Supernova Neutrinos with the JUNO Experiment

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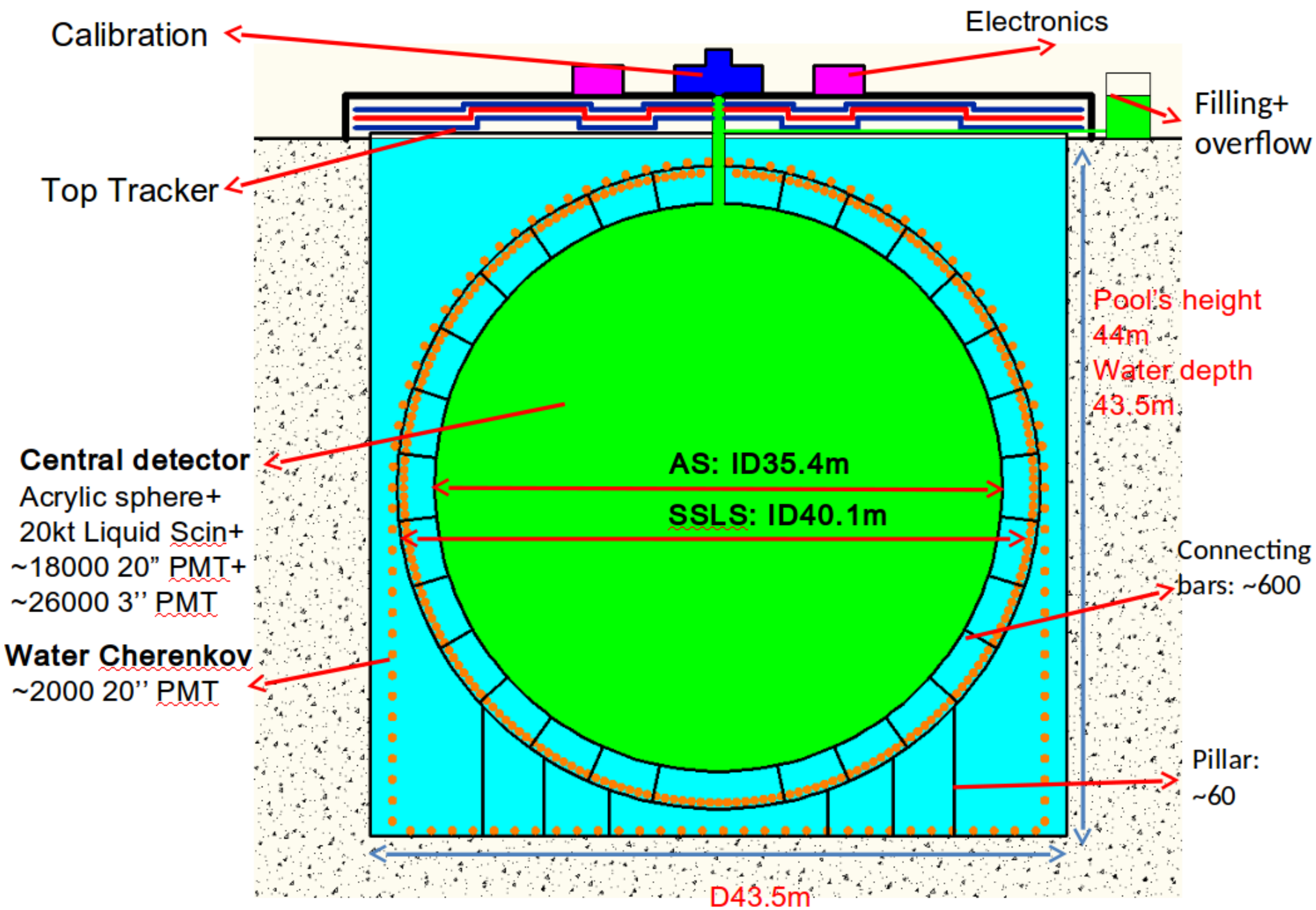
Jiangmen Underground Neutrino Observatory

