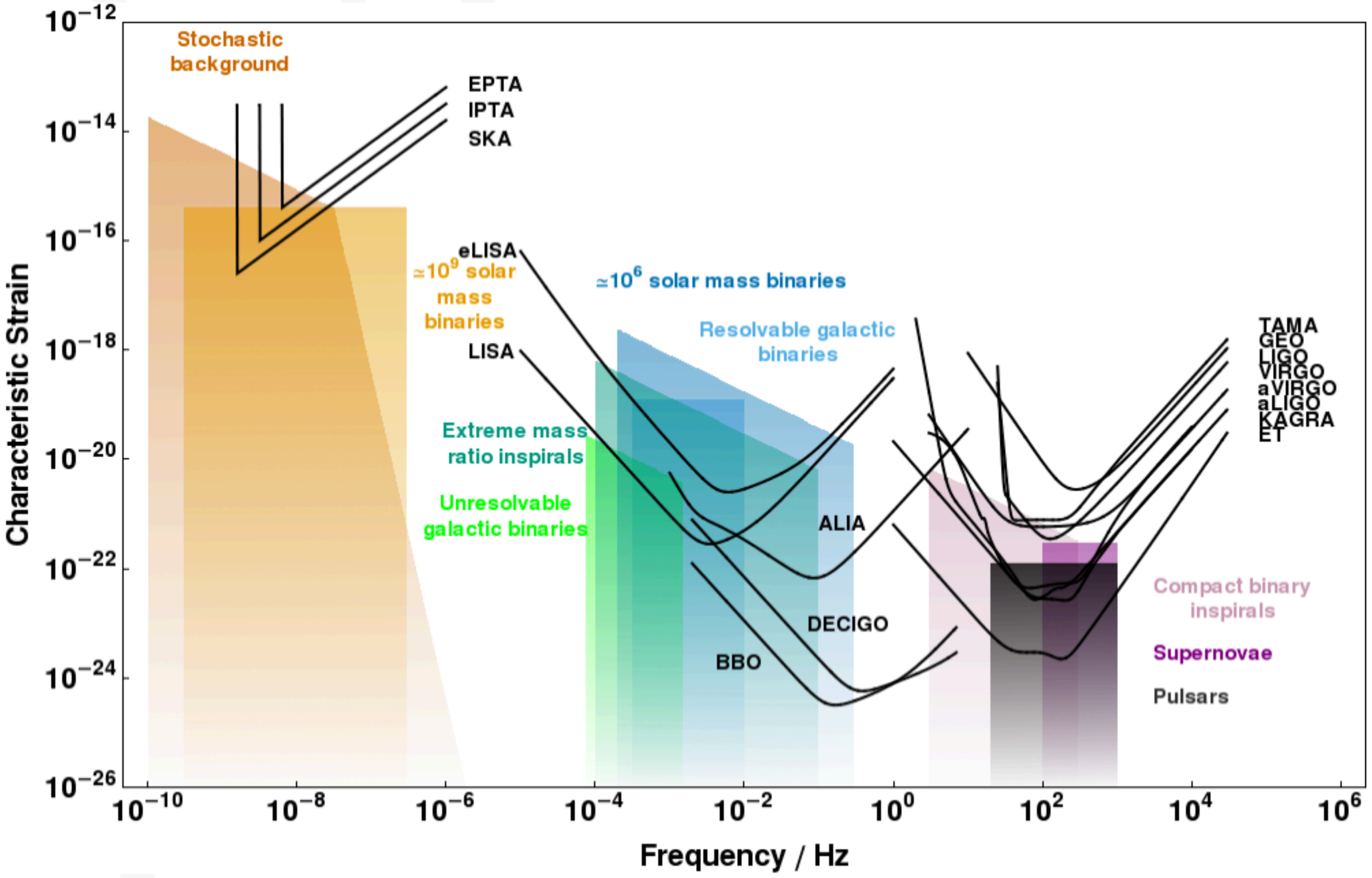
1. CCSNe: SN1987A



- SN1987A, nobel in physics, 2002
- The first-and-only detection via MeV-neutrinos in the nearby galaxies; guided by a preceeded optical sighting
    - ☑ Kamiokande II; water Cherenkov
    - ☑ Irvine-Michigan-Brookhaven (IMB); water Cherenkov
    - ☑ Baksan; scintillator
- Progenitor:
    - ✱ Sanduleak $-69^\circ\, 202\mathrm{a}$, blue supergiant,
    - ✱ magnitude 12,
    - ✱ $M_{\mathrm{prog}} \sim 15 M_\odot,\, D \sim 50\,\mathrm{kpc}$ (LMC)

1. CCSNe: GW Detectors

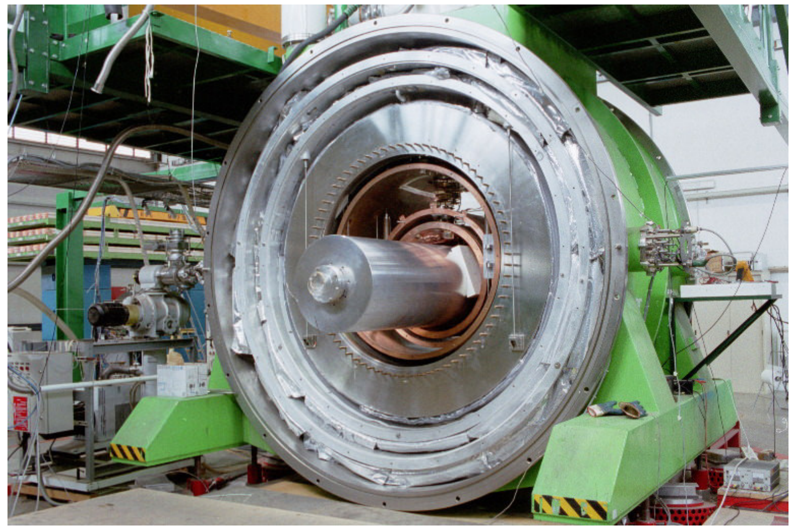
- Bar detectors, ~1970s: 800-1000 Hz
- Michelson ITF, ~1994-now: Virgo, LIGO, Kagra, GEO600
- Pulsar Timing Array
- Future: eLISA, Einstein Telescope, Cosmic Explorer,…



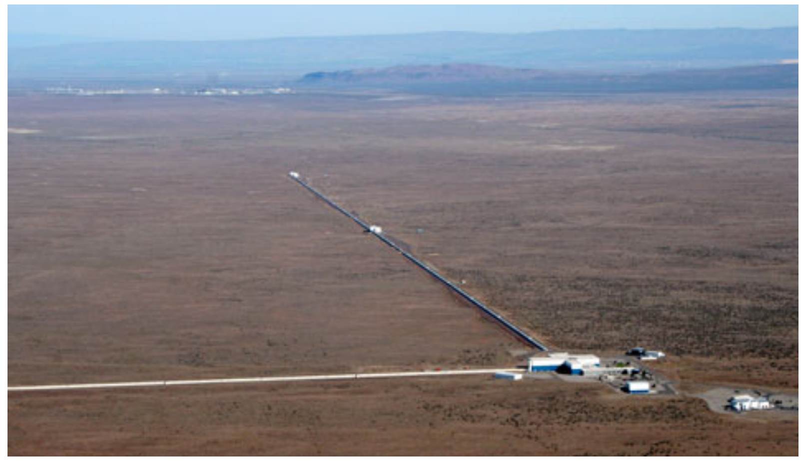
Moore, CJ, et.al. 2014. 1408.0740

Virgo, Italy

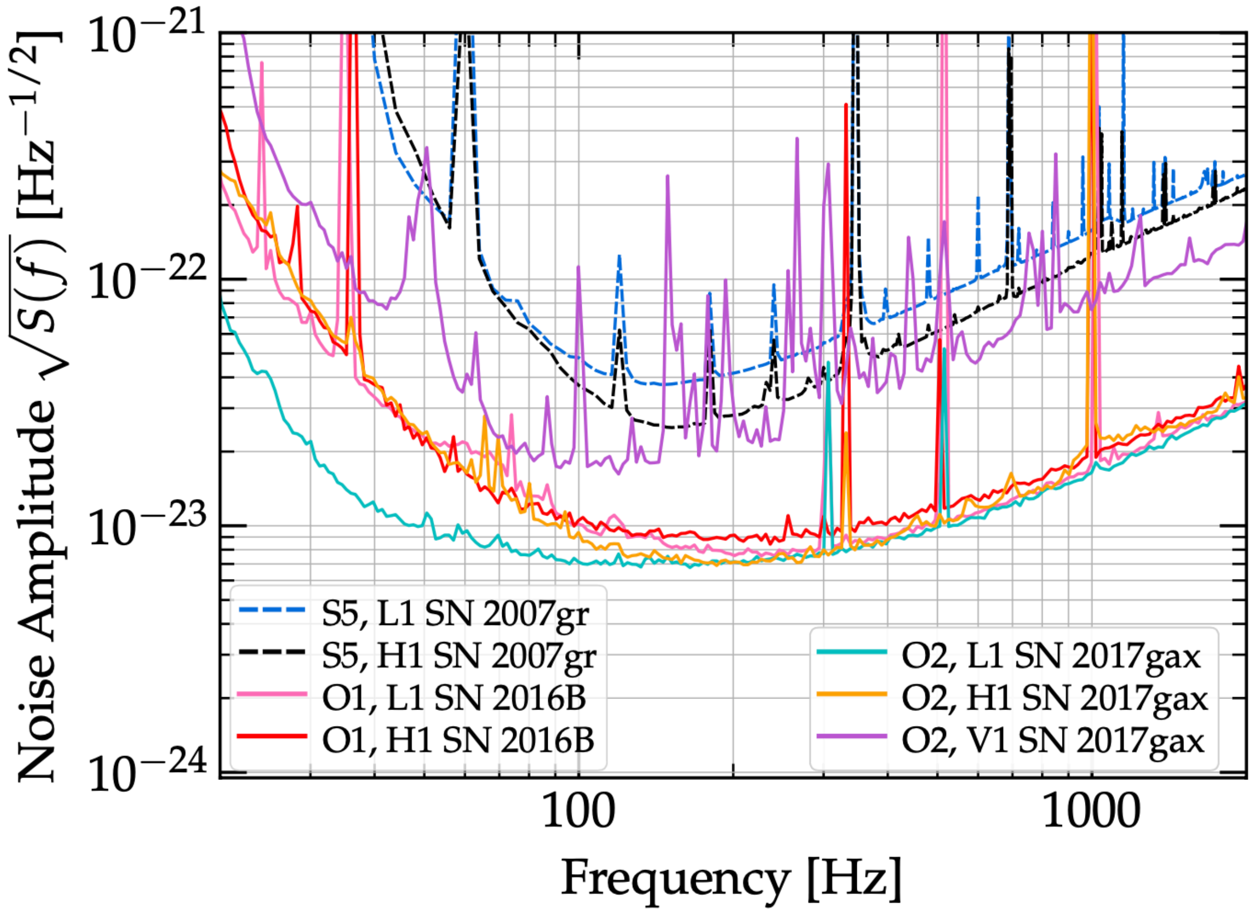
Nautilus, Rome



LIGO-H, USA



LIGO-L, USA



Abbott, BP, *et.al.* 2019

1. CCSNe: cWB and Wavelet Transform

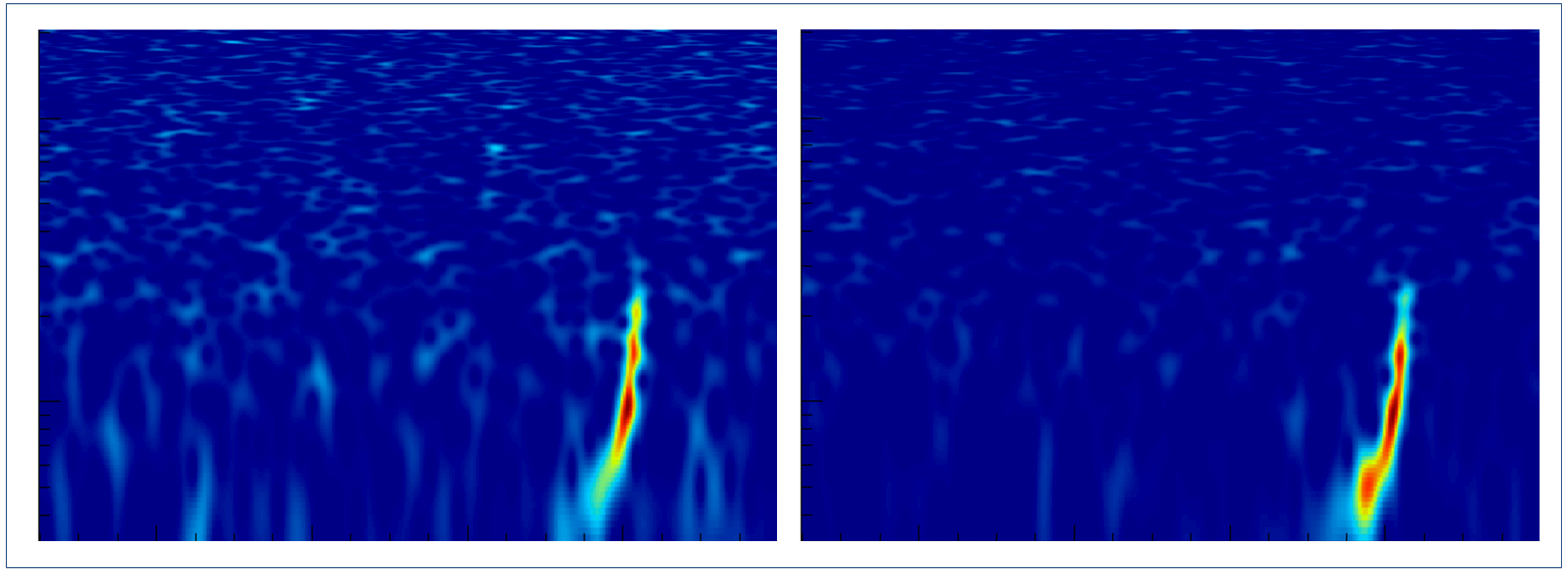
- GW burst pipeline: pyCBC, X-pipeline, coherentWave Burst (cWB)
    - ➡ pyCBC: matched filter, **needs models**, CBC model is robust
    - ➡ cWB: generic burst / short duration, online, **no prior model needed** ===> useful for CCSNe
- GW150914 **online detection by cWB**.
- Time-frequency analysis: time series data to time-frequency map.
- TF: Short-time Fourier transform (STFT), **wavelet transform**

Necula, V, et.al. 2012. 10.1088

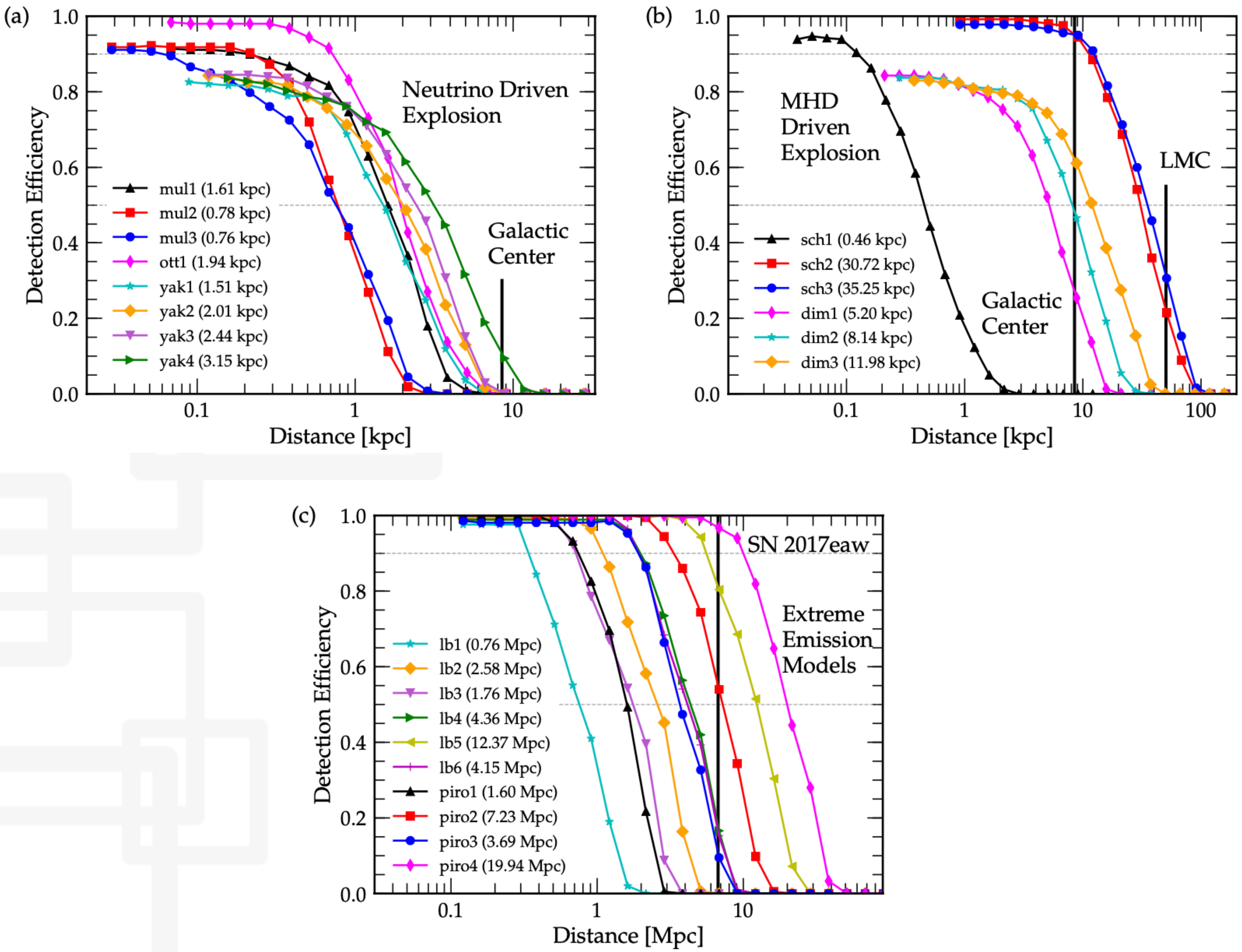
- cWB last version: fast Wilson-Daubechies time-frequency transform combined with the Meyer wavelet (**WDM**)

gwburst.gitlab.io

Left: LL; Right: LH



1. CCSNe: Efficiency of CCSN Search

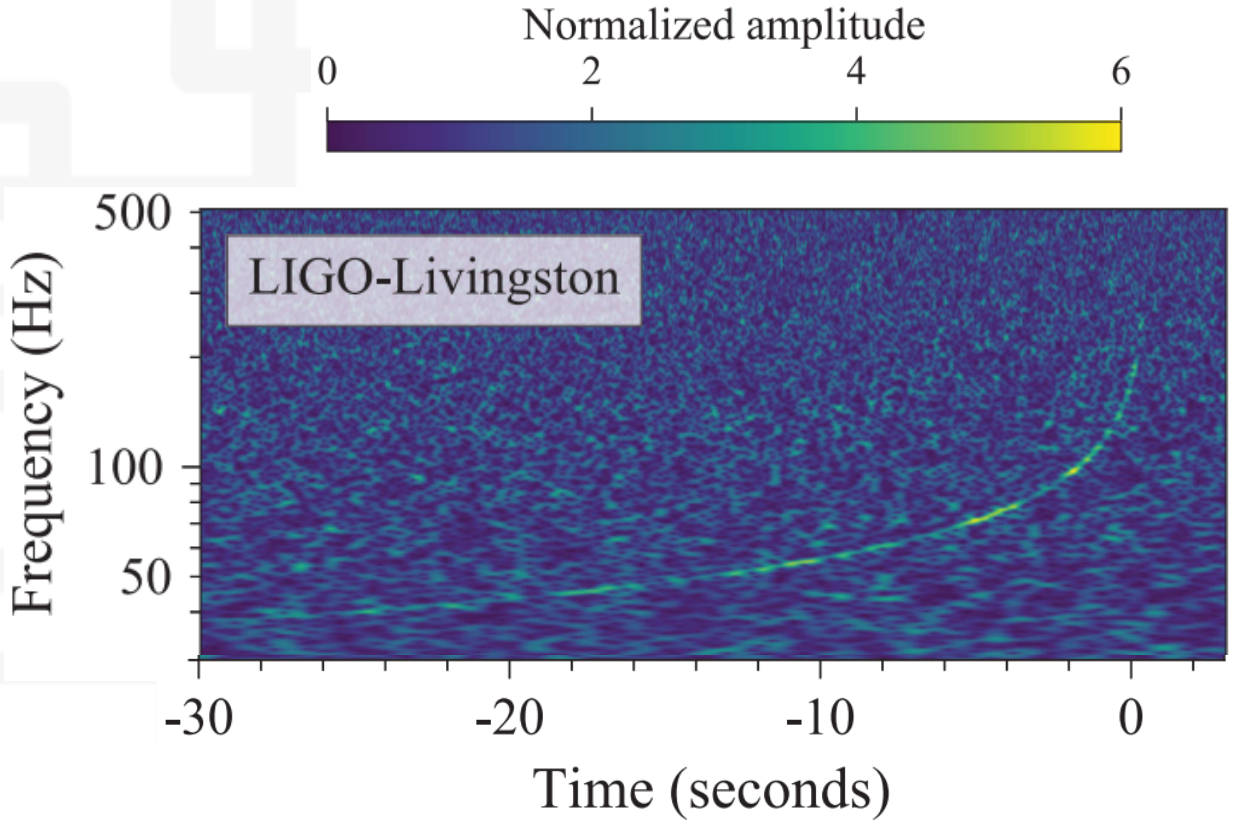


- Efficiency studies of CCSN search via cWB with EM triggers
- real EM observations < 20Mpc
- 50% efficiency:
    - ➡ 5 kpc for ν-driven explosions (**< the galactic center**)
    - ➡ 54 kpc for magnetorotational explosions

Abbott BP, *et.al.* 2019. 1908.03584

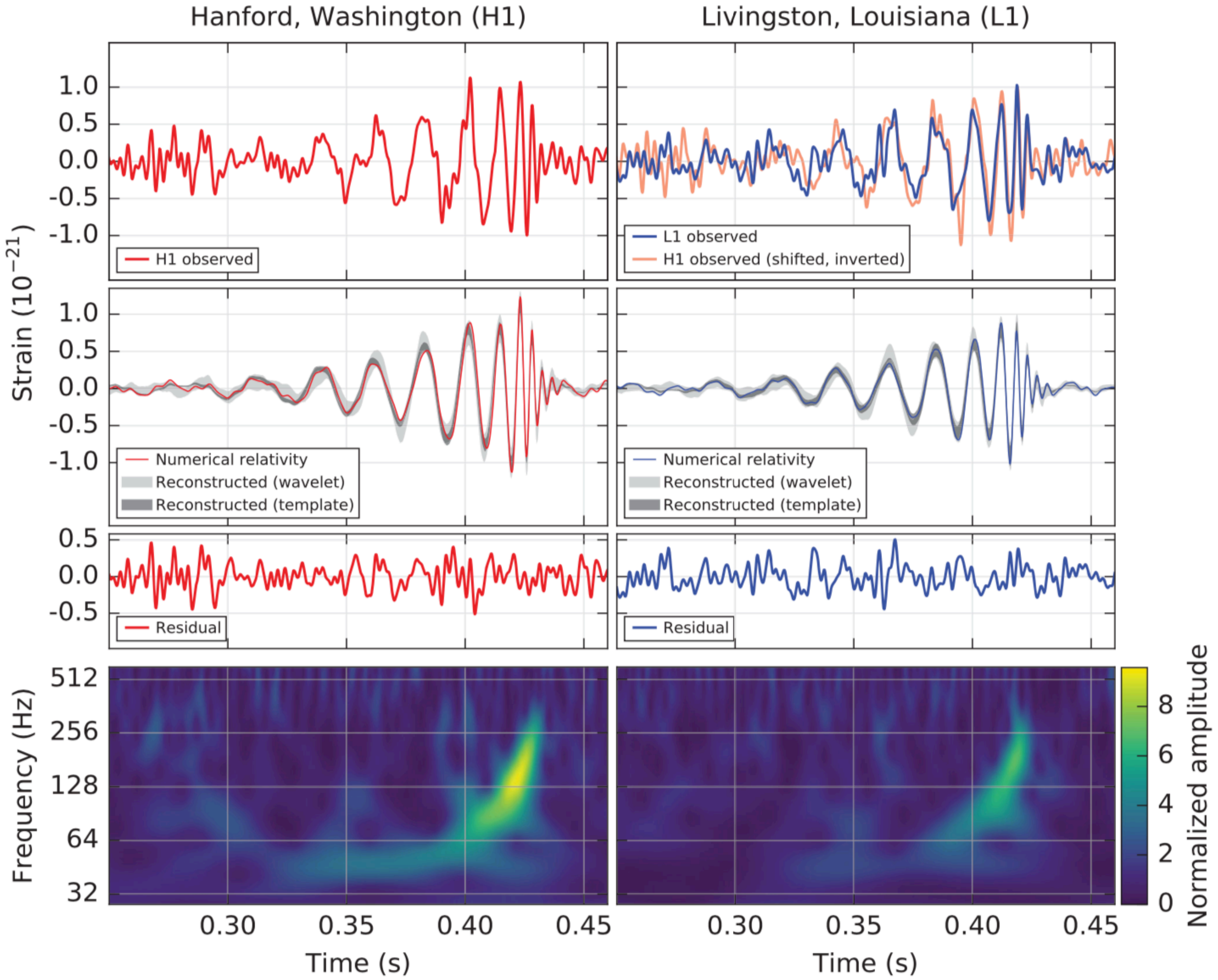
1. GW Observations

- GW150914: BBH, H-L, $h \sim O(10^{-21})$ **@440 Megaparsec**
- GW170814: BBH, H-L-V, $1160\,\mathrm{deg}^2 \rightarrow 60\,\mathrm{deg}^2$
- GW170817: BNS, multimessenger: HLV-Fermi GBM-INTEGRAL-…(+ optical, X-ray, radio, but no neutrino)
- GW from CCSN??? Not yet, but *perhaps/hopefully* soon.



