Using Neutrinos to search GW signal

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- *Temporal relation with the Bounce*
- *Emission models for* $\bar{\nu}_e$
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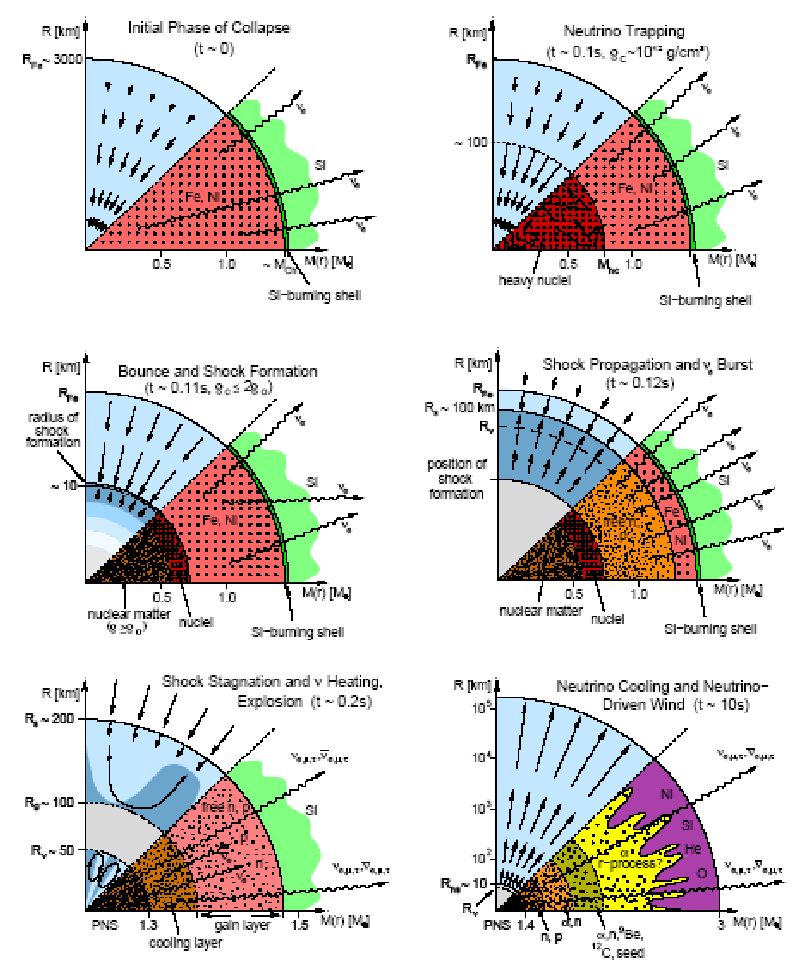
Standard Core-Collapse SN



