Supernova Neutrinos in Future LS Detectors

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Neutrino Oscillation Wokshop (NOW2016)

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Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

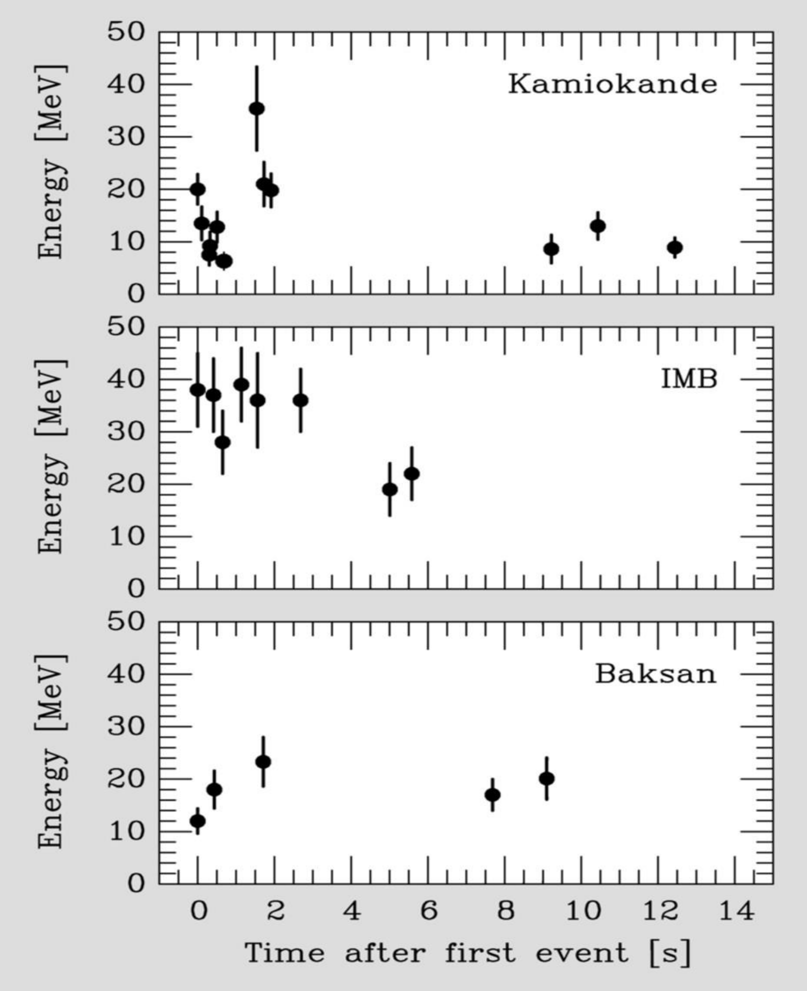
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

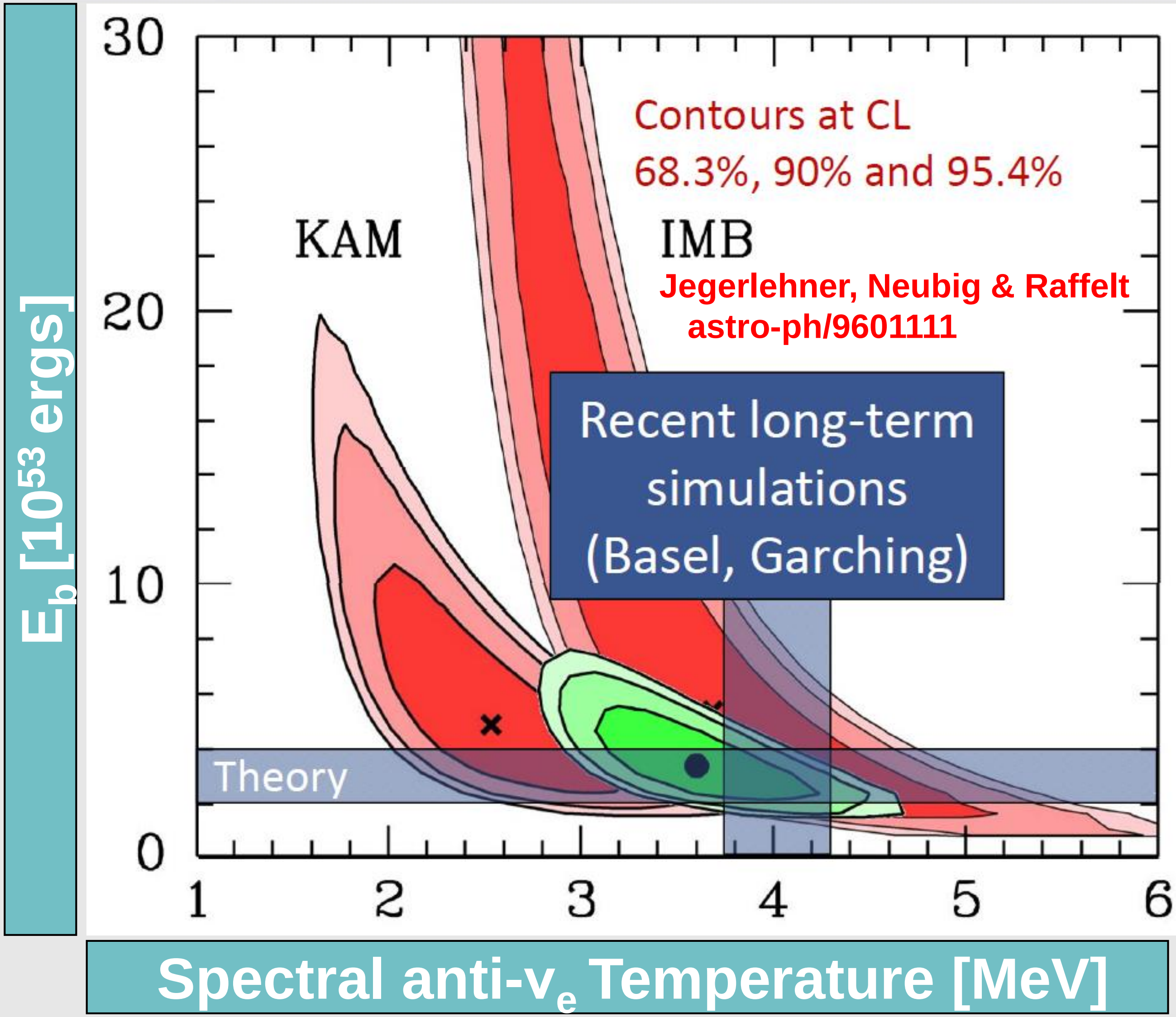
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A

