Supernova Neutrinos with the JUNO Experiment

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Jiangmen Underground Neutrino Observatory

The JUNO project was approved by Chinese Academy of Sciences in Feb 2013, and is planned to start data taking in 2020.

- 700m underground
- 20 kt LS detector
- Energy resolution $3\% / \sqrt{E/\text{MeV}}$
- Multiple-purpose experiment
  - Reactor neutrinos for mass hierarchy and precise measurement of neutrino parameters
  - Supernova neutrinos
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geo-neutrinos
  - Other searches: sterile neutrinos, nucleon decay and dark matter et al.

Location of the JUNO experiment

- JUNO
- Guang Zhou
- Shen Zhen
- Jiangmen
- Zhongshan
- Zhuhai
- Huizhou
- Lufeng NPP
- Daya Bay NPP
- 17.4GW
- 17.4GW
- 17.4GW
- 17.4GW
- 18.4GW
- Taishan NPP
- Yangjiang NPP
- 53 km

~700m underground facility
Groundbreaking on Jan 10, 2015
Core-collapse SN explosion

Main-sequence star  Helium-burning star

1. >8 Solar Masses
2. Collapse → Bounce
3. Shock wave halted
4. $\nu$ energy deposited
5. Final SN explosion

Degenerate iron core:
$\rho \approx 10^9 \text{ g cm}^{-3}$
$T \approx 10^{10} \text{ K}$
$M_{\text{Fe}} \approx 1.5 \text{ M}_{\text{sun}}$
$R_{\text{Fe}} \approx 8000 \text{ km}$

Grav. binding energy $E_b \approx 3 \times 10^{53} \text{ erg}$
99% Neutrinos
1% Kinetic energy of explosion
(1% of this into cosmic rays)
0.01% Photons, outshine host galaxy

Proto-Neutron star:
$\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$
$T \approx 30 \text{ MeV}$
Detection of SN neutrinos in JUNO

Detection of $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ from a typical SN@10kpc

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Events for different $\langle E_\nu \rangle$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>CC</td>
<td>$4.3 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + p \rightarrow \nu + p$</td>
<td>NC</td>
<td>$0.6 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + e \rightarrow \nu + e$</td>
<td>ES</td>
<td>$3.6 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + ^{12}\text{C} \rightarrow \nu + ^{12}\text{C}^*$</td>
<td>NC</td>
<td>$1.7 \times 10^2$</td>
</tr>
<tr>
<td>$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}$</td>
<td>CC</td>
<td>$0.5 \times 10^2$</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{12}\text{C} \rightarrow e^+ + ^{12}\text{B}$</td>
<td>CC</td>
<td>$0.6 \times 10^2$</td>
</tr>
</tbody>
</table>


- Real-time measurement of three-phase (burst, accretion, cooling) $\nu$ signals
- Distinguish between different flavor $\nu$
- Reconstruct $\nu$ average energy and luminosity
- Background almost free since a SN neutrino burst lasts only for about 10s.
Detection of SN neutrinos in JUNO

Time information of SN neutrinos of three phases w/ or w/o flavor conversions

For SN@10kpc
It’s assumed that the detection energy threshold is 0.2MeV.

Measured energy spectra of SN neutrinos in LS:
- IBD channel dominates at high energy range
- nu-p ES channel dominates at low energy range
- coincidence signals && single signals
- nu-e vs nu-p ES: Pulse Shape Discrimination (PSD)

The $\bar{\nu}_e$ spectrum

$\bar{\nu}_e + ^{12}C \rightarrow e^+ + ^{12}B$
$\nu_e + ^{12}C \rightarrow e^- + ^{12}N$

- Coincidence with decayed $^{12}B$ or $^{12}N$
- $\sim 100$ events

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

- Prompt signal from annihilation of the positron, delayed signal from the neutron capture: Least background
- $\sim 5000$ events, golden channel for SN neutrino observation
- Good reconstruction of energy