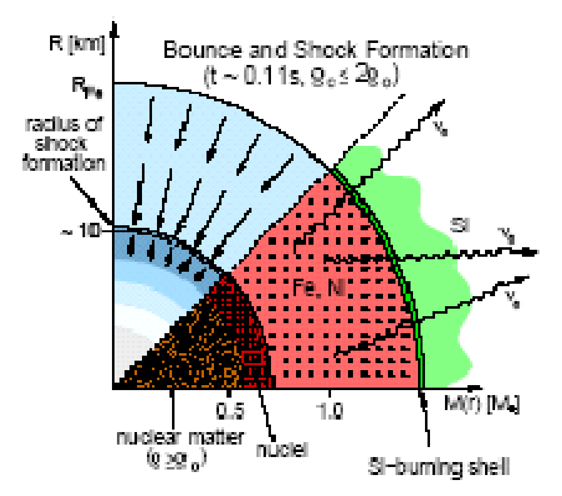
JANKA et al. Phys. Rept. 442 (2007) 38

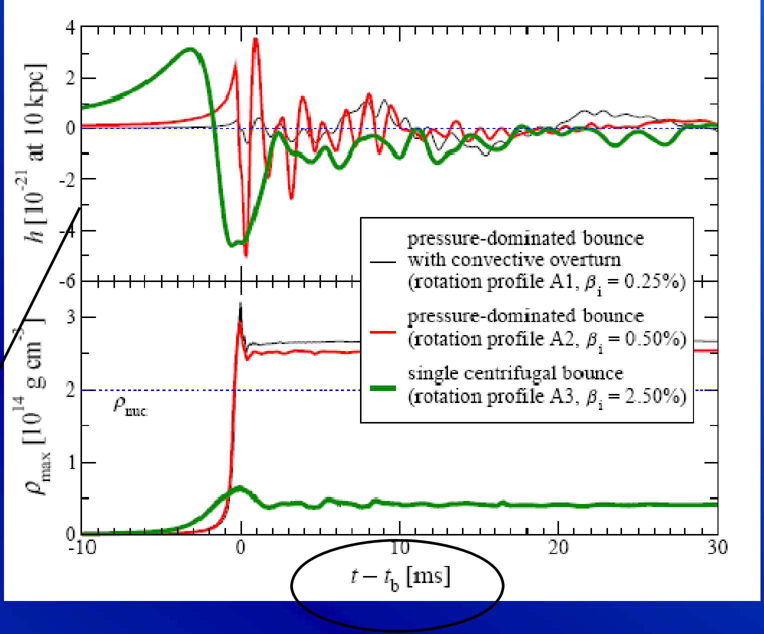
1. Collapse
2. <u>Bounce</u> ⇒ $\boxed{\varepsilon_{GW}}$
3. Shock Propagation
4. Shock Stagnation
5. <u>Accretion</u> ⇒ $\boxed{\sim 10\% \cdot \varepsilon_{\nu}}$
6. <u>Cooling PNS</u> ⇒ $\boxed{\sim 90\% \cdot \varepsilon_{\nu}}$

