Gadolinium in Water Cherenkov Detectors Improves Detection of Supernova ν_e

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Thanks to my collaborator: J. F. Beacom

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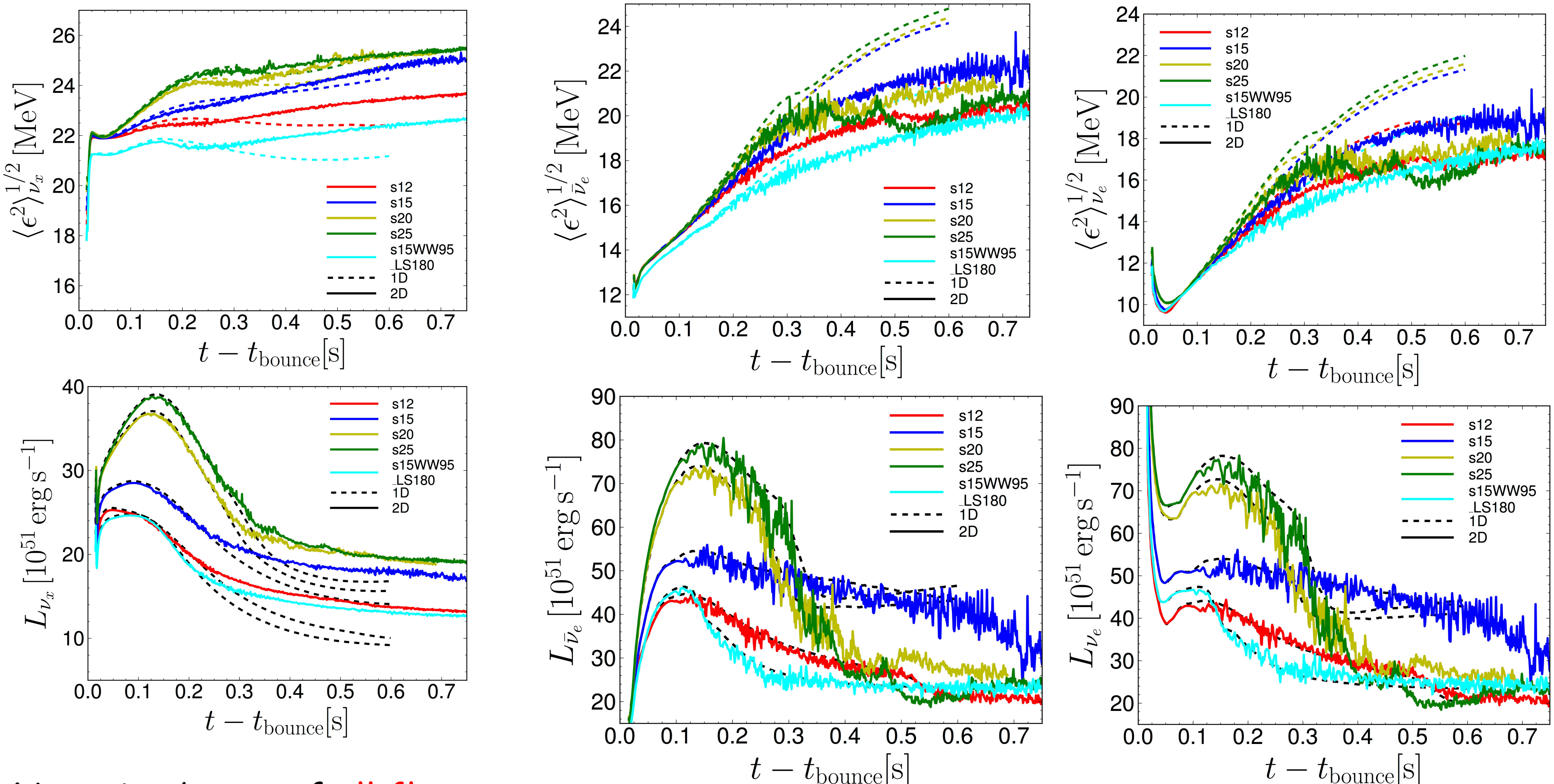
Theoretical expectations



O'Connor, Couch 1511.07443

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

Neutrinos can be detected from Galactic supernova in large numbers

See talks by Mezzacappa, O'Connor

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 (see talk by Friedland)

Supernova located at a distance of 10 kpc

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

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

water Cherenkov / liquid scintillator detector

e^+ Detected by Cherenkov radiation/ scintillation

n Difficult to detect at present; future addition of Gadolinium will vastly improve the detection prospects

$$\sigma(E_\nu) \approx 0.0952 \times 10^{-42} \, (E_\nu - 1.3\,\mathrm{MeV})^2 \left(1 - \frac{7E_\nu}{m_p}\right) \mathrm{cm}^2$$

Vogel & Beacom 1999; Strumia & Vissani 2003

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

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

See talks by Benhar and Scholberg

T_e: kinetic energy of the positron

$\bar{\nu}_e$ detection

- Neutron capture on free protons produces 2.2 MeV gamma-ray photon --- delay time ~ 200 μsec

$$n + p \rightarrow d + \gamma$$

- Neutron capture on gadolinium produces ~ 8 MeV gamma-ray photons --- delay time ~ 20 μsec --- can be more reliably detected

Beacom and Vagins PRL 2004

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

- Detecting both the final products uniquely identifies this reaction

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

Supernova neutrino detection: ν_e

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

Sensitive to all neutrino species; ν_e gives the largest number of events

Maximum number of events in water Cherenkov detectors

The electrons are forward scattered

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

$$\sigma(E_\nu) \propto G_F^2 m_e E_\nu$$

Total number of events is approximately independent of the average energy of the incoming neutrino spectrum

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

- Typical number of events in a Super-Kamiokande detector (inner volume 32 kton) ~ 200

- Even with angular cut, difficult to distinguish above backgrounds in the present configuration of Super-Kamiokande due to overwhelming large number of inverse beta backgrounds (128 signal events v/s 827 background events)