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

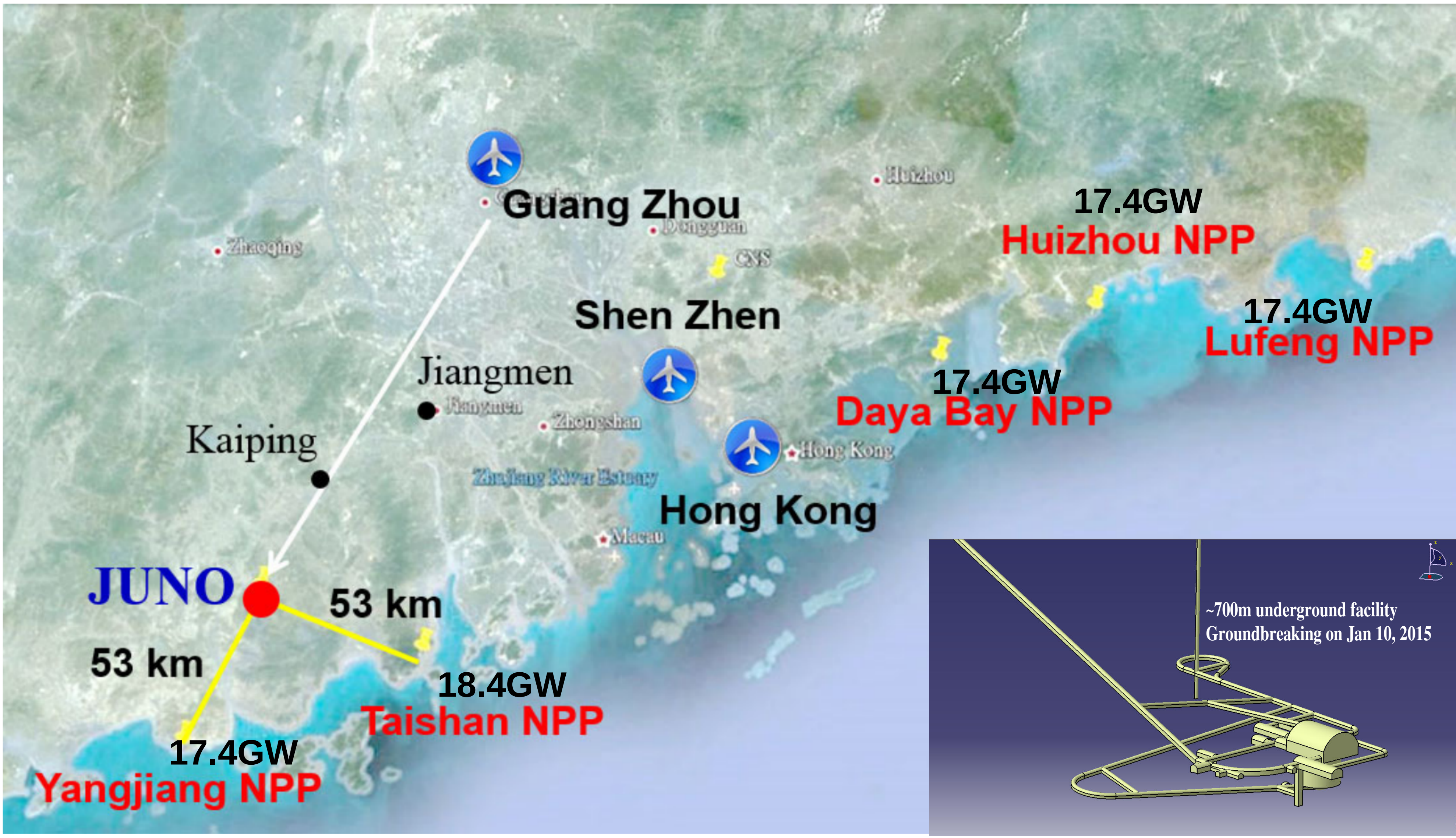


AS: Acrylic sphere; SSLS: stainless steel latticed shell

- 700m underground
- 20 kt LS detector
- Energy resolution $3\%/\sqrt{E/MeV}$
- 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.

F.P. An et al, J. Phys. G 43 (2016) 030401

Location of the JUNO experiment

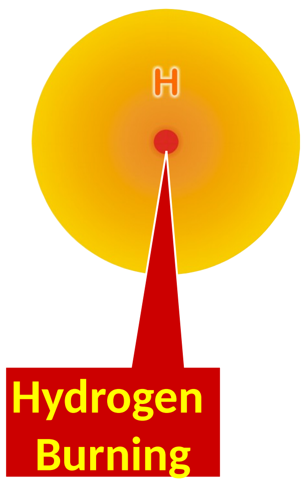


Core-collapse SN explosion

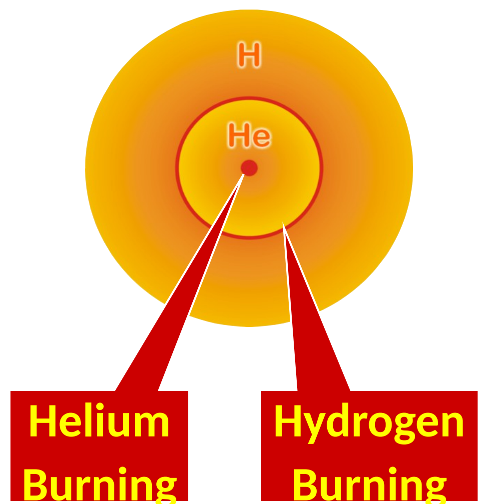
Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

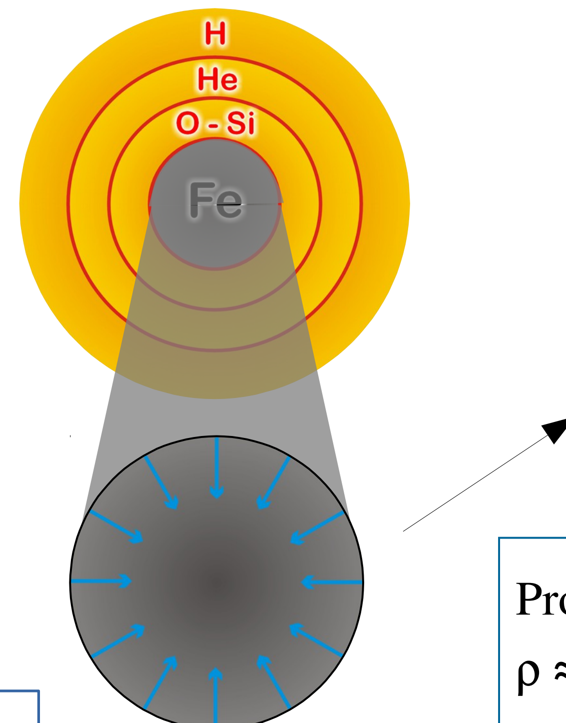
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

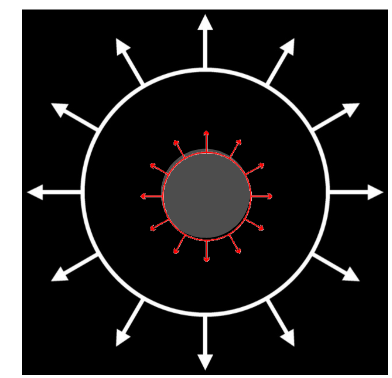
Main-sequence star



Helium-burning star







Proto-Neutron star:

$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

$T \approx 30$ MeV

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

Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\, M_{sun}$

$R_{Fe} \approx 8000$ km

Detection of SN neutrinos in JUNO

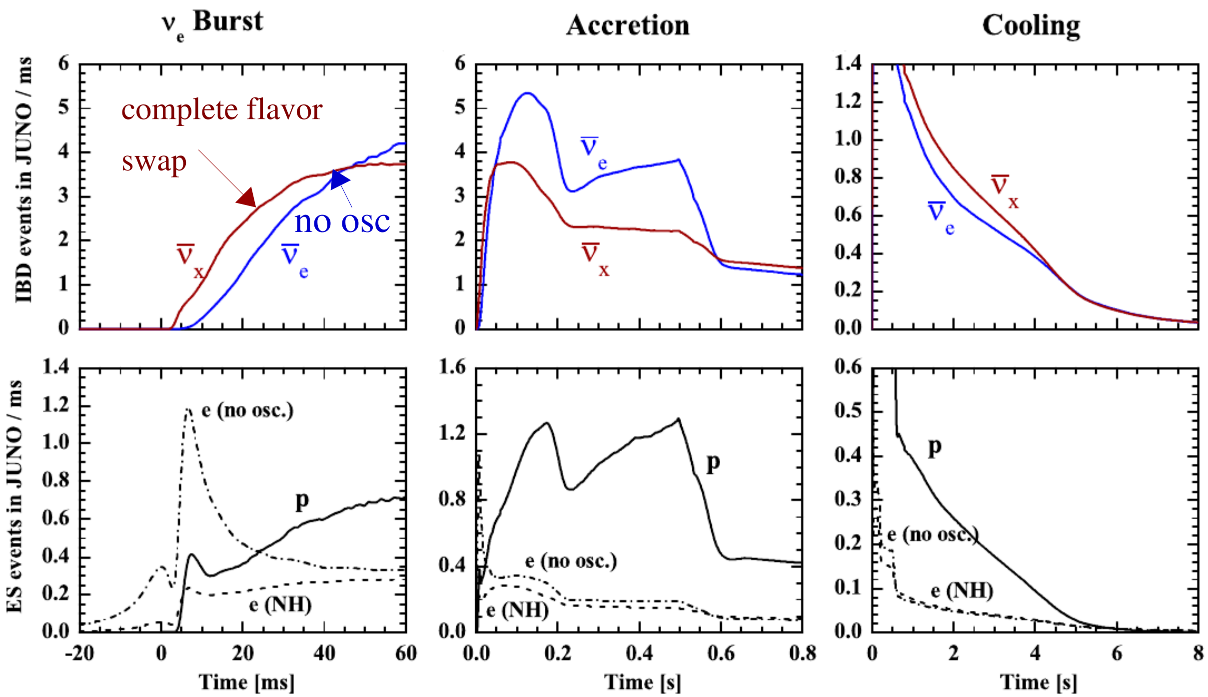
Detection of ν_e, $\bar{\nu}_e$ and ν_x from a typical SN@10kpc

