Neutrino from stellar collapses

Borodikhina L.A.[1]
NRC "Kurchatov Institute", Moscow

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SN 1987A, Quark Phase Transition in Compact Objects

and Multimessenger Astronomy

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Introduction

Neutrinos produced during the stellar collapses are not affected by influence of the interstellar medium. Therefore they bring the imprints of processes that could taking place in such phenomena as Supernova Core Collapses or Gamma Ray Bursts.

This neutrino signal can give us a clue to understand origins and mechanisms of these processes. Since several modern neutrino detectors and gravitational waves detectors performed analysis to obtain neutrino signal from different sources:

- Neutrino from the Supernova Type II distance bursts;
- Neutrino produced during the Gamma Ray Bursts;
- Neutrino produced in the processes of binary Black Holes mergers;
- Diffuse Supernova Neutrino Background;

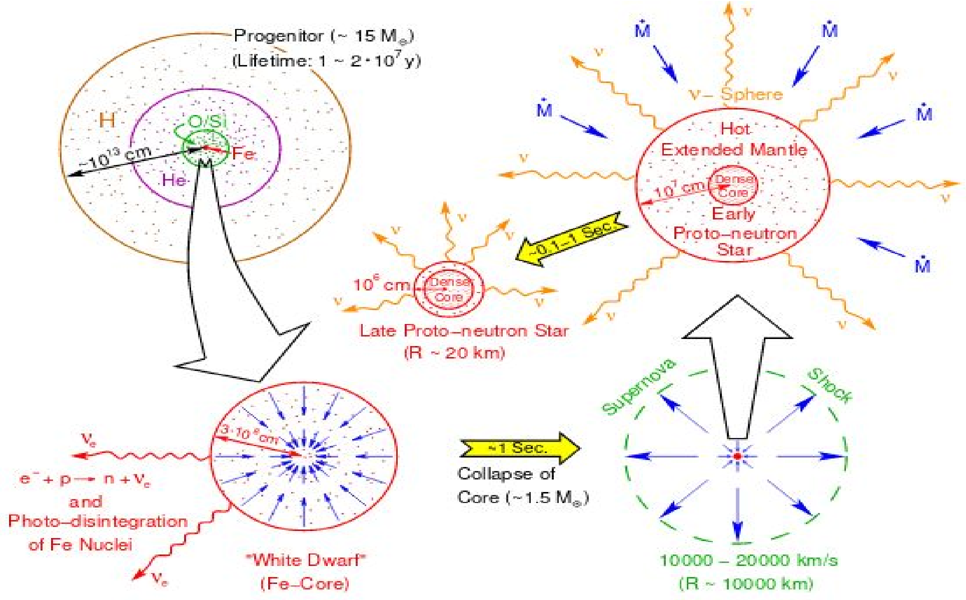
Supernova type II bursts

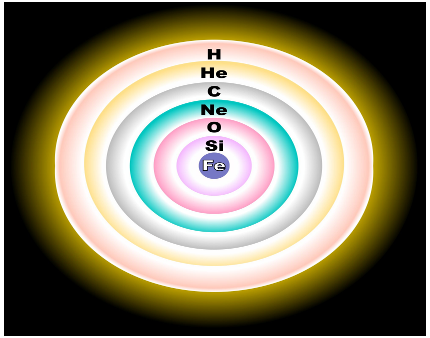
- The core of the star is surrounding of “onion” shells;
- The star becomes unstable when temperature inside is not enough to allow the photodissociation processes;

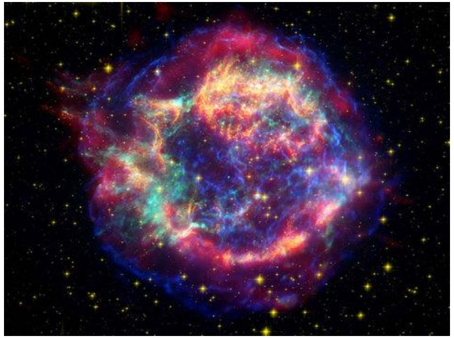
<u>**There are some steps of the SN core-collapse:**</u>

1. ***Stellar core-collapse;***
2. ***Core bounce and shock wave formation;***
3. ***Shock propagation and neutrino burst;***
4. ***Cooling of proto-neutron star;***

- The approximal burst duration: ~10 ms;
- Nuclear density: $\rho \sim 10^{14}$g cm^{-3};
- The standard neutrino luminosity: L~10^{53} erg (99% of binding energy is carried away by neutrinos);