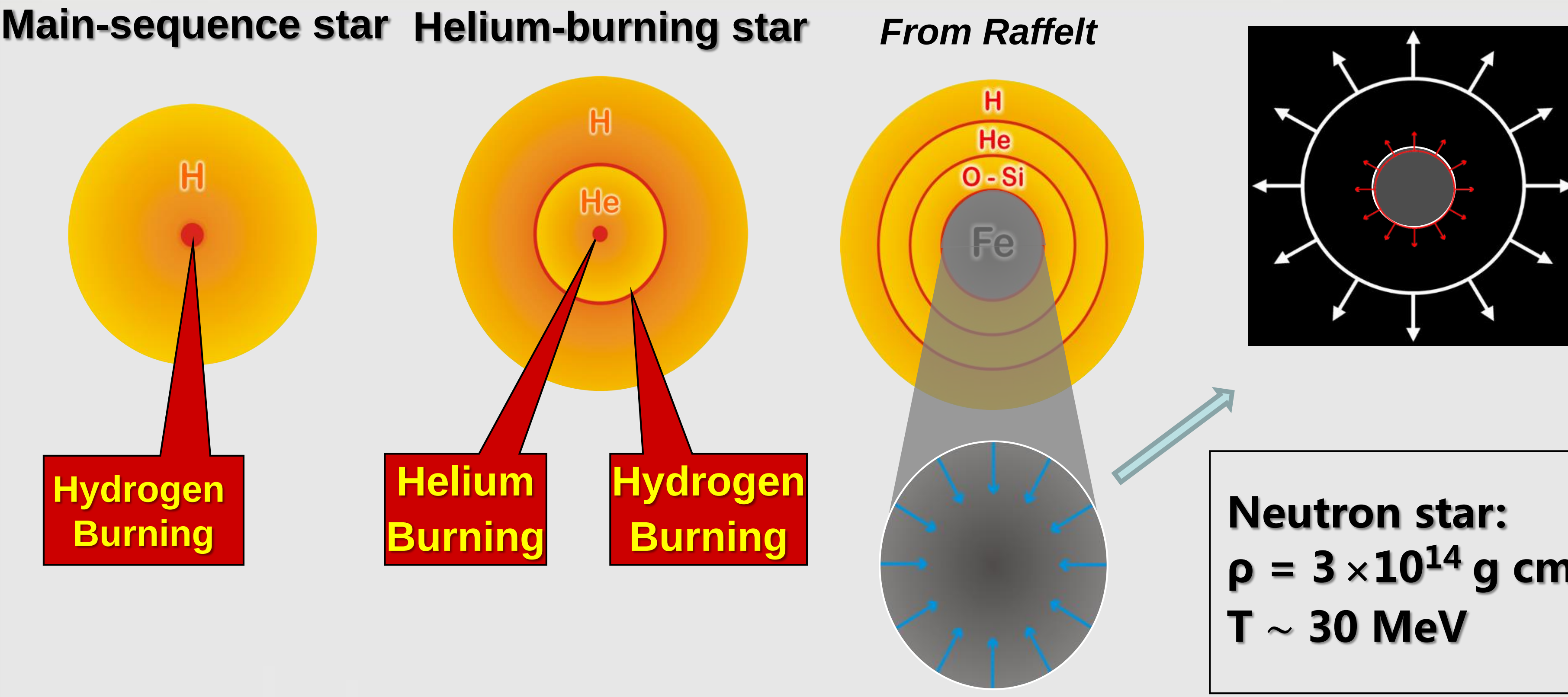


Assumptions:
Thermal spectrum
Equipartition

Conclusions:
Collapse with nus
Average Energy
Duration

Lessons:
once for a lifetime
Don’t miss the
Next Galactic SN

Neutrino-driven supernova explosion

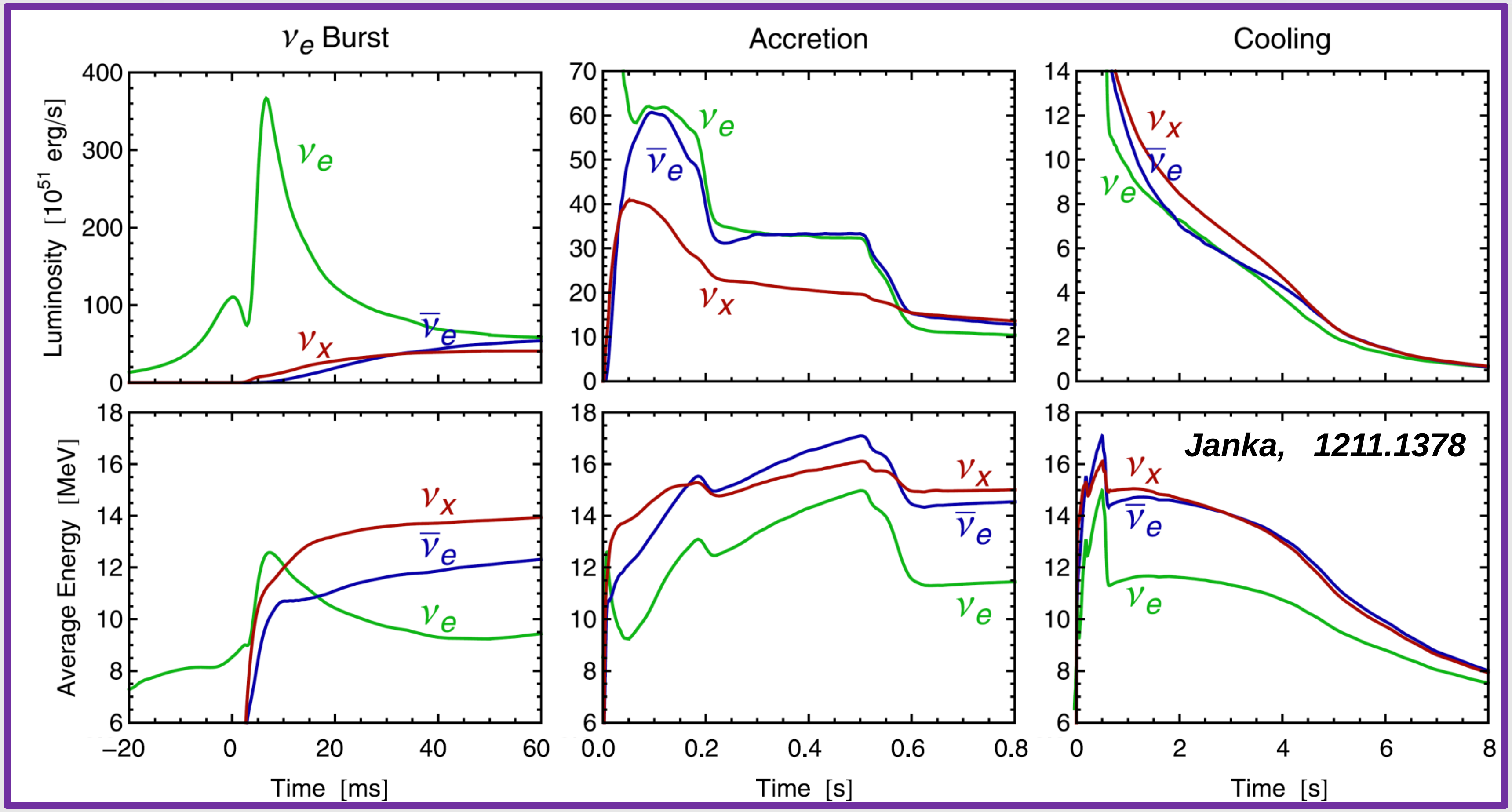


Neutron star:
$\rho = 3 \times 10^{14}$ g cm^{-3}
T ~ 30 MeV

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

SN neutrino bursts from simulation



Shock breakout

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

Shock stalls ~150 km
Neutrinos powered by infalling matter

Cooling on the neutrino diffusion time scale

Future Supernova Neutrino Detectors

(1) Water Cherenkov Detector

Hyper Kamiokande (also SuperKor 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, best energy resolution

(3) Liquid Argon Detector

DUNE: 10-40 kt, nu_edominates

(4) Ice Cherenkov Detector

Icecube: No event-by event observation, time profile

Multi-channels of neutrino detection in LS

For 20 kt LS@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

JUNO Collaboration, JPG 2016

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

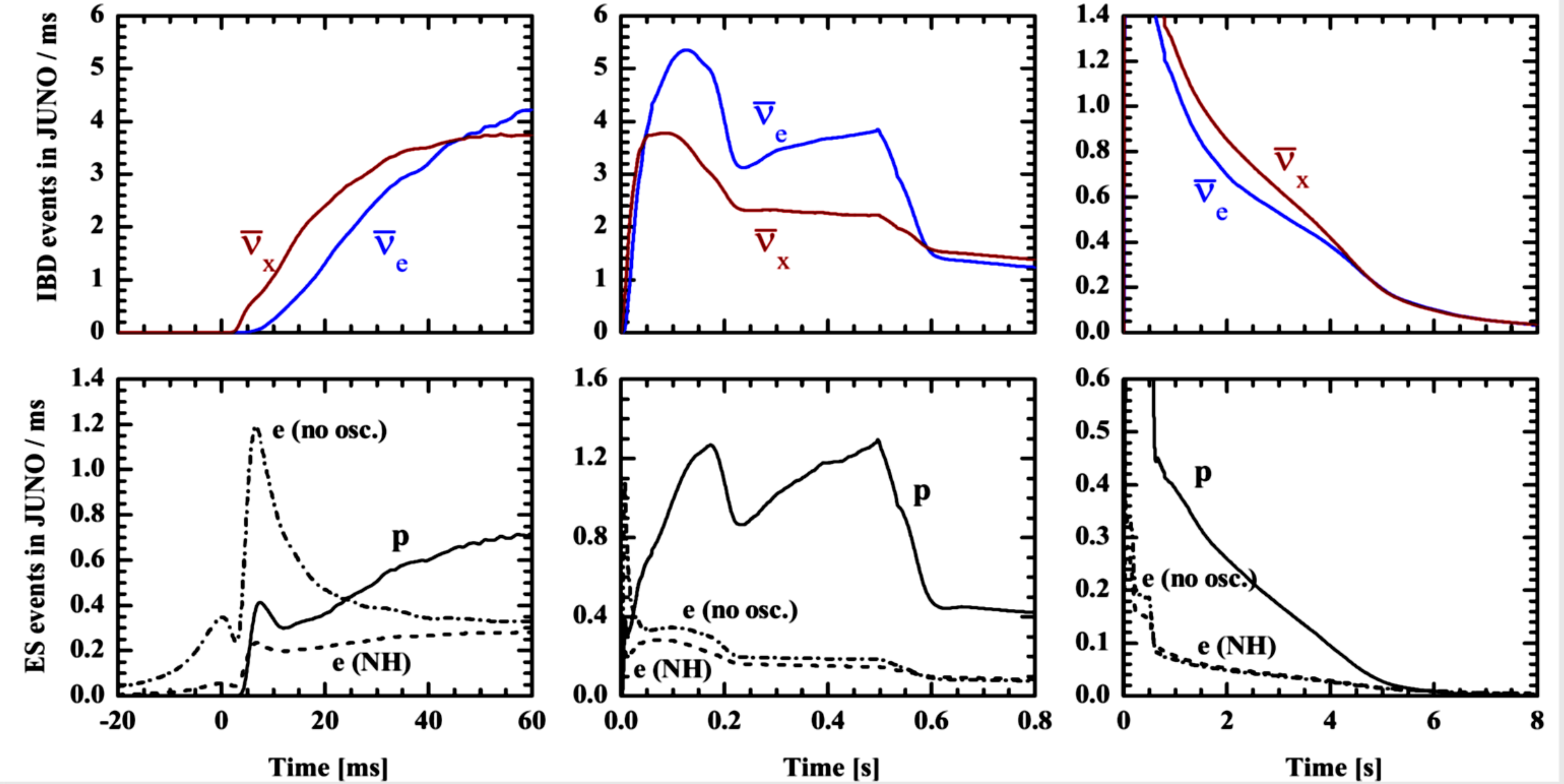
- **real-time measurement of three-phase ν signals**
- **distinguish between different ν flavors**
- **reconstruct ν energies and luminosities**
- **almost background free due to time information**