Abbott, BP, *et.al.* 2017. 119.161101

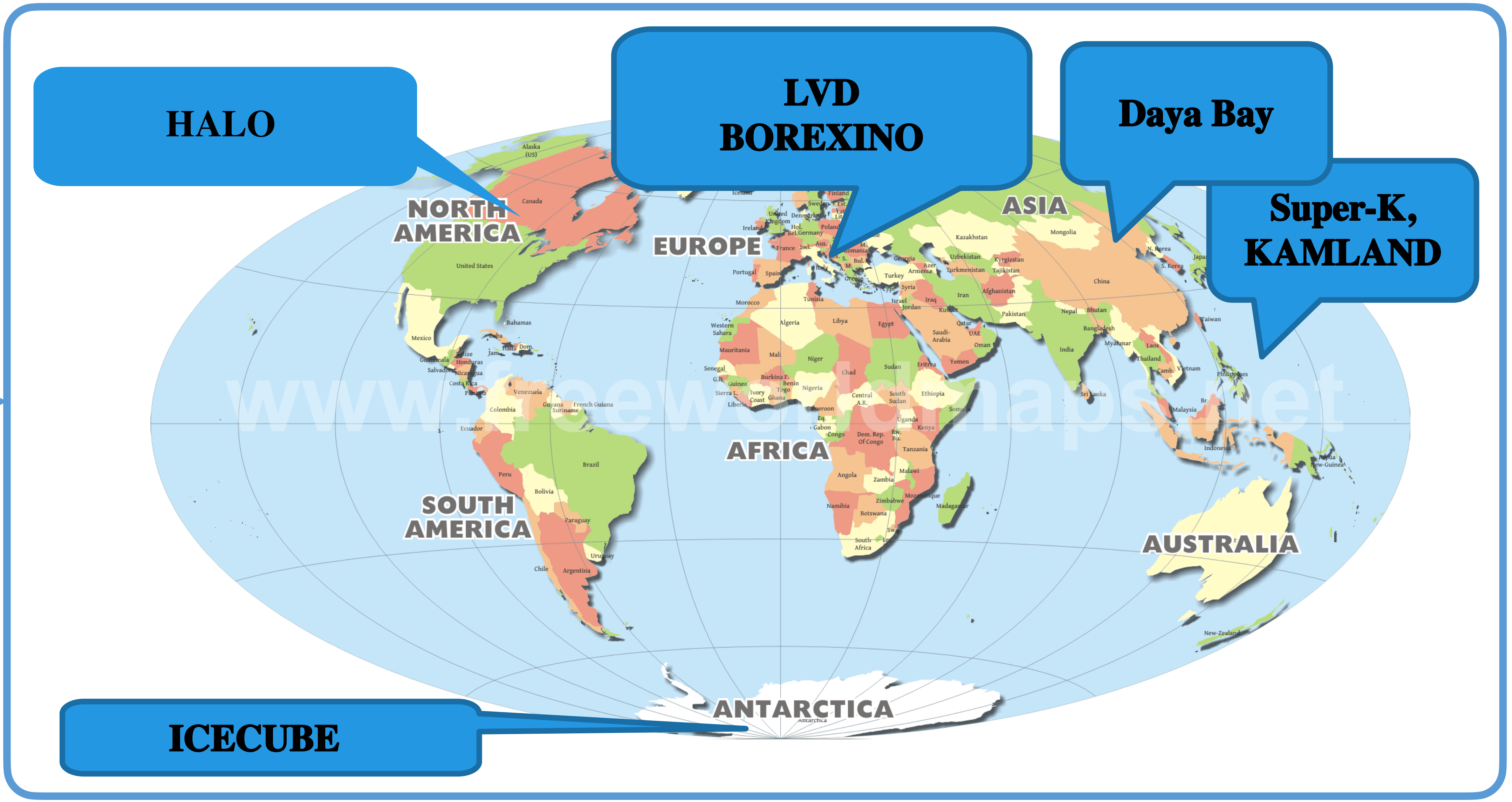
CCSN: $h \sim 10^{-22}$
@10 kiloparsec



Abbott, BP, *et.al.* 2016. 116.061102

1. CCSNe: Multimessenger Efforts

SuperNova Early Warning System (SNEWS)



GWν working group: Borexino, IceCube, LVD, LIGO-Virgo, KamLAND

SNEWS2.0

SN1987A. Credit: ESO

1. CCSNe

(a) Astrophysical mechanisms and signals

(b) Rate and distribution

(c) Neutrino and GW:

- ☑ Detectors
- ☑ Signals
- ☑ Analysis

(d) Multimessenger efforts

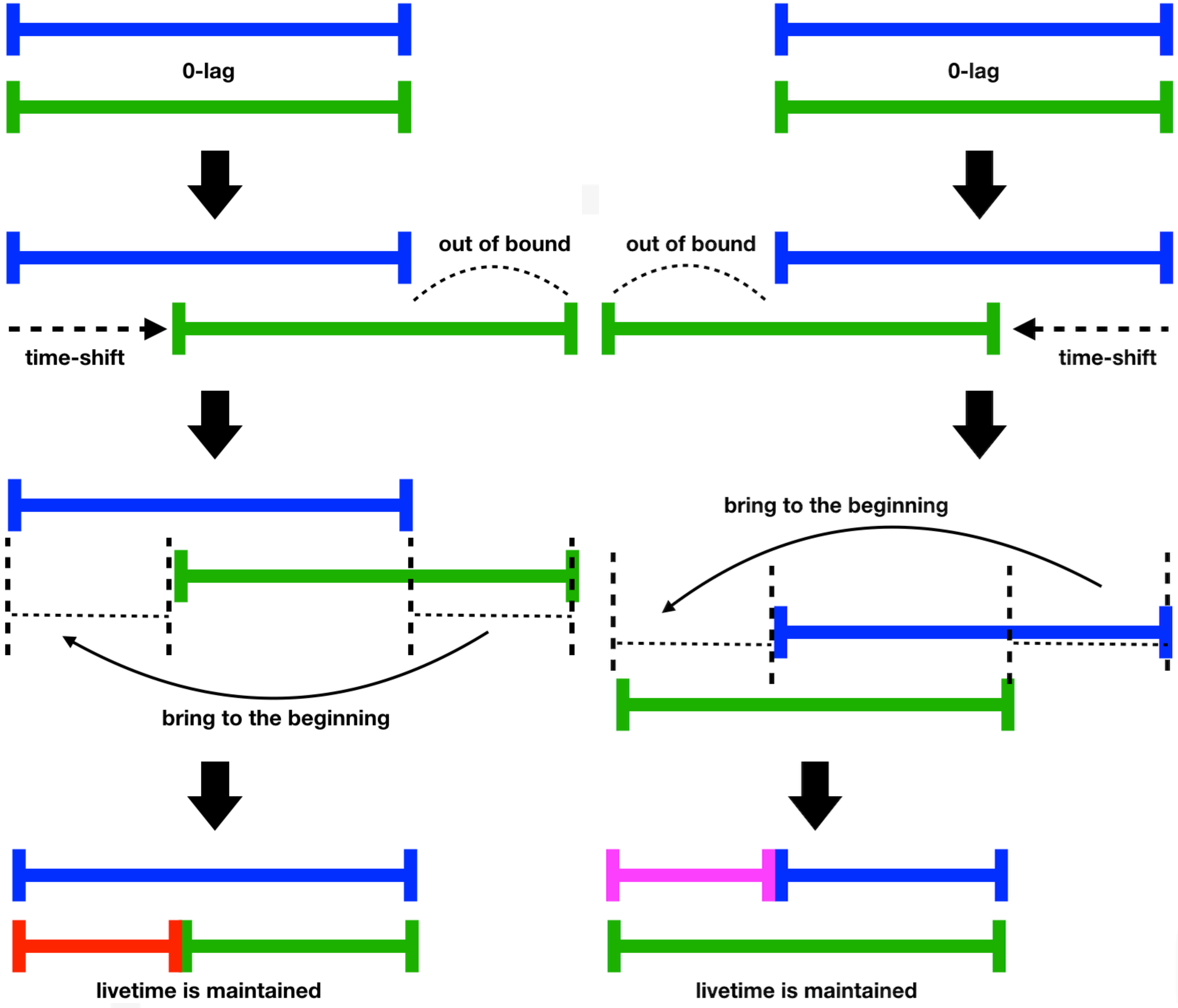
2. Coincidence Analysis

- It is used in several GW pipelines: cWB, pyCBC, GstLAL, …
- to suppress the background by cross-correlating some n time-series data sets from n different detectors
    - ☑ Neutrinos: clusters
    - ☑ GW: triggers from cWB
- 0-lag coincidences: two sets of time series data are compared with window w_c.

  ==> candidates
- The common observing time between two data sets ==> [livetime]
- Significance?
    - ✺ The time-shifting method ==> GW-like: need to have a common statistic among data sets.
    - ✺ The product method ==> SNEWS-like

2. Time-shifting

N shifts; [delay] $\gg w_c$



$$\rho_{\text{joint}} \equiv \sqrt[n]{\prod_{i=1}^{n} \rho_i}$$

$$\text{FAR}_i = \frac{[\text{number of candidates with } \rho_{\text{joint}} > \rho_{[\text{joint},0],\text{i}}]}{[\text{cumulative livetime of } N \text{ lags}]}$$

$$\text{FAP}_i = 1 - \exp(-\text{FAR}_i \times \text{livetime}_{0\text{lag}})$$

- $\text{FAP}_{5\sigma} = 5.7 \times 10^{-7}$
  - ➡ Total livetime: $N \times \text{livetime}_{0\text{lag}}$
  - ➡ Min FAR $= \dfrac{1}{[N \times \text{livetime}_{0\text{lag}}]}$
  - ➡ Min FAP $= 1 - \exp(-1/N)$
  - ➡ $N > 1.75 \times 10^6$
  - ➡ Livetime > delay * N
- Otherwise, repeating the data set configuration
- Fine for GW since $w_c = 30$ **milliseconds** ==> livetime needed O(**days**)
- Neutrino? $w_c = 20$ **seconds** ==> livetime O(**3 years**)

NO WAY

2. The Product Method

- No need to have a common statistic ==> Good for multimessenger
- No minimum livetime. It can even be: $2 \times w_c$

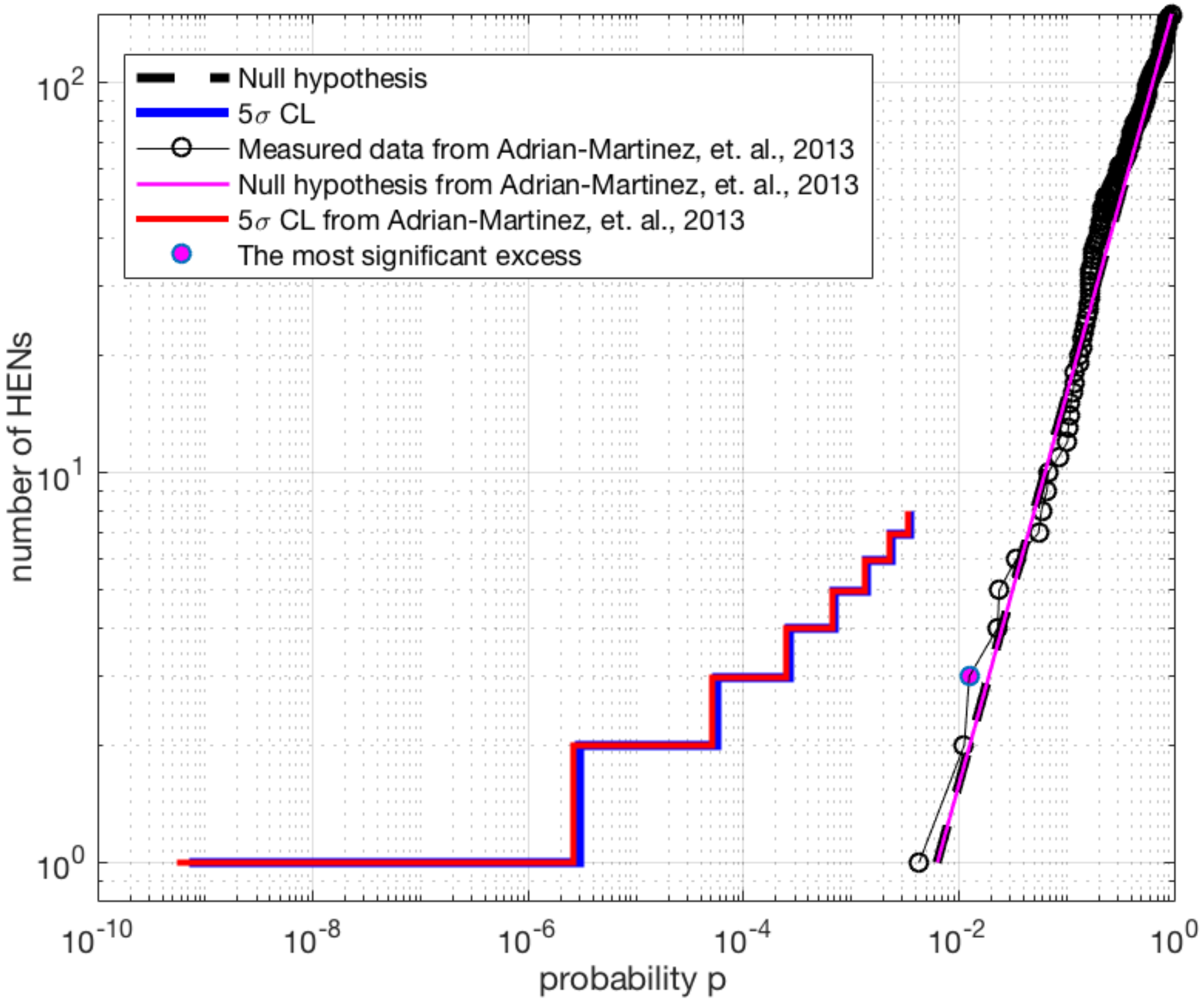
$$\mathrm{jointFAR}_i = \mathrm{Net} \times w_c^{\mathrm{Net}-1} \prod_{X=1}^{\mathrm{Net}} \mathrm{FAR}_{X,i}$$

$$\mathrm{jointFAP}_i = 1 - \exp(-\mathrm{jointFAR}_i \times \mathrm{livetime}_{0\mathrm{lag}})$$

$$i = \{\mathrm{V}, \mathrm{LL}, \mathrm{LH}, \mathrm{K}, \mathrm{SK}, \mathrm{Borexino}, \mathrm{LVD}, \ldots\}$$

3.1. Increasing Sensitivity of ν-Detectors: Binomial Test

- GW-GRB: Abbott B, *et.al.* 2008
- GW-HEN: Adrián-Martínez, S. *et.al.* 2013; Di Palma, I. 2014
- From each GRB (HEN), **no significance value**. The significance comes from GW analysis only
- Our joint-analysis of GW-LEN uses both data channels **coherently** and determine whether there is (are) interesting candidate(s).
- Our LEN triggers **have their own significance values**.
- No need to go further with this method



3.2. Increasing Sensitivity of ν-Detectors: Astrophysical Bursts of Low-Energy Neutrinos

Casentini, C. *et.al.* 2018. 10.1088

- $\varepsilon_\nu = 3 \times 10^{53}\,\mathrm{erg}$
- Equipartition for 6-neutrino species
- Double exponential model time evolution:

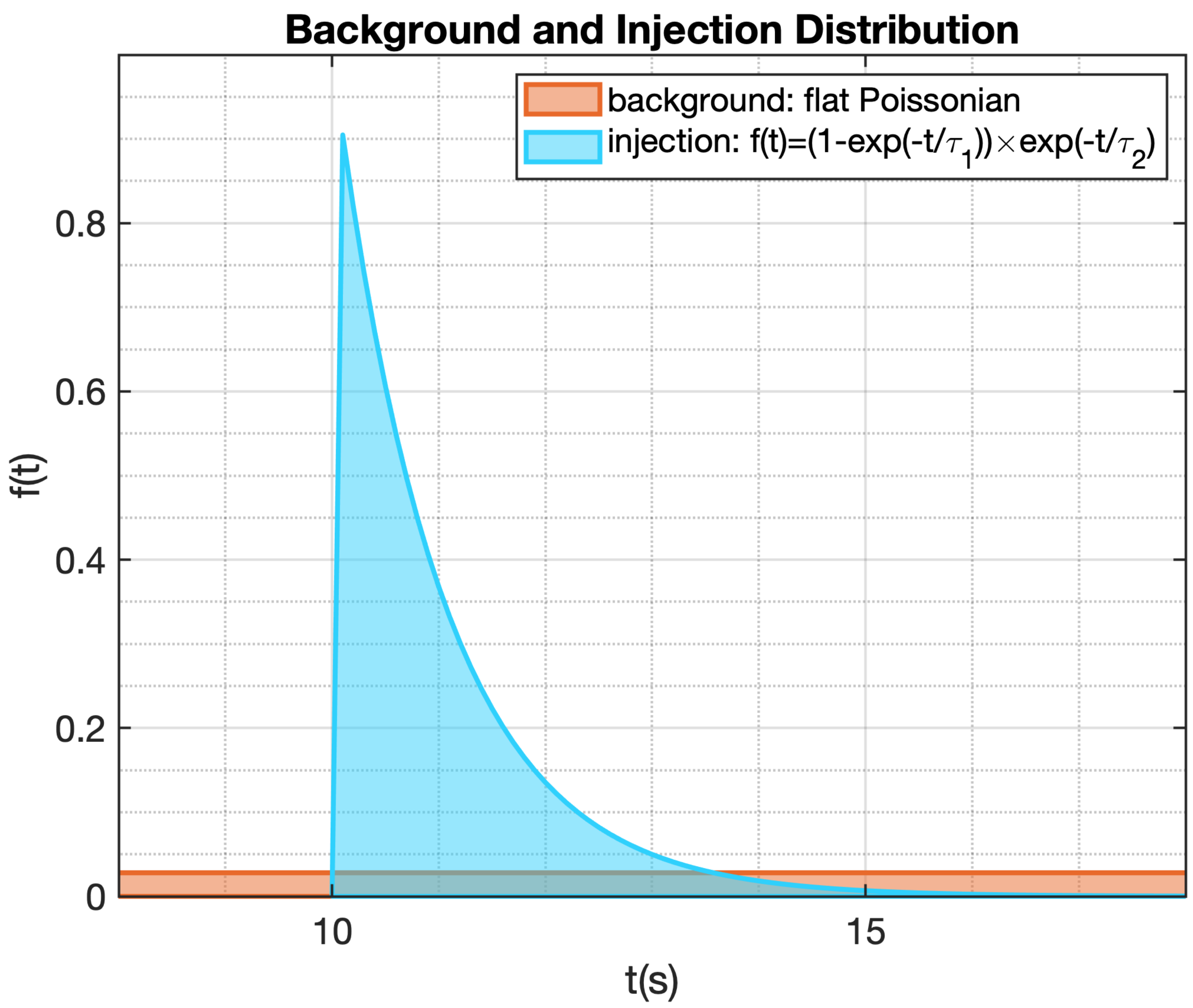
$$f(t) = \left[1 - \exp\left(\frac{-t}{\tau_1}\right)\right] \cdot \exp\left(\frac{-t}{\tau_2}\right);\ \ \tau_1 = 10 - 100\,\mathrm{ms};\ \ \tau_2 \geq 1\,\mathrm{s}$$

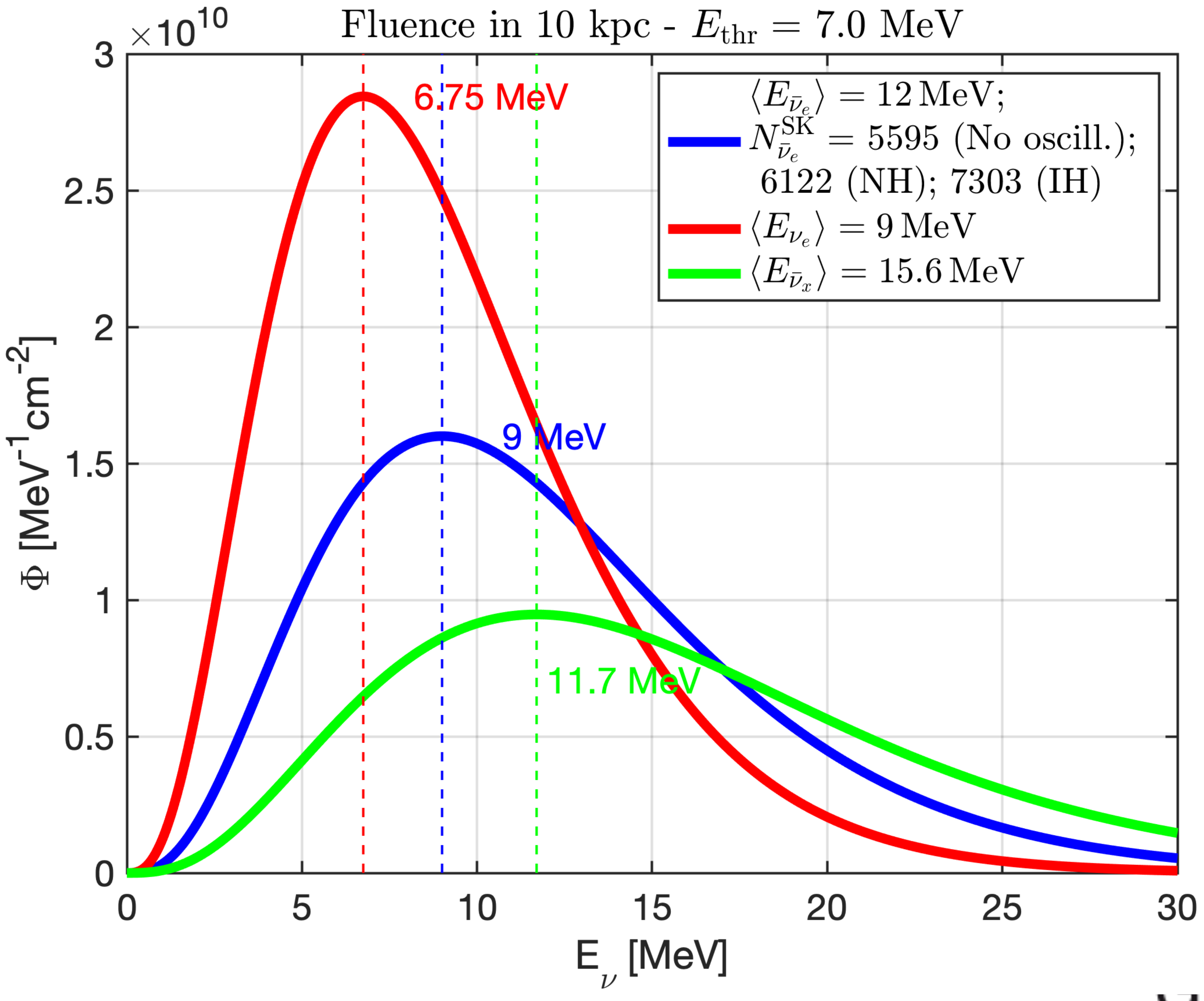
- Quasithermal spectra: $\Phi_i^0 = \dfrac{\varepsilon_i}{4\pi D^2} \times \dfrac{E^\alpha e^{-E/T_i}}{T_i^{\alpha+2}\Gamma(\alpha+2)};\ \ i = \{\nu_e, \nu_\mu, \nu_\tau \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\};$

$$\alpha = 3;\ \ \langle E_{\nu_e} \rangle = 9\,\mathrm{MeV};\ \ \langle E_{\bar{\nu}_e} \rangle = 12\,\mathrm{MeV};\ \ \langle E_{\bar{\nu}_x} \rangle = \langle E_{\nu_x} \rangle = 15.6\,\mathrm{MeV}$$

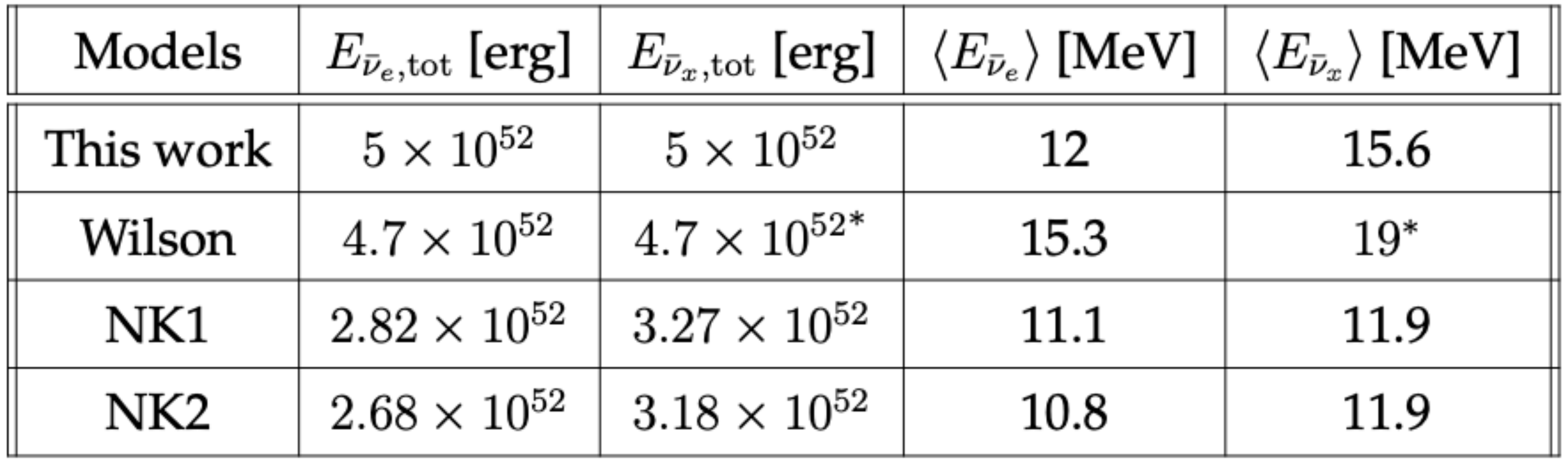
- Main channel: IBD, $\sigma_{\mathrm{IBD}} \approx 10^{-43}\left(\dfrac{E}{[\mathrm{MeV}]}\right)^2 [\mathrm{cm}^2]$
- Due to MSW effect ==> oscillation. Take Normal Hierarchy ==> smaller number of events.