Neutrino production and transport in Supernovae

1. Onset of stellar core collapse
   - neutrino stream freely;
   - the photon temperature becomes enough to dissociate the iron core;
2. Neutrino trapping
   - $\rho > \sim 10^{13}$g cm^{-3};
   - electron captures on the free protons;
   - neutrinos scatter on the heavy nuclei;
3. Core bounce and shock formation
4. Shock propagation and neutrino burst
5. Shock stagnation
6. Proto-neutron star cooling

$$
\begin{aligned}
e^- + (A,Z) &\longleftrightarrow (A,Z-1) + \nu_e \\
e^- + p &\longleftrightarrow n + \nu_e \\
e^+ + n &\longleftrightarrow p + \bar{\nu}_e
\end{aligned}
$$

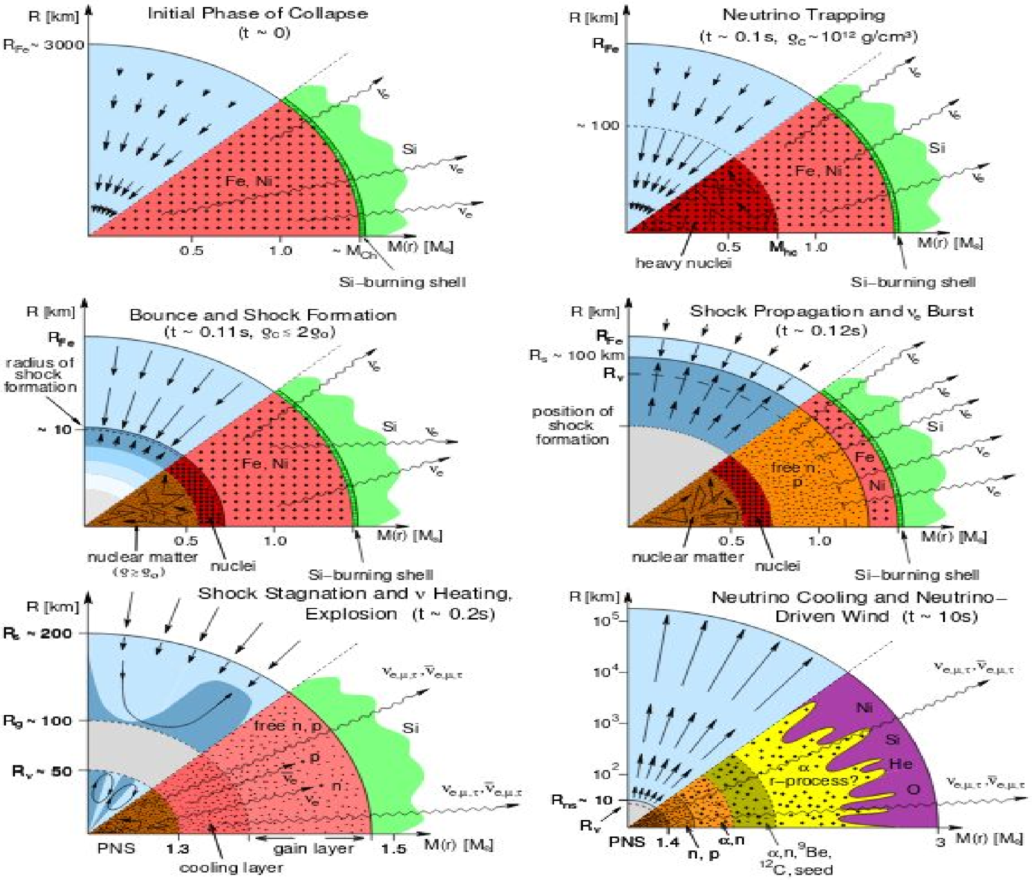
URCA processes

$$
\begin{aligned}
N + N &\longleftrightarrow N + N + \nu + \bar{\nu} \\
e^- + e^+ &\longleftrightarrow \nu + \bar{\nu} \\
\nu_e + \bar{\nu}_e &\longleftrightarrow \nu_x + \bar{\nu}_x \\
\nu_x + \{\nu_e, \bar{\nu}_e\} &\longleftrightarrow \nu_x + \{\nu_e, \bar{\nu}_e\}
\end{aligned}
$$

Thermal pair production and annihilation processes

$$
\begin{aligned}
\nu + (A,Z) &\longleftrightarrow \nu + (A,Z) \\
\nu + N &\longleftrightarrow \nu + N \\
\nu + e^{\pm} &\longleftrightarrow \nu + e^{\pm} \\
\nu + N &\longleftrightarrow \nu + N
\end{aligned}
$$

Neutrino scattering



H.-Th. Janka, Author version of chapter for 'Handbook of Supernovae', arXiv:1702.08713

