# *Supernova Neutrinos and Gravitational Waves*

*G.Pagliaroli*

*LNGS-Theory Group*

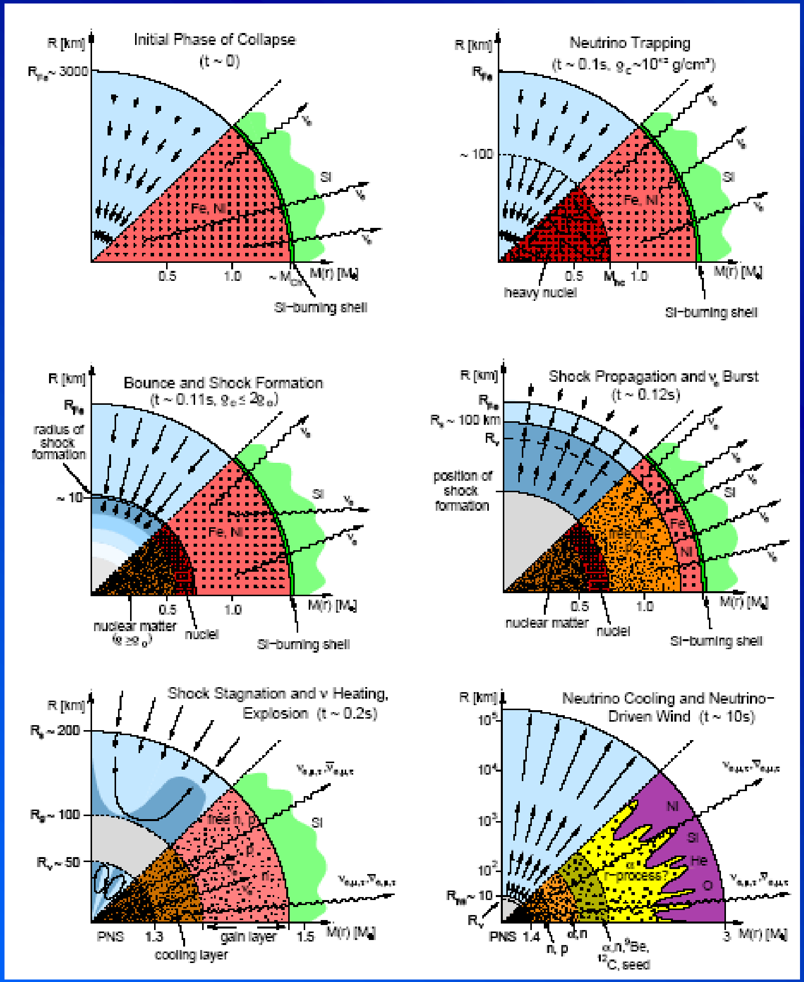
*In collaboration with*

*F.Vissani, E.Coccia and W.Fulgione*

# CONTENTS

- ***Generalities on Core-Collapse Supernovae***
- ***The idea: Neutrinos vs GW***
- ***The method: Emission models for*** $\bar{\nu}_e$
- ***The test: Events simulation***
- ***The results: Data analysis***