3.2. Simulations

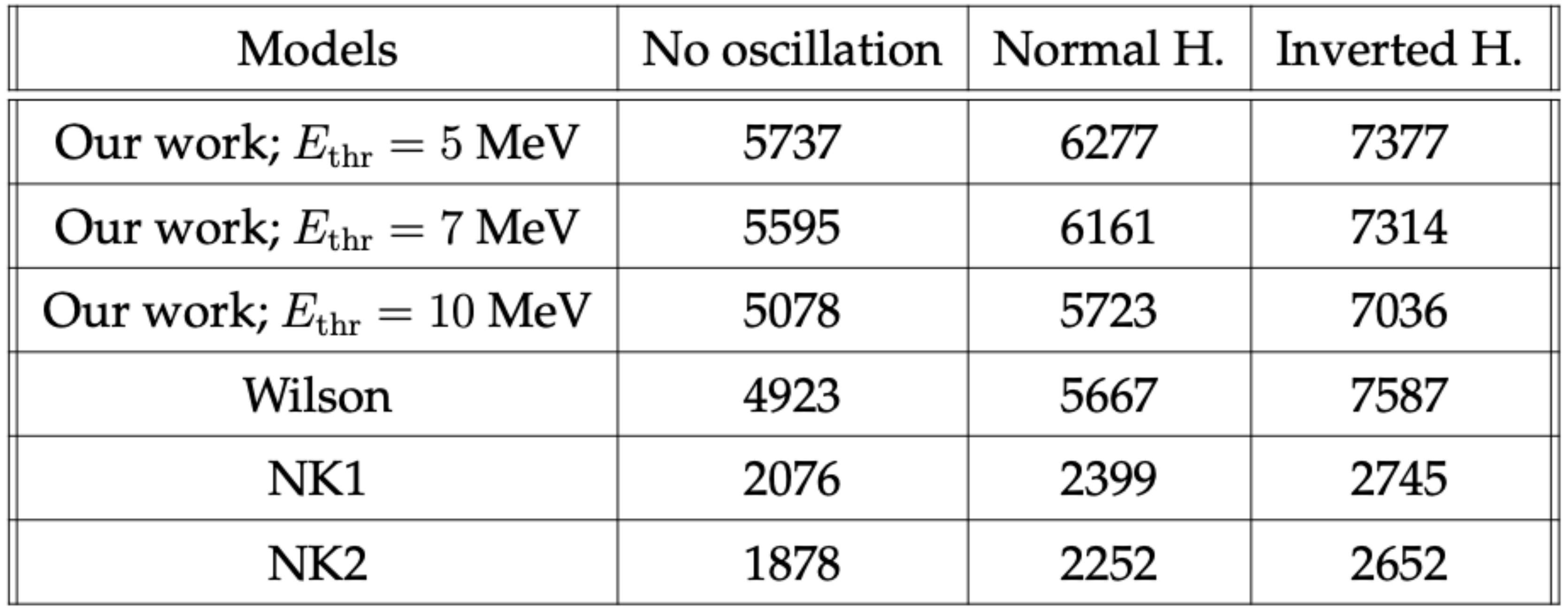




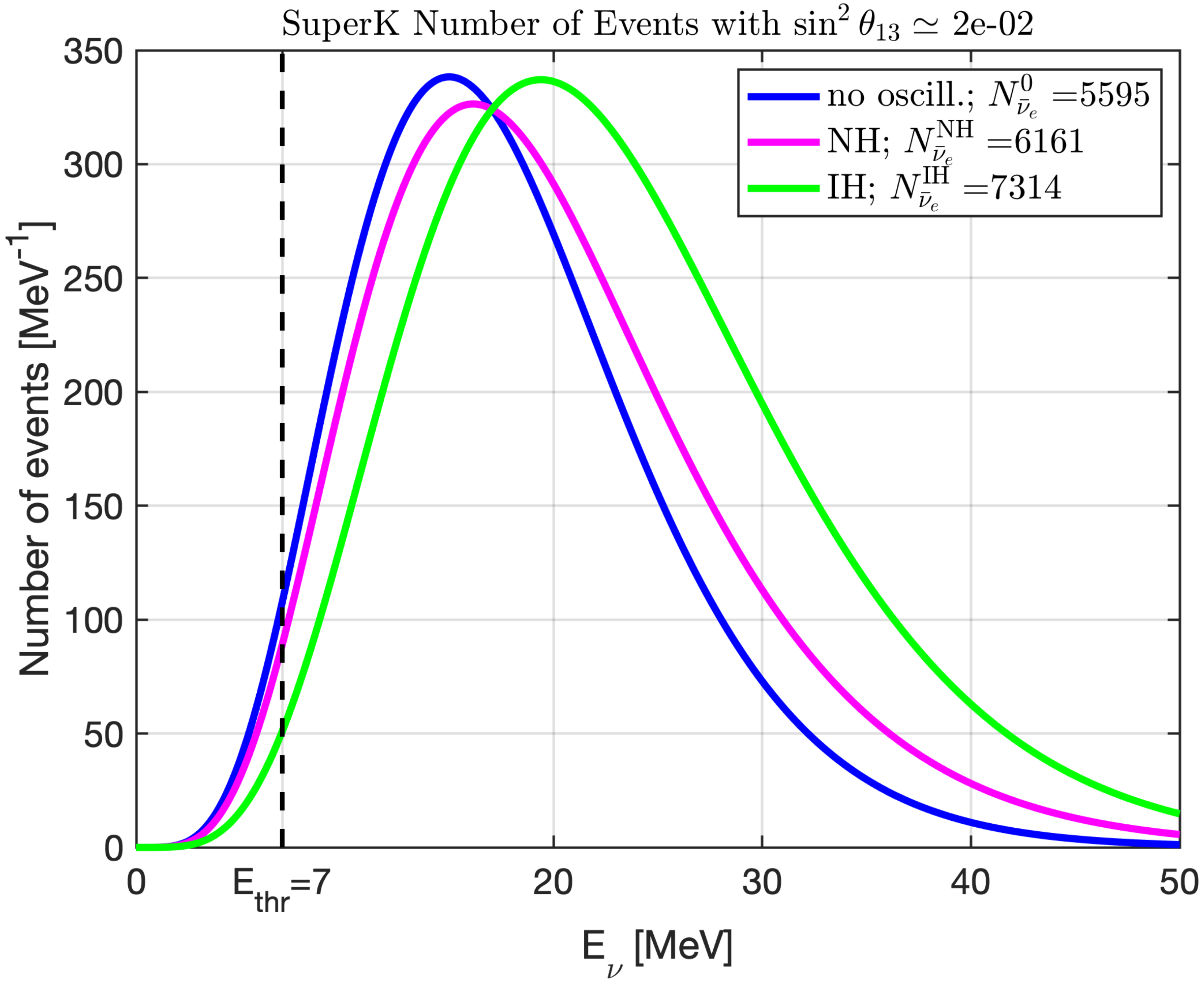
3.2. Simulations



Models	$E_{\bar{\nu}_e,\mathrm{tot}}$ [erg]	$E_{\bar{\nu}_x,\mathrm{tot}}$ [erg]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\bar{\nu}_x} \rangle$ [MeV]
This work	5×10^{52}	5×10^{52}	12	15.6
Wilson	4.7×10^{52}	$4.7 \times 10^{52*}$	15.3	19*
NK1	2.82×10^{52}	3.27×10^{52}	11.1	11.9
NK2	2.68×10^{52}	3.18×10^{52}	10.8	11.9



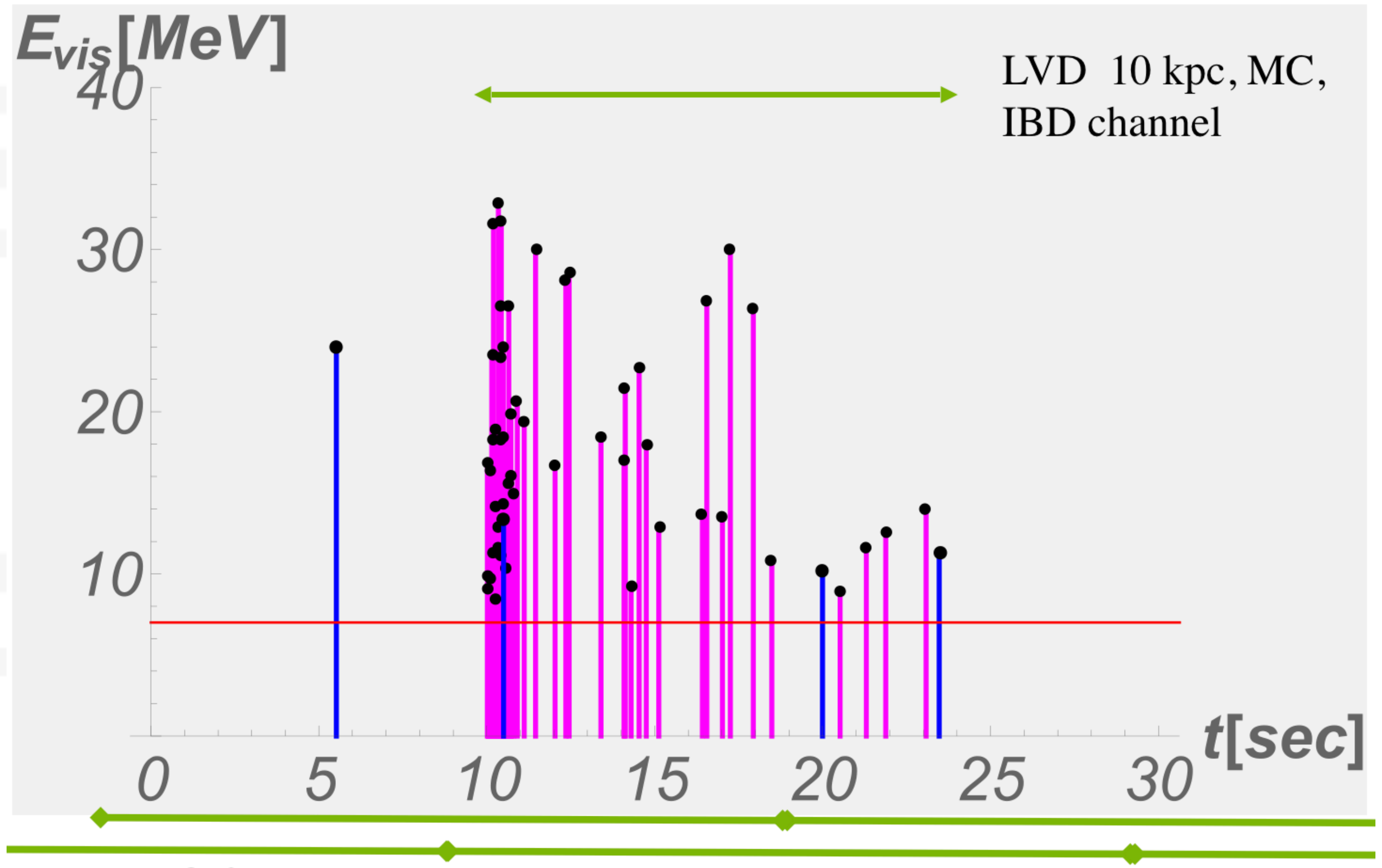
Models	No oscillation	Normal H.	Inverted H.
Our work; $E_{\mathrm{thr}} = 5$ MeV	5737	6277	7377
Our work; $E_{\mathrm{thr}} = 7$ MeV	5595	6161	7314
Our work; $E_{\mathrm{thr}} = 10$ MeV	5078	5723	7036
Wilson	4923	5667	7587
NK1	2076	2399	2745
NK2	1878	2252	2652

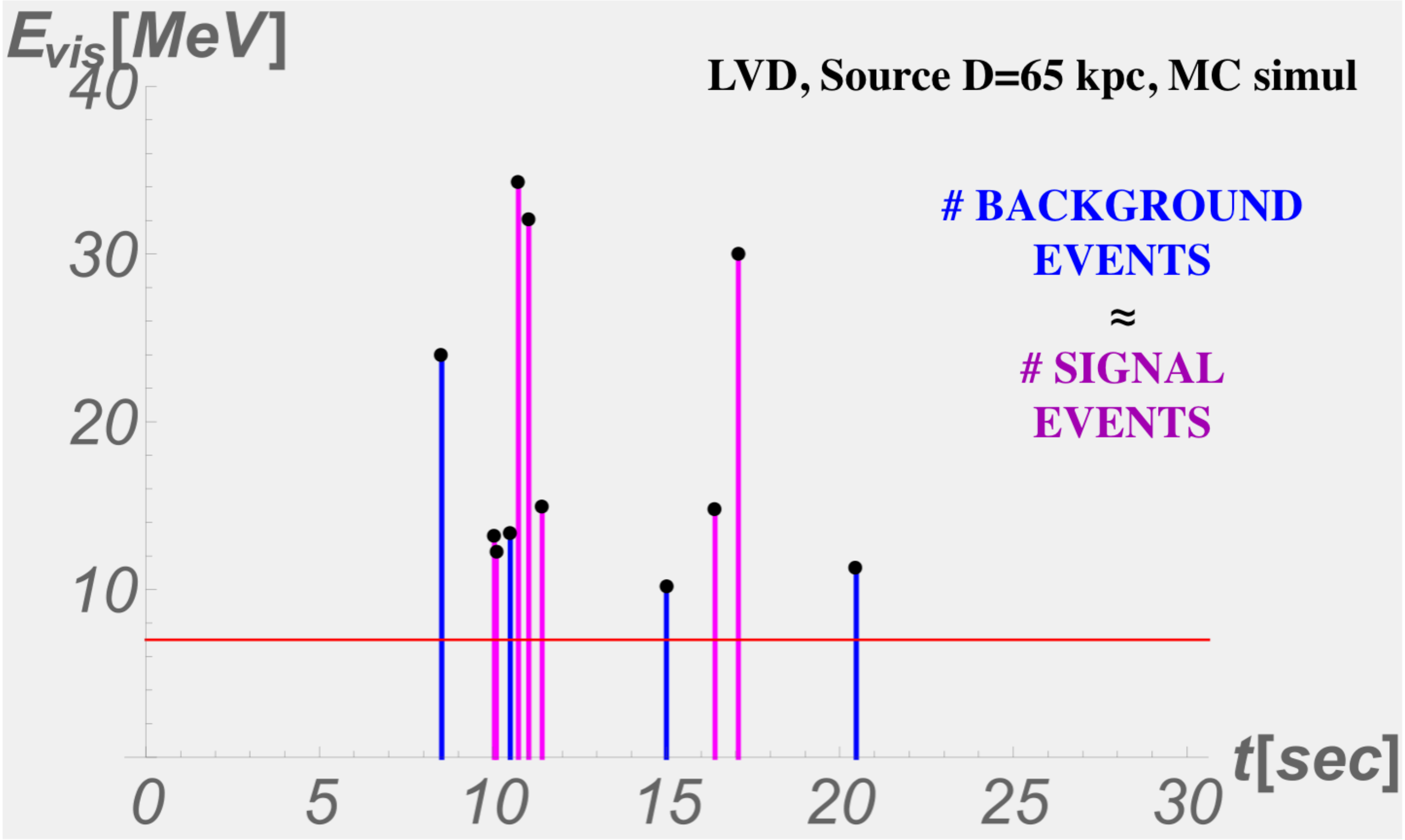


Wilson, NK1, and NK2 from: Abe, K. *et.al.* 2016

3.2. Counting Analysis

- We analyse clusters with $m_i \geq 3$ to have the lowest possible threshold





$w = 20s$

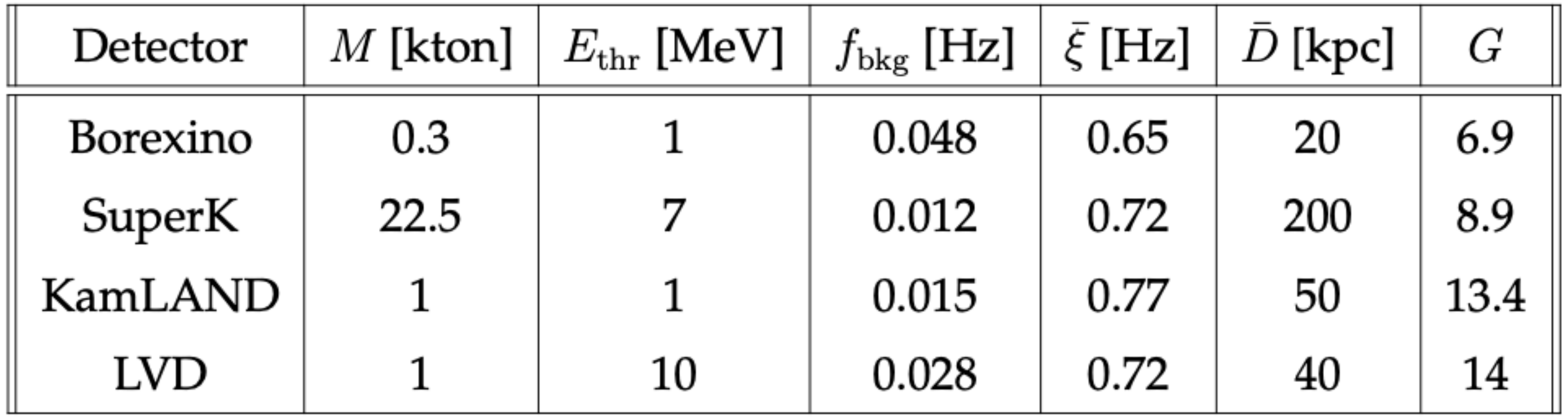
m_i

$$f_i^{\mathrm{im}} = N \times \sum_{k=m_i}^{\infty} \frac{\left(f_{\mathrm{bkg}} w\right)^k e^{-f_{\mathrm{bkg}} w}}{k!} [\mathrm{day}]^{-1}; \; N = 8640$$

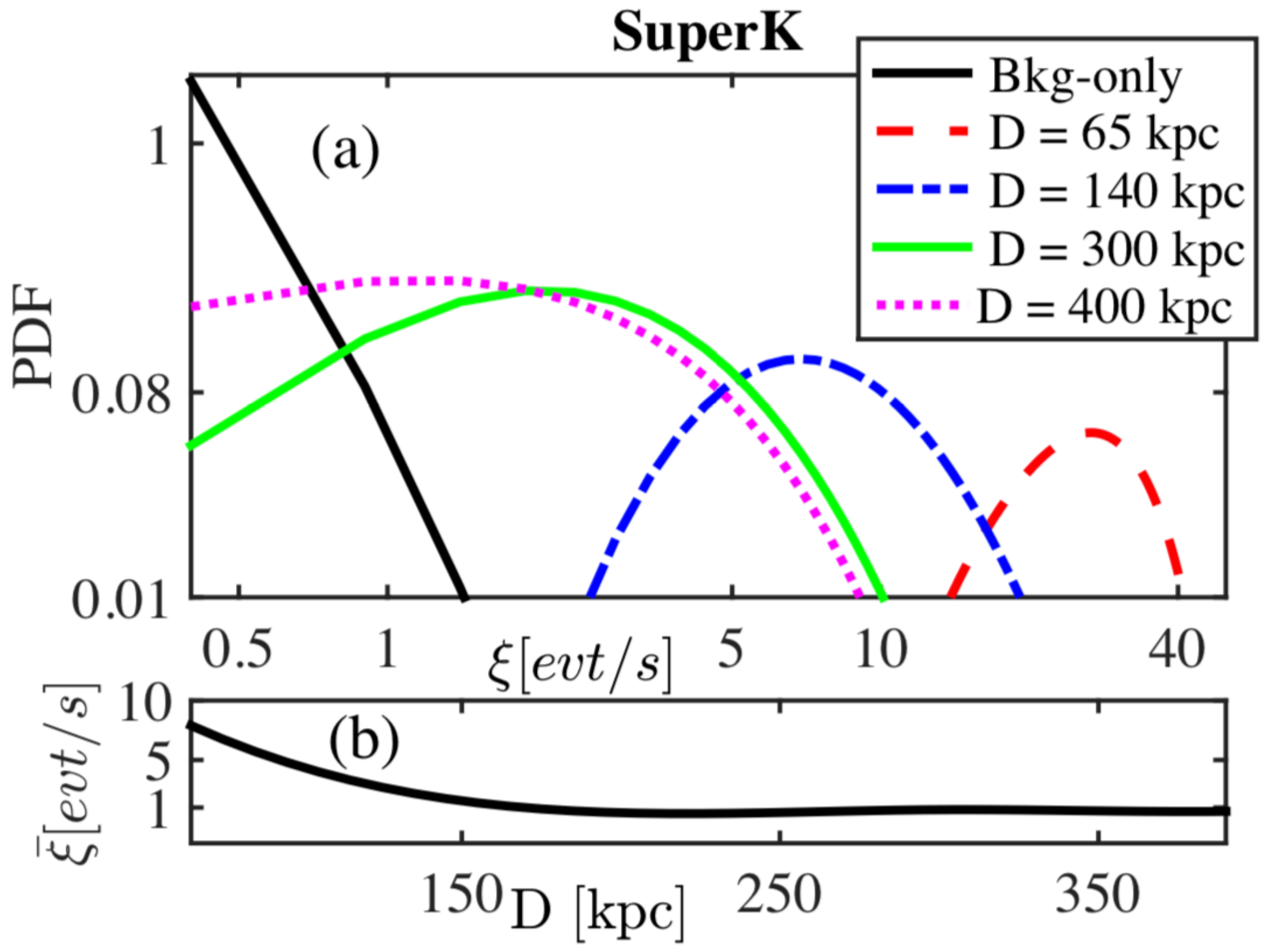
3.2. ξ-Parameter

- New parameter: $\xi_i = \dfrac{m_i}{\Delta t_i}$
- Monte Carlo method
- 10 year background
- Injections in the range of 8.5-500 kpc
- Take clusters having $\xi_i \geq \bar{\xi}$
- BG follows 4-parameter gamma distribution

TABLE 6.3: The details of involved detectors



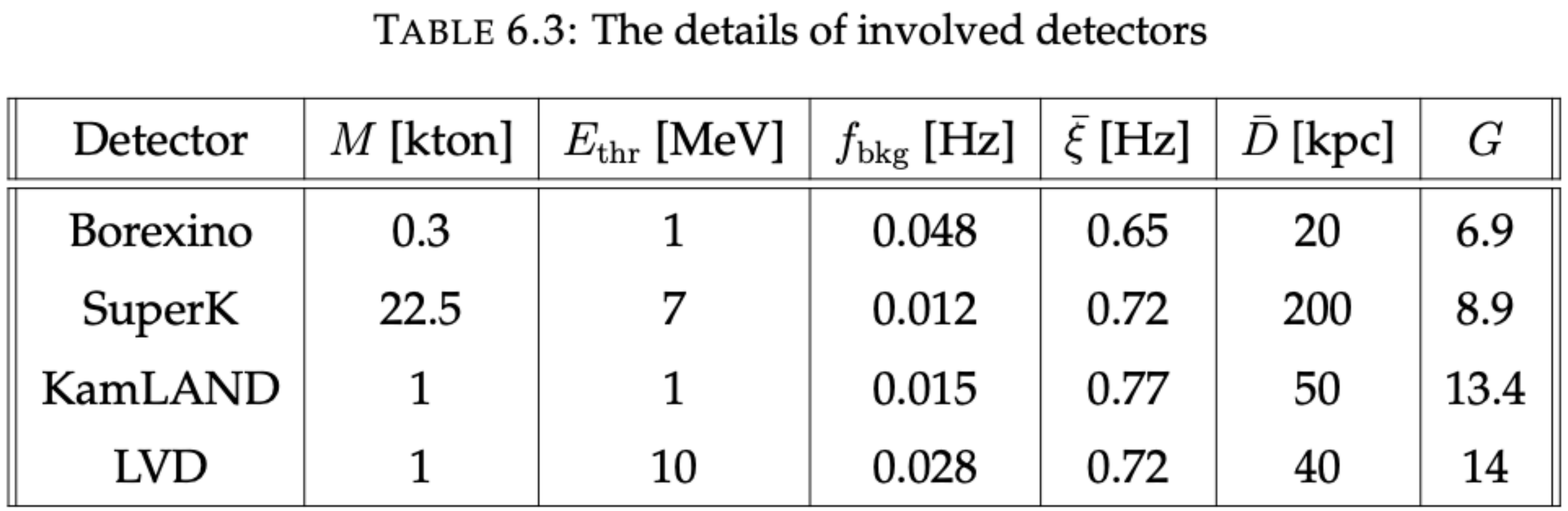
Detector	M [kton]	E_{thr} [MeV]	f_{bkg} [Hz]	$\bar{\xi}$ [Hz]	$\bar{D}$ [kpc]	G
Borexino	0.3	1	0.048	0.65	20	6.9
SuperK	22.5	7	0.012	0.72	200	8.9
KamLAND	1	1	0.015	0.77	50	13.4
LVD	1	10	0.028	0.72	40	14



Casentini, C. *et.al.* 2018. 10.1088

3.2. Results

- Gain: $G = \dfrac{\zeta'}{\zeta}$
- Gain for SK ~10
- SK online
  $m_i \geq 25;\ f_i^{\text{im}} \leq 3.5 \times 10^{-10}\,[\text{year}]^{-1};\ d \sim 147\,\text{kpc}$
- With cut:
  $m_i \geq 11;\ f_i^{\text{im}} \leq 3.5 \times 10^{-9}\,[\text{year}]^{-1};\ d \sim 221\,\text{kpc}$



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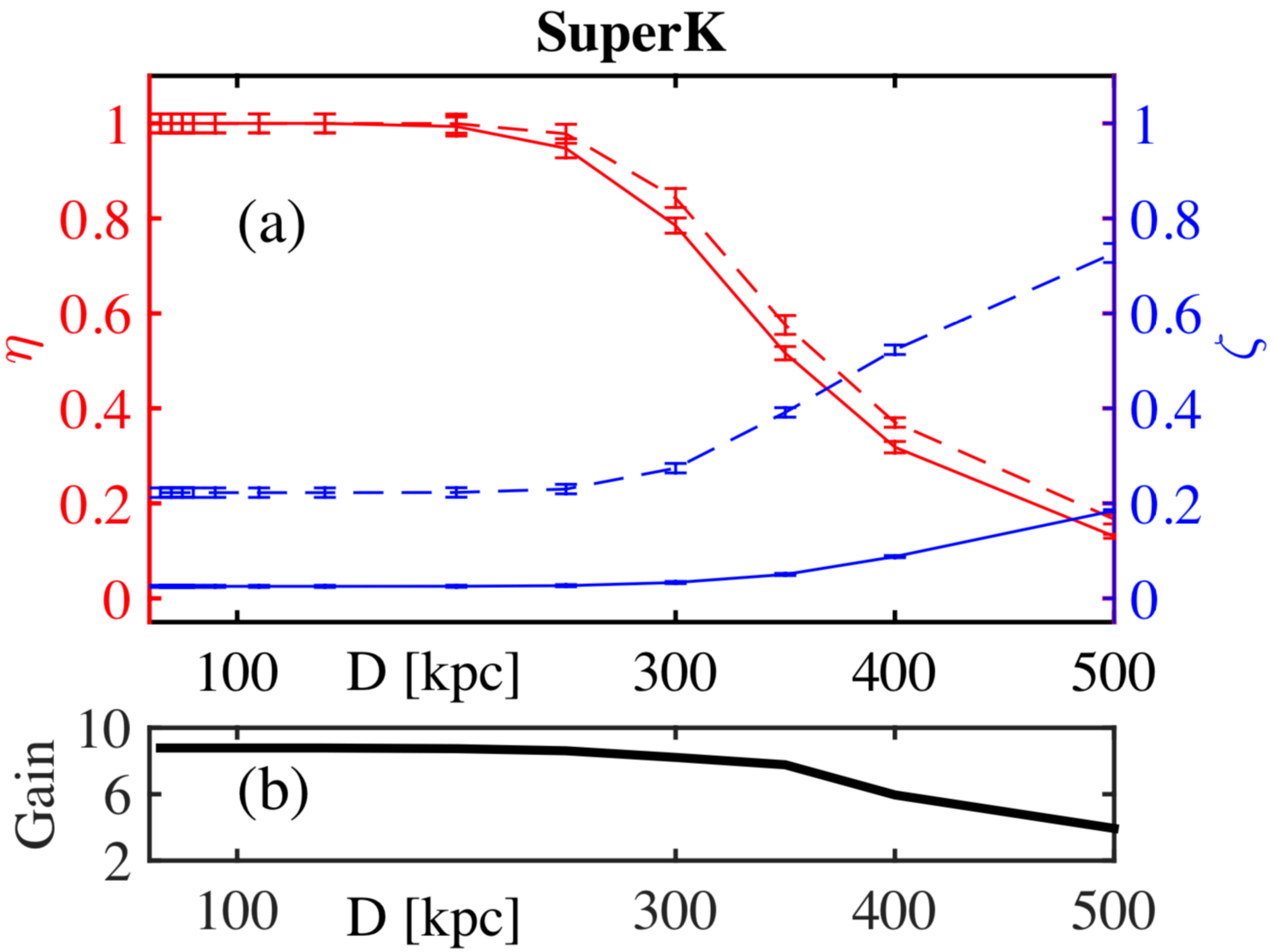


