Neutrinos and Gravitational Waves from CCSNe

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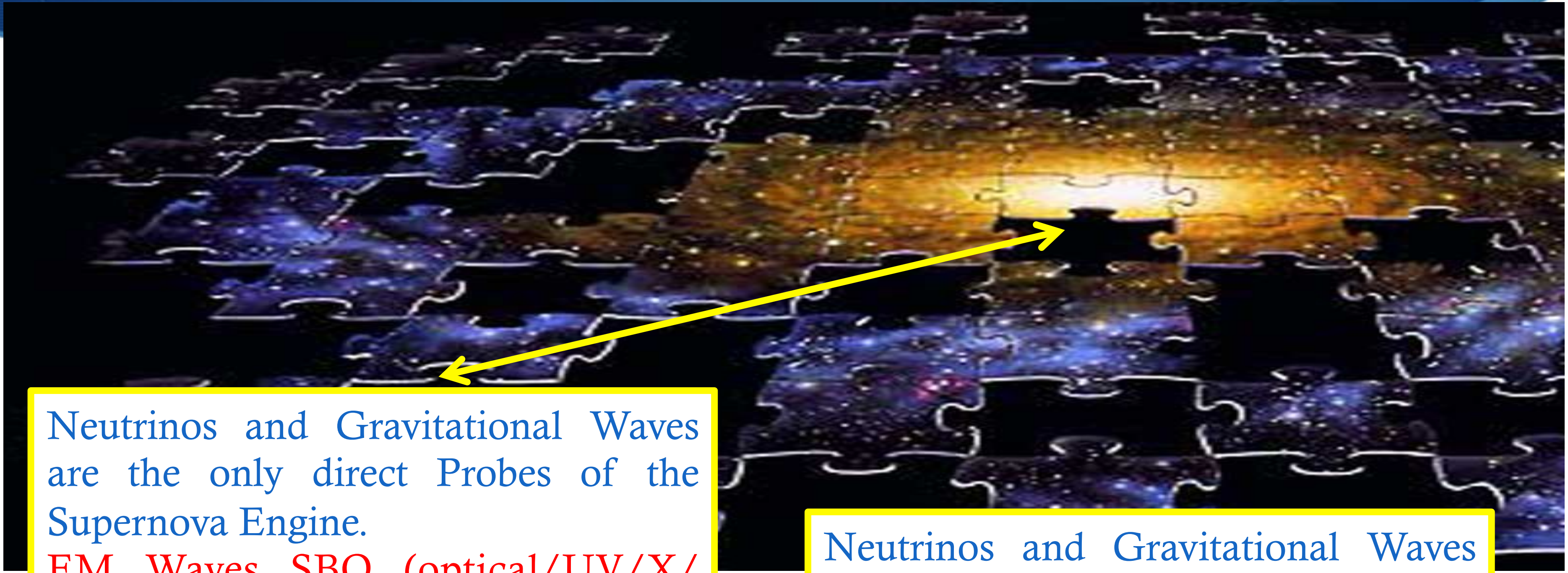
Outline

- The Science Case of Core Collapse Supernovae
- Neutrinos Emission
- Gravitational Waves Emission
- Joint Search GW- ν
- Summary

The Supernova puzzle



Neutrinos and Gravitational Waves are the only direct Probes of the Supernova Engine.

EM Waves SBO (optical/UV/X/Gamma): Late-time Probes of engine (day), Progenitor information

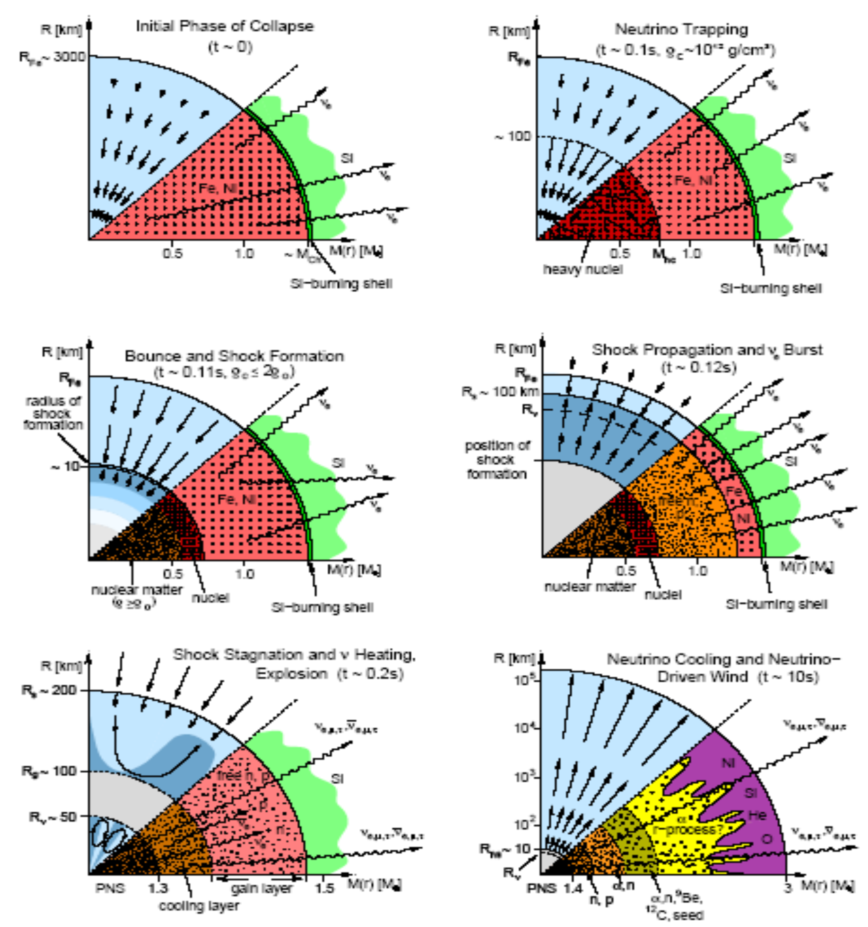
Neutrinos and Gravitational Waves carry complementary information.

Neutrinos: primarily thermodynamics

GWs: primarily dynamics

Joint observation improve the potential of physical learning.

Core-Collapse SN



From JANKA et al. Phys.Rev. 442 (2007)

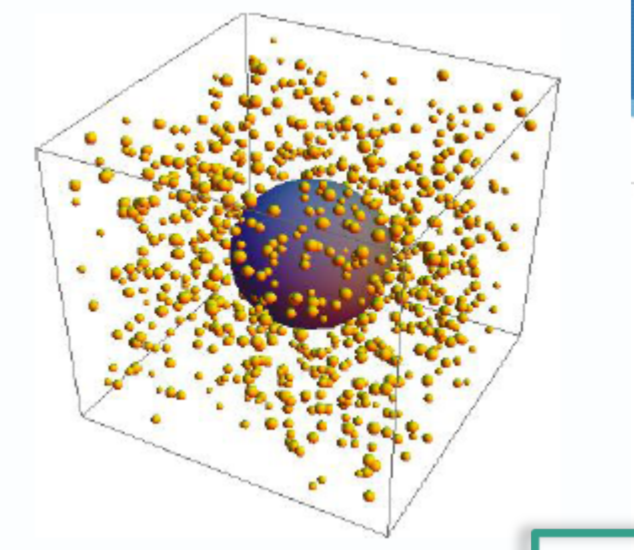
1. Collapse
2. Bounce
3. Shock Propagation
4. Shock Stagnation
5. Accretion
6. Cooling PNS

Time = 0 for GW and ν signals

Critical phase

EXPLOSION MECHANISM IS STILL UNCERTAIN

Neutrinos Expectations



ENERGY

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

$$\varepsilon_\nu = 99\%\cdot\varepsilon_B$$

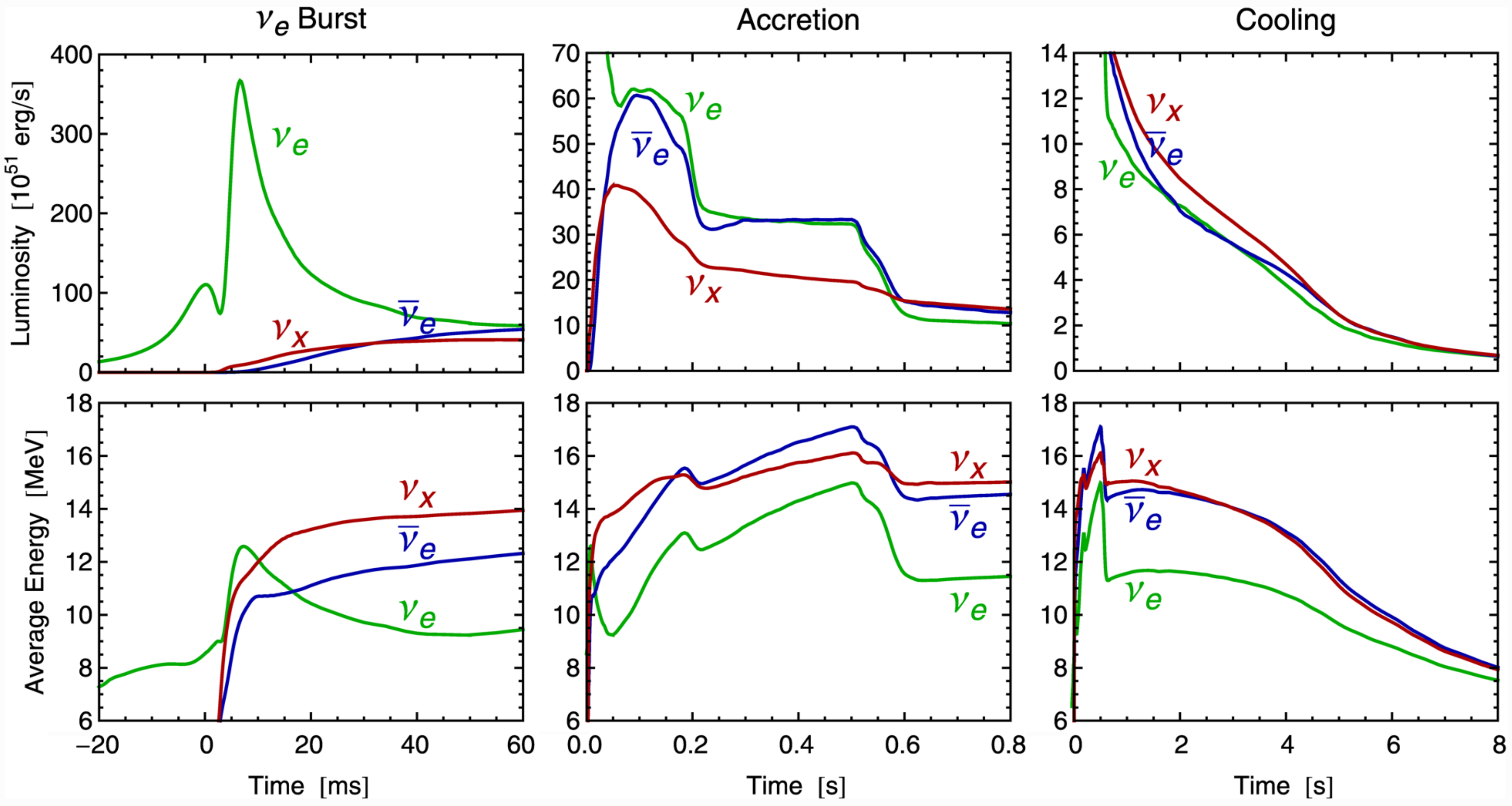
FLUENCE

$$F_{\nu_x} \cong \frac{\varepsilon_B}{6\langle E_{\nu_x}\rangle}\frac{1}{4\pi D^2} \approx 5\cdot 10^{10}\left(\frac{20\text{ kpc}}{D}\right)^2 \frac{10\text{MeV}}{\langle E_{\nu_x}\rangle}\frac{\nu_x}{cm^2}$$

DURATION

$$\Delta t = 10\,\text{sec}$$

Spherically symmetric Garching model (25 M$_\odot$)



- Neutronization burst
- Standard Candle

- Not thermal spectra
- 10% of the total energy
- Explosion Mechanism??

