Core Collapse SNe: Neutrinos as a Trigger of GW search

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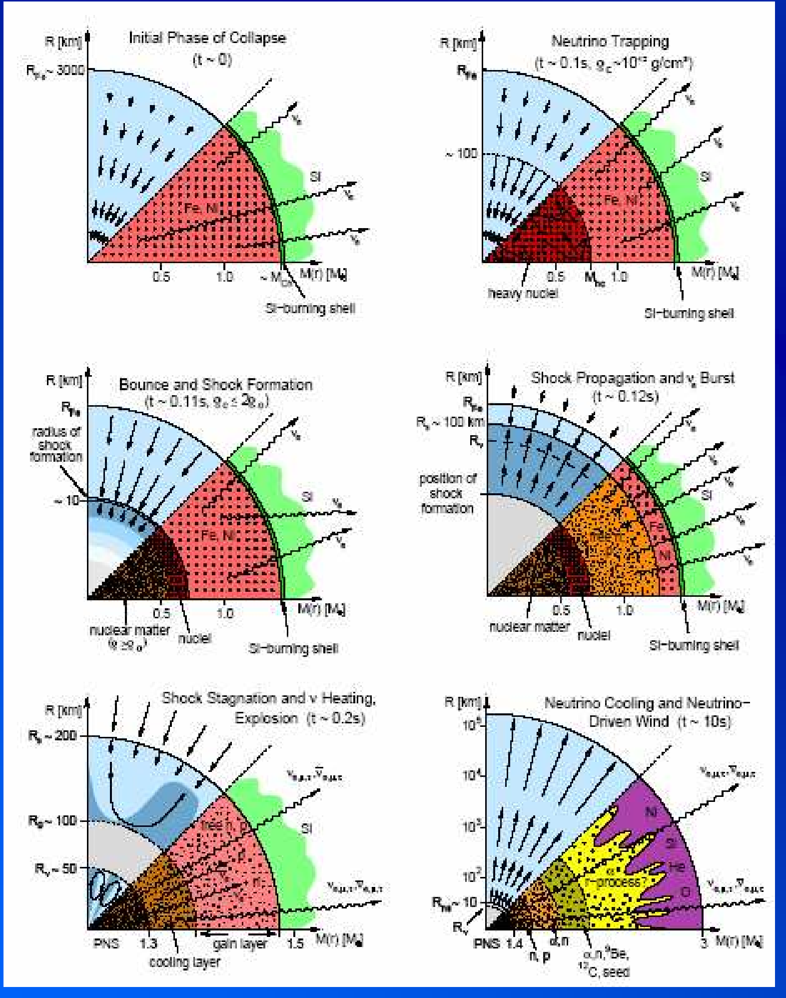
Standard Core-Collapse SN