Neutrino emission spectra

- Expected form of the neutrino spectra is quasi-thermal because of neutrino interactions with the stellar medium is energy dependent;
- The spectrum could be described by Fermi-Dirac distribution;
- Alpha is a pinched factor:
  - $\langle E^2\rangle/\langle E\rangle^2 = (2+\alpha)/(1+\alpha)$;
  - $\alpha \approx 2.3 \rightarrow \eta=0$ (for Fermi-Dirac dist.)
  - $\alpha = 2 \rightarrow$ Maxwell-Boltzmann dist.
  - $\alpha \geq 2.3 \rightarrow$ narrower spectra than F.-D.
- α = 6-7: for electron neutrino burts;
- α = 2-3: for all neutrino types >200 ms after CC;

$$f_\alpha(E) \propto \left(\frac{E}{\langle E\rangle}\right)^\alpha e^{-(\alpha+1)E/\langle E\rangle}$$

Keil MT, Raffelt GG, Janka HT (2003) , Astrophys J 590:971–991, DOI 10.1086/375130

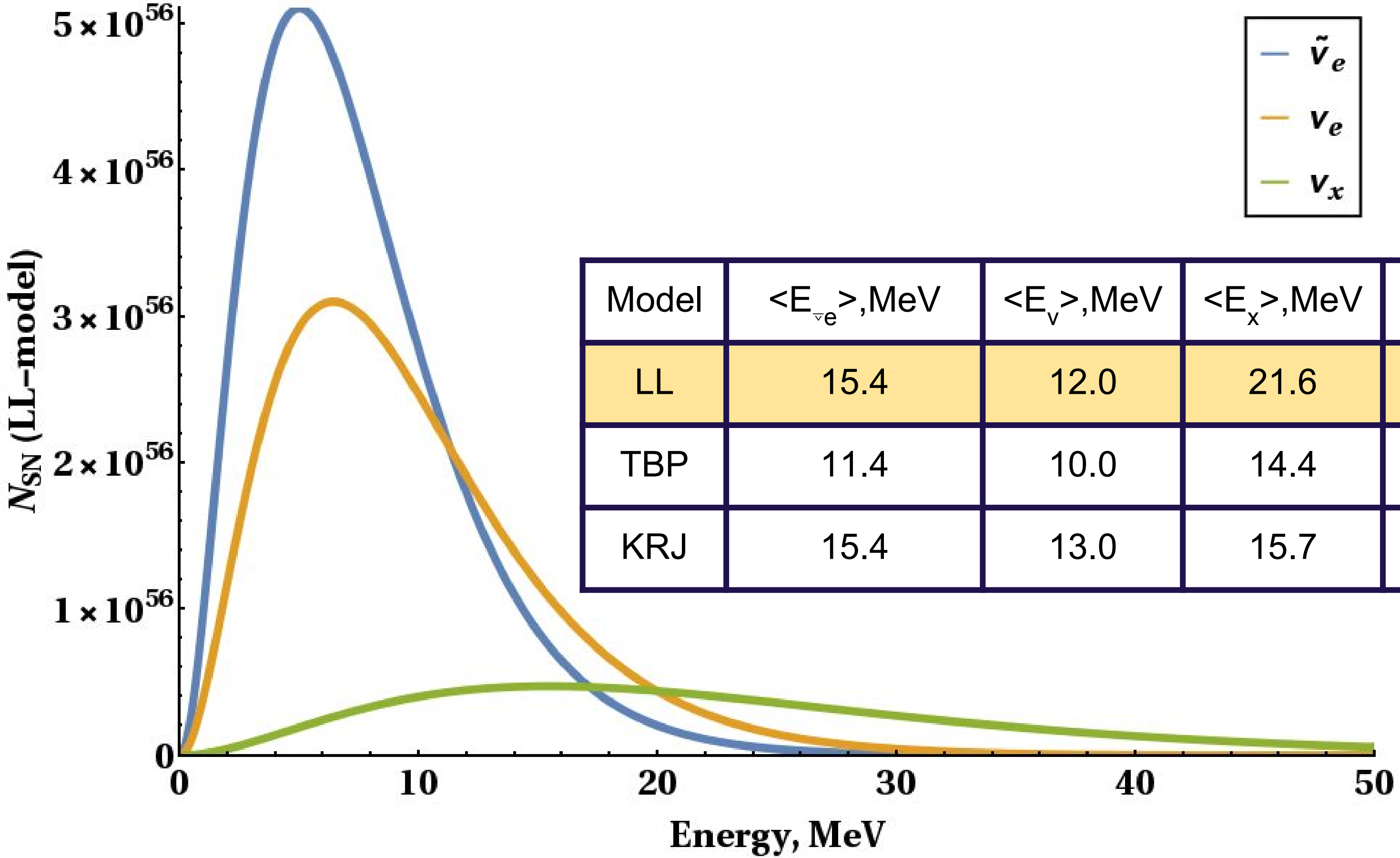
$$\langle E\rangle = \frac{\int_0^\infty \mathrm{d}E\, E\, f_\alpha(E)}{\int_0^\infty \mathrm{d}E\, f_\alpha(E)}$$

