Detection of supernova ν_e in near future neutrino detectors

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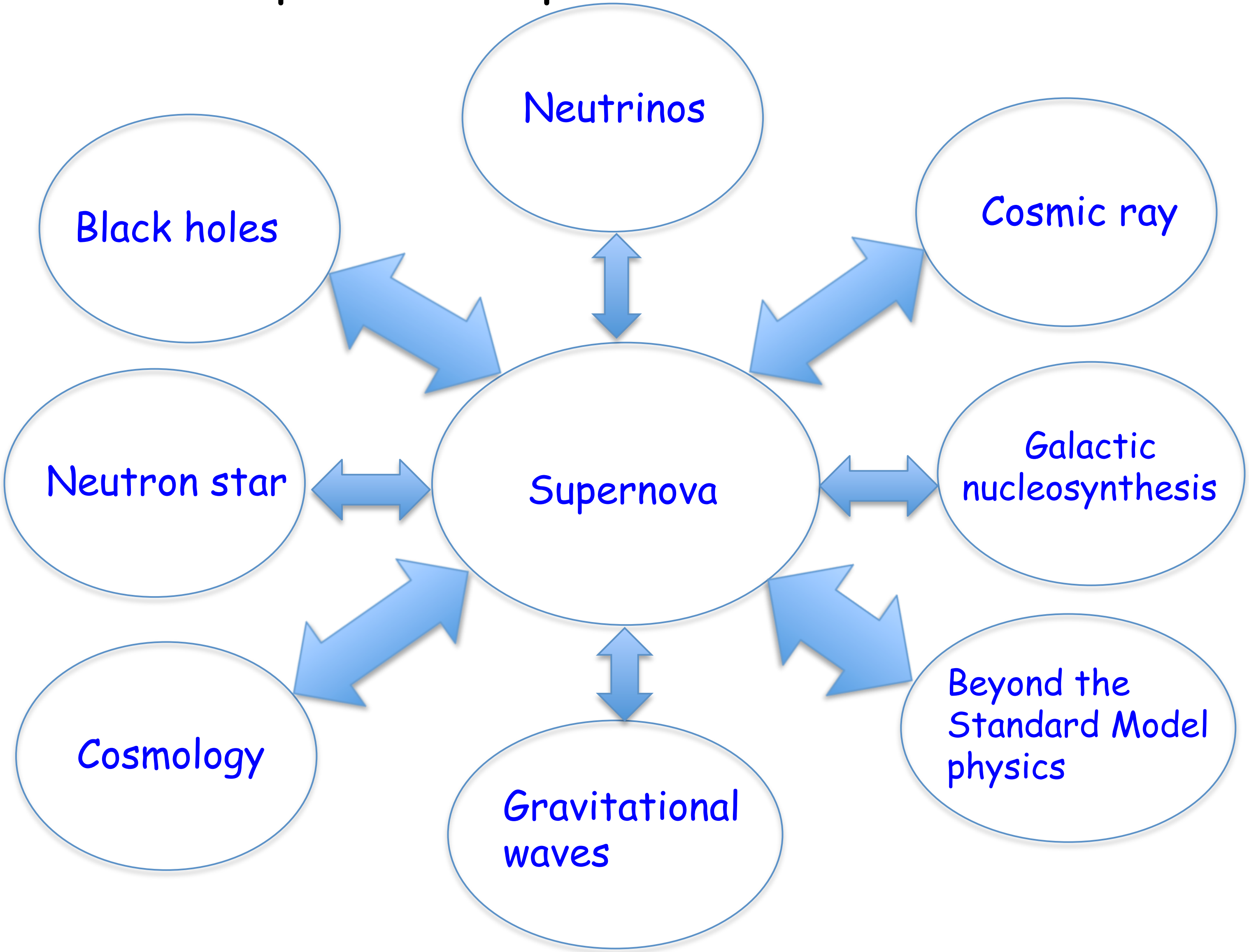
Thanks to my collaborator: J F Beacom, S Horiuchi, and A Nikrant
1311.6407, 1412.8425, 1711.00008

Why study supernovae?

- What happens to a star after it dies?
- How does a supernova explode?



Supernova

Neutrinos

Cosmic ray

Galactic nucleosynthesis

Beyond the Standard Model physics

Gravitational waves

Cosmology

Neutron star

Black holes

Supernova neutrino astroparticle physics

snap.lbl.gov

Stars must die --- we just do not know how

SN 1987A

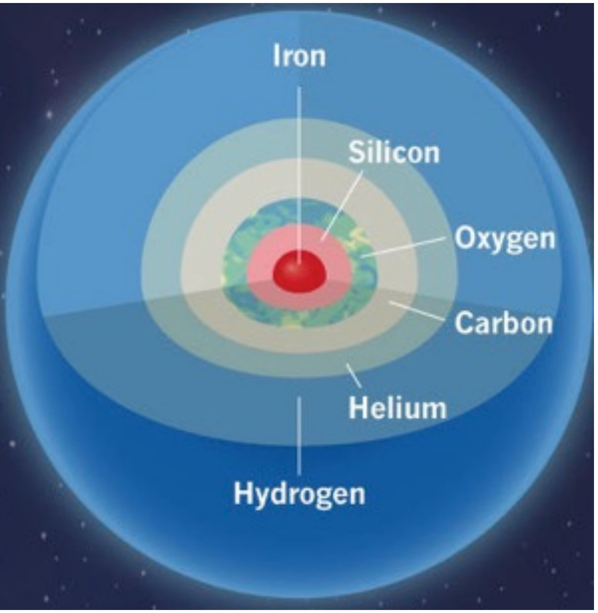
For massive stars ($> \; 8\, M_\odot$), most of the energy (~ 99%) is dissipated in neutrinos --- detecting them might solve the puzzle

Supernova explosion mechanism and supernova neutrino emission

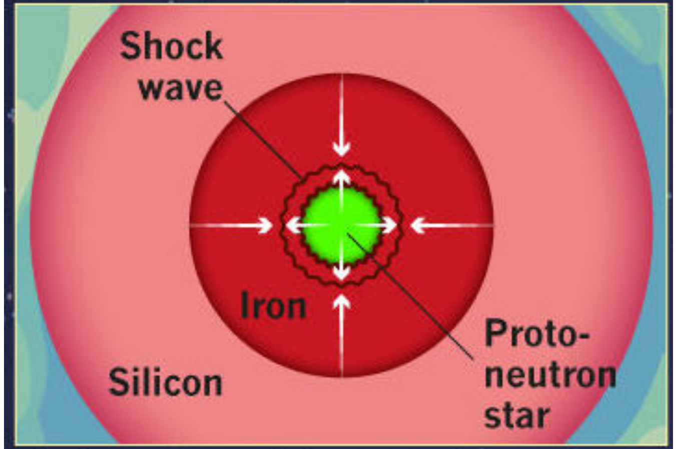
Supernova explosion

STAR'S END

When a massive star explodes, it seeds the space around it with a number of atomic species — the makings of future planets and stars. The process begins deep inside the star, as it runs low on hydrogen. As the star contracts, atoms fuse into progressively heavier elements. These form onion-like rings and a core at the centre made of iron (layers and core not shown to scale).

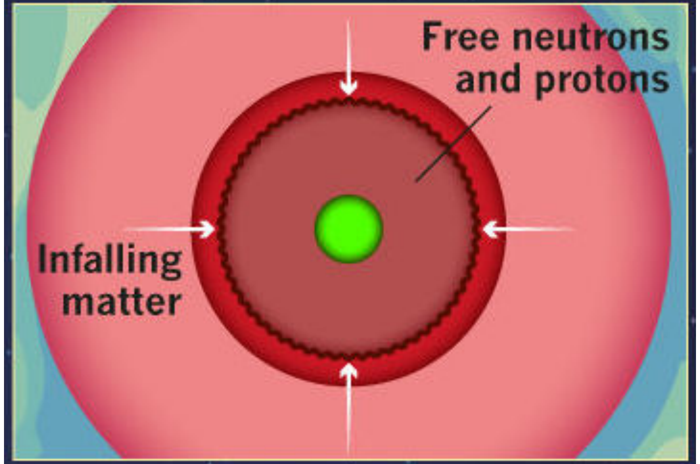


1. CORE BOUNCE



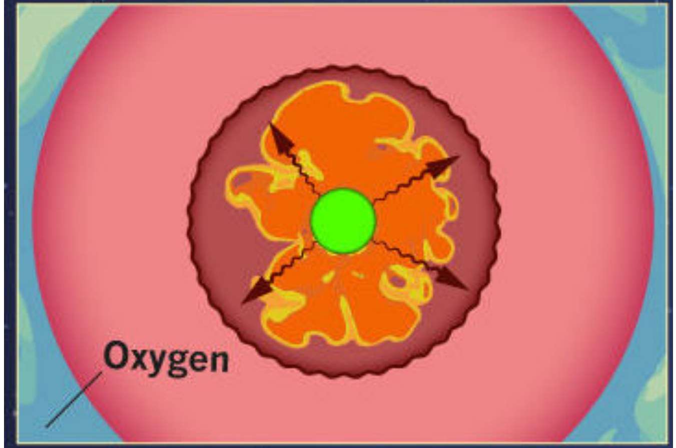
The growing iron core collapses under gravity, forming a neutron star. Infalling material bounces off the neutron star, creating a shock wave.

2. SHOCK STAGNATION



The outward-travelling shock wave collides with still-falling iron in the outer layers of the iron core and stalls.

3. NEUTRINO HEATING

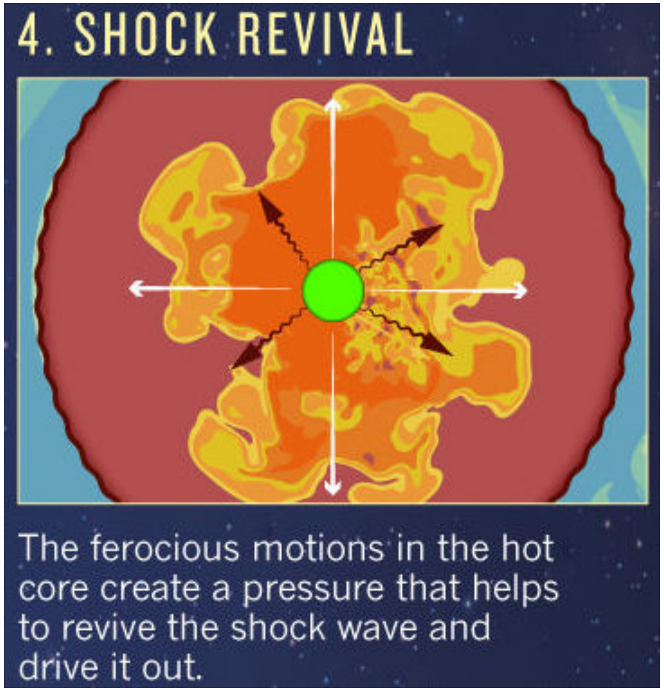


Neutrinos emerge from the neutron star and heat up surrounding matter. The heat creates violent sloshing motions and bubbling convection.

https://www.nature.com/articles/d41586-018-04601-7

Janka 1702.08825

Supernova explosion (contd.)

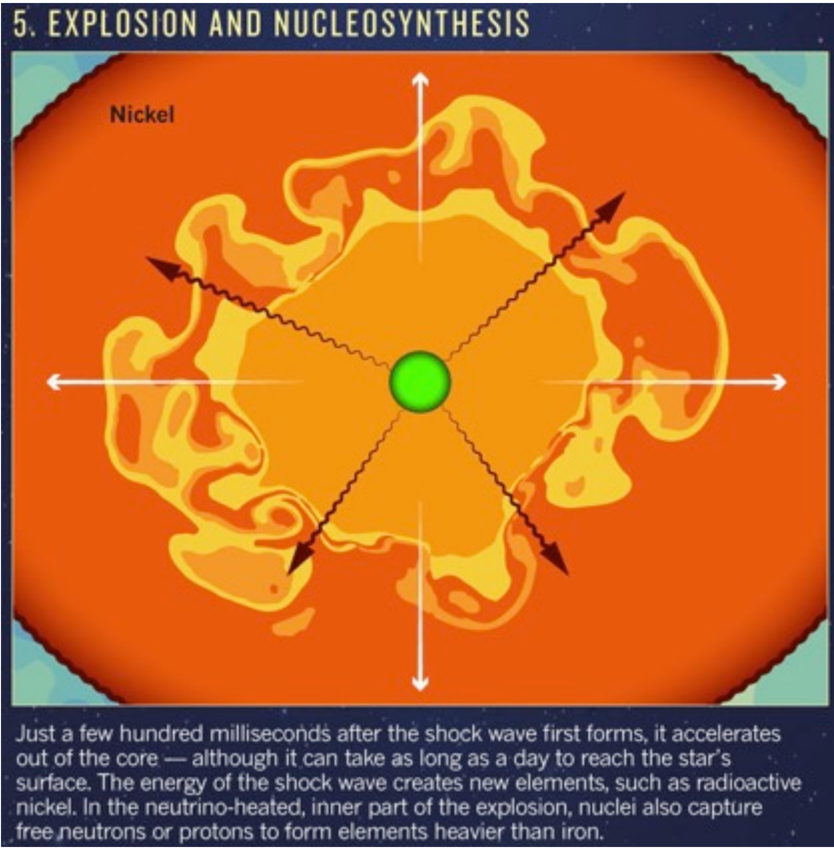


4. SHOCK REVIVAL

The ferocious motions in the hot core create a pressure that helps to revive the shock wave and drive it out.

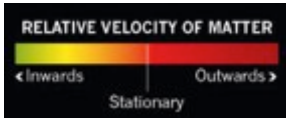
https://www.nature.com/articles/d41586-018-04601-7

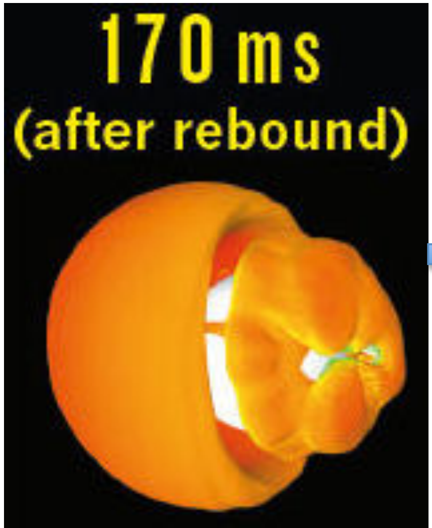
Janka 1702.08825

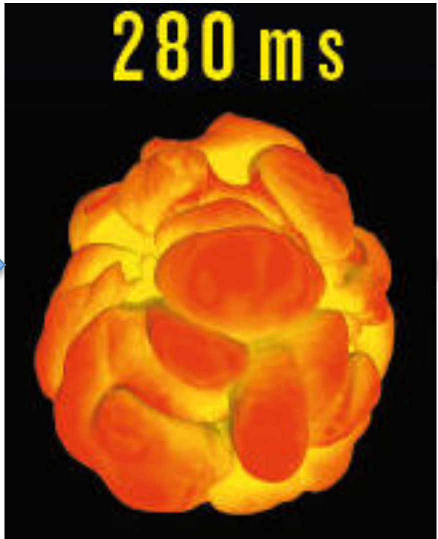


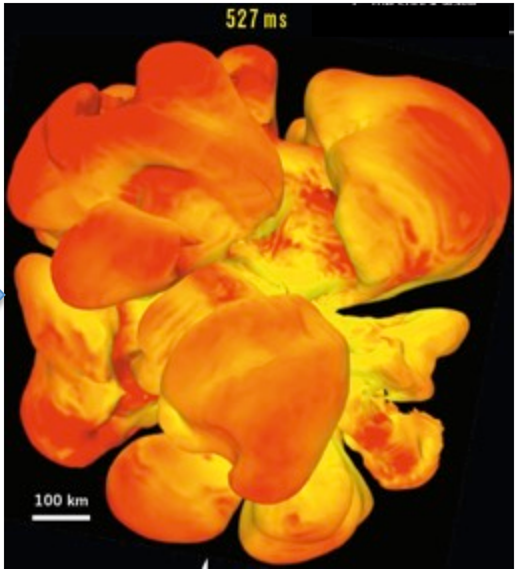
5. EXPLOSION AND NUCLEOSYNTHESIS

Just a few hundred milliseconds after the shock wave first forms, it accelerates out of the core — although it can take as long as a day to reach the star's surface. The energy of the shock wave creates new elements, such as radioactive nickel. In the neutrino-heated, inner part of the explosion, nuclei also capture free neutrons or protons to form elements heavier than iron.