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

F.P. An et al, J. Phys. G 43 (2016) 030401

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

Detection of SN neutrinos in JUNO



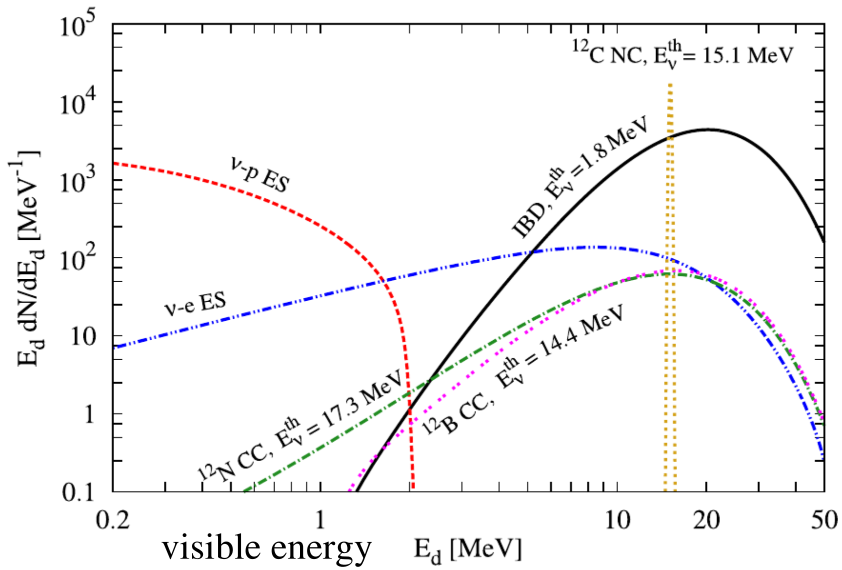
Time information of SN neutrinos of three phases w/ or w/o flavor conversions

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

F.P. An et al, J. Phys. G 43 (2016) 030401

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

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

^{12}C CC channel

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

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

IBD channel

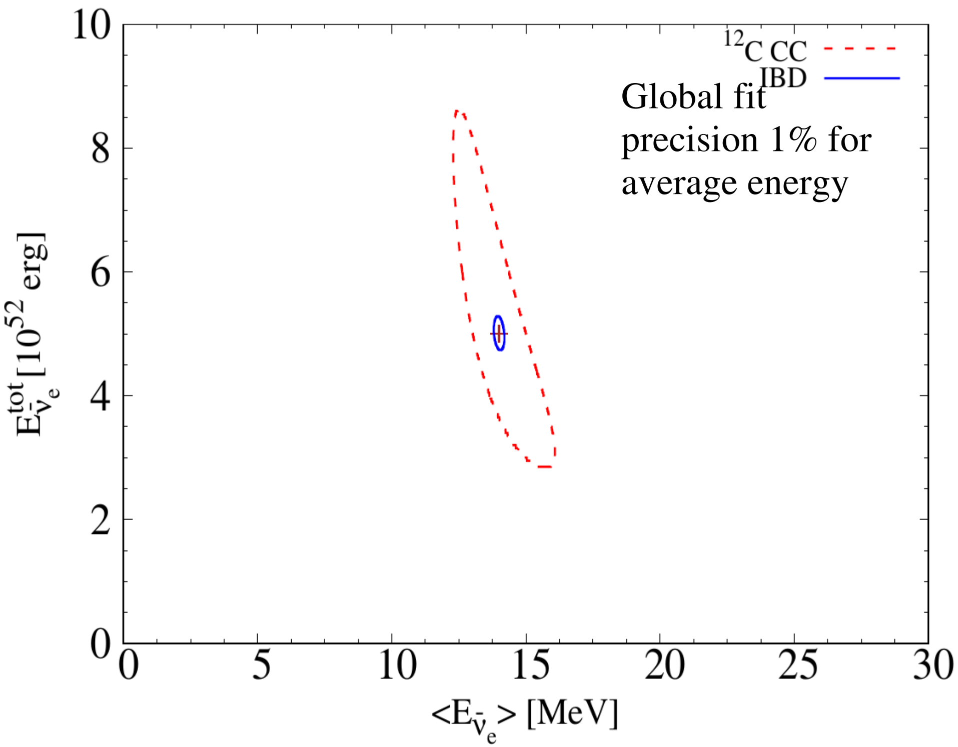
- Prompt signal from annihilation of the positron, delayed signal from the neutron capture: Least background
- ~5000 events, golden channel for SN neutrino observation
- Good reconstruction of energy

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

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

$$E^{tot}_{\nu_e} = E^{tot}_{\bar{\nu}_e} = E^{tot}_{\nu_x} = 5\times10^{52}\,erg$$

$$\langle E_{\nu_e}\rangle = 12\,MeV\,,\langle E_{\bar{\nu}_e}\rangle = 14\,MeV\,,\langle E_{\nu_x}\rangle = 16\,MeV$$



J.S Lu et al. Phys. Rev. D 94(2016)023006

The ν_e spectrum

$\nu + e^- \rightarrow \nu + e^-$ e ES

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

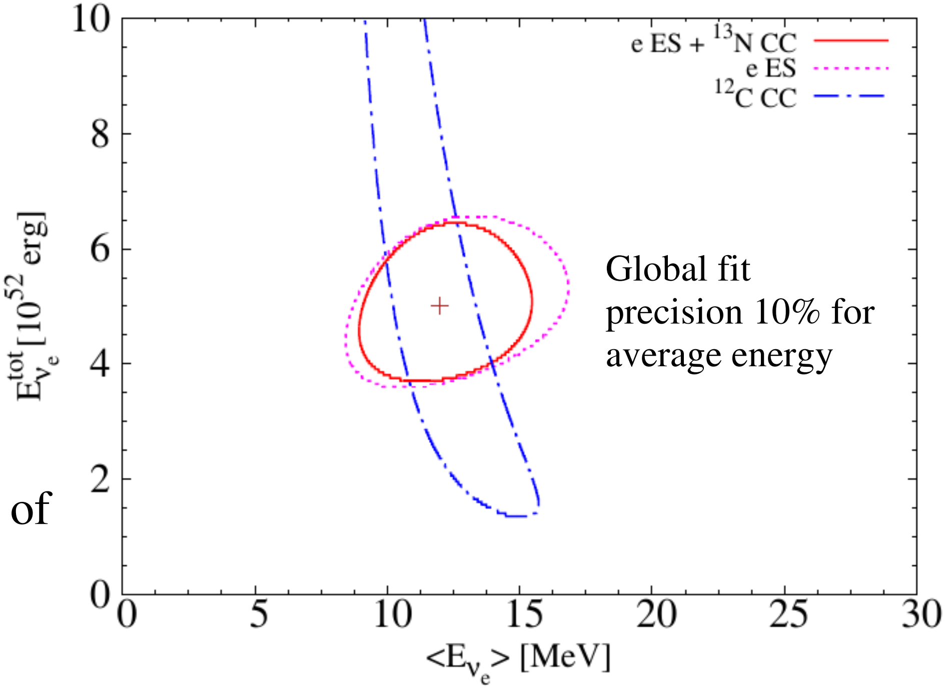
$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$ ^{13}N CC