- Trapped Neutrinos
- Thermal spectra
- 90% of the total energy

GW Emission Mechanisms

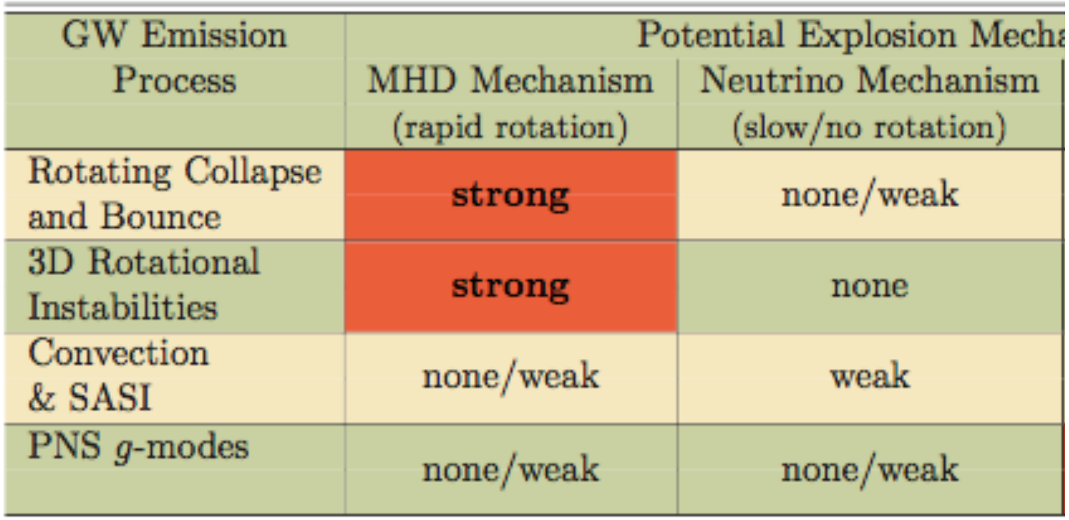
GW Emission Processes
A: PNS core oscillations
B: Rotational 3D instabilities
C: Rotating core collapse and core bounce
D: Post bounce convection and SASI

Dynamical quadrupolar matter distribution

$$\boxed{h_{+} = \frac{G}{c^{4}}\frac{1}{D}\frac{3}{2}\ddot{I}_{zz}\sin^{2}\vartheta}$$

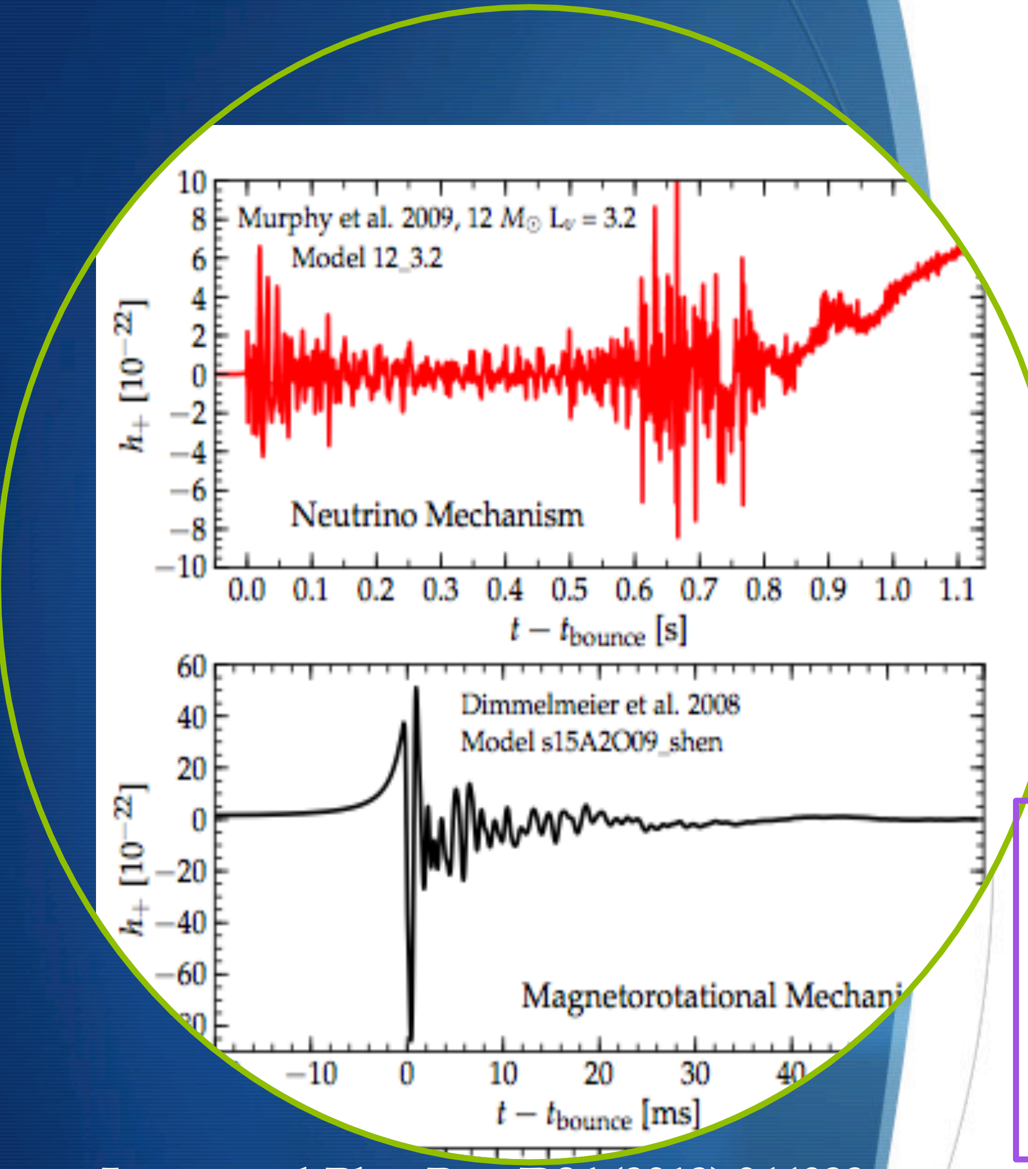
Logue *et al.* Phys.Rev. D86 (2012) 044023

Gossan *et al.* Phys.Rev. D93 (2016) 042002

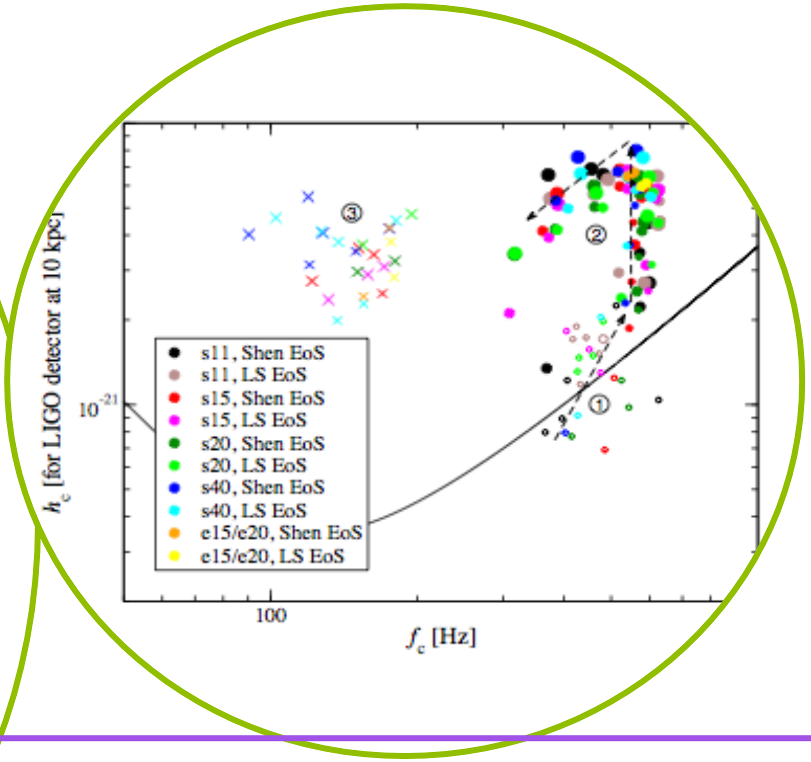


GW Emission Process	Potential Explosion Mecha	
	MHD Mechanism (rapid rotation)	Neutrino Mechanism (slow/no rotation)
Rotating Collapse and Bounce	**strong**	none/weak
3D Rotational Instabilities	**strong**	none
Convection & SASI	none/weak	weak
PNS *g*-modes	none/weak	none/weak

Expected Frequencies



Logue *et al.* Phys.Rev. D86 (2012) 044023



Amplitude: $10^{-23} < h_{\max}(10\,\mathrm{kpc}) < 10^{-20}$

Frequency: $\Delta f_{\max} = 50 - 1000$ Hz

Duration: $\Delta t = 10 - 1000\ ms$

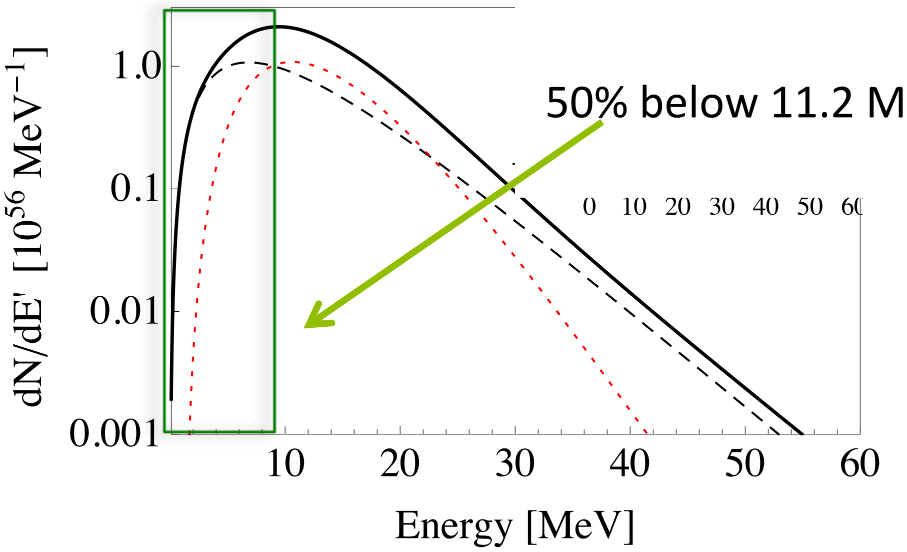
Uncertainty on the prediction of orders of magnitude