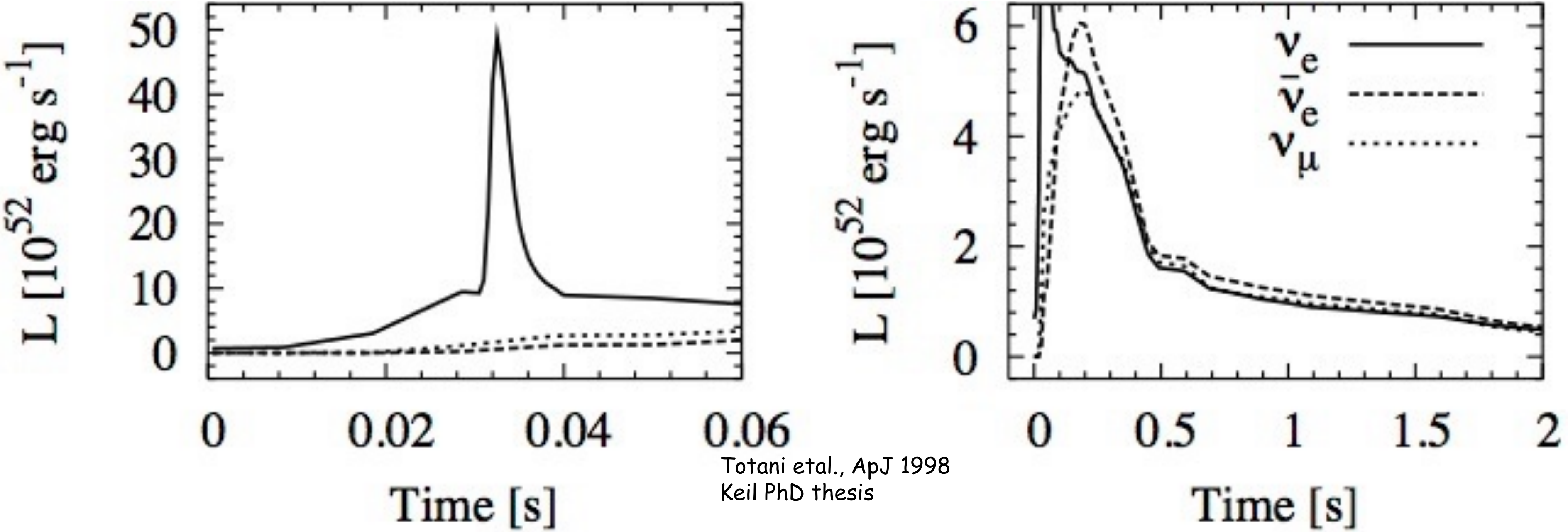








Theoretical expectations



Totani etal., ApJ 1998
Keil PhD thesis

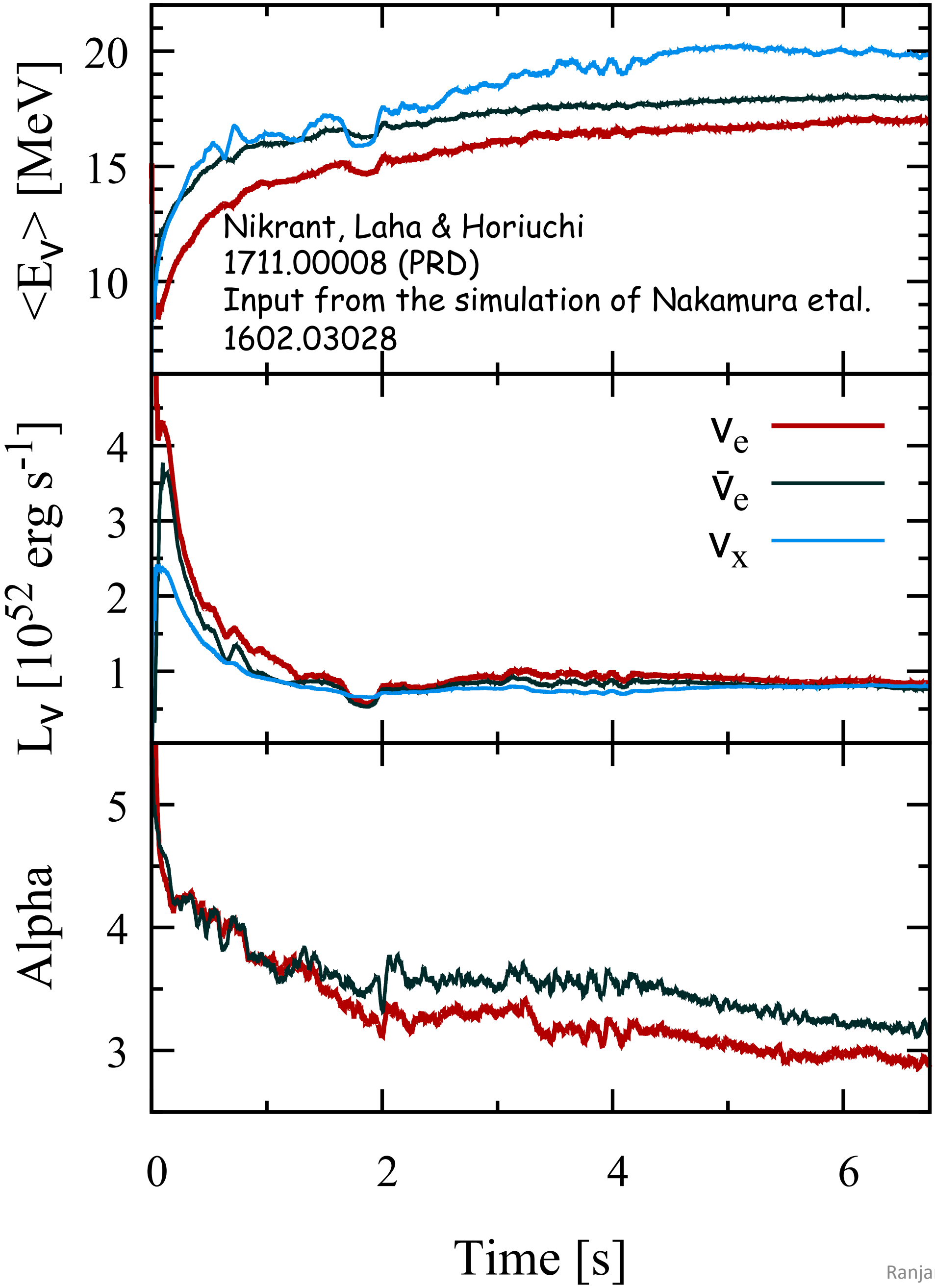
Neutrino burst of all flavors --- lasting for ~ 10 seconds

Neutrino energies up to ~ 50 MeV

Total energy carried by the neutrinos is approximately the full binding energy of the star ≈ 3×10^{53} erg --- must detect ALL the neutrinos

Neutrinos can be detected from Galactic supernova in large numbers

From numerical simulations



Nikrant, Laha & Horiuchi
1711.00008 (PRD)
Input from the simulation of Nakamura etal.
1602.03028

$$\nu_x = \nu_\mu + \nu_\tau + \mathrm{anti-particles}$$

$$\frac{dN_\nu}{dE_\nu}(E_\nu) = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \times \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

E_ν = neutrino energy

$\langle E_\nu \rangle$ = average neutrino energy of the spectrum

$$\Phi(E_\nu) = \frac{1}{4\pi d^2}\frac{E_\nu^{\mathrm{tot}}}{\langle E_\nu\rangle}\frac{dN_\nu}{dE_\nu}$$

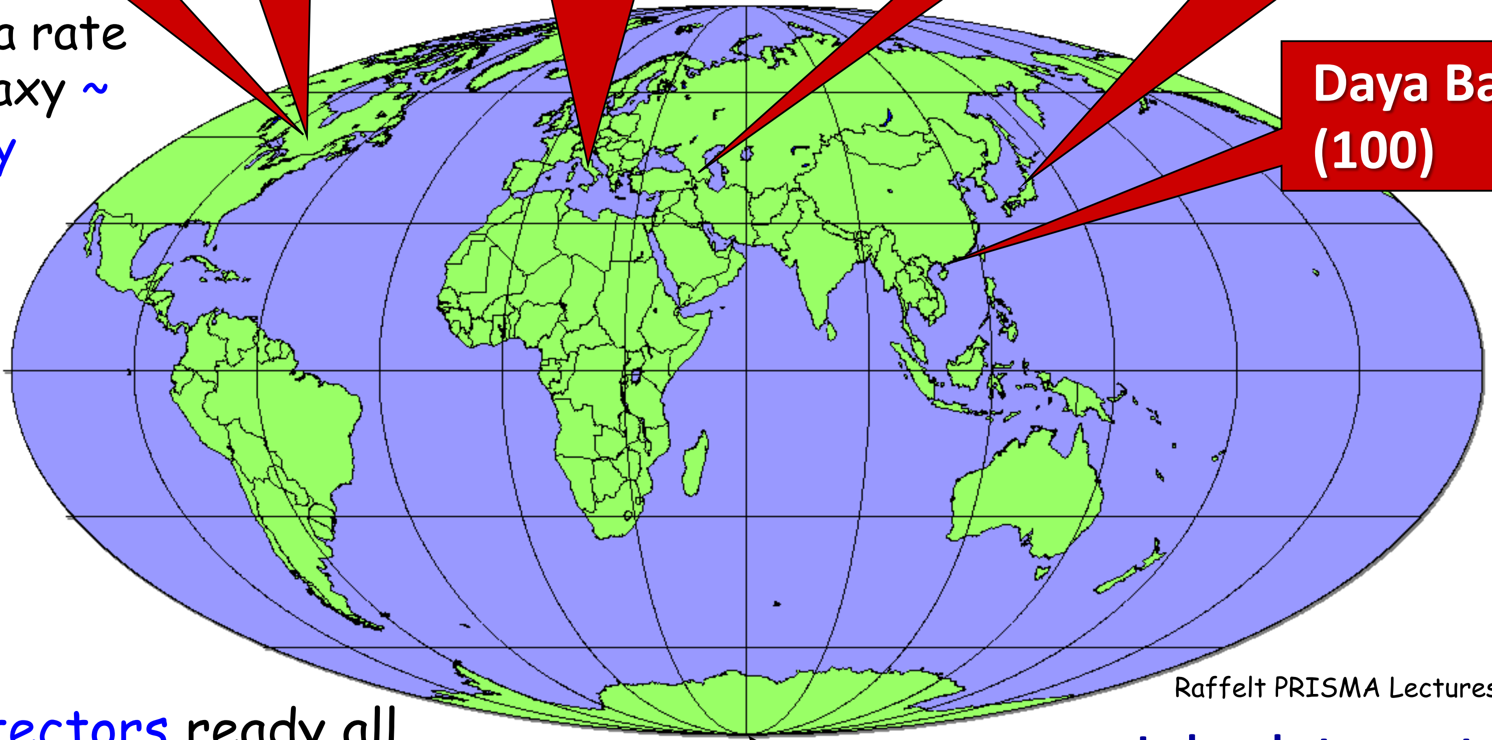
Neutrino fluence

Distance from the supernova to the Earth = 10 kpc

Supernova neutrino detectors and supernova neutrino detection

Supernova neutrino detectors all around the World

Operational Detectors for Supernova Neutrinos



SNO+ (300)

HALO (tens)

LVD (400)
Borexino (100)

Baksan (100)

Super-K (10^4)
KamLAND (400)

Daya Bay (100)

IceCube (10^6)

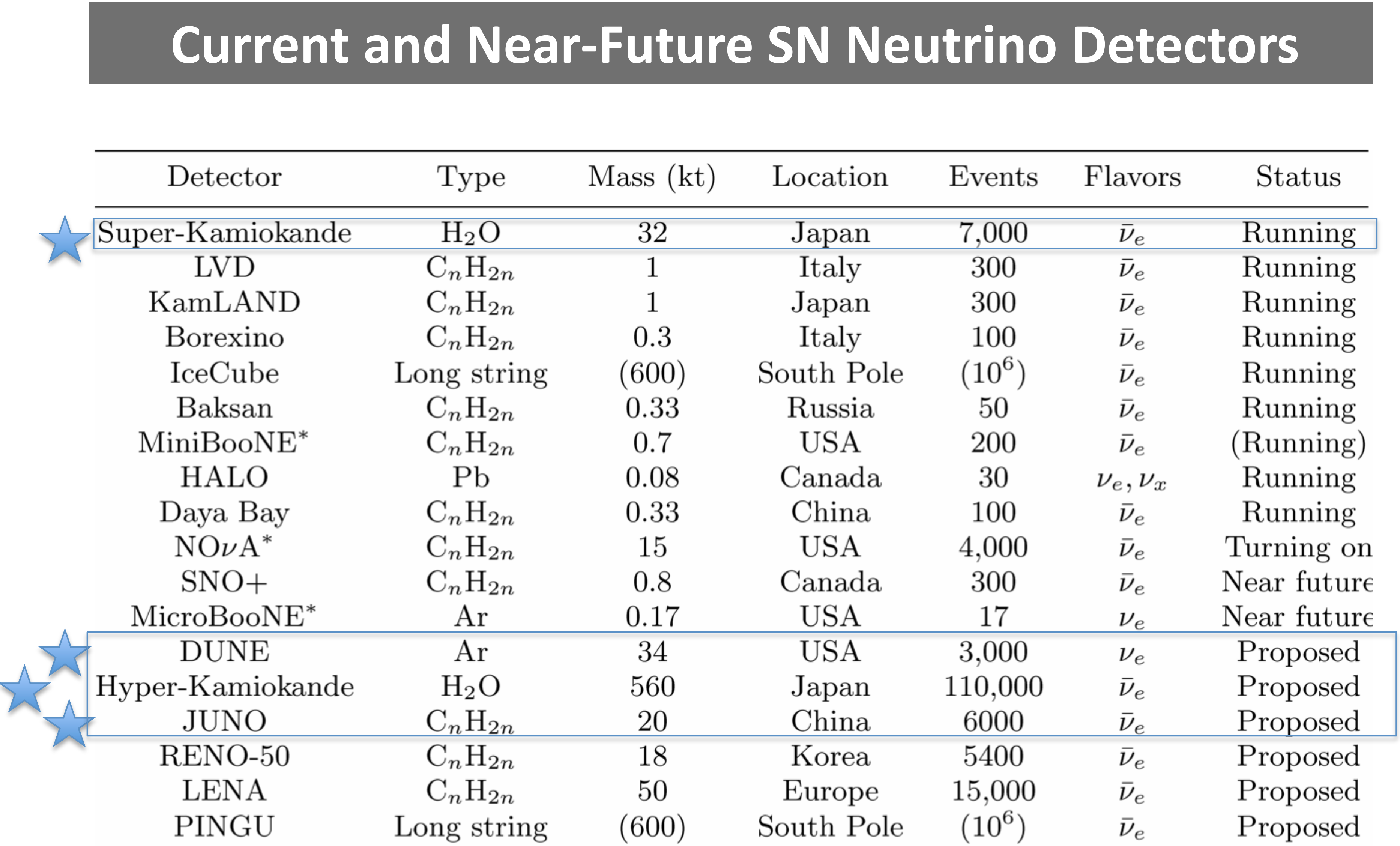
Supernova rate in our galaxy ~ 1/ century

Many detectors ready all over the world to detect the supernova neutrinos

Raffelt PRISMA Lectures in Mainz 2015

In brackets events for a "fiducial SN" at distance 10 kpc

Event numbers in various detectors



Current and Near-Future SN Neutrino Detectors

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Multiple detectors necessary --- IMB would have missed SN 1987A if there was no Kamiokande-II and if the supernova light was attenuated

K. Scholberg in arXiv:1508.00785

Supernova neutrino detection: $\bar{\nu}_e$

$\bar{\nu}_e + p \rightarrow e^+ + n$: Inverse beta (IB) interaction

water Cherenkov / liquid scintillator detector

e^+: Detected by Cherenkov radiation/ scintillation

n : At present difficult to detect via proton capture; near future addition of Gadolinium (Gd) in water Cherenkov detectors will improve detection prospects

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}\,\mathrm{cm}^2\, p_e E_e E_\nu^{-0.07056+0.02018\ln E_\nu - 0.001953\ln^3 E_\nu}$$