$$\varepsilon_{GW} = (10^{44} - 10^{48})\text{erg}$$

$$\varepsilon_{\nu} = (1-5)\cdot 10^{53}\,\text{erg}$$

BOUNCE:Gravitational Waves

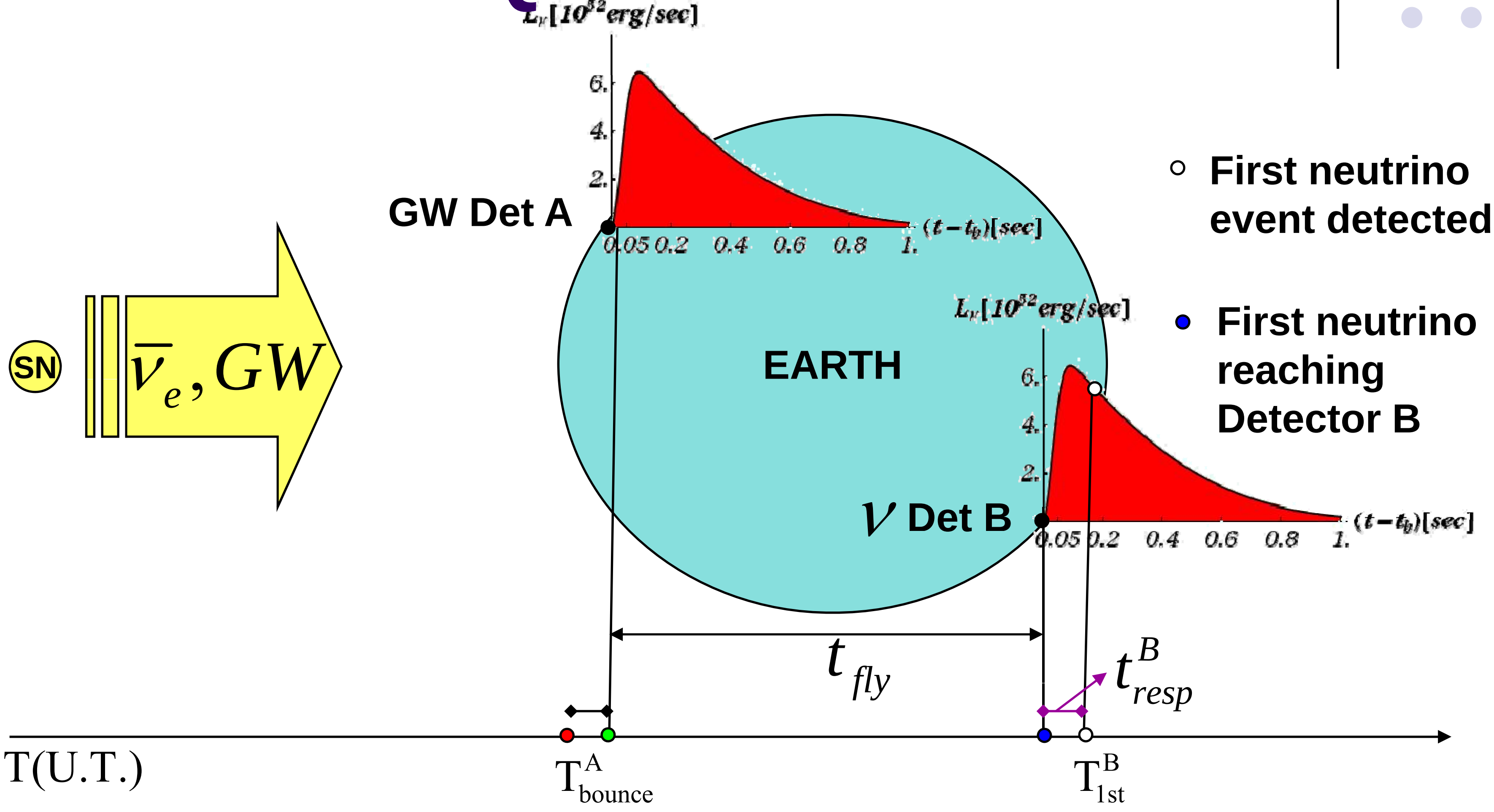




Generic gravitational wave signals expected when the external core bounces on the inner core (Dimmelmeier et al. 2007)

Using neutrino signal we can identify the bounce time $T_{bounce} \pm \delta T_{bounce}$ ***within about 10 ms***

MASTER EQUATION



- ○ First neutrino event detected
- ● First neutrino reaching Detector B

$$T^A_{bounce} = T^B_{1st} - (\overset{\bullet-\circ}{t_{resp}} \pm \overset{\bullet-\bullet}{t_{fly}} + \overset{\bullet-\bullet}{t_{mass}} + t_{GW})$$

UNCERTAINTIES

$$\mathrm{T}_{\mathrm{bounce}} = \mathrm{T}_{\mathrm{1st}} - (t_{GW} + t_{mass} \boxed{\pm t_{fly} + t_{resp})}$$

GOAL

$$\boxed{\delta \mathrm{T}_{\mathrm{bounce}} \approx 10\mathrm{ms}}$$

$$t_{mass} \sim 0.27 \left(\frac{m_\nu}{0.23}\right)^2 \left(\frac{10\mathrm{MeV}}{E_\nu}\right)^2 \left(\frac{\mathrm{D}}{10\mathrm{kpc}}\right) \mathrm{ms} \Rightarrow \delta t_{mass}$$

negligible

$$t_{GW} = (1.5 - 4.5)ms \Rightarrow \delta t_{GW} \sim 1.5\mathrm{ms}$$

Now we discuss the time of fly:

	LIGO I	LIGO II	VIRGO	LVD	SK	IceCUBE
Φ	30° 30″N	46°27′N	43° 41′N	42°28′N	36°14′N	90°S
λ	90° 45′W	119° 25′W	10°33′E	13°33′E	137° 11′E	139°16′W
d^{SK}	32.1 ms	24.9 ms	28.8 ms	28.7 ms	-	19.0 ms
d^{LVD}	26.8 ms	27.5 ms	0.9 ms	-	28.7 ms	16.9 ms
d^{IceCUBE}	20.8 ms	15.6 ms	16.5 ms	16.9 ms	19.0 ms	-

$$\delta t_{fly}$$

negligible for an astronomically identified SN and in the lucky configuration between LVD and VIRGO