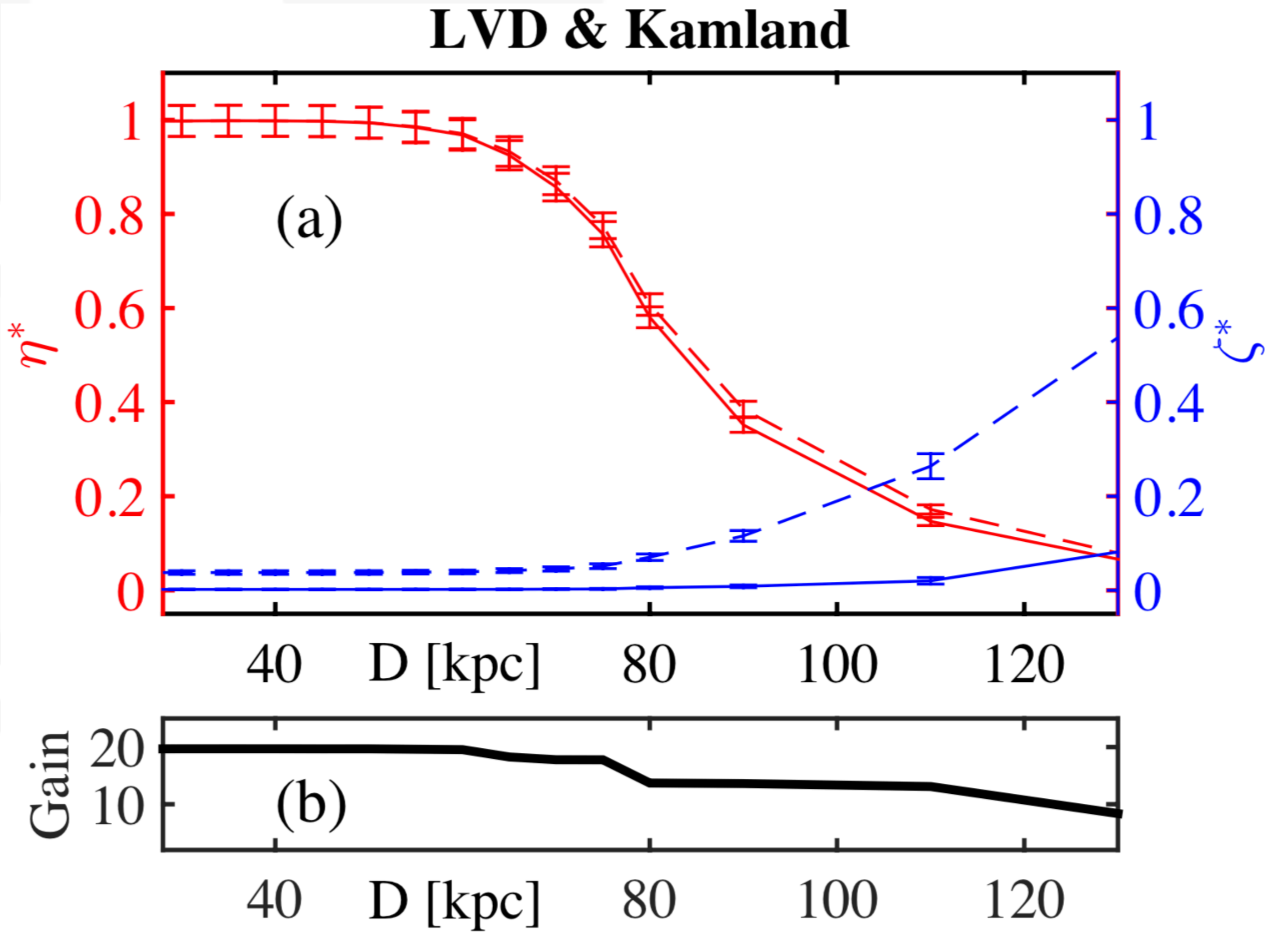
Casentini, C. *et.al.* 2018. 10.1088

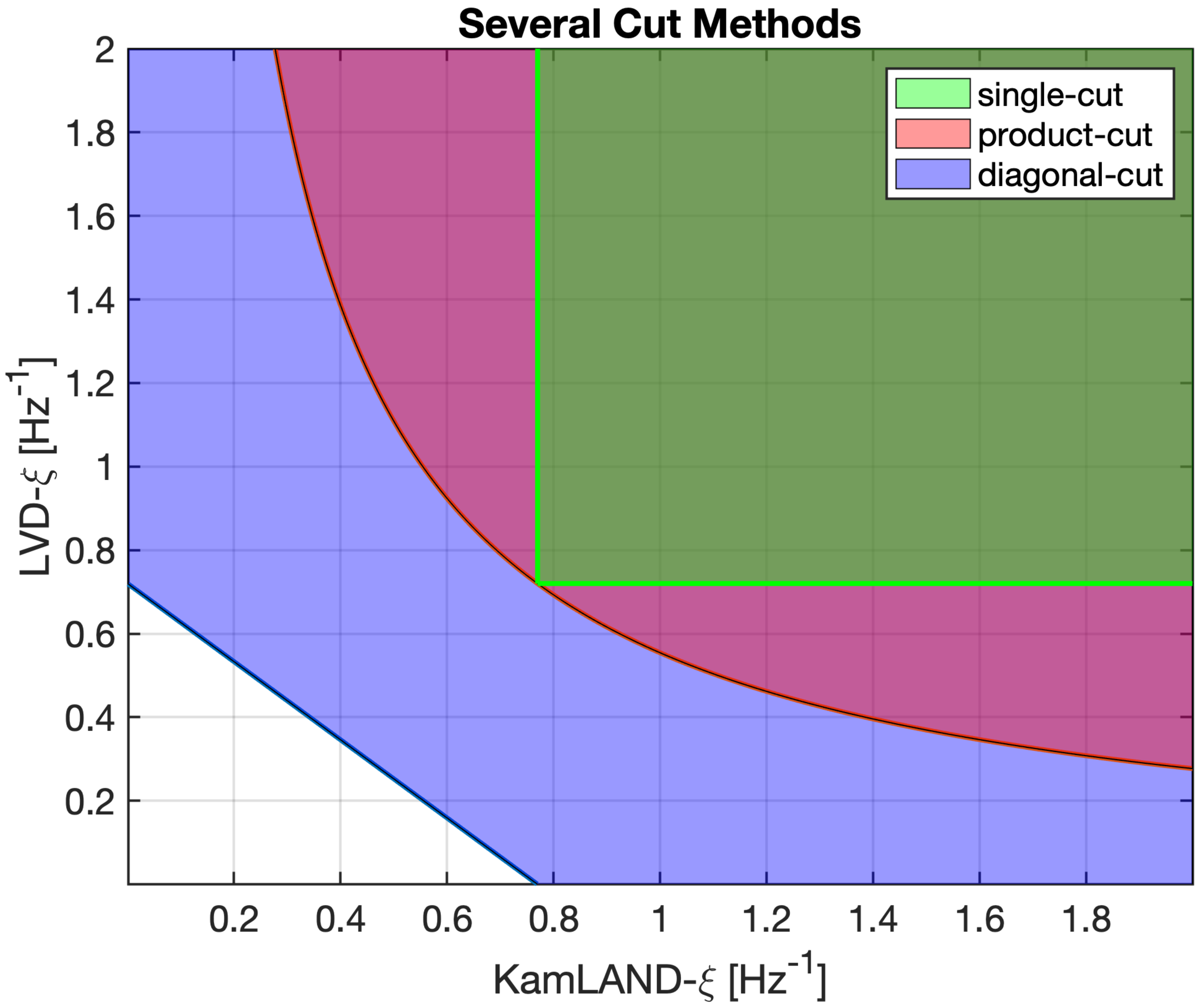
3.2. Cuts

- For network there are some possible ways:

  1. Single-cut
  2. Product-cut
  3. Diagonal-cut

- The product cut is chosen

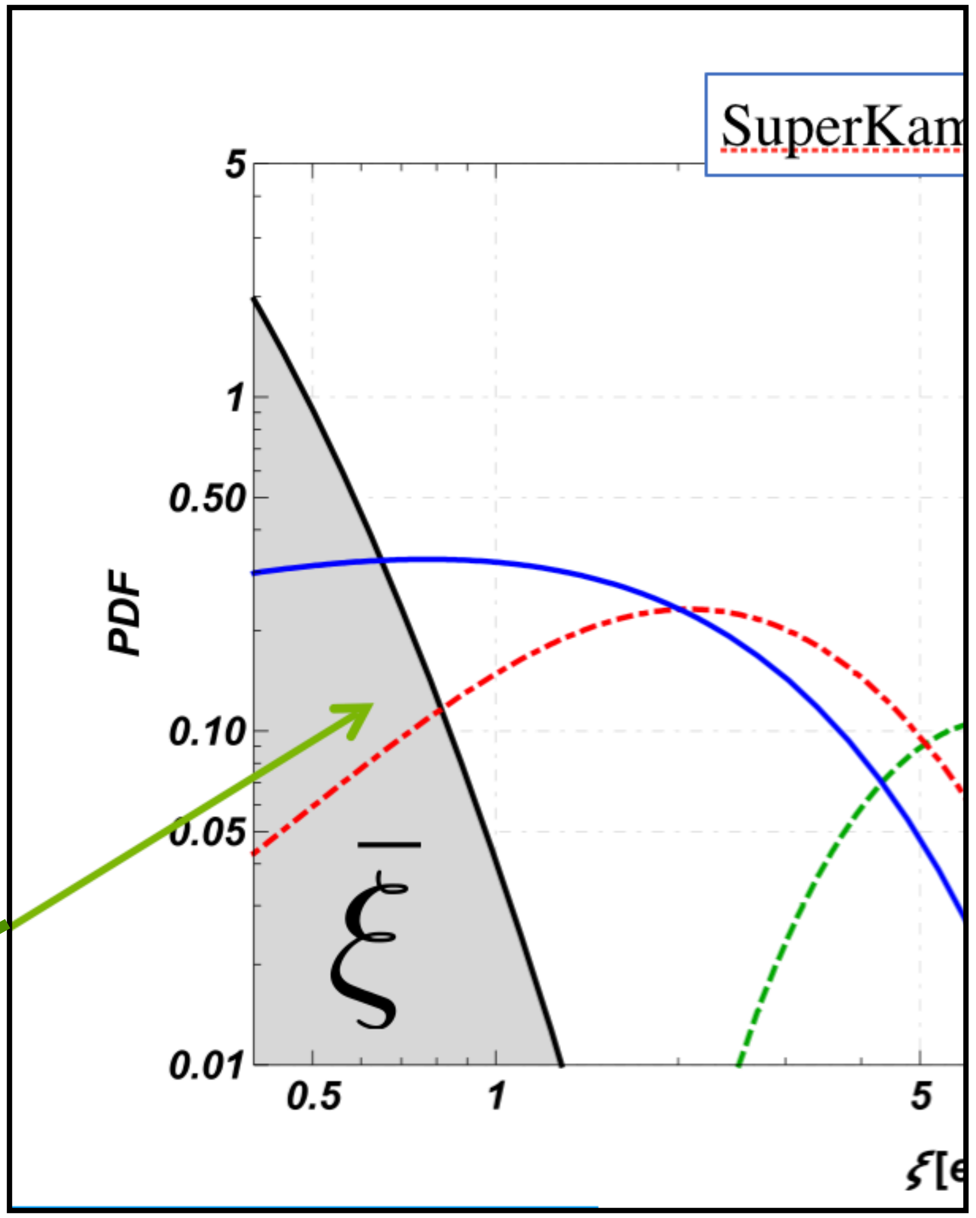




3.3. Increasing Sensitivity of ν-Detectors: The Modified Imitation Frequency

OH, Vigorito, Casentini, Pagliaroli, Drago, Fafone. 2020. 012154.

- $$f_i^{\mathrm{im}} = N \times \sum_{k=m_i}^{\infty} \frac{\left(f_{\mathrm{bkg}} w\right)^k e^{-f_{\mathrm{bkg}} w}}{k!} [\mathrm{day}]^{-1} = N \times \sum_{k=m_i}^{\infty} P(k) = N \times \sum_{k=m_i}^{\infty} PDF(k)$$
- The PDF depends only on k as multiplicity.
- What if, instead of using ξ as a cut method, we put it inside the PDF?
  - $P(k) \Rightarrow P(k, \xi)$
  - Remember: $P(k, \xi) = P(\xi \,|\, k) P(k)$
- $P(\xi \,|\, k)$ can be regarded as the ξ-background PDF curve

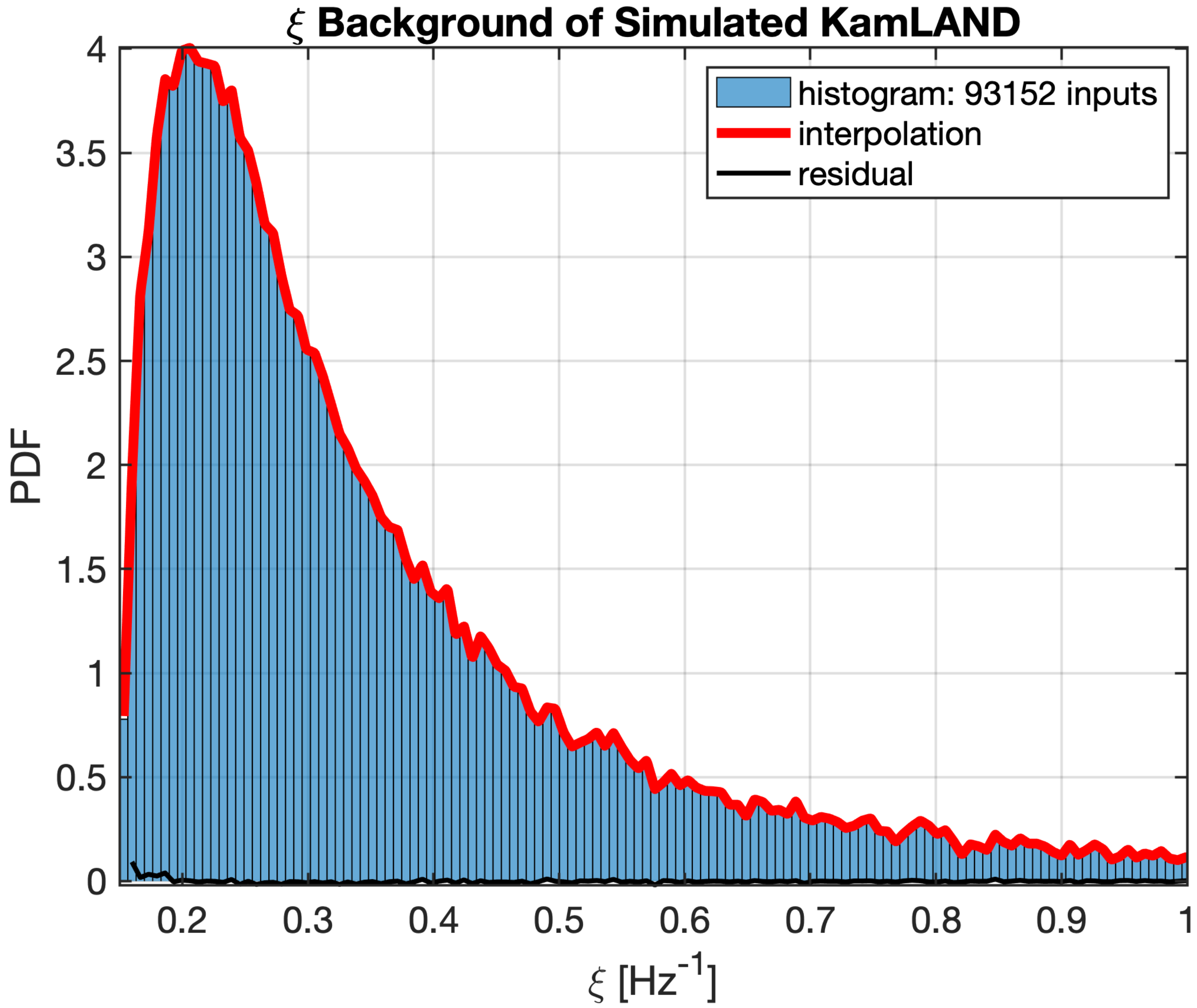


$$f_i^{\mathrm{im}} = N \times \sum_{k=m_i}^{\infty} P(k)$$

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

3.3. Distributions

- Instead of 4-parameter gamma distribution, we choose interpolation



- Complex distribution to find the fit ==> **avoiding** trial-and-error and random-unphysical fit
- Interpolation is **adaptive** ==> needed for background fluctuation in some part of data
- Adaptive for any counting detectors

3.3. Detectors

- The method is applied to the previous data: 10-year background of simulated detectors
- We take $m \geq 3$ (lowest possible threshold)

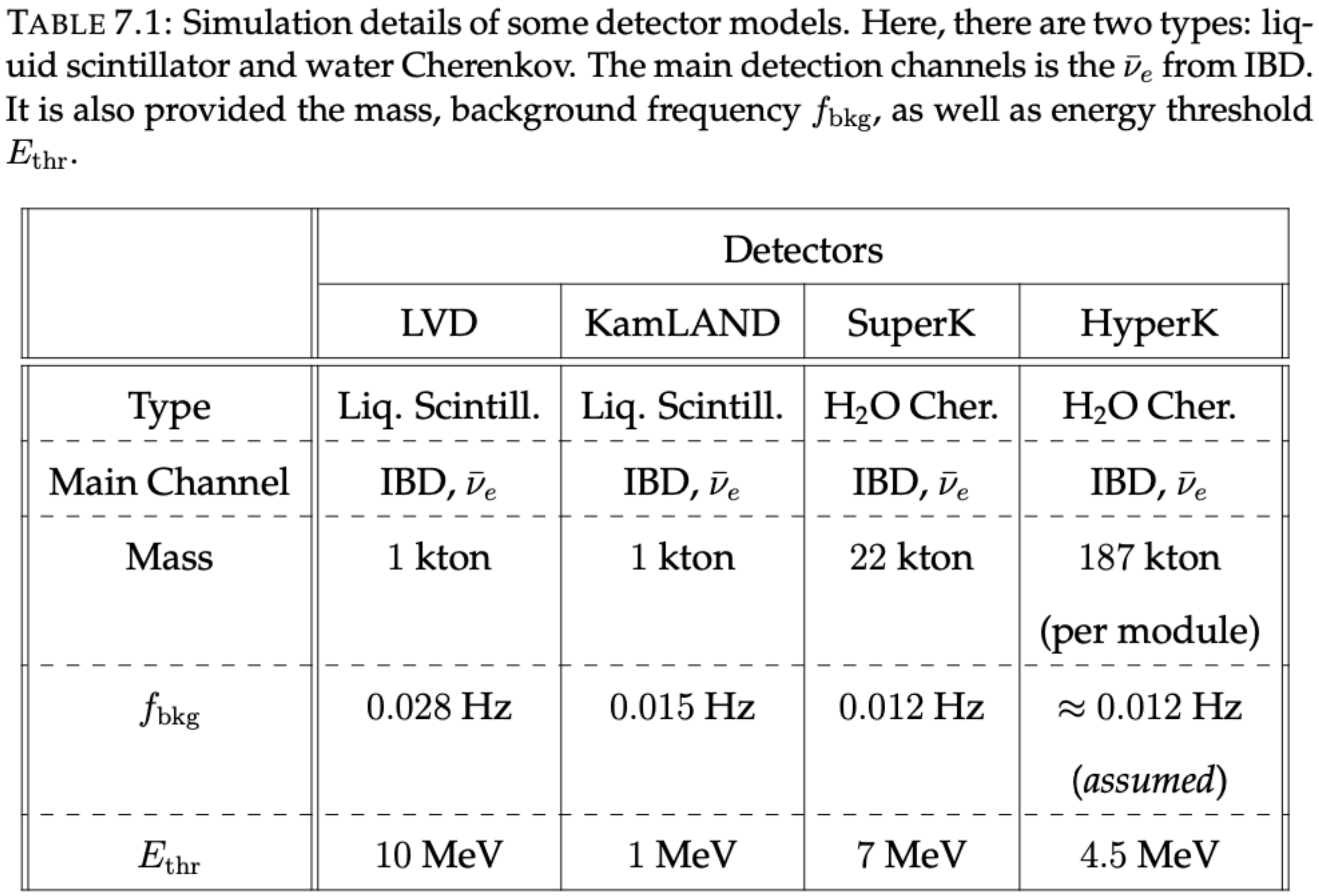
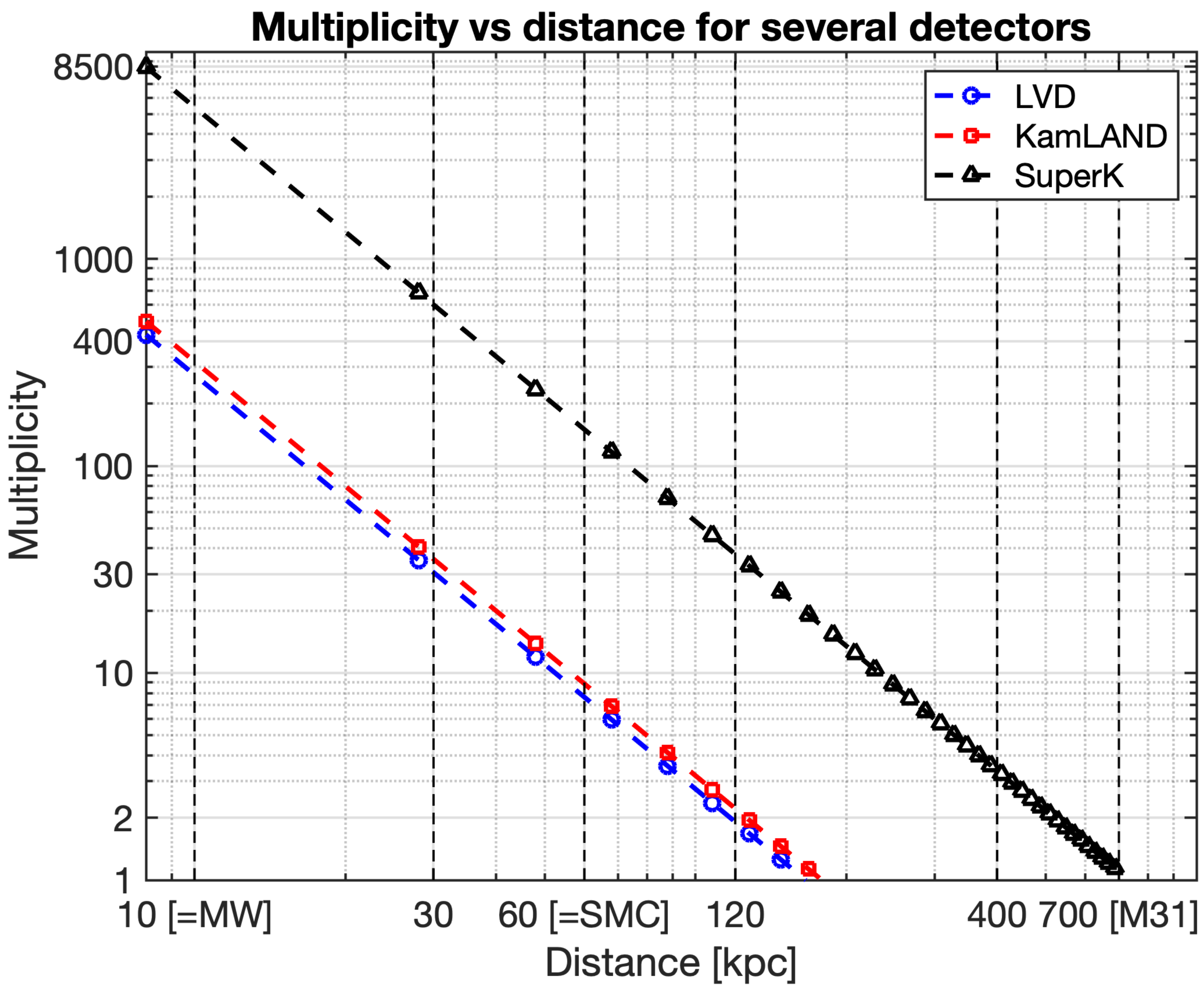


TABLE 7.1: Simulation details of some detector models. Here, there are two types: liquid scintillator and water Cherenkov. The main detection channels is the $\bar{\nu}_e$ from IBD. It is also provided the mass, background frequency f_{bkg}, as well as energy threshold E_{thr}.

