Supernova Neutrinos at Future Large Scintillator Detectors

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2015-10-26

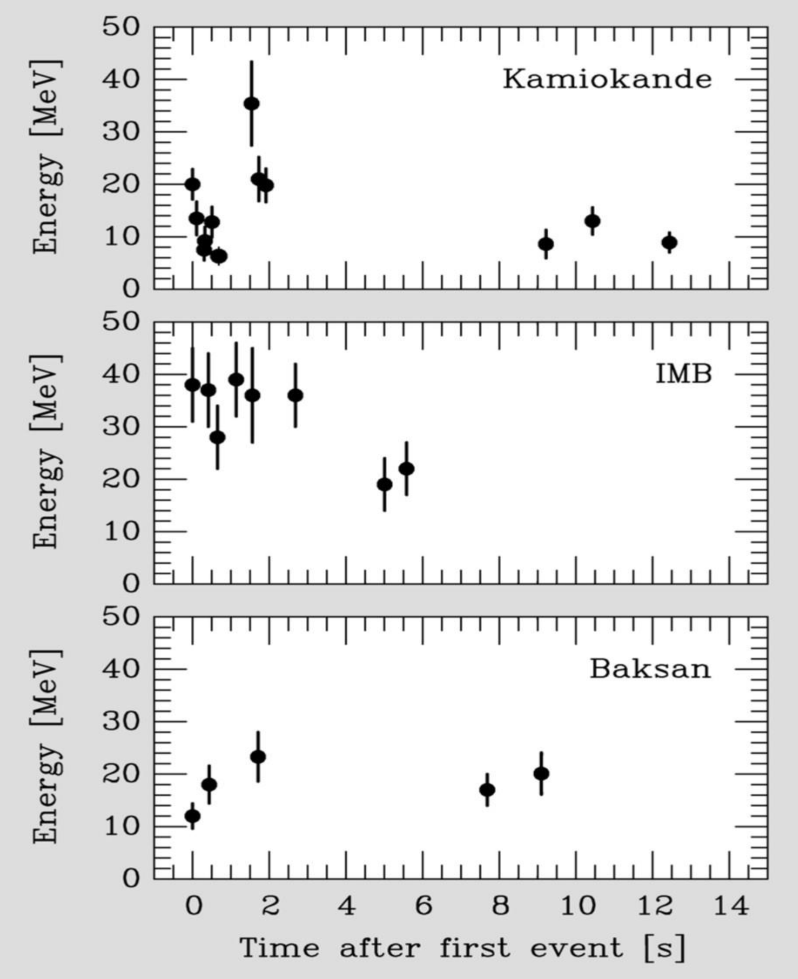
Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):
- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

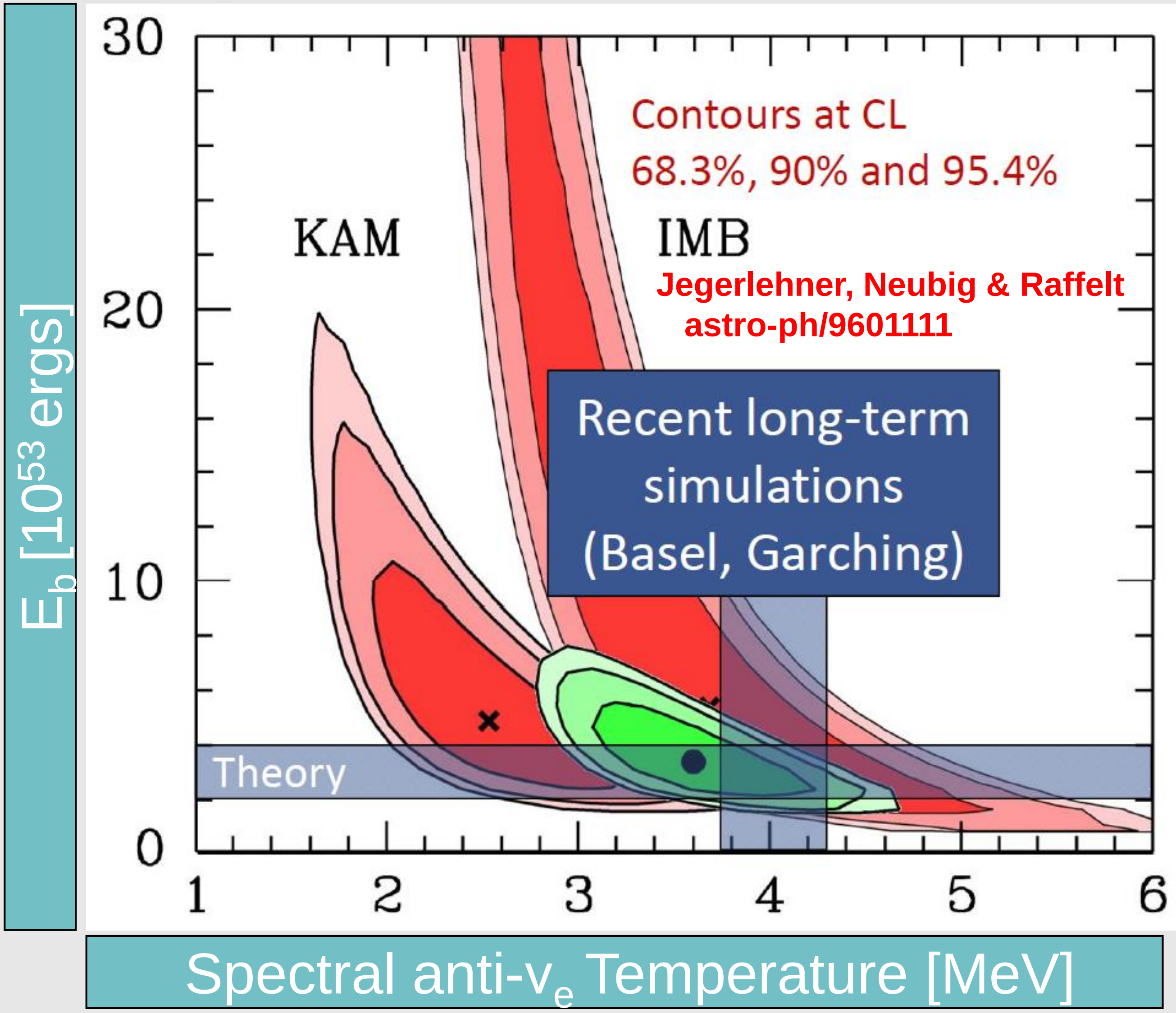
Irvine-Michigan-Brookhaven (US):
- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

Baksan LST (Soviet Union):
- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



Assumptions:
- Thermal
- Equipart.

Conclusions:
- Collapse
- Ave.Ener.
- Duration

Problems：
- 24 events
- by chance

Future Supernova Neutrino Detectors

(1) Water Cherenkov Detector

Hyper Kamiokande (also SuperK or SuperK-Gd):

1 Mt, mostly nu_e_bar, largest statistics

(2) Liquid Scintillator Detector

JUNO (also RENO50 or LENA):