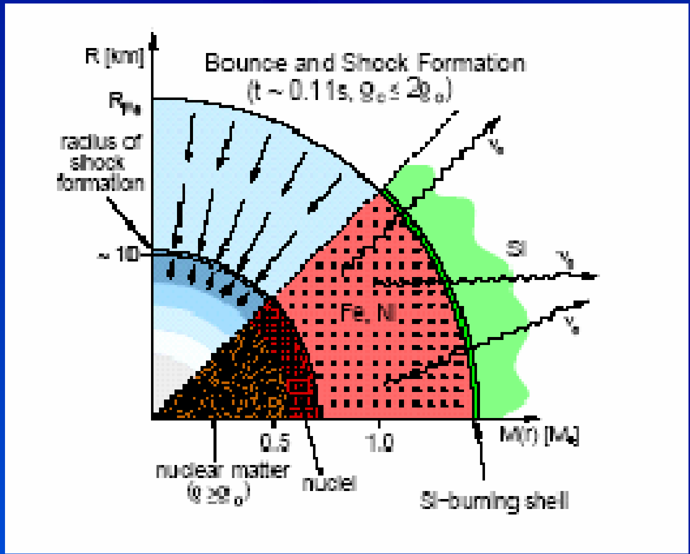
JANKA et al. Phys. Rept. 442 (2007) 38

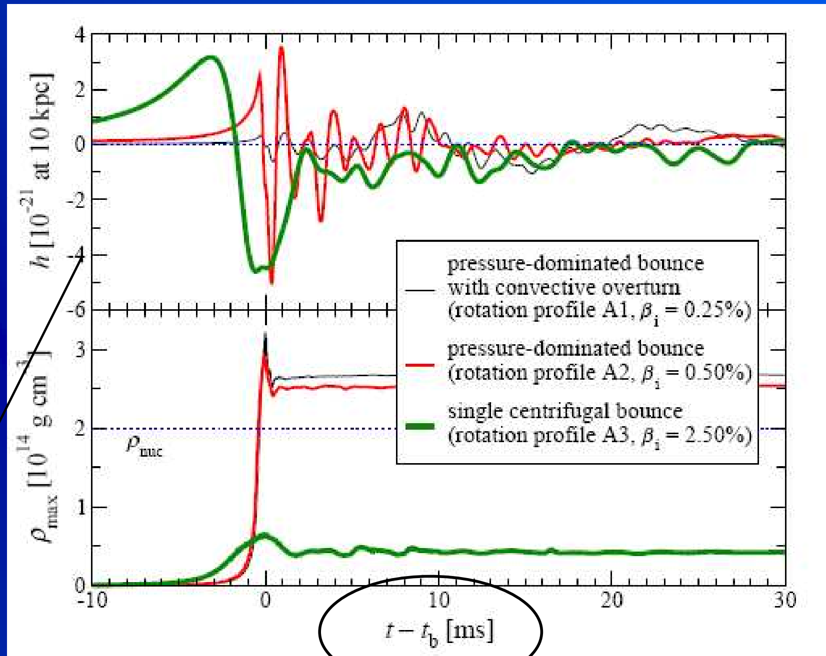
1. Collapse
2. Bounce ➡ ε_{GW}
3. Shock Propagation
4. Shock Stagnation
5. Accretion ➡ $\sim 10\% \cdot \varepsilon_{\nu}$
6. Cooling PNS ➡ $\sim 90\% \cdot \varepsilon_{\nu}$

$$\varepsilon_{GW} = (10^{48} - 10^{50})erg$$

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

BOUNCE:Gravitational Waves





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

Can we use neutrino signal to identify the bounce time t_b ***?***

NEUTRINOS from SN

Neutrinos emitted by SN event carry away the 99% of the total energy of SN explosion