To reach $\delta t_{fly} \leq 5\mathrm{ms}$ we need to determine the SN position with a precision of 20°

Neutrinos: Time of fly

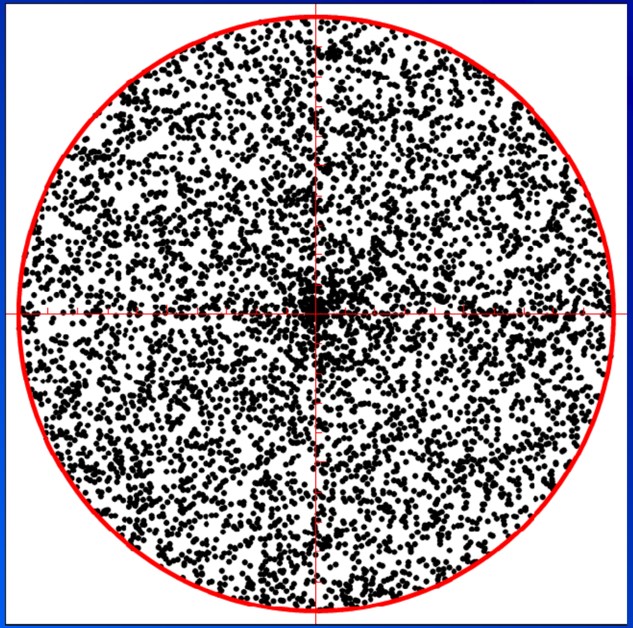
The low cross section of weak interactions : $\sigma_0 \equiv \left(10^{-44} \cdot E_\nu\right) cm^2$

Reaction Processes in $\mathrm{H_2O}$ and $\mathrm{C_nH_{2n}}$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \sigma(\nu_x e) \sim 0.16 \cdot \sigma_0$$

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad \sigma(\nu_e e) = 0.93 \cdot \sigma_0$$

Elastic Scattering (ES)



We can see here that 35 ES directional events over a background of 1050 IBD events expected in SK for a SN at 20kpc, is enough to identify the SN direction with the required precision!!!

Neutrinos: Response time

Finally we discuss the response time using the electron Antineutrinos and their main interaction process:

$\bar{\nu}_e + p \rightarrow e^+ + n$ $\sigma(\bar{\nu}_e p) \sim 9 \cdot \sigma_0 \cdot E_\nu$ $< E_\nu >= 10 - 20\ MeV$