- There is no an unique model that describes the mechanism of the Supernovae Core Collapse;
- The hydrodynamic of the surrounding and internal medium the forming neutron star has high effect on the Supernova Collapse;
- Due 3d simulation is not so easy there are some models based the SN1987A data analysis:
  - *G. Pagliaroli, F. Vissani, M.L. Costantini, A. Ianni "Improved analysis of SN1987A antineutrino events", 2009;*

and 1-D calculations:

  - **Lawrence-Livermore model** *(T. Totani, K. Sato, H.E. Dalhed, J.R. Wilson "Future Detection of Supernova Neutrino Burst and Explosion* Mechanism";
  - **TBP model**(*Thompson, T. A., A. Burrows, and P. A. Pinto, 2003, Astrophys. J. 592, 434*);

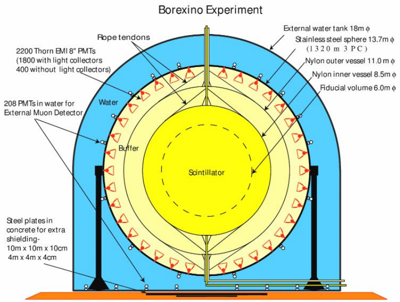
Neutrino emission spectra

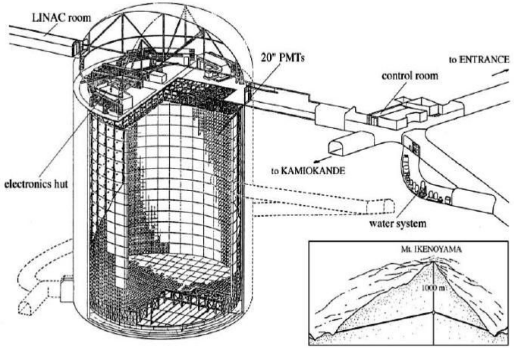


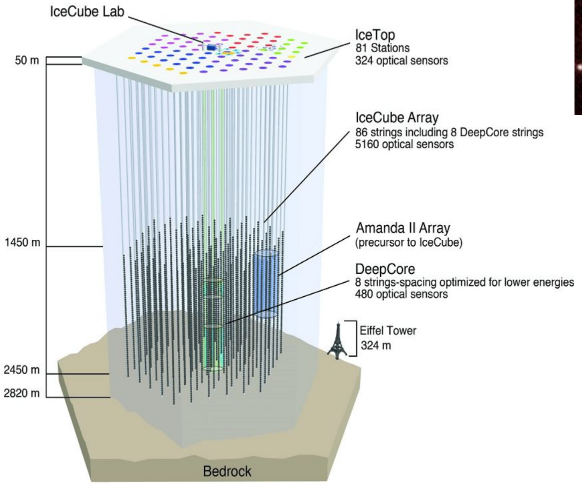
Model	$\langle E_{\bar{\nu}_e}\rangle$,MeV	$\langle E_{\nu}\rangle$,MeV	$\langle E_{x}\rangle$,MeV	α_e	α_x
LL	15.4	12.0	21.6	3.8	1.8
TBP	11.4	10.0	14.4	3.7	2.2
KRJ	15.4	13.0	15.7	4.2	2.5

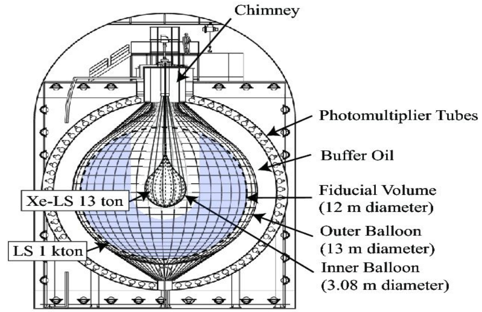
Detection neutrino from the SuperNovae type II

- High volume detectors are required;
- Nearby Supernova II-type (distance from SN1987A≈50 kPc);
- Signal from SN1987A was detected by several detectors:
  - BNO;
  - IMB;
  - Kamiokande-II;
  - LSD;
- **SNEWS system:**
  - *http://snews.bnl.gov/news.html*
  - *Borexino, IceCUBE, Super-Kamiokande, KamLAND, HALO, LVD, Daya-Bay;*
  - searches of the SuperNovae using signal from the several neutrino detectors;
  - triangulation of SN position using time stamp of several detectors;