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

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

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

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



The ν_x spectrum

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

$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$ $\boxed{{}^{12}\text{C NC}}$

15.11 MeV γ

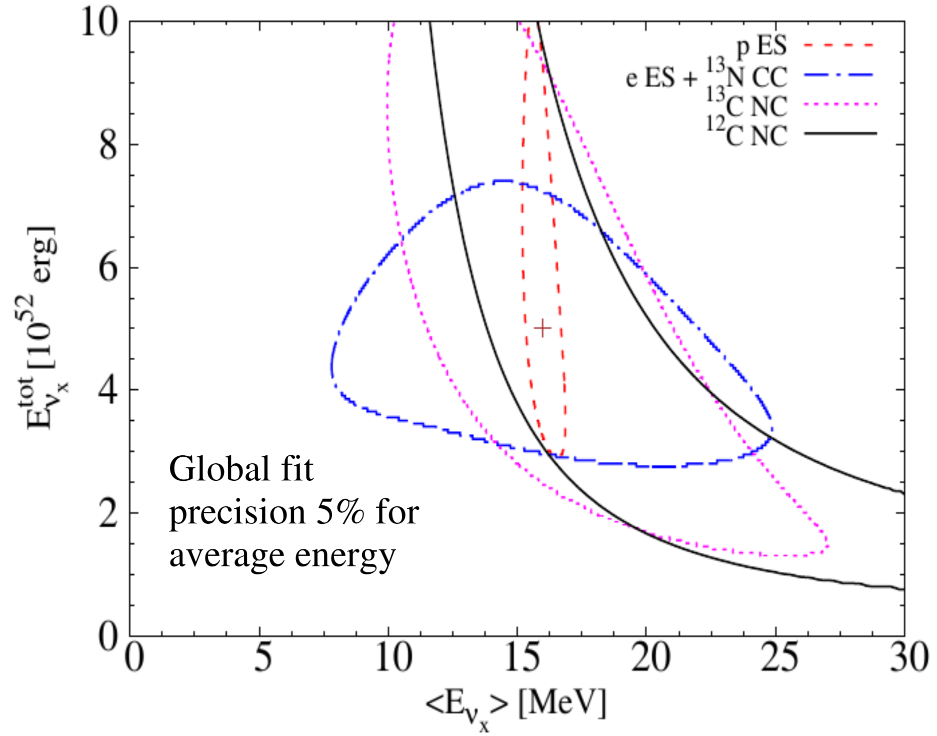
$\nu + {}^{13}C \rightarrow \nu + {}^{13}C^*$ $\boxed{{}^{13}\text{C NC}}$

3.685MeV or 7.547MeV γ

$\nu + p \rightarrow \nu + p$ $\boxed{\text{p ES}}$

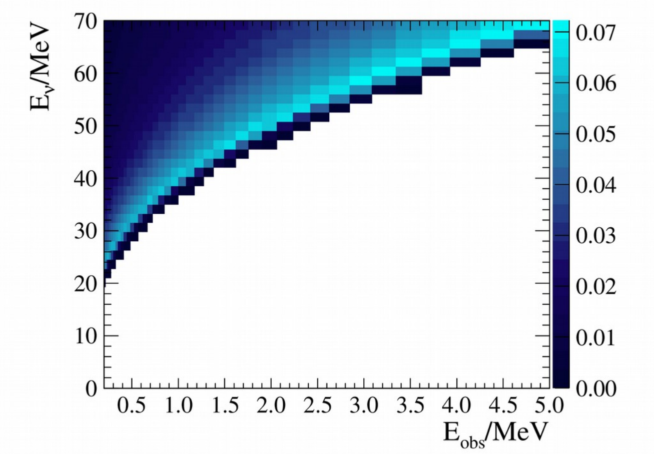
- Quenched proton
- ~2000 events, ~1500 events above 0.2MeV energy threshold

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



Reconstruction of SN neutrino spectra in JUNO

Response matrix for nu-p ES



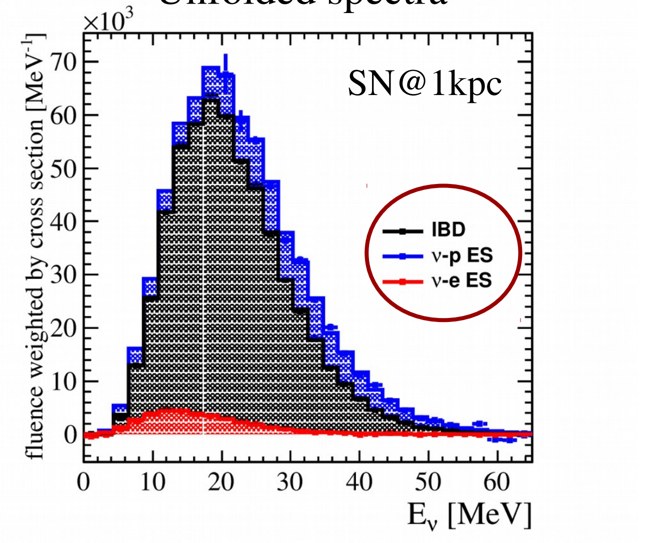
H.L Li et al, to appear

$$Ax = b \rightarrow x = A^{-1} b$$

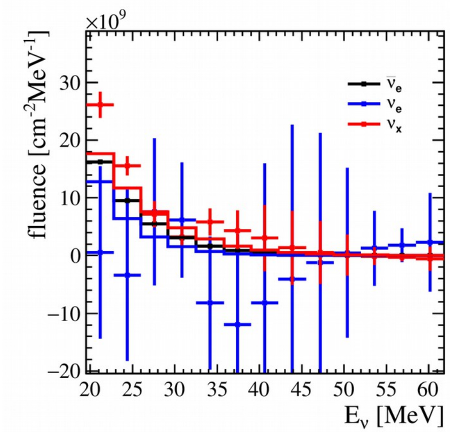
SVD unfolding method in RooUnfold to transform measured energy spectra to true spectra weighted by cross section. And it is independent of SN neutrino models.