- Elastic scattering is also induced by other flavors but they are smaller

Supernova neutrino detection: ν_e

Another important reaction in water Cherenkov detectors

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

Threshold ≈ 15 MeV

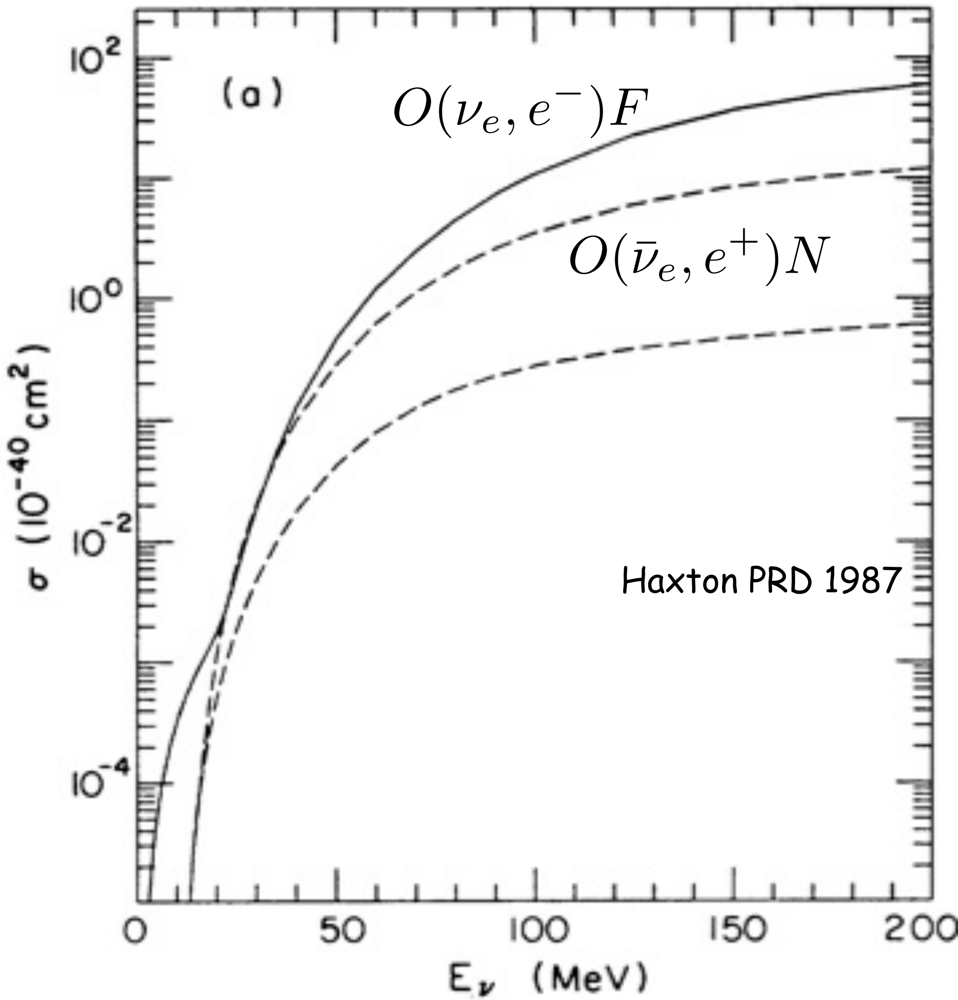
Only the electron is detectable

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

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

for supernova energies

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
- Presently undetectable in Super-Kamiokande detector (for decay of ^{16}F* see Tuli "Nuclear Wallet Cards")
- Angular dependence of electrons is backward tilted
- At present, difficult to detect above background

Neutrino mixing

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

See talk by Friedland

Number of events in Super-Kamiokande (threshold = 3 MeV & fiducial volume = 32 kton) for a Galactic supernova for various different values of the average energies. Total energy of the supernova = 3×10^{53} erg & assuming equipartition between various neutrino flavors

Detection channel	12 MeV	15 MeV	18 MeV
$\nu_e + e^- \to \nu_e + e^-$	188	203	212
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	56	64	70
$\nu_x + e^- \to \nu_x + e^-$	60	64	68
$\bar{\nu}_x + e^- \to \bar{\nu}_x + e^-$	48	54	56
$\nu_e + {}^{16}\mathrm{O} \to e^- + {}^{16}\mathrm{F}^*$	16	70	202
$\bar{\nu}_e + p \to e^+ + n$	5662	7071	8345