Strumia & Vissani 2003

Threshold of interaction $E_\nu > 1.8\,\mathrm{MeV}$

Vogel & Beacom 1999

$$T_e \approx E_\nu - 1.8\,\mathrm{MeV}$$

T_e: kinetic energy of the positron

Largest cross section at the relevant energies (~ MeV --- 50 MeV)

Supernova neutrino detection: $\bar{\nu}_e$

- Neutron capture on free proton produces 2.2 MeV photon --- delay time ~ 200 µsec --- capture cross section 0.3 barns $n + p \rightarrow d + \gamma$

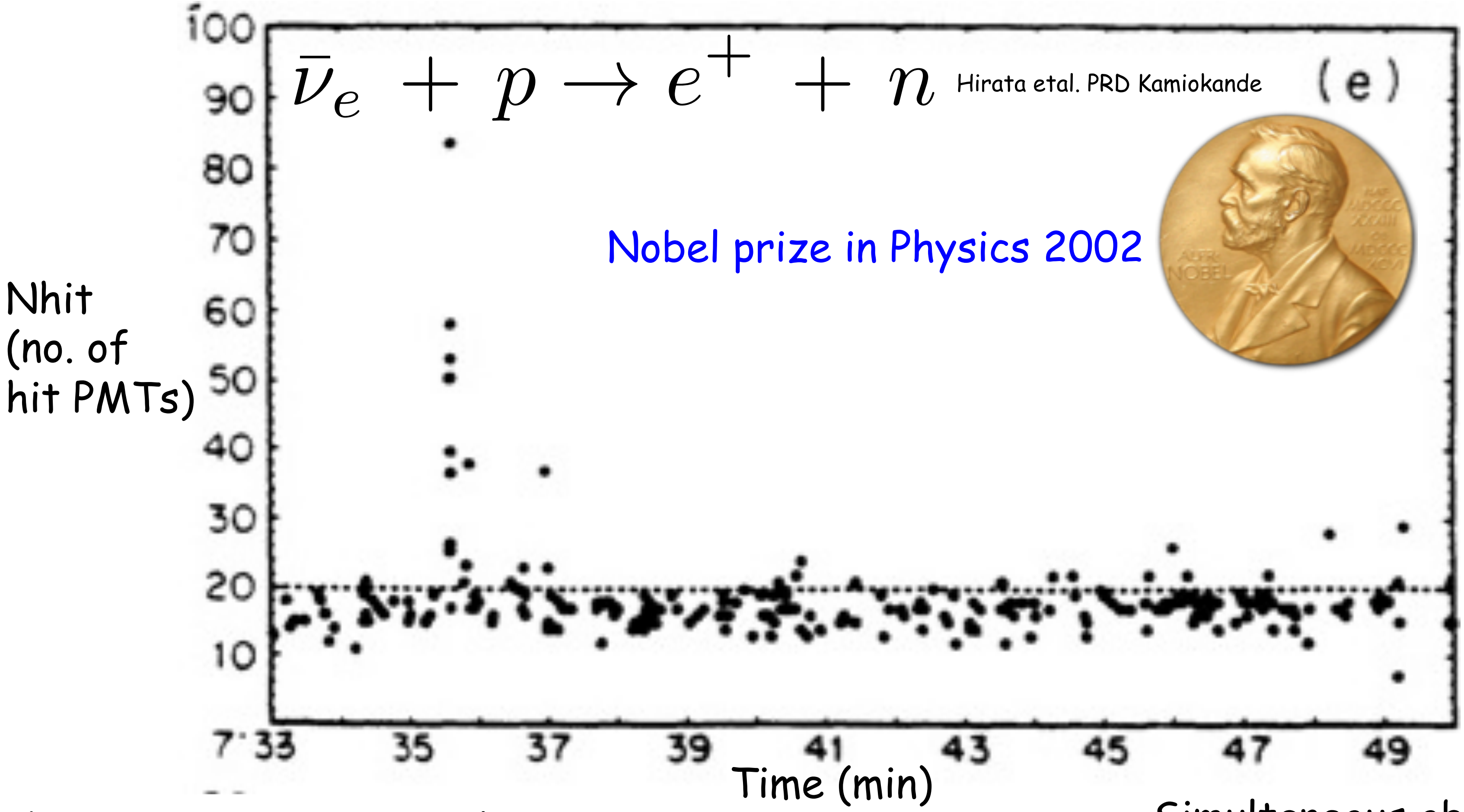
- Neutron capture on Gd produces ~ 8 MeV photons --- delay time ~ 20 µsec --- capture cross section 49000 barns

- Typical number of events in SuperKamiokande detector (inner volume 32 kton) ~ 10^4

- Detecting both the final products uniquely identifies this reaction

- Determine $\bar{\nu}_e$ properties to ~ 1%

SN 1987A in LMC



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

Hirata etal. PRD Kamiokande

Nobel prize in Physics 2002

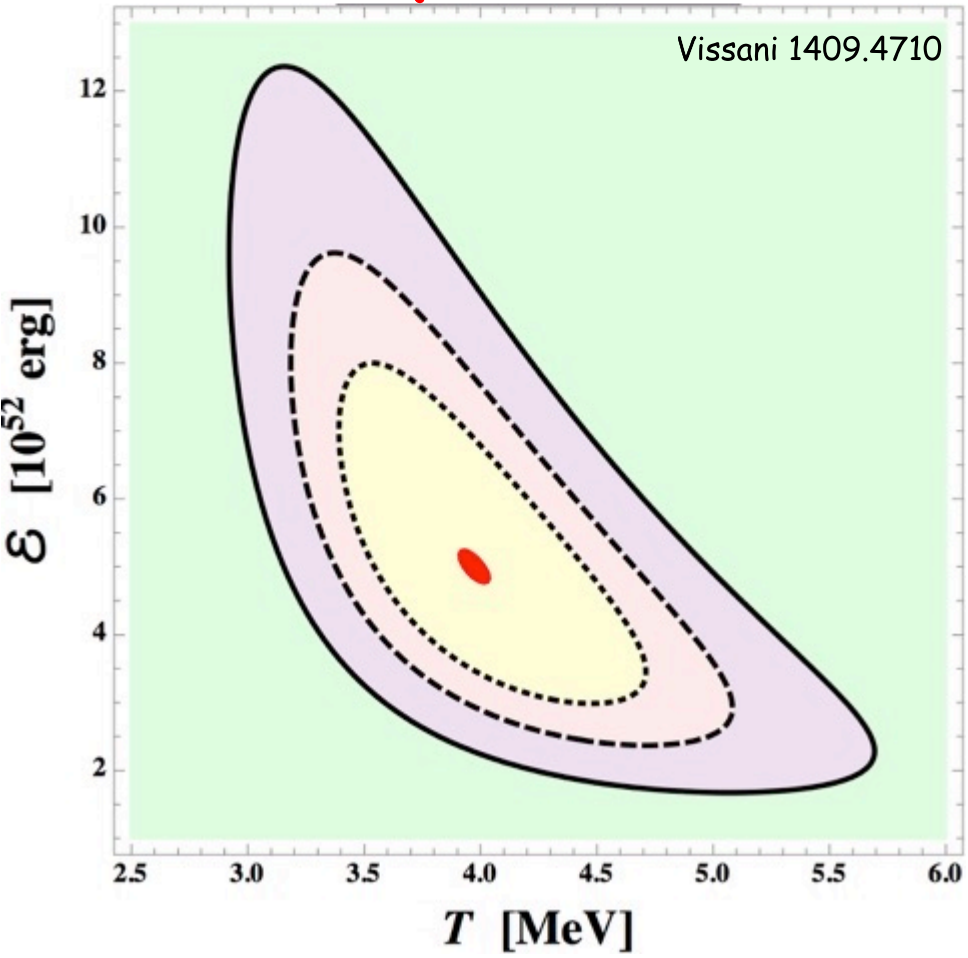
Nhit = 26 => 10 MeV total energy
Nhit = 73 => 30 MeV total energy

Simultaneous observation by IMB, Baksan

In broad agreement with the theoretical expectations

Many analyses to understand these events

Analysis of the SN 1987A data



A comprehensive analysis of the SN 1987A data by Vissani in 1409.4710

Analysis of the Kamiokande-II, IMB and Baksan data using various different models and assumptions on the signal and background

Fluence of $\bar{\nu}_e$:

$$\frac{dF}{dE_\nu} = \frac{\mathcal{E}}{4\pi D^2} \times \frac{E_\nu^2\, \mathrm{e}^{-E_\nu/T}}{6T^4}$$

$$\langle E_\nu \rangle = 3T$$

"… consistent with the hypothesis that the supernova emitted about 5 × 10^{52} erg in electron antineutrinos with an average energy of one dozen of MeV. The errors are not very large: the average energy is known within ~10%, while the radiated energy is known within –20% to +50% …" from Vissani 1409.4710

$\nu + {}^{12}\mathrm{C}$

$$\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$$

Threshold:

$$E_\nu \sim 17.34\,\mathrm{MeV}$$

Cross-section:

$$\sigma \approx 0.036 \times 10^{-42} \times (E_\nu - 18)^{1.97}\,\mathrm{cm}^2$$

for $E_\nu \in [25, 50]\,\mathrm{MeV}$

$$ {}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$

$$t_{1/2} \approx 11\,\mathrm{ms}$$

$$T_e \in [0,\ 16.8]\,\mathrm{MeV}$$

↑

kinetic energy of the electron

$$\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B}_{\mathrm{g.s.}} + e^+$$

Threshold:

$$E_\nu \sim 14.39\,\mathrm{MeV}$$

Cross-section:

$$\sigma \approx 0.086 \times 10^{-42} \times (E_\nu - 16)^{1.5}\,\mathrm{cm}^2$$

for $E_\nu \in [25, 50]\,\mathrm{MeV}$

$$ {}^{12}\mathrm{B}_{g.s.} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$$

$$t_{1/2} \approx 20\,\mathrm{ms}$$

$$T_e \in [0, 12.9]\,\mathrm{MeV}$$

↑

kinetic energy of the positron

$$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$$

$$ {}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma$$

$$E_\gamma = 15.11\,\mathrm{MeV}$$

Cross-section:

$$\sigma_\nu \approx 0.01 \times 10^{-42} \times (E_\nu - 16)^{2.08}\,\mathrm{cm}^2$$

$$\sigma_{\bar{\nu}} \approx 0.0095 \times 10^{-42} \times (E_\nu - 16)^{2.03}\,\mathrm{cm}^2$$

for

$$E_\nu \in [25, 50]\,\mathrm{MeV}$$

Lujan-Peschard, Pagliaroli and Vissani
1402.6953 (JCAP)

Laha, Beacom and Agarwalla
1412.8425

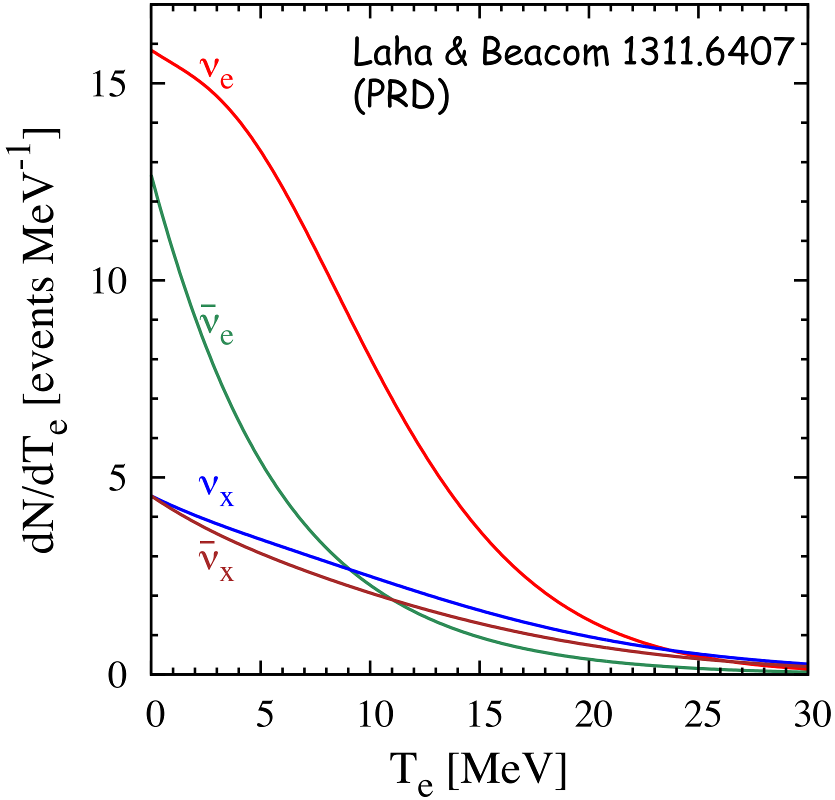
Supernova neutrino detection: ν_e

$\nu_e + e^- \rightarrow \nu_e + e^-$ Sensitive to all neutrino species; ν_e produces largest number of events

Maximum number of events in water Cherenkov detectors

The electrons are forward scattered $\sigma(E_\nu) \propto G_F^2\, m_e E_\nu$

Neutrino energy E_ν ➔ recoil electron energy $\epsilon \left[0,\ \frac{2E_\nu^2}{m_e + 2E_\nu}\right]$



Electron spectra for $\nu + e^- \rightarrow \nu + e^-$ detection channels for a Galactic Supernova in Super-K

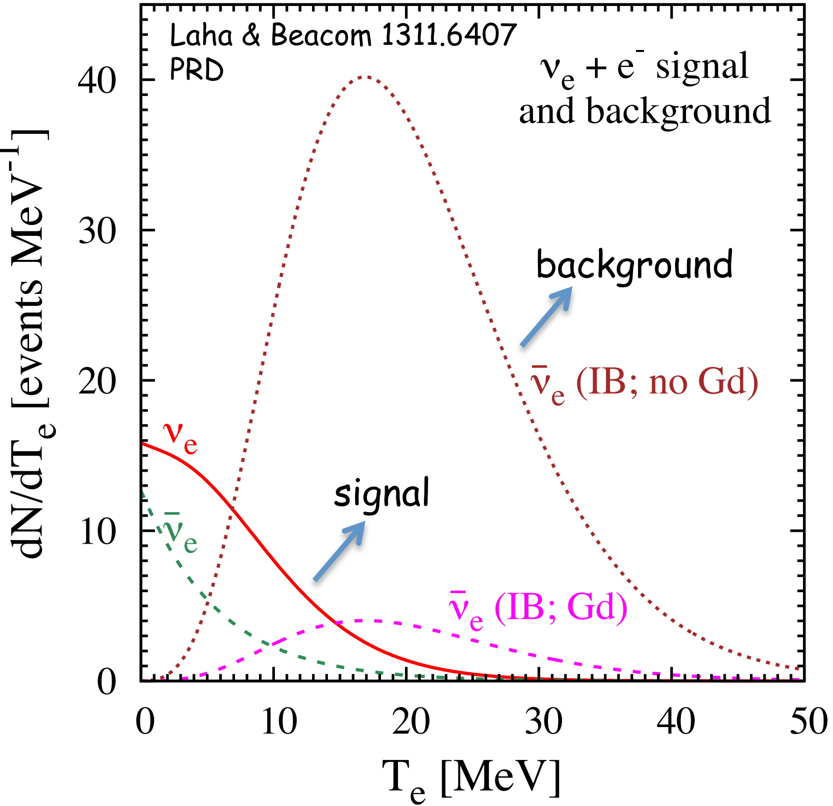
These are events in the forward 40° cone (~ 68% of the total). We take $\langle E_{\nu_e}\rangle = 12\,\mathrm{MeV}$, $\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$, and $\langle E_{\nu_x}\rangle = 18\,\mathrm{MeV}$

Number of events in a Super-K ~ 200

See also Rosso, Vissani, and Volpe 1712.05584 (JCAP)

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

- Use angular cut: 128 signal events v/s 827 background events (mostly from inverse beta interactions)
- Difficult to distinguish these in the present configuration of Super-K
- How do we utilize this important neutrino detection channel?