20 kt, nu_e_bar dominates, different flavors, better energy resolution

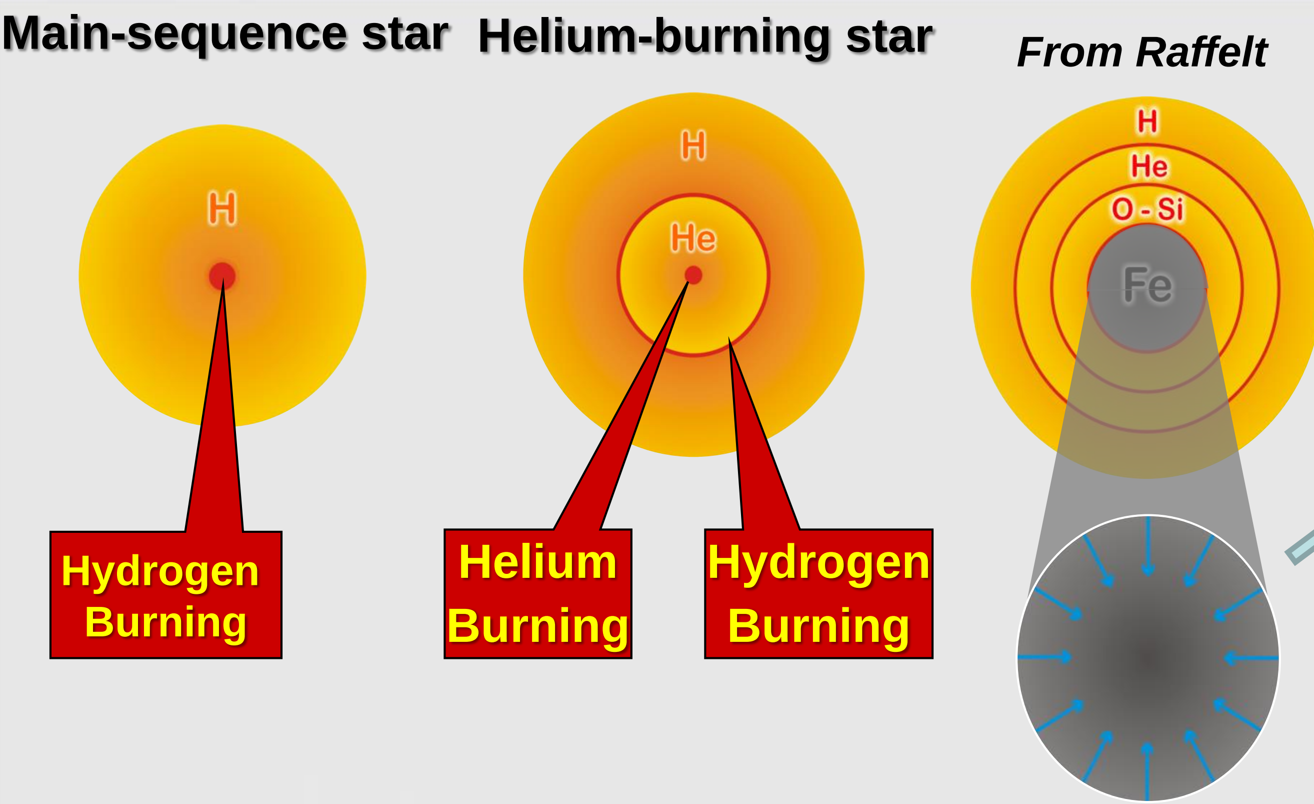
(3) Liquid Argon Detector

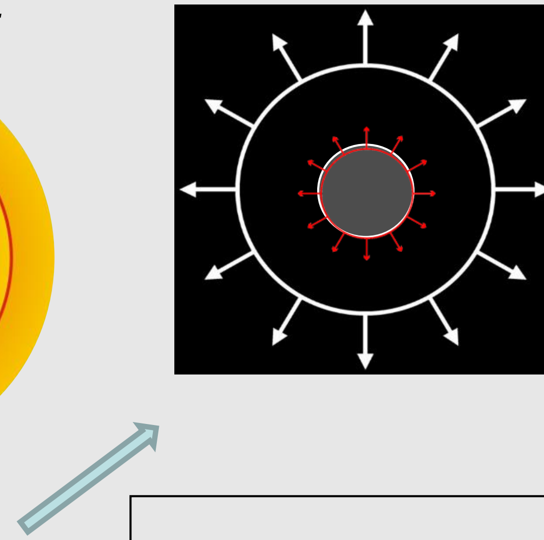
DUNE: 10-40 kt, nu_e dominates

(4) Ice Cherenkov Detector

Icecube: No event-by event observation, time profile

Neutrino-driven supernova explosion





Neutron star:
$\rho = 3 \times 10^{14}$ g cm^{-3}
$T \sim 30$ MeV

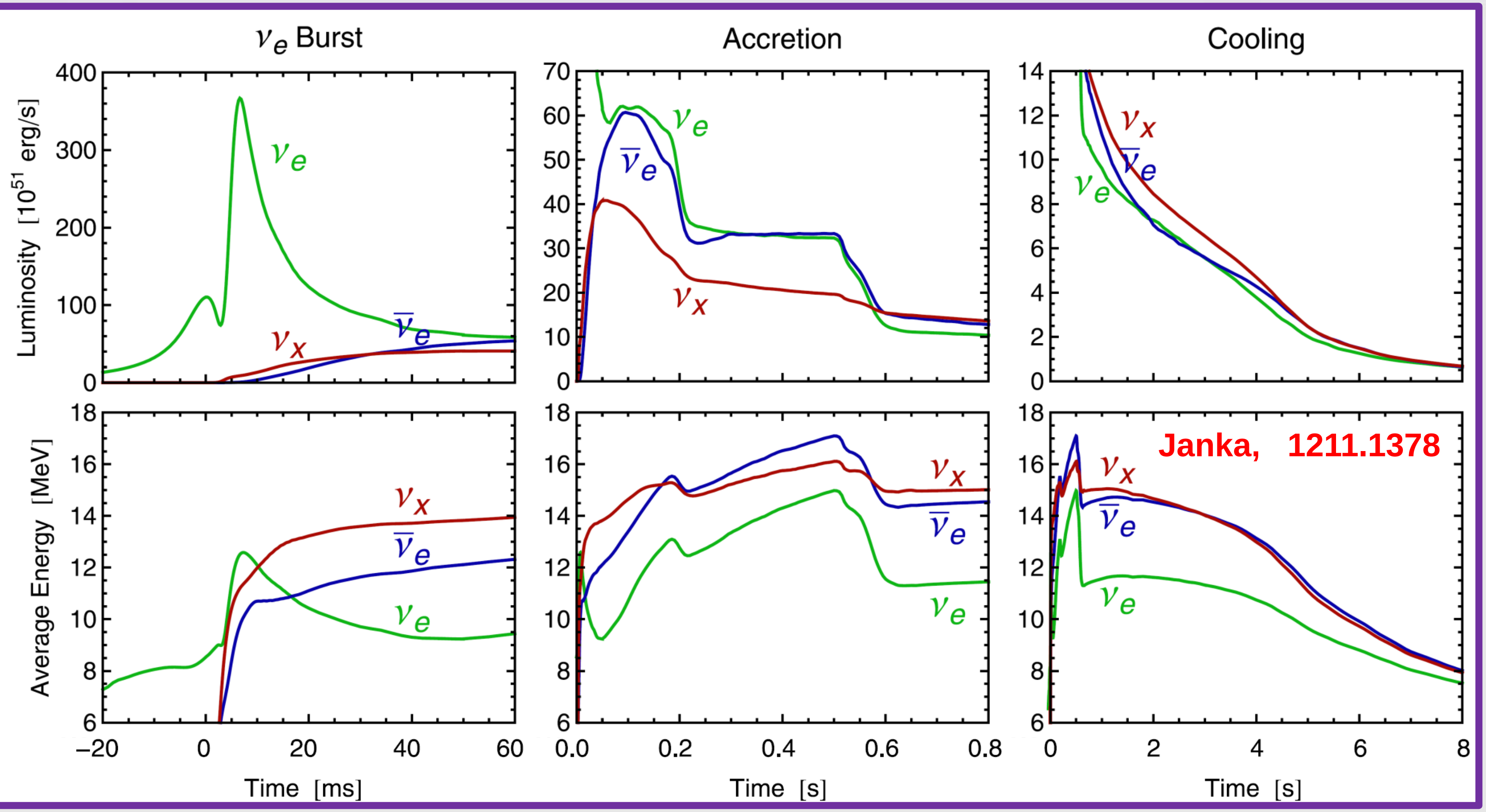
Degenerate iron core:

$\rho \approx 10^{9}$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5 \, M_{sun}$
$R_{Fe} \approx 8000$ km