Present difficulty in detecting ν_e

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

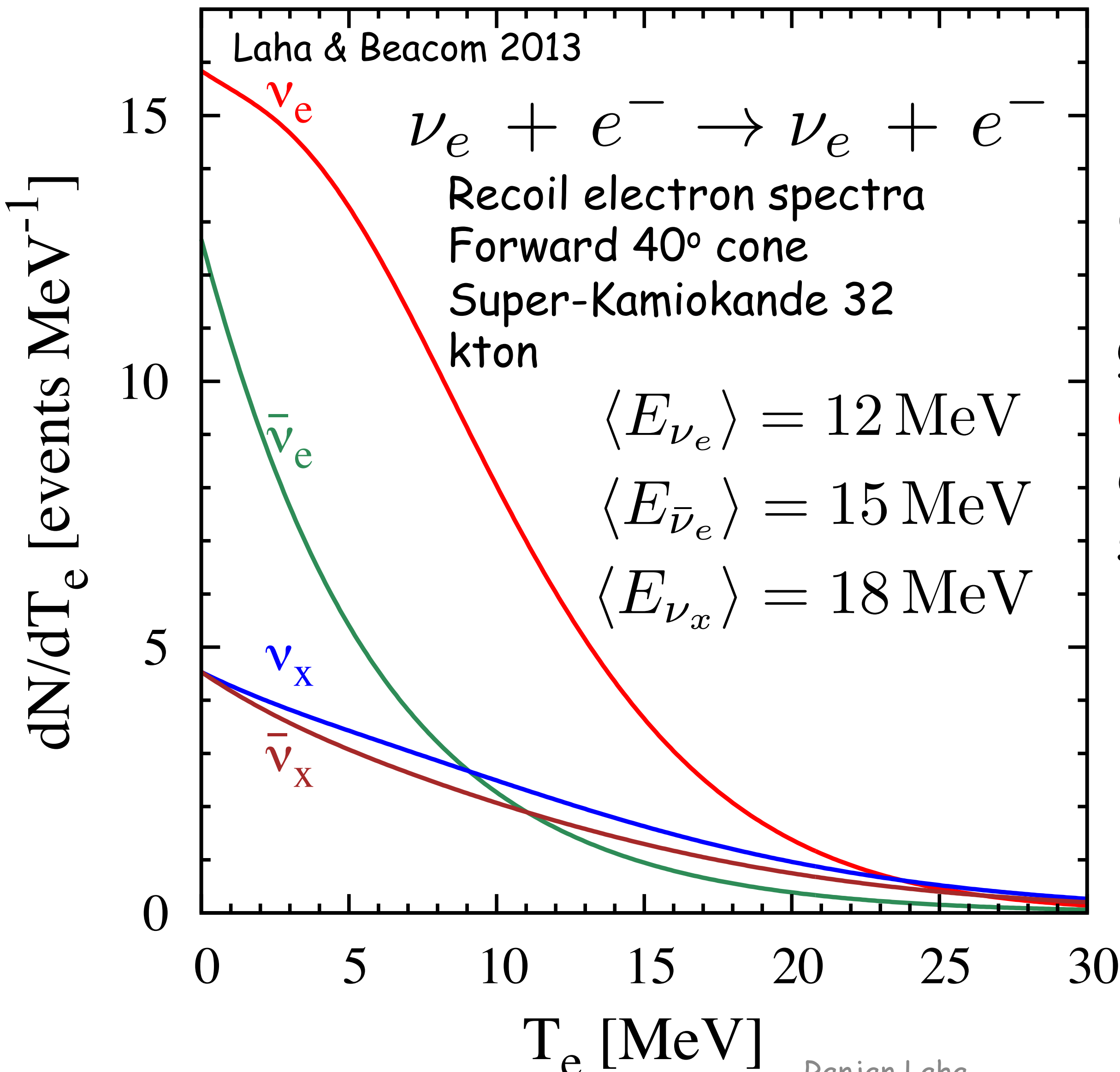
Adding Gadolinium will make it easier (future)

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

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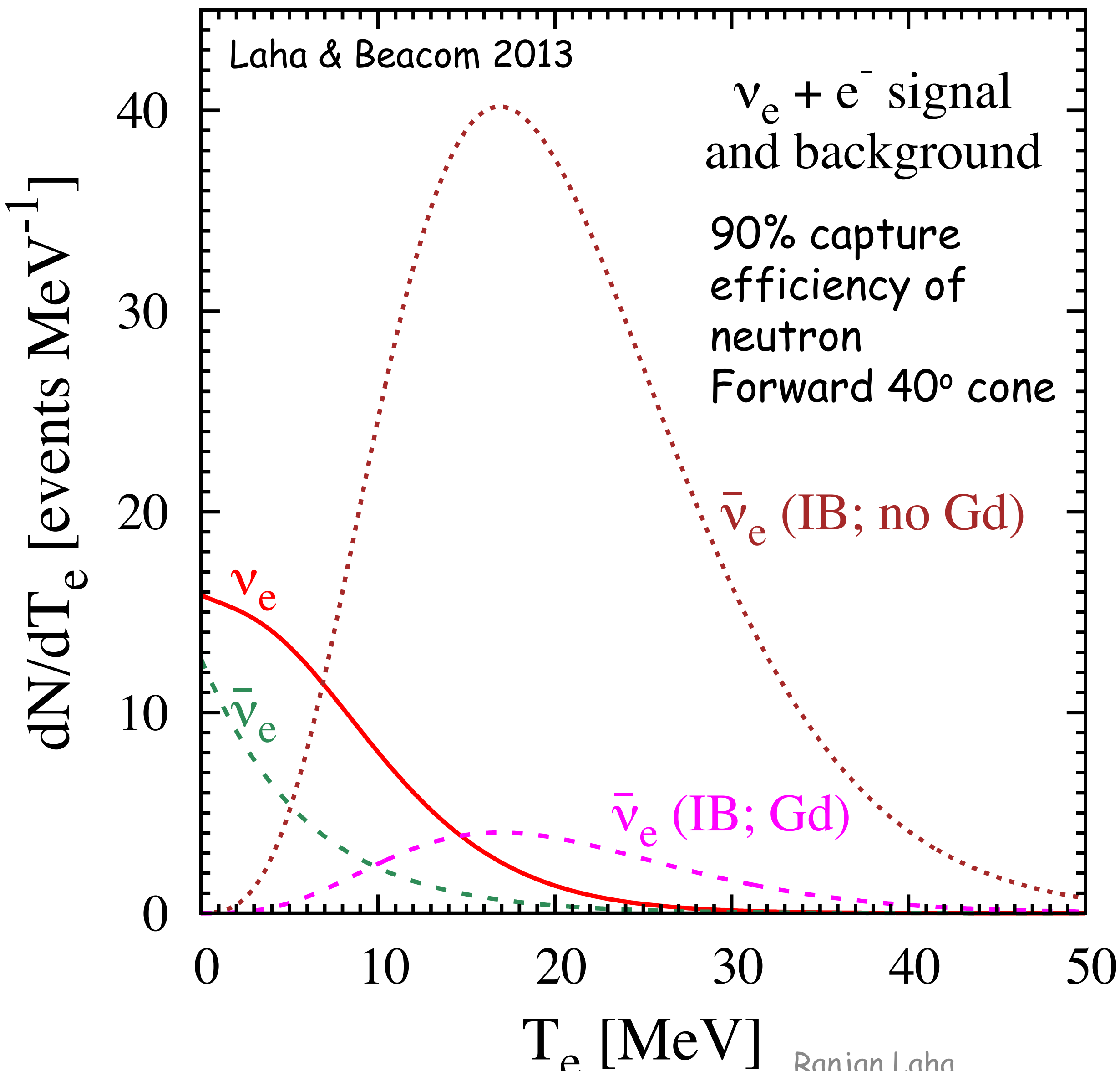
Strategy to detect ν_e