# Standard Core-Collapse SN



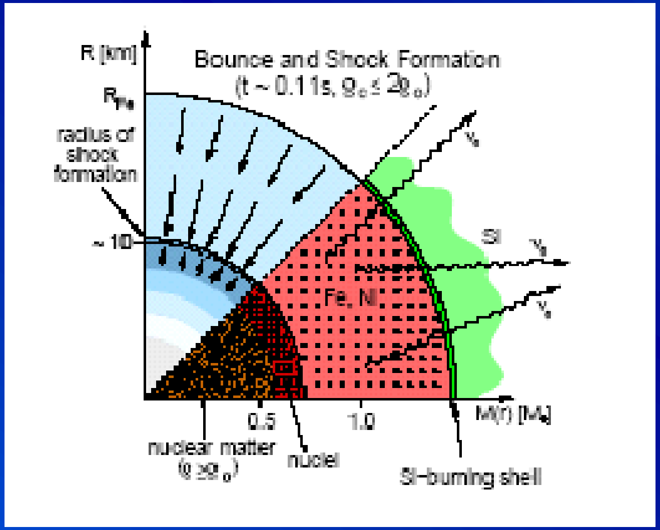

JANKA et al. Phys. Rept. 442 (2007) 38

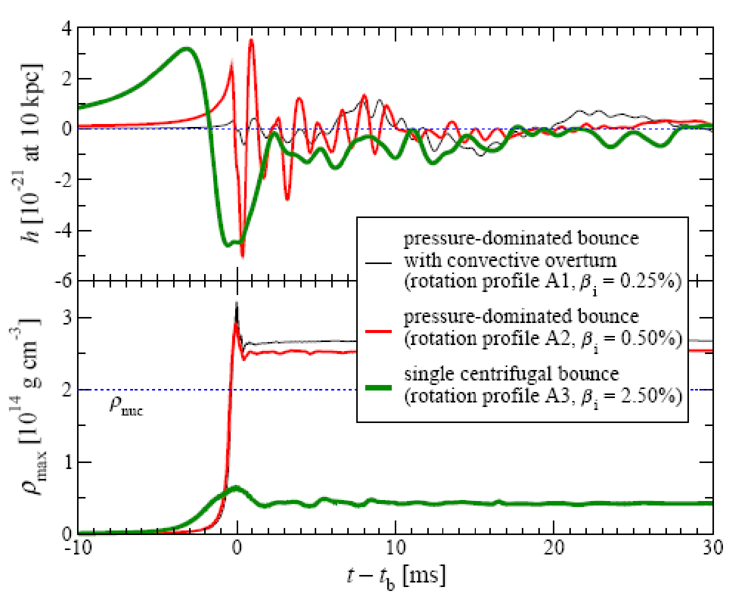
1. Collapse
2. Bounce → $\varepsilon_{GW}$
3. Shock Propagation
4. Accretion → $\sim 10\% \cdot \varepsilon_{\nu}$
5. Cooling PNS → $\sim 90\% \cdot \varepsilon_{\nu}$