- In the present configuration of Super-K, the signal is dwarfed by the background
- Important to extract this signal to improve reliability of the signal and search for various physics effects

Supernova neutrino detection: ν_e

Another important reaction in water Cherenkov detectors

$$\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}^*$$

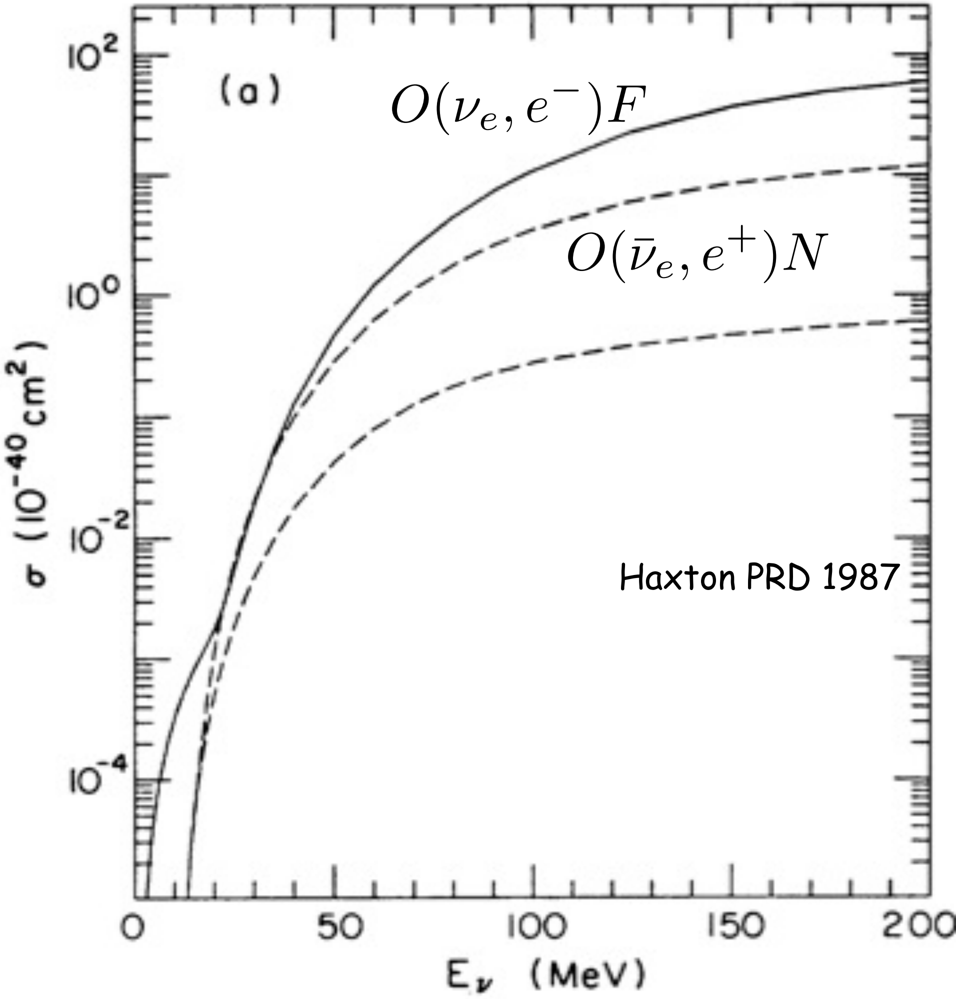
Threshold ≈ 15 MeV

Only the electron is detectable

$$T_e \approx E_\nu - 15\,\text{MeV}$$

$$\sigma(E_\nu) \approx 4.7 \times 10^{-40} \left(E_\nu^{0.25} - 15^{0.25}\right)^6 \text{ cm}^2$$

for supernova neutrino energies

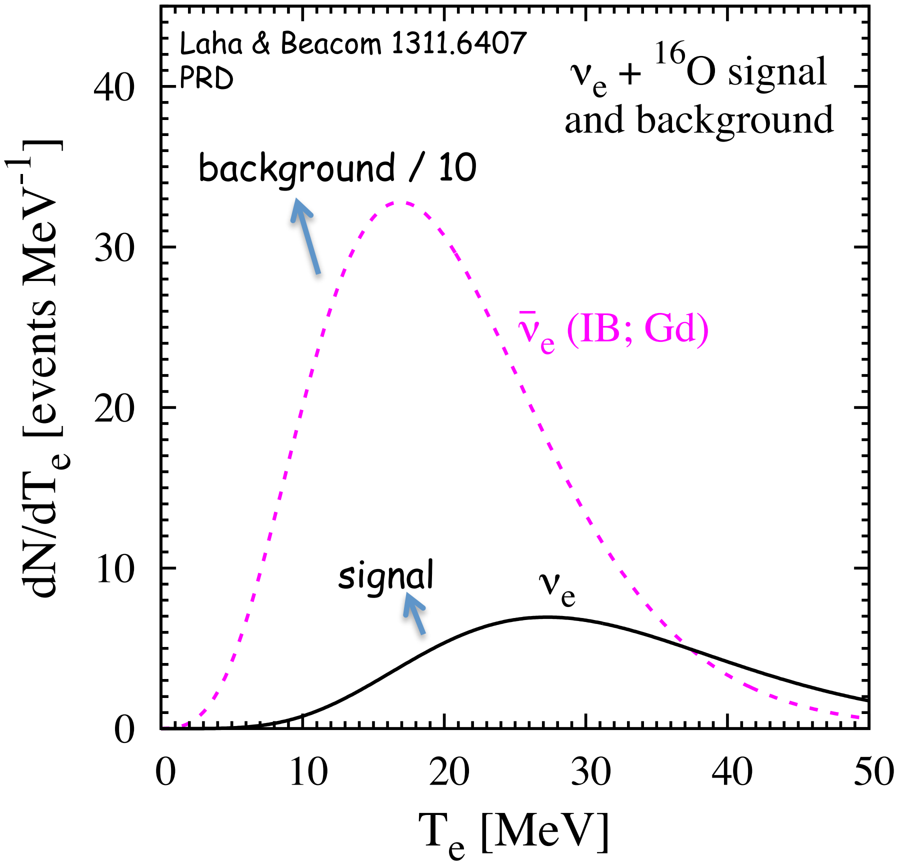


Haxton PRD 1987

Subdominant contribution for relevant supernova neutrino energies by other isotopes of oxygen

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*$$

- Very sensitive to the incoming neutrino energy
- Extremely sensitive probe of ν_e if it has a higher average energy due to mixing
- Angular dependence of electrons is backward tilted



- In the present configuration of Super-K, the signal is dwarfed by the background
- Important to extract this signal to understand the supernova completely

$\nu_e + {}^{40}\mathrm{Ar}$

Liquid Argon detectors are very sensitive to ν_e

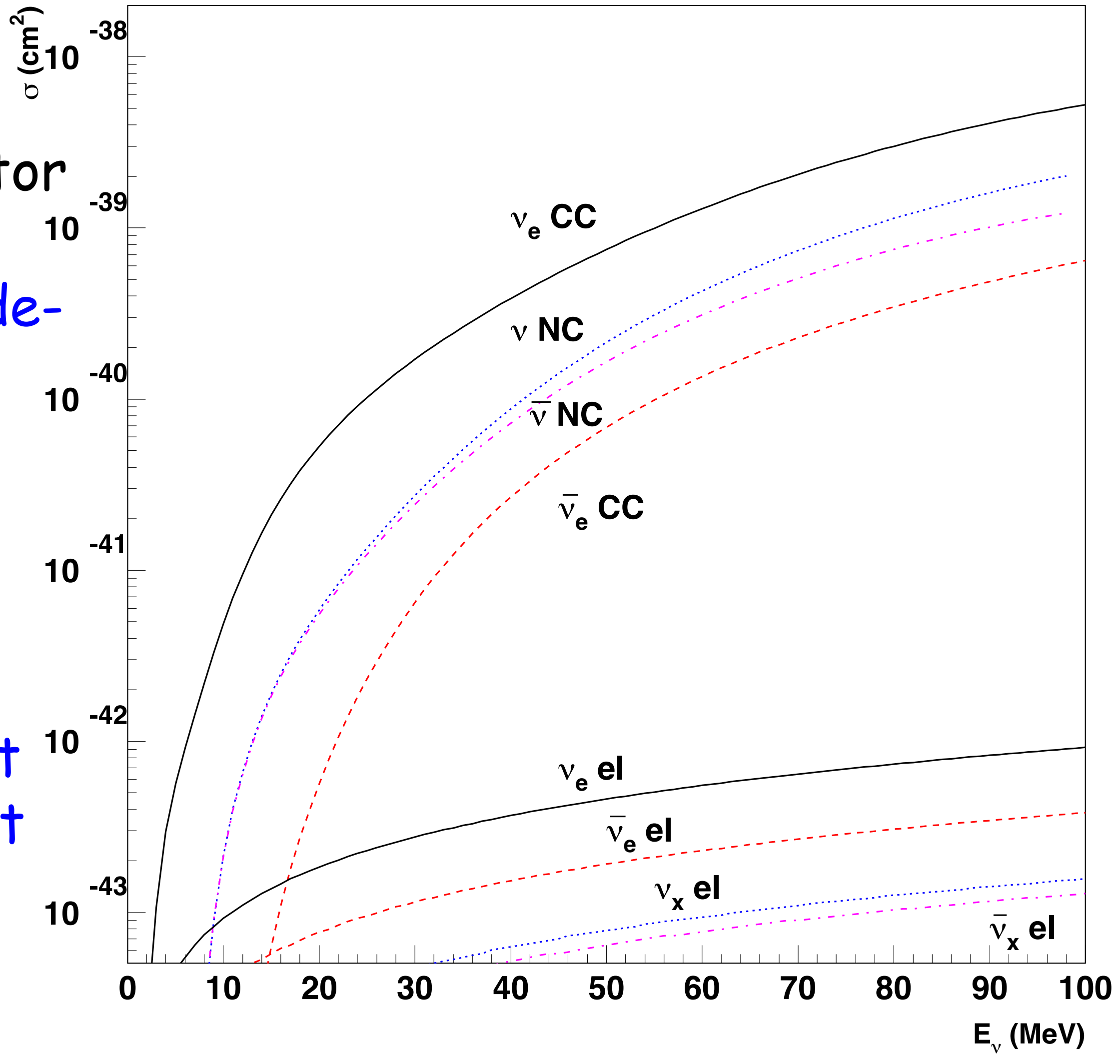
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Threshold ≈ 1.5 MeV

There is ongoing photon detector system R&D that aims to distinguish the γ-ray emitting de-excitations of ${}^{40}\mathrm{K}^*$

Uncertainty in the theoretical calculations of the cross-sections

Proposed CAPTAIN experiment to measure the cross section at CCSN energies for the first time



Cocco etal., hep-ph/0408031

Neutrino mixing

- Extremely complicated in supernova environment
- Depends on both matter density and neutrino density
- Simplifying assumptions:

(A) $\langle E_{\nu_e} \rangle \approx 12\,\mathrm{MeV}$ and $\langle E_{\nu_x} \rangle \approx 15 - 18\,\mathrm{MeV}$

(B) $\langle E_{\nu_e} \rangle \approx 15 - 18\,\mathrm{MeV}$
one flavor of ν_x has $\langle E_{\nu_x} \rangle \approx 12\,\mathrm{MeV}$
the other flavors of ν_x have $\langle E_{\nu_x} \rangle \approx 15 - 18\,\mathrm{MeV}$

(C) Consider MSW mixing in supernova

A new strategy to detect supernova ν_e in water Cherenkov detectors

Number of ν_e events in various detectors

DUNE (via ^{40}Ar inelastic scattering)	few thousand
DUNE (via $\nu_e + e^-$ elastic scattering)	few hundred
JUNO (via ^{12}C inelastic scattering)	few hundred
JUNO (via $\nu_e + e^-$ elastic scattering)	few hundred
Super-K (via ^{16}O inelastic scattering)	few hundred
Super-K (via $\nu_e + e^-$ elastic scattering)	few hundred
Hyper-K (via ^{16}O inelastic scattering)	few thousand
Hyper-K (via $\nu_e + e^-$ elastic scattering)	few thousand

Water Cherenkov detector have lots of ν_e events --- how to detect them?

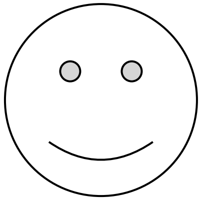
How to distinguish $\nu_e + e^- \rightarrow \nu_e + e^-$ from $\bar{\nu}_e + p \rightarrow e^+ + n$?

Important to identify all the final state products of the inverse beta interaction

Present configuration of Super-K:

- $e^{\pm}$ Easy to detect
- n Hard to detect

Neutron capture:	Gd	p
	49000 barn	0.3 barn
	8 MeV	2.2 MeV
	20 μsec	200 μsec



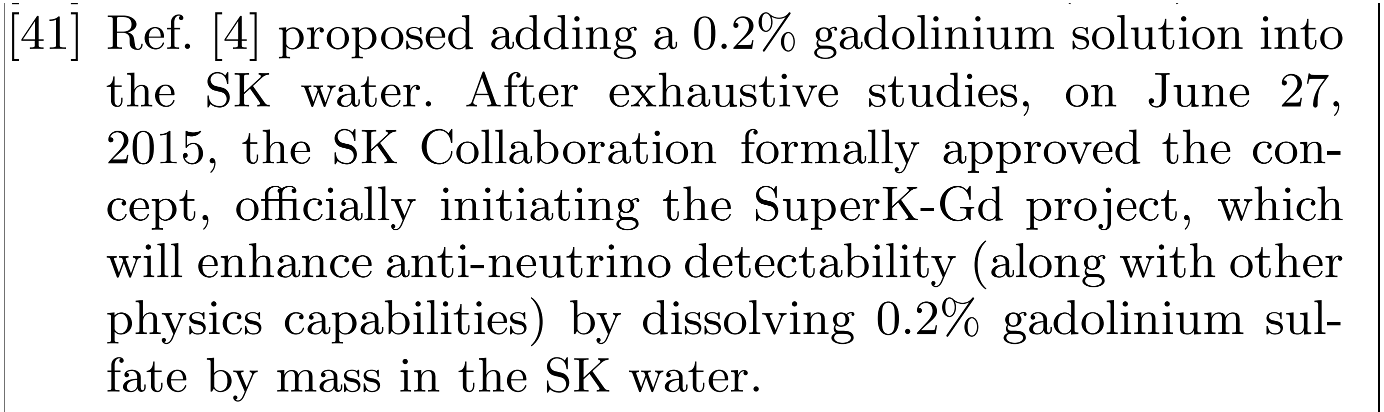
Gd makes it much easier to detect neutrons

Proposal: Dissolve Gd in Super-K to enhance neutron capture

Beacom and Vagins hep-ph/0309300

Approved

Super-K 2015



[41] Ref. [4] proposed adding a 0.2% gadolinium solution into the SK water. After exhaustive studies, on June 27, 2015, the SK Collaboration formally approved the concept, officially initiating the SuperK-Gd project, which will enhance anti-neutrino detectability (along with other physics capabilities) by dissolving 0.2% gadolinium sulfate by mass in the SK water.