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

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

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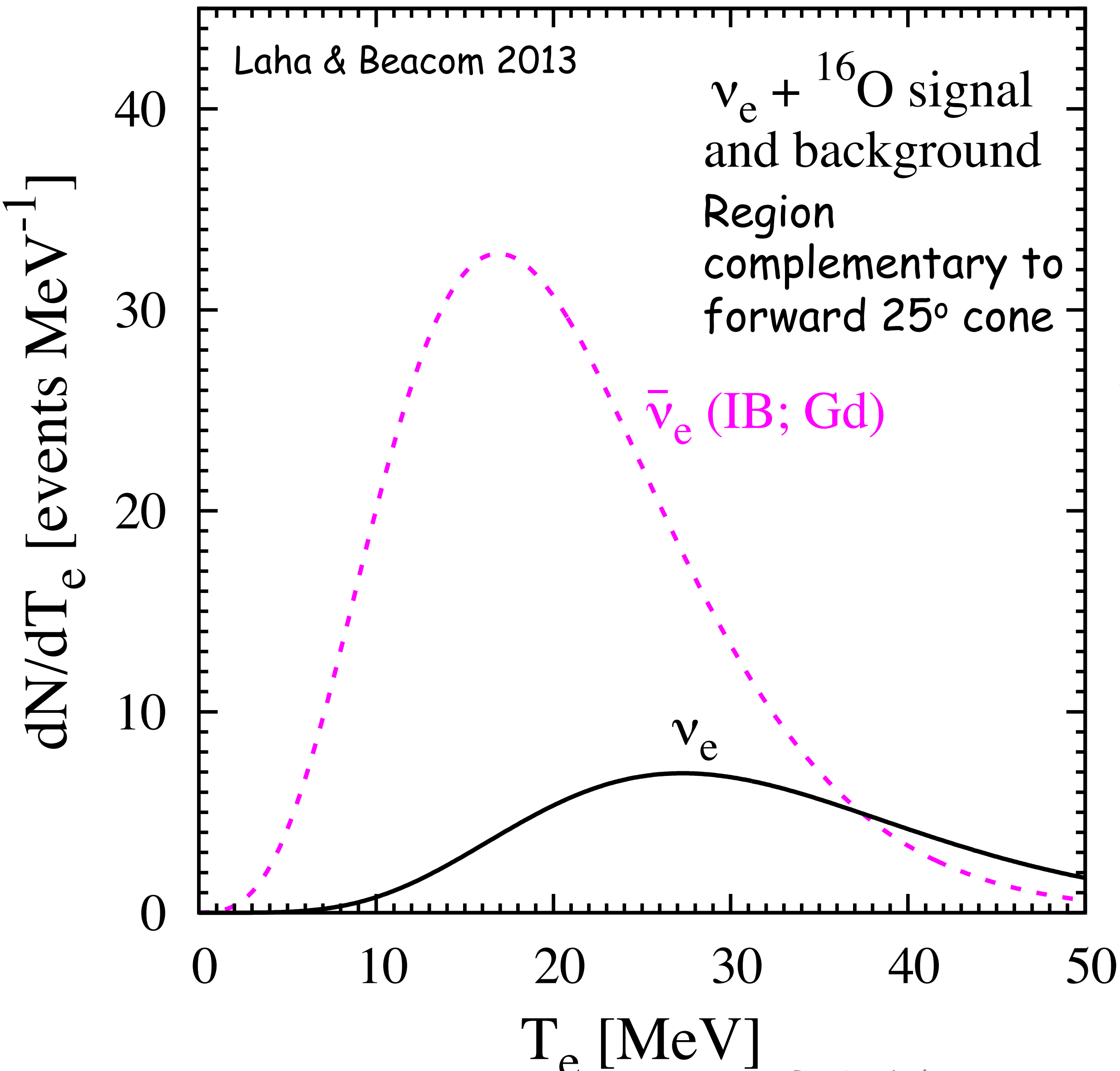
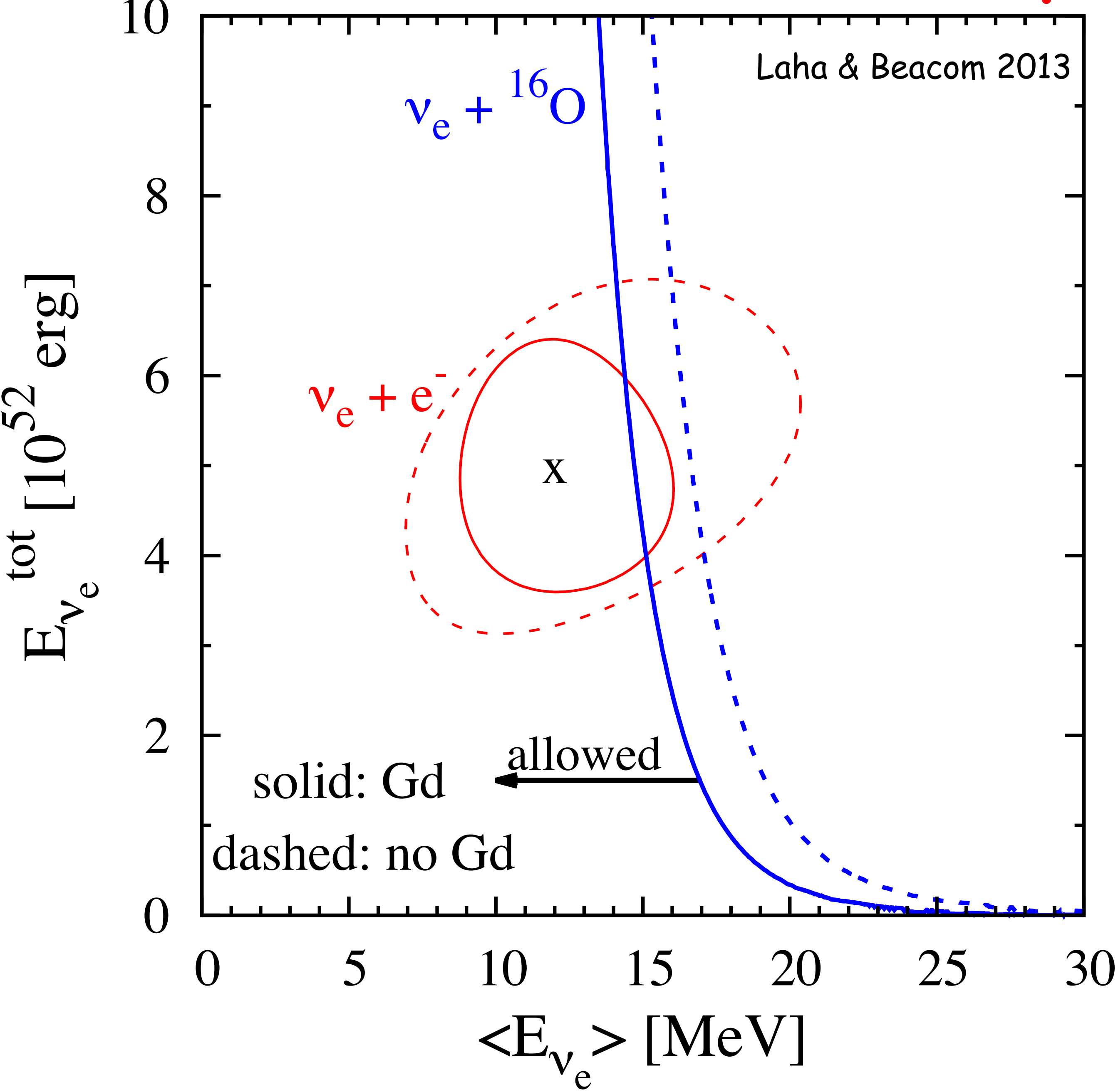
Effect of Gd on oxygen scattering events