Neutrino Detection

Number flux
of neutrinos

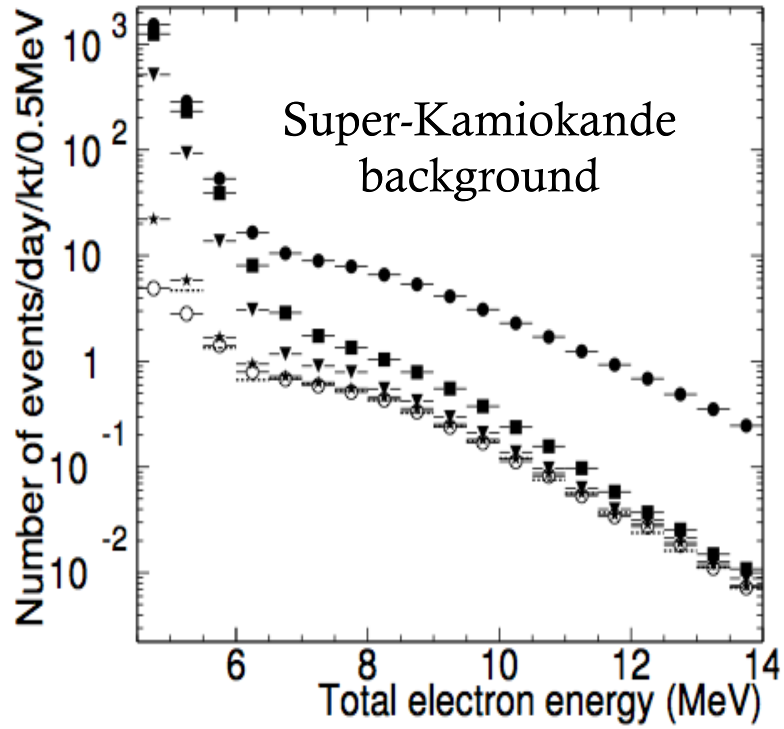
$$\boxed{N_\nu \propto \frac{1}{D^2}}$$

Neutrino Spectrum



50% below 11.2 MeV

Vissani *and GP*, **Astron.Astrophys. 528 (2011) L1**



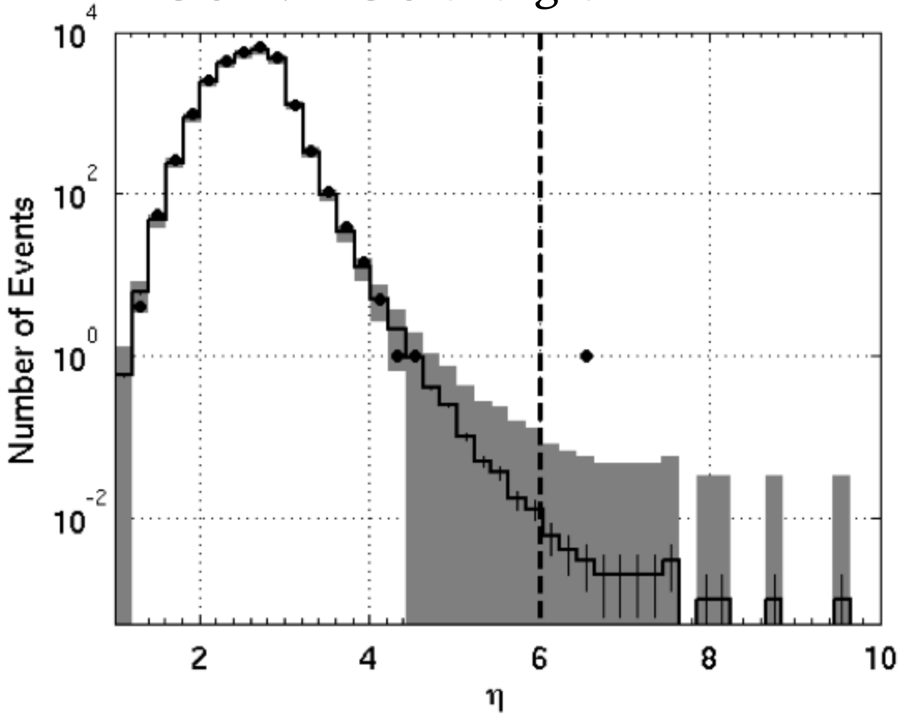
Super-Kamiokande background

The detector energy threshold plays a crucial role!

GW Detection

- Already first-generation LIGOs should be able to see some of such signals throughout the Milky Way
- Short-lived noise transients can mimic gravitational-wave bursts signals
- Requirement of a temporal Coincidence among the triggers of different GW detectors
- Occurrence of accidental coincidences at any given value of the observable, e.g. SNR.

LIGO+VIRGO background



Ababie *et al.* **Phys.Rev. D81 (2010) 102001**

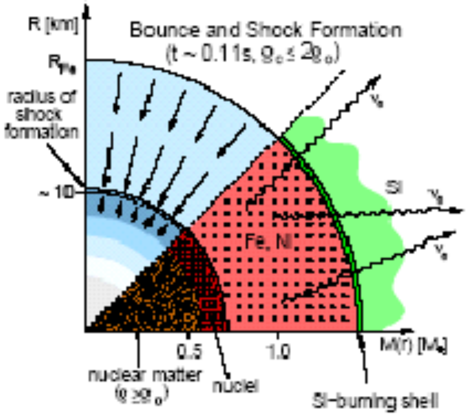
Joint Search

Will Profit of the
different Advantages allowing
GW and neutrino detectors
to operate at lower thresholds

GW-ν Working Group

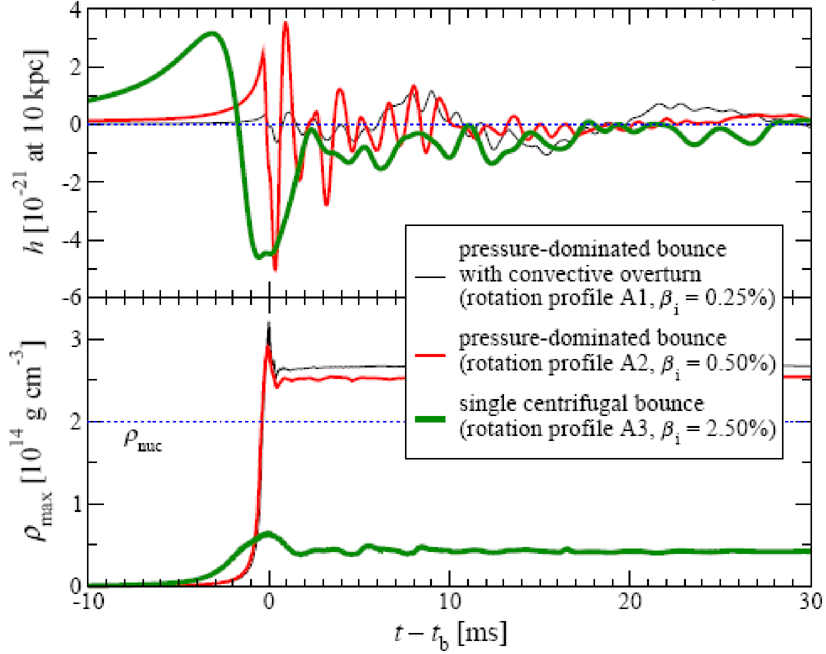
THE CORE BOUNCE

The role of temporal information



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

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



Using neutrino signal we can identify the time of the bounce to reduce the temporal window!

Joint GW-ν Search

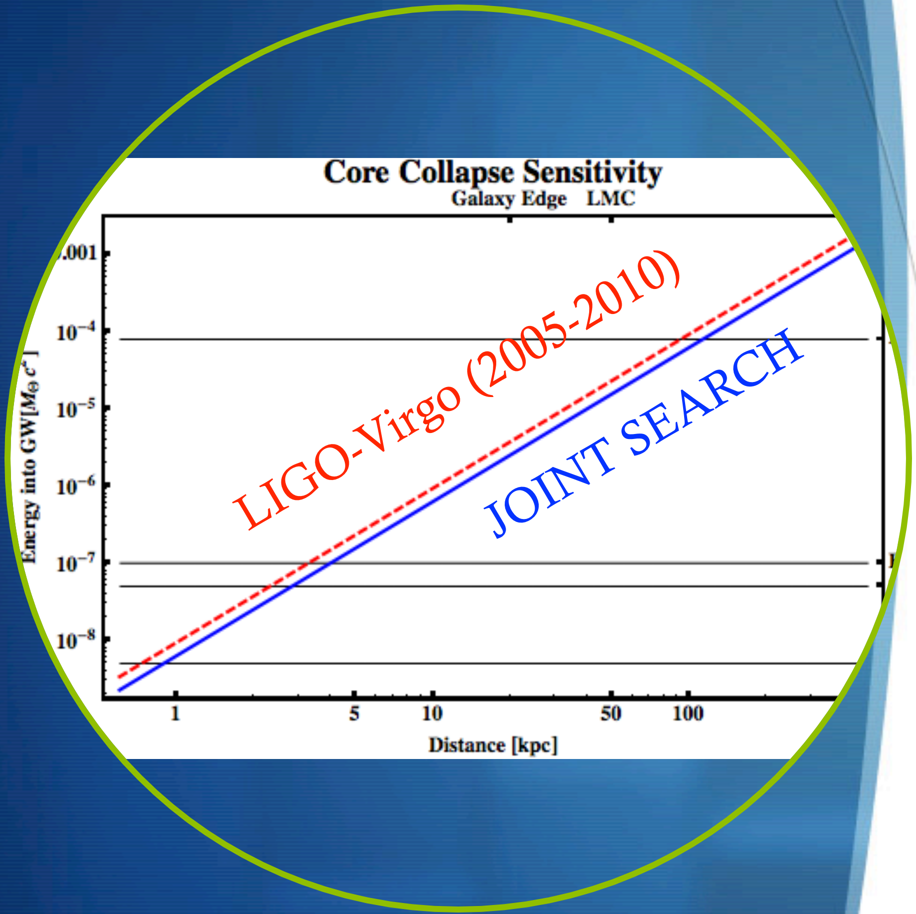
Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate GW back. Rate Neutrino back. Rate Time coincidence window

$$\boxed{\mathrm{FAR} = \mathrm{R}_{GW}(\eta_{th}) \cdot \mathrm{R}_{\nu}(\mathrm{E}_{th}) \cdot 2\mathrm{w}}$$

- We choose w=10 sec to accomodate most emission models
- **We require FAR=1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.**

LIGO-Virgo Distance Reach



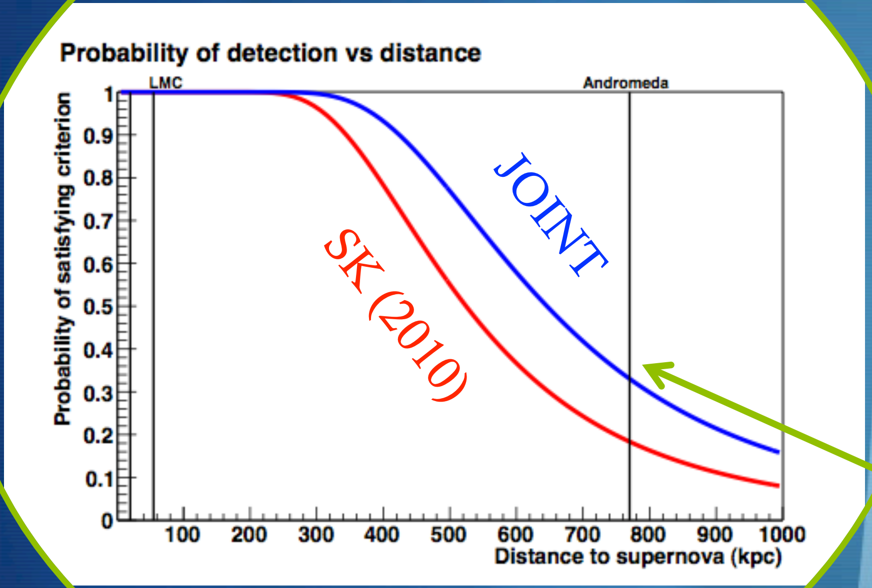
Sensitivity of the GW network in terms of the energy released at a frequency of 554 Hz

$$E_{GW}\left[M_\Theta c^2\right] \propto h^2 D \cdot f_0^2$$

for different models.