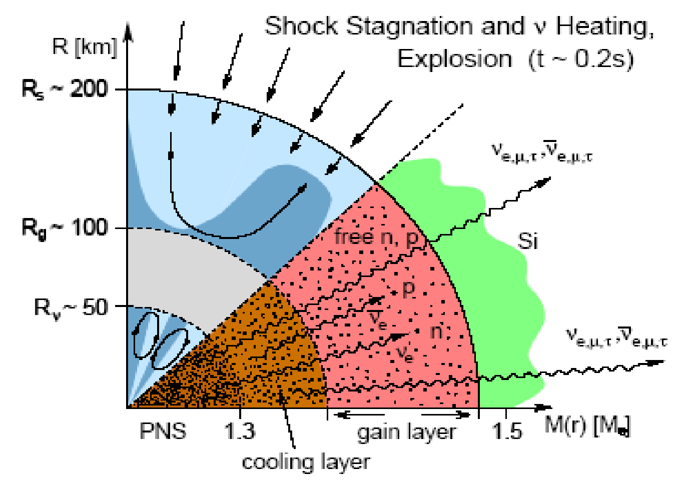
Inverse Beta Decay

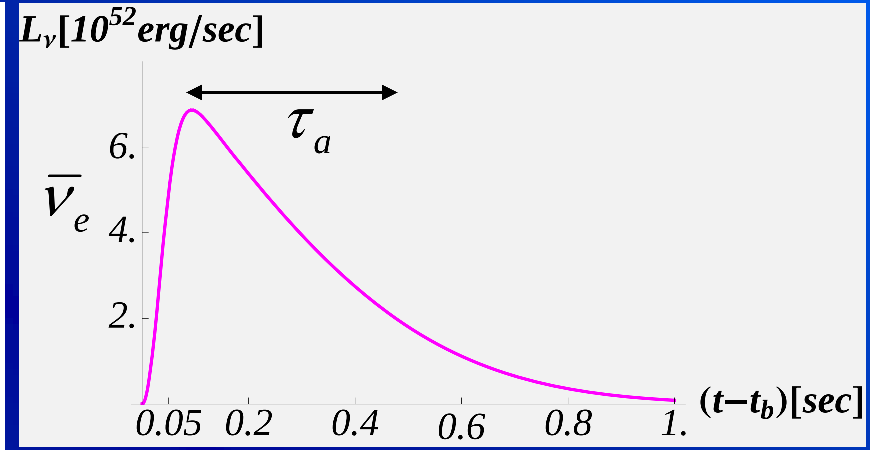
Main signal = 1050 IBD events expected in SK for a SN at 20 kpc

We use the $\bar{\nu}_e$ events to extract $\boxed{\mathrm{t}_{\mathrm{resp}}}$

we need to model the expected temporal behaviour of this signal

ACCRETION PHASE





$$L_{\bar{\nu}_e} \sim 5\times10^{52}\,\frac{\mathrm{erg}}{\mathrm{sec}}\left(\frac{M_a}{0.1M_\odot}\right)\left(\frac{Y_n}{0.6}\right)\left(\frac{T_a}{2\mathrm{MeV}}\right)^6$$

EMISSION Process: $\boxed{n+e^+ \rightarrow p+\bar{\nu}_e}$

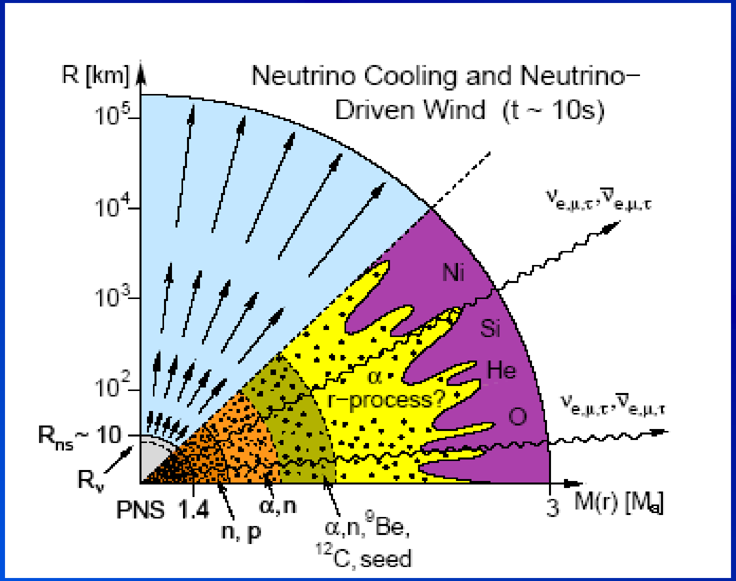
Microscopic parameterization of $\bar{\nu}_e$ flux

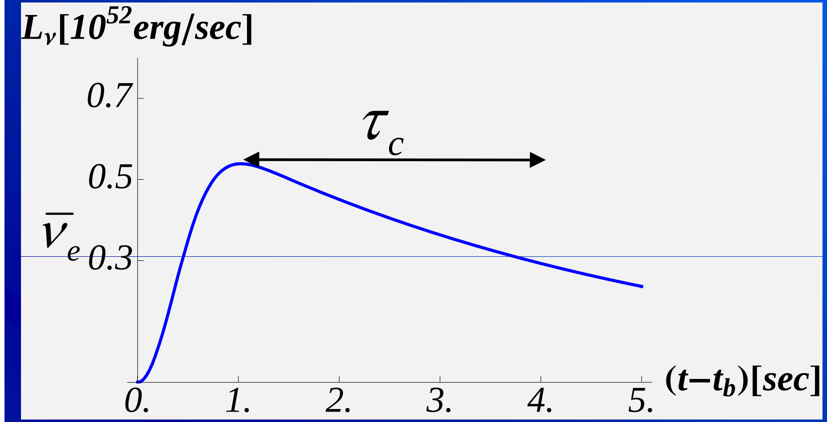
$$\Phi_{\bar{\nu}_e}(E_\nu,t) \propto f(t)N_n(t)\sigma_{e^+n}(E_{e^+})\frac{E_{e^+}^{\,2}}{1+e^{\left(\frac{E_{e^+}}{T_a(t)}\right)}}$$