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

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

Constraints on ν_e spectrum

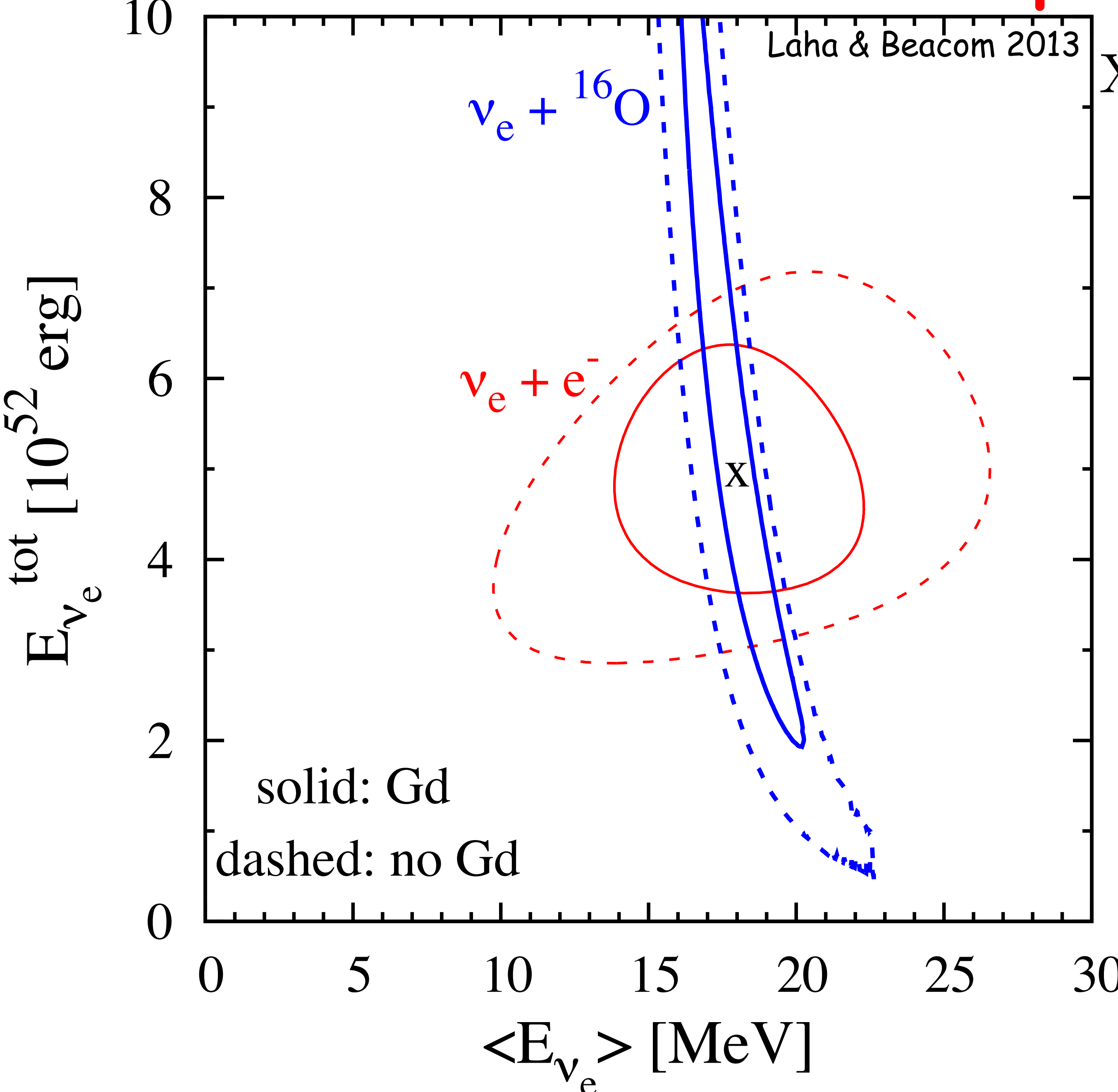


X= fiducial value

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

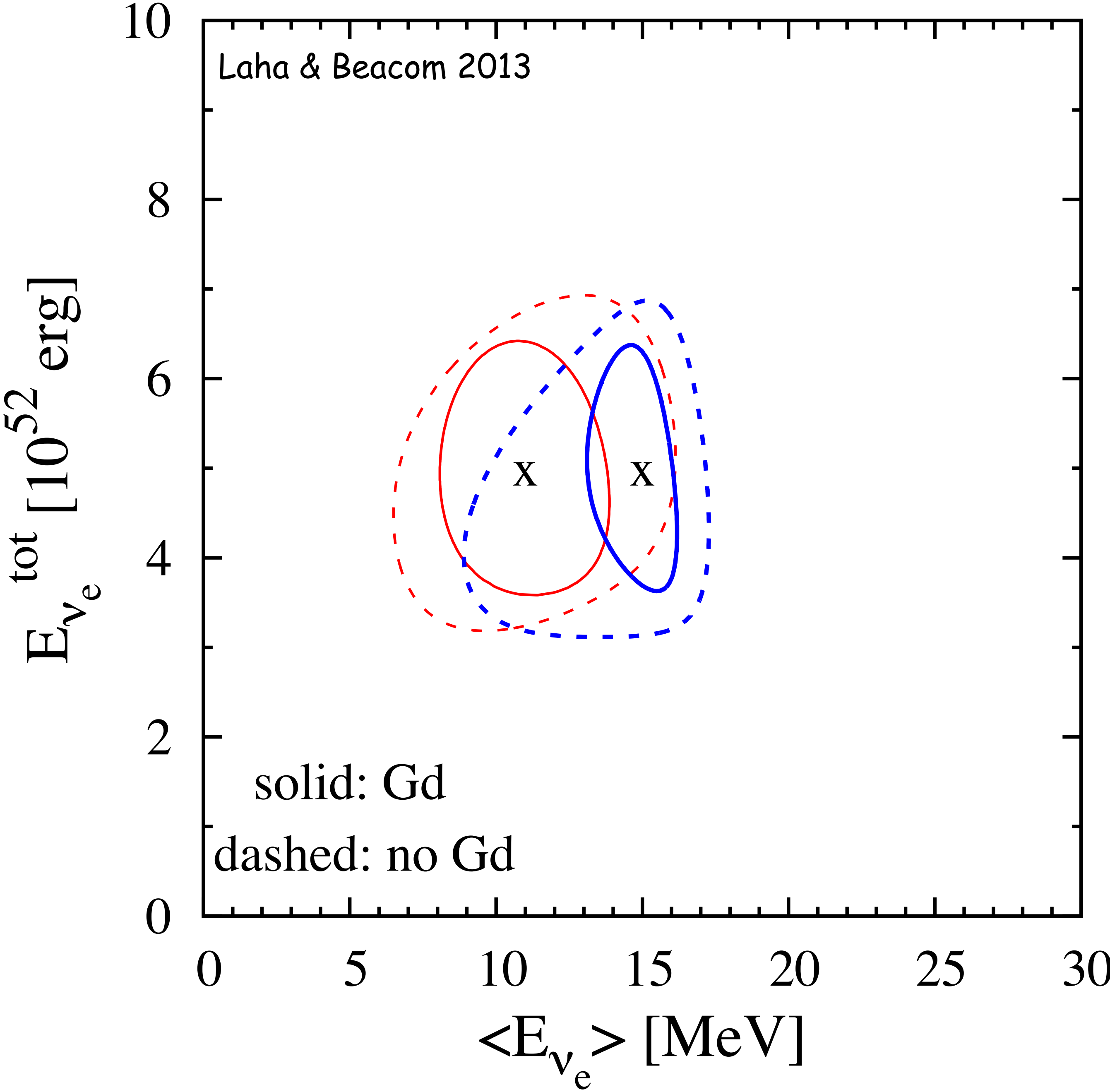


X= fiducial value