$$N_{\nu} \approx 10^{58} \qquad < E_{\nu} >= 10 - 20\ MeV$$

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

Reaction Processes in H_2O and C_nH_{2n}

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

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

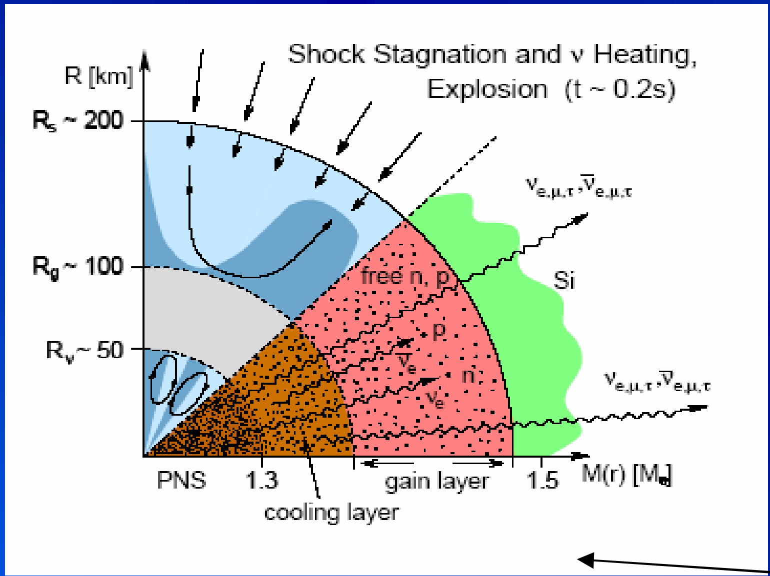
Elastic Scattering ~ 5% of events

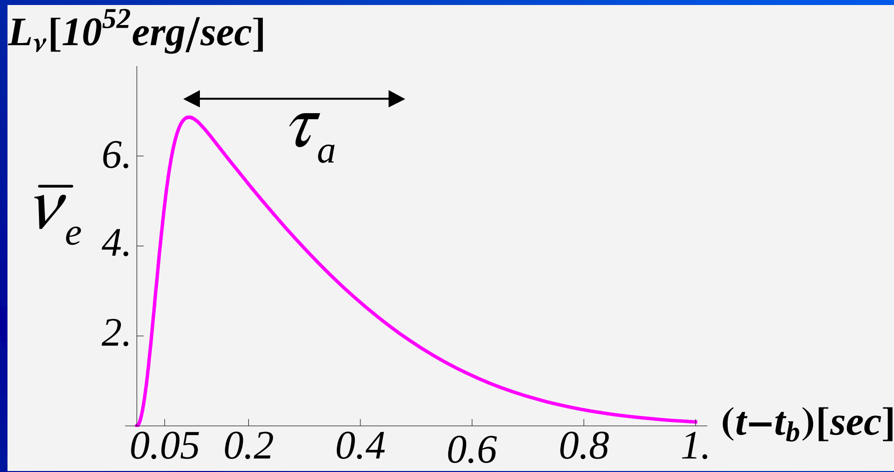
$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad \sigma(\bar{\nu}_e p) \sim 9 \cdot \sigma_0 \cdot E_{\nu}$$

We only consider $\bar{\nu}_e$ flux and IBD reaction

Inverse Beta Decay :
Main signal

ACCRETION PHASE





$$t^{em} = (t\text{-}t_b)$$

EMISSION Process:

$$n + e^+ \rightarrow p + \bar\nu_e$$

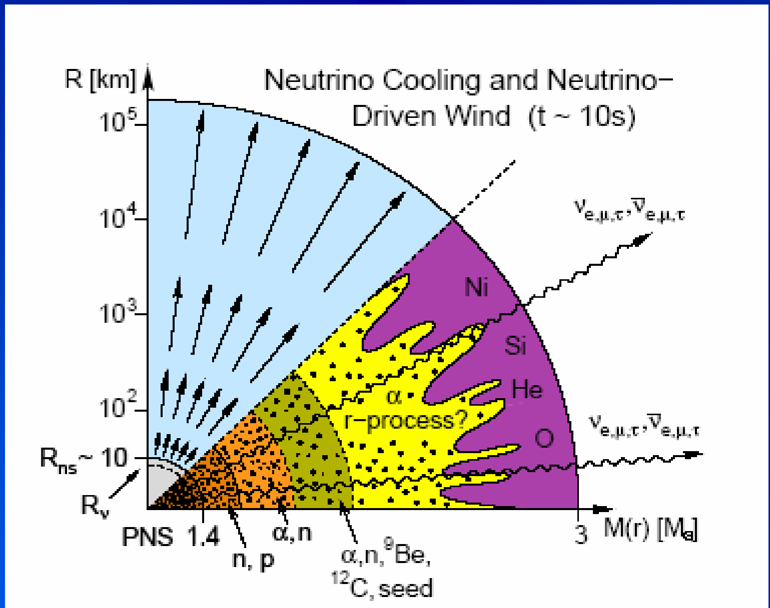
Microscopic parameterization of $\bar\nu_e$ flux