Event numbers

Input from the simulation of Nakamura etal. 1602.03028

Super-K : 32 kton, Hyper-K : 370 kton, DUNE : 40 kton

Channel	Super-K	Hyper-K	DUNE
ν_e scat.	300	3,500	260
$\bar{\nu}_e$ scat.	84	970	73
ν_x scat.	41	480	36
$\bar{\nu}_x$ scat.	31	370	28
^{16}O	110	1,300	-
IBD	9,800	110,000	-
^{40}Ar	-	-	2,200

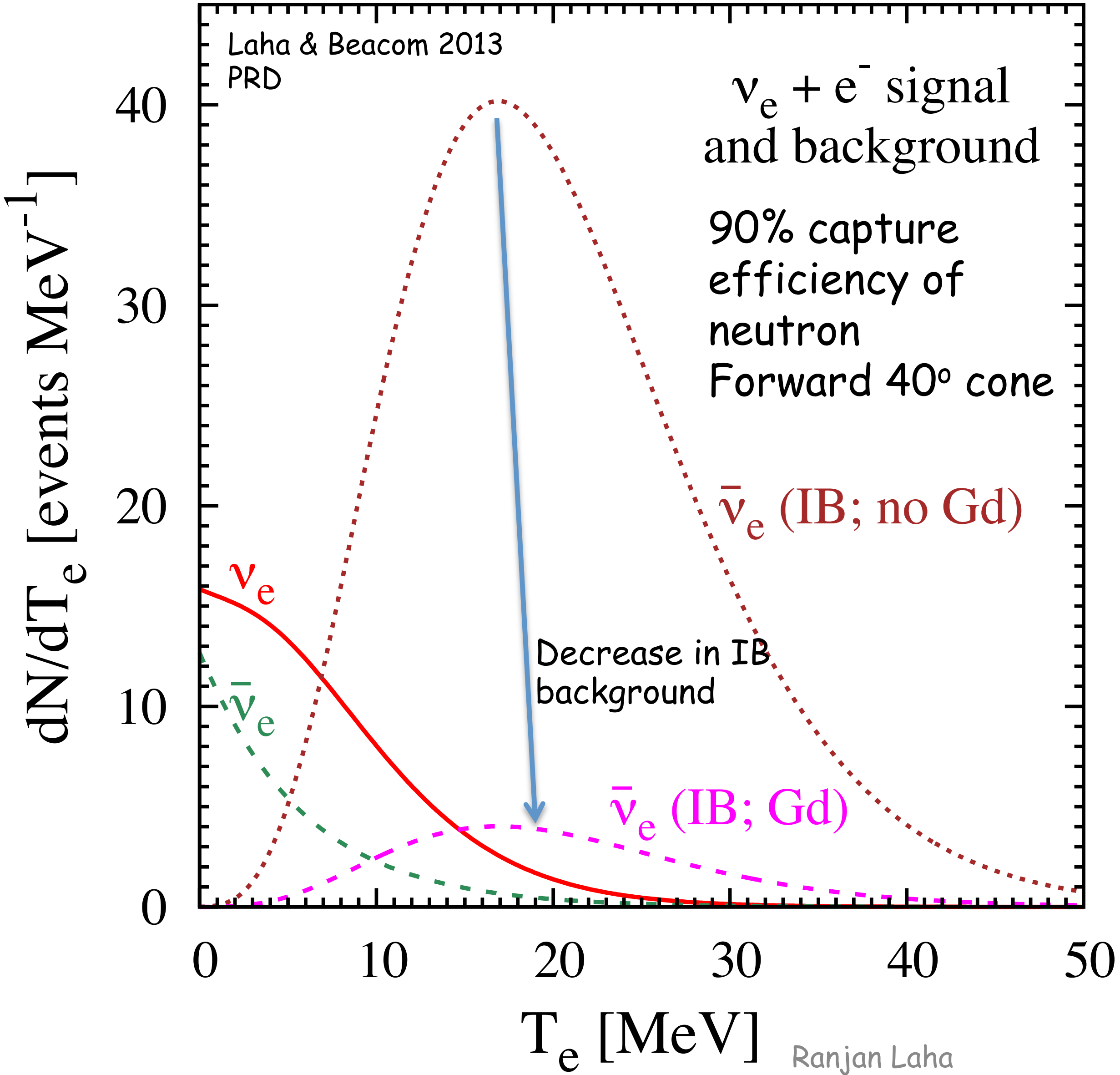
Nikrant, Laha & Horiuchi 1711.00008
PRD

A new way to detect supernova ν_e in water-Cherenkov detectors

Galactic Supernova happens

- Implement angular cut: forward cone contains most of the electron elastic scattering events; inverse beta is quasi-isotropic
- Gd can individually detect and remove the inverse beta reactions in the forward cone
- Remaining inverse beta backgrounds can be statistically subtracted
- Use the information about ν_x and $\bar{\nu}_e$ to statistically subtract the electron scattering events due to these flavors
- Addition of Gd also helps in identifying $\nu_e \, ^{16}\mathrm{O}$ events

Effect of Gd on elastic electron scattering events

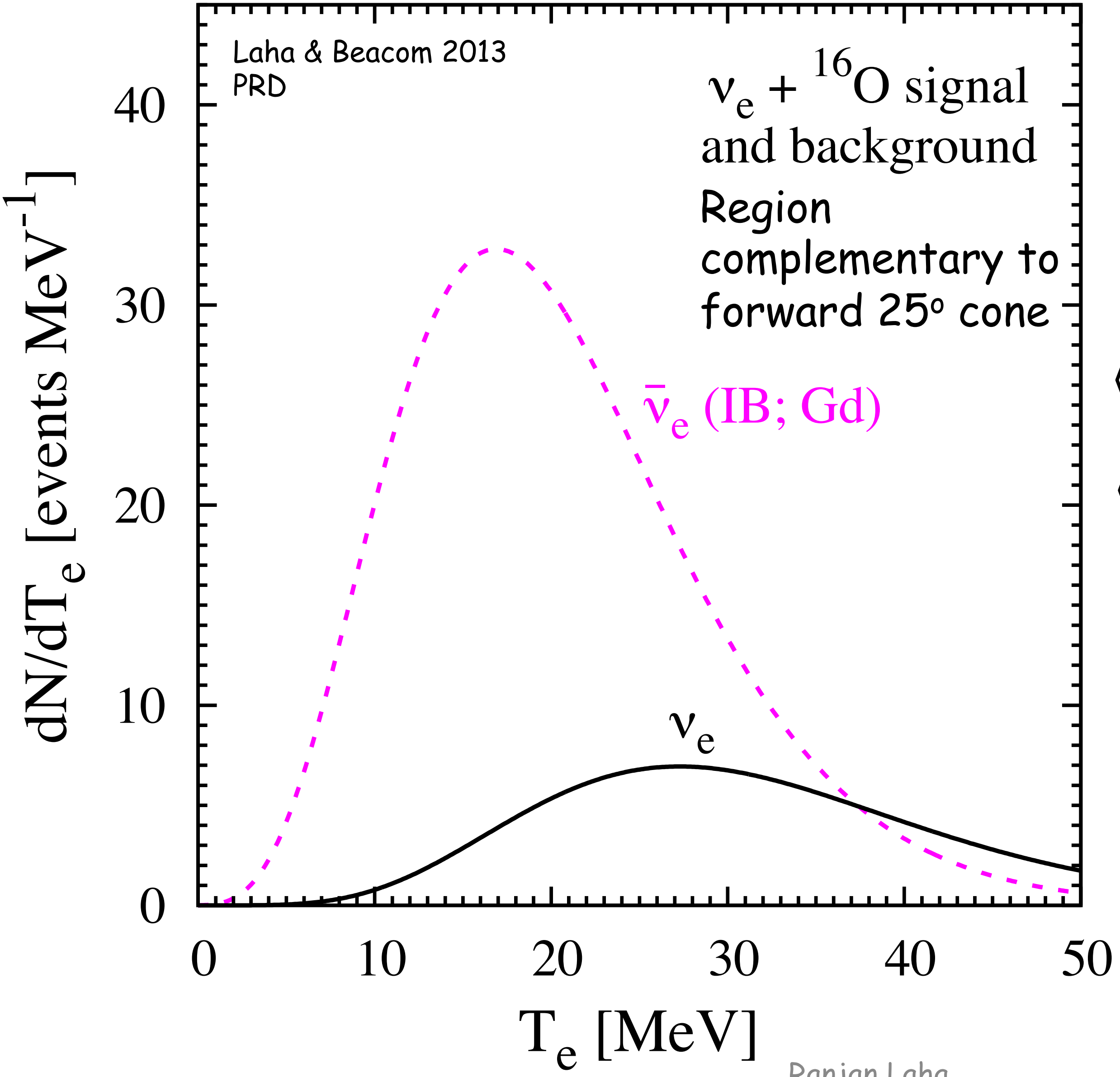


$$\langle E_{\nu_e} \rangle = 12\,\mathrm{MeV}$$
$$\langle E_{\bar{\nu}_e} \rangle = 15\,\mathrm{MeV}$$

Addition of Gadolinium reduces the inverse beta background from ~827 to ~83

Signal and background both due to Galactic supernova

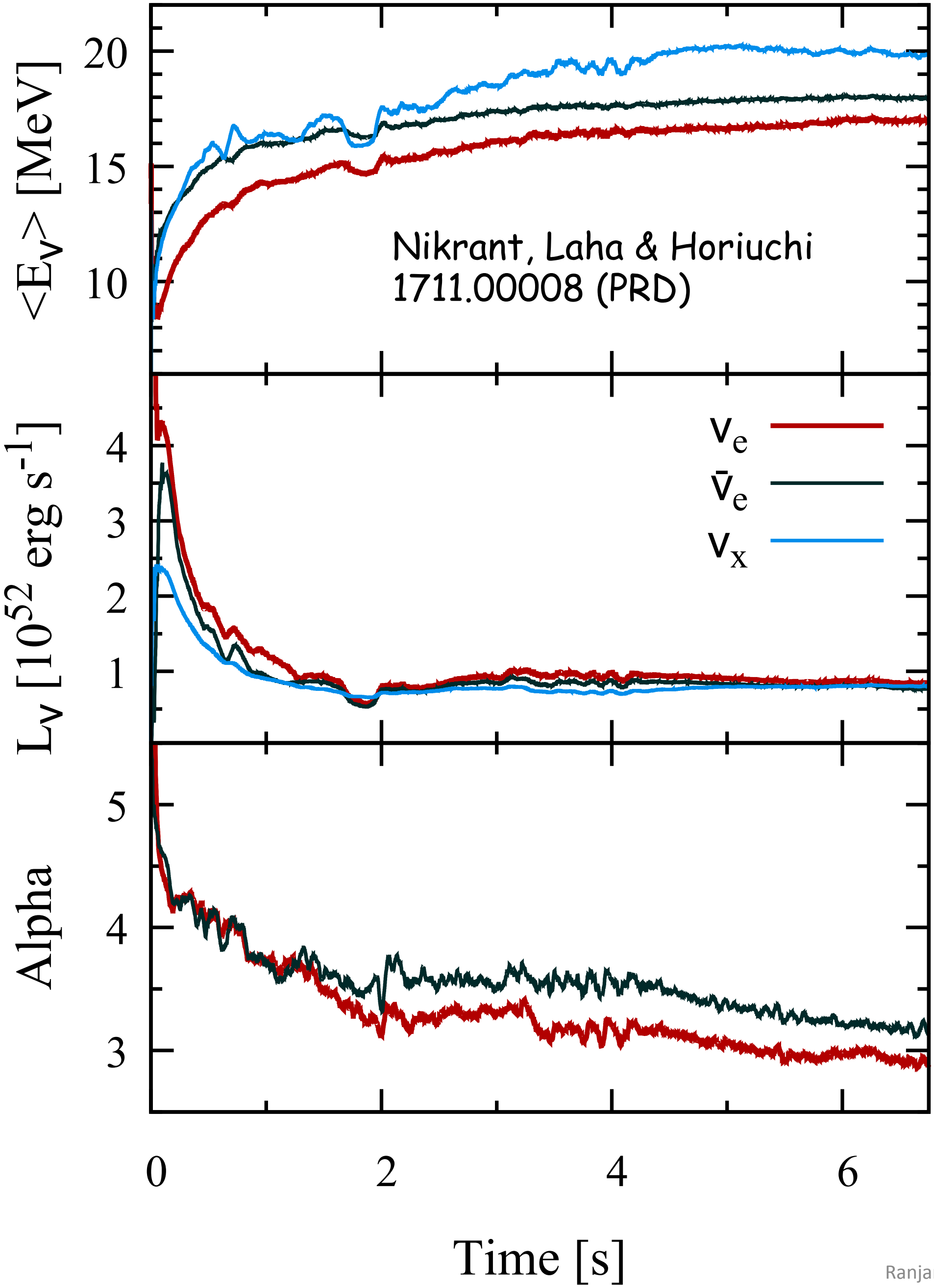
Effect of Gd on oxygen scattering events



$\bar{\nu}_e$ signal without Gd is 10 times larger

$$\langle E_{\nu_e} \rangle = 18\,\mathrm{MeV}$$
$$\langle E_{\bar{\nu}_e} \rangle = 15\,\mathrm{MeV}$$

From numerical simulations



Nikrant, Laha & Horiuchi
1711.00008 (PRD)

$$\nu_x = \nu_\mu + \nu_\tau + \text{anti} - \text{particles}$$

$$\frac{dN_\nu}{dE_\nu}(E_\nu) = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \times \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

E_ν = neutrino energy

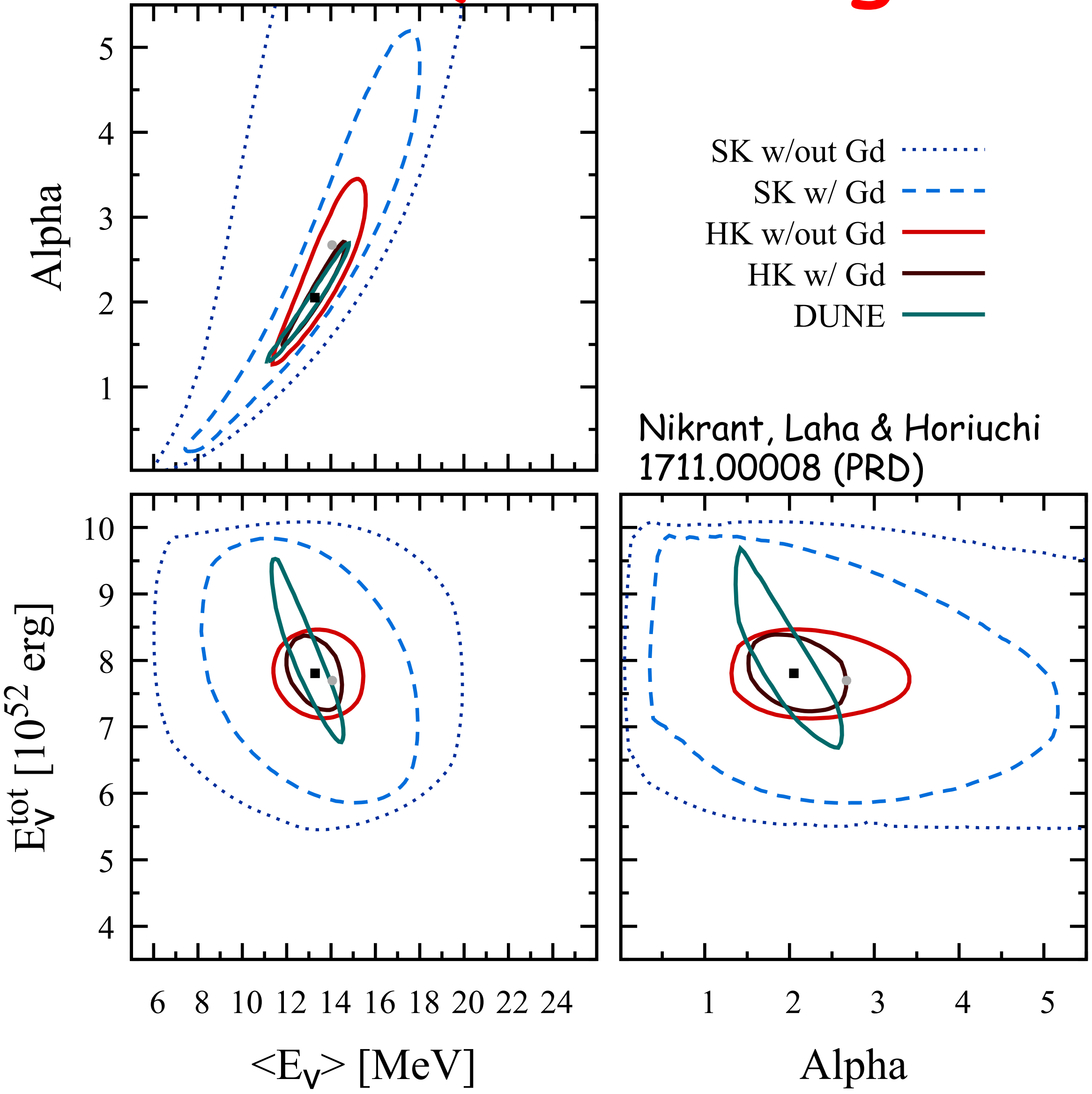
$\langle E_\nu\rangle$ = average neutrino energy of the spectrum

$$\Phi(E_\nu) = \frac{1}{4\pi d^2}\frac{E_\nu^{\text{tot}}}{\langle E_\nu\rangle}\frac{dN_\nu}{dE_\nu}$$

Neutrino fluence

Distance from the supernova to the Earth

Constraints on neutrino spectrum (no mixing scenario)