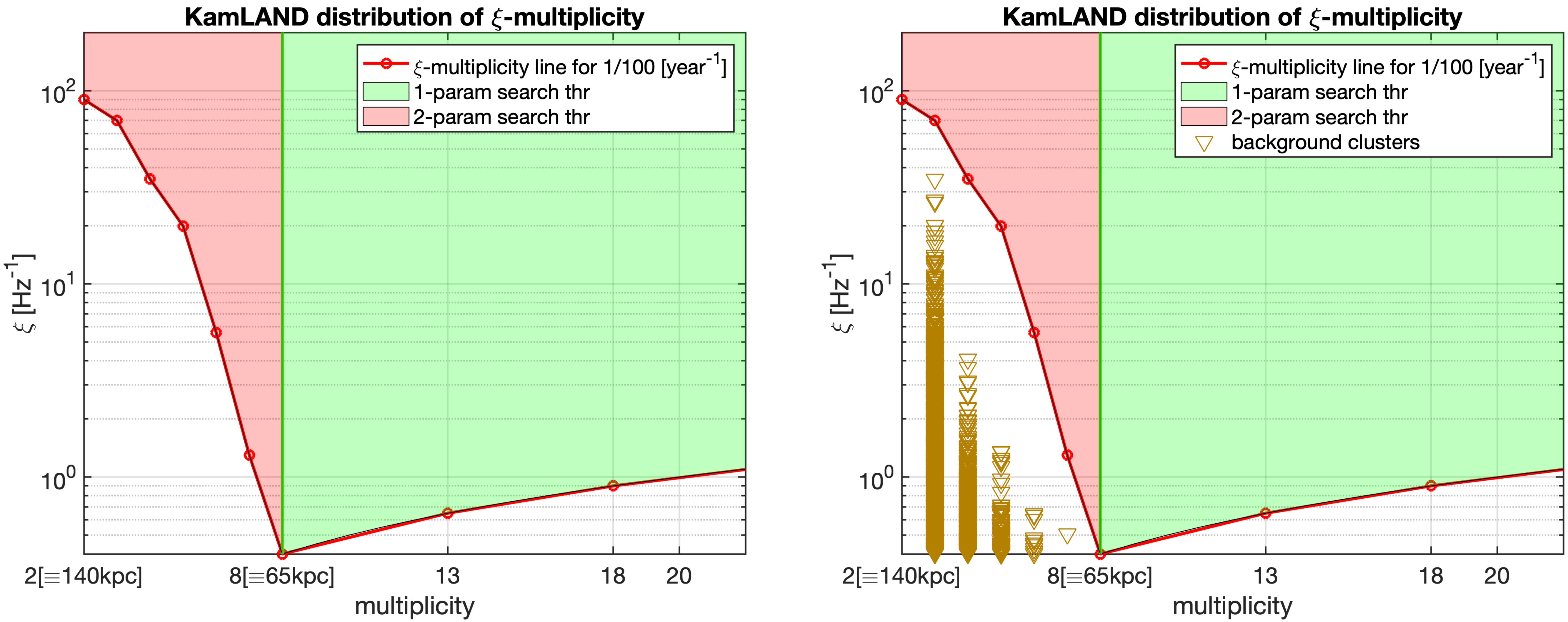
	Detectors			
	LVD	KamLAND	SuperK	HyperK
Type	Liq. Scintill.	Liq. Scintill.	H_2O Cher.	H_2O Cher.
Main Channel	IBD, $\bar{\nu}_e$	IBD, $\bar{\nu}_e$	IBD, $\bar{\nu}_e$	IBD, $\bar{\nu}_e$
Mass	1 kton	1 kton	22 kton	187 kton (per module)
f_{bkg}	0.028 Hz	0.015 Hz	0.012 Hz	$\approx$ 0.012 Hz (*assumed*)
E_{thr}	10 MeV	1 MeV	7 MeV	4.5 MeV



3.3. KamLAND

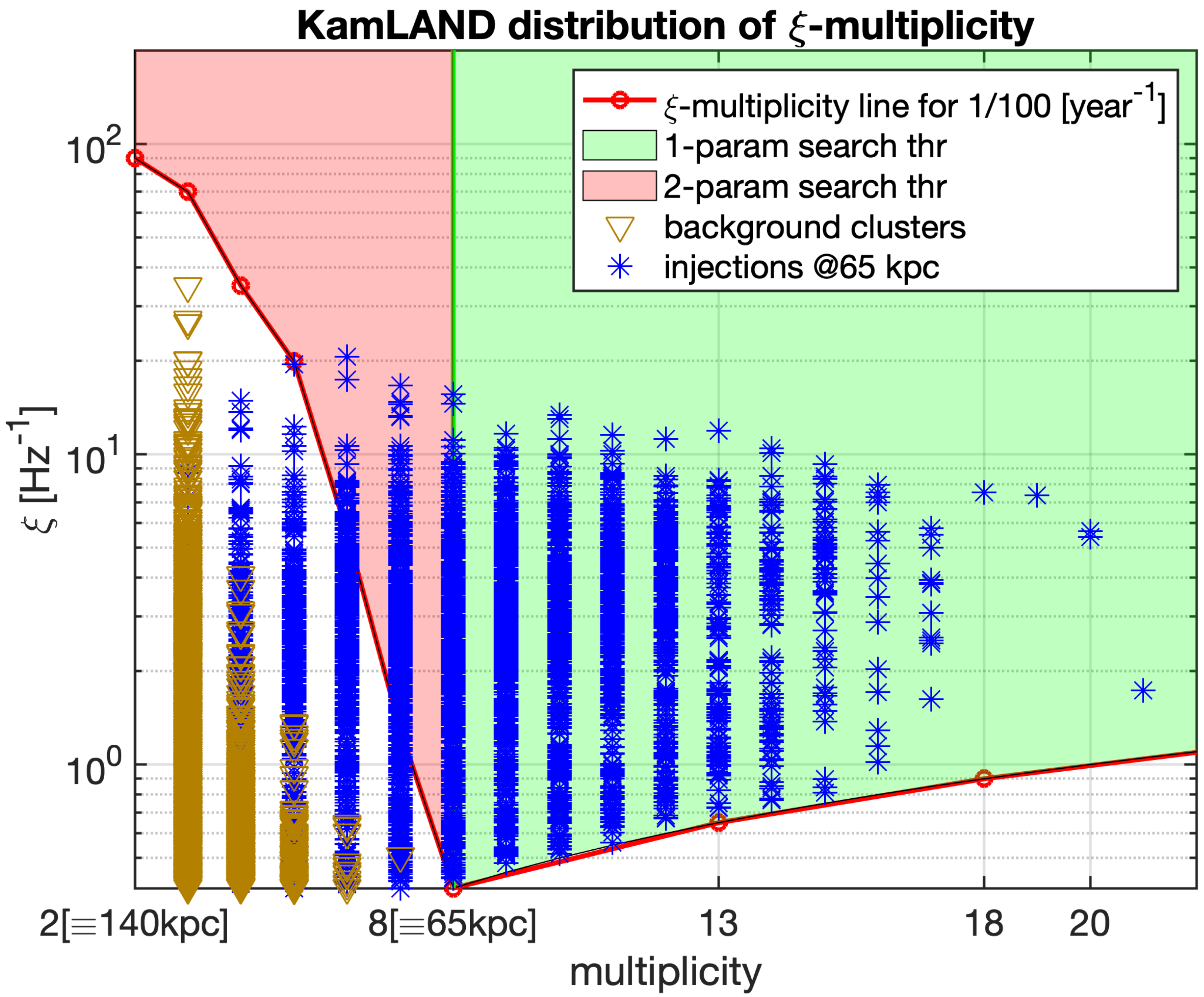
OH, Vigorito, Casentini, Pagliaroli, Drago, Fafone. 2020. 012154

- KamLAND single-detector analysis. $m = 8 \Rightarrow$ detection horizon: Small Magellanic Cloud



OH, Vigorito, Casentini, Pagliaroli, Drago, Fafone. 2020. 012154

3.3. KamLAND



- KamLAND single-detector analysis. $m = 8 \Rightarrow \text{SMC}$

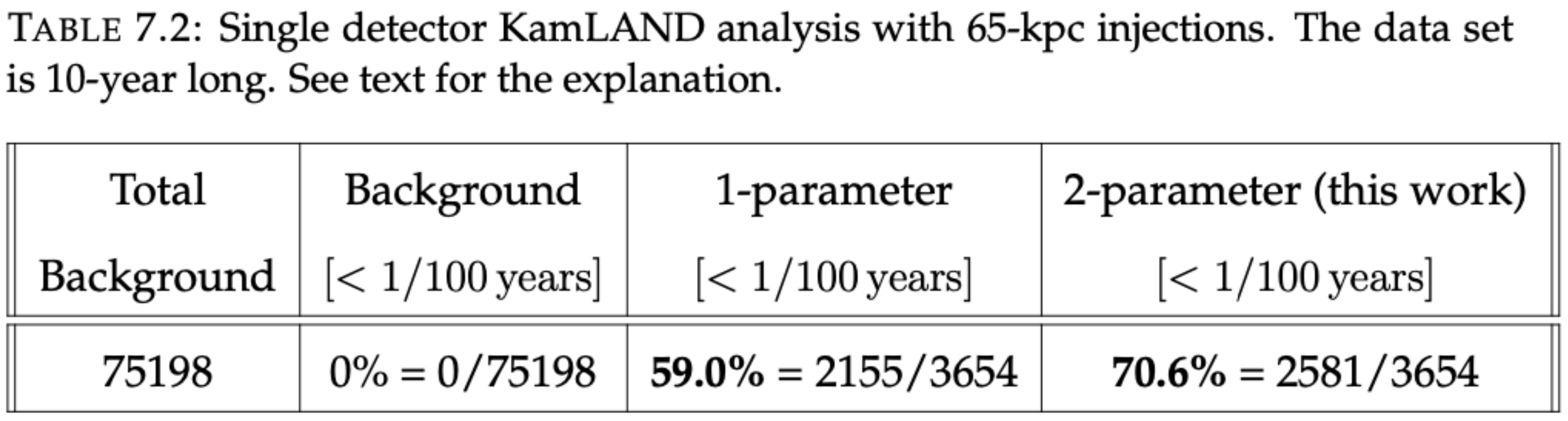


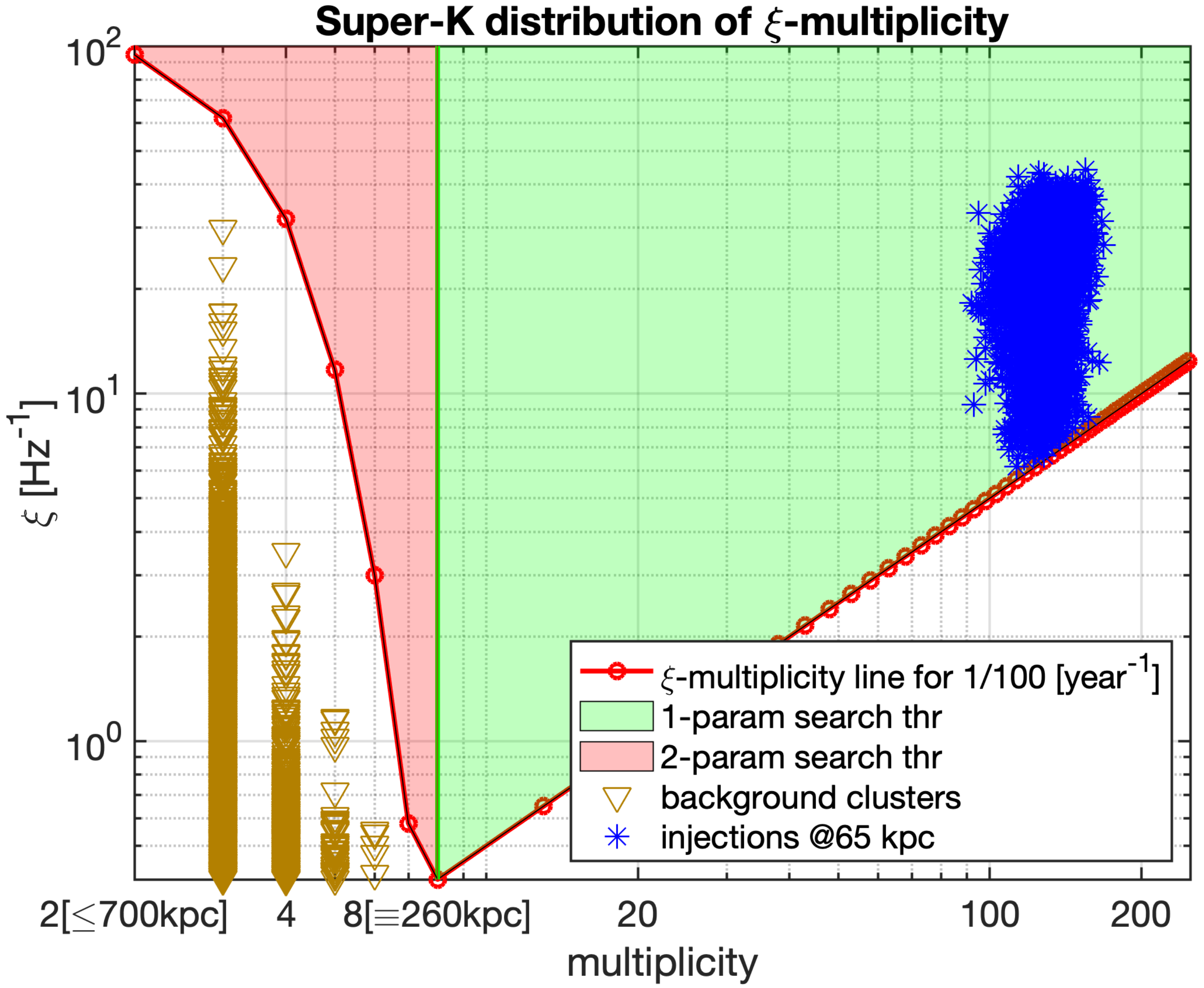
TABLE 7.2: Single detector KamLAND analysis with 65-kpc injections. The data set is 10-year long. See text for the explanation.

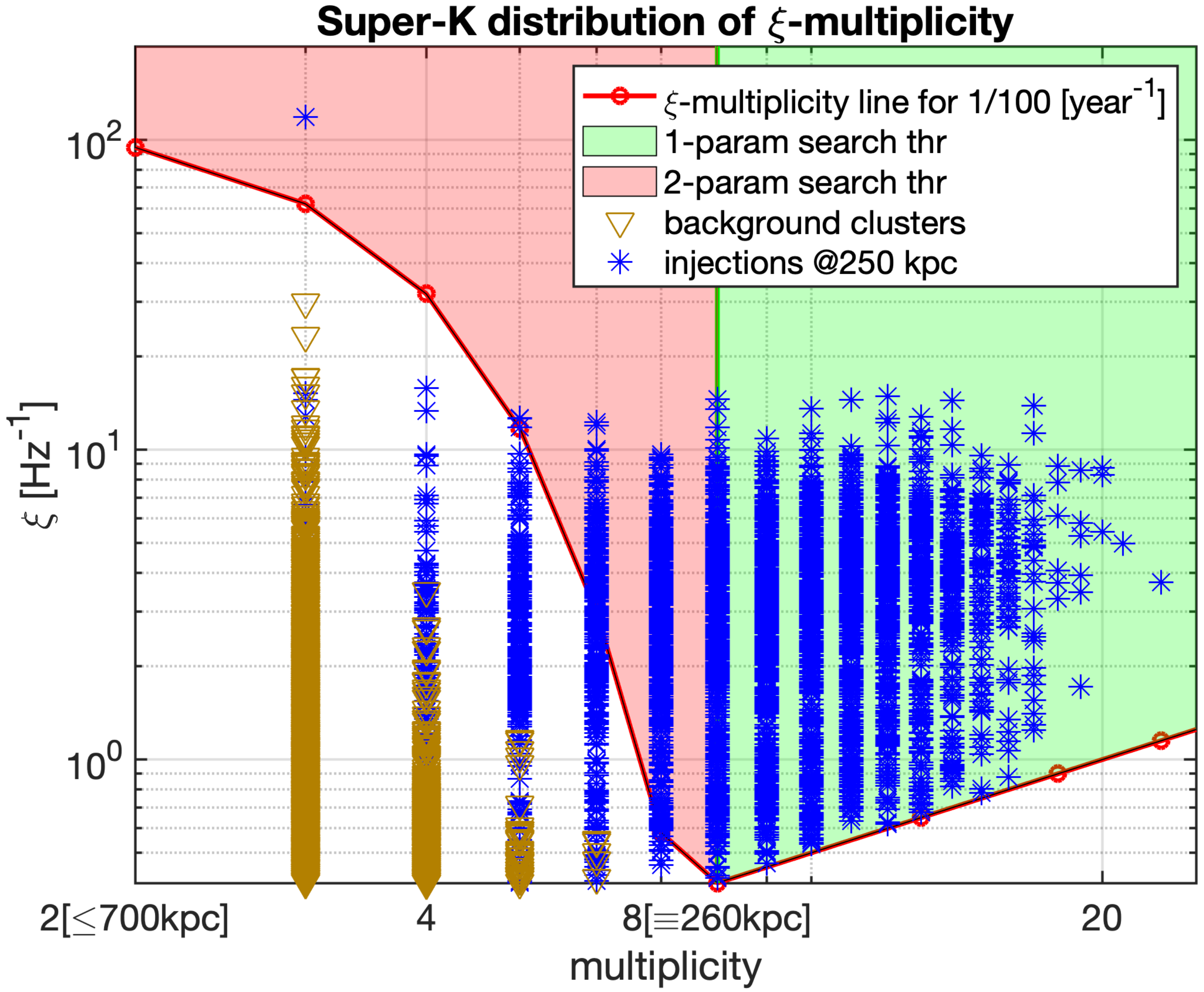
Total Background	Background [< 1/100 years]	1-parameter [< 1/100 years]	2-parameter (this work) [< 1/100 years]
75198	0% = 0/75198	**59.0%** = 2155/3654	**70.6%** = 2581/3654

OH, Vigorito, Casentini, Pagliaroli, Drago, Fafone. 2020. 012154

3.3. Super-K

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





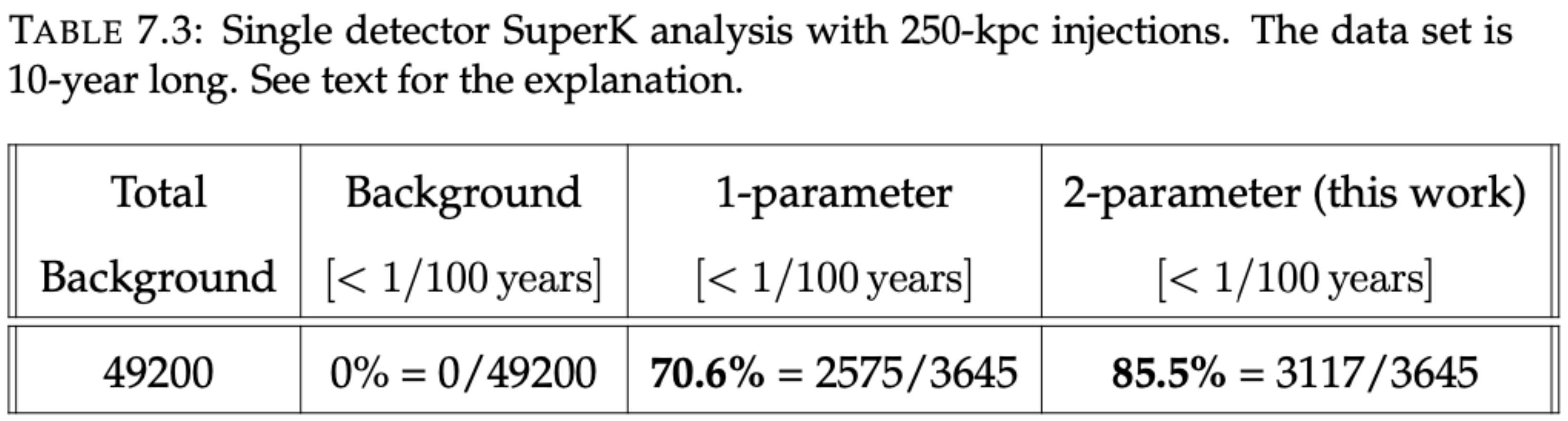


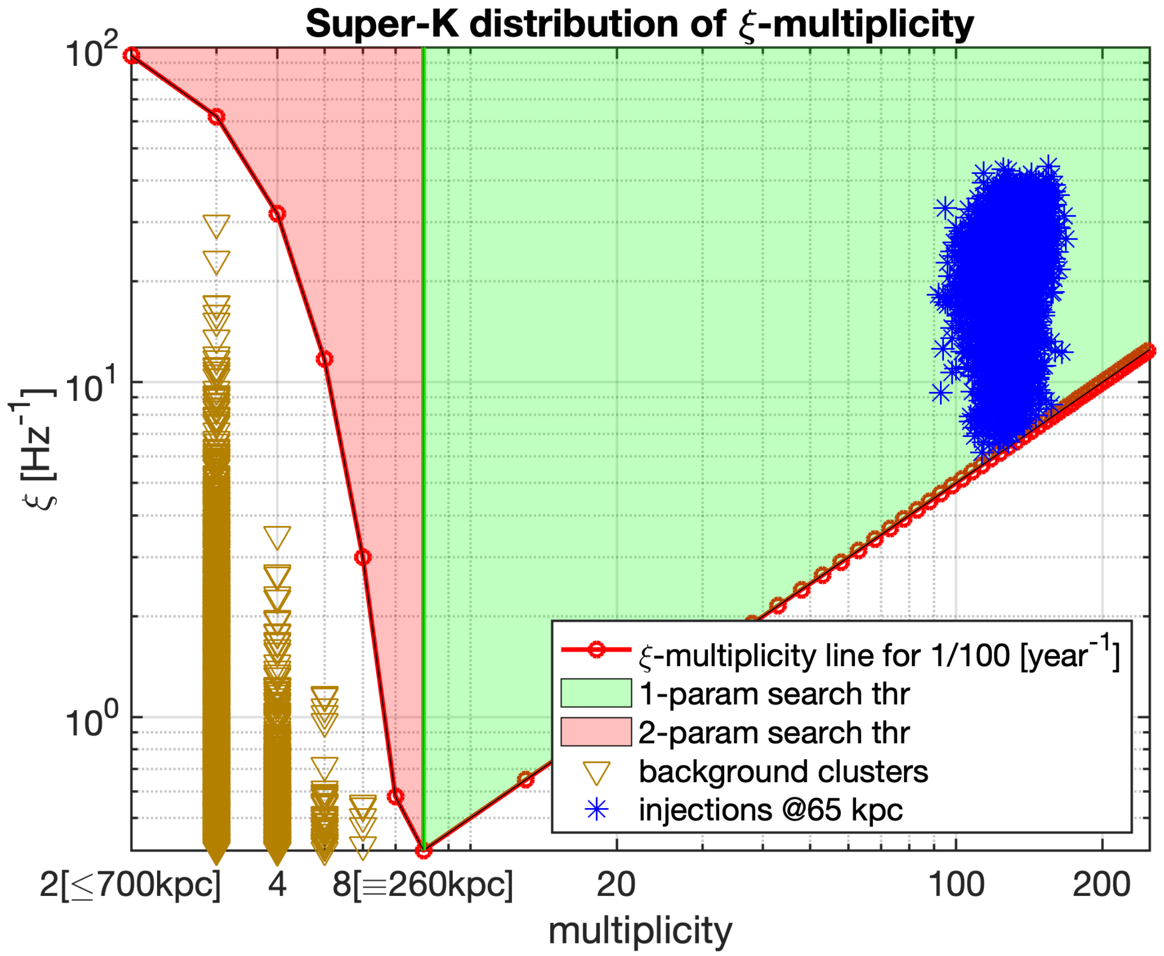
TABLE 7.3: Single detector SuperK analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

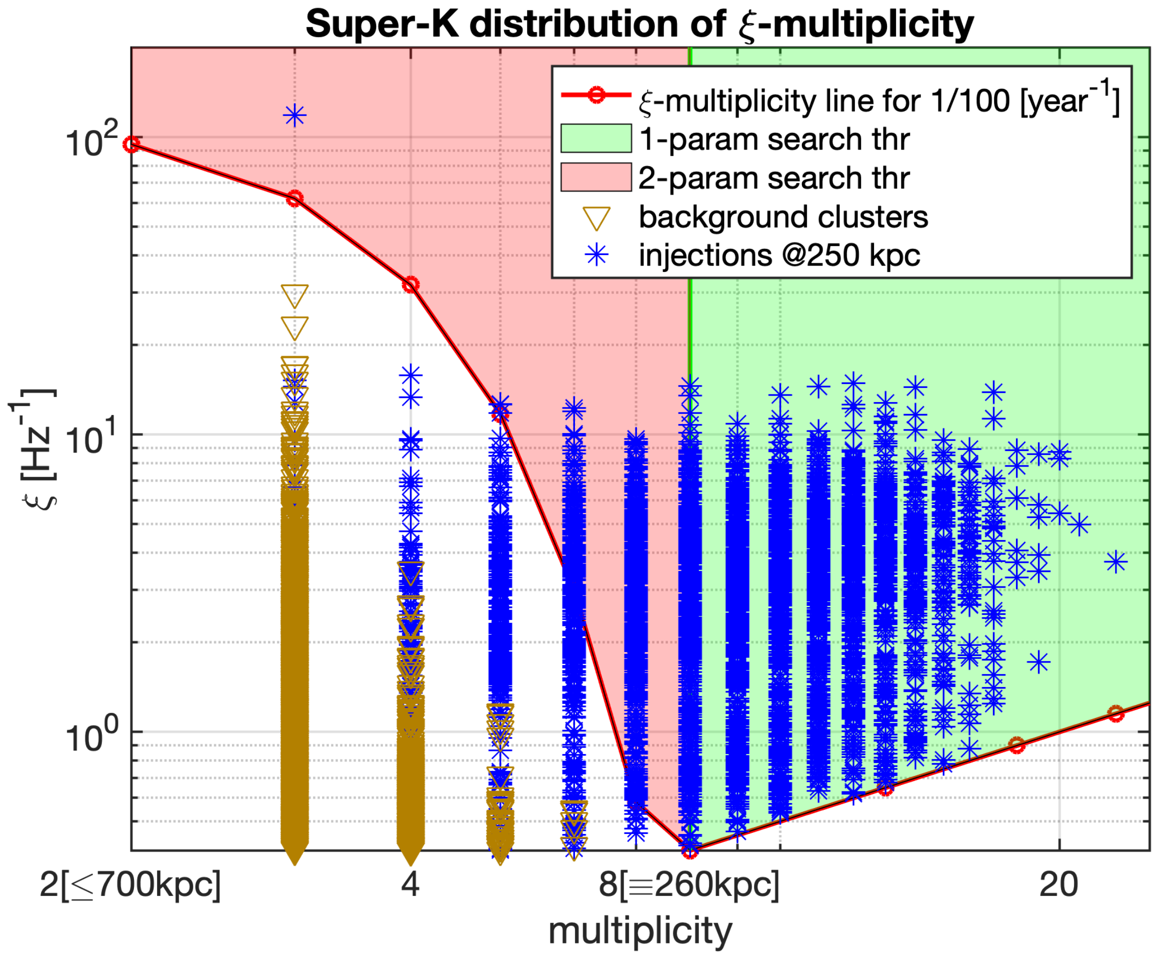
Total Background	Background [< 1/100 years]	1-parameter [< 1/100 years]	2-parameter (this work) [< 1/100 years]
49200	0% = 0/49200	**70.6%** = 2575/3645	**85.5%** = 3117/3645