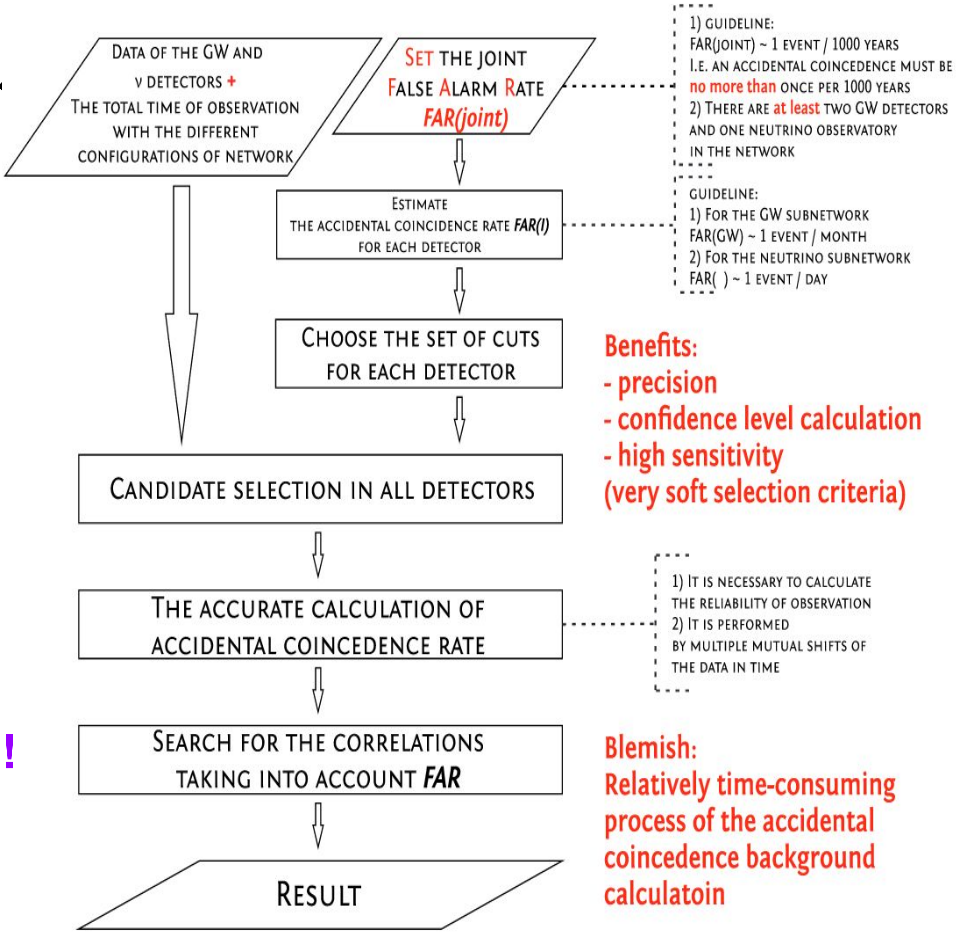
GWNU

- The essence of this method is the simultaneous dat… analysis from neutrino and gravitational waves detectors;
- This method provides:
  - detection signal from the individual distant supernovae;
  - detection signal from the “dark” supernovae;
- Neutrino and gravitational wave signals are not distorted by interstellar medium;
- High statistics;
- Complementarity of two detection methods;

The GWNU group consists of detectors such as:

- LIGO;
- LVD;
- Borexino;
- KamLAND;
- IceCUBE;

Work in progress!



Simultaneous data analysis

- **KamLAND**
  - *Gando et al., Astrophys J. Lett., 829, L34 (2016)*
  - Energy region:[1.8,111] MeV;
  - Signal from electron antineutrinos through the Inverse Beta Decay channel;
  - Time window: ± 500 sec;
  - Identification with GW events:GW150914, GW151226, the candidate event LVT151012;
  - Limit on the antineutrino flux (GW150914 and LVT151012): $3.1x10^{9}$ cm^{-2} ;
  - Limit on the antineutrino flux (GW151226): $3.6x10^{9}$ cm^{-2} ;
- **Super-Kamiokande**
  - *Abe et al., Astrophys. J., 830, L11 (2016)*
  - Energy region:[3.5 MeV,100 PeV];
  - Signal from electron neutrinos through the scattering of electrons channel;
  - Time window: ± 500 sec;
  - Identification with GW events: ;
  - Limit on the neutrino flux in energy range [3.5-75] MeV: $1.2x10^{9}$ $cm^{-2}sec^{-1}$;
  - Limit on the neutrino fluence for Fermi-Dirac spectrum with T=4 MeV: $3.6x10^{9}$ cm^{-2} ;
- **Borexino**
  - *Bellini et al., (2017)*
  - Energy region:[0.4 , 15 Mev];
  - Signal from all neutrino types through the scattering of electrons channel;
  - Signal from electron antineutrinos through the Inverse Beta Decay channel;
  - Time window: ± 500 sec;
  - Identification with GW events:GW150914, GW151226, GW170104 ;
  - Limit on the electron neutrino fluence for Fermi-Dirac spectrum with T=4 MeV: $0.36x10^{12}$ cm^{-2} ;
  - Limit on the neutrino flux in energy range [0.5-15] MeV: $2.3x10^{10}$ $cm^{-2}sec^{-1}$;