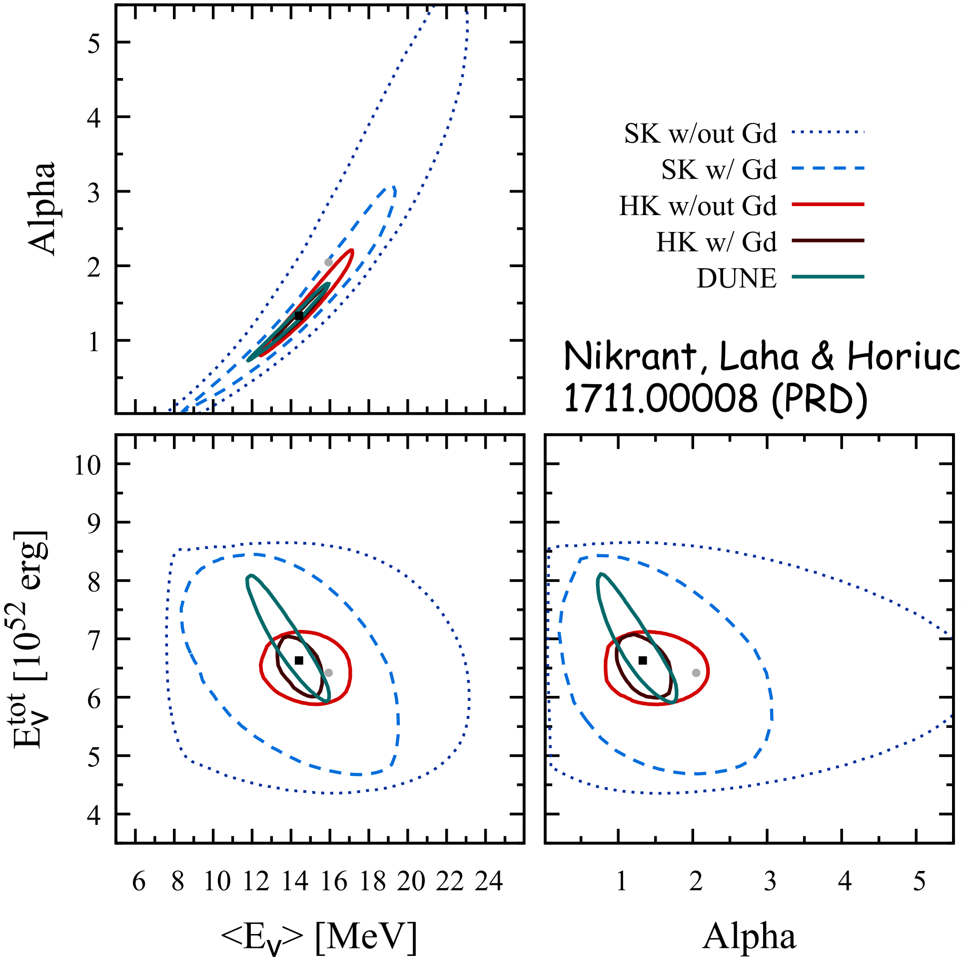
Nikrant, Laha & Horiuchi
1711.00008 (PRD)

Dramatic improvement in constraining the ν_e spectral parameters while using Gd in water Cherenkov detectors

The contours of DUNE and Hyper-K are almost orthogonal --- importance of detecting supernova neutrino in different detectors

Contour shapes are orthogonal as the water Cherenkov interactions and the Argon interactions probe different part of the underlying neutrino spectrum

Constraints on neutrino spectrum (MSW mixing scenario)



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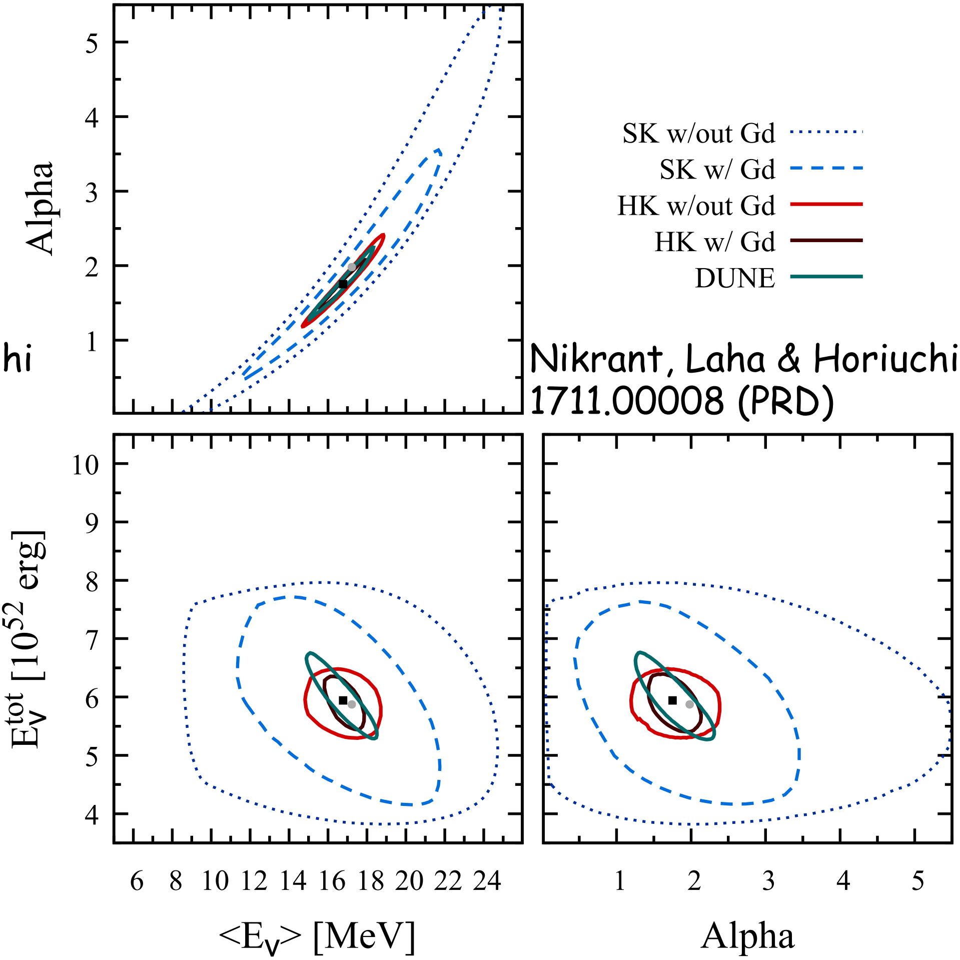
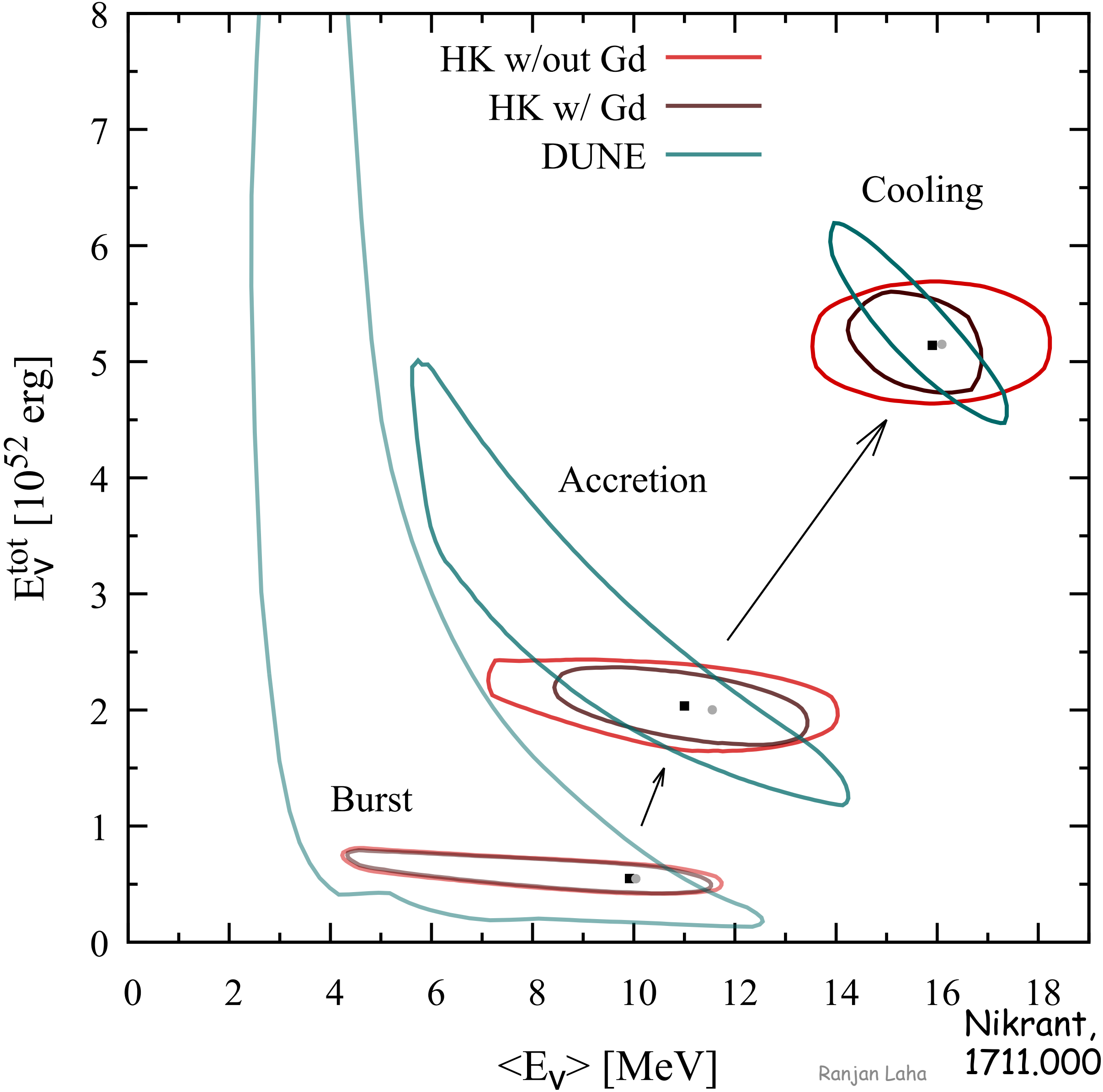


Nikrant, Laha & Horiuchi
1711.00008 (PRD)

Improvement due to our technique in water Cherenkov detectors is possible even in the case of mixing among the various flavors of supernova neutrino. The complementarity between DUNE and Hyper-K + Gd is also applicable.

Spectrum constraints during various stages of supernova neutrino emission



neutronization burst: start to 60 ms;

accretion phase: 60 ms to 1 s;

cooling phase: 1 s to end.

Hyper-K + DUNE will produce stringent constraints on ν_e spectral parameters for all the phases of the supernova

Nikrant, Laha & Horiuchi
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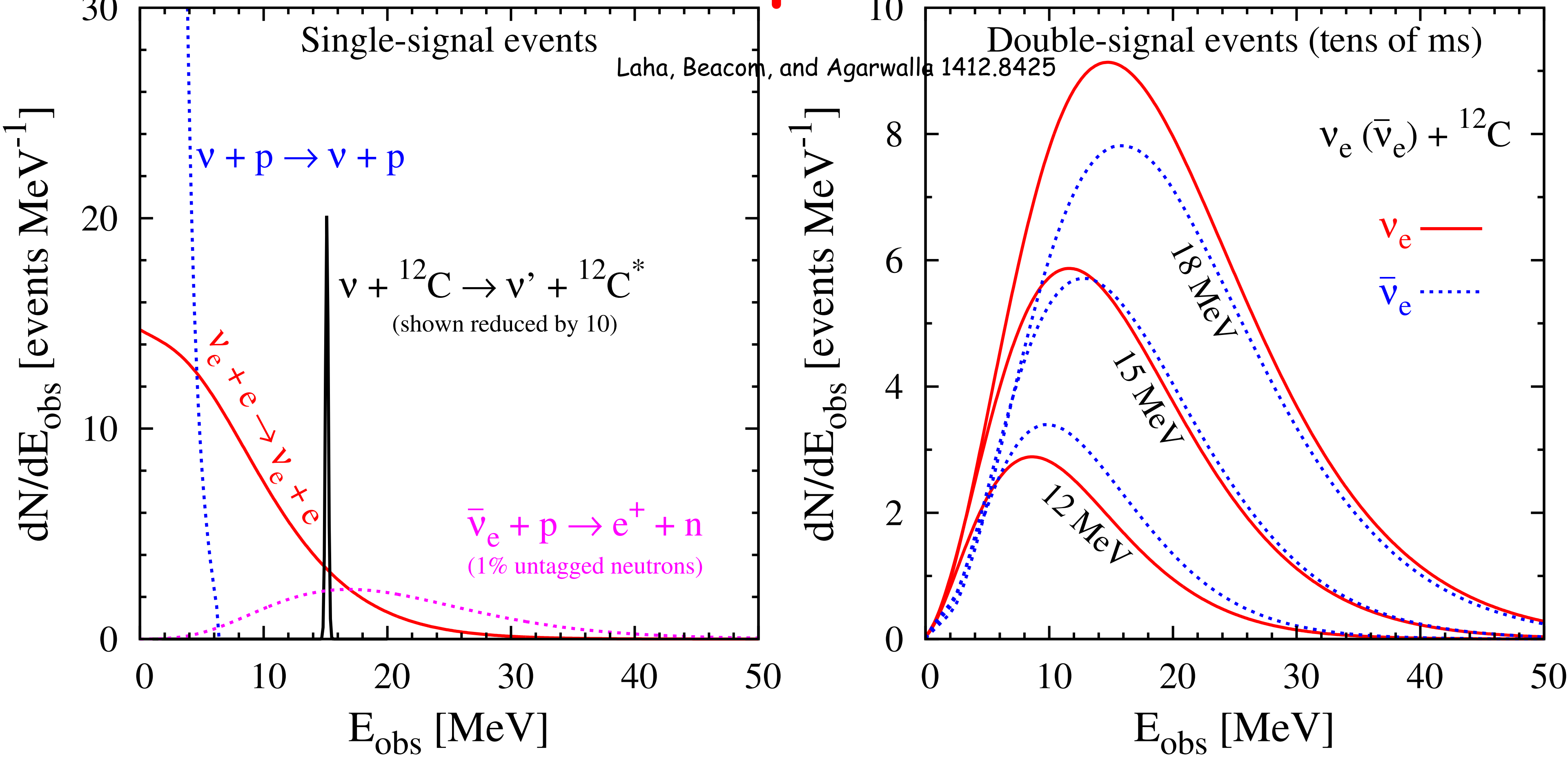
Liquid scintillator detector (JUNO)

Event spectrum



Laha, Beacom, and Agarwalla 1412.8425

JUNO can detect supernova neutrinos of all flavors

Large number of events in distinct channels imply strong constraints on supernova neutrino spectral parameters

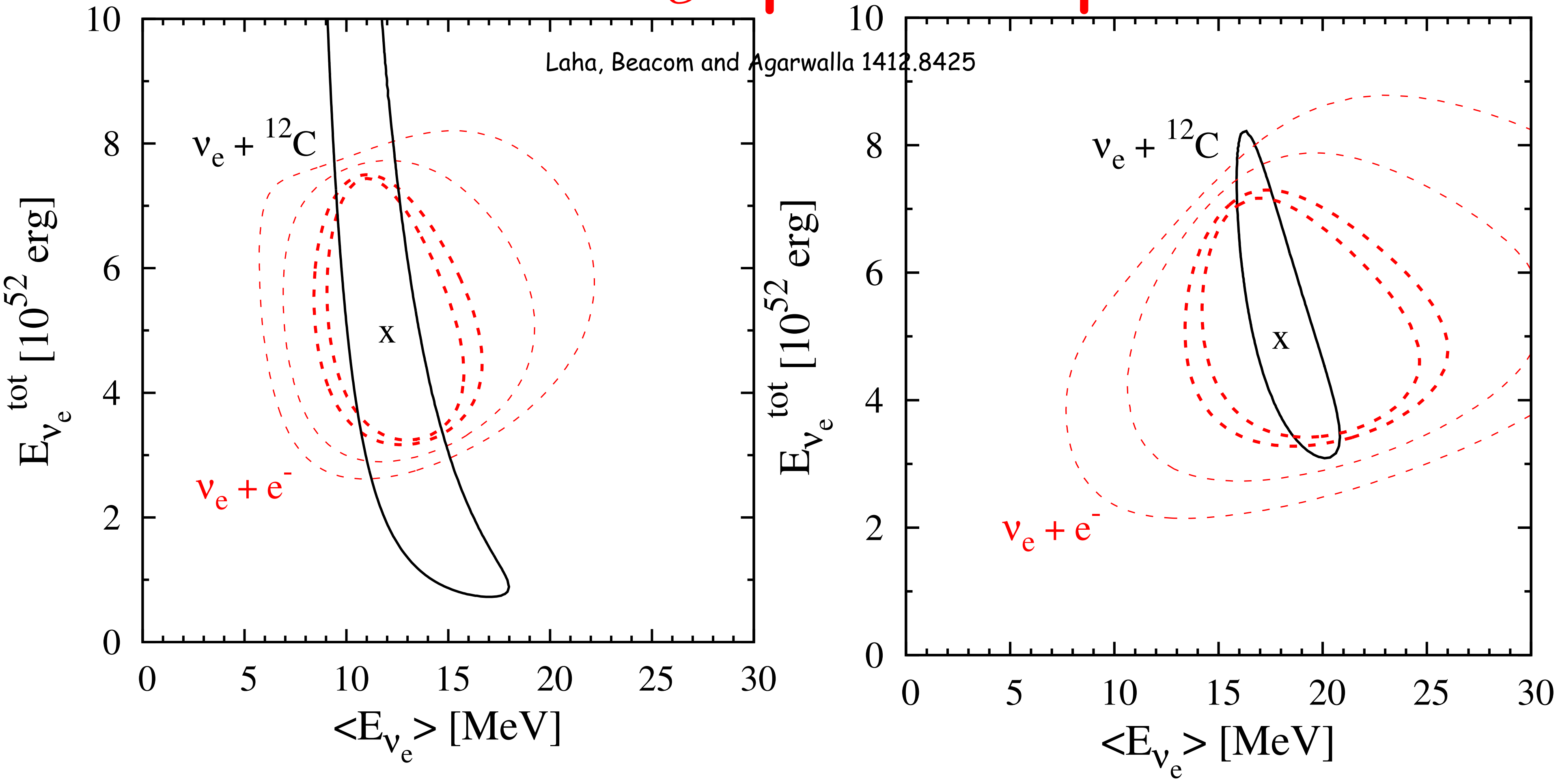
$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}_{\mathrm{g.s.}} + e^+$$