RooUnfold
arXiv:1105.1160

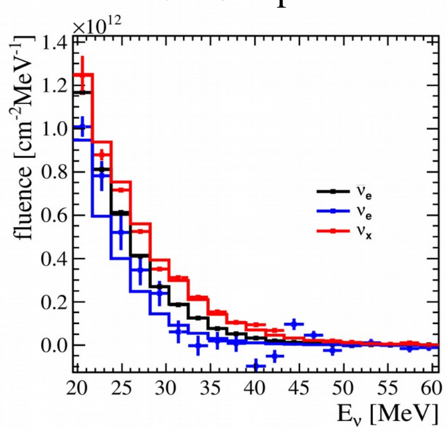
Unfolded spectra



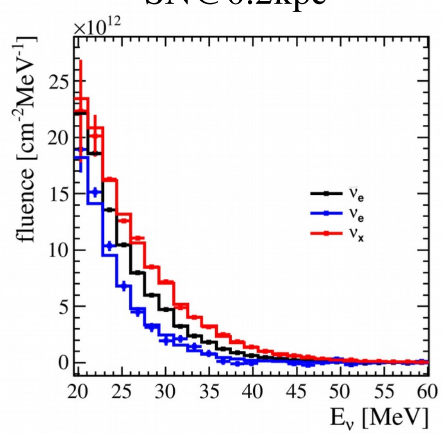
SN@10kpc



SN@1kpc



SN@0.2kpc

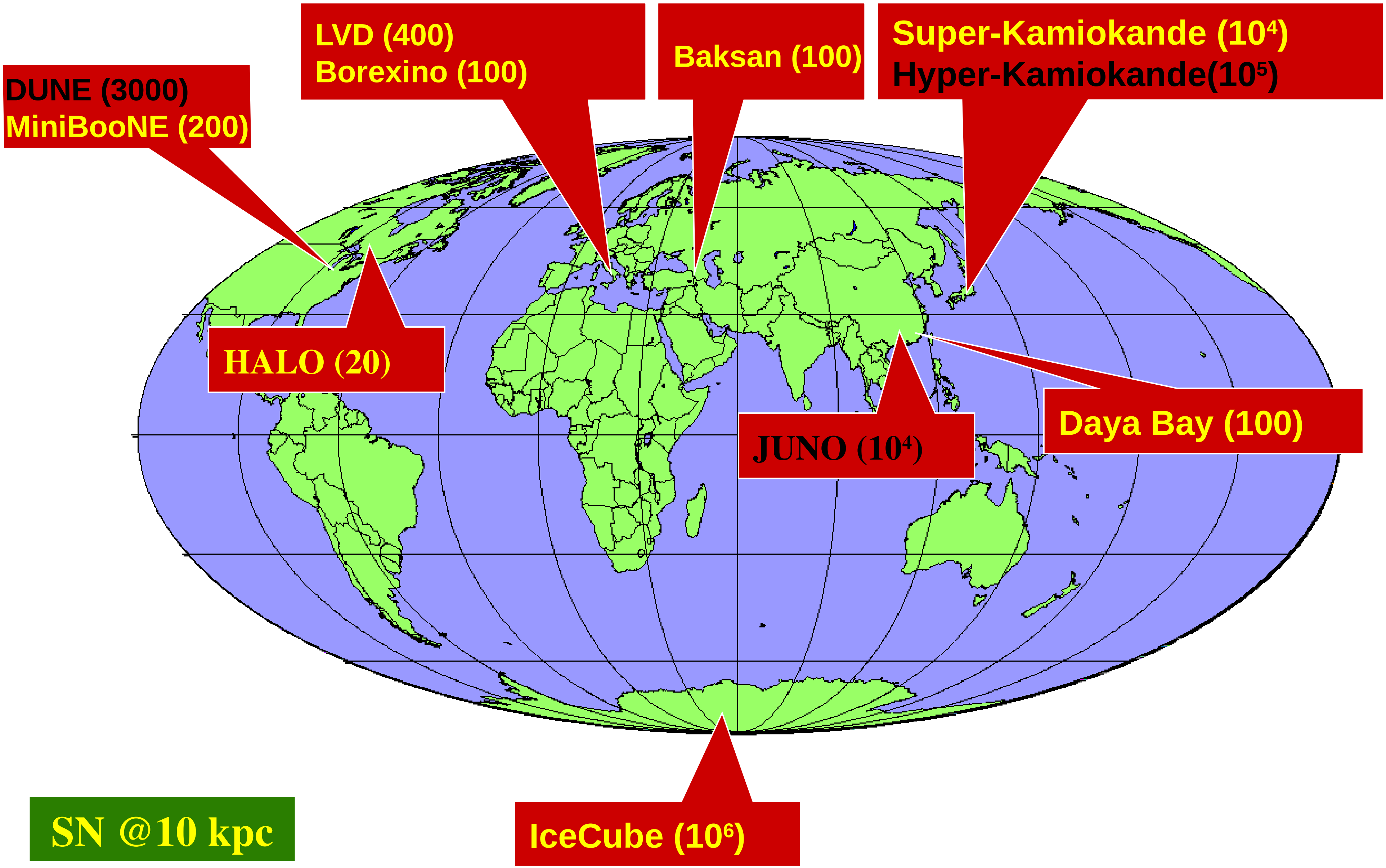


One trial result

Betelgeuse

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.

SN ν detection: present and future experiments



SN @10 kpc

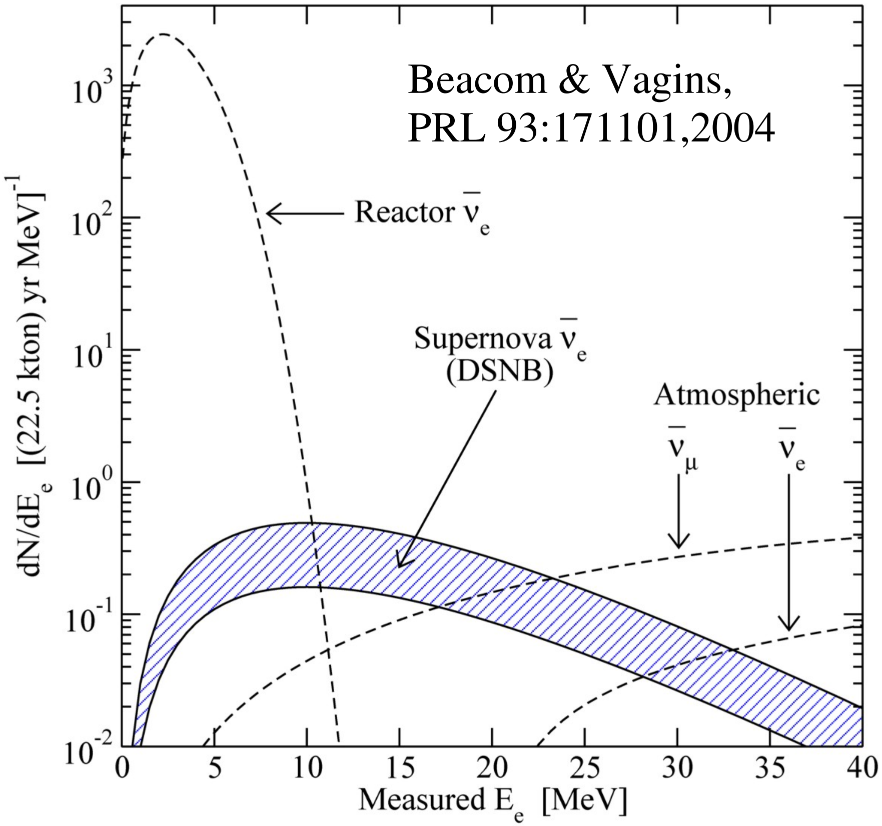
Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapse/sec in the visible universe
- Emitted ν 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 ~ 1
- Confirm star-formation rate
- Nu emission from average core collapse & balck-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances



Diffuse Supernova Neutrino Background (DSNB)

Parametric DSNB flux spectrum:

redshift-dependent co-moving SN rate

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

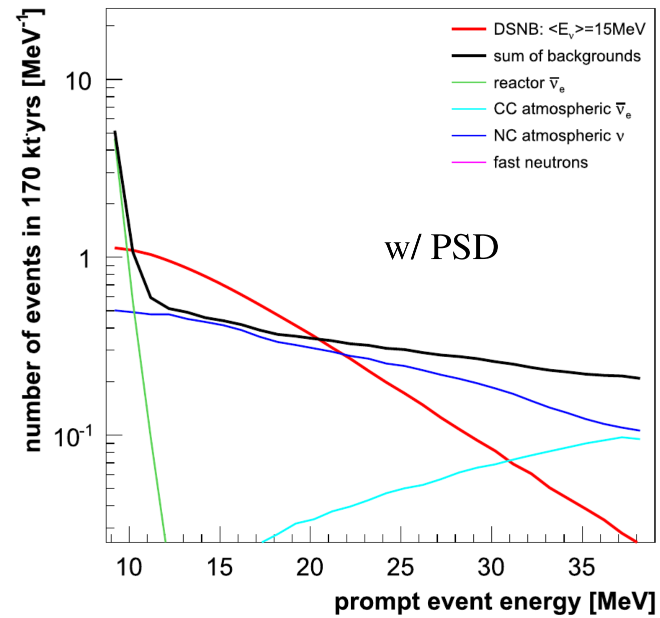
Cosmological evolution

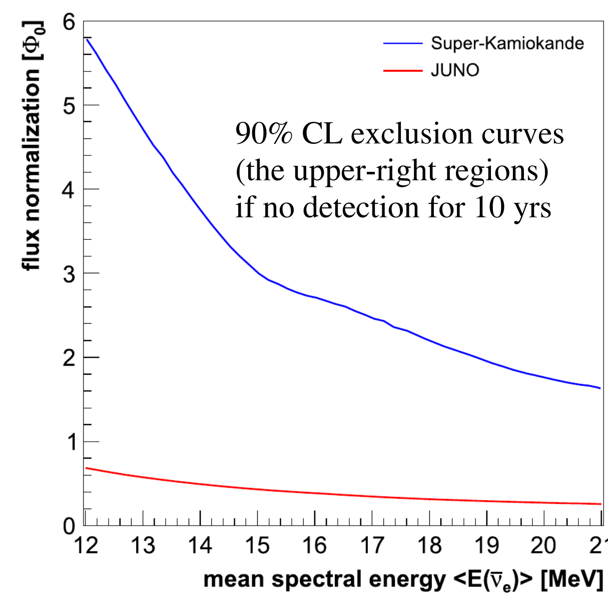
total number spectrum of $\bar{\nu}_e$ from an average core collapse

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

Syst. uncertainty BG	5%		20%	
$\langle E_{\bar{\nu}_e} \rangle$	Rate only	Spectral fit	Rate only	Spectral fit
12 MeV	2.3 σ	2.5 σ	2.0 σ	2.3 σ
15 MeV	3.5 σ	3.7 σ	3.2 σ	3.3 σ
18 MeV	4.6 σ	4.8 σ	4.1 σ	4.3 σ
21 MeV	5.5 σ	5.8 σ	4.9 σ	5.1 σ

F.P. An et al, J. Phys. G 43 (2016) 030401[arXiv:1507.05613]





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

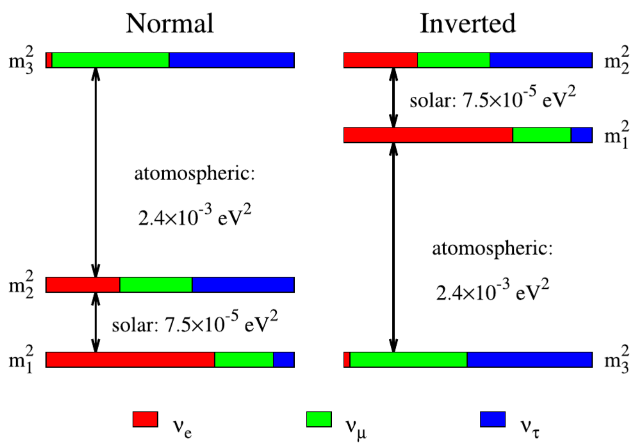
- 2013 Funding approved
- 2014 Collaboration officially formed
- 2014-2018 Civil construction
- 2016-2019 Detector component and PMT production
- 2018-2019 Detector assembly & installation
- 2020 Liquid scintillator filling
- 2020 Start of data taking