(A): Probes of all three neutrino flavors

Lu, YFL, Zhou, PRD 2016

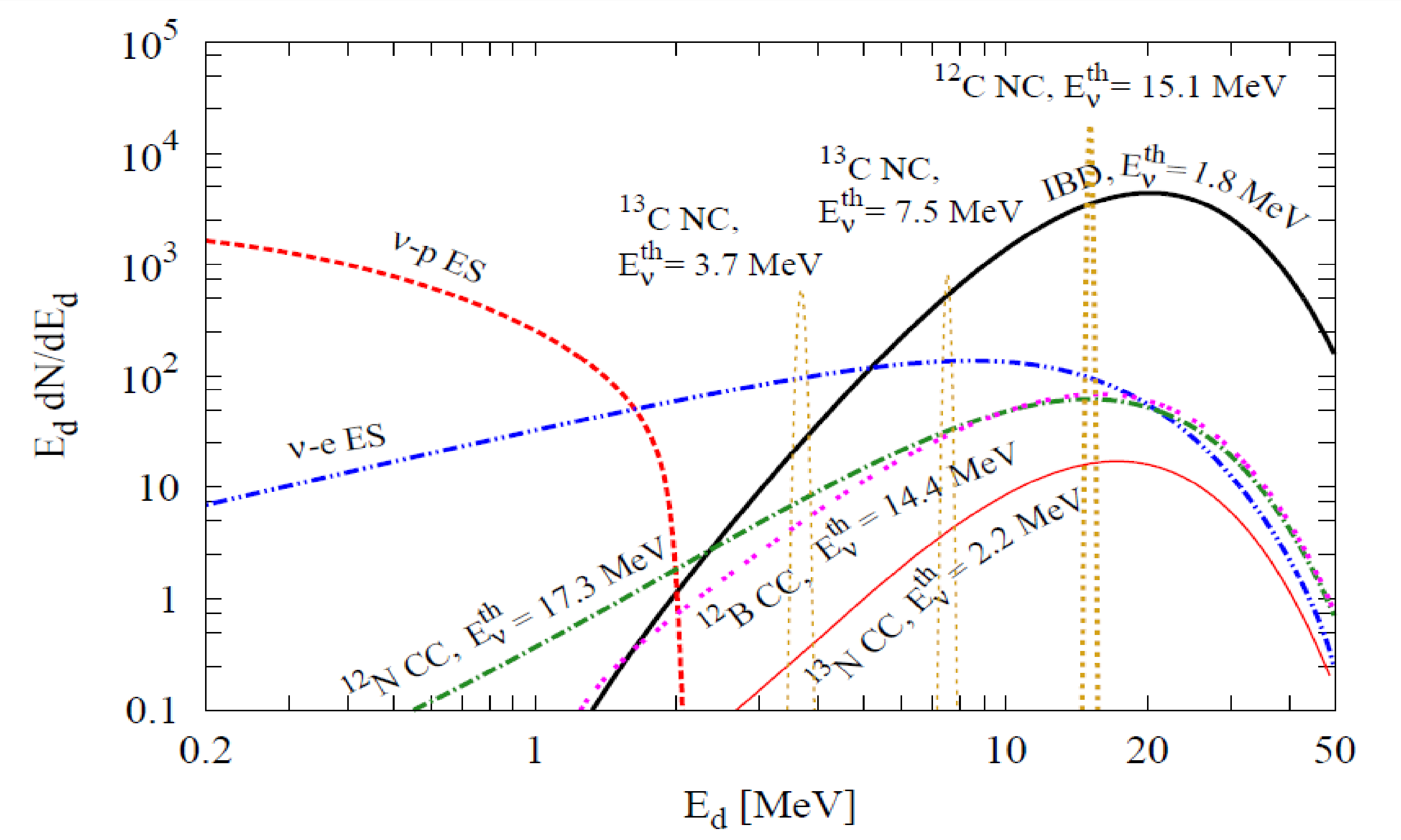
Channel	Type		Number of SN Neutrino Events at JUNO		
			No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC		43	134	106
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC		86	98	126
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226

(B): Time distribution (IBD & ES events)



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

(C): Neutrino energy distribution



Lu, YFL, Zhou, PRD 2016

See also Lujan-Peschard, Pagliaroli, Vissani, 2014

1) IBD events dominate at the high energy range
2) nu-p ES channel dominates at low energies
3) coincidence events vs. singles events
4) e. vs. p discrimination: Pulse shape discrimination

(D): Detection of SN $\bar{\nu}_e$

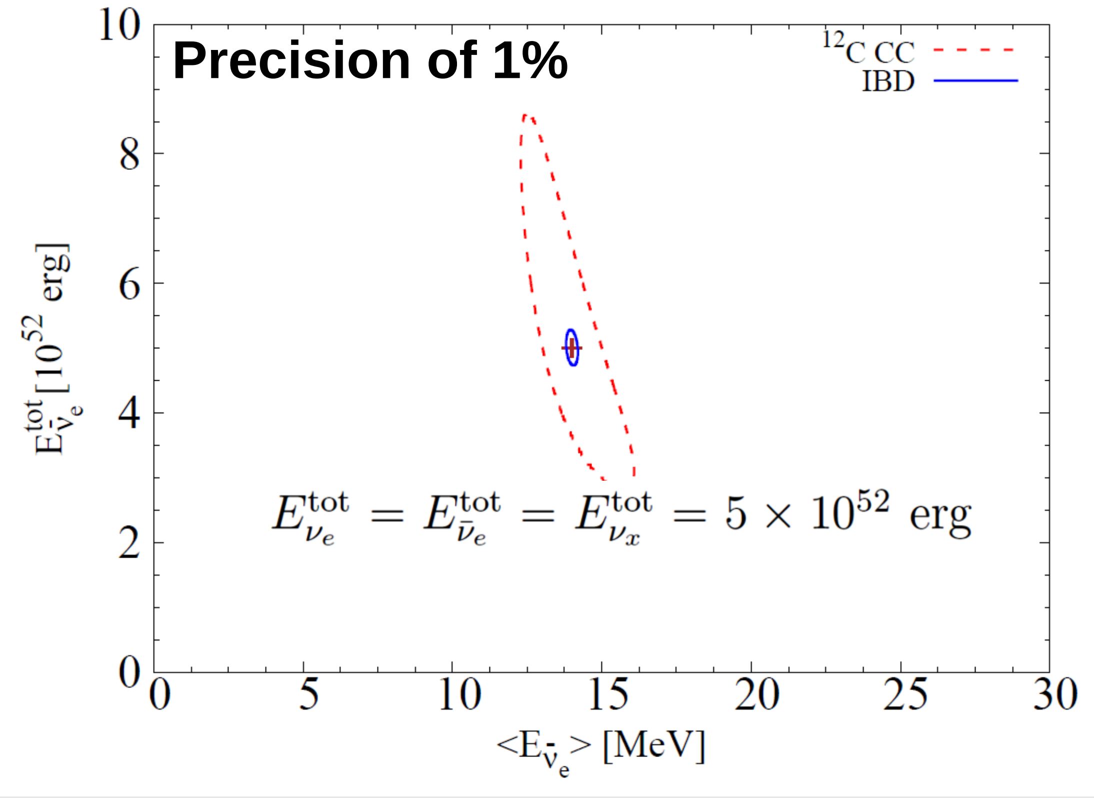
Mostly Inverse beta decay (IBD) $\bar{\nu}_e + \mathrm{p} \longrightarrow n + e^+$