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

Three phases of SN burst



Shock breakout

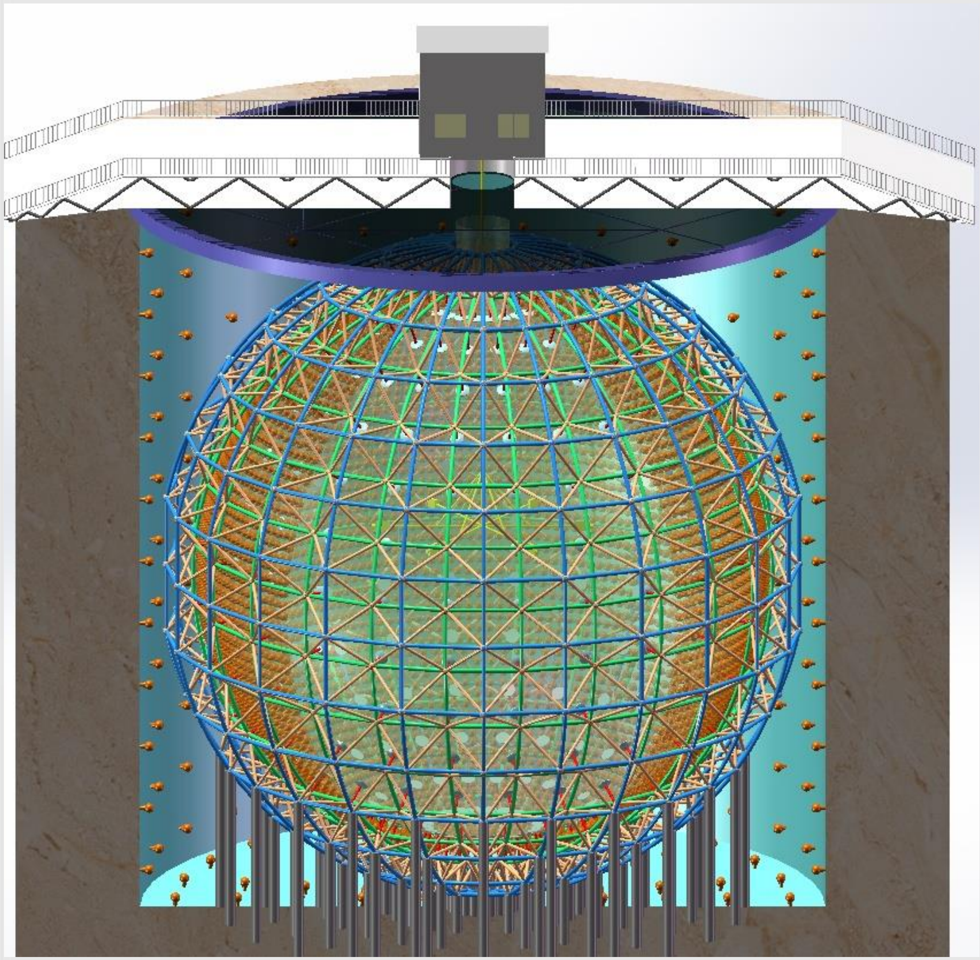
$$e^- + p \to n + \nu_e$$

Shock stalls ~150 km
Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

The JUNO experiment

Jiangmen Underground Neutrino Observatory (JUNO), a multiple-purpose neutrino experiment, approved in Feb. 2013, ~ 300 M$.



20 kton LS detector

3% energy resolution

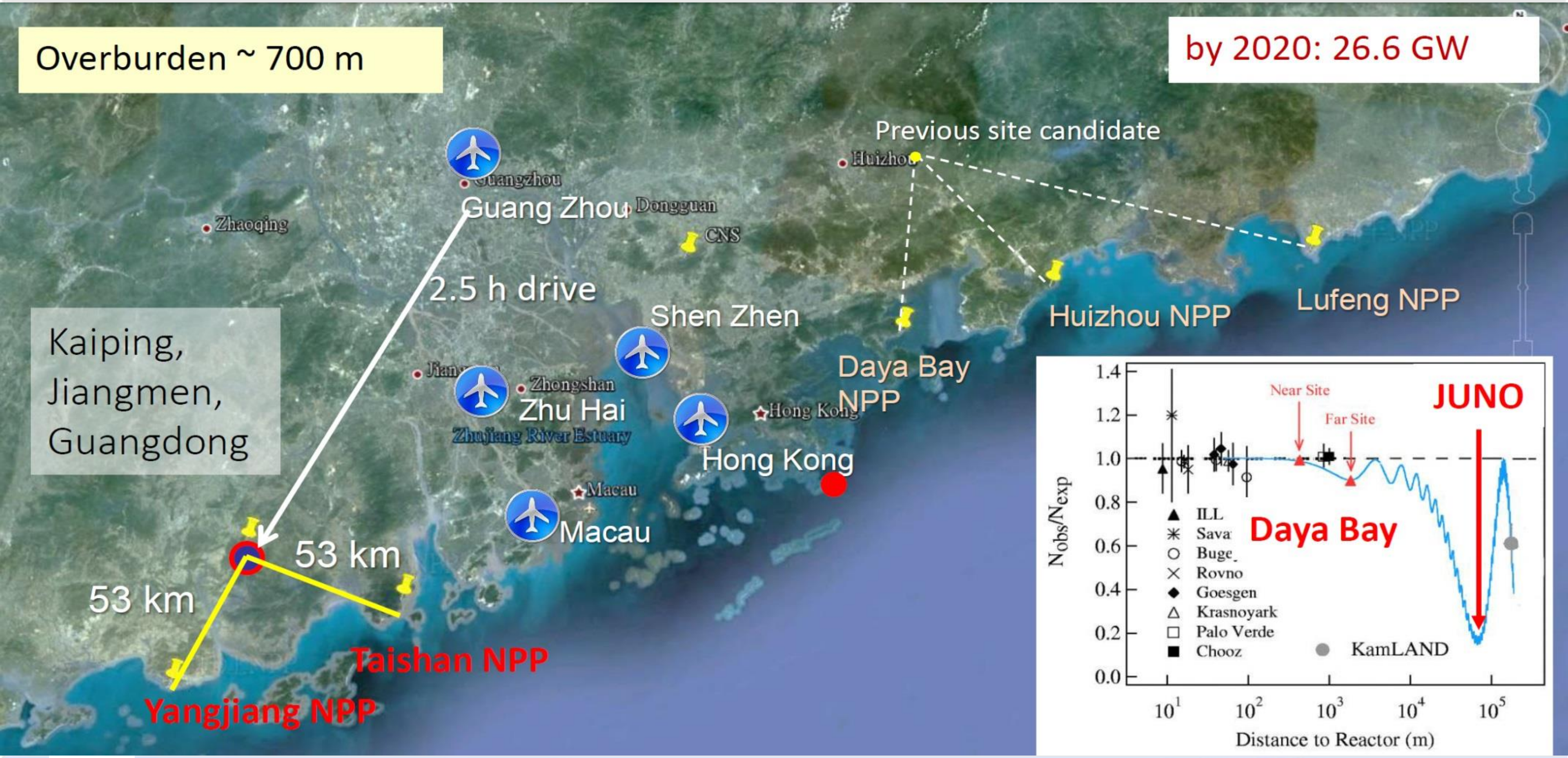
700 m underground

Rich Physics Possibilities (1507.05613: Physics Case Study)

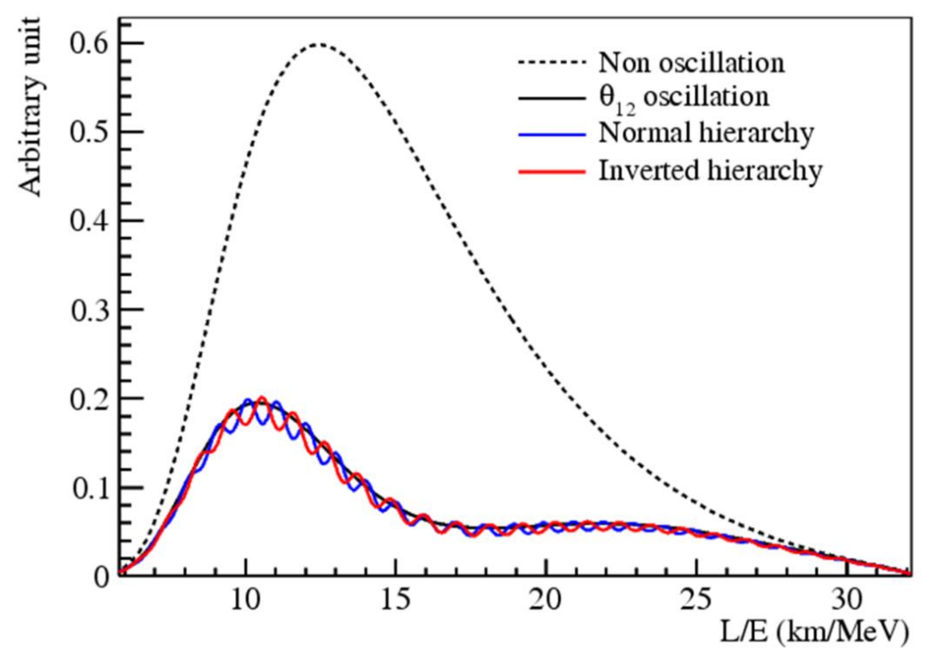
- **Reactor Neutrinos for neutrino mass hierarchy & precision measurement**
- ***Supernova Burst Neutrino***
- **Diffuse Supernova Neutrino Background**
- **Geoneutrinos**
- **Solar Neutrinos**
- **Atmospheric Neutrinos**
- **Proton Decays**
- **Exotic Searches**