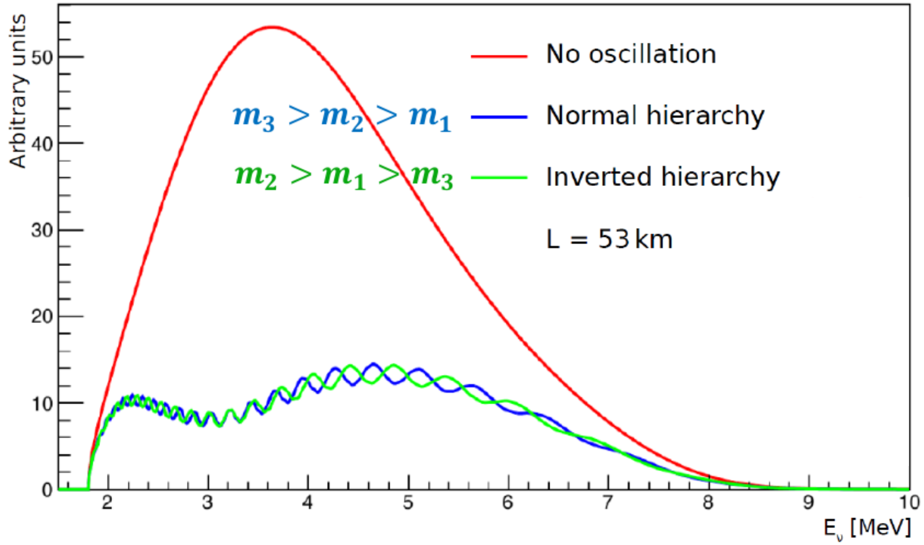
Neutrino mass hierarchy measurement

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

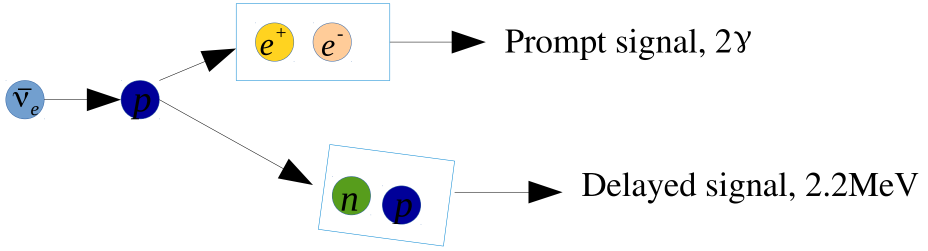
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$
$$- \sin^2 2\theta_{13} \cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$
$$- \sin^2 2\theta_{13} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

$\Delta m^2_{21} = m^2_2 - m^2_1 \qquad \Delta m^2_{31} \simeq \Delta m^2_{32} = m^2_3 - m^2_2$



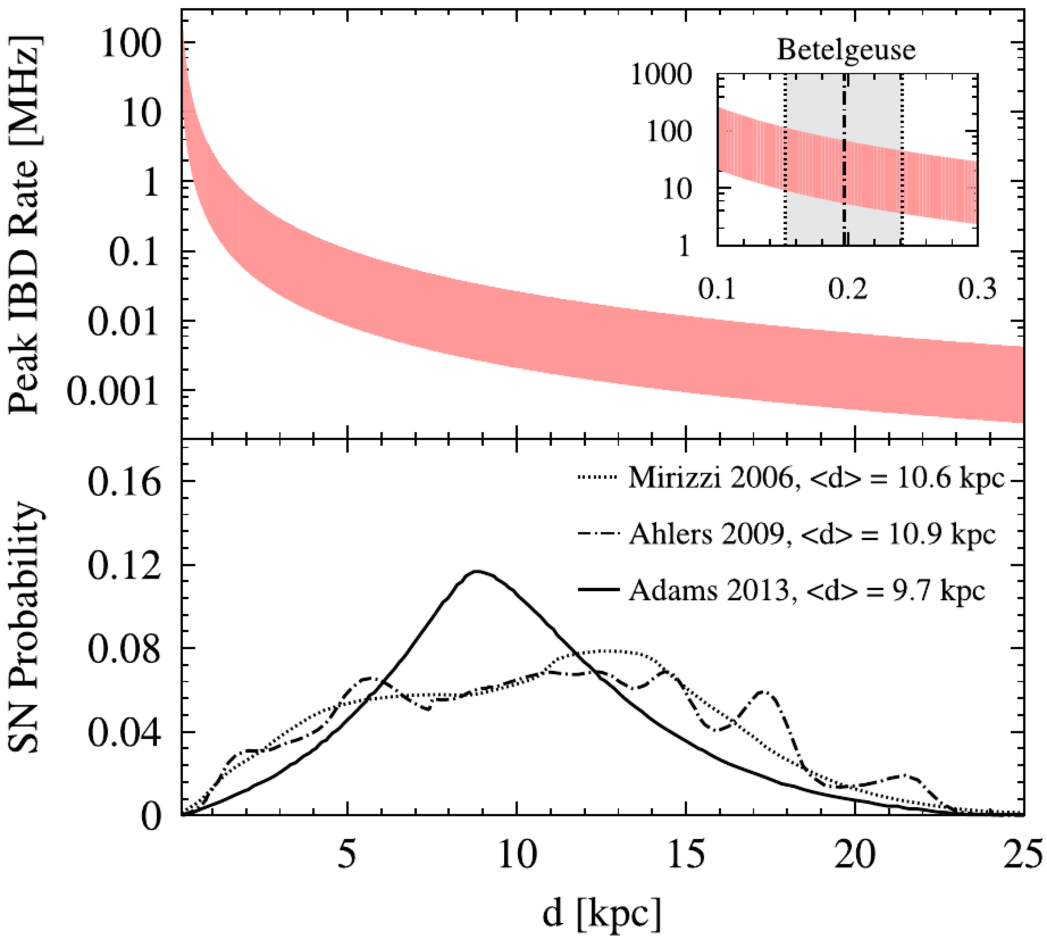


~3 σ MH sensitivity can be achieved with 6 years data taking via IBD channel in JUNO.



Data acquisition for SN neutrinos

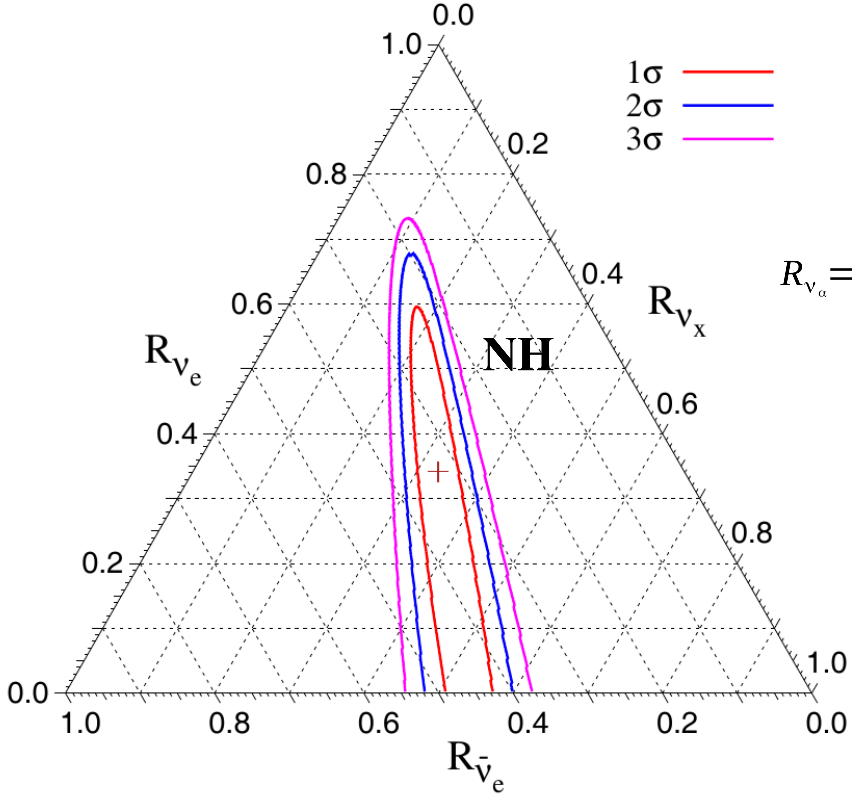
JUNO can work for a typical SN at the most probable distance 10kpc and also 0.2kpc.