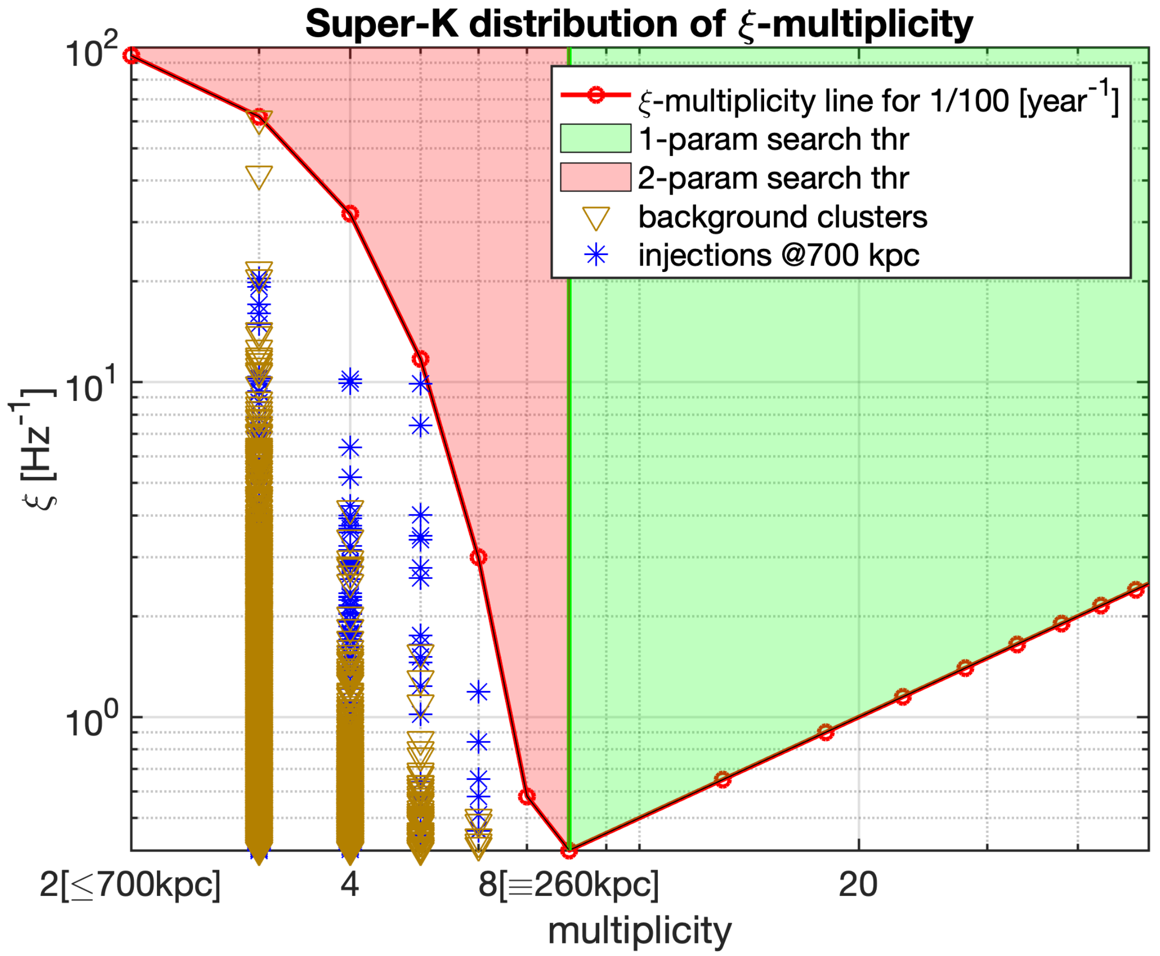
OH, Vigorito, Casentini, Pagliaroli, Drago, Fafone. 2020. 012154

3.3. Super-K

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







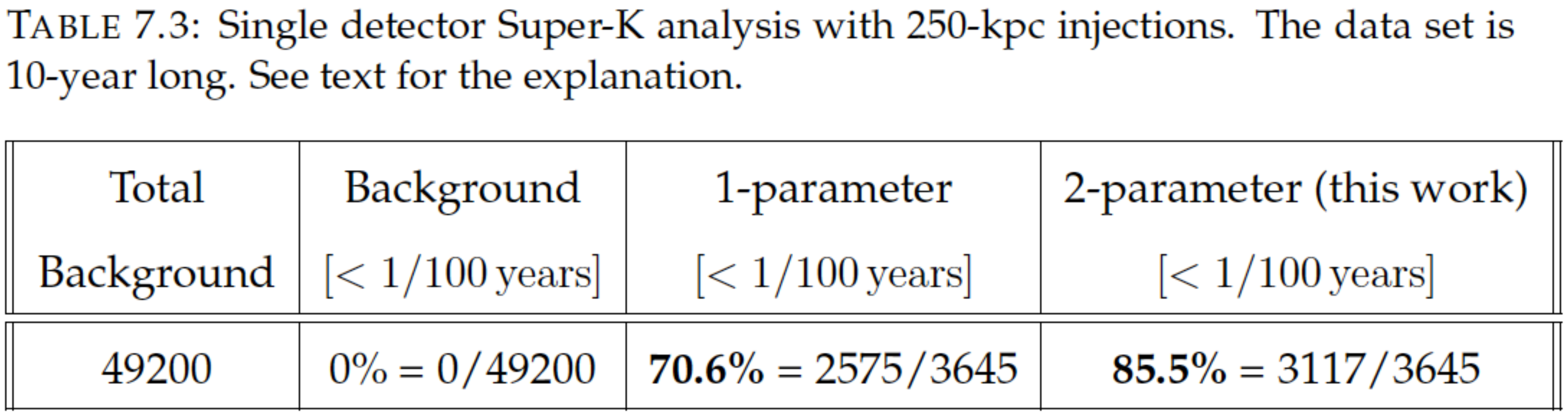
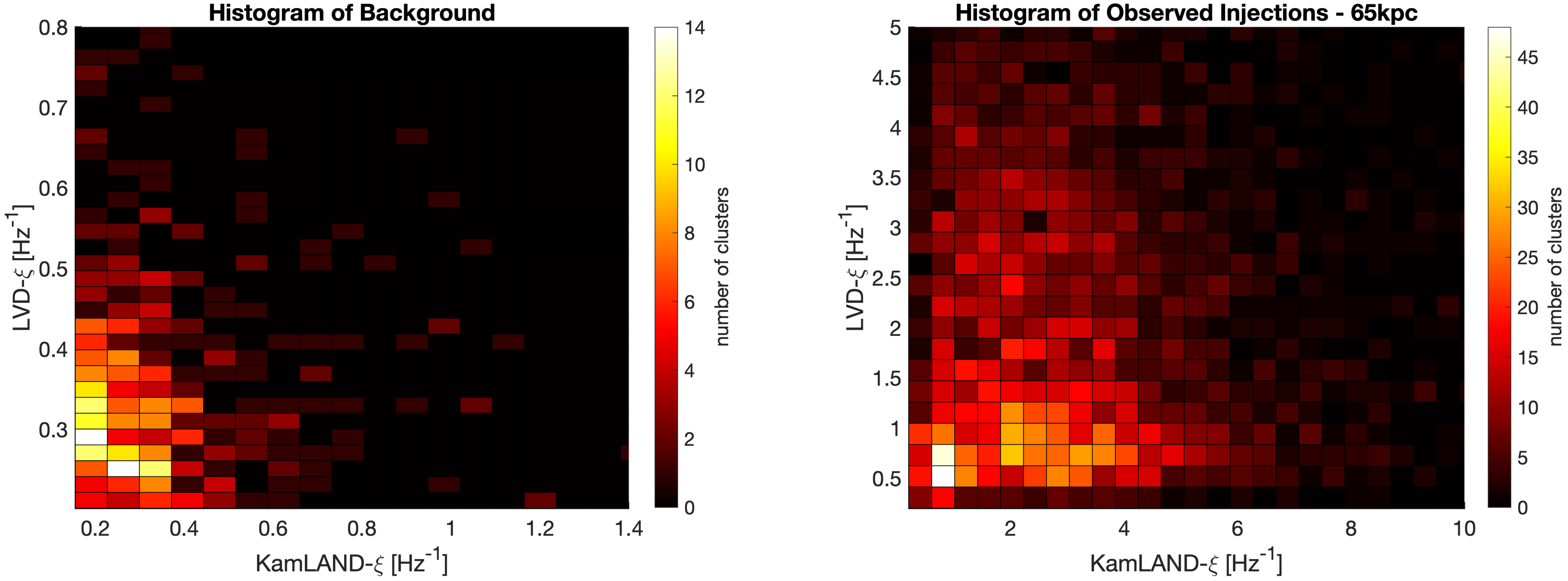


TABLE 7.3: Single detector Super-K analysis with 250-kpc injections. The data set is 10-year long. See text for the explanation.

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

3.3. LVD-KamLAND

- LVD-KamLAND joint-detector analysis.



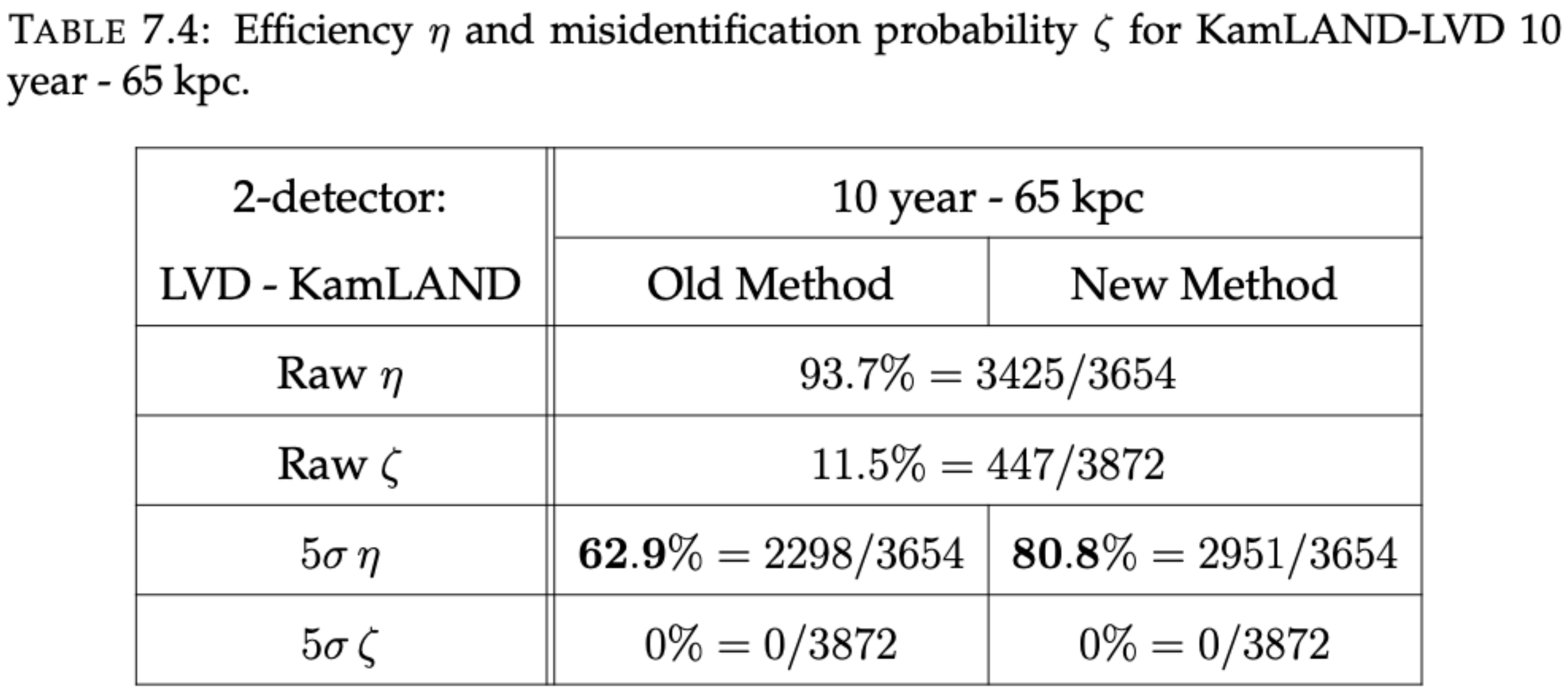


TABLE 7.4: Efficiency η and misidentification probability ζ for KamLAND-LVD 10 year - 65 kpc.

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

3.3. Hyper-K single-detector analysis

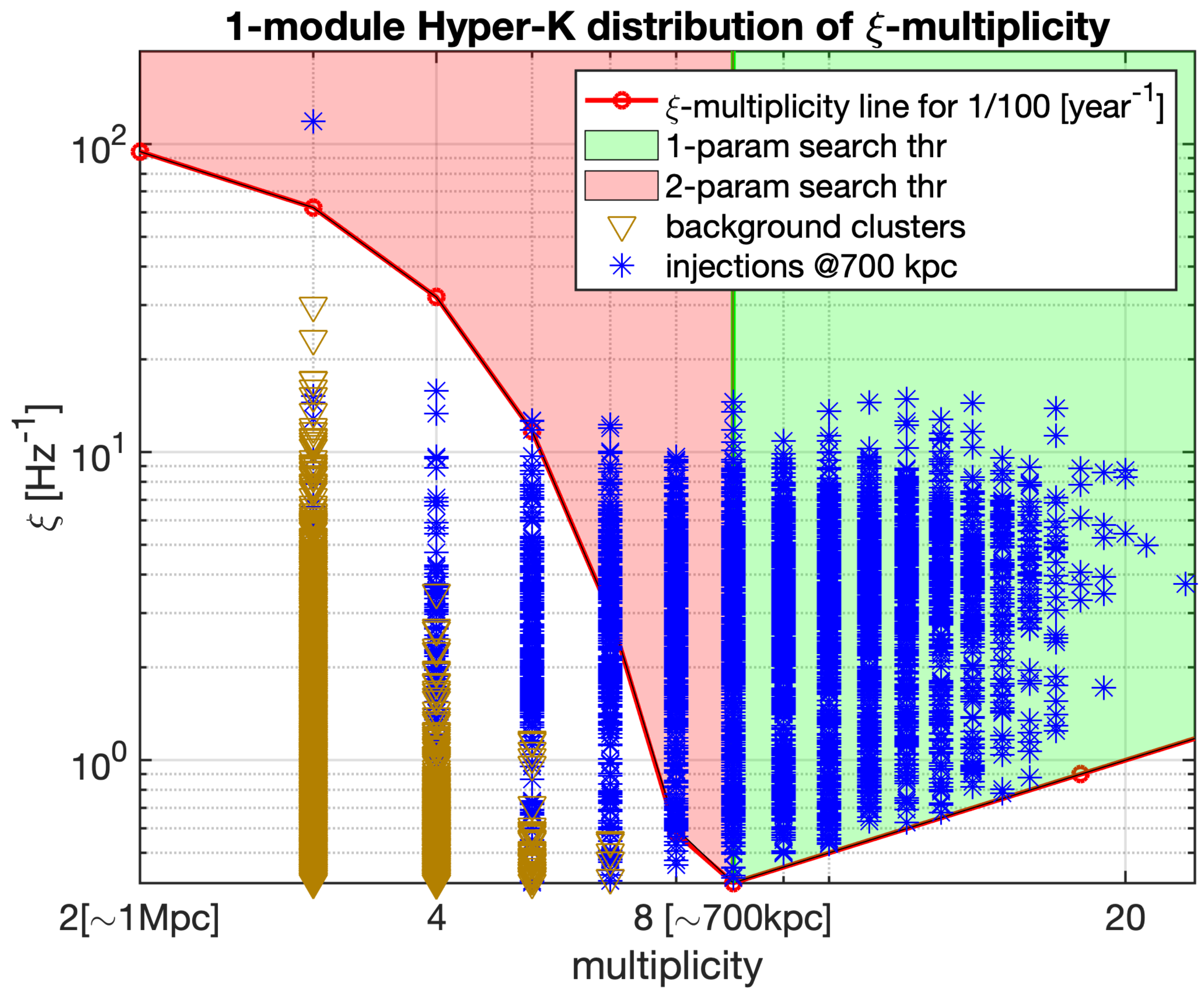
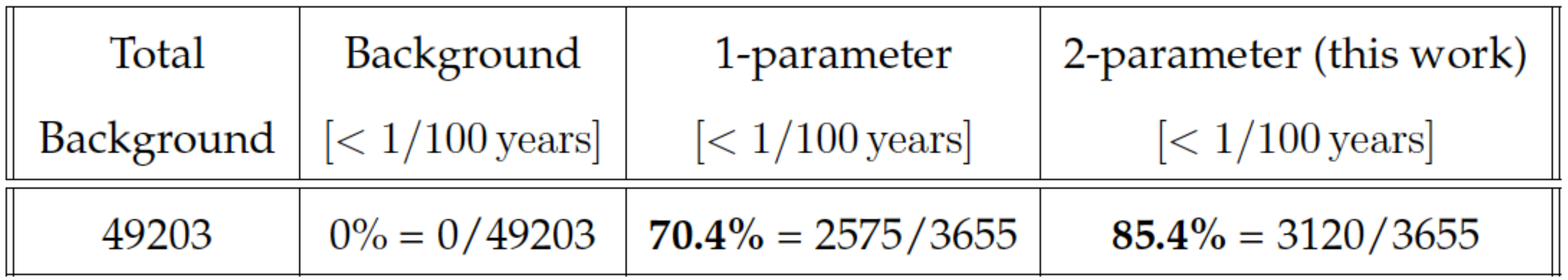


TABLE 7.5: One-module Hyper-K with 700-kpc injections.



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

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 among different experiments.

3.3. Perspectives

- 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 any 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)

O'Connor, E. 2015. 10.1088

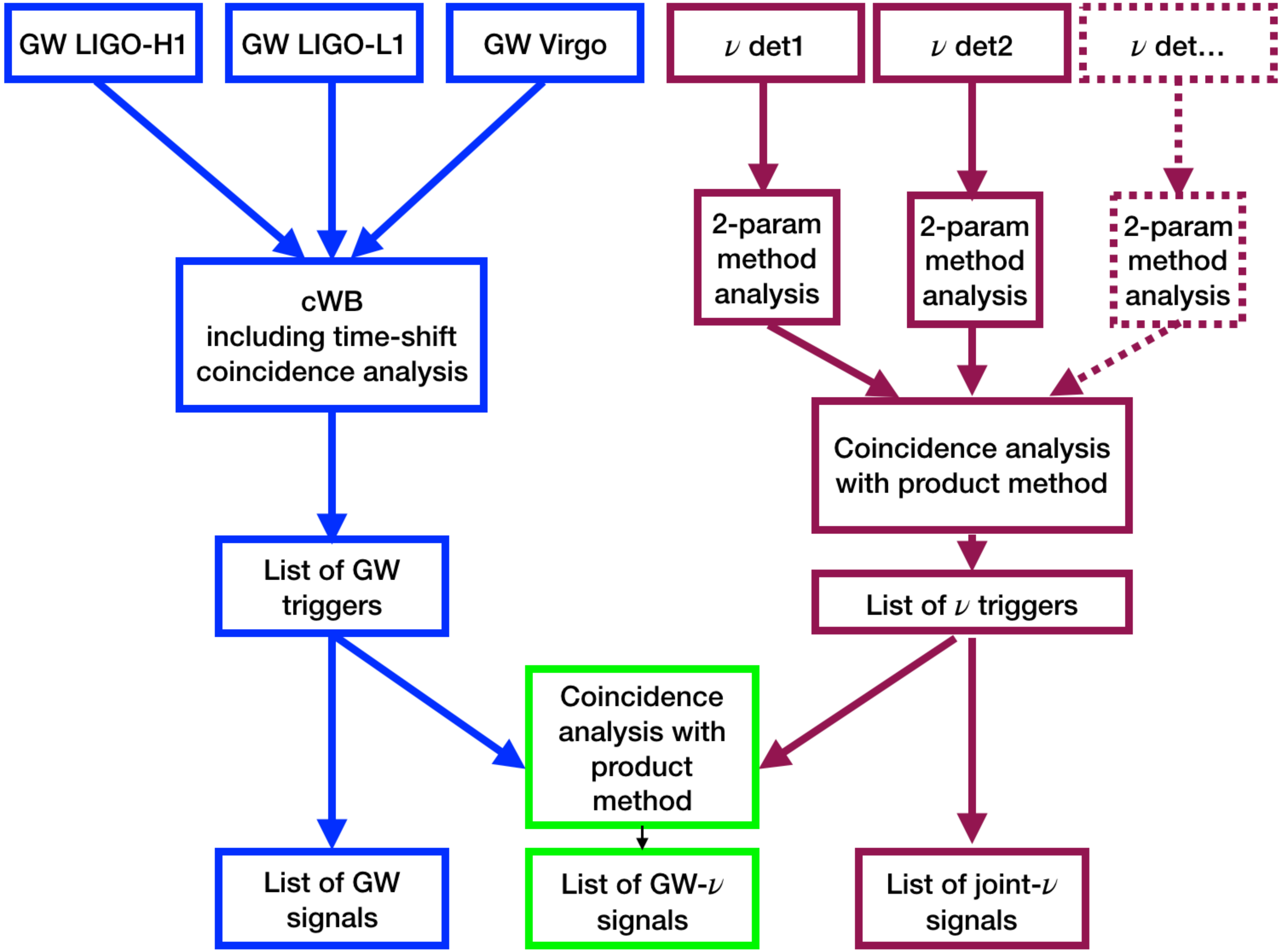
2. Coincidence analysis

3.1. Binomial test

3.2. ξ-cut

3.3. The new 2-parameter modified imitation frequency

4. GW-ν Joint Search



GW LIGO-H1

GW LIGO-L1

GW Virgo

ν det1

ν det2

ν det…

2-param method analysis

2-param method analysis

2-param method analysis

cWB including time-shift coincidence analysis

Coincidence analysis with product method

List of GW triggers

List of ν triggers

Coincidence analysis with product method

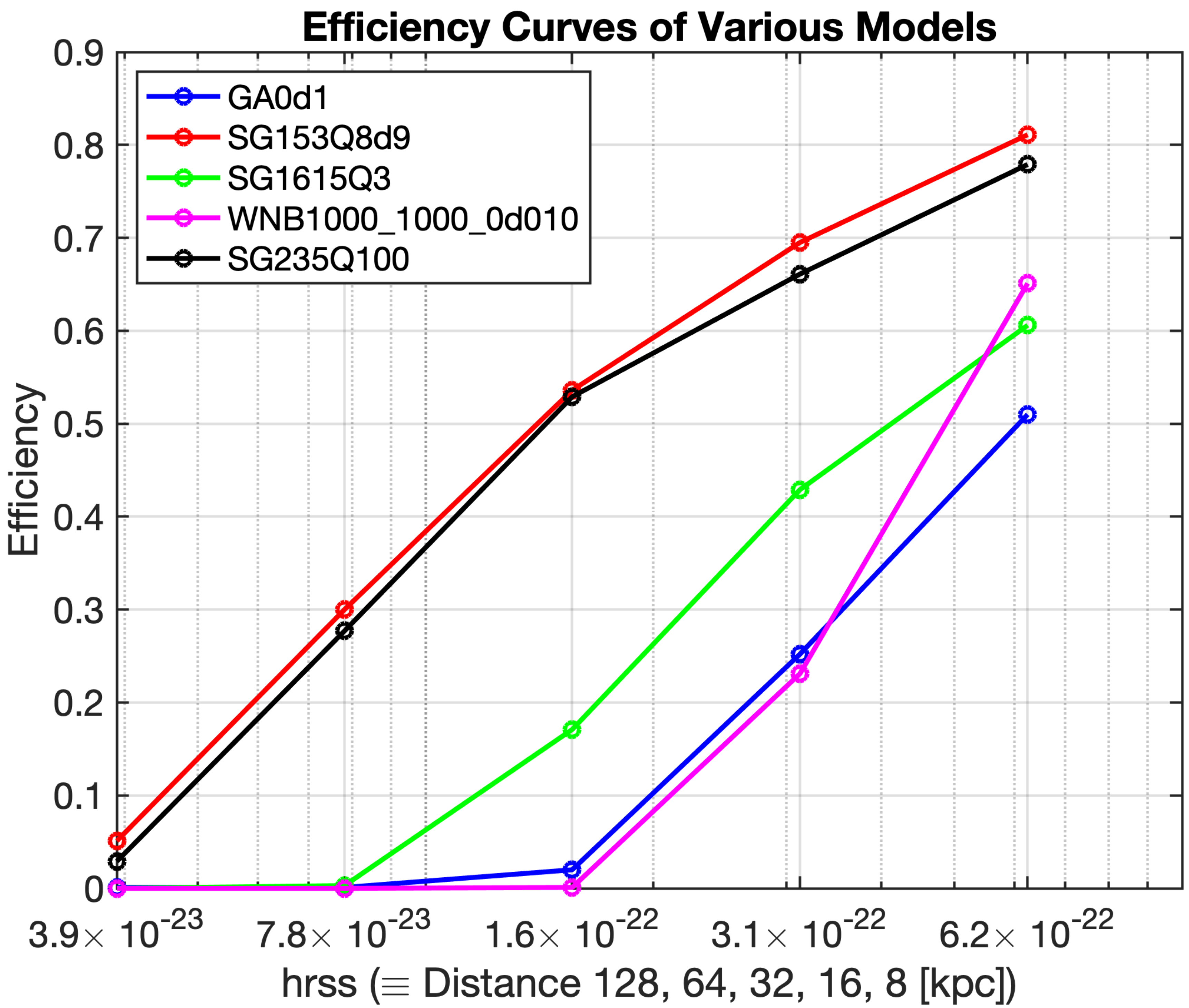
List of GW signals

List of GW-ν signals

List of joint-ν signals

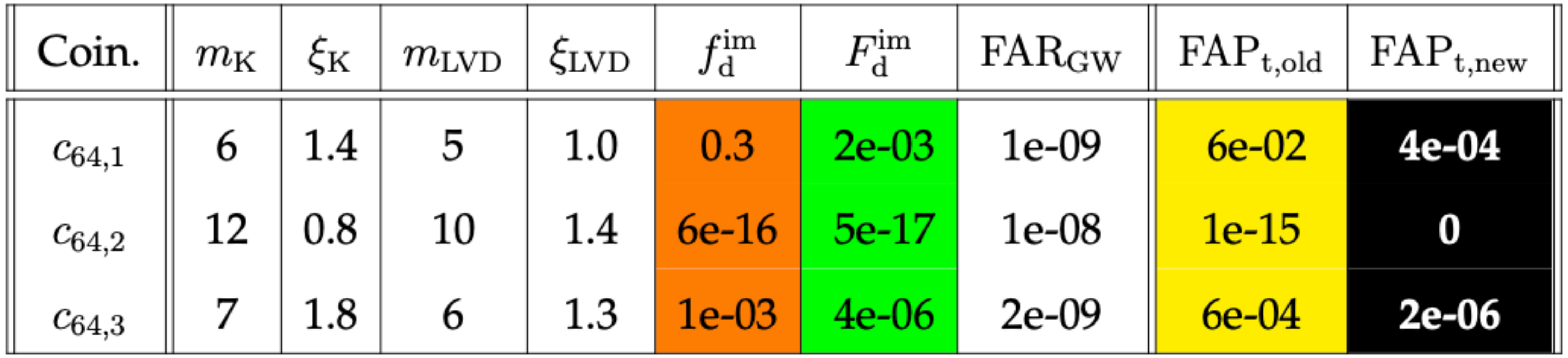
4. GW Data

- O1 GW background data with several generic injections analysed by cWB



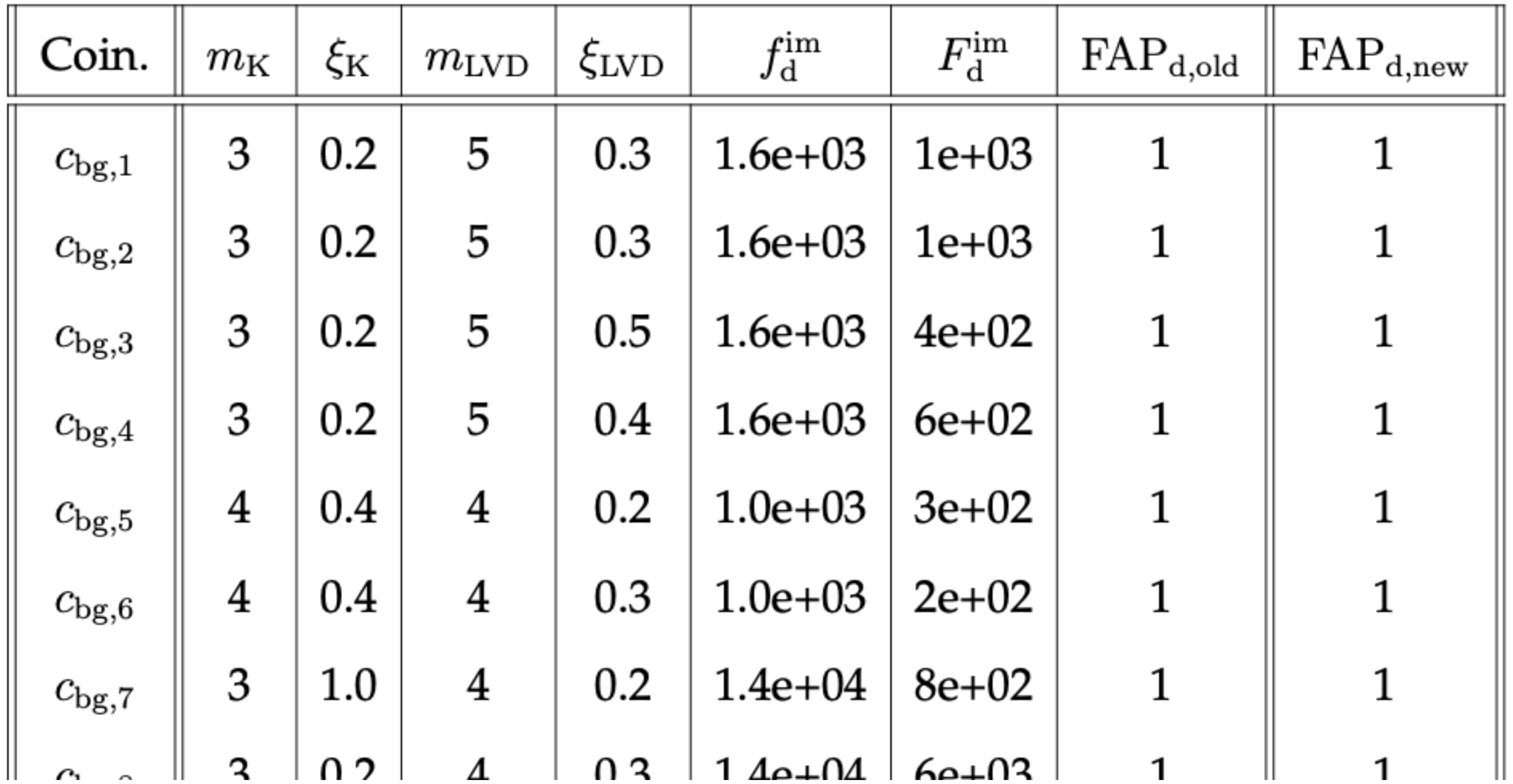
4. Results

TABLE 8.4: Details of GW-ν coincidences for 64 kpc. The legends are the same as in table 8.1.