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

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

# BOUNCE:Gravitational Waves



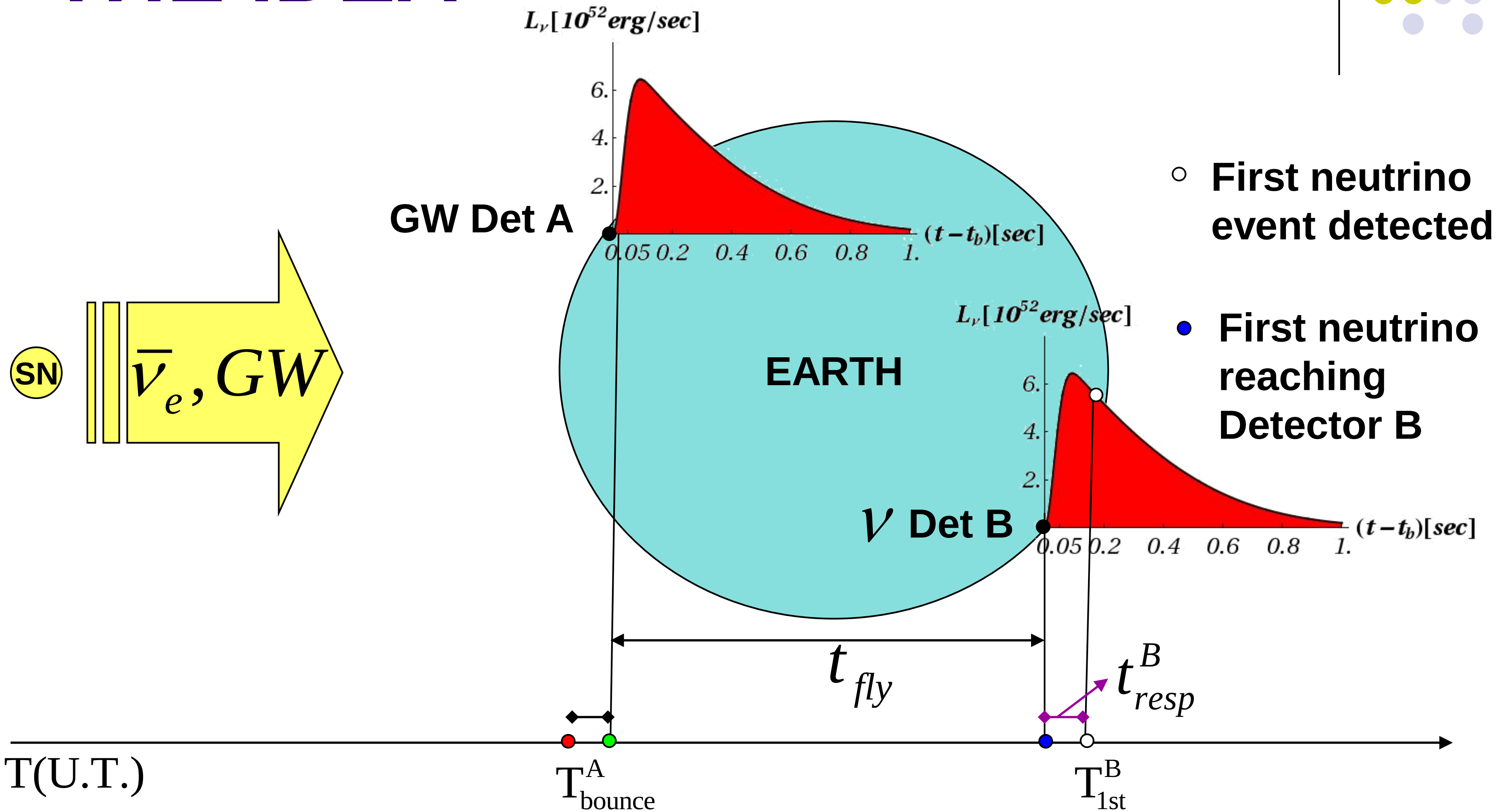




**Dimmelmeier et al. PRD78:064056, 2008**

**Generic gravitational wave signals expected when the external core bounces on the inner core**

***Using neutrino signal we can identify the bounce time*** $T_{bounce} \pm \delta T_{bounce}$ ***!!!***

# THE IDEA




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

# MASTER EQUATION

$$T_{bounce} = T_{1st} - (t_{GW} + t_{mass} \pm t_{fly} + t_{resp})$$

$$\delta T_{bounce} = \sqrt{\sum_i (\delta t_i)^2}$$ **GOAL** ➡ $\delta T_{bounce} \approx 10\text{ms}$

$$t_{GW} = (1.5 - 4.5)ms$$ ⇨ $\delta t_{GW} \sim 1.5\text{ms}$

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

The dominant terms are the last two

⇩

Both can be determined using Neutrinos Data

# TIME OF FLY

| | LIGO I | LIGO II | VIRGO | LVD | SK | IceCUBE |
|---|---|---|---|---|---|---|
| $\Phi$ | $30° 30'' N$ | $46° 27' N$ | $43° 41' N$ | $42° 28' N$ | $36° 14' N$ | $90° S$ |
| $\lambda$ | $90° 45' W$ | $119° 25' W$ | $10° 33' E$ | $13° 33' E$ | $137° 11' E$ | $139° 16' W$ |
| $d^{SK}$ | 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 | - |

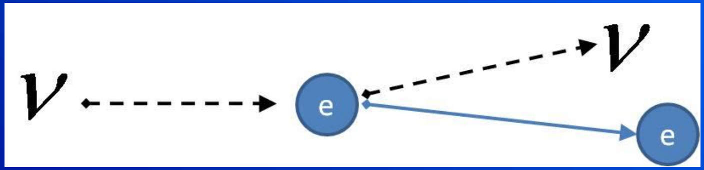
$$t_{fly} \approx 30ms$$

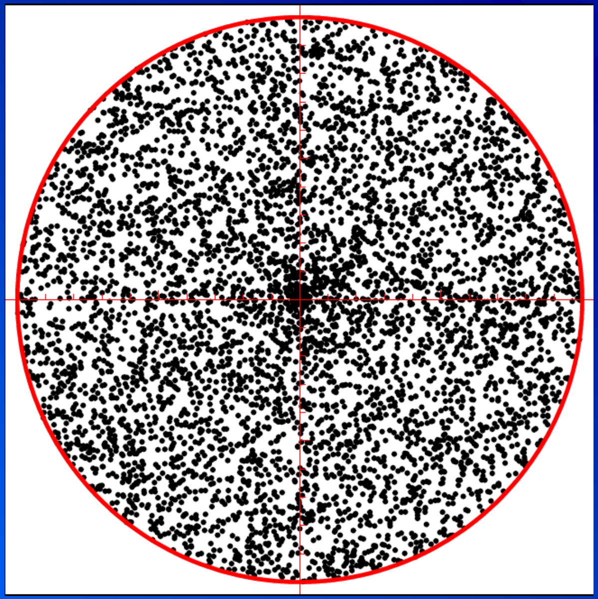
$\delta t_{fly}$ ➡ negligible for an astronomically identified SN and in the lucky configuration between LVD and VIRGO

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

# *Elastic Scattering (ES)*

Directional interaction:



SuperKamiokande and SN at 20 kpc

**35 ES** directional events
1050 Inverse beta decay

Enough to obtain $\delta t_{fly} \leq 5\mathrm{ms}$

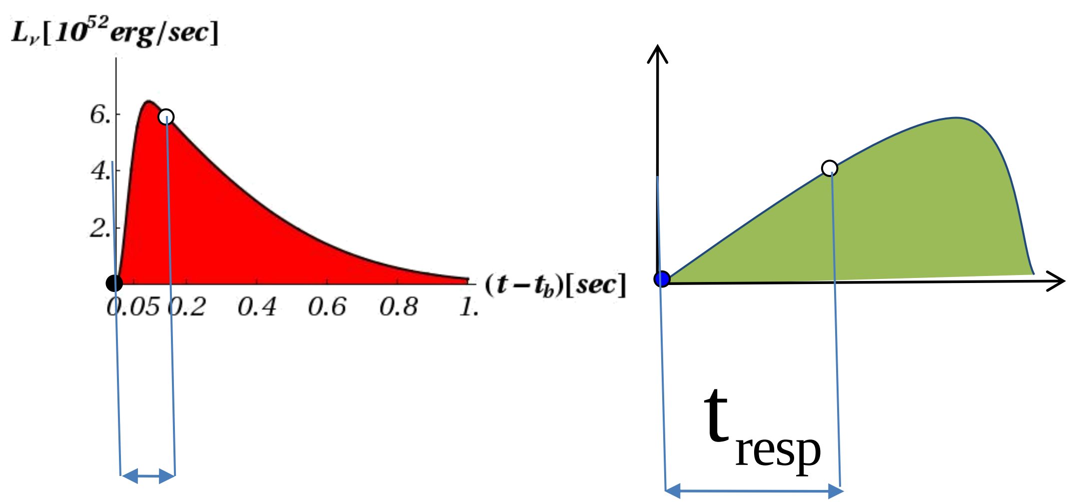
# RESPONSE TIME

- ● The first neutrino that reaches the detector
- ○ The first neutrino detected

$t_{resp} =$ ● ⟷ ○

**Ideal detector** ⇨ It sees **All** neutrinos ⇨ $t_{resp} \equiv 0$

**Real detector** ⇨ It loses a part of the signal ⇨ $t_{resp} > 0$




DEPENDS ON THE SIGNAL BEHAVIOUR !!

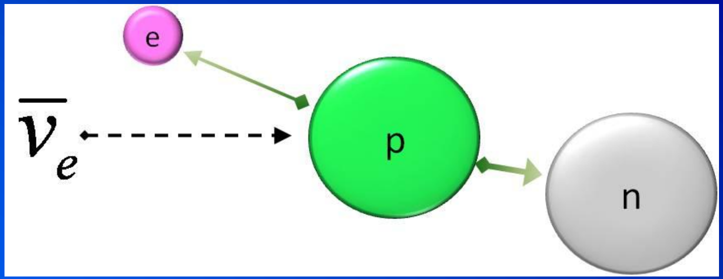
# Inverse Beta Decay (IBD)

**The main interaction process in $H_2O$ and $C_nH_{2n}$ detectors is:**

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad \sigma(\bar{\nu}_e p) \sim 9 \cdot \sigma_0 \cdot E_\nu$$

$$\sigma_0 \equiv E_\nu \cdot 10^{-44}\ cm^2$$

$$< E_\nu > = 10 - 20\ MeV$$

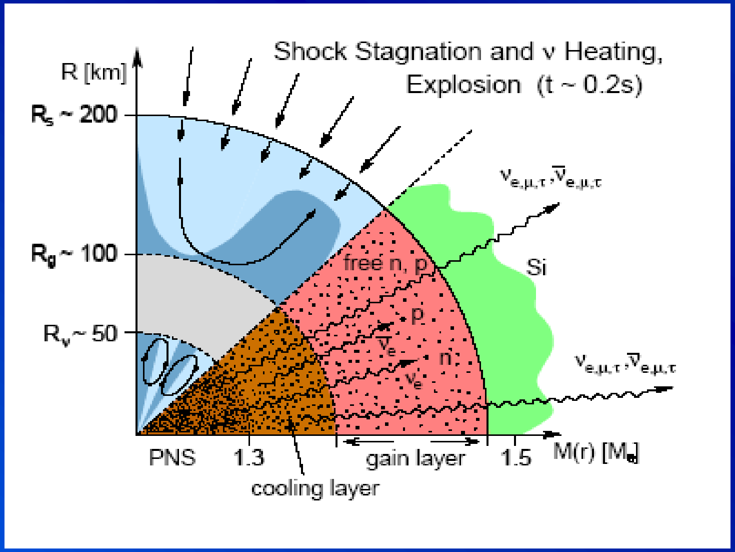


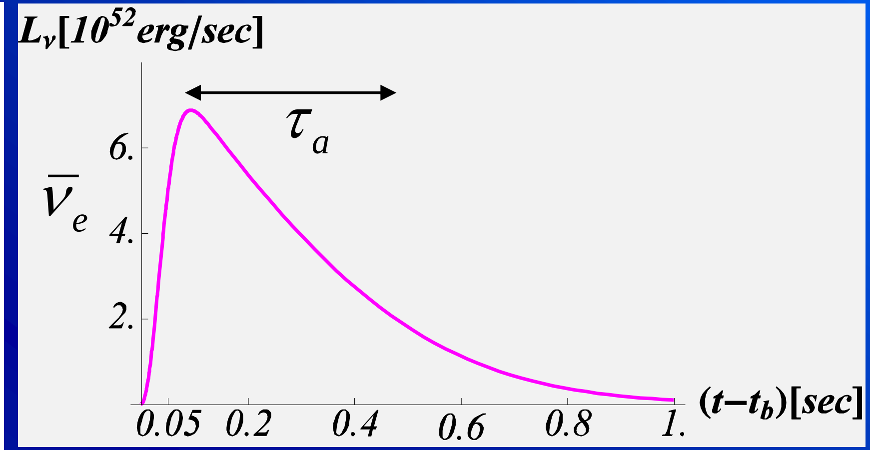

**We use the $\bar{\nu}_e$ events to extract $t_{resp}$**

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

**But we need to model the temporal behaviour of this signal**

# ACCRETION PHASE




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

EMISSION Process:

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

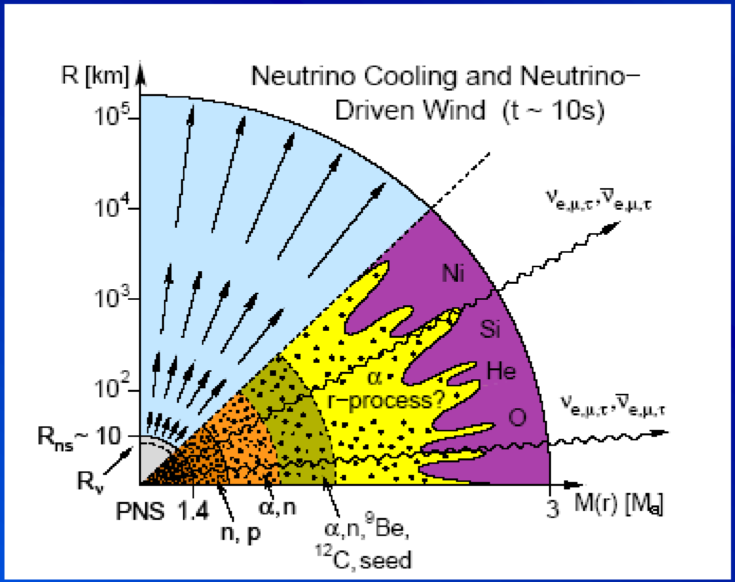
Microscopic parameterization of $\bar{\nu}_e$ flux

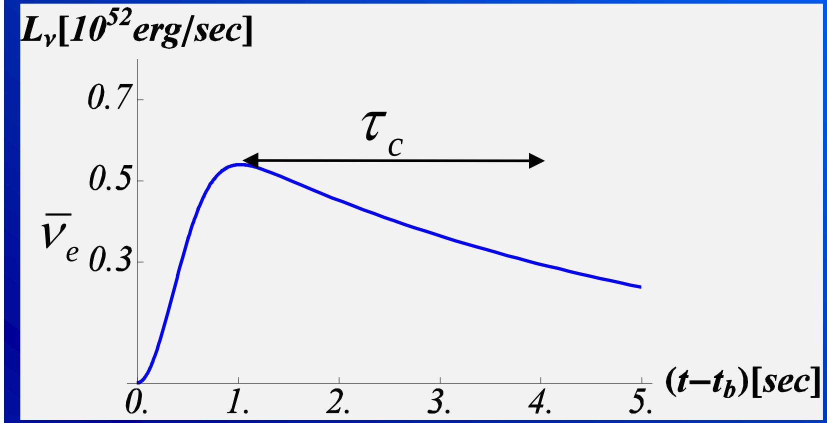
$$\Phi^0_{\bar{\nu}_e}(E_\nu,t) \propto f(t)N_n(t)\sigma_{e^+n}(E_{e^+})\frac{E_{e^+}^2}{1+e^{\left(\frac{E_{e^+}}{T_a(t)}\right)}}$$

**Model Parameters**

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

# COOLING PHASE




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

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***

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

**7** **+ 1** free parameters

# Future SN: testing the method

Using the expected flux we simulate the neutrino data for a future SN in a detector of 22.5 kton as Super-Kamiokande

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

Assuming $\eta = 0.98$ $\quad E_{th} = 6.5\mathrm{MeV}$

Values of the parameters from SN1987A:

$M_a = 0.22 M_\odot$ $\quad R_C = 16 km$

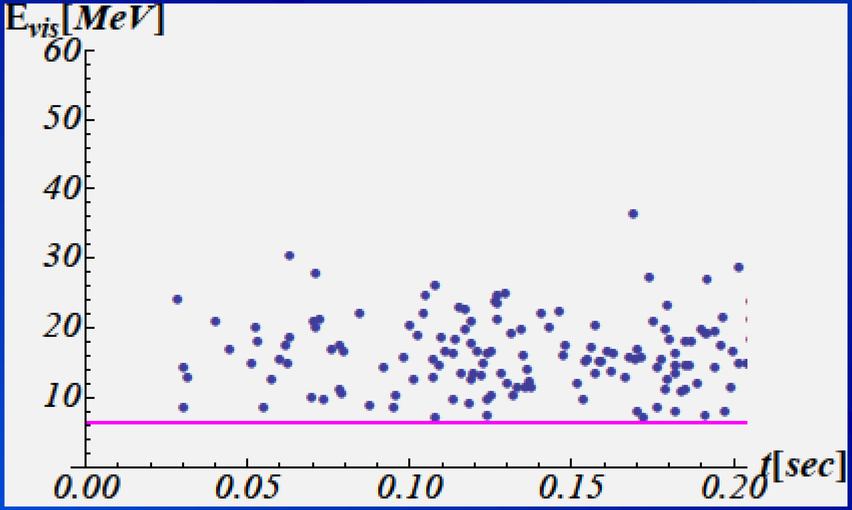
$T_a = 2.4 MeV$ $\quad T_C = 4.6 MeV$

$\tau_a = 0.55\mathrm{s}$ $\quad \tau_C = 4.7\,\mathrm{s}$

In very good agreement With theoretical expectations

[GP et al. Astr.Ph.31,163-176(2009)]