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

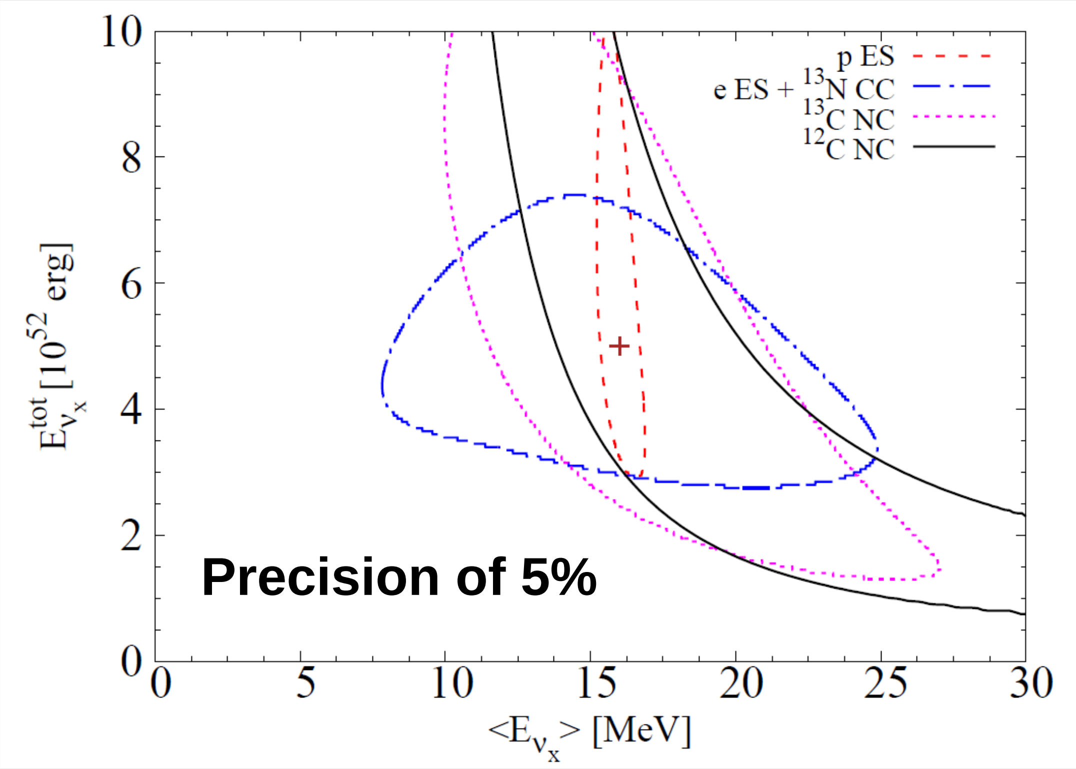


Lu, YFL, Zhou, PRD 2016

(E): Detection of SN ν_x

(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**



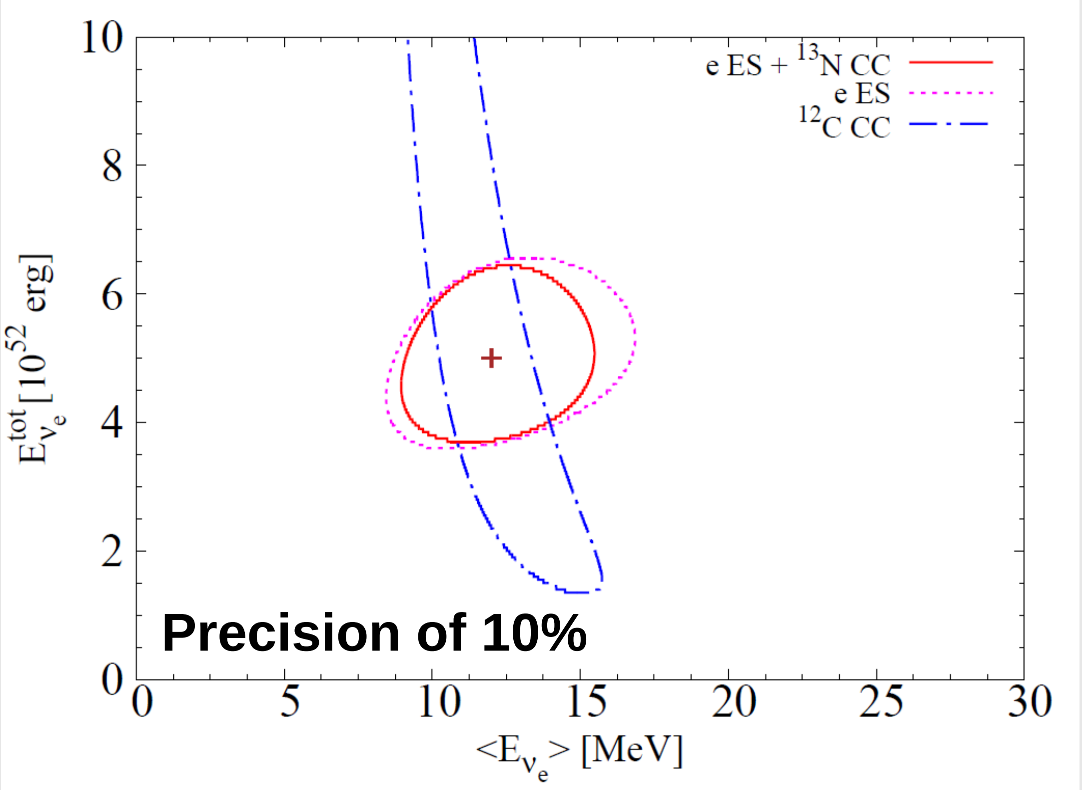
Lu, YFL, Zhou, PRD 2016

(F): Detection of SN ν_e at JUNO

(1) nu-electron scattering events: recoiled electrons

(2) nu-^{12}C CC events: coincidence with decayed ^{12}N

- ~300 eES events
- ~300 ^{12}C CC events
- Background events: from IBD in-efficiency
- electron v.s. proton: pulse shape discrimination (PSD)