Event numbers in JUNO

Detection channel	Event numbers
$\bar{\nu}_e + p \rightarrow e^+ + n$	4860
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$	110
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	70
$\nu + p \rightarrow \nu + p$	1120
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}$	480
$\nu_x + e^- \rightarrow \nu_x + e^-$	100
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$	40
$\nu_e + e^- \rightarrow \nu_e + e^-$	160

Constraints on ν_e spectral parameters



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Neutrino – nucleus scattering provides the stronger constraint on the average energy of the spectrum

Neutrino – electron scattering provides the stronger constraint on the total energy of the spectrum

Conclusions

- It is essential to detect all the flavors of supernova neutrinos
- We study how to constrain supernova ν_e in various near future neutrino detectors
- We show how to detect supernova ν_e in Gd loaded water Cherenkov detectors
- We use the directionality of $\nu_e\, e^-$ elastic scattering events and the individual detection and removal of inverse beta events using Gd to detect supernova ν_e
- Super-K + Gd, Hyper-K + Gd, DUNE and JUNO will constrain ν_e spectral parameters very strongly

Comments/ questions to ranjalah@uni-mainz.de

Production of neutrinos and their average energies

$$\nu_e + n \leftrightarrow p + e^- \qquad \bar{\nu}_e + p \leftrightarrow n + e^+$$

$$N + N \leftrightarrow N + N + \nu + \bar{\nu} \qquad \nu_e + \bar{\nu}_e \leftrightarrow \nu + \bar{\nu}$$

$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$

Lowest cross section of ν_x ➔ decouples from matter earliest ➔ highest average energy

Larger number of neutrons than protons ➔ ν_e decouples last ➔ lowest average energy

$\bar{\nu}_e$ has an average energy in between these two extremes

Simplifying assumptions about supernova

Total binding energy released in the explosion $\sim 3 \times 10^{53}\,\mathrm{erg}$

Total energy carried by each ν (or $\bar{\nu}$) flavor $\sim 5 \times 10^{52}\mathrm{erg}$

Quasi-thermal neutrino spectrum $f(E_\nu) = \frac{128}{3}\frac{E_\nu^3}{\langle E_\nu \rangle^4}\exp\left(-\frac{4E_\nu}{\langle E_\nu \rangle}\right)$

$\langle E_{\nu_e} \rangle \approx 11 - 12\,\mathrm{MeV}$ $\langle E_{\bar{\nu}_e} \rangle \approx 14 - 15\,\mathrm{MeV}$

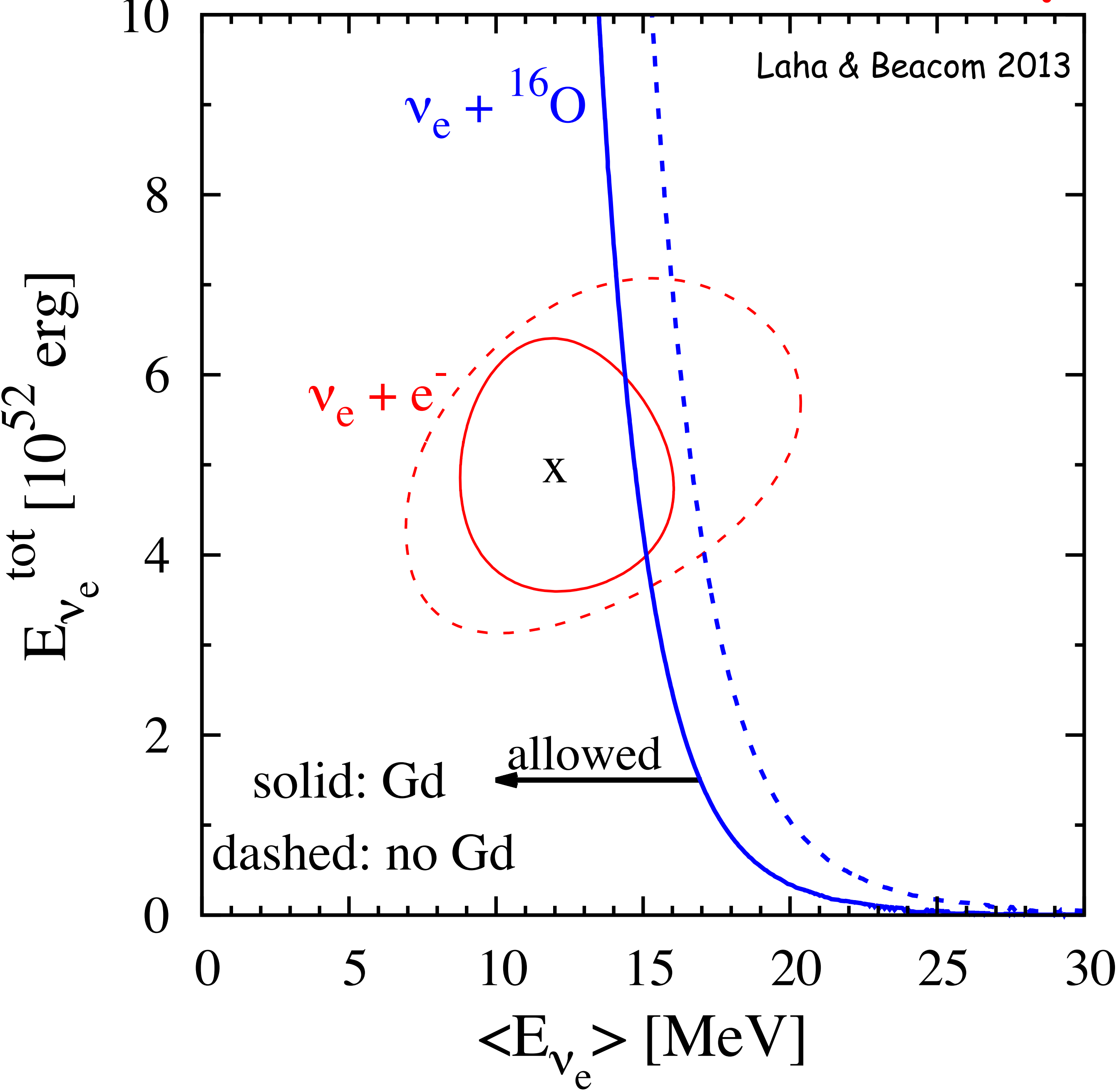
$\langle E_{\nu_x} \rangle \approx 15 - 18\,\mathrm{MeV}$

At supernova energies, $\nu_\mu = \nu_\tau$ (and their antiparticles); denoted by ν_x

Neutrino mixing can change the average energies of the detected neutrinos

Supernova located at a distance of 10 kpc

Constraints on ν_e spectrum

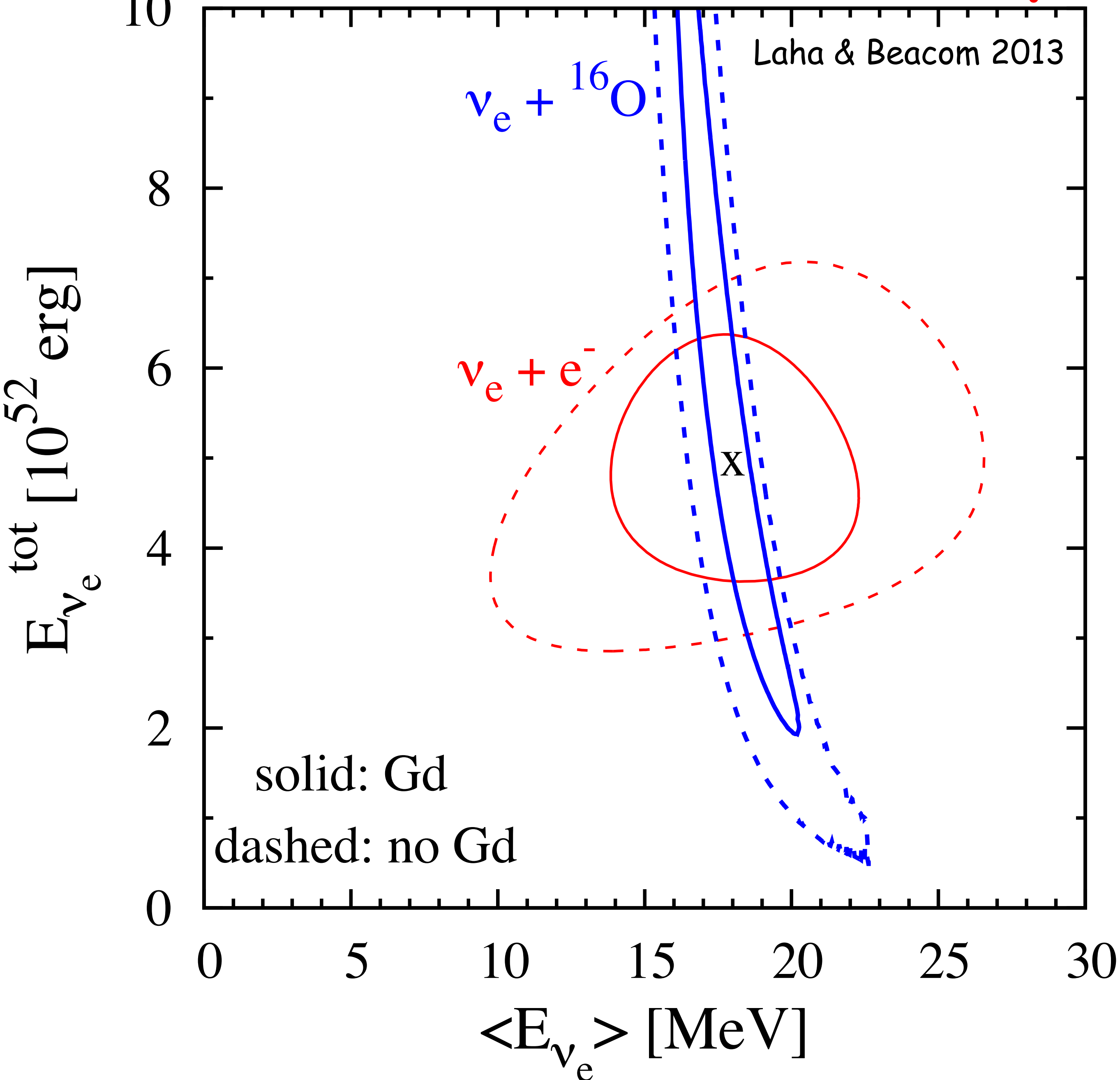


X= fiducial value

Lack of events in the oxygen channel gives an upper limit

Use of Gd and pointing determines the spectral parameters to ~20%

Constraints on ν_e spectrum

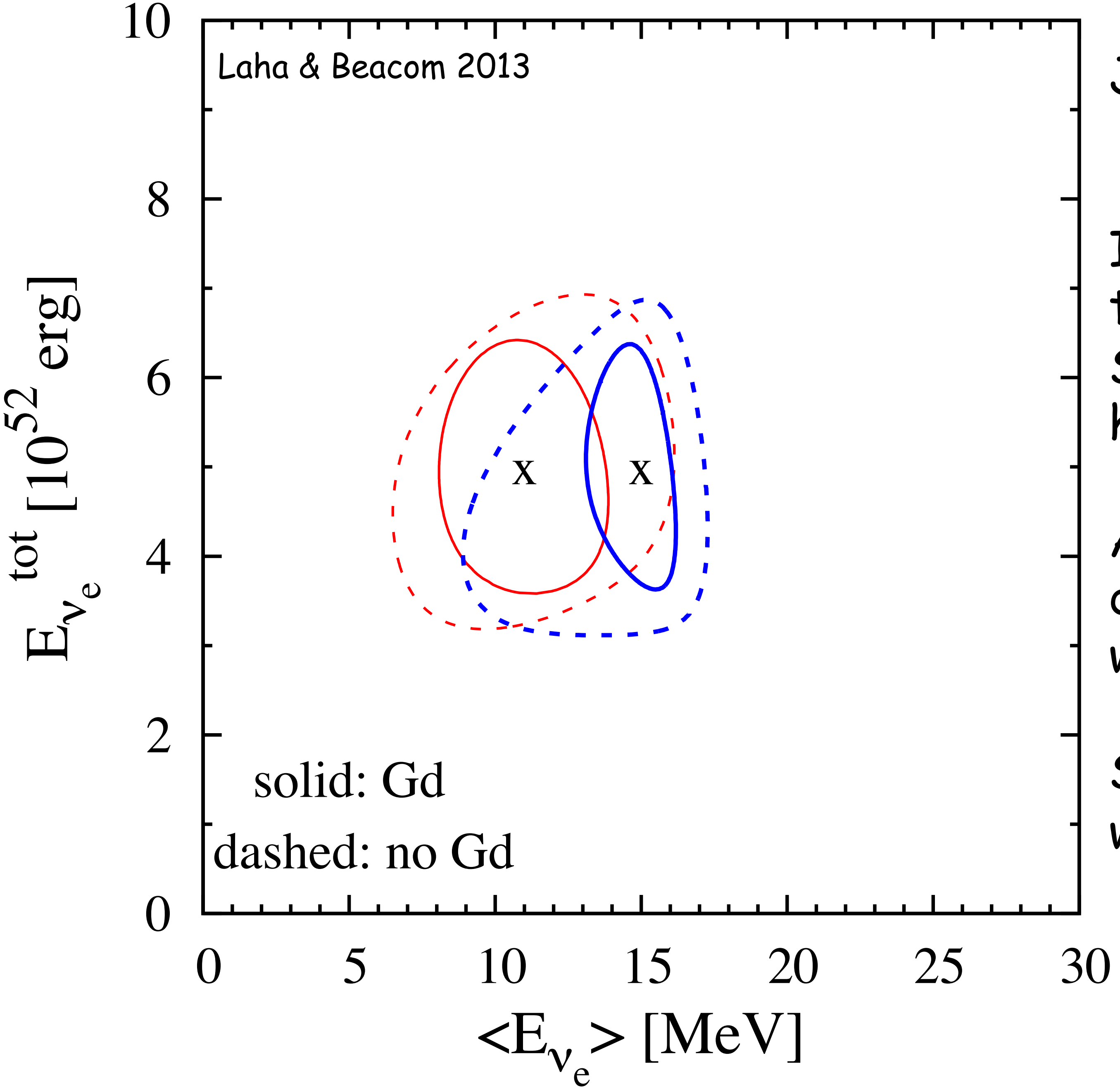


X = fiducial value

Oxygen reaction gives a very strong constraint on $\langle E_{\nu_e} \rangle$

Again Gd gives improvement in the constraints

Improvements for lower values of $\langle E_{\nu_e} \rangle$



Joint constraints

Improvements over the case when Super-Kamiokande has no Gd

Almost no discrimination without Gd

Some discrimination with Gd

Flux and event rate

Time integrated flux for single flavor

$$\frac{dF}{dE_\nu} = \frac{1}{4\pi d^2}\frac{E_\nu^{\rm tot}}{\langle E_\nu \rangle} f(E_\nu)$$