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

Conclusions

- 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 ν_e
- We can constrain the ν_e parameters to about 20%

Comments/ questions to
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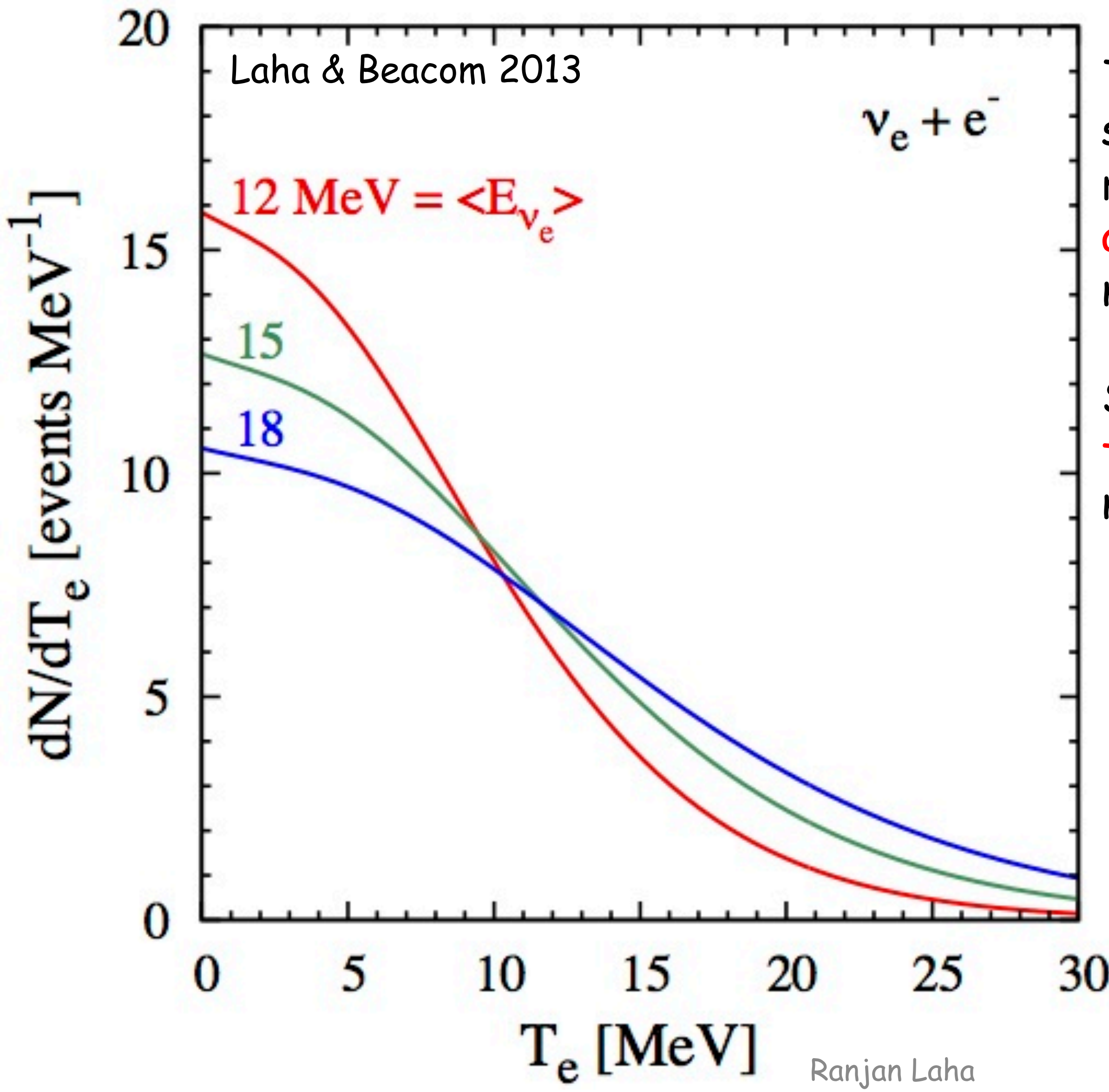
Variation of detected spectrum with different average energies