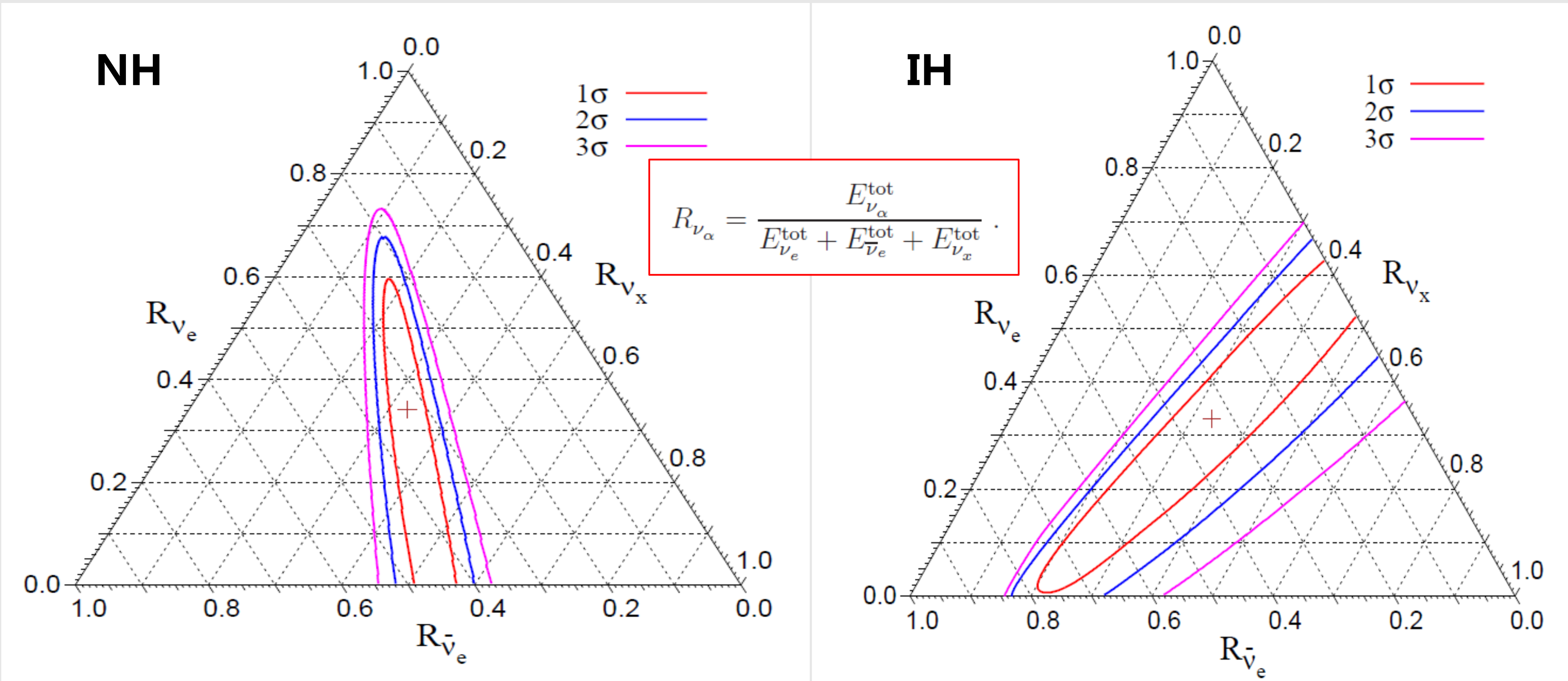


Lu, YFL, Zhou, PRD 2016

(G): Test of the energy equipartition

A fundamental assumption in SN physics
Not guaranteed in simulation

Lu, YFL, Zhou, PRD 2016



$$R_{\nu_\alpha} = \frac{E^{\rm tot}_{\nu_\alpha}}{E^{\rm tot}_{\nu_e} + E^{\rm tot}_{\overline{\nu}_e} + E^{\rm tot}_{\nu_x}} \, .$$

(1) Assuming standard MSW effects
(2) marginalization of three average energies and E_tot.

Neutrino mass scale with SN neutrinos

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

Beta decay experiments:

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

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

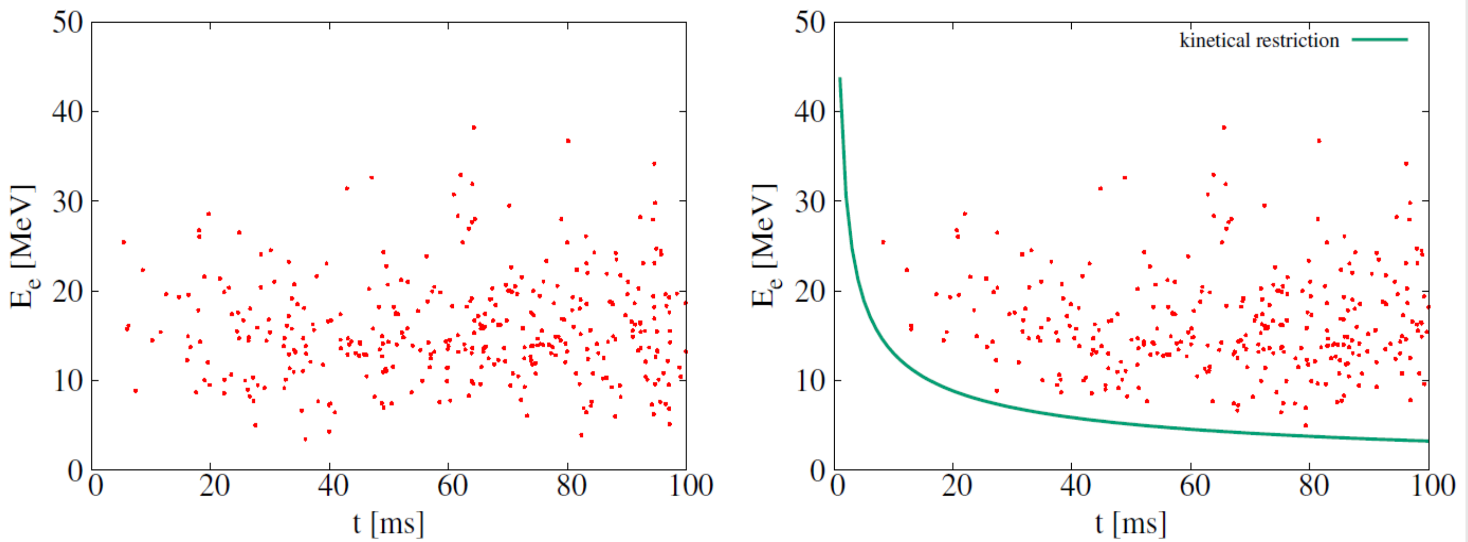


Figure: Example of time delay of SN neutrinos for a 10 kpc away SN. Left: $m_\nu = 0$. Right: $m_\nu = 2$ eV.

Method:

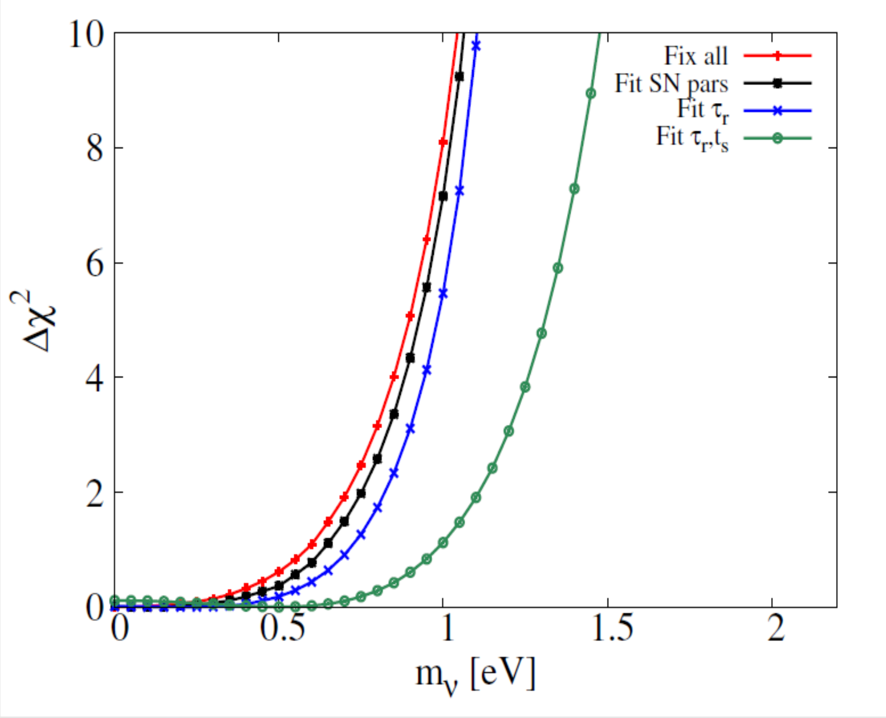
$$\mathcal{L} = e^{-\int_0^T R(t)\mathrm{d}t} \prod_{i=1}^{N} \int_{E_{\mathrm{th}}}^{\infty} R(t'_i, E_e) G(E_e + m_e, E_i; \delta E_i) \mathrm{d}E_e$$