Model Parameters

$$\tau_r \quad M_a \quad T_a \quad \tau_a$$

COOLING PHASE





$$L_{\bar{\nu}_e} \sim 5\times10^{51}\,\frac{\text{erg}}{\text{sec}}\left(\frac{R_C}{10\text{km}}\right)^2\left(\frac{T_C}{5\text{MeV}}\right)^4$$

Thermal emission from cooling of PNS all species of neutrinos are emitted

$$\Phi^0_{\bar{\nu}_e}(E_\nu,t)\propto R_C{}^2\,\frac{E_\nu{}^2}{1+e^{\left(\frac{E_\nu}{T_c(t)}\right)}}$$

Model Parameters

$R_C \quad T_C \quad \tau_C \quad \boxed{+\,t_{\text{resp}}}$

7 $\boxed{+1}$ free parameters

ANALYSIS OF SN1987A

Likelihood analysis including all data features

$$t_1, t_2, \ldots, t_{N_{ev}}$$
$$\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_{N_{ev}}$$
$$\delta\varepsilon_1, \delta\varepsilon_2, \ldots, \delta\varepsilon_{N_{ev}}$$
$$\vartheta_1, \vartheta_2, \ldots, \vartheta_{N_{ev}}$$

DATA

$N_{ev} = 29$

KII + IMB + BAKSAN

Detector Efficiency Functions

$$\eta(\varepsilon)$$

Background Spectrum Rate

$$B(\varepsilon)$$

The Best-Fit values for the parameters of the emission model:

$$M_a = 0.22^{+0.68}_{-0.15} M_\odot \qquad R_C = 16^{+9}_{-5}\, km$$
$$T_a = 2.4^{+0.6}_{-0.4}\, MeV \qquad T_C = 4.6^{+0.7}_{-0.6}\, MeV$$
$$\tau_a = 0.55^{+0.58}_{-0.17}\,\mathrm{s} \qquad \tau_C = 4.7^{+1.7}_{-1.2}\,\mathrm{s}$$

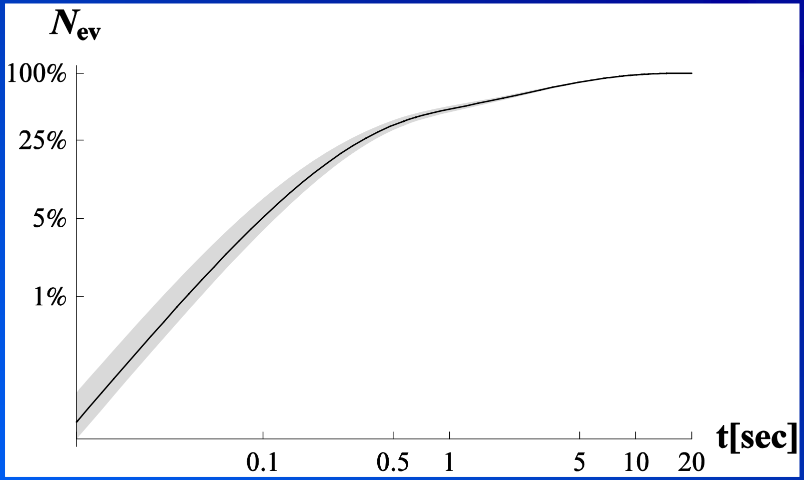
In very good agreement
With theoretical expectations
(Pagliaroli et al. Astr.Phy. 2009)