# Simulations for a SN at 20 kpc




**10 SIMULATED DATASETS**

**LIKELIHOOD FUNCTION**

**BEST FIT VALUES**

| $N_{SN}$ | $R_c$ [km] | $T_c$ [MeV] | $\tau_c$ [sec] | $M_a$ [$M_\odot$] | $T_a$ [MeV] | $\tau_a$ [sec] | $\tau_r$ [ms] |
|---|---|---|---|---|---|---|---|
| 1101 | 16 | 4.6 | 4.7 | 0.19 | 2.4 | 0.56 | 104 |

**TRUE VALUES**

| | | | | | | |
|---|---|---|---|---|---|---|
| 16 | 4.6 | 4.7 | 0.22 | 2.4 | 0.55 | 100 |

**RESPONSE TIME**

| $t^{True}_{resp}$ [ms] | $t^{Fit}_{resp}$ [ms] | $\lvert t^{True}_{resp} - t^{Fit}_{resp}\rvert$ [ms] | $2\delta t^{Fit}_{resp}$ [ms] |
|---|---|---|---|
| 5 | $7^{+5}_{-4}[1\sigma]^{+13}_{-6}[2\sigma]$ | 3 | 9 |

**AVERAGE RESPONSE TIME UNCERTAINTY**

$$\left\langle \delta t^{Fit}_{resp} \right\rangle = 5.1\,\text{ms}$$

# RESULT

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

We proposed:

- idea
- method
- statistical procedure

that will allow us to identify the time of the bounce within about 15 ms

*A very precious information for the search of GW bursts!*

Thanks!!

# References


- Pagliaroli et al. PRL 103, 031102 (2009)
- Ianni et al. PRD 80, 043007 (2009)
- Pagliaroli et al. Astr.Ph.31,163-176(2009)
- Pagliaroli et al. Astr.Ph.33, 287–291(2010)

# 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)

# SN1987A: Can we deduce the bounce time?

**Only the IMB clock worked properly**:

From 8 IMB data: STAT. SYST.

$$t^0_{\bar{\nu}_e} = 7h\,35m\,41.37s \quad -0.76s \quad \pm 0.05s$$

From 12 KII data:

$$t^0_{\bar{\nu}_e} = 7h\,35m\,33.68s \quad -0.08s \quad \pm 1m$$

From 5 Baksan data:

$$t^0_{\bar{\nu}_e} = 7h\,36m\,12s \quad -0.30s \quad {}^{+\ 2s}_{-54s}$$

*Now* SYST. ⇨ $\pm 0.1\,ms$

# NEUTRINO MASS BOUND

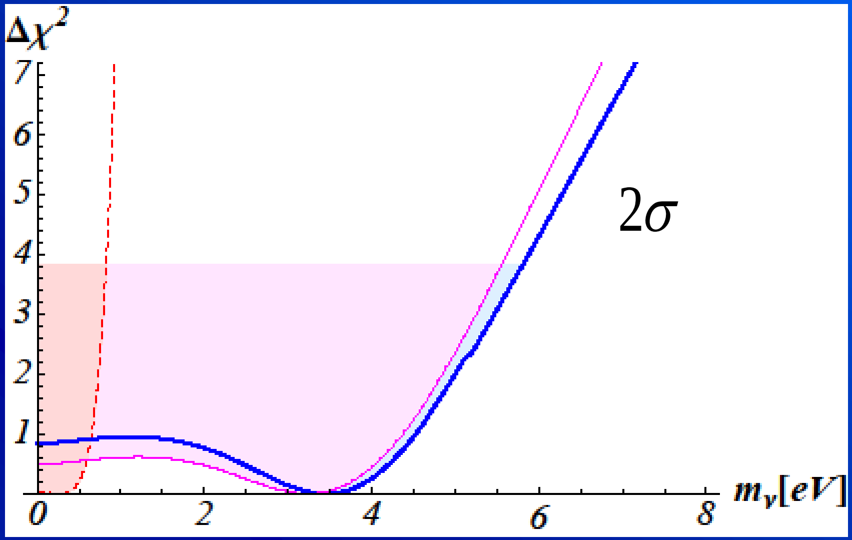
We can include in the previous analysis the delay time associated with the neutrino mass

$$t_m = 2.6\,ms\left(\frac{m_\nu}{1eV}\right)\left(\frac{10\,MeV}{E_\nu}\right)\left(\frac{D}{50\,kpc}\right)$$