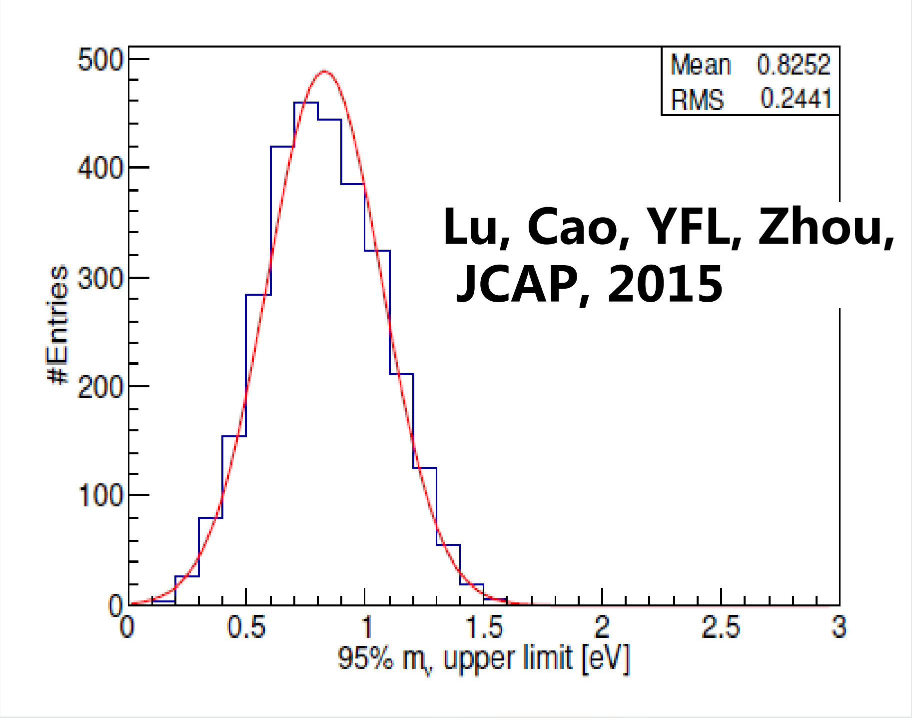
Statistical and Systematic uncertainties

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

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

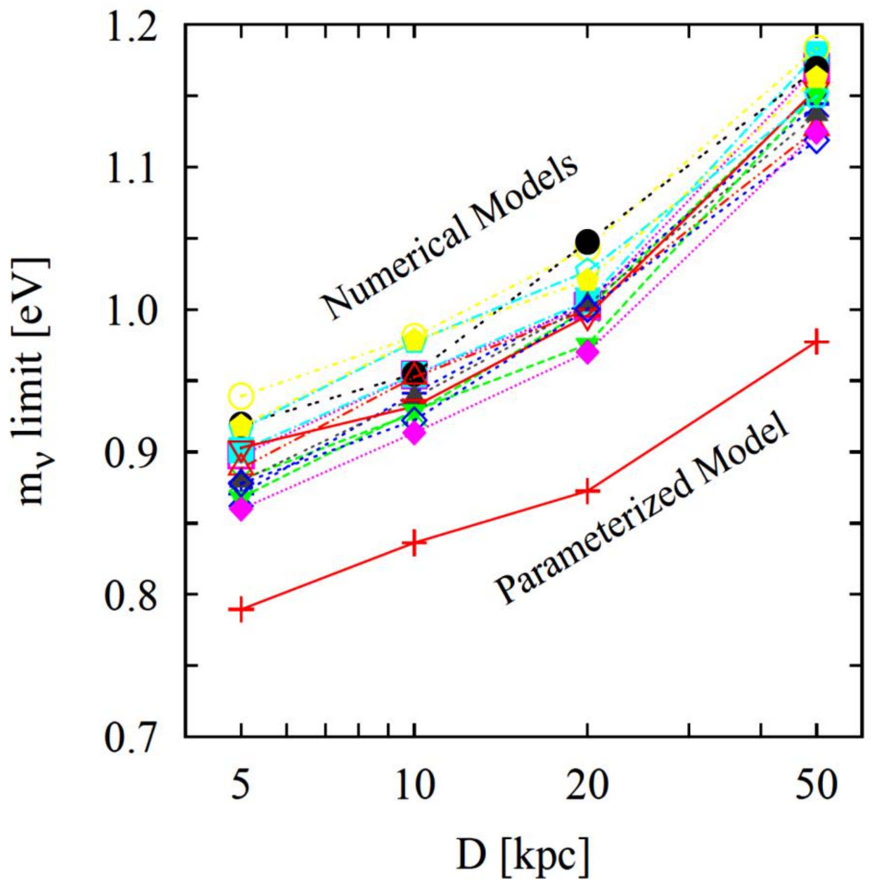
(2) With 3000 simulations, to show the fluctuation.