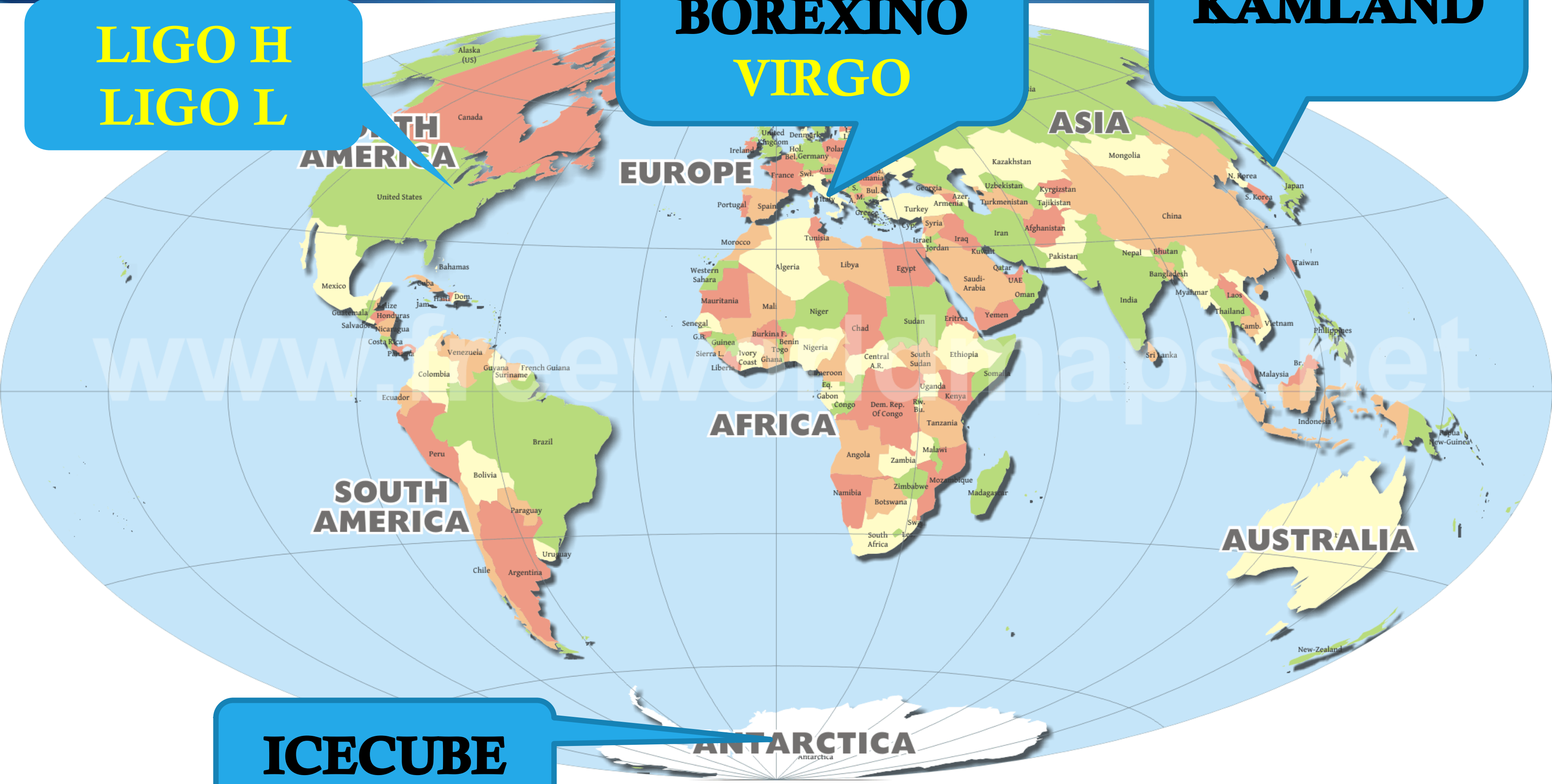
- The joint search with a neutrino detector gives a **20%** improvement in sensitivity probing a factor of ~ 1.6 lower energy emission from core-collapse supernova

What SuperKamiokande could do jointly



- Super-Kamiokande “distant” burst search requiring two neutrino events (with energy threshold 17 MeV) within 20 seconds shows a ~**18%** probability of detecting a SN in M31
- Requiring the coincidence with a GW trigger it is possible to lower the threshold to 8.5 MeV increasing the detection probability to the ~**35%**

Involved Experiments



LIGO H
LIGO L

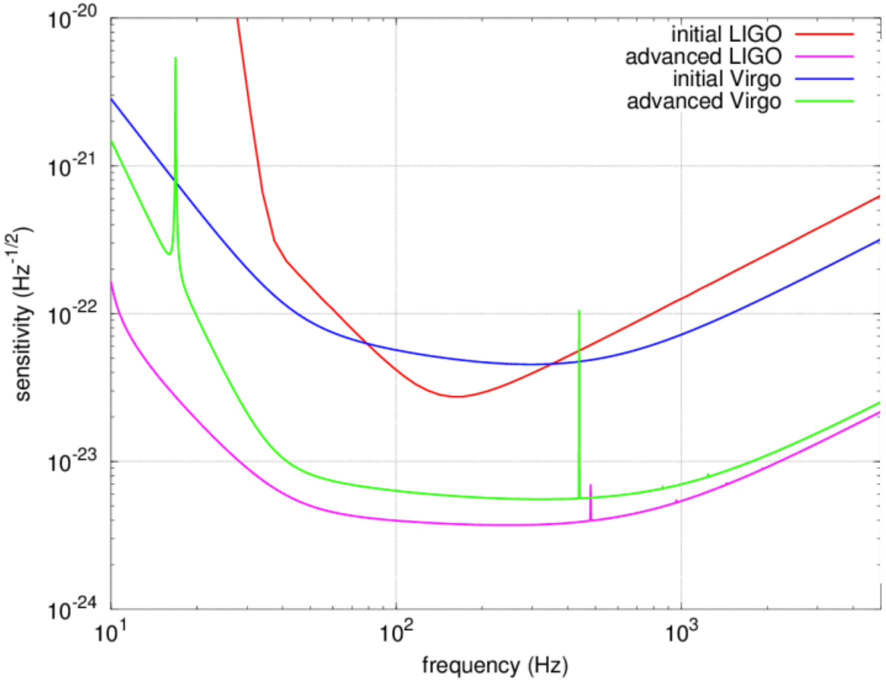
LVD
BOREXINO
VIRGO

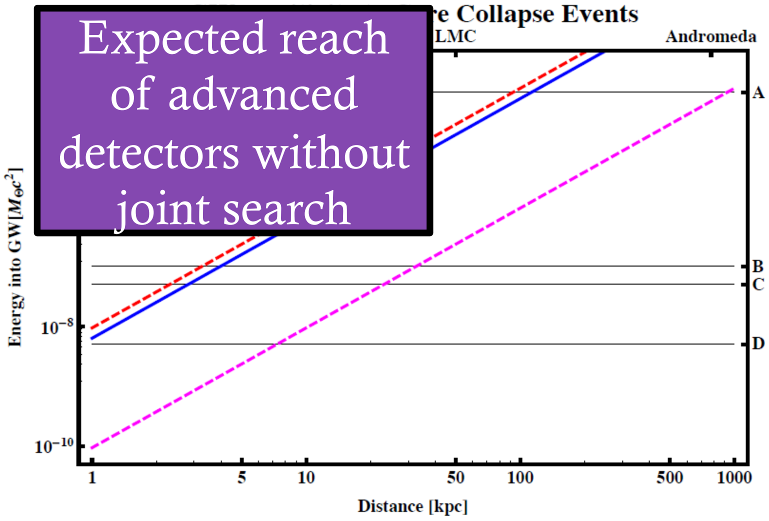
KAMLAND

ICECUBE

GW Experiments

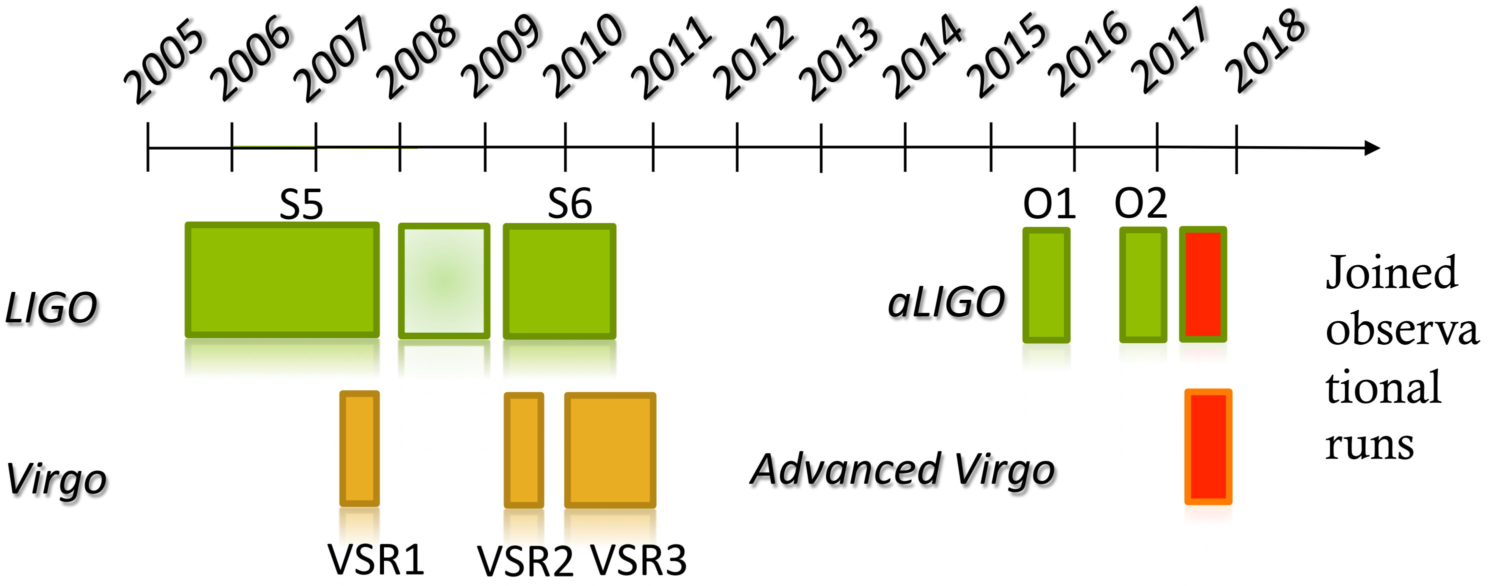

LIGO Lab/Virgo




Expected reach of advanced detectors without joint search

GW scientific runs

- A series of runs have been performed by the GW network;



