Supernova neutrinos flux reconstruction

in Čerenkov detectors

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Gallo Rosso, Vissani, Volpe, (2007) ArXiv:...

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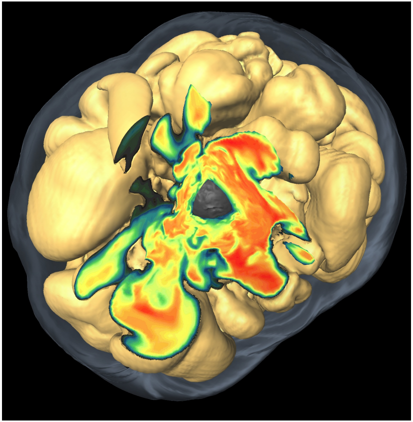
Introduction

Introduction

Delayed ν-driven explosion[1]

1. Instability & collapse
2. Bounce & shock propagation
3. Shock stallation
4. Accretion
5. Cooling

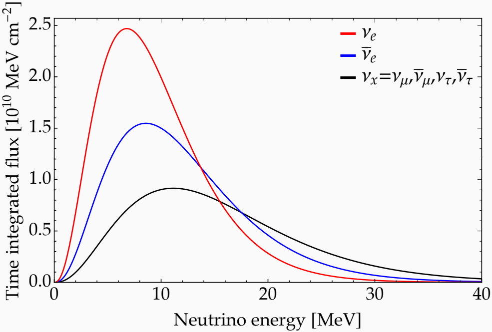


[1] H. A. Bethe and J. Wilson, R. Astrophys. J. 295, 14 (1985).
[2] Image from Leonhard Scheck and H.-Thomas Janka.

Introduction

Theoretical outcomes

- $\sim 10\,\mathrm{s}$ signal
- $\sim 10^{53}$ erg (gravitational)
- 99% in ν
- Equipartition?



Total energy $\mathcal{E}$	$\Leftrightarrow$	normalization
Mean energy $\langle E \rangle$	$\Leftrightarrow$	1^{st} moment
Pinching α	$\Leftrightarrow$	width

Introduction

SN 1987A

- Large Magellanic Cloud (51.4 kpc)
- 25 $\overline{\nu}_{\mathrm{e}}$ neutrino events
- Good agreement with predictions [3]
    - $\mathcal{E}_{\bar{\mathrm{e}}} \sim 5 \times 10^{52}\,\mathrm{erg} \pm 10\%$
    - $\langle T_{\bar{\mathrm{e}}} \rangle \sim 4\,\mathrm{MeV} + 50\% - 20\%$
- ν_{e}, ν_x still missing
    - Future detection is crucial to prove equipartition hypothesis

[3] F. Vissani, J. Phys. G **42**, 013001 (2015).

Introduction

Lu *et al.* [4]

- JUNO detector
- Importance of combining channels
  - $\mathcal{E}_{\bar{e}}$ up to 5% @ 90% C.L.
  - $\langle E_{\bar{e}} \rangle$ up to 1% @ 90% C.L.

} ◇ equipartition
◇ no oscillation
◇ pinching known

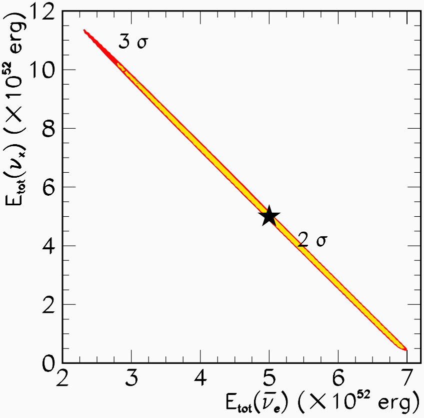
⬇ with oscillation (MSW)
w/o equipartition

$\mathcal{E}_{\text{tot}}$ known up to 13%
but for spectral shape fully known

[4] Lu *et al.* Phys. Rev. D 94, 023006 (2016)

H. Minakata *et al.* [5]

- Hyper-Kamiokande
- IBD only
- Pinching known
  - $\mathcal{E}_{\bar{e}}$ acc. 15% @ 3σ
  - $\langle E_{\bar{e}} \rangle$ acc. 2% @ 3σ
- Pinching unknown
  - $\mathcal{E}_{\bar{e}}$ acc. 50% @ 3σ
  - $\langle E_{\bar{e}} \rangle$ acc. 4% @ 3σ
  - Parameters degeneracy



[5] H. Minakata *et al.*, JCAP 0812, 006 (2008)