Coin.	m_K	ξ_K	m_{LVD}	ξ_{LVD}	f_d^{im}	F_d^{im}	FAR$_{GW}$	FAP$_{t,old}$	FAP$_{t,new}$
$c_{64,1}$	6	1.4	5	1.0	0.3	2e-03	1e-09	6e-02	4e-04
$c_{64,2}$	12	0.8	10	1.4	6e-16	5e-17	1e-08	1e-15	0
$c_{64,3}$	7	1.8	6	1.3	1e-03	4e-06	2e-09	6e-04	2e-06

TABLE 8.6: Details of background coincidences for 2ν network analysis. Column 2-5 are for KamLAND multiplicity, KamLand ξ [Hz], LVD multiplicity, and LVD ξ [Hz]. Column 6 and 7 are for the joint f^{im} [Hz] and the joint F^{im} [Hz] between KamLAND and LVD. Column 8 and 9 are for their FAPs with the f^{im} and F^{im}.



Coin.	m_K	ξ_K	m_{LVD}	ξ_{LVD}	f_d^{im}	F_d^{im}	FAP$_{d,old}$	FAP$_{d,new}$
$c_{bg,1}$	3	0.2	5	0.3	1.6e+03	1e+03	1	1
$c_{bg,2}$	3	0.2	5	0.3	1.6e+03	1e+03	1	1
$c_{bg,3}$	3	0.2	5	0.5	1.6e+03	4e+02	1	1
$c_{bg,4}$	3	0.2	5	0.4	1.6e+03	6e+02	1	1
$c_{bg,5}$	4	0.4	4	0.2	1.0e+03	3e+02	1	1
$c_{bg,6}$	4	0.4	4	0.3	1.0e+03	2e+02	1	1
$c_{bg,7}$	3	1.0	4	0.2	1.4e+04	8e+02	1	1
c	3	0.2	4	0.3	1.4e+04	6e+03	1	1

Triple **multimessenger** coincidence analysis

5. Conclusion

- We have discussed the following topics:
    1. Core-collapse supernovae (processes, detections, analyses)
    2. Coincidence analysis
    3. Increasing sensitivity of ν-detectors (binomial test, ξ-parameter, **modified analysis**)
    4. The **GW-ν joint** search strategy
- Our **new method** can be applied for current and future detectors as,
    - ✱ **single**-detector neutrino analysis,
    - ✱ **multi**-detector neutrino analysis, and
    - ✱ **multimessenger** analysis.
- **Failed-SN search** by Super-K-LVK could be done

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BACKUP SLIDES

1. CCSNe: Pagliaroli Parametrization

- Flux parametrisation on the accretion and cooling phase,
  - ❖ The accretion has slightly non-thermal spectrum

$$\Phi^0_{\mathrm{a}}(t^{\mathrm{em}}, E_\nu) = \frac{1}{4\pi D^2}\frac{8\pi c}{(hc)^3} \times \left[N_n(t^{\mathrm{em}})\sigma_{e^+n}(E_\nu)g_{e^+}(\bar{E}_{e^+}(E_\nu), T_{\mathrm{a}}(t^{\mathrm{em}}))\right],$$

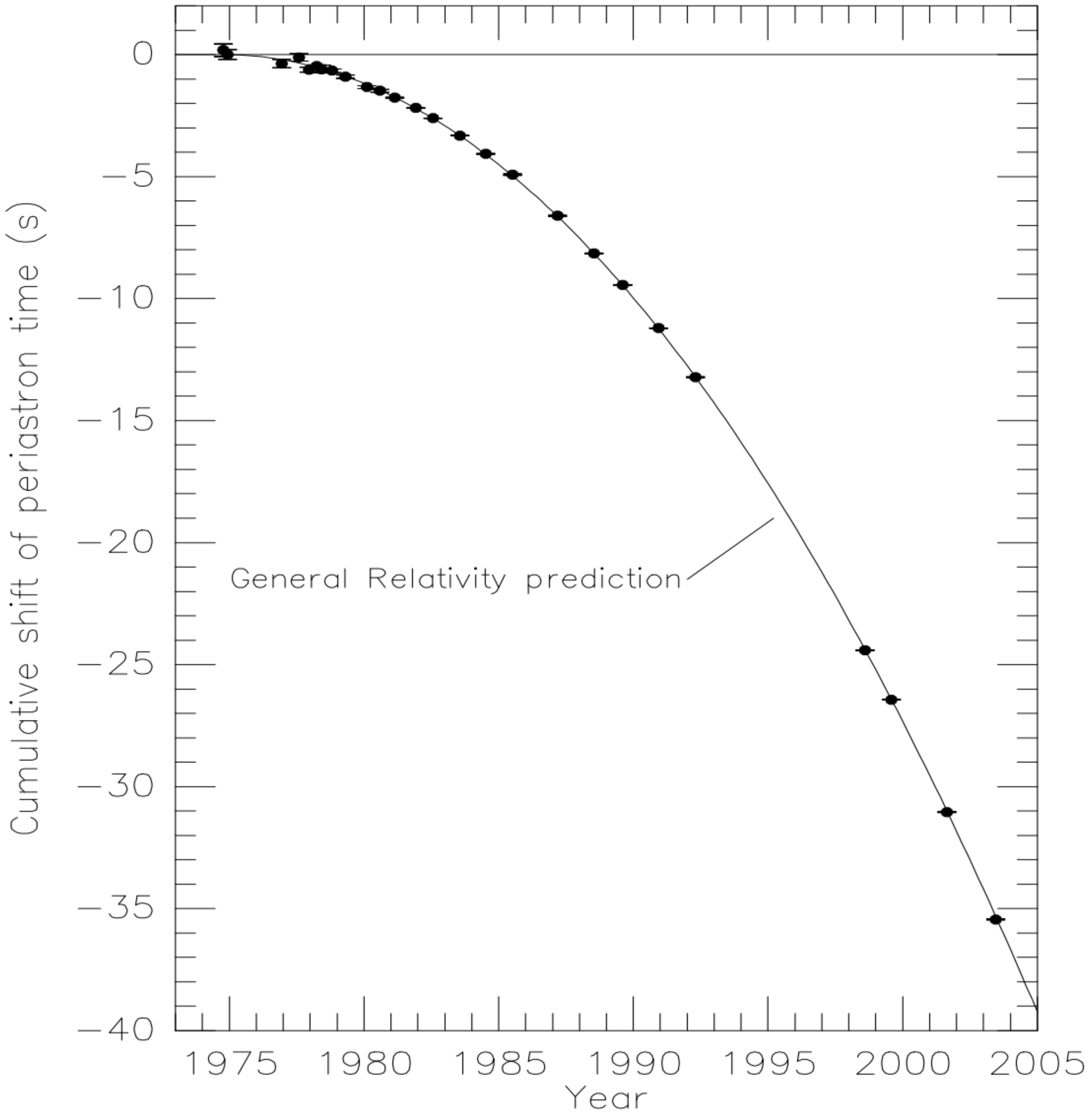
  - ❖ The cooling is thermal spectrum

$$\Phi^0_{\mathrm{c}}(t^{\mathrm{em}}, E_\nu) = \frac{1}{4\pi D^2}\frac{\pi c}{hc^3}\left[4\pi R_{\mathrm{c}}^2 g_{\bar{\nu}_e}(E_\nu, T_{\mathrm{c}}(t^{\mathrm{em}}))\right],$$

- Demonstrated to improve the analysis of SN1987A determination on M_c, T_c, R_c

Pagliaroli et al. 2009. 10.1016

1. Detection: Hulse-Taylor Pulsars



Weisberg, JM, and JH Taylor. 2005

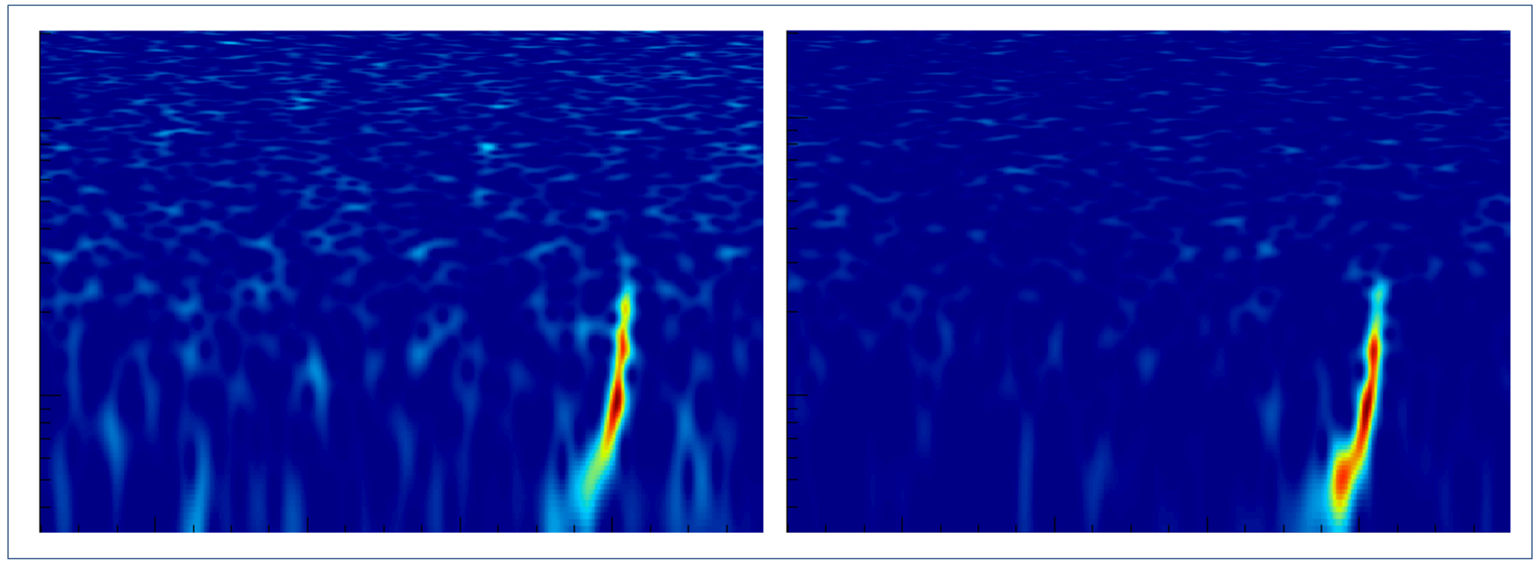
- First GW **source** detection, but *indirect*:
  - binary pulsars PSR1913+16,
  - via Arecibo radio telescope,
- Discovery paper: Hulse, RA and JH Taylor, 1975
- Nobel in physics, 1993

1. CCSNe: cWB and Wavelet Transform

- GW burst pipeline: pyCBC, X-pipeline, coherentWave Burst (cWB)
- cWB: generic burst / short duration, no prior model needed, online
- GW150914 online detection by cWB.
- Time-frequency analysis: time series data to time-frequency map.
- TF: Windowed Fourier transform (WFT) / Short-time Fourier transform (STFT), wavelet transform
- cWB last version: fast Wilson-Daubechies time-frequency transform combined with the Meyer wavelet (WDM)

gwburst.gitlab.io

Left: LL; Right: LH

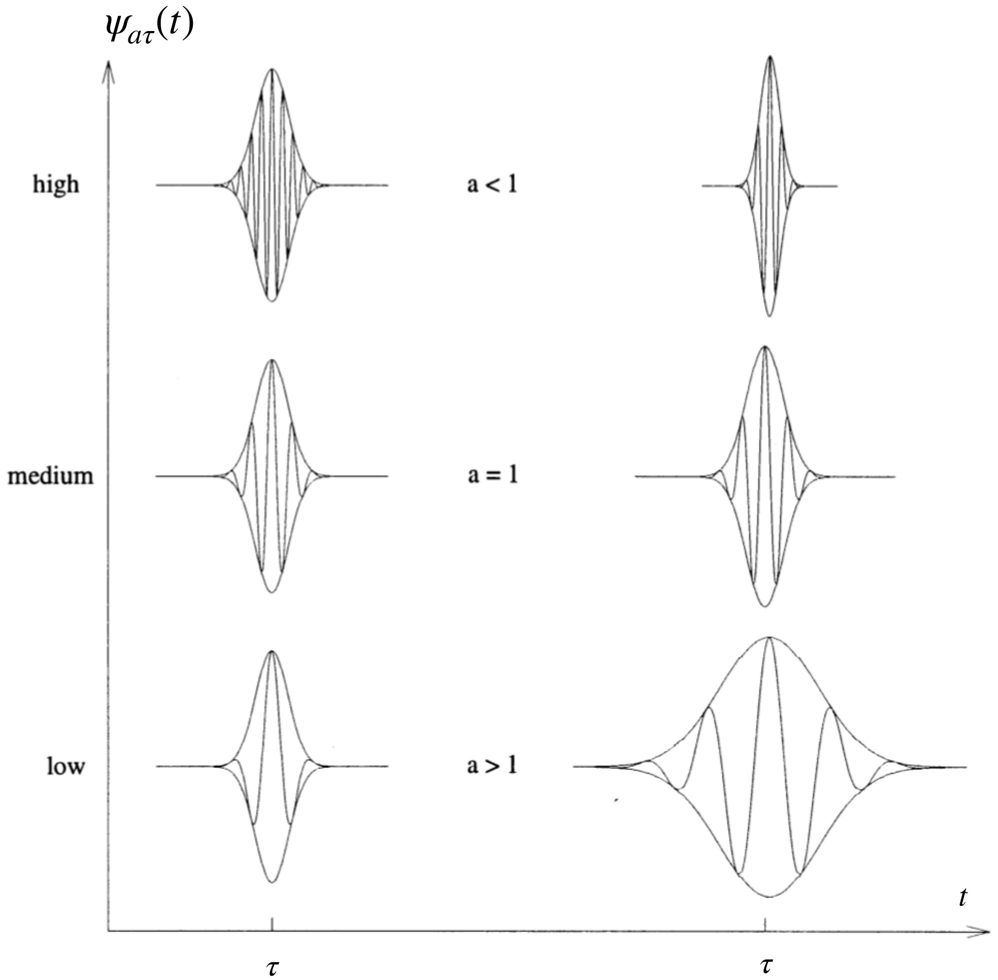


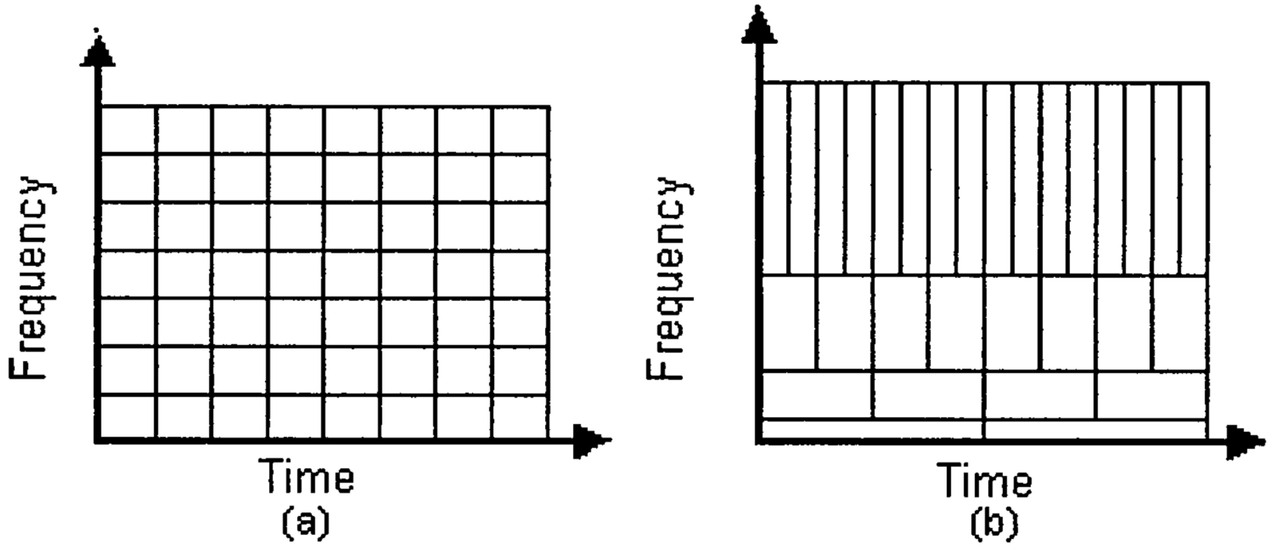
General Time-Freq (TF) transform:

$$x(t) \mapsto \mathrm{TF}_x(a,\tau) = \int_{-\infty}^{\infty} \overline{\psi_{a\tau}(t)}\, x(t)\, dt$$

Differences

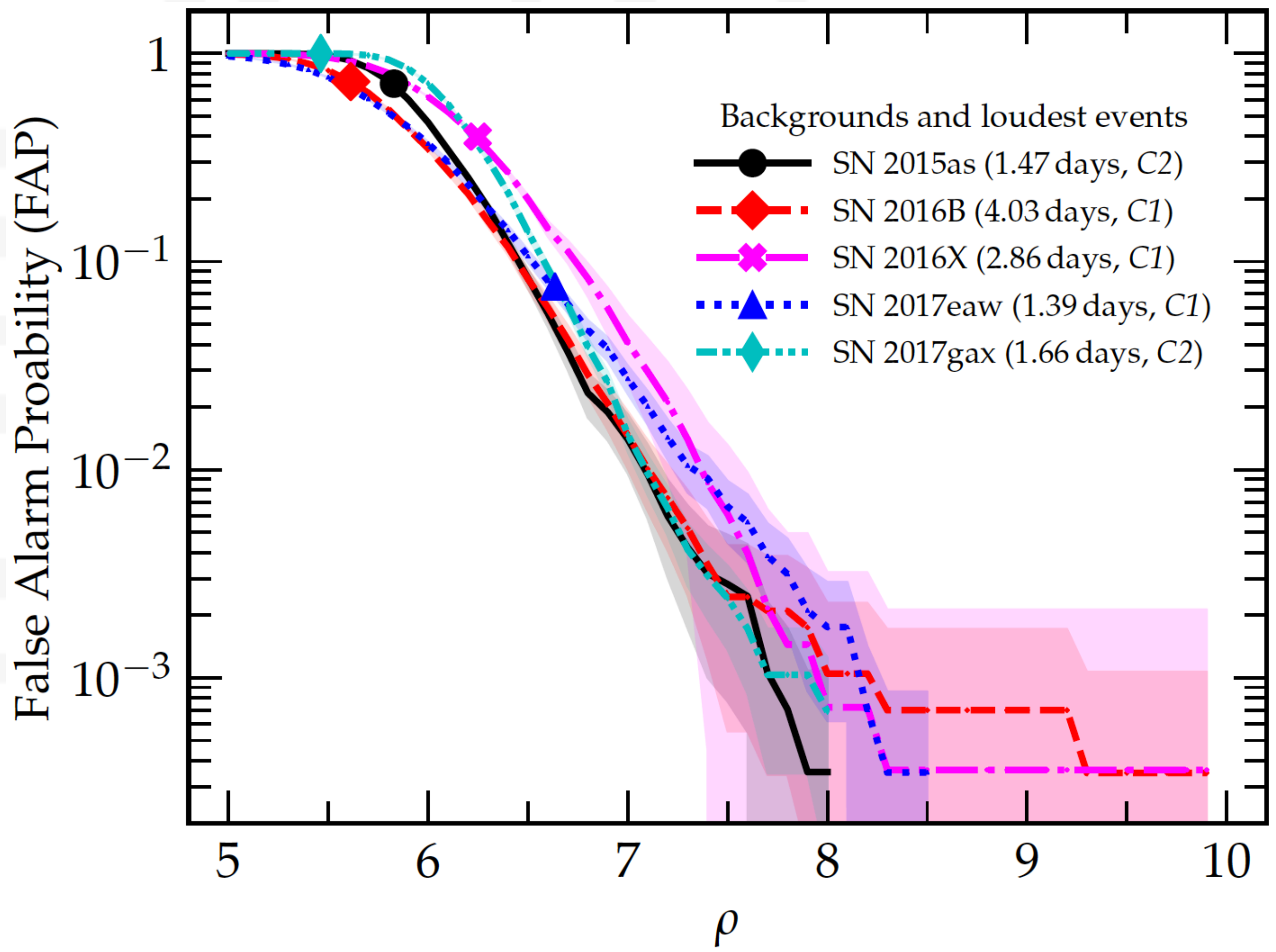
- STFT (Gabor): $\psi_{a\tau}(t) = e^{it/a}\psi(t-\tau)$
- WT: $\psi_{a\tau}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-\tau}{a}\right)$
- a is related to characteristic frequency $\left(\left[\frac{1}{a}\right] = [\mathrm{Hz}]\right)$
- τ is time translation → position in the signal
- ψ is called mother function (window function in case of STFT: Gaussian)

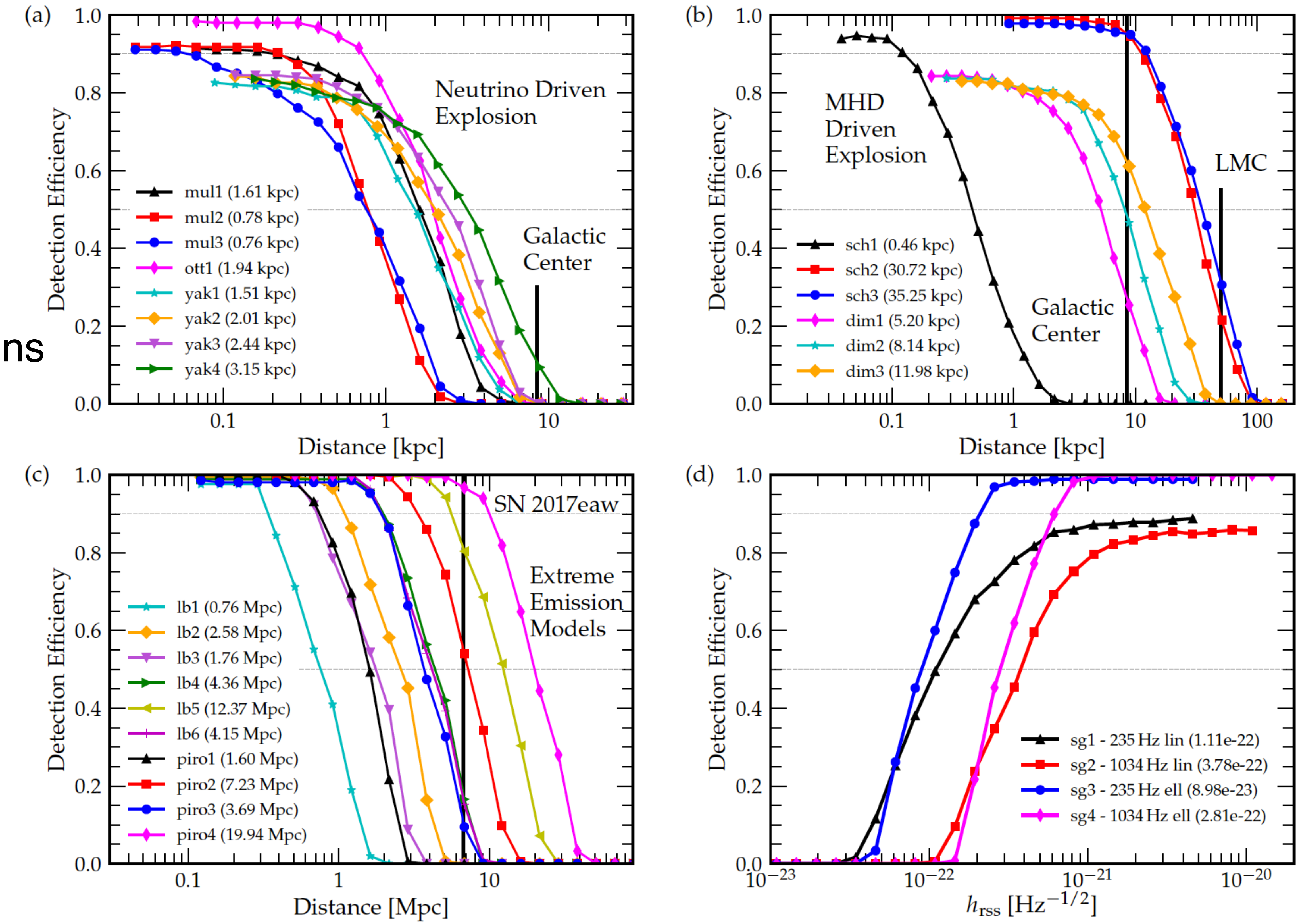




1. CCSNe: Efficiency of CCSN Search

- Efficiency studies of CCSN search via cWB with EM triggers
- real EM observations < 20Mpc
- 50% efficiency:
  - ➡ 5 kpc for ν-driven explosions
  - ➡ 54 kpc for magnetorotational explosions