Slide by Claudio Casentini

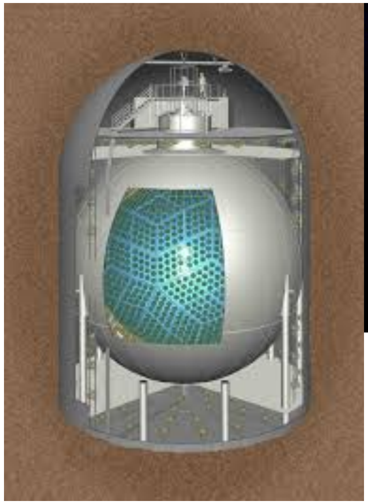
Neutrinos Experiments

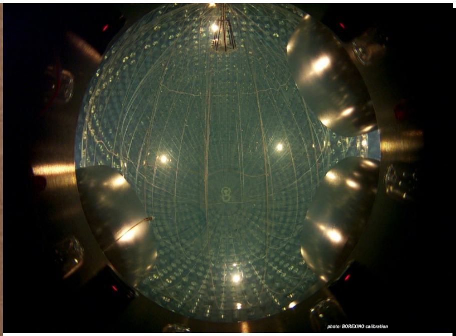
Kamland
- Liquid Scintillator
- Energy & NC
- M= 1 kton

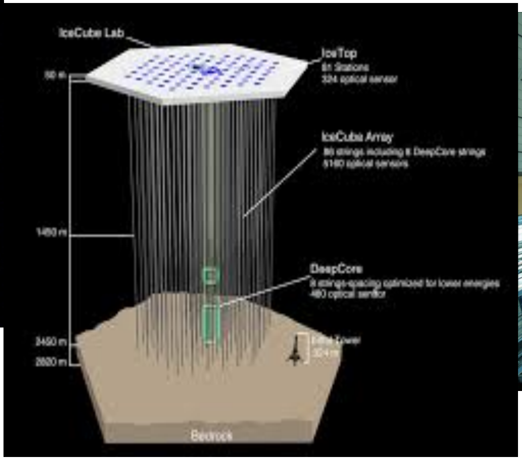
Borexino
- Liquid Scintillator
- Energy & NC
- M= 0.3 kton

IceCUBE
- Ice Cerenkov
- Statistics
- M≈ 2.7 Mton

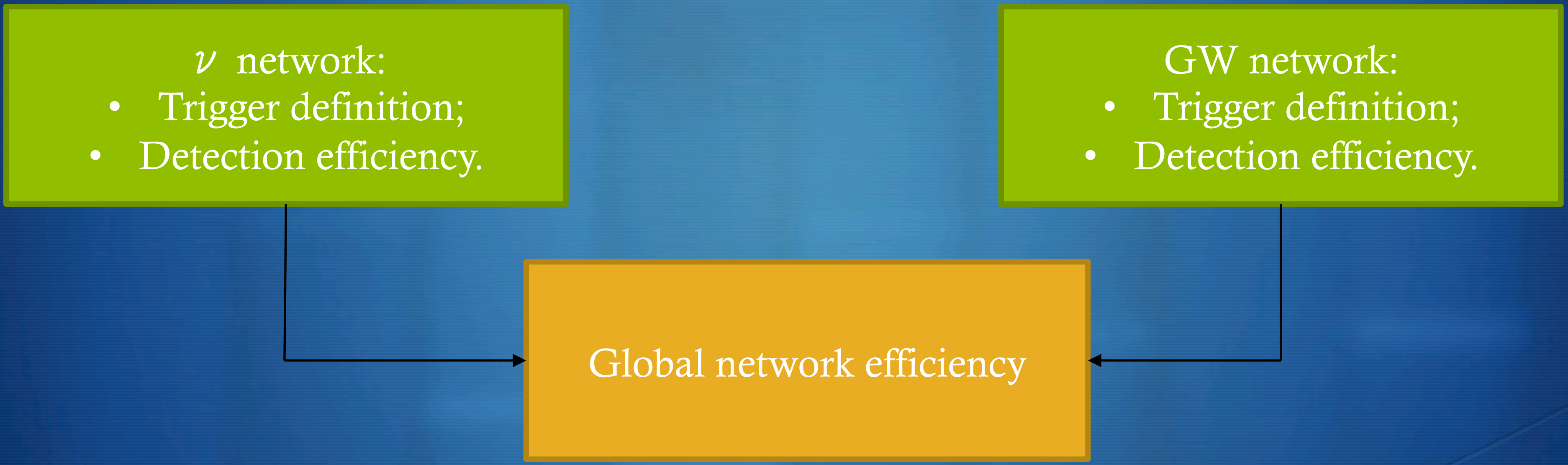
LVD
- Liquid Scintillator
- Energy & NC
- M= 1 kton







Combined search Strategy with ν and GW network



ν network:
- Trigger definition;
- Detection efficiency.

GW network:
- Trigger definition;
- Detection efficiency.

Global network efficiency

Methods

SIMULATE THE ν SIGNAL OF CCSN AS EXPECTED FOR EACH ν DETECTOR

We adopted the parametric emission model for neutrinos discussed in GP *et al.*, Astropart. Phys. 31 (2009) 163–176

INJECT THESE SIGNALS FOR DIFFERENT DISTANCES INTO…

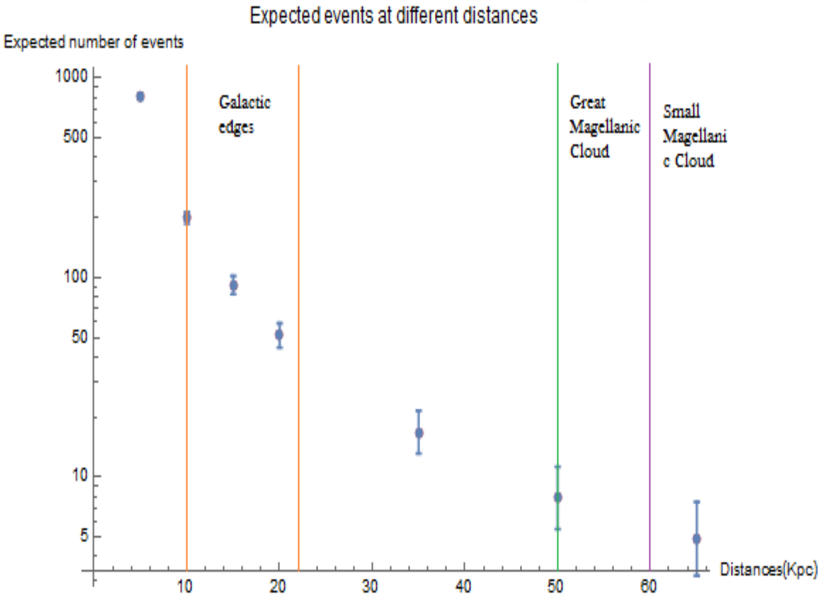
Study of the response of the neutrino Network to the same SN signal: total Number of events, average energy, burst Duration and statistical fluctuations of these quantities

SIMULATED BACKGROUND DATA

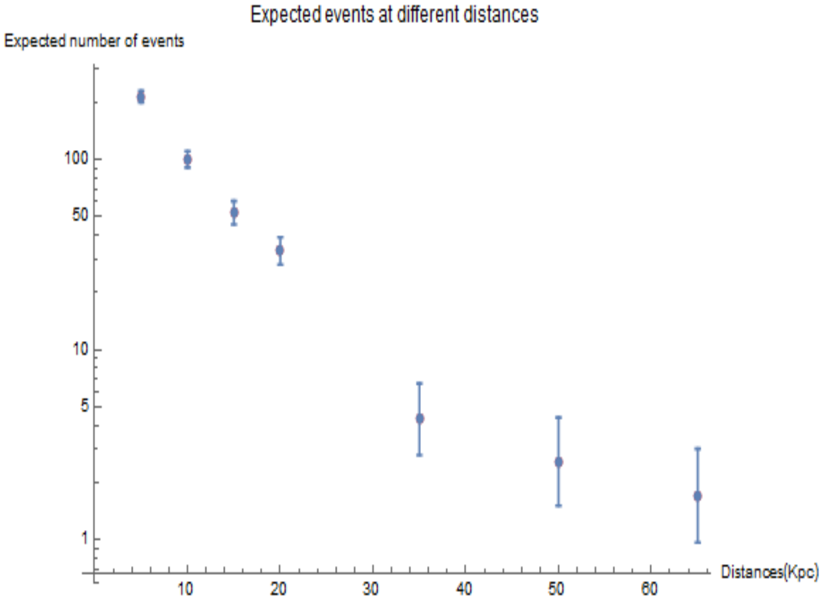
We are simulating background for each detector for different FAR

Expected number of events

LVD



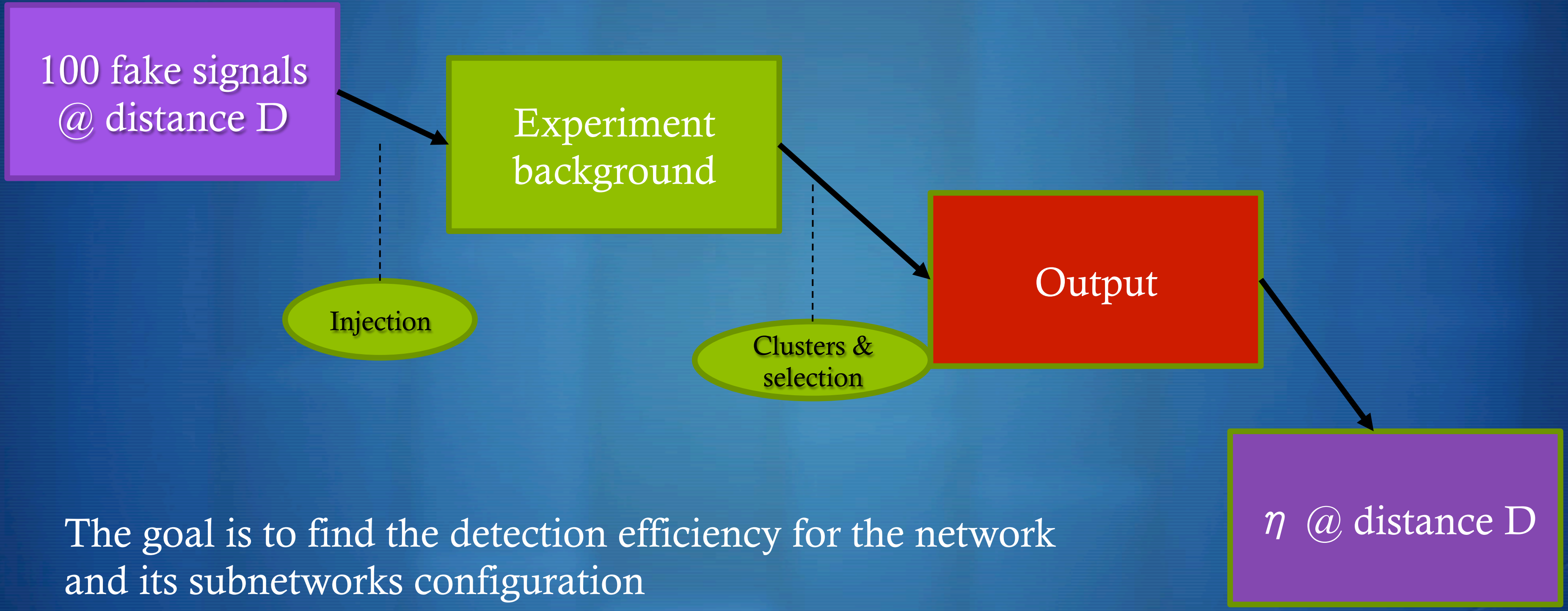
BOREXINO



Points: average of 100 signals

Error bars: Standard deviation

Network Efficiency



100 fake signals @ distance D

Injection

Experiment background

Clusters & selection

Output

η @ distance D

The goal is to find the detection efficiency for the network and its subnetworks configuration