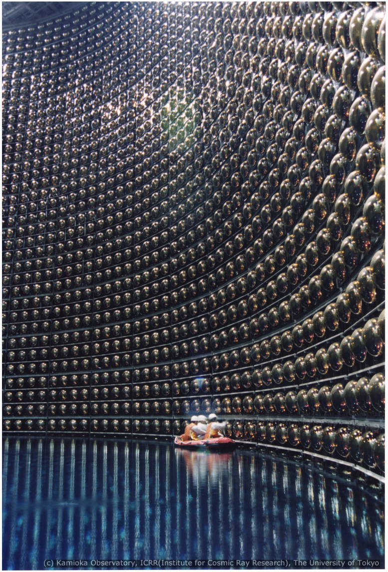
Introduction

This work

- Importance of adding channels
  - Full 3×3 analysis
- Ansätze released
  - No equipartition
  - Pinching unknown
  - (and oscillation)

Hypotheses and method

Hypotheses and method



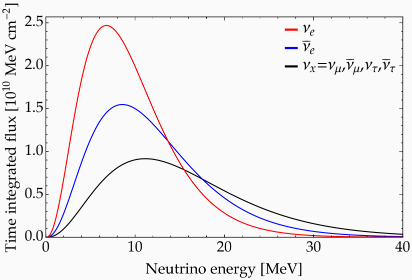
Supernova

- Distance $D^{*} = 10\,\mathrm{kpc}$
- Total energy $\mathcal{E}^{*} = 3 \times 10^{53}\,\mathrm{erg}$

Super-Kamiokande

- 22.5 kton of fiducial mass
- 5 MeV threshold
- 100% efficiency
- Channels
  - Inverse Beta Decay (IBD)
  - Elastic scattering on e^{-} (ES)
  - Neutral-currents on ^{16}O (OS)

Hypotheses and method



Fluences

- Quasi-thermal alpha-fit
- Oscillations: MSW effect (NH)
- Self-interaction neglected

$$\mathcal{F}_i^0(E_\nu) = \frac{\mathrm{d}\,F_i}{\mathrm{d}\,E_\nu} = \frac{\mathcal{E}_i}{4\pi D^2}\frac{E_\nu^{\alpha_i}\ e^{-E_\nu/T_i}}{T_i^{\alpha_i+2}\ \Gamma(\alpha_i+2)} \qquad (i = \nu_\mathrm{e},\, \overline{\nu}_\mathrm{e},\, \nu_x)$$

$$\begin{cases} \mathcal{F}_e = \mathcal{F}_x^0 \\ \mathcal{F}_{\bar{e}} = |U_{e1}|^2 \cdot \mathcal{F}_{\bar{e}}^0 + (1 - |U_{e1}|^2) \cdot \mathcal{F}_x^0 \end{cases}$$

Hypotheses and method

3×3 parameters

- Energy emitted $\mathcal{E}_i$
  - $\Rightarrow$ $\mathcal{E}_i^* = 0.5 \times 10^{53}$ erg
  - $\Rightarrow$ Initial equipartition hypothesis
- Mean energy $\langle E_i \rangle = (\alpha_i + 1)\, T_i$
  - $\Rightarrow$ $\langle E_e \rangle^* = 9.5\,\text{MeV}$
  - $\Rightarrow$ $\langle E_{\bar{e}} \rangle^* = 12\,\text{MeV}$
  - $\Rightarrow$ $\langle E_x \rangle^* = 15.6\,\text{MeV}$
- Pinching parameter α_i
  - $\Rightarrow$ $\alpha_i^* = 2.5$

Hypotheses and method

Monte Carlo

- Expected: $N^*_{IBD} = 4572$ — $N^*_{ES} = 213$ — $N^*_{OS} = 555$
- Extracted: $n_{IBD} = 4706$ — $n_{ES} = 207$ — $n_{OS} = 554$

Caveat on OS

- Signal in window of $4 \div 9\,\text{MeV}$
- Cannot disentangle from IBD and ES
- Cross section uncertainty
  - $\sigma_{OS}(E_\nu) \approx \varepsilon \cdot \sigma_0 \cdot (E_\nu/\text{MeV} - 15)^4$
  - systematic $\sim$Gauss($\varepsilon^* = 1$, $\sigma_\varepsilon = 0.1$)

$\Rightarrow$ 10th parameter ε

Hypotheses and method

Likelihood

$$\mathcal{L}_j(\text{param.}) \propto \prod_{i=1}^{N_{\text{bin}}} \frac{\nu_i^{n_i}}{n_i} e^{-\nu_i} \quad \text{with} \quad j = \text{IBD, ES}$$

$$\mathcal{L}_{OS}(\text{param.}) \propto \exp\left[-\frac{(n_{OS} - \text{N}_{OS})^2}{2\text{N}_{OS}} - \frac{(\varepsilon - 1)^2}{2\sigma_\varepsilon^2}\right]$$