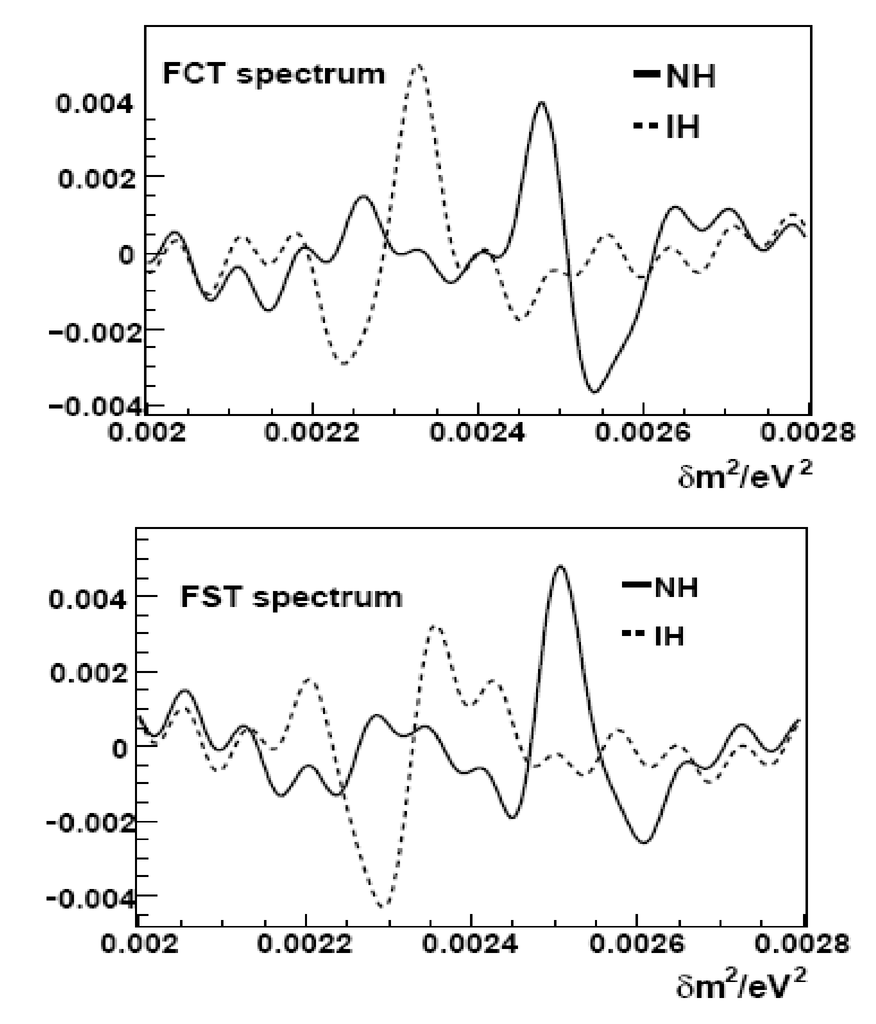
Experimental site

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Principle for the MH measurement





How the interference happens?

Fourier transform to L/E spectrum:

L/E spectrum←→Δm^2 spectrum(oscillation frequency)

J. Learned *et. al.* hep-ex/0612022

L. Zhan *et. al*. 0807.3203

Multi-channels of neutrino detection at JUNO

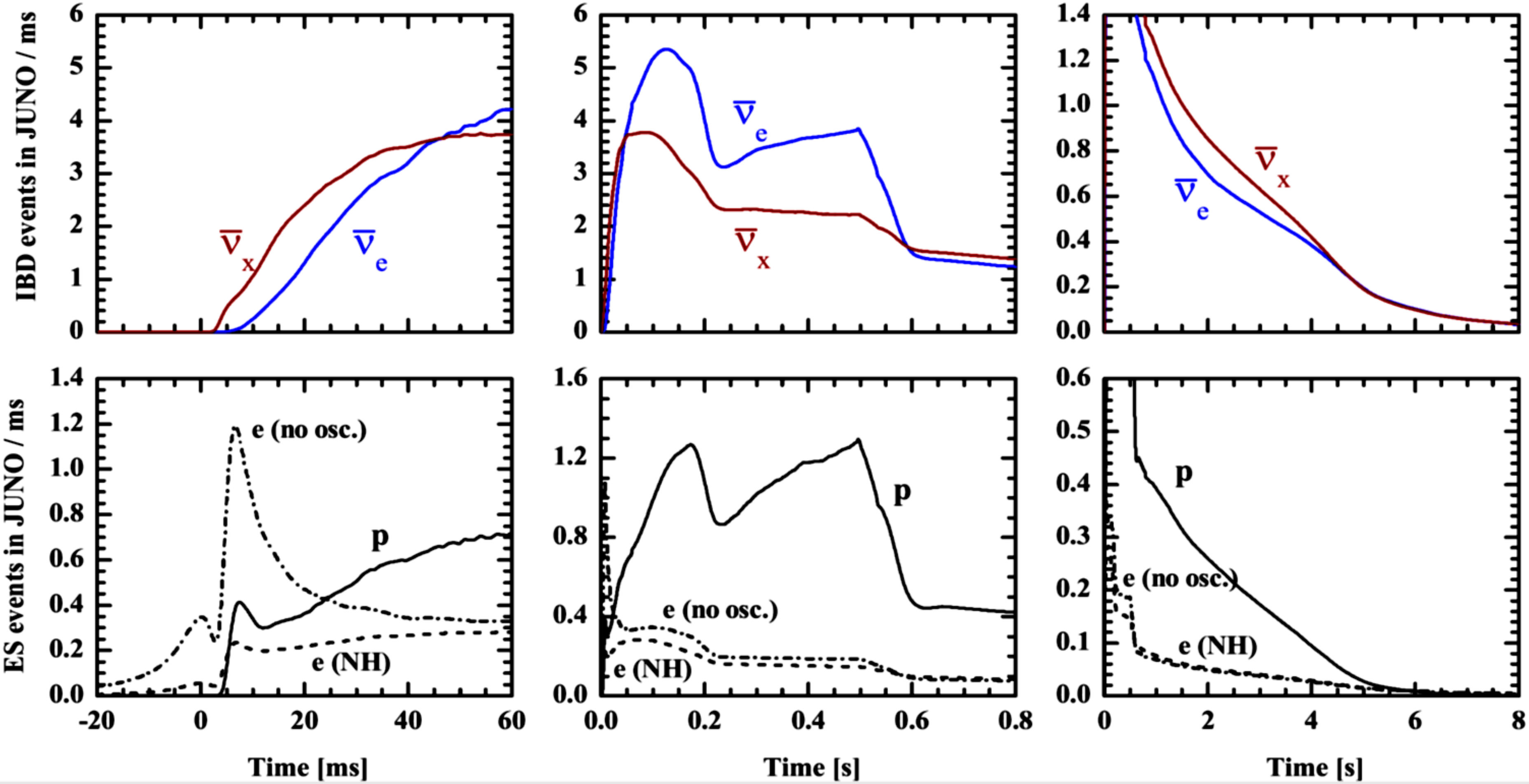
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Detect $\overline{\nu}_e, \nu_e, \nu_x$ from a galactic SN @ 10 kpc

- **real-time measurement of three-phase ν signals**
- **distinguish between different ν flavors**
- **reconstruct ν energies and luminosities**
- **almost background free due to time info.**