Summary

- Neutrinos and GW emitted from CCSNe can be fundamental probes to infer about the explosion mechanism
- A combined search increases the detection probability for distant CCSNe and the potential learning for a Galactic event
- A joint search of low energy neutrino and GW from nearby core-collapse is on-going and the expected increase of sensitivity is promising
- This is an open group join us if you are interested

Galactic Core-Collapse SNe

SN2020 by C.Ott

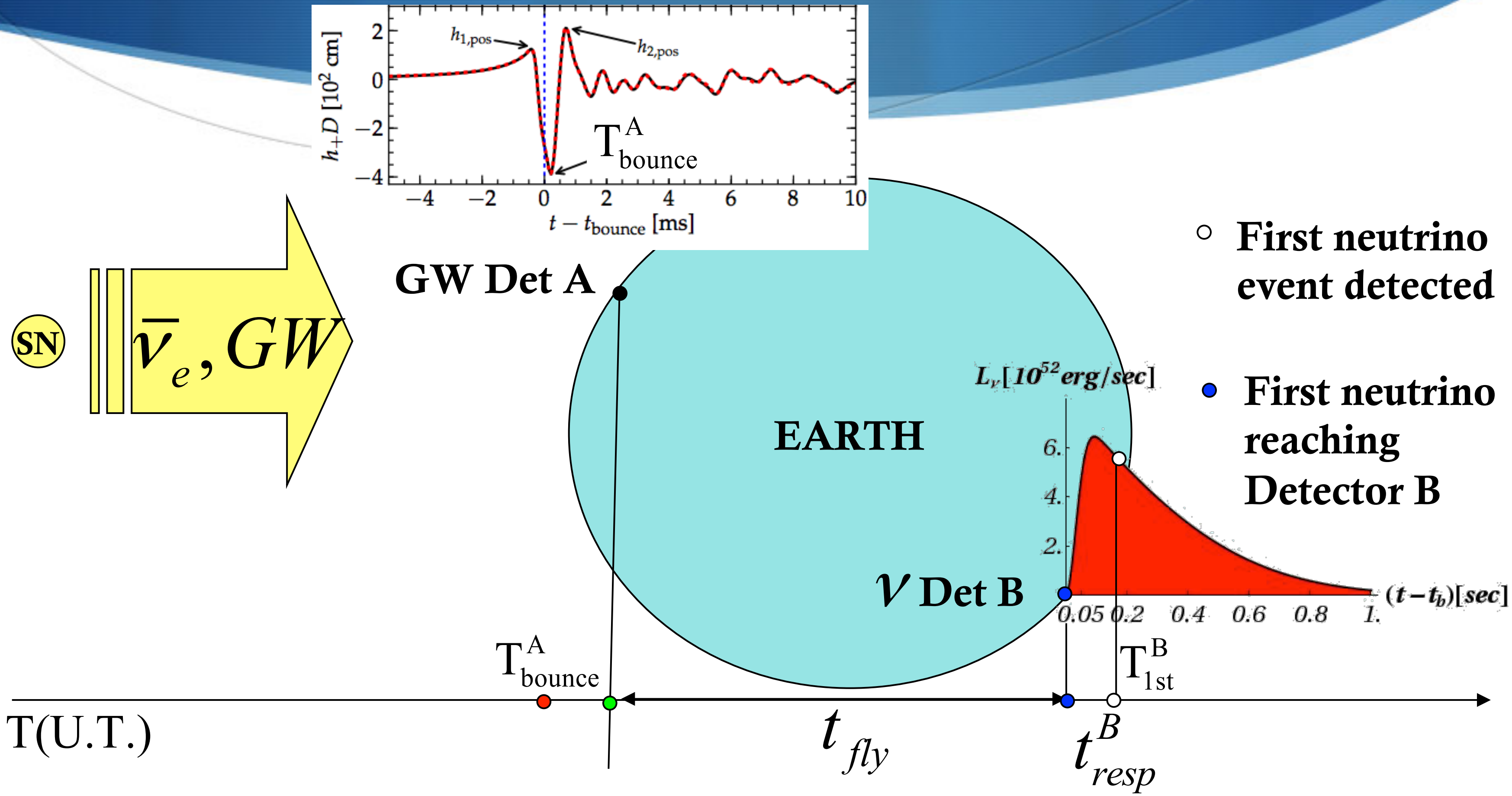
Core-Collapse behind the galactic center D~10 kpc
No electromagnetic signal (dust extinction)
High-statistics neutrino lightcurve from IceCube, LVD, Kamland and Borexino

LVD, Kamland and Borexino provide

IceCube provides a temporal window w =±3.5 ms at 95% CL around the time of the bounce

Joint analysis: Identification of the stellar core structure, rotation state, and explosion mechanism by Correlation of neutrino/GW data.
Joint observation & statistical analysis multiplies physics learned.

THE IDEA



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

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

MASTER EQUATION

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

$$\delta T_{\mathrm{bounce}} = \sqrt{\sum_{i} \left(\delta t_{i}\right)^{2}}$$

GOAL $\longrightarrow$ $\boxed{\delta T_{\mathrm{bounce}} \approx 10\mathrm{ms}}$

$$t_{\mathrm{GW}} = (1.5 - 4.5)\mathrm{ms} \longrightarrow \delta t_{GW} : 1.5\mathrm{ms}$$

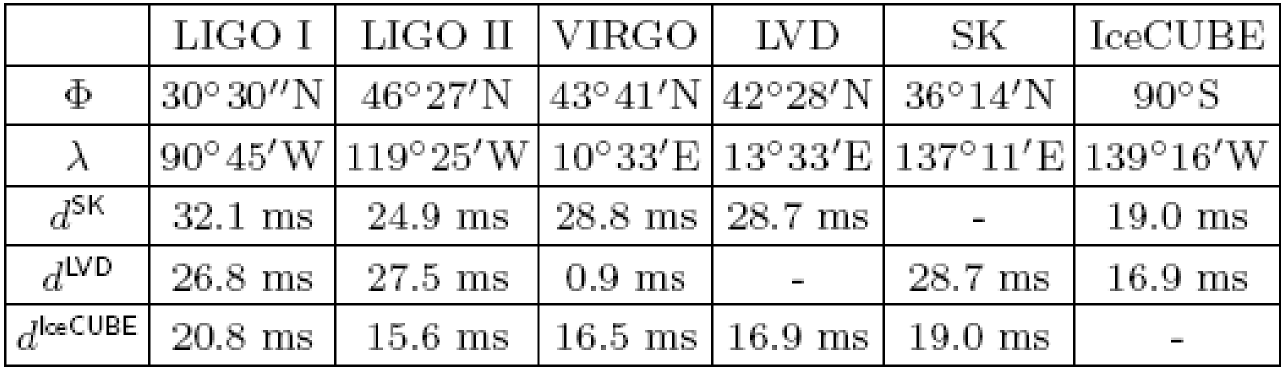
$$t_{\mathrm{mass}} \approx 0.27 \left(\frac{m_{\nu}}{0.23}\right)^{2} \left(\frac{10\mathrm{MeV}}{E_{\nu}}\right)^{2} \left(\frac{D}{10\mathrm{kpc}}\right) \mathrm{ms} \longrightarrow \delta t_{mass}$$

negligible

Time of fly and response time are dominant

Both can be determined using Neutrinos Data

TIME OF FLY



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

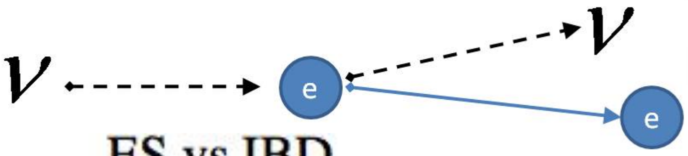
$$t_{fly} \approx 30ms$$

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

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

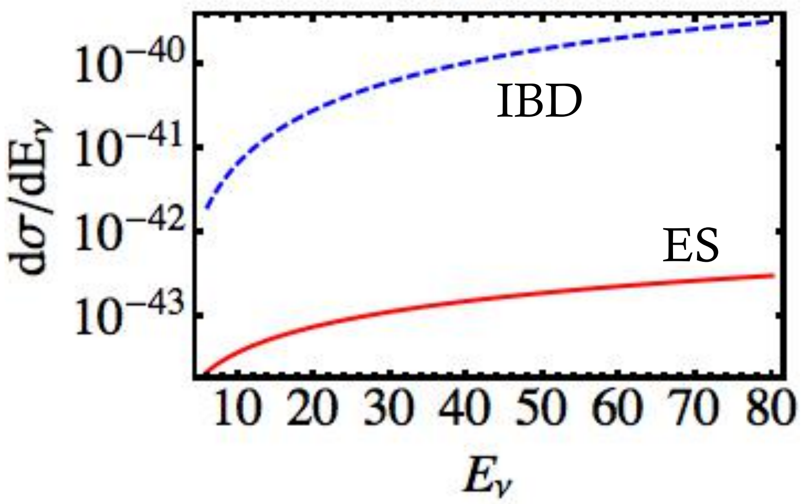
Elastic Scattering (ES)

Directional interaction

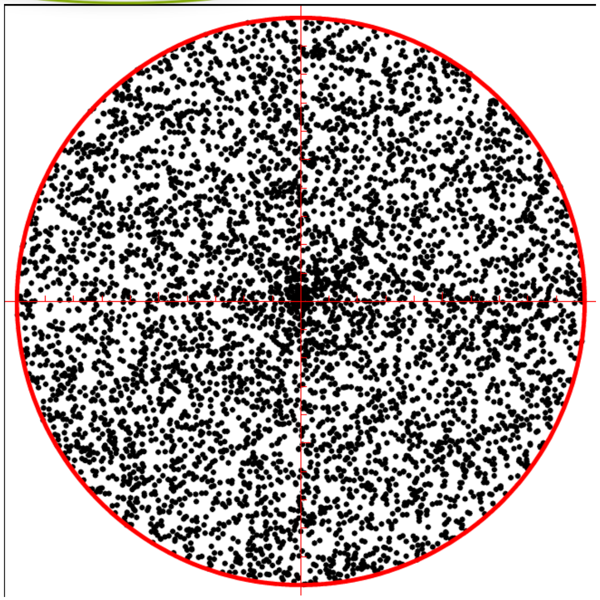


$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ES vs IBD



POINTING:
300 ES directional events among the IBD events



SK detector and D=20kpc
35 ES directional events
1050 Inverse beta decay

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

RESPONSE TIME

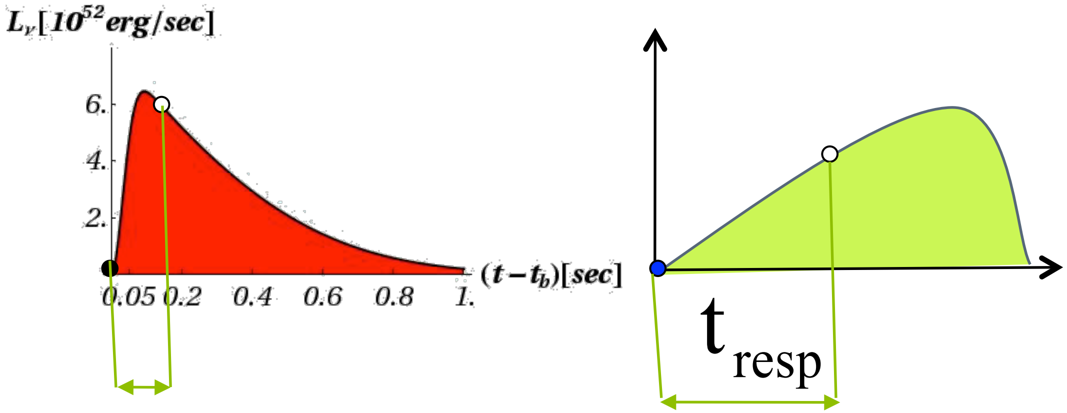
● The first neutrino that reaches the detector