Significant correlation between Gravitational Wave and neutrino events was not found

DSNB

- **Diffuse Supernova Neutrino Background (DSNB)** is the flux of neutrinos and antineutrinos from SN bursts, which occurred through the Universe history;
- Astrophysical inputs:
  - Individual neutrino emission spectra from the Supernova;
  - Rate of Supernova;
- *"DSNB will be a complementary tool for the study and possible discrimination of cosmological models", J. Barranco, Argelia Bernal, D. Delepine, arXiv:1706.03834v1*
- DSNB neutrino could provide us information about SN interior, star formation and SuperNova rates;
- Expected flux on the Earth: $\sim 10^0 cm^{-2} sec^{-1}$;

- SNO:
  - $Flux_\nu < 70\ cm^{-2} sec^{-1}$
  - for [22.9,36.9] MeV;
  - *B. Aharmim, et al,strophys. J. 653 (2006) ;*
- KamLAND:
  - $Flux_{\bar{\nu}_e} < 139 cm^{-2} sec^{-1}$
  - for energy range: [8.2,31.8] MeV;
  - *A. Gando, et al., Astrophys. J. 745 (2012) 193;*
- Super-Kamiokande:
  - **$Flux_{\bar{\nu}_e} < 39\text{-}54\ cm^{-2} sec^{-1}$**
  - for energy range: [22.9,36.9] MeV;
  - *C. Lunardini, O. L. G. Peres, JCAP 0808 (2008) 033;*
  - **$Flux_{\nu_e} < 99\text{-}148\ cm^{-2} sec^{-1}$**
  - for energy range: [13.3,31.8] MeV;
  - *H. Zhang, et al,A stropart. Phys. 60 (2015) 41-46;*
- Borexino detector has possibility to obtain upper limit for DSNB in low energy area;

The larger detectors are necessary!

Neutrinos from type Ia Supernovae

- SNe Ia are indicators of the Universe accelerating;
- The major distribution into galaxy's chemical evolution;
- Popular models of the bursts (*W. Hillebrandt,arXiv:1302.6420*):
  - Single degenerate scenario (SD):
    - Hydrogen donors;
    - Helium donor;
    - Gravitationally Confined Detonation;
  - Double detonation
  - Double degenerate mergers;
- Gravitationally Confined Detonation:
- *T. Plewa et al., ApJ 612, L37–L40 (2004)*
  - Explosion starts with off-center deflagration ignition;
  - The ash starts expands to the surface creating "plume";
  - The convergence of the ash leads to ignition of detonation;
- The SN Ia rate: 1.4 per century;
- Most probable distance: 9 kpc; *(S. M. Adams et al., ApJ778, 164 (2013))*

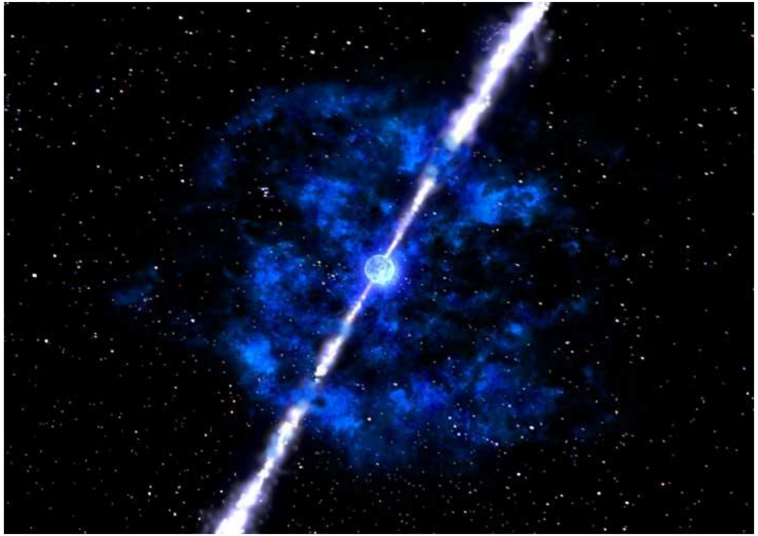
- The signal is expected four orders less than in SN Core-Collapse case;
- The mean energies of neutrinos are expected ~ in 3 MeV range;