Analysis

1. IBD ($\mathcal{L} = \mathcal{L}_{\text{IBD}}$)
2. IBD + ES ($\mathcal{L} = \mathcal{L}_{\text{IBD}} \times \mathcal{L}_{\text{ES}}$)
3. IBD + ES + OS ($\mathcal{L} = \mathcal{L}_{\text{IBD}} \times \mathcal{L}_{\text{ES}} \times \mathcal{L}_{\text{OS}}$)

Hypotheses and method

Prior

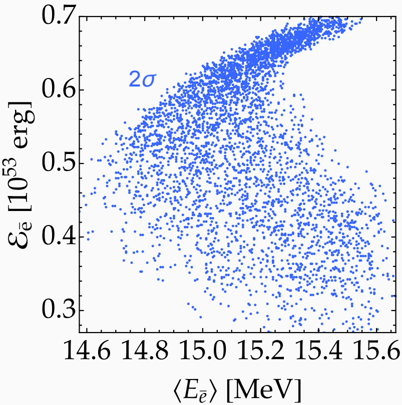
$$0.2 \times 10^{53}\,\text{erg} \leq \mathcal{E}_i \leq 1.0 \times 10^{53}\,\text{erg}$$
$$5.0\,\text{MeV} \leq \langle E_i \rangle \leq 30\,\text{MeV}$$
$$1.5 \leq \alpha_i \leq 3.5$$
$$0.8 \leq \varepsilon \leq 1.2$$

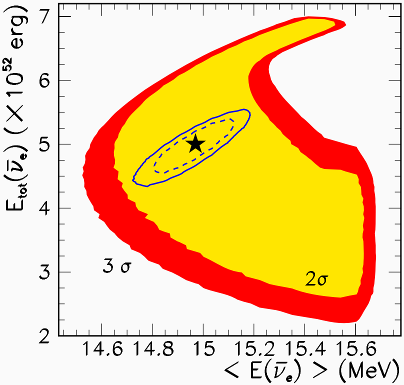
Condition

$$\log \mathcal{L} \geq \log \mathcal{L}_{max} - \frac{1}{2} A_{dof,\mathrm{CL}} \quad \text{with} \quad \int_0^A \chi^2_{dof}(z)\,\mathrm{d}\,z = \mathrm{C.L.}$$

Results

Results



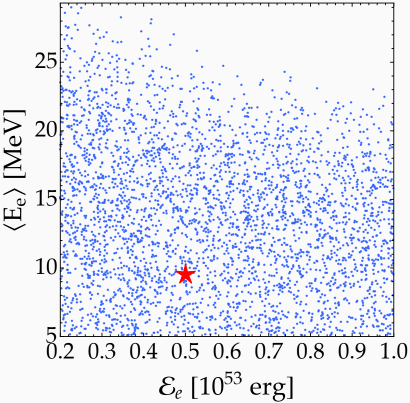


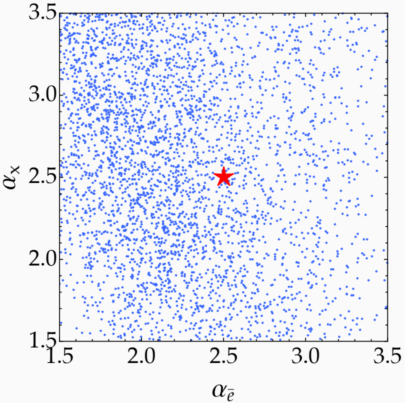
Validation

Good agreement with Minakata *et al.* (2008)

Results

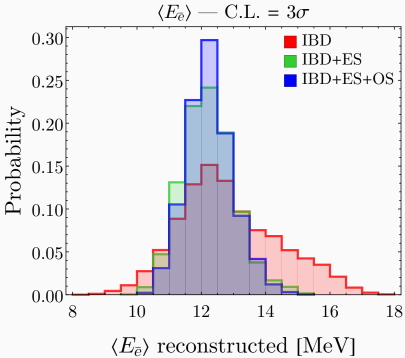
IBD+ES+OS, 10 param., no equipartition, 3σ C.L.