○ The first neutrino detected

$t_{resp} =$ ● ↔ ○

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

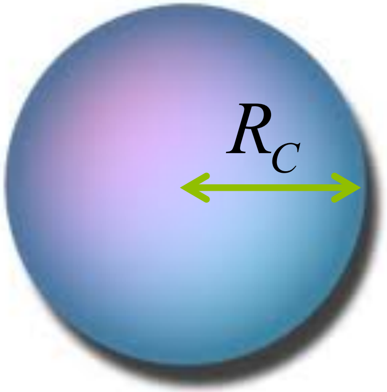
Real detector ➡ It loses a part of the signal ➡ $t_{resp} > 0$



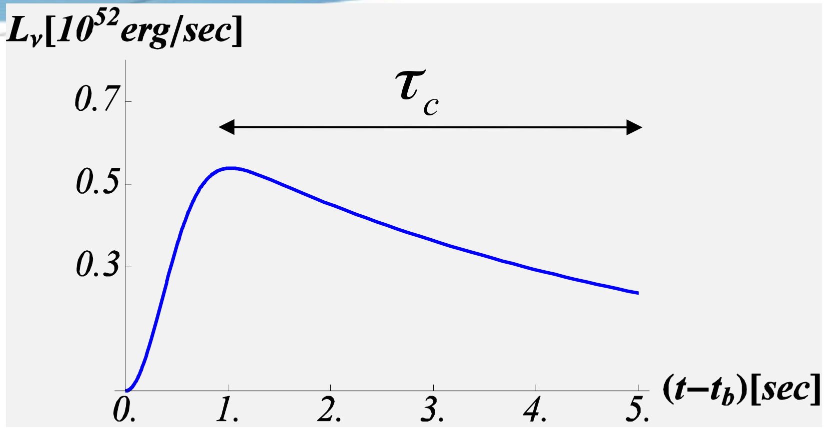
DEPENDS ON THE SIGNAL BEHAVIOUR !!

COOLING PHASE

Thermal emission from cooling of the PNS



$$\boxed{90\% \cdot \varepsilon_\nu}$$



All species of neutrinos
are emitted by Urca processes

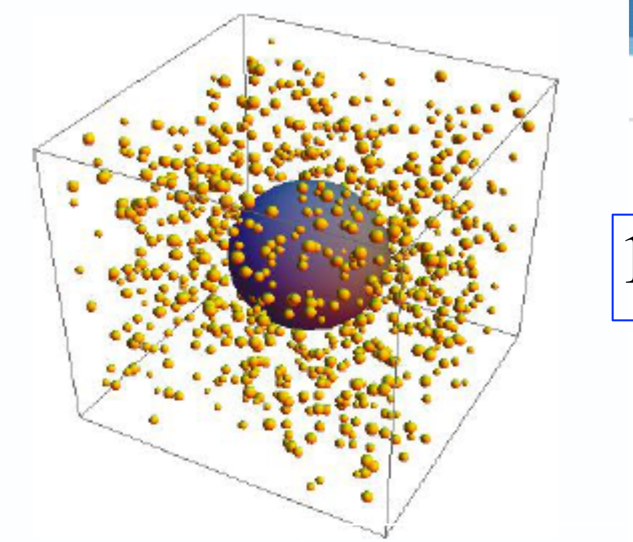
$$L_{\bar\nu_e} \sim 5\times 10^{51}\,\frac{\text{erg}}{\text{sec}}\left(\frac{R_C}{10\text{km}}\right)^2\left(\frac{T_C}{5\text{MeV}}\right)^4$$

$$\Phi^0_{\bar\nu_e}(E_\nu,t)=\frac{4\pi R_C^2}{4\pi D^2}\,\frac{\pi c}{(hc)^3}\,\frac{E_\nu^2}{1+e^{\left(\frac{E_\nu}{T_c(t)}\right)}}$$

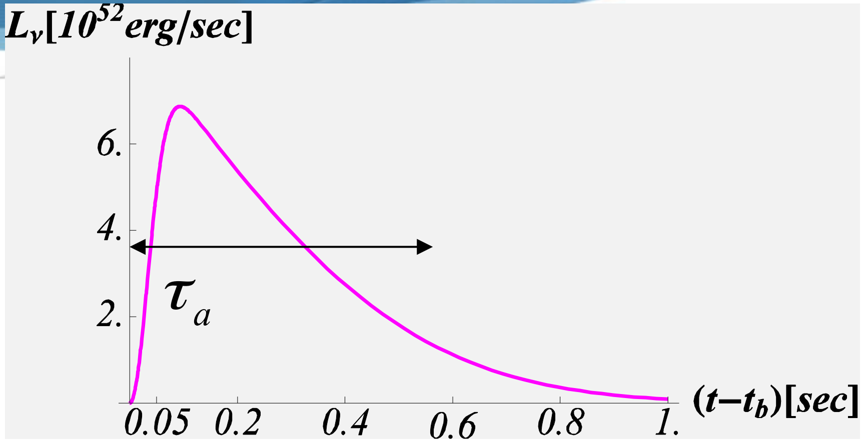
Model Parameters

$$R_C \quad T_C \quad \tau_C$$

ACCRETION PHASE



$$\boxed{10\% \cdot \varepsilon_\nu}$$



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

$$L_{\bar{\nu}_e} \sim 5\times 10^{52}\,\frac{\mathrm{erg}}{\mathrm{sec}}\left(\frac{\mathrm{M_a}}{0.1\mathrm{M_e}}\right)\left(\frac{\mathrm{T_a}}{2\mathrm{MeV}}\right)^6$$

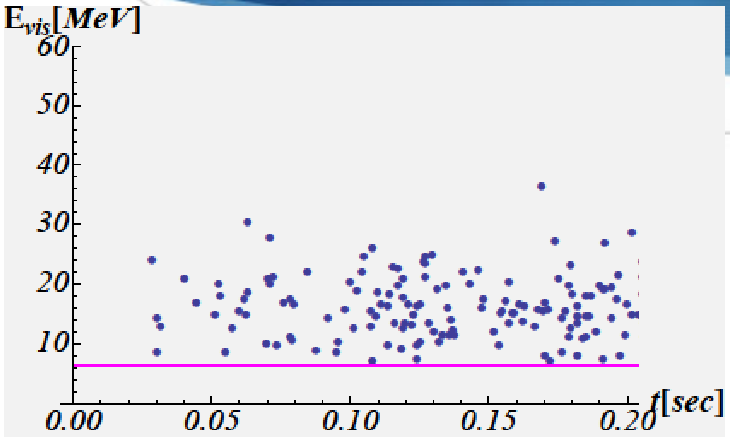
Microscopic parameterization of the flux

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

Model Parameters

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

Results for SK and a SN distance of 20 kpc



AVERAGE RESPONSE TIME UNCERTAINTY

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

Using neutrino signal detected by SK for a SN event at 20 kpc, we can determine the Universal Time of the bounce with an average error of

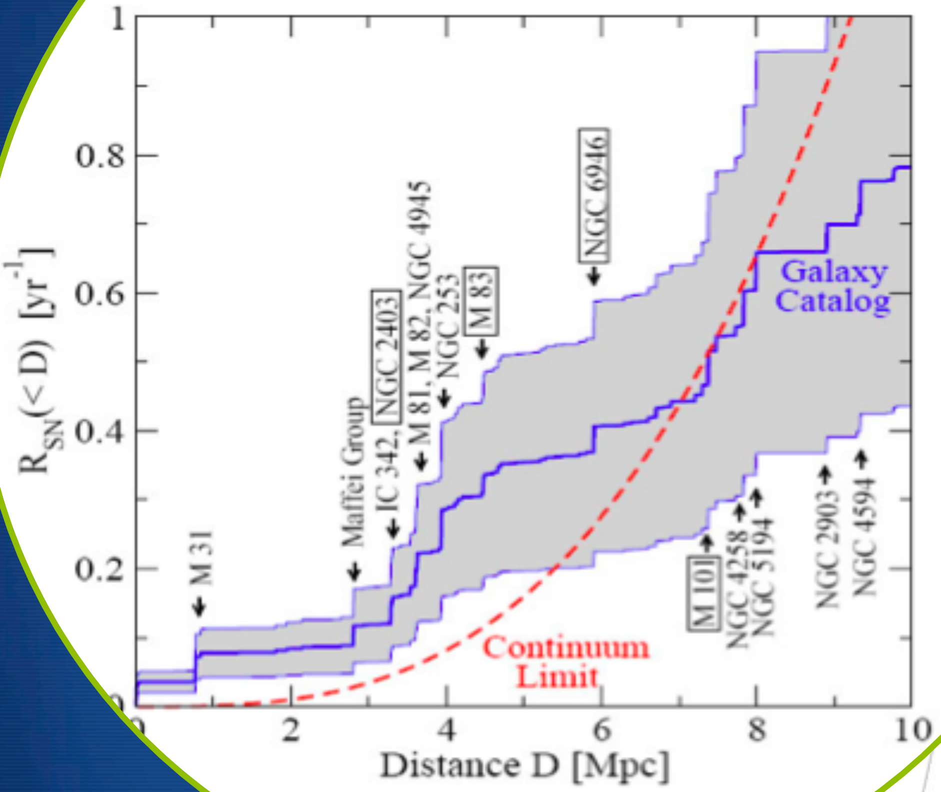
$$\delta T_{\mathrm{bounce}} = \sqrt{\delta T^2_{1\mathrm{st}} + \delta t^2_{\mathrm{GW}} + \delta t^2_{\mathrm{mass}} + \delta t^2_{\mathrm{fly}} + \delta t^2_{\mathrm{resp}}} \cong 7.2\mathrm{ms}$$

GP *et al.* **PRL 103, 031102 (2009)**

IceCube ±3.5 ms at 95% CL (SN at 10 kpc)