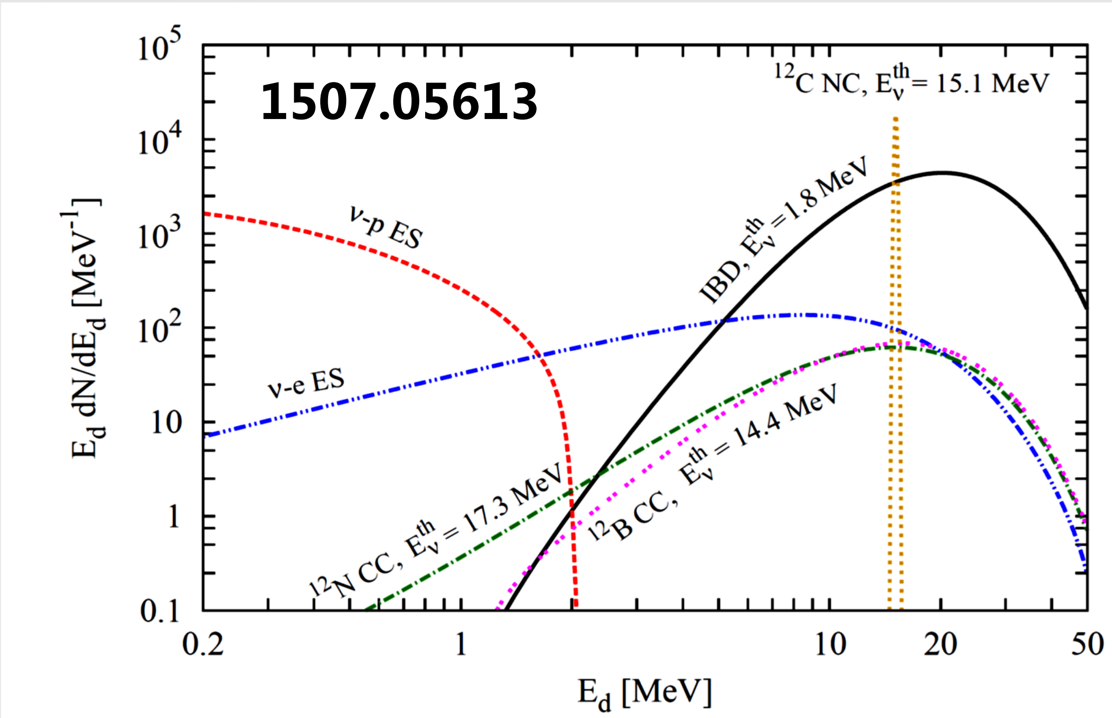
Impact of neutrino flavor conversions

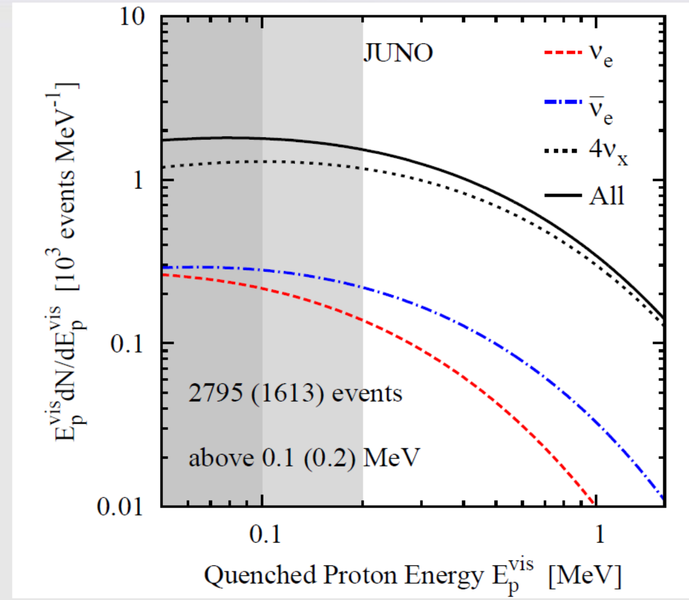
1507.05613

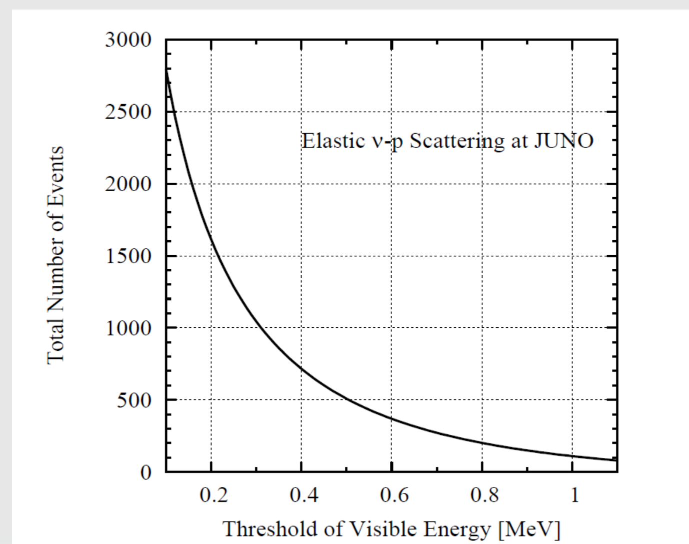


w/ oscillation or with largest transition between ν_e($\bar{\nu}_e$) and ν_x

Energy spectra







- **nu-p events are mostly ν_x flavors**
- **It is crucial to achieve a low energy threshold.**
- **e vs. p discrimination.**

Detection of SN Nu_e_bar at JUNO

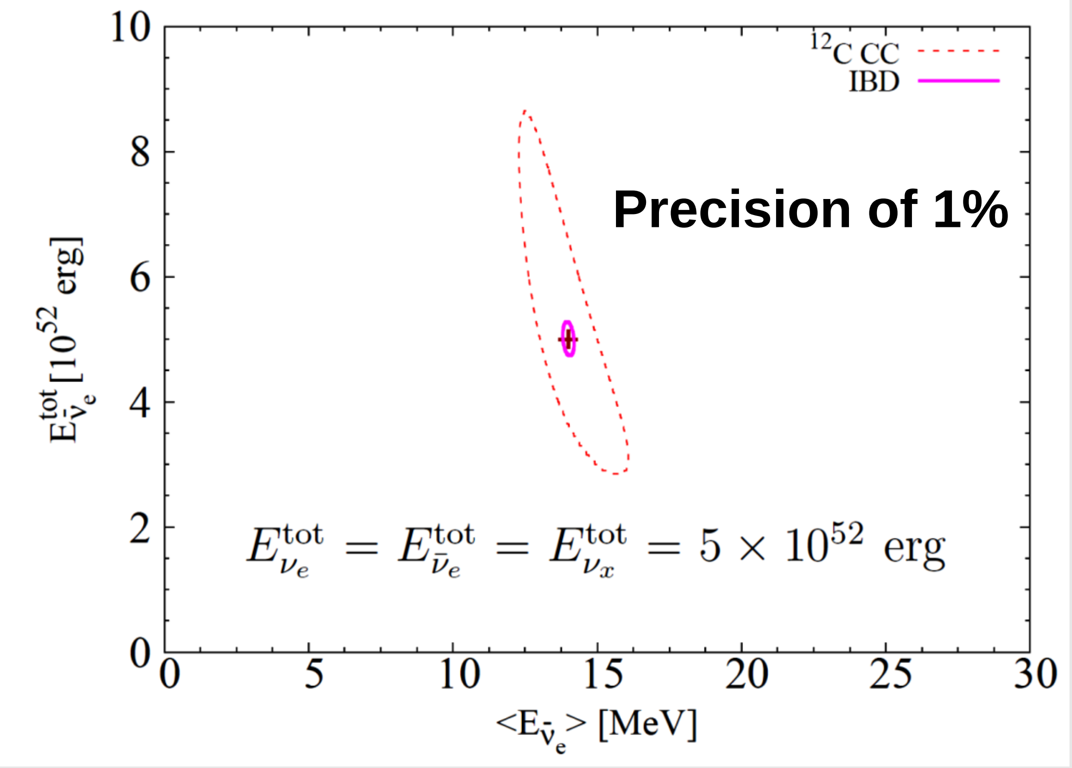
Mostly Inverse beta decay (IBD) $\bar{\nu}_e + p \longrightarrow n + e^+$

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

(1) 5000 IBD events, golden channel for SN neutrino observations

(2) Coincidence of prompt and delayed signals: least background

(3) good reconstruction of the neutrino energy Eν

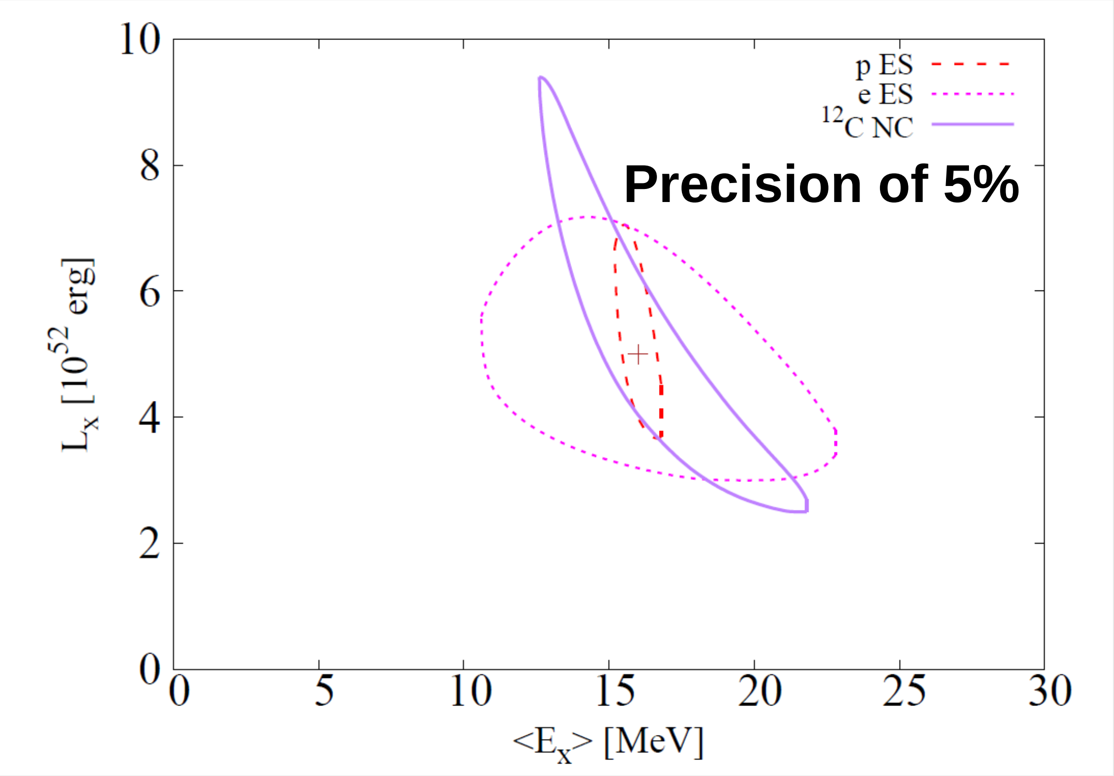


Lu, YFL, Zhou, in preparation

Detection of SN Nu_x at JUNO

(1) nu-p scattering (pES) events: quenched proton
(2) nu-^{12}C NC events: 15.11 MeV γ
(3) nu-electron scattering (eES) events: recoiled electron