Detector	**NMO**	**IMO**	**Non**
Hyper-Kamiokande	**0.0267**	**0.0478**	**0.0997**
DUNE	**0.0015**	**0.0033**	**0.0069**
JUNO	**0.0010**	**0.0018**	**0.0037**
IceCube	**0.0208**	**0.0325**	**0.0689**

Warren P. Wright, James P. Kneller, Sebastian T. Ohlmann, Friedrich K. Roepke, Kate Scholberg, Ivo R. Seitenzahl, Phys. Rev. D 95, 043006 (2017)

Gamma Ray Bursts (GRB)

- Gamma Ray Bursts --- are the most luminous and intense spontaneous explosions of the gamma-rays in the Universe;
- Gamma Ray Bursts are distributed isotropically;
- The origins of the GRB still be misunderstood;
- There are at least two types of the GRB's (based on the their duration):
    - **long** GRB's (duration is **more than 2 seconds**), possible origin is collapses of the massive stars;
    - **short** GRB's (duration is **less than 2 seconds**), possible origins are: mergers of binary neutron stars or neutron star and black hole merge;
- The estimated energy of the GRB: 10^{49}-10^{52} erg;
- Jet angle: 2-10 degrees;
- **The Fireball model** is a widely used model of the GRB jets origin;

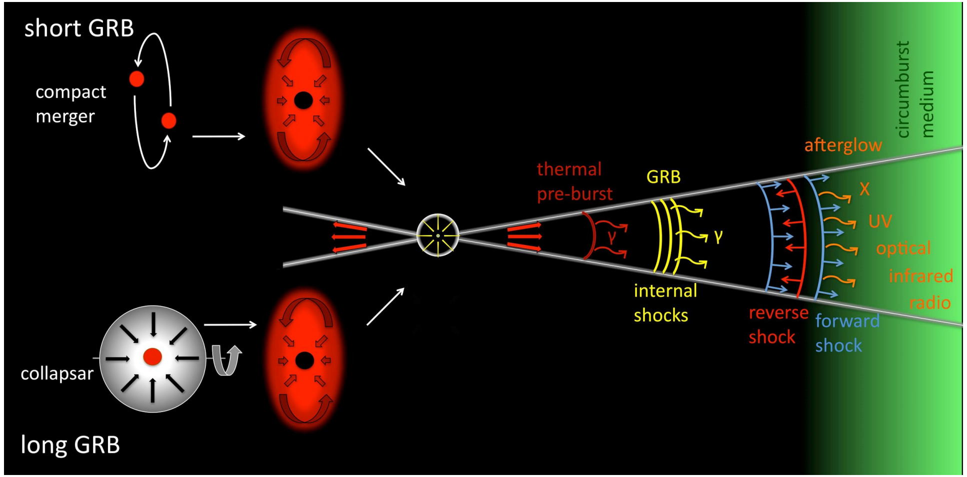


The history of the GRB research:

- **1967** the first observation of the GRB by Vela satellite;
- **1991** Compton Gamma-Ray observatory, BATSE;
- **1997** BeppoSAX satellite;
- **2004** Swift satellite;
- **2008** GLAST satellite;
- Fermi sattelite;

Fireball model of the GRB and neutrino production

- Stellar collapse (or merging of two compact objects) leads to releases a large amount of energy in a small region, about 10-100 km in size (fireball);
- Fireball consists of electron-positron pairs, photons and baryons (protons and neutrons);
- The electron-positron pairs and photons are in the thermal balance inside the fireball, so it is opaque for them;
- Fireball expands transforming thermal energy to the kinetic energy;
- Internal shock forms due to catching up the more faster plasma shells by more slowly;
- The forming of the external shocks;



Searches neutrino from GRB were performed by several detectors:

1. **Antares;**
2. **Baikal Neutrino Telescope;**
3. **Baksan Neutrino Telescope;**
4. **IceCube;**
5. **SNO;**
6. **Super-Kamiokande(best limit in the high energy area);**
7. **KamLAND;**
8. **Borexino (best limit in the low energy area)**