Neutrino fluence from SN@10kpc: w/o oscillation

$$F_\alpha^0(E) = \frac{1}{4\pi r^2} \frac{E_{\nu_{\alpha}}^{\text{tot}}}{\Gamma(1+\gamma_\alpha)} \left( \frac{E}{\langle E_{\nu_{\alpha}} \rangle} \right)^{\gamma_\alpha} \exp \left[ -\left(1 + \gamma_\alpha \right) \frac{E}{\langle E_{\nu_{\alpha}} \rangle} \right]$$

$$E_{\nu_{\alpha}}^{\text{tot}} = E_{\bar{\nu}_{\alpha}}^{\text{tot}} = 5 \times 10^{52} \text{ erg}$$

$$\langle E_{\nu_{\alpha}} \rangle = 12 \text{ MeV}, \langle E_{\bar{\nu}_{\alpha}} \rangle = 14 \text{ MeV}, \langle E_{\nu_{\alpha}} \rangle = 16 \text{ MeV}$$
**The $\nu_e$ spectrum**

\[ \nu + e^- \rightarrow \nu + e^- \quad \text{e ES} \]

- Recoiled electron
- PSD to separate $\nu$-e vs $\nu$-p ES
- \~300 events

\[ \nu_e + ^{13}C \rightarrow e^- + ^{13}N \quad \text{^{13}N CC} \]

- Hard to be distinguished from $\nu$-e ES channel, so combined them together

Background events from un-tagged positrons of IBD in-efficiency samples

\[ F_\alpha^0(E) = \frac{1}{4\pi r^2} \frac{E_\alpha^{\text{tot}} (1 + \gamma_\alpha)^{1+\gamma_\alpha}}{\Gamma(1 + \gamma_\alpha)} \left( \frac{E}{E_\alpha} \right)^{\gamma_\alpha} \text{exp} \left[ -(1 + \gamma_\alpha) \frac{E}{E_\alpha} \right] \]

J.S Lu et al. Phys. Rev. D 94, 023006

Global fit precision 10% for average energy
The $\nu_x$ spectrum

$\nu + ^{12}C \rightarrow \nu + ^{12}C^*$ [12 C NC]

15.11 MeV $\gamma$

$\nu + ^{13}C \rightarrow \nu + ^{13}C^*$ [13 C NC]

3.685 MeV or 7.547 MeV $\gamma$

$\nu + p \rightarrow \nu + p$ [p ES]

- Quenched proton
- ~2000 events, ~1500 events above 0.2MeV energy threshold

$F(\alpha)(E) = \frac{1}{4\pi^2} \frac{E^{\text{tot}}}{\langle E_{\alpha} \rangle} \frac{(1 + \gamma_{\alpha})^{1+\gamma_{\alpha}}}{\Gamma(1 + \gamma_{\alpha})} \left( \frac{E}{\langle E_{\alpha} \rangle} \right)^{\gamma_{\alpha}} \exp \left[ - (1 + \gamma_{\alpha}) \frac{E}{\langle E_{\alpha} \rangle} \right]$

Global fit precision 5% for average energy

J.S Lu et al. Phys. Rev. D 94, 023006
Reconstruction of SN neutrino spectra in JUNO

Response matrix for nu-p ES

\[ Ax = b \Rightarrow x = A^{-1} b \]

SVD unfolding method in RooUnfold to transform measured energy spectra to true spectra weighted by cross section. And it is independent of SN neutrino models.

RooUnfold
arXiv:1105.1160

H.L Li et al, to appear

SN@10kpc

SN@1kpc

SN@0.2kpc

Ignoring the differences between cross sections of \( \nu_x e \) and \( \bar{\nu}_x e \), the structures of different flavor neutrinos can be achieved by simple bin-by-bin separation. The nearer SN is, the better separation can be.