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

Supernova neutrino astrophysics

snap.lbl.gov

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

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

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

Flux and event rate

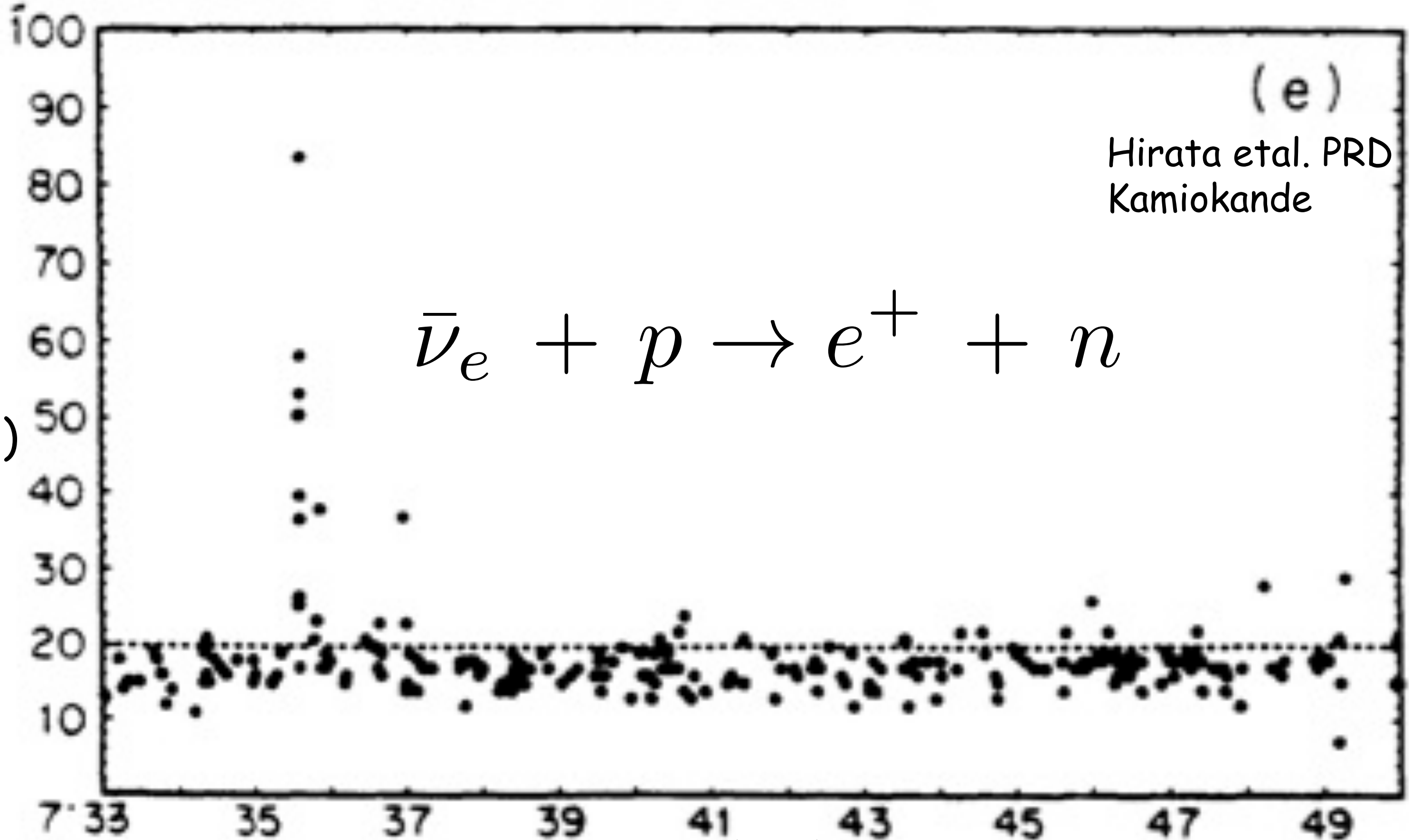
Time integrated flux for single flavor

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

Observed interaction rate

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

SN 1987A in LMC



Hirata etal. PRD
Kamiokande

Nhit
(no. of
hit PMTs)

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

Time (min)