Observed interaction rate

$$\frac{dN}{dT} = N_T \int_{E_{\rm min}}^{\infty} dE_\nu \frac{dF}{dE_\nu}(E_\nu)\frac{d\sigma}{dT}(E_\nu, T)$$

Present difficulty in detecting ν_e

At present detecting $\bar{\nu}_e$ in water Cherenkov detectors is easy

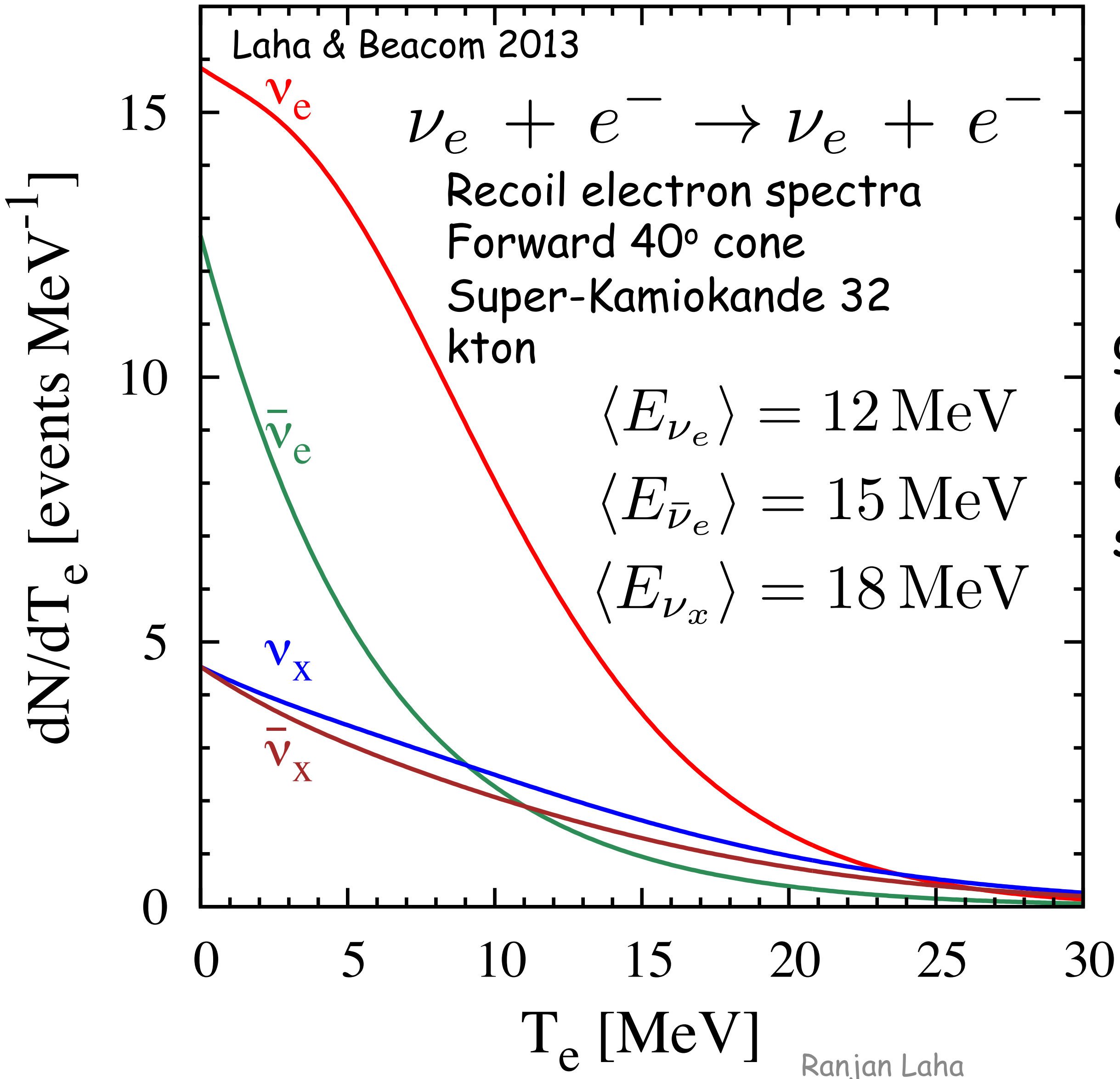
Adding Gadolinium will make it easier (future)

Detecting ν_x is easiest in liquid scintillator detectors

The remaining is ν_e : how do we detect it?

Let us concentrate on the largest neutrino detector (at these energies) at present: Super-Kamiokande

ν_e has the largest electron elastic scattering cross section



Optimistic as $\nu_e + e^- \rightarrow \nu_e + e^-$ gives the largest number of events --- other events can only be subtracted statistically

Ranjan Laha

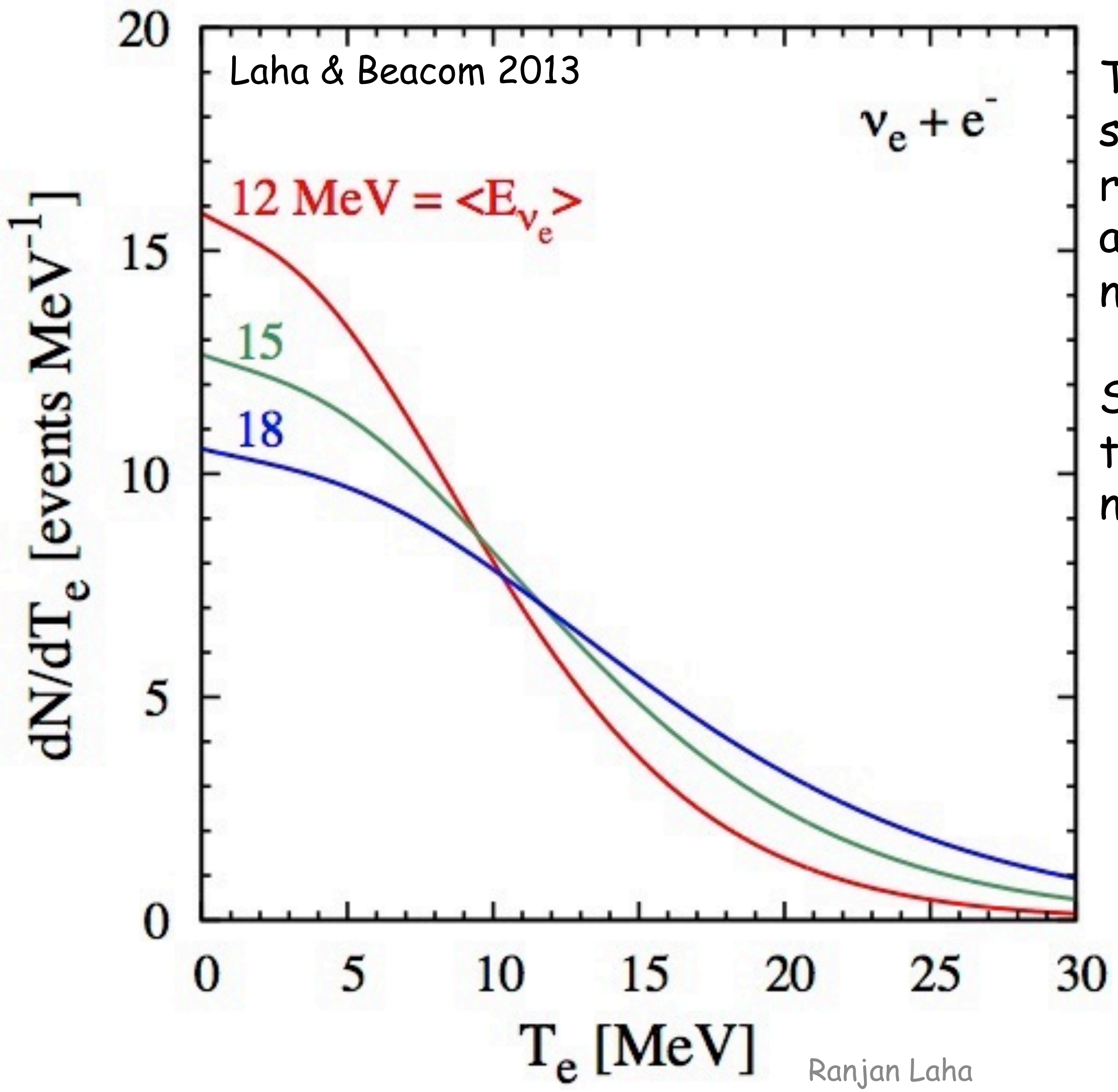
Strategy to detect ν_e

Galactic Supernova happens

Assume (i) SuperKamiokande (water Cherenkov) with Gd loading, (ii) liquid scintillator detectors are present

- Forward cone contains most of the electron elastic scattering events
- Gd can individually detect and remove the inverse beta reactions in the forward cone
- Remaining inverse beta backgrounds can be statistically subtracted
- Use the information about ν_x and $\bar{\nu}_e$ to statistically subtract the electron scattering events due to these flavors
- Addition of Gd also helps in identifying $\nu_e\,{}^{16}\mathrm{O}$ events

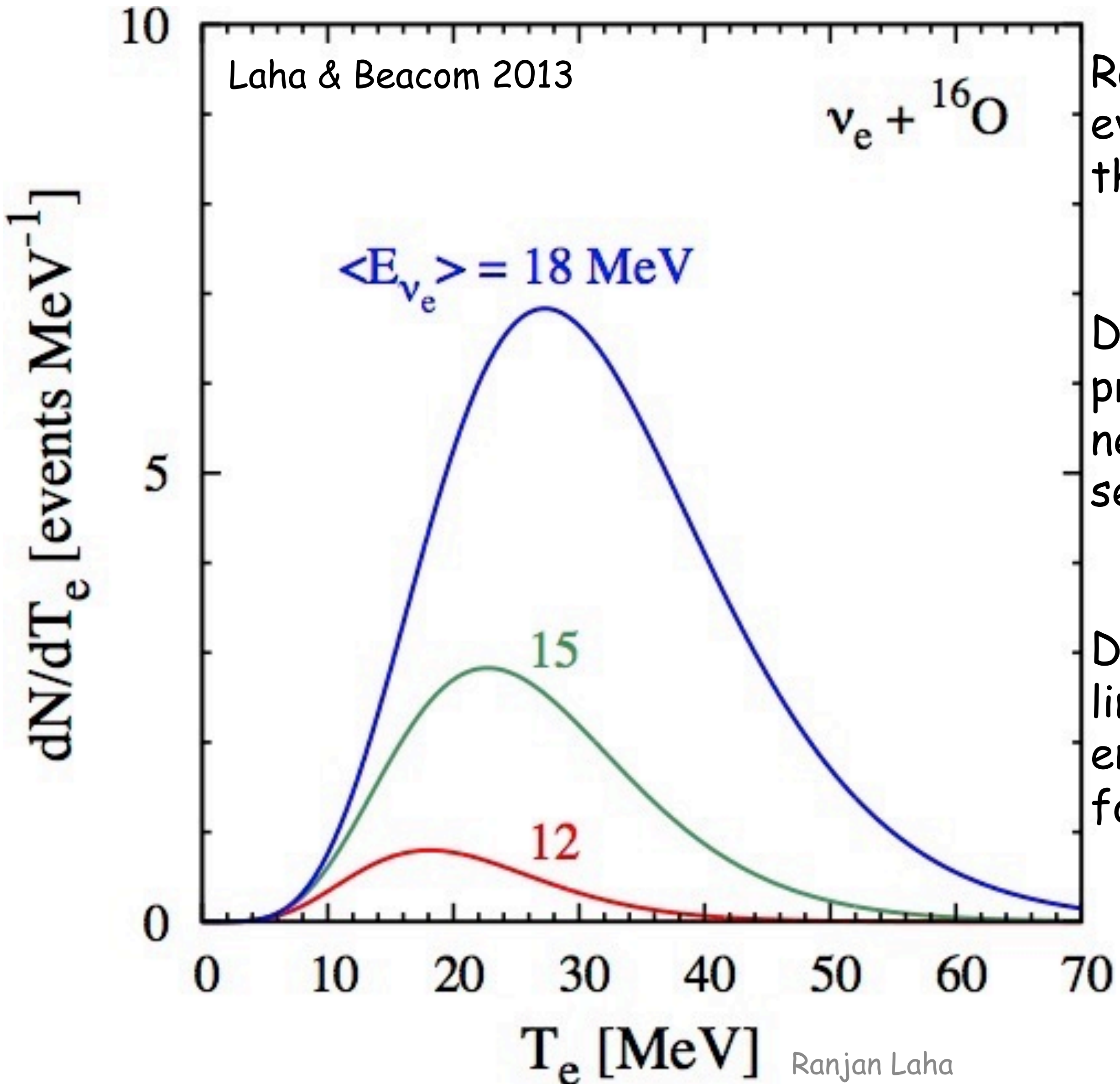
Variation of detected spectrum with different average energies



There is change in the spectrum but the total event rate in weakly dependent on the average energy of the incoming neutrino spectrum

Spectra changes linearly with total energy of the incoming neutrino spectrum

Variation of detected spectrum with different average energies



Rapid change in the number of events with average energy of the incoming neutrino spectrum

Due to the high threshold, probes the tail of the incoming neutrino spectrum --- very sensitive to the average energy

Due to few events only upper limits for lower average energies, but strong constraints for higher average energies

Supernova neutrino detection: ν_x

$$\nu_x + p \rightarrow \nu_x + p$$

Detectable part of the interaction mainly provided by ν_x

Liquid scintillator detector

Recoil protons detected by scintillation light

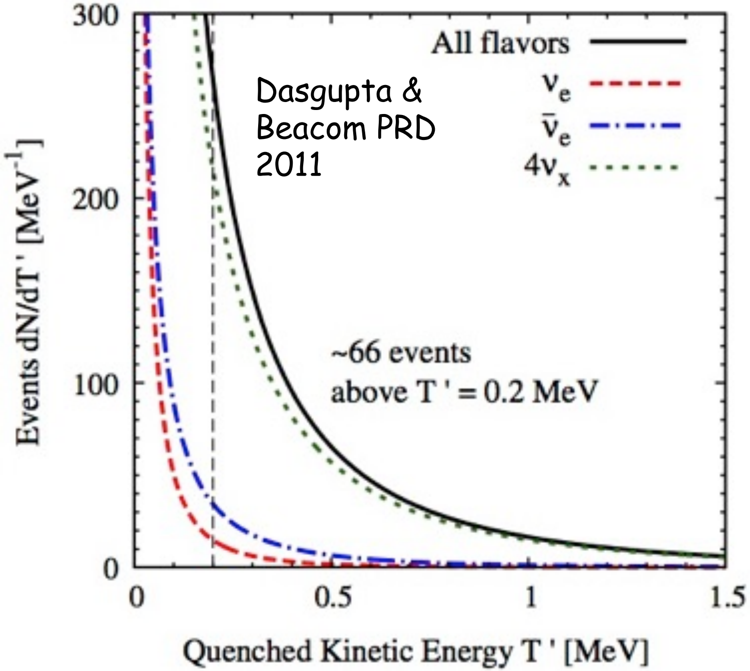
Neutral current interaction ➔ sensitive to all flavors

$$\frac{d\sigma}{dT} = \frac{4.83 \times 10^{-42}\,\mathrm{cm}^2}{\mathrm{MeV}}\left(1 + 466\frac{T}{E^2}\right)$$

T Recoil proton energy

E Incoming neutrino energy

Neutrino of energy E ➔ proton recoil energy $\epsilon \left[0, \frac{2\,E^2}{m_p}\right]$



Detectable recoil proton spectrum in KamLAND

Smaller number of events in Borexino

Beacom, Farr and Vogel hep-ph/0205220
Lujan-Peschard, Pagliaroli and Vissani 1402.6953
Laha, Beacom and Agarwalla 1412.8425

$$\nu_x + p \rightarrow \nu_x + p$$

- Number of events above threshold ~ 100/ kton
- Lowering the threshold can give more events
- Sensitive to the incoming neutrino spectrum
- There are other ways to detect ν_x , but they have smaller yields and not sensitive to the spectrum
- β-decays of ^{14}C poses a problem below 0.2 MeV --- pulse shape discrimination can be used to reject this background
(Borexino Collaboration, Phys. Rev. C 81, 034317 2010)