One trial result
Betelgeuse
SNν detection: present and future experiments

- LVD (400)
- Borexino (100)
- Baksan (100)
- Super-Kamiokande (10⁴)
- Hyper-Kamiokande (10⁵)
- DUNE (3000)
- MiniBooNE (200)
- HALO (20)
- JUNO (10⁴)
- Daya Bay (100)
- IceCube (10⁶)

SN @ 10 kpc
Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapse/sec in the visible universe
- Emitted $\nu$ energy density
  - ~extra galactic background light
  - ~10% of CMB density
- Detectable $\bar{\nu}_e$ flux at earth $\sim 10 \, cm^{-2} \, s^{-1}$
  - mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & balck-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances

Beacom & Vagins,
PRL 93:171101,2004
Diffuse Supernova Neutrino Background (DSNB)

Parametric DSNB flux spectrum:

\[ \frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0} \int_0^{z_{\text{max}}} dz \frac{R_{\text{SN}}(z)}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}} \]

redshift-dependent co-moving SN rate

Cosmological evolution

total number spectrum of $\bar{\nu}_e$ from an average core collapse

- Observational window: 11MeV $< E_\nu < 30$MeV
- PSD techniques for NC atmospheric $\nu$
- Fast Neutrons: $r < 16.8$m (equiv. 17kt mass)

Summary and outlook

- For a typical SN@10kpc, $10^4$ neutrino events can be registered in JUNO. The time evolution, energy spectra and flavor contents of SN neutrinos can be established.

- LS, WC, LAr and other neutrino detectors are complementary. Many interesting questions such as the early warning of SNe(SNEWS), the SN location, SN nucleosynthesis, absolute neutrino masses and the neutrino mass ordering can be revised or addressed.

- JUNO with 20kt LS detector is also promising in the DSNB detection.
Thank you!
Backup
JUNO schedule

- 2013 Funding approved
- 2014 Collaboration officially formed
- 2014-2018 Civil construction
- 2016-2019 Detector component and PMT production
- 2018-2019 Detector assembly & installation
- 2020 Liquid scintillator filling
- 2020 Start of data taking
Neutrino mass hierarchy measurement

Reactor $\bar{\nu}_e$ survival probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^2 \theta_{13} \sin^2 \frac{\Delta m_{21}^2 L}{4 E} - \sin^2 2\theta_{13} \cos^2 \theta_{12} \sin^2 \frac{\Delta m_{31}^2 L}{4 E} - \sin^2 2\theta_{13} \sin^2 \theta_{12} \sin^2 \frac{\Delta m_{32}^2 L}{4 E}$$

$\Delta m_{21}^2 = m_2^2 - m_1^2 \quad \Delta m_{31}^2 \approx \Delta m_{32}^2 = m_3^2 - m_2^2$

$\Delta m_{21}^2 \approx \Delta m_{32}^2 \approx 3 \text{ MeV}^2$

$\sigma_{\bar{\nu}_e p} = 6 \text{ years data taking via IBD channel in JUNO.}$

$\sim 3 \sigma$ MH sensitivity can be achieved with 6 years data taking via IBD channel in JUNO.
Data acquisition for SN neutrinos

JUNO can work for a typical SN at the most probable distance 10kpc and also 0.2kpc.

The shaded range has been obtained by considering a class of SN models the Besel, Garching and Nakazato groups.
Test hypothesis of energy equipartition

J.S Lu et al. Phys. Rev. D 94, 023006

MSW matter effects in supernova are considered. Neutrino energy ratios are constrained.
Neutrino mass bound

Time delay of massive neutrinos: \[ \Delta t(m_\nu, E_\nu) = 5.14 \text{ ms} \frac{D}{10 \text{ kpc}} \left( \frac{m_\nu}{eV} \right)^2 \left( \frac{10 \text{ MeV}}{E_\nu} \right)^2 \]

J.S. Lu et al., JCAP 15’, 1412.7418

Use likelihood to test the mass zero hypothesis to estimate the mass bound.

![Graph showing 3000 simulations and comparing numerical models with a parameterized model.](image)