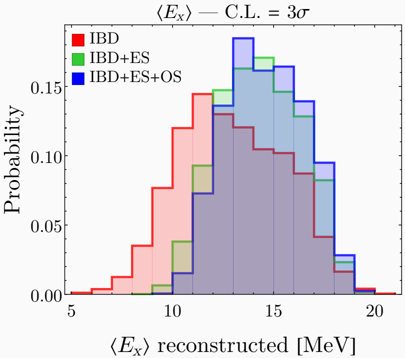




- Param. undetermined for ν_e
- Pinching undetermined for all

Results





$\overline{\nu}_e$	$\langle E \rangle$ [MeV]	Acc. %
IBD	12.9 ± 1.5	12
IBD+ES	12.2 ± 0.8	7
IBD+ES+OS	12.3 ± 0.7	6

ν_x	$\langle E \rangle$ [MeV]	Acc. %
IBD	13.0 ± 2.6	20
IBD+ES	14.3 ± 2.0	14
IBD+ES+OS	14.6 ± 1.9	13

Results: total energy

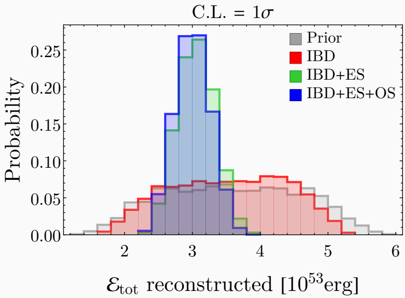
Total energy reconstruction

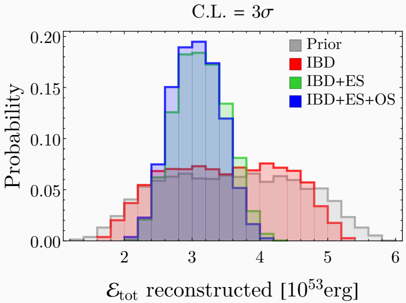
- Point P within a certain C.L.
- $\mathcal{E}_{tot}|_P = \mathcal{E}_{e,P} + \mathcal{E}_{\bar{e},P} + 4\mathcal{E}_{x,P}$

Warning

For IBD only $\mathcal{E}_{e,P}$ not measured
$\Rightarrow$ random uniform in prior $[0.2,\ 1] \times 10^{53}$ erg

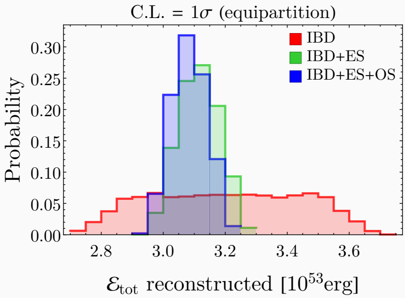
Results: total energy

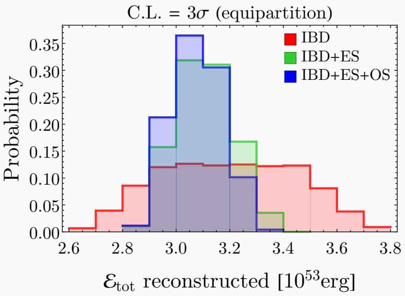




	1σ C.L.		3σ C.L	
	$\mathcal{E}$ [10^{53} erg]	$\Delta\mathcal{E}/\mathcal{E}$	$\mathcal{E}$ [10^{53} erg]	$\Delta\mathcal{E}/\mathcal{E}$
IBD	3.53 ± 0.84	24%	3.50 ± 0.85	24%
IBD+ES	3.05 ± 0.28	9%	3.13 ± 0.38	12%
IBD+ES+OS	3.00 ± 0.26	9%	3.06 ± 0.36	12%

Results: total energy





Equipartition	1σ C.L.		3σ C.L	
	$\mathcal{E}$ [10^{53} erg]	$\Delta\mathcal{E}/\mathcal{E}$	$\mathcal{E}$ [10^{53} erg]	$\Delta\mathcal{E}/\mathcal{E}$
IBD	3.20 ± 0.24	7%	3.20 ± 0.25	8%
IBD+ES	3.12 ± 0.07	2%	3.11 ± 0.10	3%
IBD+ES+OS	3.08 ± 0.06	2%	3.08 ± 0.09	3%

Summary

Summary

- Ansätze of crucial importance
- Parameters
  - ✗ If pinching is unknown it remains unknown
  - ✗ ν_{e} properties undetermined
  - ✓ $\langle E_{\bar{\mathrm{e}}} \rangle$, $\langle E_x \rangle$ known within $\sim 10\%$ @ 3σ C.L. (IBD+ES+OS)
- Total energy
  - ✓ Known within $\sim 10\%$ @ 3σ C.L. (IBD+ES+OS)
  - ✓ 1% goal achievable if equipartition holds
- Next: Hyper-K, JUNO, ...