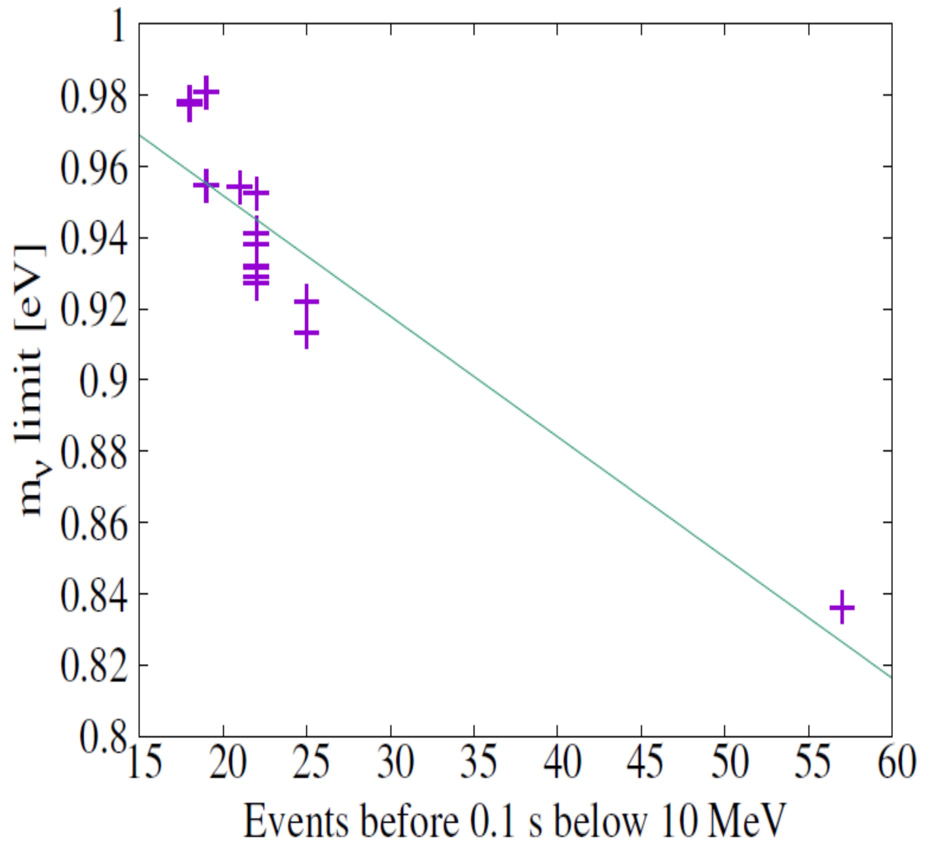




Lu, Cao, YFL, Zhou, JCAP, 2015

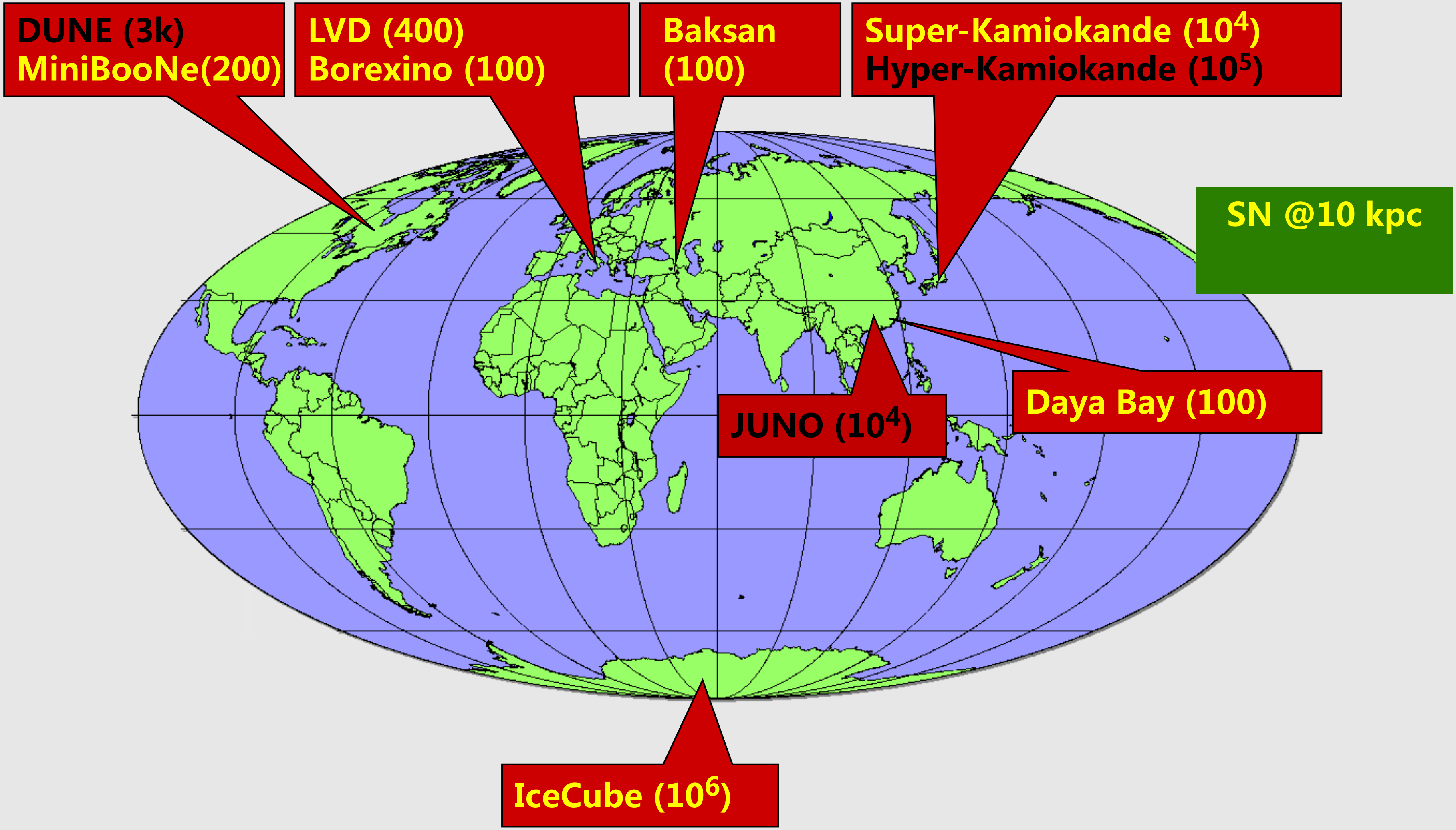
SN neutrino flux model effects





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

SN ν Detection: present and future experiments



Summary and Outlook

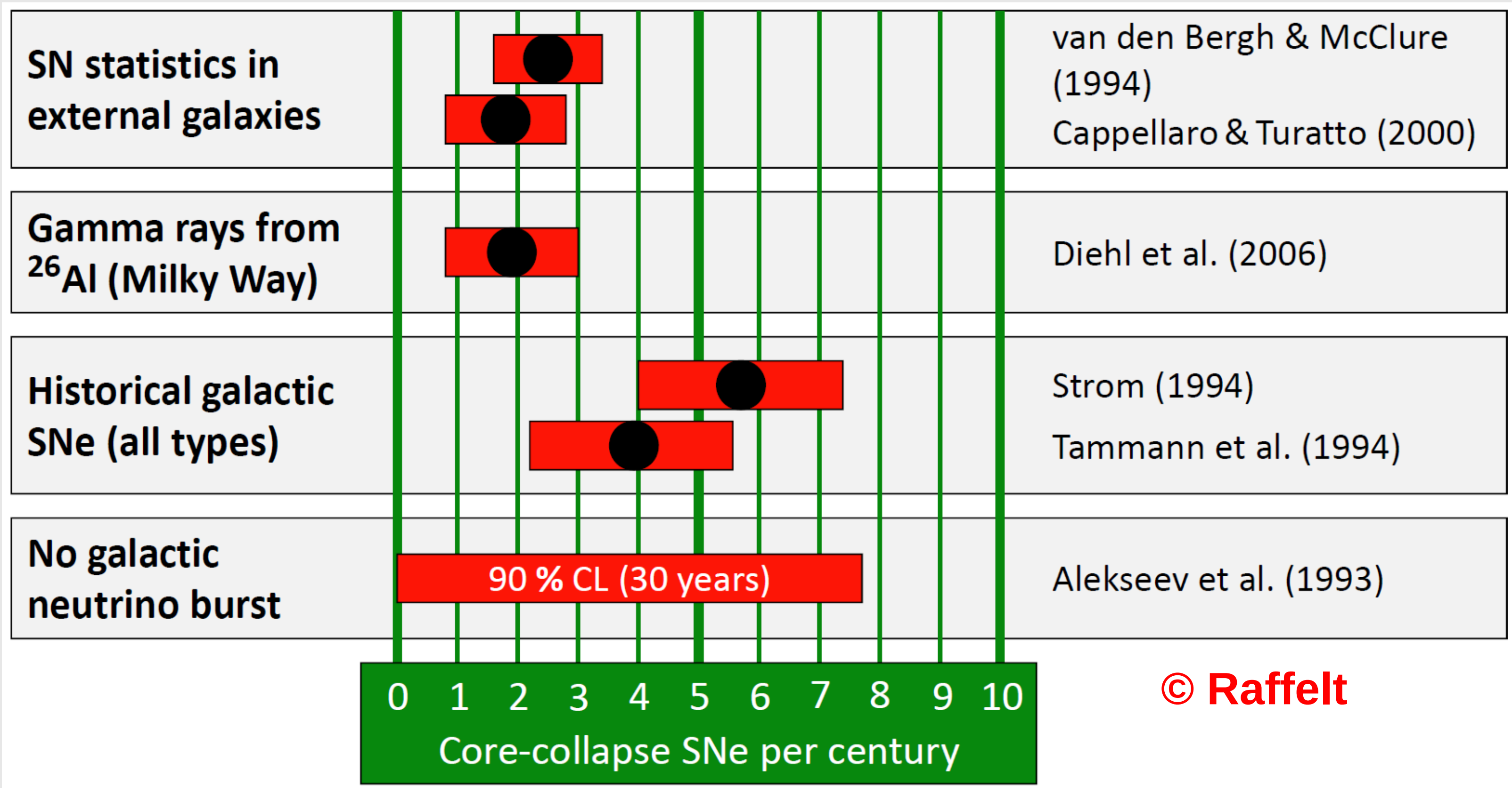
(a) Neutrinos from next nearby supernova cannot be missed (a once-in-a-lifetime opportunity!)

(b) LS, WC, LAr detectors are complementary in neutrino flavors, time distributions, energy spectra, etc.

(c) 10^4 neutrino events @ future LS detectors (JUNO) for a typical galactic SN; to reconstruct neutrino spectra, improve neutrino mass bound, probe neutrino mass ordering, directionality etc.

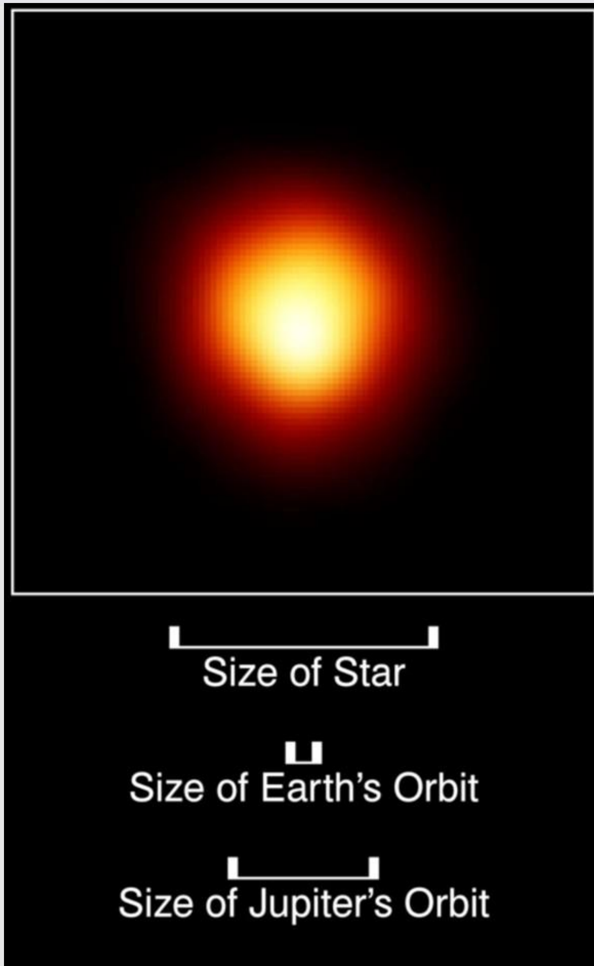
Thanks for your attention!