- **2000** pES events
- Low threshold **(0.2 MeV)**
- reconstruction of neutrino energy spectrum: **high-energy tail**

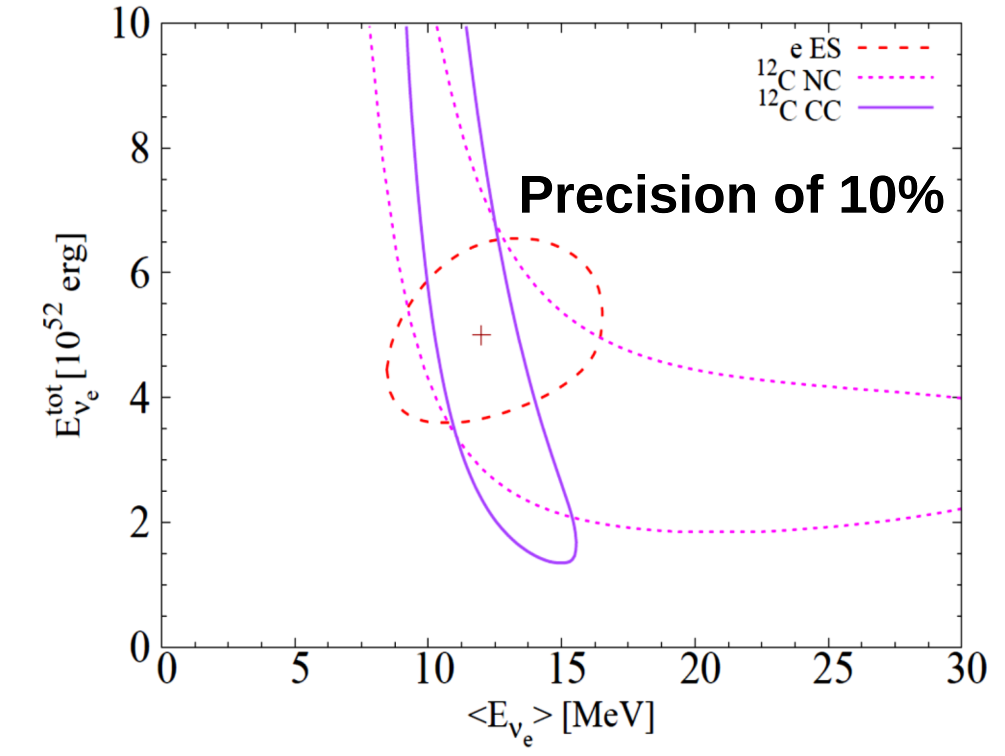


Lu, YFL, Zhou, in preparation

Detection of SN Nu_e at JUNO

(1) nu-electron scattering (eES) events: recoiled electron
(2) nu-^{12}C CC events: coincidence with decayed ^{12}N
(3) nu-^{12}C NC events: 15.11 MeV γ

- 300 eES events
- 300 ^{12}C CC events
- IBD inefficiency affects
- e v.s. p discrimination



Lu, YFL, Zhou, in preparation

Neutrino mass scale with SN neutrinos

SN1987A limits of neutrino mass scale: 5.8 eV@ 95C.L.

Beta decay experiments:

Current: 2.1 eV@ 95C.L., KATRIN: 0.2 @ 95C.L.

Cosmology probes:

Total mass smaller than 0.23 @ 95C.L.

Double beta decay:

Depending on matrix elements and Majorana phases

It is desirable to have a sub-eV test with future SN neutrinos

Principle: time of flight measurements

Time delay:

$$\Delta t(m_\nu, E_\nu) \simeq 5.14 \text{ ms} \left(\frac{m_\nu}{\text{eV}}\right)^2 \left(\frac{E_\nu}{10 \text{ MeV}}\right)^{-2} \frac{D}{10 \text{ kpc}}$$

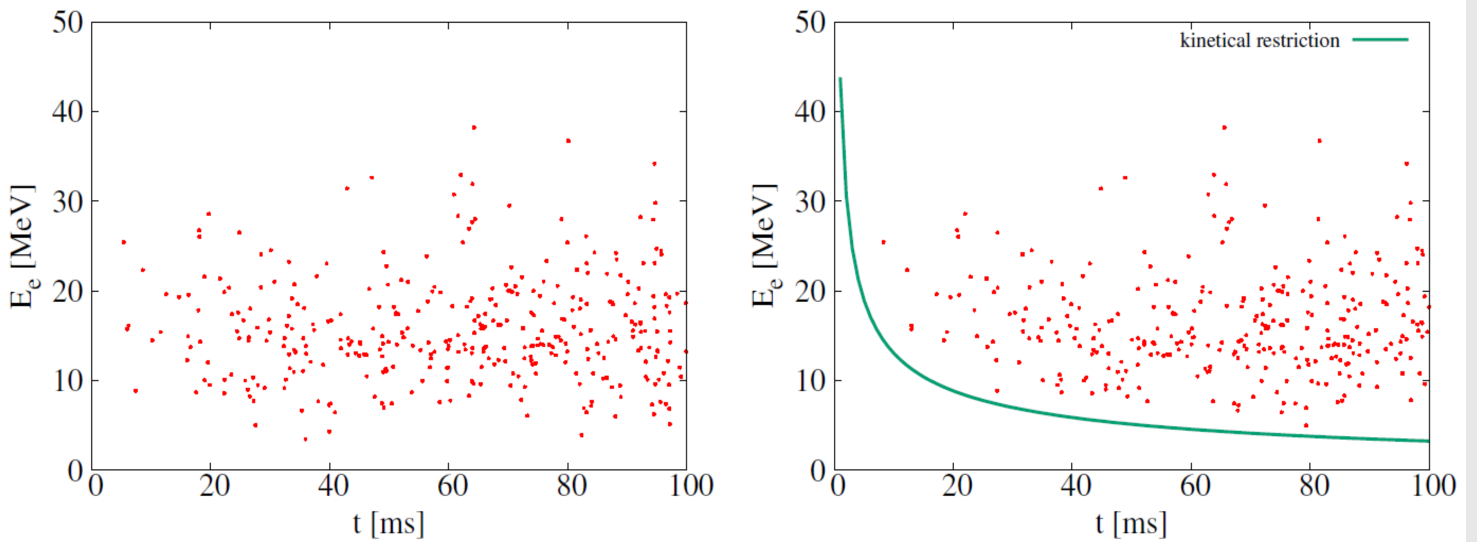


Figure: Example of time delay of SN neutrinos for a 10 kpc away SN. Left: $m_\nu = 0$. Right: $m_\nu = 2$ eV.

Method:

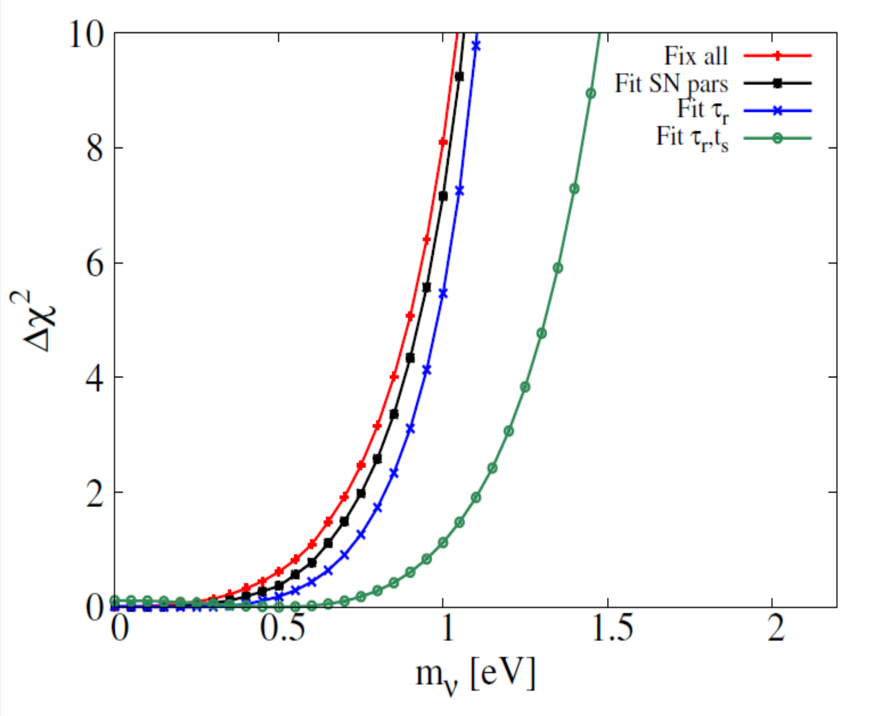
$$\mathcal{L} = e^{-\int_0^T R(t)\mathrm{d}t} \prod_{i=1}^{N} \int_{E_{\text{th}}}^{\infty} R(t_i', E_e) G(E_e + m_e, E_i; \delta E_i) \mathrm{d}E_e$$