Future SN: simulated data

Using the astrophysical parameters we simulate the neutrino signal from a future SN in a detector of 22.5 kton as Super-Kamiokande

$$\boxed{\frac{dN}{dE_\nu dt} = \sigma(\bar{\nu}_e p) N_p \eta(E_\nu) \Phi_{\bar{\nu}_e}(E_\nu, t, D)}$$

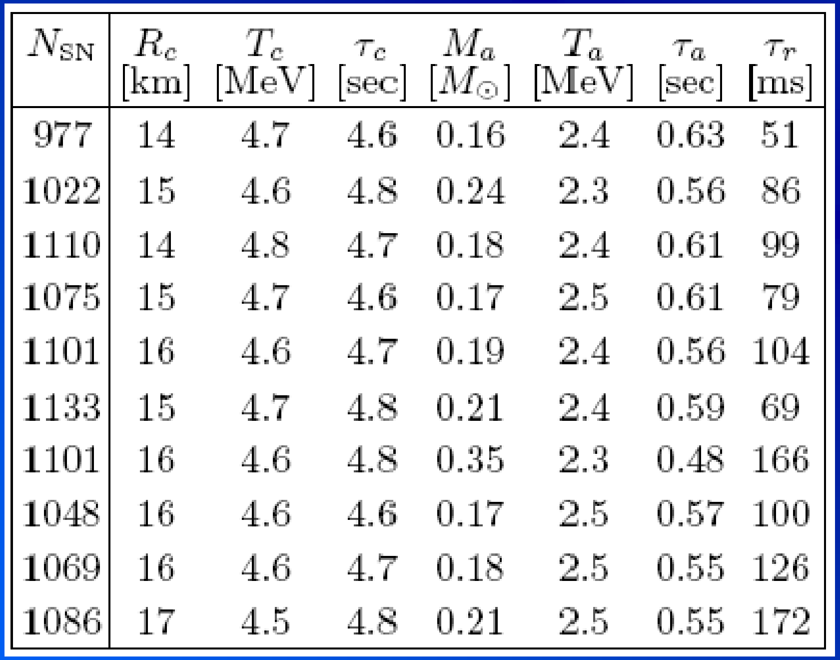
Assuming $\eta = 0.98$ $E_{th} = 6.5\,\mathrm{MeV}$ ⇨ $\mathrm{N}(D) = 4233\left(\frac{10\,\mathrm{kpc}}{D}\right)^2$