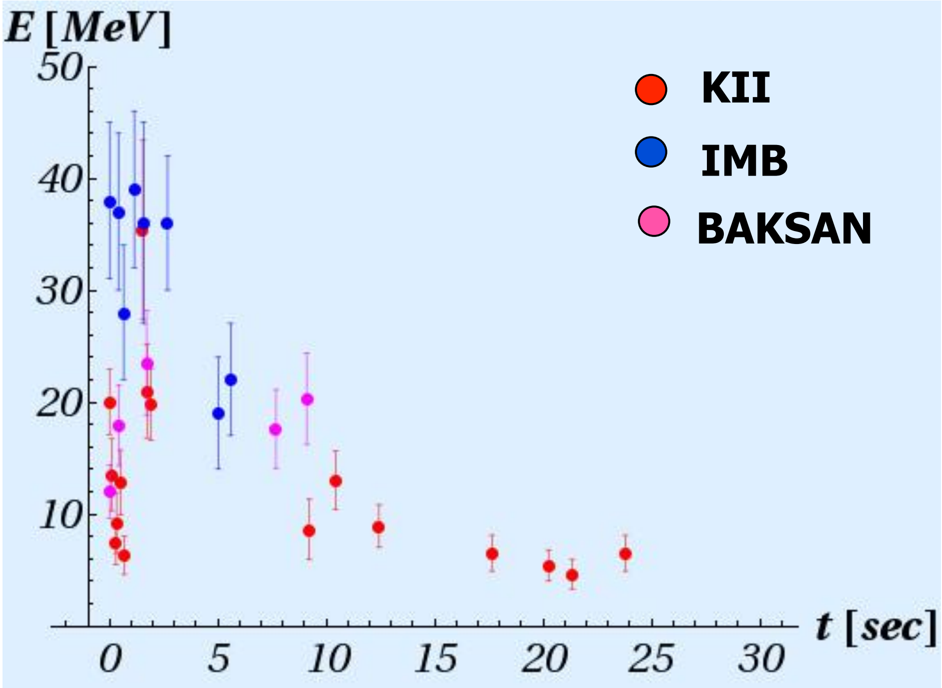
Estimates of Galactic and nearby CCSN rate

Ando, S. et al. 2005, PRL, 95, 171101



- Estimated Galactic rate is a few (~2) per century
- Estimated rate in Local Group (out to ~1 Mpc) ~twice the Galactic rate
- The uncertainties are large and the estimations are based on electromagnetic emission
- **GW and Neutrinos are not absorbed during propagation**

SN1987A data



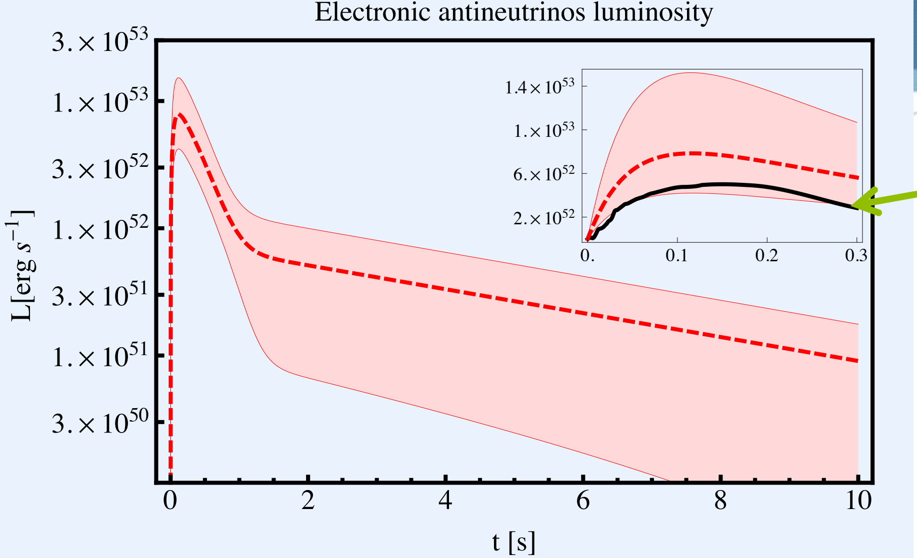
$$\boxed{N_{ev} = 29}$$

$$D = 50kpc$$

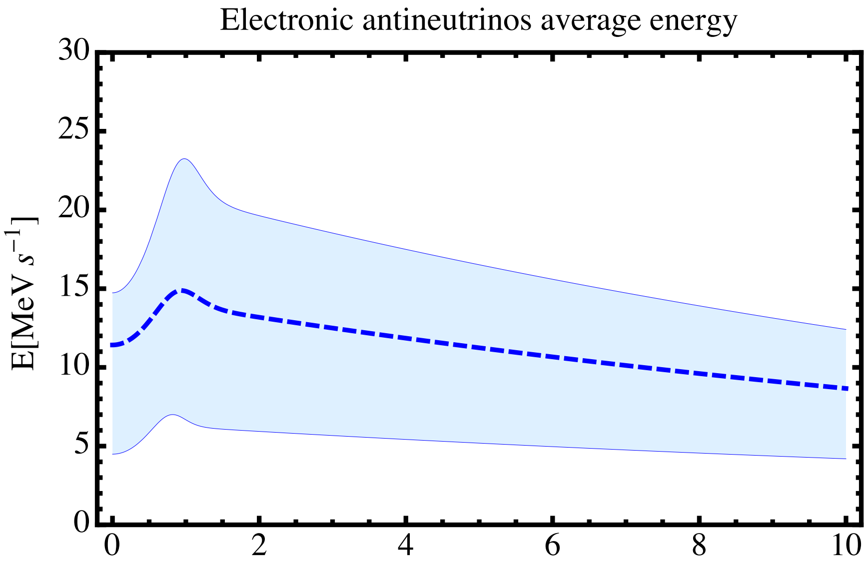
- Unbinned likelihood
- We adopt Normal Mass Hierarchy and Standard Neutrino Oscillations
- We take into account energy, time and direction of the events
- Efficiency and resolution of the three detectors

Evidence of the Accretion phase at 2.5 sigma

SN1987A vs Simulations


Electronic antineutrinos luminosity

Result from simulation
Mueller *et al.*
Astrophys.J.Suppl. 189 (2010) 104-133


Electronic antineutrinos average energy

Astroparticle Physics 31 (2009) 163–176

$M_a = 0.22^{+0.68}_{-0.15} M_\odot$

$R_C = 16^{+9}_{-5}\,\mathrm{km}$

$T_a = 2.4^{+0.6}_{-0.4}\,\mathrm{MeV}$

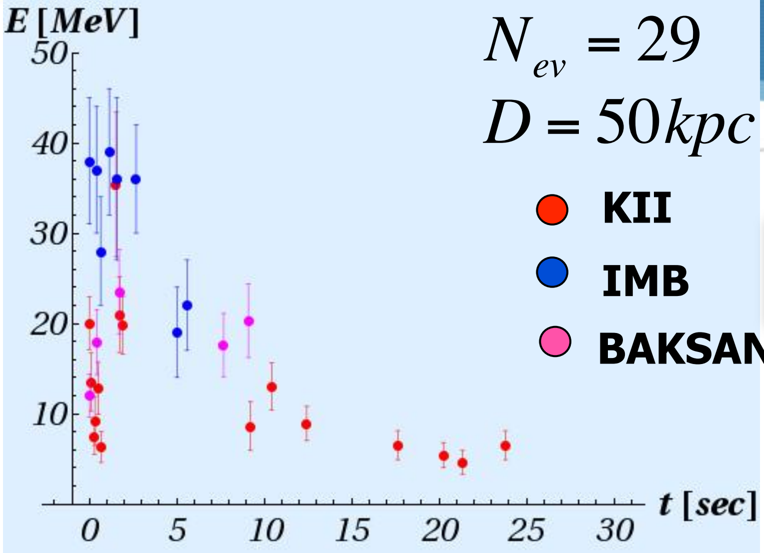
$T_C = 4.6^{+0.7}_{-0.6}\,\mathrm{MeV}$

$\tau_a = 0.55^{+0.58}_{-0.17}\,\mathrm{s}$

$\tau_C = 4.7^{+1.7}_{-1.2}\,\mathrm{s}$

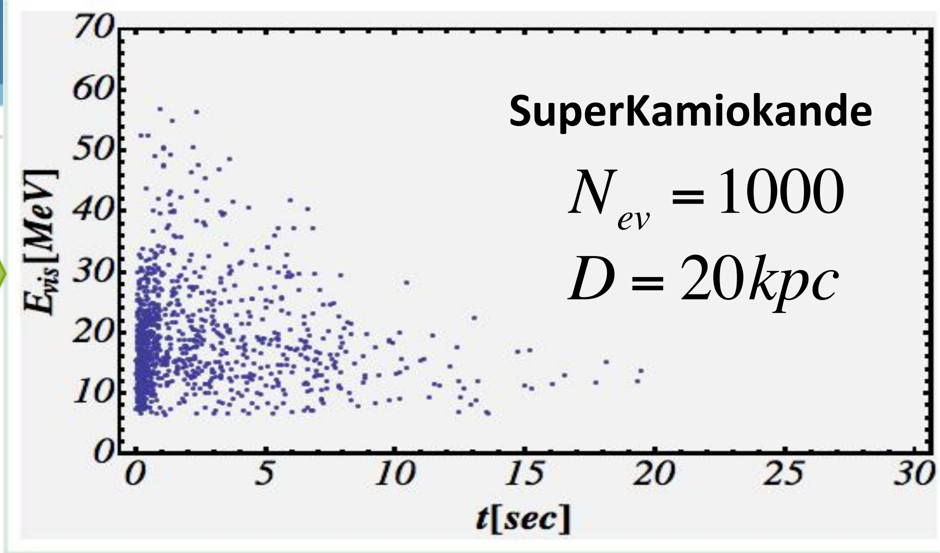
$E_b = 2.2\times10^{53}\,\mathrm{erg}$

SN1987A vs Future



$N_{ev} = 29$

$D = 50 kpc$



$N_{ev} = 1000$

$D = 20 kpc$

Yesterday

$$\delta R_c = 44\%$$
$$\delta T_c = 15\%$$
$$\delta \tau_c = 31\%$$
$$\delta M_a = 188\%$$
$$\delta T_a = 36\%$$
$$\delta \tau_a = 36\%$$

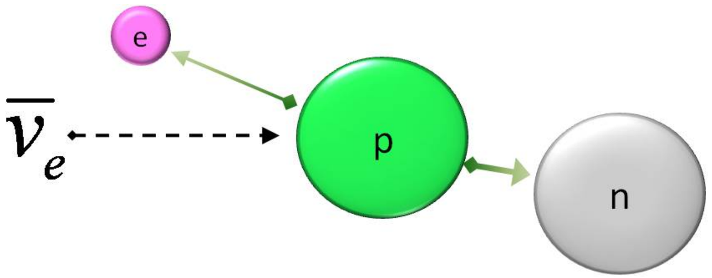
Tomorrow

$$\delta R_c = 7\%$$
$$\delta T_c = 2\%$$
$$\delta \tau_c = 2\%$$
$$\delta M_a = 27\%$$
$$\delta T_a = 3\%$$
$$\delta \tau_a = 7\%$$

GP *et al.* **PRL 103, 031102 (2009)**

Inverse Beta Decay (IBD)

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



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

$$N_{e\nu} = N_p \int_{E_{thr}}^{\infty} dE_{e^+} \sigma_{IBD}(E_\nu)\eta(E_{e^+})F_{\bar{\nu}_e}(E_\nu)G(E_\nu, E_{e^+})$$

$$\boxed{\sigma_{IBD}(E_\nu) \sim 9 \cdot 10^{-44} \cdot E_\nu^2 \ cm^2}$$

Number of protons for 1 kton of mass

$$N_p \approx 1\text{kton} \times \frac{10^9 g}{\text{kton}} \times \frac{6 \cdot 10^{23}}{g} \times \frac{2}{18} \approx 6 \cdot 10^{31}$$

5000 IBD events expected in SK=32 kton for a SN in the GC