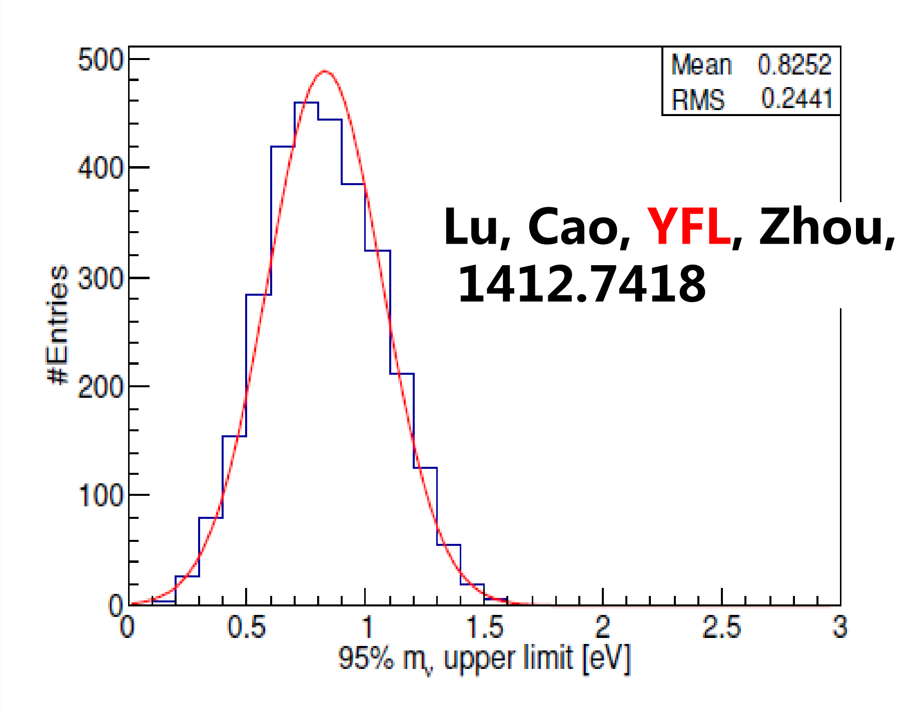
Statistical and Systematic uncertainties

Using a parametrized model from SN1987A observation.
(parametrized model from 0810.0466)

(1) In one trial, to study the model parameter effects.

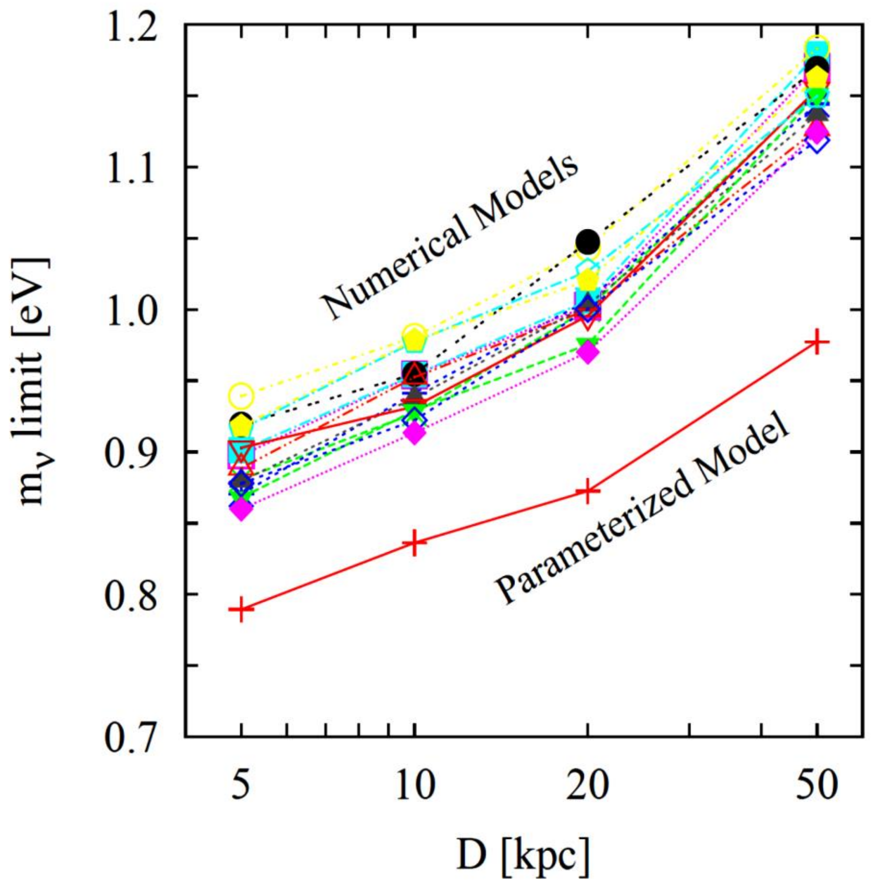
(2) With 3000 simulations, to show the fluctuation.