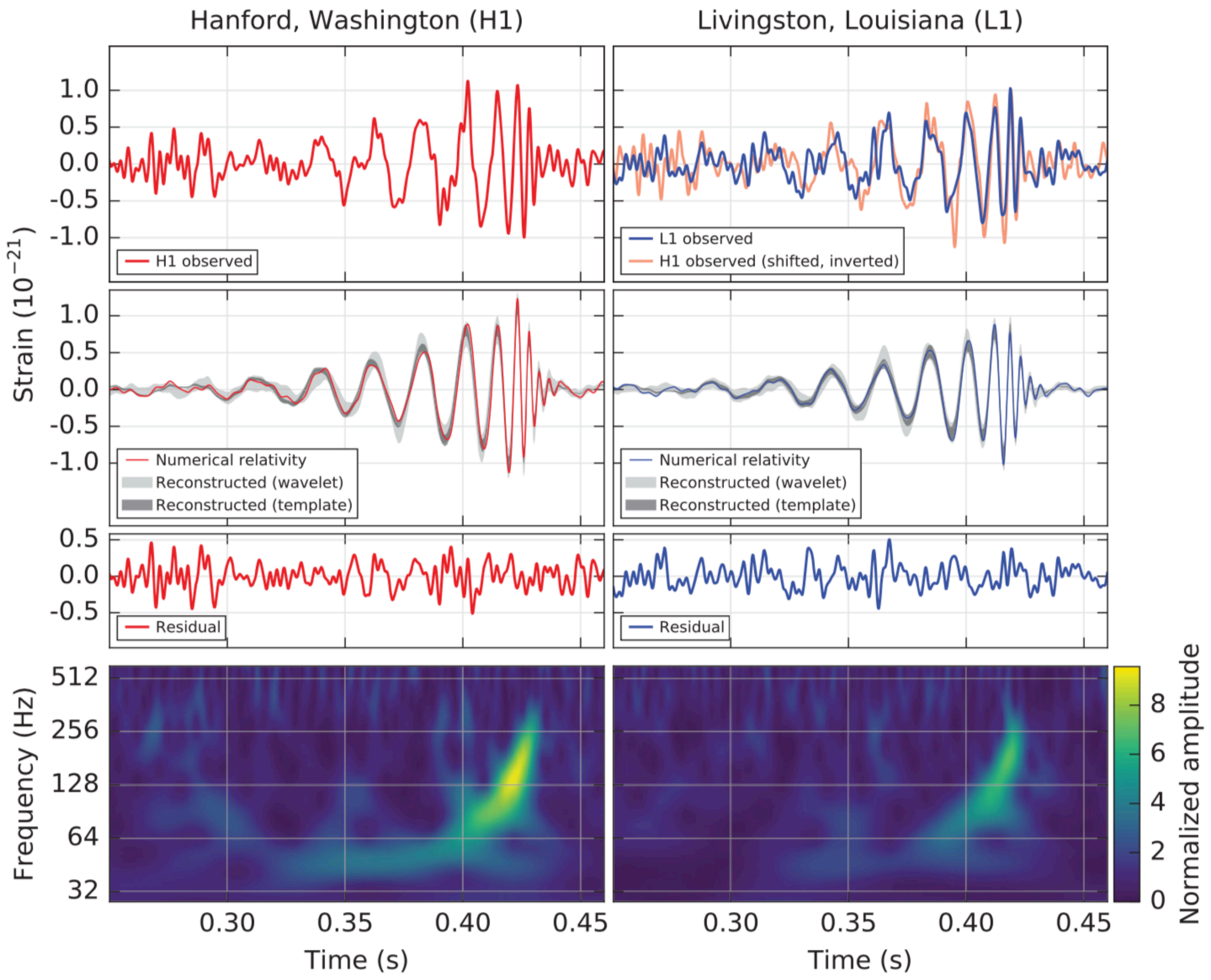




Abbott BP, *et.al.* 2019. 1908.03584

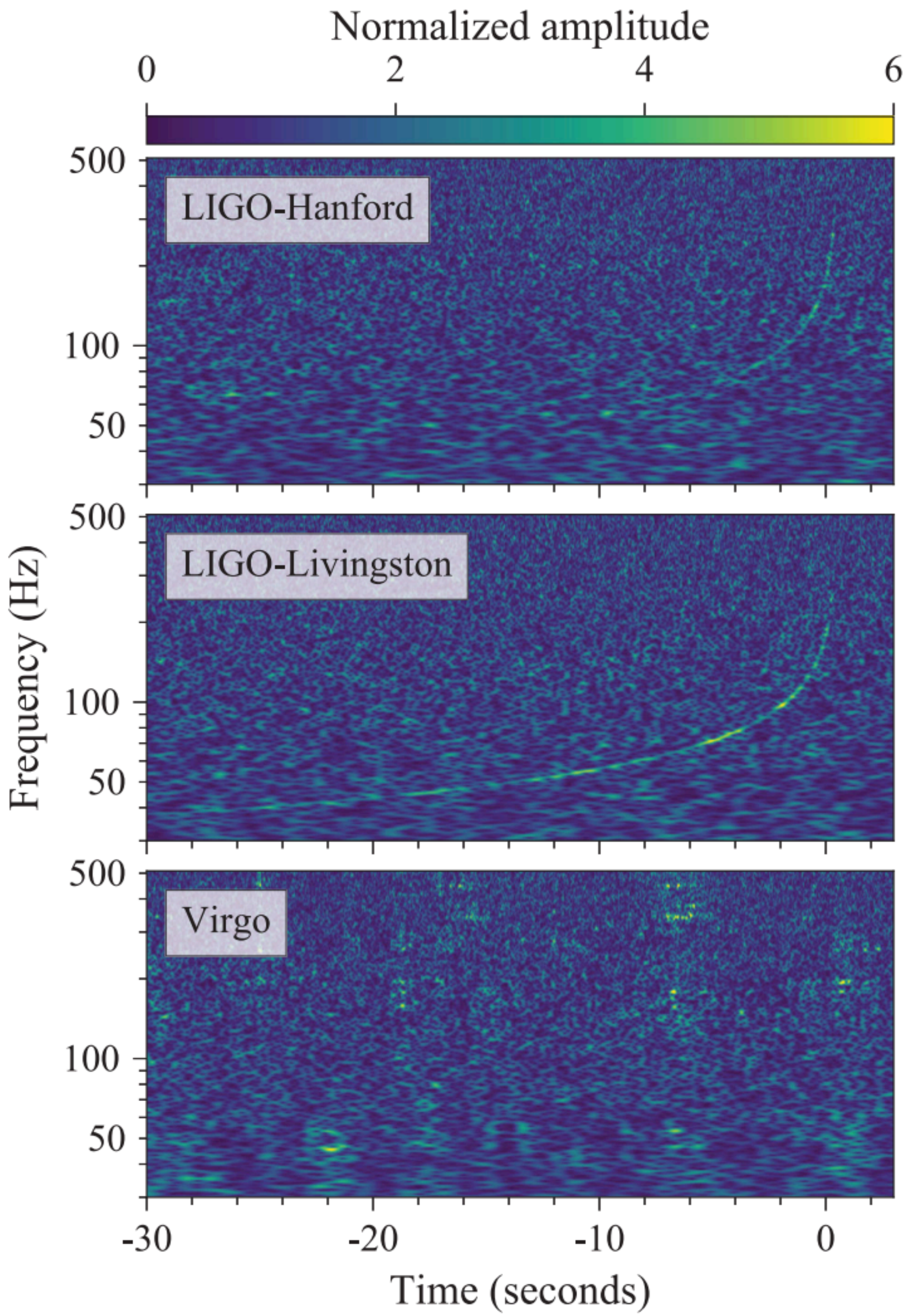
1. GW Observations

- GW150914: BBH, H-L
- GW170814: BBH, H-L-V, $1160\,\mathrm{deg}^2 \rightarrow 60\,\mathrm{deg}^2$
- GW170817: BNS, multimessenger: HLV-Fermi GBM-INTEGRAL-…(+ optical, X-ray, radio, but no neutrino)
- GW from CCSN??? Not yet, but *perhaps/hopefully* soon.



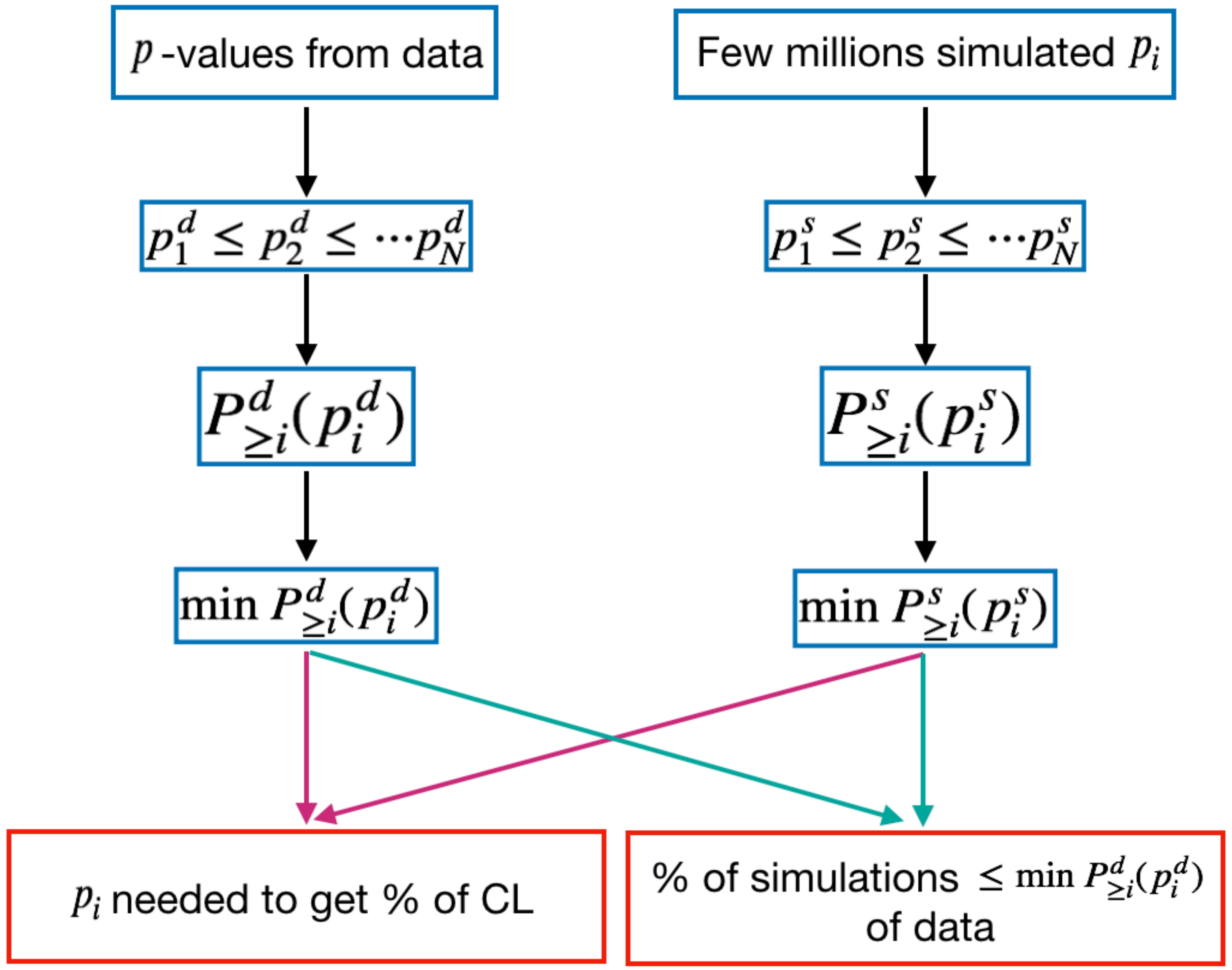
Abbott, BP, *et.al.* 2016

Abbott, BP, *et.al.* 2017. 10. 1103



3. Increasing Sensitivity of ν-Detectors: Binomial Test

- GW-GRB: Abbott B, *et.al.* 2008



p-values from data

$p_1^d \leq p_2^d \leq \cdots p_N^d$

$P^d_{\geq i}(p_i^d)$

$\min P^d_{\geq i}(p_i^d)$

Few millions simulated p_i

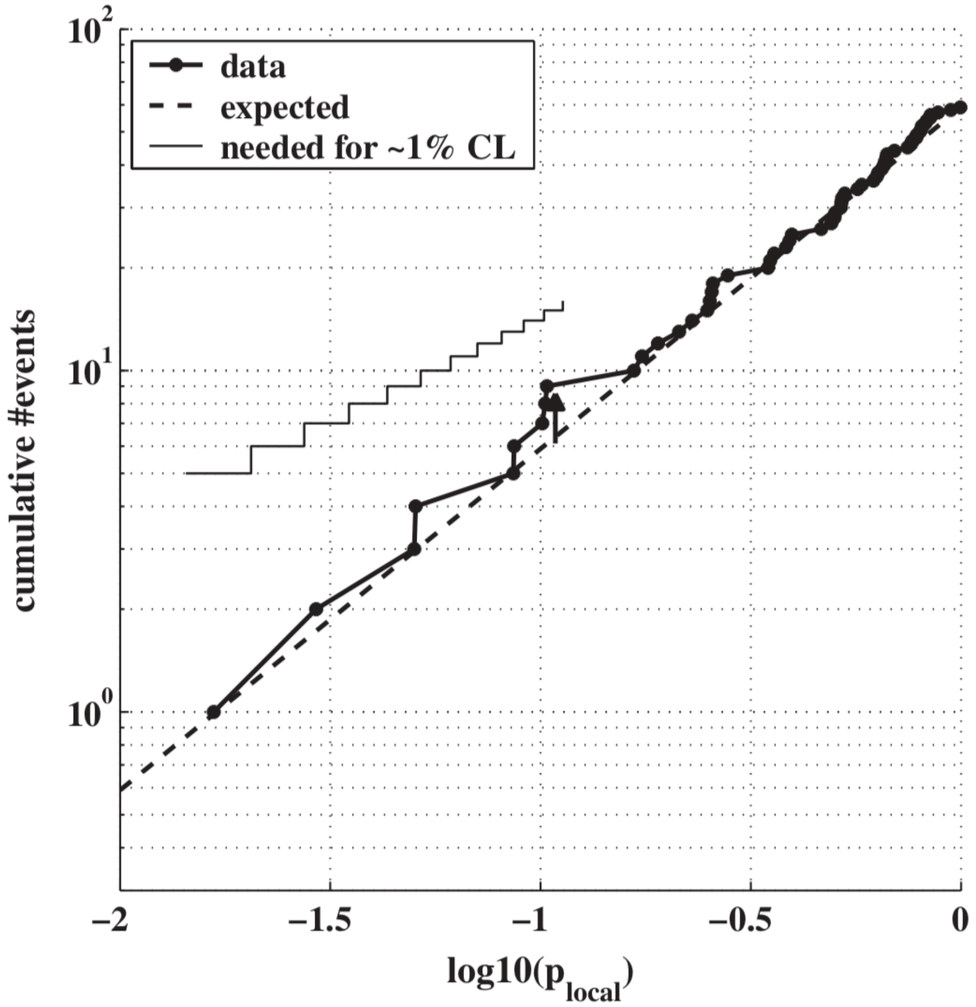
$p_1^s \leq p_2^s \leq \cdots p_N^s$

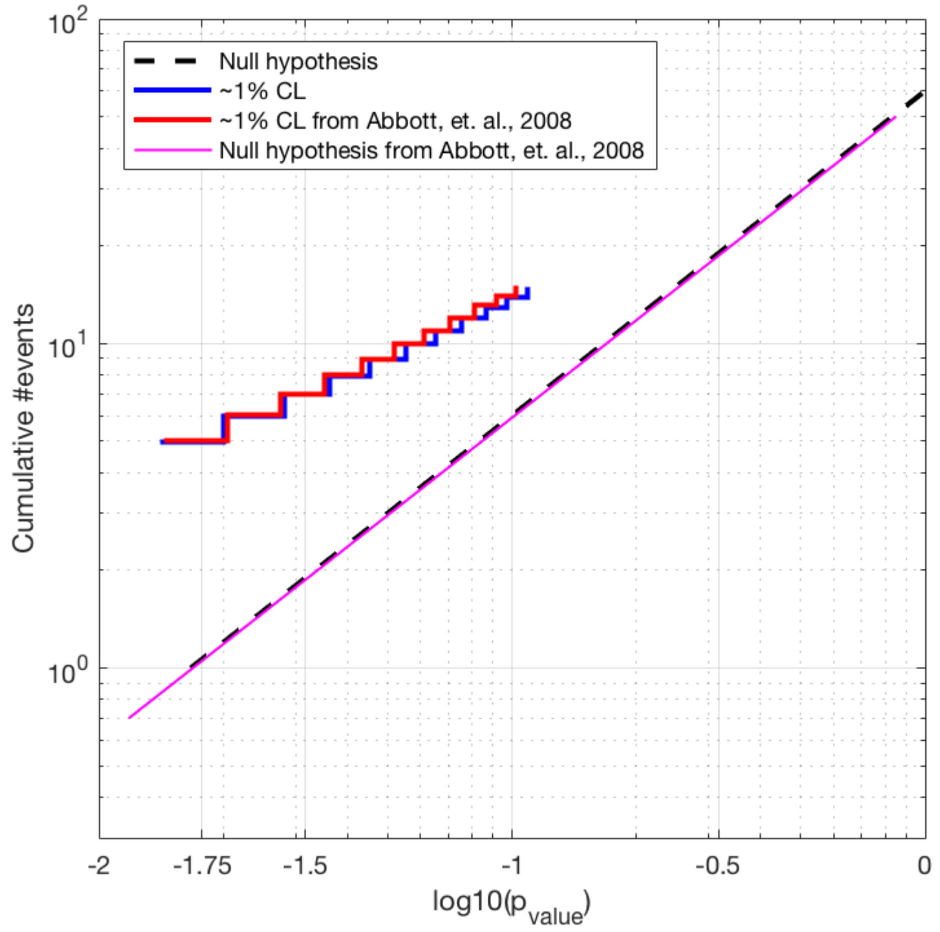
$P^s_{\geq i}(p_i^s)$

$\min P^s_{\geq i}(p_i^s)$

p_i needed to get % of CL

% of simulations $\leq \min P^d_{\geq i}(p_i^d)$ of data

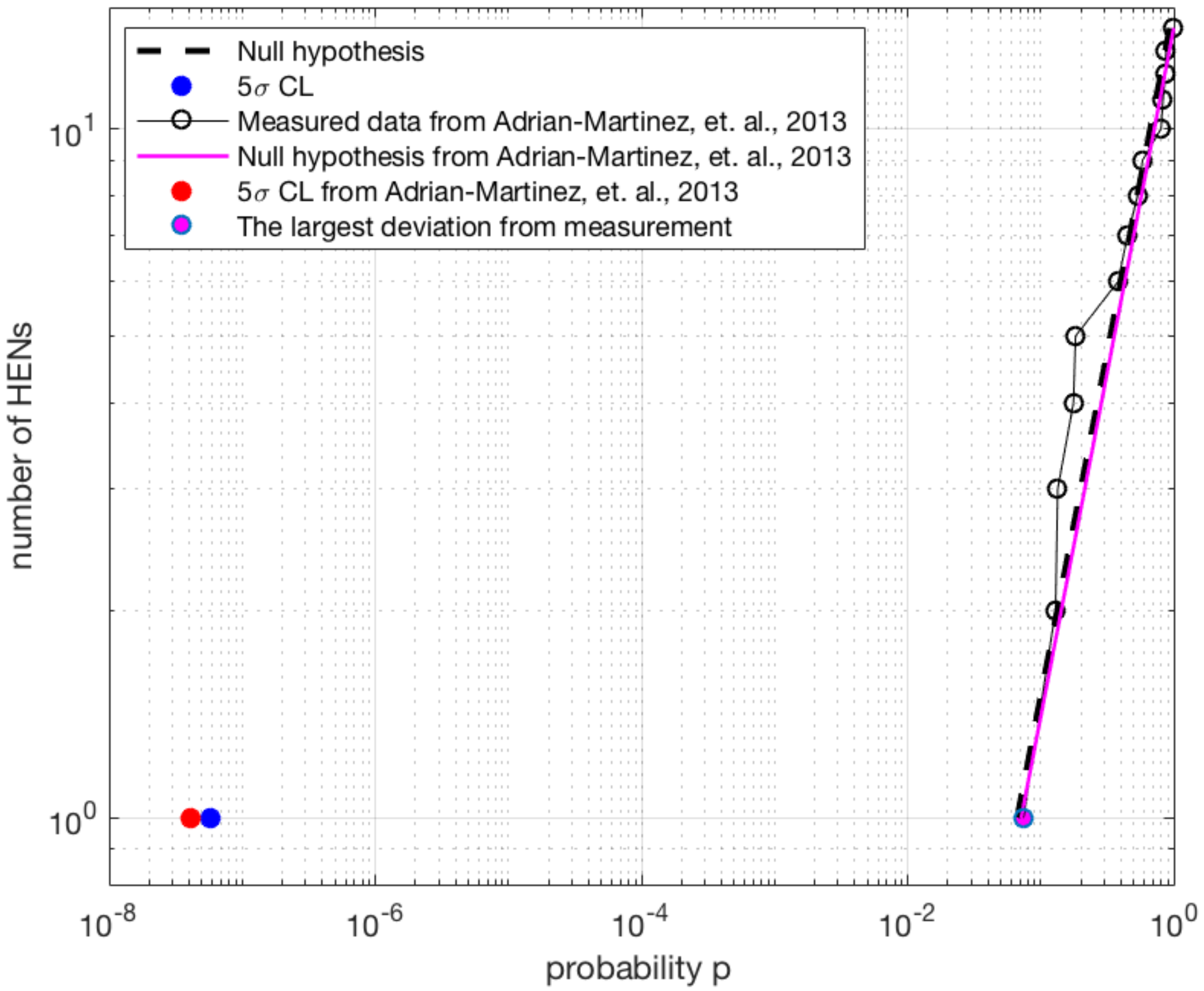


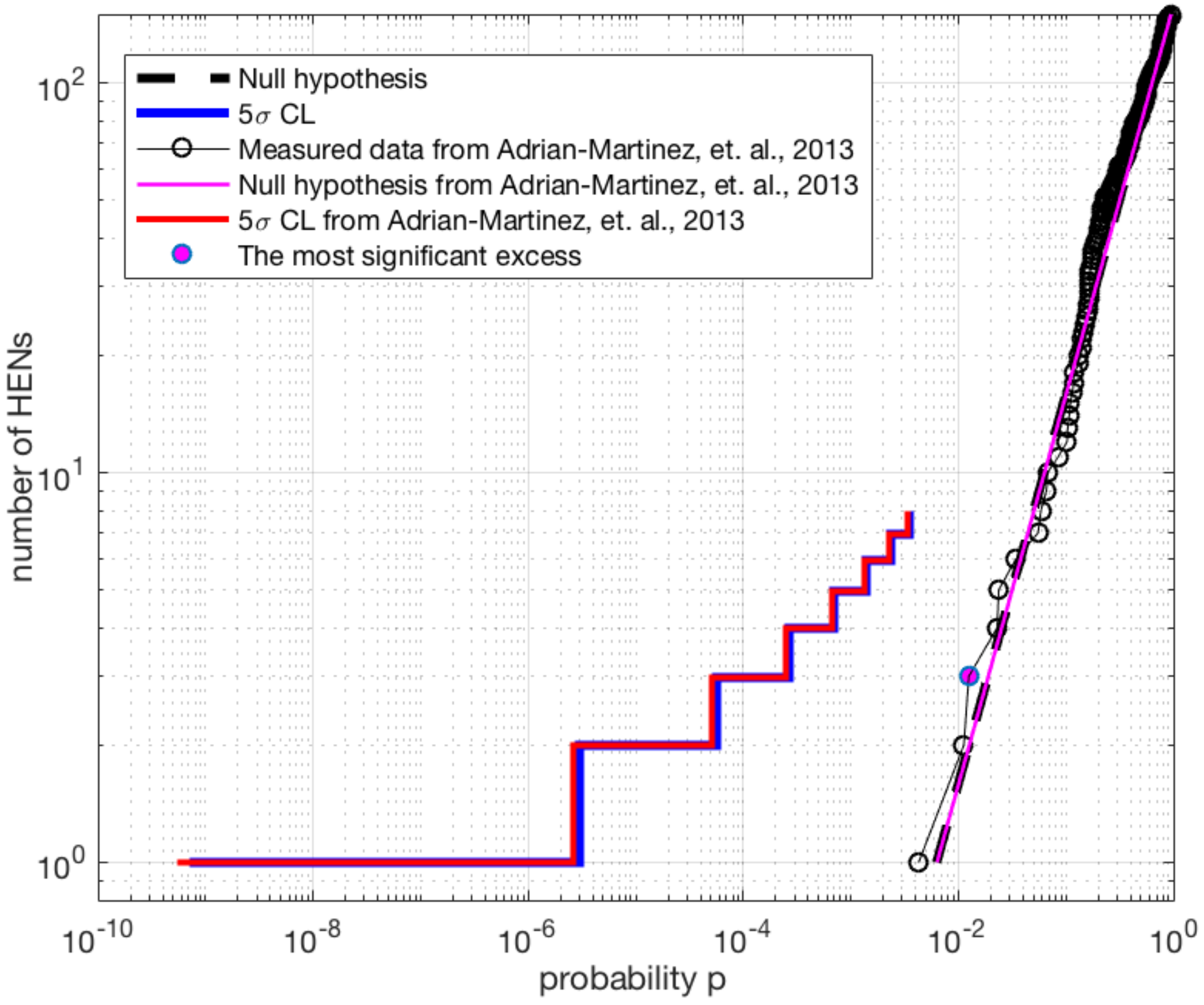


$$P^d_{\geq i}(p_i^d) = \sum_{k=i}^{N} \frac{N!}{(N-k)!k!}(p_i^d)^k(1-p_i^d)^{(N-k)}$$

3. Binomial Test

- GW-HEN: Adrián-Martínez, S. *et.al.* 2013; Di Palma, I. 2014
- From each GRB (HEN) previously, we do not assign any significance value





- Meanwhile, the joint-analysis of GW-LEN that we aim will use both data **coherently** and determine whether there is (are) interesting candidate(s).
- Our LEN triggers have their own significance.
- No need to go further with this method