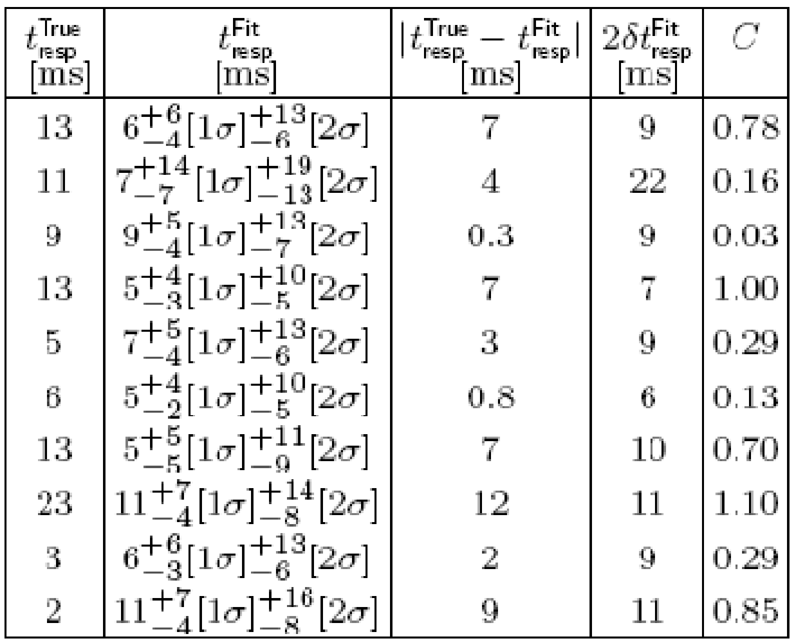
Results for a SN at 20 kpc

TRUE VALUES

16 4.6 4.7 0.22 2.4 0.55 100



N_{SN}	R_c [km]	T_c [MeV]	τ_c [sec]	M_a [$M_\odot$]	T_a [MeV]	τ_a [sec]	τ_r [ms]
977	14	4.7	4.6	0.16	2.4	0.63	51
1022	15	4.6	4.8	0.24	2.3	0.56	86
1110	14	4.8	4.7	0.18	2.4	0.61	99
1075	15	4.7	4.6	0.17	2.5	0.61	79
1101	16	4.6	4.7	0.19	2.4	0.56	104
1133	15	4.7	4.8	0.21	2.4	0.59	69
1101	16	4.6	4.8	0.35	2.3	0.48	166
1048	16	4.6	4.6	0.17	2.5	0.57	100
1069	16	4.6	4.7	0.18	2.5	0.55	126
1086	17	4.5	4.8	0.21	2.5	0.55	172



$t^{\text{True}}_{\text{resp}}$ [ms]	$t^{\text{Fit}}_{\text{resp}}$ [ms]	$\lvert t^{\text{True}}_{\text{resp}} - t^{\text{Fit}}_{\text{resp}} \rvert$ [ms]	$2\delta t^{\text{Fit}}_{\text{resp}}$ [ms]	C
13	$6^{+6}_{-4}[1\sigma]^{+13}_{-6}[2\sigma]$	7	9	0.78
11	$7^{+14}_{-7}[1\sigma]^{+19}_{-13}[2\sigma]$	4	22	0.16
9	$9^{+5}_{-4}[1\sigma]^{+13}_{-7}[2\sigma]$	0.3	9	0.03
13	$5^{+4}_{-3}[1\sigma]^{+10}_{-5}[2\sigma]$	7	7	1.00
5	$7^{+5}_{-4}[1\sigma]^{+13}_{-6}[2\sigma]$	3	9	0.29
6	$5^{+4}_{-2}[1\sigma]^{+10}_{-5}[2\sigma]$	0.8	6	0.13
13	$5^{+5}_{-5}[1\sigma]^{+11}_{-9}[2\sigma]$	7	10	0.70
23	$11^{+7}_{-4}[1\sigma]^{+14}_{-8}[2\sigma]$	12	11	1.10
3	$6^{+6}_{-3}[1\sigma]^{+13}_{-6}[2\sigma]$	2	9	0.29
2	$11^{+7}_{-4}[1\sigma]^{+16}_{-8}[2\sigma]$	9	11	0.85

$$\boxed{C = \frac{\left| t^{\text{True}}_{\text{resp}} - t^{\text{Fit}}_{\text{resp}} \right|}{2\delta t^{\text{Fit}}_{\text{resp}}}}$$

$$\left\langle 2\delta t^{\text{Fit}}_{\text{resp}} \right\rangle = 10.3\,\text{ms}$$

CONCLUSIONS

Exploiting the neutrino signal detected by SK for a SN event at 20 Kpc, we deduce the Universal Time of the bounce with an average error:

$$\delta \mathrm{T}_{\mathrm{bounce}} = \sqrt{\delta \mathrm{T}_{\mathrm{1st}}{}^2 + \delta t_{GW}{}^2 + \delta t_{mass}{}^2 + \delta t_{fly}{}^2 + \delta t_{resp}{}^2}$$

$$\cong \sqrt{\delta t_{GW}{}^2 + \delta t_{fly}{}^2 + \delta t_{resp}{}^2} = \sqrt{2 + 25 + 25} = 7.2\mathrm{ms}$$

SUMMARY

Using:

- The expectations for Standard Collapse SN
- The SN1987A data to validate them

We proposed:

- A statistical procedure that allows us to identify the U.T. of the bounce within an error window of about 15 ms

A very precious information for the search of GW bursts!

Thanks!!

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