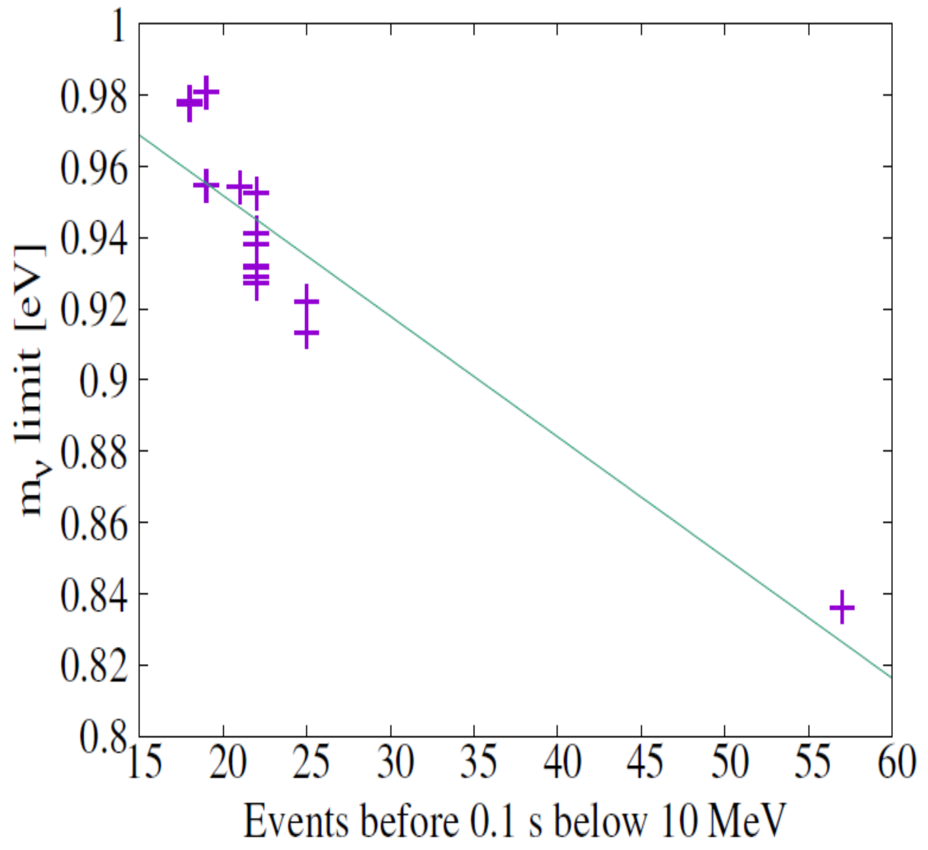




Lu, Cao, YFL, Zhou, 1412.7418

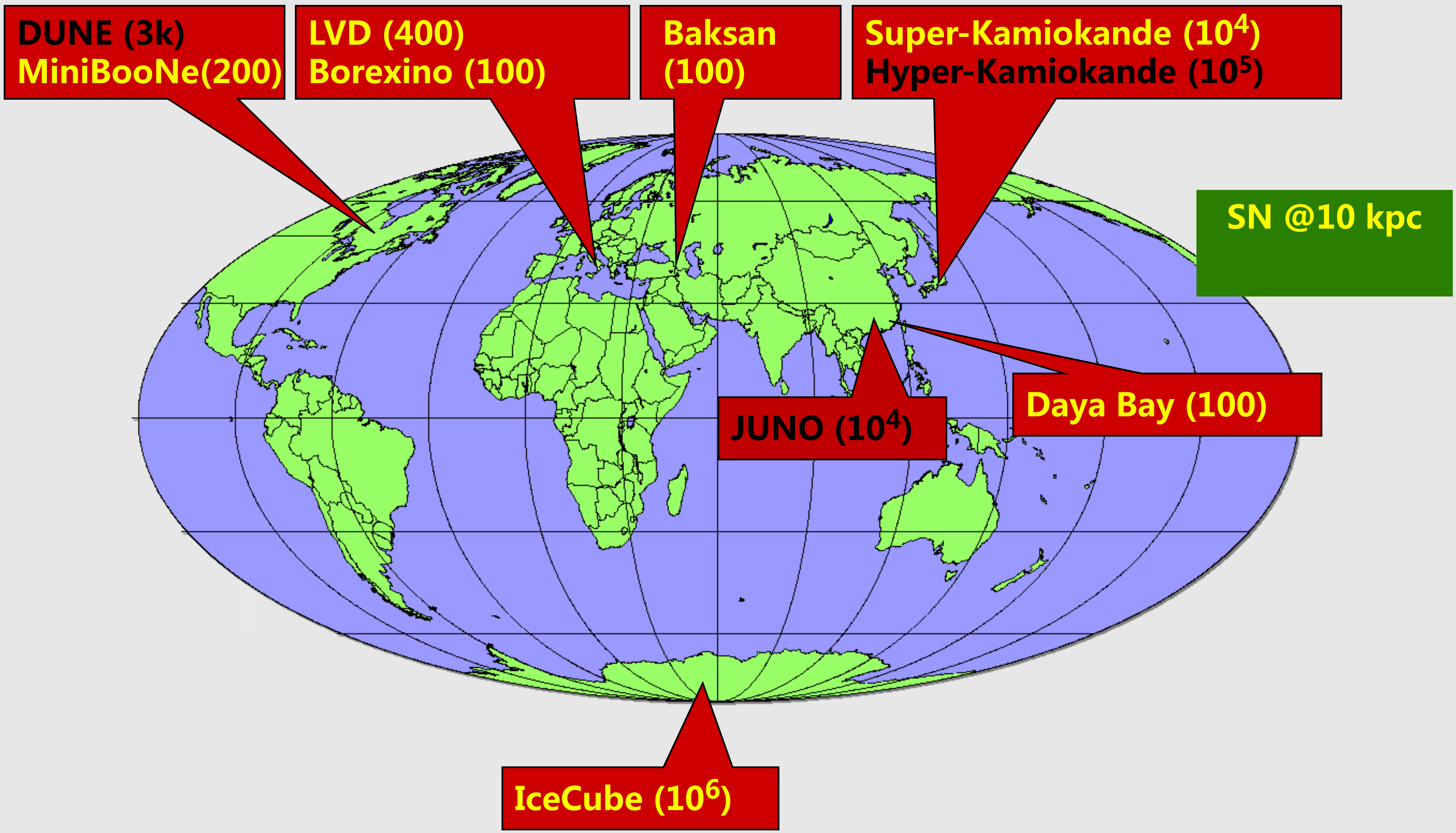
SN neutrino flux model effects





The numerical models are all from http://asphwww.ph.noda.tus.ac.jp/snn/

SN ν Detection: present and future experiments

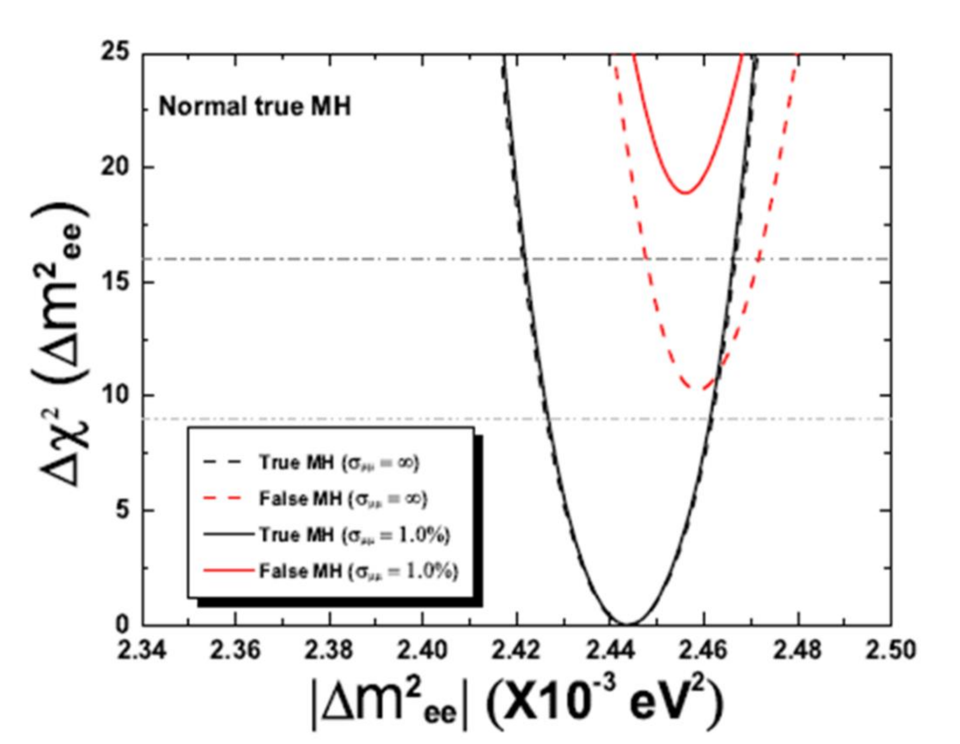


Let us hope for the next Galactic SN burst!

Thanks for your attention!

Backup

Physics Potential



Nominal assumption:

20 kton Liquid Scintillator (LS) detector

3%/sqrt(E) energy resolution

52-53 km baselines

36 GW and 6 years

Y.F Li *et al*, PRD 88, 013008 (2013)

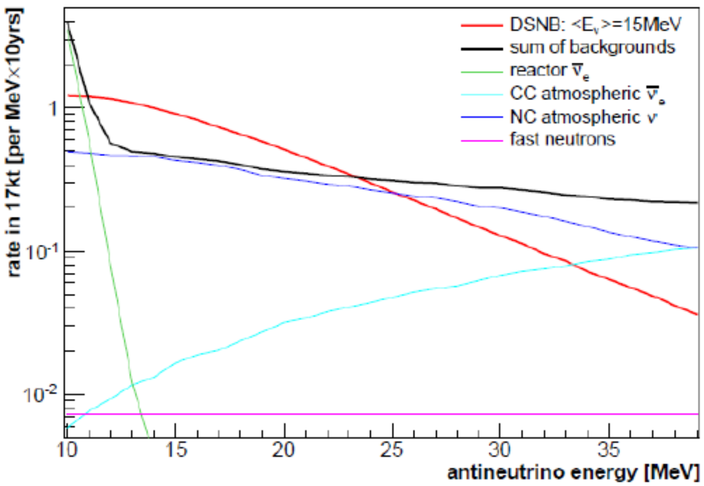
MH sensitivity for JUNO:

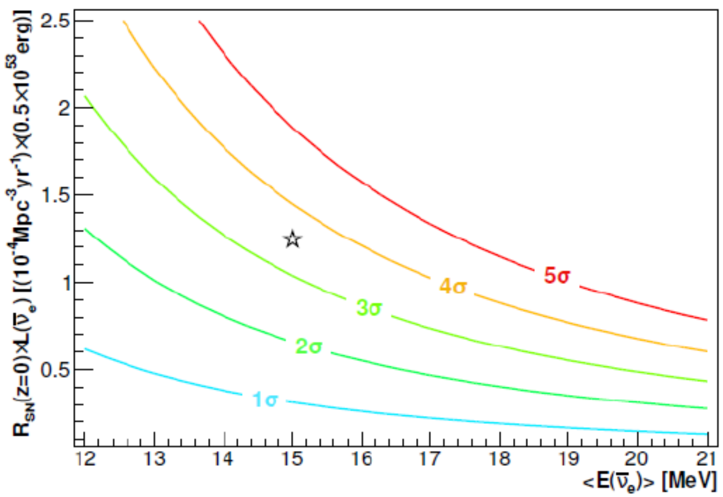
3σ ($\Delta\chi^2$>10) with the spectral measurement

4σ if including an external Δm^2(*atm*) measurement

reactor core spreads; reactor flux uncertainty; energy scale uncertainty

Diffuse Supernova Neutrino Background





- DSNB: Past core-collapse events
  - ⇨ Cosmic star-formation rate
  - ⇨ Core-collapse neutrino spectrum
  - ⇨ Rate of failed SNe

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12$ MeV	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15$ MeV	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18$ MeV	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle = 21$ MeV	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{NC} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{FN} = 1.3\,\%$	0.15
	Σ			9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	1.7 σ	1.9 σ	1.5 σ	1.7 σ
15 MeV	3.3 σ	3.5 σ	3.0 σ	3.2 σ
18 MeV	5.1 σ	5.4 σ	4.6 σ	4.7 σ
21 MeV	6.9 σ	7.3 σ	6.2 σ	6.4 σ