Continuous curves for SN1987A

Blu: astrophysical parameters free
Magenta: astrophysical parameters fixed

$$m_\nu = 0.^{+5.8}\,eV$$




[Pagliaroli et al. Astr.Ph.33, 287–291(2010)]

Dotted line: Super-Kamiokande (SK), for a SN at 10 kpc

$$m_\nu = 0.^{+0.8}\,eV$$

# 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] | $\tau_c$ [sec] | $M_a$ [$M_\odot$] | $T_a$ [MeV] | $\tau_a$ [sec] | $\tau_r$ [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 |

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

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

# TOTAL FLUX $\Phi_{\bar{\nu}_e}(E_\nu, t)$

TEMPORAL SHIFT BETWEEN THE ACCRETION AND THE COOLING PHASES

$$\Phi^0_{\bar{\nu}_e}(t) = \Phi^0_A(t) + f(t)\cdot\Phi^0_C(t-\tau_A)$$

For **normal mass hierarchy** the survival probability and the observed flux of $\bar{\nu}_e$ are:

$$\Phi_{\bar{\nu}_e} = P\cdot\Phi^0_{\bar{\nu}_e} + (1-P)\Phi^0_{\bar{\nu}_\mu}$$

$$P = cos^2(\vartheta_{12}),$$

$\theta_{12} = 35^\circ \pm 4^\circ$

$\theta_{13} < 10^\circ$

**ASSUMPTIONS**

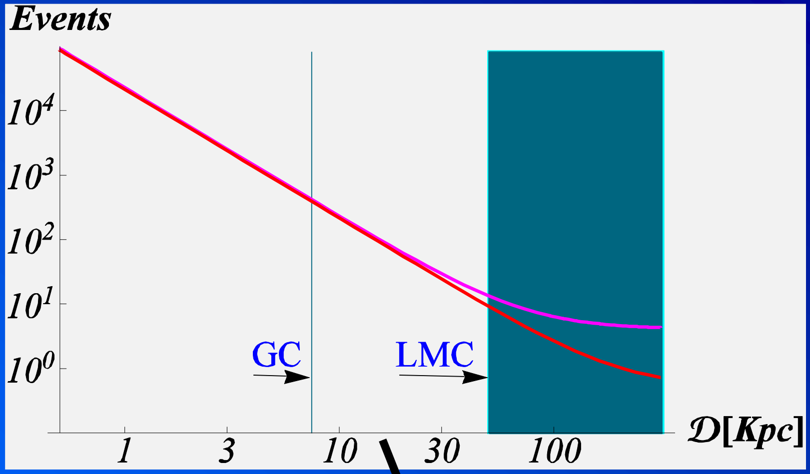
$$\Phi^0_A(\bar{\nu}_\mu) = 0 \qquad \Phi^0_C(\bar{\nu}_\mu) = \Phi^0_C(\bar{\nu}_\tau)$$

$$T_C(\bar{\nu}_\mu)/T_C(\bar{\nu}_e) = 1.2$$

# Simulated Events in LVD

The number of expected events in 20 seconds is:

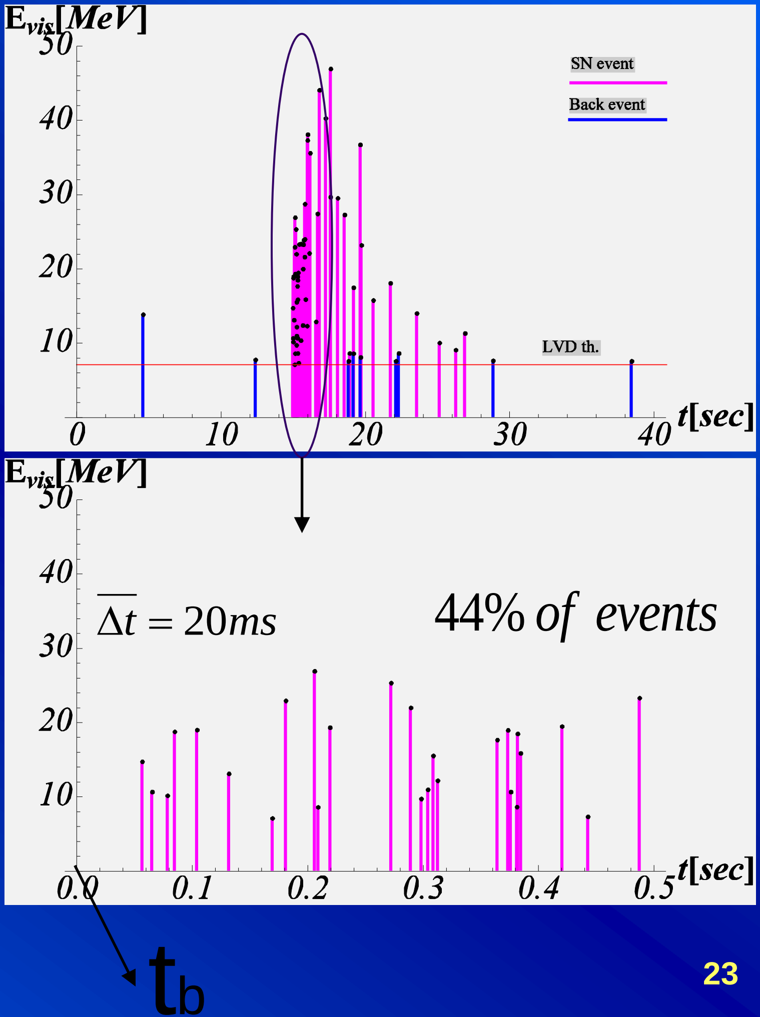
- $N_{events}(D) = 226.7 \times \left(\frac{10}{D}\right)^2 + 4. \quad \Rightarrow E_{vis} > 7MeV$
- $N_{events}(D) = 213.5 \times \left(\frac{10}{D}\right)^2 + 0.5 \quad \Rightarrow E_{vis} > 10MeV$