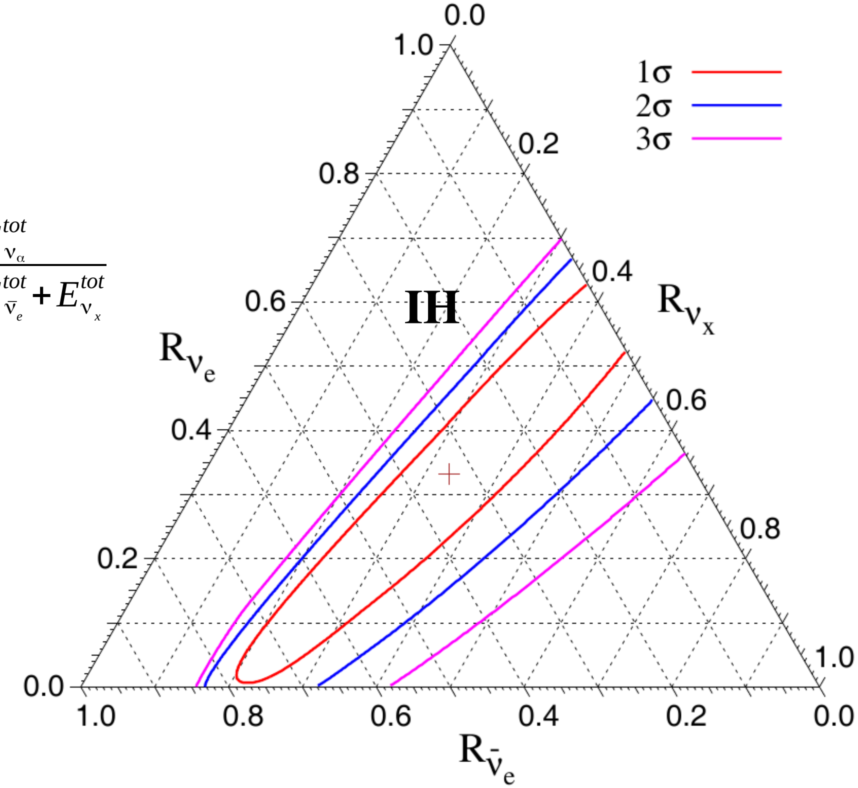
The shaded range has been obtained by considering a class of SN models the Besel, Garching and Nakazato groups.

Test hypothesis of energy equipartition

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



$$R_{\nu_\alpha} = \frac{E^{tot}_{\nu_\alpha}}{E^{tot}_{\nu_e} + E^{tot}_{\bar{\nu}_e} + E^{tot}_{\nu_x}}$$

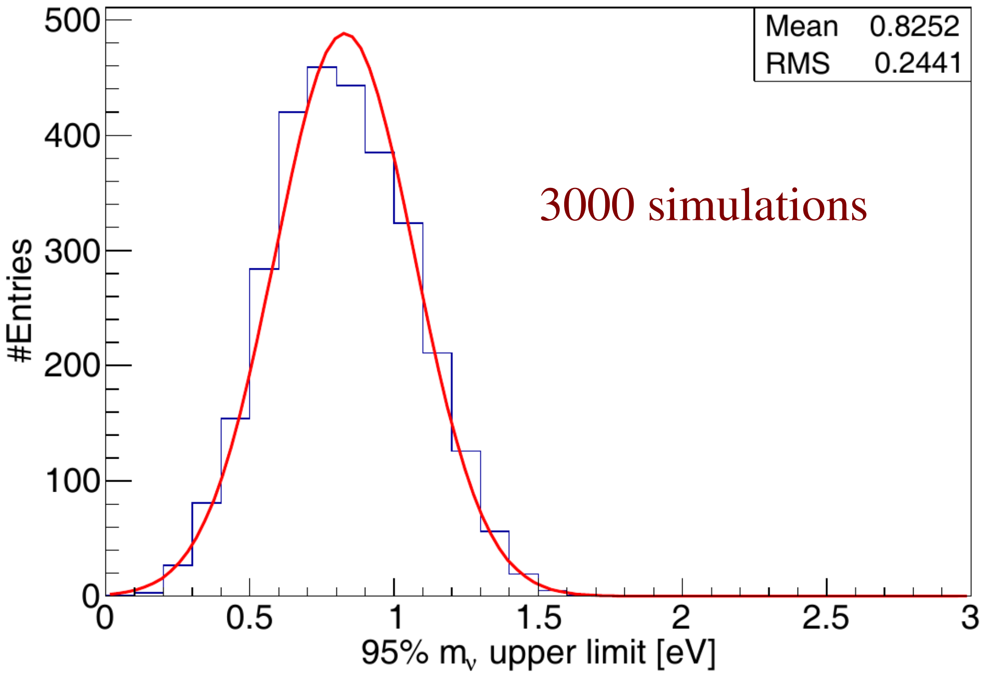


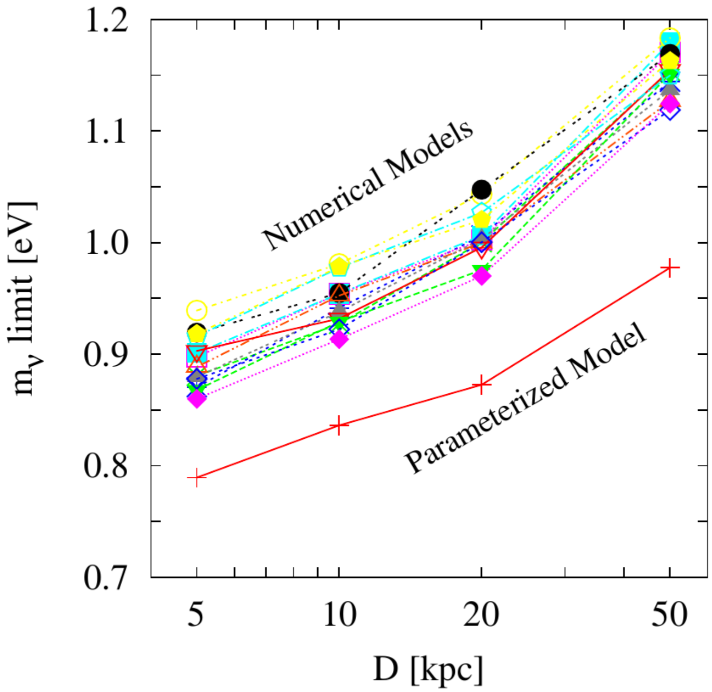
MSW matter effects in supernova are considered.
Neutrino energy ratios are constrained.

Neutrino mass bound

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

J.S. Lu et al., JCAP 15',1412.7418





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