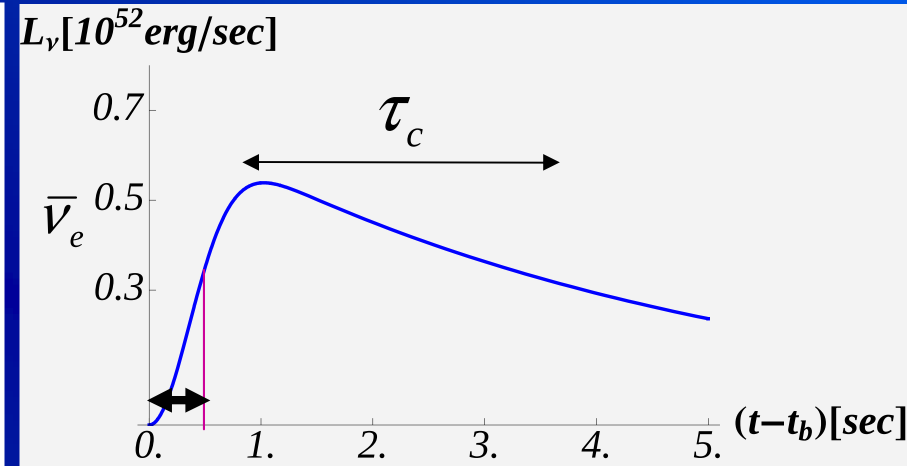
Model Parameters

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

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

COOLING PHASE





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

Model Parameters

$R_\nu \quad T_C \quad \tau_C$ $+\ t_b$

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

6 + 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:

$$M_a = 0.22^{+0.68}_{-0.15} M_\odot$$
$$T_a = 2.4^{+0.6}_{-0.4} MeV$$
$$\tau_a = 0.55^{+0.58}_{-0.17}\ \mathrm{s}$$

$$R_\nu = 16^{+9}_{-5} km$$
$$T_C = 4.6^{+0.7}_{-0.6} MeV$$
$$\tau_C = 4.7^{+1.7}_{-1.2}\ \mathrm{s}$$

Very good agreement With the theoretical Expectations (Pagliaroli et al. 2008)

LNGS/TH-01/08

Future SNe: LVD Detector

LVD(Large Volume Detector) is a liquid scintillator in LNGS with 1Kton of mass ⟶ **only 1ms of ToF from VIRGO detector**

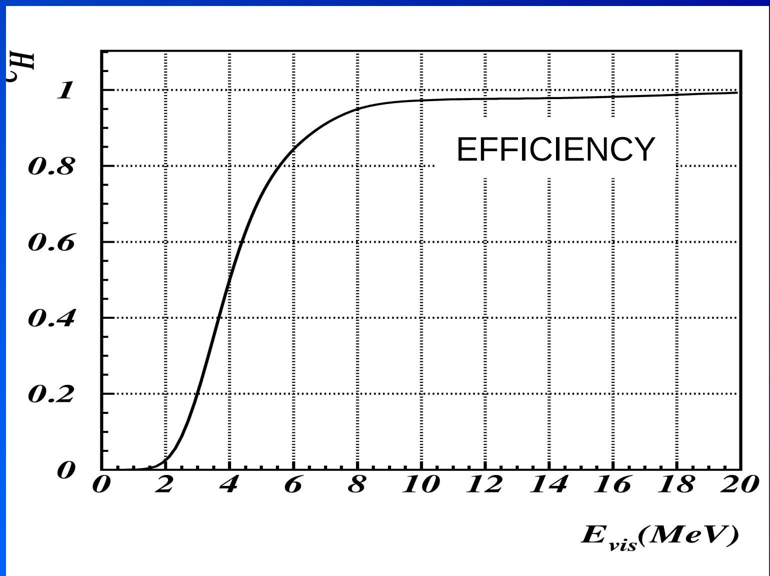
Knowing the best values of parameters we can simulate the neutrino signal expected for LVD detector from future SN explosion