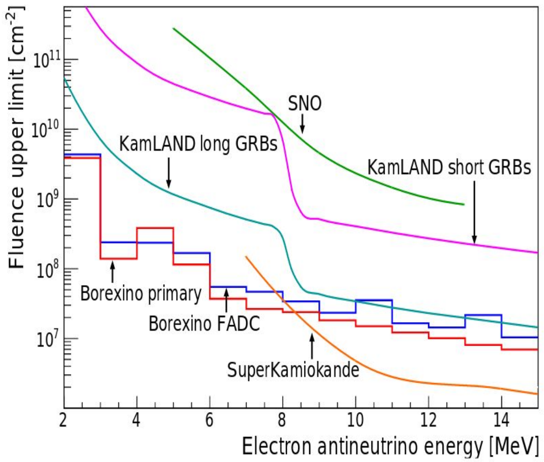
The neutrino production processes:

$$p\gamma \rightarrow \Delta^+$$

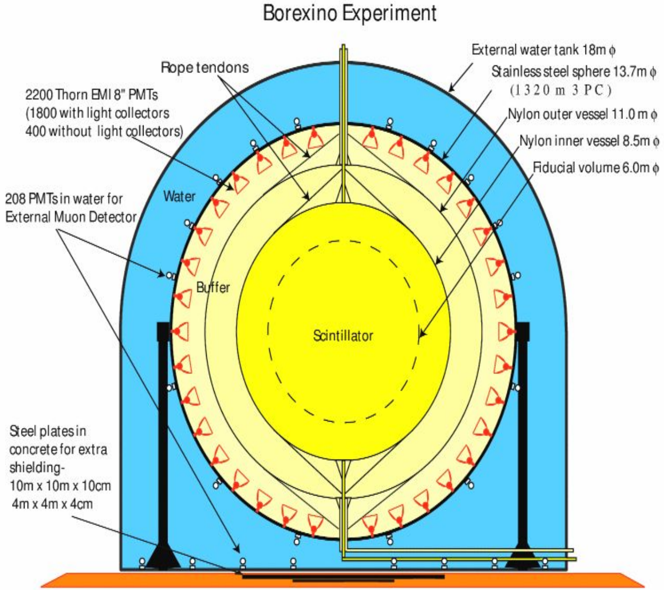
$$\Delta^+ \rightarrow n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow \overbrace{ne^+\nu_e\bar{\nu}_\mu\nu_\mu}^{\text{UHE neutrinos}}$$

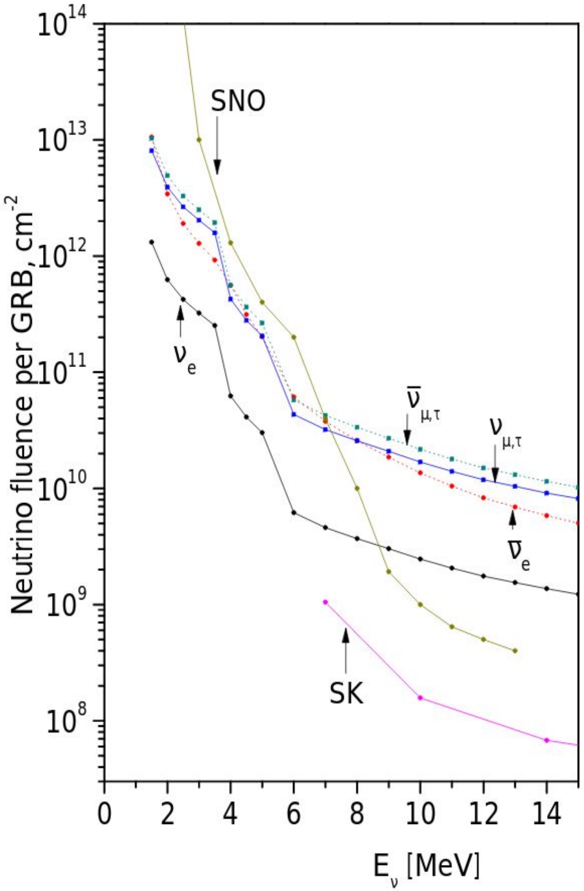
$$\left.\begin{array}{l} e^+e^- \rightarrow \nu\bar{\nu} \\ p+e^- \rightarrow n+\nu_e; \\ NN \rightarrow NN\nu\bar{\nu} \end{array}\right\} \text{MeV neutrinos}$$

Most Recent Search for MeV neutrinos from Gamma Ray Bursts



doi:10.1016/j.astropartphys.2016.10.004





- Data taking period: December 2007 - November 2015;
- Livetime: 1279 days;
- Number of used GRB: 980;
- Neutrino signal was searched trough the several reactions:
  - IBD;
  - Neutrino scattering on the electrons;

Conclusion

The modern detectors sensitivity is not enough to detect neutrino fluxes from the rare sources like as Supernovae type Ia or Distant Supernovae: it is needed more statistics and higher volumes of the neutrino detectors to obtain any significant signal .But it seems that neutrino detectors of new generation will reach it.

Also simultaneous analysis based on the common data from network of the neutrino and gravitational waves detectors could also provide obtaining the signal from the neutrino produced inside star collapses.