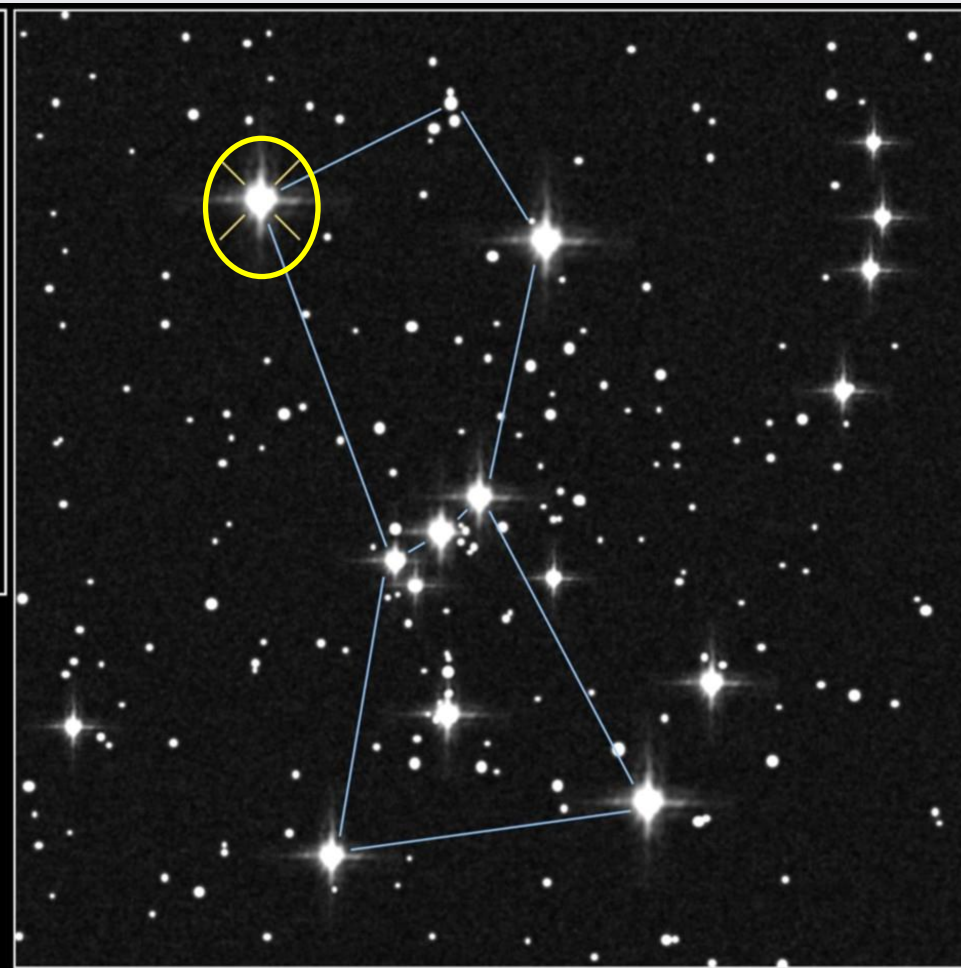
Key Problem: where and when?



(1) Estimate from SN statistics in other galaxies; (2) Only massive stars produce ^{26}Al (with a half-life 7.2×10^5 years); (3) Historical SNe in the Milky Way; (4) No neutrino bursts observed by Baksan since June 1980

SN Candidate: The Red Supergiant Betelgeuse (Alpha Orionis)





Distance: 642 ly (197 pc)
Type: Red Supergiant
Mass: ~ 18 solar masses

Expected to end its life as SN explosion
@ JUNO: 2×10^7 events

Diffuse SN Background (DSNB)

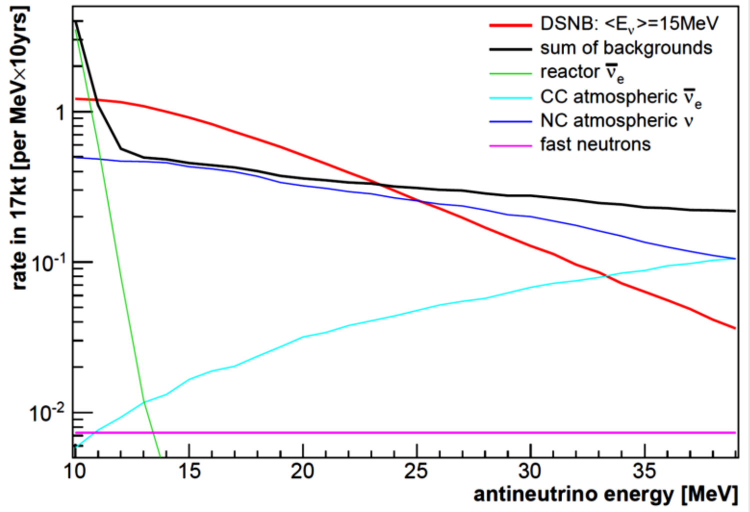
Neutrinos from all the SNe in our Universe

# of SNe per yr per Mpc³(un. SFR, IMF)

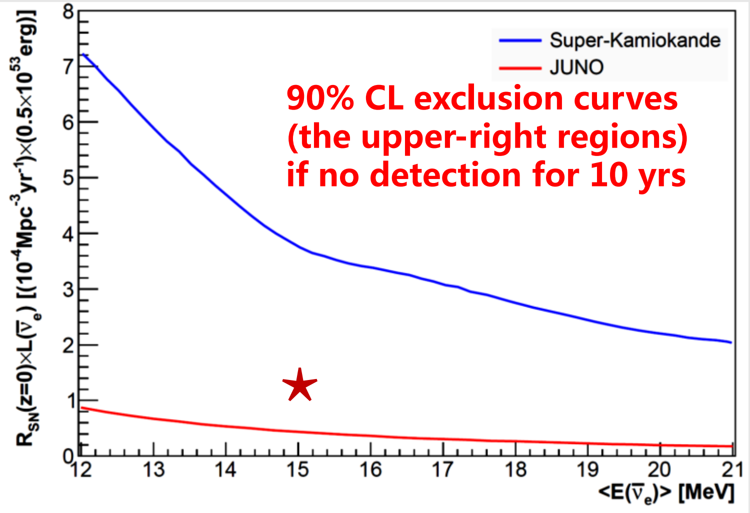
$$\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} dz \, \frac{R_{\rm SN}(z)}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}} \, \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}}$$

Cosmological evolution

ν spectrum

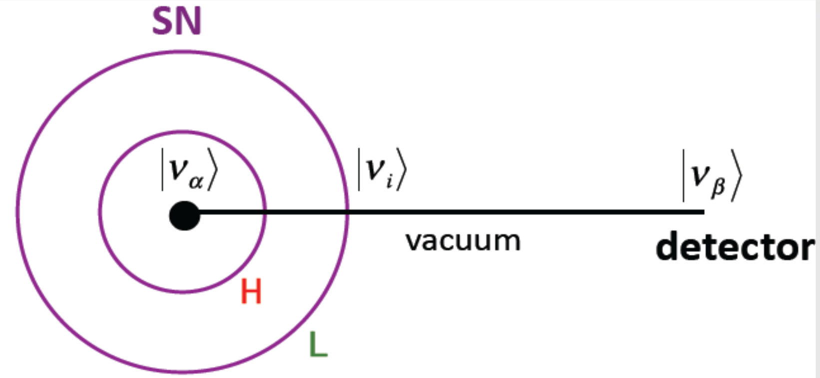


- Observation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)



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

Strategy of including oscillations



$$\phi_{\nu_e} = \phi^0_{\nu_e} P_{ee} + \phi^0_{\nu_x}(1 - P_{ee})$$

$$\phi_{\bar{\nu}_e} = \phi^0_{\bar{\nu}_e} P_{\bar{e}\bar{e}} + \phi^0_{\bar{\nu}_x}(1 - P_{\bar{e}\bar{e}})$$

$$\phi_{\nu_\mu} + \phi_{\nu_\tau} = \phi^0_{\nu_e}(1 - P_{ee}) + \phi^0_{\nu_x}(1 + P_{ee})$$

$$\phi_{\bar{\nu}_\mu} + \phi_{\bar{\nu}_\tau} = \phi^0_{\bar{\nu}_e}(1 - P_{\bar{e}\bar{e}}) + \phi^0_{\nu_x}(1 + P_{\bar{e}\bar{e}})$$