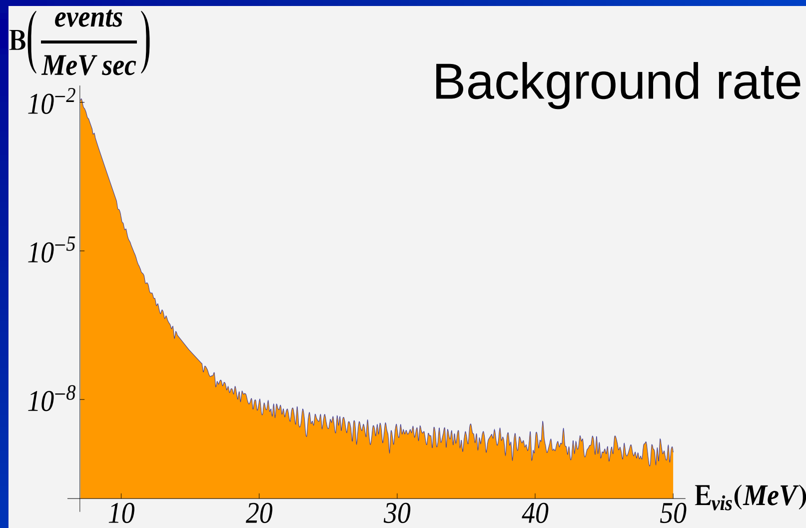
Detection process

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

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

$$E_{vis} = E_{e^+} + m_e$$

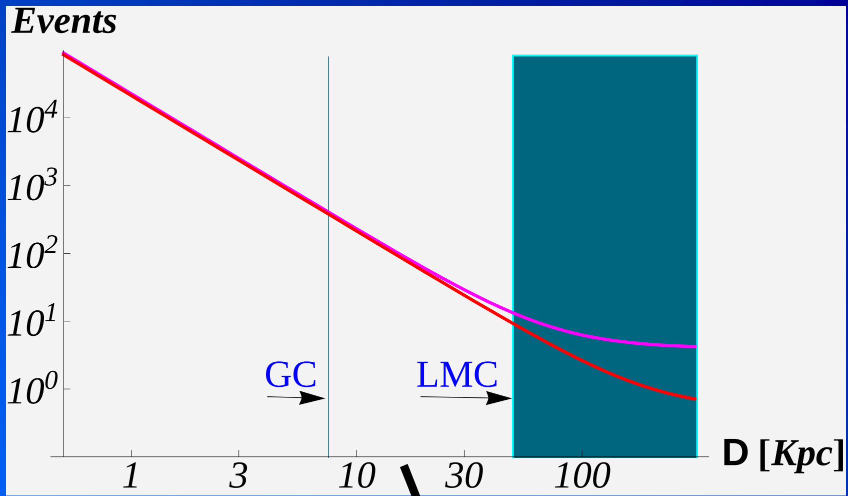


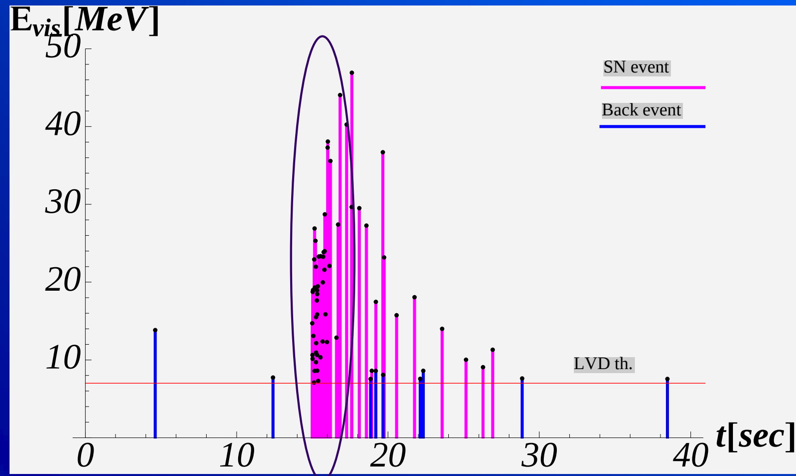


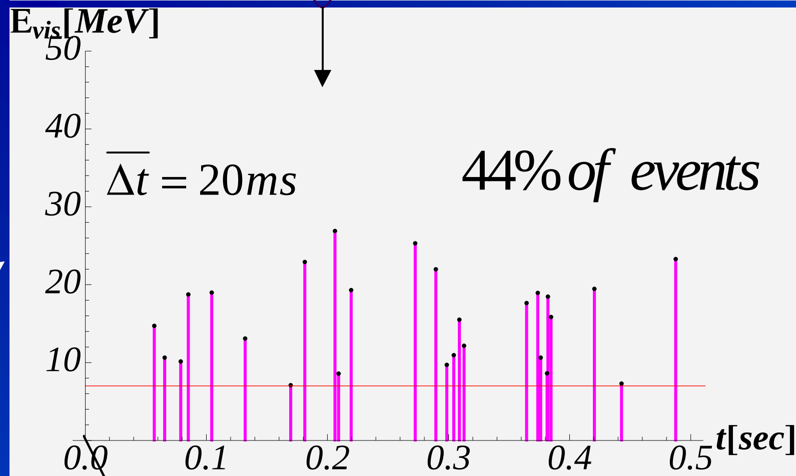
Simulated Events in LVD

The number of expected events in 20 seconds is:

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







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

57 SN events

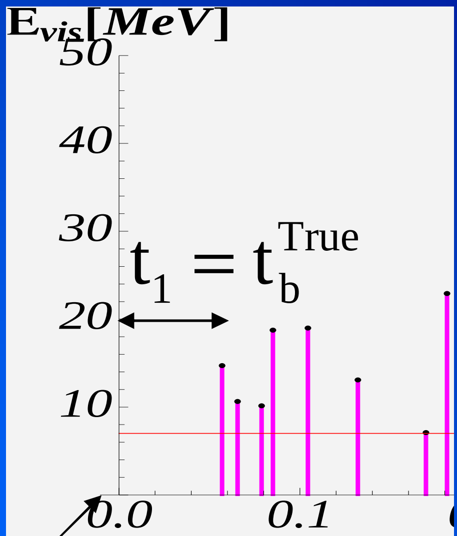
+ 4 background events

Statistical Analysis

Using Monte Carlo simulated data we compare:

1) True and estimated bounce time

2) True and estimated error on bounce time



$$t^{em} = 0 \rightarrow t = t_b$$

Statistical error by marginalization

$t_b^{True}(ms)$	$t_b^{BF}(ms)$	t_b^{True}-t_b^{BF}	$\Delta t(1\sigma)$	C
43	24	+19	+19	1
27	29	-3	-14	0.2
36	35	+1	+18	0.06
100	50	+51	+24	2
38	32	+7	+18	0.4
33	34	-2	-17	0.1
23	42	-19	-19	1
32	24	+8	+13	0.6
56	42	+14	+15	0.9
55	44	+11	+17	0.6

C → **Compatibility Error Factor: The ratio between the true error and estimated one**

RESULTS

The average statistical errors within 68% and 90% C.L. are:

$$\langle \Delta t_b(1\sigma) \rangle = ^{+16}_{-14}\ ms \qquad \langle \Delta t_b(2\sigma) \rangle = ^{+43}_{-22}\ ms$$

Exploiting the neutrino signal detected by LVD for a SN event at 20 Kpc, it is possible to know the Universal Time of the bounce with an average error:

$$\boxed{t_b(U.T.) = \left(t_1(U.T.) - t_b^{BF} \right)^{+16}_{-14} ms}$$

References

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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 $\bar{\nu}_e$ is:

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

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

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

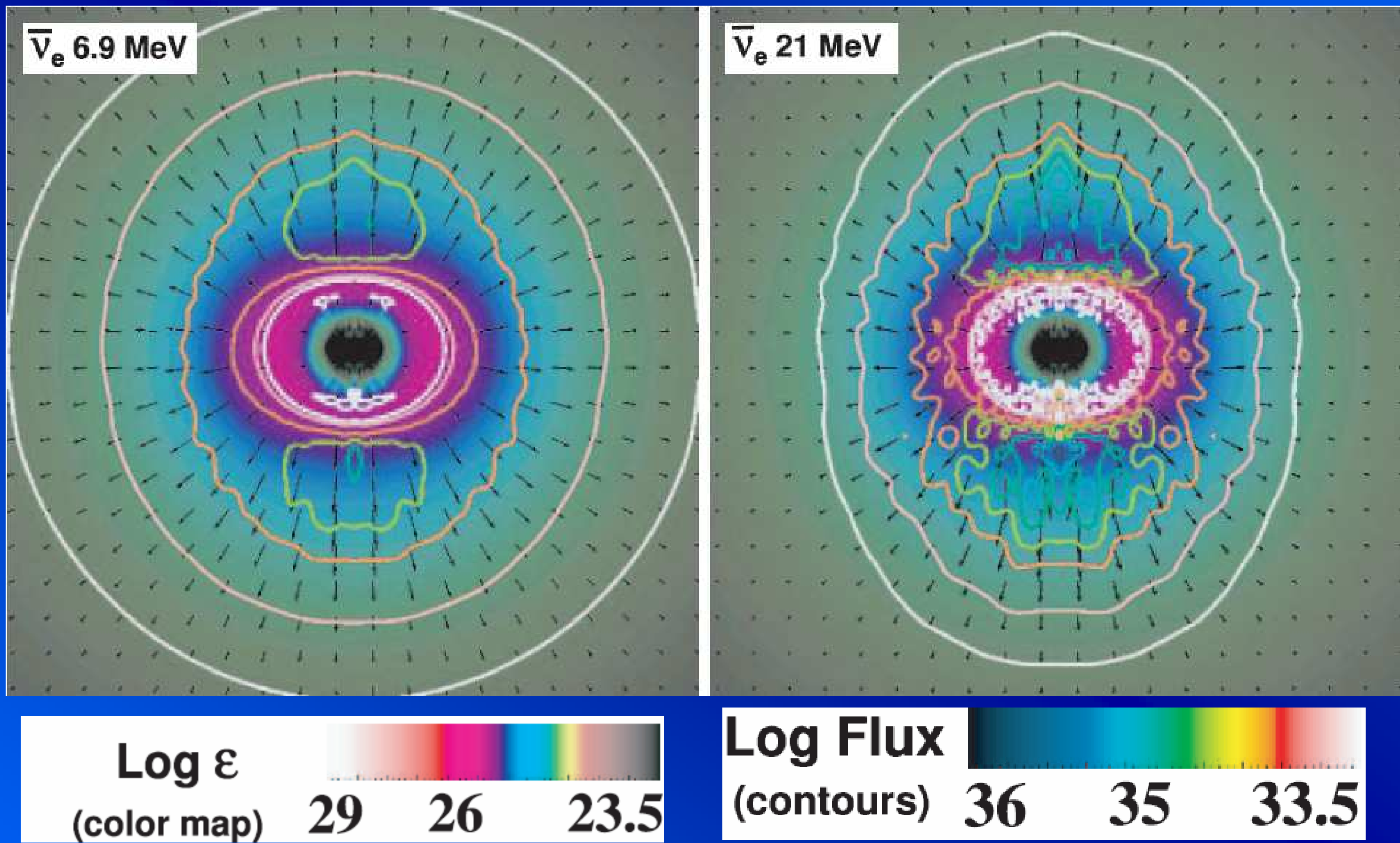
$$\theta_{13} < 10^\circ$$

ASSUMPTIONS

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

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

ROTATION



$\bar{\nu}_e$ 6.9 MeV
$\bar{\nu}_e$ 21 MeV
Log ε
(color map)
29 26 23.5
Log Flux
(contours)
36 35 33.5

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:

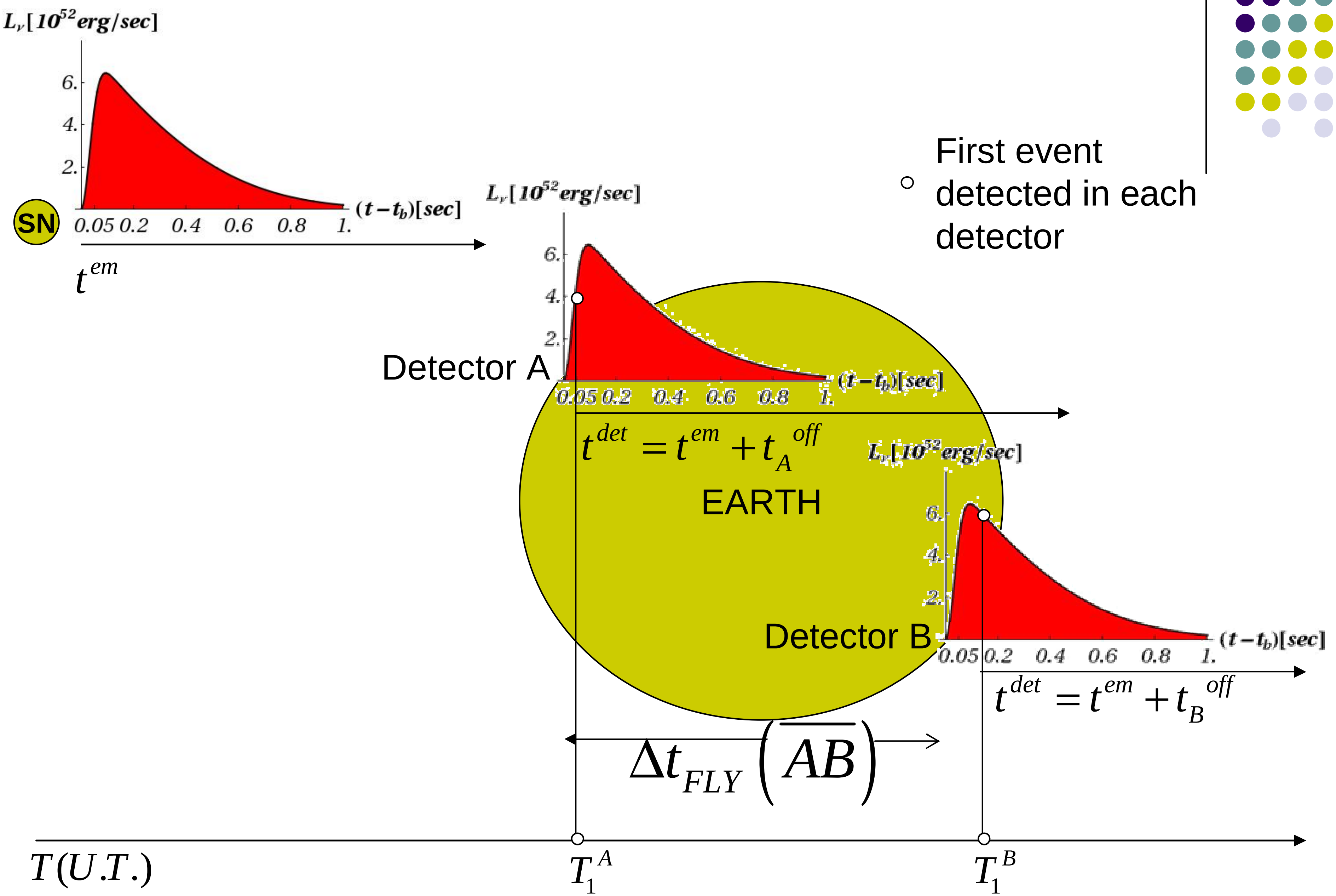
$$t^0_{\bar{\nu}_e} = 7h\,35m\,33.68s \quad -0.08s \quad \pm 1m$$

From 5 Baksan data:

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

<u>Now</u> SYST. ⇨ $\pm 0.1\,ms$

- First event detected in each detector



NEUTRINO MASS BOUND

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

$$t_i = t^{em} + t^{off} + \Delta t(E_\nu, m_\nu)$$

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

We added a new free parameter to our likelihood function

The presence of this new degree of freedom associated with the possibility To shift the IMB data produces a Likelihood function very pathological With multiple peaks. The physically Acceptable solutions are characterized By best-fit values very simular to the Previous one and best-value for the Neutrino mass of:

$$m_\nu = 0.^{+8}eV$$