Simulation with $E_{th} = 7MeV$ and **D=20 Kpc**

57 SN events

+ 4 background events



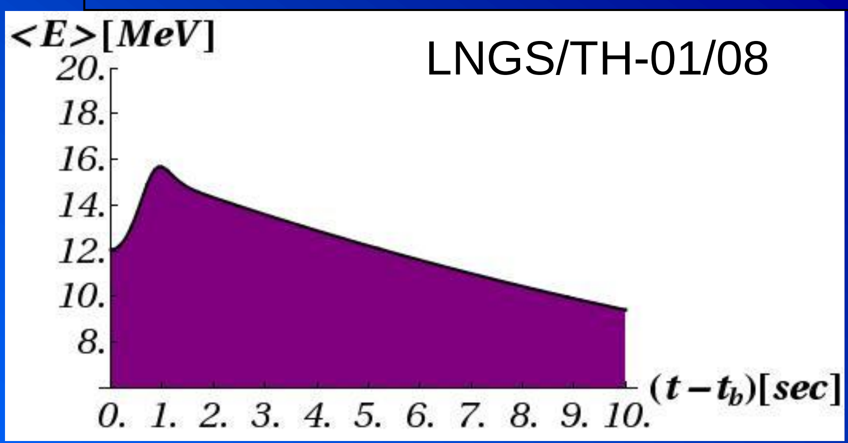
# SN1987A ANALYSIS RESULTS

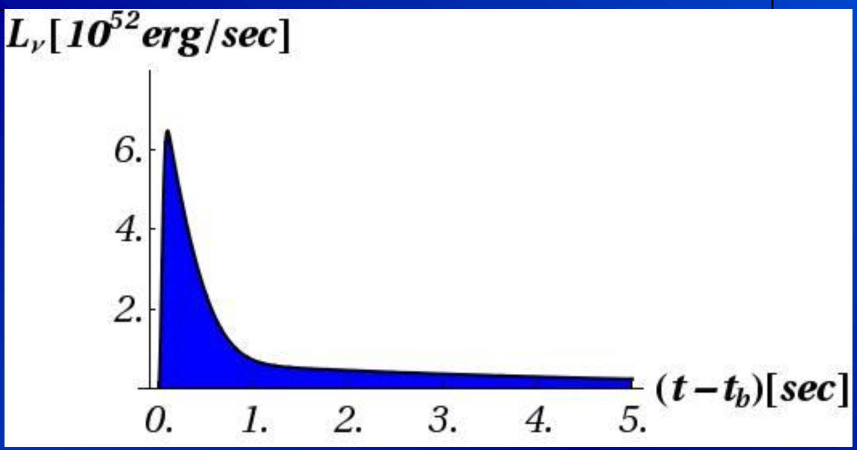
The Best-Fit values for the parameters of the emission model:

$$M_a = 0.22^{+0.68}_{-0.15} M_\odot \qquad R_\nu = 16^{+9}_{-5}\, km \qquad t^{off}_{KII} = 0.^{+0.07}\, s$$

$$T_a = 2.4^{+0.6}_{-0.4}\, MeV \qquad T_C = 4.6^{+0.7}_{-0.6}\, MeV \qquad t^{off}_{IMB} = 0.^{+0.76}\, s$$

$$\tau_a = 0.55^{+0.58}_{-0.17}\, \mathrm{s} \qquad \tau_C = 4.7^{+1.7}_{-1.2}\, \mathrm{s} \qquad t^{off}_{BAK} = 0.^{+0.23}\, s$$




Very good agreement with simulations and theoretical expectations

$$\varepsilon_B = 2.2 \cdot 10^{53}\, erg$$