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

Simultaneous observation
by IMB, Baksan

In broad agreement with the theoretical expectations

Too few events to properly utilize the information

- Show slide from simulation showing average energy – etc. (from Shunsaku)

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

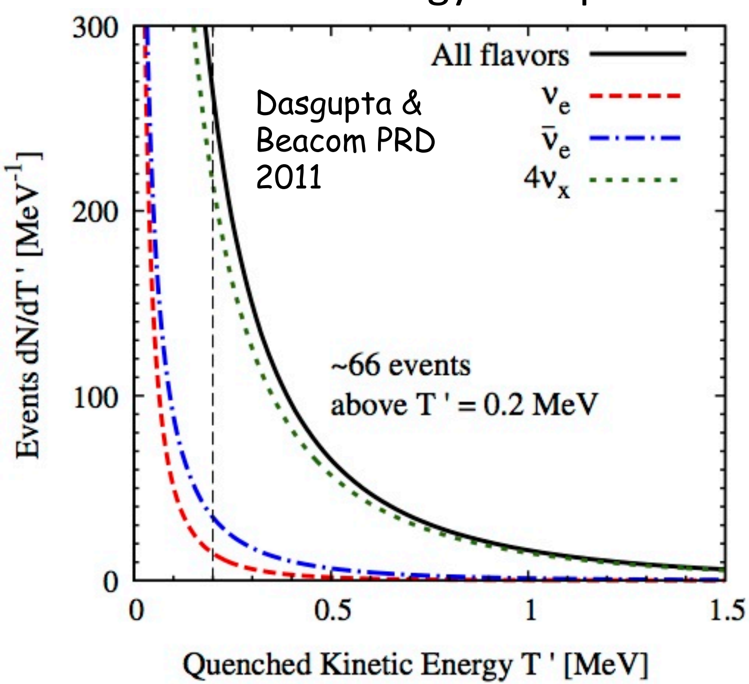
Neutral current interaction ➔ sensitive to all flavors

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

T Recoil proton energy

E Incoming neutrino energy

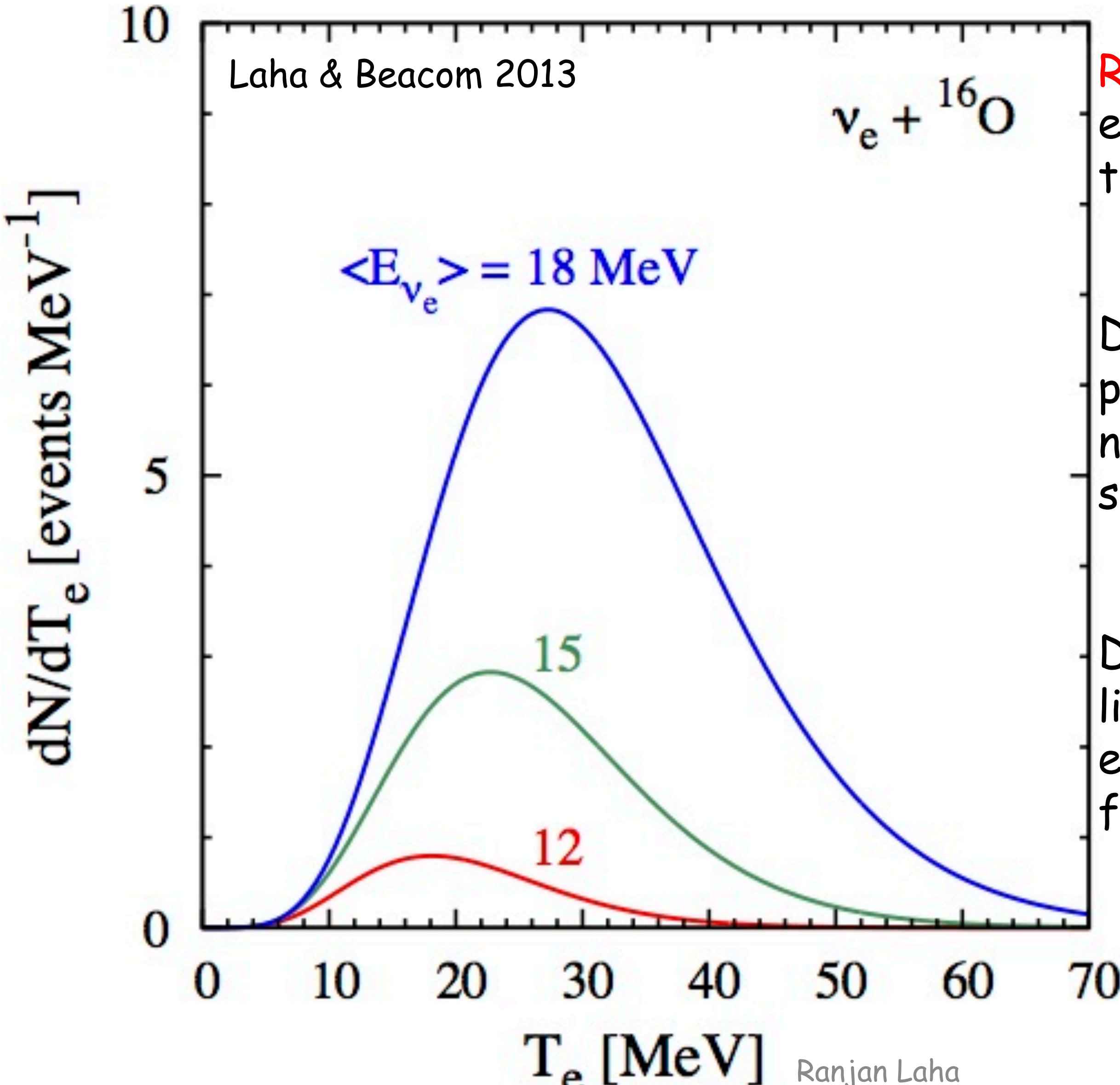
Neutrino of energy E ➔ proton recoil energy $\epsilon \left[0, \frac{2\,E^2}{m_p}\right]$



Detectable recoil proton spectrum in KamLAND

Smaller number of events in Borexino

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

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

- 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